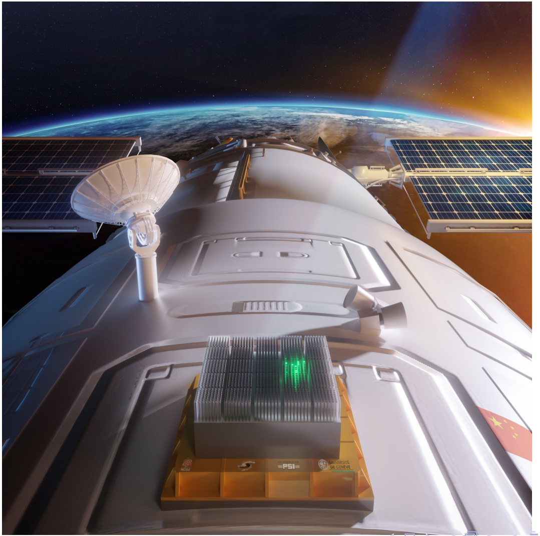
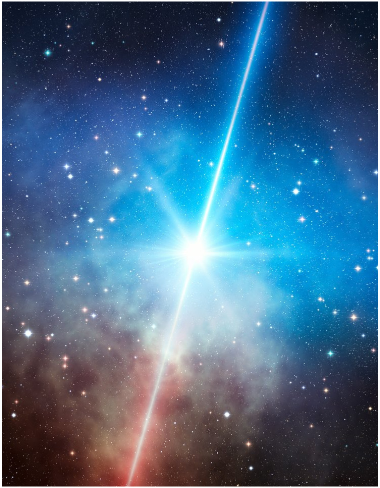
Gamma-Ray Burst Polarimetry with POLAR and POLAR-2

Merlin Kole on behalf of the POLAR and POLAR-2 Collaboration



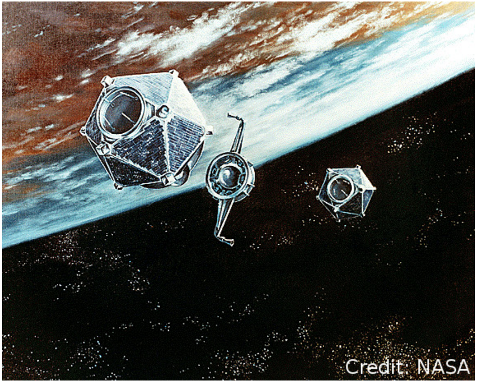
Overview

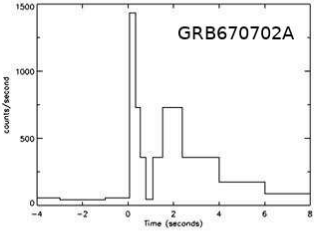
- Short Science Case
- The POLAR Mission
- Measurement Results
- The future: POLAR-2



Gamma-Ray Bursts I: Discovery

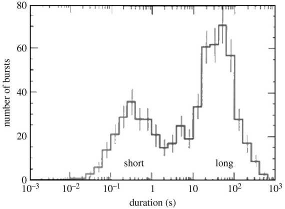
- Very bright bursts of x-/gamma-ray emission which last from fractions of a second to minutes
- Discovered July 2nd, 1967, at 14:19 UTC by US spy satellites
- Vela satellites designed to detect USSR nuclear tests found bright bursts of gamma-rays not coincident with solar flares or other activities



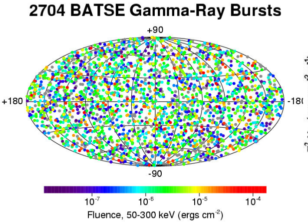


Gamma-Ray Bursts II: What we learned

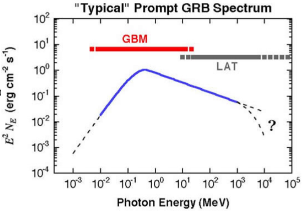
- Through timing: We can divide them into short and long bursts
- Through localization: extra-galactic events
- Through spectra: highly complex jet emission



Scott D Barthelmy, Philos Trans A Math Phys Eng Sci. (2007)



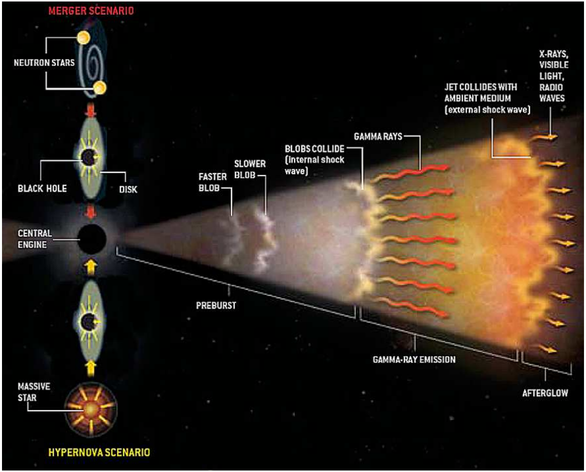
G. Fishman et al., BATSE, CGRO, NASA



source: http://polywww.in2p3.fr

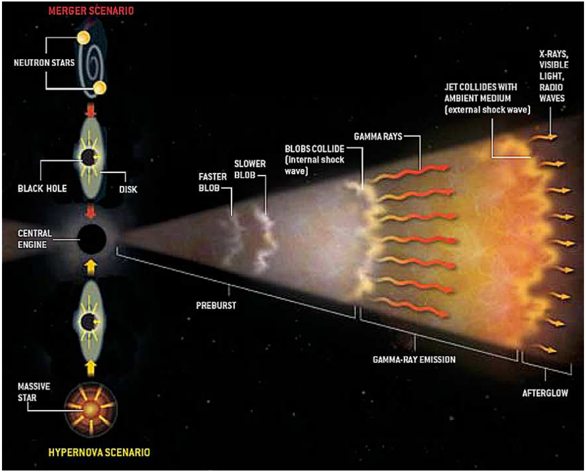
Gamma-Ray Bursts III: What we know

- Most energetic events in the universe since the big bang
- Detected in coincidence with GW in 2017
- Short GRBs from neutron stars
- Long likely from supernovae

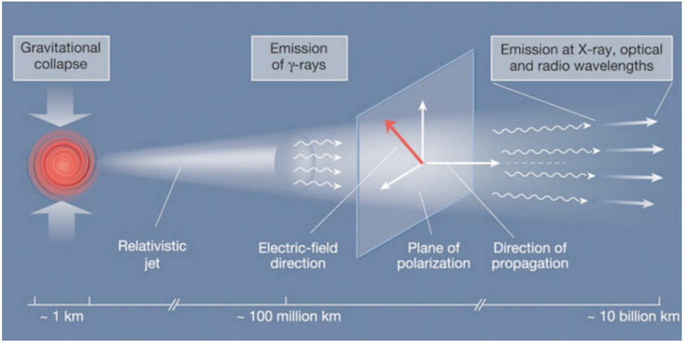


Gamma-Ray Bursts IV: What don't we know

- What happens in the jet?
- What do the jets look like?
- Are there magnetic fields?
- What produces the gamma-rays?



Gamma-Ray Burst Polarimetry



E. Waxman, Nature 423 (2006) 388

- Different emission processes predict different polarization
- Simplified: synchrotron would give high polarization, thermal emission no polarization
- Temporal profiles of the polarization degree and angle during burst can allow to distinguish between the large number of existing models
- See for example: Kenji Toma arXiv:1308.5733

Gamma-Ray Burst Polarimetry

Before POLAR measurements were performed

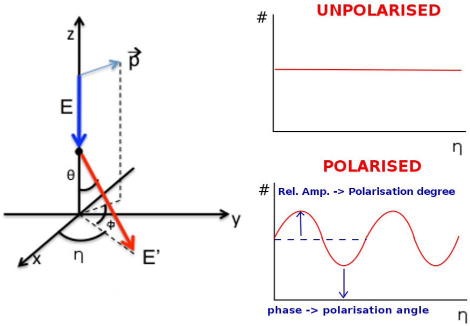
GRB	Instr./Sat.	Pol. (%)	Remark
160530A	COSI	$< 46\%$	low statistics
110721A	GAP/IKAROS	84^{+16}_{-28}	Constant Pol. Angle
110301A	GAP/IKAROS	70 ± 22	Constant Pol. Angle
100826A	GAP/IKAROS	27 ± 11	Pol. Angle changes by $\approx 90^\circ$
021206	RHESSI	80 ± 20	non dedicated instrument
021206	RHESSI	41^{+57}_{-44}	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

- Most measurements performed by non-dedicated instruments
- Non of the measurements is really constraining
- Required: A large catalog of GRB constraining measurements

Compton Polarimetry

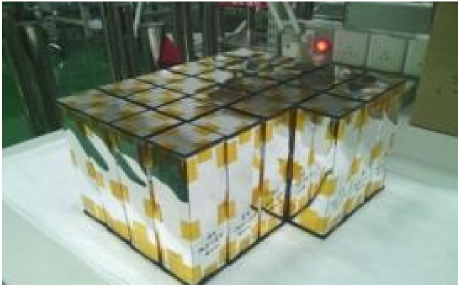
- Azimuthal scattering angle dependence on polarisation
- Figure of merit = μ_{100}: Modulation measured for a 100% polarised incoming beam
- Second figure of merit = MDP: Minimum level of polarisation distinguishable from an unpolarised flux with (typical) 3σ certainty

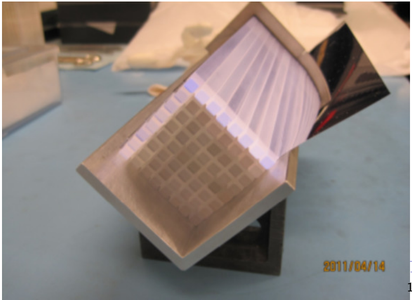
$$\frac{d\sigma}{d\Omega} = \frac{r_o^2}{2}\frac{E'^2}{E^2}\left(\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\phi\right). \quad (1)$$



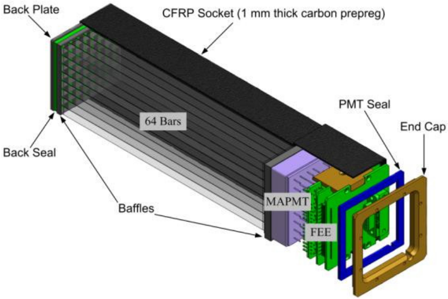
POLAR design

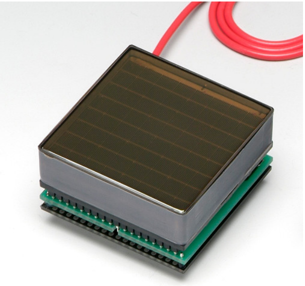
- POLAR uses a segmented scintillator array to measure the Compton scattering angle
- In total 1600 plastic scintillators, $6 \times 6 \times 176$ mm, EJ-248M
- Plastic scintillators optimize the cross section for Compton scattering in the 50-500 keV energy range
- Plastic scintillators allow for a relatively large effective area, with low mass of 30 kg
- Small granularity of the scintillator array results in high angular resolution, high sensitivity for polarisation measurements





POLAR design



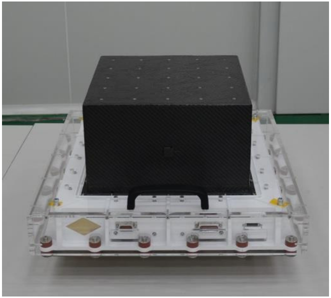


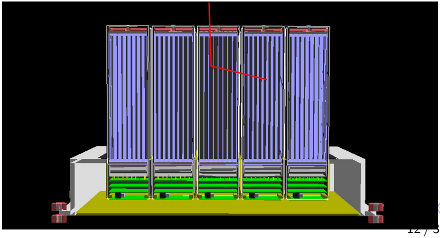
from: www.hamamatsu.com

- Each group of 64 scintillators is read-out using a single MAPMT
- MAPMT is H8500 from Hamamatsu
- Allows for the read-out many channels with a sufficient gain to measure low energy depositions
- Optical cross-talk to neighbouring channels is an issue but can be fixed in analysis
- Cross talk reduced by shaping of scintillators

The Final Product

- Effective area of $\approx 300\mathrm{cm}^2$ at 400 keV
- Small pixels allows for high precision scattering angle measurements
- Uniform effective area gives us a large Field of View
- Full description of the instrument recently published: N. Produit et al. arXiv:1709.07191



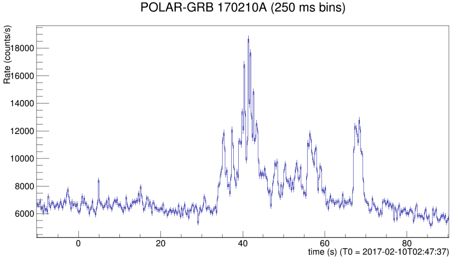


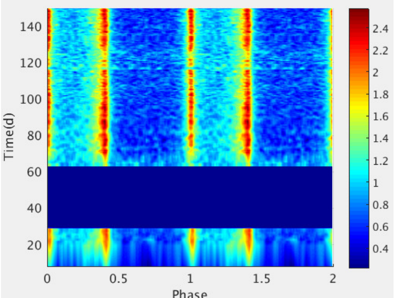
POLAR

- TG-2 Chinese Space Lab launched on September 15th 2016

What did we see?

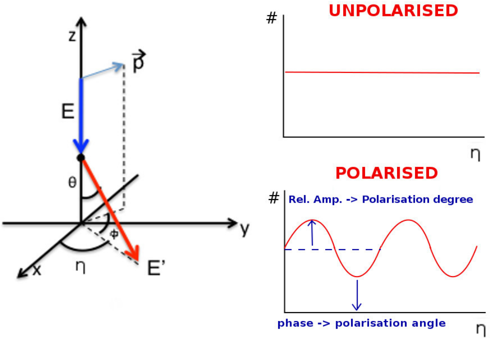
- POLAR switched on 1 week after launch
- Initial calibration period using internal sources
- First GRB observed in November 2016
- Total of 55 confirmed GRBs observed upto April 2017
- Crab pulsar + other pulsars observed in data
- HVPS failure caused data taking to stop in April 2017



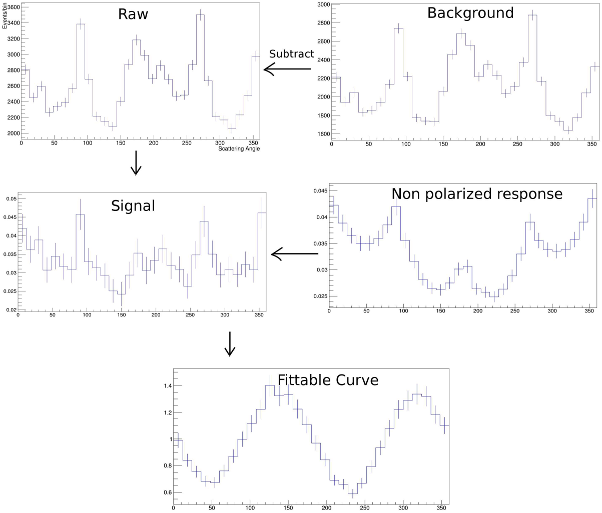


Compton Polarimetry

- Modulation cuves are a bit more complicated in reality
- Instrumental effects have to be understood in great detail
- Any mistake leads to 'polarization'

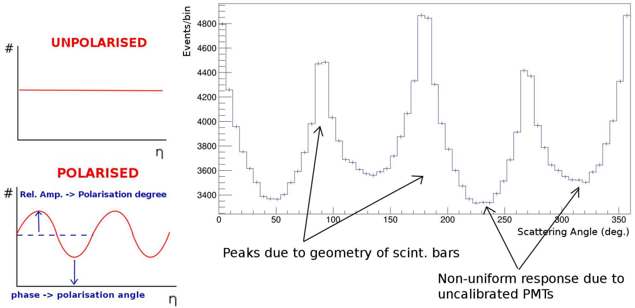


Basic Analysis method



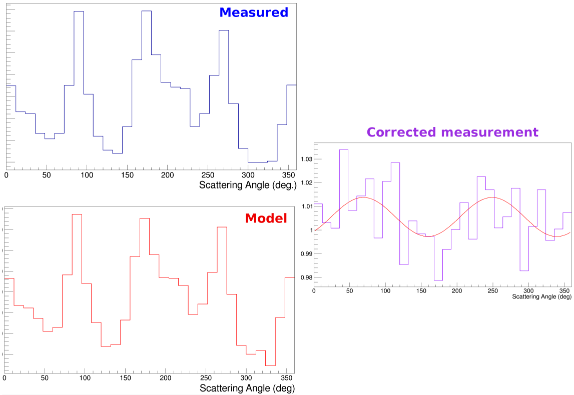
- Measure scattering angle distribution during GRB
- Subtract the scattering angle distribution measured during background
- Remove systematic effects by dividing the measured curve by a simulated unpolarized distribution
- Fit with sinusoidal function

Mistakes lead to 'polarization'



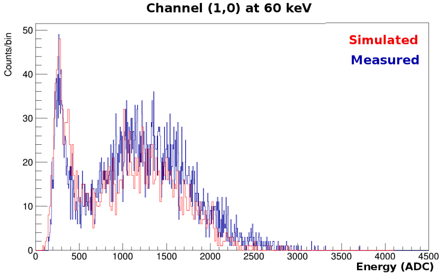
- Theory: plot the scattering angles → check amplitude → convert to polarization → publish
- Reality: limited statistics and errors in instrument response cause 'polarization'

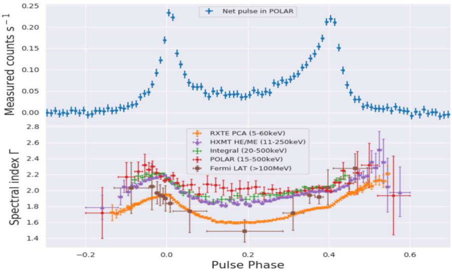
Systematic errors



- You can model the response of the instrument, any error in the model will result in 'polarization'
- Making mistakes in the analysis results in high polarization

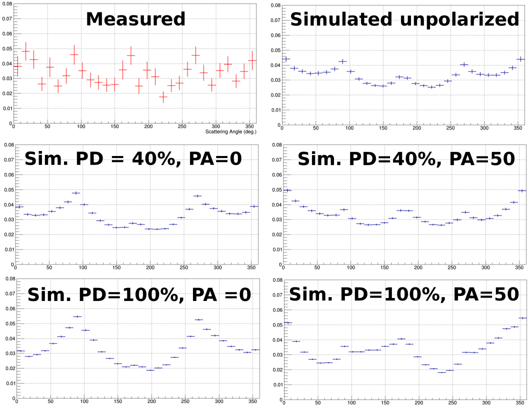
Understanding the systematic error





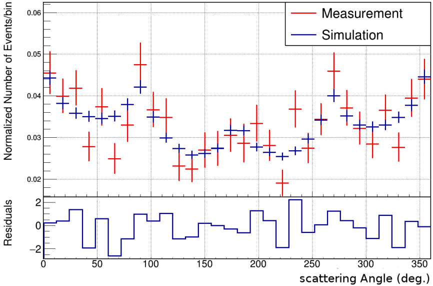
- Response includes temperature dependence on gain, threshold etc. detailed cross-talk, non-linear effects in electronics for each bar etc. etc.
- Instrument was calibrated very carefully on ground (see Kole et al. `arXiv:1708.00664`)
- Careful calibration in-orbit (see Z.H. Li et al. `arXiv:1805.07605`)
- Cross calibration on the Crab pulsar (see H.C. Li et al `arXiv:1910.07941`)

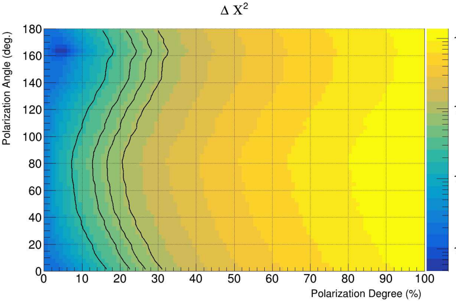
Fitting the response



- Simulate the GRB (with incoming direction and spectrum) for each polarization parameter
- Once we have the response the rest is easy
- For each individual GRB we simulate modulation curves
- Find the best curves

Fitting the response

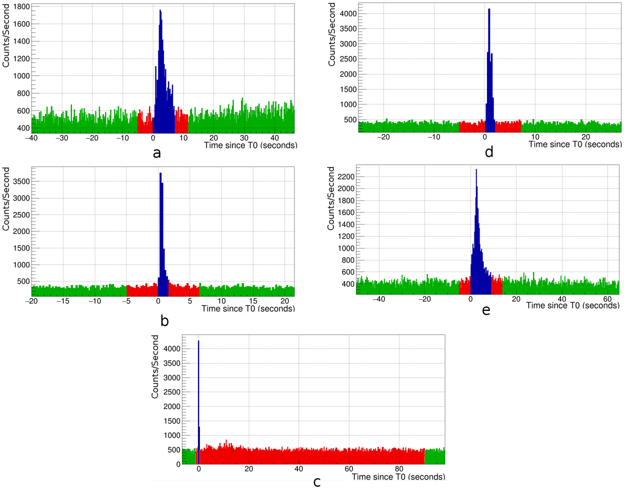




- We find the best fit
- Don't see anything in the residuals
- Use χ^2 to calculate the probability for each polarization parameter

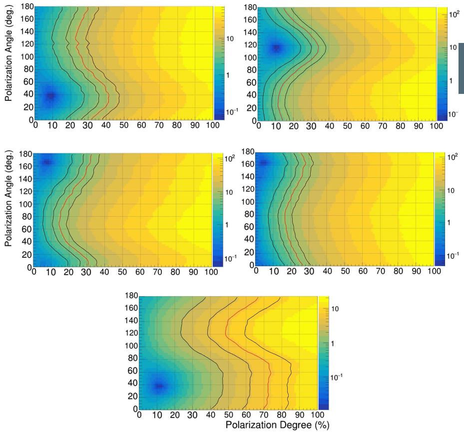
Selected GRBs

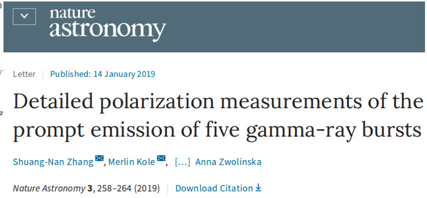
- GRB fluence larger than $5 * 10^{-6} \mathrm{erg/cm^2}$
- off-axis angle below 45°
- Spectra and location by other instruments



(Background region selection was found to have negligible effects on the polarization results)

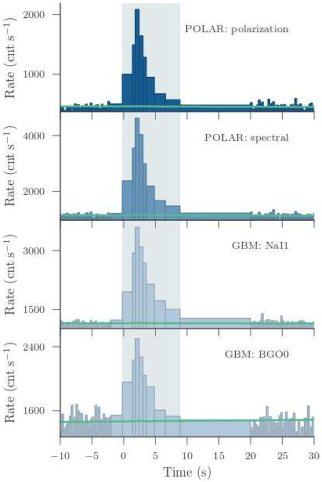
Results





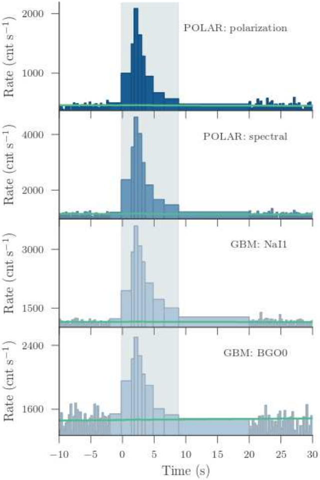
- First conclusion: Polarization is rather low!
- Results published this January in Nature Astronomy

What more can we do?



- We miss spectra for many GRBs, no analysis possible
- Many off-axis GRBs not analysed due to concerns about systematics
- Including spectral uncertainties into polarization error is cumbersome
- Analayis tools not useable for other missions...

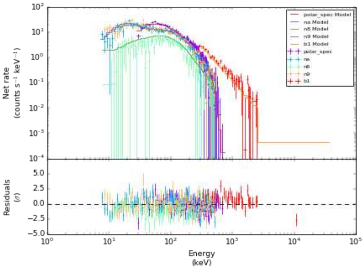
What more can we do?

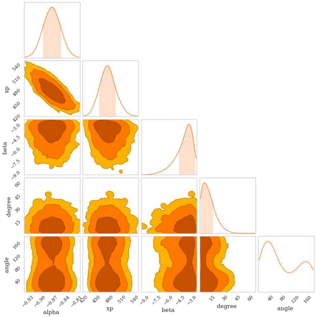


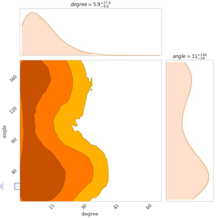
3ML
The Multi-Mission Maximum Likelihood framework

- Started putting POLAR data in general 3ML framework for spectral fitting with J.M. Burgess (MPE, Germany)
- Able to perform joint fits with GBM + POLAR data
- Also standardized the polarization response and analysis
- Reponse: modulation curve for each energy and incoming angle
- Use forward folding to fit the data

Another 50 GRBs!



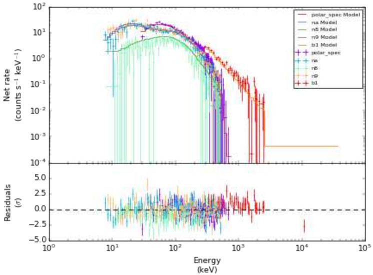


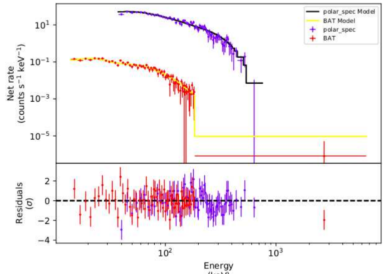


- More proper treatment of background (fitted and included in the fit)
- Spectrum and polarization are fitted at the same time
- Uncertainty on the spectrum automatically goes into the polarization results
- Uses simple format which can be ued by any other polarization mission

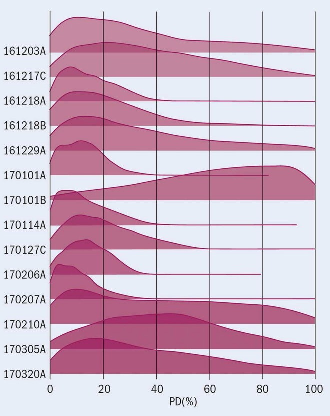
Off-axis systematics?

- Joint fits with GBM show nothing strange for any GRB
- Same for joint fits with Swift BAT data
- Effective area of POLAR correction needed with GBM 10%
- No Effective area of POLAR correction needed with Swift BAT
- Conclusion: also for off-axis GRBs our response is ok!





Summary POLAR results



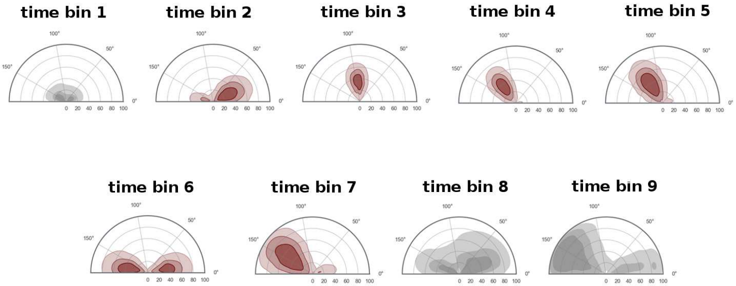
- General all polarization measurements are compatible with unpolarized emission
- No signs of polarization in time resolved analysis of multi-peak GRBs
- Two single pulse GRBs show clear hints of intra-pulse evolution of the PA
- More statistics needed to fully confirm this evolution

A&A 644, A124 (2020)

The POLAR gamma-ray burst polarization catalog

M. Kole[1], N. De Angelis[1], F. Berlato[2], J. M. Burgess[2], N. Gauvin[3], J. Greiner[2], W. Hajdas[4], H. C. Li[5,6], Z. H. Li[5,6],
A. Pollo[7,8], N. Produit[3], D. Rybka[7], L. M. Song[5,6], J. C. Sun[5,6], J. Szabelski[7], T. Tymieniecka[7], Y. H. Wang[5,6],

Time resolved study



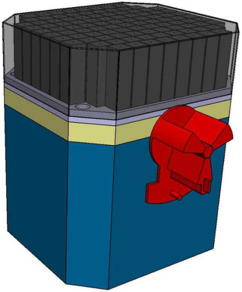
- Combined fitting allows for more detailed studies including time resolved studies
- Results hint that the polarization angle changes within single pulse GRBs
- Low polarization could be an artifact of this angular evolution
- We only see this for single pulse GRBs, overall full pulses appear unpolarized
- J.M. Burgess et al. *'Time-Resolved GRB Polarization with POLAR and GBM'* A&A 2019

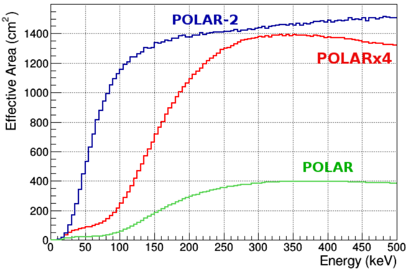
The future: POLAR-2

- POLAR results raised more questions
- We need a significantly more sensitive detector: POLAR-2
- Collaboration expanded with MPE in Germany
- Launch was approved in summer 2019 to go to the CSS in early 2024

The future: POLAR-2

- Increase number of channels by factor 4
- Improve technology to gain another factor 2.5
- Replace PMTs with SiPM with Peltier cooling to reduce low energy threshold
- Improve scintillator geometry and dead material above scintillators
- Add 12 spectrometers to provide detailed spectrum and location for all GRBs



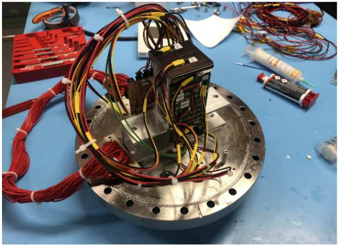


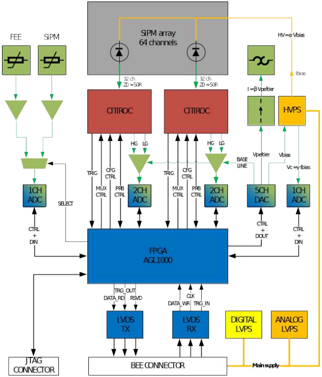
The future: POLAR-2

- New detector module design being tested
- Currently light yield per channel is 1.1 photo-electron/keV (POLAR had 0.3)
- Optical cross talk between channels around 1% (20% in POLAR)
- Low energy threshold can be reduced from 10-15 keV to 3 or 4 keV
- Further improvement possible with cooling

The future: POLAR-2

- Peltier cooling system being tested
- First front-end electronics prototype being manufactured
- Uses CITIROC-1A ASICs for SiPM readout
- FPGA either from Microsemi (american...) or GOWIN





Summary and Outlook

- POLAR data carefully analyzed
- 14 GRBs analyzed show no sign of time integrated polarization
- time resolved analysis of 2 GRBs shows strong hints of PA evolution
- POLAR-2 prototype to be finished in 2021
- POLAR-2 flight model production to start in 2022
- Launch in 2024!

Thank you for your attention!