Gamma-Ray Polarization Measurements with the POLAR-2 mission

COSPAR 2022 - Athens, Greece

44th Scientific Assembly

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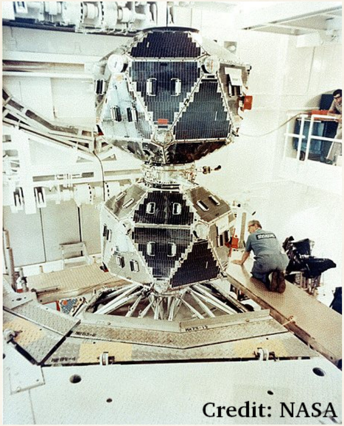
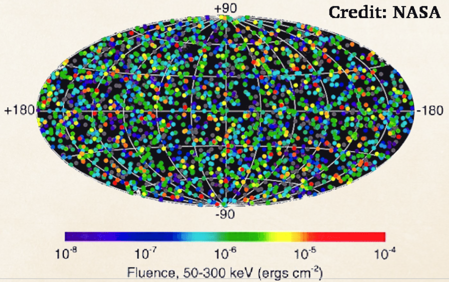
[2]`https://www.astro.unige.ch/polar/collaboration`
`https://www.unige.ch/dpnc/polar-2`

GRB history

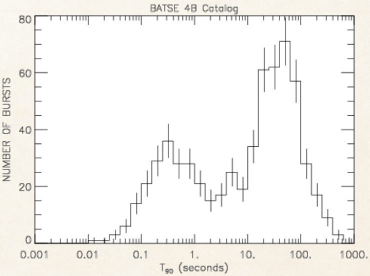


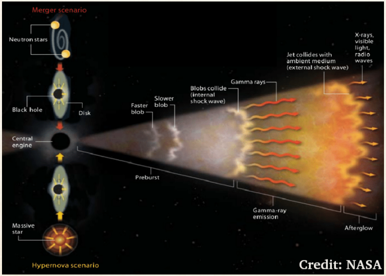
- Bright and short burst of X/γ-ray
- First discovered in 1967 by Vela US military satellite monitoring USSR nuclear weapon tests
- First breakthrough in early 90s, Burst and Transient Source Experiment (BATSE) measured position of thousands of GRBs, uniformly distributed in the sky
  $\Longrightarrow$ extragalactic sources
- Dedicated GRB polarimeter such as GAP and POLAR in the last decade



Gamma-Ray Bursts paradigm

- Extragalactic transient sources, lasting from milliseconds to minutes
- Two categories of GRBs:
  - Short bursts (T_{90}<2s) $\leftrightarrow$ neutron star mergers, detected in coincidence with GW
  - Long bursts (T_{90}>2s) $\leftrightarrow$ thought to originate from hypernovae
- Gamma prompt emission followed by an afterglow (in all wavelengths), likely from synchrotron process
- Polarization measurements can disentangle between different predicted emission models, allowing a better understanding of the jet and magnetic field structures (simplified picture: synchrotron=high PD, thermal emission=no/low polarization; ordered magnetic field=high PD, chaos=no/low polarization)





Pre-POLAR: no clear results from previous measurements:

GRB	Instr./Sat.	Pol. (%)	Remark
160530A	COSI	< 46	low statistics
110721A	GAP/IKAROS	84^{+16}_{-28}	Constant Pol. Angle
110301A	GAP/IKAROS	70 ± 22	Constant Pol. Angle
100826A	GAP/IKAROS	27 ± 11	Pol. Angle changes by $\approx 90°$
021206	RHESSI	80 ± 20	non dedicated instrument
021206	RHESSI	41^{+57}_{-44}	non dedicated instrument
140206A	IBIS/INTEGRAL	≥ 48	non dedicated instrument
061112	IBIS/INTEGRAL	≥ 60	non dedicated instrument
041219A	IBIS/INTEGRAL	$\leq 4/43 \pm 25$	non dedicated instrument
041219A	SPI/INTEGRAL	98 ± 33	non dedicated instrument
960924	BATSE/CGRO	≥ 50	non dedicated instrument
930131	BATSE/CGRO	≥ 35	non dedicated instrument

Early measurements performed by non-dedicated instruments, several measurements shown to be wrong, see *M. McConnell, New Astro Rev. Vol. 76, 2017*

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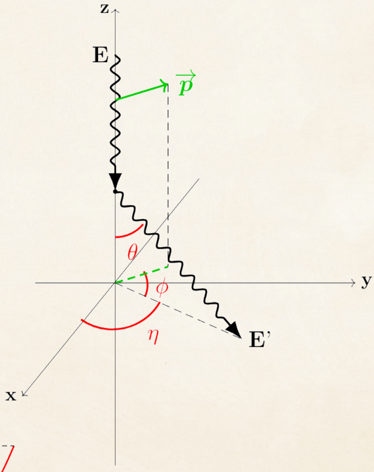
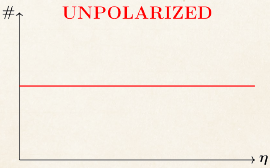
Compton scattering can be used to determine the polarization of a source:

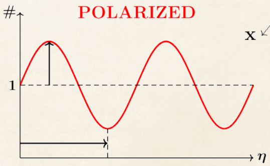
- Azimuthal scattering angle distribution provides information on polarization degree and angle
- So called modulation curved, parametrized by the Klein-Nishina cross-section:

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

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







Polarimetry with the Compton scattering

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

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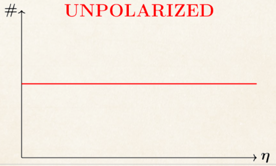
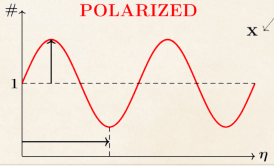
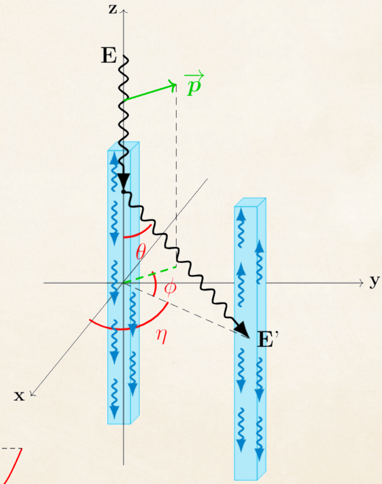
- Relative amplitude $\leftrightarrow$ PD, phase $\leftrightarrow$ PA
- **A segmented array of scintillators can be used to measure the scattering angle distribution (aka modulation curve)**

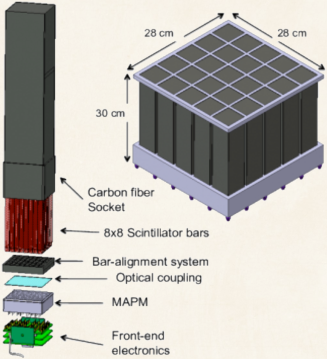


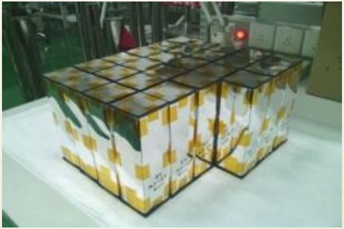




The POLAR instrument

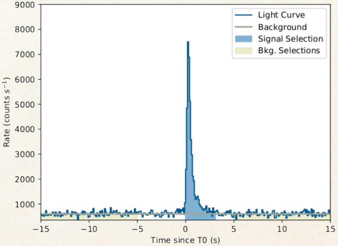
- POLAR was a dedicated gamma polarimeter composed of a 40×40 scintillator array
- Divided in 5×5 modules each made of 64 plastic scintillator bars ($176 \times 5.8 \times 5.8$ mm^3, EJ-248M), each module being readout by Multi-Anode PMTs
- Optimized for Compton scattering in the 50-500keV range thanks to its low-Z scintillators
- 30kg instrument, half-sky FoV, $\sim 300cm^2$ 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

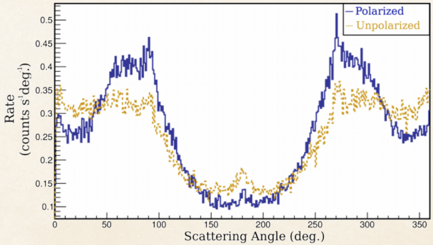




What we learned from POLAR

- 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 $\rightarrow$ 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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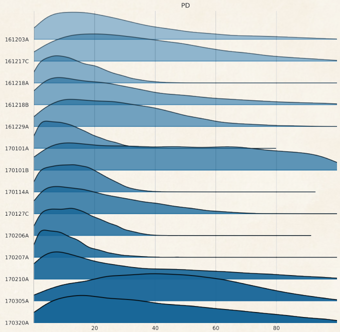
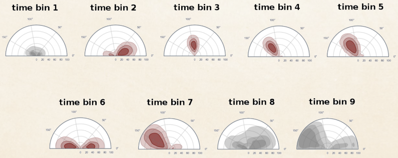
- Catalog of 14 GRBs analysed, results show a low or null polarization degree (excluding synchrotron emission models from toroidal magnetic field, compatible with photospheric emission model and other synchrotron models)
- Time resolved analysis show a hint of quickly evolving polarization angle that 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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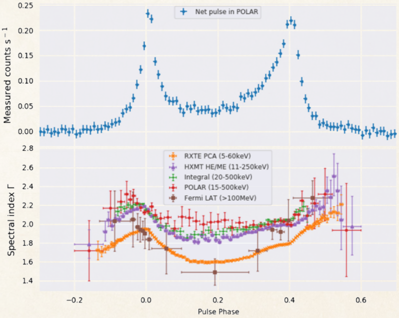
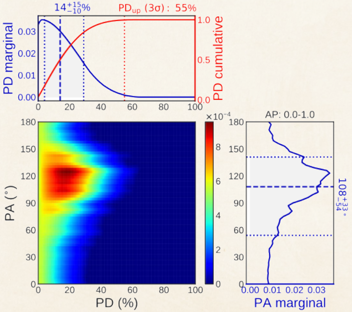
- Exposition of 400 h for spectral analysis, 1222 h for polarization analysis
- Nebula contribution subtracted, 3 pulse intervals studied: AP (0.0–1.0), P1 (0.0–0.2 || 0.8–1.0) and P2 (0.2–0.6)

	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

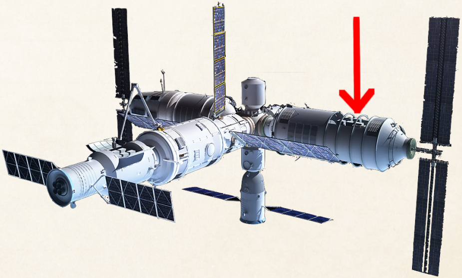


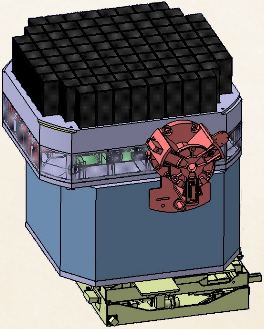
MNRAS 512, 2827–2840 (2022)

→ *presented by Hancheng Li on Tuesday (E1.12-0004-22)*

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 (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 late 2024/early 2025 (matches LIGO/VIRGO O5 run, possibility of joint observations with GW, *see M. Kole's poster E1.16*)





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

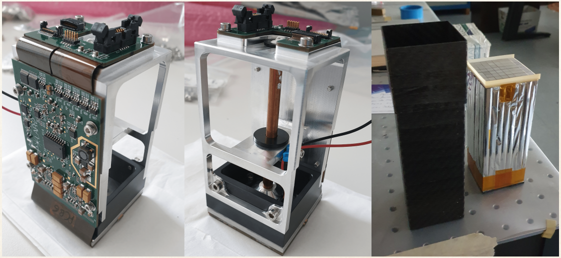
More info on `https://www.unige.ch/dpnc/polar-2`.

Polarimeter module design

- 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



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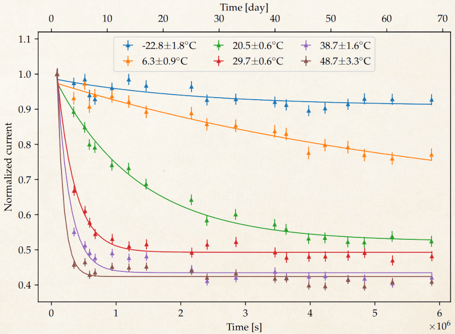
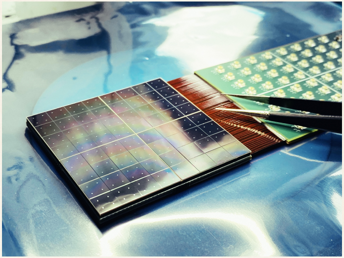
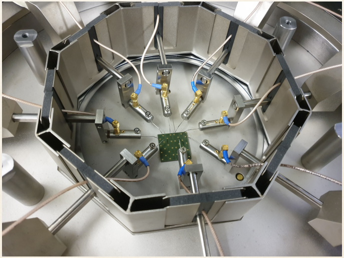
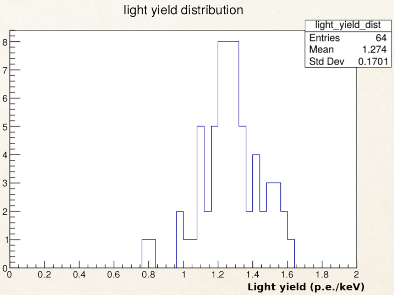
- I-V characterization of every SiPM array
- SiPMs cooled with Peltier elements to reduce dark noise
- Annealing studies allowed to estimate when/how much to heat up the sensors to recover part of the initial performances (degraded due to space radiation environment) → Paper coming soon

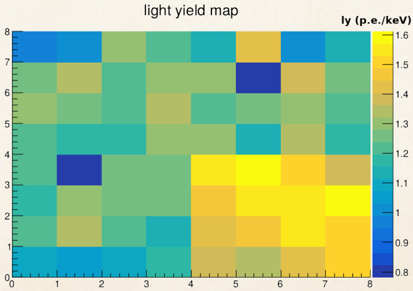






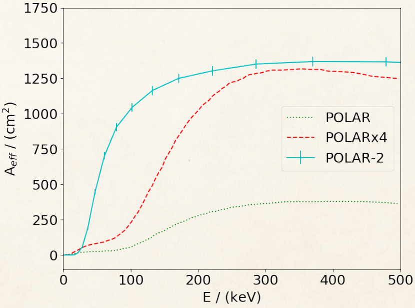
- POLAR had a light yield of 0.3 p.e./keV
- POLAR-2 is able to reach 1.6 p.e./keV, thanks to a larger contact surface between scintillators and light sensors and higher PDE
- Energy threshold can therefore go down to a few keV (∼50 keV for POLAR)
- Optical crosstalk has also been improved by an order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

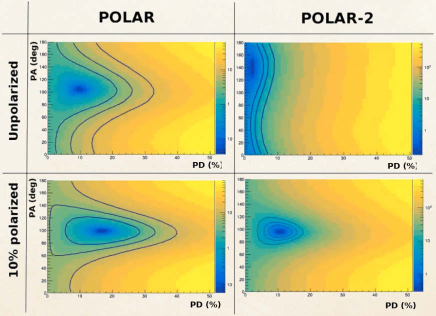




Anticipated Scientific Performance

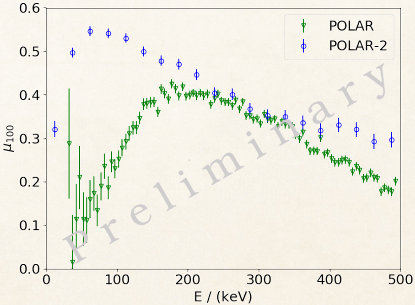
- POLAR-2 effective area will be better than 4 times POLAR due to technological improvements (e.g. for GRB170114A, 26.4° off-axis in POLAR FoV)
- Likelihood for POLAR and POLAR-2 in PA/PD phase space show that POLAR-2 will be able to distinguish an unpolarized and a 10% polarized GRB with 99% CL (here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

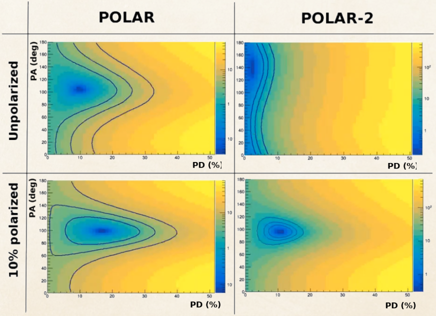




Anticipated Scientific Performance

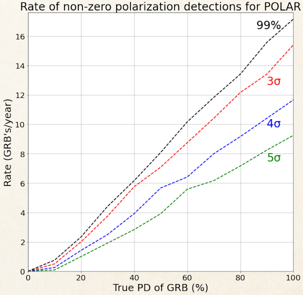
- POLAR-2 effective area will be better than 4 times POLAR due to technological improvements (e.g. for GRB170114A, 26.4° off-axis in POLAR FoV), modulation factor μ100 improved, especially at low energy
- Likelihood for POLAR and POLAR-2 in PA/PD phase space show that POLAR-2 will be able to distinguish an unpolarized and a 10% polarized GRB with 99% CL (here shown for GRB170206A, 19.5° off-axis for POLAR)

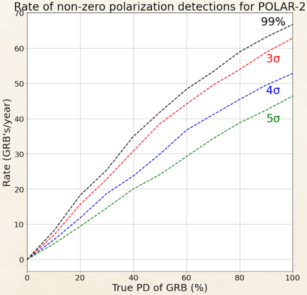




Anticipated Scientific Performance

- 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), modulation factor μ100 improved, especially at low energy
- 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

Crab predictions for POLAR-2

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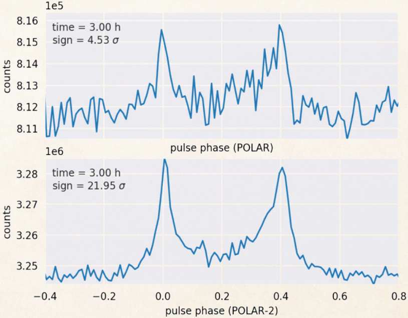
- POLAR spectral fitting: ~400h, 58.14σ $\rightarrow$ will be achieved with 33h POLAR-2 exposure
- 2yrs of POLAR-2 data $\implies$ more detailed spectral analysis of the Crab pulsar, and even of other PSRs (e.g. PSR B1509-58)
- If Crab pulsar is unpolarized: 5σ upper limits on the PD to a level of ~20%. If Crab pulsar is 10 or 20% polarized, it will be confirmed with 5 or 4σ



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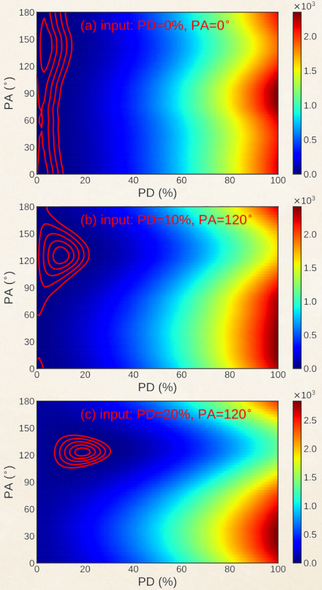


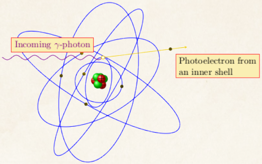
MNRAS 512, 2827–2840 (2022)

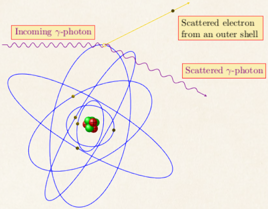
Summary

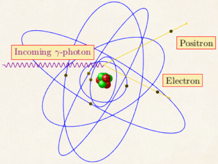
- POLAR, a dedicated GRB Compton polarimeter, detected 55 bursts in 6 months of operation
- Catalog of 14 GRBs with joint spectral and polarization analysis, hint for time evolving PA within a single pulse, Crab spectral and polarization measurement
- More statistics are needed to perform detailed analysis 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

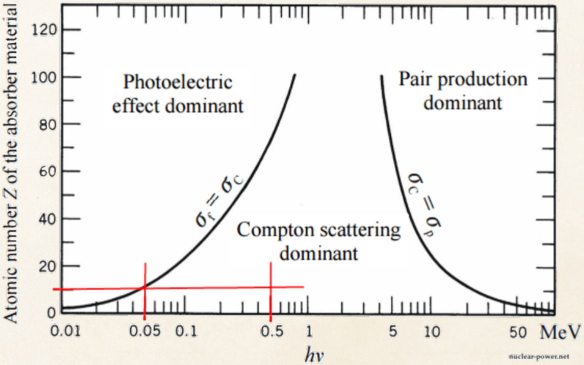
Backup slides

Low-Z scintillators for an optimized Compton cross-section









Joint polarization-spectral GRB analysis method

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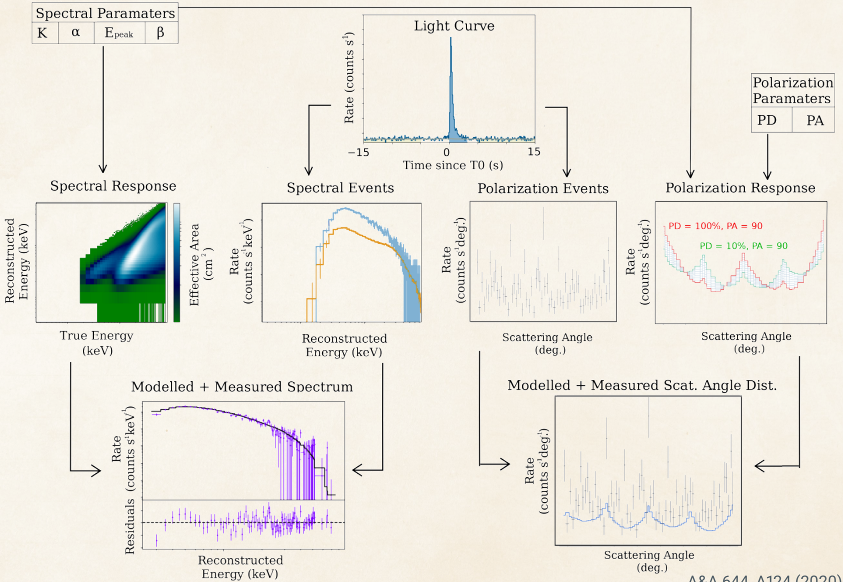

A&A 644, A124 (2020)

POLAR catalog

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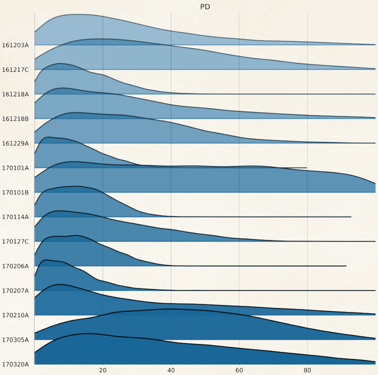
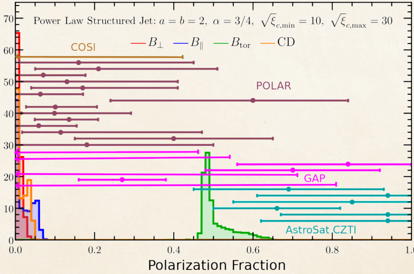


A&A 644, A124 (2020)

- 55 GRBs detected, 14 with enough statistics for proper polarization analysis

- Most GRB results from POLAR are compatible with a low or null polarization
- POLAR results discard synchrotron emission from toroidal magnetic field
- Discrepancy with results from AstroSat CZTI
- POLAR data and response are public: `www.astro.unige.ch/polar/`

Based on model figure from: R. Gill & J. Granot & P. Kumar, 2019, MNRAS, Volume 491, Issue 3



An example: GRB170114A

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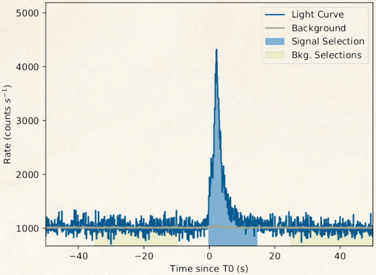

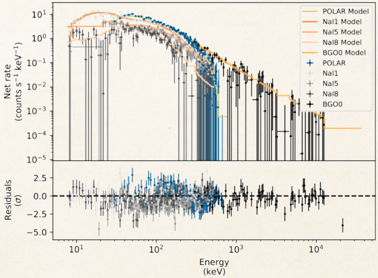

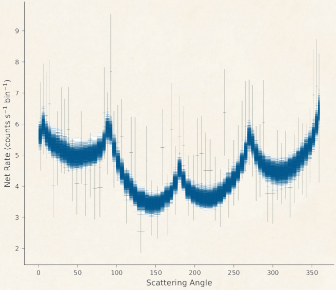

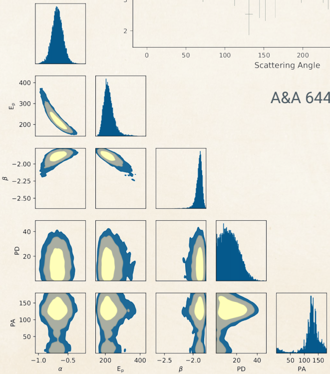

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Time resolved analysis of GRB170114A

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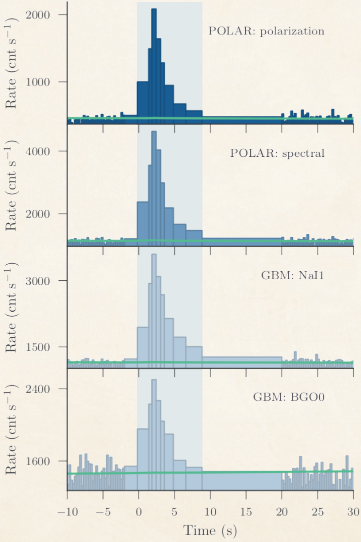
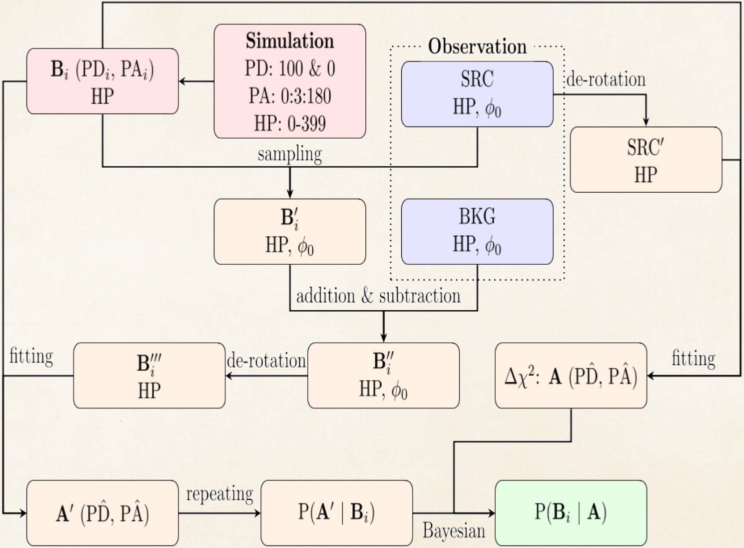
- Joint analysis using data from POLAR and Fermi-GBM using the 3ML framework
- Spectral modeling of the data is consistent with a synchrotron photon model, as has been found in a majority of similarly analyzed single-pulse GRBs
- Slight trend of growing PD in time reaching values of ∼30% at the emission peak
- PA evolution throughout the emission, whichwashes out the PD in time-integrated analysis
- Evolution of the PA reported before for multipulse GRBs using data from both the GAP and IBIS instruments (Yonetoku et al. 2011; Götz et al. 2009), but this intrapulse evolution has not been observed before



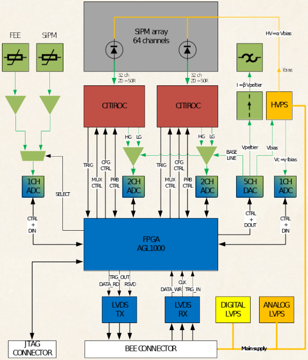
A&A 627, A105 (2019)

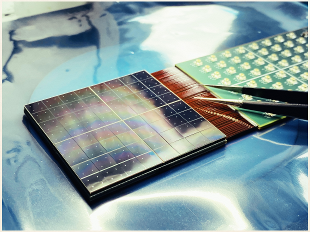
Bayesian workflow for the POLAR Crab analysis



Polarimeter module development

- I-V characteristics of all SiPM array channels are measured to extract the breakdown thermal dependency (important for breakdown non-uniformity and temperature corrections)
- Measurement of transmittance and reflectance spectra of wrapping foils used for scintillators
- Component qualification: irradiation of FPGA, DC/DC converter, Peltier, ADCs etc. with a PuBe neutron source
- SiPM irradiation with neutrons/protons: important to understand the increase of DCR and energy resolution with exposition dose
- Cooling system of the polarimeter modules is currently being tested. Heat extracted from the back of the sensors using Peltier element and heat pipe





Polarimeter module development SiPM I-V characterization

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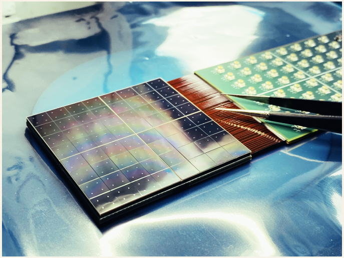
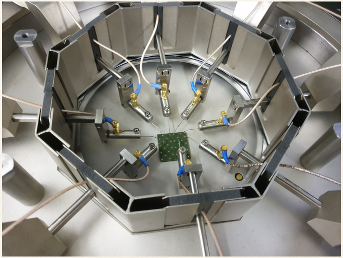
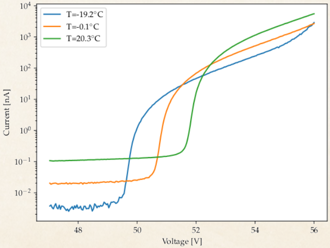
- I-V characterization of every SiPM array with semi-automatic probe station (CascadeMicrotech300)
- Measurement of breakdown vs temperature
- Breakdown non-uniformity correction at the ASIC level (with an integrated DAC) and temperature loop correction in the FEE







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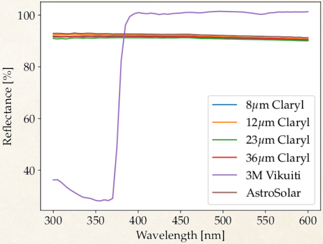
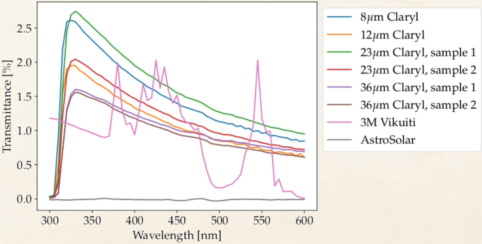
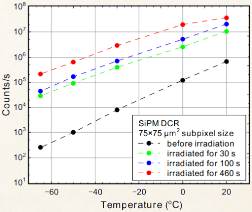
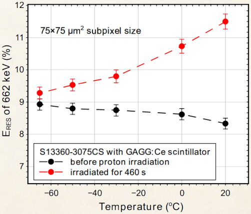
- Transmittance and reflectance measurement of several wrapping foils candidate at CERN (PerkinElmer LAMBDA 650 Spectrometer)
- Scintillators will be first wrapped with Vikuiti from 3M (reflectance of about 99%), and with Claryl from Toray afterward (reflectance of about 90%)



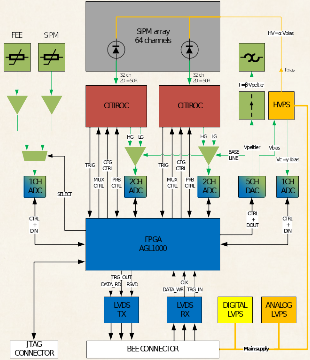


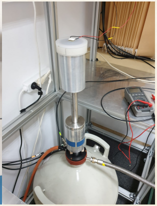
- Front-end component irradiation for space qualification: GoWiN FPGA, DC/DC converter for sensor bias from LT, Peltier element activation, ADCs...
- SiPM irradiation to study the increase of dark current after several years of exposure in space





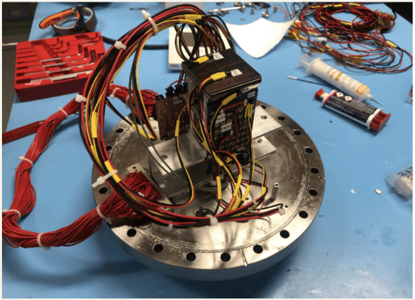
S. Mianowski et al 2020 JINST 15 P03002

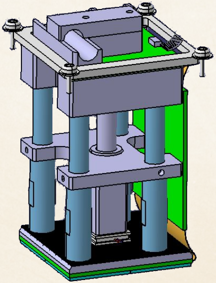




Polarimeter module development Cooling system

- Cooling system of the polarimeter modules is currently under design and several options are being tested
- Based on Peltier element on the back of the SiPM to reduce dark noise and heat pipes to extract heat from the module
- Overall instrument thermal simulations are also ongoing in order to optimize outer radiator system
- Power budget of 200W for the polarimeter (2W per module) + 100W for the BEE and spectrometer modules





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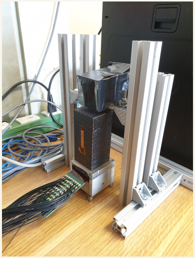
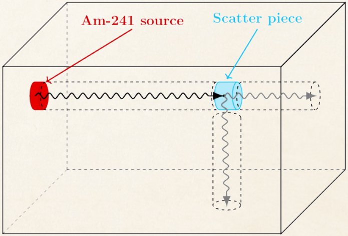
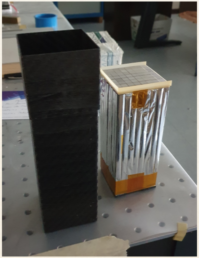
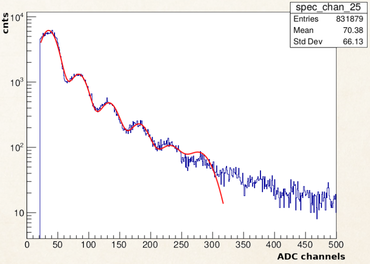
- Module calibration setup at CERN (Geneva) based on FEE used in a neutrino experiment (also using CITIROC ASIC), our own FEE is expected in a month
- 365MBq Am-241 source (59.5keV photopeak) + 3.37MBq Cs-137 source (470keV Compton edge)
- Lead shielding with integrated scatter piece designed in order to get polarized photons from the Am-241 source

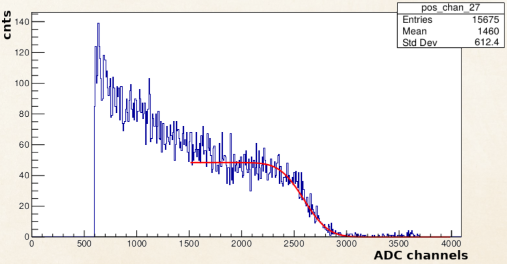






- Fitting HG finger plot to get the distance between photoelectrons $\Longrightarrow$ gain in ADC/p.e.
- Fitting HG Am241 photopeak (59.5keV) and LG Cs137 Compton edge (470keV) to get the HG-LG ADC conversion (to get a more precise light yield value)
- Dividing the ADC/keV of the cesium CE by the gain leads to the light yield in p.e./keV





Preliminary module performances Crosstalk

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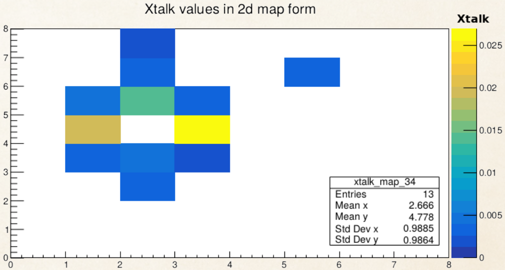
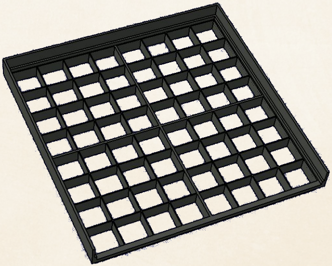
- Optical crosstalk between scintillator bars was about 15-20% for POLAR
- This goes down to 1.5-2.5% thanks to an improved scintillator wrapping method and the suppression of a thick optical coupling layer (0.7mm)
- The optical coupling between SiPM and scintillator bars is still under investigation, so the final crosstalk could be a bit worst
- Current crosstalk compatible with transmittance/reflectance measurements: wrapping foil have a transmittance of about 1% and 3m height plastic grid used to assemble the scintillators is 60% transparent $\rightarrow$(122mm/125mm)*1%+(3mm/125mm)*60%=2.416%





POLAR-2 Minimum Detectable Polarization

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