Gamma Ray Bursts

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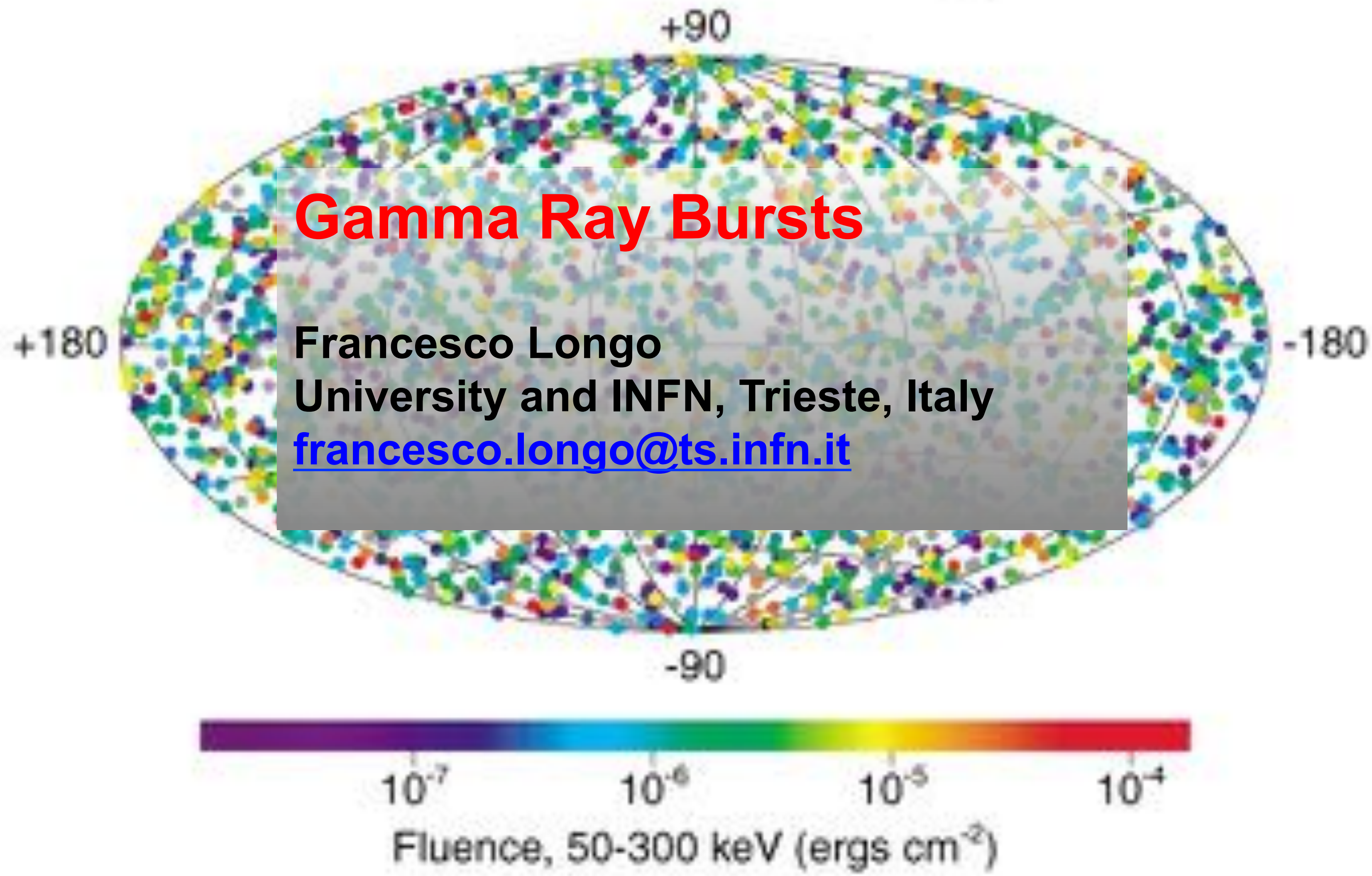
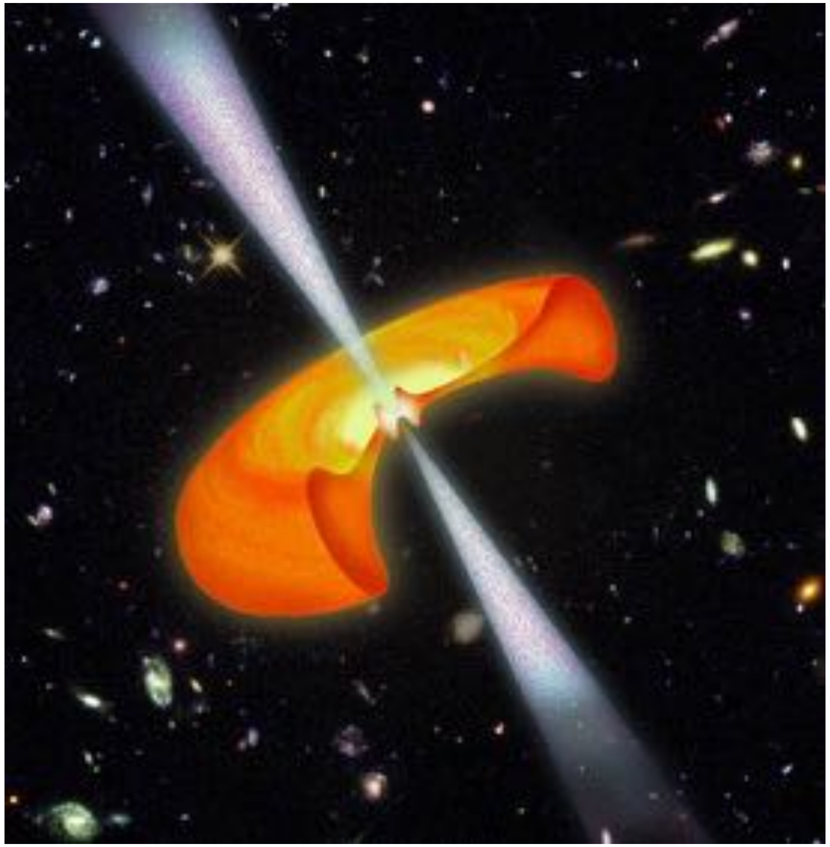


Outline of the Lectures

- GRB a puzzle being solved
  - Brief GRB history
    - Six GRB eras
  - GRB observations
    - The prompt
    - The afterglow
  - GRB theory
    - The fireball model
    - Search for Progenitors
  - HE emission from GRBs
- Detectors for GRB
  - BATSE
  - BeppoSAX
  - Swift
  - Fermi GBM and LAT



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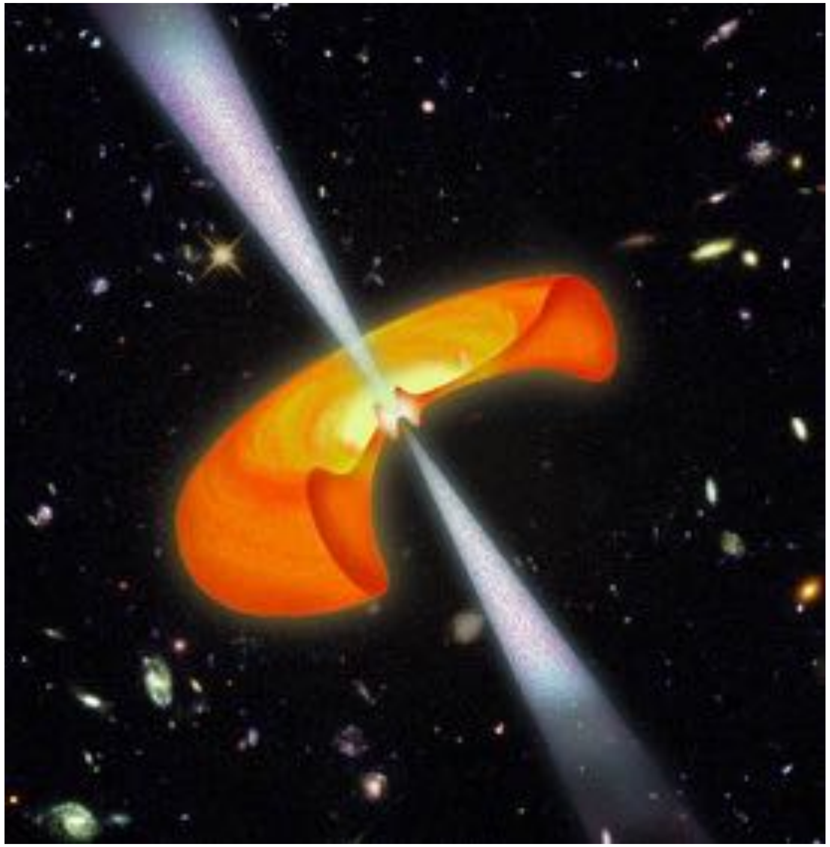
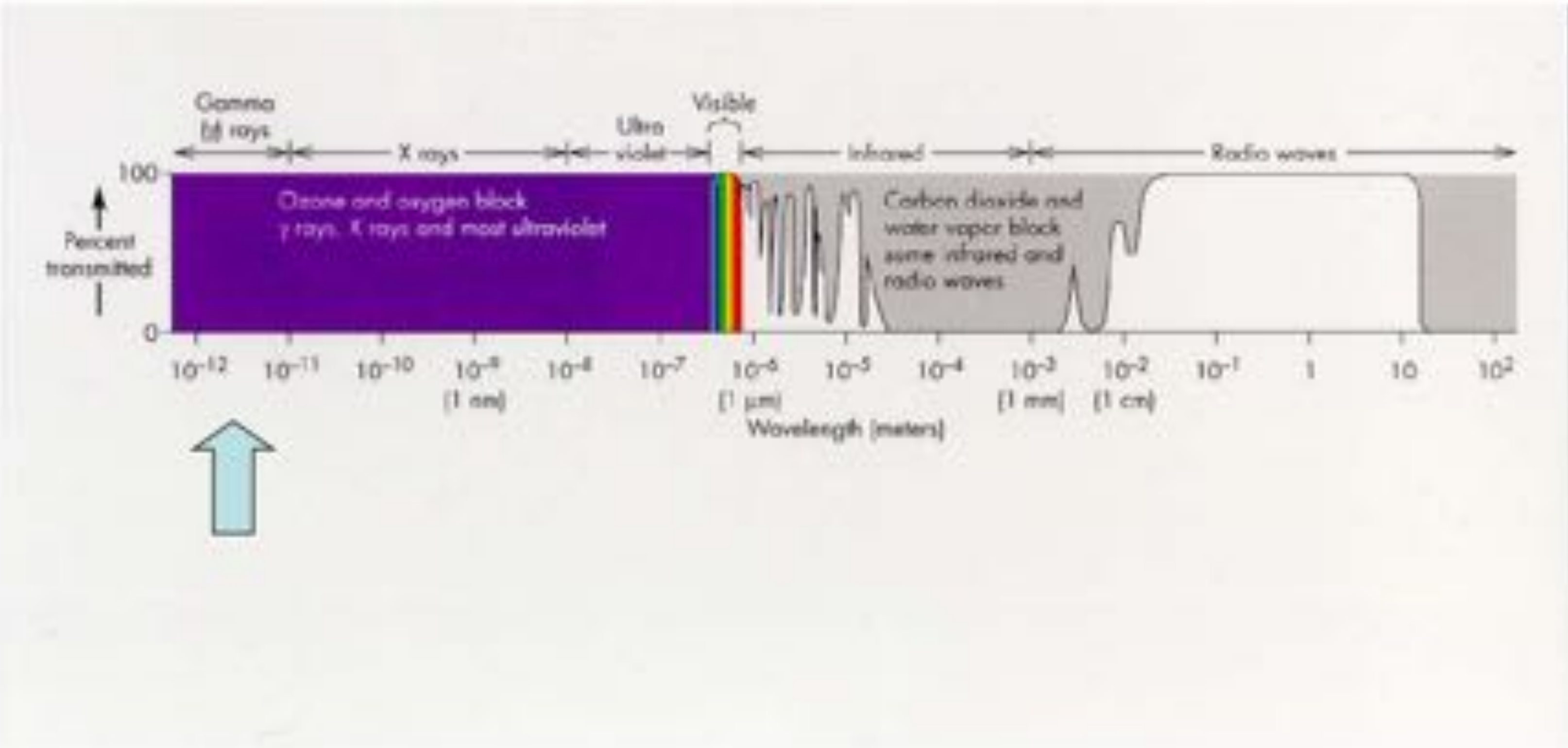


Gamma-ray Bursts



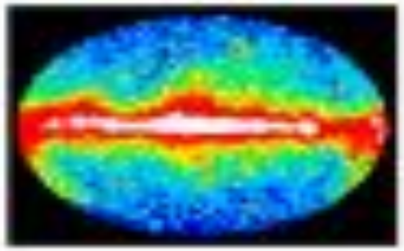
Gamma-rays are photons with energy above roughly 100keV, corresponding to temperatures above 10^9 K.

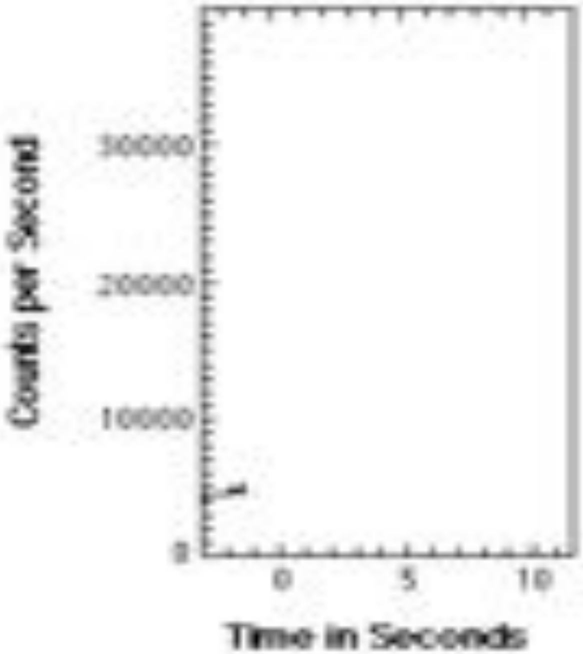
The Earth's atmosphere is optically thick to gamma-rays. Gamma-ray studies require balloons, rockets, or satellites.

Seven eras

1) "Dark" era (1973-1991): discovery
   Klebesadel, Strong & Olson's discovery (1973);
2) BATSE era (1992-1996): spatial distribution
   Meegan & Fishman's discovery (1992),
   detection rate: ~1 to 3 /day, ~3000 bursts;
3) BeppoSAX era (1997-2000): afterglows
   van Paradijs, Costa, Frail's discoveries (1997);
4) HETE-2 era (2001-2004): origin of long bursts
   Observations on GRB030329/SN2003dh
5) Swift era (2005-): very early afterglows, short-GRB afterglow, GRB subclasses? GRB cosmology?
6) Fermi era (2008-): High energy emission component, GW counterparts! – origin of short GRB
7) VHE era (2019-): VHE emission component from GRB!

The GRB phenomenon





• GRBs = sudden and unpredictable bursts of hard X / soft gamma rays with huge intensity, typical durations of tens of seconds and coming from random directions in the sky

• discovered at the end of the ’60s by military satellites, first published on an astronomical journal (ApJ) in 1973

• during ’70s and ’80s several experiments onboard satellites, but poor improvements in understanding these phenomena

The “dark” (?) era …

GRB history

- **Discovery by Vela Satellites (1967 - 1973)**

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

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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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 ~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.

Subject headings: gamma rays — X-rays — variable stars

I. INTRODUCTION

On several occasions in the past we have searched the records of data from early *Vela* spacecraft for indications of gamma-ray fluxes near the times of appearance of supernovae. These searches proved uniformly fruitless. Specific predictions of gamma-ray emission during the initial stages of the development of supernovae have since been made by Colgate (1968). Also, more recent Vela spacecraft are equipped with much improved instrumentation. This encouraged a more general search, not restricted to specific time periods. The search covered data acquired with almost continuous coverage between 1969 July and 1972 July, yielding records of 16 gamma-ray bursts distributed throughout that period. Search criteria and some characteristics of the bursts are given below.

II. INSTRUMENTATION

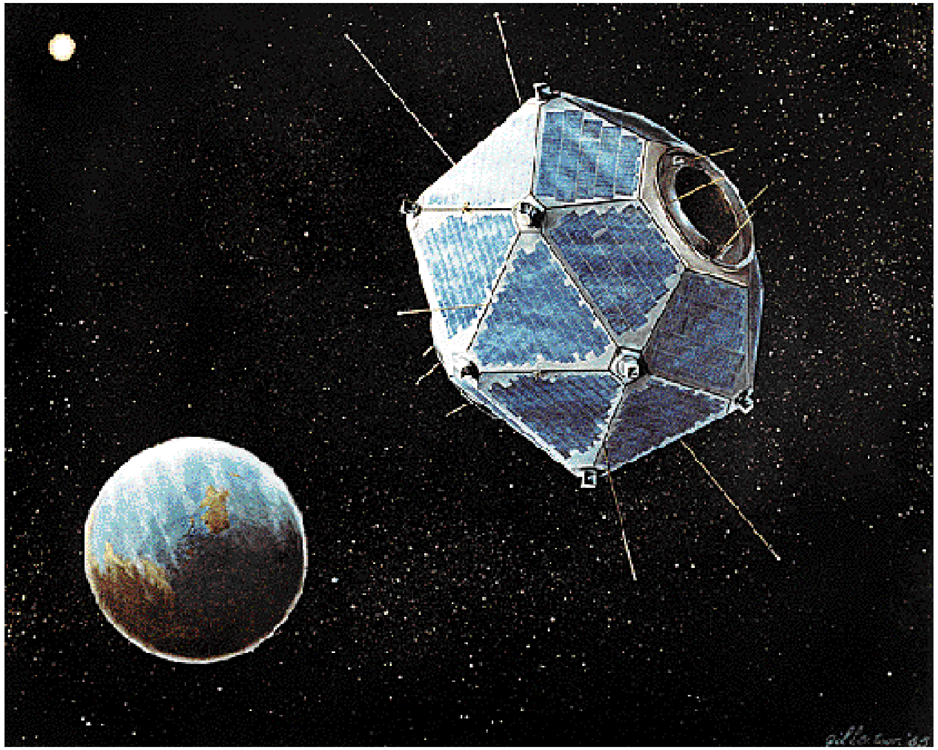
The observations were made by detectors on the four *Vela* spacecraft, *Vela 5A*, *5B*, *6A*, and *6B*, which are arranged almost equally spaced in a circular orbit with a geocentric radius of $\sim 1.2 \times 10^5$ km.

On each spacecraft six 10 cm^3 CsI scintillation counters are so distributed as to achieve a nearly isotropic sensitivity. Individual detectors respond to energy depositions of 0.2–1.0 MeV for *Vela 5* spacecraft and 0.3–1.5 MeV for *Vela 6* spacecraft, with a detection efficiency ranging between 17 and 50 percent. The scintillators are shielded against direct penetration by electrons below ~0.75 MeV and protons below ~20 MeV. A high-Z shield attenuates photons with energy below that of the counting threshold. No active anticoincidence shielding is provided.

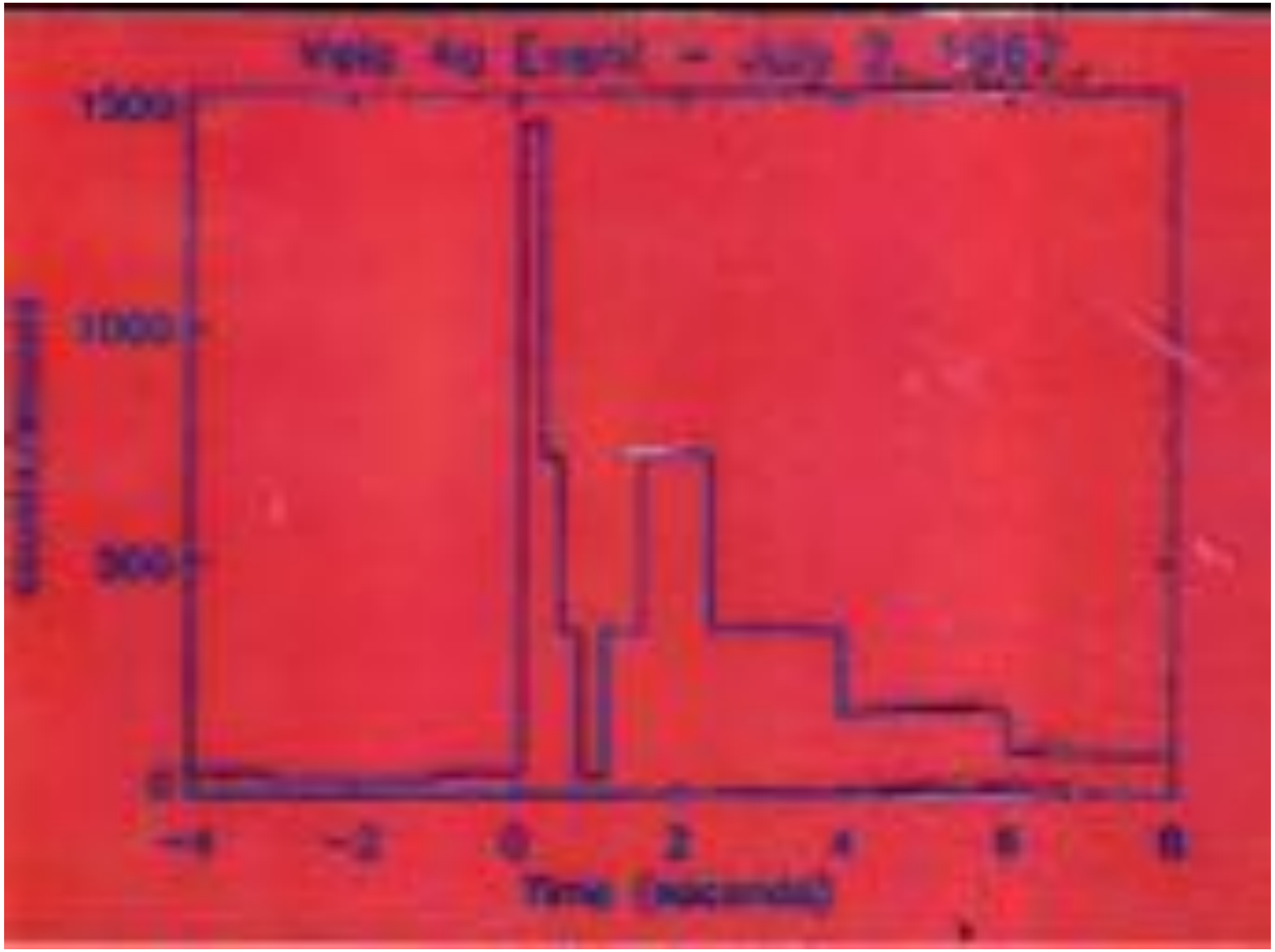
Normalized output pulses from the six detectors are summed into the counting and logics circuitry. Logical sensing of a rapid, statistically significant rise in count rate initiates the recording of discrete counts in a series of quasi-logarithmically increasing time intervals. This capability provides continuous coverage in time which, coupled with isotropic response, is unique in observatonal astronomy. A time measurement is also associated with each record.

The data accumulations include a background component due to cosmic particles and their secondary effects. The observed background rate, which is a function of the energy threshold, is ~150 counts per second for the *Vela 5* spacecraft and ~20 counts per second for the *Vela 6* spacecraft.

L85



First Detected Gamma-Ray Burst



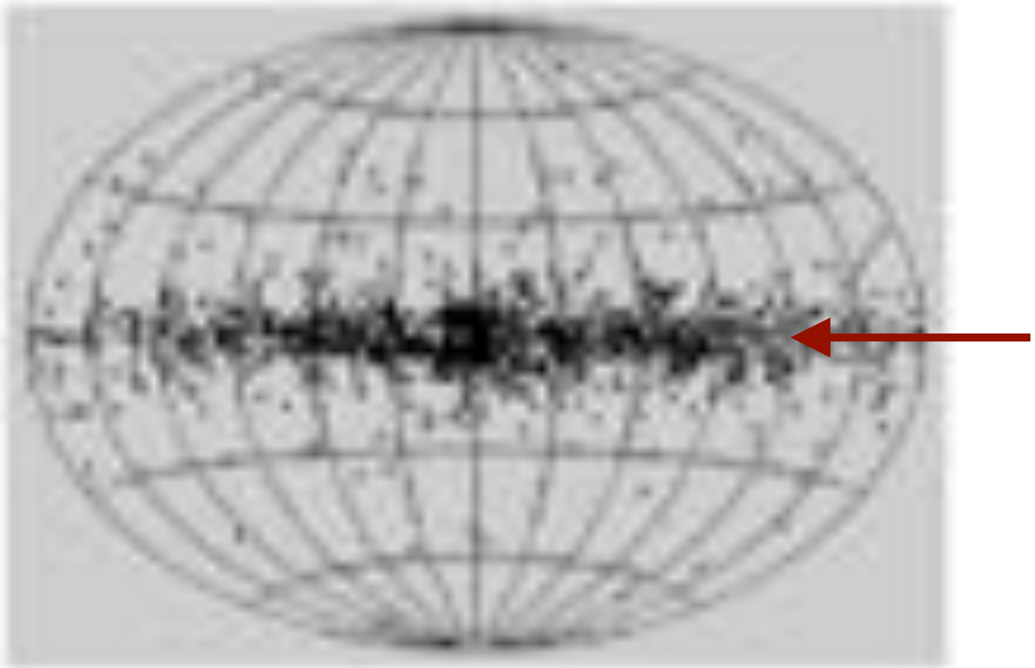
Models for Galactic GRBs

- Accretion
  I) Binary Companion
  - no companion seen
  II) SN Fallback – Too long after explosion
- Magnetic Fields

~10^{15} G Fields
-“Magnetars”

If normal GRBs are also neutron stars, GRBs should Also center around the Galactic Equator.

This is a Prediction of the Galactic Models!



Plane of the Milky Way Galaxy

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

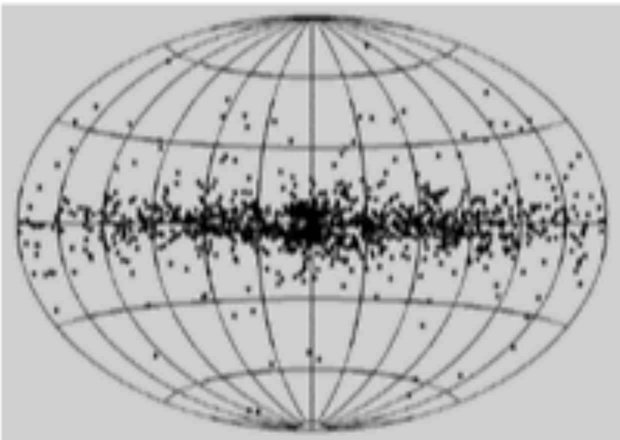
Models for Cosmological GRB

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

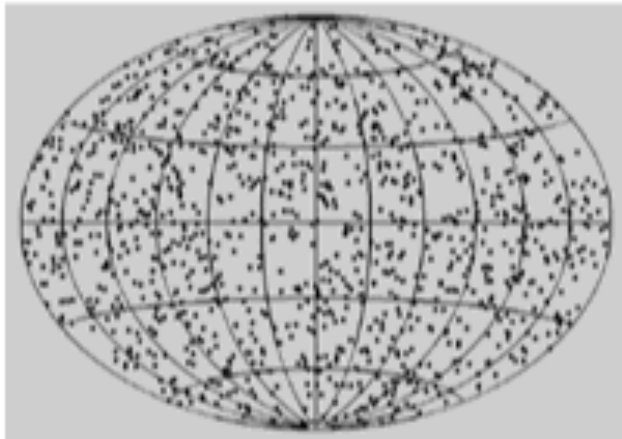
The BATSE era

GRB History

Distribution of Gamma-Ray Bursts on the Sky

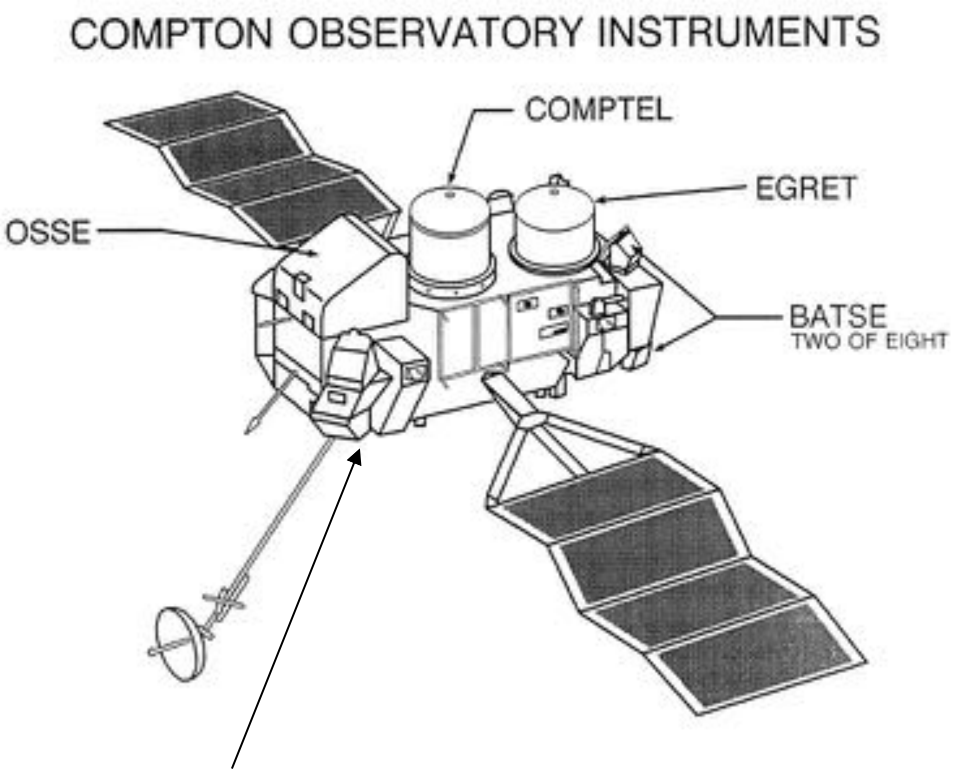


Expected



Observed

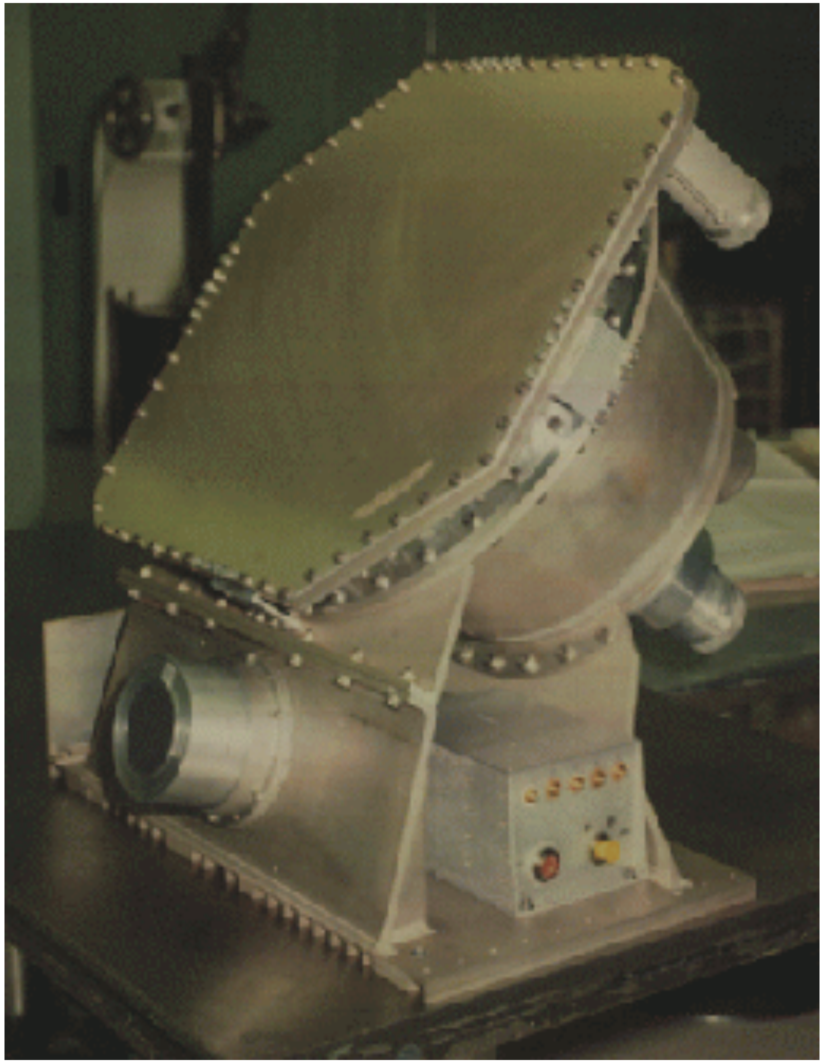
CGRO-BATSE (1991-2000)



CGRO/BATSE (25 keV÷10 MeV)

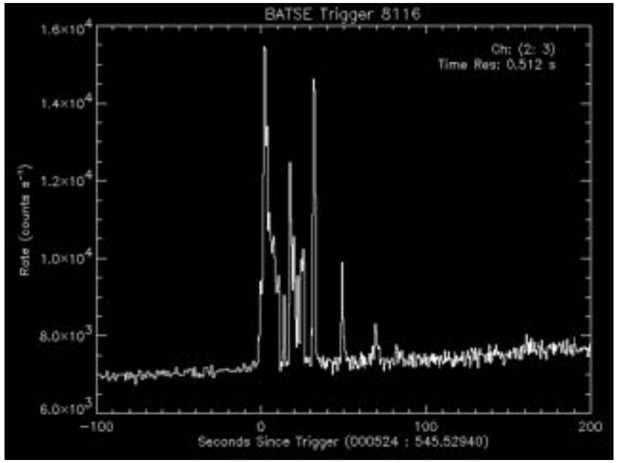
The BATSE instrument

- NaI scintillators
- 20 keV – 2 MeV
- FoV 4π

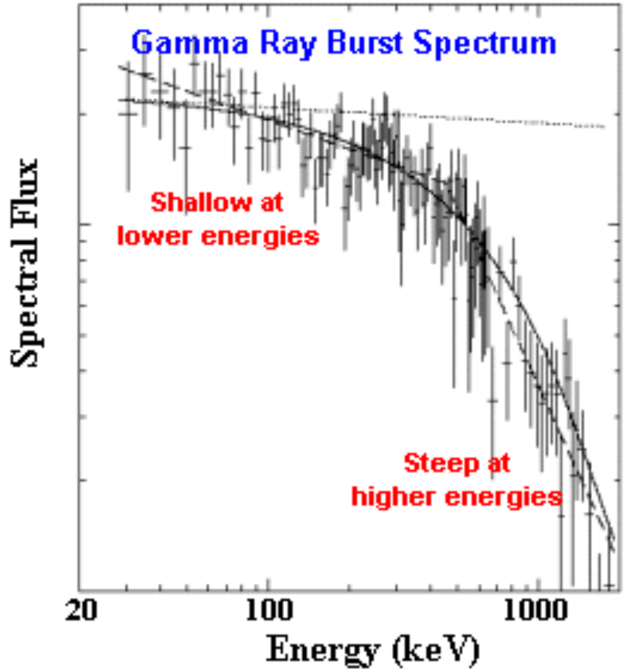


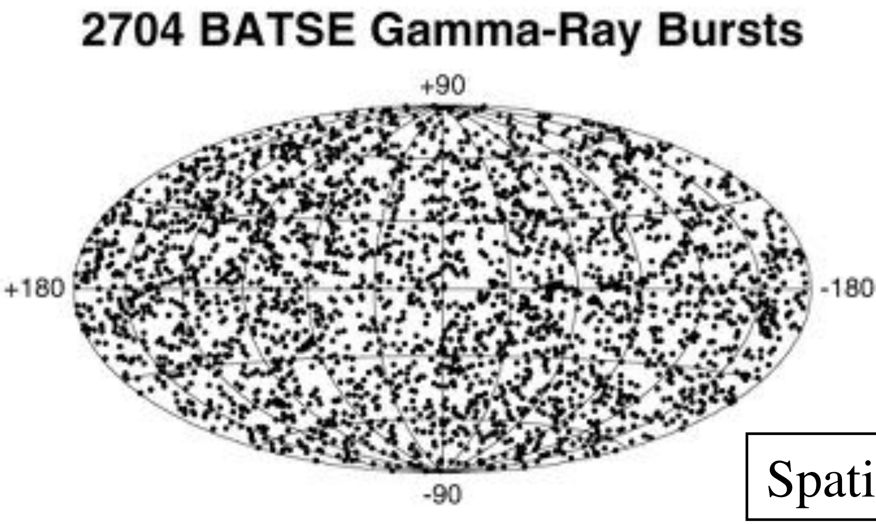
Gamma-Ray Bursts

Temporal behaviour



Spectral shape





Spatial distribution

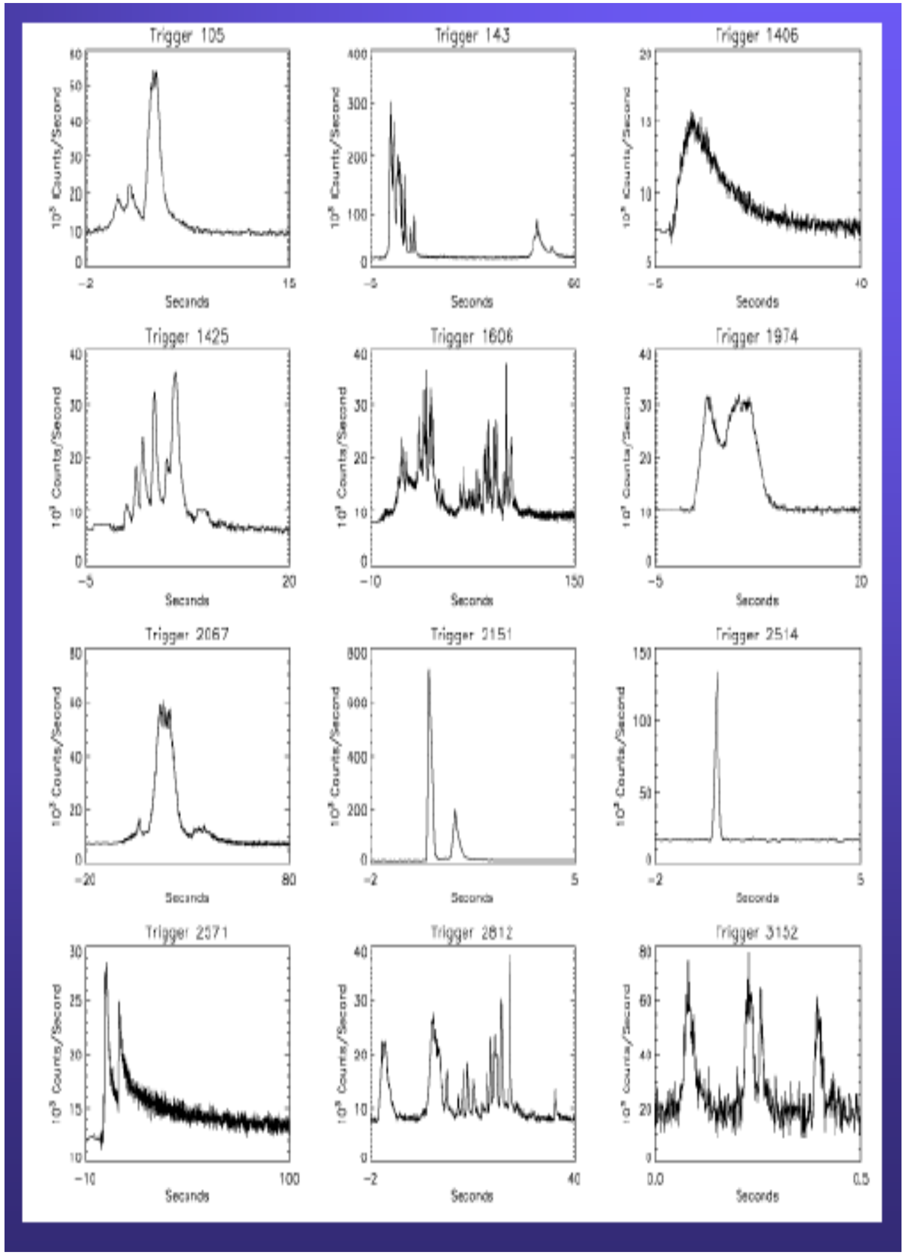
The GRB phenomenon

- most of the flux detected from 10-20 keV up to 1-2 MeV

- measured rate (by an all-sky experiment on a LEO satellite): ~0.8 / day; estimated true rate ~2 / day

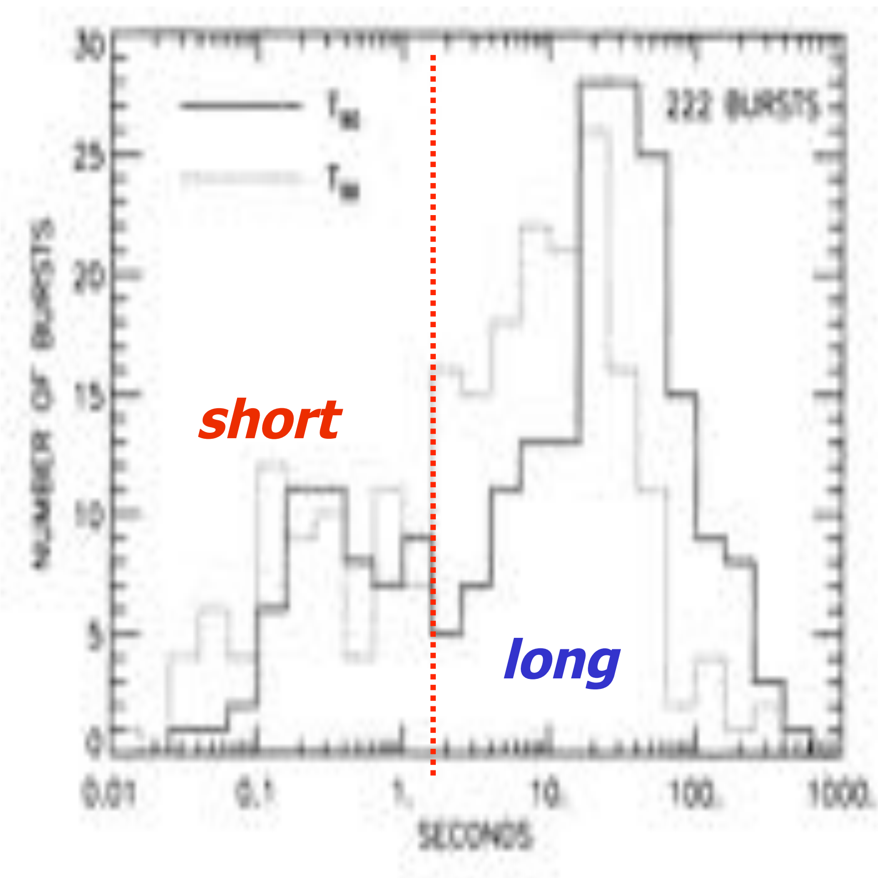
- fluences (= av.flux * duration) typically of $\sim 10^{-7} - 10^{-4}$ erg/cm^2

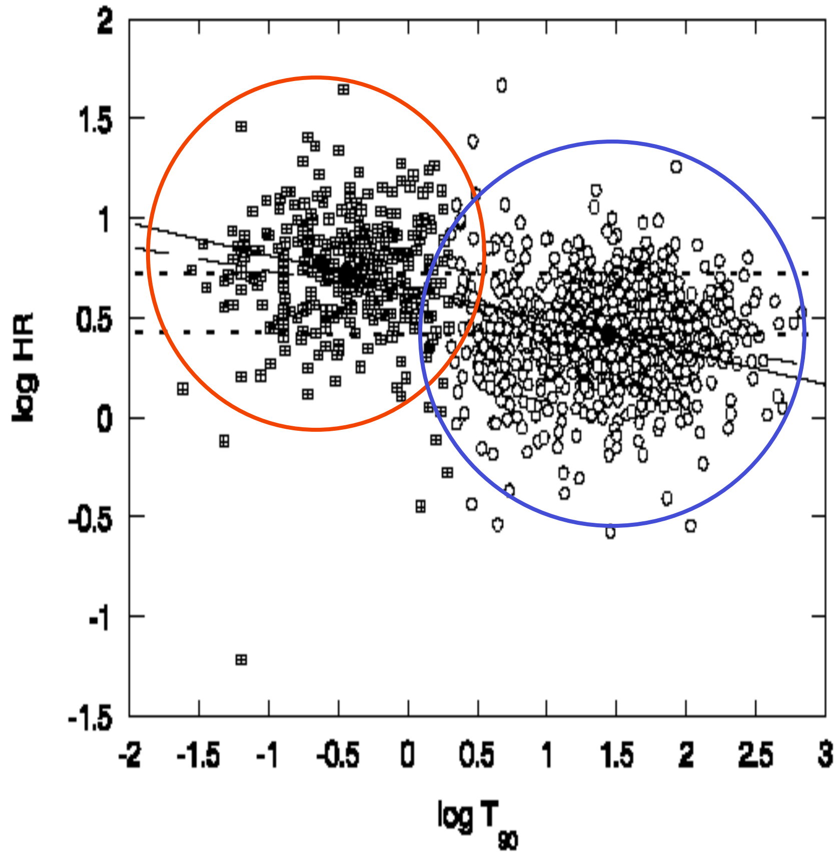
- diverse and unclassifiable light curves



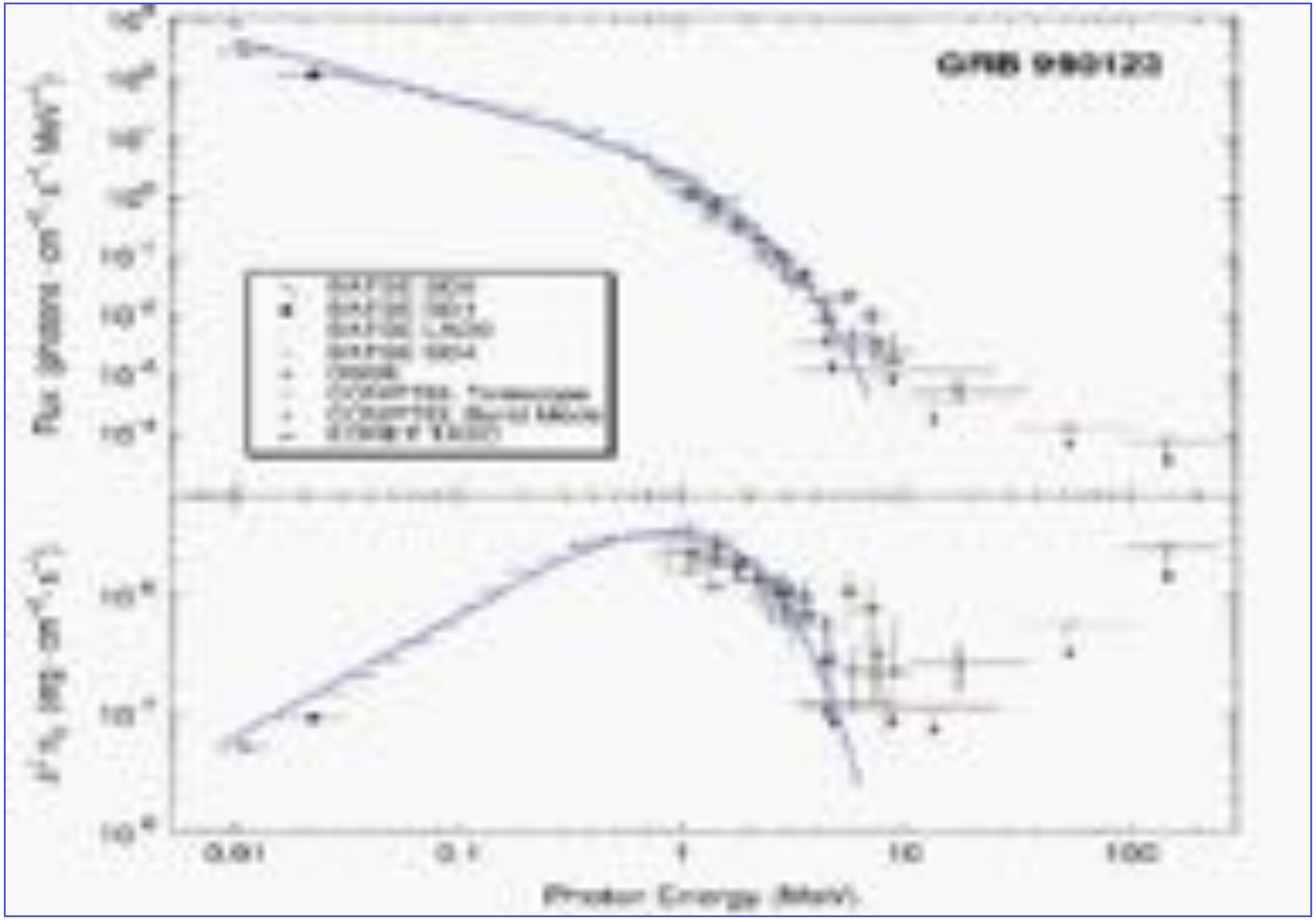
The GRB phenomenon

- bimodal distribution of durations: short and long GRBs
- short GRBs tend to be spectrally harder than long GRBs

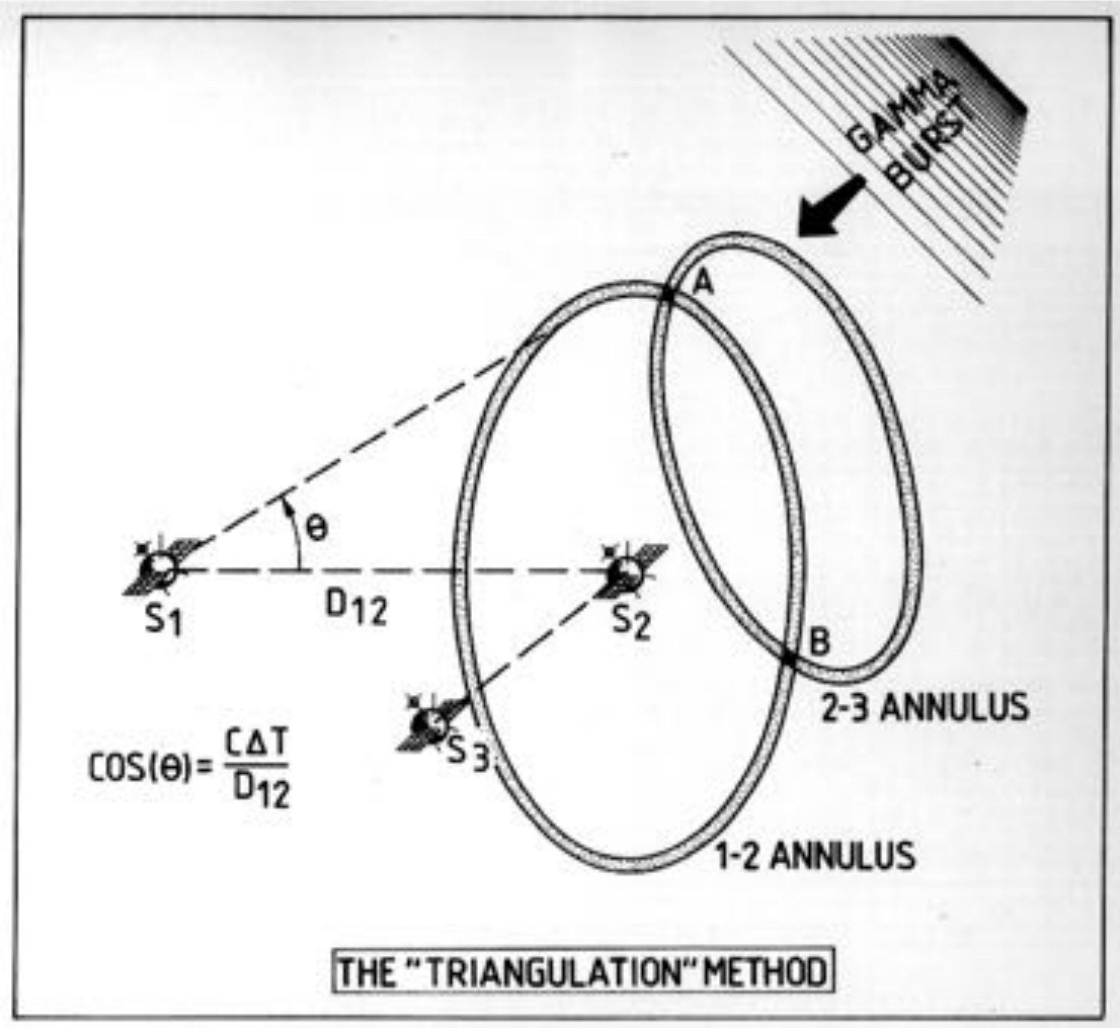




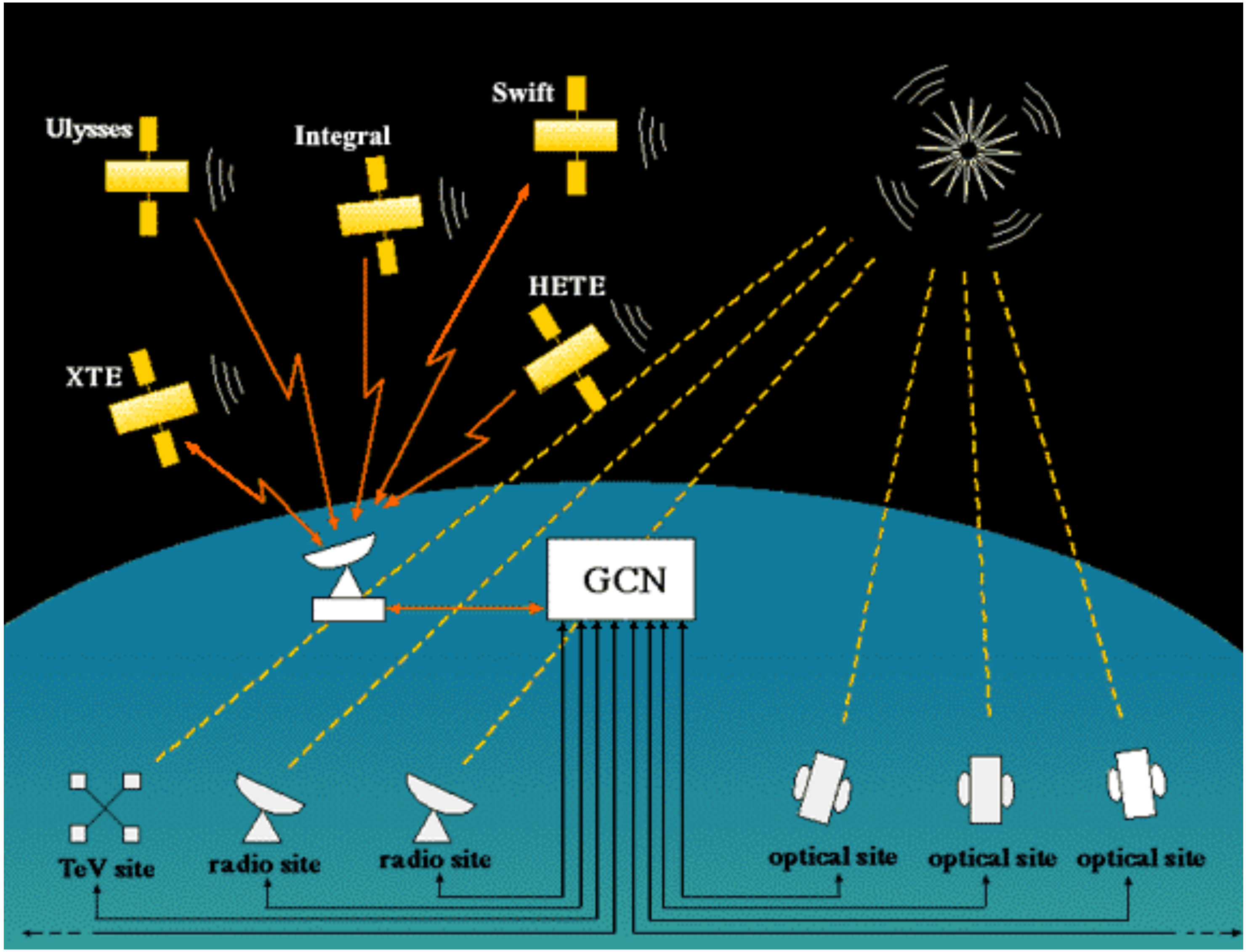
GRB spectral info



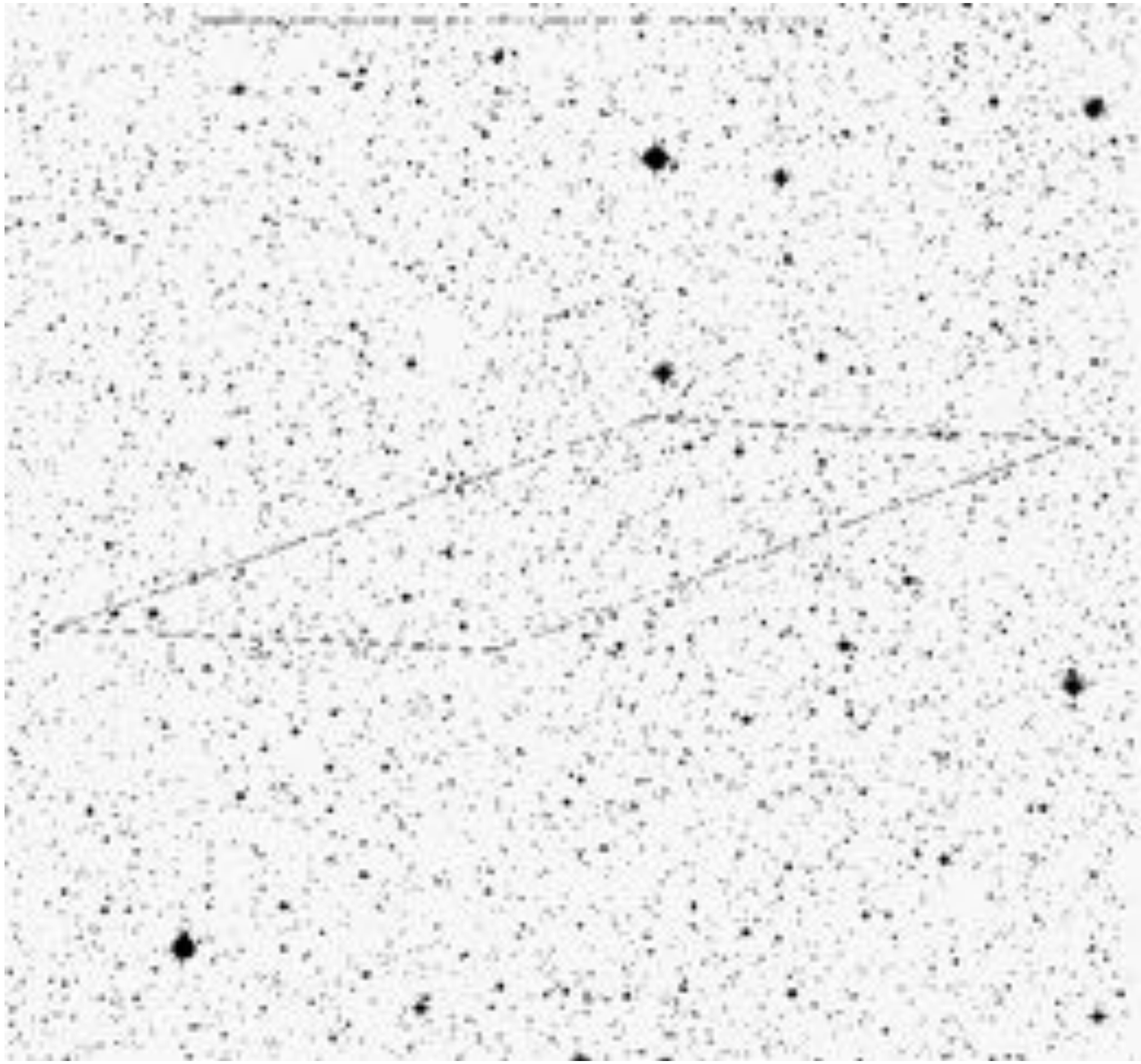
The Interplanetary network



The GRB coordinates network



No host problem



GRB: where are they?

The great debate (1995)

Flux: 10^{-7} erg cm^{-2} s^{-1}

Distance: 1 Gpc

Energy: 10^{51} erg

Distance: 100 kpc

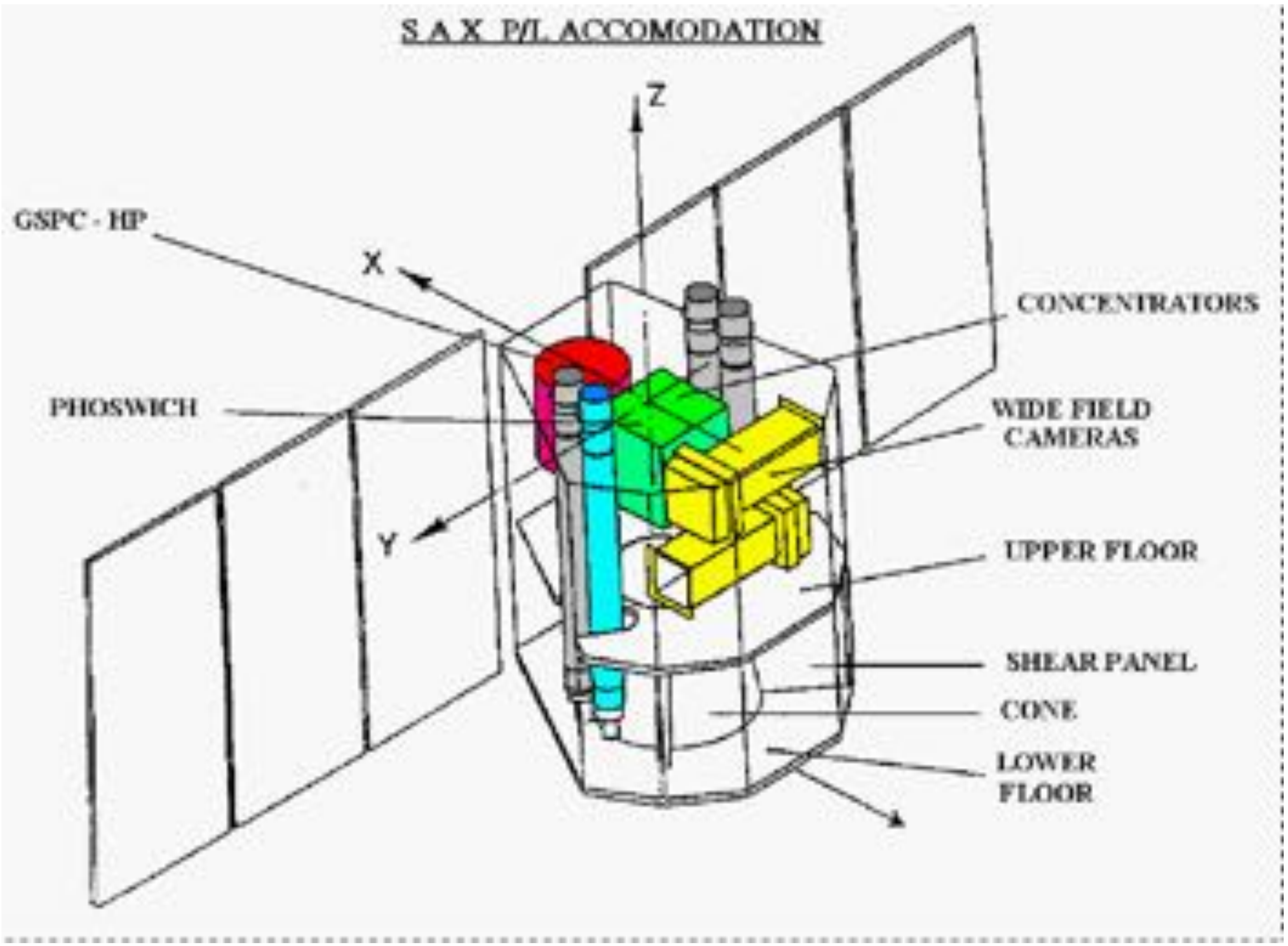
Energy: 10^{43} erg

Cosmological - Galactic?

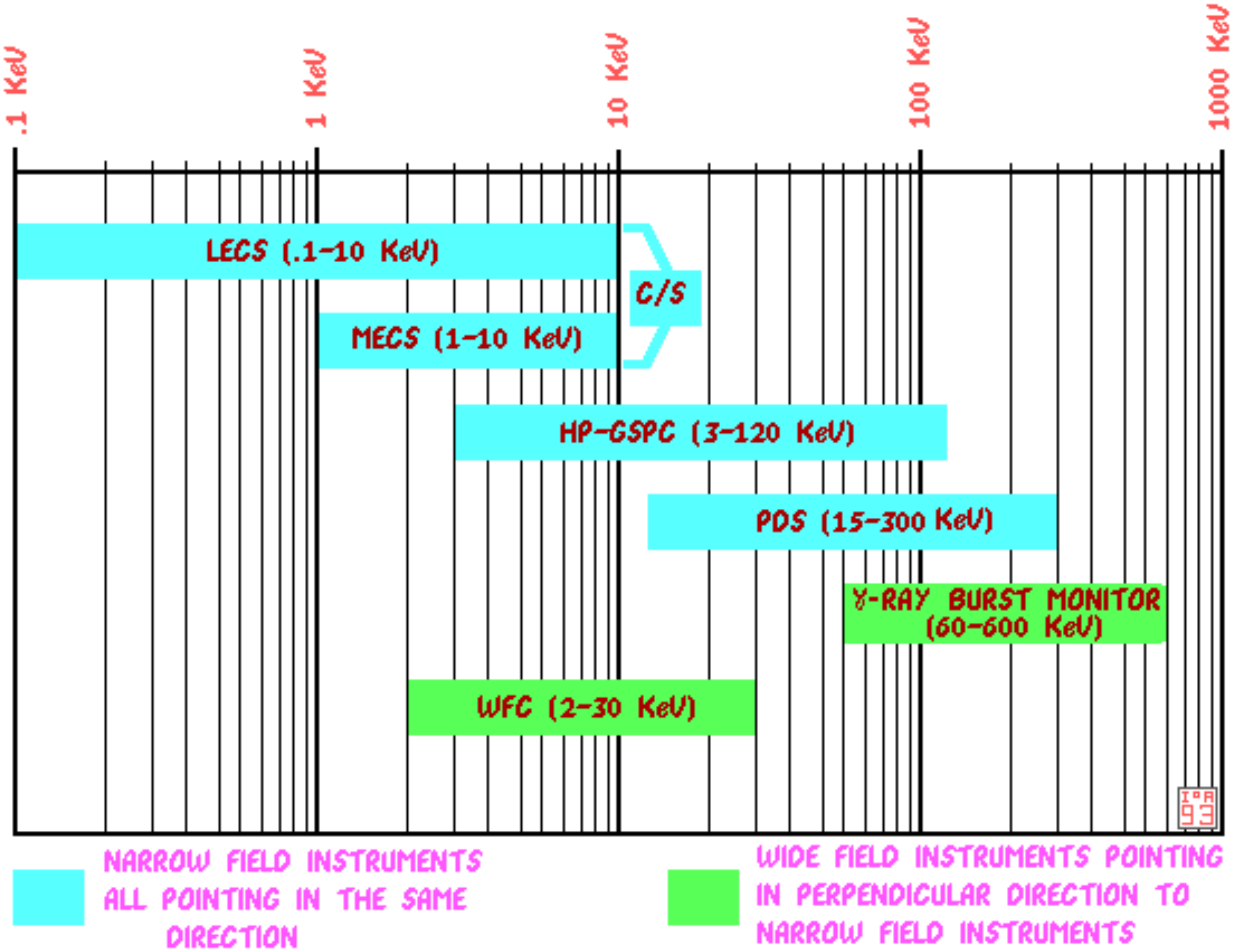
Need a new type of observation!

The BeppoSAX era

BeppoSAX (1995 - 2002)



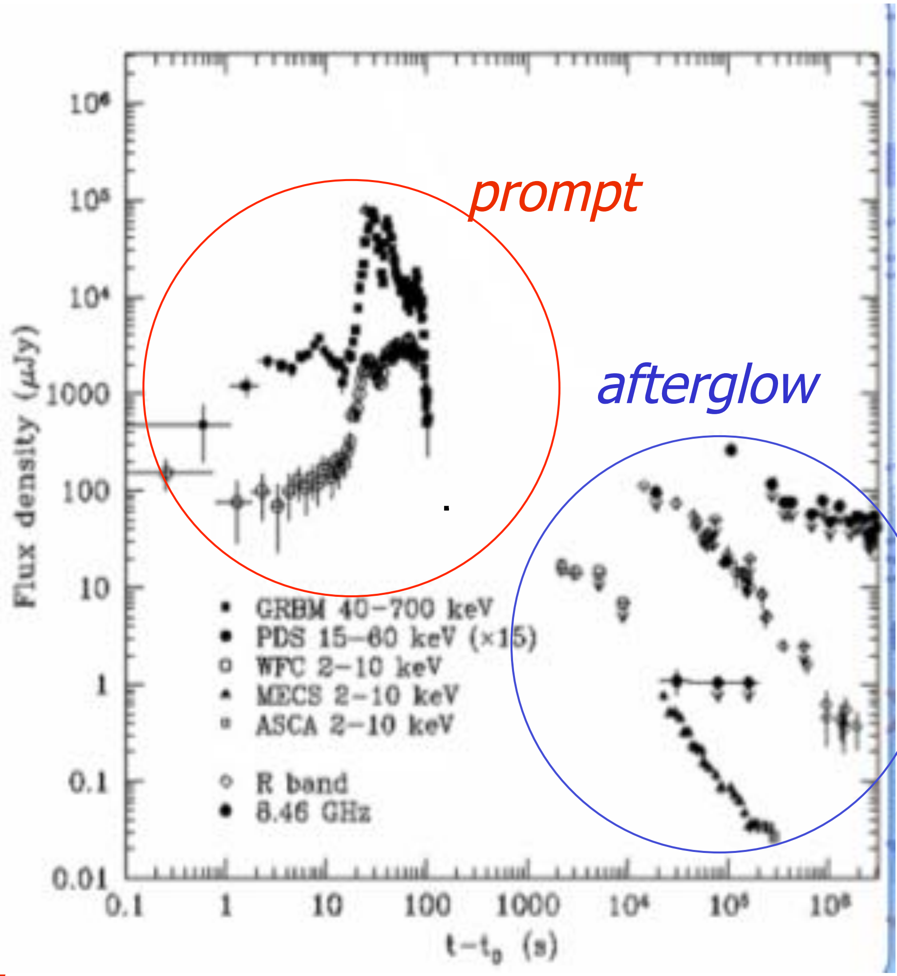
BeppoSAX


.1 KeV
1 KeV
10 KeV
100 KeV
1000 KeV
LECS (.1-10 KeV)
C/S
MECS (1-10 KeV)
HP-GSPC (3-120 KeV)
PDS (15-300 KeV)
γ-RAY BURST MONITOR (60-600 KeV)
WFC (2-30 KeV)
NARROW FIELD INSTRUMENTS ALL POINTING IN THE SAME DIRECTION
WIDE FIELD INSTRUMENTS POINTING IN PERPENDICULAR DIRECTION TO NARROW FIELD INSTRUMENTS

The GRB phenomenon

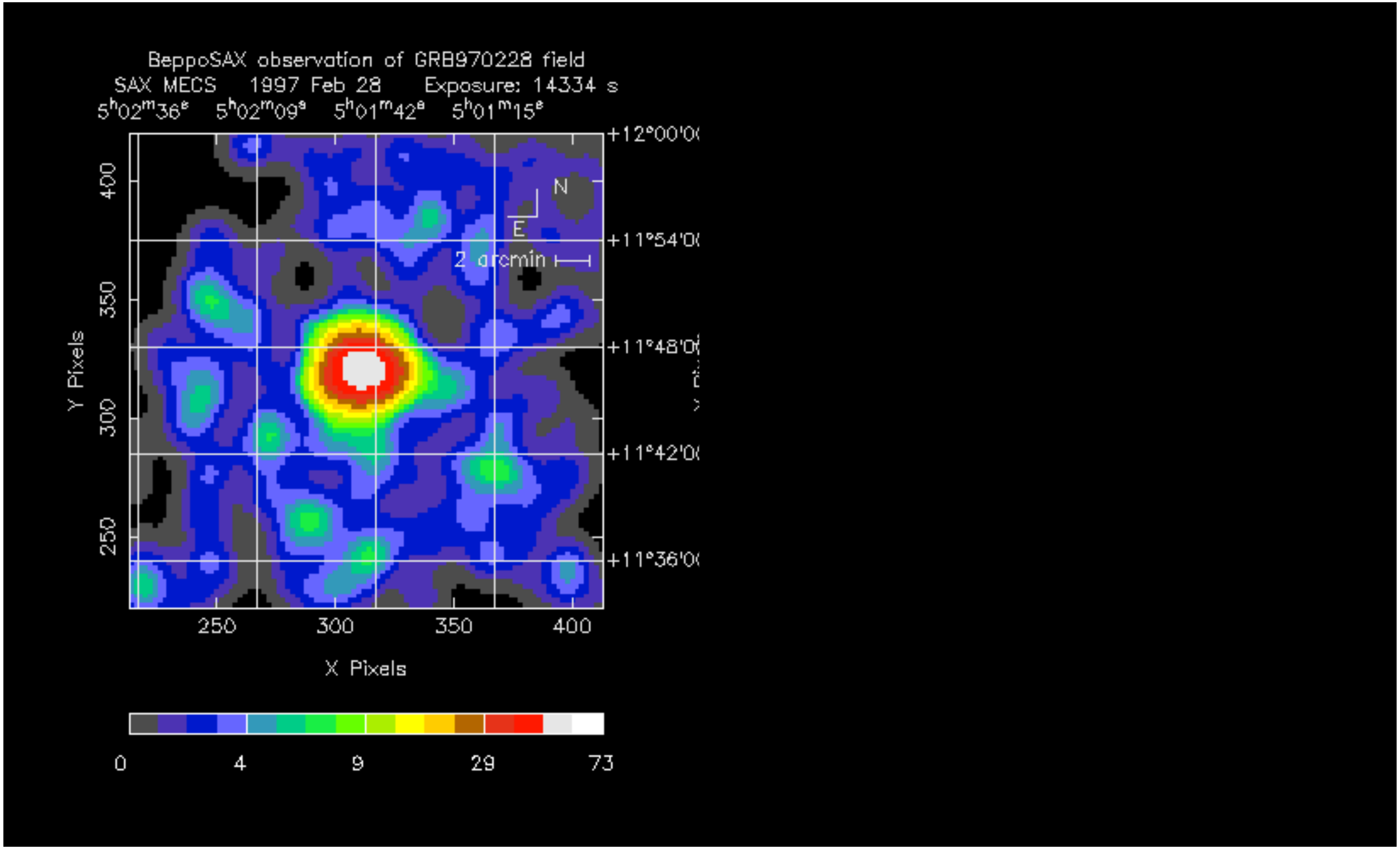
- in 1997, thanks to BeppoSAX observations, discovery of fading X-ray, optical, radio emission following the GRB

- photons received during the classical GRB phenomenon are then called "prompt emission" and the subsequent fading emission is called "afterglow emission"

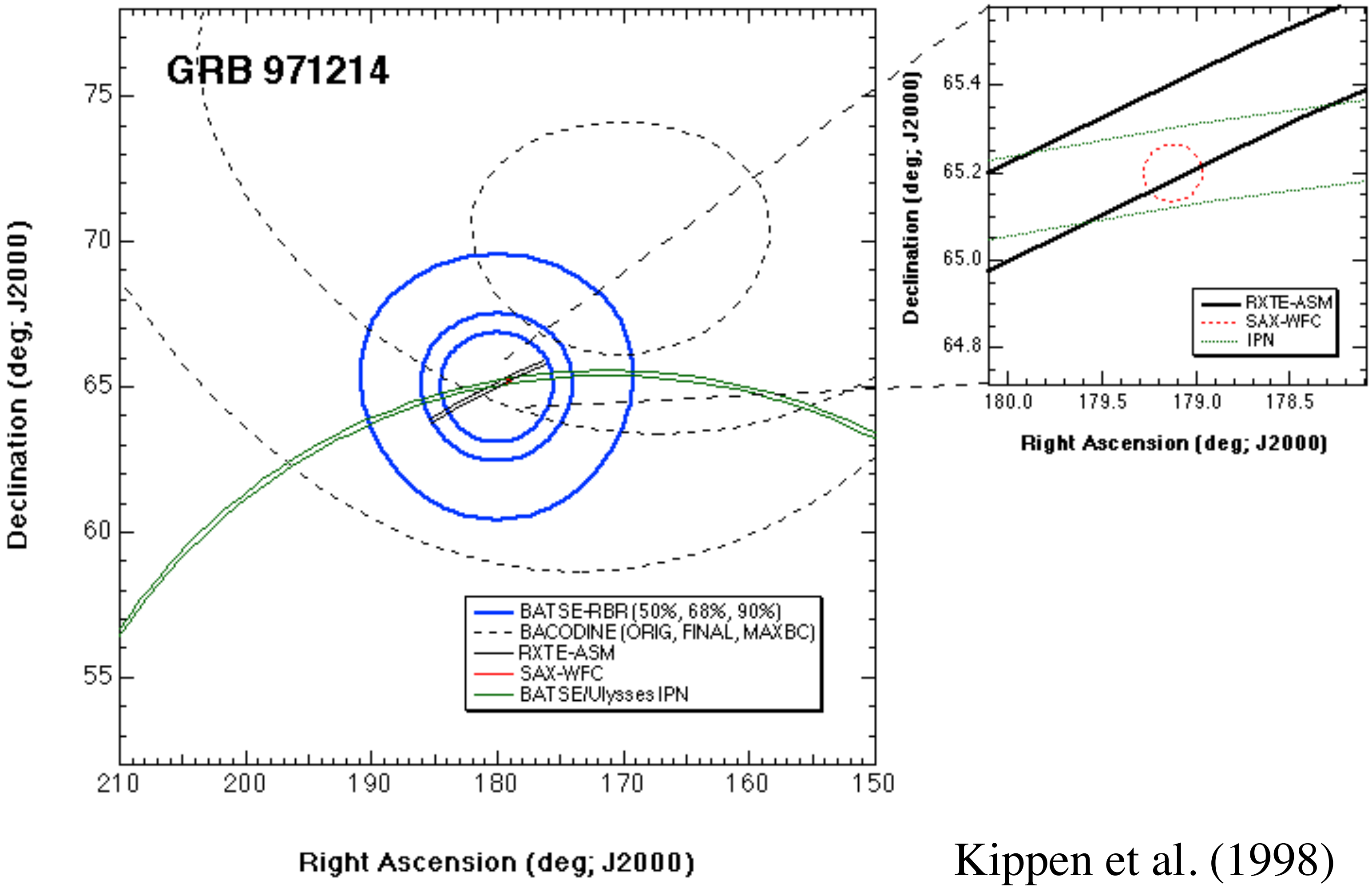


Adapted from Maiorano et al., A&A, 2005

GRB970228 – first good localization

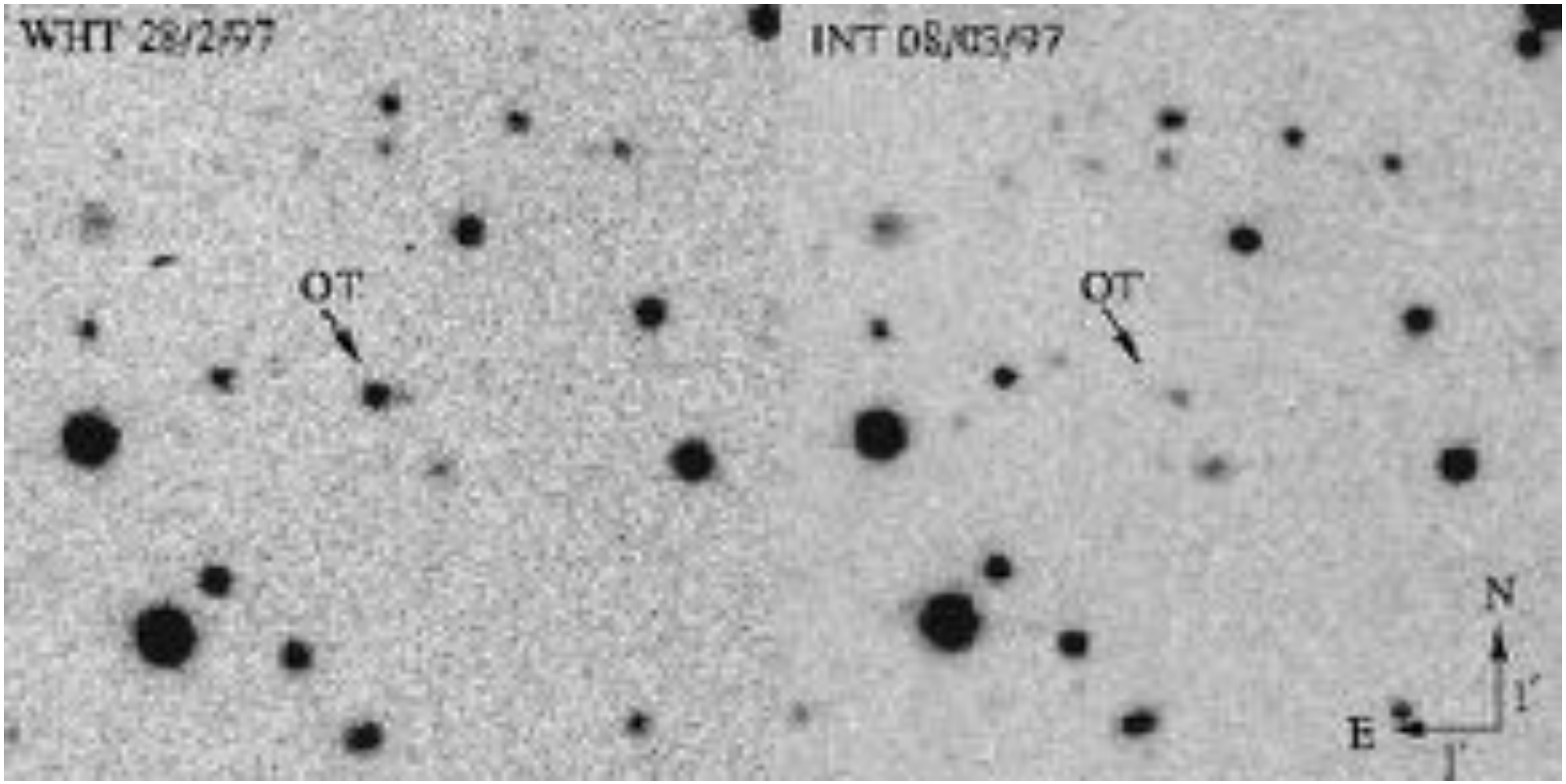


BeppoSAX

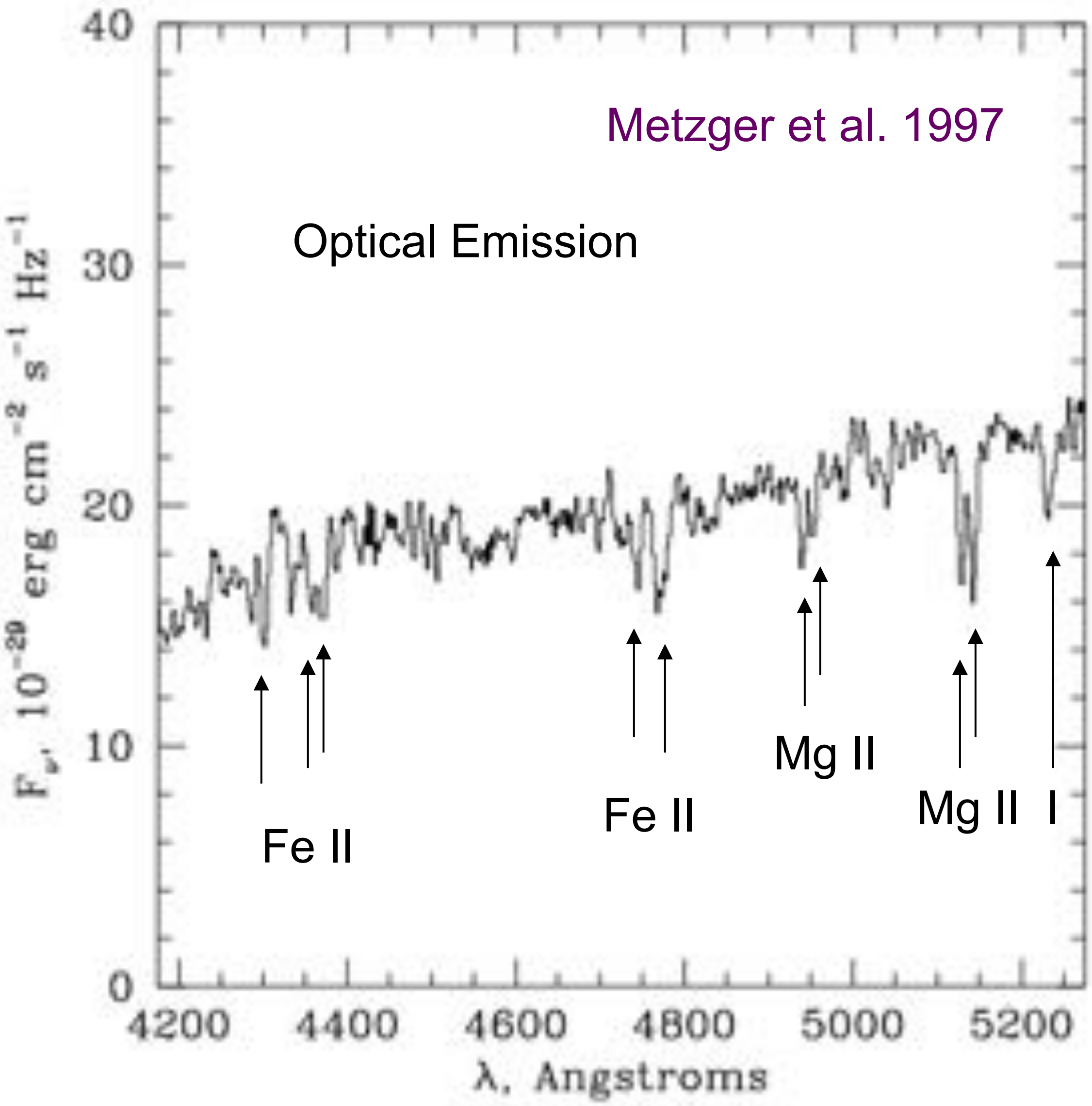


Kippen et al. (1998)

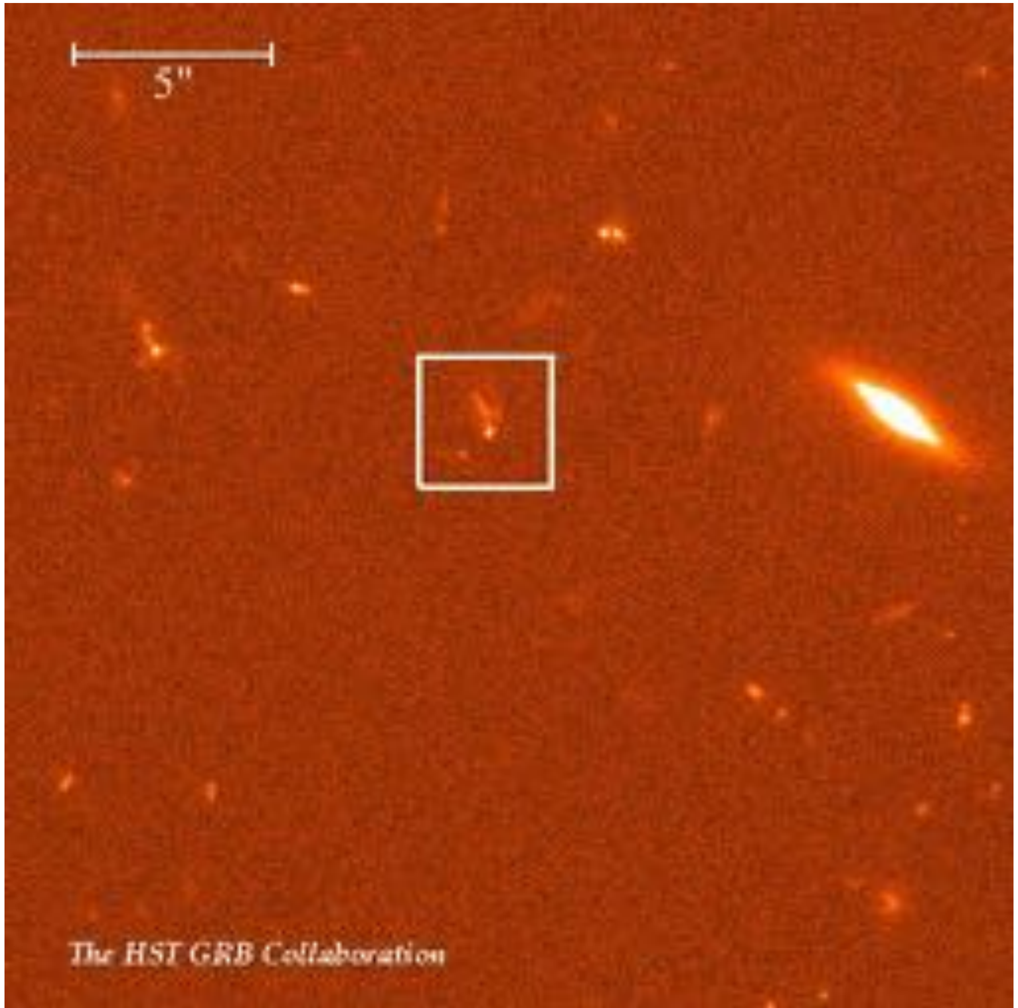
GRB970228 – Optical Counterpart Discovered (with corresponding optical localization!)



GRB970508 – Absorption Lines: z=0.835



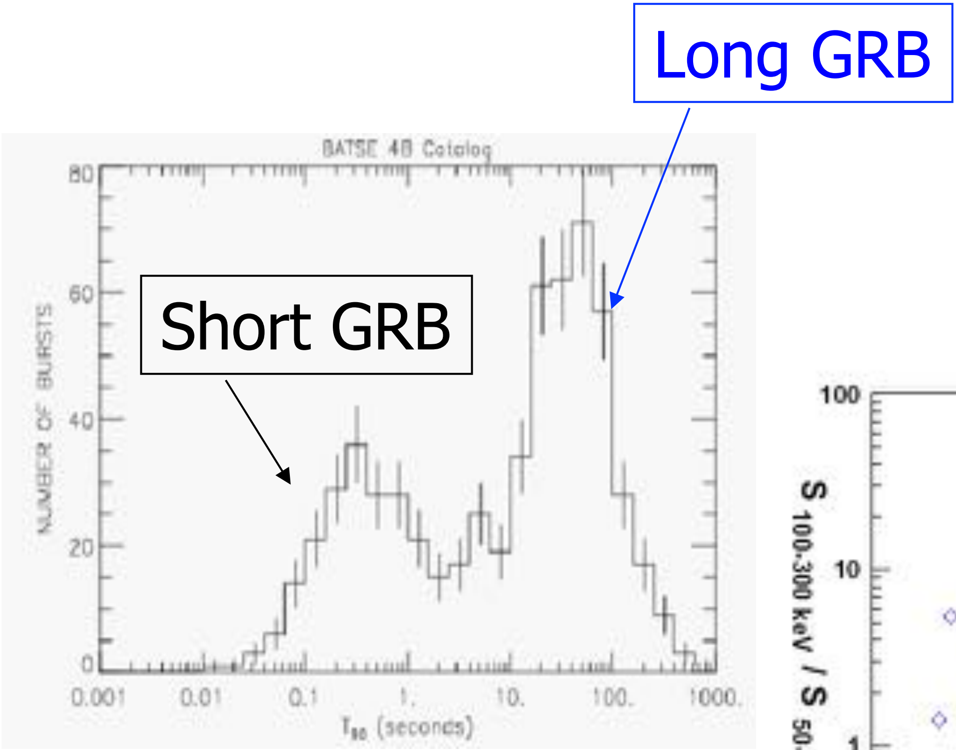
Afterglow Era

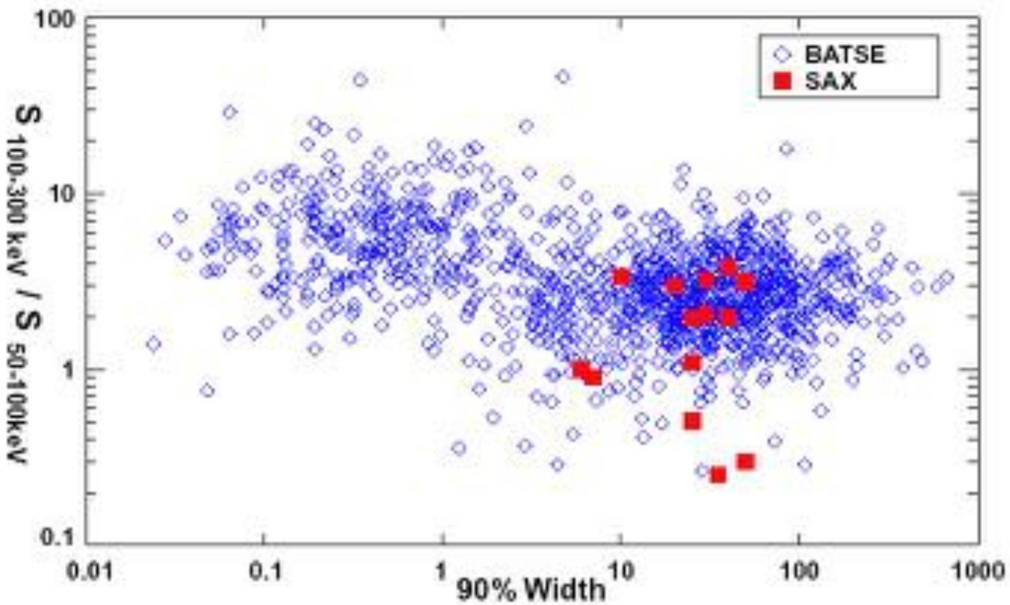


Host Galaxies identification

Fruchter et al (1999)

GRB Progenitors





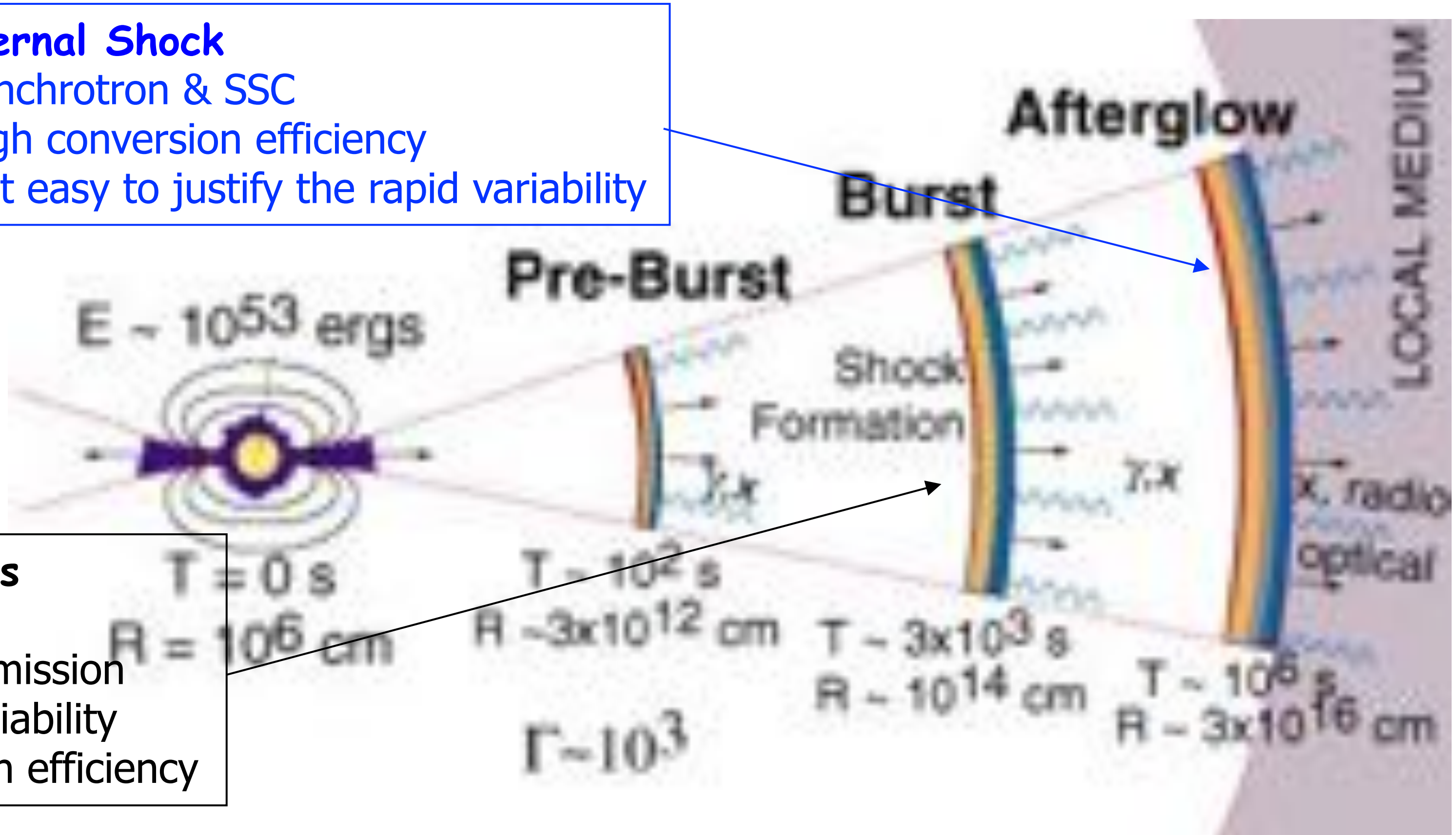
Afterglows in the BeppoSAX era

The fireball model

The Fireball "standard" model

- Relativistic motion of the emitting region
- Shock mechanism converts the kinetic energy of the shells into radiation.
- Baryon Loading problem

External Shock
- Synchrotron & SSC
- High conversion efficiency
- Not easy to justify the rapid variability



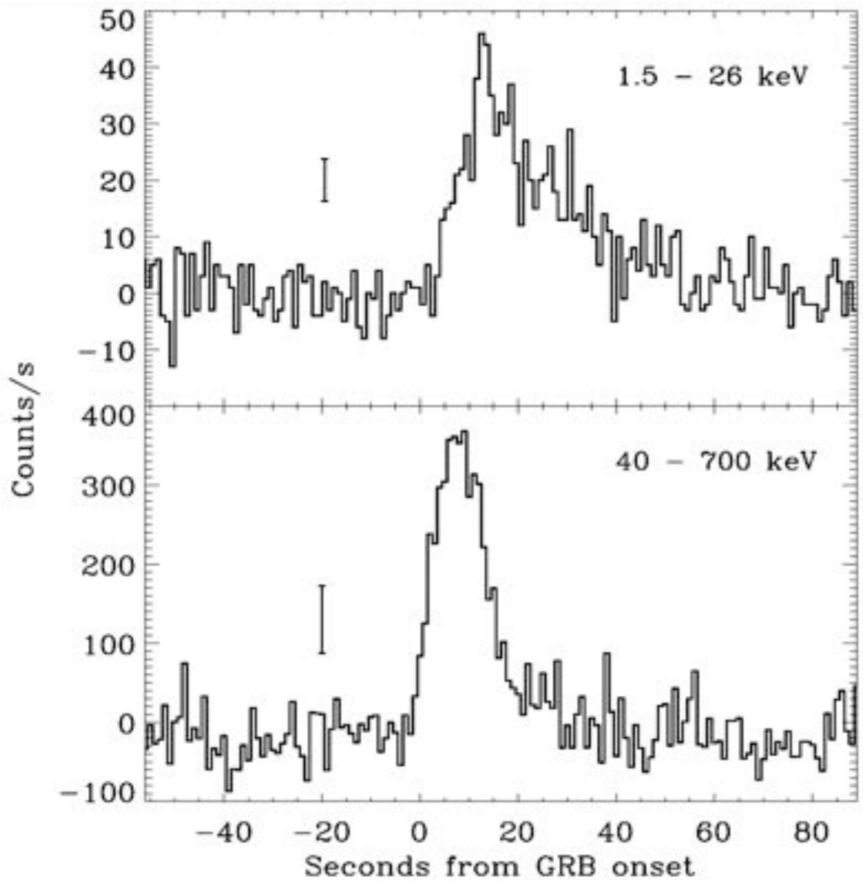
Internal Shocks
- Source activity
- Synchrotron Emission
- Rapid time Variability
- Low conversion efficiency

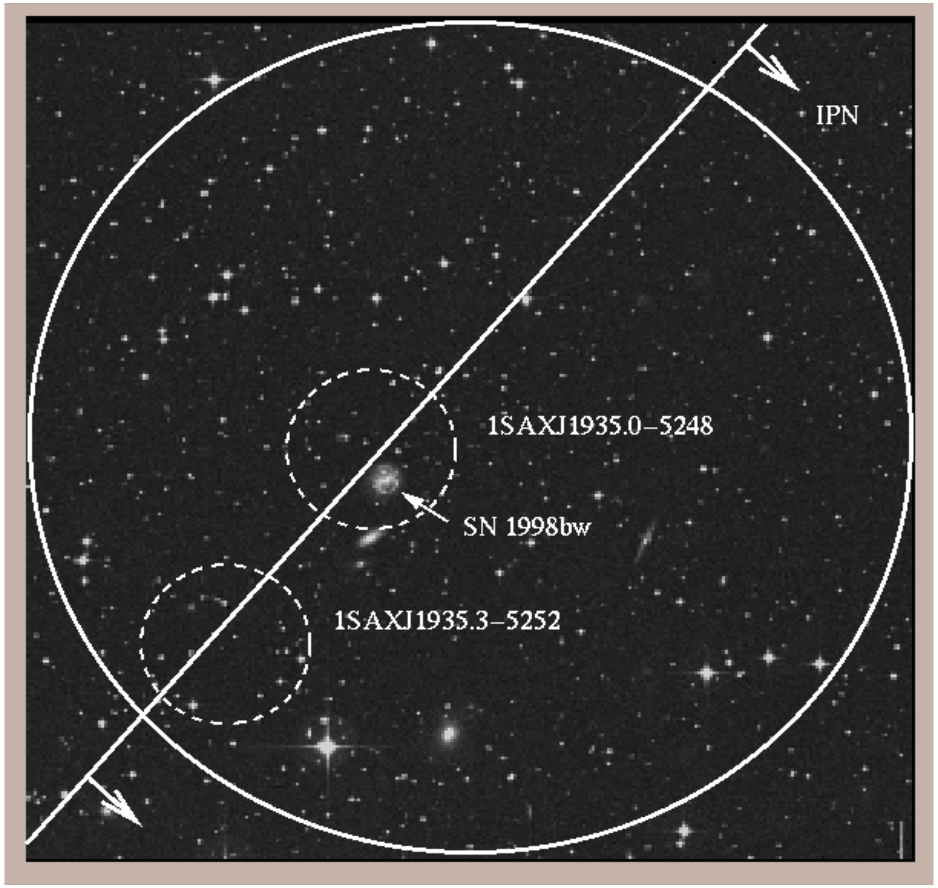
Towards the progenitors

Unvealing the progenitors

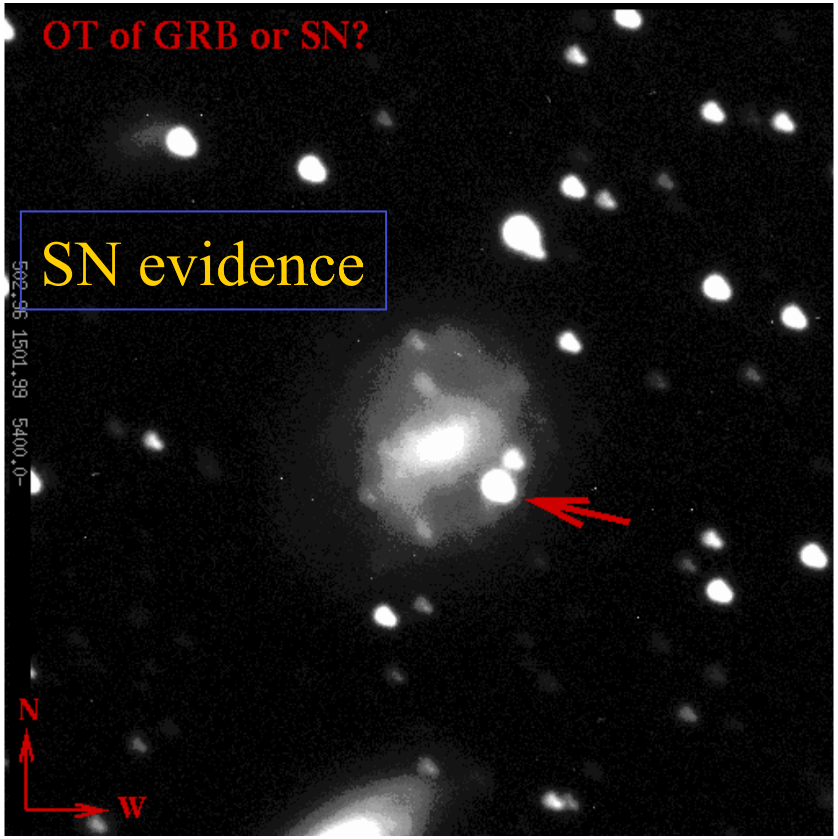
• evidence of a GRB - SN connection: GRB980425 / SN1998bw

➢ GRB 980425, a normal GRB detected and localized by WFC and NFI, but in temporal/spatial coincidence with a type Ic SN at z = 0.008 (chance prob. 0.0001)

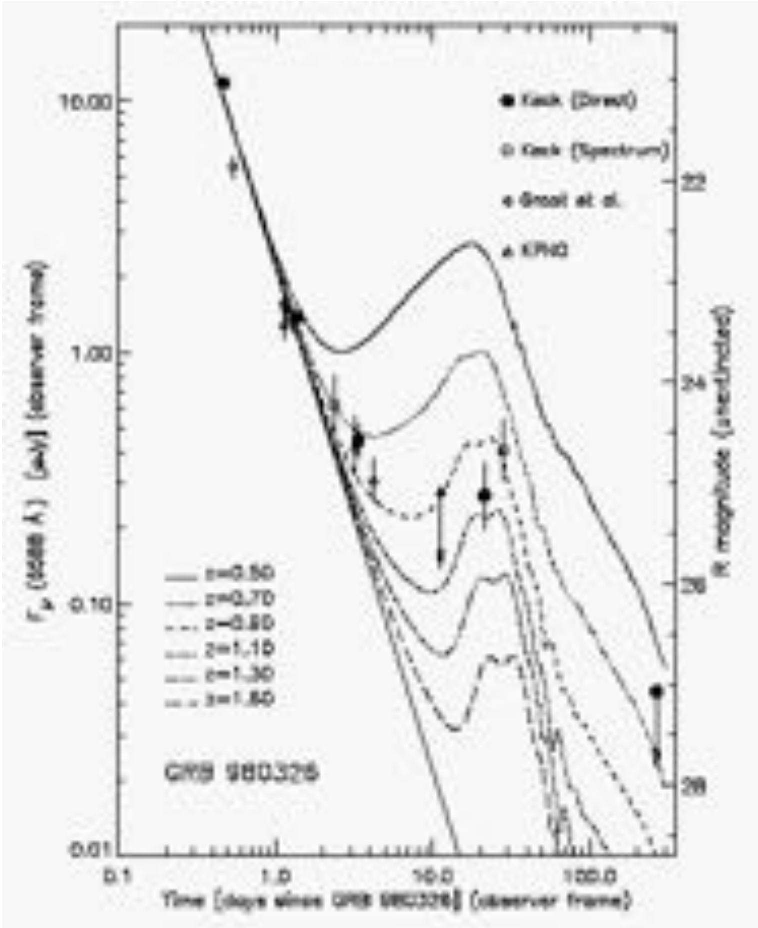




Towards a solution?



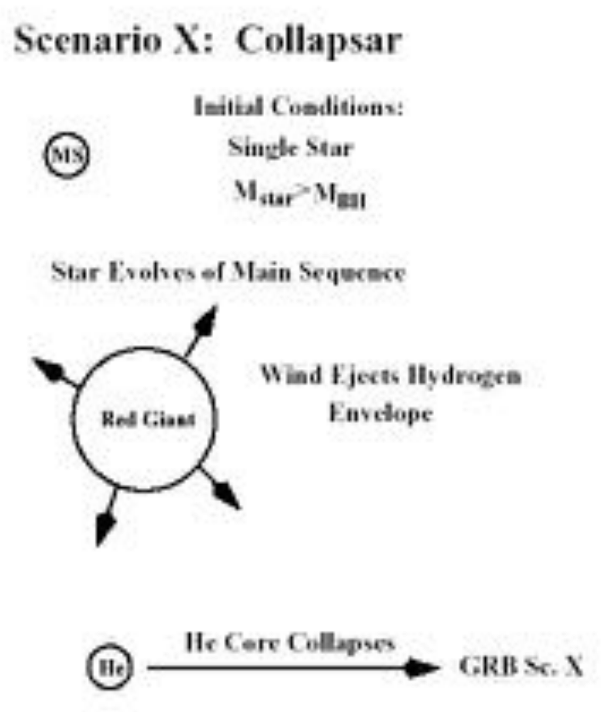
SN 1998bw - GRB 980425
(Galama et al. 98)

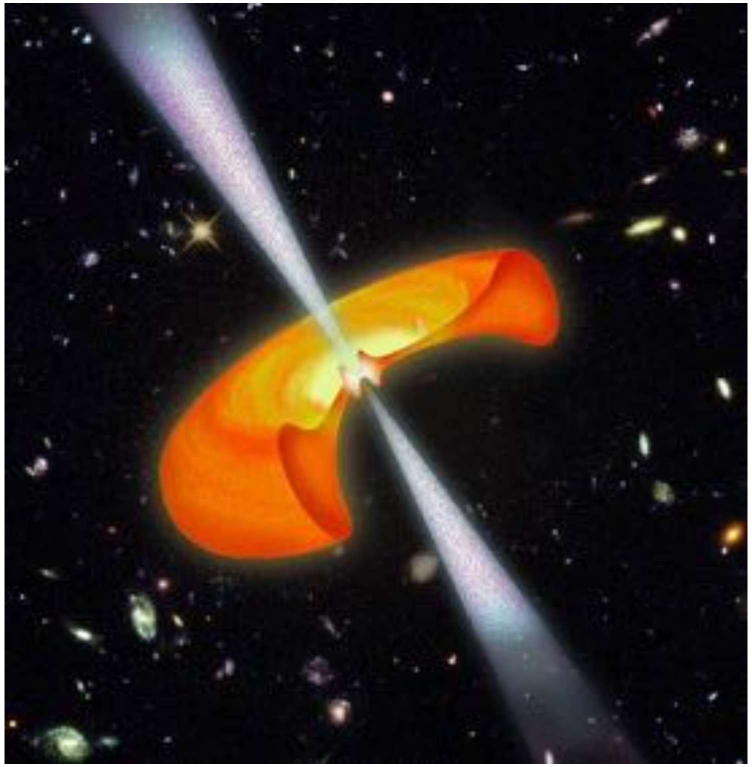


GRB 980326
(Bloom et al. 99)

Collapsar model

Woosley (1993)





- Very massive star that collapses in a rapidly spinning BH.
- Identification with SN explosion.

The Hete-2 era

Hete2

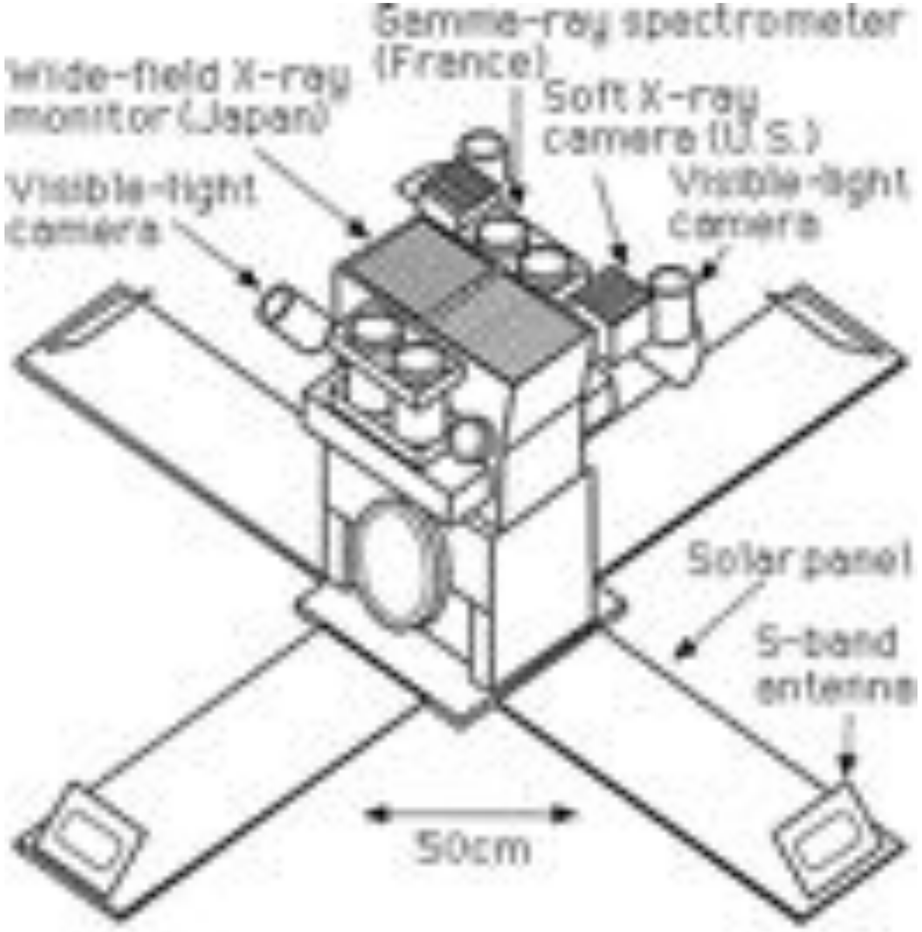
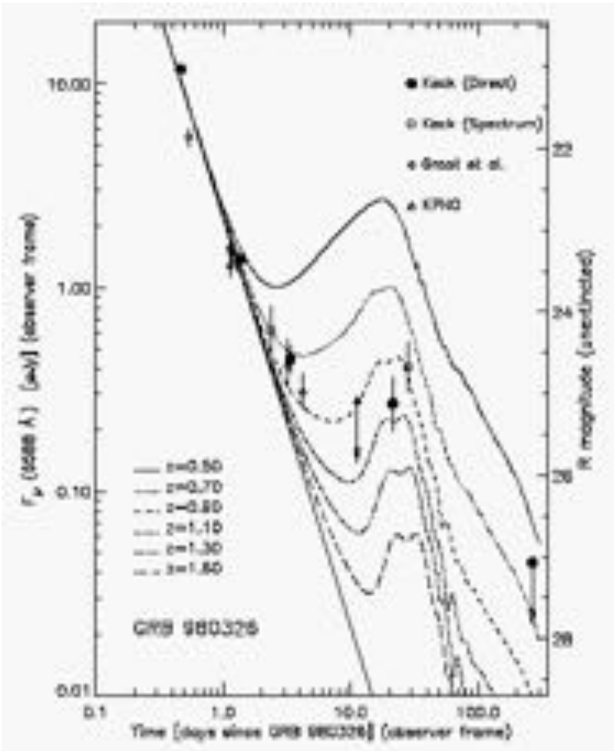


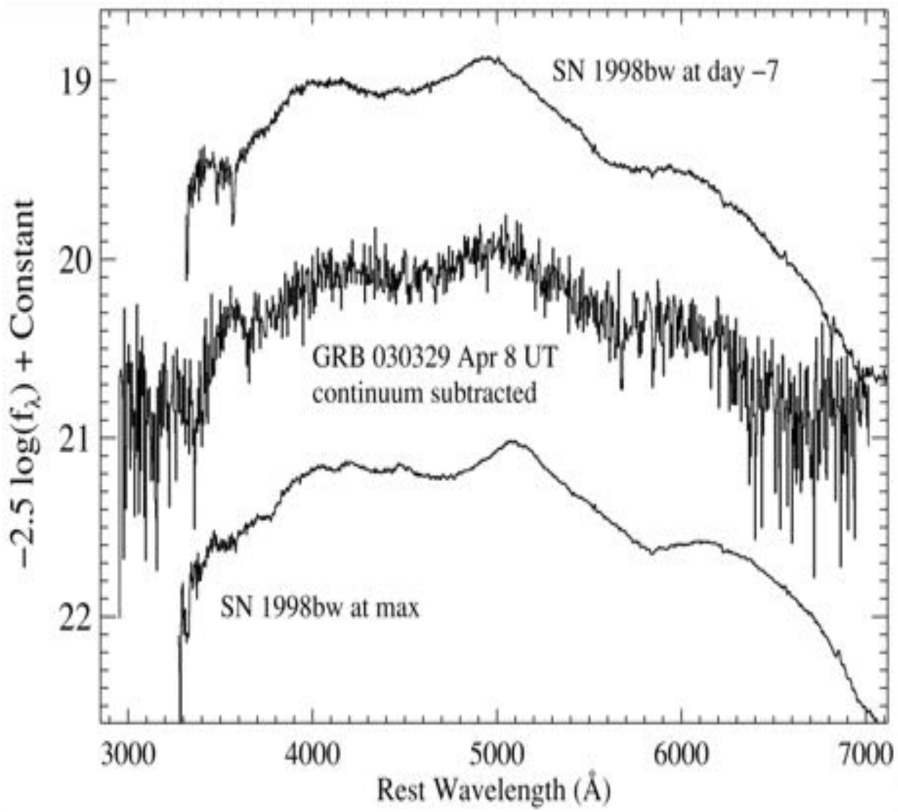
Figure 1 HETE-2 instruments

Unvealing the progenitors

• further evidences of a GRB/SN connection: bumps in optical afterglow light curves and optical spectra resembling that of GRB980425



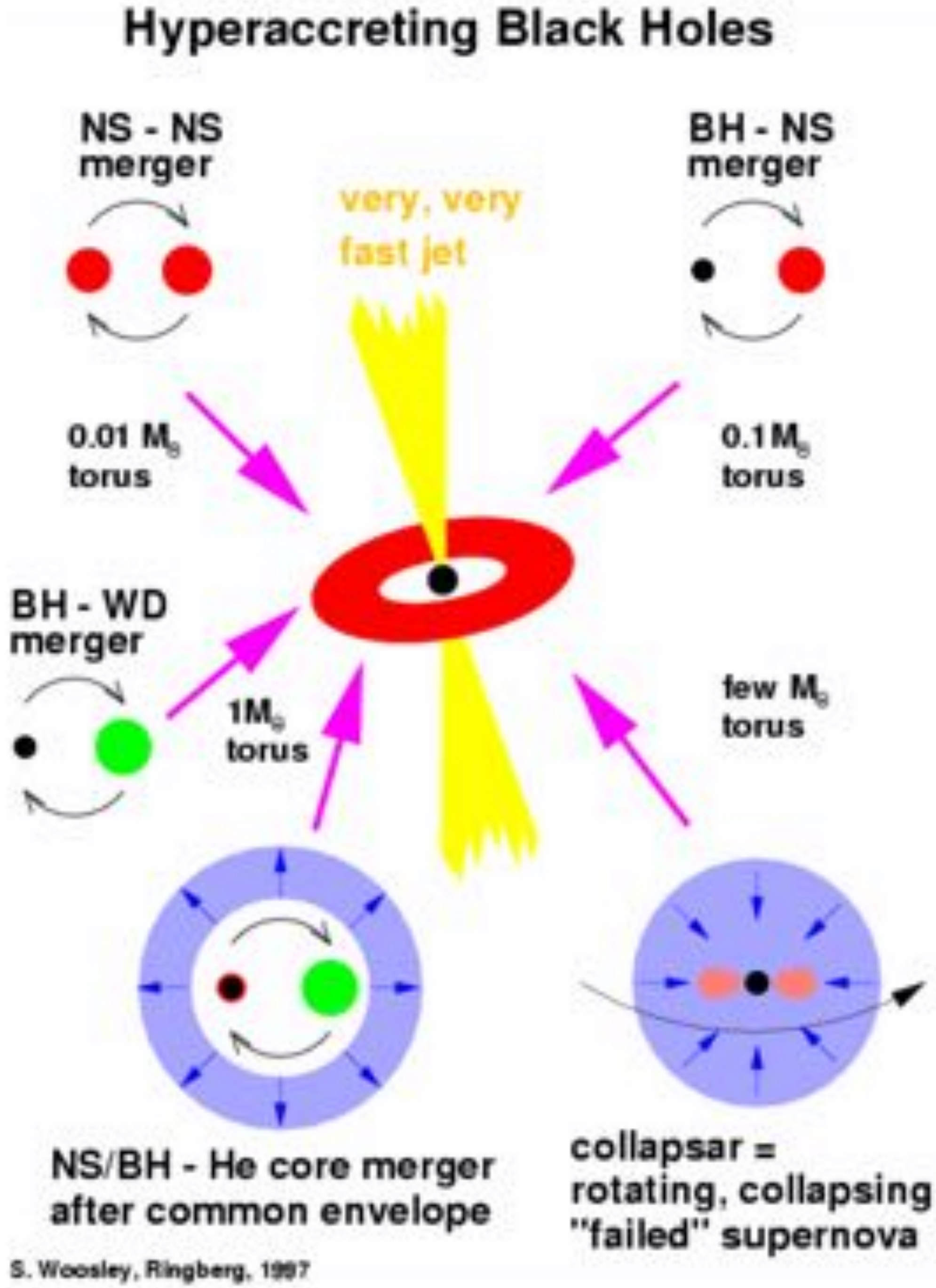
GRB980326, Bloom et al., ApJ, 1999



GRB 030329, Hjorth et al., Nature, 2003

Black-Hole Accretion Disk (BHAD) Models

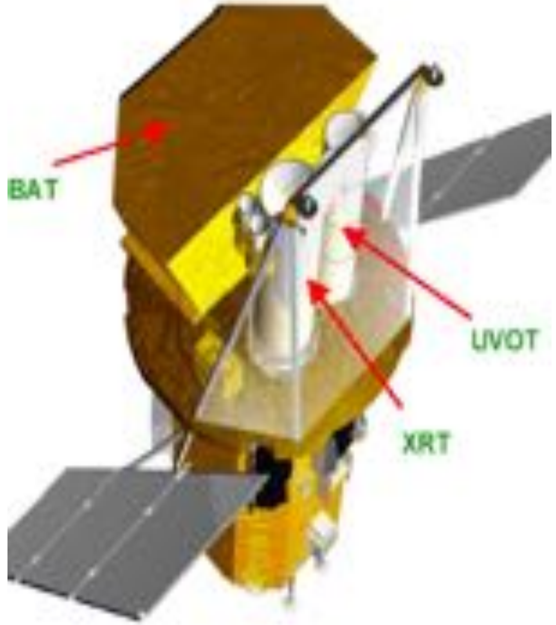
Binary merger or Collapse of rotating Star produces Rapidly accreting Disk (>0.1 solar Mass per second!) Around black hole.



The Swift era

Adding pieces to the puzzle

• **Swift**: NASA mission dedicated to GRB studies launched 20 Nov. 2004 USA / Italy / UK consortium

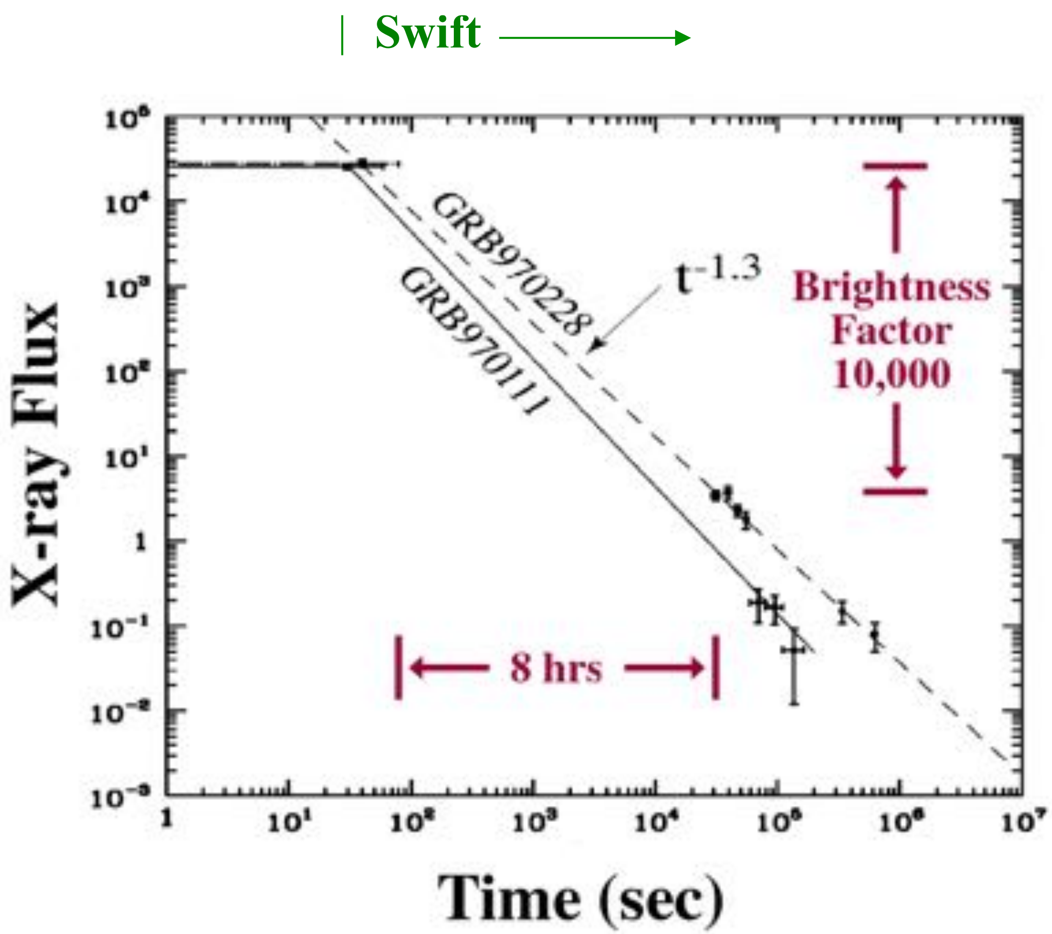


➢ main goals: afterglow onset, connection prompt-afterglow, substantially increase of conunterparts detection at all wavelengths (and thus of redshift estimates)

➢ payload: BAT (CZT+coded mask, 15-350 keV, wide FOV, arcmin ang. res.), XRT (X-ray optics, 0.3-10 keV, arcsec ang.res.), UVOT (sub-arcsec ang.res. mag 24 in 1000 s)

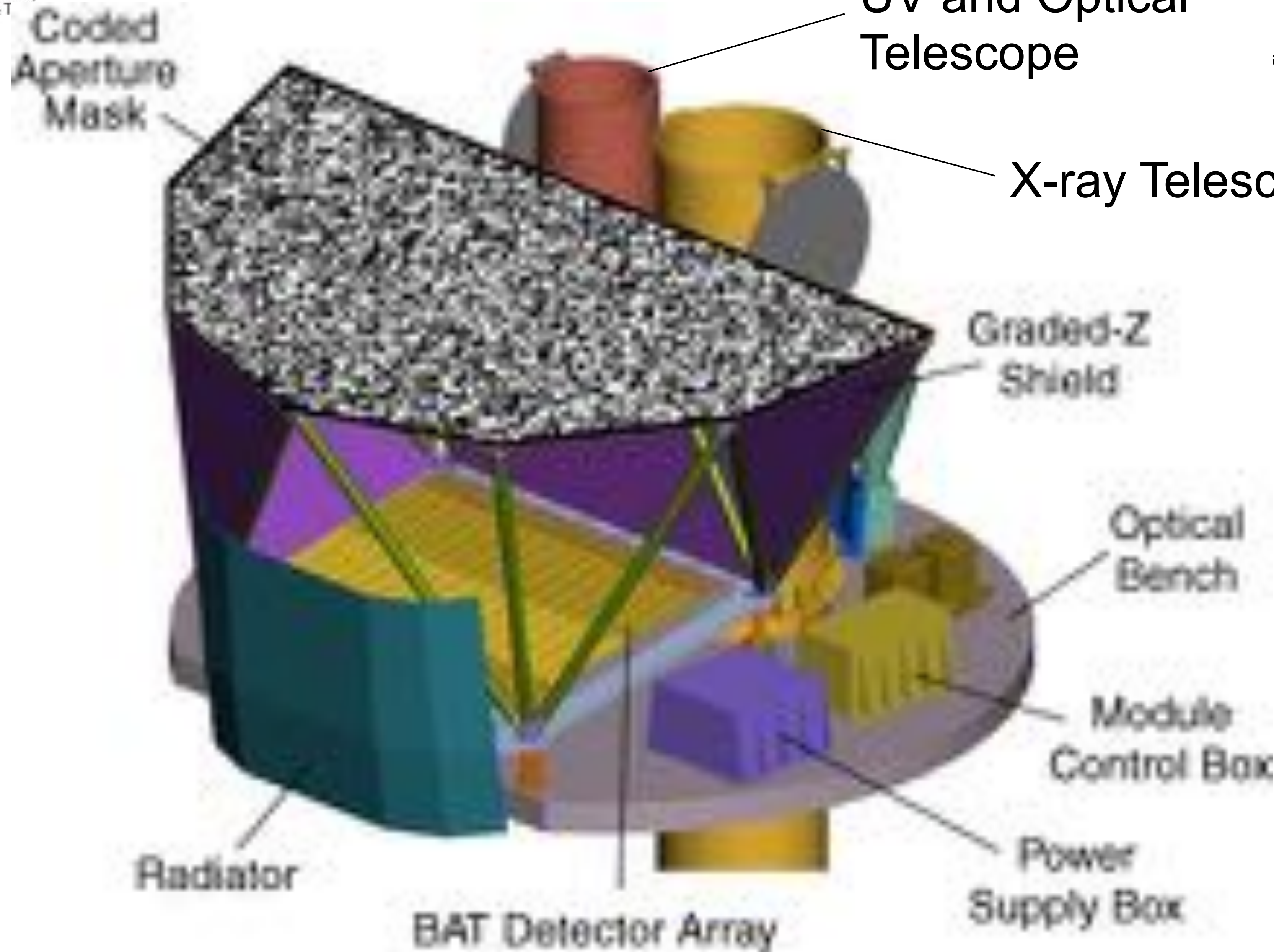
➢ spacecraft: automatic slew to target source in ~1 - 2 min.

Swift's purpose



Fill the data gap!

The Swift instrumentation

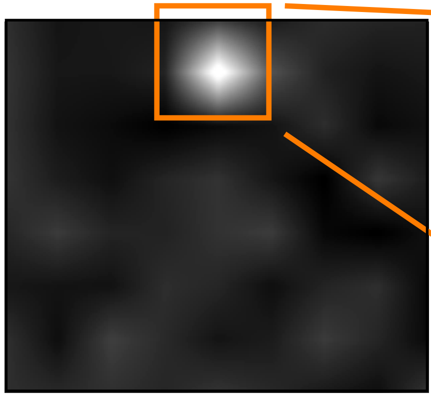


NASA

Observing Strategy

- BAT triggers on GRB, calculates position to < 4 arcmin
- Spacecraft autonomously slews to GRB position in 20-70 s
- XRT determines position to < 5 arcseconds
- UVOT images field, transmits finding chart to ground

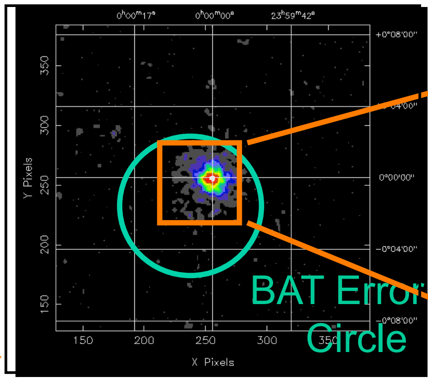
BAT Burst Image



T<10 sec

$\theta < 4'$

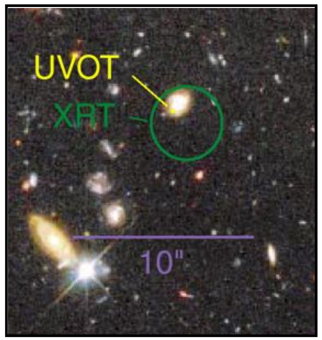
XRT Image



T<100 sec

$\theta < 5''$

UVOT Image



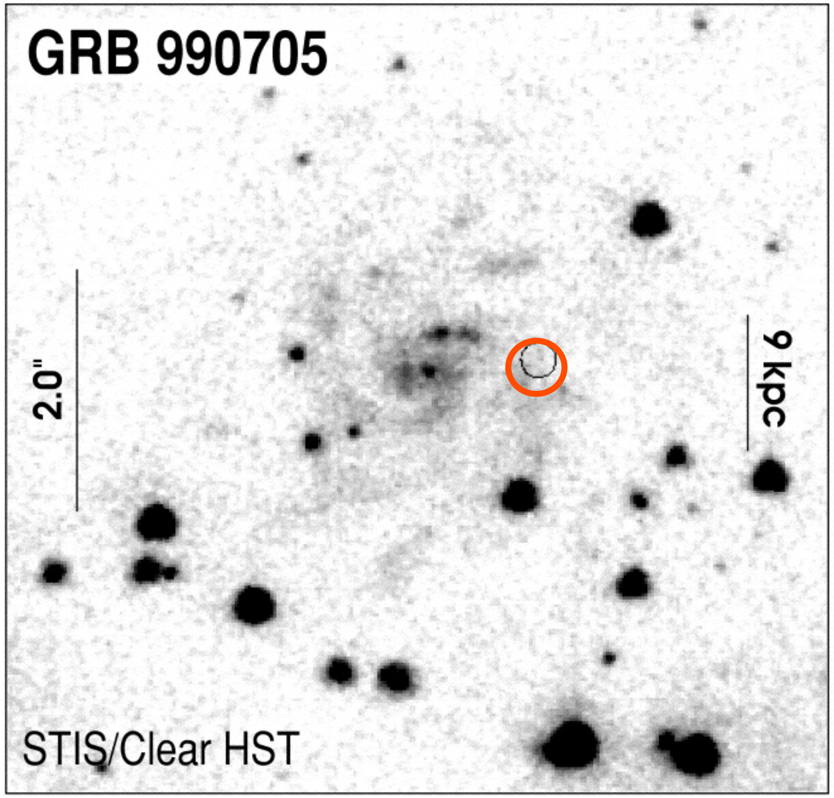
T<300 sec

Unvealing the short GRB progenitors

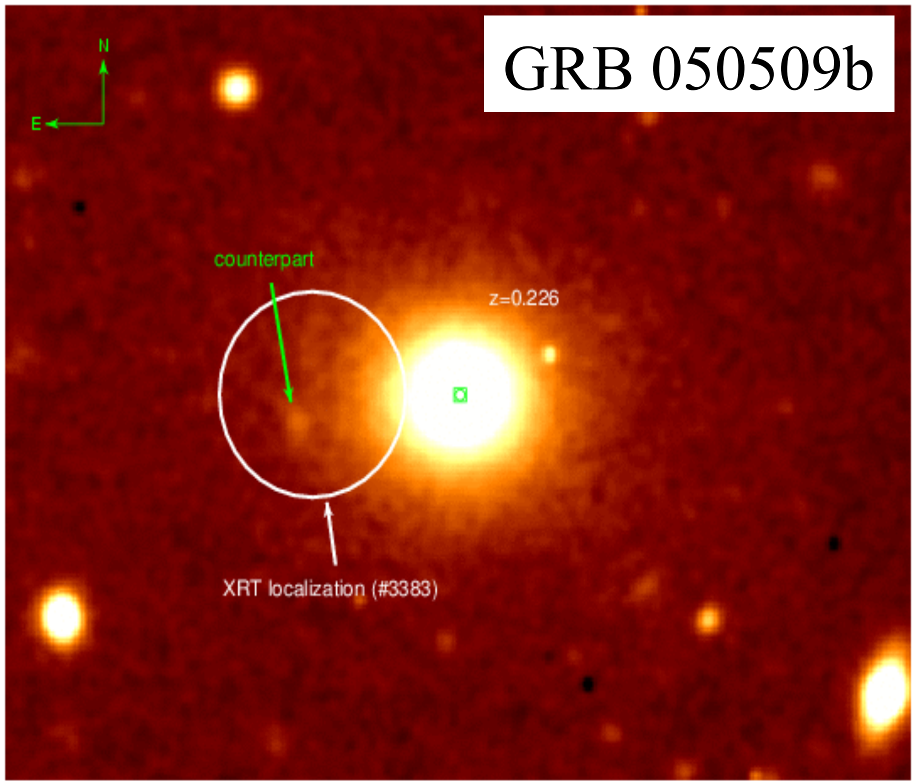
• host galaxies long GRBs: blue, usually regular and high star forming, GRB located in star forming regions

• host galaxies of short GRBs: elliptical, irregular galaxies, away from star forming region

Long



Short

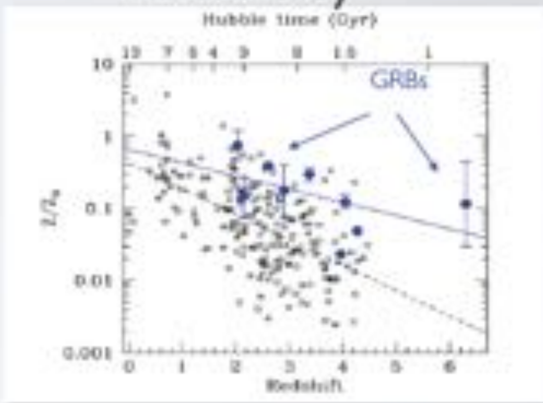


High redshift GRB

High-Redshift GRBs

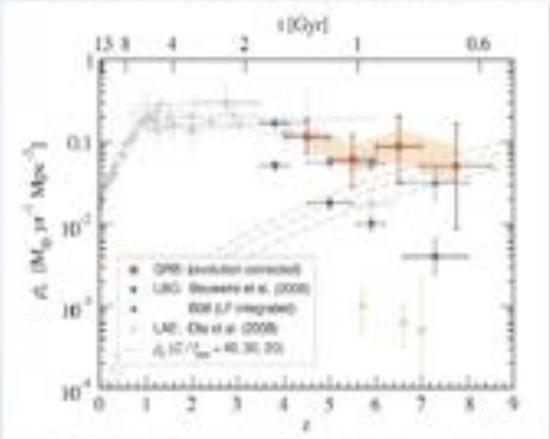
z	GRB	Optical Brightness
9.4	090429B	K = 19 @ 3 hrs
8.2	090423	K = 20 @ 20 min
6.7	080813	K = 19 @ 10 min
6.29	050904	J = 18 @ 3 hrs
5.6	060927	I = 16 @ 2 min
5.3	050814	K = 18 @ 23 hrs
5.11	060522	R = 21 @ 1.5 hrs

Metallicity



Savaglio 2006

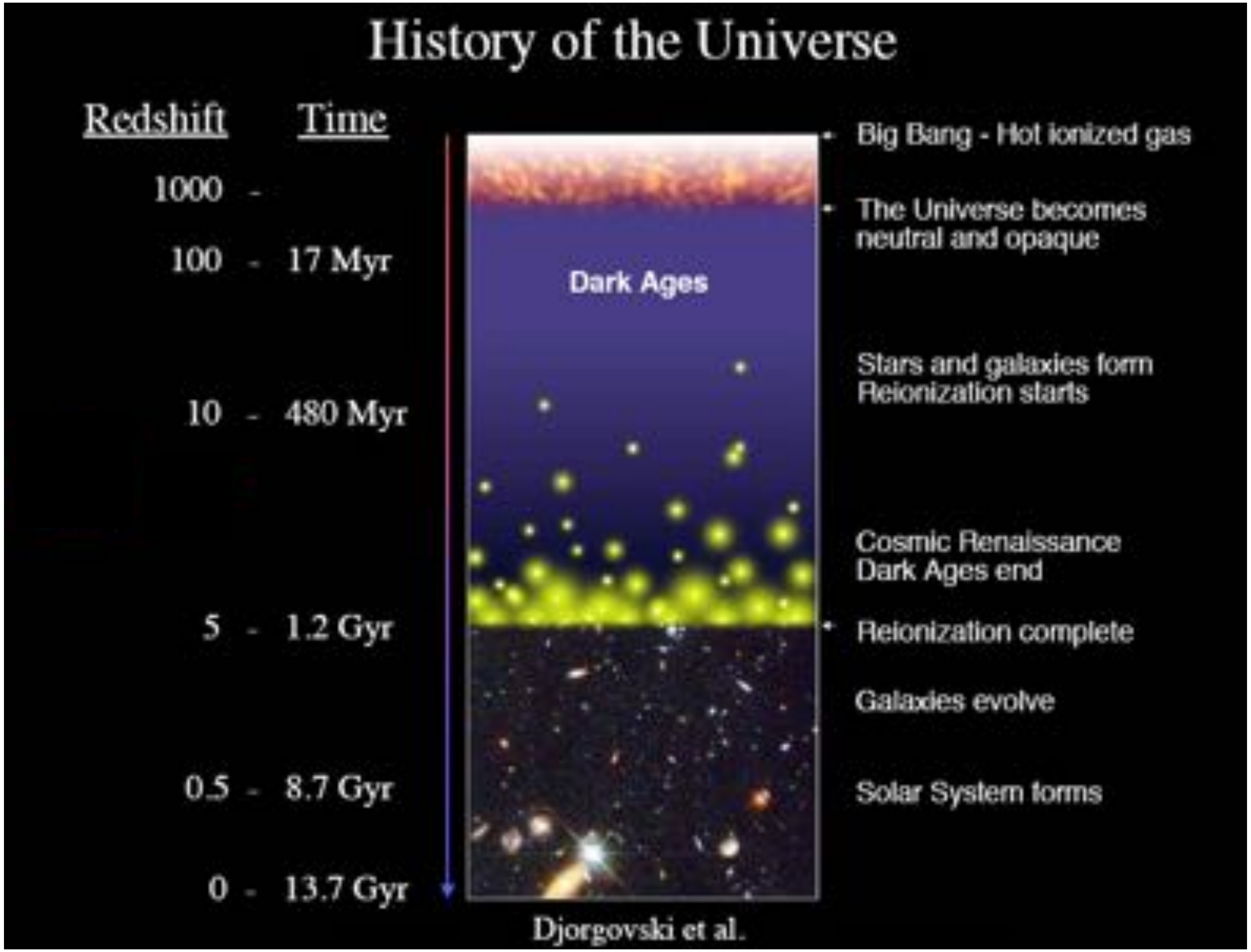
Star Formation Rate



Kistler et al. 2009;
Robertson & Ellis 2011

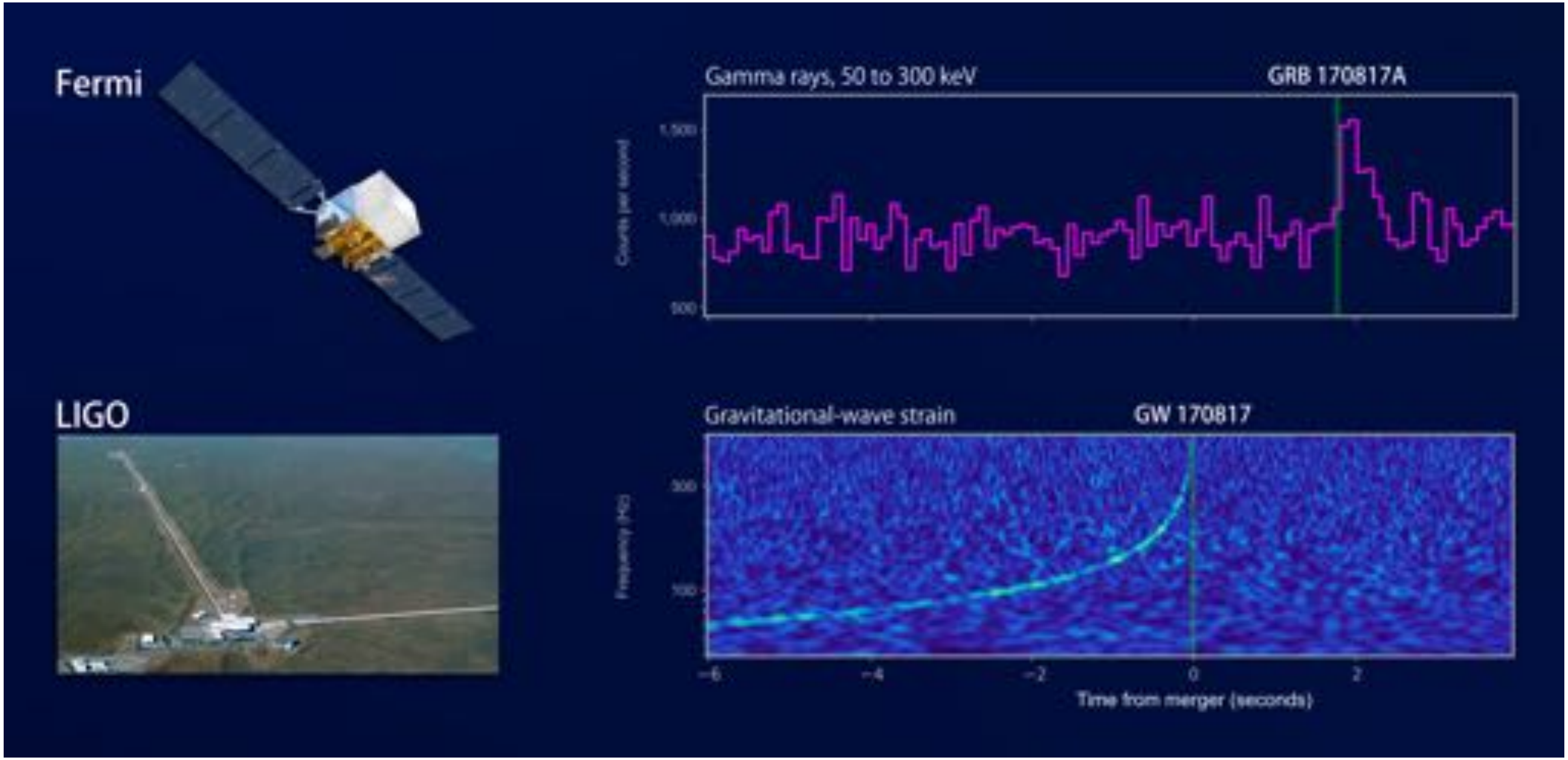
Fermi/Swift GRB Conference 2012, Munich, May 7-11, 2012

GRB & Cosmology

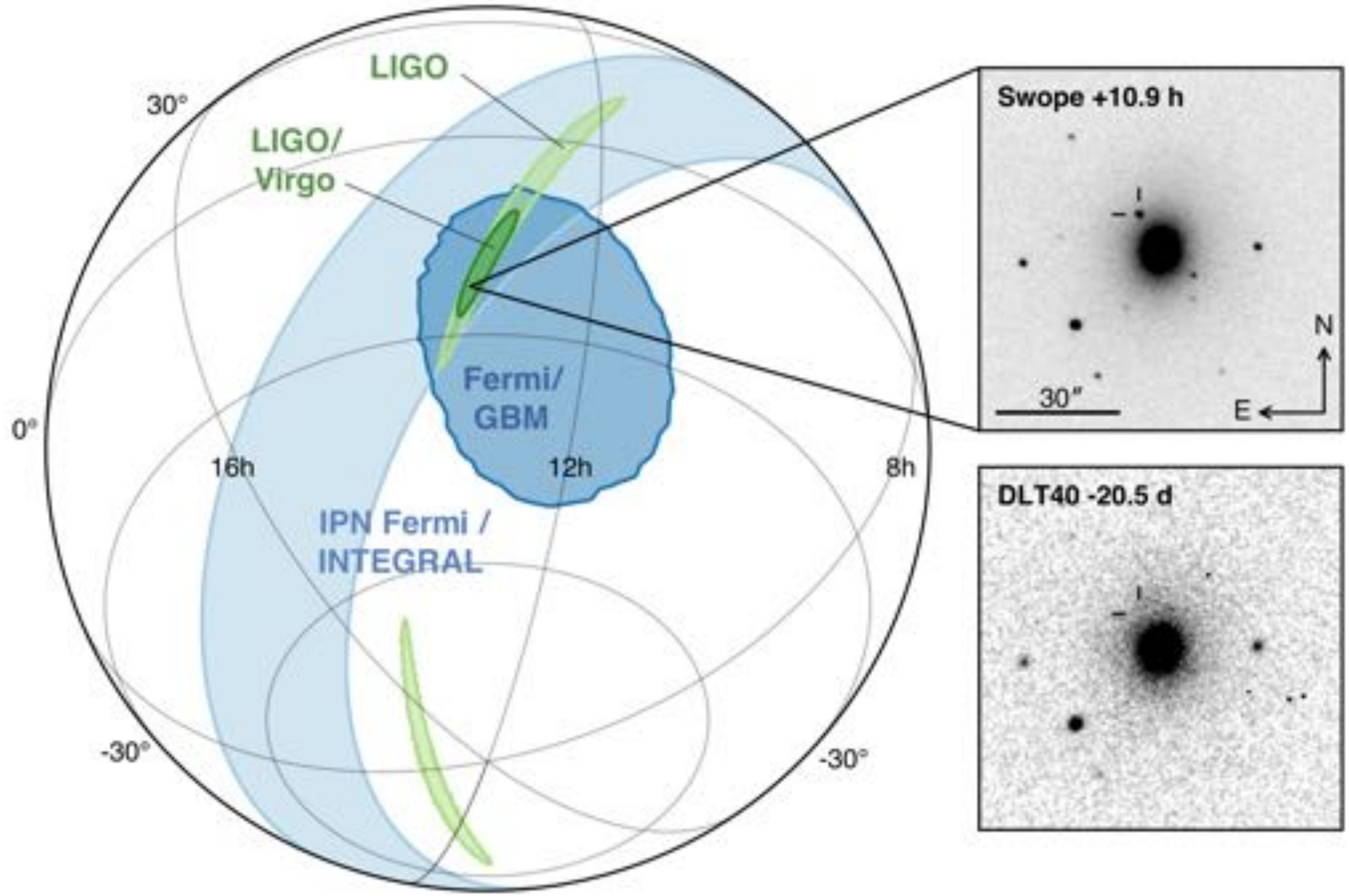


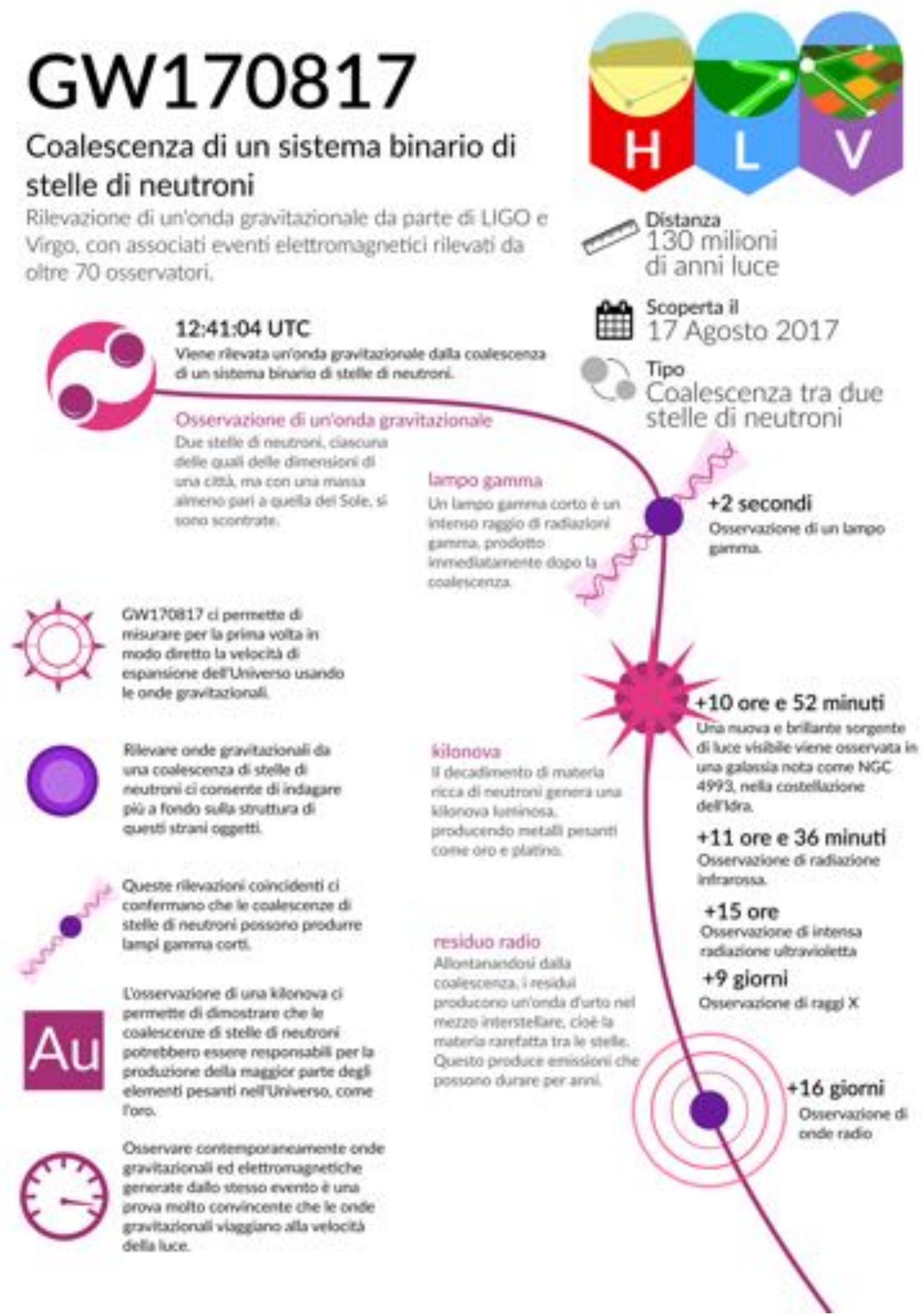
The connection with GWs

GRBs and Gravitational Waves



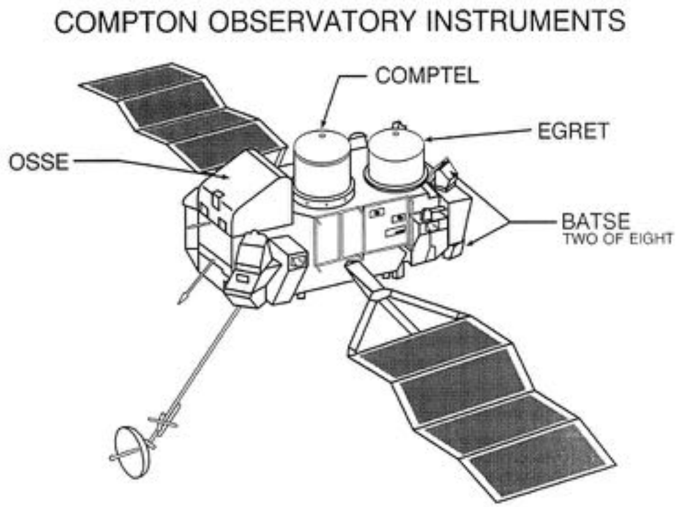
GRBs and Gravitational Waves

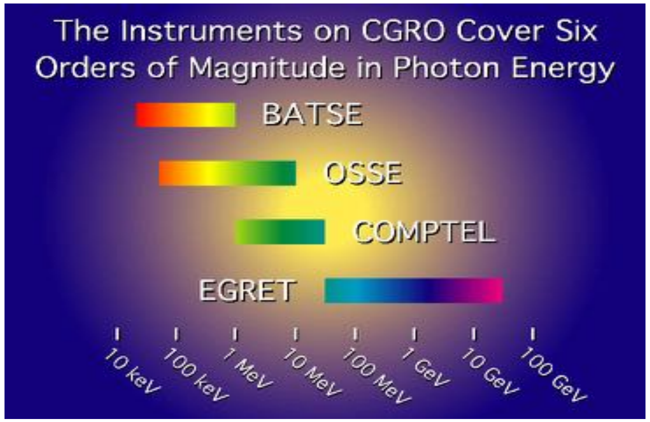


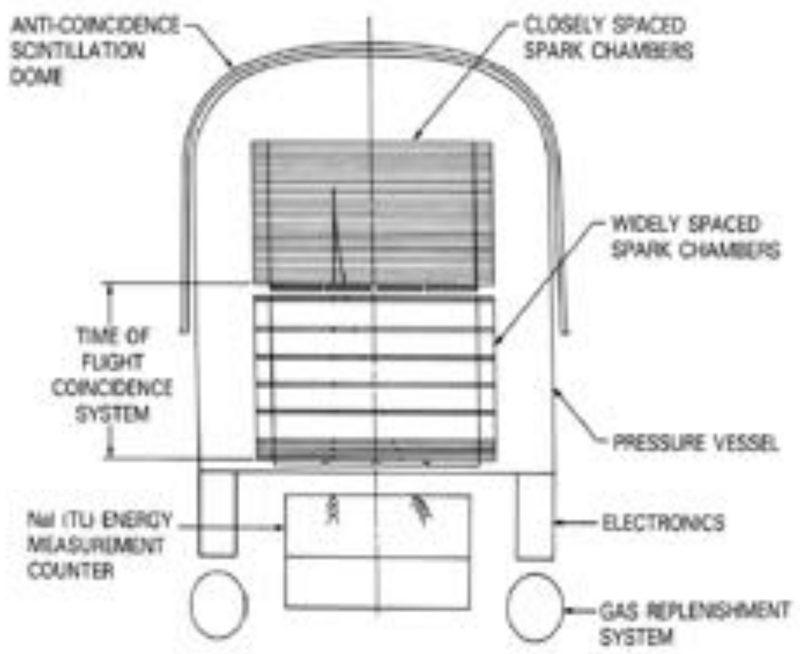

GW170817
Coalescenza di un sistema binario di stelle di neutroni
Rilevazione di un'onda gravitazionale da parte di LIGO e Virgo, con associati eventi elettromagnetici rilevati da oltre 70 osservatori.
H
L
V
Distanza
130 milioni di anni luce
Scoperta il
17 Agosto 2017
Tipo
Coalescenza tra due stelle di neutroni
12:41:04 UTC
Viene rilevata un'onda gravitazionale dalla coalescenza di un sistema binario di stelle di neutroni.
Osservazione di un'onda gravitazionale
Due stelle di neutroni, ciascuna delle quali delle dimensioni di una città, ma con una massa almeno pari a quella del Sole, si sono scontrate.
lampo gamma
Un lampo gamma corto è un intenso raggio di radiazioni gamma, prodotto immediatamente dopo la coalescenza.
+2 secondi
Osservazione di un lampo gamma.
GW170817 ci permette di misurare per la prima volta in modo diretto la velocità di espansione dell'Universo usando le onde gravitazionali.
+10 ore e 52 minuti
Una nuova e brillante sorgente di luce visibile viene osservata in una galassia nota come NGC 4993, nella costellazione dell'Idra.
Rilevare onde gravitazionali da una coalescenza di stelle di neutroni ci consente di indagare più a fondo sulla struttura di questi strani oggetti.
kilonova
Il decadimento di materia ricca di neutroni genera una kilonova luminosa, producendo metalli pesanti come oro e platino.
+11 ore e 36 minuti
Osservazione di radiazione infrarossa.
Queste rilevazioni coincidenti ci confermano che le coalescenze di stelle di neutroni possono produrre lampi gamma corti.
+15 ore
Osservazione di intensa radiazione ultravioletta
residuo radio
Allontanandosi dalla coalescenza, i residui producono un'onda d'urto nel mezzo interstellare, cioè la materia rarefatta tra le stelle. Questo produce emissioni che possono durare per anni.
+9 giorni
Osservazione di raggi X
Au
L'osservazione di una kilonova ci permette di dimostrare che le coalescenze di stelle di neutroni potrebbero essere responsabili per la produzione della maggior parte degli elementi pesanti nell'Universo, come l'oro.
+16 giorni
Osservazione di onde radio
Osservare contemporaneamente onde gravitazionali ed elettromagnetiche generate dallo stesso evento è una prova molto convincente che le onde gravitazionali viaggiano alla velocità della luce.

High Energy Emission from GRB
"The AGILE/Fermi era"

The Compton Gamma Ray Observatory



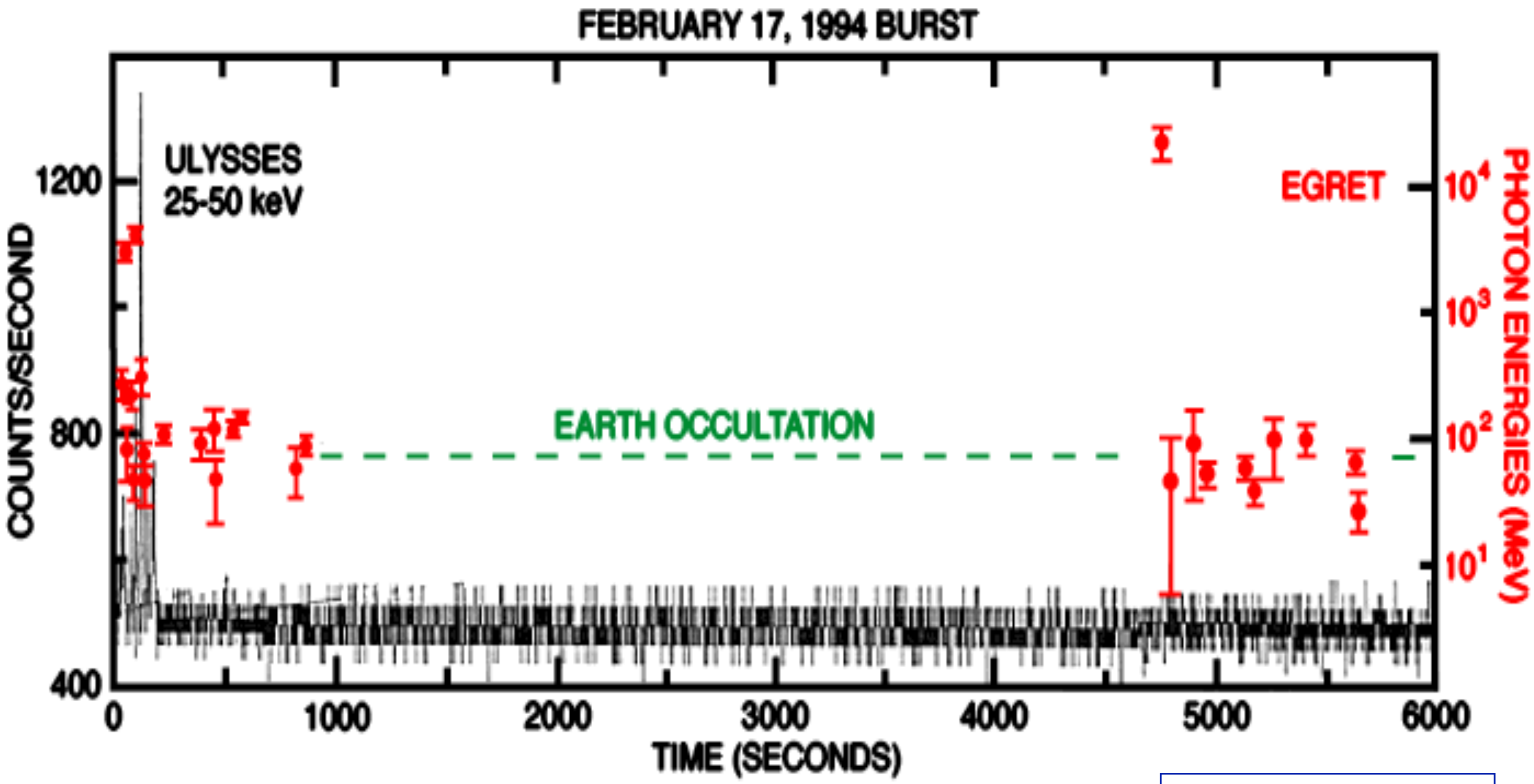




EGRET

- 1991-2000
- 30 MeV - 30 GeV
- AGN, GRB, Unidentified Sources, Diffuse Bkg

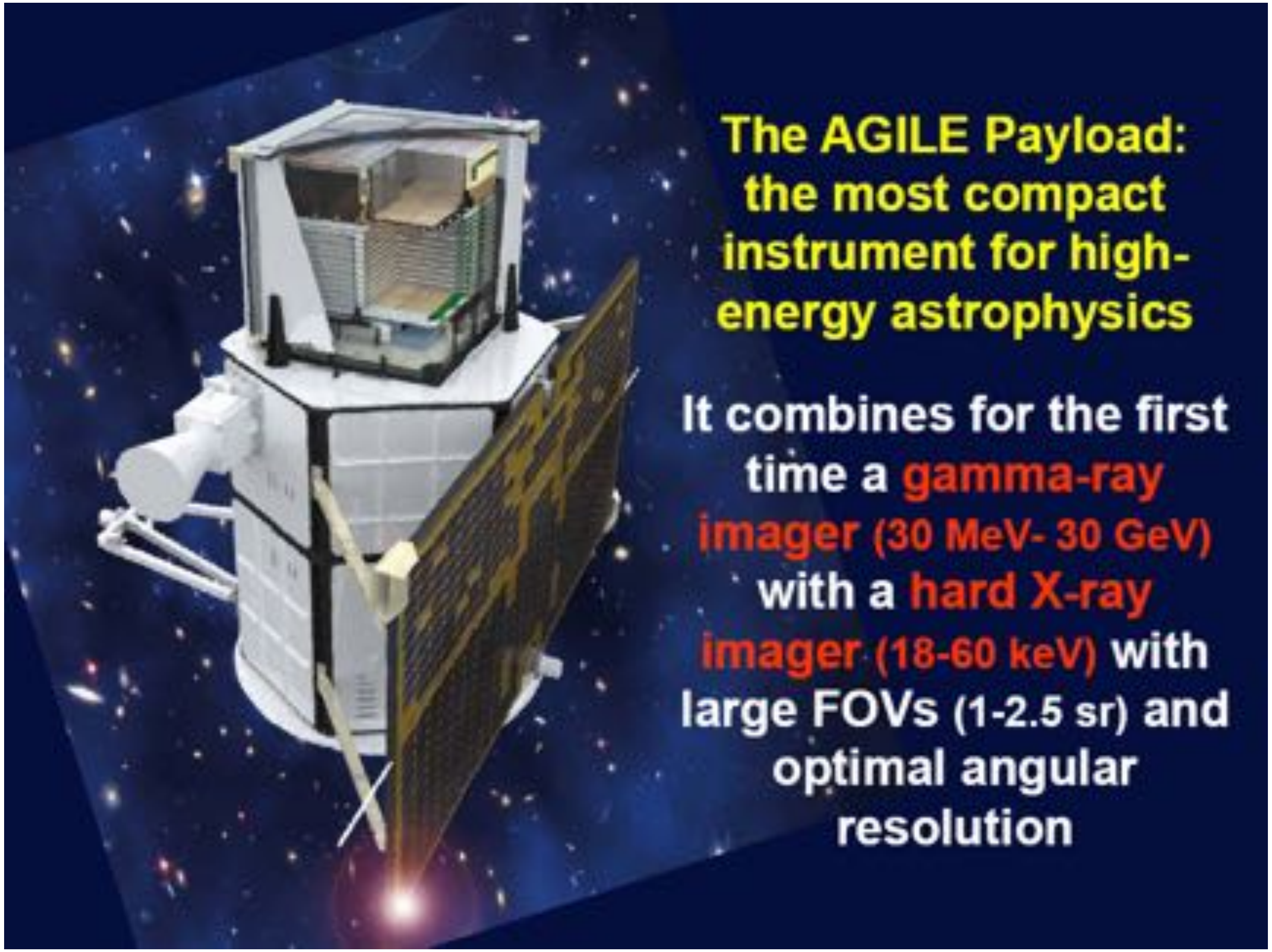
GRB delayed emission



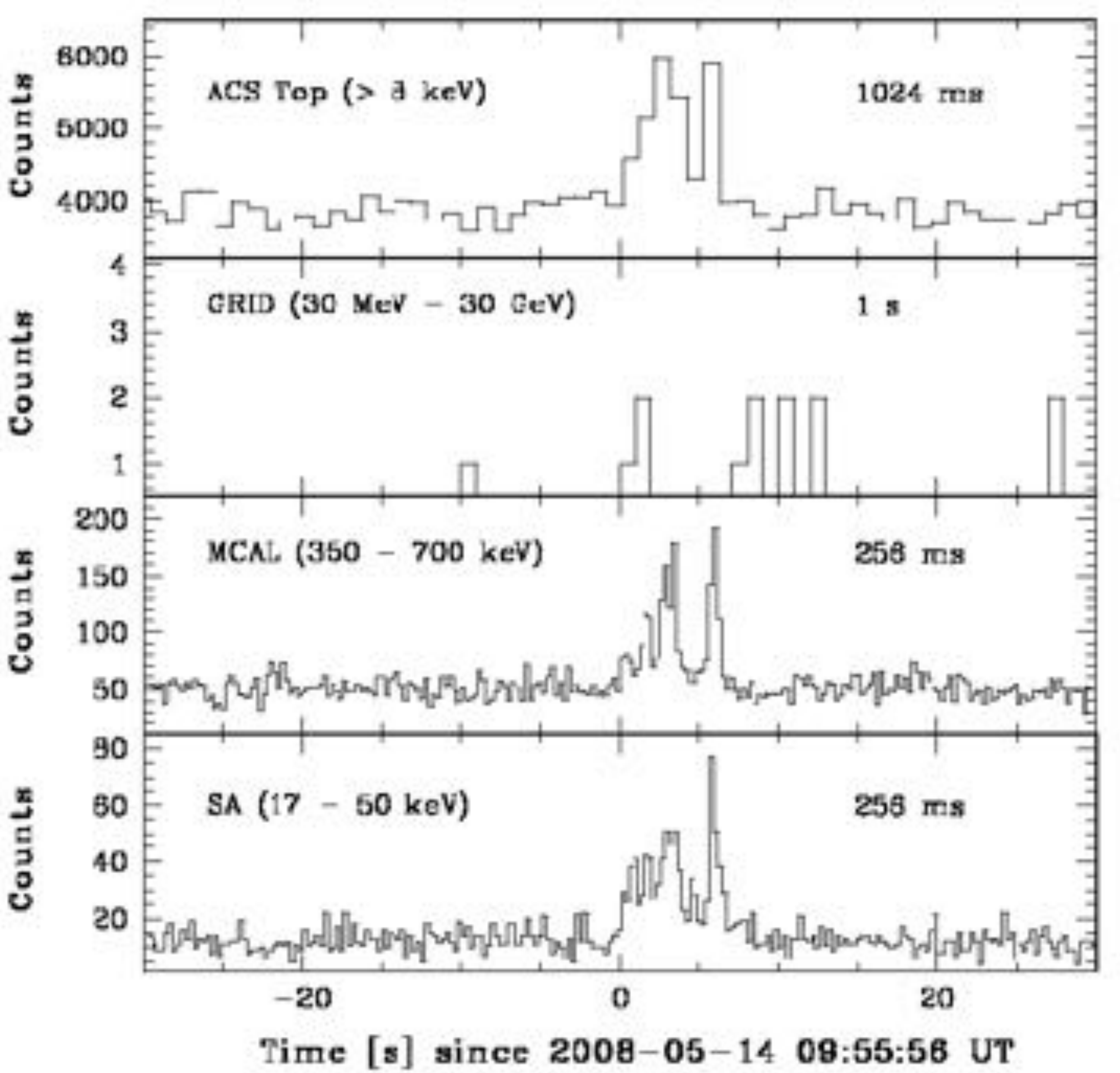
Hurley et al. 1994

AGILE and GRBs

AGILE instrument



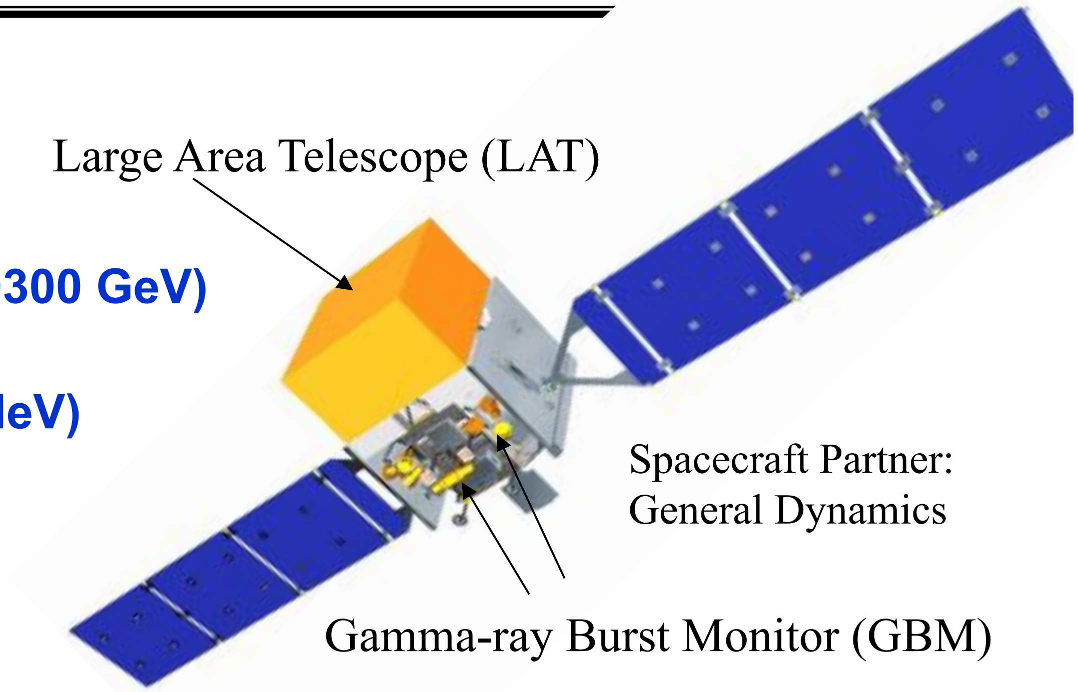
GRB 080514B


ACS Top (> 3 keV)
1024 ms
GRID (30 MeV – 30 GeV)
1 s
MCAL (350 – 700 keV)
256 ms
SA (17 – 50 keV)
256 ms
Counts
6000
5000
4000
4
3
2
1
200
150
100
50
80
60
40
20
−20
0
20
Time [s] since 2008–05–14 09:55:56 UT

Fermi and GRBs

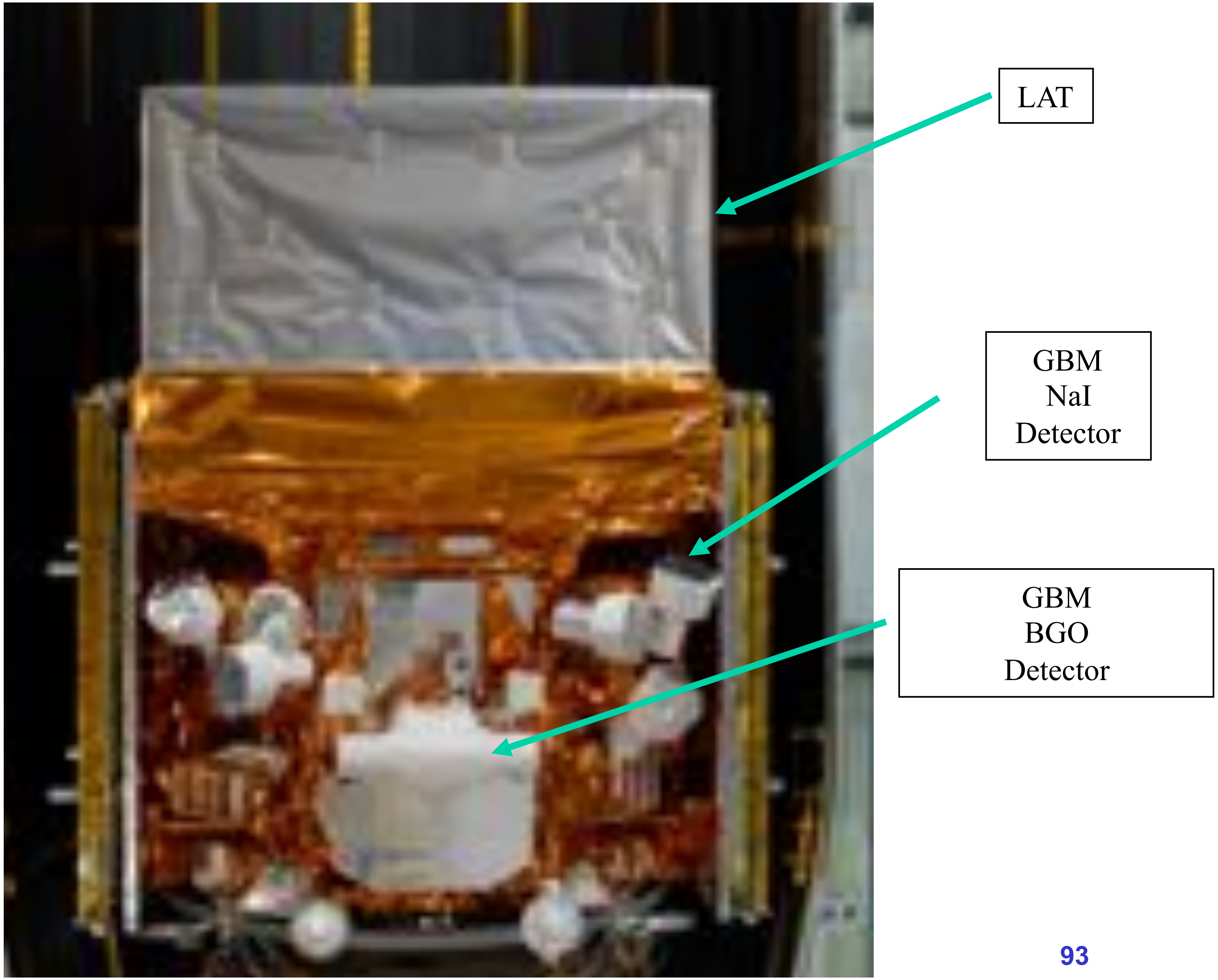
Fermi Key Features

- **Two instruments:**
  - **LAT:**
    - **high energy (20 MeV – >300 GeV)**
  - **GBM:**
    - **low energy (8 keV – 40 MeV)**

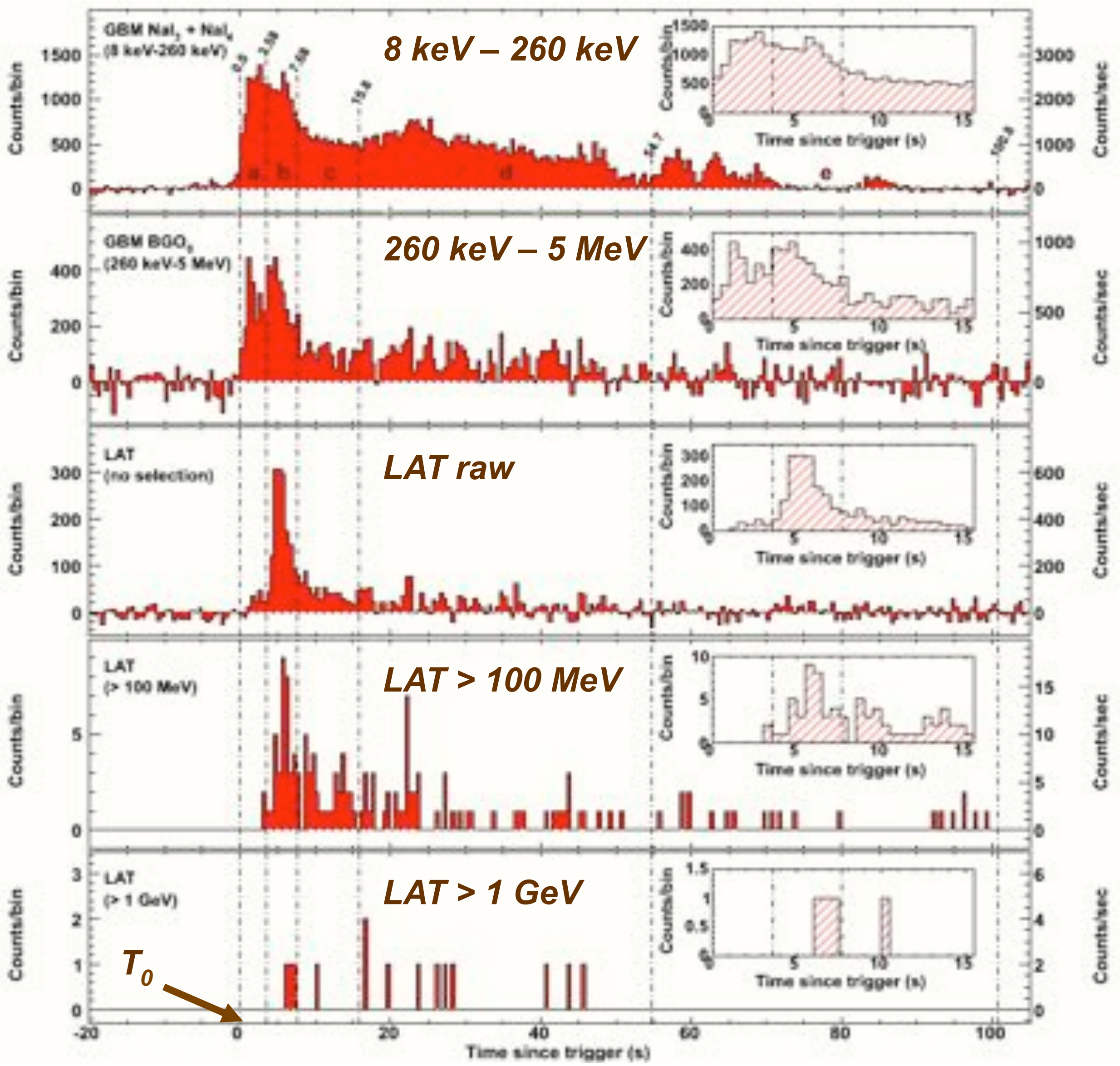


- **Huge field of view**
  - **LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.**
- **Huge energy range, including largely unexplored band 10 GeV - 100 GeV**
- **Large leap in all key capabilities. Great discovery potential.**

The Observatory



GRB080916C - Multiple detector light curve



First 3 light curves are background subtracted

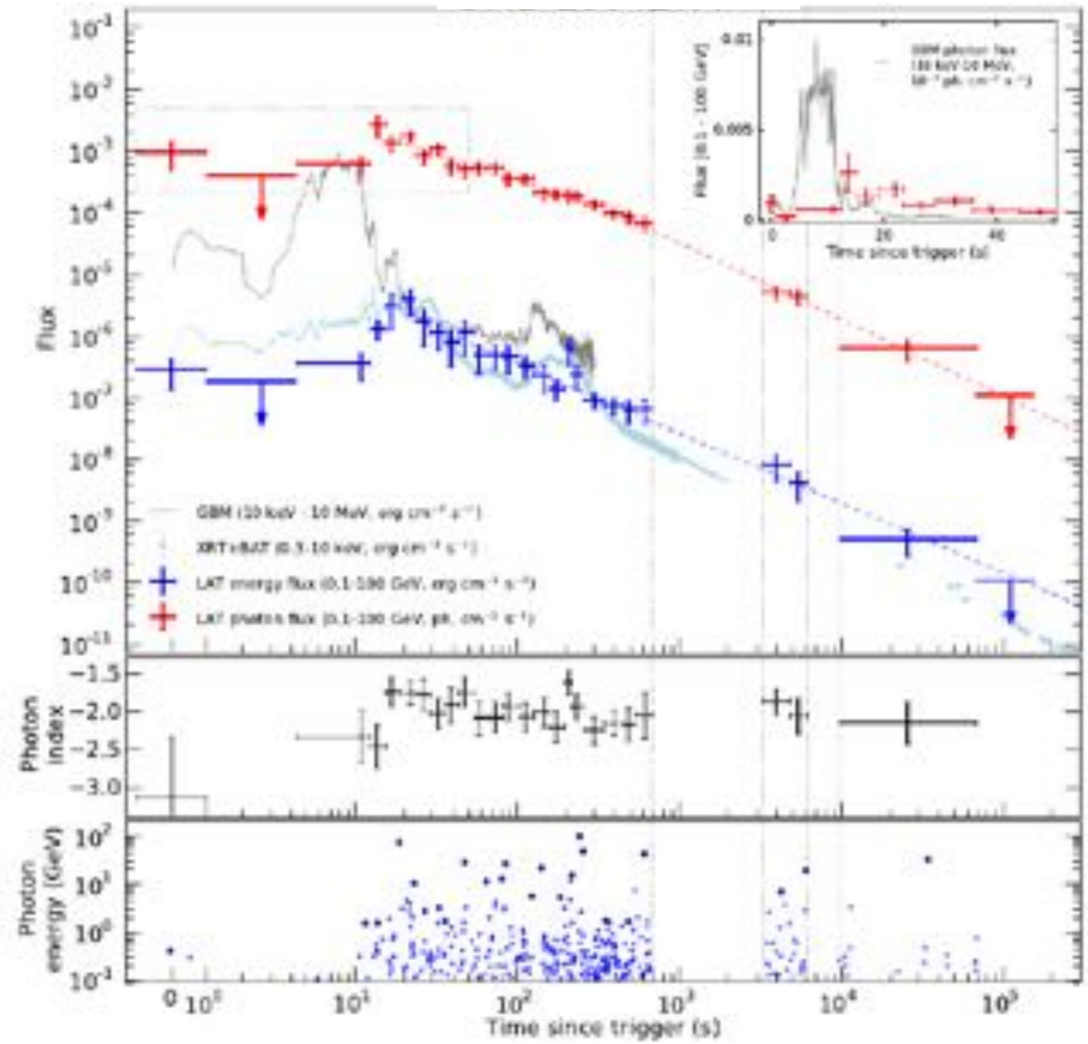
The LAT can be used as a counter to maximize the rate and to study time structures above tens of MeV

- **The first low-energy peak is nc observed at LAT energies**

Spectroscopy needs LAT event selection (>100 MeV)

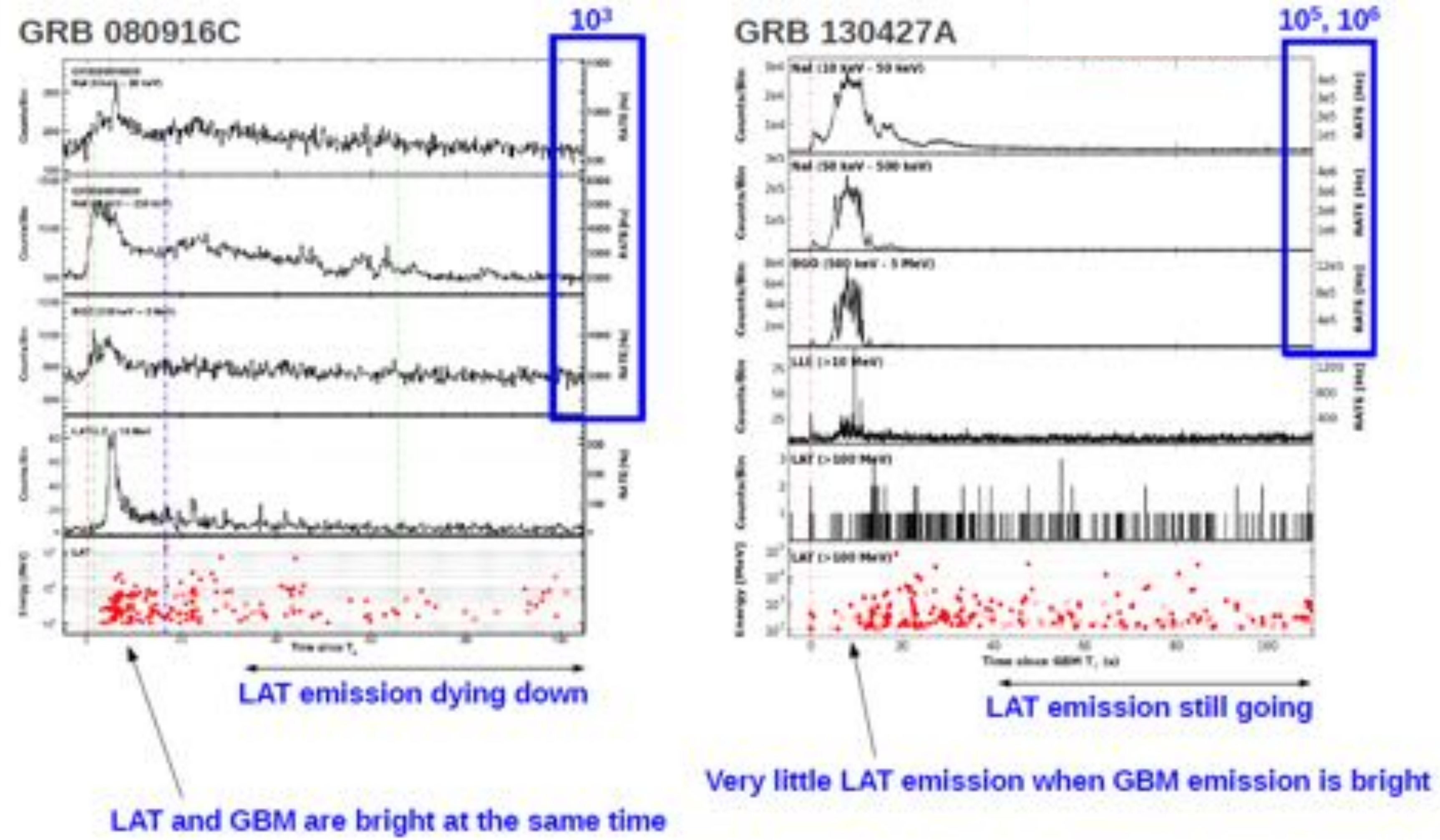
- **5 intervals for time-resolved spectral analysis: 0 – 3.6 – 7.7 – 16 – 55 – 100 s**
- **14 events above 1 GeV**

GRB 130427A



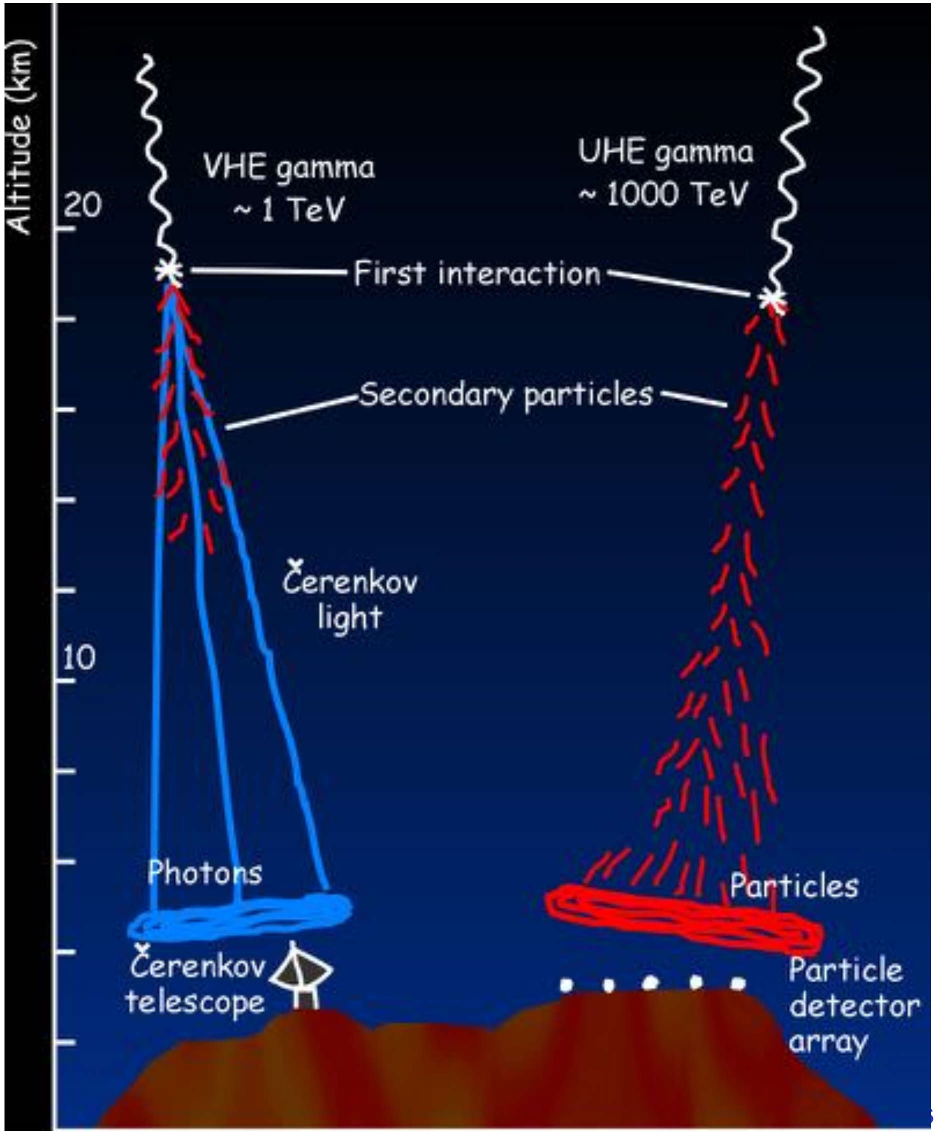
(Ackermann et al., Science, Vol. 343 no. 6166 pp. 42-47)

GRB 130427A


GRB 080916C
10^3
LAT emission dying down
LAT and GBM are bright at the same time
GRB 130427A
$10^5, 10^6$
LAT emission still going
Very little LAT emission when GBM emission is bright

Very High Energy emission from GRBs
“status and prospects”

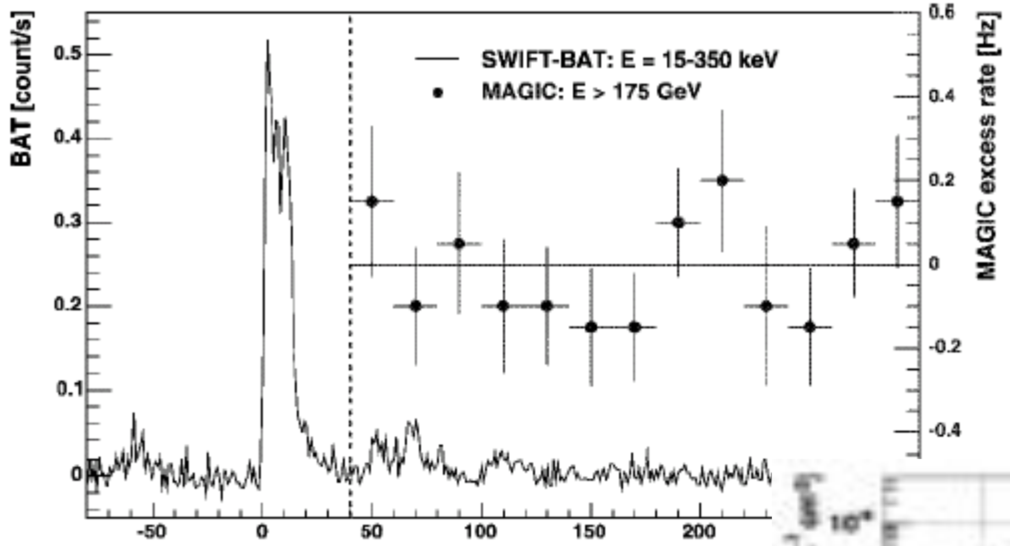
IACT & EAS experiments

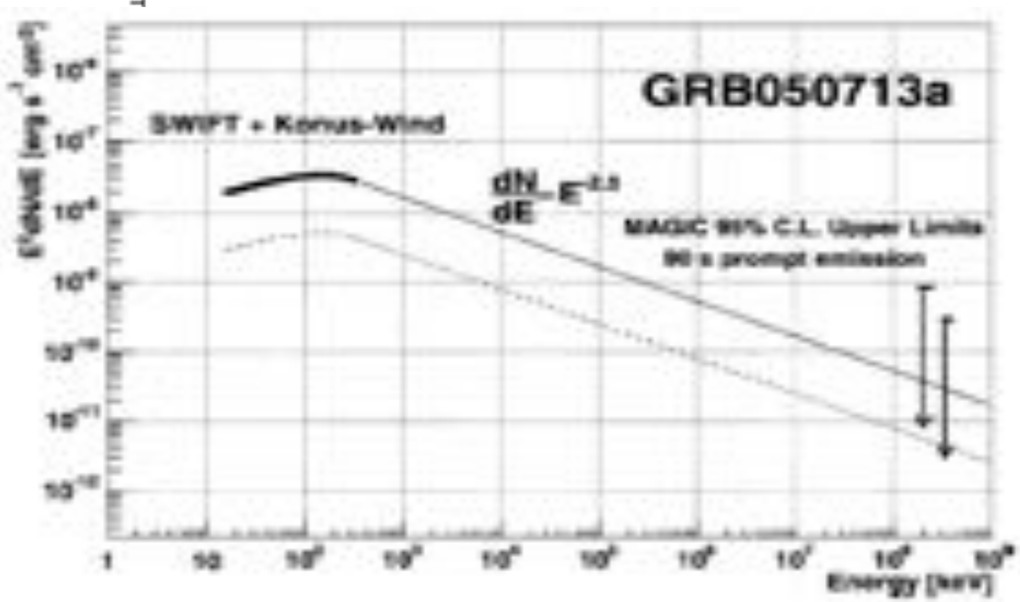


- Cherenkov experiments consist of almost-optical telescopes devoted to detect Cherenkov light.
- EAS (Extensive Air Shower) experiments are huge arrays or carpets of particle detectors.
- Cherenkov experiments have lower energy thresholds, but also a lower duty-cycle as well as a smaller field of view.

MAGIC telescopes

GRBs





Albert et al 2006, ApJ 641, L9

MAGIC detection !!!!

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; *Razmik Mirzoyan on behalf of the MAGIC Collaboration*
on 15 Jan 2019; 01:03 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

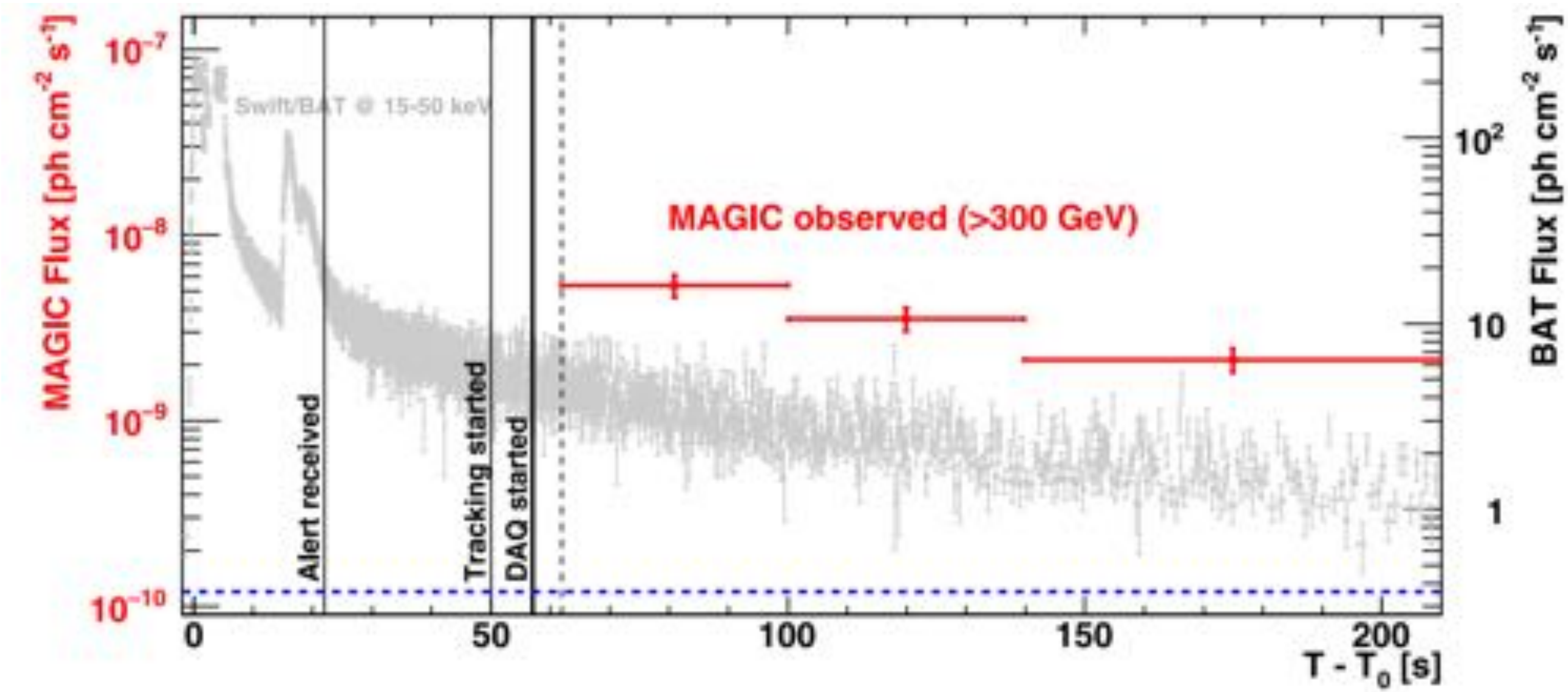
Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395, 12475

Tweet

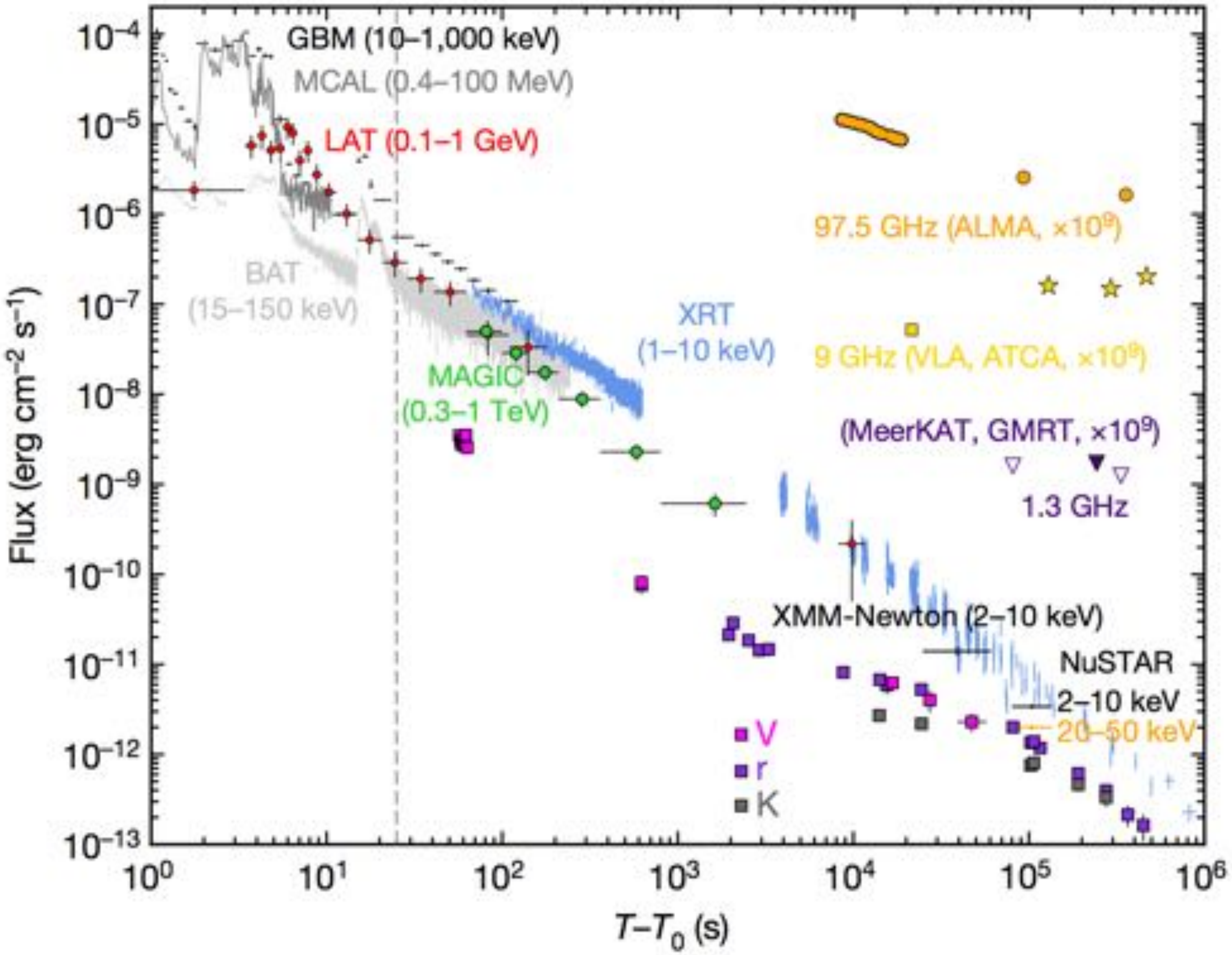
The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

MAGIC detection !!!!



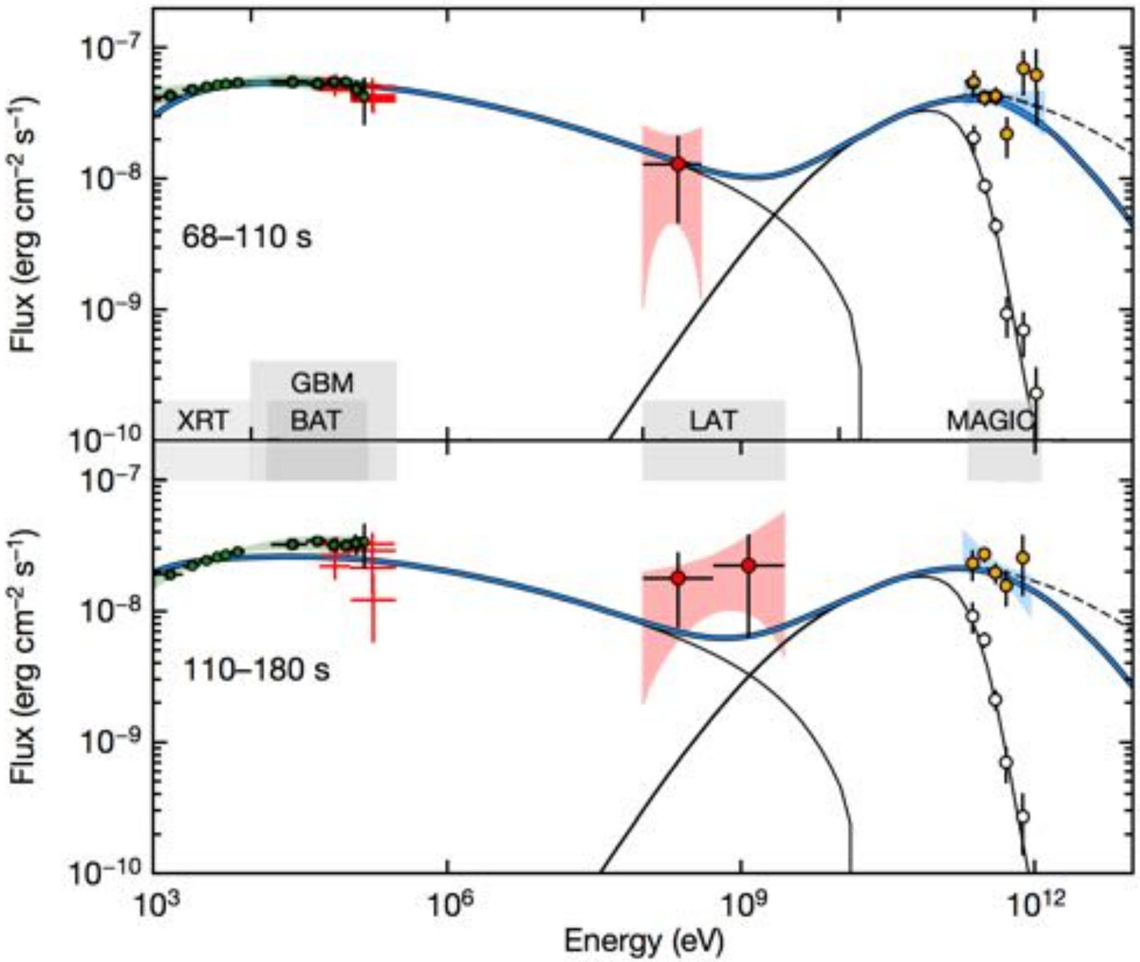
https://doi.org/10.1038/s41586-019-1750-x

MAGIC detection !!!!



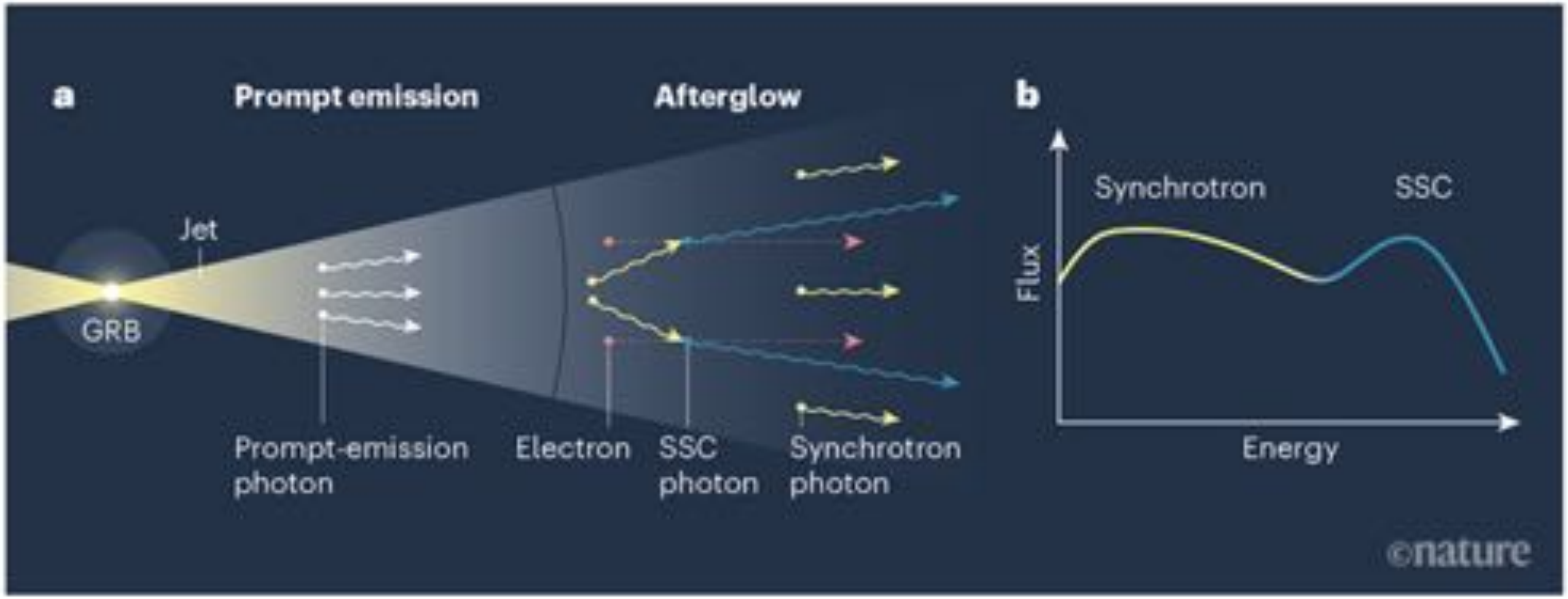
https://doi.org/10.1038/s41586-019-1754-6

MAGIC detection !!!!



https://doi.org/10.1038/s41586-019-1754-6

MAGIC detection !!!!



Zhang B., Nature News & Views (20/11/2019)

Conclusions

GRB implications