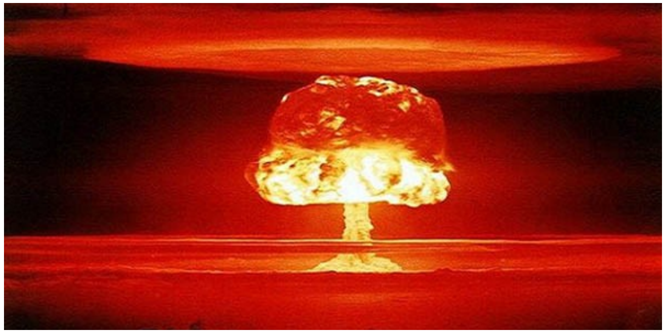
Gamma-Ray Bursts

The discovery of GRBs



Discovered by Vela satellites, launched by US Air Force to monitor the ban of **nuclear tests** in atmosphere and space

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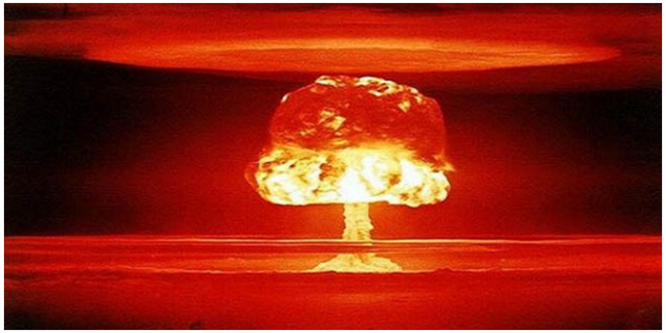

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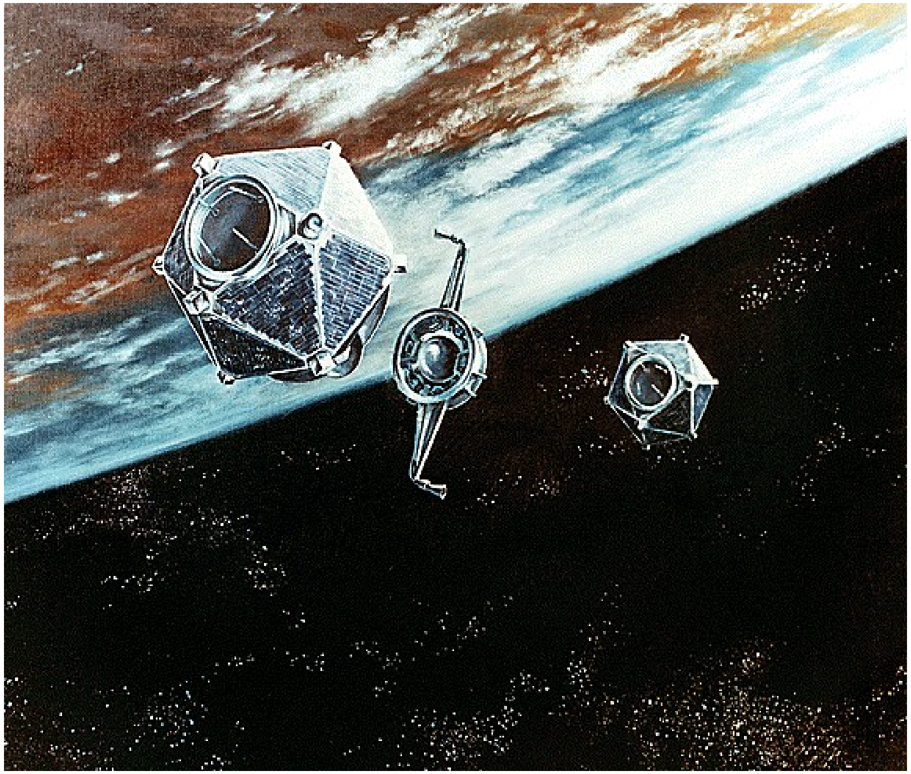

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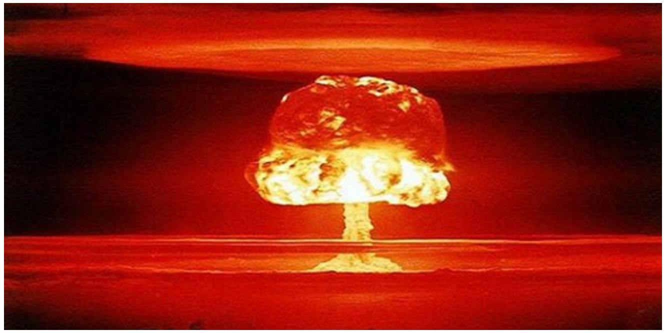

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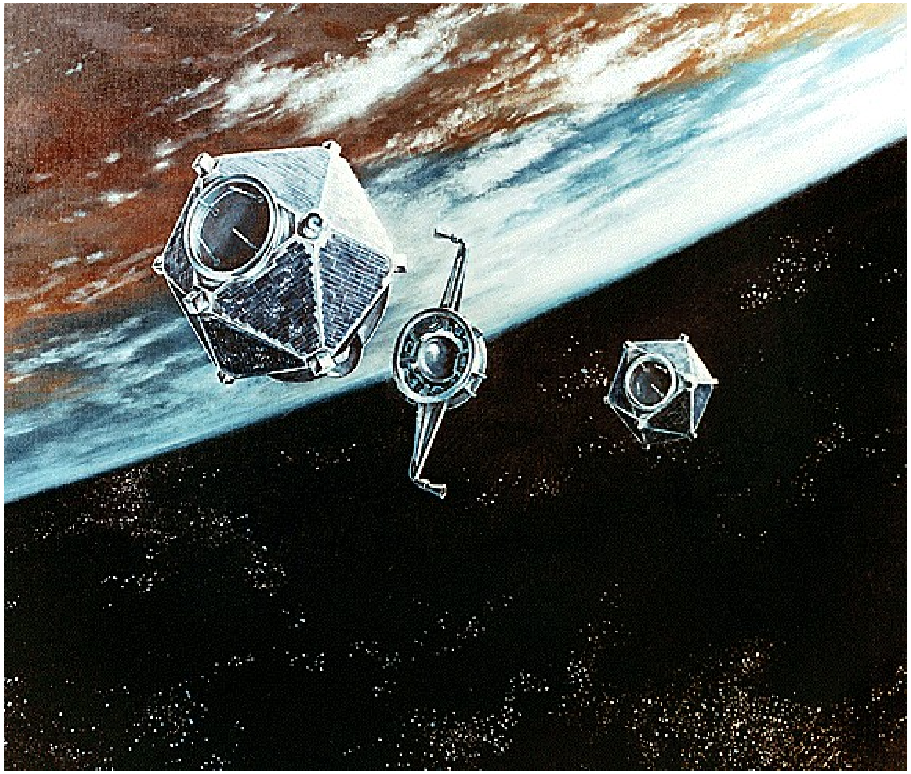

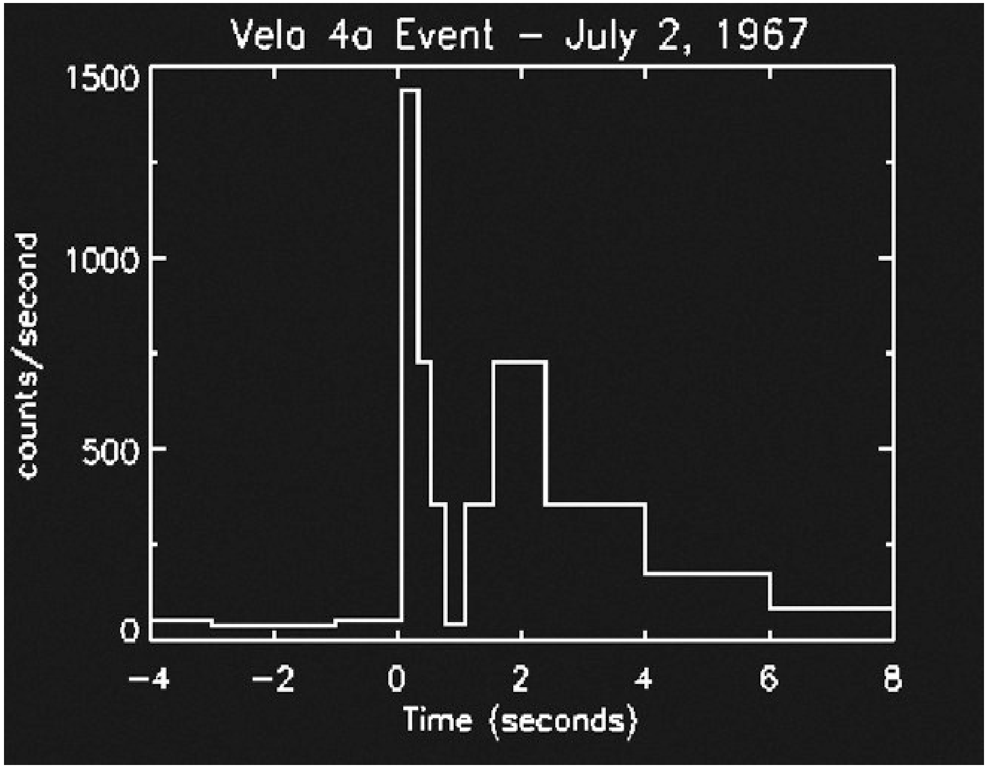

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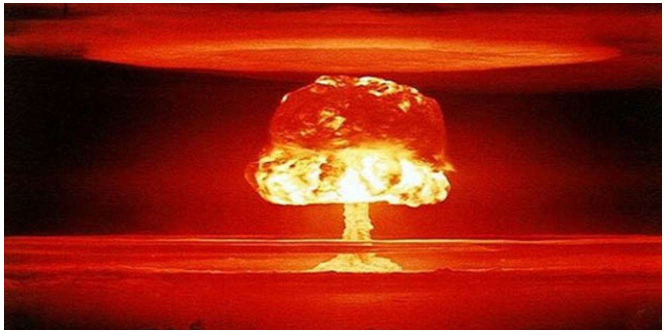

Discovered by Vela satellites, launched by US Air Force to monitor the ban of **nuclear tests** in atmosphere and space

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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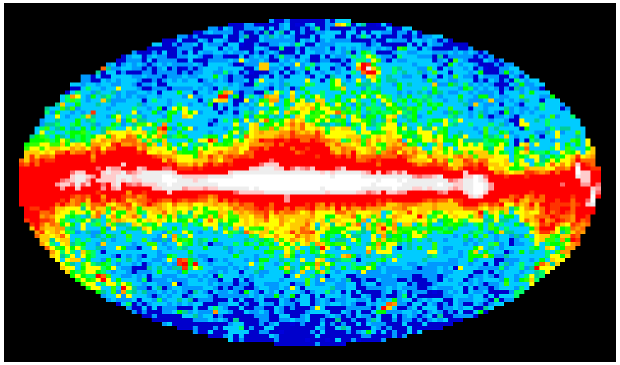
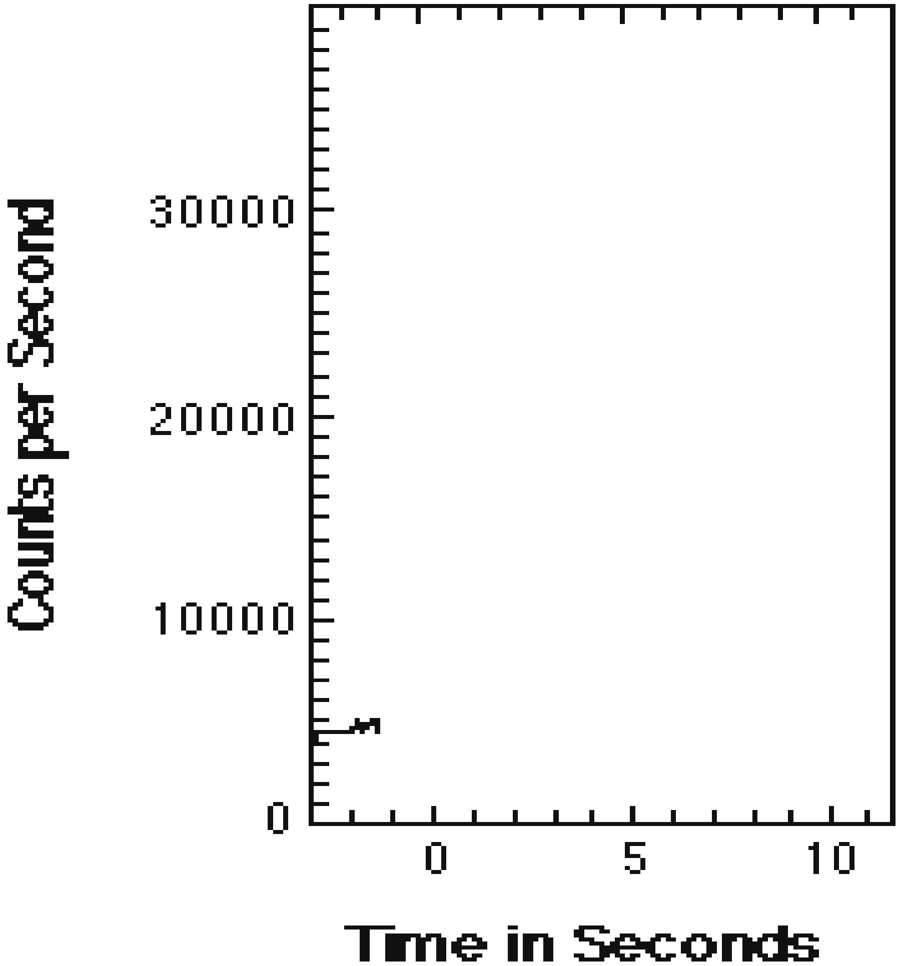
ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to $\sim$30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

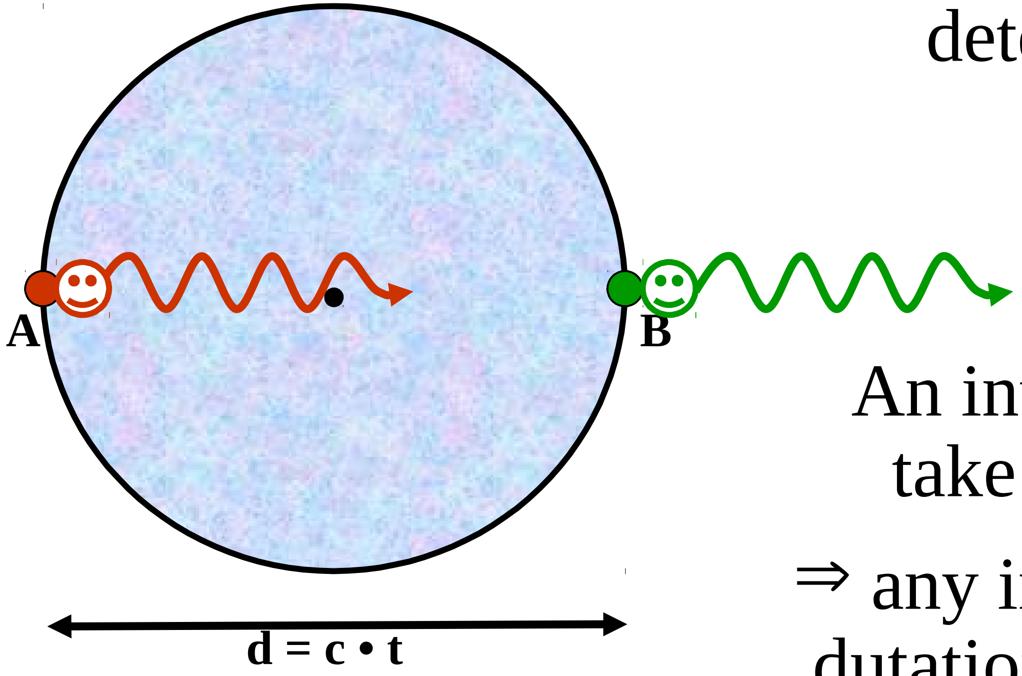
Gamma-Ray Bursts (GRBs)





Short (~1-100 s) and
bright (even brighter than the whole sky!) bursts of
gamma-rays

Time scale → size



If photons **A** and **B** are emitted simultaneously, **A** will be detected later than **B**, with a time delay: $t = d/c$

An intensity change from **A** will take a time $t=d/c$ to reach **B**

⇒ any intensity variation with time dutation ***t*** must have been emitted from a region of size:

$$d<c\bullet t$$

Fluence and Luminosity

Fluence = Flux * time = 1e-6 – 1e-4 erg / cm

Luminosity depends on distance

Where they came from ?

The Solar System →

The Galaxy →

Other Galaxies →

Fluence and Luminosity

Fluence = Flux * time = 1e-6 – 1e-4 erg / cm

Luminosity depends on distance

Where they came from ?

The Solar System → D ~ 1e14 cm → L ~ 1e25 erg

The Galaxy →

Other Galaxies →

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Luminosity depends on distance

Where they came from ?

The Solar System → D ~ 1e14 cm → L ~ 1e25 erg

The Galaxy → D ~ 1e21 cm → L ~ 1e39 erg

Other Galaxies →

Fluence and Luminosity

Fluence = Flux * time = 1e-6 – 1e-4 erg / cm

Luminosity depends on distance

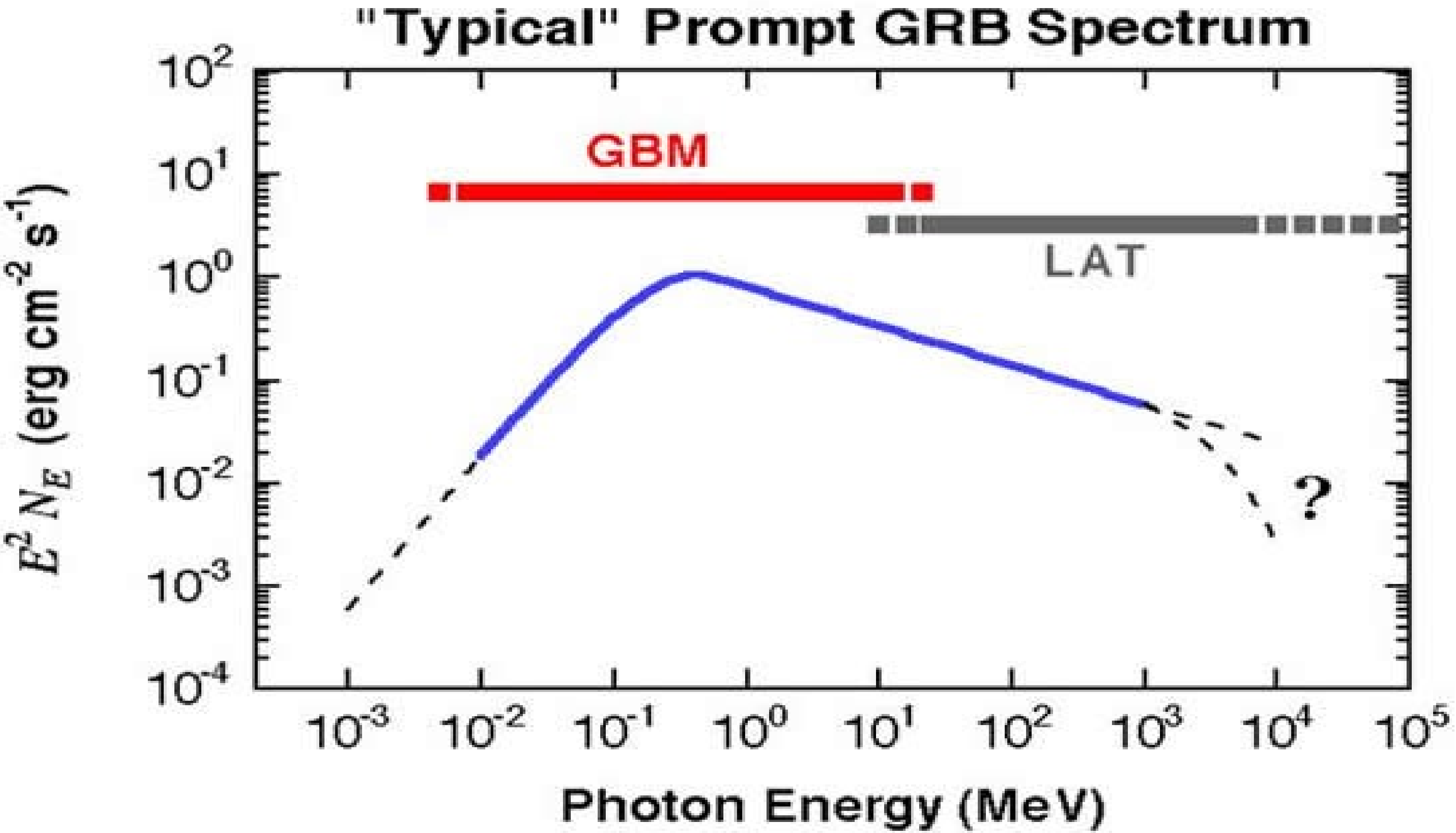
Where they came from ?

The Solar System	→	D ~ 1e14 cm	→	L ~ 1e25 erg
The Galaxy	→	D ~ 1e21 cm	→	L ~ 1e39 erg
Other Galaxies	→	D ~ 1e27 cm	→	L ~ 1e51 erg

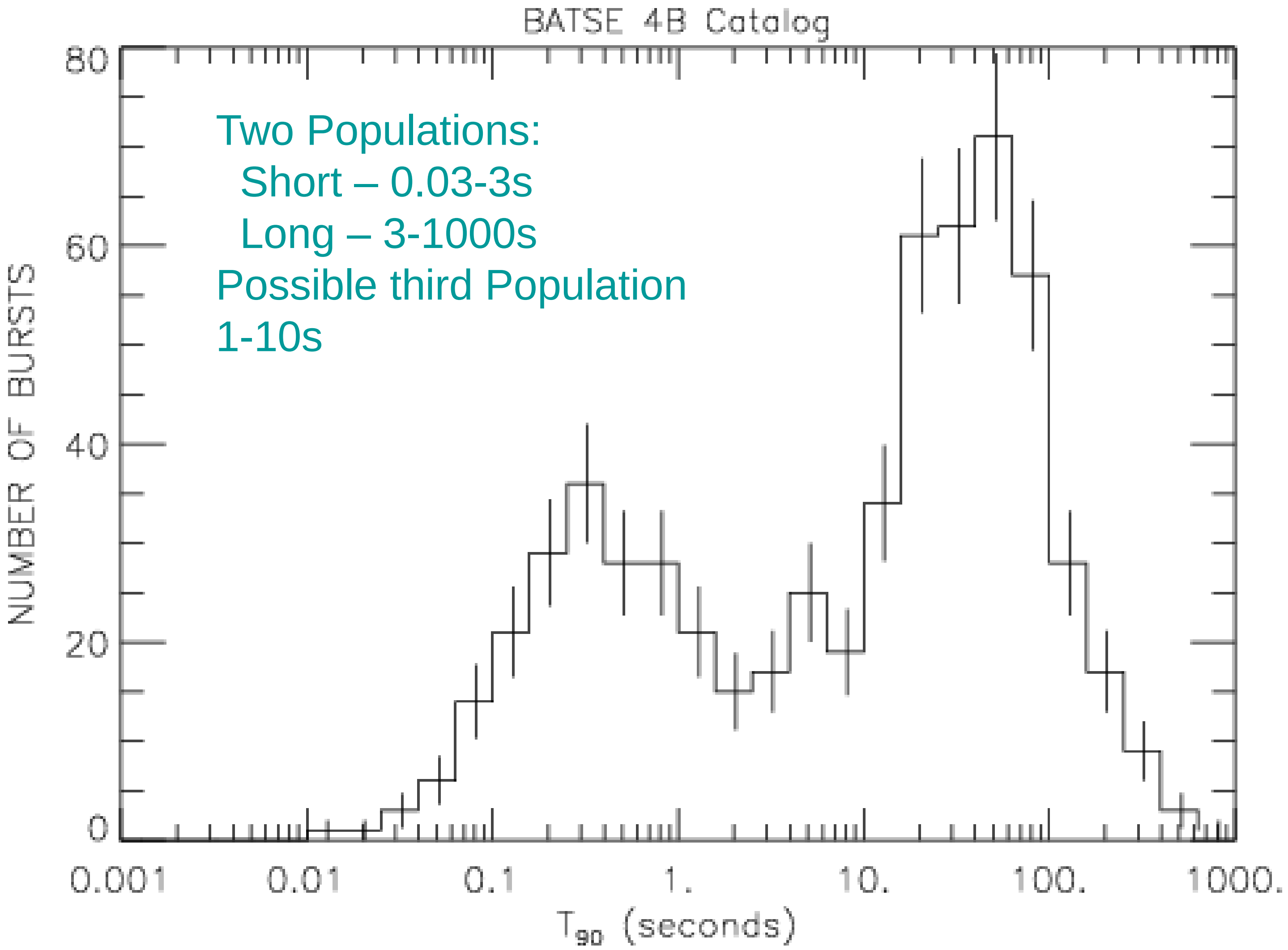
Spectrum

Peak ~ 0.1 - 1 MeV

$$N(E) = E^{\alpha} \cdot e^{-\frac{E}{E_0}} ((\alpha - \beta) E_0)^{\alpha-\beta} E^{\beta} e^{\alpha-\beta}$$



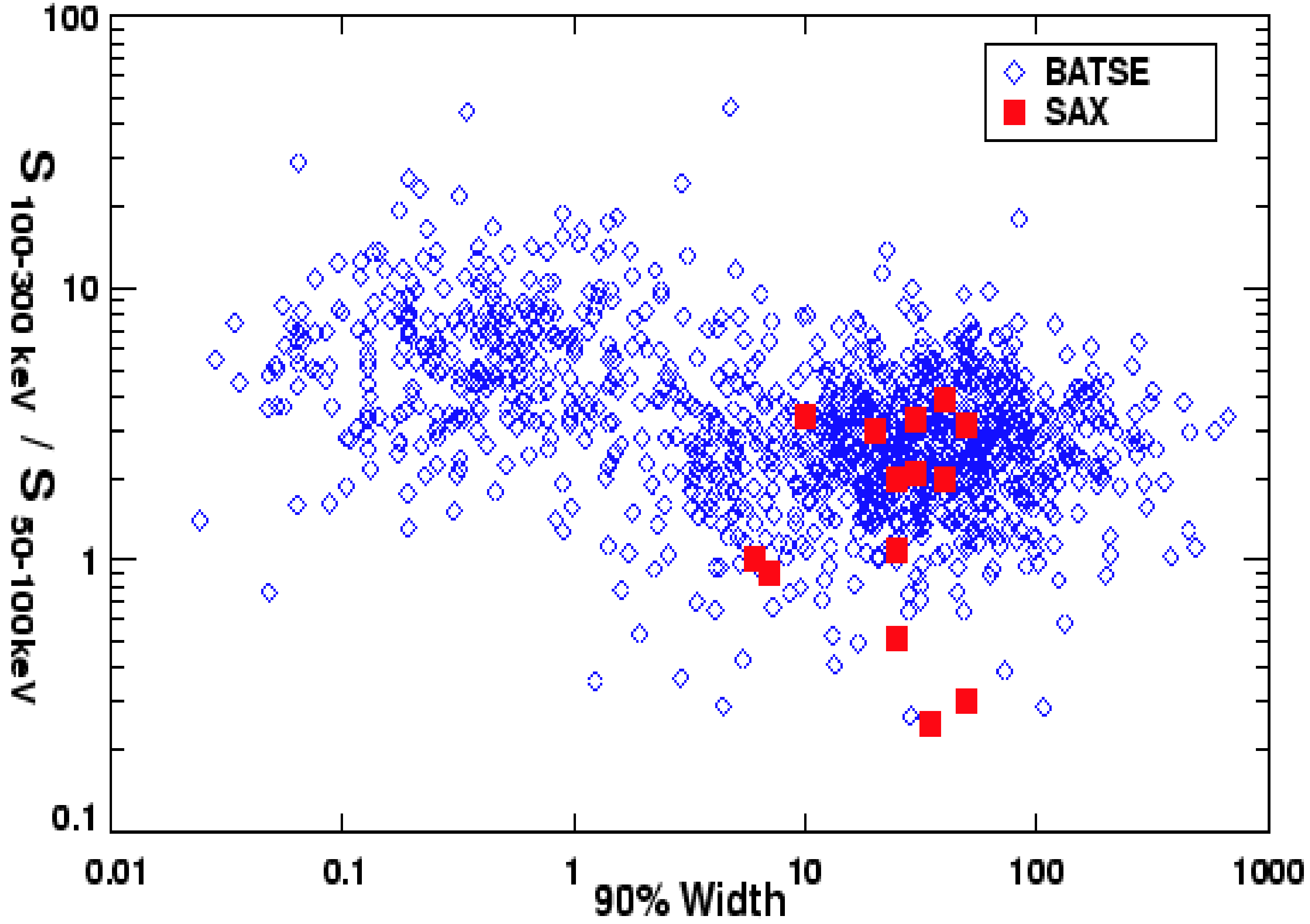
Durations



Bimodal T90 dist

Short/hard vs Long/Soft

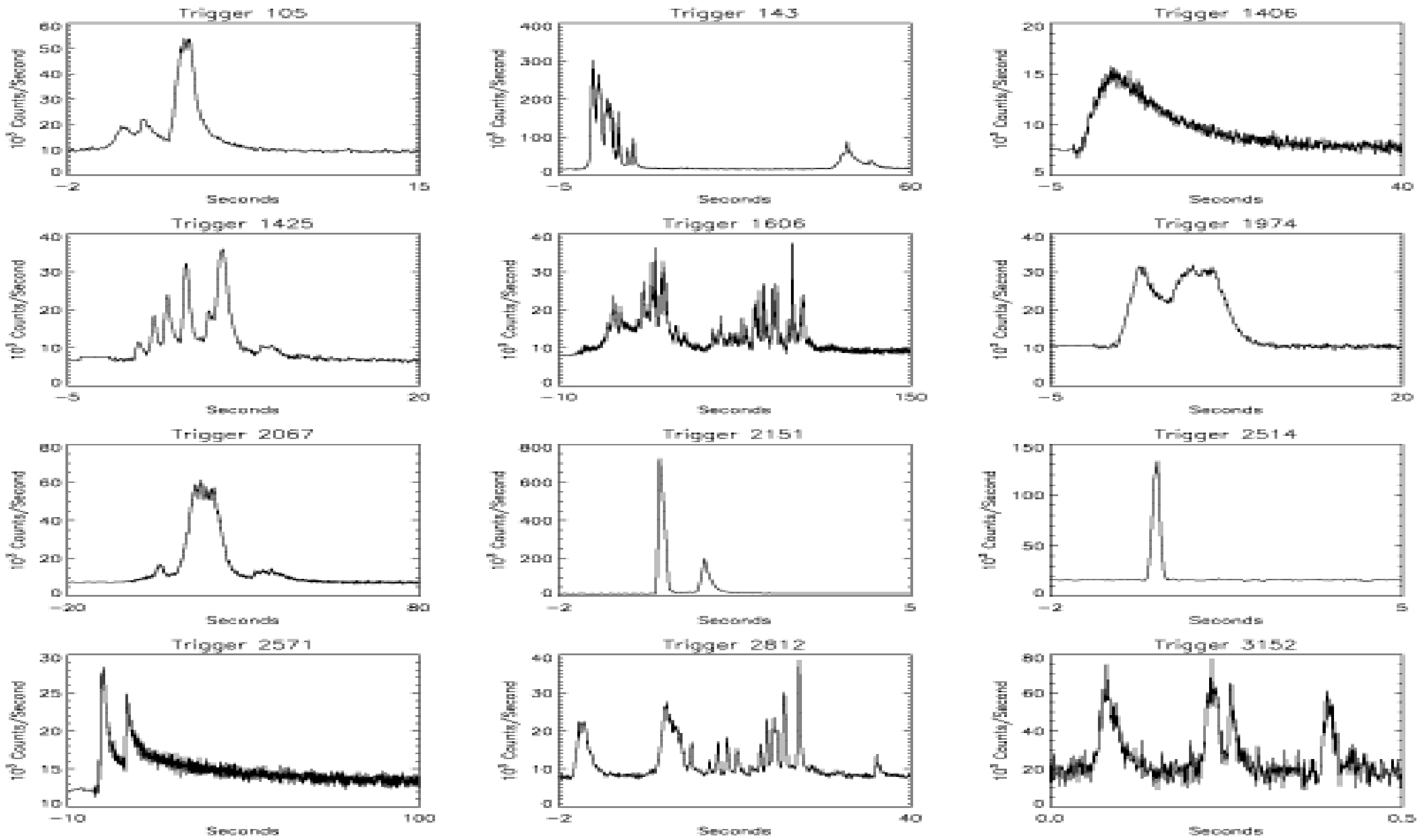
Durations



Bimodal T90 distribution

Short/hard vs Long/Soft

Light Curves

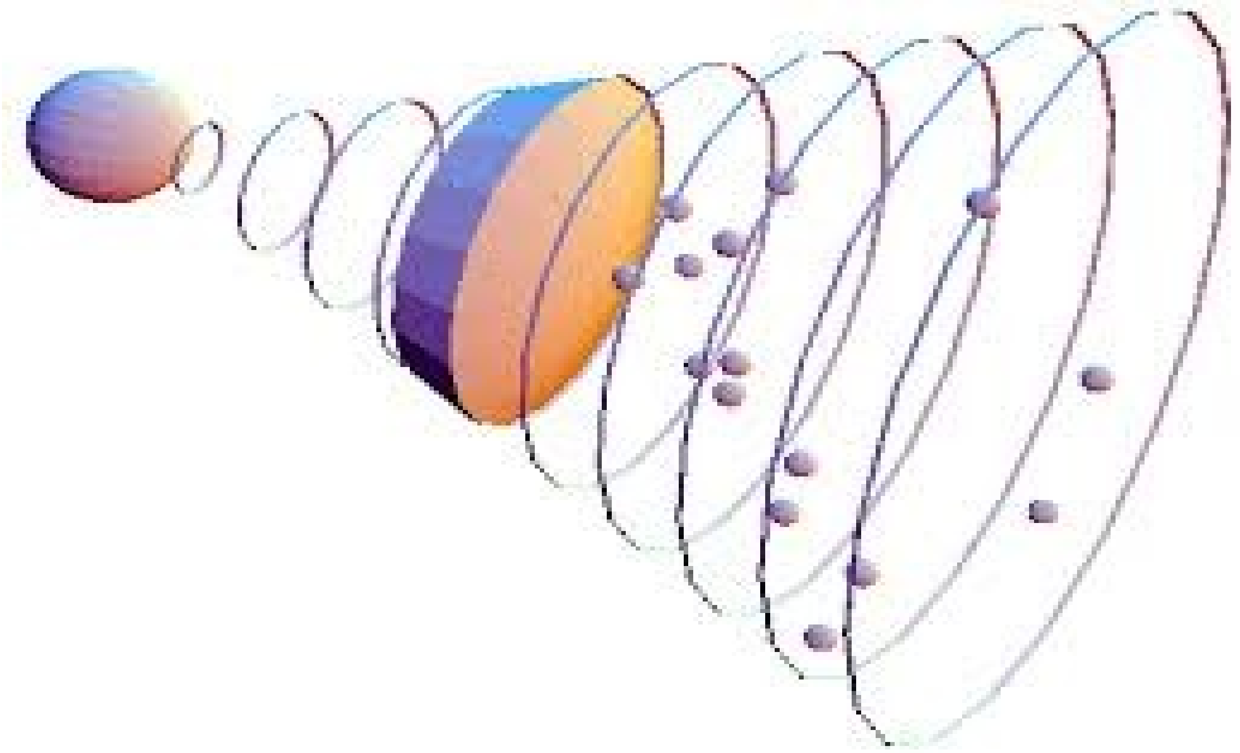


Rapid varibility (Dob. Time ~ 1e-2 s) → size

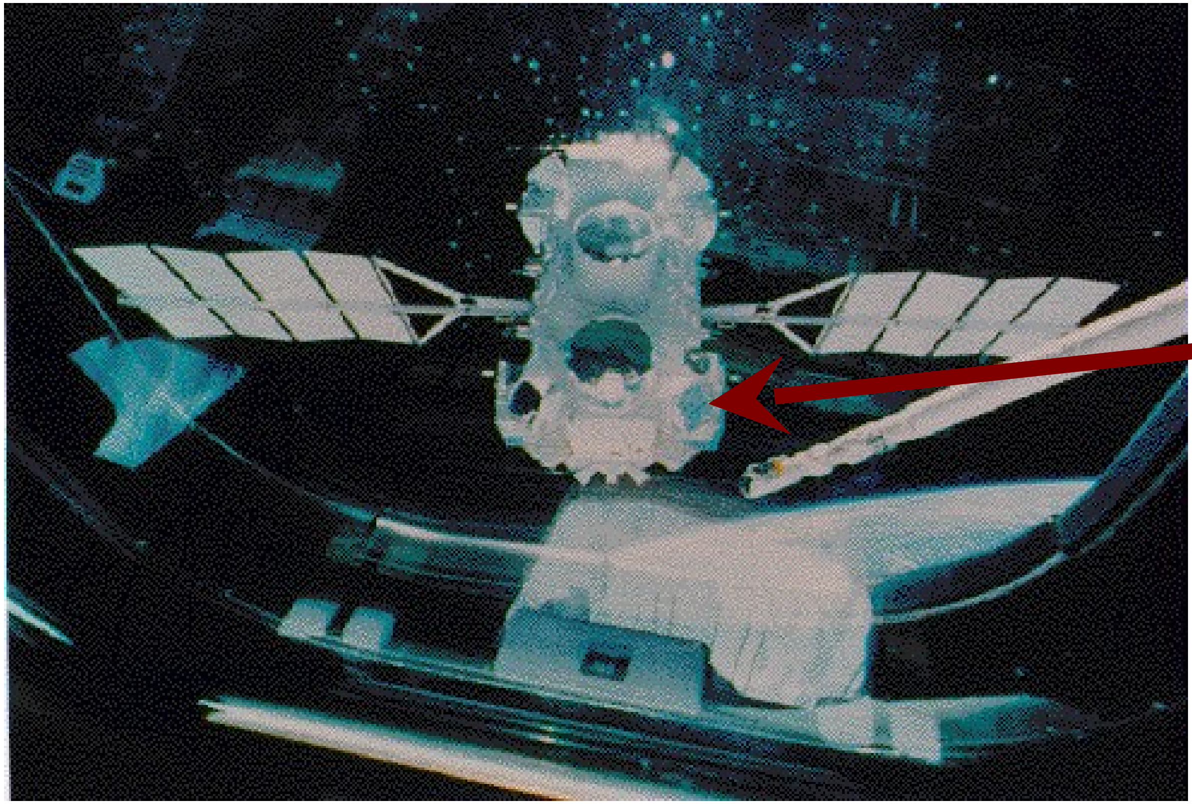
Multiple peaks , often fred-like

When you see a GRB you have seen one GRB

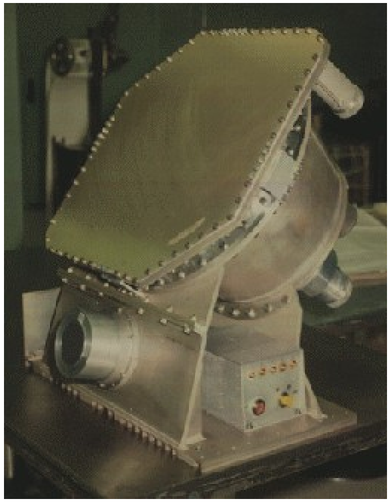
Compactness problem



GCRO / Batse

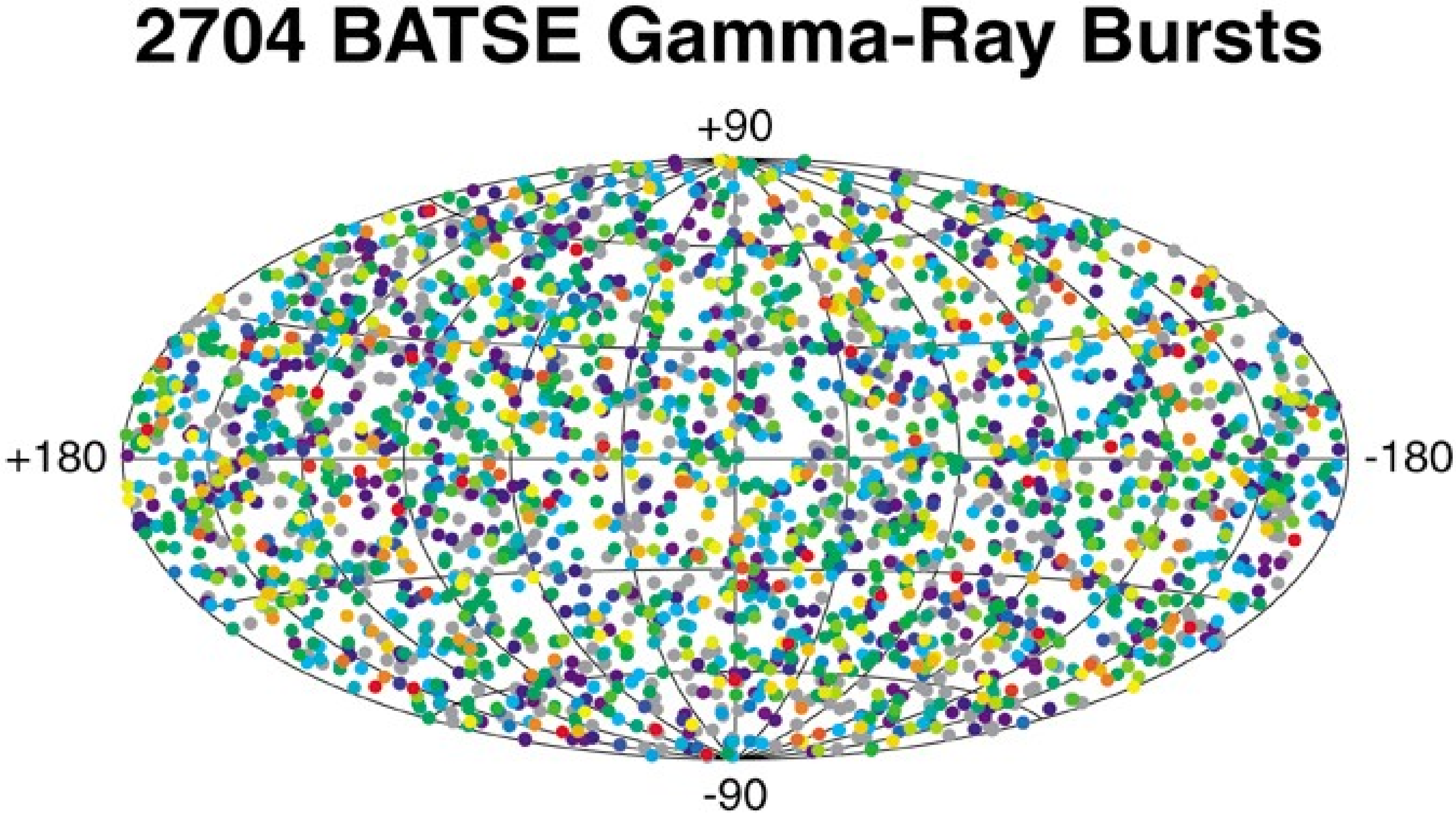


BATSE Module



8 Detectors
- Almost Full Sky Coverage
- Few Degree Resolution
- 20-600keV

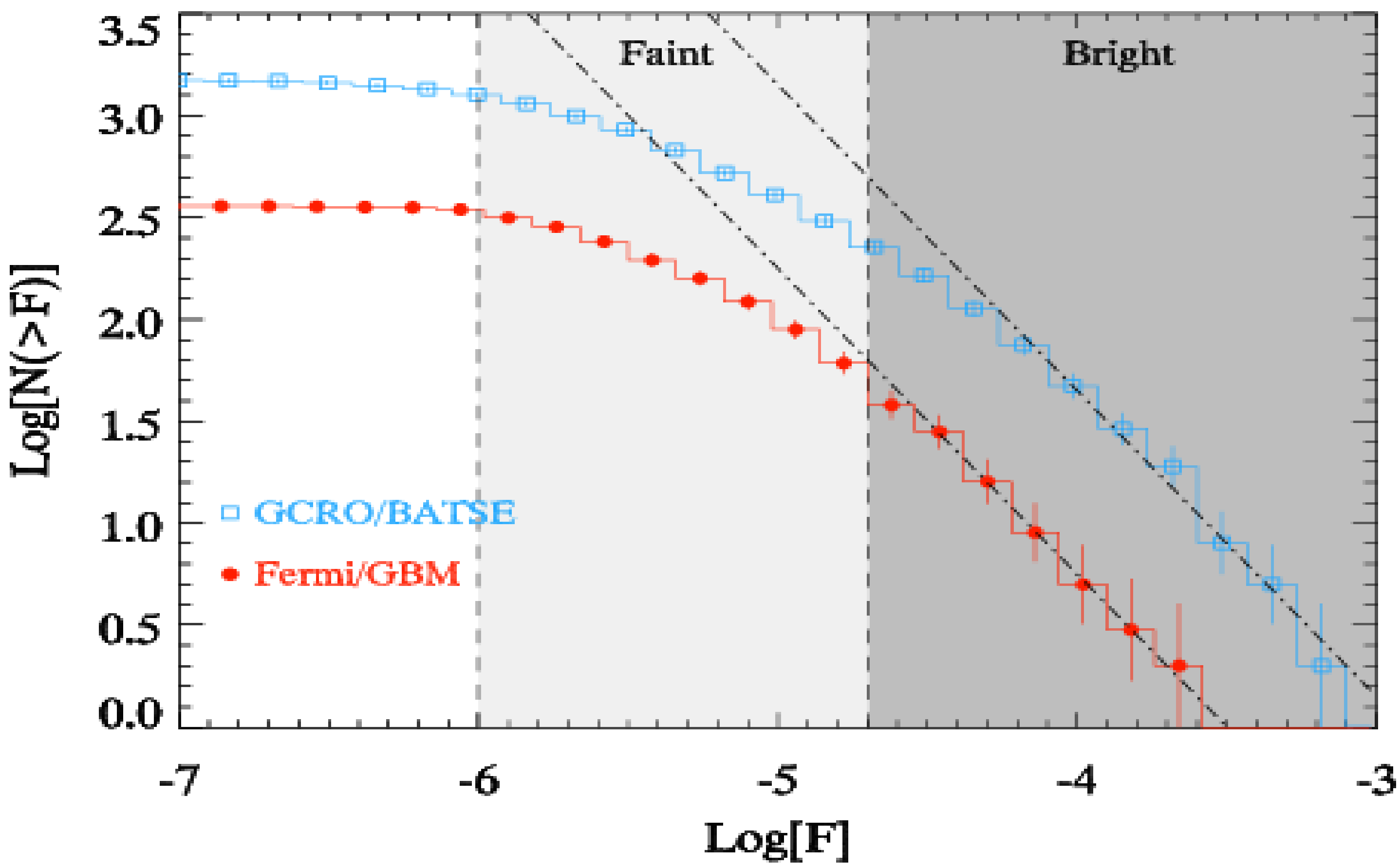
BATSE Consists of two NaI(TI) Scintillation Detectors: Large Area Detector (LAD) For sensitivity and the Spectroscopy Detector (SD) for energy coverage



Isotropic distribution, in contrast with most (Galactic) models

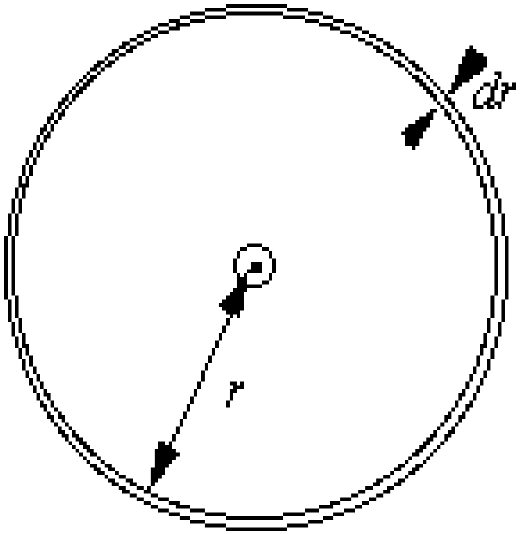
→ at cosmological distances or very nearby

LogN – LogS



Faint
Bright
GCRO/BATSE
Fermi/GBM
Log[N(>F)]
Log[F]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-7
-6
-5
-4
-3

LogN – LogS



$$f = \frac{L}{4\pi r^2} \quad \Rightarrow \frac{df}{dr} \propto r^{-3} \text{ and } r \propto f^{-1/2}$$

$$n(f)\, df = n\, 4\pi r^2\, dr$$

$$\Rightarrow n(f) = n\, 4\pi r^2 \left|\frac{dr}{df}\right|$$
$$= const\ f^{-5/2}$$

So, the number of GRBs brighter than f is

$$N(>f) = \int_f^\infty n(f)\, df = const\ f^{-3/2}$$

Theoretical input

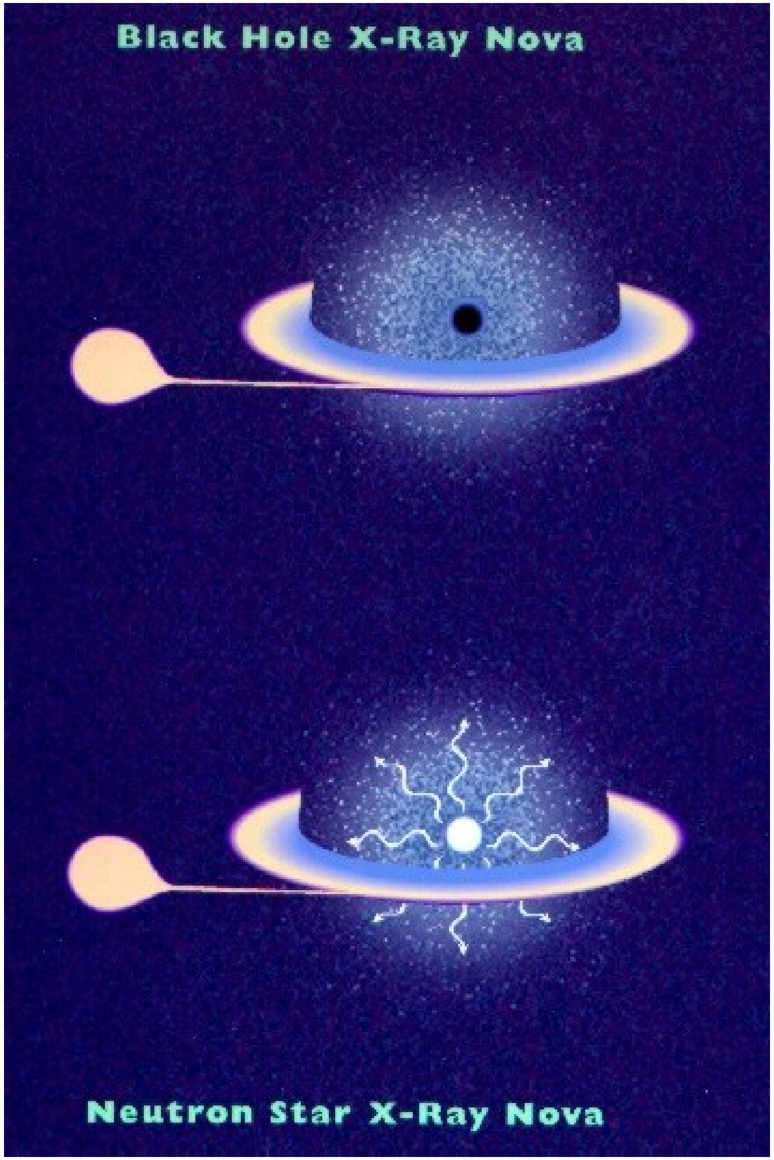
Gamma-Ray Bursts in the Solar System

- Lightning in the Earth's atmosphere (High Altitude)
- Relativistic Iron Dust Grains
- Magnetic Reconnection in the Heliopause

Red Sprite Lightning

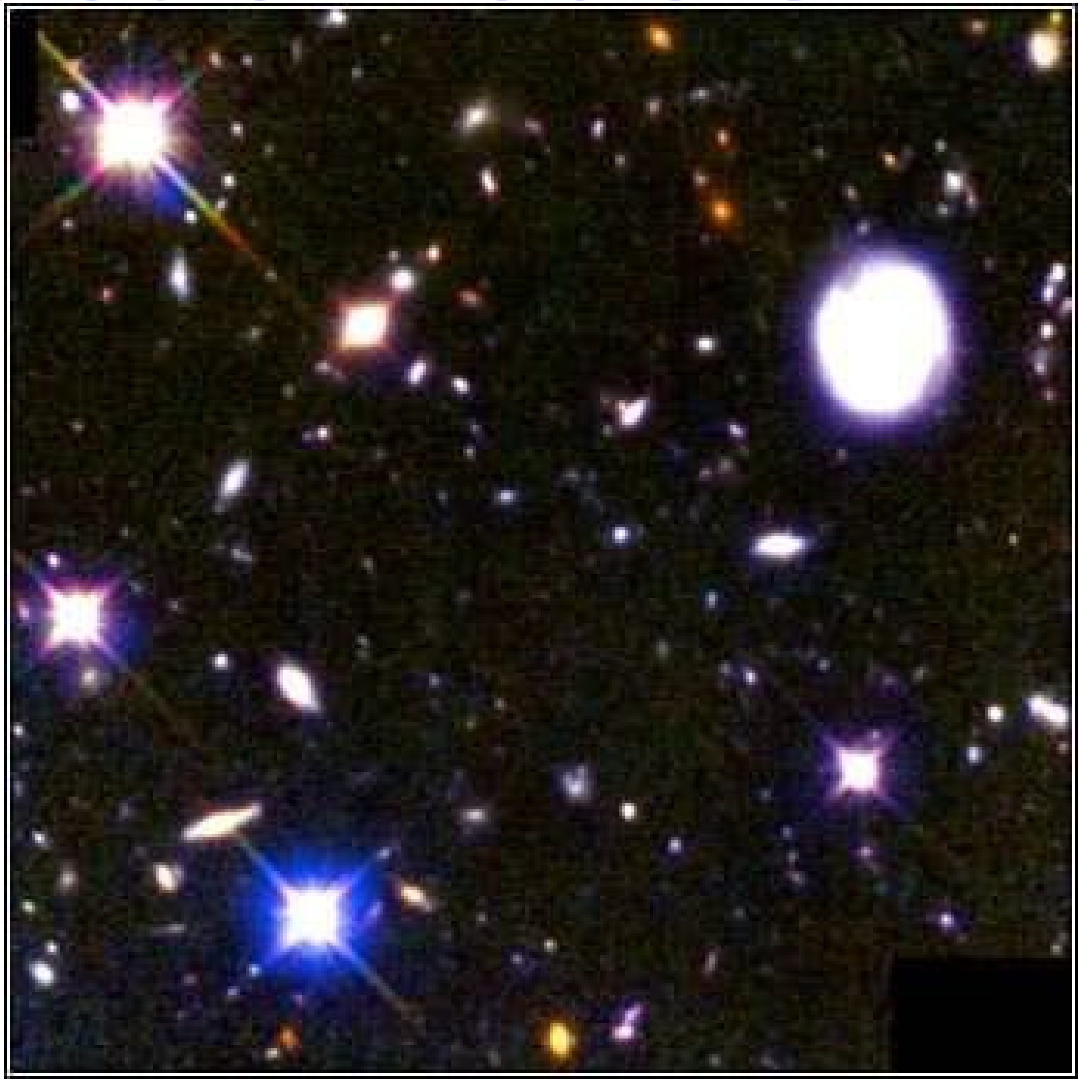
Gamma-Ray Bursts in the Milky Way

- Accretion Onto White Dwarfs
- Accretion onto neutron stars
  I) From binary companion
  II) Comets
- Neutron Star Quakes
- Magnetic Reconnection



Extragalactic Models

- Large distances means large energy requirement (10^{51}erg)
- Event rate rare (10^{-6}-10^{-5} per year in an L_* galaxy) – Object can be exotic

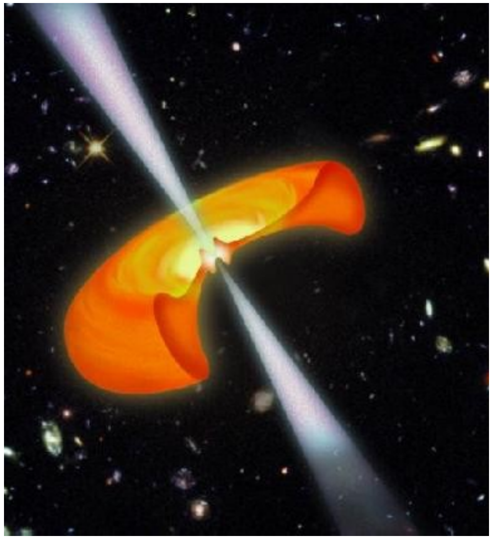


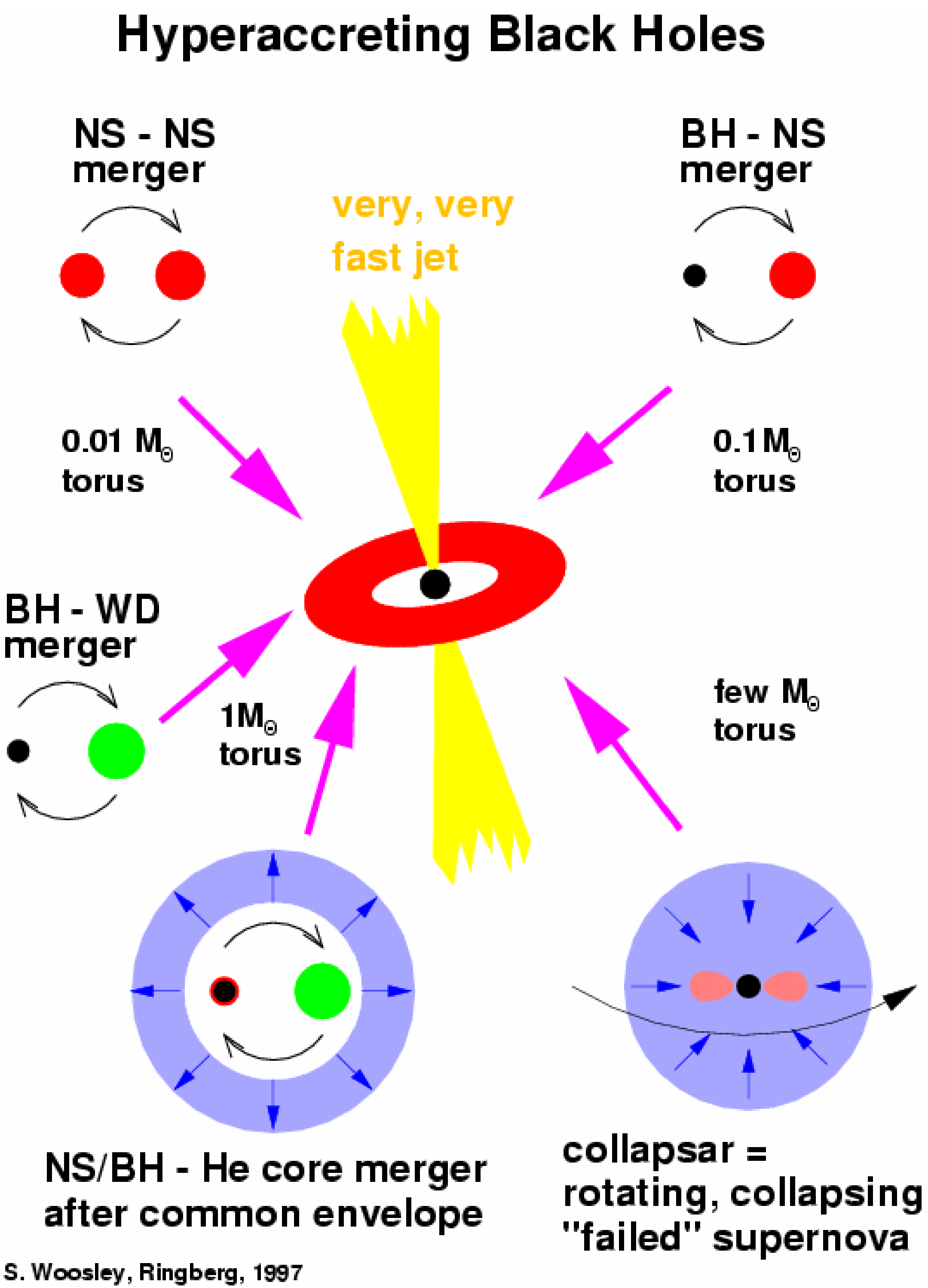
Cosmological Models

- Collapsing WDs
- Stars Accreting on AGN
- White Holes
- Cosmic Strings
- Black Hole Accretion Disks
  - I) Binary Mergers
  - II) Collapsing Stars

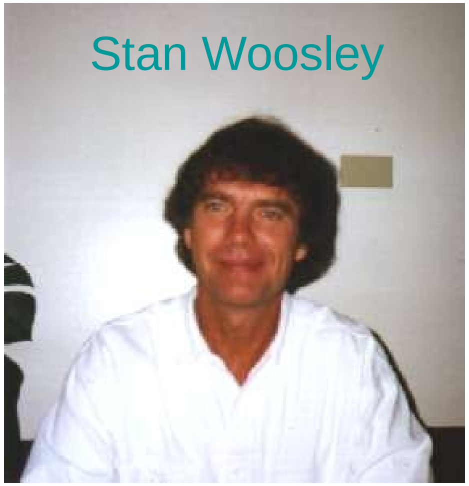
Black-Hole Accretion Disk (BHAD) Models

Binary merger or Collapse of rotating Star produces Rapidly accreting Disk (>0.1 solar Mass per second!) Around black hole.



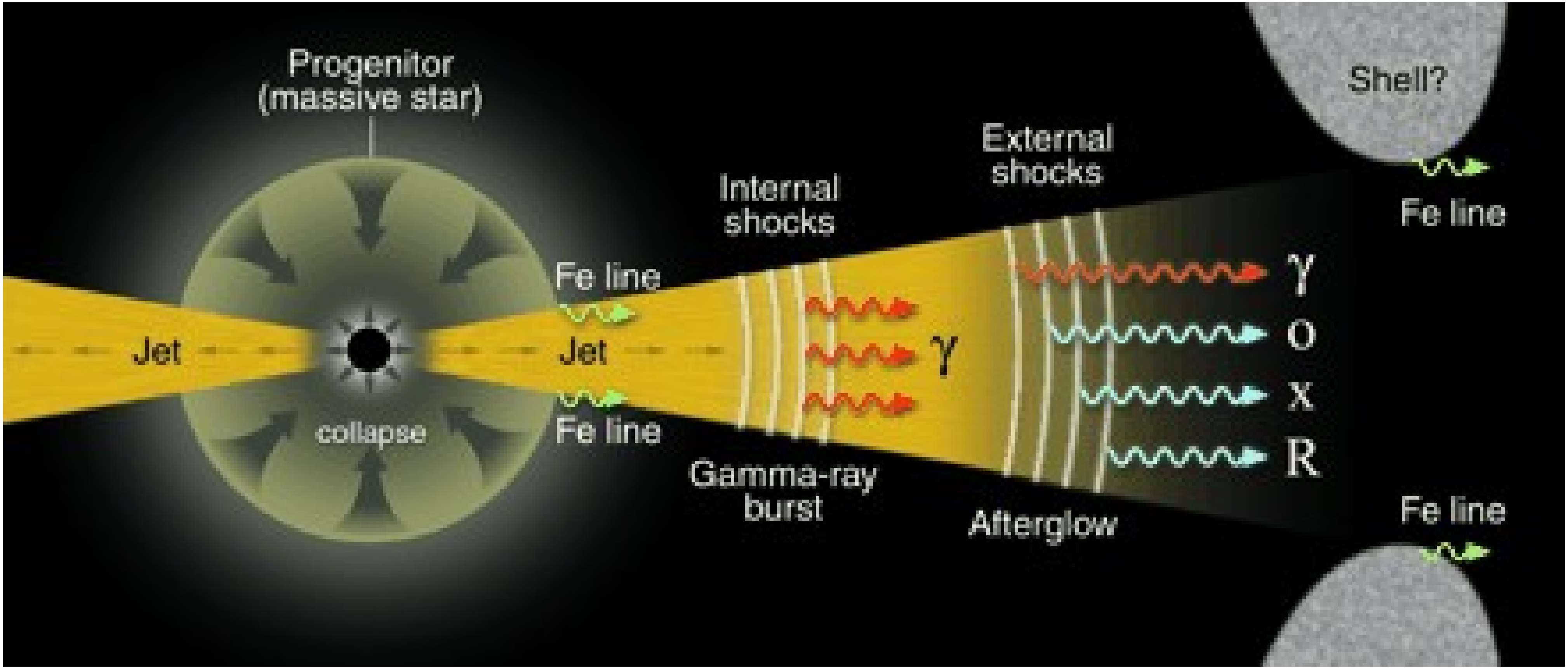


Massive Star Collapse

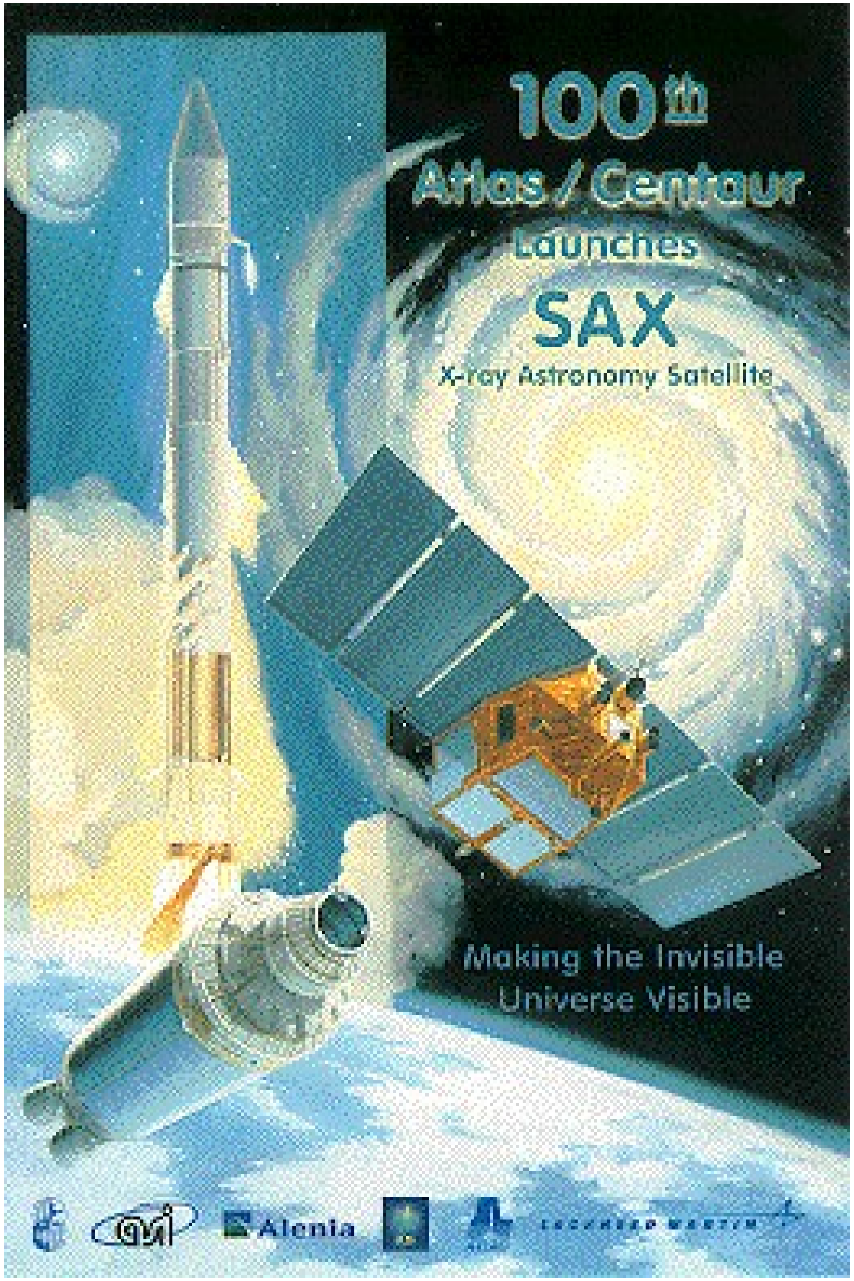


Collapsar Model – Collapse of a Rotating Massive Star into a Black Hole

Main Predictions: Beamed Explosion, Accompanying supernova-like explosion



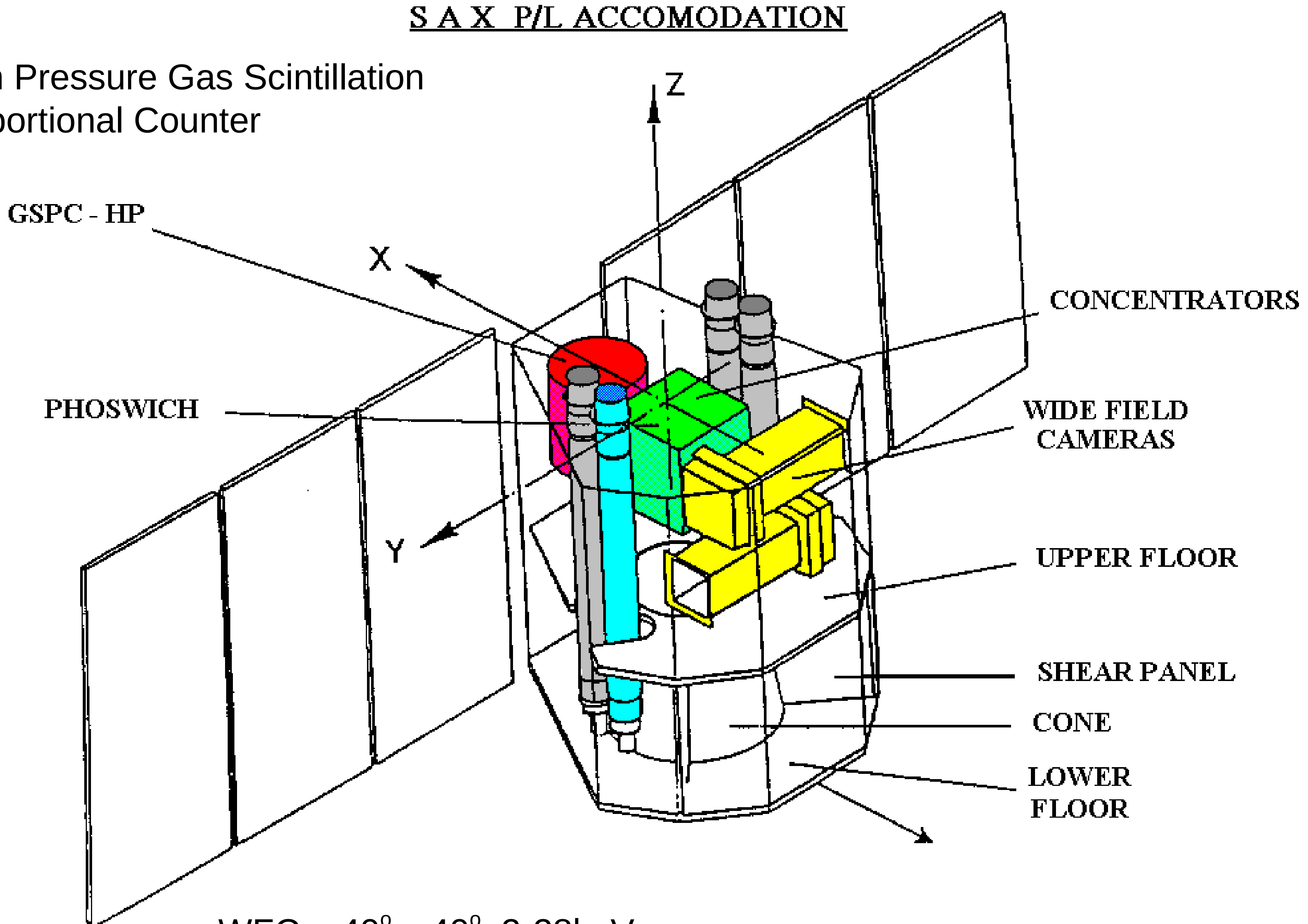
BeppoSAX



Italian-Dutch Satellite
Launch: April 30, 1996
Goal: Positional Accuracy
<5 arc minutes

Honoring Giuseppe Occhialini

High Pressure Gas Scintillation Proportional Counter



WFC – 40^o x 40^o, 2-28keV

BeppoSAX Instruments

LECS/MECS

- Xenon Gas Scintillator
- Energy Range: .1-1keV (1-10keV)
- ~1 arc minute resolution
- Goal – Localize Object

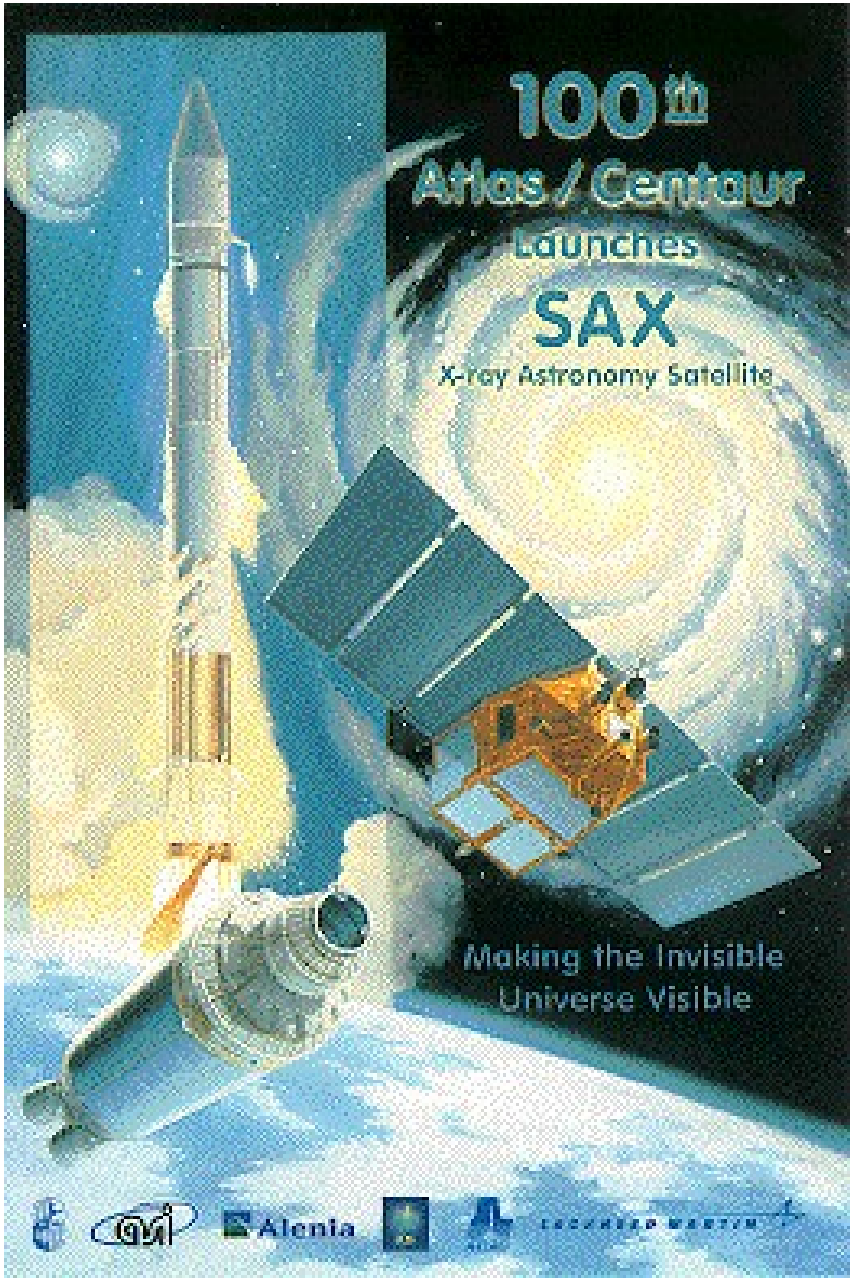
HPGSPC PDS

- HPGSPC - High Pressure Xenon/He Gas
- PDS Phoswitch - NaI(Tl), CsI(Na) Scintillators
- 4-120keV (15-300keV)
- Goal – Broad Energy resolution in X-ray narrow field

Italy in space

- ✓ X-ray astronomy pioneers (rocket in 1962 and *Uhuru* satellite in 1972): **Bruno Rossi** (1905-1993) and **Riccardo Giacconi** (1931-, Nobel in 2002)
- ✓ 3rd country launching a **satellite** (San Marco 1, 1964)
- ✓ One of the few countries with 2 national astronomy space missions: ***BeppoSAX*** (X-rays; 1996-2002) and ***AGILE*** (gamma-rays; 2007-)

BeppoSAX



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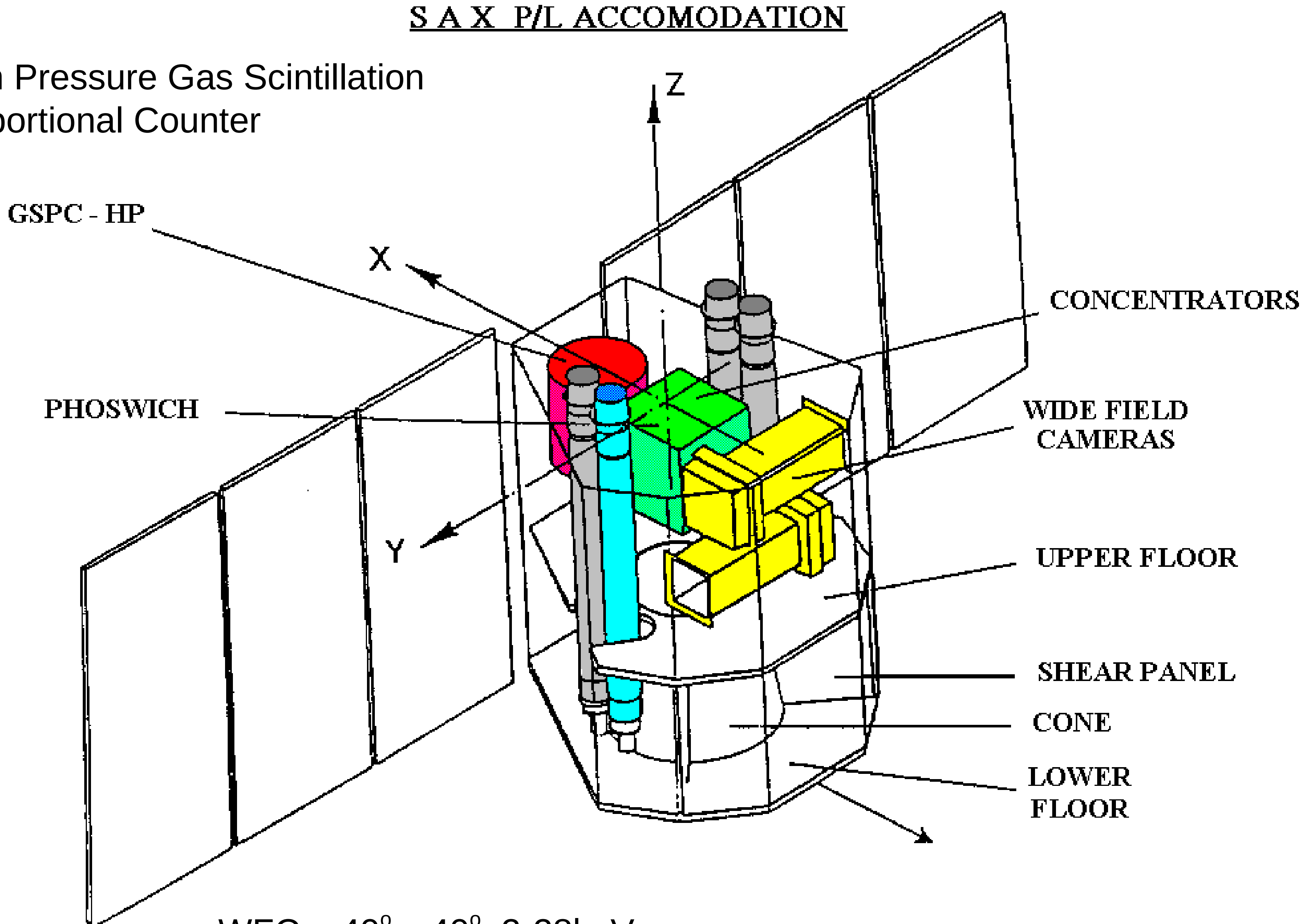

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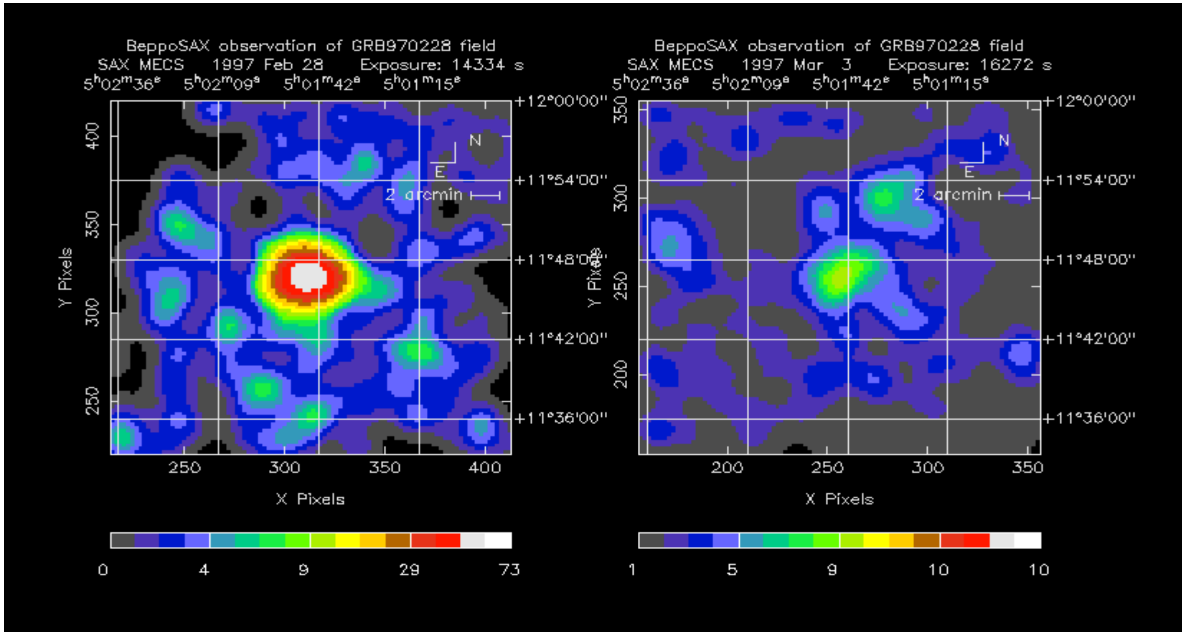
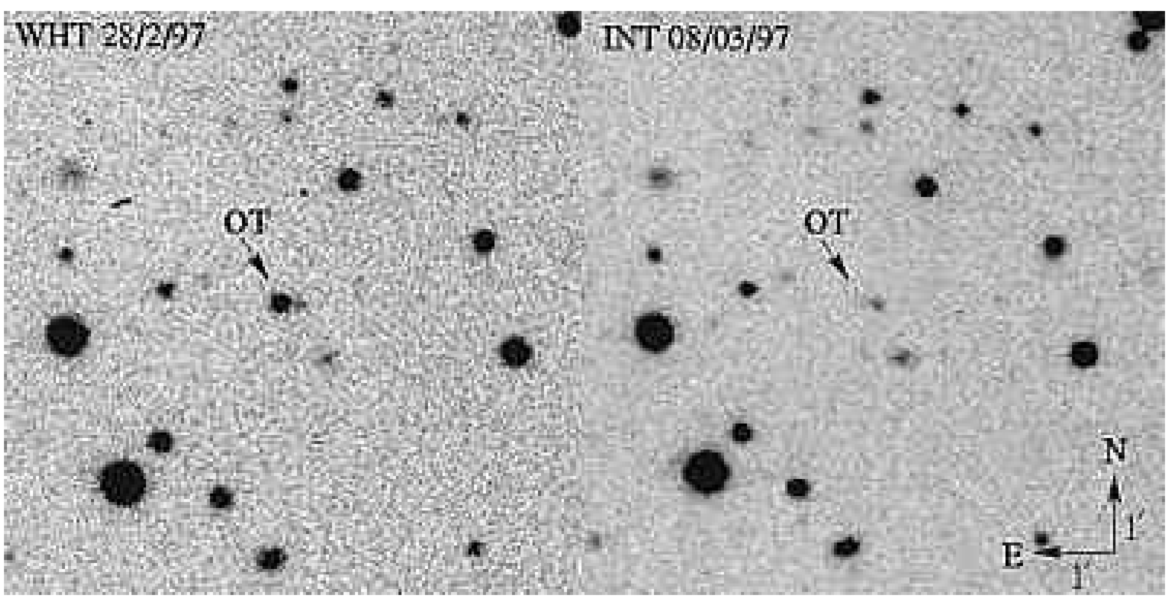
GRB afterglows: the mystery is solved!



BeppoSAX discovers **X-ray afterglows**

(Costa et al. 1997)

⇒ GRB position ~arcmin



Optical afterglow

(van Paradijs et al. 1997)

⇒ position ~1”

⇒ host galaxy and redshift

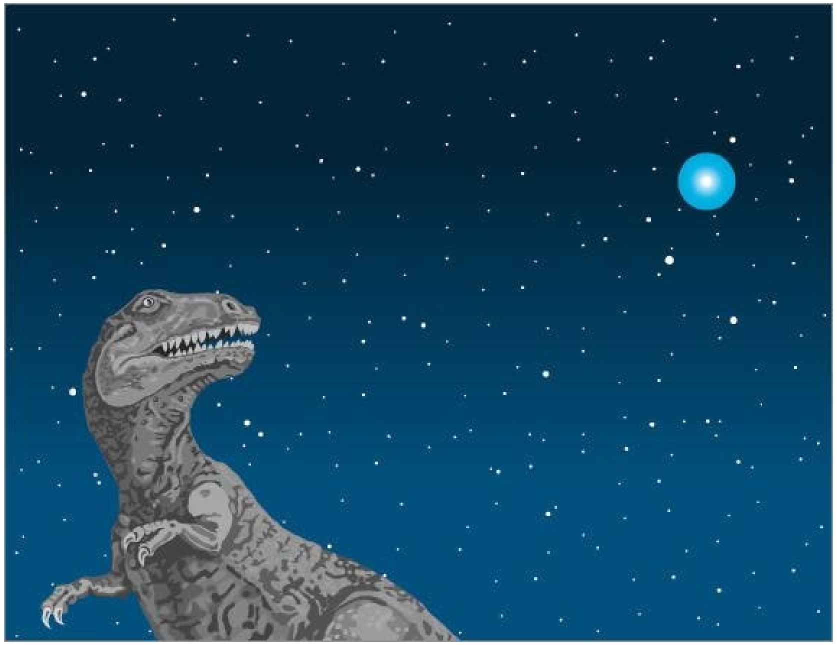
($z \sim 0.0085 - 9.4$)

⇒ **E_{iso}~10^{51}-10^{54} erg**

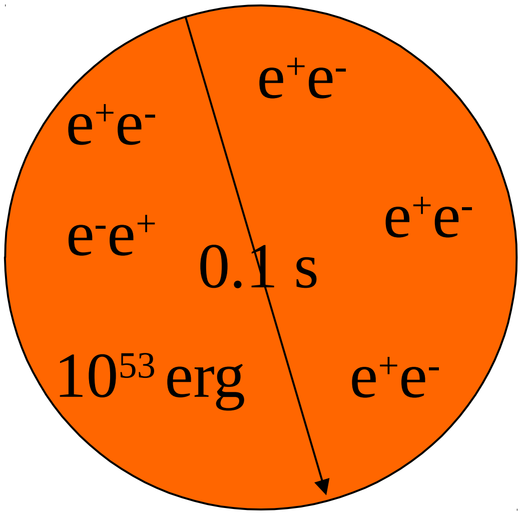
The brightest cosmic explosions (after the Big Bang)

- In less than **few minutes** a GRB emits more energy than our Galaxy in 100 years!
- GRBs are hundreds of times brighter (but less frequent) than **supernovae**!

- A GRB in our Galaxy might have caused **mass extintions**!



GRB Explosions are Highly Relativistic



A large amount of energy, ~10^{53} erg, packed in a small space of ~ c × 0.1 s.

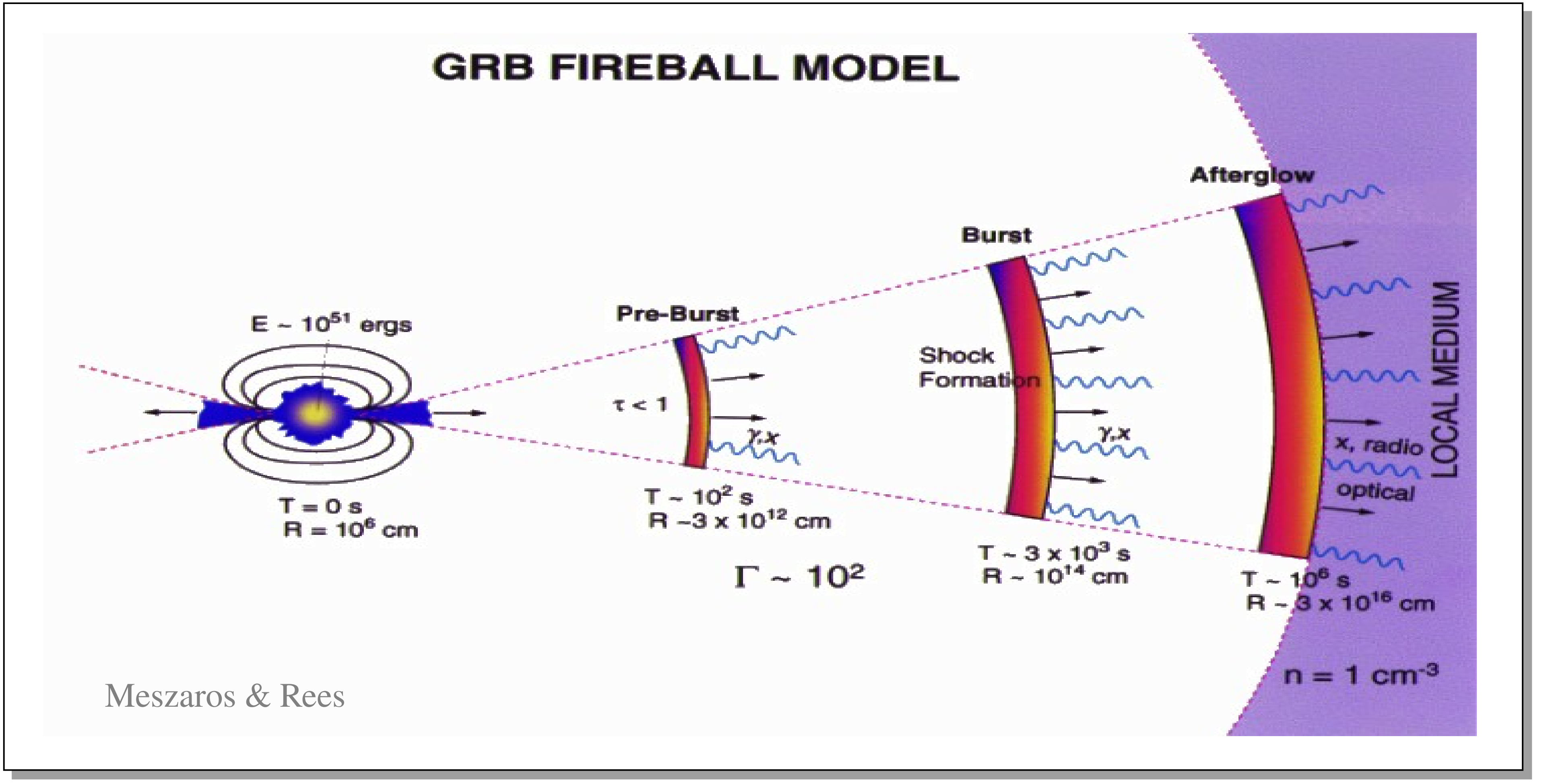
Is highly optically thick to e^+e^- pair production: $\tau \sim 10^{15}$

In this case we should not see any γ's above ~ MeV and see thermal emission

Relativistic outflow ($\Gamma \approx 100$-1000) **solves this compactness problem**

High energy density in any case leads to relativistic flow
(Paczynski 1986, ApJ 308, L43 ; Goodman 1986, ApJ 308, L47)

Fireball Model of GRBs

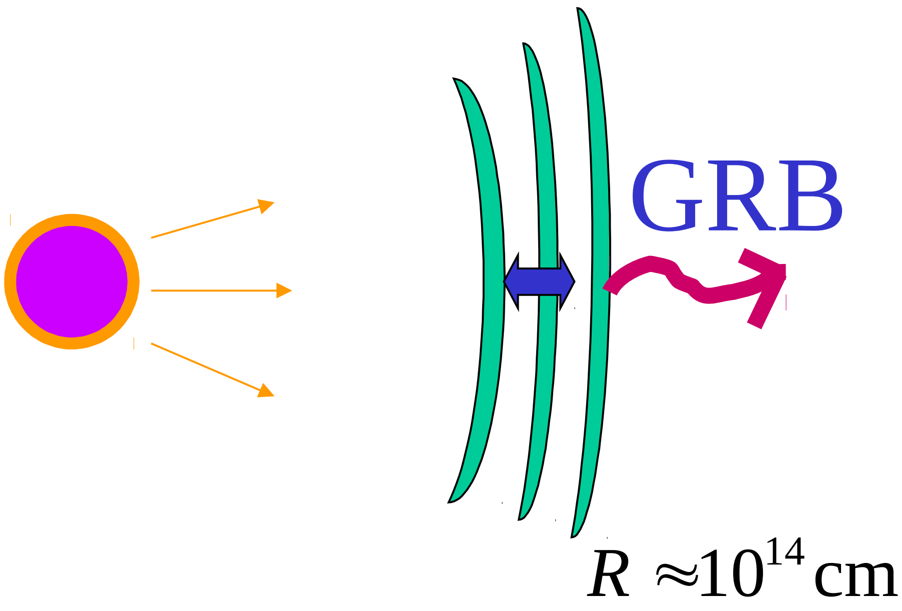


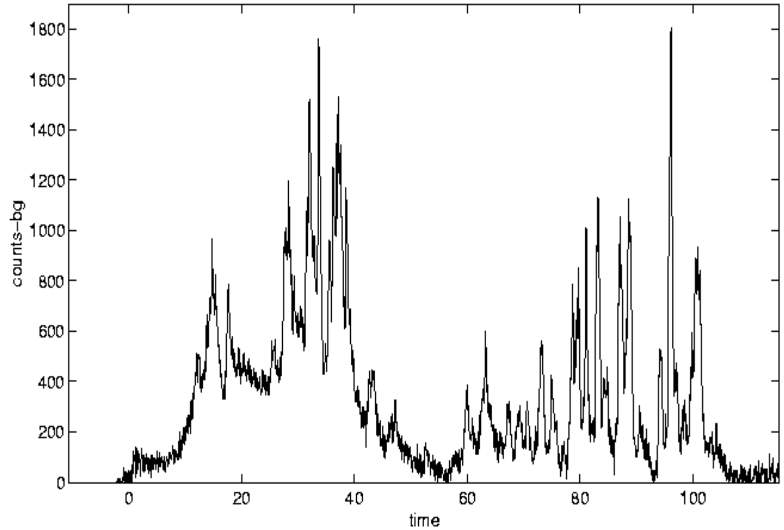
Most photons produced by relativistic electrons (**synchrotron**)

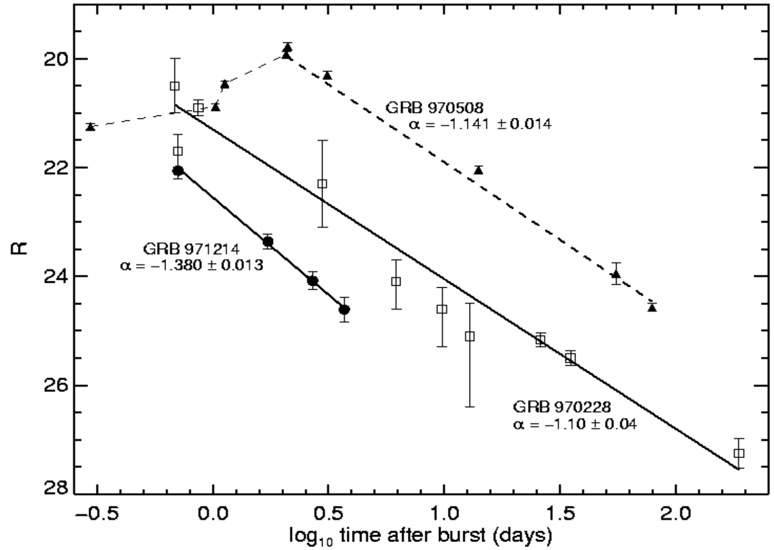
Shocks also accelerate protons ⇒ interactions with photons ⇒ pions, muons, **neutrinos** (10^{14} - 10^{19} eV)

Prompt Emission: Internal Shocks

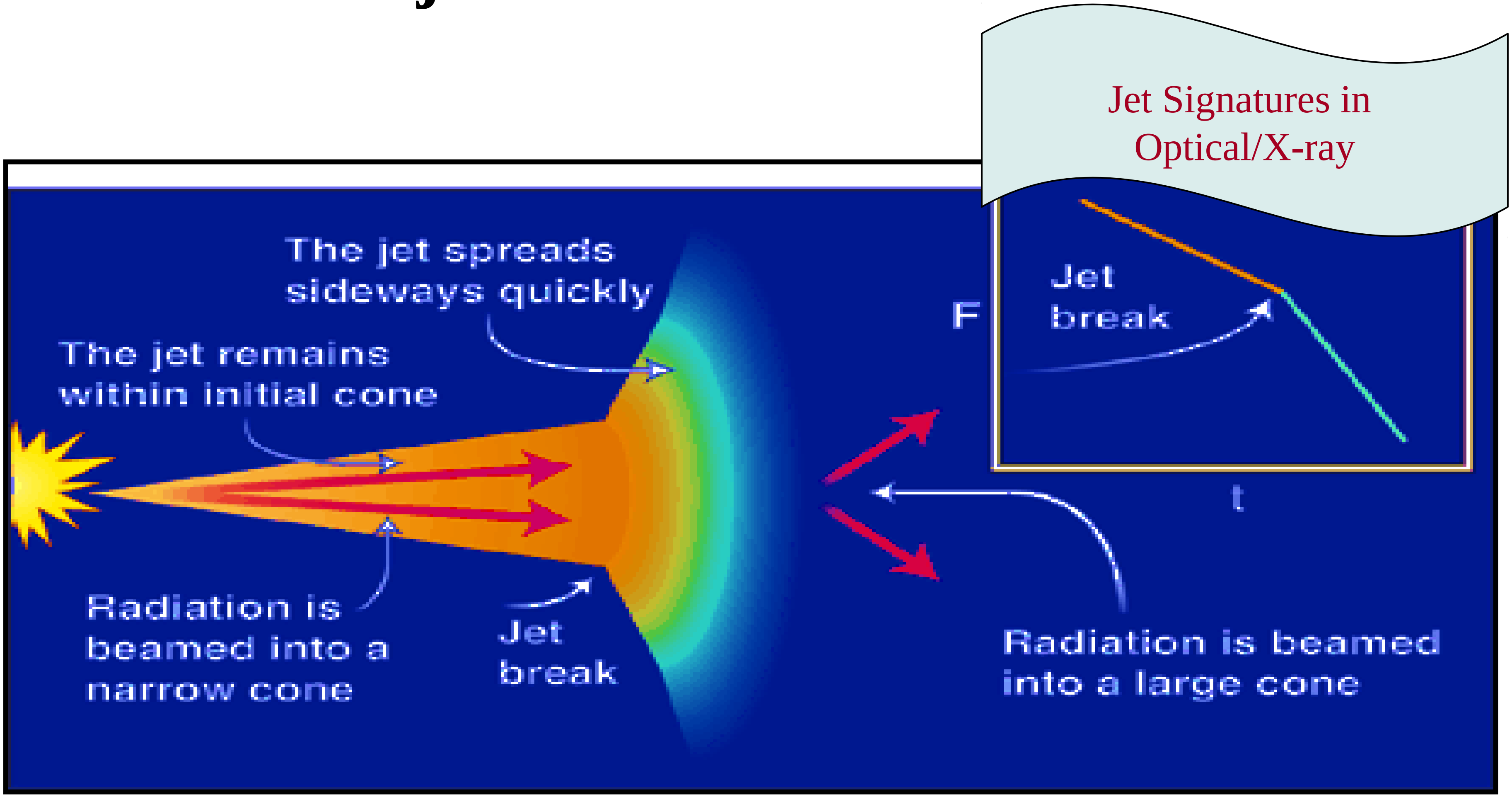
Afterglow emission: External Shocks







Relativistic jets in GRBs



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

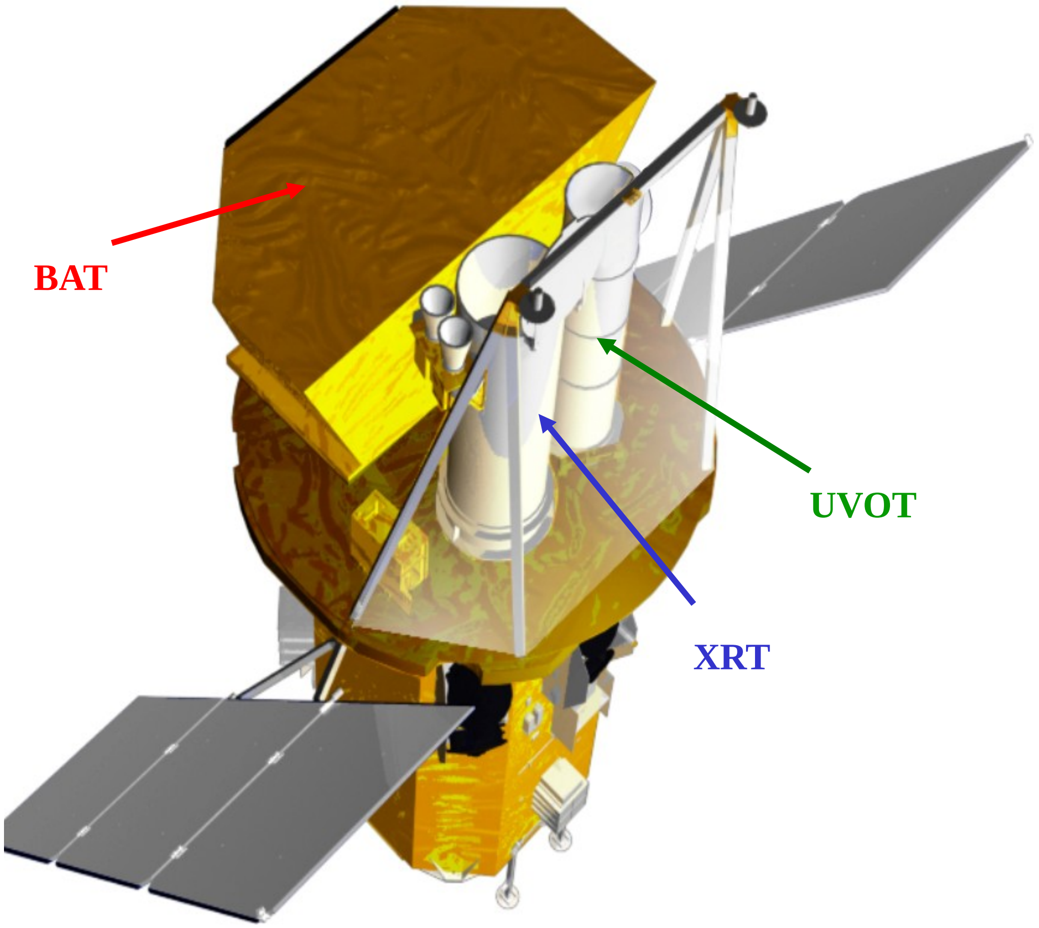
The *Swift* Satellite

Launch: 2004 November 20

Burst Alert Telescope (BAT)
- Coded mask + CdZnTe detectors
- 2 sr field of view

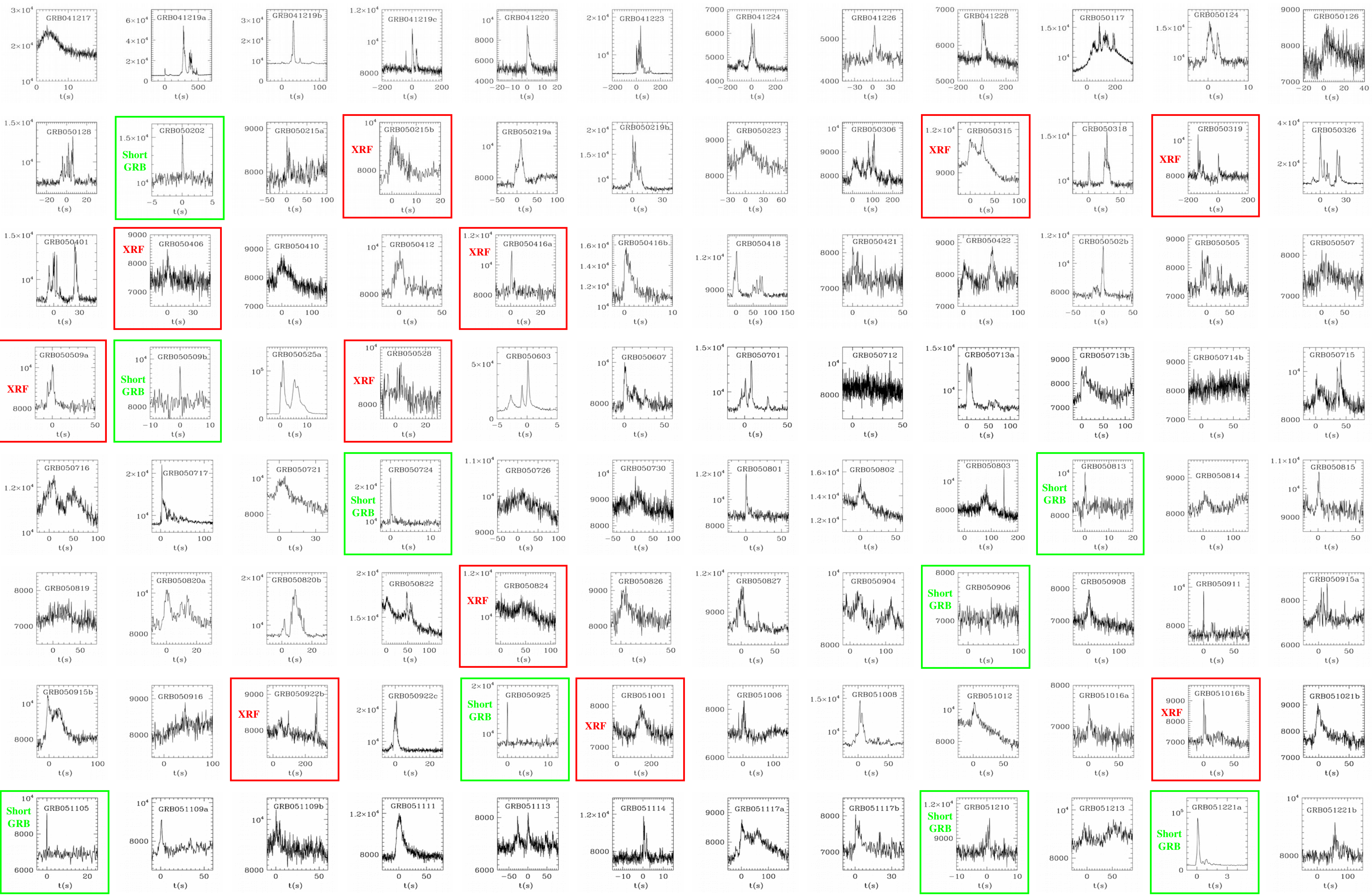
X-Ray Telescope (XRT)
- Mirror + CCD detector
- Arcsec GRB positions

UV-Optical Telescope (UVOT)
- Sub-arcsec position
- 22 mag sensitivity

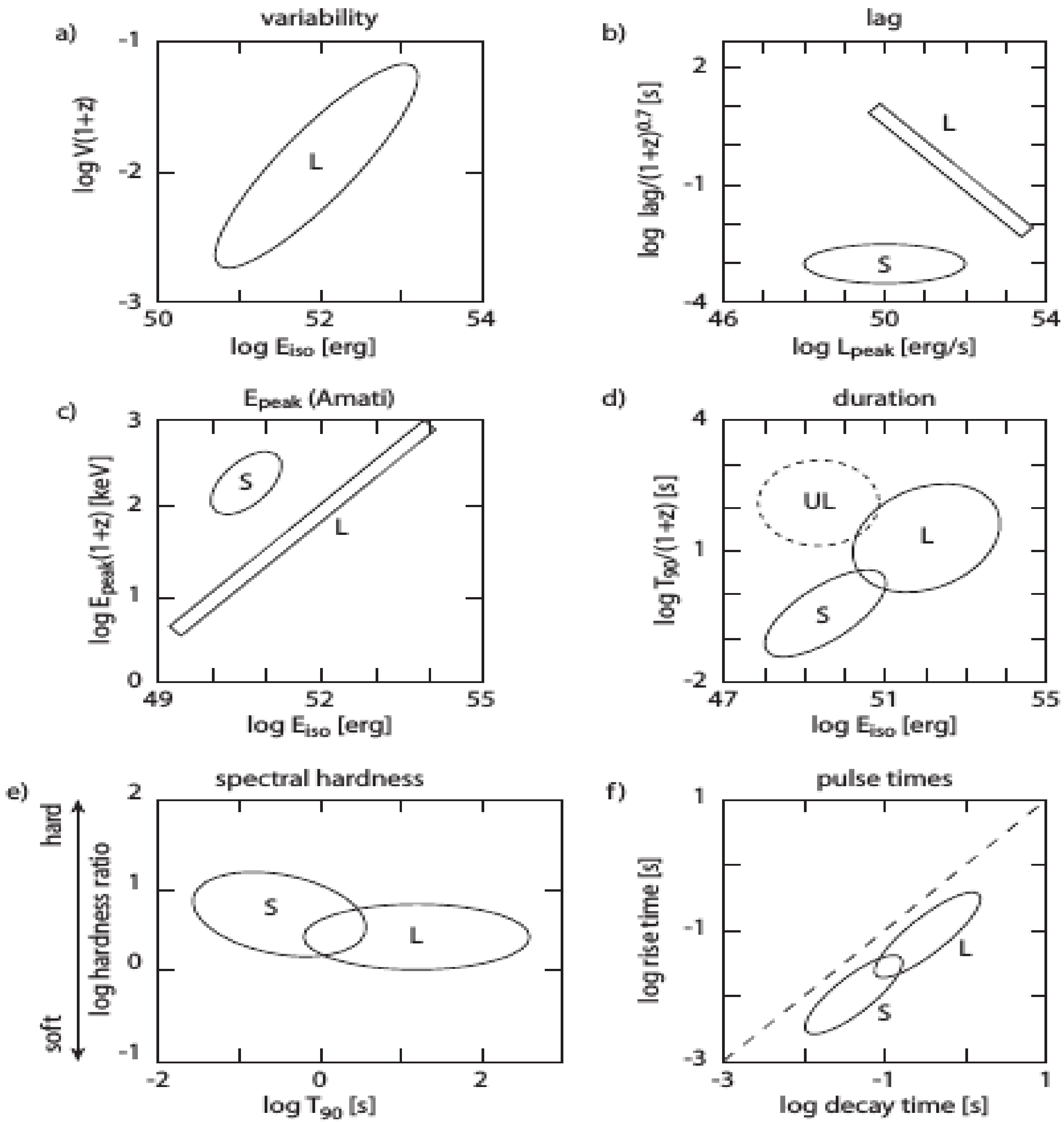


Spacecraft slews to GRB in <100 s

Swift

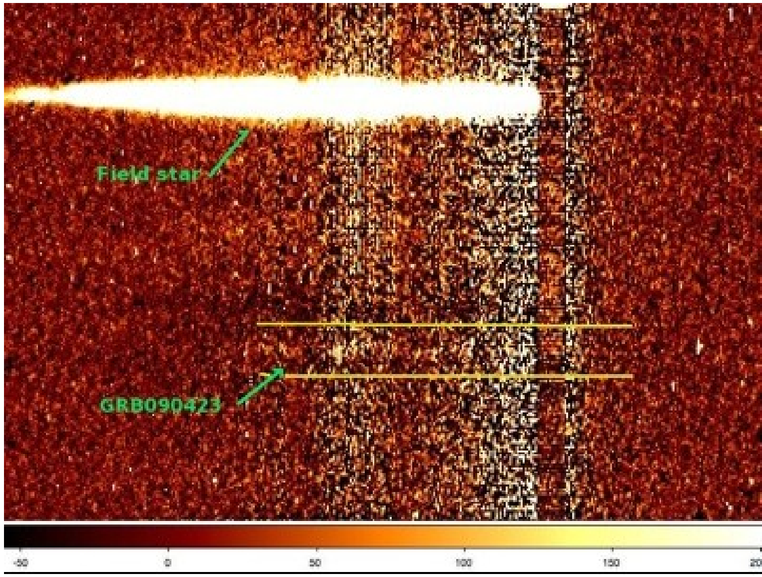

GRB041217
GRB041219a
GRB041219b
GRB041219c
GRB041220
GRB041223
GRB041224
GRB041226
GRB041228
GRB050117
GRB050124
GRB050126
GRB050128
Short GRB
GRB050202
GRB050215a
XRF
GRB050215b
GRB050219a
GRB050219b
GRB050223
GRB050306
XRF
GRB050315
GRB050318
XRF
GRB050319
GRB050326
GRB050401
XRF
GRB050406
GRB050410
GRB050412
XRF
GRB050416a
GRB050416b
GRB050418
GRB050421
GRB050422
GRB050502b
GRB050505
GRB050507
XRF
GRB050509a
Short GRB
GRB050509b
GRB050525a
XRF
GRB050528
GRB050603
GRB050607
GRB050701
GRB050712
GRB050713a
GRB050713b
GRB050714b
GRB050715
GRB050716
GRB050717
GRB050721
Short GRB
GRB050724
GRB050726
GRB050730
GRB050801
GRB050802
GRB050803
Short GRB
GRB050813
GRB050814
GRB050815
GRB050819
GRB050820a
GRB050820b
GRB050822
XRF
GRB050824
GRB050826
GRB050827
GRB050904
Short GRB
GRB050906
GRB050908
GRB050911
GRB050915a
GRB050915b
GRB050916
XRF
GRB050922b
GRB050922c
Short GRB
GRB050925
XRF
GRB051001
GRB051006
GRB051008
GRB051012
GRB051016a
XRF
GRB051016b
GRB051021b
Short GRB
GRB051105
GRB051109a
GRB051109b
GRB051111
GRB051113
GRB051114
GRB051117a
GRB051117b
Short GRB
GRB051210
GRB051213
Short GRB
GRB051221a
GRB051221b
t(s)

Prompt emission properties for long (L), short (S), and underluminous (UL)

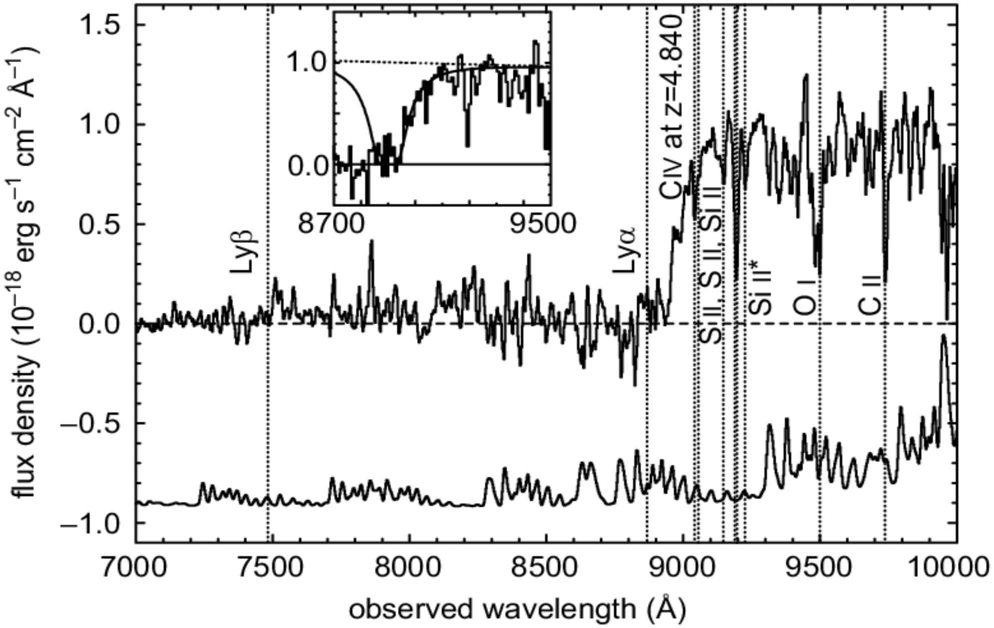


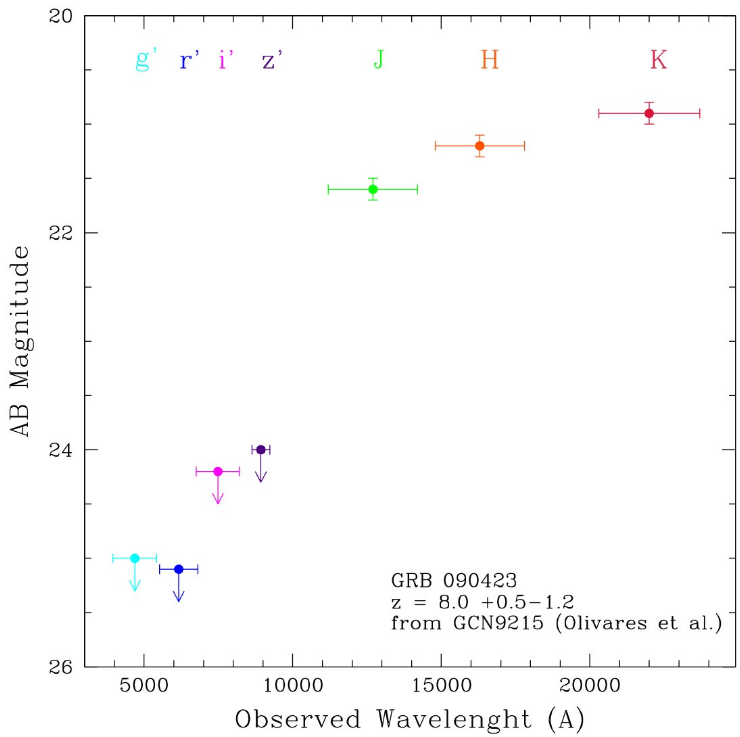
3 GRB @ z>6

GRB050904
Ly break in the IR
J=17.6 at 3.5 hours



Subaru Spectroscopy



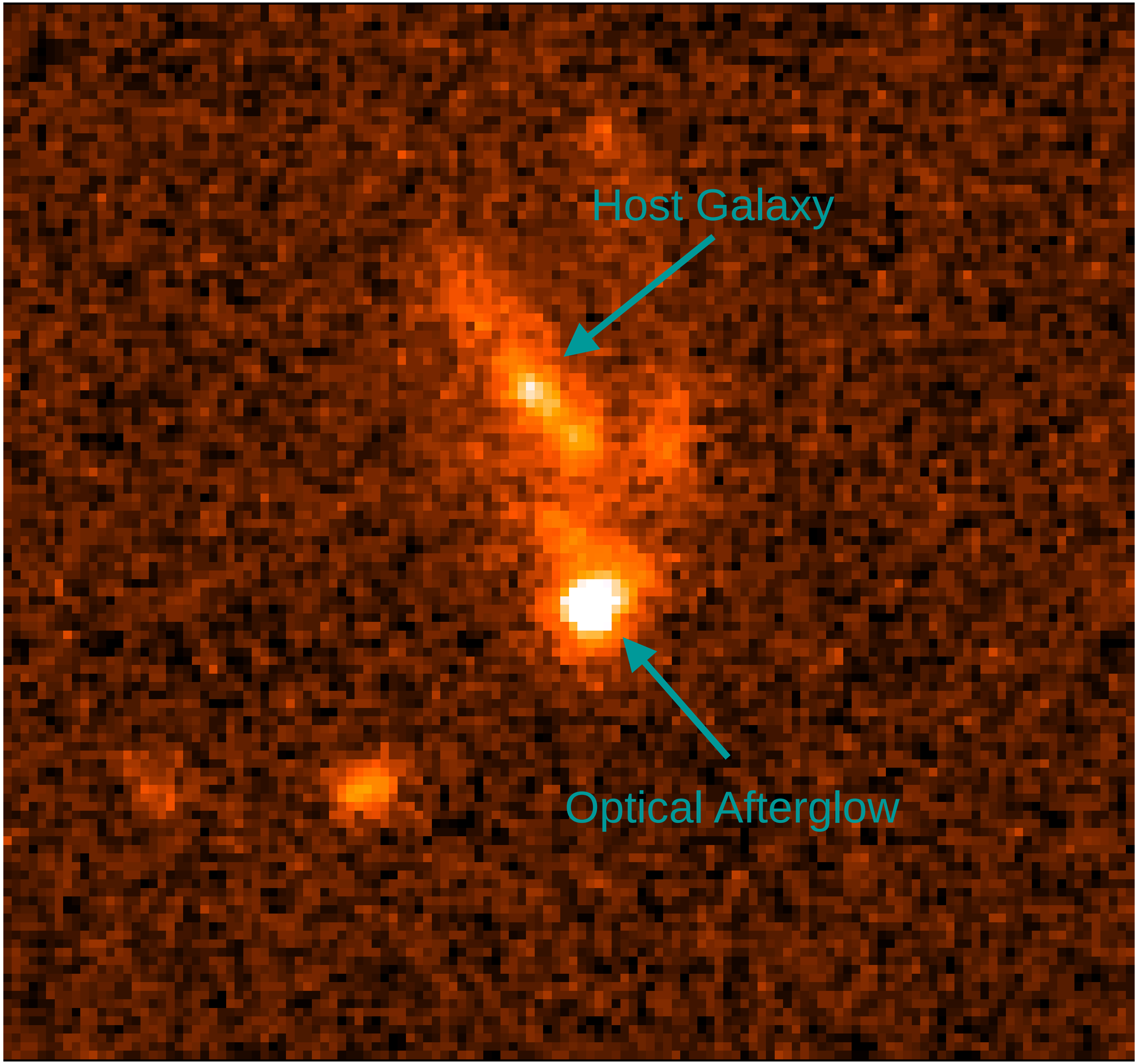


Observational Constraints on the Central Engine

- Host Galaxies
- GRB Environments
- Prompt Emission
- Bumps in the Afterglow (SN?)
- Energetics and Beaming
- Using GRBs as Cosmological Probes

Host Galaxies

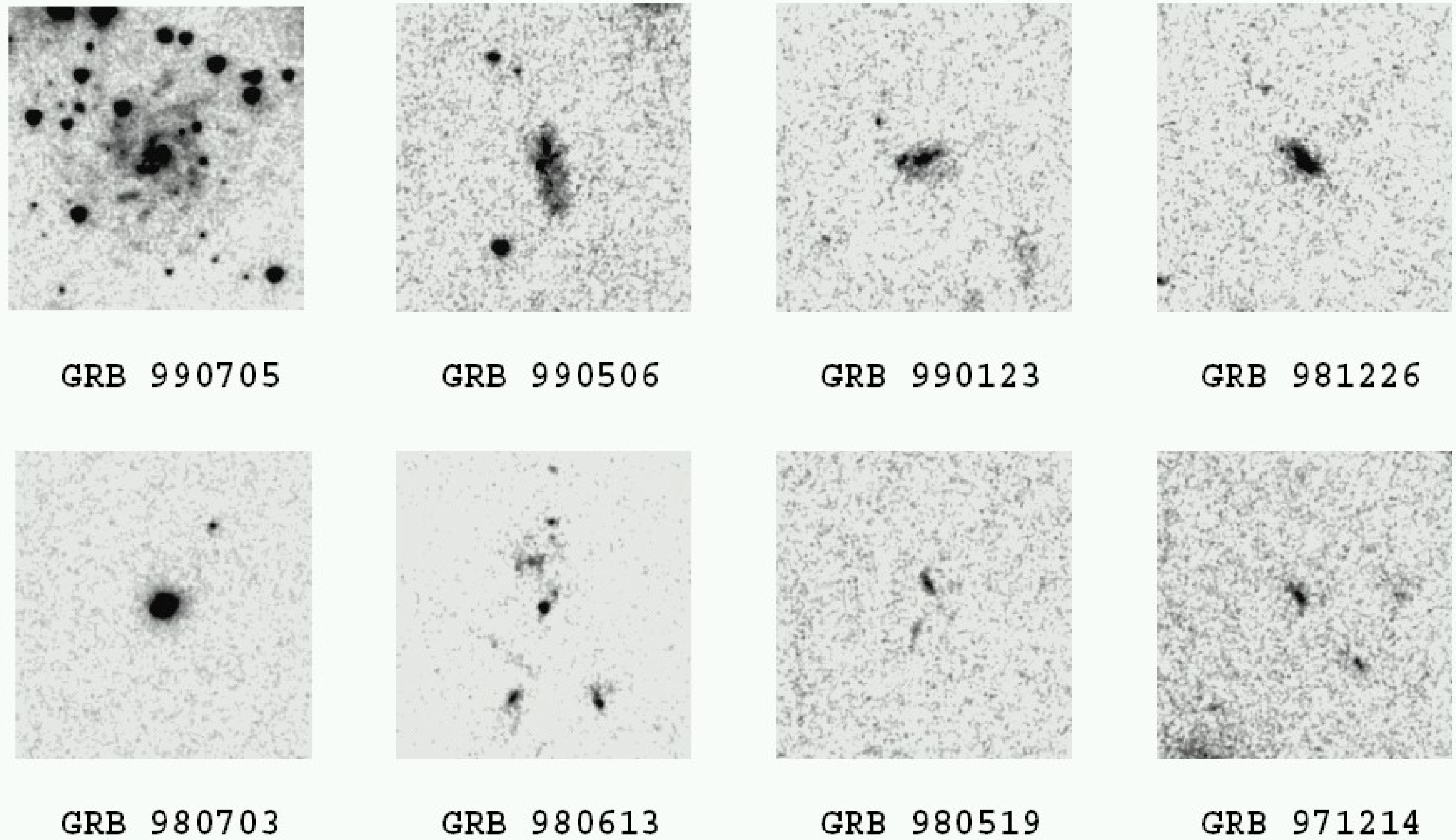
Accurate positions
Allowed Astronomers
To watch the bursts
Fade, and then
Study their Host
Galaxy!



The fading optical
afterglow of GRB 990123
as seen by HST
on Days 16, 59 and 380
after the burst.

Properties Of Host Galaxies

I) Like Many Star-forming Galaxies At that Observed redshift



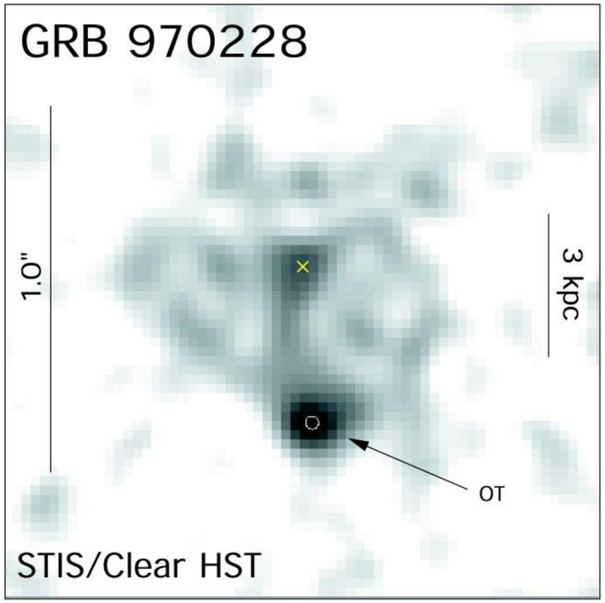
Holland 2001

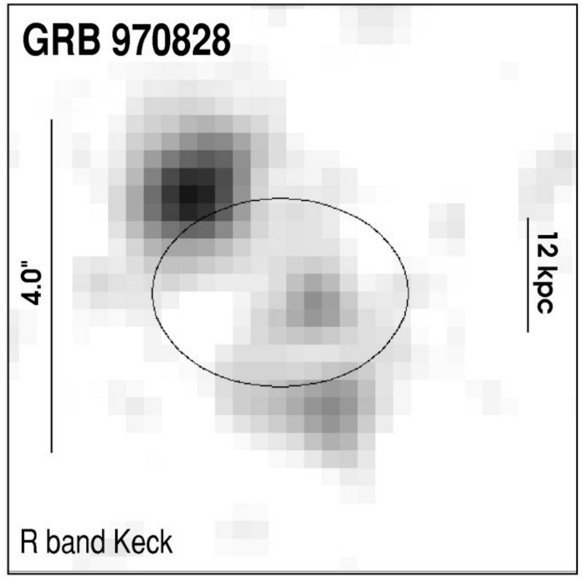
TABLE 1. Specific star-formation rates for several GRB host galaxies.

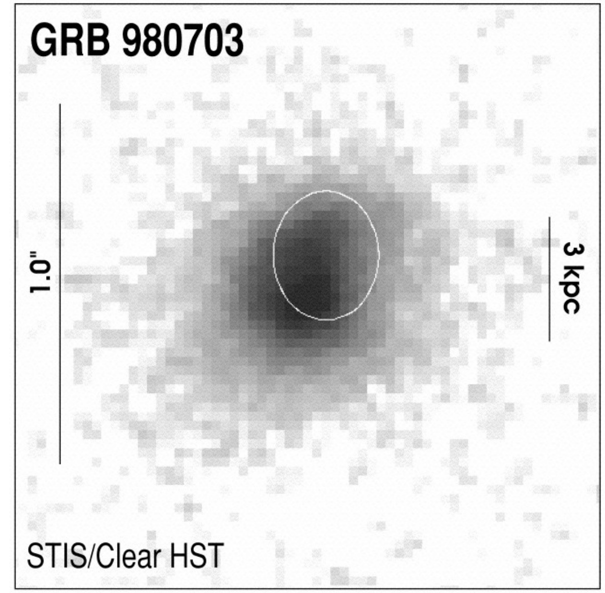
GRB	z	$R_{\rm host}$	$\mathcal{M}_{\odot}{\rm yr}^{-1}{L_B^*}^{-1}$
970508	0.835	25.20	11.0
980613	1.096	24.56	20.0
980703	0.966	22.57	6.5
990123	1.600	24.07	11.0
990712	0.434	21.91	4.4

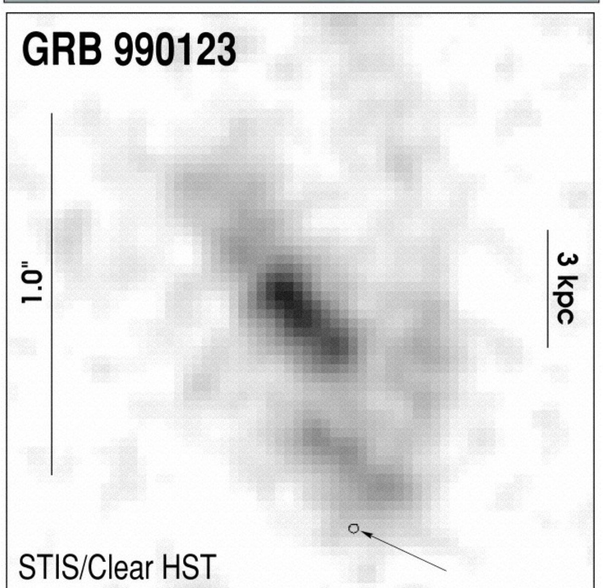
II) Star-formation rates high, but consistent With star forming galaxies.

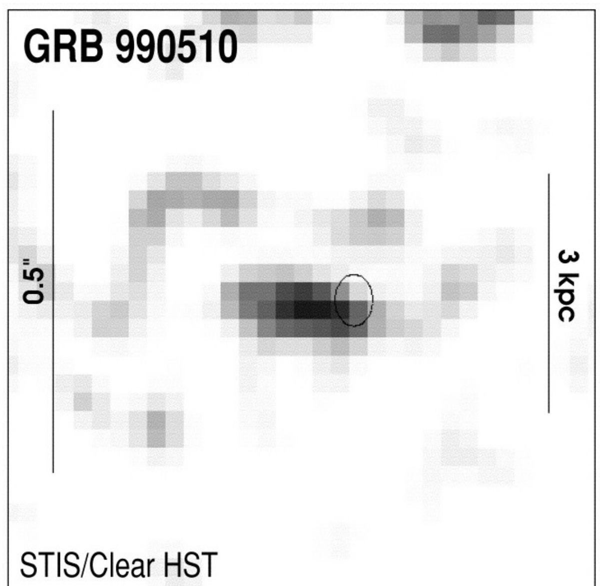
Location, Location, Location
(In addition to detecting hosts, we can determine where a burst occurs with respect to the host.

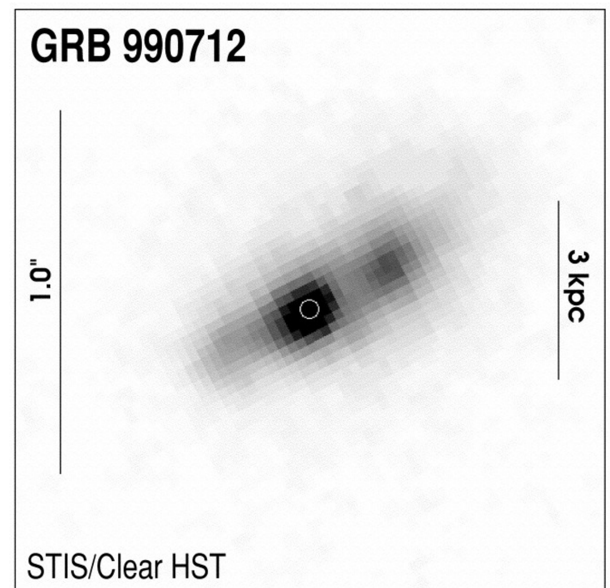










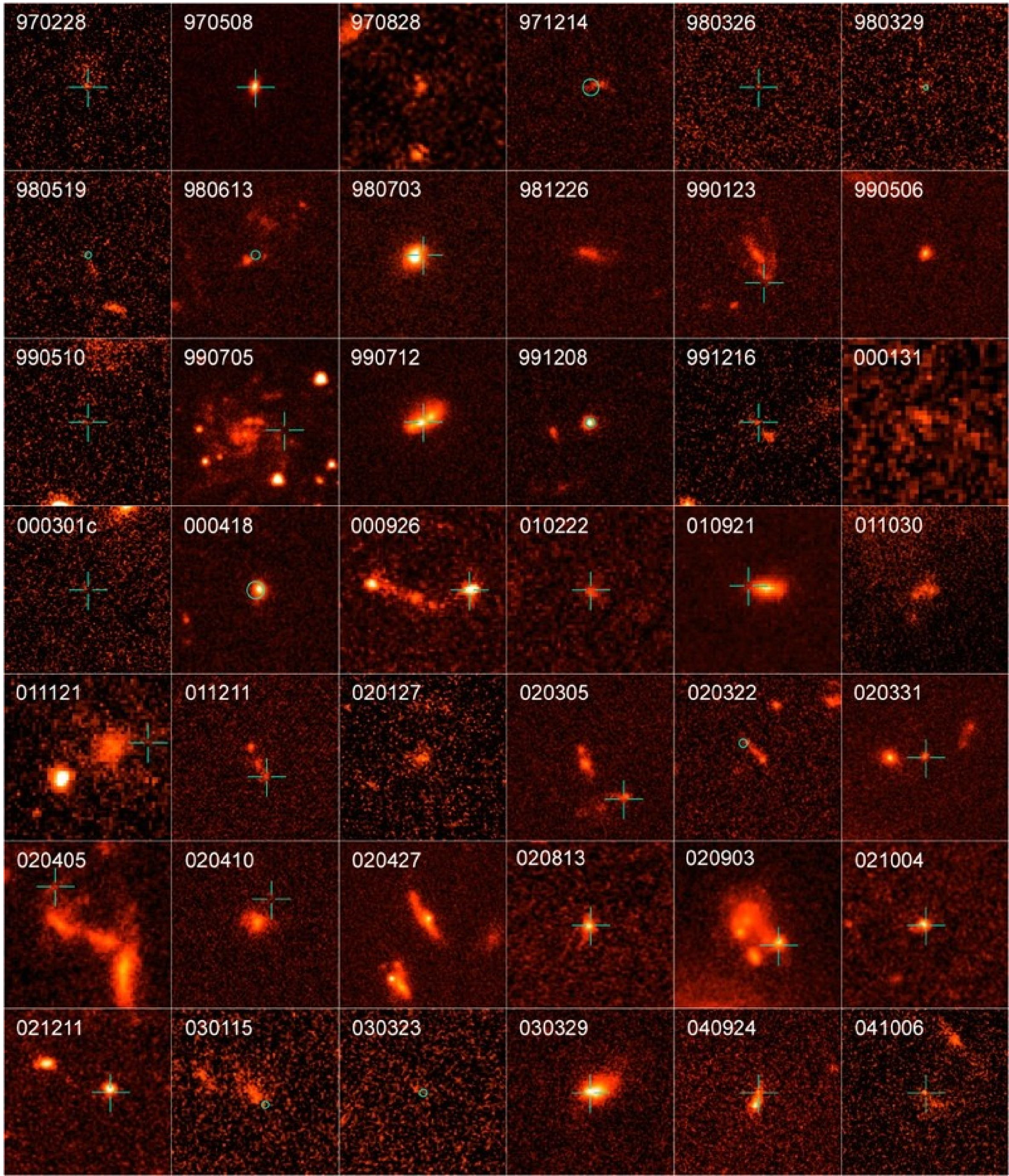


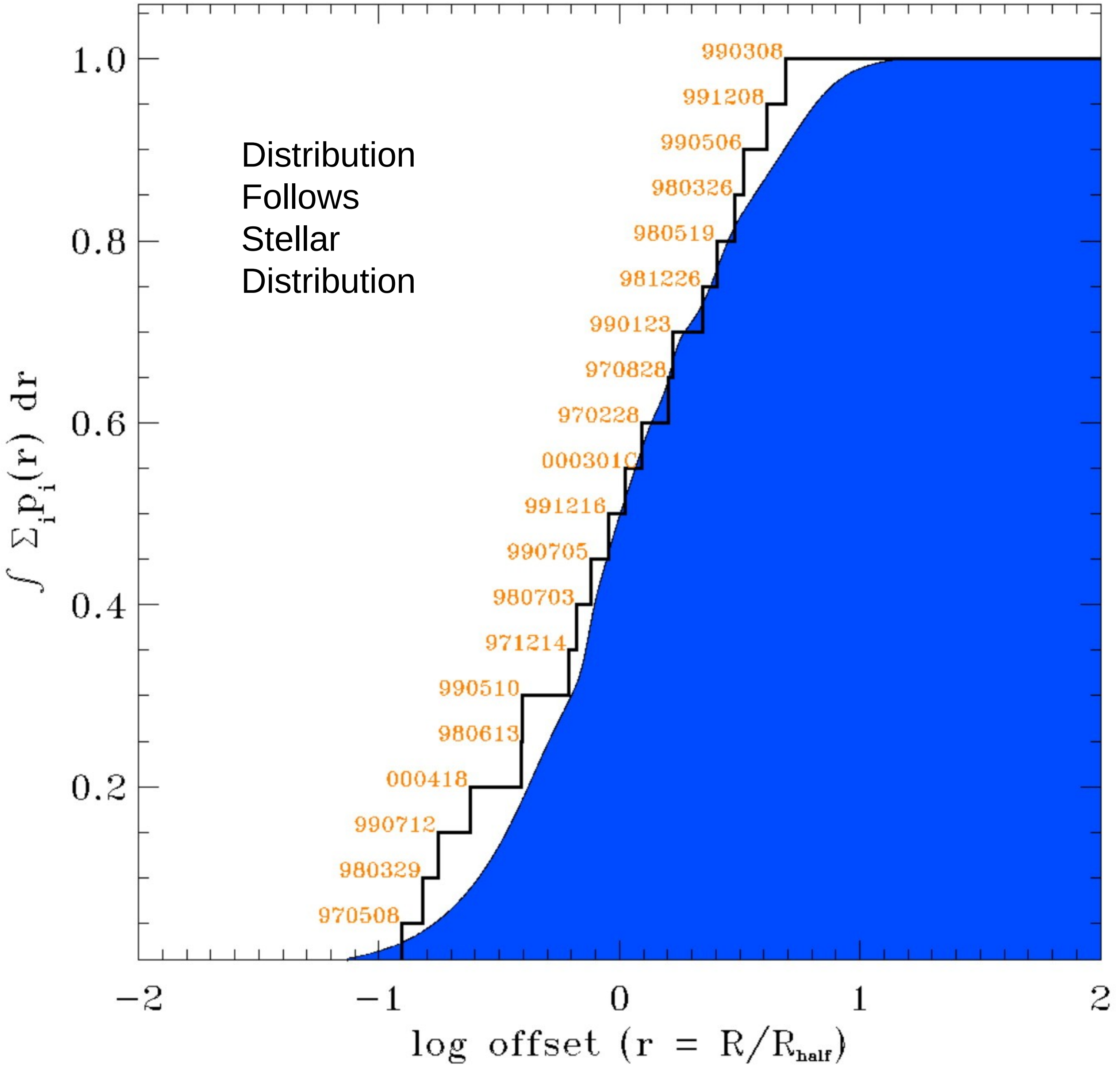
GRB hosts

- GRBs trace brightest regions in hosts
- Hosts are sub-luminous irregular galaxies

⇒ Concentrated in regions of most massive stars

⇒ Restricted to low metallicity galaxies

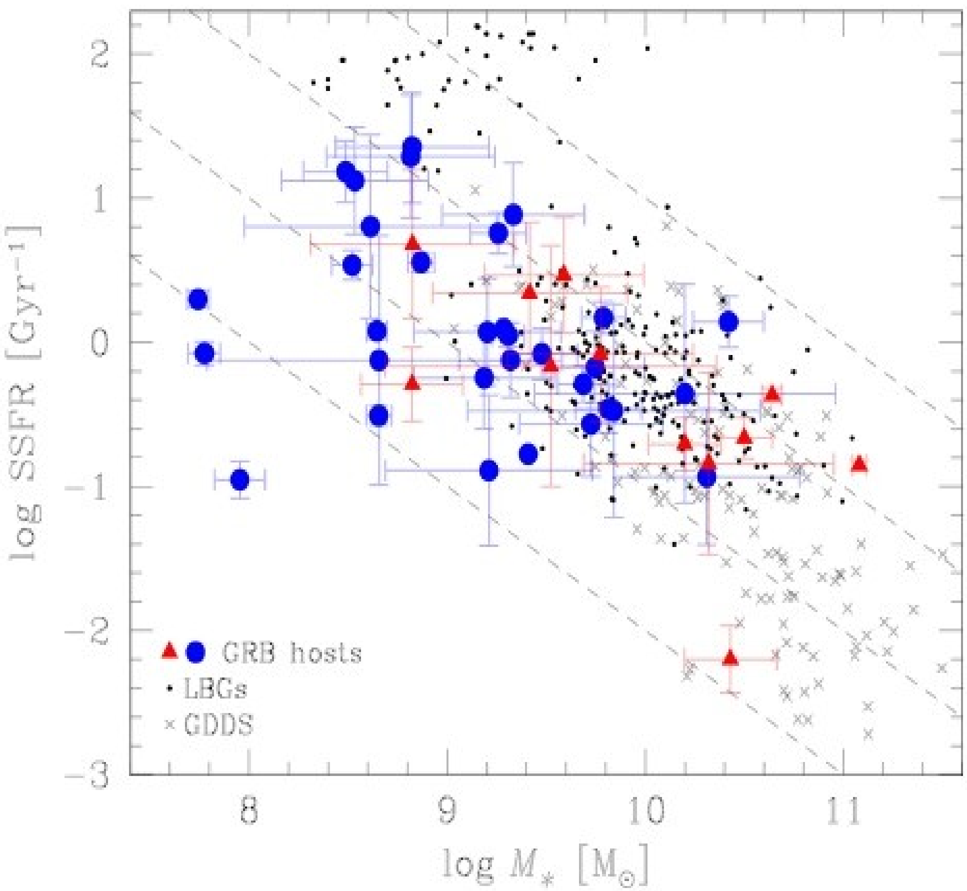




If we take
These
Positions
At face
Value,
We can
Determine
The
Distribution
Of bursts
With respect
To the half-
Light radius
Of host
Galaxies!

This Will
Constrain
The models!

Star-formation rate in GRB hosts



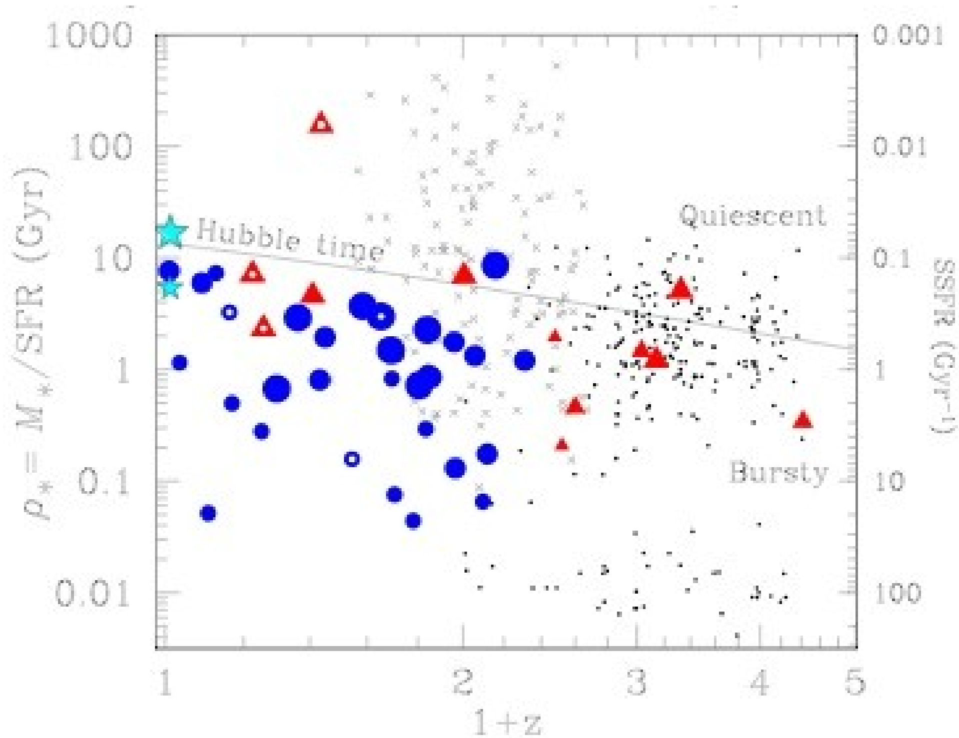


FIG. 14.— Growth time scale $\rho_* = M_*/SFR$ (left y-axis) or specific star formation rate SSFR (right y-axis) as a function of redshift. Filled circles and triangles are GRB hosts with SFRs measured from emission lines and UV luminosities, respectively. Only hosts with stellar mass uncertainties $\Delta \log M_* < 1$ are shown. Small, medium and large symbols are hosts with $M_* \leq 10^{9.0}$ $M_\odot$, $10^{9.0}$ $M_\odot < M_* \leq 10^{9.7}$ $M_\odot$, and $M_* > 10^{9.7}$ $M_\odot$, respectively. Hosts with small white dots are associated with short GRBs. The curve is the Hubble time as a function of redshift, and indicates the transition from bursty to quiescent mode for galaxies. Crosses are GDDS galaxies at $0.5 < z < 1.7$ (Juneau et al. 2005; Savaglio et al. 2005). Dots are LBGs at $1.3 \lesssim z \lesssim 3$, for which SSFRs are derived by assuming an exponential decline for star formation (Reddy et al. 2006). The big and small stars at zero redshift represent the growth time scale for the Milky Way and the Large Magellanic Cloud, respectively.

Savaglio+ 2008

What we've learned from GRB Hosts!

- Hosts of long GRBs are star-forming galaxies
- GRBs trace the stellar distribution (in distance from galaxy center)
- GRBs occur in dense environments (star forming regions?)

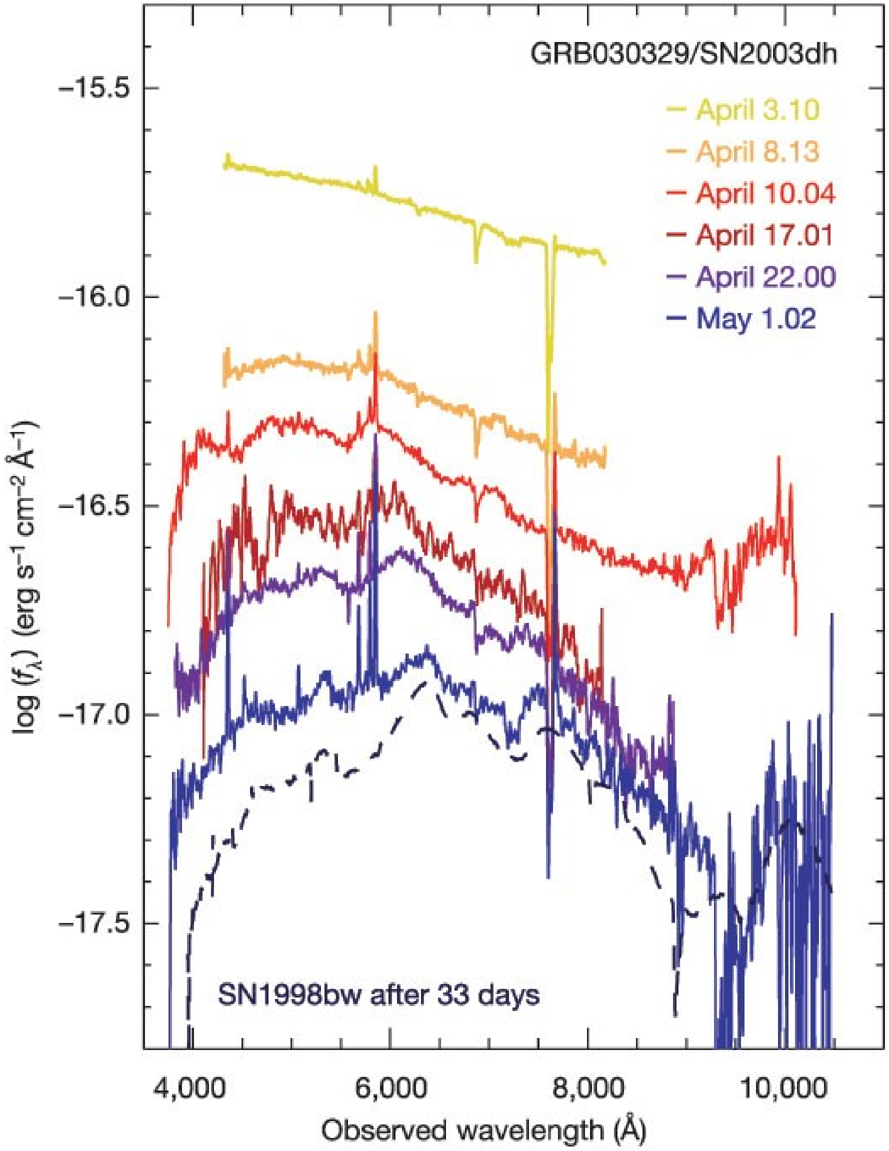
GRB/SN connection

GRB 980425/SN1998bw: z=0.0085

SN 1998bw in Spiral Galaxy ESO184-G82

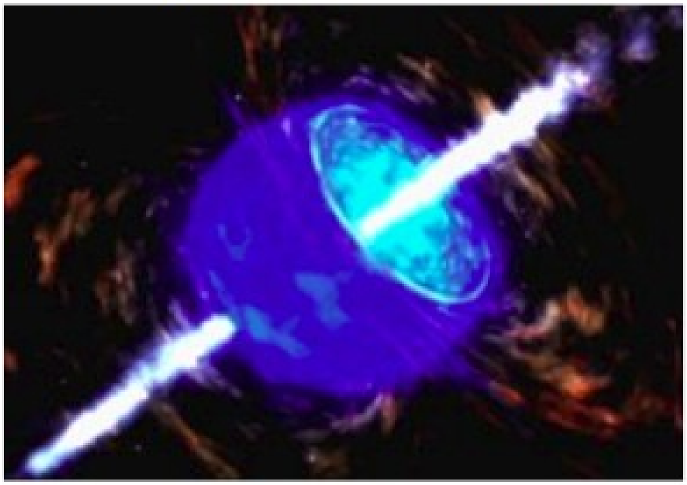
ESO PR Photo 39a/98 (15 October 1998)

GRB 030329/SN2003dh: z=0.1685

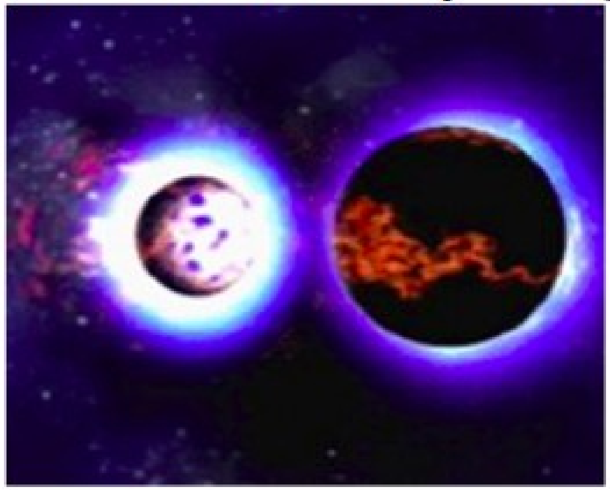


Progenitors

Long GRB: Collapsar



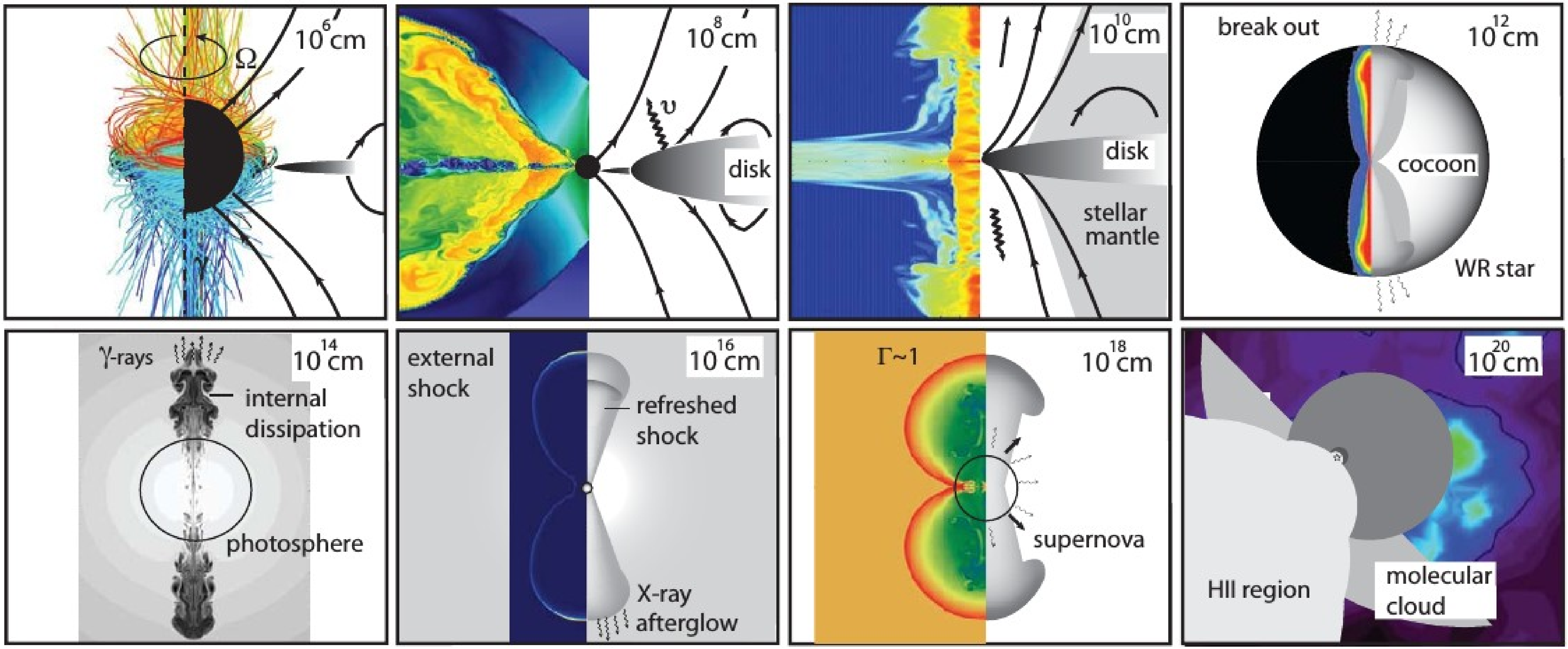
Short GRB: Binary Merger



LGRB: Collapsar model – occurs in region of massive (hence recent) star formation. Several examples known of associated super/hypernova signature

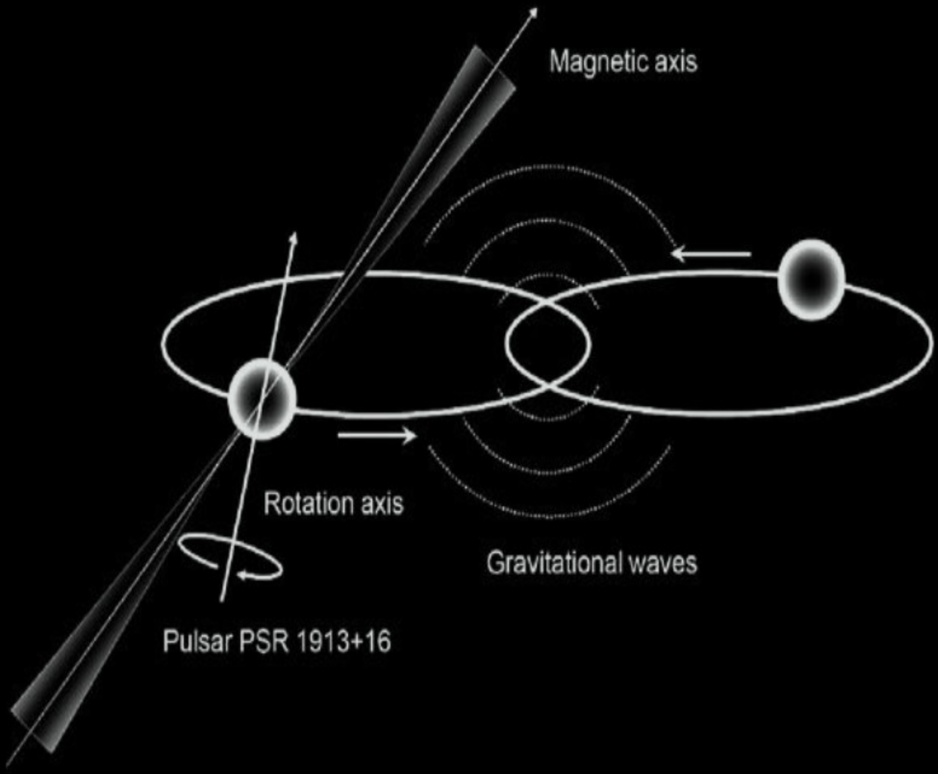
SGRB: Merger model (e.g. NS-NS) – can occur in any type of galaxy, and also off of a galaxy due to natal dynamic kick and long merger time

The "central engine" produced may be a either black hole or a "magnetar"



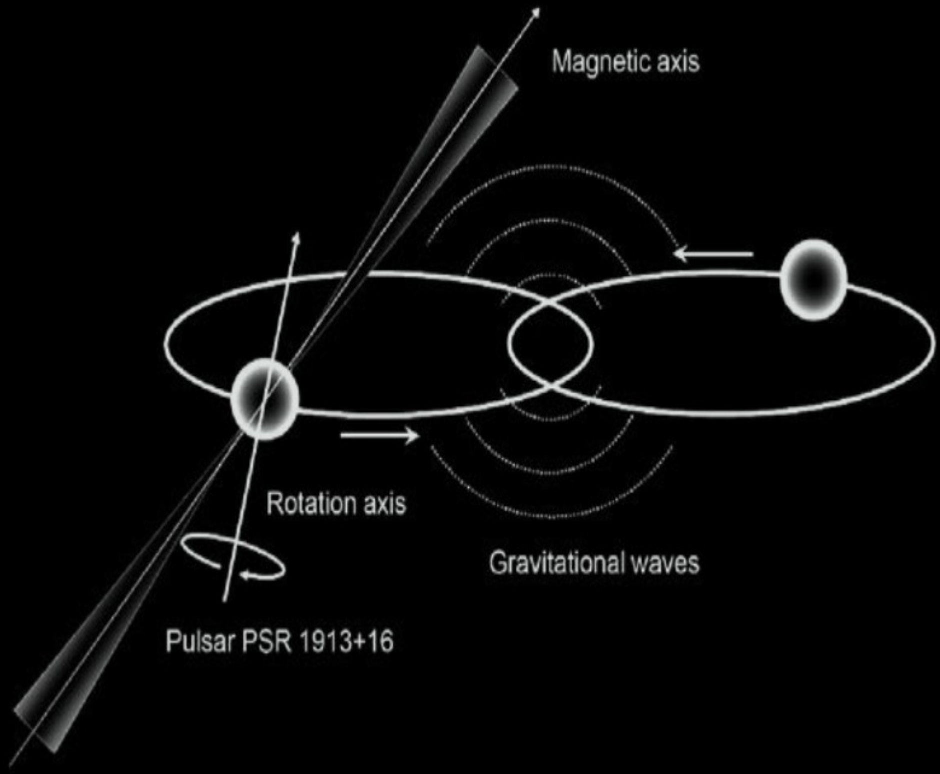
10^6 cm
Ω
γ
10^8 cm
υ
disk
10^{10} cm
disk
stellar mantle
break out
10^{12} cm
cocoon
WR star
γ-rays
10^{14} cm
internal dissipation
photosphere
external shock
10^{16} cm
refreshed shock
X-ray afterglow
Γ~1
10^{18} cm
supernova
10^{20} cm
HII region
molecular cloud

PSR B1913+16



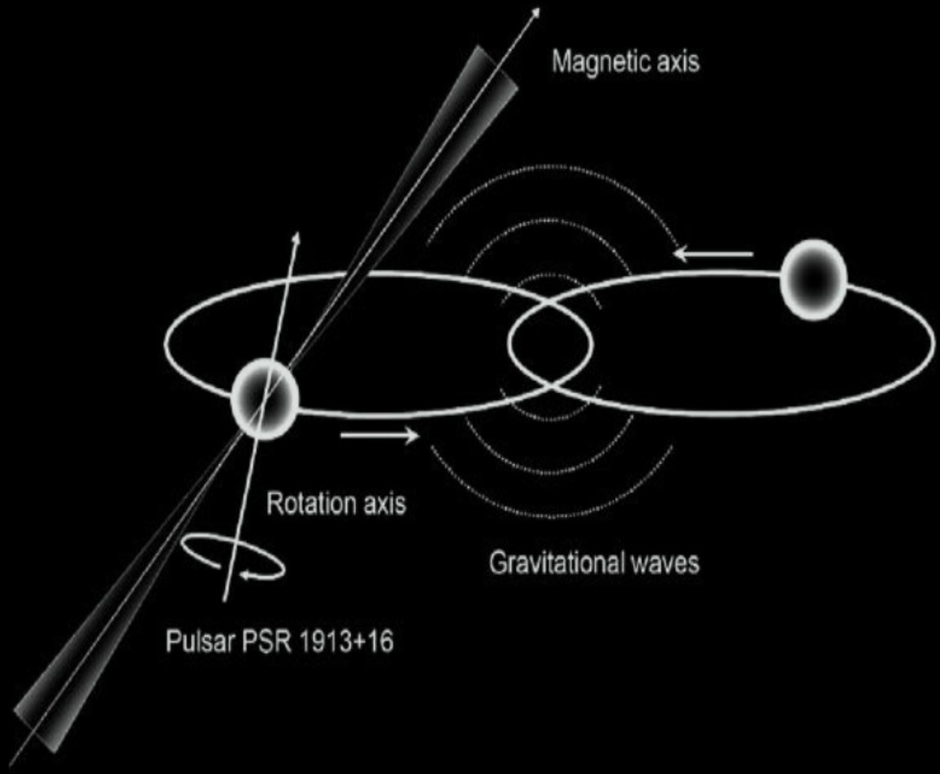
Magnetic axis
Rotation axis
Gravitational waves
Pulsar PSR 1913+16

PSR B1913+16



Pulsar	PSR J0737–3039A	PSR J0737–3039B
Spin frequency (Hz)	44.054069392744(2)	0.36056035506(1)
Spin frequency derivative (s^{-2})	$-3.4156(1) \times 10^{-15}$	$-0.116(1) \times 10^{-15}$
Eccentricity	0.0877775(9)	0.0877775(9)
Distance (pc)	~500	~500
Characteristic age (My)	210	50
Surface magnetic flux density (T)	6.3×10^5	1.6×10^8
Spin-down luminosity (W)	5.8×10^{26}	1.6×10^{23}
Mass $M_\odot$	1.3381(7)	1.2489(7)

PSR B1913+16



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