Gamma-Ray Burst Polarimetry with the POLAR and POLAR-2 missions

SPIE Optics+Photonics: UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XXIV

San Diego, USA — 05th August 2025

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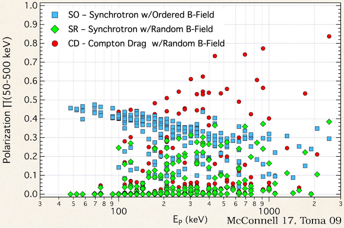
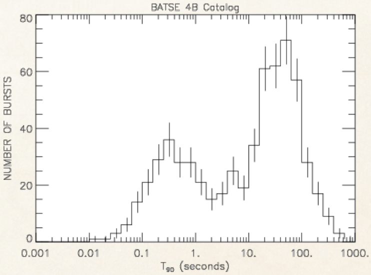
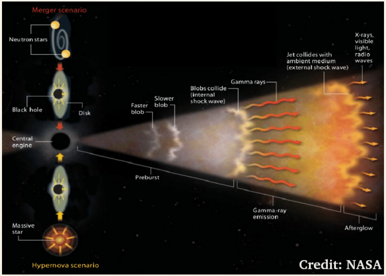
[2]`https://www.astro.unige.ch/polar/collaboration`
`https://www.unige.ch/dpnc/polar-2`

Gamma-Ray Bursts paradigm

- Bright and short transient event in γ band followed by an afterglow (in all wavelengths)
- Extragalactic, 2 categories: short (from BNS) and long (from SN)
- Polarization brings a better understanding of the jet and magnetic field structures







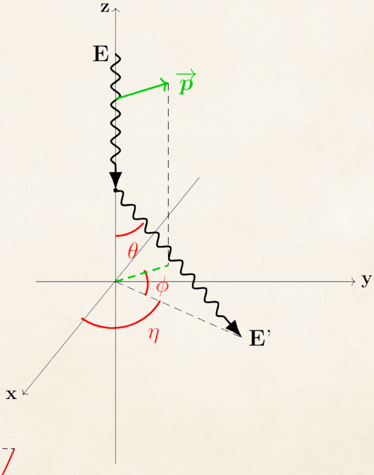
Polarimetry with the Compton scattering

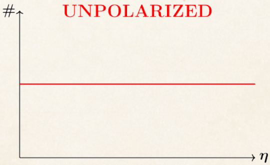
Compton scattering can be used to determine the polarization of a source:

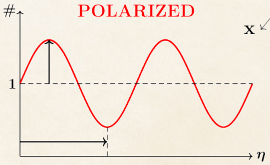
- Azimuthal scattering angle distribution provides information on polarization degree and angle
- So-called modulation curved, parameterized by the Klein-Nishina cross-section:

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{E'}{E}\right)^2\left[\frac{E'}{E} + \frac{E}{E'} - 2\sin^2(\theta)\cos^2(\phi)\right]$$

- Relative amplitude $\leftrightarrow$ PD, phase $\leftrightarrow$ PA







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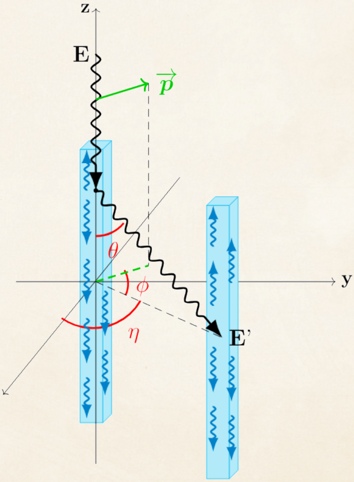
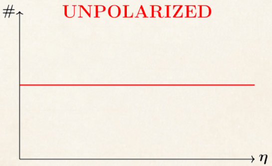
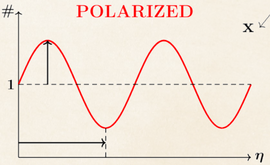
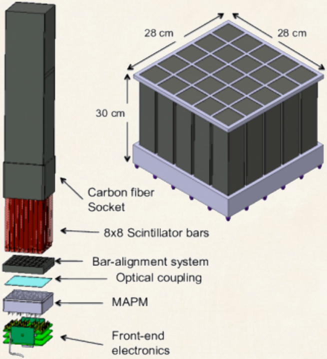
- Relative amplitude $\leftrightarrow$ PD, phase $\leftrightarrow$ PA
- **A segmented array of scintillators can be used to measure the scattering angle distribution (aka modulation curve)**

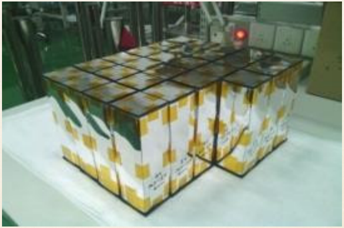






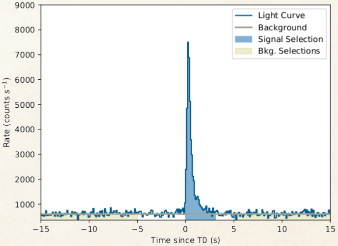
- POLAR was a dedicated gamma polarimeter composed of a 40×40 scintillator array
- Divided in 5×5 modules each made of 64 plastic scintillator bars ($176 \times 5.8 \times 5.8$ mm^3, EJ-248M), each module being readout by Multi-Anode PMTs
- Optimized for Compton scattering in the 50-500keV range thanks to its low-Z scintillators
- 30kg instrument, half-sky FoV, $\sim 300cm^2$ effective area at 400 keV
- Design described in Produit et al. 2018 (DOI: 10.1016/j.nima.2017.09.053)
- Launched in Sept 2016 on the Tiangong-2 Chinese space lab for 6 months of operation

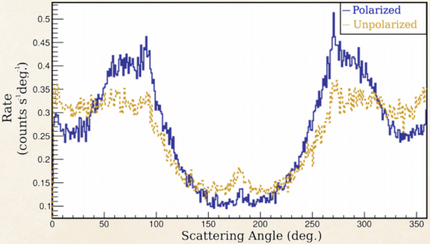




What we learned from POLAR

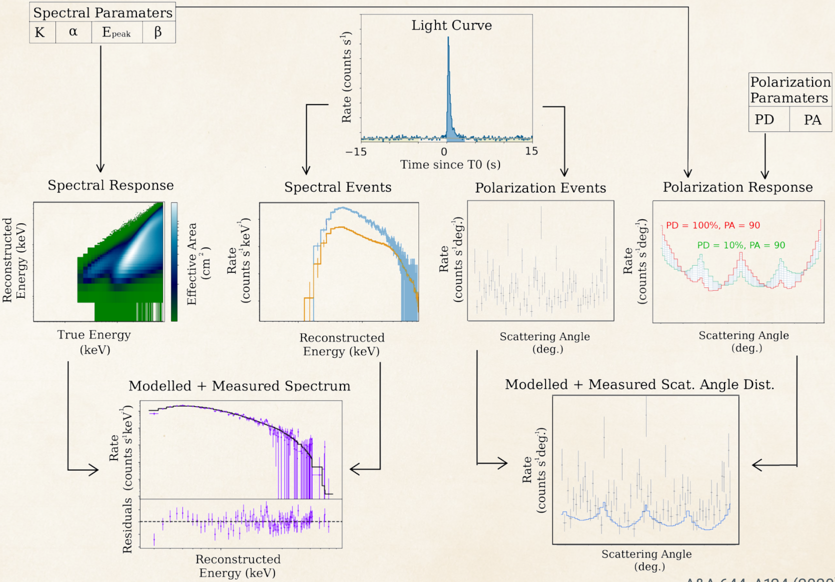
- Typical measured light and modulation curves shown below, complex modulation curve structure due to well-understood instrumental/geometrical effects
- POLAR detected 55 GRBs in 6 months of operation, 14 of which had enough statistics to be analyzed → joint spectral/polarization analysis with Fermi-GBM or Swift-BAT data using 3ML spectral fitting framework (github.com/threeML) and development of a polarization fitting plugin (github.com/grburgess/polarpy)





A&A 644, A124 (2020)

Joint polarization-spectral GRB analysis method



A&A 644, A124 (2020)

What we learned from POLAR

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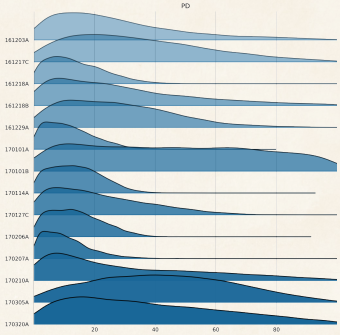
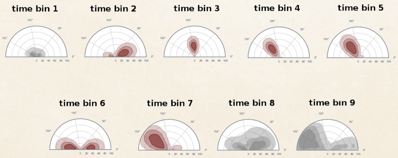
- Catalog of 14 GRBs analysed, results show a low or null polarization degree (excluding synchrotron emission models from toroidal magnetic field, compatible with photospheric emission model and other synchrotron models)
- Time resolved analysis show a hint of quickly evolving polarization angle that washes out polarization degree on time integrated analysis $\Longrightarrow$ need more statistics to make proper time resolved analysis
- No significant polarization energy-dependence $\longrightarrow$ **PoS(ICRC2023)619**
- We need more statistics in order to perform temporal and energy resolved analysis, with lowered energy threshold to probe emission models, and with bigger effective area and longer mission operation to get a larger catalog $\longrightarrow$ **the POLAR-2 mission**



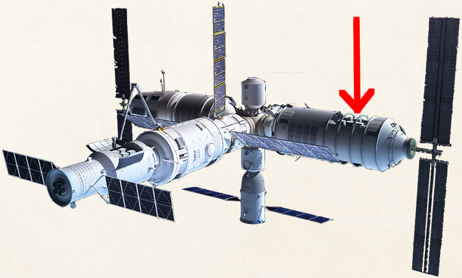
A&A 644, A124 (2020)

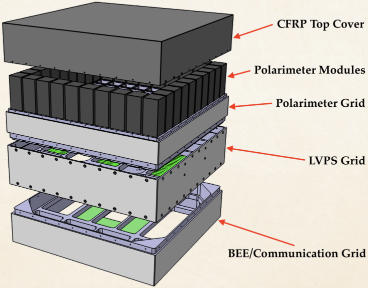


A&A 627, A105 (2019)

The POLAR-2 mission

- Large scale GRB polarimeter based on POLAR legacy
- 4 times bigger than POLAR (from 25 to 100 polarimeter modules), 10 times more efficient to typical GRB spectra (thanks to an improved design of the polarimeter modules)
- Lowered energy threshold to a few keV
- Other payloads being developed in China for joint observations: broad-band spectral imager + low-energy gas polarimeter
- Launch on China Space Station early 2027 (matches LIGO/VIRGO O5 run, possibility of joint observations with GW $\rightarrow$ **Kole et al. 2023 A&A 669 A77**)

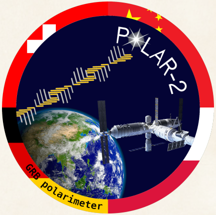




The POLAR-2 collaboration

About 20 people working on POLAR-2 from the following institutes:

- UniGe (DPNC), Switzerland: Management, polarimeter modules, instrument thermal and mechanical integration
- UniGe (DA), Switzerland: Online software system
- NCBJ, Poland: Back-End Electronics, Power Supply
- IHEP, China: Flight Model Acceptance, Spectrometers
- MPE, Germany: Qualification & Verification, Spectrometers
- + collaboration members at INAF-IAPS (Italy) and UNH (United States)



More info on `https://www.unige.ch/dpnc/polar-2`.

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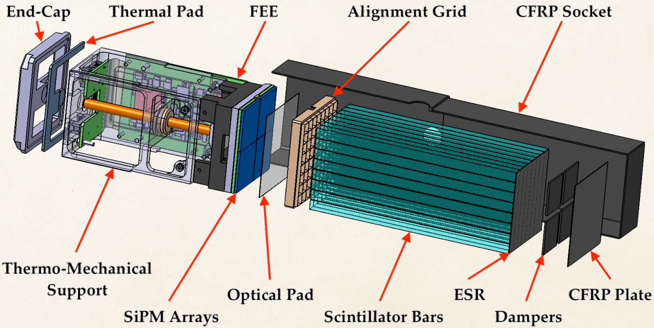
National Centre for Nuclear Research
ŚWIERK

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Max-Planck-Institut für extraterrestrische Physik

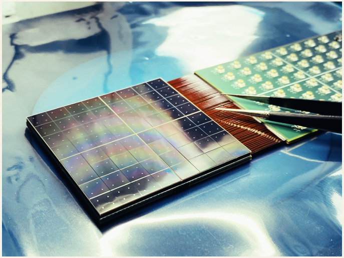
Polarimeter Module Design

- 8×8 array of elongated plastic scintillator bars read out by thermally-controlled SiPM arrays
- Many upgrades from the POLAR design:
  - From MA-PMTs to SiPM arrays: higher PDE implying a higher effective area and a lowered energy threshold
  - Thinner alignment grid allows to reduce dead-space and increase sensitivity
  - Individual scintillator wrapping + thinner optical coupling pad to improve the optical crosstalk
  - Scintillators have been shorten to improve SNR

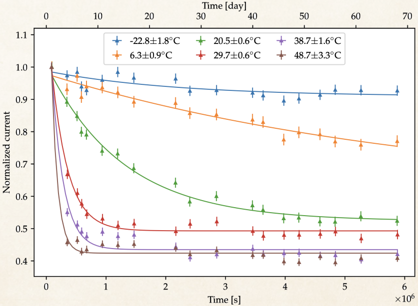


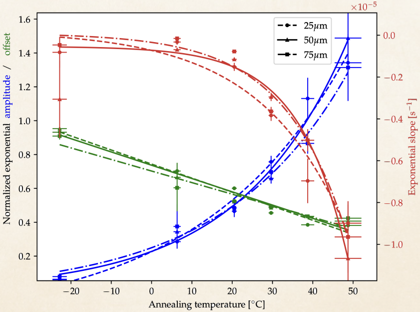
SiPM Temperature-dependent Annealing

- SiPMs cooled with Peltier elements to reduce dark noise
- Annealing studies allowed to estimate when/how much to heat up the sensors to recover part of the initial performances (degraded due to space radiation environment) $\rightarrow$ **De Angelis et al. 2023, NIM-A 1048 167934**



$$a(T) \times \exp(b(T) \cdot t) + c(T)$$





Optical Characterization

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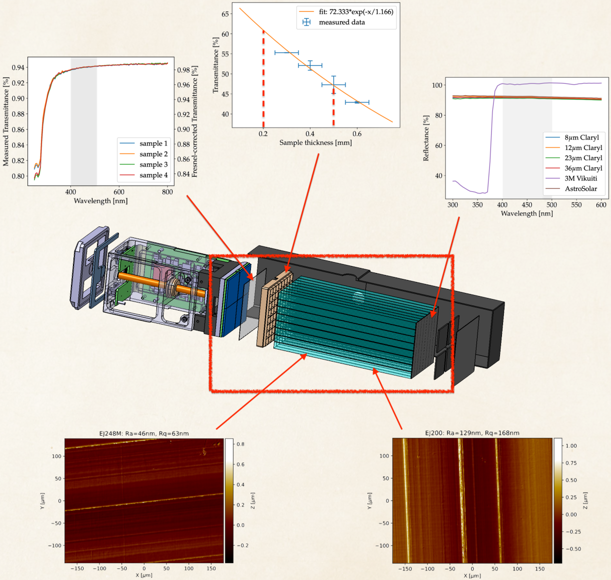
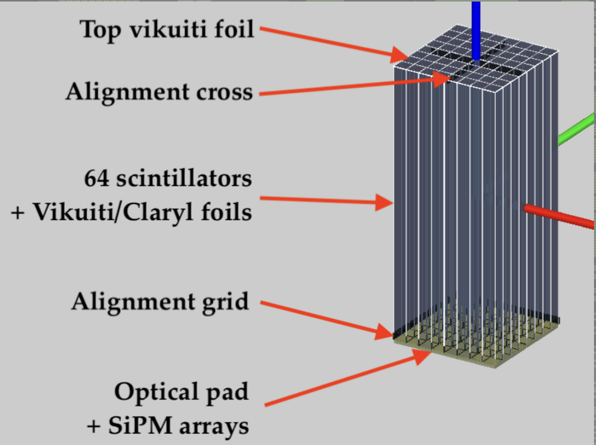
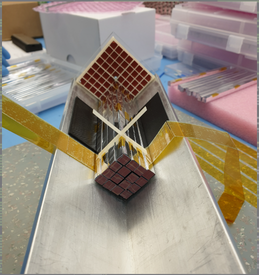
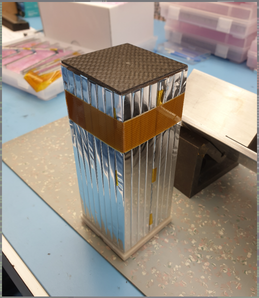


De Angelis et al. 2025, JINST 20 P02010

Geant4 Optical Simulations

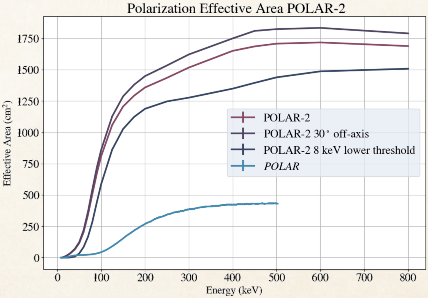


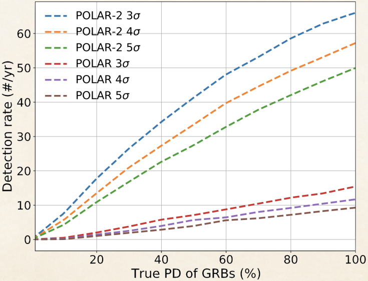




Scientific Performances

- Module light yield was increased from 0.3 to 1.6 p.e./keV, improving the sensitivity of the instrument and lowering its energy threshold
  $\longrightarrow$ **De Angelis et al. 2025, JINST 20 P02010**
- The optical crosstalk was also reduced from 15 % down to 1.5%
- Sensitivity to typical GRB spectra improved by an order of magnitude
- Improvement of the modulation factor μ_{100}, especially at low energy
  $\longrightarrow$ **Kole et al. 2024, JINST 19 P08002**





Summary & Outlook

- **POLAR** was **launched in 2016** with the aim to investigate GRB prompt emission polarization
- In detected polarization of **14 GRBs**, with a consistency for **low polarization levels**. A **hint for PA evolution** was found in time-resolved analysis, which could explain the low PD on integrated analysis. No significant energy-dependence of PD/PA was found
- POLAR-2, the successor mission, in now under development with a scheduled **launch mid-2027** to the CSS
- Sensitivity to typical GRB spectra was **increased by an order of magnitude** thanks to many design upgrades enhancing the instrumental capabilities
- This will allow to detect about **50 GRBs/yr** with quality higher or equal than the brightest observed source for POLAR, with possibility for time and energy resolved analysis.
- POLAR-2 will also be important for sending **alerts to ground**, and should match LIGO O5 Run
- Currently in its construction phase with a launch planned for late 2027
- Two other instruments to enhance the Compton polarimeter capabilities are planned by IHEP, Beijing (**BSD**, imaging spectrometer) and GuangXi University, Nanning (**LPD**, low energy photoelectric polarimeter)

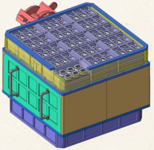
Preparing joint POLAR-2 analysis: PolPy

- 3ML-based (**Vianello et al. 2015, arXiv:1507.08343**) tool to perform joint spectro-polarimetric (+localization?) analysis between different instruments using standard polarization format based on OGIP.
- In collaboration with people from POLAR-2 and ASTROSAT-CZTI/DAKSHA, to be used by POLAR-2 HPD/LPD/BSD, DAKSHA, COSI, future version of LEAP etc.

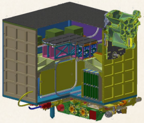
➢ Low-energy Polarization Detector: LPD
- ~2-10 keV X-ray polarimetry

➢ Broad energy-band Spectrum Detector: BSD
- ~10-2000keV
- Accurate GRB localization and spectroscopy for HPD and LPD

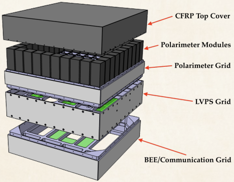
➢ Status: Selected, to be adopted



LPD



BSD



LPD/GuangXi University

BSD/IHEP

HPD/UniGe