Wax-- 01

Gamma-Ray Bursts and High-Energy ν's

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http://www.weizman.ac.il/physics/heap/WinterSchool

- Atmospheric, Solar & SN ν's
- High-energy Astrophysical ν's
- Dark Matter Search
- High-energy Photon Observations
- High-energy Cosmic Rays

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Main GRB Characteristics

1. Rate: $\sim 3/$ day

2. Flux: $\sim 10^{-6}$ erg/ cm^{2}s

3. Duration: ~ 10 s; Variability: ~ 1 ms

4. Spectrum: $E_\gamma^2 \mathrm{d}N_\gamma/\mathrm{d}E_\gamma \approx$ Const., $E_\gamma \geq 1$ MeV

   Up to 100 MeV (some to > 1 GeV)

5. Isotropic distribution over the sky

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Cosmological Fireball

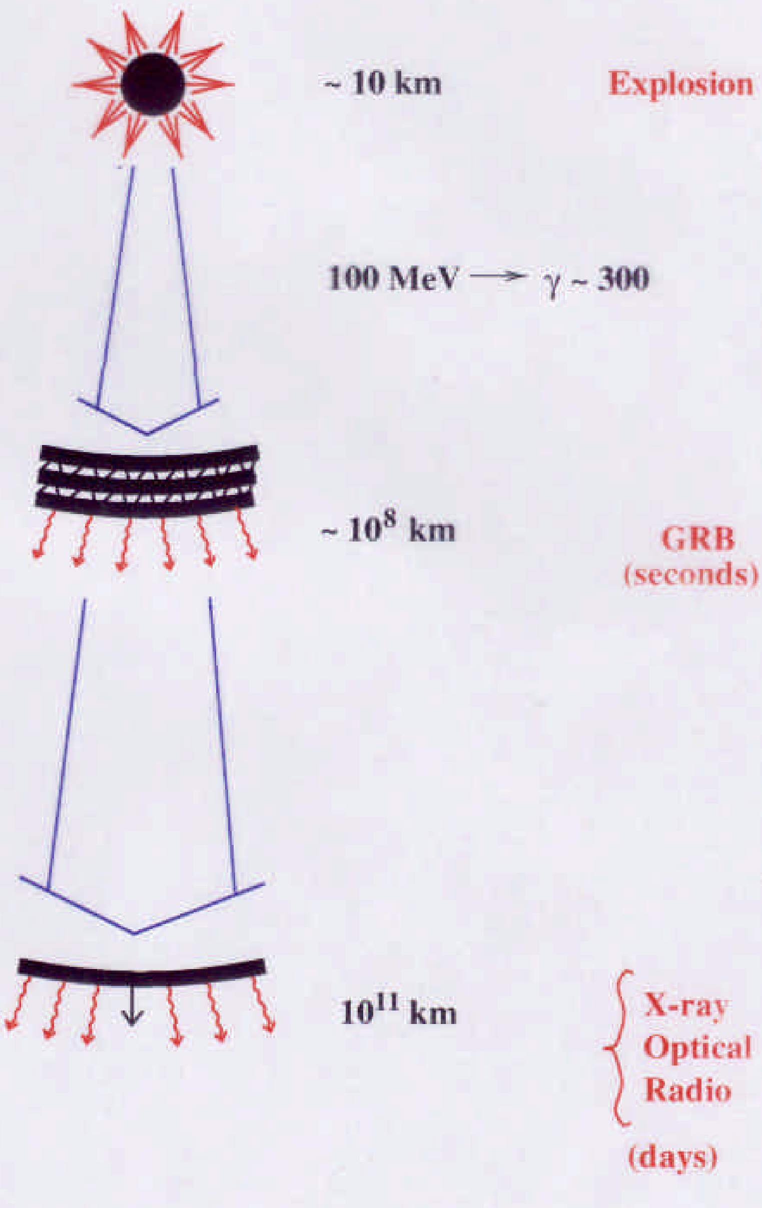
$\delta t \sim$ msec $\longrightarrow \sim 10^7$cm

$L \sim 10^{51}$ erg/s $\longrightarrow \tau_{\gamma\gamma} \sim 10^{15}$

[Goodman 86; Paczynski 86]

[Narayan, Paczynski, Piran 92;
Rees & Meszaros 92]

[Paczynski & Rhoads 93;
Katz 94;
Meszaros & Rees 97;
Vietri 97;
Waxman 97;
Wijers et al. 97;
Sari, Piran, Narayan 97]



Beppo-SAX → Afterglow

- Cosmological : $0.4 < z < 3.4$

  (Metzger et al. 97, ...)

- E_γ (Isotropic) $\approx 10^{52}$ to 10^{54} erg

- GRB rate $(z=1) \approx 10^{-8}\ Mpc^{-3}\ yr^{-1}$

- "Normal Hosts"

  (Djorgovski 99)

Scintillation

Scattering by electron density fluctuations in the local inter-stellar gas

$\Rightarrow$ Strong flux variations provided:

1. Multiple images produced:

   $\nu < \nu_o(d_{\rm sc.}, {\rm SM}) \simeq 11$ GHz

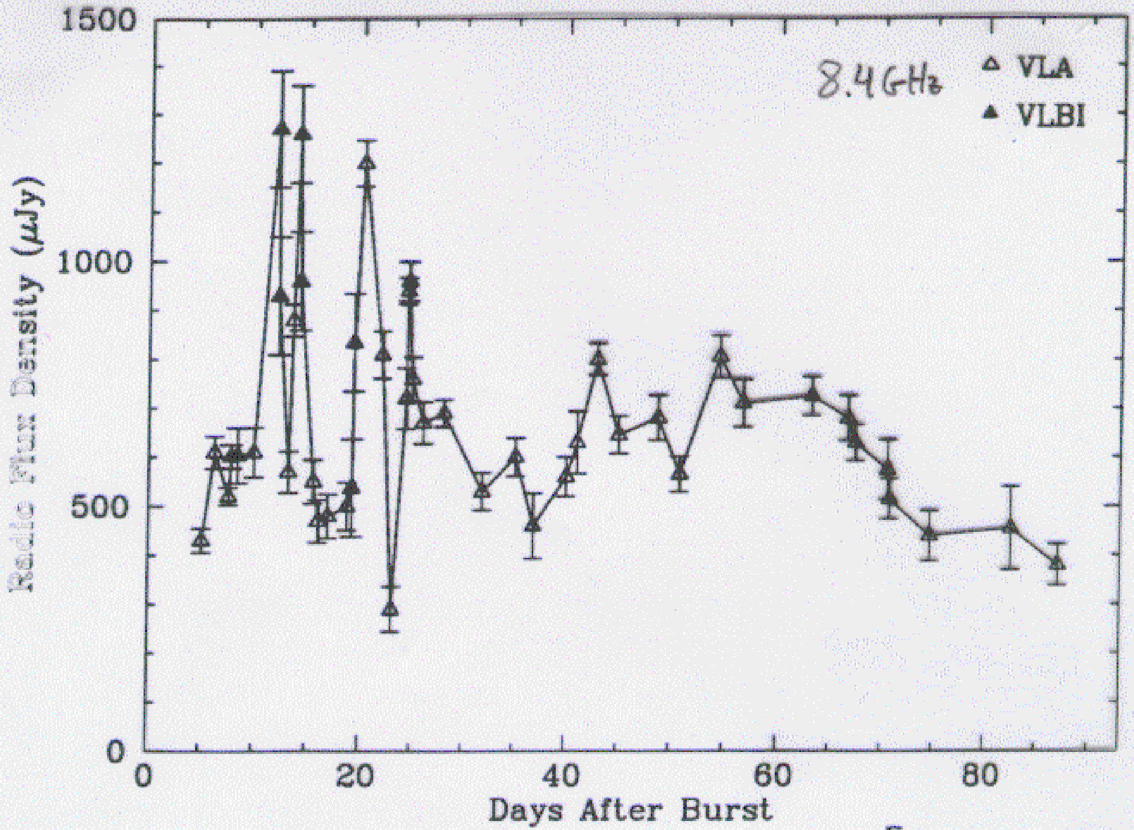
2. Apparent source size:

   $h < h_o(d_{\rm sc.}, {\rm SM}) \simeq 10^{17}$ cm

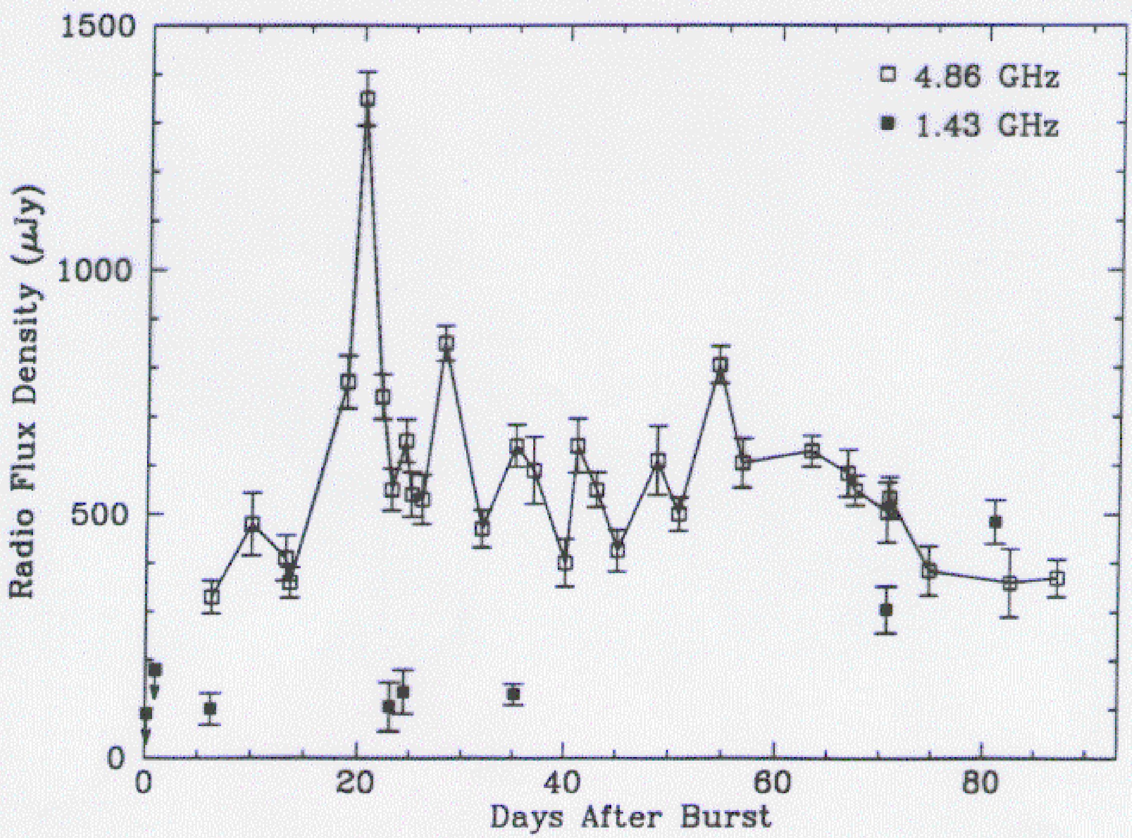
[Goodman 97]

Fireball: $h = 8 \times 10^{16} (E_{52}/n_1)^{1/8} t_{\rm week}^{5/8}$ cm

[Waxman 97]



[Frail et al. 97, Nat. 389, 261]



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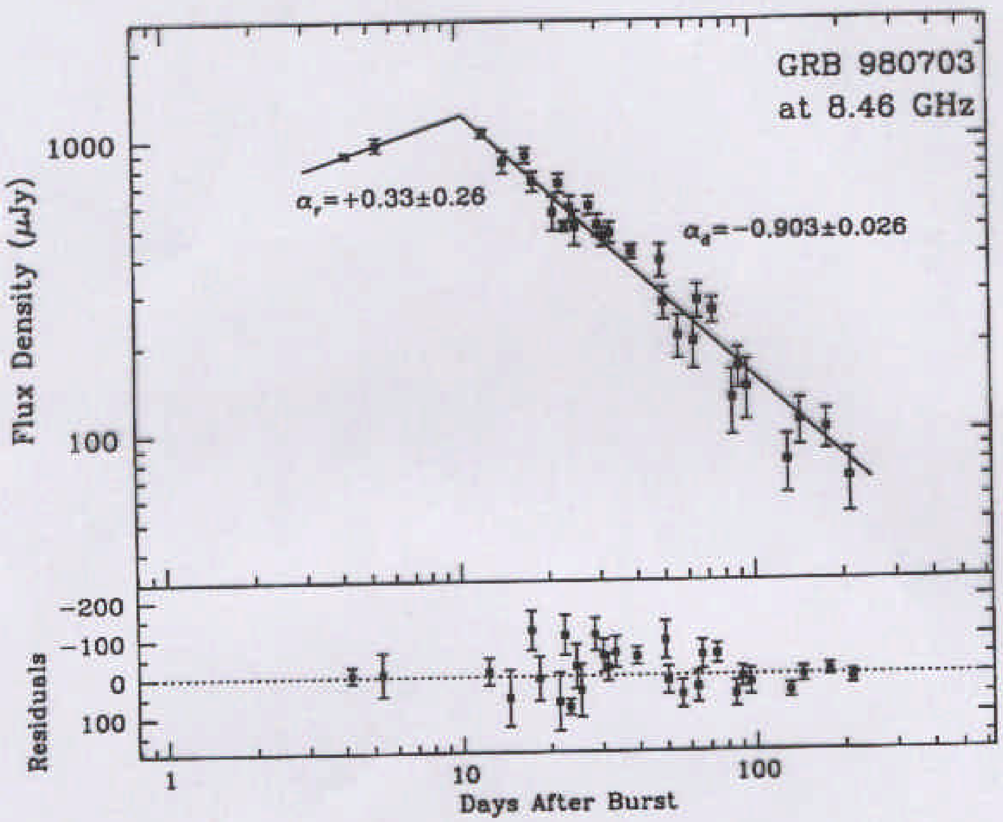
GRB 980703

Radio Light Curve & Spectrum



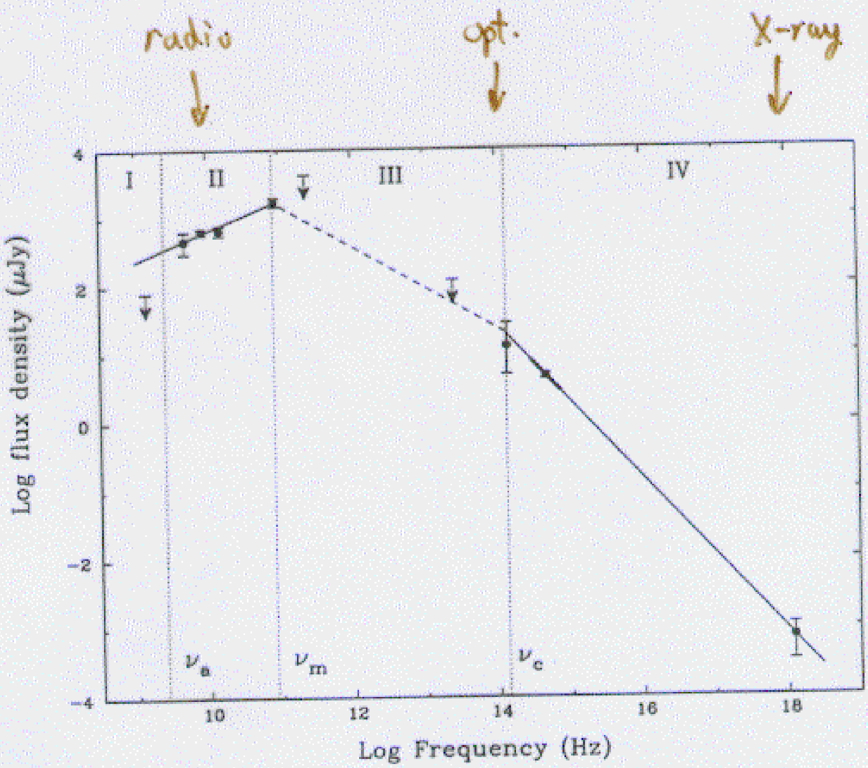
GRB 970508

$E = 10^{52}$ erg [Isotropic]

$n = 1\ cm^{-3}$

$\xi_e \simeq \xi_B \simeq 0.1$

t=12d spectrum



GRB 970508 : Fireball Calorimetry

[Frail et al., astroph/9910319]

- Deviation from model @ $t > 25d$ suggest:

  $\theta \sim 0.5$ Jet $\Rightarrow$ $E = \frac{\theta^2}{4} \cdot 10^{52}\,erg \simeq 10^{51}\,erg$

  Sub-relativistic @ $t > 100d$

- Confirmed by $t > 100d$ radio observations.

  Sub-relativistic model:

  $$E_{Tot.} \simeq 5 \cdot 10^{50}\,erg$$
  $$\Delta\Omega/4\pi \approx 5 \cdot 10^{50} / 10^{52} \approx 0.1$$
  $$n = 1\,cm^{-3}$$
  $$\xi_e \sim \xi_B \sim 0.5$$

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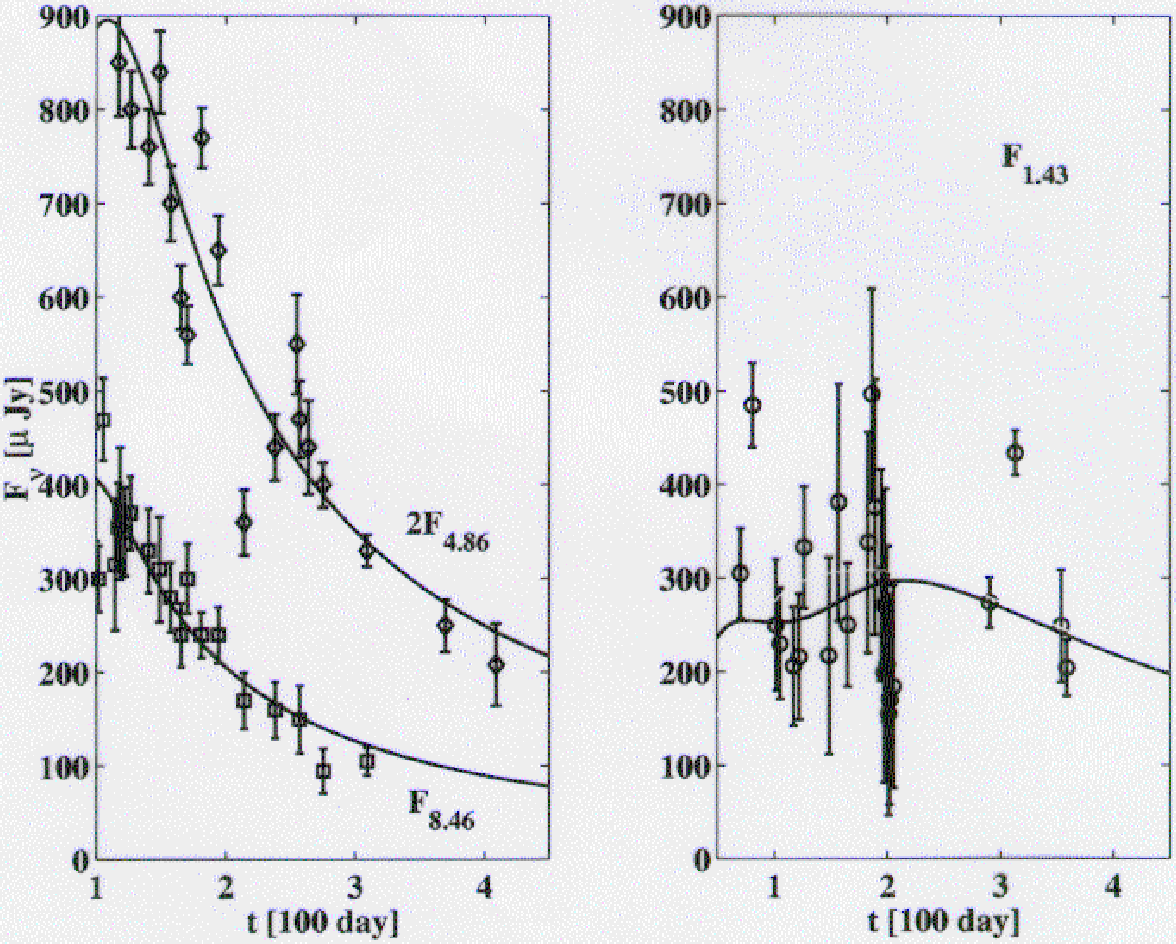
900
800
700
600
500
400
300
200
100
0
1
2
3
4
F_ν [μ Jy]
t [100 day]
$2F_{4.86}$
$F_{8.46}$
$F_{1.43}$

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Stanek et al. 99
ApJ 522, L39

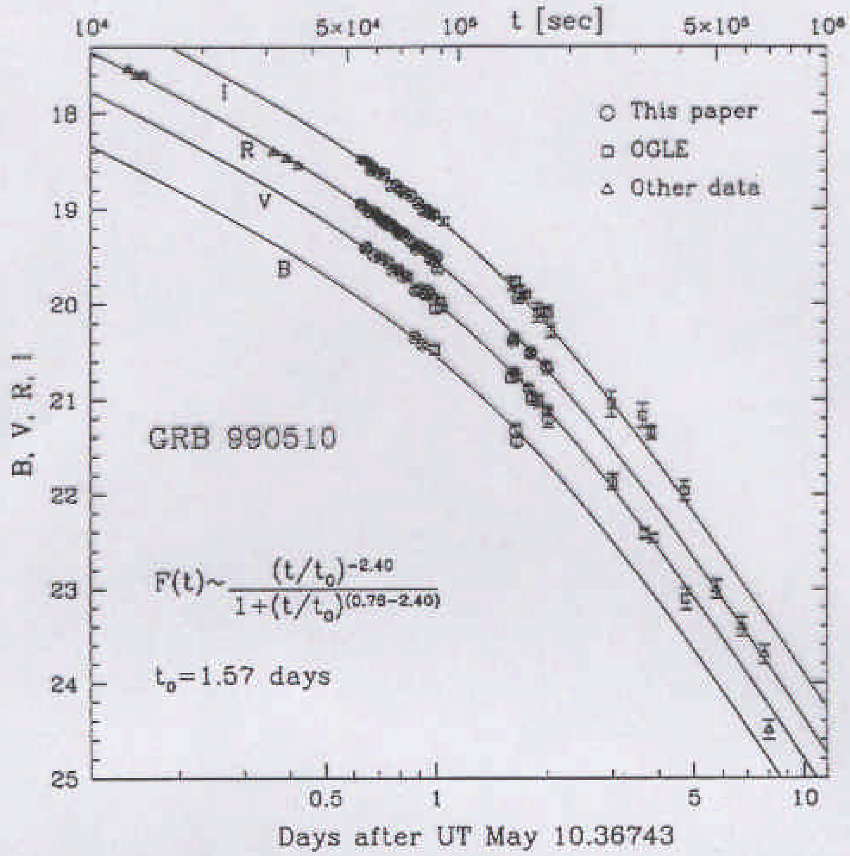

FIG. 2.—*BVRI* light curves of GRB 990510. Our data is shown with circles and OGLE data with squares. Other data used to constrain the fits is shown with triangles (for references see text). Also shown is the simple analytical fit discussed in the text.

[Freedman & Waxman 99

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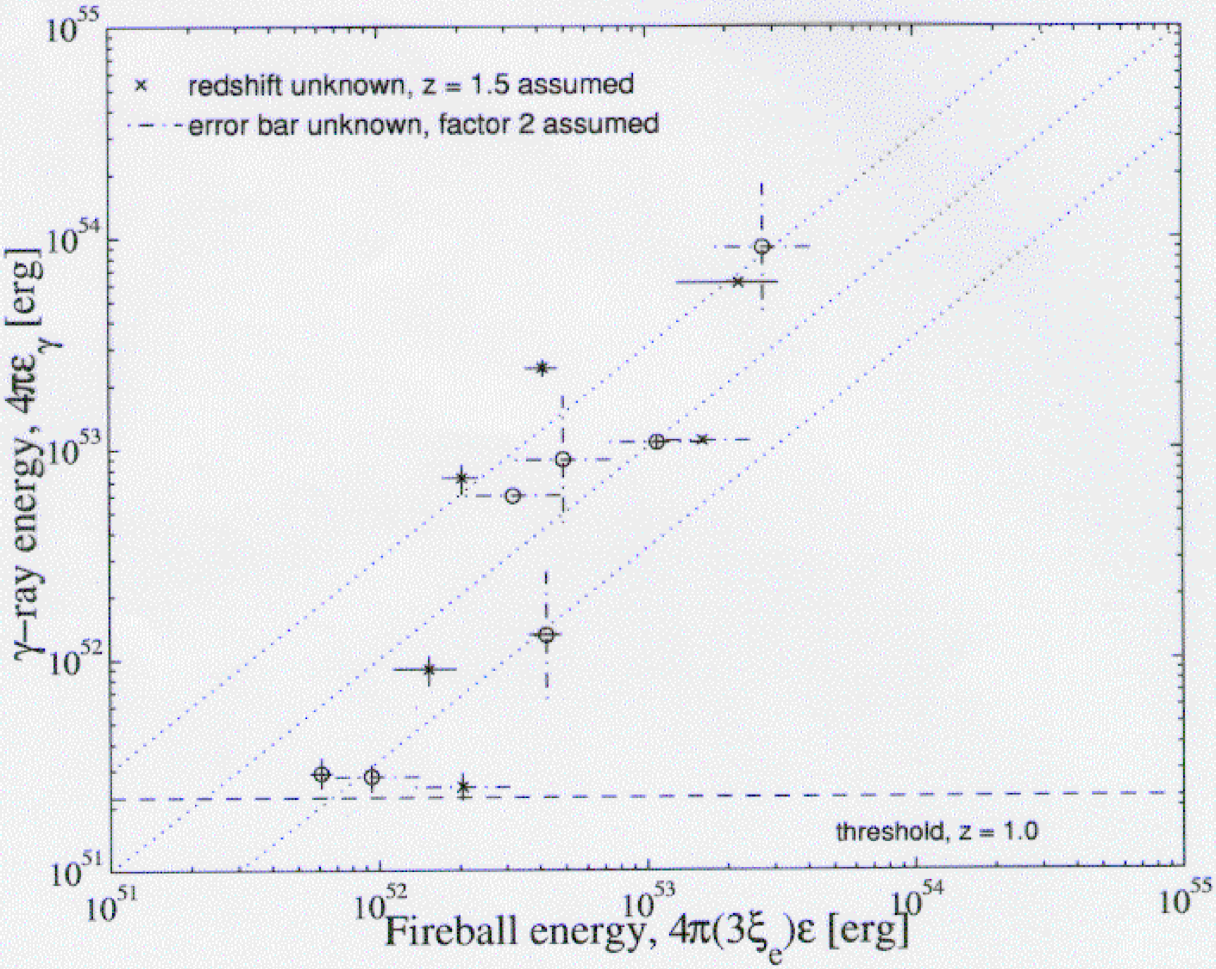


Main Open Questions

1. Underlying source

Neutron Star merger: Goodman 86, Paczyński 86

Failed SuperNova, HyperNova: Woosley 93, Paczyński 98

"Magnetars": Usov 94, Thompson 94, Vietri 99

2. Shock Processes:

- Magnetic Field Amplification:

  B energy fraction $\xi_B \sim 0.1$
- e^- Coupling:

  $\xi_e \sim 0.1, \quad dN_e/d\gamma_e \propto \gamma_e^{-2}$

3. Fireball Jet/Sphere?

- $E = E(\text{Isotropic})\,\Delta\Omega/4\pi$

  GRB970508, GRB990510: $\Delta\Omega/4\pi \sim 10\%$

Frail, Waxman & Kulkarni 99; Rhoads 99

The Flux Above 10^{17} Ev

1) SPECTRUM:

- $J(>E) \approx 1 \cdot (E/10^{19}\ \text{eV})^{-2}\ \text{Km}^{-2} \cdot \text{yr}^{-1} \cdot \text{sr}^{-1}$

- A Break $\sim 5 \cdot 10^{18}$ eV:

$$\begin{cases} J_G(E) \propto E^{-3.5} & (< 5 \cdot 10^{18}\text{eV}) \\ J_{XG}(E) \propto E^{-2.6} & (> 5 \cdot 10^{18}\text{eV}) \end{cases}$$

2) COMPOSITION: $\underset{\text{Heavy(Fe)}}{G} \longrightarrow \underset{\text{Light(p)}}{XG}$

The Flux Above 10^{17} eV

3) DIRECTIONAL:

- No evidence for anisotropy (disk), or clustering

4) HIGHEST ENERGY EVENTS ($> 10^{20}$ eV):

Fly's Eye: $3 \pm 1 \cdot 10^{20}$ eV ; $l \cong 160°, b \cong 10°$

AGASA: $1.7 - 2.6 \cdot 10^{20}$ eV ; $l \simeq 130°, b \cong -40°$

[$p - Fe$, Not a γ , ν?]

Cosmic Rays from Fireballs

1. Fermi Acceleration:

$$\frac{\xi_B}{\xi_e} \geq 0.02\gamma_{300}^2 L_{\gamma,52}^{-1} \left(\frac{E_{\rm proton}}{10^{20}\ {\rm eV}}\right)^2$$

[Waxman 95, Vietri 95]

>1997: $L_\gamma \approx 10^{52}$erg/s; $\xi_e \sim \xi_B \sim 0.1$

2. Avoid Synchrotron Losses:

$$\Gamma \geq 130 \left(\frac{E_{\rm proton}}{10^{20}\ {\rm eV}}\right)^{3/4} \left(\frac{\Delta t}{10{\rm ms}}\right)^{-1/4}$$

[Waxman 95]

>1997: $\Gamma \simeq 200$

Cosmic Rays from Fireballs

3. Mildly Relativistic (internal) Shocks →

$$\frac{dN_p}{dE_p} \propto E_p^{-n} \quad , n \simeq 2$$

4. Energy production rate:

$$\dot{\varepsilon}_{\rm CR}(>10^{19}{\rm eV}) \sim 10^{-9}\frac{1}{{\rm Mpc}^3{\rm yr}} \times 10^{53}\ {\rm erg}$$
$$= 10^{44}\frac{\rm erg}{{\rm Mpc}^3{\rm yr}}$$

[Waxman 95]

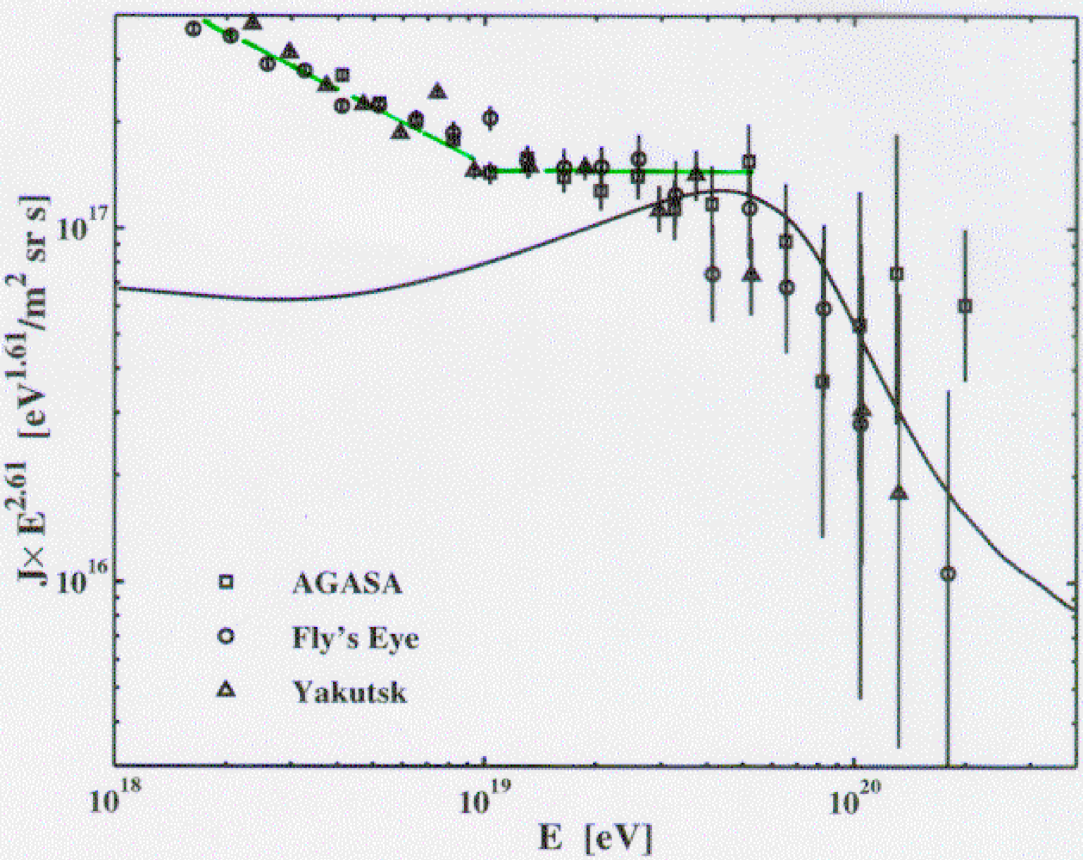
>1997: $R_{\rm GRB} = 10^{-8} - -10^{-9}/{\rm Mpc}^3{\rm yr}$,

$E_{\rm GRB} \simeq 10^{53}$ erg

Data versus Cosmological (GRB) Model

- Generation Rate & Spectrum:

$$E^2 \mathrm{d}\dot{N}/\mathrm{d}E = 0.8 \times 10^{44} \mathrm{erg\ Mpc}^{-3}\ \mathrm{yr}^{-1}$$



[Waxman 1995]

How Many "Near-By" GRB's?

- IGM B deflection:

$$\theta \simeq \sqrt{\frac{d}{\lambda}} \cdot \frac{\lambda}{R_L} \quad , \quad R_L = \frac{E}{eB}$$

$\Rightarrow$ Time spread: $\tau \simeq \frac{1}{4} \theta^2 \frac{d}{c}$

$$\tau \simeq 10^5 \, d_{100} \left(\lambda_1 B_{nG}^2\right) E_{20}^{-2} \text{ yr}$$

$$\Rightarrow \quad N_{GRB}(d,E) \simeq \tau(d,E) \cdot R_{GRB}$$
$$\simeq 10^3 \left(\lambda_1 B_{nG}^2\right)$$

[Waxman 95]

High Energy GRB Neutrinos

- Photo-meson Losses:

$$\gamma + p \rightarrow \pi + N$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_\mu + \bar{\nu}_\mu + \nu_e$$

- Threshold:

$$\frac{E_p}{\gamma}\frac{E_\gamma}{\gamma} > \varepsilon_0^2$$

GRB photons, $E_{\gamma,0} \simeq 1\text{MeV}$:

$$E_{p,0} \simeq 10^{16}\text{eV}, \quad E_{\nu,0} \simeq 5 \times 10^{14}\text{eV}$$

- Efficiency:

$$f_\pi = 0.2\frac{L_{\gamma,52}}{\gamma_{300}^4 \delta t_{10\text{ms}}}, \quad E_p \geq E_{p,0}$$

[Waxman & Bahcall 97]

Ultra High Energy "AfterGlow" Neutrinos

- Threshold:

$$\frac{E_p}{\gamma}\frac{E_\gamma}{\gamma} > \varepsilon_0^2$$

Prompt AfterGlow, $E_{\gamma,0} \simeq 100\text{eV}$:

$$E_{p,0} \simeq 10^{20}\text{eV}, \quad E_{\nu,0} \simeq 10^{19}\text{eV}$$

- Efficiency:

$$f_\pi = 0.05\frac{L_{\text{UV},49}}{\gamma_{250}^5 T_{10\text{s}}}E_{p,0}^{1/2}$$

[Waxman & Bahcall 99]

Neutrino Fluxes

- "GRB" neutrinos:

  - $\epsilon < 10^{16}$eV:

$$\varepsilon^2\Phi_\nu(\varepsilon) \simeq 3\times10^{-9}\min\left(1, \frac{\varepsilon}{100\text{TeV}}\right)\ \frac{\text{GeV}}{\text{cm}^2\,\text{s}\,\text{sr}}$$

$$J_\mu \ \sim\ 20/\text{Km}^2\ \cdot\ \text{yr}$$

Suppressed above 10^{16} eV (π,μ losses)

- "Afterglow," 10 s delay, neutrinos:

$$\varepsilon^2\Phi_\nu(\varepsilon) \simeq 2\times10^{-10}\left(\frac{\varepsilon}{10^{17}\text{eV}}\right)^\beta\ \frac{\text{GeV}}{\text{cm}^2\,\text{s}\,\text{sr}}$$

$$\beta = \begin{cases} 1/2, & \text{for } \epsilon > 10^{17}\text{ eV;} \\ 1, & \text{for } \epsilon < 10^{17}\text{ eV.} \end{cases}$$

$$J_\mu \sim\ 0.1/\text{Km}^2\ \cdot\ \text{yr}$$

Suppressed above 10^{19} eV (p acceleration)

[Waxman & Bahcall 97, 99]

- (p,n) Collisions ν's:

[Bahcall & Meszaros 00]

$E_\nu \approx 10$ GeV

$J \approx 5 /km^3 yr$

Implications:

- τ detection $\rightarrow$ Vacuum Oscillations ($\nu_\mu \rightarrow \nu_\tau$)

$$\Delta m^2 > 10^{-17} \frac{E_{\nu,14}}{D_{100}} \qquad \mathrm{eV}^2$$

- 1 sec $\nu - \gamma$ Arrival Time:

  (i) W.E.P. : $\Delta t \sim \frac{\phi}{c^2}\frac{L}{c} \sim 10^6$ sec (Galaxy)

  (ii) $1 - \frac{v}{c} = 10^{-16} \Delta t_{\mathrm{sec}} / D_{100}$

Summary

- GRB AfterGlow → Cosmological Fireballs.
- GRBs May Produce $>10^{19}$ eV CR Flux.
- High-Energy ν's:

$\varepsilon < 10^{16}$ eV: $\quad \varepsilon^2 \phi_\nu \approx 3\cdot 10^{-9} \cdot \min\left[1, \frac{\varepsilon}{100\,\text{TeV}}\right] \frac{\text{GeV}}{\text{cm}^2\cdot\text{s}\cdot\text{sr}}$

$J_\mu \approx 20 / \text{km}^2 \cdot \text{yr}$

$10^{17}\text{eV} < \varepsilon < 10^{19}\text{eV}$: $\quad \varepsilon^2 \phi_\nu \approx 2\cdot 10^{-9} \left(\varepsilon/10^{19}\text{eV}\right)^{1/2} \frac{\text{GeV}}{\text{cm}^2\cdot\text{s}\cdot\text{sr}}$

$\varepsilon \sim 10$ GeV: $\quad \varepsilon^2 \phi_\nu \approx 10^{-9} \frac{\text{GeV}}{\text{cm}^2\cdot\text{s}\cdot\text{sr}}$

- ν Detection → Test:

  $\nu_\mu - \nu_\tau$ Oscillation; W.E.P.; Lorentz Inv.

  Origin of $>10^{19}$ eV CRs

  GRB Progenitors