Space-born Gamma Ray Astronomy

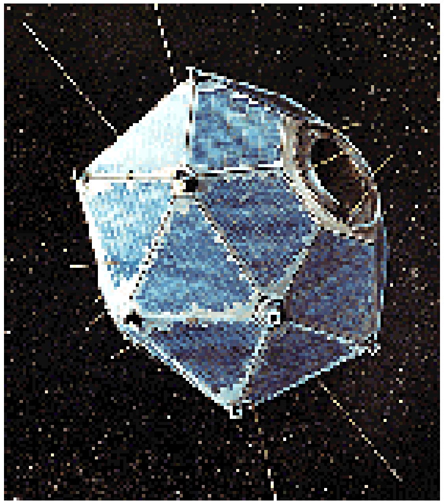
with emphasis to Gamma Ray Bursts (GRB)

A. Zehnder, Paul Scherrer Institut , Villigen

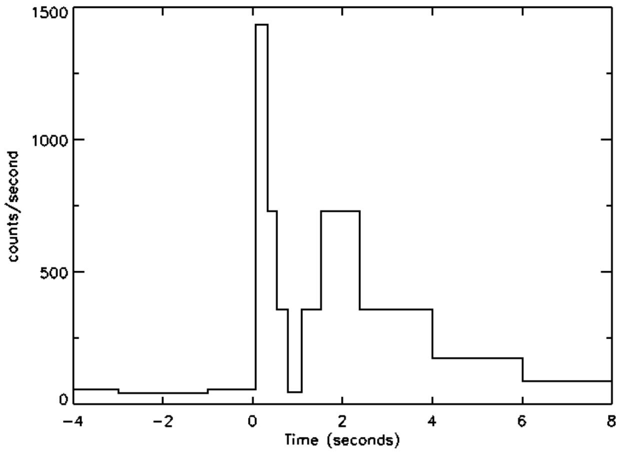
Outline:

- **Gamma Ray Sky**
- **Survey on GRB**
    - **Observation**
    - **Possible explanation(s)**
- **GRB observation with HESSI**
    - **Instrument**
    - **GRB Polarization**
    - **Connection to Solar Flare?**
- **Outlook**

The First Gamma Ray Burst



- Vela satellites launched to detect nuclear weapons test in late 60s
- Multiple satellites flown: allowed crude position determination and could test for coincidence
- In 1969 in data from 1967 showed a burst that was clearly not resulting from bomb test (see plot on right)
- 16 bursts found between 1969 and 197
(Klebesadal Strong and Olson, 1973)



Origin of GRB: Near or Far?

Isotropic distribution implies that GRB are either:

- very close: near solar system

Q: Why no faint bursts?

- very far: huge, cosmological distances

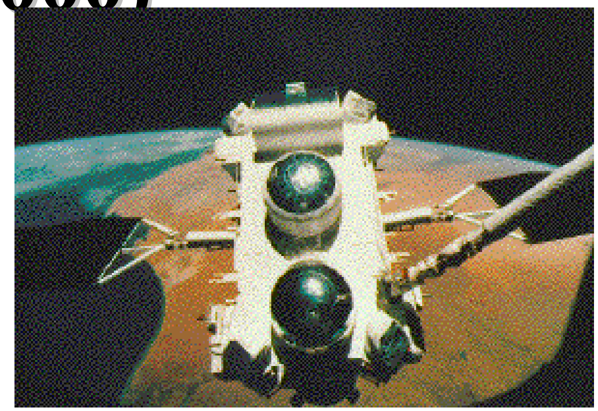
Q: What could produce such a vast amount of energy?

One possibility: events in the halo of the Milky Way, e.g. a comet hitting a neutron star

Q: Why so many events?

The only way to be sure: Better and more observations

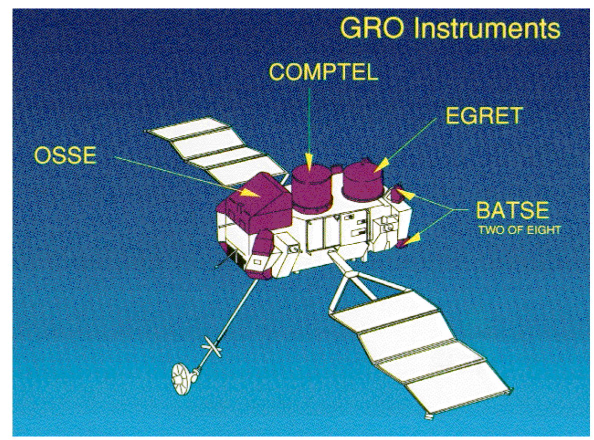
Compton Gamma Ray Observatory- BATSE (1991 – 2000)



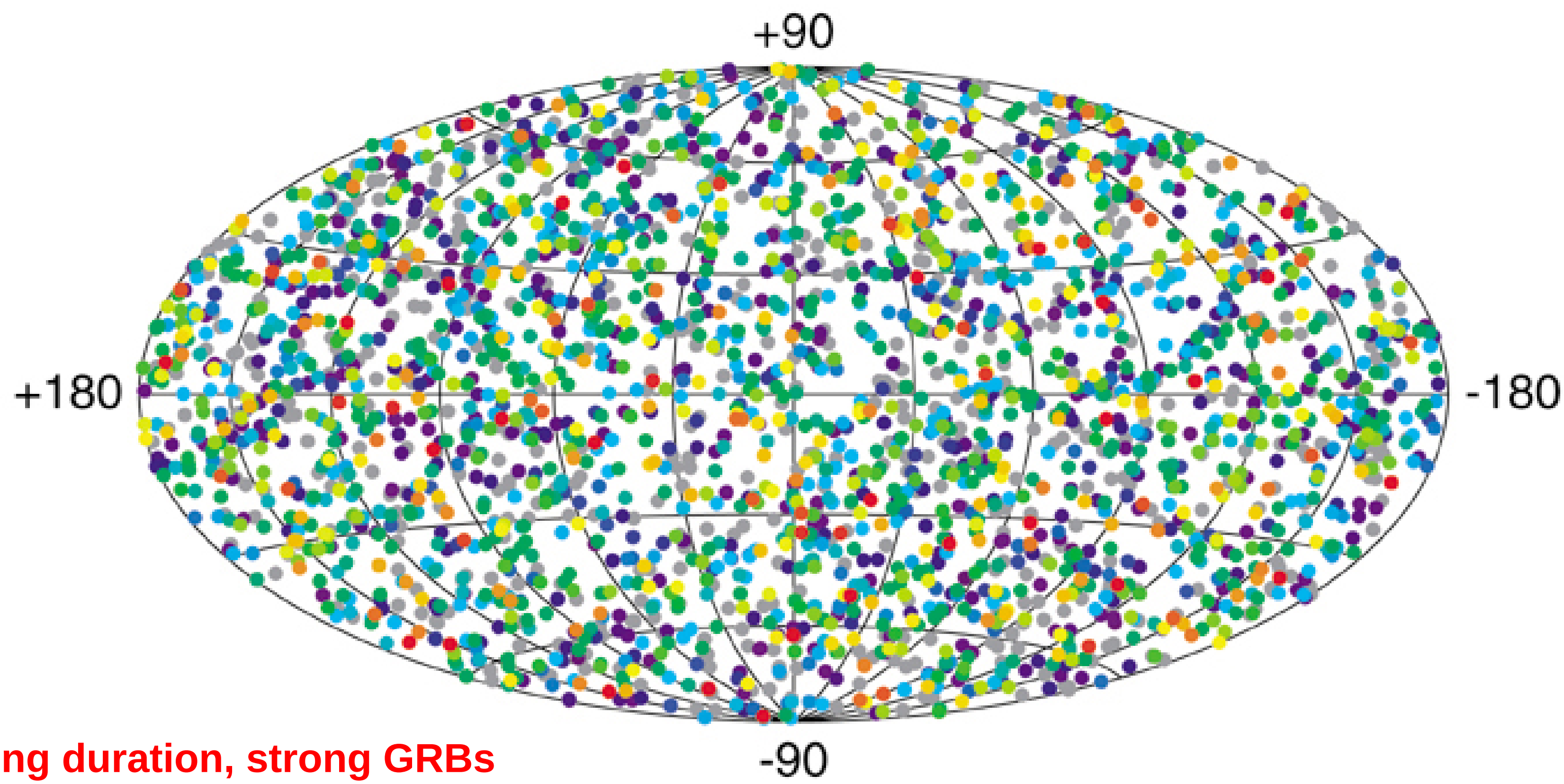
- 8 instruments on corners of spacecraft
- Detectors: NaI scintillators
- Direction: Timing information

•**Findings:**

- Isotropic angular distribution
  - Cosmological Origin implies extreme energy > 10^{50} ergs
- Two populations (long and short)
  - Two different sources ?
- 1 BATSE burst per day (~one per 10^{4-6} y/galaxy)
- Non thermal Spectrum, mean energy ~ 100keV)
- Rapid variability (some times less than 10ms)
  - small size of source ~300-1200 km !

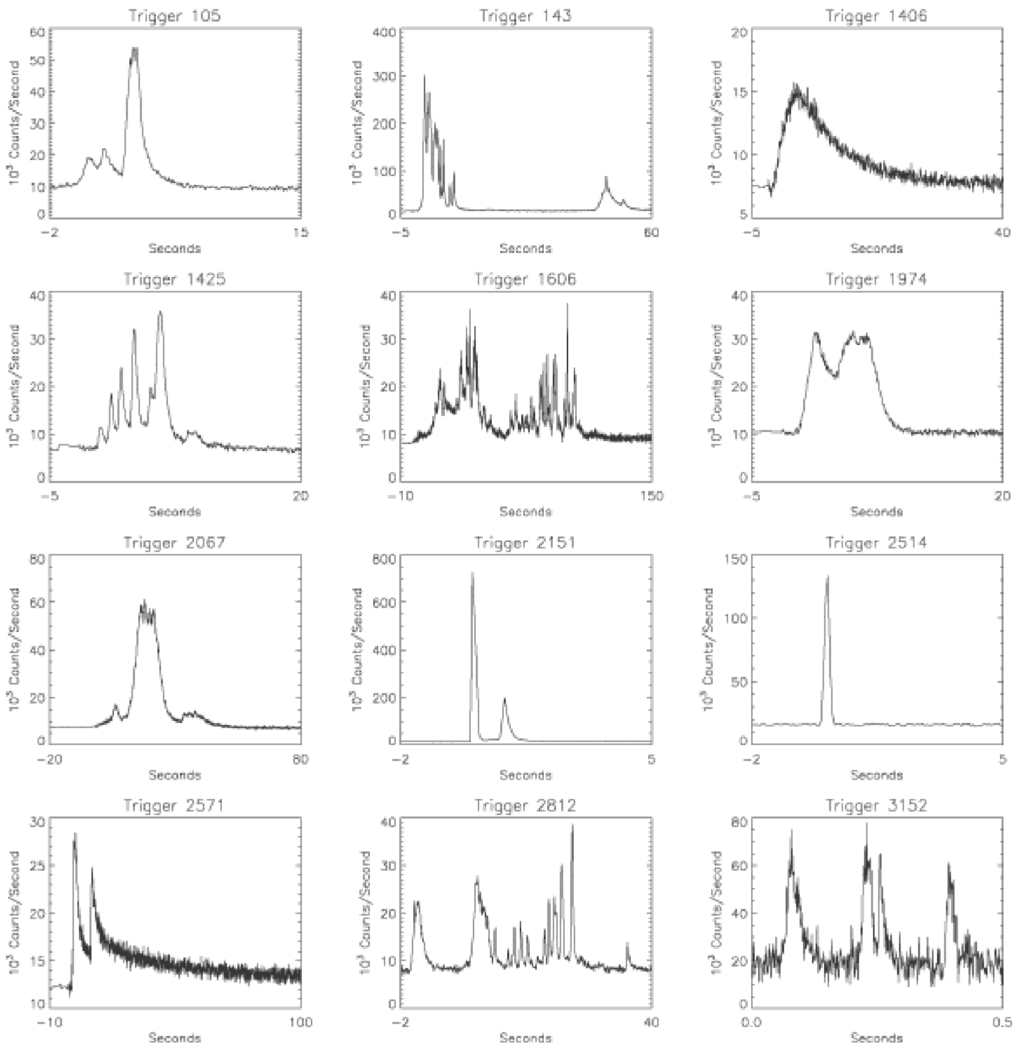


2704 BATSE Gamma-Ray Bursts



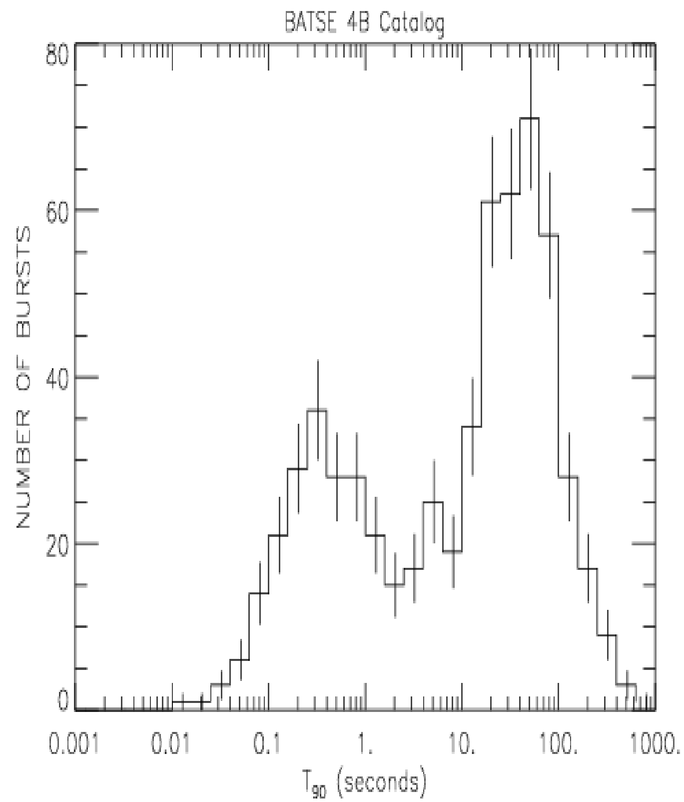
- Long duration, strong GRBs
- short duration, weak GRBs
- flux cannot be calculated due to incomplete data

The Batse GRB Gallery

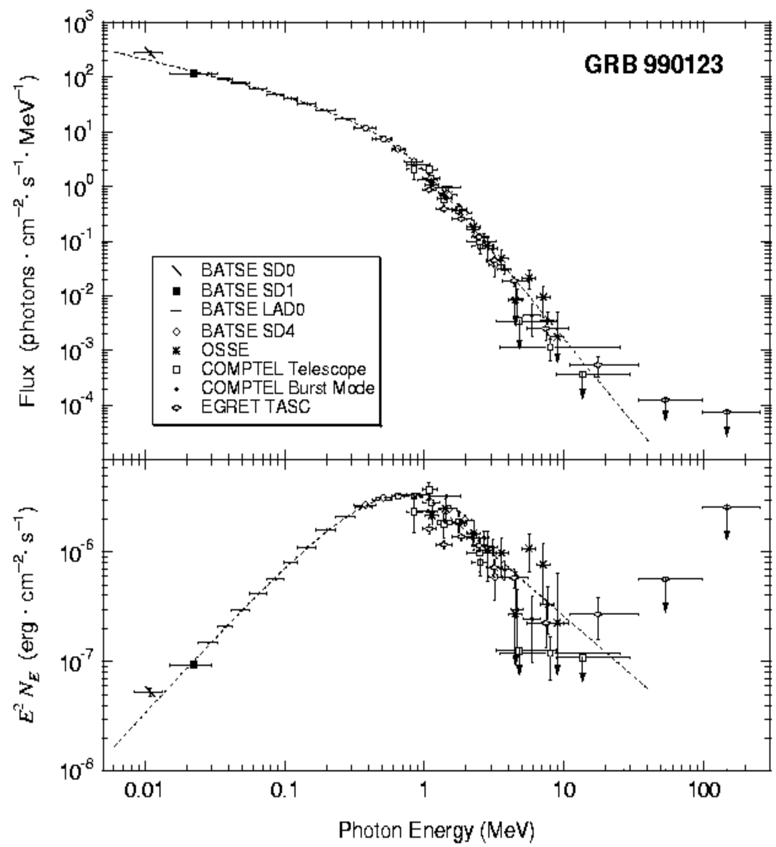


Note:
Isotropic distribution but timing of GRB very non-uniform.
However, if binned according burst duration ...

Burst duration: bimodal distribution



Spectral Information, broken power law



The data seem to indicate two kinds of GRBs

- Those with burst durations *less* than 2 seconds
- Those with burst durations *more* than 2 seconds

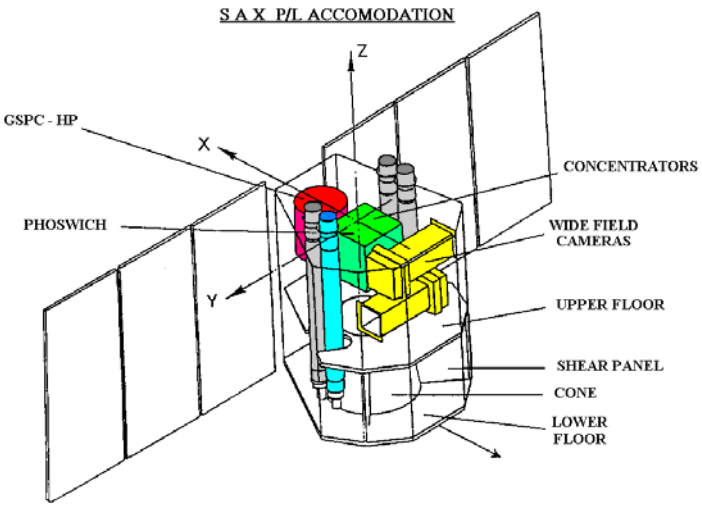
Short bursts tend to produce “harder” gamma rays,
as predicted by the NS/NS merger model

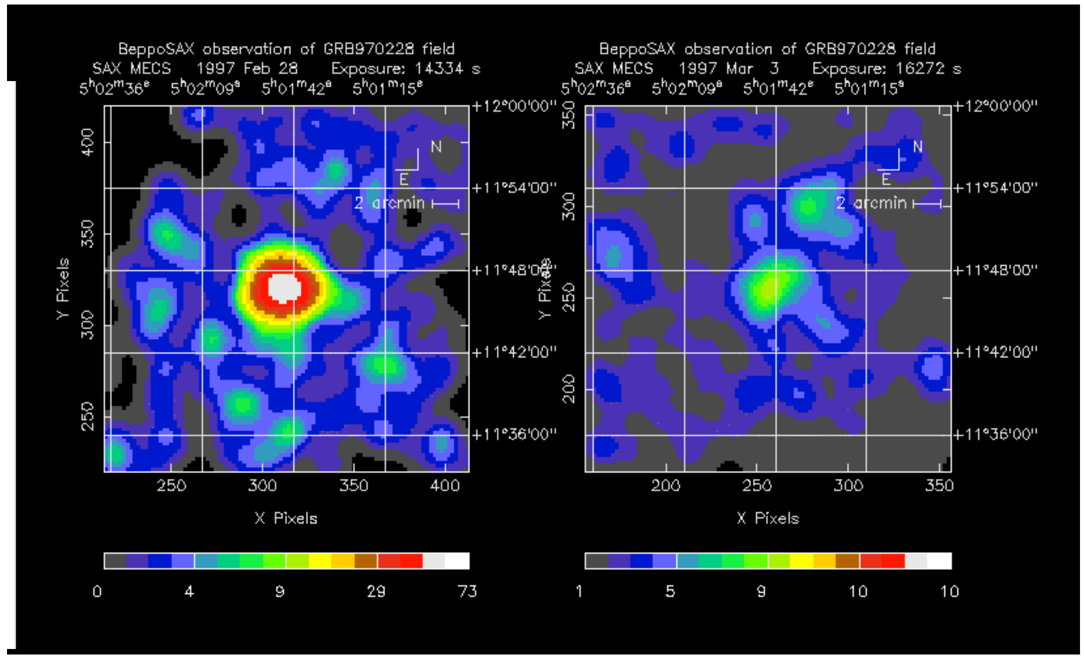
Long bursts tend to produce “softer” gamma rays,
as predicted by the hypernova merger model

Clearly, more info is needed

In 1997, BeppoSAX detects X-rays from a GRB afterglow for the first time, 8 hours after burst

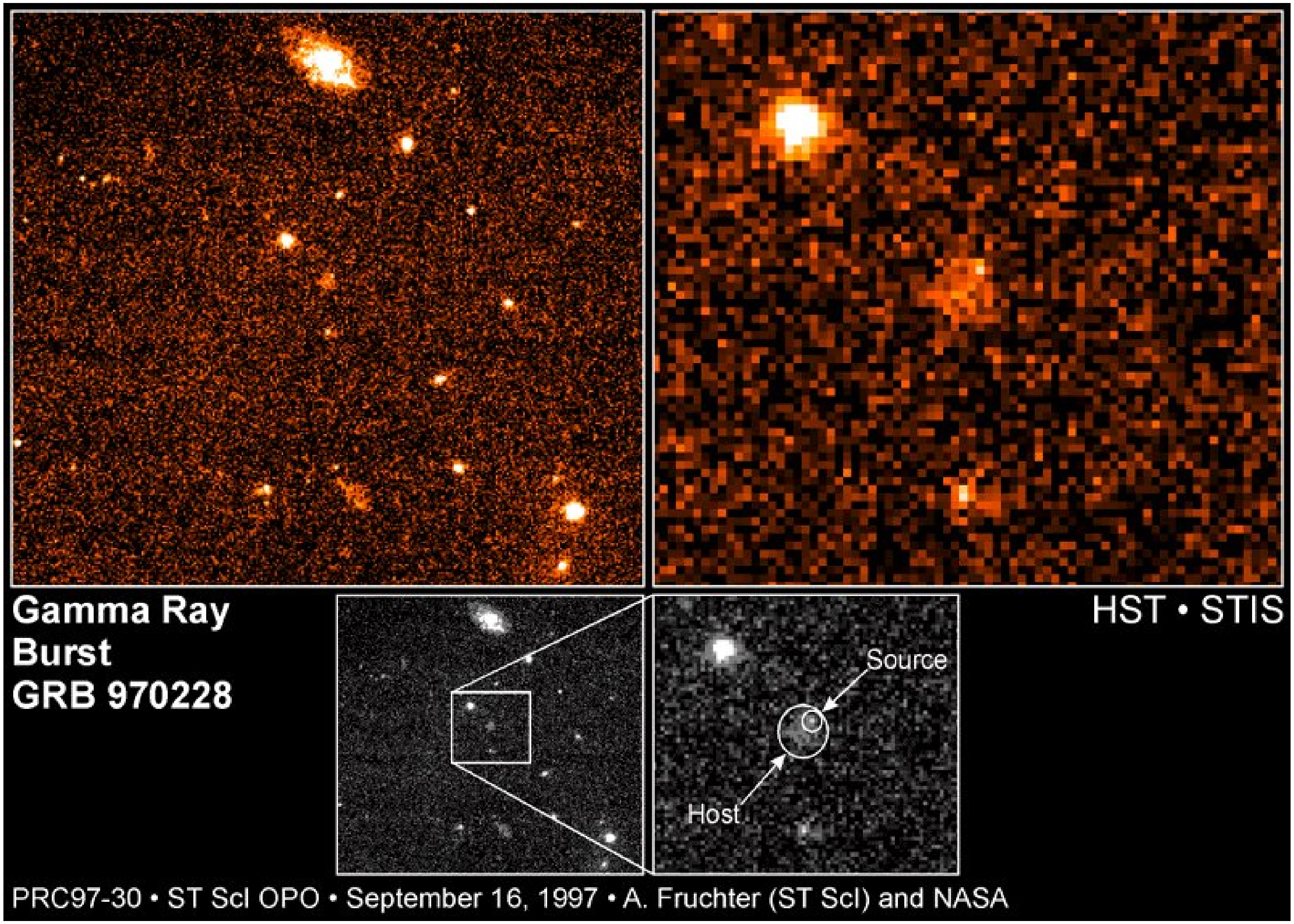
Breakthrough!





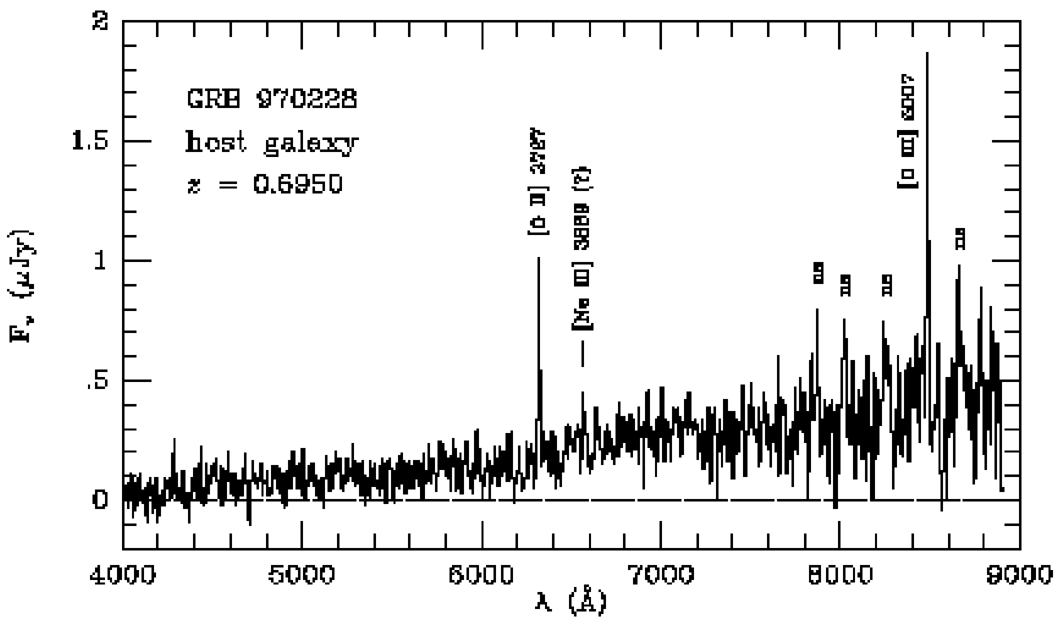
The discovery of the first X-ray afterglow of a Gamma-Ray Burst: the event of Feb. 28, 1997. The figure shows the image in the 2-10 keV range obtained by the X-ray telescopes of BeppoSAX. A previously unknown bright X-ray source was visible 8 hours after the GRB (left panel). Three days after (March 3. Right panel), the source had faded by a factor of about 20.
Luigi Piro, Europhysics News (2001) Vol. 32 No. 6

The View From Hubble/STIS, 7 months later



Measure cosmological redshift (z) of host galaxy:

- Distance (using best known cosmological model)
- Energy: 10-1000 FOE (Fifty-One Erg)



J.S. Bloom et. al.
ApJ 554,p678,2001

The Compactness Problem

See T. Piran astro-ph/9810256 (1998)

- Consider isotropically emitting source at a distance *D*

$$E = 4\pi D^2 F = 10^{50} \left(\frac{D}{3\,\mathrm{Gpc}}\right)^2 \left(\frac{F}{10^{-7}\ \mathrm{erg/cm^2}}\right) ergs$$

- Temporal variations: source radius R < 1200 km!!
- High photon energy population, production of e^+e^- pairs. f_p is fraction of photon pairs that satisfy

$$\sqrt{E_1 E_2} > m_e c^2$$

- The optical depth for this process is

$$\tau_{\gamma\gamma} = 10^{13} f_p \left(\frac{F}{10^{-7}\ \mathrm{erg/cm^2}}\right)\left(\frac{D}{3\,\mathrm{Gpc}}\right)^2 \left(\frac{\delta T}{10\ \mathrm{ms}}\right)^{-2}$$

The Compactness Problem (Cont)

- Optical depth very large-> Compton scattering-> Thermal Spectrum
- But GRB spectrum is non-thermal τ~1 not 10^{13}
- Solution: Relativistic motion with Γ:
- $E_\gamma \sim E_\gamma/\Gamma$ e.g. Number of photons for $f_p \sim f_p/\Gamma^{2\alpha}$ (α spectral index)
- Radius $R_{emission} \sim \Gamma^2 c\delta T$

$$\tau_{\gamma\gamma} = \frac{10^{13}}{\Gamma^{(4+2\alpha)}} f_p \left(\frac{F}{10^{-7}\ \mathrm{erg/cm^2}}\right)\left(\frac{D}{3\,\mathrm{Gpc}}\right)^2\left(\frac{\delta T}{10\,\mathrm{ms}}\right)^{-2}$$

GRB for τ~1: $\Gamma > 10^{13/(4+2\alpha)} \sim 100$!

"Galactic jets" Γ~ 2-10

The Compactness Problem (Cont)

Internal Shocks:

• But if Γ~100 then radiation is beam into an angle 1/ Γ, e.g observer measures only Γ^{-3} of total energy. Unrealistic (note 10^{54} ergs ~ M(Sun)c^2)

• Fireball model (Meszaros and Rees and others):

• At initial radiation fireball, radiation is trapped. Perfect fluid with pressure $p=\rho/3$

• Conversion of radiation energy into kinetic energy of baryons. (relativistic baryon fireball), Expansion and remission of gammas via inverse Compton and synchrotron. Not very efficient (~2%) with fixed Γ. Requires shocks with different Γ, (with $\Gamma_{max}/\Gamma_{min}$~10 ε~40%)

The Fireball Model: Source of GRB

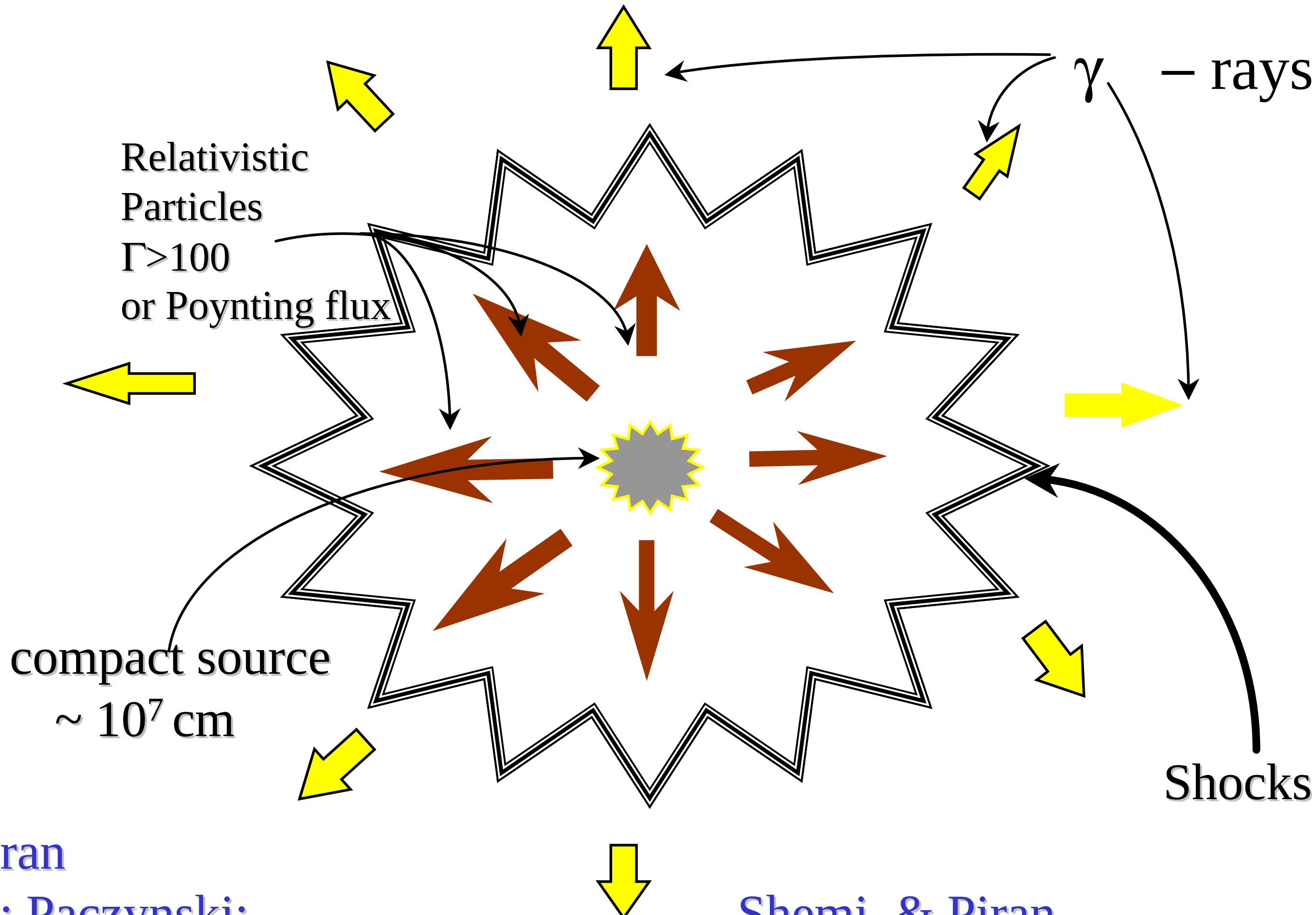
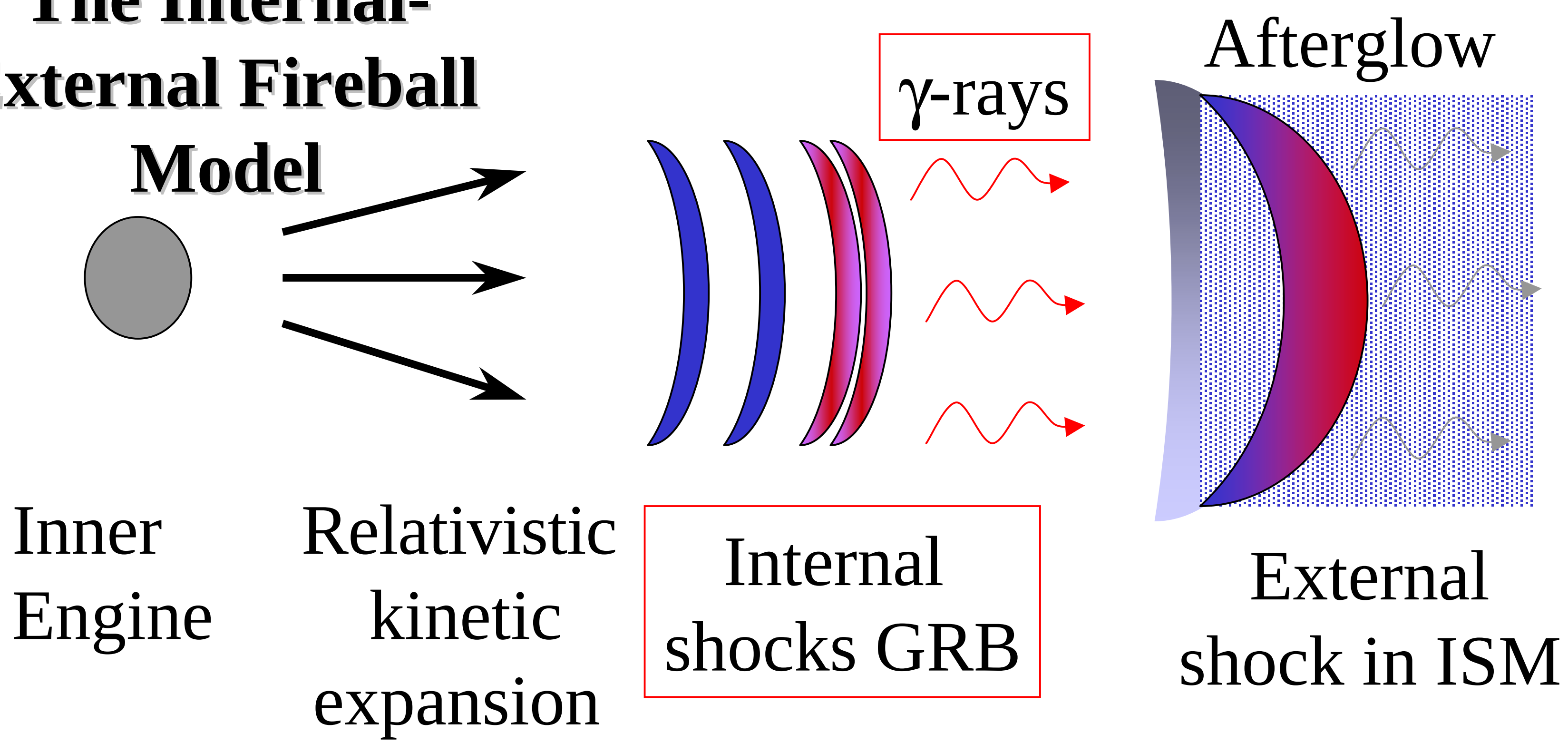


Figure: Piran
Goodman; Paczynski;
Narayan, Paczynski & Piran;

Shemi & Piran,
Meszaros & Rees,

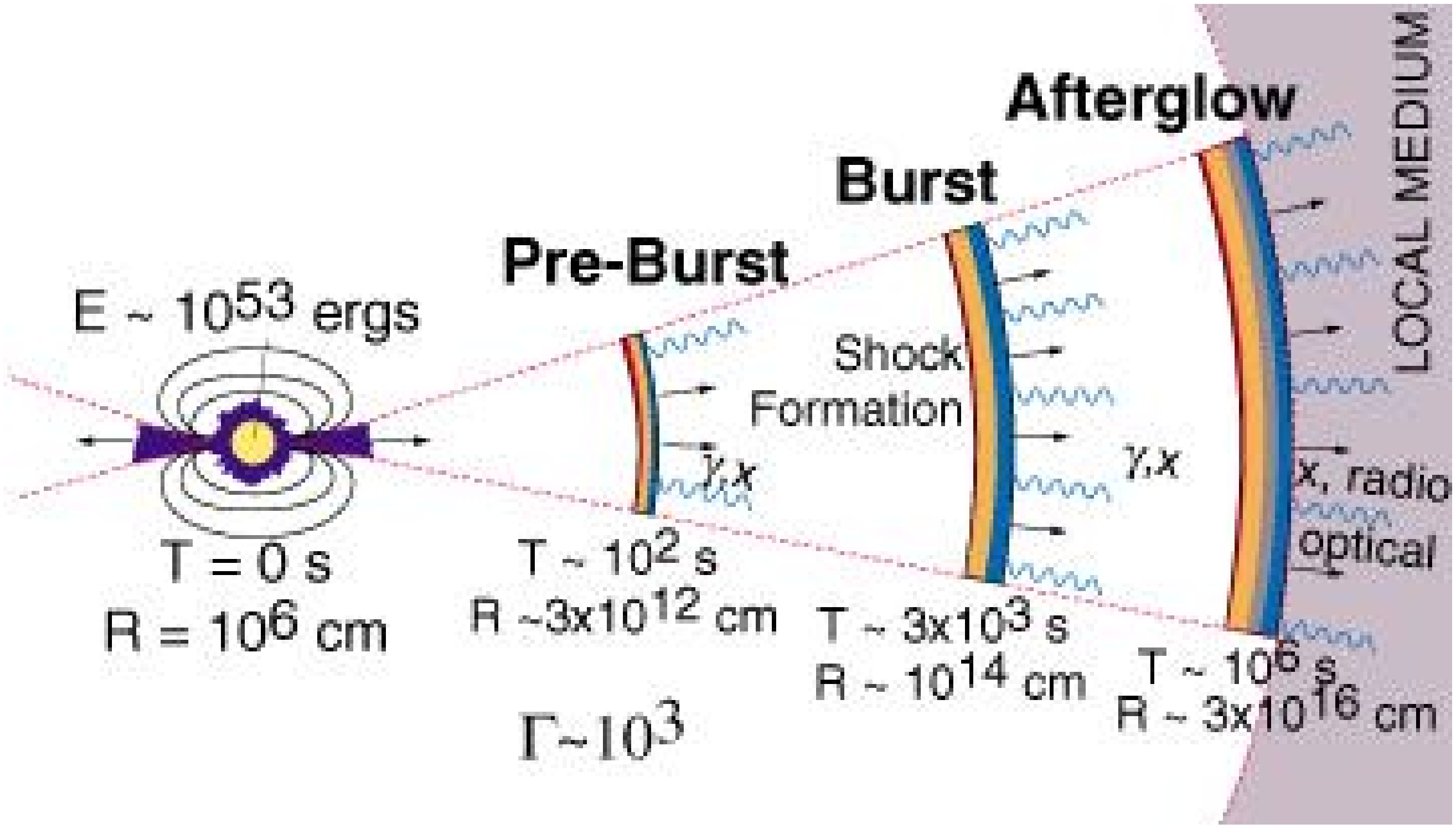
What produces the afterglow?

The Internal-External Fireball Model



There are <u>no direct observations</u> of the inner engine (Piran).

"Summary"


Afterglow
Burst
Pre-Burst
LOCAL MEDIUM
E ~ 10^53 ergs
Shock
Formation
γ,x
γ,x
x, radio
optical
T = 0 s
R = 10^6 cm
T ~ 10^2 s
R ~3x10^12 cm
T ~ 3x10^3 s
R ~ 10^14 cm
T ~ 10^6 s
R ~ 3x10^16 cm
Γ~10^3

The 4 Stages of a Gamma-Ray Burst:

1) Compact Source (not directly observed), E>10^{51}erg

2) Relativistic Kinetic Energy of baryons or electrons

3) **Radiation due to Internal shocks => GRBs**

4) Afterglow by external shocks in interstellar medium

The Central Compact Source is Hidden

"Direct" Energy Measurements

In bursts with afterglow for which the host galaxy was observed the total energy could be estimated "directly" using the redshift of the host galaxy.

GRB970508	Z=0.865	$5.5\ 10^{51}$
971214	3.418	$2.1\ 10^{53}$
980703	0.966	$6\ 10^{52}$
990123	1.6	$1.4\ 10^{54}$
000131	4.5	$1.2\ 10^{54}$
000418	1.119	$8.2\ 10^{52}$
000926	2.037	$3\ 10^{53}$

Pascos 03

How to explain 10^{54} ergs?

Once more GRBs need new Models

Solution of the Energy Crisis

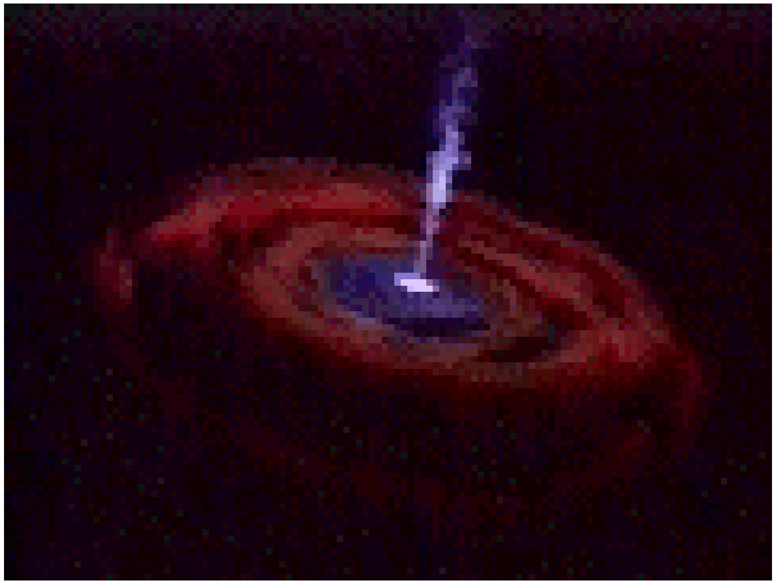
- E_{tot} - The total energy
- $E_{\gamma\, iso}$ - Observed (isotropic) γ-ray energy

$$E_{tot} = \varepsilon_\gamma^{-1} E_{\gamma iso}$$

Beaming into angle θ:

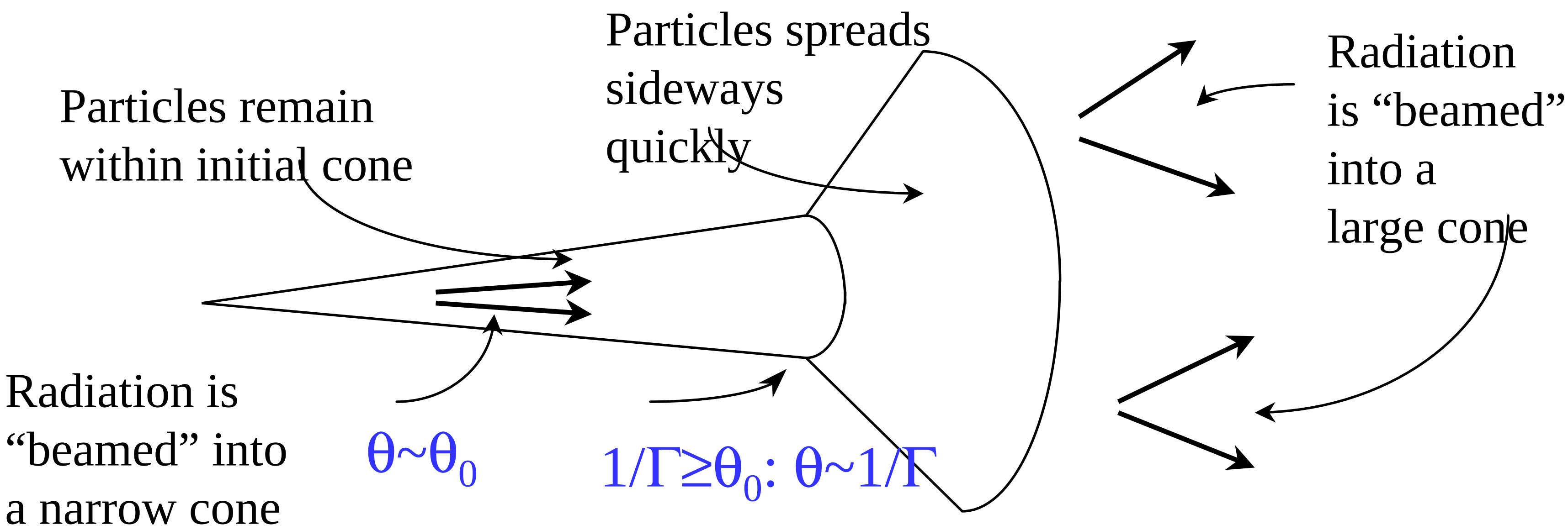
- E_γ - Actual γ-ray energy

$$E_{tot} = \varepsilon_\gamma^{-1} E_\gamma = \varepsilon_\gamma^{-1} \frac{\theta^2}{2} E_{\gamma iso}$$



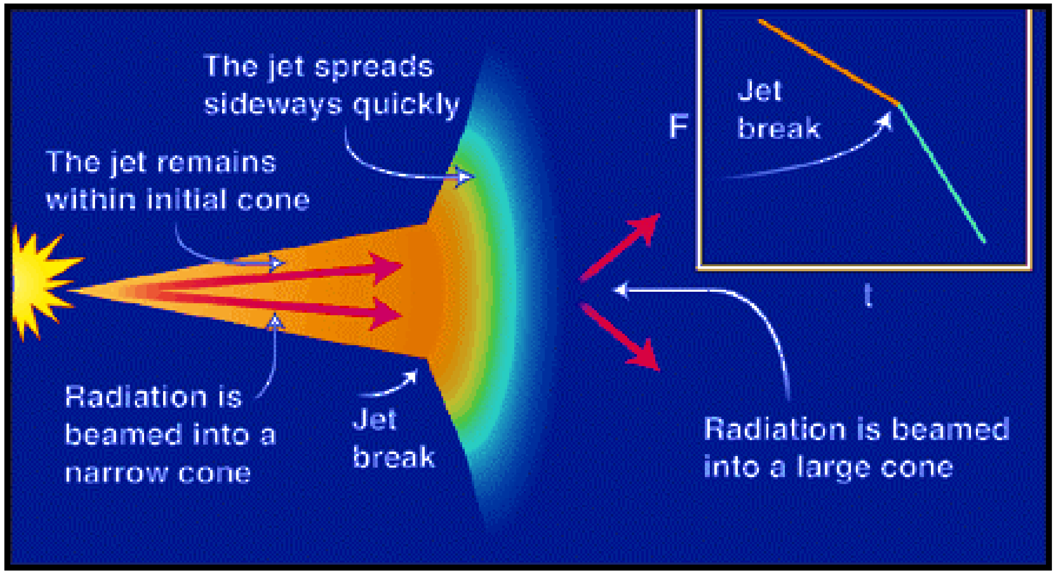
The two most powerful BeppoSAX bursts are jets (Sari, Piran & Halpern; 1999).

JETS and BEAMING

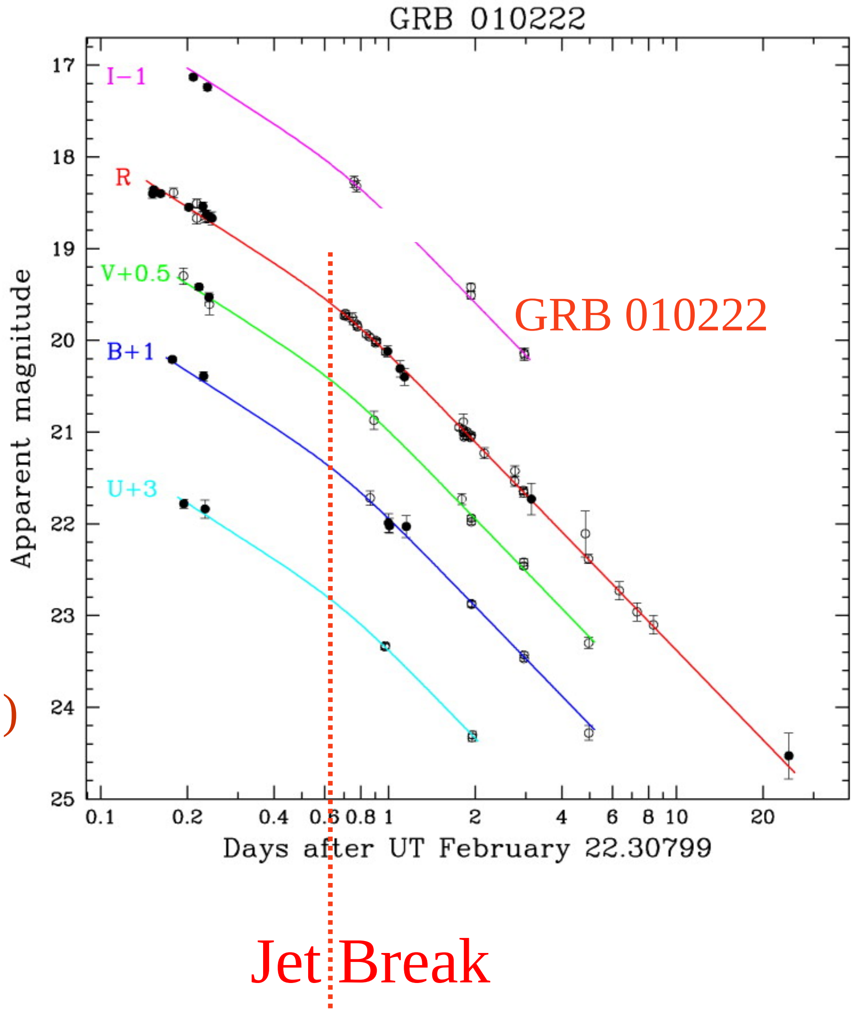


(Piran, 1995; Rhoads, 1997; Wijers et al, 1997; Panaitescu & Meszaros 1998).

Jet Signatures



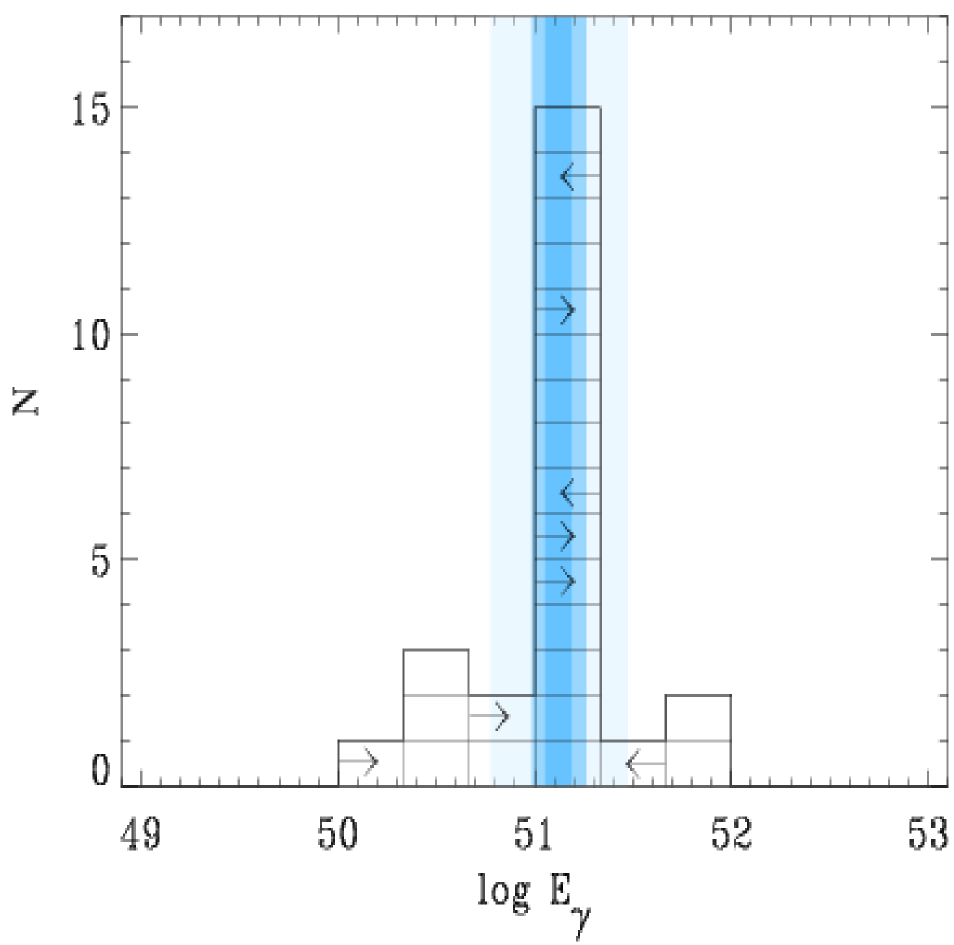
Piran, *Science*, 08 Feb 2002



Stanek et al. (2001)

Jet Break

Energy and Beaming

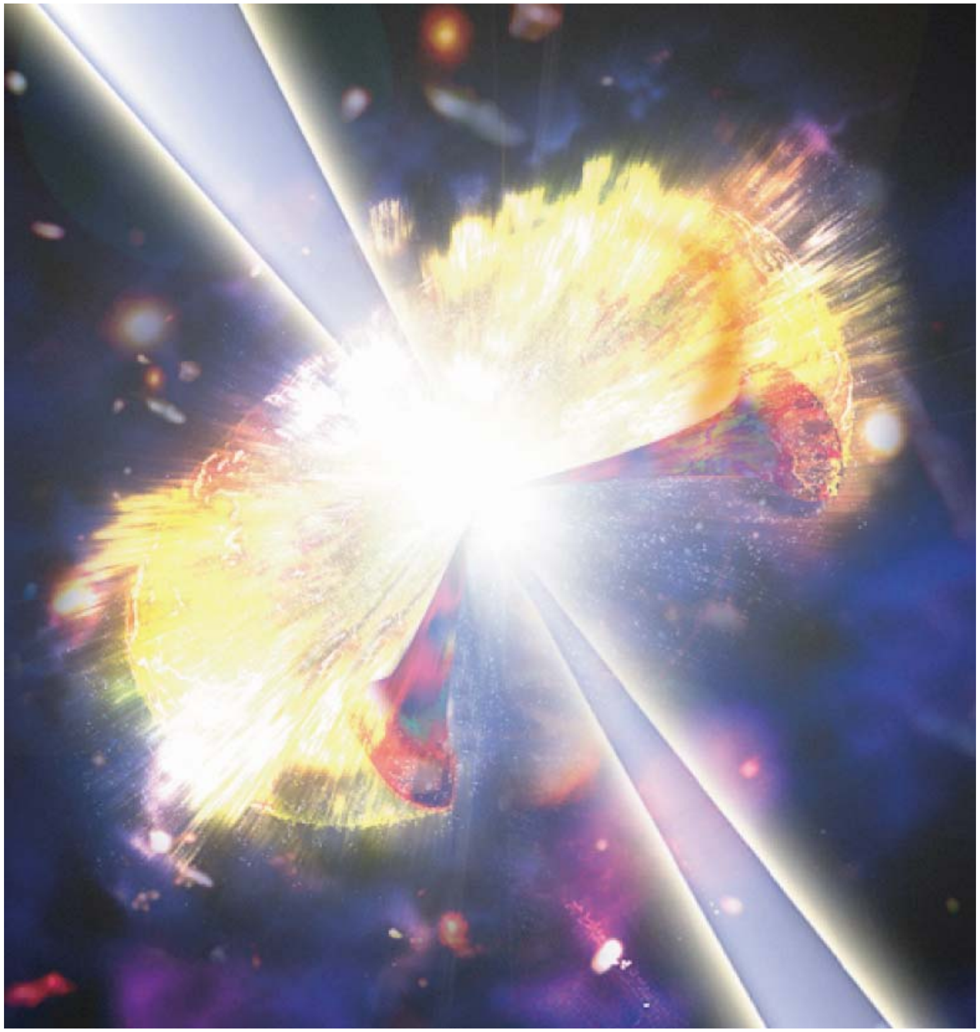


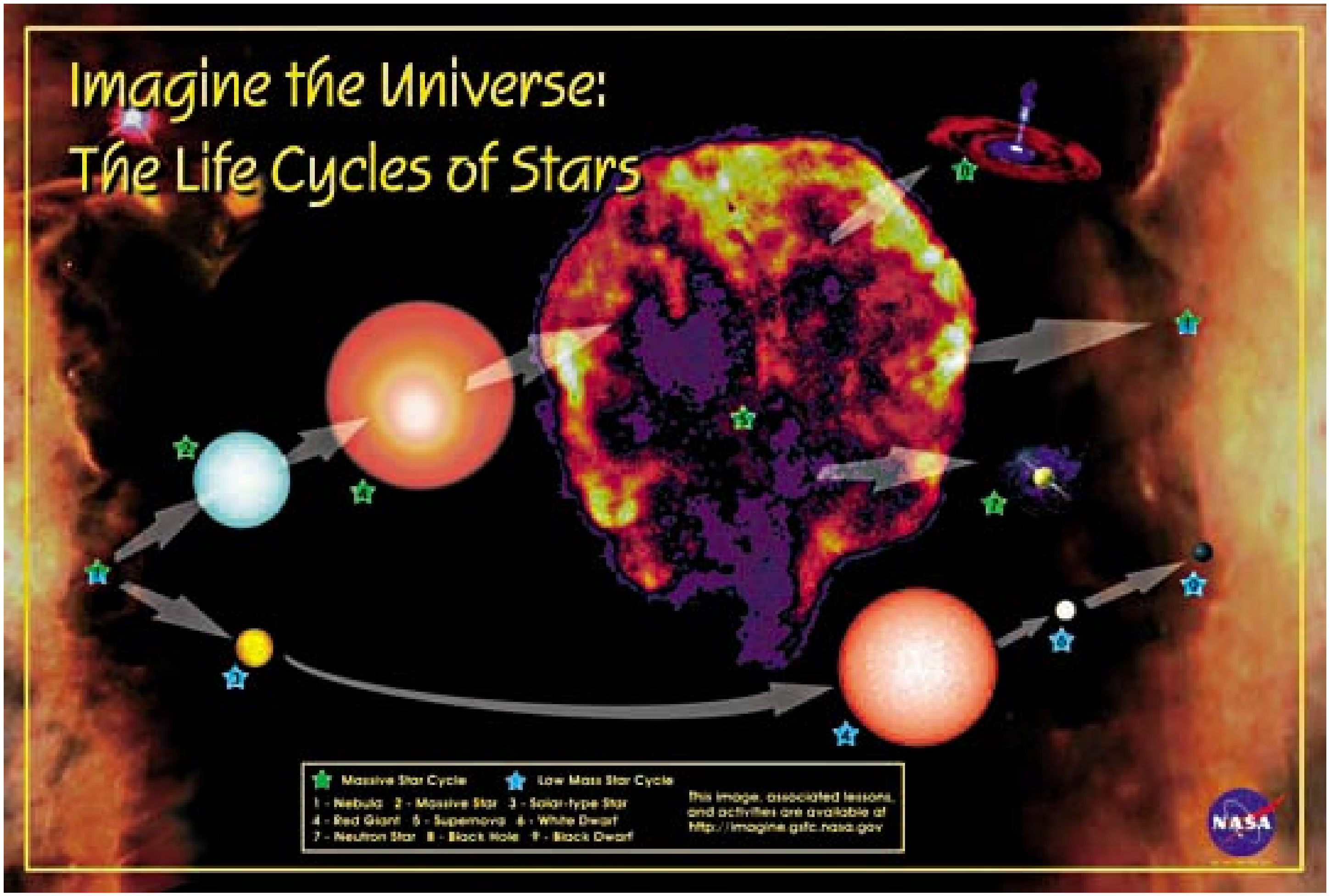
- The mean opening angle is about 4 degrees (i.e. $\langle f_b^{-1} \rangle \sim 500$)
- Geometry-corrected energies are narrowly clustered
- $<E_\gamma> \sim 1.3\ 10^{51}$ ergs
- GRB standard candle?

Bloom, Frail & Kulkarni (2003)

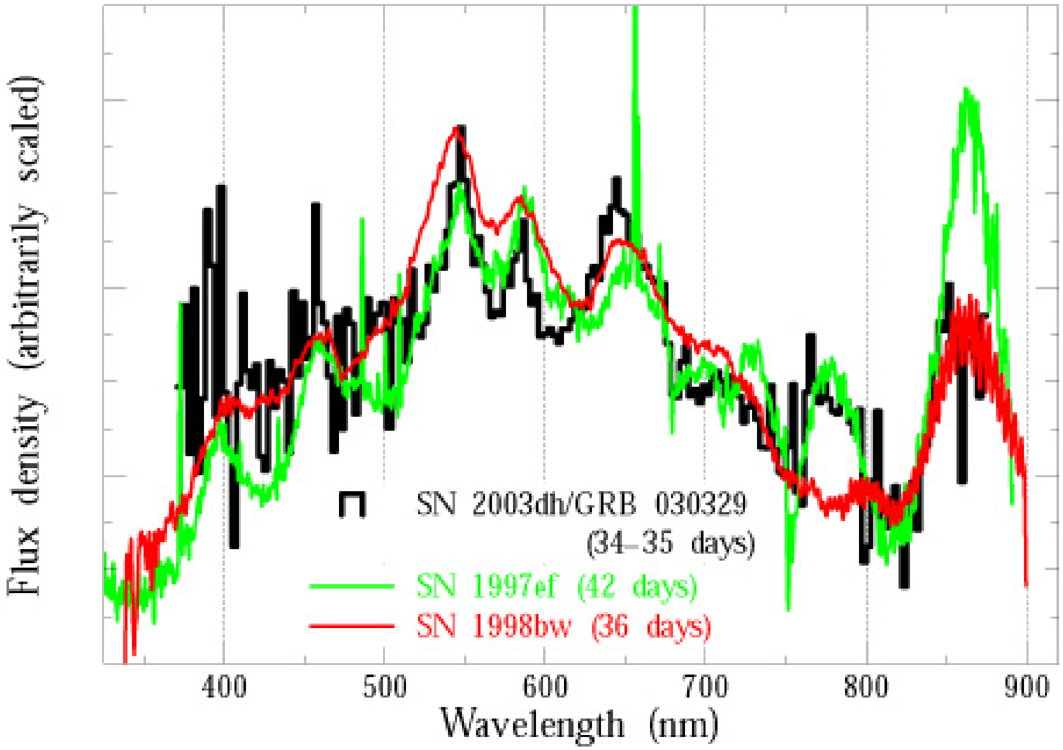
Possible sources of GRB with afterglow

Hypernovae




Imagine the Universe:
The Life Cycles of Stars
Massive Star Cycle
Low Mass Star Cycle
1 - Nebula 2 - Massive Star 3 - Solar-type Star
4 - Red Giant 5 - Supernova 6 - White Dwarf
7 - Neutron Star 8 - Black Hole 9 - Black Dwarf
This image, associated lessons, and activities are available at http://imagine.gsfc.nasa.gov
NASA

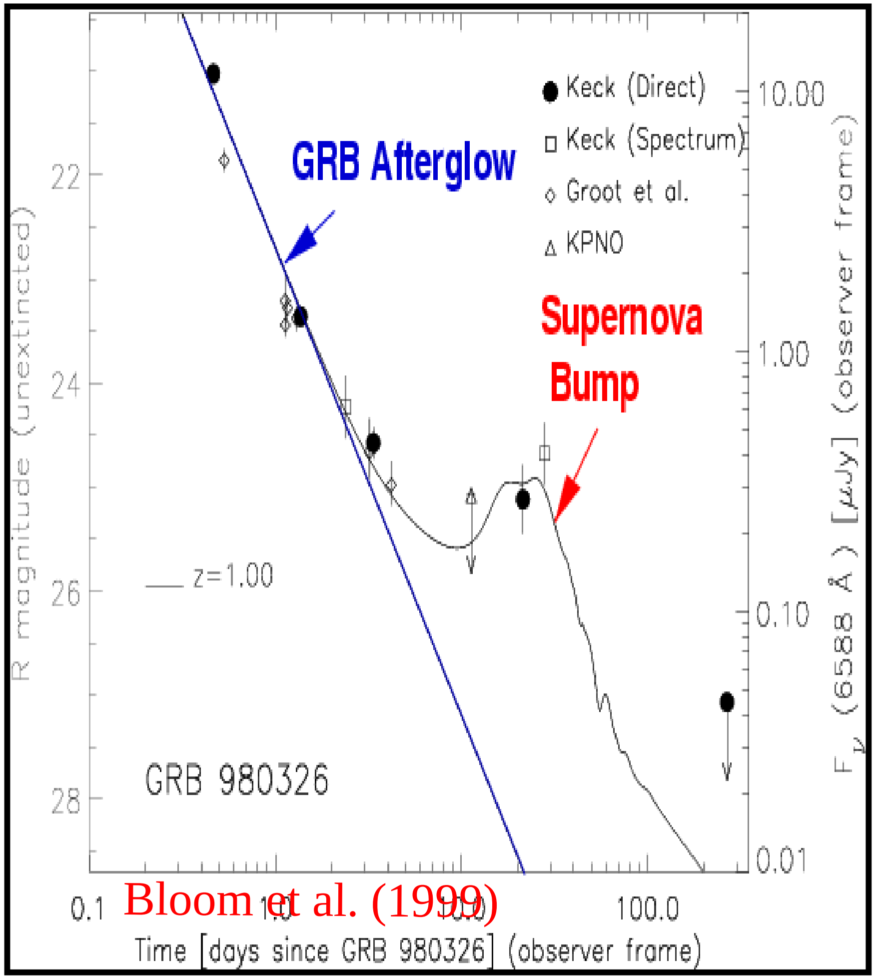
Direct Clues to the SNe/GRB Link

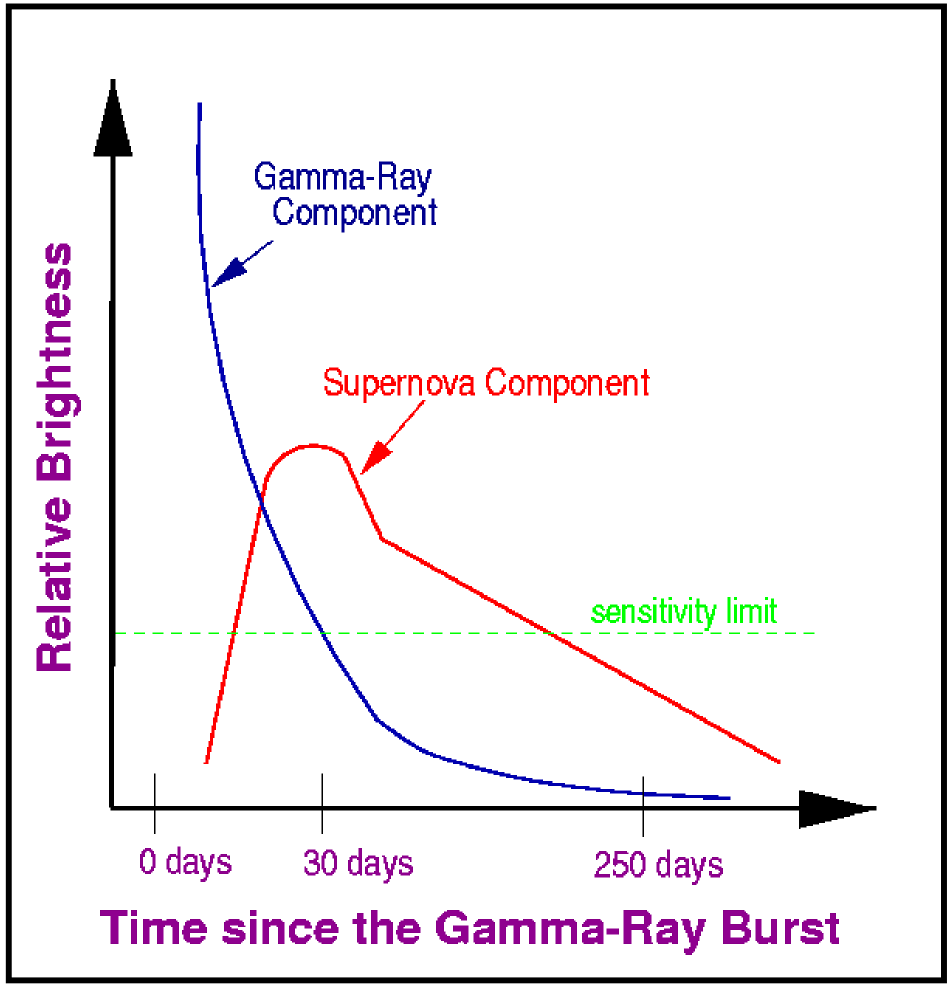


Spectral distribution of afterglow of GRB030329 and Supernovea very similar

from Matheson et al. (GCN 2120) see also Stanek et al. (2003)

Direct Clues to the SNe/GRB Link





Dale A. Frail

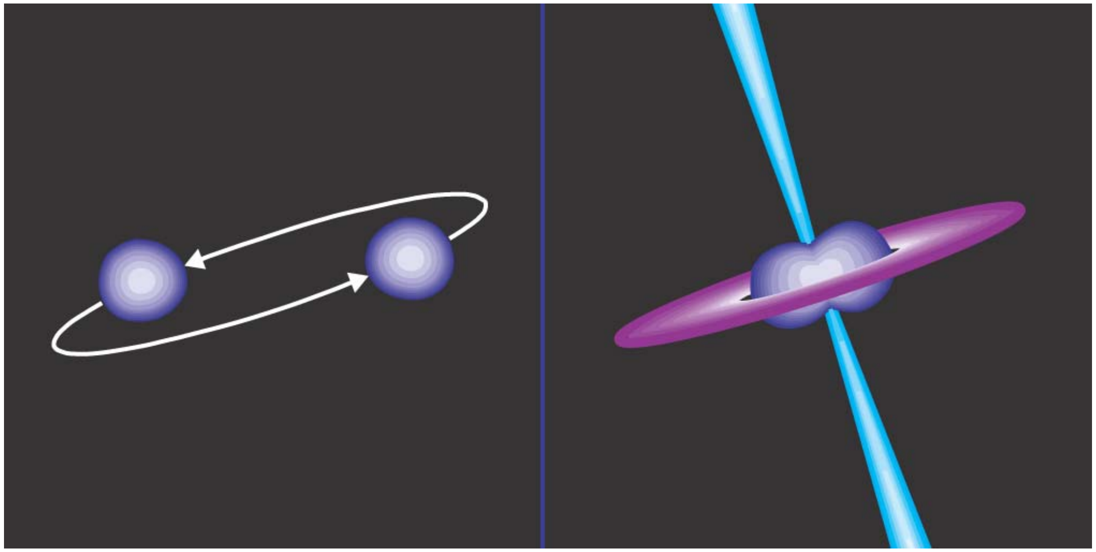
Short GRB Progenitors

No clear situation

No afterglows observed

Most likely :

Mergers of compact binaries (Pacynski, Goodman, Eichler et al., Mochkovitch et al.)

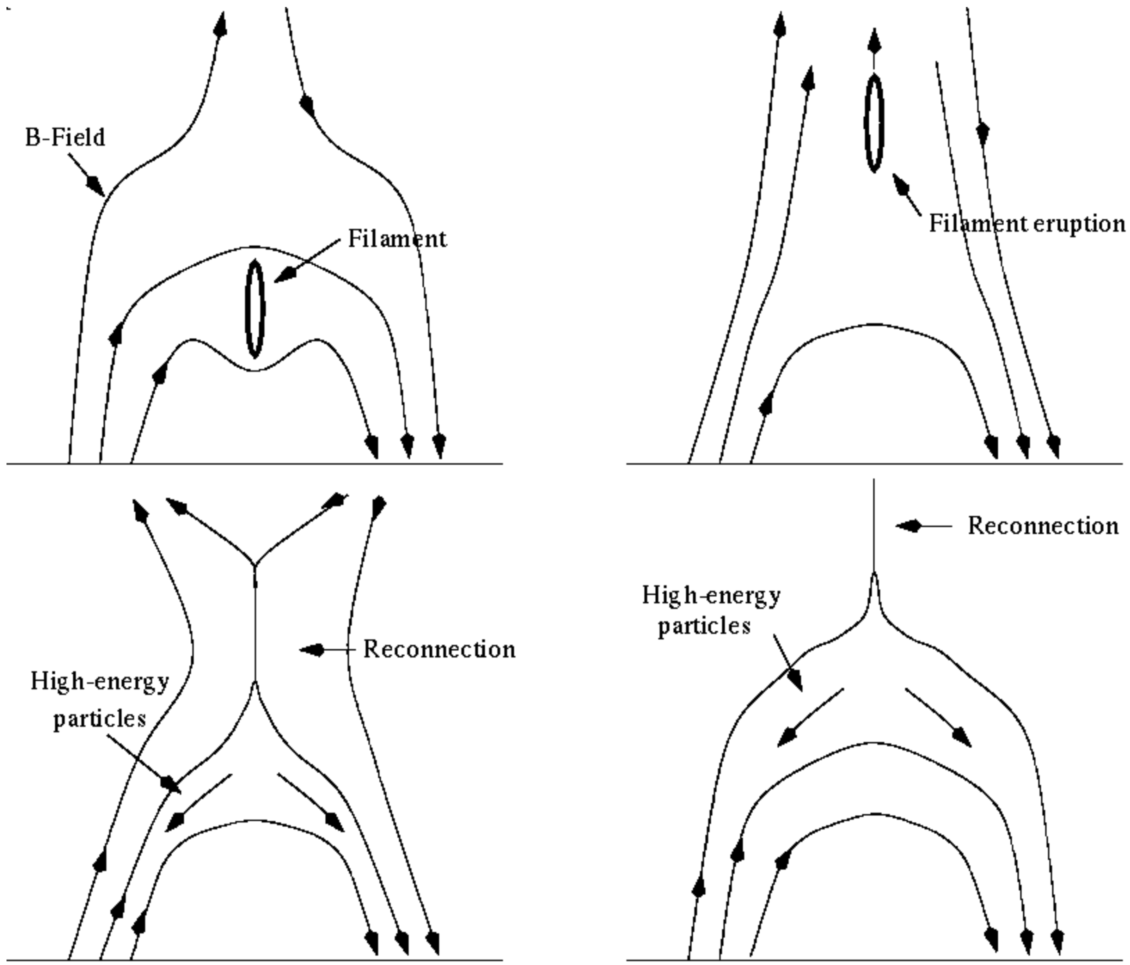


Binary neutron star merger

Acceleration of GRB outflows by Poynting flux dissipation. (astro-ph/0112509, *G. Drenkhahn, MPA Garching*)

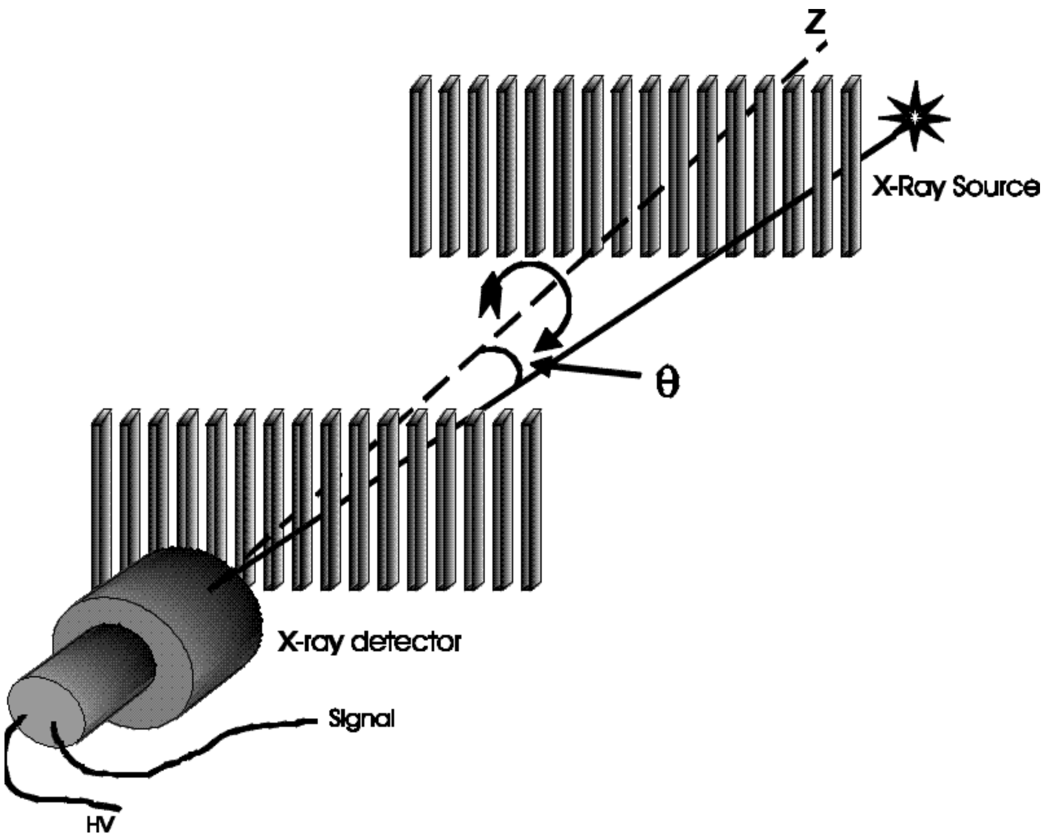
- **Magnetically powered relativistic outflows in which a part of the magnetic energy is dissipated internally by reconnection**
- **Magnetic energy is converted to kinetic energy.**
- **Such processes are studied with the HESSI (High Energy Solar Spectroscopic Imager) satellite on Solar Flares**
- **Is there a connection to the explosive impulsive energy release observed with HESSI?**
  - **The HESSI Instrument**
  - **Solar X- and Gamma Ray observation**
  - **GRB Polarization measurements with HESSI**

One Magnetic Reconnection and Particle Acceleration Model



High Energy Solar Spectroscopic Imager
HESSI and GRB

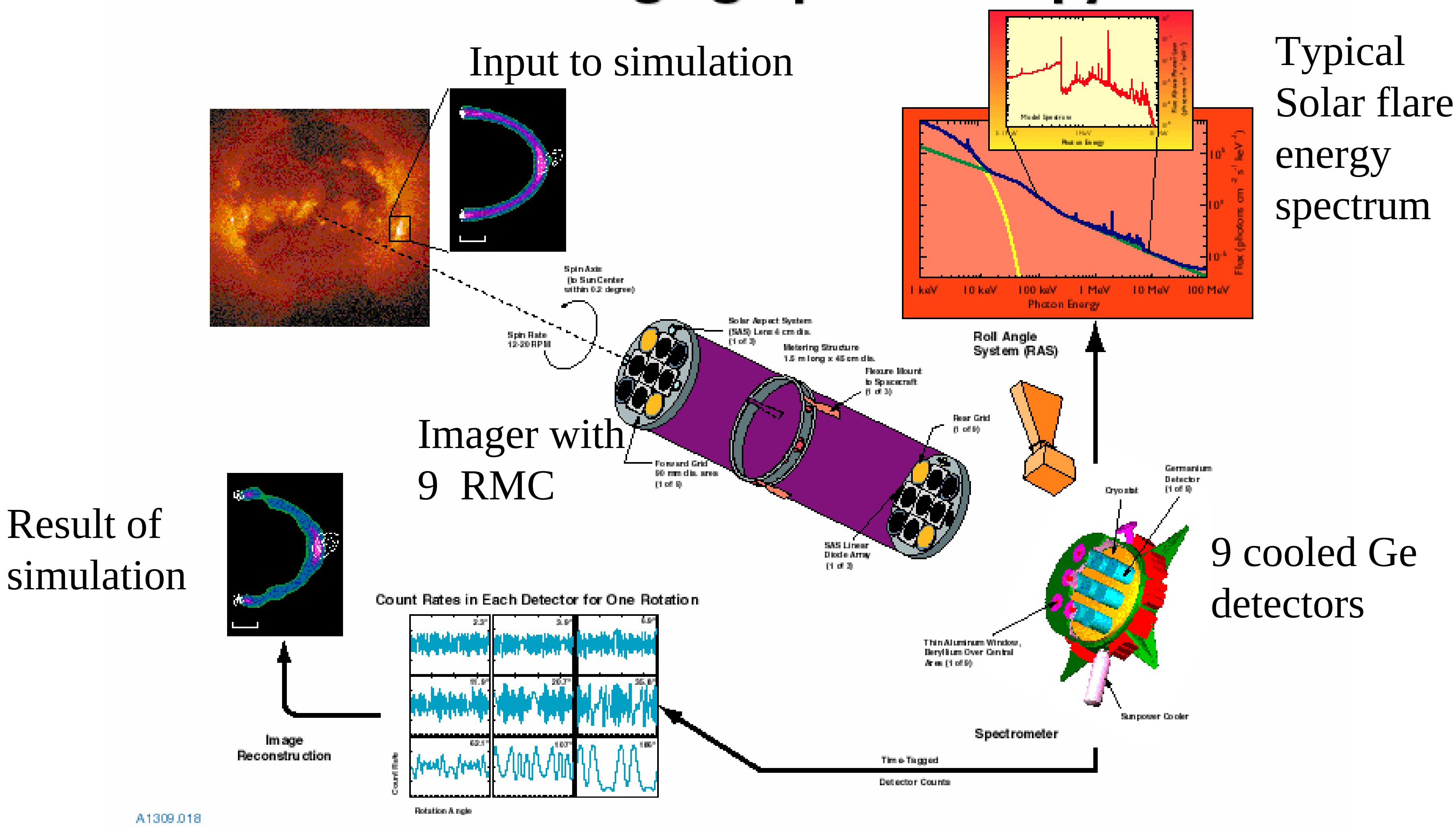
HESSI Imaging Technique
Rotating Modulation Grid Collimators (RMC)



Imaging:

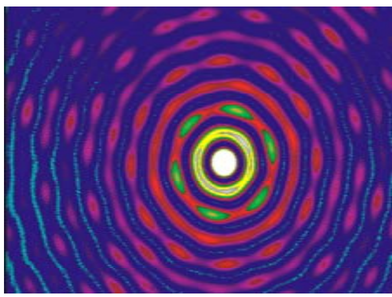
- **Measure angle via absorption**
- **Grid dimensions determine angular resolution**
- **HESSI: 2 arcsec (1/1000 of solar diameter) to 3 arcmin**
- **9 RMC 1.55m spaced, finest grid 30µm spacing (precision mechanics to 3µm)**

HESSI Imaging Spectroscopy

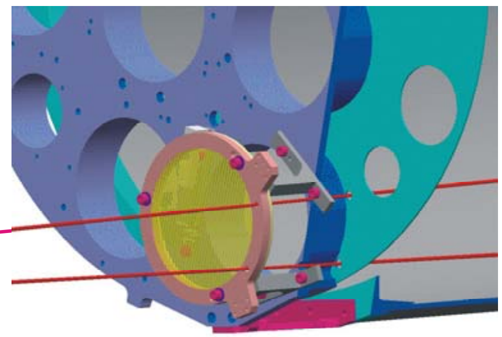


Twist Monitoring System (TMS)

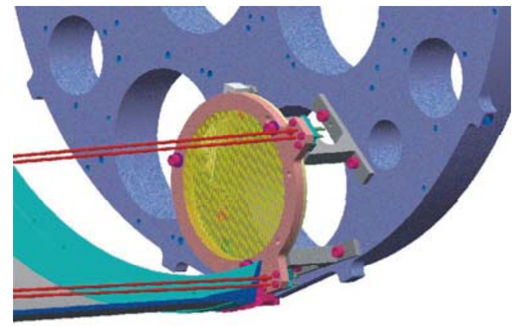
Purpose: Monitor any twist of a grid pair 1 to 9 and/or of front to rear tray



Pattern on CCD Camera



Front Tray/Grid (2 Annuli)



Rear Tray/Grid (4 Pinholes)

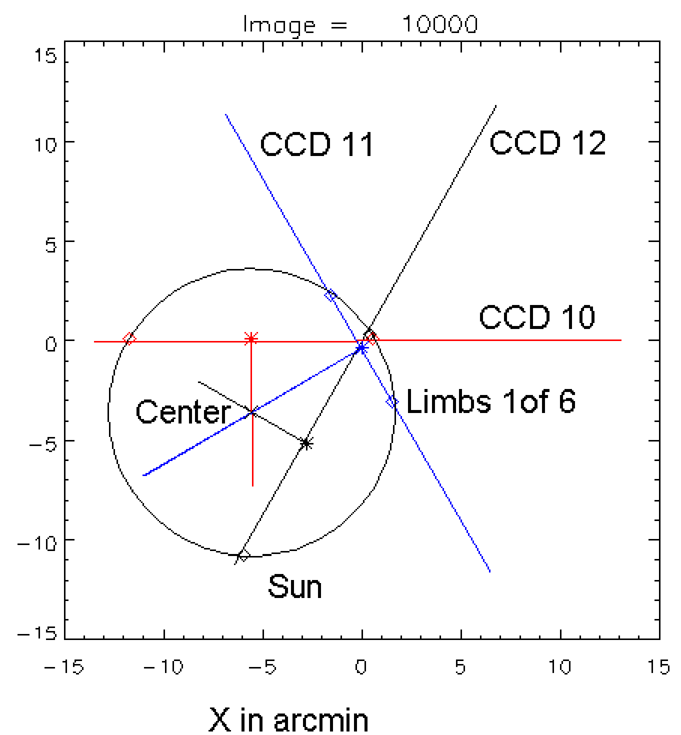
In total 11 systems, each system has:

- on rear tray: 4 diode lasers behind 30 micron pinholes (spatial filters).
- on front tray: 2 annuli 3.0/2.8 mm diameter producing interference pattern.
- all 4 rays merge on a CCD Camera, center of if-pattern can be fitted to better than 1 micron.


SSL

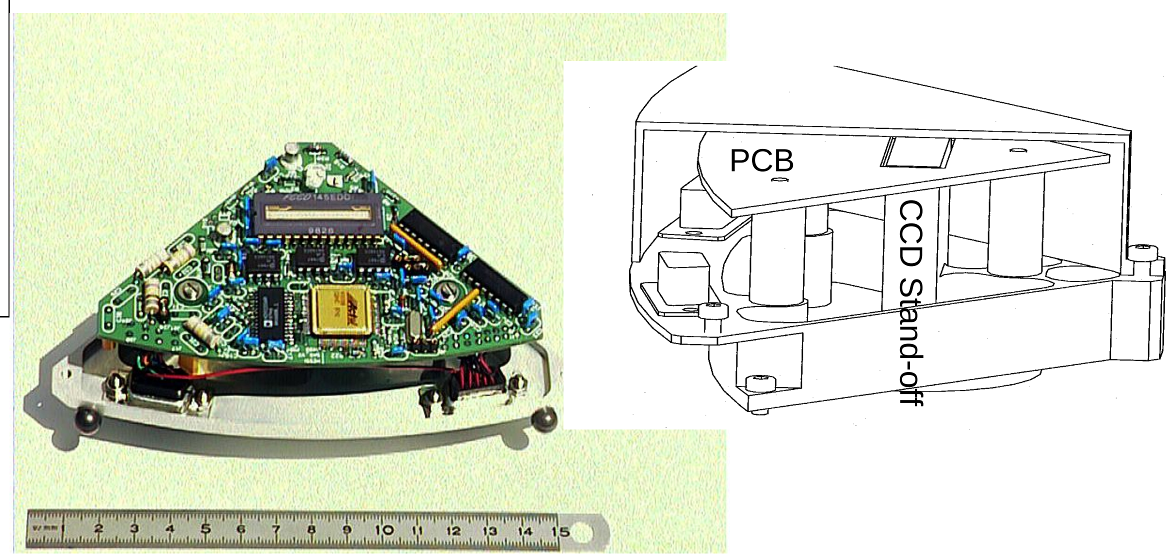

VAFB

Solar Aspect System (SAS)

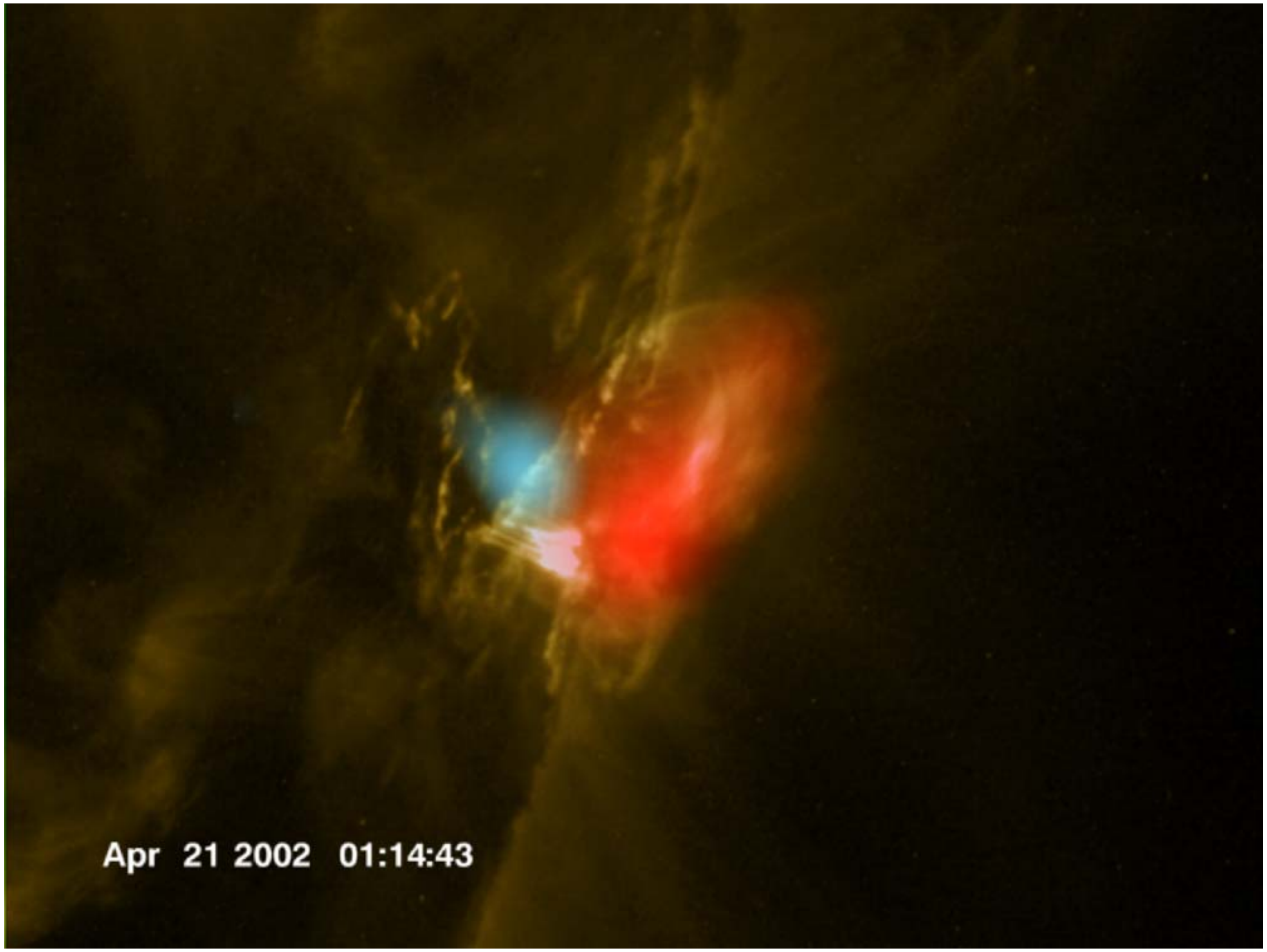


Operation Principle:

- **The Sun is imaged on 3 linear CCDs, spaced 120º.**
- **The CCDs are read out at 128Hz.**
- **Onboard processing of limb position, download of needed data.**
- **On-ground aspect reconstruction.**
- **In-flight calibration exceeds requirements of <0.4”**

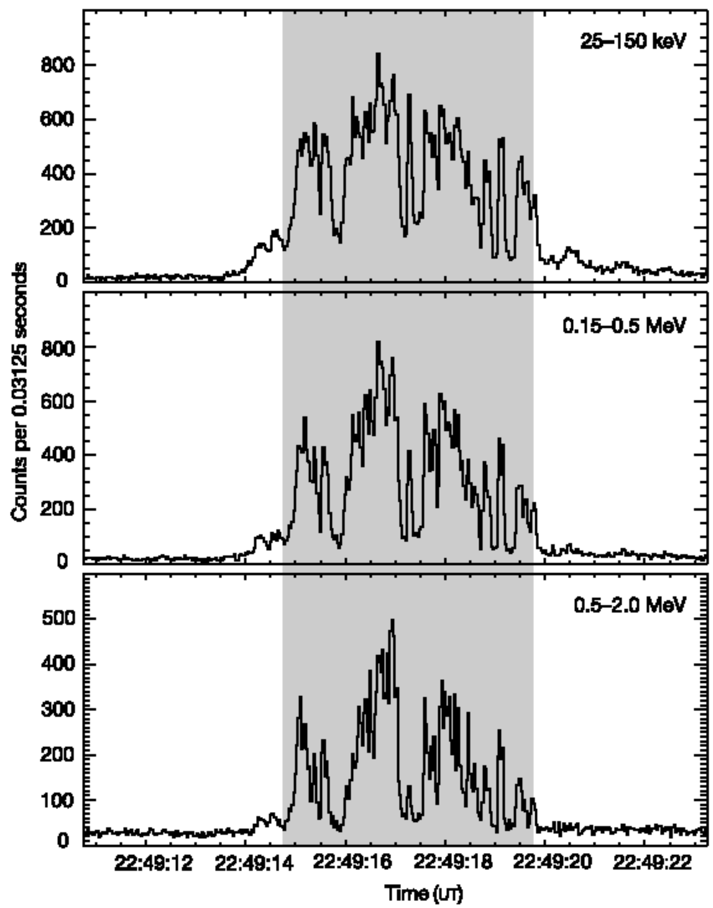


Flares at 21.4.2002 um 01:14 HESSI and TRACE Instruments



Blue (HESSI):
~100 Million K
Red (HESSI):
~ 15 Million K
Bown (TRACE):
~ 0.5 Million K

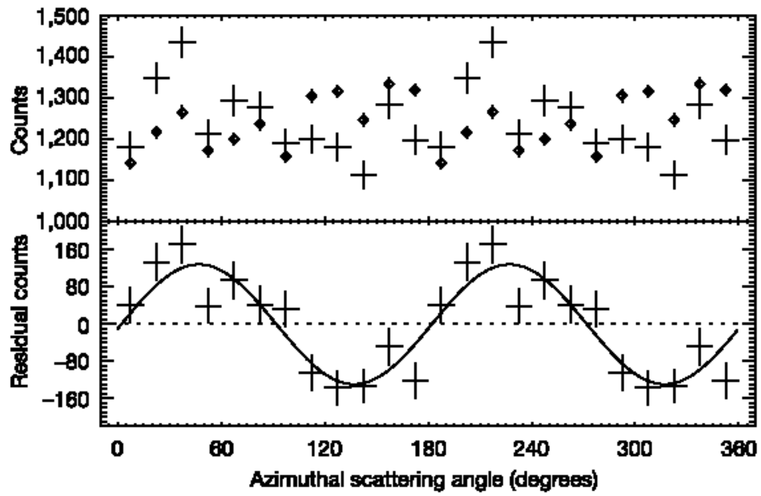
HESSI Observations (Dec. 2002)



RHESSI observations of GRB021206 reveals

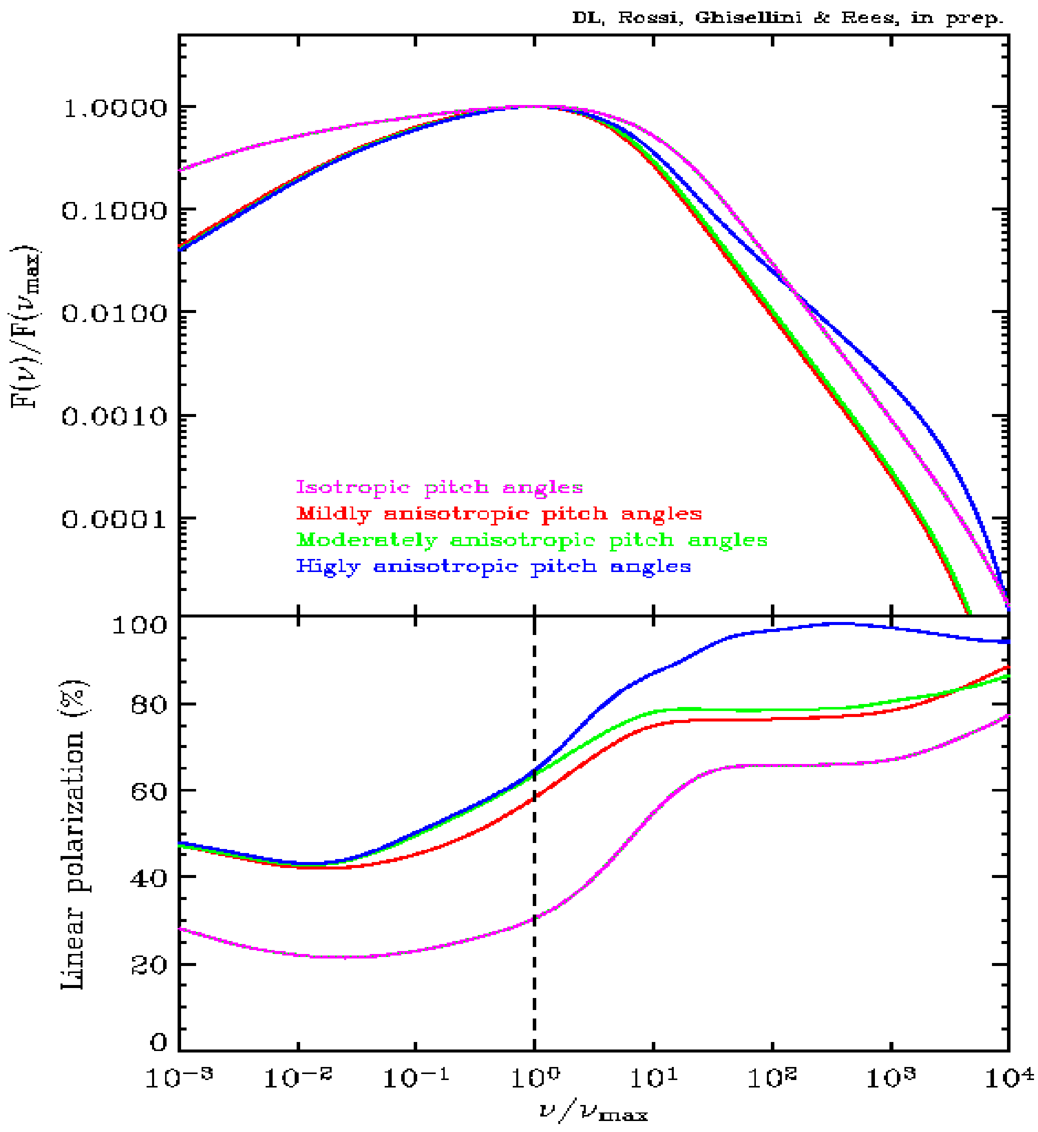
P_{lin}= 80 +/- 20 %

(Nature, Coburn & Boggs 2003)



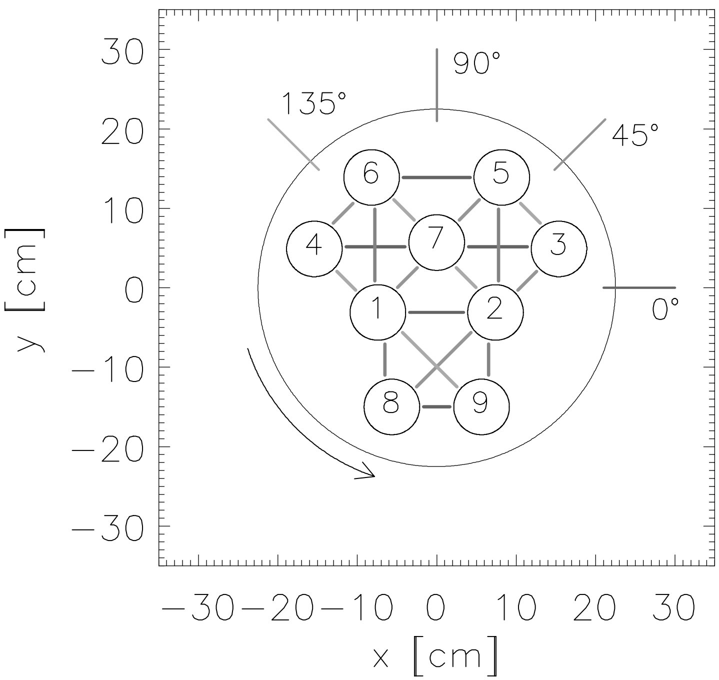
Explanation: Rossi et. al. in prep.
Rybicki & Lightman (1979)

A mildly anisotropic distribution of the pitch angles is required to suppress the relativistic dilution of linear polarization, reconciling the HESSI measurement with expectations



HESSI GRB Reanalyzed by

C. Wigger, W. Hajdas, K. Arzner, M. Guedel, A. Zehnder to be Published ApJ (2004)



The 9 cooled Ge detectors are acting as detectors and scattering devices

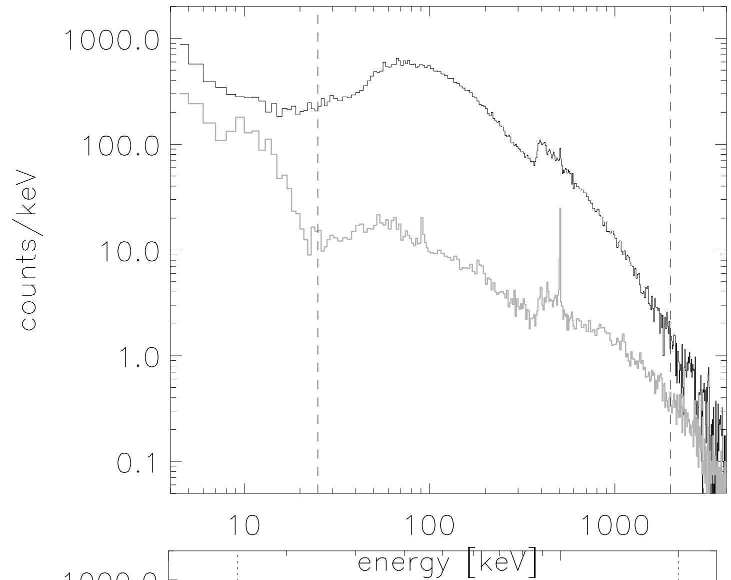
Polarimeter relies on the fact that Compton scattered photons emerge at right angle to the photon polarization

$$d\sigma = r_o^2 d\Omega \left(\frac{k'}{k}\right)^2 \left(\frac{k}{k'} + \frac{k'}{k} - 2\sin^2(\theta)\cos^2(\eta)\right)$$

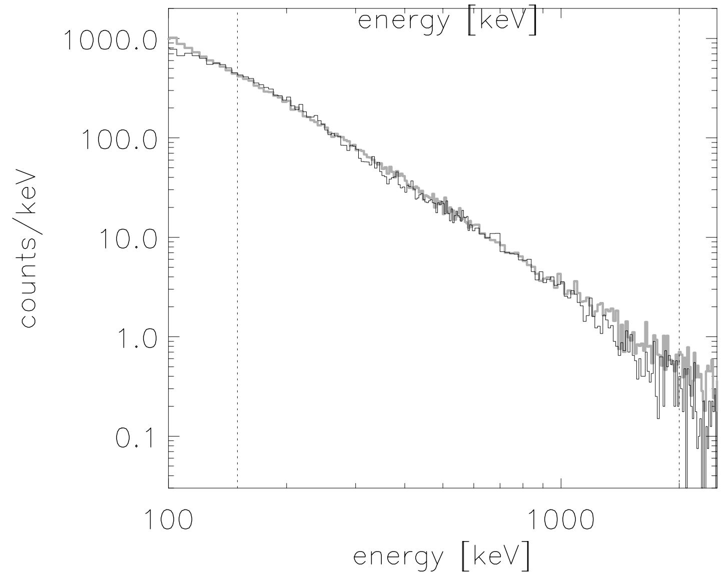
where: Θ is the Compton scattering angle

η is the azimutal angle (~90° for GRB021206 in HESSI)

Raw data energy spectrum
black: during GRB
gray: background

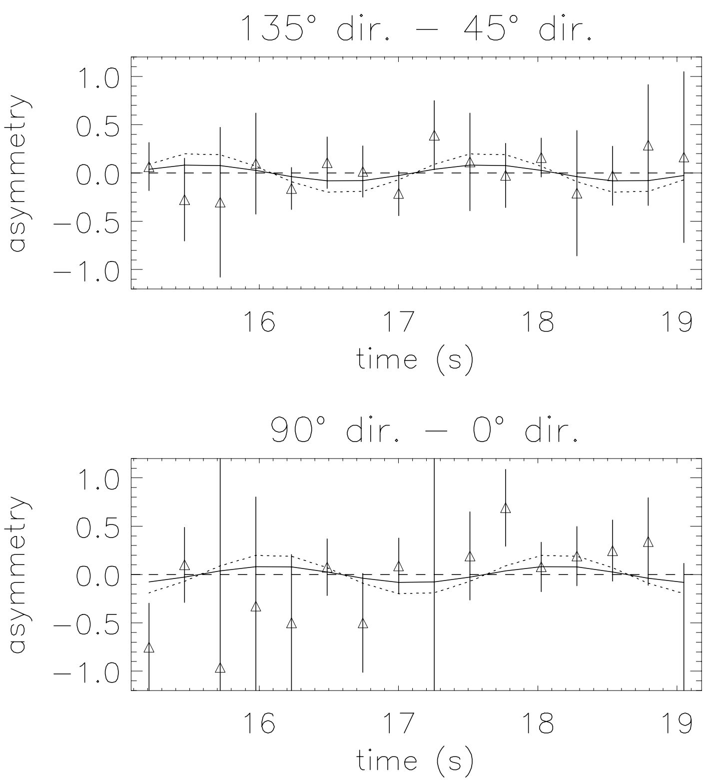


De-convoluted energy spectra
black: observation
gray: simulation

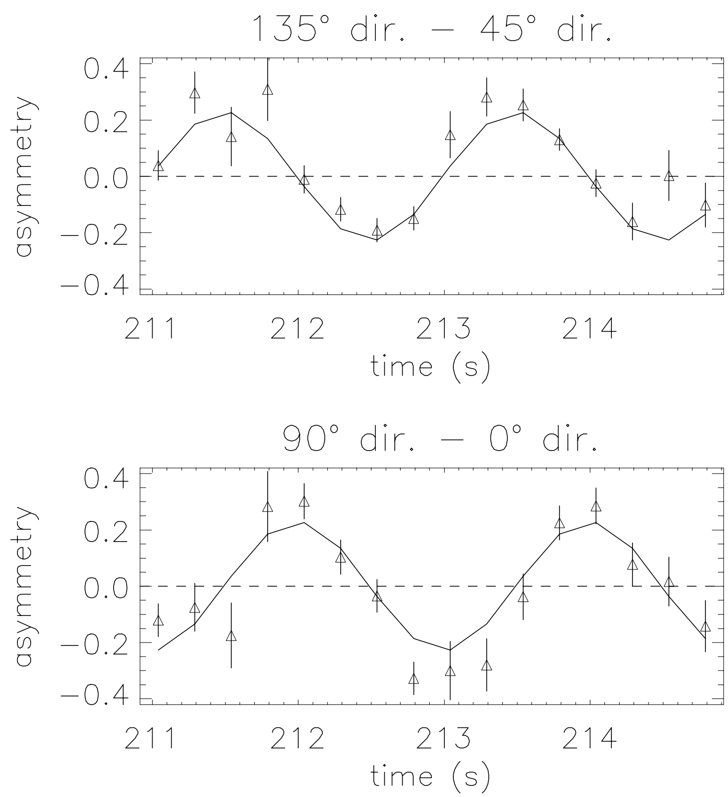


Analysis: Coincidences of detector pairs laying 90^0 to each other (0^o and 90^o, 45^o and 135^o, respectively) versus rotation angle (4sec ~ 360^o)

Real data



Simulation (100% polarization) Geant 3 incl. γ polarization



Results

Our work:

N_{tot}(E>150keV) ~65'000

N_{CS}= 770(49)

N_{cs}/N_{tot}=1.2%

$\Pi = 41_{-44}^{+57}$ %

C&B work:

N_{tot}(E>150keV) ~71'000 (not published)

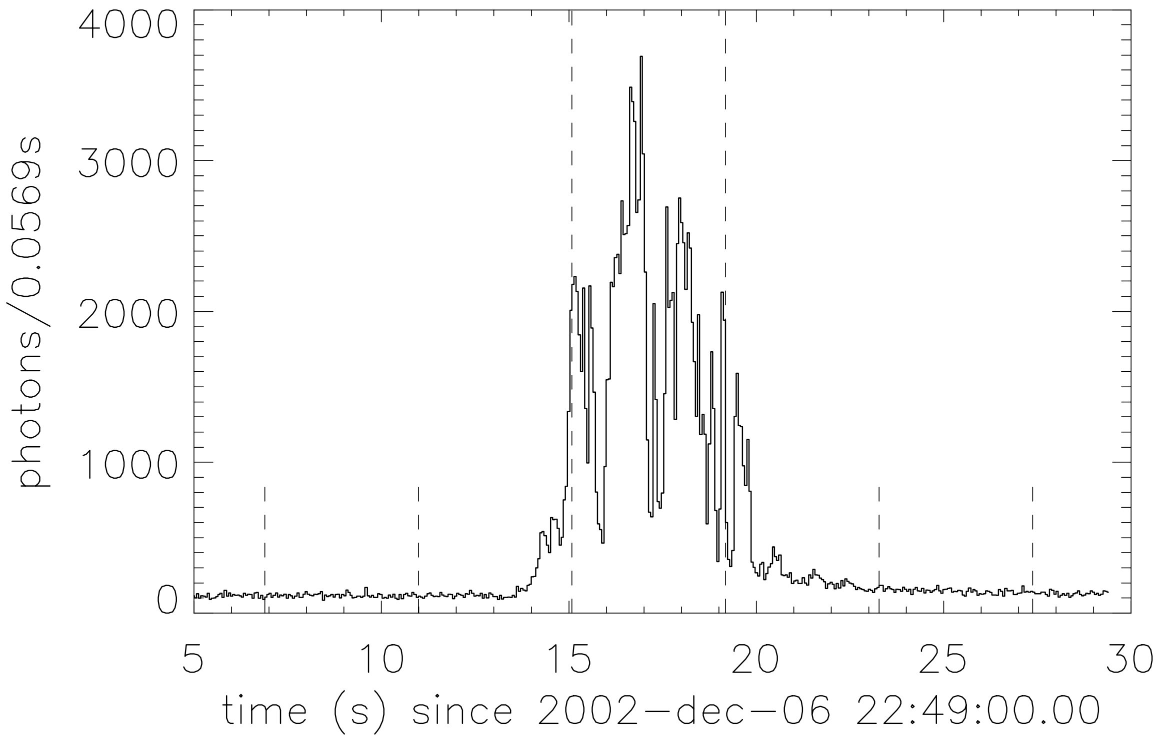
N_{CS}= 9840(96)

N_{cs}/N_{tot}=14%

Π= 80(20)%

Note: Our N_{CS} (Compton scattered coincidence events) are obtained after background subtraction, timing cuts (~1.3µsec), no multiples (3 and more), and kinematical cuts. There is large difference of N_{CS} of our and C&B's work. (Simulation: N_{cs}/N_{tot}~1.5%)

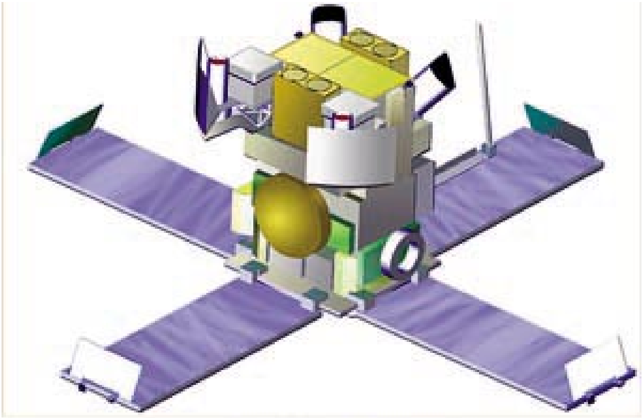
Possible explanation for C&B results



C&B have 10 times more coincidences events than we. Must include accidentals. Accidentals ~ N^2, Structure of GRB ~ 2 times 2 sec can fake a polarization signal (note: polarization signal frequency = 2 times rotation frequency ($\sin^2(\theta)$))

Getting a better look in the future

HETE-2



HETE-2 Satellite

GLAST 2006

Swift fall 2004