GAMMA RAY BURSTS

- What triggers them?
- What determines the timescales?
- Beaming and its effects?
- Internal dynamics & radiation properties?
- Environment & its effects?

collaborators:

Martin REES (Univ. Cambridge)

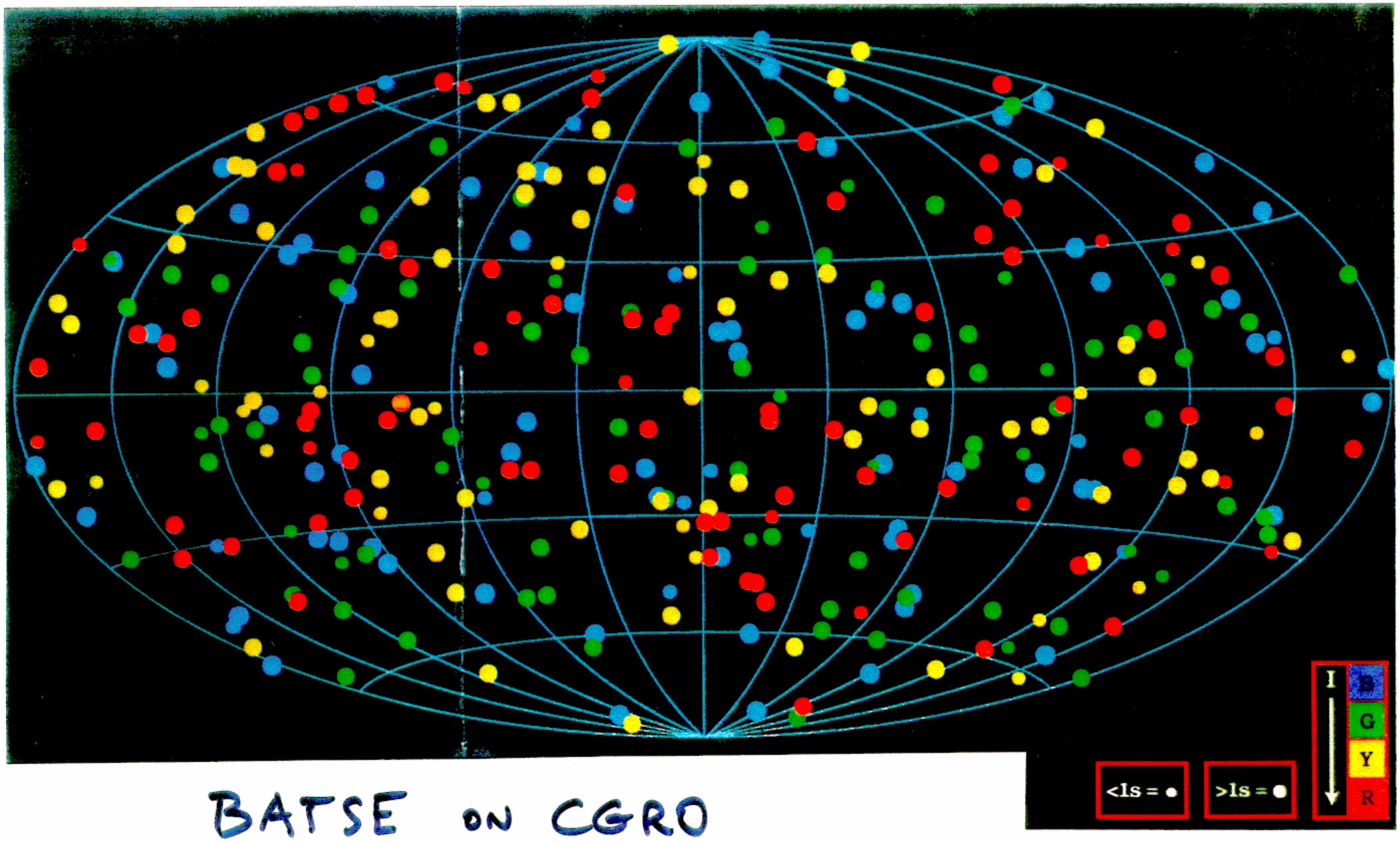
Alin PANAITESCU (Penn State)

Ralph WIJERS (Univ. Cambridge)

and

Peter MÉSZÁROS (Penn State)

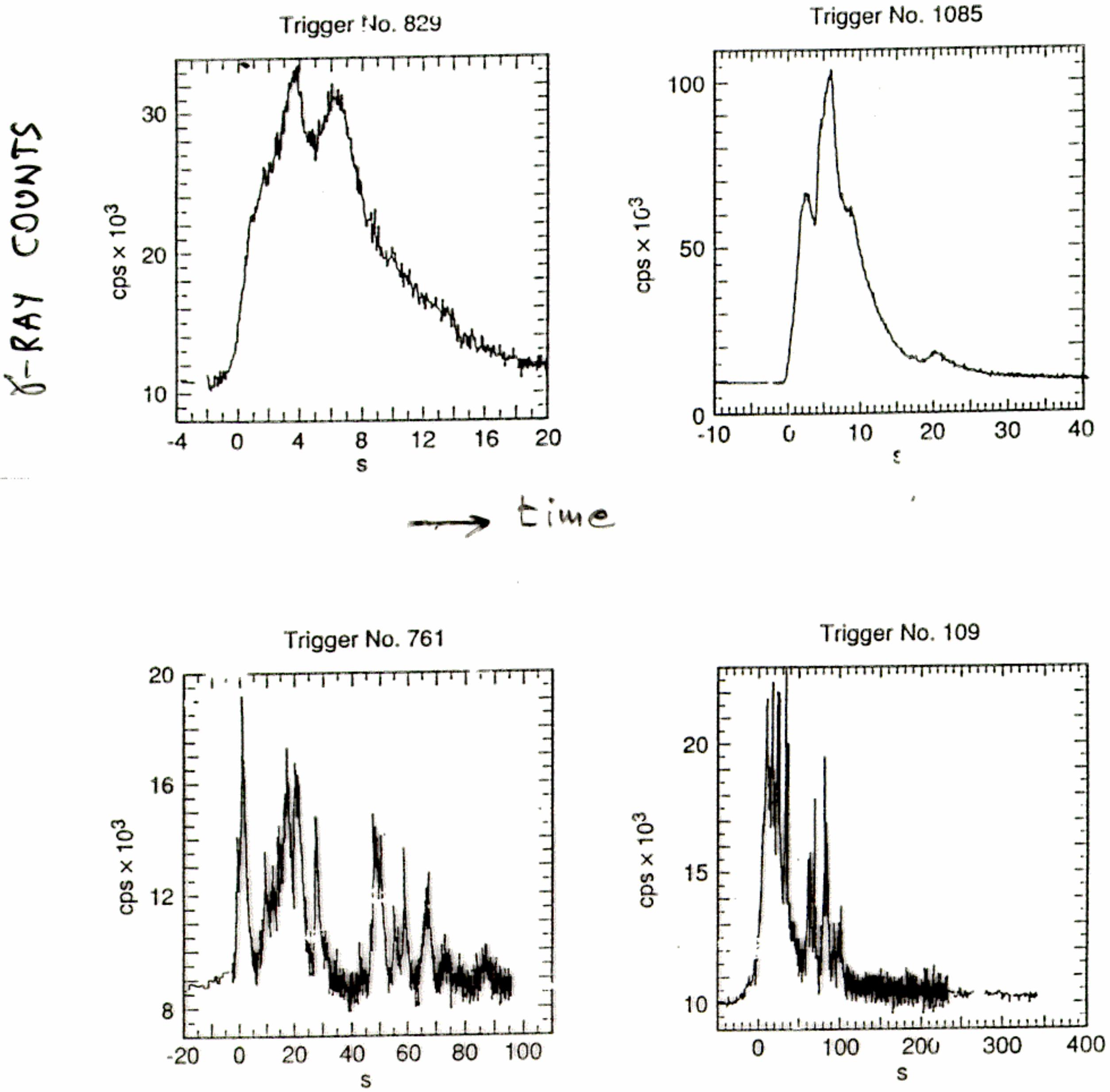
CGRO



BATSE ON CGRO

Fishman et al 97

GRB TIME PROFILES

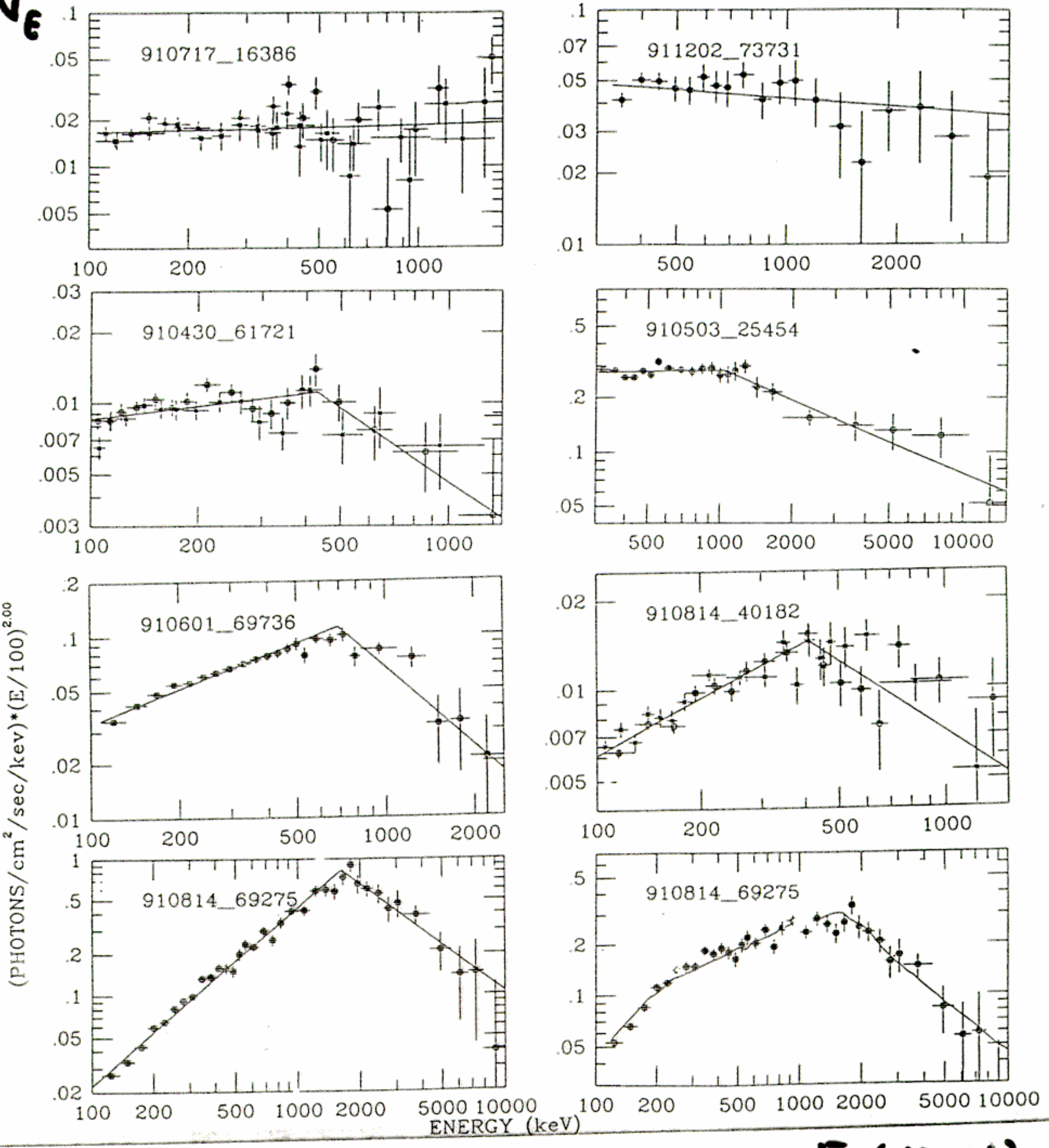


Fishman et.al 92

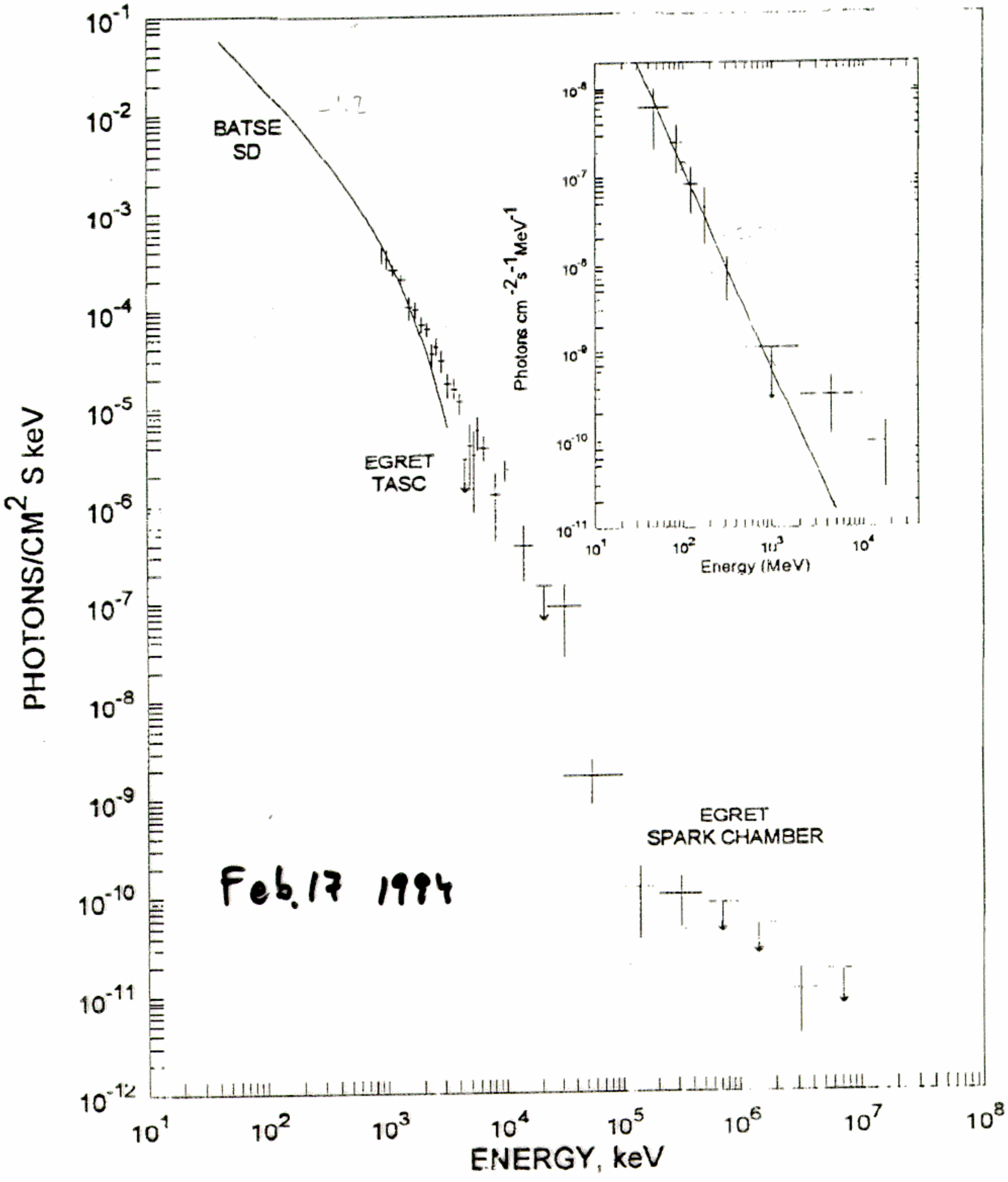
SCHAEFER ET AL. '92

$E^2 N_E$

νF_ν



E (keV)



Feb.17 1994

GRB 940217
EGRET experiment on CGRO

Hurley et al
1994

COSMOLOGICAL GRB :

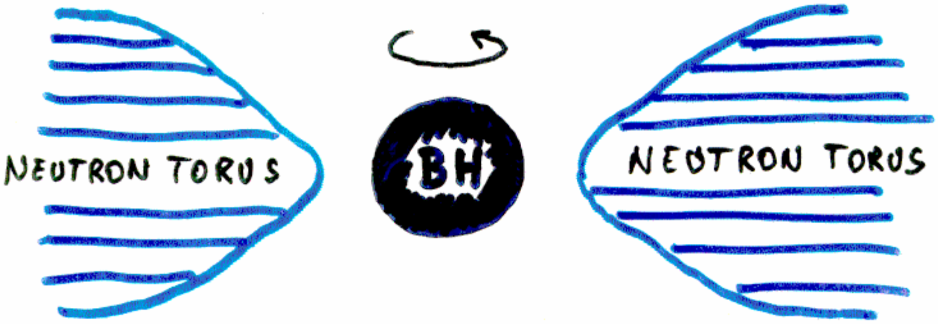
Basic Numbers

- $\mathbf{z}_{970508} \gtrsim 0.83$, $\mathbf{z}_{971214} \sim 3.4$,
  $\rightarrow D \sim 10^{28}$ cm - 10^{29} cm
- **fluence** $F = \int flux.dt \sim 10^{-5} - 10^{-6}$ erg

  $\rightarrow$
  $$E_\gamma \sim 10^{51}(\Omega/4\pi)D_{28}^2 F_{-6} - 10^{54}(\Omega/4\pi)D_{29}^2 F_{-5} \text{ erg}$$
  $$\sim (GM_\odot^2/R_{NS})(\Omega/4\pi)$$
  ($\sim$ energy release in a supernova)
- **Rate** $\sim$ 1/day observed at Earth
  $\rightarrow$ only $10^{-6}(\Omega/4\pi)^{-1}$ events/yr/galaxy
  (i.e., could be $\sim 10^4$ times rarer than supernovae)

"LIKELIEST" MODEL:

- $2 - 5\,M_\odot$ **BLACK HOLE**, orbited by $\gtrsim 0.1\,M_\odot$ **torus** of neutron star density



Could arise from:

- **NS-NS or NS-BH** mergers (known to exist, merger stats. ~ reliable)
- **Collapse** of rotating **massive** star : (failed SN Ib, binary Wolf-Rayet star)
- **He-BH or WD-BH merger** (from Red Giant/BH inspiral, common env.)

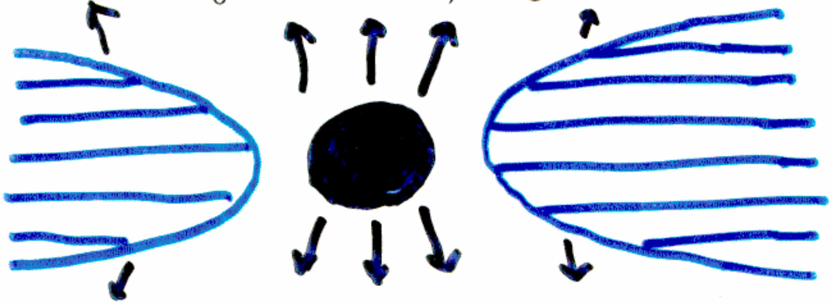
- **Energy Available:**
  - Orbital/Internal energy of **torus** ($\lesssim 0.4 M_{torus} c^2$)
  - Spin energy of **black hole** ($\lesssim 0.3 M_{hole} c^2$)

    $\rightarrow 10^{53}(4\pi/\Omega) - 10^{54}(4\pi/\Omega)$ ergs

    $\rightarrow 10^{55} - 10^{56}$ erg "isotropized" ($\Omega = 10^{-2}$)

Requirements for a Viable Model

$E_0 \lesssim 10^{54}\Omega \;,\; \Gamma_O \gtrsim 10^2$



Two Mechanisms might allow high-Γ energy escape

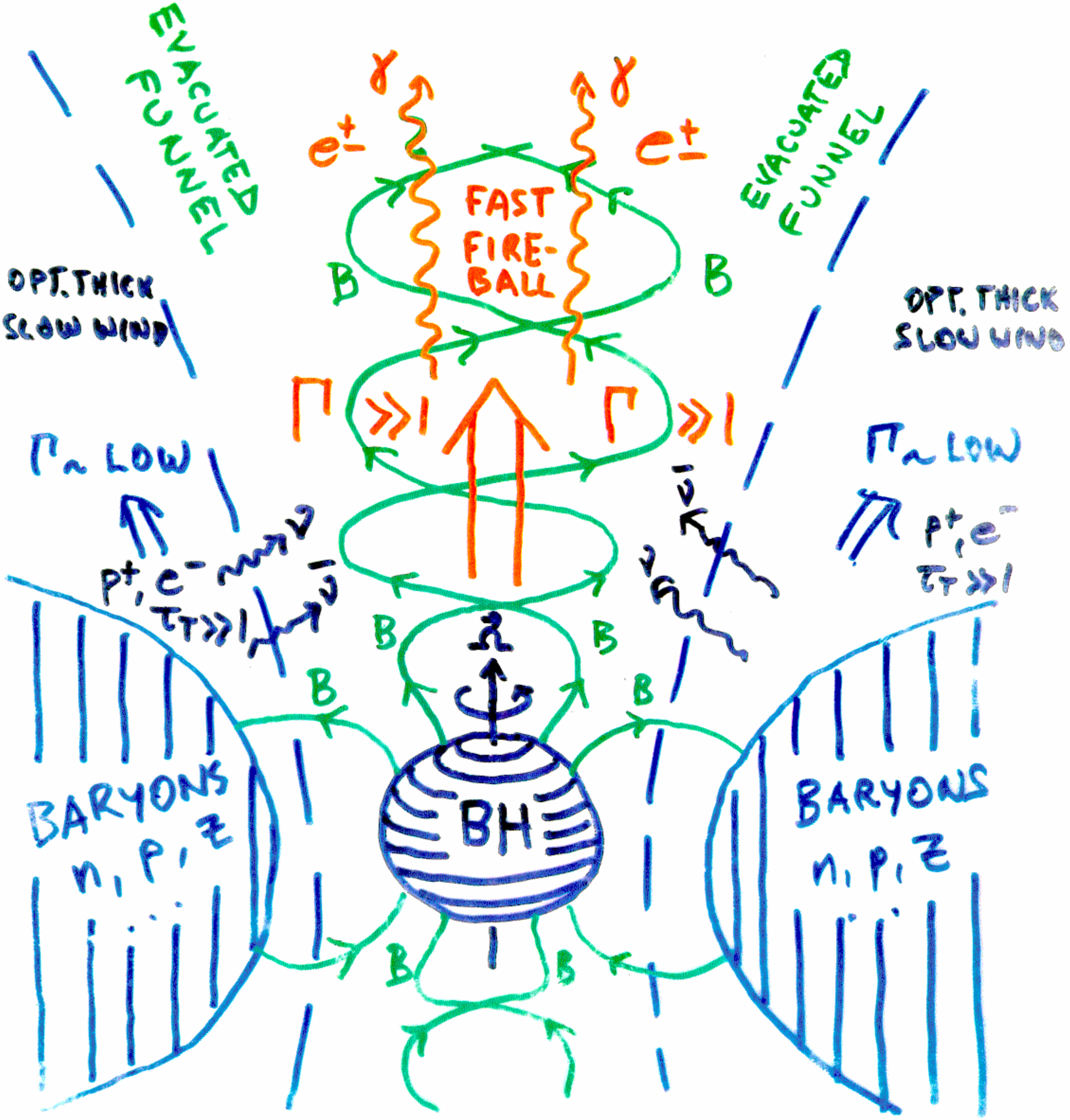
- **Thermal Neutrinos:** $\nu\bar{\nu} \to e^{\pm}, \gamma$ (Ruffert et al.'97 A&A, 319, 122)
  but: $L_{e^{\pm}} \lesssim 10^{51}(4\pi/\Omega)$ erg
- **Electromagnetic Torques :**
  - Field threading **torus** extracts **orbital** energy (c.f. pulsar winds);
  - Field threading **BH** extracts **hole's** spin energy (via Blandford-Znajek mechanism)
  - **Luminosity** requires **B** amplifies to 10^{15} G
  - Orbital timescale $\sim ms$, but debris must (sometimes) persist for up to $\sim 10^4$ orbits
  - Outflow is naturally **collimated** (c.f. AGN, $\Omega \sim 10^{-1} - 10^{-2}$) → **POYNTING JETS**

$$L_{MHD} \sim L_{e^{\pm},\gamma} \sim \boxed{10^{54}(4\pi/\Omega) \text{ erg}}$$

Mészáros & Rees '97 ApJL, 482, L29
Paczyński '98 ApJL, 494, L45

NS-NS/NS-BH
WR + COMP } MERGER ⇒ **BH + DEBRIS TORUS**
He-BH

Mészáros & Rees 97 ApJL
Paczyński 98 ApJL
Fryer, Woosley 98 ApJL



TIMESCALES:
what causes them?

Acceptable models require that torus should not drain into hole too soon (e.g. bar-mode instab, grav. rad., etc). This depends on viscosity, neutrino cooling, convection, magnetic fields, etc

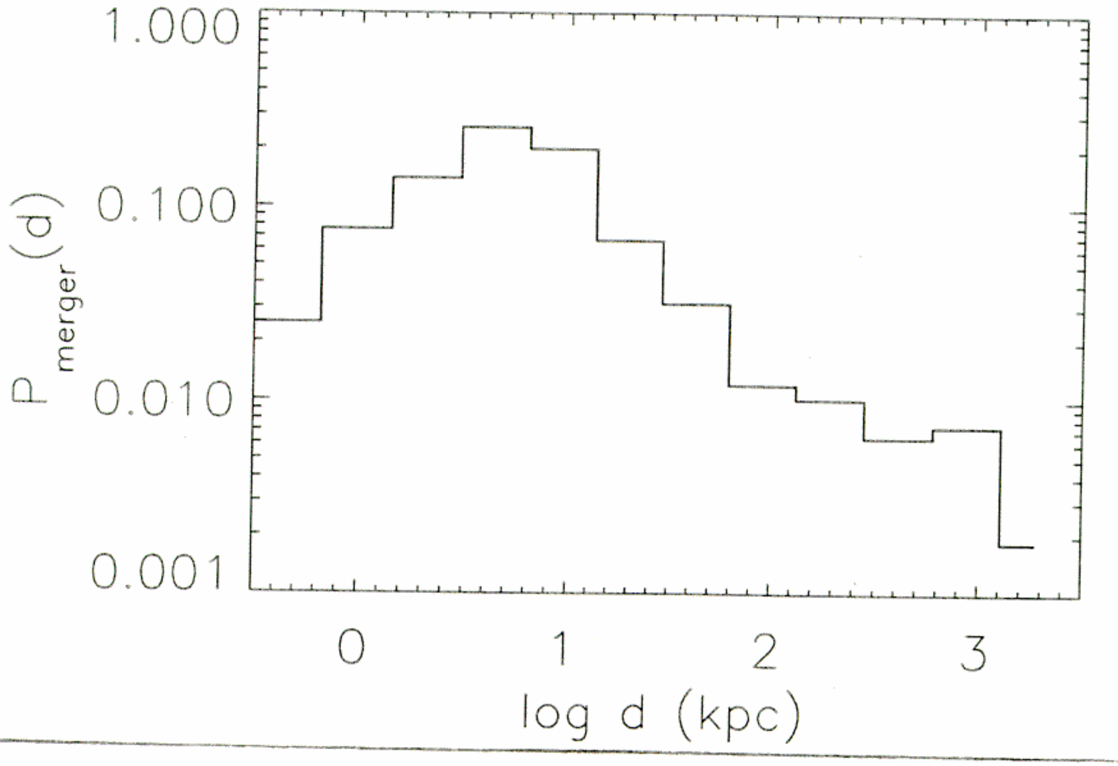
- $B \gtrsim 10^{15}$ G can be generated by convect. instab. in hot torus, which stops after neutrino cooling occurred, $t \sim 1 - 10$ s
- In cold torus, Balbus-Hawley generates azimuthal fields $B_\phi \sim 10^{17}$ G (buoyancy limit, → poloidal field $B_p \sim 10^{15}$ G); builds from seed field $B \sim 10^{12}$ G in 10^5 turns or $t \sim 16 P_{-3}$ s
- After B^2 builds up to some fraction of equipartition, → magnetic viscosity $\alpha \sim B^2/(4\pi\rho v_s^2) \sim 10^{-1} B_{15}^2 \rho_{13}^{-1} T_9^{-1}$. For outer radius $r_{tor} \sim 10^9$ cm, accretion timescale is $t \sim (\alpha\Omega)^{-1} \sim 30\, r_9^{3/2} \alpha_{-1}^{-1}$ s.
- Short and long bursts? One possibility: NS-NS→ small disk, short burst; while He/WD-BH merger → larger disk, longer burst.

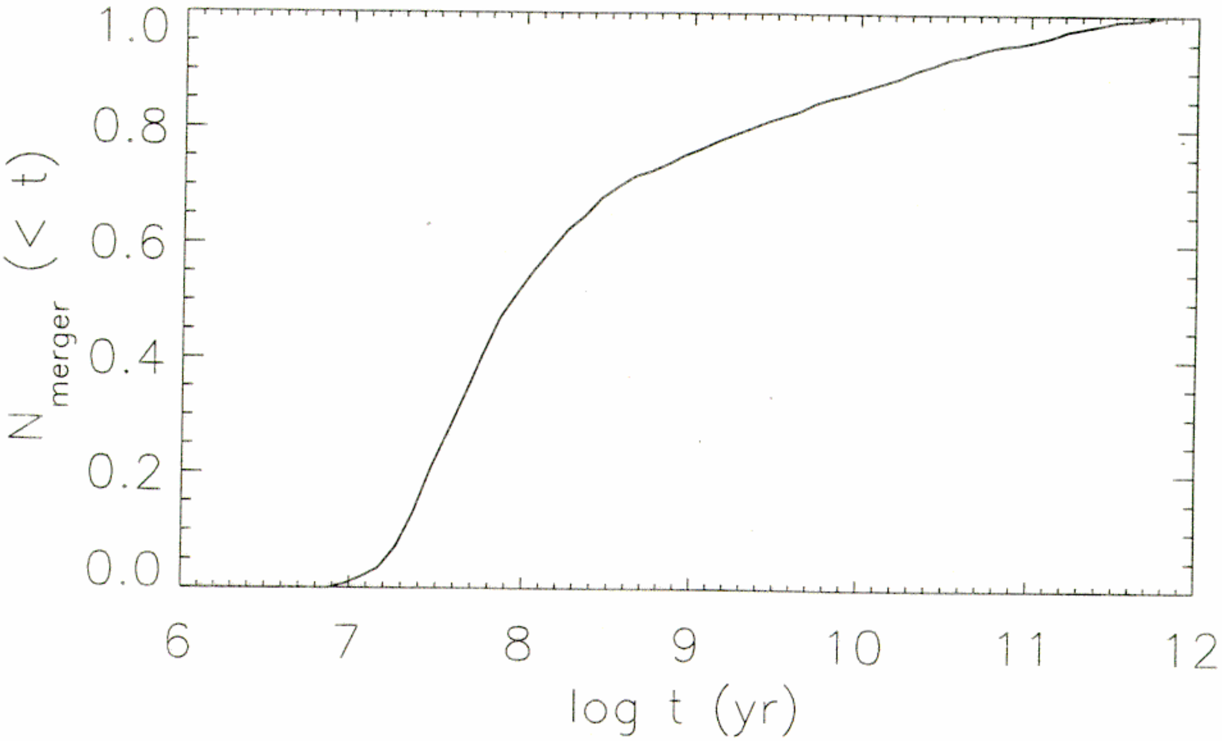
+ . . . others

- More speculative possibilities:
  a) merger → rotation stabilized massive high-field pulsar burst, after slow-down collapse to BH → 2nd burst (?)
  b) NS merges with NS of unequal mass, larger gains mass → BH+torus burst, smaller loses gradually more mass until below crit. mass → explosive deleptonization → 2nd burst (?)

  c) . . .

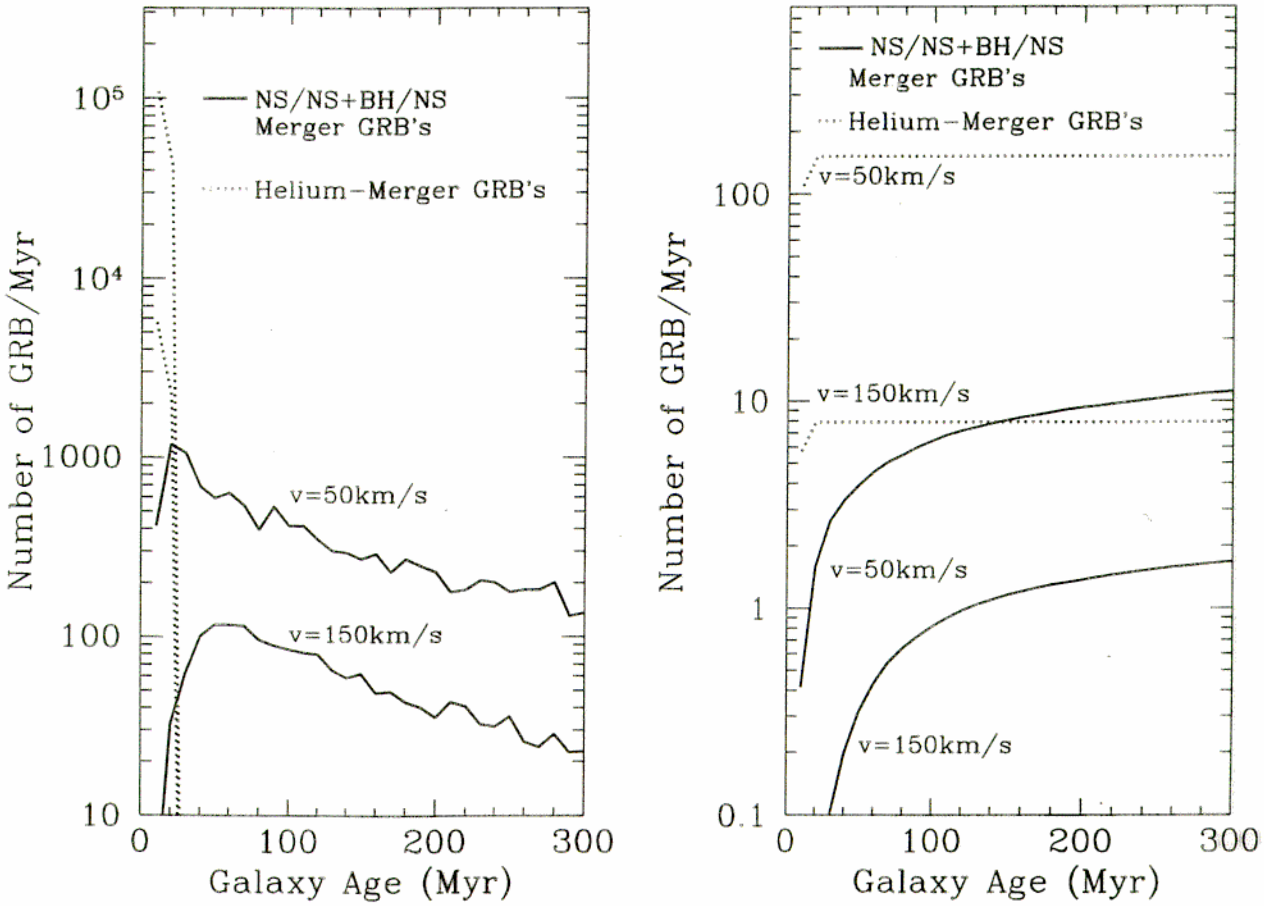
NS-NS MERGERS





L* Gal

Bloom & Sigurdsson
& Pols, 98



He core / BH merger
NS-NS + NS-BH merger from *-burst
Fryer & Woosley '98

Fig. 1.— (a) The number of gamma-ray bursts vs. age for a single burst of star formation with 10^8 supernovae. Gamma-ray bursts continue to occur from mergers of NS/NS and BH/NS binaries long after the initial burst of star formation. Helium merger gamma-ray bursts occur along with the star formation and should not be observed in old stellar populations. (b) The number of gamma-ray bursts produced per Myr vs. age assuming a constant supernova rate of 0.01 y^{-1}. The helium merger gamma-ray burst rate quickly reaches a peak and then remains flat.

GRB TRAVEL PLANS

PROGENITOR	$\bar{v}$ (Km/s)	τ (yr)	D_{median}
NS-NS	100	10^8	10 Kpc
BH-NS	10-30	$< 10^7$	$< 10^2 - 3\times10^2$ pc
BH-He/WD	100	10^6	10^2 pc

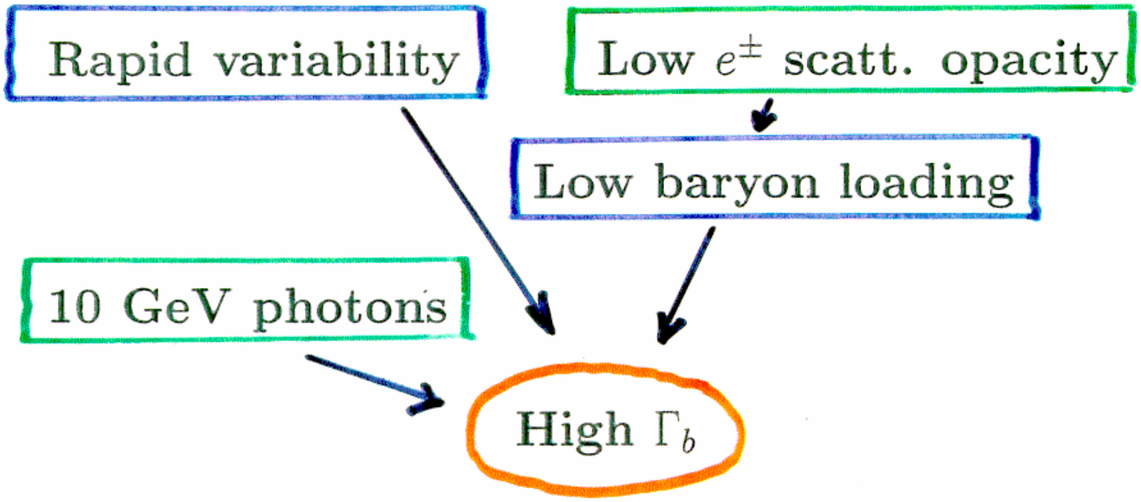
Constraints from Observations

- $\mathbf{z}_{971214} \sim 3.4 \Rightarrow E_\gamma \sim 10^{53.5}$ erg (**if isotropic**) → **constrain** $\nu\bar{\nu} \rightarrow e^{\pm}, \gamma$ mechanism in either NS-NS, NS-BH **and** in hypernovae (He/WD-BH, failed SN IB, rotating WR coll), since $E_{e^\pm} \sim 10^{51}(4\pi/\Omega)$ erg (unless $\frac{\Omega}{4\pi} \lesssim 10^{-3}$).
- **No constraint** on MHD jets from spin energy of BH+torus via BZ mechanism: NS-NS, NS-BH as well as fast-rotating hypernova models are all **equally** able to produce $\sim 10^{54}(4\pi/\Omega)$ erg (even without beaming), since hole mass is similar.
- **Possible constraint** on MHD jets from the rotational energy of torus:
  - NS-NS (fast rot. hole, $M_d \sim 0.1\, M_\odot$) $E \sim 4 \times 10^{52}(4\pi/\Omega) \rightarrow$ need beaming $\lesssim 10^{-1}$;
  - failed SN Ib (slow rot. hole, $M_d \sim 1\, M_\odot$): $E \sim 1.2 \times 10^{53}(4\pi/\Omega) \rightarrow$ need beaming $\lesssim$ 1/few;
  - NS-BH, He/WD-BH, bin WR coll: fast rot hole, disk $\sim 1\, M_\odot$, $E \sim 8 \times 10^{53}(4\pi/\Omega)$ → no beaming needed

HOW LARGE IS EMITTING REGION?

- **"Trigger" size**: $r_{trigger} \sim ct_{var} \sim 10^7 t_{var,-3}$ cm
- BUT: black body $kT \sim 0.5$ MeV, $L \sim 10^{52}$ erg/s → has **"photosphere" size** $r_{bb} \sim 3 \times 10^9$ cm
- **Observed** radiation is **non-thermal**, so it must be emitted from **optically thin** region with

$$r_{em} \gg r_{bb} \gg r_{trigger}$$



Rapid variability

Low $e^{\pm}$ scatt. opacity

Low baryon loading

10 GeV photons

High Γ_b

Variability timescale: smallest of $\begin{cases} t_{em} \sim r_{em}/(\Gamma_b^2 c); \\ t_{trigger} \sim t_{var} \end{cases}$

Acceptable models require $\Gamma_b \sim 10^2 - 10^3$

$\Rightarrow$ Mass of entrained baryons $\lesssim 10^{-5} M_{\odot}$ $E_{51} \Gamma_2^{-1}$

FIREBALL: relativistic gas dominated by $e^{\pm}, \gamma$

- $E_\gamma \gtrsim 10^{51}\Omega D_{28}^2 F_{-6}$ erg
- $R_o \sim ct_o \sim 10^7 t_{-3}$ cm

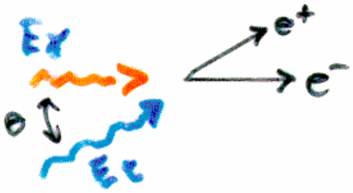
$$\Downarrow$$

- $\tau_{\gamma\gamma} \sim \frac{E_\gamma}{R_o^3 m_e c^2}\sigma_T R_o \gg 1 \quad \Rightarrow \quad e^{\pm}, \gamma$ fireball
- $L_\gamma \sim E_o/t_o \gg L_{Ed} \Rightarrow$ **expanding** fireball

RELATIVISTIC expansion:

- **observe** $h\nu \gtrsim 10$ GeV
- **but** $\tau_{\gamma\gamma} > 1 \quad \Rightarrow \quad \gamma\gamma \to e^+e^-$
  would degrade 10 GeV → < 0.5 MeV

? $\Downarrow$



$$E_\gamma > \frac{2(m_e c^2)^2}{E_t(1-\cos\theta)} \sim \frac{4(m_e c^2)^2}{E_t \theta^2}$$

- **Relativistic** outflow → $\boxed{\Gamma \gtrsim \theta^{-1} \sim 10^2}$ (causality)

$$\textbf{GRB} \begin{cases} \gamma\text{-ray burst} & (10^{-3} - 10^{3}\ \text{sec;} \\ X, O, R\ \text{afterglow} & (\text{hours} \rightarrow \text{months}) \end{cases}$$

BOTH can be understood whithin context of

COSMOLOGICAL FIREBALL SHOCK model

which can arise from the previous mechanisms

Motivation:

$$\textbf{FIREBALL SHOCK} \Leftarrow \begin{cases} \text{cosmological hypothesis} \\ \gamma - \text{ray phenomenology} \\ \text{physical considerations} \end{cases}$$

⇓ ⇑

Predicted (before detection) **Afterglows**
in fair agreement with observations

THREE KINEMATIC EFFECTS for $\Gamma \gg 1$ OUTFLOWS

- **Internal Shocks in unsteady wind or inhomogeneous fireball**
  If Γ varies by factor ~ 2 over time t_v, faster ejecta shell catches up with slower one at
  $r_{is} \sim < \Gamma^2 > c t_v \sim 10^{14} t_v$ cm
- **External Shocks when run into outside medium (e.g. ISM)**
  Occurs at
  $r_{es} \sim (E_o/\rho_{ext} c^2 \Gamma^2)^{1/3} \sim 5 \times 10^{16} (E_{52}/n_o \Gamma_2^2)^{1/3}$ cm
- **Aberration**
  Only material moving within an angle Γ^{-1} of line of sight contributes to what is observed. (Transverse pressure gradients are only effective on angles $\lesssim \Gamma^{-1}$.
  Observations currently **do not** tell us if bursts are **highly beamed**.

FIREBALL SHOCKS

1) Observe **non-thermal** power law photon spectra
$\Rightarrow$ unlike quasi-thermal, opt. thick fireball sp.

2) **Expansion**: $\Rightarrow$ Adiabatic cooling
$E_{initial} \rightarrow E_{kinetic}$

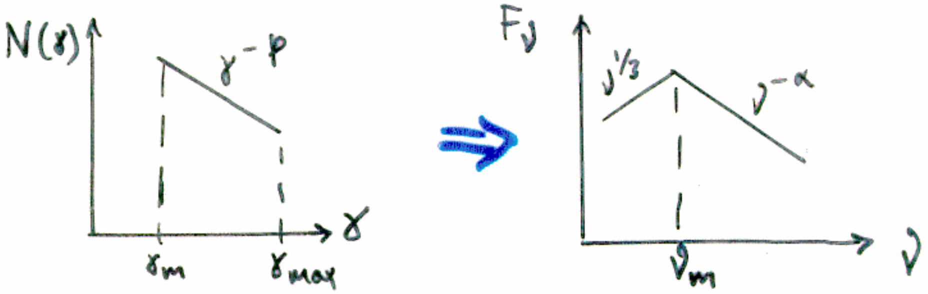
1+2 $\Rightarrow$ Need reconvert $E_{kin} \rightarrow E_\gamma$
after optically thin ($\rightarrow$ nonthermal)

$\Rightarrow$ **SHOCKS in fireball**, after opt. thin stage

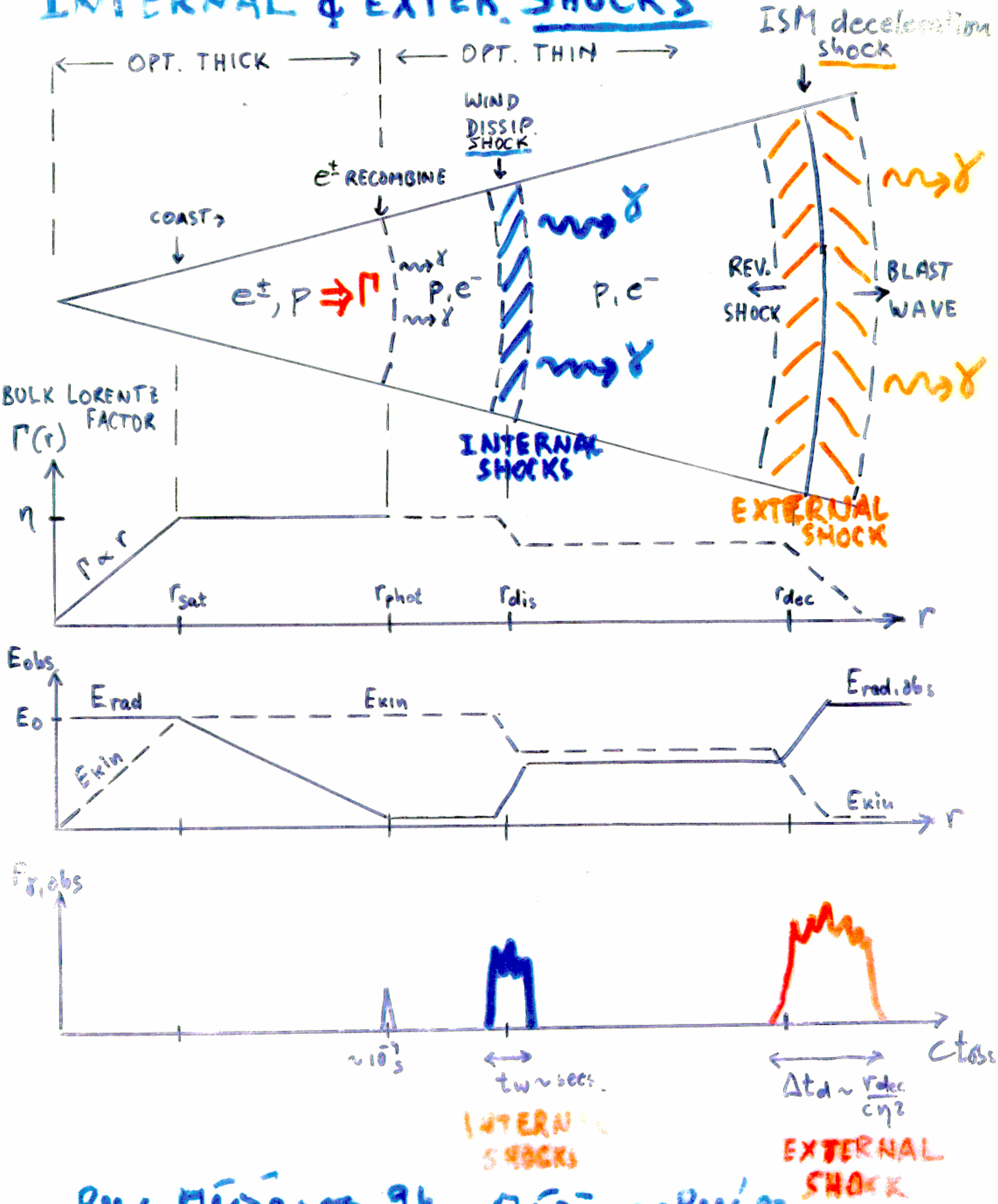
$\rightarrow$ Natural environment for

- particle acceleration $N(E) \propto E^{-p}$
  and (with turbulent B built up in shocks)
- Synchroton peak $\nu_m \sim 10^6 B \gamma_{rand}^2 \Gamma$
- Synchr spectrum $F(\varepsilon_\gamma) \propto \varepsilon_\gamma^{1/3}$ $(\nu < \nu_m)$
  $\propto \varepsilon_\gamma^{-(p+1)/2}$ $(\nu > \nu_m,\mathrm{A})$
  $\propto \varepsilon_\gamma^{-p/2}$ $(\nu > \nu_m,\mathrm{R})$

- IC spectrum : similar, shifted up by γ_{rand}^2

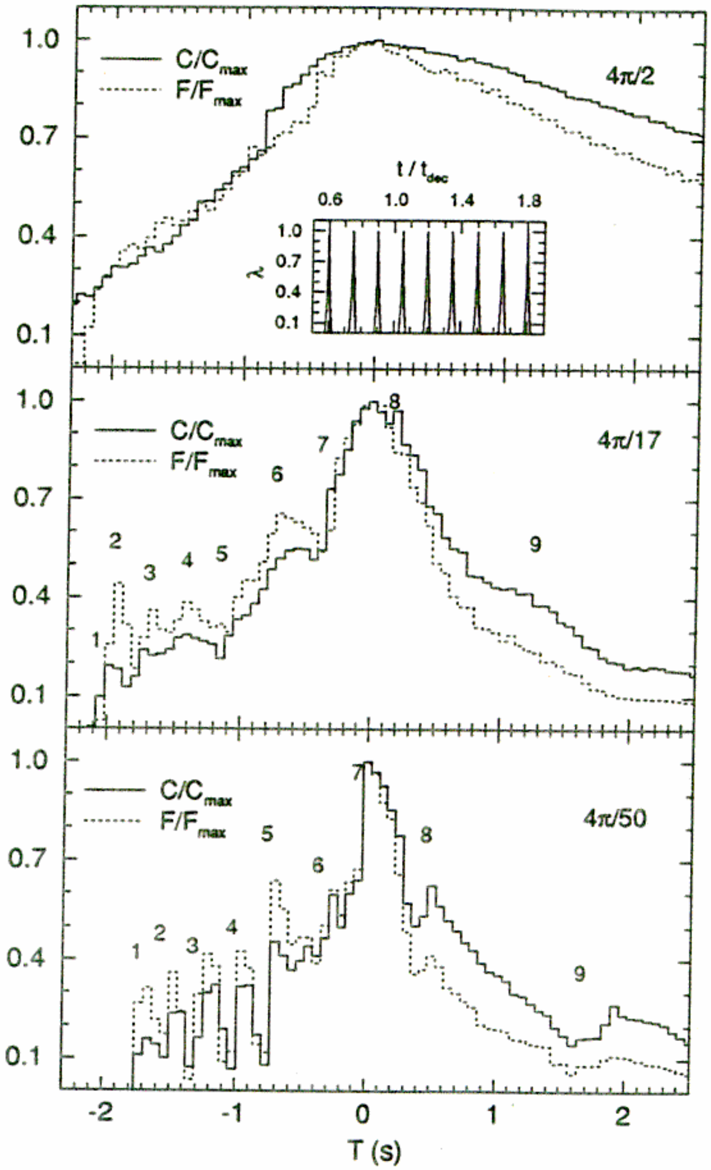


INTERNAL & EXTER. SHOCKS



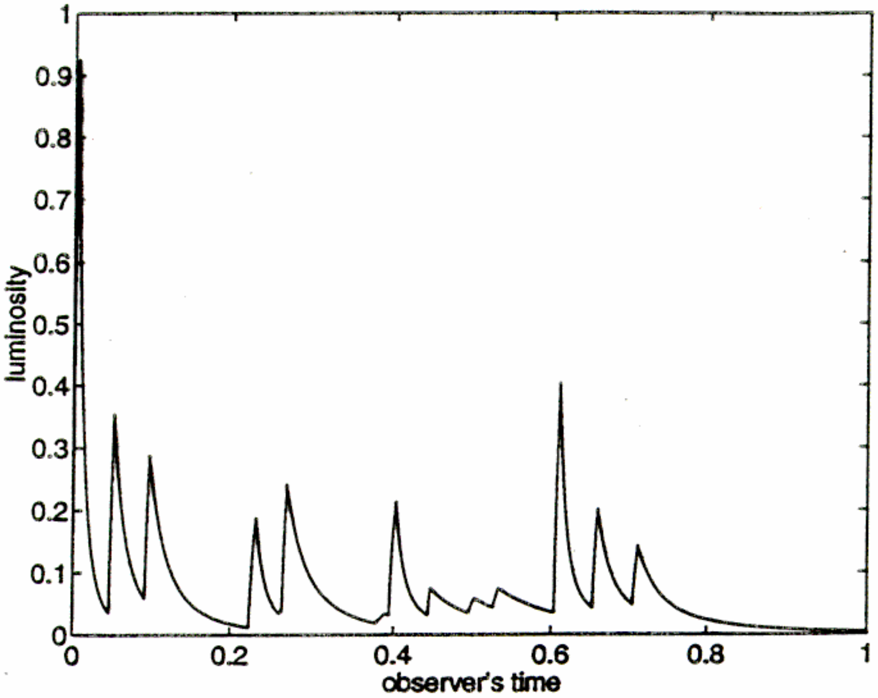
Rees, Mészáros 94, Mészáros & Rees 93

EXTERNAL SHOCK SIM. LIGHT CURVE

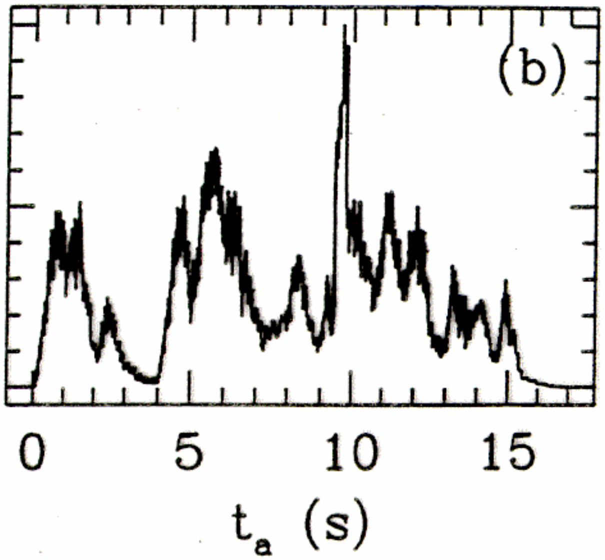


Panaitescu & Meszaros 97a

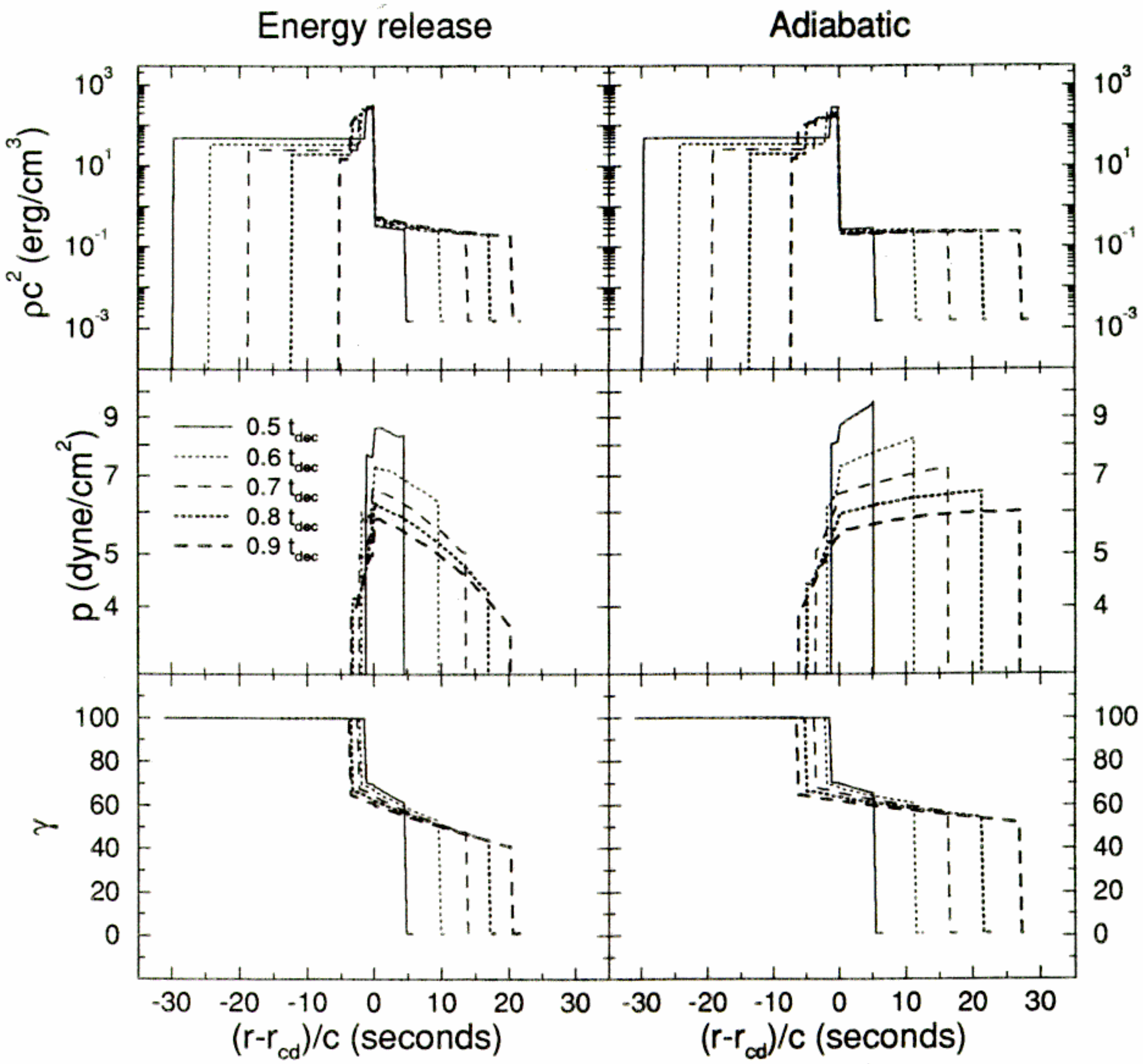
INTERNAL SHOCK SIM. LIGHT CURVES



Kobayashi, Piran, Sari 97



Daigne & Mochkovitch 97



$\eta = 100$, $E = 10^{51}$, $n_{ex} = 1\ cm^{-3}$

Figure 1

Panaitesco, Wen, Laguna & Mészáros '96

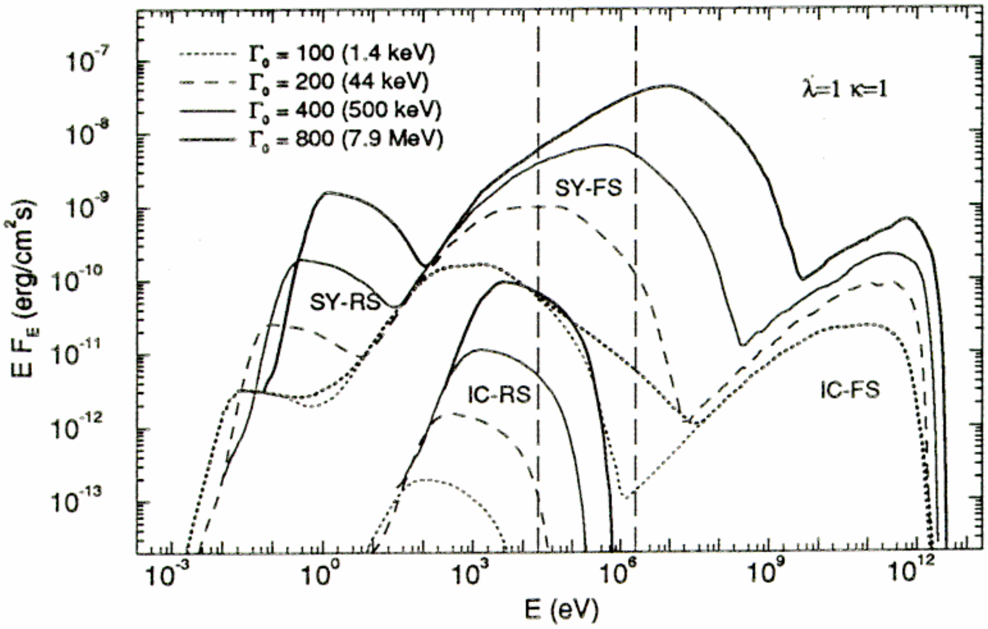
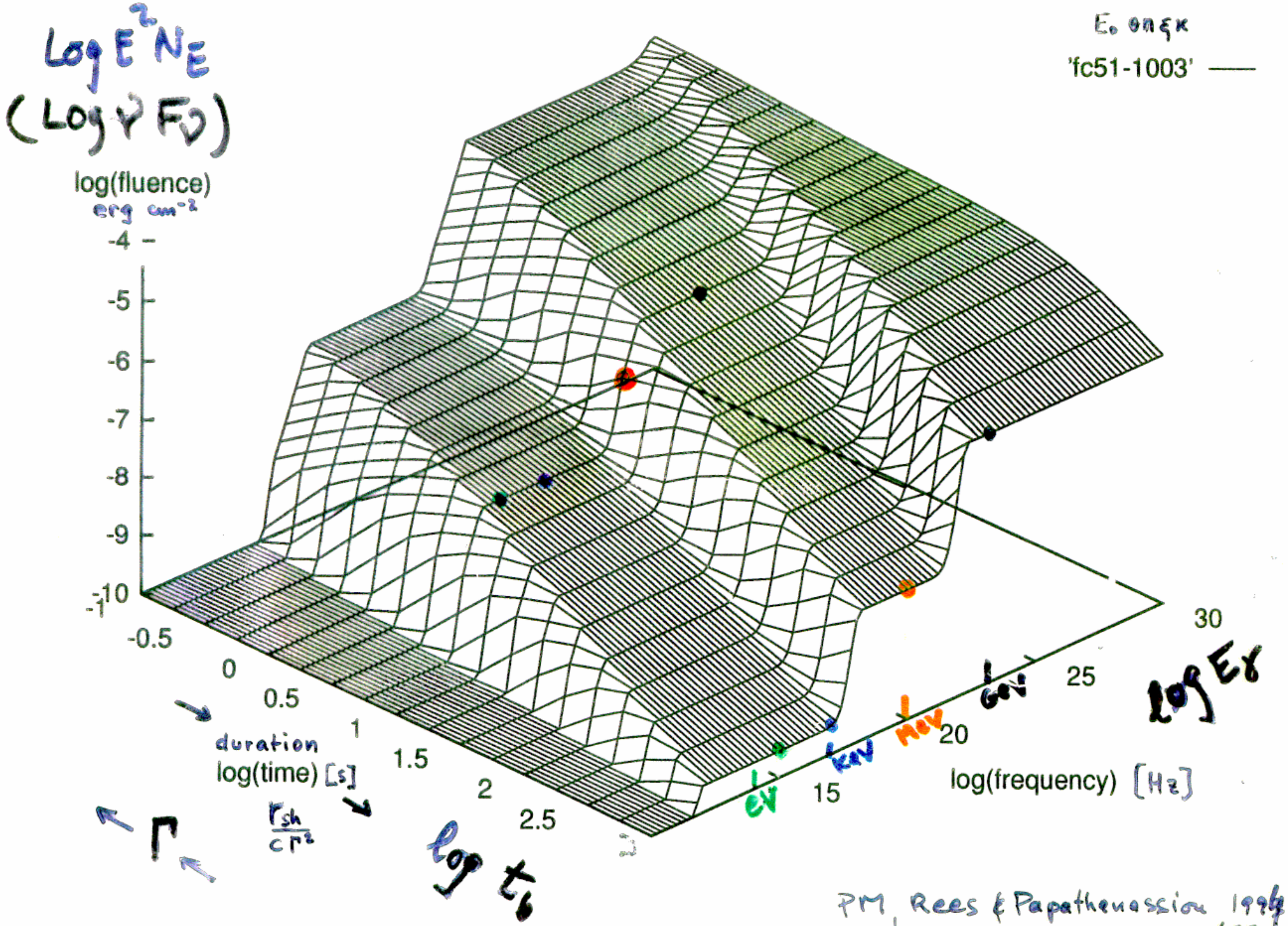


Fig. 1.— SY and IC spectra for $E_0 = 10^{51}$ ergs, $n = 1\,\mathrm{cm}^{-3}$; $D = 10^{28}$ cm, $\lambda_B = 1$, $\kappa = 1$, $\gamma_M/\gamma_m = 10$, $p = 3$, and different parameters Γ_0. The thick dotted curve is for $\Gamma_0 = 100$ and $\gamma_M/\gamma_m = 100$. Labels indicate the origin of each component: SY = synchrotron, IC = inverse Compton scattering, RS = reverse shock, FS = forward shock. $E\,F_E = \nu\,F_\nu$ is the power per logarithmic energy (or frequency) interval. Vertical dashed lines show the BATSE window. The legend also gives the spectral peak energy E_p for each parameter Γ_0.

Panaitescu & Mészáros '97

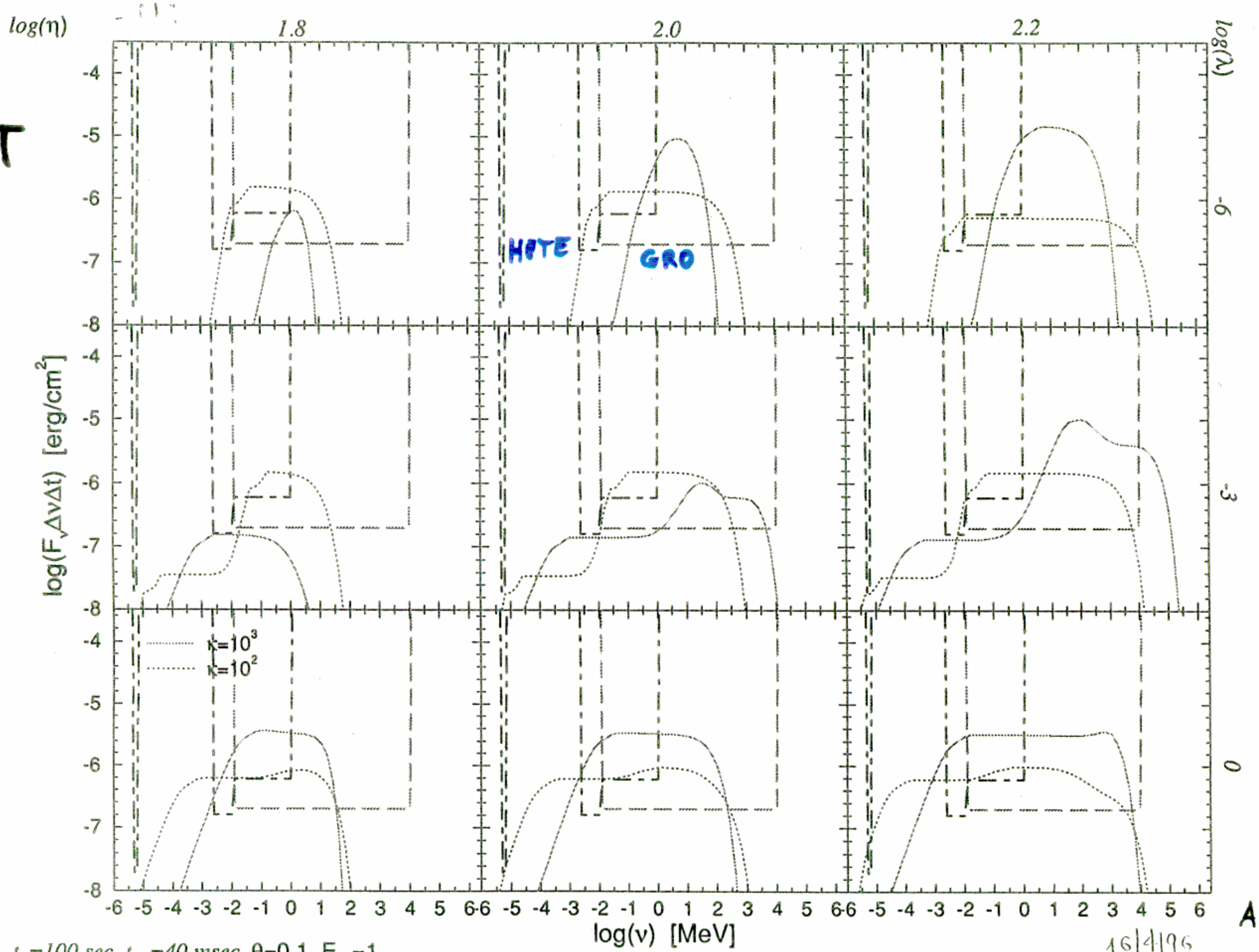
IMPULSIVE - EXT. SHOCK

F C



PM, Rees & Papathanassiou 1994, Ap.J. 432, 181

INT
CT



t_w=100 sec, t_{var}=40 msec, θ=0.1, E_{51}=1

ApJ(Lett)

16/4/96

EXTENDED WIND-INTERNAL SHOCKS

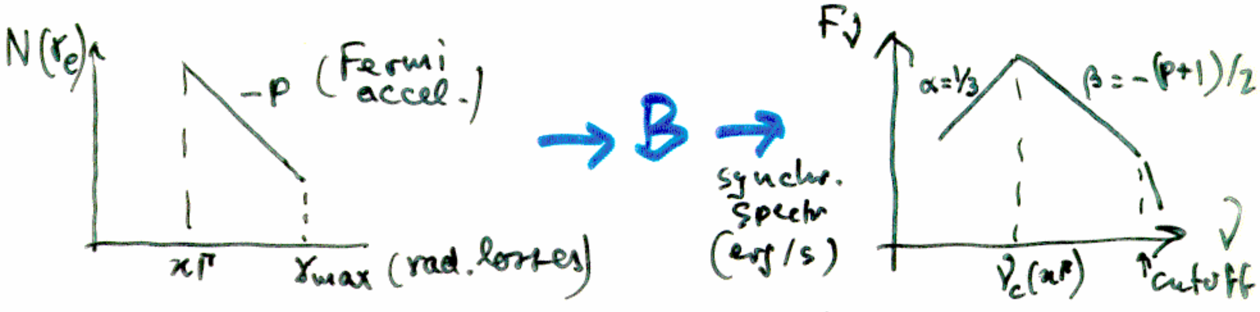
Papathassiou, Mészáros '96

"SYNCHROTRON SHOCK" MODEL :

Rees, Mészáros '92

$$\text{Shock } (\Gamma) \Rightarrow \langle \gamma_{e,\text{random}} \rangle \sim \underbrace{\kappa}_{\gtrsim 1} \Gamma$$

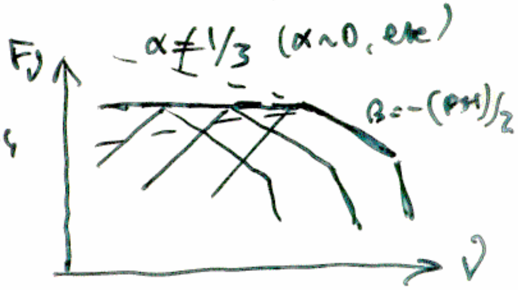
a) **ASYMPTOTIC** (SINGLE Γ, SINGLE B)



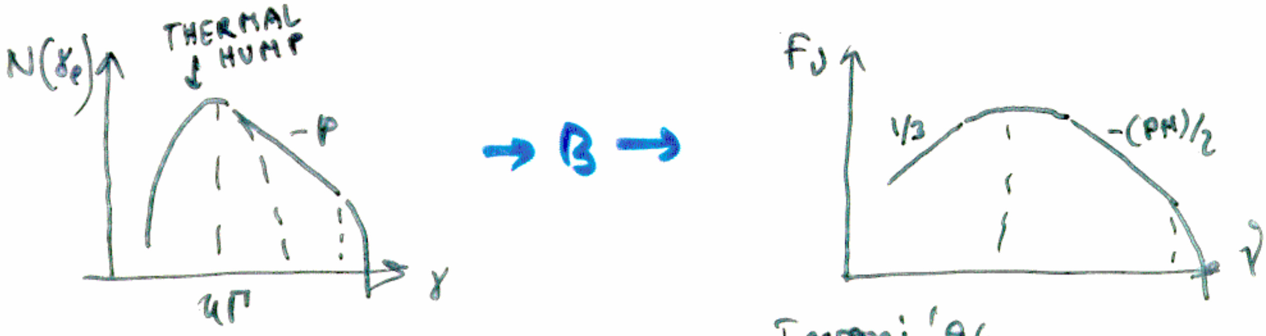
Mészáros & Rees '93; Katz '94

b) **INHOMOGENEOUS** (RANGE of Γ, B)

PM, REES, PAPATHASSIOU '94



c) **FULL DETAILS** (McDonald function in Synch. Spectrum, particular accel. mechanism, ..)

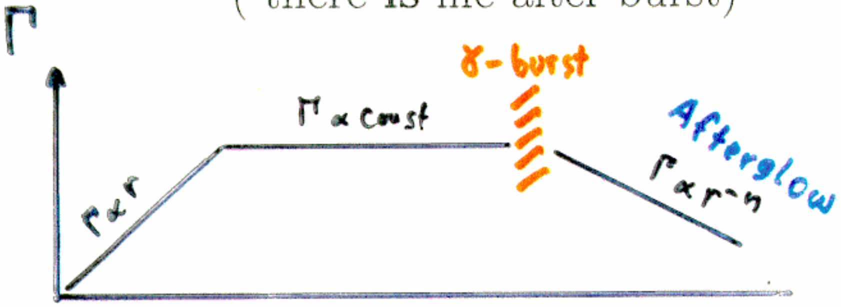


Tavani '96

d) **INVERSE COMPTON** component (Mészáros Rees 93,'94, Papathanassiou .. 94)
→ GeV, etc

AFTERGLOWS

(there **is** life after burst)



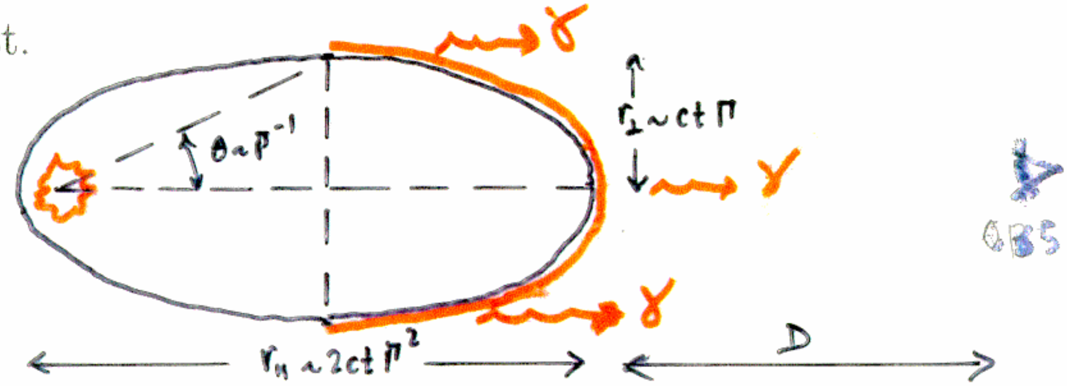
$$\rho_{ext} r^3 \Gamma \sim \text{const.} \rightarrow \Gamma \propto r^{-3} \propto t^{-3/7} \text{ radiative}$$

$$\rho_{ext} r^3 \Gamma^2 \sim \text{const.} \rightarrow \Gamma \propto r^{-3/2} \propto t^{-3/8} \text{ adiabatic}$$

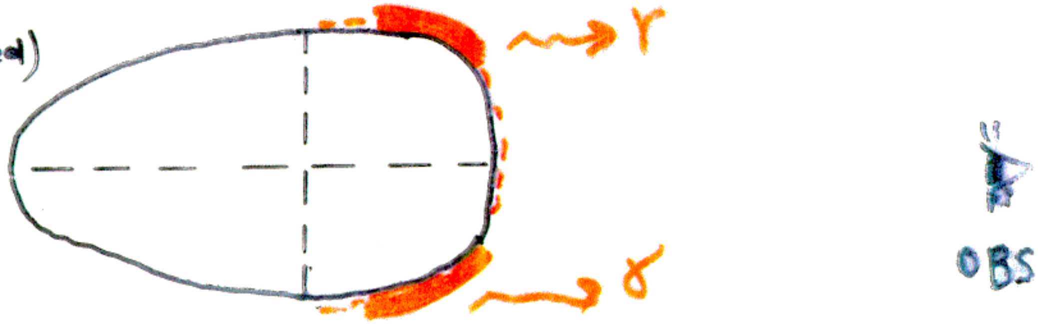
Mészáros, Rees '97, ApJ 476, 232

Equal-t (obs. time) surface:

a) $\Gamma = \text{const.}$



b) $\Gamma \propto r^{-n}$
(decelerated)



THE ASTROPHYSICAL JOURNAL, 476:232–237, 1997 February 10

OPTICAL AND LONG-WAVELENGTH AFTERGLOW FROM GAMMA-RAY BURSTS

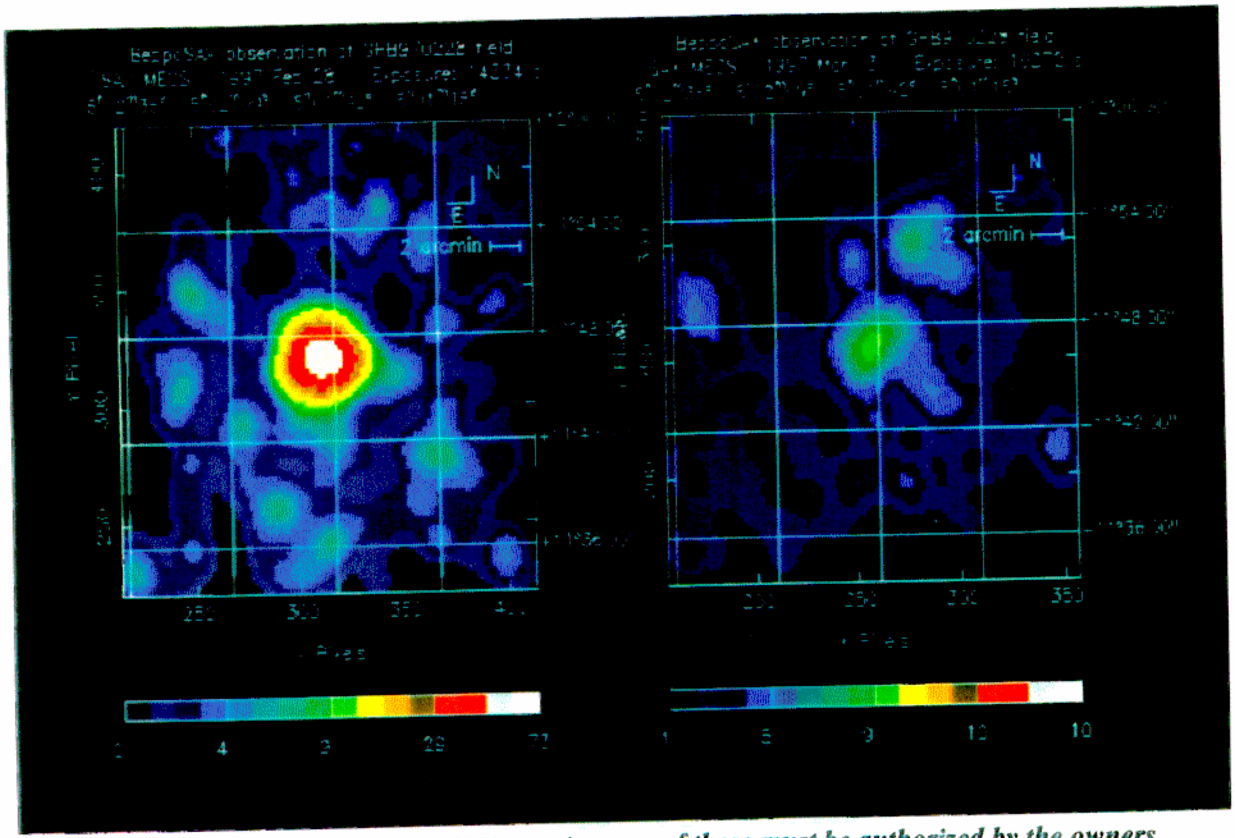
P. MÉSZÁROS[1]
525 Davey Laboratory, Pennsylvania State University, University Park, PA 16802
AND
M. J. REES
Institute of Astronomy, Cambridge University, Cambridge CB3 0HA, England, UK
Received 1996 June 5; accepted 1996 September 5

ABSTRACT

We discuss the evolution of cosmological gamma-ray burst remnants, consisting of the cooling and expanding fireball ejecta together with any swept-up external matter, after the gamma-ray event. We show that significant optical emission is predicted, which should be measurable for timescales of hours after the event, and in some cases radio emission may be expected days to weeks after the event. The flux at optical, X-ray, and other long wavelengths decays as a power of time, and the initial value of the flux or magnitude, as well as the value of the time-decay exponent, should help to distinguish between possible types of dissipative fireball models.

Subject heading: gamma rays: bursts

ApJ 970210 → GRB 970228



These data are property of BeppoSAX Team. Any use of these must be authorized by the owners.

The bright source in the field is the new X-ray source

1SAX J0501.7+1146

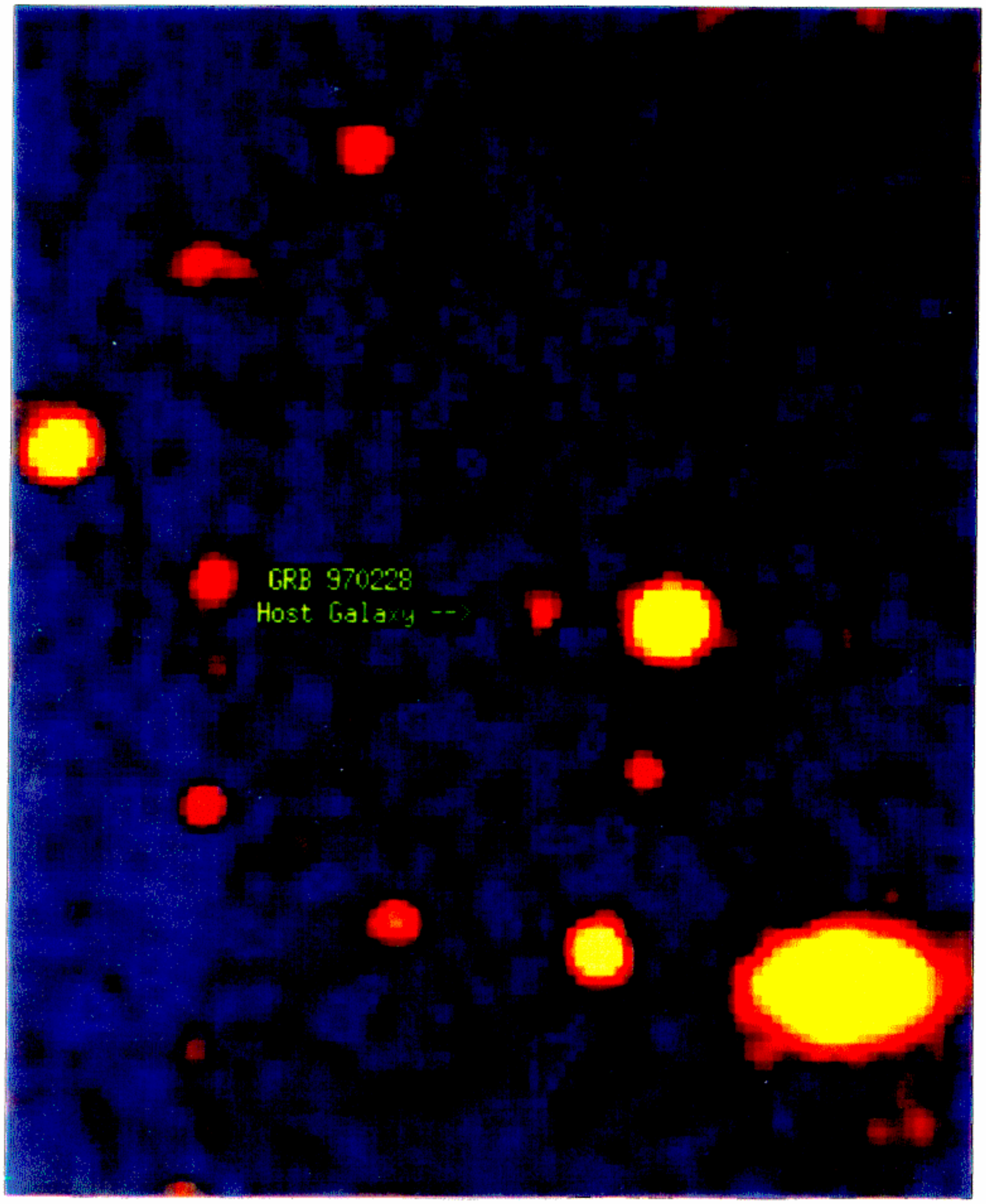
associated with the Gamma Ray Burst GRB 970228 IAUC 6576 .

SAX J0501.7+1146, has been detected by the MECS and LECS at the same position (R.A. = 5h01m44s, Decl. = +11o46'.7, equinox 2000.0; estimated error radius 50"). This position lies at the edge of the reported BeppoSAX WFC error box (IAUC 6572). The source flux is (2.8 +/- 0.4) x 10E-12 erg cmE-2 sE-1 in the MECS (2-10 keV) and (4.0 +/- 0.6) x 10E-12 erg cmE-2 sE-1 in the LECS (0.5-10 keV). The field was observed again on Mar. 3.734, and a source was detected at a position consistent with the previous one, but at a flux level lower by a factor of 20.

This page is maintained by Lucio Angelo Antonelli and Fabrizio Fiore,

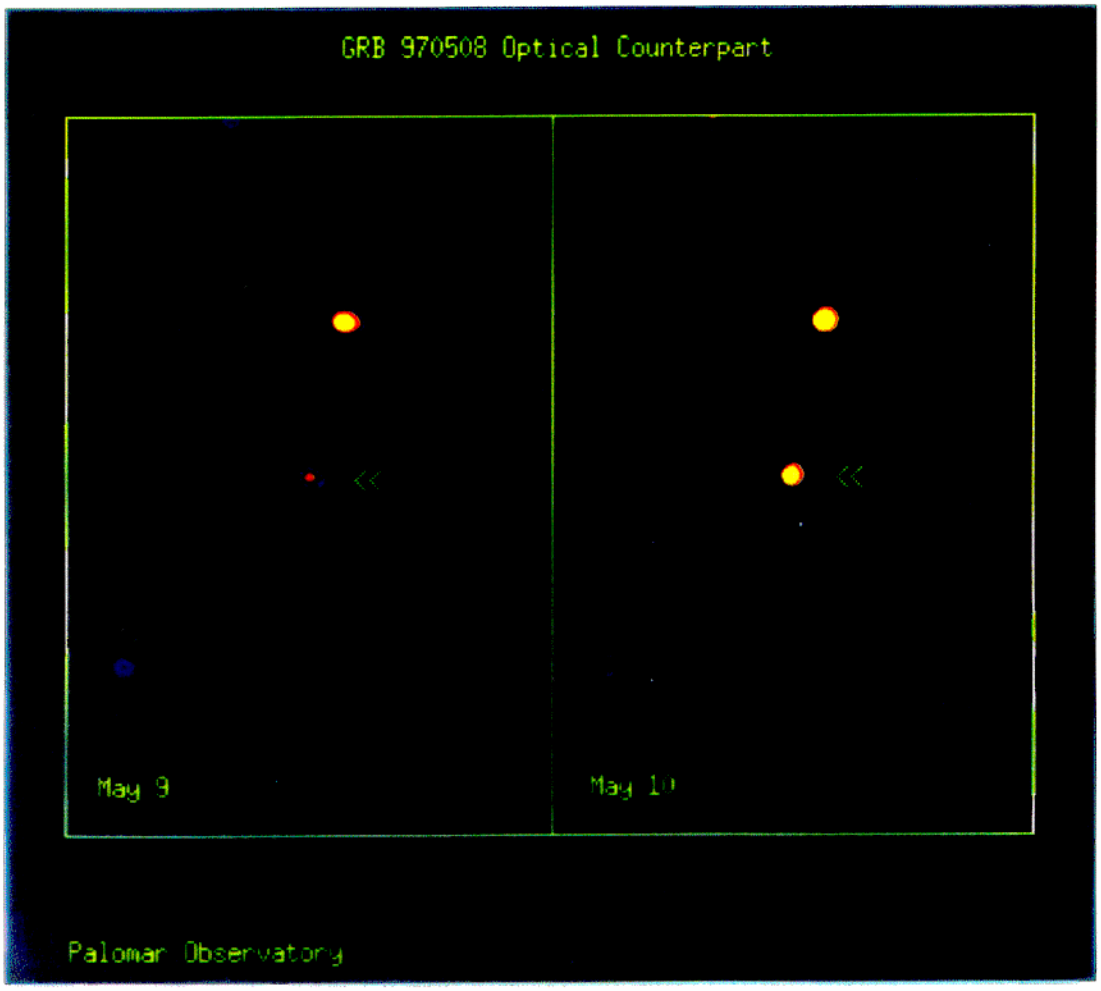
GRB 970228 : BeppoSAX team

FADING X-RAY AFTERGLOW



GRB 970228

Keck : Kulkarni et al
12 Sept 97
m_R (gal) $\simeq$ 25.8 ± 0.3
($\simeq$ same in March '97)



GRB 970508

Palomar /GRB team
200" May 9-10 '97
Djorgovski et al
Kulkarni et al

GRB 970508

letters to nature

387, 878

METZGER et al '97

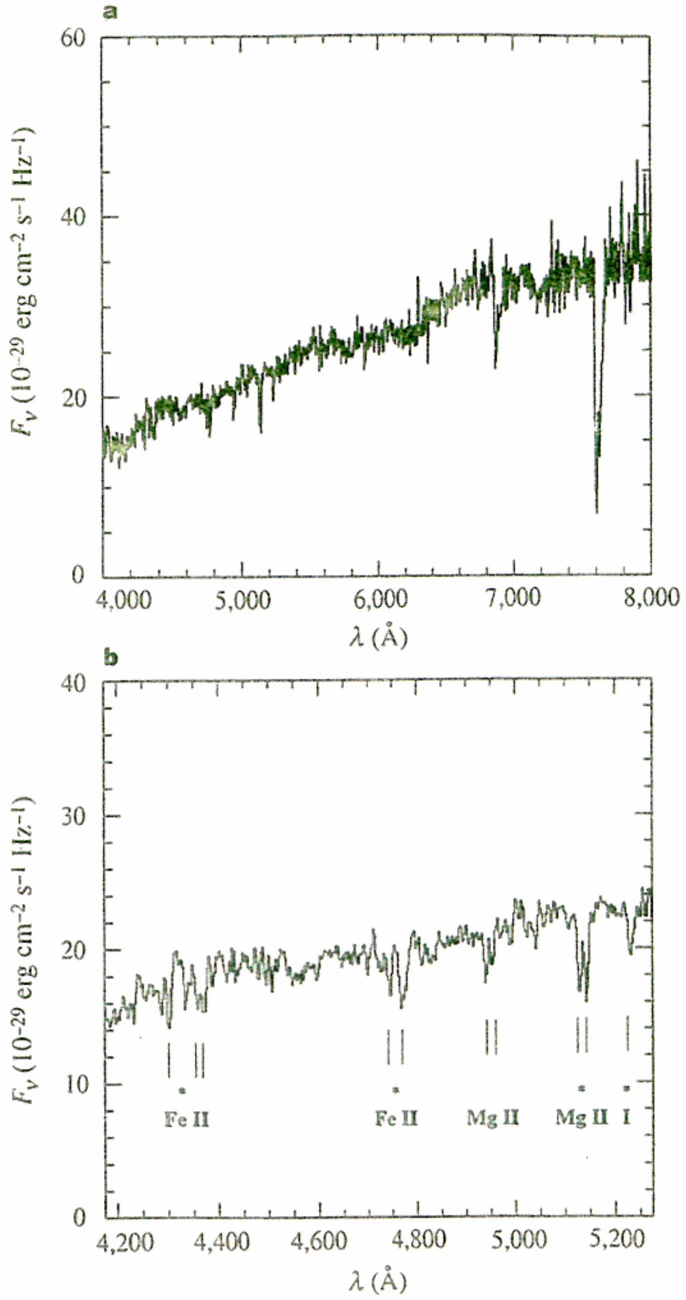
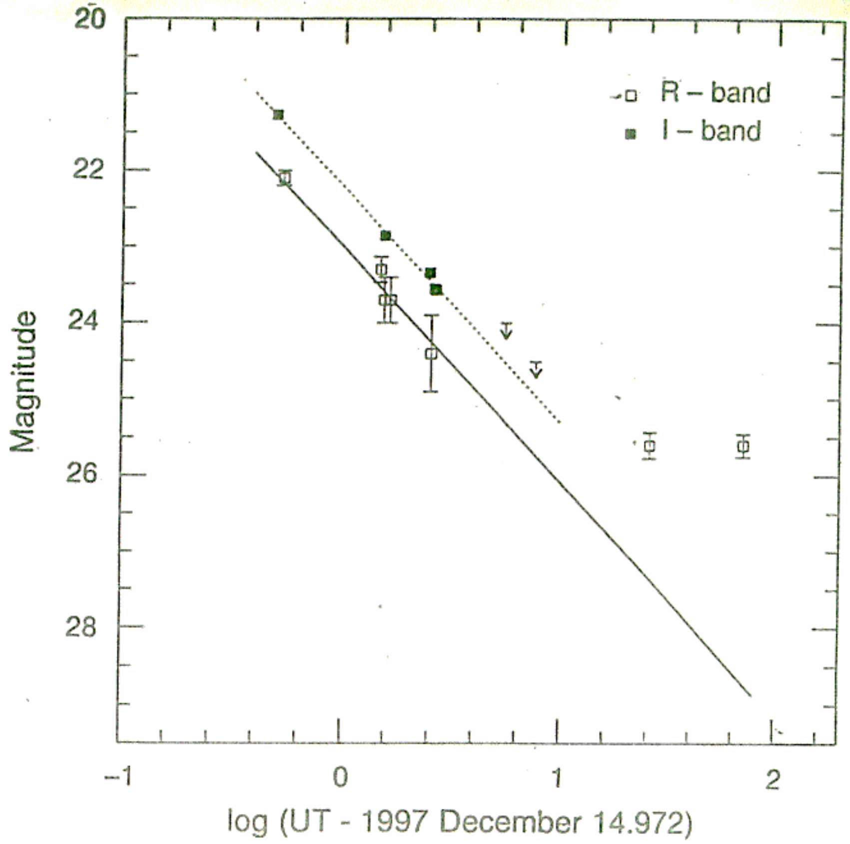
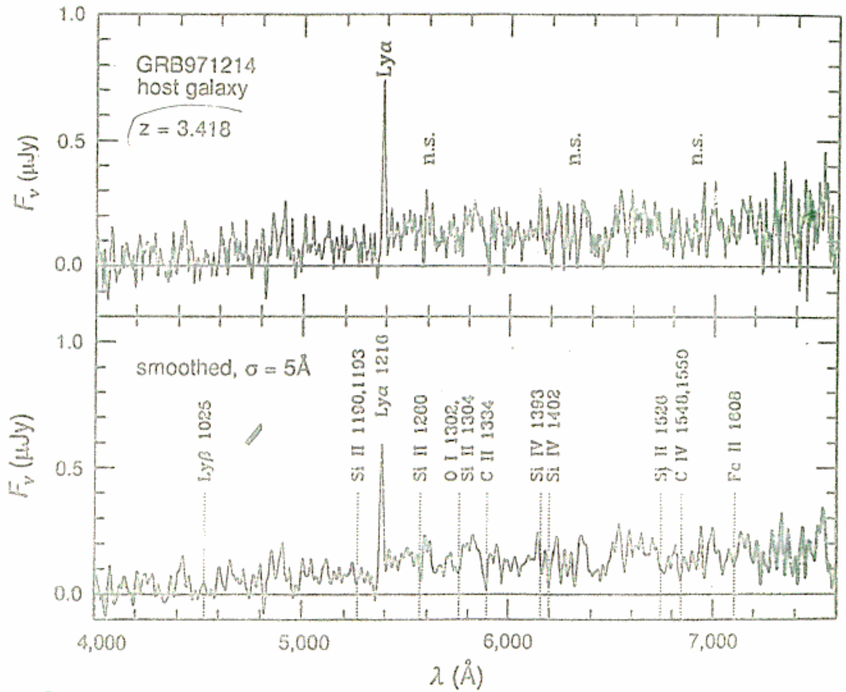


Figure 1 The spectrum of the optical variable. **a**, Full spectrum; **b**, expansion of a limited region, with strong absorption lines and identifications indicated. The lines marked with an asterisk are identified with an absorption system at redshift $z = 0.835$, the others at $z = 0.767$. The spectrum has been smoothed with a three-pixel boxcar filter. A few additional weak features (not shown) have also been tentatively identified with the $z = 0.767$ system. F_ν is the flux density, and λ is the wavelength in Å.

$0.835 \leq z \lesssim 2.3$

DECEMBER 14th





GRB 971214

z = 3.418 Kulkarni et al '98

GRB 970508 RADIO

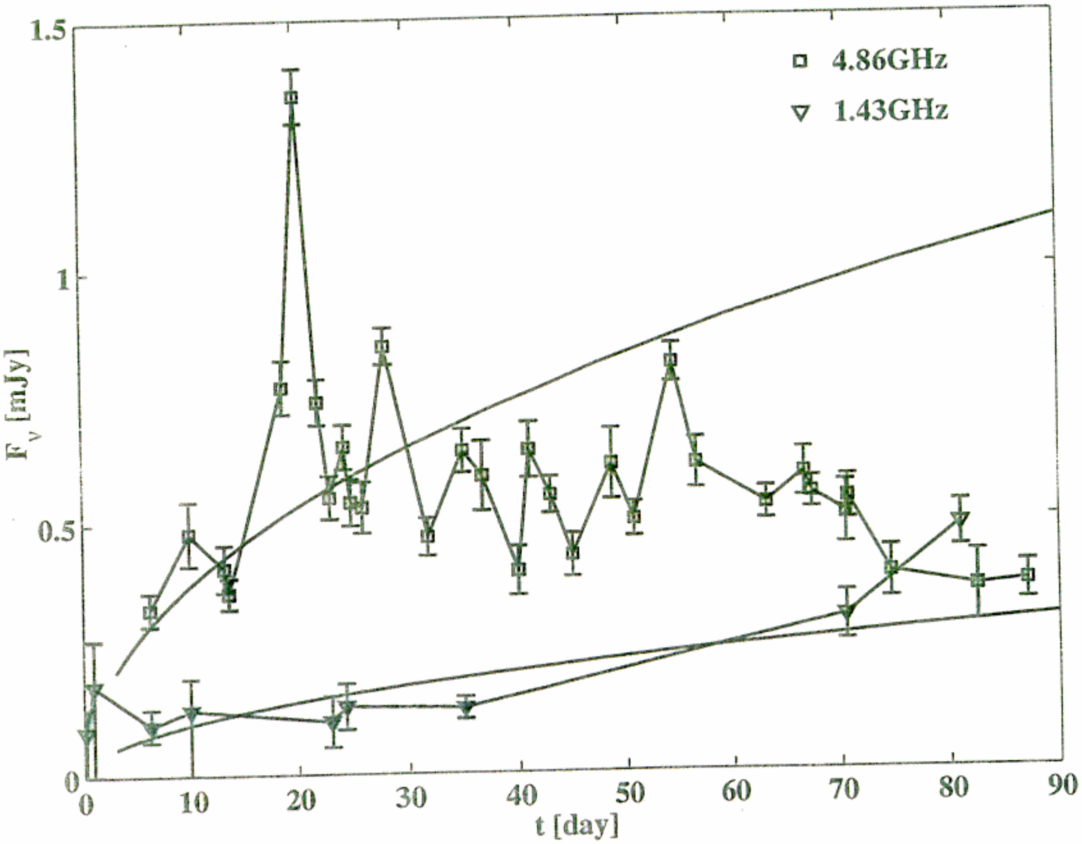


Fig. 1a.— Light curves of the radio afterglow of GRB970508 at 4.86GHz and 1.43GHz, compared with the predictions of the adiabatic fireball model (Waxman 1997b).

Frail et al '97
Taylor et al '97

Waxman, Kulkarni & Frail '97

SIMPLEST AFTERGLOW Evolution

- Spherical (or angle-indep. inside Ω_o)
- Homogeneous external medium (d=0)
- Adiabatic evolution (late) (A=1, a=1)
- Average radiation over "forward face" (no rings, etc)
- Magn. field behind blast is fraction of equip. (turb.)
- Model params (p, $\kappa+e$, ζ_e, ξ_B, ..) constant

$$\Gamma \propto t^{-q} \quad , \quad B' \propto \Gamma \quad , \quad \gamma_e \propto \Gamma$$

$$\nu_m \propto \Gamma B' \gamma_e^2 \propto \Gamma^4 \propto t^{-4q}$$

$$F_{\nu_m} \sim (r_\perp/D)^2 I'_{\nu_m} \sim (ct\Gamma/D)^2 \Gamma^3 I'_{\nu_m} \propto t^w$$

$$F_\nu \propto \nu^\alpha \quad ; \quad \alpha = 1/3 \, , \; -(p-1)/2 \;\; \text{(synchr)}$$

$$F_{\nu_D} \sim F_{\nu_m} (\nu_m/\nu_D)^\alpha \sim t^\delta$$

$$\boxed{\delta = \delta(\alpha)} = (3/2)\alpha \sim \begin{cases} 1/2 & \nu < \nu_m \\ -1 \text{ to } -1.5 & \nu > \nu_m \end{cases}$$

DECAY SLOPE
DEP. ON
SPECTR. SLOPE
ONLY
(BUT...)

- **Simplest Model Works Surprisingly Well**
- **However**, even if general framework of model is **simple**, one expects **diversity** in the details.

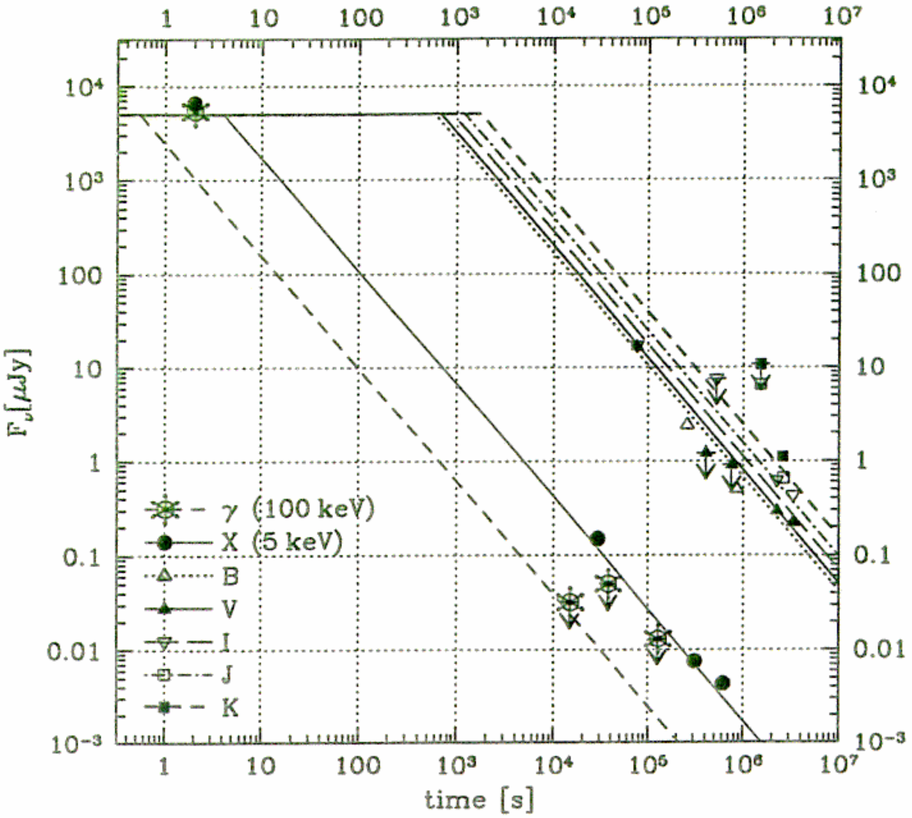


Figure 1. The light curves of GRB 970228 from γ rays to near-infrared. The lines indicate the prediction for a relativistic blast wave with $\beta' = -0.8$ and $t_V = 600$ s.

GRB 970228

Wijers, Rees, Mészáros '97: MNRAS 288, L51 '97
(models from Mészáros & Rees '97, ApJ 476, 232)

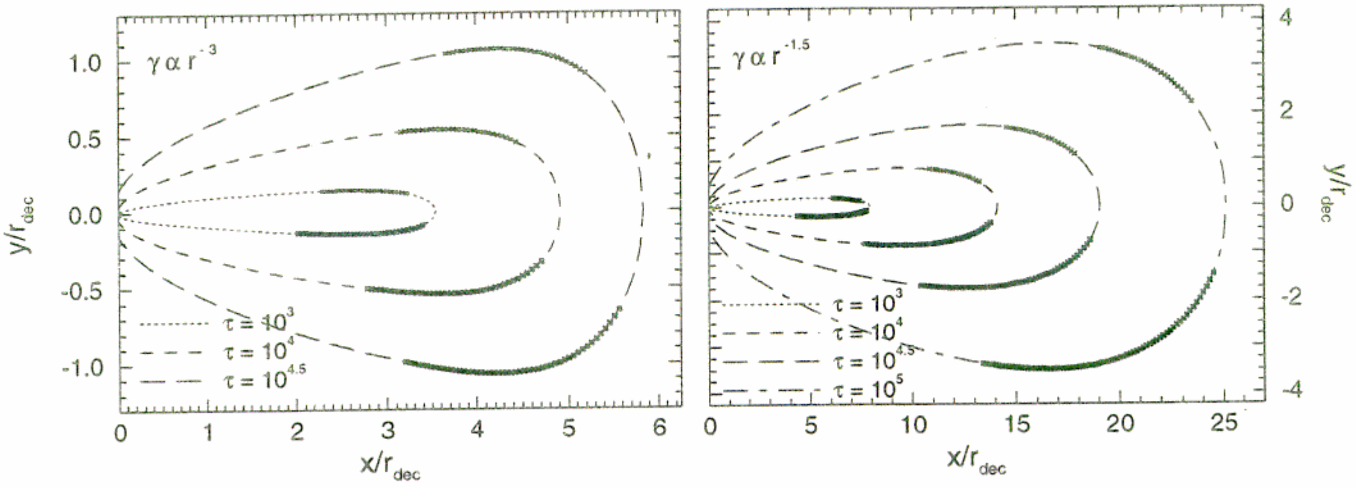
VIETRI '97; TAVANI '97; WAXMAN '97; KATZ&PIRAN '97
GOODMAN '97; SARI '97; PACZYŃSKI '97

- **Radiative/Dynamic Regimes**
  - Electrons radiative or adiabatic – could also have most e^- adiabatic ($\rightarrow$ dynamics adiabatic?) but "optical" e^- radiative $\rightarrow$ sp. slope steepens $+1/2$
  - May have adiabiatic dynamics (A=1) but radiative e^- (a=0)
  - $T_p \sim T_e$ or $T_p \gg T_e$ well behind collisionless shocks? (is $\kappa_e = T_e/T_p =$ const.?)
  - $B^2/8\pi \sim \xi_B n_p k T_p$ both in shocks & cooling zone? Is $\xi_B =$ const. a good approximation?
  - $F_{\nu_D} \propto t^\delta$, $\boxed{\delta = \delta(A, a, \alpha)}$
    $\rightarrow$ time decay dep. on more params than α
  - Expect 2nd "cooling" break ν_c ($a = 1 \rightarrow 0$)

    Mészáros , Rees & Wijers 9709273; Sari, Piran & Narayan 9712005

- **Ring Effects**
  - Γ , B' , ν'_m , t' vary over "visible surface"
    $\rightarrow$ limb brightened (gas younger, hotter in ring)
  - Ring size : influences self-absorption, scintillation
    $y_\perp \sim f_\perp . \Gamma_{eff}(t/(1+z)).c.(t/(1+z))$

Waxman 98; Panaitescu & Mészáros 98; Sari 98



RINGS IN FIREBALL AFTERGLOWS

Γ drops ⇒ Equal t surfaces no longer ellipsoids!

→ " Pear shaped " Equal Observer time surfaces

Emission : Limb-brightened

Panaitescu & Mészáros '97

astro-ph/9709284 ApJ(Lett) in press

Fig. 1.— Surfaces of equal arrival times, for a homogeneous external medium and a radiative (left) or adiabatic remnant dynamics (right). Each curve is a transverse section through the 3-dimensional equal-T surface, highlighting the regions that radiate 50% (upper half of each curve) and 80% (lower half) of the bolometric flux. Projected on the plane perpendicular to the l.o.s. toward the center of explosion, these regions appear narrower than the projection of the entire radiating surface. The Cartesian coordinates are normalized to r_{dec}, which for the putative burst parameters in the text is $\sim 4 \times 10^{16}$ cm, corresponding at a redshift $z = 1$ ($H_0 = 75\,\mathrm{km\,s^{-1}Mpc^{-1}}$, $\Omega = 1$) to an angular scale 2.5 μas.

(also: Waxman 97; Sari 97)

- INHOMOGENEOUS ENVIRONMENT:

$$\boxed{\rho_{ext} \propto r^{-d}}$$

$$\rightarrow F_{\nu_D} \propto t^{\delta} \quad , \quad \boxed{\delta = \delta(\alpha, d, \ldots)}$$

- ANISOTROPIC EJECTA ("BEAMING")

$$\boxed{E \propto \theta^{-j} \quad , \quad \Gamma \propto \theta^{-k}}$$

$$\rightarrow F_{\nu_D} \propto t^{\delta} \quad , \quad \boxed{\delta = \delta(\alpha, j, k, \ldots)}$$

(astro-ph/9709273)
ApJ 499, 301 '98

- NON-UNIFORM INJECTION

$$\boxed{E \propto \Gamma^{1-w} \quad , \quad M \propto \Gamma^{-w}}$$

$$\rightarrow F_{\nu_D} \propto t^{\delta} \quad , \quad \boxed{\delta = \delta(\alpha, w, \ldots)}$$

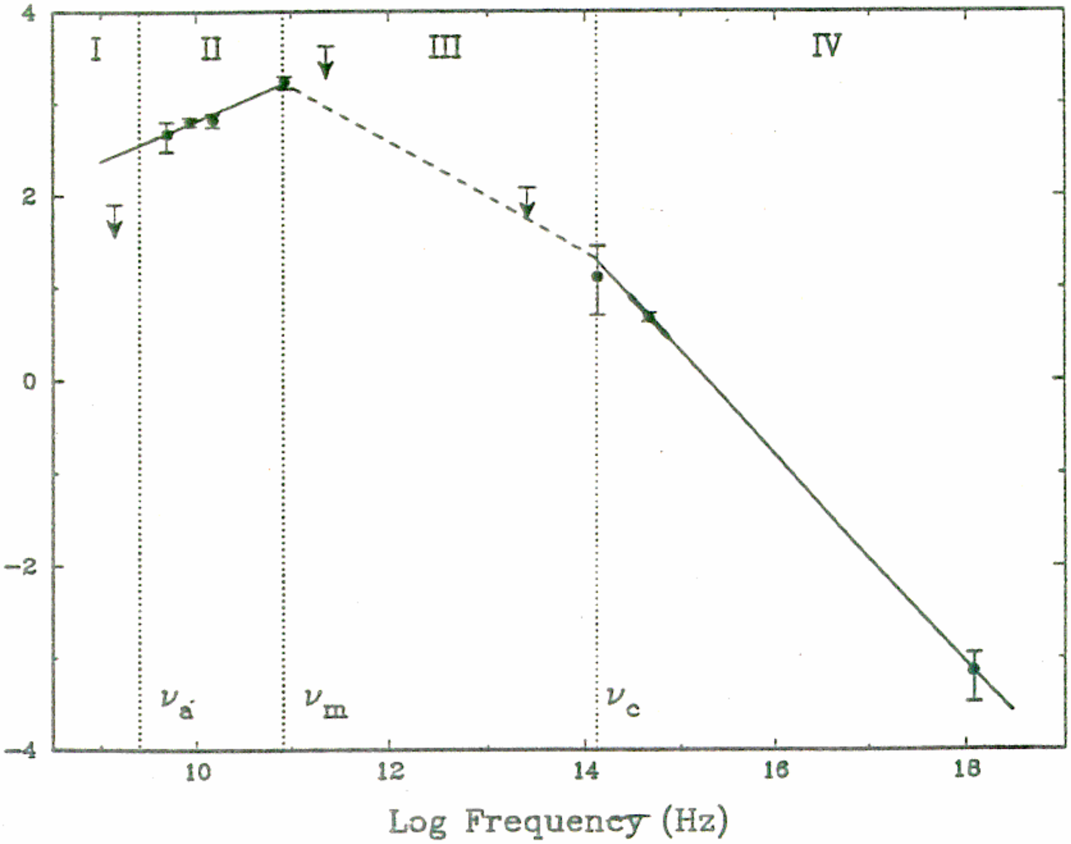
(ApJL, 496, L1
astro-ph/9712252

⇒ TIME DECAY SLOPE CAN DEPEND ON MORE PARAMS., BESIDE SPECTR. SLOPE α:

$$\delta = \delta(\alpha, d, j, k, w, a, ?.)$$

GRB 970508

("Snapshot" 12 days after event)



from Wijers, Galama '98

Fits to Simple Afterglows

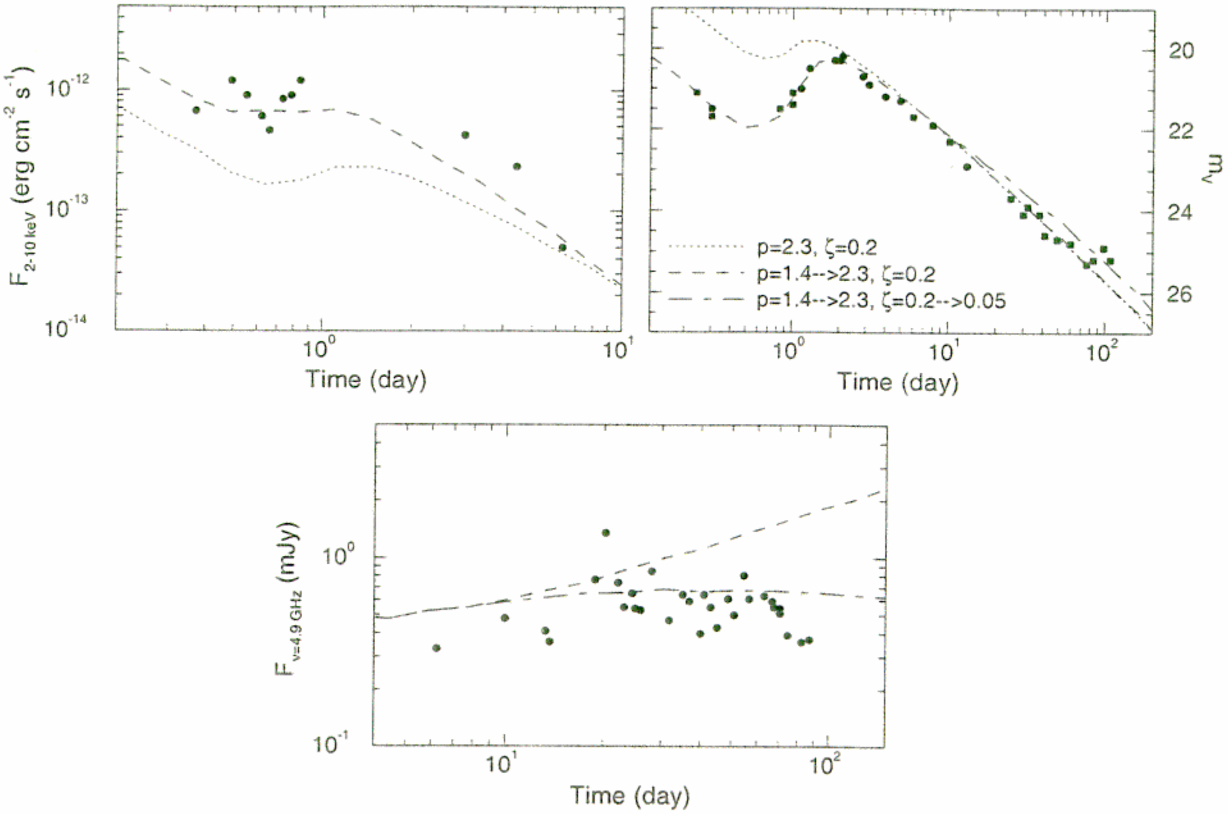
- **GRB 970~~228~~508, 971214** : have z, and 4 (3) "characteristic" numbers: ν_a, ν_m, ν_c, and peak flux of afterglow. "Simple" models imply four parameters: $\mathcal{E}$, n, ϵ_B, ϵ_e, where $\mathcal{E} = (E/\Omega)$. Four equs. w. four incognitae

  (Wijers & Galama, 1998, astro-ph/9805341)

- **Solution:** (snapshot fit at t=+12 days)
  - GRB 970508, $z = 0.83$:
    $\mathcal{E}_{52} = 3.7$, $n = 0.035$, $\epsilon_e = 0.13$, $\epsilon_B = 0.068$
    $\mathcal{E}_{\gamma 52} = 0.63$
  - GRB 971214, $z = 3.4$ (no ν_a, assume ε_B same):
    $\mathcal{E}_{52} = 0.68$, $n = 0.10$, $\epsilon_e = 0.16$, $\epsilon_B = 0.068$
    $\mathcal{E}_{\gamma 52} = 30$

- **Note:**
  - $\mathcal{E}_\gamma/\mathcal{E}$ differs from burst to burst
  - external density n differs between burts, but more typical of tenuous ("average") ISM, rather than of dense star-forming region

NON-UNIFORM INJ./REFRESHED SHOCK



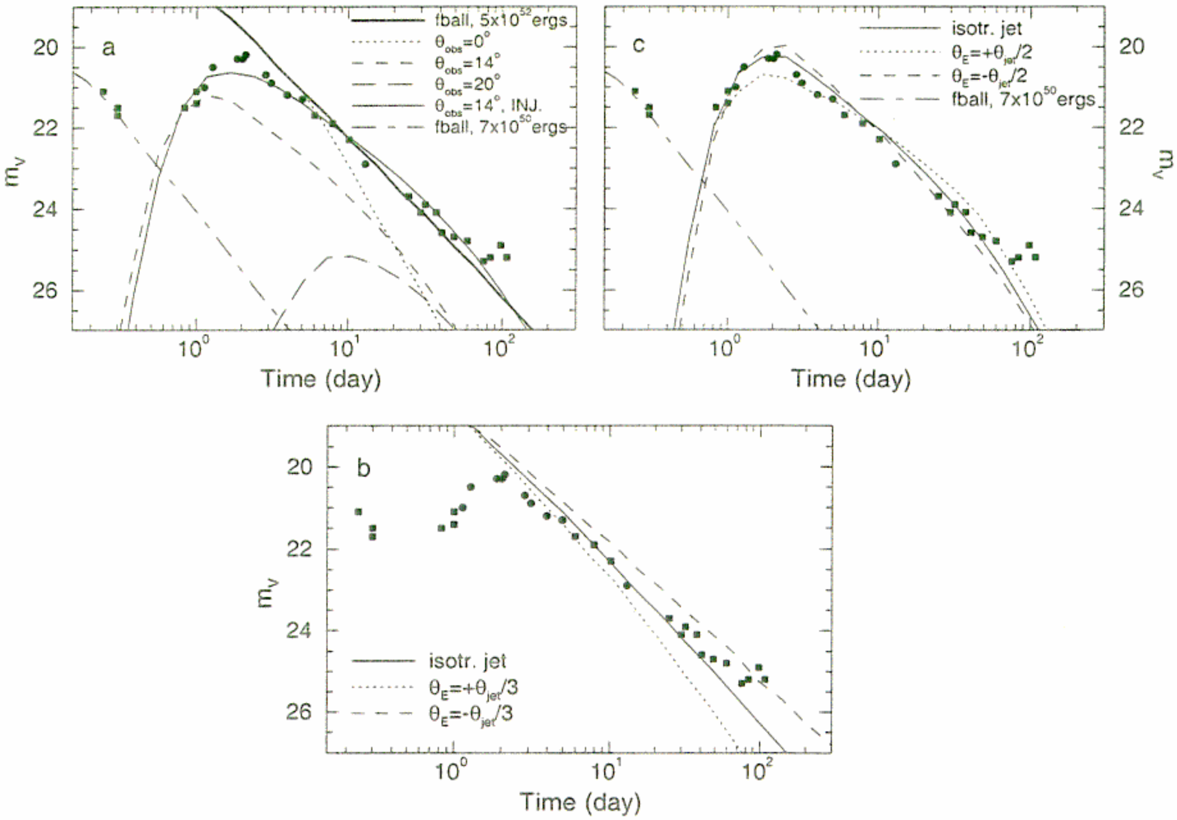
GRB 970508 time-dependent fit

Fig. 2.— Effect of refreshed shocks in an isotropic fireball, caused by a late energy input whih is a power law in the Lorentz factor Γ_f of the ejecta that catches up with the fireball (§2.2). All models have the same initial and injected energies $E_{0,52} = 0.6, E_{inj} = 3\,E_0$), as well as the same minimum Lorentz factor of the delayed energy input $\Gamma_m = 11$. The injection index s has a large value, leading to an impulsive energy input at Γ_m and to a distinctive step-like brightening of the afterglow. Other parameters are: $\varepsilon_{mag} = 0.1$, $\varepsilon_{el} = 0.1$, $n_0 = 1$, $\alpha = 0$, $z = 1$, and an absorption of $A_V = 0.25$ mag at the source redshift was assumed. The electron index p and acceleration fraction ζ for each model are given in the legend of the optical light curves. They are constant for the model shown with dotted lines, p changes at the end of the delayed energy input for the dashed and dot-dashed lines models, while ζ decreases when the remnant ends the relativistic expansion only for the model shown with a dot-dashed line. Symbols represent the data for the GRB 970508 afterglow.

Panaitescu, Mészáros, Rees 98
astro-ph/9801258

- **Detailed Fits to Afterglows - X,O,R**
  - GRB 970228, 970508, data for $\gtrsim$ 150 days ("prototypes") → $\boxed{\text{time-dependent fits}}$
  - Anisotropic and/or nonuniform injection: expected naturally, is there evidence/need for it?
  - Shock (and postshock) parameters $p,\ \zeta,\ \xi_B$ could be expected to depend on shock strenght (time), distance downstream from shock, etc. - do observations warrant/indicate $p,\ \zeta,\ \xi_B\ \neq$ const?
  - Dust absorption at source/gal. affects X,O,R fit?
- Answer: yes, there is evidence for such effects, and fits seem to require them (Panaitescu, Mészáros & Rees, 1998, ApJ in press, astro-ph/9801258)

JET + ISOTROPIC / ANISOTROPIC JET



GRB 970508

Fig. 3.— Optical light-curves from jet-like ejecta, compared to data points for GRB 970508. (a) An outflow which is isotropic within a jet of opening half-angle $\theta_{jet} = 10°$, seen at the different angles θ_{obs}, for $E_0 = 3.8 \times 10^{50}$ ergs, $n_0 = 1$, $\alpha = 0$, $\varepsilon_{mag} = 0.1$, $\varepsilon_{el} = 0.1$, $p = 2.5$, $\zeta = 1$, $z = 1$. For comparison, the afterglow from a spherically symmetric remnant with the same parameters, except $E_0 = 5 \times 10^{52}$ ergs (yielding the same energy density per solid angle), is also shown (solid thick line). A numerical light curve matching the observational data (solid thin line) corresponds to $\theta_{obs} = 14°$ and energy injection characterized by $E_{inj} = 1.5 \times 10^{51}$ ergs, $\Gamma_m = 2$ and $s = 1.5$. (b) Effect of an anisotropic angular distribution of energy inside a jet with $\theta_{jet} = 60°$, $\theta_{obs} = 0°$, $(\mathrm{d}E_0/\mathrm{d}\Omega)_{axis} = 10^{52}/\pi$ ergs/sr. Other parameters $(n_0, \alpha; \varepsilon_{mag}, \varepsilon_{el}, p)$ are the same as for graph (a). The legend gives the angular scale θ_E (see text). (c) The same jet as in (a) seen at $\theta_{obs} = 14°$, but with different energy per solid angle distributions. All jets have the same energy $E_0 = 1.5 \times 10^{51}$ ergs, isotropically distributed (solid line), exponentially decreasing toward the jet edge (dotted line) or exponentially increasing toward the edge (dashed line). Also shown in graphs (a) and (c) with dot-dashed lines is the contribution from an ejecta which is isotropic everywhere outside of the jet with opening angle $\theta_{jet} = 10°$ and orientation $\theta_{obs} = 14°$. The isotropic component has an energy 7×10^{50} ergs (other parameters are as for [a]) and can account for the early ($T \lesssim 1$ day) afterglow emission.

astro-ph/9801258 Panaitescu, Mészáros, Rees 98

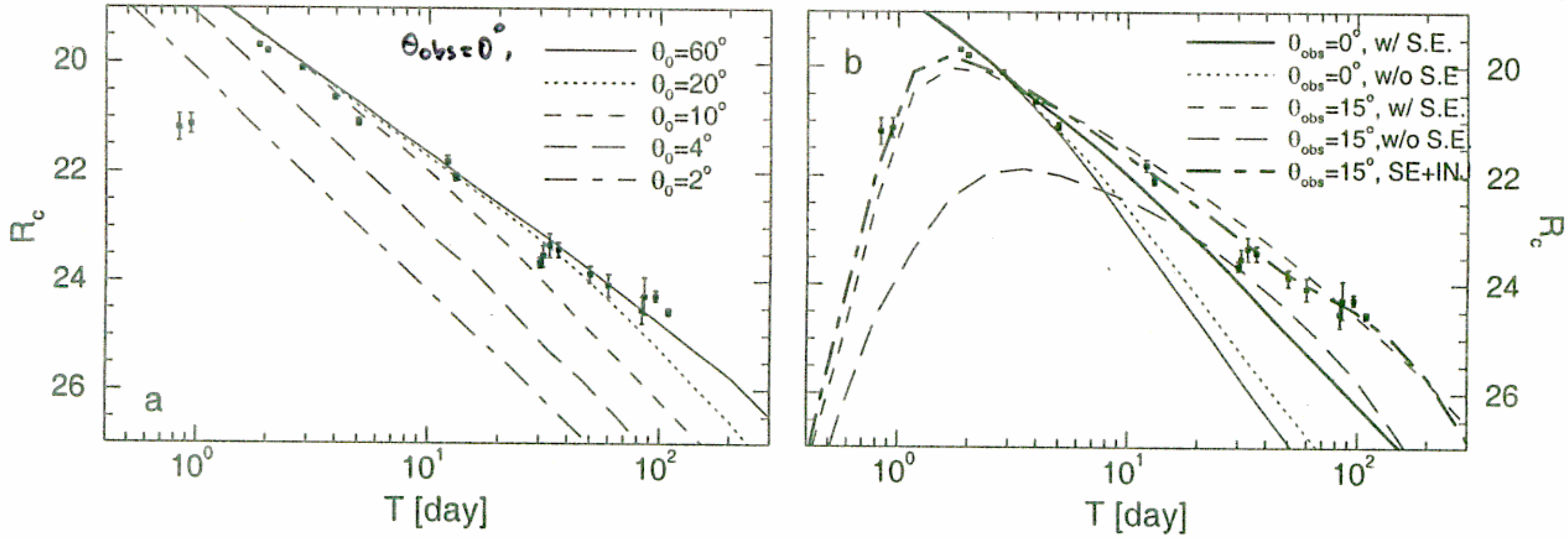
JETS (BEAMING)

Does sideways expansion lead to faster decay of light curve?

A : NO, if leads to a slower decay

because a) sweep up more matter, larger E.M.

b) surface curved, light from edges is "younger, brighter" and arrives later than "older, cooler" light from center, → "refills" the light curve



Panaitescu & Mészáros
astro-ph/9806016

SPECTRAL FEATURES IN AFTERGLOWS

* BLAST WAVE

$t \sim 10^5 t_5$ s (1 dy), $\Gamma \sim 7$, $\Sigma_p \sim 10^{17}$ cm^{-2}

cooled postshock ejecta (if good e-p coupling)

→ **EDGES**

blueshifted
$\Delta\nu/\nu \sim \Delta\Gamma/\Gamma \sim 0.3$

$$\left\{ \begin{array}{l} \tau_z \sim 0.8\, x_z Z^{-2} \Sigma_{17} \propto t_5^{-3/8} \\ h\nu_z \sim \begin{bmatrix} 0.1 \\ 0.4 \\ \cancel{9.2} \\ 64 \end{bmatrix} (1+z)^{-1} t_5^{-3/8} \text{ keV} \left\{ \begin{array}{l} \text{H} \\ \text{He} \\ \text{Fe} \end{array} \right. \end{array} \right.$$

* ISM OF HOST

Neutral gas outside $R \sim 60\, E_{52}^{4/9} n_0^{-1/6}$ pc

→ **EDGES**

$\tau_z \sim 8 \times 10^2 x_z Z^{-2} \Sigma_{n20}$

non-blueshifted
unbroadened

$h\nu_z \sim 13.6\,(1+z)^{-1}$ eV (H)

$\sim 9.2\,(1+z)^{-1}$ keV (Fe)

→ **Hα, Kα ABS. LINES** $W_\nu/\nu \sim 10^{-2} x_z^{1/2} \Sigma_{n20}^{1/2}$

* HYPERNOVA :→ DIAGNOSTIC

e.g. if $M_e \sim 1 M_\odot$ envelope, $r_e \sim 3\; 10^{15}$ cm ($\tau_T \sim 1$)

→ **Hα, Kα EMISSION** LINES, $W_\nu/\nu \sim 10^{-2}$

or if $M_e > 1 M_\odot$, $\tau_T \gg 1$

→ **REFLECTION SPECTRUM** with Ly EDGE, K-EDGE

(Mészáros & Rees '98
astro-ph/9806183)

- **Are there constraints on beaming?**
  - Afterglow obs of 970508 and 971214 give constraints **only** on E/Ω, not on Ω. For example, E_γ could be beamed into 10^{-2}, while X/O/R blast wave could be beamed into 10^{-1}

    Wijers & Galama astro-ph/9805341
  - Lack of late down-turn in light curve of 970508 does **not** constrain beaming: contrary to simple expectations, when $\Gamma < \Omega^{-1}$ the light curve does not get dimmer.

    Panaitescu & Mészáros , astro-ph/9806016
  - Late down-turn expected if $\Gamma \lesssim 2$; but this could occur as late as 6 months to 1 year in a medium whose density decreases with distance, or where the fireball is anisotropic, or where the fireball has late injection.

    Panaitescu & Mészáros , ApJ in press, astro-ph/9711339

- **– Only $\nu\bar{\nu}$ is constrained.**
  – NS-NS is not constrained
  – beaming is not constrained

OPEN QUESTIONS

- Binary merger or single/binary star collapse? (binary kicks → some remain in host, others not)
- Environment? Binary (less dense on avg.), single (more dense)
- Need $\lesssim 10^{53}\Omega$ ergs: is $\Omega \sim 10^{-2}$ plausible? Yes for γ-rays, less so for afterglow- but $\Omega_\gamma \neq \Omega_{after}$ possible (γ-rays are beamed but energy is not)
- Effect of dust abs. on X-spectrum and lack of O? Or lack of O due to fast or steepening decay? Or to decrease in external density?
- Why no R counterparts to most X afterglows? Related to environment and/or type of host?

KEY FUTURE EXPERIMENTS

- **HETE-2** : TAKE OVER FROM B-SAX

  GET 10-20 POSITIONS /YR
  FOR QUICK GROUND FOLLOW-UP

- **MIDEX** : MULTI-WAVELENGTH FOLLOW-UP
  TRIGGER $< t \lesssim$ DAY(S)

  GET $\gtrsim 100$ POSITIONS /YR

- **GLAST** : EXPLORE GeV + RANGE
  TEST ACCELERATION PHYSICS