Polarization observations of GRB prompt emission by POLAR

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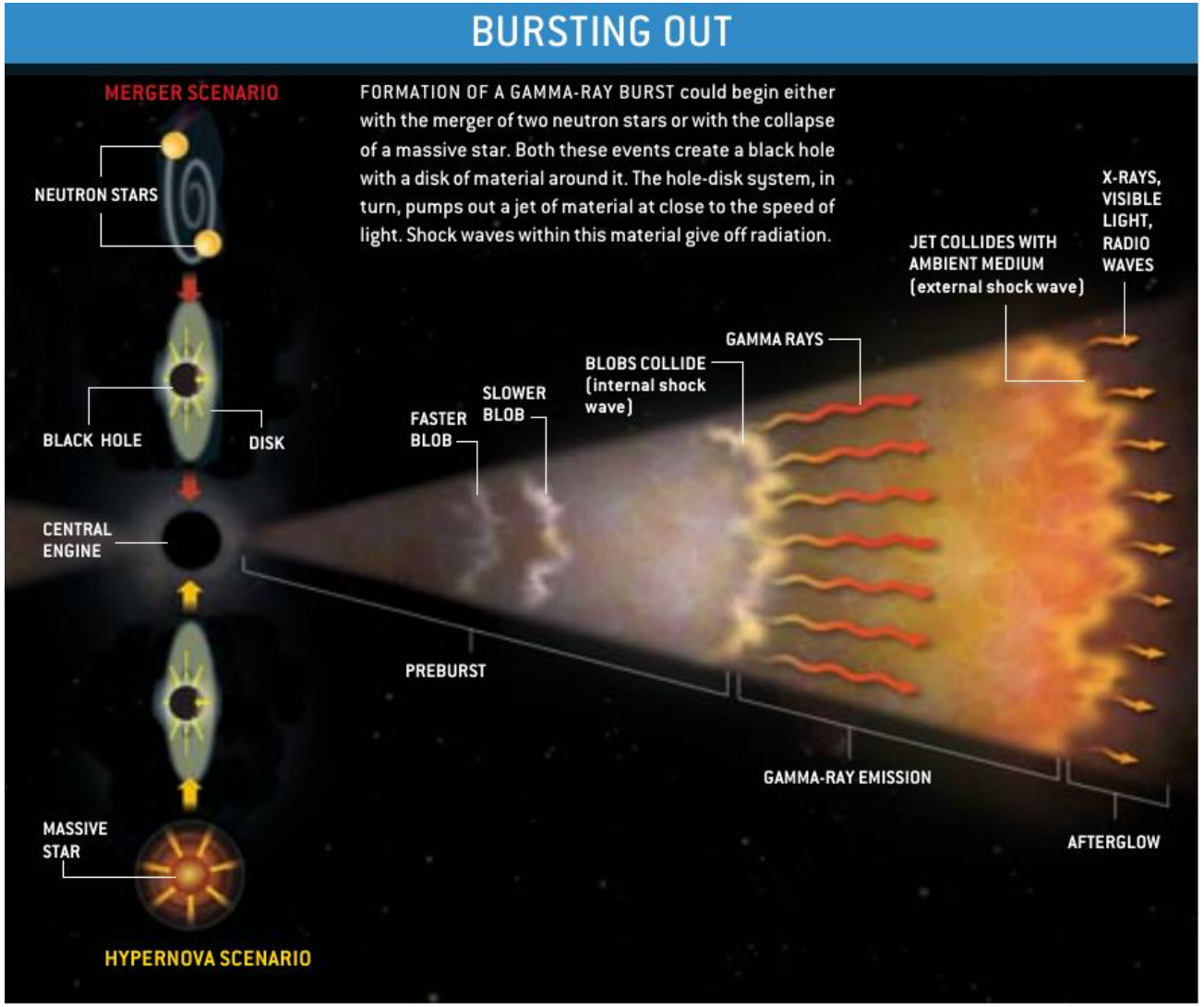
(On behalf of the POLAR collaboration)

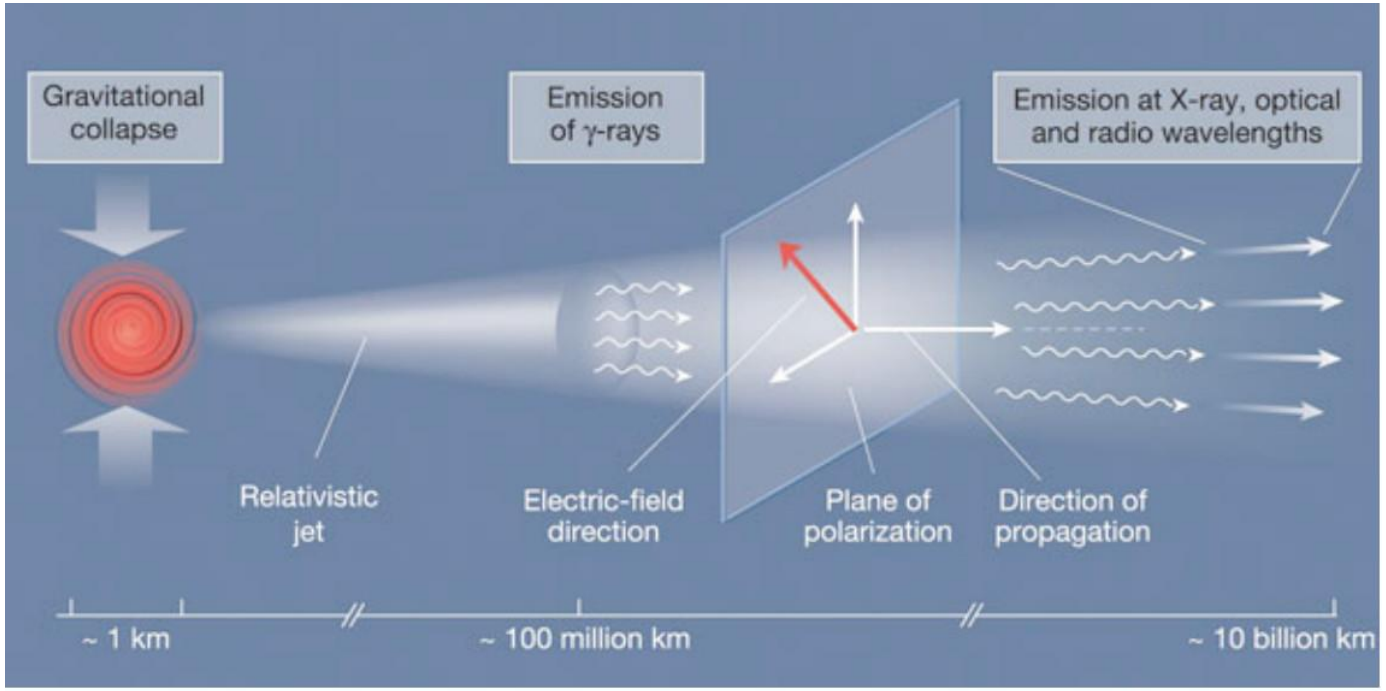
Institute of High Energy Physics (IHEP),
Chinese Academy of Sciences (CAS)

Gamma-Ray Burst (GRB)



- **Discovered** in late 1960s
- **Related Sciences**
  - star, galaxy, universe
- **Observations**
  - Prompt emission: short/long
  - Afterglow: rich features
  - Multi-messenger: GW, …
- **Open questions**
  - Progenitor
  - Central engine
  - Jet launch
  - Jet composition/structure
  - Radiation mechanism
  - Standard candle?
  - …

Polarization of the prompt gamma-rays emission



E. Waxman, Nature 423 (2006) 388

- Many models give different predictions on the polarization parameters
- Polarization holds information on emission process/emission region/magnetic field, etc.
  - Synchrotron emission, Inverse Compton, photospheric emission
  - Ordered or random magnetic field

Previous polarization measurements

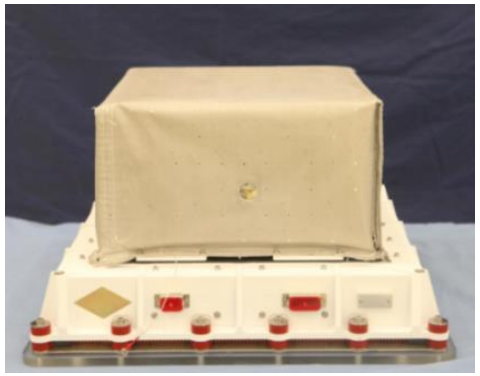
GRB	Instr./Sat.	Pol. (%)	Remark
160530A	COSI	$< 46\%$	low statistics
110721A	GAP/IKAROS	84^{+16}_{-28}	Constant Pol. Angle
110301A	GAP/IKAROS	70 ± 22	Constant Pol. Angle
100826A	GAP/IKAROS	27 ± 11	Pol. Angle changes by $\approx 90^{\circ}$
021206	RHESSI	80 ± 20	systematics
021206	RHESSI	41^{+57}_{-44}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

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

POLAR: a dedicated GRB polarimeter

- China-Europe Collaboration
- China's Space Lab. Tiangong-2
- Operation: **2016/9-2017/4**
- **Science Objectives**
  - **Polarization GRB prompt emission**
  - **GW EM counterpart**
  - **Pulsar navigation experiment**

N. Produit et al. NIMA 2005, NIMA 2018



Detector

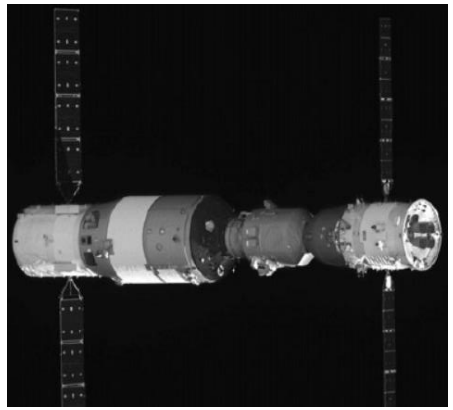
Electronics

中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

ISDC

PAUL SCHERRER INSTITUT
PSI

ANNECY
lapp

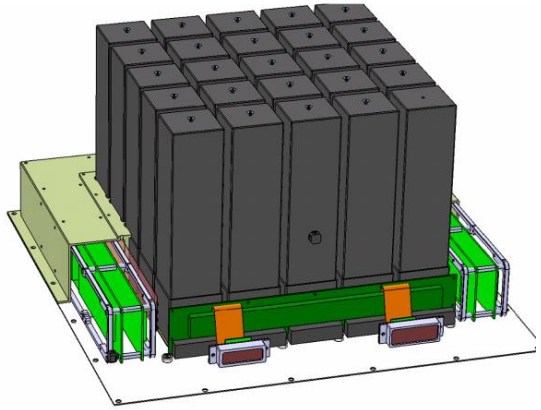


On orbit

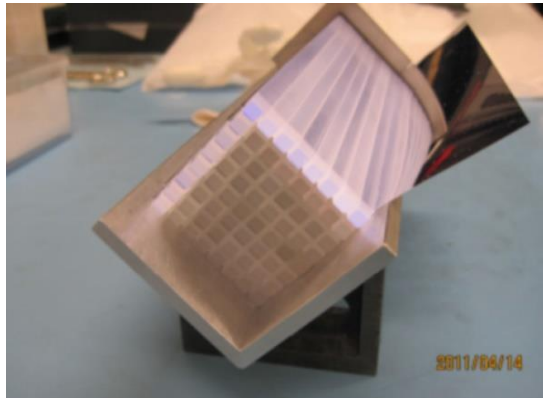
Launch

Installed on TG-2

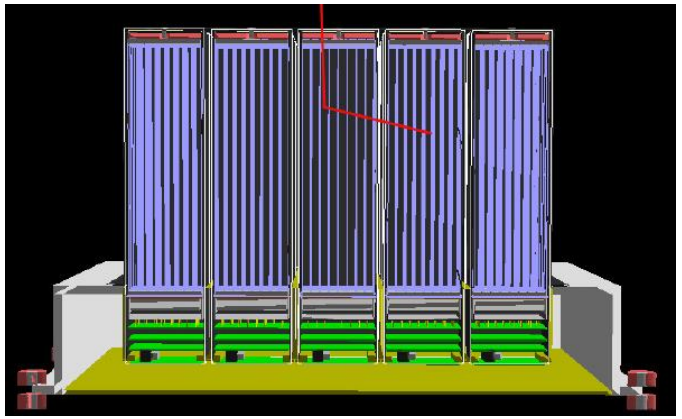
How to measure (linear) polarization of X/gamma?



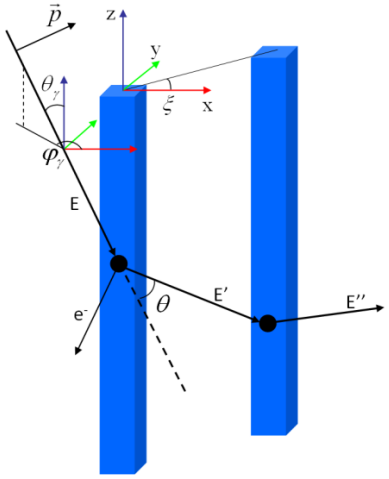
POLAR detector



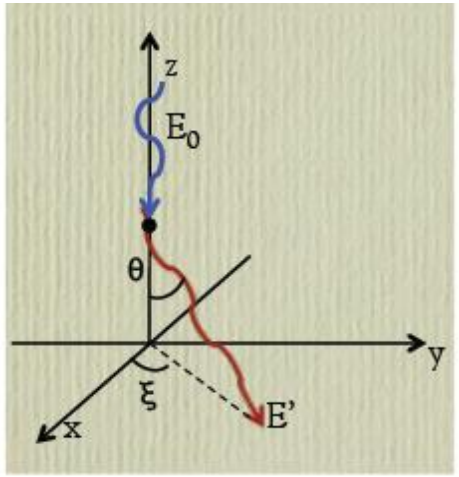
64 bars per module



1600 bars in total



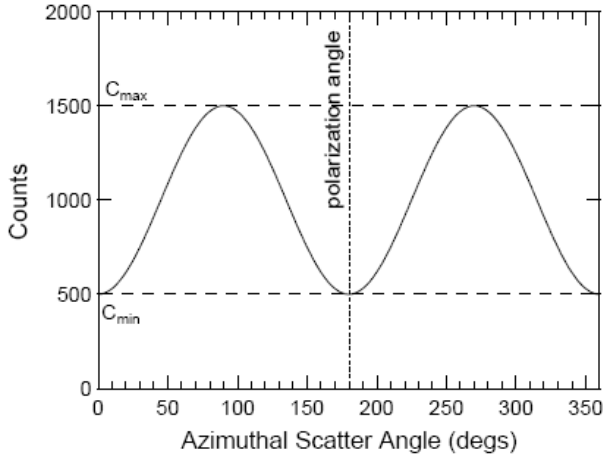
Compton event



Compton Scattering

$$d\sigma = \frac{r_o^2}{2} d\Omega \left(\frac{E'}{E_o}\right)^2 \left(\frac{E_o}{E'} + \frac{E'}{E_o} - 2\sin^2\theta\cos^2\eta\right)$$

Klein-Nishina Formula



Modulation curve

Distribution function

$$C(\xi) = A\cos(2(\xi - \varphi + \frac{\pi}{2})) + B$$

$$\mu = \frac{C_{max} - C_{min}}{C_{max} + C_{min}} \quad \Rightarrow \quad P = \frac{\mu}{\mu_{100}}$$

Modulation factor — Polarization level

Basic facts of POLAR

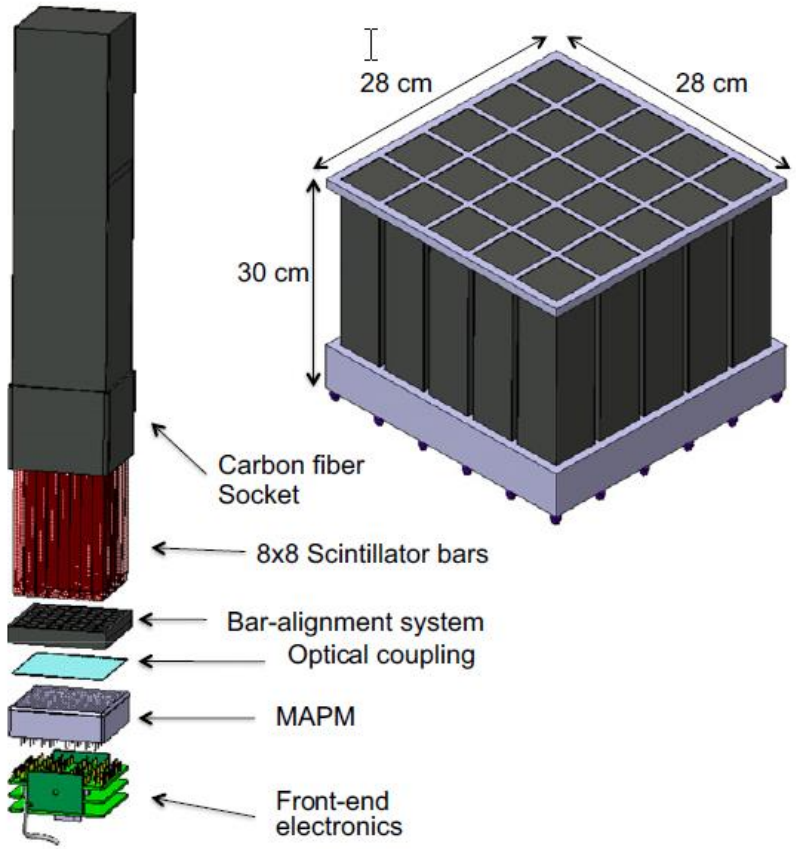
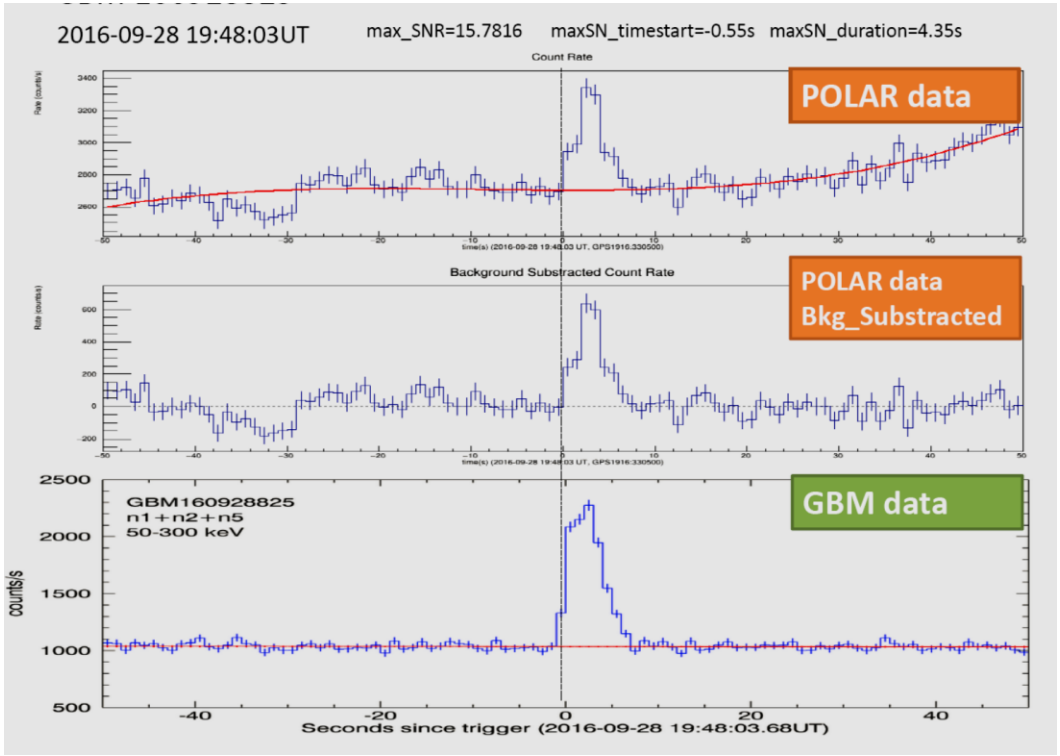


Fig. 1. Scheme of POLAR detector. *Left*: Exploded view of one module from POLAR target. *Right*: Complete POLAR target, i.e. the assembly of 25 modules, with its approximate dimensions.

N. Produit et al. NIMA 2018
Xiong et al. NIMA, 2009

Items	value
Detector material	Plastic scintillator (EJ-248M)
Yearly detectable GRBs	~50 GRBs/year
GRB localization accuracy	⩽5° (Fluence⩾10^{-5} erg cm^{-2})
Detection energy range	~50 – 500 keV
Field of view	±70° × ±70° (~1/3 of the sky)
Modulation factor	40%@200 keV
MDP	<10% (Fluence$_{total}$ ⩾ 3×10^{-5} erg cm^{-2})
Detector geometry area	~570 cm^2 (on-axis view)
Mass	OBOX: 27.6 kg, IBOX: 3.52 kg
Size	OBOX: 462×462×268.5 mm^3 IBOX: 247×160×85 mm^3
Maximum power consumption	⩽80 W
Time accuracy(UTC)	±1 ms
Reliability	0.90 (in 2 years lifetime)

GRBs detected by POLAR



The first GRB GCN Circular!

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TITLE:   GCN CIRCULAR
NUMBER:  20126
SUBJECT: GRB 160928A: The first GRB detected by POLAR
DATE:    16/11/04 15:30:06 GMT
FROM:    Shaolin Xiong at IHEP  <xiongsl@ihep.ac.cn>

S. L. Xiong (IHEP), N. Produit (UniGe), T. W. Bao (IHEP), T. Batsch (NCBJ),
T. Bernasconi, F. Cadoux, I. Cernuda (UniGe), J. Y. Chai, Y. W. Dong, M.  Z. Feng (IHEP),
N. Gauvin (UniGe), M. Y. Ge (IHEP), W. Hajdas (PSI), J. J. He, Y. Huang (IHEP),
M. R. Kole (UniGe), M. N. Kong (IHEP), C. Lechanoine-Leluc (UniGe), H.  C. Li,
L. Li, Z. H. Li, J. T. Liu, X. Liu, F. J. Lu (IHEP), R. Marcinkowski (PSI), S. Orsi, M. Pohl,
D. Rapin (UniGe), A. Rutczynska, D. Rybka (NCBJ), H. L. Shi, L. M. Song, J. C. Sun (IHEP),
J. Szabelski (NCBJ), R. J. Wang, Y. H. Wang, X. Wen, B. B. Wu (IHEP), X.  Wu (UniGe),
H. L. Xiao (PSI), H. H. Xu, M. Xu, J. Zhang, L. Zhang, L. Y. Zhang (IHEP), P. Zhang (PSI),
S. N. Zhang, X. F. Zhang, Y. J. Zhang, Y. Zhao, S. J. Zheng (IHEP), A.
Zwolinska (NCBJ)
(i.e. the POLAR team):

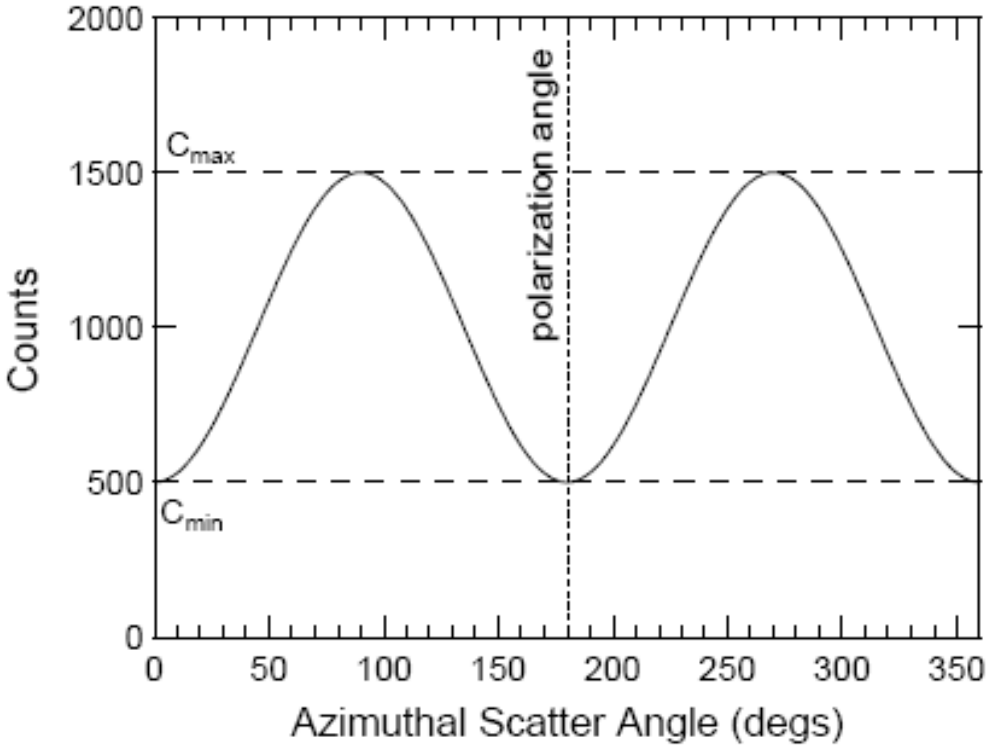
POLAR, a dedicated Gamma-Ray Burst polarimeter, has been launched successfully
on-board the Chinese space laboratory Tiangong-2 (TG-2) on Sep 15, 2016.

During the commissioning operation phase, at 19:48:05.00 UT on 28
September 2016 (T0),
POLAR detected the GRB160928A in a routine ground search of the data,
which was also observed by the Fermi/GBM (trigger 496784887/160928825),
INTEGRAL/SPI-ACS (trigger #7579) and Konus-WIND (trig #4385).
```

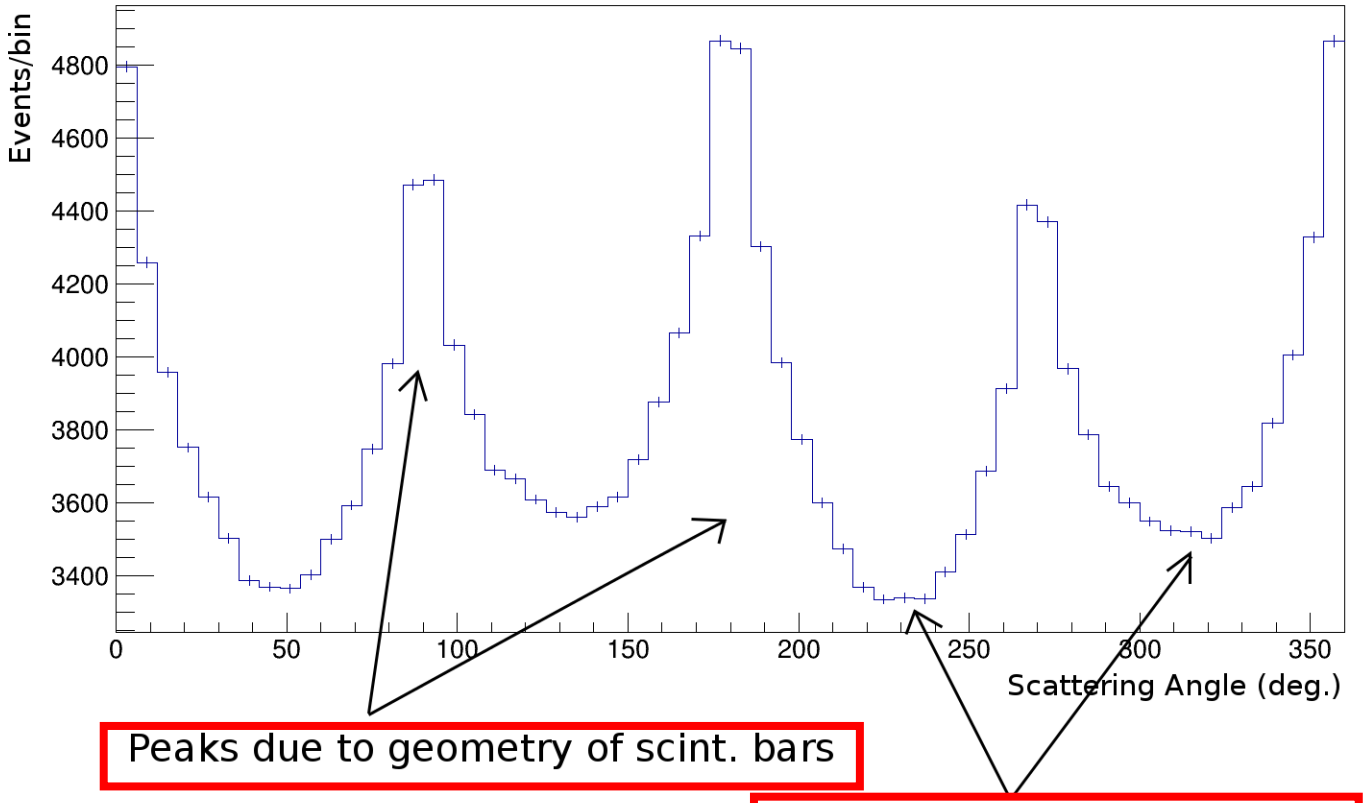
- Detected 55 GRBs, 49 GCN Circulars http://www.isdc.unige.ch/polar/lc/
- Discover ~150 GRB/year, one of the best sensitive GRB detectors
- Best polarimeter in 50-500 keV ever, with MDP~10%
- Localization error: ~ 5 degrees

Many effects in the measured modulation curve

Ideal case



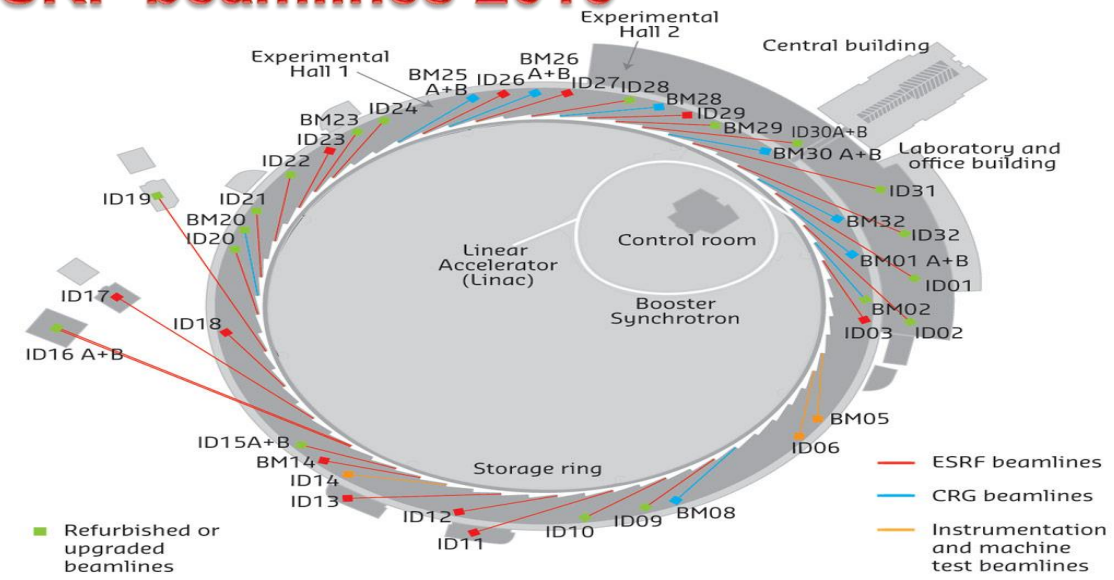
Real case

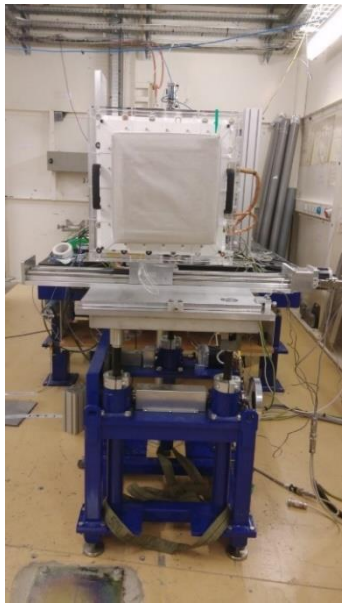


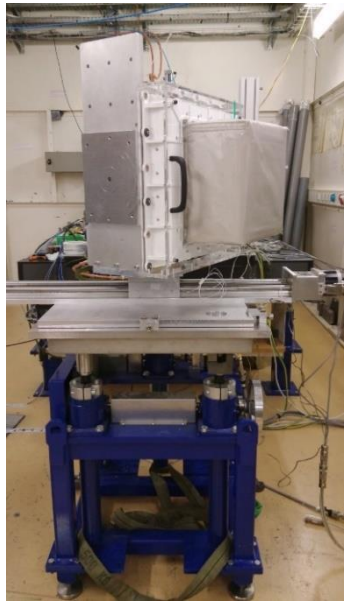
Comprehensive Calibrations

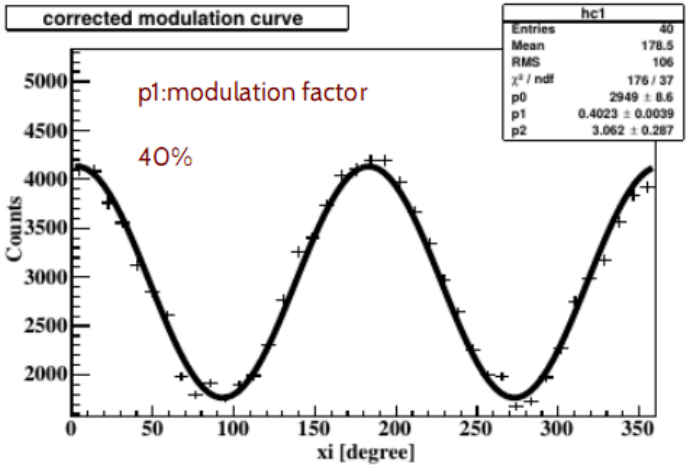
H. Xiao et al. NSS/MIC Conf. Proc. 2015
Kole et al. NIMA, 2017; Li et al. NIMA, 2018

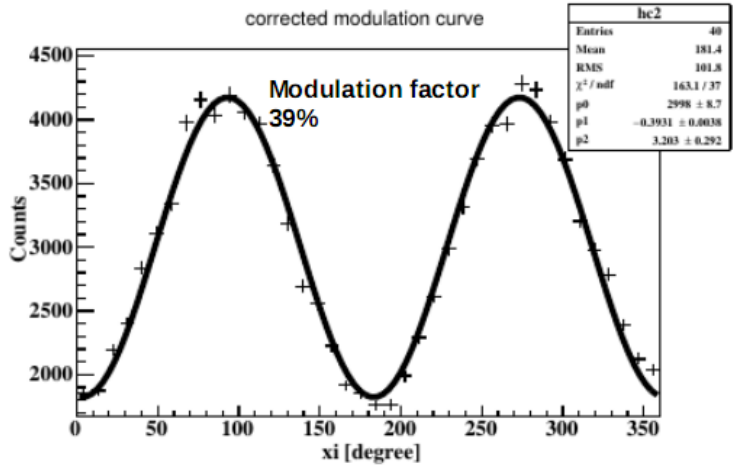
ESRF beamlines 2015

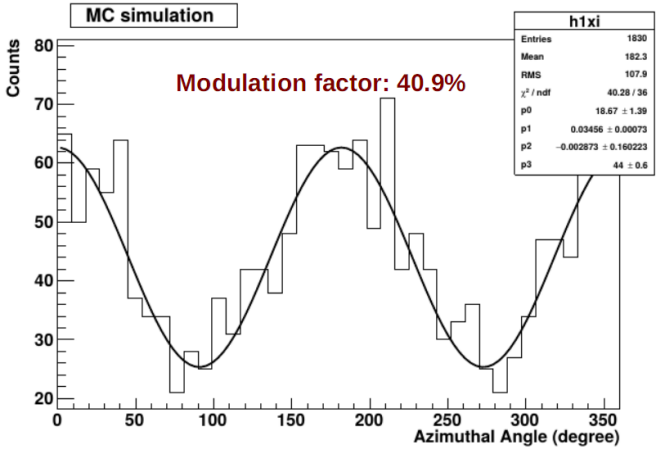






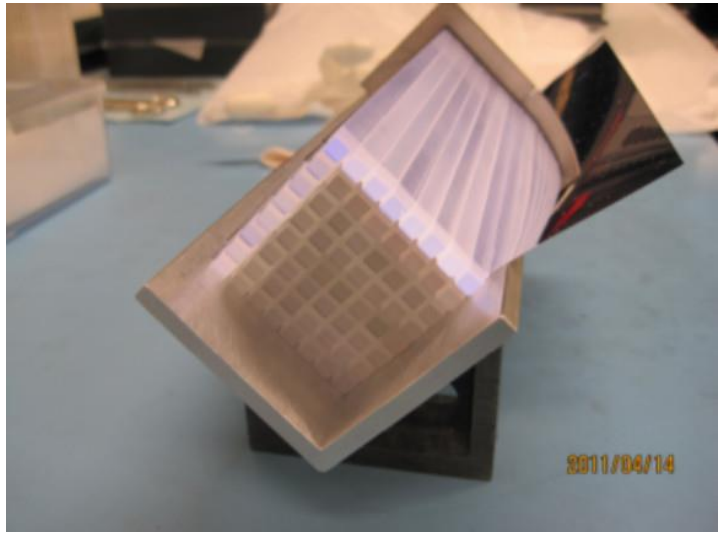


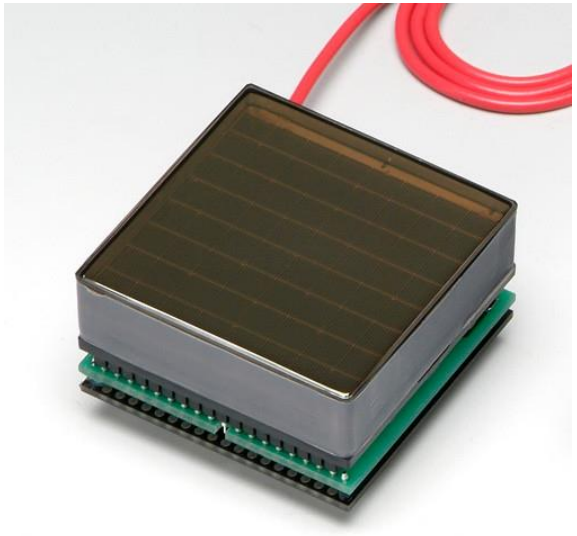




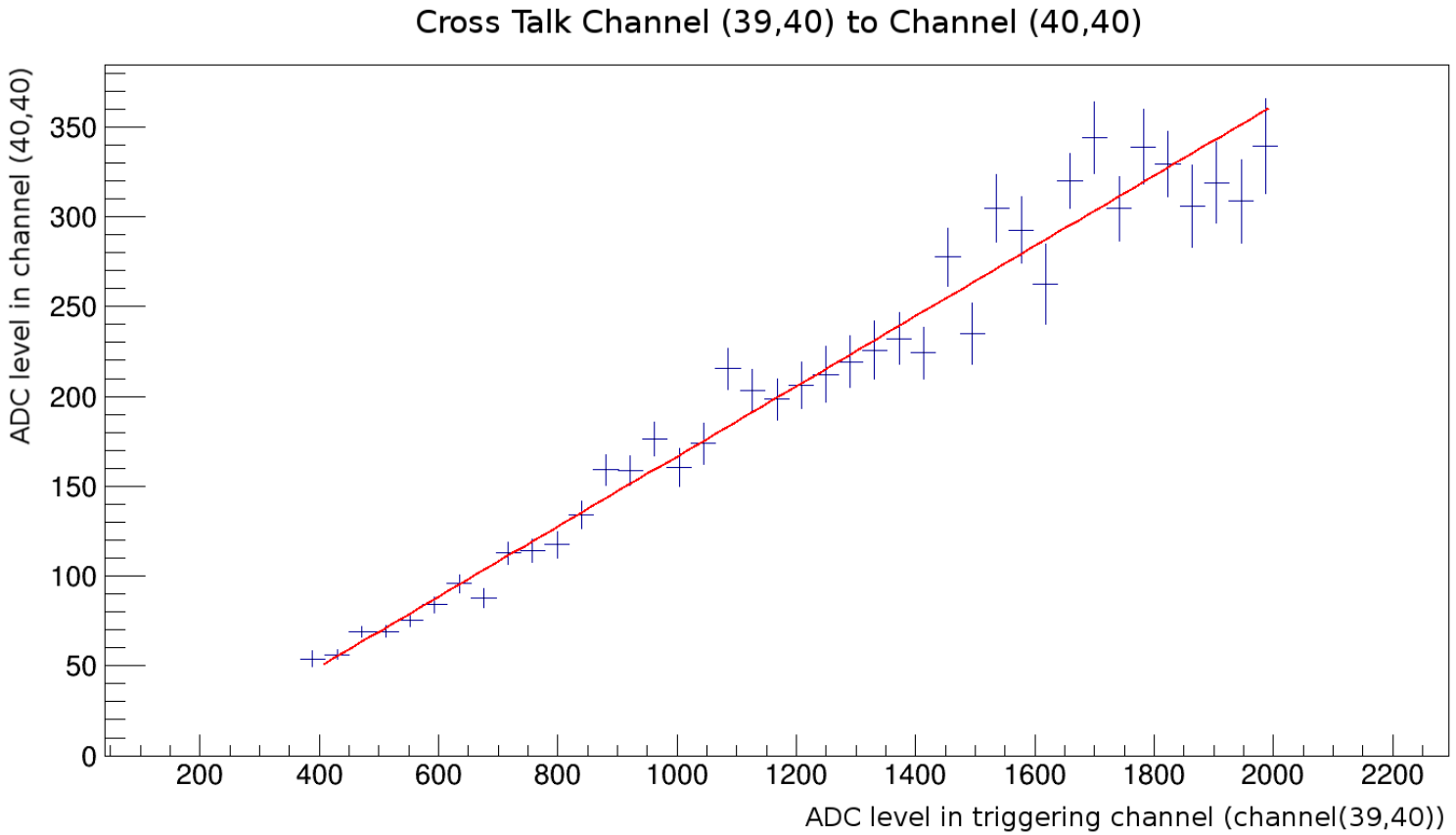
Measurement and MC simulation are well consistent!

Cross-talk effect

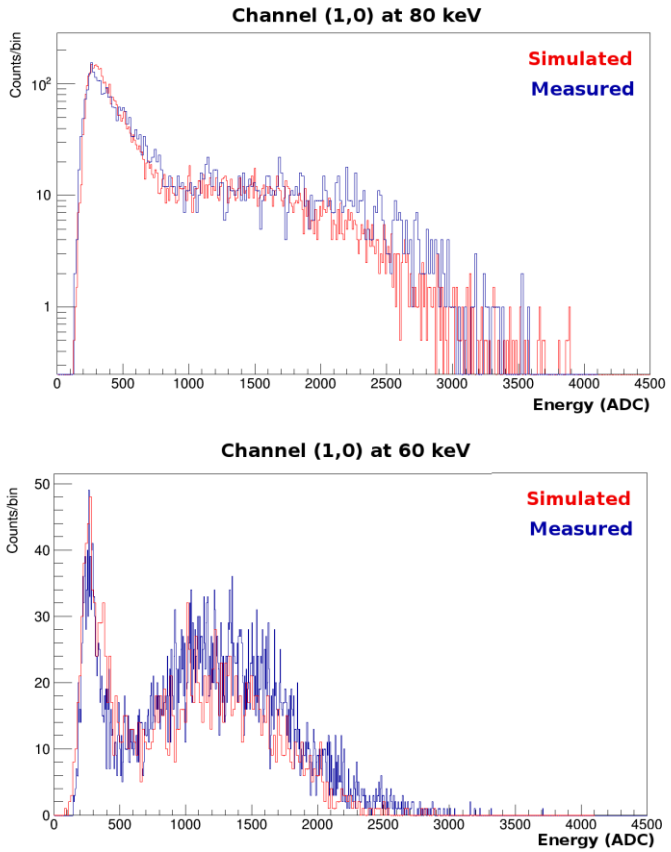


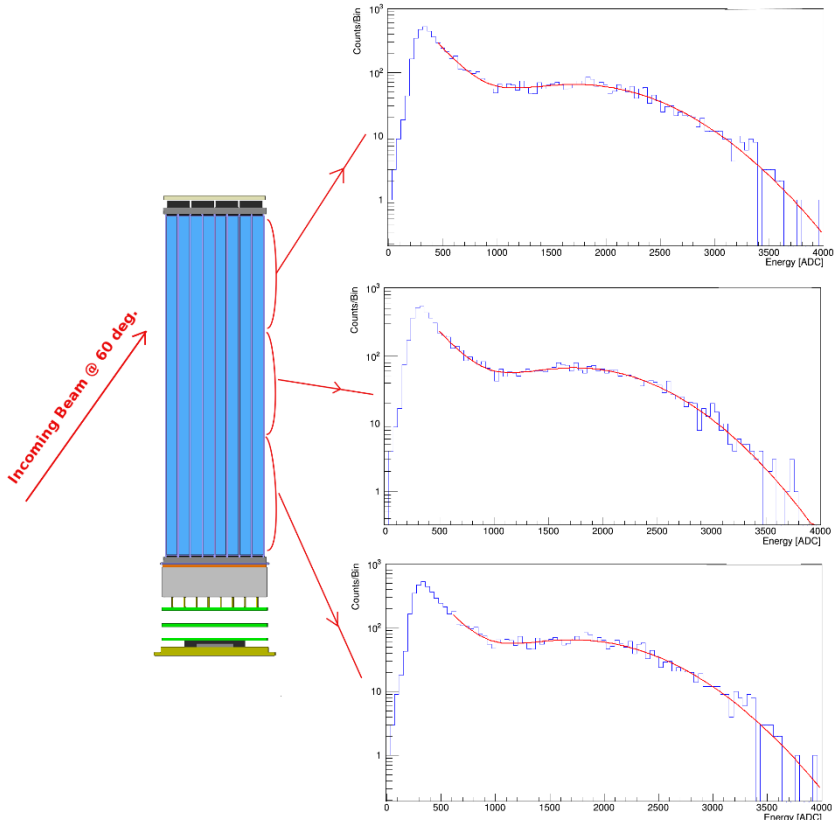


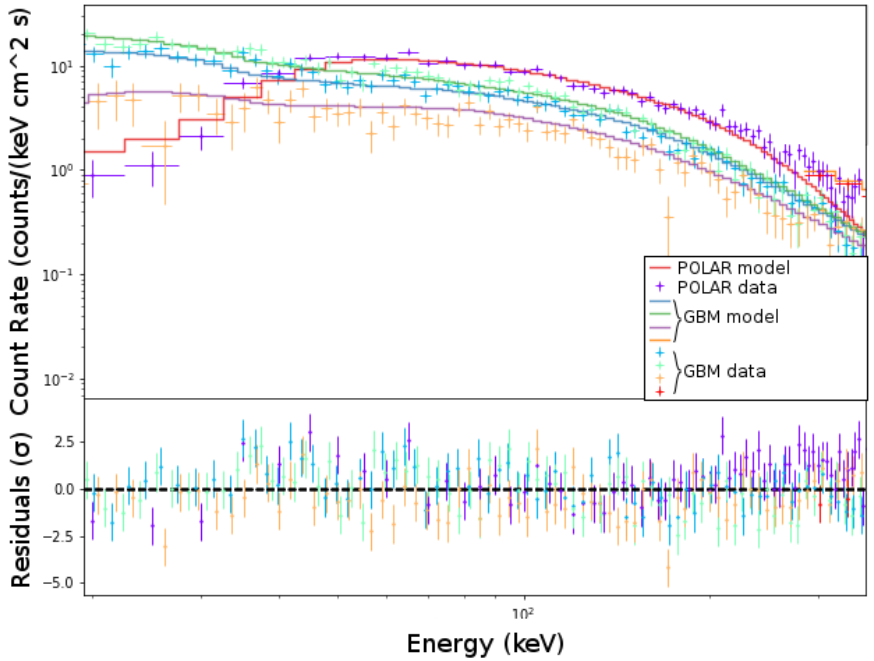
from: www.hamamatsu.com



Energy response





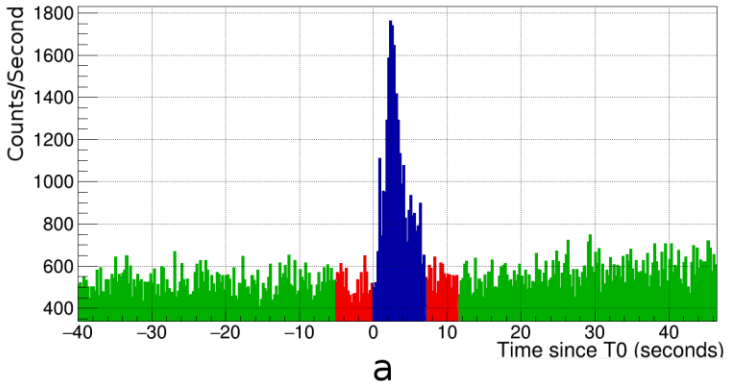


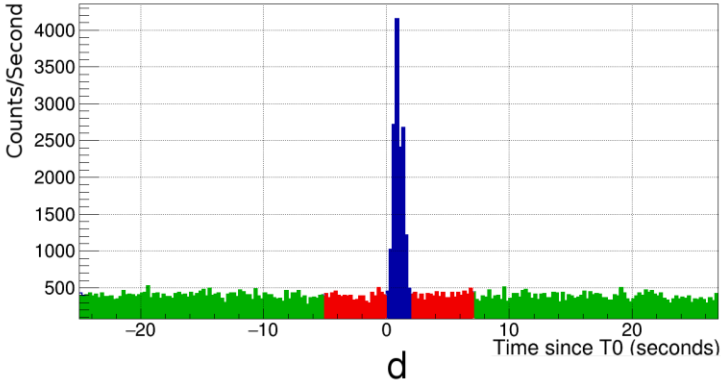
- Response includes temperature dependence, non-linear effects in electronics and interaction position in the bar
- Final calibration uncertainties result in a systematic error of 2% in polarization measurement

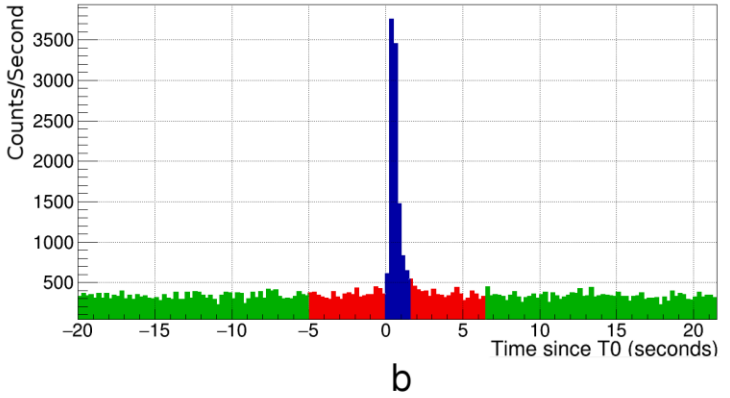
Accurate polarization measurement of 5 GRBs

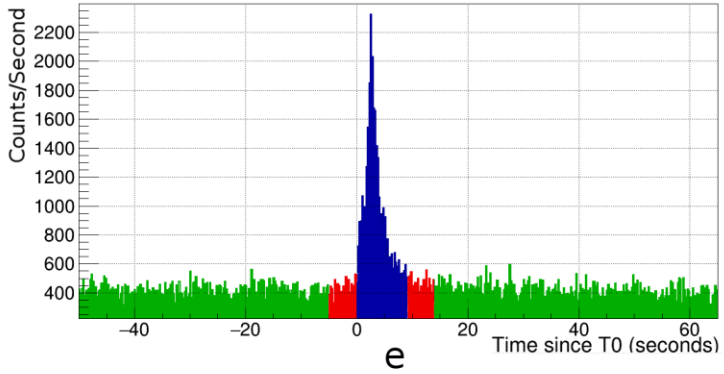
The sample
a. 161218A
b. 170101A
c. 170114A
d. 170127C
e. 170206A

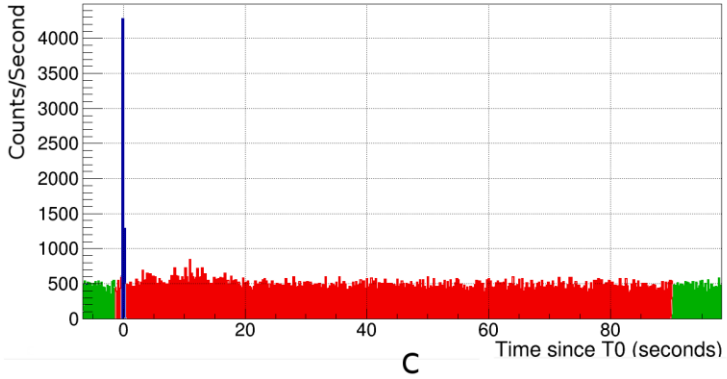
* Their location and spectra were measured by other GRB missions











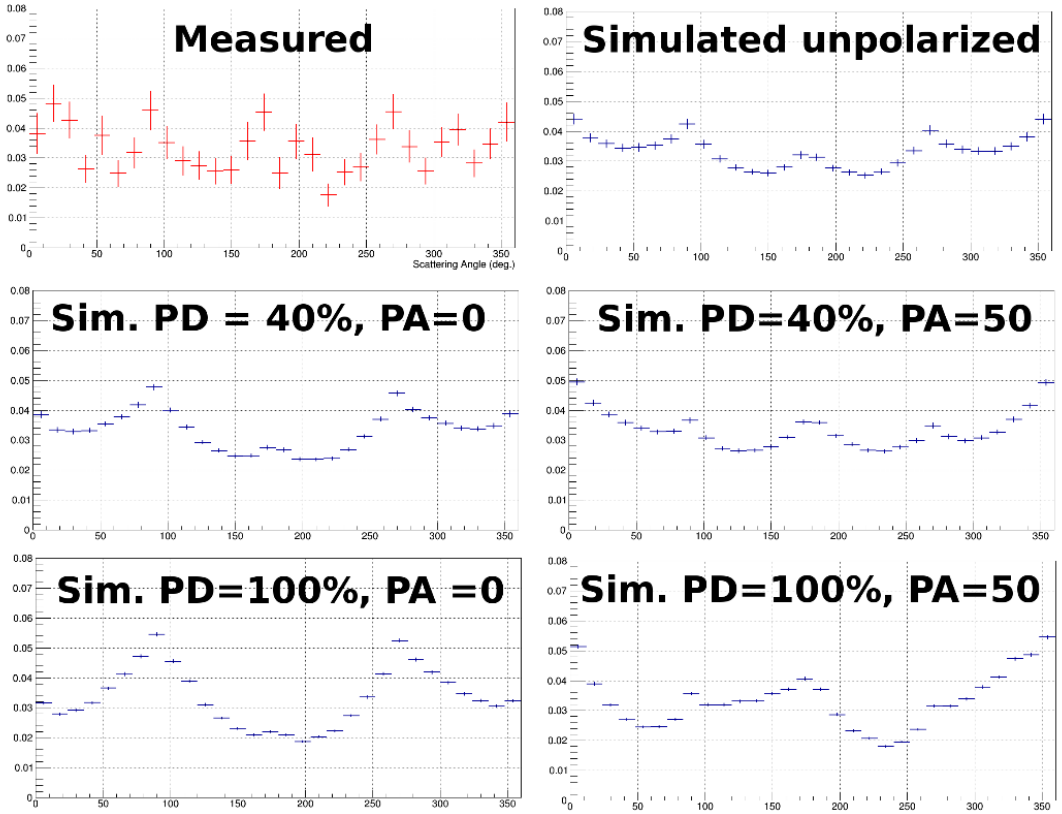
LETTERS
https://doi.org/10.1038/s41550-018-0664-0
nature astronomy

Detailed polarization measurements of the prompt emission of five gamma-ray bursts

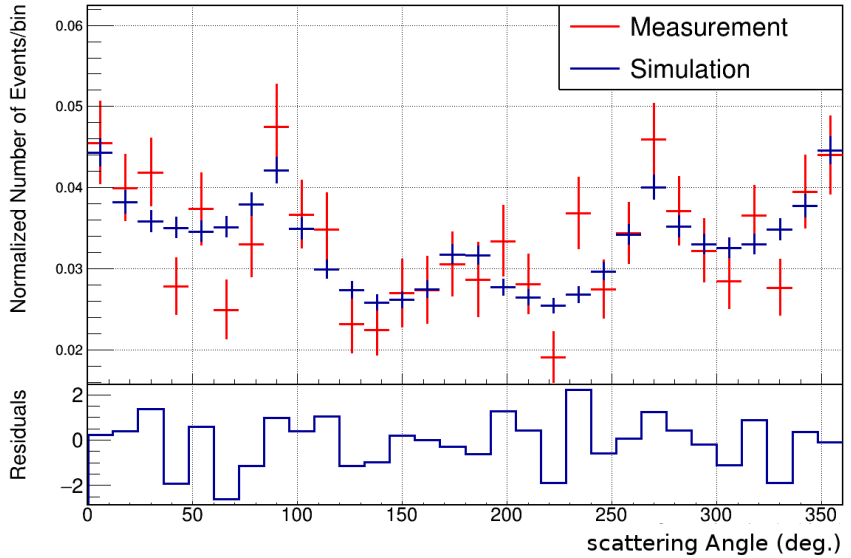
Shuang-Nan Zhang[1,2,10*], Merlin Kole[3,10*], Tian-Wei Bao[1], Tadeusz Batsch[4], Tancredi Bernasconi[5], Franck Cadoux[3], Jun-Ying Chai[1,2], Zi-Gao Dai[6,7], Yong-Wei Dong[1], Neal Gauvin[5], Wojtek Hajdas[8], Mi-Xiang Lan[6,9], Han-Cheng Li[1,2], Lu Li[1], Zheng-Heng Li[1,2], Jiang-Tao Liu[1], Xin Liu[1,2], Radoslaw Marcinkowski[8], Nicolas Produit[5], Silvio Orsi[3], Martin Pohl[3], Dominik Rybka[4], Hao-Li Shi[1], Li-Ming Song[1,2], Jian-Chao Sun[1], Jacek Szabelski[4], Teresa Tymieniecka[4], Rui-Jie Wang[1], Yuan-Hao Wang[1,2], Xing Wen[1,2], Bo-Bing Wu[1], Xin Wu[3], Xue-Feng Wu[9], Hua-Lin Xiao[1,8], Shao-Lin Xiong[1], Lai-Yu Zhang[1], Li Zhang[1], Xiao-Feng Zhang[1], Yong-Jie Zhang[1] and Anna Zwolinska[4]

S.N. Zhang et al., 2019, Nature Astron., 3, 258

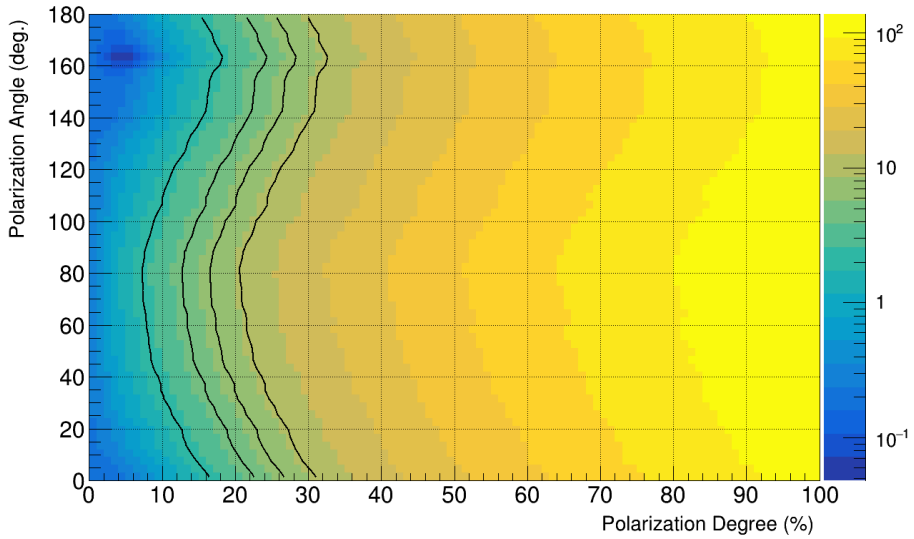
Simulate and fit the modulation curve



GRB 170114A

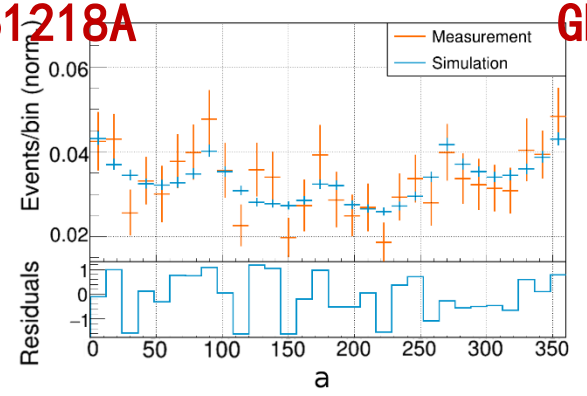


ΔX^2



Modulation curves of 5 GRBs

GRB161218A



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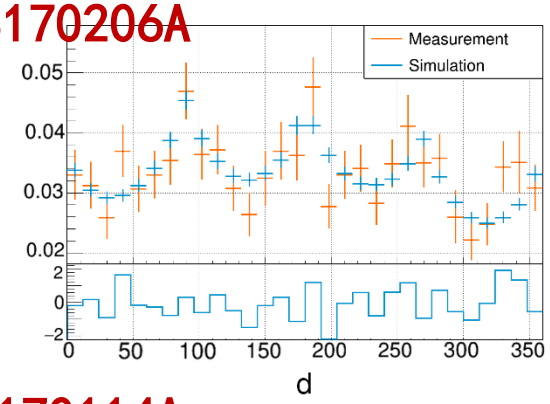

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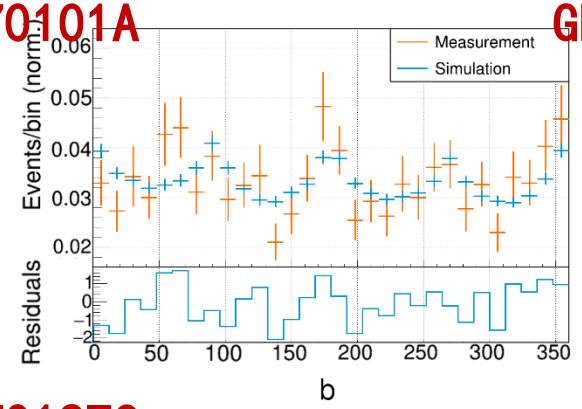

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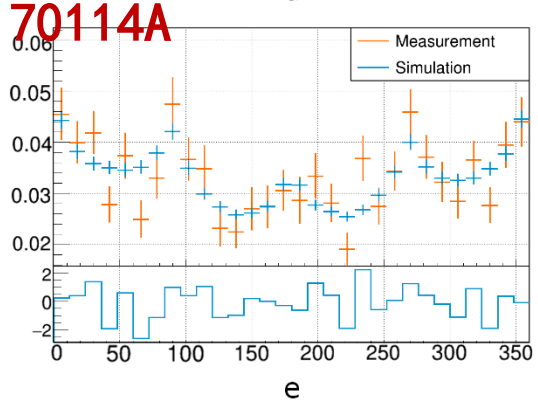
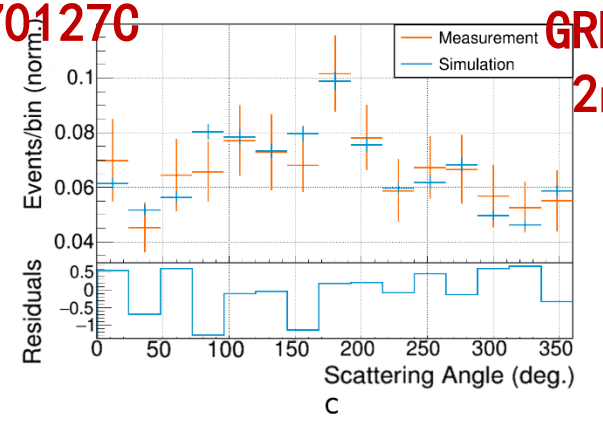
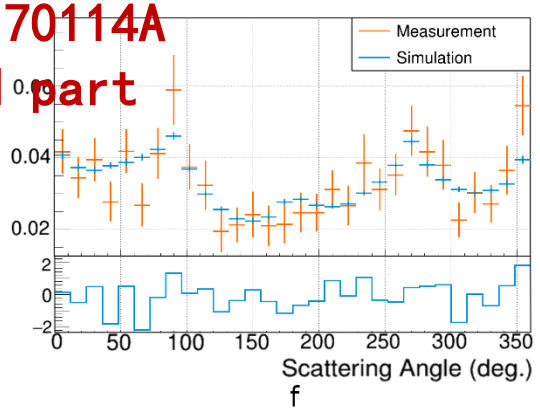


GRB170127C



GRB170114A 2nd part



Polarization degree and angle

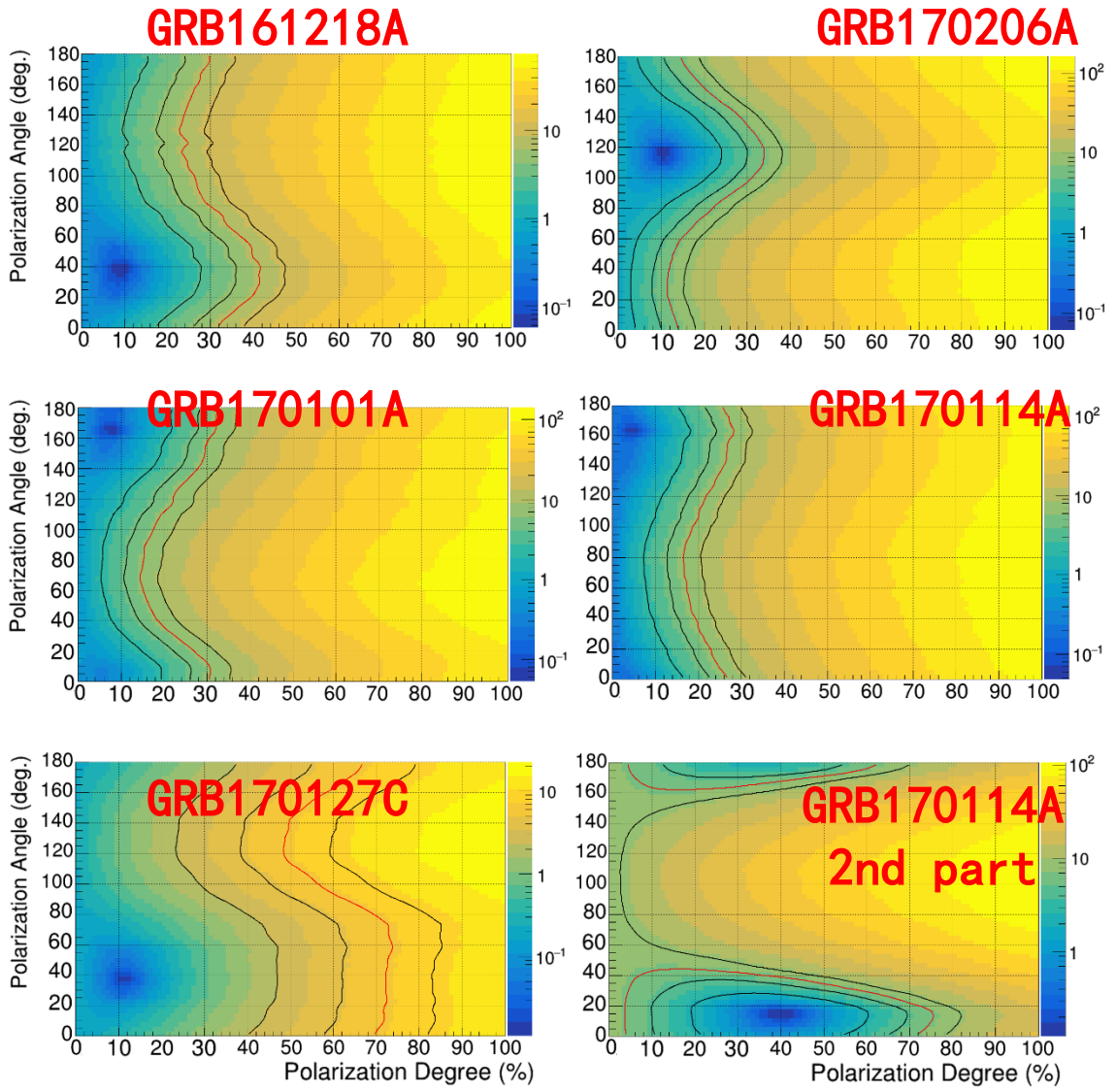
Table 1 | Summary of the five GRBs

GRB	T_{90} (s)	Fluence[a]	PD	Probability (PD < 2%)	PD_{up}(99%)	PA (°)	PA change
161218A	6.76	1.25×10^{-5}	9%	9%	45%	40	No
170101A	2.82	1.27×10^{-5}	8%	13%	31%	164	No
170127C	0.21	7.4×10^{-6}	11%	5.8%	67%	38	Unknown
170206A	1.2	1.34×10^{-5}	10%	12%	31%	106	No
170114A	8.0	1.93×10^{-5}	4%	14%	28%	164	Yes
170114Ap1	NA	NA	15%	8%	43%	122	NA
170114Ap2	NA	NA	41%	0.49%	74%	17	NA

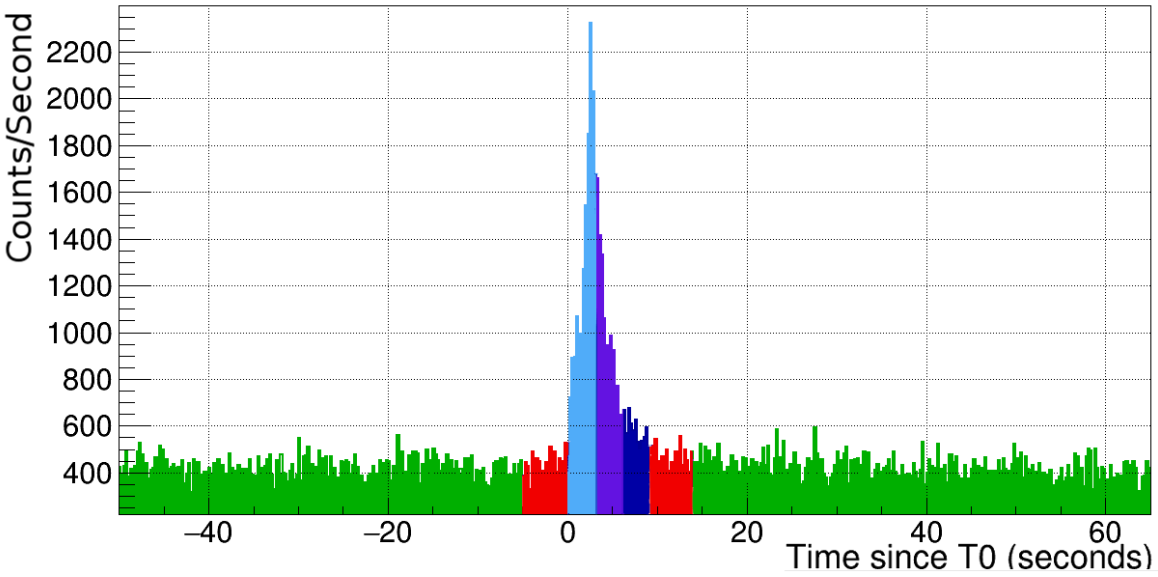
The different properties of the five GRBs and two time bins of GRB 170114A are included. [a]In units of erg cm^{-2} in the 10–1,000 keV energy range. NA, not applicable; PA, polarization angle; PD, polarization degree; PD_{up}(99%), the 99% confidence upper limit in PD.

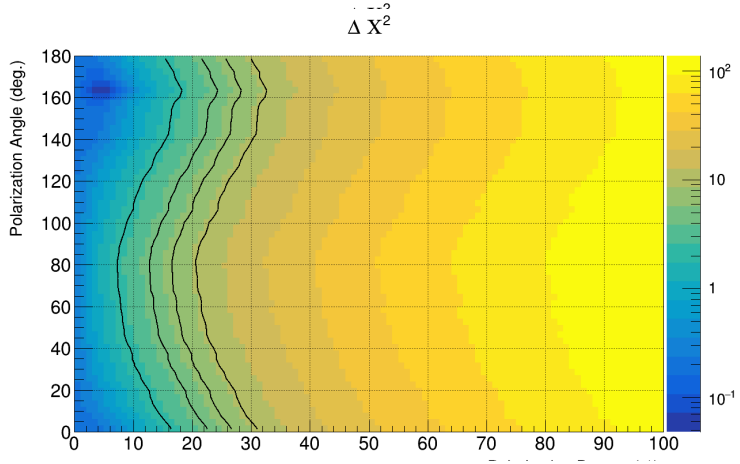
- All have rather low polarization, which disfavors high polarization models
- Discover the polarization angle evolution in a single pulse

S.N. Zhang et al., 2019, Nature Astron., 3, 258

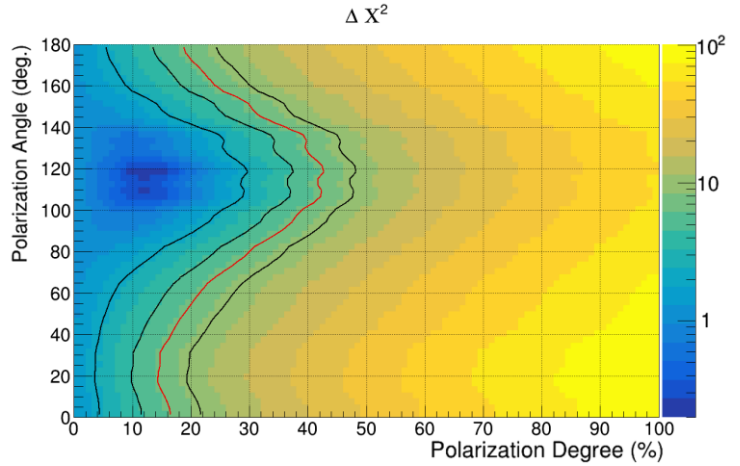


Polarization angle evolution in GRB 170114A

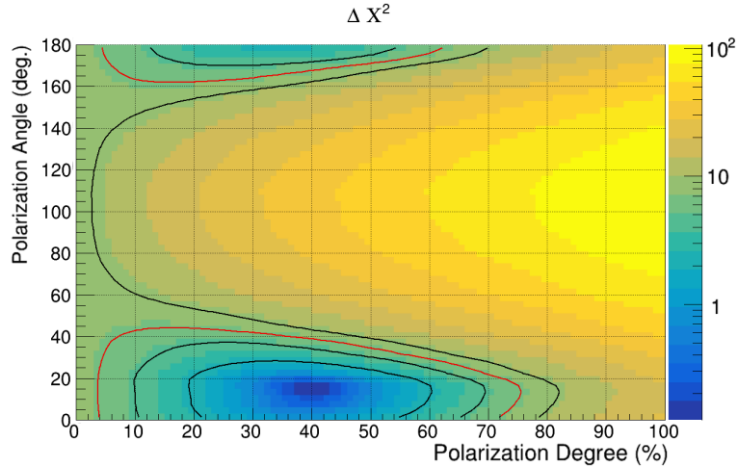




All



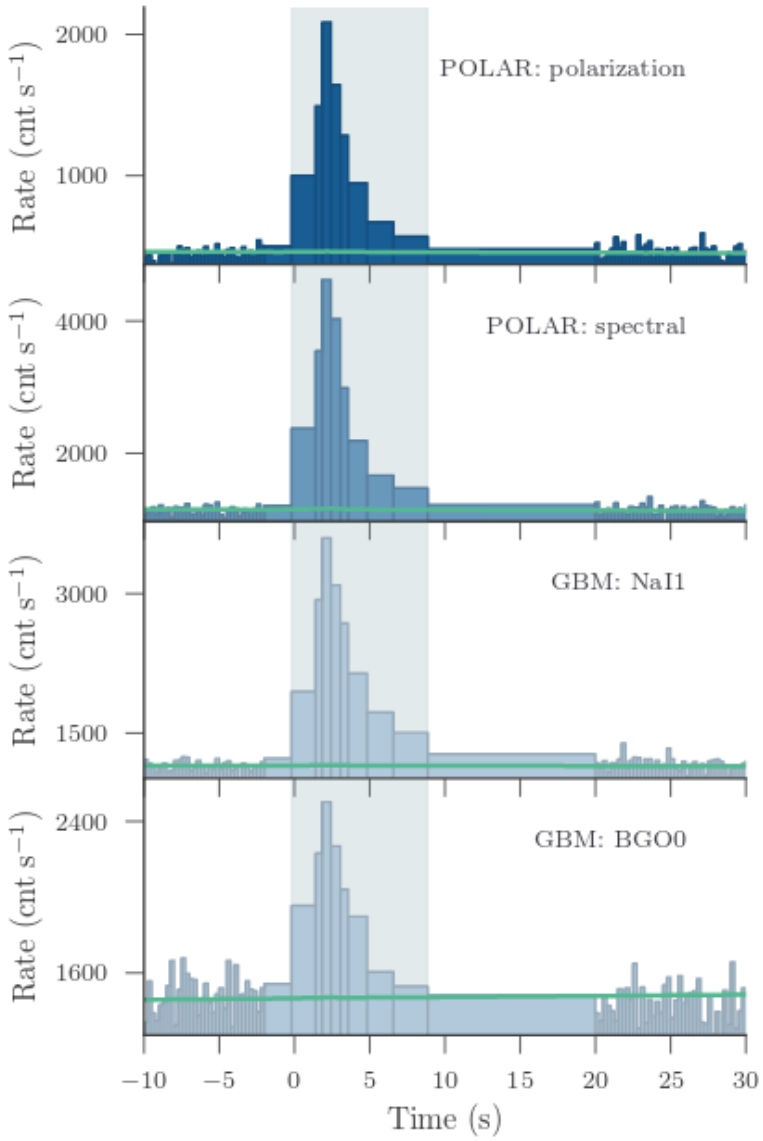
1st part

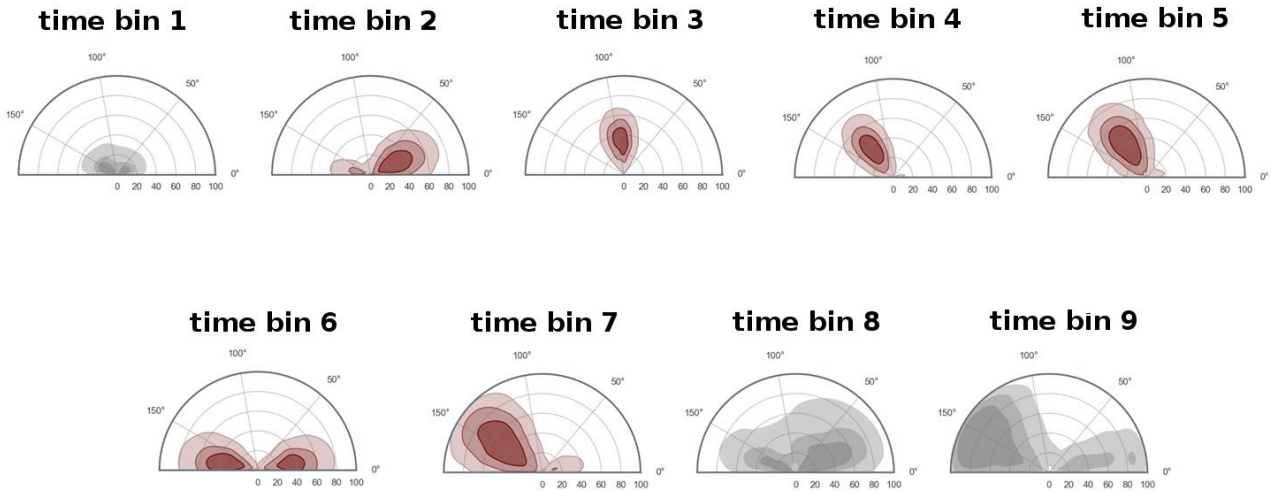


2nd part

S.N. Zhang et al., 2019, Nature Astron., 3, 258

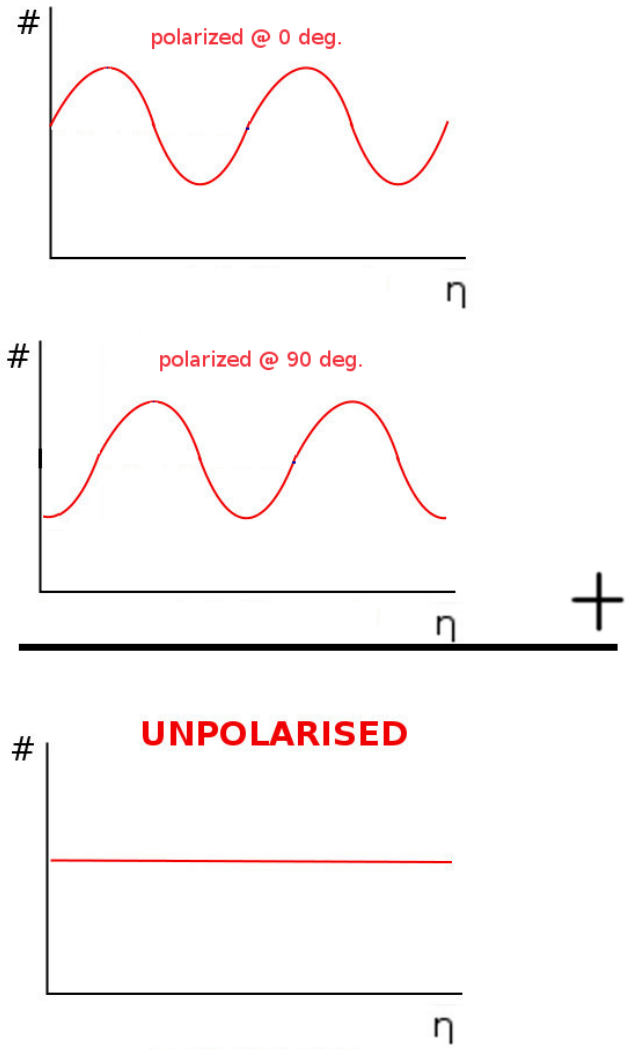
Time-resolved polarization of GRB 170114A





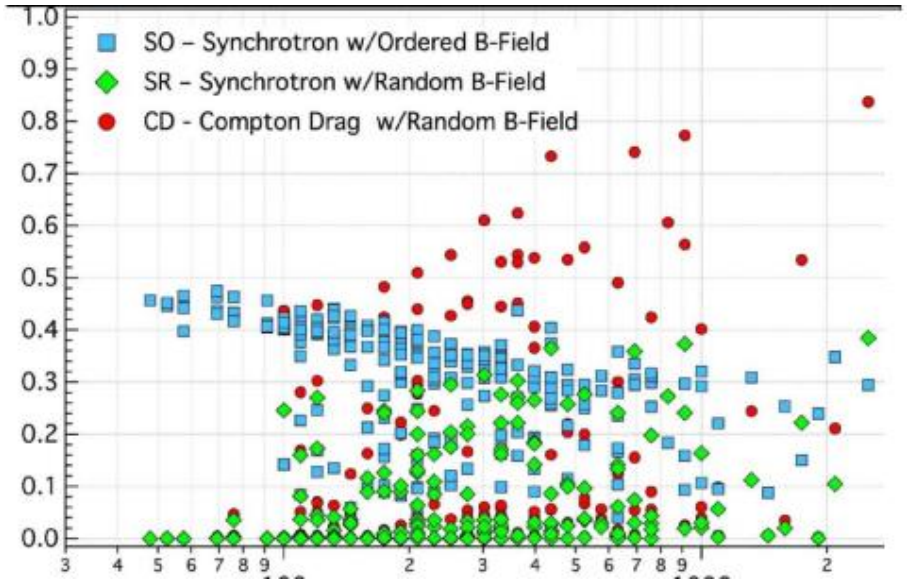
- Spectra data from both POLAR and GBM
- Polarization data from POLAR
- Results indicate the polarization angle changes during the GRB!

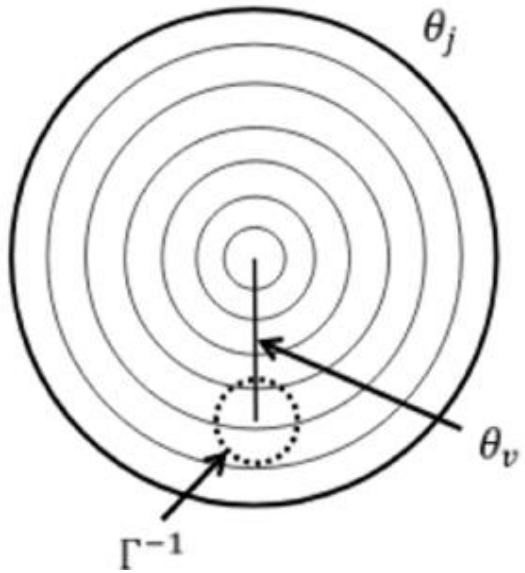
Polarization mixture effect?

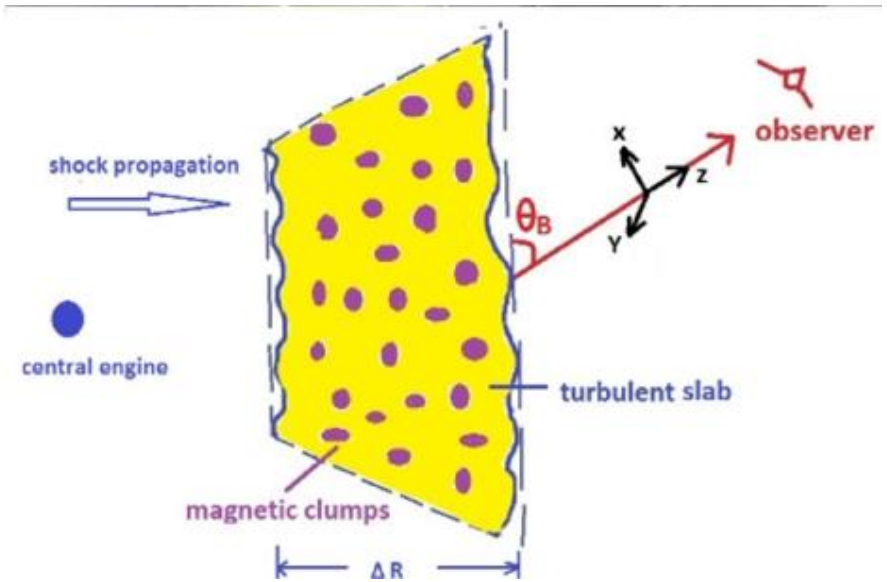


- Low polarization is caused by the evolution of polarization angle in short timescale??
- Time-resolved polarization analysis need to improve in the future due to the limited statistics

How to interpret?

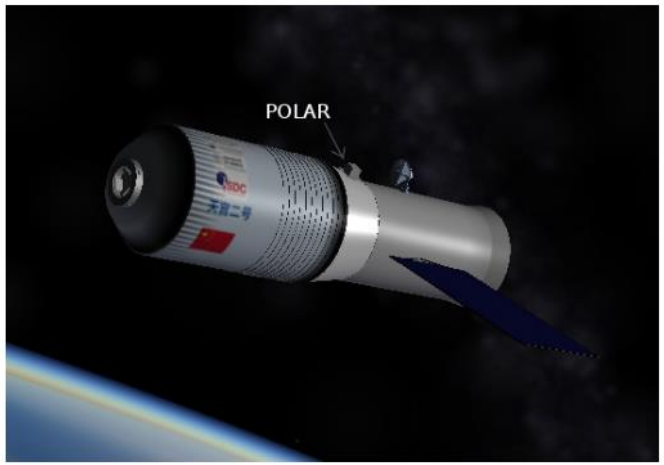


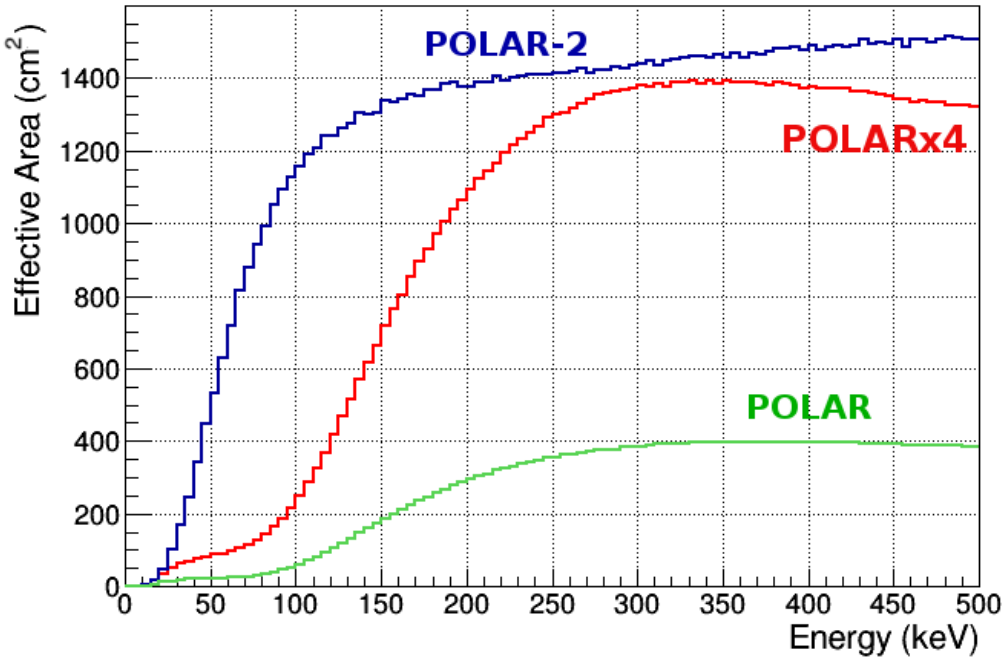




Not very clear yet, more theory work is needed

POLAR-2





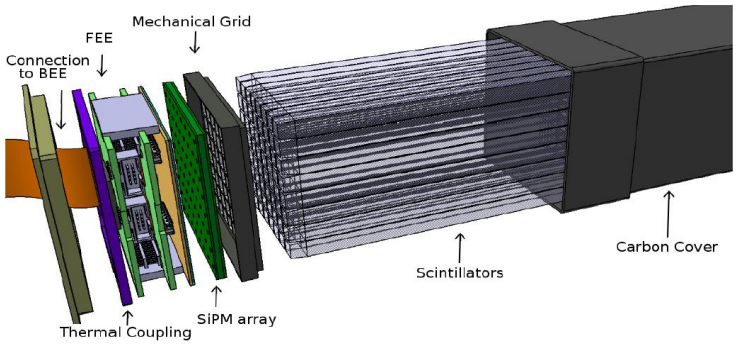
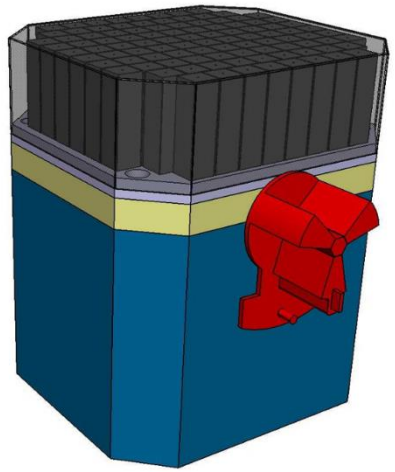


Figure 5. Schematic exploded view of a single POLAR-2 module



- Increase of modules by factor 4, technological improvement factor 2.5
- Can do polarization studies of GRBs with fluence down to 1E-7 erg/cm2 (like GRB170817A)

Summary

- **Gamma-ray polarization measurement is very important but challenging**
- **POLAR did detailed polarization measurement of 5 bright GRBs**
  - All 5 GRBs have rather low polarization degree, disfavor high polarization model
  - Polarization angle evolve in the single-pulse GRB
  - More GRB polarization analysis is ongoing
- **POLAR-2 designed to be the most sensitive GRB detector in orbit**
  - China's Space Station
  - Approved in June 2019, and launch planned in 2024

Thank you for your attention!