Gamma-Ray Burst Polarization

Diego Götz
CEA-Irfu/Service d'Astrophysique

Based on the recent review by Covino & Götz, Astronomical and Astrophysical Transactions, 37 (2016), astro-ph/1605.03588

Summary

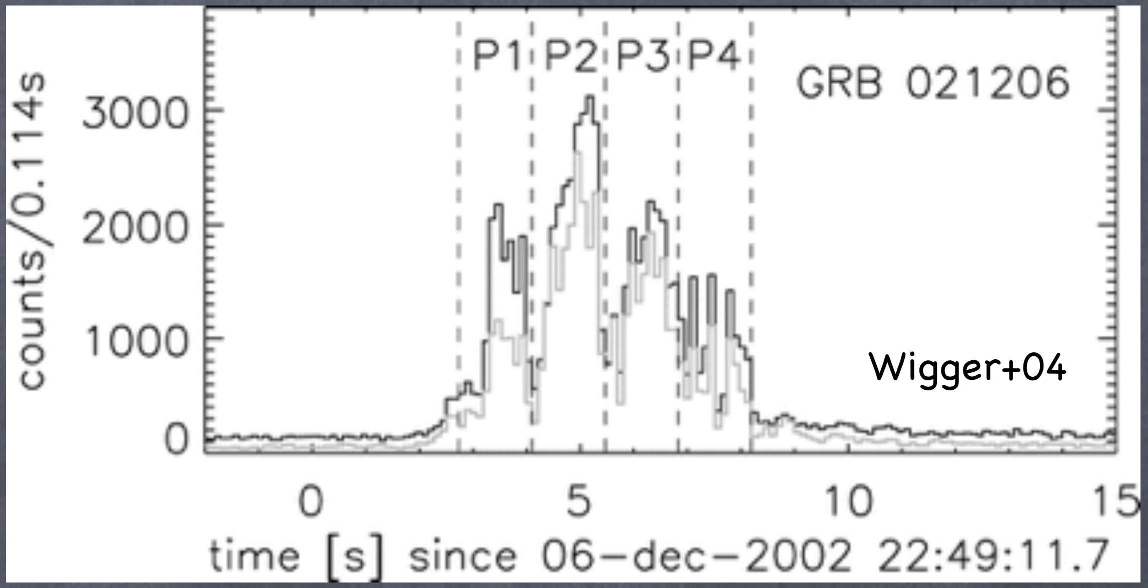
- Polarization in the prompt phase
    - Observations
        - Theory
- Polarization in the afterglow phase
    - Observations
        - Theory
- Conclusions and Perspectives

Why Polarization?

- Polarization measurements provide complementary information wrt. more classical timing and spectral measurements
- Some open points in GRB modeling that can be addressed through polarization studies:
  - Jet composition: baryon/pair dominated of Poynting flux dominated?
  - Jet geometry
- Beyond GRB physics, polarization measurements can also provide implications for fundamental physics, like quantum gravity testing

Prompt emission: early results and measurement principle

- First attempts to measure linear polarization in GRBs have been made by RHESSI for GRB 021206 (Coburn & Boggs, 2003)
- RHESSI is composed of an array of 9 co-axial Ge detectors sensitive in the 3 keV-17 MeV energy range
- In the soft gamma-ray energy band the dominant photon interaction is Compton scattering
- Polarization can be measured thanks to its dependency of the differential cross section for Compton scattering (linearly polarized photons scatter preferentially perpendicularly to the incident polarization vector)

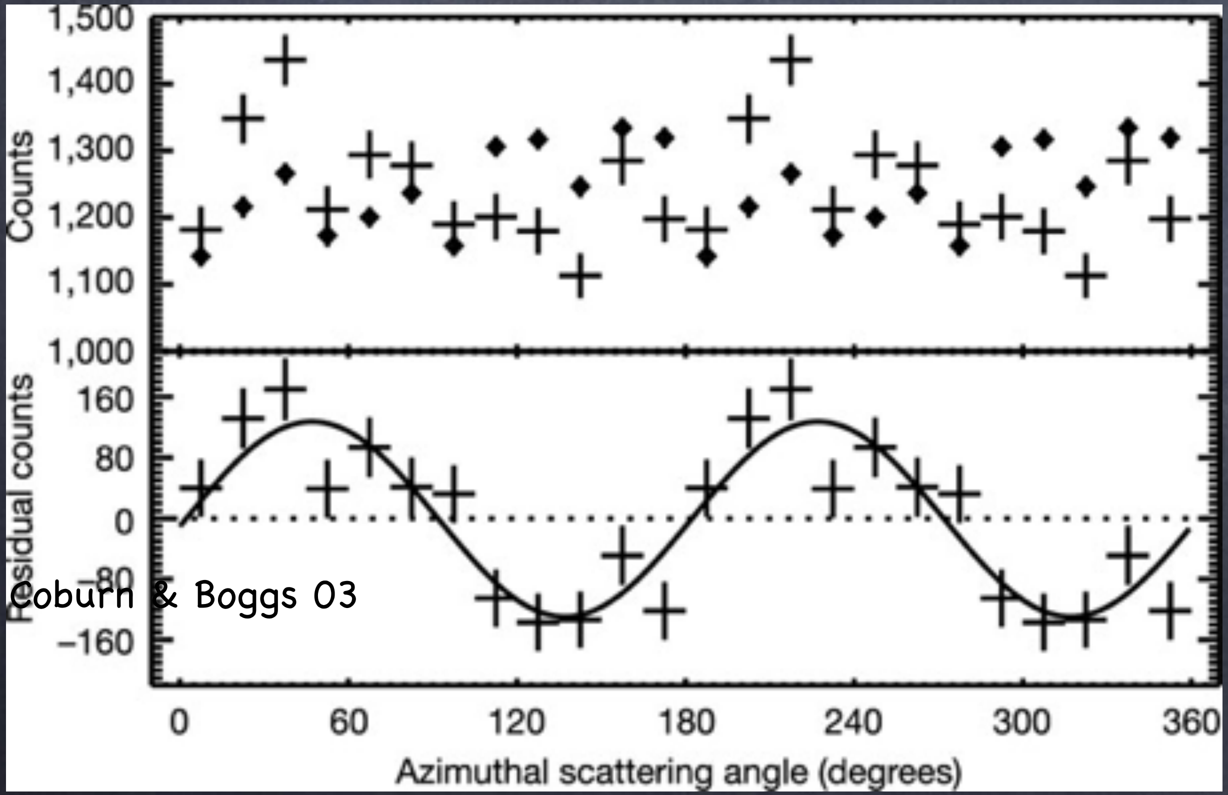


$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E_0}\right)^2\left(\frac{E'}{E_0} + \frac{E_0}{E'} - 2\sin^2\theta\cos^2\phi\right)$$

r_0 is the classical electron radius, E_0 the energy of the incident photon, E′ the energy of the scattered photon, θ the scattering angle and φ the azimuthal angle relative to the polarization direction

Prompt emission: measurement principle

- By examining the distribution of the scattering angles between different detectors one can build a so-called polarigram and derive the polarization level and angle

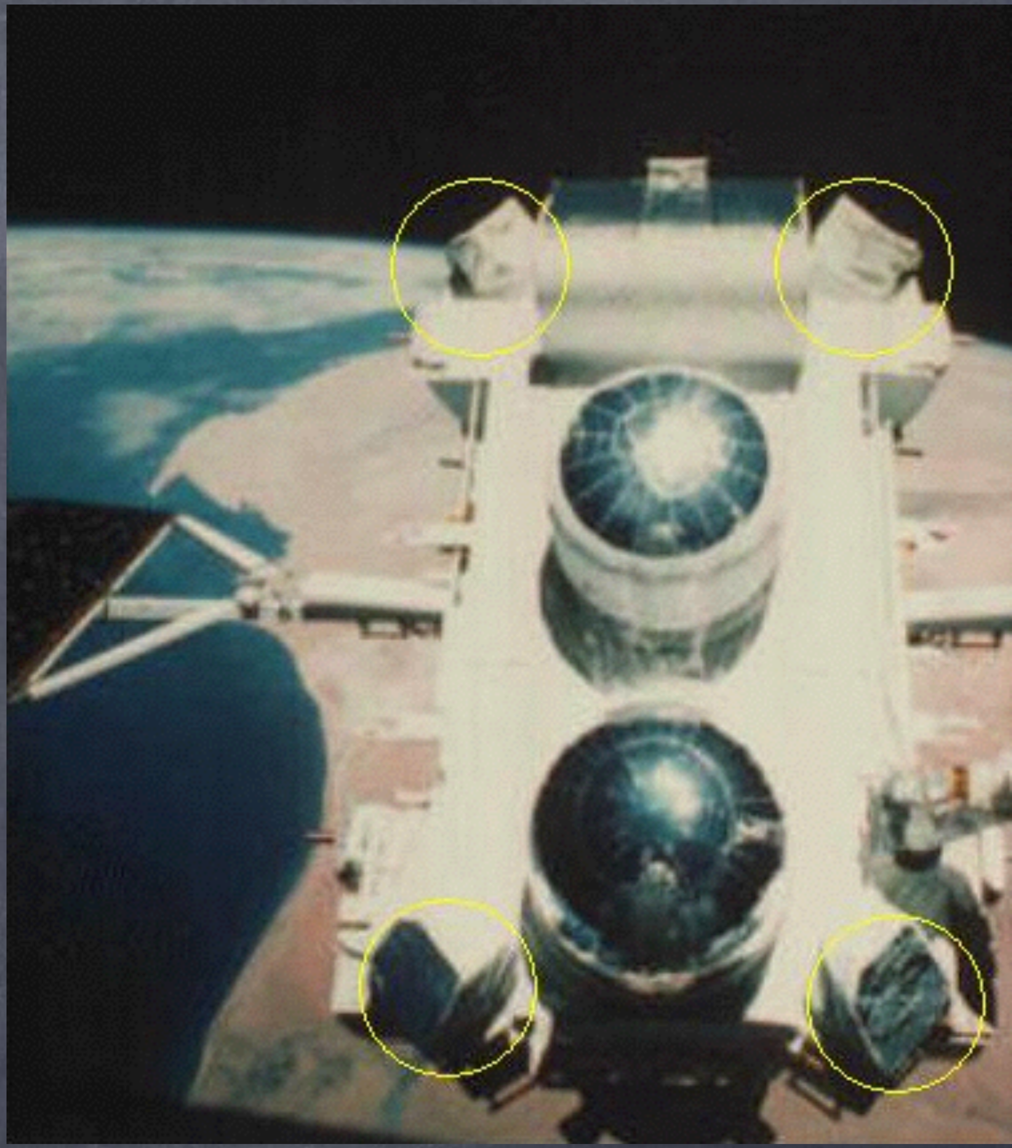


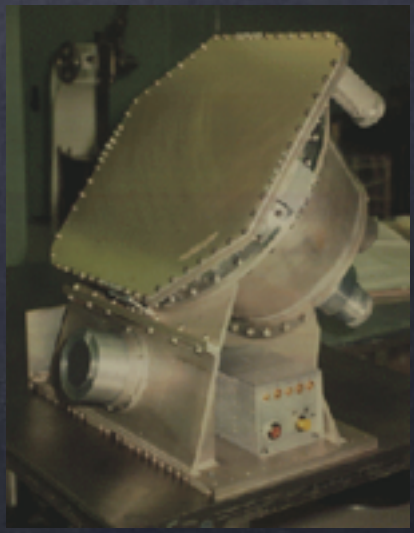
Coburn & Boggs 03

- Coburn & Boggs reported a high level of polarization Π=80±20% for GRB 021216 with a 5.7 σ c.l.
- About 10% of the GRB photons have been classified as real «coincidences» i.e. events due to Compton scattering
- However subsequent re-analysis of the same dataset by different authors (Wigger+04; Rutledge & Fox 04) did not confirm this result, stating that the polarization level was statistically compatible with 0.
  - The number of suitable events for scattering analysis had been overestimated by a factor 10 (spurious «chance» coincidences had been included in the C&B analysis)

Prompt emission measurements: early results

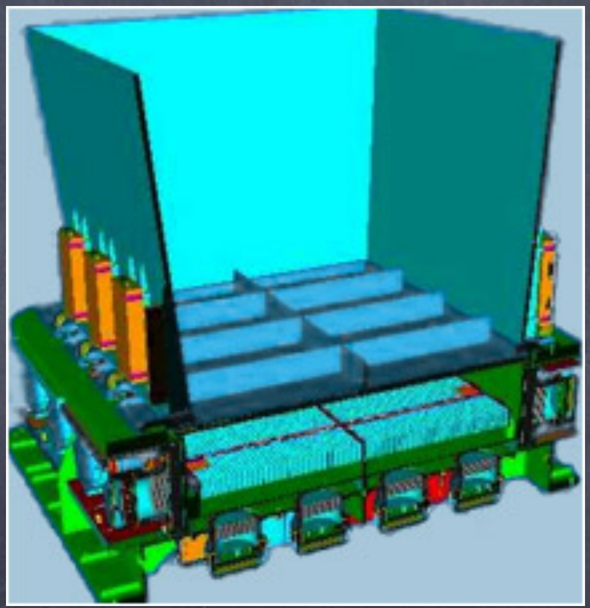
- Another early attempt to measure GRB linear polarization has been performed by Willis+05, who used the Earth atmosphere as a scatterer and CGRO/BATSE as a detector
- They reported evidence of high level of polarization in GRB 930131 (Π>35%) and GRB 960924 (Π>50%) but they could not statistically constrain their results
- The RHESSI and BATSE early results had the merit to trigger some theoretical work in order to interpret these high levels of polarization during the GRB prompt emission

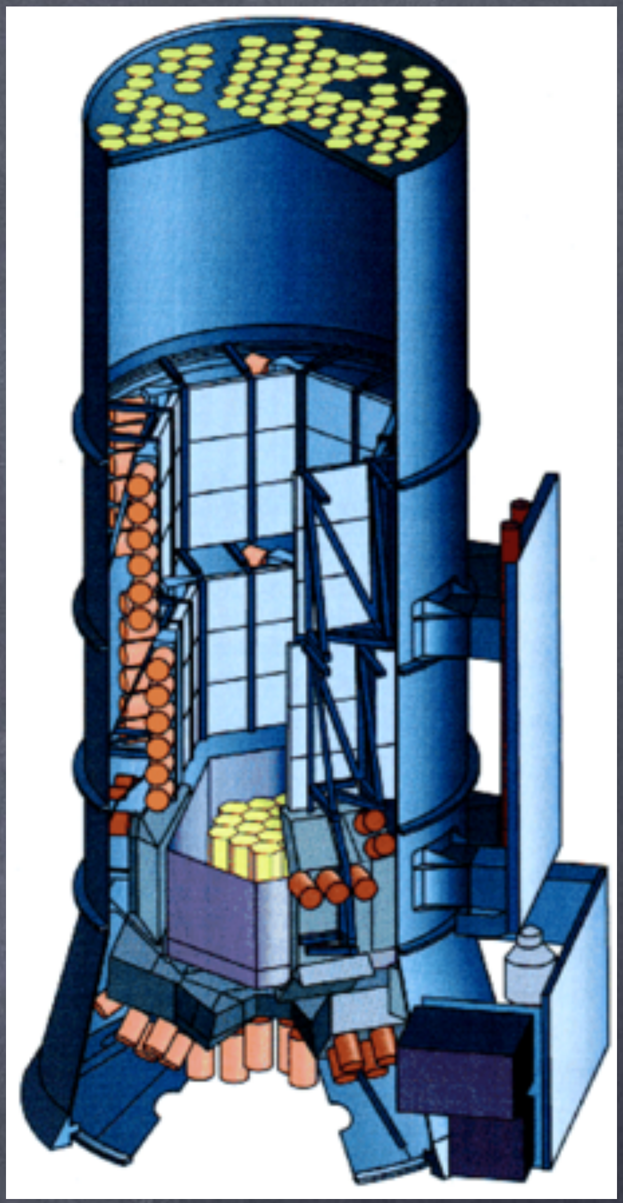




INTEGRAL (IBIS and SPI) results

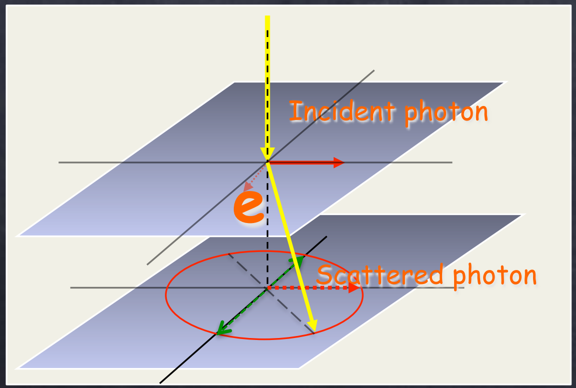
- IBIS (15 keV-10 MeV, Ubertini+03) and SPI (20 keV-8 MeV, Vedrenne+03) on board the ESA INTEGRAL mission are both coded mask instruments -> reduced background, simultaneous measure so signal and background
- Although not specifically designed, they both have some polarimetic capabilities



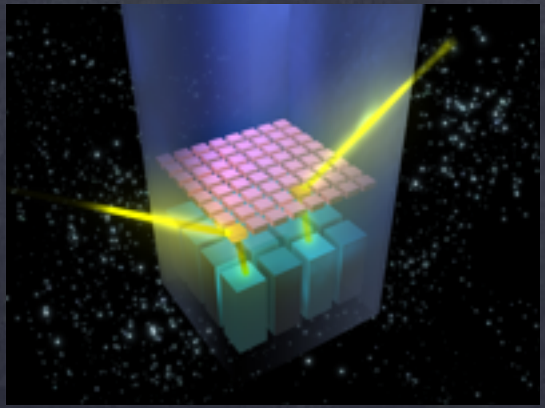


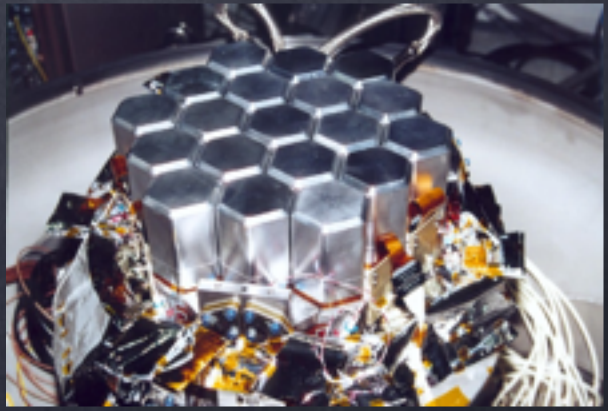
19 Ge detectors

ISGRI (CdTe)



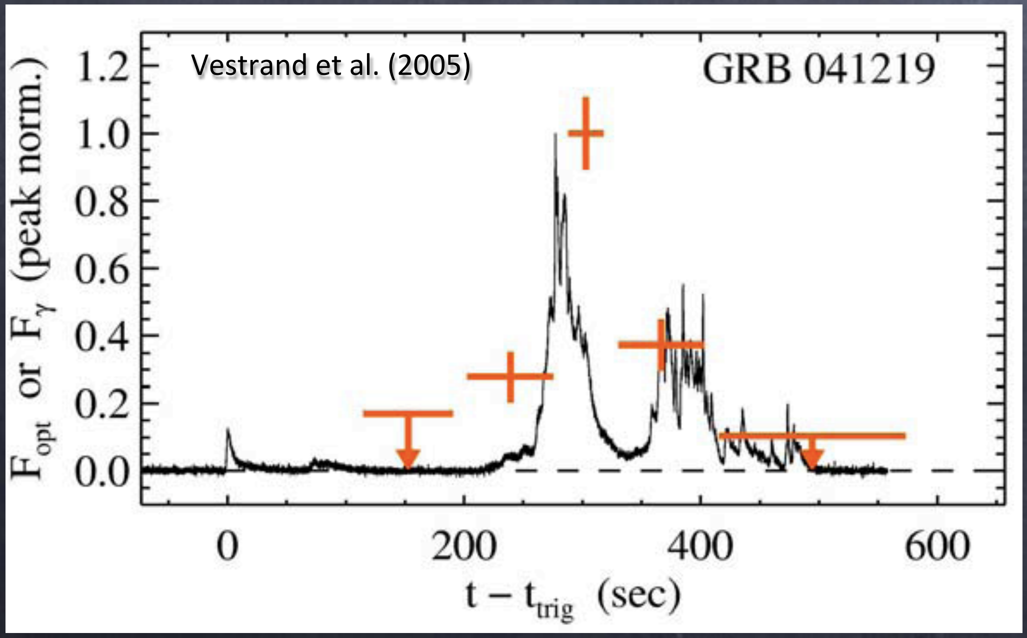
PCsIT (CsI)

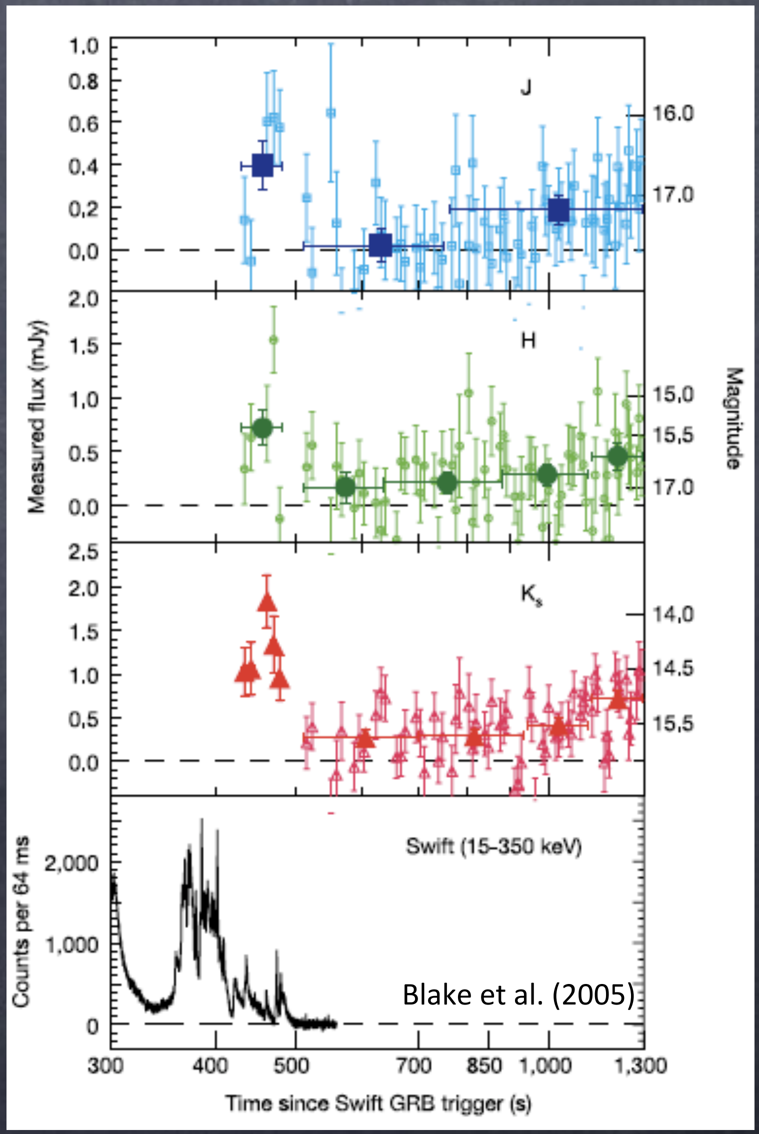




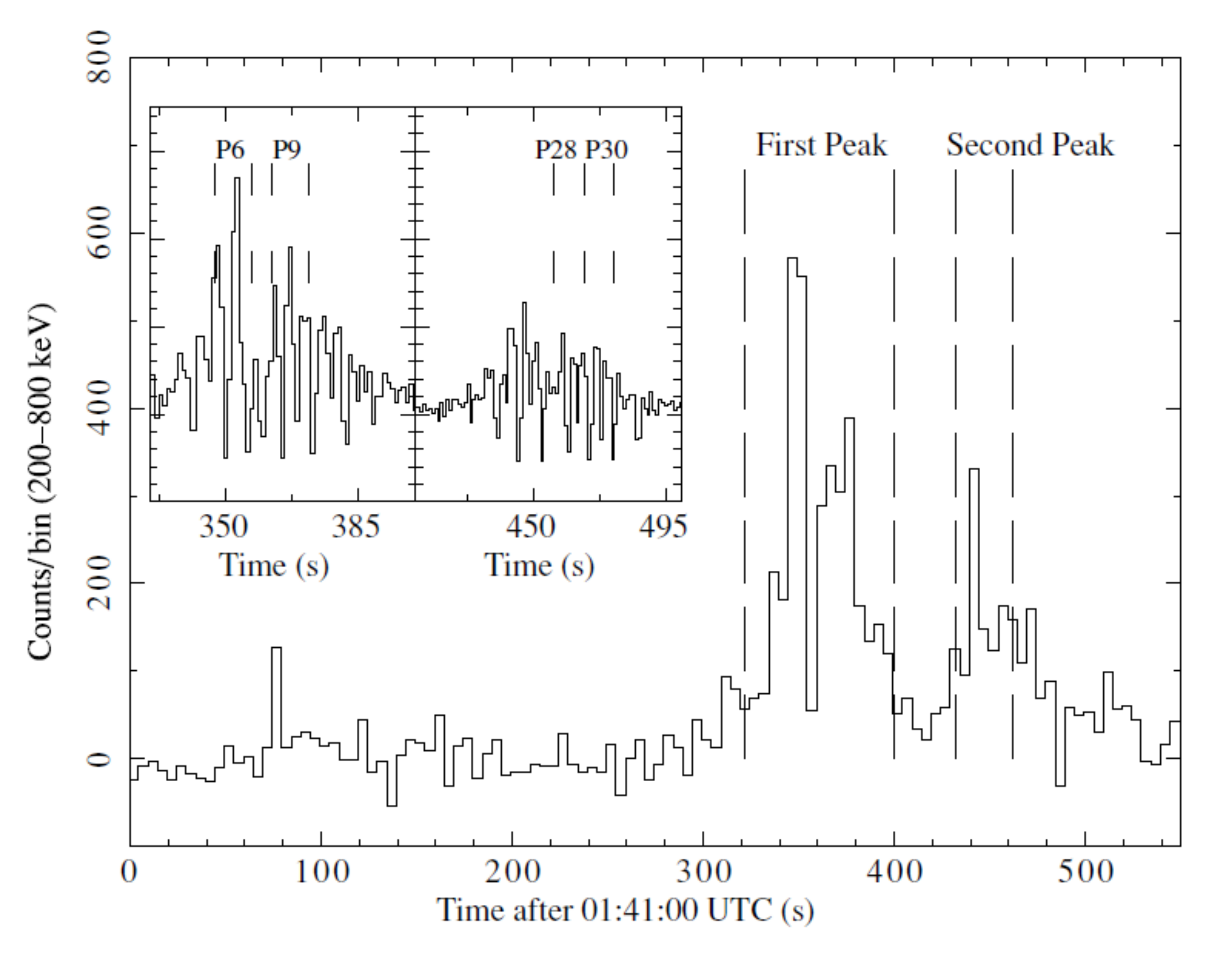
GRB 041219A

- Detected by the INTEGRAL Burst Alert system by triggering on its precurors
- Turned out to be a very long GRB: T_{90}~460 s
- Very bright: fluence $_{20\text{-}200\ keV}$ = 2.5×10^{-4} erg cm^{-2} (top 1% of the BATSE catalog)
- Two precursors and two main peaks
- Simultaneous NIR and optical flashes
- Good potential for polarization measurements

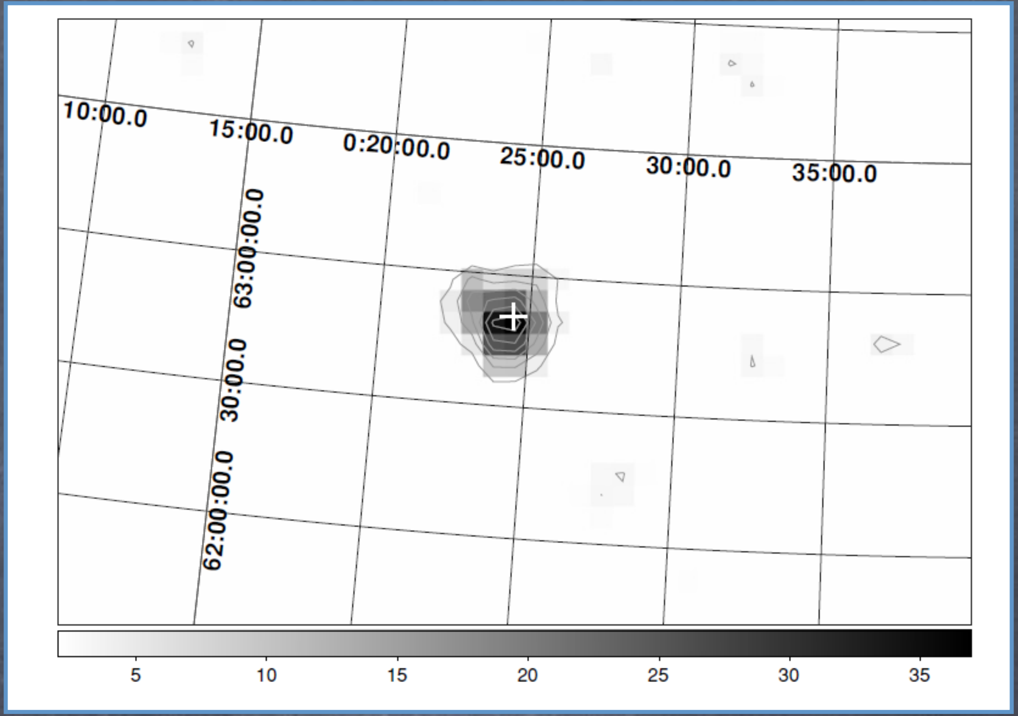




GRB 041219A: IBIS analysis

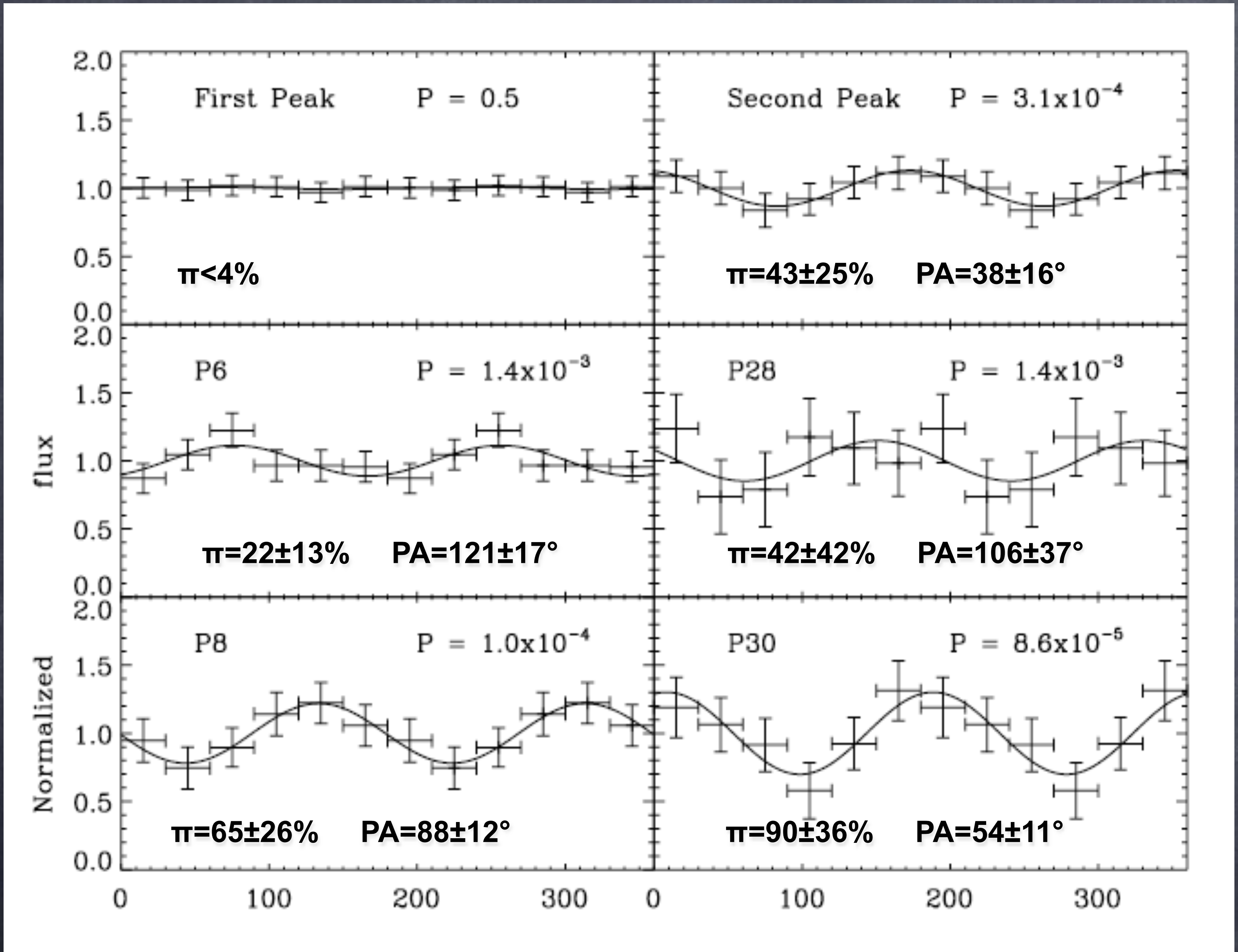


Compton mode light curve, 5 s bins
The brightness of the source allows for time resolved analysis (10 s bins)



Compton mode image:
SNR of 37 in the 200-800 keV energy band

GRB 041219A: IBIS analysis



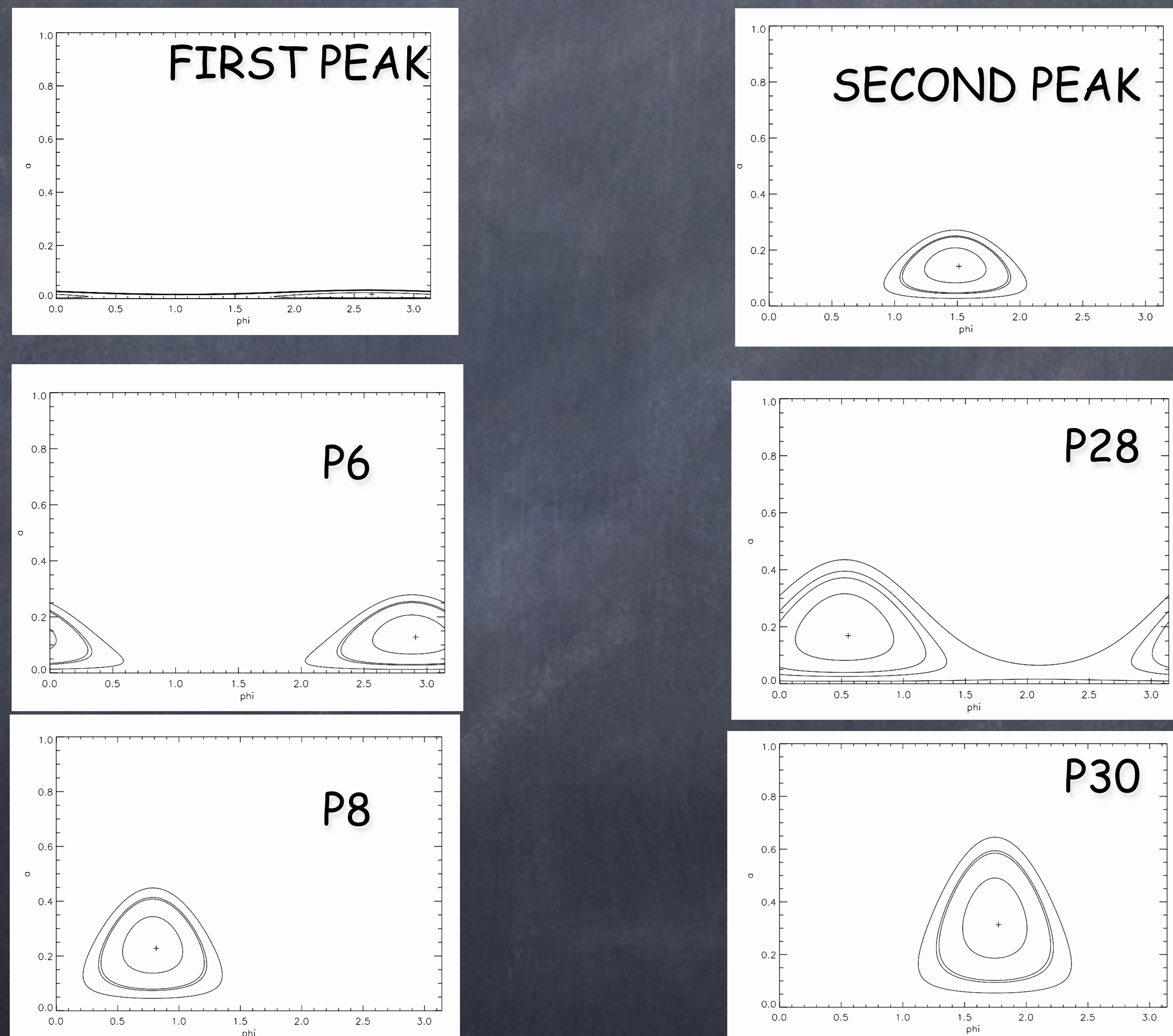
- High polarization level
- Time variable polarization angle!

Götz+09

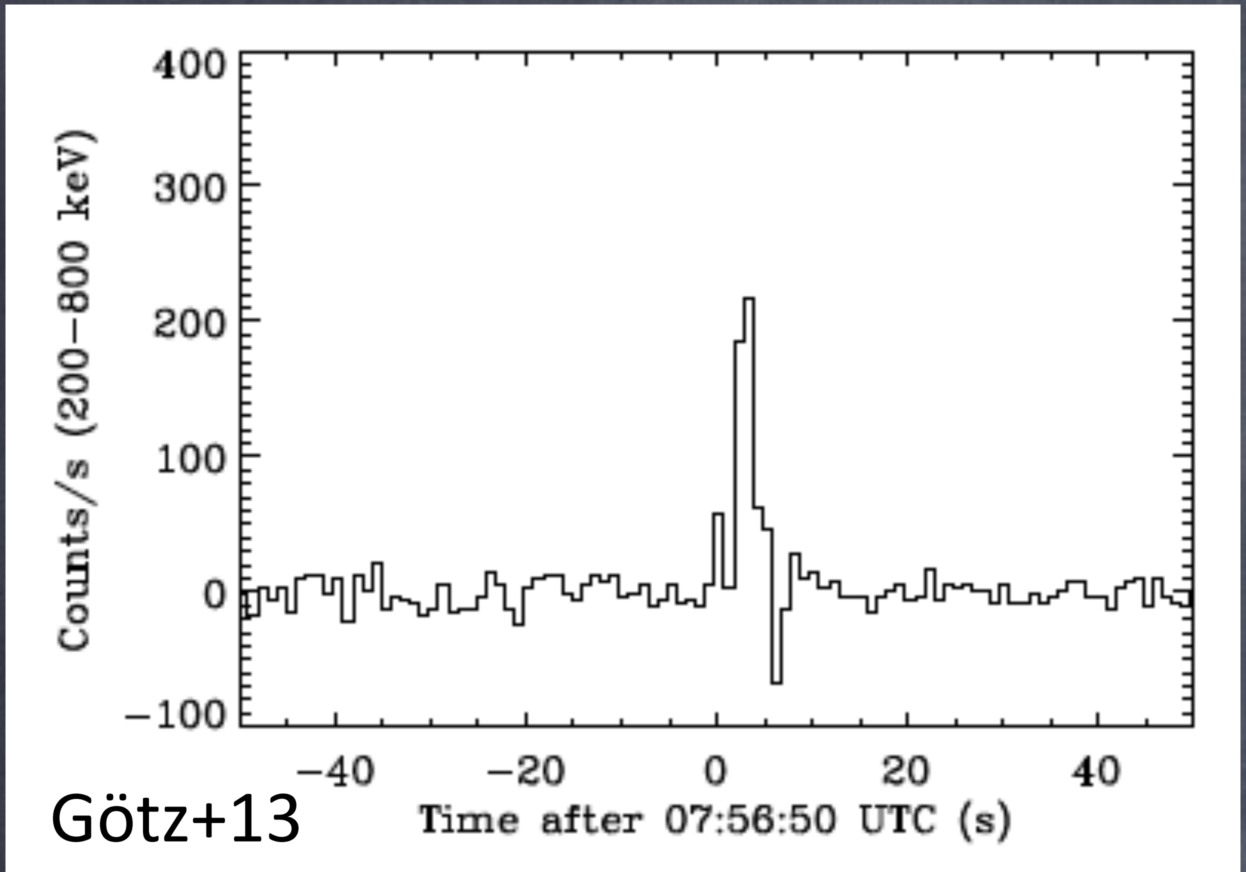
SPI measruement for P8: Π=68±29%, P.A.=$70^{\circ}{}^{+19^{\circ}}_{-27^{\circ}}$ (McGlynn+07)

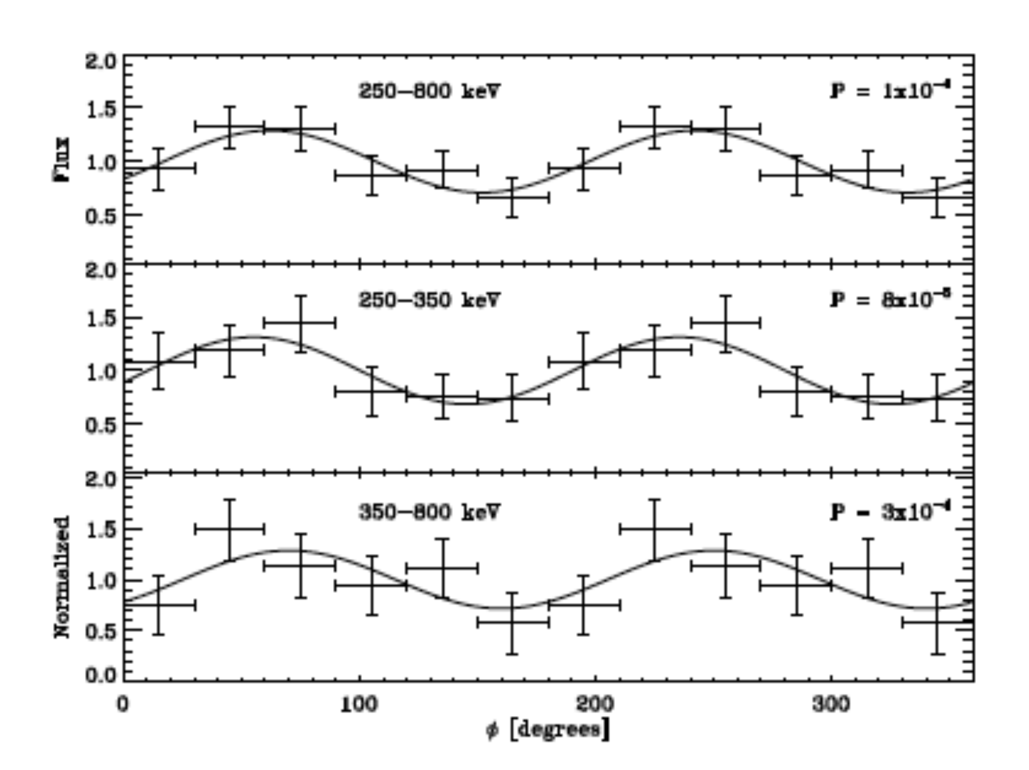
GRB 041912A: polarization statistics

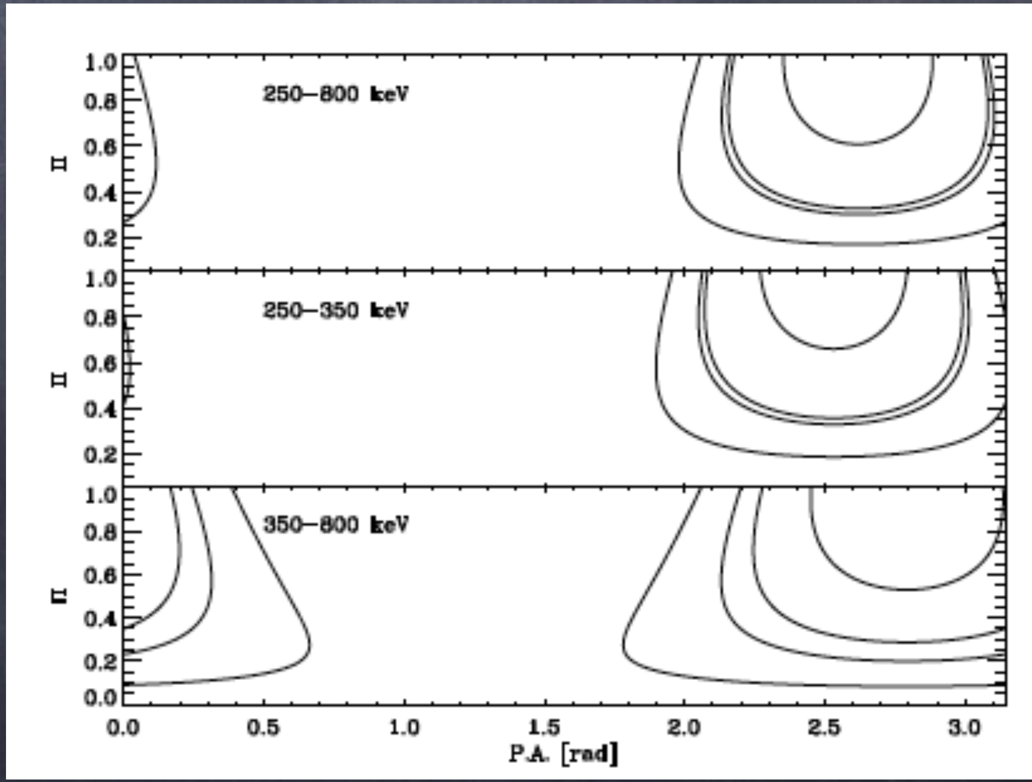
confidence levels at 67, 90, 95 and 99%



GRB 061122



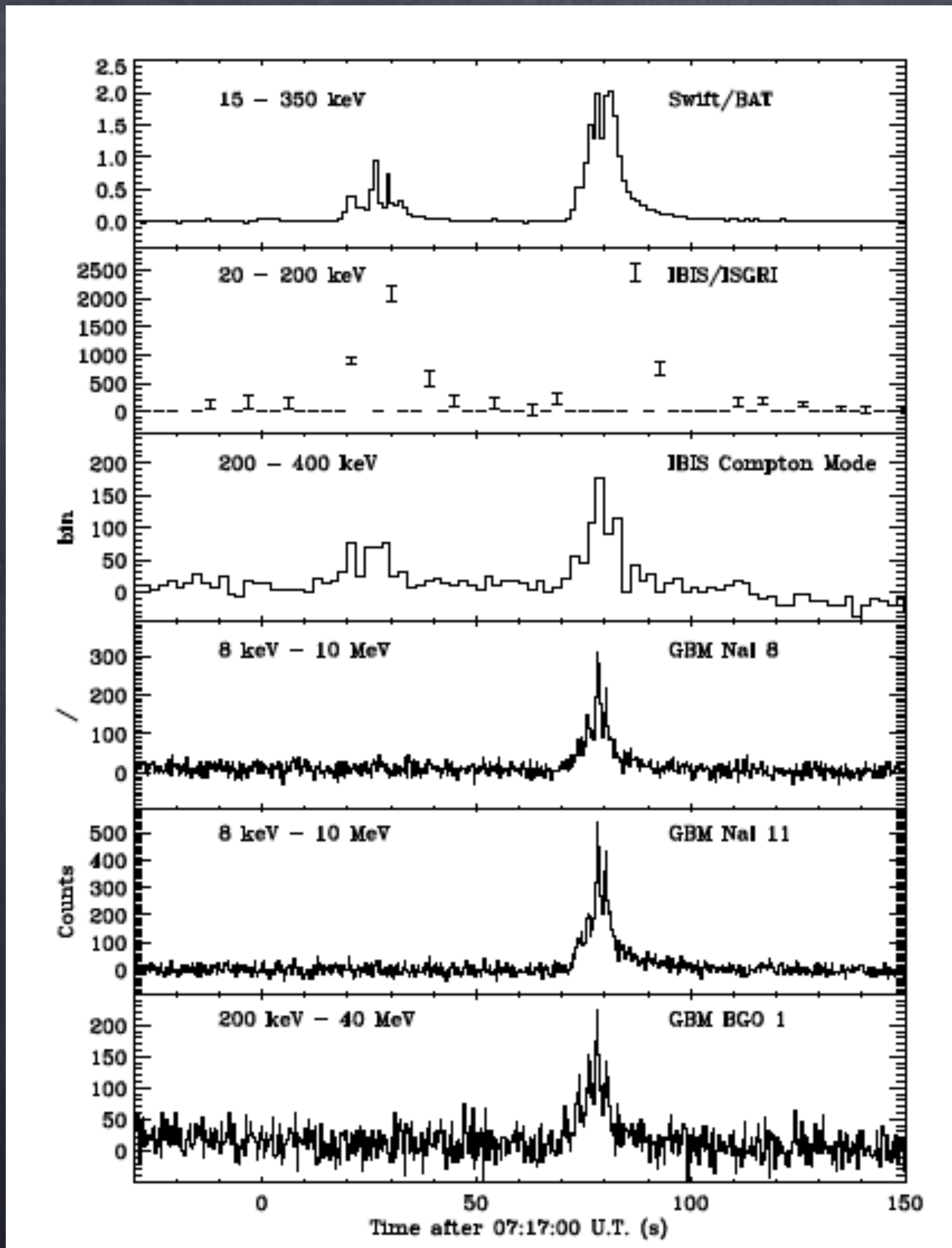


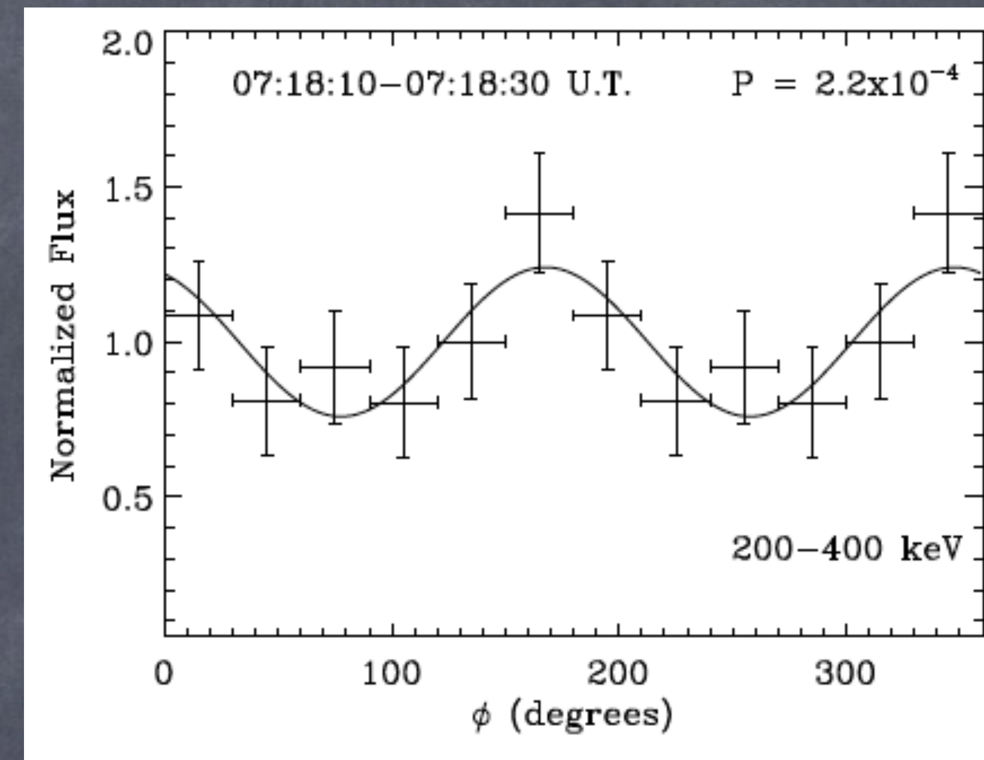


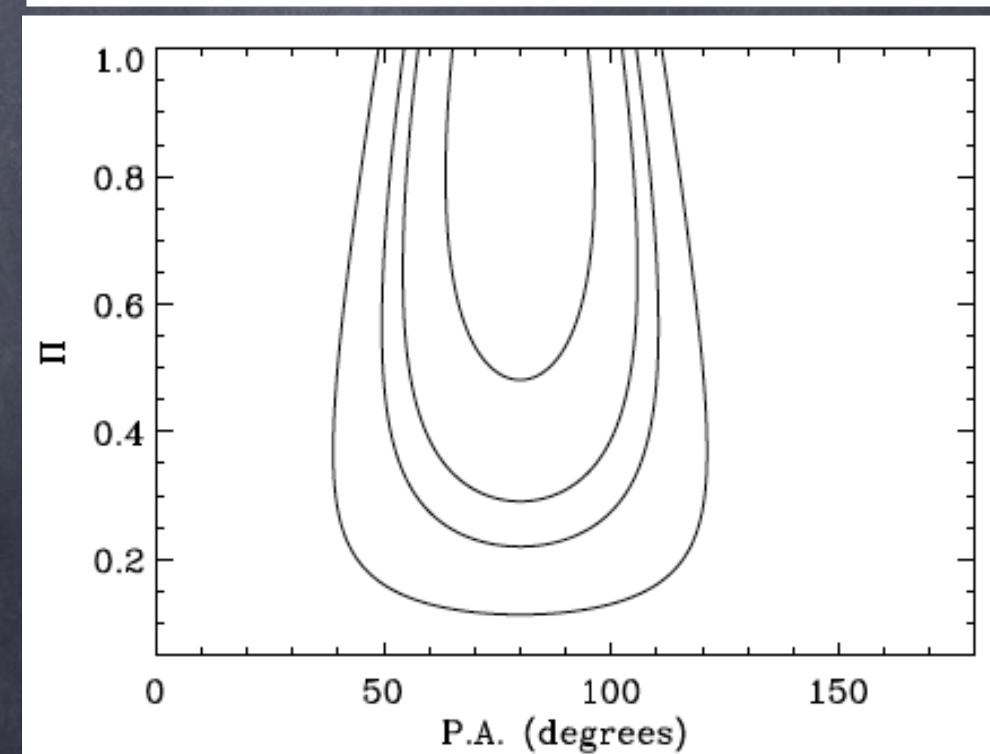
SPI u.l. < 60%McGlynn+09

Energy band (keV)	Π (%) (68% c.l.)	P.A. (°) (68% c.l.)	Π (%) (90% c.l.)	P.A. (°) (90% c.l.)
250–800	>60	150±15	>33	150±20
250–350	>65	145±15	>35	145±27
350–800	>52	160±20	>20	160±38

GRB 140206A

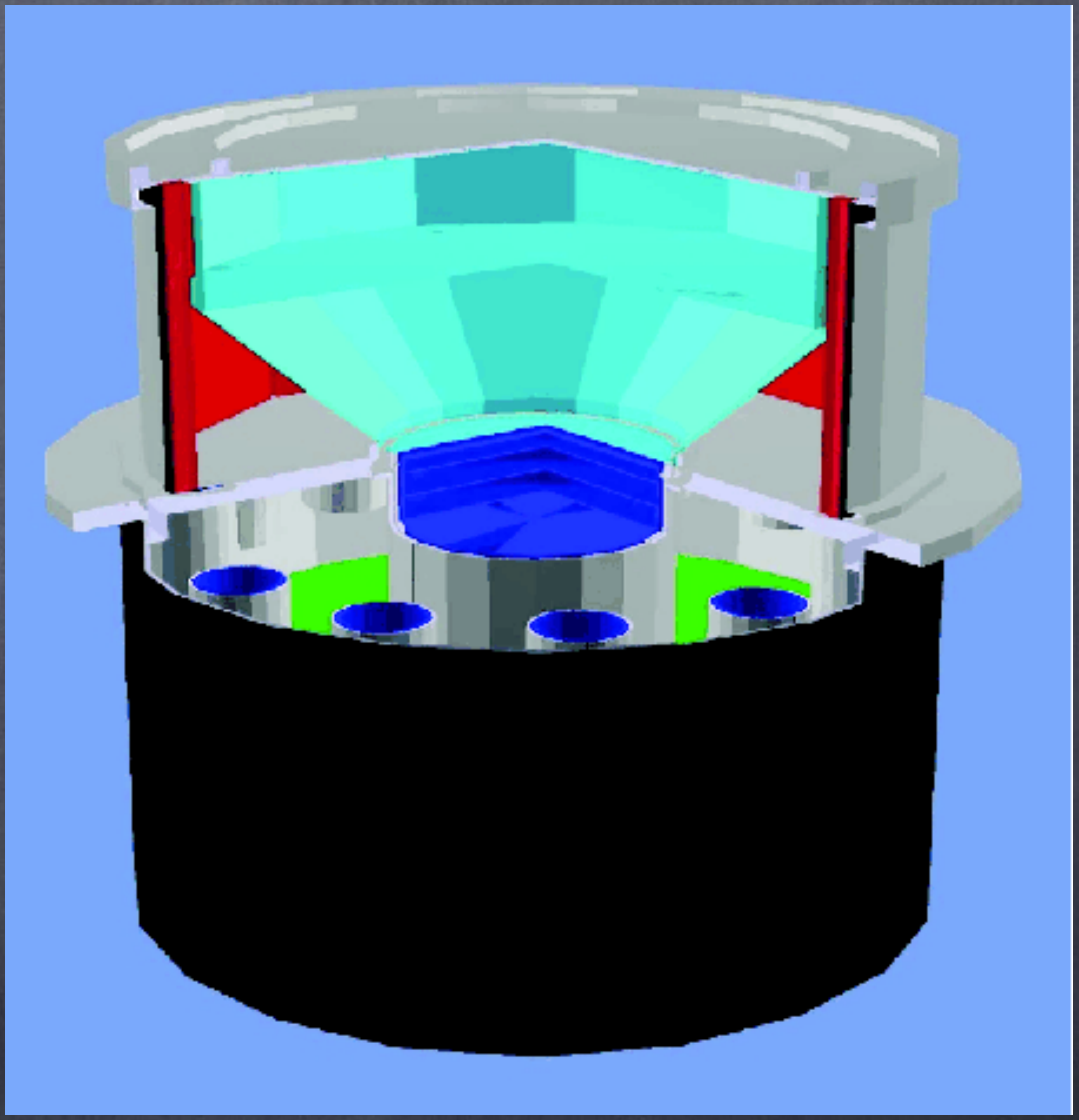

15 – 350 keV
Swift/BAT
20 – 200 keV
IBIS/ISGRI
200 – 400 keV
IBIS Compton Mode
8 keV – 10 MeV
GBM NaI 8
8 keV – 10 MeV
GBM NaI 11
200 keV – 40 MeV
GBM BGO 1
Counts
Time after 07:17:00 U.T. (s)


07:18:10–07:18:30 U.T.
P = 2.2x10^{-4}
Normalized Flux
200–400 keV
ϕ (degrees)


Π
P.A. (degrees)

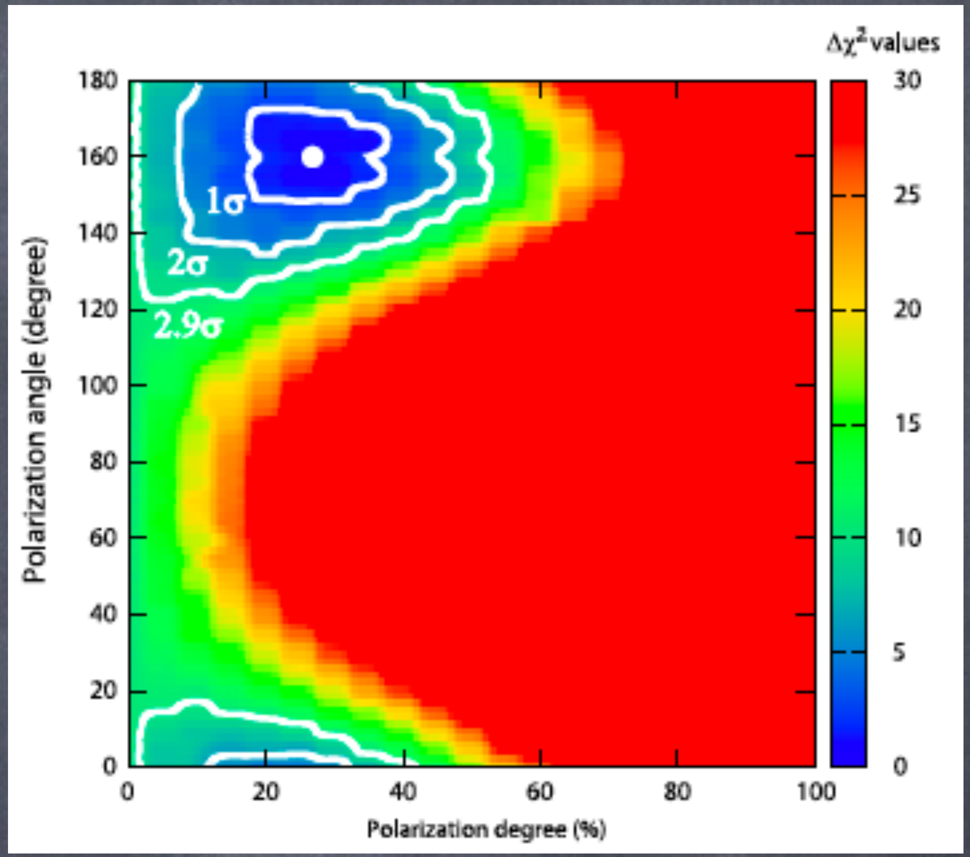
GAP on board IKAROS

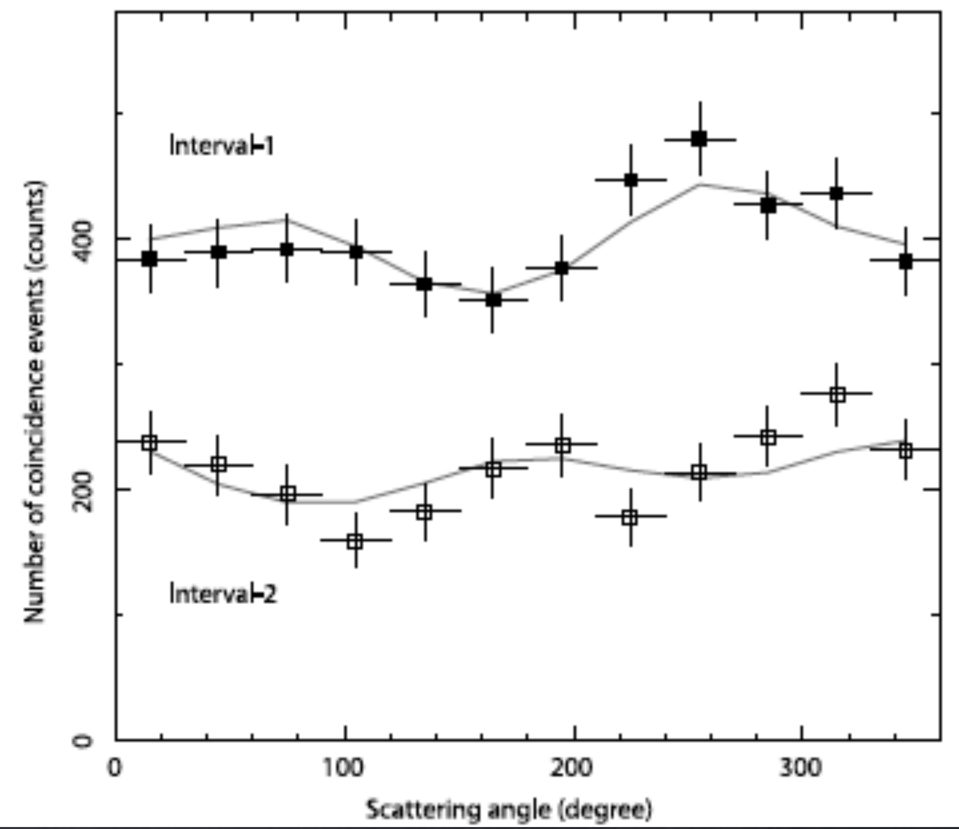
- High level of polarization during GRB prompt emission have been reported also by the GAP experiment on board the IKAROS spacecraft (Yonetoku+10)
- Specifically design to measure GRB polarization
- Consists of a central plastic scintillator surrounded by twelve CsI(Tl) scintillators with 5 mm thickness
- By examining the coincidences between the plastic scintillator and the CsI bars one can measure polarization



GAP: GRB 100826A

- Three GRB have measured polarization
- GRB 100826A had a similar fluence to GRB 0412019A
- Yonetoku+11 were able to measure a change in the polarization angle by dividing the GRB in two 50 s long time intervals: the angle changed from 159±18° to 75±20° (1σc.l.), with a 3.5 σ significance for the change
- Once more time variable polarization





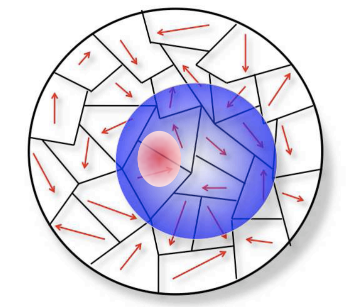
GRB Prompt emission summary

GRB	Π (68% c.l.)		Peak energy (keV)	Fluence and Energy Range (erg cm^{-2})	z	Instrument
041291A	65±26%	V	201^{+80}_{-41}	2.5×10^{-4} in 20–200 keV	$0.31^{+0.54}_{-0.26}$	IBIS
06122	>60%		188±17	2.0×10^{-5} in 20–200 keV	$1.33^{+0.77}_{-0.76}$	IBIS
100826A	25±15%	V	606^{+134}_{-109}	3.0×10^{-4} in 20 keV–10 MeV	0.71–6.84[1]	GAP
110301A	70±22%		107±2	3.6×10^{-5} in 10 keV–1 MeV	0.21–1.09[1]	GAP
110721	84^{+16}_{-28}%		393^{+199}_{-104}	3.5×10^{-4} in 10 keV–1 MeV	0.45–3.12[1]	GAP
140206A	>48%		98±17	2.0×10^{-5} in 15–350 keV	2.739±0.001	IBIS

[1] redshift based on empirical prompt emission correlations, not on afterglow observations.

Götz+14

Prompt emission interpretation(s)



(i) synchrotron emission from shock accelerated electrons in a relativistic jet with magnetic field transverse to the jet expansion (Granot 2003, Granot & Königl 2003, Nakar, Piran & Waxman 2003)

(ii) synchrotron emission from purely electromagnetic flow (Lyutikov et al. 2003, Nakar, Piran & Waxman 2003)

(iii) synchrotron emission from shock accelerated electrons in a relativistic jet with a random magnetic field (Ghisellini & Lazzati 1999, Waxman 2003)

SAME POLARIZATION LEVELS AS IN (I) BUT A PECULIAR OBSERVATION CONDITION IS NEEDED ($\Theta_{obs} \cong \Theta_{jet}+k/\Gamma$)

(iv) Inverse Compton scattering from relativistic electrons in a jet propagating in a photon field ("Compton drag") (Lazzati 2004)

POLARIZATION LEVELS can reach 60-100% BUT ONLY UNDER THE CONDITION OF A NARROW JET ($\Gamma\Theta_{jet}$<5) AND THE SAME OBSERVATION CONDITIONS AS IN (iii) APPLY

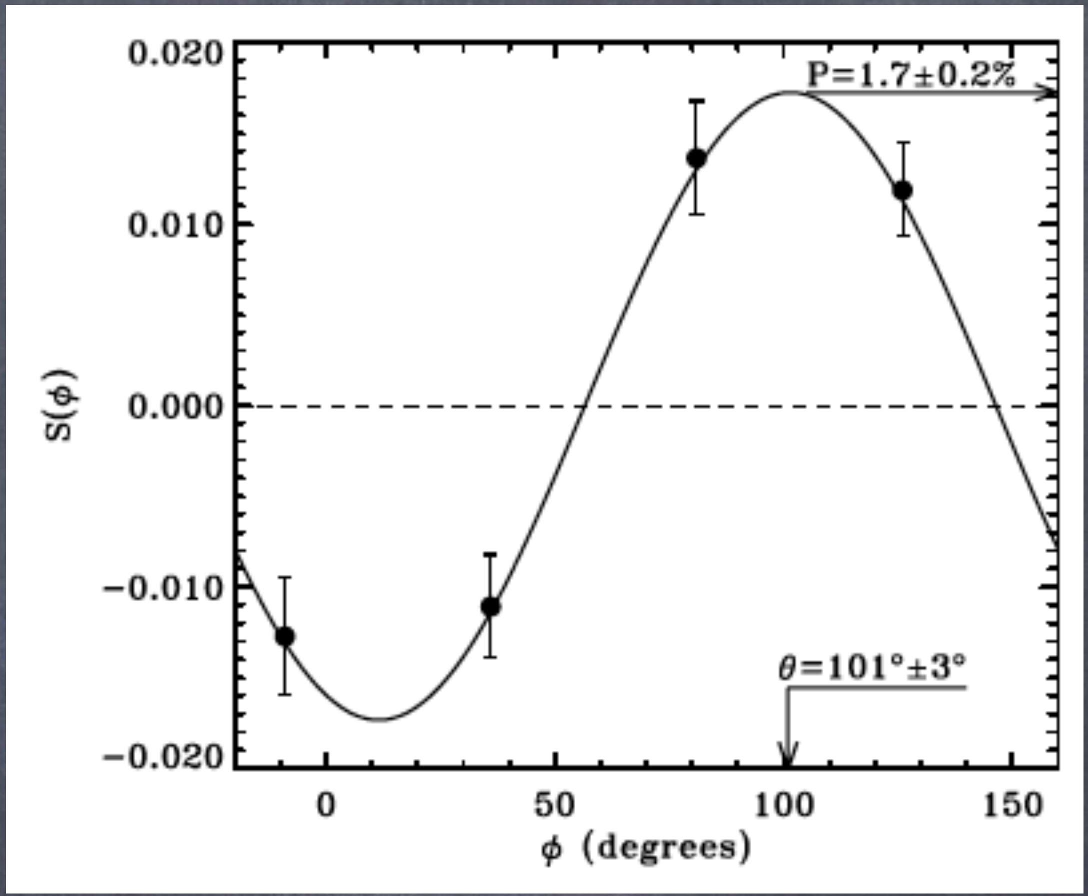
(v) Independently from the emission process (synchrotron or inverse Compton), fragmented fireballs (shotguns, cannonballs, sub-jets) can produce highly polarized emission, with a variable P.A. The fragments are responsible for the single pulses and have different Lorentz factors, opening angles and magnetic domains. (e.g. Lazzati & Begelman 2009)

Afterglow emission observations: early attempts

- First polarimetric observations were carried out with the VLA in the radio band about three weeks after GRB 980329 (Taylor+98) yielding a rather shallow u.l. (21%) and about a week after GRB 980703 with a 8% u.l. (Frail+98).
  - Both values are lower than the expected synchrotron value, but the latter depends on the frequency. Below the self-absorption frequency, polarization is smeared out.
- More stringent was the 2.3% upper limit obtained by Hjorth+99 for the bright GRB 990123 in the optical at NOT 18 hours after the event. Milder upper limits for circular and linear polarization were also obtained with the VLA (Kulkarni+99; Granot & Taylor+05)
- Polarimetry at a few percent can be demanding for rapidly fading sources such as GRBs and hence it is not a surprise that the first positive detection had to wait for the VLT to be operational

GRB 990510 @ VLT

- Covino+99 and Wijers+99 independently observed 18-21 hrs the GRB with the VLT providing a small but significant measure of its polarization level Π=1.7±0.2%
- A later measurement one day after gave a result consistent with a non-variability
- Polarization at this level is not common for extragalactic sources, however it is possible that is is induced by dust grains on the line of sight; large variations among different object are however expected due to the line of sight (local galaxy and Milky Way)
- For this GRB multi band observation allowed to rule out the dust contribution at the level of the host galaxy (low level of reddening)



- Those measurement were taken before the jet break, where only a fraction of the jet is visible

GRB 990712 & 991216

- Rol+00 obtained three epochs of linear polarization measurements from 10 to 35 hrs after the GRB
- The polarization was always in the 1-3% range but showed some variability with the minimum at the second epoch, while the angle did no vary
- Only upper limits were instead obtained for GRB 991216 in the optical (Covino+04) and radio bands (Granot & Taylor+05), being the most stringent limit at 2.7%
- Further attempts to measure the polarzation in the NIR, optical and radio (000301C, 010222, 011211) yielded percent level detection or u.l.

Time evolution measurements

- GRB 020405 was observed with VLA (Granot & Taylor 05), VLT (Masetti+03; Covino+03) and MMT (Bersier +03) between one and three days after the burst. The polarization level was in the 1.2-2% range for the VLT but much higher for the MMT (10%). The position angle possibly showed a slow change (about 10°) from the first to the last observation. The MMT results taken an hour after one of the VLT observations was hardly reconcilable with the others.
- Another rich dataset was obtained for 020813: polarization at the 1% level, no position angle change (Barth+03; Gorosabel+04; Lazzati+04)

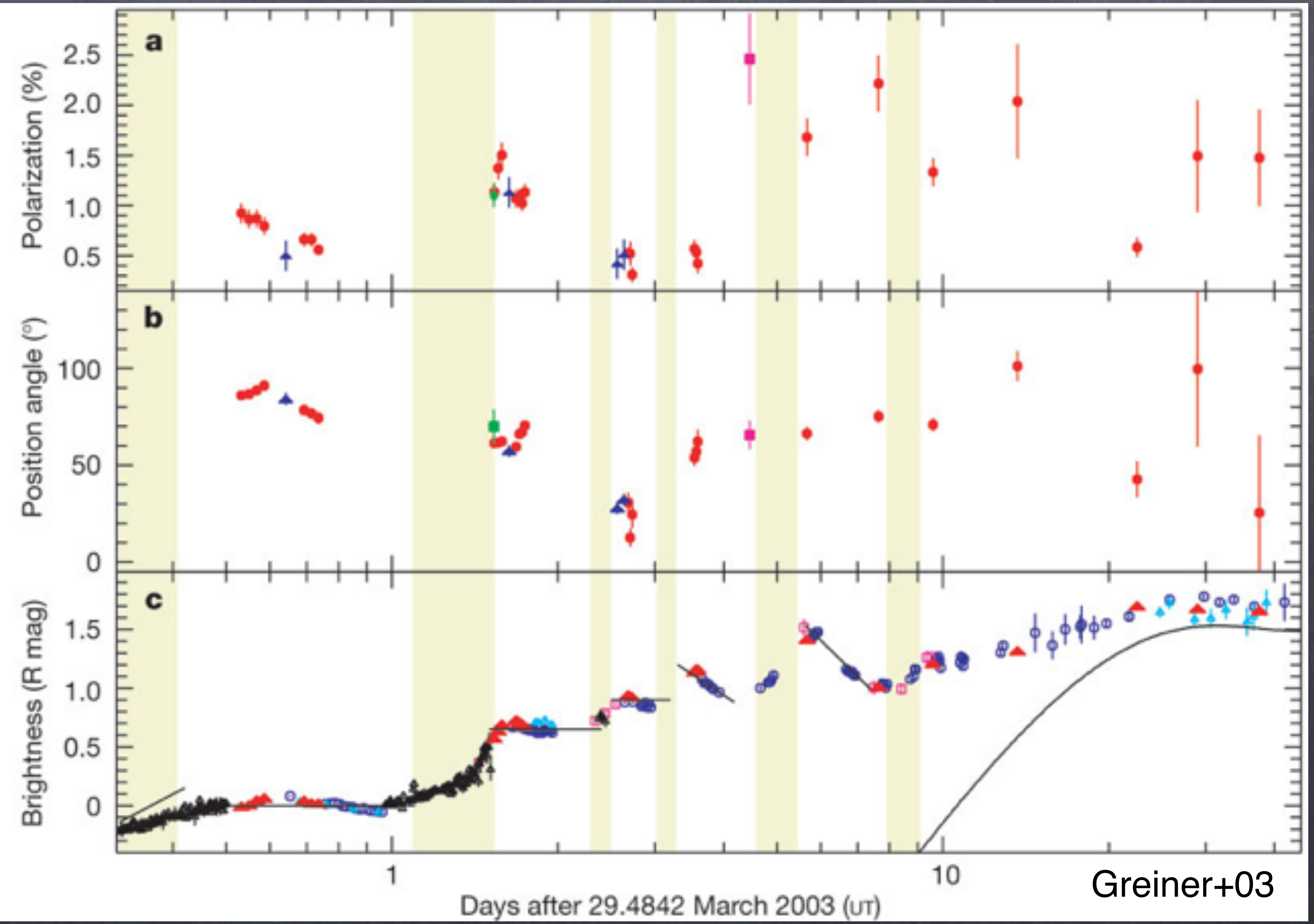
Time evolution measurements

- GRB 021004: Rol+04 reported a low degree of polarization (1-1.5%) but with a ~45° change in polarization angle. VLT measurements (Lazzati+03) confirmed a gradual 90° polarization angle change between 14 hours and 90 hours after the GRB.
- For two more events 030226 (Klose+04) and 030328 (Maiorano+06) a few polarimetric points could be measured

GRB 030329: the breakthrough (?)

- Optically very bright: allowed for one month of uninterrupted polarimetric observations in the optical domain with VLT, CAHA, NOT, IAG-USP, and in the radio with the VLBA (see C&G 16 for the complete list of references).

- The afterglow showed strong variability in polarization degree and angle, but the complex nature of this event (plenty of humps int the might curve, including a SN event) makes its modeling very complex -> clear indication that the phenomenology was much richer than expected

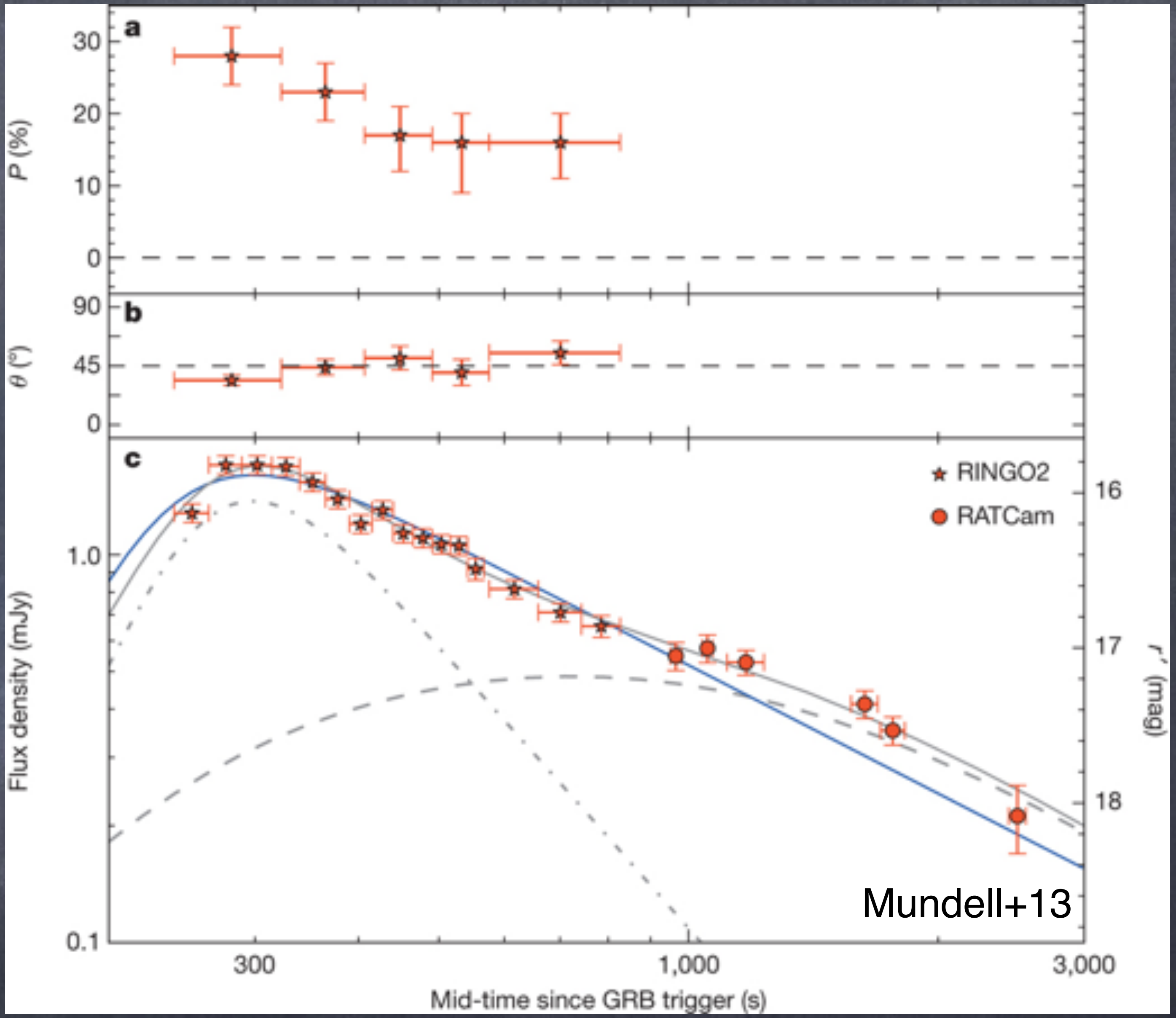


From late to early afterglow

- Lately the efforts concentrated on the early afterglow by the used or robotic and intermediate size telescopes
  - GRB 060418 (Molinari+07) three minutes after the GRB using LT: Π<8%
  - GRB 090102 (Steele+09) three minutes after the GRB Π~10% (reverse shock?)
  - GRB 091208B (Uehara+12) several minutes after the GRB with the Kanata telescope: Π~10%
  - MASTER telescope (091127, 100906A, 1221011A) upper limits in the 10-15% range

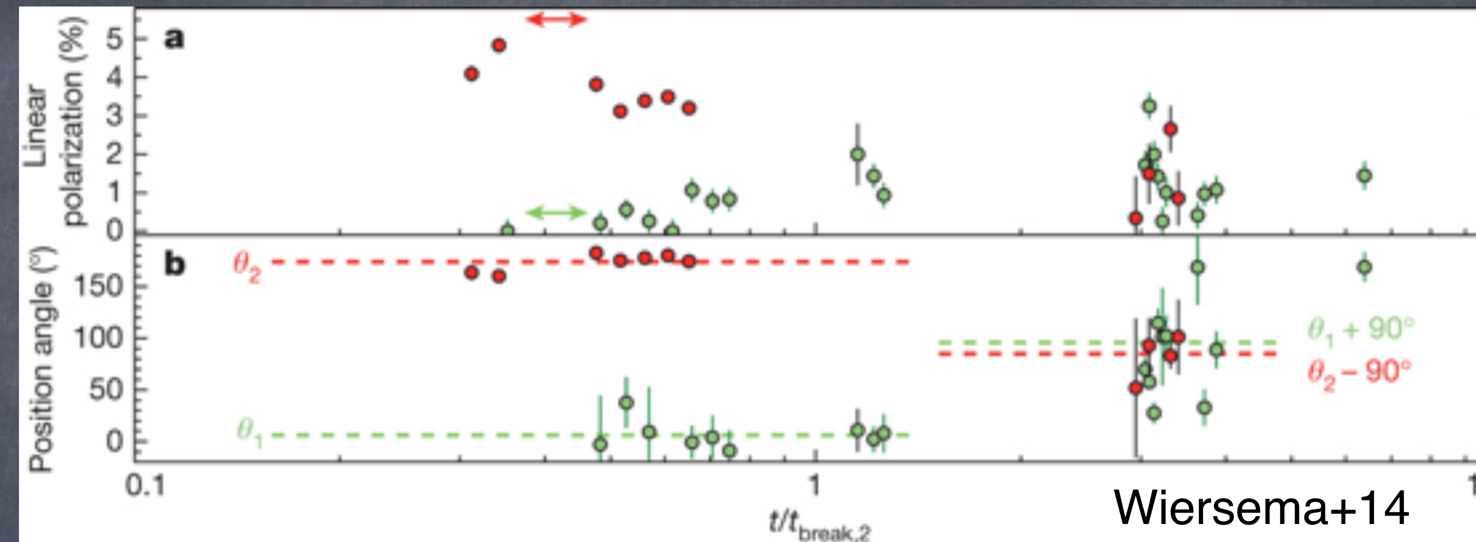
GRB 120308A

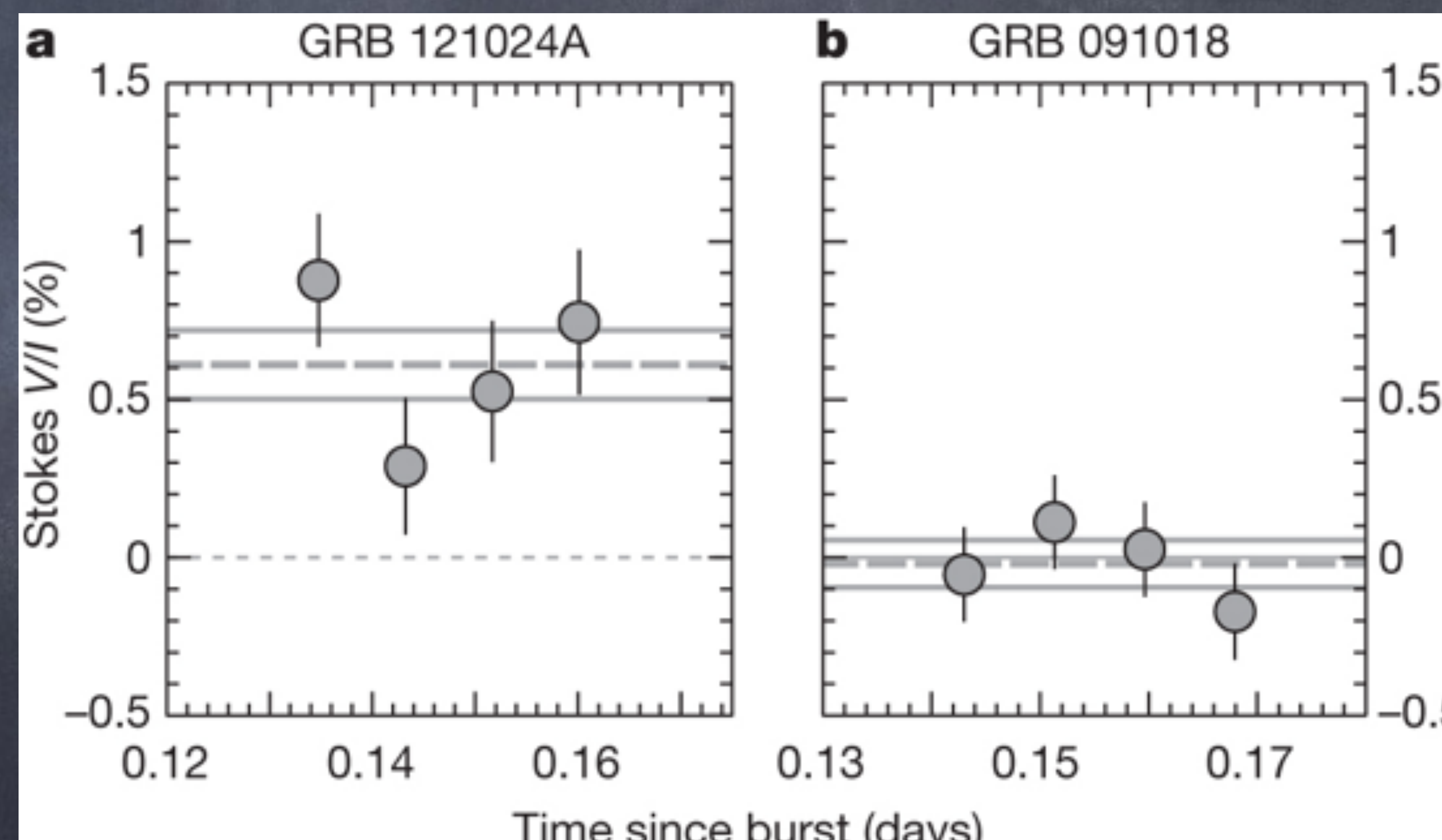
- Observation of decaying linear polarization using RINGO2 on LT (starting at Π~30%)
- Constant polarization angle
- Observations imply a magnetized baryonic jet with a large-scale uniform magnetic field (Mundell+13; Lyutikov 13)
- The strength of the magnetic field in the reverse shock region must be orders of magnitude higher than in the forward shock region (Zhang +15)
- For GRB 140430A a lower limit of Π>22% has been reported while the GRB was still active (Kopac+15)



GRB 120124A

- VLT observations starting a few hours after the GRB
- First measurement of circular polarization in a GRB afterglow P_{circ}=0.61±0.13%
- Extensive linear polarization measurement with a global decreasing trend and a constant polarization angle
- Showed the predicted 90° change in polarization angle at jet break for a uniform jet not spreading sideways
- P_{circ}/P_{lin} ~0.15, much higher than any predicted theoretical value





Afterglow polarization theory

- Intrinsic
  - a number of independent patches with locally ordered magnetic field (Gruzinov & Waxman 99). Up to 10% polarization level
  - Observations of a jet slightly off-axis (Ghisellini & Lazzati 99). Some linear polarization even for completely tangled magnetic field (for photons emitted at right angles in the shock) -> time variable
  - Structured jets (non-uniform luminosity per unit angle) can produce some polarization (Rossi+04). But uniform jets produce 90° rotation of the polarization angle at jet break, while is is not the case for gaussian or structured jets.
  - Early afterglow: if the reverse shock emission is powered by a magnetized outflow it can produce powerful optical flashes, an a high level of polarization of the order of 30-50% (Fan+04).
- Intrinsic+External
  - Microlensing by an intervening star (e.g. Loeb & Perna 97): synchrotron emission by independent jet patches, and microlensing magnifies one of the patches
- Polarization due to dust in the line of sight

Polarimetry and Lorentz invariance violation

- On general grounds one expects that the two fundamental theories of contemporary physics, the theory of General Relativity and the quantum theory in the form of the Standard Model of particle physics, can be unified at the Planck energy scale. This unification requires to quantize gravity, which leads to very fundamental difficulties: one of these is the possibility of Lorentz invariance violation
- A possible experimental test of LIV is testing the helicity dependence of the propagation velocity of photons
- Such a test that has already been performed using the SPI measurement of Crab polarization (Maccione et al. 2008)

GRB prompt emission constraints on LIV

- In this some QG theories the light dispersion relation is given by:

$$\omega^2 = k^2 \pm \frac{2\xi k^3}{M_{Pl}} \equiv \omega_\pm^2$$

M_{Pl}: reduced Planck scale ($2.4\ 10^{18}$ GeV)

$$\omega_\pm = |k|\sqrt{1 \pm \frac{2\xi k}{M_{Pl}}} \approx |k|(1 \pm \frac{\xi k}{M_{Pl}})$$

$$\Delta\theta(p) = \frac{\omega_+(k) - \omega_-(k)}{2} d \approx \xi \frac{k^2 d}{2M_{Pl}}$$

For the Crab:
$\xi < 2\ 10^{-9}$

GRB : at least 10^5 times further away

For GRB 140206A (Götz+14) at z=2.739 (23 Gpc)

$$\xi < \frac{2M_{Pl}\Delta\theta(k)}{(k_2^2 - k_1^2)\ d} \approx 1 \times 10^{-16}$$

Deepest limit to date!

Similar but less stringent limits (<2 10^{-7}) can be obtained from afterglow observations (Fan+07)

Conclusions

- Polarization measurements in the GRB field is a tough job!
- Nevertheless continuous experimental, observational and theoretical effort are required in this promising field
- The large dataset available for afterglow emission implies that the polarization is intrinsic (variability) supporting the synchrotron scenario (although other scenari cannot be completely ruled out)
- The observation of specific patterns (i.e. position angle swing) have been predicted theoretically and further support this scenario, but the detection of circular polarization challenge this interpretation
- The high level of polarization in the early afterglow support an important magnetic content of the jet
- For the prompt emission the statistic is smaller but the independent detection with different experiments of high and variable polarization points towards the presence of locally highly ordered magnetic fields in GRB jets (coherently with the early afterglow results on 120308A), and to synchrotron emission as the dominant emission process, but to sharpen this picture more high quality data using dedicated instruments are needed (e.g. POLAR)