Theoretical Models for High Energy Radiation from Gamma Ray Bursts

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GLAST Science Working Group/GRB Workshop
September 12, 2002

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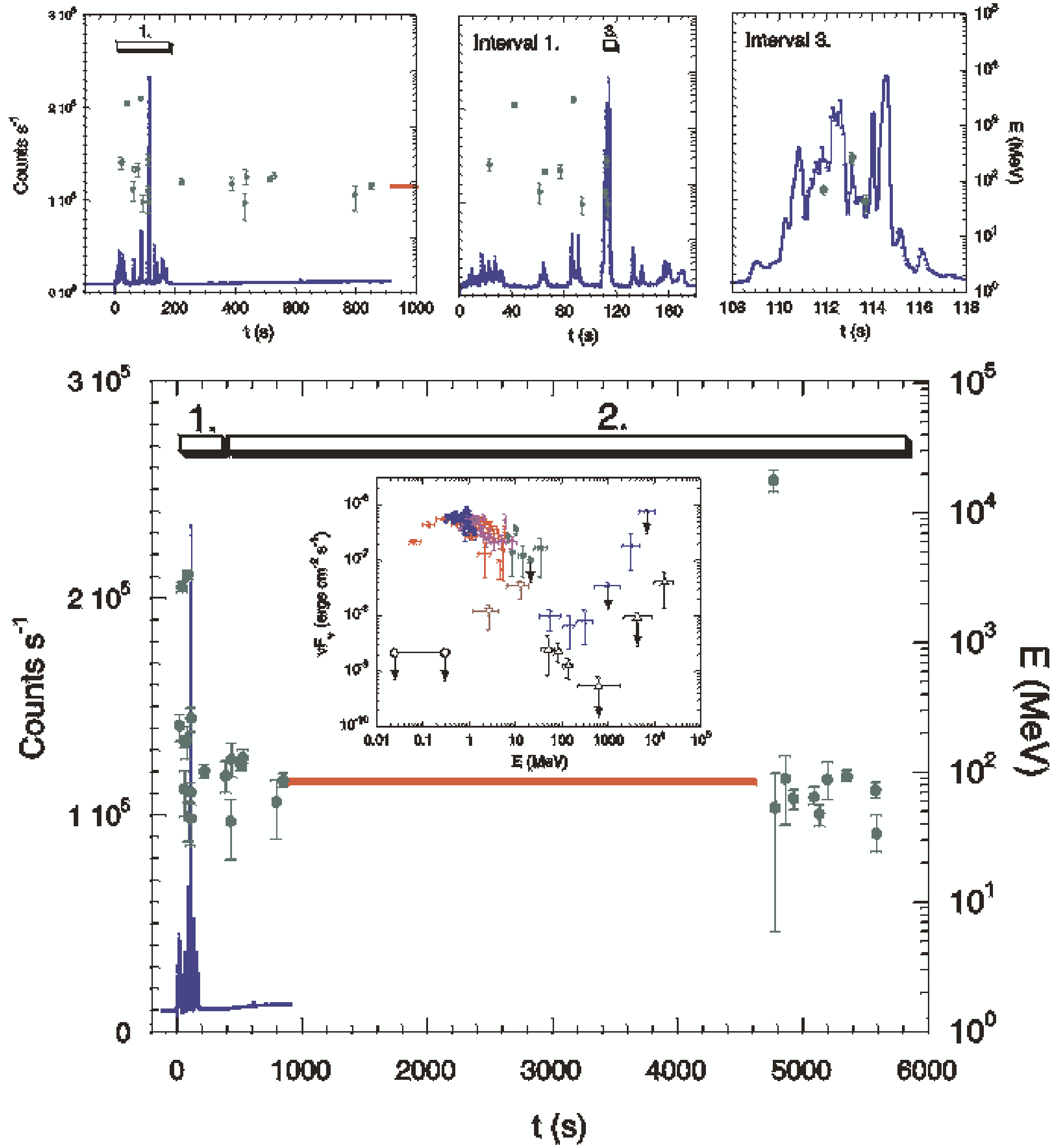
- **High Energy/ X-ray Observations**
- **Source Models: Implications for High Energy Radiation**
  Supranova/External Shock Model for both prompt gamma rays and afterglow
- **External Shock Model: Predictions and Explanations of Narrow E_{pk} distribution observed with BATSE**
- **High-Energy Radiation Signatures**

GRB 940217

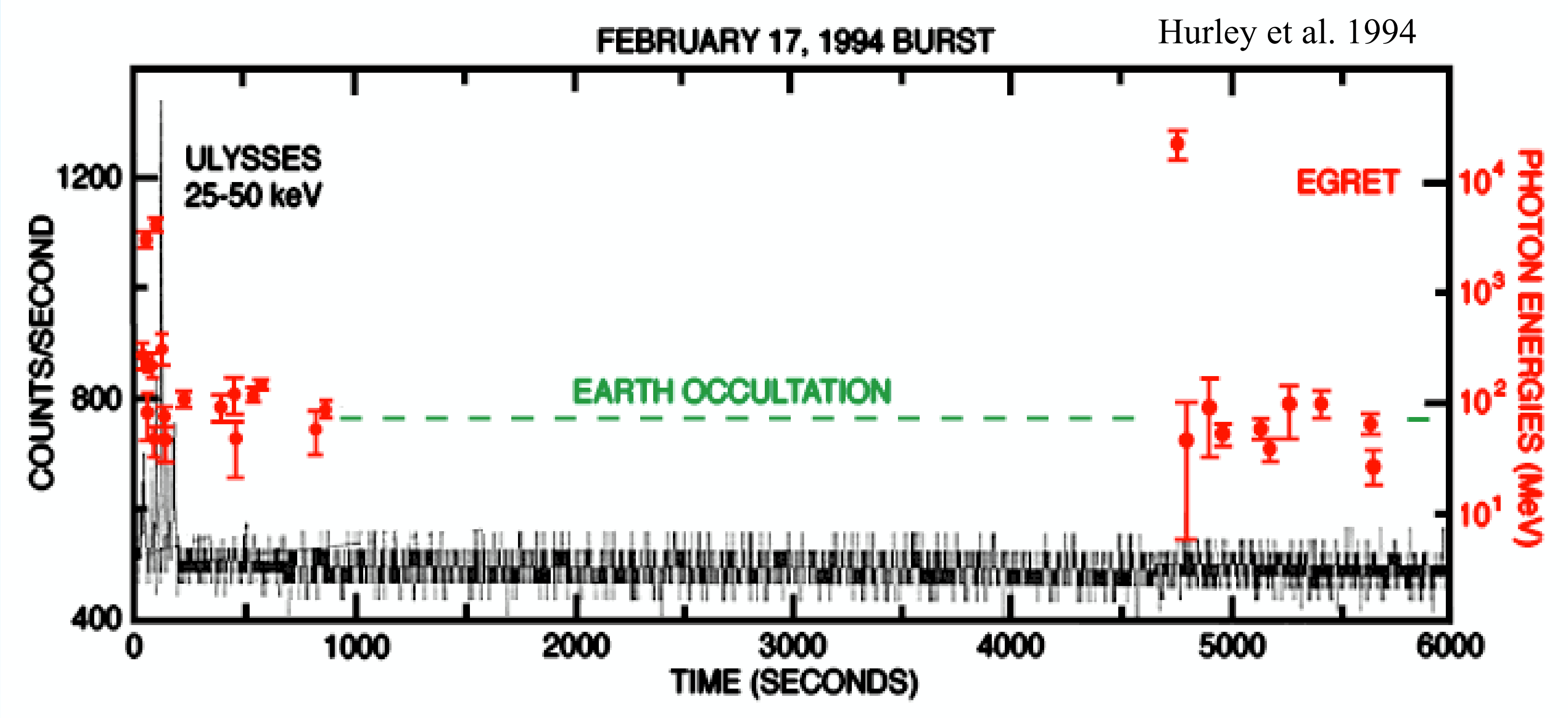
⇒ **Nonthermal processes**

Origin of hard radiation?

1. Synchrotron
2. SSC
3. External Compton Scattering
4. Hadronic Emission (proton synchrotron/ photomeson/ secondary nuclear production)



GRB 940217

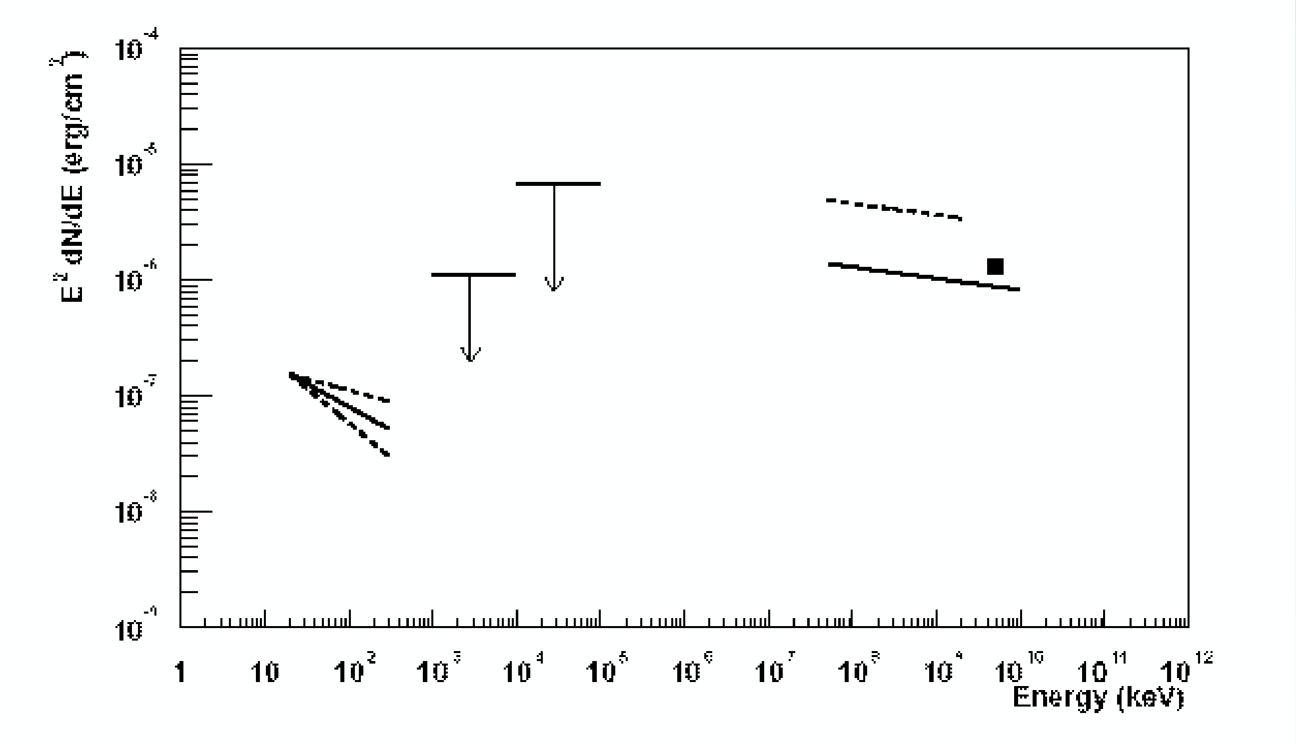


Other evidence for high-energy radiation:

Seven GRBs detected with EGRET either during prompt sub-MeV burst emission or after sub-MeV emission has decayed away (Dingus et al. 1998)

Average spectrum of 4 GRBs detected over 200 s time interval from start of BATSE emission with photon index 1.95 (±0.25) (> 30 MeV)

GRB 970417a



Observations of TeV radiation with Milagrito (Atkins et al. 2002)

Requires low-redshift GRB to avoid attenuation by diffuse IR background

$\gamma\gamma$ Transparency Arguments

In comoving frame, threshold condition for $\gamma\gamma$ interactions is

Requires low-redshift GRB to avoid attenuation by diffuse IR background

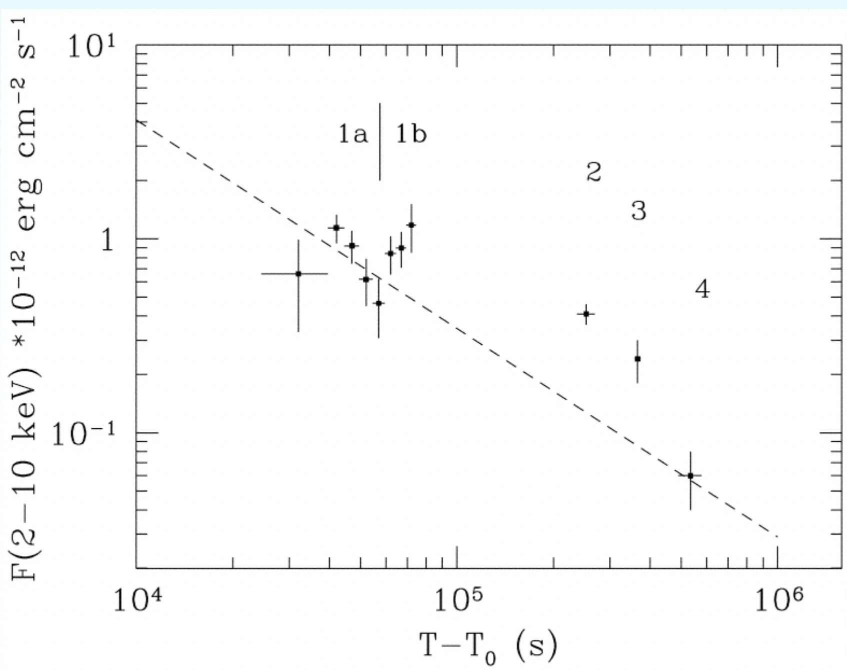
$$\varepsilon_1^{'}\varepsilon_2^{'} < 2 \Rightarrow \delta < 30(1+z)\sqrt{E_1\,(MeV)E_2(GeV)}$$

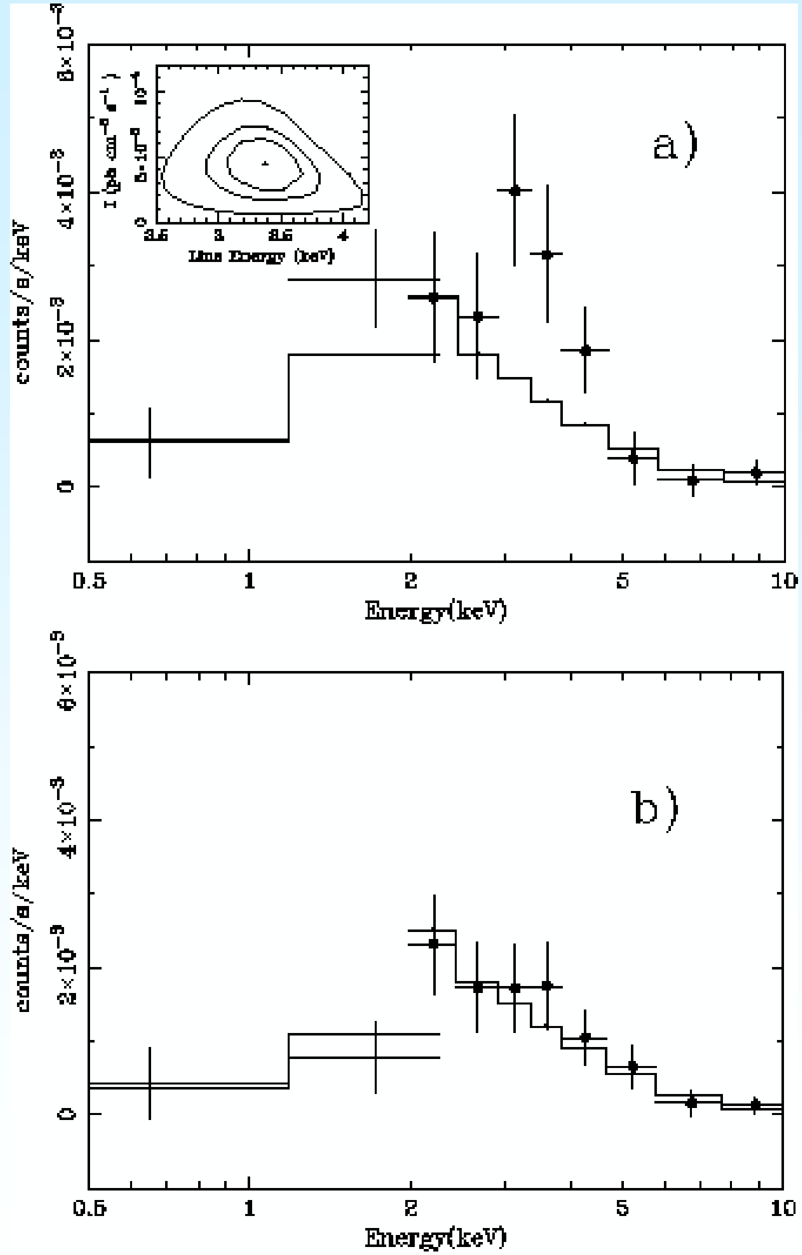
$$\tau_{\gamma\gamma} \approx \frac{\sigma_T}{3}(\frac{2}{\varepsilon_1^{'}})n_{ph}^{'}(\frac{2}{\varepsilon_1^{'}})r_b\ ,\ r_b \le \frac{ct_v\delta}{(1+z)}$$

$$\delta > 200\,[(1+z)d_{28}]^{1/3}\,[\frac{f_{-6}\ E_2(GeV)}{t_v(s)}]^{1/6}$$

GRB 970508

- Search for Fe K emission at z = 0.835 with Beppo-SAX 21-56 ks after GRB
- Line at E = 3.4(±0.3) keV; 6.2(±0.6) keV in rest frame) at 99.3% significance
- Interpretation by Vietri et al. (1999) and Bottcher (2000) as dense torus emission





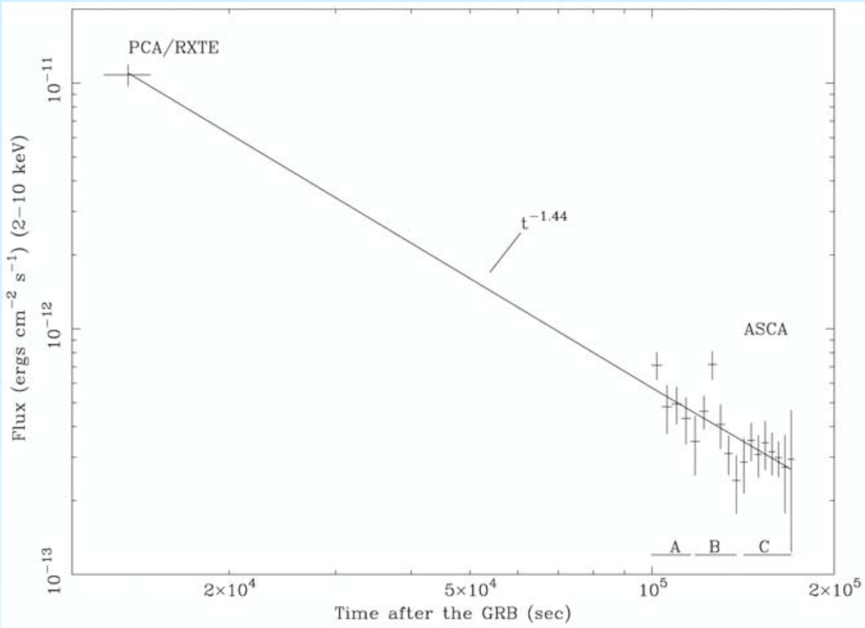
GRB 970828

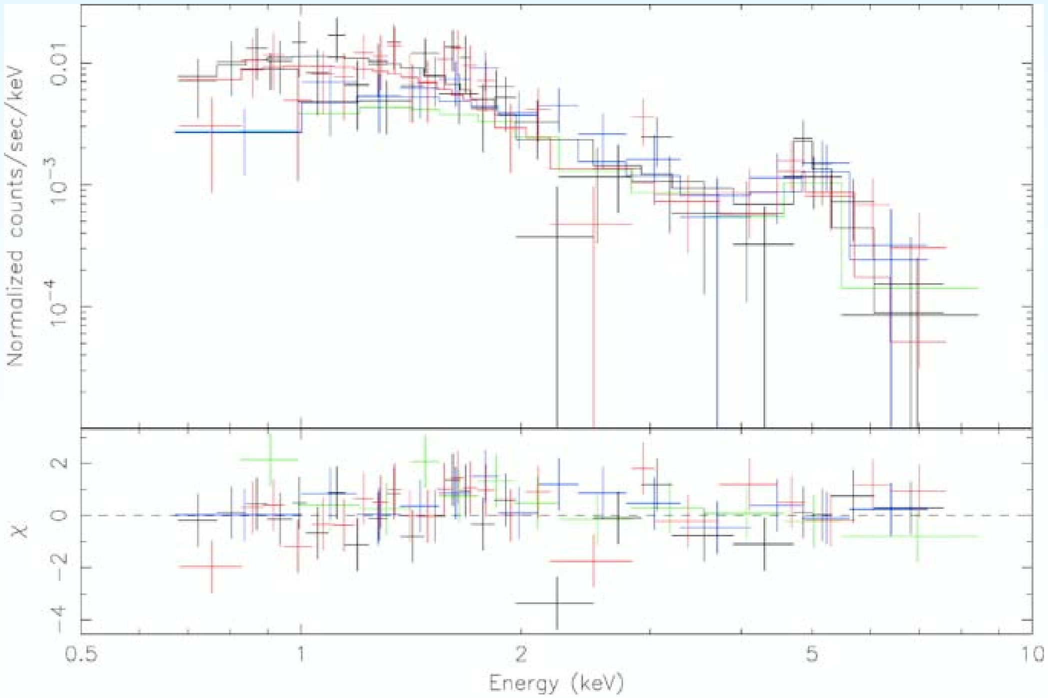
36 ks ASCA observation beginning 1.17 days after GRB (Yoshida et al. 1999, 2001)

Emission line at E ≈ 5 keV; if Fe Kα, then z ≈ 0.33

z = 0.9578 from [OII] and [NeIII] lines (Djorgovskii et al. 2001)

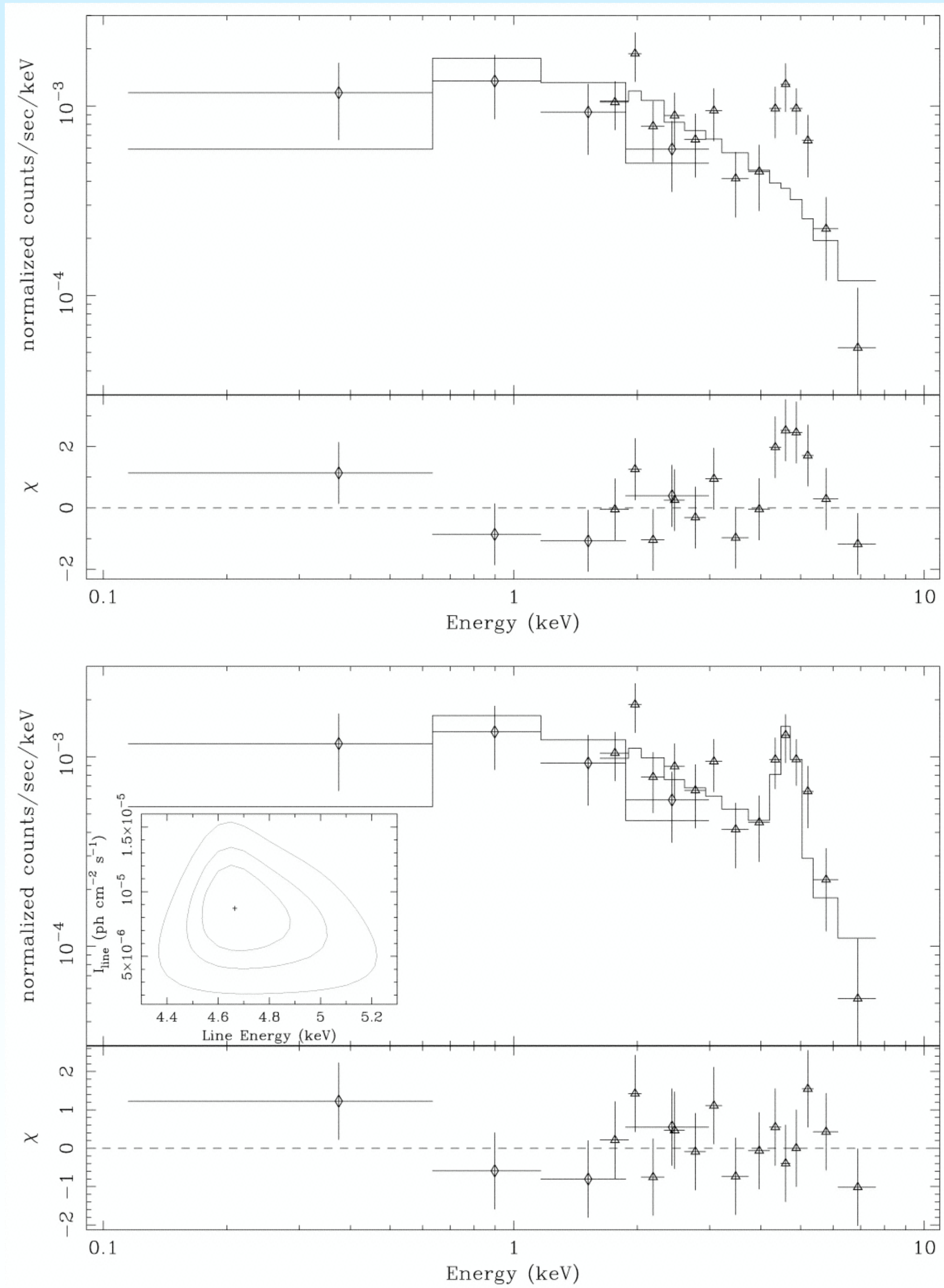
Reinterpret as Fe recombination edge; absence of Fe Kα requires highly nonequilibrium situation (Weth et al. 2000; Yonetoku et al. 2001)





GRB 000214

- 104 ks Beppo-SAX observation beginning 12 hours after GRB (Antonelli et al. 2000)
- Emission line at E ≈ 4.7(±0.2) keV; EW ~ 2 keV
- ⇒ z = 0.47
- Not easily reconciled with binary merger models or collapsar/hypernova models (insufficient mass from presupernova stellar wind)



GRB 991216

3.4 hr Chandra observation beginning 37 hours after GRB (Piro et al. 2000)

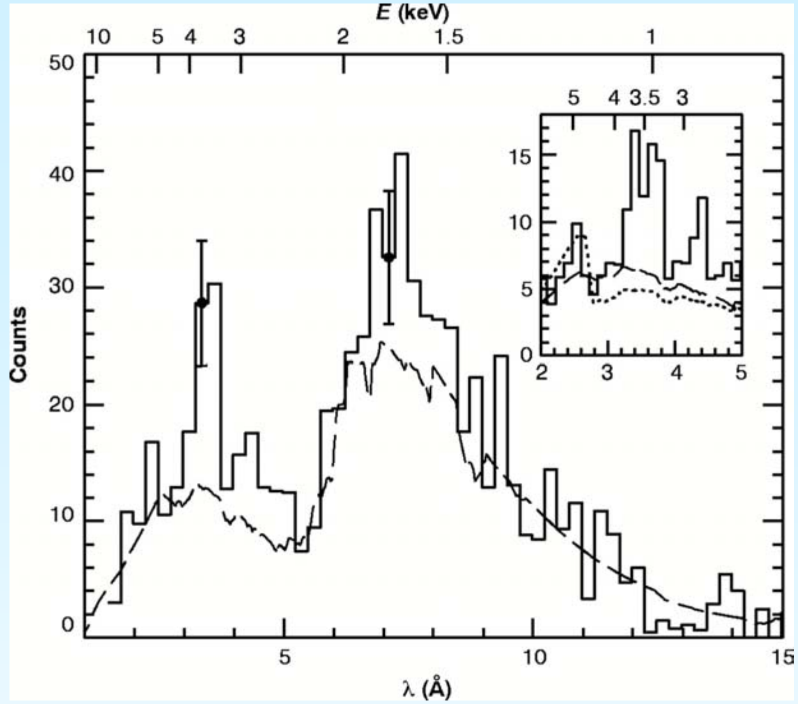
Emission line at E ≈ 3.49(±0.06) keV with 4.7σ confidence

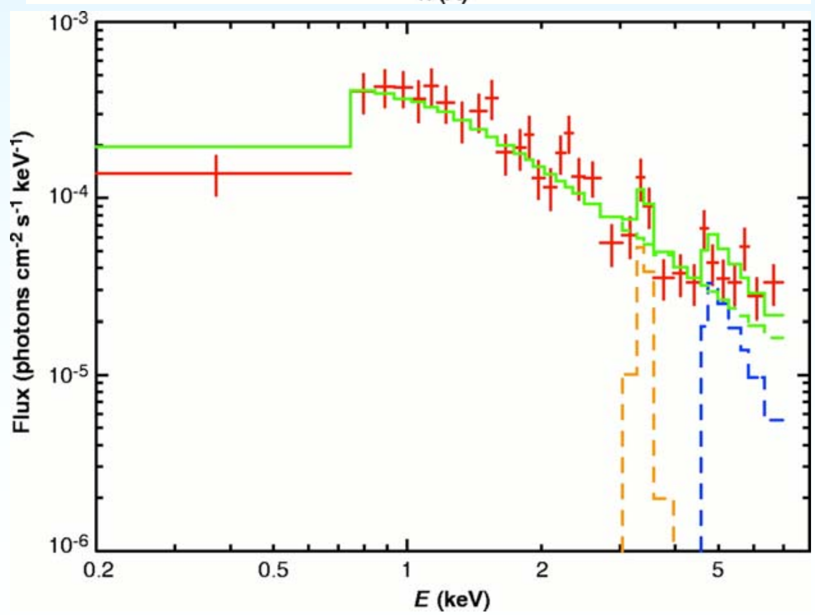
⇒ z = 1.00 (H-like Fe) in agreement with z = 1.02 from absorption lines

Weak indication of Fe recombination edge at 4.60 keV

3σ evidence for recombination edge of H-like S at 1.72 keV, H-like S Kα line at 1.29 keV

In accord with supranova model (Vietri and Stella 1998) or decaying magnetar model (Rees and Meszaros 2000)



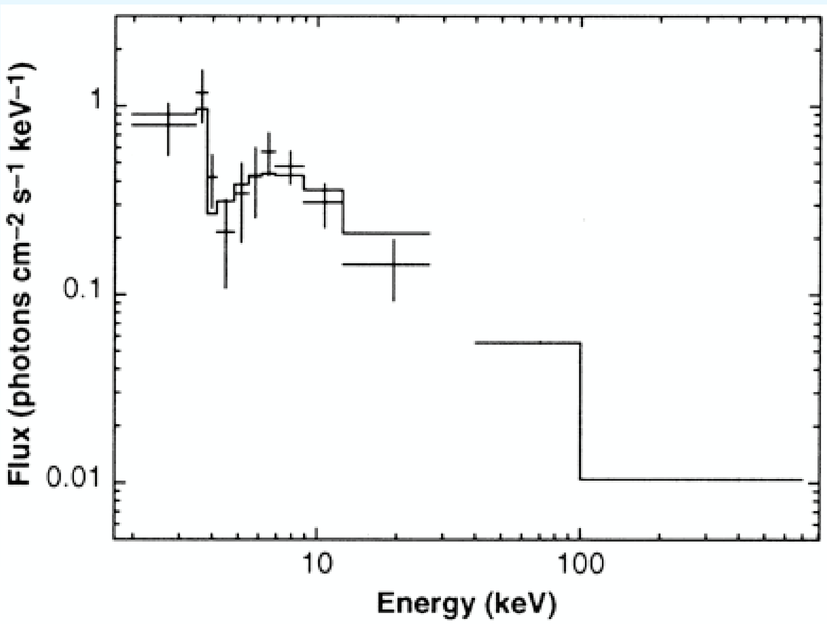


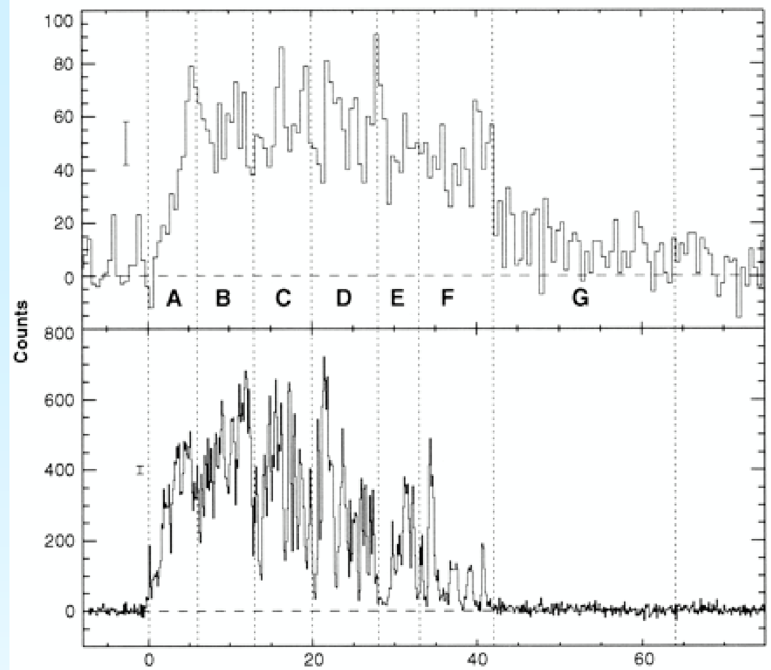
GRB 990705

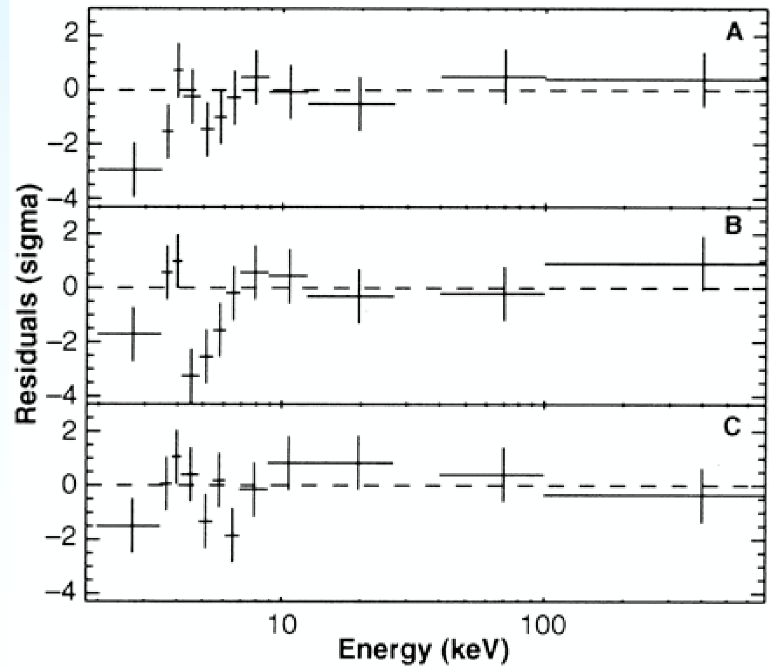
Observation of absorption edge at ~ 3.8 keV during the prompt phase (Amati et al. 2000) in intervals A and B

Photoelectric absorption at Fe K-edge ⇒ z = 0.86 (±0.17)

ESO Observations find z = 0.8435 (±0.0005) (Andersen et al. 2002)



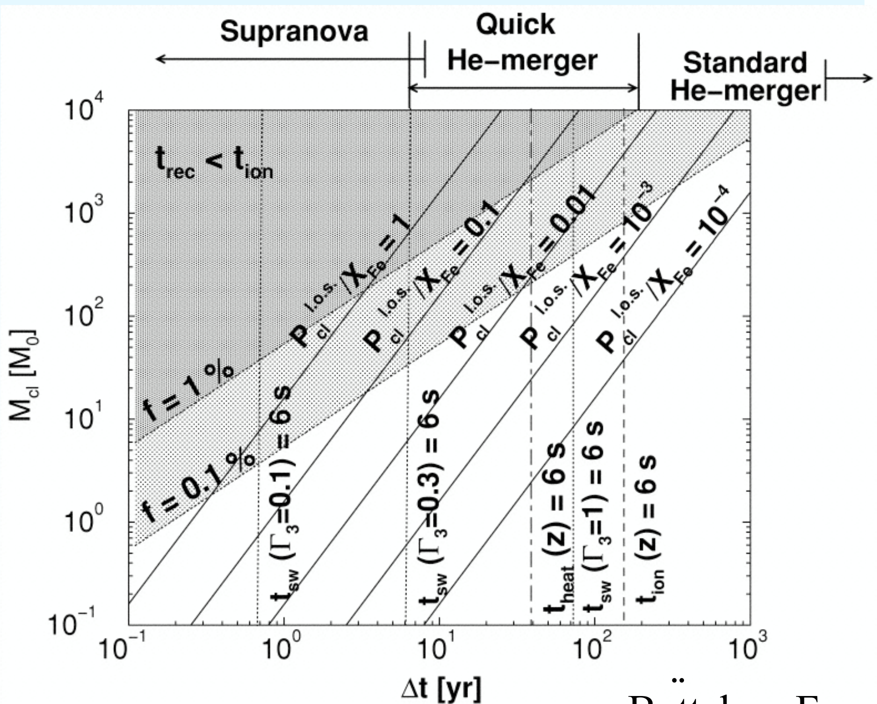


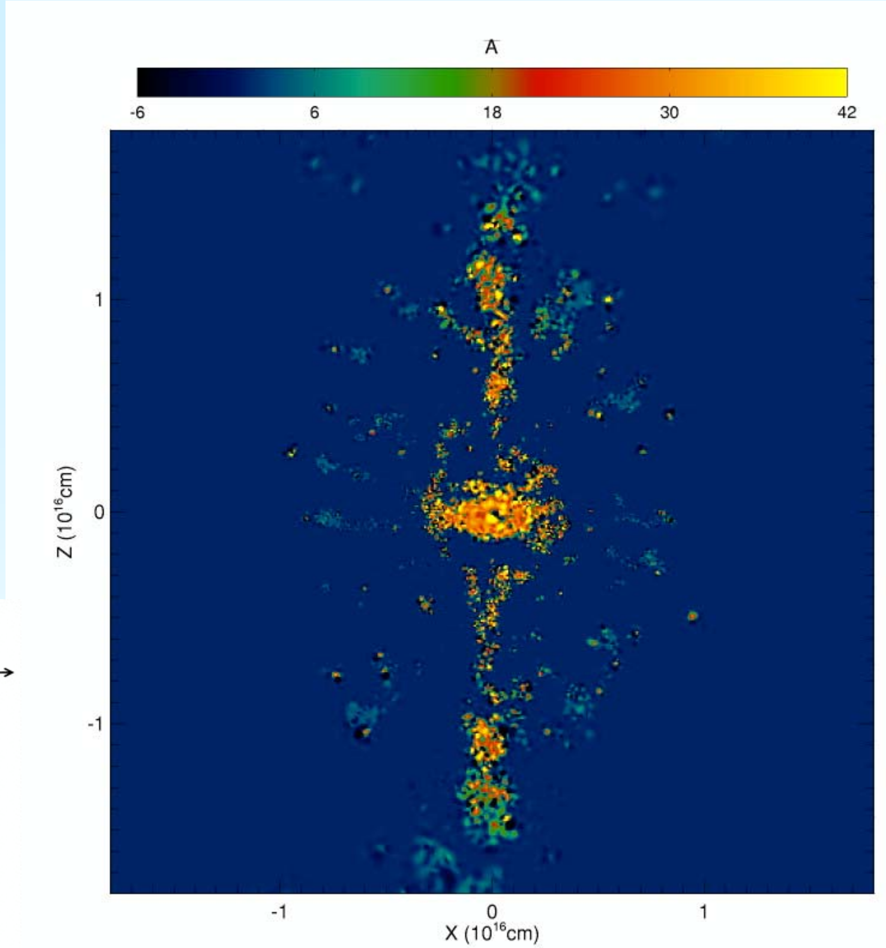


GRB 990705

Can be explained with strong Fe enhancements; large amount of Fe within 1 pc; strong clumping of ejecta

Probability of observing absorption in He-merger/collapsar model << 1%





Size scale of clumps ~< 10^{13} cm

Density >~ 10^{10} cm^{-3}

Probability of observing absorption in He-merger/collapsar model << 1%

Böttcher, Fryer and Dermer (2002)

GRB 011211

Long duration ($t_{dur} \approx 270$ s) GRB at $z = 2.140$ (± 0.001) $\Rightarrow$ apparent isotropic energy = 6.3×10^{52} ergs

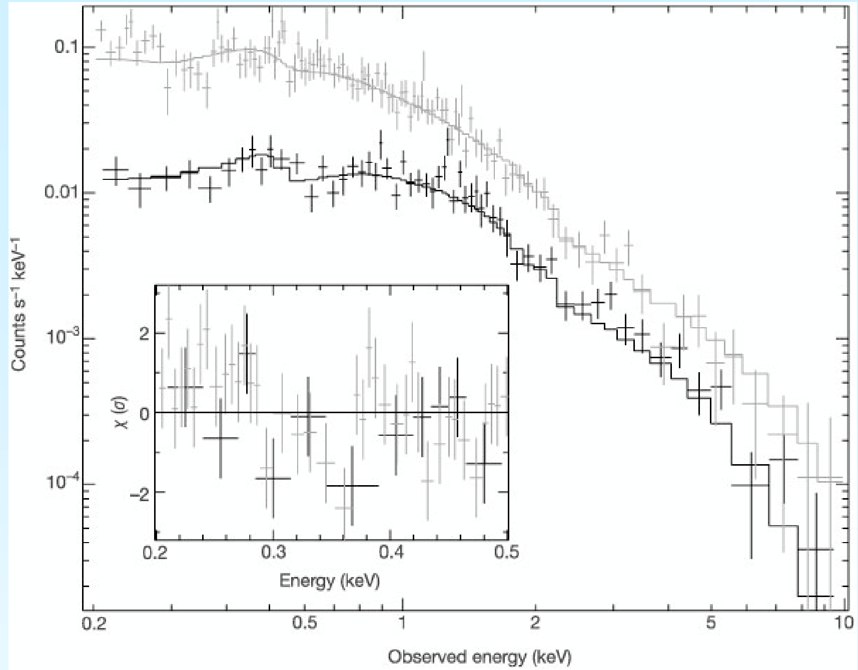
$z_{lines} = 1.88$ (± 0.06) $\Rightarrow$ emission in outflowing moving with $\beta \approx 0.1$

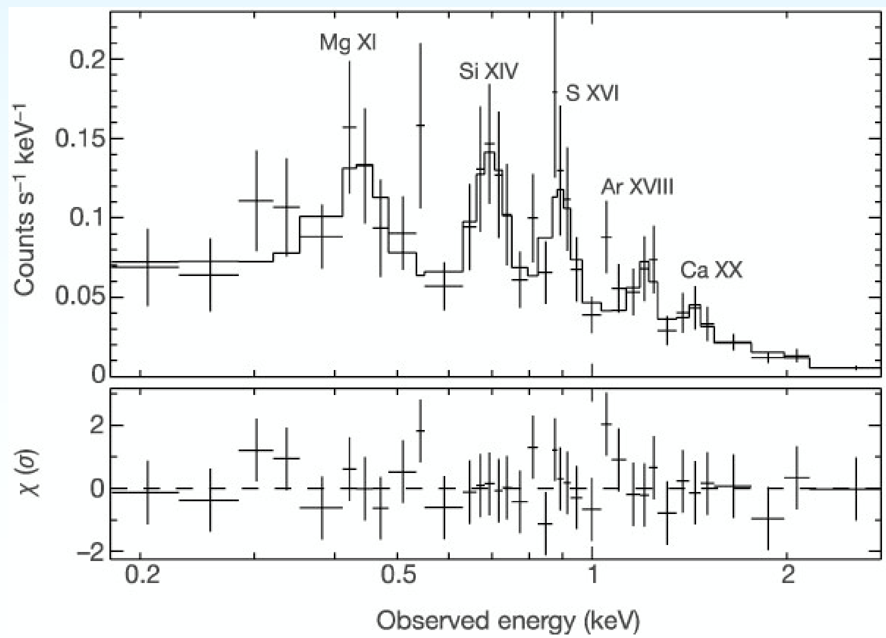
Beaming break or constant energy reservoir result $\Rightarrow$ $\theta_j \approx 3\text{-}7°$

Claimed line detection of Ka transitions in Mg XI (or XII), Si XIV, SXVI, Ar XVIII, Ca XX

Strongest line at Si XIV $\Rightarrow \approx 10^{48}$ ergs in H-like Kα line

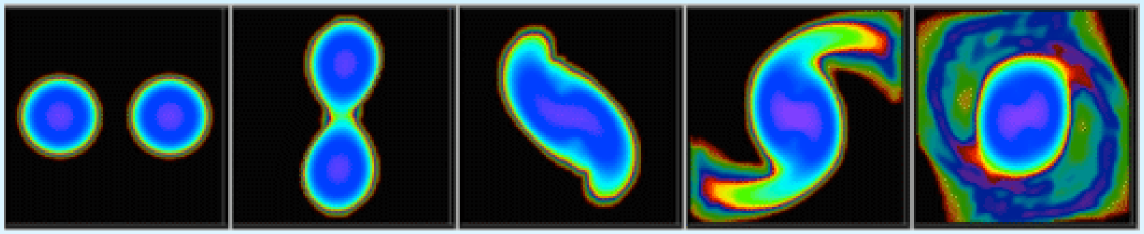
Requires very strong clumping of ejecta to make recombination proceed quickly





Reeves et al. (2002)

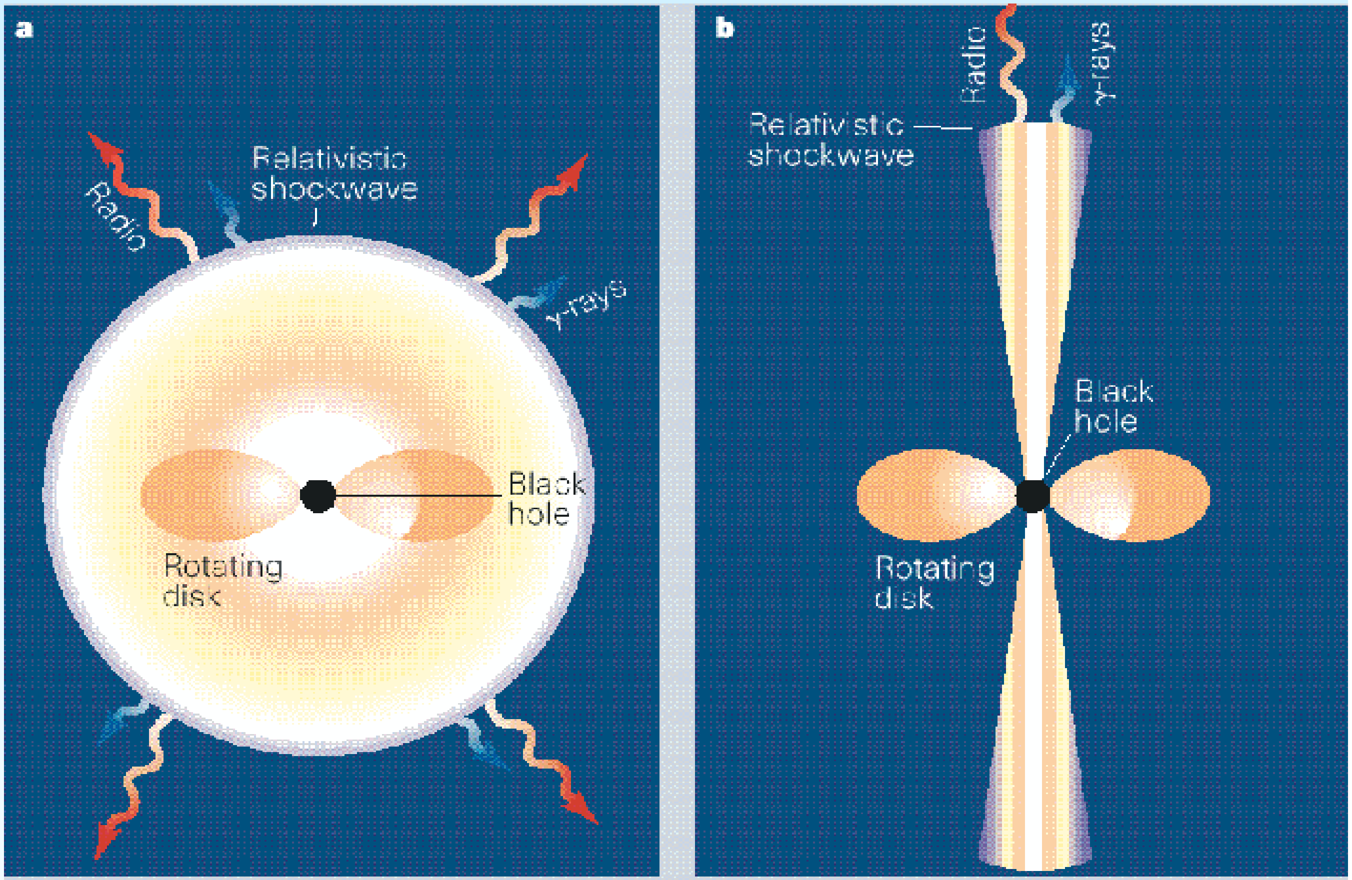
Source Models



(Eichler et al. 1989; Janka, Ruffert et al.)

- Coalescing Compact Objects
  - Binary neutron stars known in Galaxy (Hulse-Taylor pulsar)
  - Coalescence by gravitational radiation
  - Expect ~1 coalescence event per Myr per MW Galaxy (too few given beaming fraction)
  - Prompt collapse
  - Expected to be found in elliptical/non-star-forming galaxies
  - Possible candidate for short GRBs

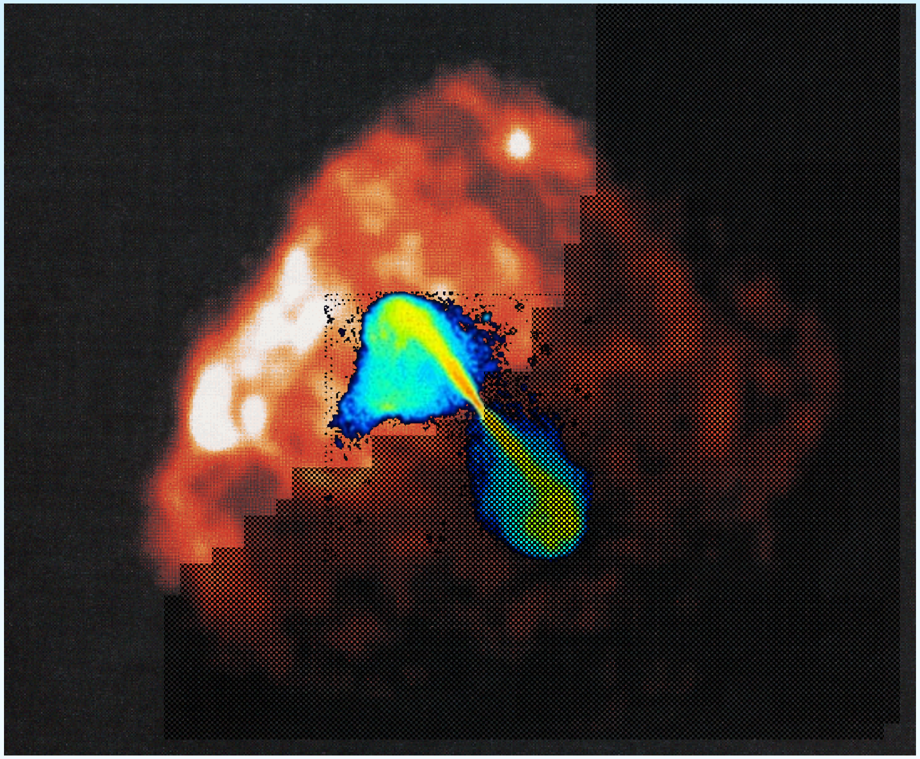
Source Models



- Hypernova/Collapsar Model (Woosley et al.; Paczynski; Meszaros and Rees)
  - Massive Star Collapse to Black Hole
  - Energy released at rotation axis: MHD energy production
  - Two orders of magnitude more energy available; no prediction (?) of constant energy reservoir
  - Requires active central engine
  - Available number of sources
  - No strong evidence for presupernova wind ($n \propto r^{-2}$)
  - **Low density surroundings (0.01 <~ n [cm^{-3}] <~ 10)**

Source Models

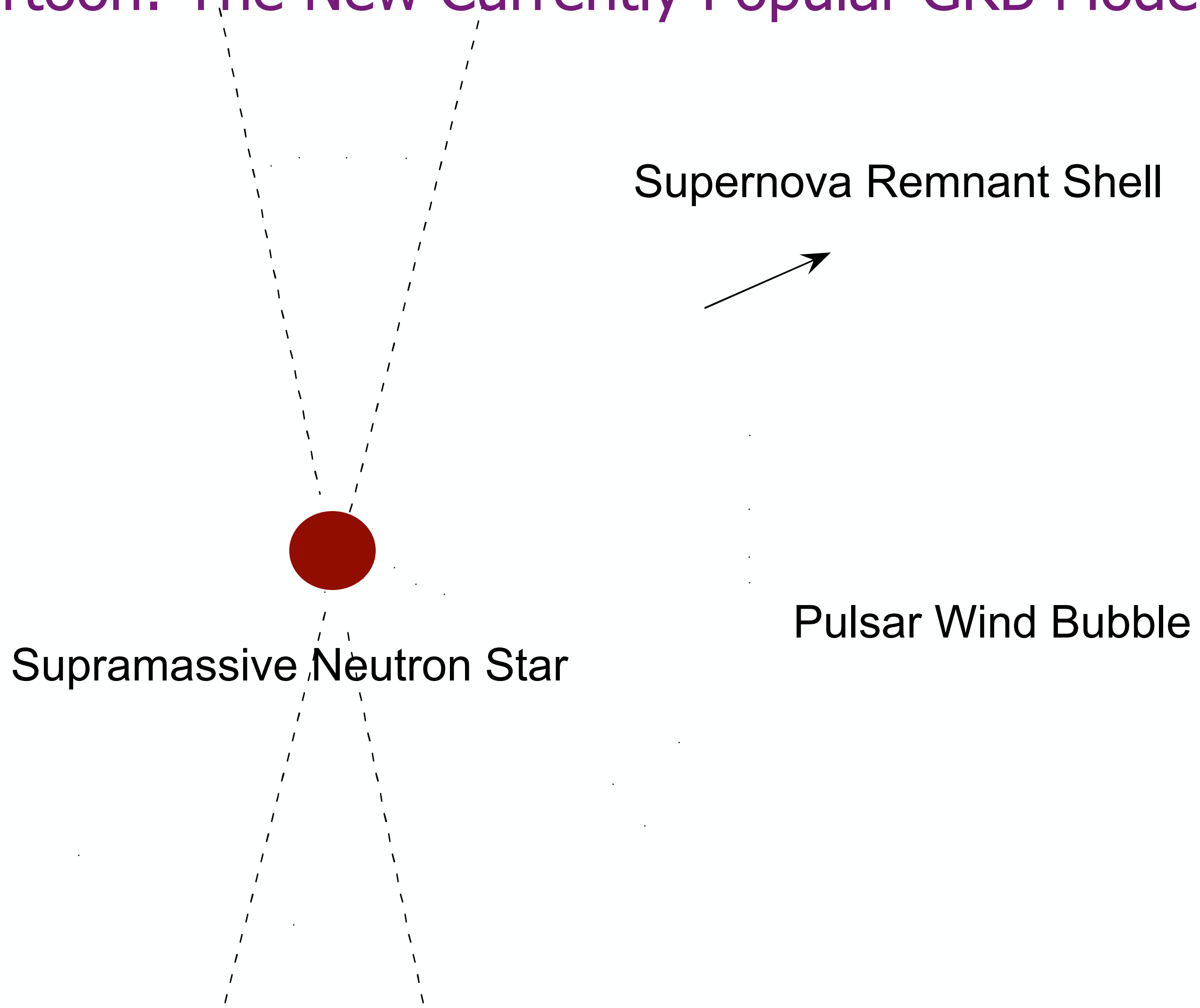
- Supranova model (Vietri and Stella 1999)
  - Two-step collapse to black hole
  - Super-Chandresekhar mass neutron star stabilized against prompt collapse by rotation
  - Supernova shell of enriched material
  - In dusty, star-forming regions (except for AIC events)
  - Standard energy reservoir (?)
  - Prompt collapse following long quiescence



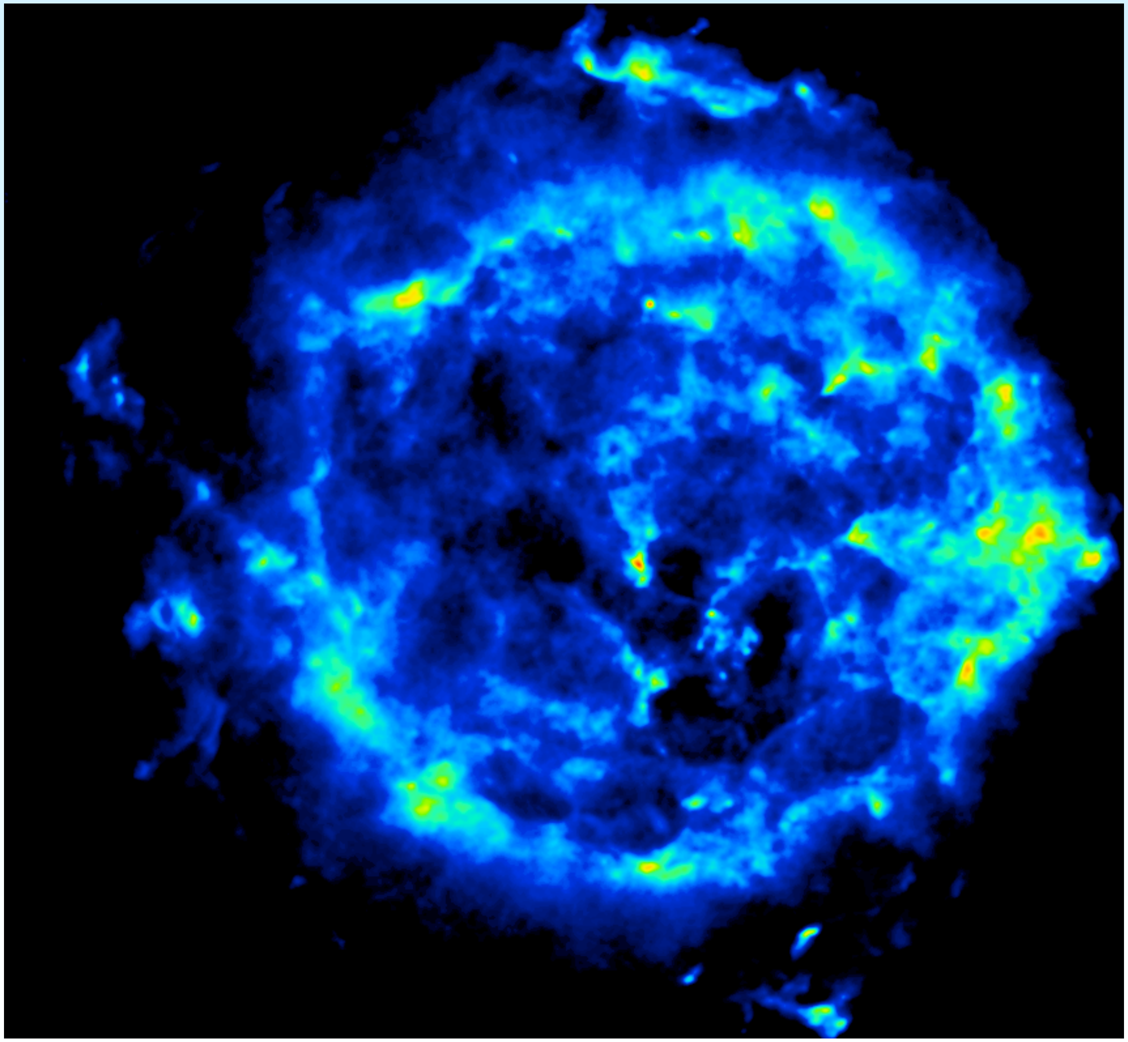
Supranova model more easily explains Iron absorption and fluorescence line observations

Cartoon: The New Currently Popular GRB Model

• **Collapse of NS to BH gives prompt explosion**



Highly Structured SN Remnant Ejecta



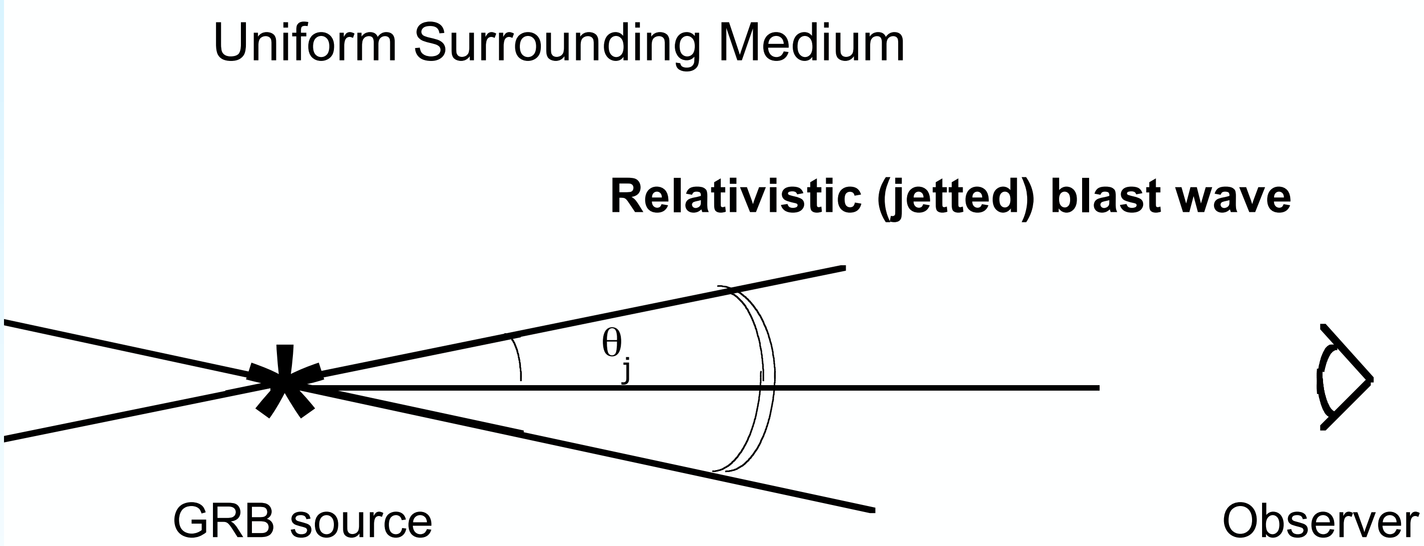
Cas A Supernova Remnant

Pulsar Wind Nebulae

Highly inhomogeneous surrounding medium

Crab (plerionic) nebulae

External Shock Model in Uniform Surroundings



Elementary Blast Wave Theory

- Nonthermal synchrotron radiation in shocked fluid
  - Joint normalization to power and number gives

$$\gamma_{\min} \cong e_e\left(\frac{p-2}{p-1}\right)\left(\frac{m_p}{m_e}\right)\Gamma \; ; \; \dot{E}'_e = e_e(dE'/dt')$$

- Magnetic field parametrized in terms of equipartition field

$$\frac{B^2}{8\pi} \cong 4e_B m_p c^2 n_* (\Gamma^2 - \Gamma) \Rightarrow B \propto \Gamma$$

- Injection of power-law electrons downstream of forward shock

$$\dot{N}(\gamma_e) = N_e \gamma_e^{-p}, \gamma_{\min} < \gamma_e < \gamma_2 \ (comoving\ \gamma_e)$$

$$N_e = 4\pi\, n_{ext} x^3 / 3$$

- Maximum injection energy: balancing losses and acceleration rate

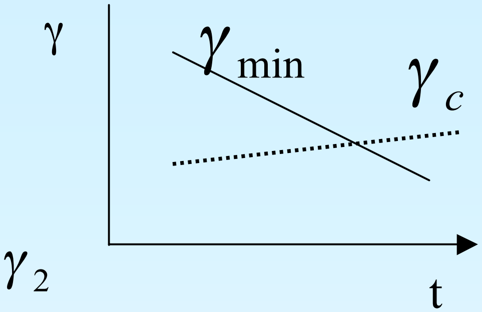
$$\gamma_2 \cong 4\times 10^7 / \sqrt{B(G)}$$

- Cooling electron break: balance synchrotron loss time with adiabatic expansion time

$$t'_{adi} \cong x/\Gamma c \cong \Gamma t \cong t'_c \cong \left(\frac{4}{3} c\sigma_T \frac{u_B}{m_e c^2}\gamma_c\right)^{-1}$$

$$\Rightarrow \gamma_c \cong \frac{3m_e}{16 e_B n_* m_p c \sigma_T \Gamma^3 t} \quad \Rightarrow \gamma_{\min} \propto t^{-3/8}, \gamma_c \propto t^{1/8}$$

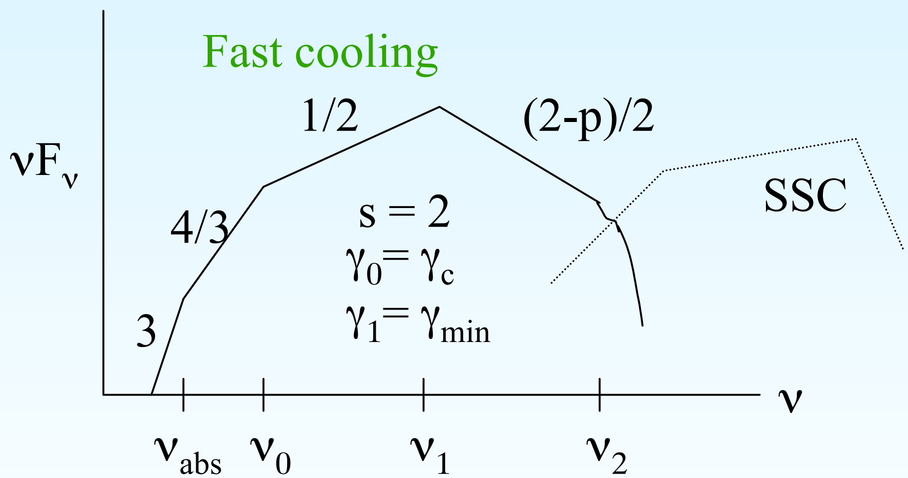
Transition from fast to slow cooling – if parameters e_e, e_B, p stay constant

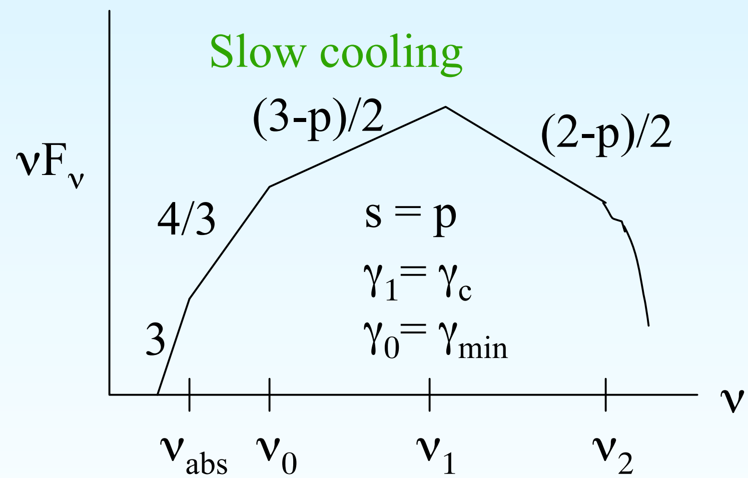


Comoving Nonthermal Electron Spectrum

$$N_e(\gamma_e) \cong N_e \gamma_o^{\,s-1} \gamma_e^{\,-s}, \gamma_0 < \gamma_e < \gamma_1$$

$$N_e(\gamma_e) \cong N_e^o \, \gamma_o^{\,s-1} \gamma_1^{\,-s} (\gamma_e / \gamma_1)^{-(p+1)}, \gamma_1 < \gamma_e < \gamma_2$$





- p > 2
- SSC important when $e_B << e_e$
- Uniform (not wind) geometry

$$\nu_i = \Gamma \gamma_i^2 eB / [2\pi m_e c(1+z)]$$

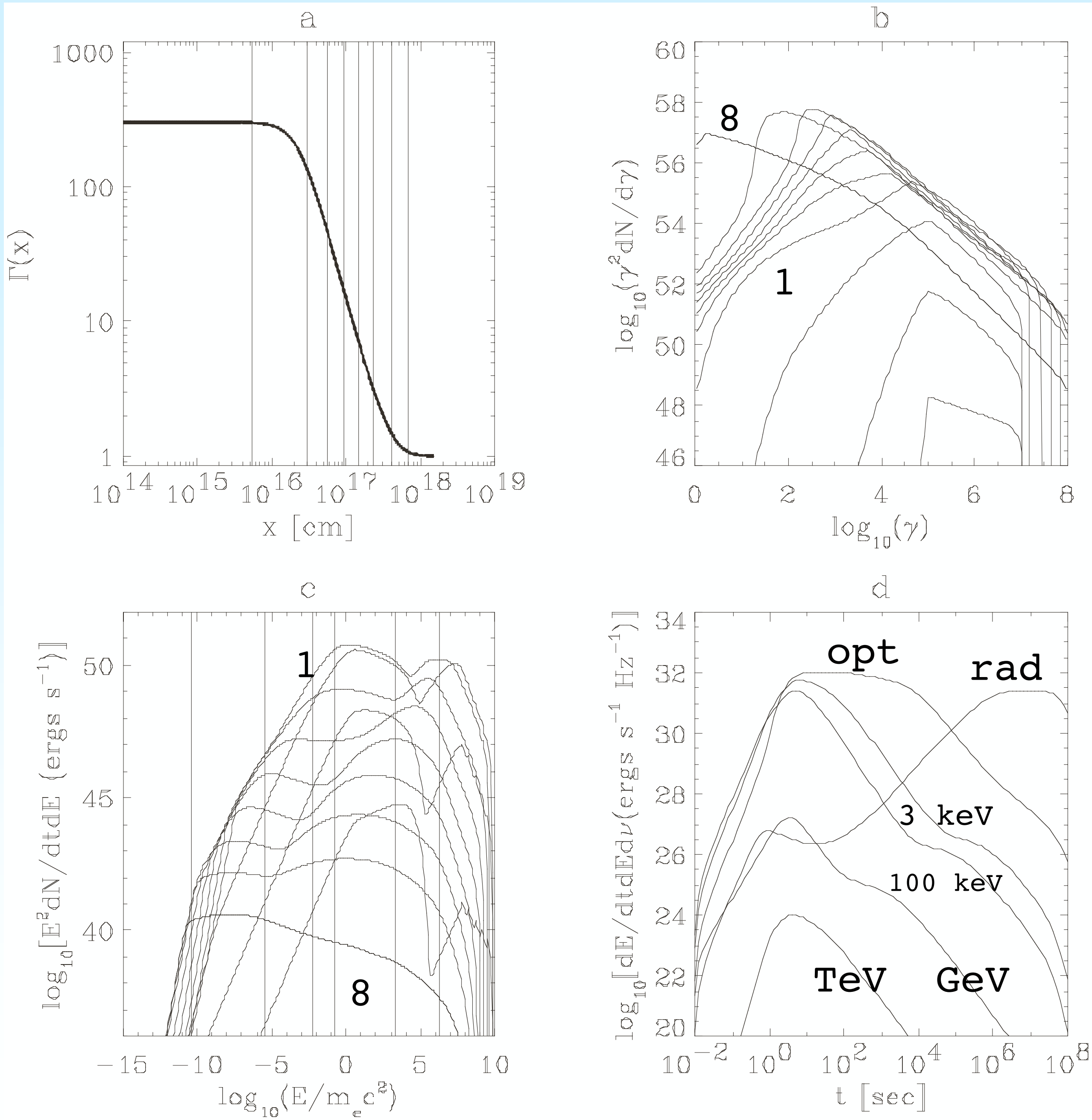
Numerical Simulation: Uniform Surrounding Medium

Two peaks in νF_ν distribution

Generic rise in intensity until t_{dec}, followed by constant or decreasing flux except in self-absorbed regime

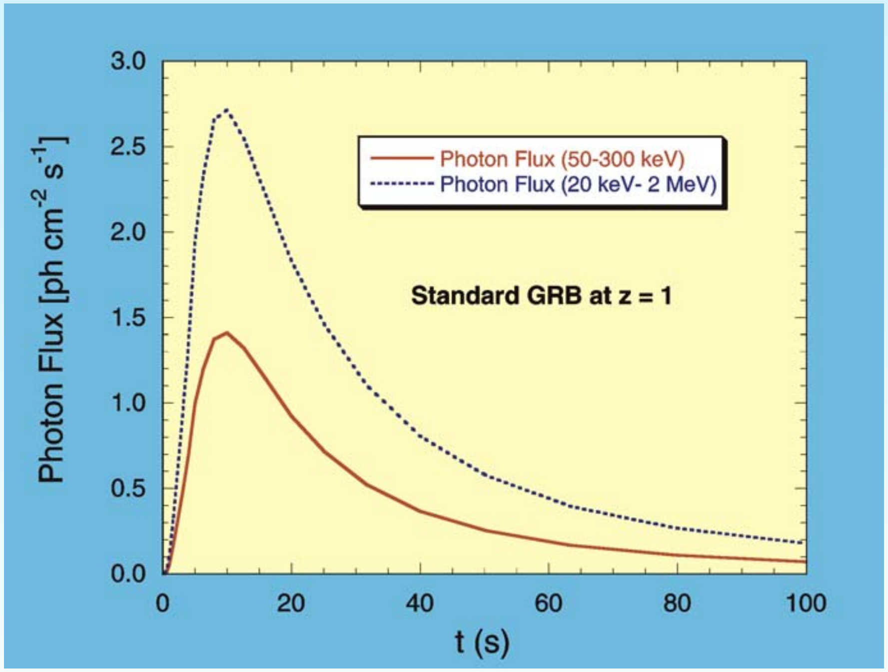
Dominant SSC component for this parameter set

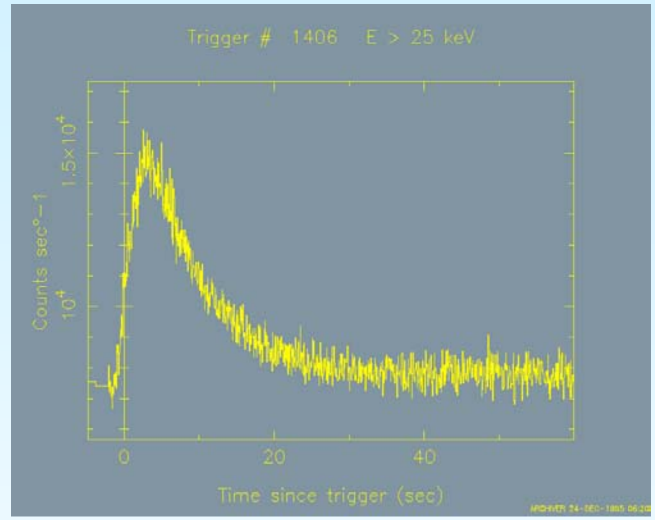
Chiang and Dermer (1999)



Most common prompt GRB light curve

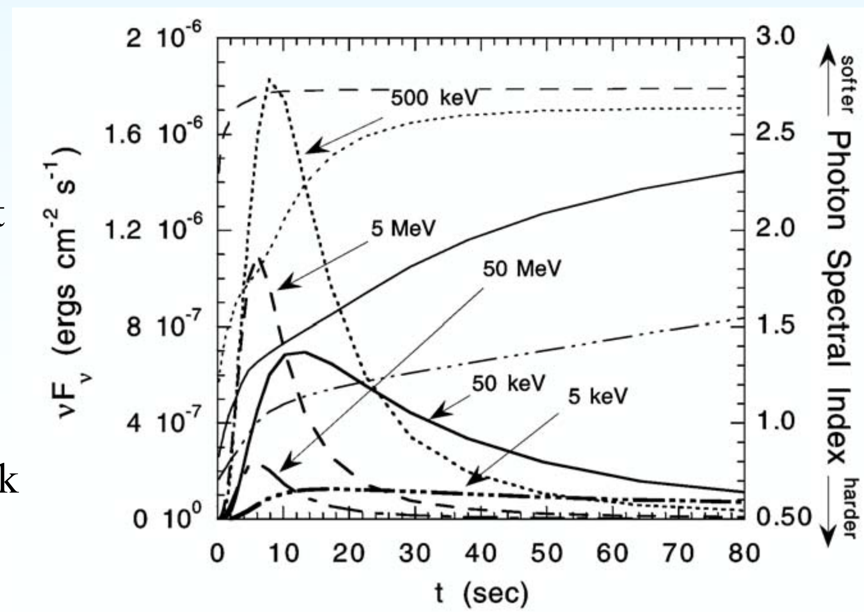
• Reproduces generic temporal behavior of FRED-type profiles
• Hardness-intensity correlation, hard to soft evolution



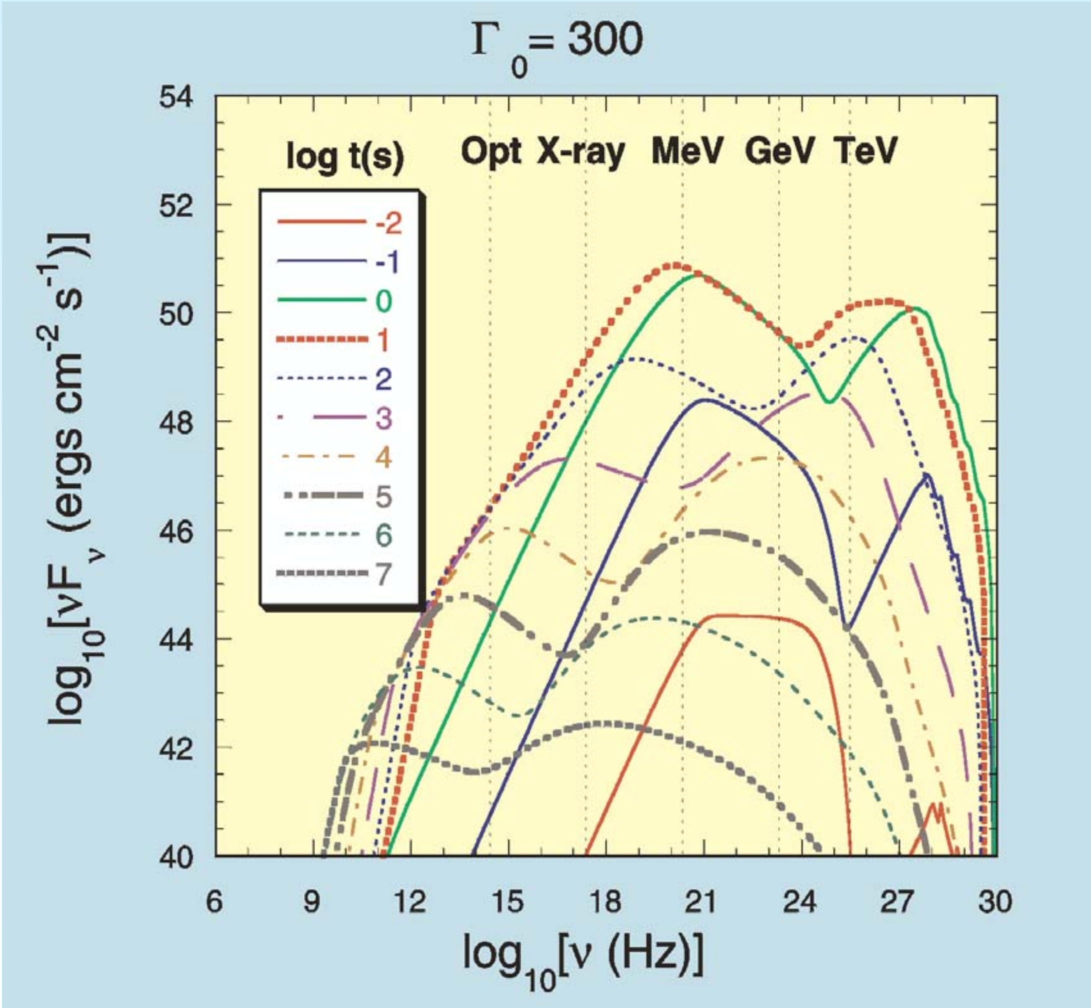


1. Near alignment at high energies; lag at lower energies
2. Predictable sequence of energy-dependent temporal indices in rising phase
3. Change in spectral indices between leading and trailing edges of GRB peak follow a well-defined behavior

Dermer, Böttcher, and Chiang (2000)



Numerical Simulation Model of GRB Radiation



- νF_ν spectra shown at observer times 10^i seconds after GRB event
- Primary radiation processes: nonthermal synchrotron and synchrotron self-Compton

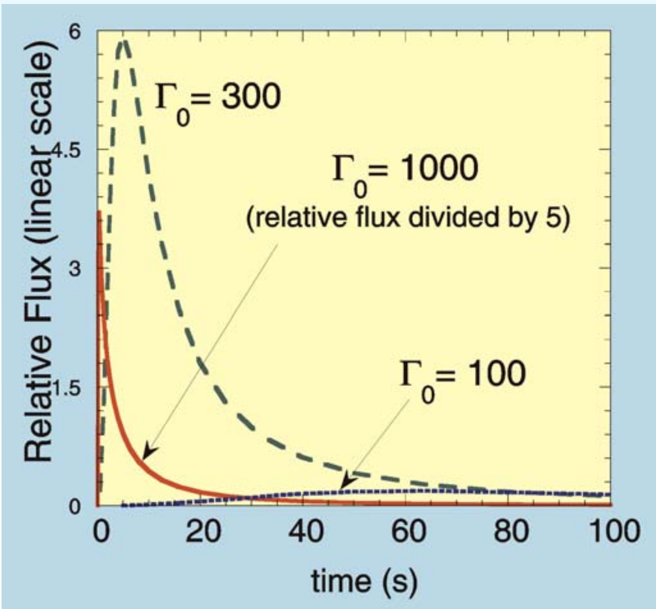
Dirty and Clean Fireballs: strong GeV/TeV sources

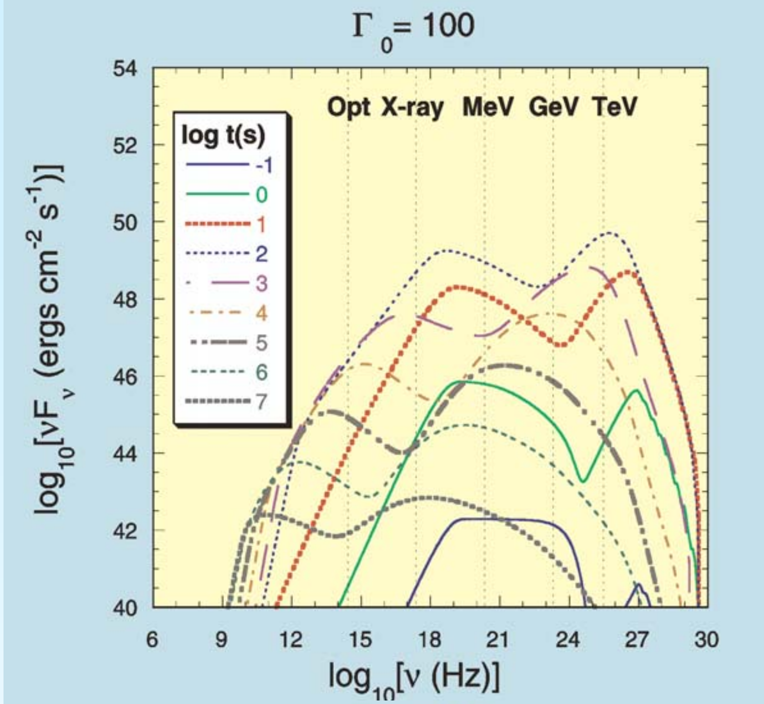
Observed properties most sensitive to initial Lorentz factor of outflow (or baryon loading)

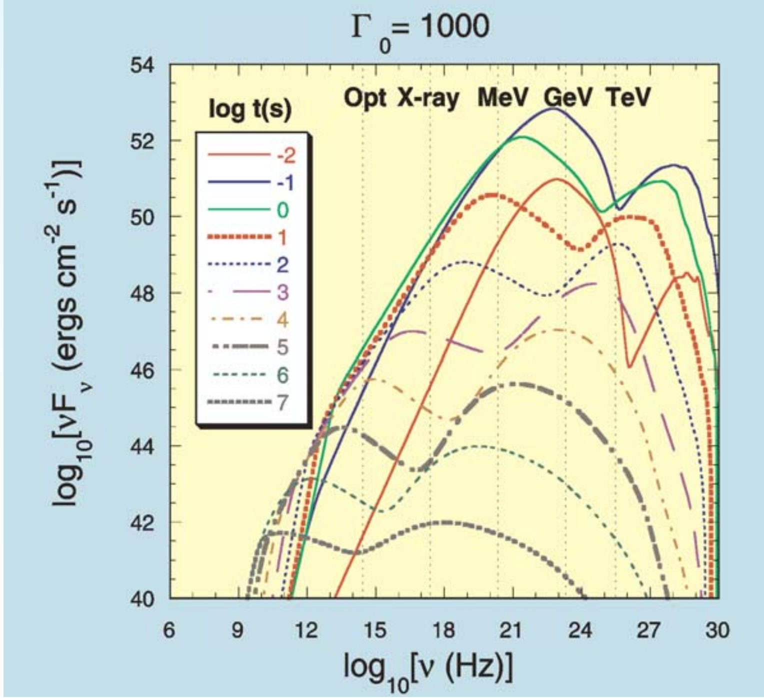
Severe instrumental selection biases against detecting fireballs with $\Gamma_0 \ll 100$ and $\Gamma_0 \gg 1000$

X-Ray Flashes (or X-ray rich GRBs) = Dirty Fireballs

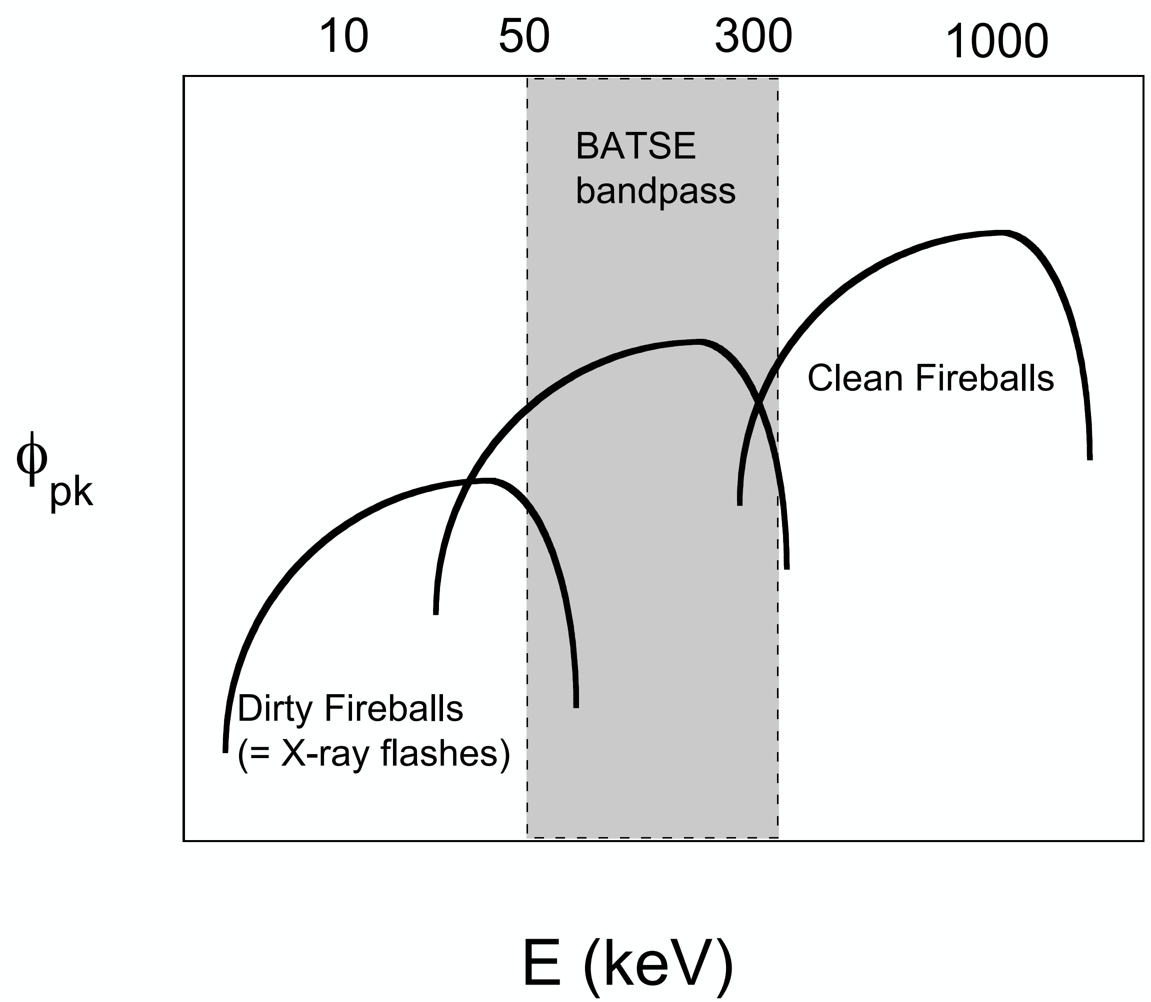
GeV Flashes = Clean Fireballs





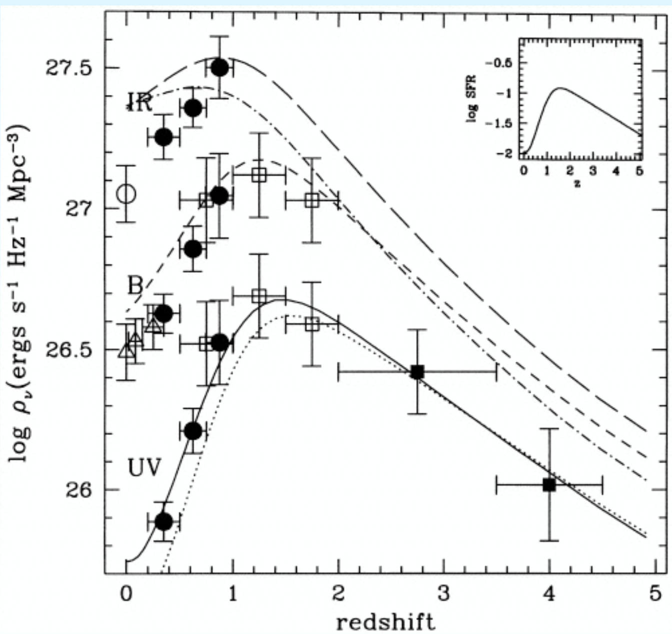


E_{pk} Distribution Explained

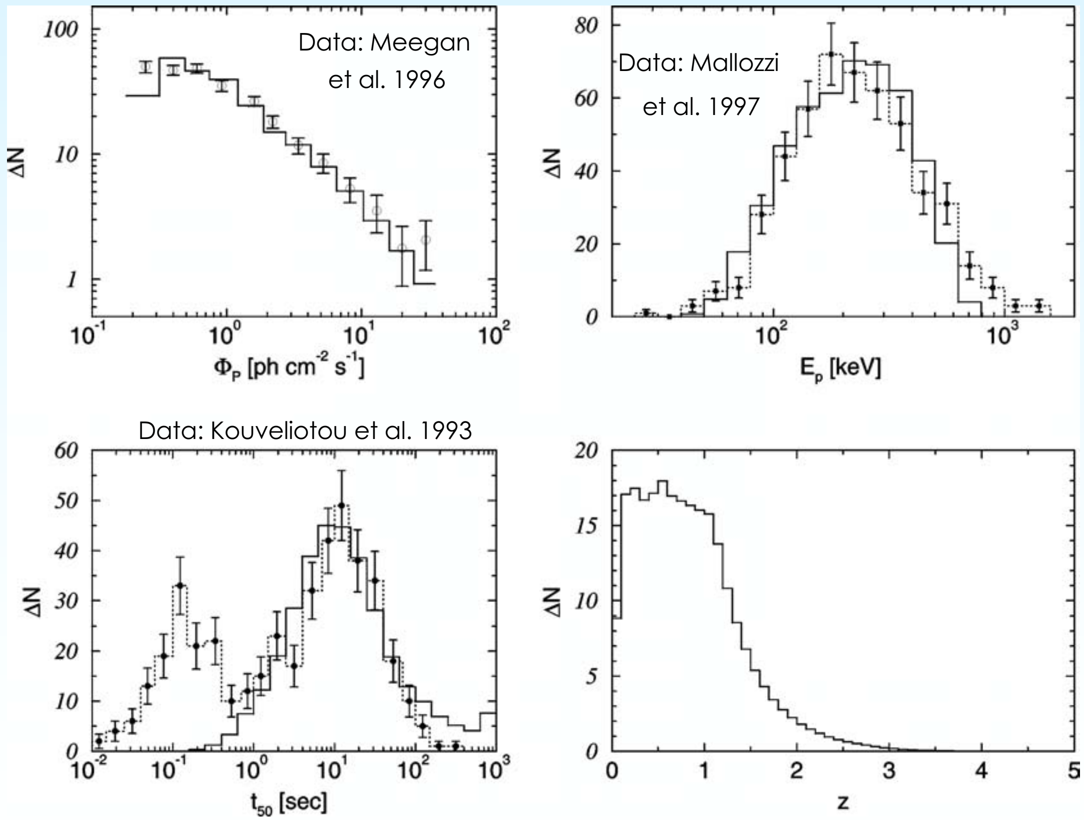


Cosmological Statistics of GRBs in the External Shock Model

- Assume that distribution of GRB progenitors follows star formation history of universe Trigger on 1024 ms timescale using BATSE trigger efficiencies (Fishman et al. 1994)
- Broad distributions of baryon-loading Γ_0 and directional energy releases are required. Assume power laws for these quantities.
  - $10^{-6} < E_{54} < 1$; $N(E_{54}) \propto E_{54}^{-1.52}$; $\Gamma_0 < 260$; $N(\Gamma_0) \propto \Gamma_0^{-0.25}$



(Madau et al. 1998)



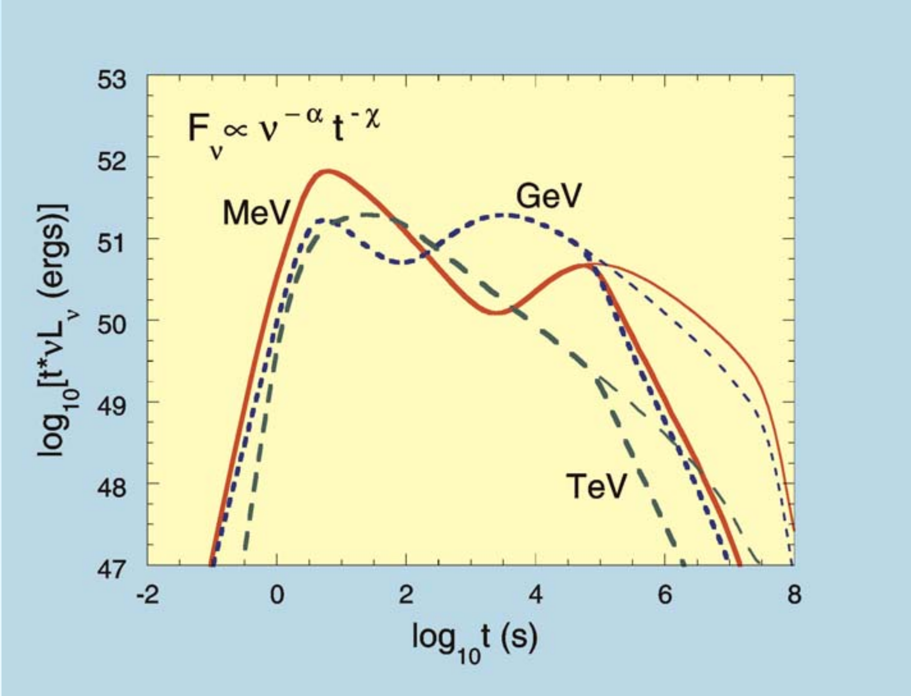
Unfortunately, rather few clean fireballs

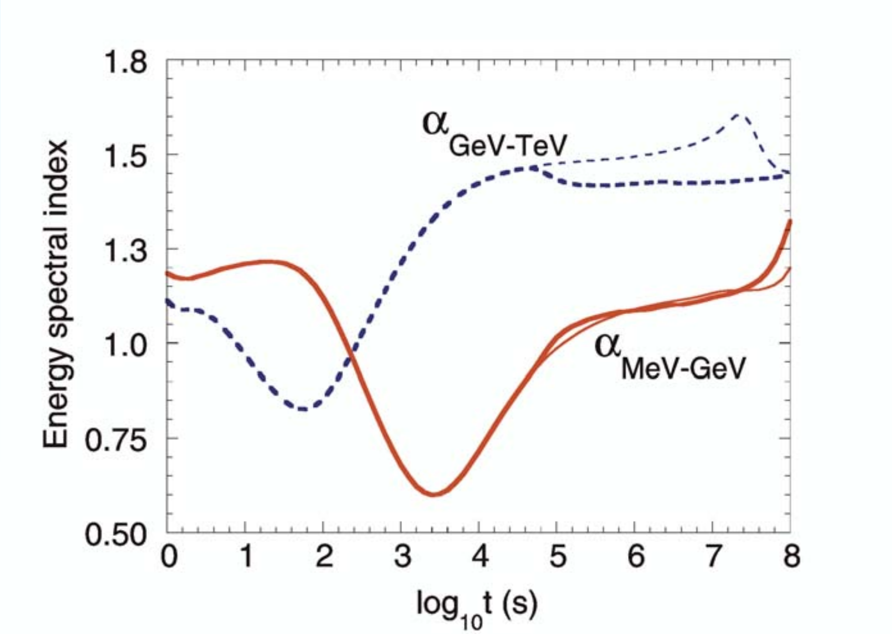
Böttcher & Dermer (ApJ, 2000, 529, 635)

Gamma Ray Light Curves

SSC component introduces a delayed hardening in **MeV** light curves several orders of magnitude below the flux of the prompt emission

Onset of SSC hardening at MeV energies occurs at $t \approx 10^3$ s, GeV energies at $t \approx 5000$ s





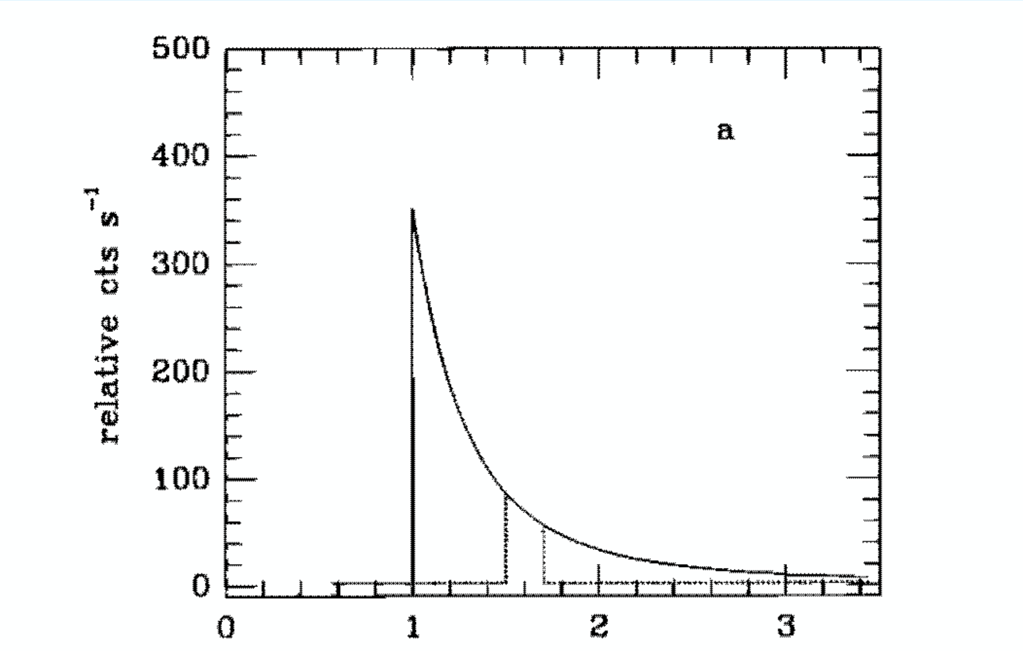
TeV component roughly coincident in time with prompt MeV radiation

Can obtain larger ratio of TeV to MeV nF_n flux for dirtier fireballs

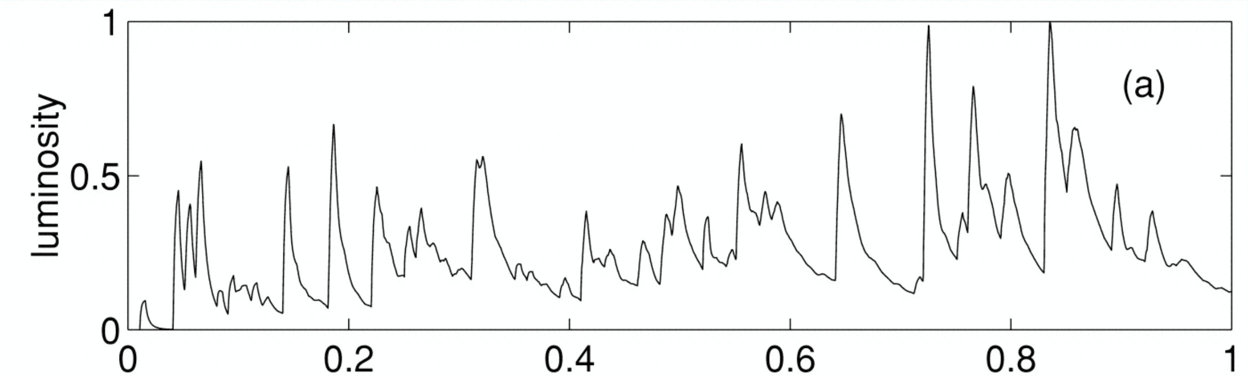
TeV emission also signature of UHECR acceleration

Internal or External Shock Model?

1. **Relativistic Wind: Large Variation of Lorentz Factors**
2. **Asymmetric profiles from kinematics**



Colliding Shells Produces Generic Pulse Profile (Fenimore et al. 1996)

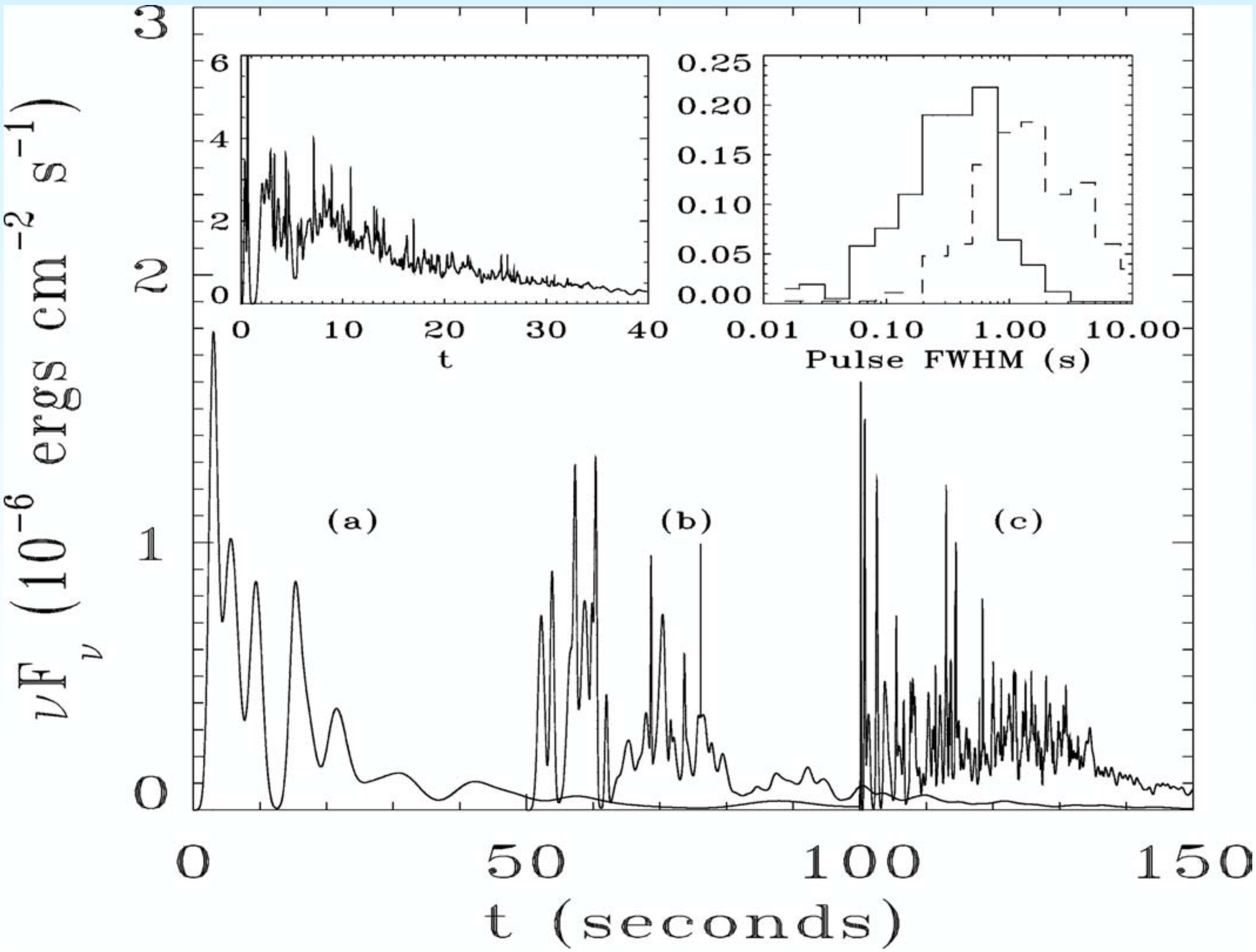


Synthetic Time Histories (Kobayashi and Sari 2001)

Short Timescale Variability due to inhomogeneities in surrounding medium

- Clouds with thick columns (>4×10^{18} cm^{-2})
  - Total cloud mass still small (>10^{-4} M_o)
- Varying cloud radii << R/Γ

Synthetic Time Histories (Dermer and Mitman 1999)

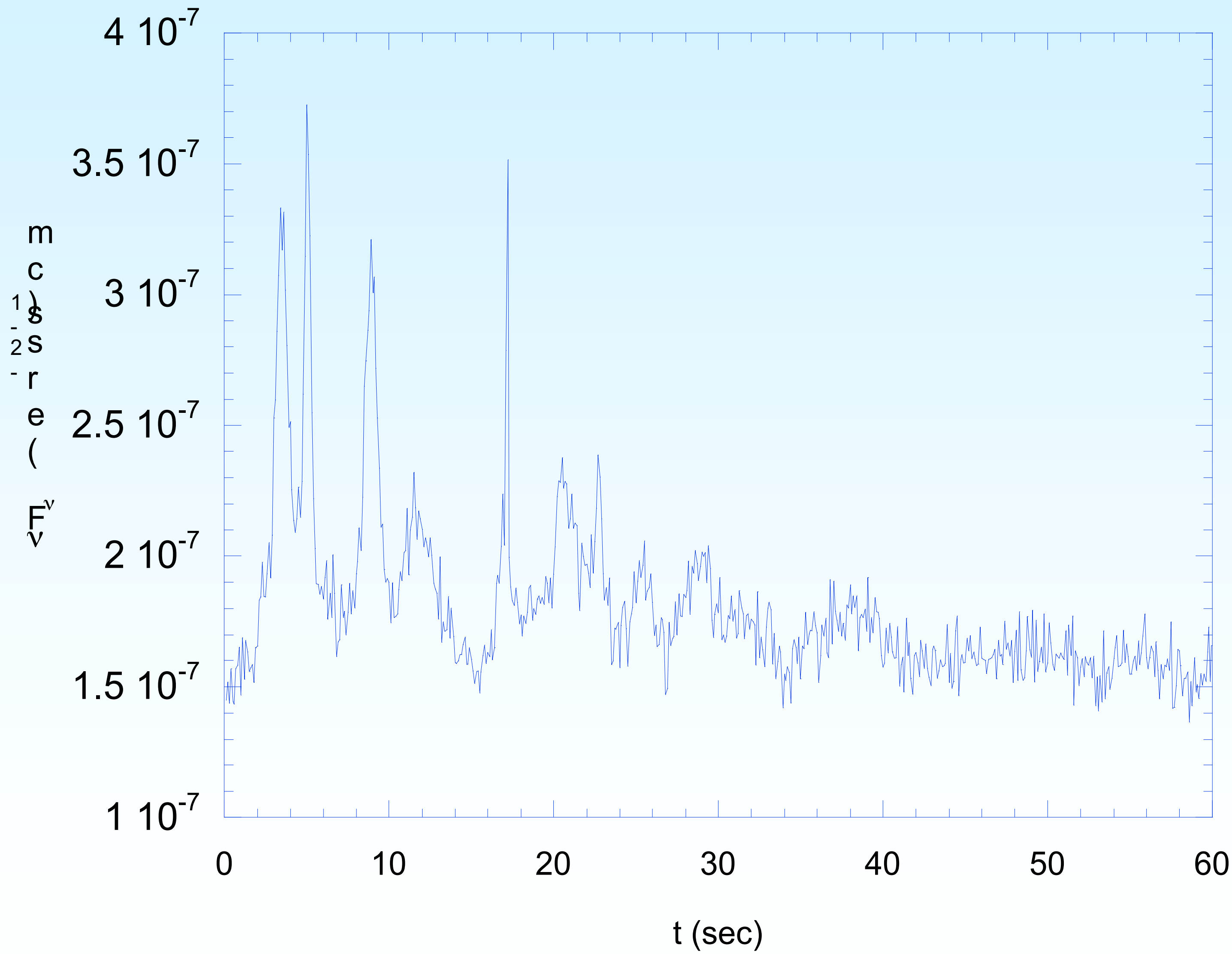


Cloud sizes ≈ 10^{12} – 10^{13} cm in agreement with inferences of absorption in GRB 990705

Standard Simulation

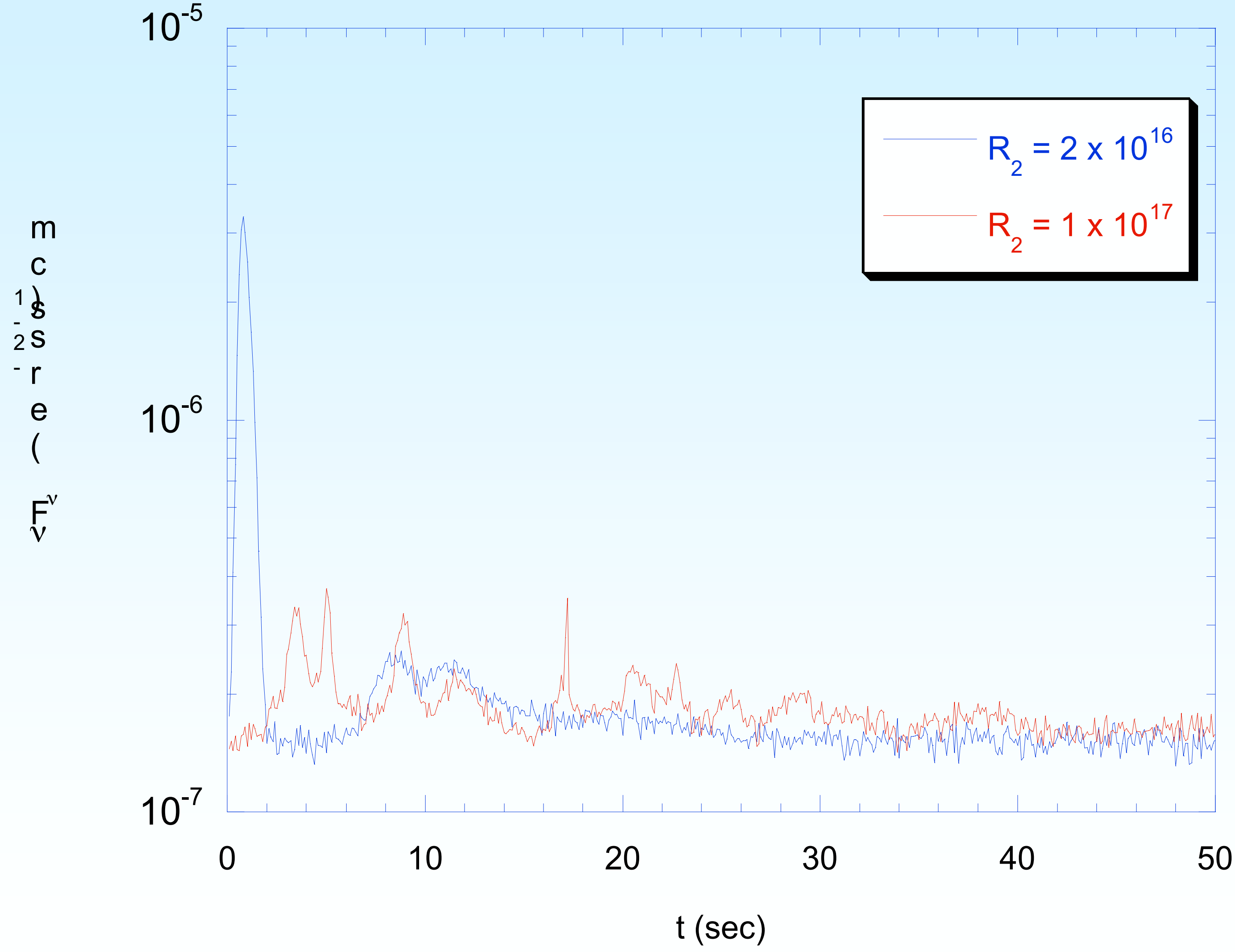
Uniform random distribution

Cloud radius is 10^{13} cm (all clouds equal)



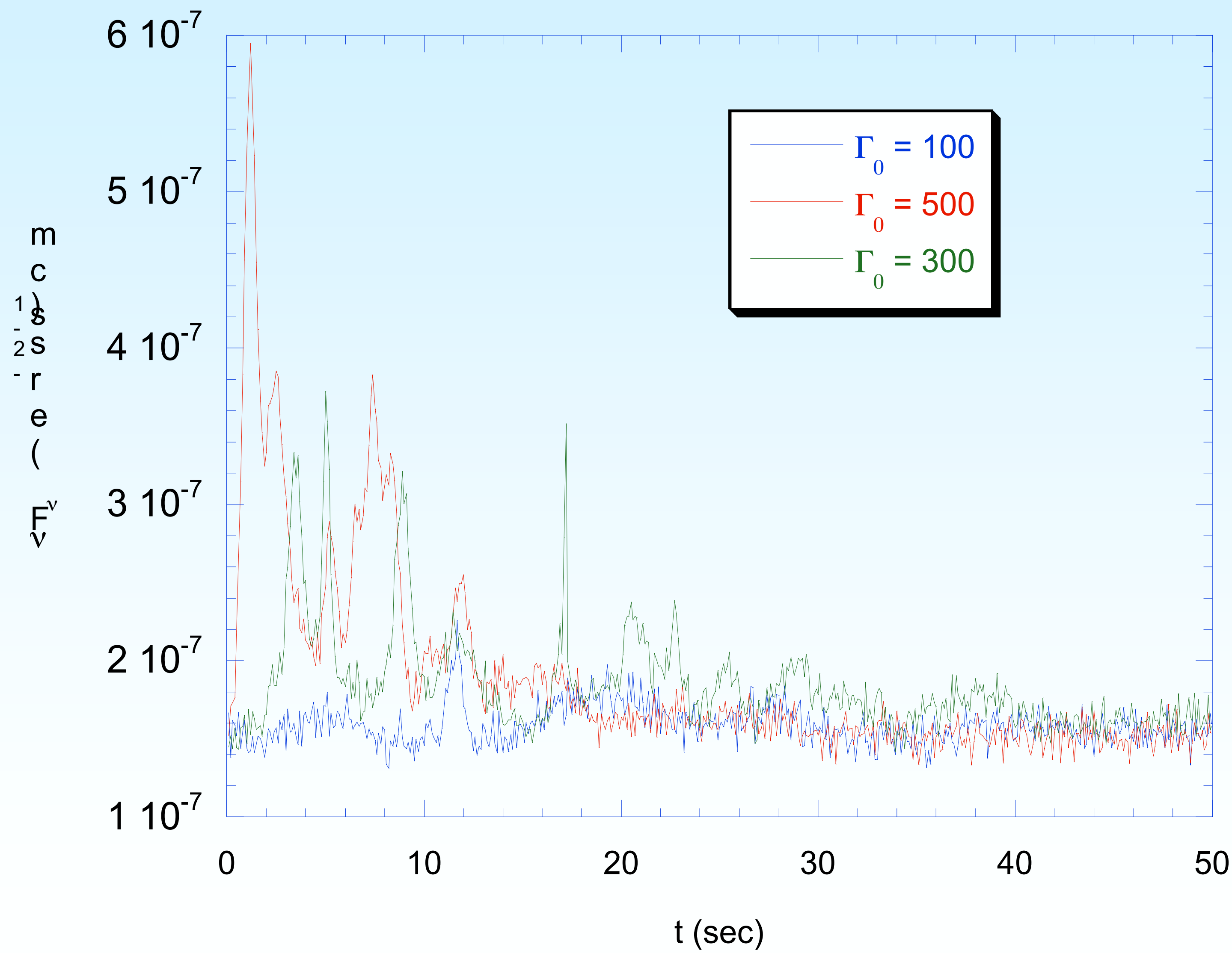
Variation in Shell Distance of Outer Edge of Shell

Same as previously but for log-linear



Variation in Γ_0

Background noise included

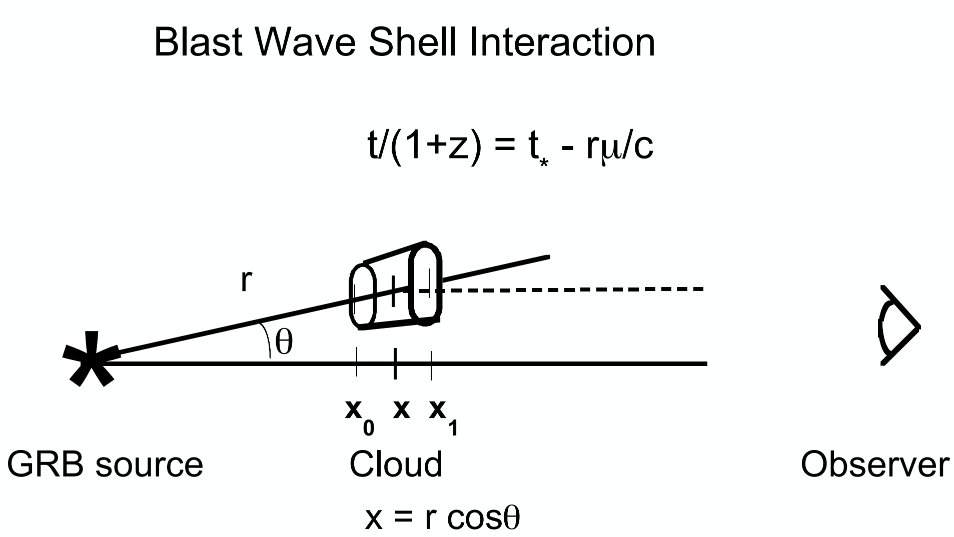


GeV Gamma Ray Emission from Secondary Nuclear Production

Secondary nuclear production in dense shell surrounding GRB: explanation for GRB 40217 (Katz 1994)

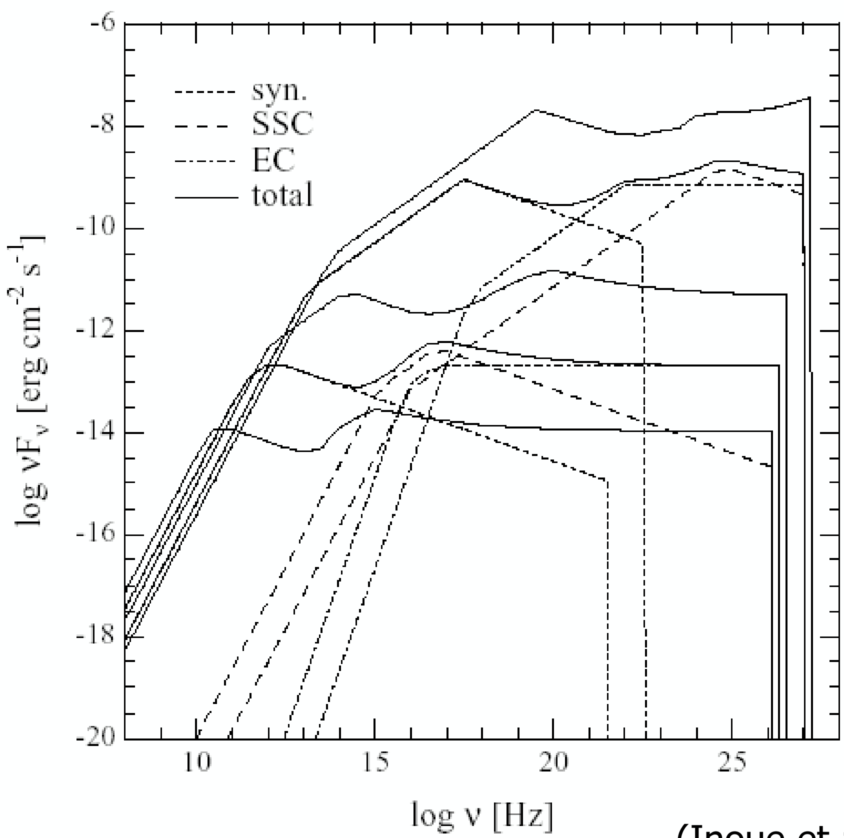
$p+p \rightarrow \pi^0 \rightarrow 2\gamma$

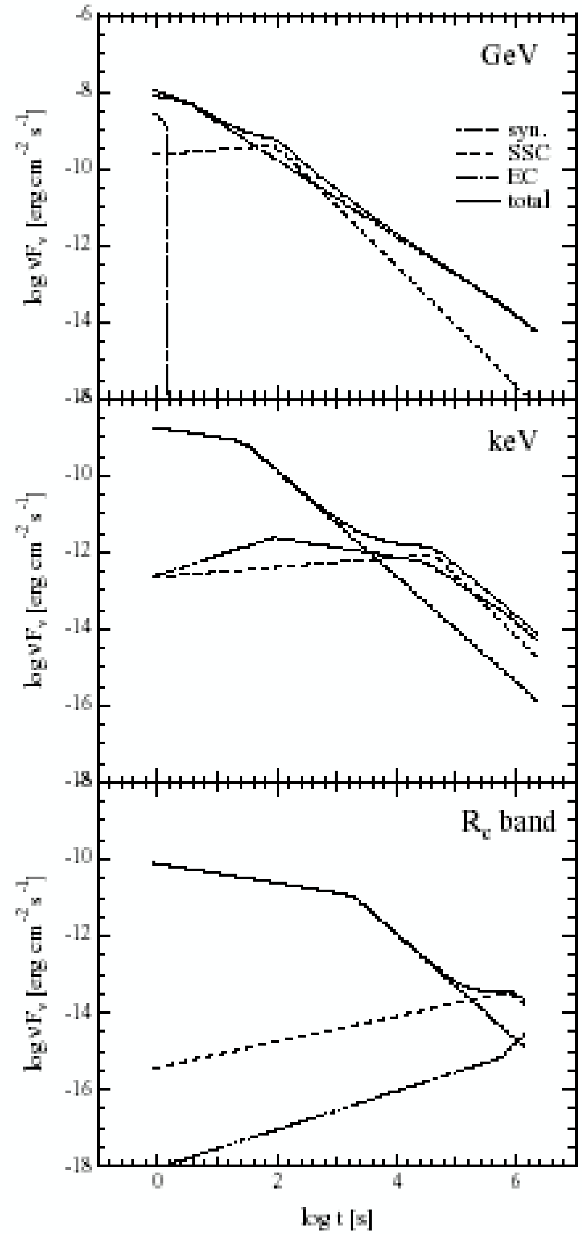
(no subsequent acceleration required)



External Compton Component

Requires strong background radiation field (as in blazars)





(Inoue et al. 2002)

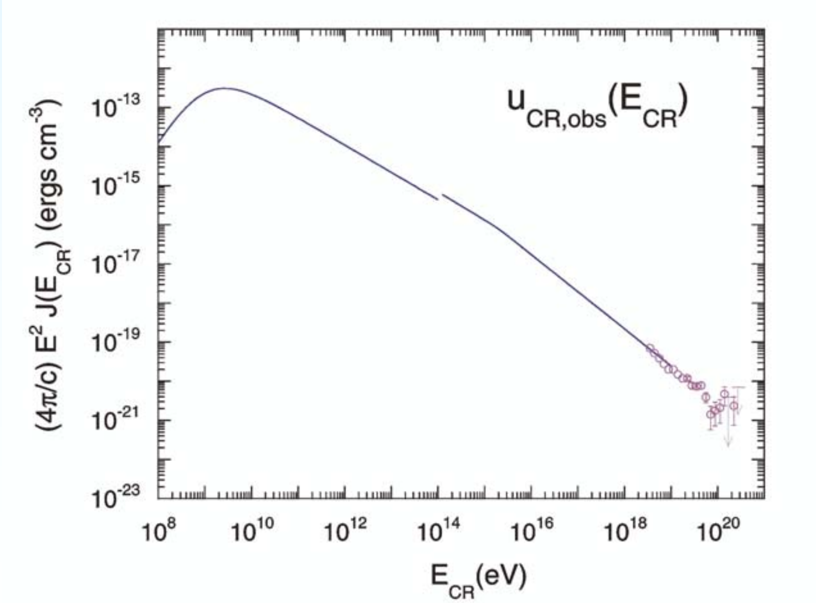
UHECRs from GRBs

Waxman (1995); Vietri (1995); Dermer (2002)

- Typical fluence and rate of BATSE GRBs:
  - $F_\gamma \approx 10^{-6}$ ergs cm^{-2} ; $\dot{N}_{GRB} \approx 1$/day
- If weakest GRBs at $z \sim 1$, then $d \cong 10^{28}$ cm
  - $E_\gamma \approx 4\pi d^2 F_\gamma \approx 10^{51}$ ergs; $E_{GRB} \approx 10^{52}$ ergs
- UHECRs lose energy due to photomeson processes with CMB
  - $p + \gamma \rightarrow p + \pi^0$, $n + \pi^+$
  - GZK Radius $x_{1/2}(10^{20}$ eV$) \cong$ 140 Mpc

Stanev et al. (2000)

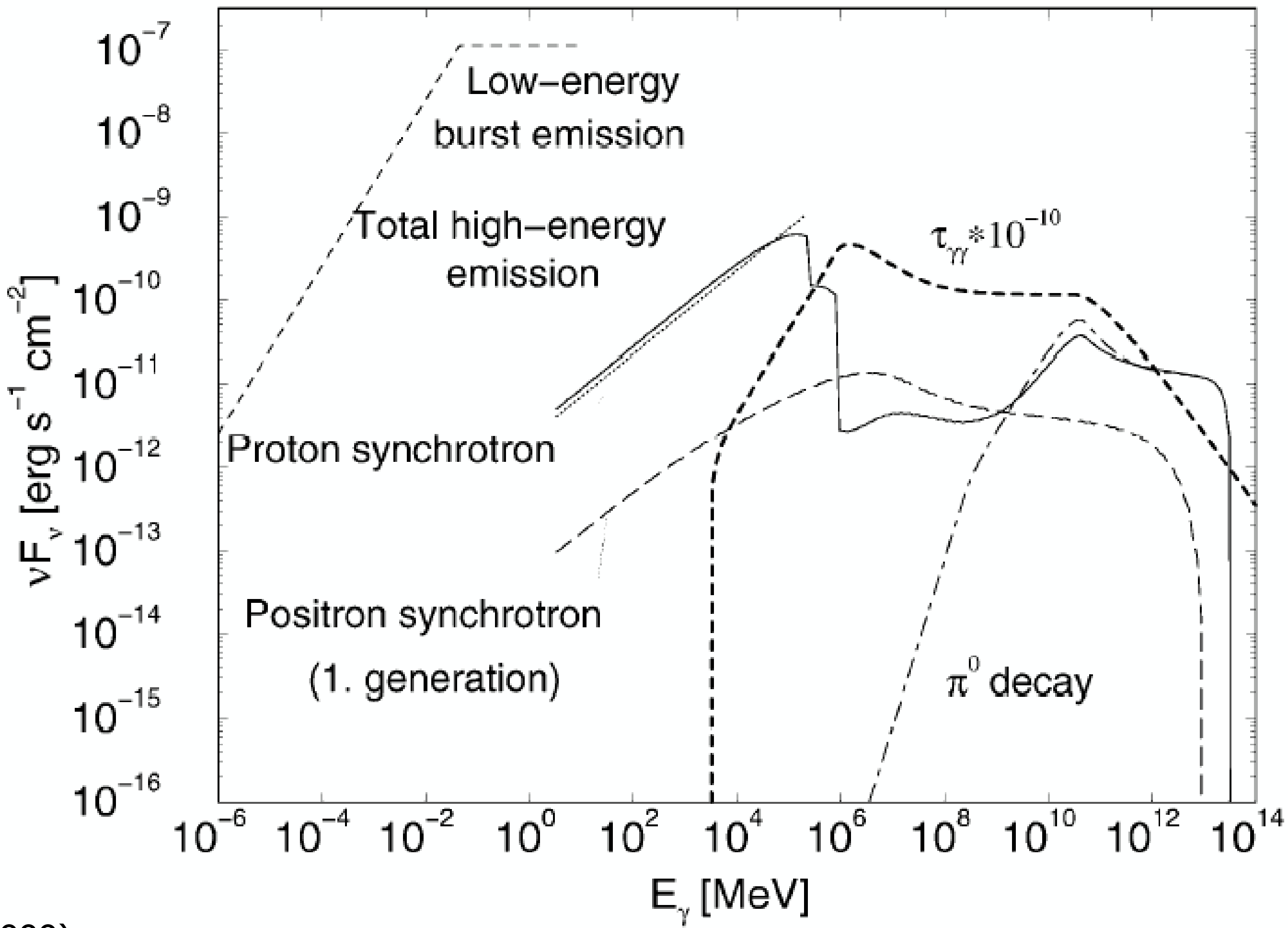
- Energy density within GZK Radius:
  - $$u_{UHECR} \cong \zeta\, \varepsilon_{GRB}\,(x_{1/2}/c) \cong \frac{\zeta\, E_{GRB}\ (140\ \text{Mpc}/c)}{\text{day}\times(4\pi/3)(10^{28}\text{cm})^3} \cong \zeta\, 5\times10^{-22}\ \text{ergs/cm}^3$$



Energetic Hadron Component in GRB Blast Waves

Requires proton acceleration to high energies

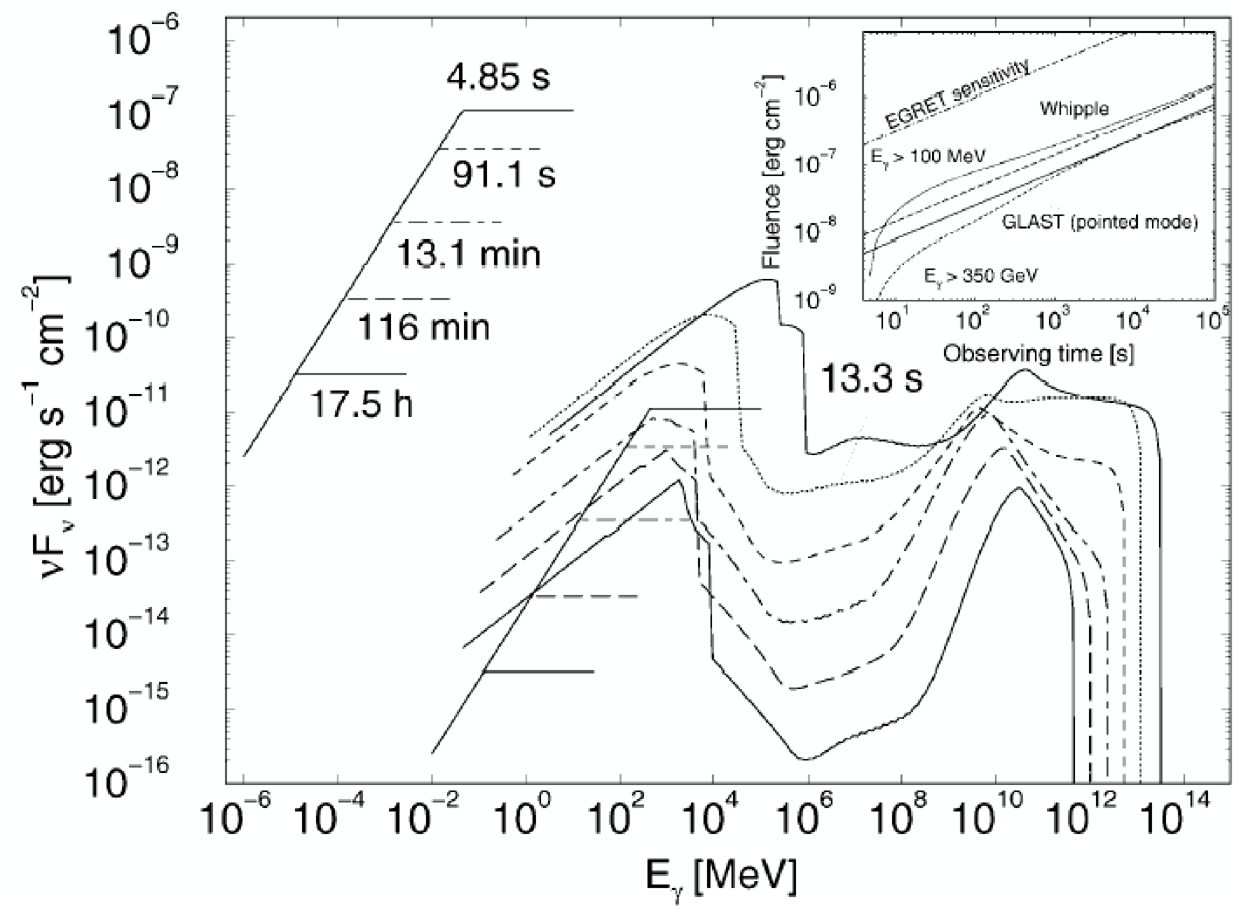
Proton synchrotron component observed with GLAST



(Böttcher and Dermer 1999)

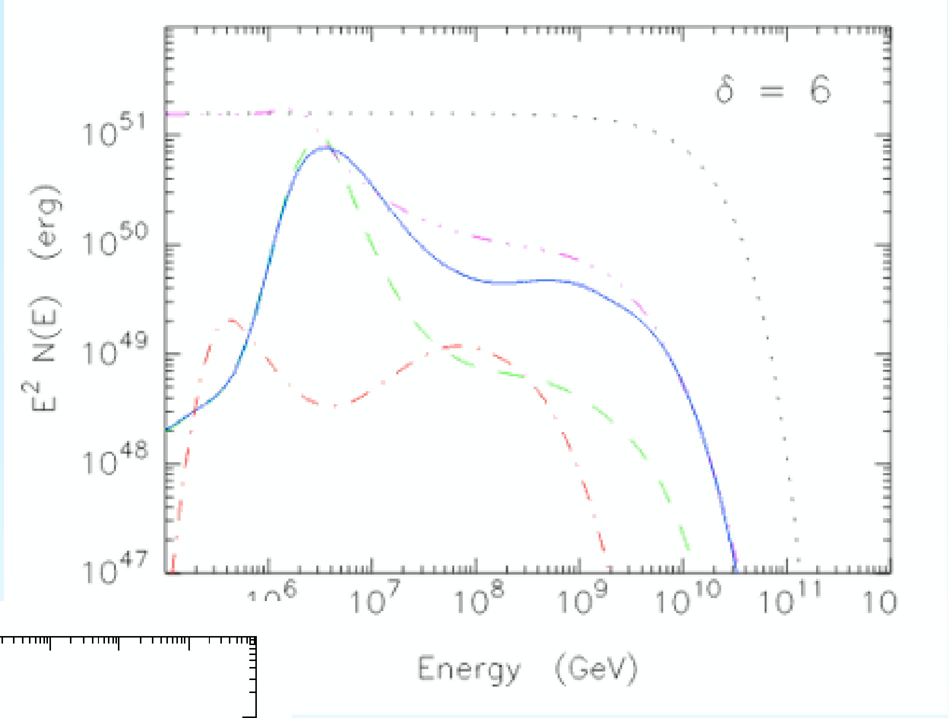
Proton Synchrotron Emission

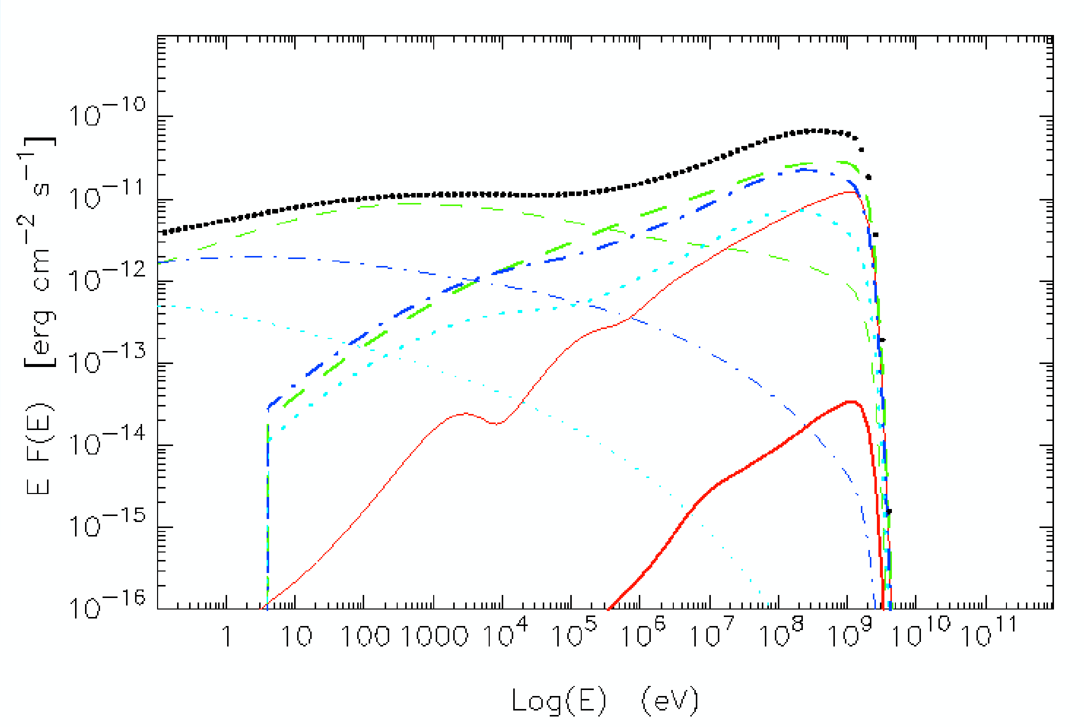
Slow decay of proton emission



Photomeson Production

Intense neutrino, neutron, and ultra-high energy gamma-ray production





Atoyan and Dermer (2002) for blazars

Synchrotron and Compton Neutron-Decay Halos

- Neutrons formed through photomeson processes during cosmic ray acceleration escape from blast wave $n \to p + e^- + \nu_e$
- Decay of neutrons occurs at $\gamma \approx \gamma_n$
  - Produce nonthermal synchrotron radiation, depending on strength of halo magnetic field
  - Produce nonthermal γ rays from Compton scattering of CMB
    - γ rays materialize through $\gamma\gamma \to e^+e^-$
    - form extended pair and gamma-ray halo

Summary

• **MeV Gamma Ray Observations**

Well explained as nonthermal synchrotron radiation in relativistic fireball/blast wave model. GRB prompt and afterglow phenomenology explained by a single relativistic blast wave interacting with external medium

• **Source Model:** **External Shock/Supranova Model**

• **High Energy γ-Radiation**

SSC (definite predictions for FRED/smooth GRBs)

Other components:

- **Secondary Nuclear Production**
- **Proton synchrotron (slow decay)**
- **External Compton**
- **Photo-hadron (neutron-decay halos; neutrinos)**