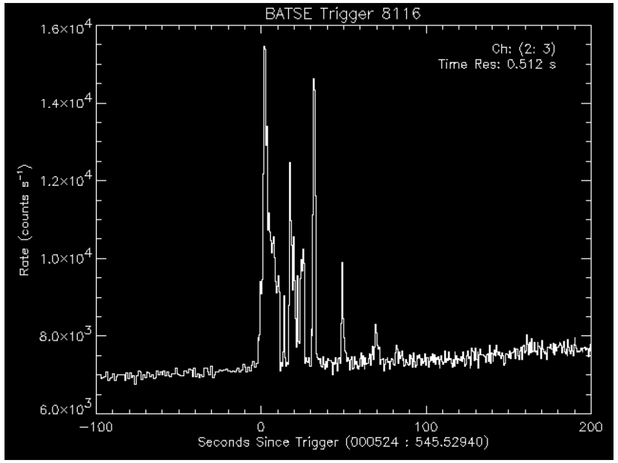
Astrofisica Nucleare e Subnucleare

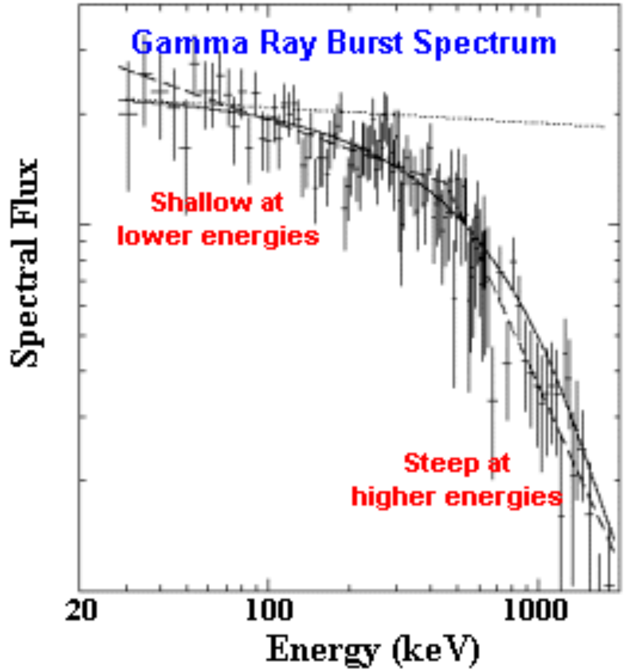
Gamma ray Bursts – III

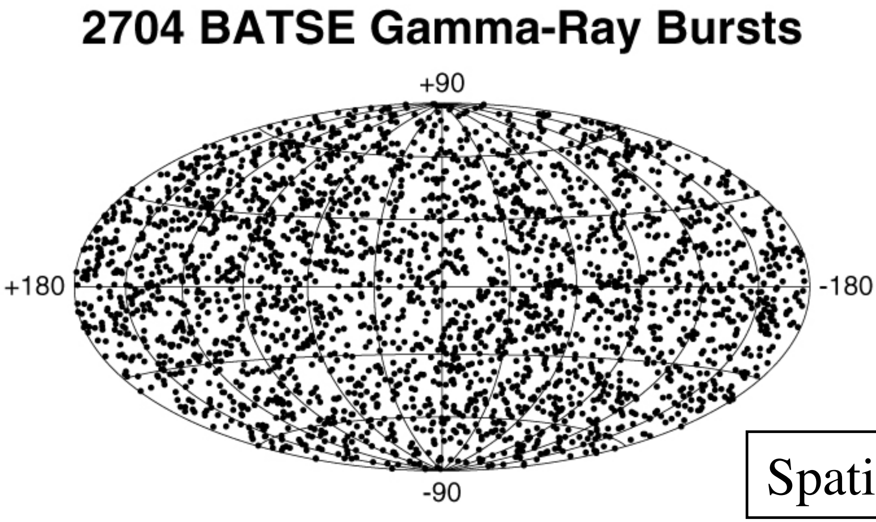
Gamma-Ray Bursts

Temporal behaviour



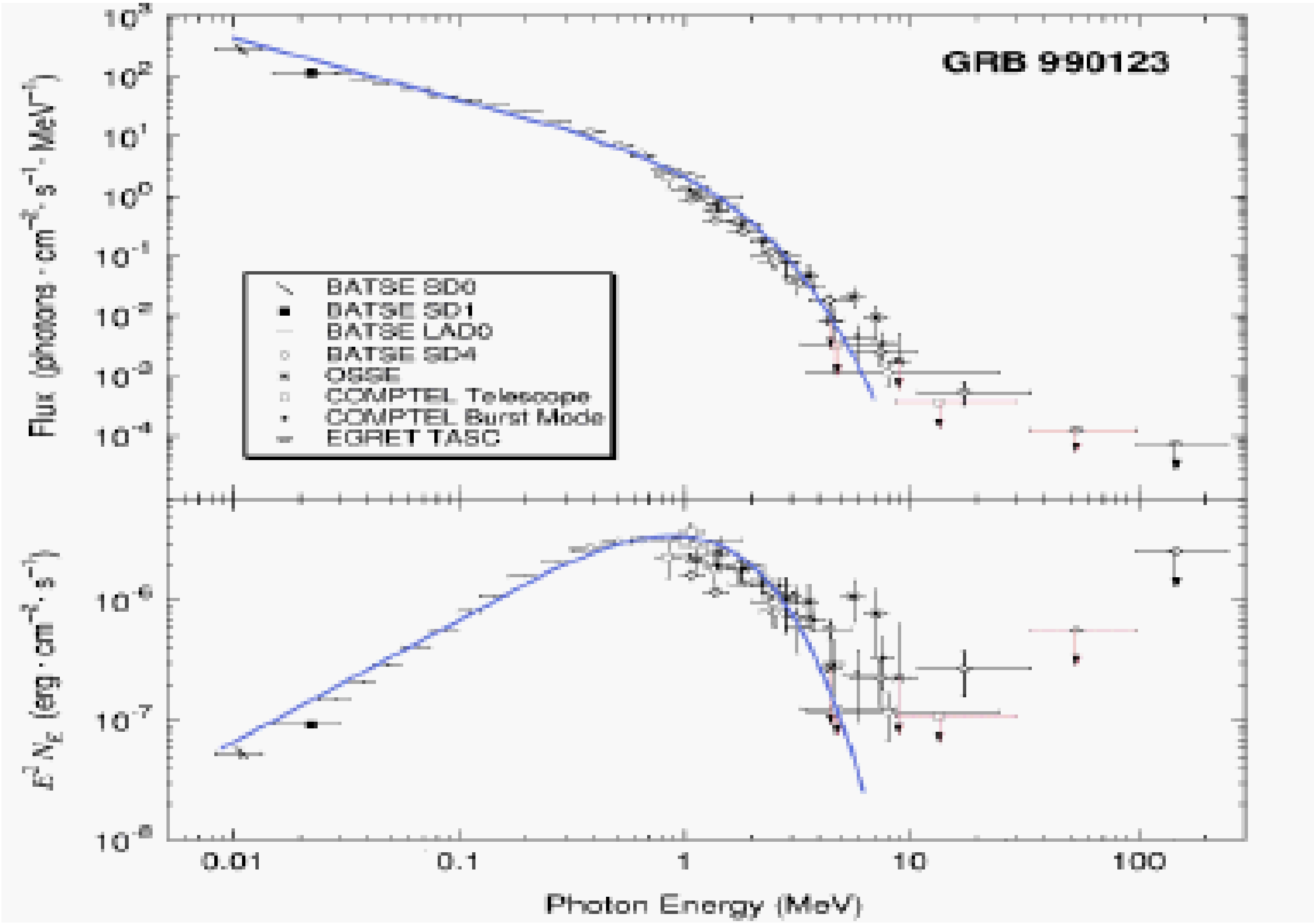
Spectral shape



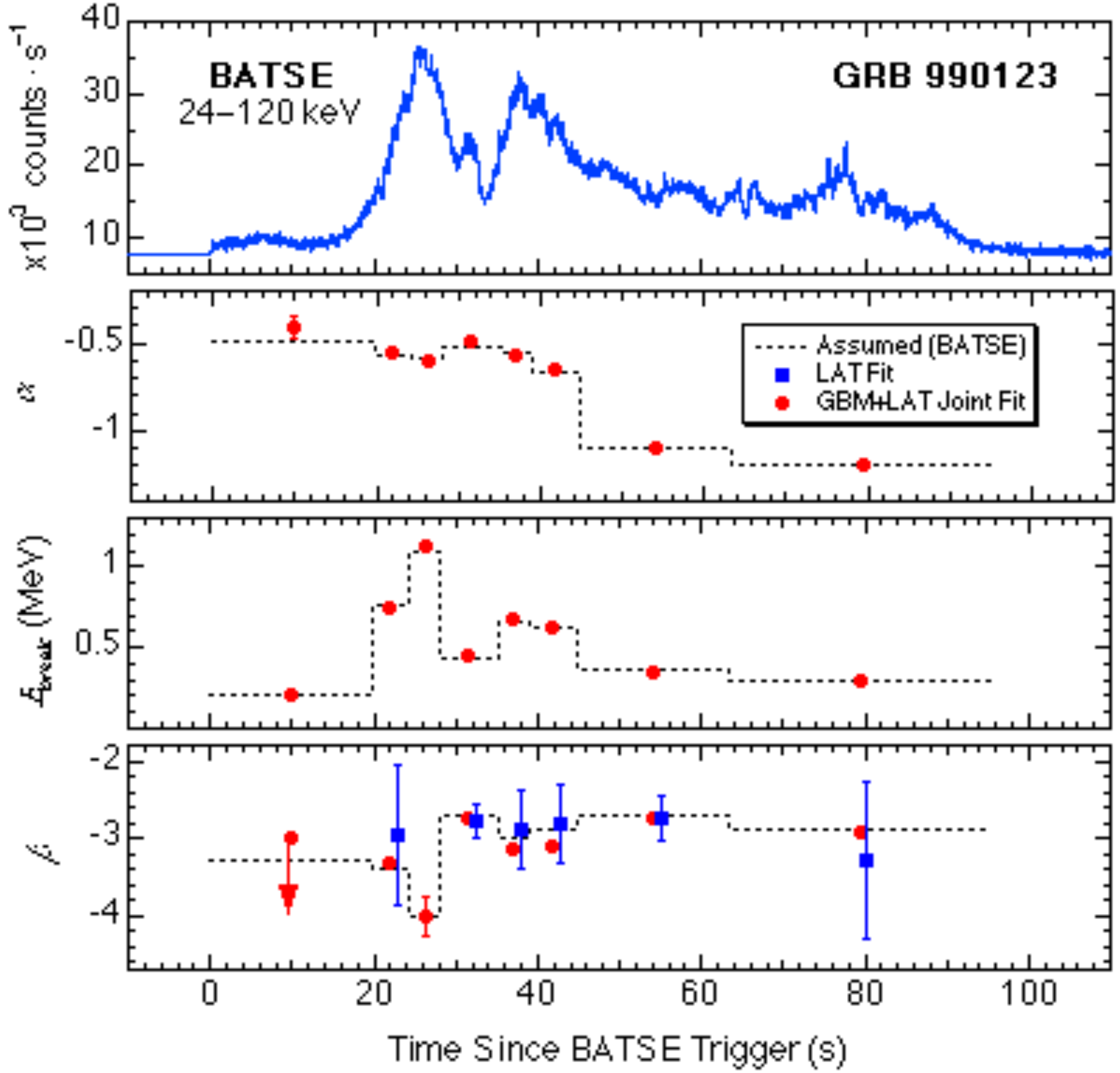


Spatial distribution

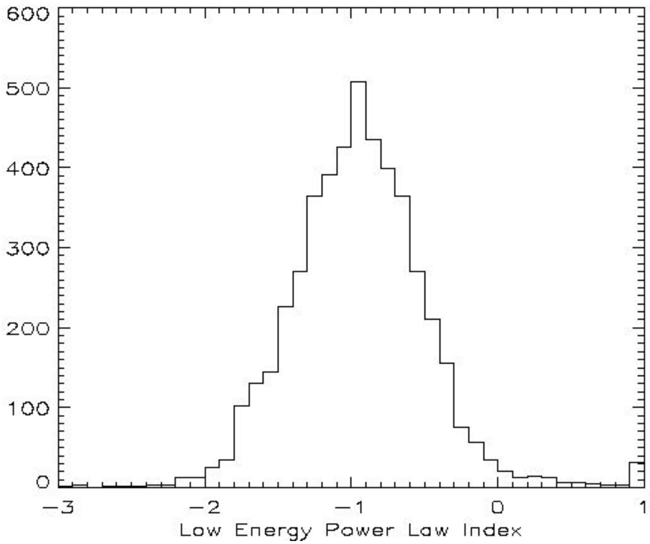
BATSE (1991-2000)



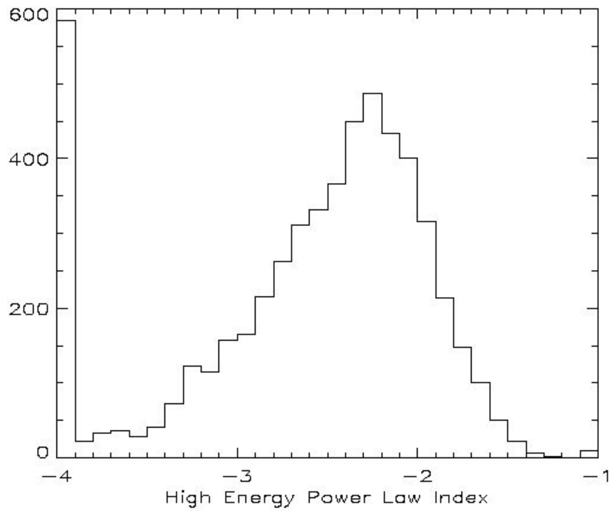
Spectral Evolution



Spectral variability

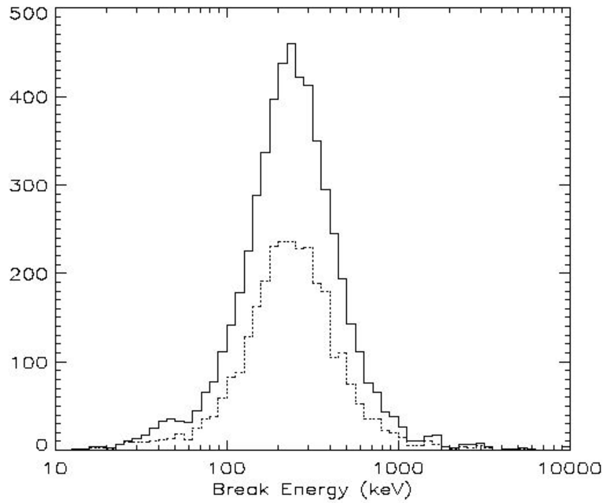


alpha



beta

Epeak



Preece et al. (2000)

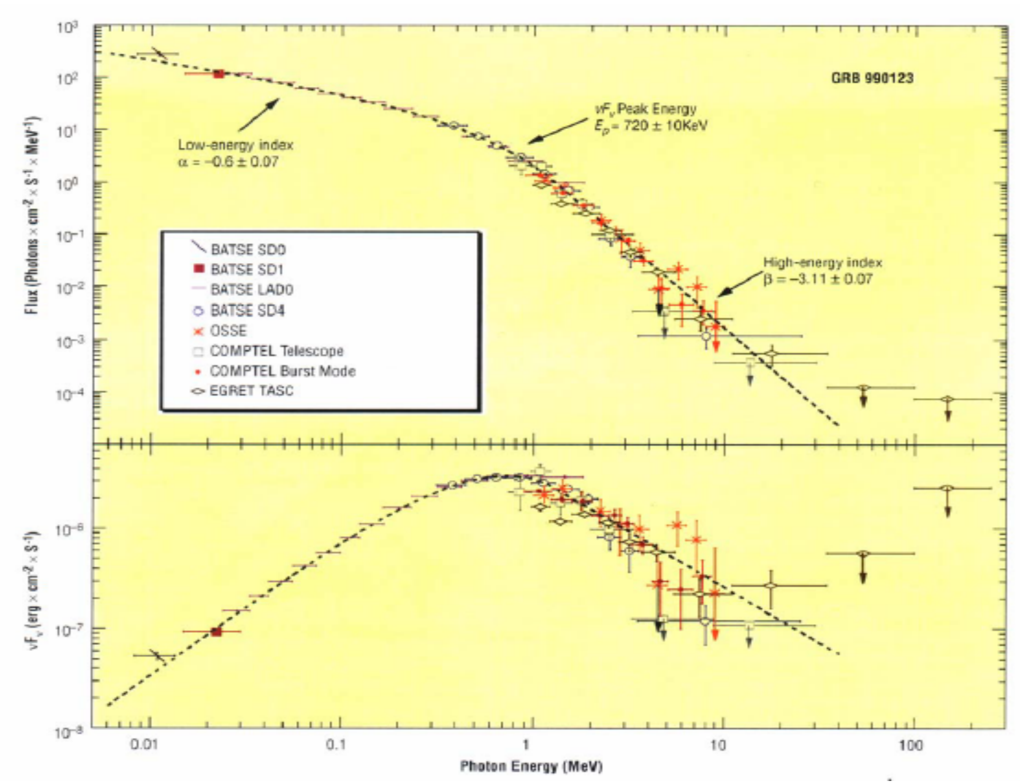
The Ep,i – Eiso correlation

- spectra typically described by the empirical Band function with parameters α= low-energy index, β= high-energy index, E_0=break energy

- $E_p = E_0 \times (2 + \alpha)$ = peak energy of the $\nu F\nu$ spectrum

$$N_E(E) = A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right), \quad (\alpha - \beta)E_0 \geq E$$

$$= A\left[\frac{(\alpha - \beta)E_0}{100\ \mathrm{keV}}\right]^{\alpha - \beta} \exp(\beta - \alpha)\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta}, \quad (\alpha - \beta)E_0 \leq E$$

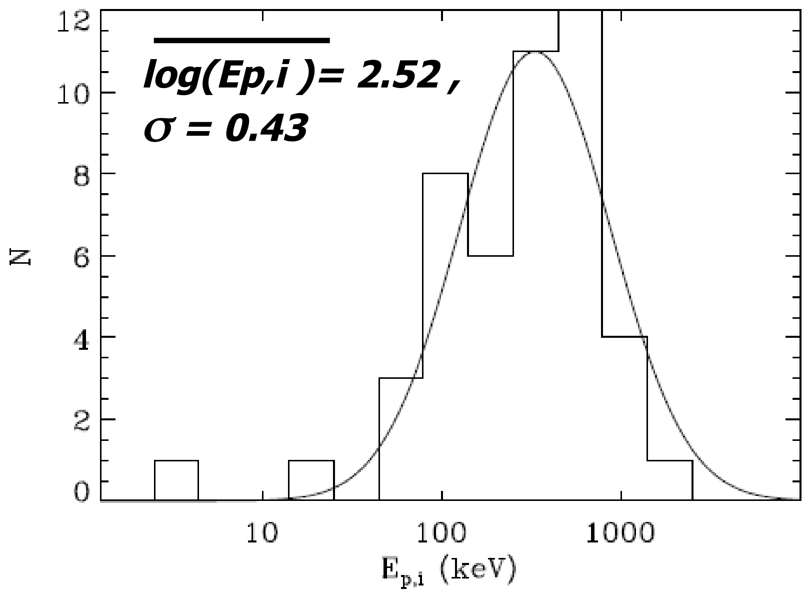


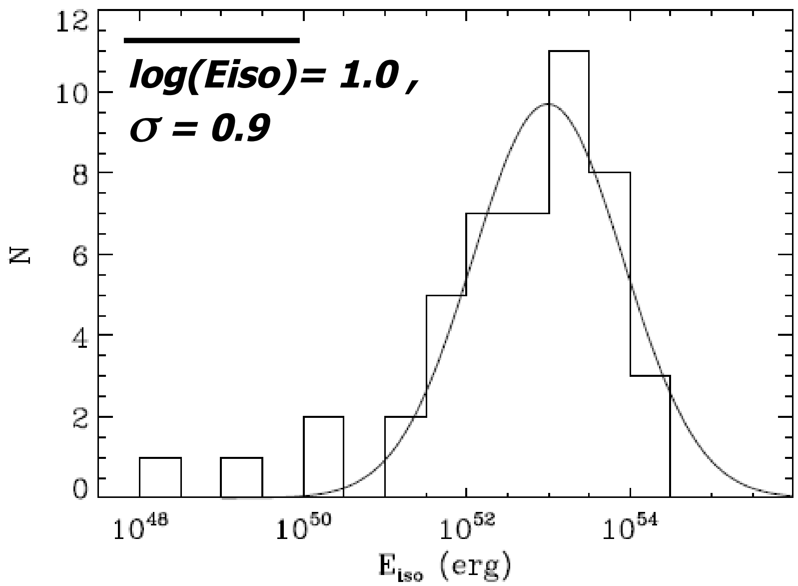
- all GRBs with measured redshift lie at cosmological distances (z = 0.033 – 6.3) (except for the peculiar GRB980425, z=0.0085)

- **from distance, fluence and spectrum, it is possible to estimate the cosmologica-rest farme peak energy Ep,i and the radiated energy assuming isotropic emission, Eiso**

$$E_{p,i} = E_p \times (1 + z)$$

$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg}$$



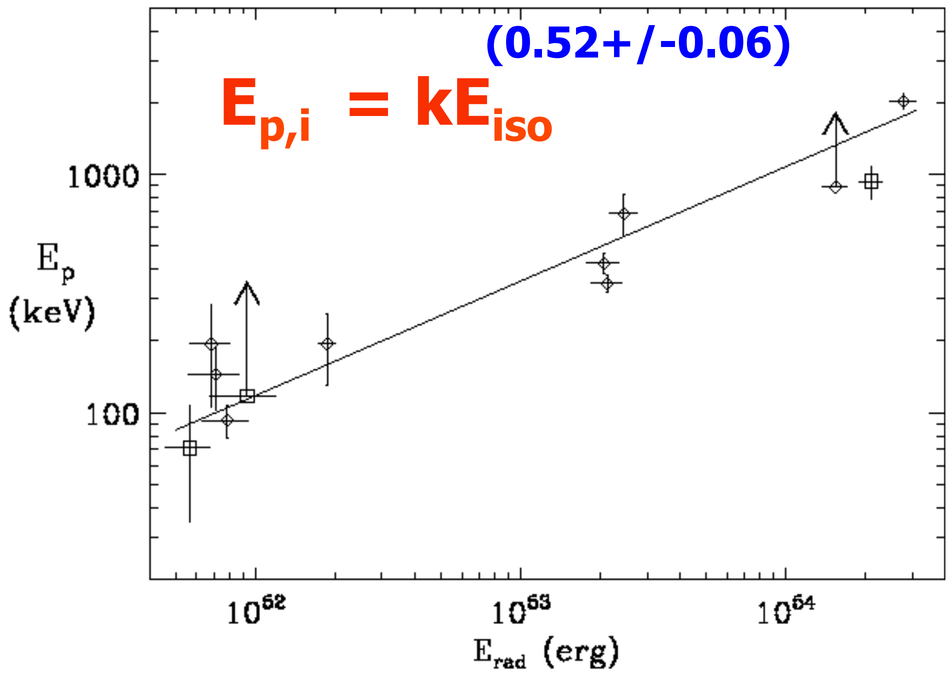


Ep,i and Eiso distributions for a sample of 41 long GRBs (Amati 2006)

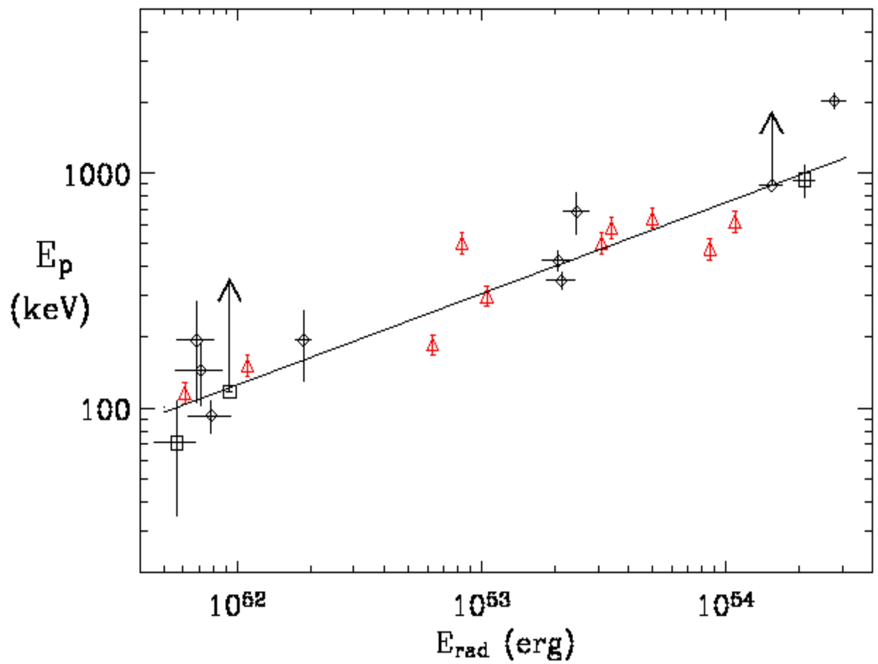
The Ep,i – Eiso correlation

➢ Amati et al. (2002) analyzed a sample of 12 BeppoSAX events with known redshif found evidence of a strong correlation between Ep,i and Eiso , highly significant (ρ = 0.949, chance prob. 0.005%)

➢ by adding data from BATSE and HETE-2 of 10 more GRBs the correlation was confirmed and its significance increased

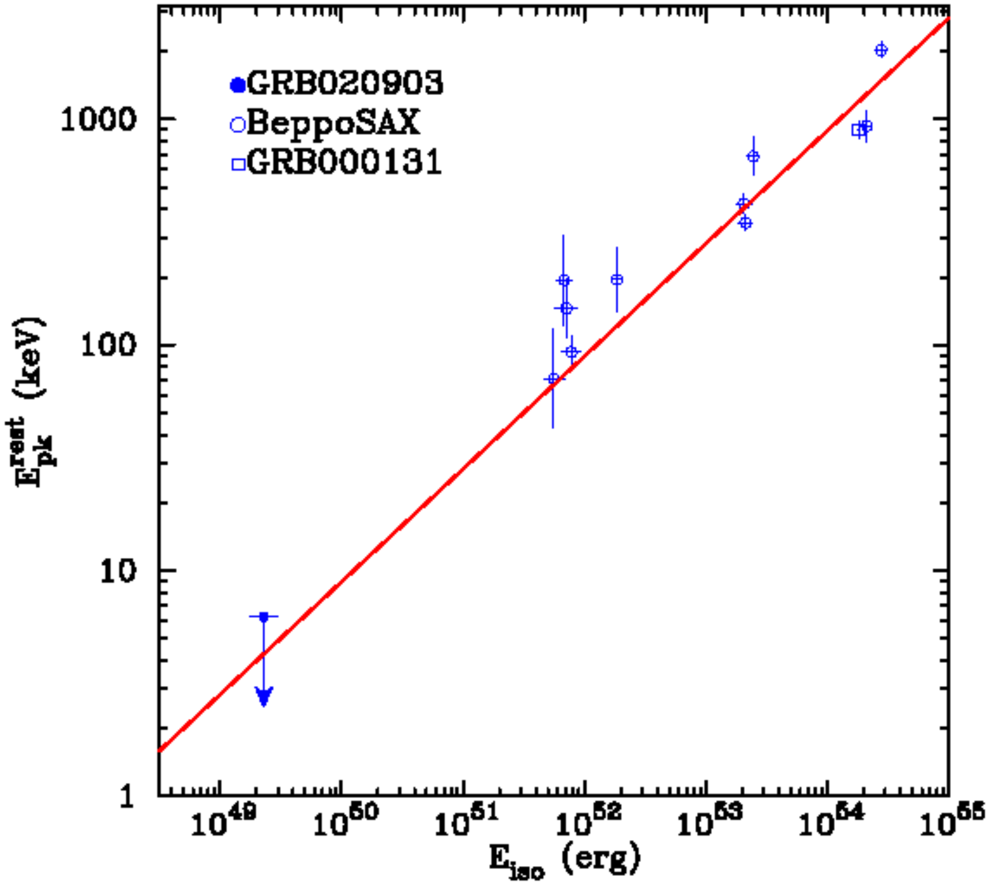


Amati et al. , A&A, 2002



Amati, ChJAA, 2003

Peak Energy – Isotropic Energy

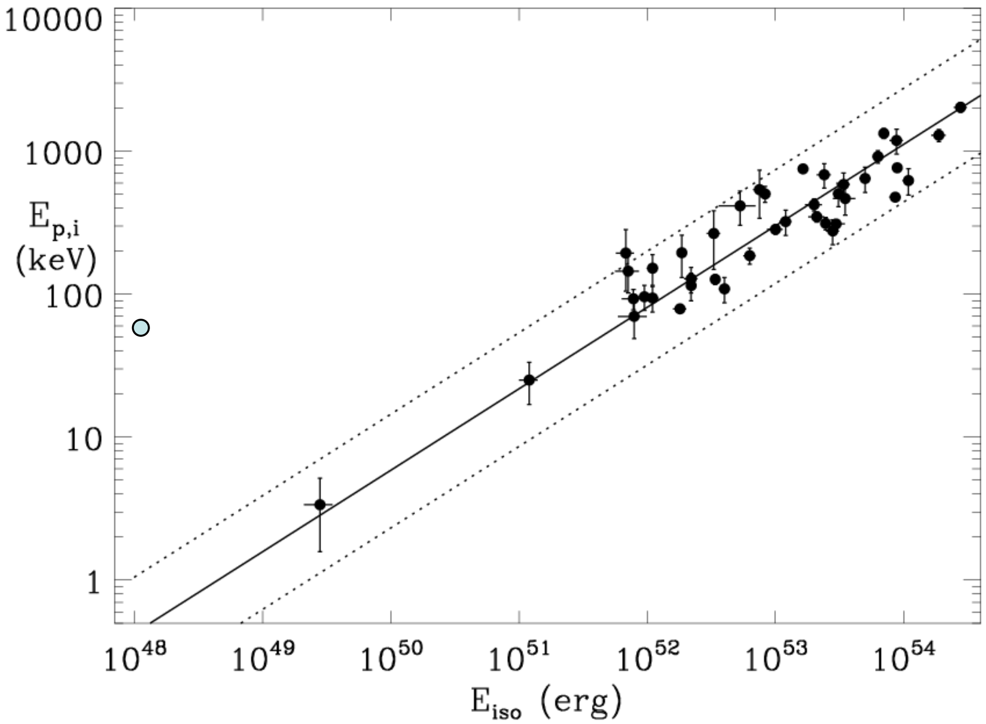


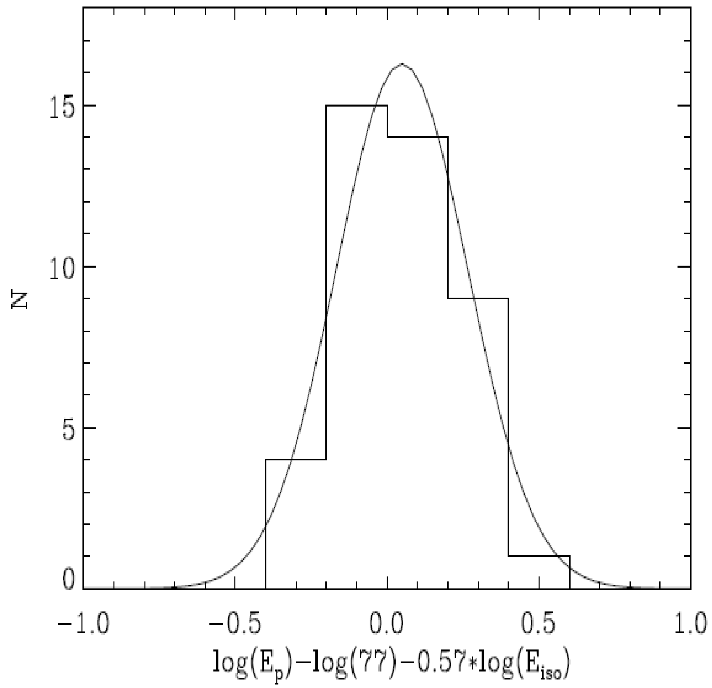
Sakamoto et al. (2003)

➢ analysis of the most updated sample of *long* GRBs/XRFs with firm estimates of z and Ep,i (41 events) gives a chance probability for the Ep,i-Eiso correlation of ~10^{-15} and a slope of 0.57+/-0.02

➢ the scatter of the data around the best fit power-law can be fitted with a Gaussian with σ(logEp,i) ~ 0.2 (~0.15 extra-poissonian)

➢ only firm outlier the local peculiar GRB 980425

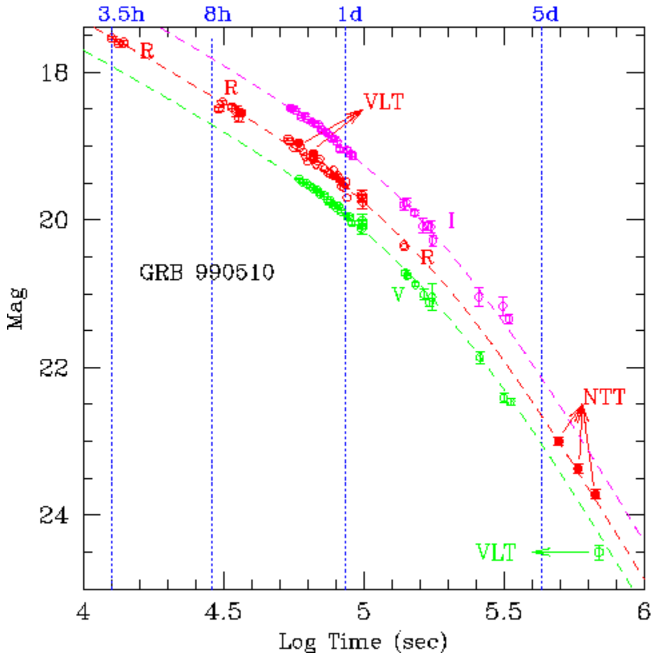




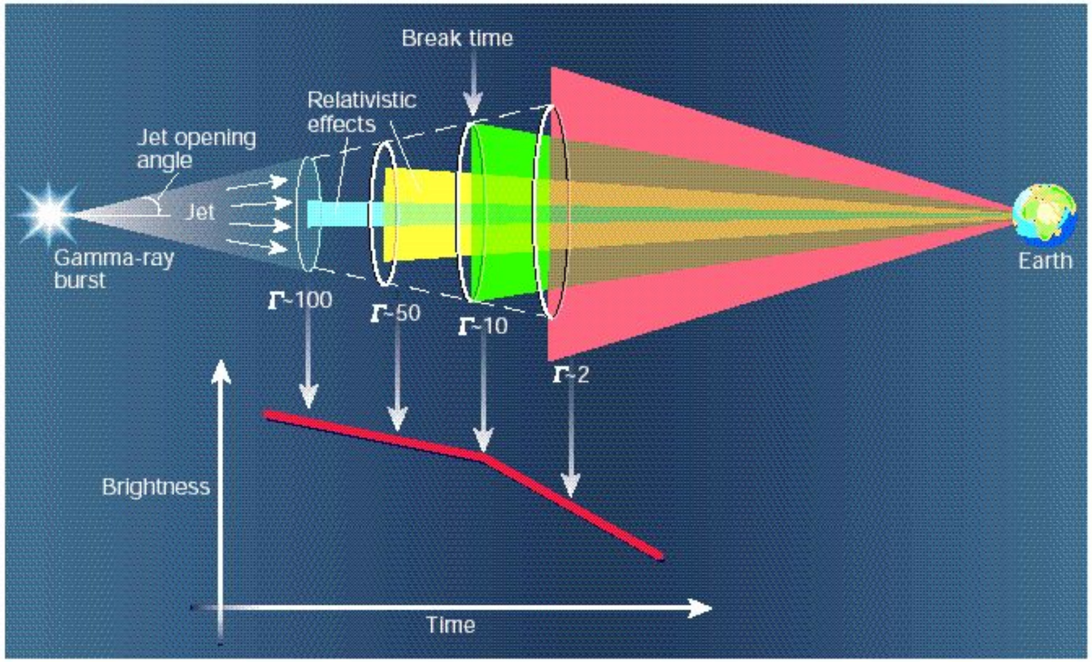
Updated from Amati, MNRAS, 2006

Afterglow Observations

Harrison et al (1999)

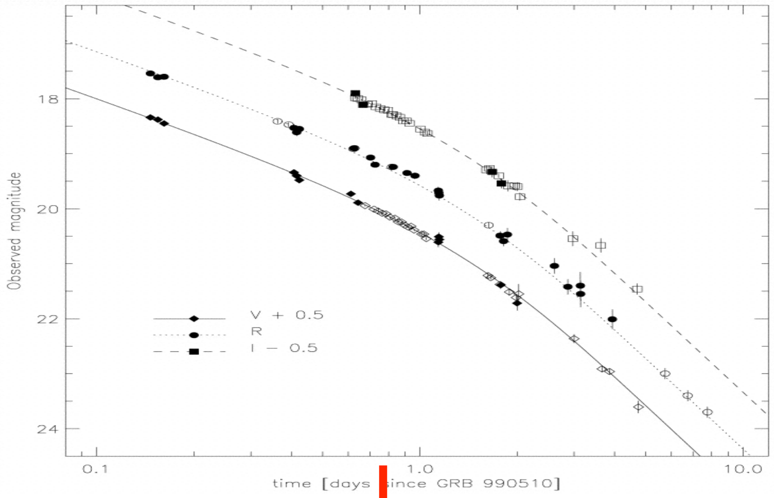


Achromatic Break



Woosley (2001)

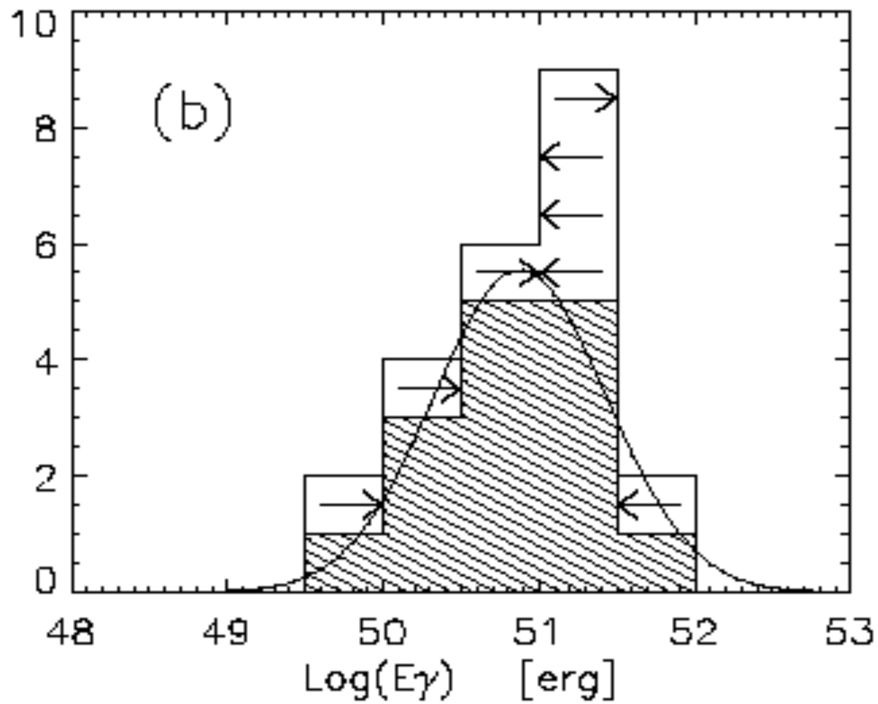
Cosmology with spectrum-energy correlation



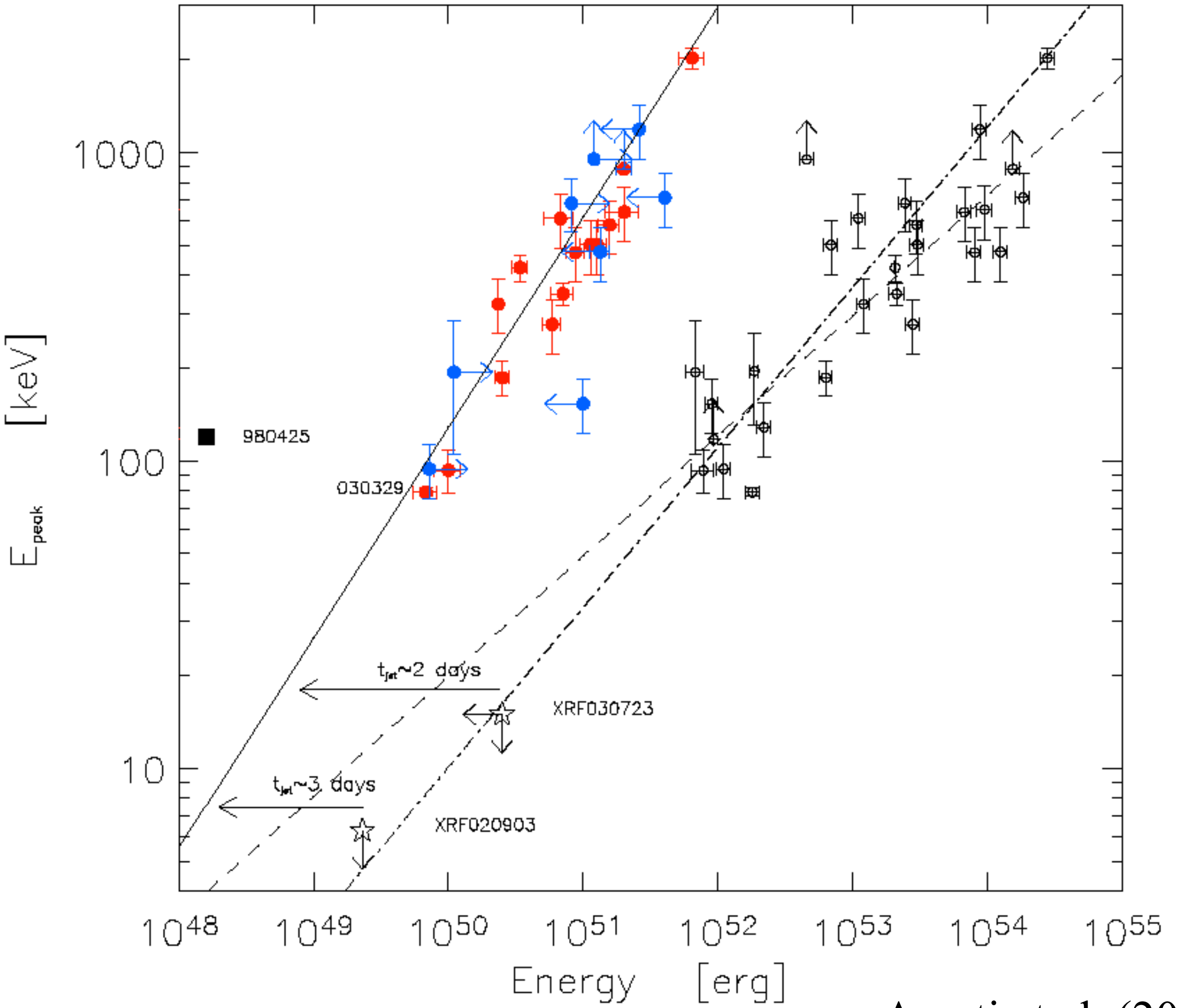
➢ breaks in the afterglow decay light curves -> collimation ?

$$\theta = 0.09 \left(\frac{t_{jet,d}}{1+z}\right)^{3/8} \left(\frac{n\,\eta_\gamma}{E_{\gamma,iso,52}}\right)^{1/8}$$

$$E_\gamma = (1-\cos\theta) E_{\gamma,iso}.$$

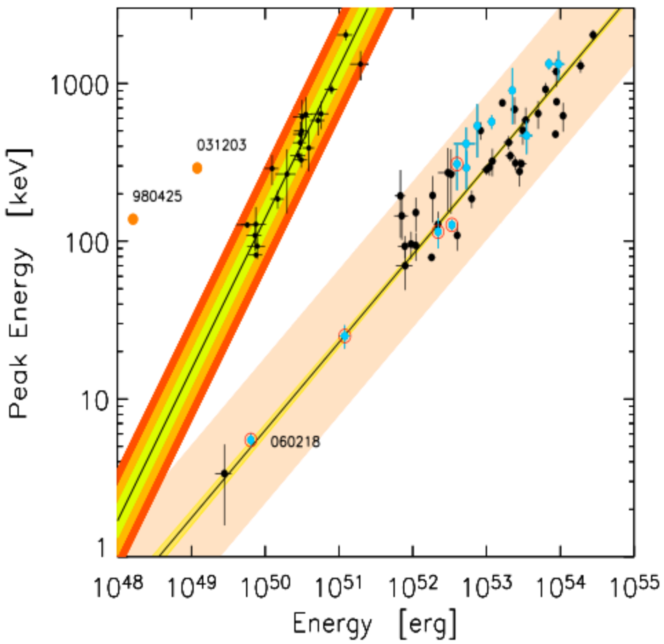


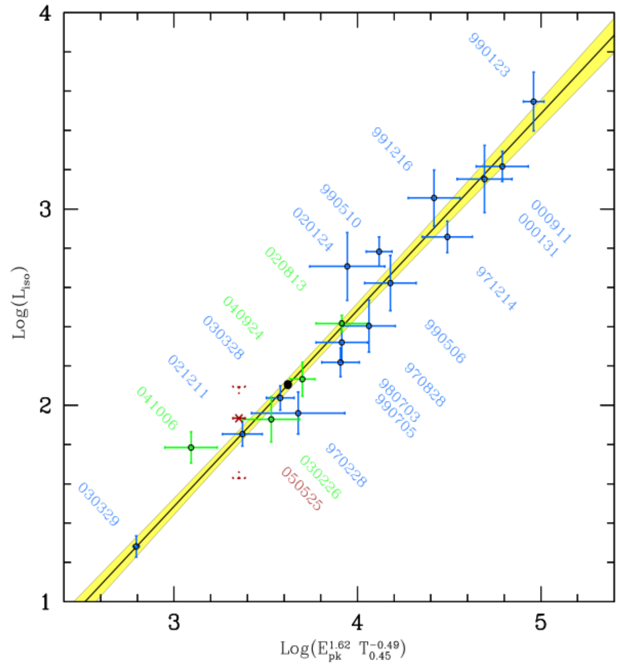
GRB for Cosmology



Amati et al. (2002)
Ghirlanda et al. (2004)

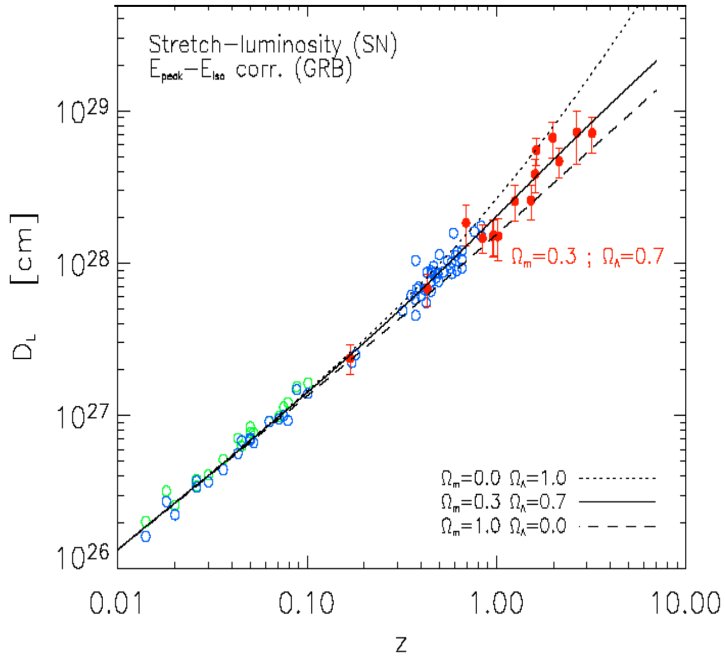
The "Relationships"



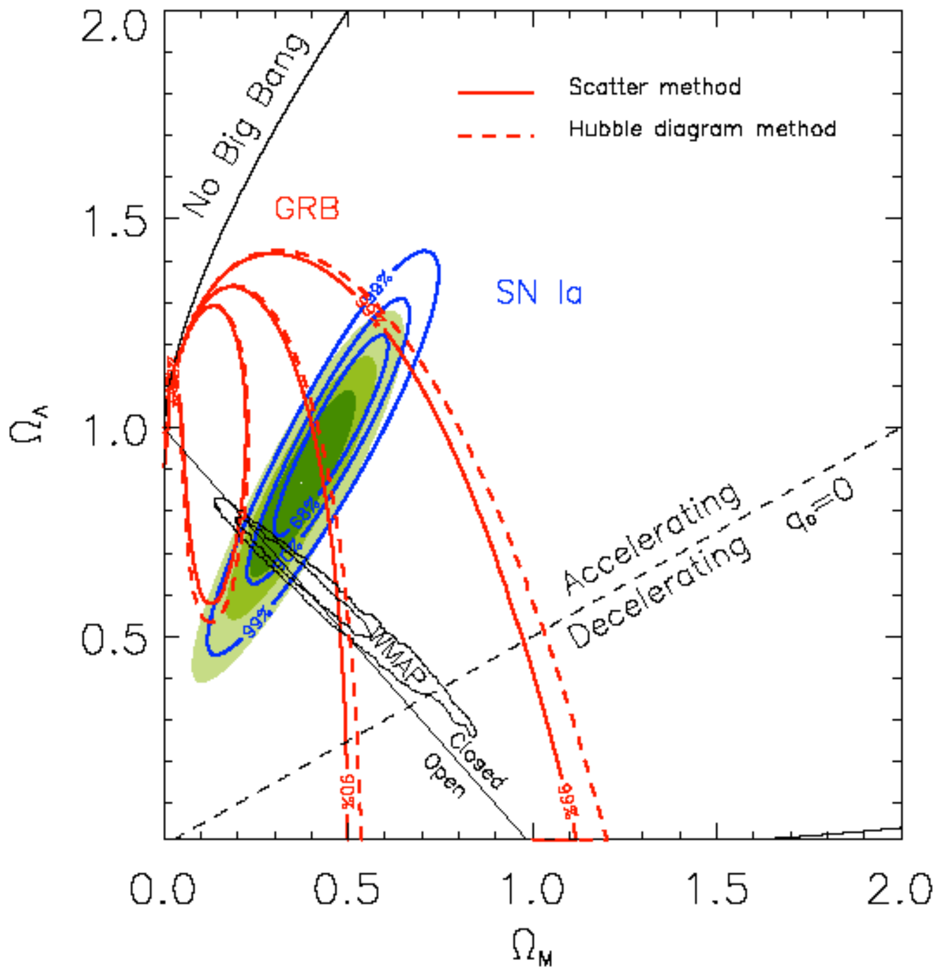


- Amati (et al. 2002): E_{peak}-E_{iso} (E_{peak}, redshift)
- Ghirlanda (et al. 2004): E_{peak}-E_{gamma} (Epeak, redshift, Tbreak)
- Firmani (et al. 2006): bring T_{45} into Epeak and Eiso.
- Fenimore & Ramirez-Ruiz (2000): E_{iso} - variability in Gamma-rays
- Norris (et al. 2000): lag-luminosity relation. Short lag = luminous.
  - (Lags measured in observer frame i.e. not z-corrected)
- Use these relationships to infer a pseudo-redshift from a measurement of spectral parameters or lags and luminosities in observer frame.... many more bursts without measured z than with.
  - =>GRB as cosmological probe

GRB for Cosmology



Ghirlanda et al. (2004)



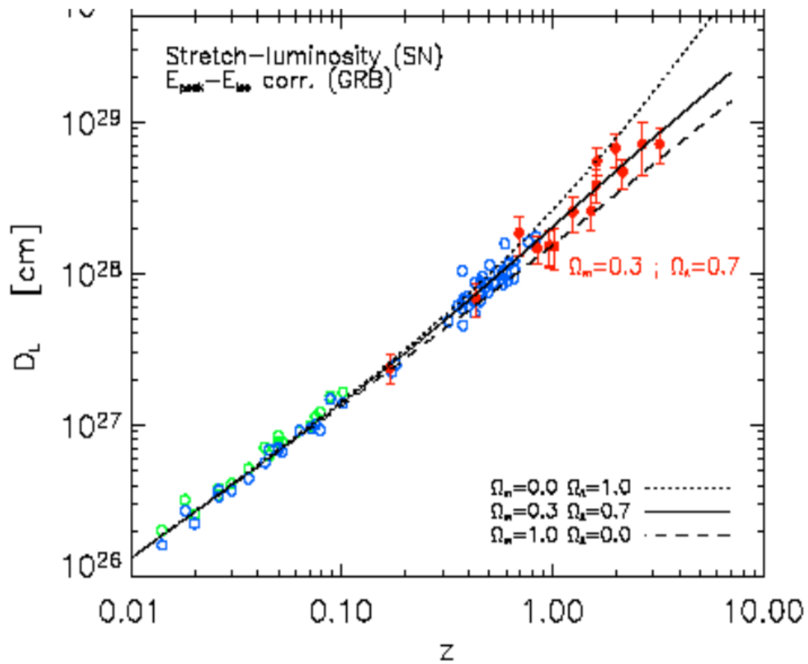
❑ **Method** (e.g., Ghirlanda et al, Firmani et al., Dai et al., Zhang et al.):

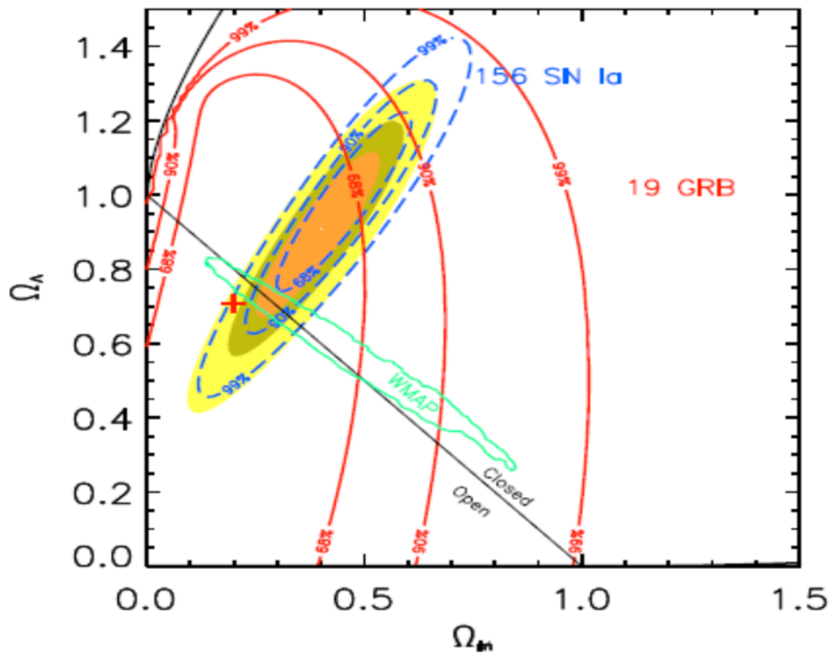
$$E_{p,i} = E_{p,obs} \times (1 + z)\ ,\ t_{b,i} = t_b / (1 + z)$$

$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg}$$

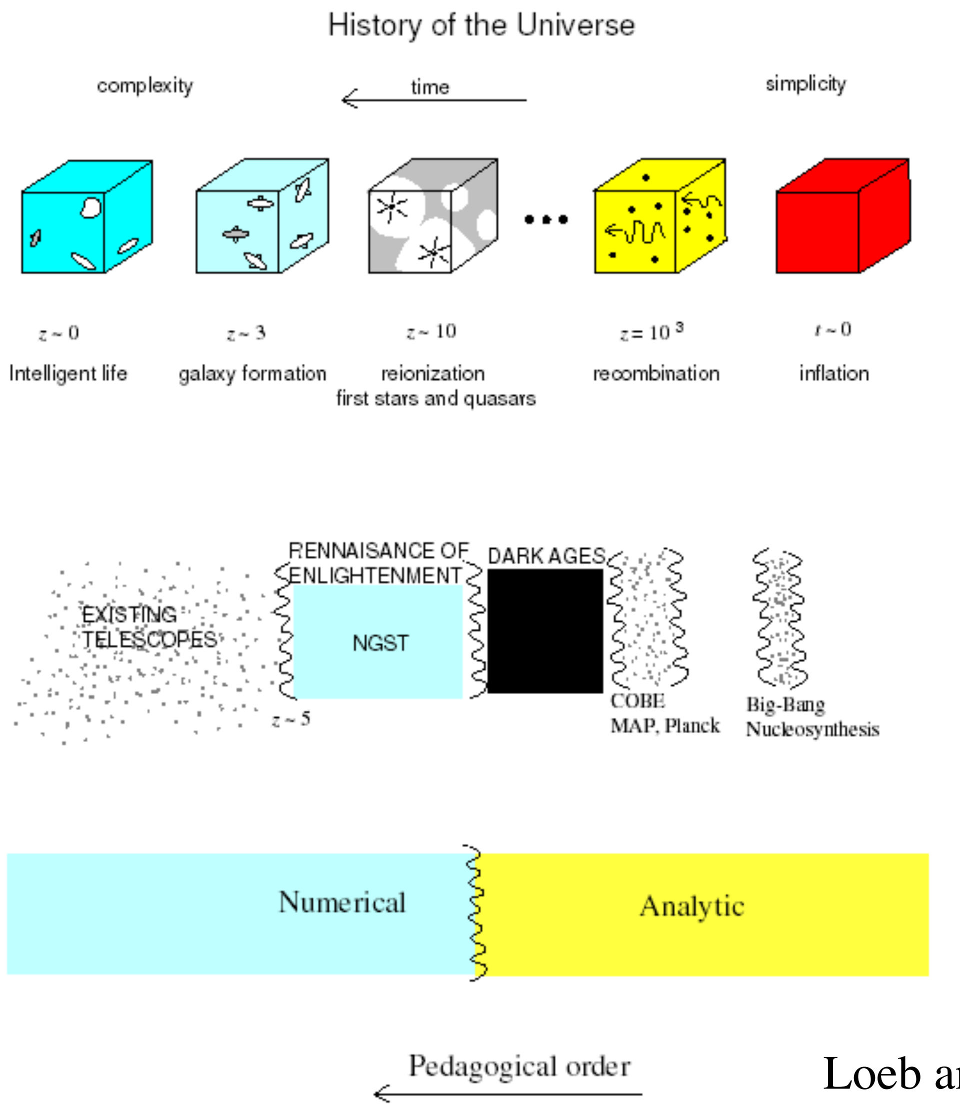
$$D_l = D_l(z\ ,\ H_0,\ \Omega_M,\ \Omega_\Lambda, \ldots)$$

➢ fit the correlation and construct an Hubble diagram for each set of cosmological parameters -> derive c.l. contours based on chi-square





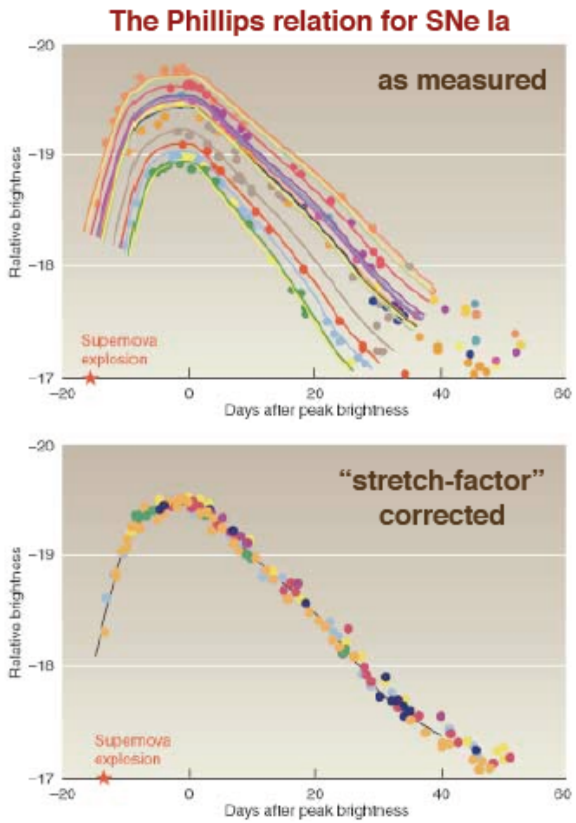
GRB Cosmology

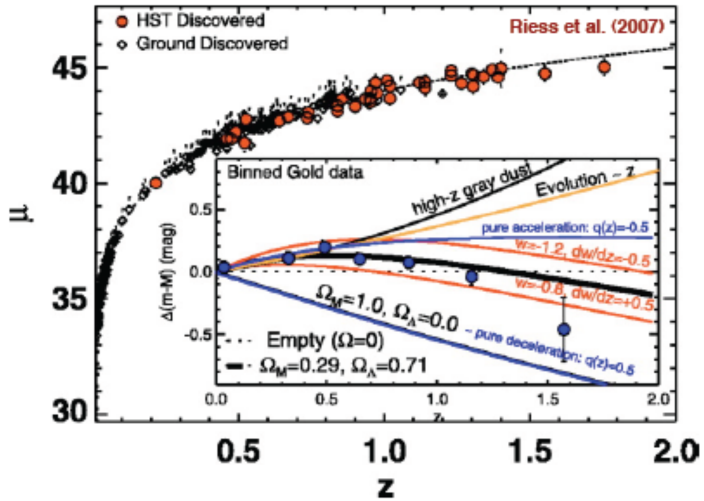


Loeb and Barkana (2000)

SN Ia Cosmology

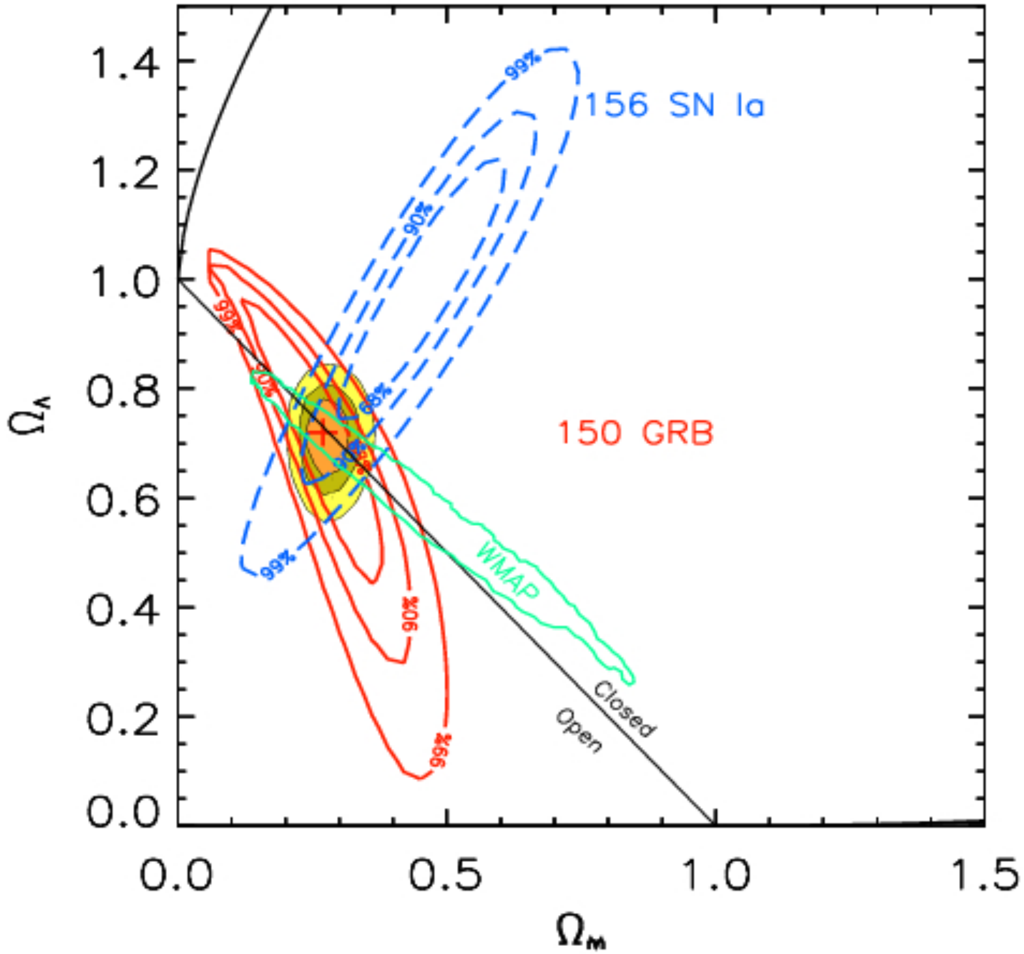
SNe Ia as a "standard candle"





Can we apply GRBs as a standardized candle?

- results obtainable with 150 GRBs with estimates of z, $E_{p,i}$ and tb



Ghirlanda et al. 2006 A&A

Ghirlanda et al. 2006 JOP Review, GRB Special Issue

Caveats

GRBs as a standard candle?

Caveats:

- lack of a low-z calibration sample
- $E_{peak} \in [10\ \text{keV}, 1\ \text{MeV}]$, not always well constrained
- Θ_{jet} is model dependent

For a homogeneous circumburst medium (Sari et al. 1999)

$$\theta_{\rm jet} = 0.161 \left(\frac{t_{\rm jet,d}}{1+z}\right)^{3/8} \left(\frac{n\,\eta_\gamma}{E_{\rm iso,52}}\right)^{1/8}$$

For a wind profile from massive stars (Nava et al. 2006)

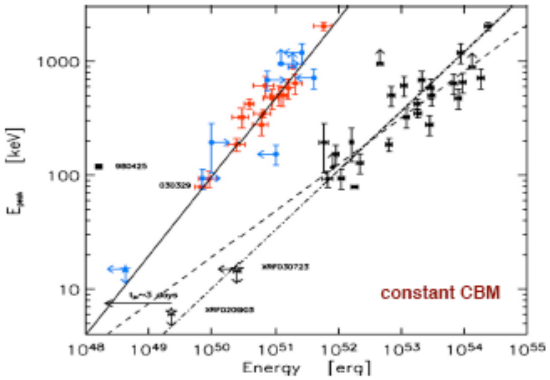
$$n(r) = A/r^2$$

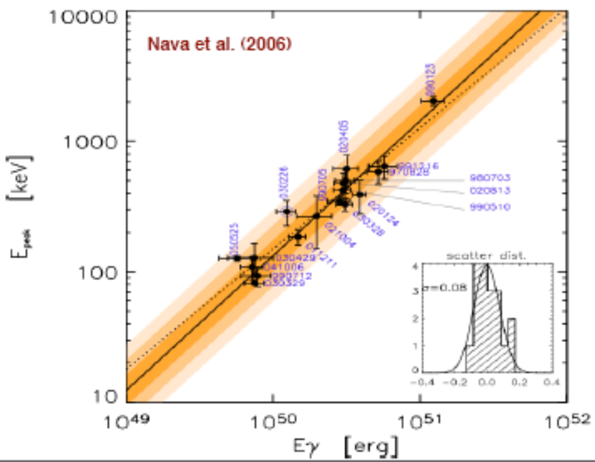
$$\theta_{\rm jet} = 0.206 \left(\frac{t_{\rm jet,d}}{1+z}\right)^{1/4} \left(\frac{A_*\,\eta_\gamma}{E_{\rm iso,52}}\right)^{1/4}$$

$$A = \dot{M}_{\rm w}/(4\pi v_{\rm w}) = 5\times 10^{11} A_*\ {\rm g\,cm^{-1}}$$

- uncertain jet break time and CBM density

The Ghirlanda E_p - E_γ relation (2004)





Luminosity distance

Distance measures in cosmology

David W. Hogg

Institute for Advanced Study, 1 Einstein Drive, Princeton NJ 08540
hogg@ias.edu

2000 December

1 Introduction

In cosmology (or to be more specific, *cosmography*, the measurement of the Universe) there are many ways to specify the distance between two points, because in the expanding Universe, the distances between comoving objects are constantly changing, and Earth-bound observers look back in time as they look out in distance. The unifying aspect is that all distance measures somehow measure the separation between events on radial null trajectories, ie, trajectories of photons which terminate at the observer.

In this note, formulae for many different cosmological distance measures are provided. I treat the concept of "distance measure" very liberally, so, for instance, the lookback time and comoving volume are both considered distance measures. The bibliography of source material can be consulted for many of the derivations; this is merely a "cheat sheet." Minimal *C* routines (KR) which compute all of these distance measures are available from the author upon request. Comments and corrections are highly appreciated, as are acknowledgments or citation in research that makes use of this summary or the associated code.

2 Cosmographic parameters

The *Hubble constant* H_0 is the constant of proportionality between recession speed v and distance d in the expanding Universe;

$$v = H_0\, d \tag{1}$$

The subscripted "0" refers to the present epoch because in general H changes with time.

The Luminosity Distance

$$\Omega_{\mathrm{M}} + \Omega_{\Lambda} + \Omega_k = 1 \qquad z \equiv \frac{\nu_{\mathrm{e}}}{\nu_{\mathrm{o}}} - 1 = \frac{\lambda_{\mathrm{o}}}{\lambda_{\mathrm{e}}} - 1$$

$$E(z) \equiv \sqrt{\Omega_{\mathrm{M}}\,(1+z)^3 + \Omega_k\,(1+z)^2 + \Omega_{\Lambda}}$$

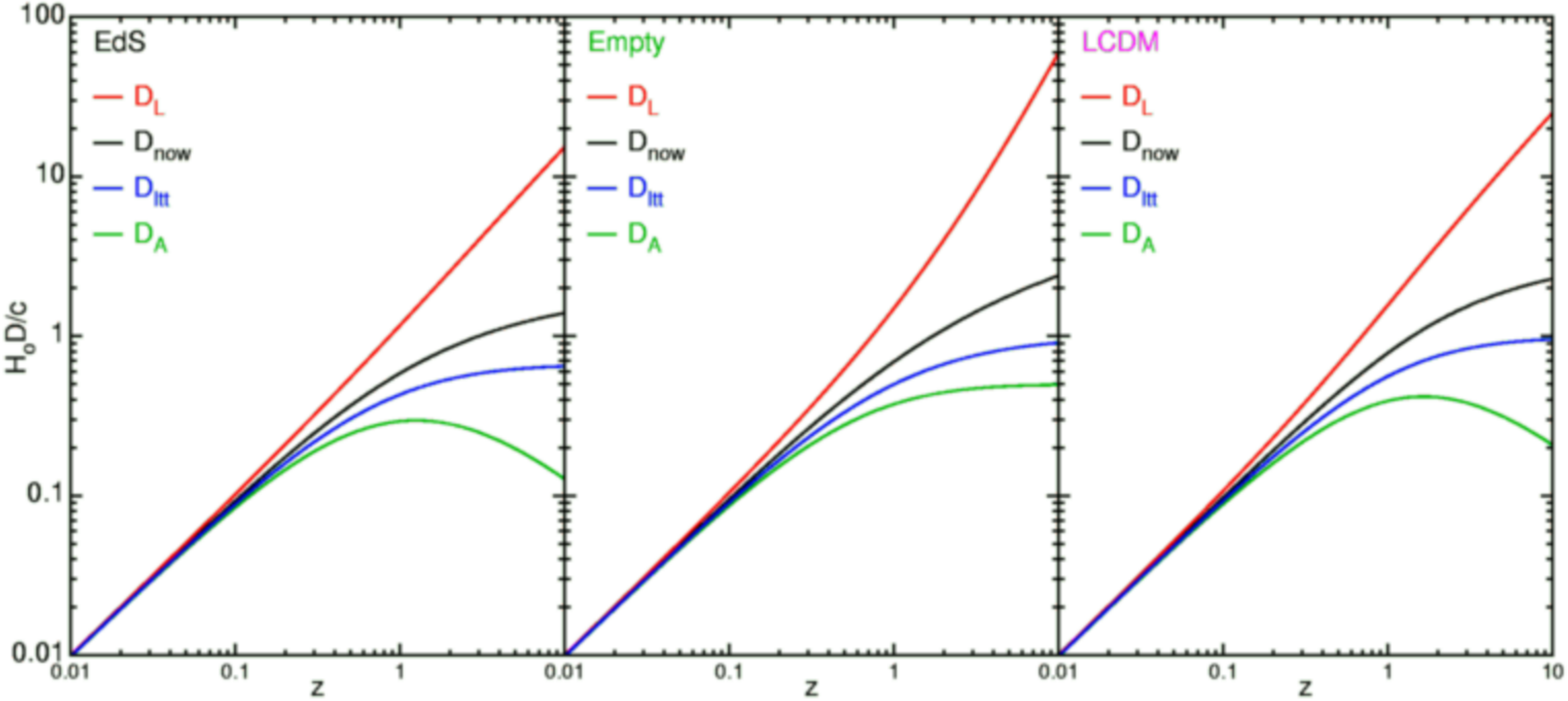
$$H_0 = 100\,h\ \mathrm{km\,s^{-1}\,Mpc^{-1}} \qquad D_{\mathrm{H}} \equiv \frac{c}{H_0} \qquad D_{\mathrm{C}} = D_{\mathrm{H}} \int_0^z \frac{dz'}{E(z')}$$

$$D_{\mathrm{M}} = \begin{cases} D_{\mathrm{H}}\,\frac{1}{\sqrt{\Omega_k}}\,\sinh\left[\sqrt{\Omega_k}\,D_{\mathrm{C}}/D_{\mathrm{H}}\right] & \text{for } \Omega_k > 0 \\ D_{\mathrm{C}} & \text{for } \Omega_k = 0 \\ D_{\mathrm{H}}\,\frac{1}{\sqrt{|\Omega_k|}}\,\sin\left[\sqrt{|\Omega_k|}\,D_{\mathrm{C}}/D_{\mathrm{H}}\right] & \text{for } \Omega_k < 0 \end{cases}$$

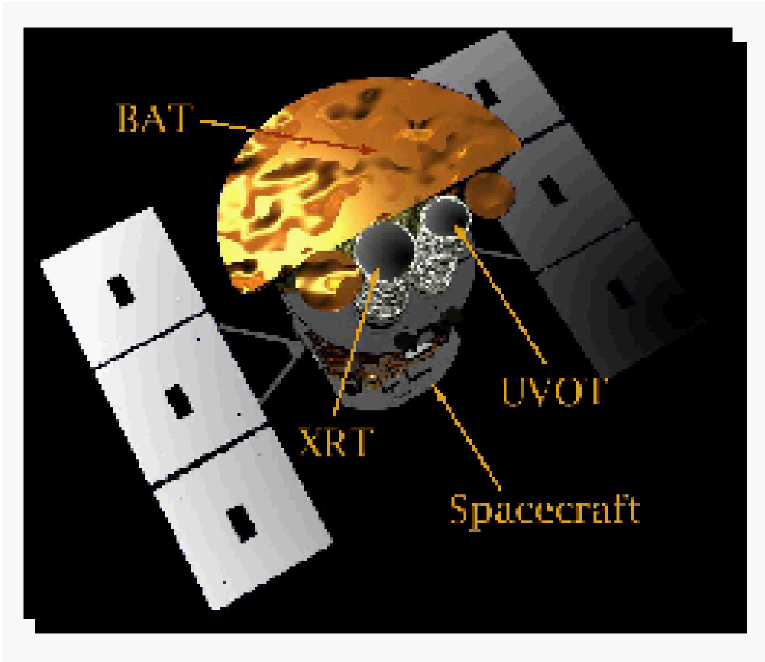
$$D_{\mathrm{L}} = (1+z)\,D_{\mathrm{M}}$$

astro-ph/9905116v4

Luminosity distance and redshift



SWIFT

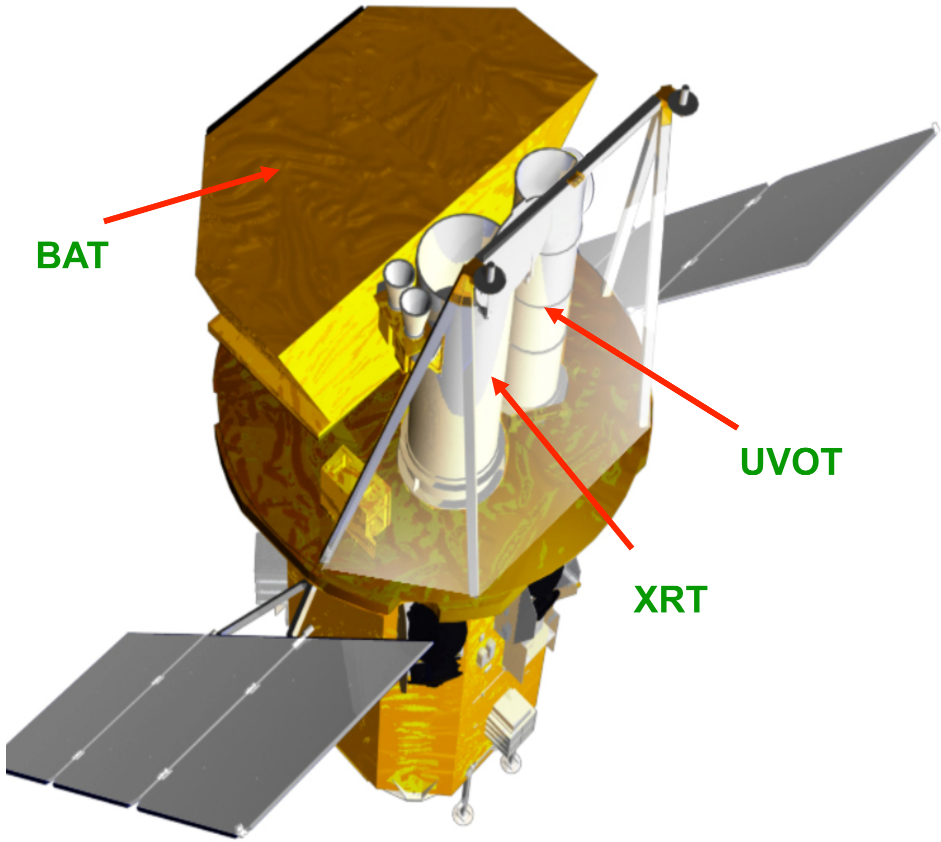


In orbita dal 2004

Swift Instruments

Instruments

- **Burst Alert Telescope (BAT)**
  - **New CdZnTe detectors**
  - **Most sensitive gamma-ray imager ever**
- **X-Ray Telescope (XRT)**
  - **Arcsecond GRB positions**
  - **CCD spectroscopy**
- **UV/Optical Telescope (UVOT)**
  - **Sub-arcsec positions**
  - **Grism spectroscopy**
  - **24^{th} mag sensitivity (1000 sec)**
  - **Finding chart for other observers**



Spacecraft

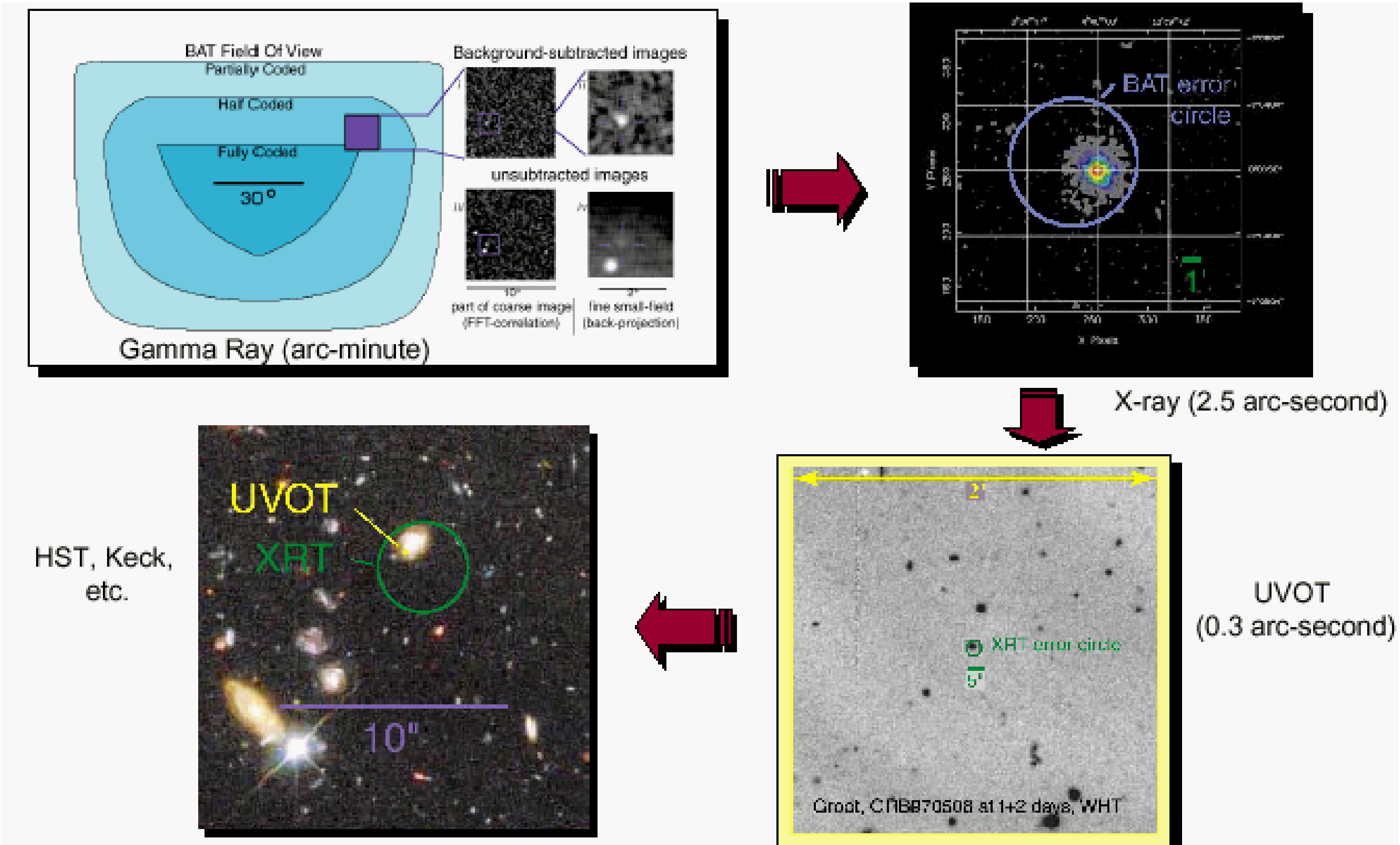
- **Autonomous re-pointing, 20 - 75 s**
- **Onboard and ground triggers**

Swift

Details

- **BAT** (15-350 keV). Large (2 sr) field of view – detects bursts with arc min accuracy. And tells observers immediately.
- *Swift* automatically determines if it can view the GRB, and if so, slews to it.
- **XRT** (0.3-10 keV) and **UVOT** (~1000-6000 Å) begin observing typically within 100 s of the trigger.
- XRT can automatically detect afterglows, and downlinks limited data immediately. ~90% of BAT GRBs have promptly detected XRT afterglows.

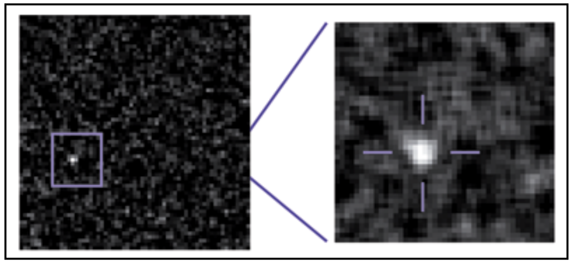
SWIFT


BAT Field Of View
Partially Coded
Half Coded
Fully Coded
30°
Background-subtracted images
unsubtracted images
part of coarse image (FFT-correlation)
fine small-field (back-projection)
Gamma Ray (arc-minute)
BAT error circle
X-ray (2.5 arc-second)
2'
XRT error circle
5"
Groot, GRB970508 at 1+2 days, WHT
UVOT
(0.3 arc-second)
UVOT
XRT
10"
HST, Keck,
etc.

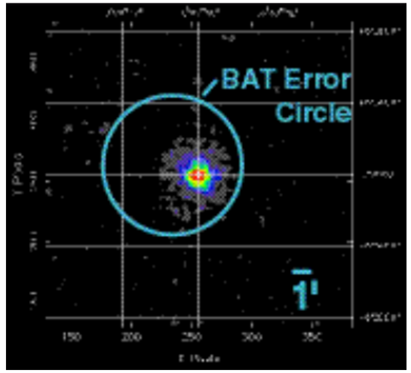
Mission Capabilities

- **Multiwavelength observations on all time scales**
- **>100 GRBs per year of all types**
- **BAT sensitivity 2 - 5 time better than BATSE**
- **Arcsec positions & counterparts for 100’s GRBs**
- **Rapid GRB notifications via GCN**
- **Identification of host galaxies offsets**
- **X-ray and UV/optical spectroscopy**
- **Upload capability to slew to GRB and transients detected by other observatories**

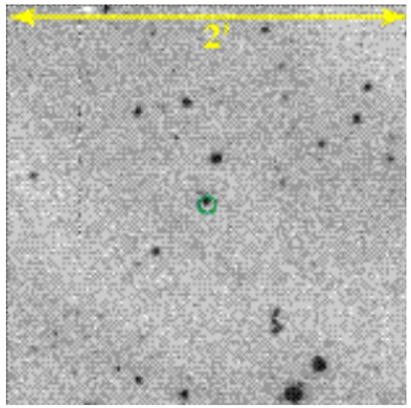
BAT



XRT



UVOT



Swift Observatory in Goddard Clean Room

Swift discoveries

Summary

- Currently >300 GRBs with arc second positions from *Swift* (more from optical follow-up).
- >100 *Swift* GRBs have redshifts (>70% of world total).
- Includes brightest GRB ever seen, and most distant one.

Questions for *Swift*

- Do short GRBs have afterglows, and hence can we locate them more precisely?
- Can we pin down the progenitors?
- Are there new subclasses of GRBs?
- Can we find high-redshift bursts and study the early universe?

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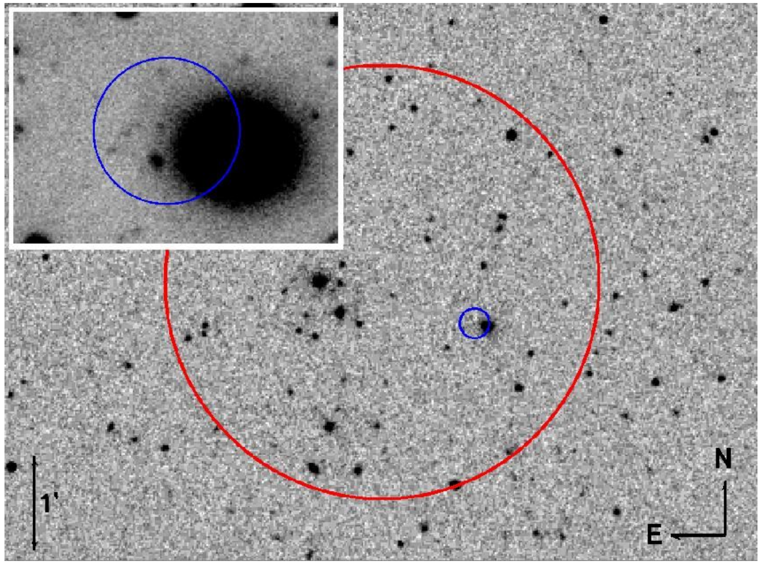
Swift discoveries

Short GRBs.

- GRB 050509B was a short GRB discovered by *Swift*, with an X-ray afterglow reported 2:29 after the trigger.

- Outskirts of an elliptical galaxy.
- Later sGRBs had optical afterglows too.
- Subsequently found in all galaxy types.

VLT image
Hjorth et al.



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- Do short GRBs have afterglows, and hence can we locate them more precisely?
- Can we pin down the progenitors?
- Are there new subclasses of GRBs?
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Swift discoveries

Progenitors

- Short GRBs found in all types of galaxy – old population (compact merger/magnetar)
- Long GRBs always found in star forming galaxies and regions – deaths of massive stars.

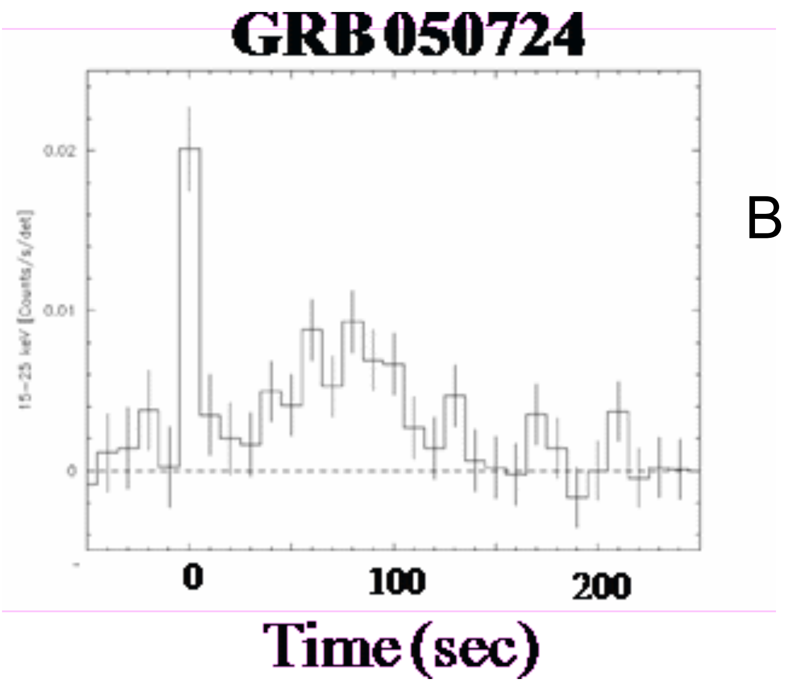
Questions for *Swift*

- Do short GRBs have afterglows, and hence can we locate them more precisely?
- Can we pin down the progenitors?
- Are there new subclasses of GRBs?
- Can we find high-redshift bursts and study the early universe?

Swift discoveries

Short GRB with extended emission

- Blurred the distinction between "short" and "long" bursts, and made it more detector-dependent.



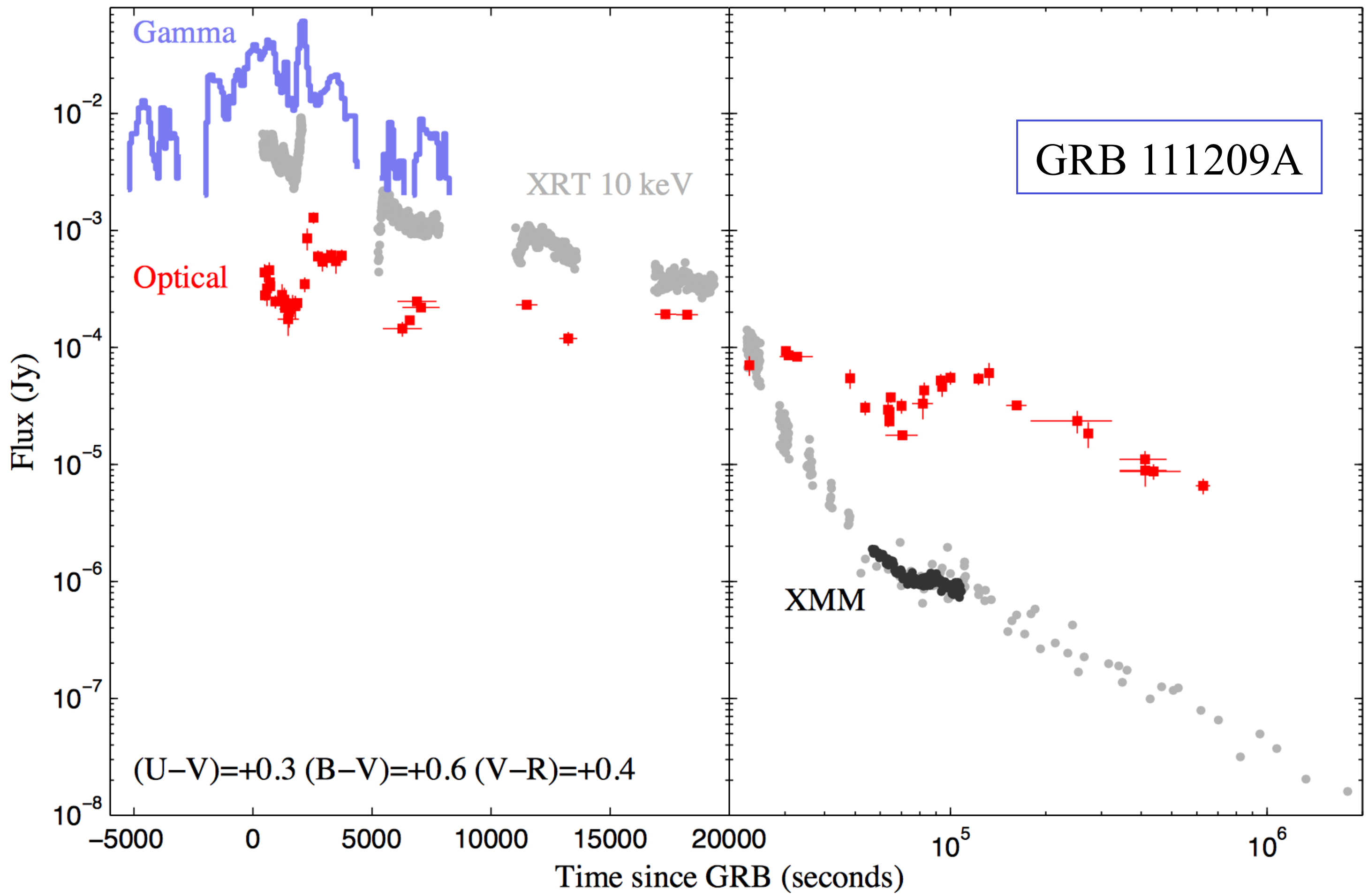
Barthelmy et al. 2005

Swift discoveries

Long GRBs with no SNe

- GRB 060614 and GRB 060505 were nearby, apparantly long GRBs, with no related supernova, down to deep limits.
- The GRB taxonomy is clearly more complex than previously thought.
- Maybe a new, progenitor-based classification is needed?

Ultra Long GRBs



Questions for *Swift*

- Do short GRBs have afterglows, and hence can we locate them more precisely?
- Can we pin down the progenitors?
- Are there new subclasses of GRBs?
- Can we find high-redshift bursts and study the early universe?

Swift discoveries

High redshift bursts

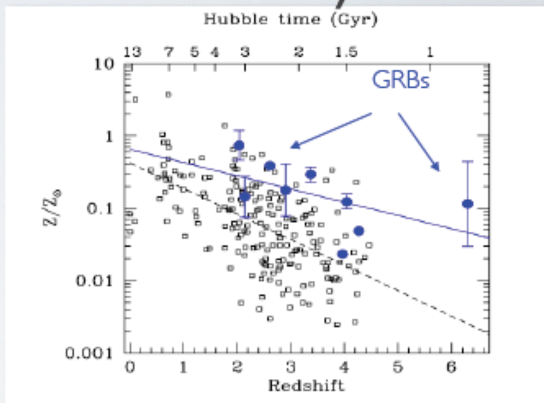
- 17 GRBs observed by *Swift* have *z*>3.5
- 10 have *z*>4, and 5 have *z* > 5 – a large, rapidly growing population of distant objects.
- GRB 050904 was at z=6.29 (Cusumano et al. 2007)
- GRB 080913 was at z=6.7, and was a fainter-than-normal burst! (Greiner et al. 2009)
- GRB 090423 was at z=8.26 !!!!
- GRB 090429B was at z=9.2 !!!!!!

High redshift GRB

High-Redshift GRBs

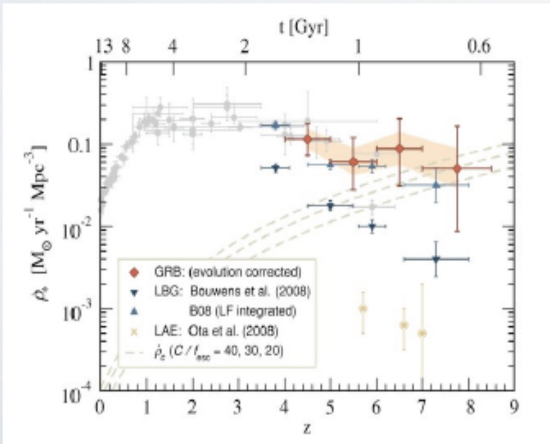
z	GRB	Optical Brightness
9.4	090429B	K = 19 @ 3 hrs
8.2	090423	K = 20 @ 20 min
6.7	080813	K = 19 @ 10 min
6.29	050904	J = 18 @ 3 hrs
5.6	060927	I = 16 @ 2 min
5.3	050814	K = 18 @ 23 hrs
5.11	060522	R = 21 @ 1.5 hrs

Metallicity



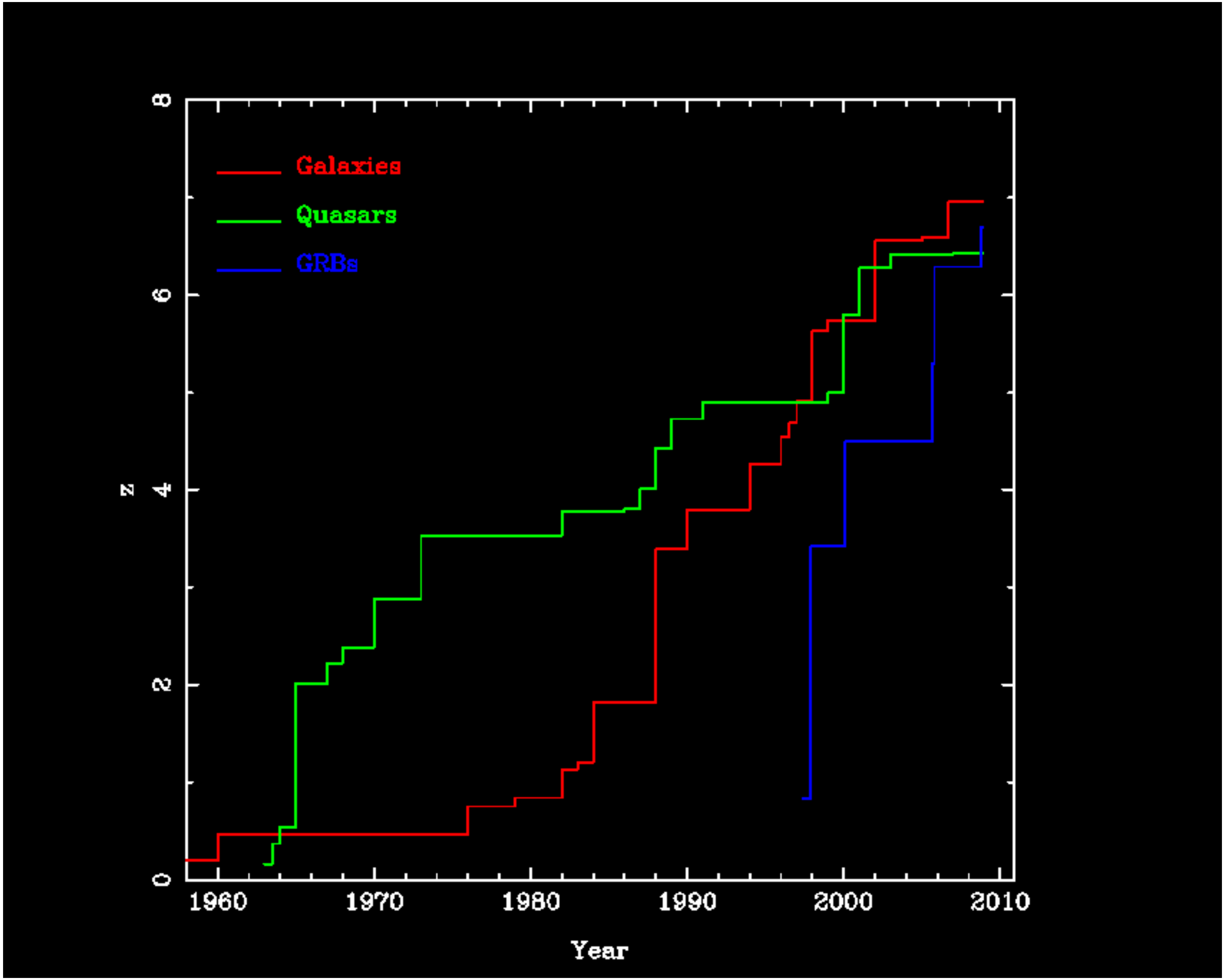
Savaglio 2006

Star Formation Rate



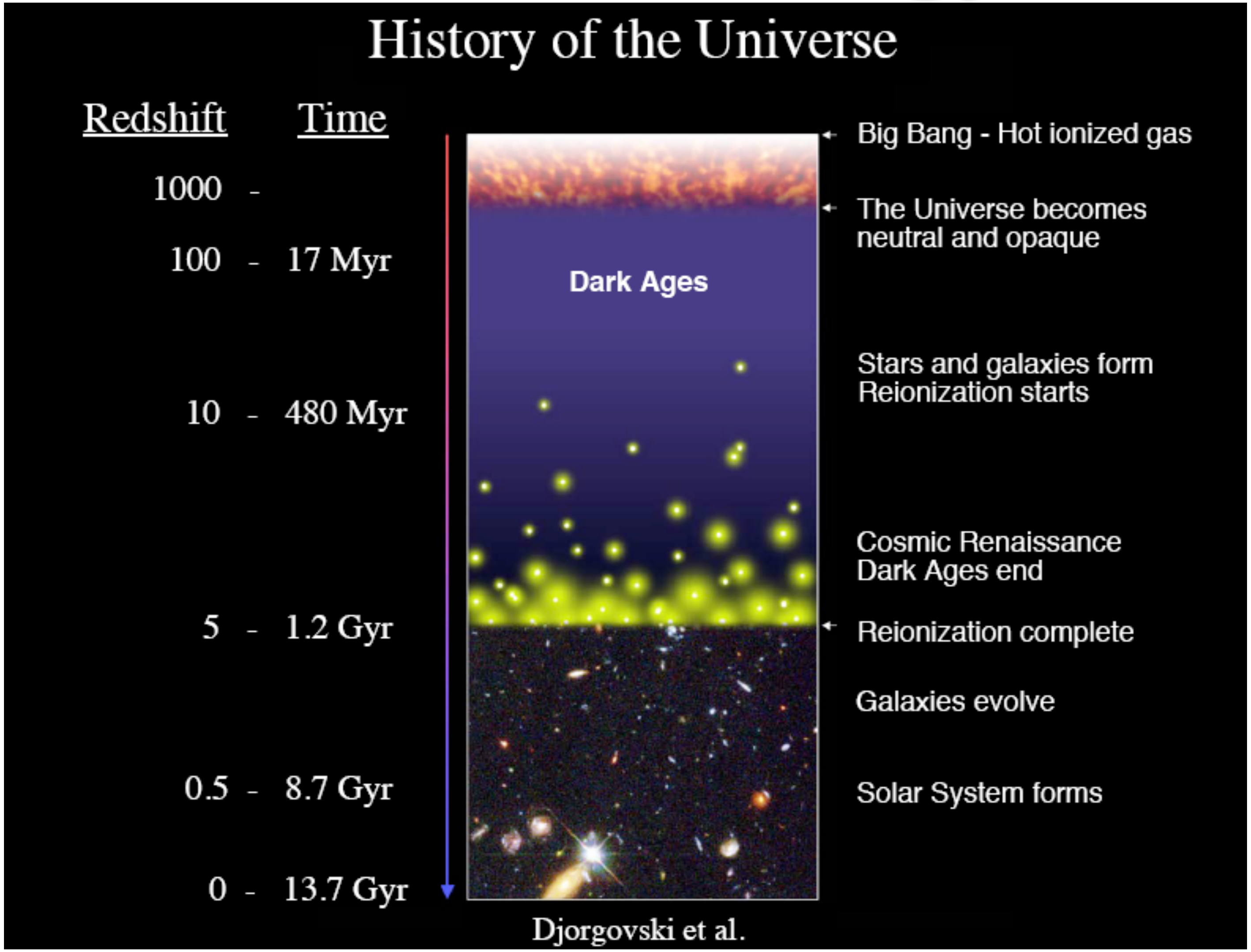
Kistler et al. 2009;
Robertson & Ellis 2011

Fermi/Swift GRB Conference 2012, Munich, May 7-11, 2012



Galaxies
Quasars
GRBs
z
0
2
4
6
8
1960
1970
1980
1990
2000
2010
Year

GRB & Cosmology



Swift discoveries

High redshift bursts

- 2-m class telescopes should give reliable photo-z for many z>6 bursts.
- With GROND online, X-shooter, and increasing numbers of small (ish) telescopes observing every GRB, the next high-z burst could be just round the corner....

High z - searches

High-z Universe: searching for the best probe

Galaxies

Pros

★ Multiband data are available (some)

★ Refurbished HST

★ Different technique (LBG/Lyα emission)

★ Do not "disappear"

Cons

★ Small region of the sky (11 arcmin^2)

★ Required several hours of observations

★ Very faint objects

★ Galaxy templates are complex

★ Difficult determination of Age/dust/SFR

Gamma-ray Bursts

Pros

★ Very bright

★ Happens everywhere

★ Can be followed quickly from space and ground (now at least)

★ **Have a very simple spectrum** (synchrotron, simple power-law)

★ Allow better investigation of τ_{HI}

Cons

★ Rare (few "good ones")

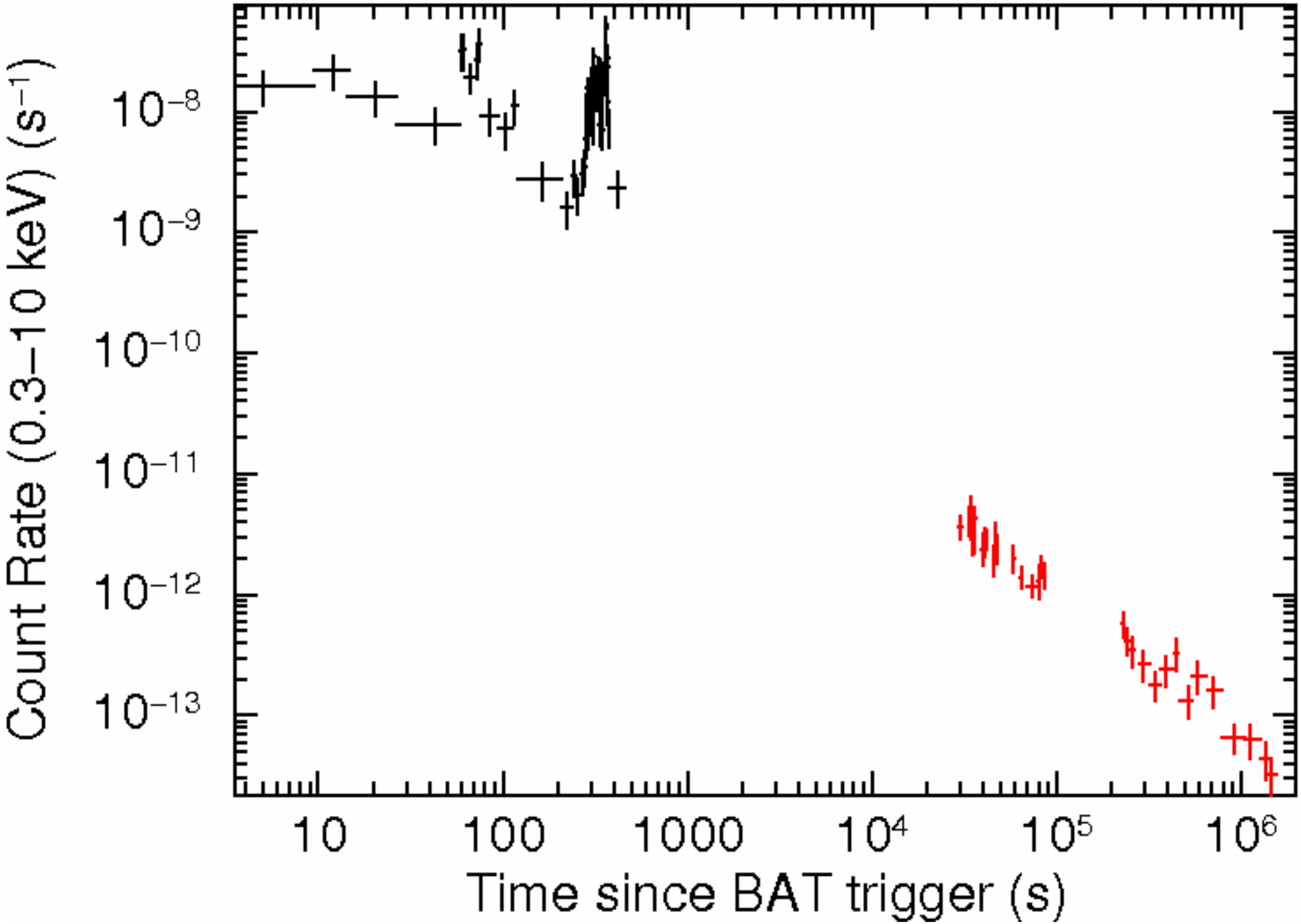
★ Fade fast, ~minute position identification (space mission)

★ Require multiband observations

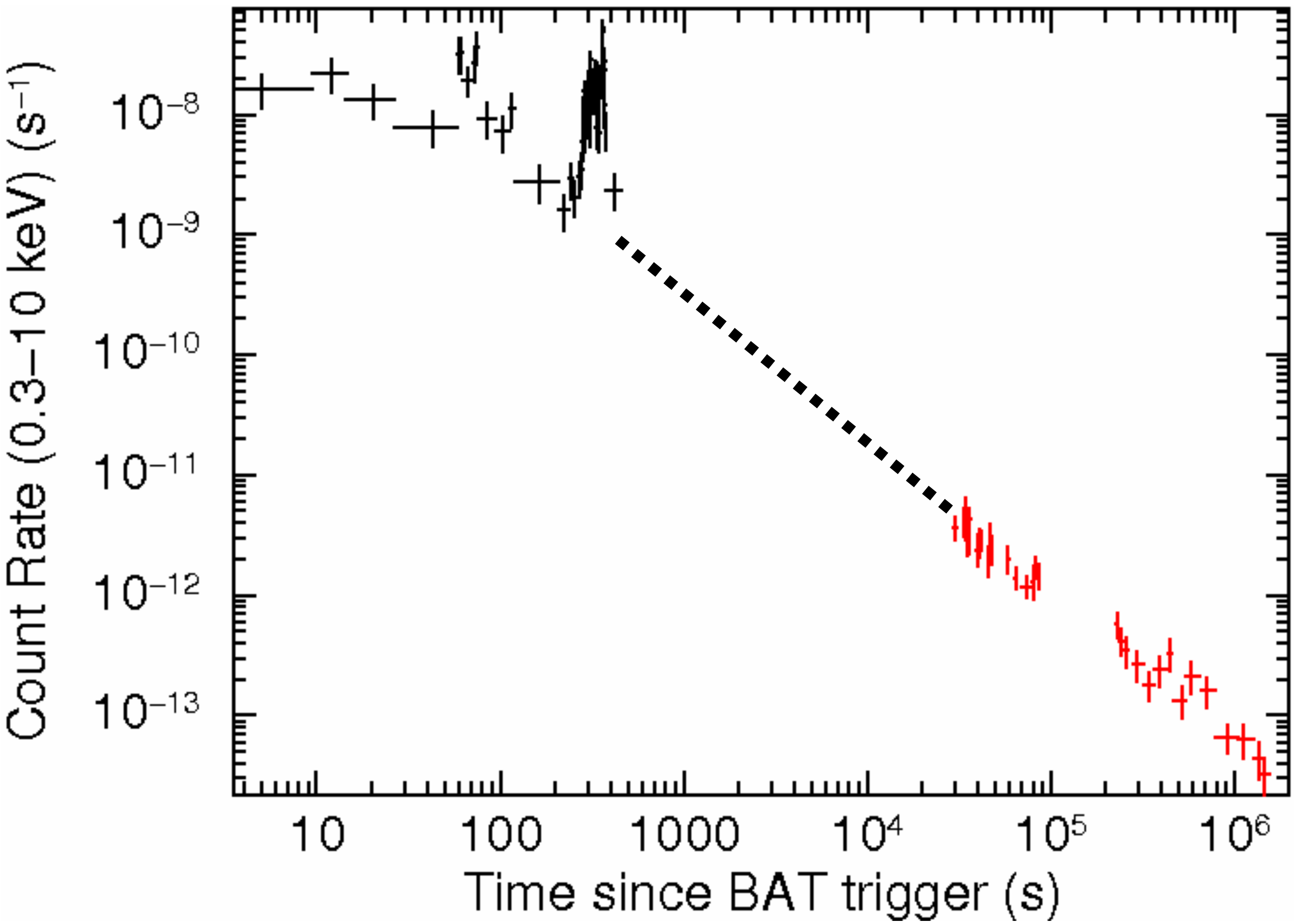
Questions from *Swift*

New mysteries

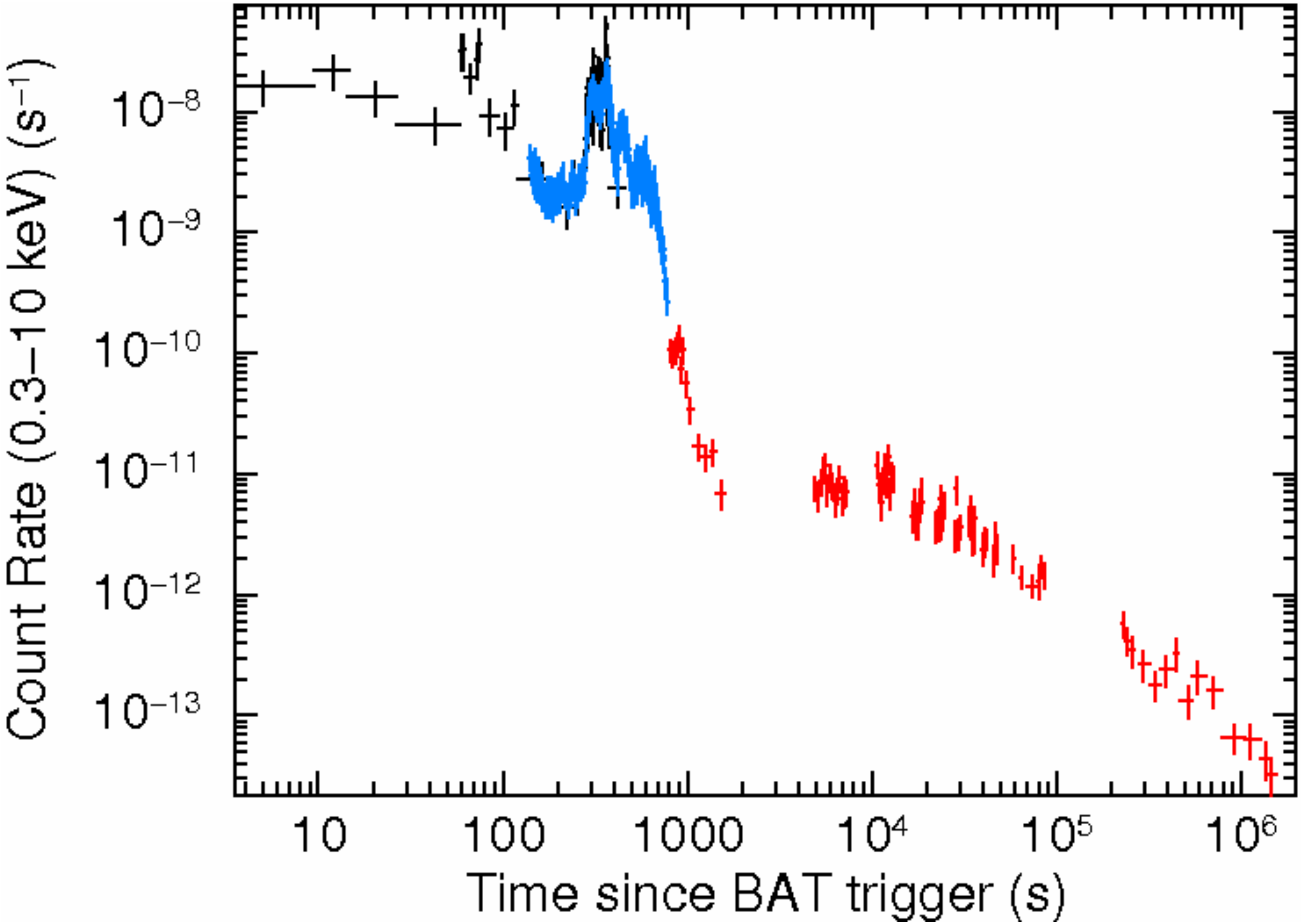
- Complex X-ray afterglows.
- X-ray flares
- Jet breaks?
- Why do the different types of GRB have such similar afterglows?
- Why is the ambient medium (apparently) constant-density, not WR-wind type environment?
- What are the microphysics parameters?



Count Rate (0.3–10 keV) (s^{-1})
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10
100
1000
10^{4}
10^{5}
10^{6}
Time since BAT trigger (s)



Count Rate (0.3–10 keV) (s^{-1})
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10
100
1000
10^{4}
10^{5}
10^{6}
Time since BAT trigger (s)

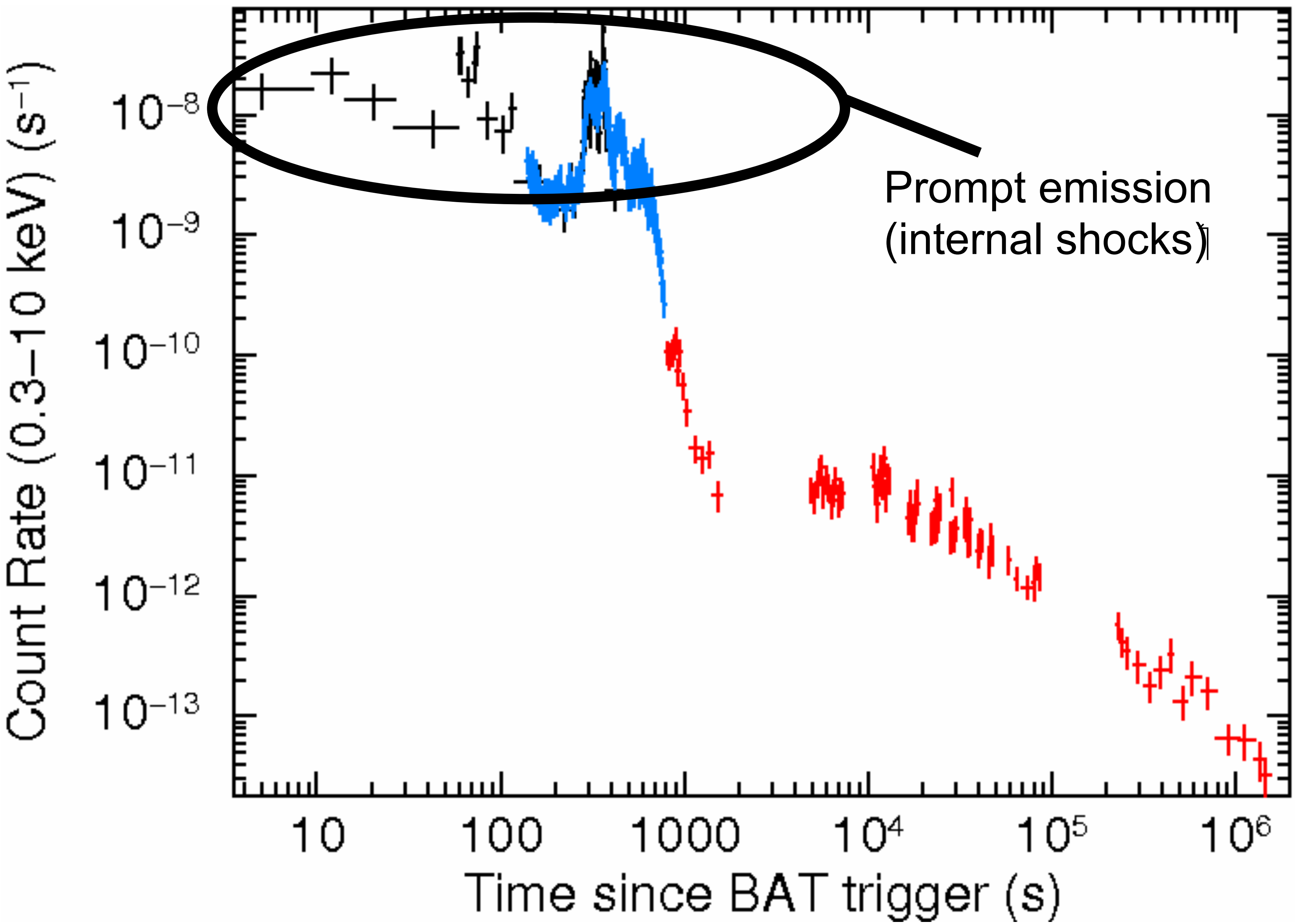


Count Rate (0.3–10 keV) (s^{-1})
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10
100
1000
10^4
10^5
10^6
Time since BAT trigger (s)

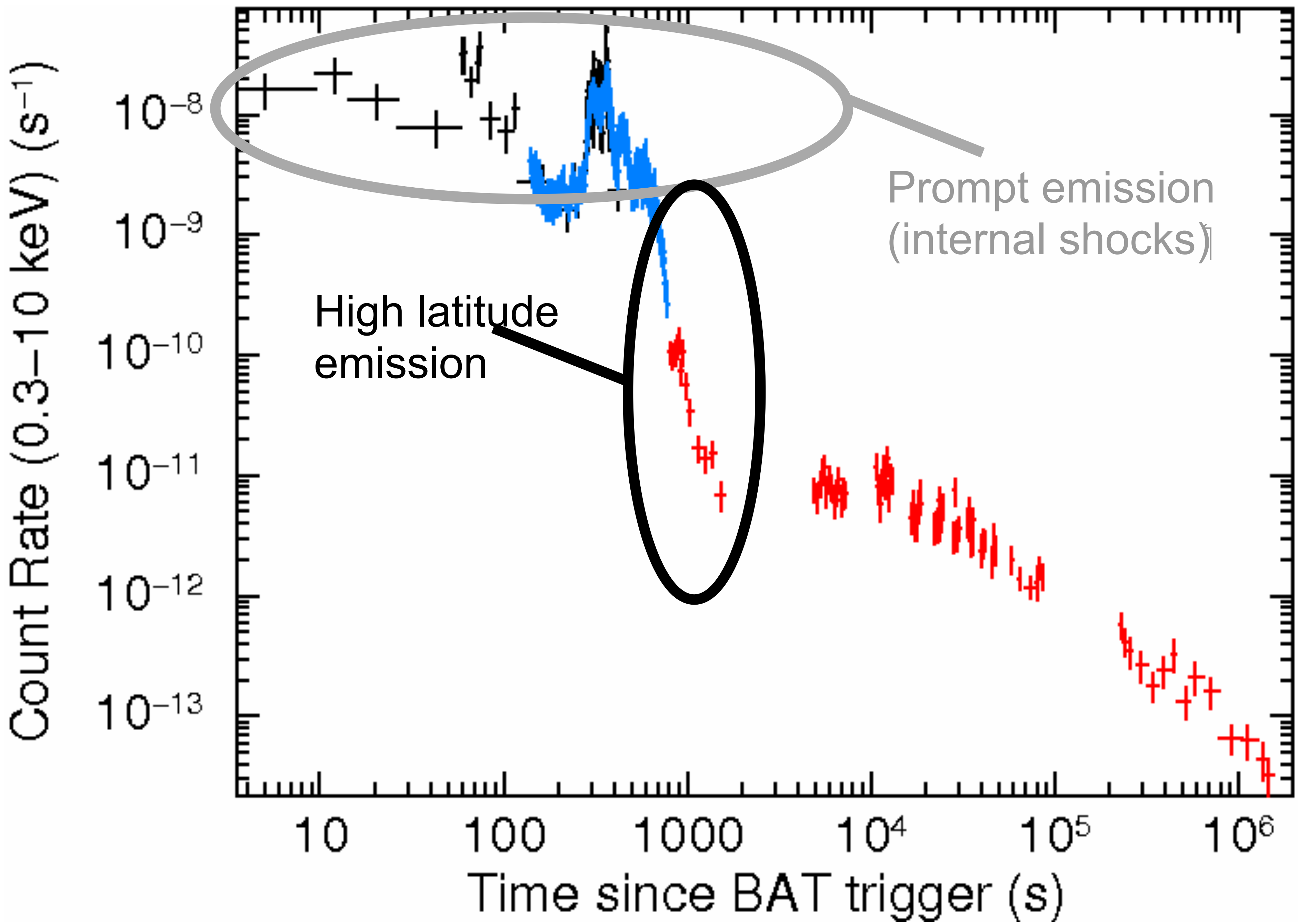
Swift discoveries

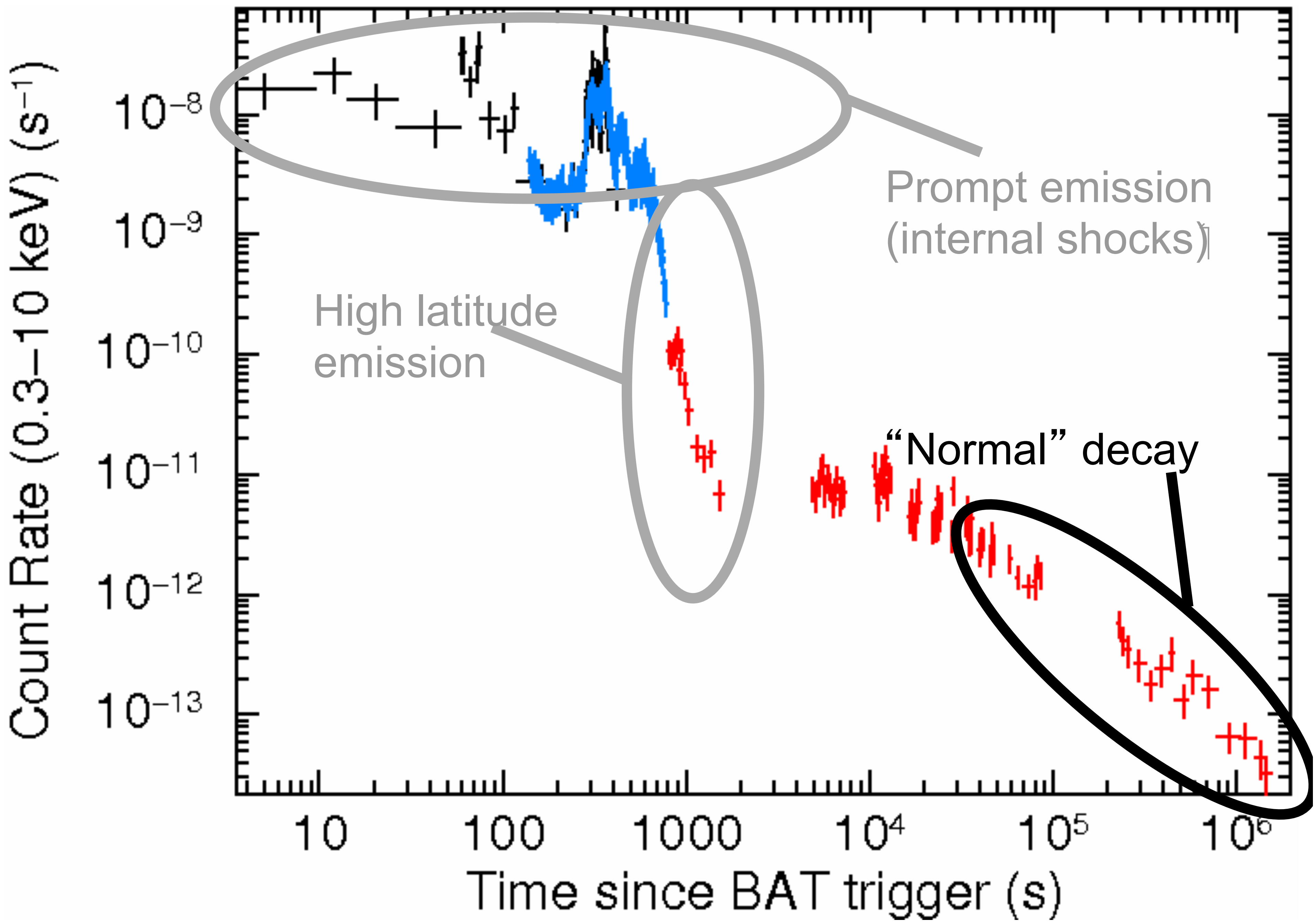
Complex X-ray light curves

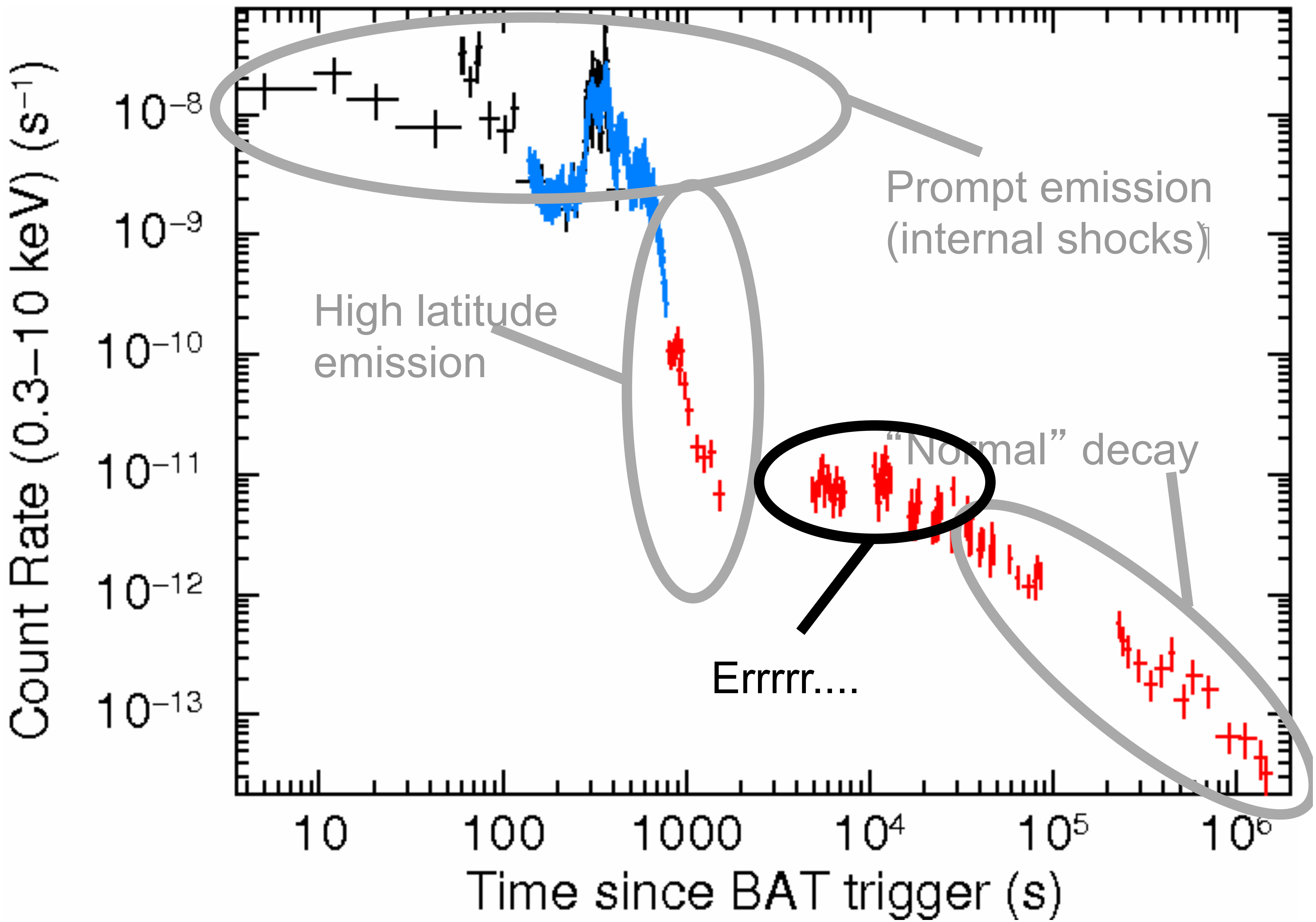
- Most X-ray afterglows don't show the simple power-law decay seen at late times.
- The “canonical” light curves has 3 phases:



Prompt emission
(internal shocks)
Count Rate (0.3–10 keV) (s⁻¹)
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10
100
1000
10⁴
10⁵
10⁶
Time since BAT trigger (s)


Count Rate (0.3–10 keV) (s⁻¹)
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10
100
1000
10⁴
10⁵
10⁶
Time since BAT trigger (s)
Prompt emission
(internal shocks)
High latitude
emission


Count Rate (0.3–10 keV) (s−1)
10−8
10−9
10−10
10−11
10−12
10−13
10
100
1000
10^4
10^5
10^6
Time since BAT trigger (s)
Prompt emission
(internal shocks)
High latitude
emission
"Normal" decay



Count Rate (0.3–10 keV) (s⁻¹)
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10
100
1000
10⁴
10⁵
10⁶
Time since BAT trigger (s)
Prompt emission
(internal shocks)
High latitude
emission
"Normal" decay
Errrrr....

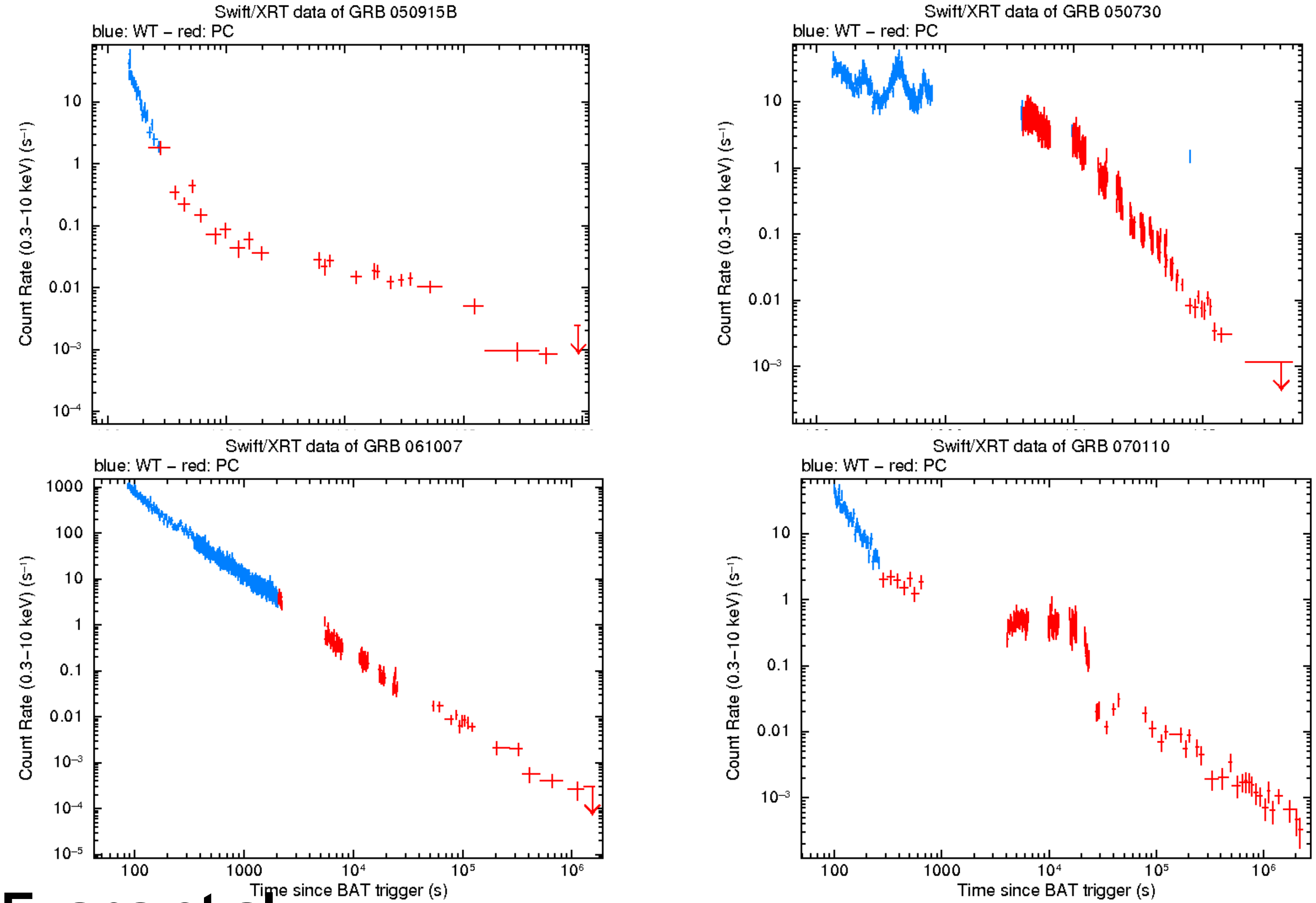
Swift discoveries

Shallow decay phase

- Energy injection? (Zhang et al 2006). *But it has to go on for ~1 day.*
- Dust? [models light curves really well – Shao & Dai (2007). *But not the spectra (Shen et al. 2009)*.
- Upscattered forward shock emission?
- Long-lived central engine (i.e. internal shock emission).
- And more....

Swift discoveries

Complex X-ray afterglows



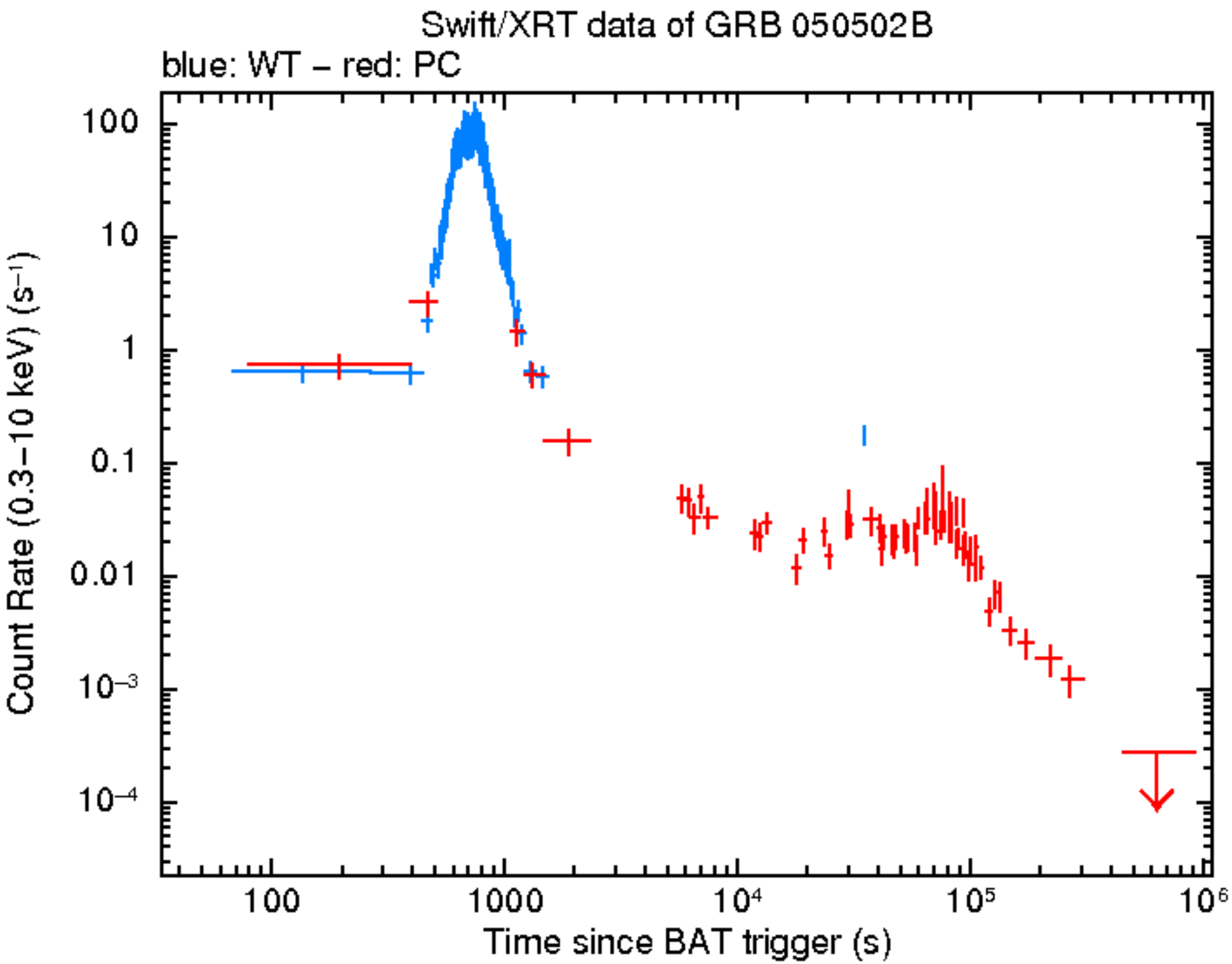
Evans et al. 2009

Questions from *Swift*

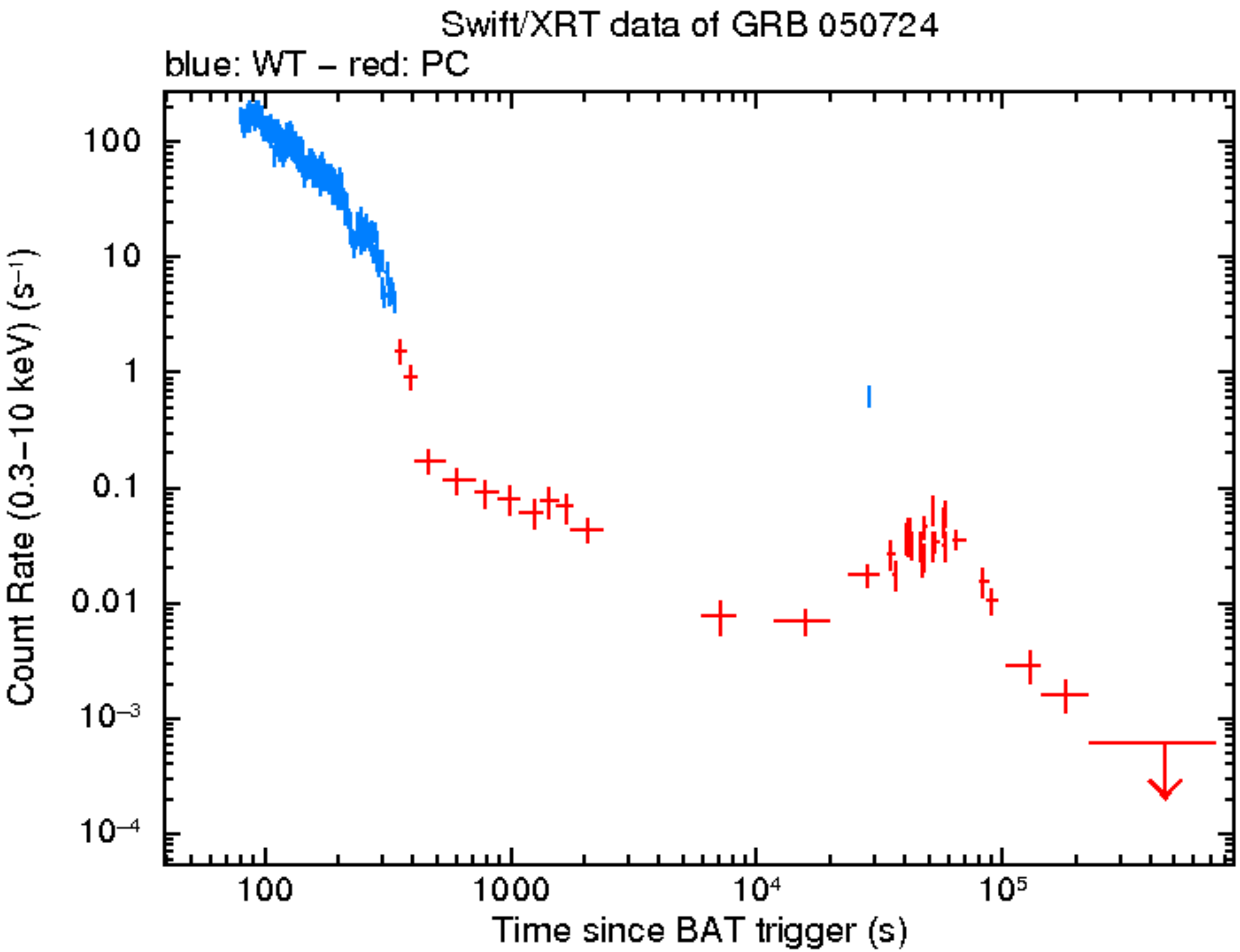
New mysteries

- Complex X-ray afterglows.
- X-ray flares
- Jet breaks?
- Why do the different GRBs have such similar afterglows?
- Why is the ambient medium (apparently) constant-density?
- What are the microphysics parameters?

Swift discoveries



Swift discoveries



Questions from *Swift*

New mysteries

- Complex X-ray afterglows.
- X-ray flares
- Jet breaks?
- Why do the different GRBs have such similar afterglows?
- Why is the ambient medium (apparently) constant-density?
- What are the microphysics parameters?

Swift discoveries

Where are the jet breaks?

- Strong, achromatic light curve steepening was expected in most/all GRBs – it's now exciting if we think we've got one!
- They could be hidden (Curran et al. 2008), or we're not considering enough possibilities (Racusin et al. 2009)
- Perhaps the jets are structured/complex, so breaks are not achromatic? (e.g. Oates et al. 2007, de Pasquale et al. 2008).

Swift discoveries

GRB 080319B

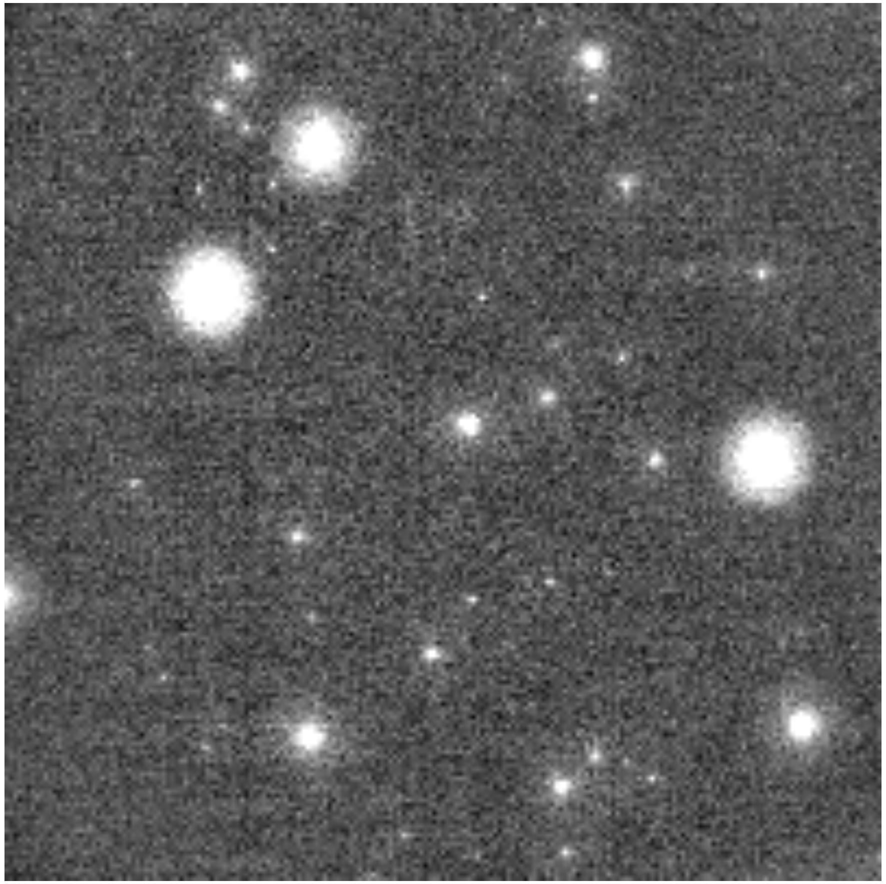
- Very bright – reached m_v=5.3.

Swift discoveries

GRB 080319B

- Very bright – reached m_v=5.3

Movie from Pi of the sky.



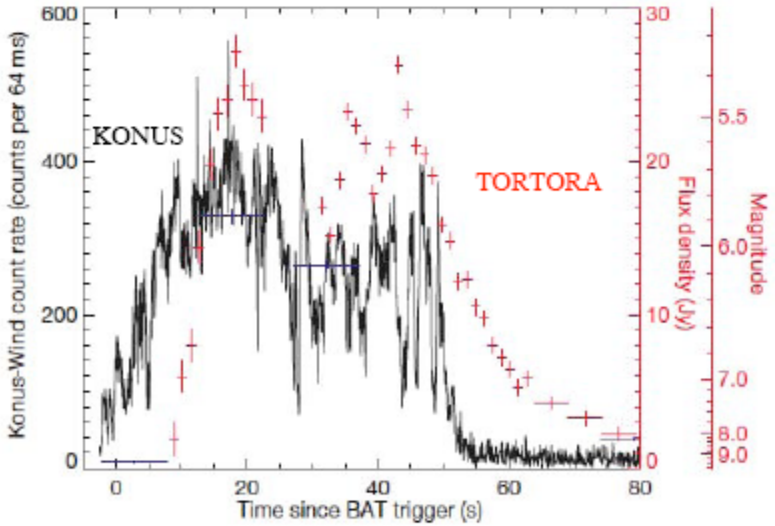
Swift discoveries

GRB 080319B

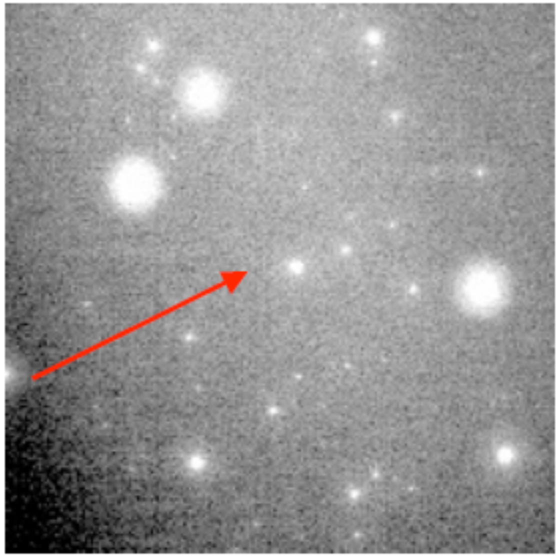
- Very bright – reached m_v=5.3
- z=0.9
- If it were at the Galactic centre, it would appear as bright as the Sun!
- Bright in X-rays and Gamma-rays, but nothing like as extraordinary as in the optical.
- Implies a complex jet structure (Racusin et al. 2008, Nature).

080319B

First "naked-eye" Burst GRB 080319B



Racusin et al. 2008



Pi-of-the-Sky

T90 = 50s   z = 0.94

Prompt optical observations:

Pi-of-the-Sky (Chile) pre-burst

RAPTOR (New Mexico)

REM/TORTORA (Chile)

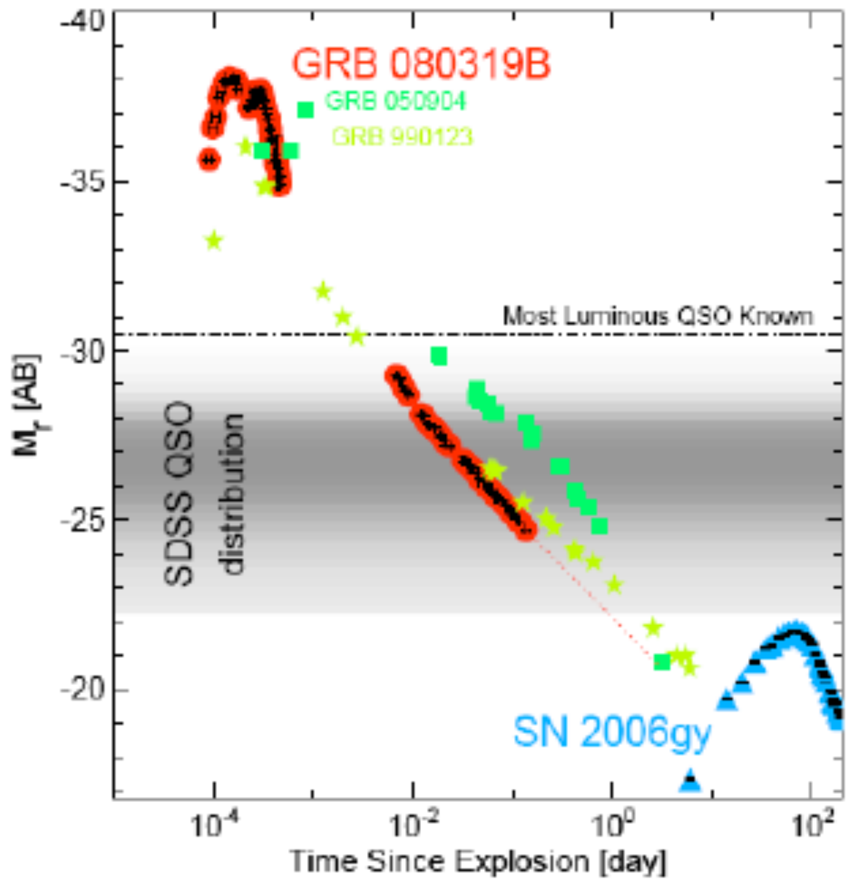
Peak brightness of 5.6 magnitudes!!

080319B

Even corrected for distance, brightest optical burst

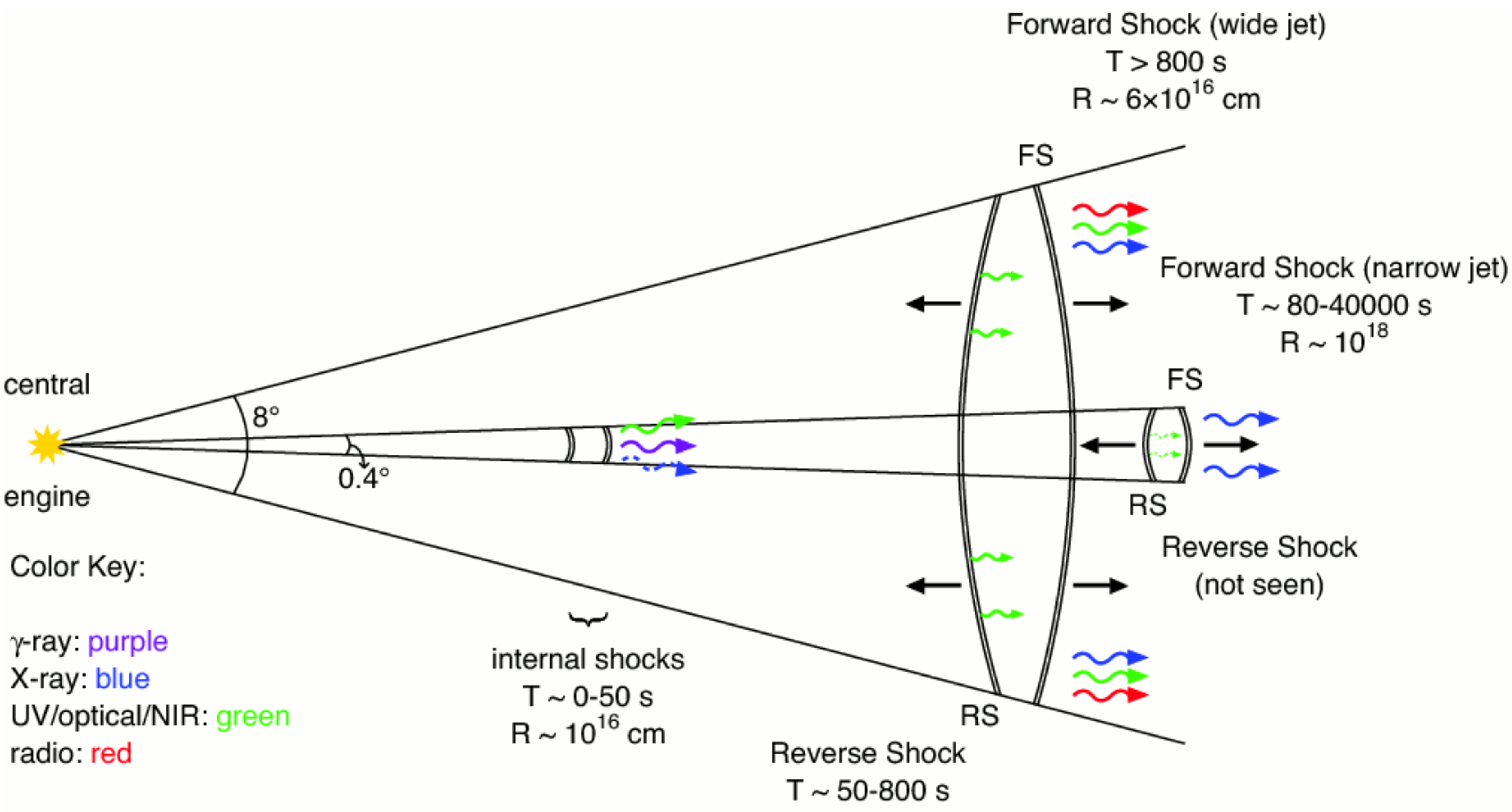
In our Galaxy, such a burst would be brighter than the sun!

GRBs much more luminous than most energetic quasars & SNe

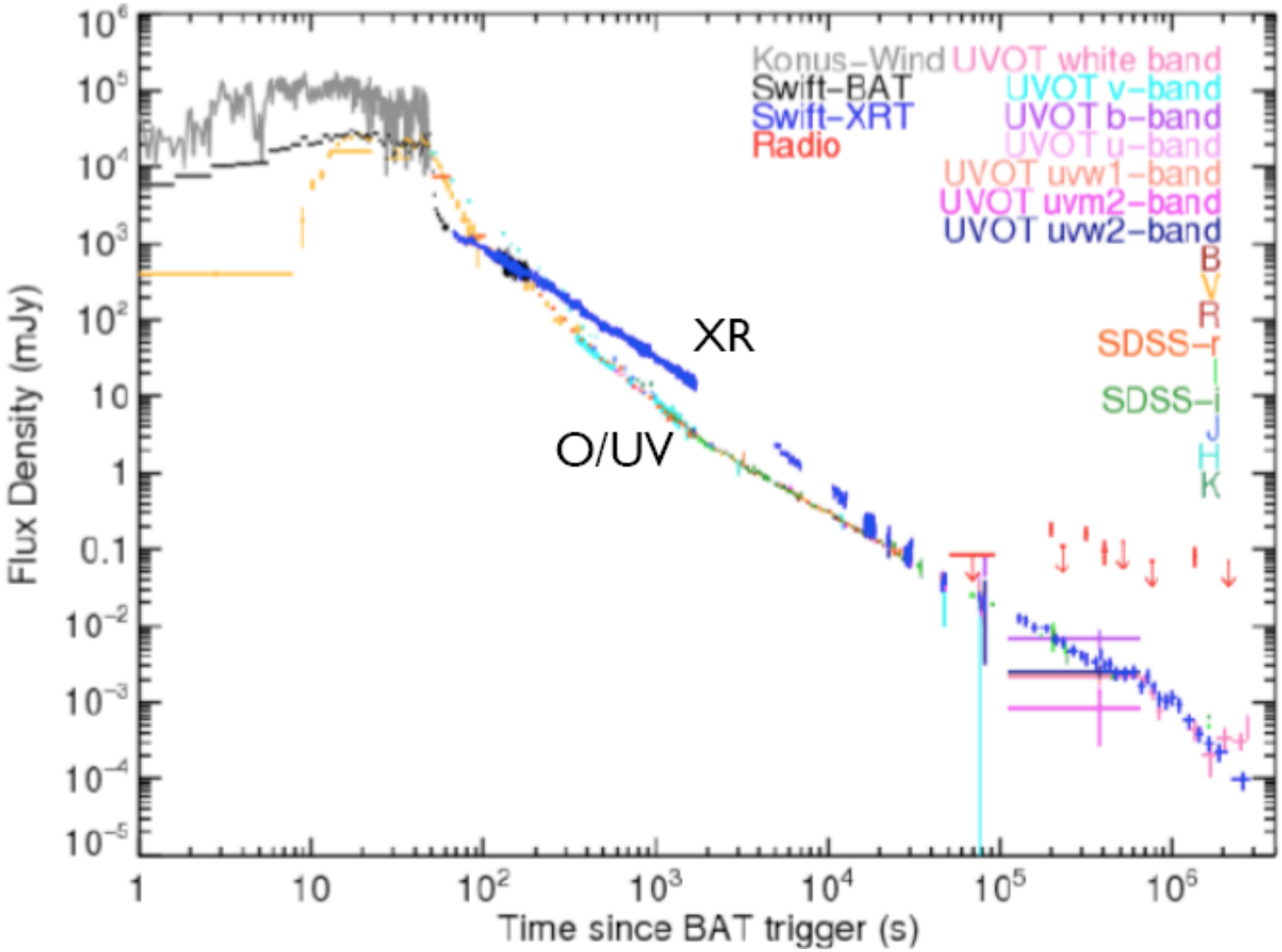


Bloom et al. 2008

Swift discoveries



080319B

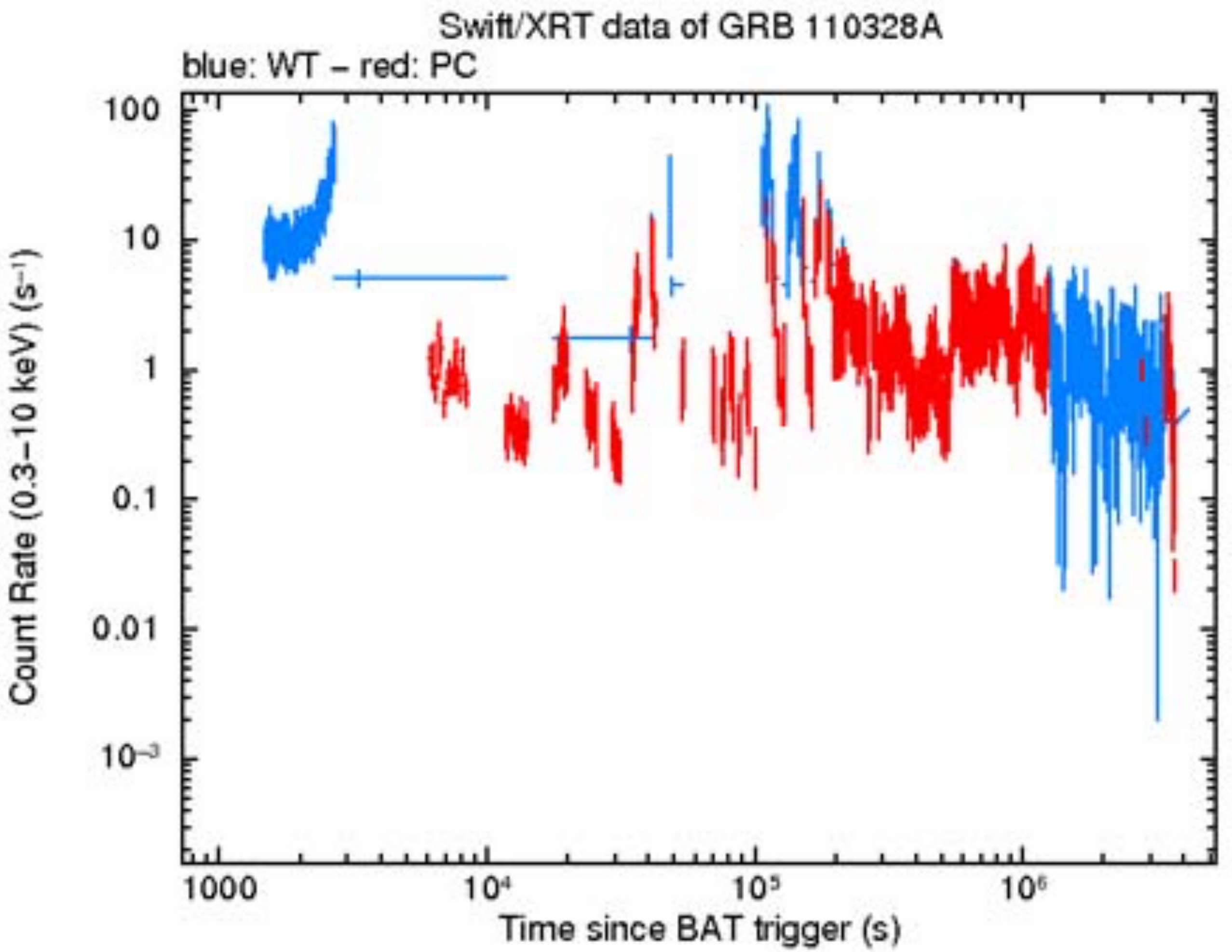


Konus-Wind
Swift-BAT
Swift-XRT
Radio
UVOT white band
UVOT v-band
UVOT b-band
UVOT u-band
UVOT uvw1-band
UVOT uvm2-band
UVOT uvw2-band
B
V
R
SDSS-r
I
SDSS-i
J
H
K
XR
O/UV
Flux Density (mJy)
Time since BAT trigger (s)

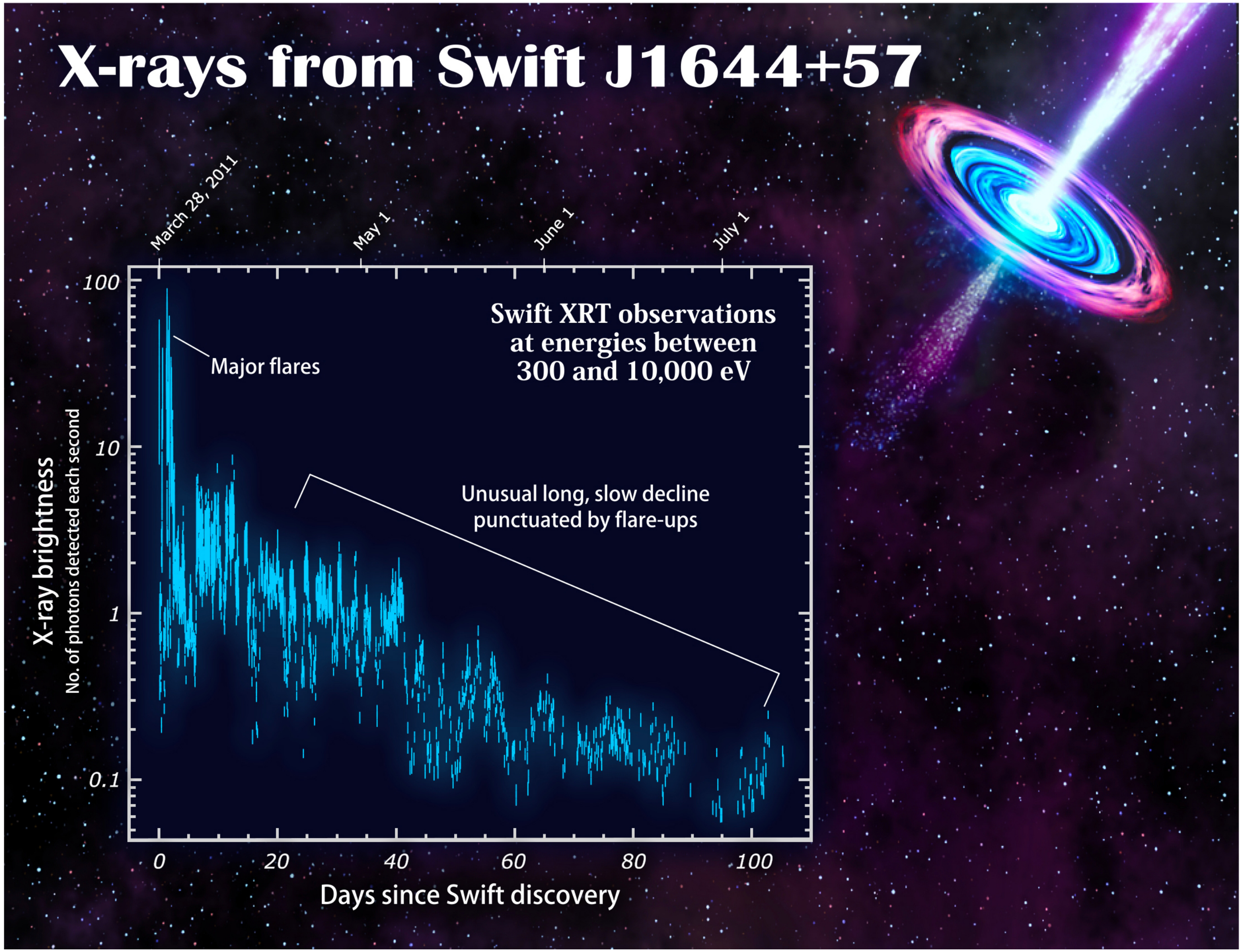
Summary

- *Swift* has helped to answer some questions:
  - Localised short GRBs
  - Supported collapsar and compact merger progenitor models.
- Asked a load of new questions!
  - What are the subtypes?
  - How do we get X-ray afterglows? And flares?
  - What is the jet structure?

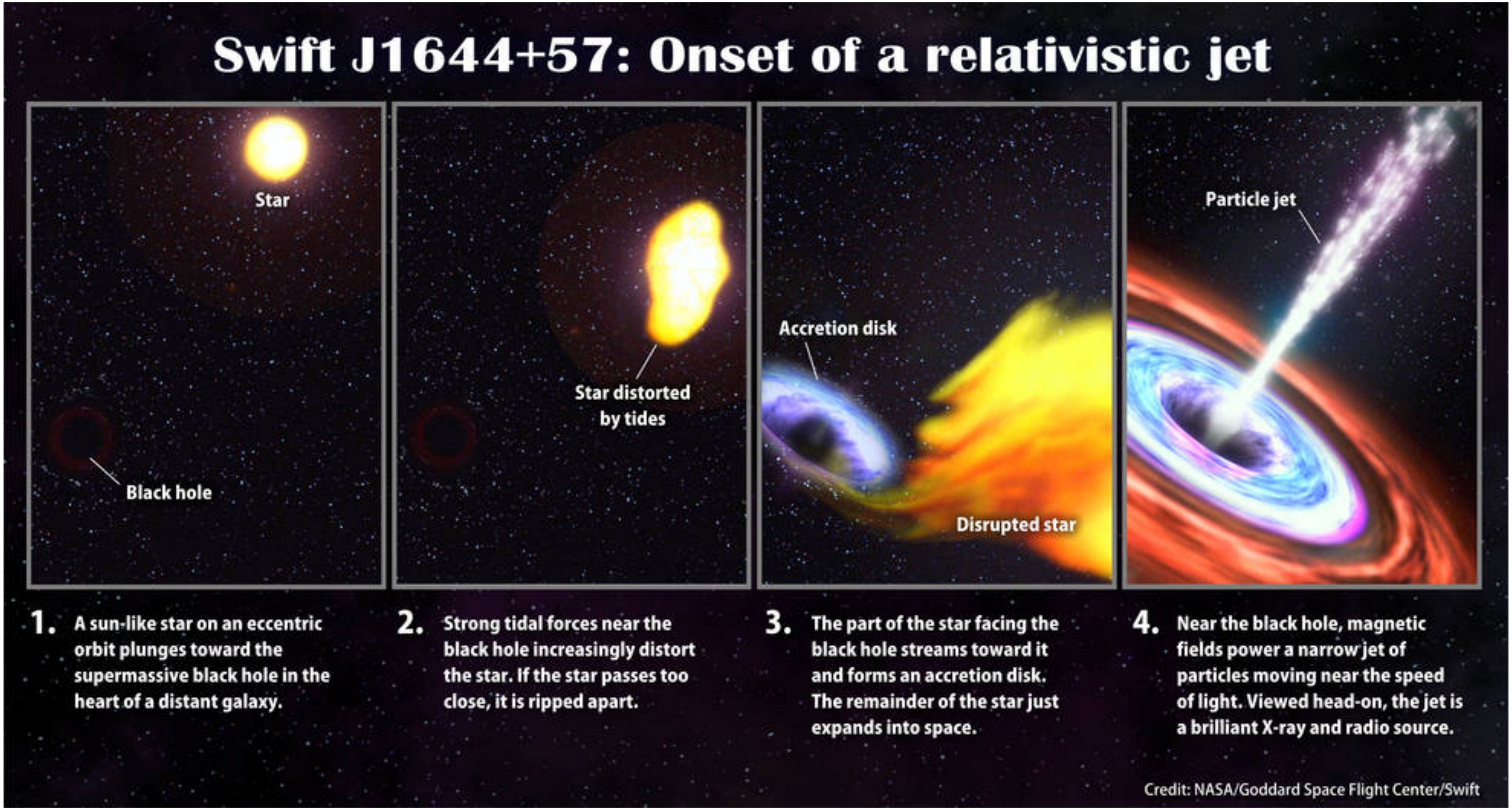
A peculiar GRB?



A peculiar GRB?



A peculiar GRB?

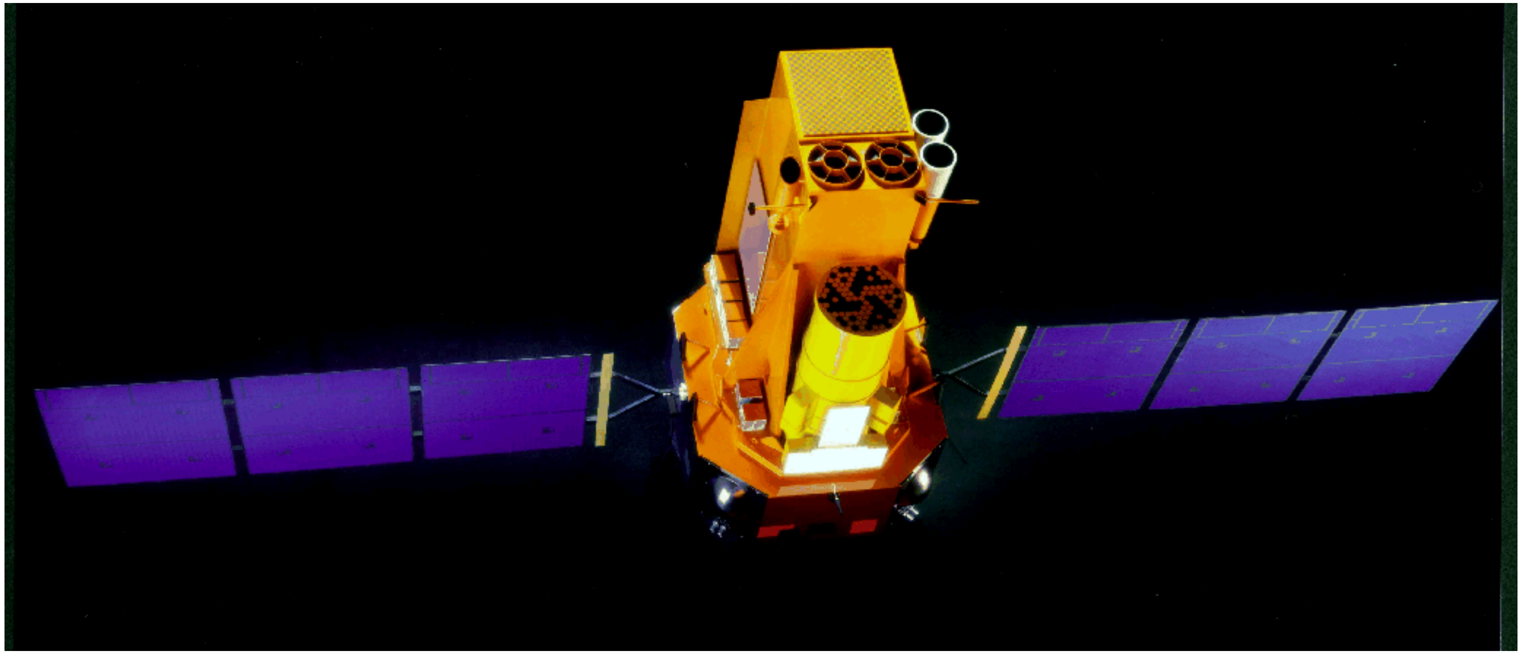


Astrofisica Nucleare e Subnucleare

MeV Astrophysics

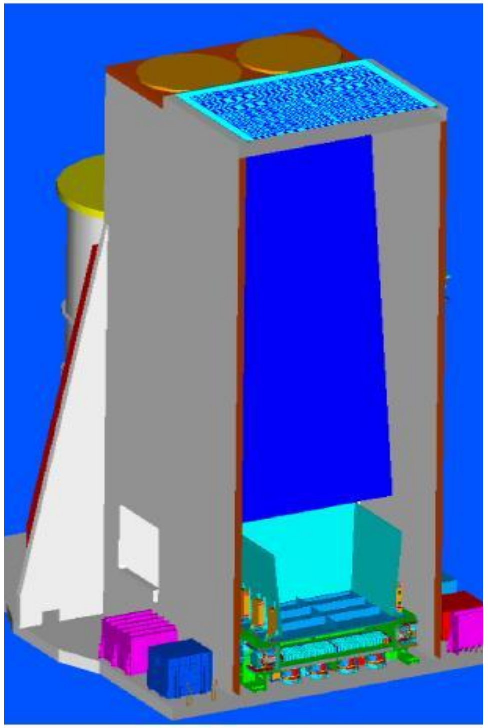
INTEGRAL

INTEGRAL, the International Gamma-Ray Astrophysics Laboratory
Fine spectroscopy (E/dE=500) and fine imaging (angular resolution of 12' FWHM)
Energy range 15 keV to 10 MeV
plus simultaneous X-ray (3-35 keV) and optical (550 nm) monitoring capability
Two main -ray instruments: SPI (spectroscopy) and IBIS (imager)

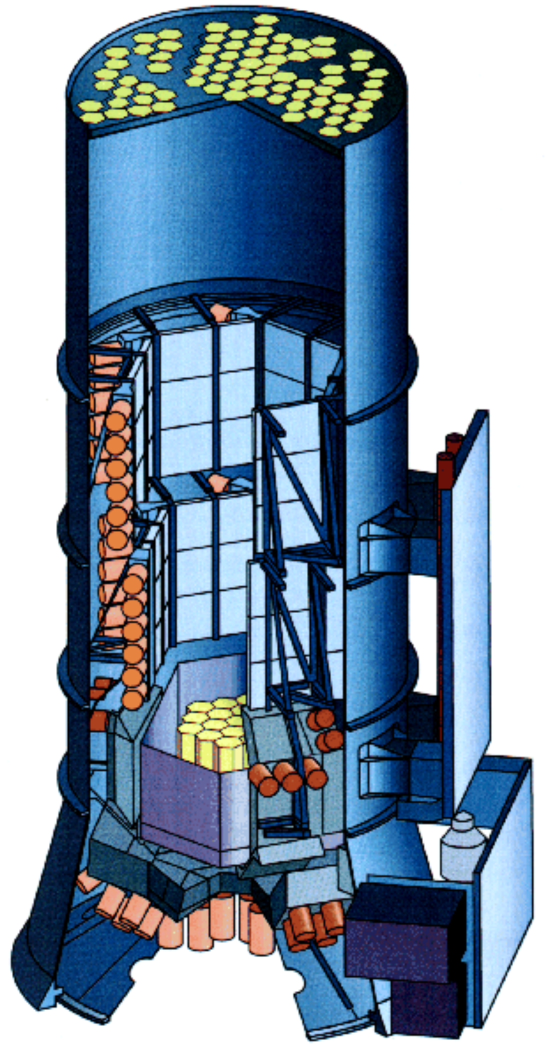


http://integral.esa.int

INTEGRAL

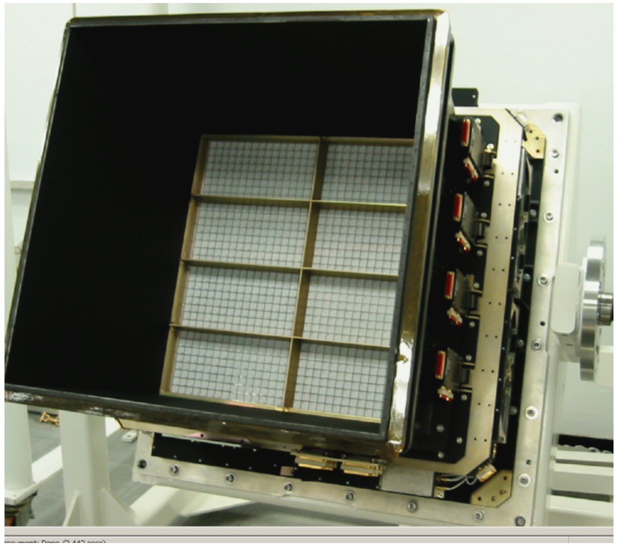


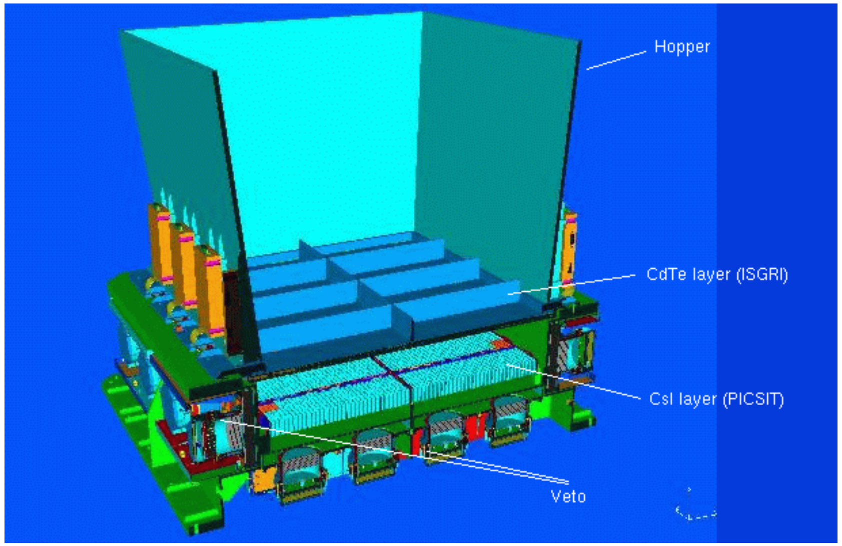
Imager IBIS



Spectrometer SPI

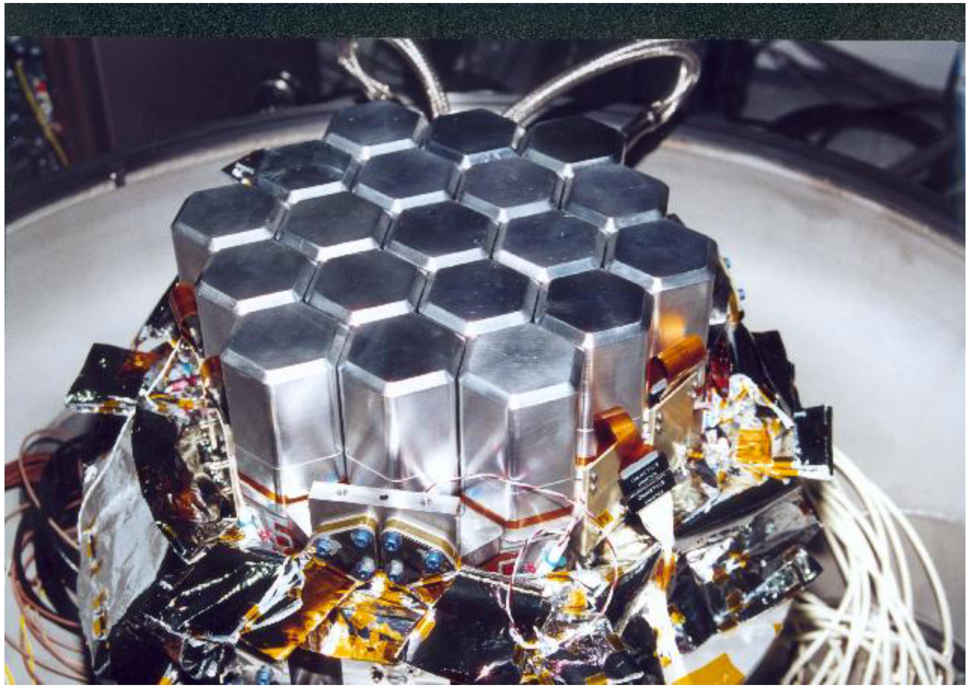
IBIS





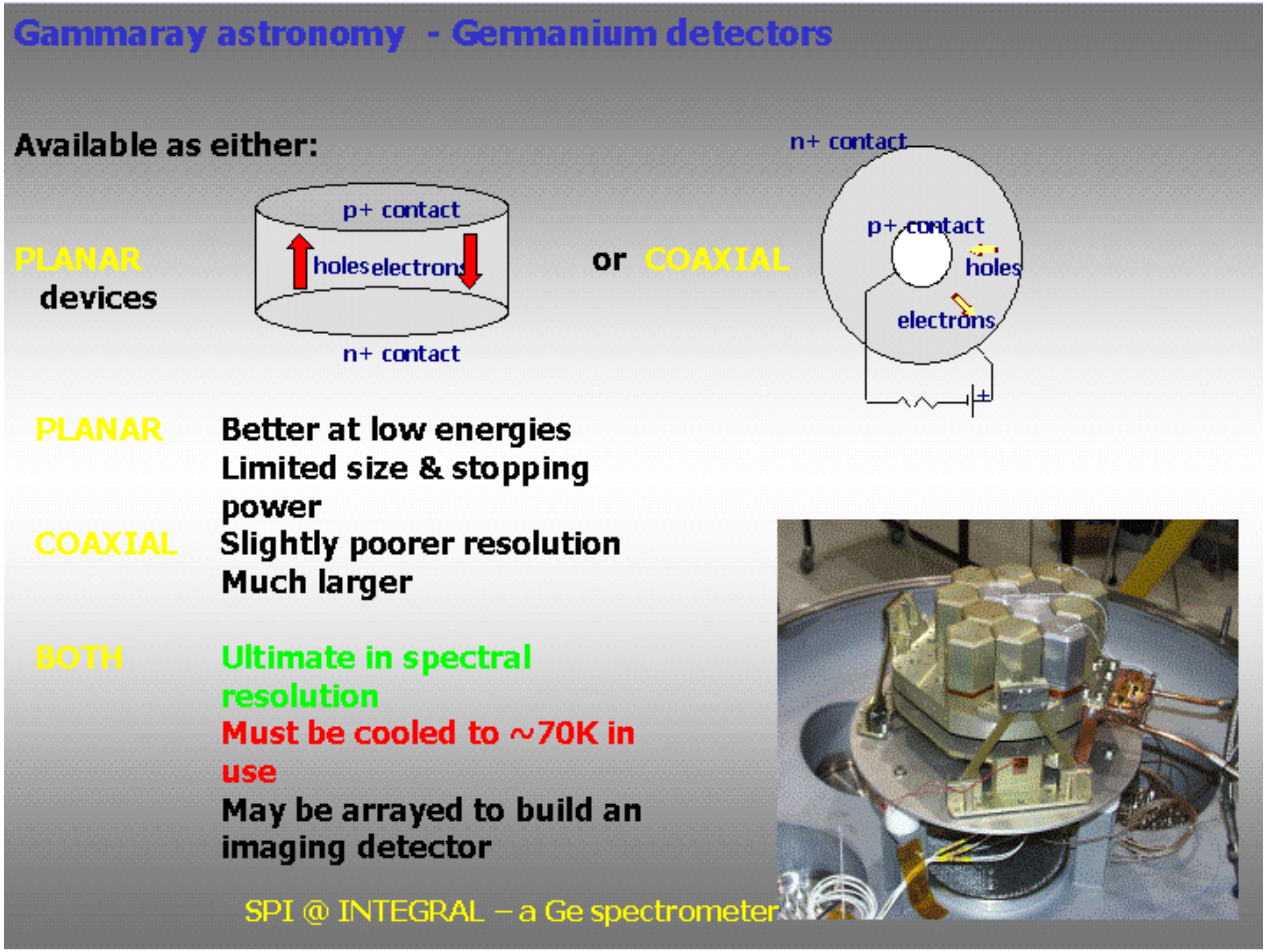
The Imager IBIS (Imager on Board the Integral Satellite) provides diagnostic capabilities of fine imaging (12 arcmin FWHM), source identification and spectral sensitivity to both continuum and broad lines over a broad (15 keV - 10 MeV) energy range. The Imager will exploit simultanesously with the other instruments on Integral celestial objects of all classes ranging from the most compact galactic systems to extragalactic objects.
A tungsten coded-aperture mask (located at 3.2 m above the detection plane) is optimised for high angular resolution. As diffraction is negligible at gamma-ray wavelengths, the angular resolution obtainable with a coded mask telescope is limited by the spatial resolution of the detector array. The Imager design takes advantage of this by utilising a detector with a large number of spatially resolved pixels, implemented as physically distinct elements.
The detector uses two planes, one 2600 cm^2 front layer of CdTe pixels, each (4x4x2) mm (width x depth x height), and a 3000 cm^2 layer of CsI pixels, each (9x9x30) mm. The CdTe array (ISGRI) and the CsI array (PICsIT) are separated by 90 mm. The detector provides the wide energy range and high sensitivity continuum spectroscopy required for Integral. The division into two layers allows the paths of the photons to be tracked in 3D, as they scatter and interact with more than one element. Events can be categorised and the signal to noise ratio improved by rejecting those which are unlikely to correspond to real (celestial) photons, e.g. towards the high end of the energy range.
The aperture is restricted by a lead shielding tube and shielded in all other directions by an active BGO scintillator veto.

SPI

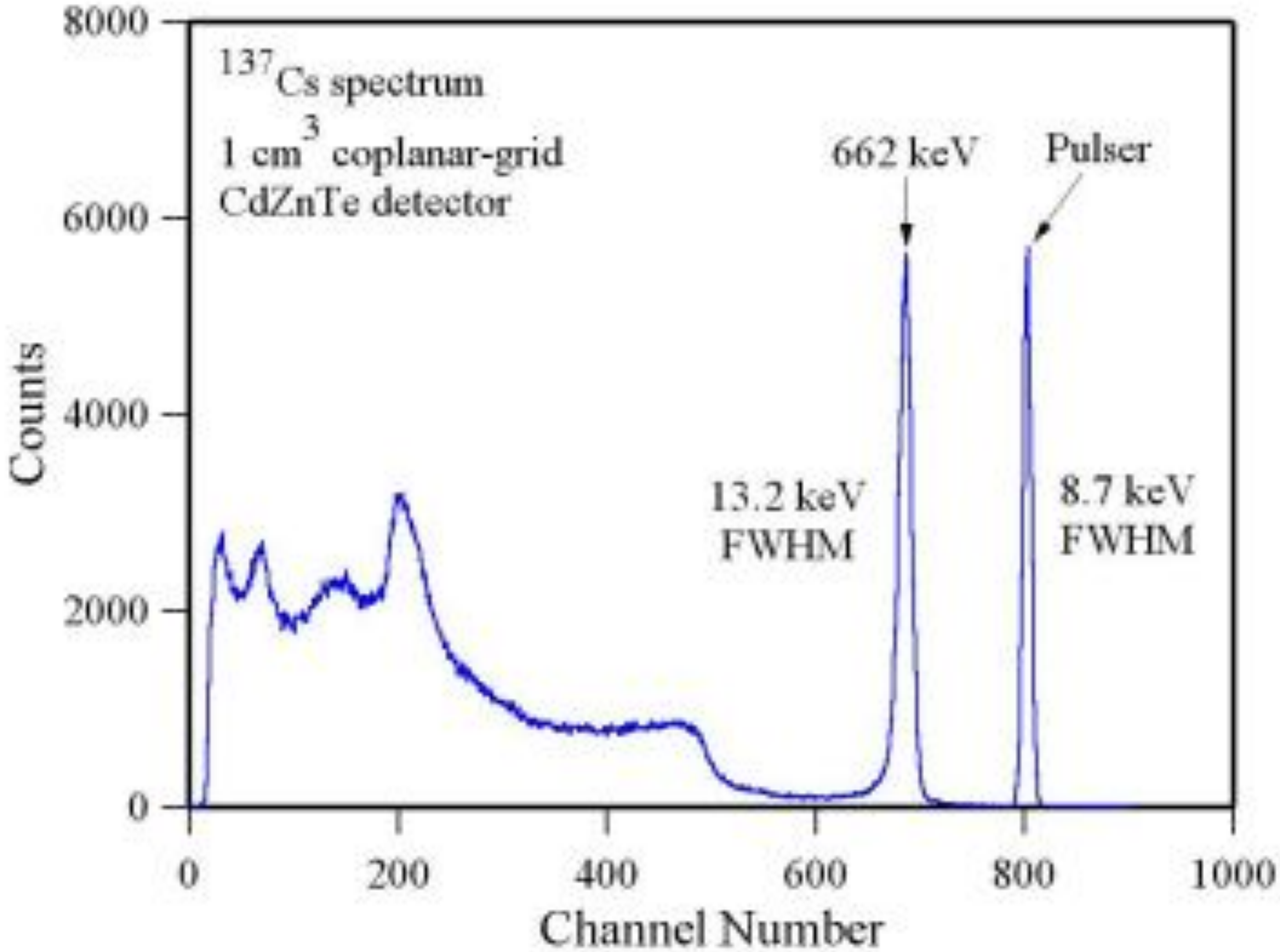


The spectrometer SPI (SPectrometer on INTEGRAL) will perform spectral analysis of gamma-ray point sources and extended regions in the 18 keV - 8 MeV energy range with an energy resolution of 2.2 keV (FWHM) at 1.33 MeV. This will be accomplished using an array of 19 hexagonal high purity Germanium detectors cooled by a Stirling cooler system to an operating temperature of 85 K. A hexagonal coded aperture mask is located 1.7 m above the detection plane in order to image large regions of the sky (fully coded field of view = 16 degrees) with an angular resolution of 2.5 degrees. In order to reduce background radiation, the detector assembly is shielded by a veto (anticoincidence) system which extends around the bottom and side of the detector almost completely up to the coded mask. The aperture (and hence contribution by cosmic diffuse radiation) is limited to ~ 30 degr. A plastic veto is provided below the mask to further reduce the 511 keV background.

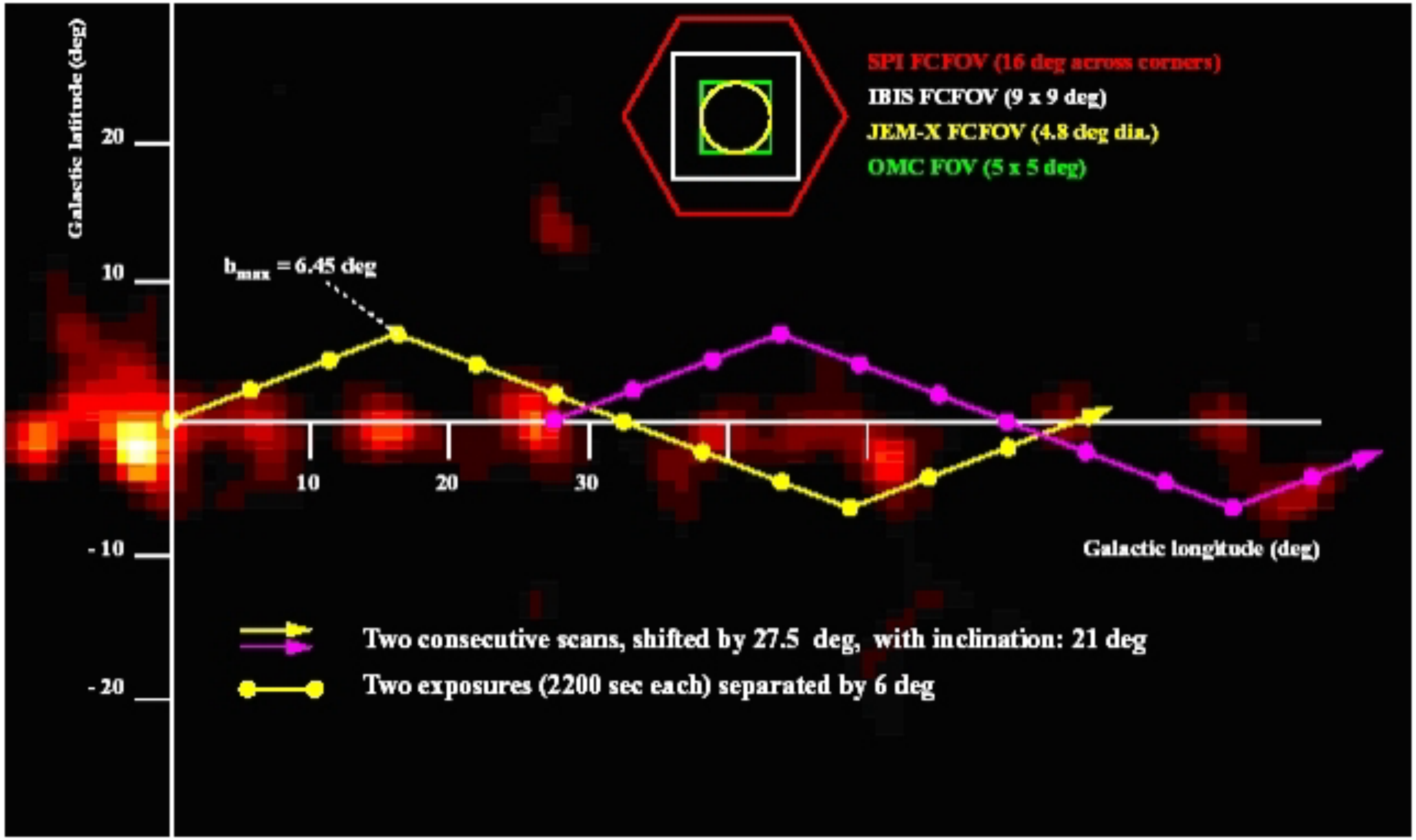
Gamma Spectroscopy



Gamma Spectroscopy

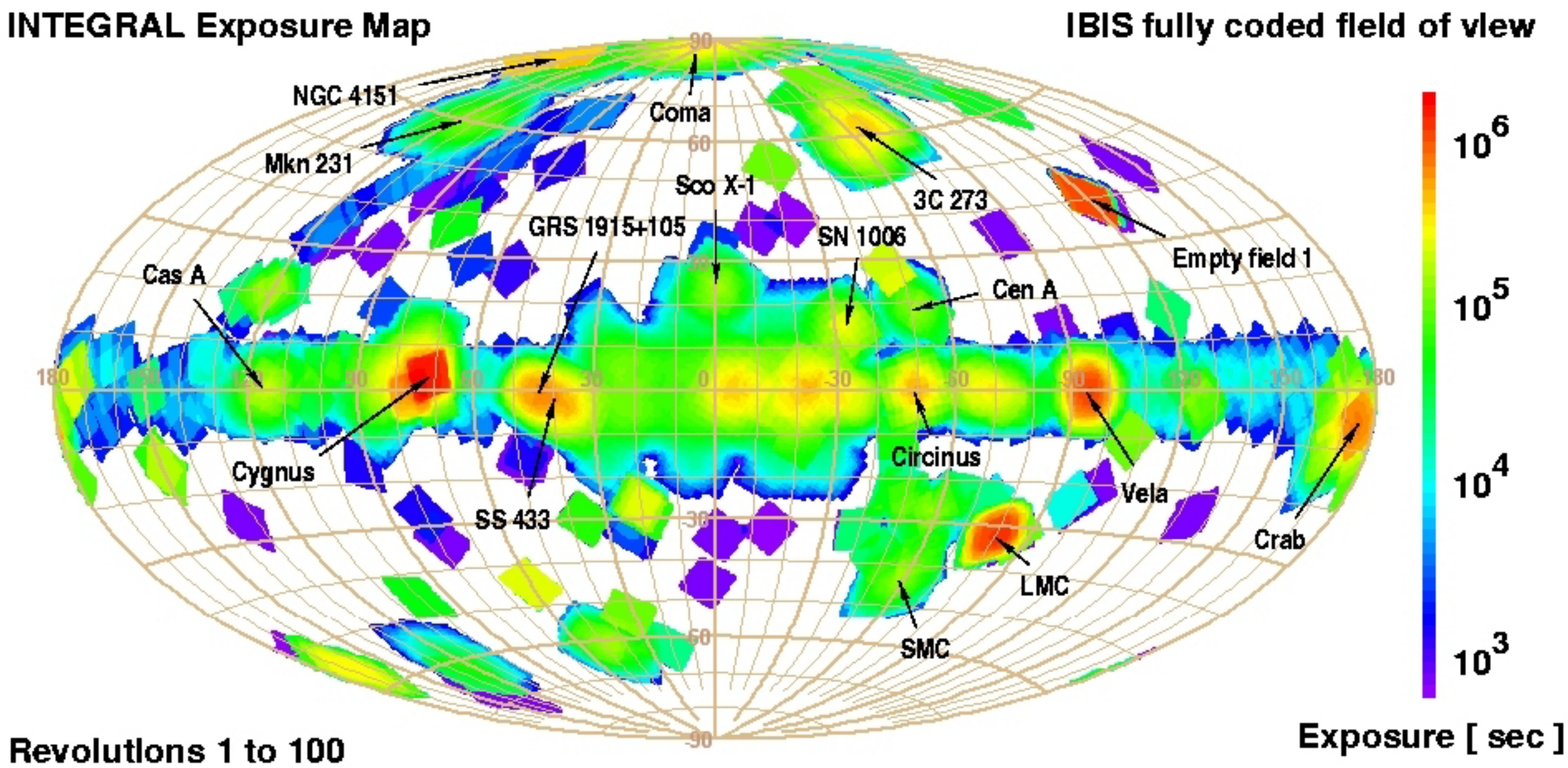


INTEGRAL

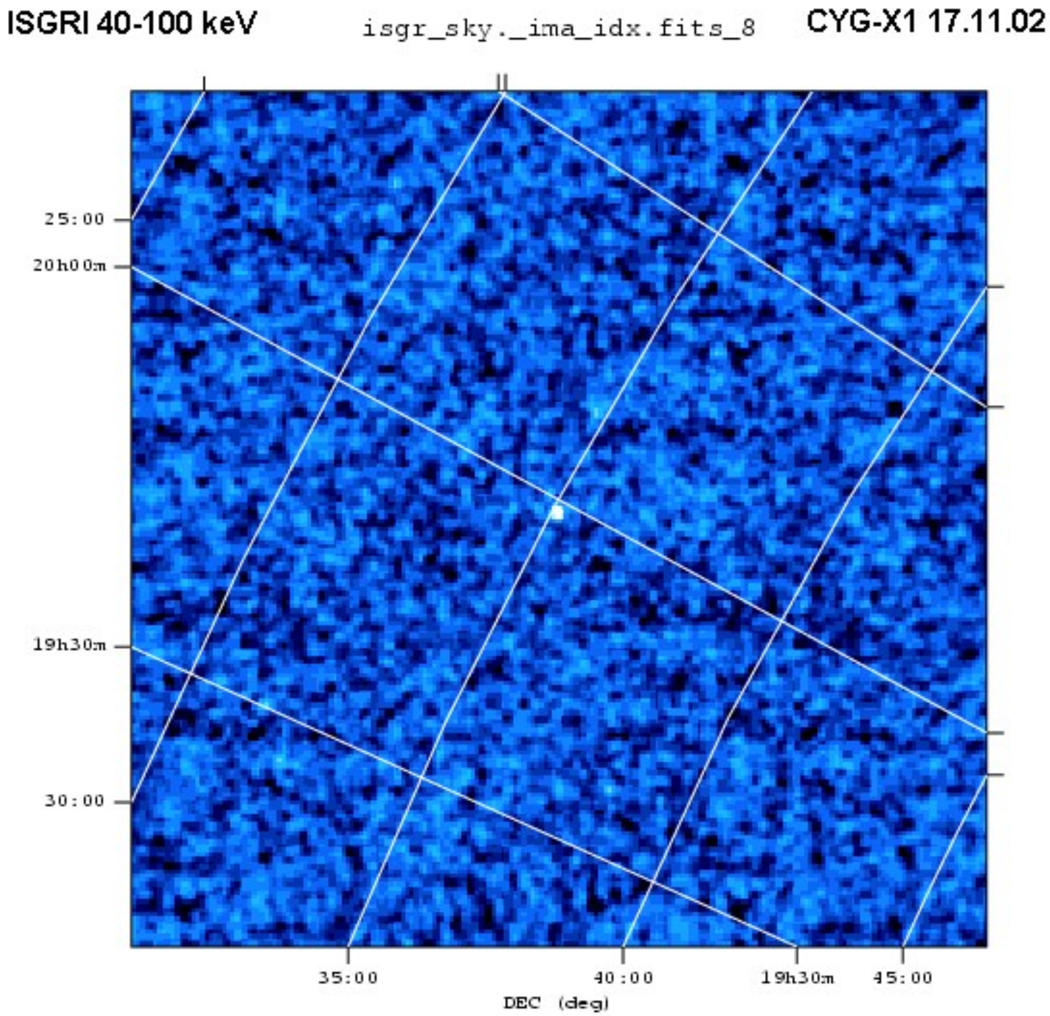


SPI FCFOV (16 deg across corners)
IBIS FCFOV (9 x 9 deg)
JEM-X FCFOV (4.8 deg dia.)
OMC FOV (5 x 5 deg)
Galactic latitude (deg)
20
10
- 10
- 20
b_{max} = 6.45 deg
10
20
30
Galactic longitude (deg)
Two consecutive scans, shifted by 27.5 deg, with inclination: 21 deg
Two exposures (2200 sec each) separated by 6 deg

INTEGRAL


INTEGRAL Exposure Map
IBIS fully coded field of view
NGC 4151
Coma
Mkn 231
3C 273
Sco X-1
GRS 1915+105
SN 1006
Empty field 1
Cas A
Cen A
Cygnus
Circinus
Vela
SS 433
Crab
LMC
SMC
Revolutions 1 to 100
Exposure [sec]

INTEGRAL



ISGRI 40-100 keV
isgr_sky._ima_idx.fits_8
CYG-X1 17.11.02
25:00
20h00m
19h30m
30:00
35:00
40:00
19h30m
45:00
DEC (deg)

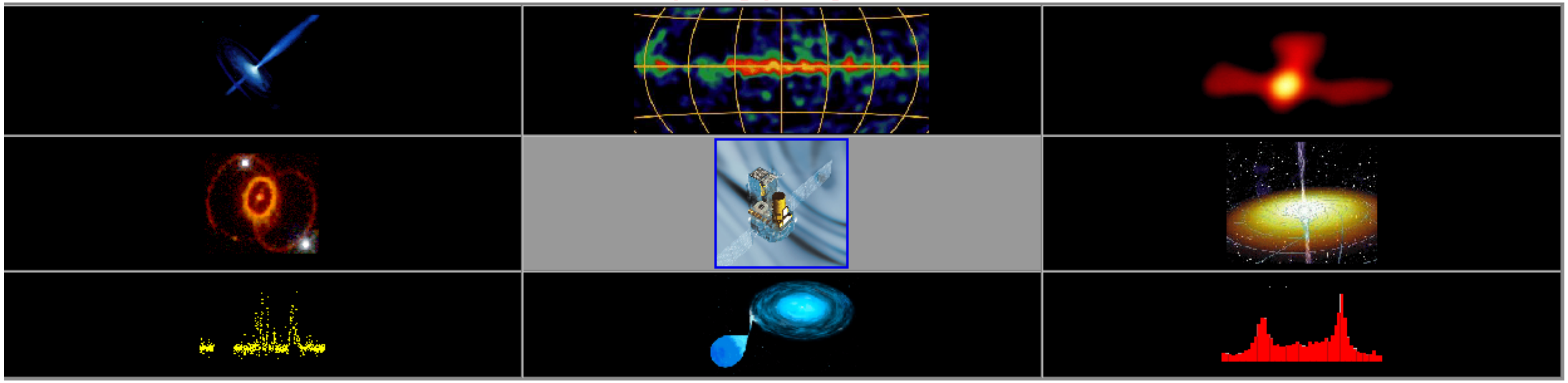
INTEGRAL Science Objectives

Outline INTEGRAL Science Objectives

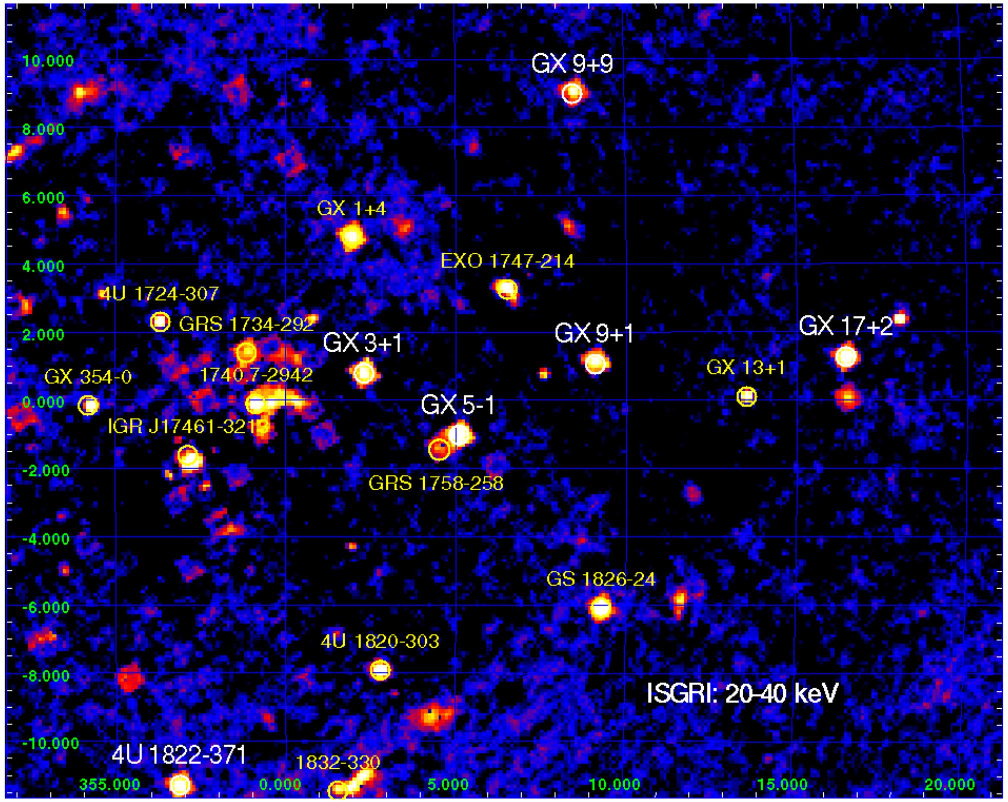
The scientific goals of Integral are addressed through the use of high resolution spectroscopy with fine imaging and accurate positioning of celestial sources in the gamma-ray domain. The following list of topics will be addressed by Integral:

- Compact Objects *(White Dwarfs, Neutron Stars, Black Hole Candidates, High Energy Transients and Gamma-Ray Bursts)*
- Extragalactic Astronomy *(Galaxies, Clusters, AGN, Seyferts, Blazars, Cosmic Diffuse Background)*
- Stellar Nucleosynthesis *(Hydrostatic Nucleosynthesis (AGB, WR Stars), Explosive Nucleosynthesis (Supernovae, Novae))*
- Galactic Structure *(Cloud Complex Regions, Mapping of continuum and line emission, ISM, CR distribution)*
- The Galactic Centre
- Particle Processes and Acceleration *(Transrelativistic Pair Plasmas, Beams, Jets)*
- Identification of High Energy Sources *(Unidentified Gamma-Ray Objects as a Class)*
- PLUS: Unexpected Discoveries

Gamma-Ray Astrophysics before INTEGRAL

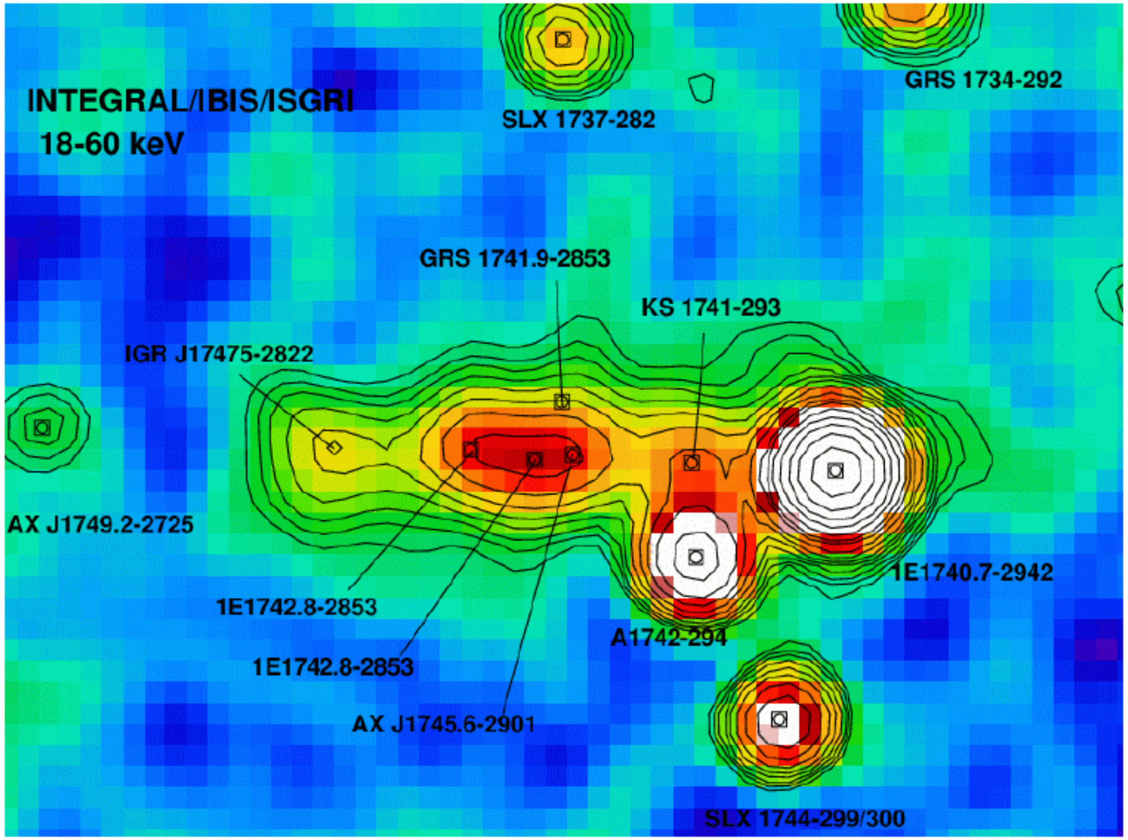


INTEGRAL



The image is an IBIS/ISGRI image of the Galactic Centre in the 20-40 keV band. The analysis of IBIS/ISGRI data is based on GCDE (Galactic Center Deep Exposure) and GPS (Galactic Plane Scan) data from revolution 30 to 64 i.e. January 11th to April 22nd, 2003 for a total of one thousand pointings (about 2 Msec exposure)

INTEGRAL



INTEGRAL views a Compton mirror at the Galactic Centre. M. Revnivtsev et al. report on the association of IGR J17475-2822, recently discovered by INTEGRAL, with the giant molecular cloud Sgr B2 in the Galactic Center region. Data from different observatories strongly support the idea that the hard X-ray emission of Sgr B2 is Compton scattered and reprocessed radiation emitted in the past by the Sgr A* source, the supermassive black-hole candidate in the center of our Galaxy. The IBIS/ISGRI image (18-60 keV) shows the inner 3.5 degree by 2.5 degree region of the center of the Galaxy. Contours represent signal-to-noise levels starting at S/N = 5 and increasing with a factor 1.4. The image has a total effective exposure time of 2.3 Ms.

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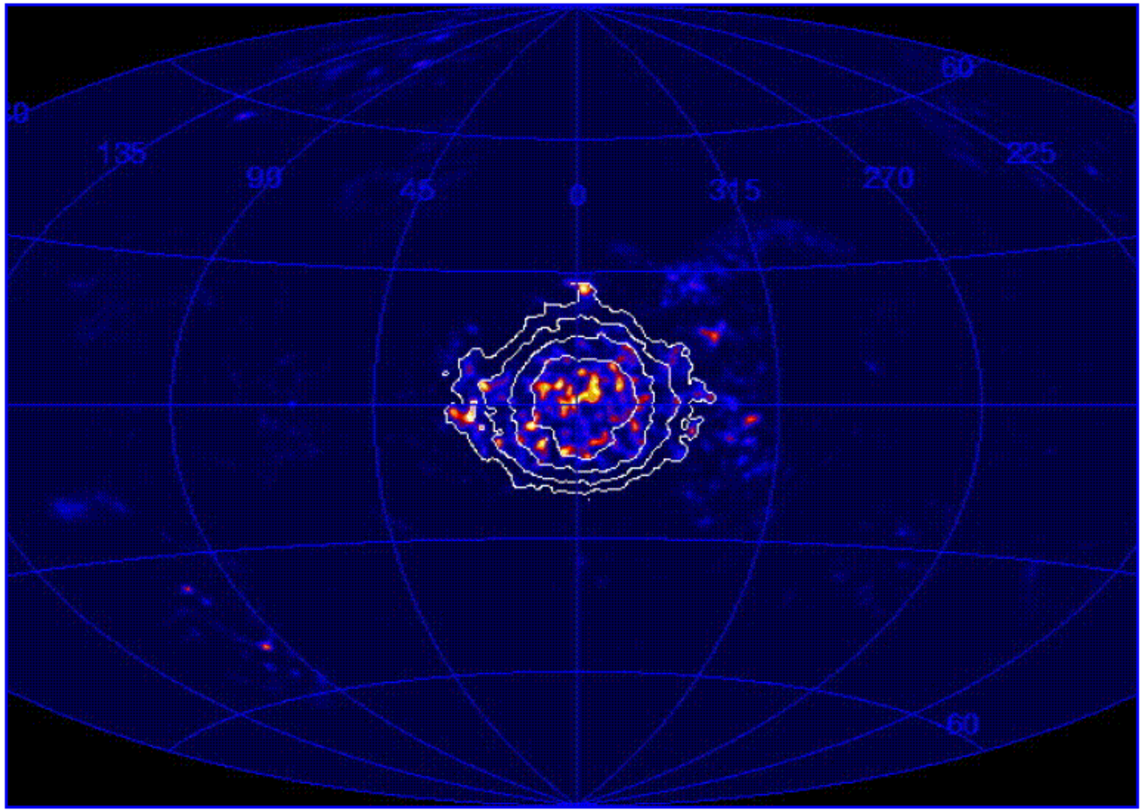

The SPI instrument onboard INTEGRAL has performed a search for 511 keV emission (resulting from positron-electron annihilation) all over the sky. The figure represents the results of this search: the all-sky map in galactic co-ordinates shows that 511 keV emission is - so far - only seen towards the center of our Galaxy. The SPI data are equally compatible with galactic bulge or halo distributions, the combination of a bulge and a disk component, or a combination of a number of point sources. Such distributions are expected if positrons originate either from low-mass X-ray binaries, novae, Type Ia supernovae, or possibly light dark matter.

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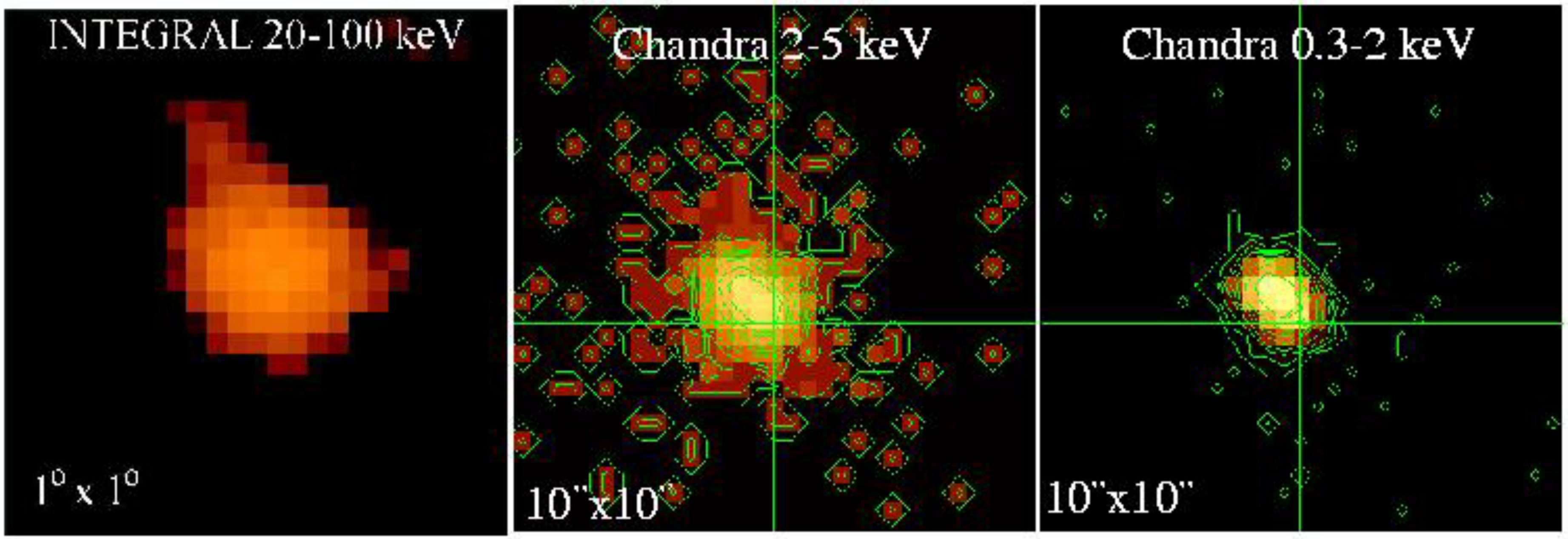

The blazar PKS 1830-211 is one of the most distant objects observed so far by INTEGRAL, it was reported as an ISGRI source in the galactic centre region. The source is clearly detected in 20-100 keV band. The image from IBIS/ISGRI is shown in the left panel. Notwithstanding its high redshift (z=2.507) it is a bright X-ray source, due to gravitational lensing by an intervening galaxy at z=0.89. Radio observations show two compact components separated by about 1 arcsecond; this effect (just at the limit of the angular resolution of Chandra), is clearly visible in the elliptically shaped Chandra images (central and right panels).

By assuming a magnification factor due to the lensing of the order of 10, the bolometric luminosity of PKS 1830-211 is huge: about 10^48 erg/s! The spectrum can be modelled adding an external source of low energy photons scattered up to gamma-ray energies by relativistic electrons. As observed in some high redshift quasars, Chandra spectra of PKS 1830-211 show evidence of absorption below 5 keV (rest frame). This effect could be due either to the lens galaxy at z=0.89 or to an intrinsic warm (ionized) gas at redshift of the source.

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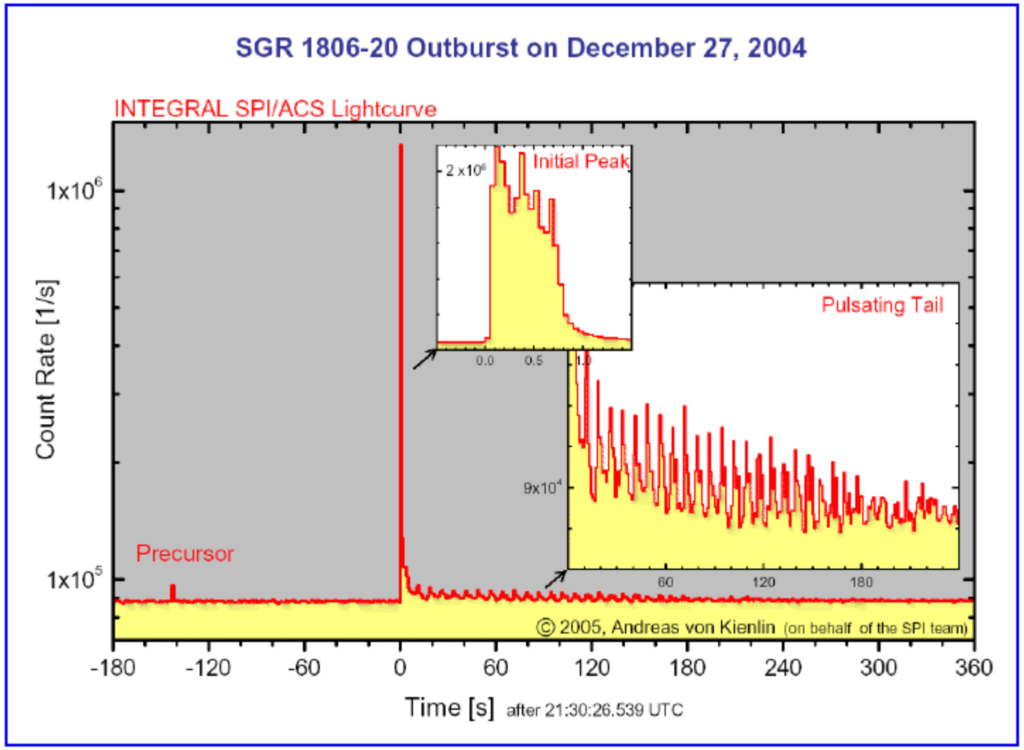

SGR 1806-20 which belongs to the class of soft gamma-ray repeaters (SGR) is believed to be a rotating neutron star with a super-strong magnetic field (10^15 Gauss); a so-called magnetar. The tremendous outburst of SGR 1806-20 on December 27, 2004 as seen by the large anticoincidence shield (ACS) of the INTEGRAL-spectrometer SPI is shown in the figure. The mean veto count rate of the ACS (~88000 counts/s) is interrupted at 21:30:26.539 UTC (T=0) by a steep count-rate increase (about a factor 25) for about 0.7 s. This outburst is thought to be caused by a large-scale rearrangement to a state of lower energy of a magnetar's super-strong magnetic field ($10^{\wedge 15}$ Gauss), which is the current model for soft gamma-ray repeaters. The ~300 s long pulsating tail with a period of 7.56 s is clearly seen and can be explained by a trapped fireball which is co-rotating with the neutron star (magnetar).
The initial peak is proceeded at T= -143 s by a small precursor, which could be shown via triangulation to originate from the position of SGR 1806-20.

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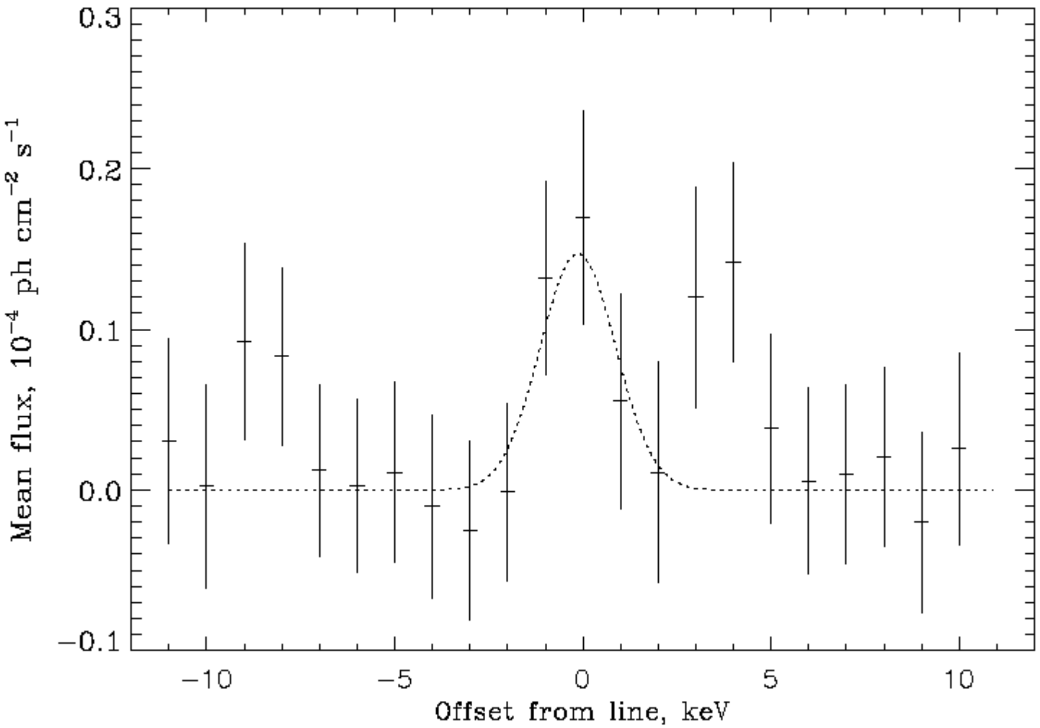

The SPI instrument on board INTEGRAL has observed the ^{60}Fe lines (at 1173 and 1333 keV) from the inner galaxy. The picture shows the combined ^{60}Fe signal from the two lines. The line flux is 3.7 ± 1.1 x 10^5 cm^{-2} s^{-1} per line.

The origin of the iron line is believed to be core-collapse supernovae which seed the interstellar medium with isotopes such as ^{60}Fe. From other SPI measurements of the ^{26}Al line the ratio $^{60}Fe/^{26}Al$ = 0.11 ±0.03 is derived, which is substantially smaller than predictions (0.40) for massive stars. This ratio supports the idea that there is an extra source of ^{26}Al in addition to the core-collapse supernovae.

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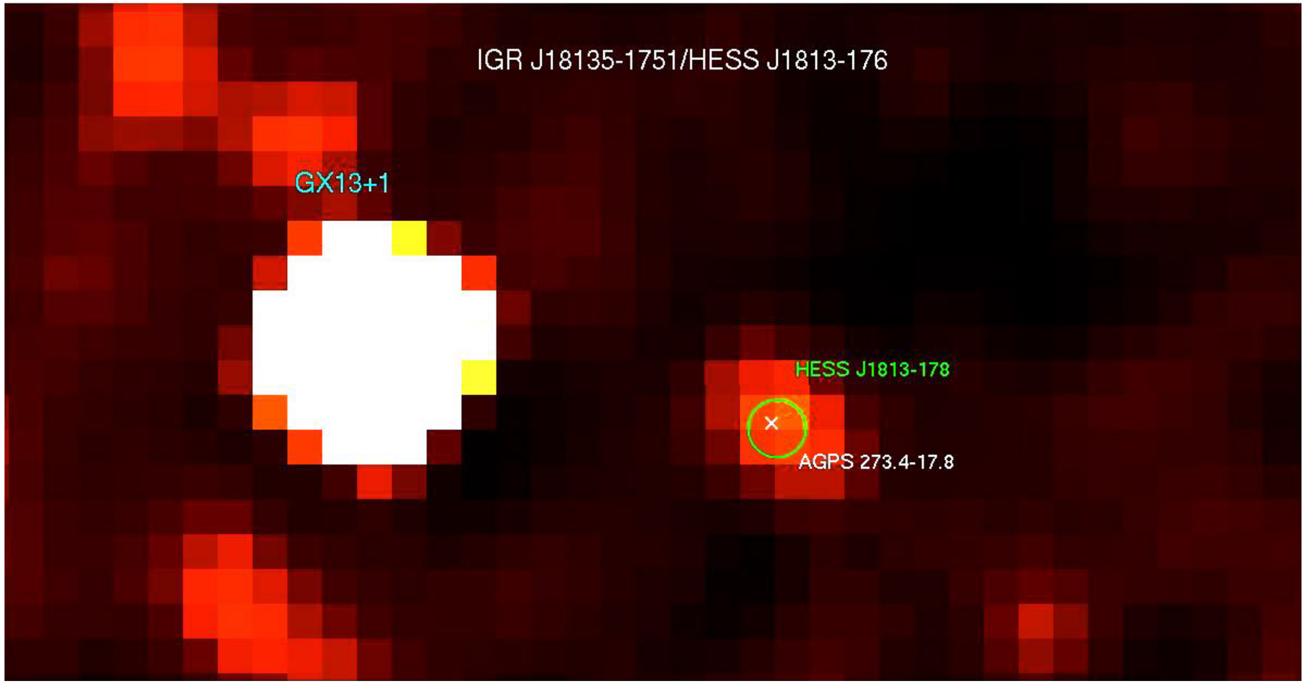

INTEGRAL has discovered, using the IBIS instrument, a new gamma-ray source (IGR J18135-1751). This source is remarkable, since it coincides spatially with one of the ten objects which have been seen during the first survey at TeV energies of the inner part of the galaxy: HESS J1813-178. This source is a powerful ultra-high energy emitter in the 0.2-10 TeV range. The X-ray counterpart (AGPS273.4-17.8) of the INTEGRAL source has an absorbed spectrum and is thought to be either a pulsar wind nebula or a supernova remnant. This picture shows the IBIS/ISGRI 20-100 keV image of IGR J18135-1751 as well as the position of HESS J1813-178 (green circle) and AGPS273.4-17.8 (white cross). The white spot on the left is the saturated image of the bright LMXB GX 13+1.

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The central regions of our Galaxy, the Milky Way, as seen by INTEGRAL in gamma rays. With its superior ability to see faint details, INTEGRAL reveals the individual sources that comprised the foggy, soft gamma-ray background seen by previous observatories. The brightest 91 objects seen in this image were classified by INTEGRAL as individual sources, while the others appear too faint to be properly characterized at this stage.

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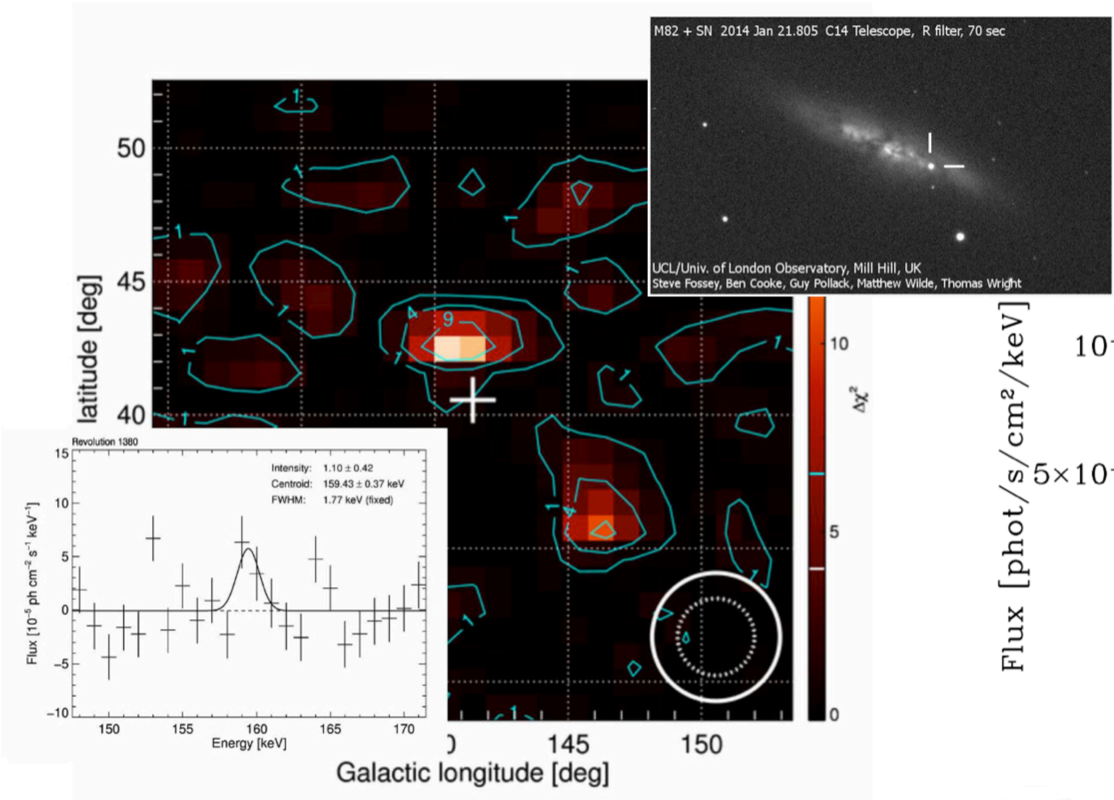

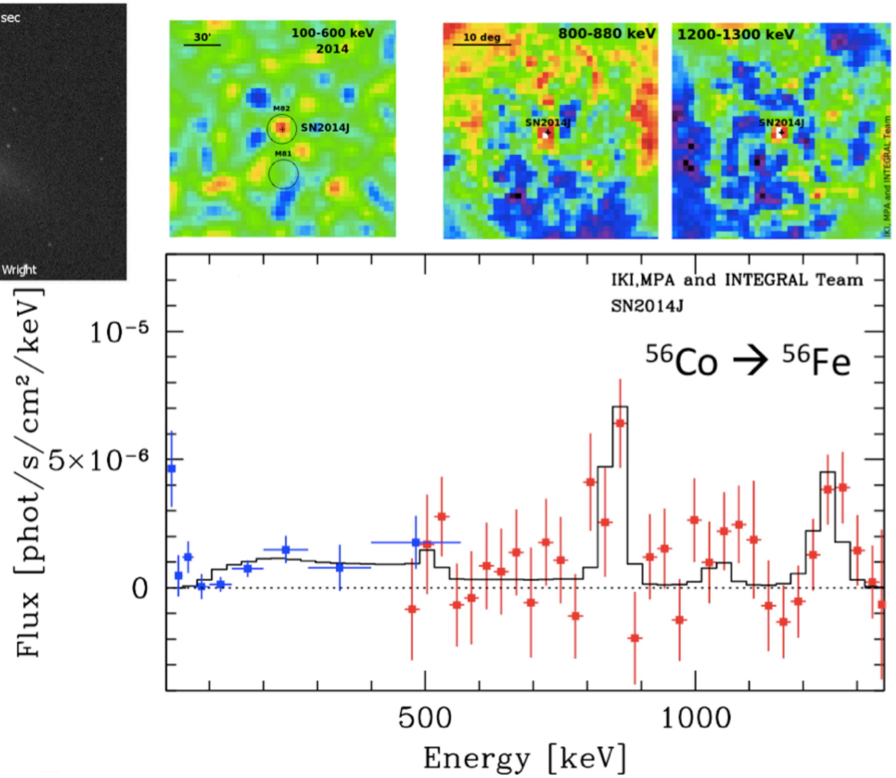

INTEGRAL for the first time, confirms by direct measurement of the primary gamma-ray lines the ^{56}Ni origins of SN light. The INTEGRAL measurements of this sufficiently-nearby SN provide a unique opportunity to compare the direct gamma-rays from the SN's energy source with the more-indirect other radiation. This will help astrophysicists to refine their models on how in fact these explosions do occur, because the explosion details affect how much new nuclei are created, and how they move and interact with the remainder of the exploding star. These observations constitute a reference in SNIa science, and thus an important scientific legacy for years to come.

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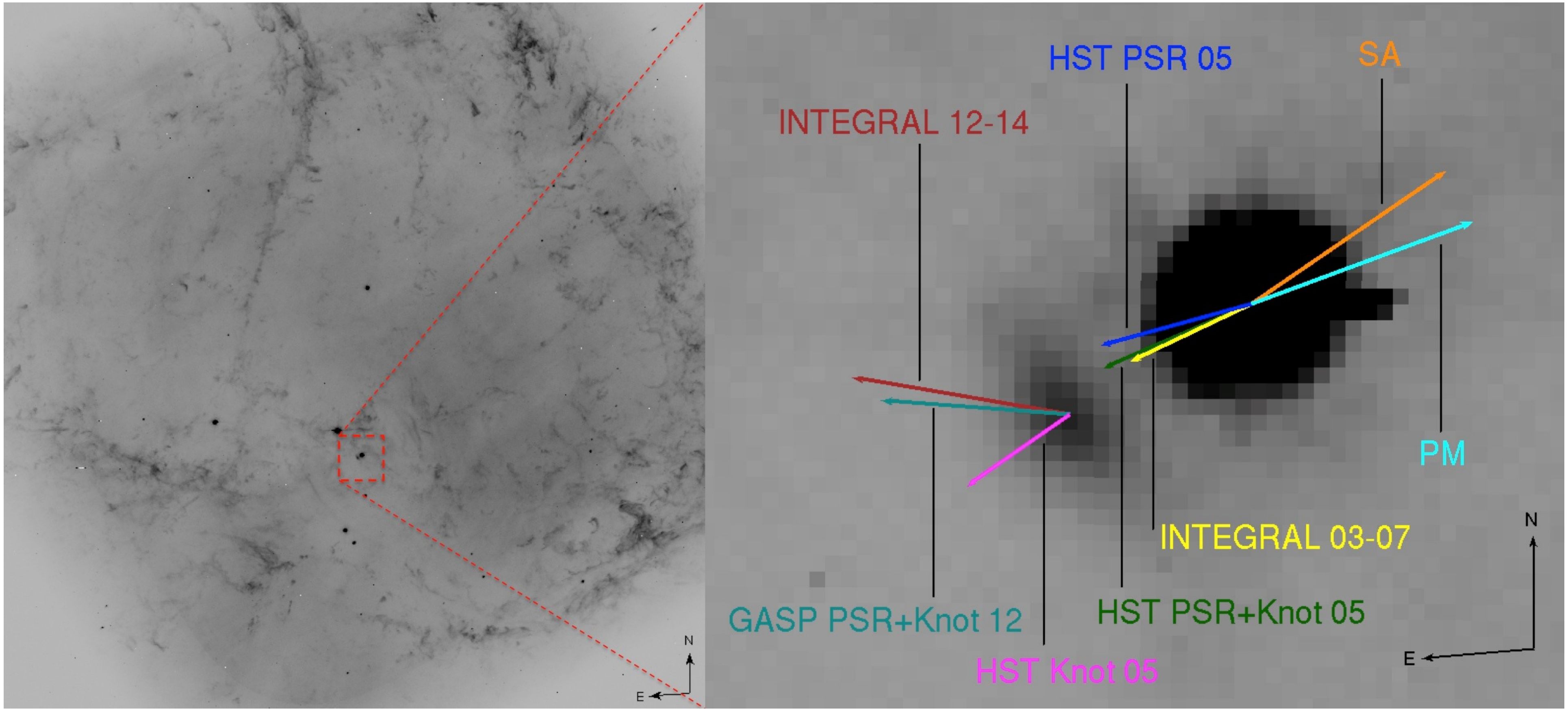

On the left, this HST image shows the inner part of the Crab nebula with the Crab pulsar and its near-by knot located 0.65" (1300 AU) south-east of the pulsar inside the red box. On the right, a zoomed view of the image is shown. The arrows indicate at different periods in time the polarization angle in the optical (HST in 2005 and GASP in 2012) and in hard X-rays (Integral in the period 2003-2007 and 2012-2014). Also indicated are the directions of the proper motion (PM) and spin axis (SA) of the pulsar.