



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

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Nicolas De Angelis¹ for the POLAR and POLAR-2 collaborations²

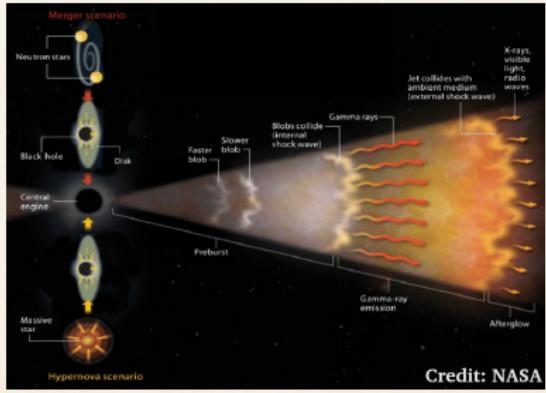
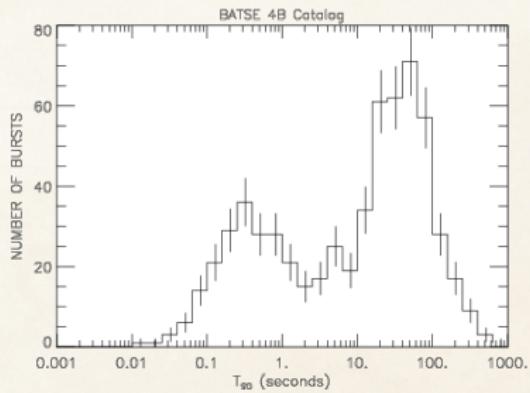
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²<https://www.astro.unige.ch/polar/collaboration>
<https://www.unige.ch/dpnc/polar-2>

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

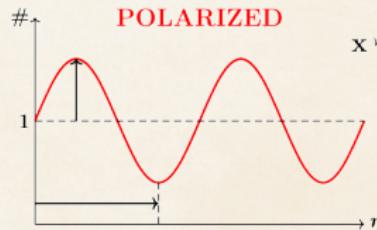
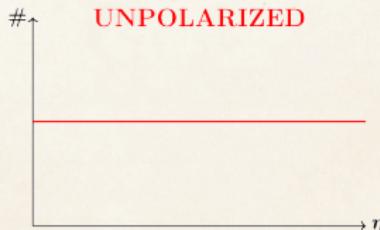
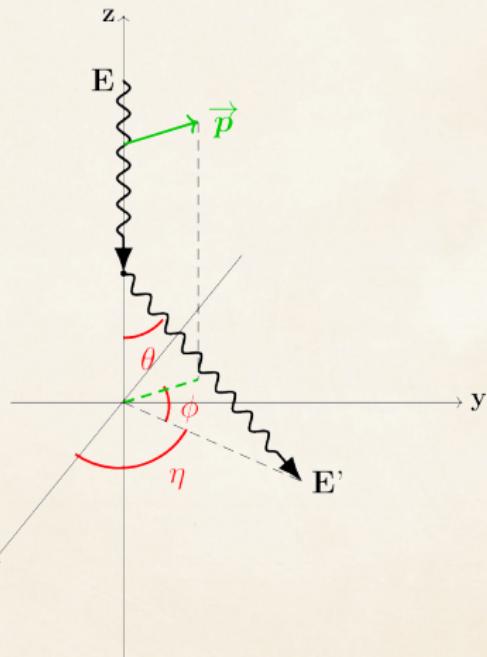


Compton scattering can be used to determine the polarization of a source:

- 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



Polarimetry with the Compton scattering

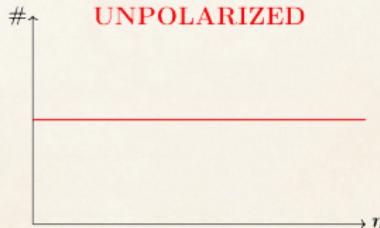
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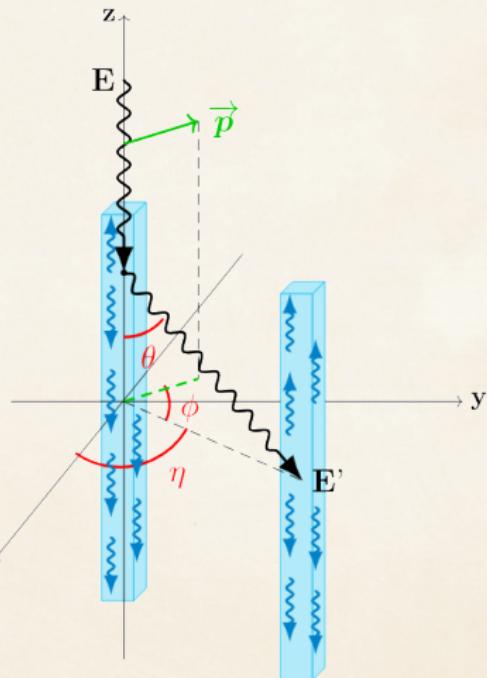
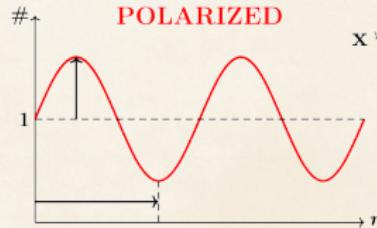
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- Relative amplitude \leftrightarrow PD, phase \leftrightarrow PA
- **A segmented array of scintillators can be used to measure the scattering angle distribution (aka modulation curve)**

UNPOLARIZED

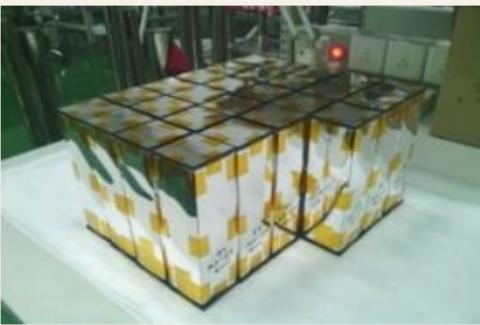
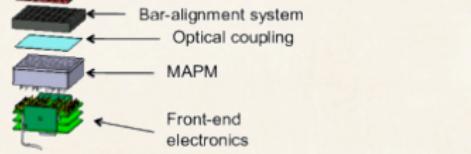
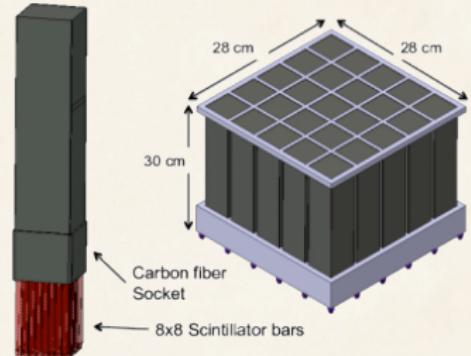


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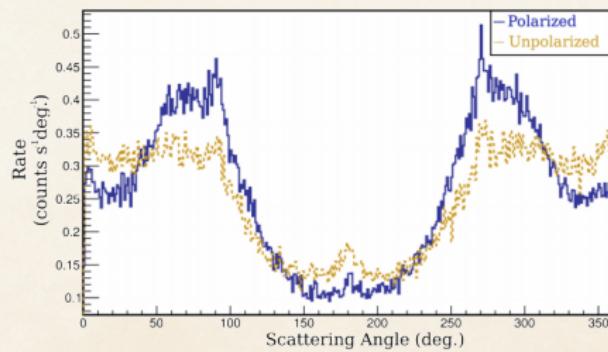
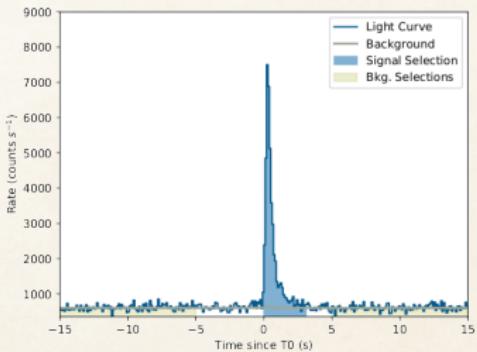
The POLAR instrument

- 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 ($176 \times 5.8 \times 5.8 \text{ mm}^3$, 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, $\sim 300\text{cm}^2$ effective area at 400 keV
- Design described in [Produit et al. 2018](#) (DOI: [10.1016/j.nima.2017.09.053](https://doi.org/10.1016/j.nima.2017.09.053))
- Launched in Sept 2016 on the Tiangong-2 Chinese space lab for 6 months of operation



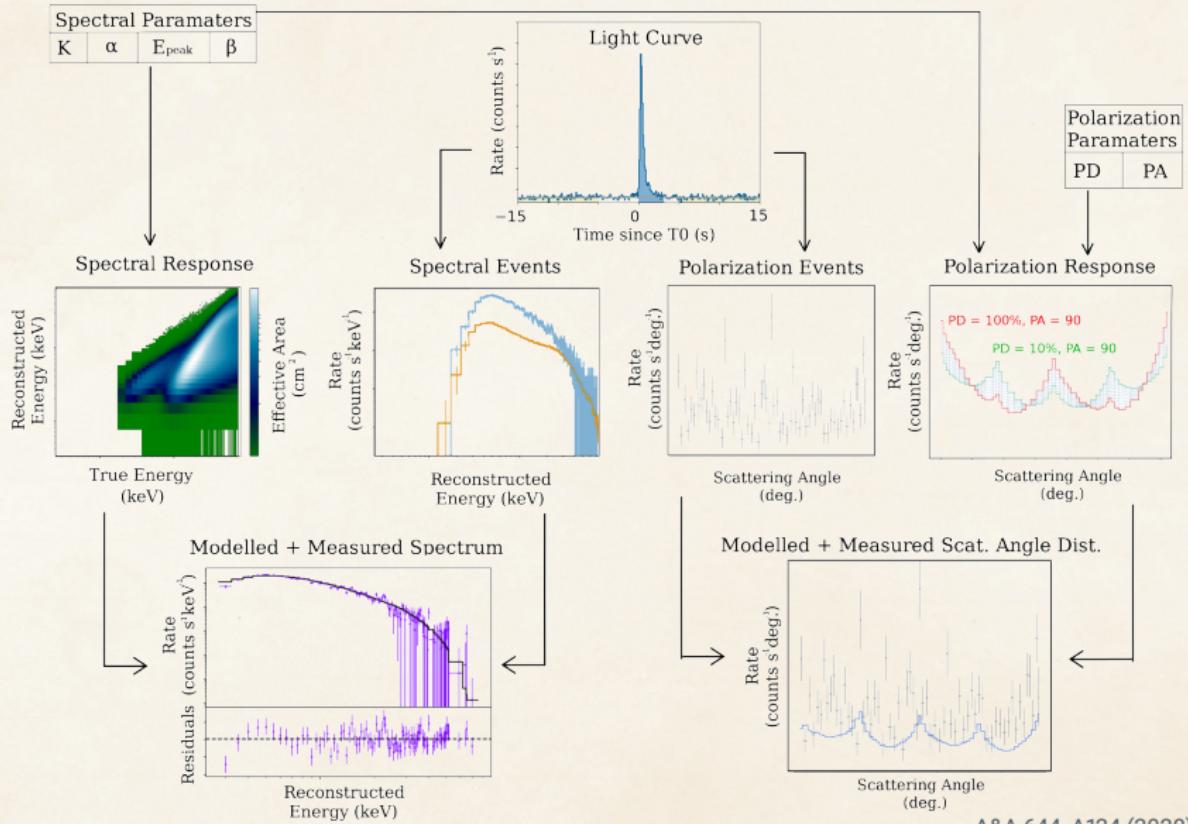
What we learned from POLAR

- 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)



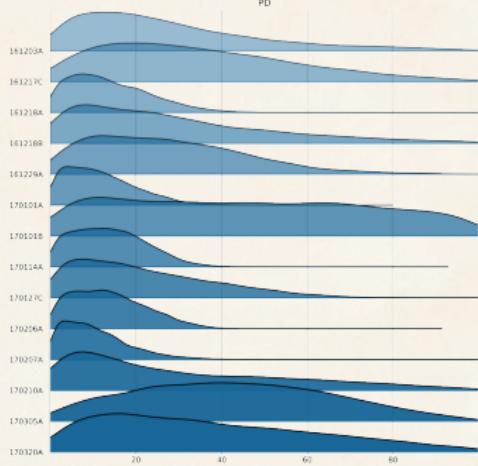
A&A 644, A124 (2020)

Joint polarization-spectral GRB analysis method



What we learned from POLAR

- 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 \Rightarrow need more statistics to make proper time resolved analysis
- No significant polarization energy-dependence \rightarrow 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 \rightarrow the POLAR-2 mission



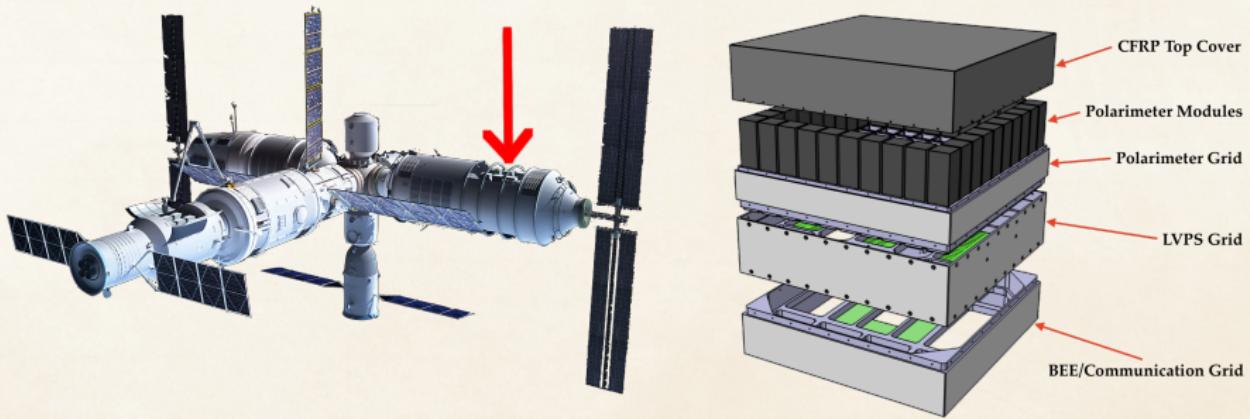
A&A 644, A124 (2020)



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 05 run, possibility of joint observations with GW → **Kole et al. 2023 A&A 669 A77**)

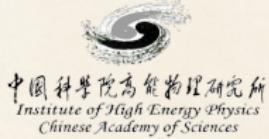


The POLAR-2 collaboration

About 20 people working on POLAR-2 from 4 countries:

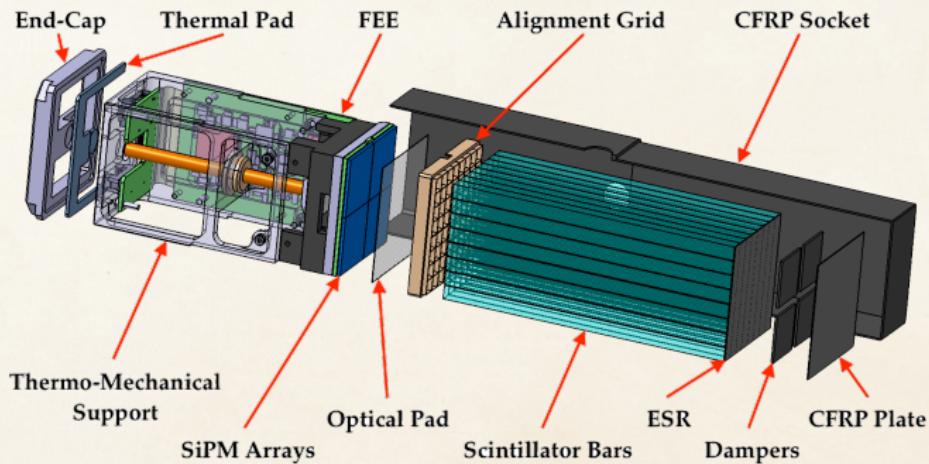
- UniGe (DPNC), Switzerland: Management, polarimeter modules, instrument thermal and mechanical integration
- UniGe (DA), Switzerland: Online software system
- NCBJ, Poland: Back-End Electronics, Power Supply
- IHEP, China: Flight Model Acceptance, Spectrometers
- MPE, Germany: Qualification & Verification, Spectrometers

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



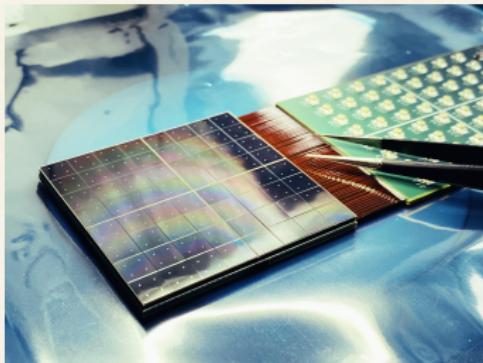
Max-Planck-Institut für
extraterrestrische Physik

- 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

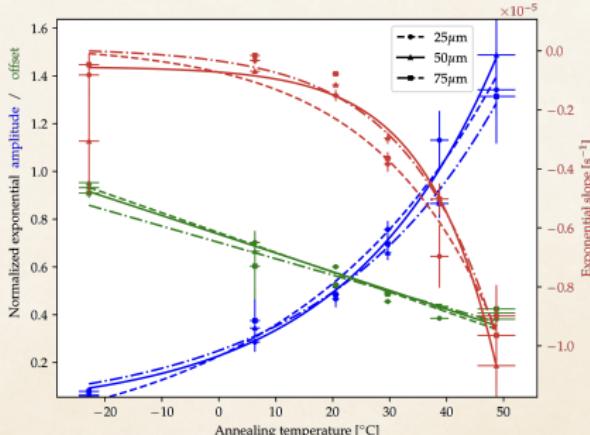
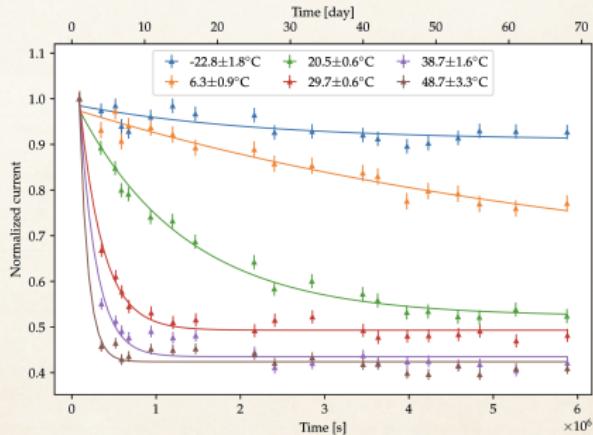


- SiPMs cooled with Peltier elements to reduce dark noise
- Annealing studies allowed to estimate when/how much to heat up the sensors to recover part of the initial performances (degraded due to space radiation environment) → **NIM-A 1048 (2023)**

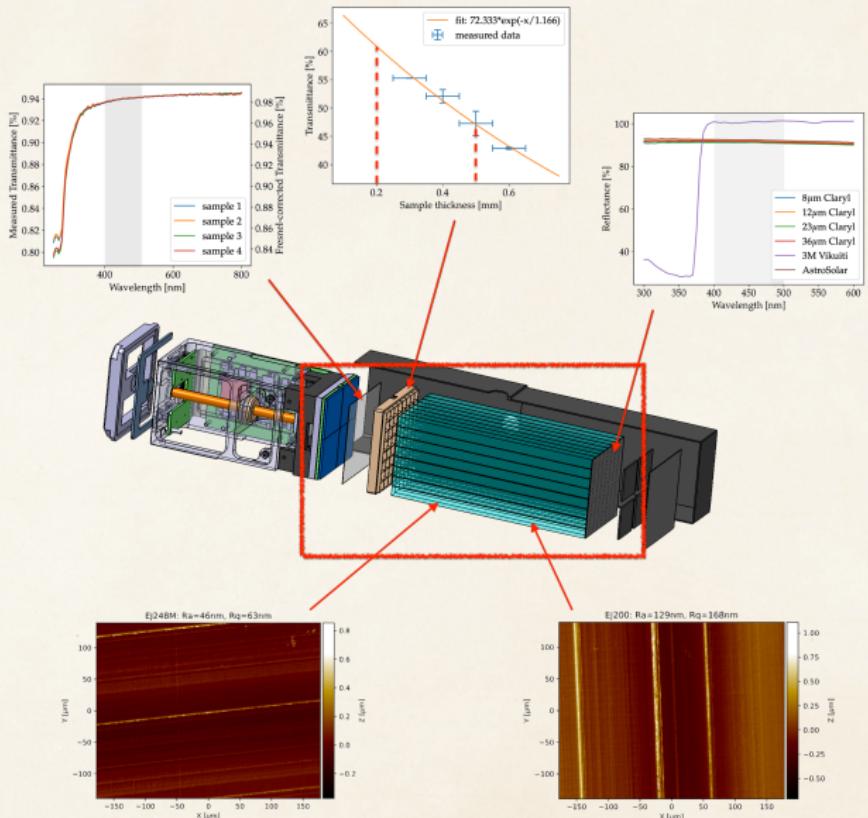
167934



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

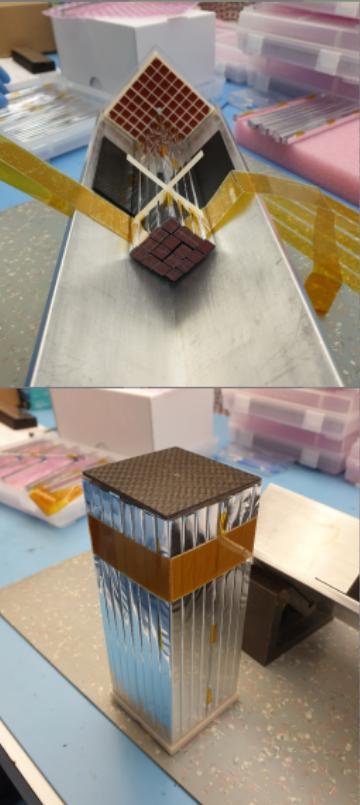
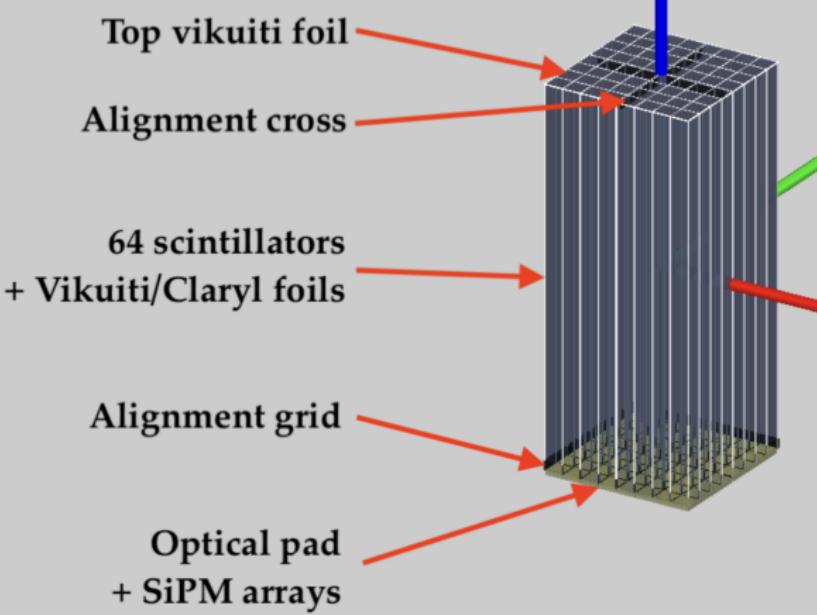


Optical Characterization

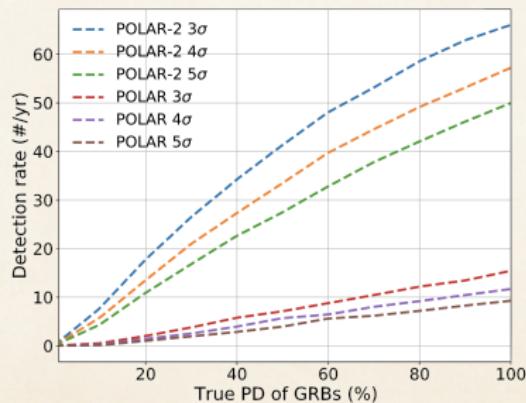
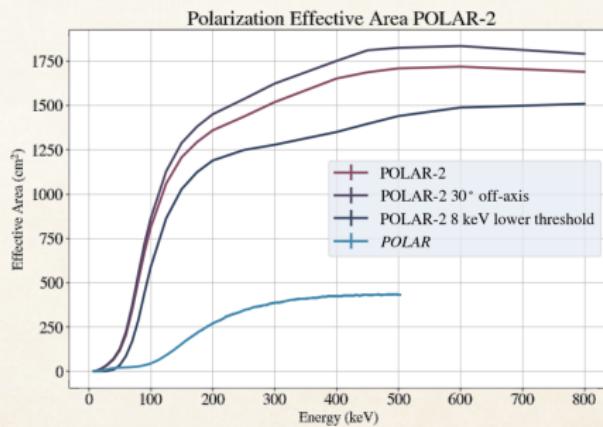


De Angelis et al. 2024, submitted to JINST

Geant4 Optical Simulations



- 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
→ **De Angelis et al. 2024, submitted to JINST**
- 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
→ **Kole et al. 2024, accepted for pub. in JINST**



- **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, is 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 GRB/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
- 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)

- 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

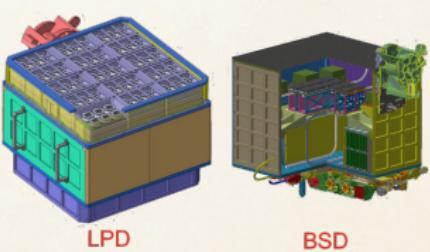
➤ Broad energy-band Spectrum

Detector: BSD

- ~10-2000keV

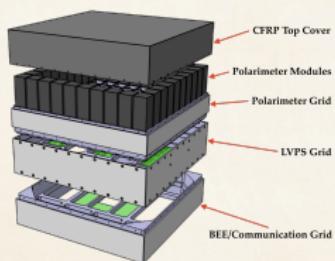
- Accurate GRB localization and spectroscopy for HPD and LPD

➤ Status: Selected, to be adopted



LPD/GuangXi University

BSD/IHEP



HPD/UniGe