INTEGRAL Results on Gamma-Ray Bursts

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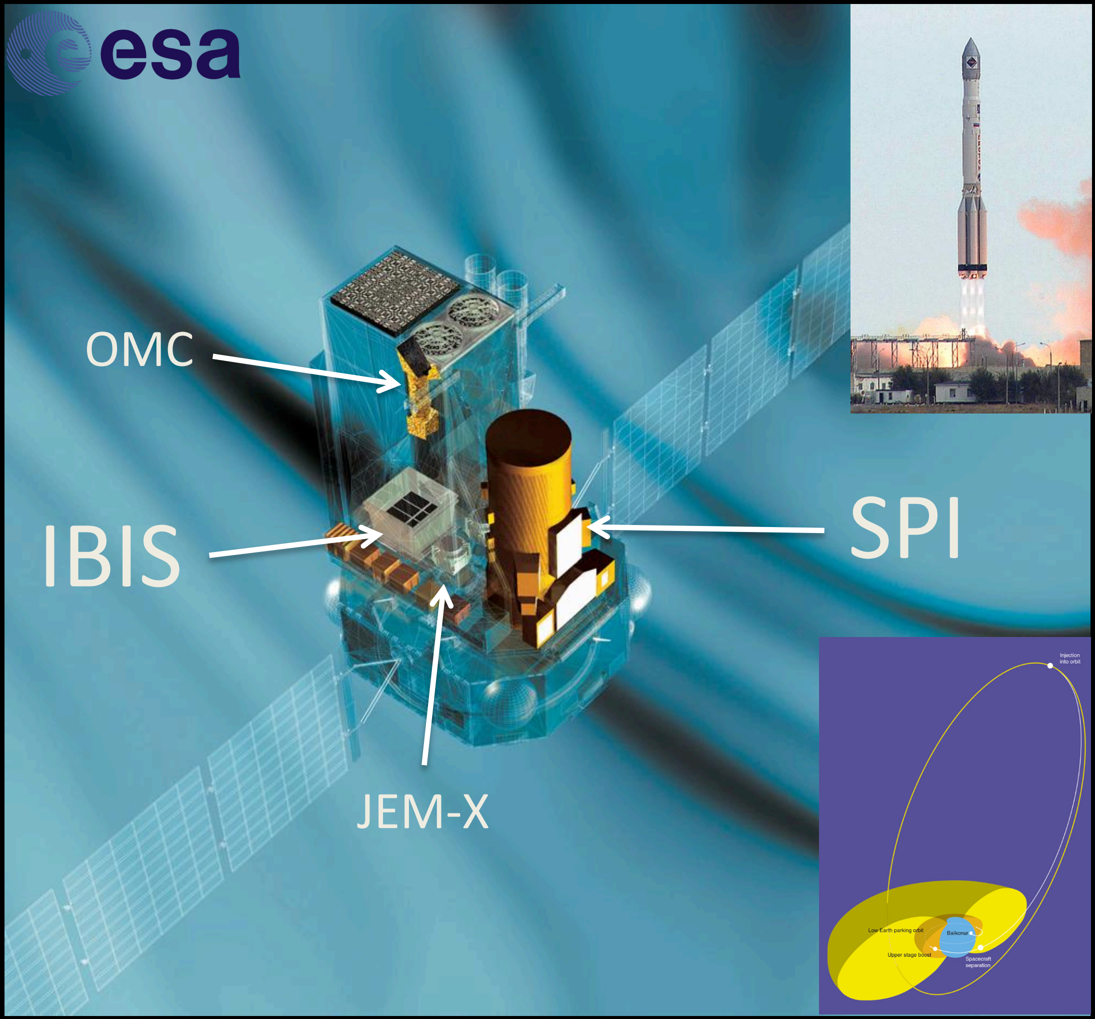
Plan

- Localizing Gamma-Ray Bursts with INTEGRAL
- Selection of INTEGRAL Results
  - Global (spectral) properties
  - GRB 031203/SN 2003lw
  - GRB 041219A
    - Prompt visible/NIR emission
  - Polarization & LIV (041219A, 061122, 120711A, 140206A)
- Conclusions and lessons learnt

The INTErnational Gamma-Ray Astrophysics Laboratory



Launched on October 17th 2002 in an inclined (51.6°) ~3 days orbit (apogee: 9000 km, perigee 153000 km). ESA mission with contributions from NASA and RKA.

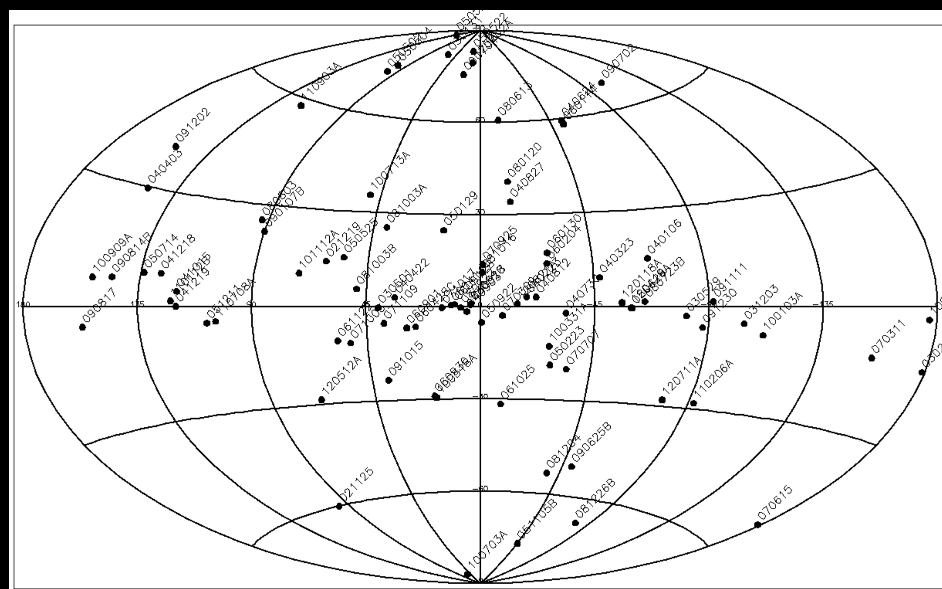
Carries two main instruments, based on coded mask imaging technique: the “imager” IBIS (15 keV-10 MeV, 12 arc min PSF) and the “spectrometer” SPI (20 keV-8 MeV, ΔE=2.2 keV (FWHM) @ 1.33 MeV).

X-ray (JEM-X) and an optical (OMC) monitors are also present on board.

The INTEGRAL Burst Alert System

- INTEGRAL GRBs are localized in real-time thanks to the INTEGRAL Burst Alert System.
- Rate increase and imaging algorithms are running at ISDC looking for new transients. Time scales from 2 ms to 100 s are searched for. Nominal energy range: 15-200 keV.

- 100 GRBs localized so far in real-time (a few exceptions)
- 8 redshifts

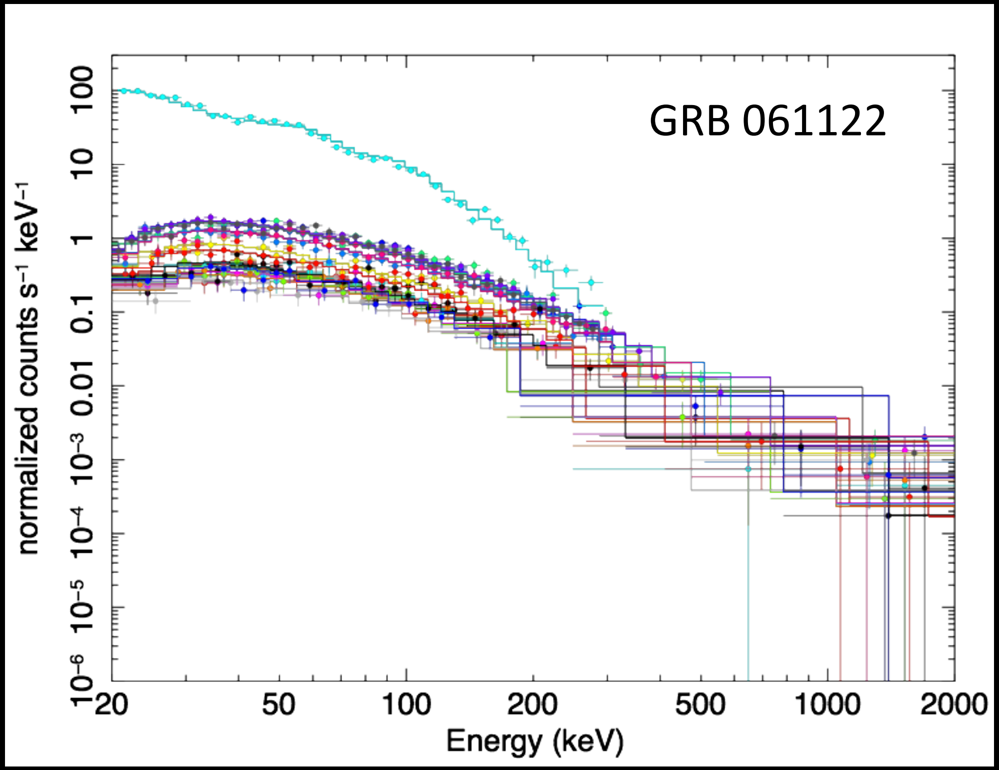


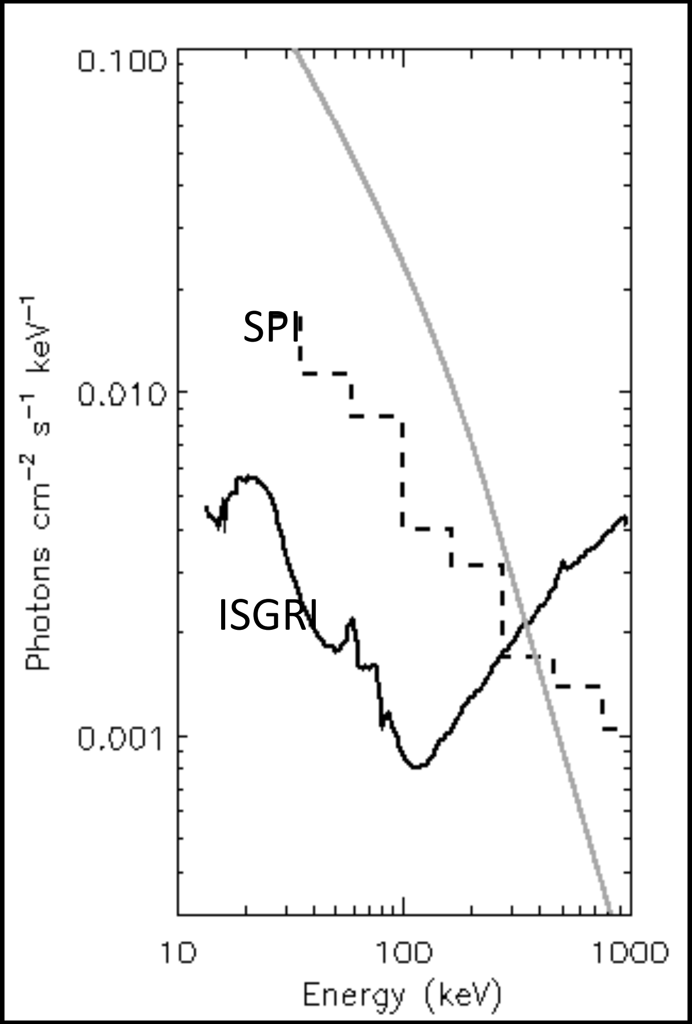
Galactic coordinates

Global Properties

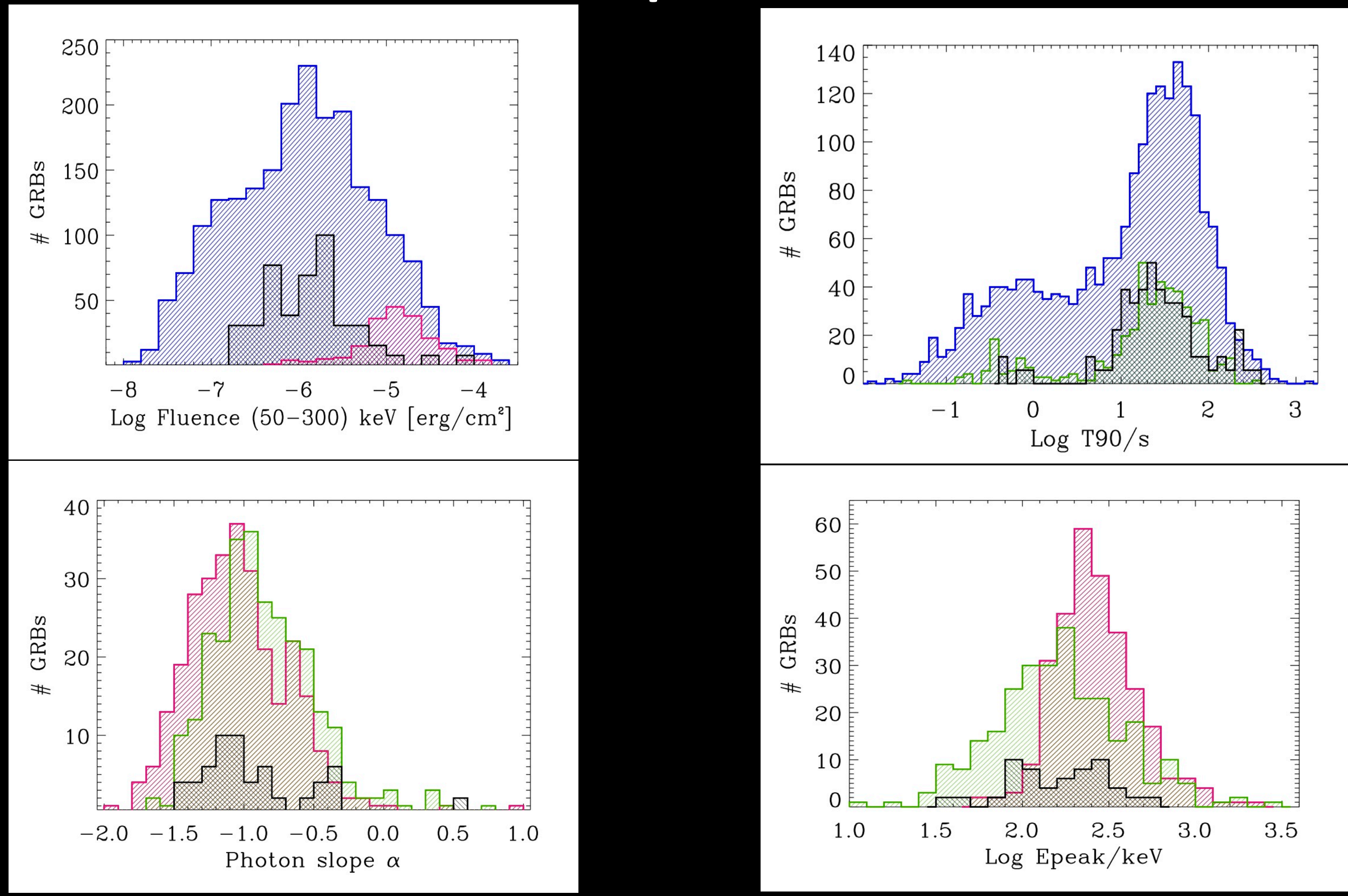
A new spectral catalogue, using non-standard S/W has been produced.

The GRBs have been analyzed using both SPI and IBIS -> E_{Peak}





Global Properties



BATSE whole sample

brightest BATSE GRBs analyzed by Kaneko et al.

Fermi/GBM GRBs analyzed by Nava et al. 2011

INTEGRAL GRBs.

Bosnjak+14

GRB 031203

GRB/SN association

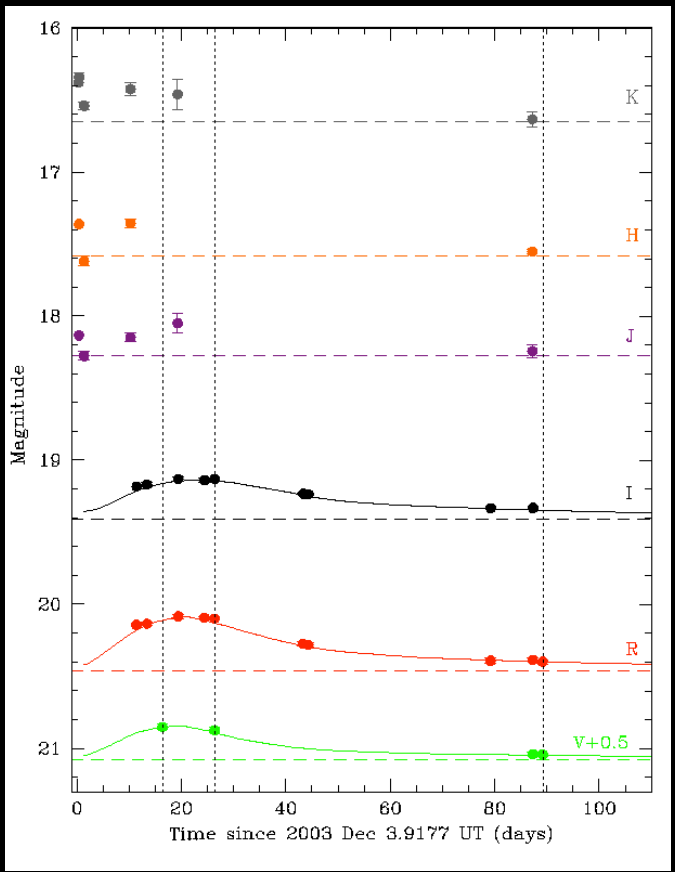
A handful of GRBs are spectroscopically associated with a generally ultraluminous type Ib/c SN (GRB980425 with SN 1998bw, GRB 030329/SN 2003dh, GRB 031203/SN 2003lw, GRB 060218/SN 2006aj, GRB100316D/SN 2010bh, GRB120422A/SN 2012bz, GRB130427A/SN 2013cq, GRB 130207A/SN 2013dx), plus a dozen presenting a SN late bump in their light curves.

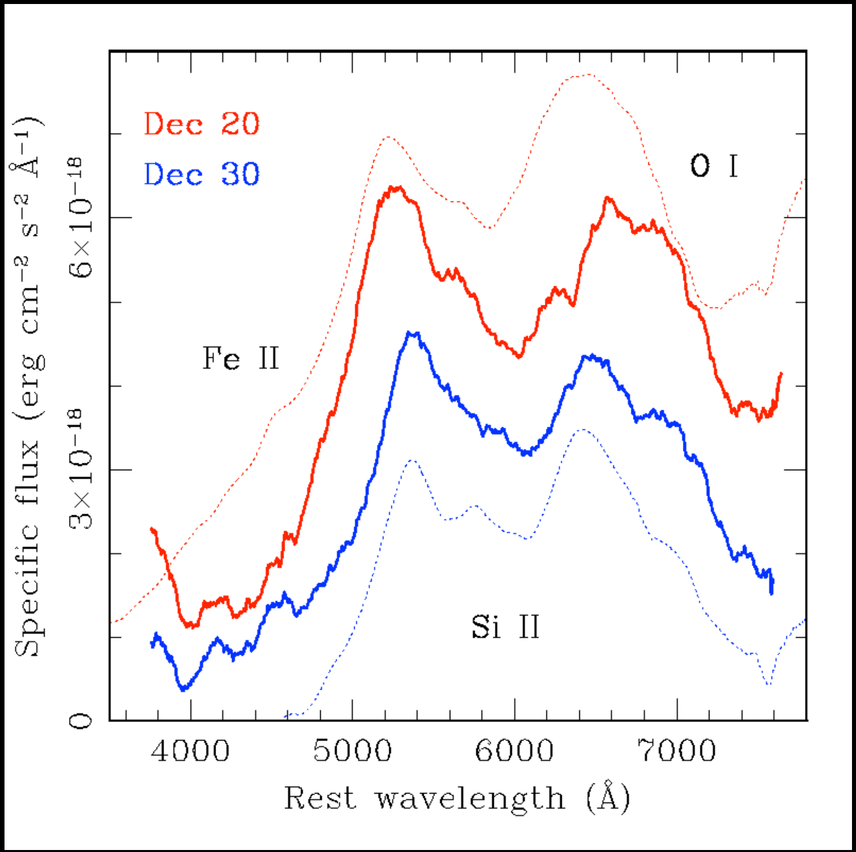
z=0.1055

A very luminous SN

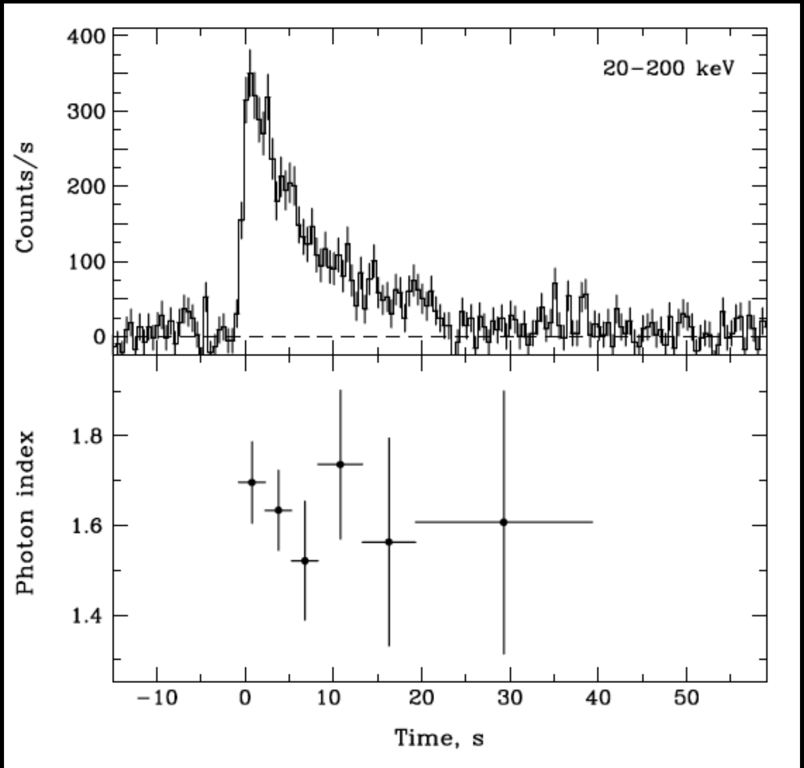
$M_V = -19.75$

Malesani+04





031203 prompt emission



Sazonov+04

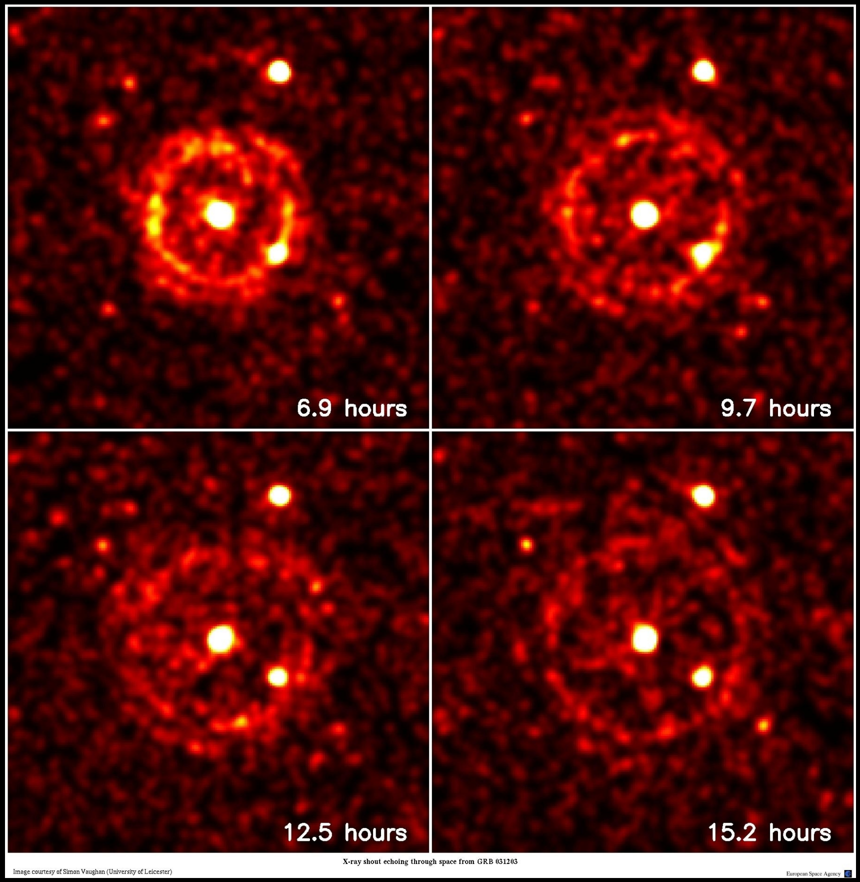
Single power law, Γ=-1.63±0.06

E_{peak} > 190 keV

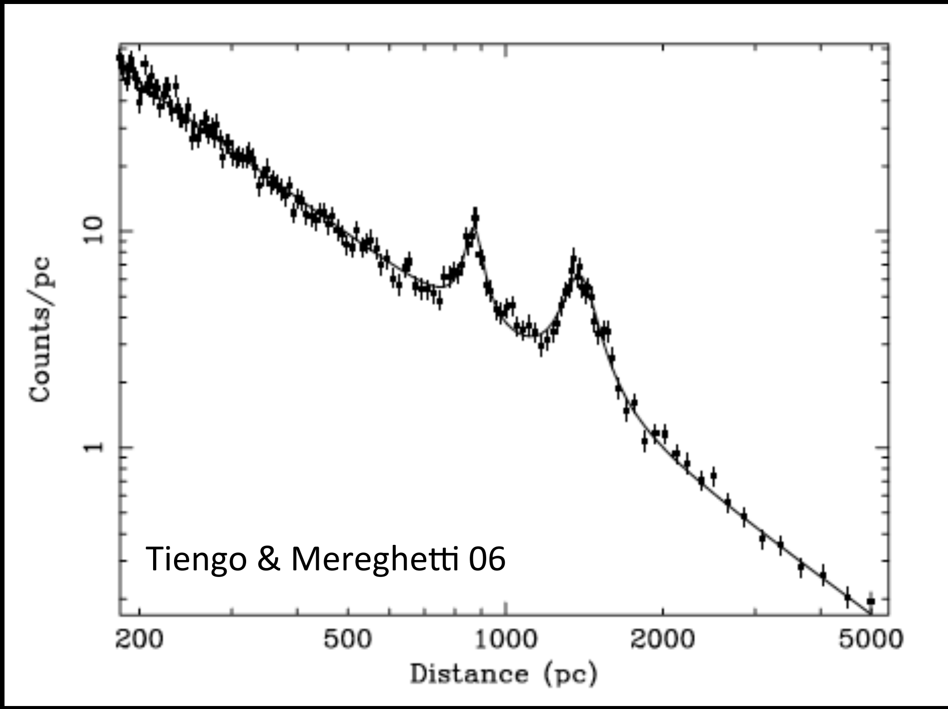
6 x 10^{49} erg < $E_{\gamma,iso}$ < 1.4 x10^{50} erg

Quite a faint GRB!

031203: X-ray Echo

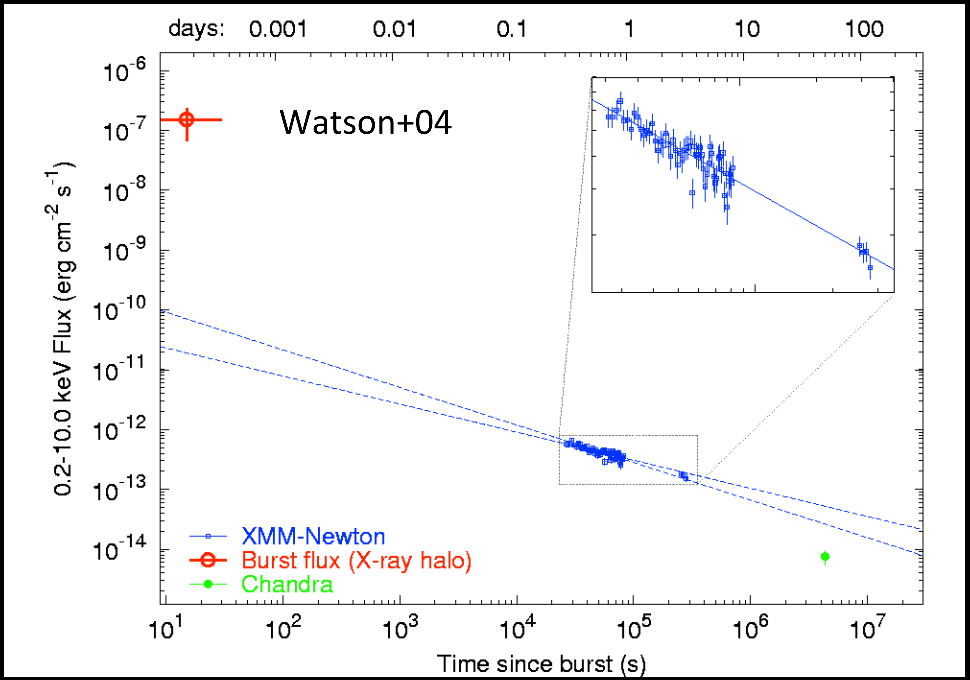


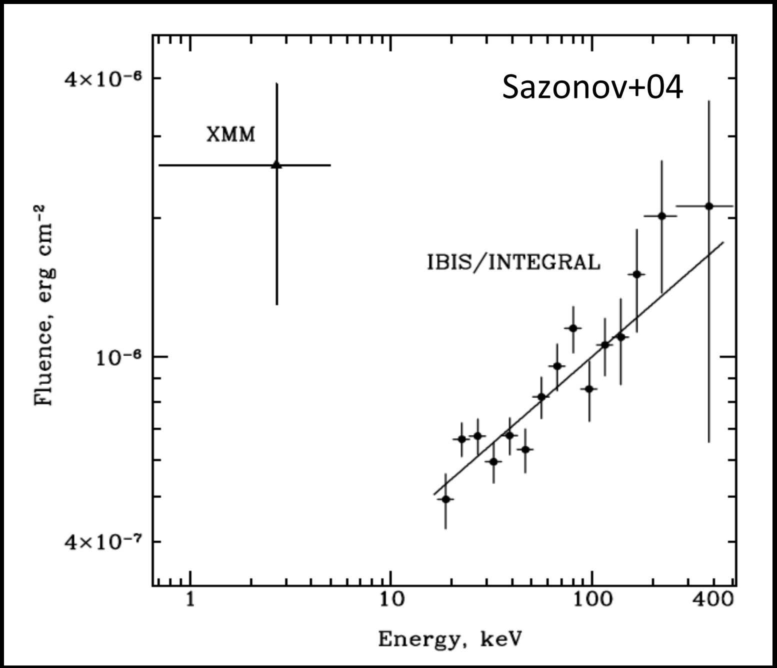
Vaughan+04



X-ray data allowed to measure precisely the distance of the scattering clouds within our Galaxy.

031203: X-ray Echo





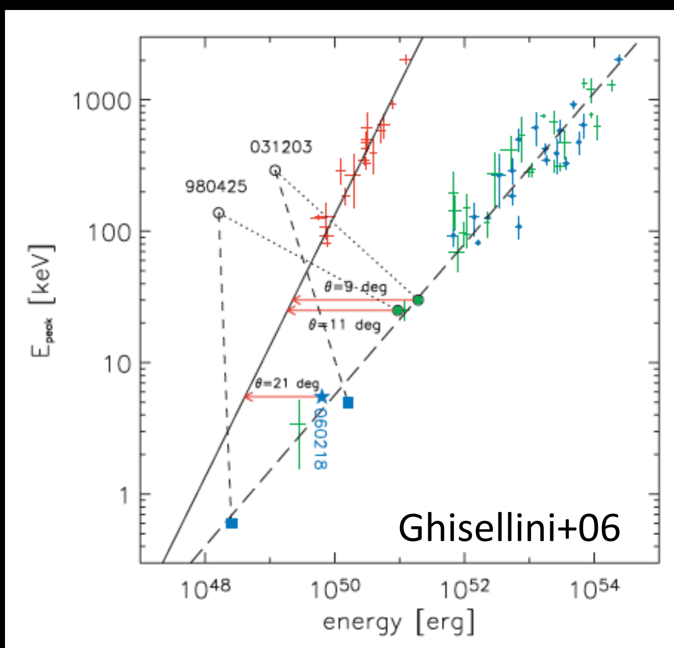
The prompt X-ray flux derived from the rings modeling is not compatible (in terms of fluence and spectrum) with the INTEGRAL prompt gamma-ray emission

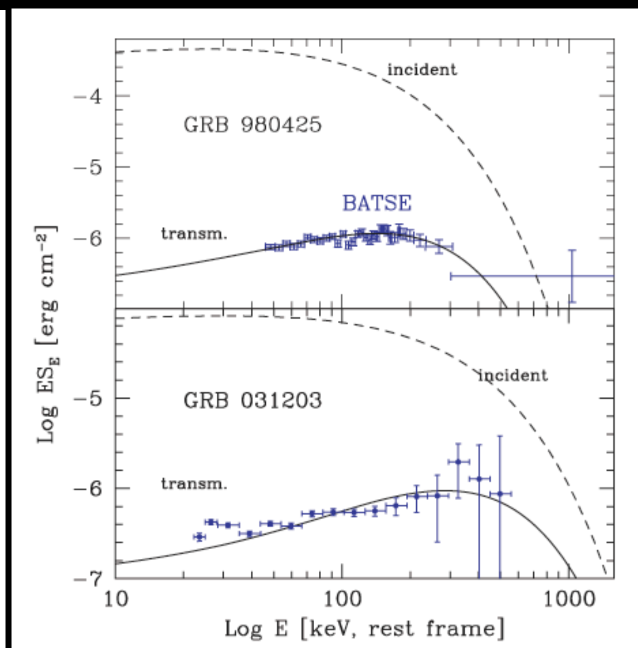
Reconciling energetics

One of the rare firm GRB-SN connection events
BUT…

The GRB is faint is gamma with a possibly large peak energy, but with a possible soft X-ray counterpart undetected by IBIS

The supernova is exceptionally bright





031203 seen off-axis
Ramirez-Ruiz+05

or

031202 seen through an absorber (scattering cloud close the to GRB site)
Ghisellini+06

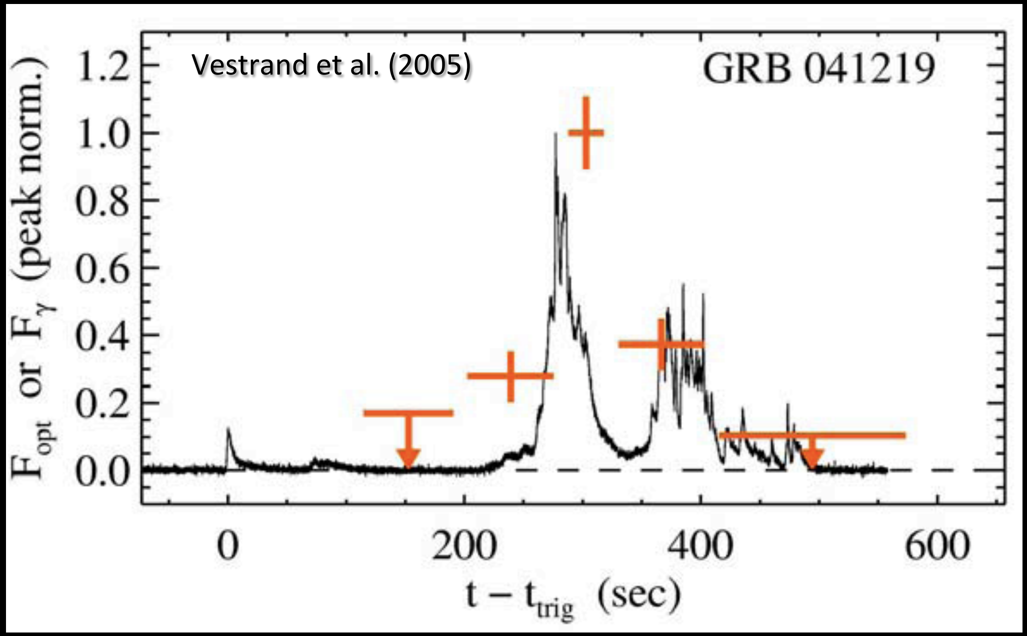
or

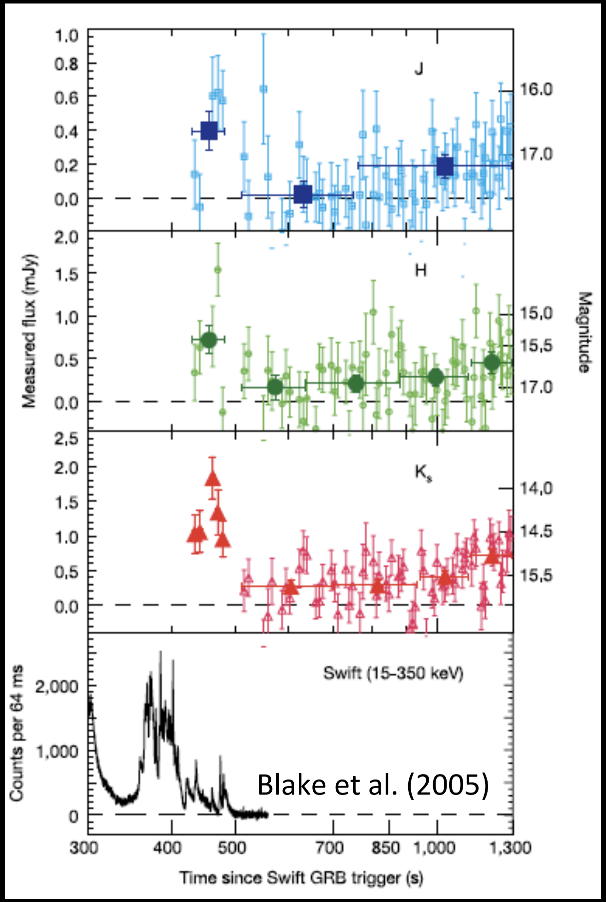
strong hard-to soft spectral evolution (only the short-hard part is detected by ISGRI), like GRB061218!

GRB 041219A

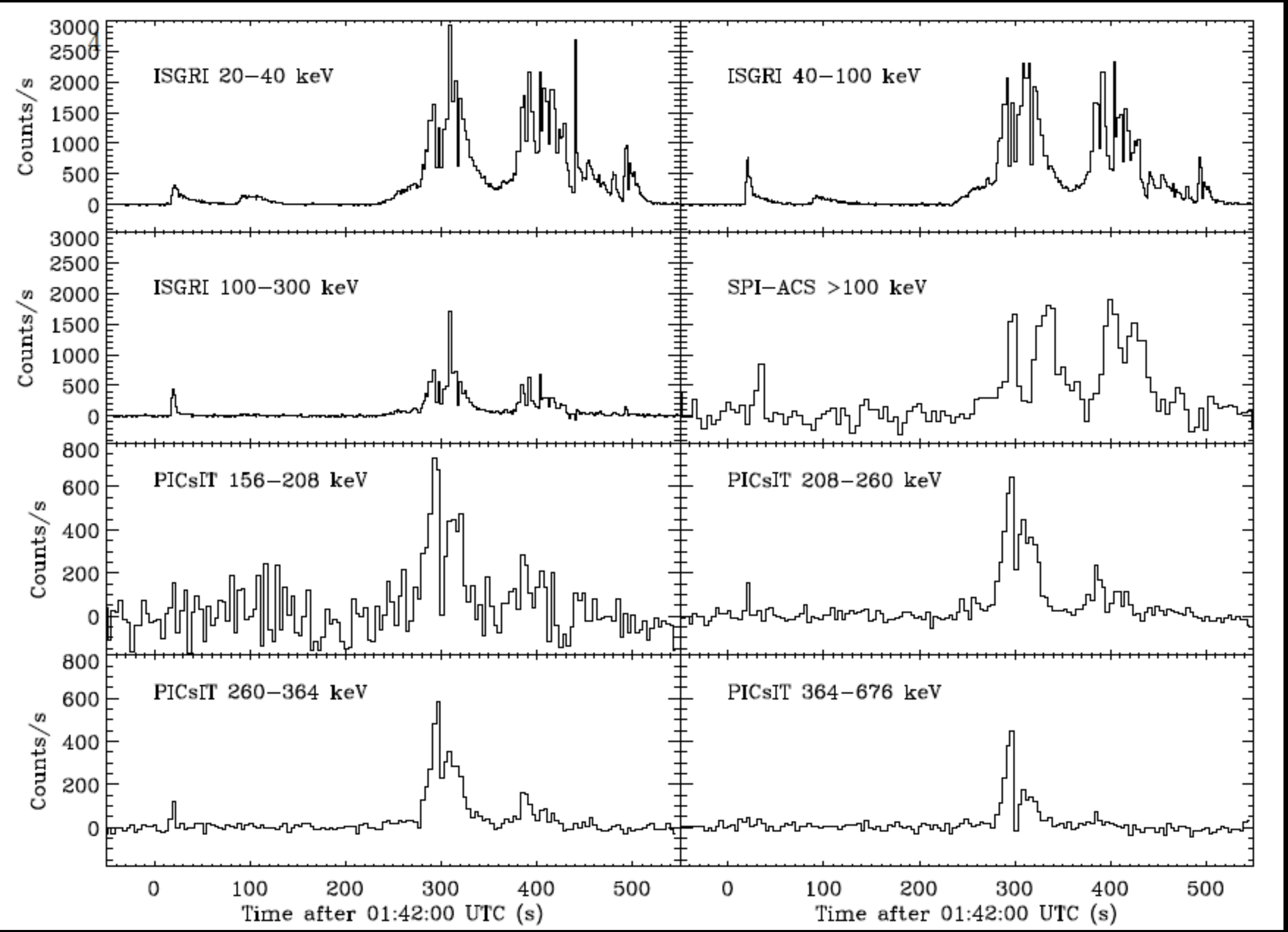
GRB 041219 story

- Detected by the *INTEGRAL* Burst Alert System by triggering on its precursor
- Turned out to be a very long burst: T_{90}~460 s
- Very bright: fluence $_{20\text{-}200\ \mathrm{keV}}$ = 2.5 x10^{-4} erg cm^{-2} (top 1% of the BATSE sample)
- Two precursors and two main peaks
- Simultaneous NIR and optical flashes
- Measure of variable γ-polarization (Götz+09, McGlynn+07)

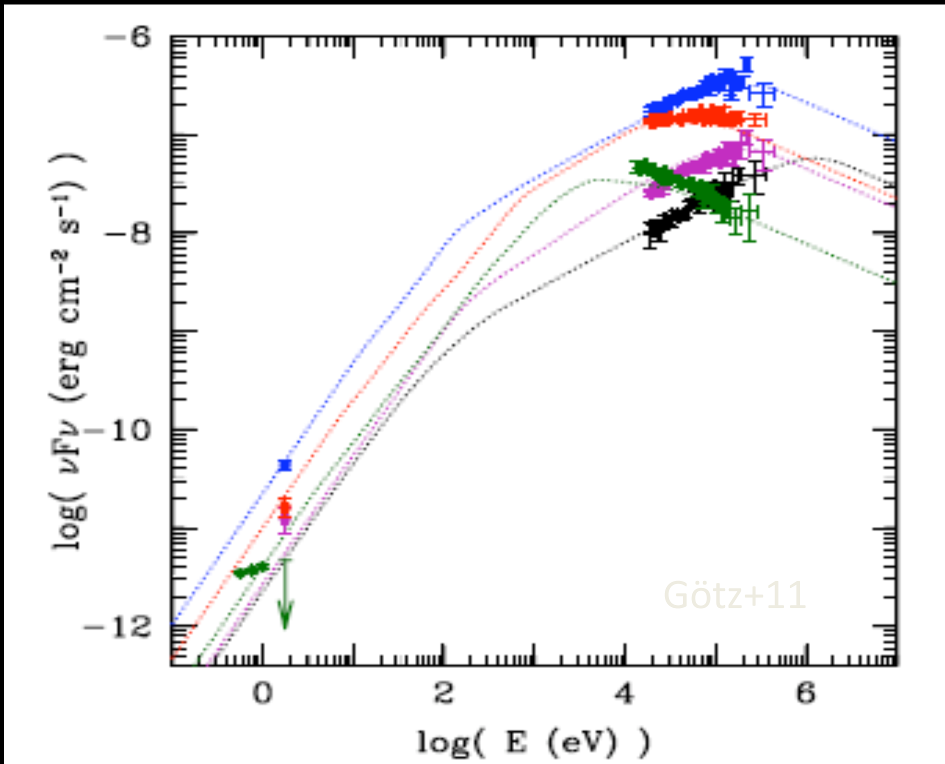




IBIS light curves



Broad band modelling of the prompt emission



- Internal Shocks :
  - relativistic electrons accelerated by propagating shock waves
  - magnetic field amplification
  - multiple-shell numerical model (*Daigne & Mochkovitch 1998*)
- Synchrotron radiation : (*Sari, Piran & Narayan 1998*)
- Due to the very long duration of GRB 041219A, the deceleration of the ejecta by the external medium begins before the end of the prompt emission. (for realistic external medium densities)

-> Outflow dynamics which includes the contribution of the reverse shock

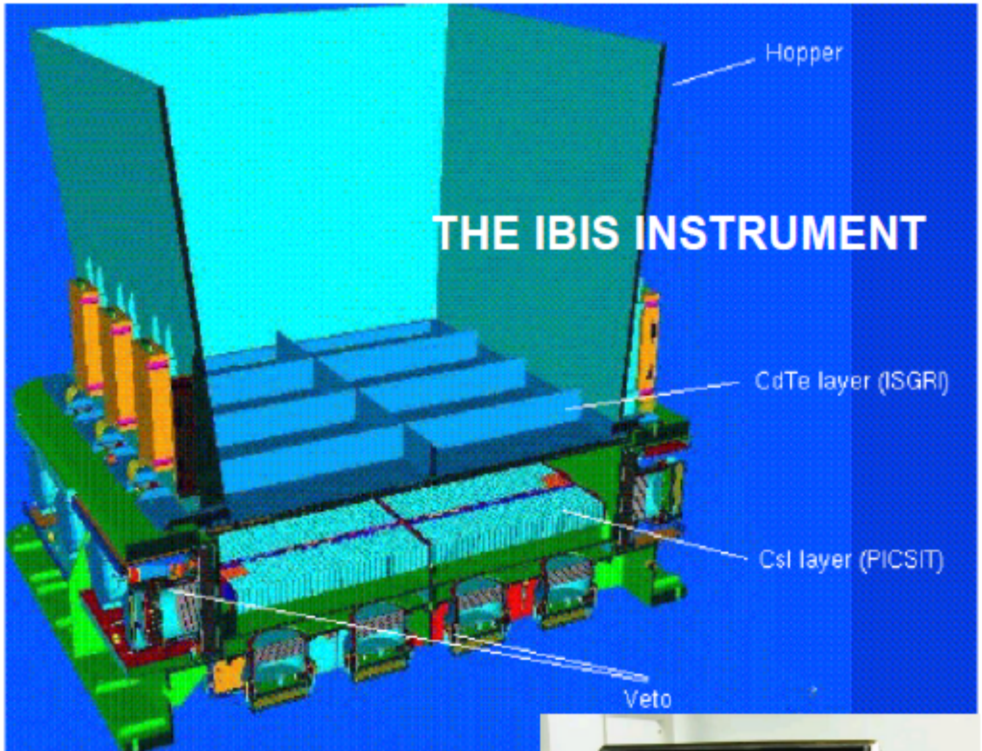
Potential IR emission origins

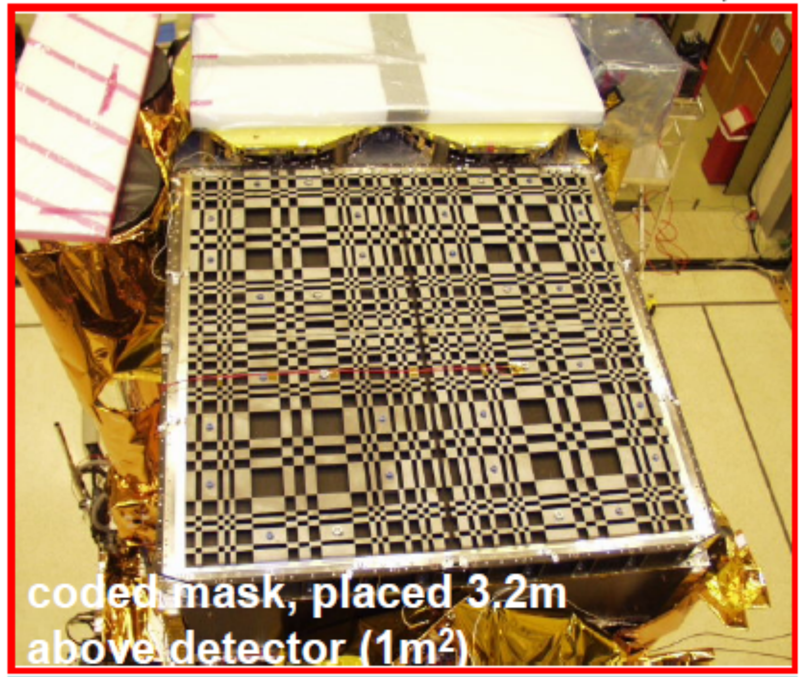
- External shock : the observed IR flare could be the main rise of the external shock afterglow. Timing problem : the delay compared to the main prompt event is huge. (very low external densities or very low Lorentz factors are necessary)

- Late collision (or Reverse Shock) : main contribution at low frequencies. Spectral problem : without any change in the microphysics parameters, impossible to get the right spectral slope.

Polarization of GRBs

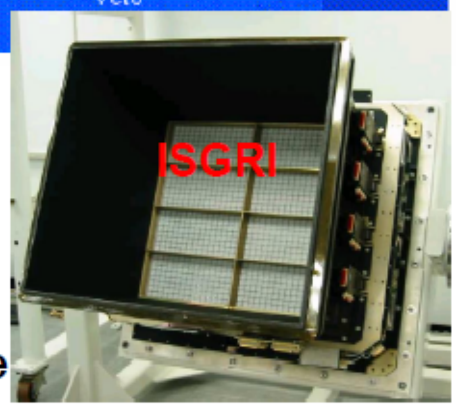
The IBIS Telescope





IBIS detector assembly:

two stacked detection planes, lateral and bottom veto anticoincidence, passive tungsten shield



Collection area ~ 3000 cm^2

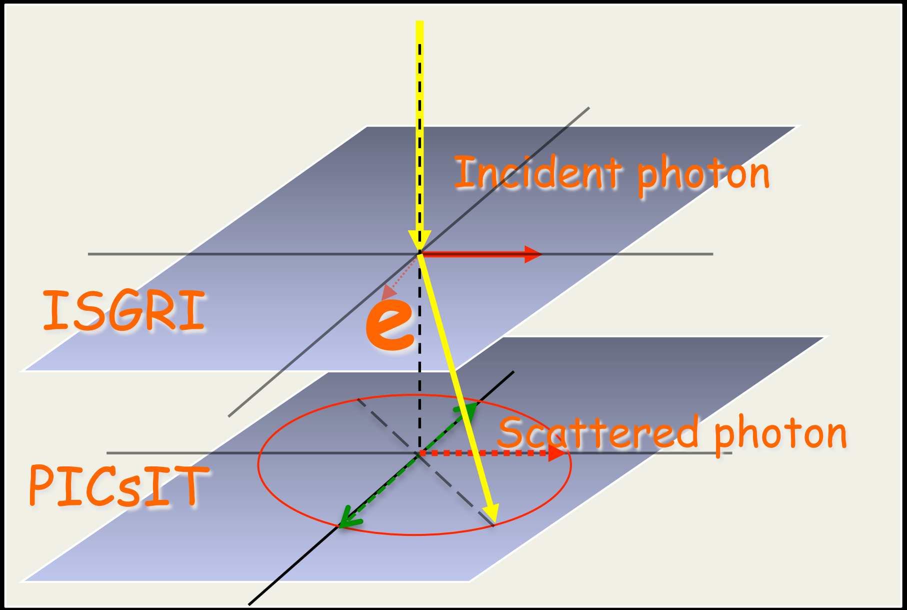
Two-Layers detector:

1) 2mm thick CdTe (ISGRI)

2) 30mm thick CsI (PICsIT)

Field-of-view: ±14.5° FWZR (± 4.5° fully coded)

IBIS as a Compton telescope



- The IBIS telescope is a coded mask telescope which could be used as a Compton telescope.
- The Compton mode events are ISGRI and PICSIT events in temporal coincidence, within a window $\tau_W \approx$ 3.8 μs.

- Within this window, chance coincidence, called hereafter "spurious events", may also occur.

The IBIS Compton Telescope Advantages

It is a coded mask Compton telescope, so it takes advantage of the two imaging techniques:

- It produces sky images using the coded mask with the same capabilities as ISGRI.
- It has an inherent very low background (~ 90 cts/s) compared to SPI and PICsIT.
- We can use the Compton effect to further reduce the background, by selecting with the Compton kinetics, events coming only from the coded mask FOV.
- We can do polarimetry !

Compton Polarimetry Principles

- Compton scattering cross section is maximum for photons scattered at right angle to the direction of the incident electric vector ⇒ asymmetry in the azimuthal profile S of scattered events.

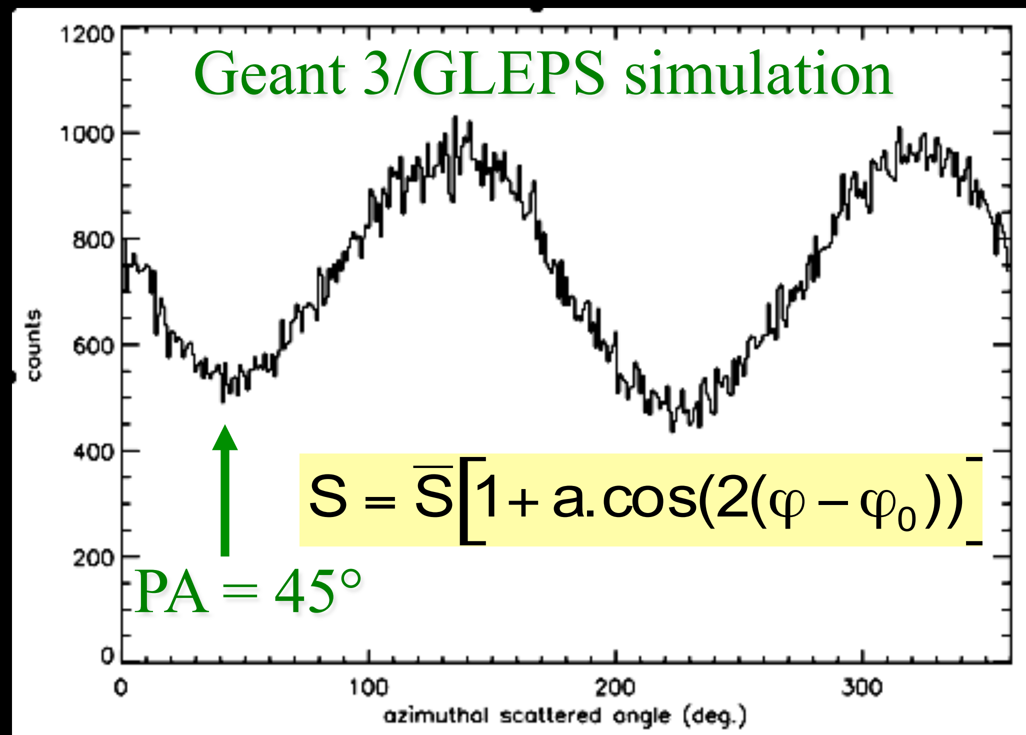
$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E_0}\right)^2\left(\frac{E'}{E_0} + \frac{E_0}{E'} - 2\sin^2\theta\cos^2\phi\right)$$

- Modulation:
  a = modulation factor

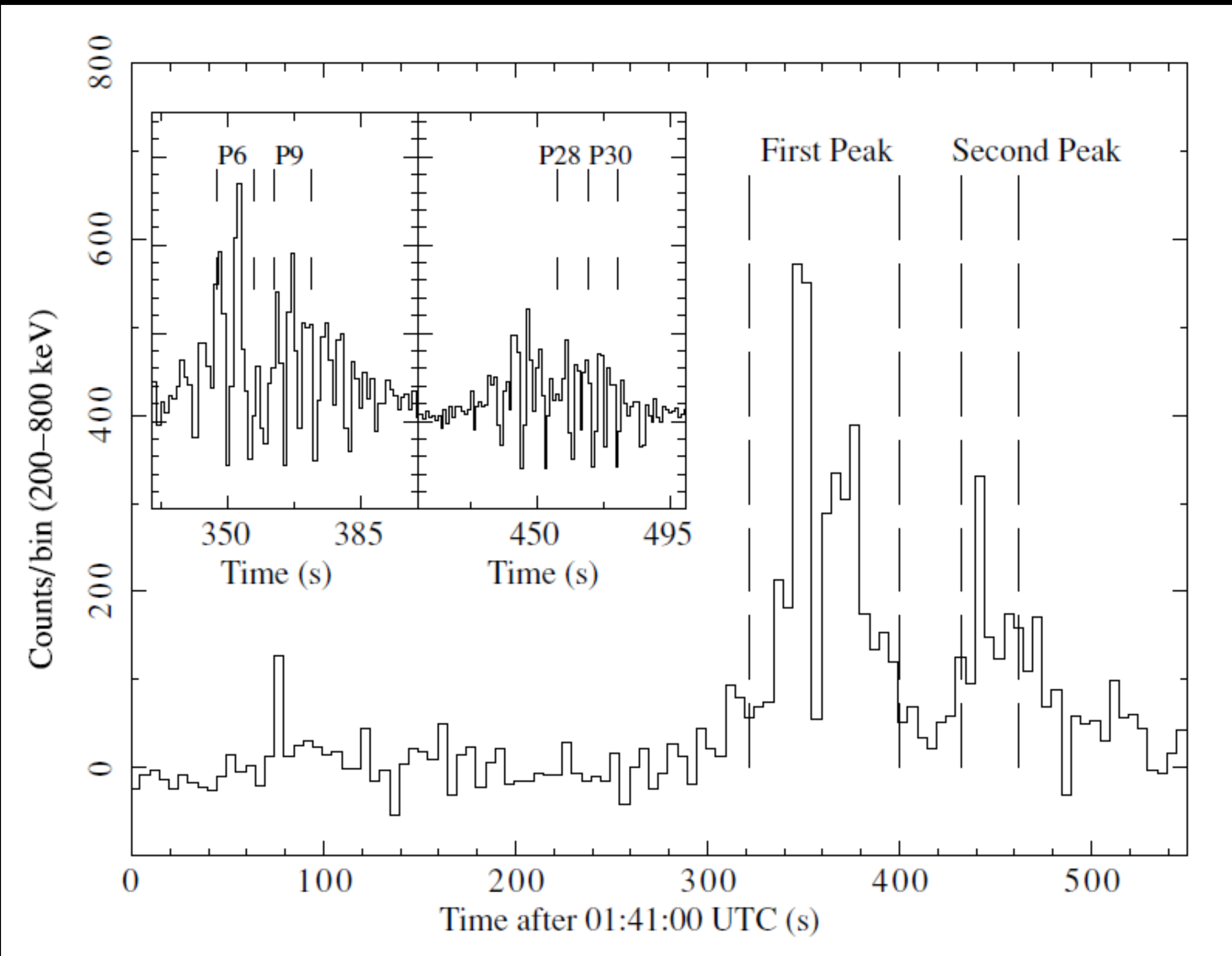
  polar. Fraction (PF) = a/a_{100}

  a_{100} = modulation for a 100 % polarized source.

  polar. angle = PA = $\varphi_0 - \pi/2 + n\pi$



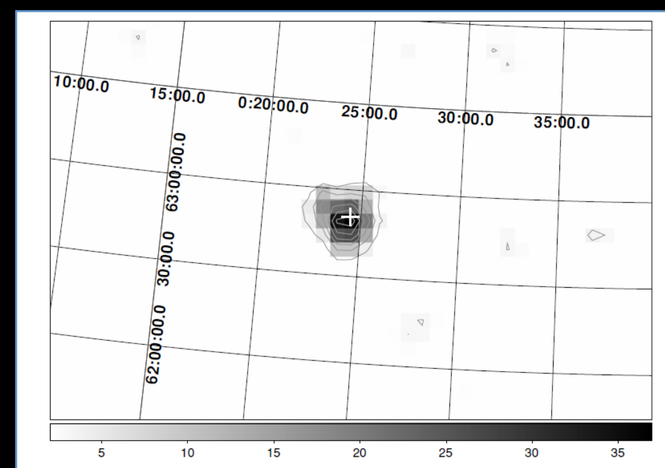
GRB 041219A: Compton mode light curve



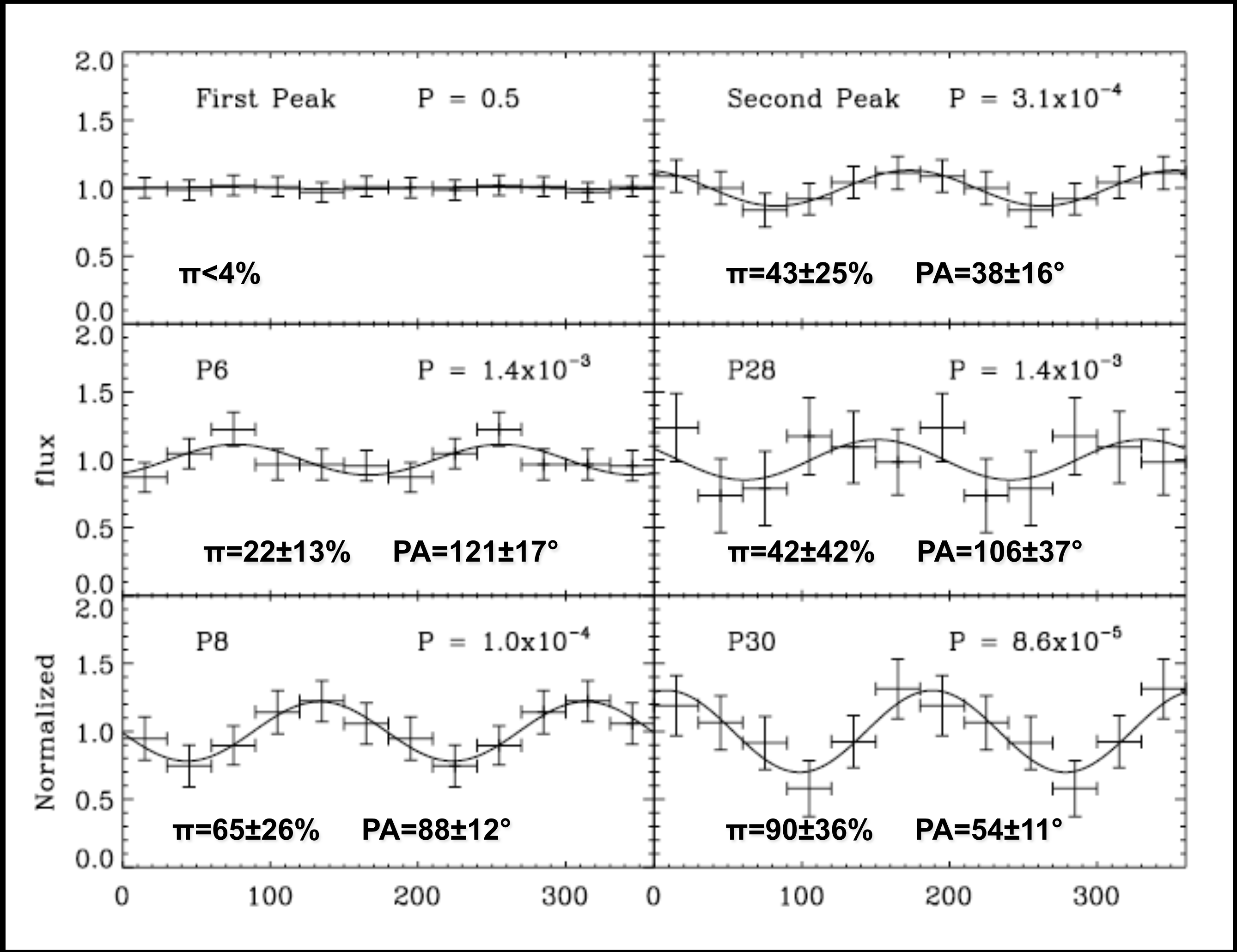
5s bins

Analysis in 10s bins

Total S/N (200-800 keV) 37 σ



GRB 041219A: polarization results



Götz+09

SPI: π=68±29% PA=70°$^{+19°}_{-27°}$
McGlynn et al. (2007)

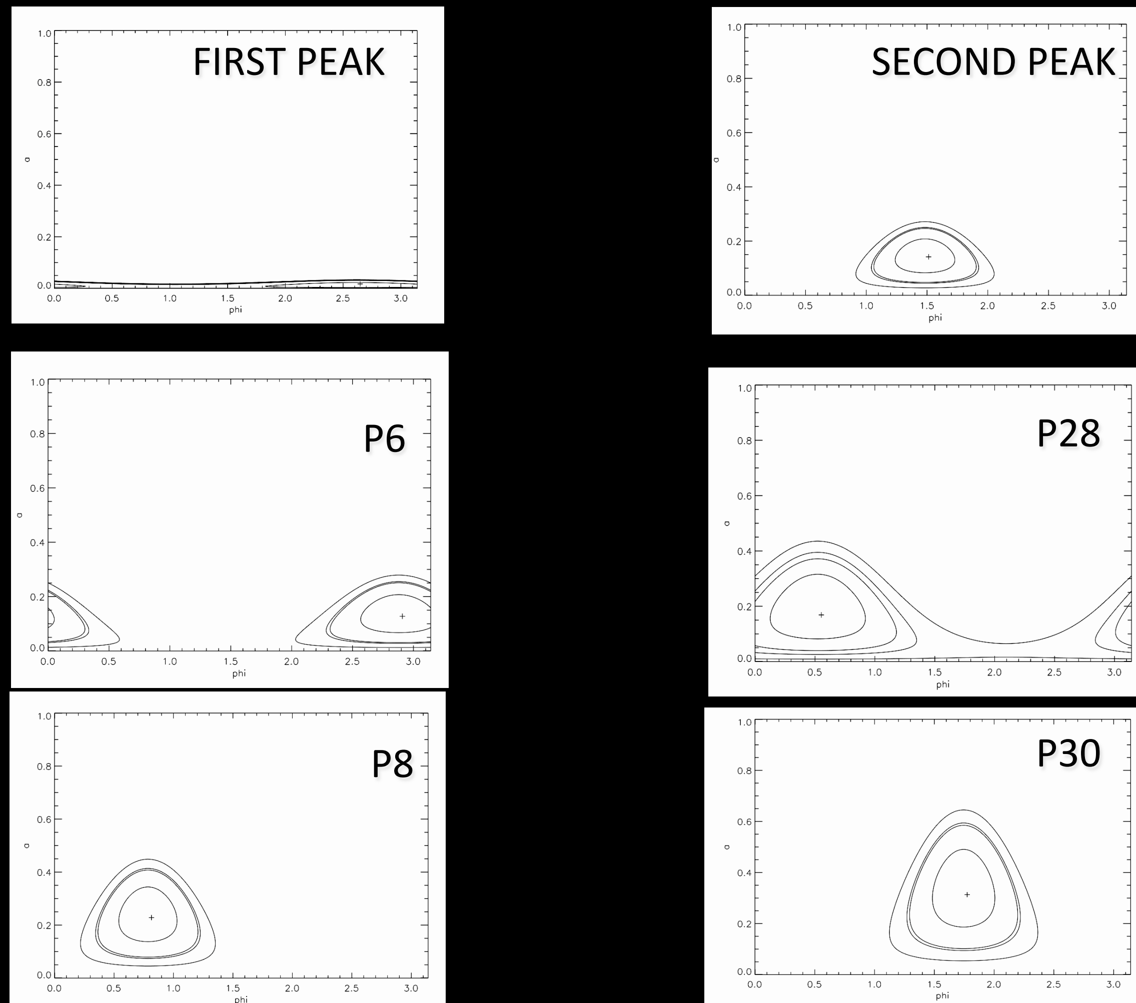
041219A: polarization statistics

confidence levels at 67, 90, 95, and 99 %

Ao

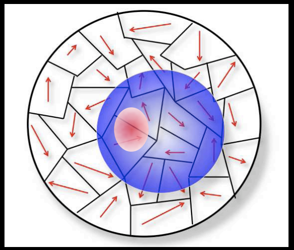
Ao

Ao



PHI0 PHI0

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)

GRB 041219A: constraints on LIV

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 041219A: constraints on LIV

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

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

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

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

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

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

GRB : at least 10^5 times further away

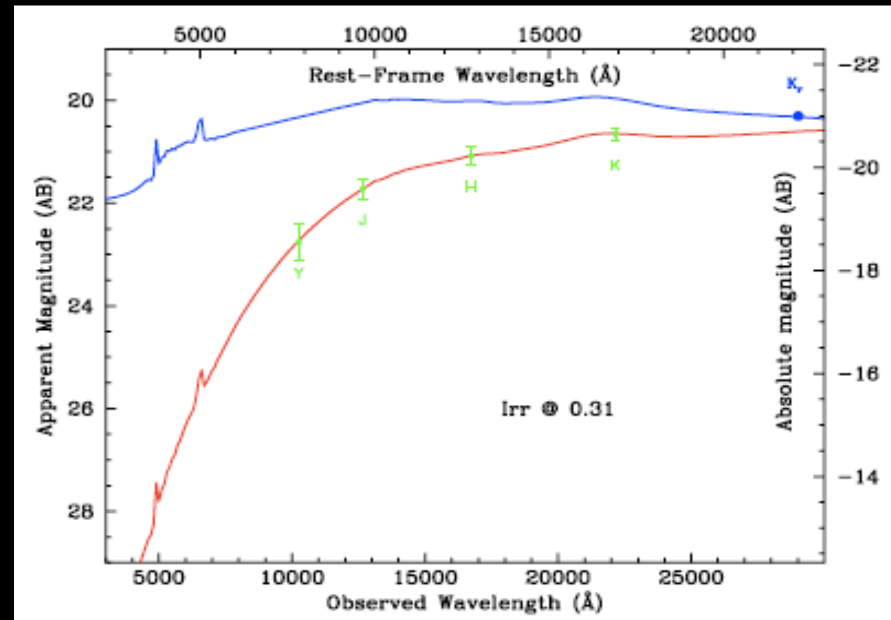
GRB 041219A: distance detemination

Host galaxy identification and photometric redshift measurement with the CFHT/WIRCam instrument :

=> $z = 0.31^{+0.54}_{-0.26}$ (68% c.l.)

=> d = [0.222-5.406] Gpc

with standard cosmological parameters (Ω_m=0.3, Ω_λ=0.7, H=70 km/s/Mpc)



Parameter	*Value*
R.A. (J2000)	$00^h24^m27.6^s$
Dec. (J2000)	$+62°50'33.5''$
Y	22.16 ± 0.35
J	20.81 ± 0.20
H	19.73 ± 0.17
Ks	18.86 ± 0.12

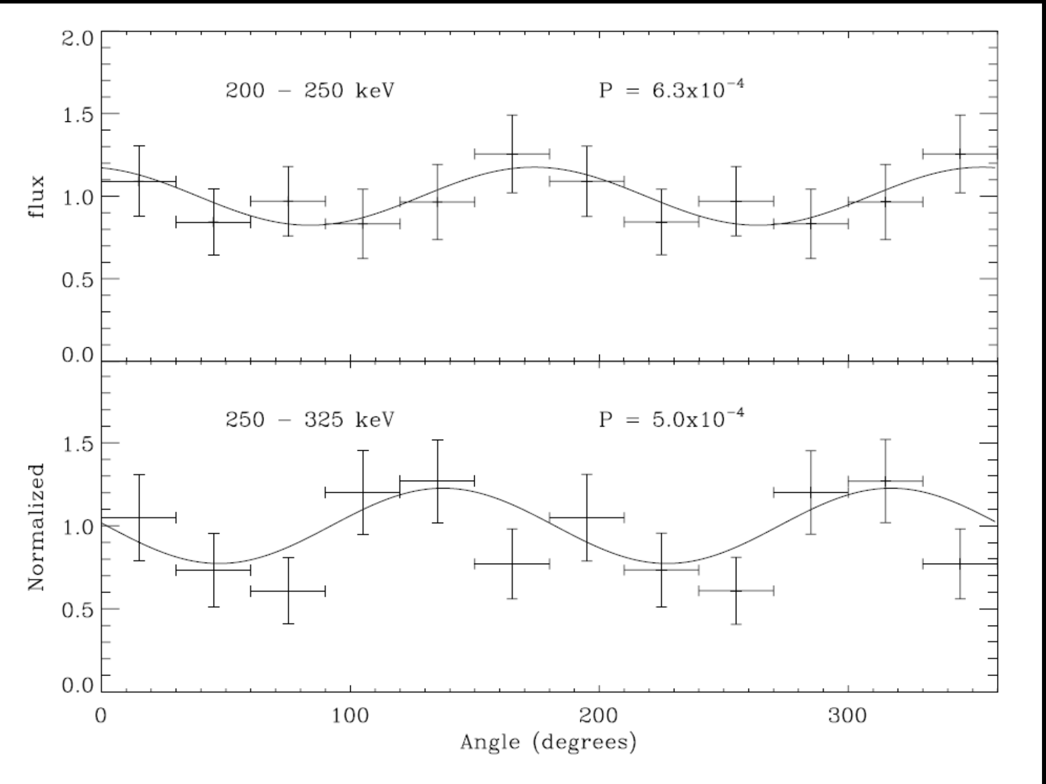
Irr @ z=0.31 is the best fit, but different solutions cannot be fully excluded.

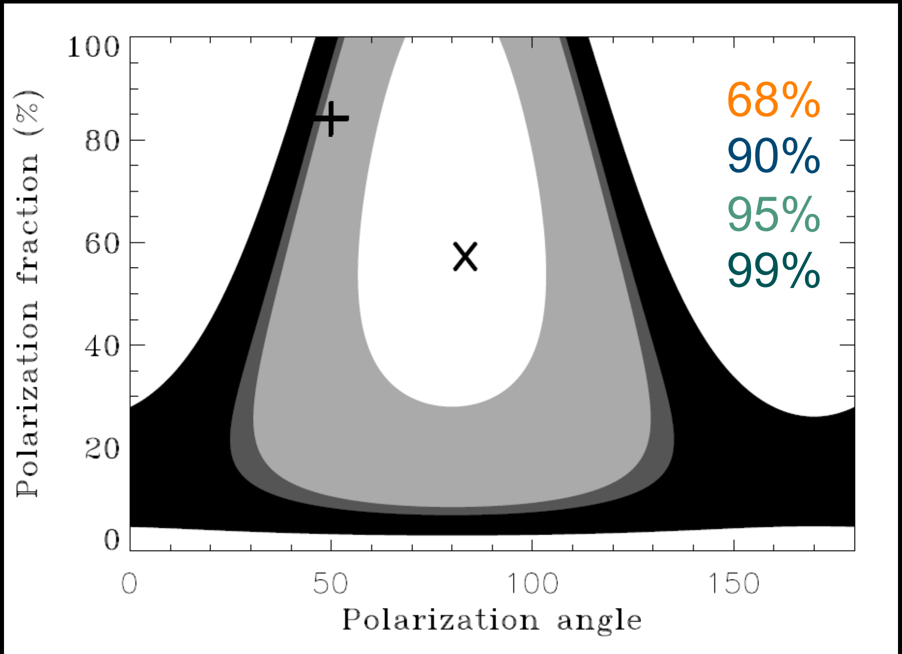
Absolute rest-frame K-band magnitude = −21.0, which corresponds approximately to a ≈ $0.1L^*$ galaxy, to a mass of ≈ $5 \times 10^9 M_\odot$

Götz+11

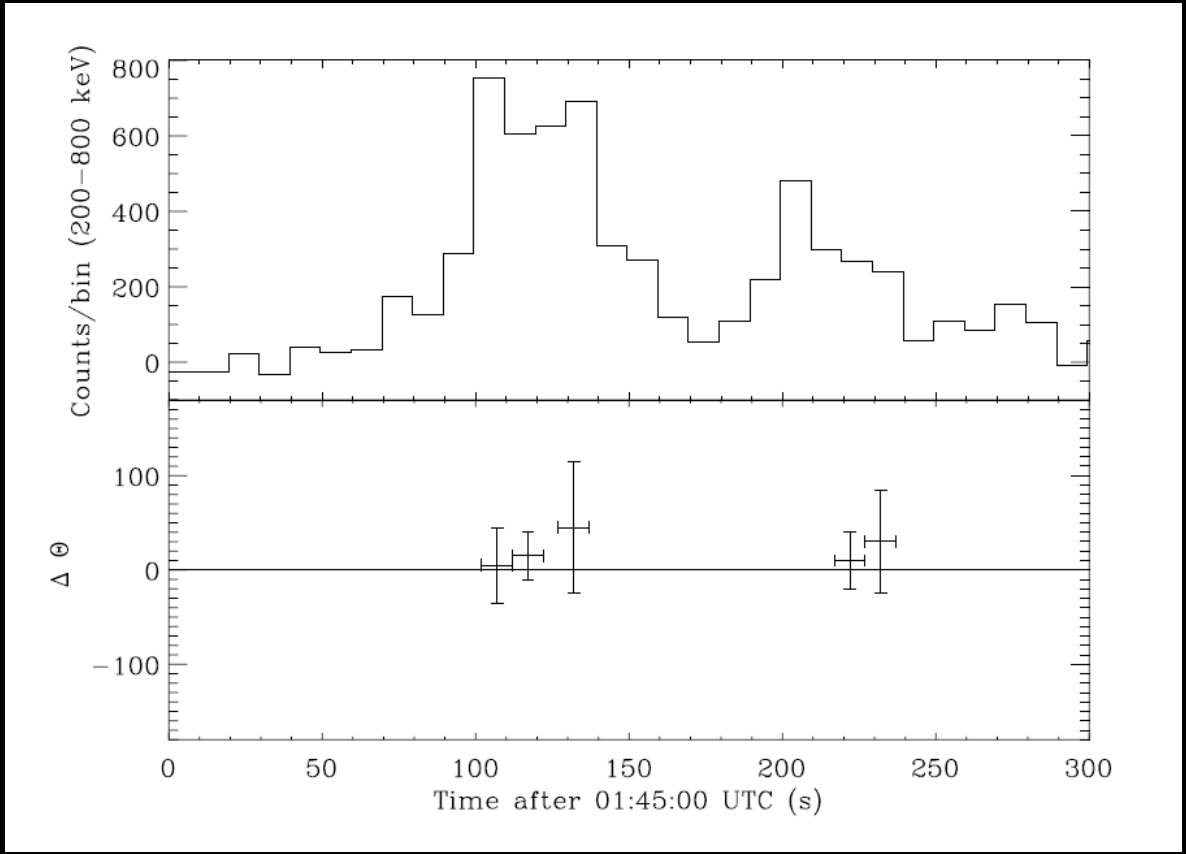
GRB 041219A: measure of $\Delta\theta$

Comparaison of PA between 2 energy bands with similar signal to noise





GRB 041219A: constraints on LIV



200-250 keV vs.
250-325 keV

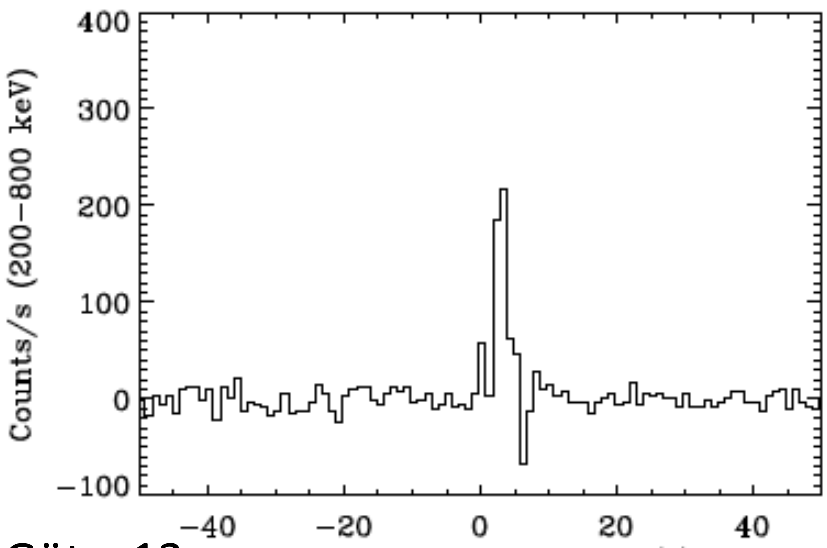
$\Delta\theta = 21 \pm 47°$

D > 85 Mpc (90% c.l.)

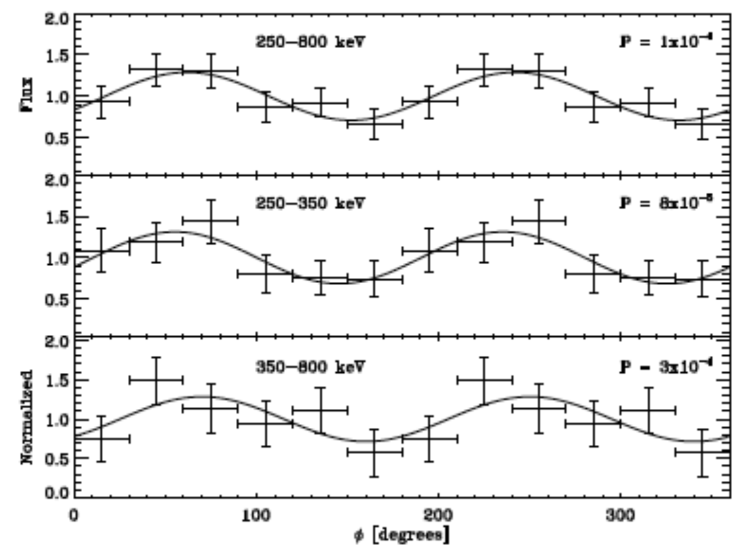
$\xi < 1.1\text{x}10^{-14}$

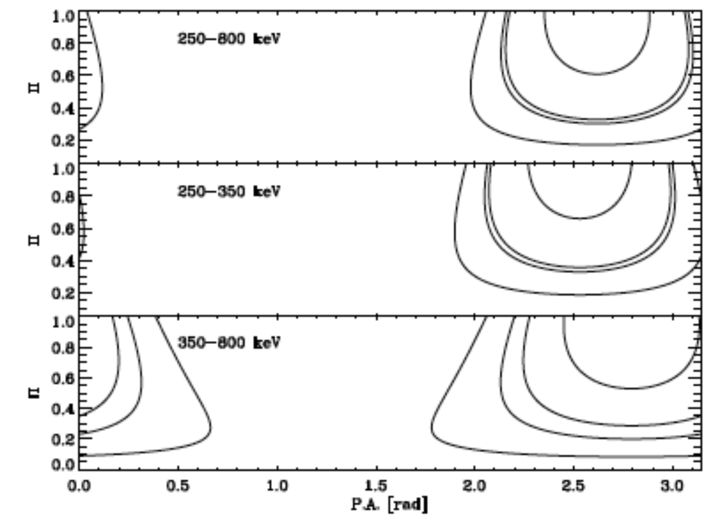
Laurent+11

GRB 061122



Götz+13





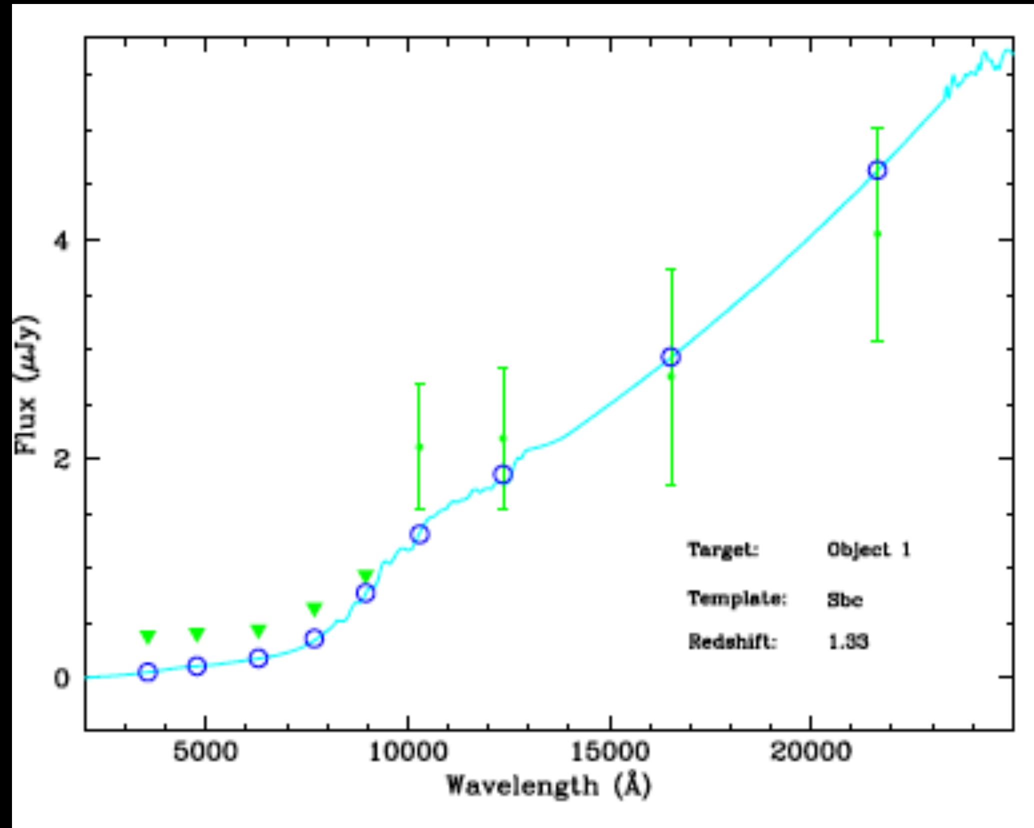
SPI u.l. < 60%McGlynn+09

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 061122

CFHT, TNG and GTC Opt./NIR follow-up. GRB Host identification and photometric redshift

Filter (System)	CFHT Exp. Time (ks)	TNG Exp. Time (ks)	Mag. Object 1	Mag. Object 2
$u^*(AB)$	4.5		>24.5 (3σ)	>24.75 (3σ)
$g'(AB)$	1.5		>24.25 (3σ)	23.60 ± 0.12
$r'(AB)$	1.2	1.9	>24.0 (3σ)	23.15 ± 0.10
$i'(AB)$	1.1	1.8	>23.5 (3σ)	22.23 ± 0.08
$z'(AB)$	0.5	1.8	>23.0 (3σ)	21.74 ± 0.10
$Y(Vega)$	7.6		22.66 ± 0.25	20.64 ± 0.07
$J(Vega)$	7.6	2.6	22.31 ± 0.27	20.16 ± 0.06
$H(Vega)$	4.9		21.52 ± 0.33	19.65 ± 0.09
$K_s(Vega)$	5.7	5.3	20.63 ± 0.22	19.37 ± 0.10

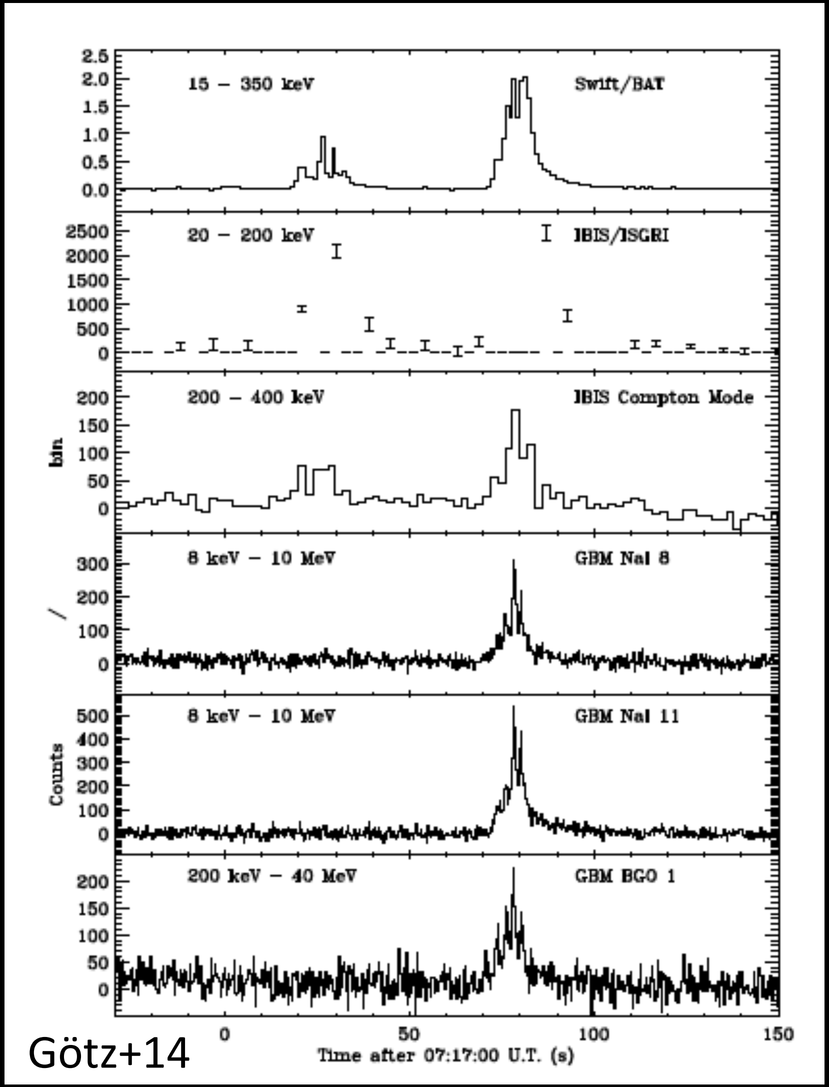


0.57<z<2.10 for an Sb/c galaxy

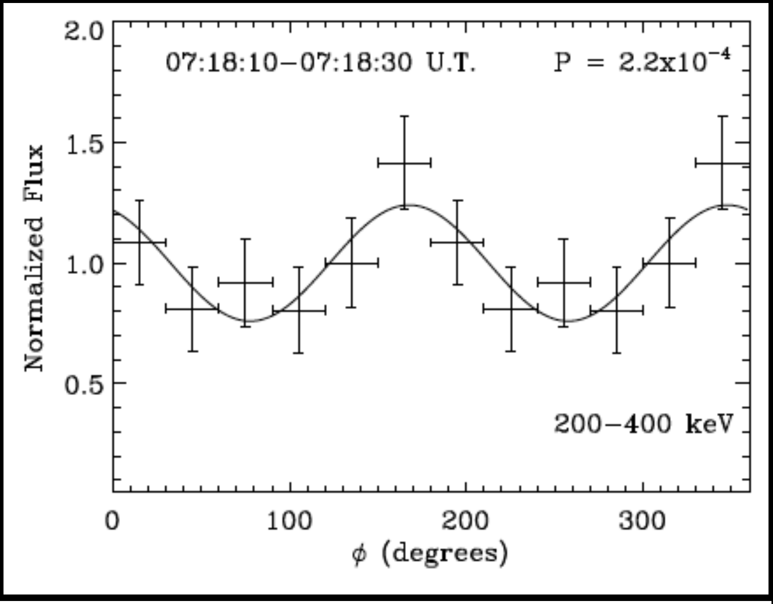
z>0.54; d>3.3 Gpc (90% c.l.)

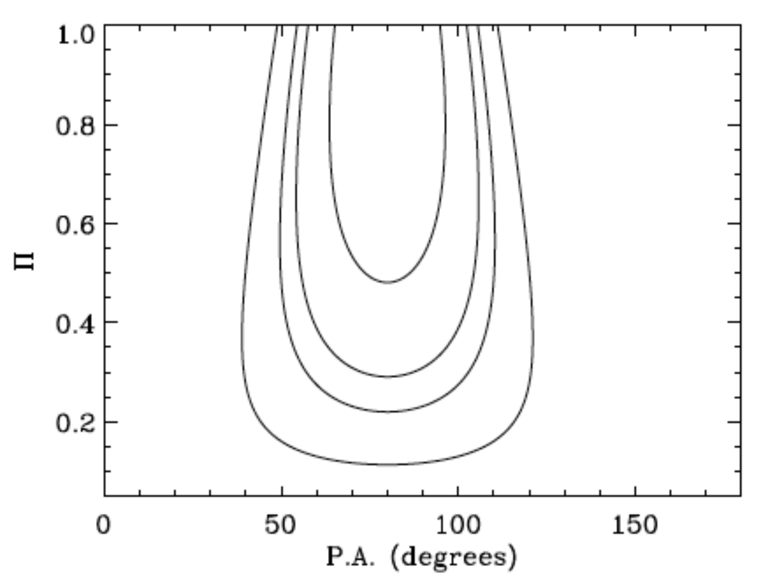
$$\xi < \frac{2M_{Pl}\Delta\theta(k)}{(k_2^2 - k_1^2)\,d} \approx 3.4 \times 10^{-16}$$

GRB 140206A (in press)



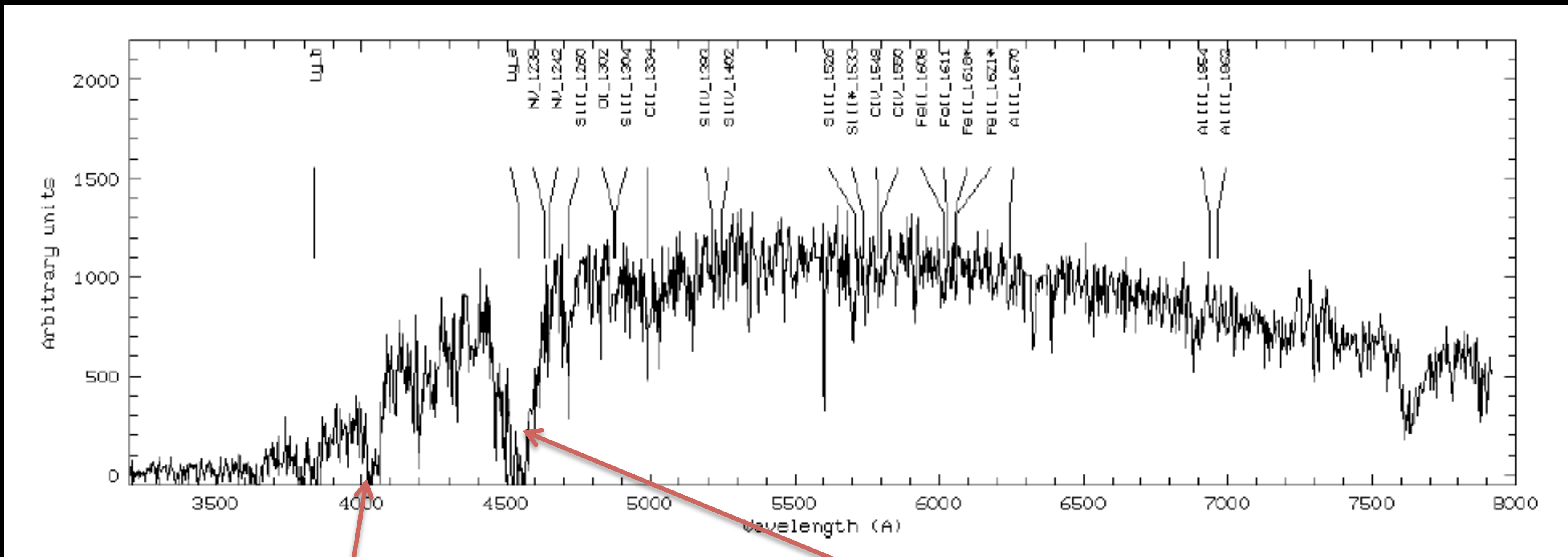
Götz+14





GRB 140206A

Bright optical afterglow: TNG spectrum available



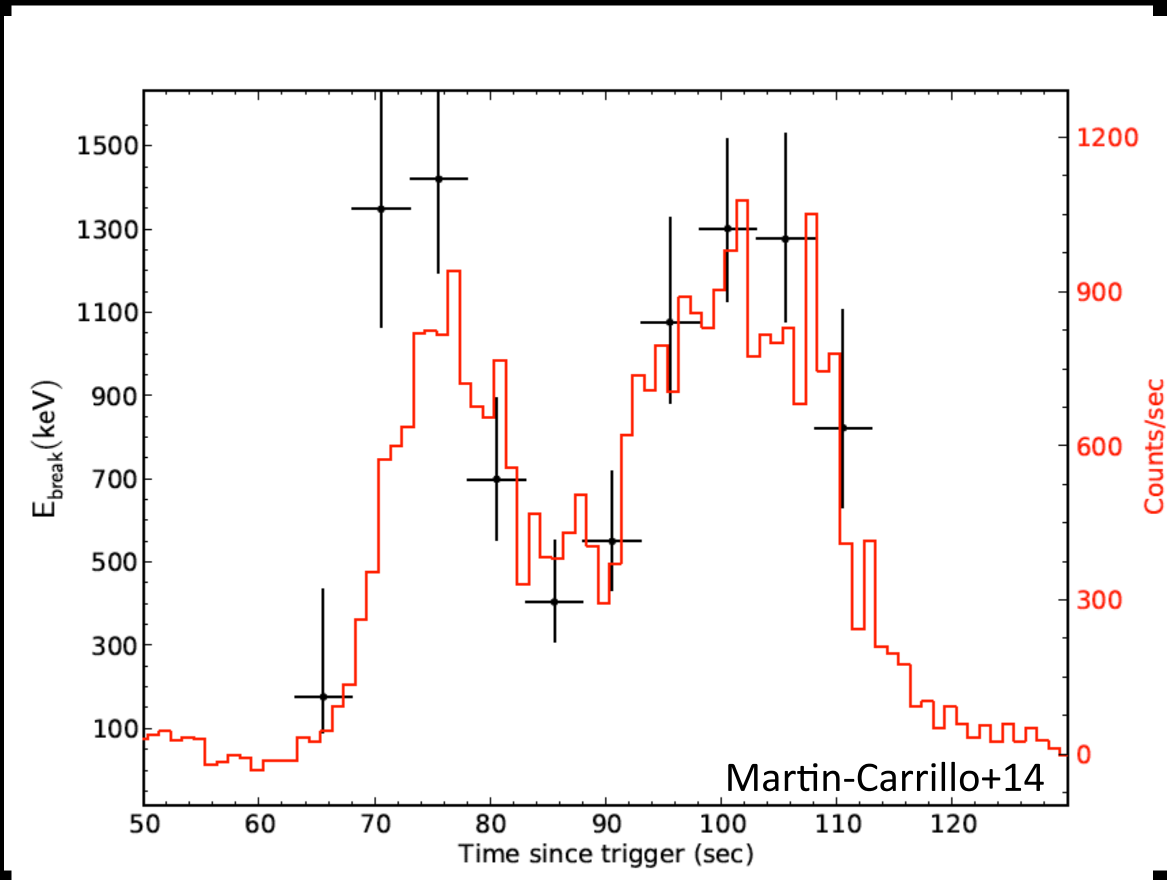
Intervening system at z=2.32 Ly-α

Host galaxy Ly-α

z=2.739+/-0.001; d=23 Gpc

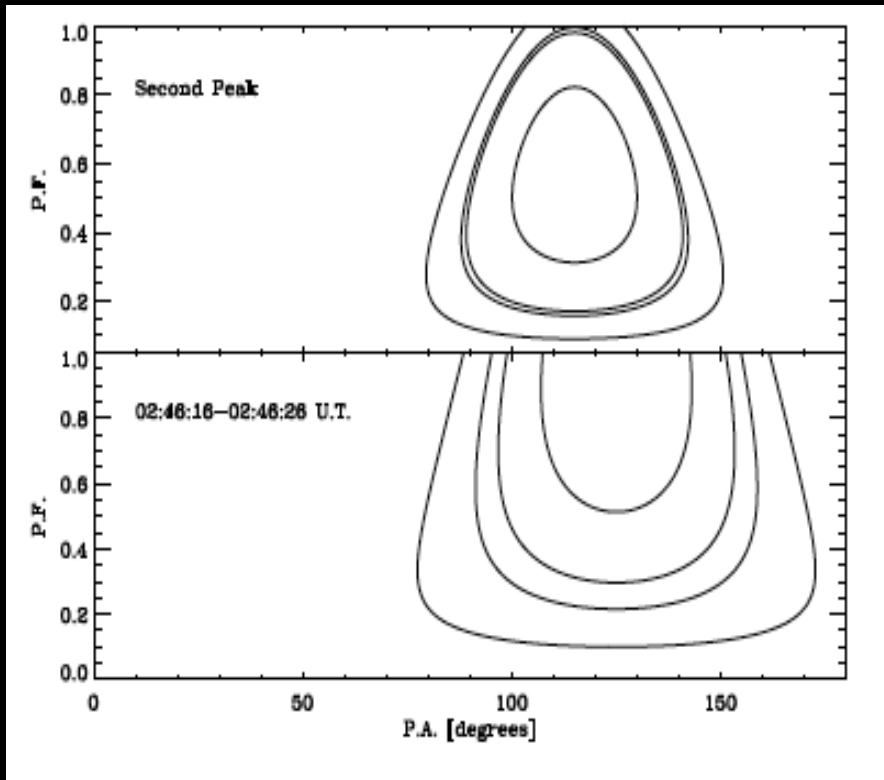
$$\xi < \frac{2M_{Pl}\Delta\theta(k)}{(k_2^2 - k_1^2)\, d} \approx 1 \times 10^{-16}$$

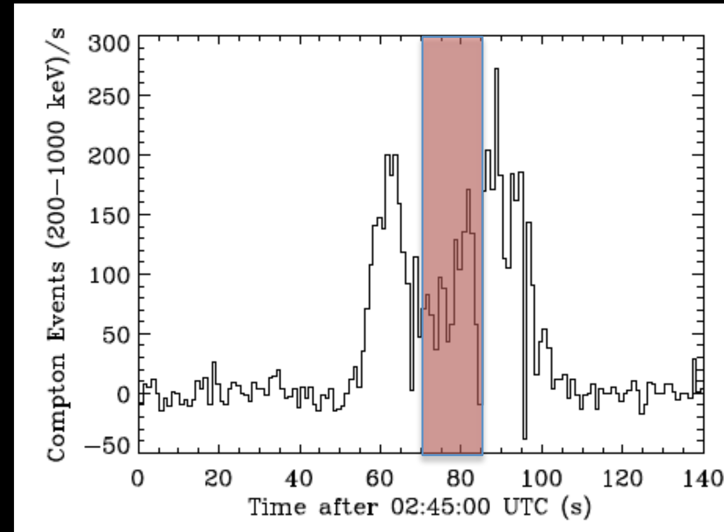
GRB 120711A (to be submitted)



- Very bright event
  - T_{90}~150 s, peak flux=26.7 ph cm^{-2} s^{-1}, fluence 2x10^{-4} erg cm^{-2} (10-1000 keV); Epeak ≈1 MeV!
- Bright optical counterpart peaking at R=12.1 , H=11.9 @ 1-2 minutes after trigger
- Hard X-ray afterglow lasting several ks
- Delayed LAT detection (GeV "afterglow")
- z=1.405

GRB 120711A





- No polarization signal on the first peak
- Polarization ***only*** on the second peak, and especially its rising part -> interpretation still needed (ICMART?)
- Polarization confirmation by SPI (2 sigma)

Start Time (UTC)	End Time (UTC)	Imaging SNR	PA (°; 68% c.l.)	Π (%; 68% c.l.)	Null-hyp. Prob.
2h46m16s	2h46m26s	10.3	125±20	>37	0.2×10^{-3}
2h46m26s	2h46m36s	14.8	120±20	45±35	1.2×10^{-3}
Second Peak					
2h46m15s	2h46m45s	19.3	115±15	54±27	0.3×10^{-3}

Summary on polarization results

GRB	Π (68% c.l.)	Peak energy (keV)	Fluence and Energy Range (erg cm^{-2})	z	Instrument
041291A	65±26%	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%	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

GRB	P.F. (68% c.l.)	Fluence	Peak Energy	Z	Instr.
120711A	54+/-27 %	3.8×10^{-4} erg/cm^2 (20 keV – 10 MeV)	~ 1 MeV	1.405	IBIS

Conclusions and lessons learnt

- INTEGRAL GRB studies have risen more questions than provided answers (probably true also for Swift and Fermi), e.g. on nature of the prompt gamma-ray emission wrt to other energy bands
- INTEGRAL has shown the potential of polarization studies for GRB science (and fundamental physics!), pointing out the necessity of this kind of experiment in the future (e.g. POLAR, POET). Only a statistical approach may be able to solve model degeneracies (e.g. Toma+09)
- Deepest <u>and most reliable</u> limit to date for the possibility of LIV in the photon sector through the vacuum birefringence effect: $\xi < 1 \times 10^{-16}$
- General purpose X-ray and Gamma-Ray observatories can often be used for GRB science at a relatively low additional cost, providing interesting results for a broad community
- A wide field of view X-ray monitoring experiment is mandatory for the near future, not only for GRB science, but also because it provides the necessary inputs for other wavelengths/astrophysical domains and upcoming observatories (GW detectors, neutrino, large radio arrays, etc.)

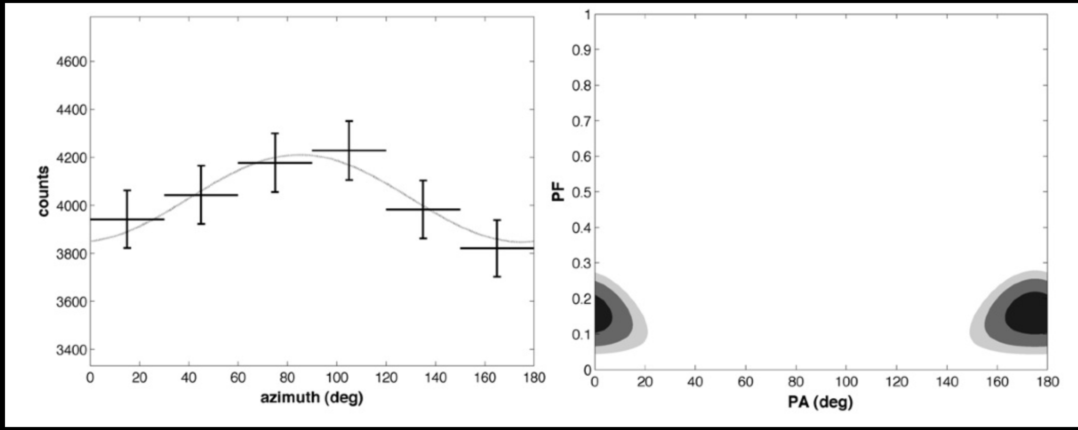
BACKUP SLIDES

Check for systematic effects

maximum modulation for unpolarized data?

(square detectors, grids, pixels, mask pattern…)

- Strong calibration source
  - at 392, 511, 662 keV
  - a < 5-7 %
- empty fields
  - a < 5 %
- observations at different source-detector angles
  - same results
- spurious event files
  - a = 15 % @ 180°



Spurious events

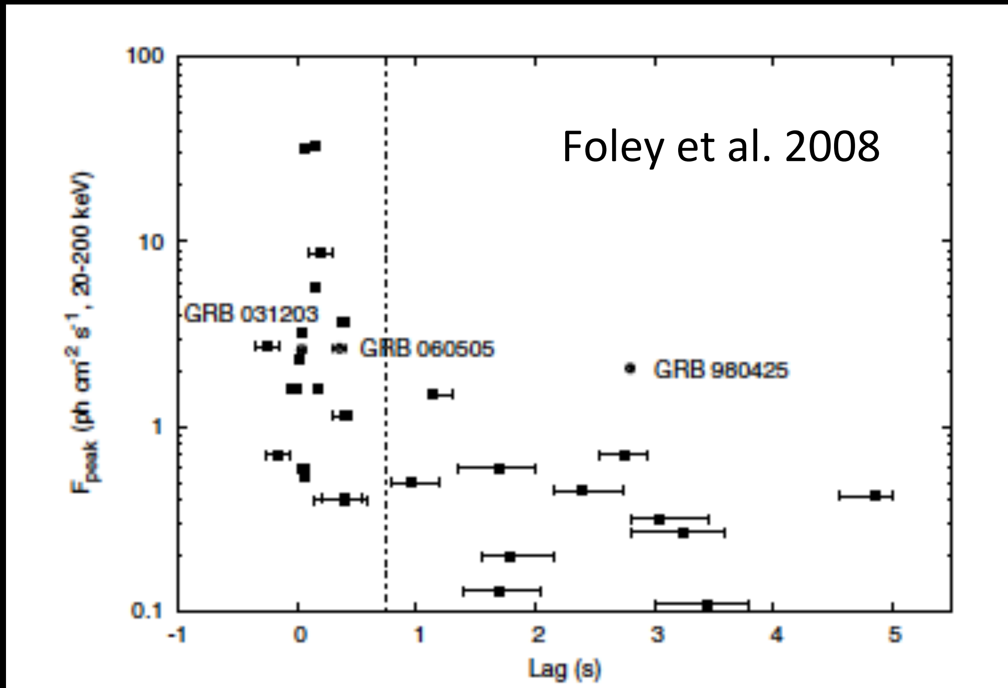
Probability law

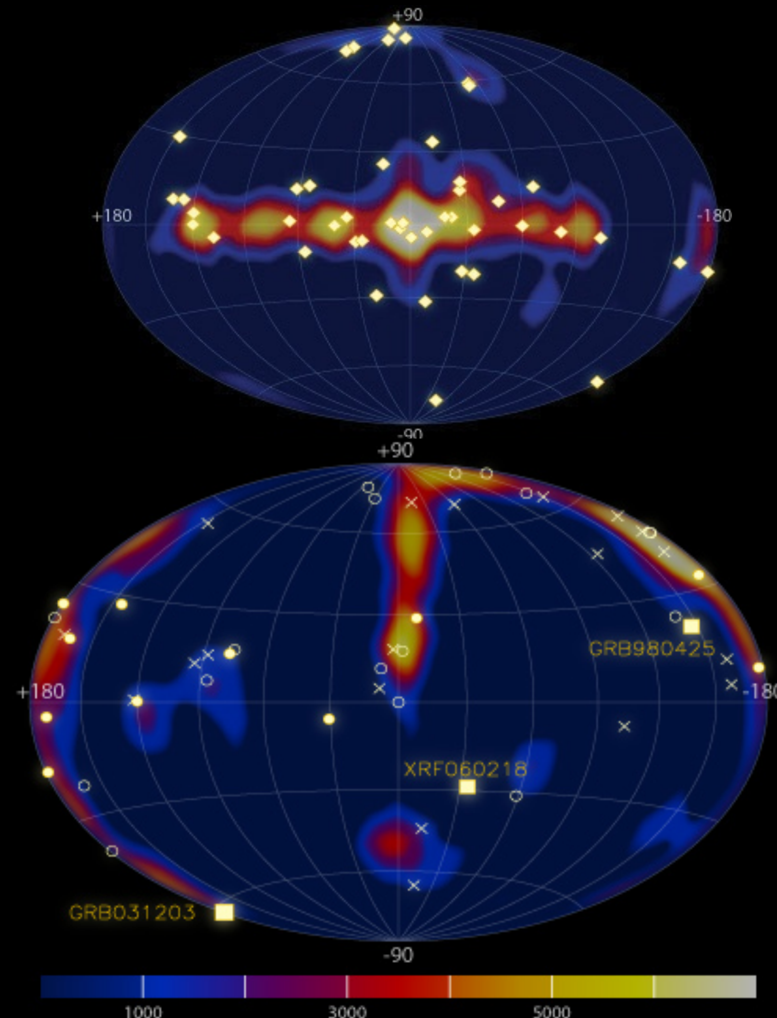
We use the following probability law, which take into account that PA and PF are not independent, and based on gaussian distributions for the orthogonal Stokes components:

$$dP(a,\psi) = \frac{N_{pt}\ S^2}{\pi\ \sigma_S^2} exp[-\frac{N_{pt}\ S^2}{2\ \sigma_S^2}[a^2 + a_0^2 - 2aa_0cos(2\psi - 2\psi_0)]]\ a\ da\ d\psi$$

$$N(\psi) = S[1 + a_0cos(2\psi - 2\psi_0)]$$

Long-lag GRBs





Long-lag GRBs are associated with the Super-Galactic Plane.

May be « local », hence faint

2.5 sigma -> 3 sigma Vianello+09