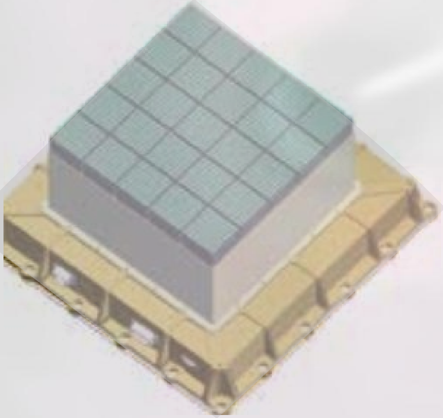
Polarimetry of GRB prompt emission with POLAR and POLAR-2

Hancheng Li (李汉成) on behalf of
POLAR & POLAR-2 collaborations

14/12/2023, Texas in Shanghai



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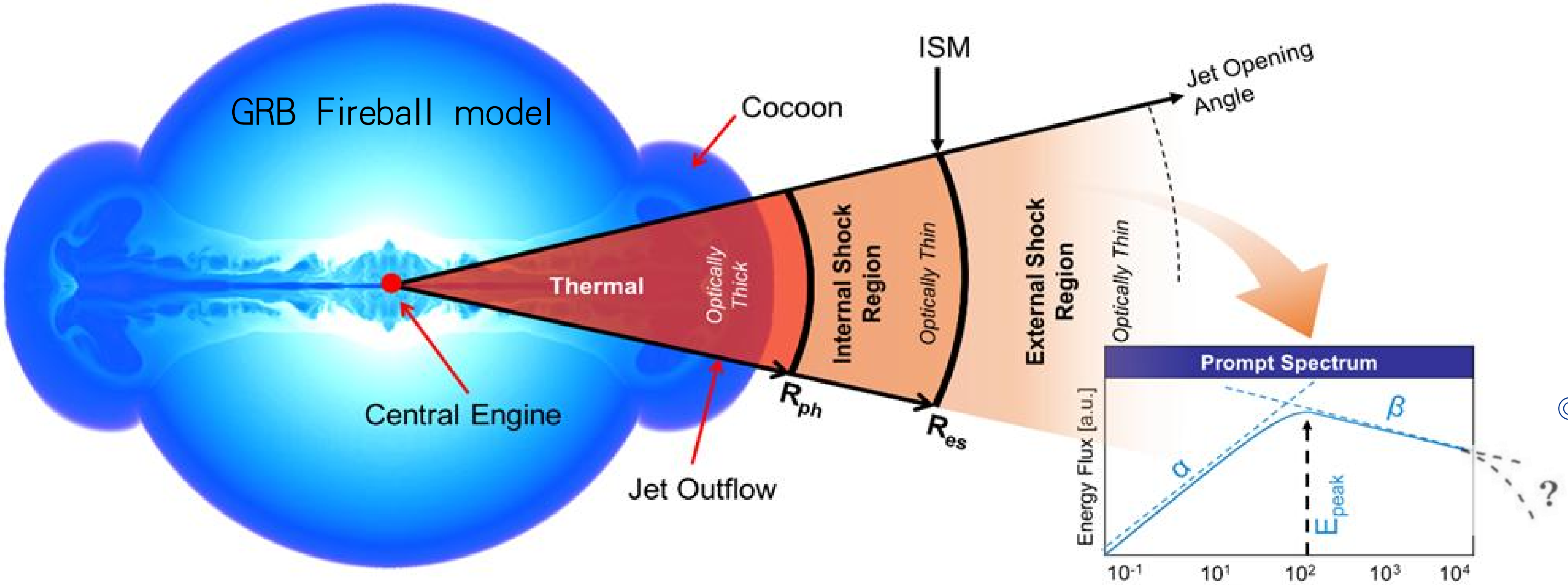
1. Why polarimetry for GRB



◎ Unknowns remain：

○ composition of source： $e^{\pm}$? e—p ?

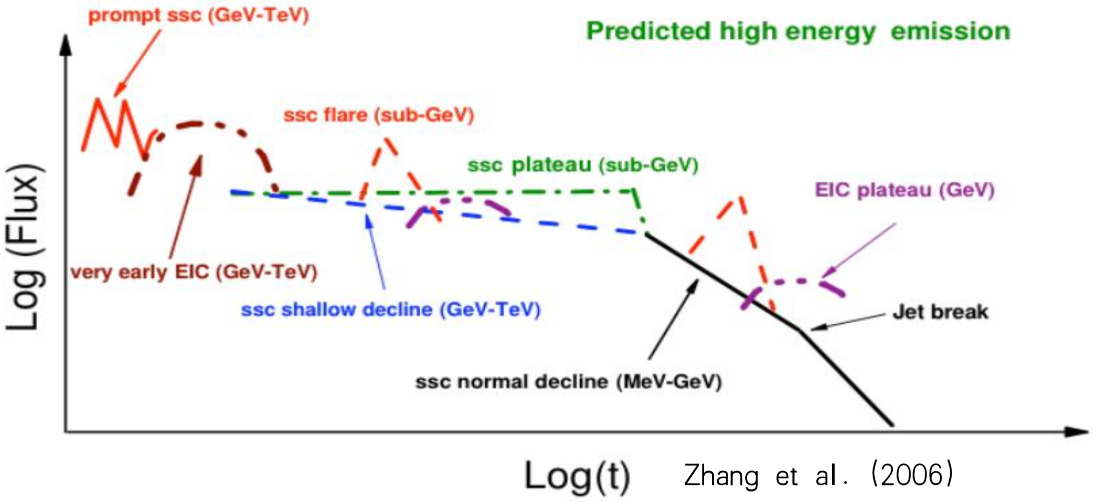
○ emission mechanism： dominant process v.s. time

○ geometry of source：

jet structure ? magnetic field ?

○ ……

◎ Polarization —> a new probe



Zhang et al. (2006)

◎ Prompt

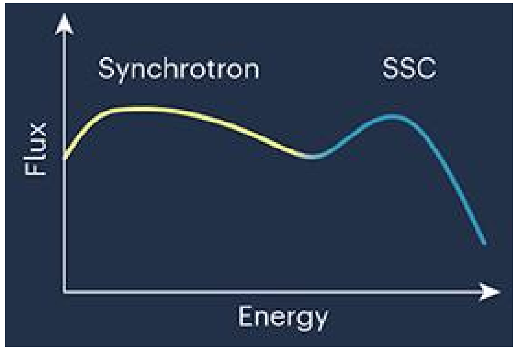
○ empirical Band function (Band et al. 1993)

$$F(E) = A\begin{cases}\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} e^{\left[-\frac{E}{E_0}\right]}, \\ E \leqslant (\alpha-\beta)E_0, \\ \left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta} e^{(\beta-\alpha)}\left(\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right)^{\alpha-\beta}, \\ E > (\alpha-\beta)E_0,\end{cases}$$

◎ Multi—wavelength SED：

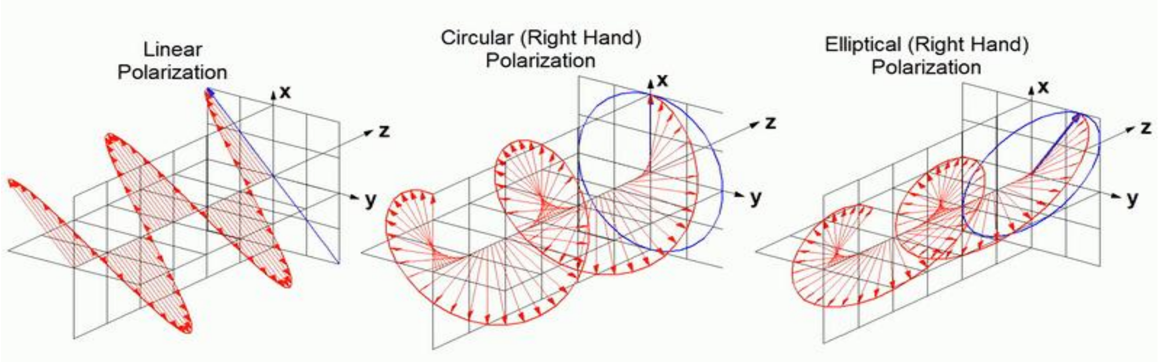
○ synchrotron (mainly electron)；

○ inverse—Compton： SSC (synchrotron self—Compton) and/or EIC (external inverse—Compton)



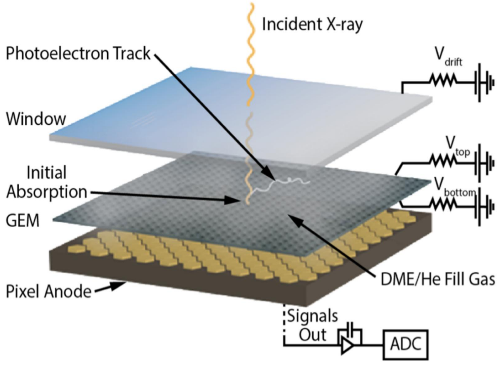
Nature 575, 448—449 (2019)

2. High-energy polarimetry: what and how

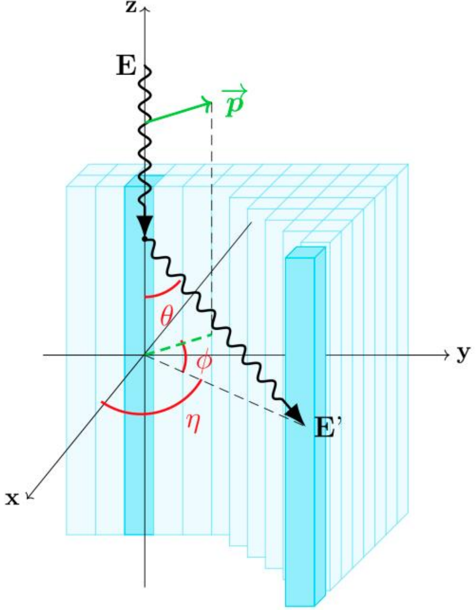


$$E_x = E_{0x}\cos(\omega t - kz + \varphi_x)$$
$$E_y = E_{0y}\cos(\omega t - kz + \varphi_y)$$

$$\left(\frac{E_x}{E_{0x}}\right)^2 + \left(\frac{E_y}{E_{0y}}\right)^2 - 2\left(\frac{E_x}{E_{0x}}\right)\left(\frac{E_y}{E_{0y}}\right)\cos\varphi = \sin^2\varphi$$

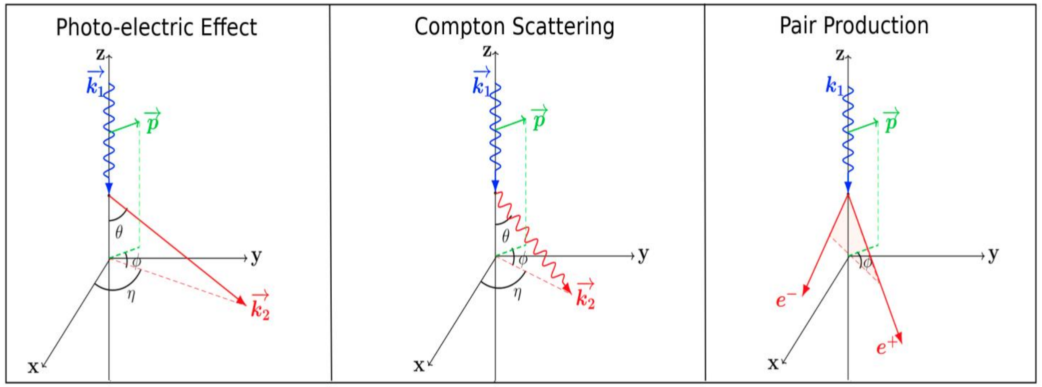


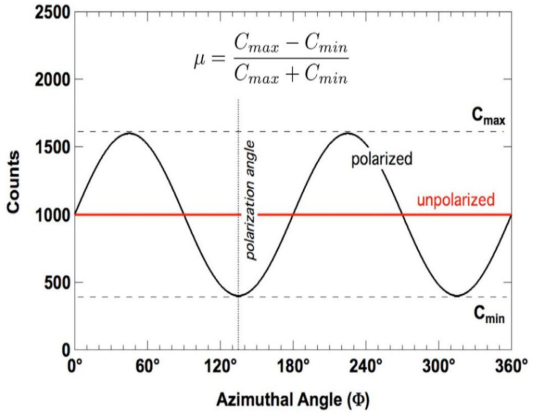
X-ray (2–10 keV)
Photo-electric in a gas chamber
@ IXPE collab.

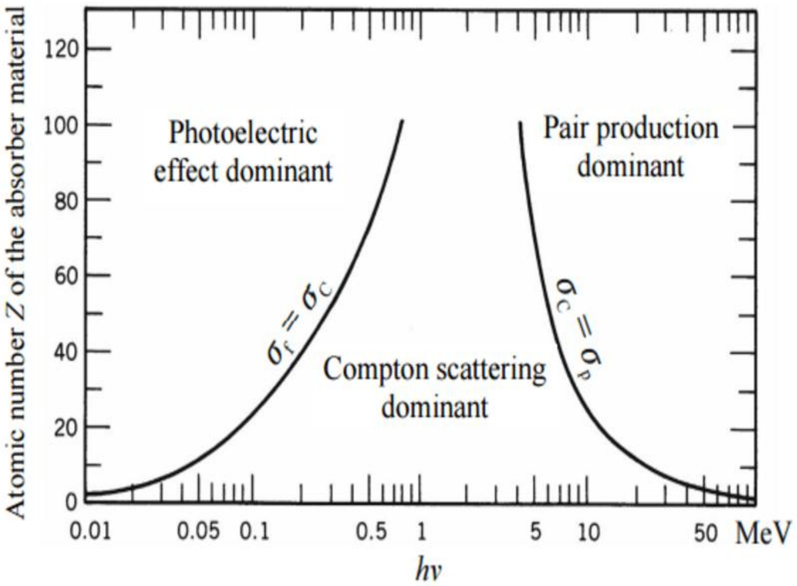


Gamma-ray (50–500 keV)
Compton scattering in plastics
@ POLAR collab

◎ Linear polarization (when $\varphi = n\pi,\ n \in \mathbb{Z}_0^+$)







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

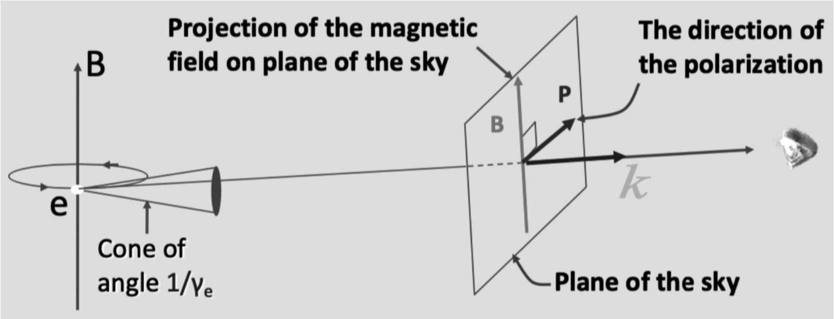
10.3390/galaxies9040082

Glenn F. Knoll 2015

2. High-energy polarimetry: link to physical process

◎ Synchrotron polarization

○ resulted ***e*** is ⊥ ***B*** projected on sky for a distant observer



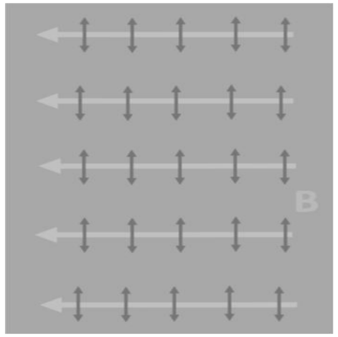
○ *Rybicki & Lightman 1979*:

—— a power-law spectrum of electr $N_e(\gamma) \propto \gamma^{-p}$

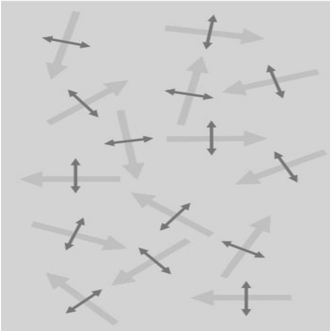
—— produce a power-law EM spectr $F_\nu \propto \nu^{-\alpha}$ $\alpha = (p-1)/2$

—— maximal polarization (ordered B) $\Pi_{\rm powerlaw} = \dfrac{p+1}{p+7/3} = \dfrac{\alpha+1}{\alpha+5/3}$

p : 1.5~5.0 –> Π: 65%~80%



Ordered B



Tangled B

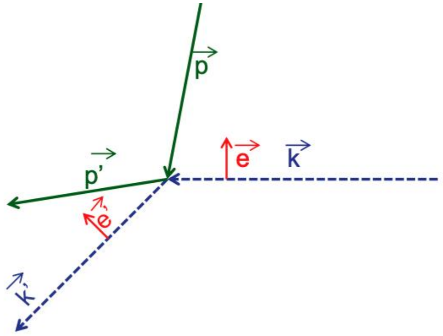
Proved by IXPE obs on Vela PWN , Xie et al., 2023

◎ Compton polarization

○ $\dfrac{d\sigma}{d\Omega} = \dfrac{r_0^2}{4}\left(\dfrac{\epsilon'}{\epsilon}\right)^2\left(\dfrac{\epsilon}{\epsilon'} + \dfrac{\epsilon'}{\epsilon} - 2 + 4\left[\vec{e}\cdot\vec{e}'\right]^2\right)$

○ in a Thomson regime: $\epsilon' \approx \epsilon \Rightarrow \dfrac{d\sigma}{d\Omega} = 0 \left(at\ \vec{e}\cdot\vec{e'} = 0\right)$

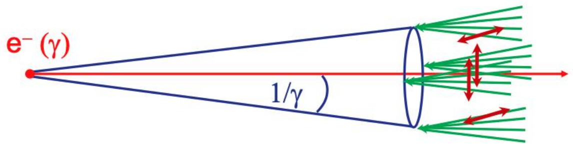
○ resulted **e'** is preferred in the plane that ⊥ original **e**



○ an anisotropic radiation by non-relativistic electrons:

—— will introduce a polarization that is ⊥ the bulk original **e**

○ axisymmetric ... c electrons:



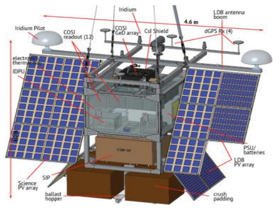
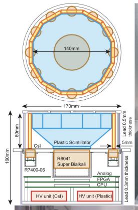
—— unpolarized external seds (EC) –> unpolarized output

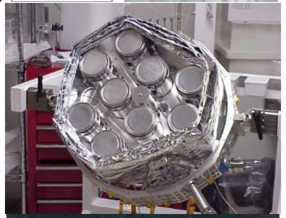
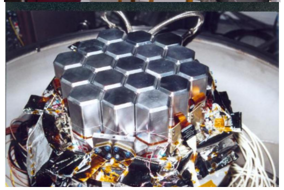
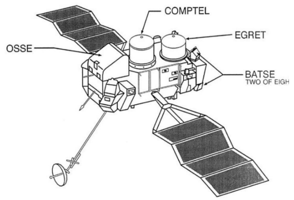
—— polarized seds (SSC) –> reduced polarization

~1/2 of the target (synchrotron) photon polarization

2. High–energy polarimetry: early measurements on GRBs

- Early measurements performed by non–dedicated instruments;
- A wide range of PD distribution, covering 0–100 % ;
- All suffer from large systematics and/or poor statistics. (M. McConnell et al., 2017)

GRB	Instrument/SAT	PD(%)	E-range(keV)	Remarks
160530A	COSI	< 46%	200-5000	Low statistics
110721A	GAP/IKAROS	84^{+16}_{-28}	70-300	Constant Pol. Angle
110301A	GAP/IKAROS	70 ± 22	70-300	Constant Pol. Angle
100826A	GAP/IKAROS	27 ± 11	70-300	Multi-peaks, PA changes by ~ 90°
021206	RHESSI	80 ± 20; 41^{+57}_{-44}	150-2000	Large systematic uncertainty
140206A	IBIS/INTEGRAL	>28	200-400	
061122	IBIS/INTEGRAL	>33;	250-800;	
041219A	IBIS/INTEGRAL IBIS/INTEGRAL SPI/INTEGRAL	<4; 43 ± 25; 98 ± 33	200-800; 200-800; 100-350	Large systematic uncertainty
960924	BATSE/CGRO	>50	20-1000	
930131	BATSE/CGRO	>35	20-1000	

3. GRB Polarimetry with POLAR: the mission

$$\frac{d\sigma_C}{d\Omega} = \frac{r_e^2}{2}\,\varepsilon^2 \left\{\varepsilon + \varepsilon^{-1} - \sin^2\theta + \sin^2\theta\cos\left[2\left(\eta + \frac{\pi}{2}\right)\right]\right\}$$

◎ Collaboration

○ China/IHEP, Swiss/UniGE&PSI, Poland/NCBJ

◎ Development period (~10 years)

○ 2005—2010, concept and prototype

○ 2011—2013, qualification model

○ 2013—2016, flight mode

◎ Detector characteristics

○ Plastic scintillator array (8*8 x 5*5)

○ MA—PMT; E band 50—500 keV

○ Eff. area ~ 300 cm^2, FoV ~ 2π sr

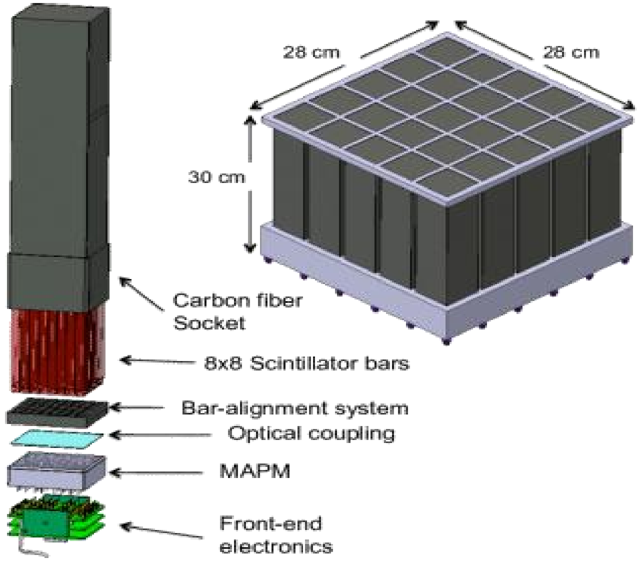
◎ Launch and operation

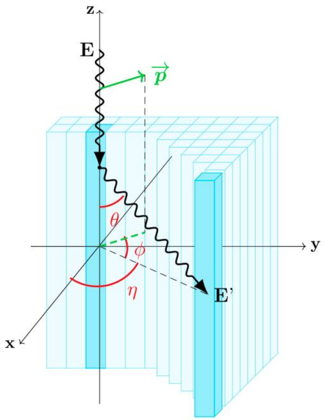
○ Tiangong—2 space lab

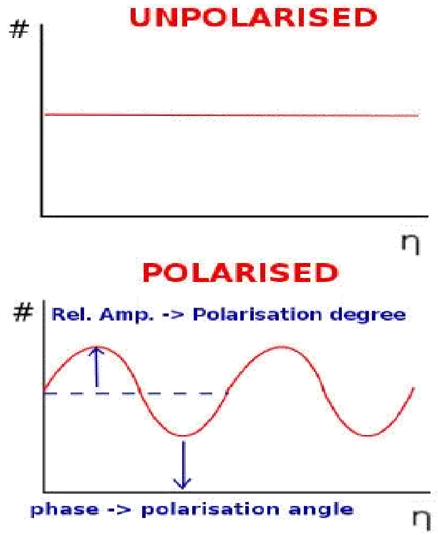
○ Launched on 15/09/2016

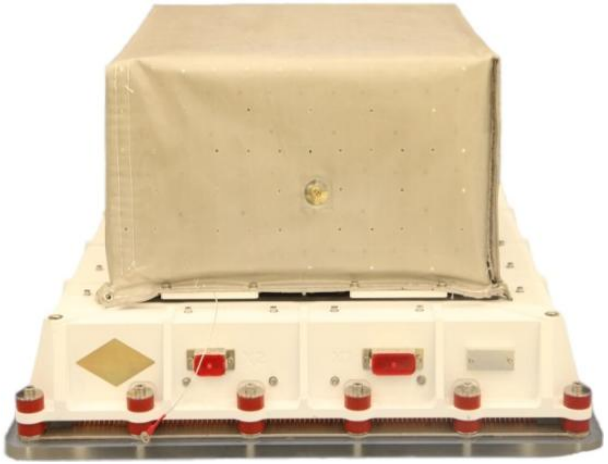
○ Scanning sky with the lab's orbit

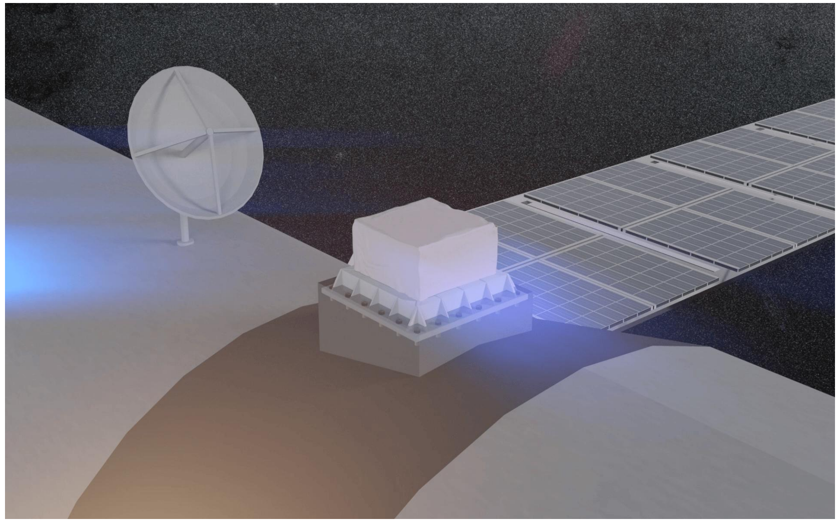
○ 6 months of observation (HV failure)











3. GRB Polarimetry with POLAR: on-ground/in-orbit calibrations

Calibration means validation!

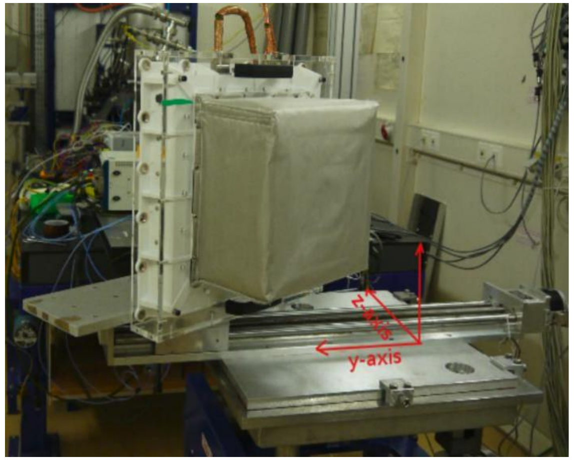
- To verify the methodology
- To evaluate systematic effect

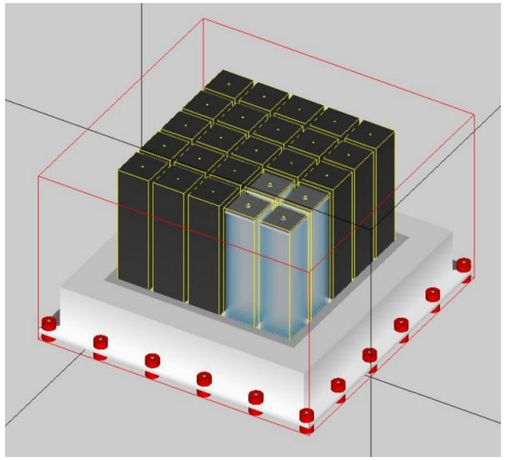
On ground: ESRF beam test

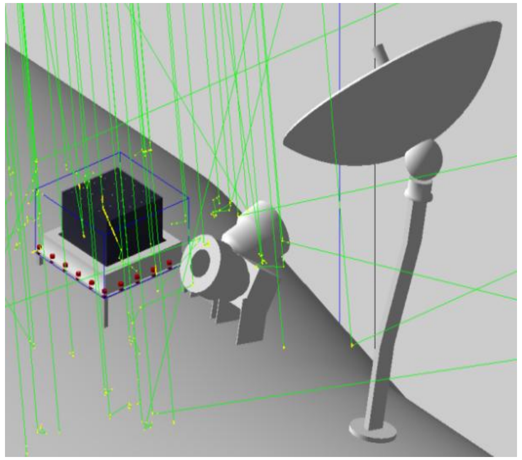
- Polarized (PD 100%, PA H/V)
- Energy (60,80,110,140 keV)
- Incident angel (0°, 30°, 60°)
- Geant-4 simulation verification (Kole M., et al, 2017)

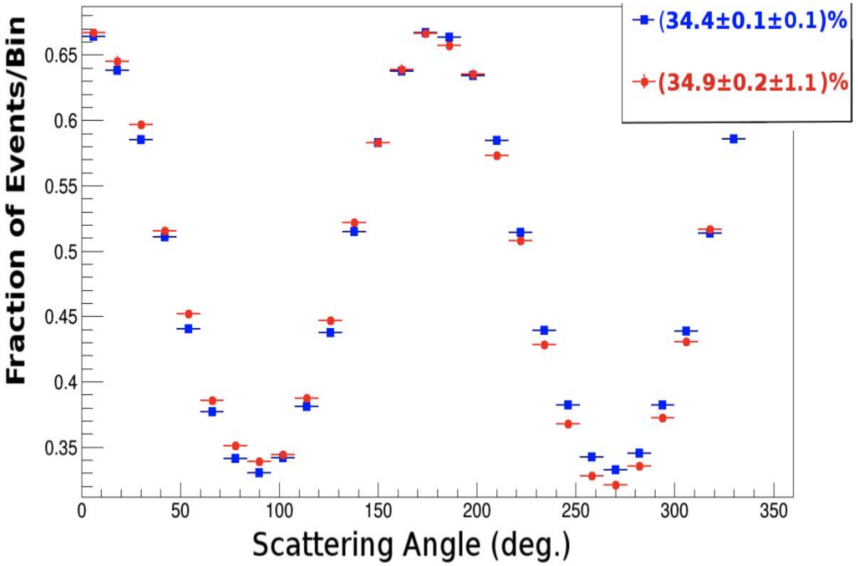
In orbit:

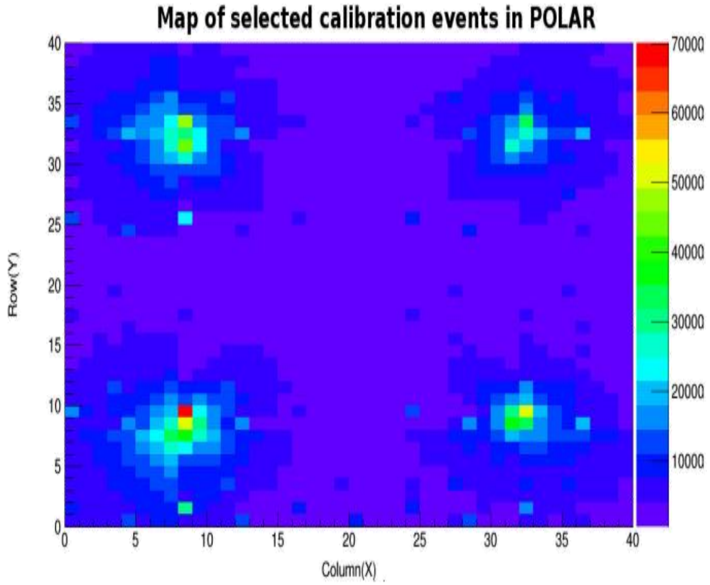
- ^{22}Na sources: (100 Bq) x 4 Multi-parameter calibration
- Geant-4 simulation verification (Li, Z. H., et al, 2018)
- Crab pulsar









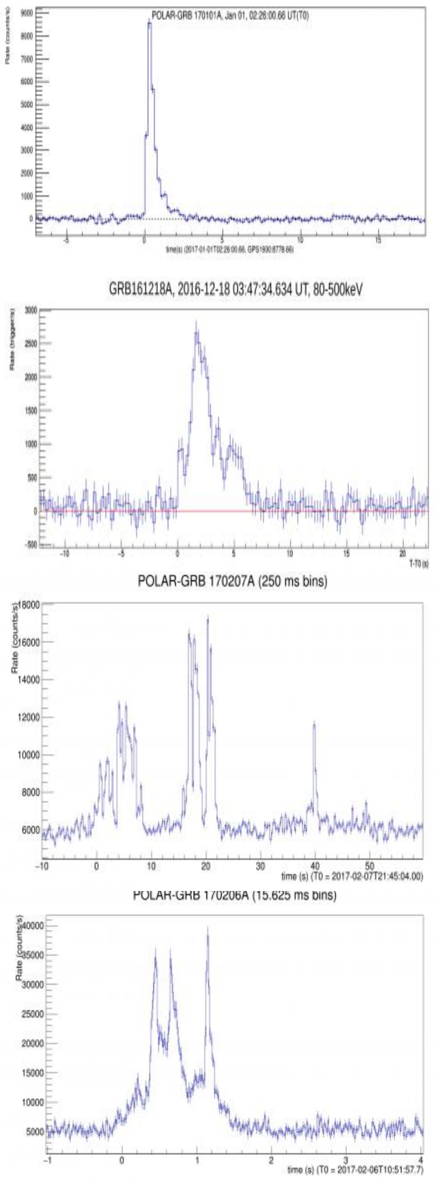


Kole et al., 2017, Li et al., 2018

3. GRB Polarimetry with POLAR: GRB detections

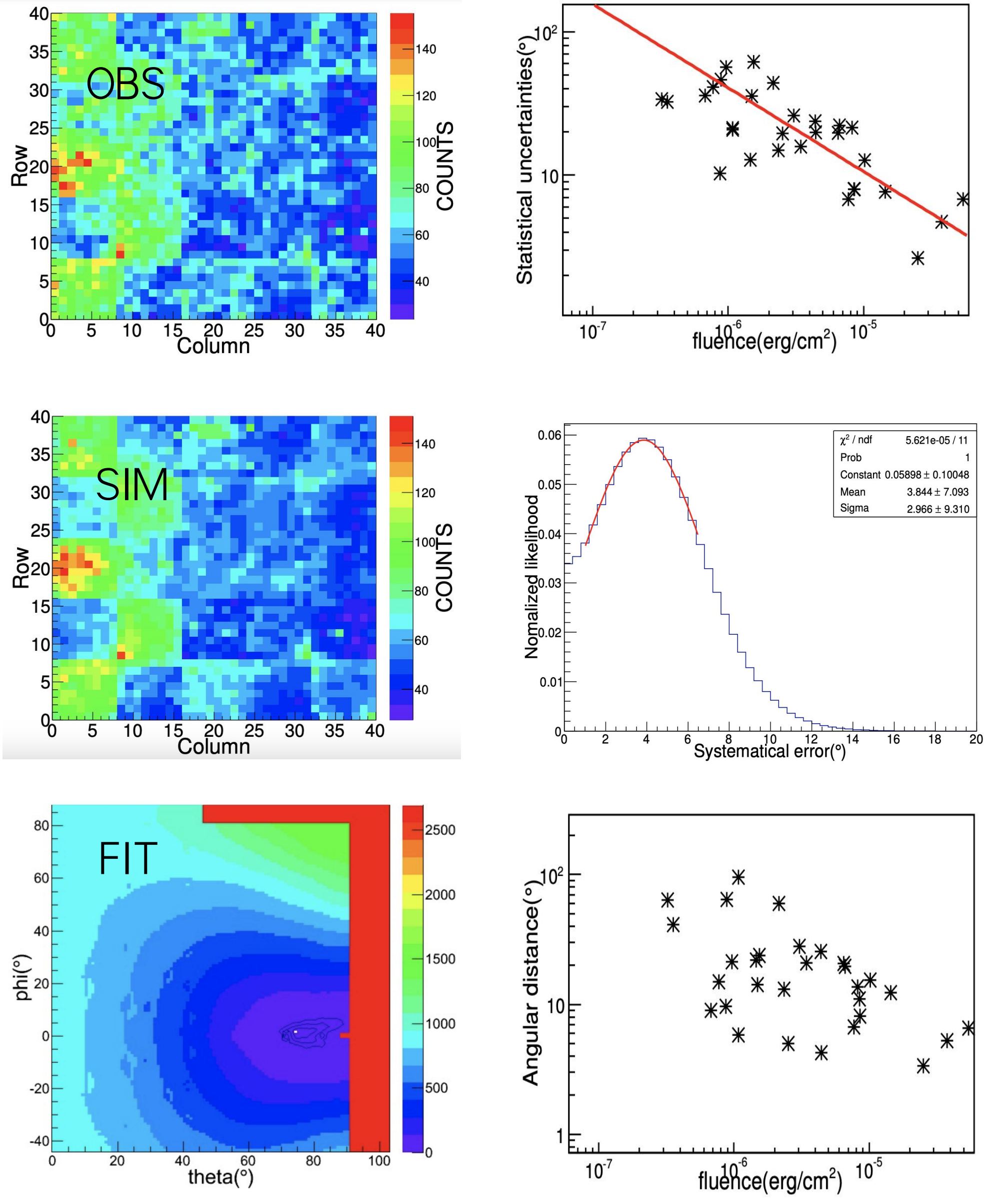
55 joint detections *Xiong et al., 2017*

Number	GRB Name	Trigger time (UTC)	Joint observation
1	GRB 160924A	2016-09-24T06:04:09.040	Fermi/GBM, SPI-ACS
2	GRB 160928A	2016-09-28T19:48:05.000	Fermi/GBM, SPI-ACS, KW
3	GRB 161009651	2016-10-09T15:38:07.190	Fermi/GBM
4	GRB 161011217	2016-10-11T05:13:44.420	KW
5	GRB 161012989	2016-10-12T23:45:11.380	KW
6	GRB 161013948	2016-10-13T22:44:40.100	Fermi/GBM
7	GRB 161120401	2016-11-20T09:38:33.520	SPI-ACS
8	GRB 161129A	2016-11-29T07:11:40.000	Swift/BAT, Fermi/GBM, AstroSAT
9	GRB 161203A	2016-12-03T18:41:07.750	KW,SPI-ACS, CALET/CGBM, AstroSAT
10	GRB 161205A	2016-12-05T13:27:18.000	Fermi/GBM
11	GRB 161207A	2016-12-07T20:42:55.000	Fermi/GBM, CALET/CGBM
12	GRB 161207B	2016-12-07T05:22:44.000	Fermi/GBM
13	GRB 161210A	2016-12-10T12:33:54.000	Fermi/GBM
14	GRB 161212A	2016-12-12T15:38:59.000	Fermi/GBM
15	GRB 161213A	2016-12-13T07:05:02.000	Fermi/GBM, SPI-ACS
16	GRB 161217B	2016-12-17T03:03:44.000	Fermi/GBM
17	GRB 161217C	2016-12-17T03:53:15.000	KW
18	GRB 161218A	2016-12-18T03:47:34.634	Swift/BAT
19	GRB 161218B	2016-12-18T08:32:41.341	Fermi/GBM
20	GRB 161219B	2016-12-19T18:48:39.000	Swift/BAT
21	GRB 161228A	2016-12-28T09:43:24.000	Fermi/GBM
22	GRB 161228B	2016-12-28T13:15:40.000	Fermi/GBM, SPI-ACS
23	GRB 161228C	2016-12-28T00:46:20.000	Fermi/GBM
24	GRB 161229A	2016-12-29T21:03:49.000	Fermi/GBM
25	GRB 161230A	2016-12-30T12:16:07.000	Fermi/GBM
26	GRB 170101A	2017-01-01T02:26:00.660	Swift/BAT
27	GRB 170101B	2017-01-01T02:47:18.270	Fermi/GBM
28	GRB 170102A	2017-01-02T02:51:18.000	KW
29	GRB 170105A	2017-01-05T06:14:07.000	SPI-ACS, KW
30	GRB 170109A	2017-01-09T03:17:35.000	Fermi/GBM
31	GRB 170112B	2017-01-12T23:16:09.000	Fermi/GBM
32	GRB 170114A	2017-01-14T22:01:10.000	Fermi/GBM
33	GRB 170114B	2017-01-14T19:59:12.000	Fermi/GBM, KW
34	GRB 170120A	2017-01-20T11:18:30.000	Fermi/GBM
35	GRB 170121A	2017-01-21T01:36:55.200	Fermi/GBM
36	GRB 170124A	2017-01-24T20:58:06.000	Fermi/GBM, KW, CALET/CGBM
37	GRB 170127C	2017-01-27T01:35:49.000	Fermi/GBM, Fermi/LAT, AGILE, AstroSAT
38	GRB 170130A	2017-01-30T07:14:45.000	Fermi/GBM
39	GRB 170131A	2017-01-31T23:14:59.000	Fermi/GBM, Swift, KW
40	GRB 170202B	2017-02-02T07:19:54.000	KW
41	GRB 170206A	2017-02-06T10:51:57.700	Fermi/GBM, Fermi/LAT, SPI-ACS
42	GRB 170206C	2017-02-06T11:40:10.000	SPI-ACS
43	GRB 170207A	2017-02-07T21:45:04.000	Fermi/GBM, IPN, KW
44	GRB 170208C	2017-02-08T13:16:33.000	Fermi/GBM, SPI-ACS
45	GRB 170210A	2017-02-10T02:47:37.000	Fermi/GBM, IPN, KW
46	GRB 170219A	2017-02-19T00:03:07.000	Fermi/GBM, CALET/CGBM, SPI-ACS, KW, IPN
47	GRB 170220A	2017-02-20T18:48:01.000	KW
48	GRB 170228B	2017-02-28T18:32:56.000	Fermi/GBM
49	GRB 170305A	2017-03-05T06:09:06.800	Fermi/GBM, KW, SPI-ACS, Swift/BAT
50	GRB 170306B	2017-03-06T14:07:20.000	Fermi/GBM, Fermi/LAT, SPI-ACS
51	GRB 170309A	2017-03-09T12:26:42.000	CALET/CGBM
52	GRB 170315A	2017-03-15T13:57:53.000	Fermi/GBM
53	GRB 170317A	2017-03-17T09:45:56.000	Swift/BAT
54	GRB 170320A	2017-03-20T03:42:39.000	SPI-ACS, KW
55	GRB 170325B	2017-03-25T21:50:01.000	KW



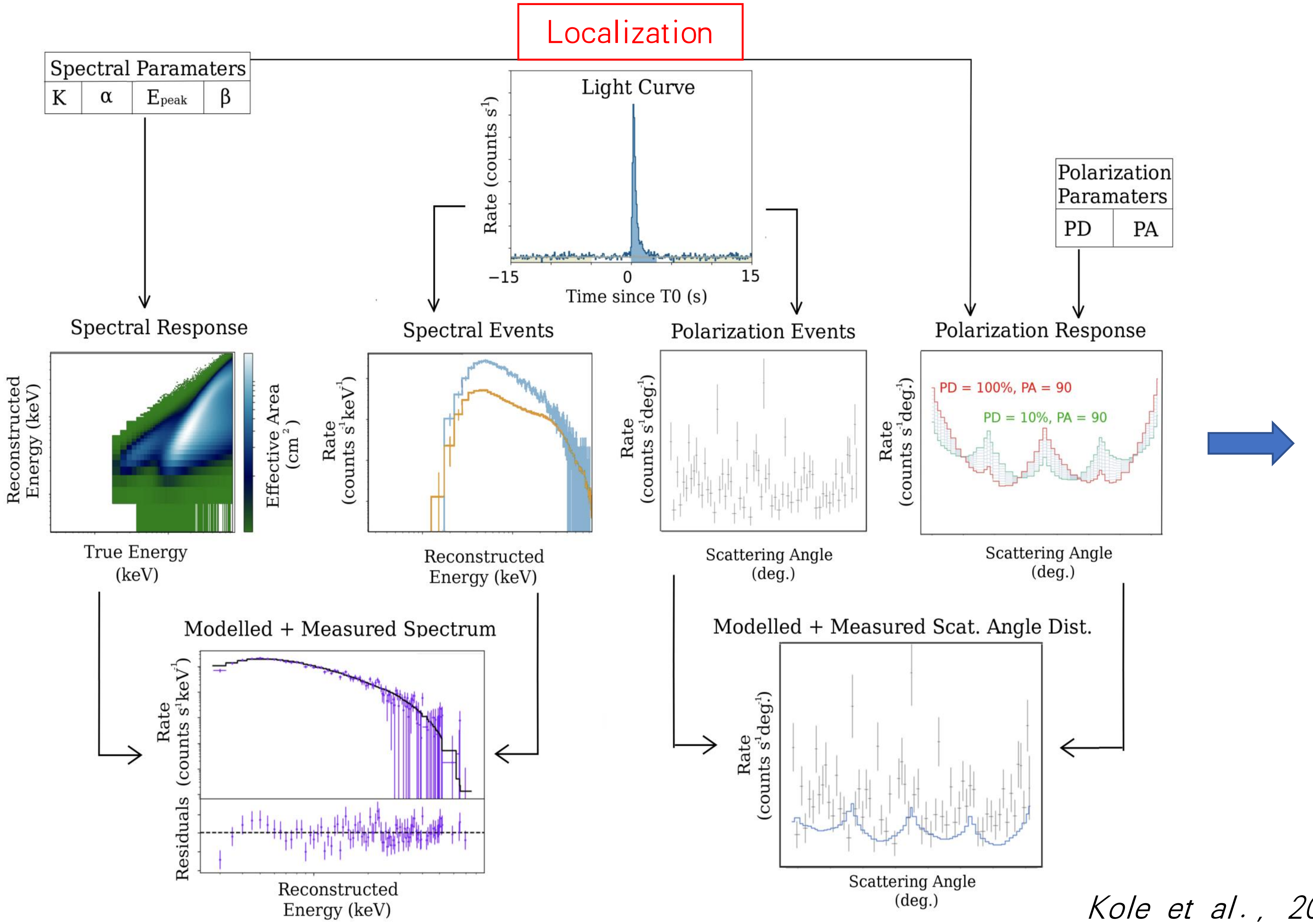
astro.unige.ch/polar/grb-light-curves

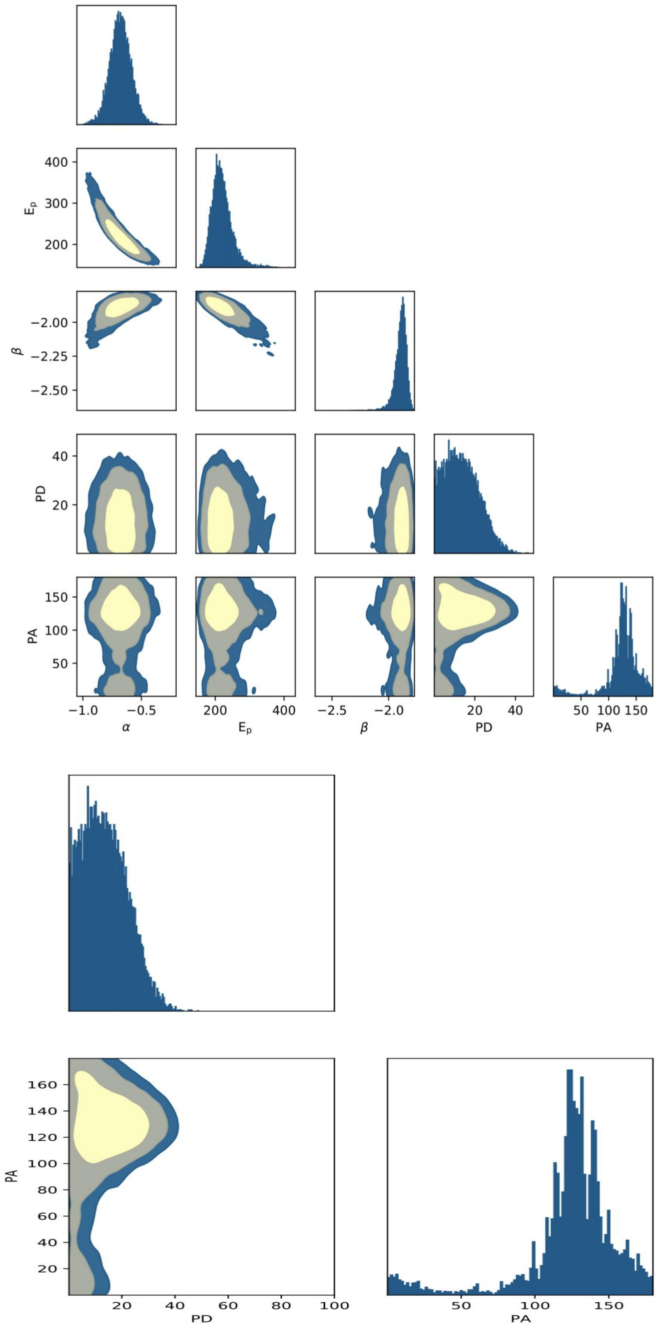
Wang et al., 2021



See also Merlin's HAGRID

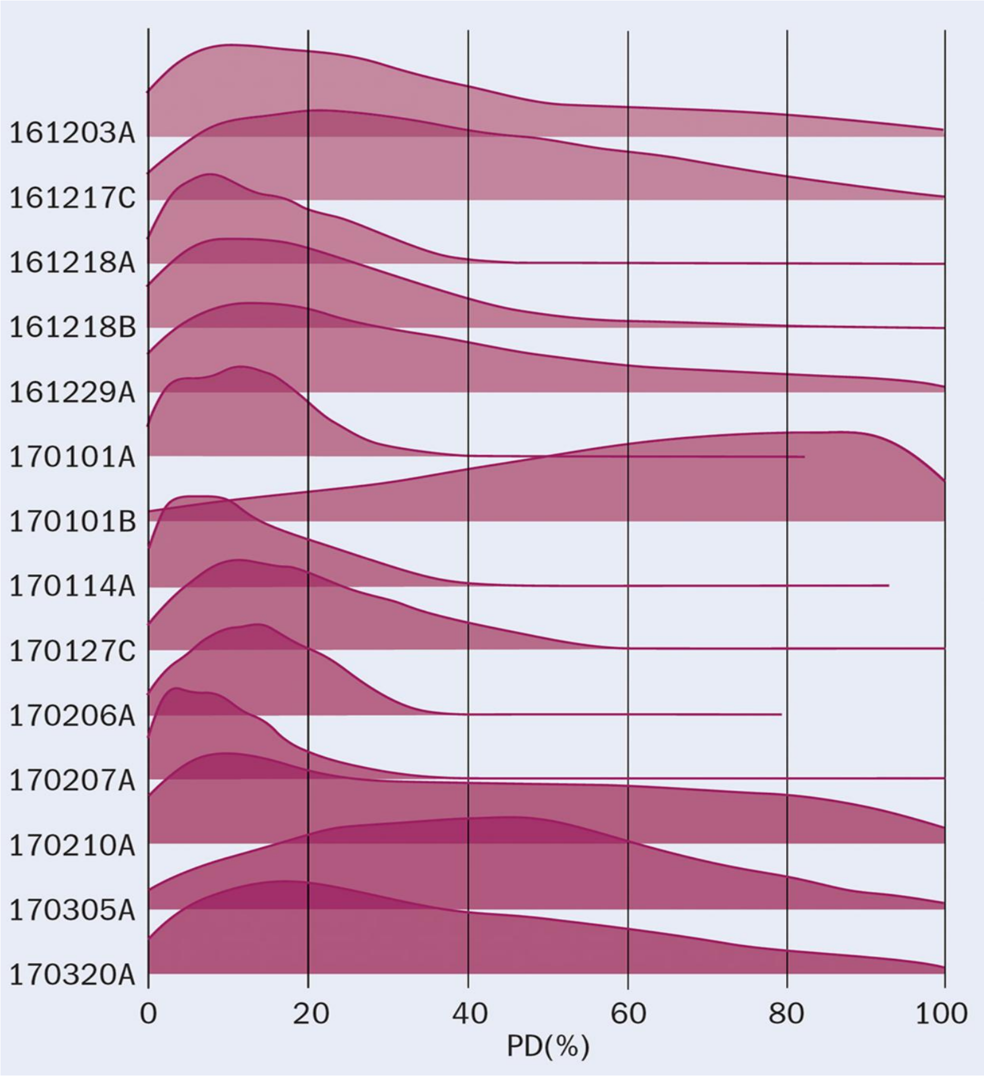
3. GRB Polarimetry with POLAR：analysis approach



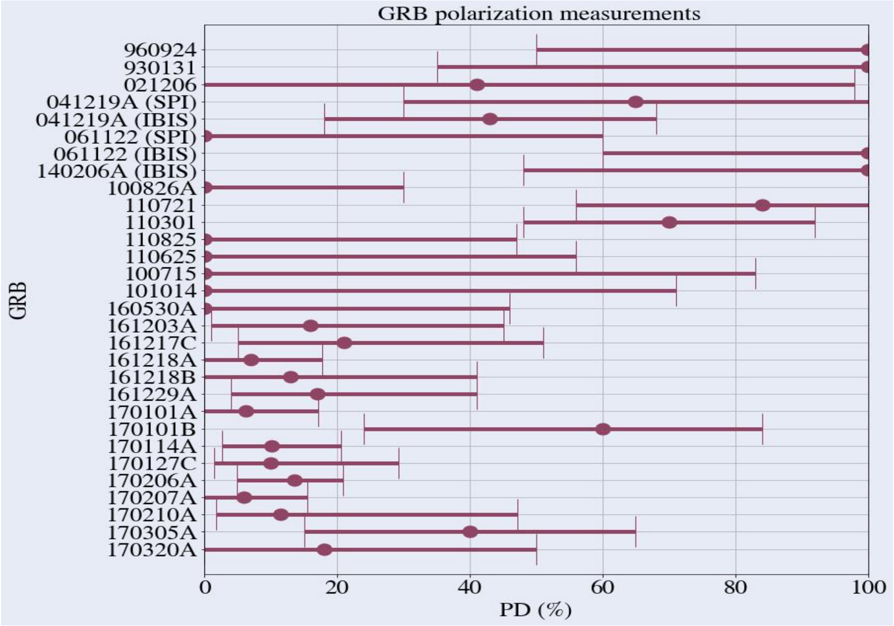


Kole et al., 2020

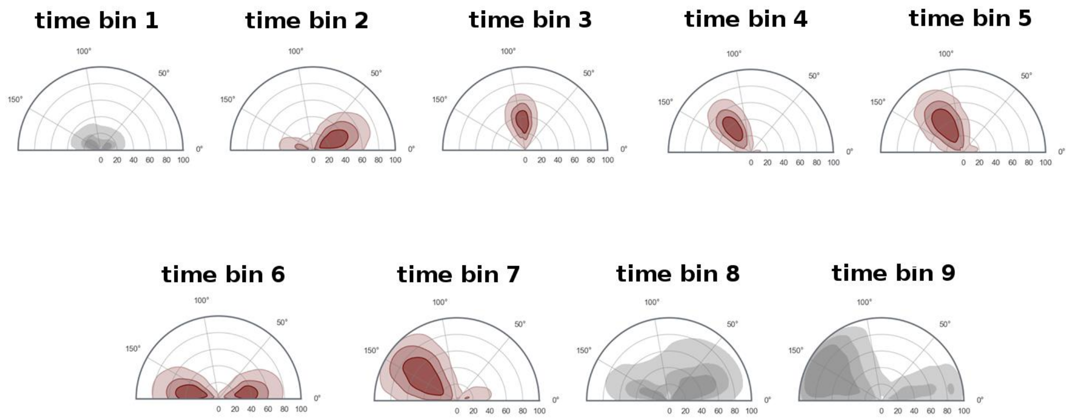
3. GRB Polarimetry with POLAR: time integrated/resolved results



Kole et al., 2020, 14 GRBs, best fitted mostly at ~10%



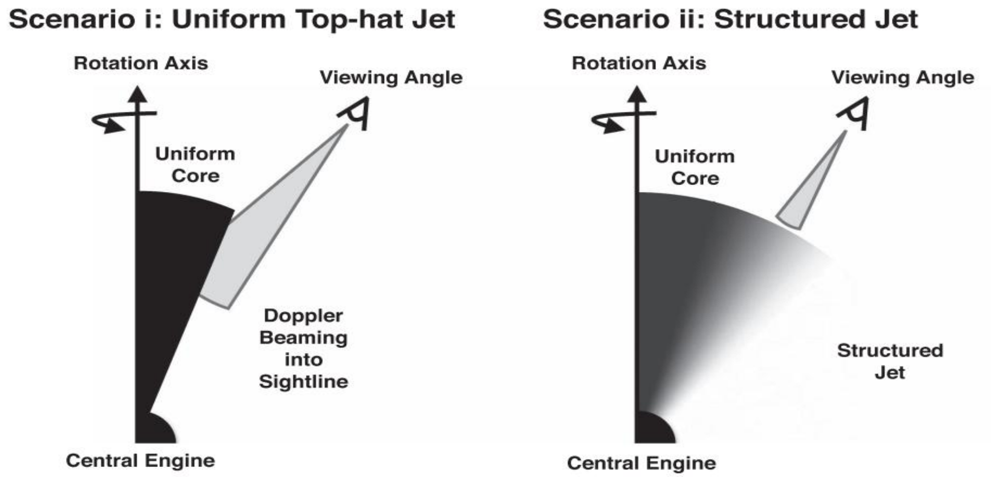
Measured PD distributions



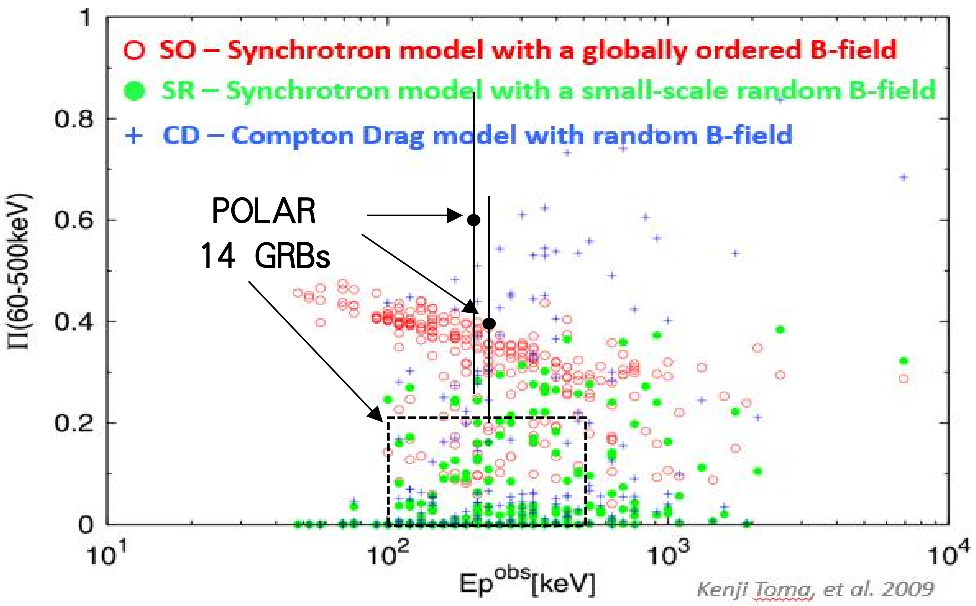
Zhang et al., 2019, Burgess et al. 2019

GRB 170114A -> a hit of PA evolution

3. GRB Polarimetry with POLAR: comparing with models



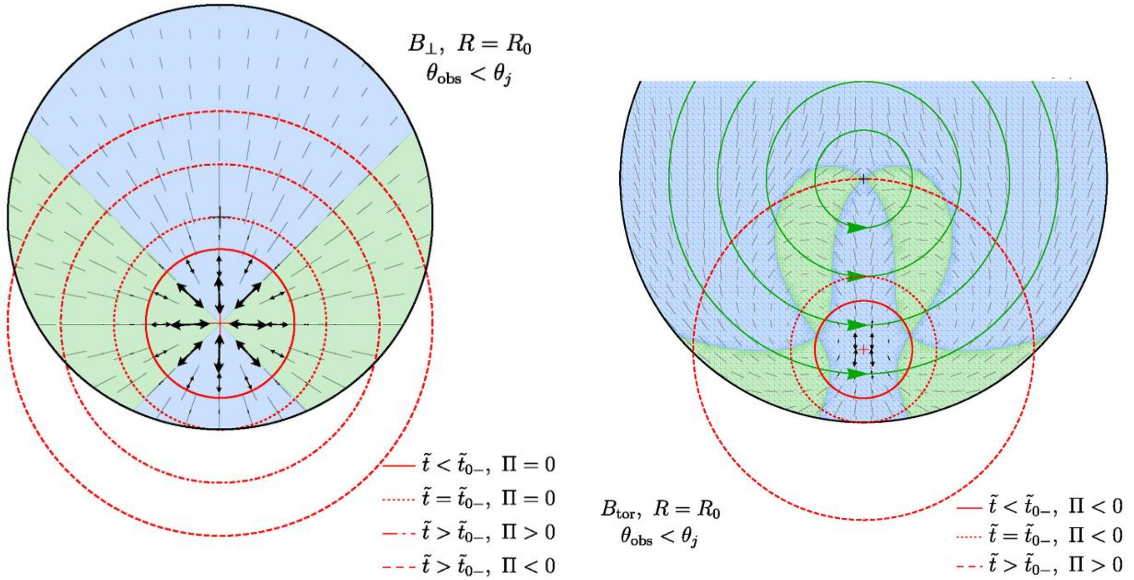
10.3847/2041-8213/aa920c



Color scale: 0% – 100%

		Synchrotron $B_\perp$	Synchrotron $B_\parallel$	Synchrotron B_{tor}	Photospheric	Compton Drag
Structured Jet	$\theta_{obs} \gtrsim \theta_c$	7% – 18%	14% – 35%	38% – 52%	5% – 15%	10% – 25%
Structured Jet / Top-Hat Jet	$\theta_{obs} \ll \theta_c$ / $\theta_{obs} \ll \theta_j$	0%	0%	0% – 50%	0%	0%
Top-Hat Jet	$\theta_{obs} \approx \theta_j$	4% – 28%	10% – 56%	10% – 60%	4% – 20%	5% – 50%

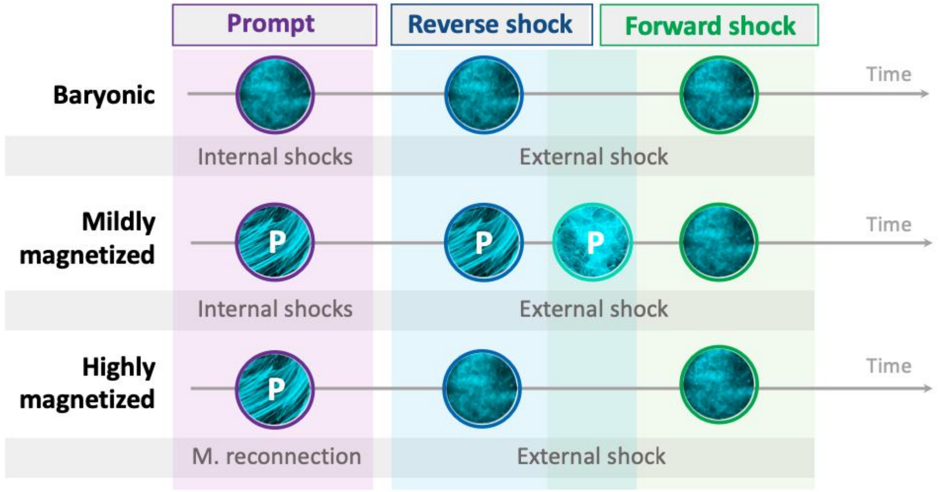
10.3390/galaxies9040082

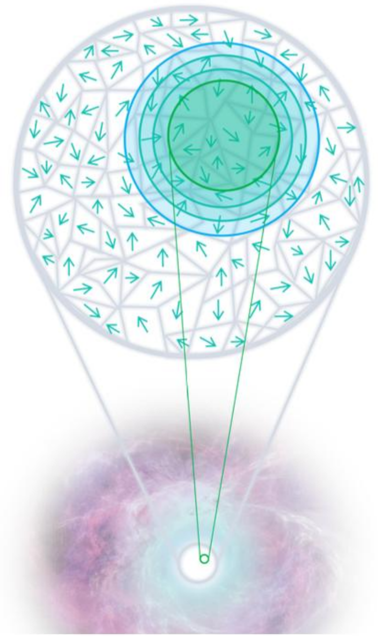


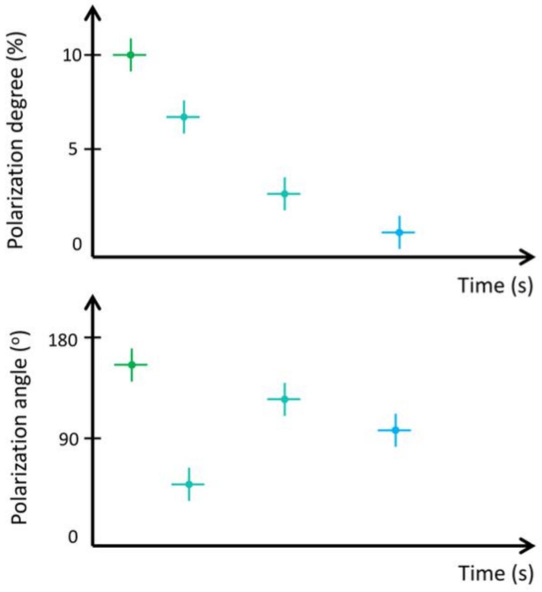
Top-Hat Jet, Gill, R. & Granot, J., 2021

Only allow 90° changes

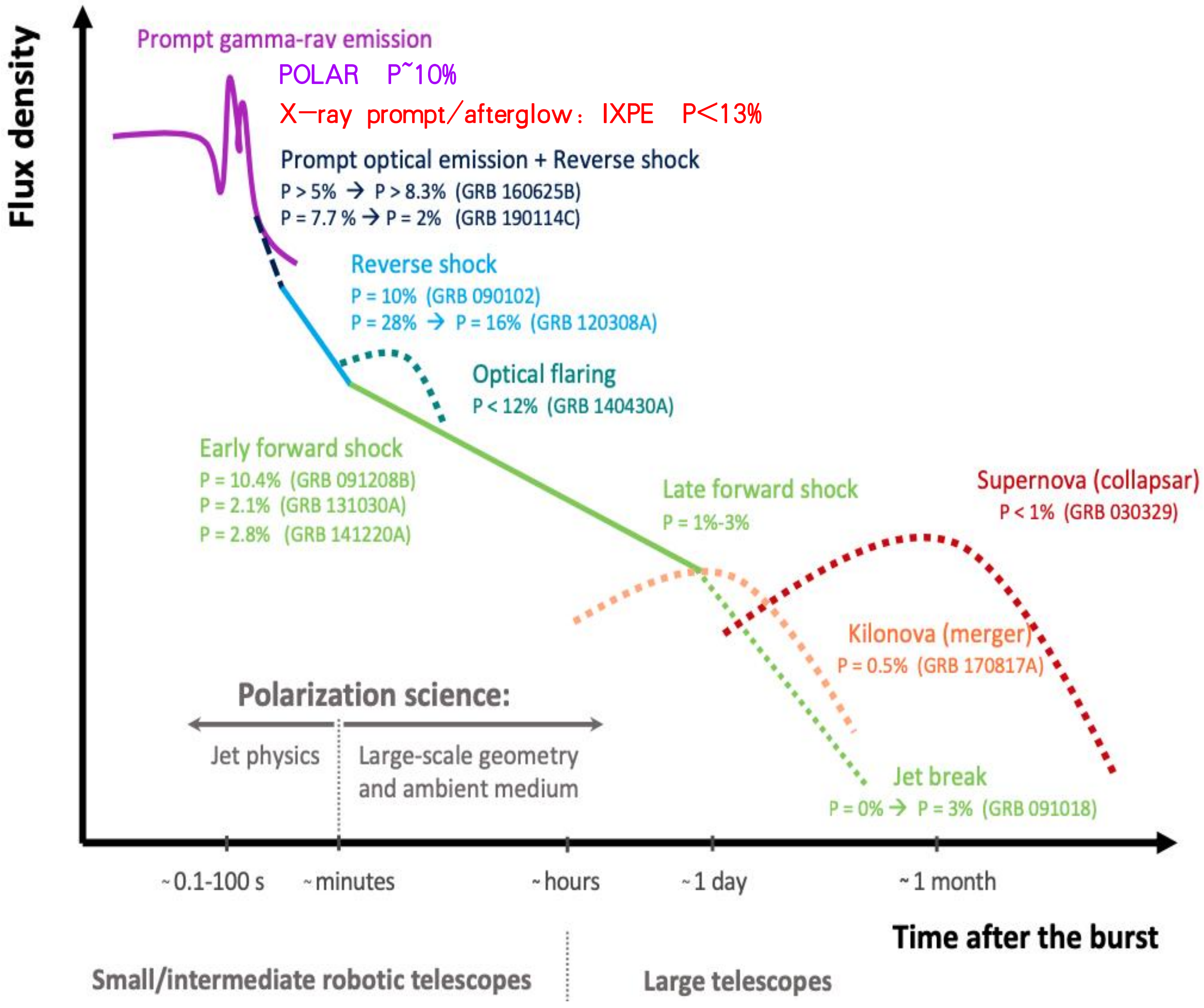
3. GRB Polarimetry with POLAR: multi—wavelength results







Non—symmetric: patchy—shell

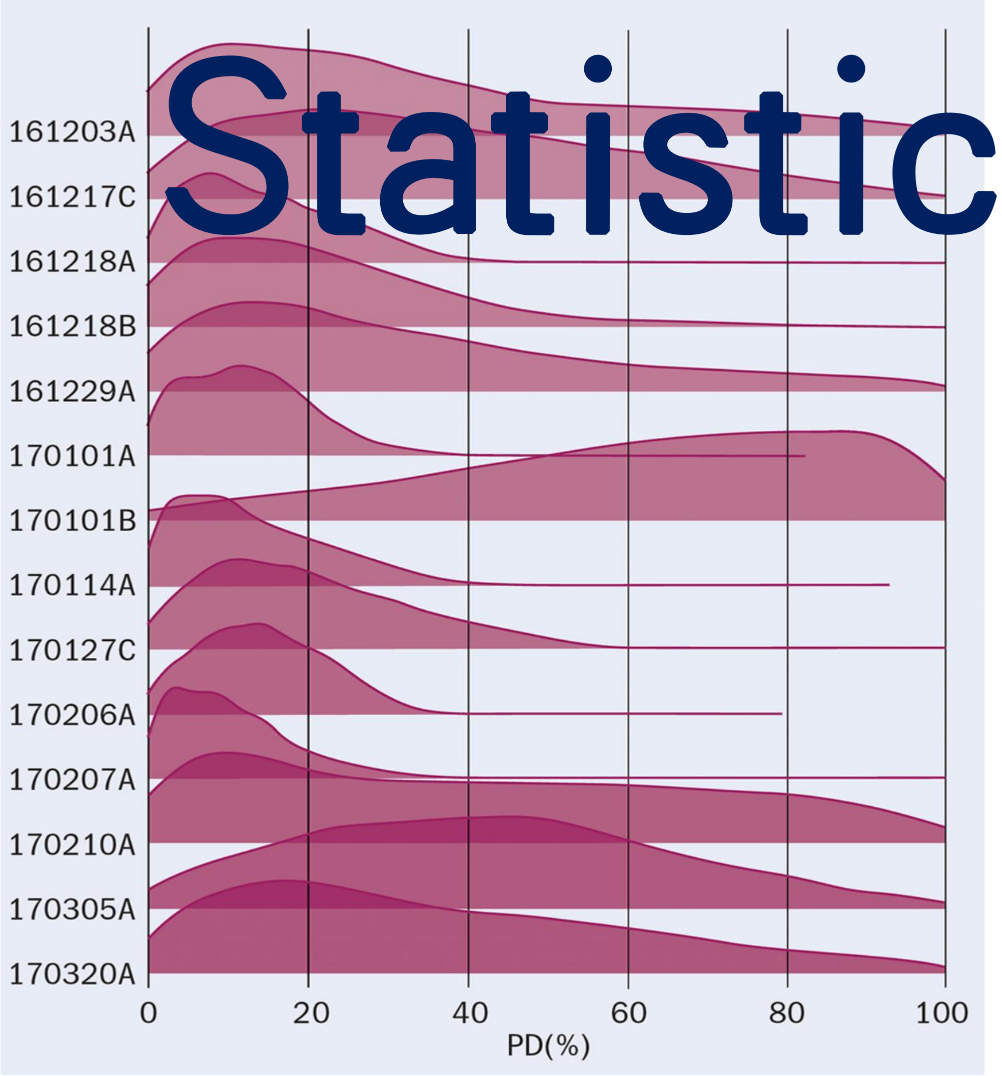


Jordana—Mitjans et al., 2022

3. GRB Polarimetry with POLAR: time integrated/resolved results

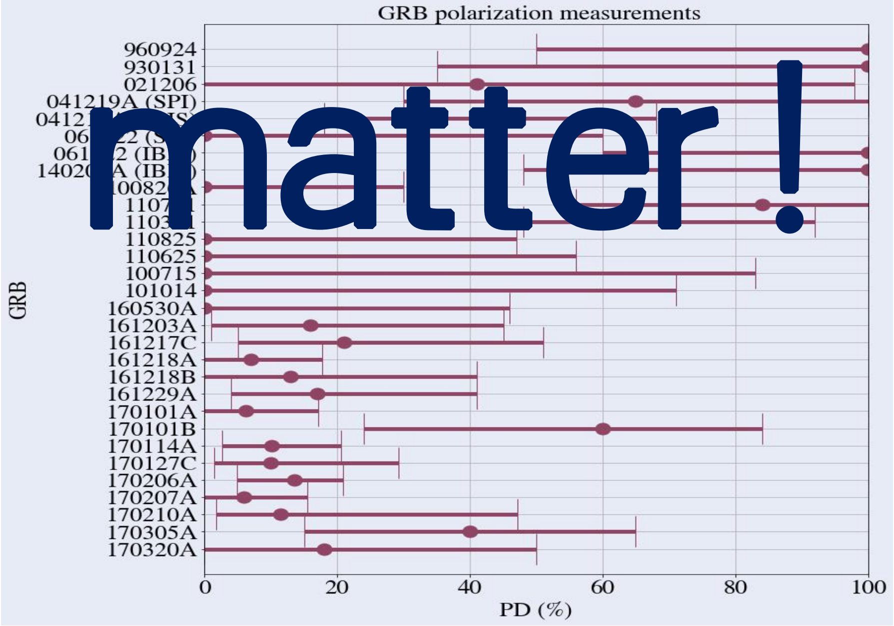
Statistics matter!

Methodology established

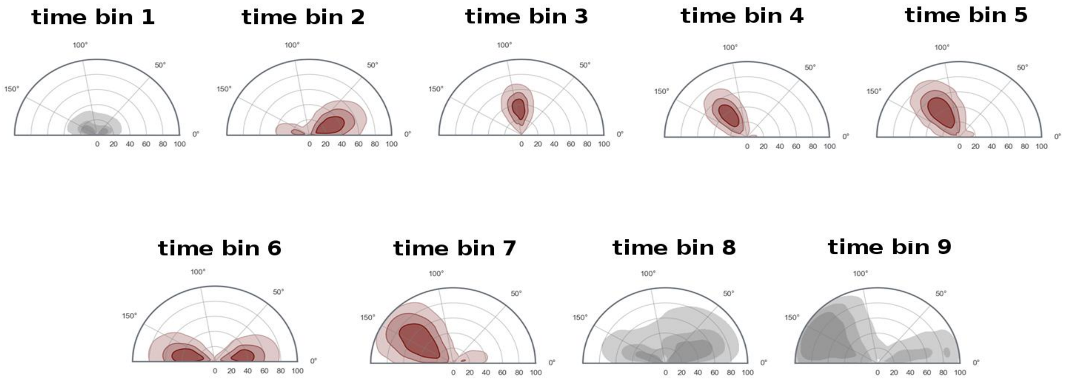


Kole et al., 2020, 14 GRBs, best fitted mostly at ~10%

Systematics understood



Measured PD distributions



Zhang et al., 2019, Burgess et al. 2019

GRB 170114A —> a hit of PA evolution

4. GRB Polarimetry with POLAR—2

- The successor of POLAR with some upgrades
- Officially selected by CSS through UN/OOSA in 2019, aims to launch around 2026

Announcement of selection
Jun./2019

UNITED NATIONS
Office for Outer Space Affairs

CMS

United Nations/China Cooperation on the Utilization of the China Space Station (CSS)

联合国/中国围绕中国空间站应用开展合作

Selected Experiment Projects to be executed on board the CSS for the 1st Cycle

Announced on the occasion of the 62nd Session of the Committee on the Peaceful Uses of Outer Space

12 June 2019 Vienna, Austria

第一轮合作入选项目

2019 年 6 月 12 日在奥地利维也纳举行的第 62 届和平利用外空委员会大会期间发布

I. Fully accepted experiment projects:

完全入选项目

No.1: POLAR-2: Gamma-Ray Burst Polarimetry on the China Space Station

Building on the previous investigation on China's TG-2 space lab, this project aims to answer the most important open questions in astrophysics regarding the nature of Gamma-Ray Bursts (GRBs) by using the most promising investigation approach of polarization measurements allowing to observe even the weakest gamma-ray transients, such as those connected to gravitational waves.

It is an experiment project in astronomy in space. It was applied and will be implemented by four institutions from four countries, which are: The University of Geneva from Switzerland, the National Center for Nuclear Research of Poland, the Max Plank Institute for Extra-terrestrial Physics of Germany, and the Institute of High Energy Physics of Chinese Academy of Sciences.

第 1 个项目： POLAR-2: 中国空间站上的伽玛暴偏振探测仪

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Xin Wu

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences
Shuang—Nan Zhang

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK
Agnieszka Pollo

MPE
Jochen Greiner

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NEWS · 17 JUNE 2019

China reveals scientific experiments for its next space station

Other winners include a detector called POLAR-2, a more powerful follow-up to a sensor launched on Tiangong-2 to study the polarization of energetic γ-ray bursts from distant cosmic phenomena. POLAR-2, which will be built by an international collaboration, could even allow astronomers to observe the weak radiation associated with sources of gravitational waves.

4. GRB Polarimetry with POLAR-2

◎ Bigger

○ 100 polarimeter modules

◎ More than bigger

○ Optimized bar length (less BKG)

○ Bar + Vikuiti (LY 0.3 to 1.3 p.e./keV)

○ Optical pad (CT 15% to 2.5%)

○ SiPM: lower threshold (<10 keV)

○ Cooling & annealing (against degradation)

◎ Effective Area (ARF)

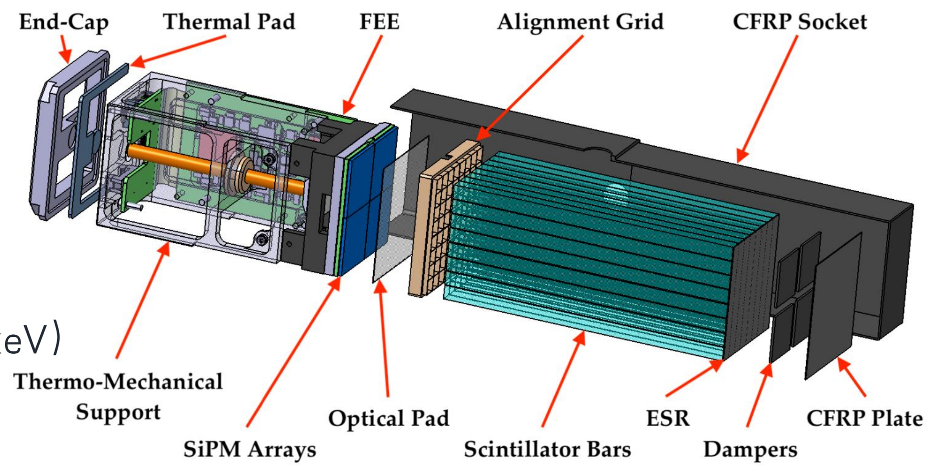
○ ARF ~ 1300 cm^2

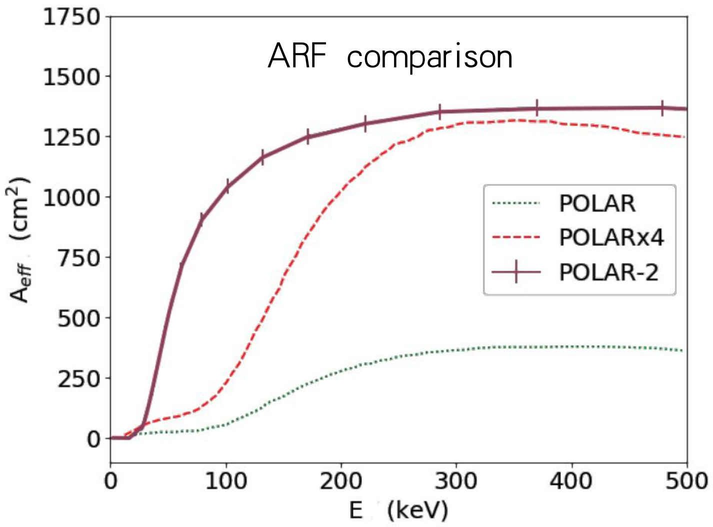
(300 for POLAR)

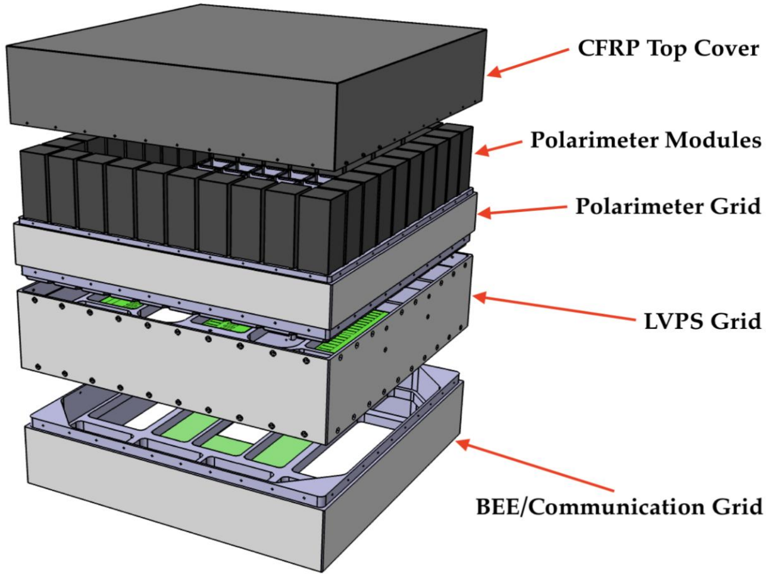
◎ Modulation factor (μ_{100})

○ μ_{100} >50% for 40-150 keV

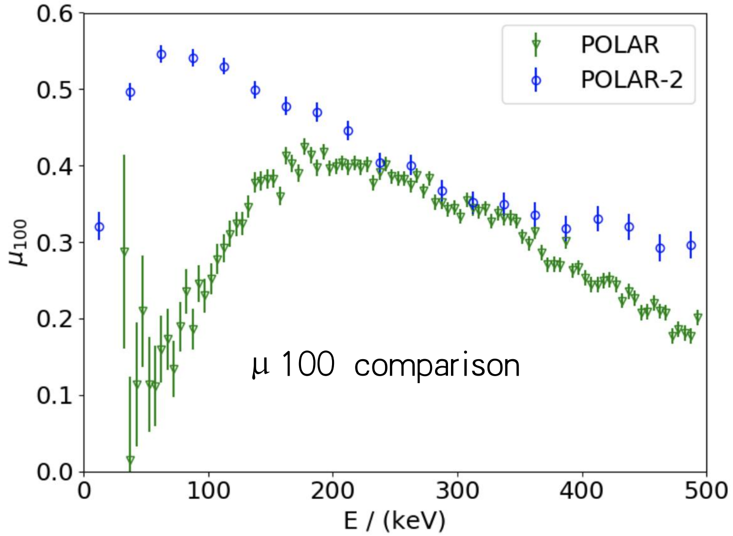
(<30% for POLAR)



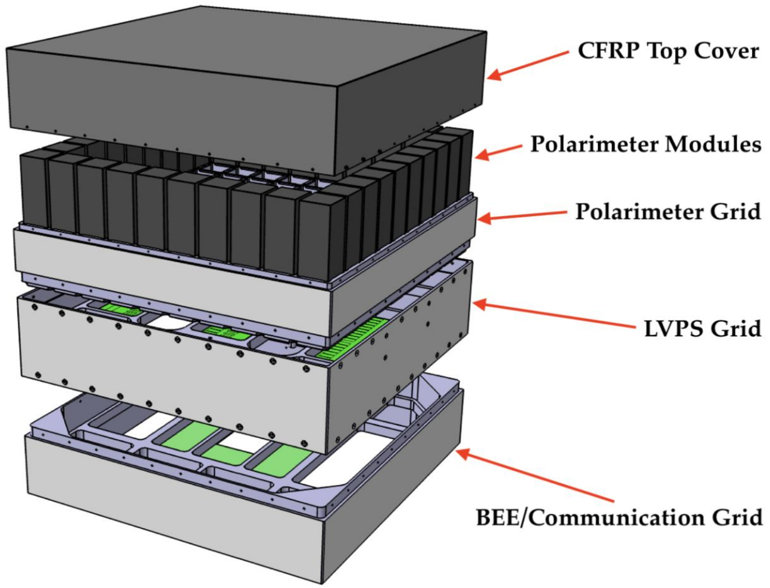




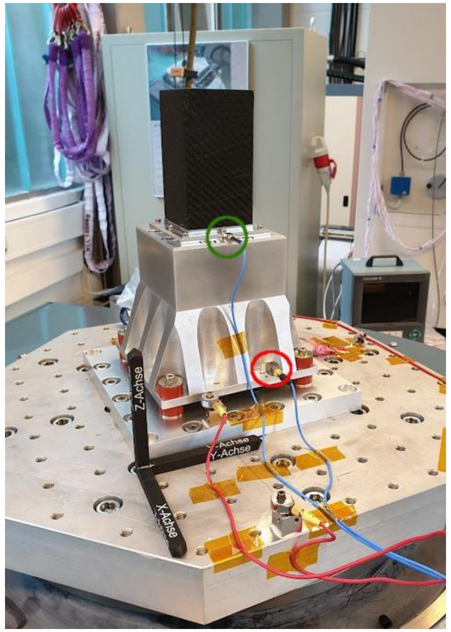
100 polarimeter modules (4 times of POLAR)



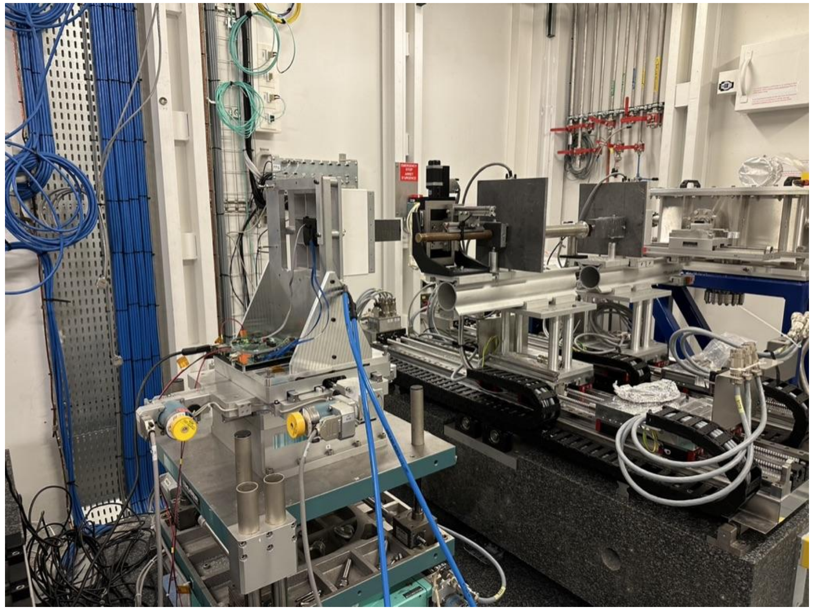
4. GRB Polarimetry with POLAR-2



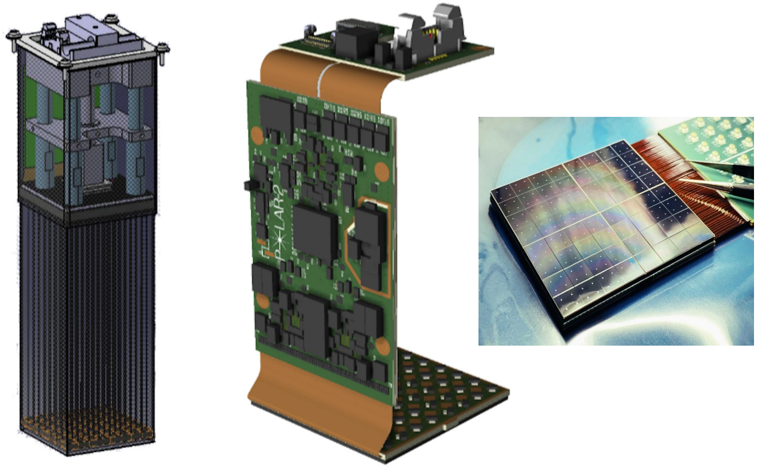
100 polarimeter modules (4 times of POLAR)



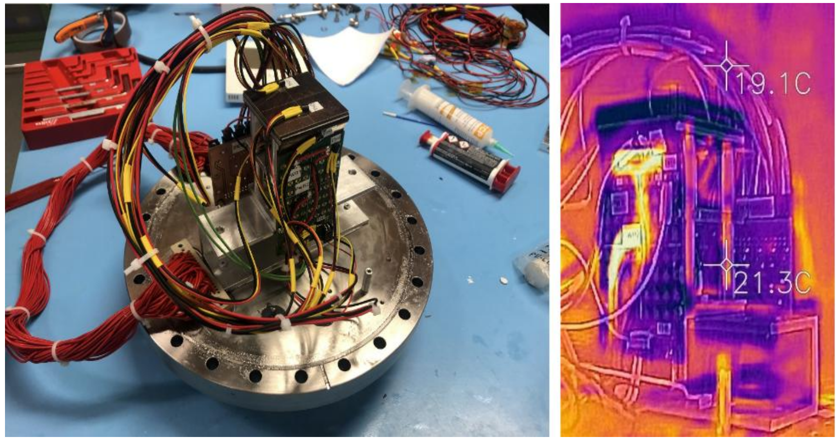
Vibration test



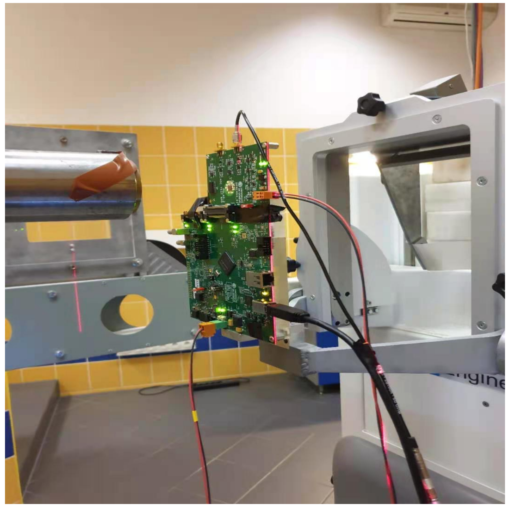
ESRF polarized source calibration



Compact SiPM readout unit

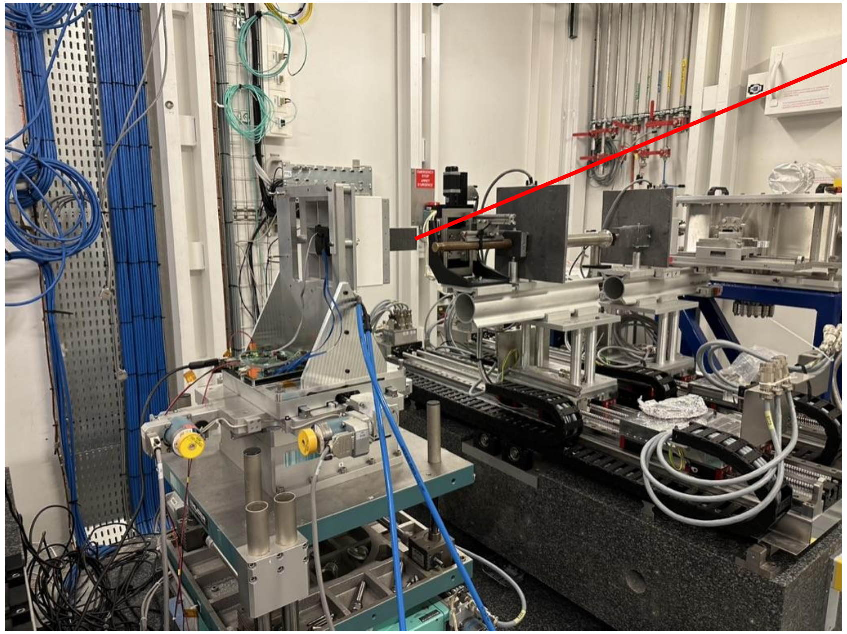


Thermal-Vacuum test



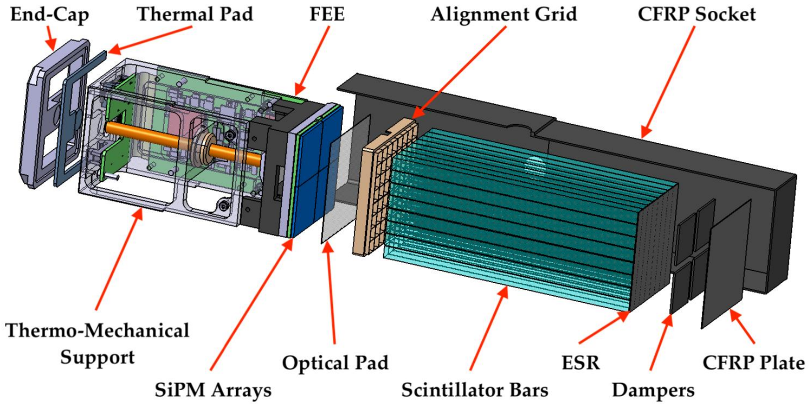
Proton irradiation

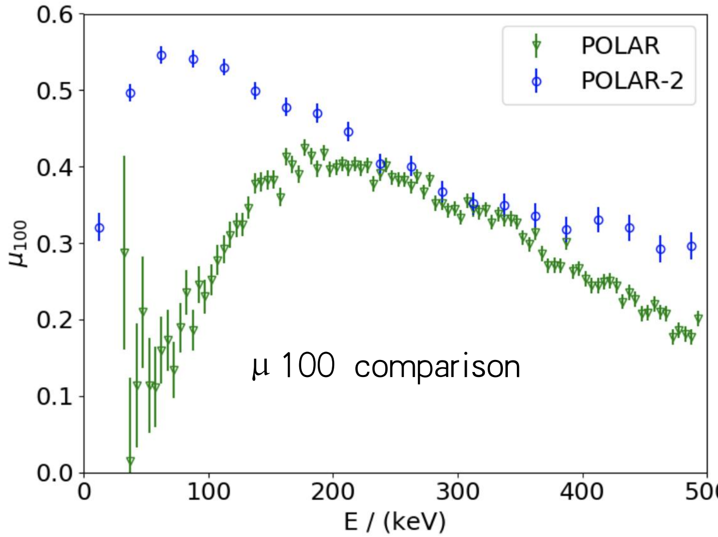
4. GRB Polarimetry with POLAR-2

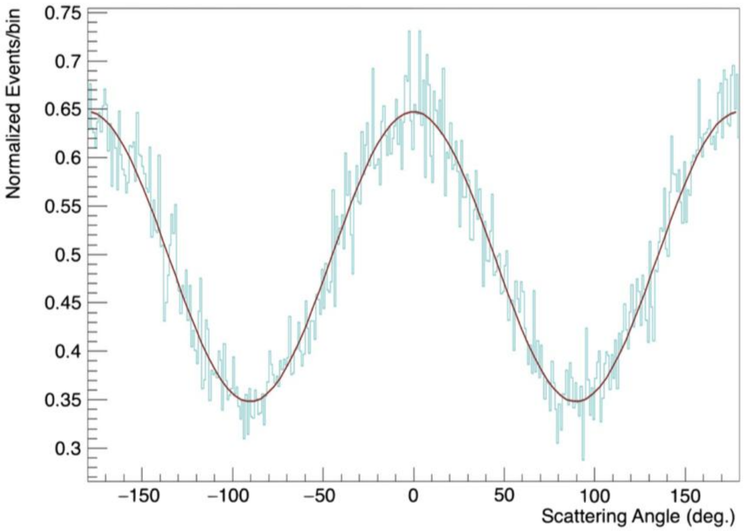


ESRF polarized source calibration

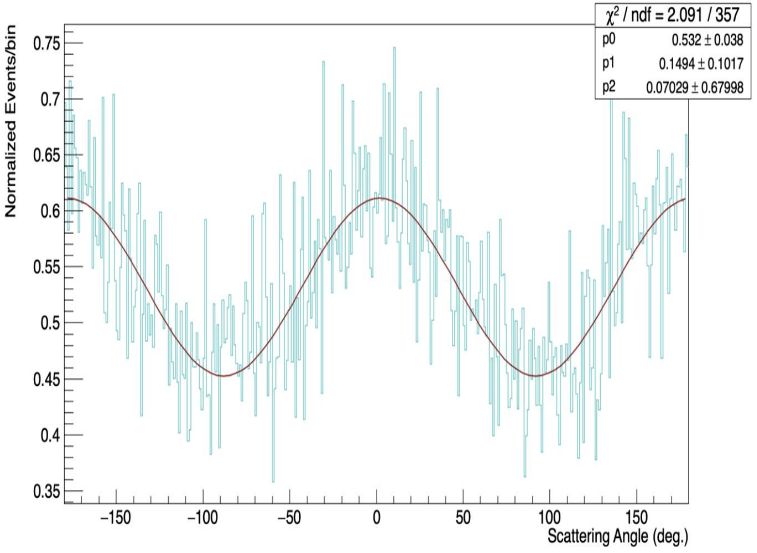
Single module!







μ_{100} = 30% @ 100 keV



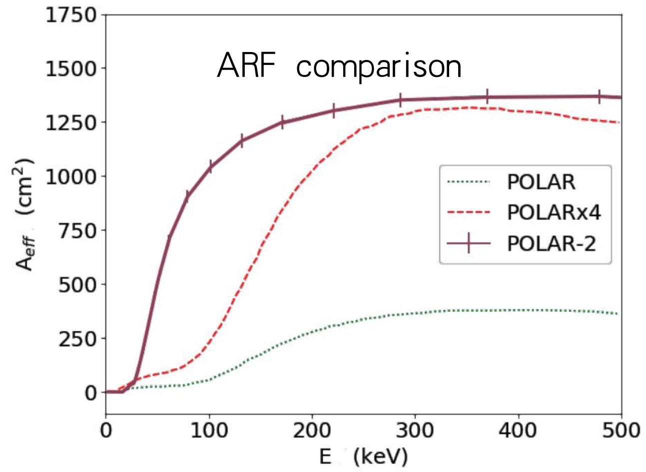
μ_{100} = 15% @ 40 keV

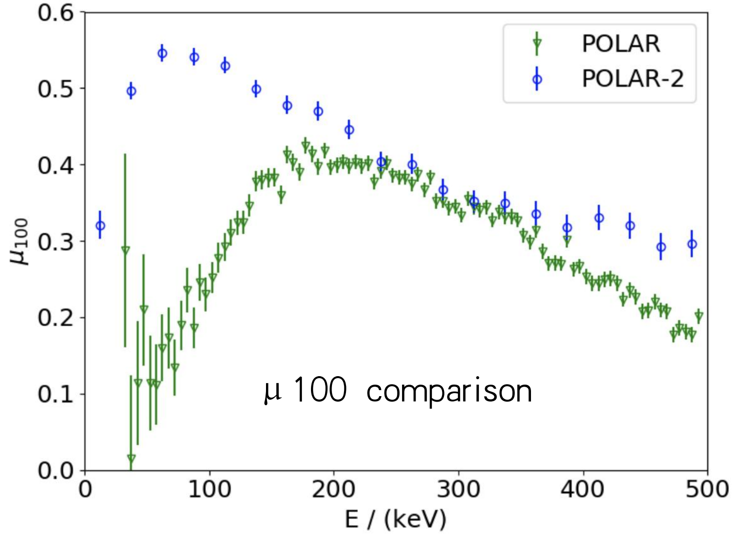
Kole et al., 2024, in preparation

4. GRB Polarimetry with POLAR-2: performances

Sensitivity improvement

- ○ 4 times larger ARF
- ○ Optimized bar length (less BKG)
- ○ SiPM: lower threshold (<10 keV)
- ○ 10 times more sensitive

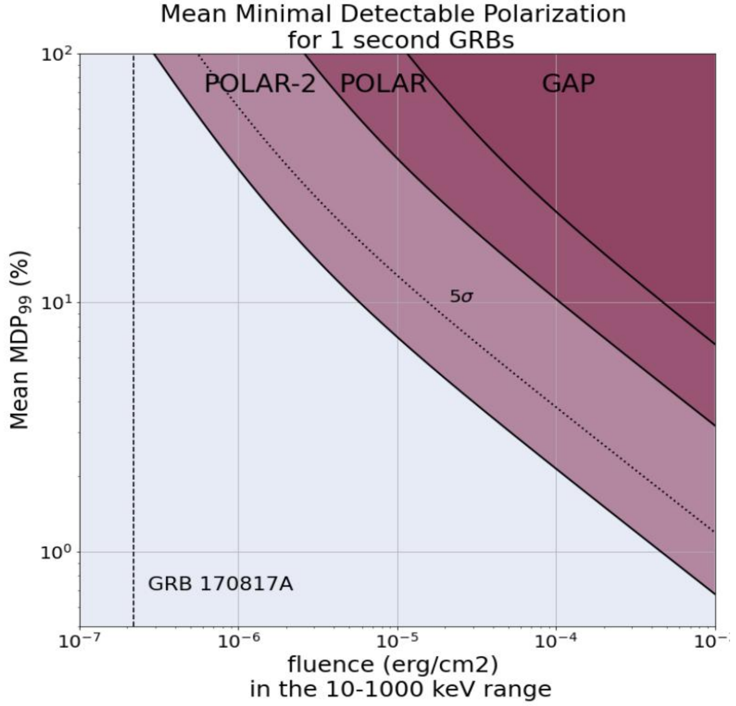


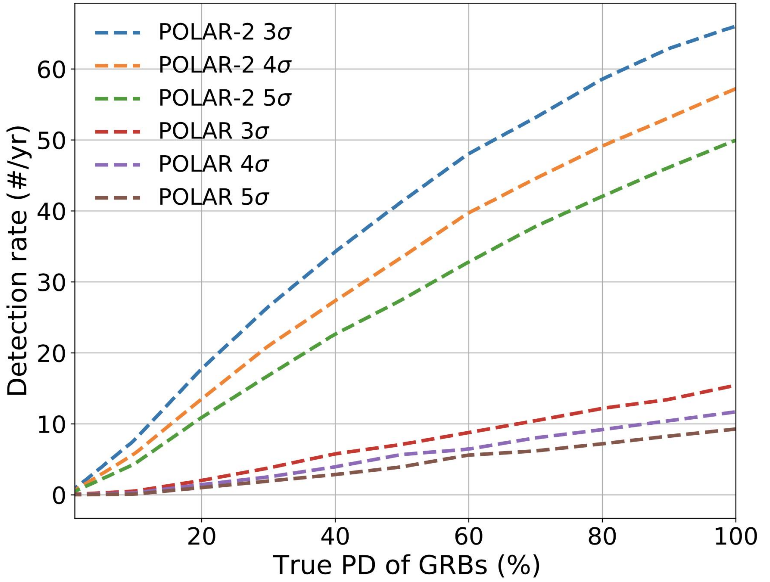


Performance anticipation

- ○ Eff. area ~ 1300 cm^2
- ○ For a GRB with fluence 10^{-5} erg/cm^2,

  5 σ measurement when PD_{true} ~10%





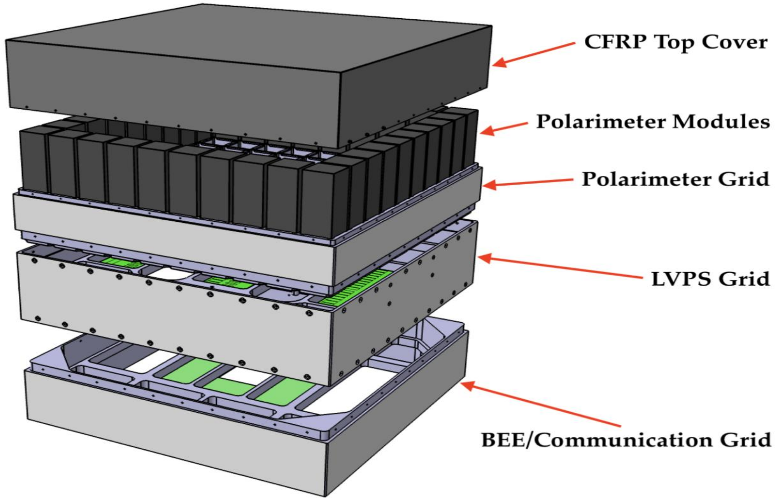
Significant measurements (#/yr)

- ○ If PD_{true} ~10%, #10 (3 σ), #5 (5 σ)
- ○ If PD_{true} ~20%, #20 (3 σ), #10 (5 σ)

GRBs, *Kole et al. 2021*

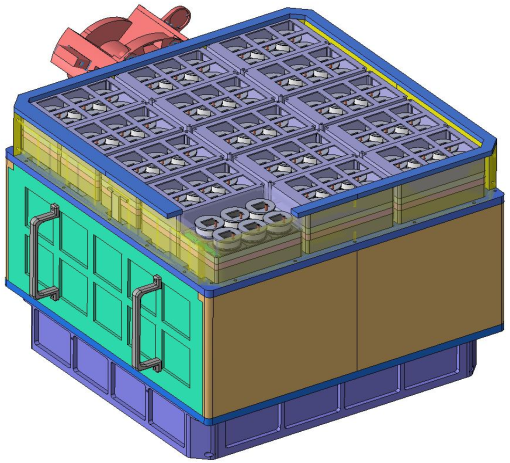
4. GRB Polarimetry with POLAR-2: enhanced by two more payloads

- High-energy Polarization Detector: HPD
  - ~30-800 keV for gamma-ray polarimetry
  - 100 modules, 6400 plastic scintillator bars
  - Effective area: ~2000cm^2, > 1200cm^2 for Pol.
  - FoV: ~50% sky
  - Collaborations: UNIGE/IHEP/MPE/NCBJ
- Status of HPD: approved and design finalized

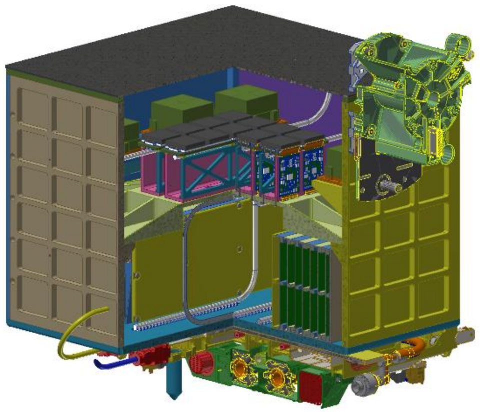


HPD

- Low-energy Polarization Detector: LPD, GXU
  - ~2-10 keV for X-ray polarimetry
- Broad energy-band Spectrum Detector: BSD, IHEP/CAS, China
  - ~10-2000 keV for spectroscopy
  - Accurate GRB localization: < 1°
- Status of LPD & BSD: under review for approval



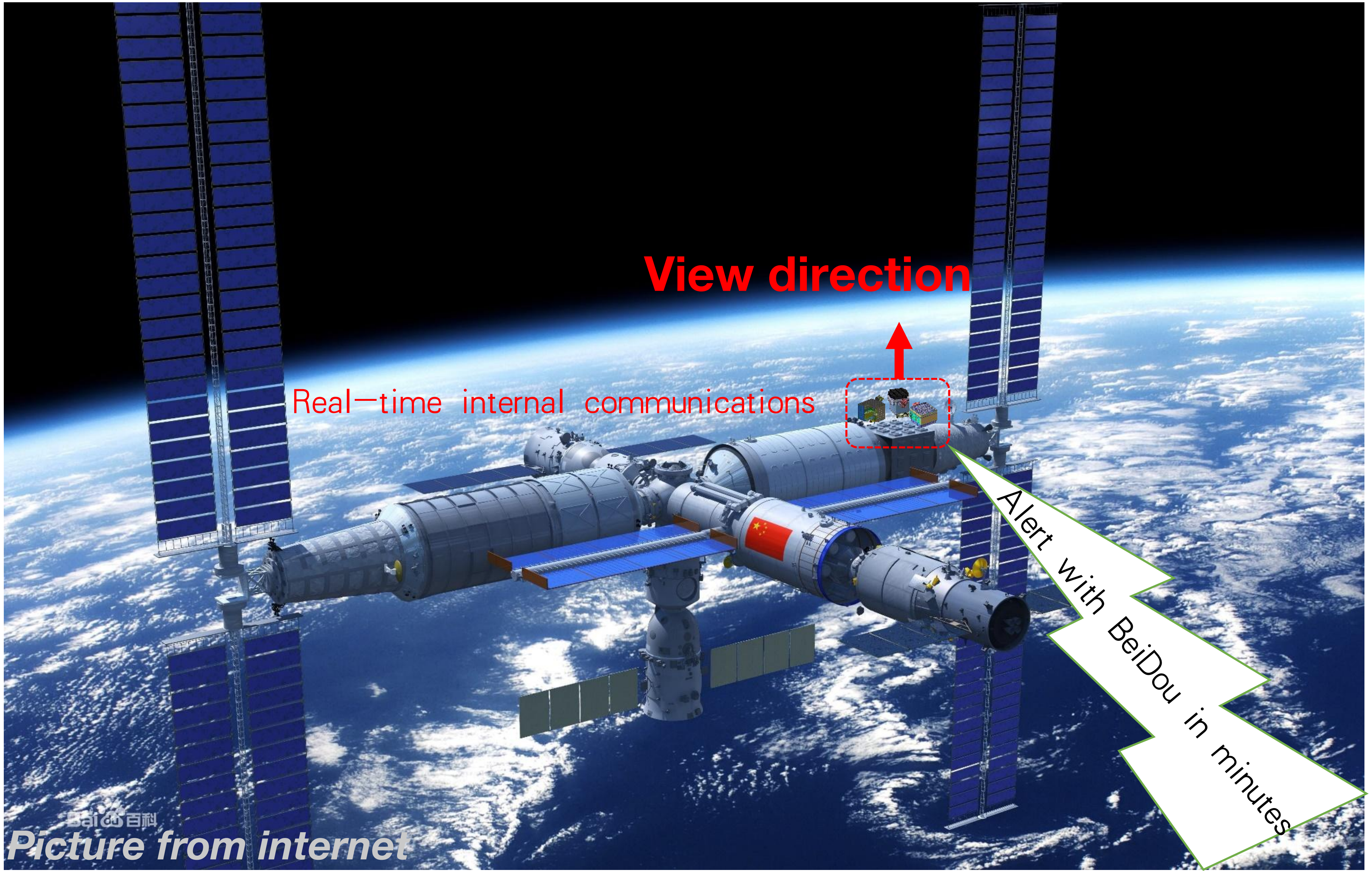
LPD



BSD

4. GRB Polarimetry with POLAR-2: synergies among the three

- Joint detection and alert (follow-ups): HPD (>2π sr), LPD (~π), BSD(~1.3π)



5. Summary and outlook

◎ Polarimetry helps understanding GRBs

- ○ Probing magnetic field configuration
- ○ Diagnosing radiation mechanism
- ○ Determining emission geometry

Stay tuned!

Thanks for your attention.

◎ POLAR (2016–2017)

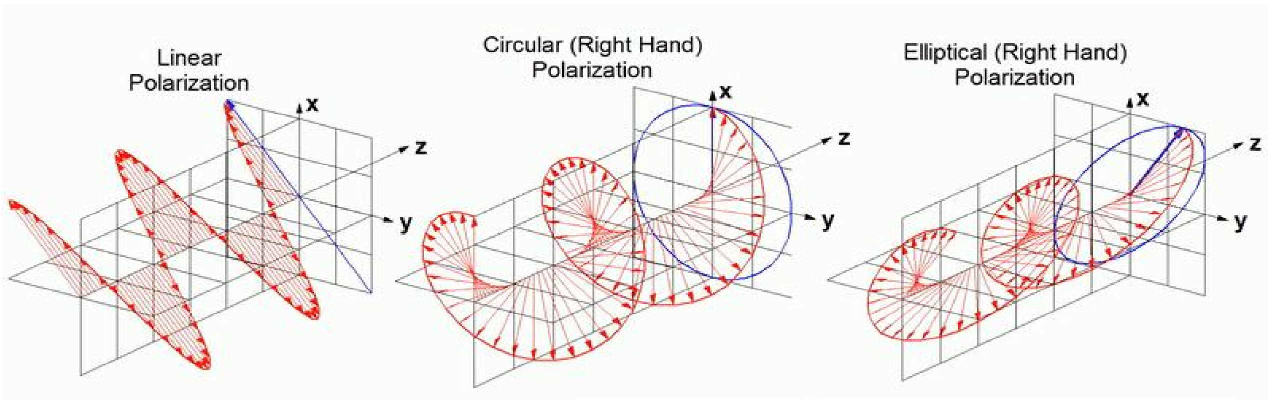
- ○ GRBs: moderate PD (~10%) + hint of PA evolution
- ○ Currently are still not able to discriminate plenty of models (limited by statistics)
- ○ Future orientation: time-/energy-resolved polarimetry & large sample studies

◎ POLAR-2 (2026–20XX)

- ○ 4 times bigger and 10 times more sensitive than POLAR
- ○ HPD, LPD, BSD joint detections: fixed spectral & location dependences; energy-resolved by default
- ○ Will enlarge the sample of GRB polarimetry with better precision (some >5 sigma)
- ○ Alert system hopefully triggers multi-wavelength/-messenger campaigns

Backup slides

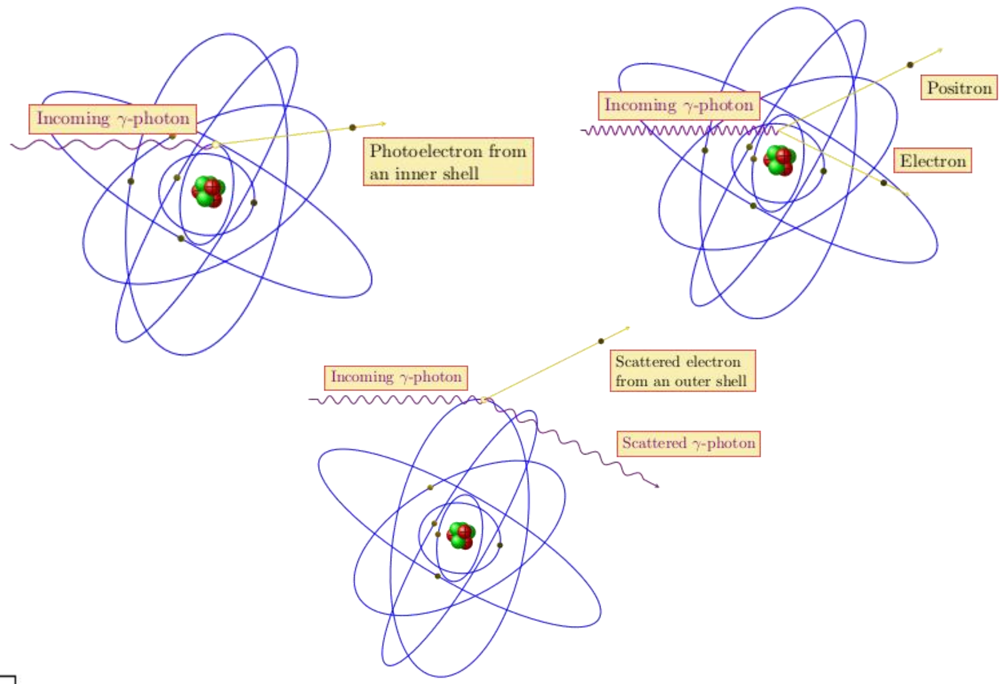
1. Polarimetry and POLAR: first principles

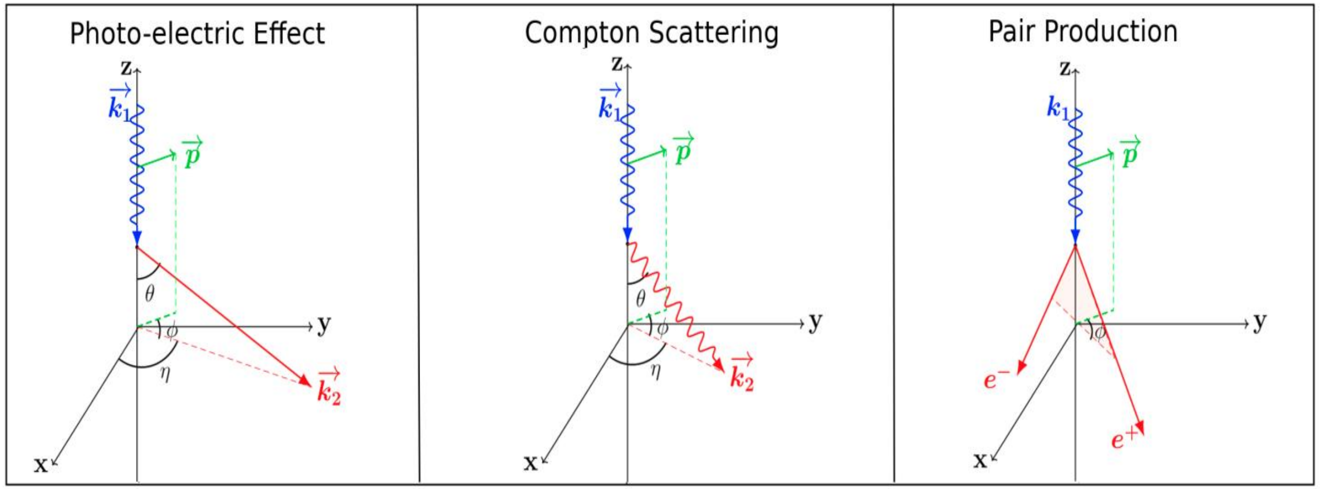


$$E_x = E_{0x}\cos(\omega t - kz + \varphi_x)$$
$$E_y = E_{0y}\cos(\omega t - kz + \varphi_y)$$

$$\left(\frac{E_x}{E_{0x}}\right)^2 + \left(\frac{E_y}{E_{0y}}\right)^2 - 2\left(\frac{E_x}{E_{0x}}\right)\left(\frac{E_y}{E_{0y}}\right)\cos\varphi = \sin^2\varphi$$

◎ Linear polarization (when $\varphi = n\pi,\ n \in \mathbb{Z}_0^+$)



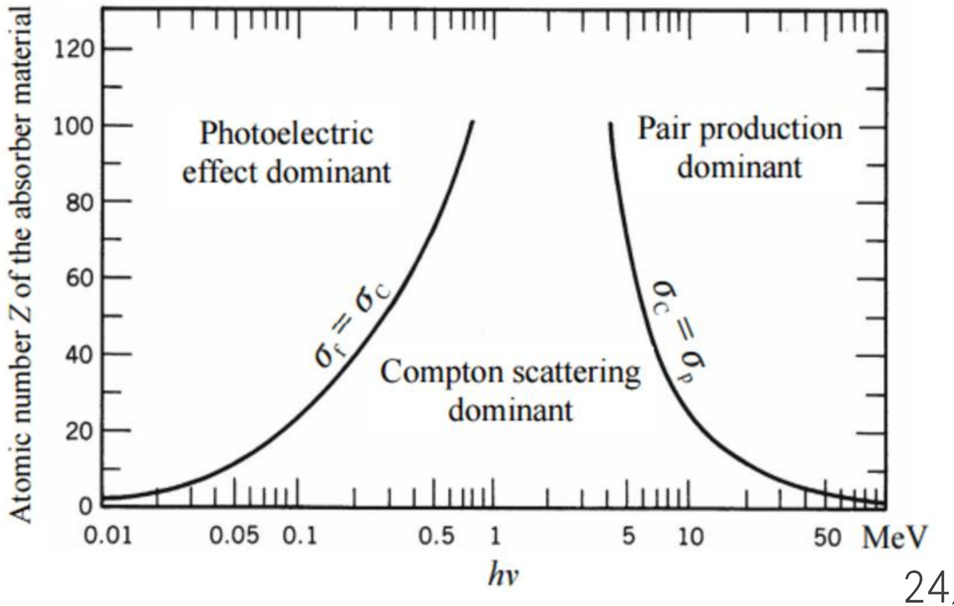


$$\frac{d\sigma}{d\Omega} \propto \cos^2\phi$$

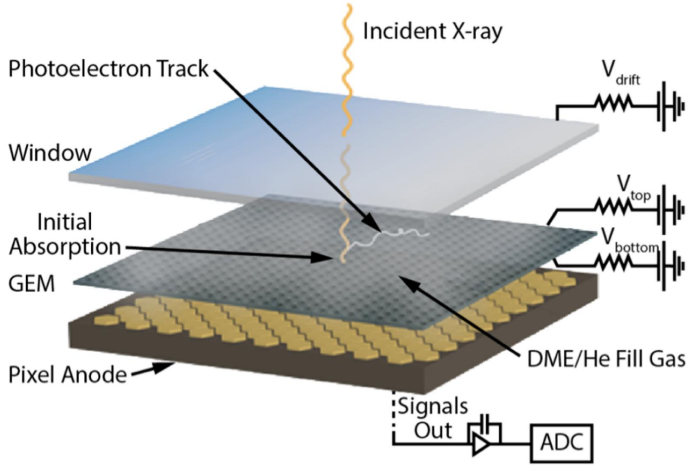
$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\frac{E'^2}{E^2}\left(\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\phi\right)$$

$$d\sigma/d\Omega \propto 1 + A(\cos 2\phi)$$

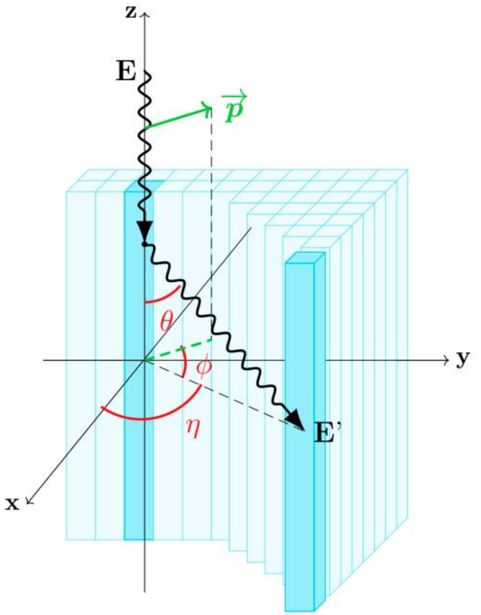
10.3390/galaxies9040082



1. Polarimetry and POLAR: measuring techniques



Photo—electric in a gas chamber



Compton scattering in plastics

Stokes parameters:

$$S_0 = I = \langle E_x^2 + E_y^2 \rangle,$$
$$S_1 = Q = \langle E_x^2 - E_y^2 \rangle,$$
$$S_2 = U = \langle 2E_xE_y \cos\delta \rangle,$$
$$S_3 = V = \langle 2E_xE_y \sin\delta \rangle$$

$$Q = \cos 2\psi \qquad I = \sqrt{Q^2+U^2}$$
$$U = \sin 2\psi$$

$$p_l = \frac{\sqrt{Q^2+U^2}}{I} \qquad \tan 2\psi = \frac{U}{Q}$$

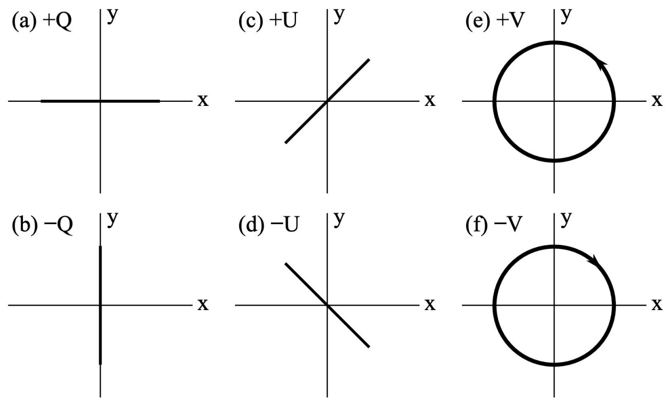


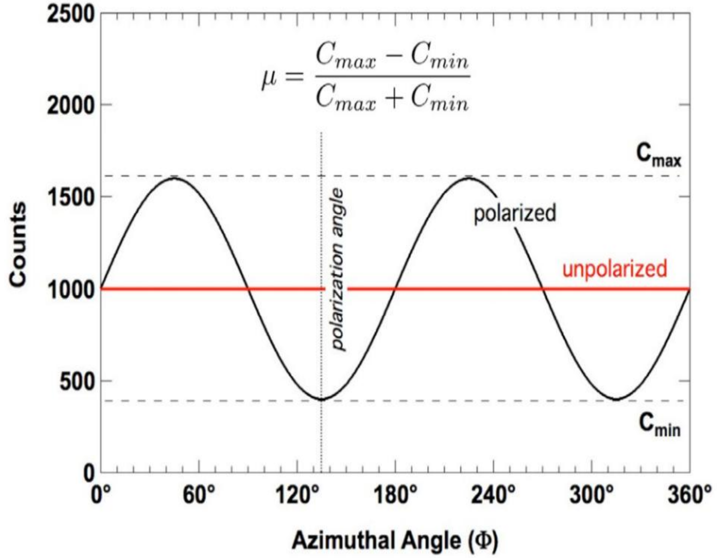
Figure 1: Polarization for different values of the Stokes parameters. (a) $Q > 0, U = 0, V = 0$; (b) $Q < 0, U = 0, V = 0$; (c) $U > 0, Q = 0, V = 0$; (d) $U < 0, Q = 0, V = 0$; (e) $V > 0, Q = 0, U = 0$; (f) $V < 0, Q = 0, U = 0$.

Kislat et al. 2015

Fitting modulation curves:

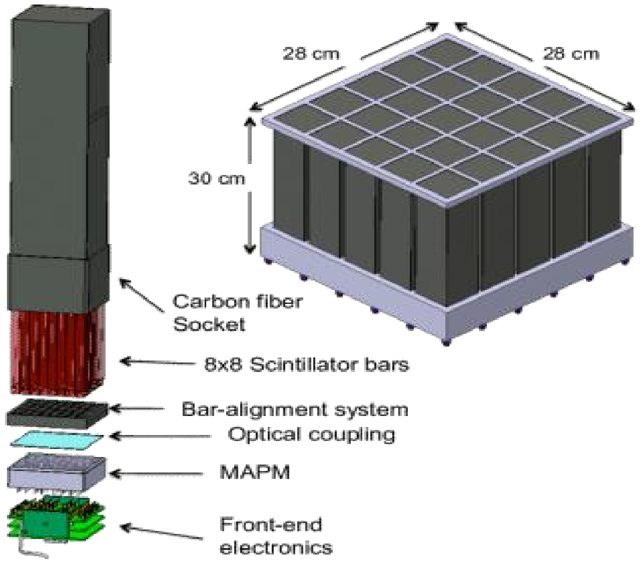
$$C(\eta, \Phi) = A \times \cos\left[2\left(\eta - \Phi + \frac{\pi}{2}\right)\right] + B\,.$$

$$\mu = \frac{A}{B} = \frac{C_{max} - C_{min}}{C_{max} - C_{min}}, \qquad \Pi = \frac{\mu}{\mu_{100}}\,.$$

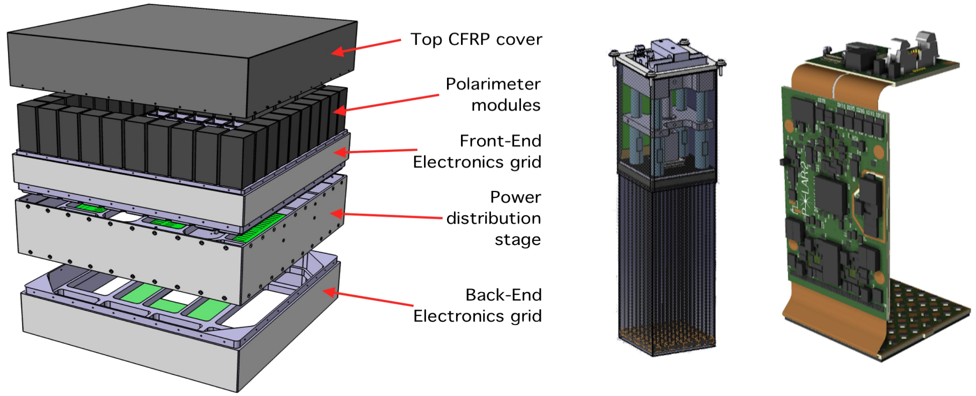


e.g. Li et al. 2022

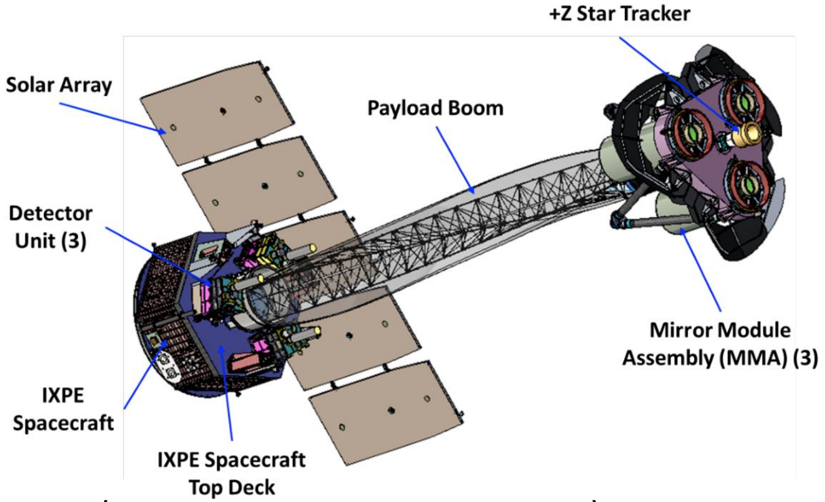
1. Polarimetry and POLAR: state-of-art polarimeters



POLAR (50–500 keV, GRB/Pulsar) 2016 – 2017



POLAR-2 (10–800 keV, GRB/Pulsar/SFL) 2025 – 2



IXPE (2–10 keV, multi-class) 2021 – now

eXTP (2–10 keV multi-class) 2027 – 20XX

1. Polarimetry and POLAR: collaboration and the mission

Collaboration

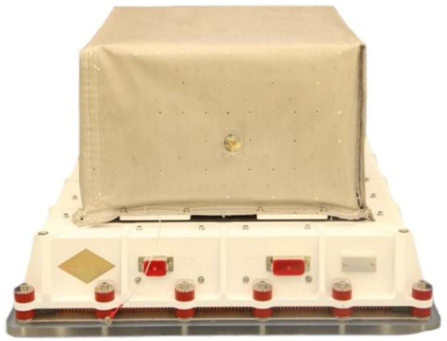
- ○ China (IHEP)
- ○ Switzerland (UNIGE, PSI, ISDC)
- ○ Poland (NCBJ)

Development phases

- ○ 2005—2010, concept and prototype
- ○ 2011—2013, qualification model
- ○ 2013—2016, flight model

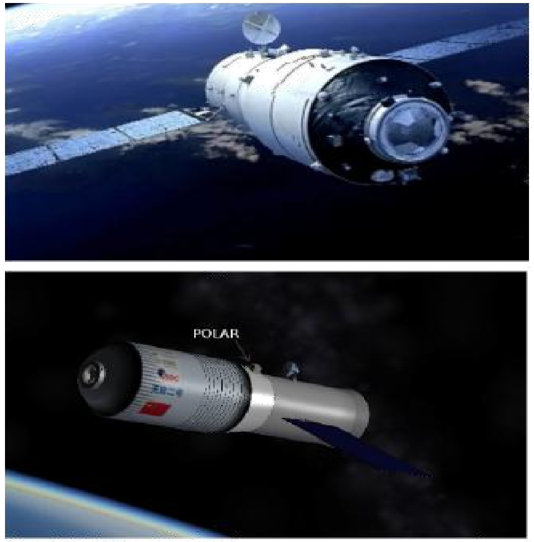
Launch and operation

- ○ Tiangong—2 space lab
- ○ Launched on 15/09/2016
- ○ Pointing to the sky always
- ○ Scanning / periodic orbit
- ○ Six months of observation (HV failure)

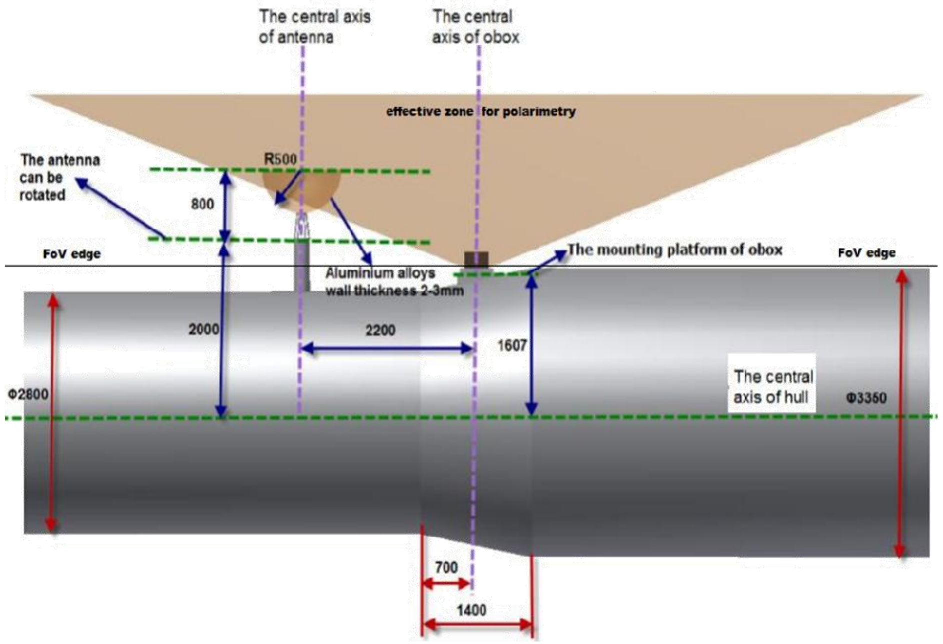


OBOX
Sensitive detector

IBOX
Electronics & interfaces

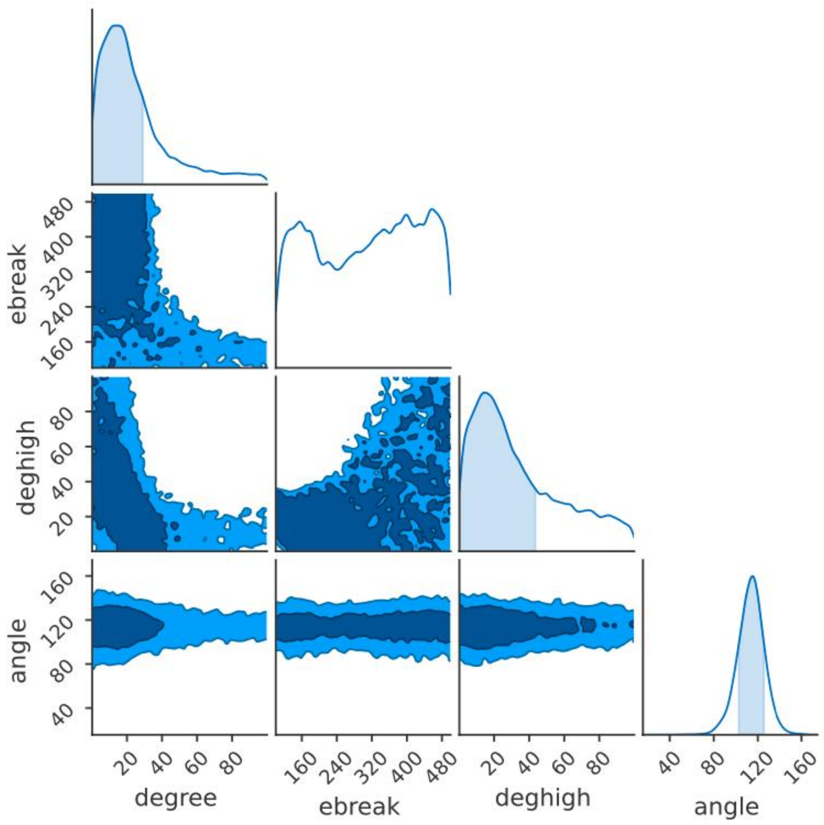


Credit: South China Morning Post



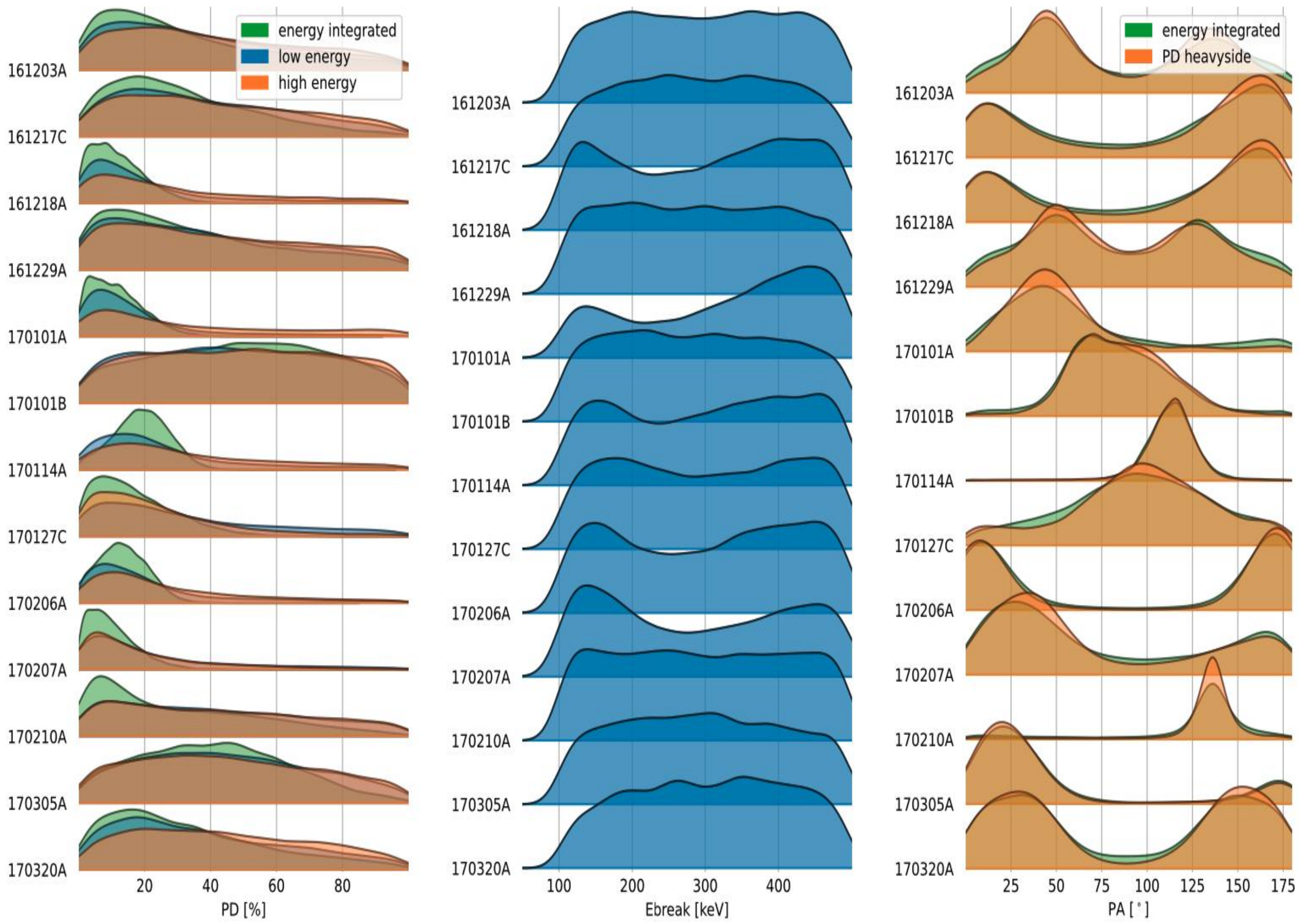
1. GRB observations with POLAR: energy-resolved results

$$PD = \begin{cases} PD_{low} & if\ E < E_{break} \\ PD_{high} & if\ E > E_{break} \end{cases} \qquad PA = cst.$$



Two energy bins, dynamic E_{break}

Ongoing with other E-dependent models

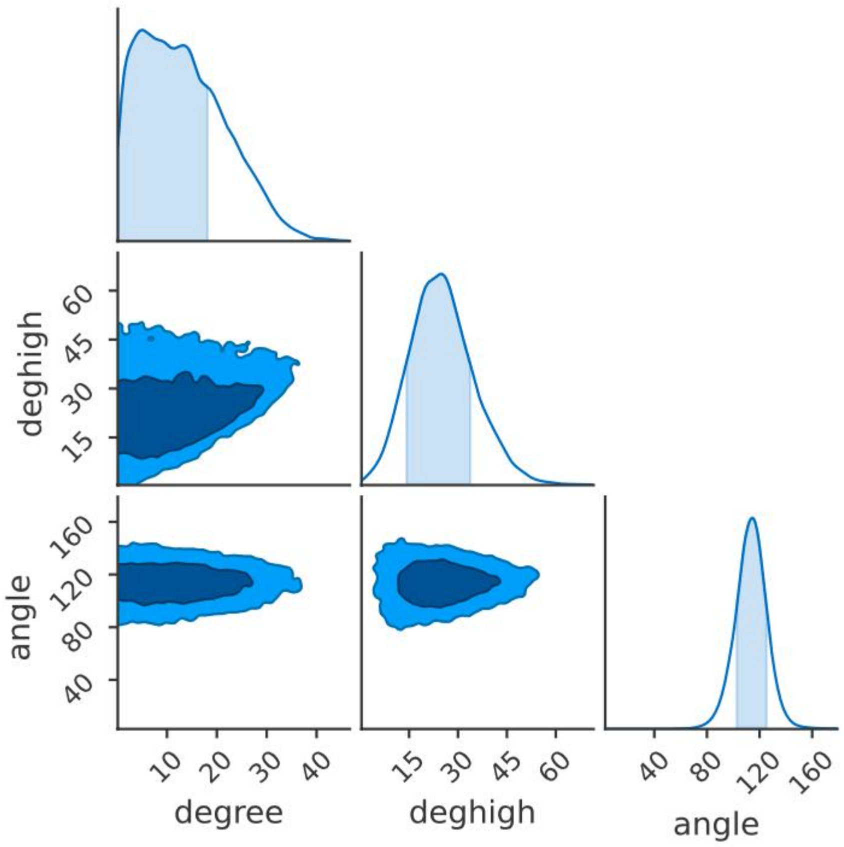


No significant energy dependence, need better statistics

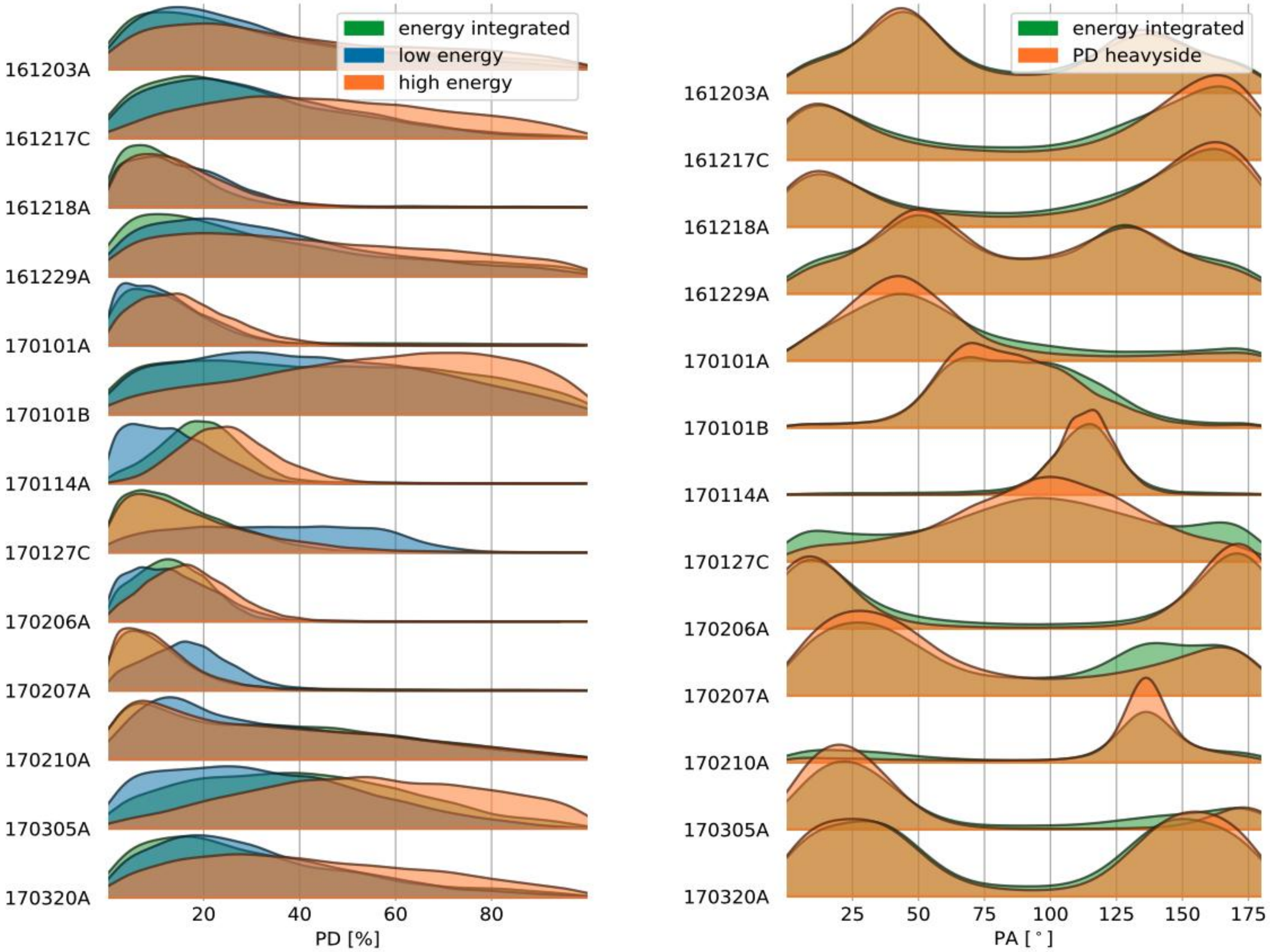
De-Angelis et al., 2023

1. GRB observations with POLAR: energy-resolved results

$$PD = \begin{cases} PD_{low} & if\ \ E < 150\ keV \\ PD_{high} & if\ \ E > 150\ keV \end{cases} \qquad PA = cst.$$



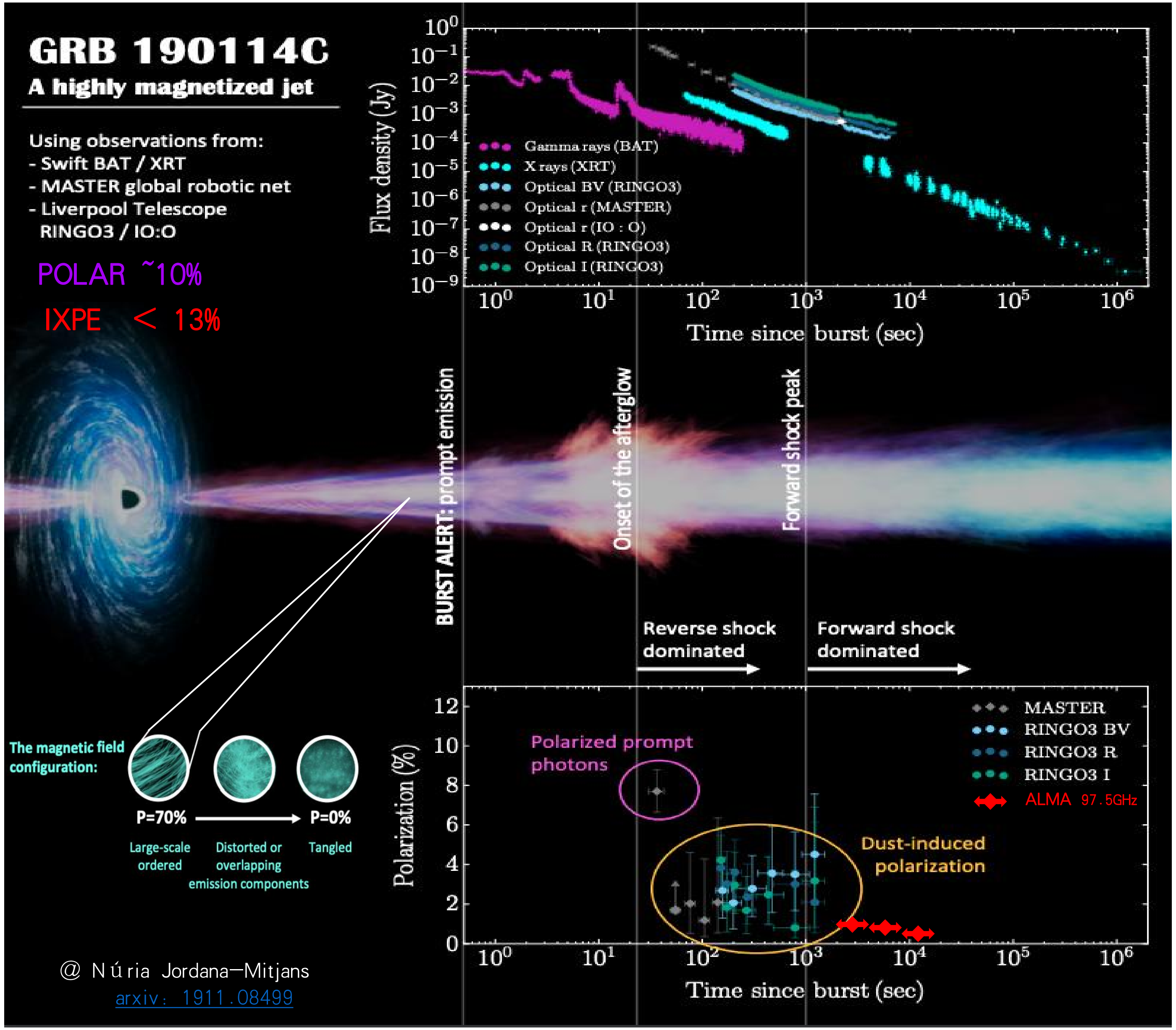
Two energy bins, E_{break} fixed at 150 keV
Ongoing with other E-dependent models



No significant energy dependence, need better statistics

De-Angelis et al., 2023

2. GRB observations with POLAR

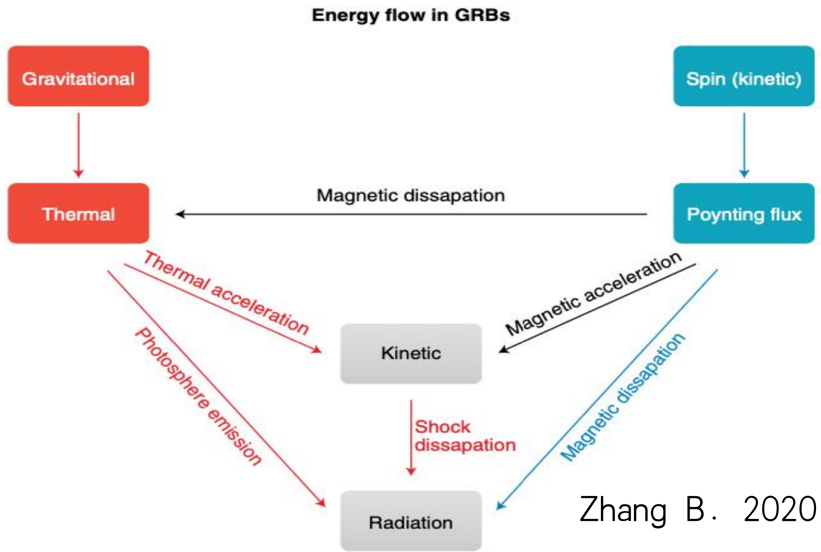


◎ GRB 190114C: optical polarization probe the magnetic field

- prompt PD ~ 7.7% -> large-scaled ordered magnetic field
- afterglow PD ~ 2% (PA not changing) in ambient medium
- radio (97.5Hz) afterglow PD decrease from 0.87% to 0.60%
- jet was launched highly magnetized, and advected to prompt phase, then distorted on timescales prior to reverse shock
- support magnetic dissipation mechanisms (e.g., reconnection)
- forward shock SSC is favored for explaining sub-TeV and low PD

◎ X/γ ray polarimetry (multi-wavelength and time evolution)

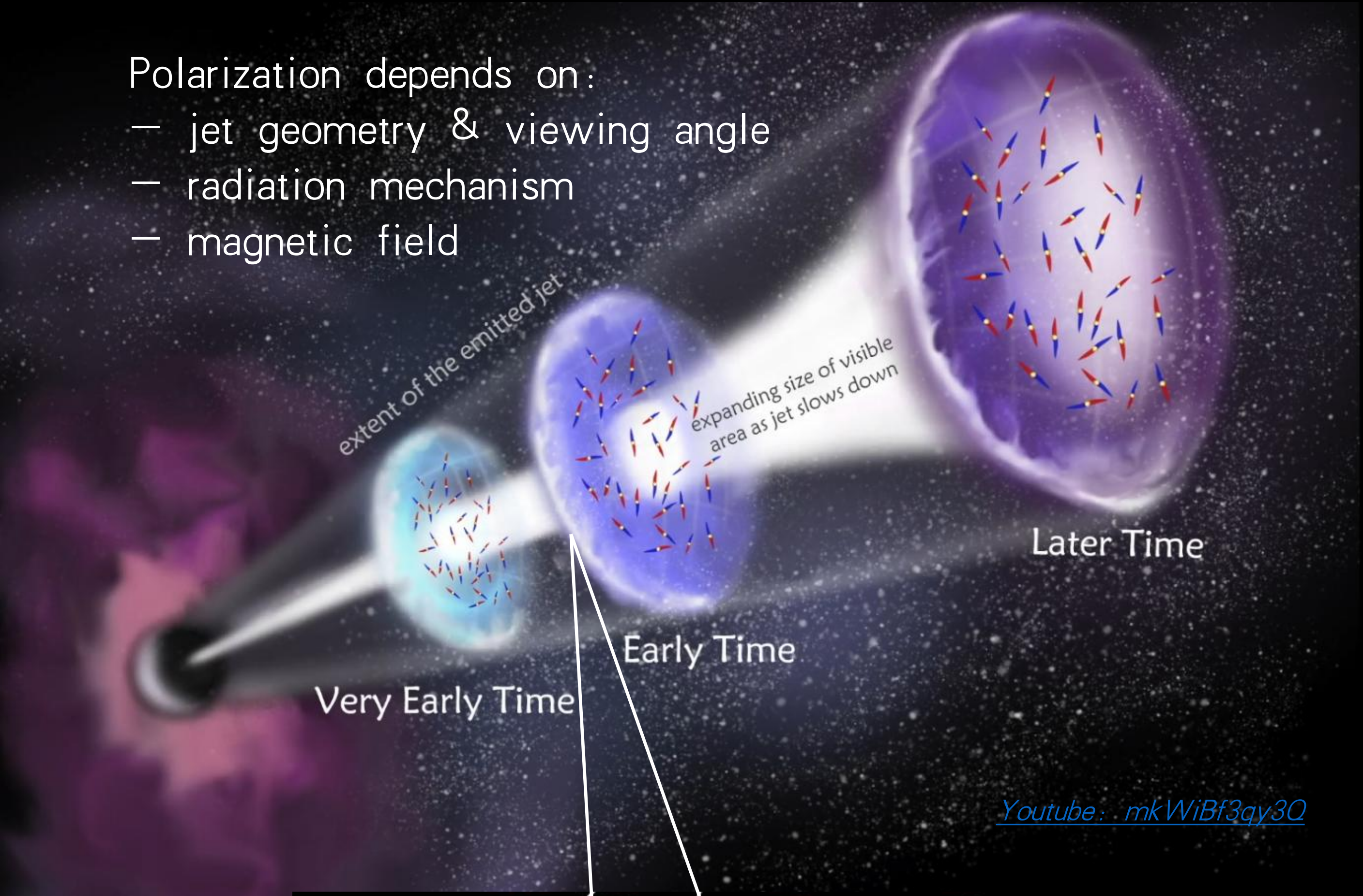
- POLAR (50-500 keV): 14 GRBs PD ~10%; a hint of PA evolution
- IXPE (2-8 keV): afterglow PD < 13% for GRB 221009A, which has 5000 VHE photons (up to 18 TeV) detected by LHASSO
- LC + SED + polarization (SSC frame) -> jet geometry and models



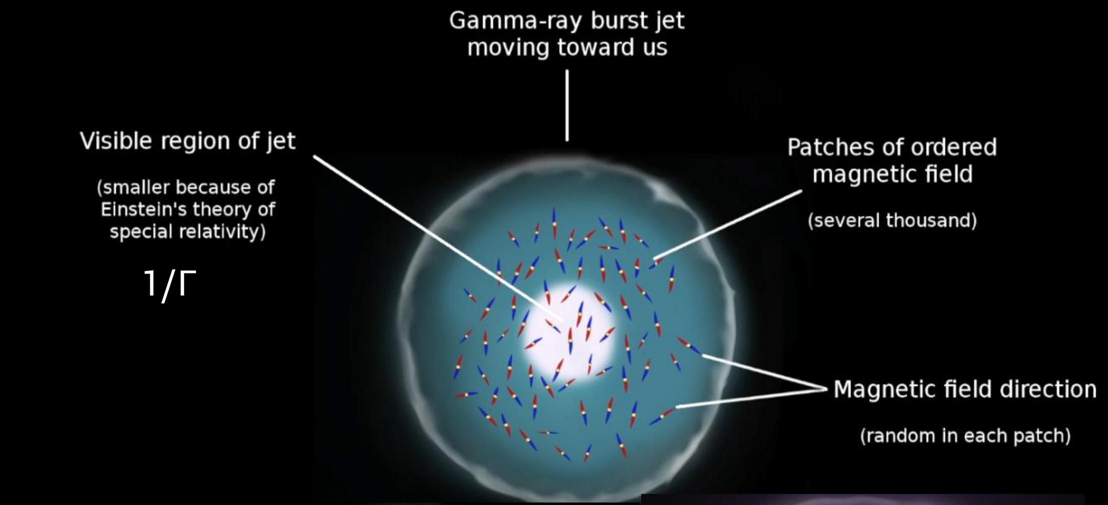
Zhang B. 2020

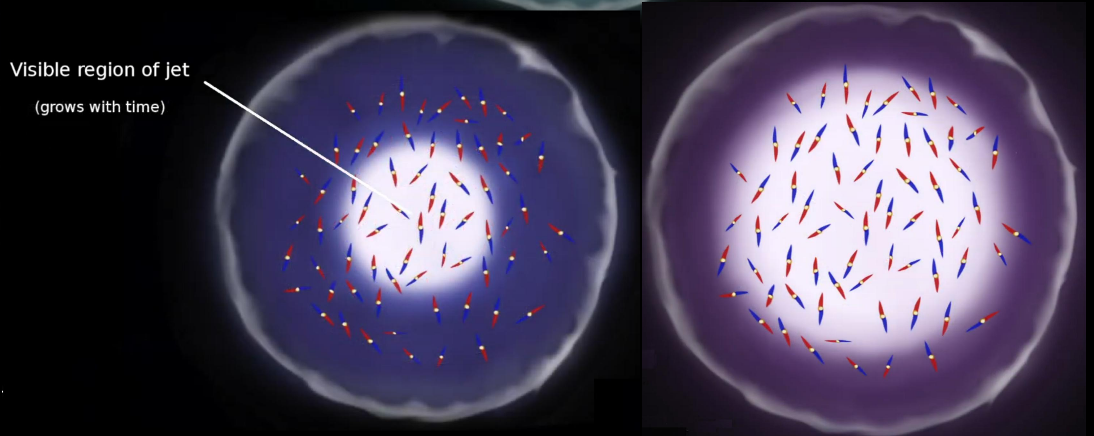
2. GRB observations with POLAR

Polarization depends on:
- jet geometry & viewing angle
- radiation mechanism
- magnetic field

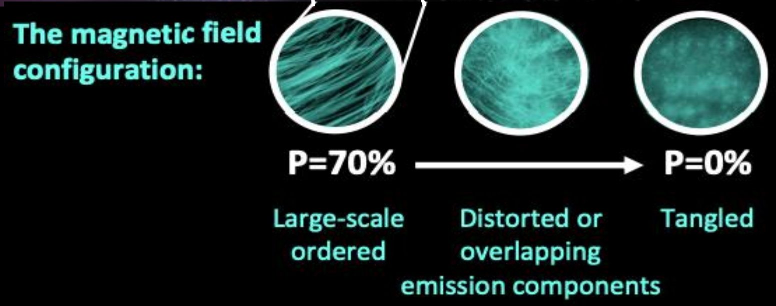


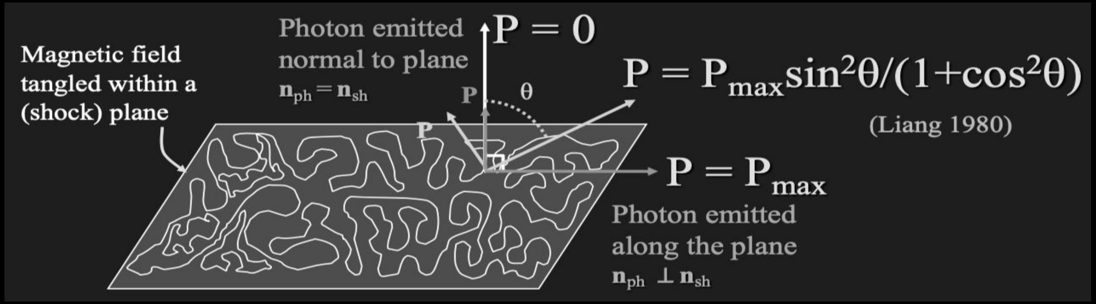
Youtube: . mkWiBf3gy3Q



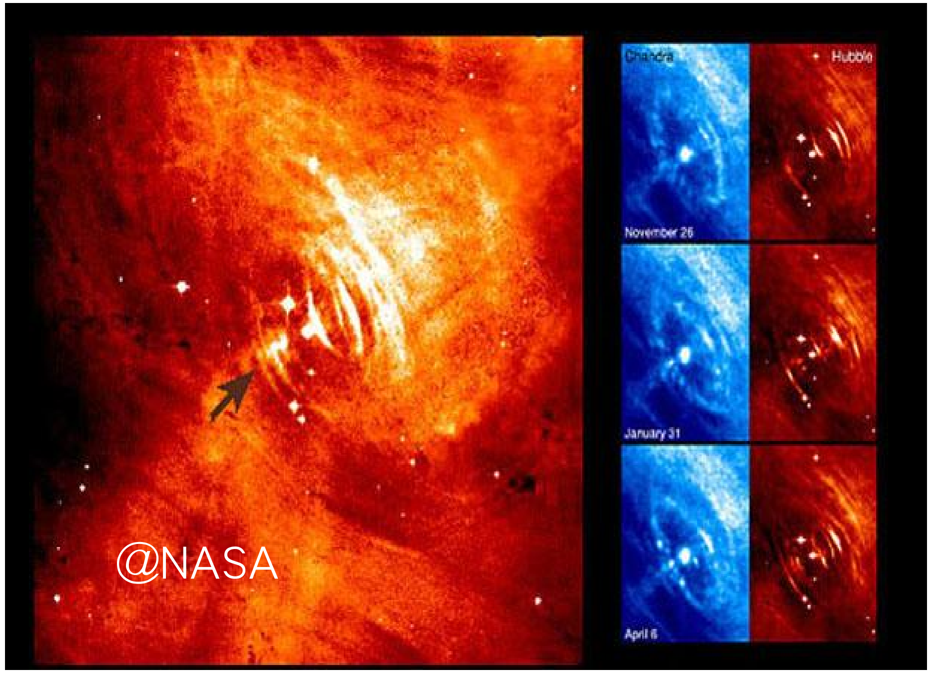


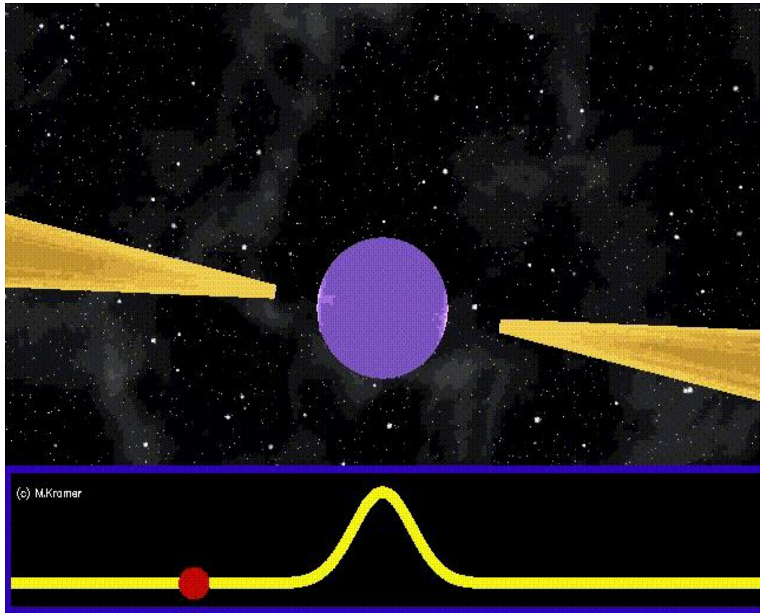
Polarization cancels partially when more patches being observed

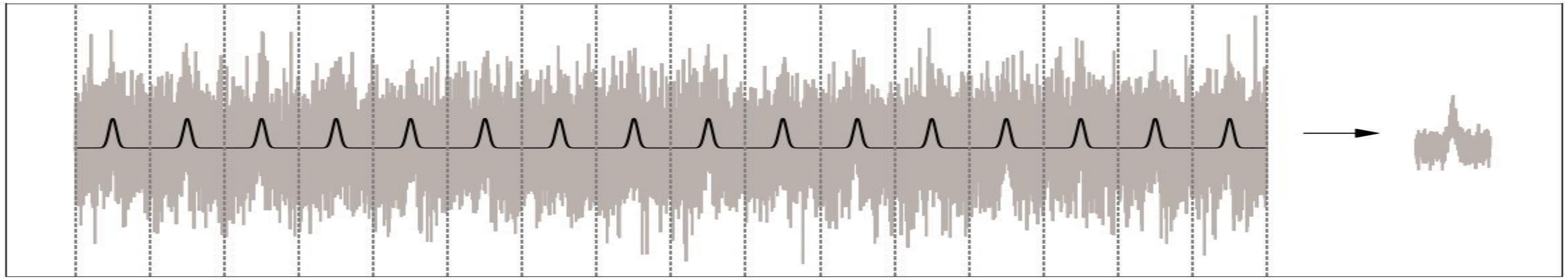




3. Pulsar observations with POLAR: stacking the periodic signal



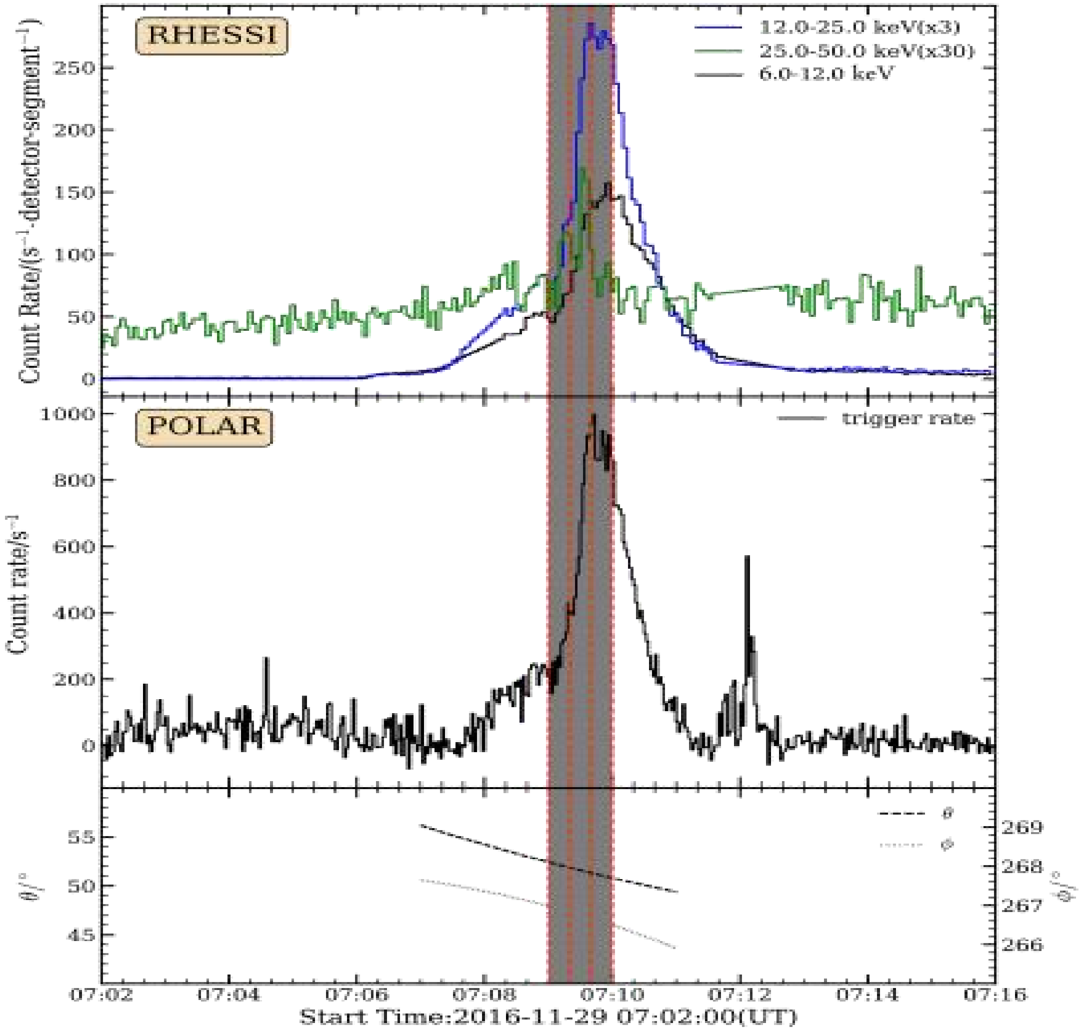




4. Other observations: solar flares

No.	编号	峰值时间 (UTC)	持续时间 (seconds)	总光子数 (counts)	入射角 (°) (θ, ϕ)	运行模式	备注
1	SFL161012498	2016-10-12T11:53:58	67	5561	(41, 228)	DM	-
2	SFL161128330	2016-11-28T07:59:55	135	8463	(71, 268)	DM	-
3	SFL161129299	2016-11-29T07:09:42	161	72038	(51, 267)	DM	-
4	SFL161130056	2016-11-30T01:19:21	229	77519	(86, 269)	DM	-
5	SFL161130645	2016-11-30T15:24:35	64	5644	(43, 267)	DM	-
6	SFL170209293	2017-02-09T07:01:43	120	23377	(56, 62)	SM	-
7	SFL170327764	2017-03-27T18:18:09	119	6447	(42, 258)	DM	单模块触发
8	SFL170328139	2017-03-28T03:23:04	164	12601	(54, 259)	DM	-
9	SFL170328205	2017-03-28T04:54:06	375	10902	(55, 259)	DM	单模块触发

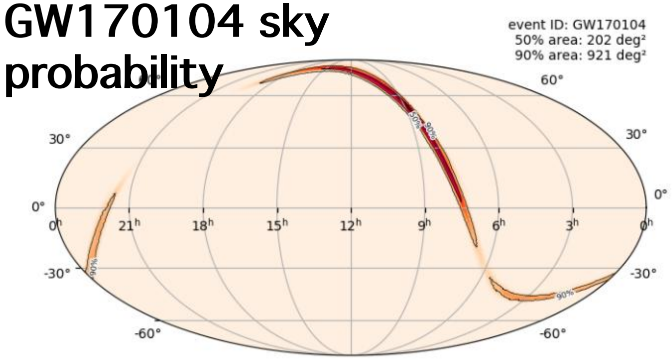
A list of 9 solar flares

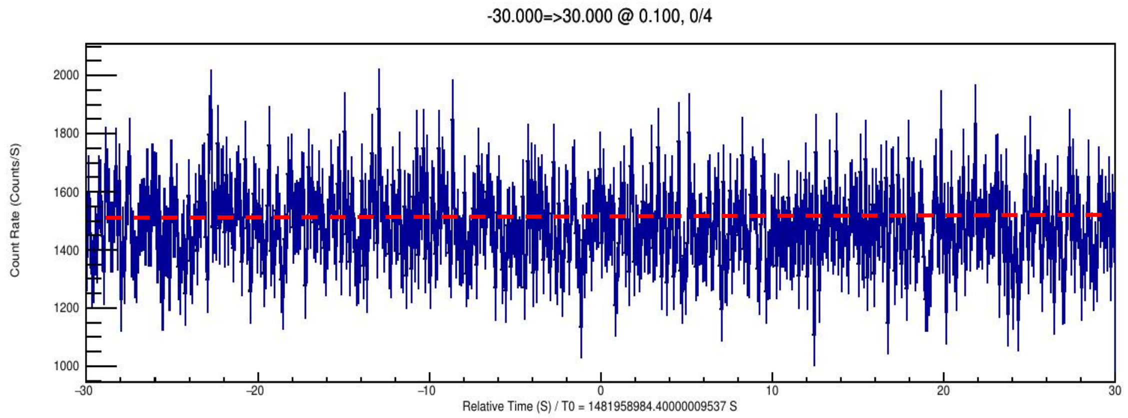


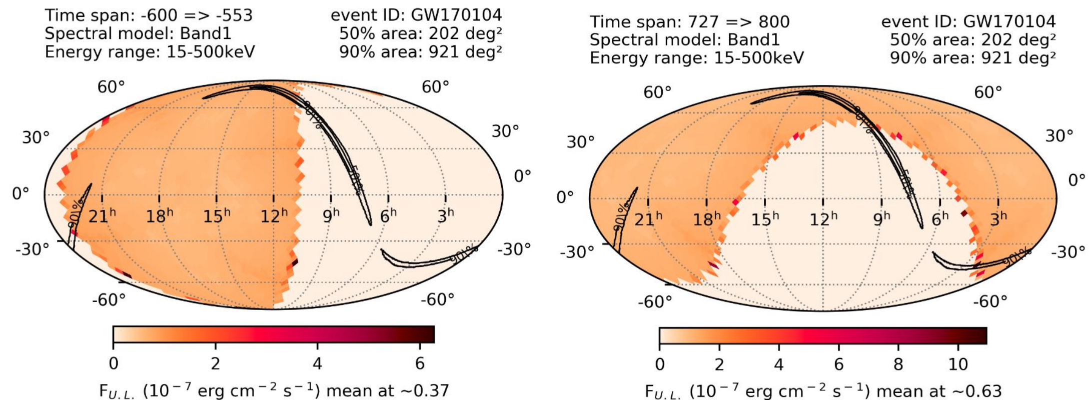
(Zhang, P., et al, 2020)

4. Other observations: GW follow-up observations

GW170104 sky probability





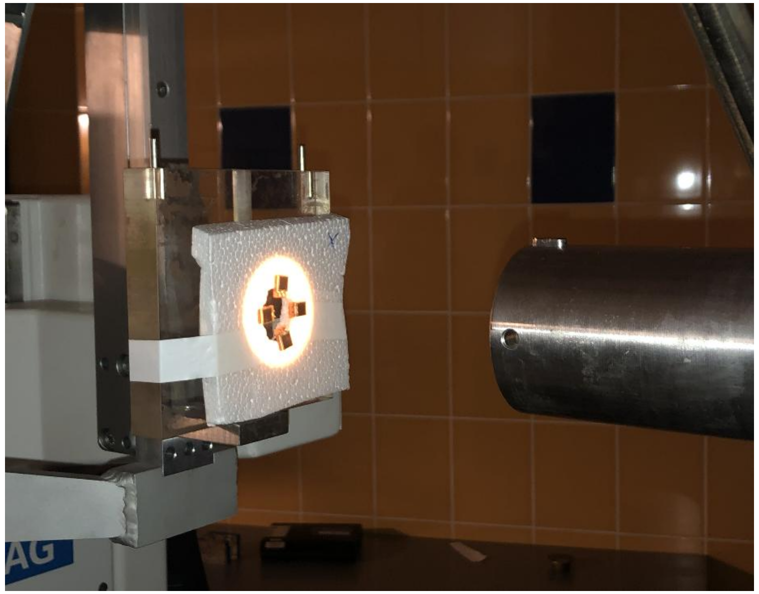


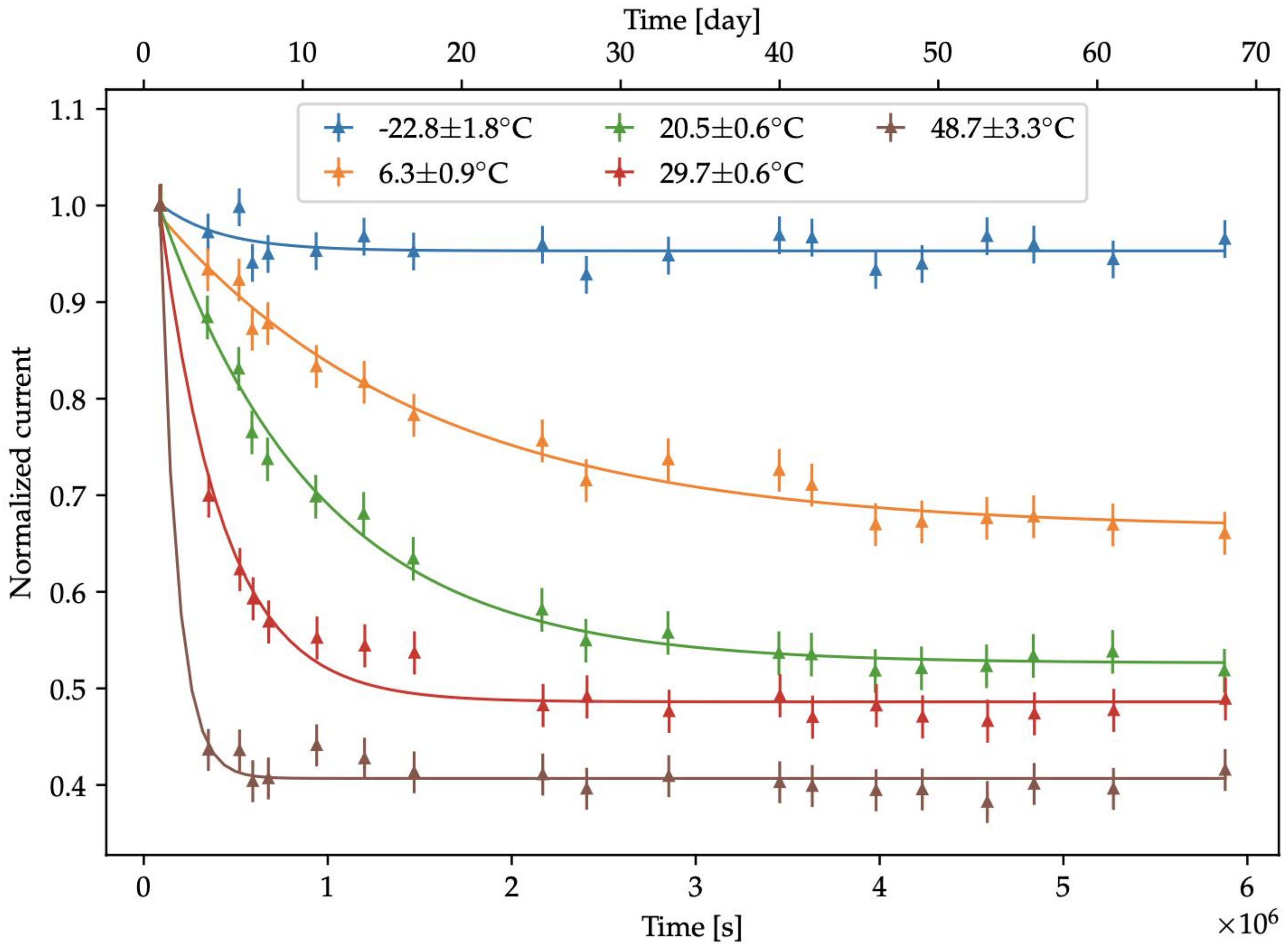
UID	UTC-T_0	T_{start} (s)	T_{end} (s)	Band1	Band2	Band3
170104	*2017-01-04T10:11:58.6*	*-600*	*-553*	*3.7E-8*	*2.8E-8*	*2.1E-8*
170104	*2017-01-04T10:11:58.6*	*+727*	*+800*	*6.3E-8*	*4.7E-8*	*3.5E-8*
161202	*2016-12-02T03:53:44.9*	*-826*	*-816*	*7.3E-8*	*5.5E-8*	*4.1E-8*
161202	*2016-12-02T03:53:44.9*	*+555*	*+600*	*3.9E-8*	*2.9E-8*	*2.2E-8*
161217	2016-12-17T07:16:24.4	-30	+30	7.3E-9	8.5E-9	1.1E-8
170208	*2017-02-08T10:39:25.8*	*-712*	*-703*	*3.1E-8*	*3.6E-8*	*4.8E-8*
170208	*2017-02-08T10:39:25.8*	*+619*	*+700*	*1.5E-8*	*1.8E-8*	*2.4E-8*
170219	2017-02-19T14:04:09.0	-30	+30	1.4E-8	1.7E-8	2.2E-8

instrument	particle	energy	$F_{U.L.}$ erg cm^{-2} s^{-1}
Fermi/GBM	photon	10 ~ 1000 keV	5.2E-7 ~ 9.4E-7
Fermi/LAT	photon	0.11 GeV	0.2E-9 ~ 90E-9
INTEGRAL	photon	75 keV ~ 2 MeV	1.9E-7 ~ 1E-6
AGILE/MCAL	photon	50 MeV ~ 10 GeV	2.9E-8 ~ 1.1E-6
Antares	neutrino	3.2 TeV ~ 3.6 PeV 5% ~ 95% quantiles	1.2E+55 erg

Li et al., to be published

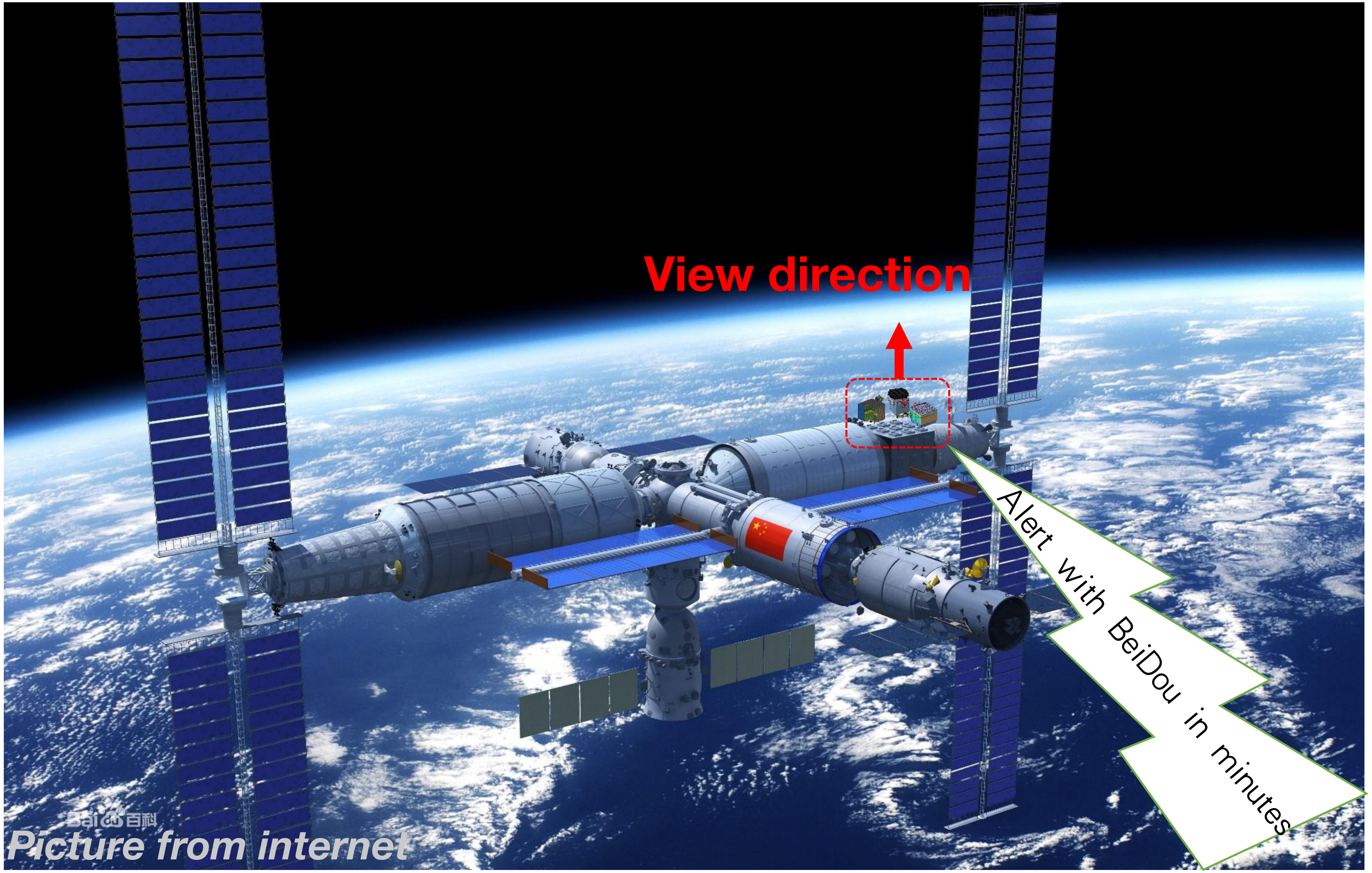
SiPM annealing



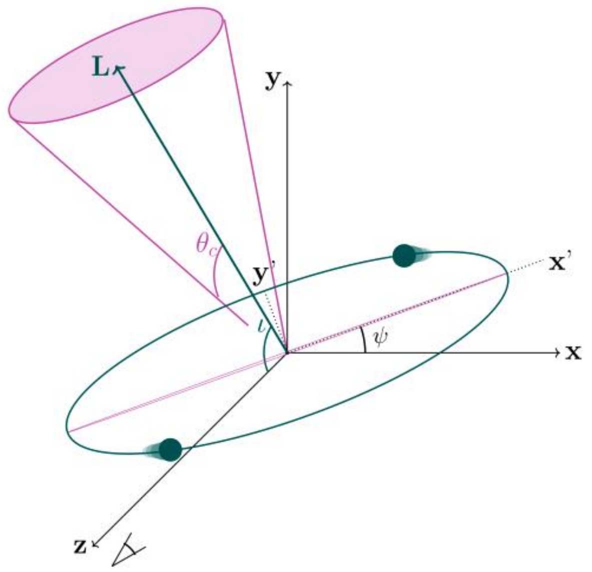


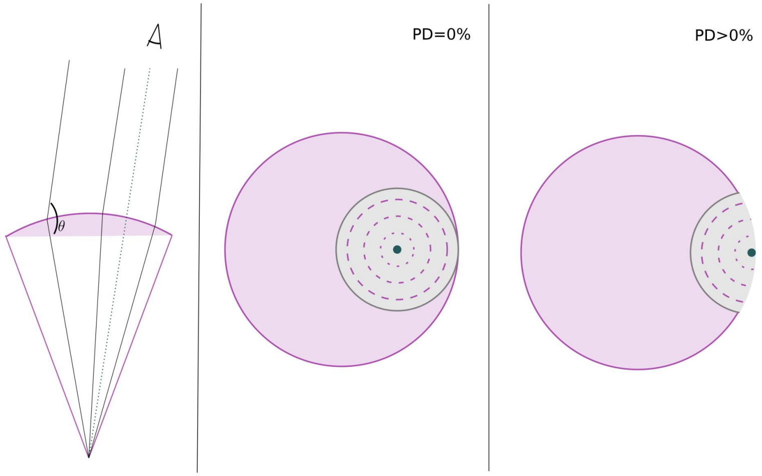
5. POLAR—2： performances (see Merlin's talk)

- Joint detection and alert：HPD (~180 ° ×180 °), LPD (~90 ° ×90 °), BSD(~120 ° ×120 °)

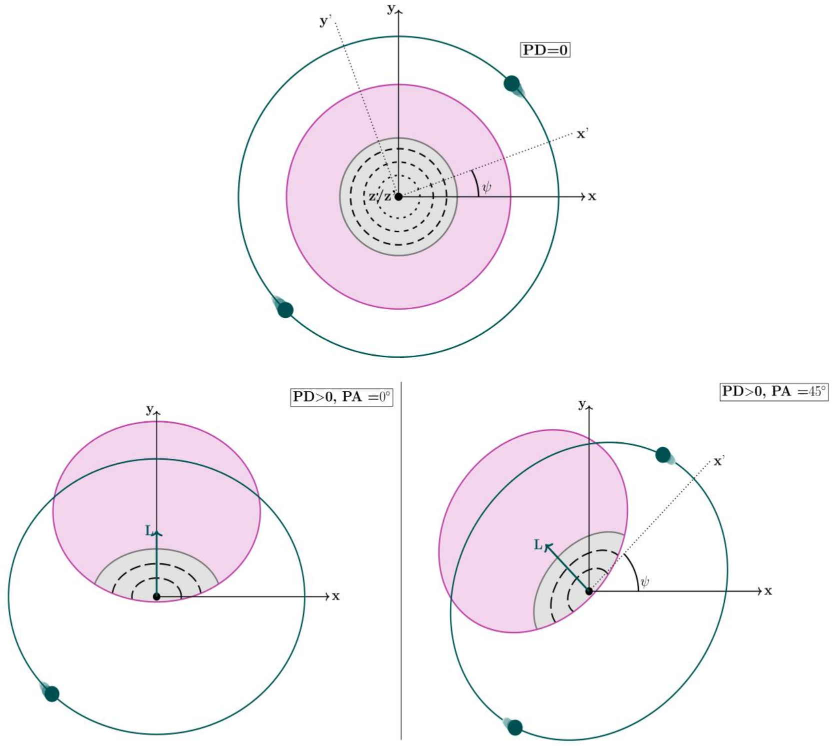


4. POLAR-2





Photosphere model



Parameter	Description	Units	Prior range
m_1	detector–frame primary mass	$M_\odot$	$(0, +\infty)$
m_2	detector–frame secondary mass	$M_\odot$	$(0, m_1]$
d_L	luminosity distance	Gpc	$(0, +\infty)$
θ, ϕ	polar and azimutal sky angles	rad	$[0, \pi]$, $[0, 2\pi]$
ι	inclination angle w.r.t. orbital angular momentum	rad	$[0, \pi]$
ψ	polarization angle	rad	$[0, \pi]$
t_c	time of coalescence GMST	day	$[0, 1]$
Φ_c	phase at coalescence	rad	$[0, 2\pi]$
$\chi_{i,z}$	spin component of object $i = \{1, 2\}$ along axis z	–	$[-1, 1]$
Λ_i	adimensional tidal deformability of object $i = \{1, 2\}$	–	$[0, +\infty)$

Emission model predictions				
Model	PD ($\iota < \theta_c$)	PD ($\iota > \theta_c$)	PA ($\iota < \theta_c$)	PA ($\iota > \theta_c$)
Photosphere	0	Low (< 20%)	–	ψ
Compton Drag	0	Medium (< 40%)	–	ψ
Synch. Rand.	0	Medium (< 40%)	–	$\psi + \pi/2$
Synch. Tor.	High (∼ 50%)	0	$\psi + \pi/2$	–
Synch. $B_\parallel$	0	High (> 50%)	–	random

Number of GW detections							
Network	$\Theta \leq 20°$	$\Theta \leq 33°$	$\Delta\psi \leq 30°$	$\Delta\iota \leq 30°$	$\Theta \leq 20°$ & $\Delta\psi \leq 30°$	$\Theta \leq 33°$ & $\Delta\psi \leq 30°$	$\Theta \leq 33°$ & $\Delta\iota \leq 30°$
LVKI O5	2	7	3	5	0	0	0
LVKI Voyager	74	148	100	78	8	26	1
ET	1573	3774	1561	4007	26	63	54
ET+2CE	4680	12035	16973	21423	59	172	144

Kole et al. 2022

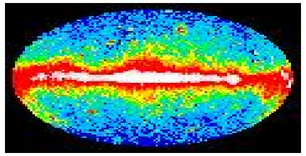
1. Polarization and GRB polarimetry: what are GRBs

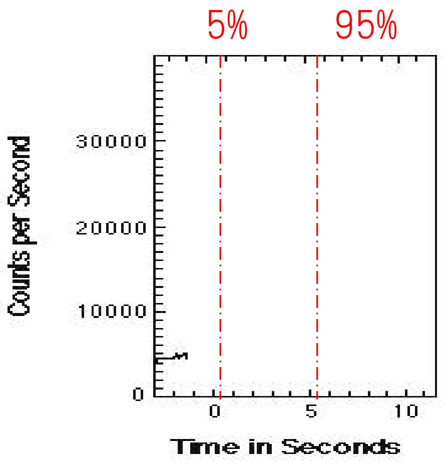
◎ Light curve

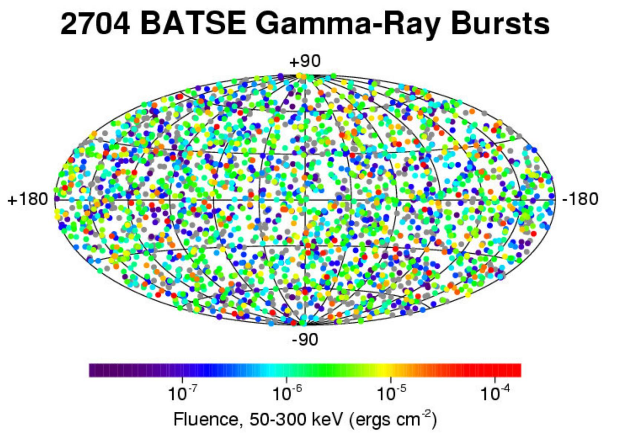
○ (One of) the most energetic explosions in the universe;

○ Irregular light curves ;

○ Asymmetric pulses;







G. Fishman et al., BATSE, CGRO

◎ T90: sensitivity—dependent

○ Total fluence from 5% to 95 % ;

○ Long/Short GRB dividing line: 3s ;

○ Reference of Prompt/Afterglow ;

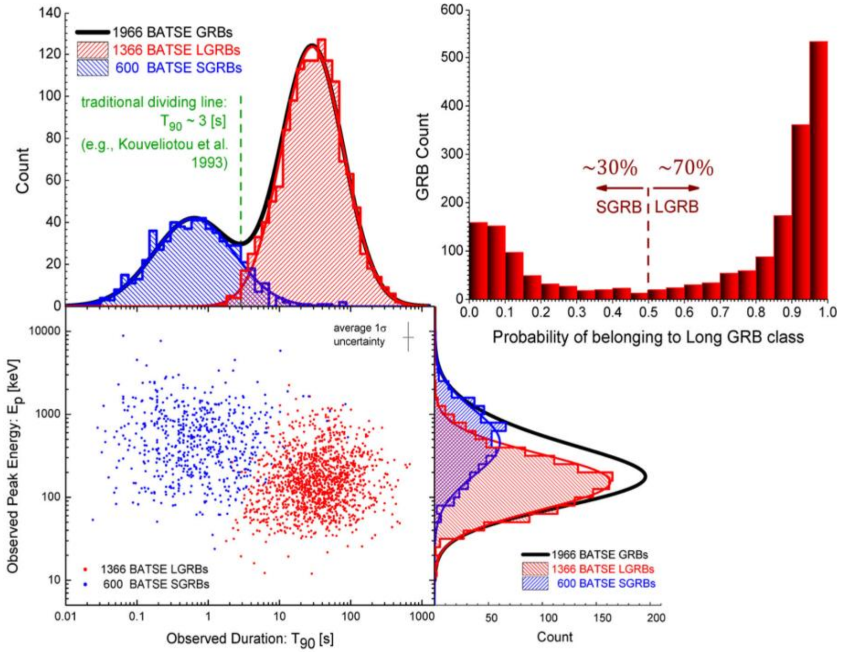
◎ Afterglow flux decay

○ Power—law: $F(t) \propto t^{\beta}$;

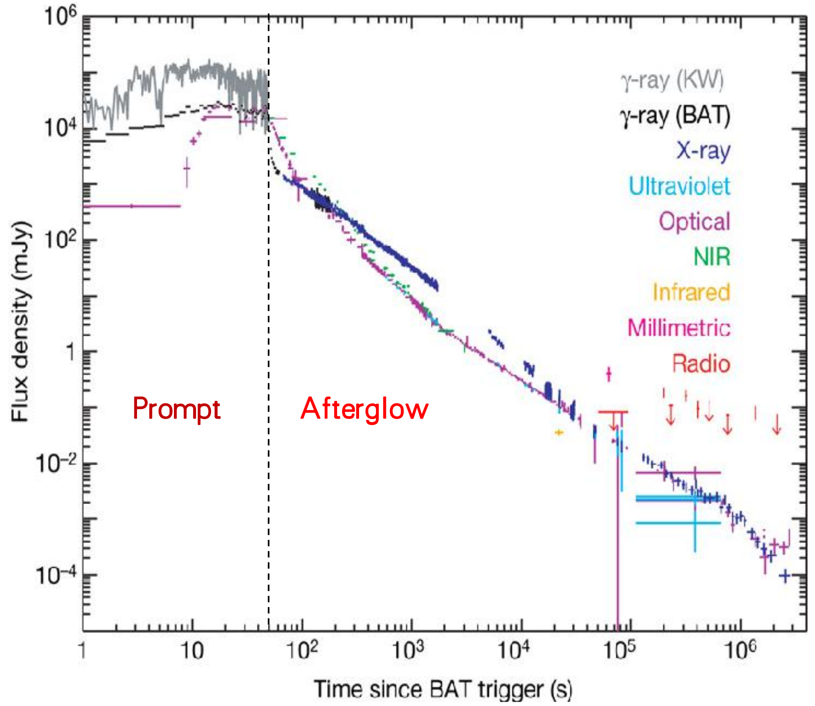
○ It has flares sometimes.

◎ Cosmic origin:

○ BATSE catalog —> uniform distribution



BATSE catalogue, A. Shahmoradi et al. (2015)



Multiwavelength OBS, Racusin+(Nature 455)

1. Polarization and GRB polarimetry: what GRBs are

◎ GRB Origin

○ Short GRB –> NS–NS(NS–BH) ;

○ Long GRB –> Hypernova ;

◎ Emission origin

○ Prompt –> internal shock ;

○ Afterglow–> external shock ;

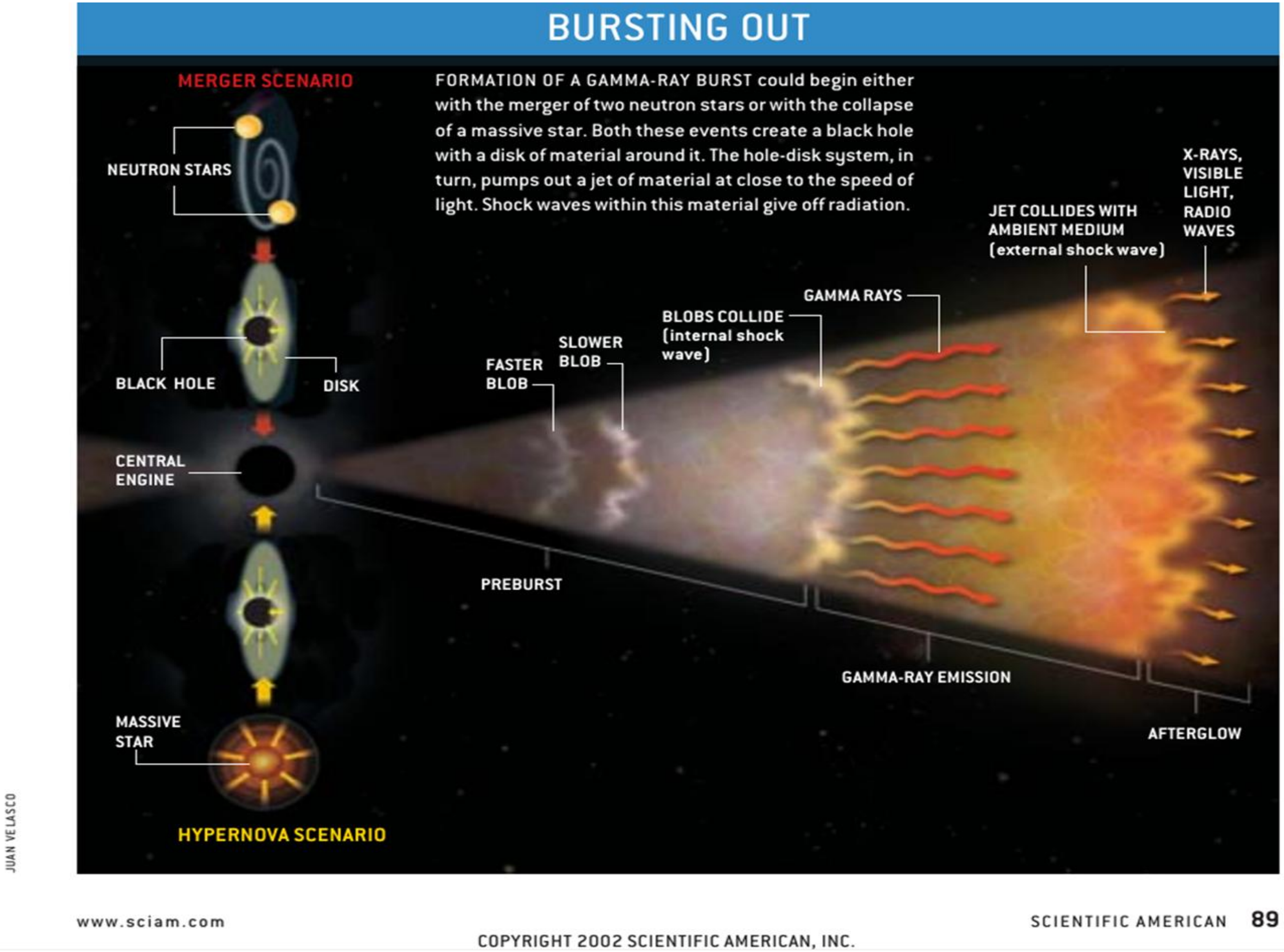
◎ Radiative processes

○ Synchrotron (mainly electron);

○ Inverse–Compton ;

○ Photo–pion:

$$p\gamma \rightarrow (\Delta^+ \rightarrow) \begin{cases} n\pi^+ \rightarrow n\mu^+\nu_\mu \rightarrow ne^+\nu_e\bar{\nu}_\mu\nu_\mu, & \text{fraction } 1/3 \\ p\pi^0 \rightarrow p\gamma\gamma, & \text{fraction } 2/3. \end{cases}$$



2. Pulsar observations with POLAR: two pulsars detected

◎Observation mode: single bar event

- ○ Double Mode (DM): pre-scale (1%)
- ○ Single Mode (SM): no pre-scale, >1 month

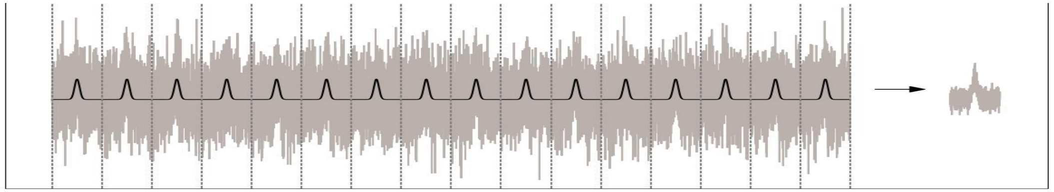
◎Timing analysis

- ○ Correction on time of arrival: SSB clock

$$T_{\mathrm{SSB}} = T_{\mathrm{obs}} + T_{\mathrm{clk}} + \Delta_R + \Delta_S + \Delta_E + \Delta_P + \Delta_B + \ \dots,$$

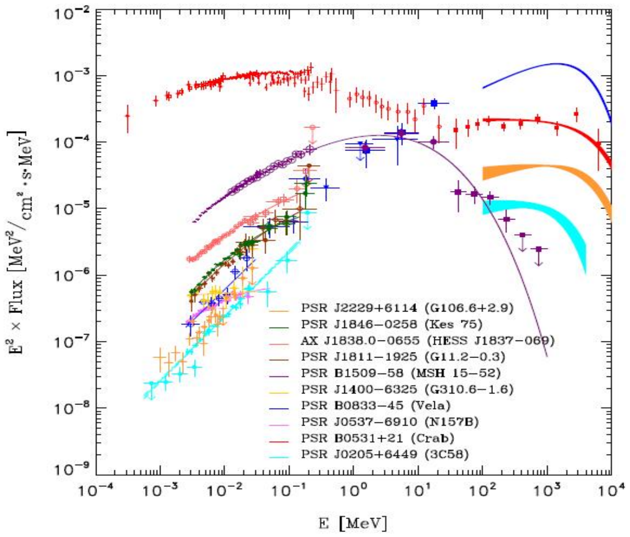
- ○ Periodic parameters and phase folding

$$\phi_i = f_0(t_i - t_0) + \frac{1}{2} f_1 (t_i - t_0)^2 + \frac{1}{6} f_2 (t_i - t_0)^3 + \frac{1}{24} f_3 (t_i - t_0)^4 + \cdots,$$



◎Confirmed Pulsars: to be continued

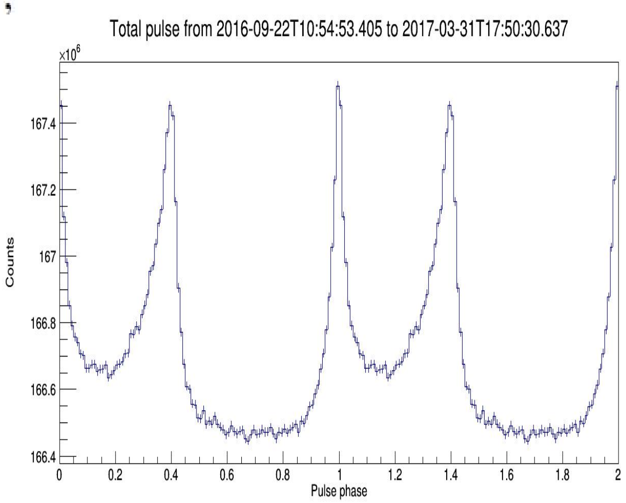
- ○ Crab Pulsar
- ○ PSR B1509−58

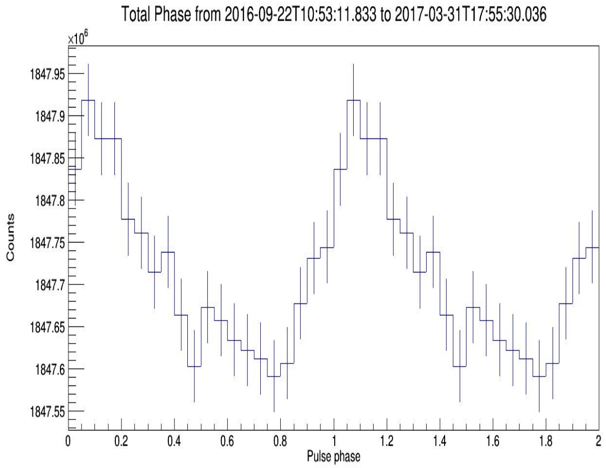


10.1051/0004−6361:20011256

表 2.1 Crab 脉冲星和 B1509-58 的最佳自转参数

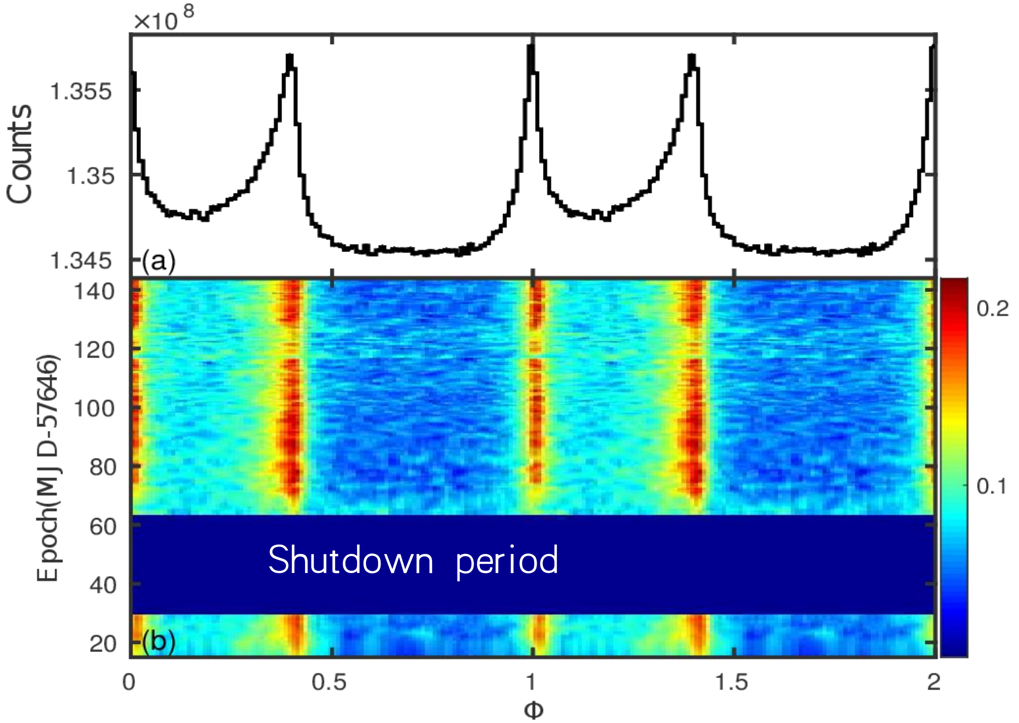
Parameters	Crab pulsar	B1509-58
t_0 (MJD)	57697.040344079745	55336.0
f_0 (Hz)	29.6484272934(4)	6.59709206418
f_1 (Hz s^{-1})	-3.689865(1)E-10	-6.6531338E-11
f_2 (Hz s^{-2})	1.16(1)E-20	1.8948E-21
f_3 (Hz s^{-3})	3.4(3)E-28	0.0

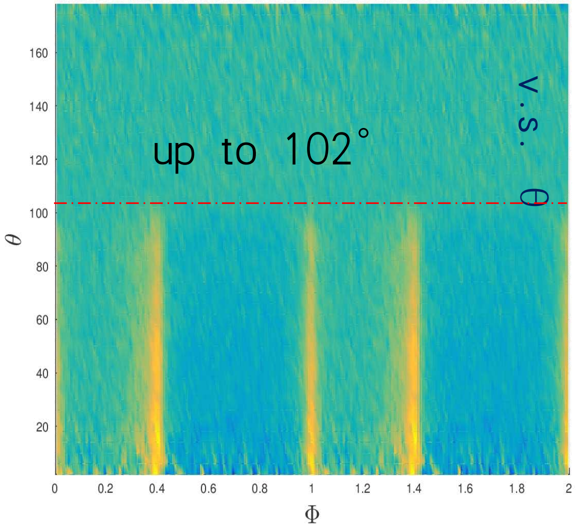


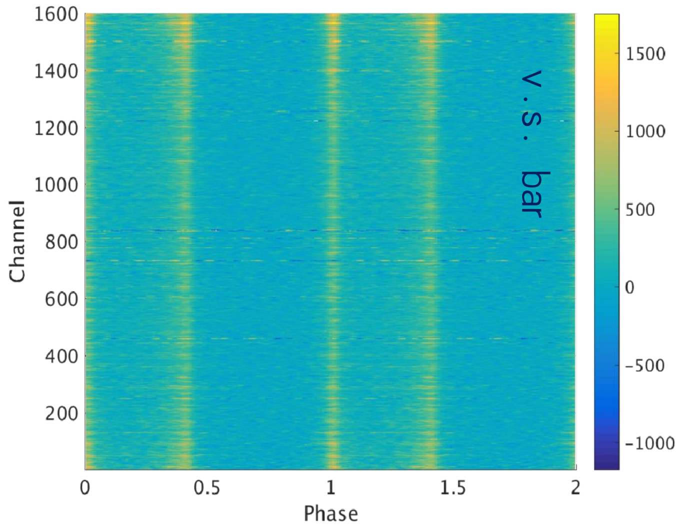


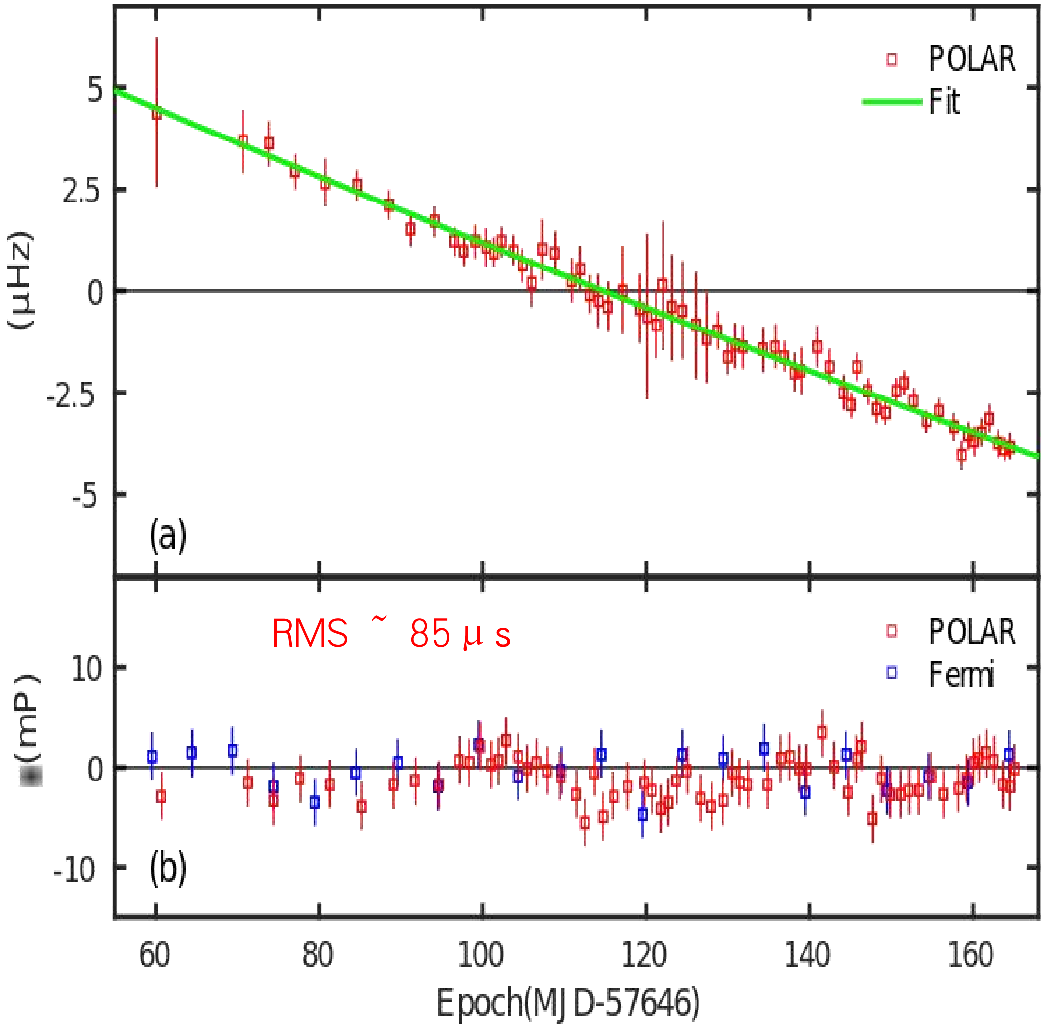
Li et al., 2021

2. Pulsar observations with POLAR: Crab timing



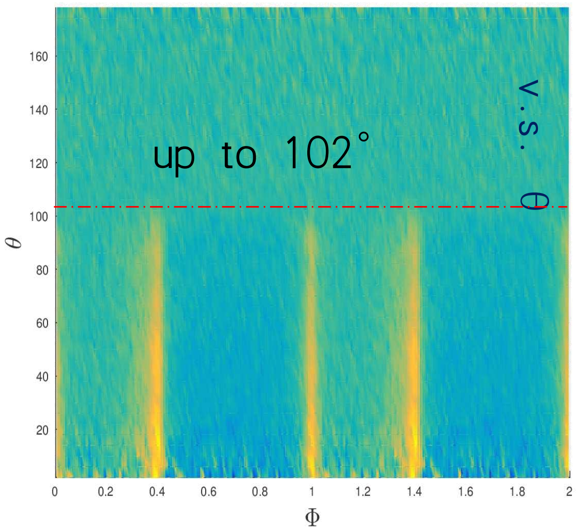


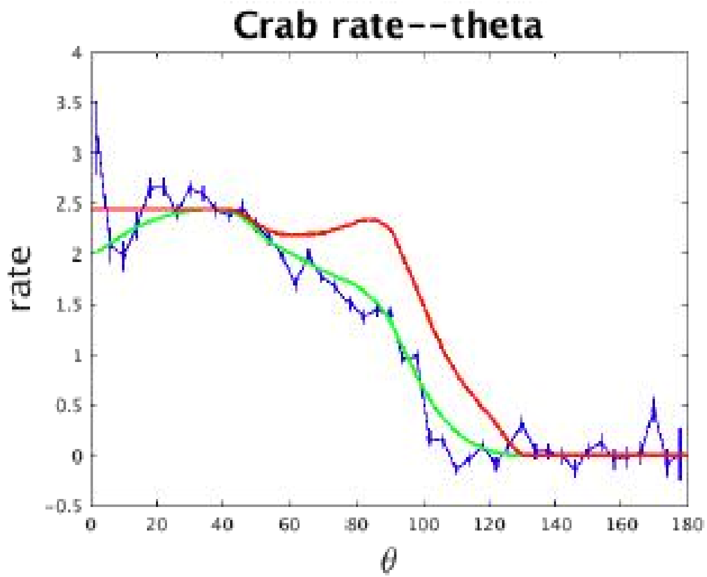


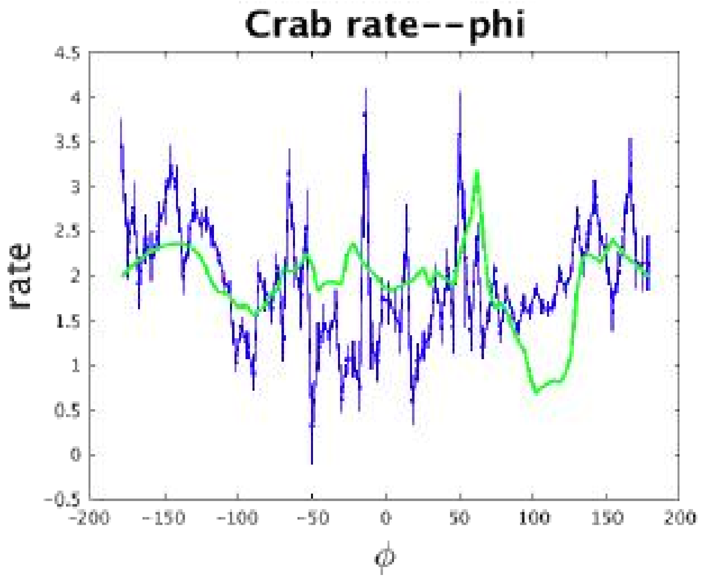


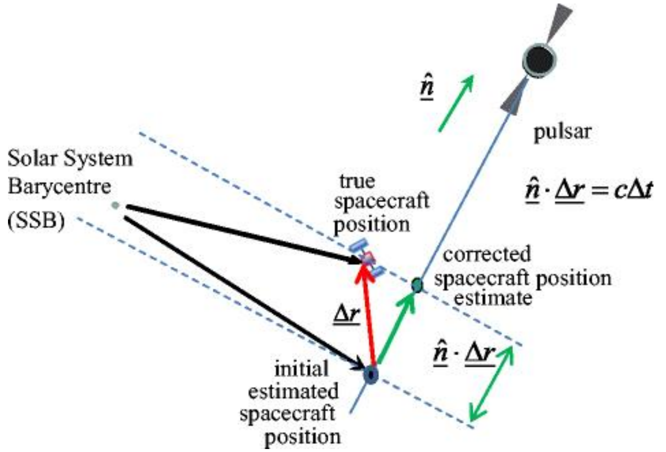
Li et al., (2017), Zheng et al., 2017

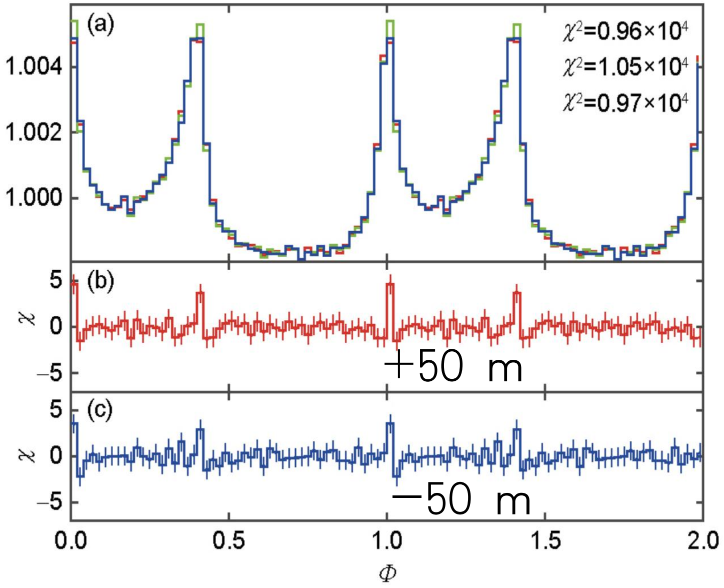
2. Pulsar observations with POLAR: Crab navigation (highlight)

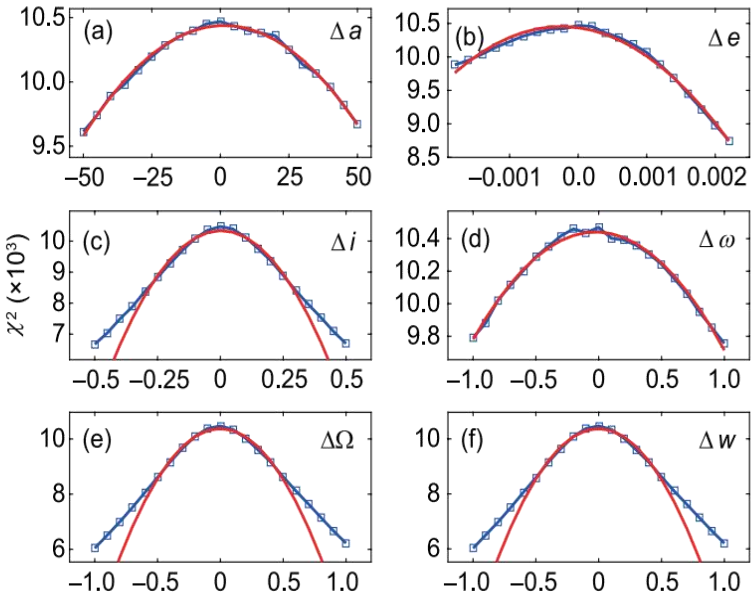








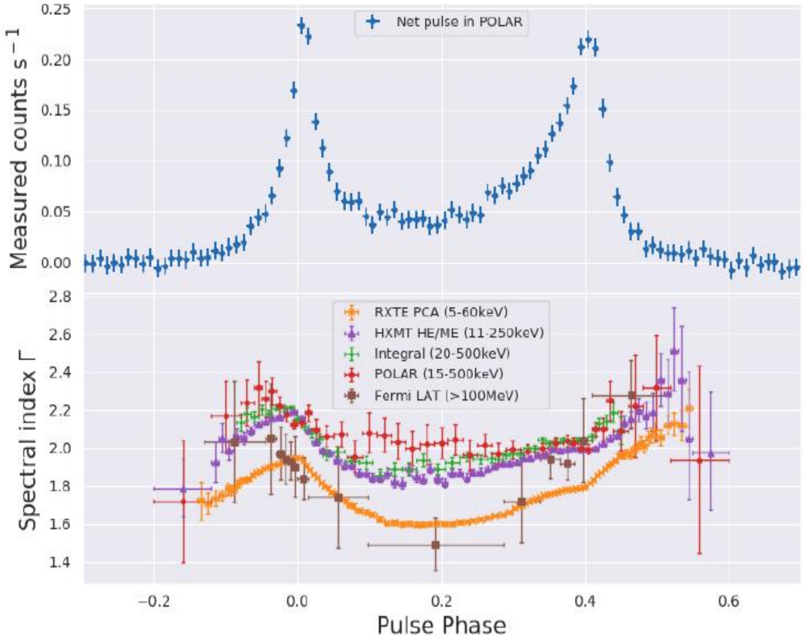




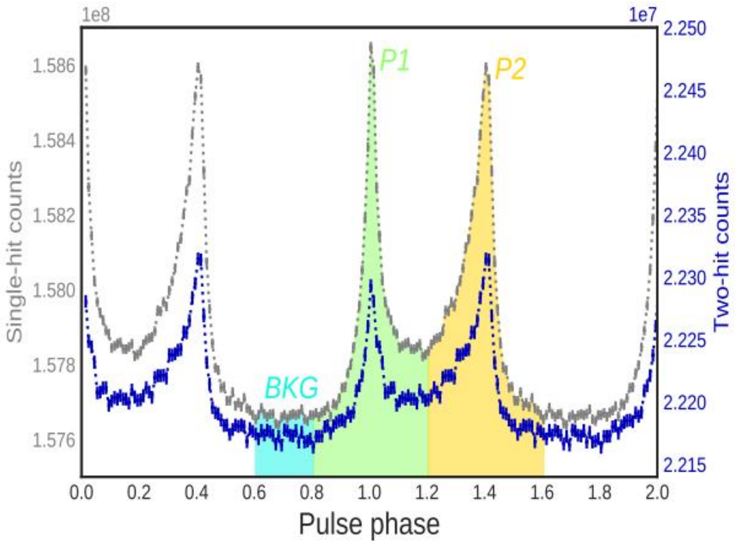
X (km)	11.5
Y (km)	13.1
Z (km)	9.1
Vx (km/s)	0.30
Vy (km/s)	0.31
Vz (km/s)	0.010

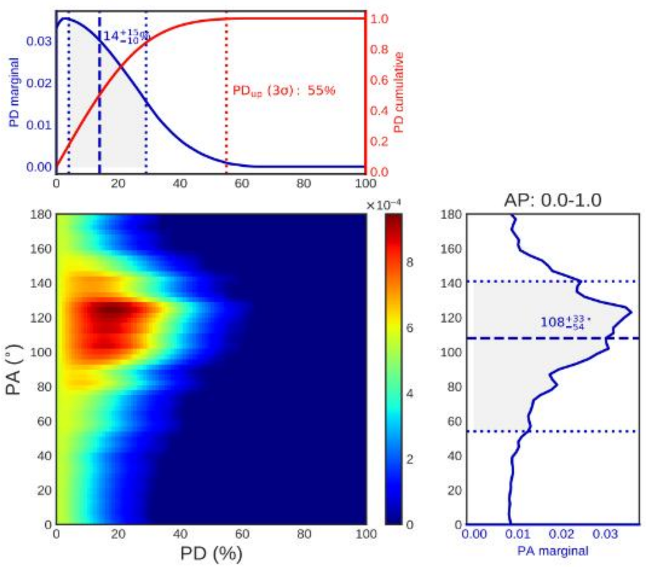
Zheng et al., 2017

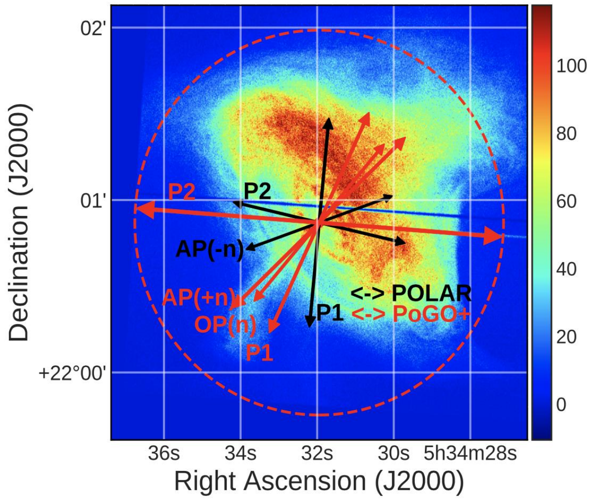
2. Pulsar observations with POLAR: Crab spectra & polarization



Li et al., 2019

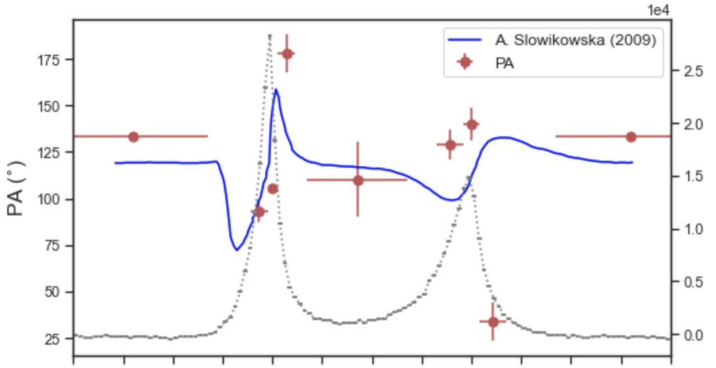


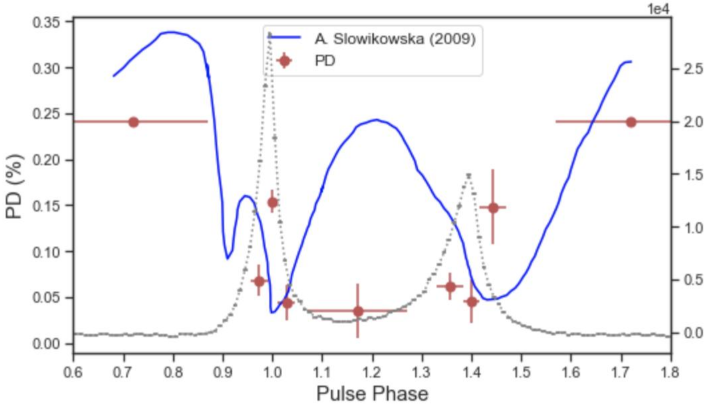




Li et al., 2022

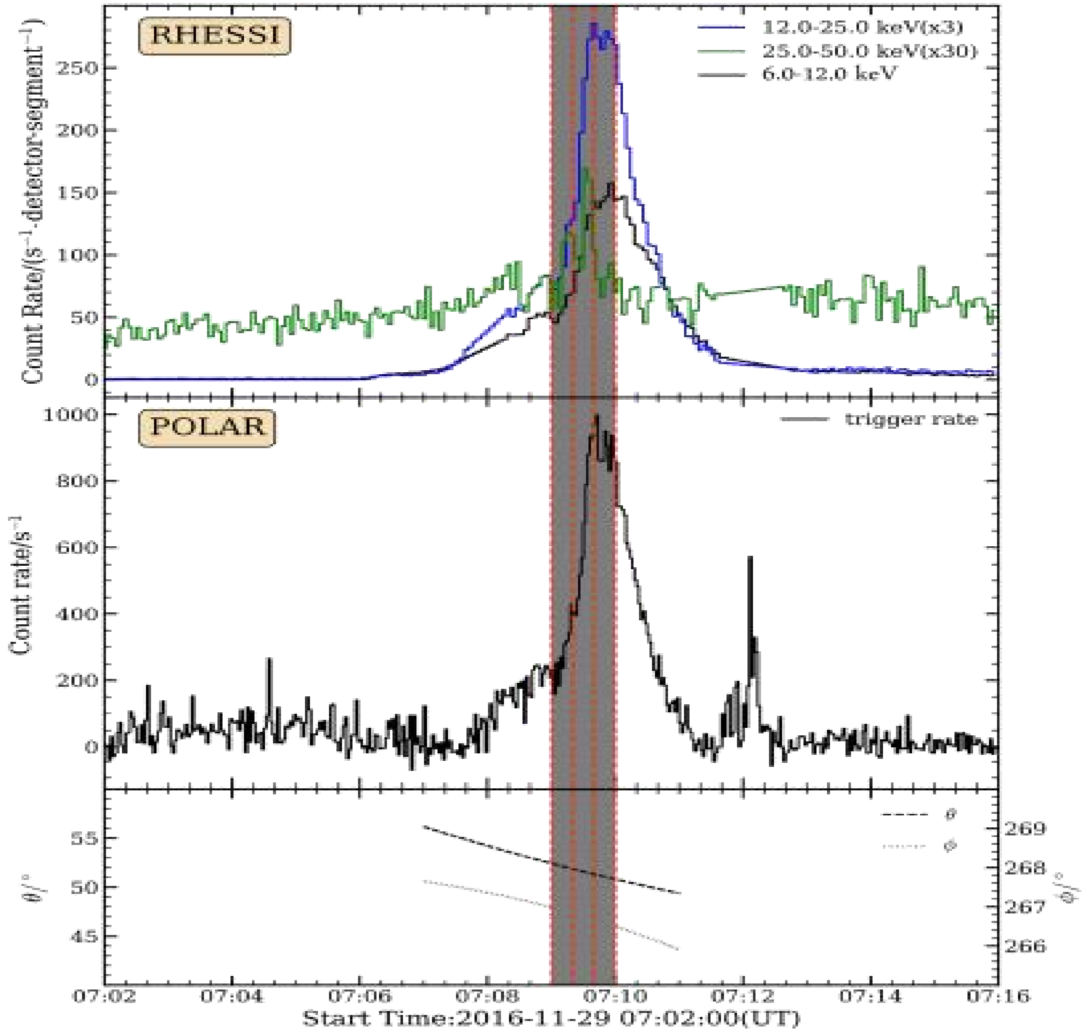
Phase range	PA (°)	PD(%)	3σ PD_{up} (%)
AP (0.0-1.0)	108^{+33}_{-54}	14^{+15}_{-10}	55
P1 (0.2-0.6)	174^{+39}_{-36}	17^{+18}_{-12}	66
P2 (0.8-1.2)	78^{+39}_{-30}	16^{+16}_{-11}	57





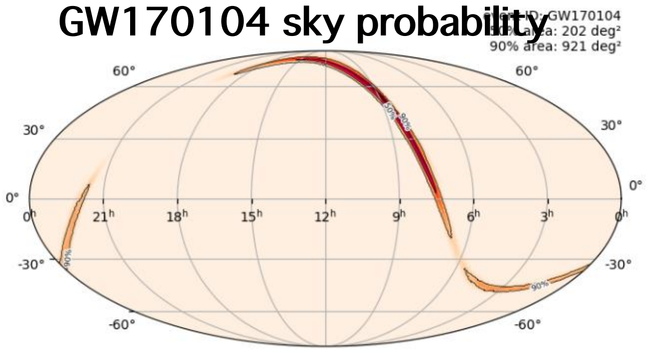
IXPE / OPTIMA results
Arxiv: 0901.4559, 2207.05573

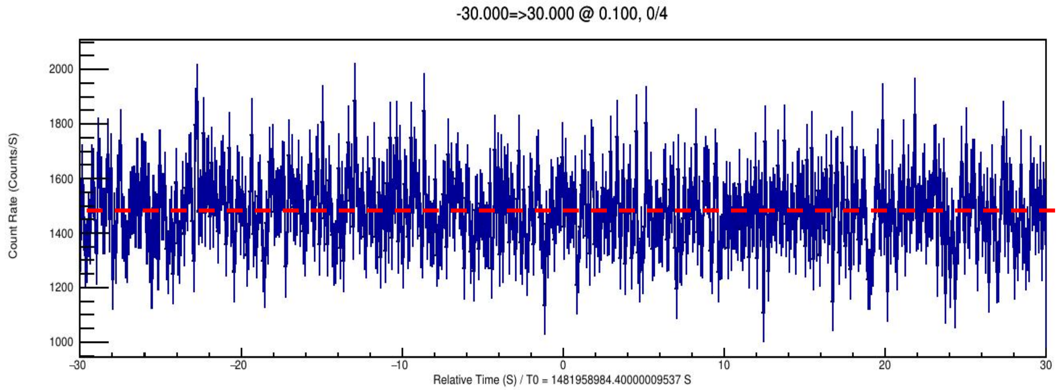
3. Other observations: solar flares & GW follow-up

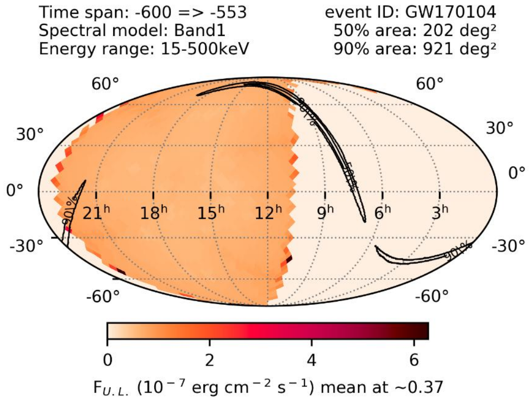


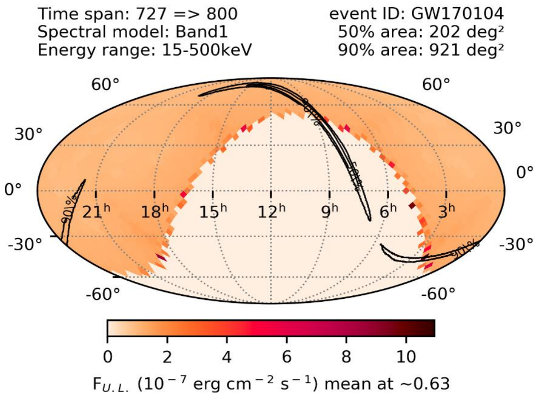
Zhang et al, 2020, 1 of the 9 events

GW170104 sky probability









Not yet published

Thanks for your attention.

POLAR collab. meeting in 2017

POLAR−2 collab. meeting in 2019