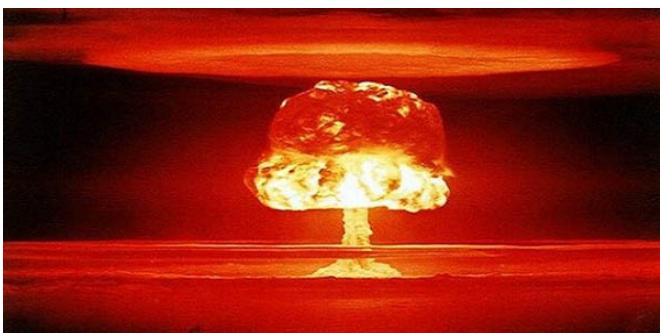


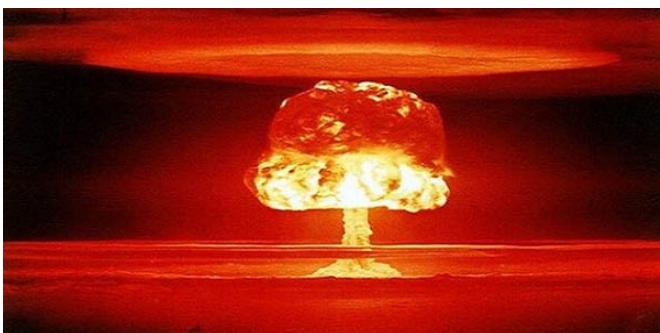
***From
Supernovae
to
Gamma-Ray
Bursts***

The discovery of GRBs

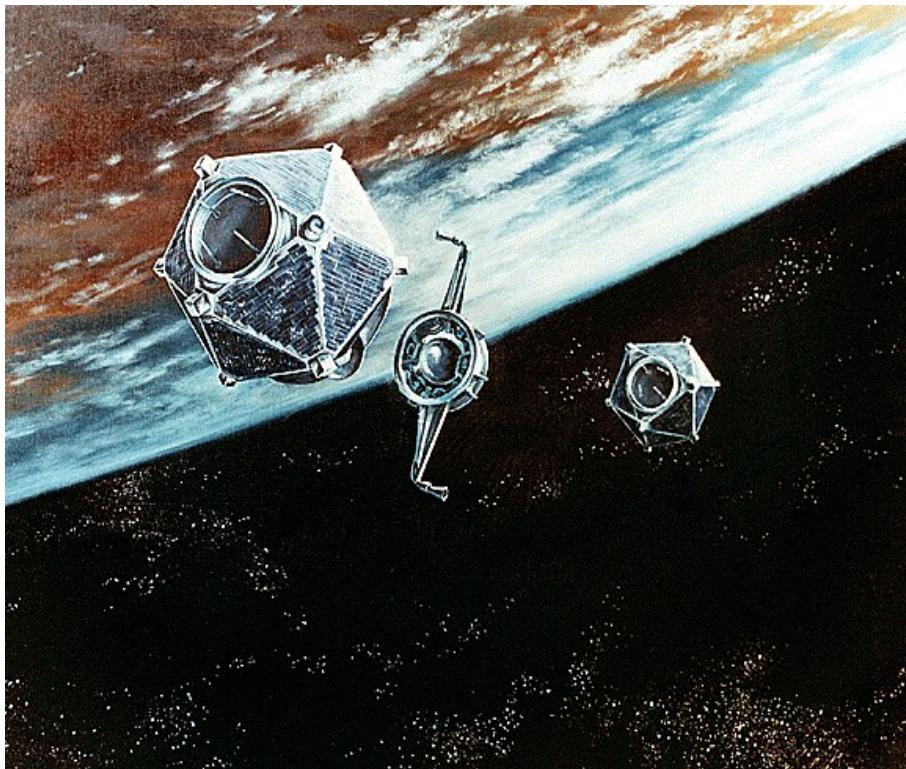


Discovered by Vela satellites, launched by US Air Force to monitor the ban of **nuclear tests** in atmosphere and space

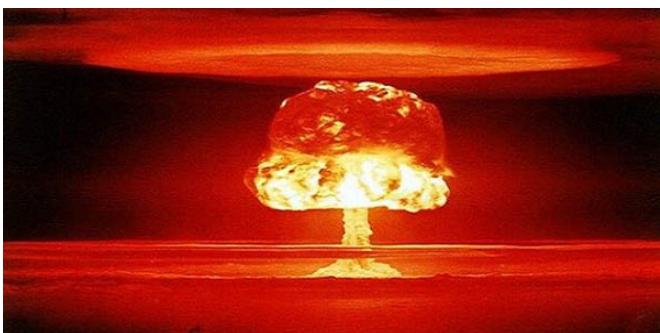
The discovery of GRBs



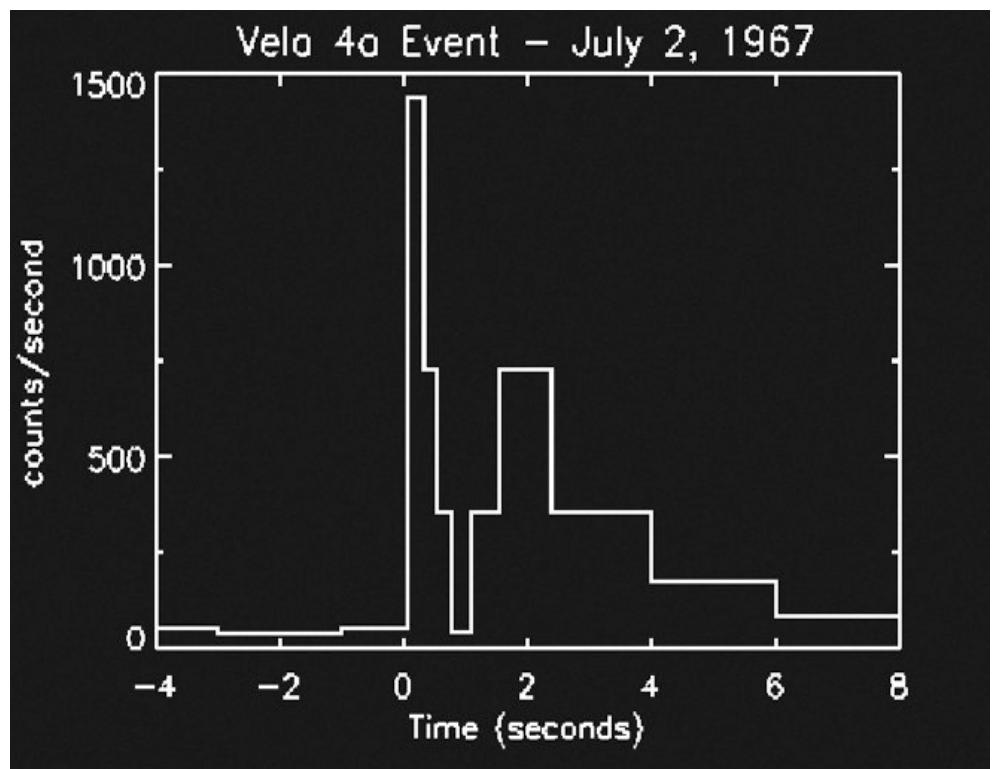
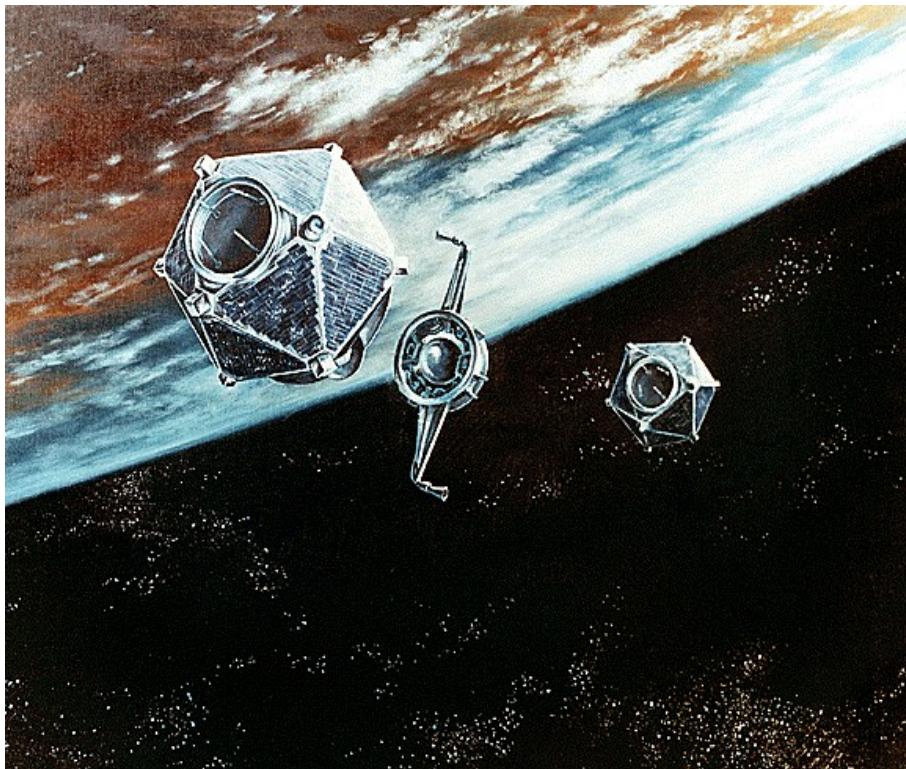
Discovered by Vela satellites, launched by US Air Force to monitor the ban of **nuclear tests** in atmosphere and space



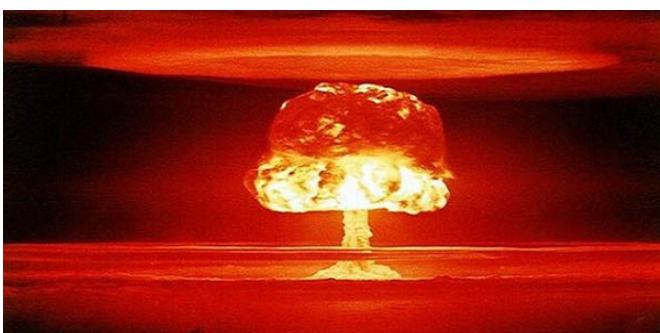
The discovery of GRBs



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



The discovery of GRBs



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

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

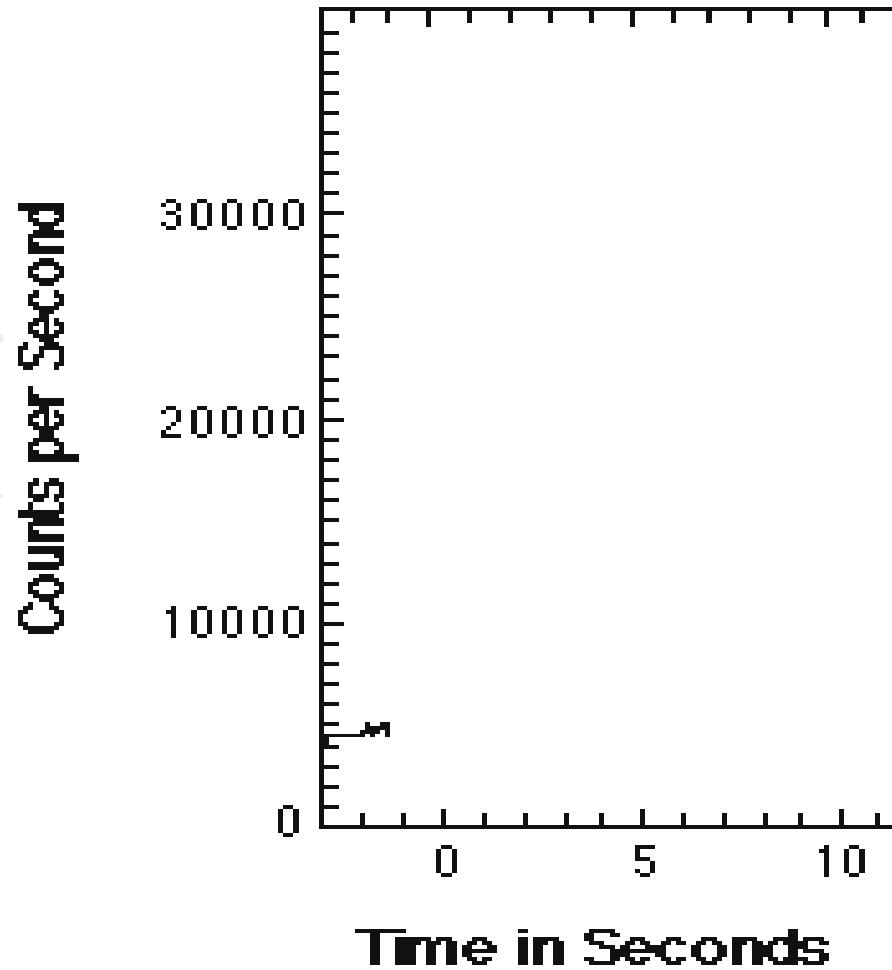
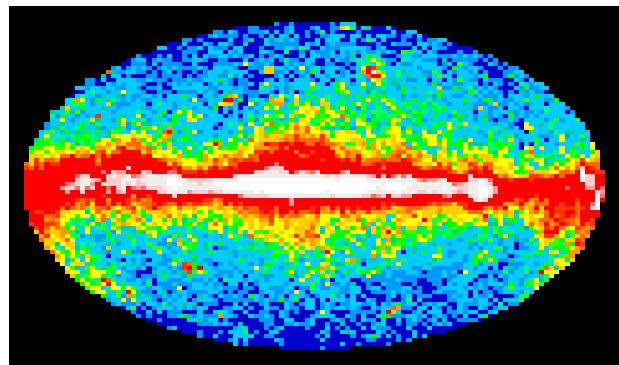
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

Received 1973 March 16; revised 1973 April 2

ABSTRACT

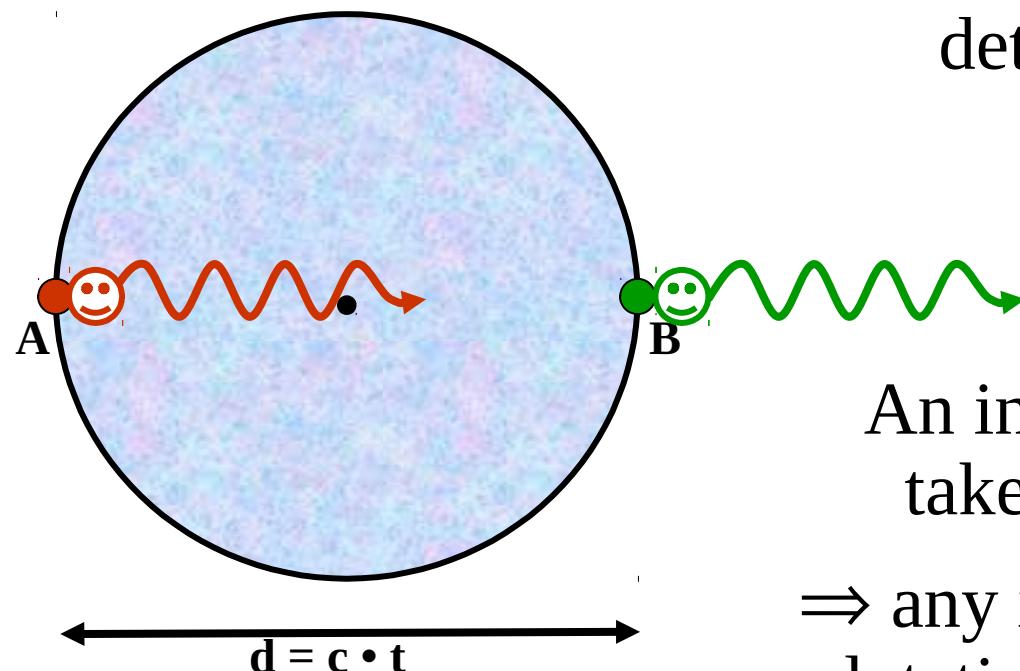
Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to \sim 30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ 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 (\sim 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 duration t must have been emitted from a region of size:

$$d < c \cdot t$$

Fluence and Luminosity

$$\text{Fluence} = \text{Flux} * \text{time} = 1\text{e-}6 - 1\text{e-}4 \text{ erg / cm}^2$$

Luminosity depends on distance

Where they came from ?

The Solar System →

The Galaxy →

Other Galaxies →

Fluence and Luminosity

$$\text{Fluence} = \text{Flux} * \text{time} = 1\text{e-6} - 1\text{e-4} \text{ erg / cm}^2$$

Luminosity depends on distance

Where they came from ?

The Solar System → $D \sim 1\text{e}14 \text{ cm}$ → $L \sim 1\text{e}25 \text{ erg}$

The Galaxy →

Other Galaxies →

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The Solar System → $D \sim 1\text{e}14 \text{ cm}$ → $L \sim 1\text{e}25 \text{ erg}$

The Galaxy → $D \sim 1\text{e}21 \text{ cm}$ → $L \sim 1\text{e}39 \text{ erg}$

Other Galaxies →

Fluence and Luminosity

$$\text{Fluence} = \text{Flux} * \text{time} = 1\text{e-6} - 1\text{e-4} \text{ erg / cm}^2$$

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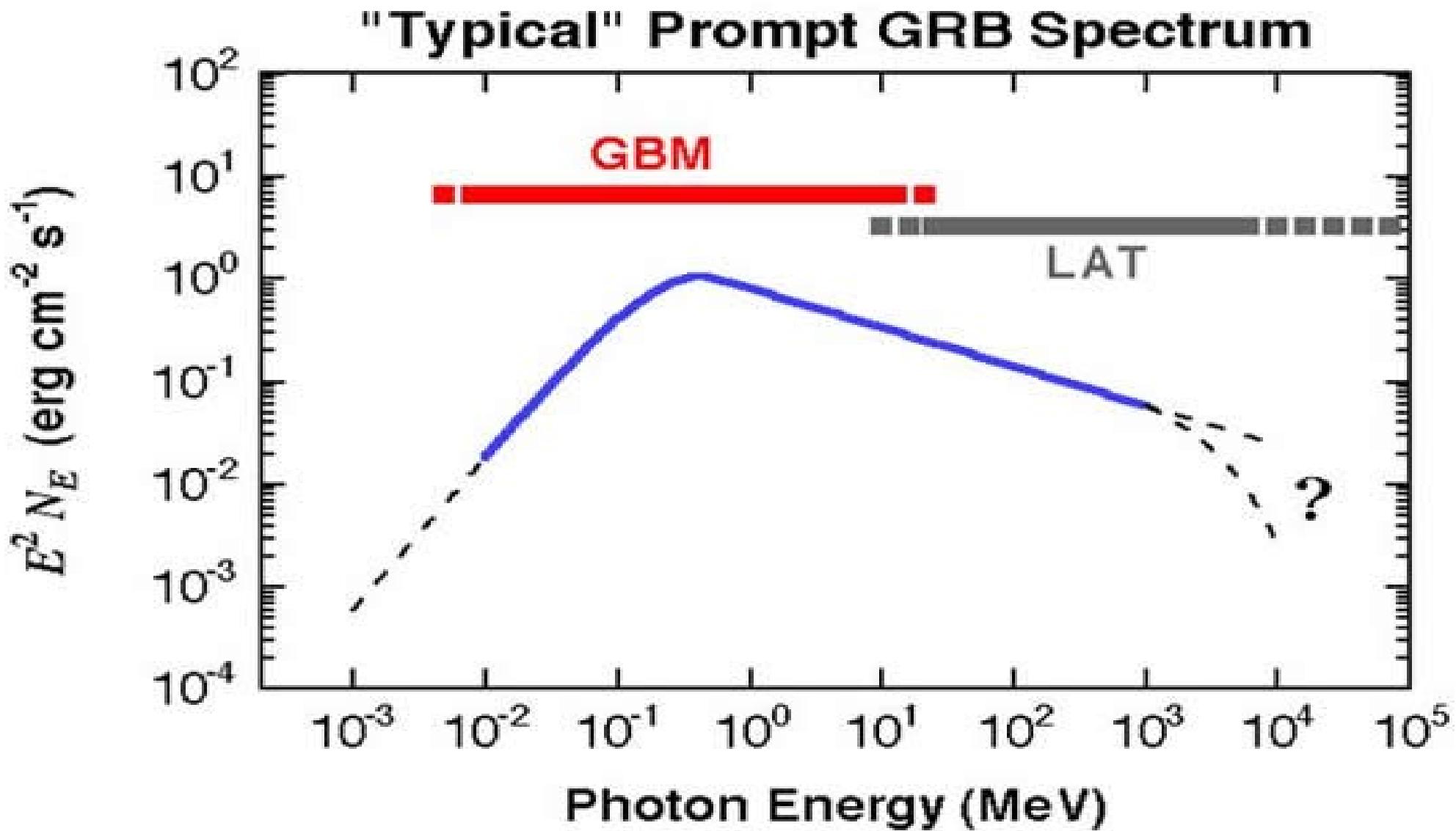
The Galaxy → $D \sim 1\text{e}21 \text{ cm}$ → $L \sim 1\text{e}39 \text{ erg}$

Other Galaxies → $D \sim 1\text{e}27 \text{ cm}$ → $L \sim 1\text{e}51 \text{ erg}$

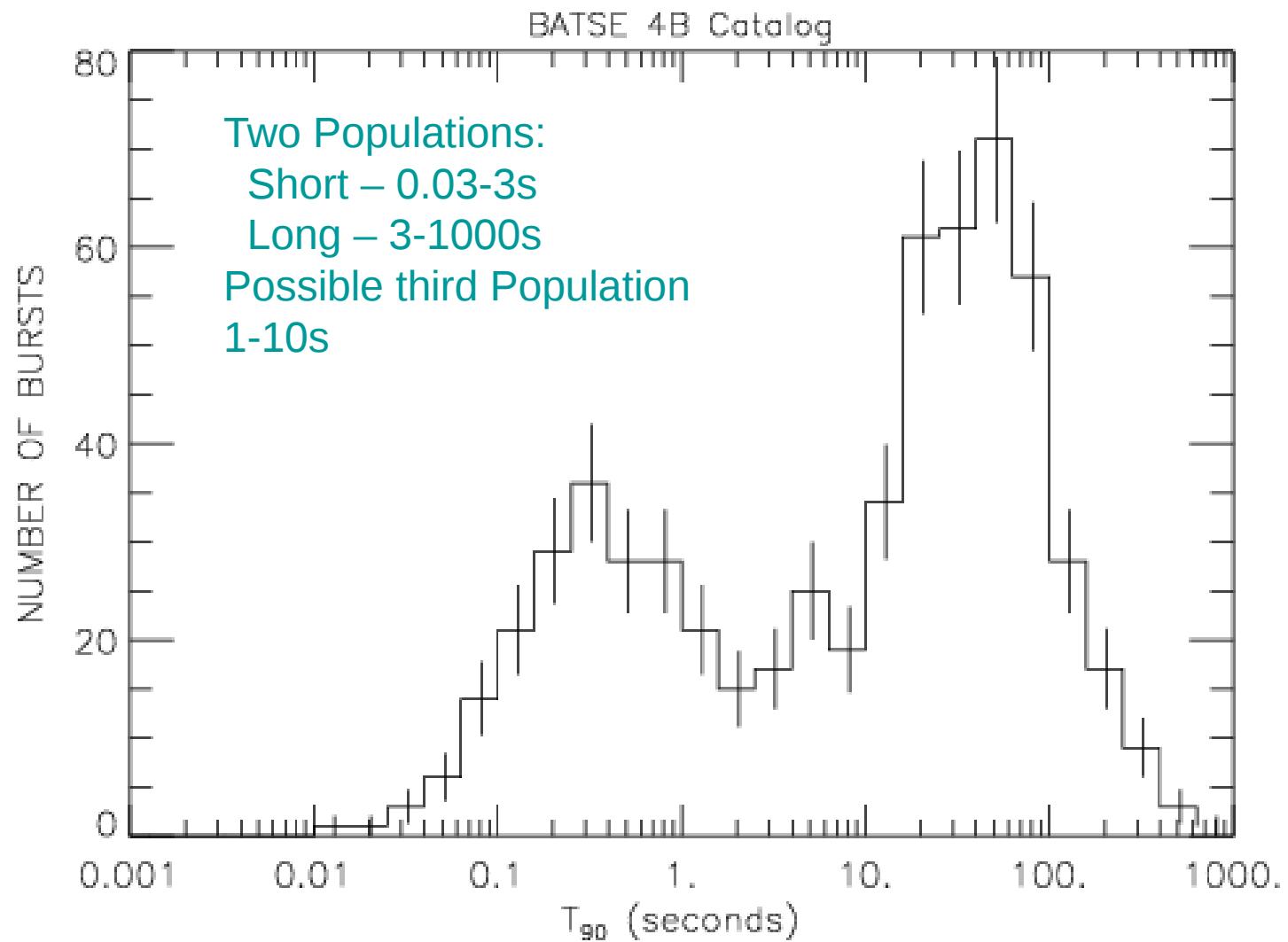
Spectrum

Peak ~ 0.1 - 1 MeV

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



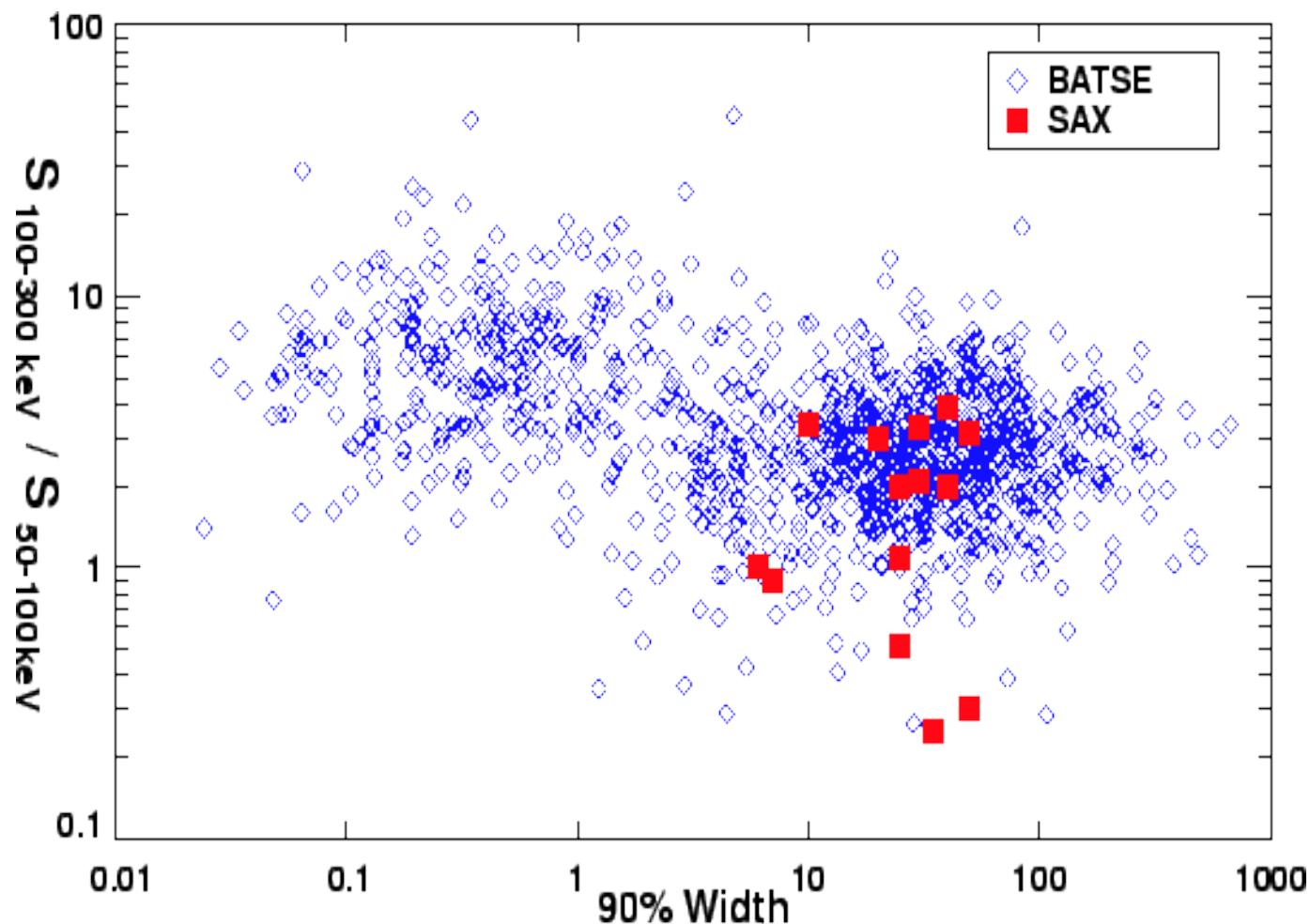
Durations



Bimodal T90 dist

Short/hard vs Long/Soft

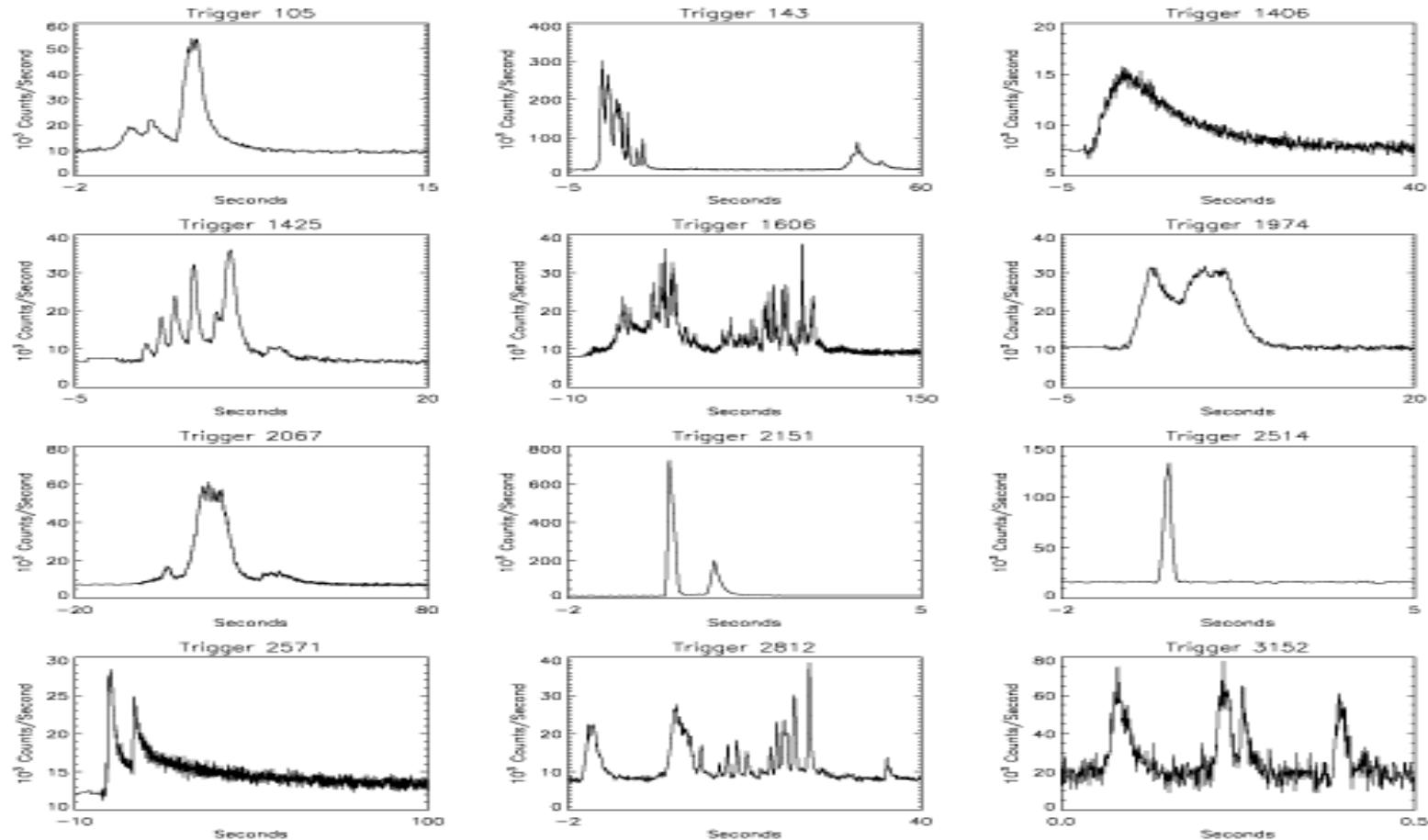
Durations



Bimodal T90 distribution

Short/hard vs Long/Soft

Light Curves

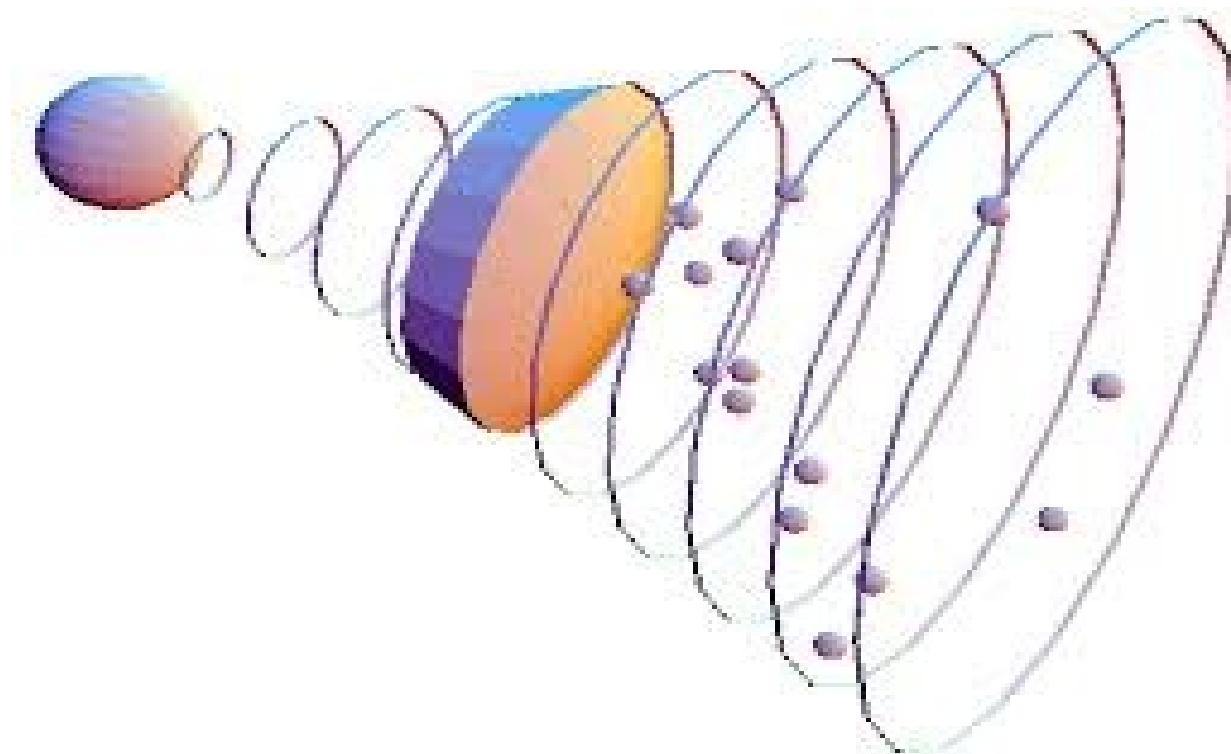


Rapid variability (Dob. Time $\sim 1e-2$ s) \rightarrow size

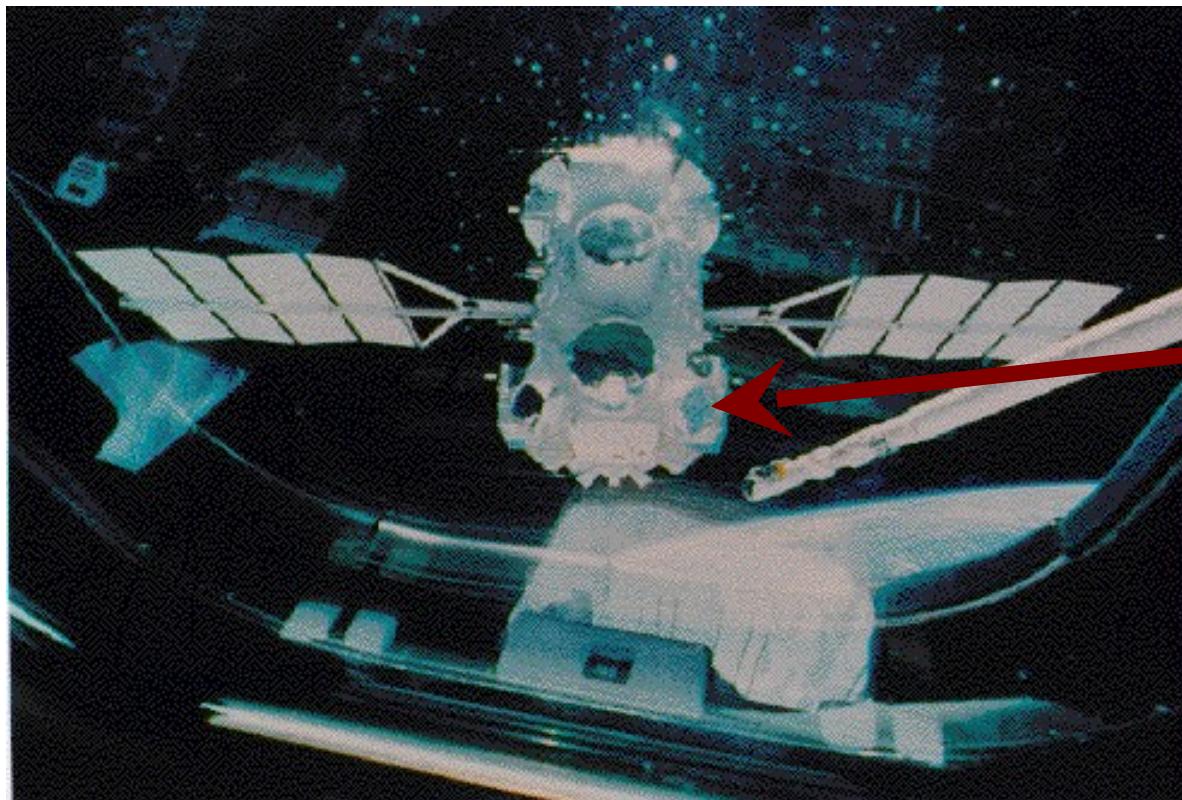
Multiple peaks , often fred-like

When you see a GRB you have seen one GRB

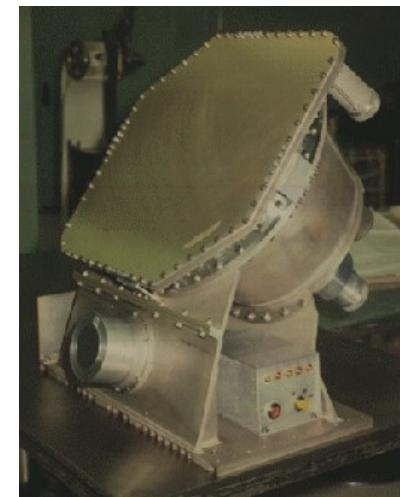
Compactness problem



GCRO / Batse



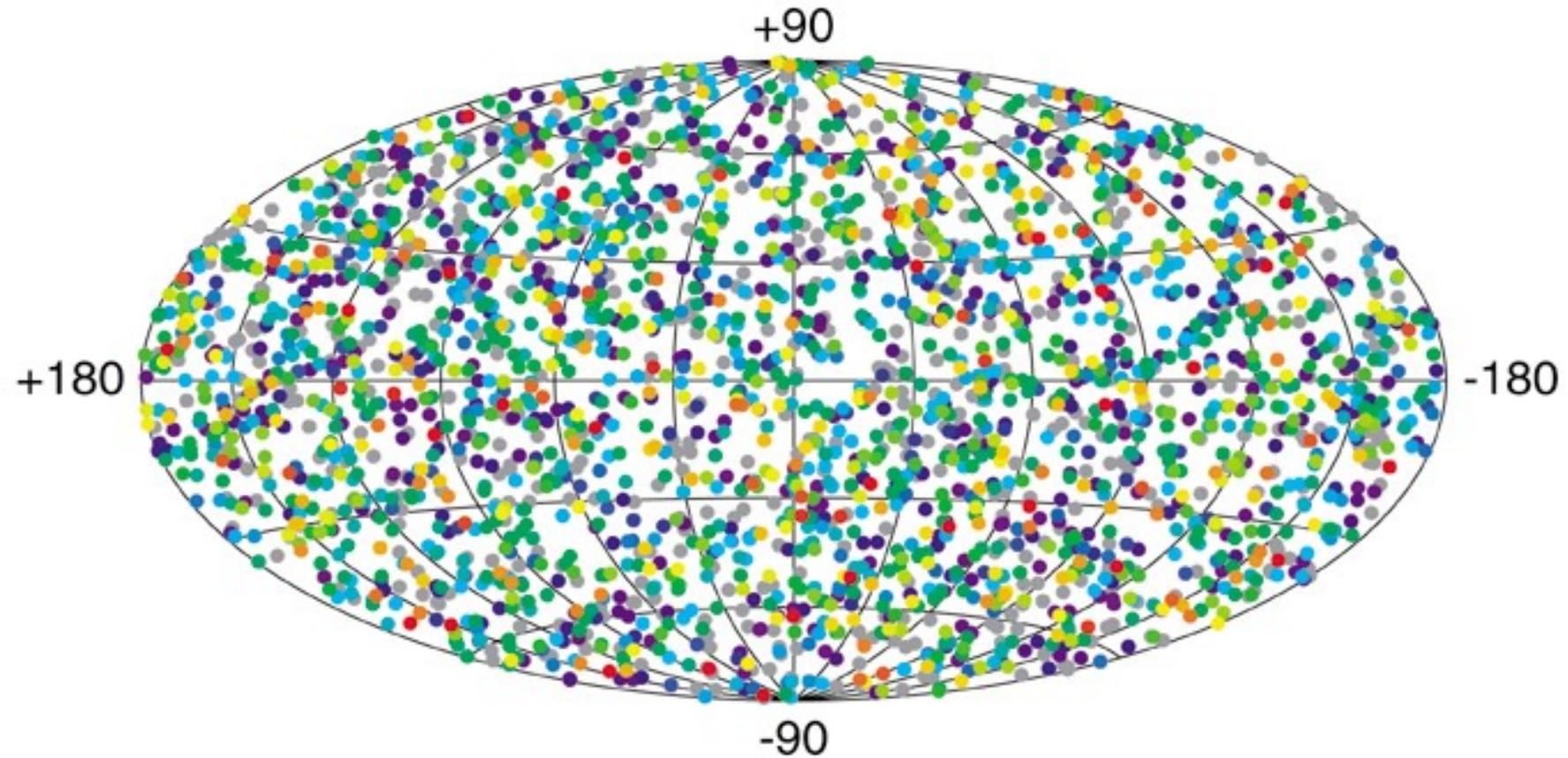
BATSE Module



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

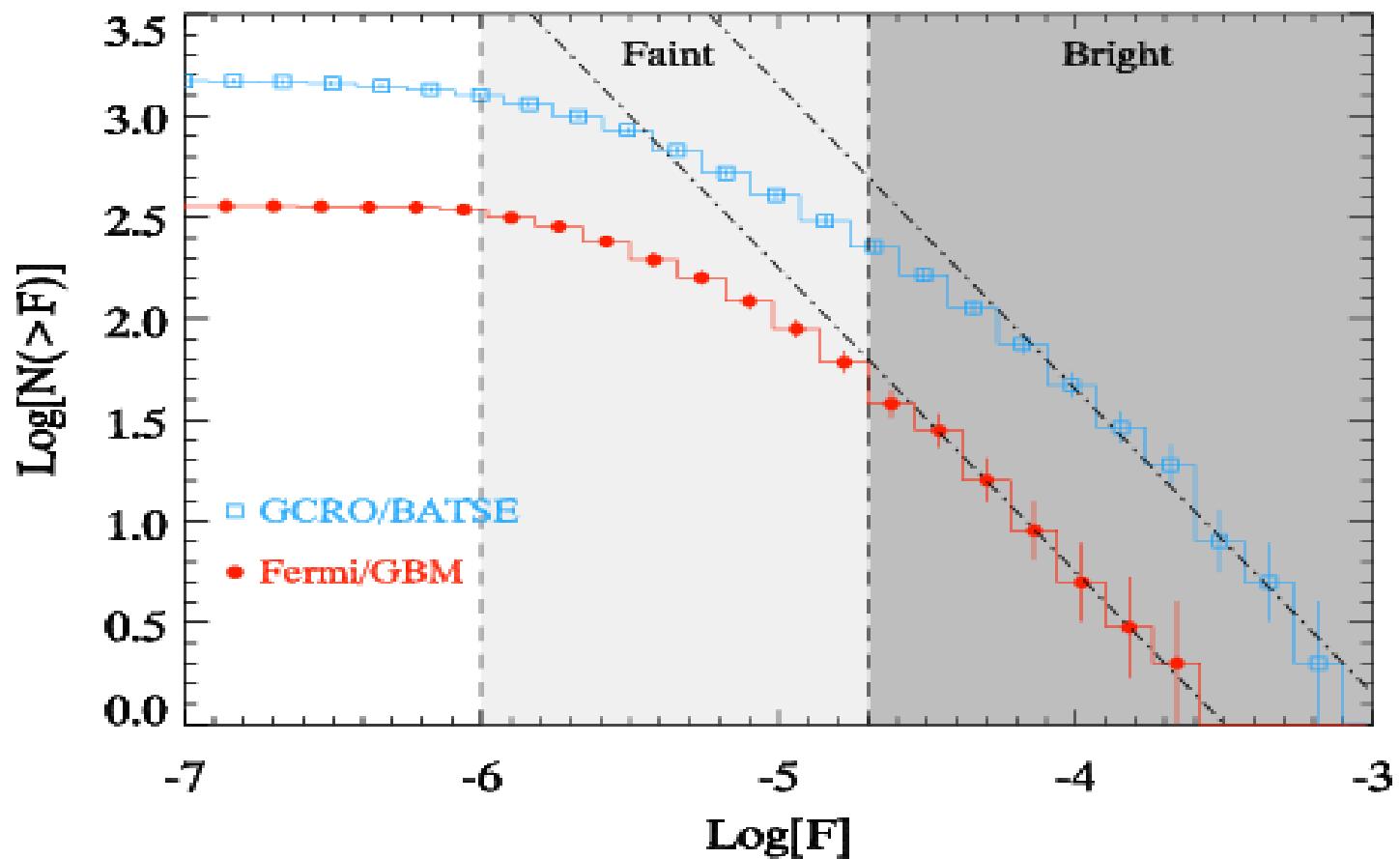
BATSE Consists of two NaI(Tl) Scintillation Detectors: Large Area Detector (LAD) For sensitivity and the Spectroscopy Detector (SD) for energy coverage

2704 BATSE Gamma-Ray Bursts

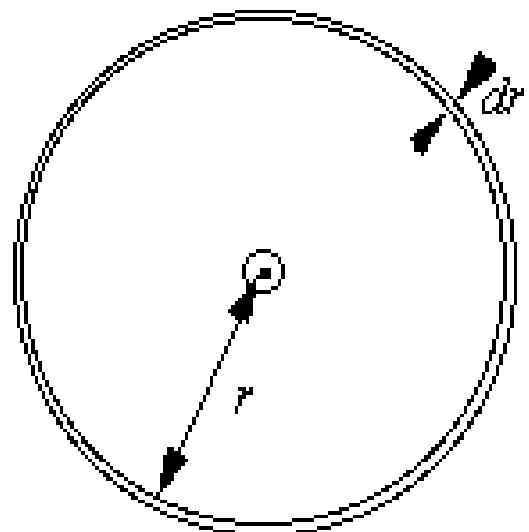


Isotropic distribution, in contrast with most (Galactic) models
→ at cosmological distances or very nearby

LogN - LogS



LogN - LogS



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

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

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

So, the number of GRBs brighter than f is

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

Theoretical input

Gamma-Ray Bursts in the Solar System

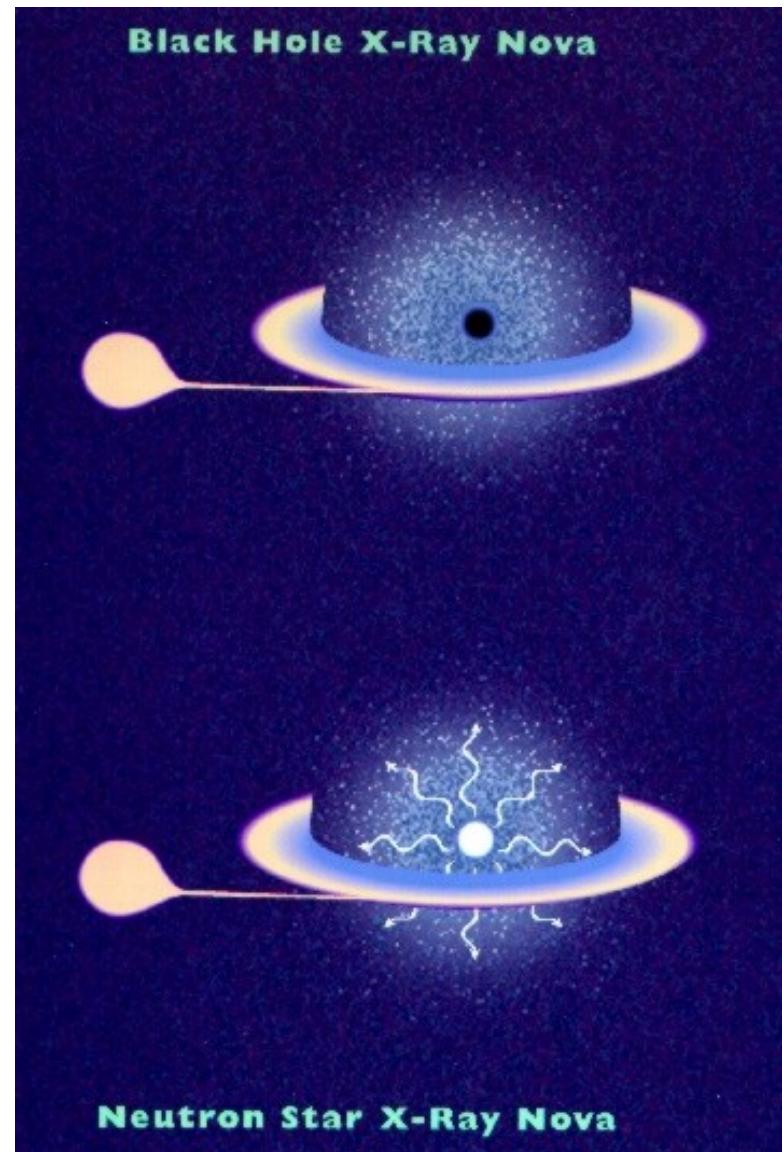
- Lightning in the Earth's atmosphere (High Altitude)
- Relativistic Iron Dust Grains
- Magnetic Reconnection in the Heliopause



Red Sprite Lightning

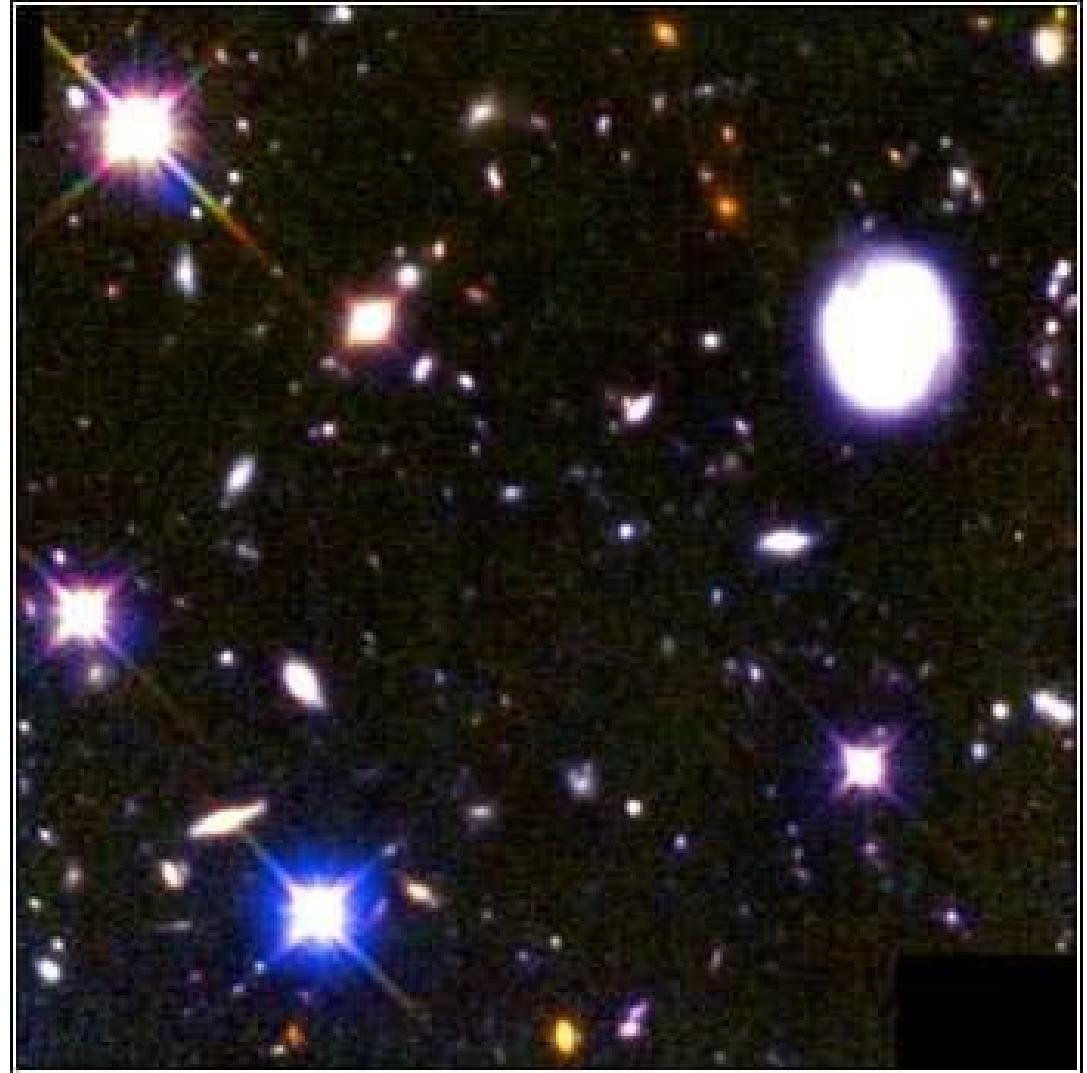
Gamma-Ray Bursts in the Milky Way

- 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



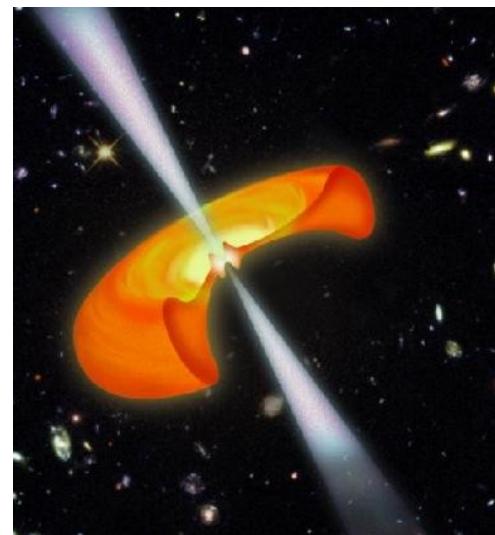
Cosmological Models



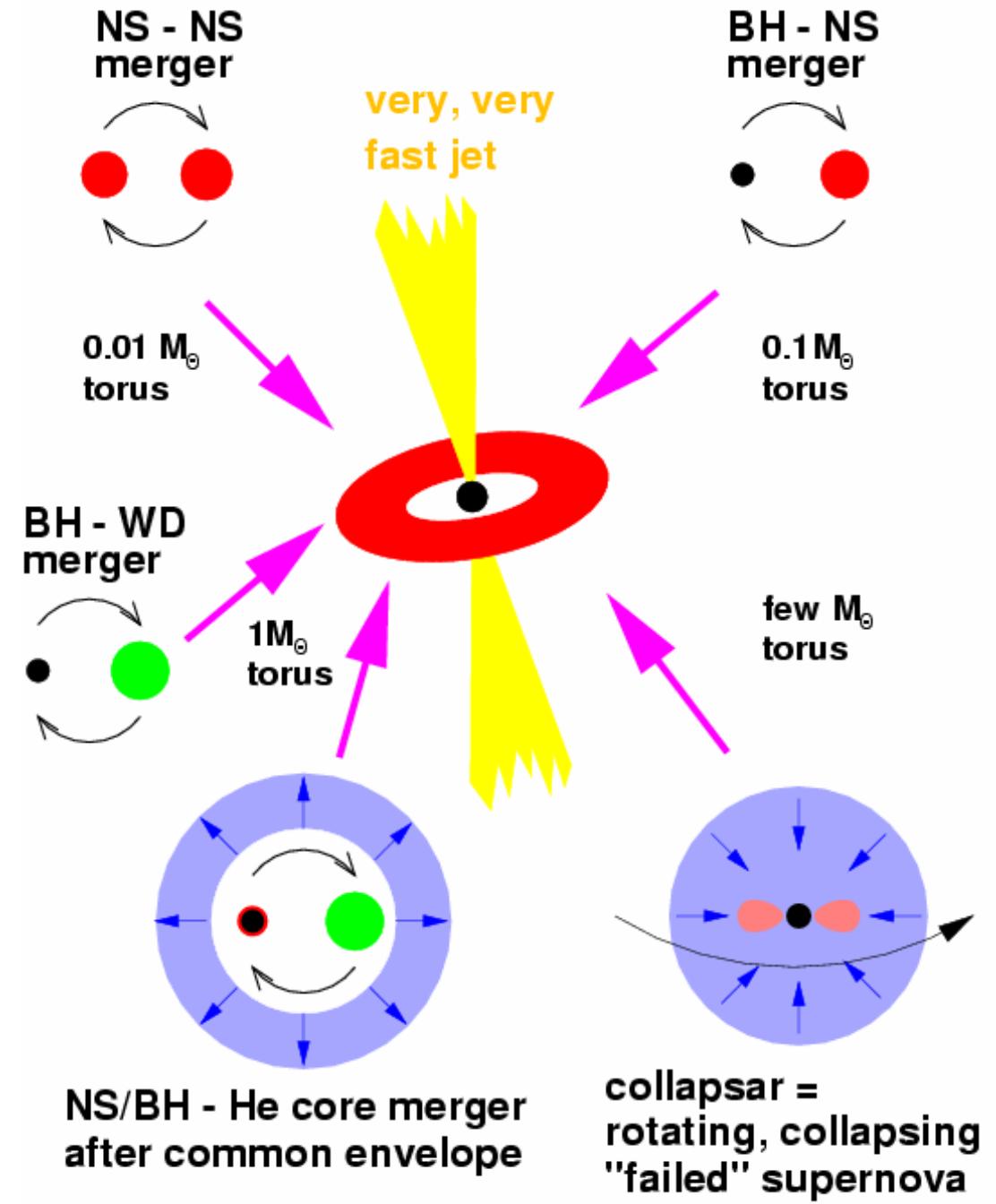
- Collapsing WDs
- Stars Accreting on AGN
- White Holes
- Cosmic Strings
- Black Hole Accretion Disks
 - I) Binary Mergers
 - II) Collapsing Stars

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.



Hyperaccreting Black Holes

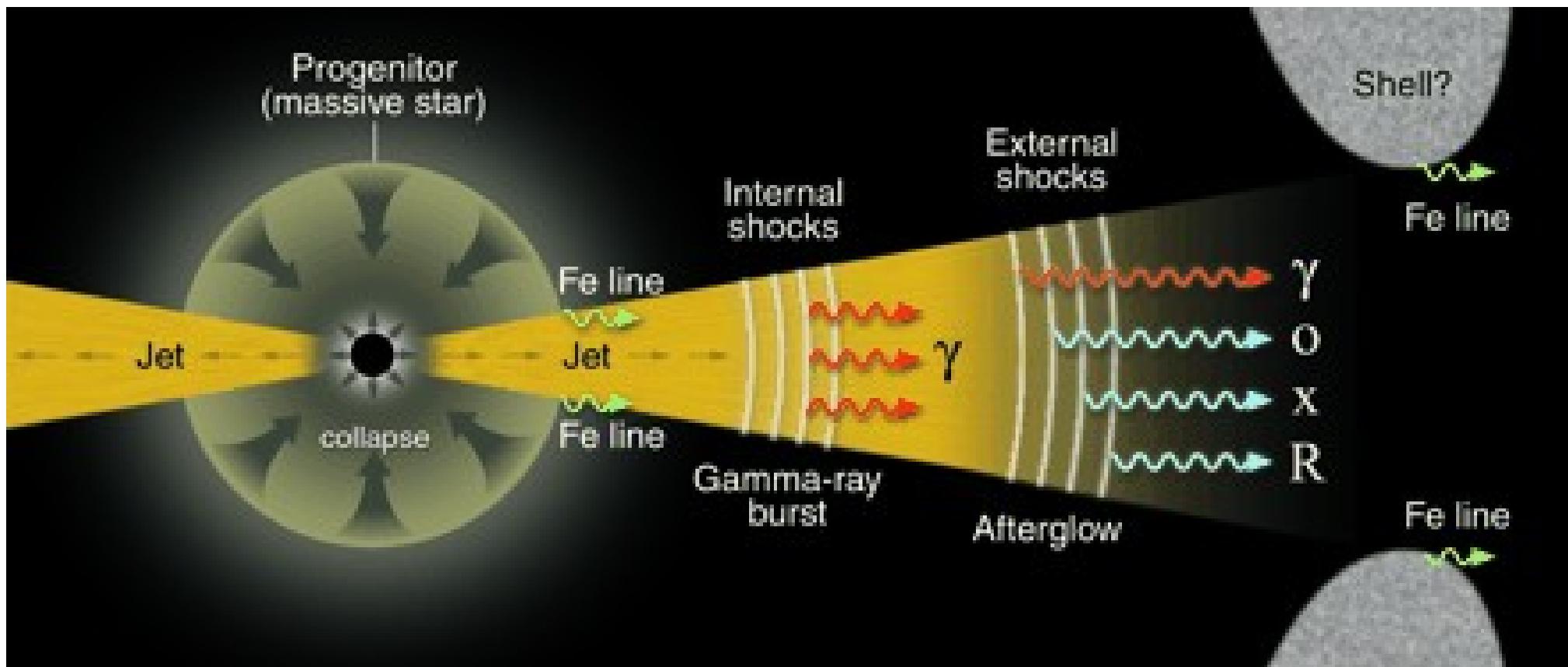
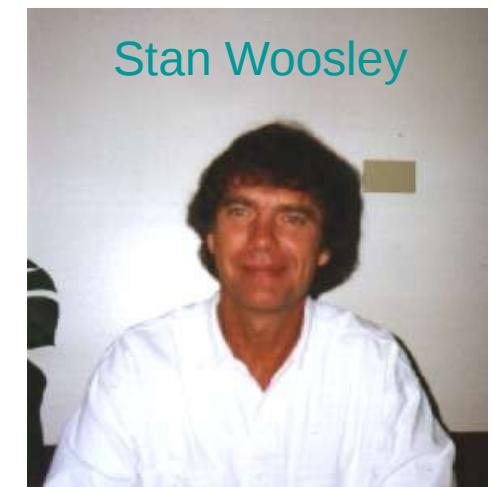


Massive Star Collapse

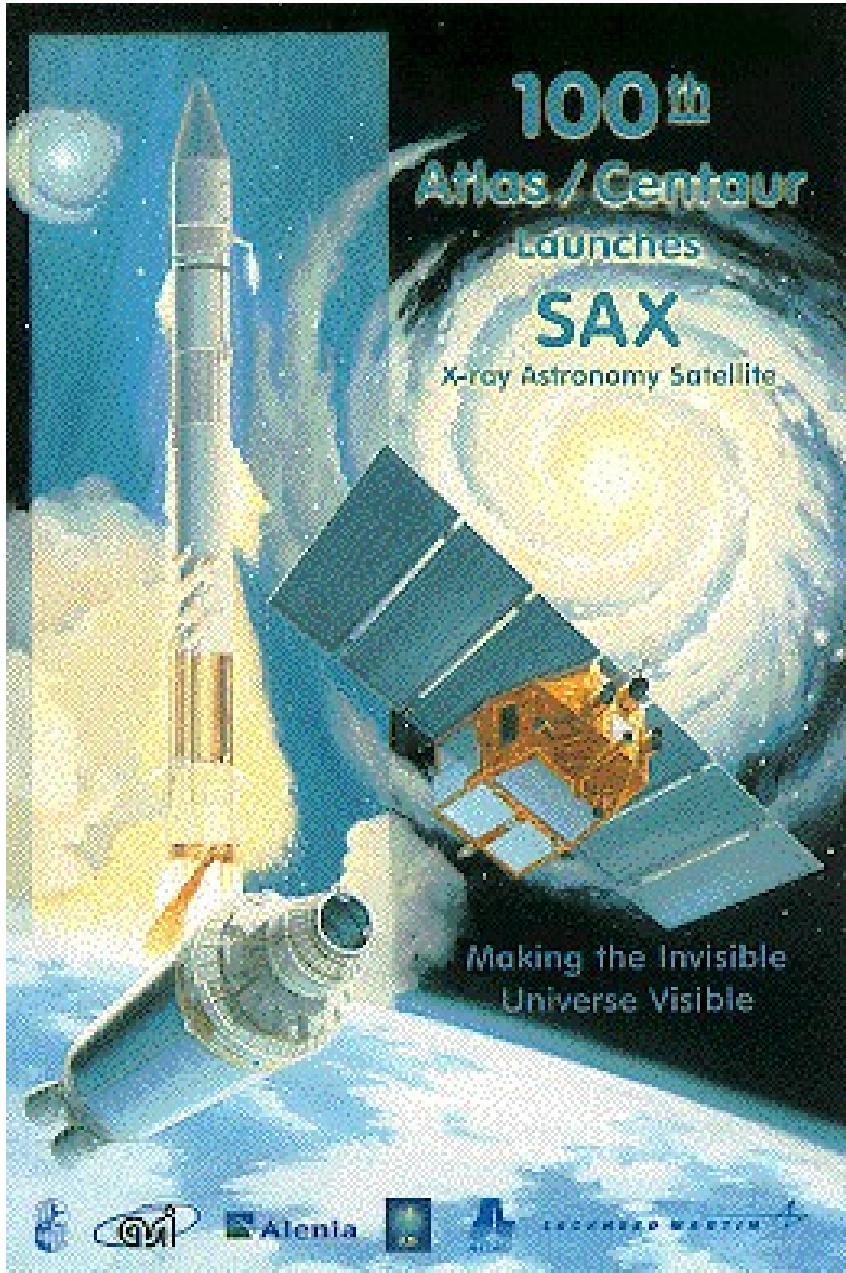
Collapsar Model – Collapse of a Rotating Massive Star into a Black Hole

Main Predictions: Beamed Explosion,
Accompanying supernova-like explosion

Stan Woosley



BeppoSAX



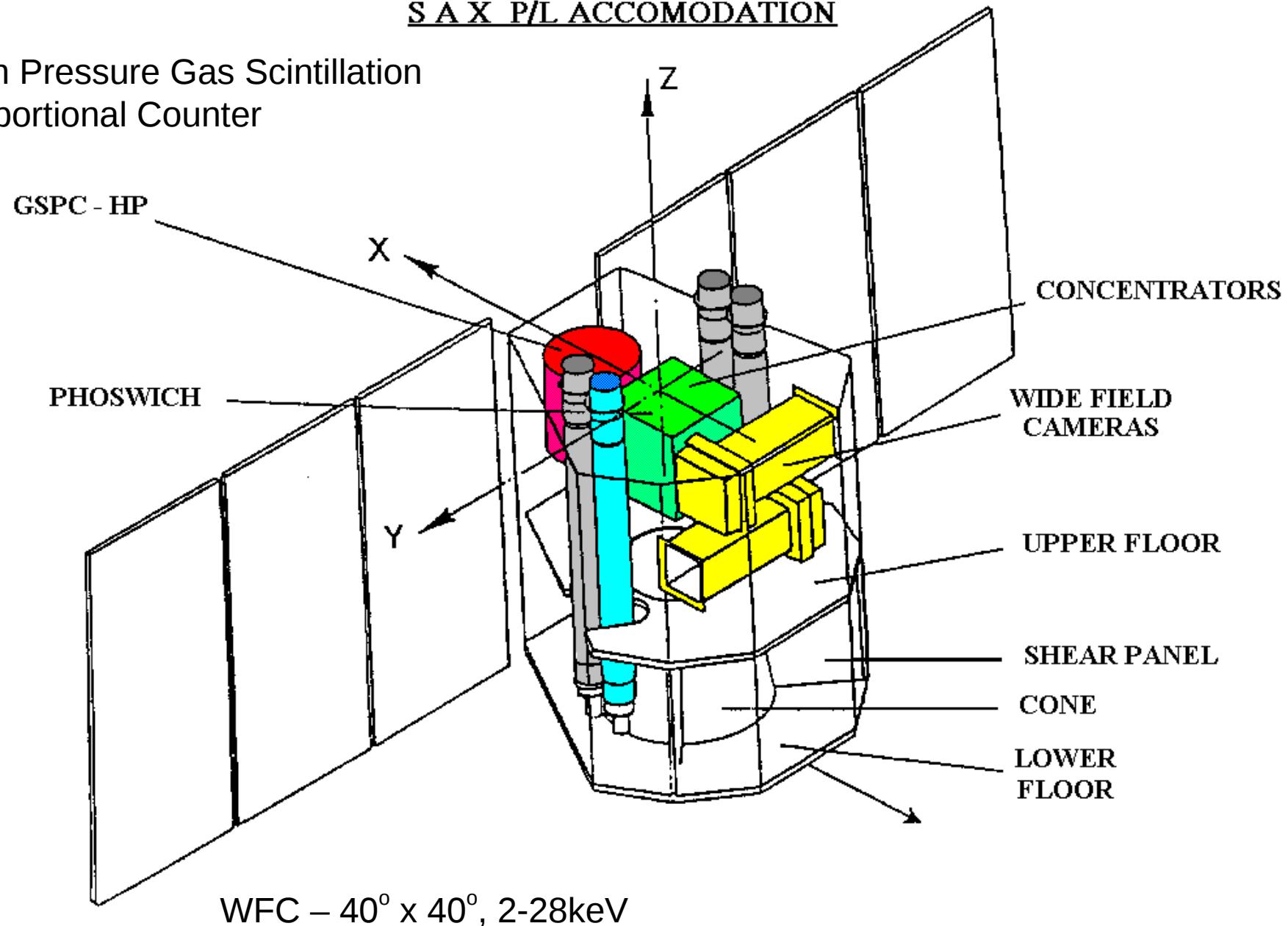
Italian-Dutch Satellite
Launch: April 30, 1996
Goal: Positional Accuracy
<5 arc minutes

Honoring Giuseppe Occhialini



SAX P/L ACCOMODATION

High Pressure Gas Scintillation
Proportional Counter



BeppoSAX Instruments

LECS/MECS

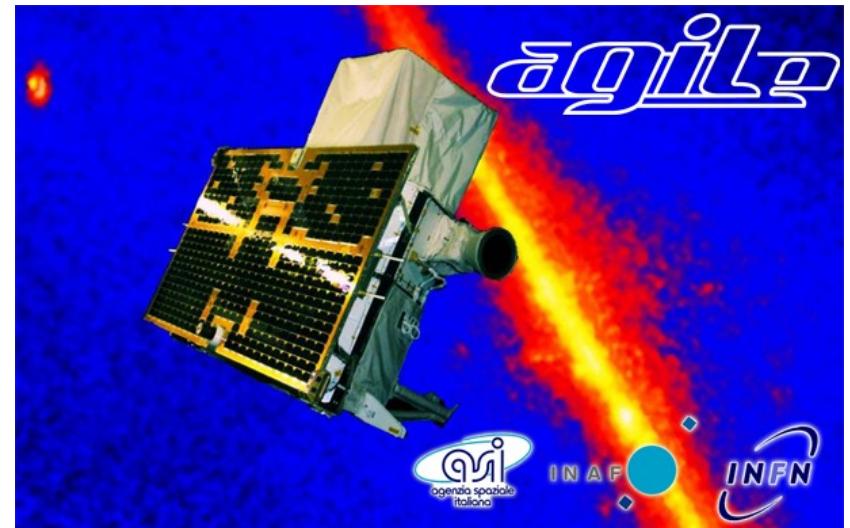
- Xenon Gas Scintillator
- Energy Range: .1-1keV (1-10keV)
- ~1 arc minute resolution
- Goal – Localize Object

HPGSPC PDS

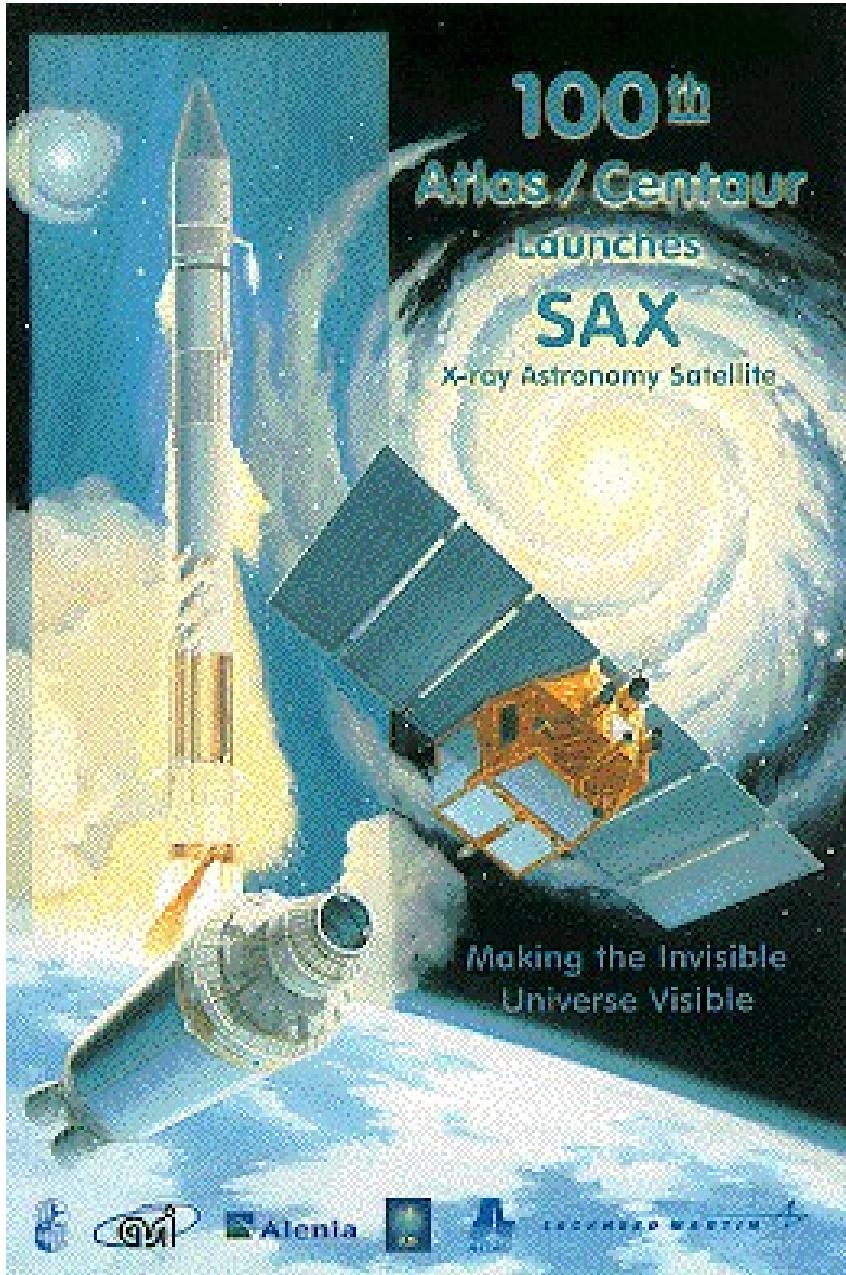
- HPGSPC - High Pressure Xenon/He Gas
- PDS Phoswitch - NaI(Tl), CsI(Na) Scintillators
- 4-120keV (15-300keV)
- Goal – Broad Energy resolution in X-ray narrow field

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-)

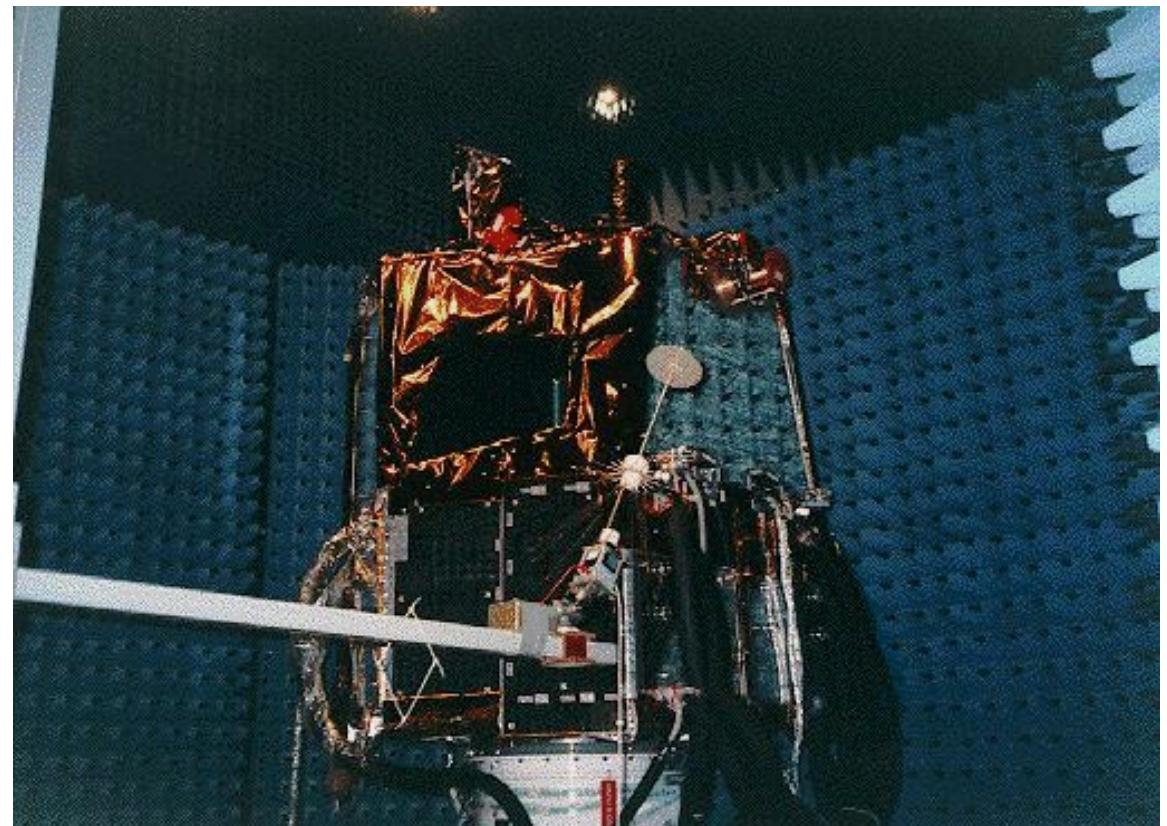


BeppoSAX



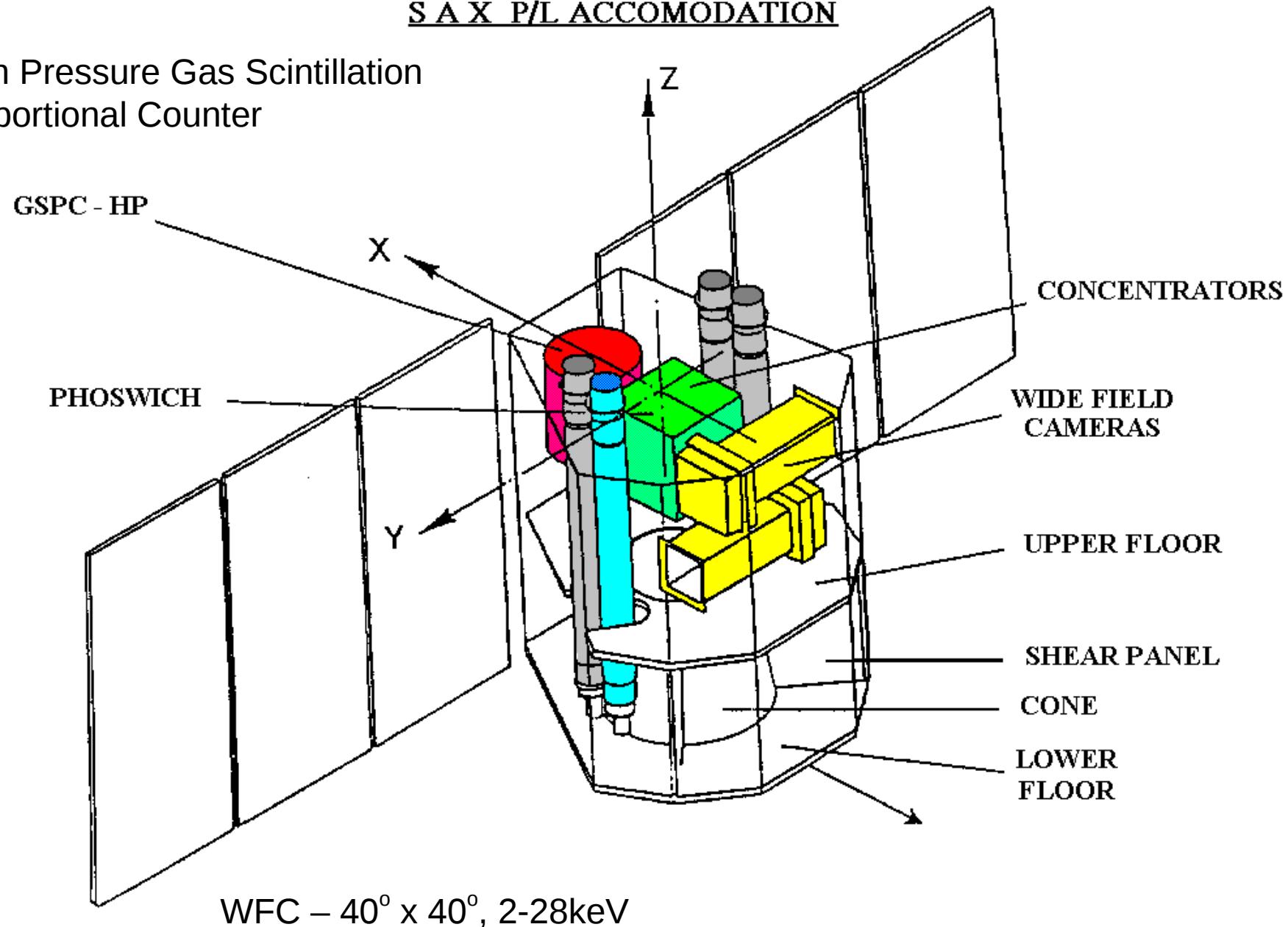
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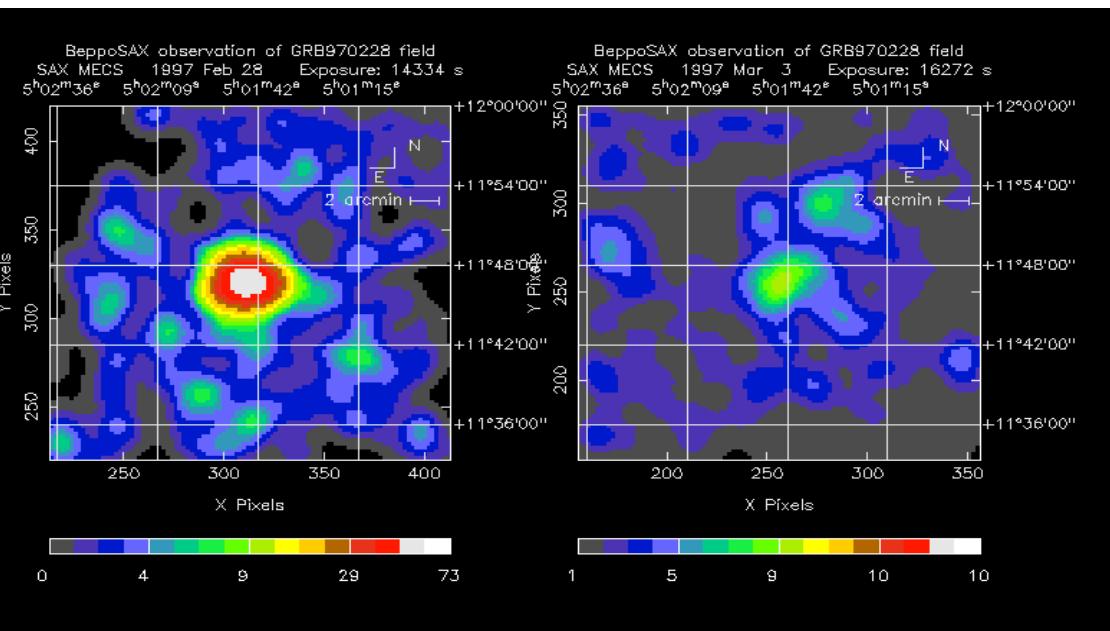
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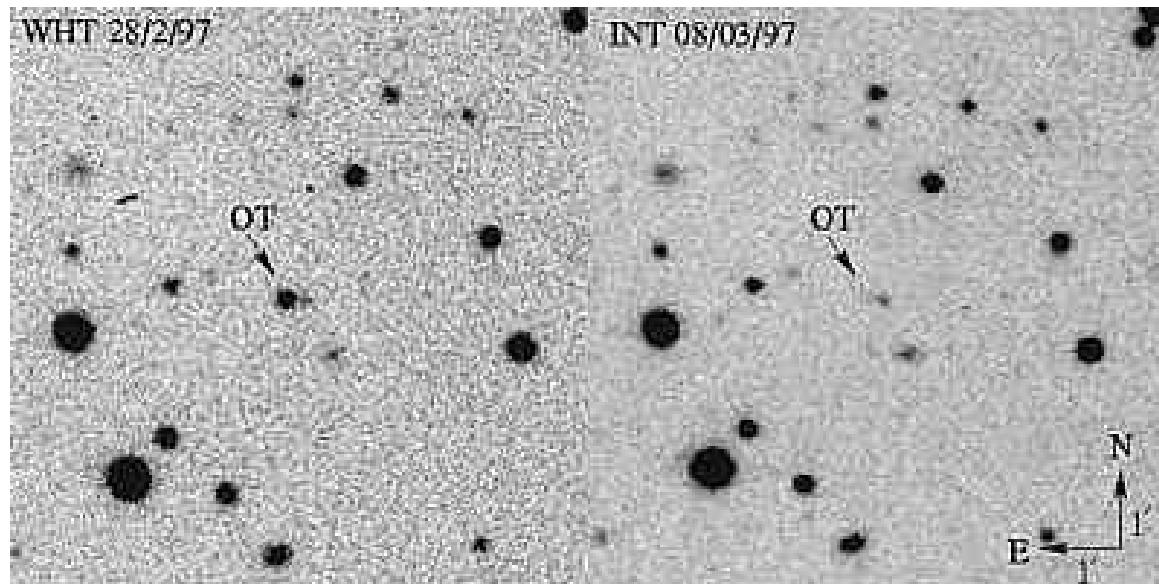
GRB afterglows: the mystery is solved!



BeppoSAX discovers X-ray afterglows

(Costa et al. 1997)

⇒ GRB position \sim arcmin



Optical afterglow

(van Paradijs et al. 1997)

⇒ position $\sim 1''$

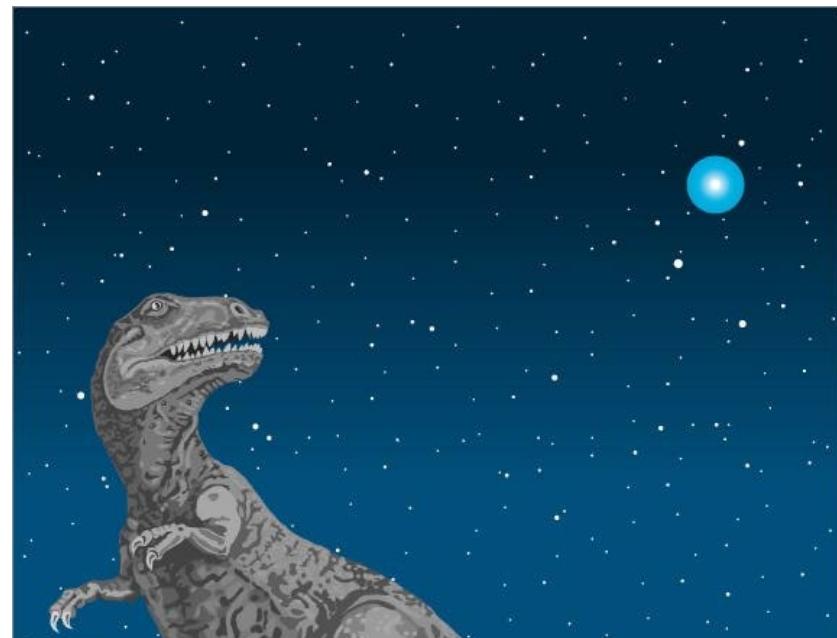
⇒ host galaxy and redshift

($z \sim 0.0085 - 9.4$)

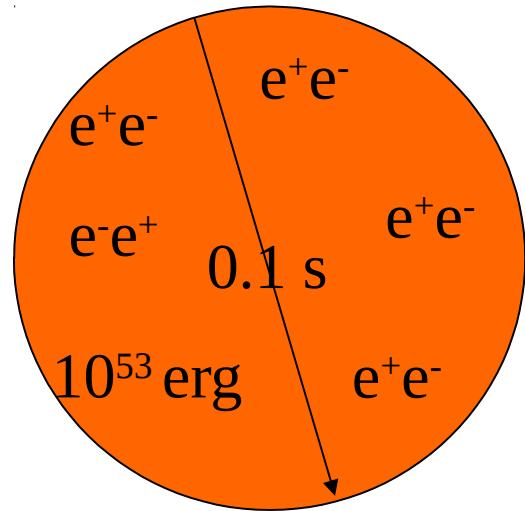
⇒ $E_{iso} \sim 10^{51} - 10^{54}$ erg

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 extinctions**!



GRB Explosions are Highly Relativistic



A large amount of energy, $\sim 10^{53}$ erg, packed in a small space of $\sim c \times 0.1$ s.

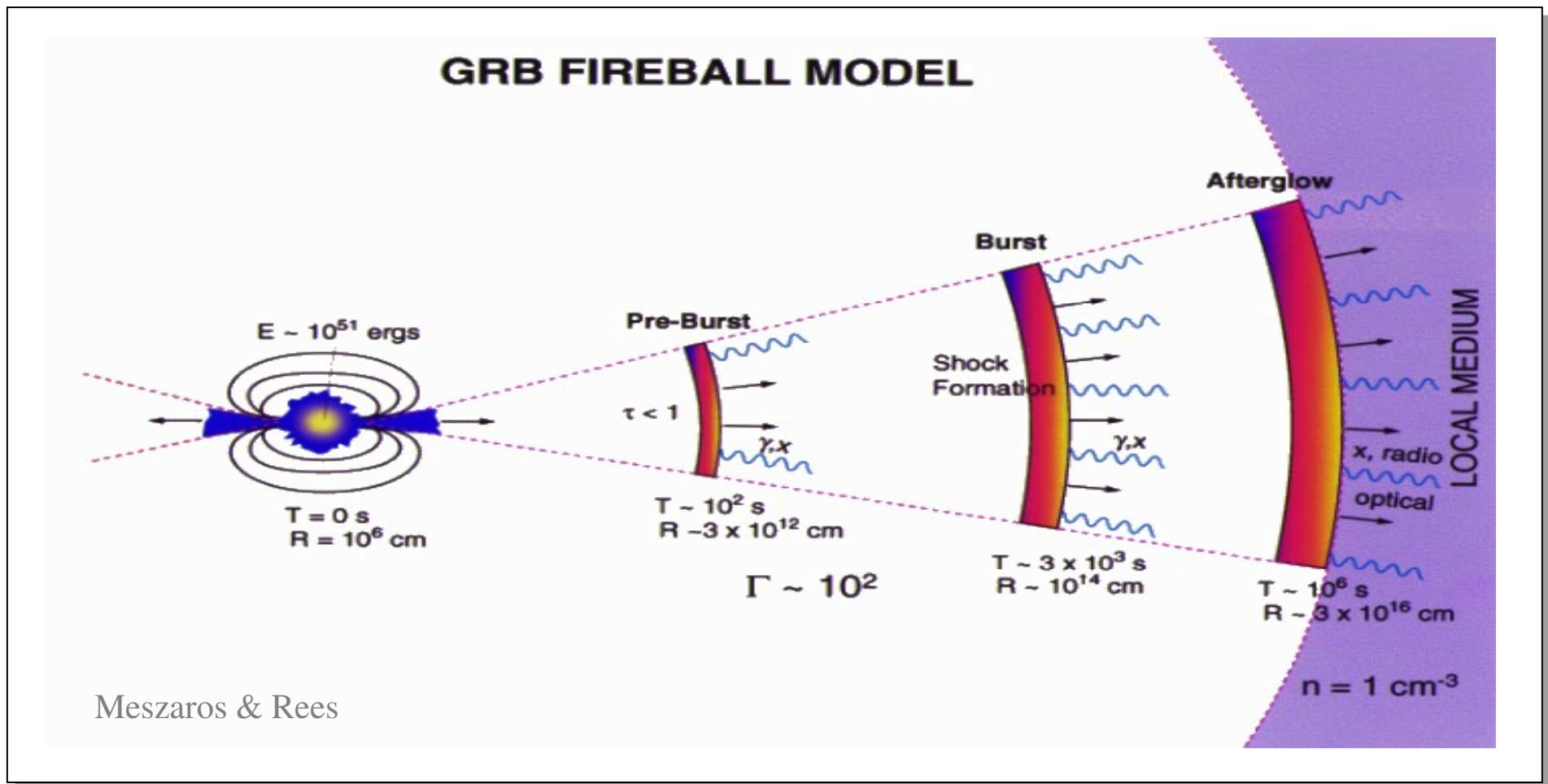
Is highly optically thick to e^+e^- pair production: $\tau \sim 10^{15}$

In this case we should not see any γ 's above \sim 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)

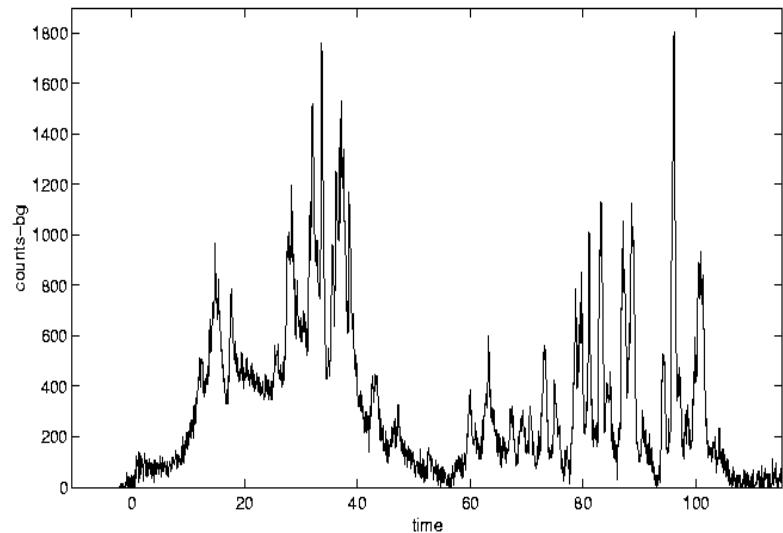
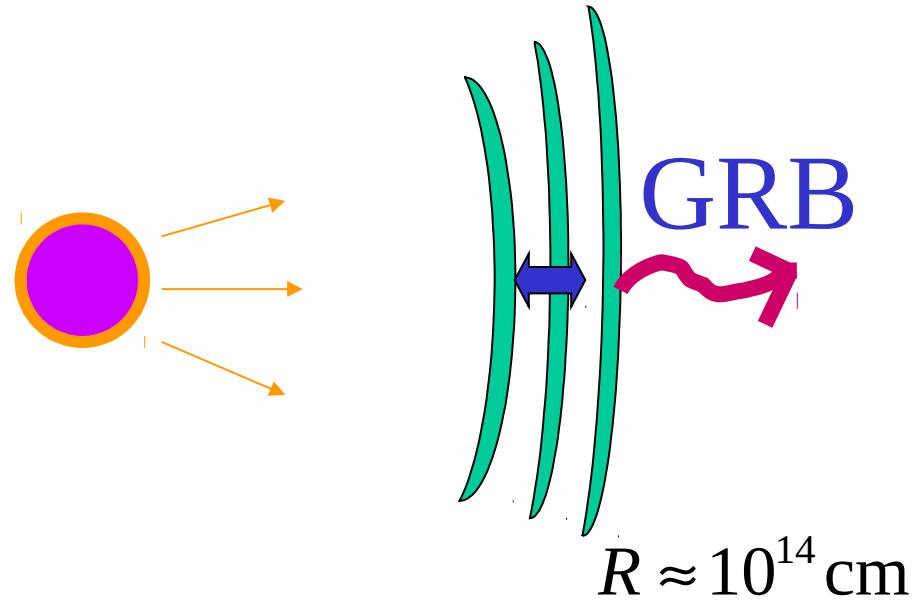
Fireball Model of GRBs



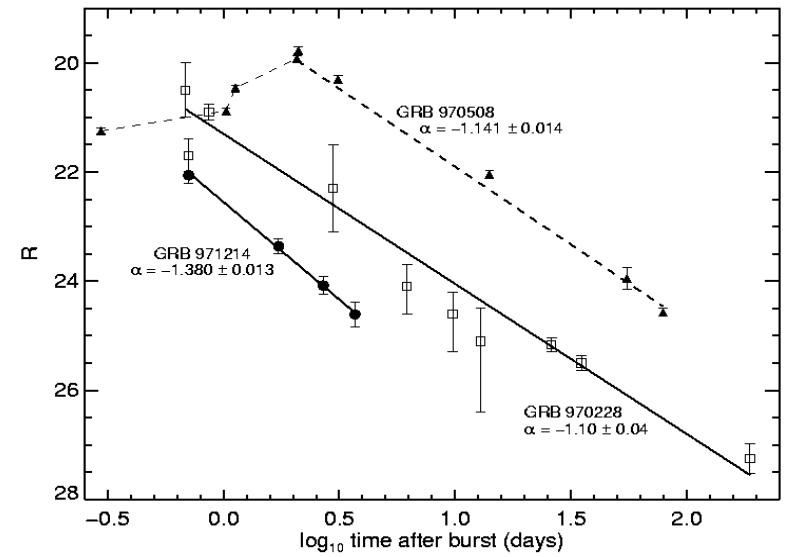
Most photons produced by relativistic electrons (**synchrotron**)

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

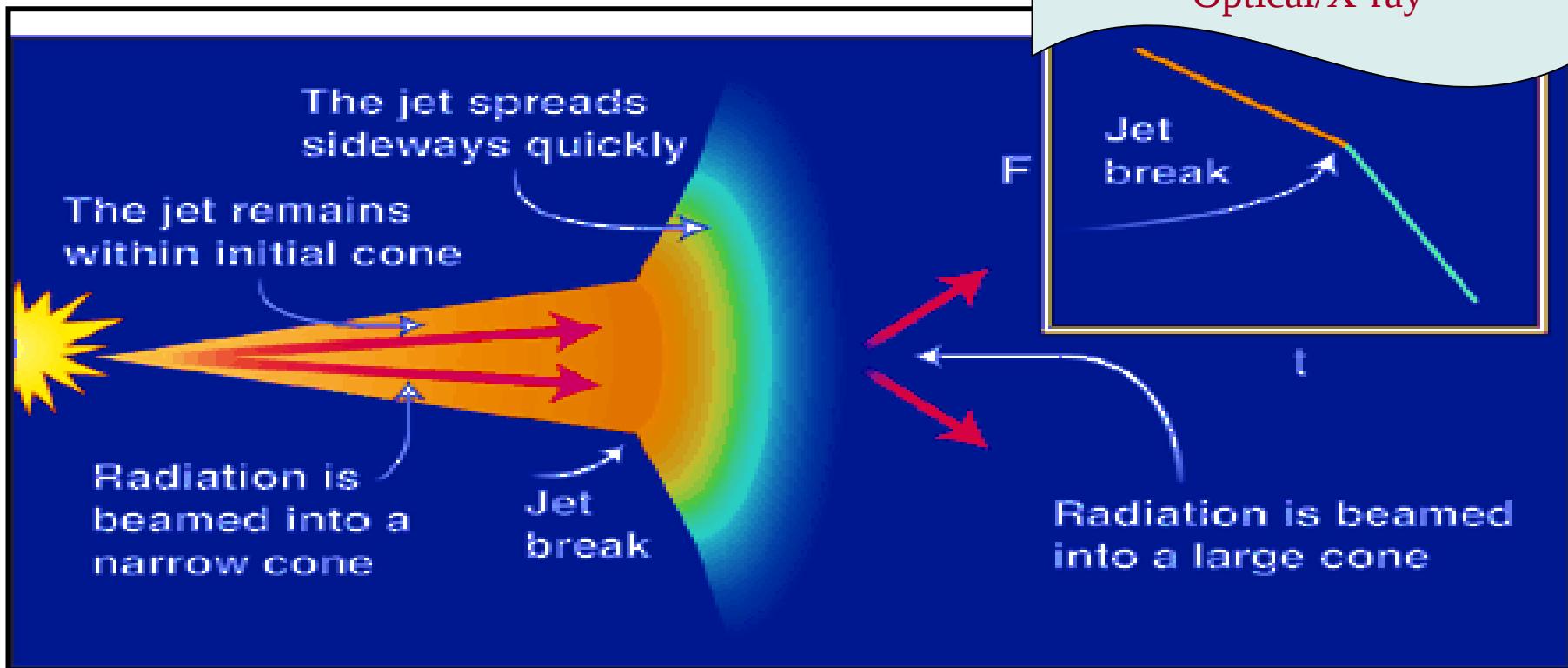
Prompt Emission: Internal Shocks



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)

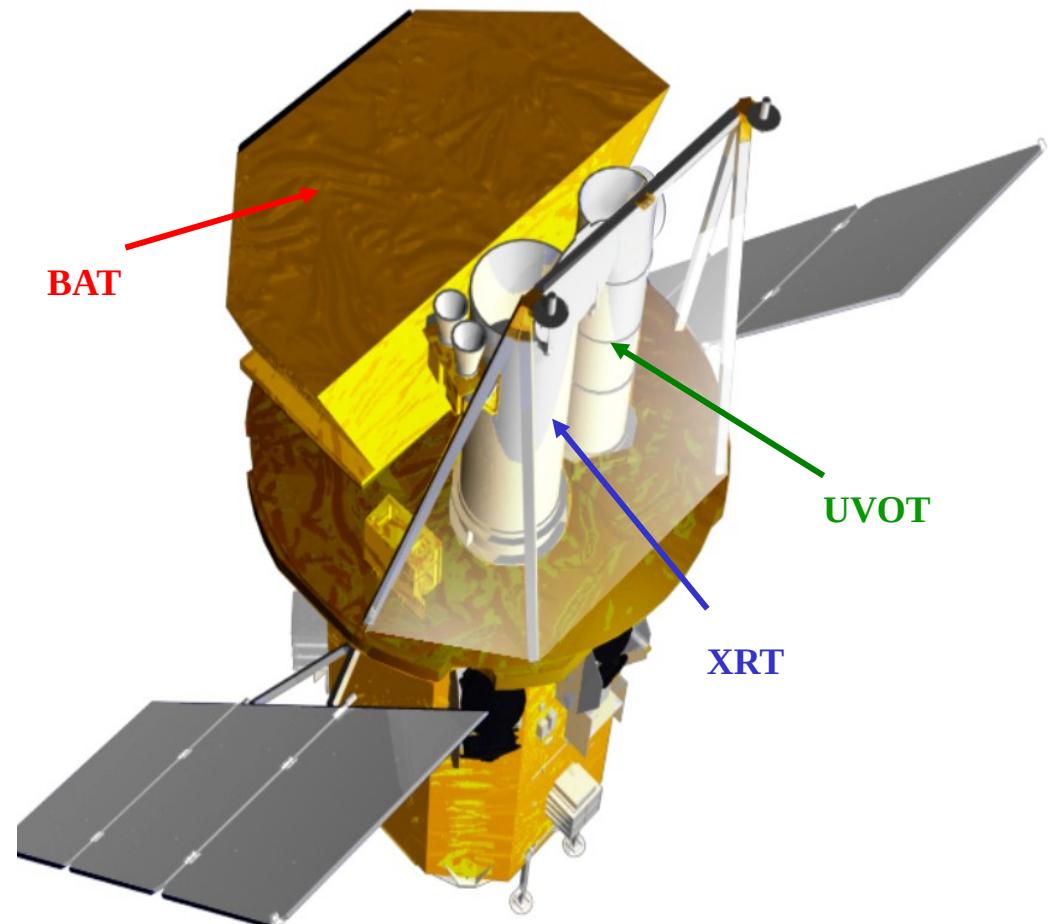
- Coded mask + CdZnTe detectors
- 2 sr field of view

X-Ray Telescope (XRT)

- Mirror + CCD detector
- Arcsec GRB positions

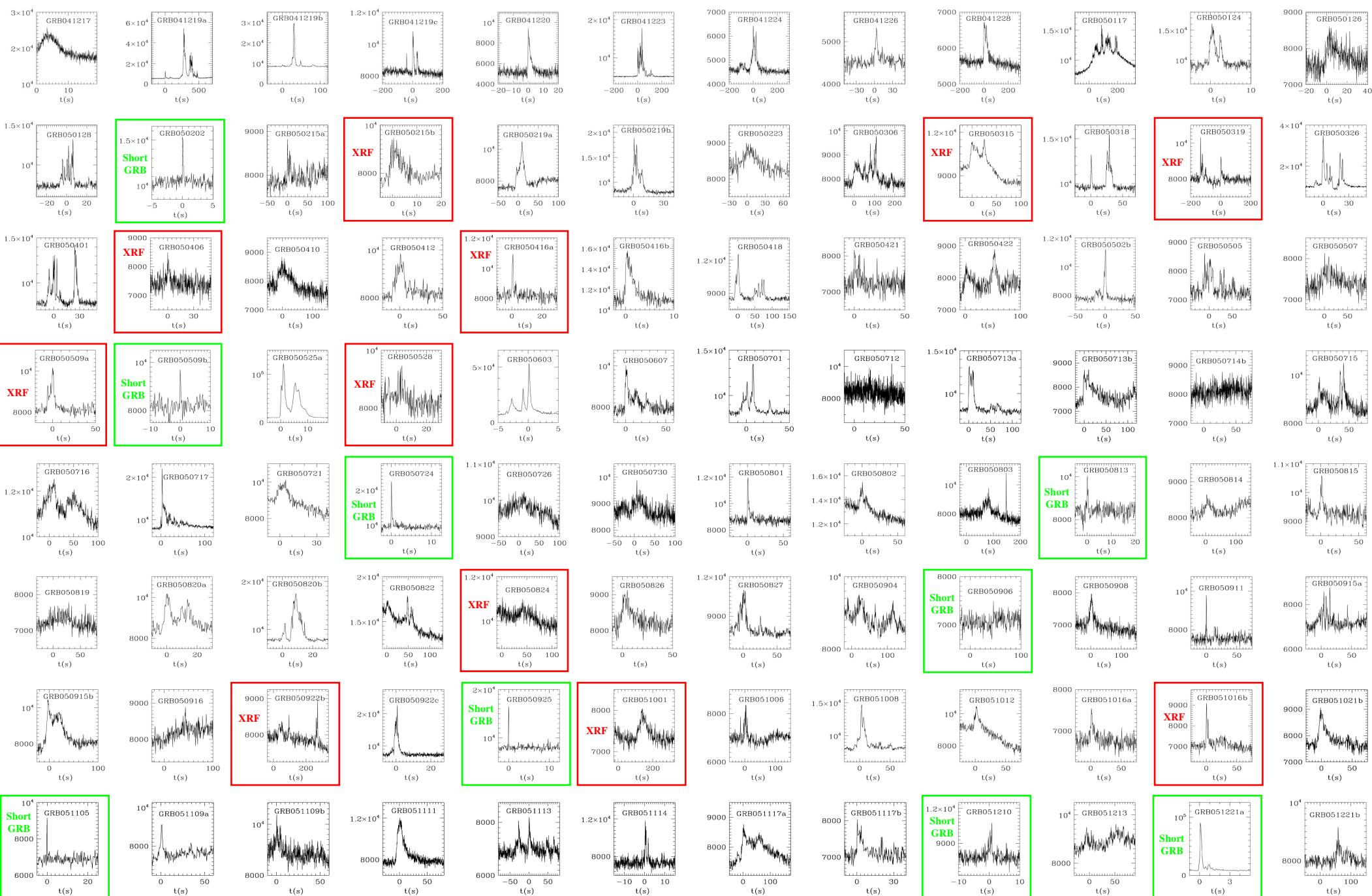
UV-Optical Telescope (UVOT)

- Sub-arcsec position
- 22 mag sensitivity



Spacecraft slews to GRB in <100 s

Swift



TITLE: GCN CIRCULAR

NUMBER: 13182

SUBJECT: **GRB 120401A:** Swift detection of a burst

DATE: **12/04/01 05:33:59 GMT**

FROM: David Palmer at LANL <palmer@lanl.gov>

A. P. Beardmore (U Leicester), W. H. Baumgartner (GSFC/UMBC), V. D'Elia (ASDC), A. Maselli (INAF-IASFPA), C. J. Mountford (U Leicester), C. Pagani (U Leicester), K. L. Page (U Leicester), D. M. Palmer (LANL), T. Sakamoto (NASA/UMBC), M. H. Siegel (PSU), R. L. C. Starling (U Leicester) and B.-B. Zhang (PSU) report **on behalf of the Swift Team**:

At **05:24:15 UT**, the Swift Burst Alert Telescope (**BAT**) triggered and located GRB 120401A (trigger=519043). **Swift slewed immediately to the burst.** The BAT on-board calculated location is RA, Dec 58.068, -17.671 which is

RA(J2000) = 03h 52m 16s

Dec(J2000) = -17d 40' 15"

with an **uncertainty of 3 arcmin** (radius, 90% containment, including systematic uncertainty). As is typical for an image trigger, no activity is apparent in the immediately available light curve.

The **XRT** began observing the field at **05:26:14.1 UT, 118.3 seconds after the BAT trigger.** XRT found a bright, uncatalogued X-ray source located at RA, Dec 58.0835, -17.6349 which is equivalent to:

RA(J2000) = +03h 52m 20.04s

Dec(J2000) = -17d 38' 05.6"

with an **uncertainty of 5.4 arcseconds** (radius, 90% containment). This location is 140 arcseconds from the BAT onboard position, within the BAT error circle. No event data are yet available to determine the column density using X-ray spectroscopy.

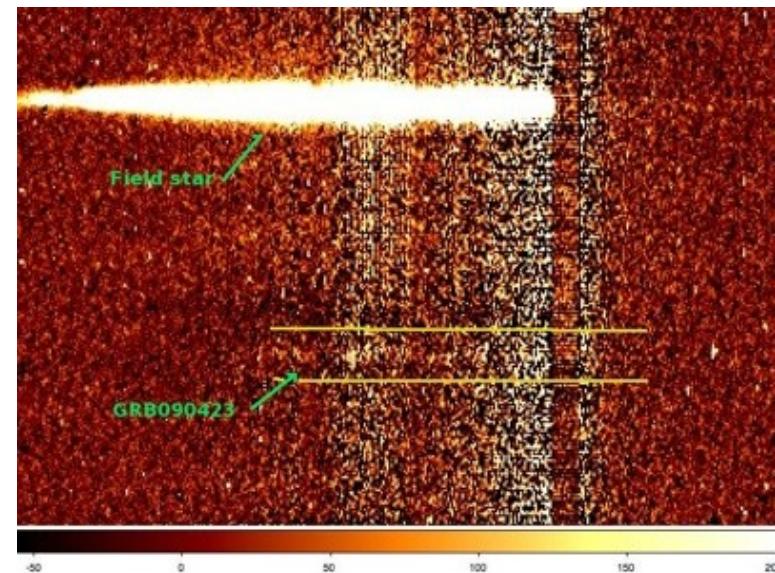
The **initial flux** in the 2.5 s image was 1.35e-09 erg cm⁻² s⁻¹ (0.2-10keV).

UVOT took a finding chart exposure of 150 seconds with the White filter starting 127 seconds after the BAT trigger. **No credible afterglow candidate** has been found in the initial data products. The 2.7'x2.7' sub-image **covers 100%** of the XRT error circle. The typical 3-sigma upper limit has been about 19.6 mag. The 8'x8' region for the list of sources generated on-board covers 100% of the XRT error circle. The list of sources is typically complete to about 18 mag. No correction has been made for the expected extinction corresponding to E(B-V) of 0.05.

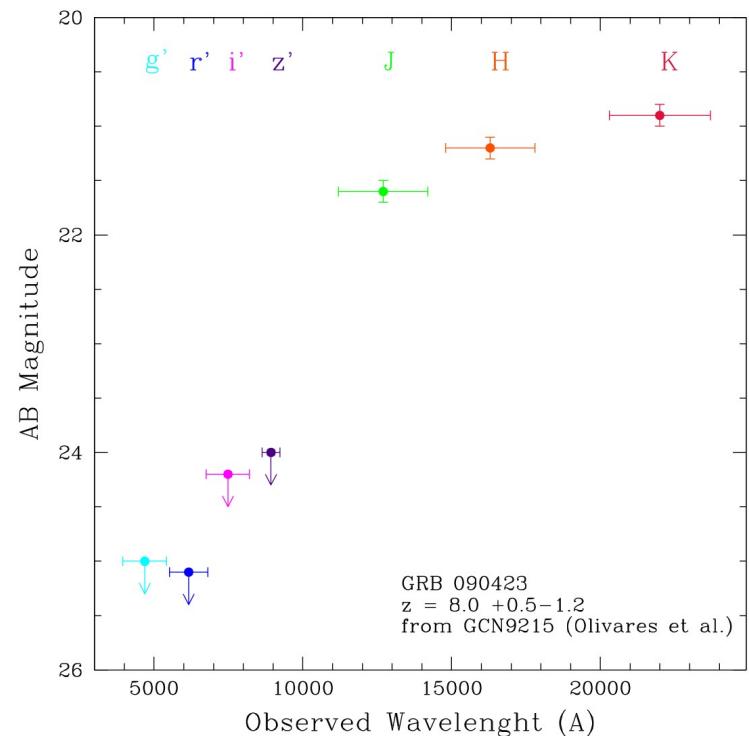
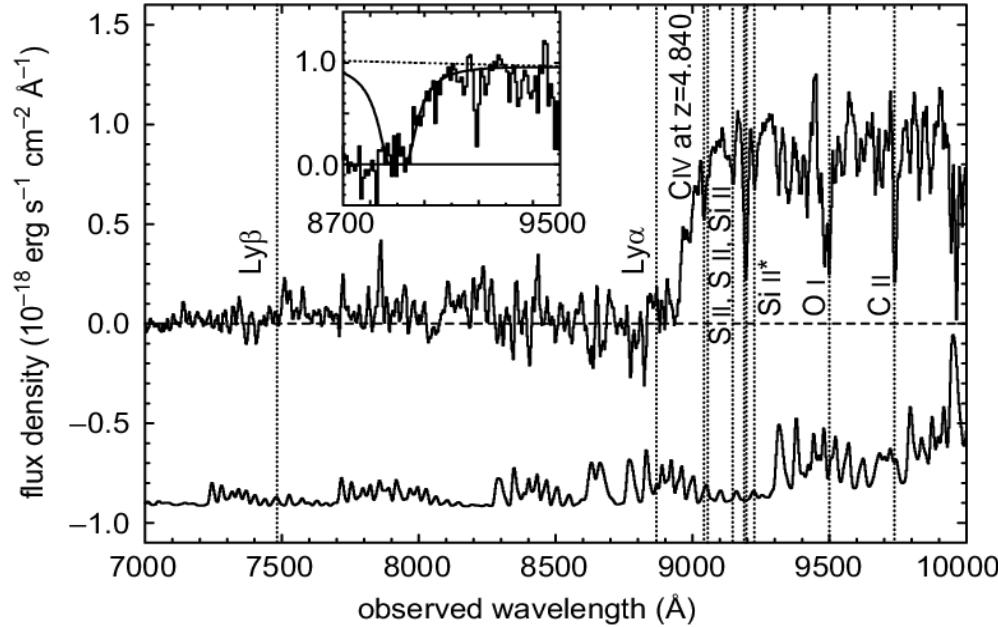
Burst Advocate for this burst is A. P. Beardmore (apb AT star.le.ac.uk). Please contact the BA by email if you require additional information regarding Swift follow-up of this burst. In extremely urgent cases, after trying the Burst Advocate, **you can contact the Swift PI by phone** (see Swift TOO web site for information:
<http://www.swift.psu.edu/too.html.>)

3 GRB @ z>6

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



Subaru Spectroscopy



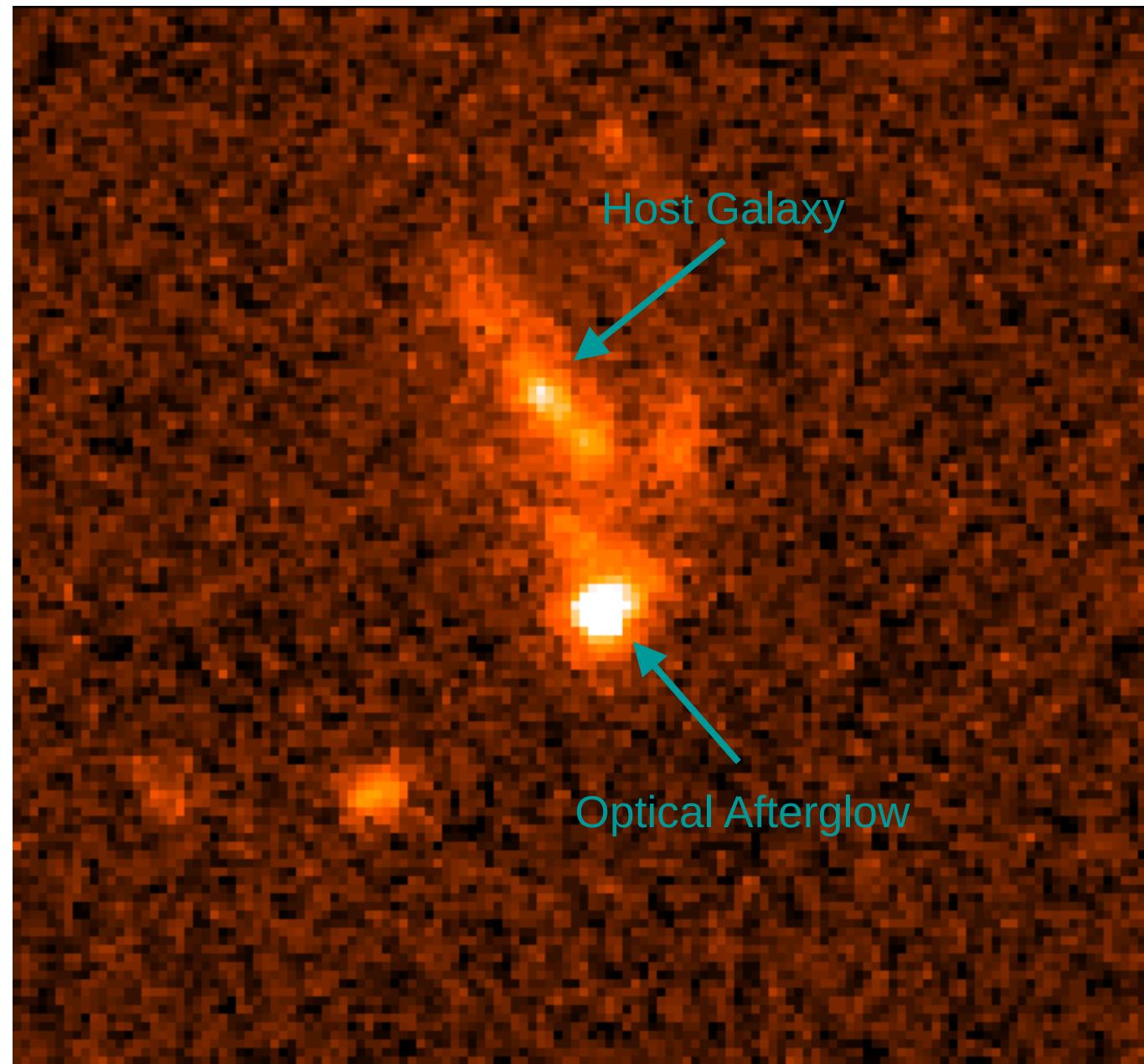
Observational Constraints on the Central Engine

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

Host Galaxies

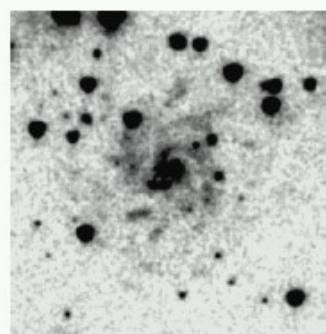
Accurate positions
Allowed Astronomers
To watch the bursts
Fade, and then
Study their Host
Galaxy!

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

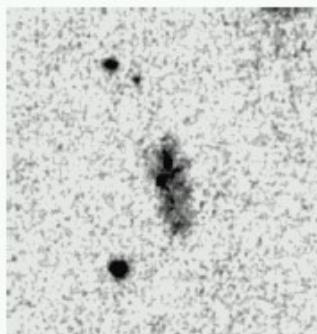


Properties Of Host Galaxies

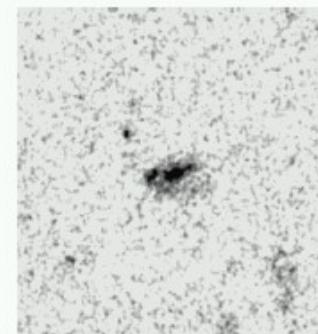
I) Like Many
Star-forming
Galaxies
At that
Observed
redshift



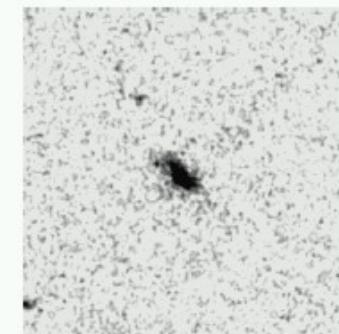
GRB 990705



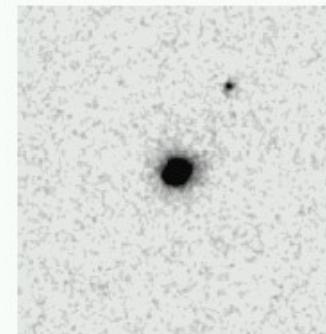
GRB 990506



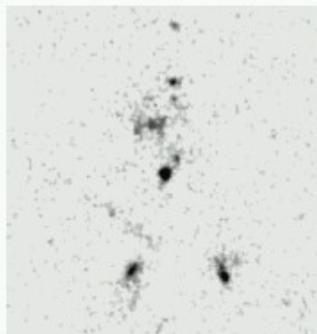
GRB 990123



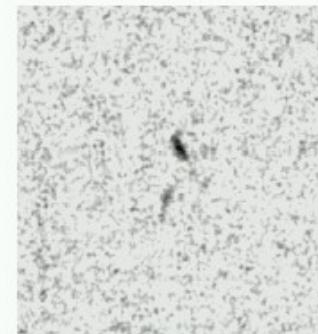
GRB 981226



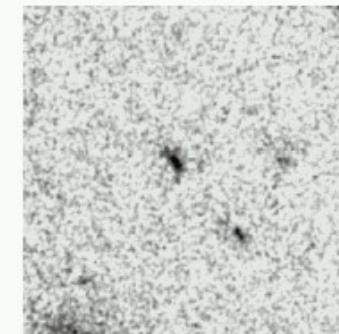
GRB 980703



GRB 980613



GRB 980519



GRB 971214

Holland 2001

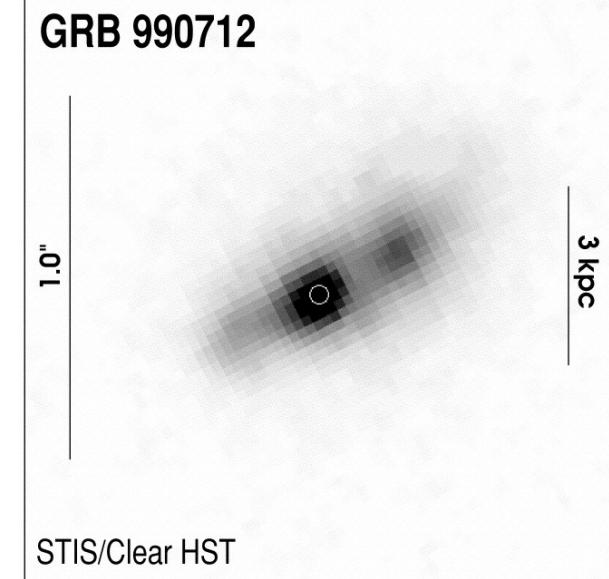
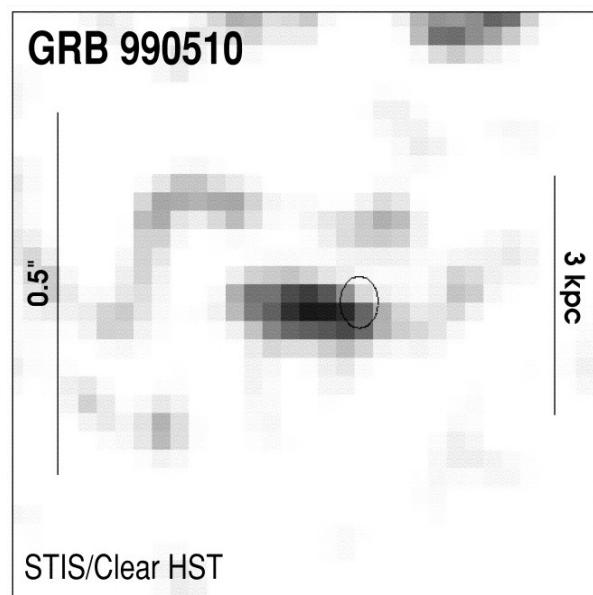
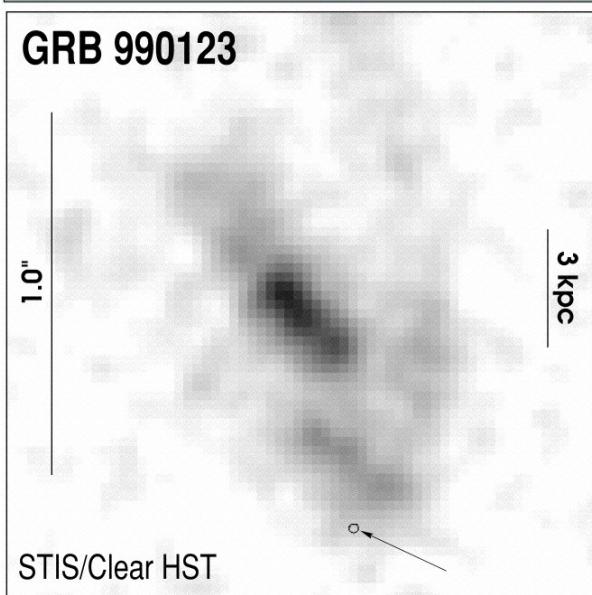
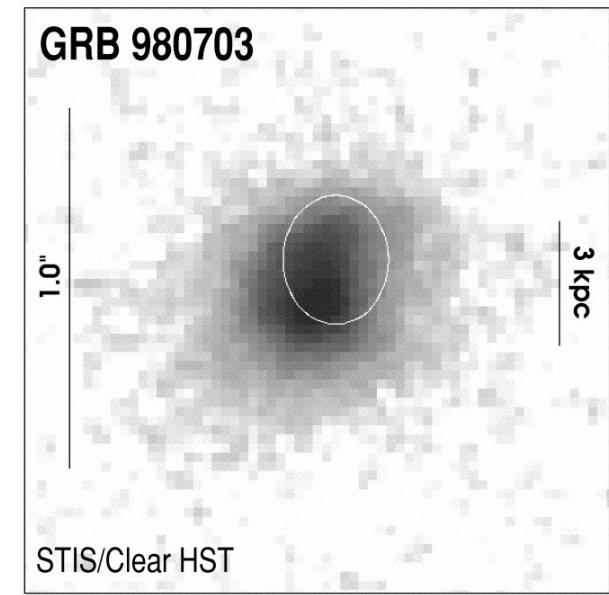
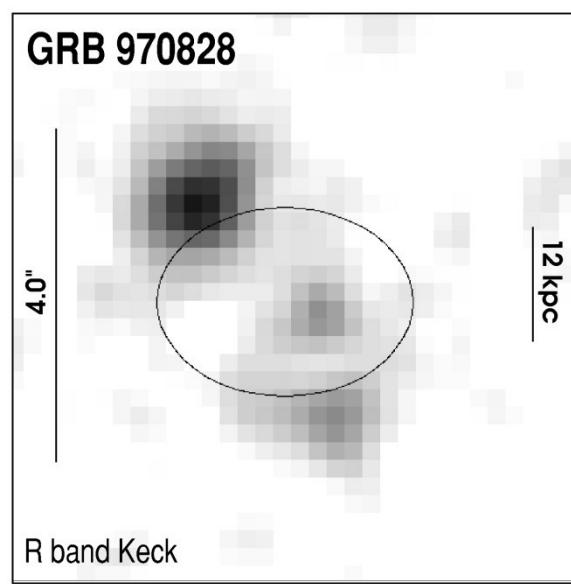
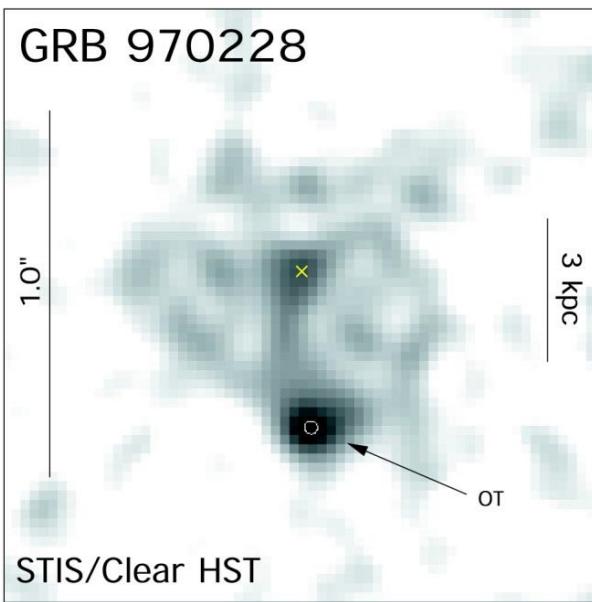
TABLE 1. Specific star-formation rates for several GRB host galaxies.

GRB	z	R_{host}	$\mathcal{M}_{\odot} \text{yr}^{-1} L_B^{*-1}$
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.

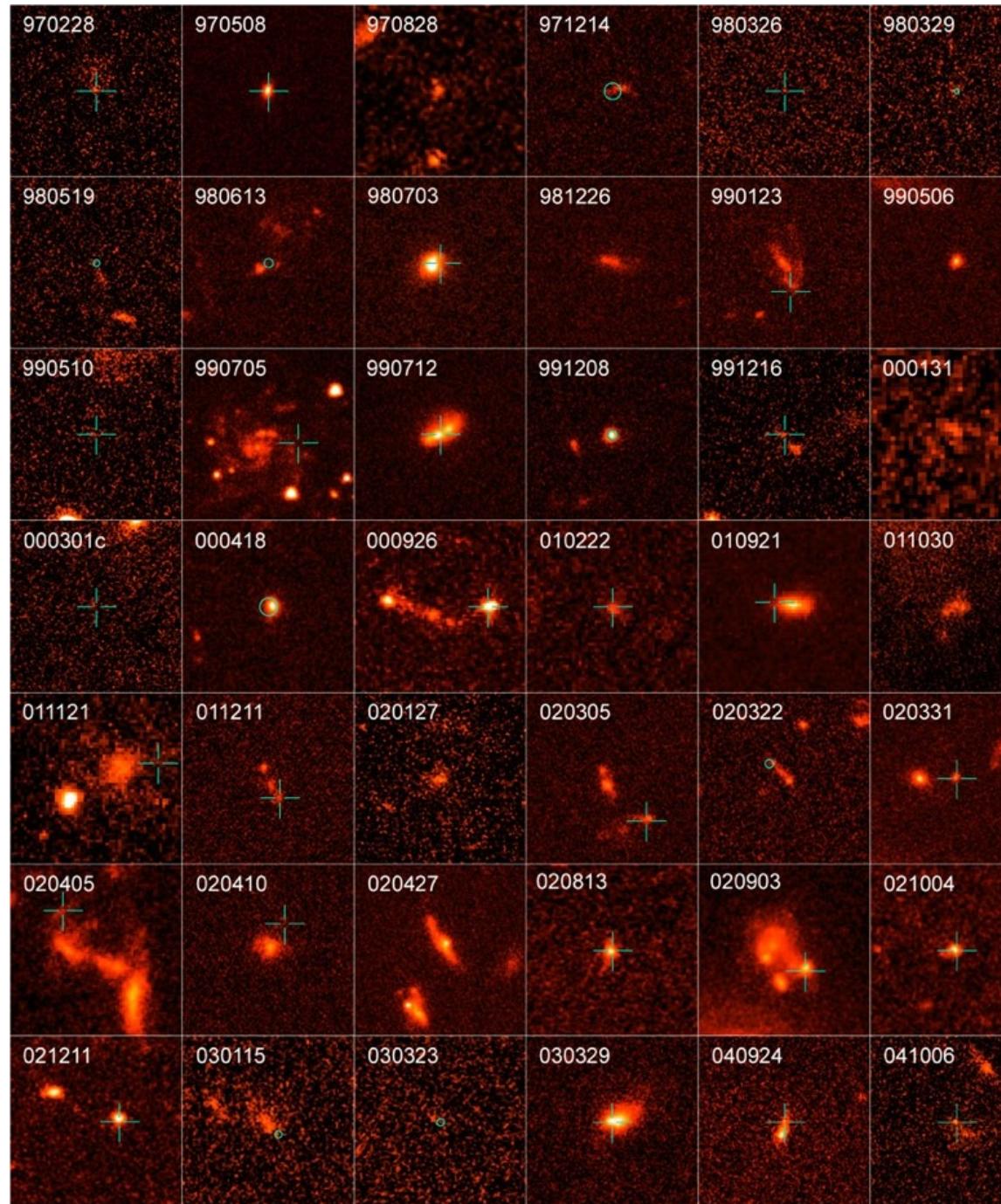
Location, Location, Location

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



GRB hosts

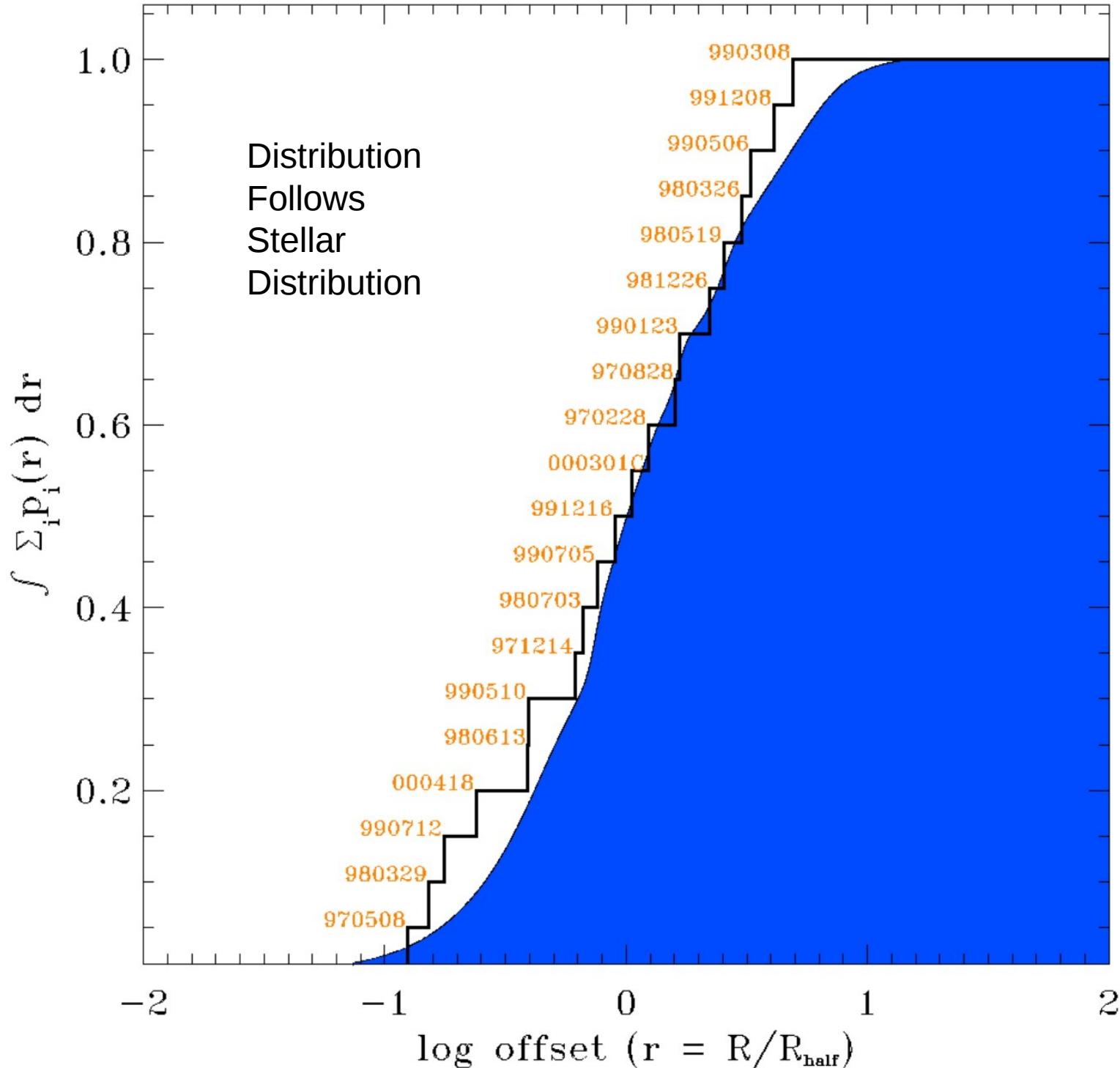
- GRBs trace brightest regions in hosts
 - Hosts are sub-luminous irregular galaxies
- ⇒ Concentrated in regions of most massive stars
- ⇒ Restricted to low metallicity galaxies



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!

Distribution
Follows
Stellar
Distribution



Star-formation rate in GRB hosts

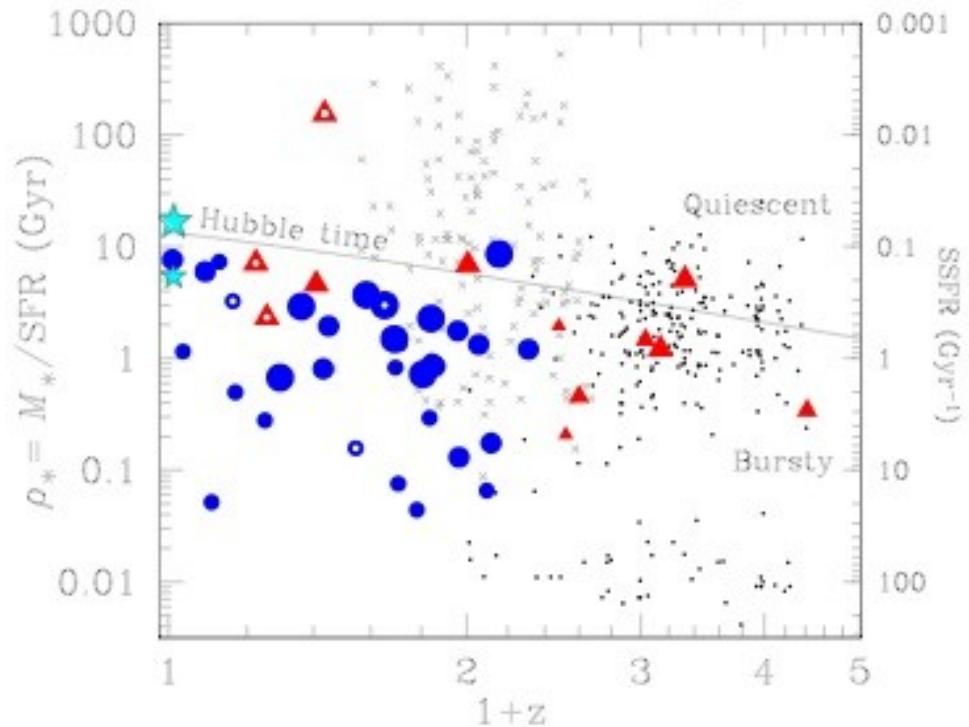
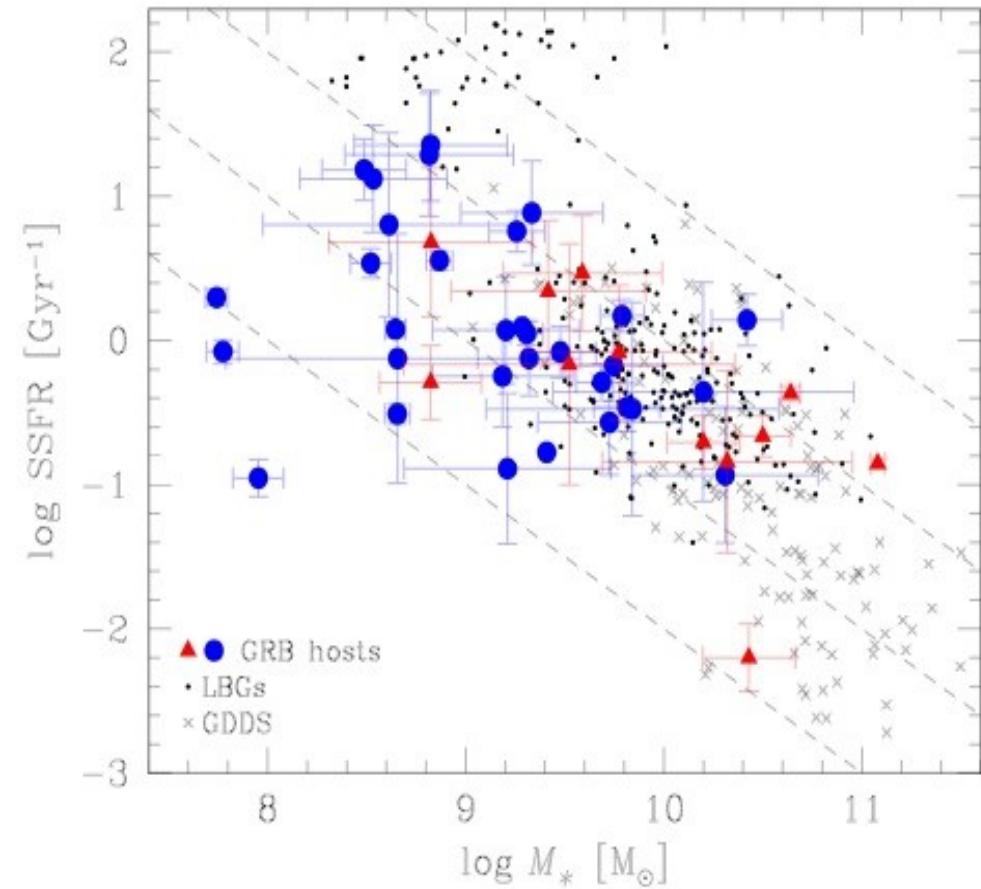


FIG. 14.— Growth time scale $\rho_* = M_*/\text{SFR}$ (left y-axis) or specific star formation rate SSFR (right y-axis) as a function of redshift. Filled circles and triangles are GRB hosts with SFRs measured from emission lines and UV luminosities, respectively. Only hosts with stellar mass uncertainties $\Delta \log M_* < 1$ 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.

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)

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GRB 030329/SN2003dh: z=0.1685

