Gamma-ray Bursts

@ Mera-TeV

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04/10/2011

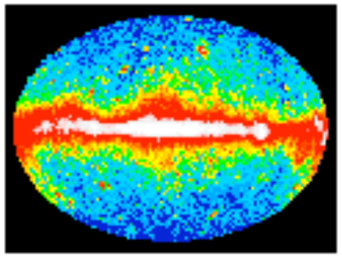
Outline

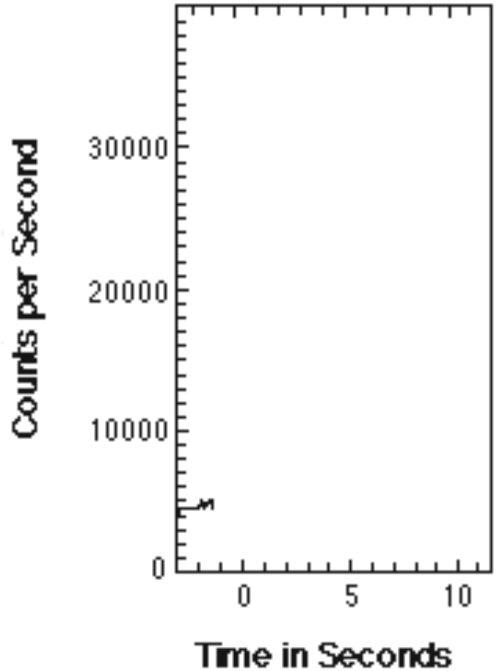
- ✓ The GRB phenomenon
- ✓ Prompt & Afterglow
- ✓ Space observations
- ✓ Ground-based observations
- ✓ Expectations for VHE of GRBs

What is a Gamma-Ray Burst?

Brief, sudden, intense flash of gamma-ray radiation

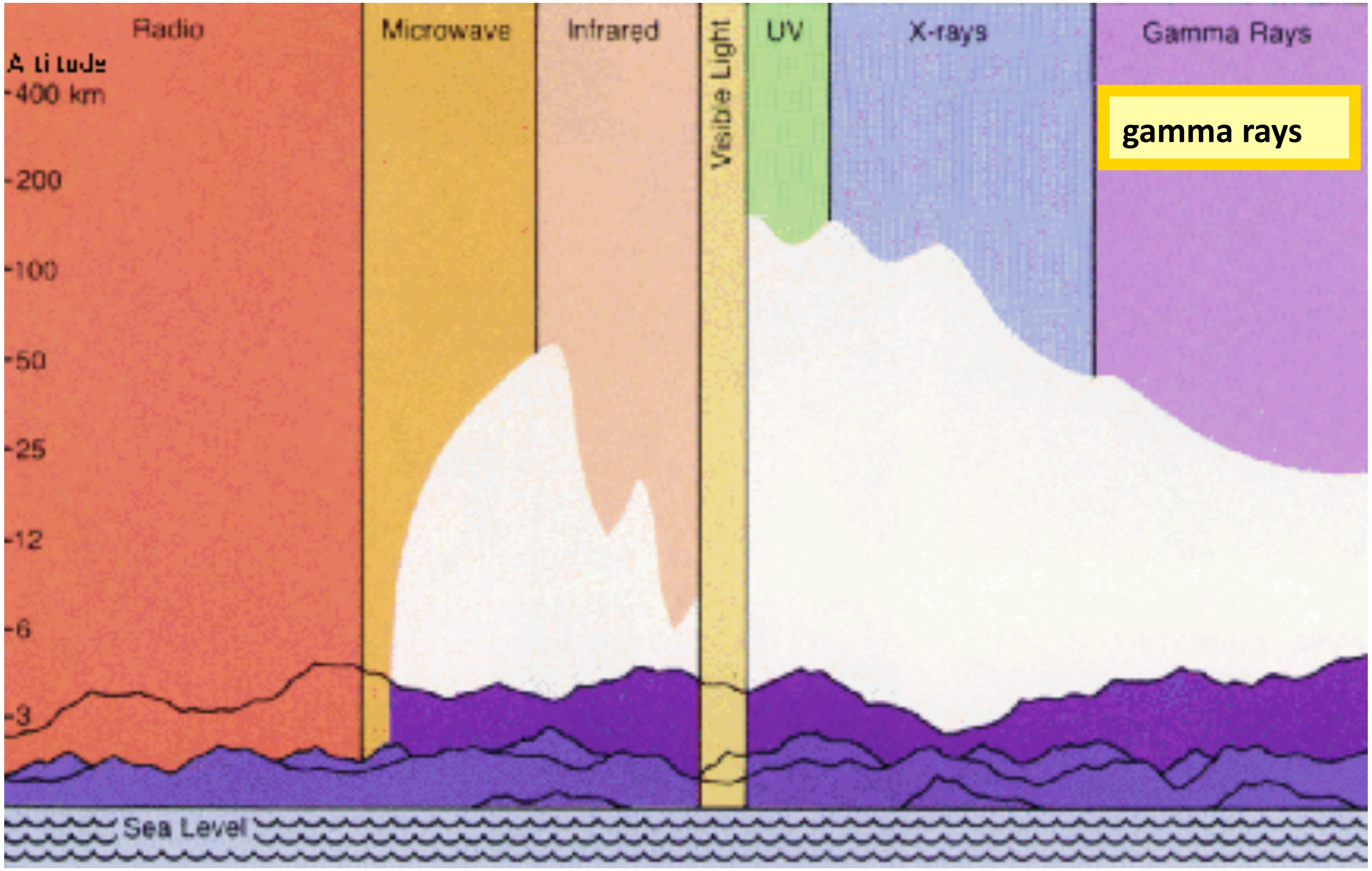
Duration: from few ms to hundreds of s
Frequency: 10 keV – 1 MeV
Fluence: 10^{-7} - 10^{-3} erg cm^{-2}
Flux: 10^{-8} - 10^{-4} erg cm^{-2} s^{-1}





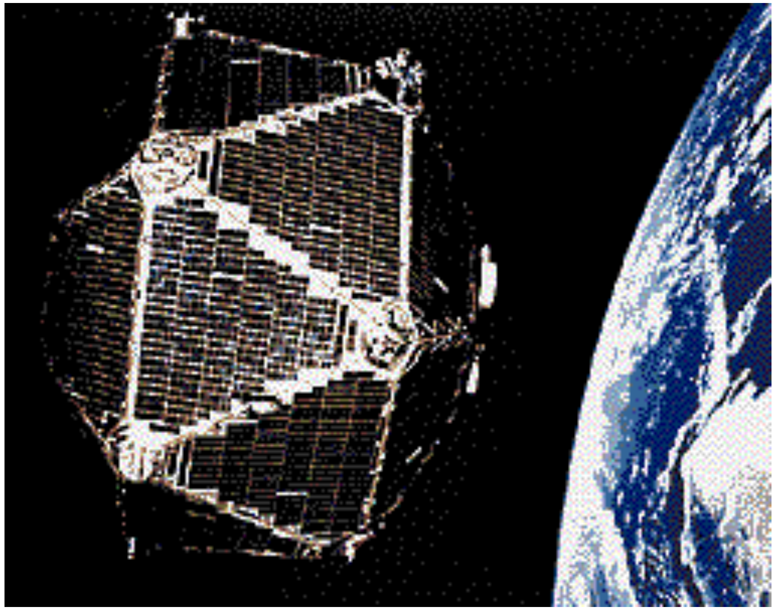
Detecting GRBs

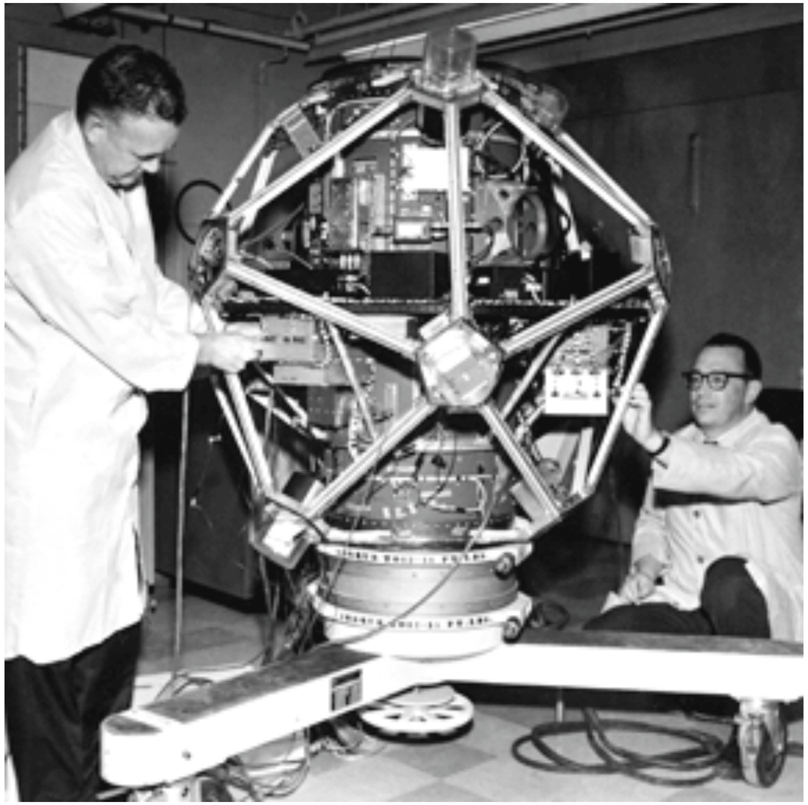
The Earth atmosphere is opaque to gamma-ray radiation



So, we have to use satellites…

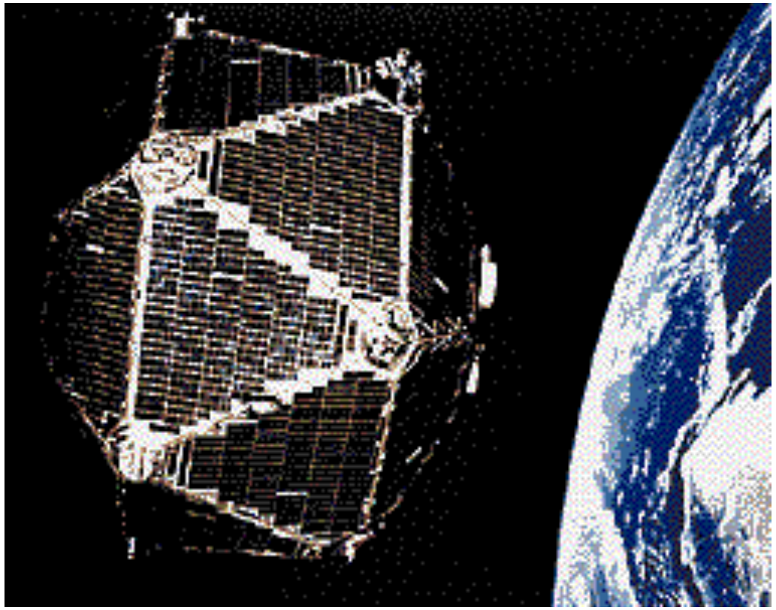
The strange story of GRBs

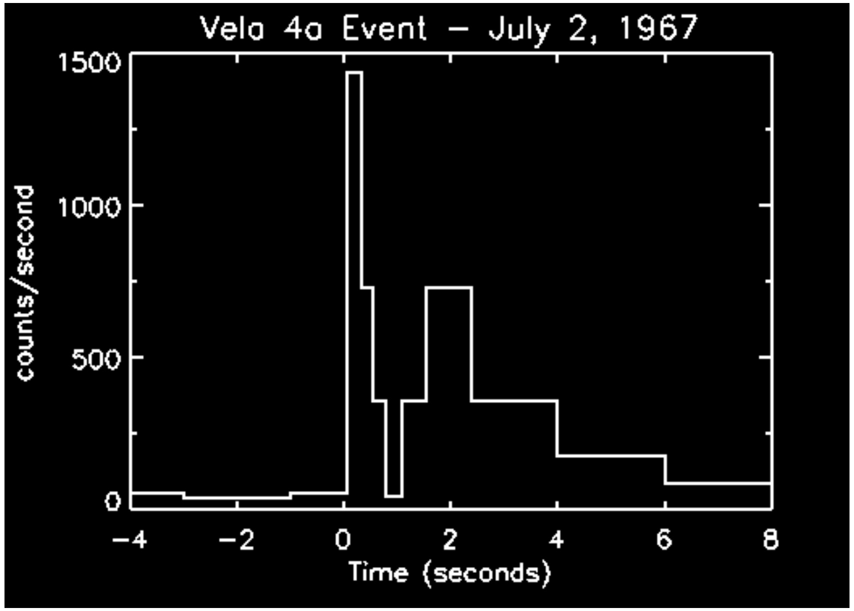




Military **Vela** satellites monitoring for nuclear explosions in violation of the "Nuclear Test Ban Treaty"

The strange story of GRBs





THE ASTROPHYSICAL JOURNAL, **182**:L85–L88, 1973 June 1

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

GRB spectrum

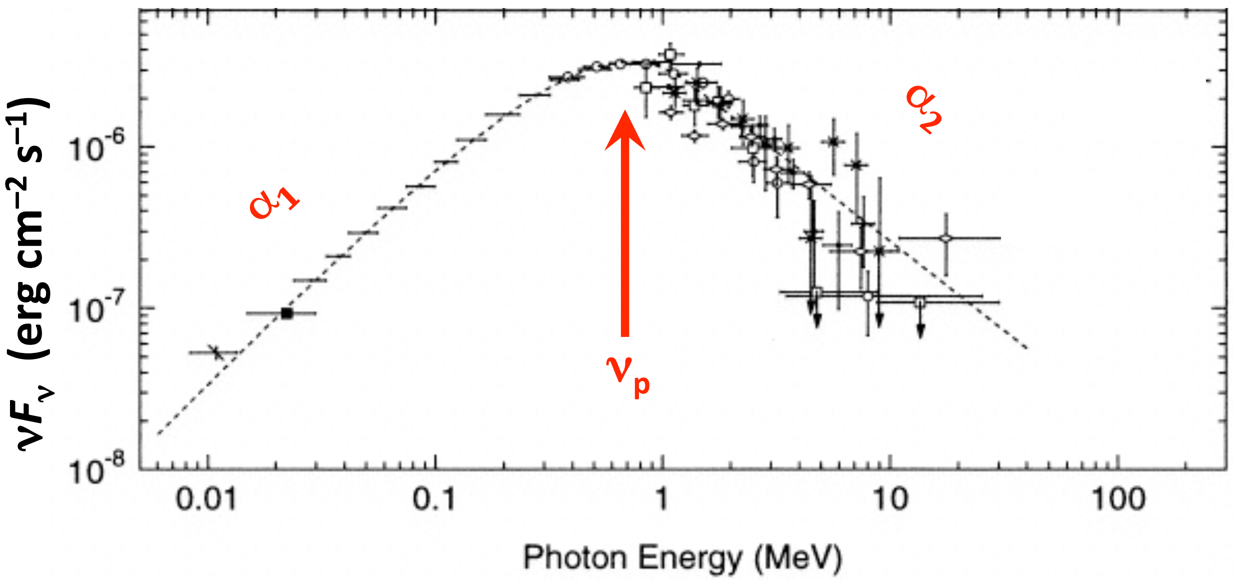
GRB spectra are typically described by a smoothly broken power law

$$F(\nu) \propto \begin{cases} \nu^{-\alpha_1} & \nu < \nu_p \\ \nu^{-\alpha_2} & \nu > \nu_p \end{cases}$$

Power-law slopes

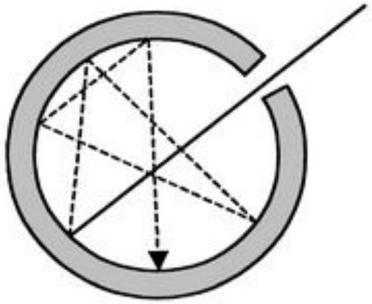
Peak frequency

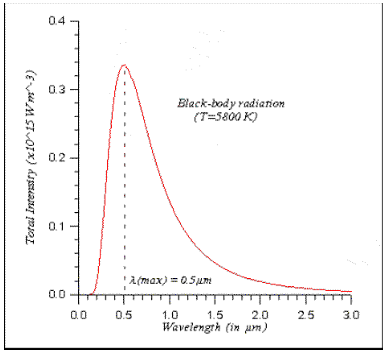
<u>They are non-thermal</u>



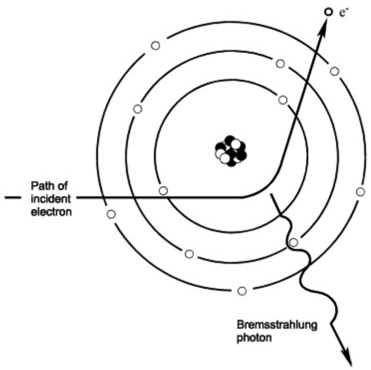
Interlude: radiative processes (I)

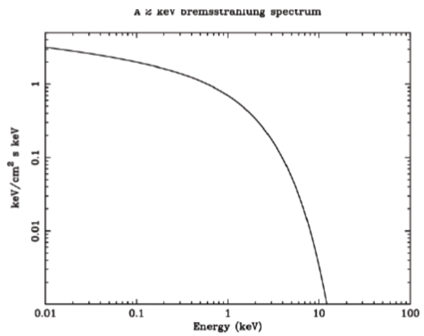
Thermal





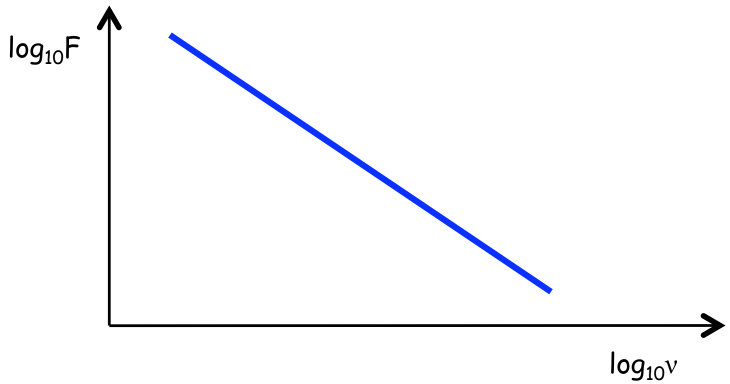
Black body





Bremsstrahlung

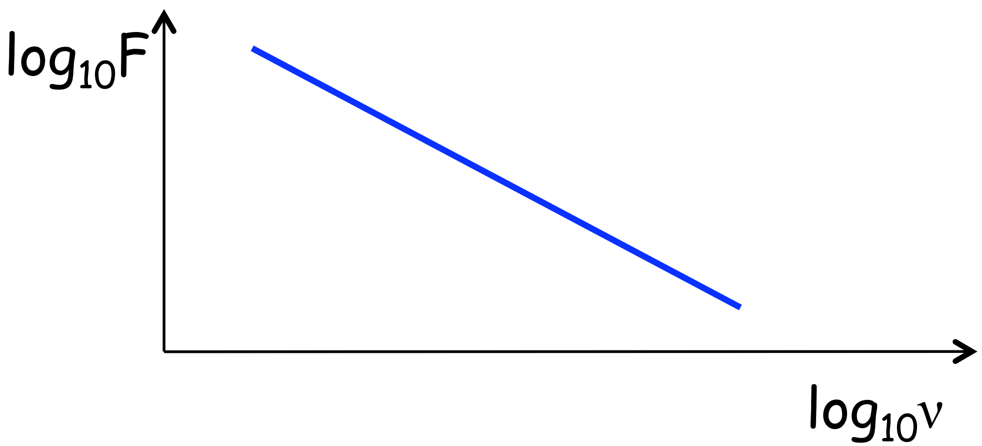
Non-thermal



Synchrotron

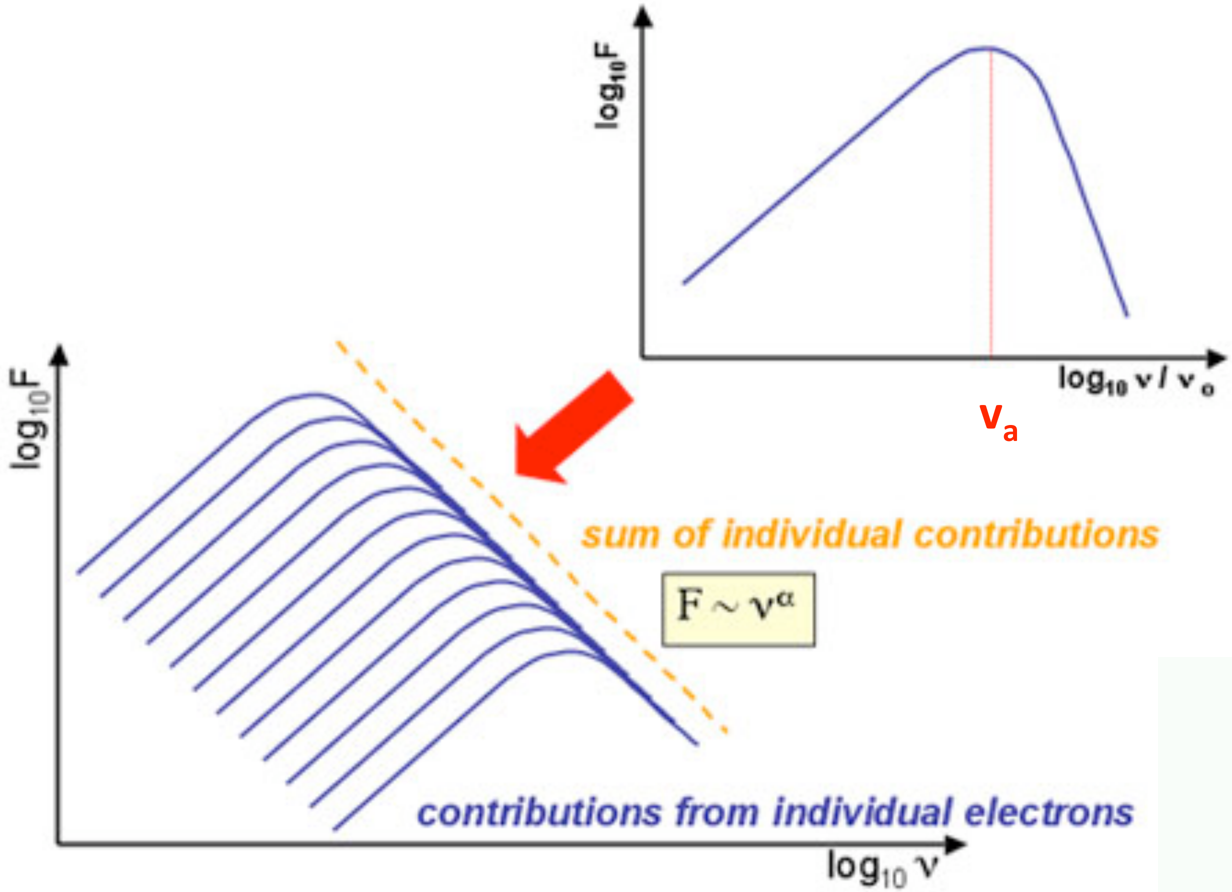
Interlude: radiative processes (II)

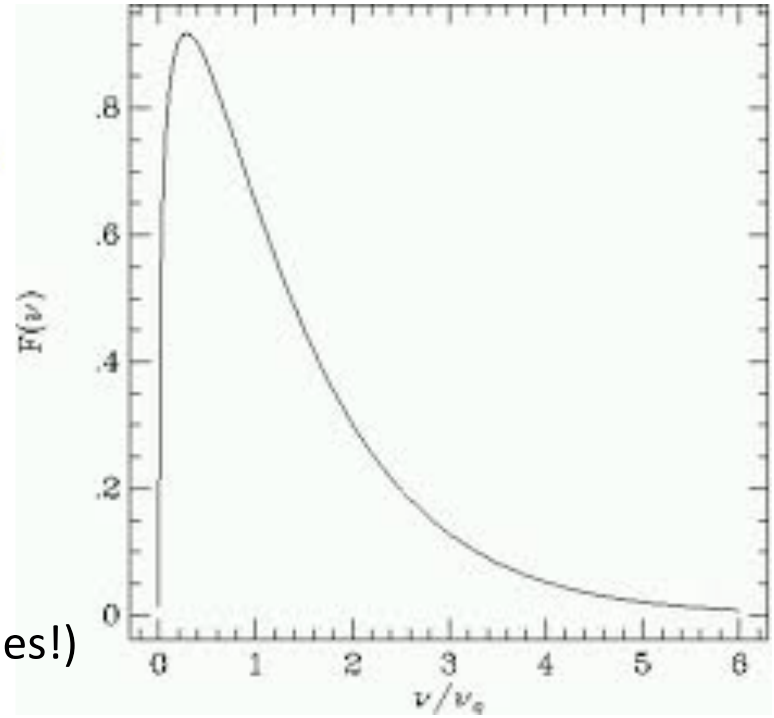
- When relativistic electrons encounter a magnetic field, they spiral along the field lines in a helical path. This means that their direction is constantly changing, and hence they are accelerating and therefore emit radiation. This radiation is called **synchrotron radiation**.



This straight line behaviour comes from the sum of each electron's contribution can be represented by the formula $\log_{10}F \sim -\alpha \log_{10} \nu$

where α is a constant. The flux has a 'power law dependence' on frequency: $F \sim \nu^{-\alpha}$.





Synchrotron self-absorption frequency = ν_a

Injection frequency = ν_m (synchrotron emission)

Cooling frequency = ν_c (it moves from high to low energies!)

GRB spectrum

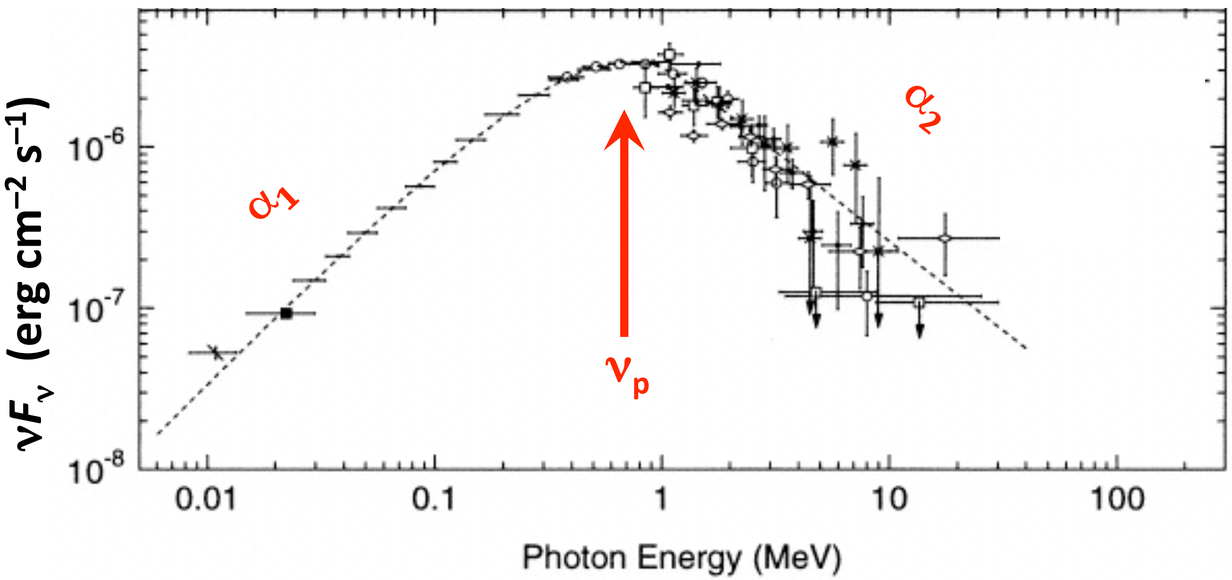
GRB spectra are typically described by a smoothly broken power law

<u>They are non-thermal</u>

$$F(\nu) \propto \begin{cases} \nu^{-\alpha_1} & \nu < \nu_p \\ \nu^{-\alpha_2} & \nu > \nu_p \end{cases}$$

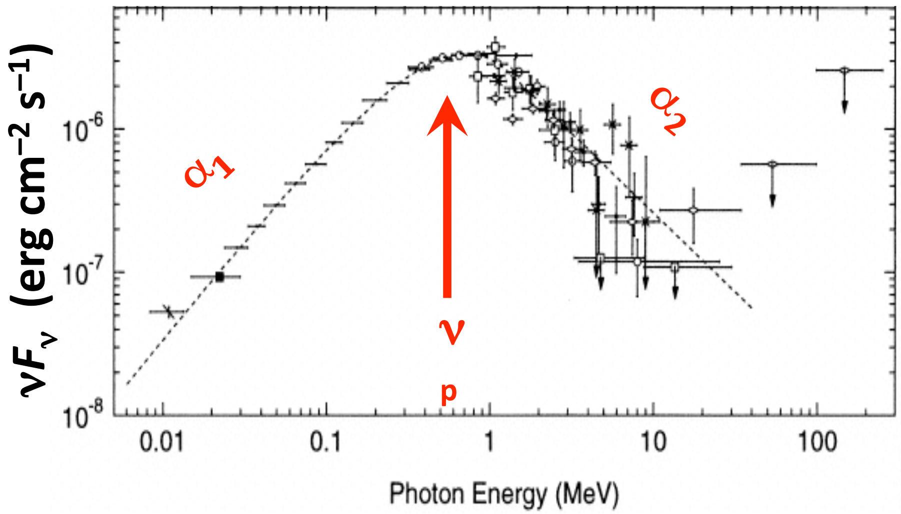
Peak frequency

Power-law slopes

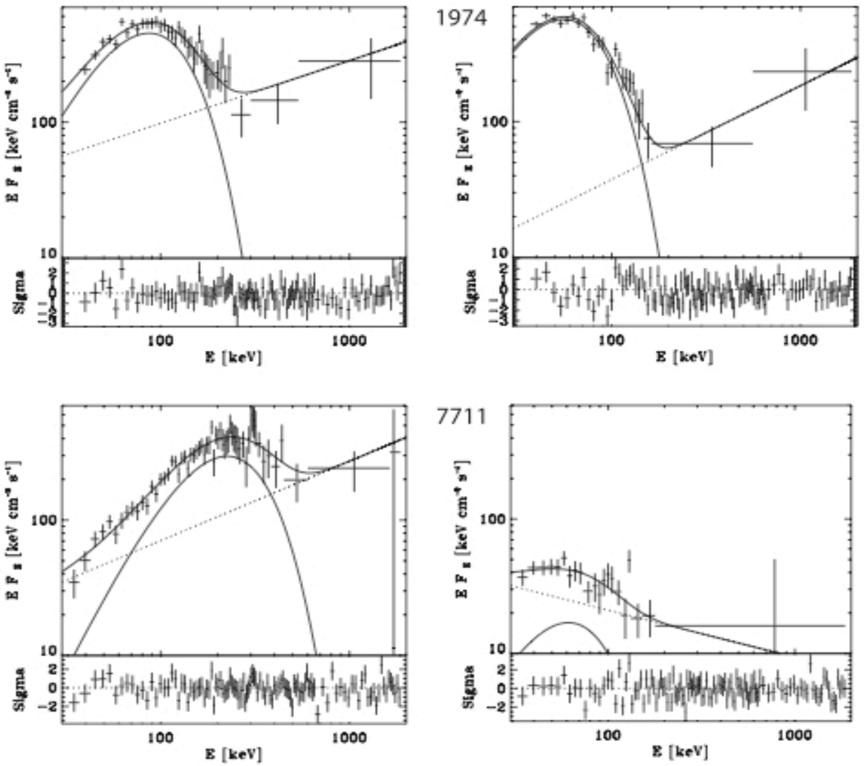


GRB spectrum

GRB spectra are typically described by a smoothly broken power law



They are non-thermal ??



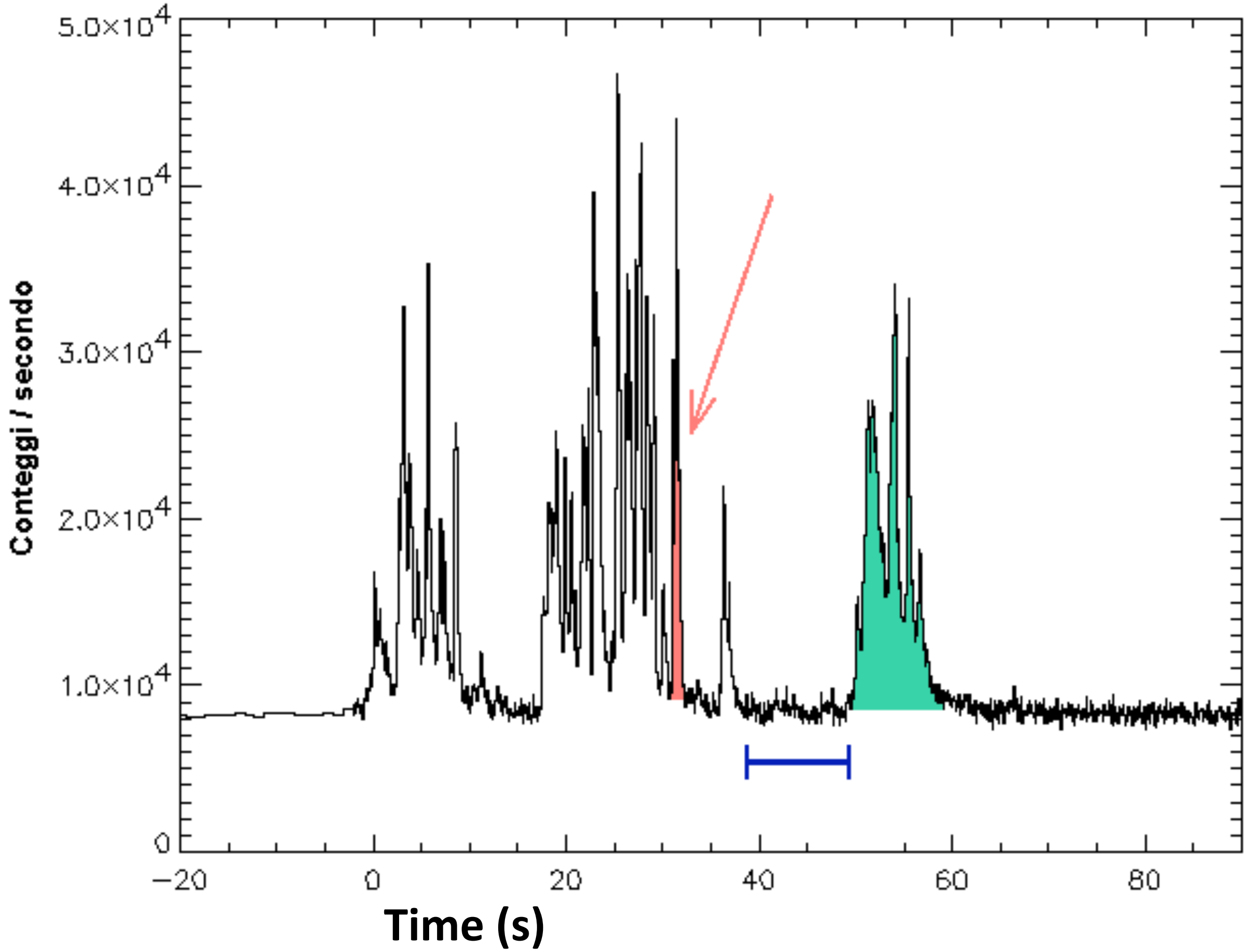
For some GRBs a thermal component seems to fit better tha data !!

Ryde & Pe'er 2009

GRB light curves

- Fast variability
- Phases of activity and quiescence

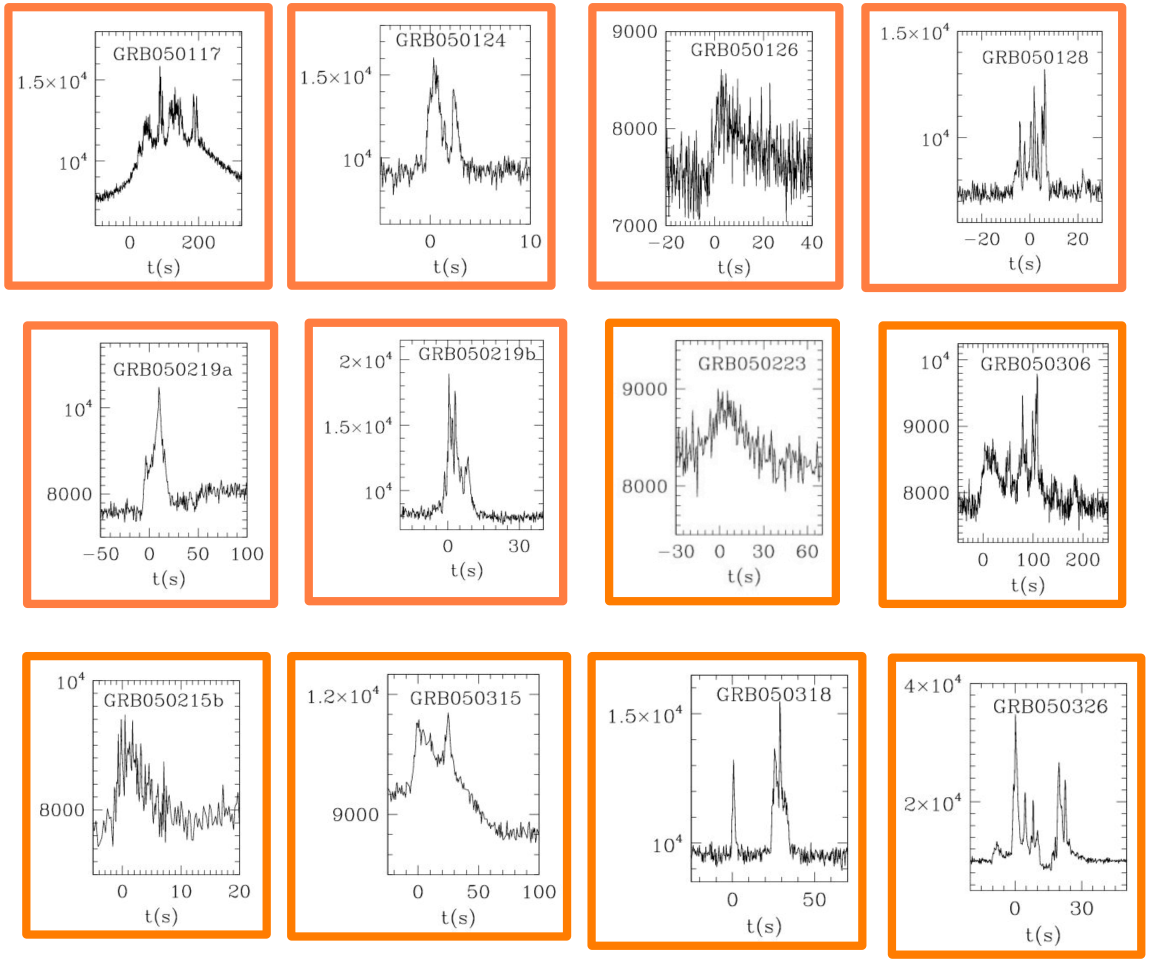
Flux **vs.** time



GRB light curves

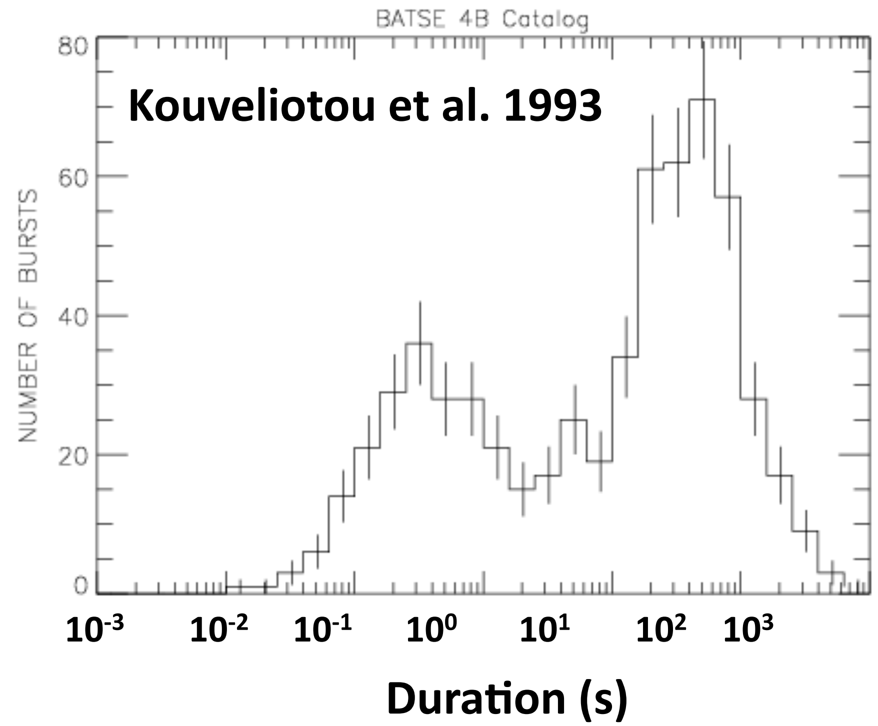
- Fast variability
- Phases of activity and quiescence
- Many types of light curves
- This is called the "prompt" emission

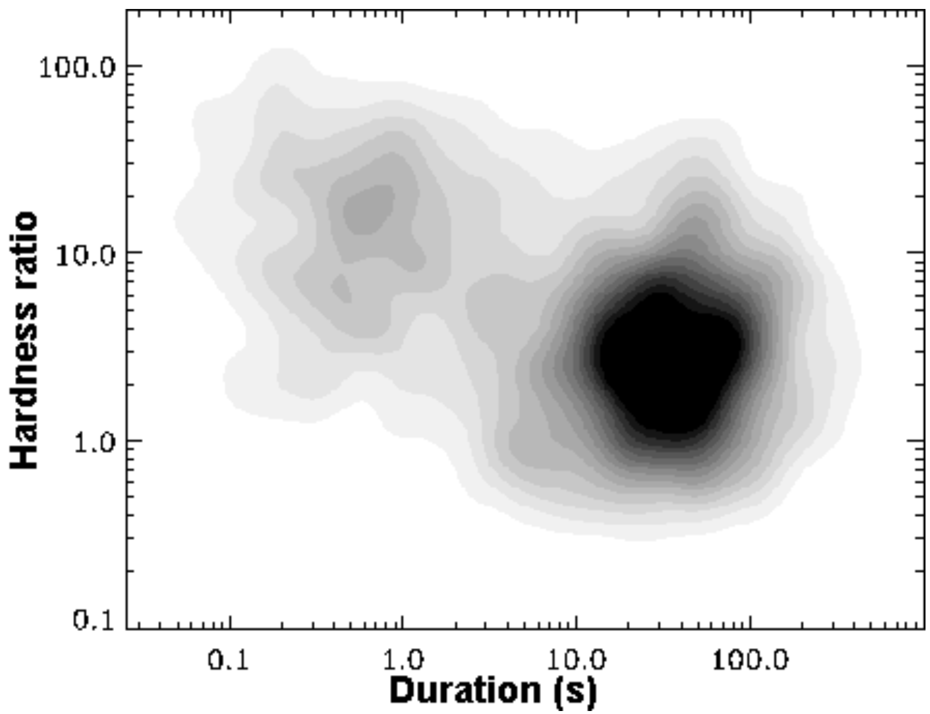
Flux vs. time



Two classes of GRBs

Bimodal distribution of durations:
we have short and long GRBs



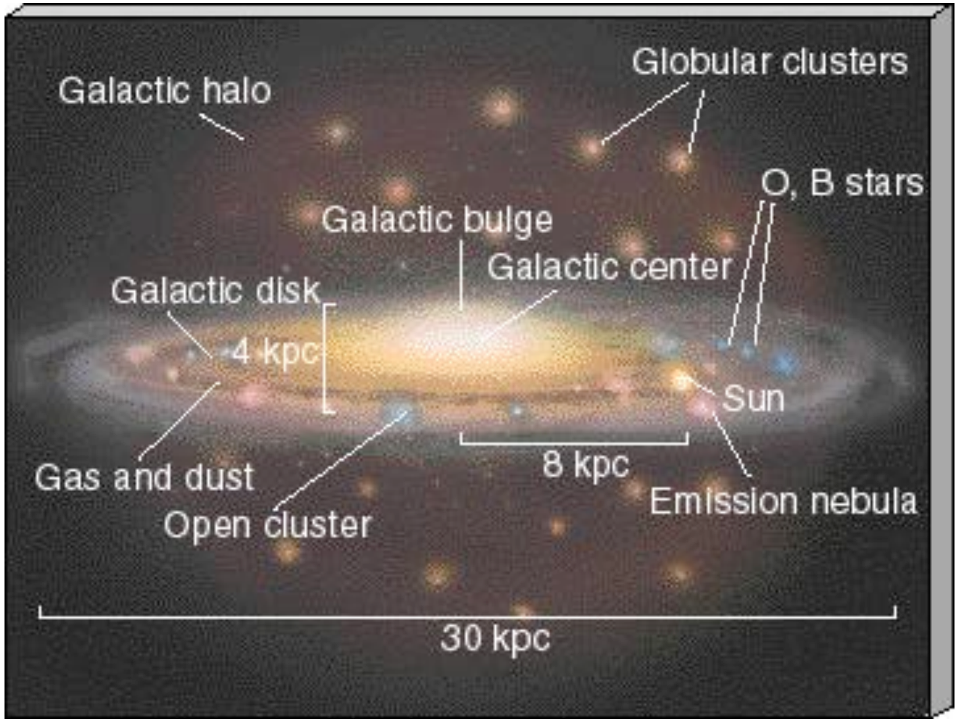


Hardness ratio:
HR=countrate(hard)/countrate(soft)

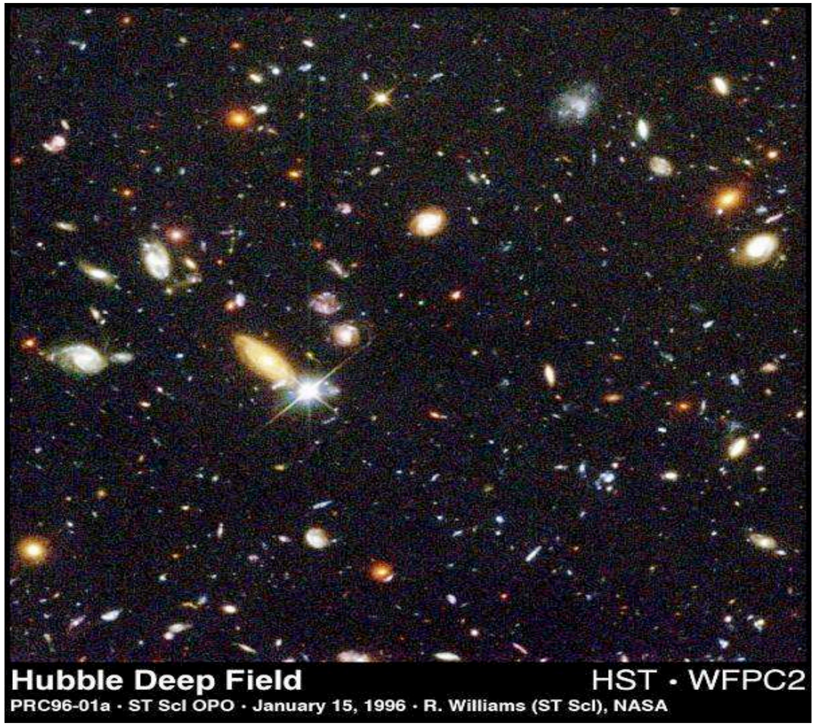
Spectral properties (HR) confirms this classification:
long/soft
short/hard

The distance problem (I)

Galactic events?



Cosmological events?

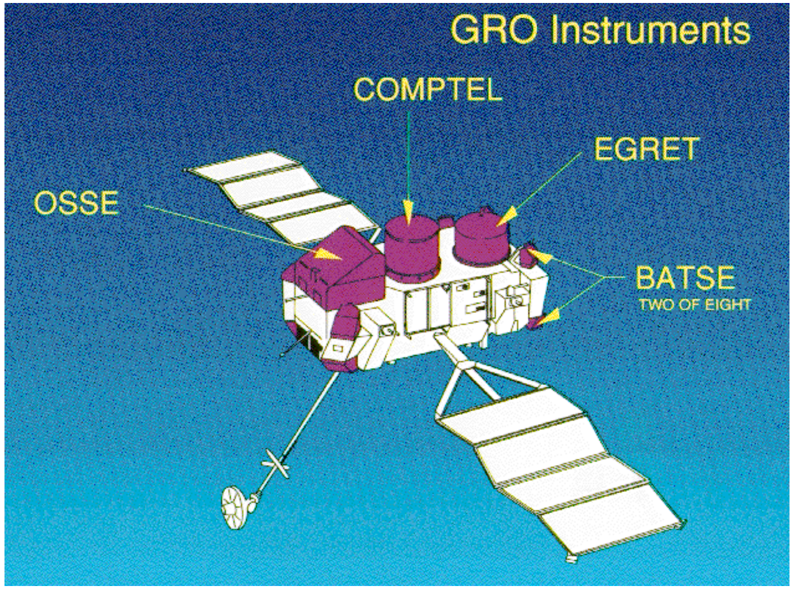


The two possibilities imply huge difference in luminosity

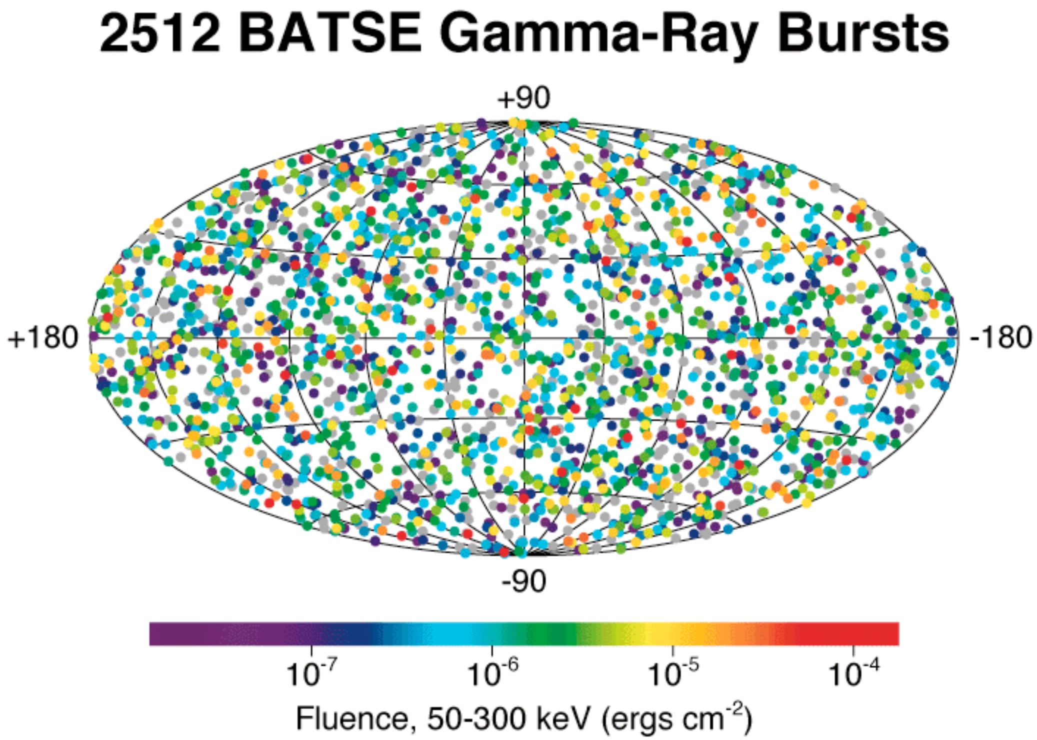
$L = 4\pi D^2 F$

(and thus in energy)

A first hint: isotropic emission



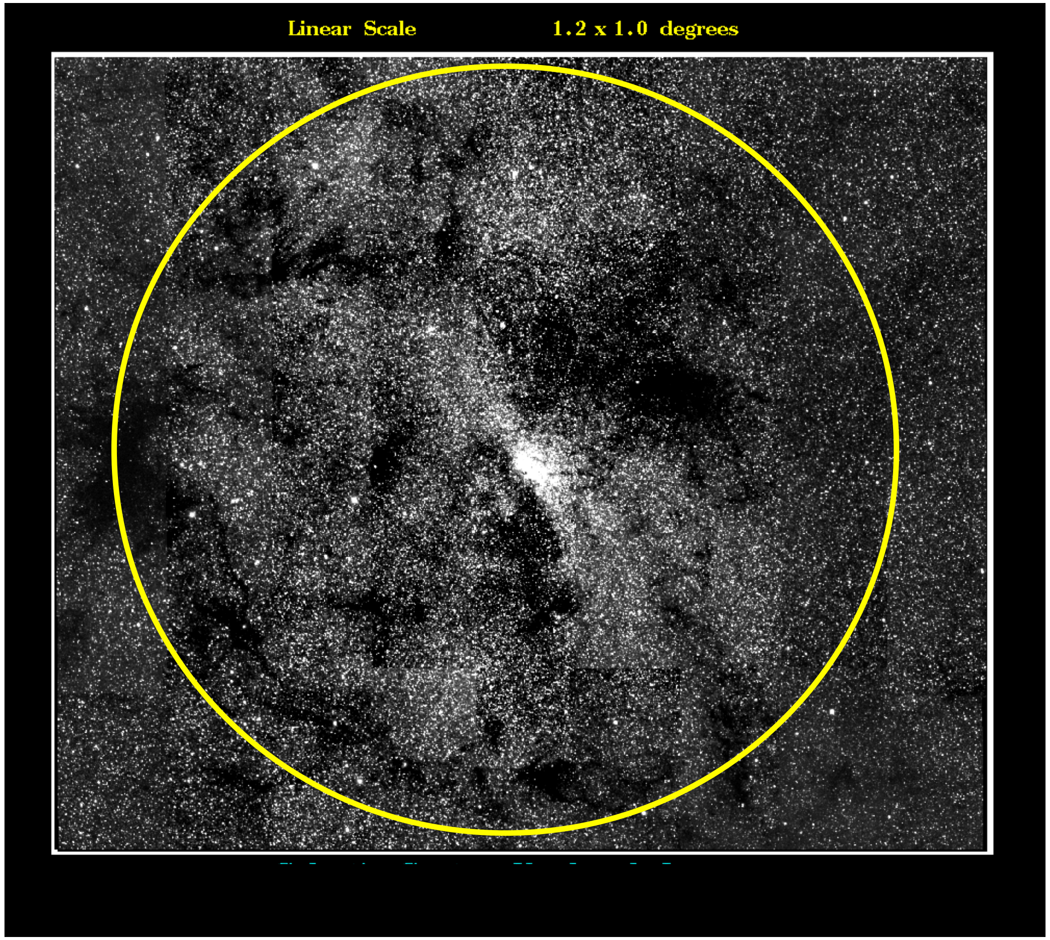
April 1991: Compton Gamma-Ray Observatory



The distance problem (II)

Up to 1997, GRBs were observed with gamma-ray instruments only:
- Position determined with poor precision (~1-2 deg)
- GRB is dominant in the gamma-ray band but…
- …crowded fields when observing at lower energies (X, UV, opt, IR, radio)

No way to measure the distance

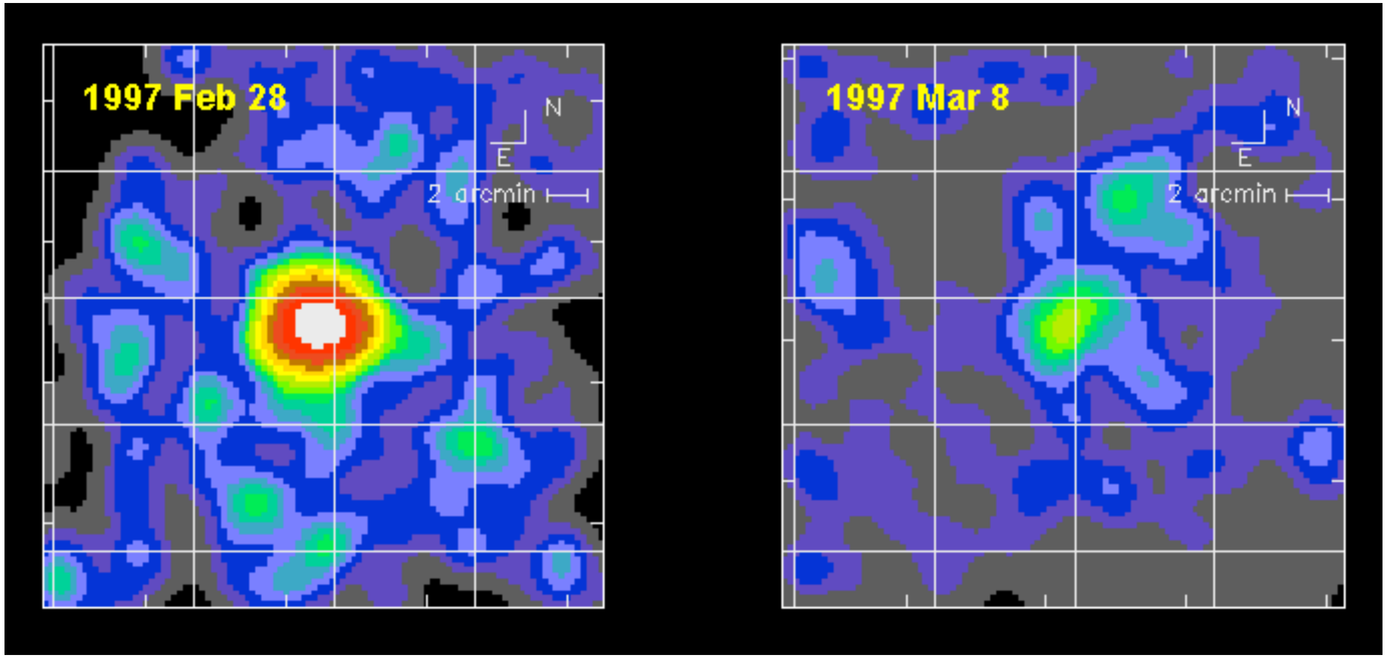


The discovery of the "afterglow" (I)

1996: Italian-Dutch **BeppoSAX** satellite, equipped with a wide-field X-ray telescope.

Precise position determination + "fast" (few hours) repointing

GRB 970228: Detection of a variable X-ray counterpart

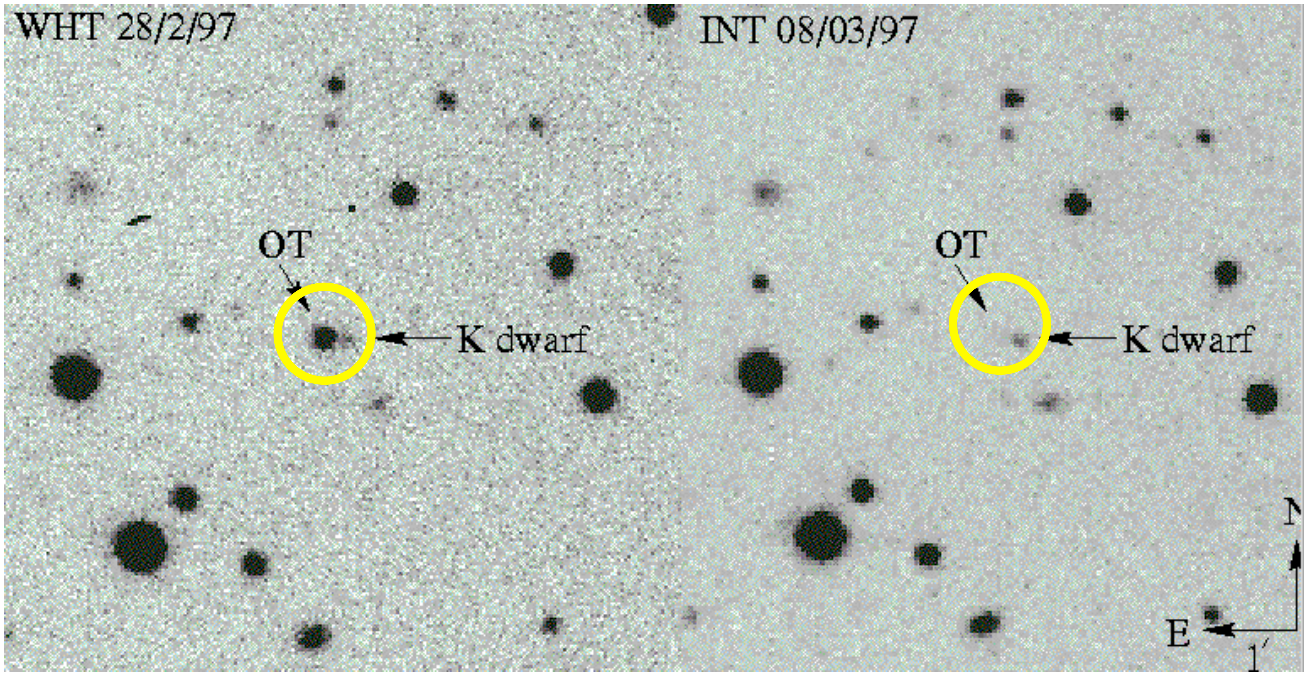


Costa et al. 1997

The discovery of the "afterglow" (II)

Ground-based follow-up

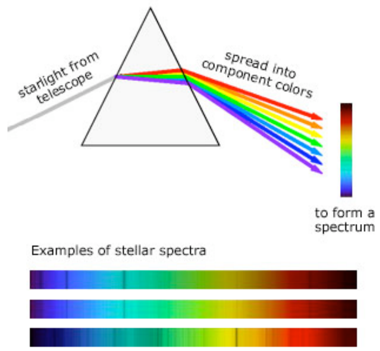
GRB 970228: Detection of a variable OPTICAL counterpart



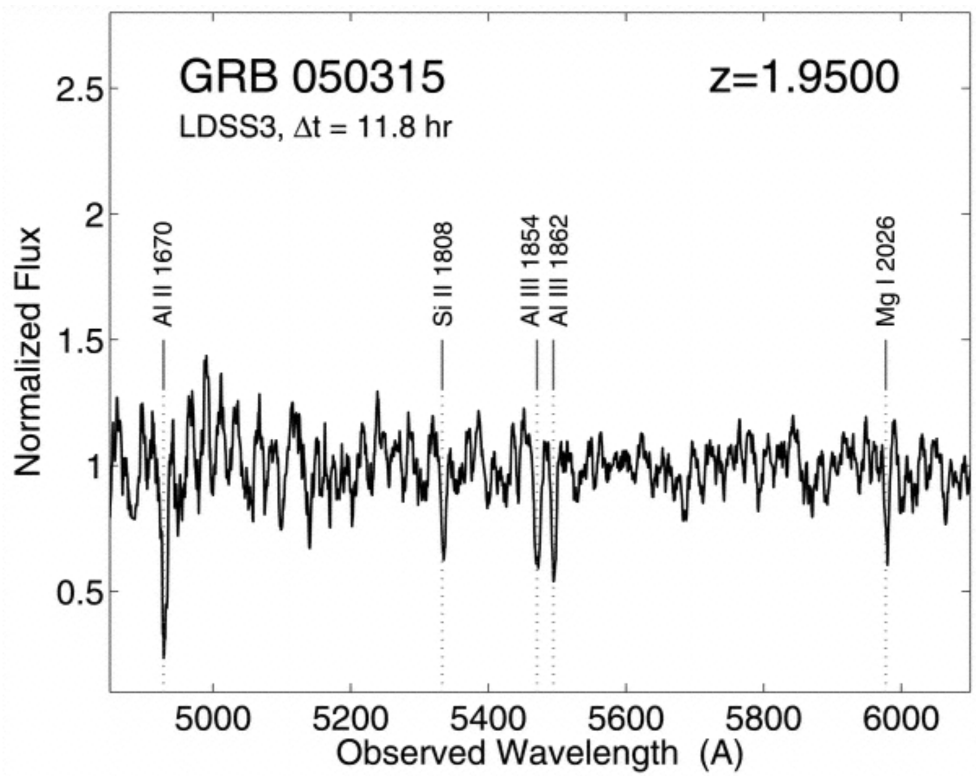
van Paradijs et al. 1997

The distance problem: solved!

Spectroscopy of GRB optical counterparts enable the measure of the redshift (z) and, consequently, of the distance

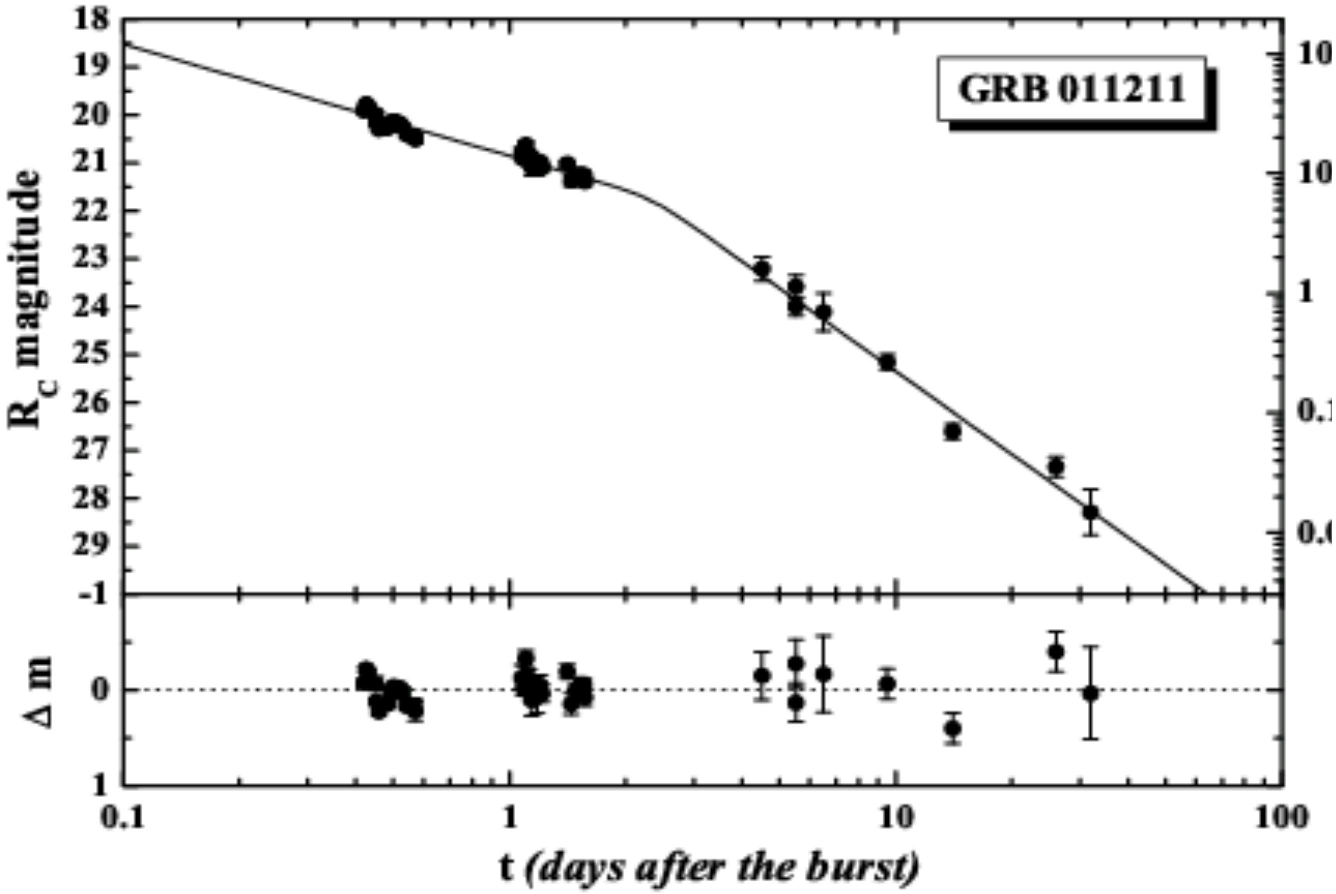


$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$

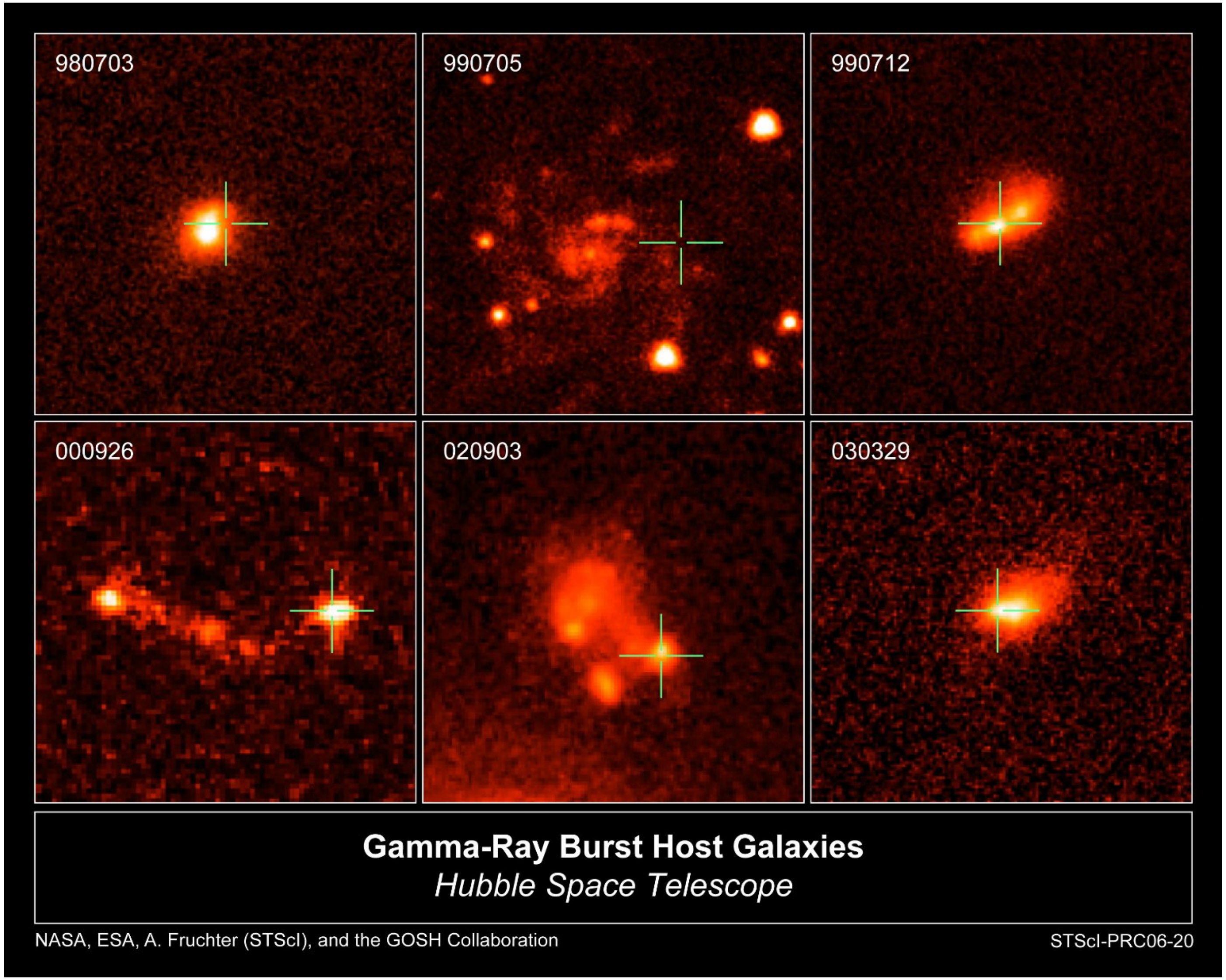


But you have to be fast…

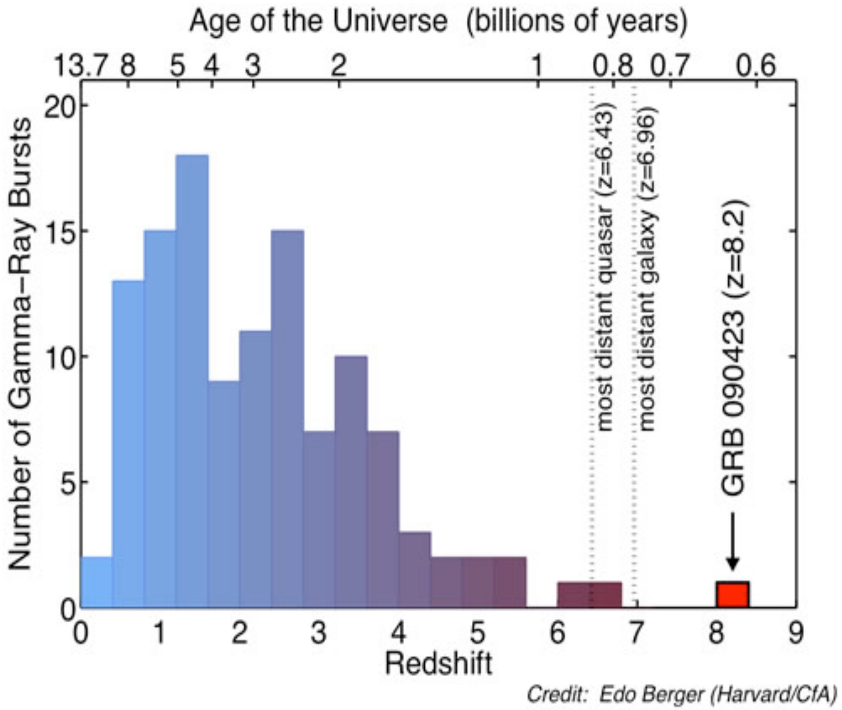
Afterglows decay in time: $F(t) \propto t^{-\alpha}$



GRBs are cosmological and occur in galaxies



GRB energetics



Fluence: 10^{-5} erg cm^{-2}

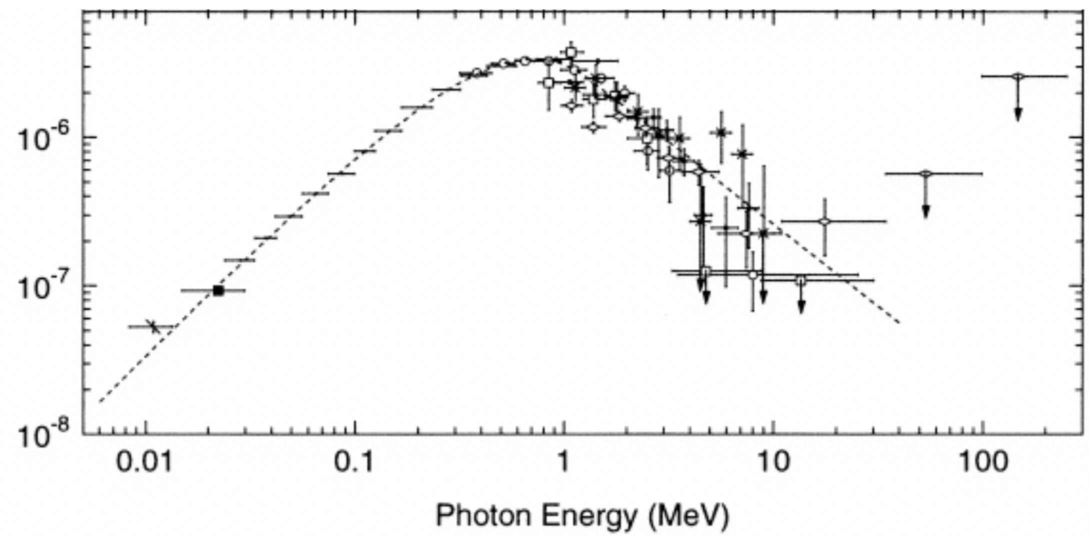
Distance: <z>=2.3 ~ 10^{29} cm

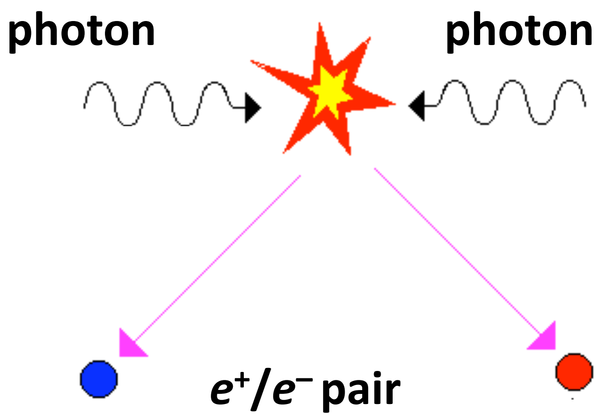
Energy: ~10^{53} erg

Like the energy emitted by our Galaxy in 10 years

How does it work?

GRB spectra extends up to high energies (MeV, GeV and up to TeV?)

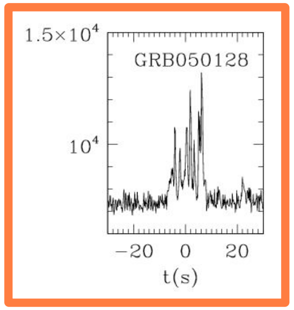




These photons might have an energy high enough ($m_e c^2$~0.5 MeV) to produce electron-positron pairs

How does it work?

however…

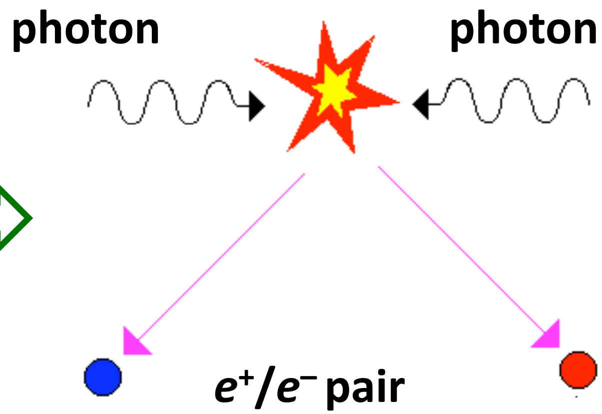


GRBs show variability on short time-scale -> the source is compact

$R < c \times \delta t$

$\delta t \sim 0.01$ s $\Rightarrow$ $R < 3000$ km = 3e8 cm

Many photons in a small volume



Opacity for pair production

How does it work?

Optical depth: $\tau_{\gamma\gamma} = n\,\sigma R \sim 10^{14}$ >> 1 → optically thick

$n = N/V$ (photon density)
$N = \eta E_{GRB} / m_e c^2 \sim 10^{57}$ photons
$\sigma \sim \sigma_T = 6.7 \times 10^{-25}$ cm^2 (Thomson cross section)
$R \sim c \times \delta t \sim 3\times10^8$ cm

But non-thermal (power-law) spectrum → optically thin!

"Compactness problem"

The solution: ultrarelativistic motion

$$\beta = \frac{v}{c} \sim 1, \quad \Gamma = \frac{1}{\sqrt{1-\beta^2}} >> 1$$

The source can be in ultrarelativistic motion

Combining Doppler effect and special relativity:

-Observed frequencies blueshifted -> energy at source= $h\nu_{obs}/\Gamma$
- $R < \Gamma\, c \times \delta t$

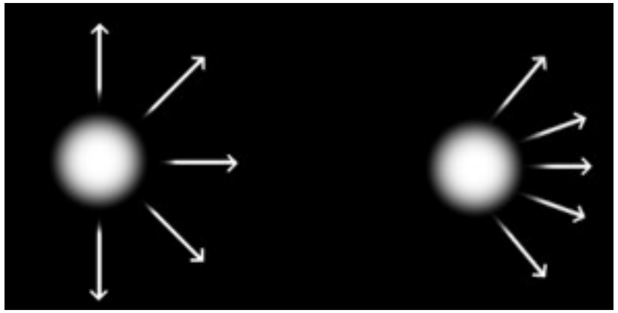
$\tau_{\gamma\gamma} \propto \Gamma^{-(2\alpha+2)}$ -> $\tau_{\gamma\gamma} < 1$ -> $\Gamma > 100$

α = spectral index

Relativistic effects: beaming

v = 0
Γ = 1

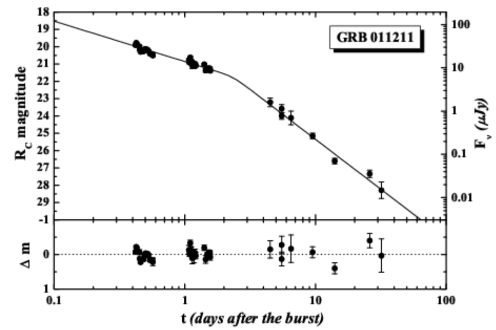
v ~ c
Γ >> 1

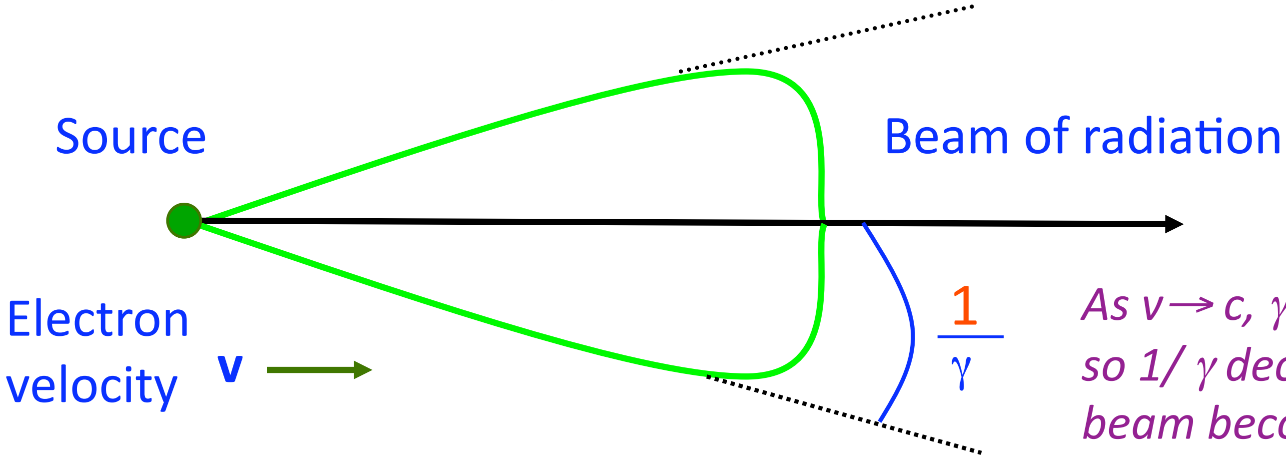


It is a property of matter moving close to the speed of light that it emits its radiation in a small angle along its direction of motion.
The angle is inversely proportional to Γ

As the beam runs into interstellar matter it slows down.

Steepening in the afterglow light curve

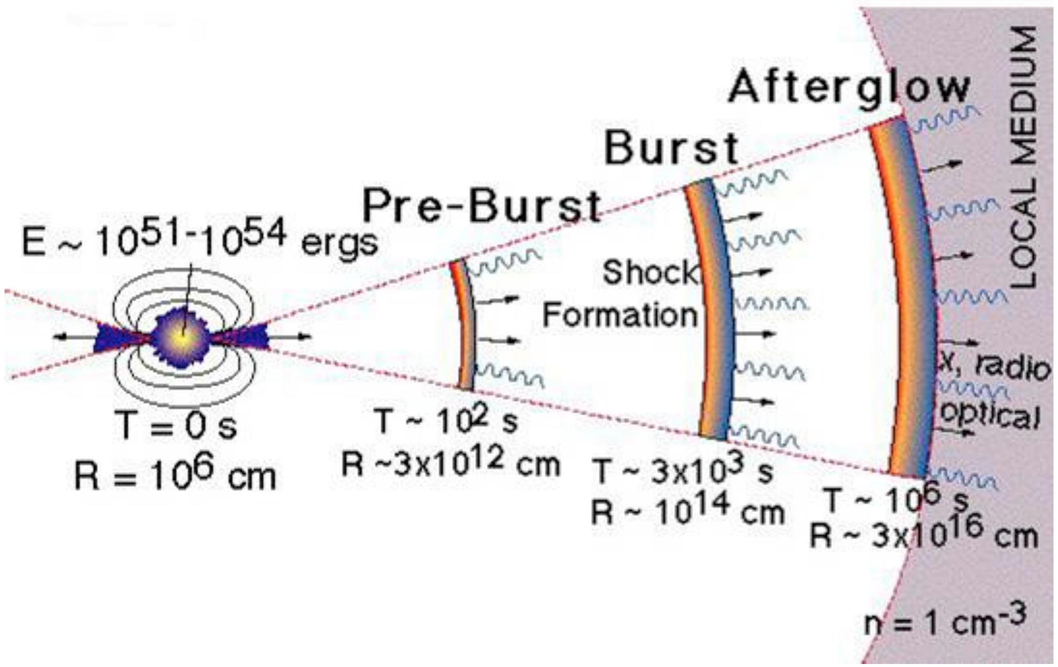


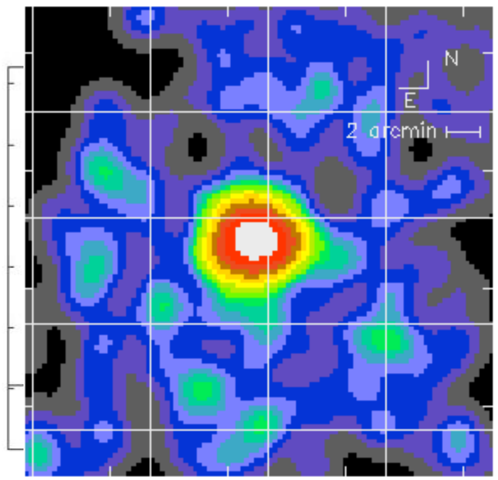


As v→ c, γ increases, so 1/ γ decreases and the beam becomes more collimated.

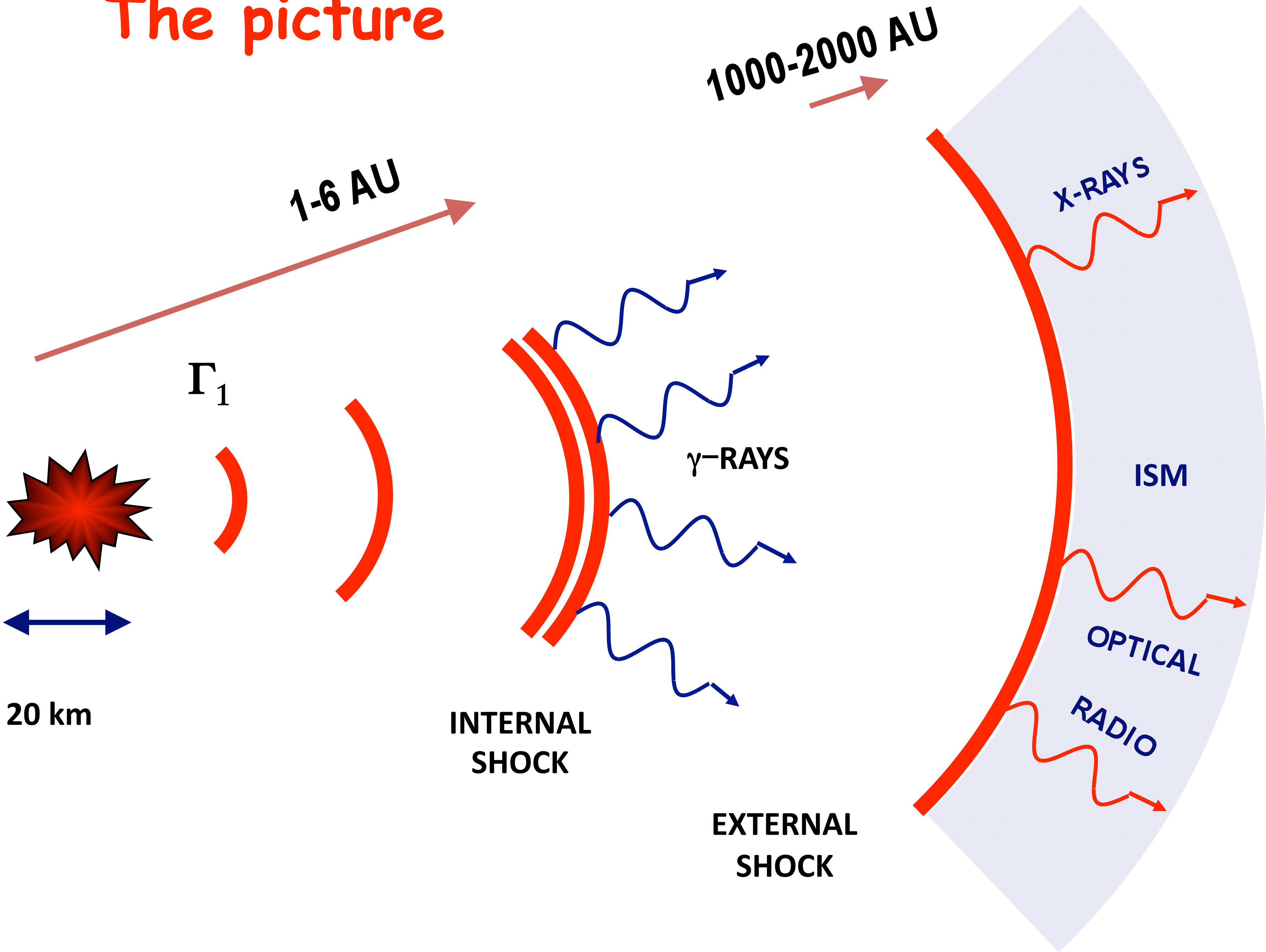
The standard "fireball" model

- Huge amount of energy in a small volume → **opaque fireball**
- The fireball expands with $v \sim c$
- Collision between different fireball shells → **prompt emission**
- The fireball hits the surrounding medium → **afterglow**





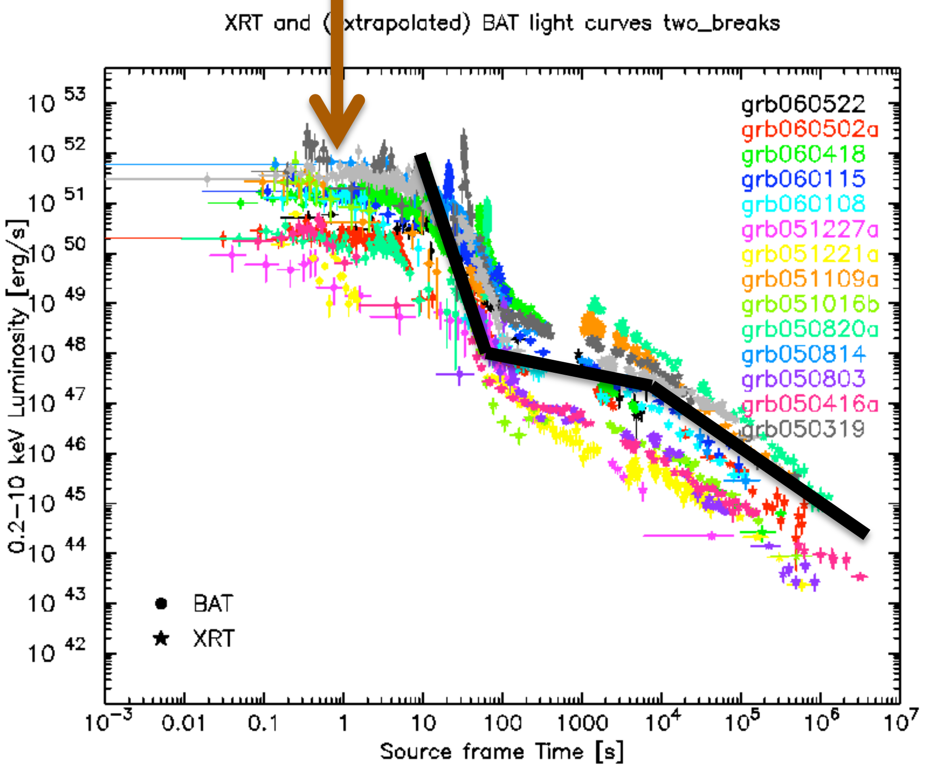
The picture



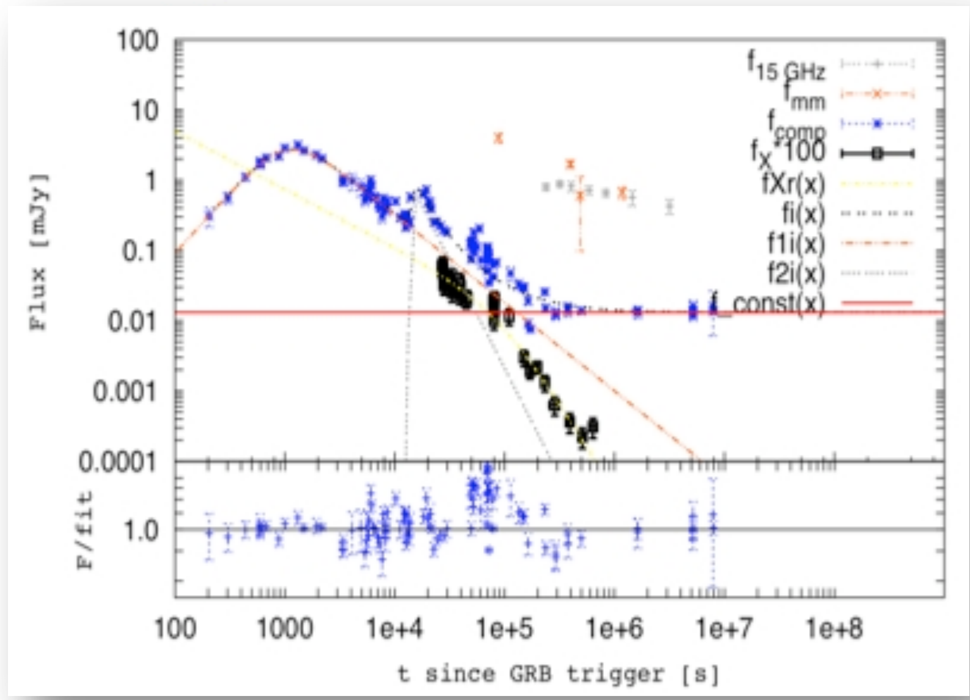
1000-2000 AU
1-6 AU
Γ_1
X-RAYS
γ–RAYS
ISM
OPTICAL
RADIO
20 km
INTERNAL SHOCK
EXTERNAL SHOCK

Light Curves

Prompt



Optical light curve in the observed frame

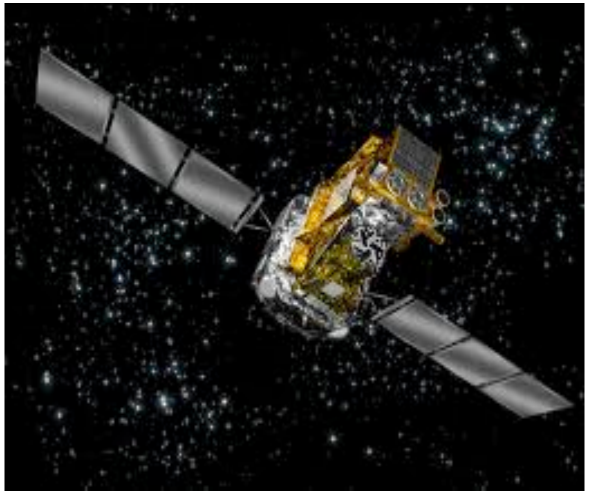


Lorentz factor !!

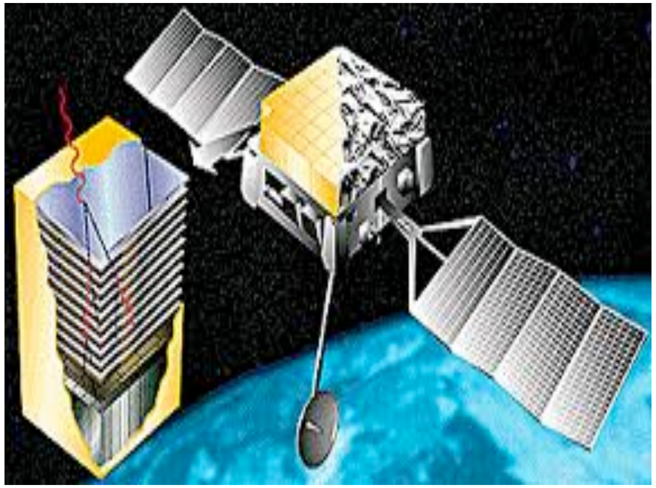
$$\Gamma(t_{\rm peak}) = \left[\frac{3E_\gamma(1+z)^3}{32\pi n m_p c^5 \eta t_{\rm peak}^3}\right]^{1/8} \approx 160\left[\frac{E_{\gamma,53}(1+z)^3}{\eta_{0.2} n_0 t_{\rm peak,2}^3}\right]^{1/8}$$

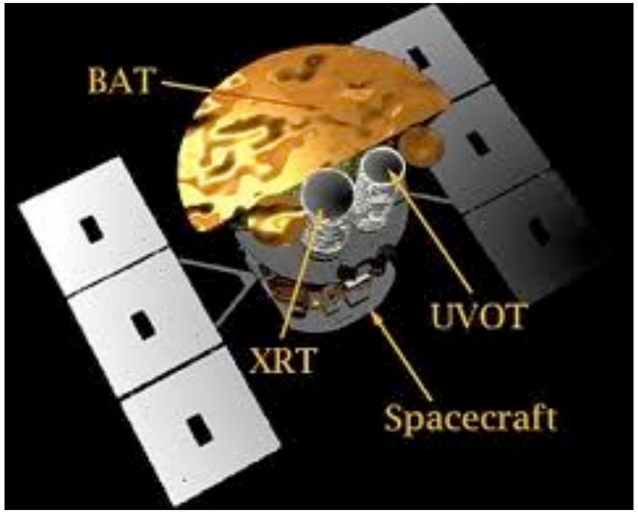
From Space

INTEGRAL



FERMI



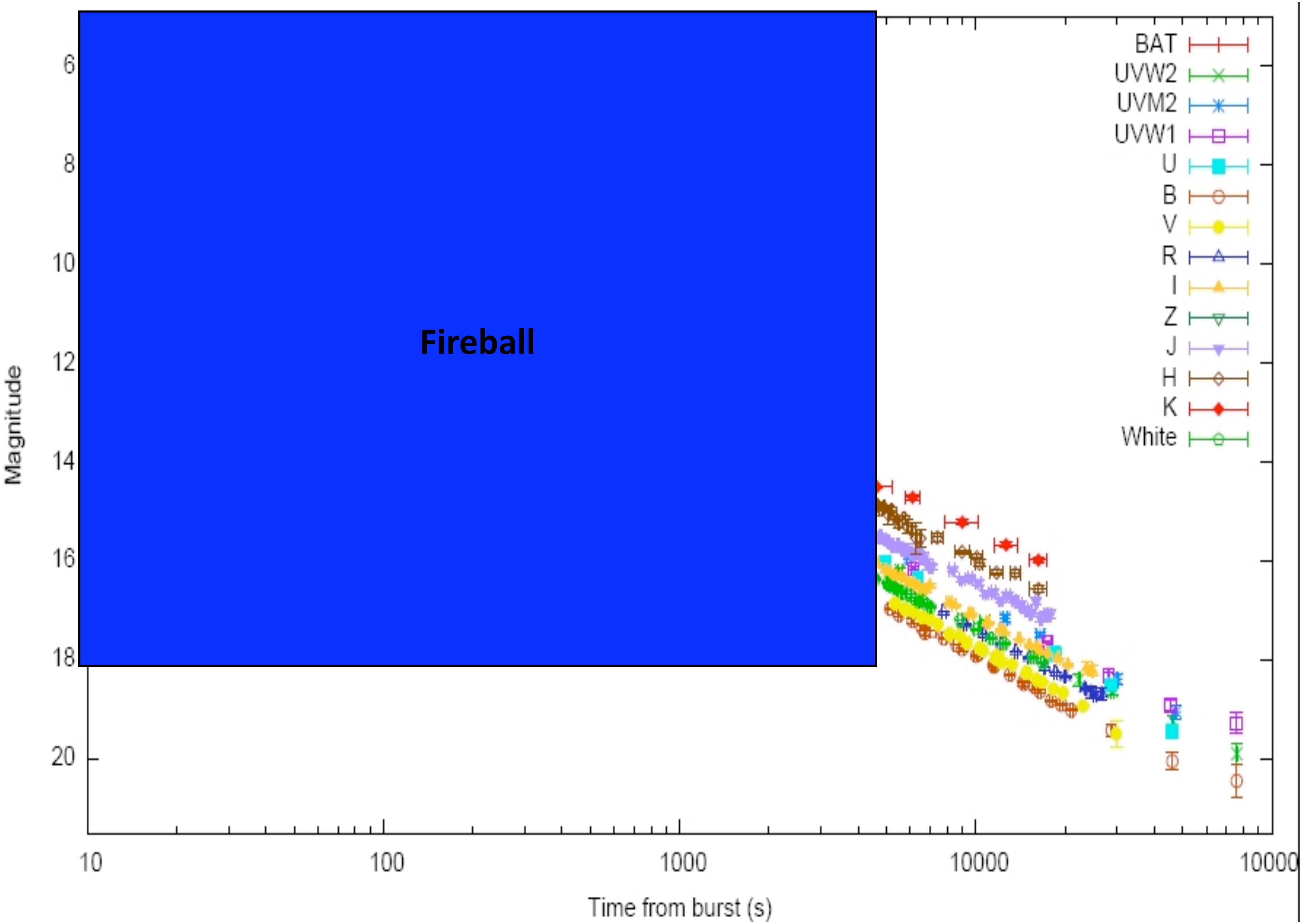


SWIFT

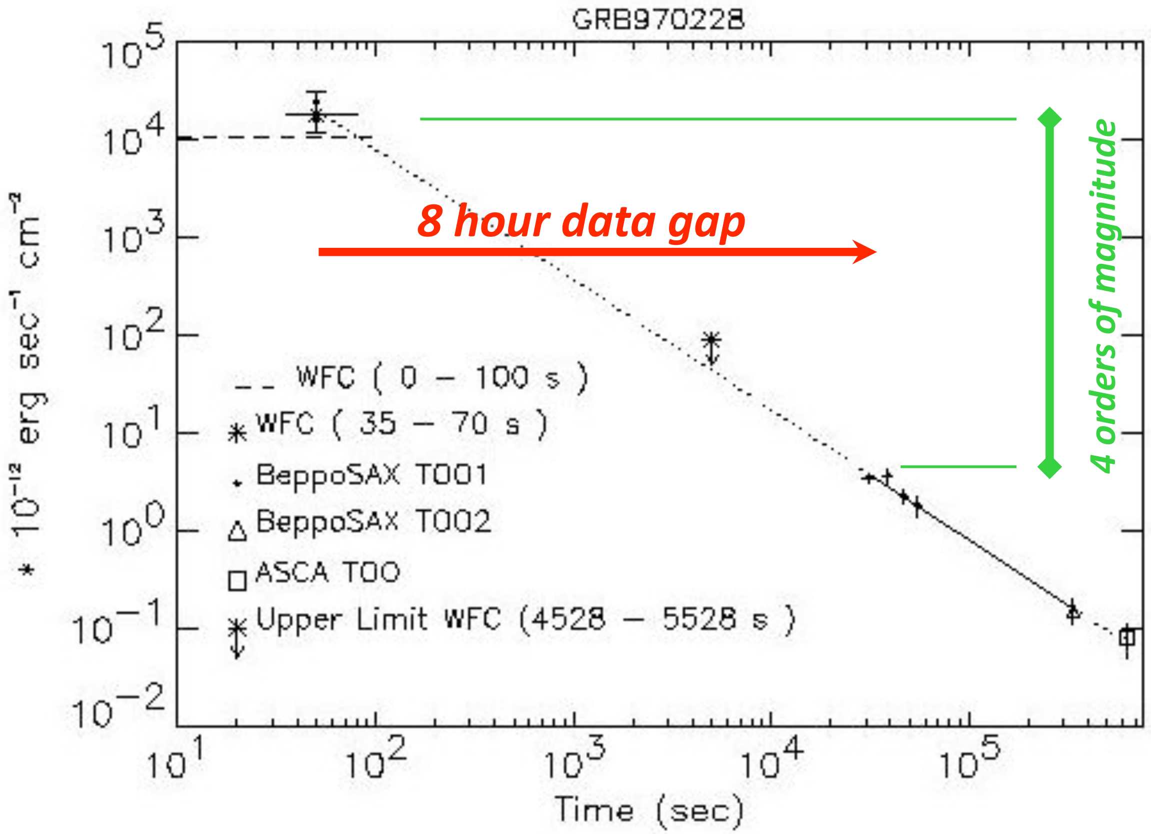
KONUS WIND

MAXI

BeppoSAX Era



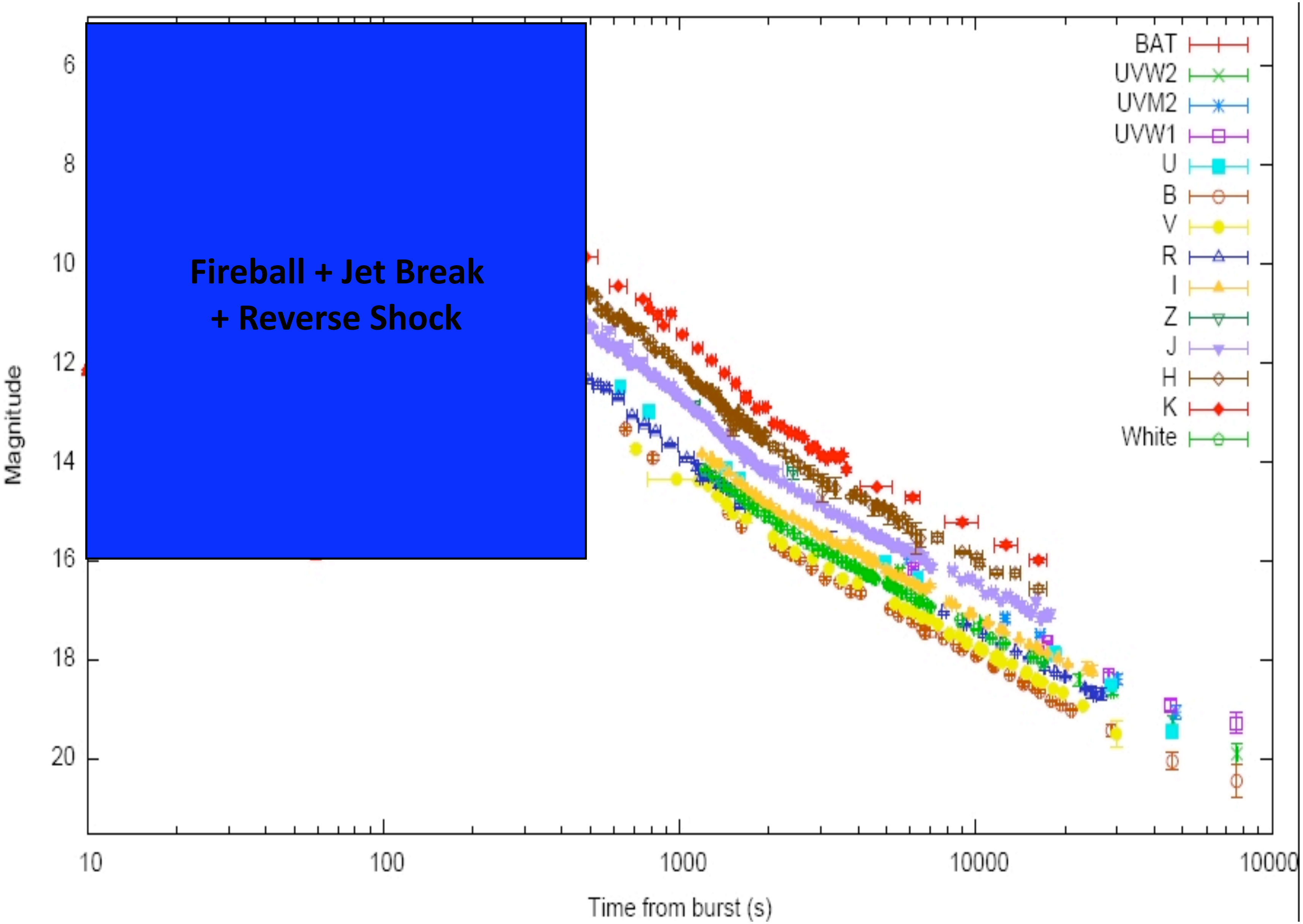
GRB-prehistory : the data gap



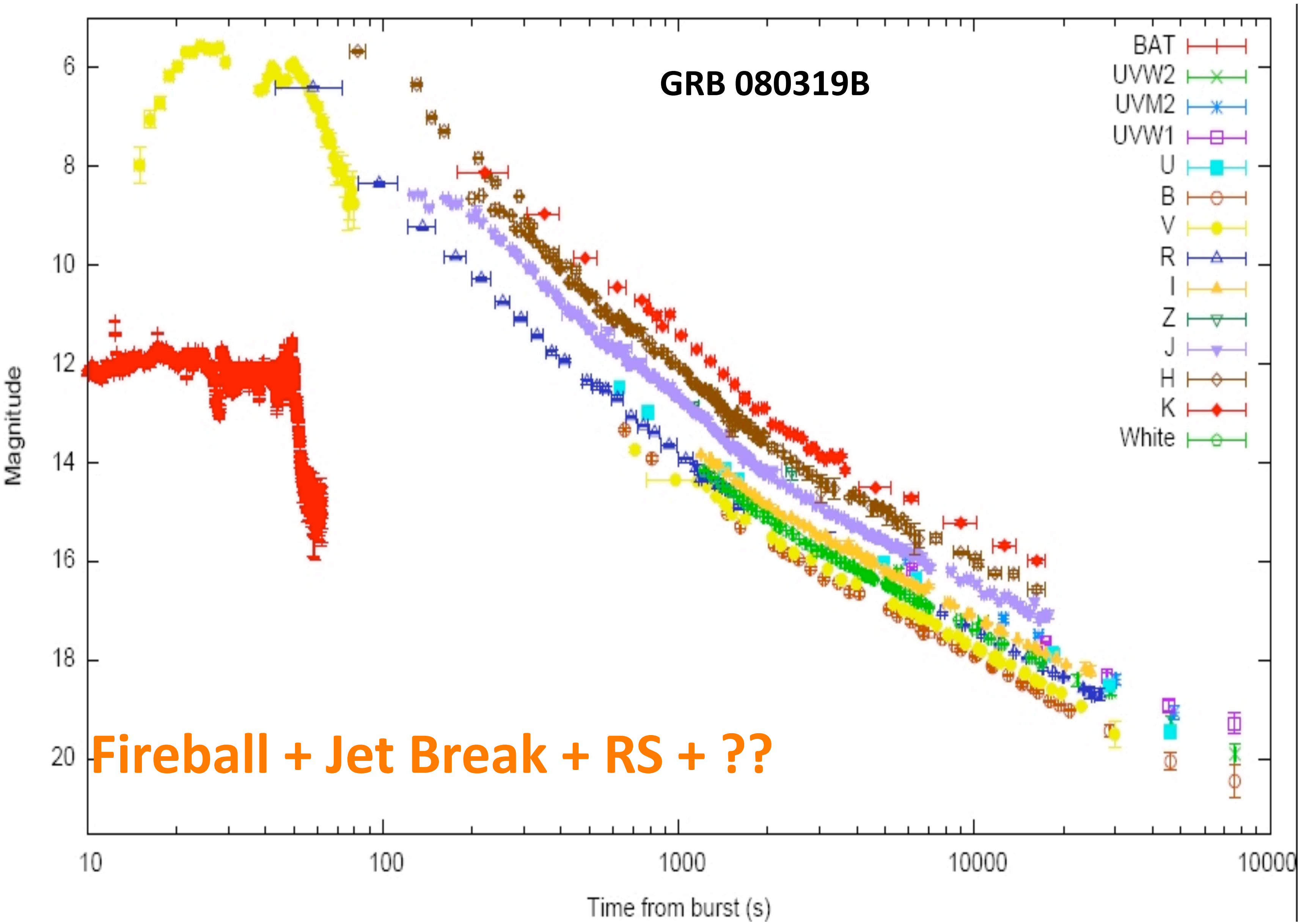
Beppo-SAX needed at least 6-8 hours to perform an afterglow follow-up observation with its narrow field instruments.

During this time, afterglow fades orders of magnitude.

Hete-II / INTEGRAL Era

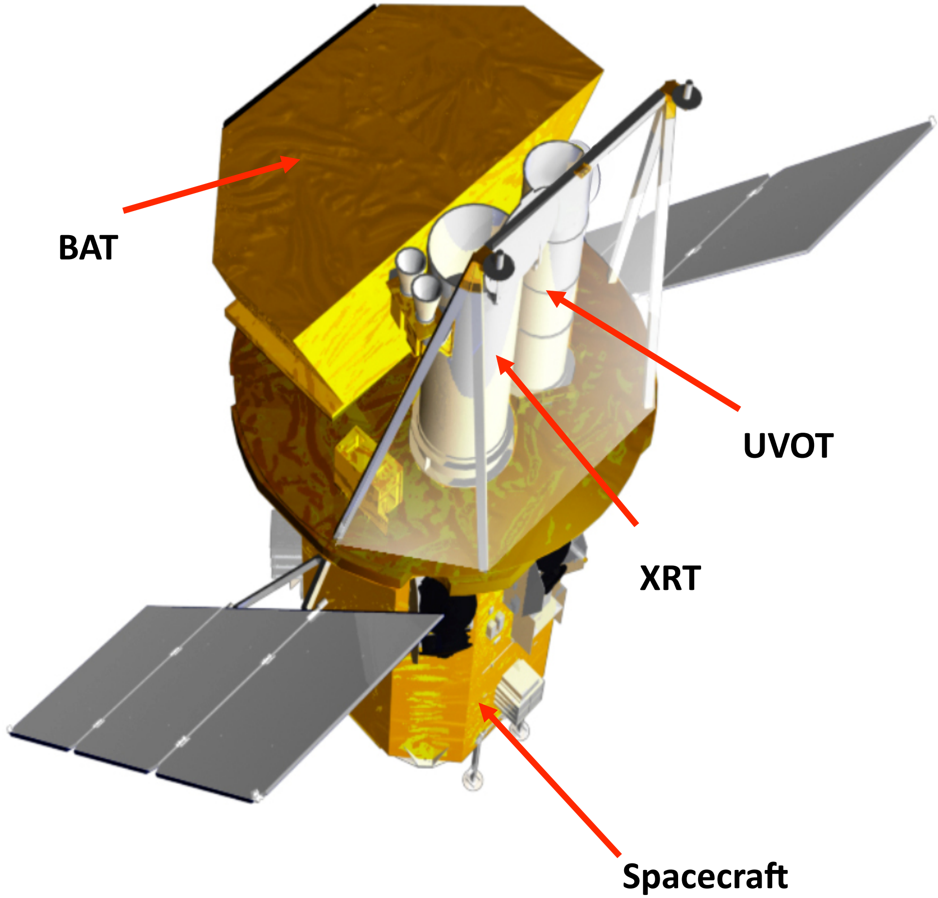


Swift (Fermi-Agile) Era !!!



Swift Mission

- **Burst Alert Telescope (BAT)**
  - 15-150 keV
  - FOV: 2 steradiants
  - Centroid accuracy: 1' - 4'
- **X-Ray Telescope (XRT)**
  - 0.2-10.0 keV
  - FOV: 23.6' x 23.6'
  - Centroid accuracy: 5"
- **UV/Optical Telescope (UVOT)**
  - 30 cm telescope
  - 6 filters (170 nm – 600 nm)
  - FOV: 17' x 17'
  - 24^{th} mag sensitivity (1000 sec)
  - Centroid accuracy: 0.5"

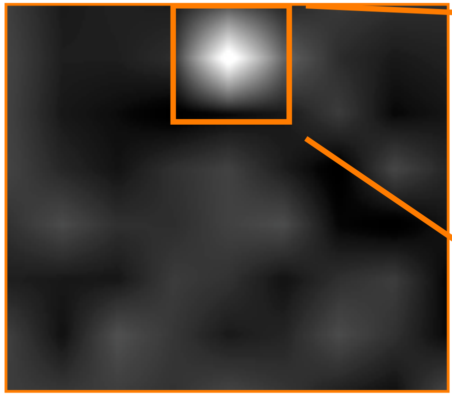


Swift was designed to fill in the gap making very early observations of the afterglows, beginning approximately 1 minute after the burst.

Observing Scenario

1. Burst Alert Telescope triggers on GRB, calculates position on sky to < 3 arcmin
2. Spacecraft autonomously slews to GRB position in 20-70 s
3. X-ray Telescope determines position to < 5 arcseconds
4. UV/Optical Telescope images field, transmits finding chart to ground

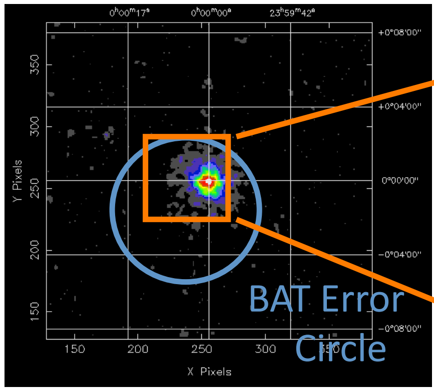
BAT Burst Image



T<10 sec

θ < 3'

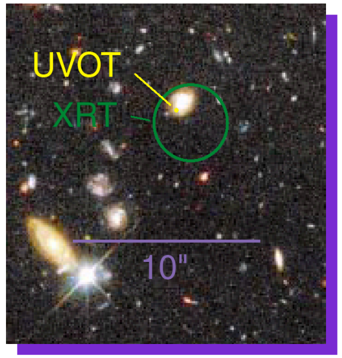
XRT Image



T<100 sec

θ < 5''

UVOT Image



T<300 sec

θ < 0.5''

Fermi Mission (LAT Overview)

Overall LAT Design:

- 4x4 array of identical towers
- 3000 kg, 650 W (allocation)
- 1.8 m × 1.8 m × 1.0 m
- **20 MeV – >300 GeV**

Anticoincidence Detector:

- 89 scintillator tiles
- **First step in reduction of large charged cosmic ray background**
- **Segmentation reduces self veto at high energy**

Thermal Blanket:

- And micro-meteorite shield

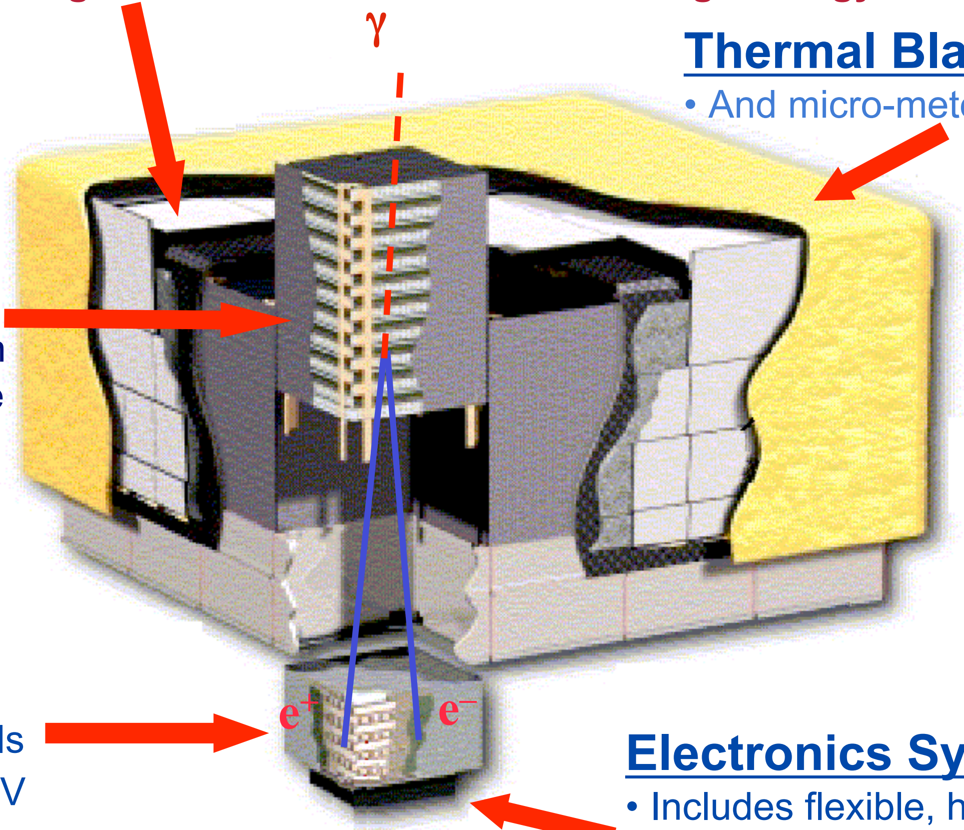
Precision Si-strip Tracker:

Measures incident gamma direction

18 XY tracking planes. 228 mm pitch. High efficiency. Good position resolution

12 x 0.03 X0 front end => reduce multiple scattering.

4 x 0.18 X0 back-end => increase sensitivity >1GeV

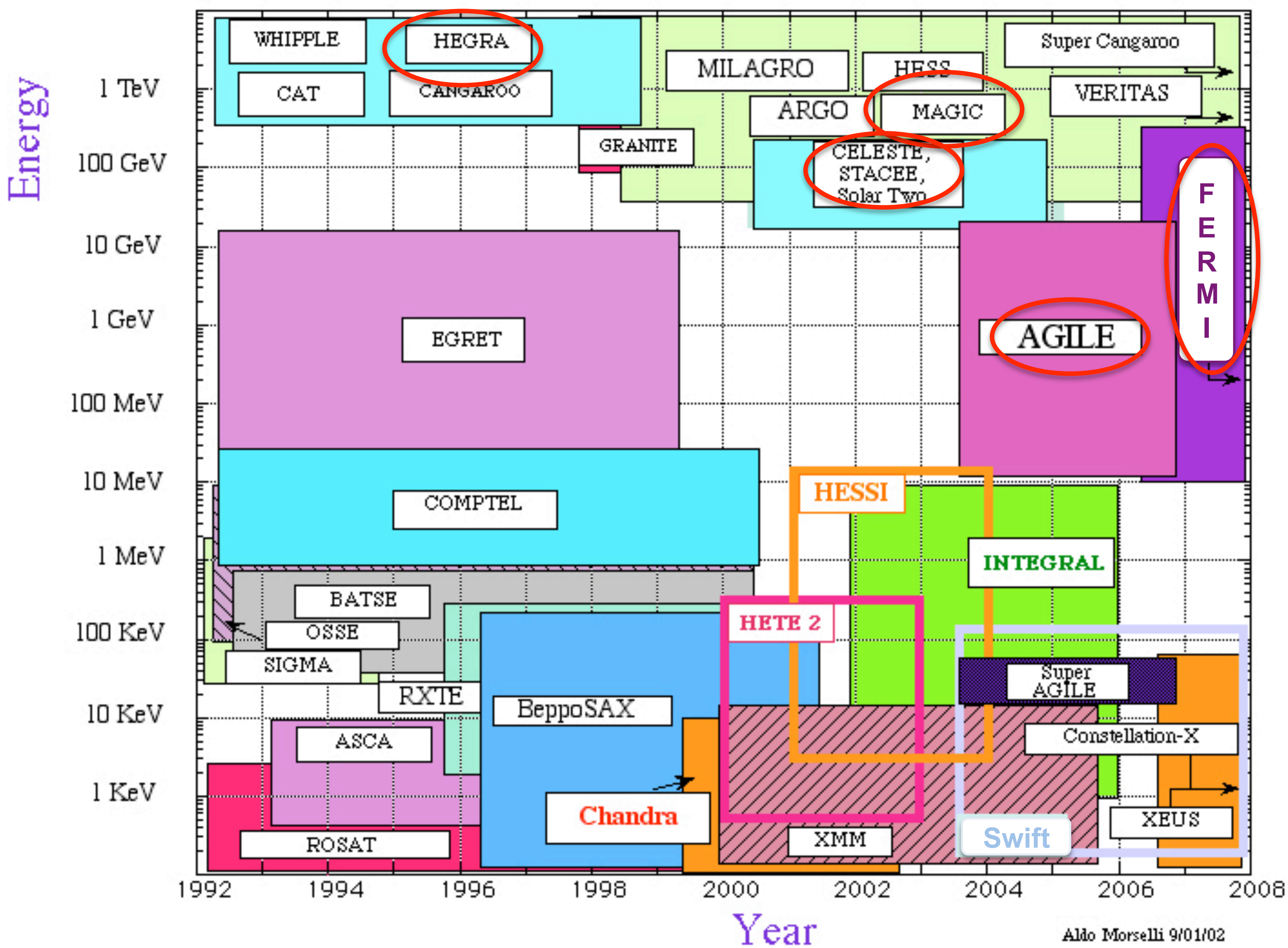


Hodoscopic CsI Calorimeter:

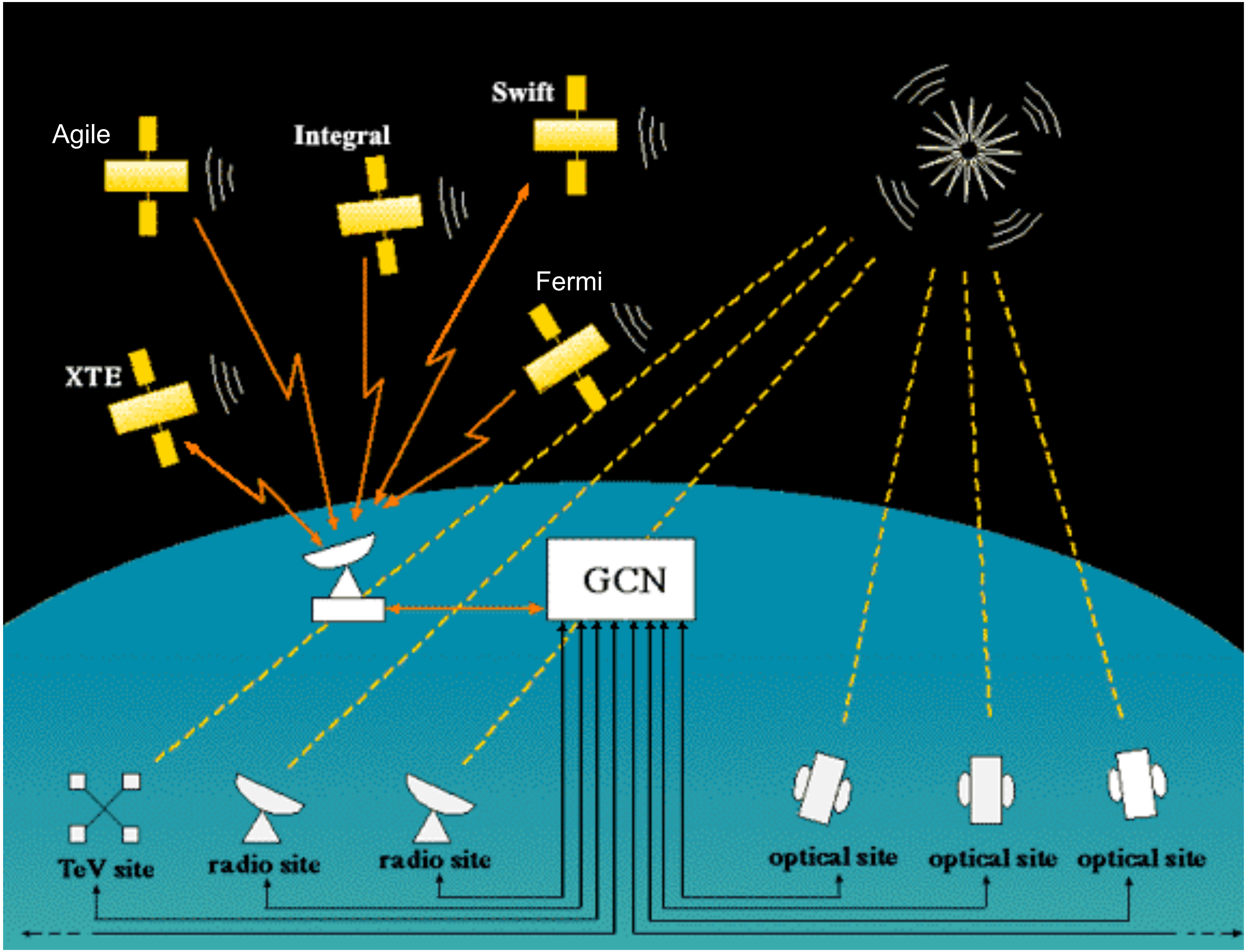
- Segmented array of 1536 CsI(Tl) crystals
- 8.5 X0: shower max contained <100 GeV
- **Measures the incident gamma energy**
- **Rejects cosmic ray backgrounds**

Electronics System:

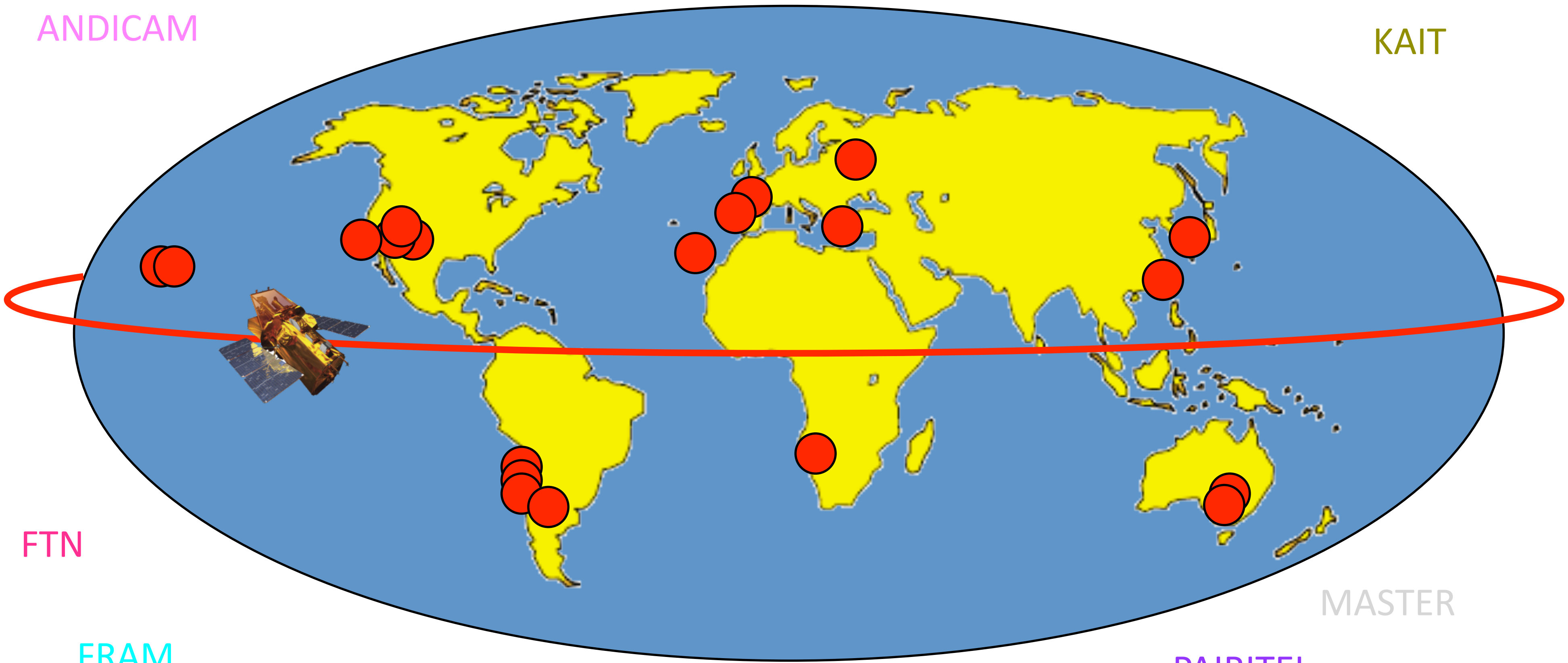
- Includes flexible, highly-efficient, multi-level trigger



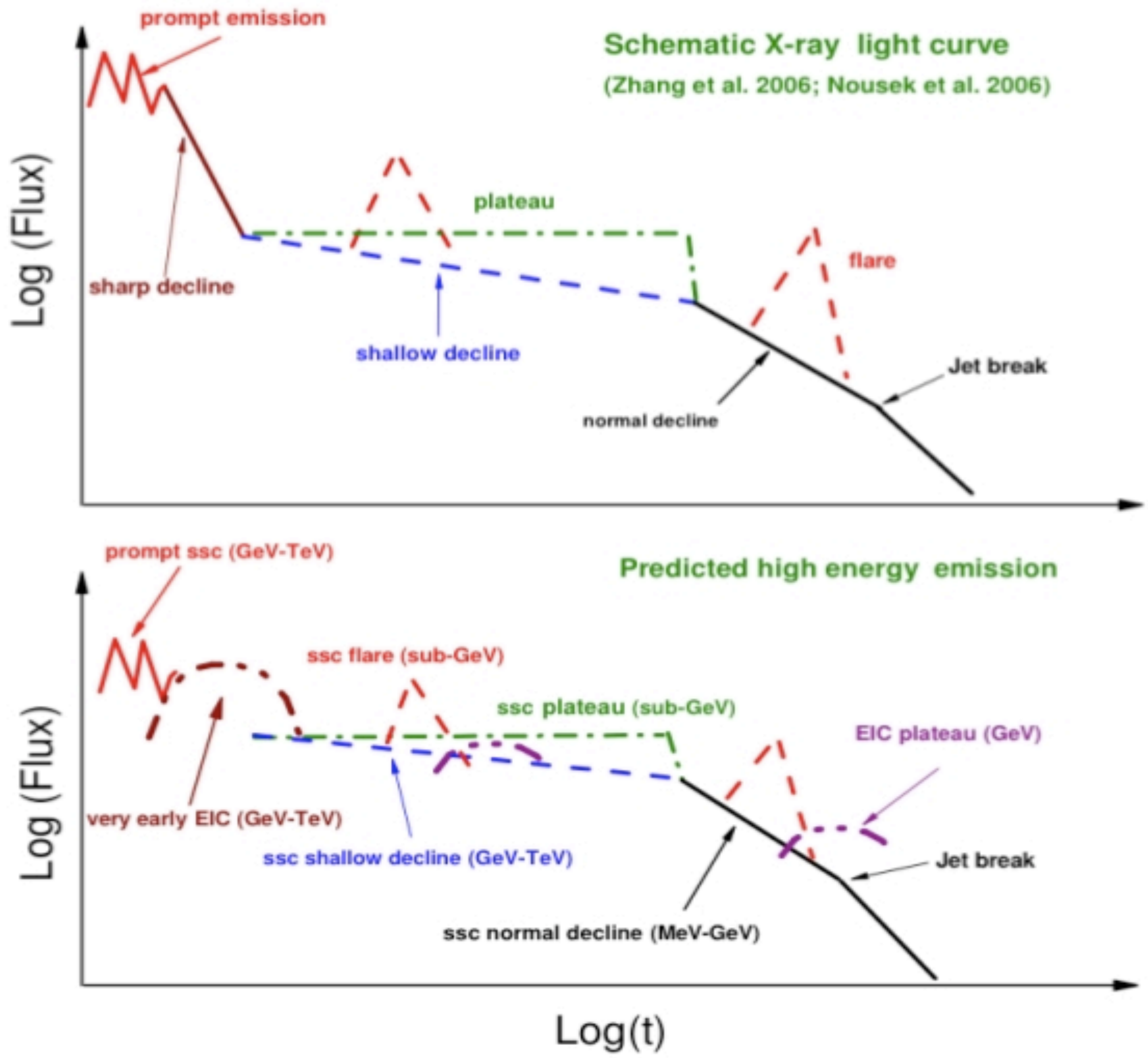
Energy
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
100 KeV
10 KeV
1 KeV
WHIPPLE
HEGRA
CAT
CANGAROO
MILAGRO
HESS
Super Cangaroo
VERITAS
ARGO
MAGIC
GRANITE
CELESTE, STACEE, Solar Two
FERMI
EGRET
AGILE
COMPTEL
HESSI
INTEGRAL
BATSE
OSSE
SIGMA
RXTE
BeppoSAX
HETE 2
Super AGILE
Constellation-X
ASCA
Chandra
ROSAT
XMM
Swift
XEUS
1992
1994
1996
1998
2000
2002
2004
2006
2008
Year
Aldo Morselli 9/01/02


Agile
Integral
Swift
Fermi
XTE
GCN
TeV site
radio site
radio site
optical site
optical site
optical site

From ground: time of robots



GRB @ VHE

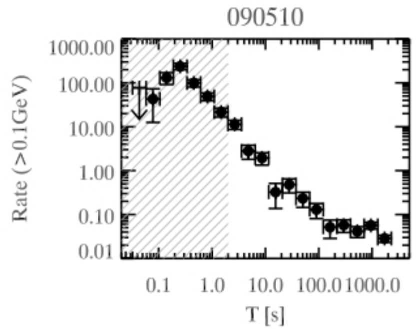


Fan & Piran 2008

GRB @ VHE

a) Several detections at MeV-GeV by EGRET

b) Time coincidence of HE emission with prompt (GRB 941017) or delayed/afterglow (GRB 940217) emission



c) **MeV-GeV emission observed** by AGILE and FERMI (few)

d) **So far…..no convincing detections at TeV**

e) Null detections reported by various Imaging Atmospheric Cherenkov Telescopes (HESS, VERITAS and MAGIC) → follow-up observations of Swift (via GCN) alerts

f) The fireball model (relativistic outflow with $\Gamma \sim 10^2\text{-}10^3$) prompt + afterglow synchrotron emission → **high energy cut-off expected** (pair production and Thomson scattering)…..photons up to GeV-TeV (prompt) or MeV (afterglow)

g) **IACT+Fermi** observations promising for VHE….**but**: moderate z & very early obs.