Proposal template: technical annex

(for full proposals: single stage submission procedure and 2nd stage of a two-stage submission procedure)

Research and Innovation actions

This template is to be used in a single- stage submission procedure or at the 2nd stage of a two-stage submission

The structure of this template must be followed. It has been designed to ensure that the important aspects of your planned work are presented in a way that will enable the experts to make an effective assessment against the evaluation criteria. Sections 1, 2 and 3 each correspond to an evaluation criterion.

Please be aware that proposals will be evaluated as they were submitted, rather than on their potential if certain changes were to be made. This means that only proposals that successfully address all the required aspects will have a chance of being funded. There will be no possibility for significant changes to content, budget and consortium composition during grant preparation.

⚠ **Page limit**: The title, list of participants and sections 1, 2 and 3, together, should not be longer than 70 pages. All tables, figures, references and any other element pertaining to these sections must be included as an integral part of these sections and are thus counted against this page limit.

The page limit will be applied automatically; thus you must remove this instruction page before submitting.

If you attempt to upload a proposal longer than the specified limit before the deadline, you will receive an automatic warning and will be advised to shorten and re-upload the proposal. After the deadline, excess pages (in over-long proposals) will be automatically made invisible, and will not be taken into consideration by the experts. The proposal is a self-contained document. Experts will be instructed to ignore hyperlinks to information that is specifically designed to expand the proposal, thus circumventing the page limit.

Please, do not consider the page limit as a target! It is in your interest to keep your text as concise as possible, since experts rarely view unnecessarily long proposals in a positive light.

⚠ The following formatting conditions apply.

The reference font for the body text of H2020 proposals is Times New Roman (Windows platforms), Times/Times New Roman (Apple platforms) or Nimbus Roman No. 9 L (Linux distributions).

The use of a different font for the body text is not advised and is subject to the cumulative conditions that the font is legible and that its use does not significantly shorten the representation of the proposal in number of pages compared to using the reference font (for example with a view to bypass the page limit).

The minimum font size allowed is 11 points. Standard character spacing and a minimum of single line spacing is to be used.

Text elements other than the body text, such as headers, foot/end notes, captions, formula's, may deviate, but must be legible.

The page size is A4, and all margins (top, bottom, left, right) should be at least 15 mm (not including any footers or headers).

All ⚠ and red-marked text is from EU Template, and will be deleted prior to submission

Green-colored background are EU template suggestions which we think are properly handled

Green phrases are remarks for things to be done/solved

Yellow marked phrases are suggestions what needs to be changed in the following paragraph

Possible Acronyms:

EuPols – European Polarisation study, EuPol exists: EU Police mission in Palestine! And Afghanistan

EuGaPos – European Gamma-ray Polarisation study

POLCA – Polarisation of cosmic accelerators [Tolkien: pig ☹]

NEW DISCOVERIES FROM GAMMA-RAY POLARIZATION OF COSMIC ACCELERATORS **POLCA**

List of participants

Participant No.	Participant organisation name	Country
1 (Coordinator)	**MPE -** Max-Planck Society / MPI for Extraterrestrial Physics	DE
2	**UNIGE -** University Geneva / Dept. de Physique Nucleaire & Corpusculaire	CH
3	**Tel Aviv -** Tel Aviv University / School of Physics & Astronomy	IL

1. Excellence

1.1 Objectives

- Describe the overall and specific objectives for the project, which should be clear, measurable, realistic and achievable within the duration of the project. Objectives should be consistent with the expected exploitation and impact of the project (see section 2).

We propose to re-analyse all data of suitably bright cosmic sources measured with the instruments IBIS (*I*mager on *B*oard the *I*ntegral *S*atellite) and SPI (*SP*ectrometer on *I*ntegral) of ESA's INTEGRAL satellite with newly developed analysis tools in order to investigate the gamma-ray polarization properties of these sources.

Our science goals are built on four pillars:

Our new method has the potential to better constrain polarization parameters due to the inclusion of other information (e.g. the spectrum) **See § 1(C2)**	The success of our time-resolved analysis approach calls for re-analysis of old data, since the previous approach of co-adding all data did not maximize S/N **See § 1(B3)**	Extend our approach of time-resolved polarization to energy-resolved polarization measurements **See § 1(D3)**	INTEGRAL IBIS & SPI are the best-suited instruments with a large database to perform systematic new polarization analysis **See § 1(C3)**

Our science goals/questions can be reached by re-analysing all INTEGRAL data of the brightest sources of various source types, and can be summarized as follows:

1) Is a changing polarization angle throughout the burst activity a general feature in GRB prompt emission? (So far it is measured only in one GRB.)
2) Will we find consistent polarization results for the Crab between different instruments? (Previous IBIS and SPI results are contradictory.)

3) Is the jet-emission of microquasars polarized? V404 Cyg had a super-bright high-energy outburst in 2015, nicely covered with INTEGRAL observations, and showed rapidly changing jet orientation in the radio, interpreted as Lense-Thirring precession. This provides the unique possibility to measure polarisation at different viewing angles towards a jet.
4) Is the high-energy emission of Soft Gamma Repeaters (SGRs) polarized? SGRs are highly-magnetized neutron stars, but there is a heavy debate on whether the observed X-ray emission is due to the disk (largely unpolarized) or closer to the NS surface (implying high polarisation).
5) Push the theoretical modelling of jet sources in terms of expected polarization, and gain analytic understanding of the physical conditions that can generate the observed polarization and its temporal evolution. (Presently there is no predictive model for the temporal evolution of high-energy polarization in jet sources.)

Beyond the scientific goals, our objectives include

6) Developing, together with ESA, a standardized format for high-energy polarization data.
7) Providing tools to enable the astronomical community to analyze observational data from polarimetry instruments
8) Preparing ourselves and the community for the next (already approved for flight) polarimetry missions.

1.2 Relation to the work programme

- Indicate the work program topic your proposal relates to, and explain how your proposal addresses the specific challenge and scope of that topic, as set out in the work programme.

This proposal relates to call H2020-SPACE-2018-2020, topic SPACE-30-SCI-2020 with the specific challenge: *Support the data exploitation of European missions and instruments, in conjunction, when relevant, with international missions.* We propose to take a completely new look at the data of the "International Gamma-Ray Astrophysics Laboratory" INTEGRAL, the M2 mission of the Horizon 2000 program of ESA. The INTEGRAL satellite was launched in October 2002, and is still operating successfully. In particular, we propose to concentrate on the data content, which allows astronomers to measure the polarization plane of the measured gamma-ray radiation. Both main INTEGRAL instruments provide such data, the imager (IBIS) and the spectrometer (SPI). In both cases, the analysis (including proper calibration and analysis software) has been largely neglected, despite the very high potential to gain detailed insight into the physical working of cosmic phenomena, impossible to achieve with more canonical approaches.

Our proposed analysis and objectives conform to the scope of the SPACE-30-SCI-2020 call:

1. **Exploit European space data:** our proposed activity will cover the exploitation of all available INTEGRAL data of the instruments IBIS and SPI of all sources bright enough that a polarization analysis returns a significant result (positive or negative). The data are freely available from the ESA archive as well as the international INTEGRAL Scientific Data Center (ISDC) in Geneva, except for the most recent 12 months proprietary period.
2. **Add scientific value:** Previous polarisation analysis was performed by many groups (see Tab. 1), employed many different methods, and used different data selection schemes. In many cases, the published results are not only not statistically significant, but in many cases not trustworthy. With our new methodology we anticipate that many previous "polarisation detections" will go away, but that trustworthy and reproducible results obtained with a coherent approach and using

publicly available software will push our understanding and pave the way for future missions. We expect a major scientific advance, based on the 16+ years of INTEGRAL data as well as other instruments with polarization measurement capabilities, which will be published in a timely manner in refereed astrophysical journals.

3. **Develop new tools:** We will develop a standardized format for polarisation data and corresponding response files, and will propose an easy-to-use system for analysis of future polarisation data (akin to XSPEC for X-/gamma-ray spectroscopy).
   In addition, we will build a new Online tool that will allow users to evaluate in selected systems the most probable magnetic field configuration which can generate the observed polarization and how it changes with time.
4. **Employ new methods:** We will complete and bring to perfection our newly developed method of fitting spectra and polarisation at the same time. This also allows us for the first time to perform joint fitting of data from different instruments, thus increasing the significance of any signal.
5. **Combine with other data sets:** Combination and correlation of the analysis results of this data will be done with measurements performed worldwide of the same sources at other wavelengths.
6. **Prepare future missions:** The new scientific and methodological insight obtained by our proposed activity will boost the preparation and scientific exploitation of the next major, international satellite mission (POLAR-2), approved for launch in 2024, and completely dedicated to polarization measurements of gamma-ray bursts. Two more approved satellite missions are in preparation, all with European participation or leadership. Our data analysis tools, methodology and theoretical modelling will provide a robust preparation for reaching a completely new polarisation horizon.
7. **Support European science:** Together with the newly developed tools and a comprehensive description of the new methodology we plan to make all results (and high-level data products) available through ESA's INTEGRAL data archive.

Polarization is a property of electromagnetic (em) waves: it specifies the geometrical orientation of the oscillations. In em waves such as visible light or γ-ray radiation, the oscillating electric and magnetic field are always perpendicular to each other. By definition, the "polarization" refers to the oscillation plane of the electric field.
Linear polarization: The electric field oscillates in a single direction/plane. We measure two quantities: the degree of polarization (between 0%-100%) and the polarization angle (between 0^{o} - 180^{o}).
Changing polarization angle: This single plane changes orientation in time.
Circular polarization: the speed of the angle change is constant in time. Circular polarisation has been measured from the Sun, but is rare in other astrophysical sources.
Nomenclature in this project: we only study linear polarization, i.e. we will refer to (un)polarized electromagnetic emission (photons) from astrophysical phenomena.

1.3 Concept and methodology

(A) State-of-the-art of high-energy polarization studies

(A1) <u>Polarization</u>

The scientific importance of polarization has been recognized for a long time, as it can provide information otherwise impossible to obtain. It can be expressed via the colloquial astrophysical idiom:

"but what about magnetic fields?". Indeed, the measurement of polarization via its simple two parameter description immediately provides information about the magnetic field structure, strength, and more importantly, its presence or absence in an astrophysical source. There are virtually no other ways to *directly* measure these quantities via other observables. Thus, the answer to one of the most critical questions in any astrophysical theory is locked in the measurement of polarization. Examples include understanding the partitioning of energy in GRB outflows between matter, radiation and magnetic fields, or as the ASTRONET and ASPERA roadmaps for European Astrophysics and Astroparticle physics phrase it: “to understand the astrophysics of compact objects and their progenitors, particularly the functioning of supernova explosions and gamma-ray bursts”. Great advancements have been made in examining these objects via spectroscopy, but degeneracies in these analyses can only be broken with a polarization measurement.

Sources emitting polarized high-energy (~1 keV – TeV) photons:
Pulsars: magnetized, spinning neutron stars in the emitting pulsations of photons via a yet unspecified mechanism.
Gamma-Ray Bursts (GRBs): the most powerful cosmic explosions, produced by the collapse of massive stars to black holes (long-duration sub-class) or by the coalescence of two neutron stars (short-duration).
Microquasars: X-ray binaries in our Galaxy with a stellar-mass black hole accreting matter from its companion star.
Active galactic nuclei (AGN): super-massive black holes at the center of galaxies which are actively accreting material.
Soft Gamma-ray Repeaters (SGRs): X-ray sources in our Galaxy believed to be neutron stars with the strongest magnetic field in the Universe.

(A2) <u>Polarization: Theory for cosmic sources</u>

Photon energies between hard X-rays of 20 keV and γ-rays up to a few MeV cover the range where many of the most-spectacular cosmic sources have their peak emissivity, so that essential physical processes of high-energy astrophysics can be studied most directly. Polarized radiation can occur due to numerous processes at the source, e.g. when (1) photons are emitted by electrons in the presence of magnetic fields via cyclotron or synchrotron processes, (2) scattering at free electrons or small particles, (3) Zeeman and Stark effects, and many others, preferentially at lower energies. Thus, many sources emit polarized light, from asteroids and planetary atmospheres over normal (magnetic) stars and the Sun, to white dwarfs, pulsars, accreting binaries, and jets in AGN. Even at high energies, polarization is expected for a number of sources, which are shortly described below:

Polarization in Gamma-Ray Bursts: Despite 40 years of measuring energy spectra and light curves of GRBs, the origin of the burst emission and its fundamental physical emission process is a matter of heated debate. The two main contenders are photospheric emission (e.g. Ryde 2004, ApJ 614, 827) and synchrotron emission (Meszaros & Rees 1993, ApJ 418, L59; Burgess et al. 2019, Nat. Astron. 3, **???**). Both models predict polarized γ-ray emission, but with different time- and energy-dependence (e.g. Beloborodov & Meszaros 2017, SSRv 207, 87). This might allow us to distinguish between these two prime models (Toma et al. 2009, ApJ 698, 1042), which provides one of the main scientific drivers of this project.

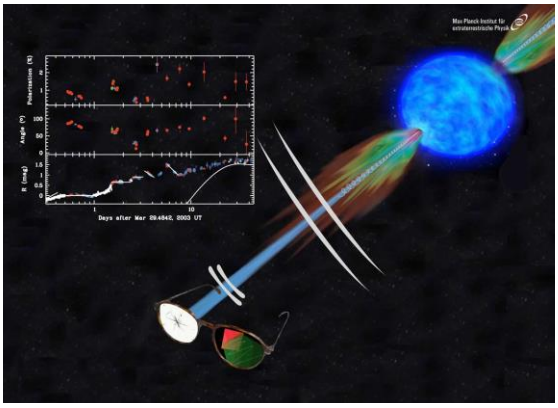


Figure 1: Scetch of polarized radiation being produced in the jet of a GRB.

Polarization in Pulsars: Pulsar γ-radiation is produced by extremely relativistic ($\gamma \sim 10^6$ - 10^7) electrons (and positrons) propagating along the curved field lines close to the speed-of-light cylinder, which marks the outer extent of the co-rotating magnetosphere. Photon-electron cascades are generated by the interplay of electron curvature radiation, inverse Compton scattering (at GeV energies), synchrotron processes (MeV range) and pair creation from photon-B-field interactions. Since the particle flow is aligned with the magnetic field, the emitted γ-rays delineate the field geometry. Furthermore, one expects a significant polarisation of the emitted radiation, because the geometry is very anisotropic and the relevant emission processes are *per se* highly polarized from the predefined magnetic-field direction. Depending on the specific model for the generation of γ-rays, the prediction of the polarization is different. A common feature, however, is the change of polarisation degree and angle with both, the magnetic field inclination relative to the rotation axis, and the observer viewing angle. Thus, phase-resolved polarization measurements are a must. The most prominent γ-ray pulsar (with a surrounding pulsar wind nebula, PWN) is the Crab, for which time-dependent polarization results have been recently published by the ASTROSAT team (Vadawale et al. 2018, Nat. Astron. 2, 50), but are widely criticized for both, wrong methodology and overestimated significance. Thus, a thorough analysis of complementary INTEGRAL data is highly warranted.

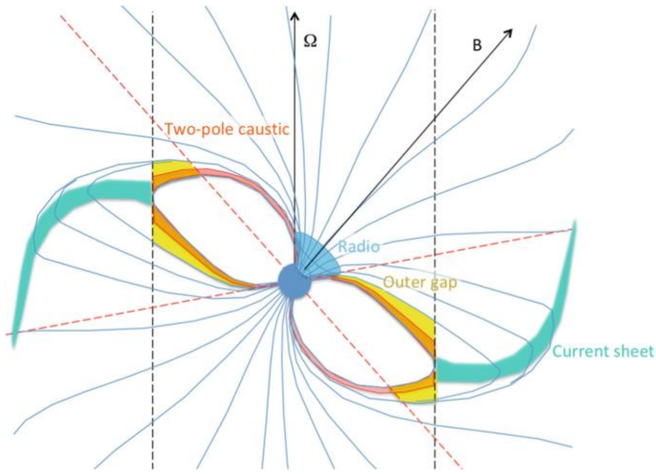


Figure 2: Scetch of the magnetic field configuration in a pulsar [From Harding 2019, in "Astronomical Polarisation from the Infrared to Gamma Rays", eds. R. Mignani et al, ASSL 460, p. 277]

Polarization in Soft Gamma Repeaters (SGR): SGRs are neutron stars with particularly strong magnetic field, up to 10^{14}-10^{15} Gauss, which show occasional periods of outbursts of high-energy emission similar to GRBs. Many models exist for the origin of this emission, and correspondingly a variety of possibilities for polarized emission, among others (i) resonant Comptonization of thermal photons by charges moving in a twisted magnetosphere, (ii) scattered radiation from a trapped fireball in a closed-field-line region, (iii) resonant cyclotron upscattering of soft thermal photons from the stellar surface by relativistic electrons in the magnetosphere, (iv) magnetic photon-splitting (50-500 keV) in the presence of a strongly magnetized electron-positron plasma.

Polarization in Galactic jet sources (incl. microquasars) and Blazars: The geometry and origin of the X-/gamma-emission in these two classes of jet sources is heavily debated. In microquasars, a comptonized corona is usually considered as the source of high-energy emission, but a report on 75%±32% polarization in the hard state has spurred the interpretation of synchrotron self-Compton emission from the jets (Rodriguez et al. 2015, ApJ 807, 17). In blazars, leptonic models do predict polarization due to the prevalence of synchrotron radiation from the jet, but hadronic (unpolarised) models are popular, though a smoking gun for accelerated protons is still missing. Polarization results of Cyg X-1 have been reported with both INTEGRAL instruments (Jourdain et al. 2012, ApJ 761, 27; Rodriguez et al. 2015, ApJ 807, 17).

Polarization of disk-dominated AGN: The standard model for the origin of the high-energy emission is Compton upscattering of the thermal, soft accretion disk photons by a (trans-)relativistic plasma located as a corona around the central disk. Polarization of these Compton-scattered photons, since views away from the symmetry axis, will allow us to measure the unknown origin and geometry (via the polarization angle) of this coronal source (Krawczynski et al. 2012, ApJ 744, 30): optically thin accretion disks have predicted polarization levels of order 30-60%, while optically thick disks show only low levels (10%).

Polarization in Solar flares: Solar flares are thought to be produced in magnetised, non-thermal plasmas which accelerate protons and electrons up to GeV energies. The interaction of the accelerated particle beams with the ambient denser plasma produces non-thermal bremsstrahlung which is polarized due to the anisotropic character of the interaction. Theory predicts up to 40% polarization in the 20-40 keV range. Polarisation measurements therefore provide us clues for disentangling the dynamic processes in solar flare particle acceleration. Since this requires spatially-resolved polarization measurements of the flare, INTEGRAL IBIS and SPI are both not suited.

Klein-Nishina cross-section function that compares the

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{4}\left(\frac{E_1}{E_0}\right)^2\left(\frac{E_0}{E_1} + \frac{E_1}{E_0} - 2 + 4\cos^2\Theta\right)$$

with r_o^2 the classical electron radius, E_0 and E_1 the energy of the incident and scattered photon, respectively, and θ the angle between the photon polarization angle before and after the scattering. For an initially unpolarized beam of photons, the scattered photons will be partially polarized. For polarized photons this results in the photon angular distribution after scattering not being symmetric around the initial photon momentum.

(A3) Polarization measurement method

Pre-POLAR(-1): To date, dedicated and non-dedicated polarization measurements at high energies have relied on the measurement of photon Compton-scattering angles to infer the polarization of an observed source. The Klein-Nishina differential cross-section (see Box) depends on the energy ratio between the scattered and initial photon (epsilon), as well as the polar (θ; also Compton scattering angle) and the azimuthal scattering angle (Φ). The latter is defined as angle between the scattered photon and the polarization vector η in the plane of the detector/pixel array (see Fig. 3). Any non-zero polarization amplitude of a γ-ray source will thus alter the expected distribution of angles from pure Compton scattering. For small energies (~< 500 keV), this effect provides the largest modulation, and becomes more and more isotropic for energies above 1 MeV (see equation in Box). However, for very low energies (~<50 keV, depending on detector material), the absolute interaction probability is dominated by photo-absorption so that the polarization sensitivity decreases in general terms.

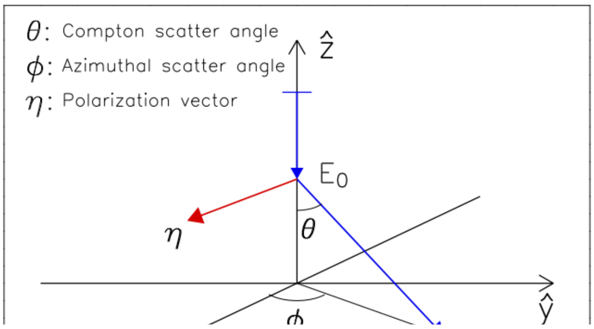


Figure 3: Scheme of scattering angles and polarization vector on a detector array (x-y-plane). [From Kalemci et al. 2004, in Proc. 5th INTEGRAL workshop, ESA SP-552, p 859]

While a relatively simple concept, in practice, the measurement is difficult: it is plagued with unknown backgrounds, instrument systematics, and weak signals due to the rarity of a photon Compton scattering within the detector. The production of well-calibrated instrument responses is computationally expensive, requires dedicated specialists, and often relies on non-existing extensive ground-based calibration. This has led to a variety of ad hoc methodologies for extracting, analyzing, and comparing polarization signals to models. Moreover, these ad hoc methods typically lead to closed-source software approaches that lack comparative studies by competing teams leaving any claim of measured polarization open to untestable scrutiny. Data and auxiliary files (such as response matrices which are always in an ad-hoc format) related to these studies are often private, even if taken from public repositories, as the extraction process is performed with proprietary software. As a result, while a number of polarization studies have been attempted in the past, also with different instruments, the scientific impact was very small due to the diversity and non-reproducibility of the results.

POLAR(-1) was a classical Compton-scatter polarimeter, built in part at Geneva University and flown on the second Chinese Space Lab in 2016/2017. It returned amazing data on the gamma-ray polarization of GRBs. While the first analysis of the brightest GRBs was done in the classical way (Zhang et al. 2019, Nature Astron. 3, 258), the instrument was built solely for polarization measurements, and thus was properly calibrated on ground (Kole et al. 2017, Nucl. Instr. & Methods in Phys. Res. 872, 28). In a second step, two additional analysis methods were tested: (i) a combined fitting of polarization (from POLAR) and spectral (from Fermi/GBM) information, and (ii) the use of the 3ML framework (Vianello et al. 2015, arXiv:1507.08343) with its modelling capabilities, including proper error propagation (Burgess et al. 2019, A&A 627, A105). This our earlier work provides the basis for this proposal, and the confidence that we are capable of fulfilling our promises.

(A4) Deficiencies in previous polarization analysis

The previous polarization analysis methods are very diverse, and the problems are often hidden in the details of each individual measurement method and/or instrument used. A thorough summary of problematic data analysis issues is given by McConnell et al. (2017, New Astron Rev 76, 1), and a criticism of the conceptual (e.g. background) and/or statistical treatments is given in Burgess et al. (2019, A&A 627, A105), which we shortly summarize below.

Measurement principle and proper statistics: Until recently, the current state-of-the-art in the analysis of high-energy polarization data relied heavily on developments in the field of optical polarimetry (cite Vallincourt ???year???Journal). However, this notably different measurement regime differs from high-energy polarimetry in two distinct ways:

1) Polarization degree and angle are measured indirectly in high-energy astronomy. In the field of optical polarimetry, via the use of linear polarizers, the degree and angle of polarization are directly measured and thus not parameters to be estimated from the data. Conversely, in high-energy astronomy, measurements suffer the classical inverse problem, i.e., the polarization degree and angle are convolved with the non-invertible instrument response during the measurement process. Thus, the measured signals are related to, but indirectly, the true polarization parameters. Such an impediment to measurement requires a statistical deconvolution of the signal from the response via a process referred to colloquial as forward-folding and formally as the Backus-Gilbert method. The process involves proposing a model in its true signal space, convolving that model with the instrument response, and then comparing this convolution with the observed data statistically.
2) The number of photons in high-energy polarimetry is in the low-count regime requiring a proper Poisson likelihood. The number of optical photons measured in optical polarimetry is high enough to invoke the so-called central limit theorem allowing for the use of the χ^2 or Gaussian likelihoods as well as the assumption of Gaussian-distributed uncertainties on the directly measured polarization parameters. This allows for several approximations in the estimation of polarization parameters, including the derivation of analytic parameter uncertainties. However, these conditions do not hold at high-energies where the paucity of signal photons does not allow for the above assumptions and analytic derivations to hold. Thus, these derivations, while frequently used in high-energy polarimetry, are not valid.

The combination of these two effects requires a proper derivation of the data likelihood for the types of measurements that the POLCA project is designed to enable. In fact, the members of the team have made progress in this aspect of the project already with the derivation of the proper data likelihood for POLAR(-I) (Burgess et al. 2019, A&A 627, 105). The project will build upon this success to derive the proper likelihoods for all instruments involved in the study.

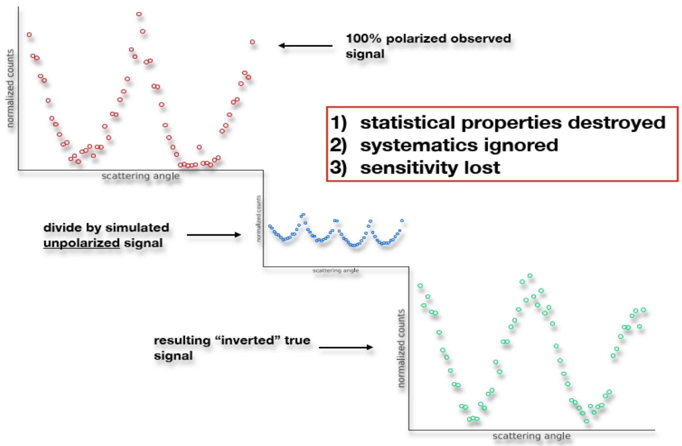


Figure 4: Scetch of standard-practice previous analysis with background subtraction.

Global issues with analysis: In order to make perfect measurements, high-energy polarimeters must be able to measure the Compton scattering angle uniformly and with infinite precision. The segmented nature of these detectors unfortunately prevents the measurement of continuous scattering angles causing them to be descretized into so-called scattering angle bins. However, this discretization can be augmented if the polarimeter is rotated about its detector plane axis creating additional "virtual" scattering angle bins which asymptotically allows for a continuous measurement of scattering angles. Even so, any realistic instrument will imprint its detection mechanism upon the true signal causing deviations from the pure sinusoidal expected signal pattern.

Thus, a major part of previous polarization analysis has focused on removing or circumventing this pollution of the true polarization signal by the observing instrument. While differing in detail, all past approaches have adopted the method of inverting the detected signal into a pure polarization signal. These methods can be summarized with the following steps:

- A simulation of the polarized signals being detected by the instrument is created. This results in a histograms of theoretical distributions for observed Compton scattering angles in the instrument's native data space
- The observed data, in the form of Compton scattering angle histograms, are divided by the simulated histograms for the unpolarised case, thereby theoretically removing all effects with the exception of those induced by the polarization. Technically, this can be understood as an effort to invert the observed data into the true signal space.
- The inverted signal is then normalized and fit with simplistic chi^2 statistics to a sinusoidal curve, from which the polarization parameters are obtained.

While this method appears correct upon a first look, several issues with inverting must be considered. First, the instrument responses are highly singular, and numerical inversion of them is well-established to be numerically unstable. Moreover, the distribution of events into Compton bins suffers from dispersion due to both the energy-dependence of the Compton scattering and the discrete nature of the measured angles i.e., the detected bin is probablistic and no one-to-one mapping between measured and true angle can be uniquely determined. Even if such a mapping existed, the energy of the photon itself also suffers from dispersion, making it impossible to uniquely determine its true value. These effects alone combine to make direct inversion of the polarization signal impossible. This has not, however, stopped such methodology from being practiced.

Ignoring the difficulties of signal inversion can lead to several immediate issues with derived results even disregarding the statistical issues inherent in past analysis discussed below. First, inversion can lead to plainly incorrect results. As the inversion is unstable and cannot include the higher dimensions of both angle and energy dispersion, the resulting analysis can incorrectly identify features (amplitudes, phase) in the observed data as the true parameters of the signal. The instrument response will never be perfect, despite enormous efforts. Using the method described here, all imperfections in the instrument response will result in deviations in the measured distribution. These deviations, even if they are minor, can easily be mistaken for polarization signals. Moreover, these results will be arrived at with over-confidence (smaller than actual uncertainties) due to the loss of information in the true instrument response (e.g. dispersion). Thus, while the derived parameters can appear to be very exact, it is likely that they are incorrect and too certain.

Further complicating the issue is the use of improper statistical methodology in the estimation of polarization parameters. The above incorrect inversion technique result is pseudo polarization parameters very similar to what are measured in optical polarimeters. This leads to the incorrect assumption that the "data" are polarization variables and when in reality, the data are Poisson distributed counts in Compton scattering bins. This incorrect assumption leads to the use of the incorrect likelihood on the data. Specifically, the likelihood used derives from optical polarization with Gaussian uncertainty on the values. An issue with this classical analysis is that polarization parameters are bound to specific ranges. For example, the polarization degree is a percentage between 0 and 100. It is not statistically valid to include these bounds in the classical analysis. Thus, one often finds unphysical (nonsensical) statistical errors on the polarization degree such as 90±30% (e.g. the ASTROSAT paper mention earlier). We have shown in our previous work (Burgess et al. 2019, A&A 627, 105) that this can be avoided by using proper Bayesian analysis that introduces physically principled priors.

We conclude in this section that a significant investment in developing proper analysis techniques will not only aid in more deeply exploiting existing EU instrument data, but will also add value to this data beyond what is currently available. We have demonstrated in our past work with POLAR that we have the expertise, technology, and ambition to tackle these issues and seek to further develop in this program.

The following 2 sentences are supposed to be the final sentences of sect. A (State-of-the-art)

Scientifically, polarisation results are generally considered as "curiosity" or "interesting aspect", but have not (and do not) drive(n) the astrophysical modelling of cosmic sources or the theoretical thinking. The situation is equally bad in optical or high-energy astrophysics.

(B) Preparatory work by the proposing team

> **Astrophysical polarisation measurements are difficult:** With present-day technology, a position of an astrophysical source can be measured to decent significance with a handful of photons. The measurement of the energy spectrum of an astrophysical source requires about 100 photons (per energy decade). In contrast, a polarization measurement requires at least about 1000 photons!

Our present proposal has developed as a result of decades-long study of physical processes leading to polarized emission, activities to measure polarized emission, development of new analysis software, and engagement to push for new polarization instruments. This history, which represents our domain of experience and heritage, is shortly described in the following paragraphs.

(B1) **Combined fitting:** Typically, high-energy instruments measure more than one photon property, i.e. time of arrival and spectrum, or sky position and spectrum. Yet, standard analysis techniques nearly exclusively fit models to one of these measured quantities at a time. Since several years, we have been developing a toolkit for the analysis of Fermi/GBM (Gama-ray Burst Monitor) data to fit the spectrum and the sky position of a GRB at the same time (Burgess et al. 2018, MN 476, 1427; Berlato et al. 2019, ApJ 873, 60). While the whole process of GRB localization with Fermi/GBM and CGRO/BATSE (Burst and Transient spectrometer Experiment on the Compton Gamma-Ray Observatory) is based on the different spectral appearances in differently oriented detectors, the analysis since 30 years has been split into two steps: first deriving a position under the assumption of a fixed spectral model, and then using that position to fit the spectrum (Pendleton et al. 1999, ApJ 512, 362). That is, the deficiency of the algorithm was known, but it took 30 years to be corrected. In a similar spirit we developed a fitting engine for a combined spectral and polarisation analysis, applicable to the POLAR instrument (see below item B4 for yet another improvement for POLAR GRB data analysis).

(B2) **Rigorous statistical treatment:** Temporal or spectral re-binning of low-significance data points has long been the default approach. Yet, information is lost in this process. Dealing with unbinned data then implies the use of proper statistical treatment in the low-count regime. The conclusions reached with such approach can be dramatically different (Greiner et al. 2016, ApJ 827, L38). Another problematic area is the fact that statistical uncertainties are frequently only applied to the last step of an analysis, however, the systematics and unknowns of instrumental calibration can also induce uncertainties in an analysis, even if they are typically ignored. Lee et al. (2011, ApJ 731, 126) found that including a statistical approach to calibration improves the ability to recover the true parameters in an X-ray analysis. We will leverage this cutting-edge approach to the much more uncertain calibration regime of X-ray polarization. Our unique, and innovative combination of statistical analysis from the instrument to the observation will not only provide a novel and robust framework for polarization studies, but have an *ambitious impact* beyond the current study as the approach can be adopted into areas outside our current focus.

(B3) **Fitting physical spectral models:** For decades, and still standard practice today, the spectra of synchrotron emission sources are fit with a power law model, and physical interpretation is thereafter based on the best-fit slope of the power law. First demonstrated for a single GRB (Burgess et al. 2014, ApJ 784, 17), but recently demonstrated for a complete sample of Fermi/GBM-detected GRBs, fitting proper synchrotron spectra (incl. electron cooling) rather than power laws leads to a surprisingly different result: instead of 25% of all spectra violating the so-called “synchrotron death line” (in case of power law fitting), the synchrotron model fits 95% of all time-resolved spectra (Burgess et al. 2019, Nat Astron 3**, ???).**

(B4) **Physically appropriate data selection:** Gamma-ray bursts are rapidly evolving events, with many measurable parameters (like energy spectrum) changing on timescales down to the measurement accuracy. Yet, standard polarization analysis often tried to maximize the “signal-to-noise” (S/N) ratio by analysing all events, integrated over the full GRB duration. For spectral analysis it is well known that time-integrated results have not much resemblance with time-resolved results. Time-resolved analysis, however, implies low-count regime, and thus requires proper statistical treatment (see above item B1). Our re-analysis of one GRB of the POLAR sample (Zhang et al. 2019, Nat Astron 3, 258) therefore incorporated two improvements: first, the inclusion of Fermi/GBM data and a combined fitting of the spectrum (GBM data) and polarisation (POLAR data), and second, a time-resolved analysis. For this, the data were divided into 9 time bins, roughly on the order of the minimum variability timescale, and both the spectrum and the polarisation angle and degree were allowed to vary between the time bins. We found a trend of growing polarization in time reaching values of about 30% at the temporal peak of the emission. Even more interesting, we also observed that the polarization angle evolves with time throughout the emission (Burgess et al. 2019, A&A 627, 105). If this is a generic property of all GRBs, then in the time-integrated polarization analysis in the past, including that of INTEGRAL data (Götz et al. 2013, MNRAS 431, 3550, Laurent et al. 2016, 41th COSPAR Sci. Assembly, id. E1.15-18-16), the polarization signal was smeared out. Thus, our results of the POLAR analysis call for a re-analysis of the INTEGRAL polarization measurements.

(B5) **Building theoretical understanding of the sources of polarized emission:** Polarized light in the hard X-ray and gamma rays bands originate from sources which are either relativistically hot (e.g. SGRs emission) or move at relativistic velocities (e.g. GRB prompt and afterglow emission). In the later case the boost from the emitting to the observer frame change the angle of the polarization vector. Rotation of the observed electric vector position angle (EVPA) in such systems can teach us on both the configuration of the magnetic field as well as on the evolution in the dynamics of the system. This is different from the case of non-relativistically moving sources where only the magnetic field dictates the polarization angle.

Linear polarization at a level of a few percent was first detected in the afterglow (AG) light of GRB 990123 (Hjorth et al. 1999, Science 283, 2073), 990510 (Wijers et al. 1999, ApJ 523, L33) and GRB 990712 (Rol et al. 2000, ApJ 544, 707). It was followed by several theoretical models that calculated the polarization of synchrotron emission originating from an AG forward shock, assuming a random magnetic field configuration and synchrotron emission by a powerlaw distribution of electrons (Ghisellini & Lazzati 1999, MNRAS 309, L7; Gruzinov & Waxman 1999, ApJ 511, 852; Sari 1999, ApJ 524, L43). The polarization from a uniform planar field was first calculated by Granot & Königl (2003, ApJ 594, L83) and for a patchy geometry by Nakar & Oren (2004, ApJ 602, L97).

Polarization in γ-rays during the prompt GRB phase was first claimed for GRB 061202 (Coburn & Boggs, 2003, Nature 423, 415) from RHESSI observations, and later by the IBIS imager on board INTEGRAL for GRB 041219A (Laurent et al. 2010, in X-ray Polarimetry, CUP, p. 230). It was followed by models that generalized the polarization of the AG light to the prompt phase, assuming the internal shock scenario (Lyutikov et al. 2003, ApJ 597, 998; Nakar et al. 2003, JCAP 10, 5; Granot 2003, ApJ 596, L17) for linear polarization, or circular polarization (Blandford 2003, ASS 288, 155). Since then dozens measurements were made of polarized light with different polarization degree from both GRB afterglows as well as from the prompt emission. A list of GRBs with detected polarization in their prompt phase is given in Gill et al. 2019, MNRAS 2582). They also review the expected degree of polarization from various plausible magnetic field configurations on the shock plane of the shock plane and their resultant polarization degrees. Other discussions on the expected polarization on the prompt phase from various field configurations can be found in Lazzati 2006 (J. Phys. 8, 131), Toma 2013 (arXiv:1308.57) and Nava et al. 2016 (MNRAS 455, 1594).

The analytic polarization models in the various works presented were made for specific configuration of magnetic fields, electron energy distributions and assuming uniform radial velocity profile. There calculations are also limited for emission from two dimensional optically thin surfaces and cannot be applied to more involved environments, which emits from 3D volumetric regions. Recently, we have constructed a numerical tool, based on the method presented in Nava et al. (2016, MNRAS 455, 1594) that can calculate the observed polarization from arbitrary jet structures, magnetic field configurations and electrons distributions. It can also follow the evolution in time of the polarization including the rotation of the EVPA. Currently our tool is limited for 2D surfaces, however, we are now in the process of generalizing the calculation to 3D, volumetric regions (see sec. D4). In its present status, our tool is capable of fitting the observed polarization in GRB emissions with the most probable magnetic field configuration on the shock surface. The expansion to 3D will allow the analysis of radiation from other sources such as SGRs and PWN.

(B6) **Organized international conference:** Given the lack of predictive theoretical concepts for the polarization in high-energy sources, we organized a conference on "the way forward" for high-energy polarisation measurements, inviting all European players in the field. This 2-day meeting was held in Geneva (Nov. 29/30, 2018), and was orchestred as a discussion forum with extensive debates on all relevant aspects. Indeed, the outcome of this meeting formed the idea that more and much improved data analysis is needed before theoreticians get (or can be) motivated to labour-intensive simulations. Also, a dedicated discussion on standardized polarization data format(s) was part of this conference, and shaped the baseline design for such a format.

(B7) **Polarization heritage:** Our consortium comes with a strong heritage in polarization studies. Foremost to mention is the construction and successful flight of POLAR (by the Geneva group) on the Chinese Space Station in 2016, and the seminal results obtained on GRBs. At MPE Garching, high-energy polarization measurements date back to COMPTEL (on CGRO) analysis of the Crab and Cyg X-1, but also on INTEGRAL/SPI studies together with our French and Irish colleagues. Phase-resolved optical polarimetry of the Crab at 10 microsecond time-resolution with OPTIMA revealed a complicated polarization variation pattern over the pulse cycle (Kanbach et al. 2005, AIPC 801, 306; Slowikowska et al. 2009, MN 397, 103), still unexplained 15 years later. Similarly, a 50 hrs ESO/Very-Large-Telescope observing campaign of the bright afterglow of GRB 030329 pioneered polarization measurements of optical afterglows (Greiner et al. 2003, Nature 426, 157), but the resulting polarization ‘lightcurve’ has escaped theoretical explanation so far. We have led a big European consortium which prepared proposals for large-scale gamma-ray polarimetry satellites (called GRIPS at the time) following two ESA calls for medium-sized missions (Greiner et al. 2009, Exp Astron 23, 91; Greiner et al. 2012, Exp Astron 34, 551). Last but not least, we have successfully initiated the POLAR-2 project, officially adapted in 2019 by the Chinese Space Agency, and with formal contracts between China and Switzerland signed.

(C) Concept

- Describe and explain the overall concept underpinning the project. Describe the main ideas, models or assumptions involved. Identify any inter-disciplinary considerations and, where relevant, use of stakeholder knowledge. Where relevant, include measures taken for public/societal engagement on issues related to the project. Describe the positioning of the project e.g. where it is situated in the spectrum from 'idea to application', or from 'lab to market'. Refer to Technology Readiness Levels where relevant. (See General Annex G of the work programme);

This section can be rather short, since we have introduced the topics in (A), and will write details on how to do this in (D)

(C1) Applying new data analysis method

The core concept is to take the wealth of data collected by a variety of polarization measurement capable instruments and apply our developed analysis techniques. This entails proper statistical methodology allowing for low count analysis, including in the time-resolved regime. We further extend this to the simultaneous spectral and polarization regime to gain information about the microphysical processes generating the emission as well as the geometry and magnetic field structure of the macrophysical processes.

(C2) Applying new multi-instrument data modelling concept (3ML)

The concept of our analysis method is wrapped into our 3ML framework (Vianello et al. 2015, arXiv:1507.08343) allowing for complex, multi-dimensional, multi-instrument, statistically sound data analysis. 3ML is a framework developed to directly model all data simultaneously with a joint likelihood in each dataset's appropriate space. As a hub for data collection, interaction, and modeling, 3ML provides the ideal vessel for these concepts to improve upon and extract the maximal amount of value from existing instruments. The open-source nature of this project allows for the entire community to interact, improve upon and disseminate the concepts embedded in our project.

(C3) Analyse all suitable INTEGRAL data

Analysis of gamma-ray bursts or other short-duration transients has commonly be considered to be easier targets for polarization analysis because the emission is bright relative to the background, and thus the background treatment was considered to have little impact on the result. With our thorough and rigorous background treatment, this is not a valid argument anymore. Thus, we plan to look at all sources for which (i) previous polarization analysis attempts have been made, and (ii) theory suggests polarized emission and which are bright enough to promise a detection. The INTEGRAL mission is the best-suited astronomical mission for this kind of analysis, since three different polarization detection methods are available, and thus allow us to cross-check the instrument response and software quality with a given source. While two of these polarization detection methods are well-known and have been utilized, we herewith propose to also develop a third method which relies on inter-ISGRI detections only.

(C4) Push theoretical studies

We intend to use our numerical tool to build a better understanding of the conditions that lead to the creation of polarized light in various astrophysical systems. The tool will also be publicly accessible via an online system and will be connected to the database of the observations in this proposal. It will allow the users of the database to fit for themselves the different system parameters that can generate the observed emission and polarization, including its evolution with time.

(C5) Apply new theoretical insight to possibly new observational results

- Describe any national or international research and innovation activities which will be linked with the project, especially where the outputs from these will feed into the project;

(C6) Link to national or international research

We have contacted all INTEGRAL instrument teams, but could not convince more partners to join this project, implying that there is no coherent polarization analysis concept on the ESA mission level. On a broader scale, there is the Integrated Activities for High Energy Astrophysics (AHEAD) project funded under the Horizon2020 Research Infrastructure Program, recently accepted for another funding period. While their main goals are to provide access to large European infrastructure and to support technology development in High Energy Astrophysics, one of the sub-topics is the support of cross-calibration activities and simulation studies (http://ahead.iaps.inaf.it/?page_id=22). We plan to reach out and make use of any possible synergy with their planned activities re. INTEGRAL. As the plan for the new funding period has not been released yet, no further details can be provided; since polarization was not a topic in the past, we expect instrument calibration to be the only area of potential synergy. With MPE and UNIGE being partners in AHEAD, we can guarantee close connections and optimal use of opportunities.

(D) Methodology

- Describe and explain the overall methodology, distinguishing, as appropriate, activities indicated in the relevant section of the work programme, e.g. for research, demonstration, piloting, first market replication, etc.

Our main methodological approach is to apply newly developed concepts (as described in the previous section) to the archival data of ESA's gamma-ray mission INTEGRAL. The result of our research project is expected to serve multiple areas: (i) gain new scientific insight into the emission mechanism in various source types, (ii) develop a universal data format for polarization data which is appropriate for present-day analysis tools, (iii) develop new methods of data analysis with rigorous error handling and propagation, and (iv) prepare the ground for future high-energy missions to measure polarization which are presently under construction. Thus, in the language of science management, this is a research project which will demonstrate the superior performance of new data analysis tools, where their application to INTEGRAL data serves as a pilot project for the application to future science missions with the goal of substantially increasing the science return.

The basics of our methodology is shown in the figure below, and the various components are described in the following sub-sections D1—D8.

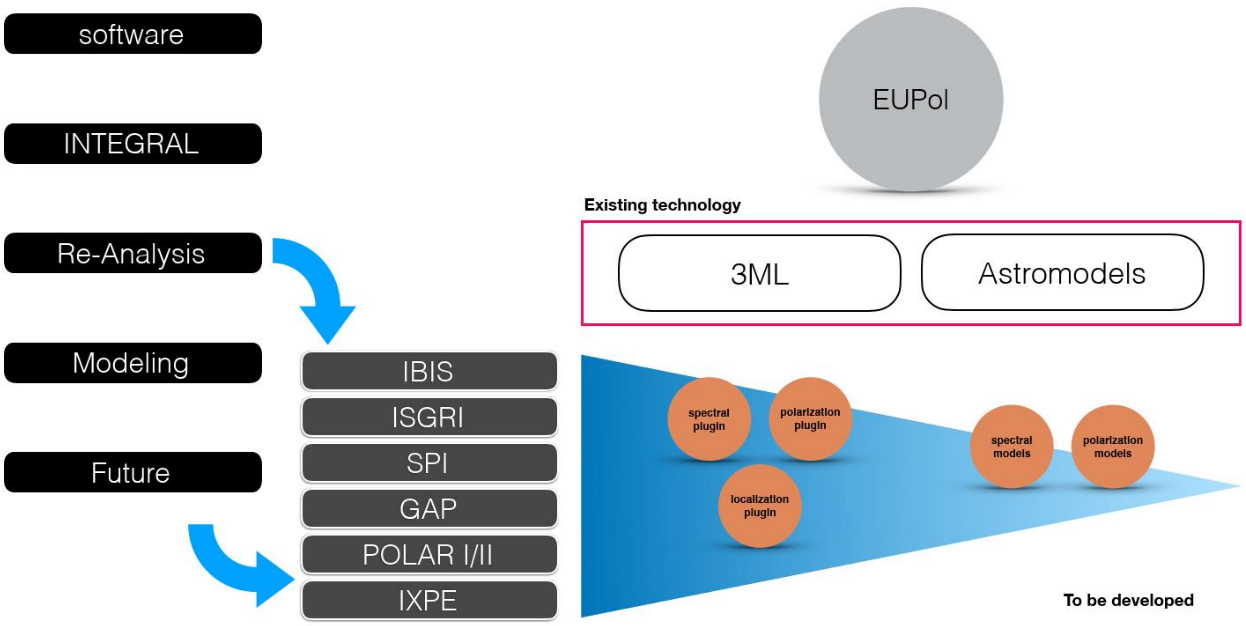


Figure 5: Scheme of the proposed methodology: using the existing 3ML framework and earlier developed Astromodels as the central hub of our software development and analysis strategy.

(D1) Standardized Data format

The explosion of scientific value and knowledge that has occurred over the last several decades in high-energy astronomy is due to two key innovations: common, standardized data formats and definitions as well as open-source standardized analysis software. These two concepts enable astronomers to test theories against data from multiple instruments without the burden of deep instrument knowledge and low-level processing. Key examples of this are the generic `define' (OGIP) X-ray FITS file formats which are easily read by the open source XSPEC software and the Fermi GT science tools (https://fermi.gsfc.nasa.gov/ssc/data/analysis). Instrument teams release their data in the formats required for the analysis tools, and then astronomers readily test their models against the data in a proper way. The success of these tools to enable science can be measured in both the citations to the tools and the number of papers written by external scientists using these high-energy instruments. Thus, building such a framework for the polarization data will lead to the same explosion of data use by existing ESA/EU missions addressing a key component of this RIA call ("advanced processing of data"), as well as more generally the mission of ESA to shape the development of Europe's space capability and ensure that investment in space continues to deliver benefits to the citizens of Europe and the world.

The POLCA project will leverage from the heritage of high-energy spectroscopy to:

- **Define/propose a standardized format for high-energy polarization data.** Using the team's expertise as well as consultation with field experts, we will develop a data format and storage system that will allow for instruments with polarization capable data to disseminate these data in standardized form. The processing tools developed within the project will be open-source and provided to instrument teams fully documented and unit-tested. Similarly as the standard ARF/RMF formats make it easy for everyone to analyse spectroscopic data, our response format will provide the same ease for polarization analysis.
- **Create multi-mission public analysis tools which interact with this data format.** Even if data are standardized, a framework for the proper analysis of the data must be defined and created. We will leverage our experience in developing multi-mission data analysis and modeling tools to create a user-friendly open-source framework enabling novice to expert astronomers to interact with and model polarization data collected with various instruments.

The considerations of defining a standardized data format must include the following components:

- ✓ **Interpretability:** Any data format defined must be readible/serializable to enable quick understanding of its content, size, and validity. Examples of interpretability can be found in the ASCII-based text headers of FITS files. These allow astronomers to understand the contents of data on any system even when FITS reading software has not been installed.
- ✓ **Access to software tools** to read/manipulate/store the data: A data format that lacks open-source tools to read and operate on the core data product is useless to astronomers outside of instrument teams. In order to disseminate and broaden the use of data to the largest possible user-base, a format must be designed such that the tools available to read and operate on the data are easily obtained, stable, and have an active development team to support future issues.
- ✓ **Flexibility:** While the goal of the POLCA project is to fully exploit the capabilities of existing and past instrument data, considerations must be made for the capabilities of future observatories which may require more parameters, larger data, etc. to adopt the data format such that past and future instruments can have their data analyzed in consistent, tested manner. Examples of where this is important include the FITS file format. As datasets have become richer and larger, the FITS file format has troubles adapting to the speed, and parallel capabilities of modern computer systems. However, the heritage of FITS in astronomy should be considered as it is the standard of most instruments.
- ✓ **Longevity:** In order to maximize the long-term use of existing data, any data format must have both a history of use as well as an active team of developers which will enable its maintainability many years after the instrument generating the data has stopped taking data.

In order to address these issues, the POLCA project will examine the current status of data formats in high-energy astronomy and weigh their pros and cons. Additionally, consultations with our partner advisory board will help us to ensure that our proposed data format will be applicable to the current and future goals of ESA as well as the community at large. An investigation of modern and past data formats will be undertaken to understand whether we will adopt proven and widely used storage systems such as FITS or opt for modern formats with richer capabilities such as HDF5 (list here things like advanced fits etc. probably need bullets and descriptions.)

(D2) The 3ML framework

An important objective of the POLCA project is enabling the astronomer community at large to easily access and model the data from instruments which measure polarization. This requires a well-tested, user-friendly interface between data, models, and proper statistical likelihoods. Such a framework exists in the Multi-Mission Maximum Likelihood (3ML) framework co-developed by our team. 3ML provides an abstract data interface via plugin system where instrument teams or individuals create an interface to the data by specifying the way in which a spectral/temporal/spatial model interacts with the instrument's data likelihood. Thus, an end-user only needs to provide the specific data and model for the analysis at hand, combine them in the plugin, and compute the model inference via either sampling or optimization techniques (see Fig. 6). As this framework exists and is used by several instrument teams (Fermi, HAWC, POLAR), the project will design generic and specific polarization plugins which will link existing data to the models developed within the POLCA project.

A subsequent impact of integrating the polarization capabilities of various instruments into the 3ML framework will be the automatic ability to combine polarization analysis from different instruments as well as with other information including spectroscopy. Therefore, models that include both polarization and energy in their predictions can simultaneously be fitted to data (even from different instruments) covering both of these axes.

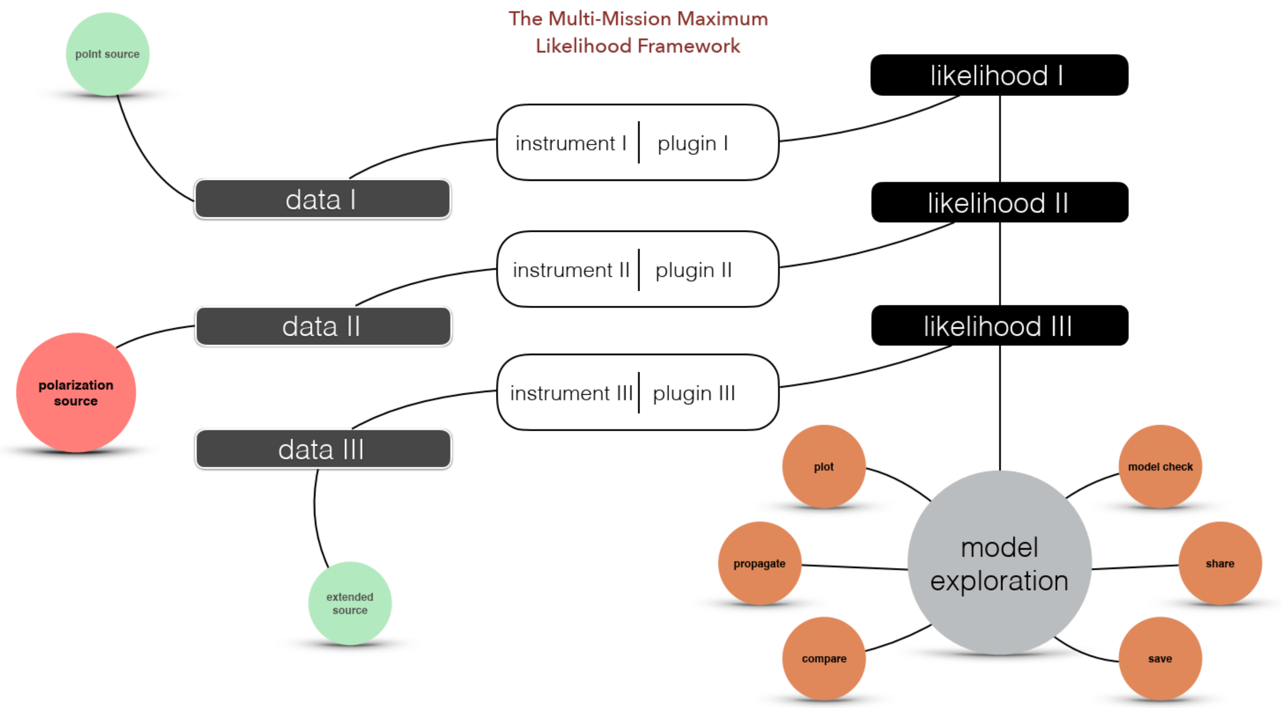


Figure 6: Visualization of the 3ML framework. More details

(D3) Data Analysis Concept

D3.1 Pushing boundaries

By combining our innovative data analysis framework with our instrumental calibration for polarization, we will enable the ability to push polarization analysis to new levels to fully exploit the information contained in the data.

D3.1.1 Time-resolved polarization

Our team has already demonstrated that the use of proper statistics and calibration allows for existing data to be analyzed in a time-resolved manner to much higher precision (compare Kole 2018, arXiv:1804.04864; PoS(MULTIF2017) to Burgess 2019, A&A 627, 105). As time intervals are made finer, the number of observed events drops. The use of classical methods requires the data to be temporally binned such that the number of events is high enough to apply asymptotics. Thus, a trade-off is made between resolution and so-called sufficient statistics. If this approach is followed, then time-resolved analysis will never advance as the number of photons is limited by the source.

To resolve this conflict, we will employ proper counting statistics likelihoods derived from Poisson distributions that are not limited by asymptotics. These likelihoods are valid even when no photons are detected in a time/energy/scattering bin. Thus, data can be sub-divided into arbitrarily small time intervals fully exploiting the critical temporal evolution of the polarization parameters.

The lack of signal at high-temporal resolution does, at first look, imply that while we can obtain information at a high temporal cadence, this information will be statistically uncertain (large error bars). To address this issue, we will rely on our development of time-resolved polarization models. Rather than simply analyzing individual time slices, we will use our models to link information across time thus providing tighter predictions.

Therefore, we will ambitiously push the temporal boundary currently faced by the field.

D3.2.1 Energy-resolved polarization

Different physical processes arise in sources at different energies. As an example, GRB emission could be dominated by thermal emission at high energies, and synchrotron emission at low energies (e.g. Lundman et al. 2018, ApJ 856, 145). Just as these two processes imprint different shapes on the spectral distribution of photons at different energies, they will also produce different polarization signatures at different energies (see Fig. 7). The ability to simultaneously analyze both dimensions in the data provides the ability to test richer models, have tighter constraints on parameters, and fully exploit the information of every detected photon by existing instruments.

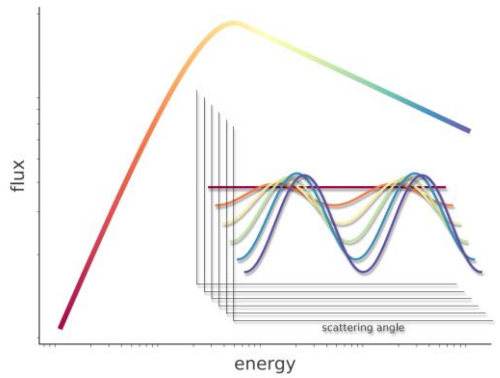


Figure 7: Schematics of energy-dependent polarization: different parts of the high-energy spectrum can have different degrees of polarization. For instance, synchrotron emission is predicted to be much stronger polarized above the cooling frequency.

To enable this capability, we expand upon our approach of forward-folding (Fig. 8) both the polarization and spectral model through the response of the instruments in our project. However, we will further subdivide the scattering bins to fully account for their change as a function of energy. Thus, an individual scattering bin will have a fully detailed spectral response. The results will be that after an analysis, a signal can be decomposed into polarization parameters that are a function of energy.

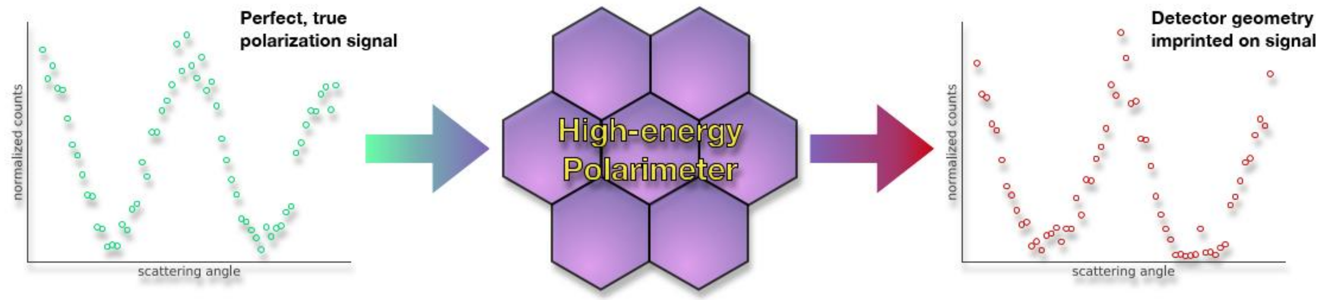


Figure 8: Scetch of proposed proper analysis method via forward-folding.

D3.2 Polarisation response

The translation of an astrophysical polarization signal into an instrument's electronic data space is encoded in a response function. X-ray polarization signals are encoded in the data via their energy-dependent Compton scattering angles. Due to the finite nature of recording these angles and energies, polarization suffers from dispersion, i.e., a non-unique mapping from data to the original signal. Thus, it is impossible to invert this response function to recover the original signal. This leads to the process of forward-folding which is the established practice in X-ray spectroscopy. For X-ray polarization this entails a convolution of a proposed polarization signal with the response, which mathematical converts the signal into the space of the recorded data. While this process is standardized in spectroscopy, both the process for using this response and its data format are not universally defined for polarization.

The design of the response for Compton-based polarization instruments can be cast as three-dimensional matrix. The axes of this matrix are as follows:

- the true spectral energy
- the polarization
- the measured scattering angle

As these response matrices can contain many elements, and often also depend on instrument-related details (instrument coordinates, energy dispersion, angular resolution), a clever data format and storage needs to be designed. For example, the polarization response intends to describe deviations from a non-polarized source, i.e. how the scattering angle distributions vary as a function of polarization angle and degree. However, many instruments do not measure the scattering angles directly, but record a characteristic change in their native photon-counting data space. Any extraction of polarigrams will be flawed as individual instrument designs and the nature of Compton scattering are ignored. An example is shown for the SPI telescope aboard INTEGRAL in Sec. D3.2.1.

Another main task will be investigating the heritage of spectral response storage and leveraging `calibration'. Similar to the imaging and energy response, the additional polarization dimension requires an absolute gauge for each instrument. While many astrophysical sources are expected to show polarized emission in the soft gamma-ray band, the true emission spectrum as well as the true polarization (as a function of energy) is hardly known for any source. The Crab Nebula is the classical calibration source as the absolute flux at hard X-rays has been shown to vary only by ±5% over a time period of ~10 years (e.g. Wilson-Hodge et al. 2011, ApJ 727, L40), and the spectral index is also stable (e.g. Jourdain & Roques 2009, A&A 704, 1). It turns out that also the polarization parameters of the Crab appear constant over time and energy (e.g. Jourdain & Roques 2019, A&A 882, 129), at a degree of 24% and an angle of 120°. As the measurements from different instruments coincide, the Crab Nebula can be used as a 'standard protractor'.

In order to calibrate, and later consistently calculate the response, a large amount of simulations is required: As an example we note that for POLAR, a response for a single GRB with sufficient statistics took 1 day to produce on a cluster with ~100 cores. This implies that each zenith/azimuth location takes about one day on such a cluster, a full response would therefore take about half a year - per instrument. While this is manageable, it certainly requires (and has room for) considerable optimization.

Here talk about designing the response with components ….

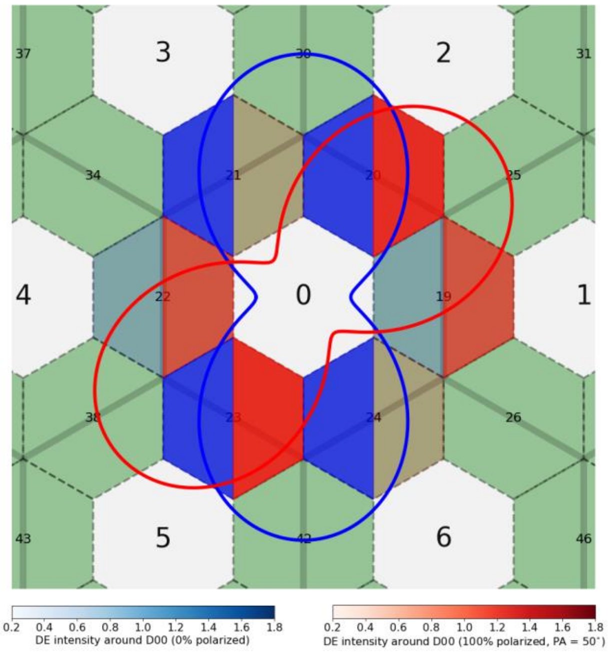
(i) we will create component-level responses that allow for us to incorporate the statistical uncertainties in the responses themselves.

D3.2.1 SPI

SPI is a coded-mask spectrometer-telescope which utilizes a hexagonal 19-element, high-purity Germanium detector (6 cm thick) array in a honeycomb configuration. It is sensitive to photons in the energy range between 20 and 8000 keV, with a spectral resolution of ~2.1 keV at 1 MeV, and a field of view of 16x16 deg^2. While SPI is not a classical Compton telescope, it can still be used for Compton polarimetry since also multiple scatters are recorded: For example, Compton scattering of a photon from its initial interaction detector into a neighboring one where it is photo-absorbed would be termed a double-event, if this falls into a 350 ns coincidence window. Due to the geometry of SPI, there are 42 of these 'double detectors', which would define six possible azimuthal scattering angles. However, SPI is not measuring these angles as no 'Compton reconstruction' is performed. Instead, the 42 double detectors include all the information required to determine the polarization parameters of a source in the above-described full-forward modeling approach (see XY): Based on previous simulation studies (Kalemci et al. 2004, in Proc. 5th INTEGRAL workshop, ESA SP-552, p 859; Kalemci et al. 2007, ApJS 169, 75), it has been suggested that the modulation for SPI is in the range between ~30 % for 100 keV photons to ~15 % for 600 keV. In terms of the polarization response for SPI, polarized sources will change the expected photon count pattern of 'double-detectors' which would naturally be dominated by the mask's coding (determining the position of the source), and Compton scattering.

A visualization of this transformation is provided in Fig. 8: Here, the SPI single detector array (numbered grey hexagons, thick boundaries, 0–18) and the definition of double detectors (green, dashed boundaries, 19–60) is shown. The differential Klein-Nishina cross-section is indicated for a source, emitting at 500 keV, either unpolarized (blue solid line) or 100 % polarized (red solid line; PA = 50 deg) - both as seen with a Compton scattering angle of 90 deg. The six neighboring detectors of detector 0 (i.e. 1–6) result in six pseudo-detectors, numbered 19–24. Depending on the polarization degree and angle, the relative pseudo-detector count rates (blue and red shading) change. This is shown for the case of detector 0 and its neighboring detectors only: The instrument-specific data space of 'counts per (pseudo-)detector' is clearly seen , as for a specific energy and Compton scatter angle, the neighboring detector share un-equal amounts of scattered photons. This asymmetry is enhanced by a polarized emission, and leads to a different expected count rate for each double-detector. As the Compton scattering angle is not measured, different values 'overlap' in the SPI data space, and also scatterings from other detectors imprint their patterns in the limited, 42-element data space. This total relative change is stored in the polarization response, for each aspect angle and energy.

It must be noted that especially at hard X-ray and soft γ-ray energies, the instrumental background from cosmic-ray interactions in the instruments and satellite material is contributing typically more than 99% of the total measured counts. This must be taken into account in a proper statistical analysis - in particular when the background is determined from an independent data set (e.g., before and after a GRB). For persistent sources, a widely applicable background model has been developed at MPE (Diehl et al. 2018, A&A 611, 12; Siegert et al. 2019, A&A 626, 73) and tested for different sources using SPI's single events. An extension of this background modeling method to multiple events is straight-forward, but requires testing and validation.



Changing instrument parameters require separate (spectral and) polarization responses: During the 17 mission years of INTEGRAL, four out of 19 SPI detectors failed at different times until 2010. Such a dead detector modifies the expected response dramatically because initial double events, scattering in a dead detector, will be counted as single events in the neighboring detectors. This has to be taken into account as it might falsely be interpreted as a possible polarization signal. Thus, for each camera configuration of SPI, an individual response is required.

Finally, the SPI polarization response includes the following dimensions for each camera configuration as imprinted in the relative counts in each 'double detector': Source position (zenith/azimuth), initial and scattered photon energy (energy redistribution matrix), polarization parameters degree (Pi) and angle (eta).

D3.2.2 Standard IBIS approach

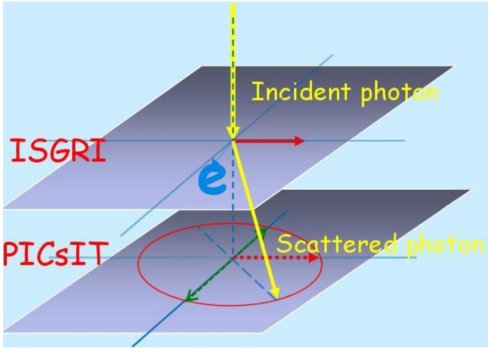


Figure 8: Schematics of the Compton scattering between the two IBIS sub-detectors ISGRI and PICsIT [From Laurent 2017, talk at Hiroshima Conf., Feb. 2017].

The INTEGRAL/IBIS instrument is a coded aperture telescope with a dual detection layer. The top detector, ISGRI, consists of 128x128 CdTe pixels for the energy range up to 1 MeV (Lebrun et al. 2003, A&A 411, L141). The lower detector, PICsIT, comprising 64x64 CsI scintillation pixels, operates in the 190 keV – 10 MeV range. In the so-called Compton mode, photons are scattered from a CdTe pixel in the IBIS plane to the PICsIT plane, appearing as two events at the same time. The measured quantities are the deposited energies and the two 2D coordinate positions in each detector. The direction of the incoming γ-ray can be confined to an event circle determined by the base of the cone with its opening angle Φ, with the axis defined by the connecting line between the two detector plane coordinates. An inherent problem is that the mask imaging is a statistical deconvolution, so cannot be used at the same time as Compton imaging. For the polarization analysis, two properties are important: (i) the energy resolution, as it determines the Compton scatter angle, with the resultant modulation being angle-dependent, and (ii) the number of background events, as it determines the rate of accidental coincidences. In practice, the energy resolution of about 20%-25% (FWHM) is acceptable, but the background rate in PICsIT is so large that the proper selection of true Compton events is a very delicate process (and prone to errors).

Following the above approach with SPI, a forward modeling approach including the complete response to be applied to the combined 'Compton mode'-IBIS data is needed: This requires simulations of the full IBIS configuration, i.e. the mask, ISGRI, and PICsIT, to obtain the expected counts per pixel, just as in the ISGRI imaging response, but including the polarization parameters as well. This allows an energy-dependent polarization analysis (see D3.2.1) without the intermediate step of extracting scattering angles, which is in itself uncertain (Zoglauer & Kanbach 2003, SPIE 4851, 1302).

The IBIS 'Compton mode' response for polarization is thus made of different 'images' (relative pixel counts) for ISGRI and PICsIT as a function of source position (zenith/azimuth), incident and scattered photon energy (dispersion matrix), as well as the polarization parameters degree (Pi) and angle (eta).

Need to describe how we want to do the Compton selection better than the IBIS team, calibrating against their Calibration source – see Forot et al. (2004ESASP.552..463F); joint analysis with SPI should be possible to verify, possibly even to improve, the calibration

TS: I don't understand that. We don't want to 'select' Compton events, we want to forward-model the expectations. This means, we will not use photon-by-photon extractions. However, if we use the Compton reconstruction to have yet another response to be created (because IBIS 'can' measure the distribution quite accurately as a Compton-telescope), we could also improve this by using GLMs which might tell us which photons are Compton events and which not.

D3.2.3 New ISGRI-only approach

As described in B1, typically only one measured quantity is used for analyzing high-energy data. Especially in the case of ISGRI with its mask coding and sub-module geometry, the timing information will provide additional discriminative power with respect to measuring polarization. The timing between individual events allows us to identify Compton scatterings inside ISGRI alone: Only the time differences of events that accumulate close to zero would be chosen to identify (select) possible Compton events. Furthermore, for pixels at the edges or corners of the sub-modules (see sketch in Fig. 11), only the opposing side will potentially be populated by Compton events (as the boundaries are 'dark'). However, since the mask also blocks certain neighboring pixels, other neighboring pixel events cannot be due to Compton scattering. This applies to several pixels along the edges of ISGRI's sub-modules, and would then provide again a distribution of Compton scattering angles (counts per azimuthal scattering angle bin), translating the initial measurement (counts per pixel and time modulo mask).

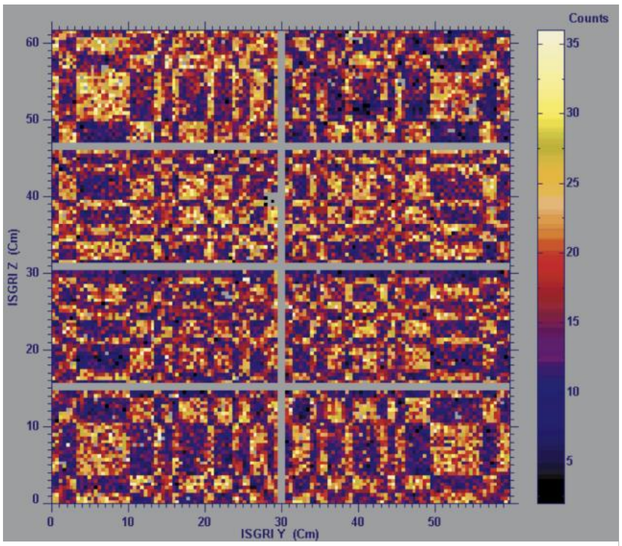


Figure 9: ISGRI shadowgram of an ~on-axis source (Lebrun et al. 2003, A&A 411, L141). The bottom panel shows the histogram of time differences for hits between two blocks, allowing for a clean cut in Compton-scattered events close to the block boundaries (grey stripes in the top panel).

A full forward modeling of this detailed data selection is challenging but will provide both, a cross-check between the classical IBIS 'Compton mode' and SPI polarization measurements, and a new approach to utilize the measured quantities directly, and infer polarization parameters directly.

Simulating such a response will result in pixel patterns for near-edge pixels as a function of source position, photon energy and redistribution, and polarization parameters. It should be noted, however, that the preceding data selection is critical and that this approach might not be adequate for off-axis sources [I think].

D3.2.4 Looking at 'old' instrument data: GAP/COMPTEL

The GAP instrument was the first dedicated GRB polarimeter to perform measurements in space. Despite its small size, the instrument performed polarization measurements for 7 GRBs. It is important to note here that only the results for 3 of these GRBs have been published to date as the other 4 measurements, although constraining in the parameter space, were not deemed precise enough by the instrument team. The analysis performed by the GAP team made use of the classical polarization analysis method described before. As GAP was designed as a dedicated GRB polarimeter and thus detailed instrument calibrations were performed, the GAP data is ideal for re-analysis using the method proposed here. Due to the inherently higher precision achievable with our method, we expect to produce measurement results with a higher precision for all 7 GRBs. The precision can be further improved by the fact that the majority of all these 7 GRBs were additionally measured by Fermi-GBM, allowing for a joint analysis and potentially detailed energy dependent polarization measurements. Initial discussions with the GAP team have taken place and they are positive towards the idea of re-analysis, particularly regarding the currently unpublished 4 GRBs. The GAP PI is member of our Advisory Board.

The COMPTEL instrument, flown between 1991-2000 on the Compton Gamma-Ray Observatory, was the first proper space detector based on Compton scattering, and thus was expected to provide unique measurements of the polarization in the 0.7-30 MeV band. Unfortunately, due to the combination of higher-than-expected gamma-ray background and poor (though best-possible at the time) instrument simulation and calibration, COMPTEL has significantly detected only a dozen sources plus two dozen GRBs, and polarization analyses always remained ambiguous. At MPE, we still maintain a workable database of the COMPTEL telescope, and recently have also dramatically improved upon the instrument simulation, allowing us to much better distinguish background from source photons (prior to Maximum-Entropy fitting). With our new analysis tools we are convinced that a new attempt of looking at the polarization properties of the Crab and Cyg X-1 is very promising.

(D4) Theoretical Modelling

We are developing a numerical tool that can calculate the observed polarization from a relativistically moving source with arbitrary geometry, velocity and magnetic field profile. Such a tool can be used to evaluate the polarization from a variety of systems. It can be used to fit the most probable magnetic field configuration and system parameters from the observed degree of polarization (DOP) and evolution in time of the electric vector position angle (EVPA).

Presently we can calculate the polarization from 2D surfaces propagating at relativistic velocities. The polarization can be calculated from arbitrary magnetic field configurations, spectral energy distribution (SED) of the emitted particles and velocity profiles. We can then fit the evolution with time of the DOP as well as the EVPA to observations of polarized radiation from GRB prompt and afterglow emissions (see Fig. 10). The tool can work on both analytic input as well as simulations data files.

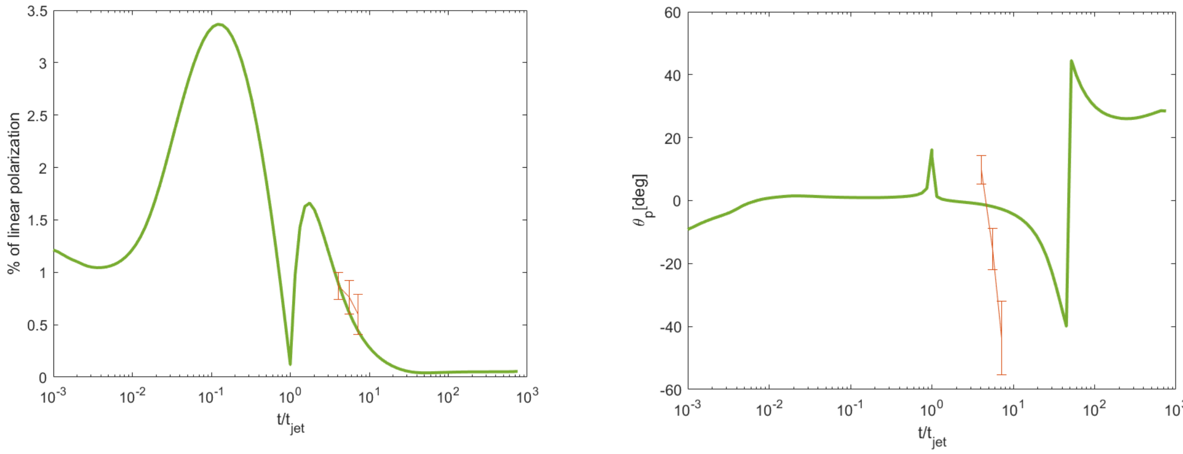


Figure 10: Present status of the modelling of the change of the degree of polarization DOP (left) and polarization angle EVPA (right) over time for the specific application of the gamma-ray burst GRB 190114C.

In the second stage we intend to generalize our tool to account for emission from 3D volumetric regions. If the source is moving at relativistic velocity, the observed emission at each time interval arrives from distinct surfaces (surfaces if equal arrival time), the shape of which is dictated by the velocity distribution in the system. These surfaces need to be calculated for each system independently. The calculation will be done following a similar method that was used by Bromberg et al. 2018 (MNRAS 475, 2971) and Nakar et al. 2018 (ApJ 867, 18). In order to account for line of sight effects through the 3D emitting region such as the synchrotron self-absorption or Compton scattering, which may also contribute to the polarization, we will implement a Monte-Carlo method to account for the effects from different regions in the system. The Monte-Carlo module will be developed separately from the polarization tool and will be implemented with it. The development of such a tool can help us to better understand the polarization from a broader set of objects such as SGRs giant flares, PWNs, extragalactic jets and more.

(D5) Attempt to gain new insight into sources

With (i) our new data analysis tools (proper statistics, multi-instrument fitting, improved data and response matrix formats), (ii) data handling and modelling tools (3ML, time-resolved, energy-resolved), and (iii) improved and new INTEGRAL calibration and data reduction tools we will be in a privileged position to obtain polarization measurements which are much more accurate (due to the better base knowledge) and precise (due to proper error propagation) than any measurements before. In addition, we will likely obtain time- and energy-dependent results per instrument, not being possible in the past. These new measurements will enable completely new physical questions to be asked. Together with our new theoretical modelling we will able to address these questions at a unprecedented level of physical depth. We anticipate that this will set the standard for future polarization measurements, and trigger completely new observational approaches to address the new questions we will pose. This may create also new theoretical challenges.

(D6) Serving the community: add tools, data and theory to archive

Possibly add what IXPE might gain from us? Also eXTP is interesting here since it is partly an ESA mission (approved for phase B by now + Geneva is involved). Launch is foreseen for 2027 and the polarimeter will be basically that of IXPE but 4 times larger.

(D7) Preparation for future missions

(lessons learned; what should future missions pay special attention to?)

- In the past each polarimeter mission started by 'reinventing the wheel' regarding the analysis method, this is both time consuming and resulted in many mistakes.
- Future missions can quickly start the analysis of their data thanks to the available tools.
- Additionally they will immediately know how to produce their data and response in such a way to allow for optimum data analysis.

(D8) Optimization of the POLAR-2 mission

POLAR-2 is the follow-up of the successful POLAR mission which produced the largest set of constraining GRB polarization measurements to date. POLAR-2 will start taking data in 2024 as the largest and most sensitive gamma-ray polarimeter with GRB polarimetry as the primary science goal. The POLAR-2 mission greatly benefits from the heritage of the POLAR mission and in particular the lessons learned from the analysis of the POLAR data.
We aim to optimize the scientific potential of this mission in 2 separate ways. The first is by building a framework based on the analysis tools developed in this project for the future analysis of the POLAR-2 data. POLAR-2 is an optimum candidate for this not only due to the time of its launch but

also as the analysis procedure described here is largely based on lessons learned from the POLAR mission. The aim is that as soon as data from POLAR-2 is downloaded to ground, analysis with the optimized open source tools can commence, forming the first future application of all the tools developed here. This not only ensures an efficient and transparent data analysis but also allows to advertise the work performed during the POLCA project.
Secondly, an important lesson learned from the POLAR project is the sensitivity of the polarization analysis on the spectral parameters of the observed source. In order to solve this issue the joined fitting of POLAR data with spectrometer data from Fermi-GBM was started which formed the basis of the future polarization tools we present here. Although the development of an optimized analysis procedure solves part of the problem, no spectral measurements were performed for the majority of the GRBs detected by POLAR. Large errors on polarization parameters are therefore induced by the lack of spectral data. A similar argument can be made for localization of the GRB. In order to overcome both problems, the MPE group has proposed to place a dedicated spectrometer on the POLAR-2 mission. Thanks to the heritage of this group with spectrometer development for space missions (Fermi-GBM, INTEGRAL-SPI) such detectors can be developed for a low cost while greatly enhancing the scientific performance of the POLAR-2 mission. Therefore, WP6 contains a task to develop such a spectrometer, and the corresponding budget is listed under "Other direct costs" (see Tab. 3.4b). Additionally, the access to dedicated spectral, location and polarization data from a single mission will allow us to test all the products developed during the POLCA project to its maximum effect within a year of the end of the funding period. Contributions to the POLAR-2 project will therefore fully ensure continued use of the applications developed here after the funding period ends.

- Where relevant, describe how *the gender dimension, i.e.* sex and/or gender analysis is taken into account in the project's content.

⚠ *Please note that this question does not refer to gender balance in the teams in charge of carrying out the project but to the content of the planned research and innovation activities . Sex and gender analysis refers to biological characteristics and social/cultural factors respectively. For guidance on methods of sex / gender analysis and the issues to be taken into account, please refer to http://ec.europa.eu/research/swafs/gendered-innovations/index_en.cfm?pg=home*

(D9) Gender dimension

The gender dimension in research and innovation content is an essential aspect of research excellence, as it increases the societal relevance of the knowledge produced, as well as technologies and innovations. Addressing sex and/or gender aspects is an emerging and important dimension of research in many scientific and technological fields, representing a valuable source of innovation. Most obvious fields include "applied" sciences such as health, demographic change, future transport and mobility or robotics. Also in space there are a number of relevant areas, including female astronauts or the diversity of future inhabitants on Moon and Mars. In our field of basic research the gender dimension comes down to the question of emotional intelligence, creativity, and critical reflection.

We do believe that intellectual capacity, and cognitivity of hitherto unknown facts and relations are equally distributed between men and woman. Yet, women are typically considered to possess higher emotional intelligence and creativity. This is particularly important in collaborative work as the one we propose here. Diverse teams are known to be more effective. Collaboration in (or with) a diverse team will drive innovation. In this context, diversity encompasses quite a wide range of properties, such as gender, race, religion or social and cultural style and habits. Each of these properties leads to different viewpoints, forcing more discussion, and thus more collaborative communication. A short-hand version of this connection is the statement that “women promote collaboration” (Bear & Woolley 2011, Interdisc. Sci. Ret., Vol. 36, p. 146).

Another aspect in research is that innovation, when reached in a collaborative environment, creates equity (Misra et al. 2017, Soc. Sci. 6, p. 25) in the collaboration itself, but also in its broader environment by not promoting egos to grow. With more equity easing more collaboration, the circle closes. The consequence is that a team is scientifically strenghtend by having diverse viewpoints (including women), and this in turn promotes future equity.

One particular application for our collaboration will be the cultural differences with respect to our collaborating partner country Israel. As described above, we consider this part of the diversity and thus beneficial for our collaborative communication style. We do will pay special attention to e.g. different opportunities and constraints in the mobility concerning mutual research visits.

1.4 Ambition

- Describe the advance your proposal would provide beyond the state-of-the-art, and the extent the proposed work is ambitious.
- Describe the innovation potential **(e.g. ground-breaking objectives, novel concepts and approaches, new products, services or business and organisational models)** which the proposal represents. Where relevant, refer to products and services already available on the market.

The goal of our proposal is to enable the measurement of high-energy polarization which, we note, has been attempted in the past. Our ambition exceeds the current state-of-the-art and these past attempts in three notable ways:

- we present a generic framework for all high-energy polarization analysis
- we provide usable, public models for the community to test their own theory and data
- our work and software are open source providing the community the ability to improve and scrutinize our approach.

The last ~40 years have seen an unprecedented gain in knowledge due to the instrumentation, methodology, and the availability of high-energy spectroscopic data analysis tools such as XSPEC. Our understanding of relativistic and nuclear physical processes from these advancements has been made even deeper with the new multi-wavelength era by extending measurements of astrophysical phenomena across the electromagnetic spectrum. However, we have yet to extract all the information carried across the Universe from the photon messengers. Now we bring that frontier to science of high-energy polarization.

In fact, some of the most important signatures of physical processes is locked away in the *polarization* of these photons. While there exist instruments designed to measure polarization, both still active and retired, the extraction of these signals from the data have been hampered by multitude of issues including the difficultly in measuring high-energy polarization, the unavoidable lack of a large number of photons at high-energy, lack of open access to the data and analysis tools, as well as relatively immature analysis techniques. Thus, polarization is the last frontier in high-energy electromagnetic science as well as a modern challenge on many fronts.

Our proposed task is to eliminate the burdens of the past, develop tools for the future and apply these advances to past data providing a tested framework for future missions. We will leverage the well-proven heritage of the high-energy spectroscopy field to develop open, accessible tools, databases, and methodology enabling a critical mass of astronomers the ability to analyze sources with their chosen physical models, extending the success of the last 40 years in X-ray spectroscopy to a virtually untapped innovation potential.

2. Impact

2.1 Expected impacts

⚠ *Please be specific, and provide only information that applies to the proposal and its objectives. Wherever possible, use quantified indicators and targets.*

The expected impact from the call – we should mention each of these:

"A higher number of scientific publications based on Europe's space data, high-level data products made available through appropriate archives, and tools and methods developed for the advanced processing of data. Proposals are also expected to add value to existing activities on European and international levels, and to enhance and broaden research partnerships."

- Describe how your project will contribute to:
  - each of the expected impacts mentioned in the work programme, under the relevant topic;
  - any substantial impacts not mentioned in the work programme, that would enhance innovation capacity; create new market opportunities, strengthen competitiveness and growth of companies, address issues related to climate change or the environment, or bring other important benefits for society

    impact on other mission's instruments

    encourage community to do open source research

- Describe any barriers/obstacles, and any framework conditions (such as regulation, standards, public acceptance, workforce considerations, financing of follow-up steps, cooperation of other links in the value chain), that may determine whether and to what extent the expected impacts will be achieved. (This should not include any risk factors concerning implementation, as covered in section 3.2.)

  Data format standard

  We hope that our results will be accepted by the instrument PIs…

The measurement of polarization provides an impact far beyond its face value due to the fact that polarization information uniquely allows for an observer to infer properties about the physical and magnetic geometry of the emitting object. There then exists secondary multipliers of impact on other EU observatories. For example, the ability to measure high-energy polarization from blazars via archival data from EU-member-states- and ESA-funded instruments such as INTEGRAL improves our understanding of these object's jet geometry and magnetic field strengths. The EU-funded KM3NeT neutrino observatory can use this complimentary information to build more precise models for the expected neutrino emission from blazars. As neutrino detection is dominated by local backgrounds, having the information from polarization enables the use of highly predictive models which allows for signals to be identified in the backgrounds. Thus, the impact of our proposed program extends far beyond the project.

In the same light, measurement of polarization from GRB jets helps to identify the extent of their jet opening angles. With the recent connection of short GRBs to neutron star mergers (detected via gravitational waves) and the associated infrared/optical kilonova, understanding the opening angle of these jets is a direct measurement of their population detectability. There are many EU/ERC/Marie-Curie funded programs (e.g. TEDE, TReX, JetNS, PHAROS, GWVerse, BinGraSp, MAGNESIA) focused on searching for kilonovae (either via ESO's telescopes or those national facilities for which access is granted via OPTICON) or understanding the related physics of GRBs or gravitational waves. Thus, using polarization measurements to understand the physical geometry of GRB jets supplements the high-impact science of other EU observatories directly.

2.2 Measures to maximise impact

a) Dissemination and exploitation[1] of results

- Provide a draft '**plan for the dissemination and exploitation of the project's results'**. Please note that such a draft plan is an admissibility condition, unless the work programme topic explicitly states that such a plan is not required.

  Show how the proposed measures will help to achieve the expected impact of the project

  The plan, should be proportionate to the scale of the project, and should contain measures to be implemented both during and after the end of the project. For innovation actions, in particular, describe a credible path to deliver these innovations to the market.

⚠ *Your plan for the dissemination and exploitation of the project's results is key to maximising their* ***impact****. This plan should describe, in a concrete and comprehensive manner, the* ***area*** *in which you expect to make an impact and* ***who*** *are the potential users of your results. Your plan should also describe* ***how*** *you intend to use the appropriate channels of dissemination and interaction with potential users.*

⚠ *Consider the full range of potential users and uses, including research, commercial, investment, social, environmental, policy-making, setting standards, skills and educational training where relevant.*

⚠ *Your plan should give due consideration to the possible* ***follow-up*** *of your project, once it is finished. Its exploitation could require additional investments, wider testing or scaling up. Its exploitation could also require other pre-conditions like regulation to be adapted, or value chains to adopt the results, or the public at large being receptive to your results.*

MPE's PR representative will not provide support, neither for the proposal, nor later for dissemination/propaganda: could we get support from UNIGE/TelAviv??

- Include a business plan where relevant.
- As relevant, include information on how the participants will manage the research data generated and/or collected during the project, in particular addressing the following issues:
  - What types of data will the project generate/collect?
  - What standards will be used?

[1] See participant portal FAQ on how to address dissemination and exploitation in Horizon 2020

- How will this data be exploited and/or shared/made accessible for verification and re-use? If data cannot be made available, explain why.
- How will this data be curated and preserved?
- How will the costs for data curation and preservation be covered?

⚠ *Actions under Horizon 2020 participate in the extended 'Pilot on Open Research Data in Horizon 2020 ('open research data by default'), except if they indicate otherwise ('opt-out'.)*[2]*. Once the action has started (**not** at application stage) those beneficaries which do not opt-out, will need to create a more detailed Data Management Plan for making their data findable, accessible, interoperable and reusable (FAIR).*

⚠ *You will need an appropriate consortium agreement to manage (amongst other things) the ownership and access to key knowledge (IPR, research data etc.). Where relevant, these will allow you, collectively and individually, to pursue market opportunities arising from the project's results.*

⚠ *The appropriate structure of the consortium to support exploitation is addressed in section 3.3.*

- Outline the strategy **for knowledge management and protection**. Include measures to provide **open access** (free on-line access, such as the 'green' or 'gold' model) to peer-reviewed scientific publications which might result from the project[3].

⚠ *Open access publishing (also called 'gold' open access) means that an article is immediately provided in open access mode by the scientific publisher. The associated costs are usually shifted **away from readers, and instead (for example) to the university or research institute to which the** researcher is affiliated, or to the funding agency supporting the research. Gold open access costs are fully eligible as part of the grant. Note that if the gold route is chosen, a copy of the publication has to be deposited in a repository as well.*

⚠ *Self-archiving (also called 'green' open access) means that the published article or the final peer-reviewed manuscript is archived by the researcher - or a representative - in an online repository before, after or alongside its publication. Access to this article is often - but not necessarily - delayed ('embargo period'), as some scientific publishers may wish to recoup their investment by selling subscriptions and charging pay-per-download/view fees during an exclusivity period*

The raw data which we plan to re-analyse are archived at the ISDC (INTEGRAL Science Data Center) in Geneva as well as within ESA/ESOC (European Space Operations Centre). We plan to add our processed data as well as the necessary auxiliary data (simulations, response matrices) to this data base. ESA has started planning for both, an extended science archive, as well as a new data query form, commonly called DataLab. If this project proposal is accepted, we will immediately contact ESA in order to support the definition of these new facilities, in order to make sure that polarization parameters can be ingested as well. We anticipate that after the end of this project, ESA will take care of preserving and curating our results and tools. Also, since it will be part of the larger INTEGRAL catalogue/data access, there will be little additional costs, which we anticipate ESA to cover. Direct contact to the INTEGRAL science project is guaranteed through its Project Scientist being member of our Advisory Board.

[2] Opting out of the Open Research Data Pilot is possible, both before and after the grant signature. For further guidance on open research data and data management, please refer to the H2020 Online Manual on the Participant Portal.

[3] Open access must be granted to all scientific publications resulting from Horizon 2020 actions (in particular scientific peer reviewed articles). Further guidance on open access is available in the H2020 Online Manual on the Participant Portal.

We will be happy to participate in the Open Research Data Pilot program under H2020. A large part of our impact does hinge on making our software analysis tools publicly available, and thus we will plan for a Data Management Plan as an early deliverable. As to open-access publications, we are all for it, but we note that (i) the Max-Planck Society has a special agreement with EDP Sciences (which publishes our default journal "Astronomy & Astrophysics") which covers all Gold open access costs from Max-Planck authors, (ii) the journal "Astronomy & Astrophysics" publishes articles in the sections "Astronomical instrumentation", "Catalogs and data" and "Numerical methods and codes" in free access at no cost to authors. Since this covers 90% of our anticipated publication costs for free access, we only add costs for two theoretical papers in our budget below.

As all our work is meant to foster science and deepening the understanding of the physical processes in the astrophysical sources we observe, we plan to make all results and tools publicly available after the end of this project. Thus, there is nothing like "knowledge protection". Quite the opposite is true: we want the astrophysical community to adopt (and potentially further develop) our tools.

b) Communication activities[4,5]

- Describe the proposed communication measures for promoting the project and its findings during the period of the grant. Measures should be proportionate to the scale of the project, with clear objectives. They should be tailored to the needs of different target audiences, including groups beyond the project's own community.

We plan several different communication measures, each tailored at a specific audience:

1) Scientific publications: these are directed to the (high-energy) astrophysics community and shall describe the main scientific results. This will include separate publications on the analysis methodology, the developed software, as well as on separate source types (foremost GRBs and the Crab).
2) Conferences/Workshops: we plan the organisation of one or two major workshops for the (high-energy) polarization community to a) show work in progress, b) get more (free) input, c) spread our knowledge and make polarisation measurements valuable and popular
3) Internet outreach: we plan a dedicated homepage for introducing the team, describing the (long-term) goals, and providing frequent updates on major milestones.
4) We intend to also use social media (twitter, facebook, Instagram) to popularize our research topic, and reach-out to polarization aficionados in other wavelength domains as well as data analysis and/or statistics groups.
5) We plan to continue our past engagement with the general public through public talks in existing talk series like "Modern Physics" in Munich, or "astronomy-on-tap" which exist in Munich and Tel Aviv.

[4] See participant portal FAQ on how to address **communication activities** in Horizon 2020

[5] For further guidance on communicating EU research and innovation for project participants, please refer to the H2020 Online Manual on the Participant Portal.

3. Implementation

3.1 Work plan — Work packages, deliverables

We structure our work plan into 8 work packages (WPs). One WP will be solely dedicated to all data and software aspects, which are not instrument-specific (WP1), including data and response format, 3ML, Virtual Observatory interface, and the newly-to-develop energy-resolved polarization. Then we have two WPs with instrument-specific developments, one each for IBIS (WP2) and SPI (WP3), including calibrations, response generation/simulation, and the plugins for 3ML. Next, there is one WP to use the tools for re-analysis of all the INTEGRAL data (WP 4). WP5 covers the theoretical modelling of polarization in jet sources. Finally, a separate WP is devoted to applications beyond INTEGRAL, i.e. looking at the data of the previous COMPTEL mission, and looking ahead to our approved POLAR-2 mission, including a test-setup development for its new polarimeter. Two WPs will cover the management and the outreach/dissemination aspects, so in summary, our proposed structure looks as follows:

0. Management
1. Software Development
2. Polarization with the INTEGRAL/IBIS instrument
3. Polarization with the INTEGRAL/SPI instrument
4. Archival Analysis of published sources
5. Modelling
6. Application
7. Outreach and Dissemination

Full details including the various sub-packages are given in the 8 pages of Tab. 3.1b. A graphical presentation of these WPs and their inter-relations is given in the following figure.

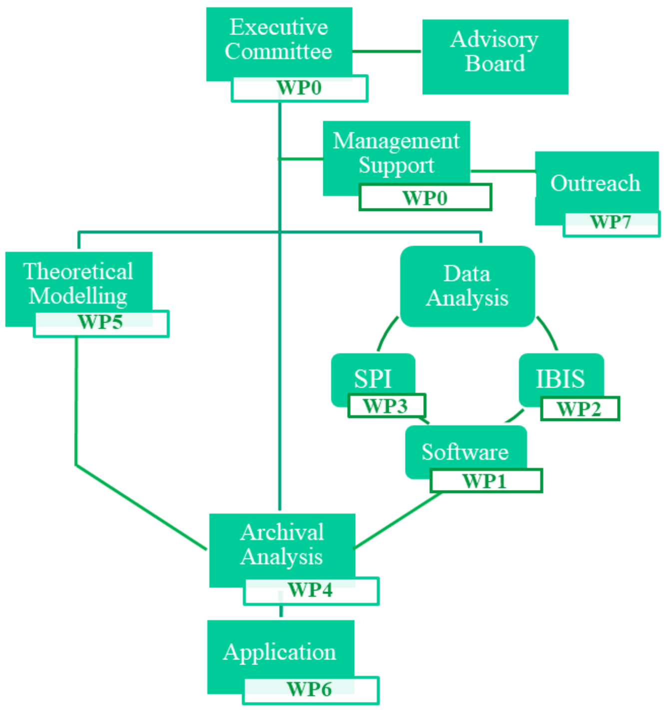


Figure 11: General structure of the work plan and inter-relation of the various work packages.

The timing of the different WPs is rather simple: WP1 should be the first priority in order to establish the tools, and WP2 and WP3 can thereafter be done in parallel (consistent with different groups being responsible for the two different detectors). The theoretical modelling will be ongoing all the time, with little influence on the other WPs until the last year. The detailed account of the allocated work load for each sub-WP and the corresponding assignment to one of the three participating groups including the distinction between PhD and post-doc assignment based on the complexity of the work is given in the table below. A Gantt chart showing the time flow of the WPs including all the separate sub-WPs is given in the figure on the next page.

Detailed assignment of work-packages to personnel (units: man-months).

Work Package	**MPE**			**UNIGE**		**Tel Aviv**	
	Managem.	PD	PhD	PD	PhD	PD	PhD
WP0	21						
WP1.1		2		2			
WP1.2		2		2			
WP1.3				2			
WP1.4		2					
WP1.5		2					
WP1.6		1	2	1	1		
WP1.7		1		1			
WP2.1				5	8		
WP2.2				5	7		
WP2.3		2					
WP2.4				1	10		
WP2.5				15	15		
WP3.1		8	10				
WP3.2		7	10				
WP3.3		2					
WP3.4		7	13				
WP4.1		1		1		1	
WP4.2		1	2				
WP4.3					2		
WP4.4					2		
WP4.5			2			1	
WP5.1		1		1		32	
WP5.2							32
WP5.3						10	10
WP5.4						3	6
WP6.1		1	3				
WP6.2				1	3		
WP6.3		1					
WP7.1				1			
WP7.2						1	
WP7.3		1					

The most challenging tasks are (1) the development of the polarization response for IBIS incl. the development of the new ISGRI-only method, (2) the development of the polarization response for SPI, and (3) the design and physical implementation of the new radiation code. Each of these tasks requires an experienced post-doctoral researcher. The assignment of the theory post-doc to Tel Aviv is obvious; for the two polarization responses we have split the responsibility between MPE (for SPI) and UNIGE (for IBIS). Most of the other tasks can be handled by clever PhD students (under supervision of the institutes senior staff and working closely with the post-doctoral researchers), and again we split the tasks (though this happens quite naturally) such that one PhD student each goes to one of the three participating nodes. The detailed distribution of the various tasks to the 6 individual researchers is presented in the table above.

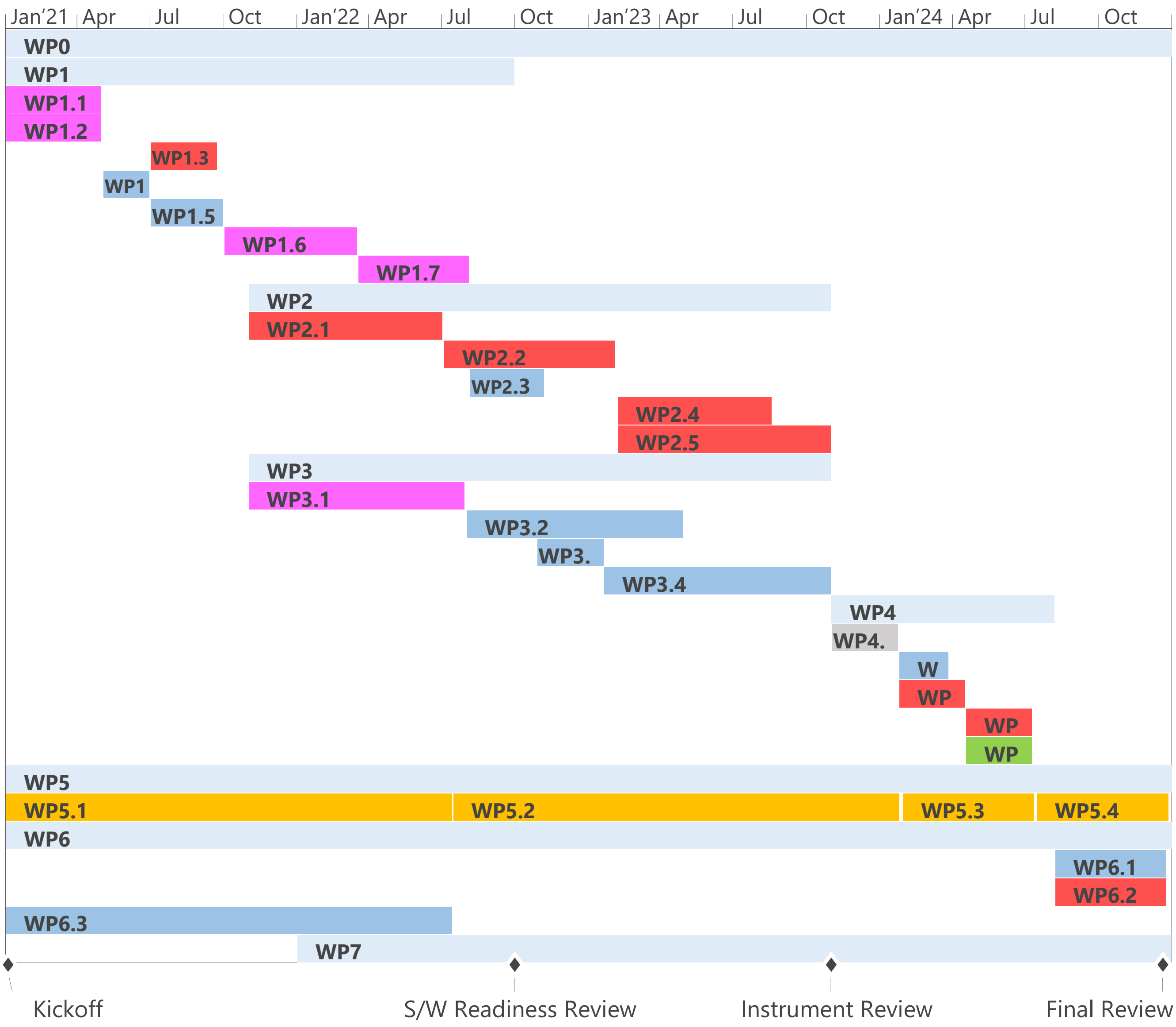


Figure 12: Gantt chart of the timing of the work packages. The main work packages W0-W7are shown in light blue. For the sub-WPs the contribution of the 3 nodes is coded, with the base colors blue (MPE), red (UNIGE) and yellow (Tel Aviv) showing sub-WPs to be executed by single nodes, and the corresponding additive color for collaborative sub-WPs (pink for MPE+UNIGE, green for MPE+Tel Aviv, and gray for MPE+UNIGE+Tel Aviv. Since each node plans to fund 1 post-doc and 1 PhD student, the length of the bars does not reflect the exact number of man-months, but rather the duration over which the work should be executed (most obviously for WP0 and WP7, where a few man-months are distributed over the full duration of the project).

Management section

Please provide the following:

- brief presentation of the overall structure of the work plan;
- timing of the different work packages and their components (Gantt chart or similar);
- detailed work description, i.e.:
  - a list of work packages (table 3.1a);
  - a description of each work package (table 3.1b);
  - a list of major deliverables (table 3.1c);
- graphical presentation of the components showing how they inter-relate (Pert chart or similar).

⚠ *Give full details. Base your account on the logical structure of the project and the stages in which it is to be carried out. The number of work packages should be proportionate to the scale and complexity of the project.*

⚠ *You should give enough detail in each work package to justify the proposed resources to be allocated and also quantified information so that progress can be monitored, including by the Commission*

⚠ *Resources assigned to work packages should be in line with their objectives and deliverables. You are advised to include a distinct work package on 'management' (see section 3.2) and to give due visibility in the work plan to 'dissemination and exploitation' and 'communication activities', either with distinct tasks or distinct work packages.*

⚠ *You will be required to include an updated (or confirmed) 'plan for the dissemination and exploitation of results' in both the periodic and final reports. (This does not apply to topics where a draft plan was not required.) This should include a record of activities related to dissemination and exploitation that have been undertaken and those still planned. A report of completed and planned communication activities will also be required.*

⚠ *If your project is taking part in the Pilot on Open Research Data, you must include a 'data management plan' as a distinct deliverable within the first 6 months of the project. A template for such a plan is given in the guidelines on data management in the H2020 Online Manual. This deliverable will evolve during the lifetime of the project in order to present the status of the project's reflections on data management.*

Definitions:

'Work package' means a major sub-division of the proposed project.

'Deliverable' means a distinct output of the project, meaningful in terms of the project's overall objectives and constituted by a report, a document, a technical diagram, a software etc.

3.2 Management structure, milestones and procedures

3.2.1 Organisational structure

- Describe the organisational structure and the decision-making (including a list of milestones (table 3.2a))
- Explain why the organisational structure and decision-making mechanisms are appropriate to the complexity and scale of the project.

We anticipate that in addition to the five scientists funded through this H2020 program, there will be another 8-10 scientists involved in the various aspects of this activity. This includes technical staff for software development or executing simulations, supervisors of the PhD students, but also senior scientists for topics like connecting to ESA-internal infrastructure development (data format, data access, data storage), or links to other future (IXPE) or past (COMPTEL) instrumentation. In order to facilitate a quick decision process, foster tight connection to ESA's INTEGRAL project management team, and to allow for efficient management, we take the following measures:

1. **Project Coordinator:** the project coordinator (PC) is based at the coordinator institute (MPE) and is responsible for the organization of the administrative and scientific activities of the overall project. He will act as point of contact between the consortium and the European Commission and will ensure an efficient communication and dissemination of information between all parties. Moreover, the PC will monitor the development of the project, the time schedule, the quality of the work and of the documentation produced by each project unit and take actions to recover from eventual deviations from the planned schedule.
2. We plan for **management support** for the PC which will also coordinate the outreach and dissemination work (budgeted with 0.5 FTE over 3.5 years).
3. **Executive Committee:** we have agreed to form an Executive Committee (EC), which will consist of one representative of each of the three participating nodes. The EC will discuss and decide upon the most relevant and urgent project directives. Considering that each participant is based in a single physical place, critical issues can be efficiently discussed within each participating team before the final discussion restricted to the SEB (e.g. in a teleconference). It is expected that decisions will be taken by a general consensus; otherwise, decisions will be based on a majority vote with the PC having a casting vote.
4. **Advisory Board:** We have also opted to assign an Advisory Board for our activity, comprising the following members:

Name	Function	Benefit for this action
Dr. Erik Kuulkers (ESA)	INTEGRAL Project Scientist	Support in INTEGRAL and science related questions; coordination of software compatibility; Curation of data and products beyond this activity
Prof. Nicolas Produit (ISDC)*	INTEGRAL IBIS Calibration Team	Specialized knowledge of IBIS instrument
Prof. Daisuke Yonetoku (Kanazawa University, Japan)	Principal Investigator of GAP	Specialized knowledge of instrumental issues of a Compton Polarimeter

*ISDC = INTEGRAL Science Data Center

The over-arching goal of having this Advisory Board is to ensure that the proposed polarization analysis is done with the broadest support of the high-energy astrophysics community, and to coordinate with efforts at ESA for a future data archive structure, called DataLab. We plan to make our analysis as well as the software easily available for future use, and an ESA-developed structure is the most appropriate for INTEGRAL (being an ESA mission) data.

5. Routine **teleconferences** and **consortium meetings** will be held, where all the members are invited to participate and present their work. will be organized with the following schedule:
6. In addition, we will establish an **email list** for the distribution of generic information important for everyone, but also a number of **Slack channels** for quick, but archived and searchable communication on dedicated sub-topics.

Given that the size of the combined project group (6 scientists requested here for funding, plus about 6-9 scientists at the three institutes) is about 12-15 scientists, these management methods and communication channels are considered fully appropriate. There are very few management decisions to be taken, so more complex methods are not needed.

3.3.2. Innovation management

- Describe, where relevant, how effective innovation management will be addressed in the management structure and work plan.

➢ *Innovation management is a process which requires an understanding of both market and technical problems, with a goal of successfully implementing appropriate creative ideas. A new or improved product, service or process is its typical output. It also allows a consortium to respond to an external or internal opportunity.*

This activity, while proposed as a standalone project, is not defined by one (or more) parameter or the preference of one (or more) astrophysicist, but is intended to serve as a tool for the larger community. High-energy data analysis is not as easy as many think, due to many subtle effects which change the properties of the measured count ensemble. Also, 20-year old ‘standard-tools’ (as presently available for INTEGRAL) cannot provide reliable results, as they are based on biased procedures or compute-power-saving mathematical procedures. One classical example is the iterative source removal in the INTEGRAL/SPI analysis (so-called spiros task), which introduces large systematic uncertainties for observations of weak sources. Polarisation analysis is even more difficult as there are nearly no available tools to do this analysis. In addition, it requires computationally expensive simulations of how the instrument responds to polarisation which were not technically possible at the launch of the mission. The proper statistical treatment of soft gamma-ray polarisation data is still in its infancy. (We have shown with the POLAR paper of how this could work, and why most of the previous things were badly designed, e.g. “150%” polarisation!).

Since we intend to provide an XSPEC-like polarization analysis environment, including data acquisition from open-access data archives (INTEGRAL), for any user, we need to make sure that our tools will be accepted by the community. For this to happen, we will

➢ keep very tight contact to the INTEGRAL instrument teams,
➢ contact selected instrument team members to verify and approve our approach,
➢ provide jupyter-style demonstration analysis, so anyone can repeat our analysis within a day,
➢ get outside-the-box suggestions from our Advisory Board
➢ by enhancing our POLAR software package prepare the analysis tools for POLAR-2, so our deliverables can demonstrate to stand the test-of-life at the end of this activity (the launch of POLAR-2 is presently planned a few months before the end of this project)
➢ provide generic templates for other collaborations to include in their pipeline

This approach should guarantee that current and future instruments, capable of measuring polarisation in the high-energy regime, will benefit immediately from our tools.

3.3.3. Risks

- Describe any critical risks, relating to project implementation, that the stated project's objectives may not be achieved. Detail any risk mitigation measures. Please provide a table with critical risks identified and mitigating actions (table 3.2b)

Definition:

> *'Milestones' means control points in the project that help to chart progress. Milestones may correspond to the completion of a key deliverable, allowing the next phase of the work to begin. They may also be needed at intermediary points so that, if problems have arisen, corrective measures can be taken. A milestone may be a critical decision point in the project where, for example, the consortium must decide which of several technologies to adopt for further development.*

As science is the exploration of the unknown, any scientific endeavour is not without risk. Though, not discovering polarization in any of the sources/data that we explore is also an important finding: It is possible that with any statistically and physically robust framework which we develop, the data are not powerful enough to make a conclusive statement. The research teams accept this possibility but also recognizes that the value of properly developing a framework far exceeds the task at hand. Indeed, the first X-ray spectrometers developed did not possess the sensitivity or spectral resolution required to make definitive statements about emission processes. Nevertheless, the techniques and software developed to analyze these data are still of great value today. Similarly, the POLCA deliverables possess a long-standing value that provide a foundation for future instruments and experiments.

Another associated risk with the project is that in our research it may be impossible to locate and or fully replicate the response of some of the instruments in our study. In this case, the risk would be mitigated by using approximations for these responses which combine both our experience with the instrument themselves as well as gathered knowledge from other instruments in the studies. Nevertheless, such a lack of knowledge would have direct impacts on the quality of our results. This in turn can be used to inform the construction an experimental design of future instruments. A managerial mitigation action that we have taken is to connect the INTEGRAL Project Scientist via our Advisory Board to the POLCA project. This ensures that the INTEGRAL project and its instrument teams are interested in our work, and that e have direct contact to all instrument specialists in case of questions.

3.3 Consortium as a whole

⚠ *The individual members of the consortium are described in a separate section 4. There is no need to repeat that information here.*

- Describe the consortium. How will it match the project's objectives, and bring together the necessary expertise? How do the members complement one another (and cover the value chain, where appropriate),?

- In what way does each of them contribute to the project? Show that each has a valid role, and adequate resources in the project to fulfil that role.

The POLCA Consortium brings together high level expertise in different fields, mainly in high-energy astrophysics (both, observation and theory), computer science, and statistics, all focused on the same objective of fully exploiting data from the INTEGRAL mission to study the polarization of gamma-rays from cosmic sources.
blabla

3.4 Resources to be committed

⚠ *Please make sure the information in this section matches the costs as stated in the budget table in section 3 of the administrative proposal forms, and the number of person months, shown in the detailed work package descriptions.*

Please provide the following:

- a table showing number of person months required (table 3.4a)
- a table showing 'other direct costs' (table 3.4b) for participants where those costs exceed 15% of the personnel costs (according to the budget table in section 3 of the administrative proposal forms)

For all participants, costs have been divided into direct and indirect costs. Direct costs have been split up into two types of costs: personnel costs and travel & other costs. Personnel costs have been calculated according to the individual personnel rates supplied by each partner. Since official rates do not exist yet beyond 2021, a 2% increase has been assumed. PhD students in Germany and Switzerland get about 300 Euro/month less in their first year, thus the difference between the first and second year is larger than 2%. The nominal duration of PhDs at MPE is presently 3.5 years, so we also budget only for 3.5 years.

The overall budget of the POLCA project over the full 48 months duration, as reported on the A3 form, is 3.56 MEur, and the requested grant from the EC is 1.99 MEur. The total effort dedicated to the project is equal to 291 (requested from EC) + 231 (own contribution) = 522 person-months.

Breakdown by type of activity: A percentage of total costs equal to 92% (prior to overhead) will be allocated to the core RTD activities (including WP1-WP6). Dissemination activities (WP7, including implementation of a didactic projects) account for 2% of total costs. Management activities (WP0) are budgeted at 6% of the total costs (the staff specifically dedicated to the project, involved in the daily coordination and the reporting of the project).

Breakdown by cost factors: The above mentioned resources will be integrated to give to POLCA the necessary critical mass to achieve the project milestones and deliverables. All the resources have been estimated analytically per cost category.

The net costs (prior overhead) will cover:

Personnel costs (1,37 MEur, 83%): they represent the main share of the budget. The allocation of person-months to the different partners reflects the activities they will carry out within the project. The overall effort of the project is 522 person months, 291 for new personnel hired specifically for the implementation of the project, with different levels of qualification and experience according to different needs, and 231 from the personnel working in the different partner organizations (see table below).

Other direct costs (279.200 Euro, 17%): they include:

* Travel costs (10.800 Euro per node) provide, for each partner, the necessary budget for participating to the pre-planned project meetings (Kick-off at Month 1, Consortium meetings at months 12, 24 and 36, as well as a final informal meeting during an International Workshop dedicated to the release of our products to the Community). Although we will make extensive use of teleconference systems as well as of web-based information exchange systems, we also foresee temporary visits and exchange of researchers between the participating sites. We budget 750 Euro per flight, and 120 Euro per accommodation, i.e. 1350 Euro per 5-day visit of one person. We account for 4 travels per node, for each of the two EU-funded scientists. The share of the travel costs for dissemination activities, i.e. allowing partners to participate at conferences in order to present the status and the preliminary results of the project, as well as the travel costs for the institutional team members, will be covered by the institutions.

* Equipment costs (175.000 Euro) include hardware to the spectrometer for POLAR-2. This exclusively covers the extra costs for the add-on detector in order to allow the measurement of the GRB position and spectrum. We do not request support for computing facilities: Computer hardware (workstations and PCs) will be covered by the host institutions. Also, core data analysis will be performed on high performance computing facilities already available to the partner institutions.

* Gold Open access: As described above (sect. 2.2), we only budget for two theoretical publications (assigned to Tel Aviv) which are not covered by the EDS publication rules and/or the special contracts with the Max-Planck Society. We use the latest number available (i.e. 2019 EDS price): 1900 Euro per publication.

* Other specific costs (16.000 Euro): 10.000 Euro are requested for UNIGE for the organization of the final International Workshop in Switzerland (mainly aimed at covering expenses for invited speakers). 2.000 Euro are requested for each participant to prepare material (booklets, handbooks, flyers) for didactic activity in Switzerland, Germany and Israel, as well as for outreach to general audience (Astronomy-on-tap, etc).

<u>Partner's resources which will complement the EC contribution:</u> The main contribution provided by participants are (i) the personnel costs of the institutional team members, (ii) travel money of the institutional team members, and (iii) the use and share of their own laboratories and facilities to carry out the foreseen research activities, in particular the high performance computing facilities needed to carry out the systematic analysis and simulation of the instrument responses. A rough estimate gives 1.575 kEur; a break-down is given in the table below.

	Institutional Personnell & costs (kEur / year) times the fraction spend for the project	Travel cost for institutional team members (kEur / year)	Cost of Resources (kEur / year)
MPE	Greiner 120x30% Burgess 90x50% PhD student 50x100%	2.7 2.7 2.7	10 10

UNIGE	Kole Produit PhD student	110x30% 120x30% 75x100%	2.7 2.7 2.7	10
Tel Aviv	Bromberg Nakar PhD student	40x30% 50x15% 25x100%	2.7 2.7 2.7	10 10

Tables for section 3.1

Table 3.1a: List of work packages

2 persons/node: MPE – 2x 3.5 yrs + 21 mm Managm.; Geneva – 1x 3.5 + 1x 4yrs; Tel Aviv – 2x 4 yrs: total person months = 291

Work package No	Work Package Title	Lead Participant No	Lead Participant Short Name	Person-Months	Start Month	End month
0	Management	1	MPE	21	1	48
1	Software development	1	MPE	21	1	24
2	IBIS	2	UNIGE	68	1	48
3	SPI	1	MPE	62	1	48
4	Archival analysis	2	UNIGE	12	25	48
5	Theoretical Modelling	3	TelAviv	95	1	48
6	Past and Future	2	UNIGE	9	25	48
7	Outreach	Volunteer?		3	12	48
				Total person-months: 291		

Table 3.1b: Work package description

Work package number	0	**Lead beneficiary**			MPE		
Work package title	Management						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TelAviv				
Person months per participant:	21	0	0				
Start month	1			**End month**	48		

Objectives: Guarantee the execution of the scheduled tasks, the creation of the deliverables, the interactions of all parties involved, and the timely reporting to the EC.

Description of work

This WP is led by the project coordinator (PC), supported by the team leaders of the other two participating institutions, and the administrative staff of the hosting institutes. The main tasks are the following:

Task 0.1: Project Management (coordination and monitoring): The administrative coordination between the different participants will be guaranteed mainly through routine teleconferences, Slack channels, and yearly Consortium meeting. A password restricted area of the POLCA website will be created and maintained as repository of internal documentations.
Task 0.2: Financial management: Organize the budget and cash flow plan, produce the required financial reports according to EU requirements.
Task 0.3: Advisory Board (AB): Maintain communication with the Advisory Board in both directions (inform AB about progress; receive suggestions/criticism from AB).
Task 0.4: Interface between partners and Commission: Activate administrative procedures relating the participant partners and preparation of the required reports according to EU requirements. To officially start the project, a kick-off meeting with the Consortium and the EC will be organized.
Task 0.5: Innovation Management: Organize discussions and decision-making process for final delivery of tools and data products to ESA. Guarantee appropriate instructions for use by external groups. Prepare follow-up use by POLAR-2 team.

Deliverables

D0.1 First year administrative/financial report (T_o + 12 months)

D0.2 Second year administrative/financial report (T_o + 24 months)

D0.3 Final administrative/financial report (T_o + 48 months)

Work package number	1	**Lead beneficiary**		MPE			
Work package title	Software Development						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TelAviv				
Person months per participant:	12	9	0				
Start month	1			**End month**	24		

Objectives: Design polarization data format and develop software for the analysis of IBIS&SPI and the corresponding interfaces (3ML, archive, VO).

Description of work (where appropriate, broken down into tasks), lead partner and role of participants

Task 1: Data format definition for polarization data
Task 2: Definition of polarization response "matrix"
Task 3: Virtual-Observatory interface to data
Task 4: 3ML simulation and documentation (potential early deliverable)
Task 5: Derivation of proper statistics
Task 6: Energy-resolved polarization analysis (potential early deliverable)
Task 7: Software Manual

Deliverables (brief description and month of delivery)

D1.1 Data Management Plan. T_o + 6 months

D1.X Software Manual

Work package number	2	Lead beneficiary			UNIGE		
Work package title	Polarization with the INTEGRAL/IBIS instrument						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TelAviv				
Person months per participant:	2	66	0				
Start month	1			**End month**	48		

Objectives: Simulation and calibration of the instrument modes, and generation of polarization response matrices. Preparation of the plugin for 3ML. Preparation of the software for the polarization analysis, including a completely new method with ISGRI-only Compton-scattered events.

Description of work

Task 1: Calibration: Simulate energy-dependent polarization response, cross-correlate with Crab results (spectrum, normalization); Determine predicted modulation as function of energy
Task 2: Response generation: Over time, 4 of the 19 detectors failed, so there are 5 detector configurations for which a response has to be derived via simulations.
Task 3: Plugin for 3ML
Task 4: Polarization analysis part I: "canonical" analysis using ISGRI and PICsIT
Task 5: Polarization analysis part II: new method with ISGRI-only

Deliverables (brief description and month of delivery)

D2.1 – list of sources for which IBIS/SPI polarization analysis will be made. T_o+12 months.

Work package number	3	**Lead beneficiary**			MPE		
Work package title	Polarization with the INTEGRAL/SPI instrument						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TelAviv				
Person months per participant:	57	4	0				
Start month	1			**End month**	48		

Objectives: Simulation and calibration of the instrument modes, and generation of polarization response matrices. Preparation of the plugin for 3ML. Preparation of the software for the polarization analysis.

Description of work (where appropriate, broken down into tasks), lead partner and role of participants

Task 1: Calibration: Simulate energy-dependent polarization response, cross-correlate with Crab results (spectrum, normalization); Determine predicted modulation as function of energy

Task 2: Response generation: Over time, 4 of the 19 detectors failed, so there are 5 detector configurations for which a response has to be derived via simulations.

Task 3: Plugin for 3ML

Task 4: Polarization analysis

Deliverables (brief description and month of delivery)

D3.1

Work package number	4		**Lead beneficiary**		UNIGE		
Work package title	Archival Analysis of published sources						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TelAviv				
Person months per participant:	6	5	2				
Start month	25			**End month**	48		

Objectives: This WP is lead by the UNIGE group who previously lead the analysis of the POLAR-1 data. The WP will ensure reanalysis of already published data from POLAR, GAP, the INTEGRAL instruments and any additional instruments if possible. This study serves to both qualify the newly developed methodology as well as to produce new scientific results. Additionally, analysis will be performed on previously not analyzed sources using data from these instruments.

Description of work

Task 1: Proof-of-concept with POLAR-1 data: applying the full methodology and software to the GRBs measured with POLAR-1. Also, newly develop energy-dependent polarization analysis tools.

Task 2: Gamma-Ray Bursts (GRBs): Data from both INTEGRAL instruments as well as that from GAP will be used together with the new analysis method to perform the first multi-instrument polarization studies. Where possible time- and energy-resolved polarization studies will be done.

Task 3: Soft Gamma Repeaters (SGRs): A list of all possible SGRs visible by any of the above mentioned instruments will be composed. Subsequently polarization analysis will be performed for all SGRs in this list. Where possible time- and energy-resolved polarization studies will be done.

Task 4: Bright steady sources (Crab / Cyg X-1): Non-imaging instruments (GAP, POLAR-1) can not be used for steady sources, while data from both INTEGRAL instruments can be used to analyze all kind of sources. Due to their steady states, these sources will allow for multi-instrument analysis. Where possible time- and energy-resolved polarization studies will be done.

Task 5: Transients (V404 Cyg, GRS 1915+105, Cen A etc.): All the above instruments are capable of performing polarization measurements of transients (if in their field of view). A list of possible transients observed by all the instruments will be compiled, followed by polarization analysis of these transients. Where possible time- and energy-resolved polarization studies will be done.

Deliverables (brief description and month of delivery)

D4.1 – provide the tools for energy-dependent polarization analysis. (T_o+12 months)

Work package number	5	Lead beneficiary			TelAviv		
Work package title	Theoretical Modelling of Polarization in Astrophysical Sources						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TelAviv				
Person months per participant:	1	1	93				
Start month	1			End month	48		

Objectives: This WP is led by the Tel Aviv group and will develop theoretical models for the expected polarization properties, based on present-day knowledge of jet physics.

Description of work

Task 1: Expand the existing code to include 3D matrices and efficient calculation of the surfaces of equal arrival time.
Task 2: Implementation of the Monte-Carlo module and the radiation transfer effects that will be accounted for.
Task 3: Development of a GUI that will allow the code to be accessible to the public via an online platform. The platform will be connected with a resource that will include the observational data from the project and will allow an independent analysis of the data.

Task 4: With the proposed extension our model will be applicable to a wider range of sources, thus the theoretical framework developed here in WP5 will be applied to the data of the different source types as deduced in WP4 and WP6.

Deliverables (brief description and month of delivery)

D5.1 ?? an early delivery within the first 2 years might be good

D5.2 Develop an Online GUI connecting the new theoretical model with the data base. (T_o + 36 months)

D5.3 Publication with the scientific results of applying the new theoretical description to the INTEGRAL data. (T_o + 48 months)

Work package number	6	**Lead beneficiary**			UNIGE		
Work package title	Application						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TelAviv				
Person months per participant:	5	4	0				
Start month	25			**End month**	48		

Objectives: This WP has the goal of ensuring application of the work developed during the project after the funding finishes. For this purpose, it aims to produce the tools to make use of existing data and advertising these products, to produce the tools required to ensure the application of the products of this project in a future mission and finally to optimize a future mission for applying the products and findings developed in the project.

Description of work

Task 1: Past instruments with strong European contribution: The WP1 and WP5 products will be used to provide a foundation for re-analysis of data from past instrumentation. An example is COMPTEL (CGRO), which will firstly be used to produce the data format defined in WP1 while also an instrument response is produced using the same format. The data, response and available models will be detailed in a dedicated publication, thereby advertising its use to the wider community ensuring future use.

Task 2: POLAR-2 as a first costumer: With a launch in 2024, soon after this project finishes, POLAR-2 forms an ideal candidate as a first customer. This WP will prepare the instrument response and the pipeline to produce the POLAR-2 data in the format defined by WP1, thereby ensuring direct use of the products developed in the project.

Task 3: Hardware contribution to POLAR-2 (spectrometer): This WP will develop a spectrometer to be placed on the POLAR-2 mission with the aim of optimizing the capability to perform joined spectral and polarization analysis.

Deliverables (brief description and month of delivery)

D6.1

Work package number	7	**Lead beneficiary**			MPE		
Work package title	Outreach and Dissemination						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TelAviv				
Person months per participant:	1	1	1				
Start month	12			**End month**	48		

Objectives: Make sure that our results and products are disseminated to both, to the scientific community, and the wider audience. Enable exploitation of the results and tools for future missions. Organize events to inform the public about our main astrophysical new insight.

Description of work

Task 1: Dissemination of results and software tools to the astrophysical community by special conferences, workshops, or Hands-on courses, or corresponding contributions towards this goal to large-audience conferences. Prepare exploitation of results for future projects.

Task 2: Communication activities, i.e. outreach via a variety of channels, incl. news papers, social media, and the Internet in general (dedicated Web-pages).

Task 3: Scientific Publications: Our main results, both technical (data format, data analysis methodology, software) as well as scientific (actual polarization measurements of astrophysical sources) shall be published in the refereed literature, and made publicly available under the Gold Open access rules.

Deliverables (brief description and month of delivery)

D7.1 Provide ESA/ESOC with requirements to include polarization parameters in their database and query forms. (T_o+ 6 months)

Table 3.1c: List of Deliverables[6]

Deliverable (number)	Deliverable name	Work package number	Short name of lead participant	Type	Dissemination level	Delivery date (in months)
1.1	Data Management Plan	1	MPE	R	PU	6

KEY

Deliverable numbers in order of delivery dates. Please use the numbering convention <WP number>.<number of deliverable within that WP>.

For example, deliverable 4.2 would be the second deliverable from work package 4.

Type:
Use one of the following codes:
- R: Document, report (excluding the periodic and final reports)
- DEM: Demonstrator, pilot, prototype, plan designs
- DEC: Websites, patents filing, press & media actions, videos, etc.
- OTHER: Software, technical diagram, etc.

Dissemination level:
Use one of the following codes:
- PU = Public, fully open, e.g. web
- CO = Confidential, restricted under conditions set out in Model Grant Agreement
- CI = Classified, information as referred to in Commission Decision 2001/844/EC.

Delivery date
Measured in months from the project start date (month 1)

[6] If your action is taking part in the Pilot on Open Research Data, you must include a data management plan as a distinct deliverable within the first 6 months of the project. This deliverable will evolve during the lifetime of the project in order to present the status of the project's reflections on data management. A template for such a plan is available in the H2020 Online Manual on the Participant Portal.

Tables for section 3.2

Table 3.2a: List of milestones

Milestone number	Milestone name	Related work package(s)	Due date (in month)	Means of verification

KEY

Due date
Measured in months from the project start date (month 1)

Means of verification
Show how you will confirm that the milestone has been attained. Refer to indicators if appropriate. For example: a laboratory prototype that is 'up and running'; software released and validated by a user group; field survey complete and data quality validated.

Table 3.2b: Critical risks for implementation

Description of risk (indicate level of likelihood: Low/Medium/High)	Work package(s) involved	Proposed risk-mitigation measures

Definition critical risk:
A critical risk is a plausible event or issue that could have a high adverse impact on the ability of the project to achieve its objectives.

Level of likelihood *to occur:* **Low/medium/high**
The likelihood is the estimated probability that the risk will materialise even after taking account of the mitigating measures put in place.

Tables for section 3.4

Table 3.4a: Summary of staff effort

Please indicate the number of person/months over the whole duration of the planned work, for each work package, for each participant. Identify the work-package leader for each WP by showing the relevant person-month figure in bold.

	WP0	WP1	WP2	WP3	WP4	WP5	WP6	WP7	Total Person-Months per Participant
1 / MPG	**21**	**12**	2	**57**	6	1	5	1	105
2 / UNIGE	0	9	**66**	4	**5**	1	**4**	1	90
3 / Tel Aviv	0	0	0	0	2	**93**	0	1	96
Total Person Months	21	21	68	61	13	95	9	3	(291)

Table 3.4b: 'Other direct cost' items (travel, equipment, other goods and services, large research infrastructure)

Please complete the table below for each participant if the sum of the costs for' travel', 'equipment', and 'goods and services' exceeds 15% of the personnel costs for that participant (according to the budget table in section 3 of the proposal administrative forms).

Travel and outreach costs are the same for each participant. For the other two participants, the direct other costs are far below the 15% limit for this table, so are not specified here.

1 / MPE	Cost (€)	Justification
Travel	10.800	4 travels (see text for break-down)
Equipment	175.000	Invest for POLAR-2 spectrometer
Other goods and services	2.000	For outreach and didactic material
Total	187.800	

Please complete the table below for all participants that would like to declare costs of large research infrastructure under Article 6.2 of the General Model Agreement[7], irrespective of the percentage of personnel costs. Please indicate (in the justification) if the beneficiary's methodology for declaring the costs for large research infrastructure has already been positively assessed by the Commission.

Participant Number/Short Name	Cost (€)	Justification
Large research infrastructure		

[7] Large research infrastructure means research infrastructure of a total value of at least EUR 20 million, for a beneficiary. More information and further guidance on the direct costing for the large research infrastructure is available in the H2020 Online Manual on the Participant Portal.