Gamma ray bursts

1. **Cavity Detection**

- Centaurus - broad, soft, hard (inc. source-filled)
- Sanders et al. 2016, CADET, Allen et al. 2006
- unsharp masking / beta modelling / CADET (one or more methods)
- students will get kT, ne profiles -> E, Pjet

2. **Supernova remnant**

- SN1006, Winkler et al. 2014
- CIAO -> fluximages (2003, 2012)
- expansion rate using DS9 / astropy
- narrow band images -> metal distribution

3. **GRB properties**

- GRB230307,
- data from GRBalpha, VZLUSAT2
- orientation, T90, HR
- neutron star collision -> kilonova

4. **Spectral fitting - thermal (cluster)**

- Centaurus, Sanders et al. 2006
- real Chandra data
- estimate temperature (1T, 2T, 3T, gdem) & metallicity

5. **Spectral fitting - thermal (XRISM)**

- Perseus, XRISM spectrum, SPEX / Xspec
- velocity broadening, redshift, temperature, metallicity

6. **Spectral fitting - deprojection (giant elliptical)**

- NGC4649, real Chandra data,
- deproject (Sherpa)
- kT, ne, P, K, M(<r)

7. **Spectral fitting - non-thermal (AGN)**

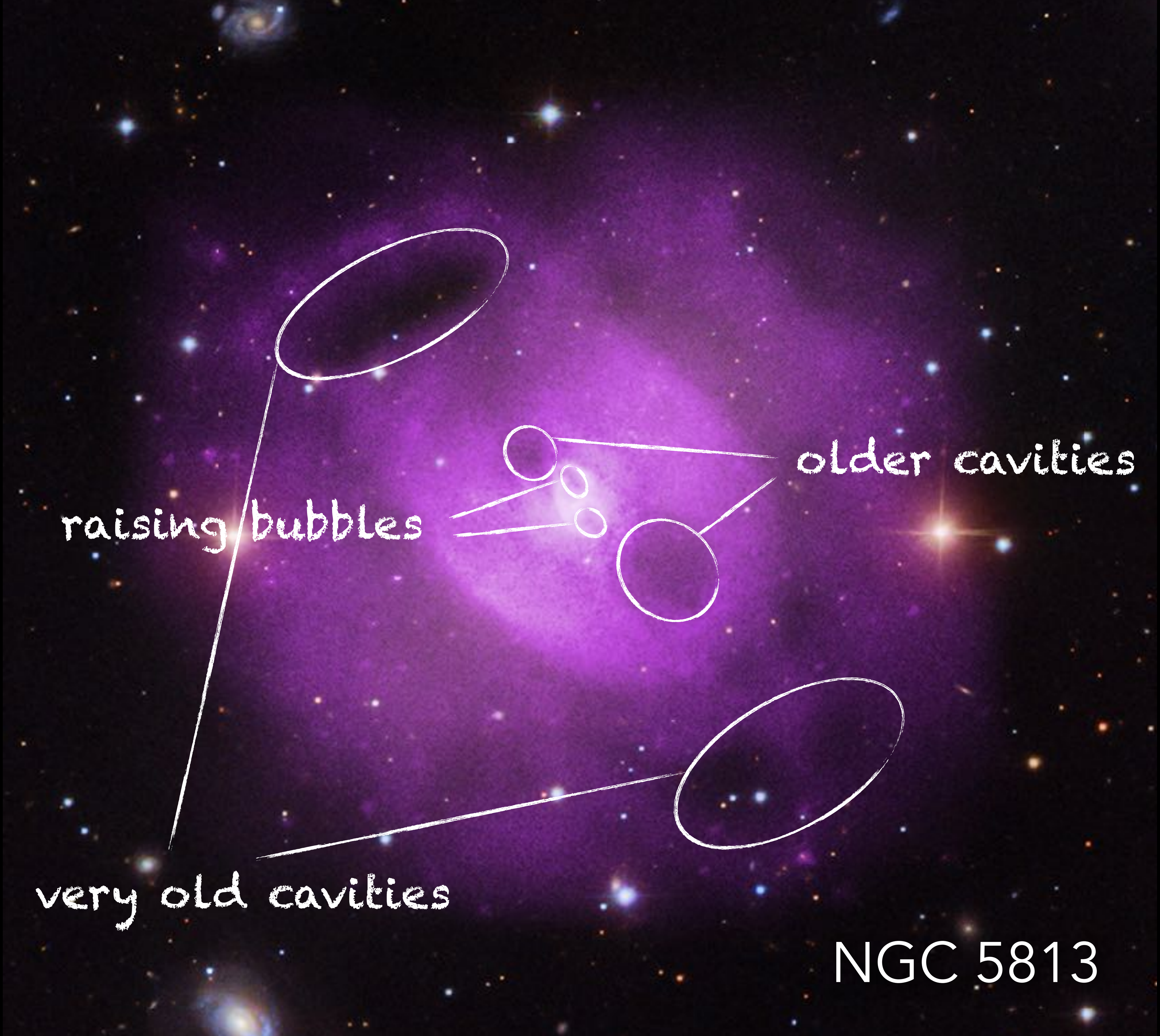
- simulated data, SPEX
- compton-thin AGN - powerlaw with AGN wind
- estimate nH, phoindex, wind parameters
-

Cavity Detection

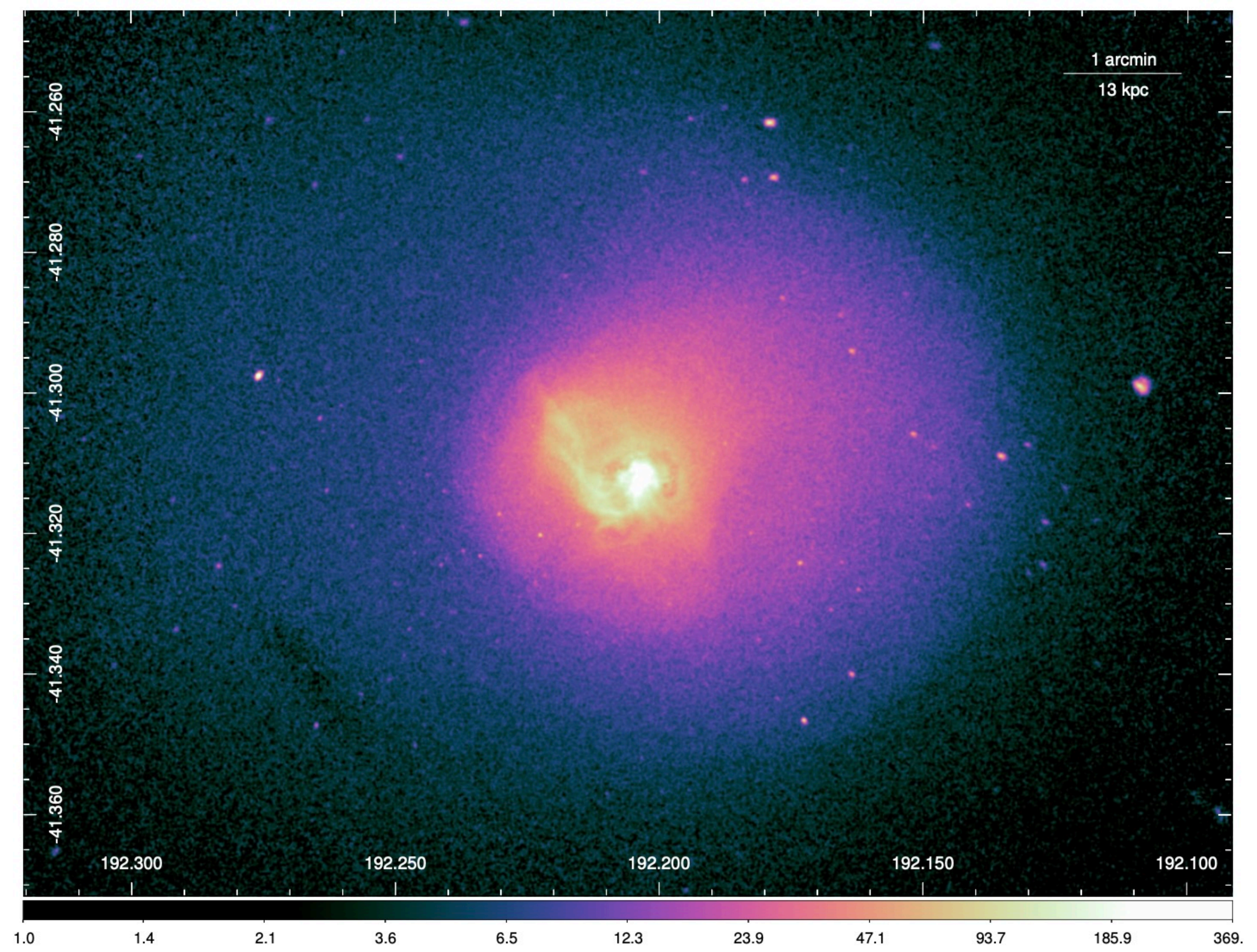
NGC 5813

NGC 5813

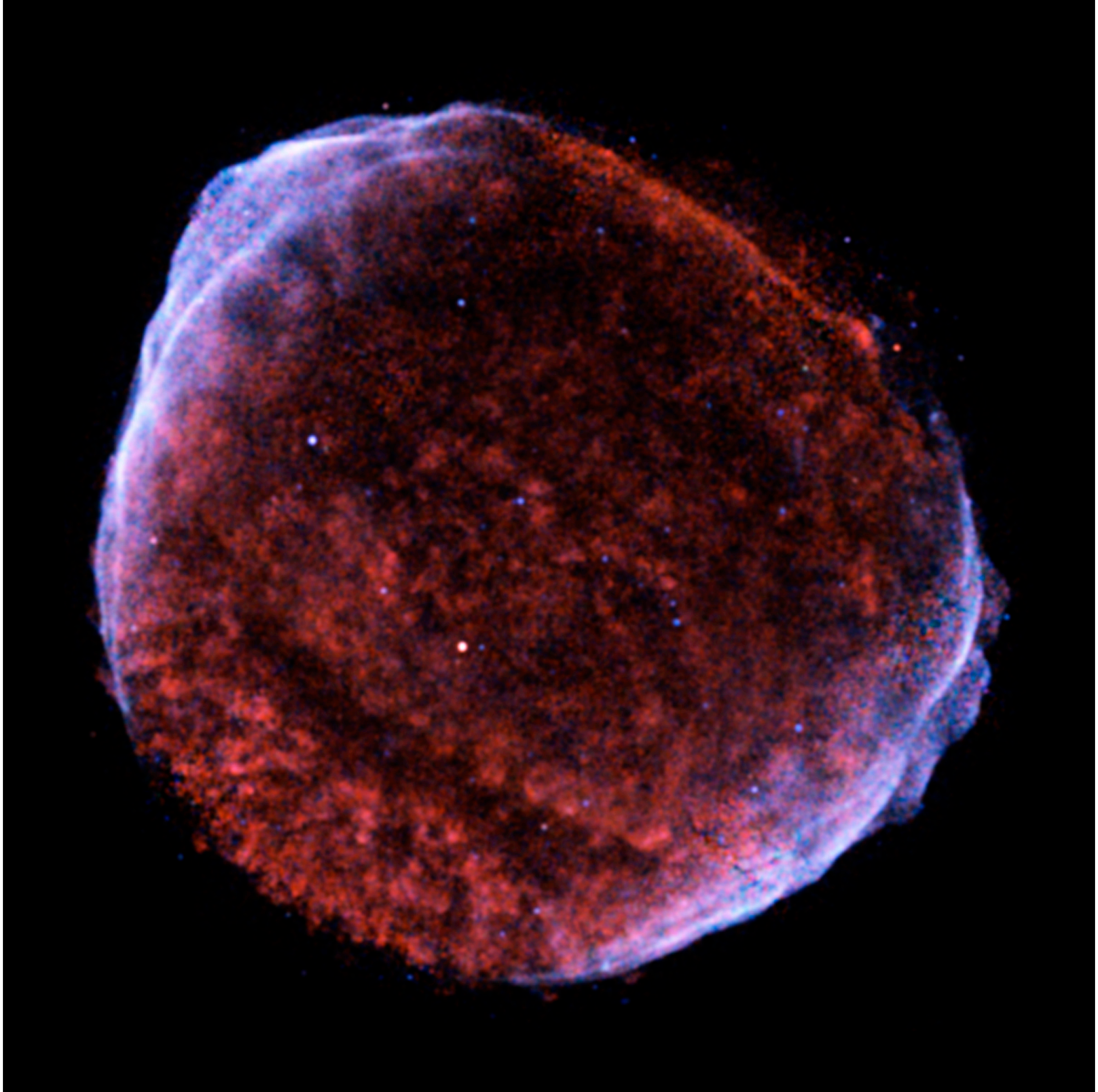
NGC 5813



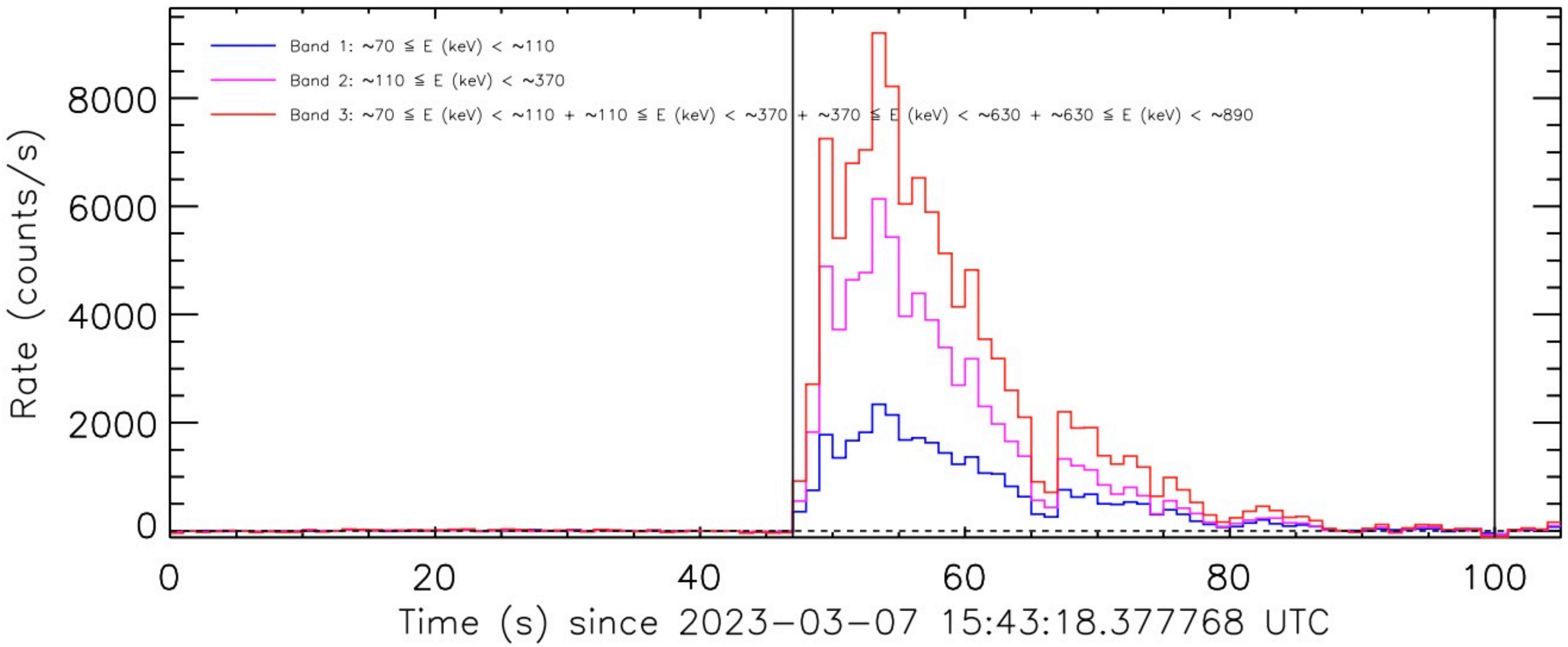
NGC 5813


1 arcmin
13 kpc
-41.260
-41.280
-41.300
-41.320
-41.340
-41.360
192.300
192.250
192.200
192.150
192.100
1.0
1.4
2.1
3.6
6.5
12.3
23.9
47.1
93.7
185.9
369.

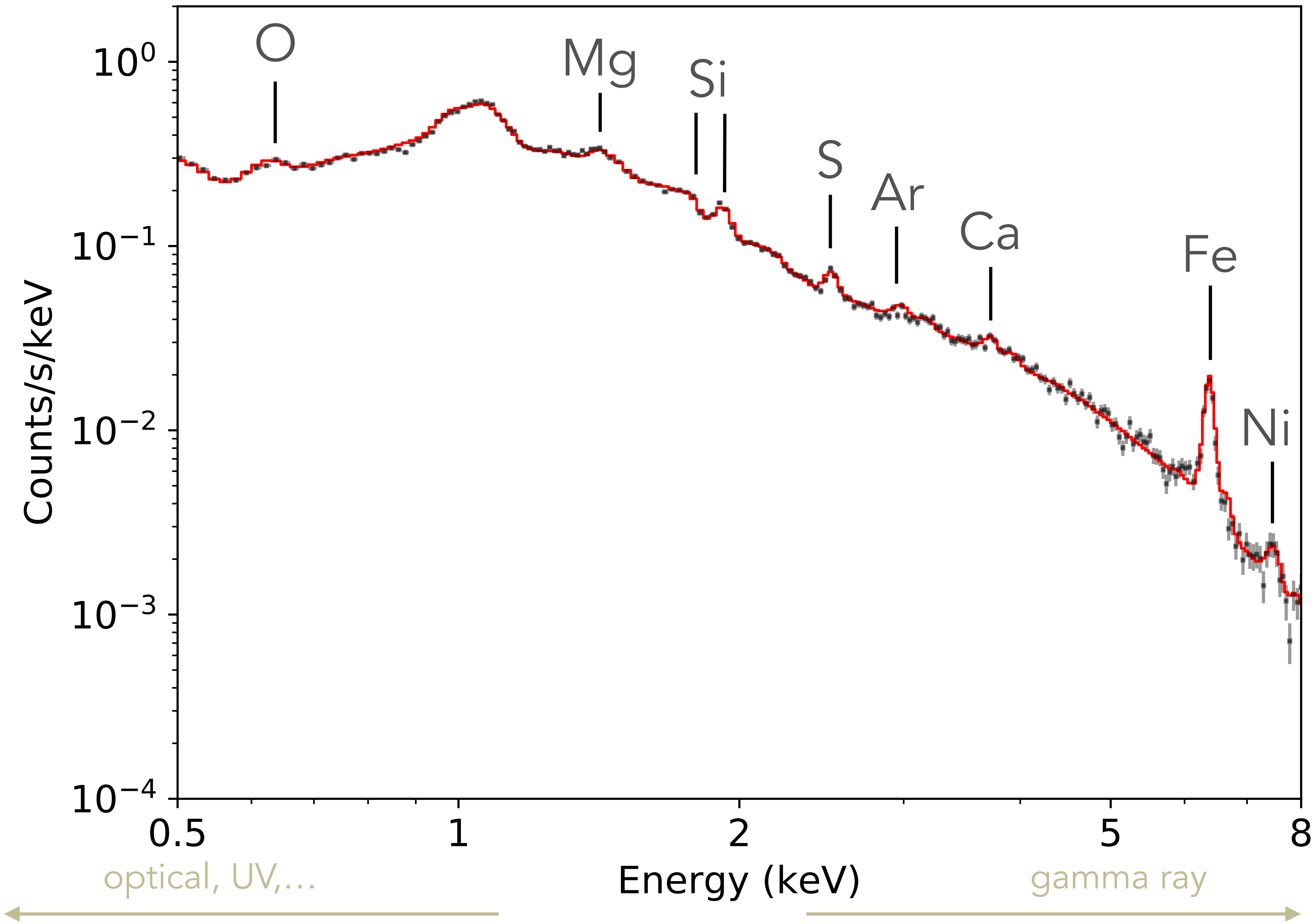
Supernova remnant



GRB properties

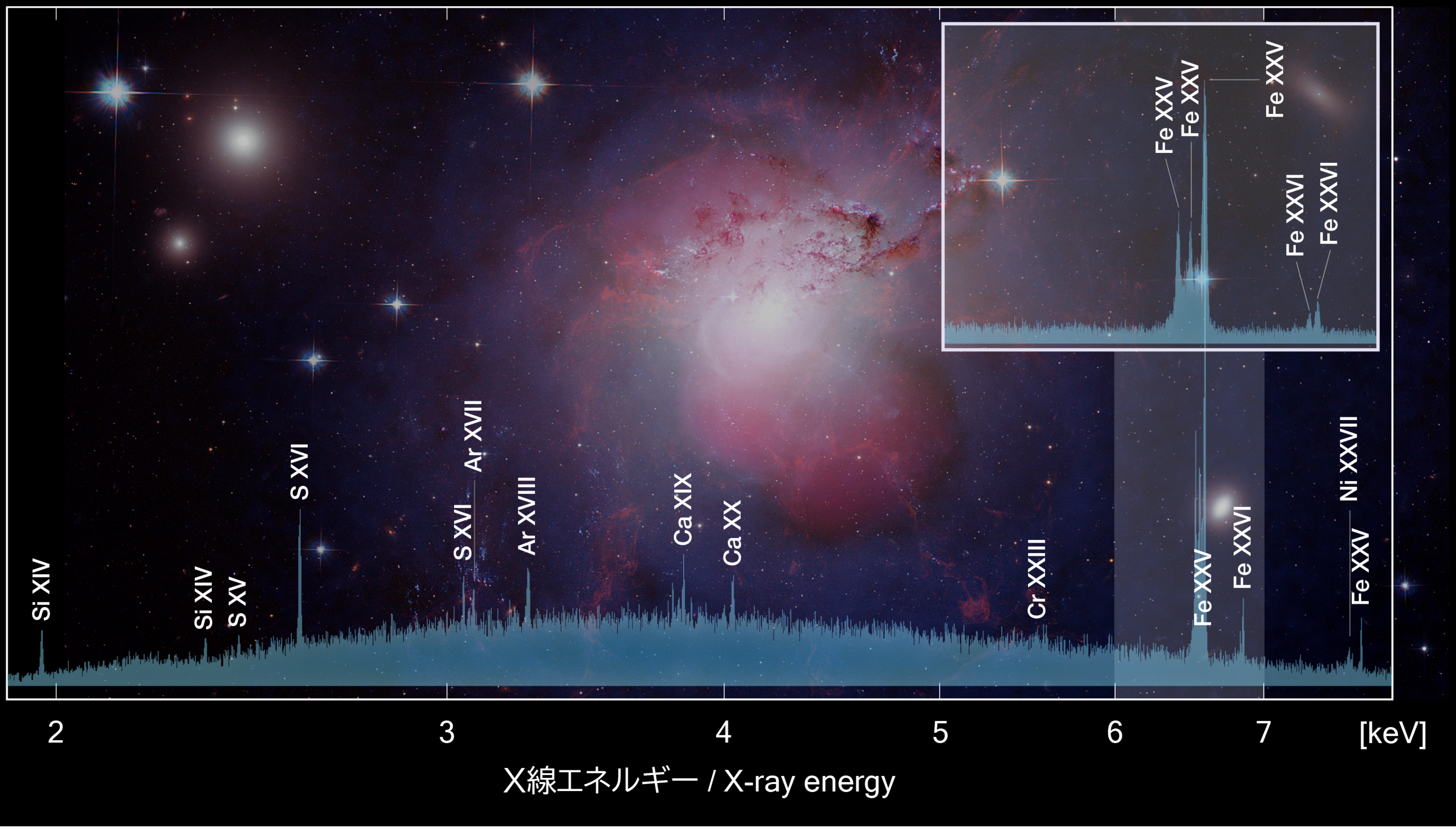

Band 1: ~70 ≦ E (keV) < ~110
Band 2: ~110 ≦ E (keV) < ~370
Band 3: ~70 ≦ E (keV) < ~110 + ~110 ≦ E (keV) < ~370 + ~370 ≦ E (keV) < ~630 + ~630 ≦ E (keV) < ~890
Rate (counts/s)
0
2000
4000
6000
8000
0
20
40
60
80
100
Time (s) since 2023-03-07 15:43:18.377768 UTC

Spectral fitting of a galaxy cluster


O
Mg
Si
S
Ar
Ca
Fe
Ni
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Counts/s/keV
0.5
1
2
5
8
Energy (keV)
optical, UV,…
gamma ray

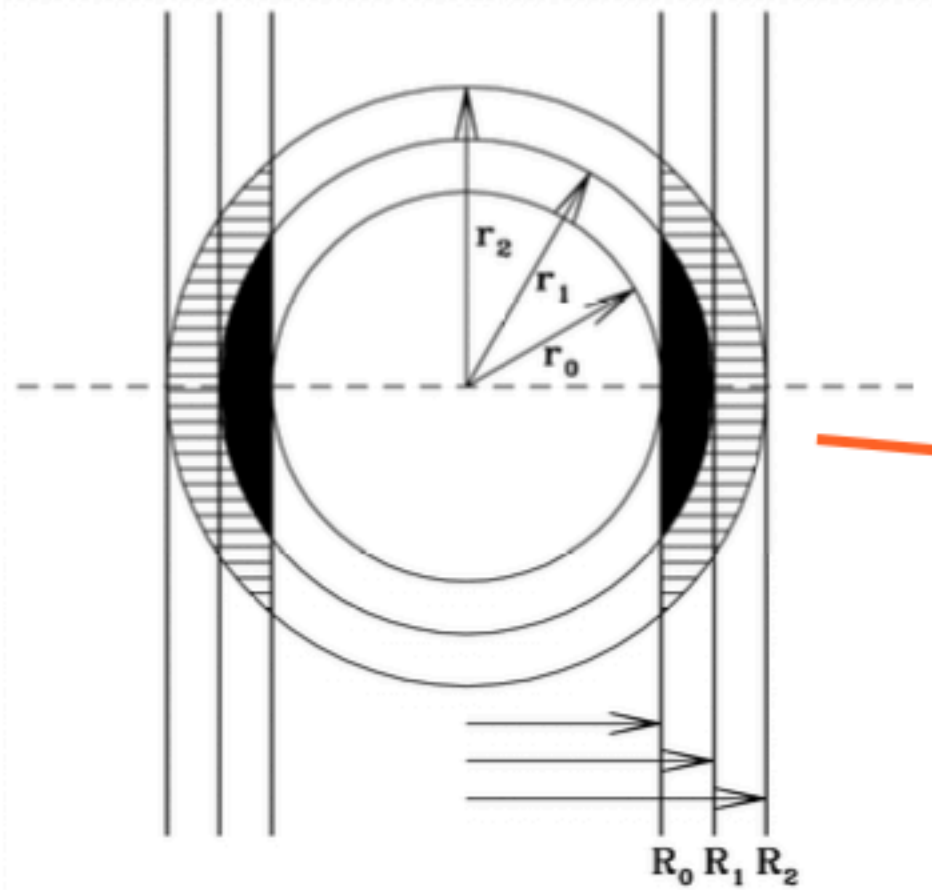
High-resolution spectrum of a galaxy cluster

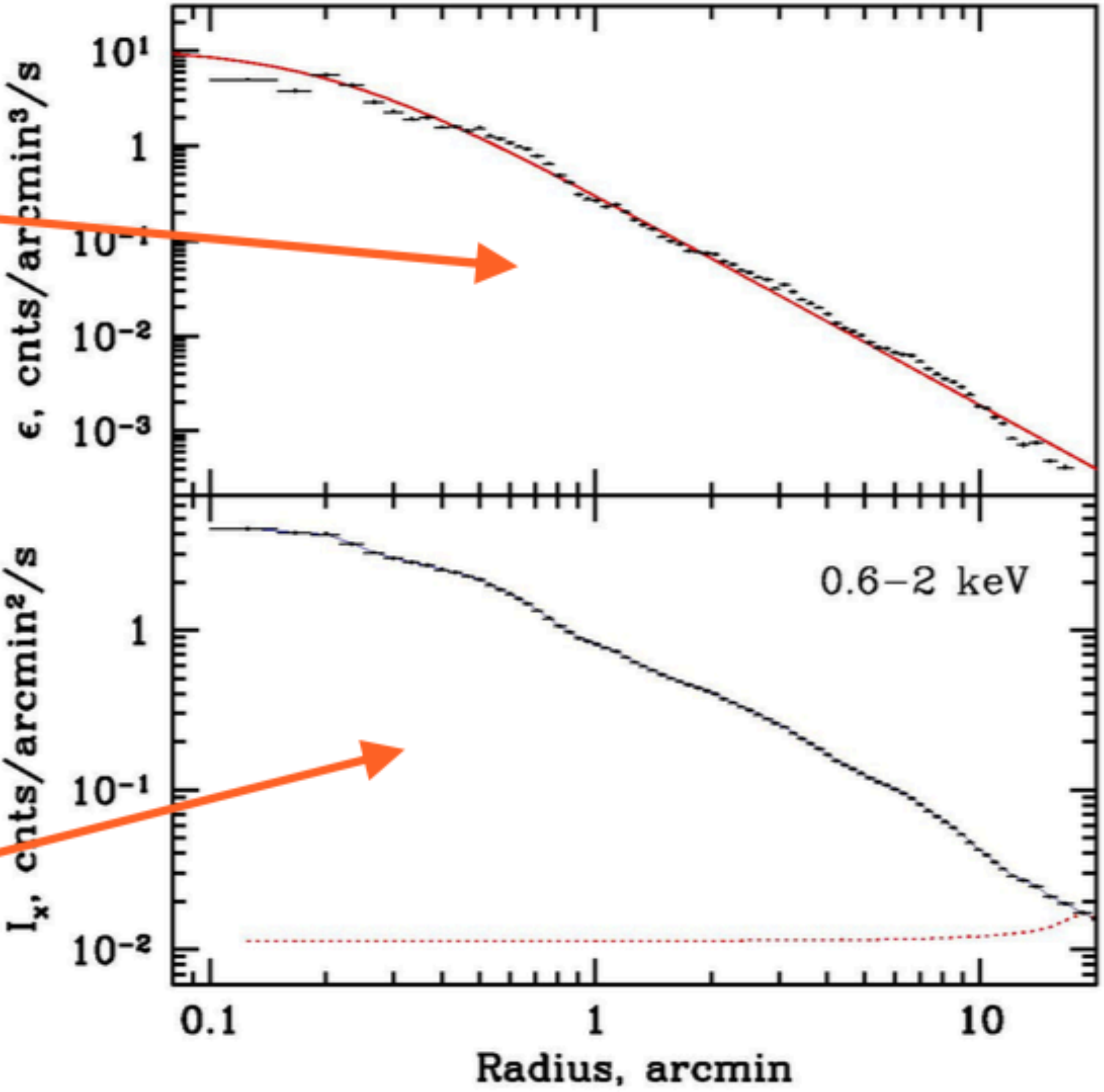
X-ray Spectrum of Perseus Galaxy Cluster Measured by ***XRISM Resolve***

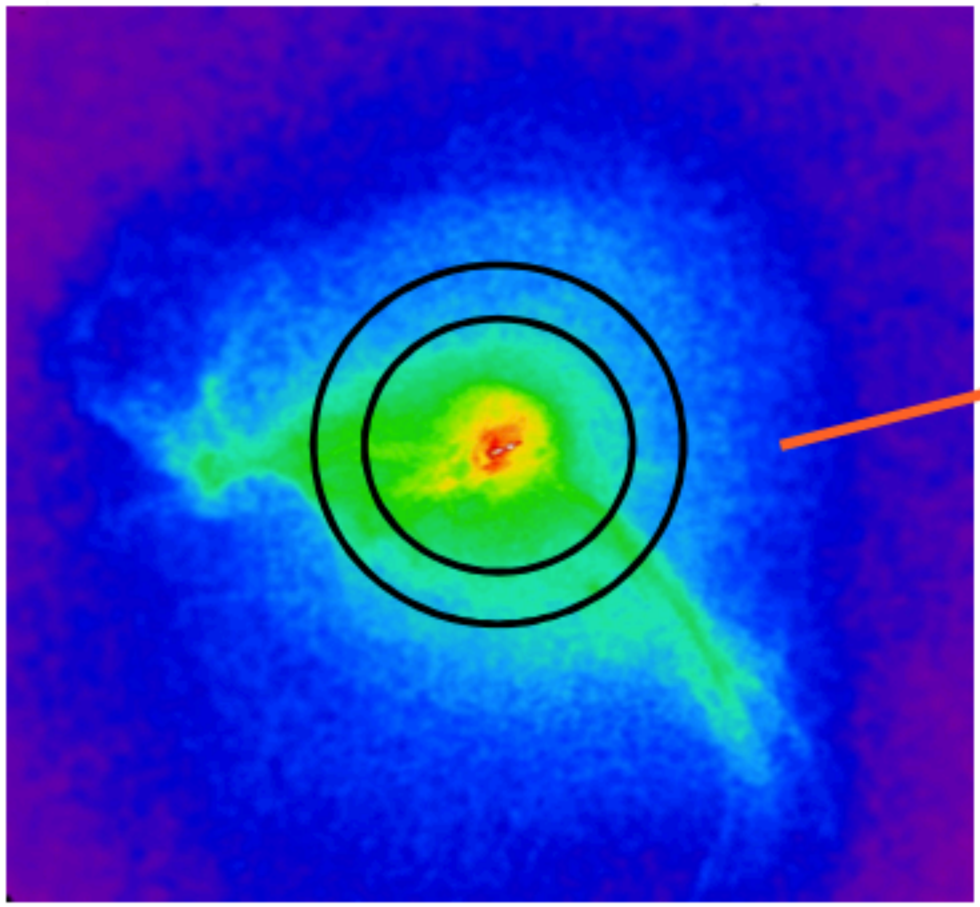


Spectral deprojection of an elliptical galaxy

Deprojection of X-ray data







Repeat the same exercise at all energies

$\varepsilon(r,E)=n(r)^2 S(E,T(r))$

Spectral fitting of an AGN

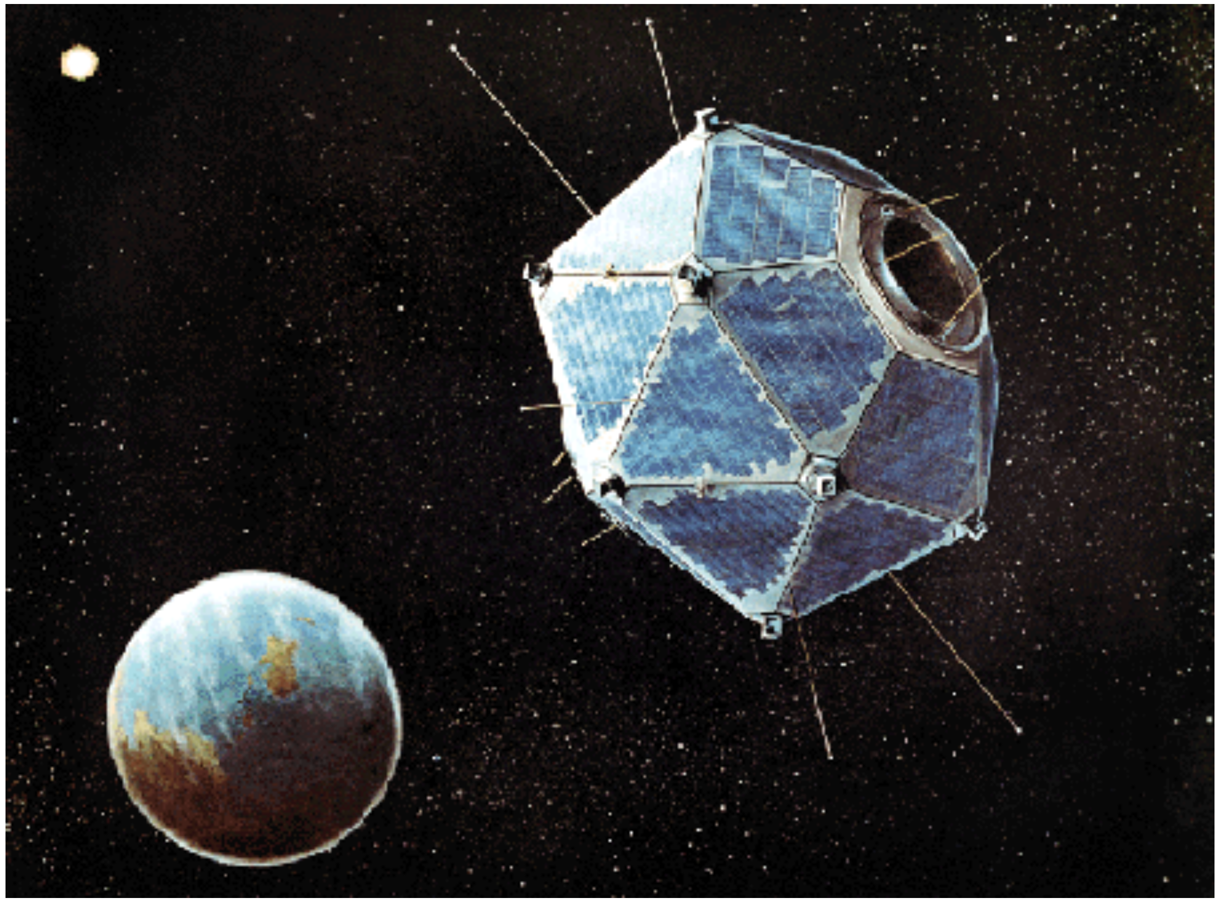
The discovery of gamma ray bursts

- discovered in 1967 by the VELA satellites monitoring the nuclear test ban treaty

- nuclear explosion in space produces X-rays, gamma rays, and neutrons (no visible radiation or sound)

- orbits at altitude of 100,000 km (to be outside radiation belts and to detect detonations behind the Moon!)

- “*16 gamma-ray bursts of cosmic origin*” published in 1973 (Klebasadel et al. 1973, ApJ, 182, L85)

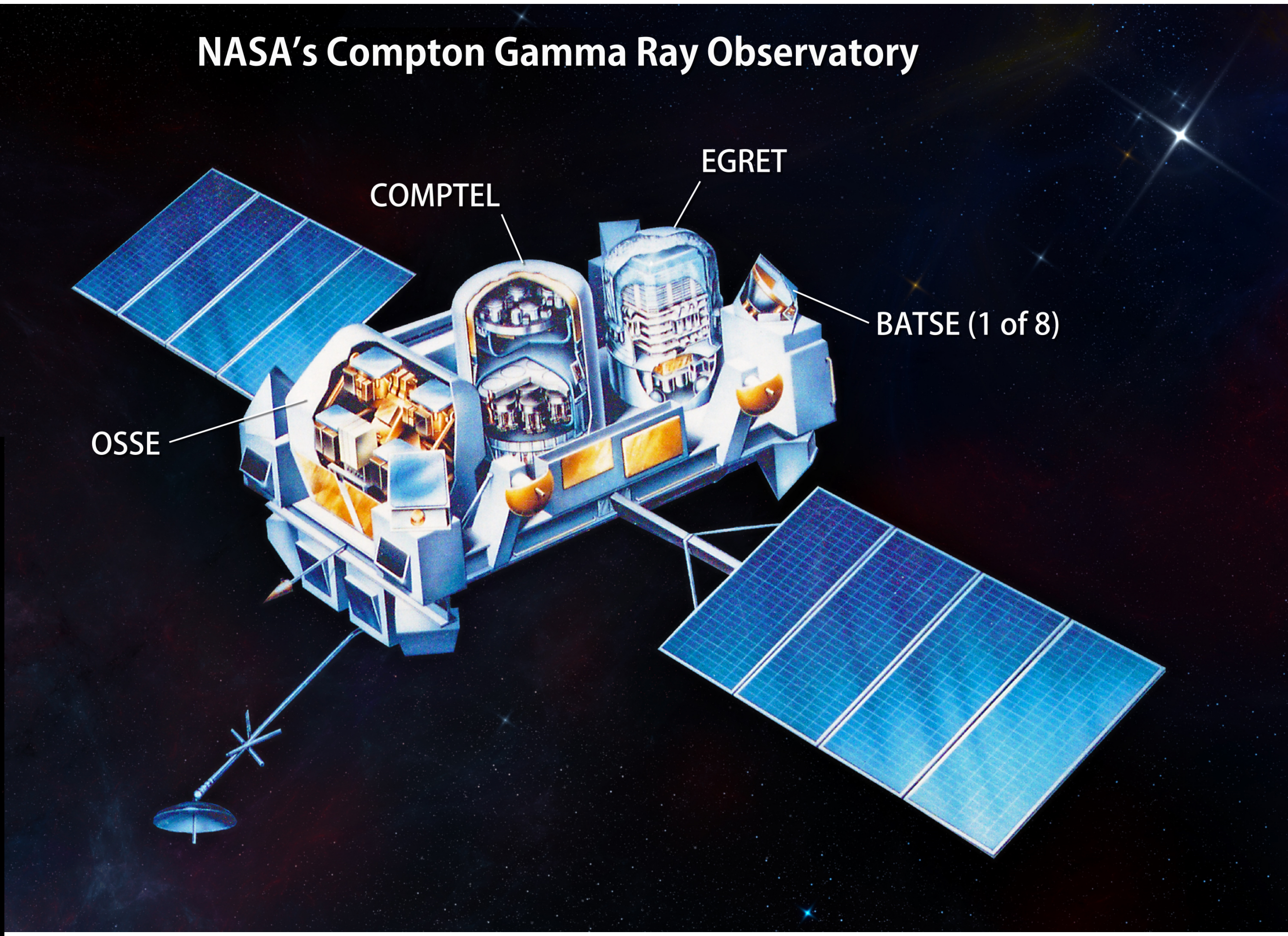


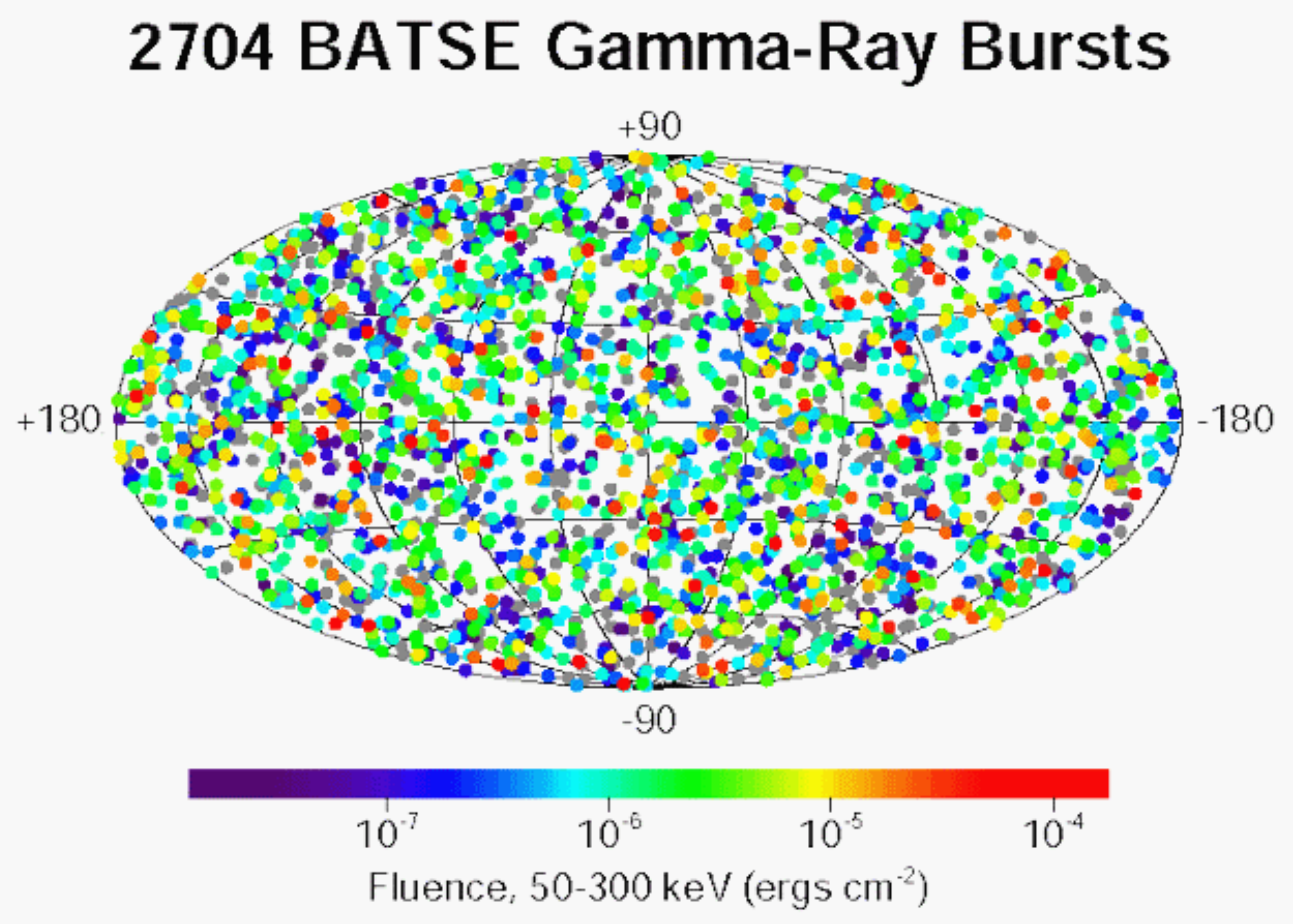
The discovery of gamma ray bursts

- many different ideas and models about their origin, perhaps more than the number of GRBs
- light curves vary on time scales of $\Delta t \sim 1\text{ms}$
- *D* < cΔt ~ 300 km —> explosions must involve a compact object
- the consensus at the end of 1980s was that GRBs originate in our Galaxy

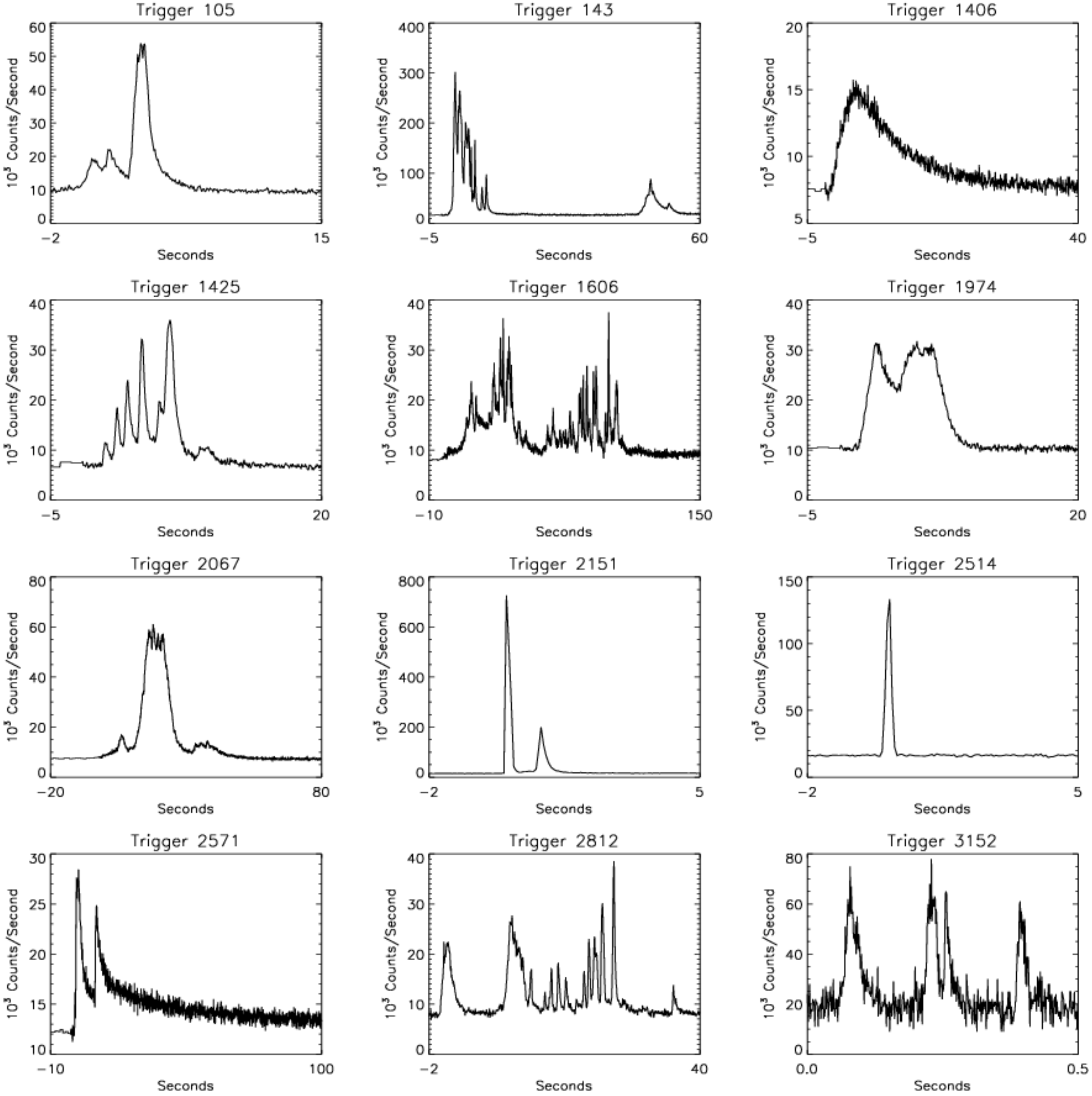
The Compton Gamma-Ray Observatory

Burst and Transient Source Experiment (BATSE)





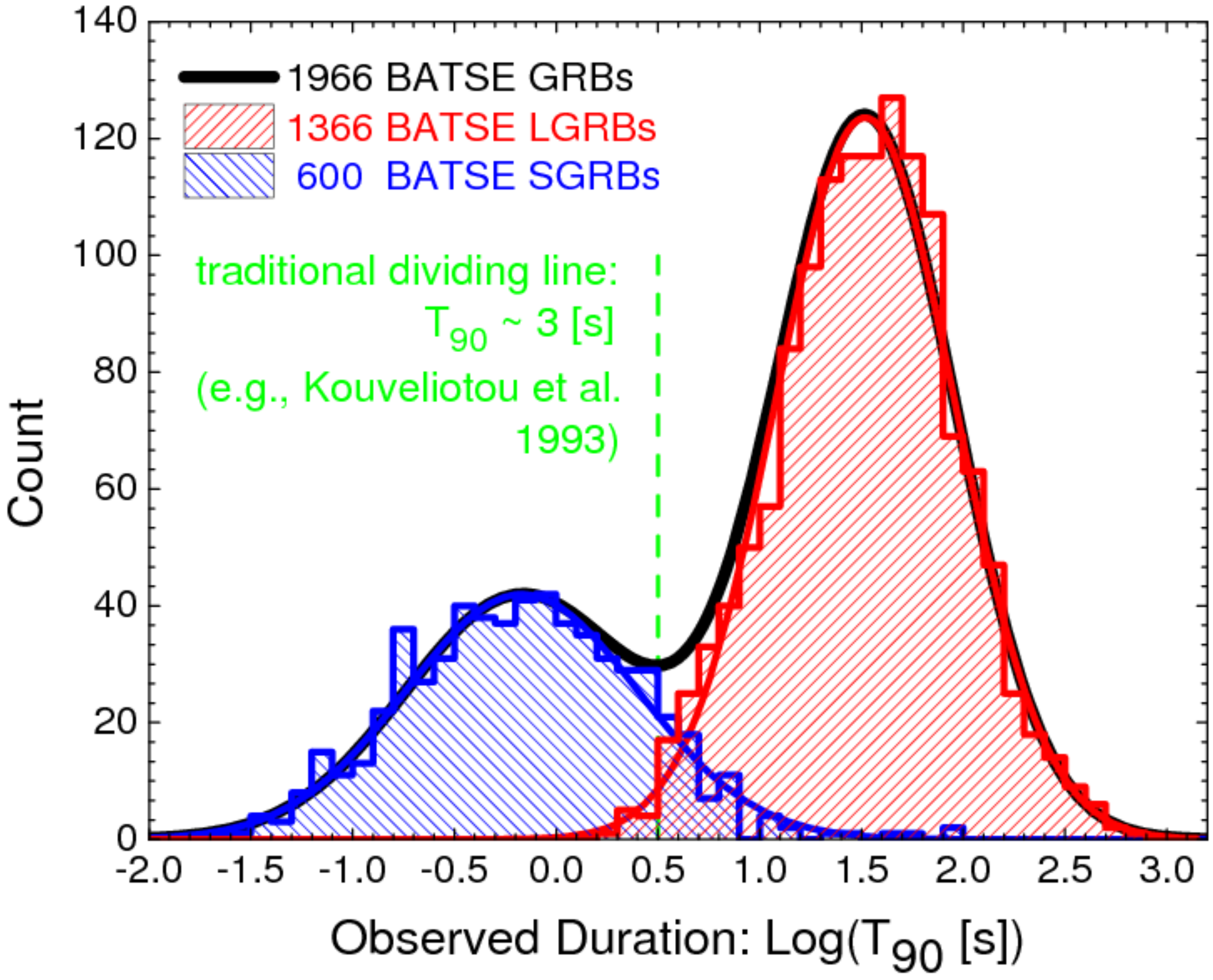
Gamma Ray Bursts distributed isotropically

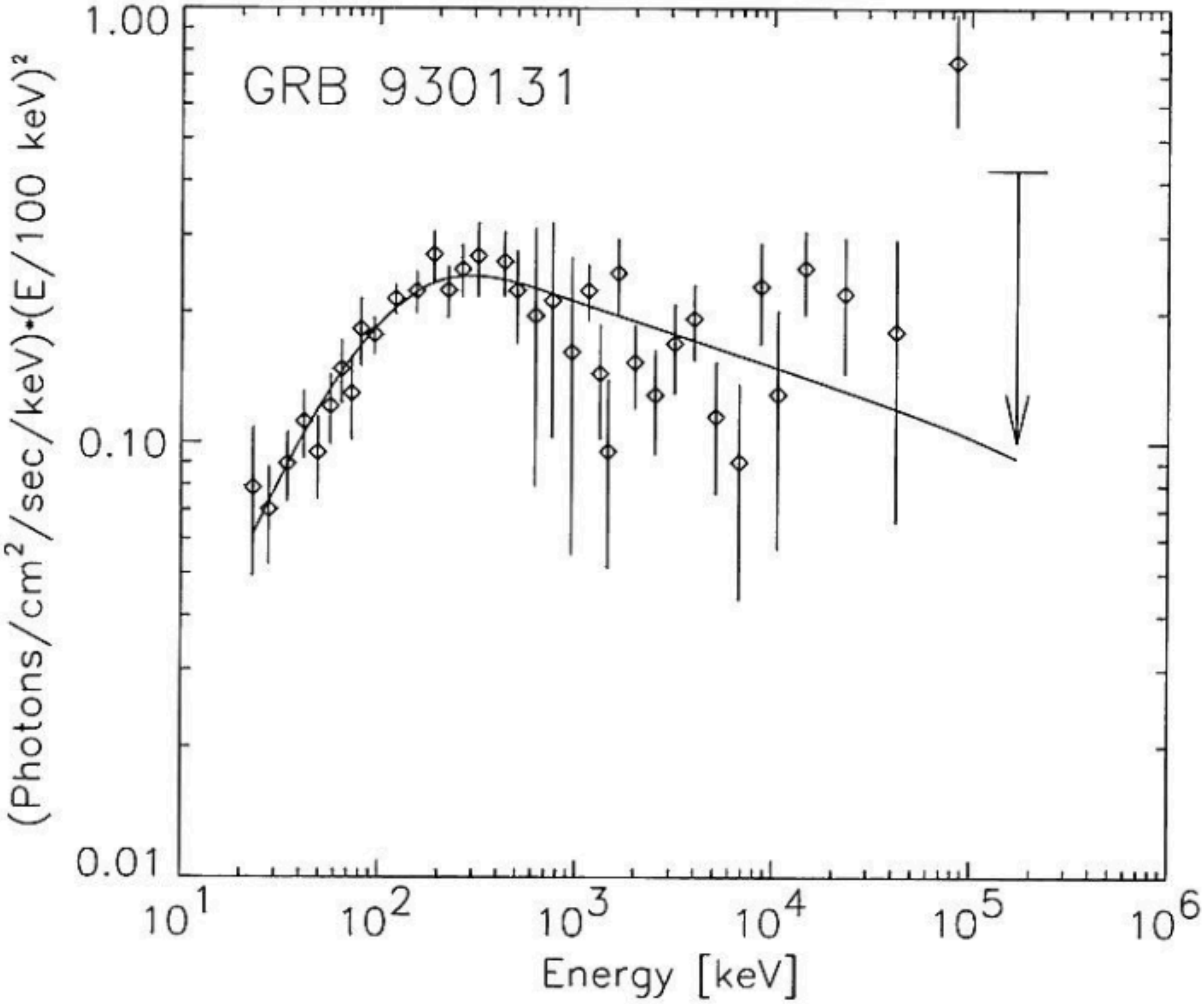


Large diversity of bursts

Two flavors of GRBs

- short GRBs with a duration of a fraction of a second
- long GRBs lasting ~ 10s of seconds
- dividing line T_{90}~3s (T_{90} contains 90% of the counts)



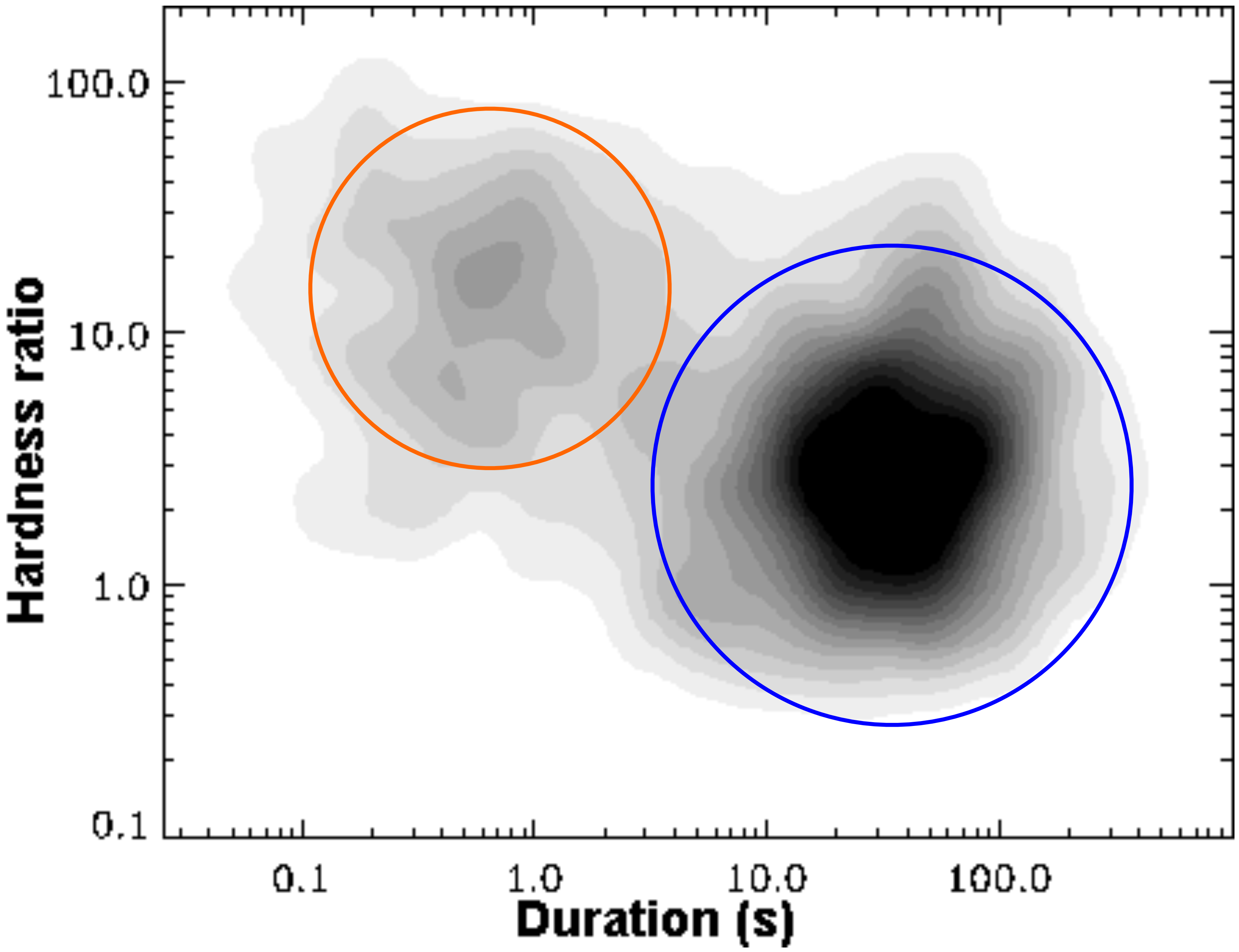

GRB 930131
(Photons/cm²/sec/keV)•(E/100 keV)²
1.00
0.10
0.01
10¹
10²
10³
10⁴
10⁵
10⁶
Energy [keV]

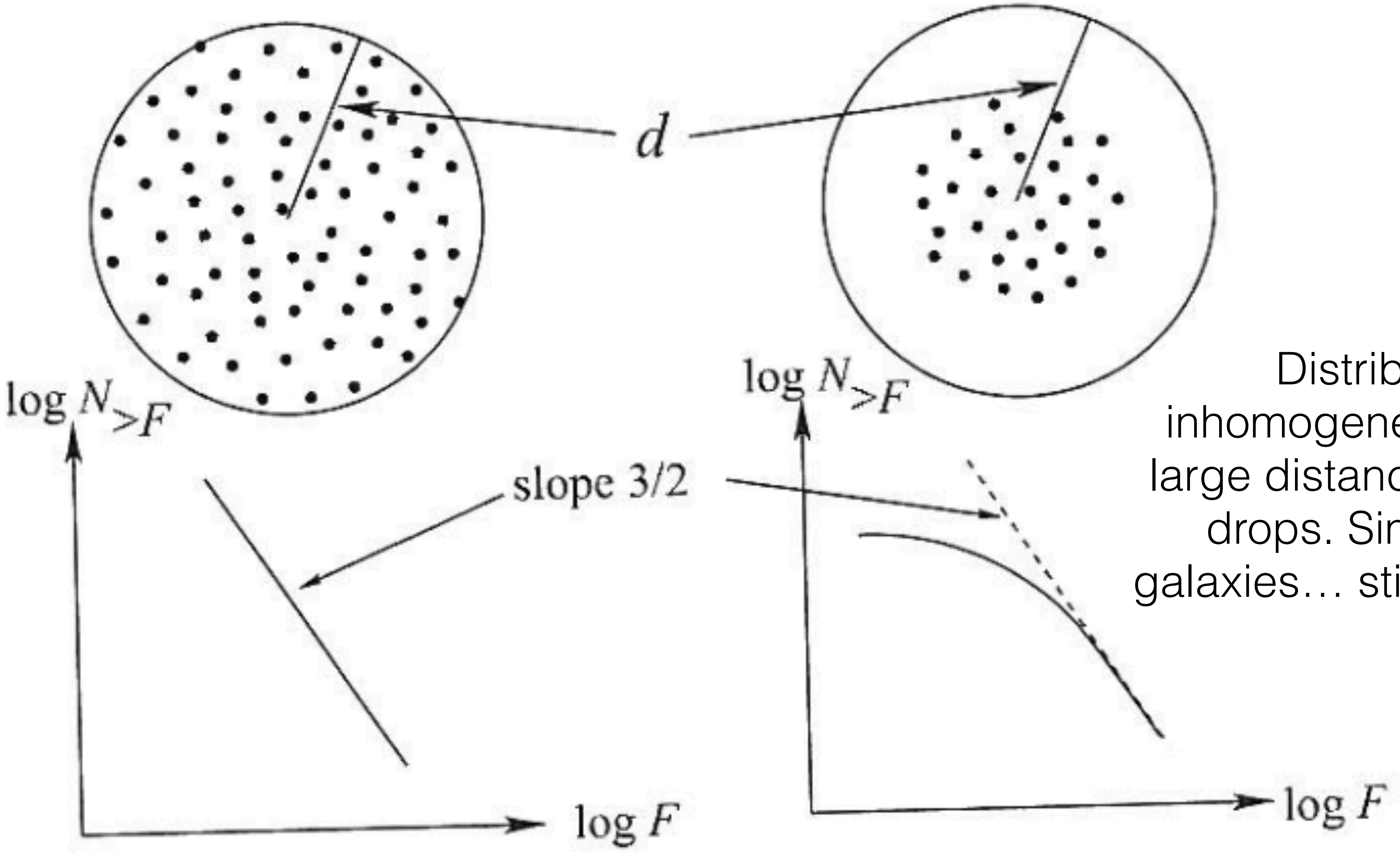
Two flavors of GRBs

Hardness ratio = *count rate* (hard) / *coun trate* (soft)

hard: 100—300 keV
soft: 50—100 keV

Long/soft
Short/hard



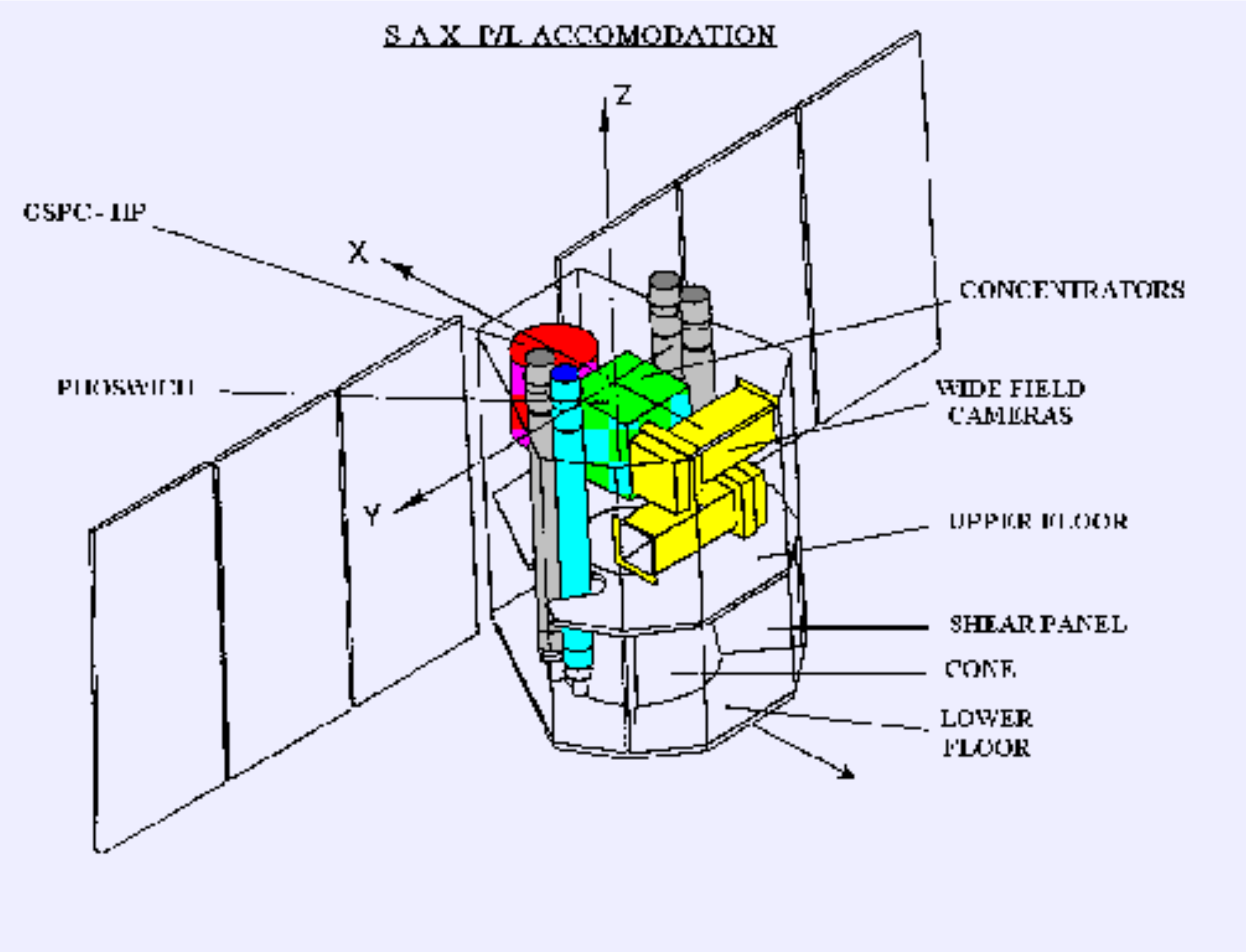


Distribution is isotropic, but inhomogeneous. Homogeneous out to large distance, then the number density drops. Similar to the distribution of galaxies… still Galactic halo not ruled out

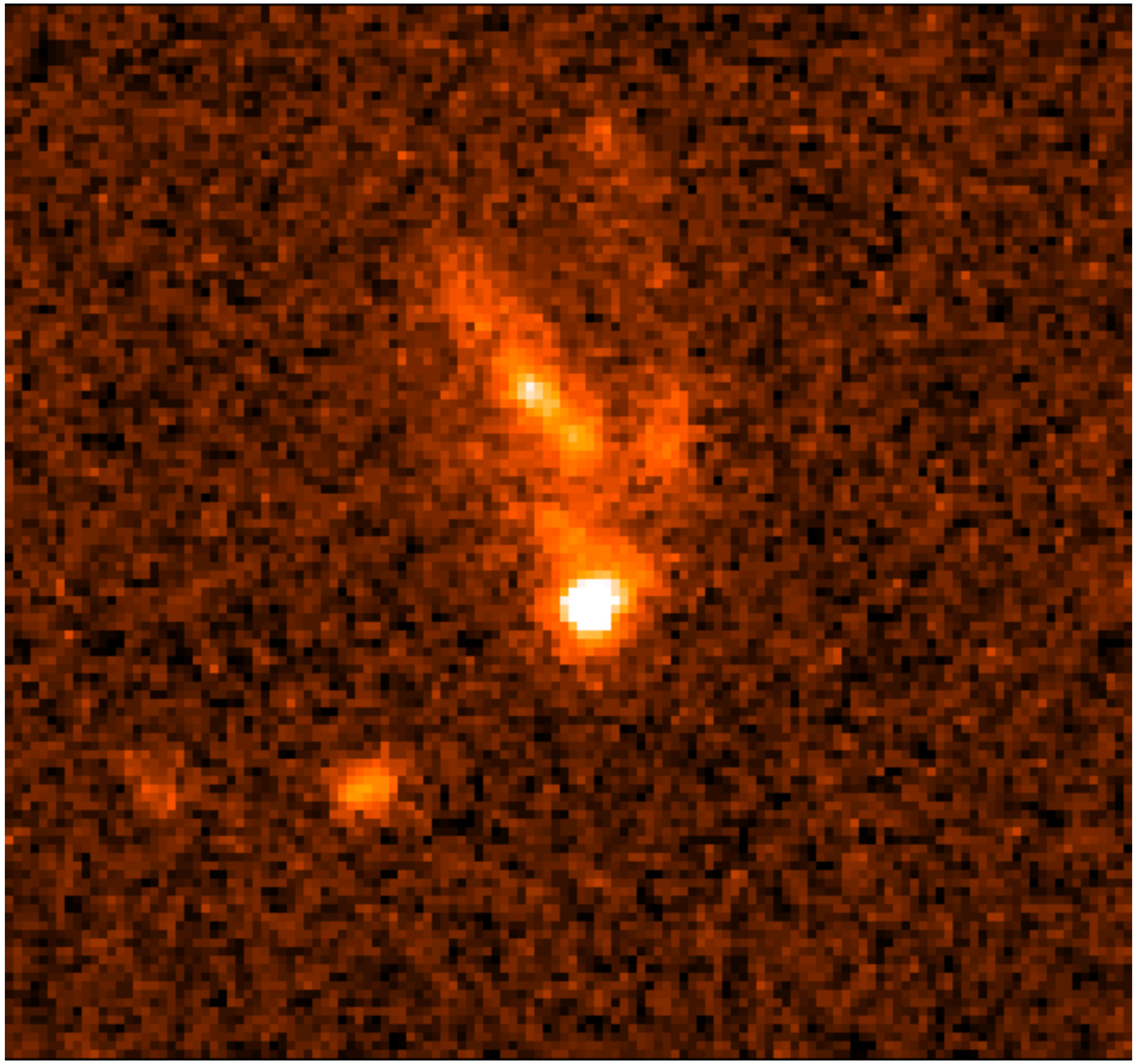
$$N \propto d^3$$
$$F \propto d^{-2}$$
$$N \propto F^{-3/2}$$

$$E_{iso} = 4\pi d^2 f = 2x10^{40} \text{ erg for } d=15 \text{ kpc}$$
$$= 2x10^{41} \text{ erg for } d=50 \text{ kpc}$$
$$= 2x10^{51} \text{ erg for } d=5 \text{ Gpc}$$

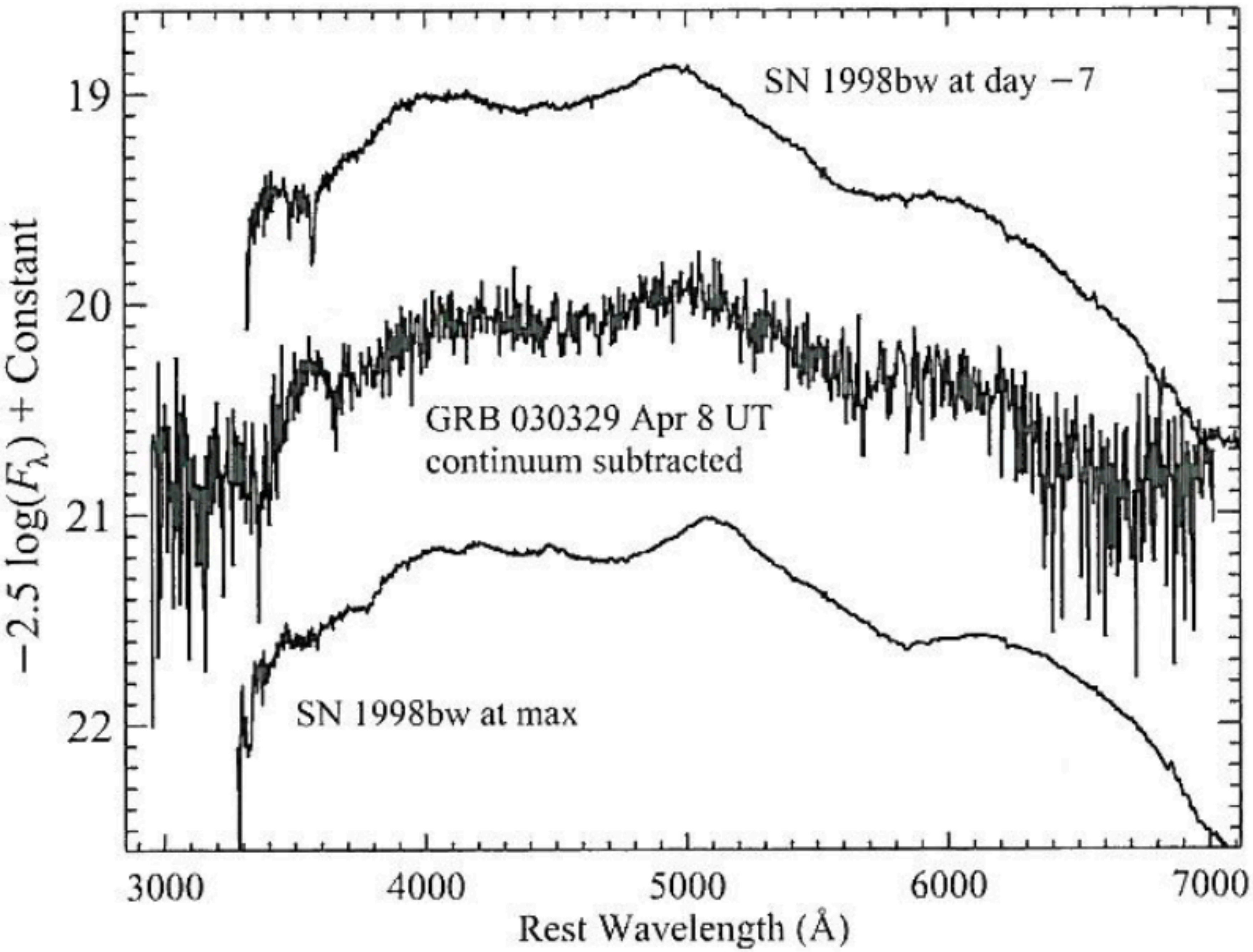
Solving the mystery



The Italian-Dutch BeppoSax satellite with its Wide Field Cameras was the first to find a GRB X-ray afterglow and determine its position on the sky



GRBs are of extragalactic origin!
Association with “Hypernovae”

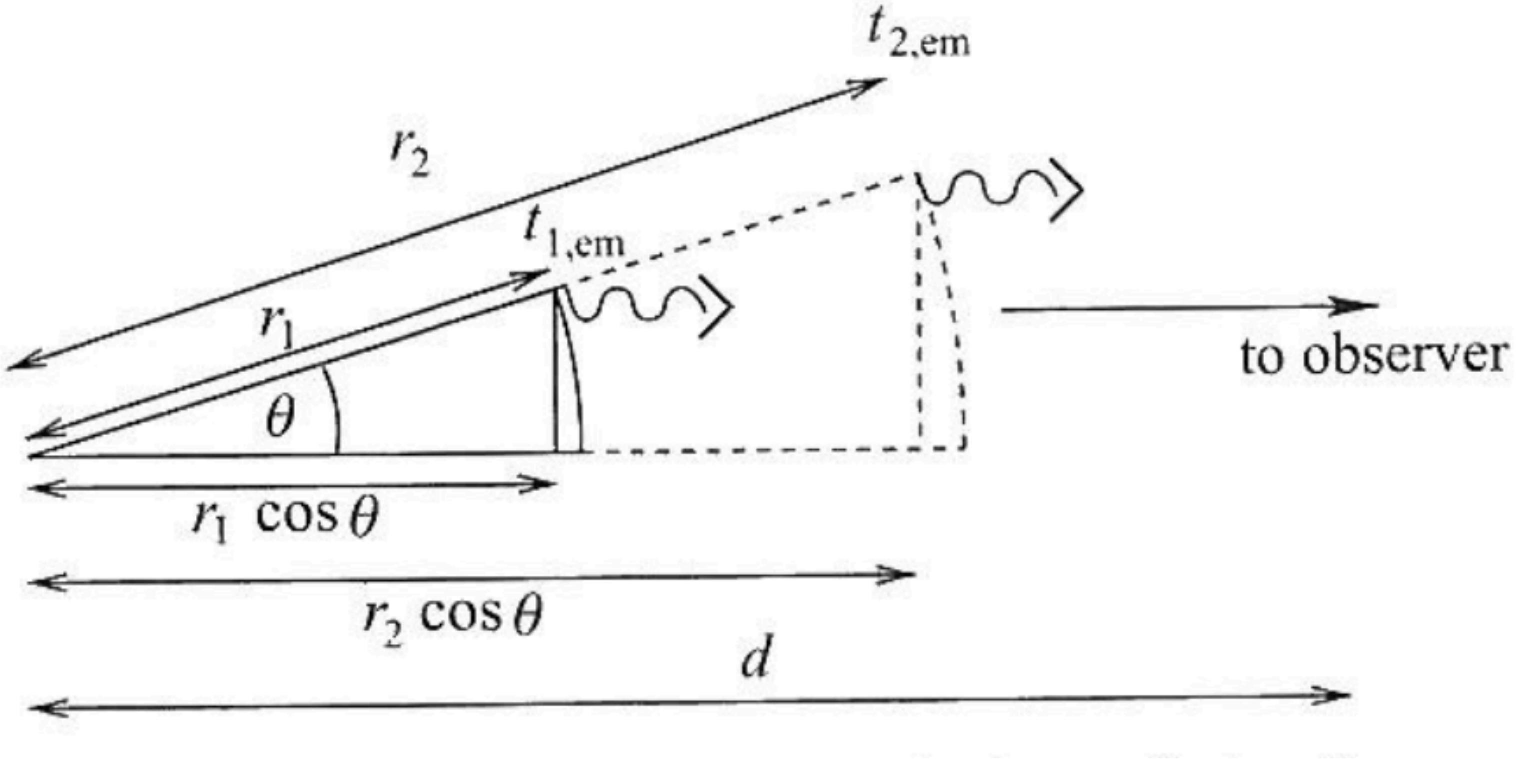


6 days after the GRB a supernova became visible as a bump in the optical light-curve. This established the connection of long GRBs and supernovae.

The compactness problem

- $E \sim 4\pi d^2 f$ (total energy involved; fluence *f* is the flux s^{-1})
- $D < \mathrm{c}\,\Delta \mathrm{t} \sim 300\ \mathrm{km}$ (size of the source)
- $n_\gamma \sim 4\pi d^2 f/(E_\gamma D^3)$ (number density of photons with energy E_γ)
- $n_e = f_e\, n_\gamma$ (fraction of photons producing electron positron pairs 2 x 0.511 MeV)
- $\tau \sim 10^{16} f_{\mathrm{e}} \left(\frac{d}{5\ \mathrm{Gpc}}\right)^2 \left(\frac{f}{10^{-6}\ \mathrm{erg\ cm^{-2}}}\right) \left(\frac{1\ \mathrm{MeV}}{\bar{E}_\gamma}\right) \left(\frac{0.01\ \mathrm{s}}{\Delta t}\right)^2$

if true then large number of pairs produced resulting in thermal spectra
- contrary to observations



- the source can be larger by a factor of γ^2 (Lorenz factor $\gamma^2=1/(1-v^2/c^2)$)
- $t_{1,\mathrm{obs}} = t_{1,\mathrm{em}} + (d - r_1\cos\theta)/c$; $t_{2,\mathrm{obs}} = t_{2,\mathrm{em}} + (d - r_2\cos\theta)/c$
- $\Delta t_{obs} = t_{2,\mathrm{obs}} - t_{1,\mathrm{obs}} = \Delta t_{em}(1-\beta\cos\theta) \sim \Delta t_{em}/2\,\gamma^2$
- photons blue shifted, $E_{\gamma,obs} = E_{\gamma,em}\,\gamma$, in reality only a small fraction of photons is energetic enough to produce electron-positron pairs
- **to circumvent the compactness problem, relativistic motions with Lorenz factors of hundreds toward the observer required**

Collimated outflows

$$E_{\rm true} = E_{\rm iso}\left(\frac{\Delta\Omega}{4\pi}\right)$$

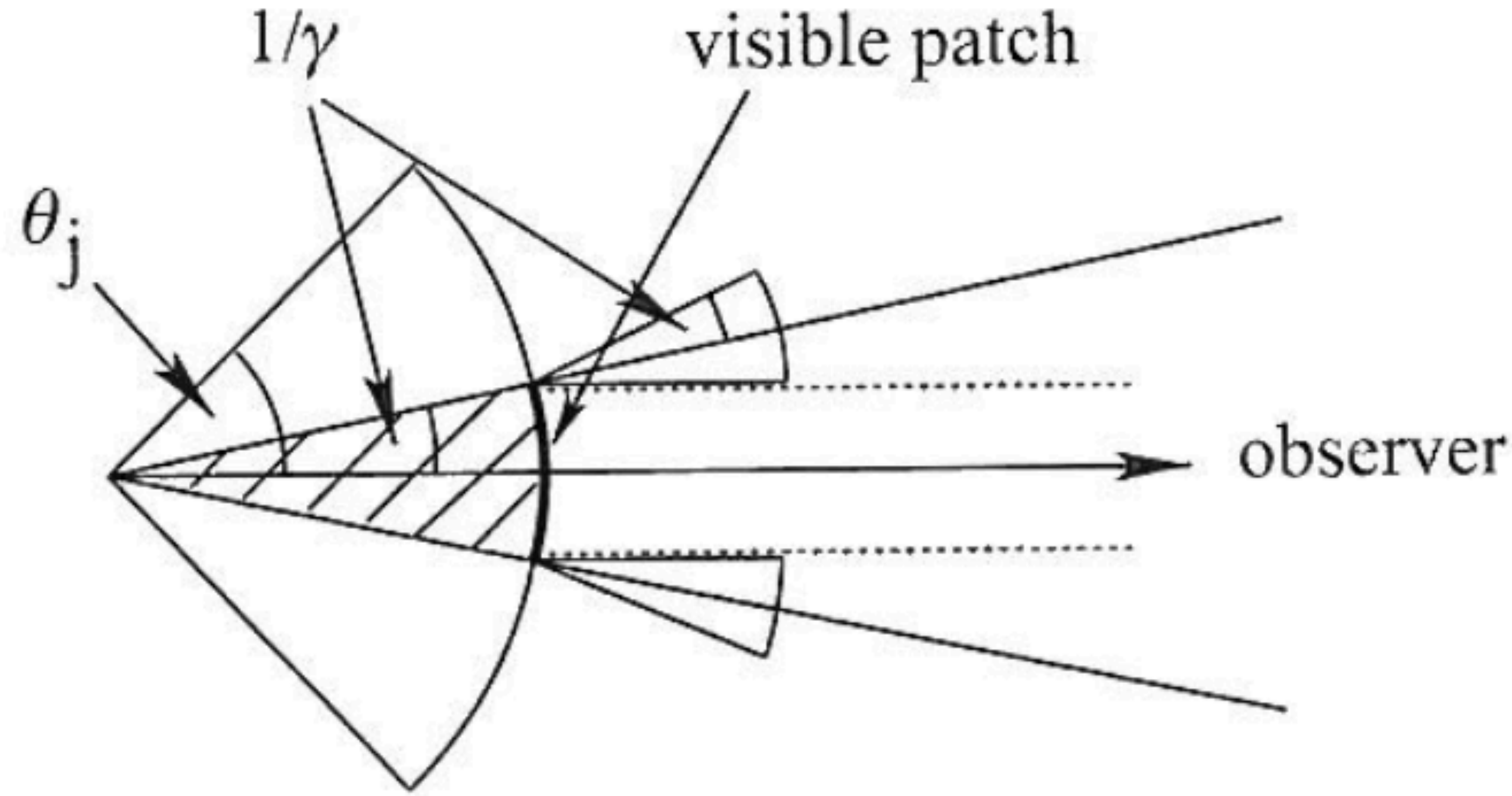
$$\Delta\Omega = 2\cdot\int_0^{2\pi}\int_0^{\theta_j}\sin\theta\, d\theta\, d\varphi = 4\pi(1-\cos\theta_j) \approx 4\pi\left(\frac{\theta_j^2}{2}\right)$$

$$E_{\rm true} \approx E_{\rm iso}\left(\frac{\theta_j^2}{2}\right) \approx \frac{E_{\rm iso}}{65}\left(\frac{\theta_j}{10^\circ}\right)^2$$

4π/ΔΩ is called the beaming factor f_b

GRB 990123 at z=1.6 had an isotropic energy of 4.5 x 10^{54} erg!
For comparison: $M_{\rm Sun}c^2$=1.8x10^{54} erg

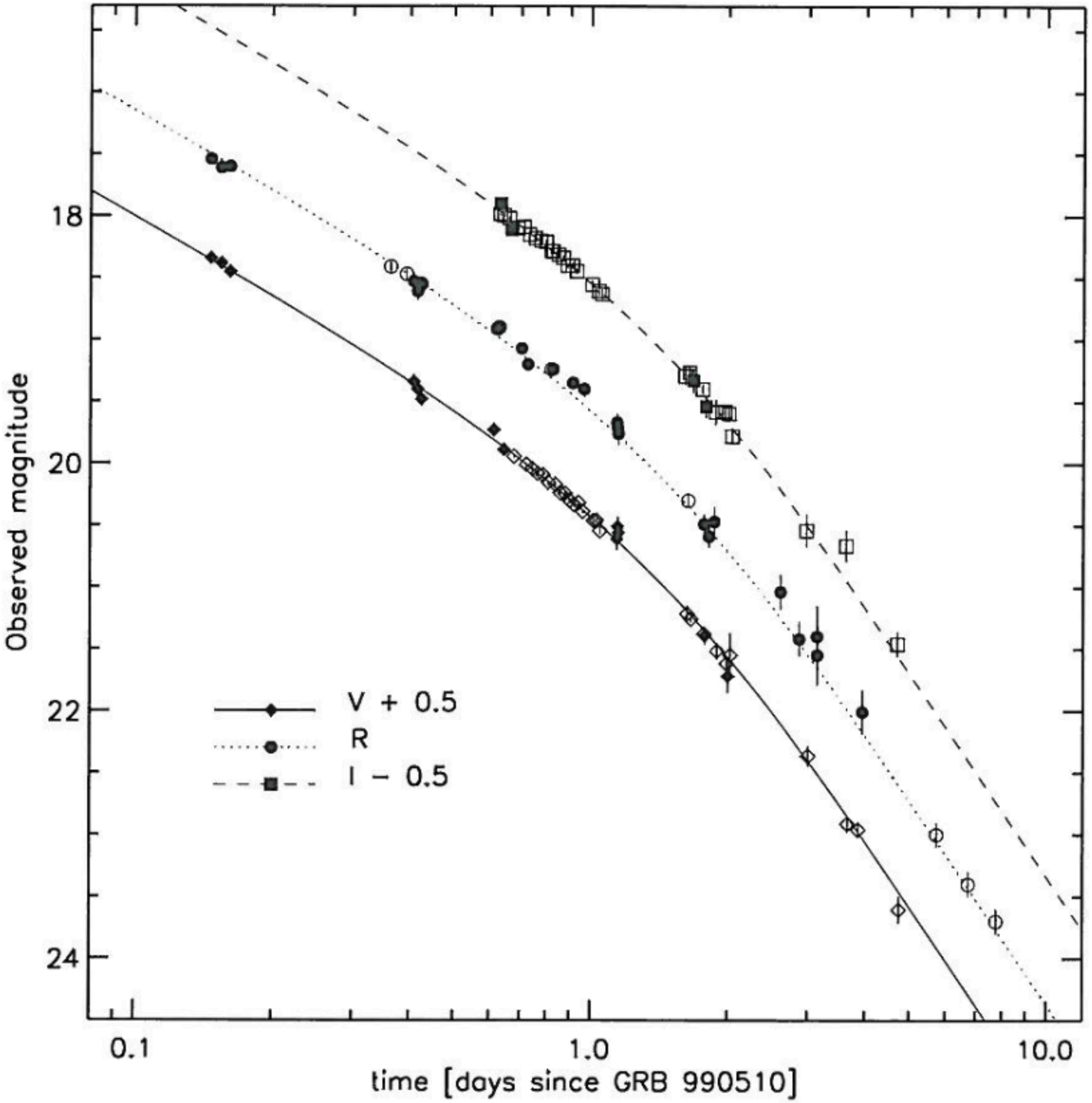
Achromatic break



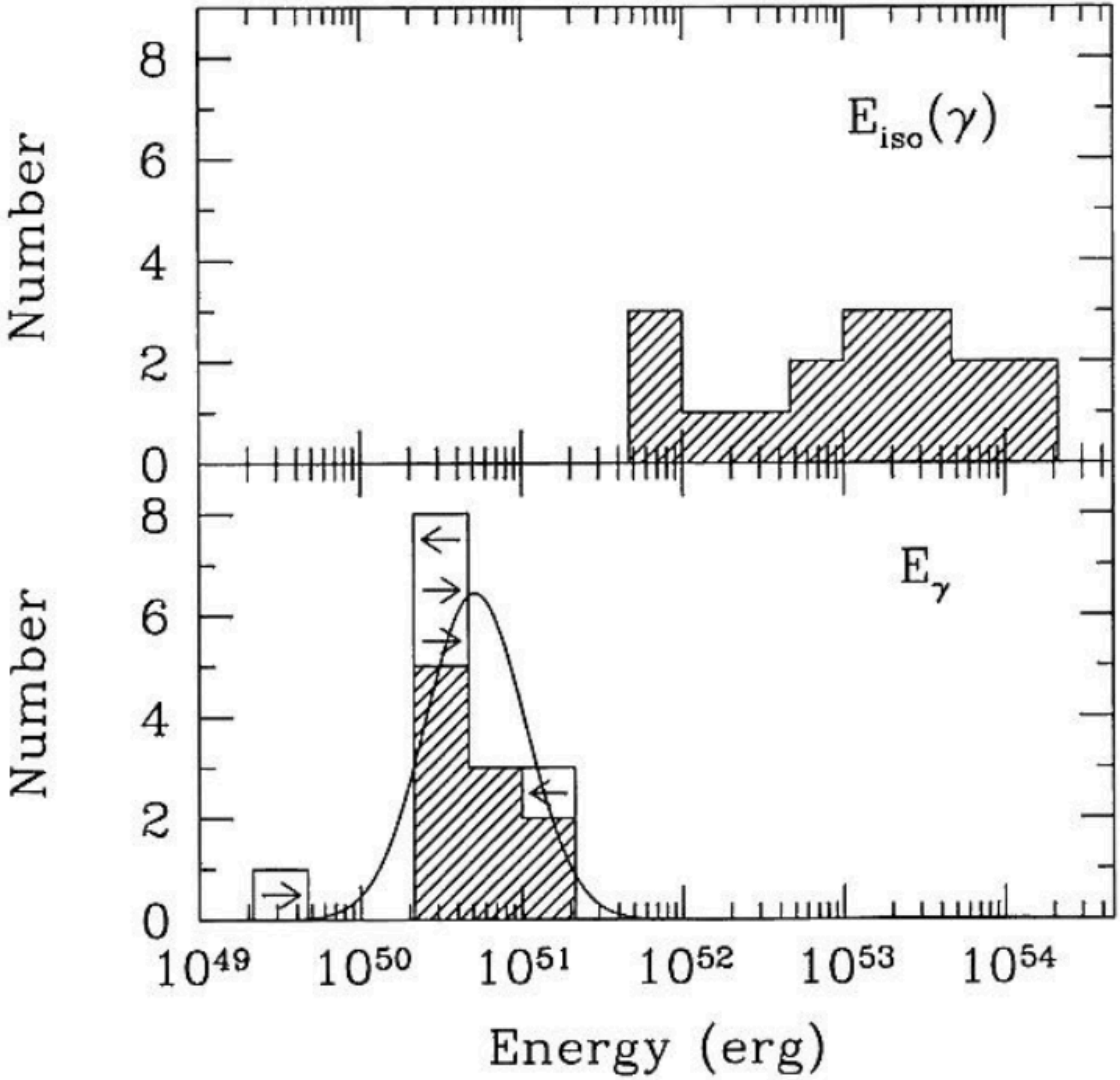
Jet with opening angle θ_j moves with Lorentz factor γ
The radiation is beamed into a forward cone with opening angle $1/\gamma$, observer sees only part of the cone

As it slows down and $1/\gamma > \theta_j$, the light curve will drop faster than before at all wavelengths

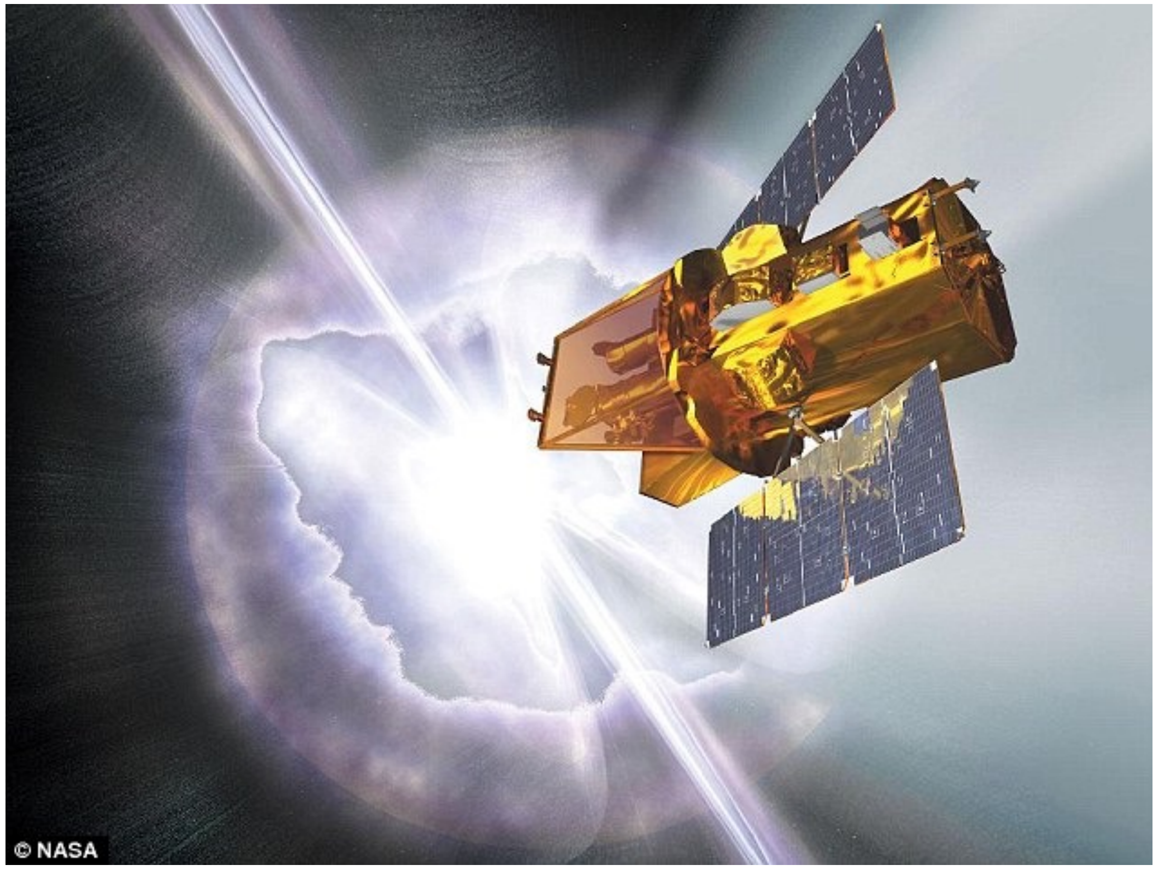
Achromatic break

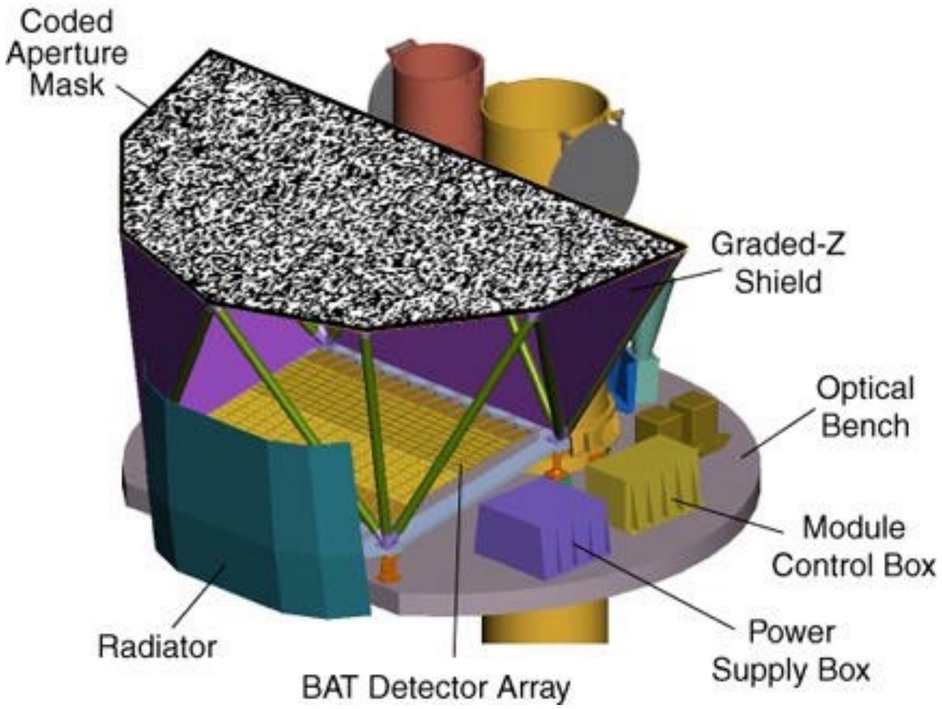


Typical θ_j are around
4 degrees

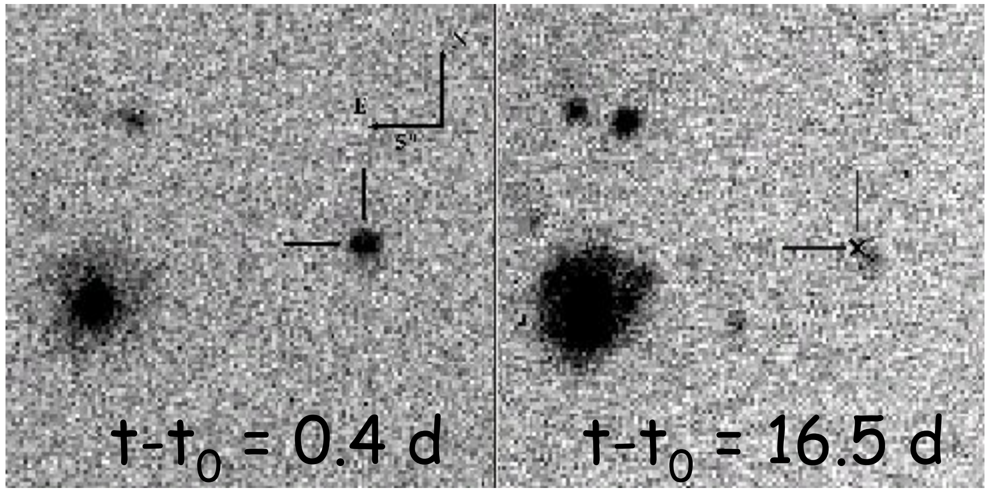

$E_{iso}(\gamma)$
E_γ
Number
Number
0
2
4
6
8
0
2
4
6
8
10^{49}
10^{50}
10^{51}
10^{52}
10^{53}
10^{54}
Energy (erg)

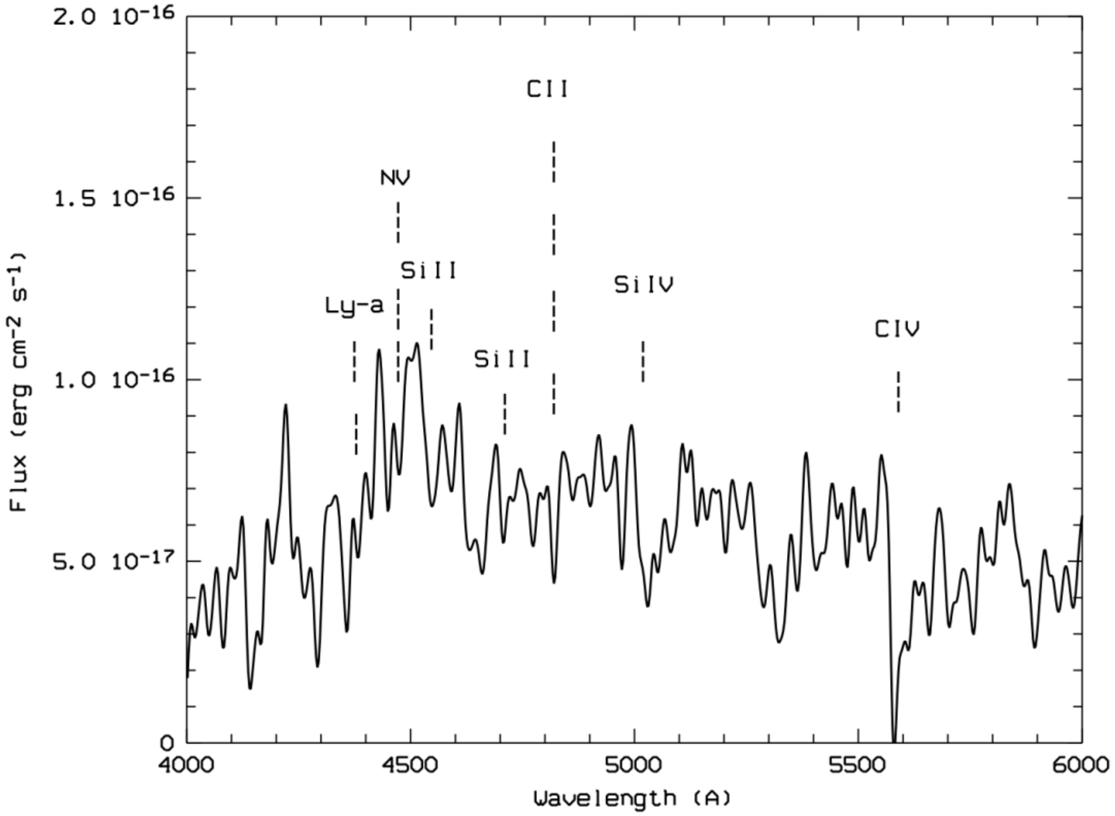
The afterglows of short GRBs

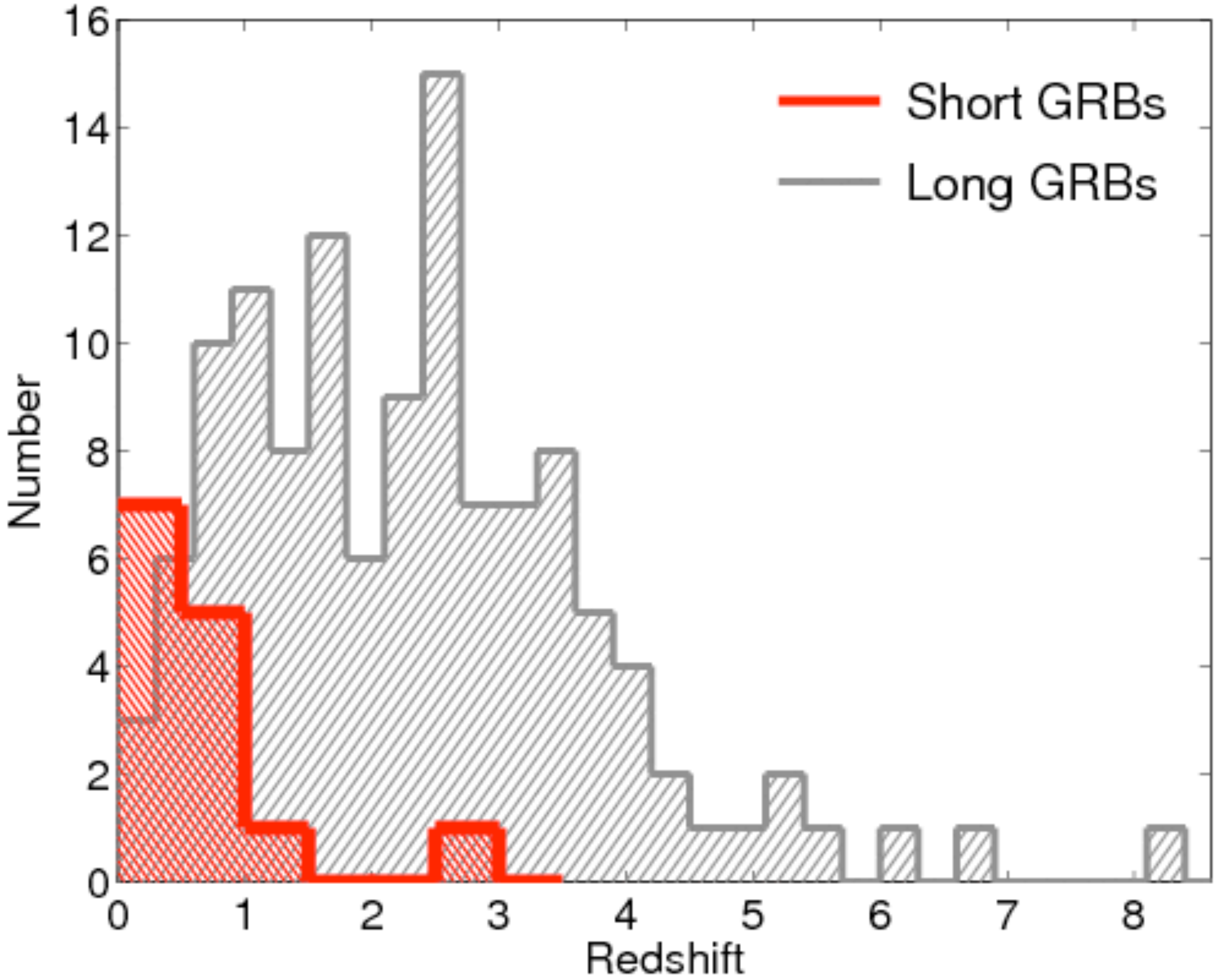




- The detection of the first afterglow of a short GRB had to wait until 2005, *the SWIFT satellite*
- The involved energies are smaller by ~3 orders of magnitude
- Short GRBs have systematically lower redshifts
- They occur in all types of galaxies, also galaxies with no star formation. This points to older stellar population


N
E
5"
t-t$_0$ = 0.4 d
t-t$_0$ = 16.5 d

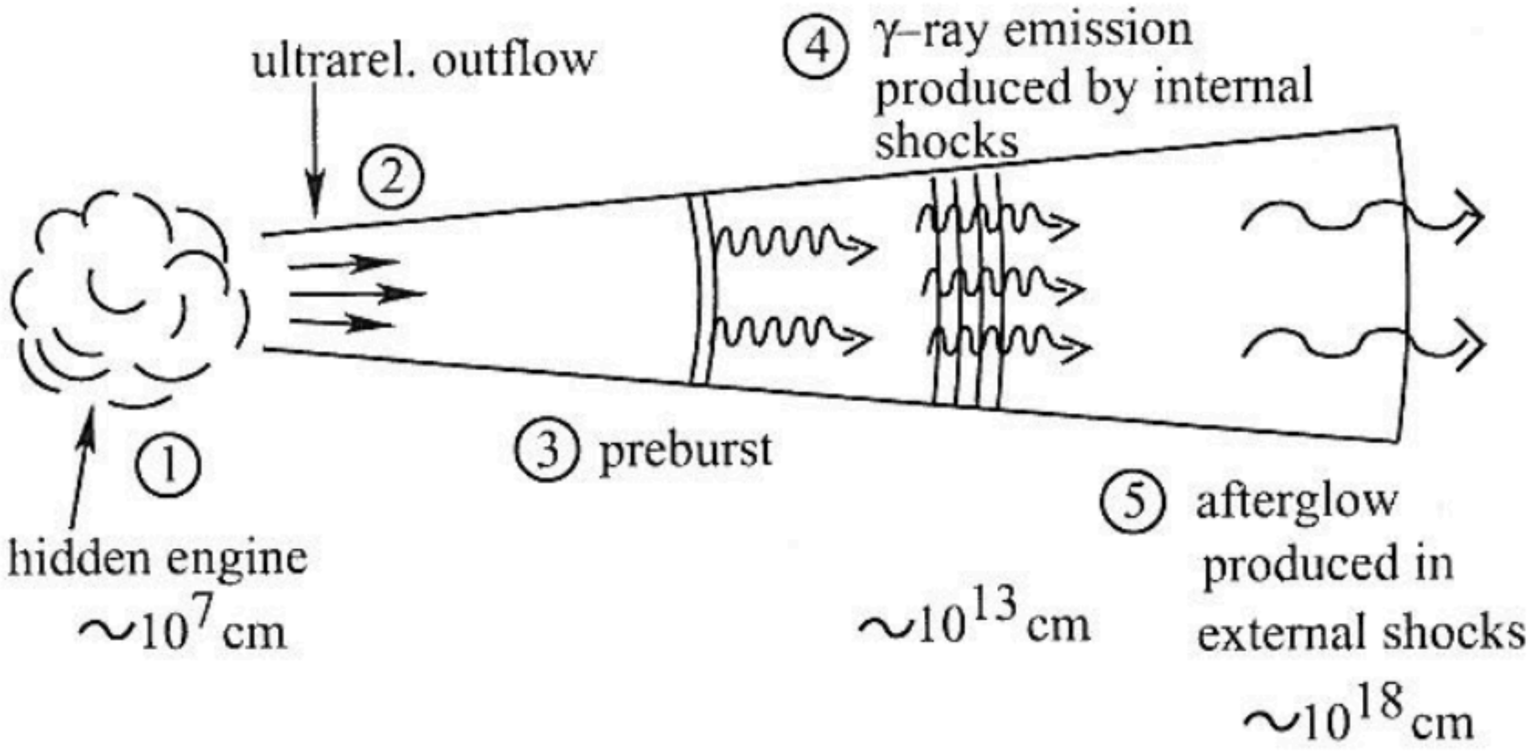

2.0 10^{-16}
1.5 10^{-16}
1.0 10^{-16}
5.0 10^{-17}
0
Flux (erg cm^{-2} s^{-1})
4000
4500
5000
5500
6000
Wavelength (A)
Ly-a
NV
SiII
SiII
CII
SiIV
CIV


Short GRBs
Long GRBs
Number
0
2
4
6
8
10
12
14
16
Redshift
0
1
2
3
4
5
6
7
8

Two flavors of GRBs

- long GRBs only in blue star-forming galaxies - young stars
- short GRB in non-star-forming elliptical galaxies - old stars

The fireball model

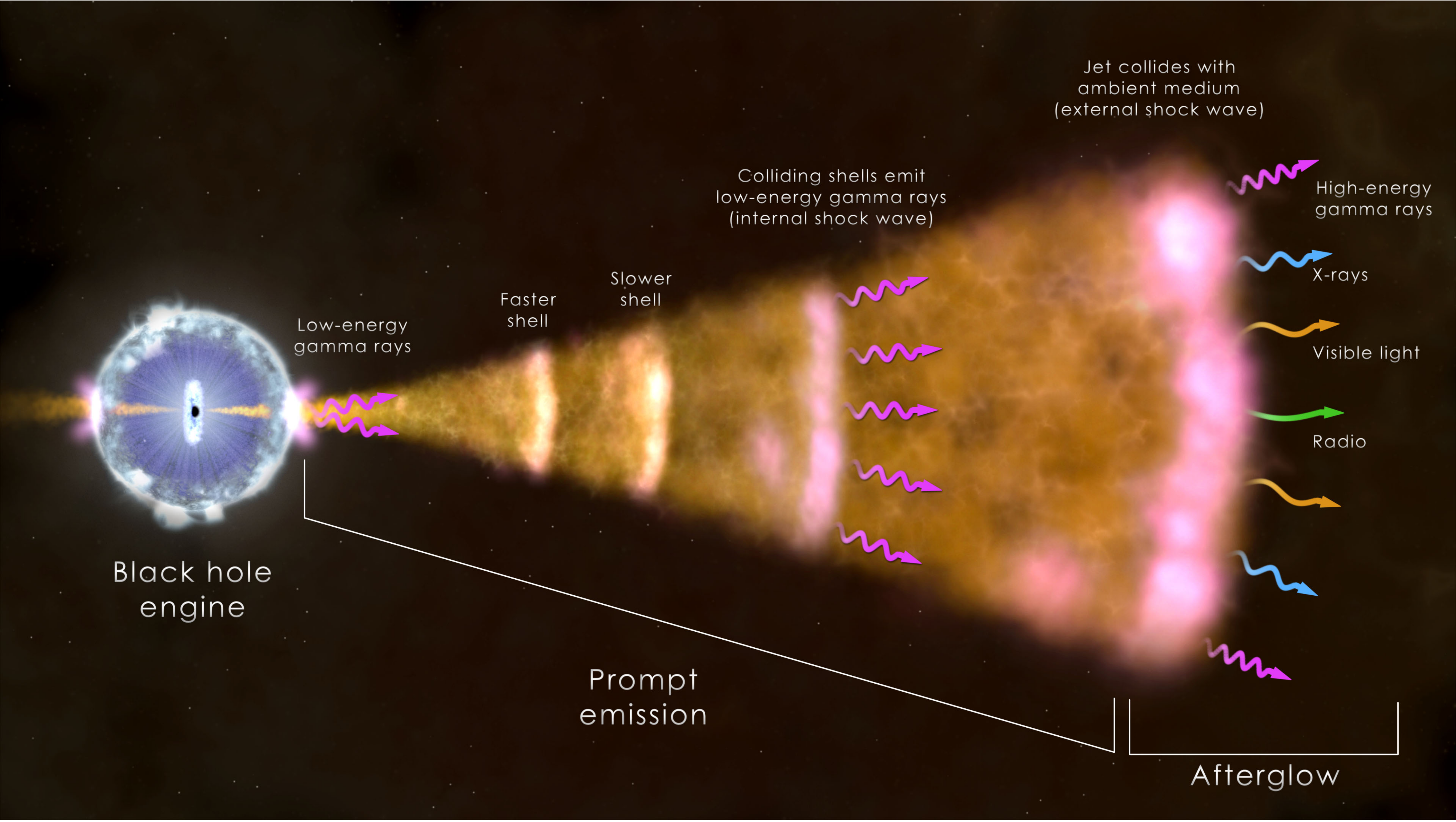


- Central engine, 10^{51} erg in $r_0 = 100$ km, $E/M_{\text{baryons}}c^2 > 100$ ($M_{\text{baryons}}=E/\gamma c^2 = 6\text{x}10^{-6}\ M_{\text{Sun}}(E/10^{51}\ \text{erg})\ (100/\gamma)$)

- expansion to ultra-relativistic velocities (requires low baryon loading)

- optical depth drops below 1, thermal preburst

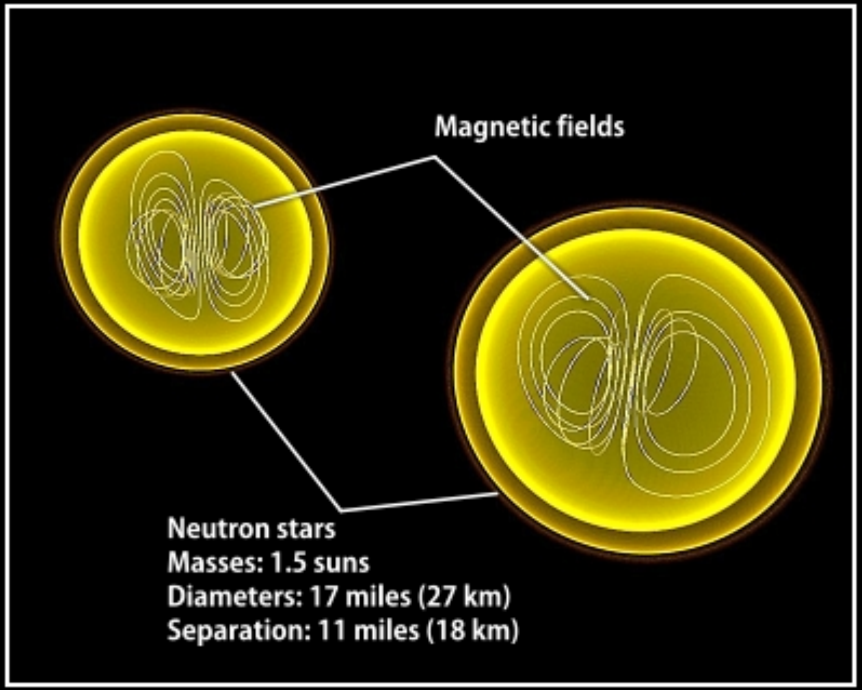
- production of gamma rays via internal shocks (outflow not completely homogeneous, contains portions with different Lorenz factors that collide with each other)


Jet collides with ambient medium (external shock wave)
Colliding shells emit low-energy gamma rays (internal shock wave)
High-energy gamma rays
X-rays
Visible light
Radio
Slower shell
Faster shell
Low-energy gamma rays
Black hole engine
Prompt emission
Afterglow

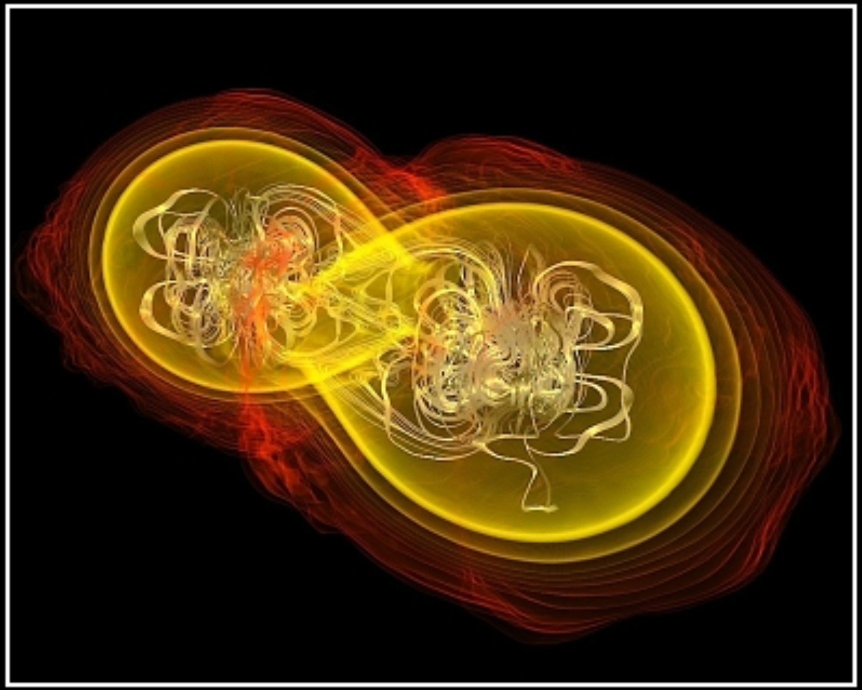
Short GRB are due to NS-NS or NS-BH merger

- several times 10^{53} erg of binding energy released
- 10^{-5} mergers per galaxy (observed burst rate 10^{-7})
- $\tau_{dyn,ns} = 0.4\ \mathrm{ms}(10^{14}\mathrm{g\ cm}^{-3}/\rho)^{1/2}$
- $\tau = 2\pi/\omega_{K,ISCO} \sim 1\mathrm{ms}\ (M_{BH}/3M_{Sun})$
- because of long in-spiral of the compact binary, mergers occur late in the evolution of the Universe

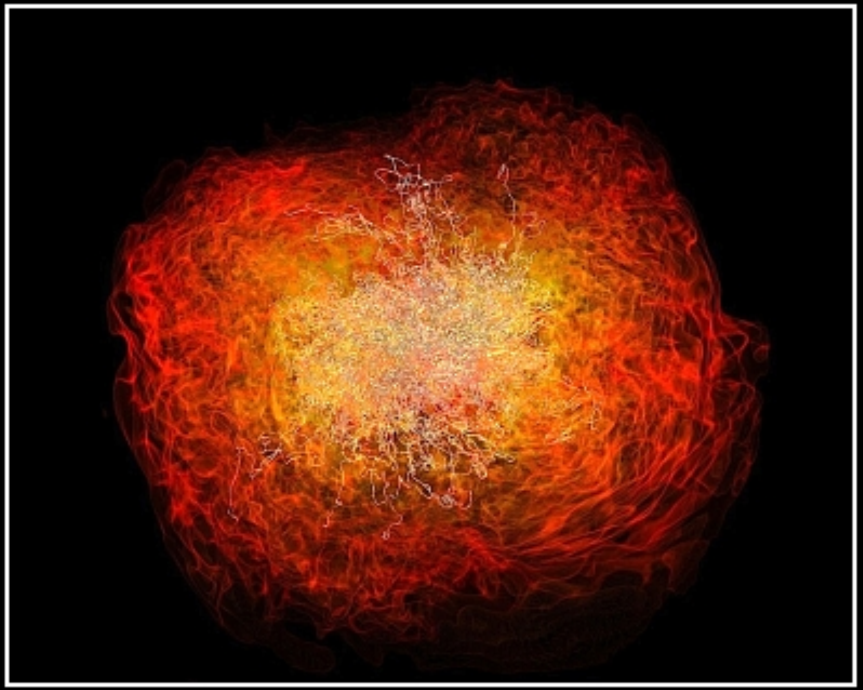
Crashing neutron stars can make gamma-ray burst jets



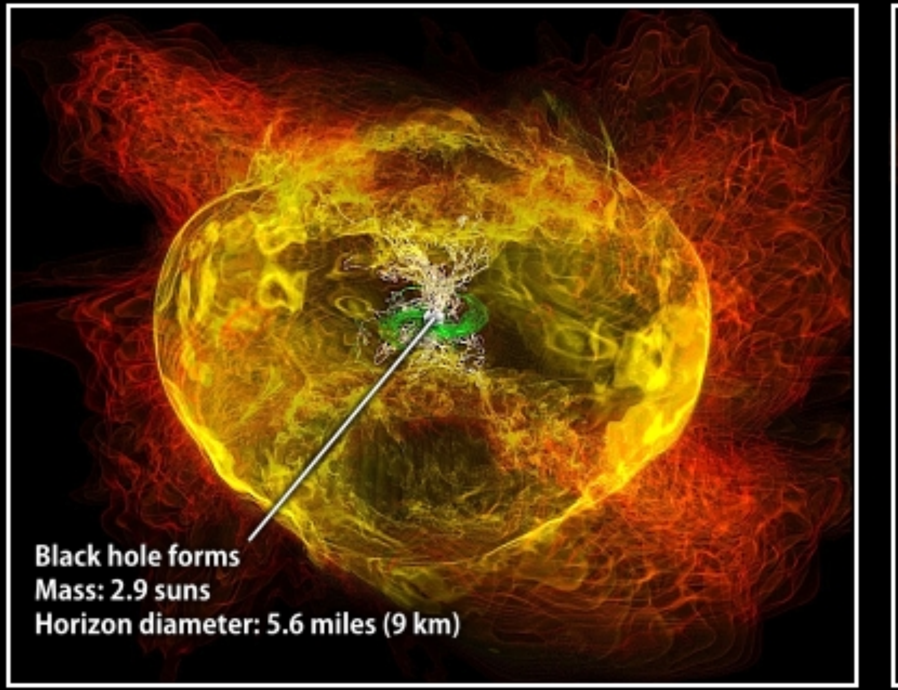
Simulation begins



7.4 milliseconds

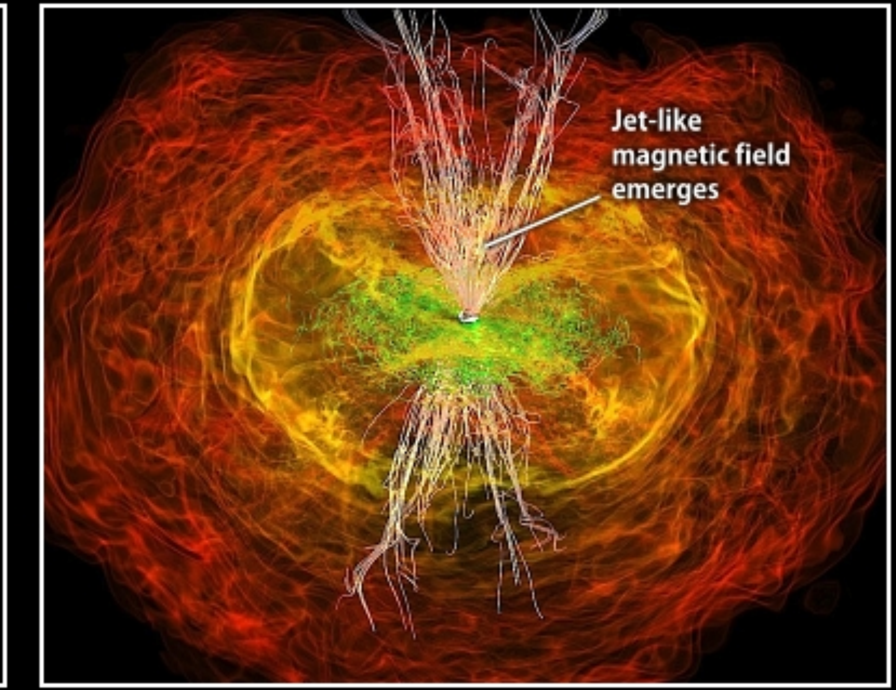


13.8 milliseconds



15.3 milliseconds

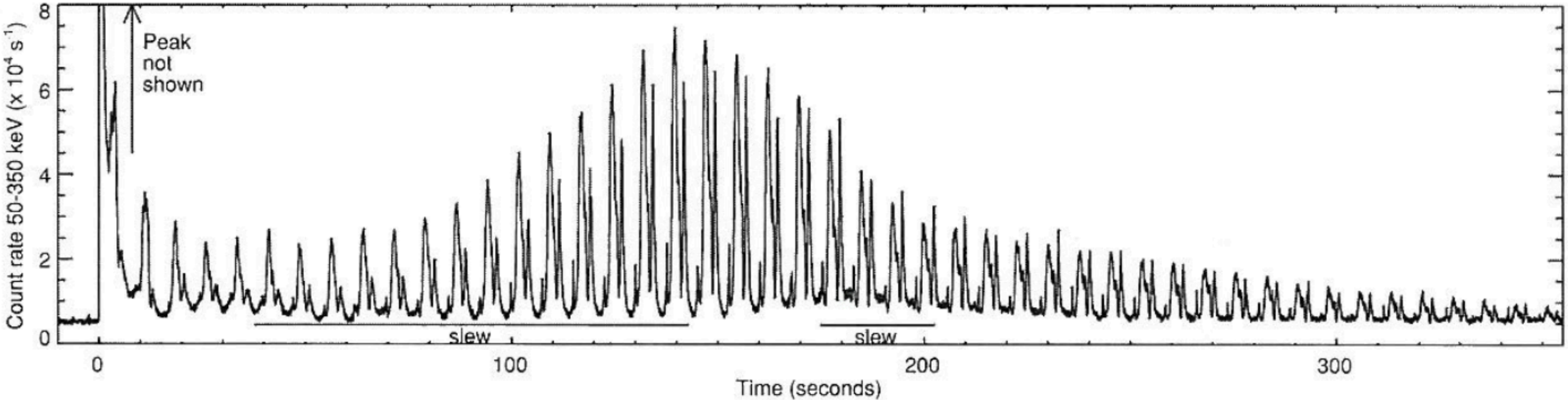
21.2 milliseconds



26.5 milliseconds

Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

Soft-Gamma Ray Repeaters



- strongest burst with $E=2\times10^{46}$ erg (10^{43} ergs s^{-1}) in December 2004 from SGR 1806-20

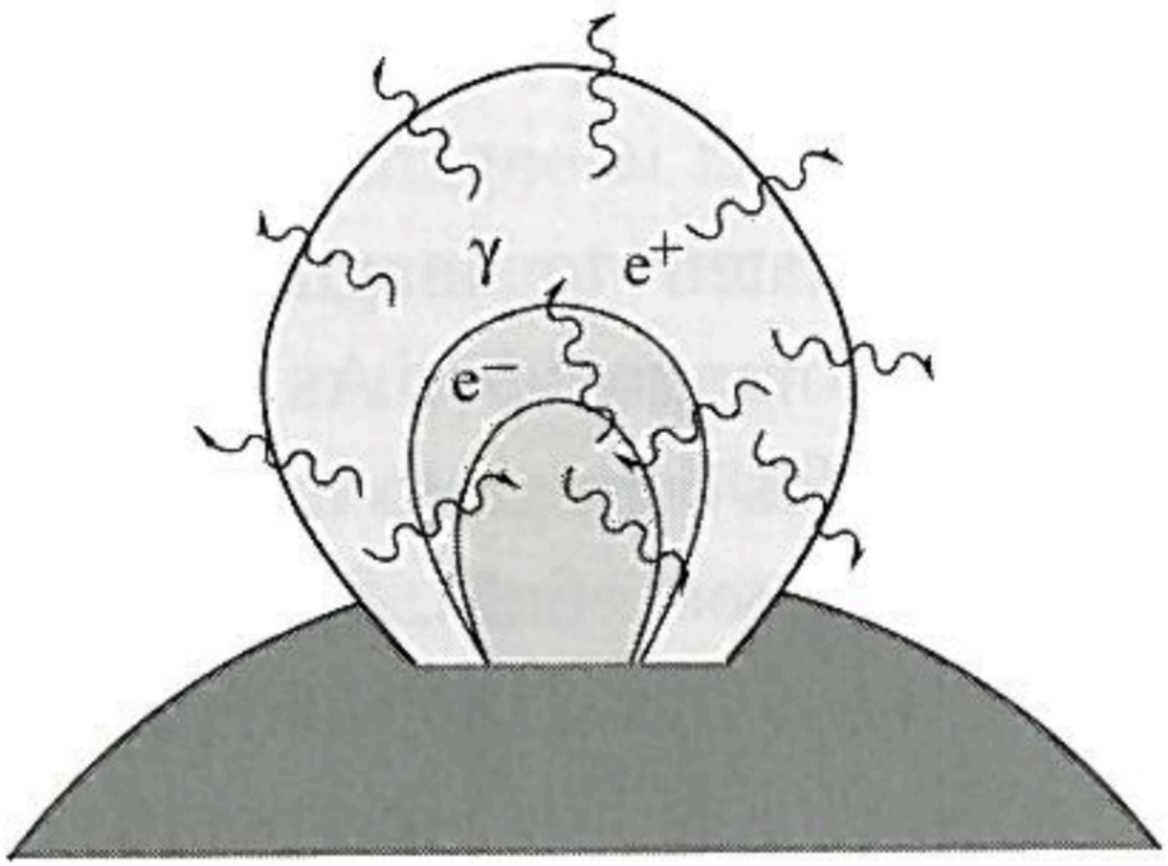
- hard spike with a rise time of ~1 ms, the rest released in a softer tail with pulsations dye to neutron star rotation

Magnetars

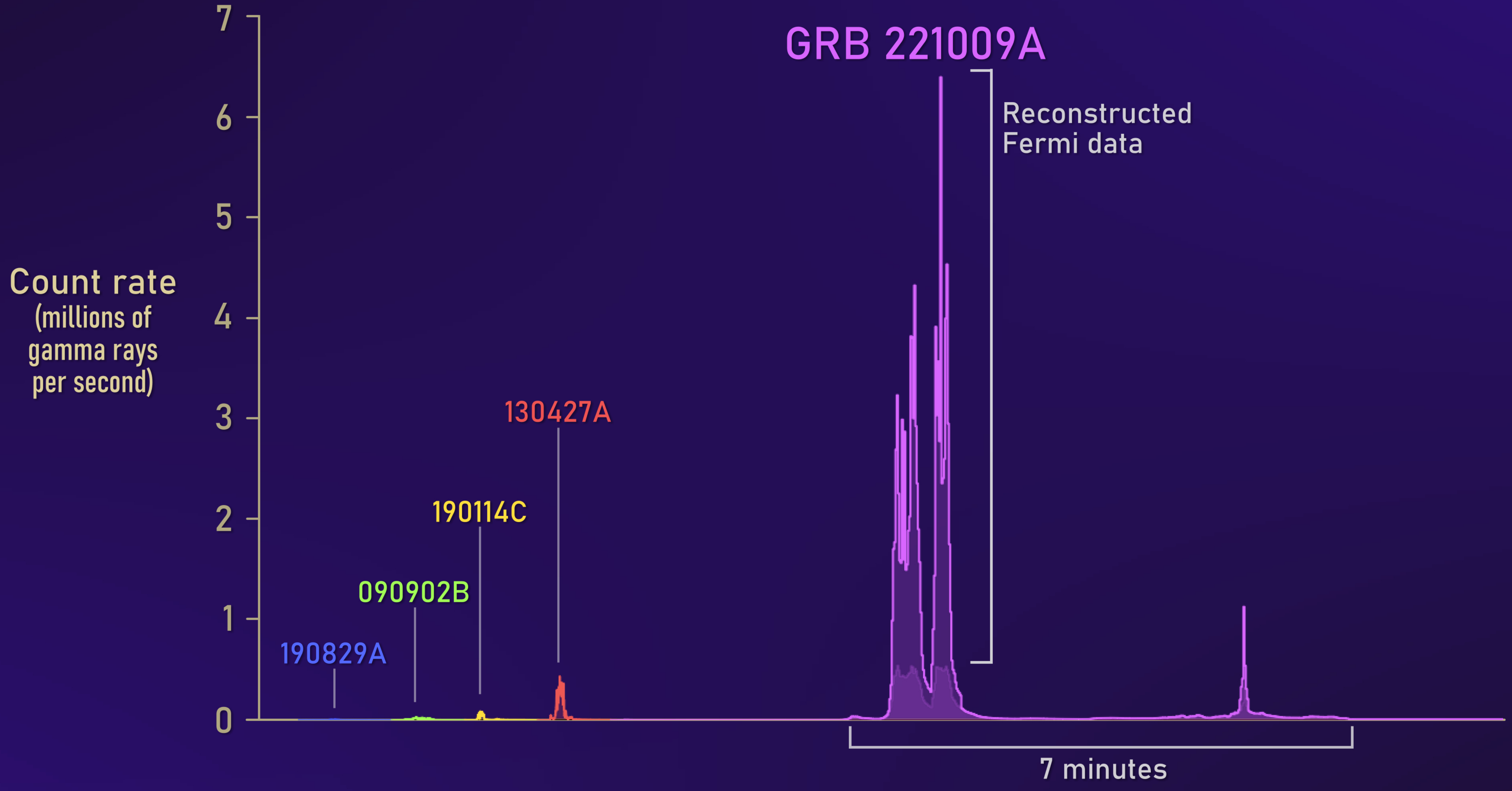
- if the rotation period at birth is shorter than the convective overturn time, $\tau_{\mathrm{conv}} \sim 10$ ms magnetic field can be amplified by dynamo action to 10^{14}—10^{15} Gauss (convection because of entropy and lepton-number gradient due to neutrino radiation)
- field strengths are larger than the quantum-critical magnetic field where Larmor radius $r_{\mathrm{L}}=vm_{\mathrm{e}}c/eB < \lambda_{\mathrm{dB}}=h/m_{\mathrm{e}}v$; $B_{\mathrm{QC}}=4.4x10^{13}$ G (other effects: photons propagate speeds depending on polarisation, atoms in a magnetar atmosphere have needle like shapes
- P = 5–8 s
- Pdot ~ 7x10^{-11} s s^{-1} (they spin down in ~300 years)

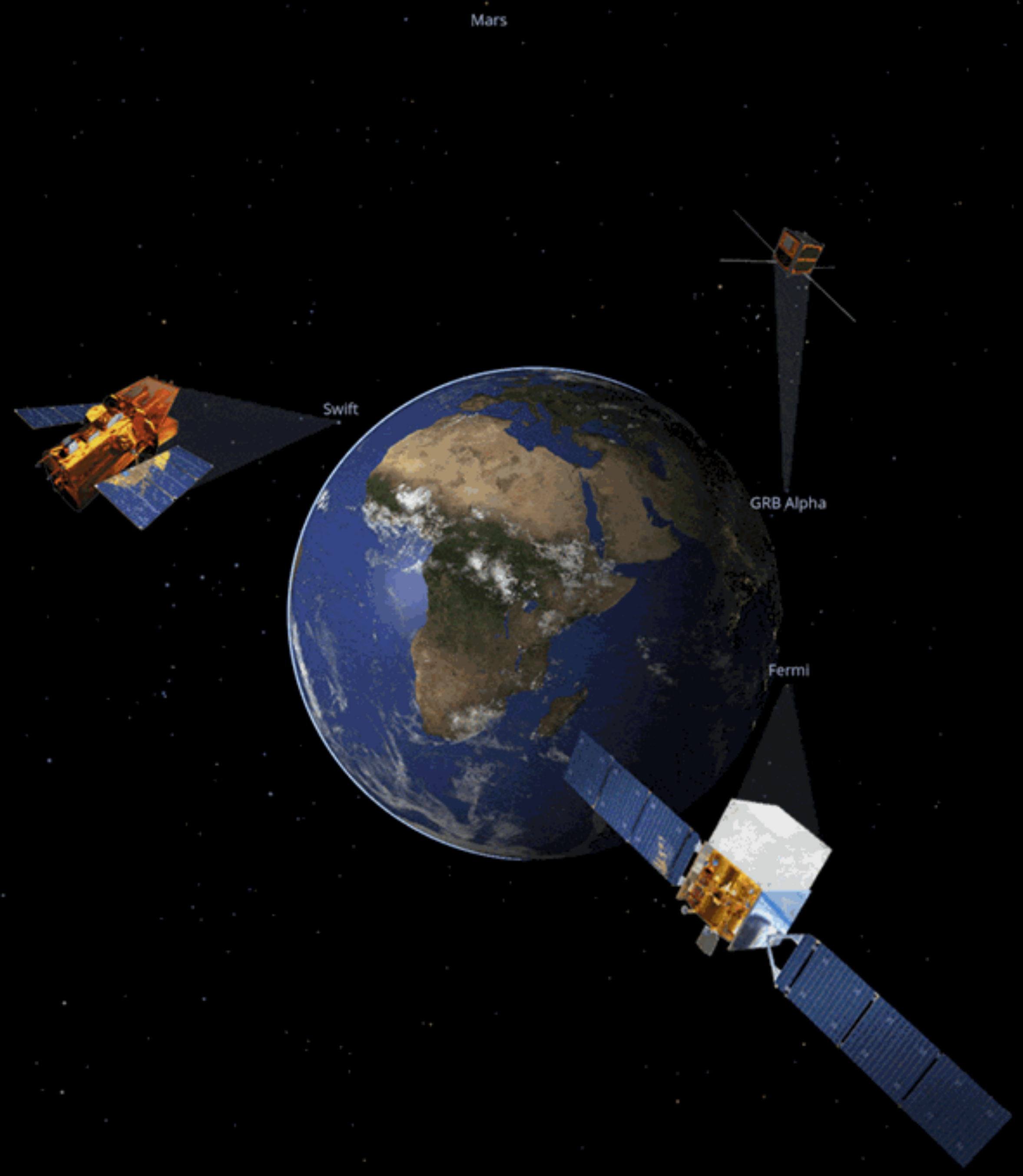
Soft-Gamma
Ray Repeaters

- $E_{\mathrm{mag}} \sim u_{\mathrm{mag}}\, V \sim B^2/8\pi\ 4/3\ \pi R^3 \sim 10^{48}$ erg
- magnetar quake releases few percent of the magnetic energy reservoir
- create a fireball and a trapped (evaporating) fireball



The BOAT GRB in Context




Mars
Swift
GRB Alpha
Fermi

First two papers in *Astronomy and Astrophysics*

A&A 677, L2 (2023)
https://doi.org/10.1051/0004-6361/202346128

Astronomy & Astrophysics

LETTER TO THE EDITOR

The peak flux of GRB 221009A measured with GRBAlpha

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Received 12 February 2023 / Accepted 14 March 2023

ABSTRACT

Context. On 2022 October 9 the brightest gamma-ray burst (GRB) ever observed lit up the high-energy sky. It was detected by a multitude of instruments, attracting the close attention of the GRB community, and saturated many detectors.
Aims. GRBAlpha, a nano-satellite with a form factor of a 1U CubeSat, detected this extraordinarily bright long-duration GRB, GRB 221009A, without saturation but affected by pile-up. We present light curves of the prompt emission in 13 energy bands, from 80 keV to 950 keV, and performed a spectral analysis to calculate the peak flux and peak isotropic-equivalent luminosity.
Methods. Since the satellite's attitude information is not available for the time of this GRB, more than 200 incident directions were probed in order to find the median luminosity and its systematic uncertainty.
Results. We find that the peak flux in the 80−800 keV range (observer frame) was $F^{\rm p}_{\rm ph} = 1300^{+1200}_{-200}$ ph cm^{-2} s^{-1}, or $F^{\rm p}_{\rm erg} = 5.7^{+3.7}_{-0.7} \times 10^{-4}$ erg cm^{-2} s^{-1}, and the fluence in the same energy range of the first GRB episode, which lasted 300 s and was observable by GRBAlpha, was $S = 2.2^{+1.4}_{-0.3} \times 10^{-2}$ erg cm^{-2}, or $S^{\rm bol} = 4.9^{+0.8}_{-0.5} \times 10^{-2}$ erg cm^{-2} for the extrapolated range of 0.9−8690 keV. We infer the isotropic-equivalent released energy of the first GRB episode to be $E^{\rm bol}_{\rm iso} = 2.8^{+0.8}_{-0.5} \times 10^{54}$ erg in the 1−10 000 keV band (rest frame at $z = 0.15$). The peak isotropic-equivalent luminosity in the 92−920 keV range (rest frame) was $L^{\rm p}_{\rm iso} = 3.7^{+2.5}_{-0.5} \times 10^{52}$ erg s^{-1}, and the bolometric peak isotropic-equivalent luminosity was $L^{\rm p,bol}_{\rm iso} = 8.4^{+2.5}_{-1.5} \times 10^{52}$ erg s^{-1} (4 s scale) in the 1−10 000 keV range (rest frame). The peak emitted energy is $E^*_{\rm p} = E_{\rm p}(1+z) = 1120 \pm 470$ keV. Our measurement of $L^{\rm p,bol}_{\rm iso}$ is consistent with the Yonetoku relation. It is possible that, due to the spectral evolution of this GRB and the orientation of GRBAlpha at the peak time, the true values of peak flux, fluence, $L_{\rm iso}$, and $E_{\rm iso}$ are even higher.

Key words. gamma-ray burst: individual: GRB 221009A

1. Introduction

On 2022 October 9 at 13:16:59.988 UT, the *Fermi* Gamma-ray Burst Monitor (GBM) detected the exceptionally bright long gamma-ray burst (GRB) GRB 221009A (Veres et al. 2022; Lesage et al. 2022, 2023). The burst was also observed by the *Fermi* Large Area Telescope (LAT) up to the energy of 100 GeV (Pillera et al. 2022). Potentially remarkable detections of over 5000 very high-energy photons with energies up to 18 TeV were reported by the Large High Altitude Air Shower Observatory (LHAASO; Huang et al. 2022), and a possible 251 TeV photon was reported by Carpet-2 (Dzhappuev et al. 2022), triggering the interest of the broader physics community.

The burst was localised by the *Neil Gehrels Swift* Observatory's Burst Alert Telescope (Dichiara et al. 2022) and followed up by the Very Large Telescope (VLT) X-shooter instrument (de Ugarte Postigo et al. 2022; Malesani et al. 2023), which determined that it occurred at a redshift of 0.151 and belongs to very near long GRBs (Oates 2023). It was also detected by a multitude of other instruments: AGILE/GRID (Piano et al. 2022), AGILE/MCAL (Ursi et al. 2022), BepiColombo/MGNS (Kozyrev et al. 2022), Insight-HXMT and SATech-01/GECAM-C (HEBS; An et al. 2023), INTEGRAL/SPI-ACS (Gotz et al. 2022), Konus-WIND & SRG/ART-XC (Frederiks et al. 2023), MAXI and NICER (Williams et al. 2023), Solar Orbiter/STIX (Xiao et al. 2022), STPSat-6/SIRI-2 (Mitchell et al. 2022), and *XMM-Newton* (Tiengo et al. 2023).

This brightest ever recorded GRB (Burns et al. 2023; O'Connor et al. 2023) saturated many of the GRB detectors in orbit, hampering the efforts to determine its peak luminosity. In this Letter, we present the peak flux and peak isotropic-equivalent luminosity of this extraordinary transient as measured by the GRBAlpha nano-satellite.

2. GRBAlpha

GRBAlpha (Pál et al. 2020) is a 1U CubeSat carrying a GRB detector as a technology demonstration for an envisioned future CubeSat constellation (Werner et al. 2018; Mészáros et al. 2022). It was launched on 2021 March 22 into a Sun-synchronous

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A&A 677, A40 (2023)
https://doi.org/10.1051/0004-6361/202346182

Astronomy & Astrophysics

GRBAlpha: The smallest astrophysical space observatory

I. Detector design, system description, and satellite operations

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Received 18 February 2023 / Accepted 27 March 2023

ABSTRACT

Aims. Since it launched on 22 March 2021, the 1U-sized CubeSat GRBAlpha operates and collects scientific data on high-energy transients, making it the smallest astrophysical space observatory to date. GRBAlpha is an in-orbit demonstration of a gamma-ray burst (GRB) detector concept suitably small to fit into a standard 1U volume. As was demonstrated in a companion paper, GRBAlpha adds significant value to the scientific community with accurate characterization of bright GRBs, including the recent outstanding event of GRB 221009A.
Methods. The GRB detector is a 75 × 75 × 5 mm CsI(Tl) scintillator wrapped in a reflective foil (ESR) read out by an array of SiPM detectors, multi-pixel photon counters by Hamamatsu, driven by two separate redundant units. To further protect the scintillator block from sunlight and protect the SiPM detectors from particle radiation, we applied a multi-layer structure of Tedlar wrapping, anodized aluminium casing, and a lead-alloy shielding on one edge of the assembly. The setup allows observations of gamma radiation within the energy range of 70−890 keV with an energy resolution of ∼30%.
Results. Here, we summarize the system design of the GRBAlpha mission, including the electronics and software components of the detector, some aspects of the platform, and the current semi-autonomous operations. In addition, details are given about the raw data products and telemetry in order to encourage the community to expand the receiver network for our initiatives with GRBAlpha and related experiments.

Key words. instrumentation: detectors – space vehicles: instruments – gamma rays: general

GRBAlpha mentioned along big famous observatories

2. OBSERVATIONS

GRB 221009A was identified by a large number of space-based γ-ray observatories. These ir
(Veres et al. 2022), *Fermi*-LAT (Bissaldi et al. 2022), *AGILE*/MCAL (Ursi et al. 2022), *AGILE*,
2022), *INTEGRAL* (Gotz et al. 2022), Konus-*Wind* (Frederiks et al. 2022) *Insight*-HMXT (Tan e
6/SIRI-2 (Mitchell et al. 2022), *SATech-01/GECAM-C* HEBS (Liu et al. 2022), *SRG*/ART-XC (I
Solar Orbiter/STIX (Xiao et al. 2022), and *GRBalpha* (Ripa et al. 2022). The initial brightness
was sufficiently extreme (and also considering its location on the sky in the plane of the Milk
proposed to be a new Galactic transient rather than a GRB, despite the fact that *Swift* actua
afterglow emission (Dichiara et al. 2022)

Following the identification of the source as a GRB (Kennea et al. 2022), ground-based observat
a redshift measurement of $z = 0.151$ (de Ugarte Postigo et al. 2022b; Malesani & Stargate 2023
observations continued until the source entered Sun-block and found a typical GRB afterglow dec
also showed evidence for emission from an accompanying supernova Fulton et al. (2023), althoug
in Section 3.3.1, isolation of such a supernova component is challenging.

2.1. *James Webb Space Telescope*

On 22 October 2022 we obtained observations of the afterglow of GRB 221009A with JWST (p
PI Levan). A single, uninterrupted set of observations were obtained with NIRSPEC and MIRI. NI
began at 17:13 UT and MIRI at 18:12, corresponding to time since burst of 13.16 and 13.20 da
image of the field at the time is shown in Figure 1, and the resulting spectra in Figure 2.

For NIRSPEC we utilized the prism, spanning a spectral range from 0.5-5.5 microns at a low (a
resolution. MIRI observations were undertaken in low resolution mode, and span the range fror
both NIRSPEC and MIRI observations we re-process the data with the most up to date calibrat
2022, and obtain our own 1D extractions. We compare these with products obtained with the a

(64-ms scale), making GRB 221009A the most energetic and or
since the beginning of the GRB cosmological era in 1997. Th
nicely both 'Amati' and 'Yonetoku' hardness-intensity correlatio
that GRB 221009A is most likely a very hard, super-energetic v

Keywords: Gamma-ray bursts (629); Transient sources (1851); I

1. INTRODUCTION

Cosmological gamma-ray bursts (GRBs) are thought to be produced by
events: mergers of binary compact objects, such as two neutron stars or
produce short, $\lesssim 2$ s, so called Type I GRBs; the core collapse of massive sta
see, e.g., Zhang et al. (2009) for more information on the Type I/II classifi

The measured GRB isotropic-equivalent energy release $E_{\rm iso}$ and isotropic
with the most intense GRBs reaching close to $E_{\rm iso} \sim 10^{55}$ erg and $L_{\rm iso}$ as h
of Konus-*WIND* and *Fermi*-GBM samples of GRBs with known redshifts
has a cutoff at $E_{\rm iso} \sim 1$–3×10^{54} erg (Atteia et al. 2017; Tsvetkova et al. 2(
extremely energetic GRBs. Bright nearby gamma-ray bursts provide a uniq
physics, prompt emission and afterglow emission mechanisms, as well as C
such bursts have been observed.

On 2022 October 9 at T_0 =13:17:00 UTC an extremely intense GRB 22
missions: *Fermi* (GBM and LAT; Veres et al. 2022; Lesage et al. 2022; Biss
Wind (Svinkin et al. 2022; Frederiks et al. 2022), *AGILE* (MCAL and G
INTEGRAL (SPI-ACS; Gotz et al. 2022), *Insight*-HMXT (Tan et al. 2022
Spektr-RG (ART-XC; Lapshov et al. 2022), *GRBAlpha* (Ripa et al. 2022)
C (Liu et al. 2022), and *BepiColombo* (MGNS; Kozyrev et al. 2022). The initial analysis of the burst showed that the
prompt emission was so intense that it saturated almost all instruments.

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bright transient denoted as *Swift* J1913.1+1946 (triggers 1126853 and 1126854, Dichiara et al. 2022a,b). *Swift* slewed immediately to the position and its narrow-field instruments, the X-ray telescope (XRT, Burrows et al. 2005) and the Ultra-Violet/Optical Telescope (UVOT, Roming et al. 2005) discovered a transient, which was very bright in X-rays (> 800 ct/s) and moderately bright in the optical (unfiltered finding chart, *white* = 16.63 ± 0.14 mag). The optical detection was somewhat remarkable as the transient lies in the Galactic plane and extinction along the line-of-sight is very high, $E_{(B-V)} = 1.32$ mag/$A_V = 4.1$ mag (Schlafly & Finkbeiner 2011, henceforth SF11). It was furthermore reported that the source was also detected over ten minutes earlier by the Gas-Slit Camera (GSC) of the *MAXI* X-ray detector onboard the International Space Station (ISS, Negoro et al. 2022; Kobayashi et al. 2022; Williams et al. 2023). Overall, this is in agreement with a new Galactic transient.

About 6.5 hours after the *Swift* trigger, it was reported by Kennea et al. (2022a) that this source may be a GRB, GRB 221009A, as both the Gamma-Ray Burst Monitor (GBM, Meegan et al. 2009) and the Large Area Telescope (LAT, Atwood et al. 2009) of the *Fermi* ob-

SPI/ACS (Gotz et al. 2022) analysis finds 1.3×10^{-2} erg/cm^2, *Fermi* GBM finds (2.912 ± 0.001)$\times10^{-2}$ erg/cm^2 and peak flux 2385 ± 3 ph s^{-1} cm^{-2}, Konus-*Wind* report 5.2×10^{-2} erg/cm^2 (Frederiks et al. 2022), and Kann & Agui Fernandez (2022) estimate $\approx 9\times10^{-2}$ erg/cm^2. Even these preliminary estimates show GRB 221009A exceeded GRB 130427A in fluence by a factor of at least 10.

Several smaller orbital detectors were not saturated, stemming from size, environment, or off-axis detection, such as detectors on *Insight* (the Low-Energy (LE) telescope and the Particle Monitors, Ge et al. 2022), *SATech-01/GECAM-C* HEBS (Liu et al. 2022), *GRB-Alpha* (Ripa et al. 2022), *STPSat-6*/SIRI-2 (Mitchell et al. 2022), and *SRG*/ART-XC (Lapshov et al. 2022).

Optical spectroscopy of the transient showed it to indeed be a GRB afterglow, with a redshift $z = 0.151$ measured both in absorption and emission (de Ugarte Postigo et al. 2022; Castro-Tirado et al. 2022; Izzo et al. 2022, Malesani et al., in prep.), making it even closer than GRB 030329. Such an event is ultra-rare, e.g., Atteia (2022) estimate it to occur only once every half-millenium (see also Williams et al. 2023, Burns et al., in prep.).

(Lapshov et al. 2022), *Solar Orbiter*/STIX (Xiao et al. 2022), and *GRBalpha* (Ripa et al. 2022). However, the event was first reported by a *Swift* detection of the afterglow over 50 minutes later (Dichiara et al. 2022b). The location of the burst within the Galactic plane (l = 52.96°, b = 4.32°), combined with its brightness, led to confusion over the nature of the outburst: initially it was suspected to be due to a new Galactic X-ray transient (Dichiara et al. 2022b,a), but its subsequent behaviour appeared more like that of an extragalactic GRB (Kennea et al. 2022).

Despite high foreground extinction (Section 3.2), an optical afterglow was seen by various telescopes (e.g. Dichiara et al. 2022b; Lipunov et al. 2022; Fulton et al. 2023 and many more). The counterpart was localised at coordinates (J2000): RA = $19^{\rm h}13^{\rm m}03\overset{\rm s}{.}500792(2)$, dec = $19°46'24\overset{''}{.}22891(7)$ by the VLBA at 15.2 GHz (Atri et al. 2022).

Detection with several high energy instruments have also been reported, including GeV emission with *Fermi*-LAT (potentially up to 400 GeV; Xia et al. 2022), TeV emission extending to 18 TeV from LHAASO (Huang et al. 2022), and even a suggestion of a possible association with a 250 TeV photon (Dzhappuev et al. 2022).

computed from the acquisition camera or from a broa
tometric set (de Ugarte Postigo et al. 2023, in preparati
nally, we have applied a telluric correction using mod
mated using the line-by-line radiative transfer model (LE
Clough et al. 1992) and atmospheric properties, such as
ity, temperature, pressure and zenith angle, which are s
the header of each exposure.

The observations revealed a very bright trace in the
infrared, strongly attenuated towards the blue end by t
Galactic extinction. Figure 1 shows the overall shape of t
trum and zoom-in panels highlighting specific features.

We subsequently obtained further X-shooter observa
follow the afterglow evolution. These are discussed in c
de Ugarte Postigo et al. (2023, in preparation). Among t
spectra, here we only exploit the 4 × 600 s spectrum tak
mid time 2022 Oct 20 00:19:38 UT, which provides the
tection of the emission features (Fig. 1 and Sec. 3.3).

The results reported in this paper supersede our
nary analysis (de Ugarte Postigo et al. 2022; Izzo et al
Our spectroscopic measurement was subsequently confi
Castro-Tirado et al. (2022).

The Astrophysical Journal Letters, 942:L30 (5pp), 2023 January 10 https://doi.org/10.3847/2041-8213/acac2f

Deciphering the ∼18 TeV Photons from GRB 221009A

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Received 2022 November 8; revised 2022 December 3; accepted 2022 December 9; published 2023 January 11

Abstract

On 2022 October 9, an extremely powerful gamma-ray burst, GRB 221009A, was detected by several instruments. Despite being obstructed by the Milky Way galaxy, its afterglow outburst outshone all other GRBs seen before. LHAASO detected several thousand very high energy photons extending up to 18 TeV. Detection of such energetic photons is unexpected due to the large opacity of the universe. It is possible that in the afterglow epoch, the intrinsic very high energy photon flux from the source might have increased manifolds, which could compensate for the attenuation by pair production with the extragalactic background light. We propose such a scenario and show that very high energy photons can be observed on the Earth from the interaction of very high energy protons with the seed synchrotron photons in the external forward shock region of the GRB jet.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Particle astrophysics (96)

1. Introduction

On 2022 October 9, at T0 = 13:16:59.000 UT (Veres et al. 2022), a long-duration gamma-ray burst (GRB) identified as GRB 221009A (also known as Swift J1913.1+1946) was detected in the direction of the constellation Sagitta by the Gamma-ray Burst Monitor (GBM; Meegan et al. 2009) on board the Fermi Gamma-ray Space Telescope. The prompt emission was also detected by several other space observatories, such as the Fermi Large Area Telescope (LAT), Swift (Dichiara et al. 2022; Krimm et al. 2022), AGILE (Piano et al. 2022; Ursi et al. 2022), INTEGRAL (Gotz et al. 2022), Solar Orbiter (Xiao et al. 2022), SRG (Lapshov et al. 2022), Konus (Frederiks et al. 2022), GRBAlpha (Ripa et al. 2022), and STPSat-6 (Mitchell et al. 2022). The GRB 221009A is located at the coordinate R.A. = 288.282 and decl. = 19.495 (Pillera et al. 2022). Fermi-LAT detected the most energetic photon of energy, 99.3 GeV (at $t_0 + 240$ s). It is the highest-energy photon ever detected by Fermi-LAT from a GRB in the prompt phase (Bissaldi et al. 2022; Pillera et al. 2022). The afterglow emission was also observed at different wavelengths (Das &

detector observed more than 5000 very high energy (VHE) photons within $T_0 + 2000$ s in the 500 GeV–18 TeV energy range, making them the most energetic photons ever observed from a GRB (Huang et al. 2022). Surprisingly, the ground-based Cherenkov detector Carpet-2 at Baksan Neutrino Observatory reported the detection of what is undoubtedly a very rare air shower originating from a 251 TeV photon 4536 s after the GBM trigger from the direction of GRB 221009A (Dzhappuev et al. 2022). Observations of these unusually VHE gamma rays by LHAASO and Carpet-2 from GRB 221009A are incomprehensible and led to speculation about nonstandard physics explanations of these observed events. However, there is a caveat concerning the observation of the 251 TeV gamma ray. The angular resolution of Carpet-2 is several degrees, and the two previously reported Galactic VHE sources, 3HWC J1928+178 and LHASSO J1929+1745, are located close to the position of GRB 221009A (Fraija & Gonzalez 2022). It remains uncertain whether the observed 251 TeV photon is from GRB 221009A or either of these Galactic sources. Nevertheless, the temporal and spatial coincidence of this event

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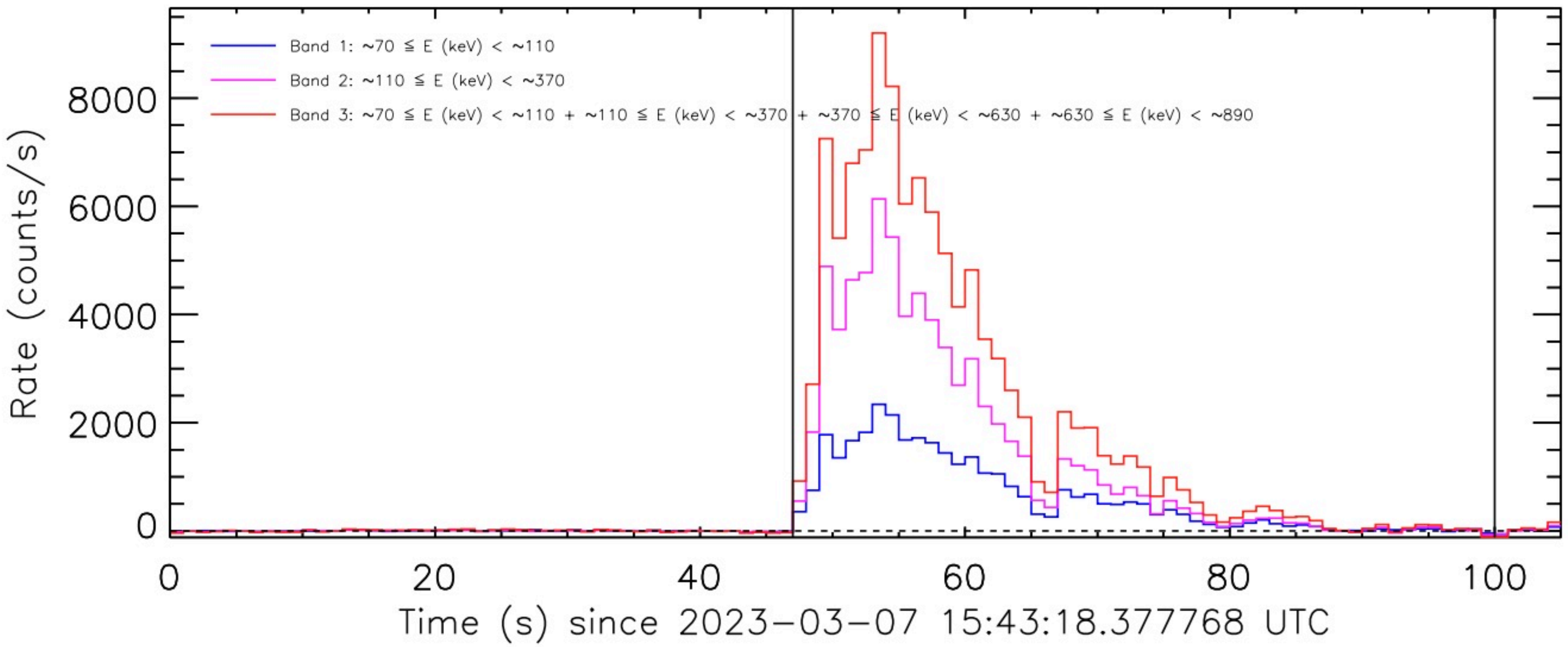
ground light (EBL; (*4*,*5*)).

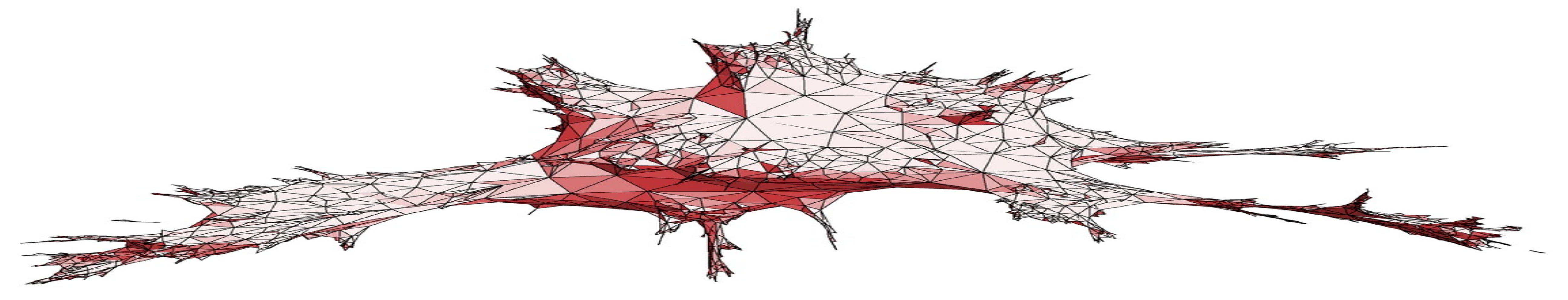
$10^{-7} - 10^{-4}$ erg cm^{-2} (*1*) and spectra up to the MeV or, less frequently, GeV range (*6*).

On October 10, 2022 at 13:16:59 UT (hereafter referred to as T_0), the Gamma-ray Burst Monitor (GBM) aboard *Fermi* (*7, 8*), among many other high-energy satellites (*INTEGRAL*, *Konus-Wind*, *AGILE*, *SRG*, *GRBAlpha*, *HEBS*; (*9*–*13*)), detected an unprecedented, extremely bright burst lasting hundreds of seconds. This burst, dubbed GRB 221009A, is the brightest GRB ever detected in nearly 55 years of operating gamma-ray observatories, with an observed fluence of $\approx 5\times10^{-2}$ erg cm^{-2} in the 20 keV − 10 MeV band, more than an order of magnitude brighter than GRB 840304 and GRB 130427A (*14*), the previous record holders (Fig. 1). Its high-energy radiation was so intense that it disturbed Earth's ionosphere (*15, 16*).

GRB 230307A the second brightest burst ever!



QUANTUM GRAVITY EXPERIMENT



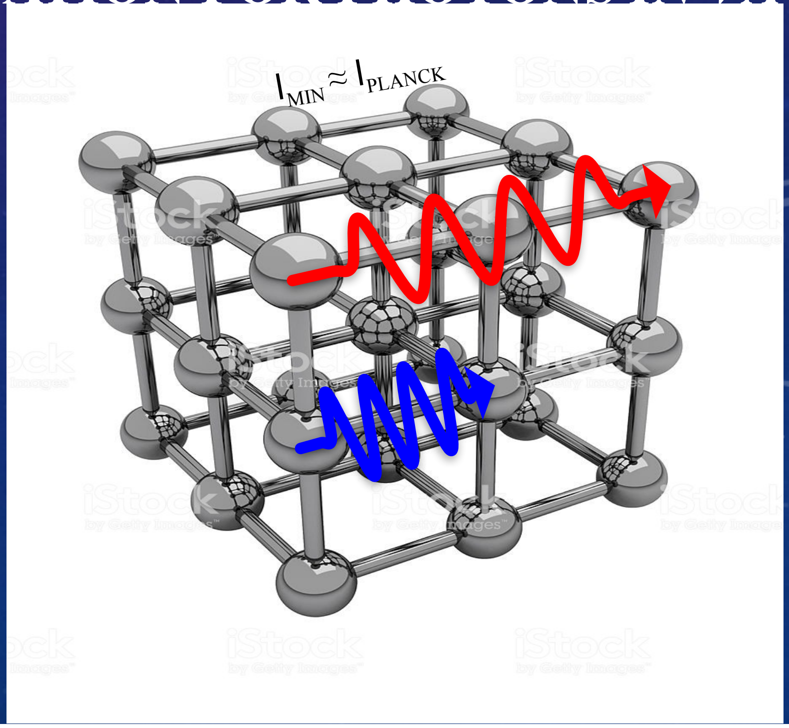
QUANTUM GRAVITY
MINIMAL LENGTH HYPOTHESIS, LIV AND DISPERSION RELATION FOR PHOTONS *IN VACUO*

Existence of a Minimal Length (String theories, etc.)

$$l_{MIN} \approx l_{PLANCK} = [Gh/(2\pi c^3)]^{1/2} = 1.6 \times 10^{-33}\ \text{cm}$$

implies:

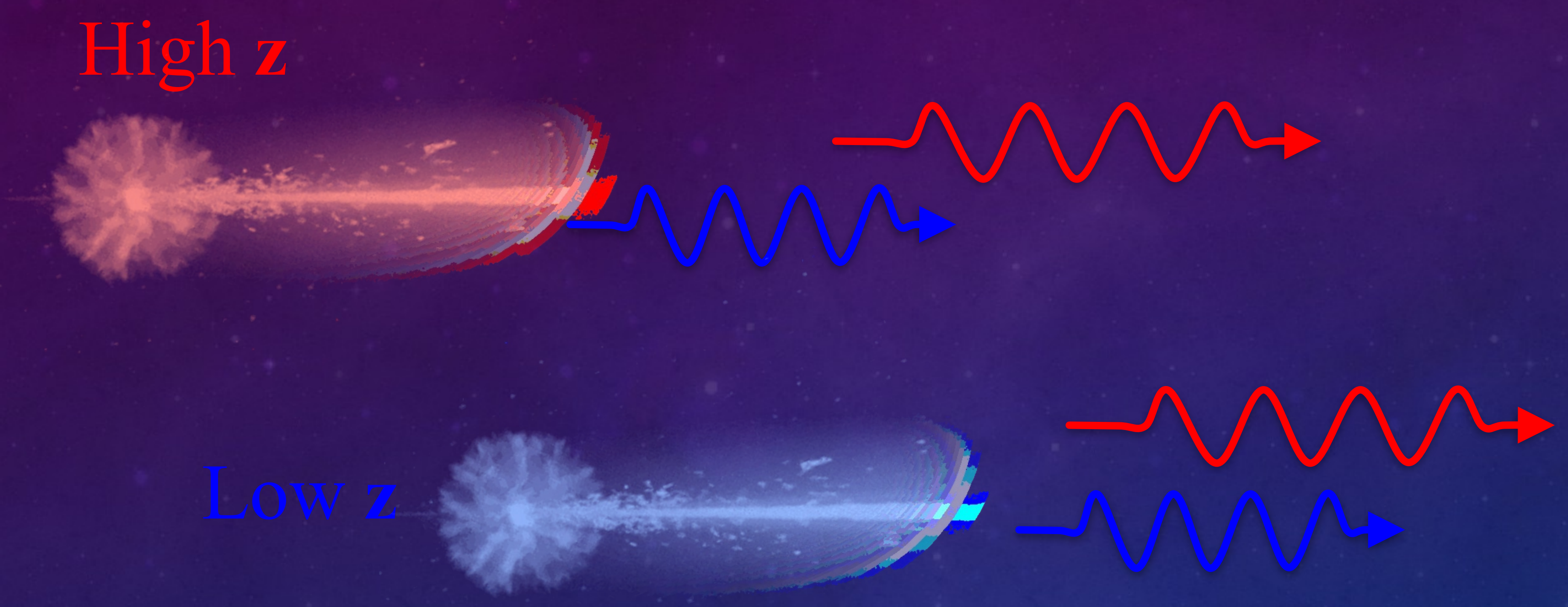
i) Lorentz Invariance Violation (LIV): no further Lorentz contraction
ii) Space has the structure of a crystal lattice
iii) Existence of a dispersion law for photons *in vacuo*



By Andrea Sanna

QUANTUM GRAVITY EXPERIMENT

THE ENERGY AND REDSHIFT DELAY DEPENDENCE



Time lags caused by Quantum Gravity effects:

- $\propto |E_{phot}(\text{Band II}) - E_{phot}(\text{Band I})|$
- $\propto D_{TRAV}(z_{GRB})$

Time lags caused by prompt emission mechanism:

- complex dependence from E_{phot}(Band II) and E_{phot}(Band I)
- independent of $D_{TRAV}(z_{GRB})$

By Andrea Sanna