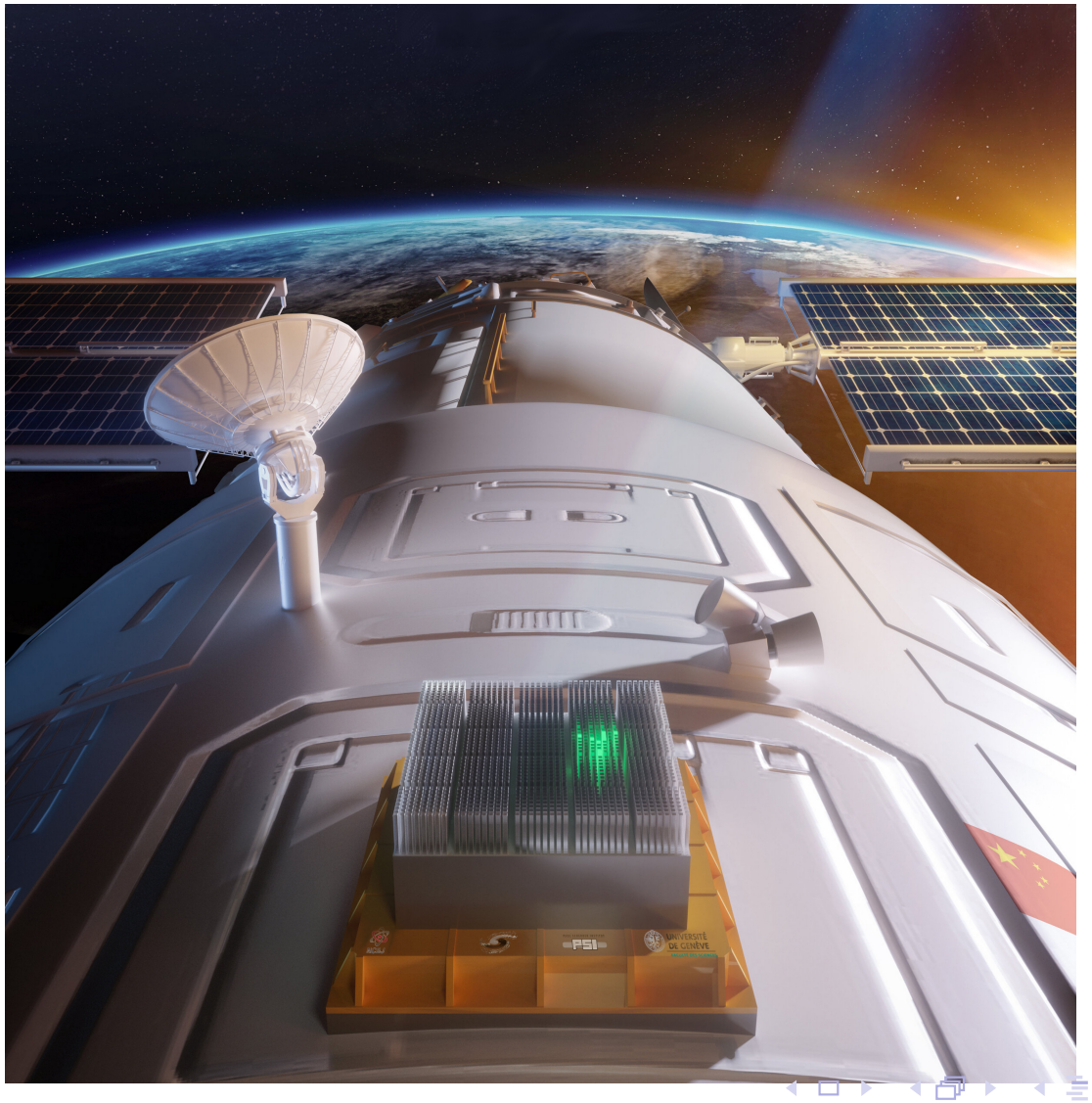
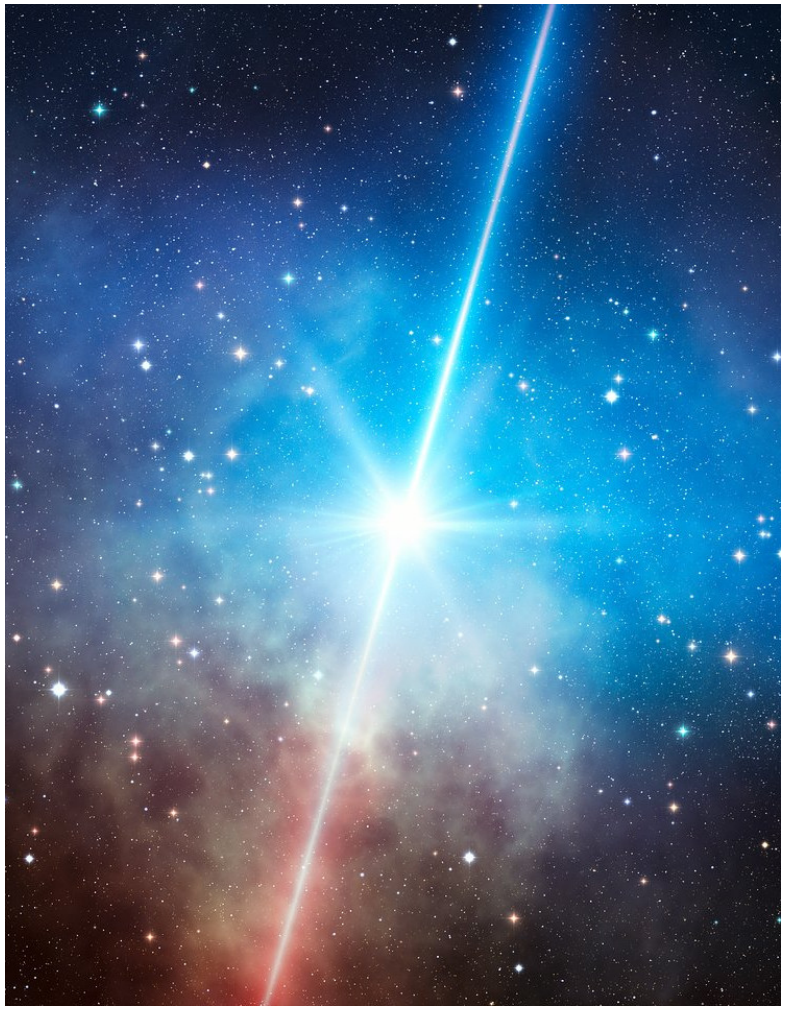
Gamma-Ray Burst Polarization Measurements with POLAR

Merlin Kole on behalf of the POLAR Collaboration



Overview

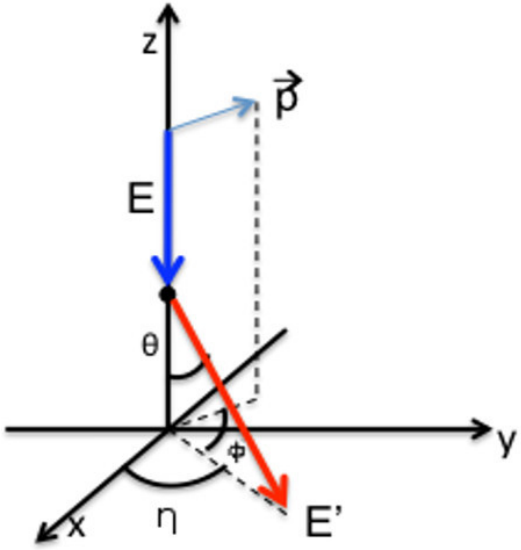
- How to measure polarization
- POLAR mission
- Catalog results
- What's next?

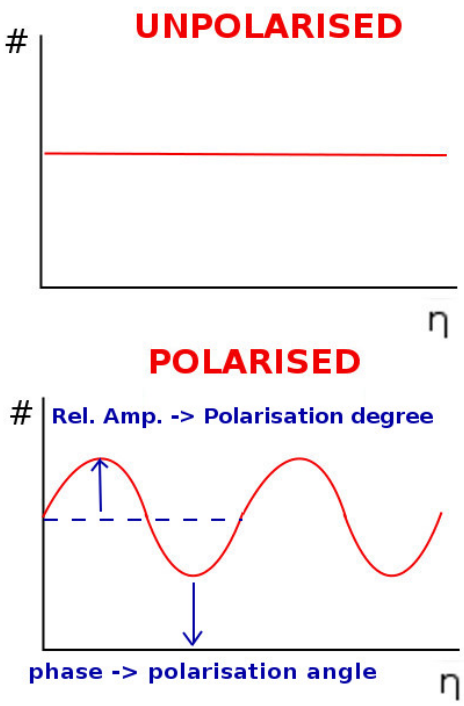


Compton Polarimetry

- Azimuthal scattering angle dependence on polarization
- Photons preferentially scatter perpendicular to their polarization angle

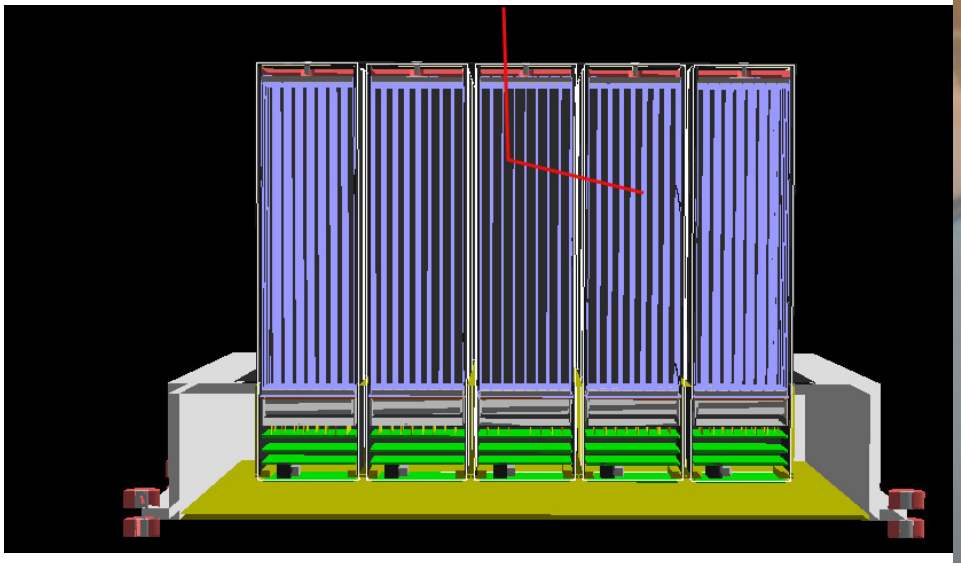
$$\frac{d\sigma}{d\Omega} = \frac{r_o^2}{2}\frac{E'^2}{E^2}\left(\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\phi\right). \tag{1}$$

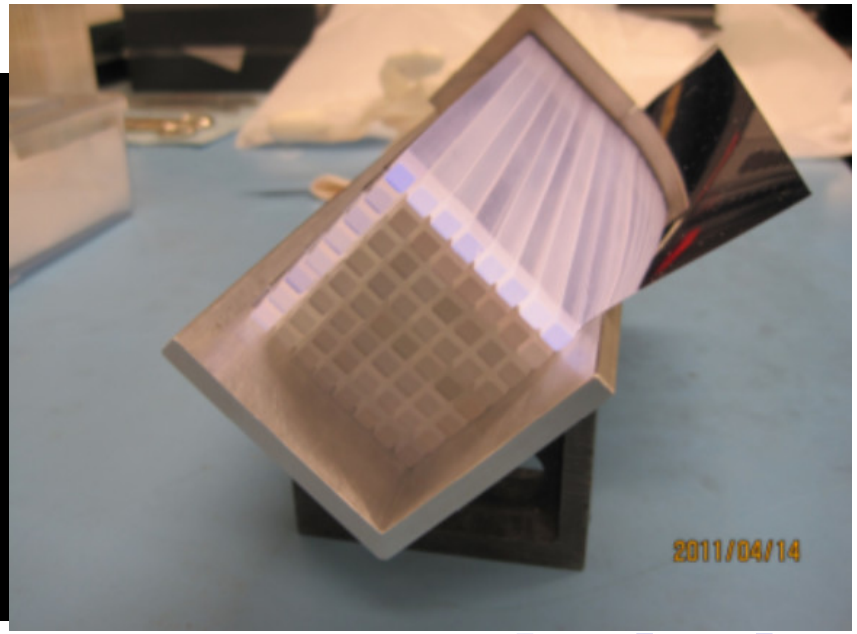




POLAR design

- POLAR uses a segmented scintillator array to measure the Compton scattering angle
- In total 1600 plastic scintillators, $6 \times 6 \times 176$ mm
- About 10% of all incoming photons can be used for polarization studies
- Plastic scintillators optimize the cross section for Compton scattering in the 50-500 keV energy range





We're not the first to think of this

GRB	Instr./Sat.	Pol. (%)	Remark
160821A	AstroSAT	...	...
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	systematics
021206	RHESSI	41^{+57}_{-44}	systematics
140206A	IBIS/INTEGRAL	≥ 48	-
061112	IBIS/INTEGRAL	≥ 60	
041219A	IBIS/INTEGRAL	$\leq 4/43 \pm 25$	Changing Angle and Degree
041219A	SPI/INTEGRAL	98 ± 33	Inconsistent with IBIS
960924	BATSE/CGRO	≥ 50	-
930131	BATSE/CGRO	≥ 35	-

- Older measurements performed by non-dedicated instruments
- Many mistakes in the analysis: M. McConnel, High energy polarimetry of prompt GRB emission. New Astr. (2017)

Bias towards publishing high polarization

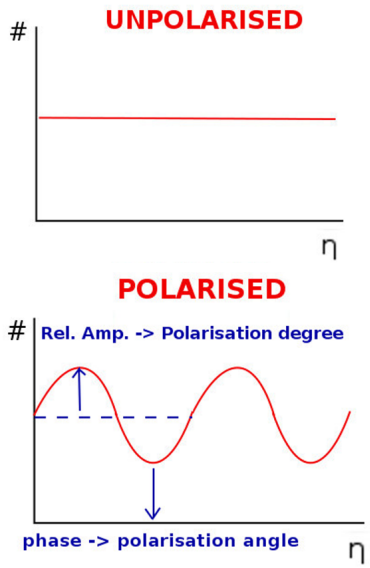
Results of Polarization Analyses

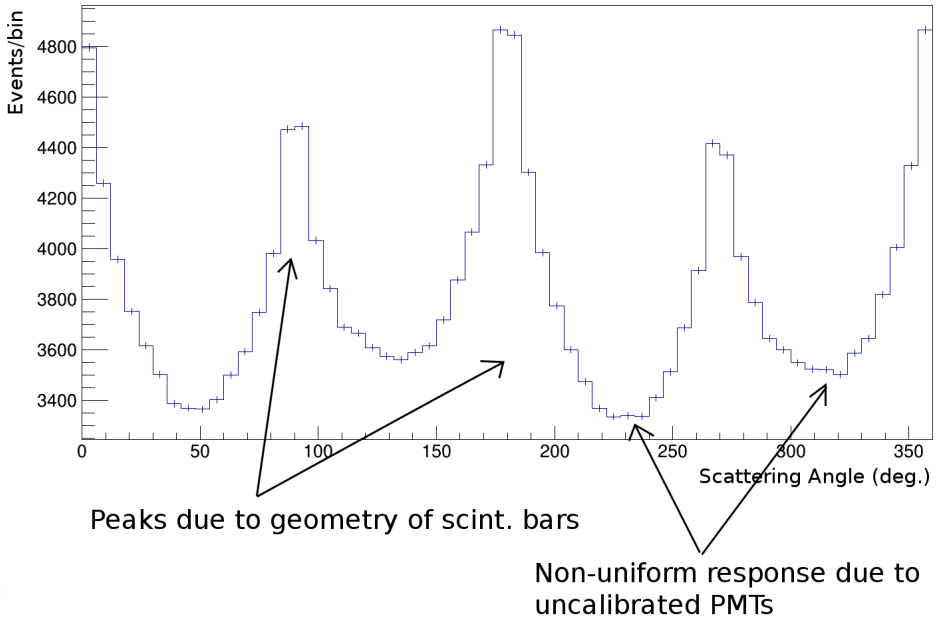
GRB	Polarization Degree (%)	Duration T90 (sec)	Incident Angle (deg)	E_p (keV)	fluence (erg cm^{-2})	flux (photon cm^{-2} s^{-1})
100826	27 ± 11	100	20	606^{+134}_{-109}	2.94×10^{-4}	9.03
110721	84^{+16}_{-28}	11	30	$375.5^{+26.5}_{-23.6}$	3.43×10^{-5}	6.71
110301	70 ± 22	7	48	$106.80^{+1.85}_{-1.75}$	3.35×10^{-5}	75.59
110825	< 47	12	29	$233.6^{+21.9}_{-19.9}$	5.06×10^{-5}	6.16
110625	< 56	27	41	190^{+17}_{-14}	6.09×10^{-5}	8.21
100715	< 83	30	19	-	-	-
101014	< 71	30	54	$181.40^{+5.66}_{-5.44}$	1.88×10^{-4}	3.74

90% upper-limit

- When measuring flux an upper limit is not super interesting
- Not seeing enough flux can be interpreted as not seeing anything
- Not so in polarization: excluding above 99% as important below 1%

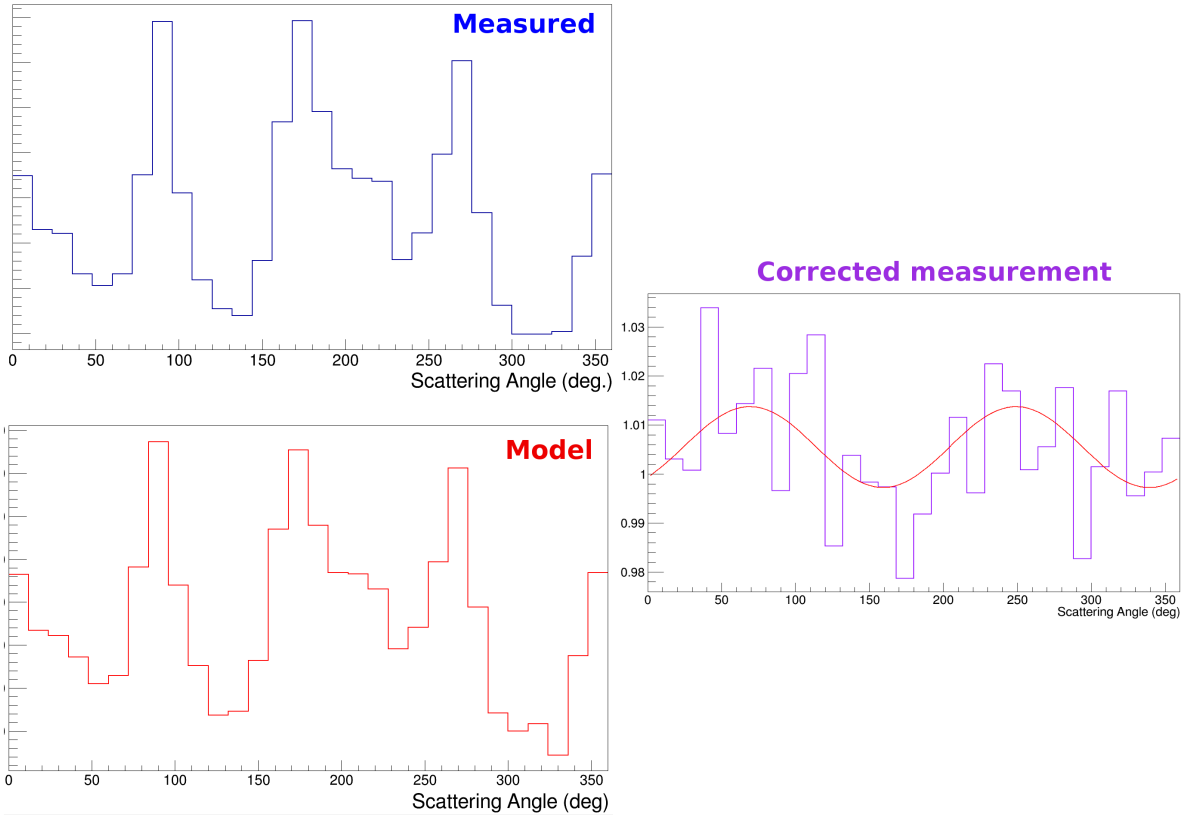
Mistakes lead to 'polarization'





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

Systematic errors

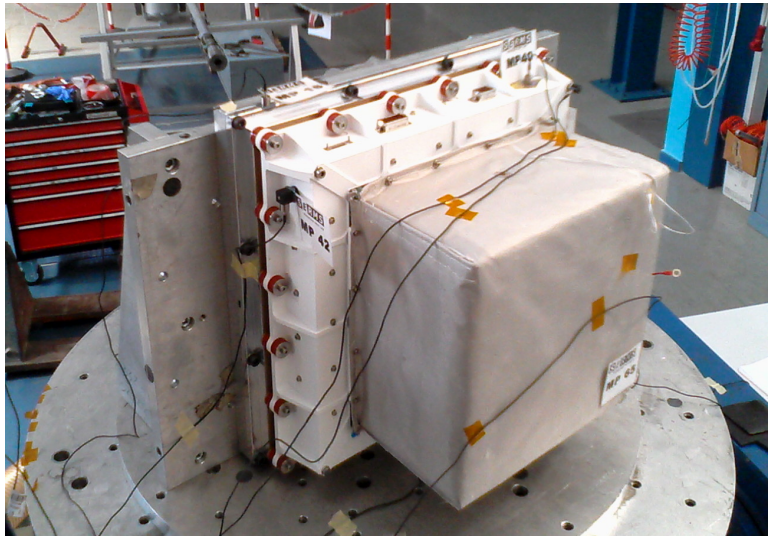


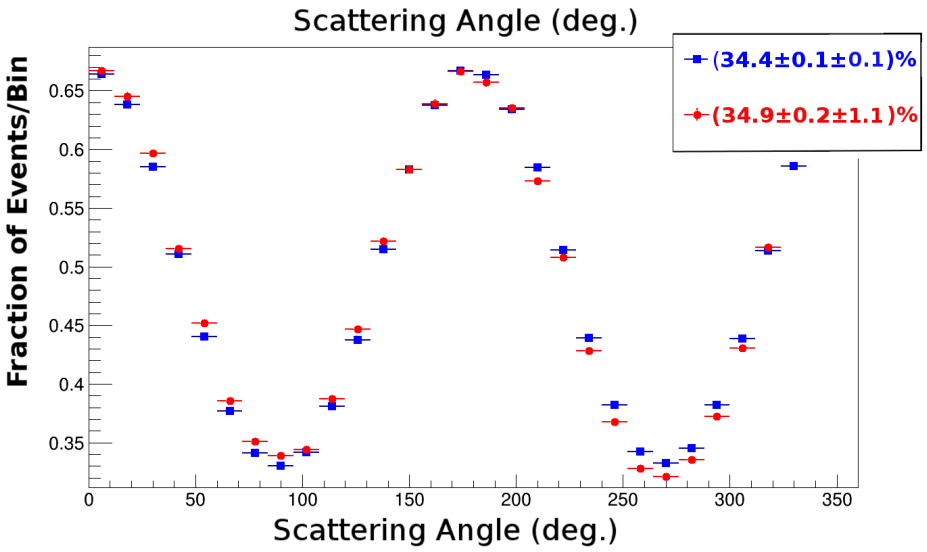
- You can model the response of the instrument, any error in the model will result in 'polarization'
- Making mistakes in the analysis results in high polarization
- Produit's Law: 'If you play enough with the parameters you will find polarization'

Polarization Measurements

- **Problem:** Measurements difficult due to inefficiency in the measurements
- **Solution:** Large instrument with large field of view

- **Problem:** Errors in instrument understanding give fake polarization
- **Solution:** Carefully calibrate your instrument



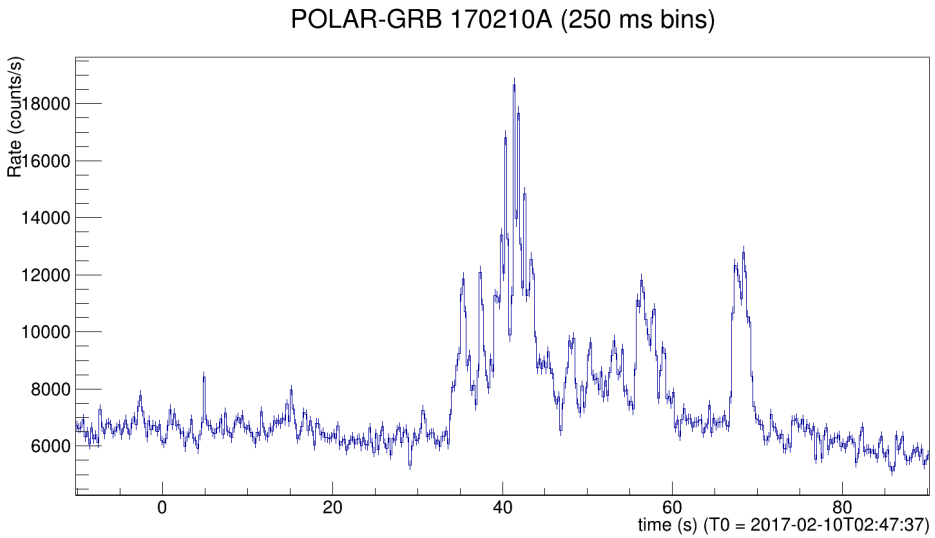


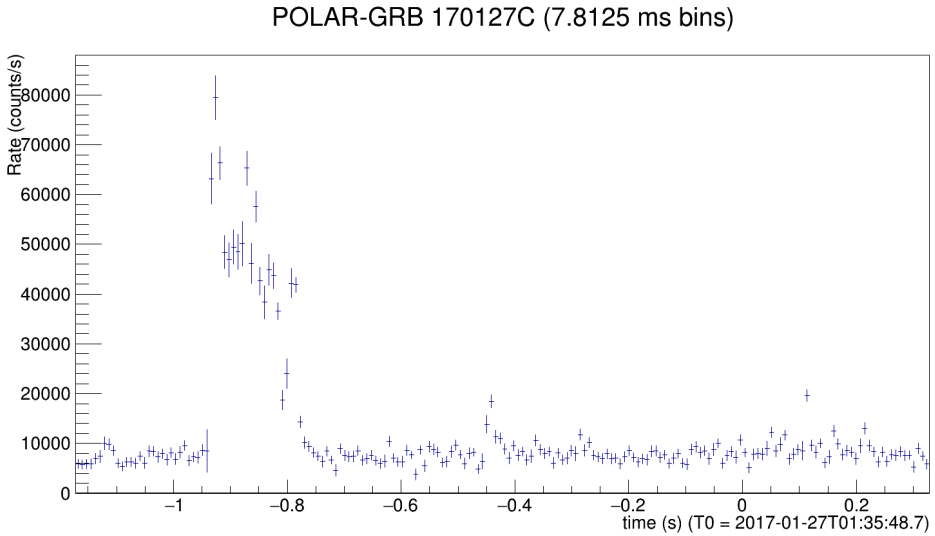
POLAR

- Dedicated mission to GRB polarization
- Careful calibration
- TG-2 Chinese Space Lab launched on September 15th 2016

Do we see GRBs?

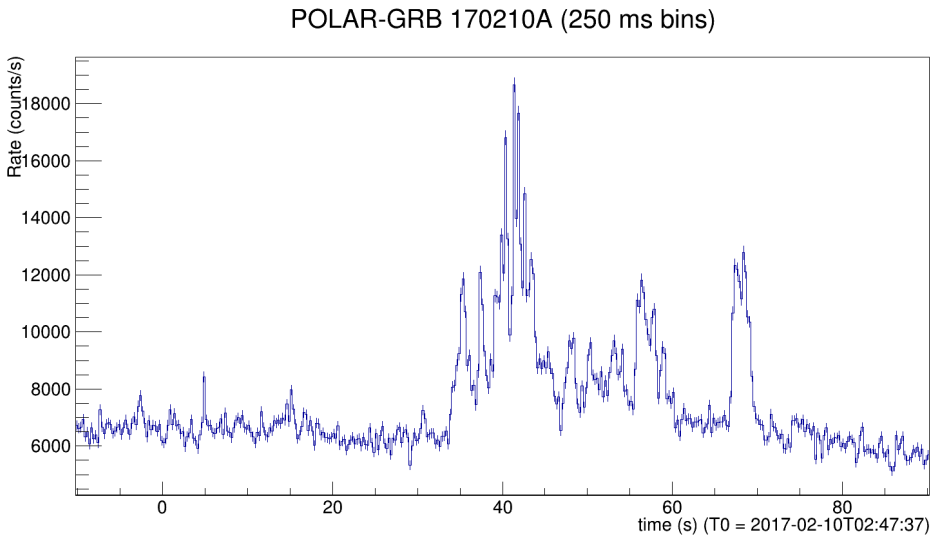
- Total of 55 GRBs detected
- Light curves on: `http://www.isdc.unige.ch/polar/lc/`
- Shortest GRB is 100 ms (170127C)
- Longest is 100 seconds (170210A)
- Not lucky enough to catch a super bright GRB

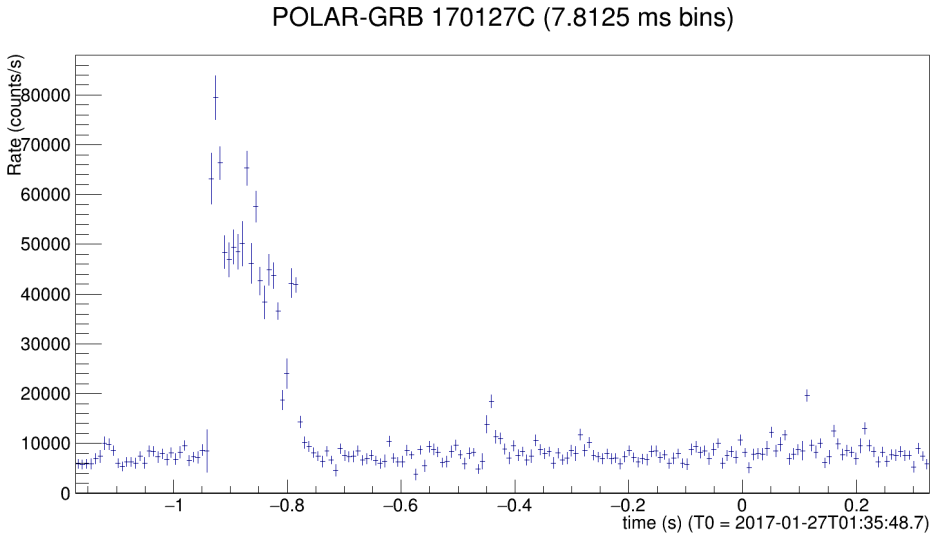




Do we see GRBs?

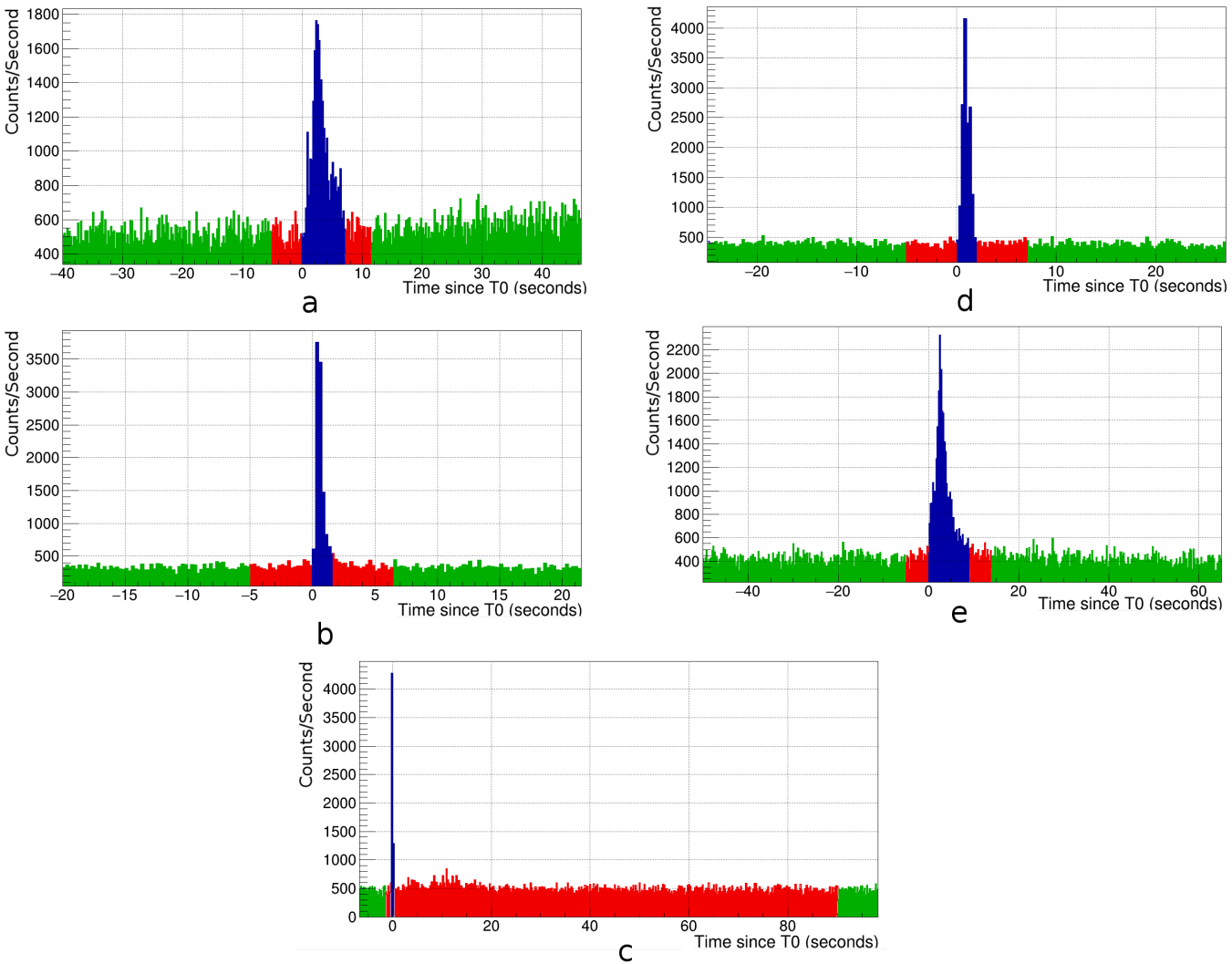
- First analysis on 5 GRBs
- Fluence above $5 \times 10^{-6} \mathrm{erg/cm^2}$
- Off-axis angle below 45°
- GRB has to be detected by other instruments





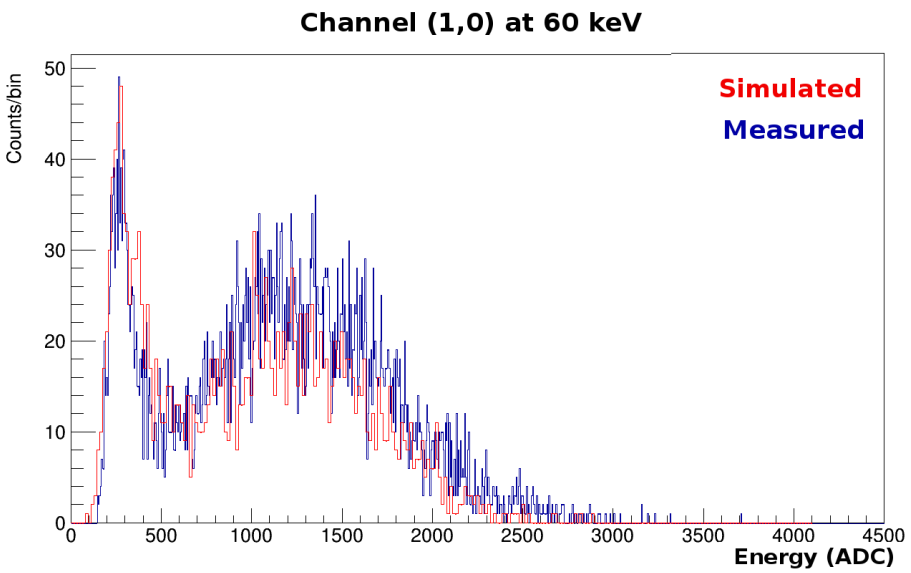
Selected GRBs

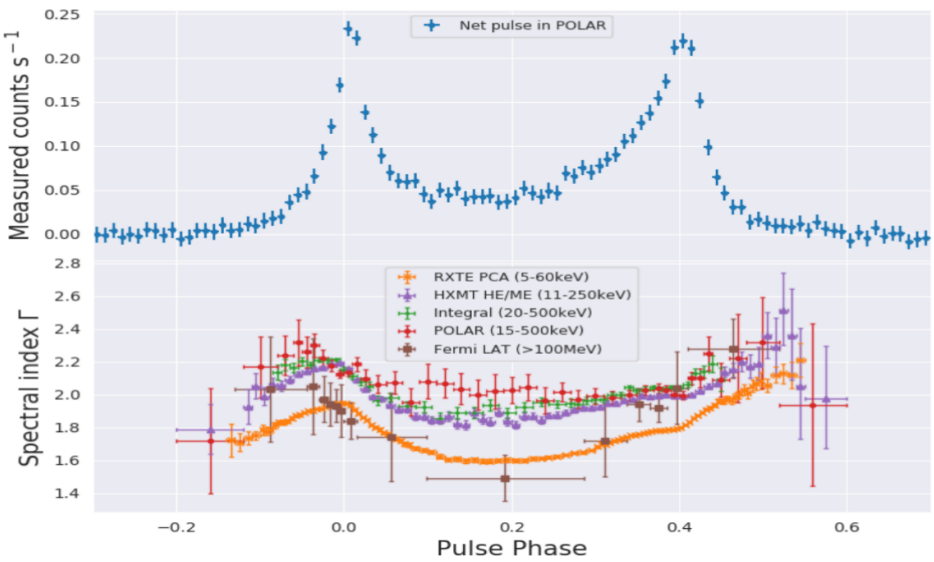
- 161218A
- 170101A
- 170114A
- 170127C
- 170206A



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

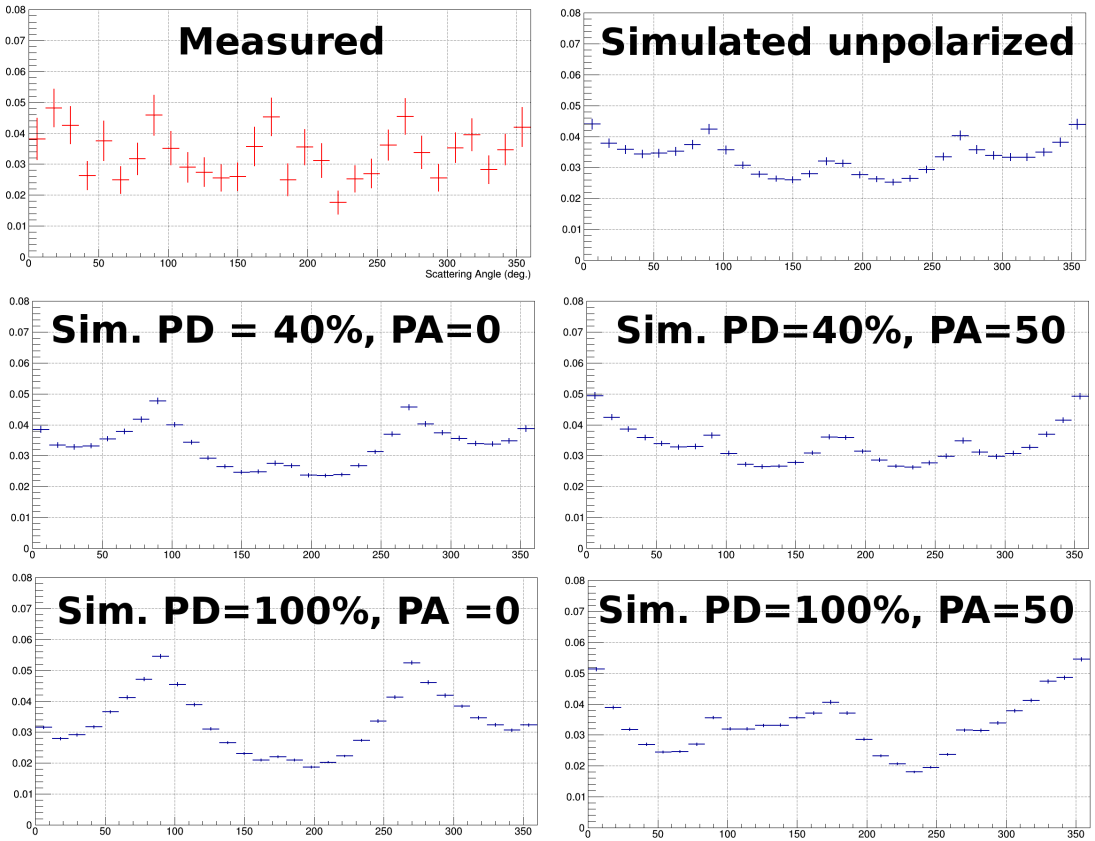
Understanding the systematic error





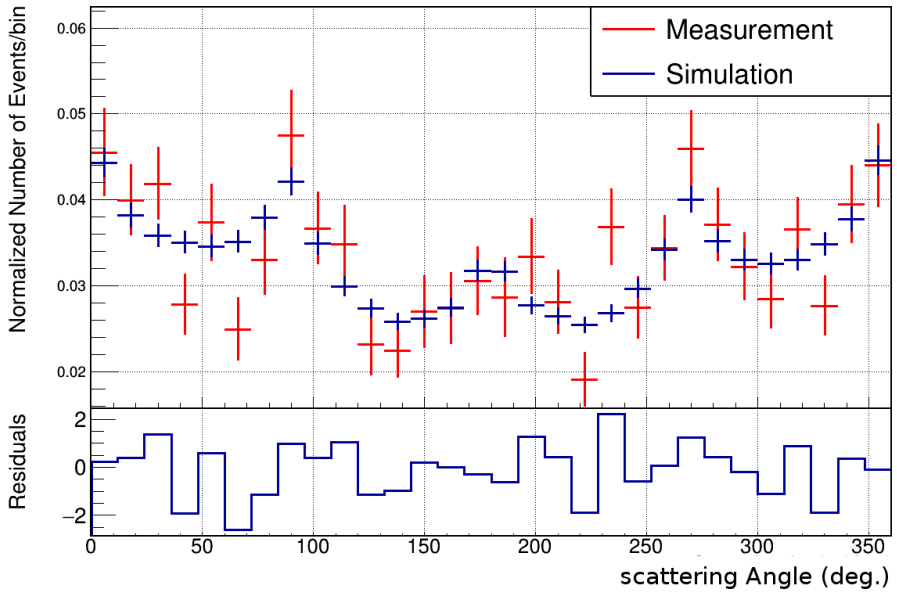
- Response includes temperature dependence, non-linear effects in electronics for each bar
- Instrument was calibrated very carefully on ground (see Kole et al. `arXiv:1708.00664`)
- Careful calibration in-orbit (see Z.H. Li et al. `arXiv:1805.07605`)
- Cross calibration on the Crab pulsar (see H.C. Li et al `arXiv:1910.07941`)
- Final uncertainties calibration result in a systematic error of 2% in the polarization measurements

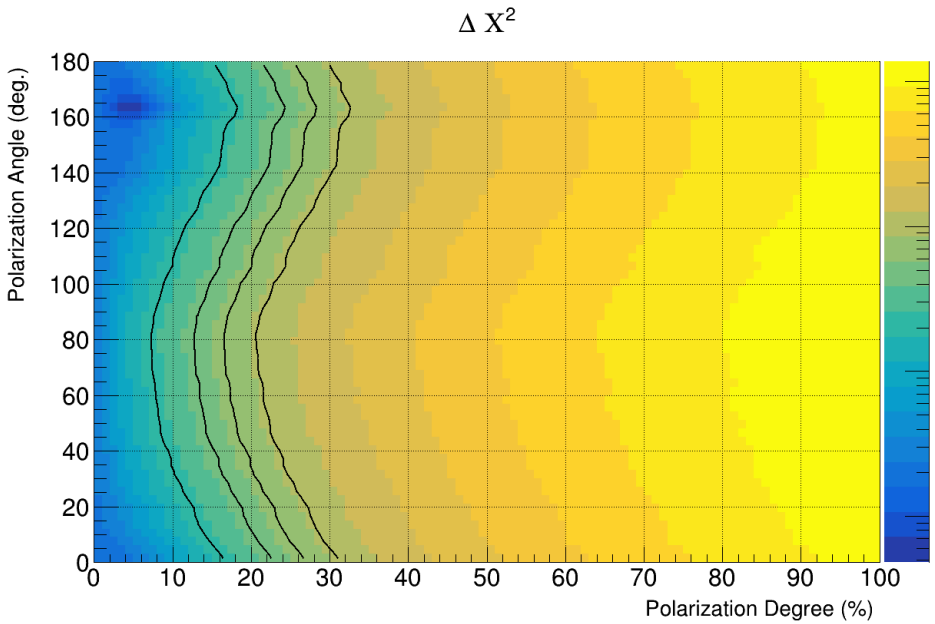
Fitting the response



- 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

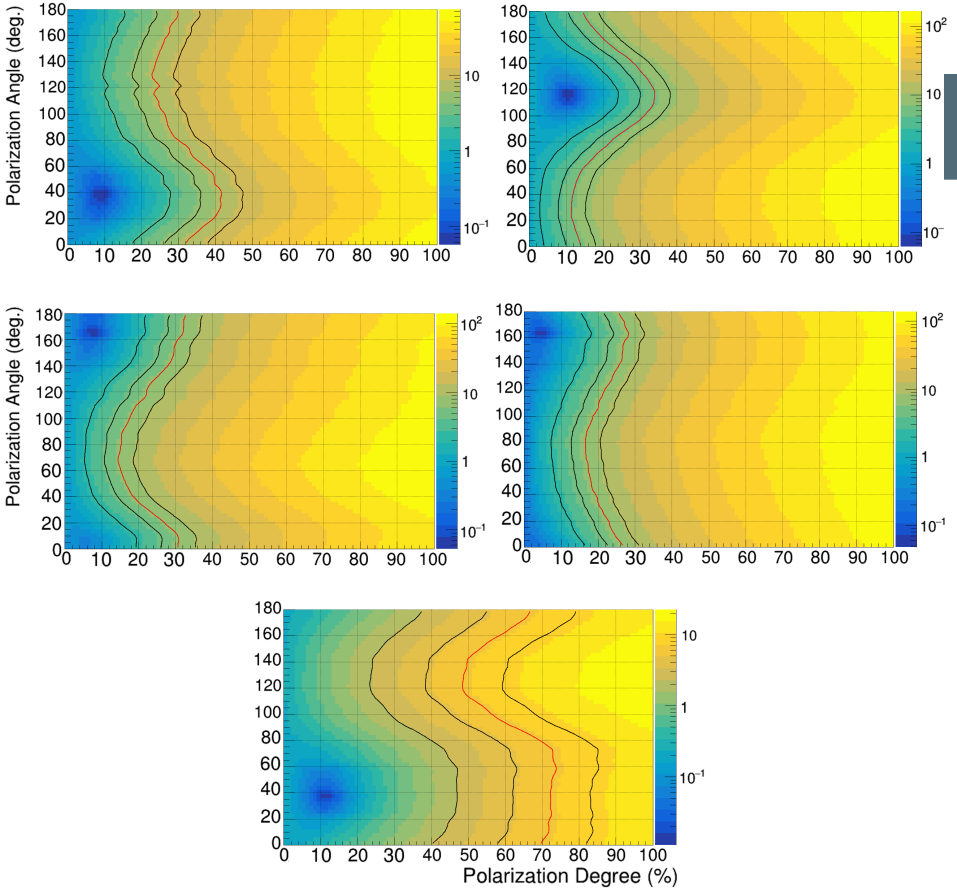
Fitting the response

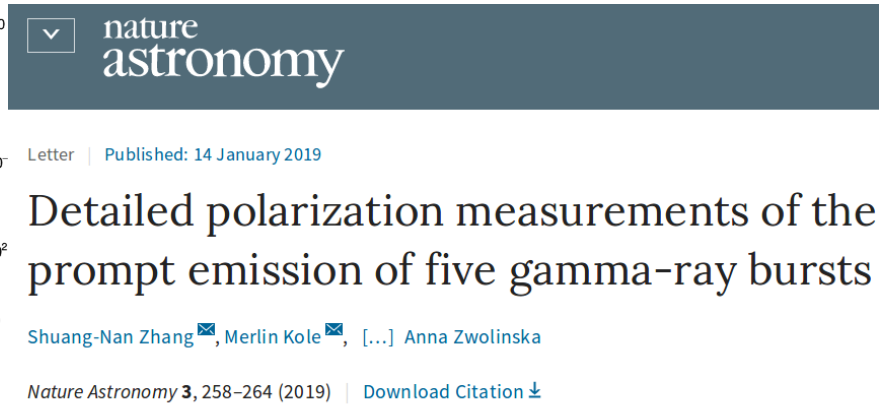




- We find the best fit
- Don't see anything in the residuals
- Use χ^2 to calculate the probability for each polarization parameter

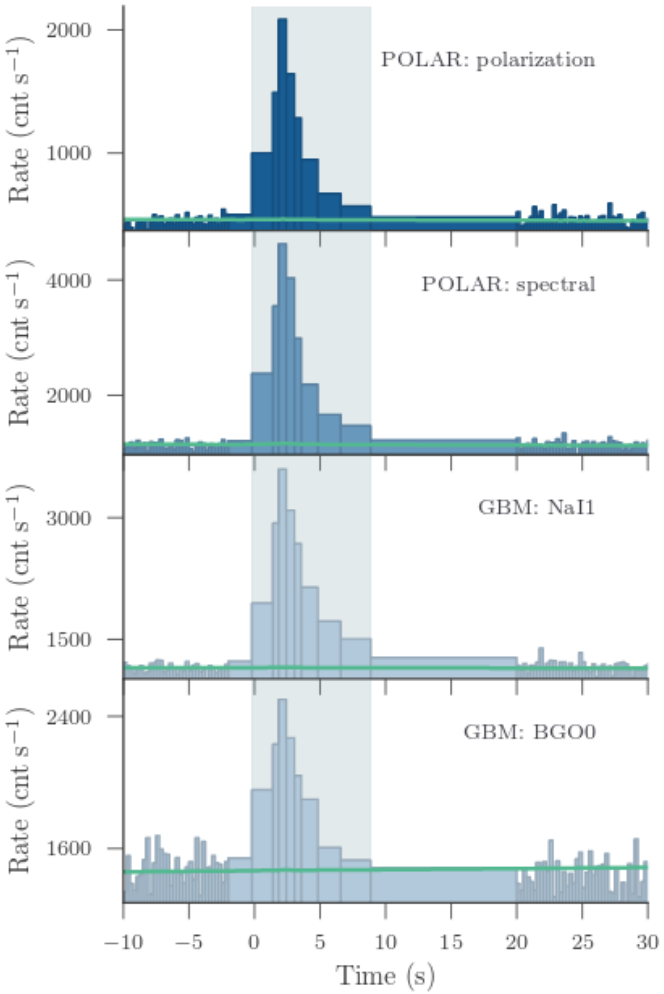
Results





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

What more can we do?

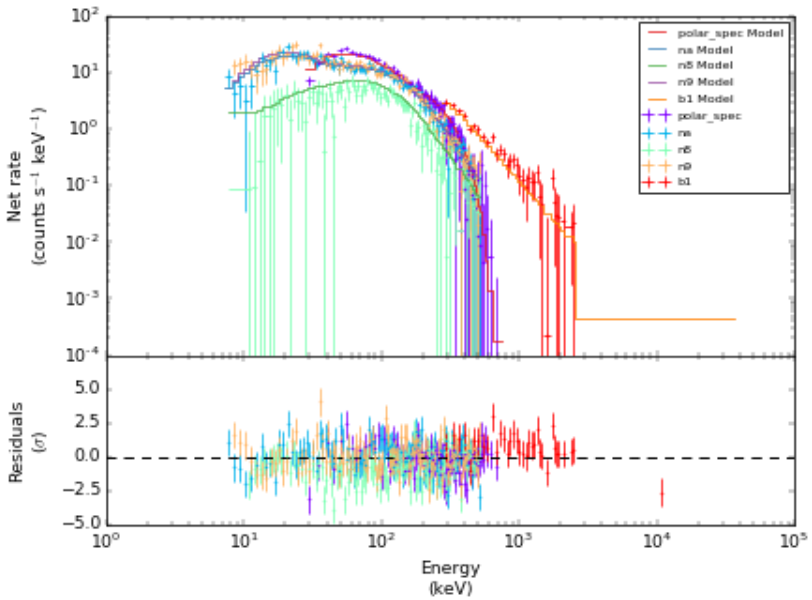


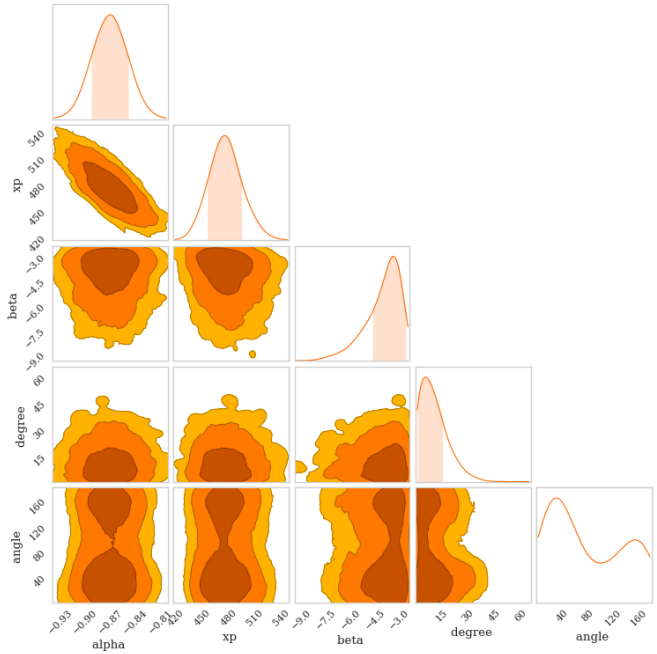
3ML

The Multi-Mission Maximum Likelihood framework

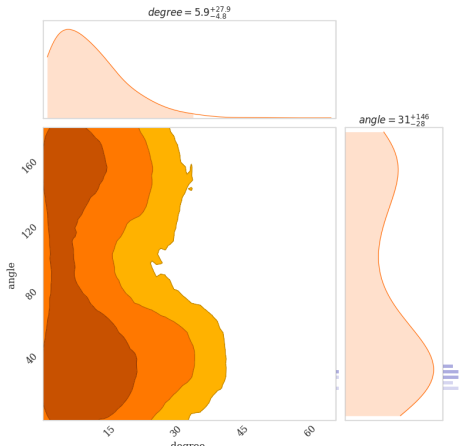
- POLAR does not measure the spectrum or position of a GRB very well
- Error on the spectrum results in an error on the response...
- However GRBs are often seen by other instruments like Fermi-GBM
- New analysis method developed using 3ML framework
- Use spectral data from Fermi-GBM and POLAR and polarization data from POLAR

Another 50 GRBs!

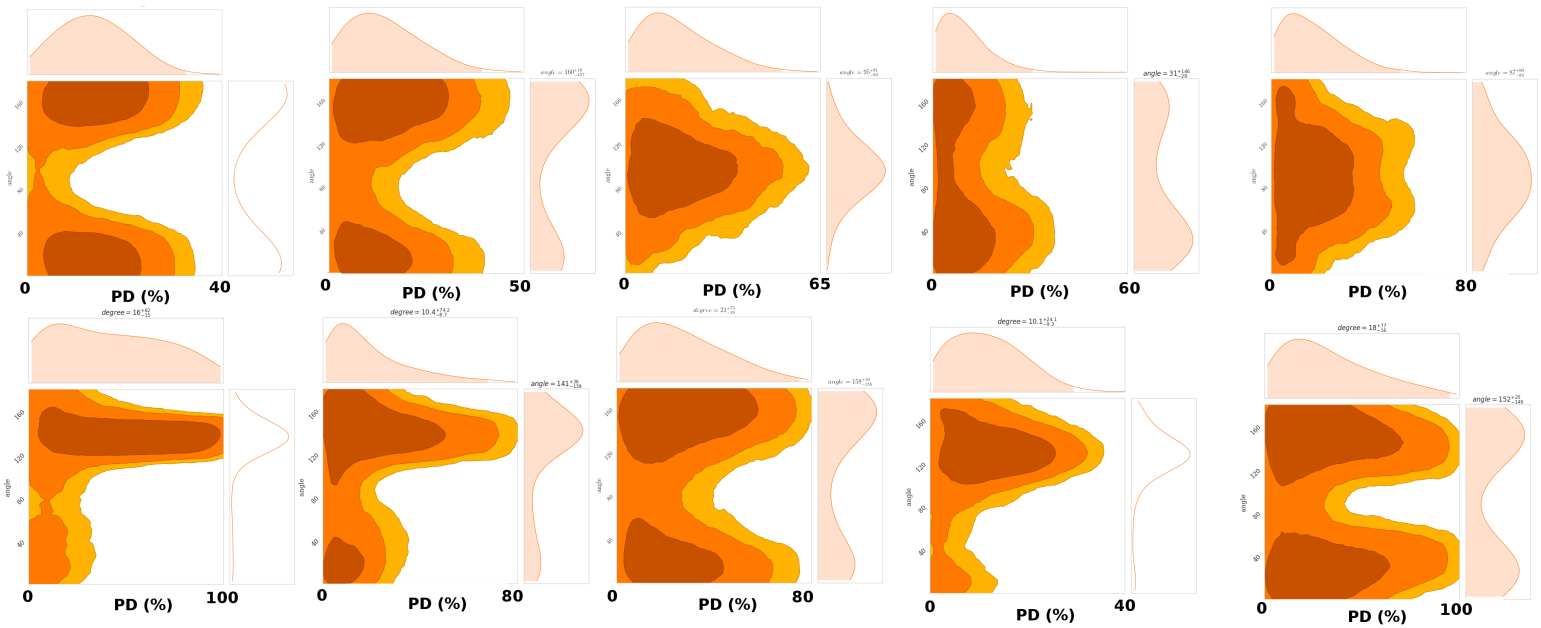




- Using spectrum and localization we can get more precise measurements
- Cross checking spectrum tells us we understand response well
- We can do off-axis GRBs as well, here 170207A

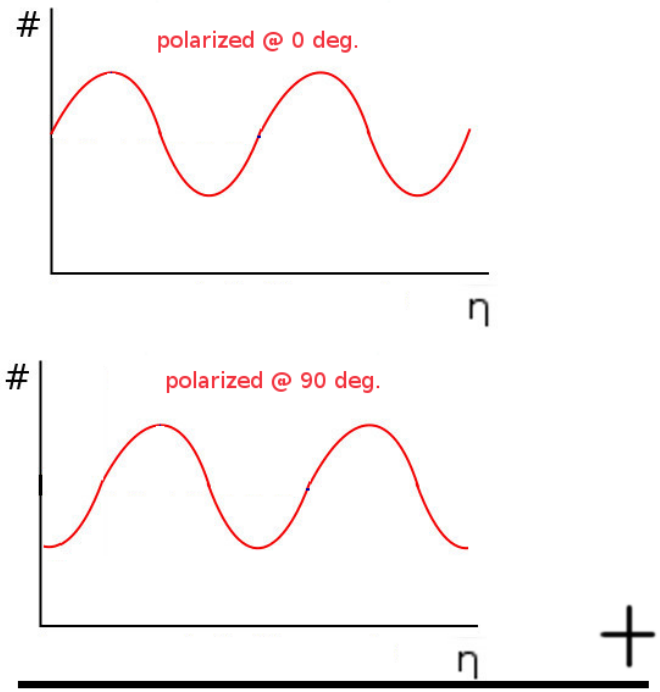


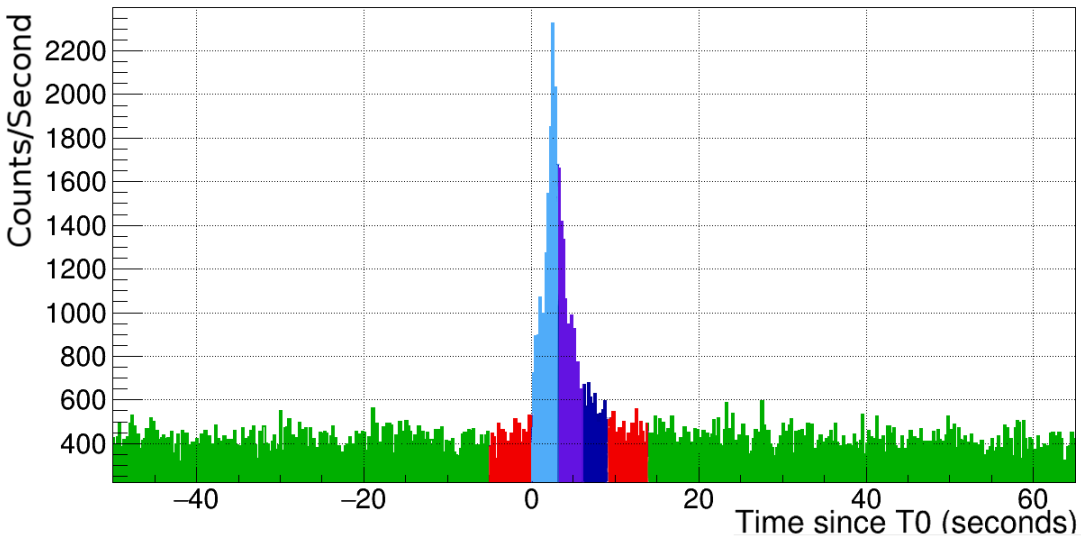
POLAR results

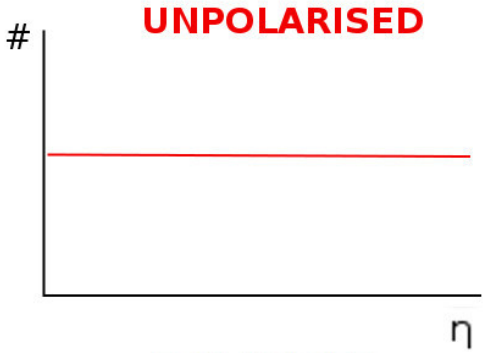


- First 5 published GRBs polarization results show no sign of polarization
- 10 more GRBs now analyzed, consistent results, also no signs of inter-pulse evolution
- Based on 15 GRBs: If there is polarization it is low, but....

Time resolved study

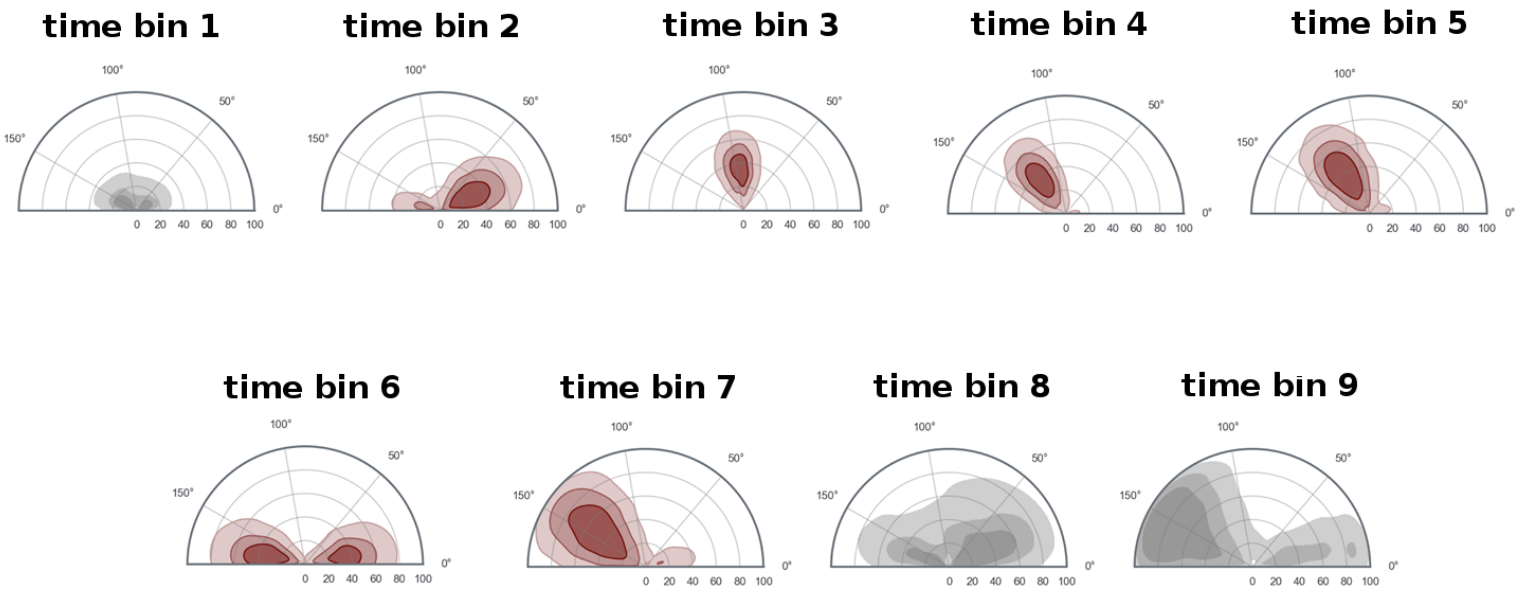






- polarized + polarized = unpolarized
- Time resolved analysis means less statistics
- Need to improve analysis

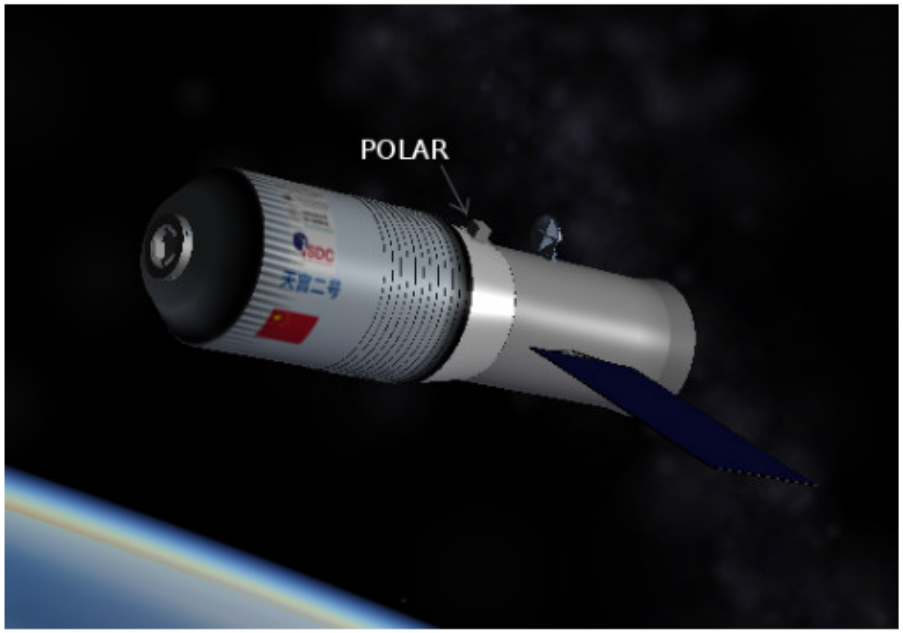
Time resolved study II



- Combined fit with Fermi-GBM data
- Time bin selection following Minimum Variability Timescale (MVT) (see G. Vianello et al 2018b)
- Results indicate the polarization angle changes during the GRB!
- 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

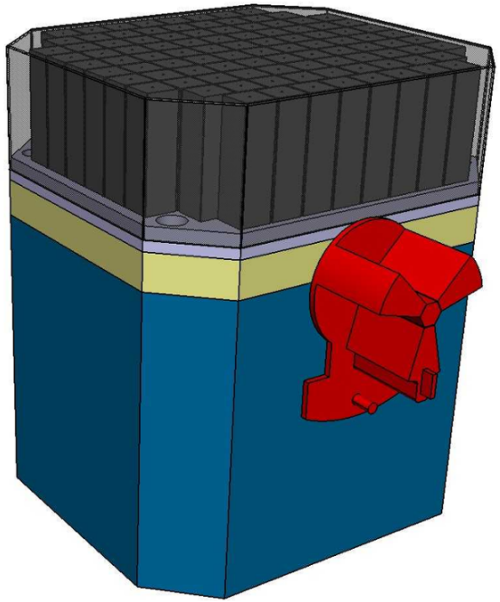
Future of POLAR

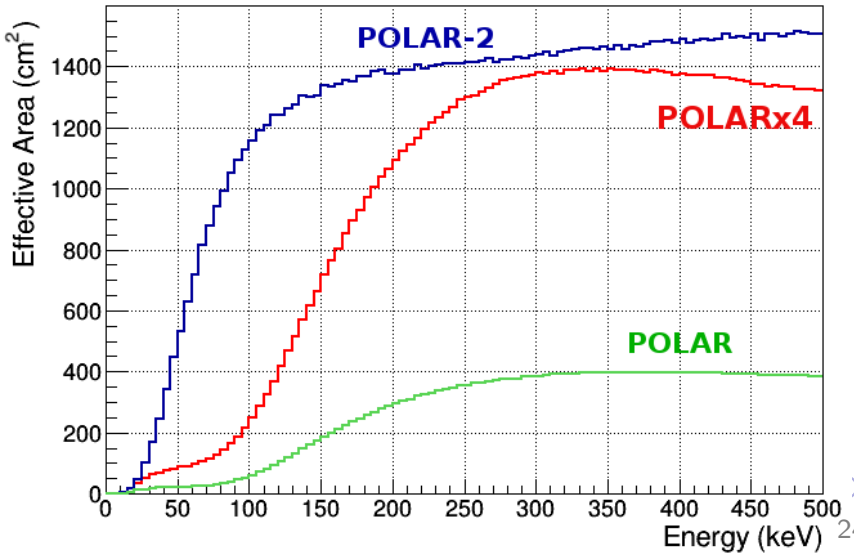
- Developing energy resolved analysis tools
- Potential to use 3ML to do joined analysis with AstroSAT
- POLAR is somewhere in the pacific ocean right now along with TG-2
- POLAR results do show time resolved studies are needed
- This requires a bigger instrument: POLAR-2



The future: POLAR-2

- Increase number of channels by factor 4
- Improve technology to gain another factor 2.5
- Allowing for fine time binning in analysis and stricter upper limits
- Can do polarization studies of GRBs with fluence down to $10^{-7}\mathrm{erg/cm^2}$ (like 170817A)
- Approved for launch in 2024 to CSS, project funding approved by Swiss Space Office
- Collaboration: University of Geneva, Max Planck Extraterrestrial Physics, NCBJ, IHEP





Summary and Outlook

- Analysis of 15 GRBs shows GRBs are not highly polarized
- Signs of polarization angle evolution within a single pulse
- No sign of evolution between different pulses
- Some more work to do with POLAR data
- Also busy with building POLAR-2
- Launch planned in 2024

Thank you for your attention!