united nations educational, scientific and cultural organization
international atomic energy agency

the **abdus salam** international centre for theoretical physics

ICTP 40th Anniversary

H4.SMR/1574-22

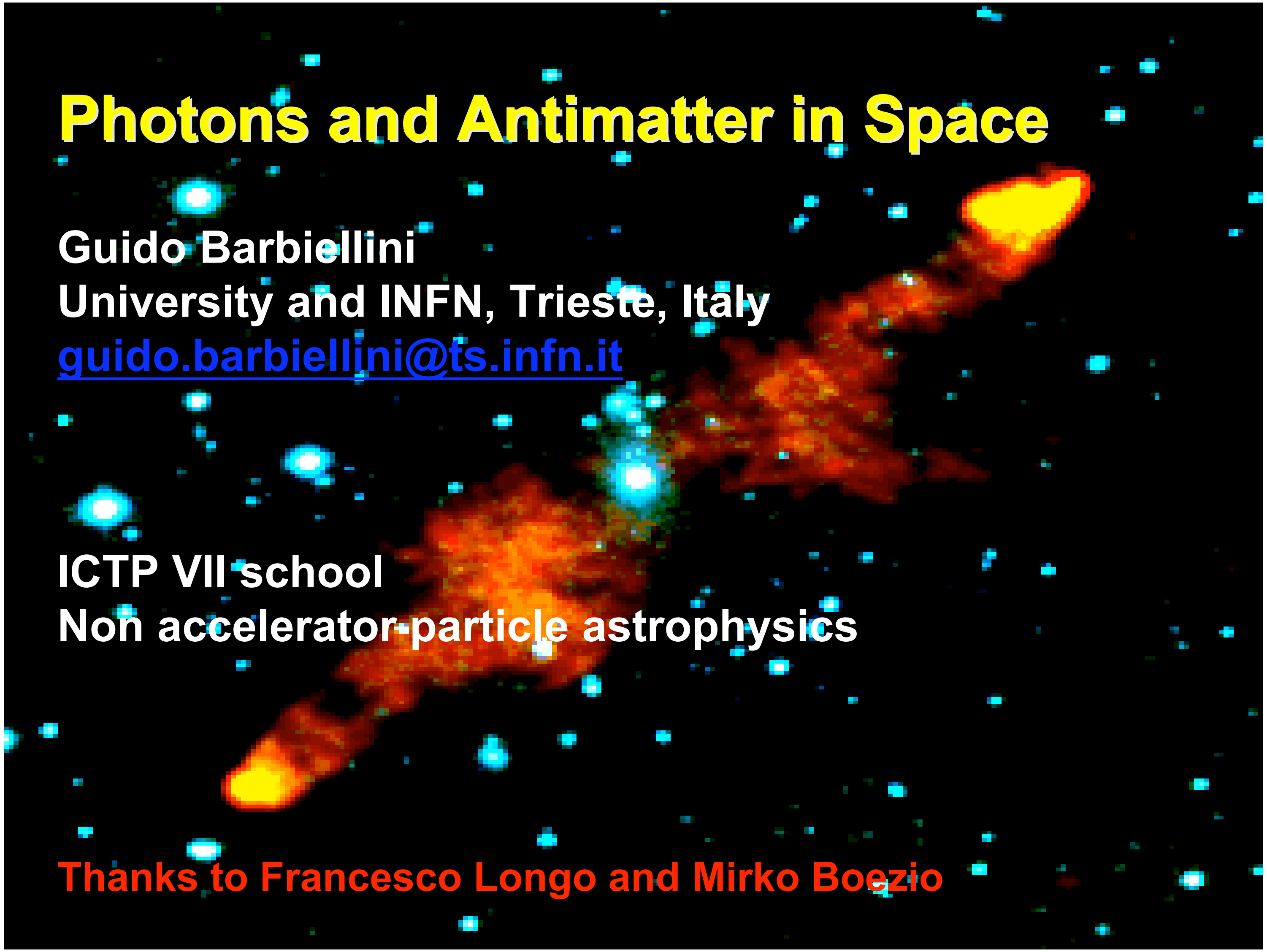
"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Photons and Antimatter in Space

Guido Barbiellini

University and INFN, Trieste, Italy



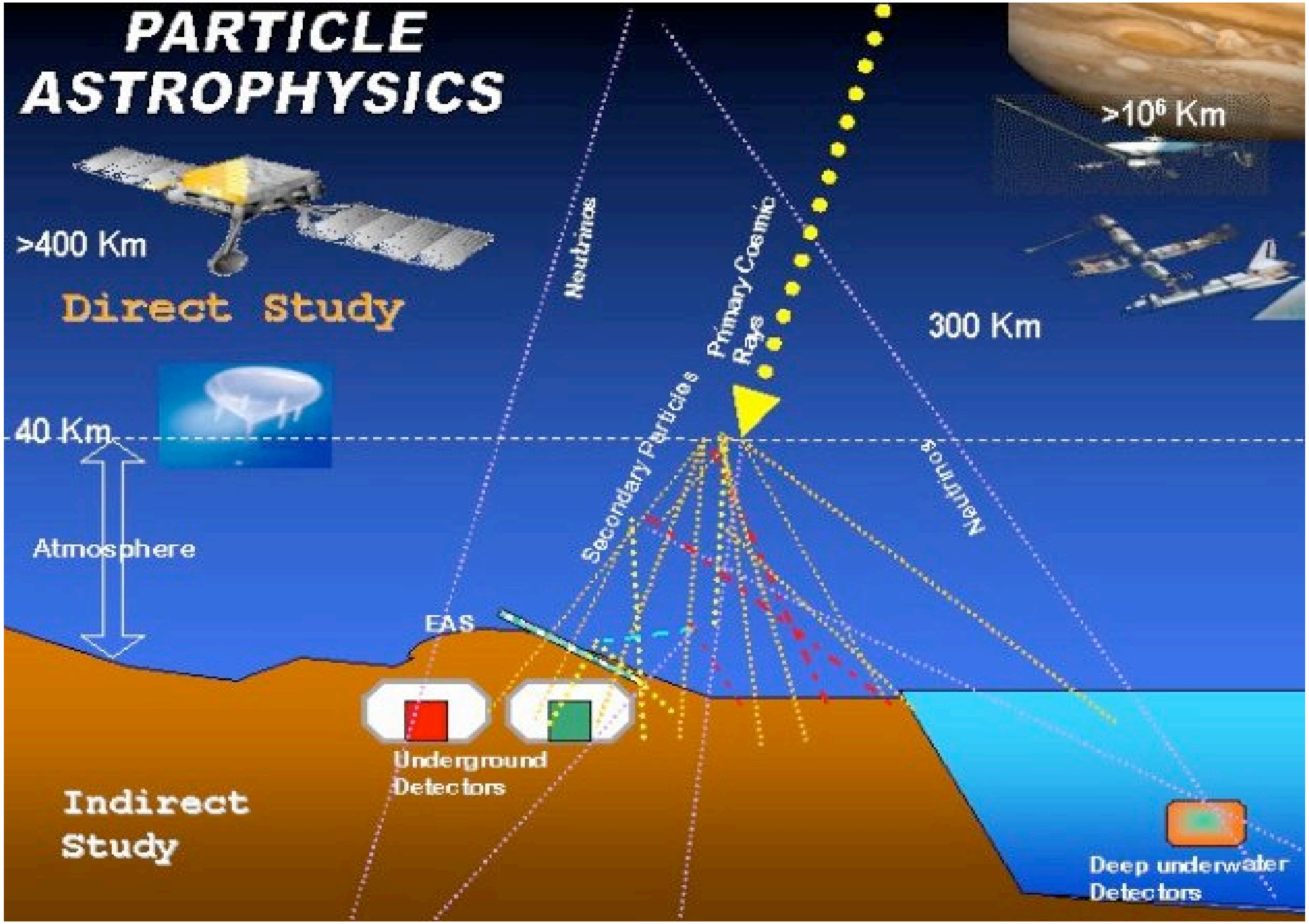
Photons and Antimatter in Space

Guido Barbiellini
University and INFN, Trieste, Italy
guido.barbiellini@ts.infn.it

ICTP VII school
Non accelerator particle astrophysics

Thanks to Francesco Longo and Mirko Boezio

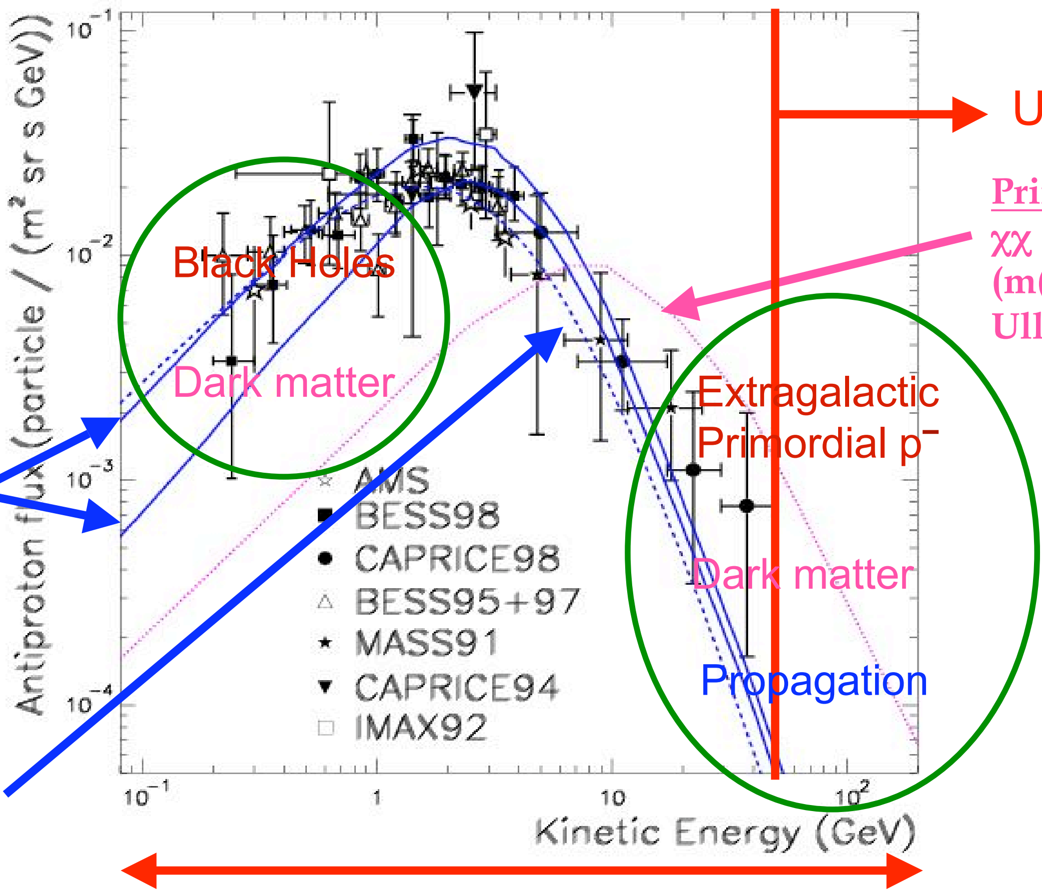
Particle Astrophysics



OUTLINE

- Antimatter Research in Space
  - Physics Motivation
  - New experiments
    - PAMELA
    - AMS
- Gamma-Ray Astrophysics
  - Physics
    - Galactic sources
    - Extragalactic sources
  - New experiments
    - AGILE
    - GLAST
- Highlights
  - GRB and Cosmology

Cosmic-Ray Antiparticle Measurements: Antiprotons



Unexplored Region

Primary production from χχ annihilation (m(χ) = 964 GeV, Ullio 2002)

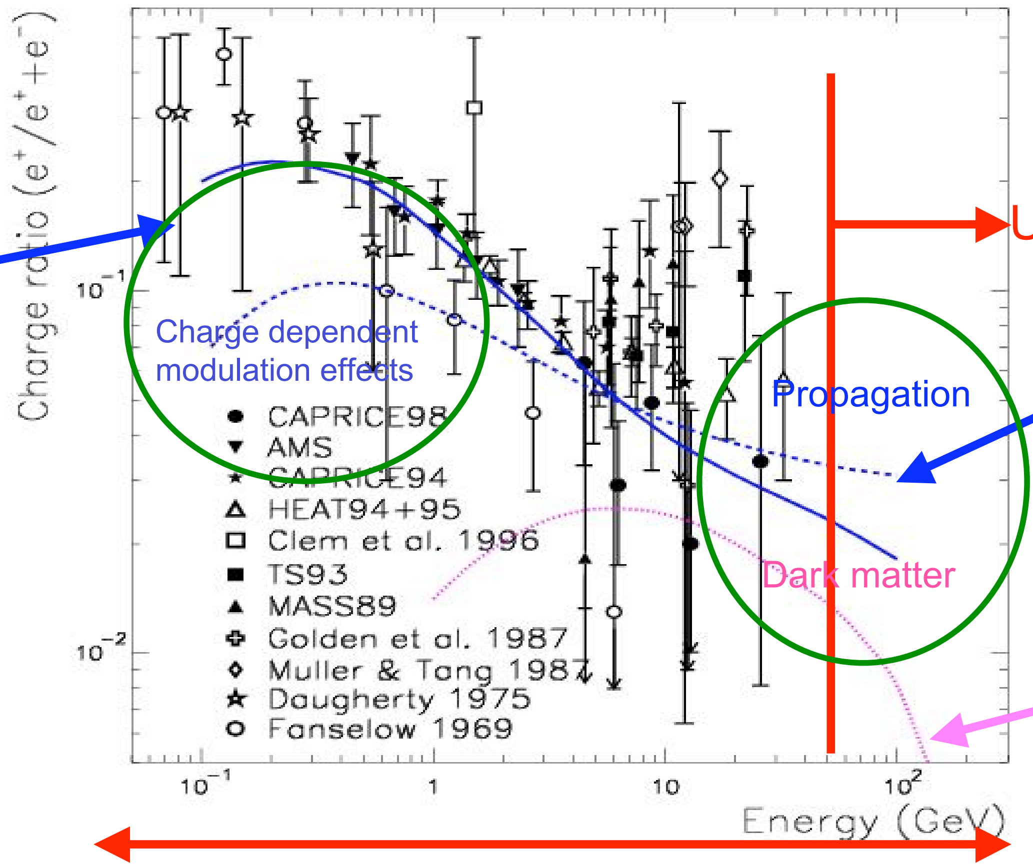
Secondary production (upper and lower limits) Simon et al.

Secondary production (CAPRICE94-based) Bergström et al.

PAMELA energy range

Cosmic-Ray Antiparticle Measurements: Positrons

Secondary production
'Moskalenko + Strong model' (1998) without reacceleration



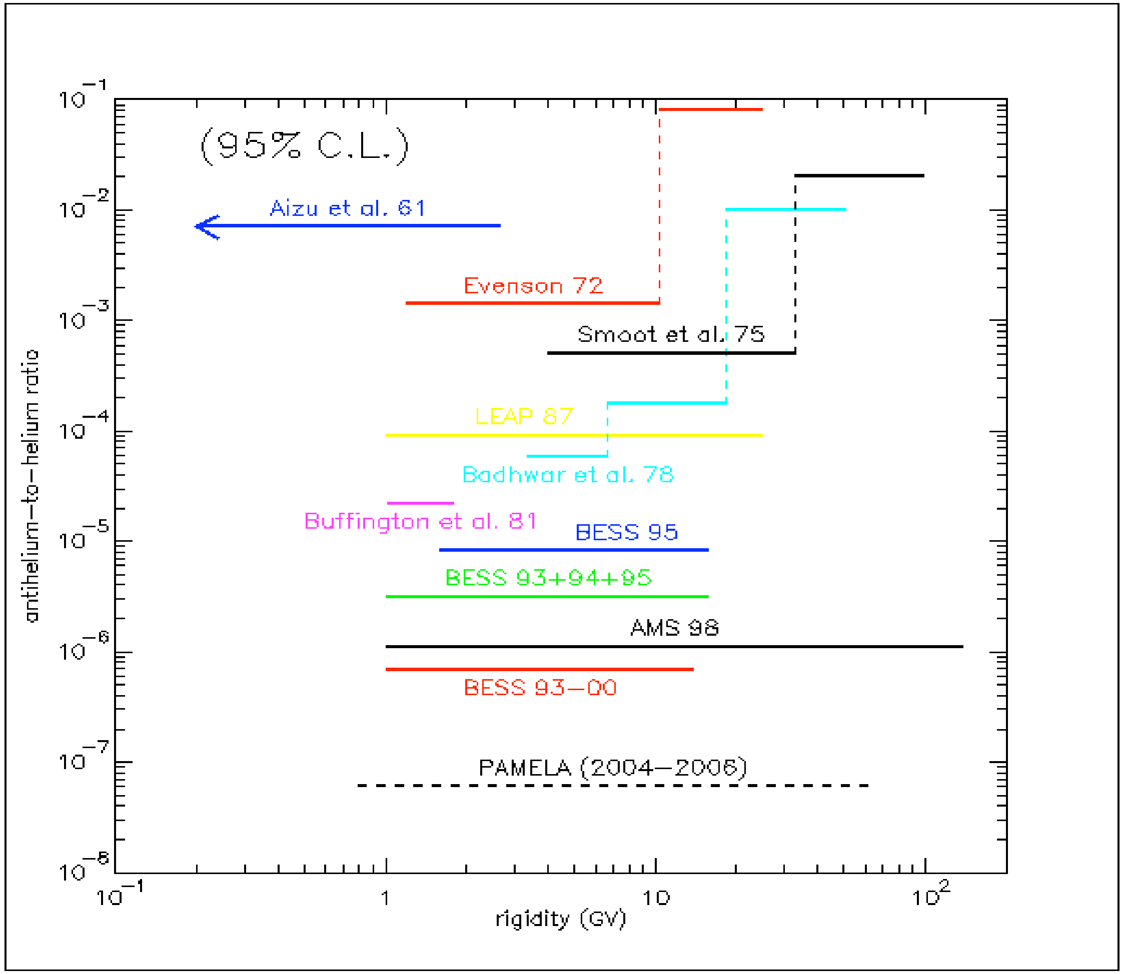
Unexplored Region

Secondary production
'Leaky box model' (Protheroe 1982)

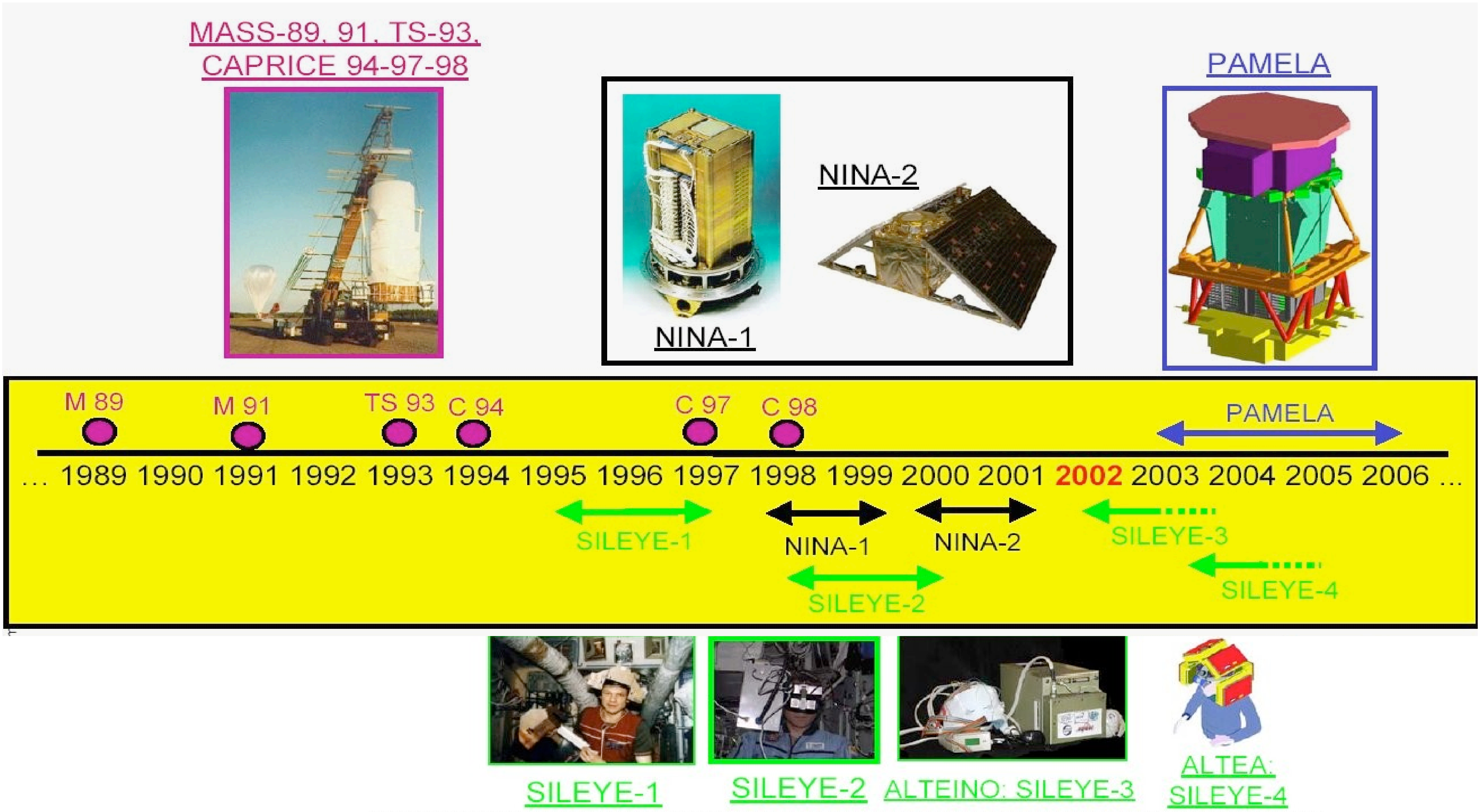
Primary production from χχ annihilation (m(χ) = 336 GeV, Baltz & Edsjö 1999)

PAMELA energy range

Cosmic-ray Antimatter Search



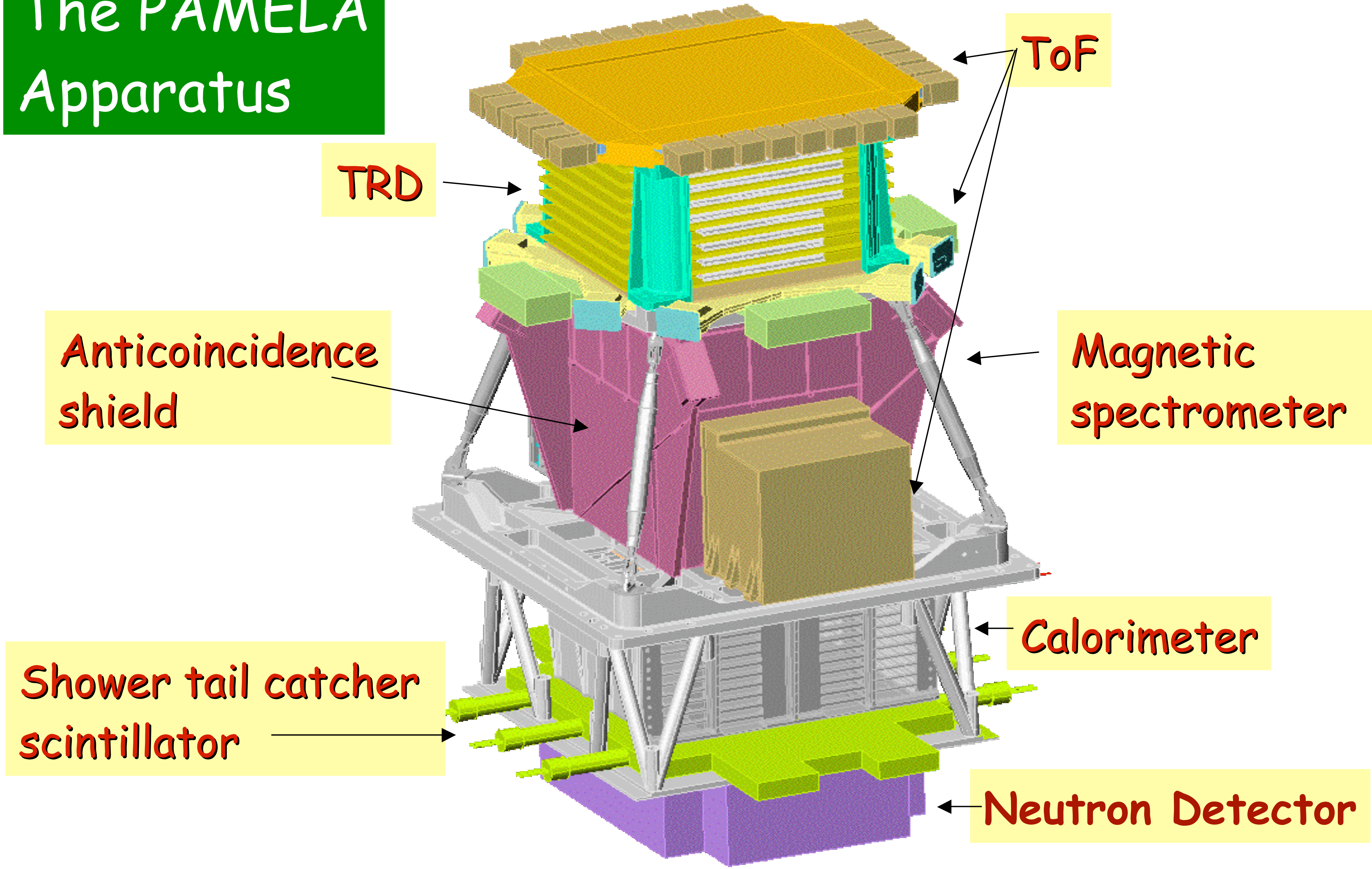
The WiZard Collaboration Experiments



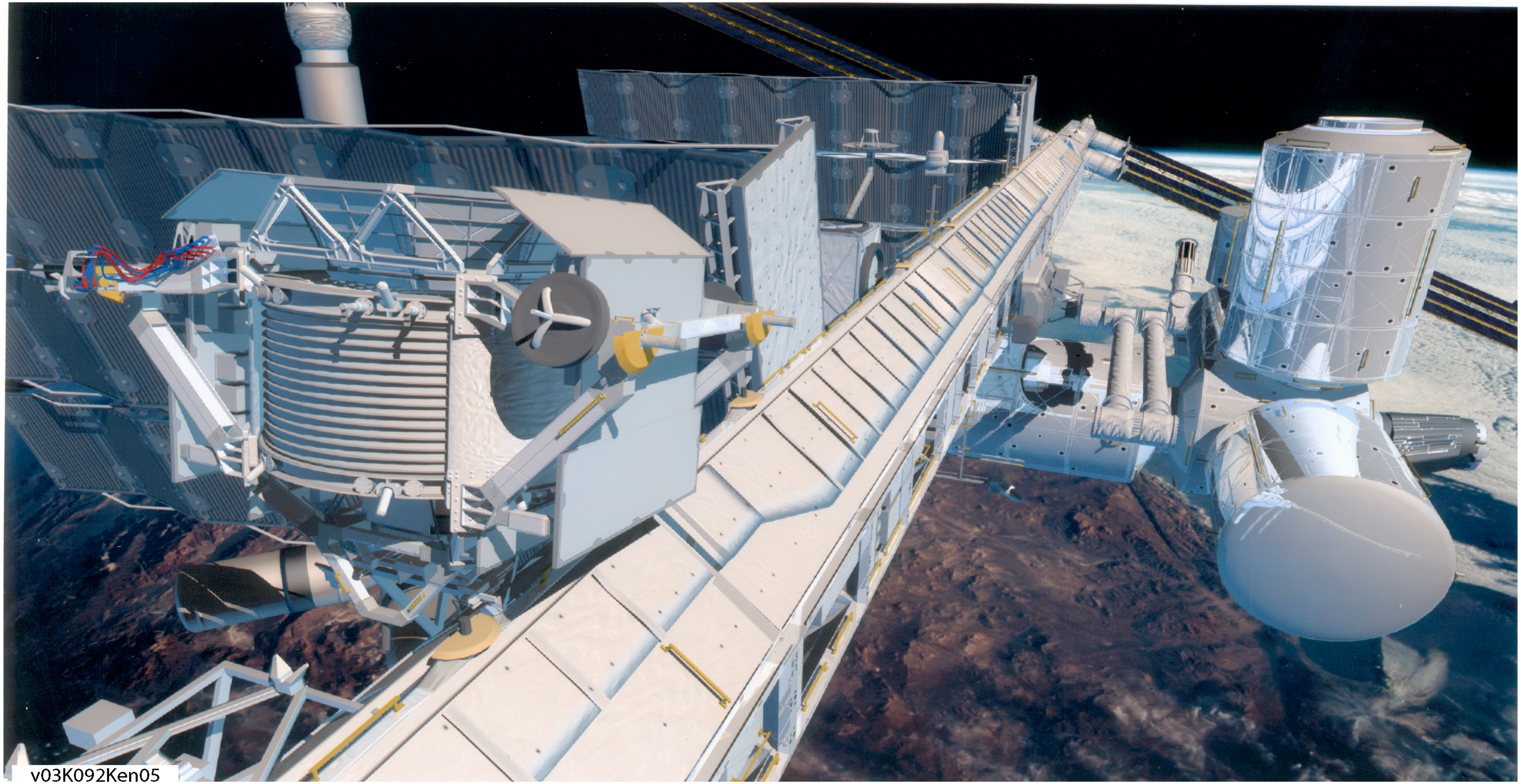
PAMELA Capabilities

• Antiproton flux	80 MeV - 190 GeV
• Positron flux	50 MeV – 270 GeV
• Electron flux	up to 400 GeV
• Proton flux	up to 700 GeV
• Electron/positron flux	up to 2 TeV
• Light nuclei (up to Z=6)	up to 200 GeV/n
• Antinuclei search	(sensitivity of 10^{-7} in He/He)

The PAMELA Apparatus



AMS-02 on ISS (ARTIST VIEW)



AMS

On the International Space Station as from 2007 for at least 3 years

PHYSICS GOALS

- **Study of charged particles and nuclei in cosmic rays with high precision and high statistics in rigidity range 0.5 GV– few TV**

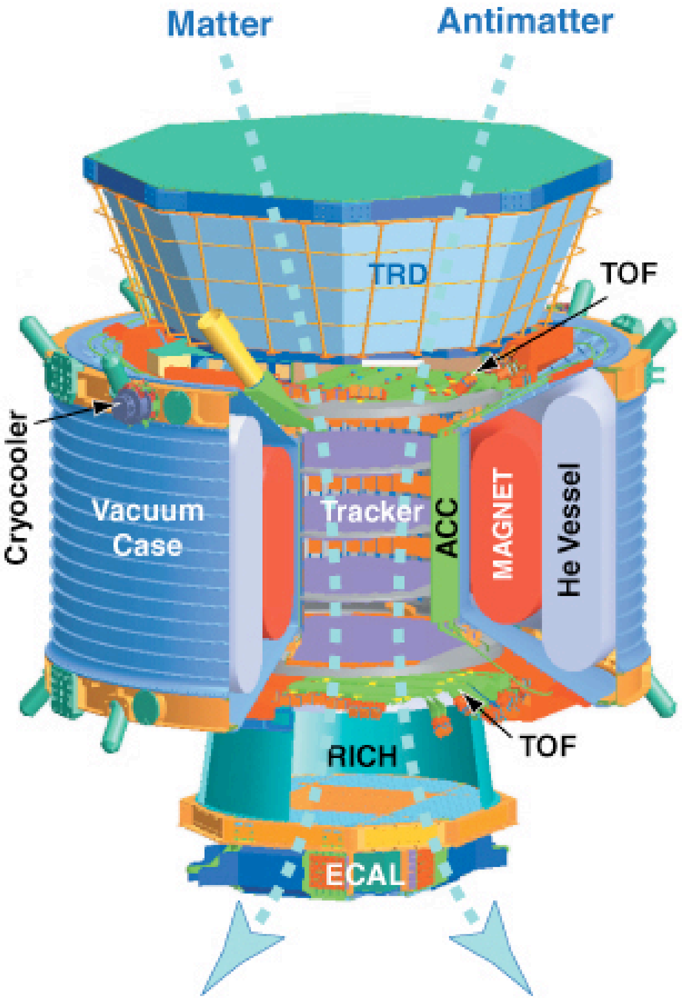
- **Direct search for antimatter (antihelium). Sensitivity 10^{-9} to antihelium/helium**

- **Indirect search for non-baryonic Dark Matter (neutralino $\chi + \chi$ _e^+, p, $\bar{\_}$, +…)**

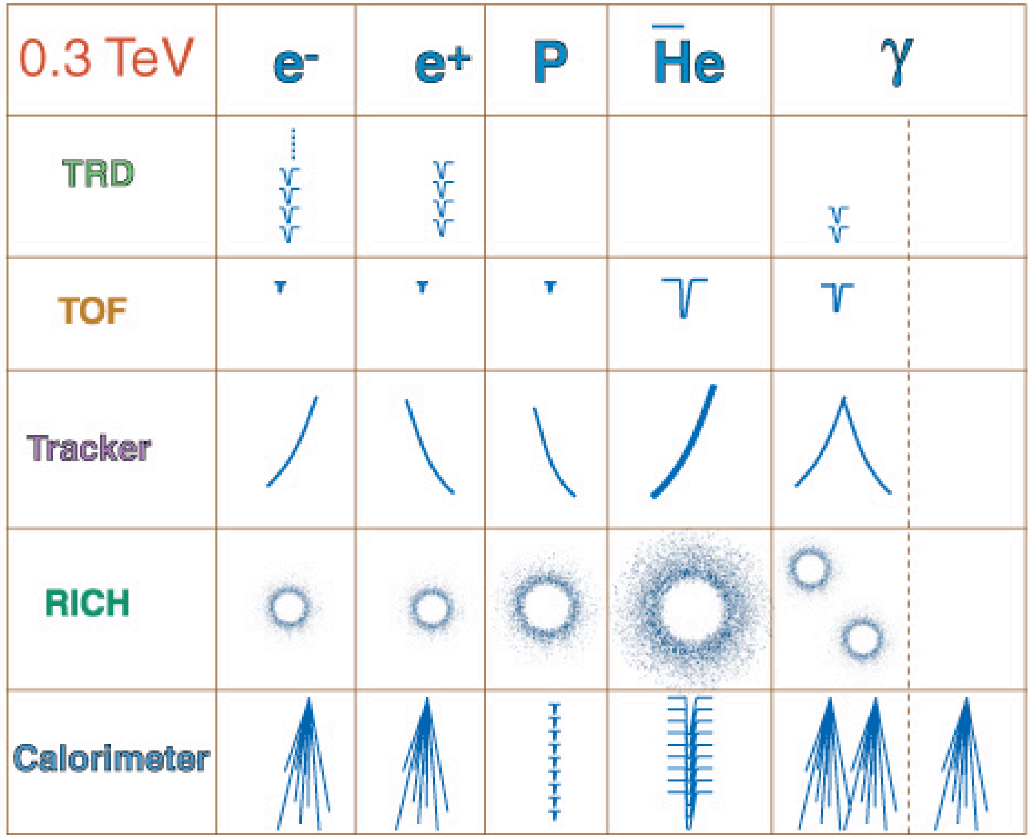
- **High energy cosmic gamma-rays physics.**

Total statistics expected above 10^{10} events.

AMS: A TeV Magnetic Spectrometer in Space (3m x 3m x 3m, 7t)



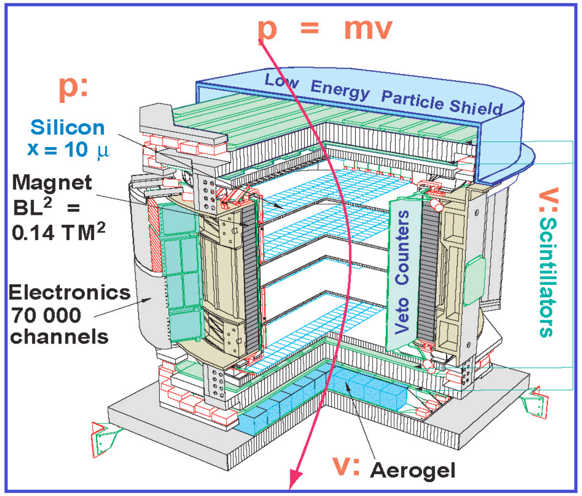
300,000 channels of electronics Δt = 100 ps, Δx = 10μ



ALPHA MAGNETIC SPECTROMETER AMS01 MISSION

STS91 flight on Discovery 2-12 June 1998

10 days in space. 10^8 cosmic ray triggers



Several important physics results published
(Overview in Physics Reports 366 (2002))

Limit on primordial antimatter :
Search for antihelium in C.R. PL B461 (1999)

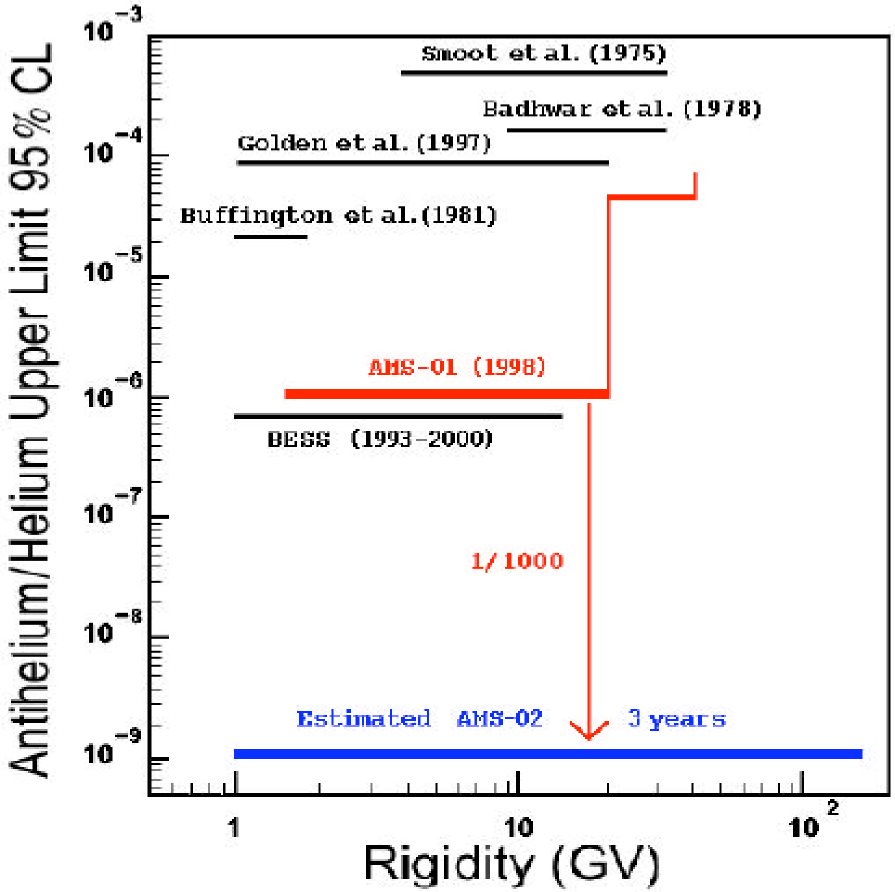
Measurement of primary fluxes p, He, e-, e+, ..., detection of secondary fluxes, geomagnetic field effect and particles trapping:
Protons in near earth orbit PL B472 (2000)
Leptons in near earth orbit PL B484 (2000)
Cosmic protons PL B490 (2000)
Helium in near earth orbit PL B494 (2000)

Use of results for other fluxes calculations:
A 3D simulation of atmospheric neutrinos PRD68 (2003)

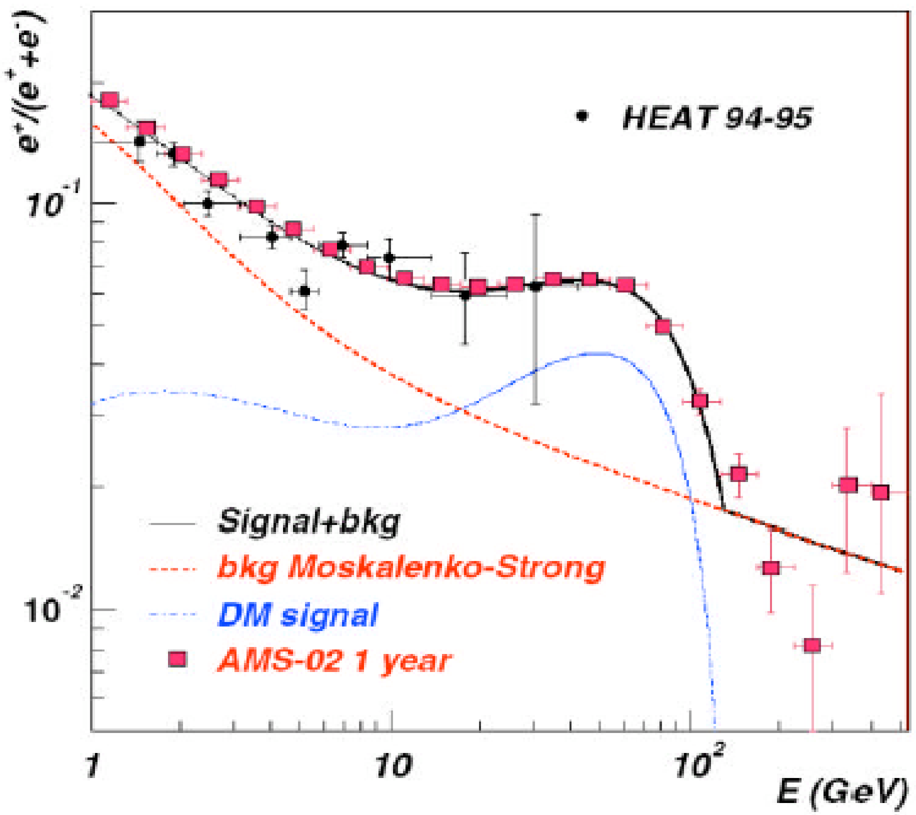
AMS01 SEEN FROM MIR IN THE CARGO BAY OF DISCOVERY

Physics performances of AMS-02

PRIMORDIAL ANTIMATTER
Limit on antihelium
1 year data taking



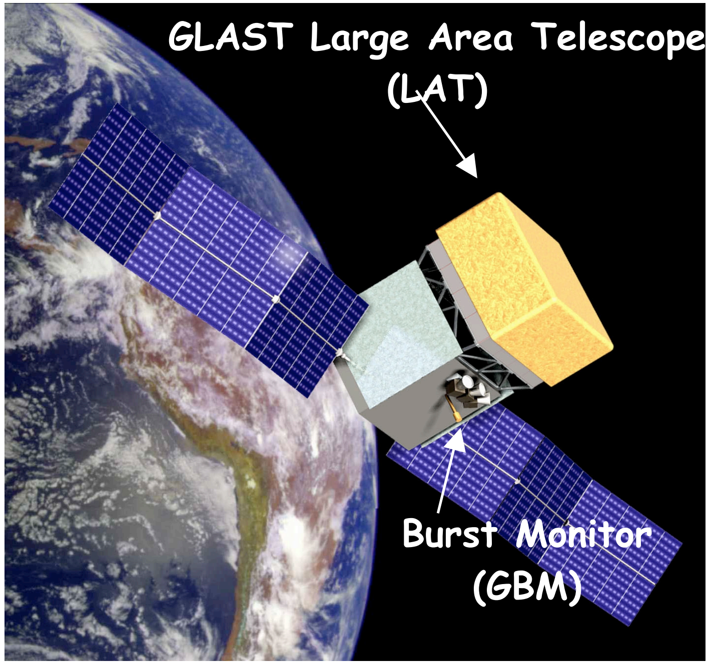
DARK MATTER
Positron spectra with neutralino of mass 130.3 GeV/c2
1 year data taking



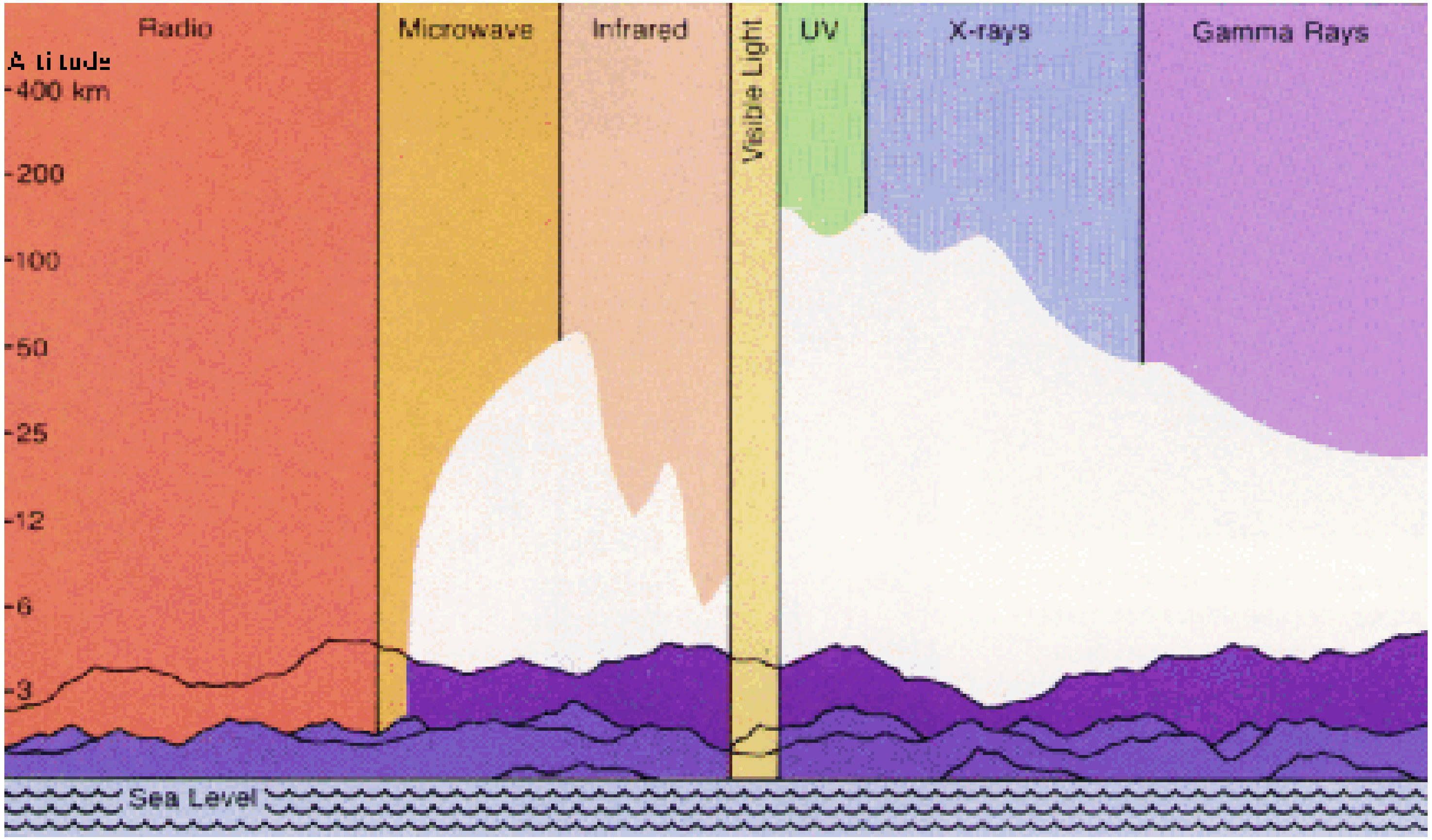
Why study γ's?

Gamma rays carry a wealth of information:

- γ rays do not interact much at their source: they offer a direct view into Nature's largest accelerators.
- similarly, the Universe is mainly transparent to γ rays: can probe cosmological volumes. Any opacity is energy-dependent.
- conversely, γ rays readily interact in detectors, with a clear signature.
- γ rays are neutral: no complications due to magnetic fields. Point directly back to sources, etc.

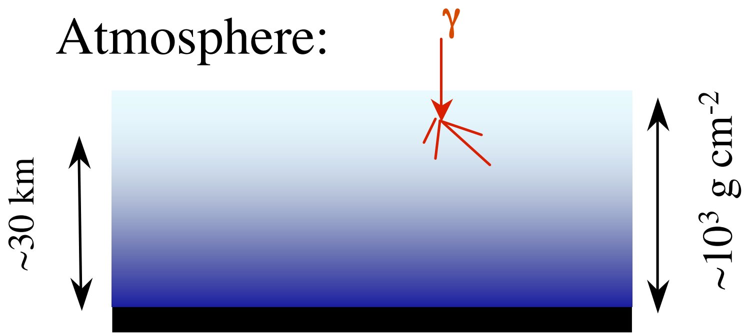


Gamma-Ray Astrophysics



γ-ray Measurement Techniques

Atmosphere:



For E_γ < ~ 100 GeV, must detect above atmosphere (balloons, satellites)

For E_γ > 100 GeV, information from showers penetrates to the ground (Cerenkov, air showers)

Energy loss mechanisms:

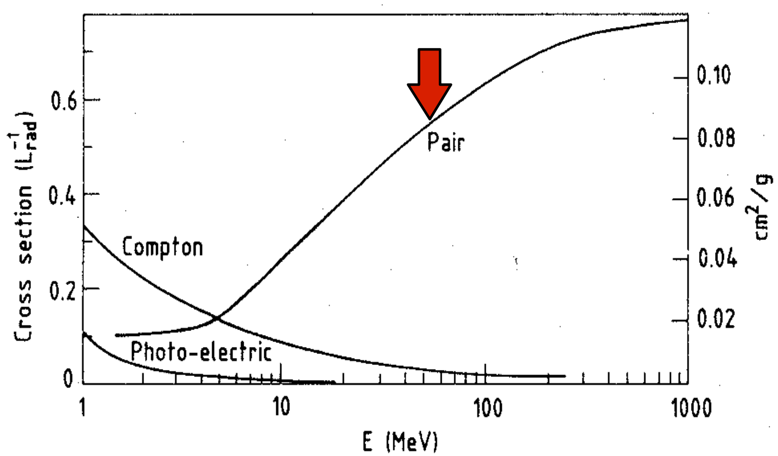
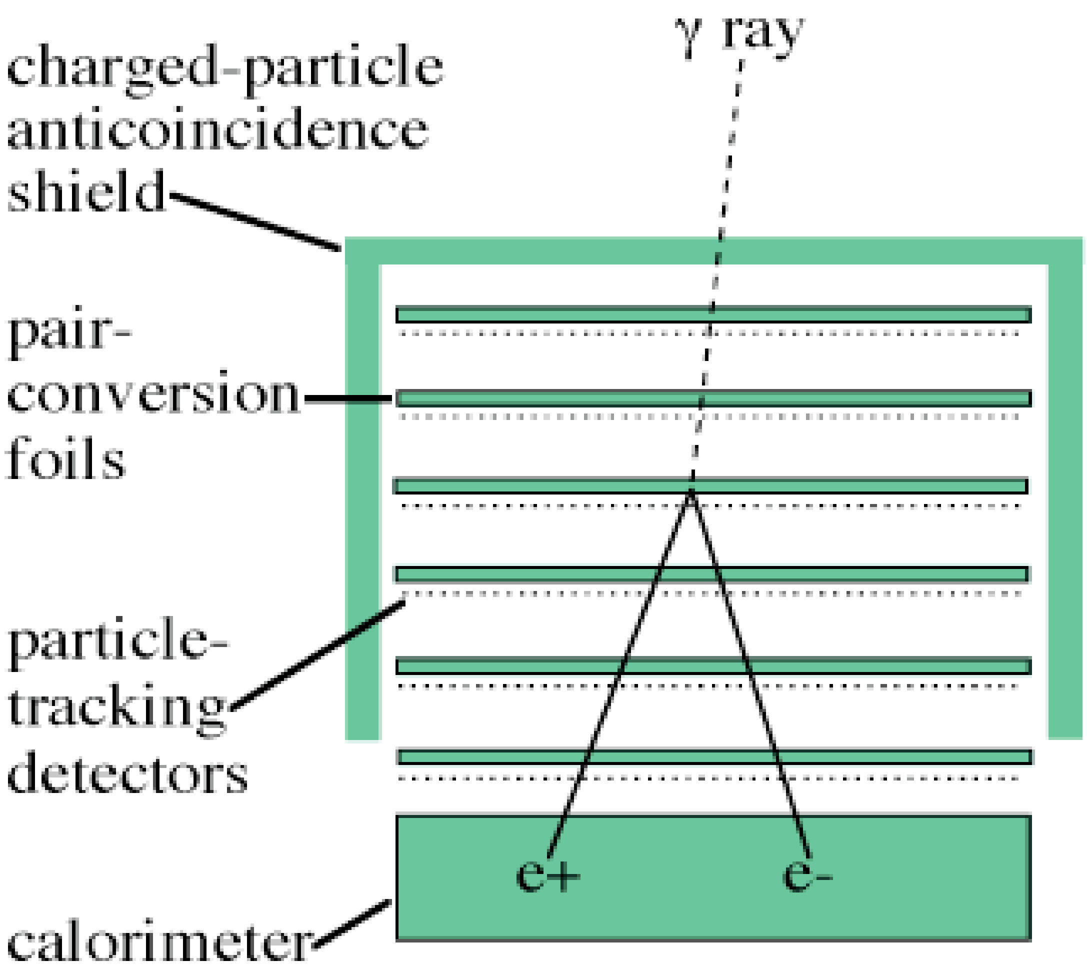


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

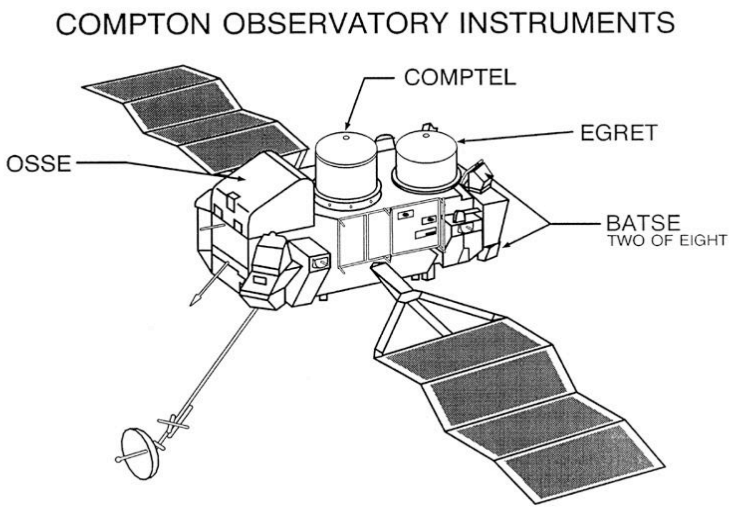
Detection Technique

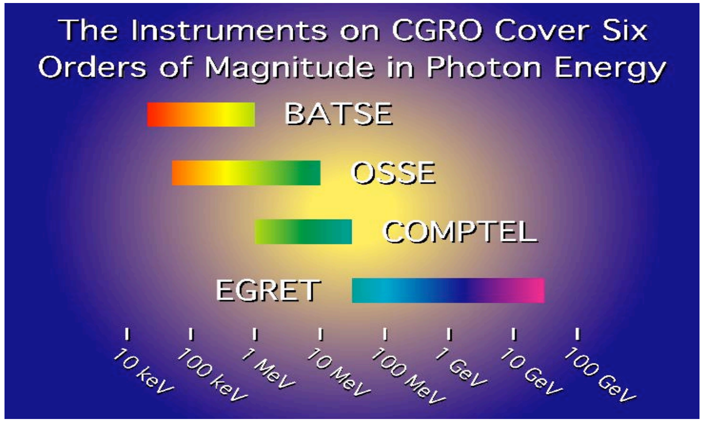


The Compton Gamma Ray Observatory

CGRO satellite (1991-2000)

EGRET





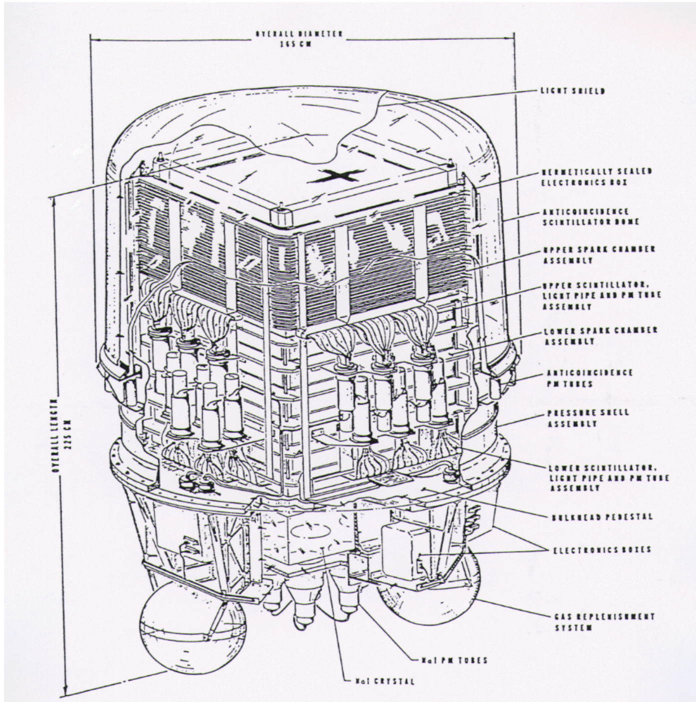
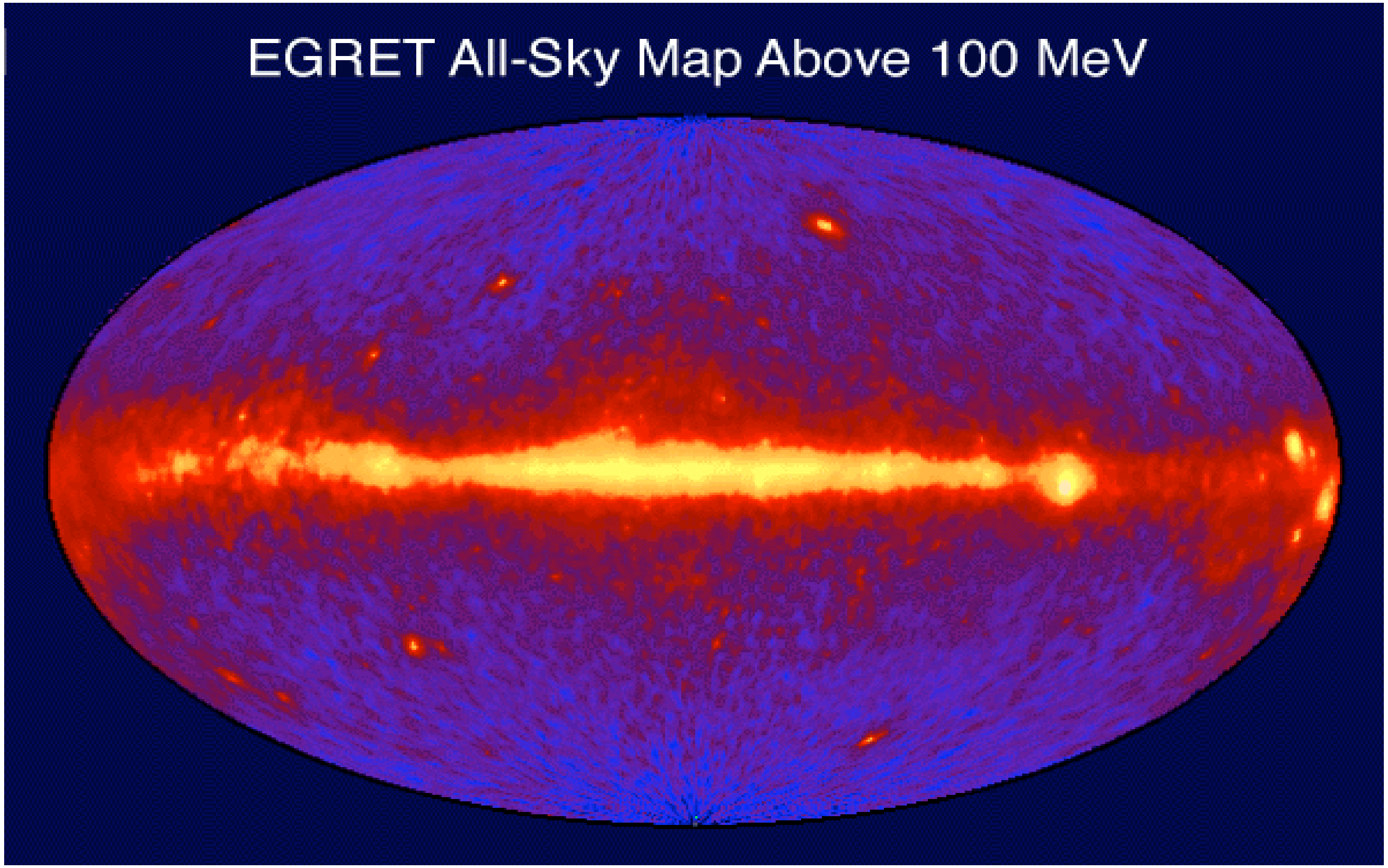


Figure IV-1. The EGRET Instrument

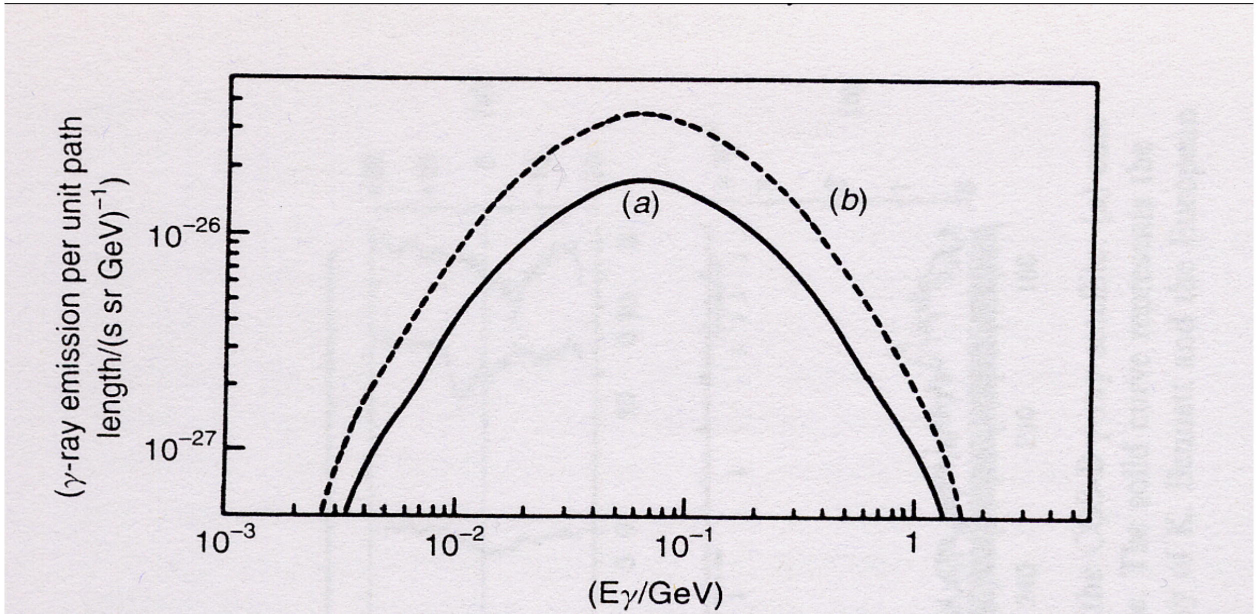
EGRET

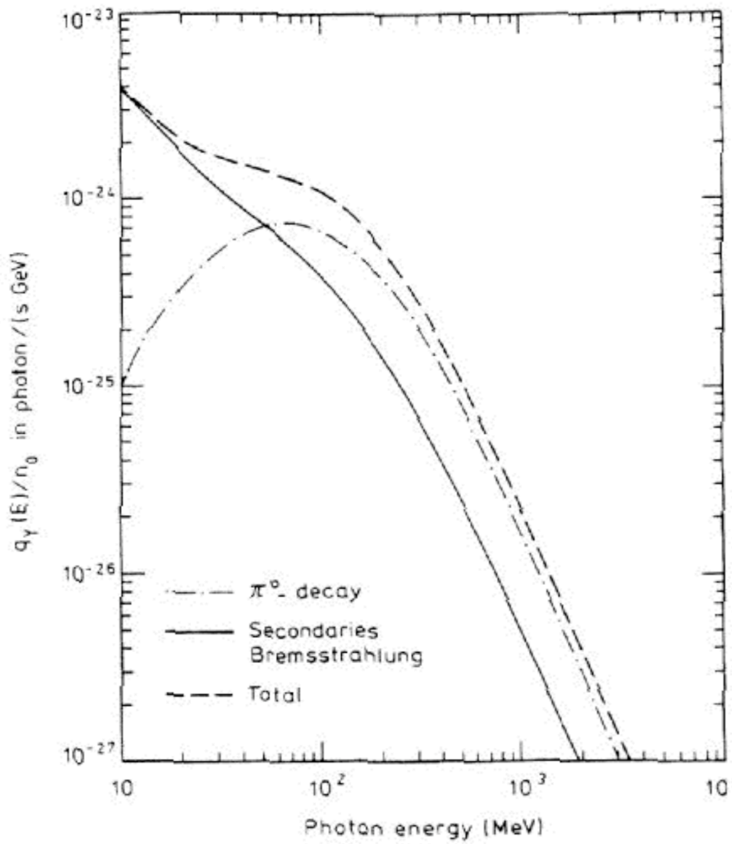
- 1991-2000
- 30 MeV - 30 GeV
- AGN, GRB, Unidentified Sources, Diffuse Bkg

Gamma-Ray Astrophysics



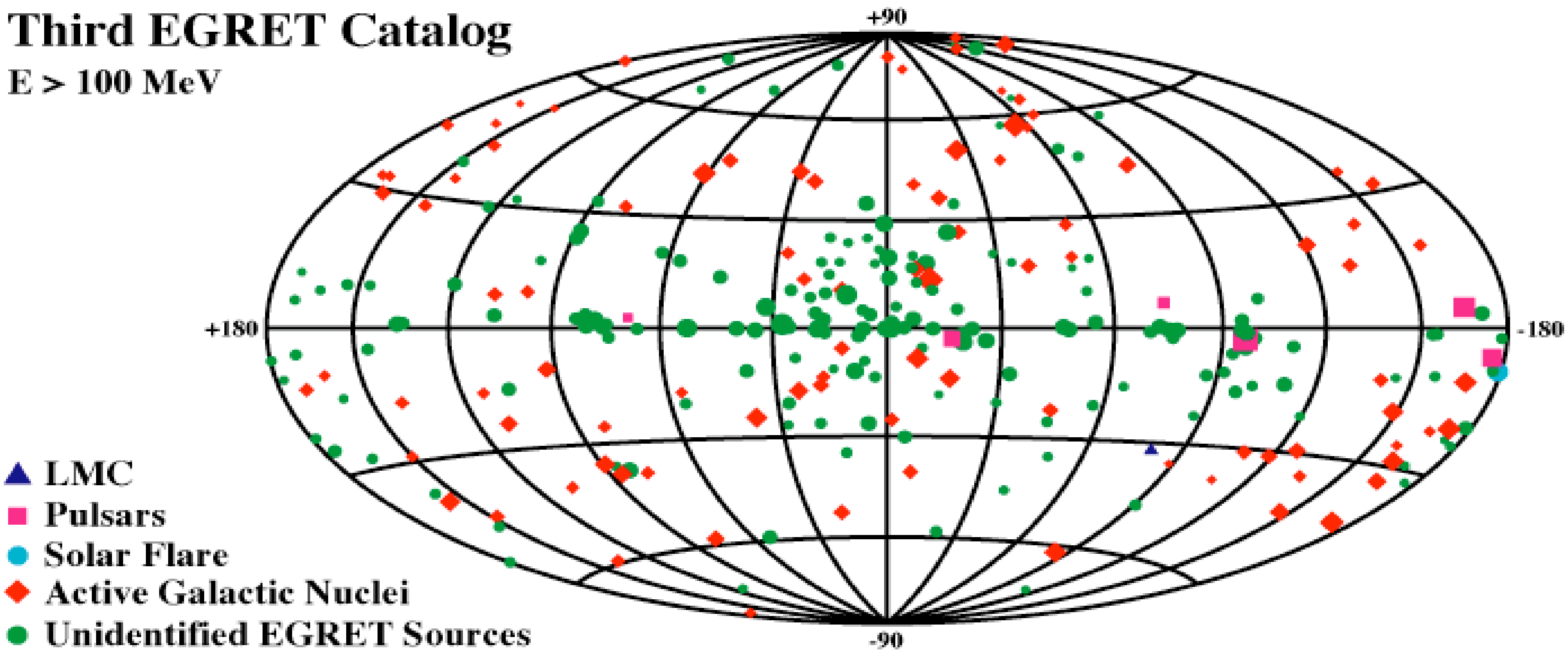
Pion Decay



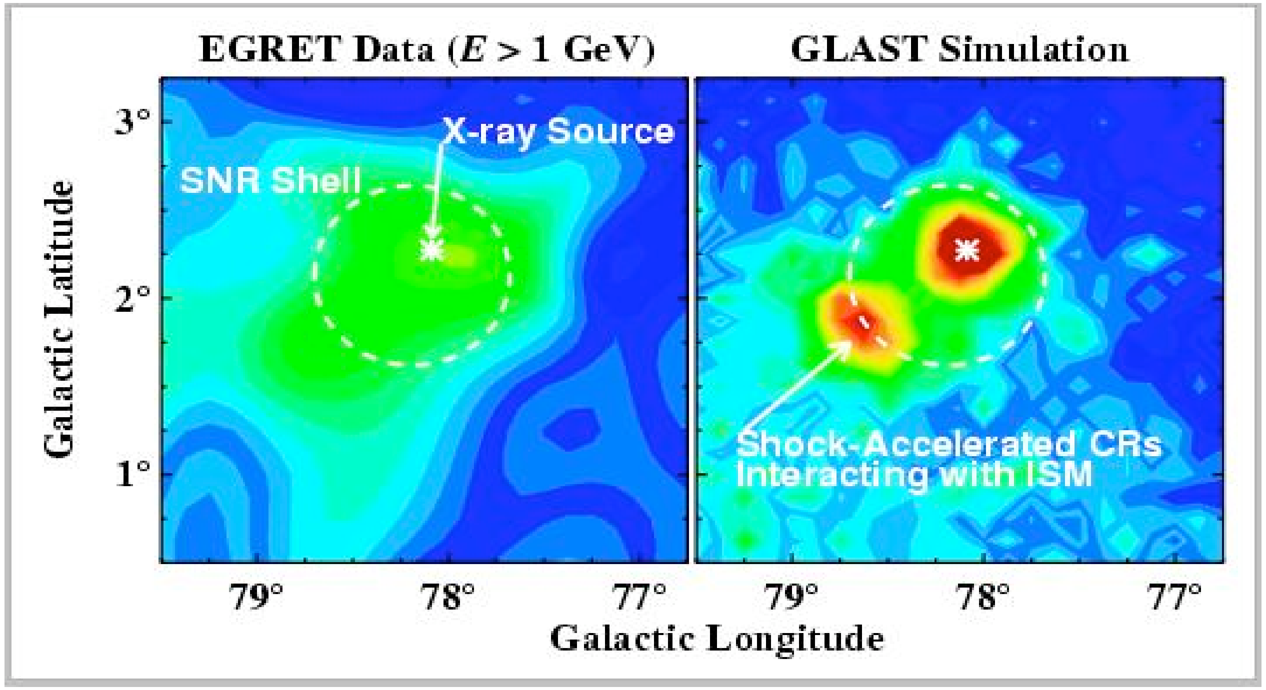


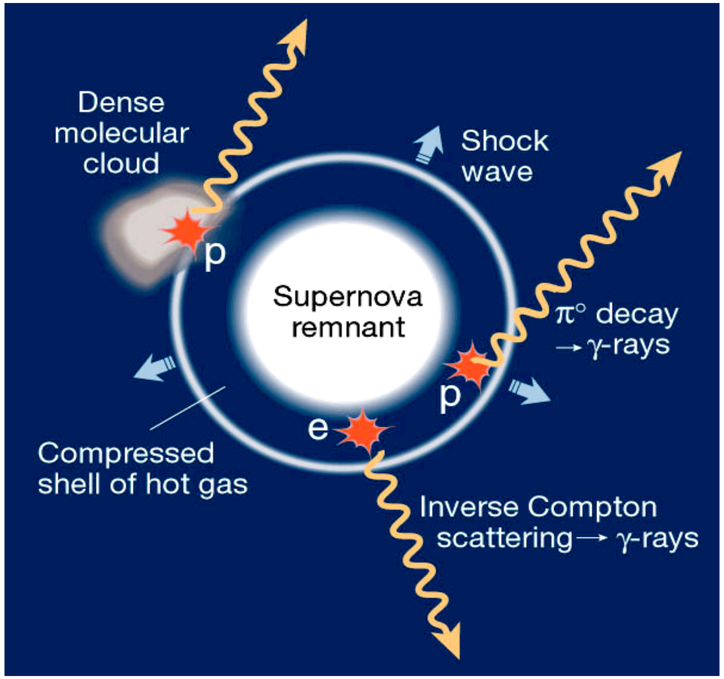
Decay of neutral pion →2 γ

Gamma-Ray Astrophysics

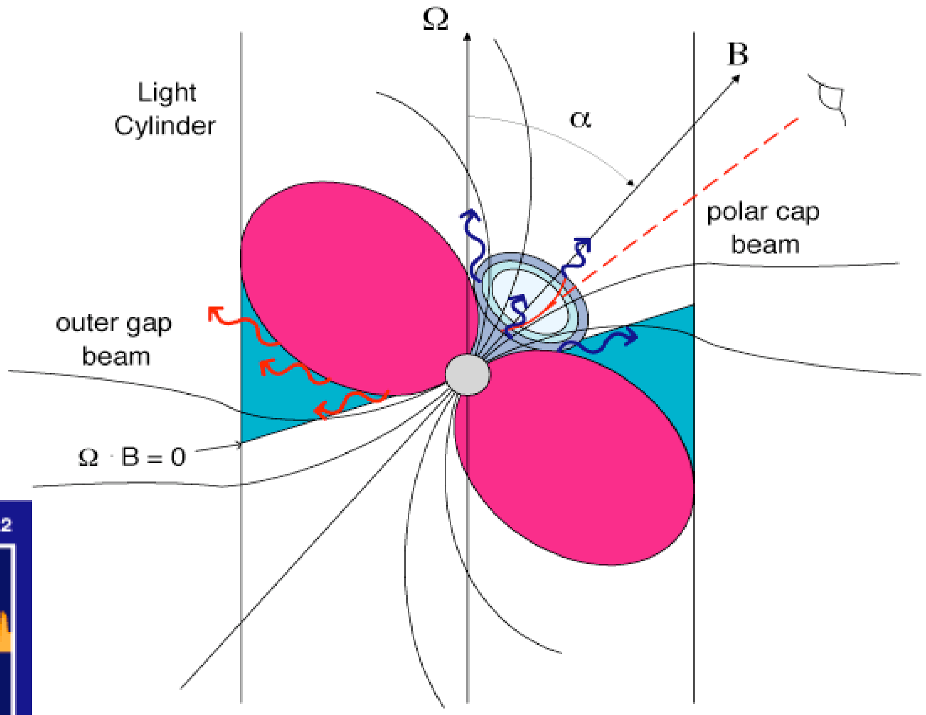


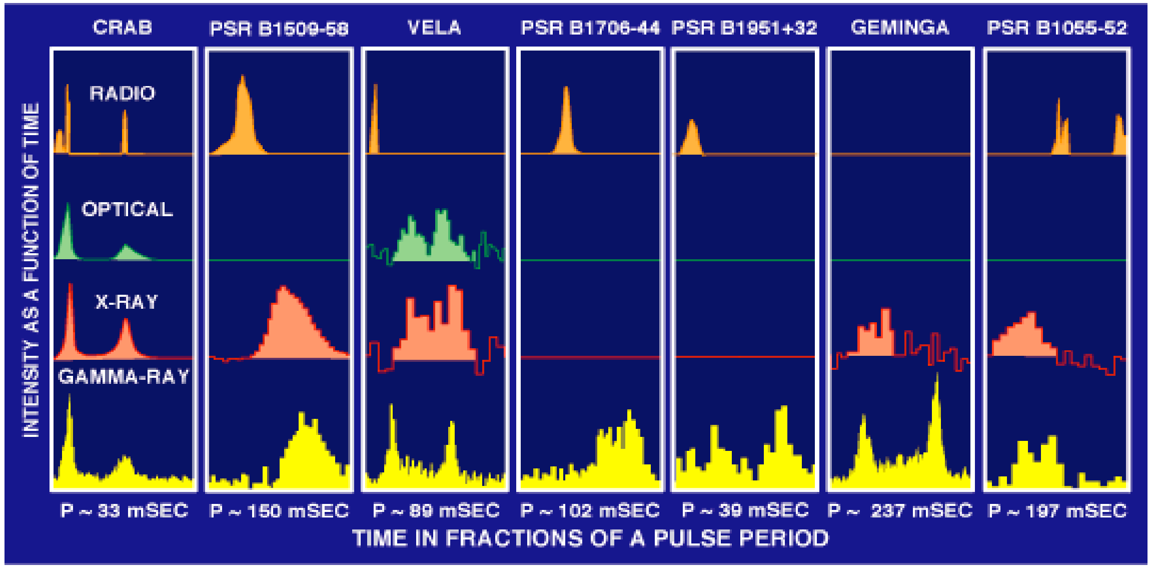
Supernova Remnants



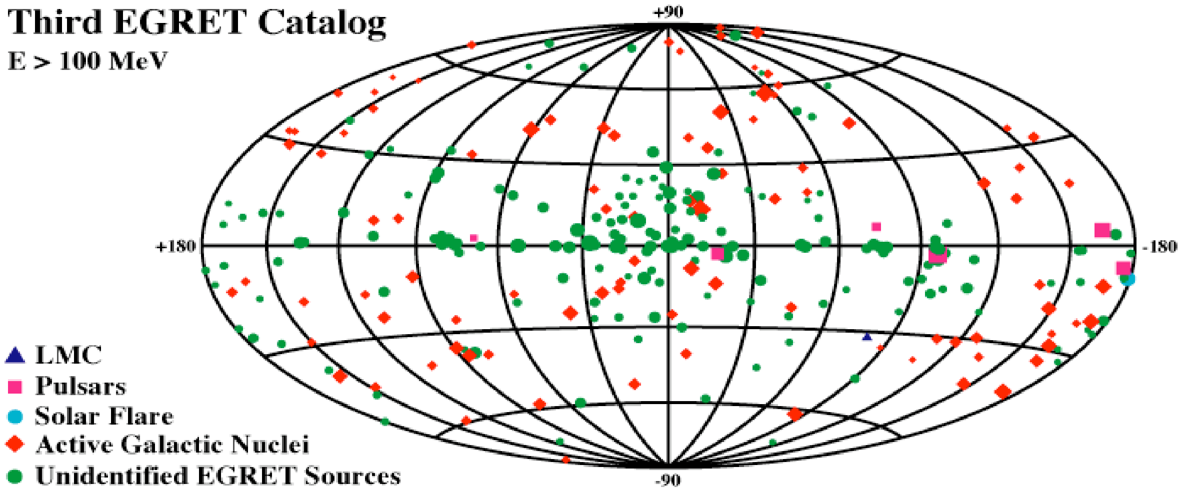


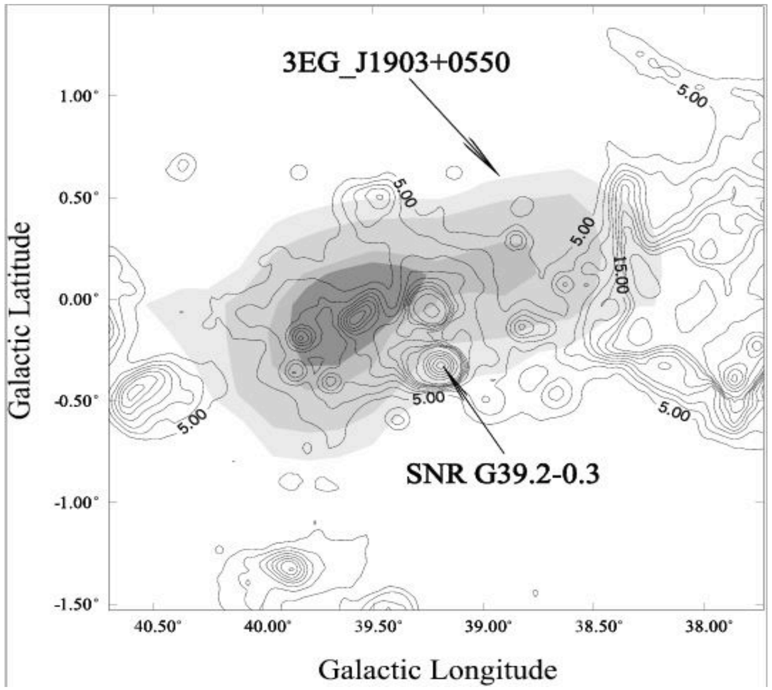
Pulsars

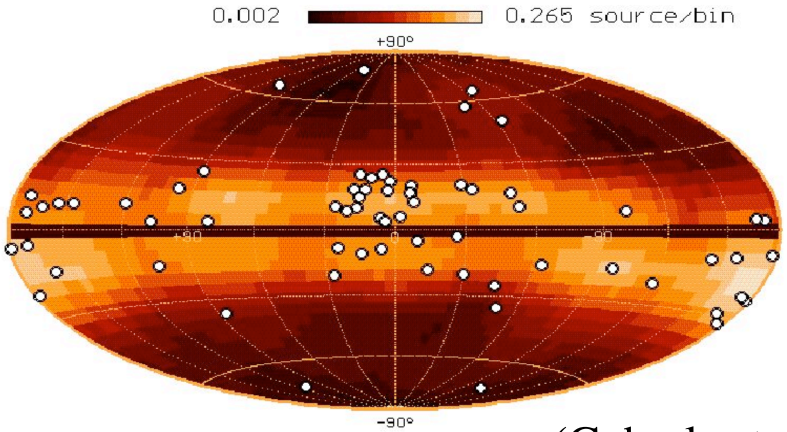

Ω
B
Light
Cylinder
α
polar cap
beam
outer gap
beam
Ω · B = 0


CRAB
PSR B1509-58
VELA
PSR B1706-44
PSR B1951+32
GEMINGA
PSR B1055-52
RADIO
OPTICAL
X-RAY
GAMMA-RAY
INTENSITY AS A FUNCTION OF TIME
P ~ 33 mSEC
P ~ 150 mSEC
P ~ 89 mSEC
P ~ 102 mSEC
P ~ 39 mSEC
P ~ 237 mSEC
P ~ 197 mSEC
TIME IN FRACTIONS OF A PULSE PERIOD

Unidentified Gamma-Ray Sources



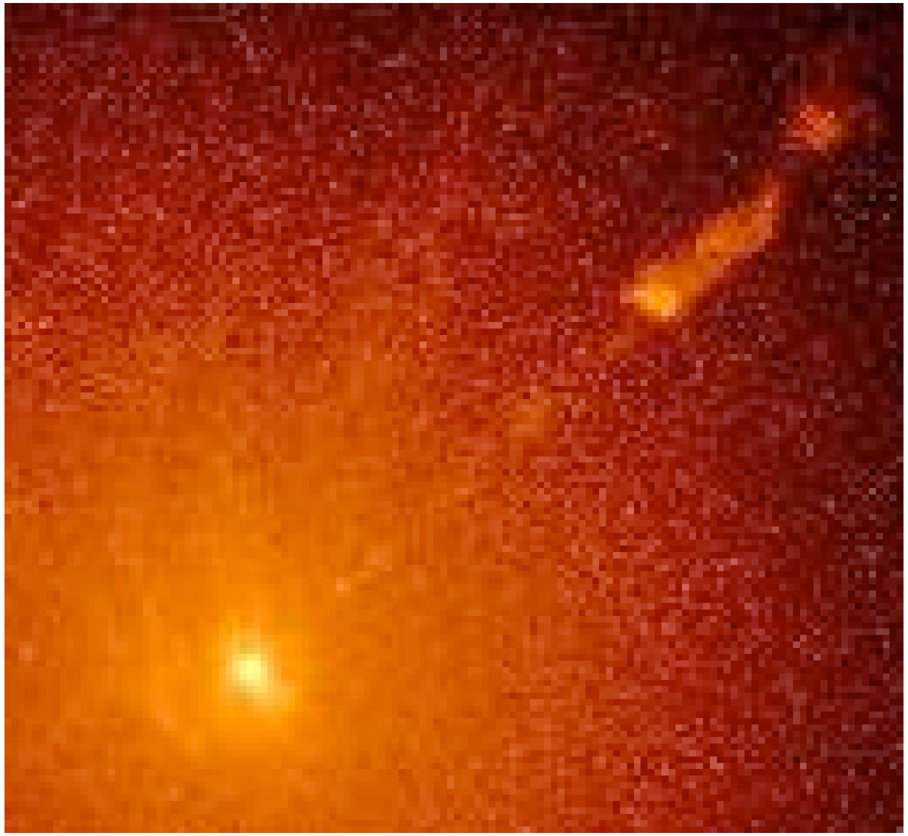


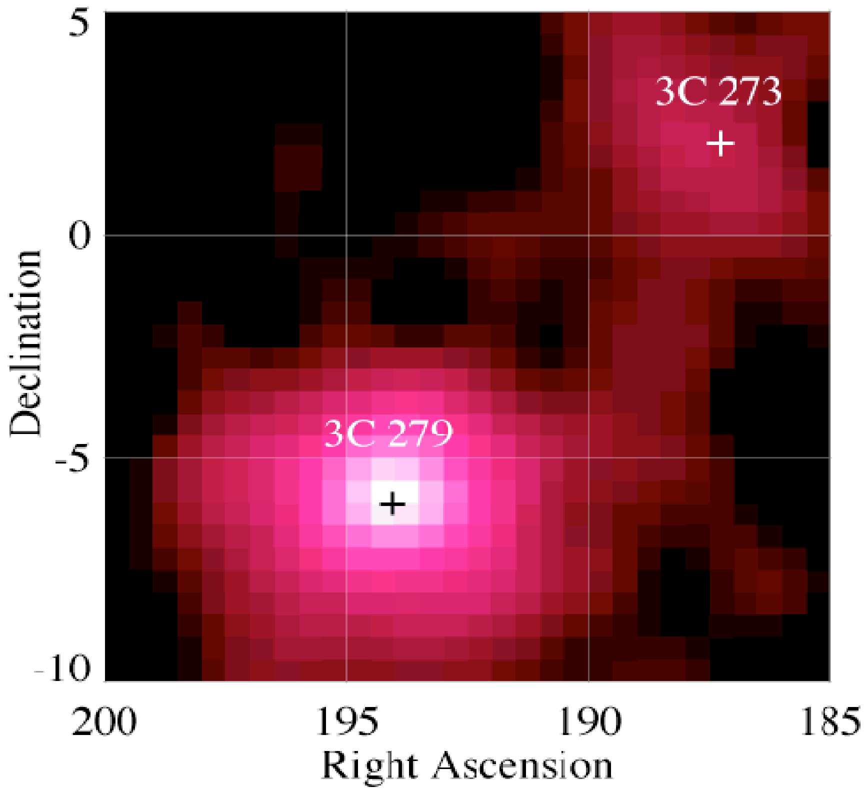


(Butt et al. 2002)

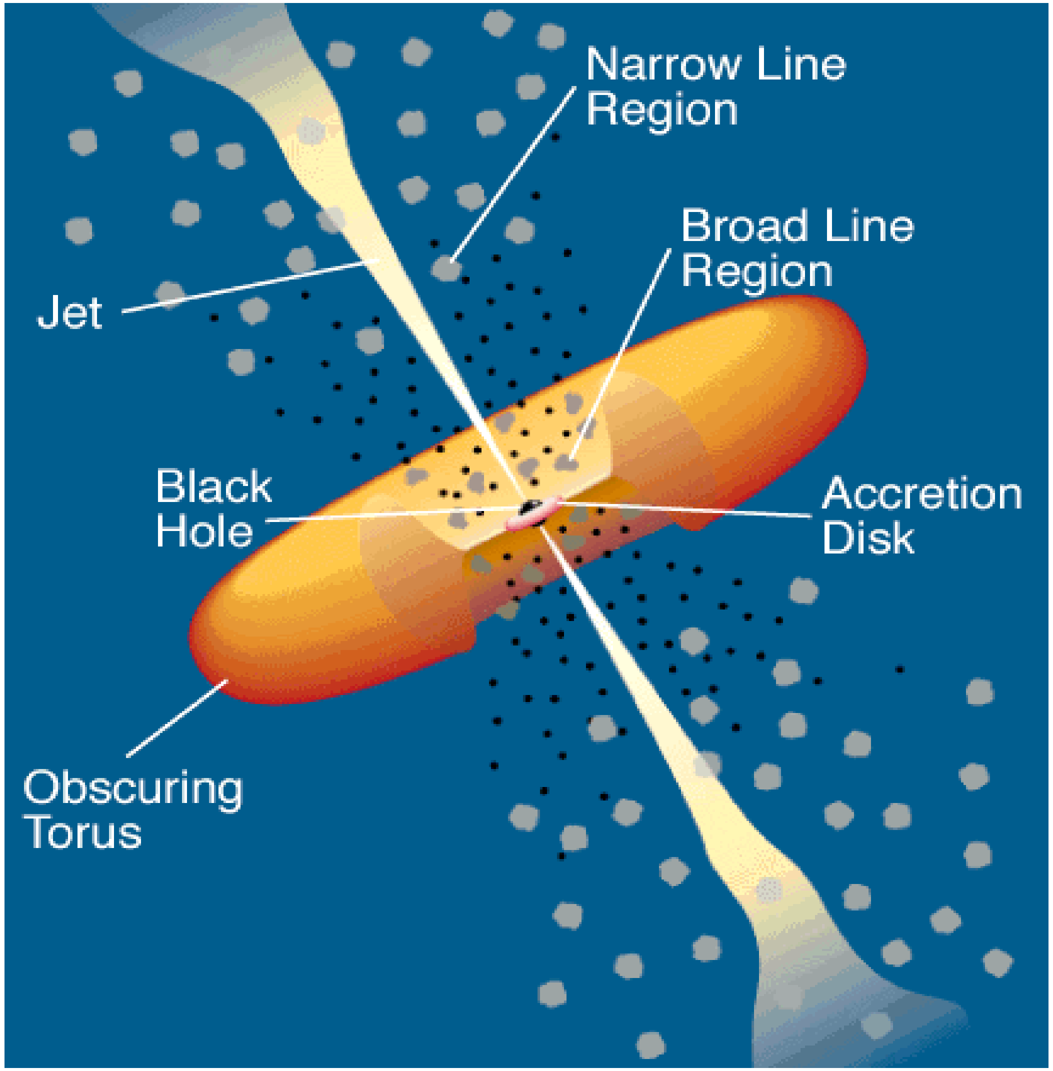
(Gehrels et al. 2000)

Active Galactic Nuclei

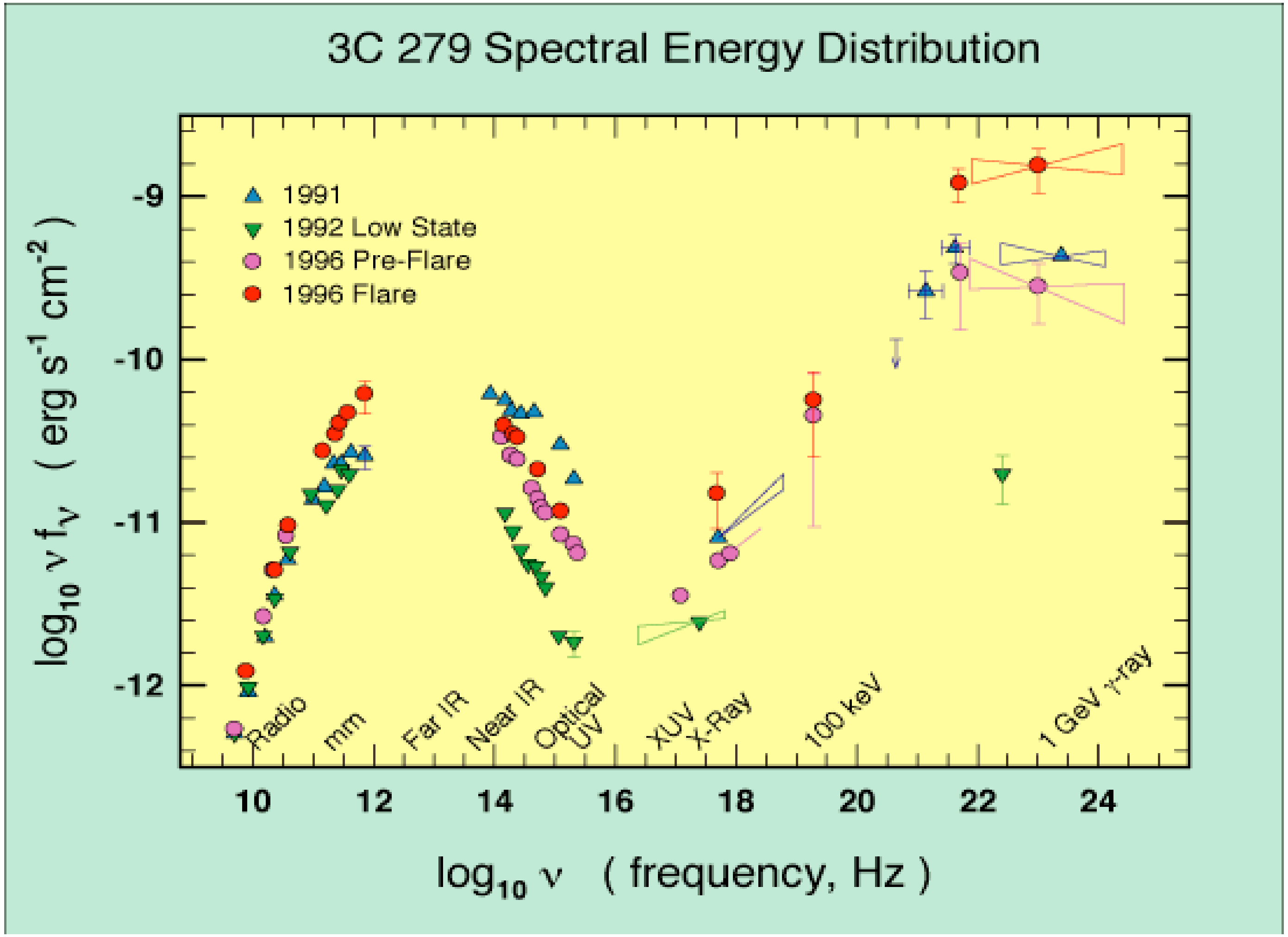




Active Galactic Nuclei



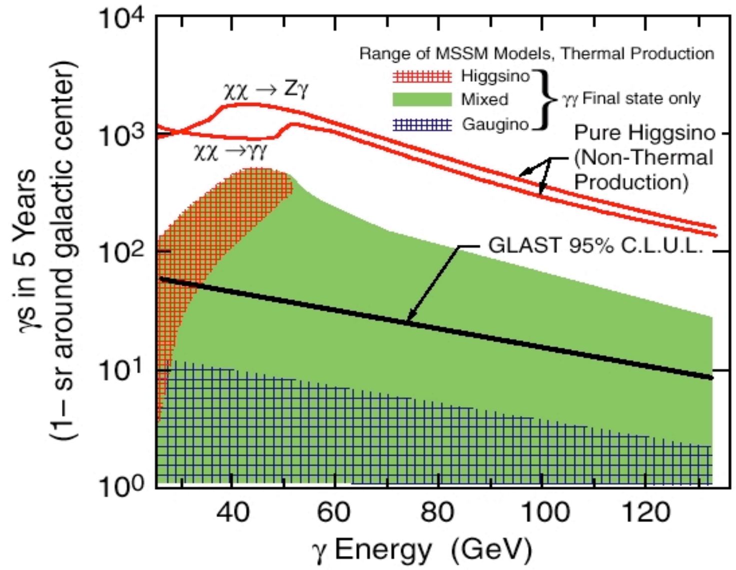
AGN spectra

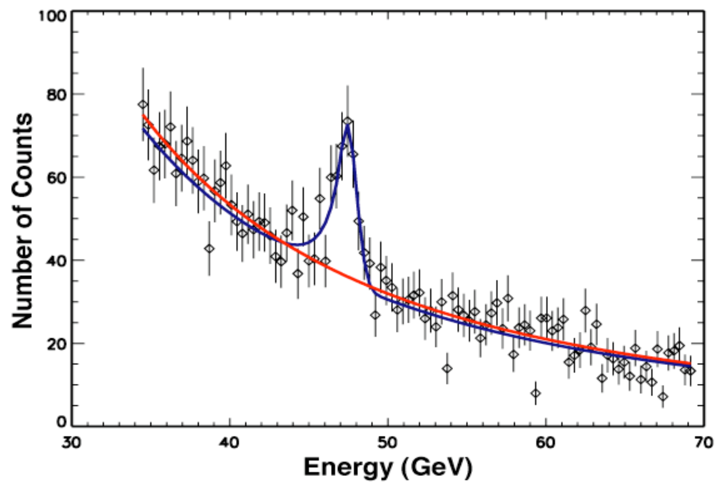

3C 279 Spectral Energy Distribution
1991
1992 Low State
1996 Pre-Flare
1996 Flare
log10 ν fν (erg s-1 cm-2)
-9
-10
-11
-12
Radio
mm
Far IR
Near IR
Optical
UV
XUV
X-Ray
100 keV
1 GeV γ-ray
10
12
14
16
18
20
22
24
log10 ν (frequency, Hz)

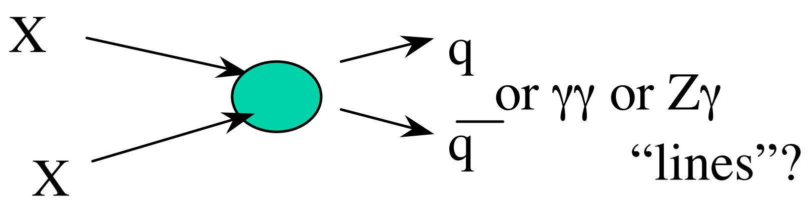
Dark Matter

If the SUSY LSP is the galactic dark matter there may be observable halo annihilations into mono-energetic gamma rays.

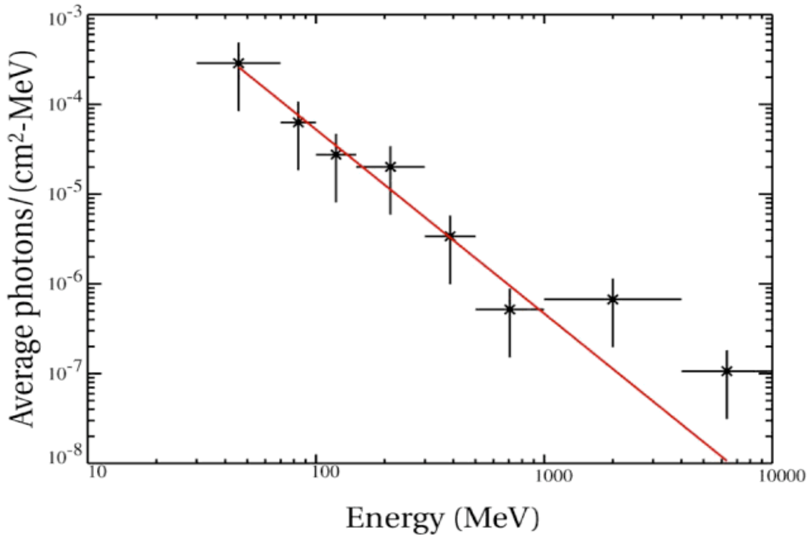
- Constrain cold dark matter candidates
- Identify relatively narrow spectral lines





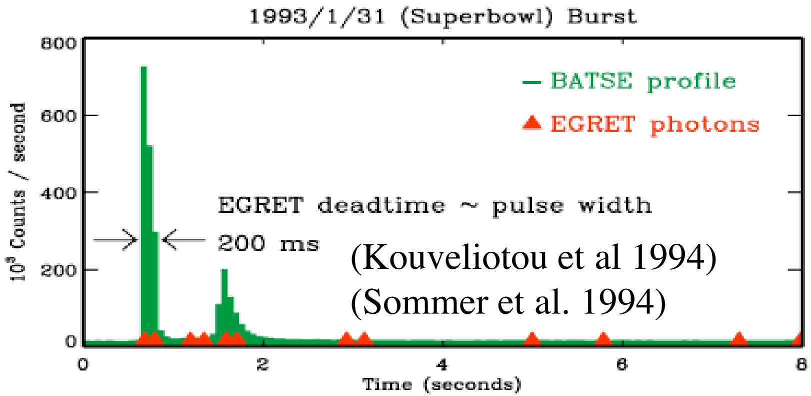


Gamma-Ray Bursts



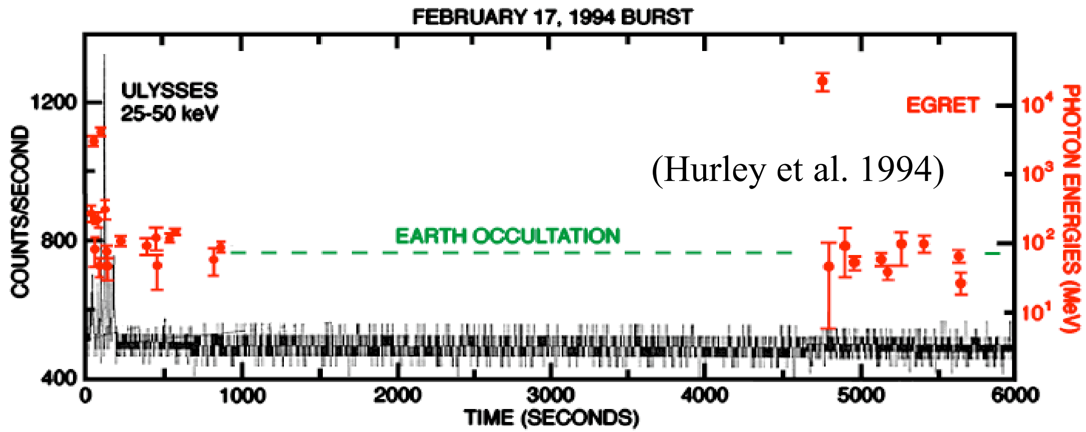
(Dingus et al. 1998)

Prompt Emission (GRB 930131)



(Kouveliotou et al 1994)
(Sommer et al. 1994)

Delayed Emission (GRB 940217)

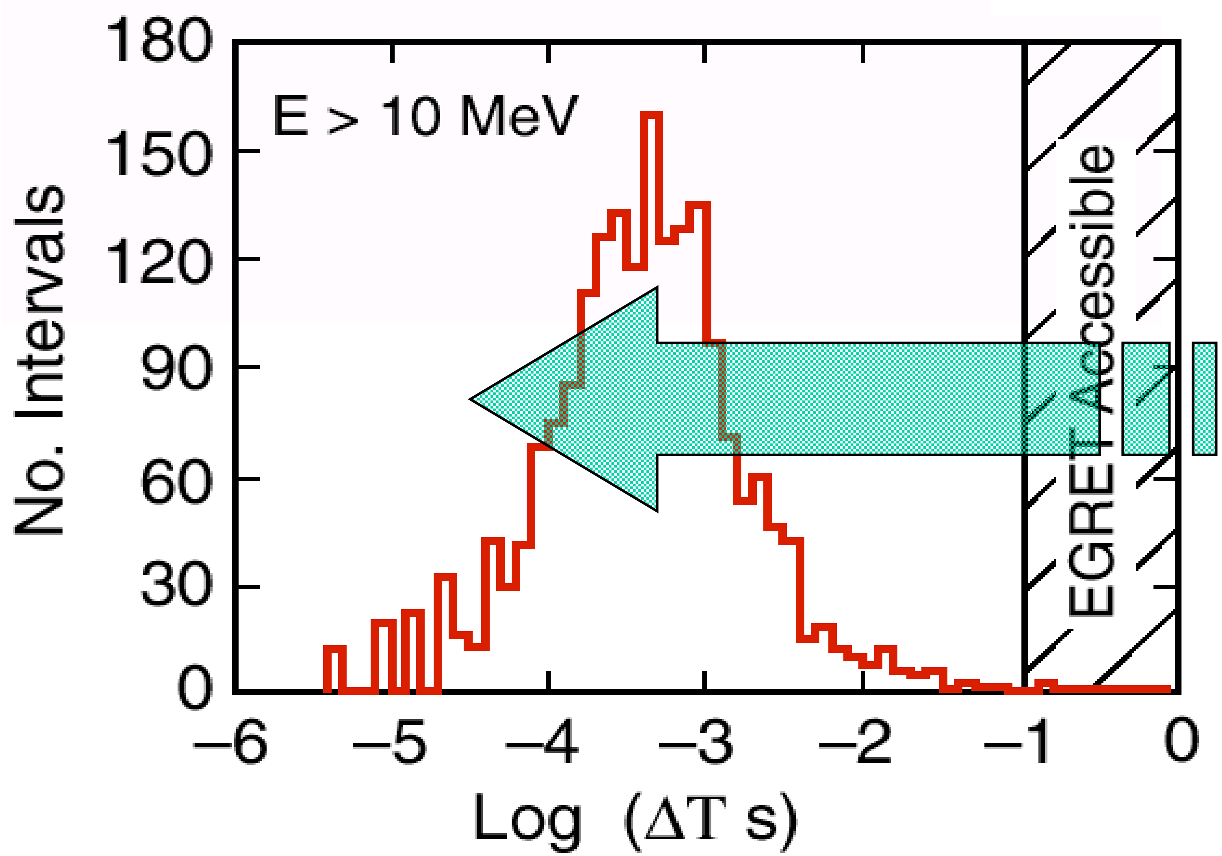


(Hurley et al. 1994)

- EGRET discovered high energy GRB afterglow
  - only one burst
  - dead time limited observations
- GLAST will observe many more high energy afterglows
  - strong constraint to GRB models

GRBs and Instrument Deadtime

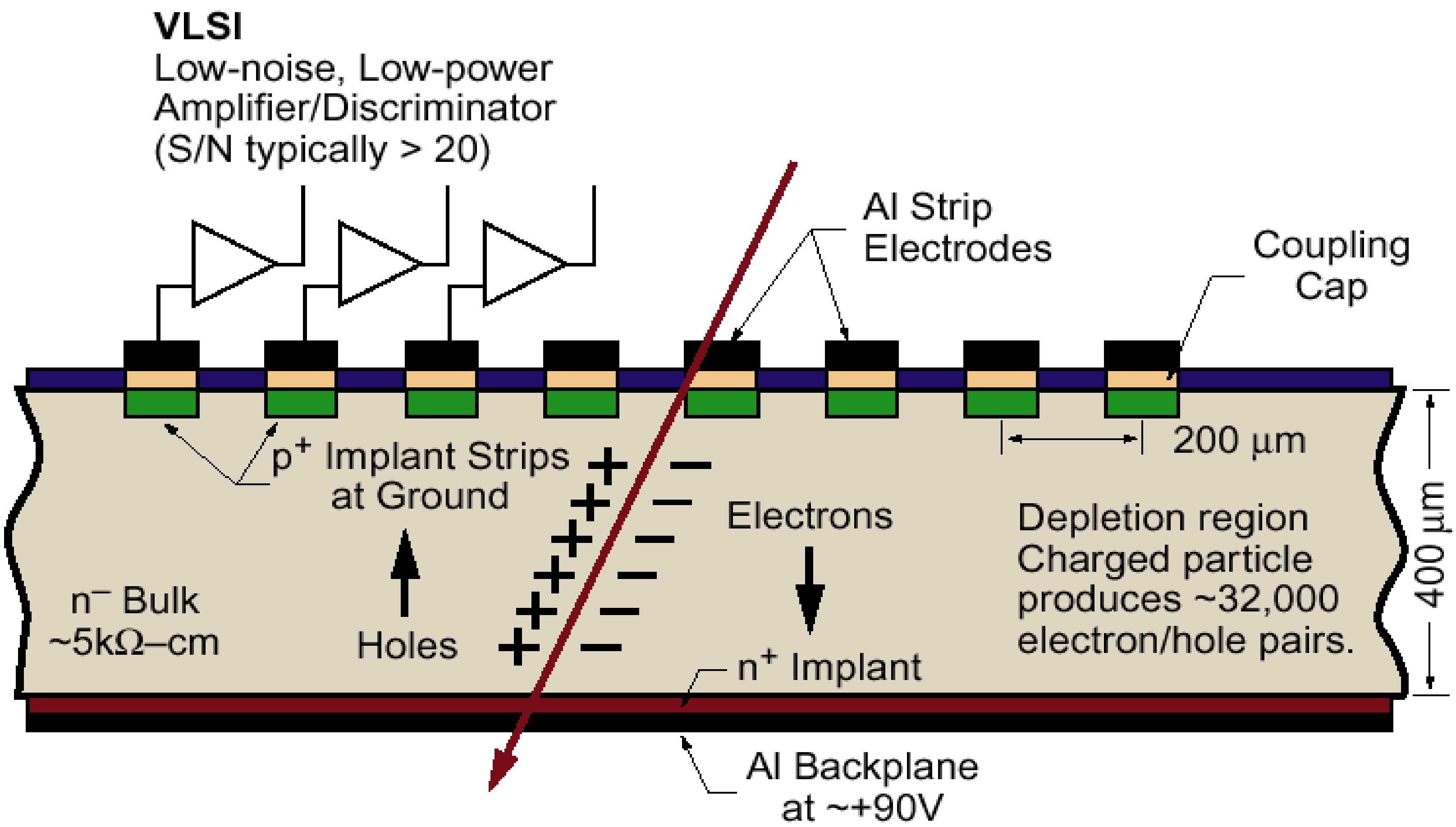
Distribution for the 20th brightest burst in a year



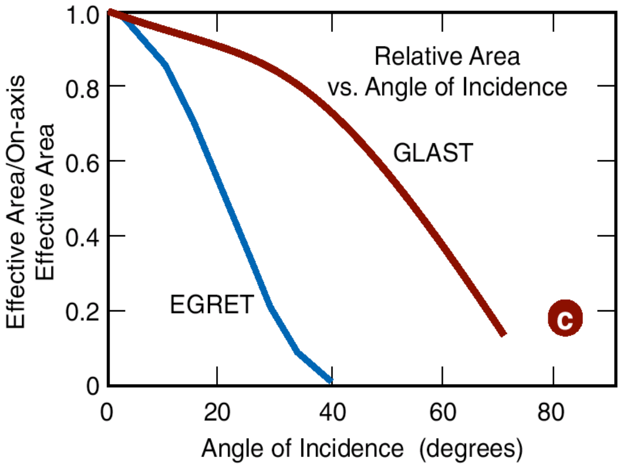
Time between consecutive arriving photons

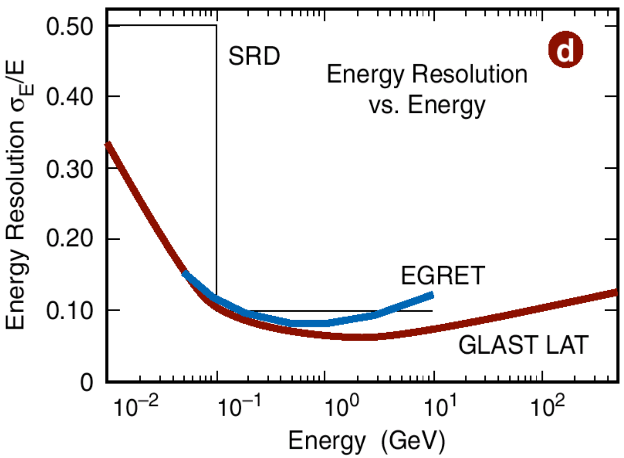
LAT will open a wide window on the study of the high energy behavior of bursts.

Silicon Strip Detector Principle



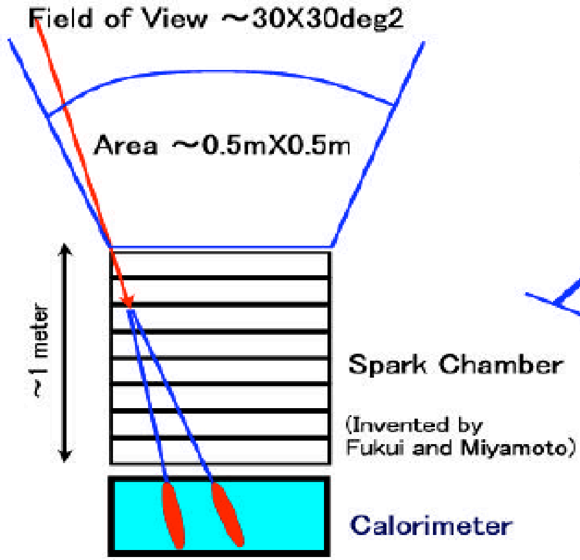
Field of View and Instrument Aspect Ratio



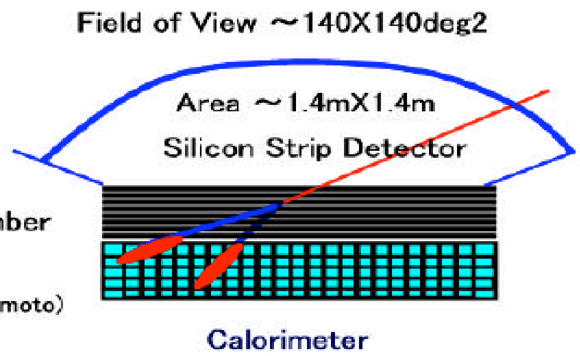


The aspect ratio (Area/Height) then governs the main field of view of the tracker:

EGRET had a relatively small aspect ratio
AGILE and GLAST have a large aspect ratio



EGRET on Compton GRO
(1991-2000)

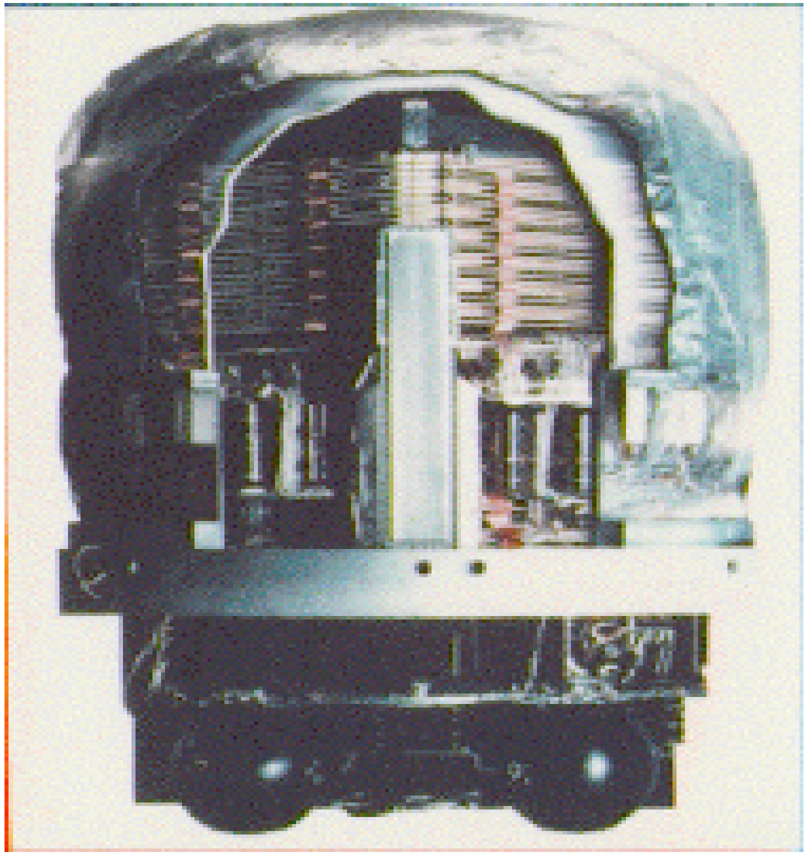


GLAST Large Area Telescope
(2006-2015)

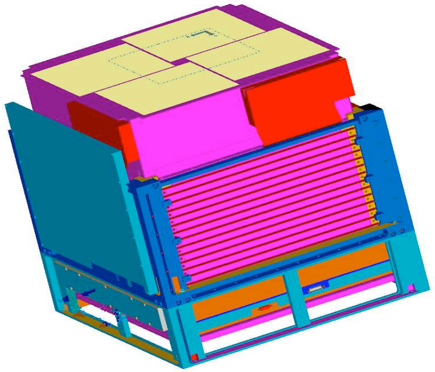
AGILE Mission

- AGILE is an ASI Small Scientific Mission dedicated to gamma-ray astrophysics
- (Imaging 30 MeV-50 GeV, 10-40 keV)
- Planned to be operational in 2004
- Only mission entirely dedicated to gamma-ray astrophysics (E>30 MeV) during the period 2004-2006
- Emphasis to rapid reaction to transients
- Multiwavelength follow-up program
- Small Mission with a Guest Observer Program

EGRET and AGILE



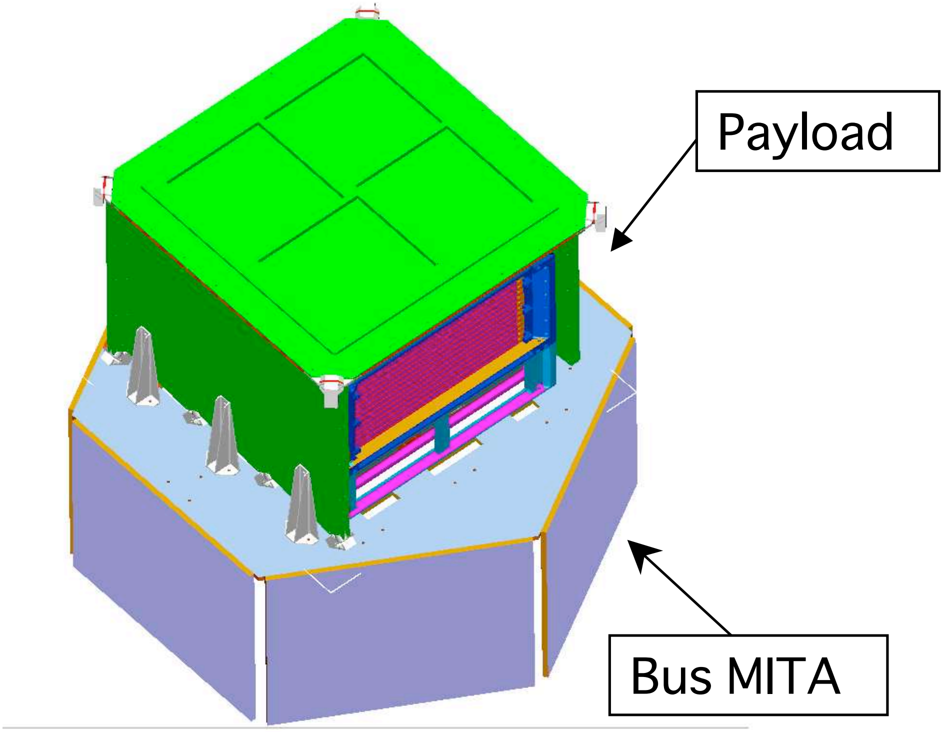
EGRET

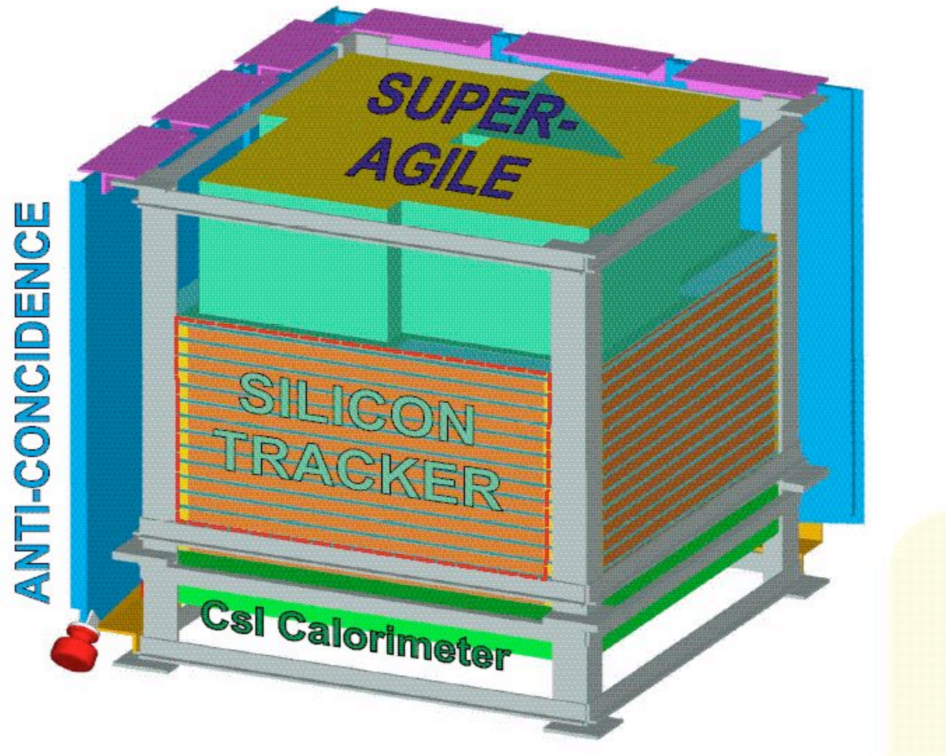


AGILE

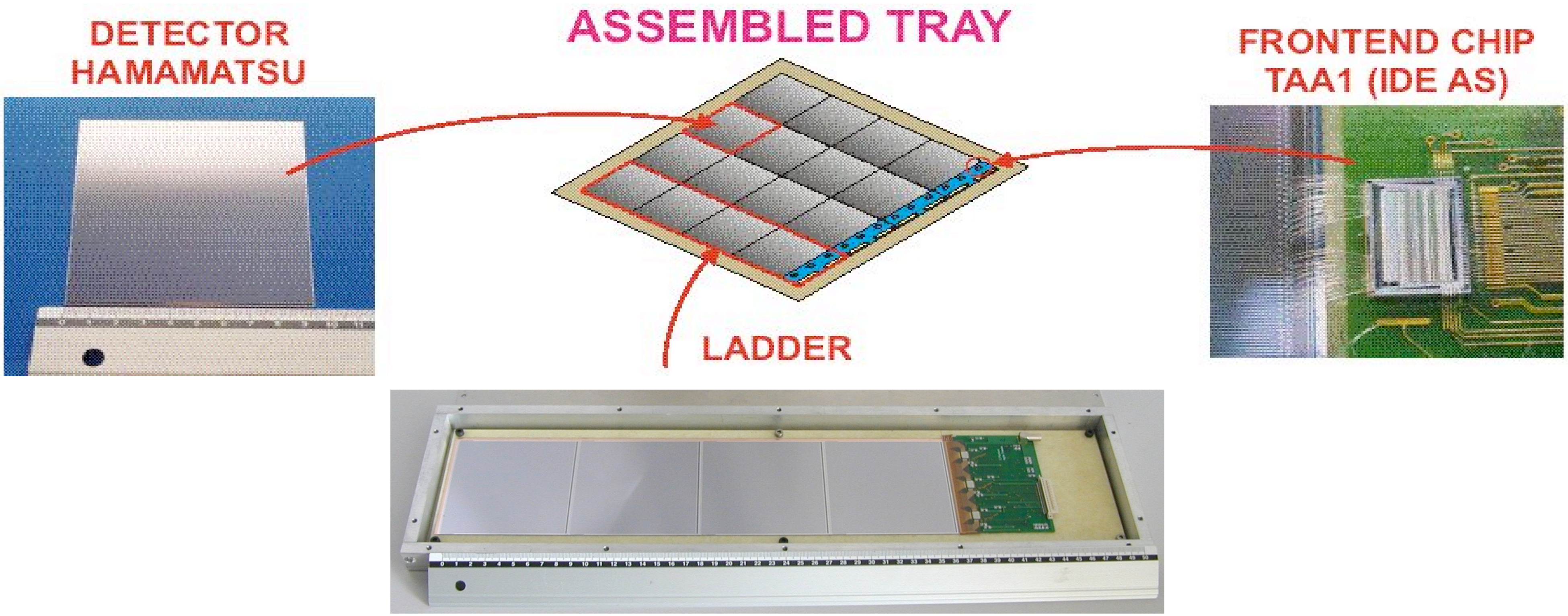
	EGRET	AGILE
Mass	1830 kg	100 kg
Field of View	0.15 π	0.8 π
Dead Time	100 ms	0.1 ms
Energy Range	0.03- 30 GeV	0.03 - 50 GeV 17 - 40 keV

AGILE Instrument





The Silicon Tracker

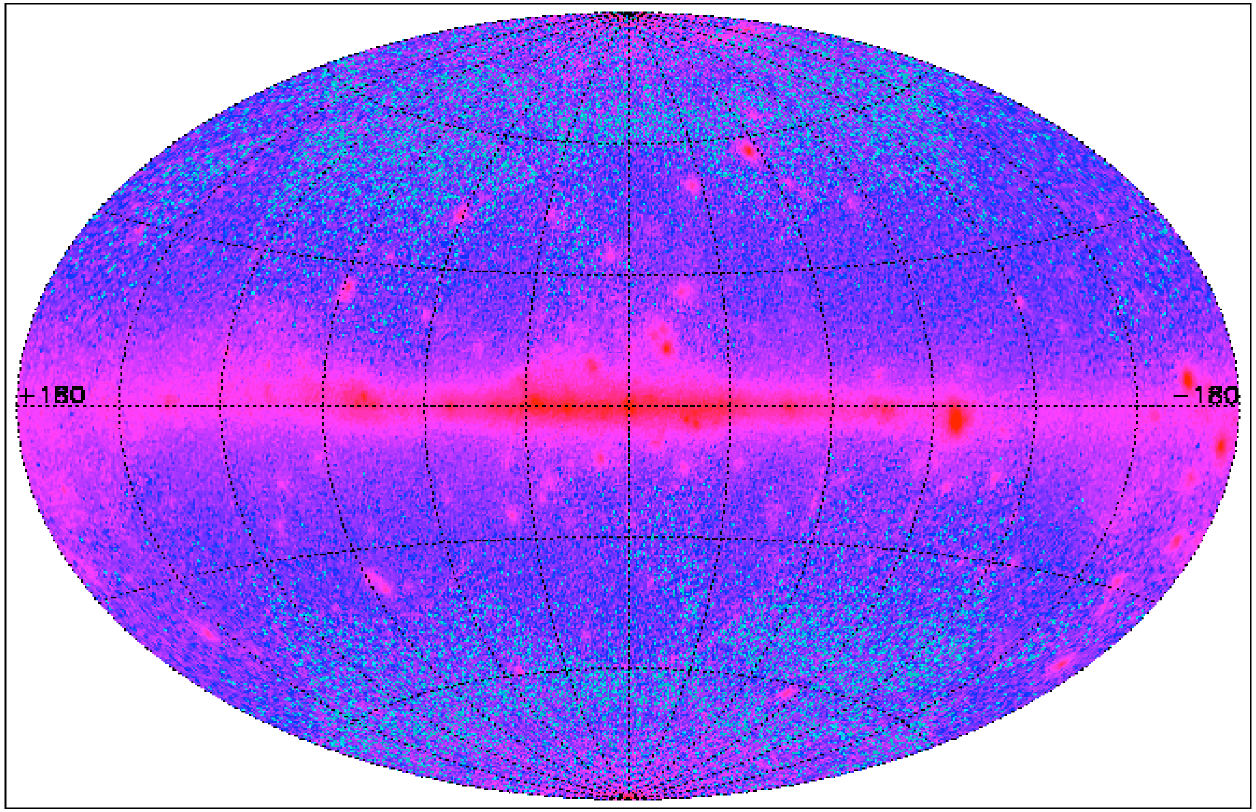


AGILE scientific capabilities

- Excellent gamma-ray imager
  (Spatial resol. ~ 40_m; FOV ~ 1/5 of the sky)
- Simultaneous hard X-ray/gamma-ray data
- Fast Timing (~ a few microseconds)
- Burst Search Procedure
- Large Field-of-View : GRID: ~ 3 sr SA: ~ 1 sr
- Optimal Temporal Resolution :
  (1) absolute timing ~ 2 _s
  (2) deadtime ~ 100 _s (GRID)
  ~ 5 _s (SA, MCAL)
- Simultaneous hard X-ray / gamma-ray information

AGILE Simulated all-sky intensity map

AGILE all−sky simulated intensity map − 6 pnts, 4 weeks eff. time each



GLAST – Basic Information

GLAST: Gamma-ray Large Area Space Telescope is the observatory, not the instruments.

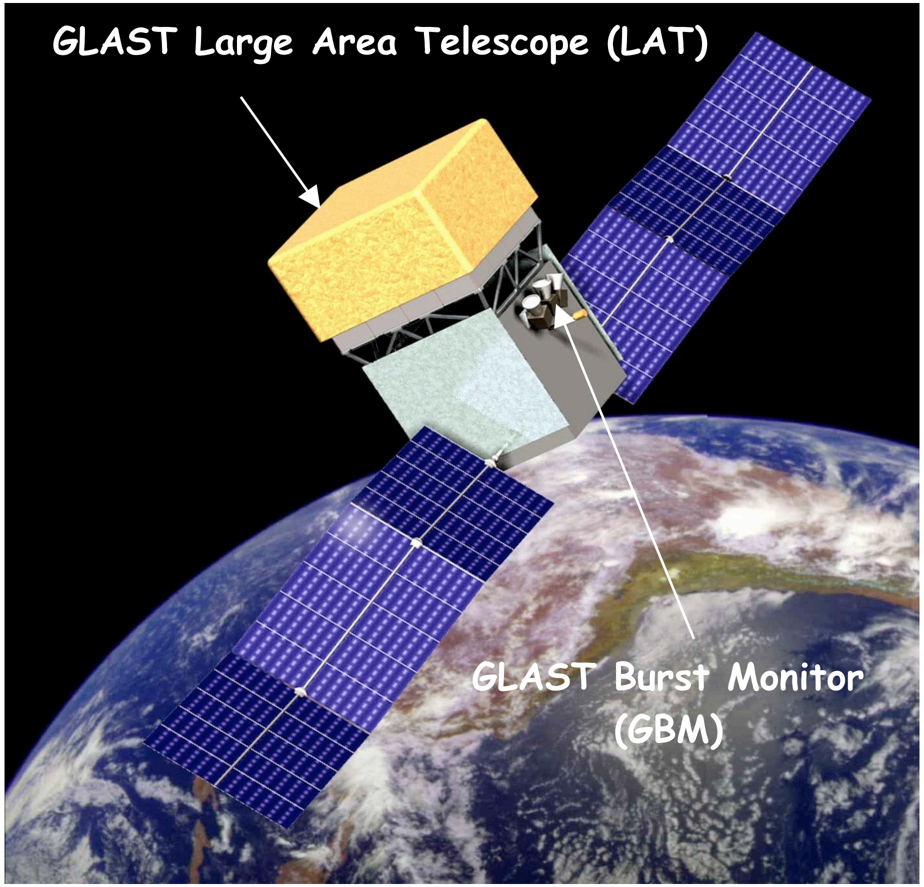
Two GLAST instruments:

LAT: 20 MeV – >300 GeV (LAT was originally called GLAST by itself)

GBM: 10 keV – 25 MeV

Launch: February 2007

Lifetime: 5 years minimum

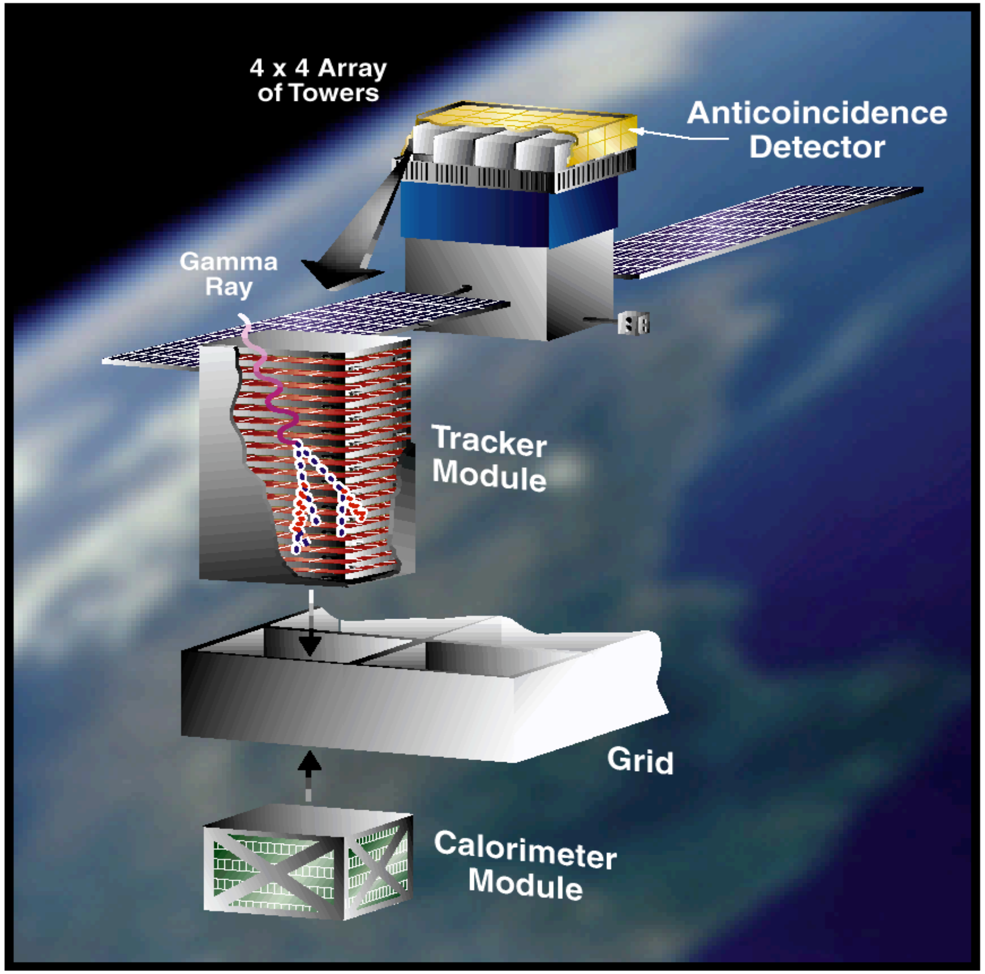


GLAST High Energy Capabilities

- Huge FOV (~20% of sky)
- Broadband (4 decades in energy, including unexplored region > 10 GeV)
- Unprecedented PSF for gamma rays (factor > 3 better than EGRET for E>1 GeV)
- Large effective area (factor > 4 better than EGRET)
- **Results in factor > 30-100 improvement in sensitivity**
- No expendables → long mission without degradation

Overview of LAT

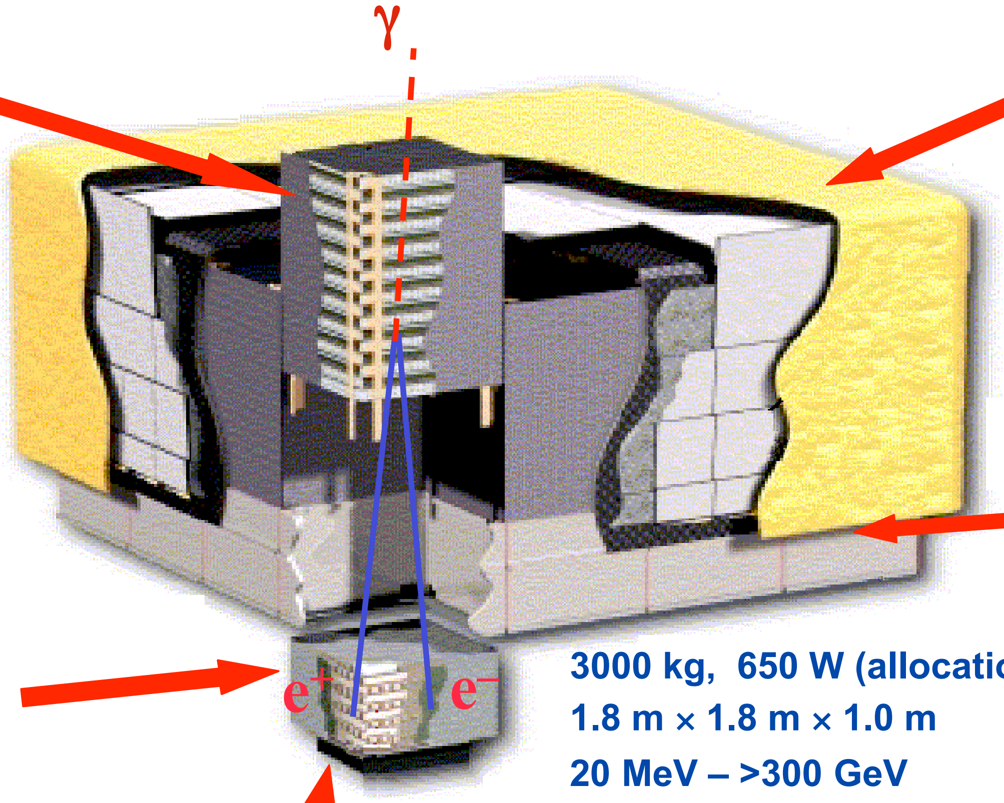
- 4x4 array of identical towers Advantages of modular design.
- Precision Si-strip Tracker (TKR) Detectors and converters arranged in 18 XY tracking planes. Measure the photon direction.
- Hodoscopic CsI Calorimeter(CAL) Segmented array of CsI(Tl) crystals. Measure the photon energy.
- Segmented Anticoincidence Detector (ACD) First step in reducing the large background of charged cosmic rays. Segmentation removes self-veto effects at high energy.
- Electronics System Includes flexible, highly-efficient, multi-level trigger.



Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

GLAST LAT Overview: Design

Si Tracker
pitch = 228 µm
8.8 10^5 channels
12 layers _ 3% X_0
+ 4 layers _ 18% X_0
+ 2 layers



ACD
Segmented scintillator tiles
0.9997 efficiency
⇒ minimize self-veto

Grid (& Thermal Radiators)

3000 kg, 650 W (allocation)
1.8 m × 1.8 m × 1.0 m
20 MeV – >300 GeV

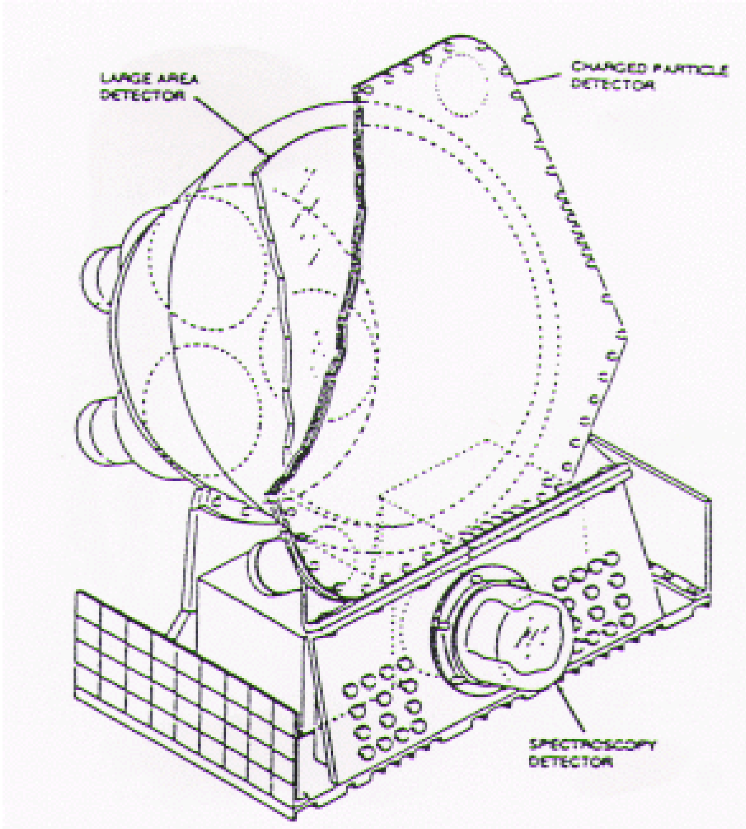
LAT managed at SLAC

CsI Calorimeter
Hodoscopic array
8.4 X_0 8 _ 12 bars
2.0 _ 2.7 _ 33.6 cm
⇒ cosmic-ray rejection
⇒ shower leakage correction

Data acquisition

Flight Hardware & Spares
16 Tracker Flight Modules + 2 spares
16 Calorimeter Modules + 2 spares
1 Flight Anticoincidence Detector
Data Acquisition Electronics + Flight Software

GRB

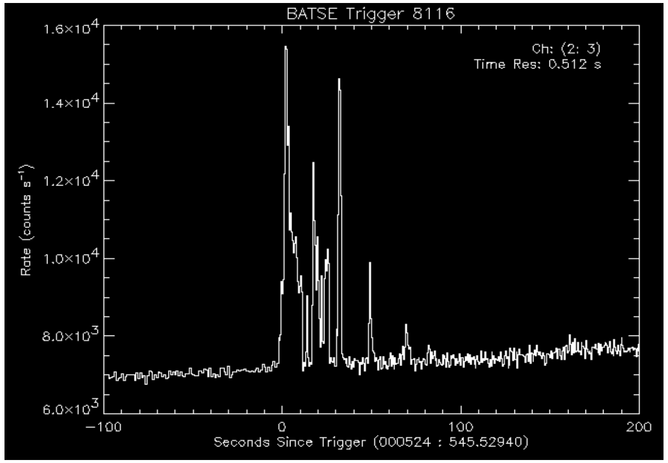


BATSE

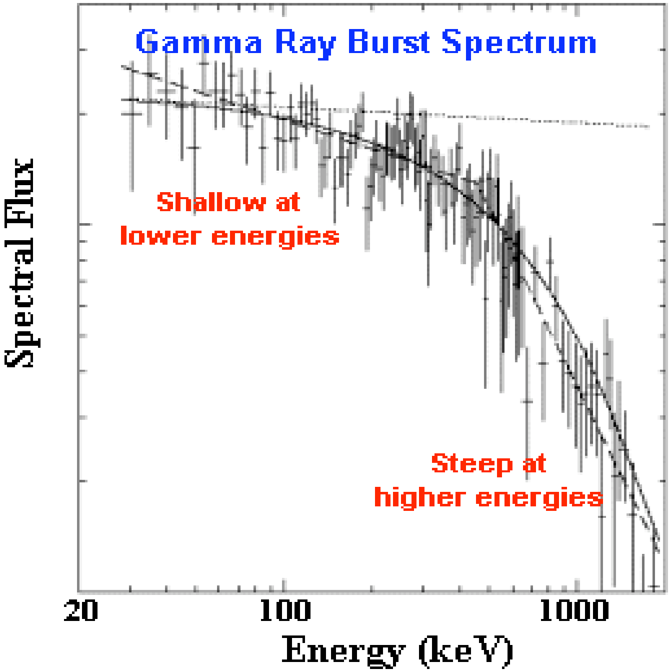
- 20 keV -10 MeV
- GRB, SGR, X-ray sources

GRB

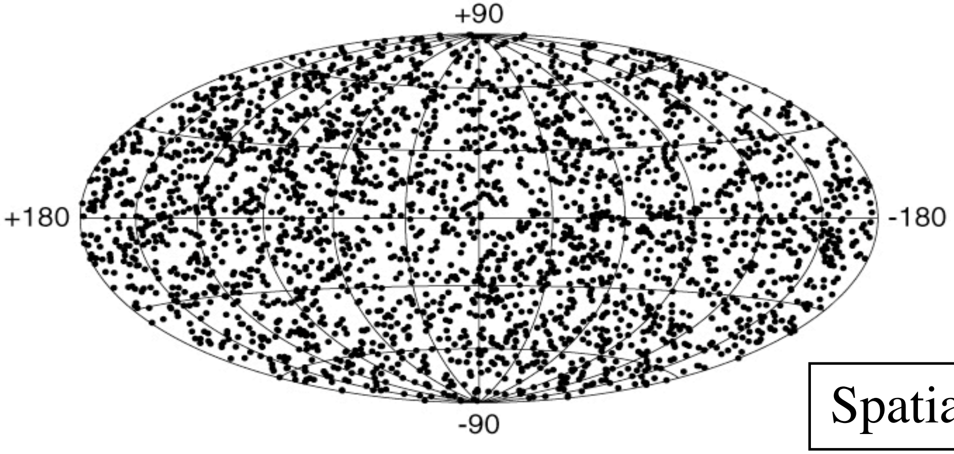
Temporal behaviour



Spectral shape

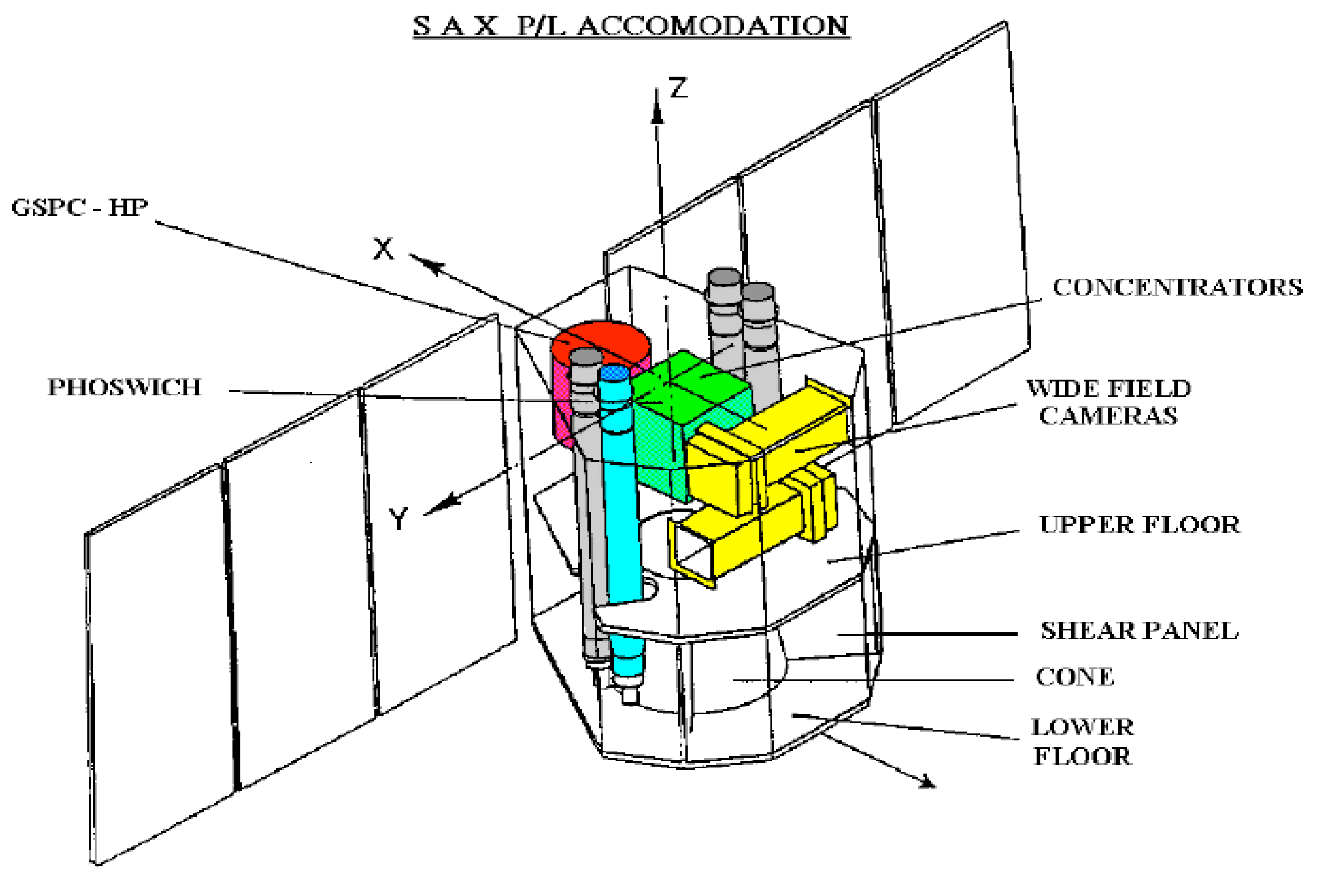


2704 BATSE Gamma-Ray Bursts

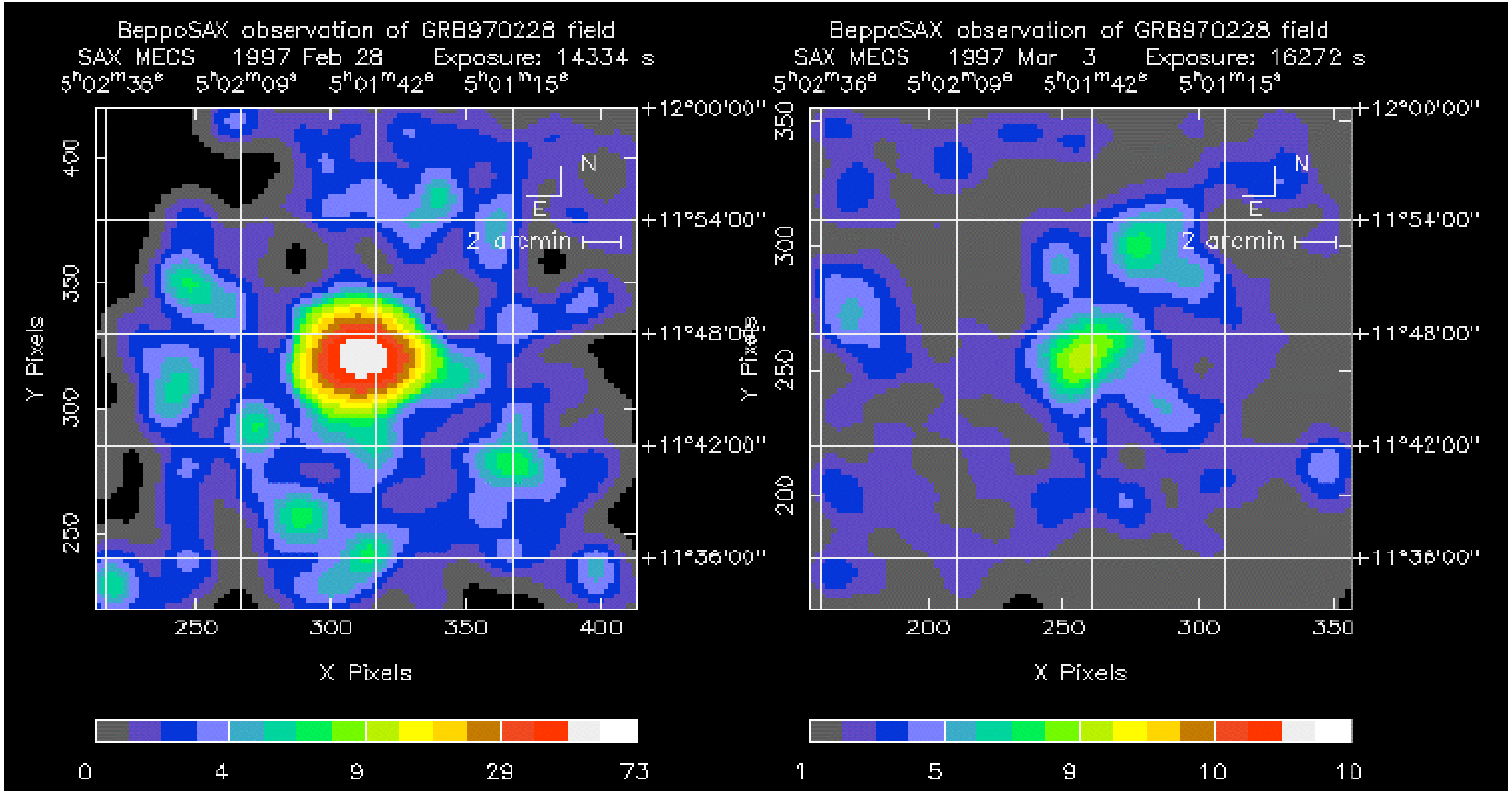


Spatial distribution

GRB

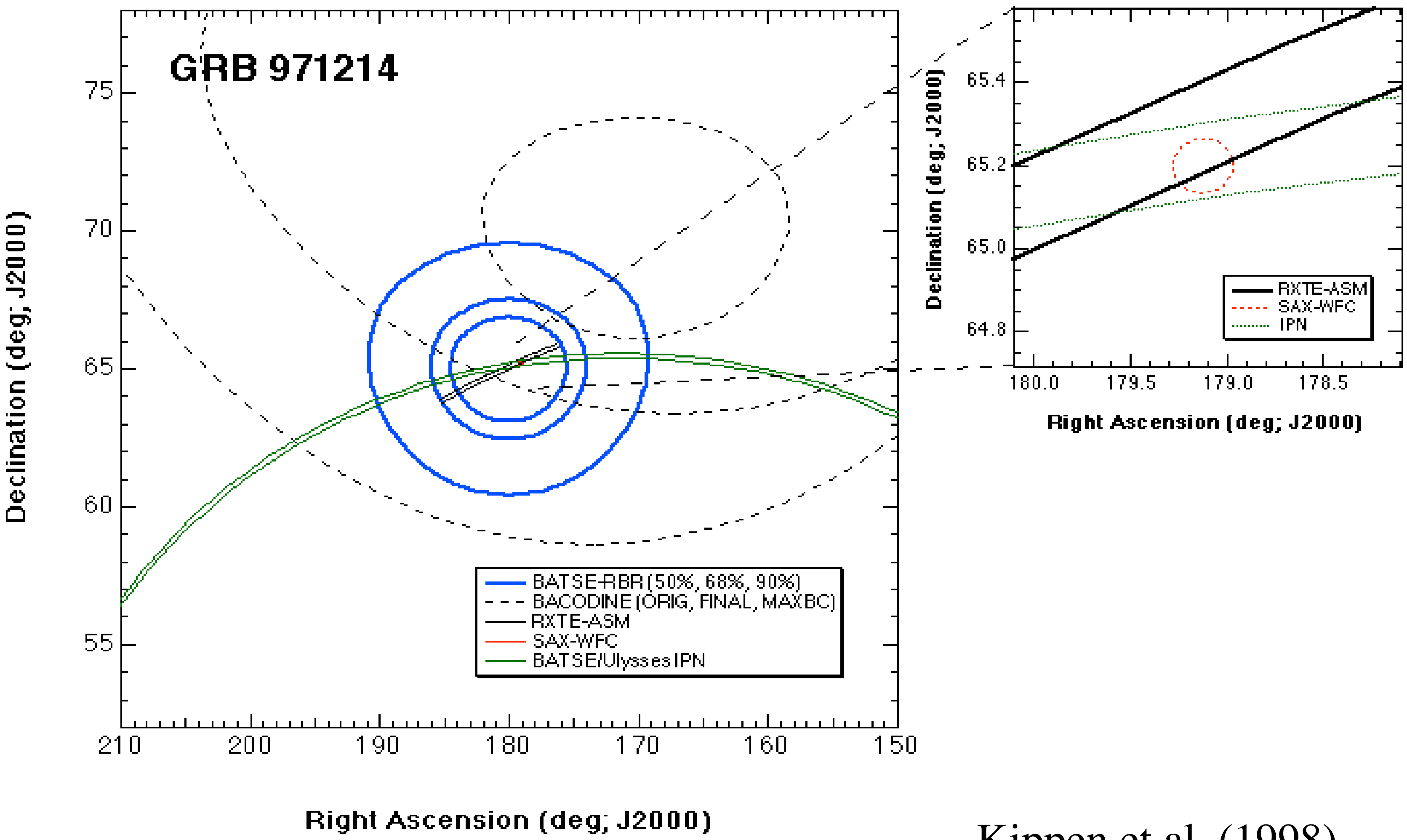

S A X P/L ACCOMODATION
Z
X
Y
GSPC - HP
PHOSWICH
CONCENTRATORS
WIDE FIELD
CAMERAS
UPPER FLOOR
SHEAR PANEL
CONE
LOWER
FLOOR

GRB



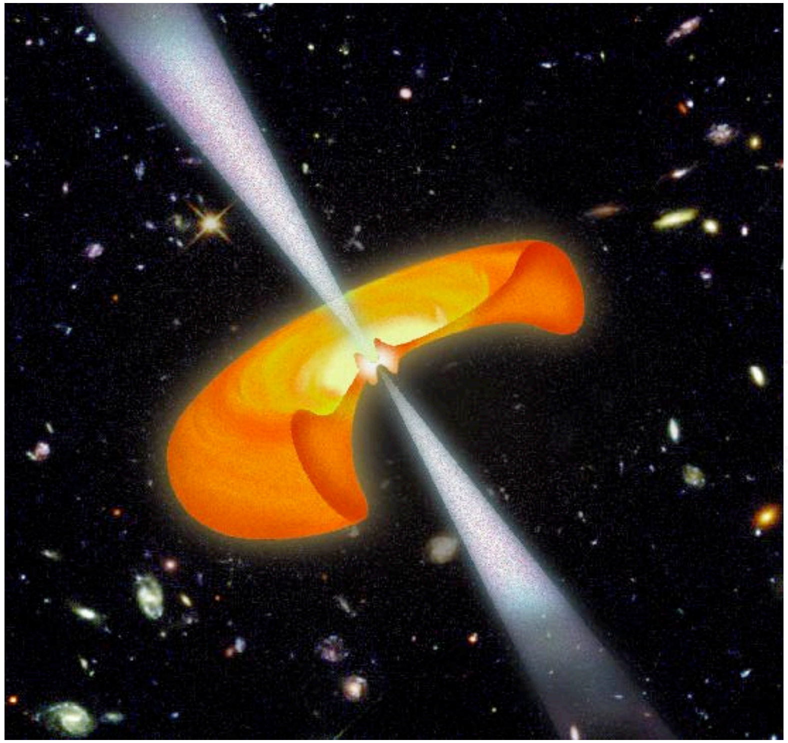
Costa et al. (1997)

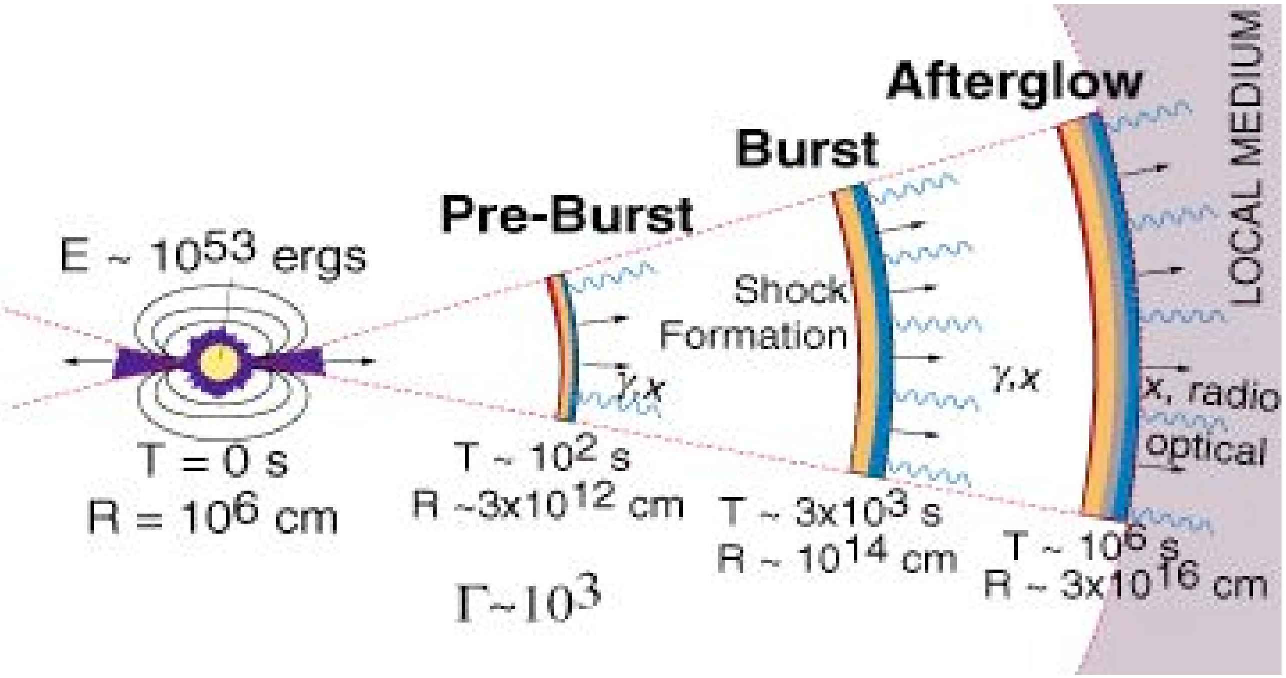
GRB



Kippen et al. (1998)

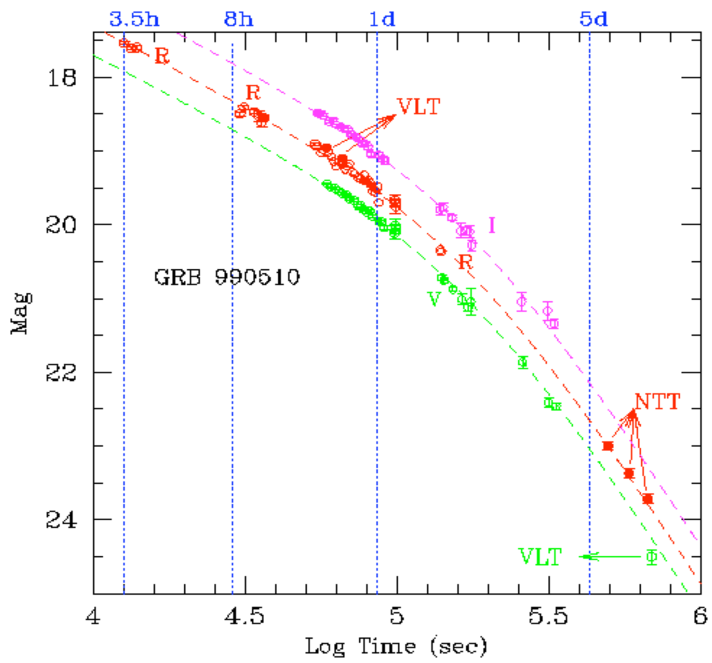
Gamma-Ray Bursts



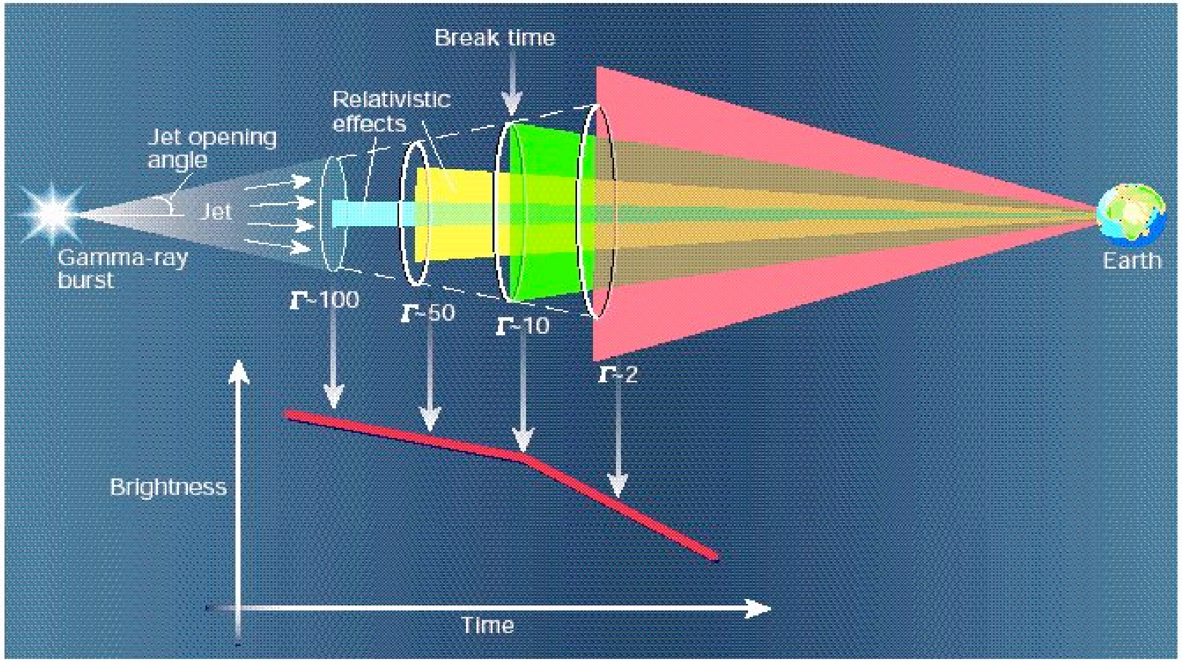


Afterglow Observations

Harrison et al (1999)

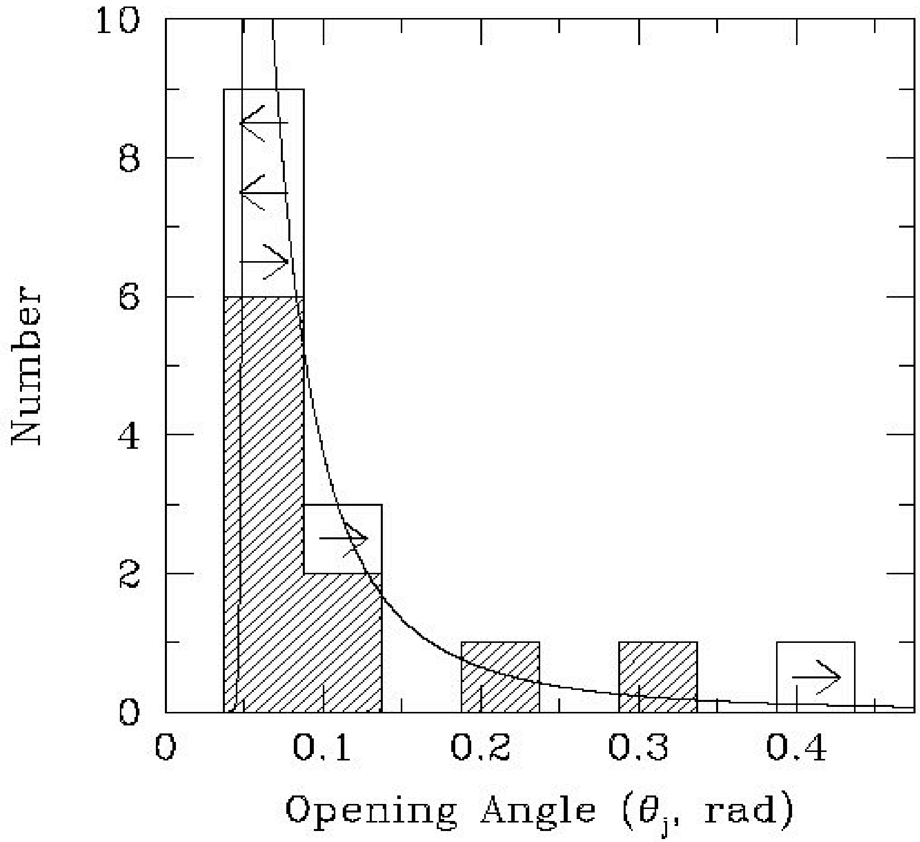


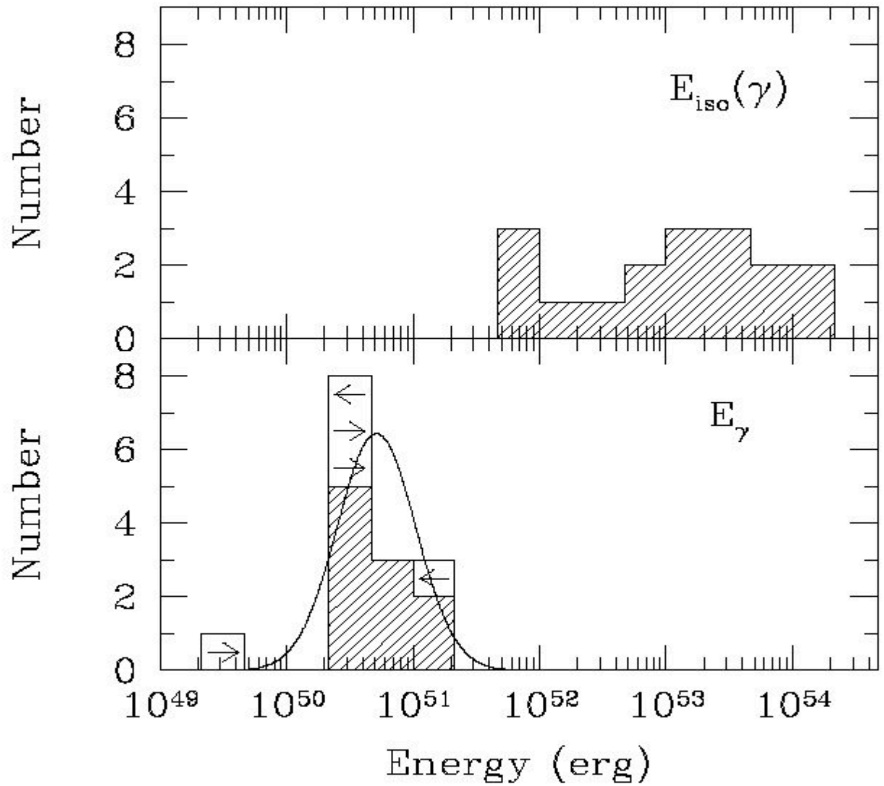
Achromatic Break



Woosley (2001)

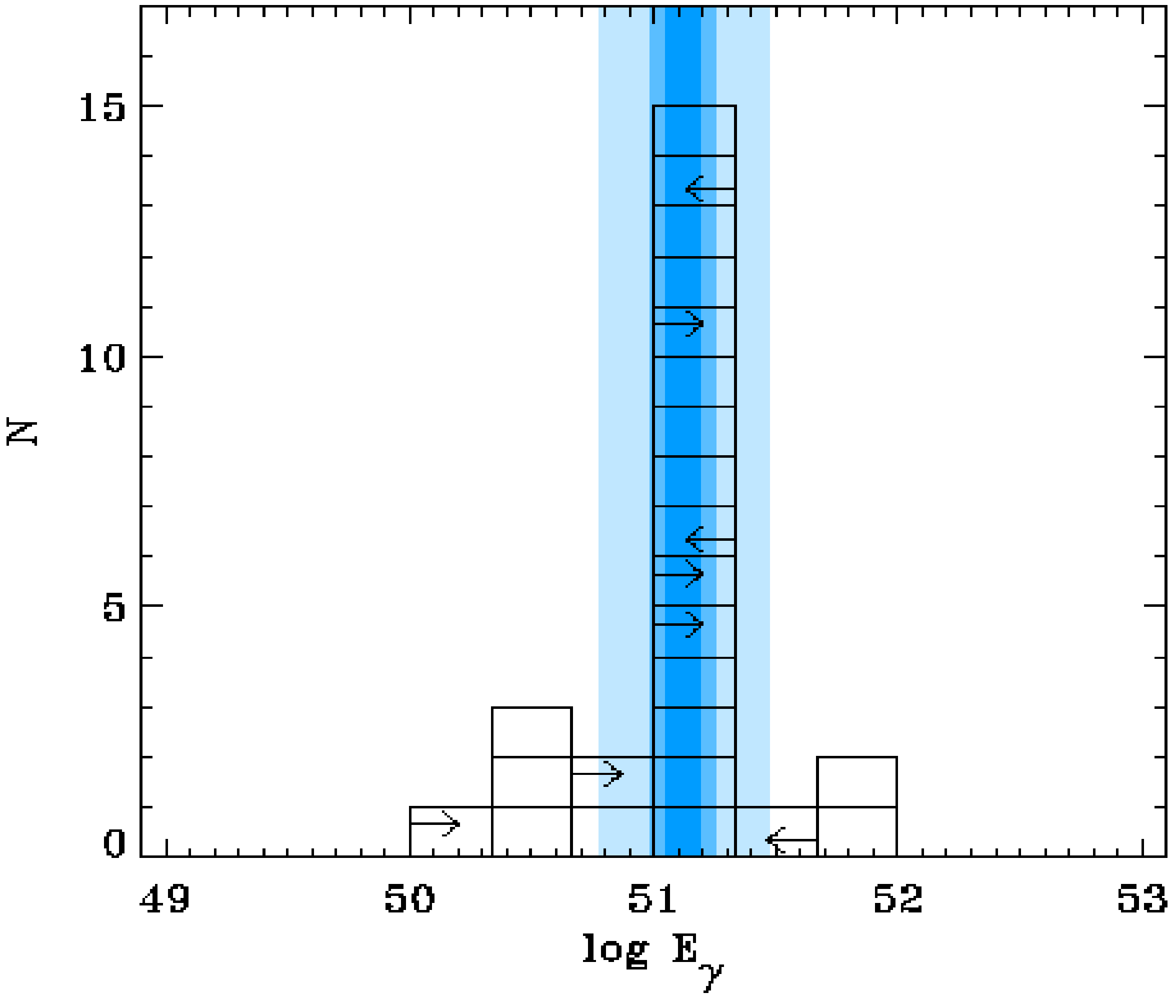
Jet and Energy Requirements





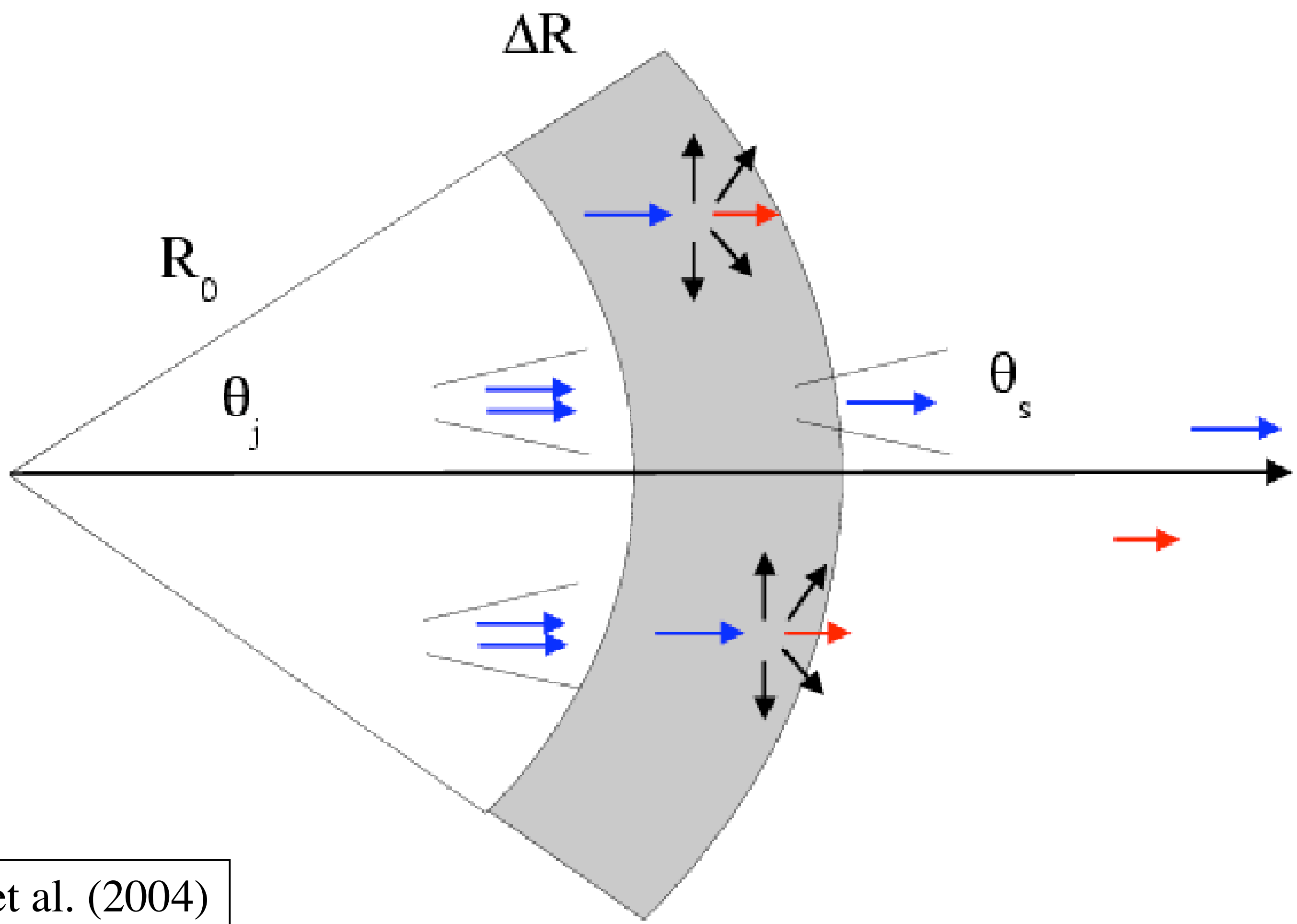
Frail et al. (2001)

Jet and Energy Requirements



Bloom et al. (2003)

The Compton Tail



Barbiellini et al. (2004)

The Compton tail

- “Prompt” luminosity

- $$\langle L_{\rm s}\rangle = \langle \frac{dn_{\rm s}}{d\Omega\ dt}\rangle \simeq \frac{n_{\rm p}\ e^{-\tau}}{\pi\theta_{\rm s}^2\ t_{\rm grb}} \cdot \frac{\theta_{\rm s}^2}{\theta_{\rm j}^2}$$

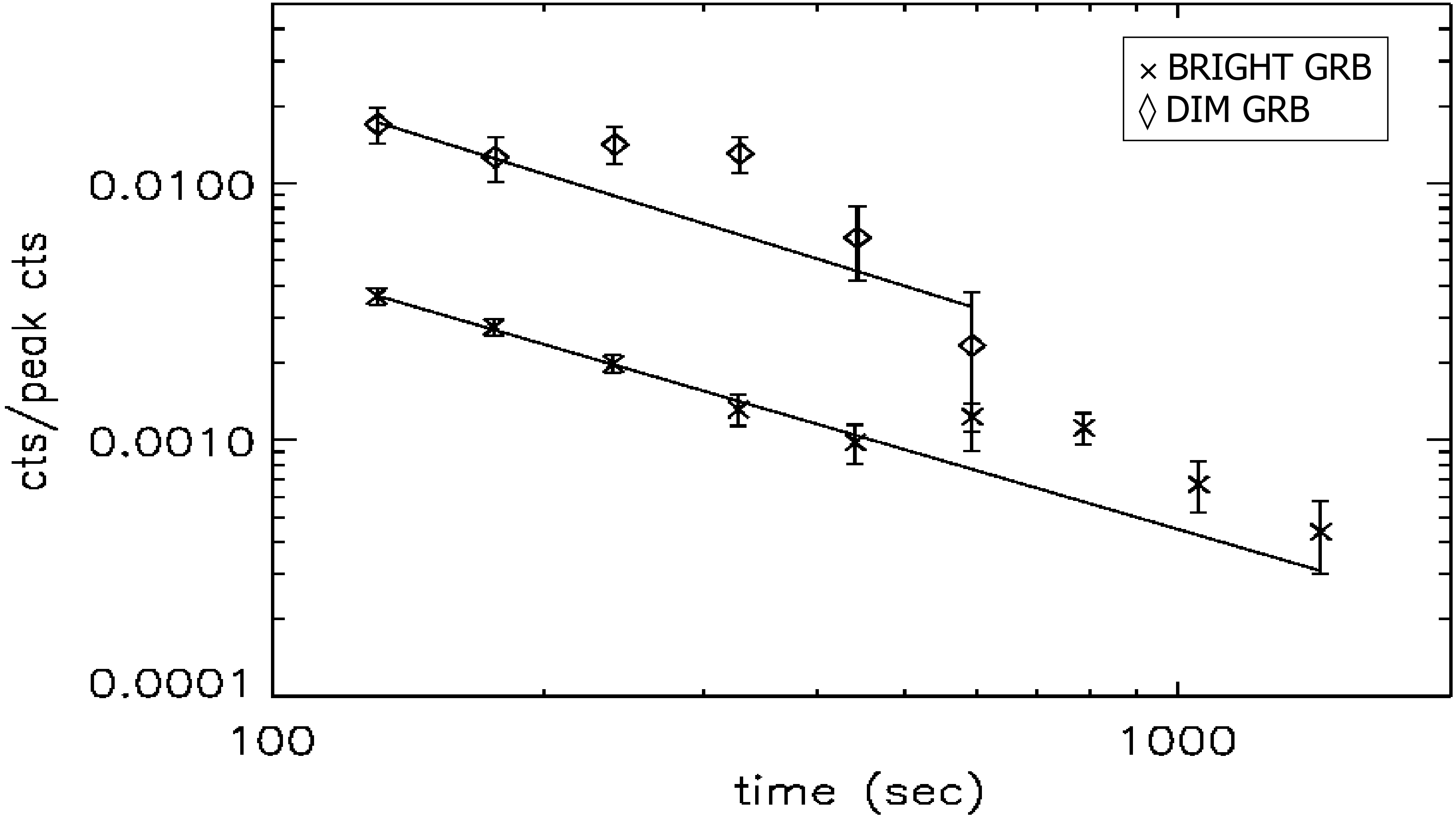
- $$\langle L_{\rm c}\rangle = \frac{n_{\rm p}\ (1-e^{-\tau})}{2\pi\ t_{\rm geom}} \qquad t_{\rm geom} \sim \frac{(R_0+\Delta R)\theta_{\rm j}^2}{c}$$

$$Q = \frac{\langle L_{\rm c}\rangle}{\langle L_{\rm s}\rangle} = (e^{\tau}-1)\cdot\frac{c\ t_{\rm grb}}{(R_0+\Delta R)}$$

Bright and Dim GRB

(Connaughton 2002)

Q = cts/peak cts



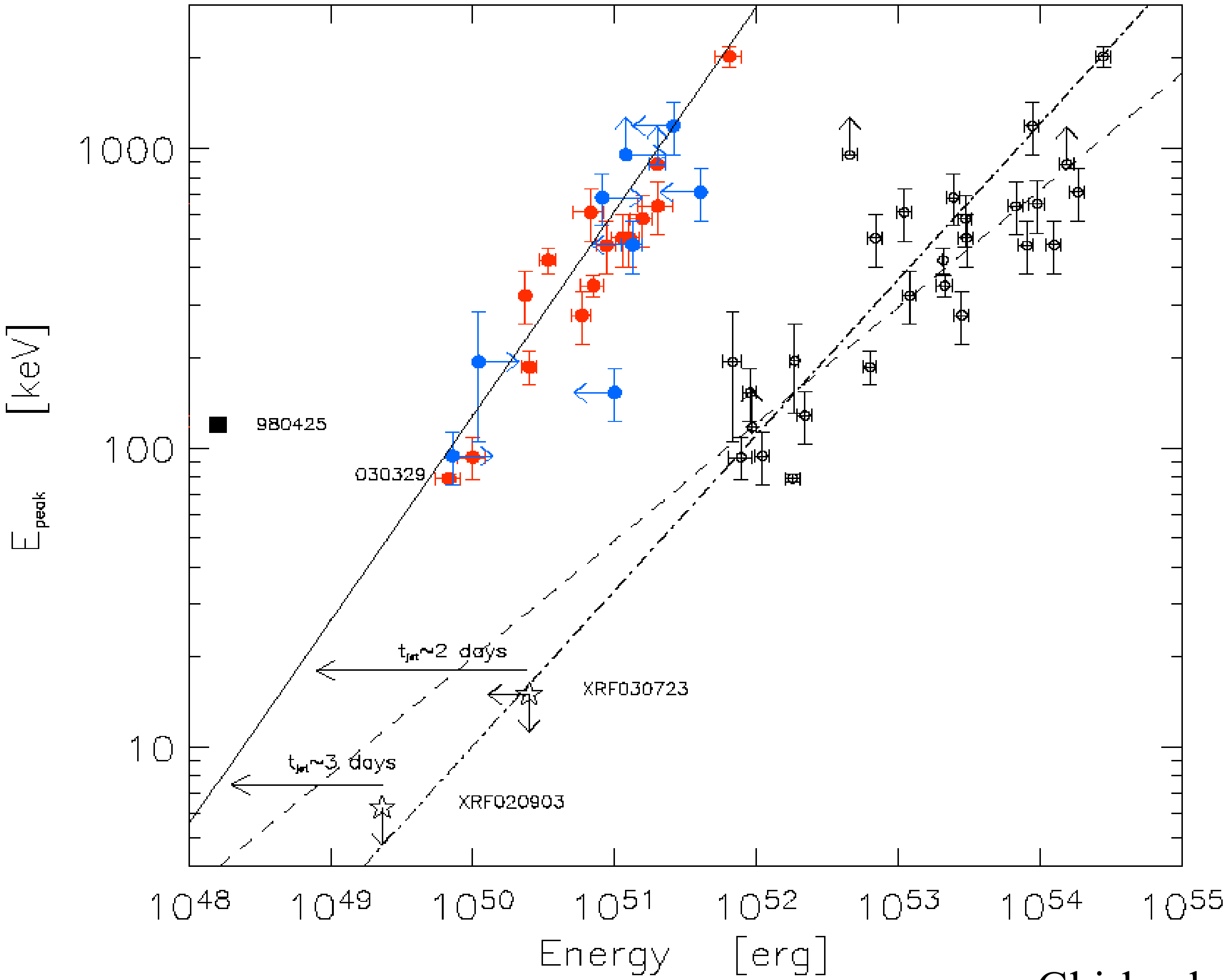
Bright and Dim Bursts

- Bright bursts (peak counts >1.5 $cm^{-2}\ s^{-1}$)
  - $Q = 4.0 \pm 0.8\ 10^{-4}$ ($5\ \sigma$)
  - $\tau = 1.3$
- Dim bursts (peak counts < 0.75 $cm^{-2}\ s^{-1}$)
  - $Q = 5.6 \pm 1.4\ 10^{-3}$ ($4\ \sigma$)
  - $\tau = 2.8$
- Mean fluence ratio = 11
- "Compton" correction

$$E = e^{\tau} E_{\text{obs}}$$

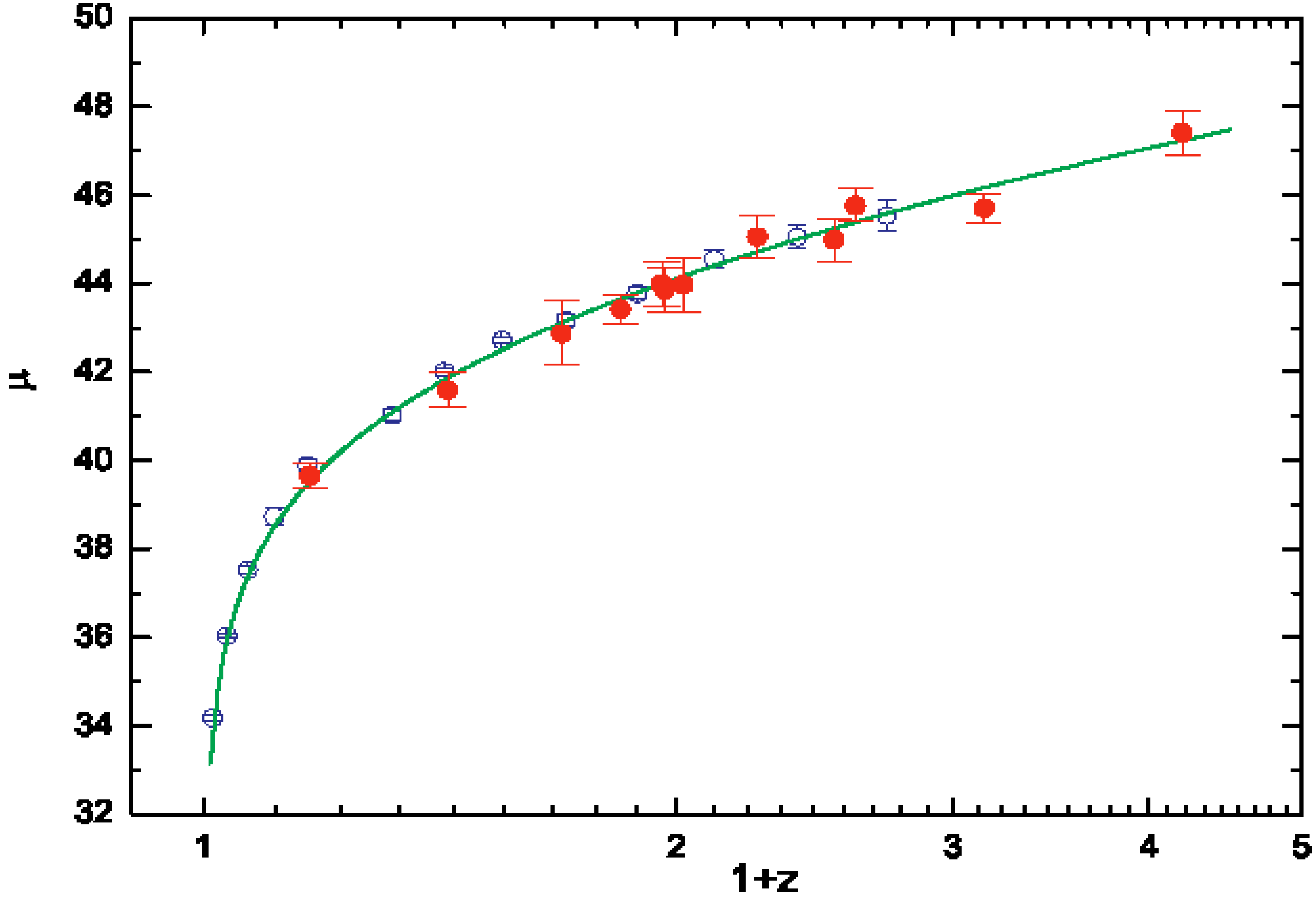
- Corrected fluence ratio = 2.8
- A cosmological effect?

GRB for Cosmology



Ghirlanda et al. (2004)

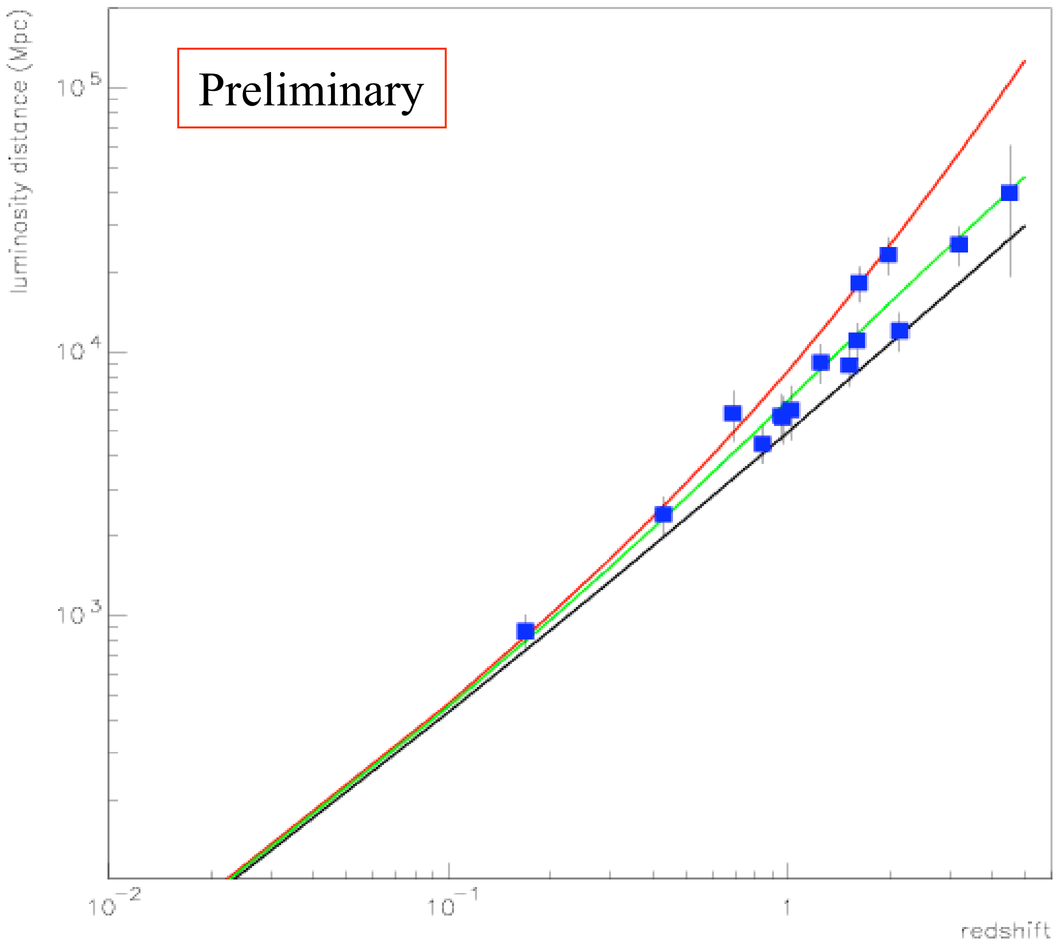
GRB for Cosmology



Dai, Liang & Xu (2004)

GRB for Cosmology

Luminosity Distance



redshift

SWIFT