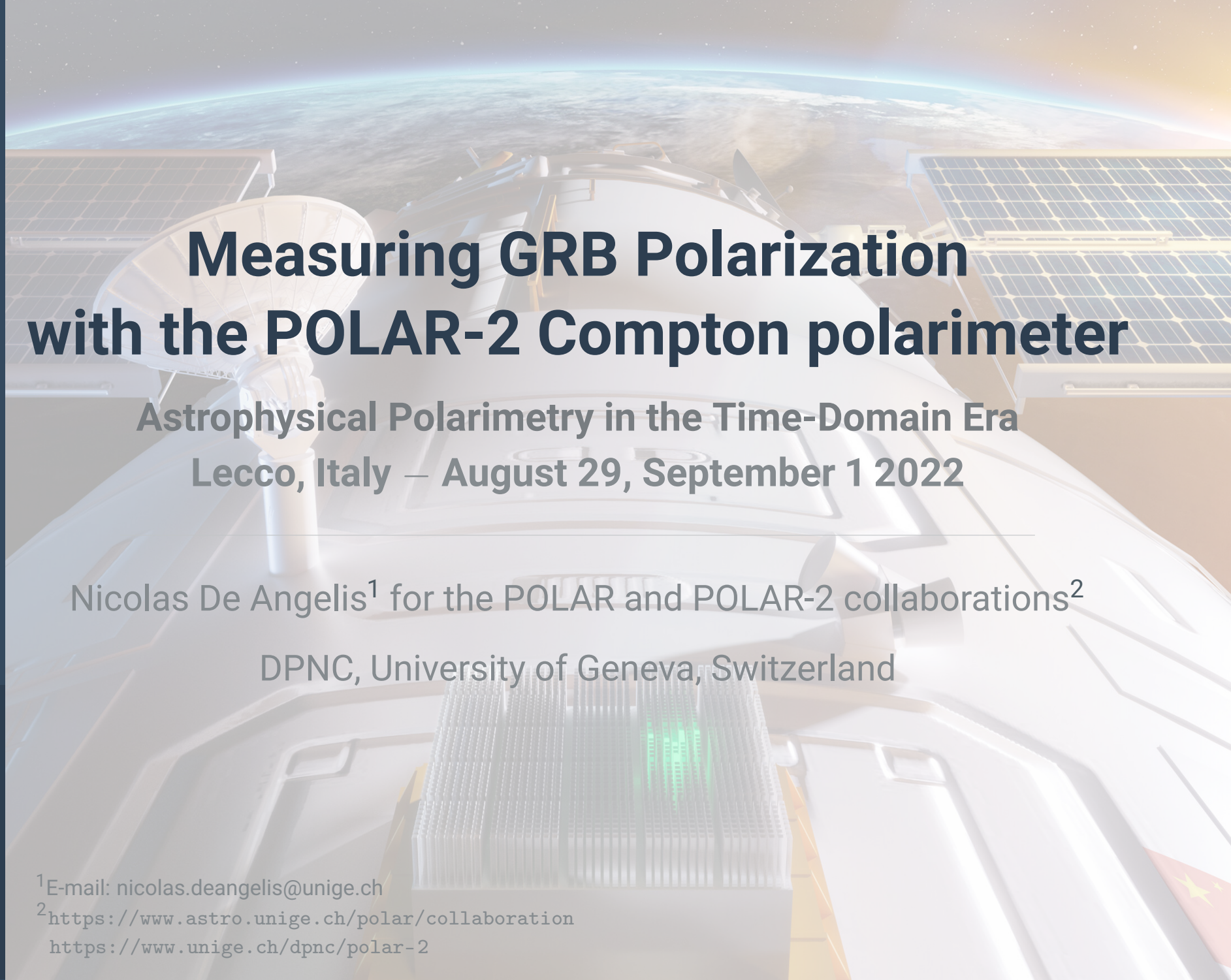

Measuring GRB Polarization with the POLAR-2 Compton polarimeter

Astrophysical Polarimetry in the Time-Domain Era
Lecco, Italy – August 29, September 1 2022

Nicolas De Angelis[1] for the POLAR and POLAR-2 collaborations[2]

DPNC, University of Geneva, Switzerland

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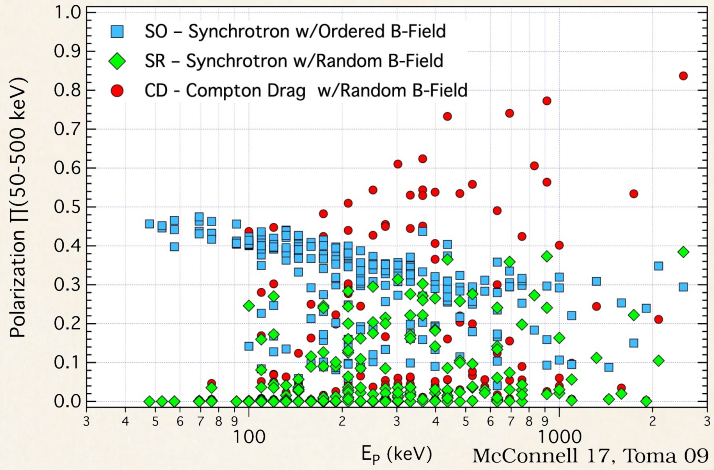
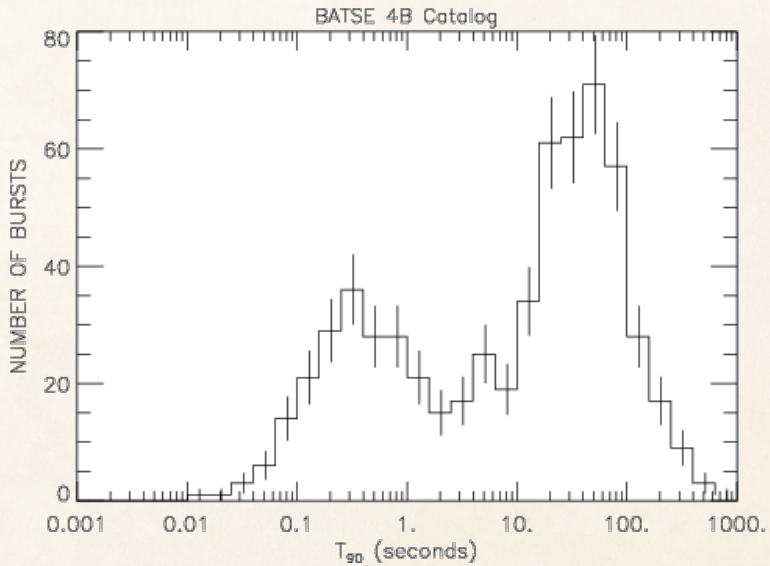
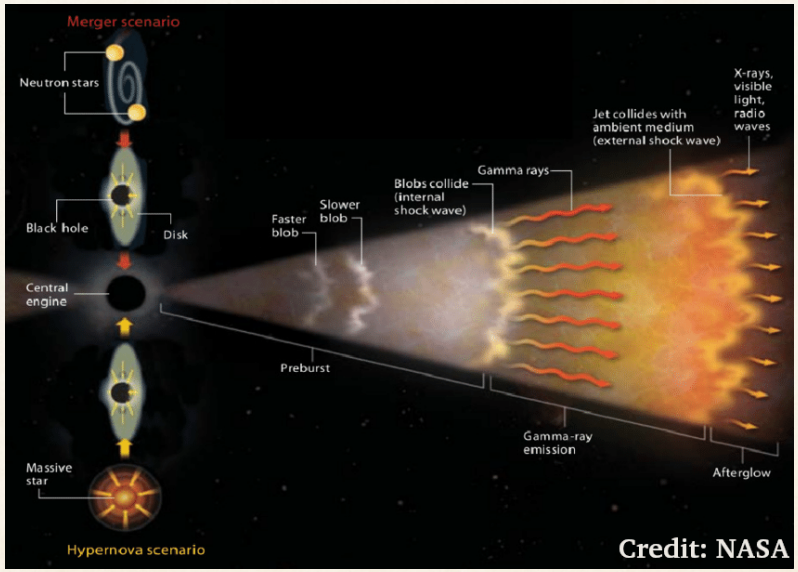
[2]https://www.astro.unige.ch/polar/collaboration
https://www.unige.ch/dpnc/polar-2

Gamma-Ray Bursts paradigm

- Bright and short transient event in γ band followedd 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





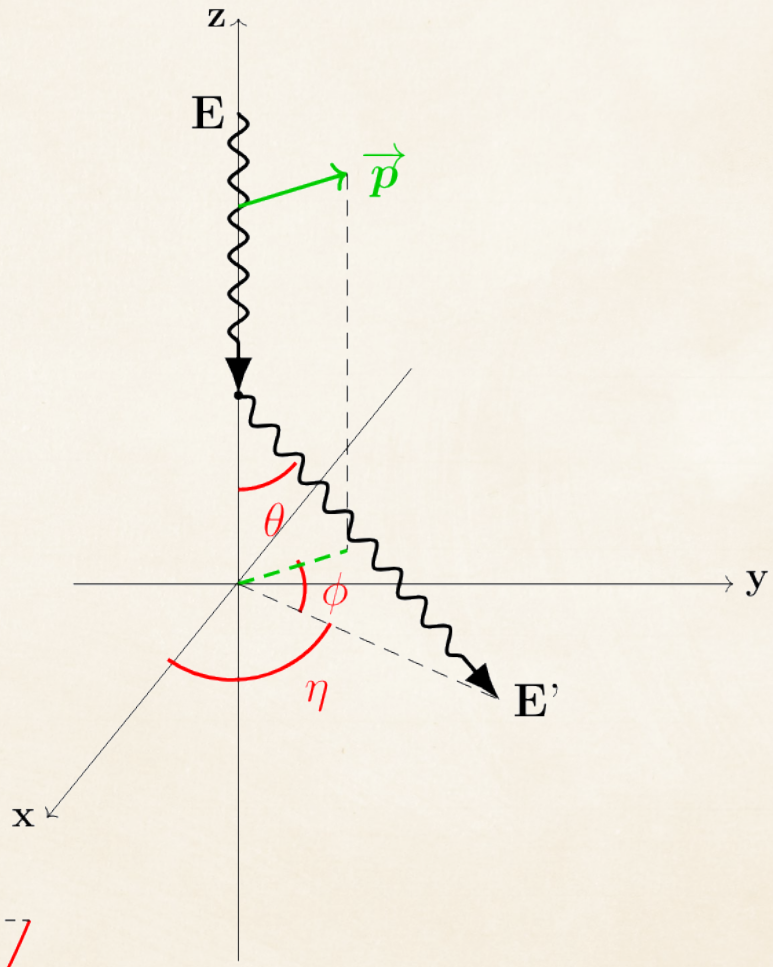


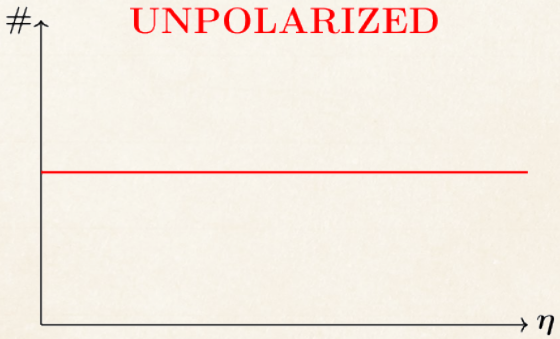
Compton scattering can be used to determine the polarization of a source:

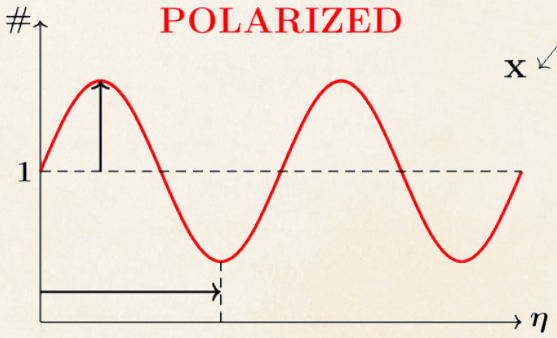
- Azimuthal scattering angle distribution provides information on polarization degree and angle
- So called modulation curved, parametrized by the Klein-Nishina cross-section:

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

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







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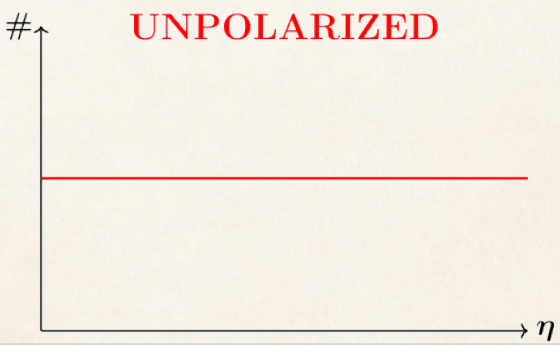
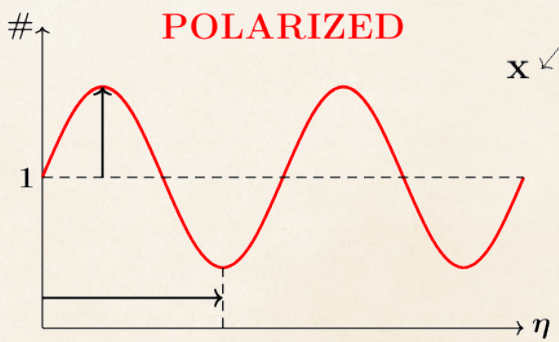
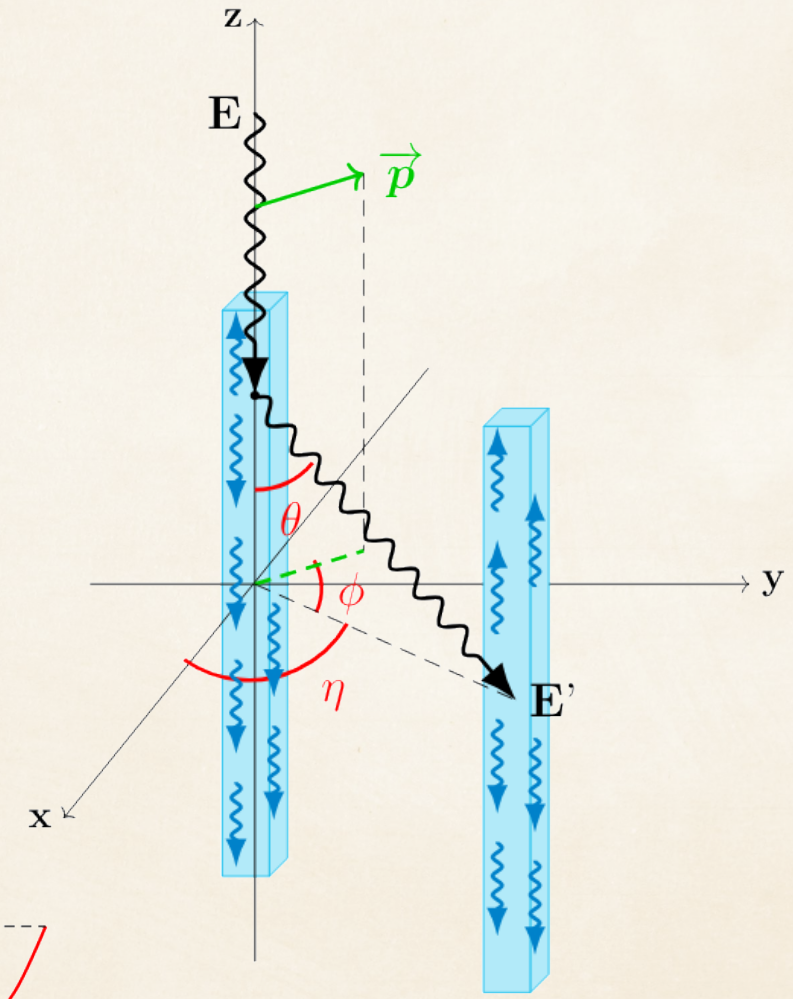
- Relative amplitude $\leftrightarrow$ PD, phase $\leftrightarrow$ PA
- **A segmented array of scintillators can be used to measure the scattering angle distribution (aka modulation curve)**

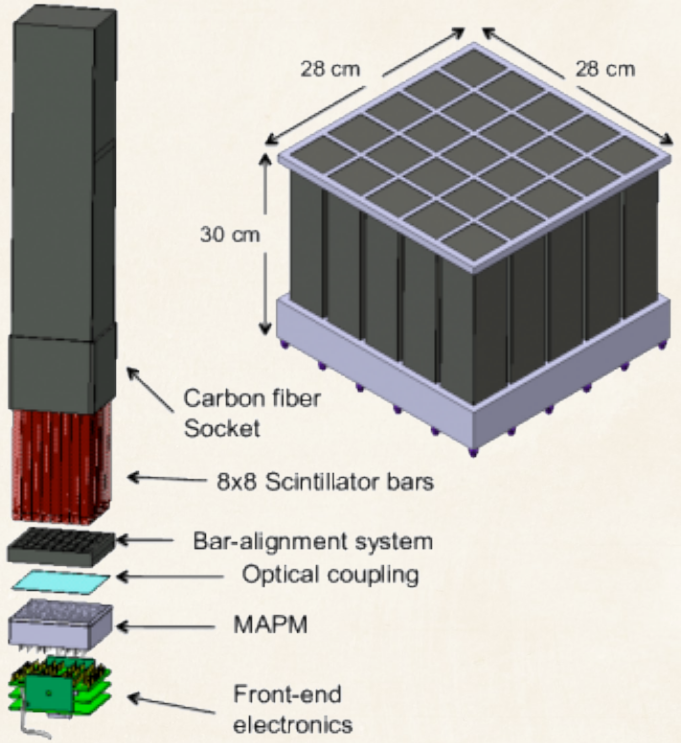


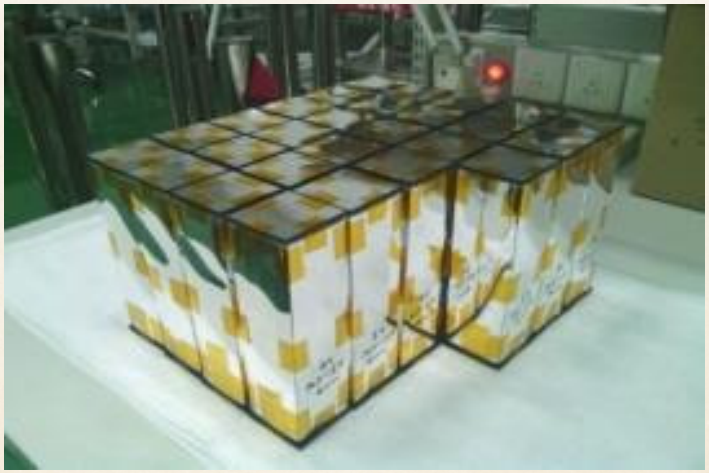




The POLAR instrument

- 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 ($176 \times 5.8 \times 5.8$ 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, $\sim 300 cm^2$ 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

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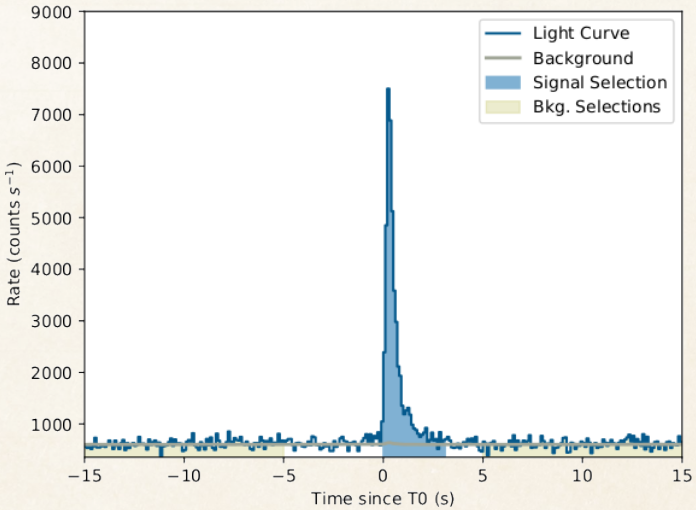
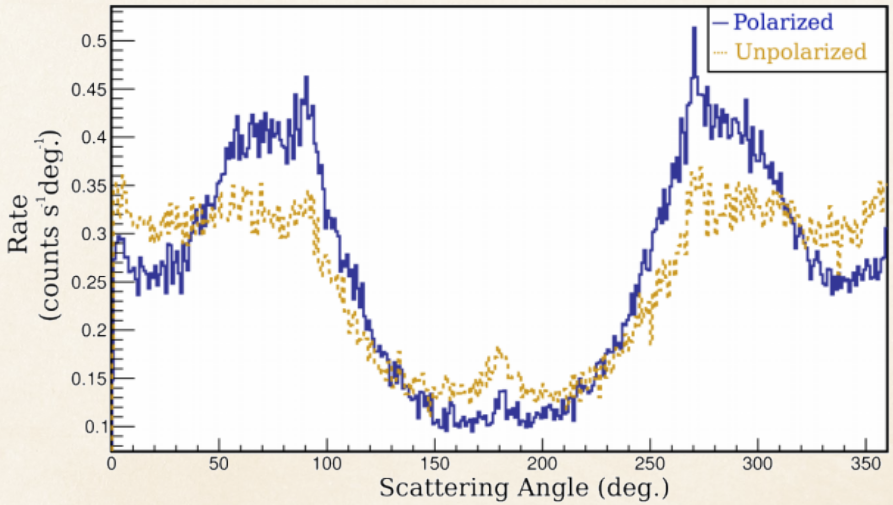
- Typical measured light and modulation curves shown below, complex modulation curve structure due to well-understood instrumental/geometrical effects
- POLAR detected 55 GRBs in 6 months of operation, 14 of which had enough statistics to be analyzed → joint spectral/polarization analysis with Fermi-GBM 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)

What we learned from POLAR

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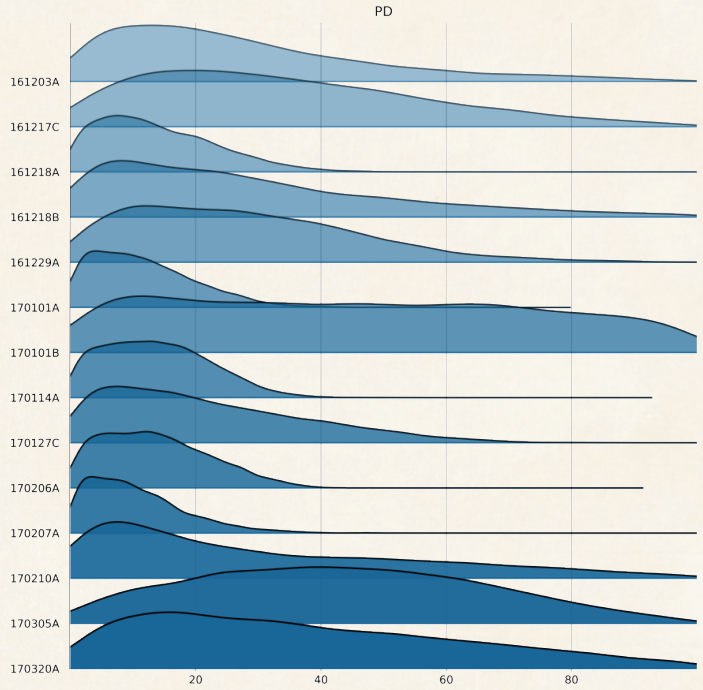
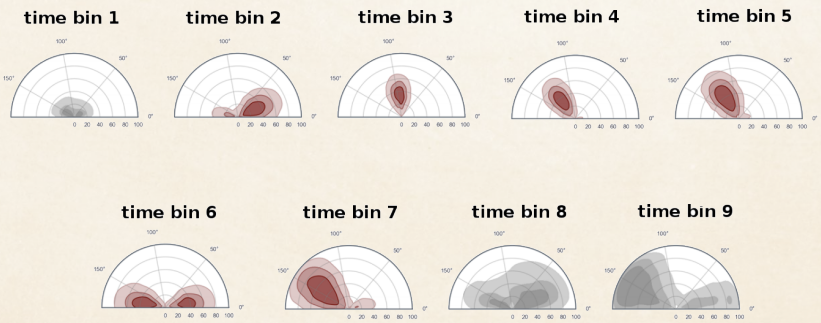
- Catalog of 14 GRBs analysed, results show a low or null polarization degree (excluding synchrotron emission models from toroidal magnetic field, compatible with photospheric emission model and other synchrotron models)
- Time resolved analysis show a hint of quickly evolving polarization angle that washes out polarization degree on time integrated analysis $\Longrightarrow$ need more statistics to make proper time resolved analysis
- 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)

Crab pulsar (PSR B0531+21) results from POLAR

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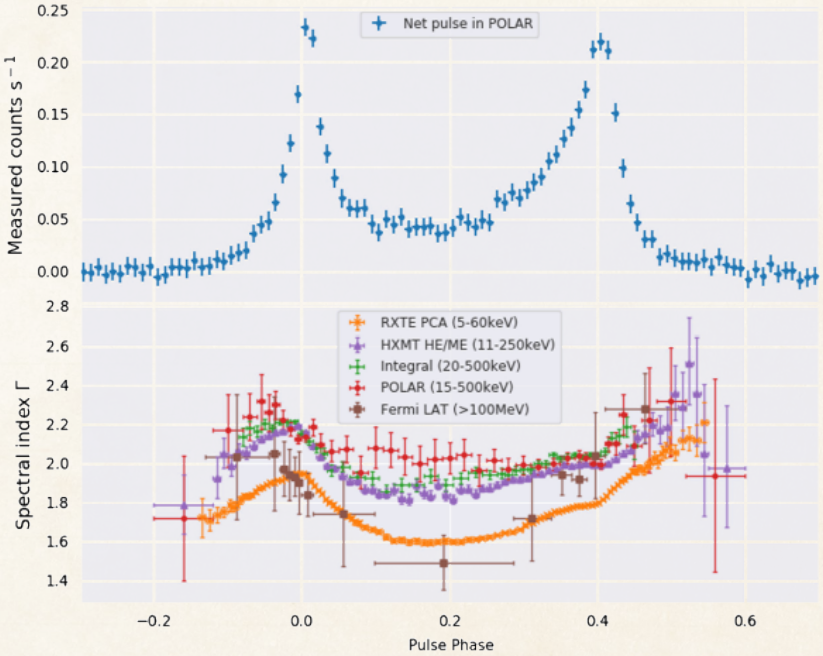
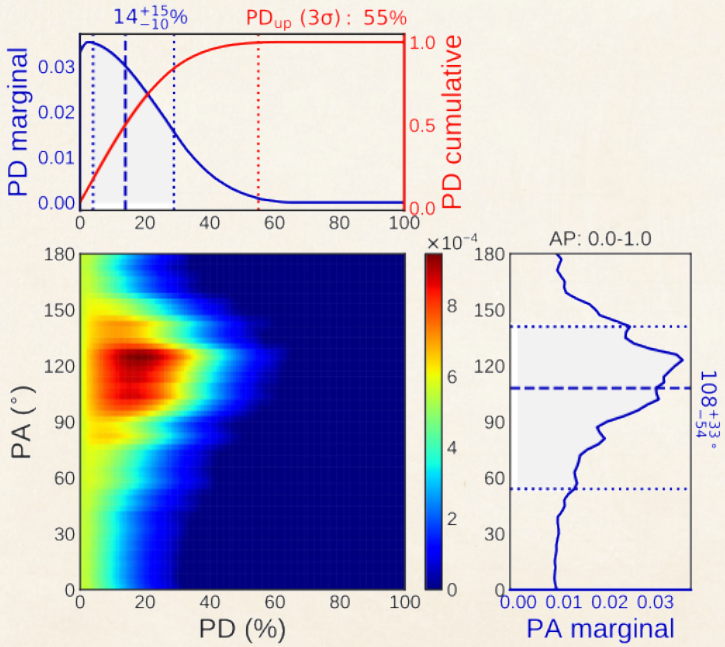
- Exposition of 400 h for spectral analysis, 1222 h for polarization analysis
- Nebula contribution subtracted, 3 pulse intervals studied: AP (0.0–1.0), P1 (0.0–0.2 || 0.8–1.0) and P2 (0.2–0.6)

	PD [%]	PA [°]
AP	14^{+15}_{-10}	108^{+33}_{-54}
P1	17^{+18}_{-12}	174^{+39}_{-36}
P2	16^{+16}_{-11}	78^{+39}_{-30}



Journal of High Energy Astrophysics 24 (2019) 15–22



MNRAS 512, 2827–2840 (2022)

The POLAR-2 mission

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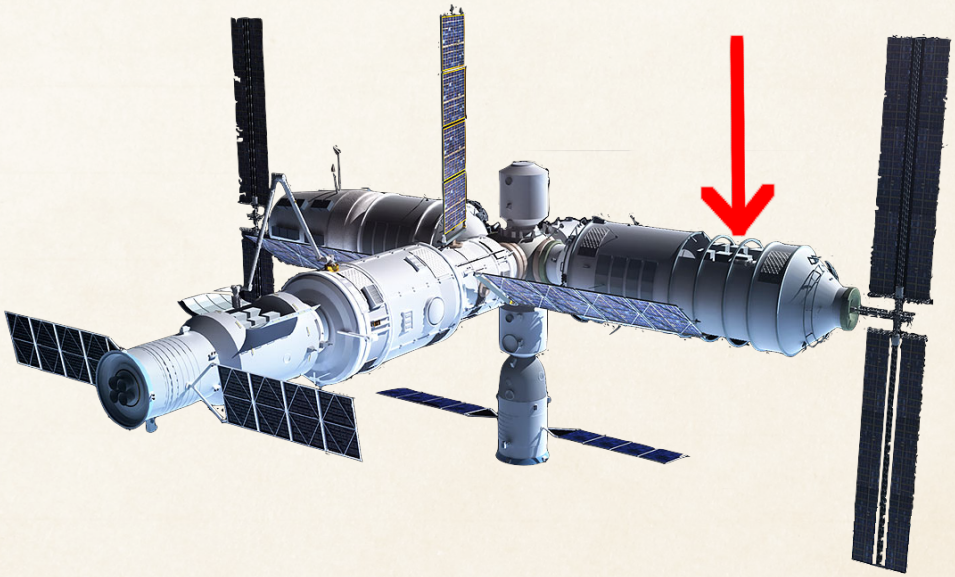
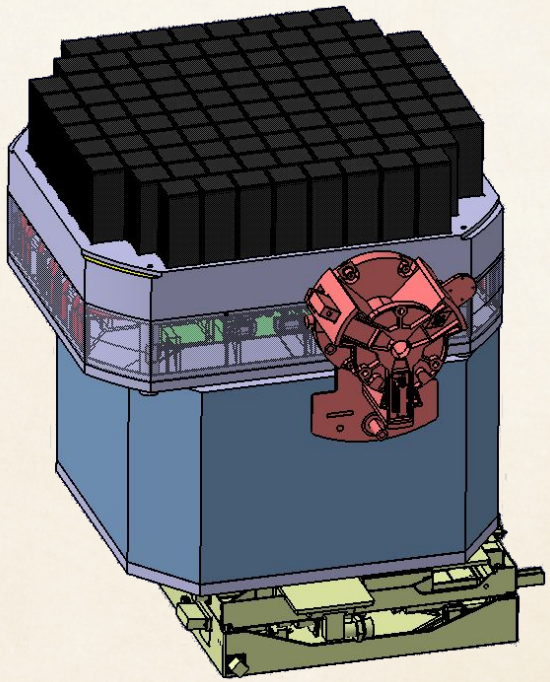
- Large scale GRB polarimeter based on POLAR legacy
- 4 times bigger than POLAR (from 25 to 100 polarimeter modules), 10 times more efficient (thanks to an improved design of the polarimeter modules)
- Lowered energy threshold to a few keV
- Equipped with spectrometer modules (CeBr3 or LaBr3) for joint spectral, localization, and polarization analysis
- Launch on China Space Station early 2025 (matches LIGO/VIRGO O5 run, possibility of joint observations with GW $\rightarrow$ Kole et al. 2022, in prep)



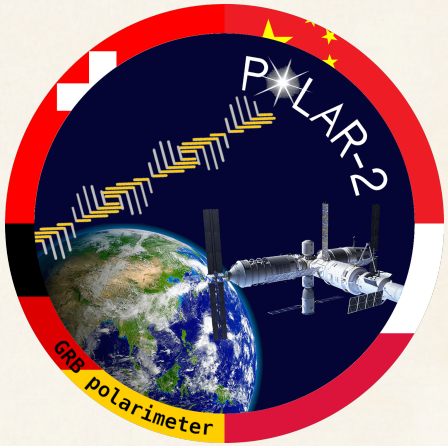


The POLAR-2 collaboration

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`.



Polarimeter module design

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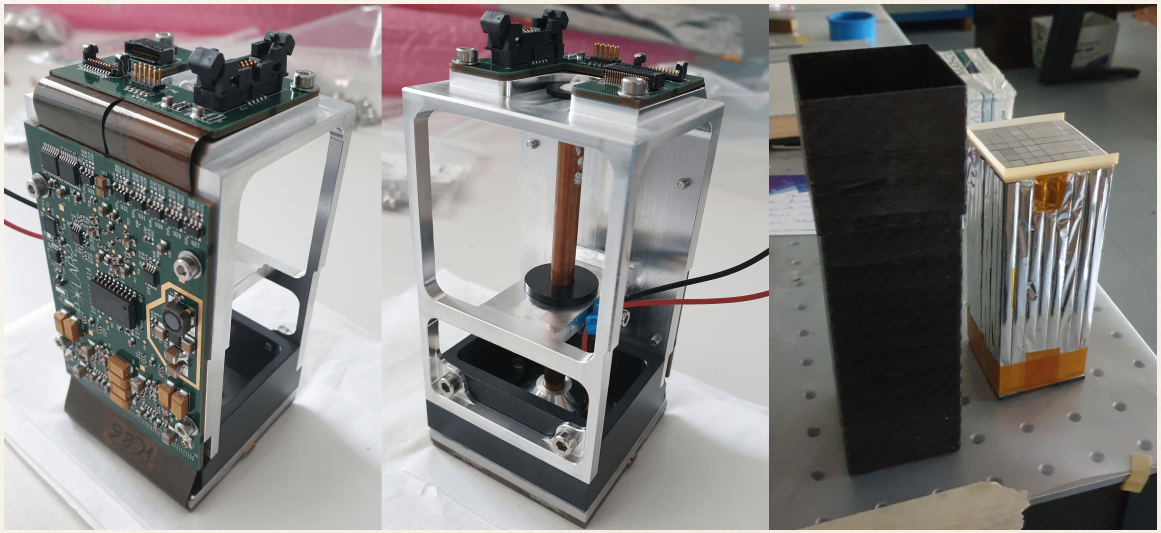
- 8×8 array of plastic scintillator bars ($5.9 \times 5.9 \times 125$mm) wrapped with highly reflective foils
- Readout with SiPM arrays from Hamamatsu (S13361-6075NE-04)
- 3D printed plastic alignment grid for scintillators
- Carbon fiber housing socket, Sorbothane pad at the top
- Back part of the module composed of FEE (based on CITIROC ASICs) and cooling system

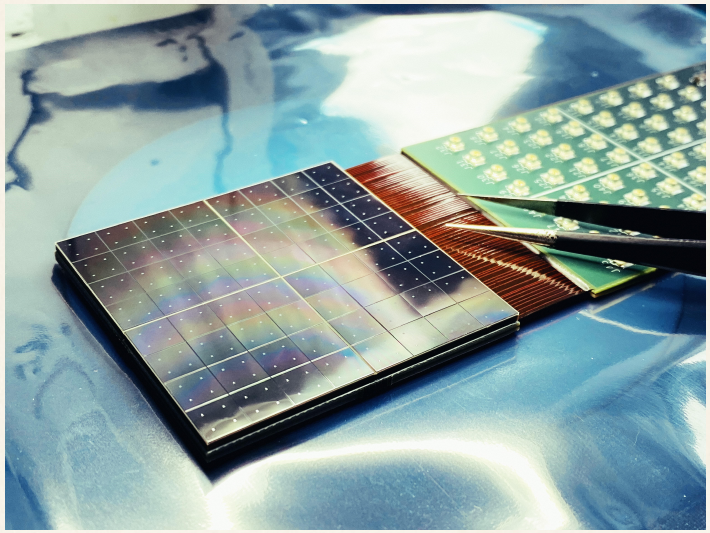
Improvements compared to POLAR:

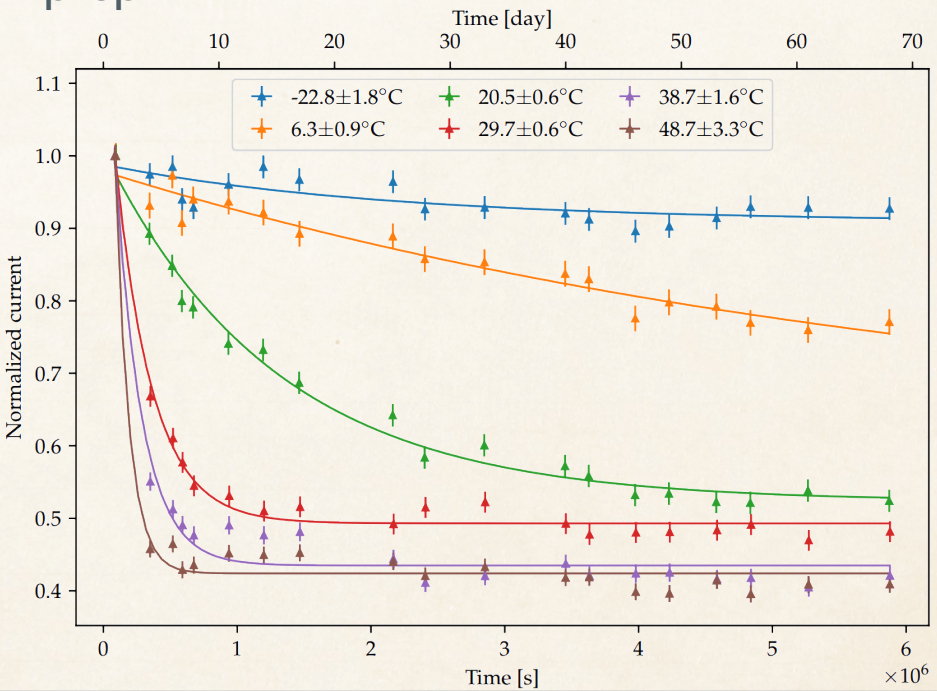
- Multi Anode PMTs are replaced by SiPM arrays $\Longrightarrow$ higher PDE (from 0.2 to 0.5)
- Shorter ($\Longrightarrow$ better SNR) and wider ($\Longrightarrow$ less dead volume between channels) scintillator bars
- Non-truncated scintillators $\Longrightarrow$ bigger readout surface $\Longrightarrow$ better light yield $\Longrightarrow$ lower energy threshold
- Reduced crosstalk by about an order of magnitude

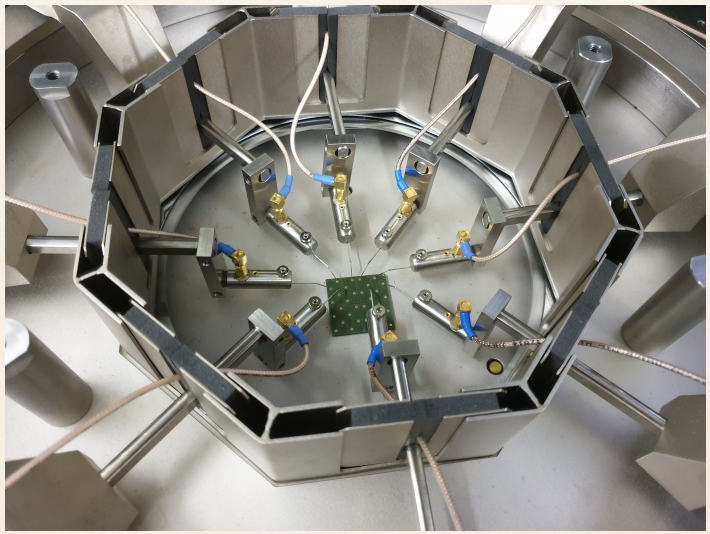


Polarimeter module development SiPM annealing studies

- I-V characterization of every SiPM array
- 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) → De Angelis et al. 2022a, in prep

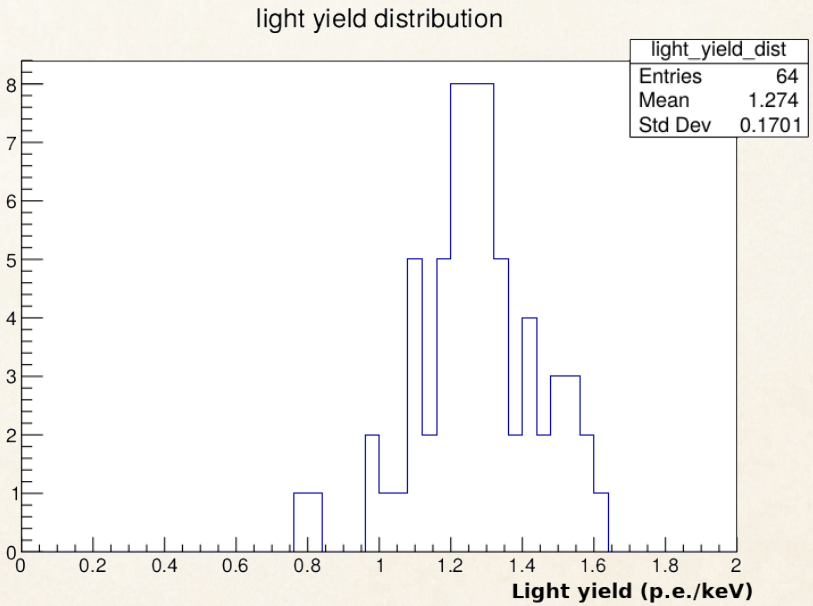


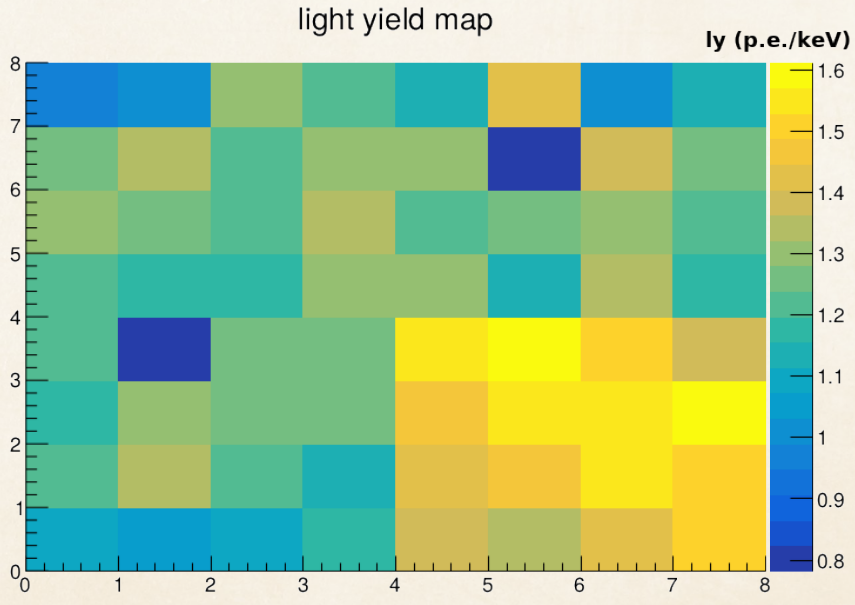




Preliminary module performances Light yield and crosstalk

- POLAR had a light yield of 0.3 p.e./keV
- POLAR-2 is able to reach 1.6 p.e./keV, thanks to a larger contact surface between scintillators and light sensors and higher PDE
  $\rightarrow$ De Angelis et al. 2022b, in prep
- Energy threshold can therefore go down to a few keV ($\sim$50 keV for POLAR)
- Optical crosstalk has also been improved by an order of magnitude compared to POLAR





Anticipated Scientific Performance

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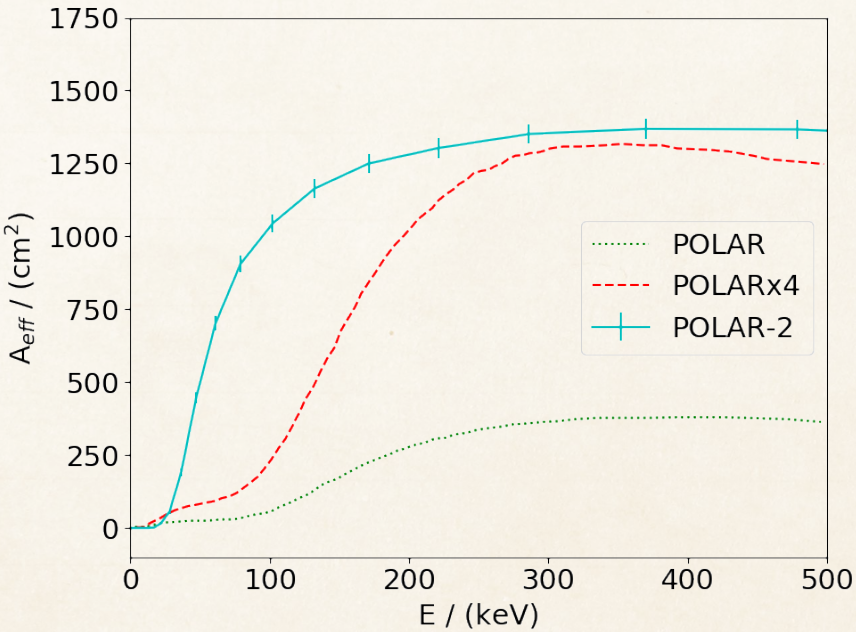
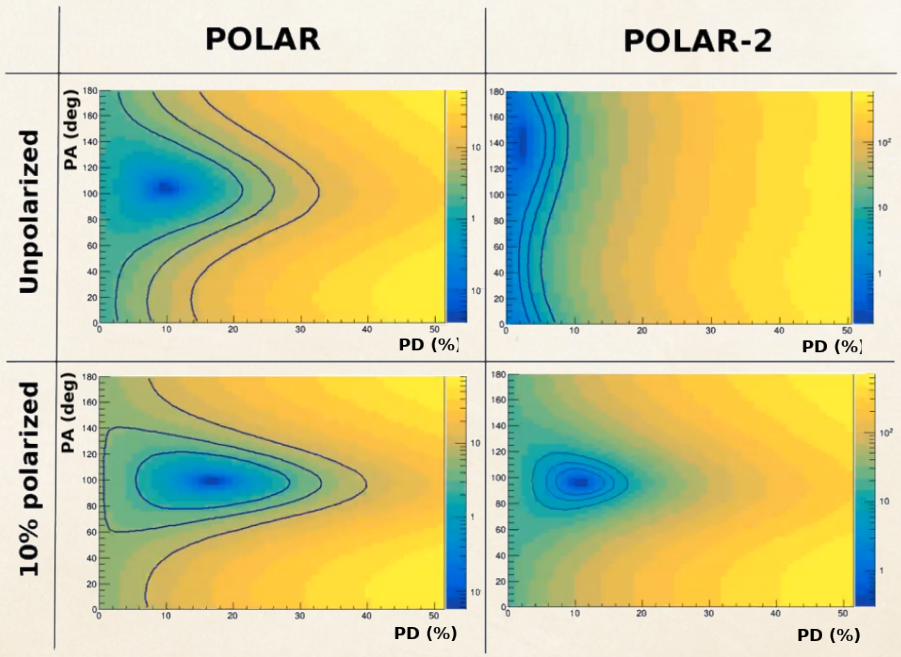
- POLAR-2 effective area will be better than 4 times POLAR due to technological improvements (e.g. for GRB170114A, 26.4° off-axis in POLAR FoV)
- Likelihood for POLAR and POLAR-2 in PA/PD phase space show that POLAR-2 will be able to distinguish an unpolarized and a 10% polarized GRB with 99% CL (here shown for GRB170206A, 19.5° off-axis for POLAR)





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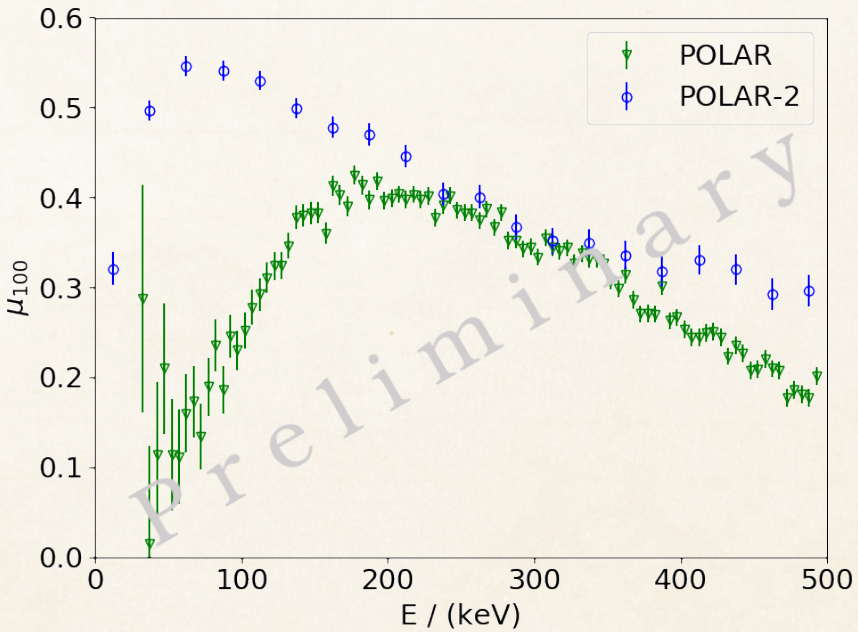

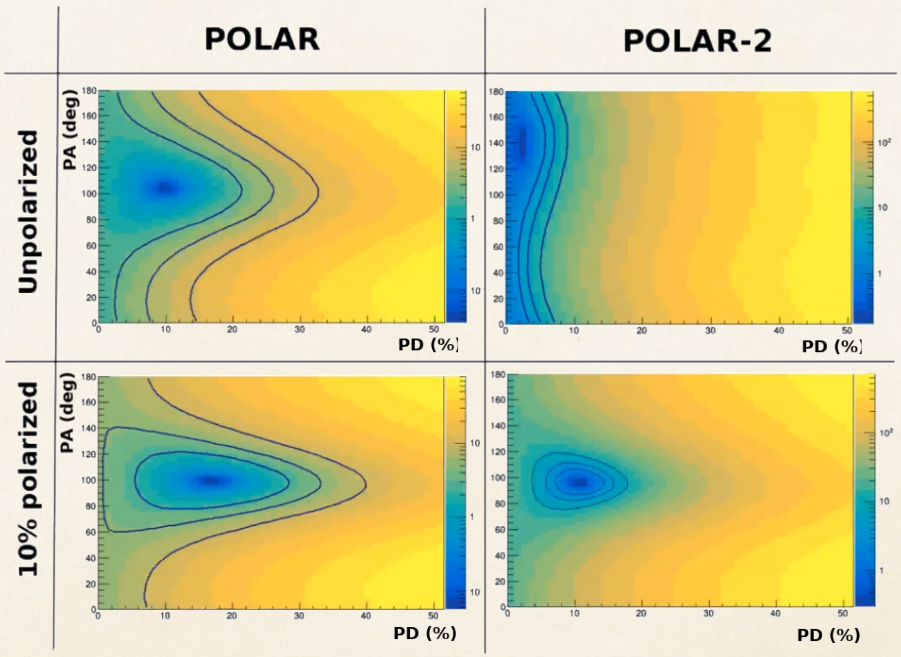

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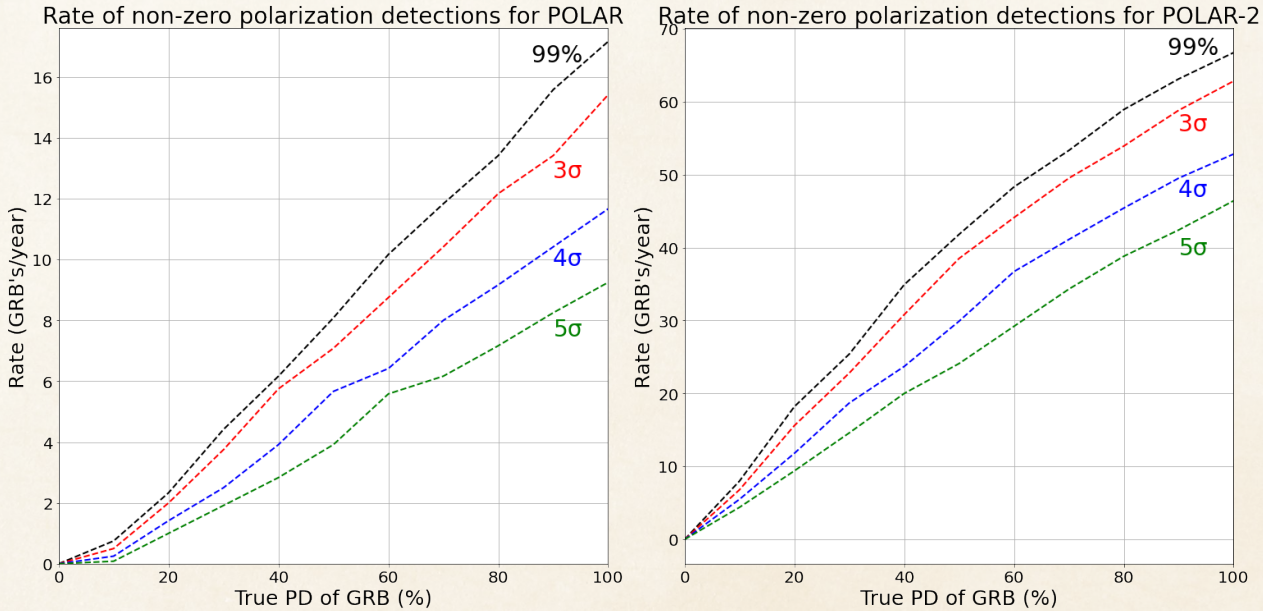
- Likelihood for POLAR and POLAR-2 in PA/PD phase space show that POLAR-2 will be able to distinguish an unpolarized and a 10% polarized GRB with 99% CL (here shown for GRB170206A, 19.5° off-axis for POLAR)
- About 50 GRBs/year with quality equal or higher than the best POLAR measurements (fluence $\geq 2\mu$erg/cm^2)



Galaxies 2021, 9(4), 82

Summary

- POLAR, a dedicated GRB Compton polarimeter, detected 55 bursts in 6 months of operation
- Catalog of 14 GRBs with joint spectral and polarization analysis, hint for time evolving PA within a single pulse, Crab spectral and polarization measurement
- More statistics are needed to perform detailed analysis of the polarization (e.g. for time/energy-dependant analysis)
- POLAR-2 successor mission of POLAR, 4 times bigger and 10 times more efficient, spectrometer modules for localization/joint spectral analysis, launch planned in 2024 to CSS
- Polarimeter module design optimize to lower the energy threshold and higher the efficiency (MAPMTs upgraded to SiPMs, dead space reduced)
- POLAR-2 will be able to provide about 50 high quality polarization measurements of GRBs every year