



Gamma-Ray Burst Polarization Measurements with the POLAR-2 mission

**1st Mondragone Frontiers of Astronomy Series
Latest Advances in X-ray Spectroscopy and Polarimetry**

Nicolas De Angelis¹ for the POLAR and POLAR-2 collaborations²

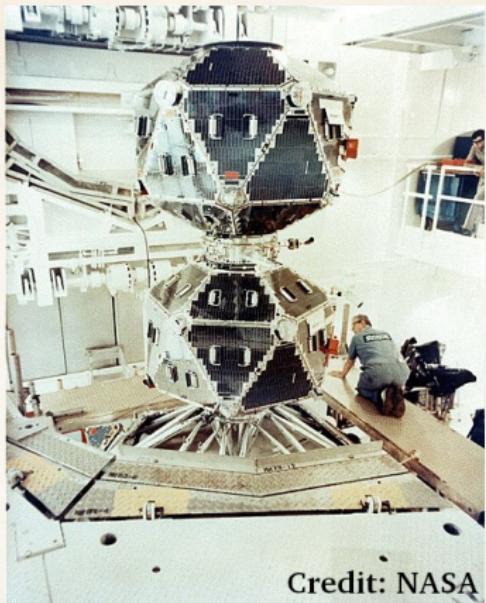
DPNC, University of Geneva, Switzerland

May 18-20th, 2022

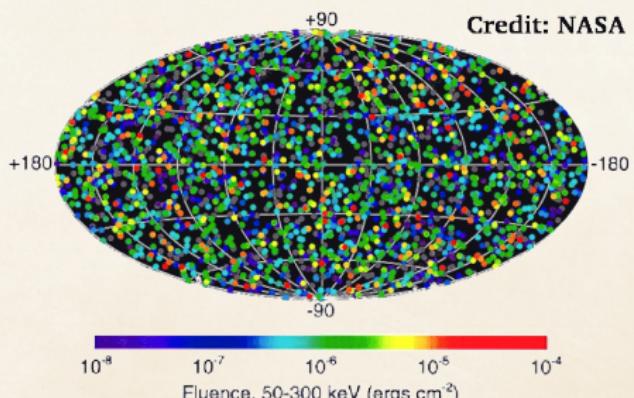
¹E-mail: nicolas.deangelis@unige.ch

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

GRB history

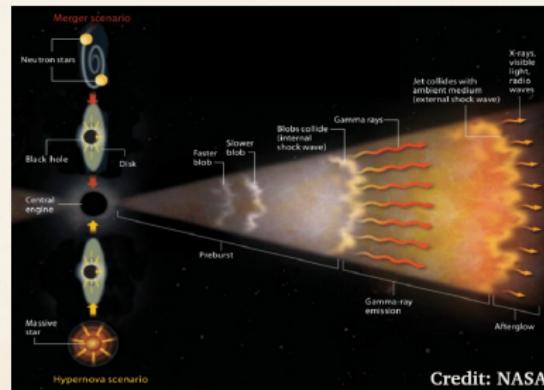
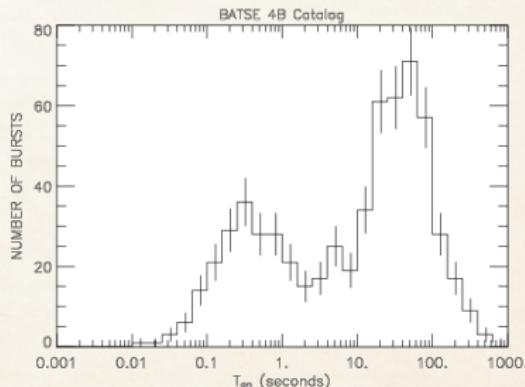


- Bright and short burst of X/ γ -ray
- First discovered in 1967 by Vela US military satellite monitoring USSR nuclear weapon tests
- First breakthrough in early 90s, Burst and Transient Source Experiment (BATSE) measured position of thousands of GRBs, uniformly distributed in the sky
 \Rightarrow extragalactic 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 ($T_{90} < 2$ s) \leftrightarrow neutron star mergers, detected in coincidence with GW
 - Long bursts ($T_{90} > 2$ s) \leftrightarrow thought to originate from hypernovae
- Gamma prompt emission followed by an afterglow (in all wavelengths) 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)



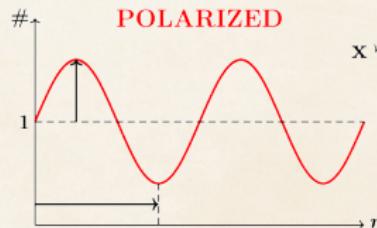
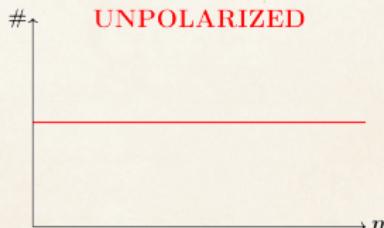
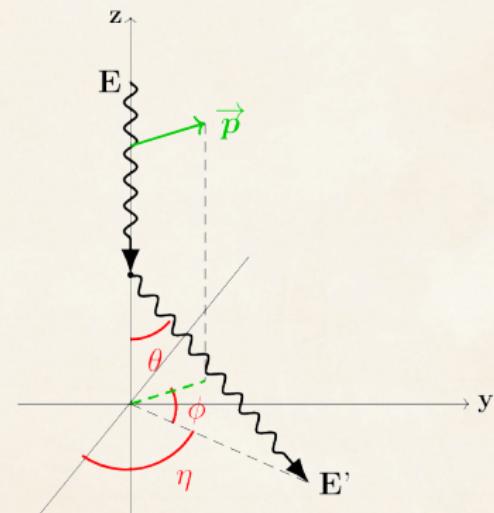
Polarimetry with the Compton scattering

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, parametrized 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

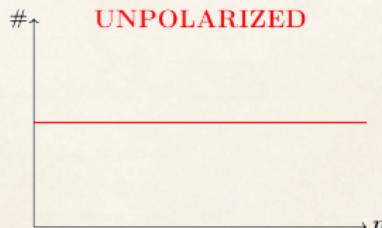
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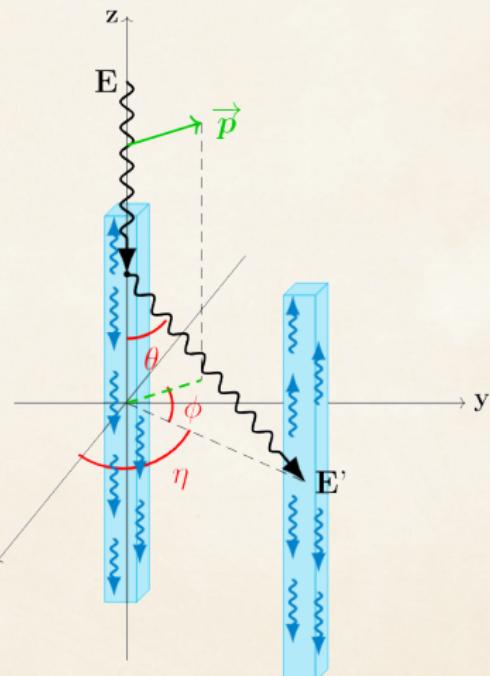
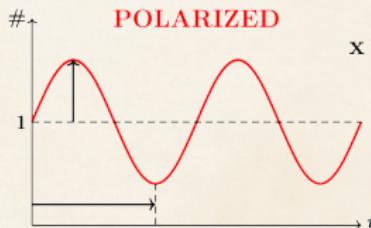
$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2} \left(\frac{E'}{E} \right)^2 \left[\frac{E'}{E} + \frac{E}{E'} - 2 \sin^2(\theta) \cos^2(\phi) \right]$$

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

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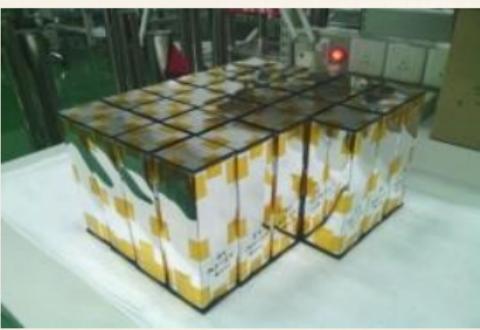
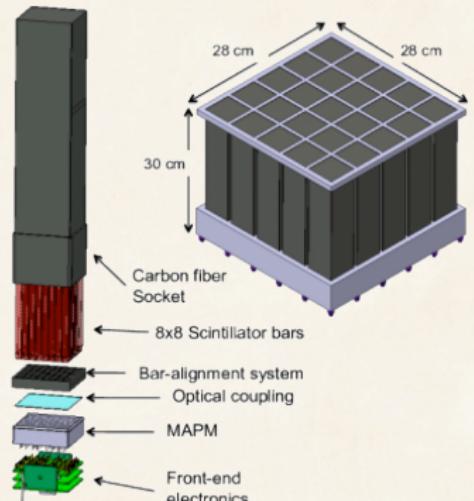


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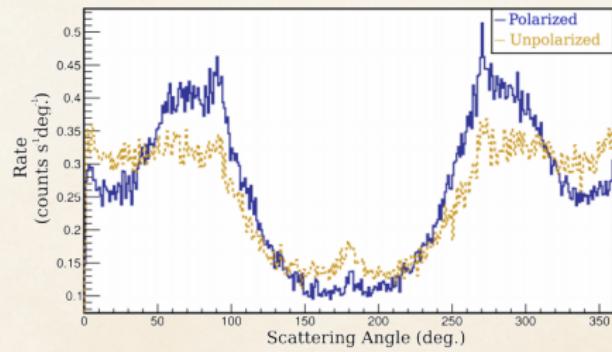
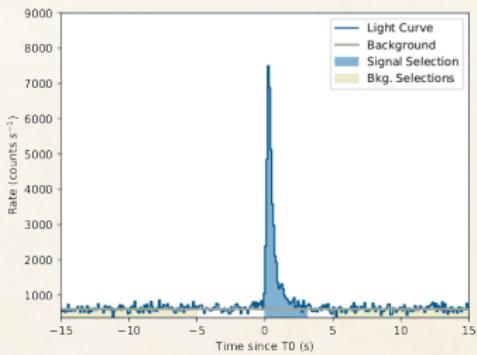
The POLAR instrument

- 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

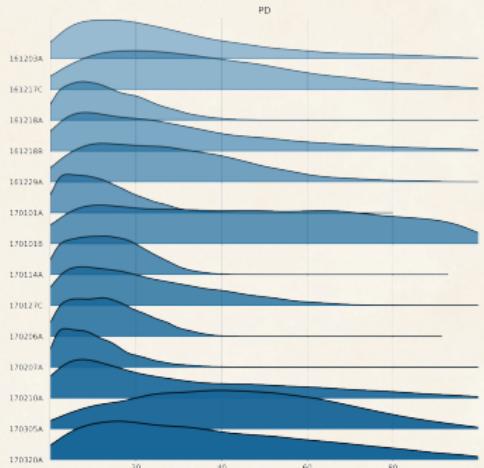
- Typical measured light and modulation curves shown below, complex modulation curve structure due to well-understood instrumental/geometrical effects
- POLAR detected 55 GRBs in 6 months of operation, 14 of which had enough statistics to be analyzed → joint spectral/polarization analysis with Fermi-GBM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



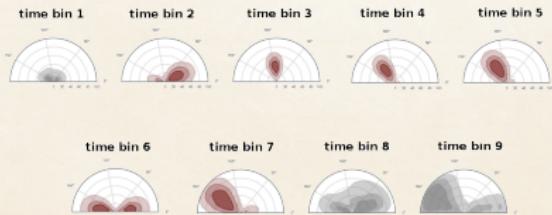
A&A 644, A124 (2020)

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 \implies 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



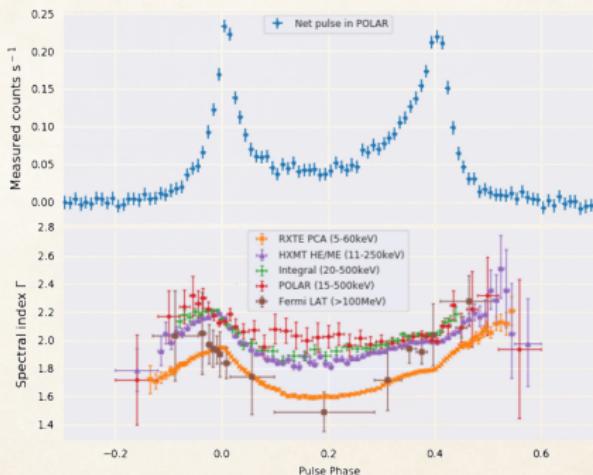
A&A 644, A124 (2020)



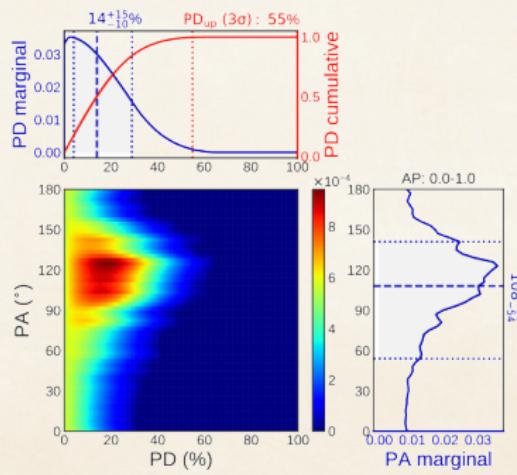
A&A 627, A105 (2019)

Crab pulsar (PSR B0531+21) results from POLAR

- Exposition of 400 h for spectral analysis, 1222 h for polarization analysis
- Phase-resolved spectral index analysis matches other instruments → good understanding of the detector response
 - 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)

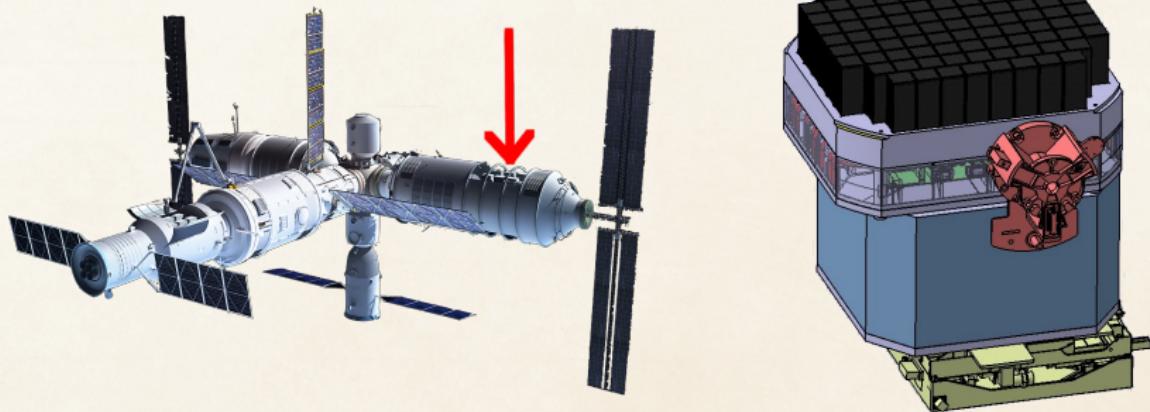


	PD [%]	PA [°]
AP	14^{+15}_{-10}	108^{+33}_{-54}
P1	17^{+18}_{-12}	174^{+39}_{-36}
P2	16^{+16}_{-11}	78^{+39}_{-30}



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



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>.



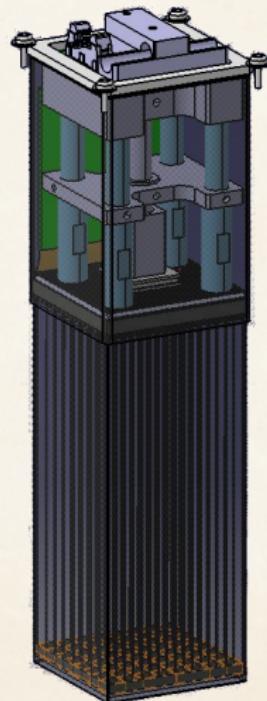
Max-Planck-Institut für
extraterrestrische Physik

Polarimeter module design

- 8×8 array of plastic scintillator bars ($5.9 \times 5.9 \times 125\text{mm}$) 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 (using CITIROC ASICs) and cooling system (based on Peltier element and heat pipe, still under design)

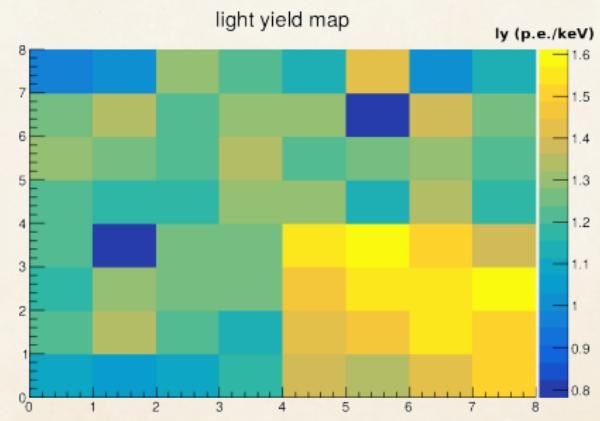
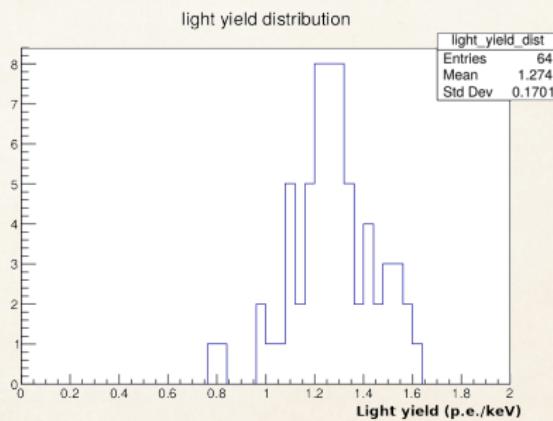
Improvements compared to POLAR:

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



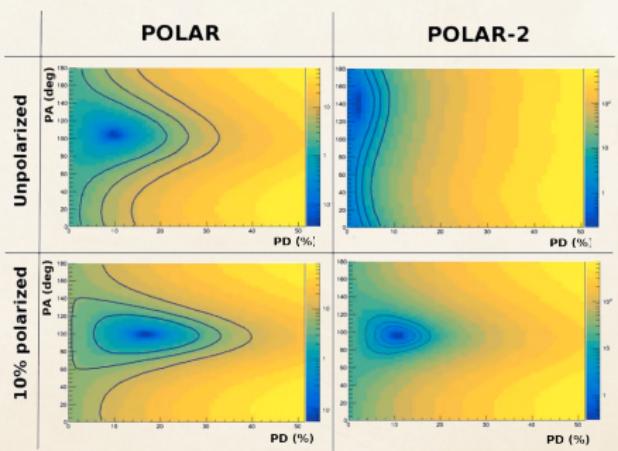
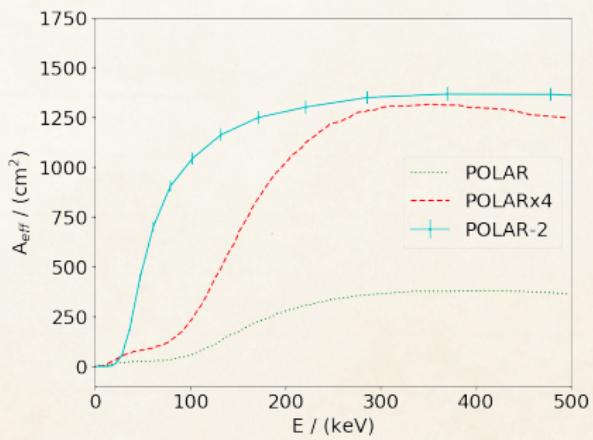
Preliminary module performances Light yield and crosstalk

- 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
- 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



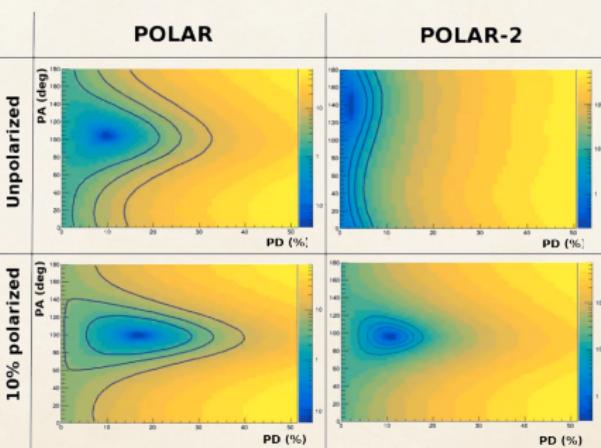
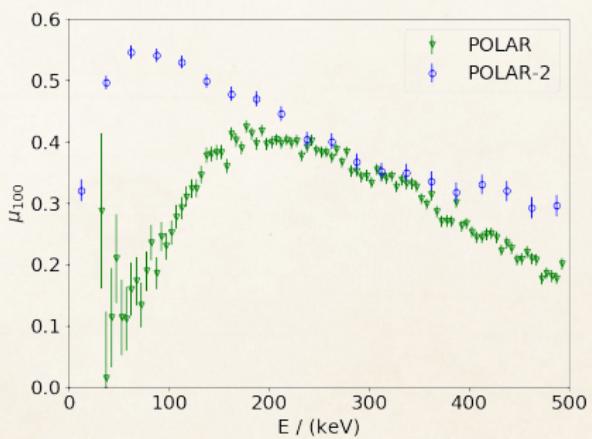
Anticipated Scientific Performance

- 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)



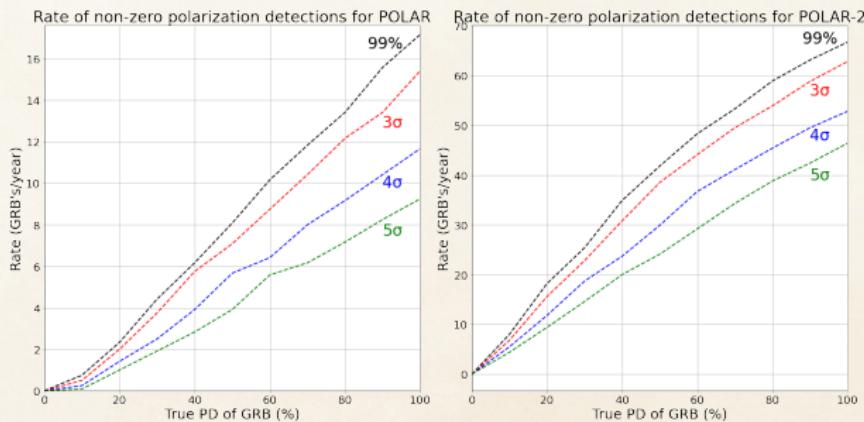
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- POLAR-2 effective area will be better than 4 times POLAR due to technological improvements (e.g. for GRB170114A, 26.4° off-axis in POLAR FoV), modulation factor μ_{100} improved, especially at low energy
- Likelihood for POLAR and POLAR-2 in PA/PD 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

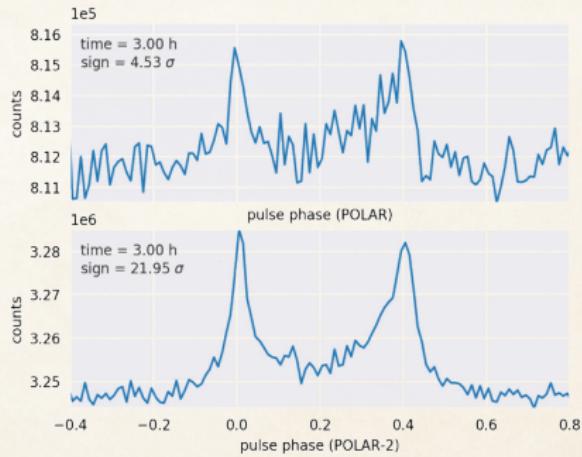
- POLAR-2 effective area will be better than 4 times POLAR due to technological improvements (e.g. for GRB170114A, 26.4° off-axis in POLAR FoV), modulation factor $\mu 100$ improved, especially at low energy
- Likelihood for POLAR and POLAR-2 in PA/PD phase space show that POLAR-2 will be able to distinguish 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 $\geq 2\mu\text{erg/cm}^2$)



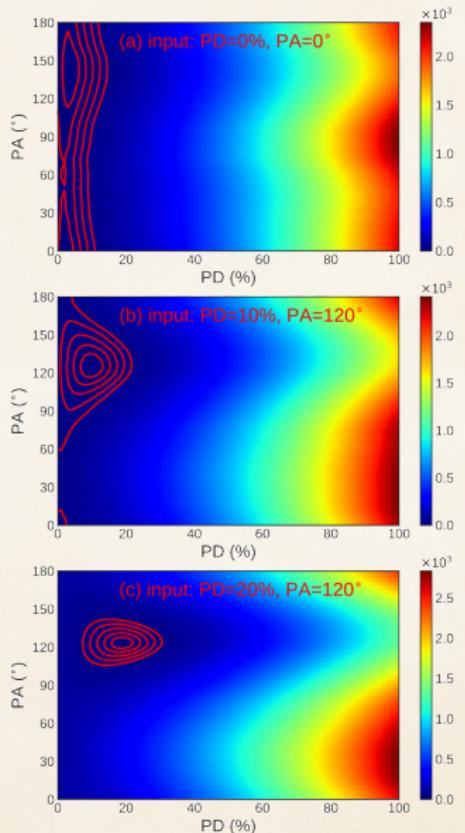
Galaxies 2021, 9(4), 82

Crab predictions for POLAR-2

- POLAR spectral fitting: $\sim 400\text{h}$, $58.14\sigma \rightarrow$ 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 $\sim 20\%$. If Crab pulsar is 10 or 20% polarized, it will be confirmed with 5 or 4σ



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



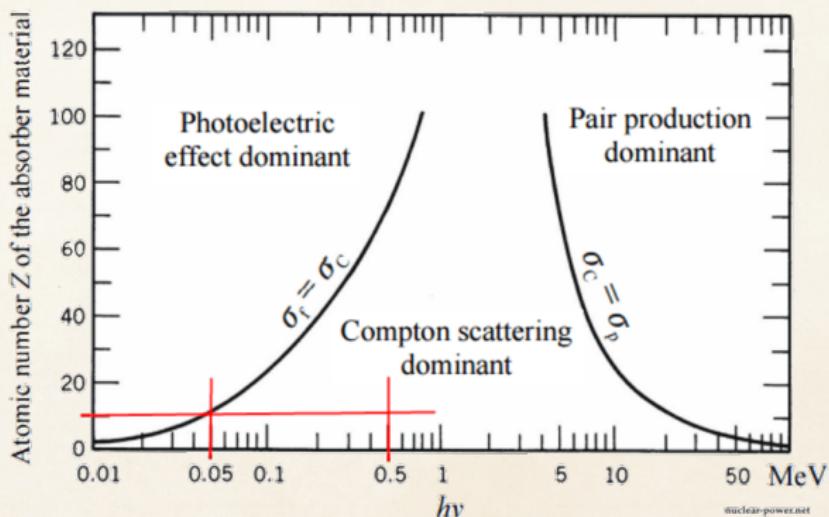
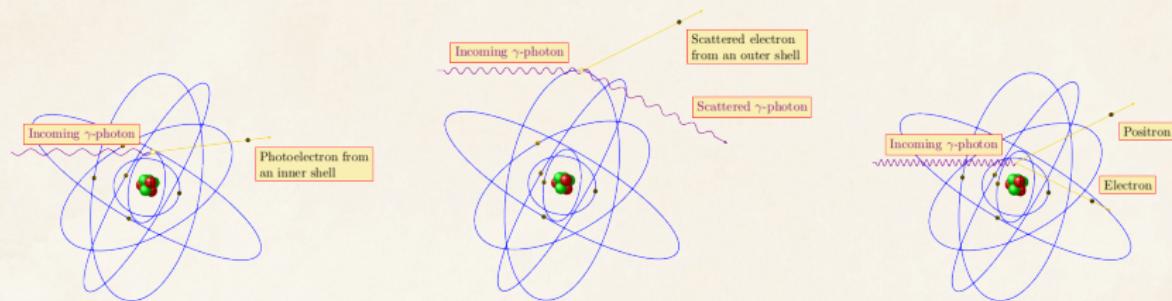
MNRAS 512, 2827–2840 (2022)

Summary

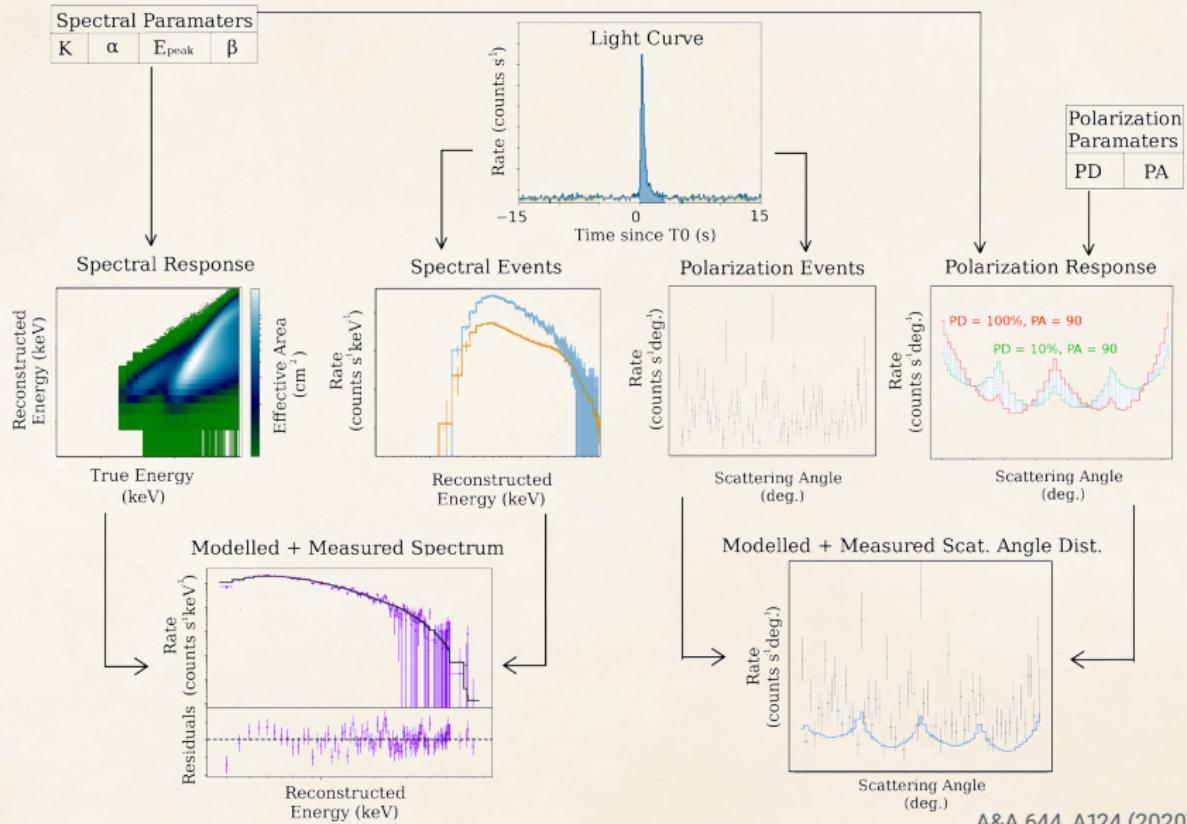
- POLAR, a dedicated GRB Compton polarimeter, detected 55 bursts in 6 months of operation
- Catalog of 14 GRBs with joint spectral and polarization analysis, hint for time evolving PA within a single pulse, Crab spectral and polarization measurement
- More statistics are needed to perform detailed analysis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

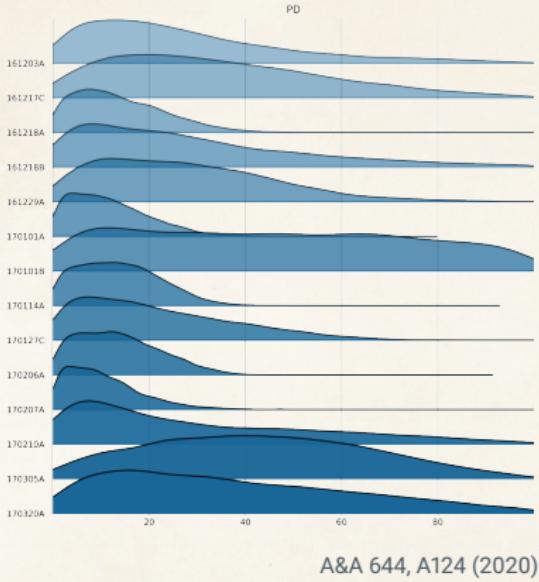


Joint polarization-spectral GRB analysis method



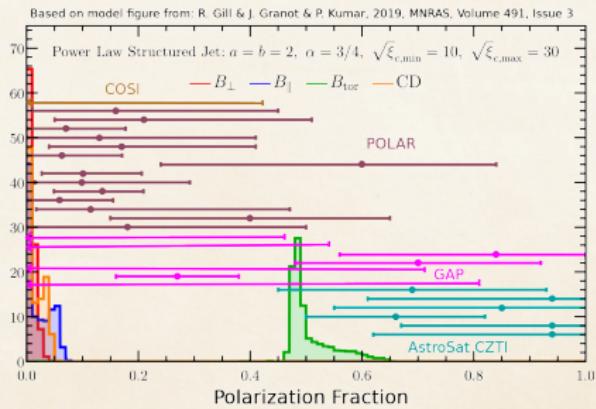
A&A 644, A124 (2020)

POLAR catalog

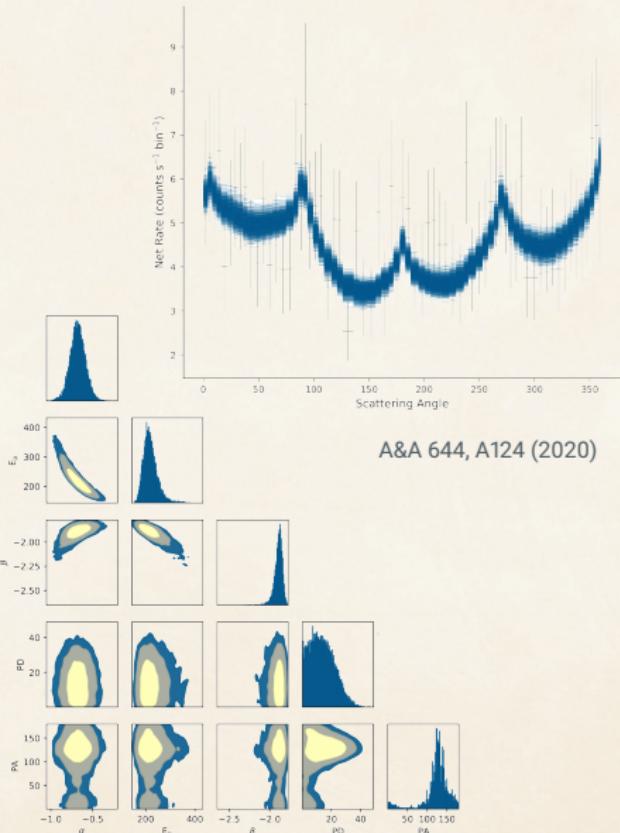
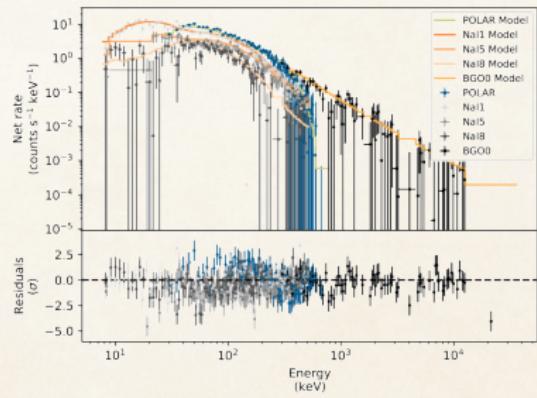
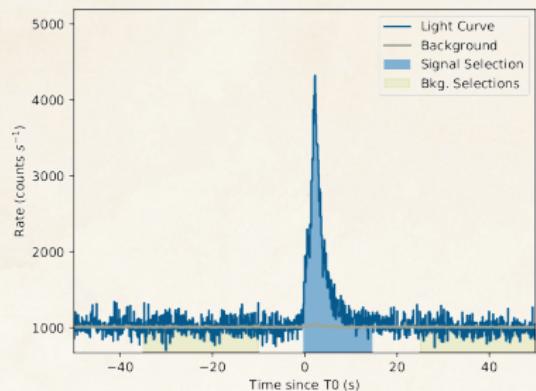


- 55 GRBs detected, 14 with enough statistics for proper polarization analysis

- 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/



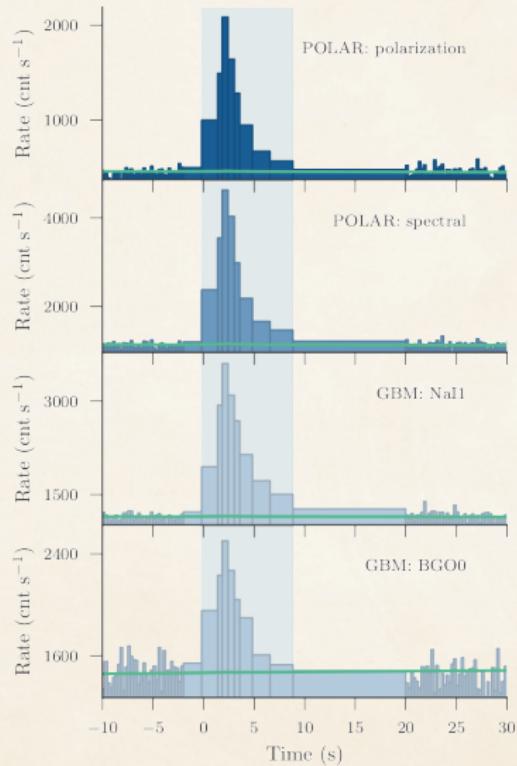
An example: GRB170114A



A&A 644, A124 (2020)

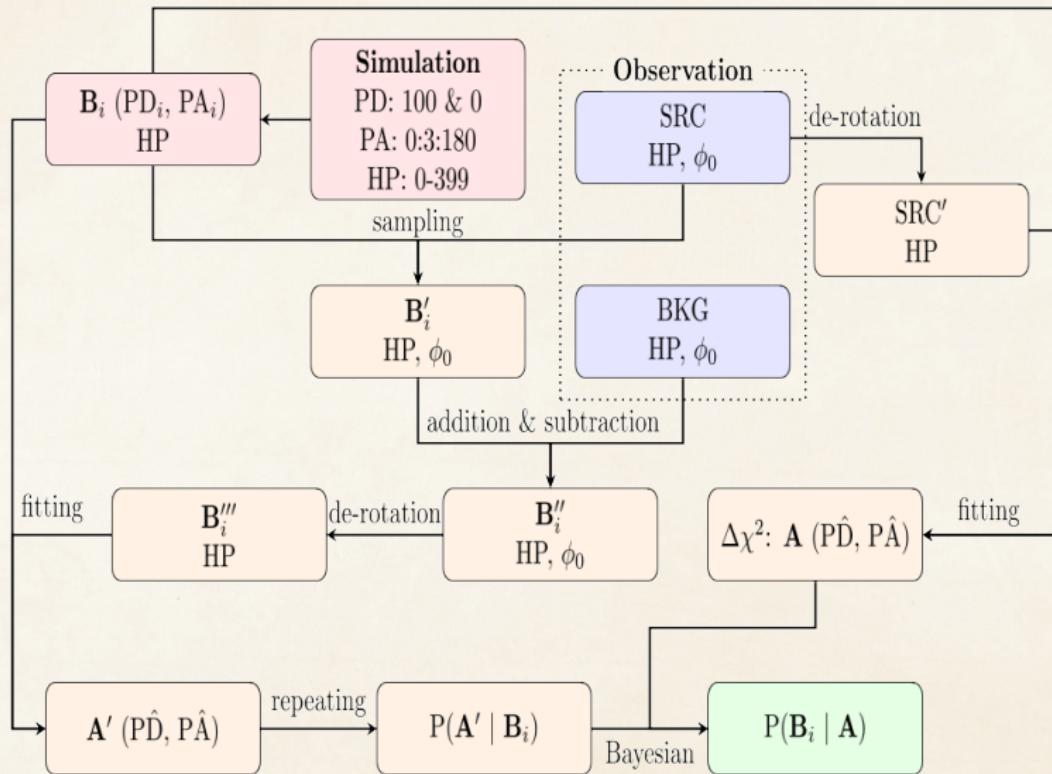
Time resolved analysis of GRB170114A

- 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 $\sim 30\%$ at the emission peak
- PA evolution throughout the emission, which washes 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



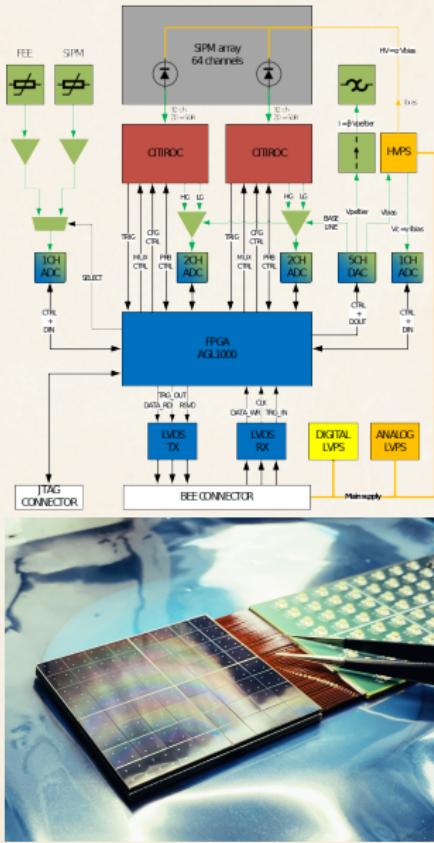
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Bayesian workflow for the POLAR Crab analysis



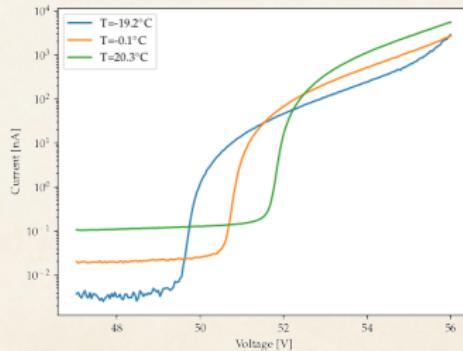
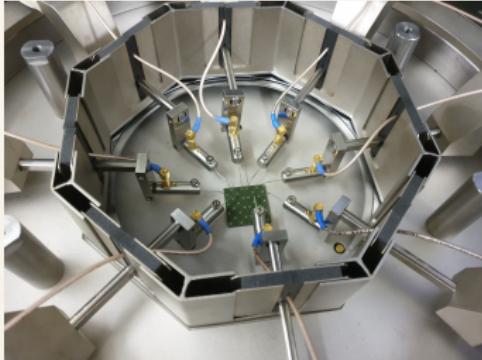
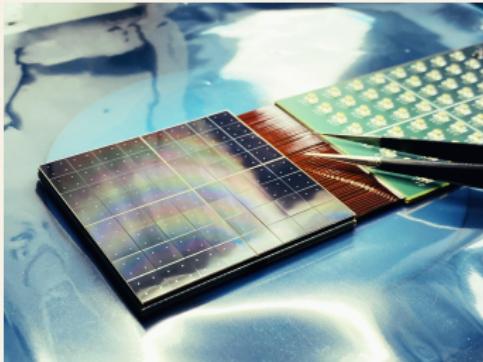
Polarimeter module development

- 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



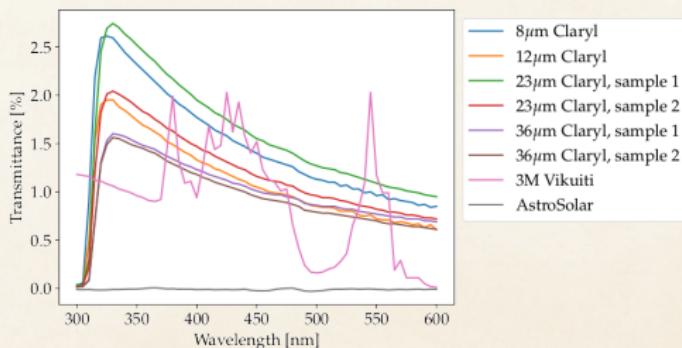
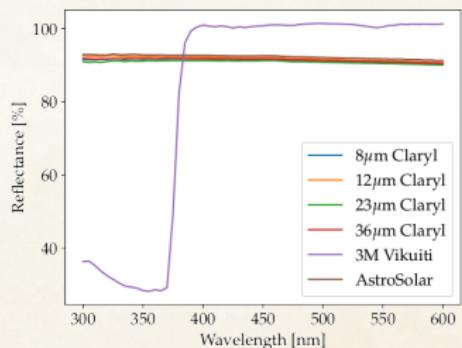
Polarimeter module development SiPM I-V characterization

- 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



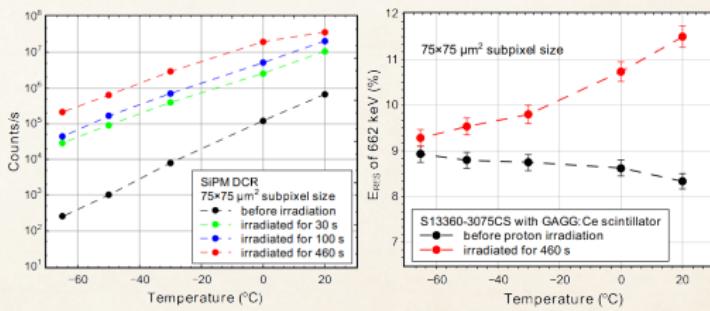
Polarimeter module development Wrapping foils investigation

- 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%)

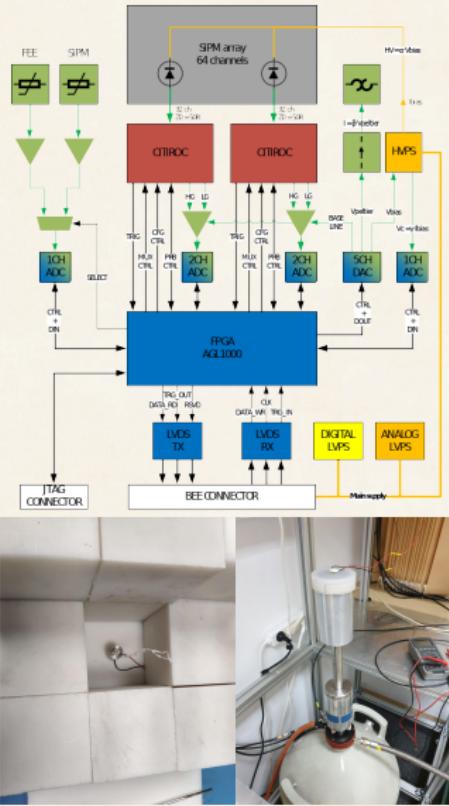


Polarimeter module development Radiation hardness qualification

- 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

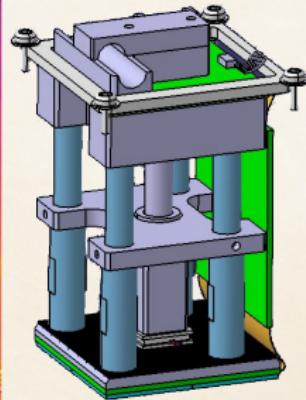
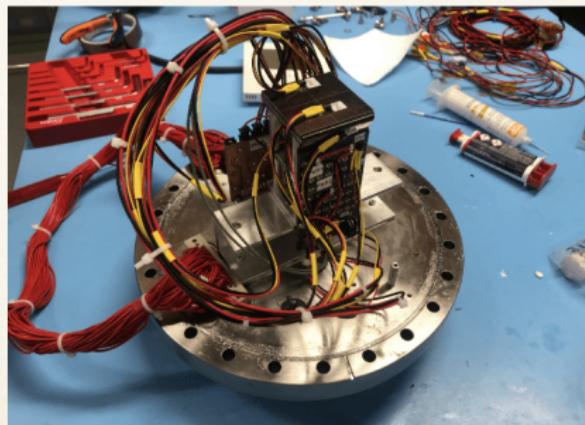


S. Mianowski et al 2020 JINST 15 P03002



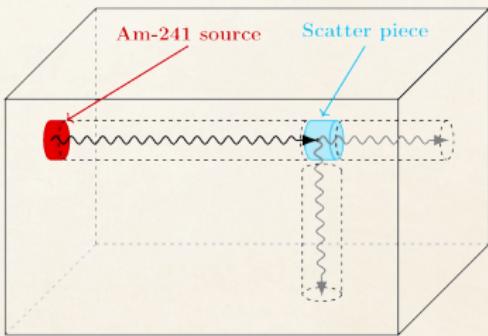
Polarimeter module development Cooling system

- 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



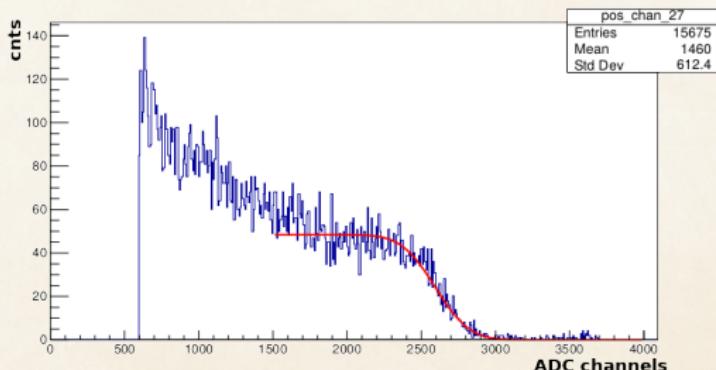
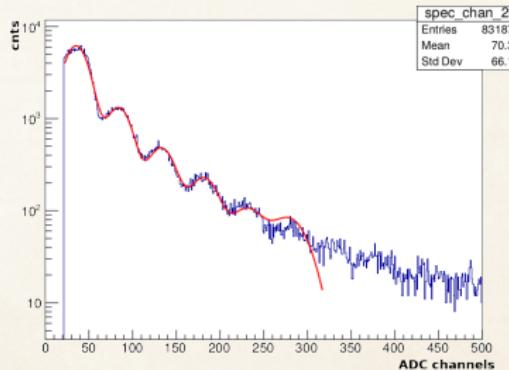
Preliminary module performances Module calibration setup

- 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



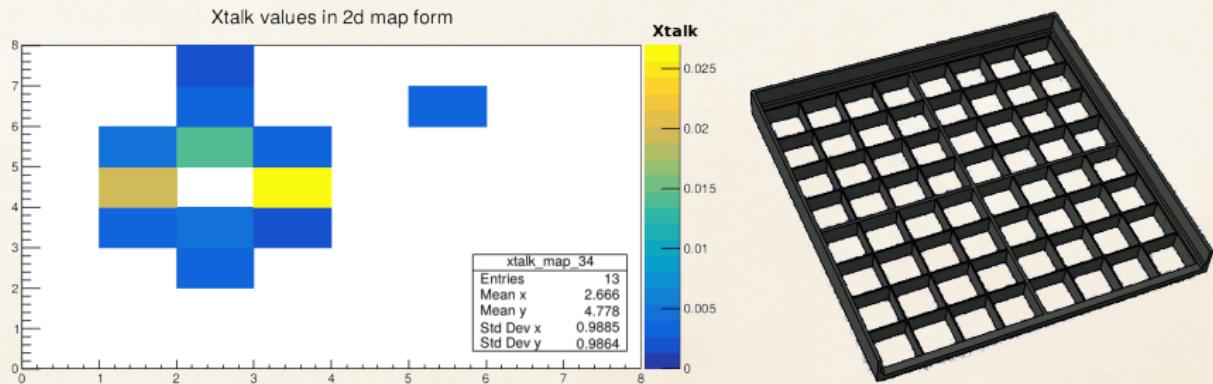
Preliminary module performances Computing the light yield

- Fitting HG finger plot to get the distance between photoelectrons \Rightarrow 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

- 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
 $\rightarrow (122\text{mm}/125\text{mm}) * 1\% + (3\text{mm}/125\text{mm}) * 60\% = 2.416\%$



POLAR-2 Minimum Detectable Polarization

