High Energy Radiation from GRBs

KITP, February 9, 2006

High Energy Radiation from GRBs

2006

Swift Impact

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Recipe for GRB emissions

E_0/n_0	10^{52} ergs-cm^3
Γ_0	300
Δ_0	$<< 3\text{x}10^{10}$ cm
ε_e	1/3
ε_B	$>10^{-4}$ $(10^{-4},10^{-2})$
p	2.3
ε_{max}	0.1
θ_{jet}	0.1

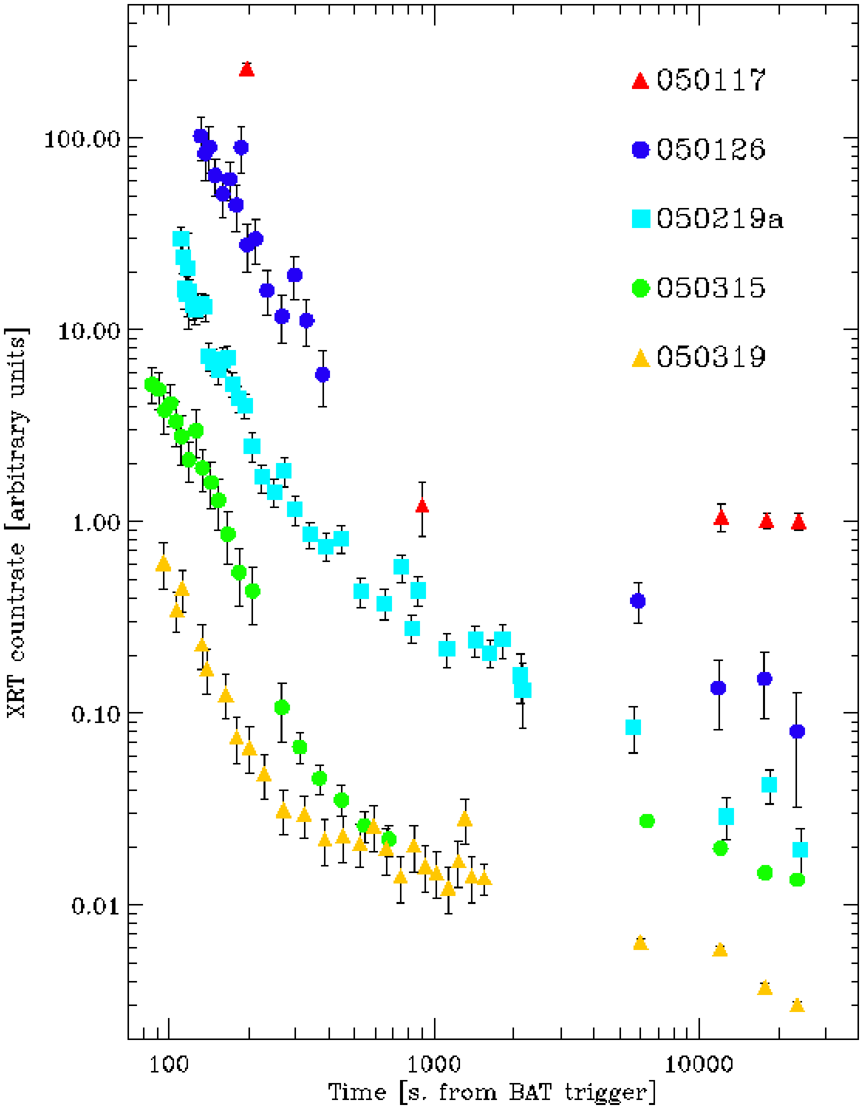
Prompt γ-ray pulses:

n_{cl}	10^6 cm^{-3}
x_0	10^{15} cm
x_1	$1.02\text{x}10^{15}$ cm

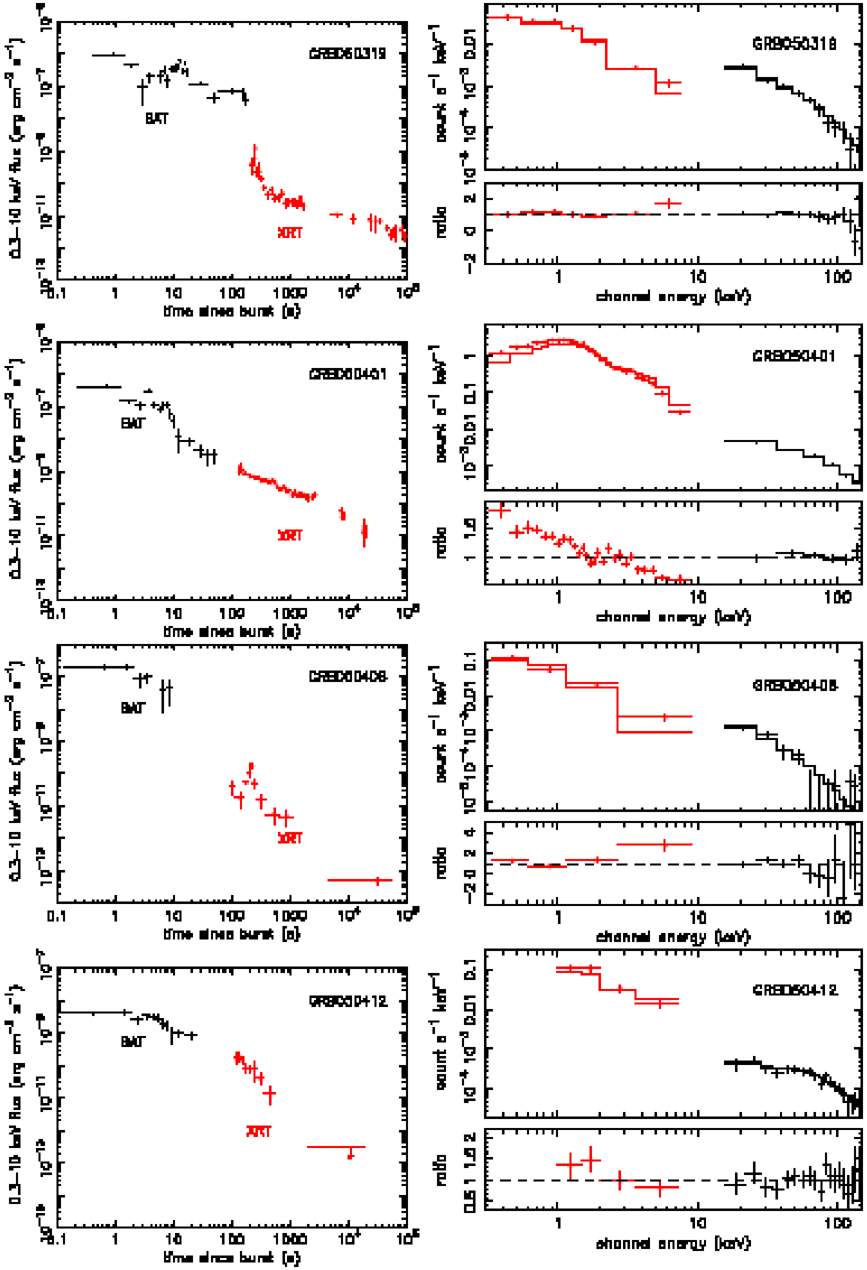
X-ray flares:

n_{cl}	10^2 cm^{-3}
x_0	10^{17} cm
x_1	$1.02\text{x}10^{17}$ cm

Swift Observations of Rapid X-Ray Temporal Decay

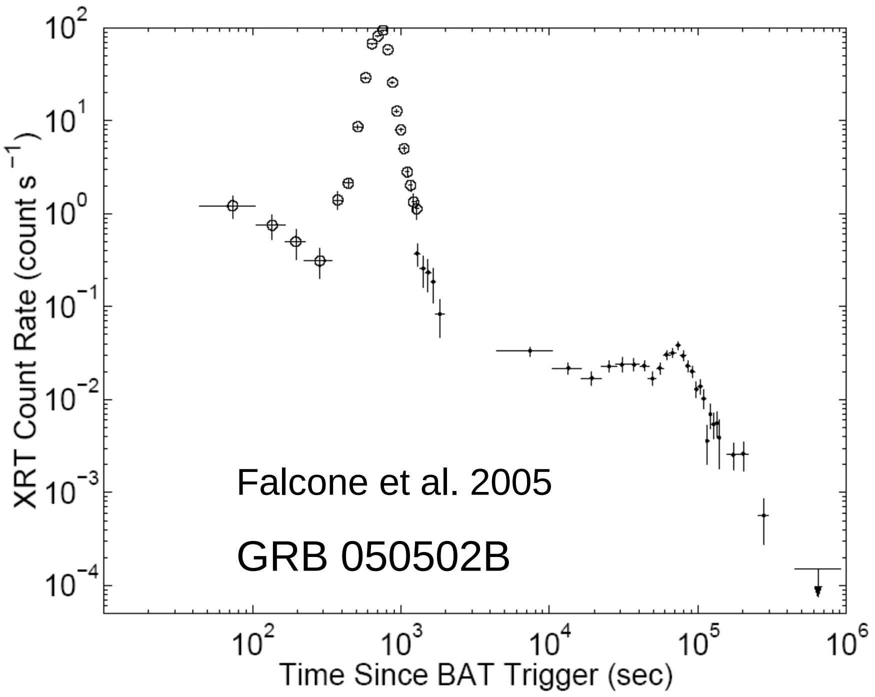


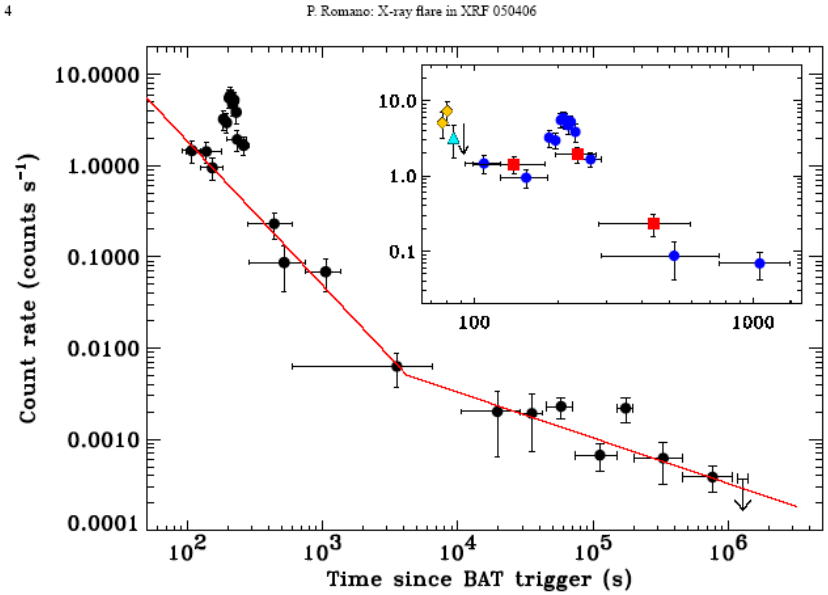
Tagliaferri et al. 2005



O’Brien et al. 2005

Swift Observations of X-Ray Flares and Light-Curve Structure

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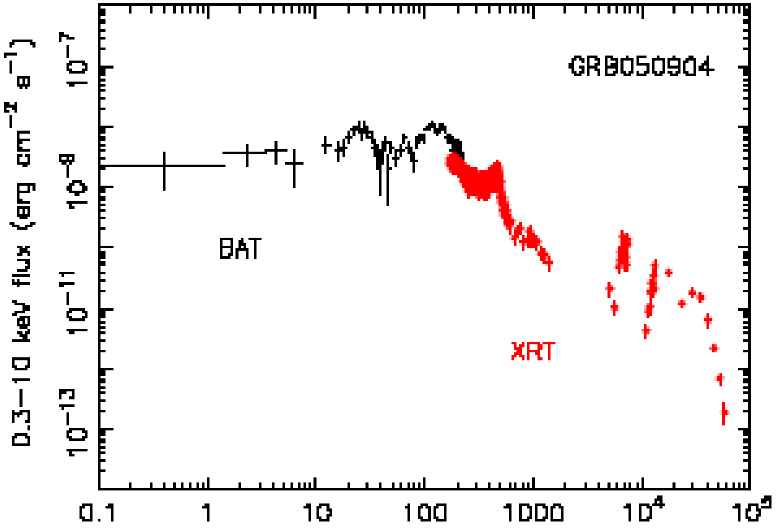
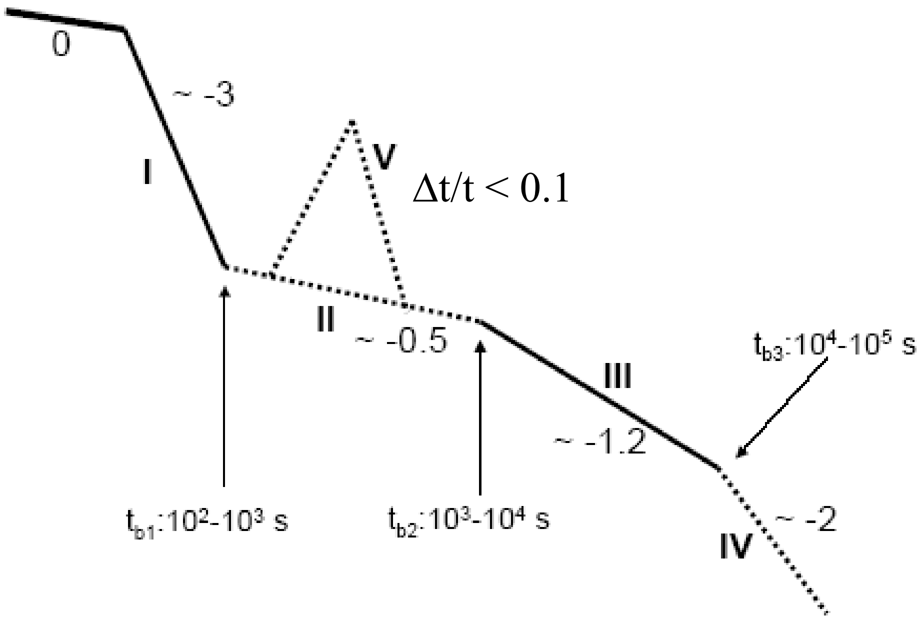
P. Romano: X-ray flare in XRF 050406



Generic GRB X-ray Behavior

$$\boxed{\nu F_\nu = f_\varepsilon(t) \propto \varepsilon^a t^\chi}$$



Zhang et al. 2005

$$F_\nu \propto \nu^{-\alpha}$$

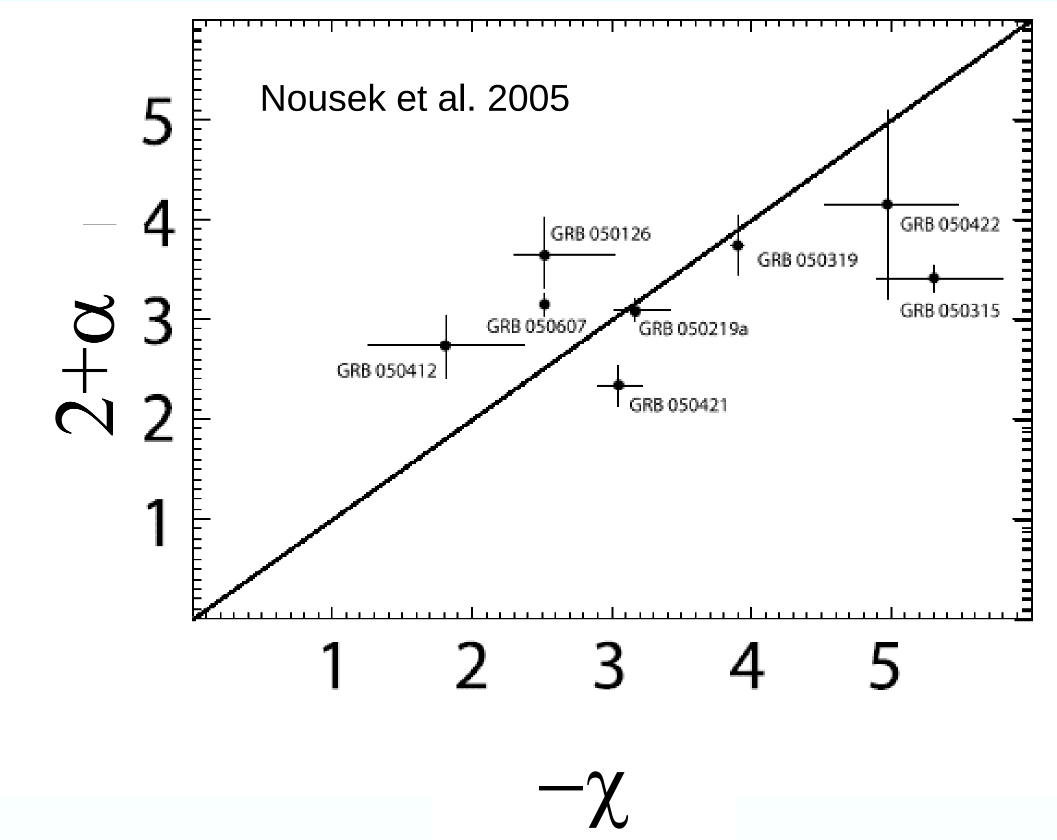
$$\varepsilon = \frac{h\nu}{m_e c^2}$$

$$a = 1 - \alpha$$

Curvature "High-Latitude" Effect

$$f_{\varepsilon}(t) \propto \varepsilon^{1-\alpha} t^{-2-\alpha} \propto \varepsilon^{a} t^{-3+a}$$

Kumar and Panaitescu (2000), Dermer (2004)



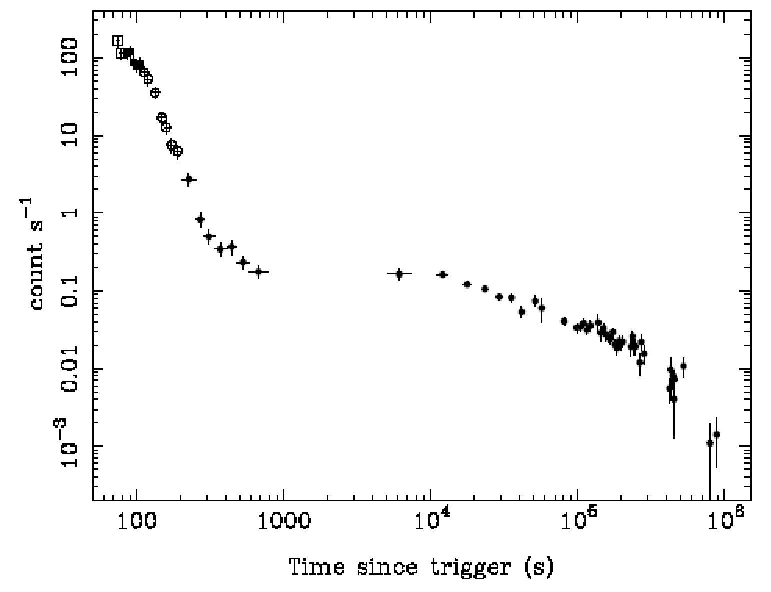


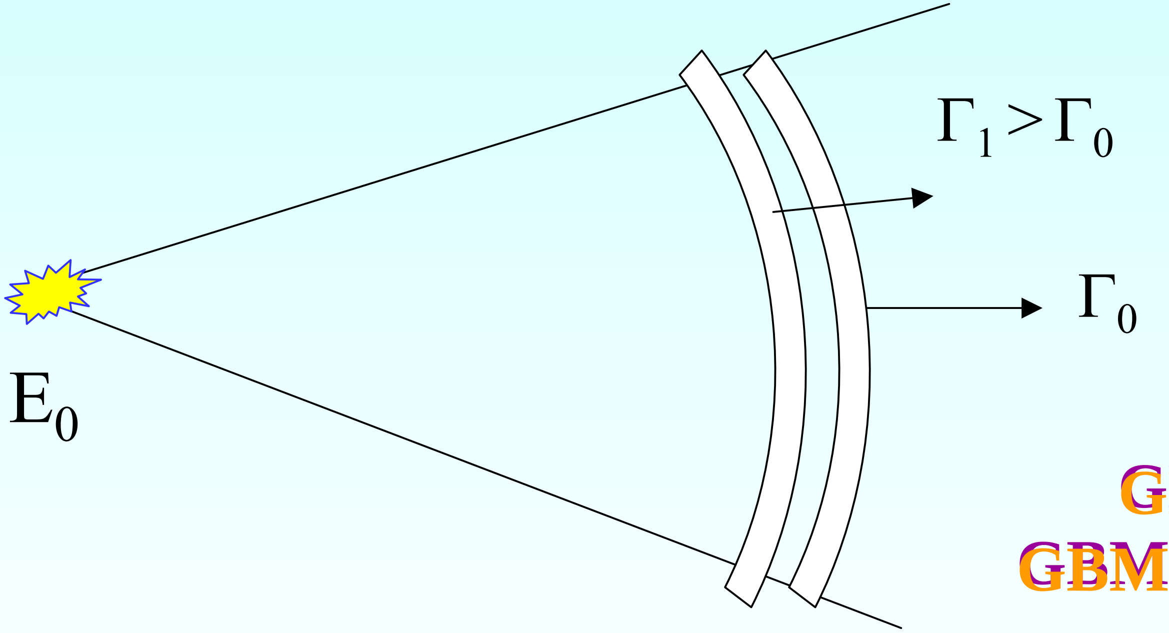
FIG. 5.— Light curve of GRB 050315 in the 0.2 − 5 keV band. These data

Vaughan et al. 2005

$$\chi = -3+a = -2-\alpha$$

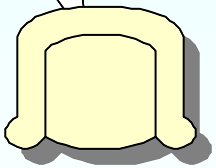
How to turn emission off?

Curvature “High-Latitude” Effect with Colliding shells



Corollary:

$$f_{\varepsilon_{pk}} \propto \varepsilon_{pk}^{\;3}$$



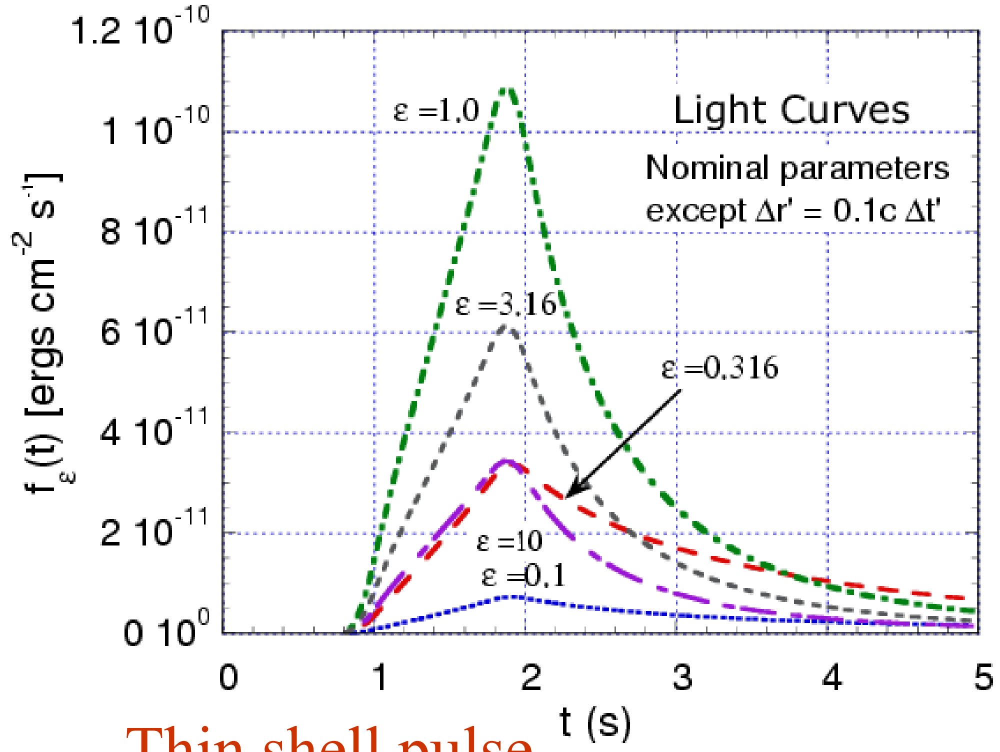
GLAST
GBM and LAT
!!

Condition of local spherical symmetry within θ~ 1/Γ

Fenimore et al. (1996)

Decaying spectral flash: a model-independent study

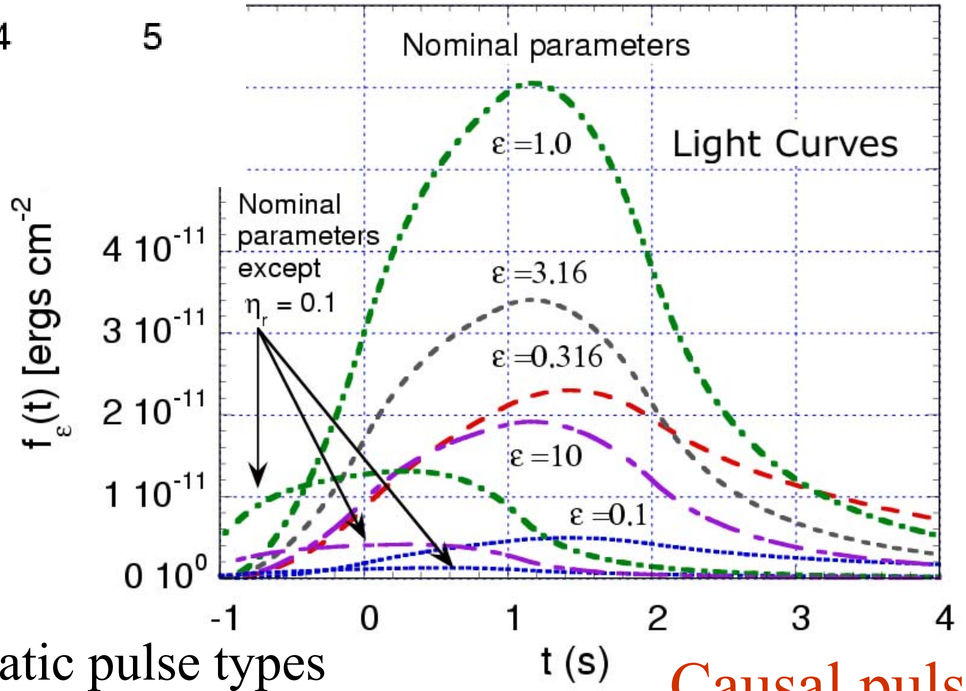
Kinematic Pulses: What do they really look like?



Thin shell pulse

Pulse paradigm

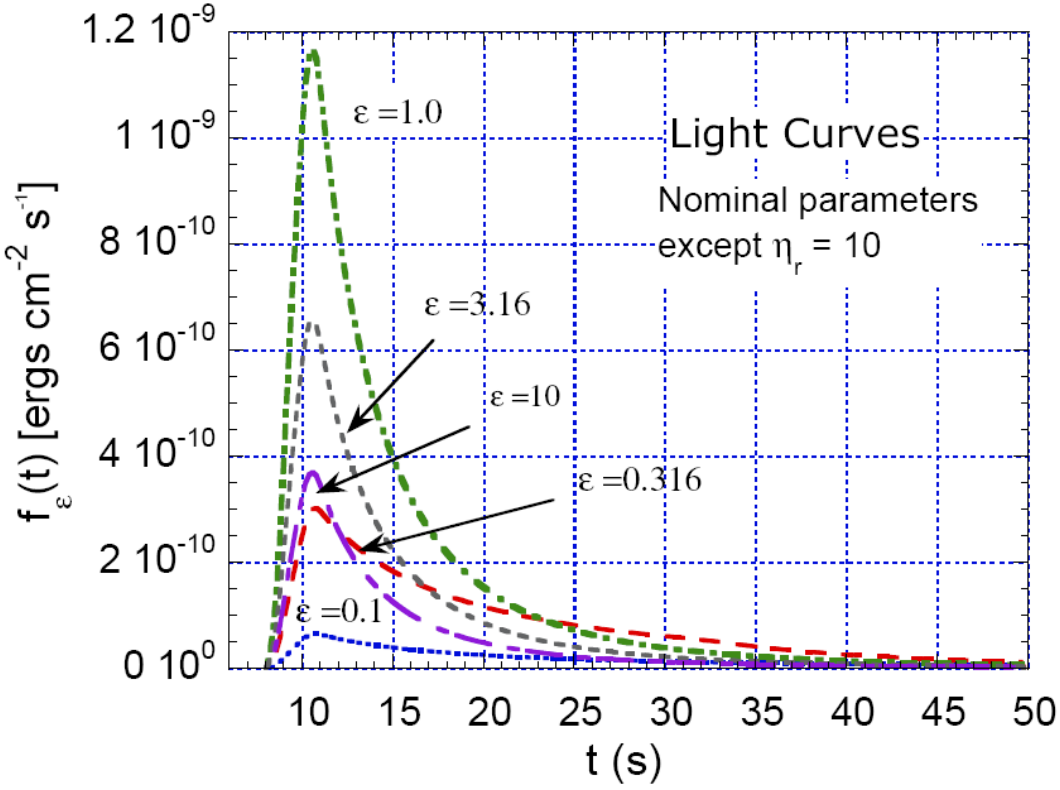
- Width
- Duration
- Location



Dermer (2004) Classification of kinematic pulse types

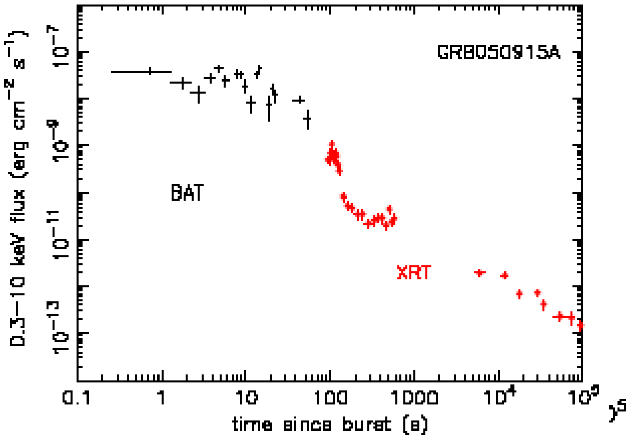
Causal pulse

Curvature Pulse



Relate minimum variability timescale t_{var} with x, Γ, z

$$t_{\rm var} \geq 0.26 \frac{x(1+z)}{\Gamma_0^2 c}$$

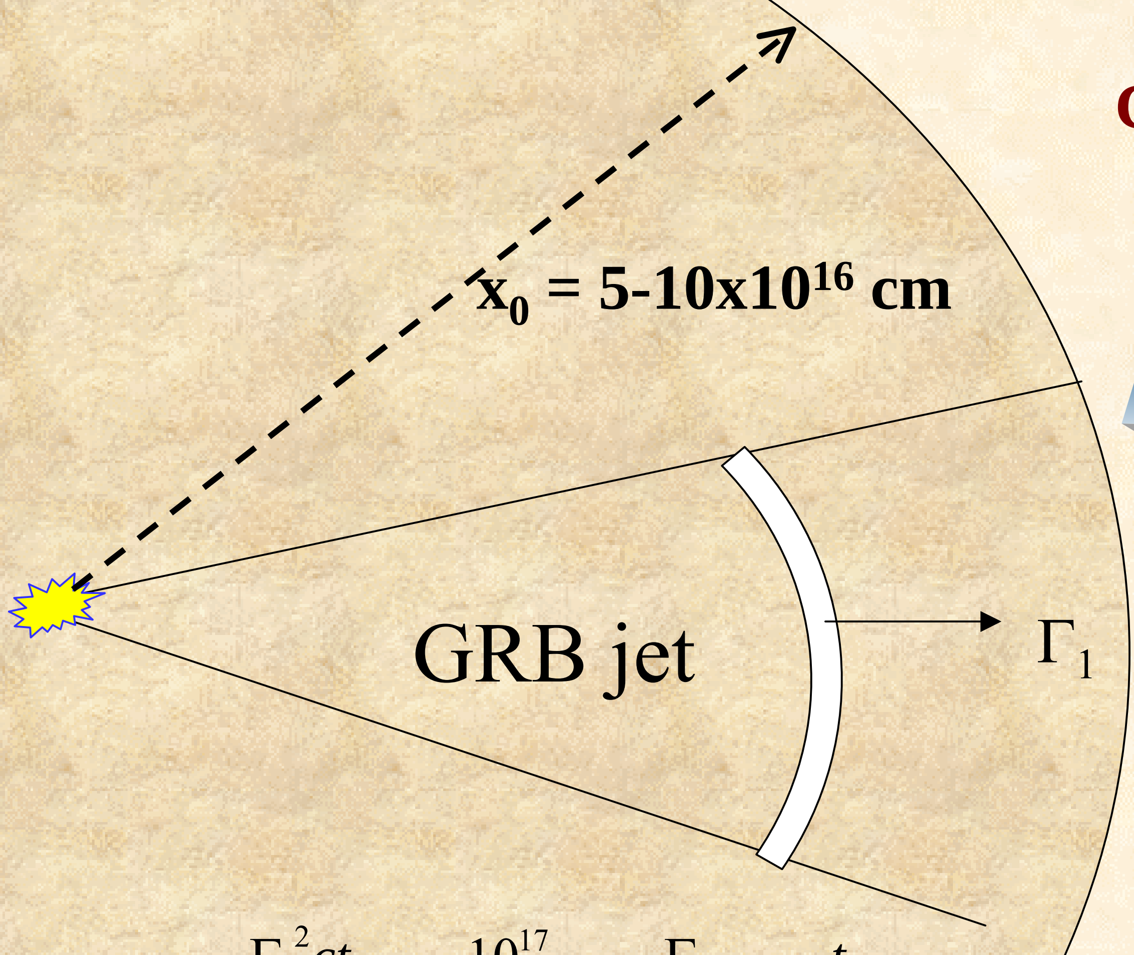


Rising phase of light curve always shorter than declining phase

Conclusions: Colliding Shells are

1. Candidate X-ray flare mechanism, but
2. Inconsistent with Swift Observations of rapid X-ray decays

Curvature "High-Latitude" Effect with External Shocks



x_0 = 5-10x10^{16} cm

$$x \approx \frac{\Gamma_0^{\,2} ct}{1+z} \approx \frac{10^{17}}{(1+z)/2}\left(\frac{\Gamma_0}{300}\right)^2 \frac{t}{100\ s}\ cm$$

$n_0 = 100\ \mathrm{cm}^{-3}$

$n_0 = 1\ \mathrm{cm}^{-3}$

Density (or ε_B) jump turns GRB emissions off (gives curvature relation)

Jetted flow
with $\psi \sim 1^o$

System Evolution

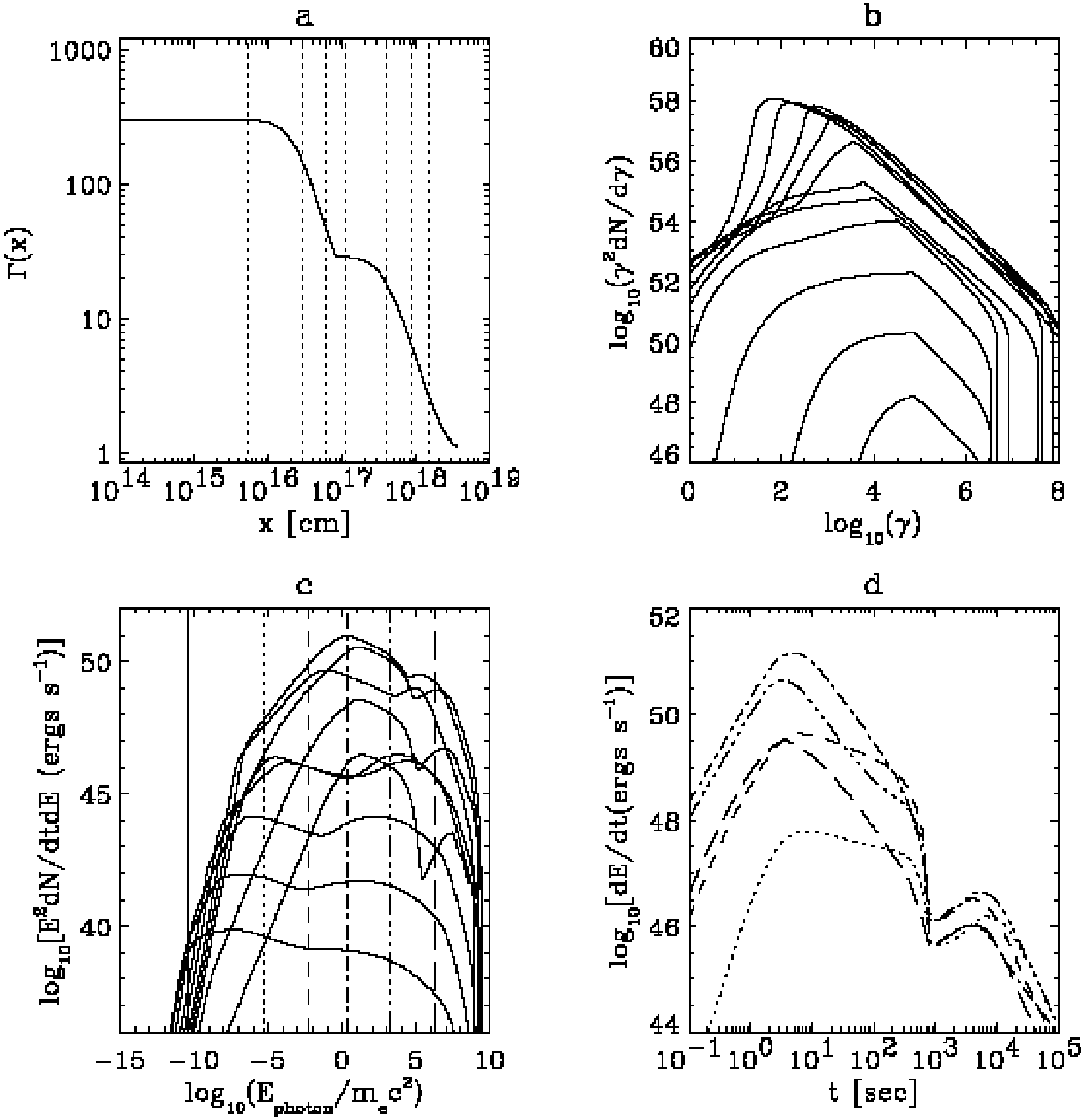
Jim Chiang's code
Chiang and Dermer (1998)

Full treatment of Forward Shock Physics, (special) relativity, dynamical evolution of blast wave, synchrotron, SSC, and adiabatic losses on electrons (injected as a power law)

Gives evolving Nonthermal synchrotron and SSC spectrum

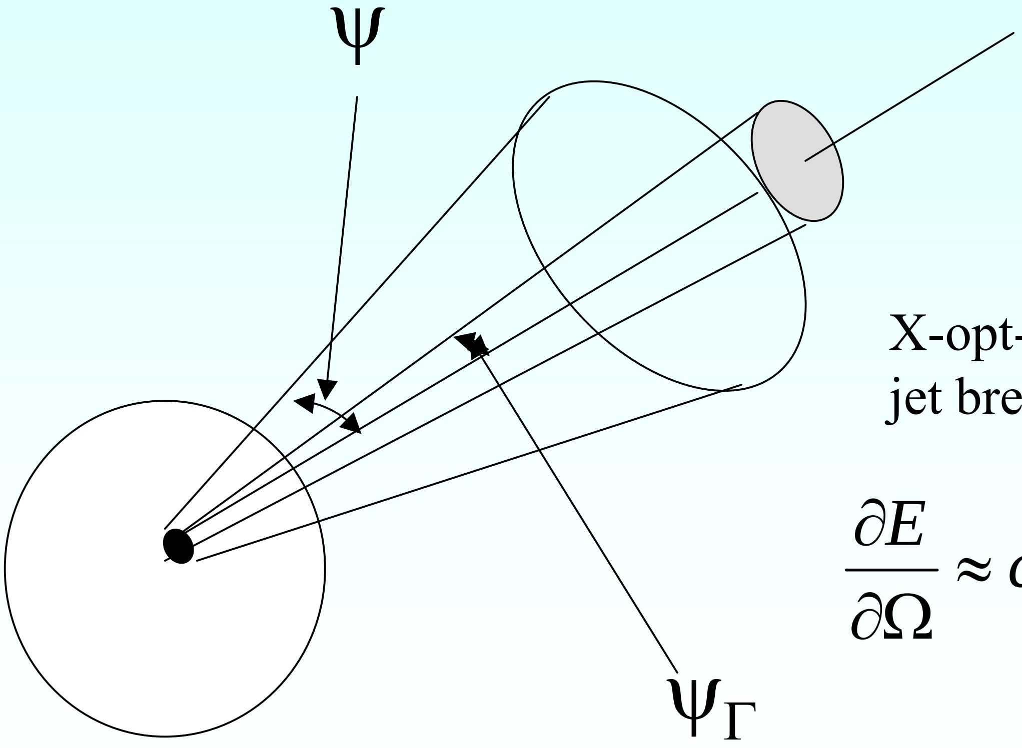
Hi-B

$\varepsilon_B = 10^{-2}$



GRB Blast Wave Geometry in accord with Swift observations

Structured Jet



Gamma jet: makes GRB

X-opt-rad jet: makes afterglow, jet break

$$\frac{\partial E}{\partial \Omega} \approx const \ \ for\ \theta < \psi$$

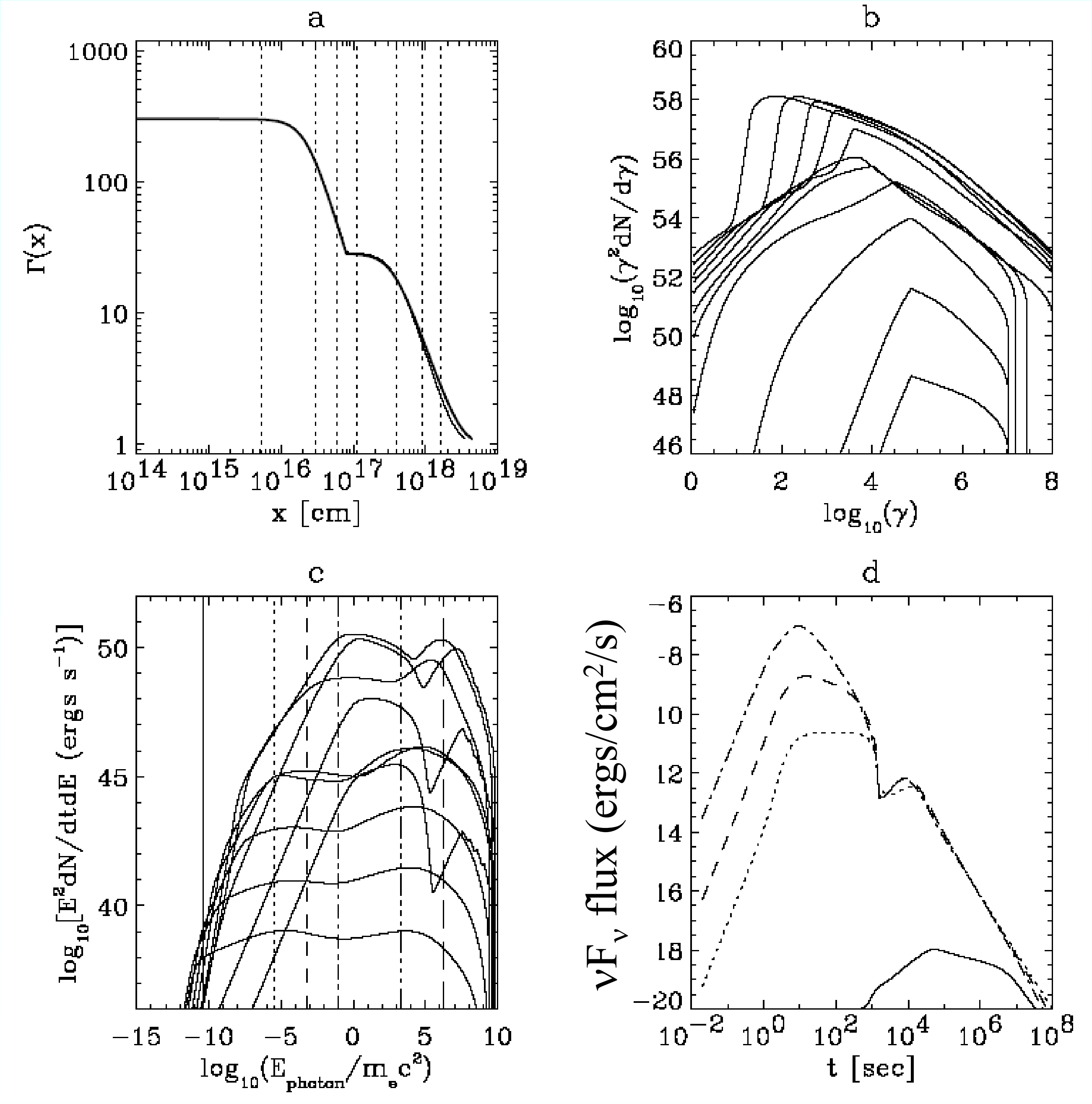
Lo B

$\varepsilon_B = 10^{-4}$

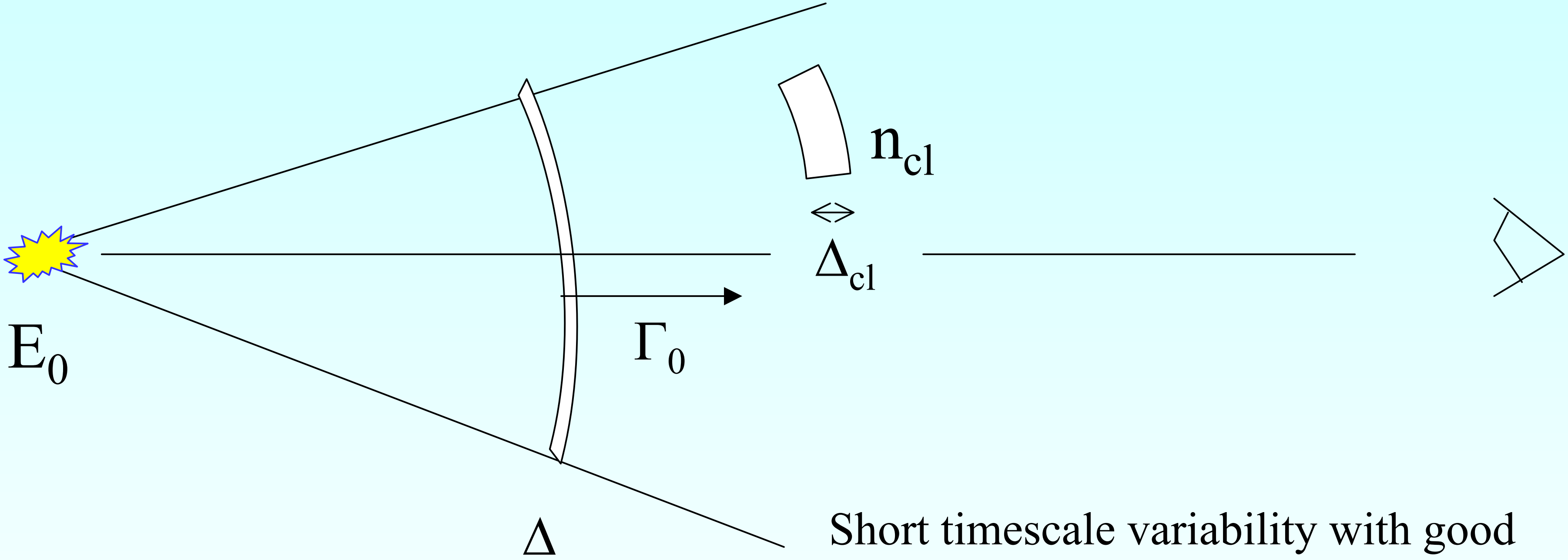
Strong SSC component

Quantitative solution to rapidly declining X-ray light
curves in GRBs

What causes change in system parameters at 10^{16} – 10^{17} cm?



Making the GRB Prompt Emission and X-ray Flares



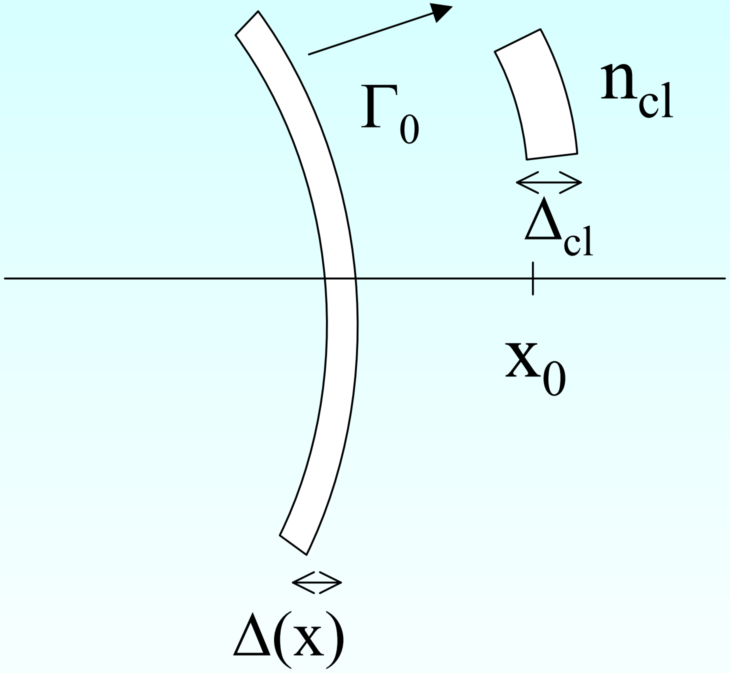
Short timescale variability with good efficiency (> 10%) requires existence of clouds with typical sizes << x/Γ_0

and dominant forward shock

Thick Column: $$\Delta_{cl} > \frac{E_0}{4\pi x_0^2 m_p c^2 \Gamma_0^2 n_{cl}}$$

Dermer and Mitman (1999, 2003)

Require Strong Forward Shock to make Bright, Rapidly Variable GRB Emission



Shell width: $\Delta(x) \approx \Delta_0,\ x < \Gamma_0^2\Delta_0 = x_{spr}$

$\Delta(x) \approx \eta x/\Gamma_0^2,\ x > x_{spr}$

Need thin shell, i.e., $\eta << 1$

Shell density: $n(x) = \dfrac{E_0}{4\pi x^2 m_p c^2 \Gamma_0^2 \Delta(x)}$

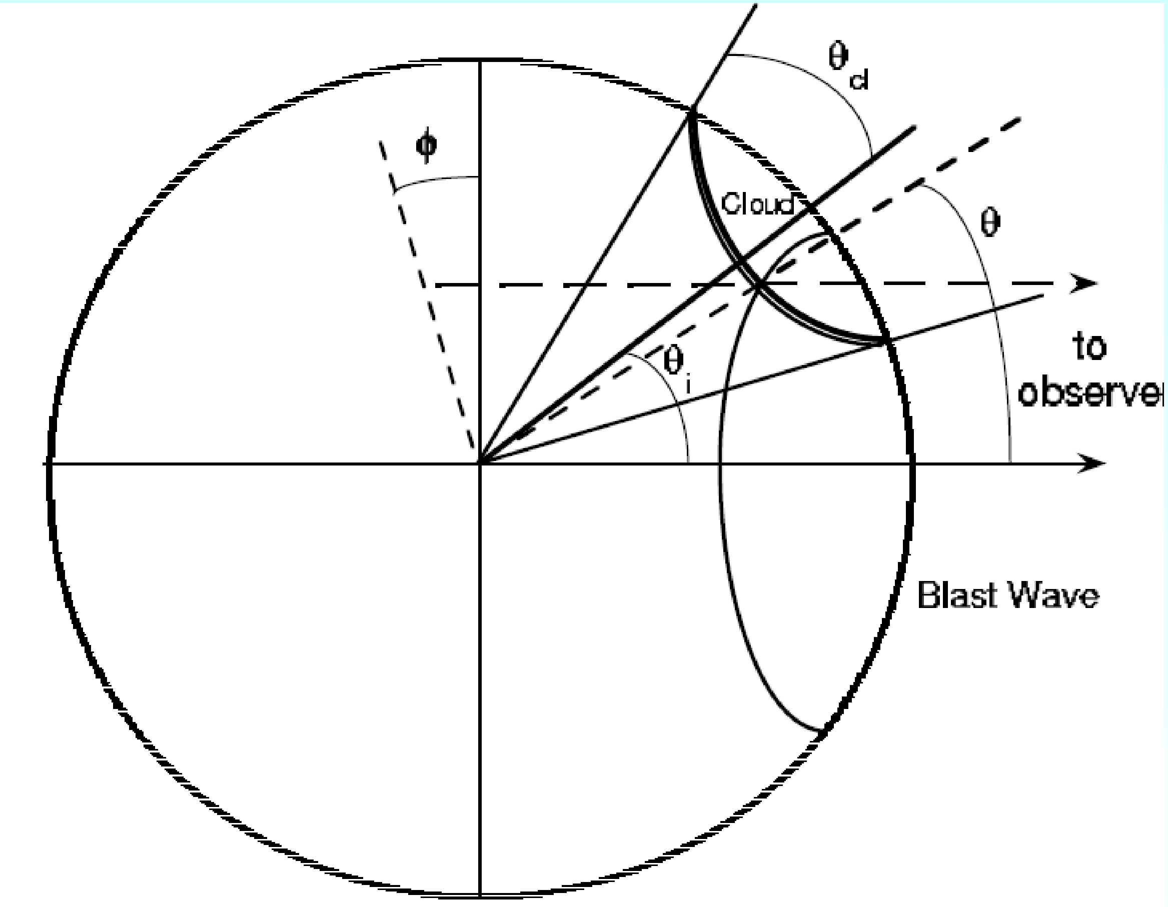
1. Nonrelativistic reverse shock: $n(x_0) >> \Gamma_0^2 n_{cl}$
2. Thick Column: $\Delta_{cl} > \dfrac{\Delta(x_0)n(x_0)}{n_{cl}}$
3. STV: $\Delta_{cl} << x/\Gamma_0$

$1. + 2. \Rightarrow \Delta_{cl} > \Gamma_0^2\Delta(x_0)$

With 3. and shell-width relation ⇒→← unless $\eta << 1$

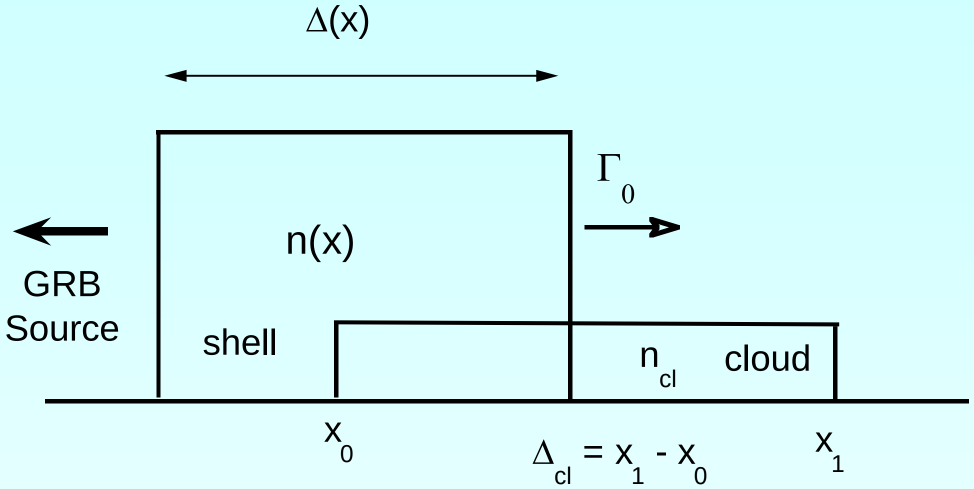
$\eta << 1$: a requirement on the external shock model

Blast Wave Shell/Cloud Physics: The Elementary Interaction



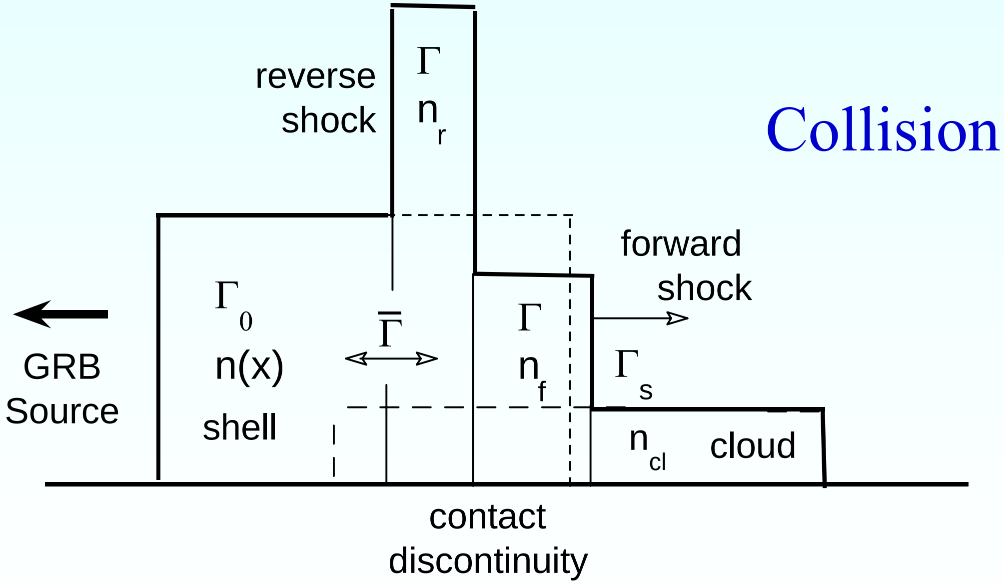
- **Cloud** = SN Remnant/Circumburst Material
- Blast Wave/Jet **Shell**

Analysis of the Interaction



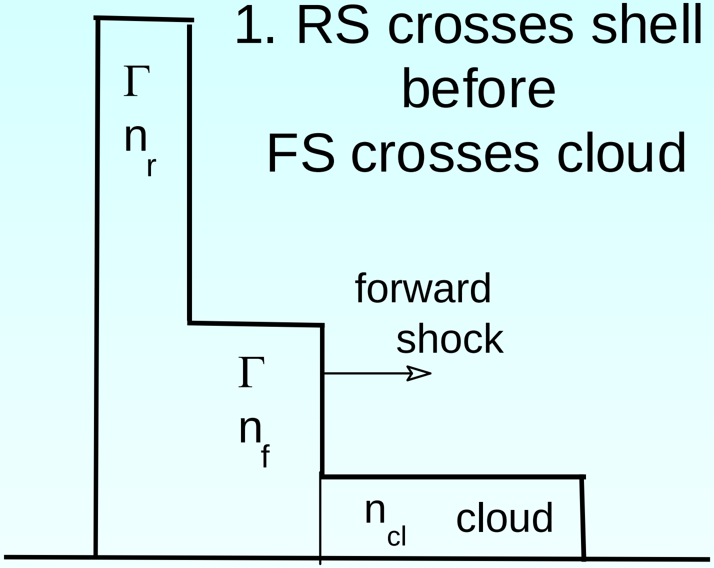
Assumption:

$$x_1 - x_0 << x_0$$

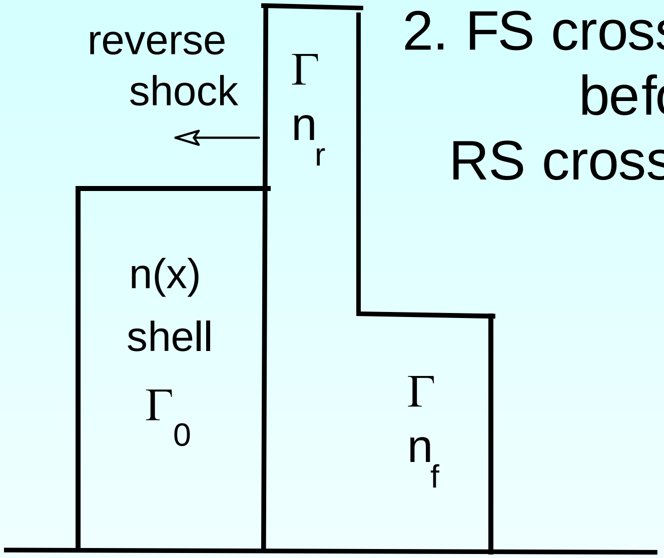


Collision Phase 1

Penetration Phase 2



1. RS crosses shell before FS crosses cloud



2. FS crosses cloud before RS crosses shell

$$f_\varepsilon(t) = (2\pi d_L^2)^{-1} \int_{\theta_i-\theta_{cl}}^{\theta_i+\theta_{cl}} d\theta \,|\sin\theta| \int_0^\infty dx\, x^2 \varepsilon' j'(\varepsilon', \vec{x}; t')$$

Use Sari, Piran and Narayan (1998)
formalism for some fluid phases

Expansion Phase 3

Synchrotron and adiabatic cooling

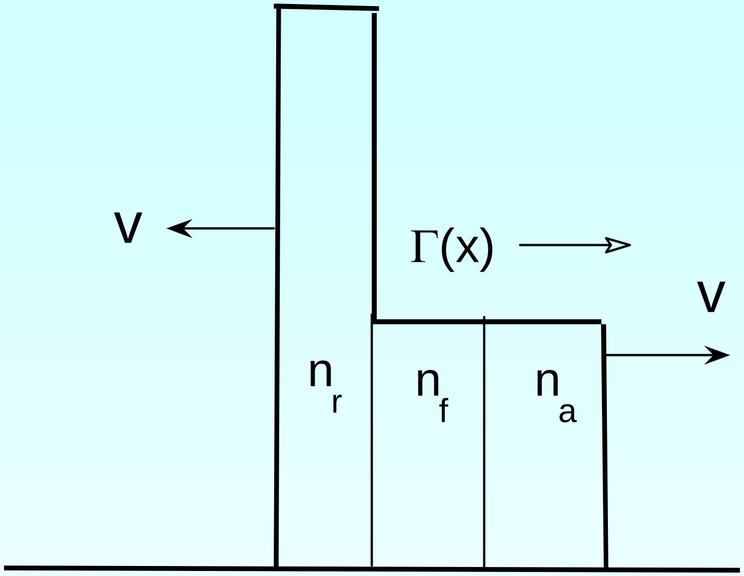
Conservation of magnetic flux ⇒ B

$$B_\perp R_\parallel^2 \propto const$$

$$-\frac{d\gamma}{d\tau} = \frac{\gamma}{\tau} + b\frac{\gamma^2}{\tau^4}$$

$$\tau = 1 + \frac{vt'}{R'_\parallel}, \; b = \frac{R'_\parallel}{v}\frac{\sigma_T B_0^2}{6\pi m_e c}$$

$$\gamma(\tau) = \frac{4\tau^3}{b(\tau^4 - 1) + (4\tau^4/\gamma_i)}$$



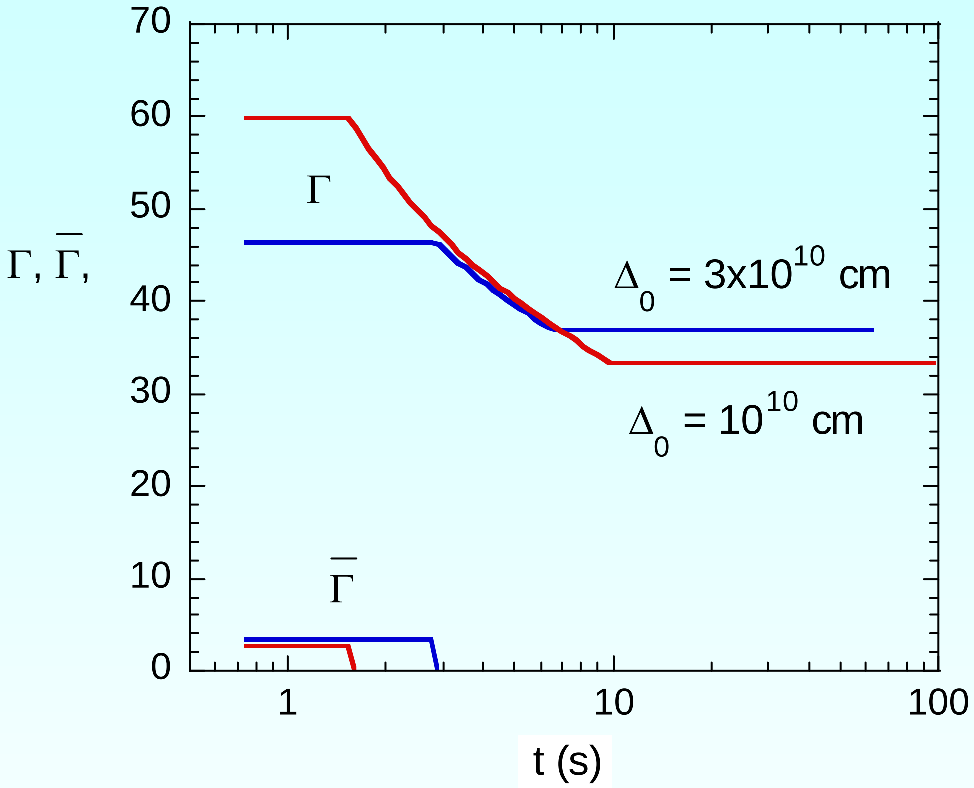
Take $v = c/\sqrt{3}$

Gupta, Böttcher, and Dermer (2005)

Standard Parameters

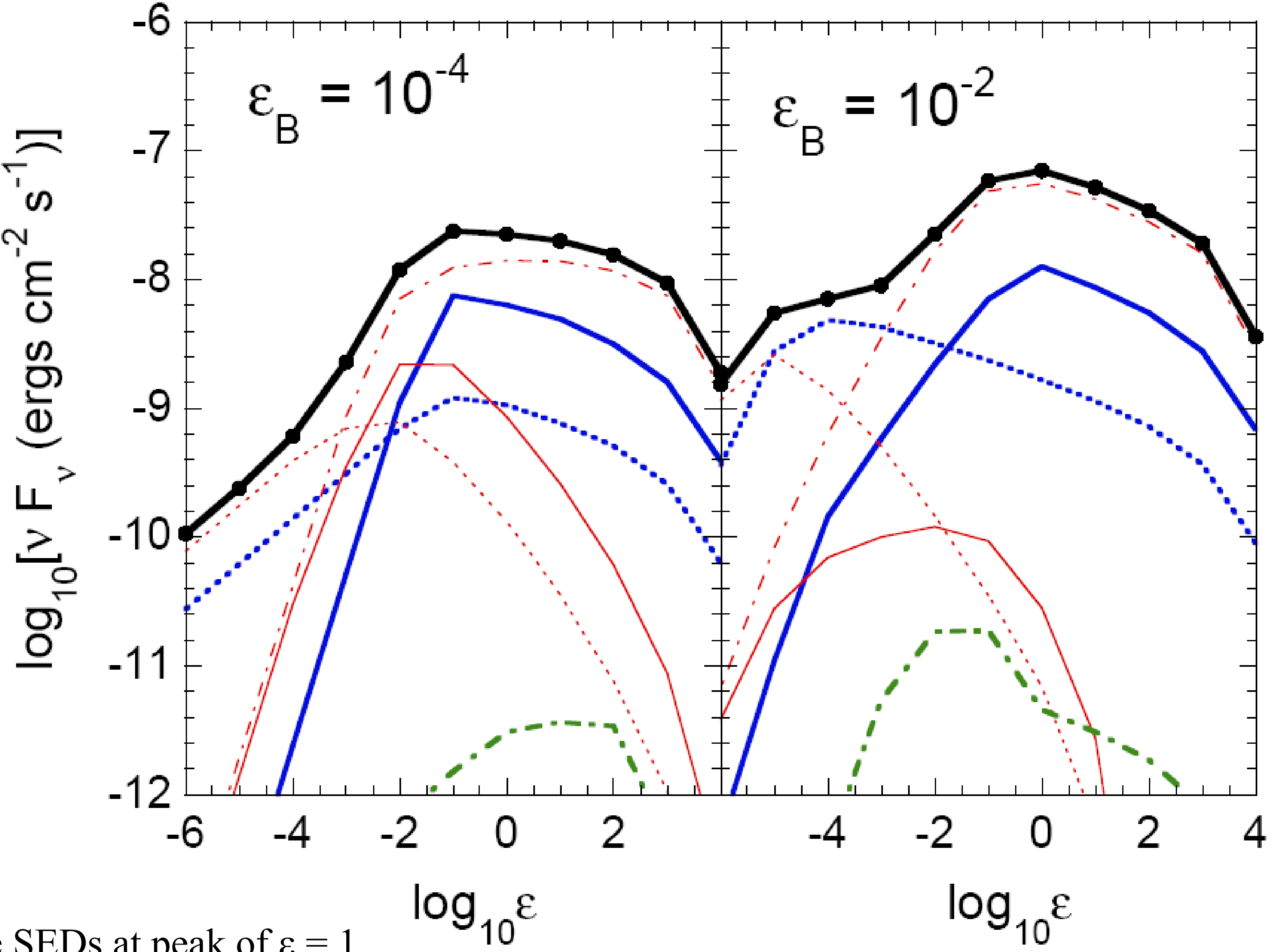
E_0	10^{52} ergs
Γ_0	300
Δ_0	$3\mathrm{x}10^{10}$ cm
z	1.0
n_{cl}	10^6 cm^{-3}
x_0	10^{15} cm
x_1	$1.02\mathrm{x}10^{15}$ cm
ε_e	0.333
ε_B	10^{-4}
ε_{max}	0.1
p	2.3

$\eta = 1$



Assume same parameters for forward and reverse shocked fluids, and forward shocked fluid in penetration/deceleration phase

Blast-wave/Cloud SED: Standard parameters



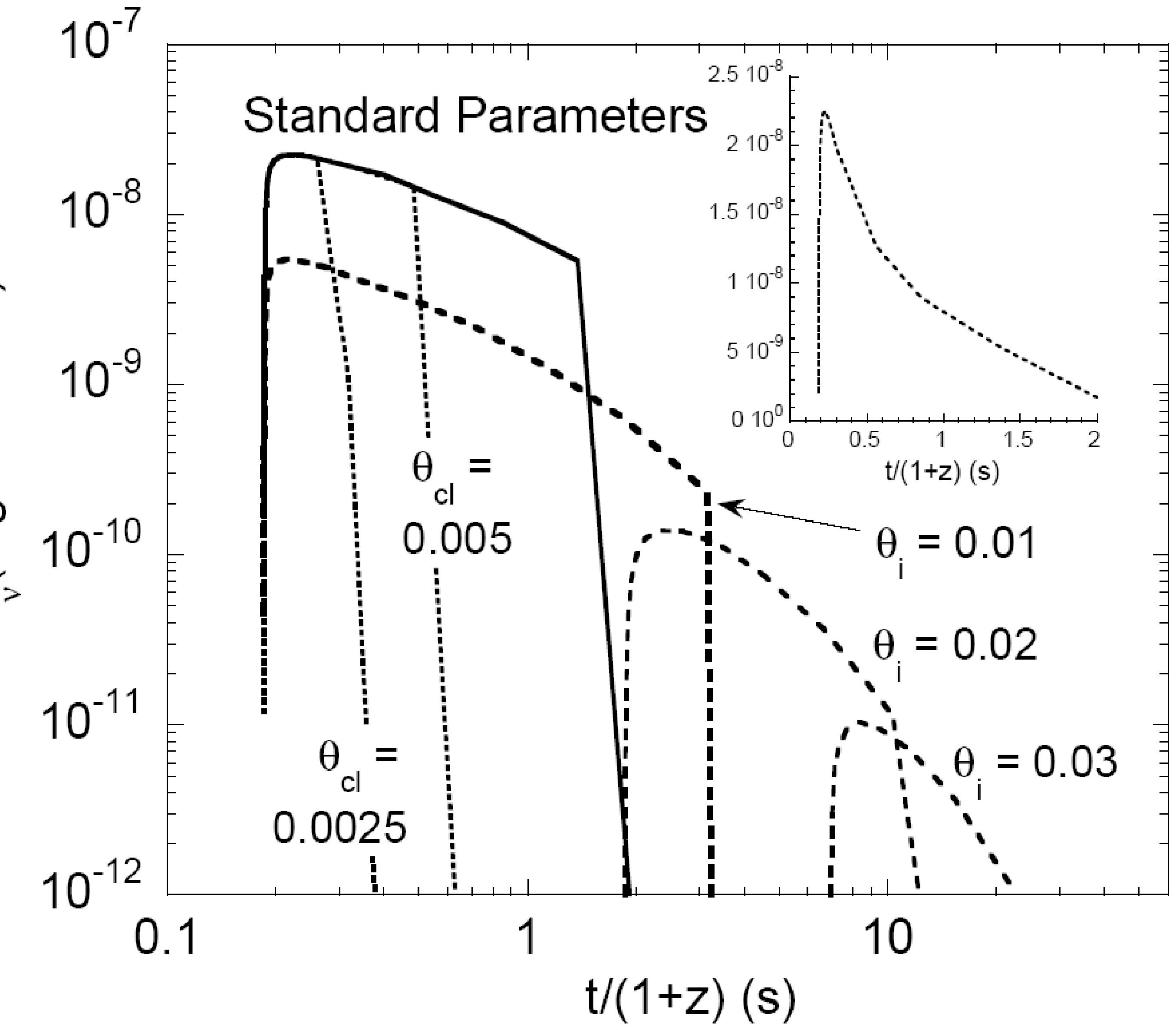
- Calculate SEDs at peak of ε = 1 lightcurve

$\eta = 0.01$, $\theta_{cl} = 0.01$, $\theta_i = 0$

Light Curves for Equivalent Events

$\epsilon_B = 10^{-4}$

Curvature pulse



Solution to Swift Observations of Rapid Decays and X-ray Flares

Transition in medium properties at $\approx 10^{16} - 10^{17}$ cm

Narrow high-Γ_0 jet in cases of steepest light curves

γ-ray pulses and X-ray flares: Very clumpy medium

External shock model with impulsive injection event

Thermal Neutral Beams in Jets

$$x_{n\,decay} \approx 900\ s \times 300\,(\frac{\Gamma}{300})c$$

$$\approx 10^{16}(\frac{\Gamma}{300})\ cm$$

Neutron decoupling

Derishev et al. 1999, Bahcall and Meszaros (2000)

Neutron decay: preconditioning of the surrounding medium

Beloborodov (2003)

Proton heating

Rossi et al. (2006)

Nonthermal Neutral Beams in Jets

Photohadronic processes followed by electromagnetic cascade

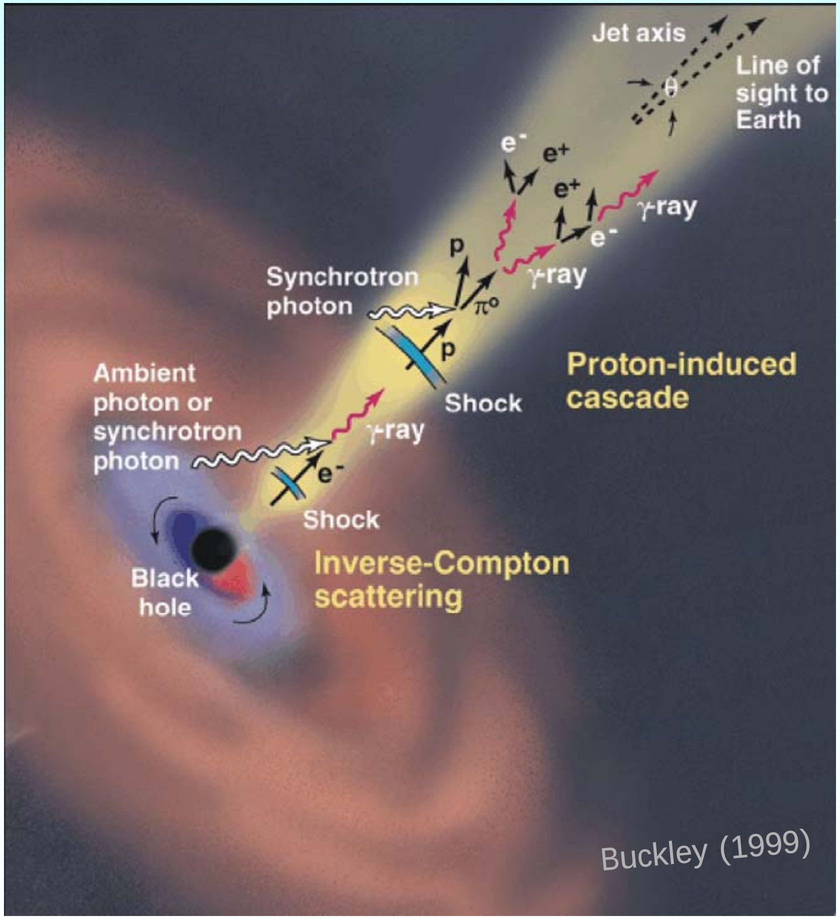
Hadron as well as lepton acceleration

Nonthermal gamma-rays ⇒
nonthermal particles
+ Intense photon fields

$$p+\gamma' \rightarrow n+\pi^{+}, p+\pi^{0} \rightarrow \gamma$$

$$\pi^{+} \rightarrow e^{+} + \nu_{e} + \nu_{\mu} + \bar{\nu}_{\mu}$$

⇒ Strong photomeson production
Large neutrino efficiency ,
Neutron momentum outflow,
Intense γ-ray beam



Buckley (1999)

Gamma-Ray Bursts as Sources of High-Energy Cosmic Rays

Complete Solution to Cosmic Ray Origin

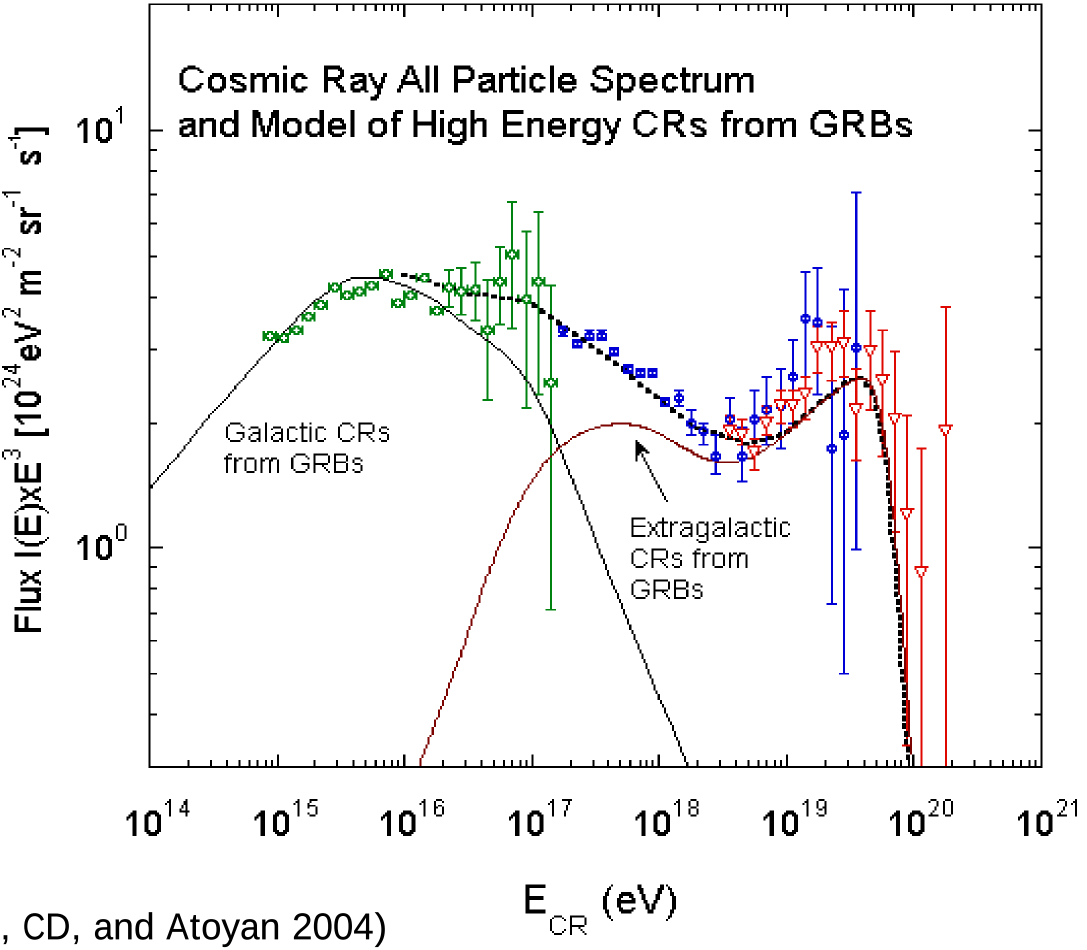
Cosmic Rays below ≈ 10^{14} eV from SNe that collapse to neutron stars

Cosmic Rays above ≈ 10^{14} eV from SNe that collapse to black holes

- CRs between knee and second knee from GRBs in Galaxy
- CRs at higher energy from extragalactic/ cosmological origin

Requires large baryon load to explain cosmic ray origin from GRBs (f_b >~ 50)

GRBs in the Galaxy



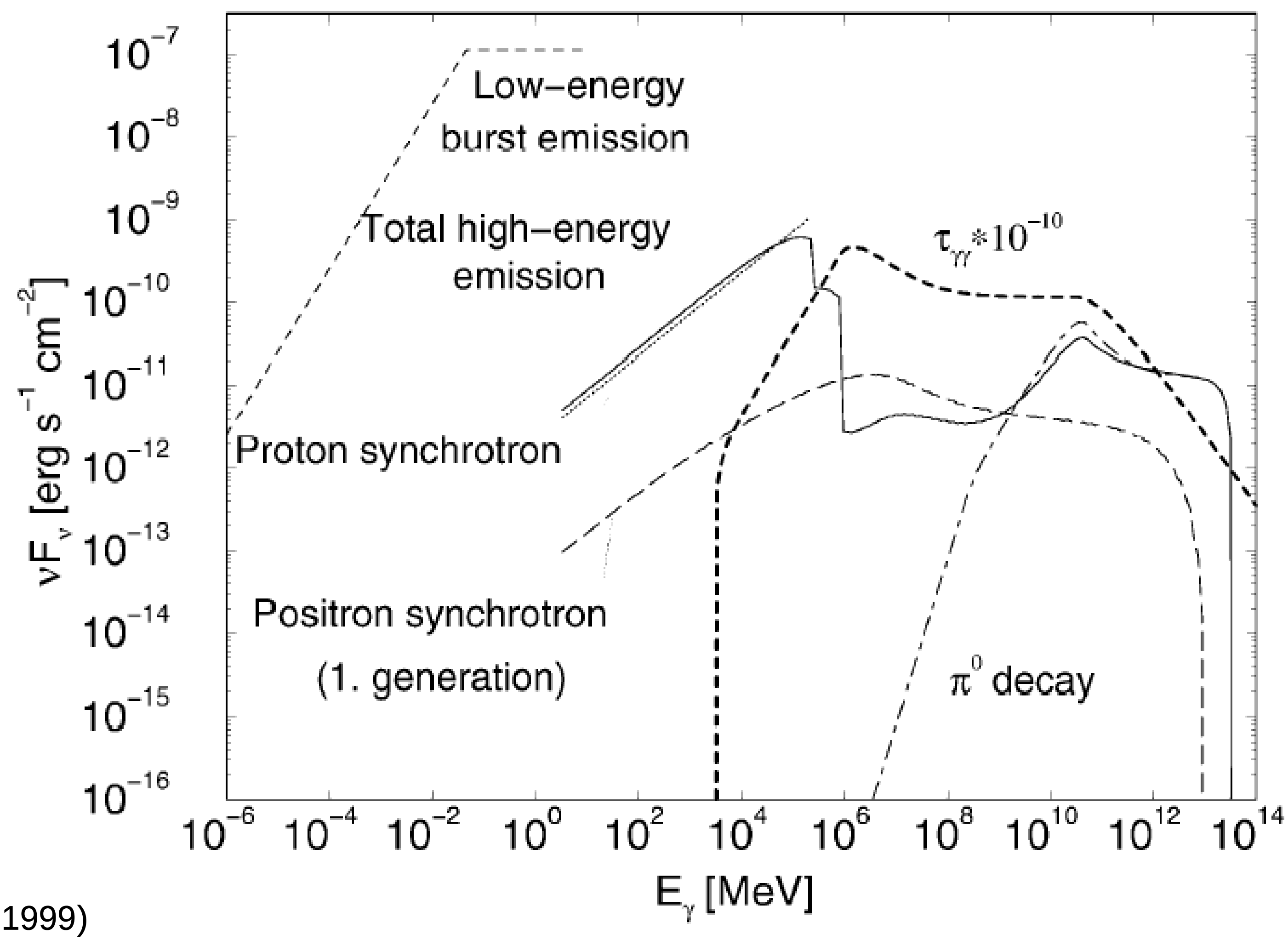
(Wick, CD, and Atoyan 2004)

Energetic Hadron-Synchrotron Component in GRB Blast Waves

Requires proton acceleration to high energies

Large B fields

Proton synchrotron component could be observed with GLAST

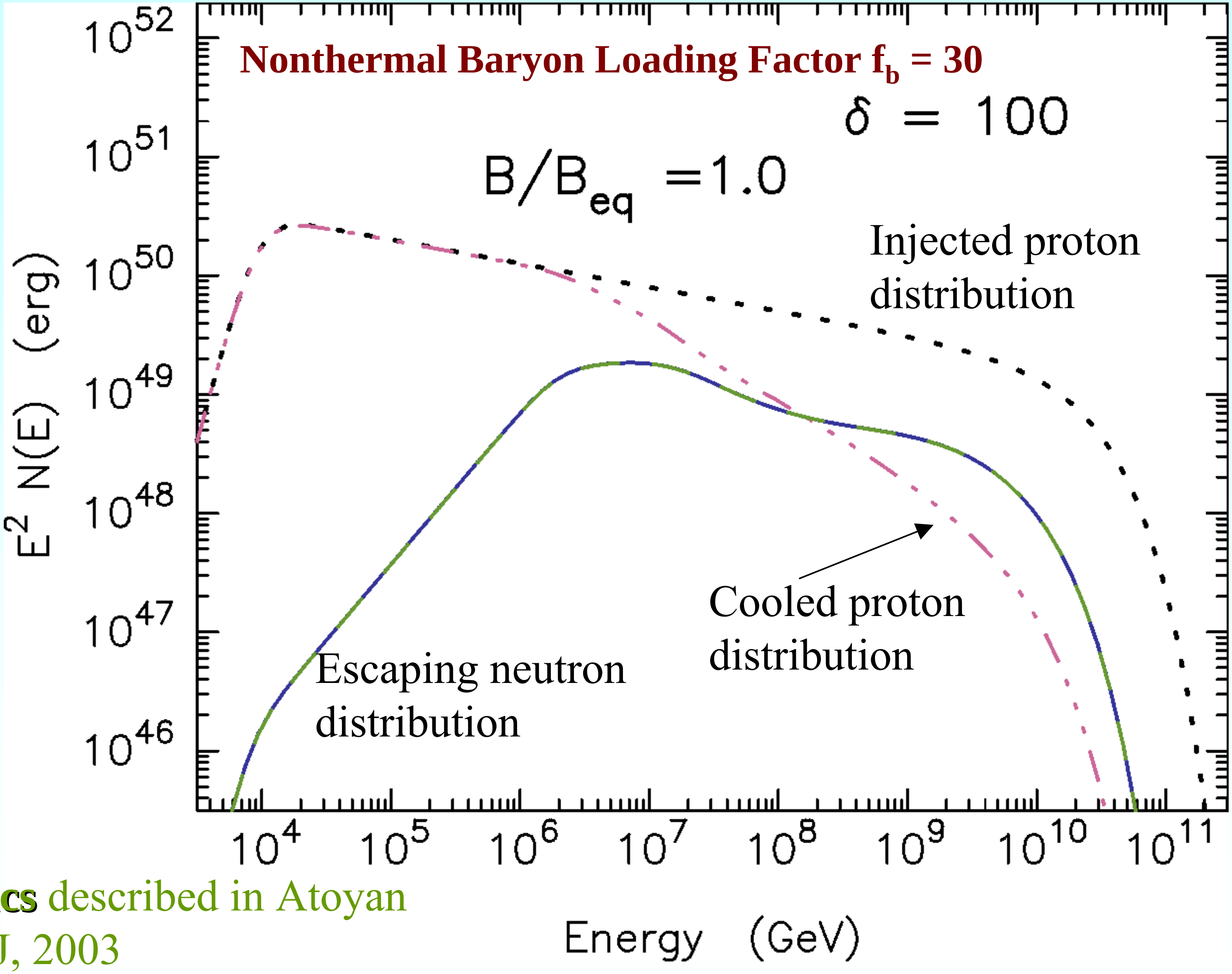


(Böttcher and Dermer 1999)

Proton Injection and Cooling Spectra

GRB
synchrotron
fluence

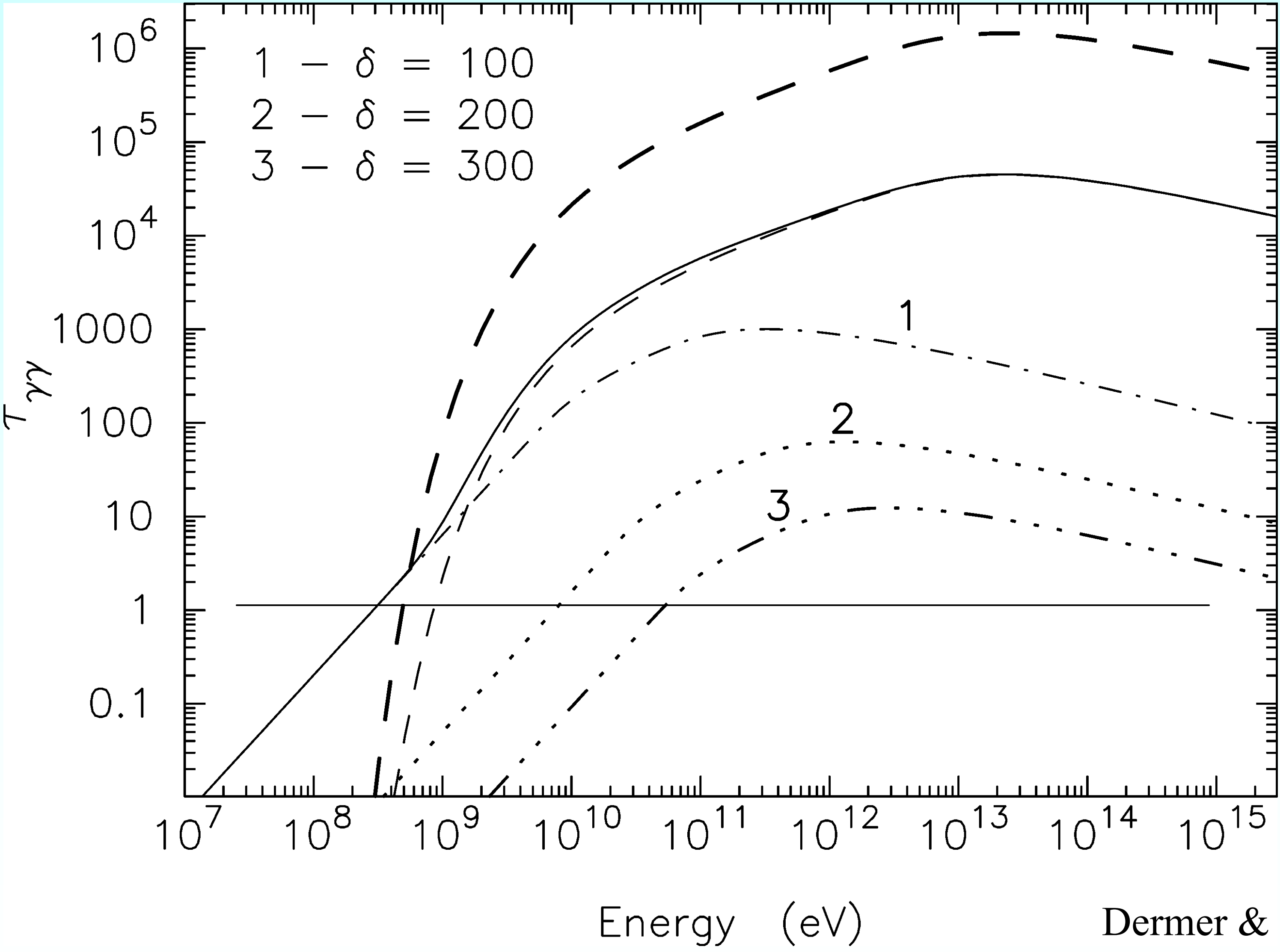
$\Phi_{tot} = 3 \times 10^{-4}$ *ergs cm*$^{-2}$,
50 *one* sec
pulses



Code and physics described in Atoyan and Dermer, ApJ, 2003

$\gamma\gamma$ Optical Depth

Photon attenuation strongly dependent on δ and t_{var} in collapsar model

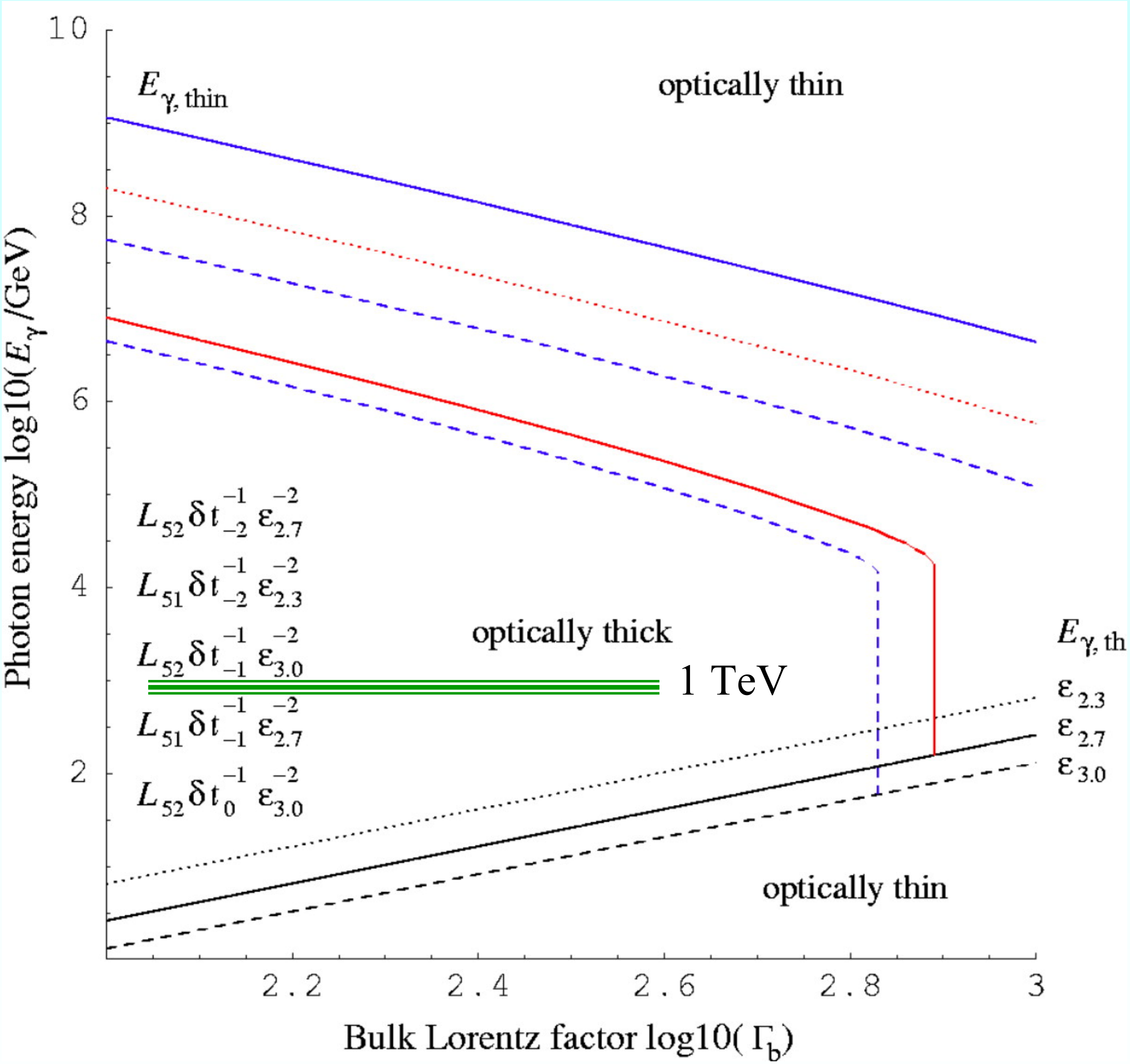


$\Phi_{tot} = 3\times10^{-4}$ *ergs* cm^{-2}, 50 *one* sec *pulses*

$\tau_{\gamma\gamma}$ evolves in collapsar model due to evolving Doppler factor and internal radiation field

Dermer & Atoyan, 2003

High Energy Emission from GRB Colliding Shells



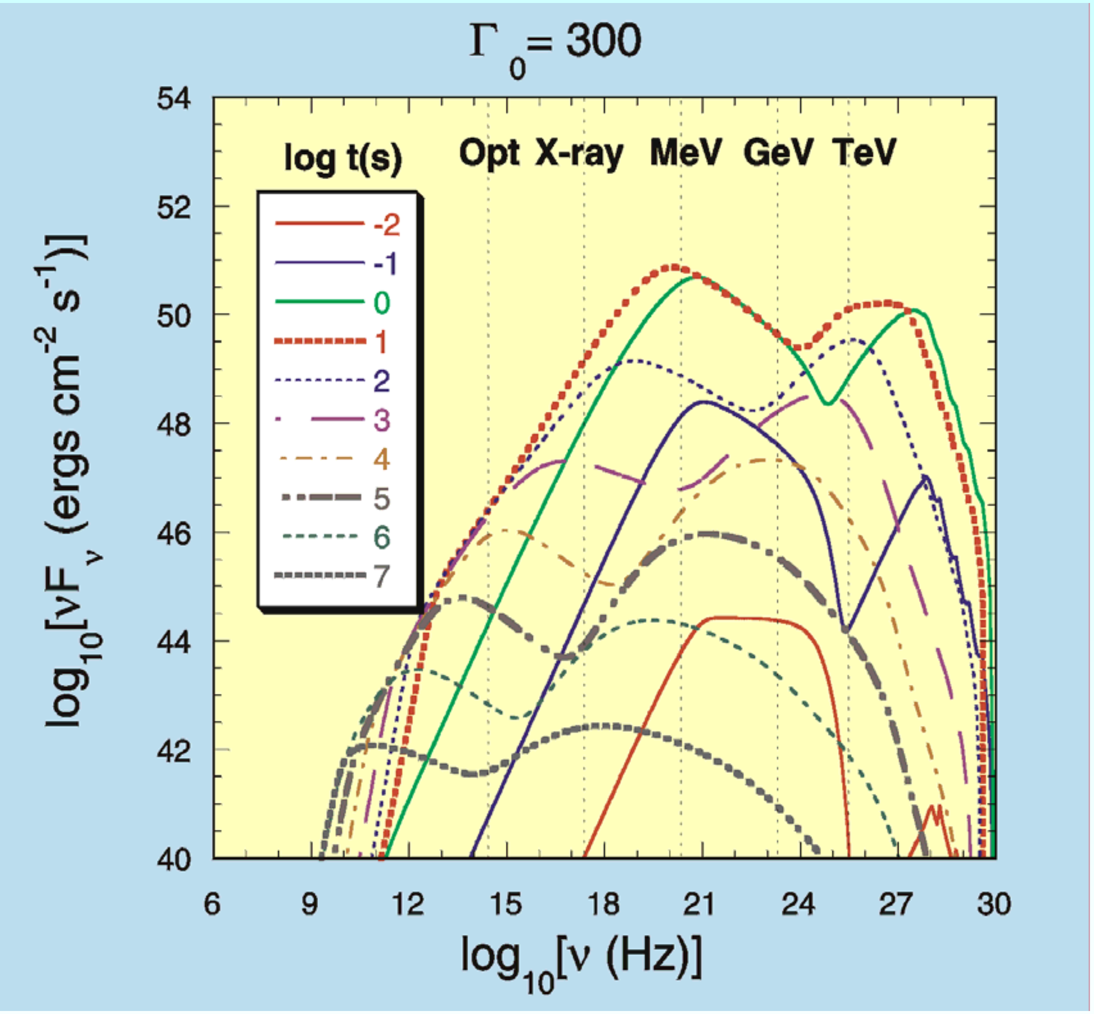
Very optically thick to γγ attenuation in TeV range

unless Γ >~ 1000

Discriminate between external and internal shock model

Razzaque, Kobayashi, & Mészáros (2004)

Numerical Simulation Model of GRB Leptonic Radiation



$E=10^{54}$ ergs

$n_0=100$ cm^{-3}

$\varepsilon_B = 10^{-4}$

- νF_ν spectra shown at observer times 10^i seconds after GRB event
- Calculations have $\gamma\gamma$ opacity included

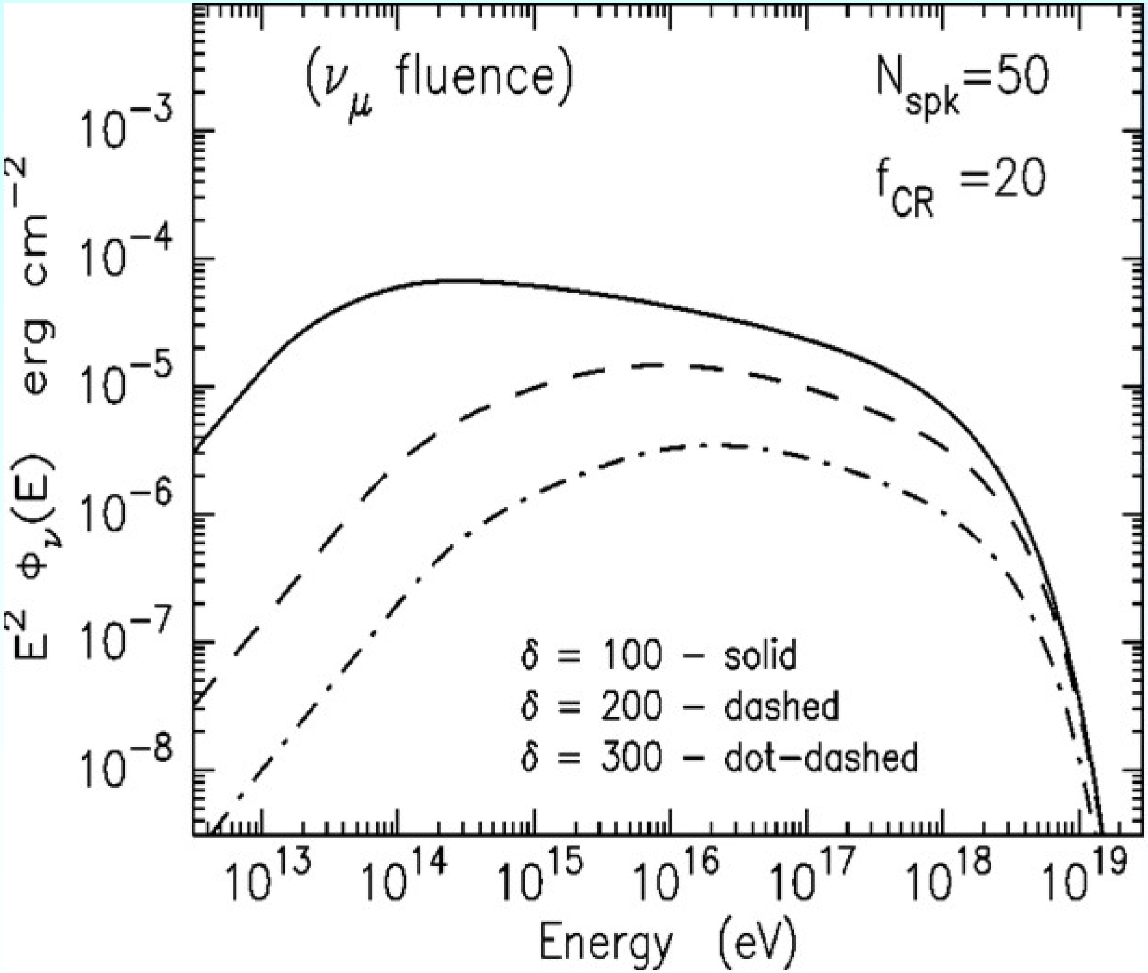
Neutrino Detection from GRBs only with Large Baryon-Loading

For a fluence of 3×10^{-4} ergs/cm^2, (~2/yr)

N_ν predicted by IceCube:

$N_\nu \approx$ 1.3, 0.1, 0.016 for δ = 100, 200, and 300, respectively in collapsar model for f_{CR} = 20

Nonthermal Baryon Loading Factor f_b = 20



Photomeson Cascade Radiation Fluxes

Photon index between −1.5 and −2

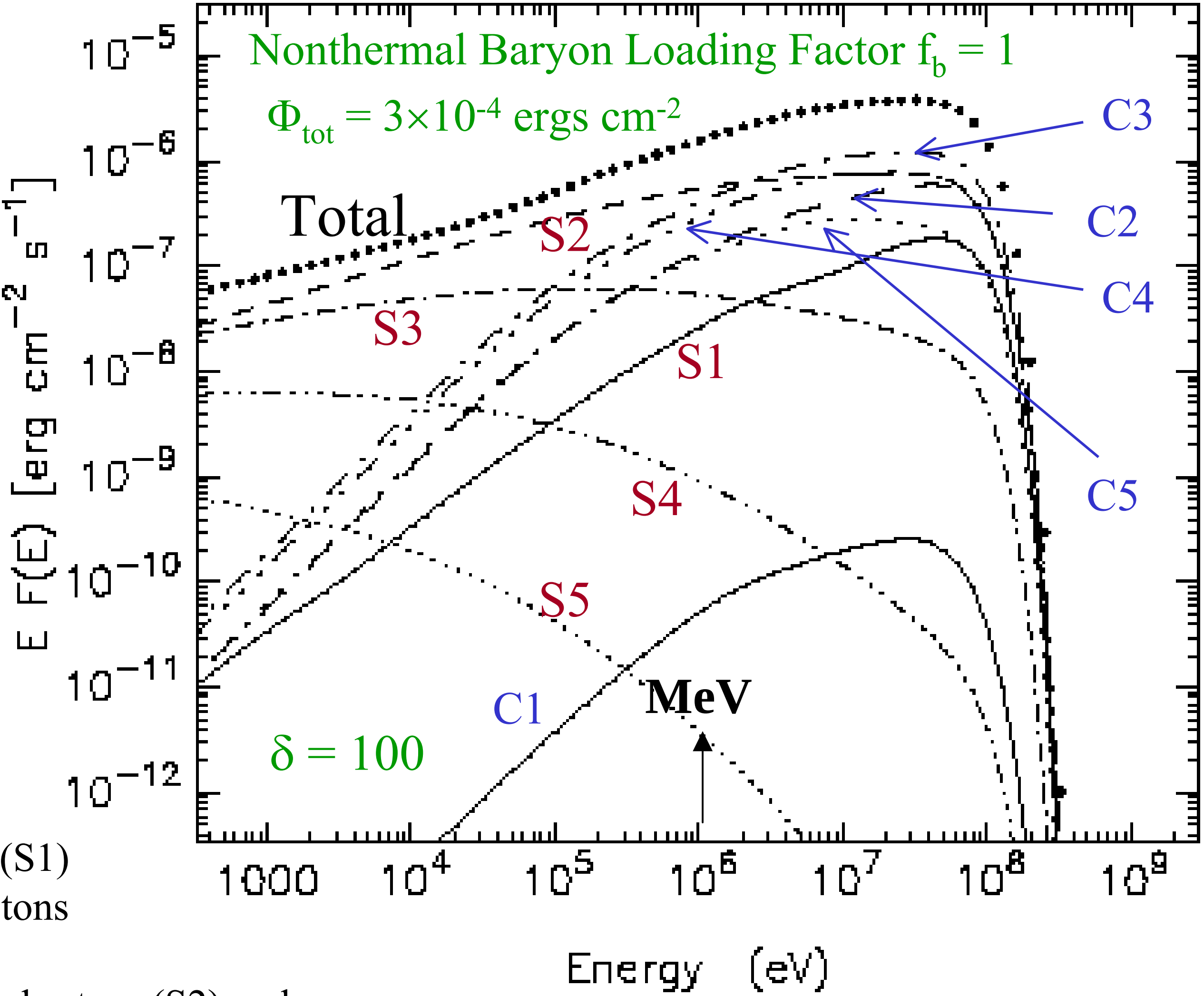
Fits data for GRB 941017 spectrum during prompt phase

Photomeson Cascade:

$$p\gamma \rightarrow \pi^{\pm} \rightarrow e^{\pm}$$

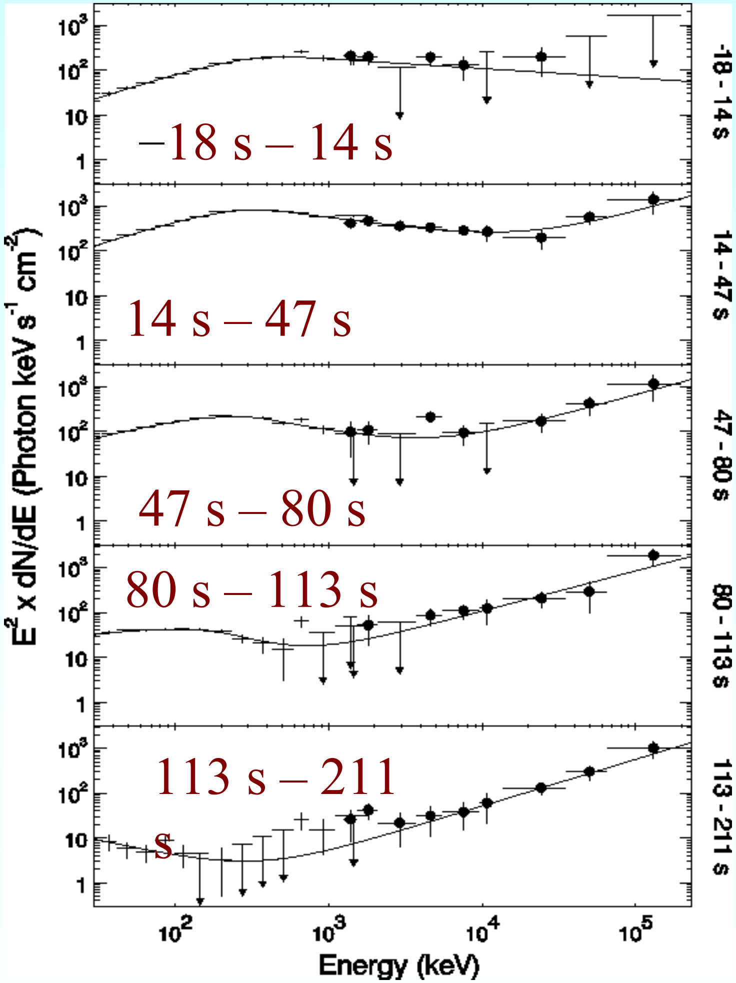
$e^{\pm}$ emits synchrotron (S1) and Compton (C1) photons

$\gamma\gamma' \rightarrow e^{\pm}$ emits synchrotron (S2) and Compton (C2) photons, etc.



Anomalous High-Energy Emission Components in GRBs

Evidence for Second Component from BATSE/TASC Analysis



−18 s – 14 s

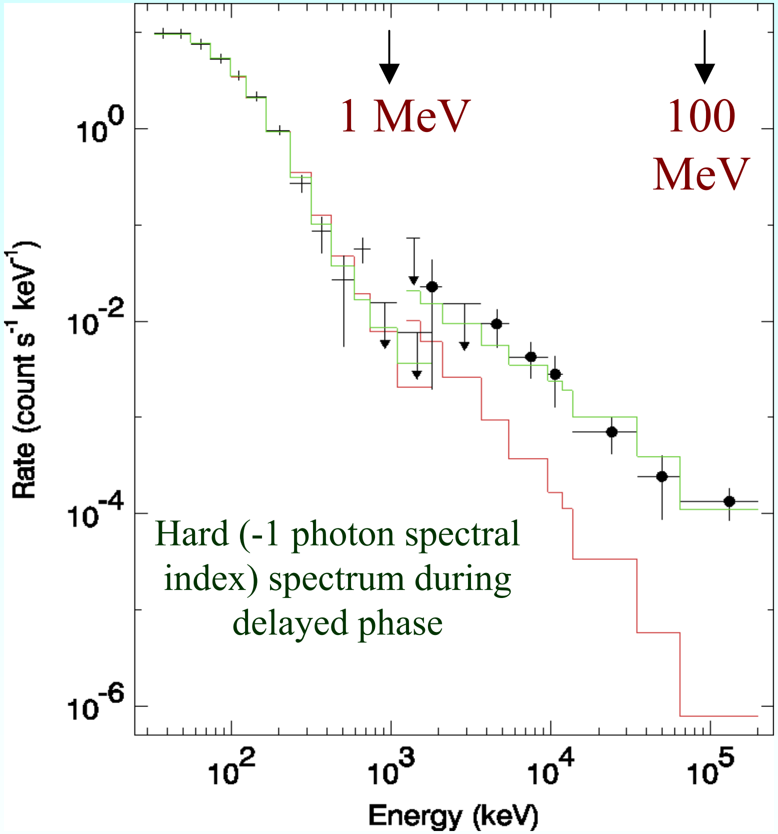
14 s – 47 s

47 s – 80 s

80 s – 113 s

113 s – 211 s

(González et al. 2003)



1 MeV

100 MeV

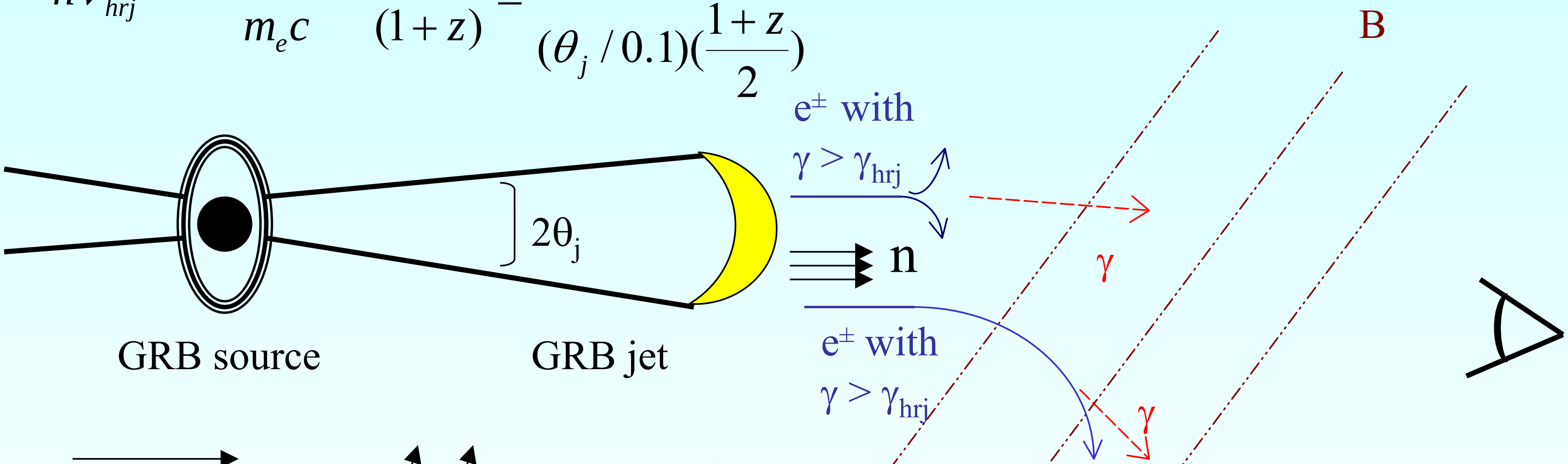
Hard (-1 photon spectral index) spectrum during delayed phase

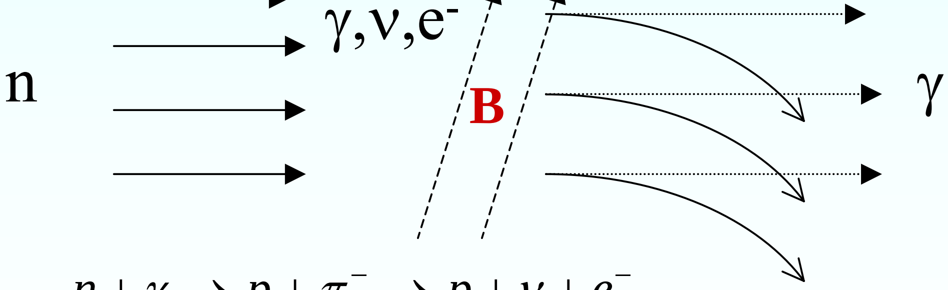
GRB 941017

Hyper-relativistic Electron Synchrotron Radiation

Mean energy of synchrotron photons emitted by electrons with $\gamma = \gamma_{hrj}$:

$$h\nu_{hrj} = \frac{\hbar e B \sin\psi}{m_e c}\frac{\gamma_{hrj}^2}{(1+z)} \cong \frac{500}{(\theta_j/0.1)(\frac{1+z}{2})}$$





$$n + \gamma \rightarrow p + \pi^- \rightarrow p + \nu + e^-$$

$$\rightarrow n + \pi^0 \rightarrow e^+ + e^-$$

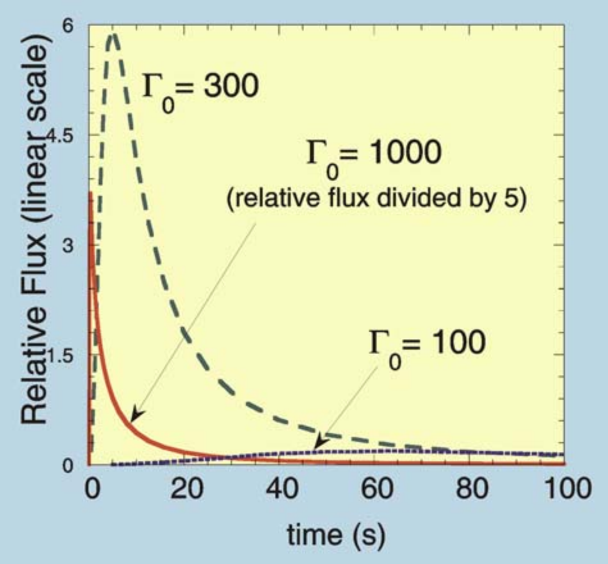
$$\frac{dE}{d\varepsilon} \cong 2\pi \int_0^{(3\varepsilon_B/\gamma\varepsilon)^{1/3}} d\theta \cdot \theta \cdot \left(\frac{dE}{d\varepsilon d\Omega}\right)_{syn} \cong \frac{3e^2}{\pi \bar{\lambda}_C} \propto \varepsilon^0$$

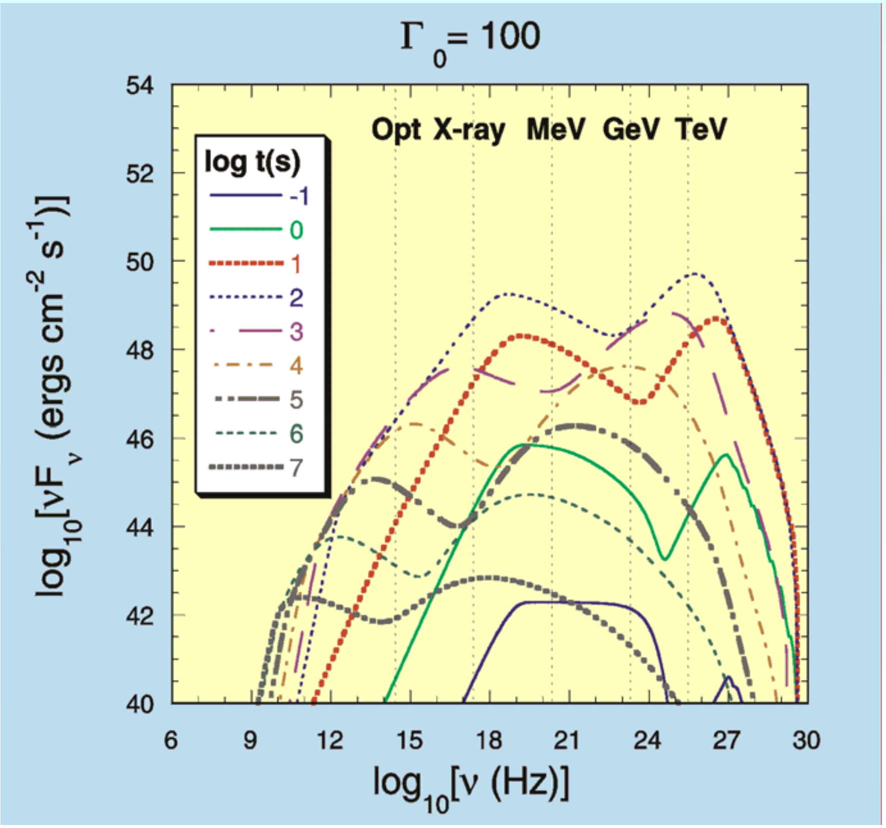
i.e., a −1 photon spectrum

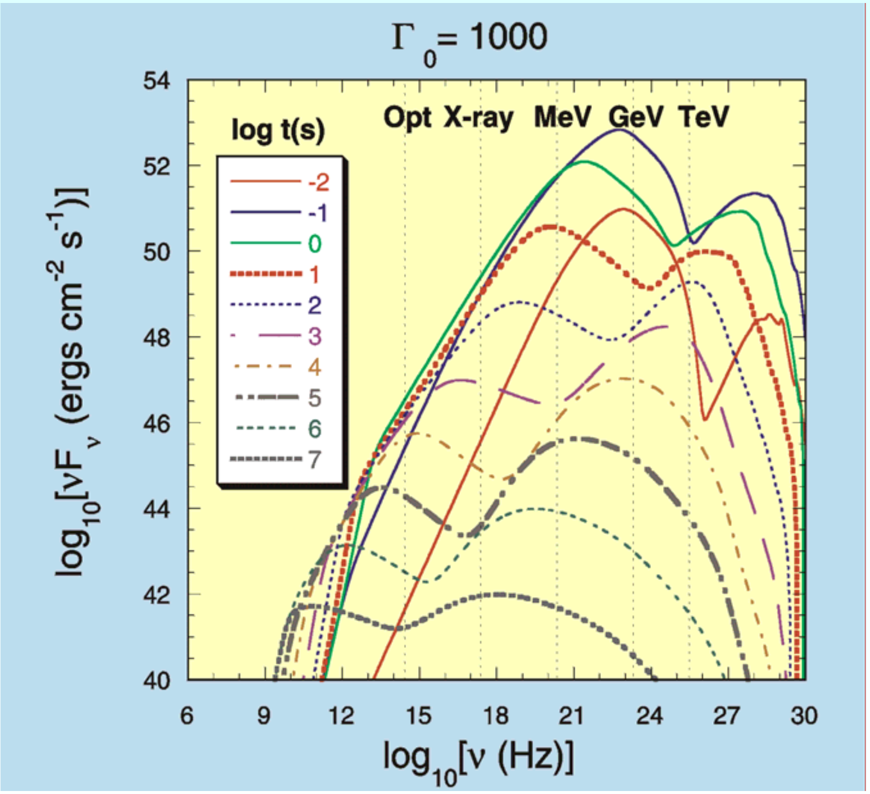
High Energy Radiation from Dirty and Clean Fireballs: strong GeV/TeV sources

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

Dermer, Chiang, and Böttcher (2000)

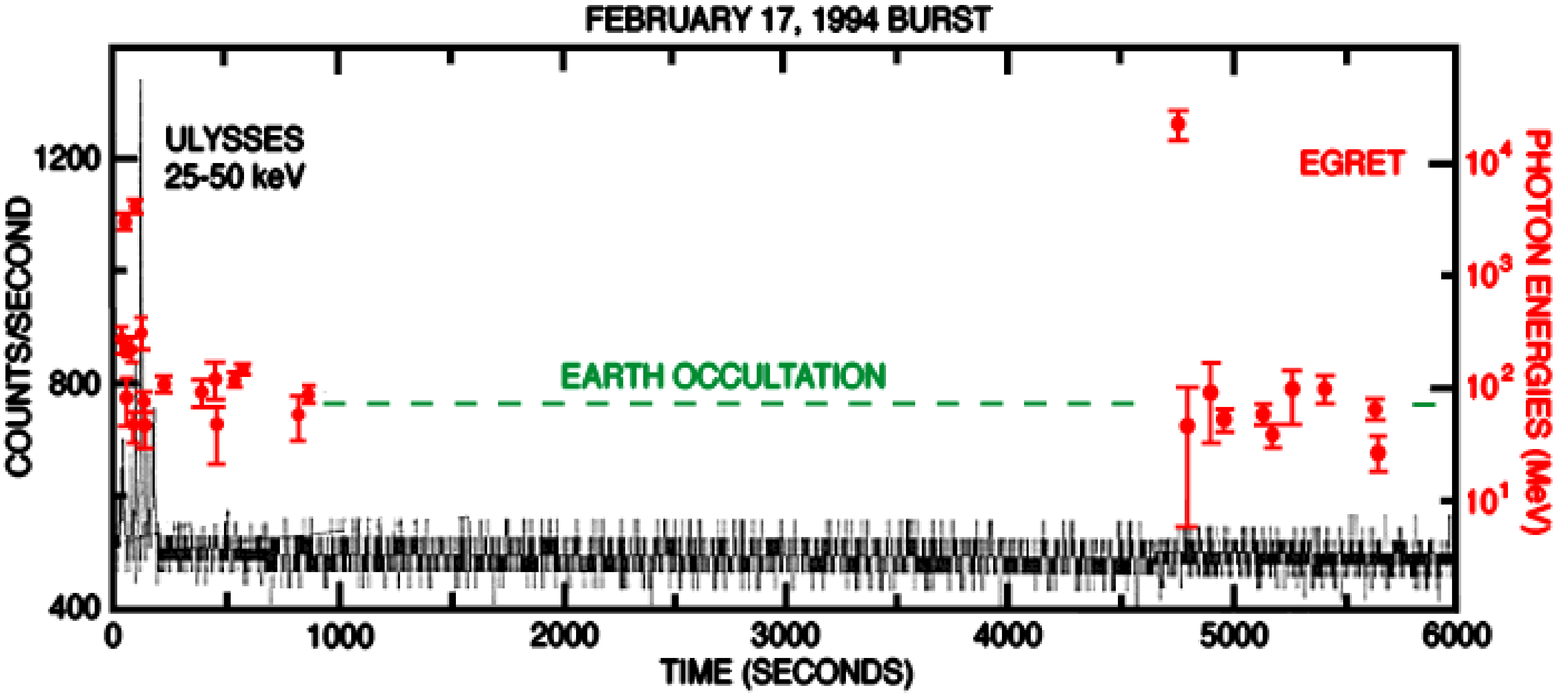






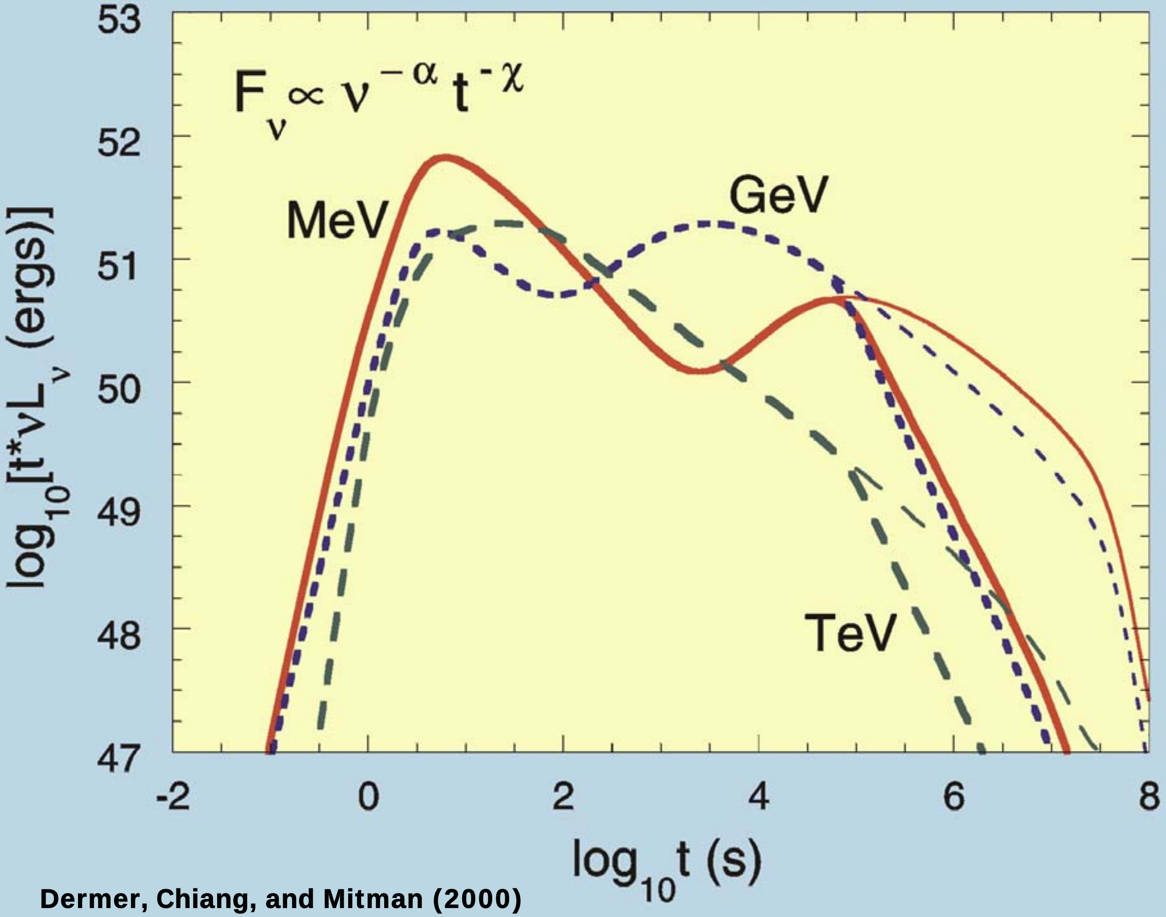
GRB 940217

Longest (>90 min) γ-ray emission



Gamma Ray Light Curves

SSC bump in XRT light curves?

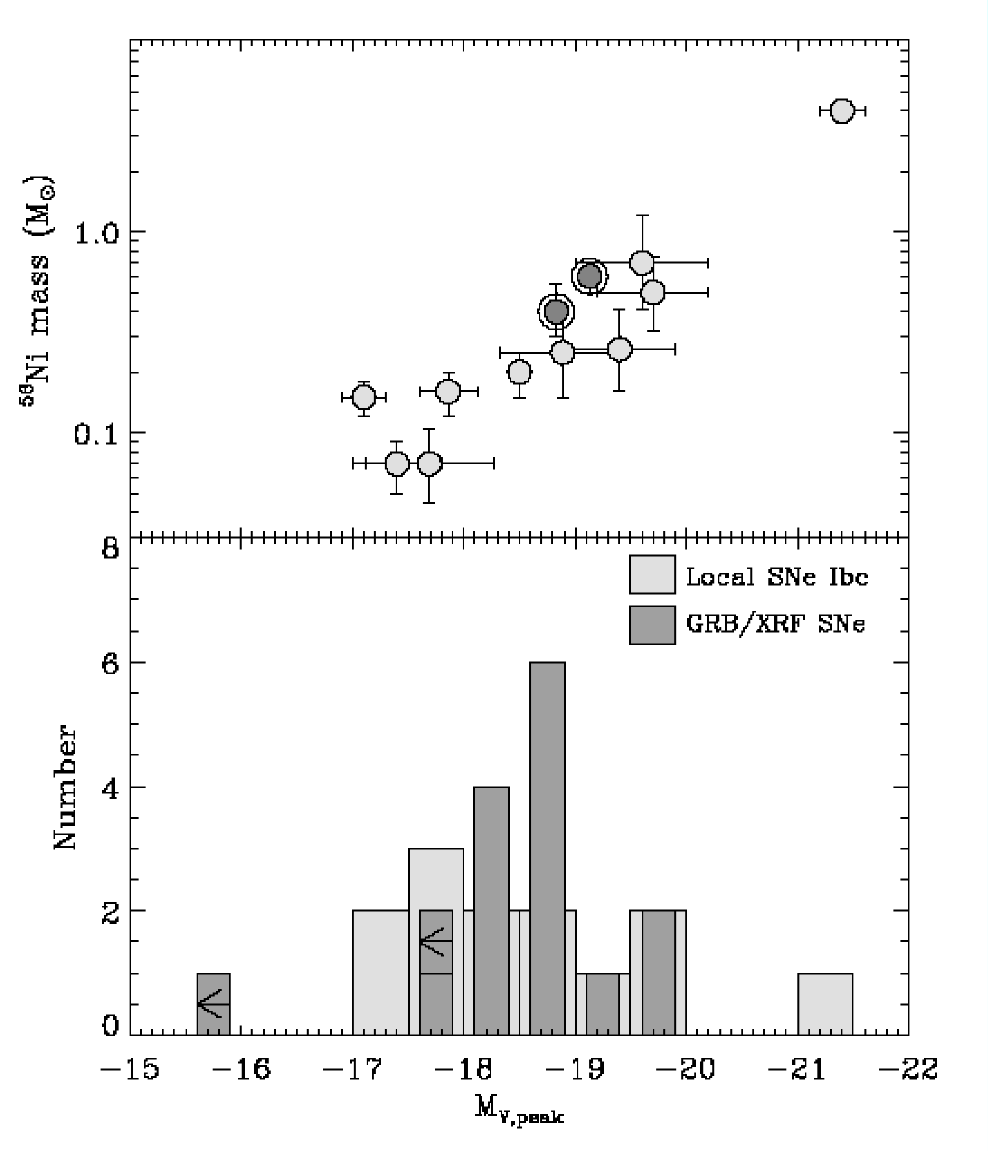


Dermer, Chiang, and Mitman (2000)

What does it all mean?

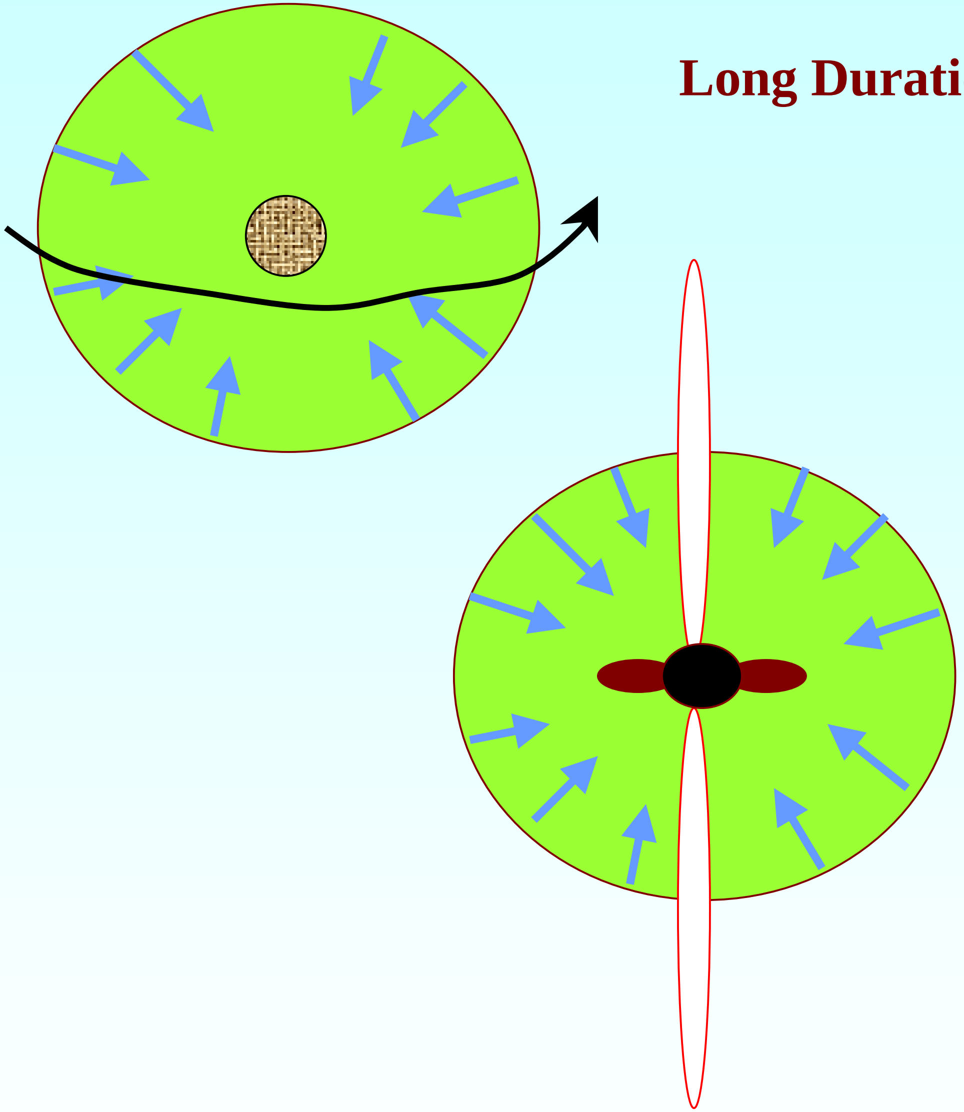
^{56}Ni Production

Same distributions (within limited statistics) for GRB SNe and SNe Ib/c (neutron star remnant)



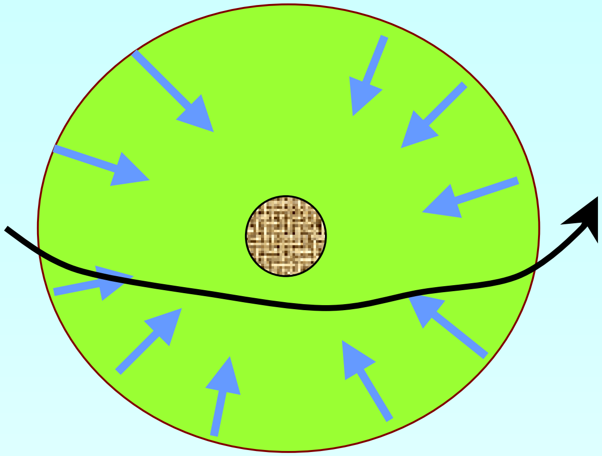
Soderberg et al. 2006

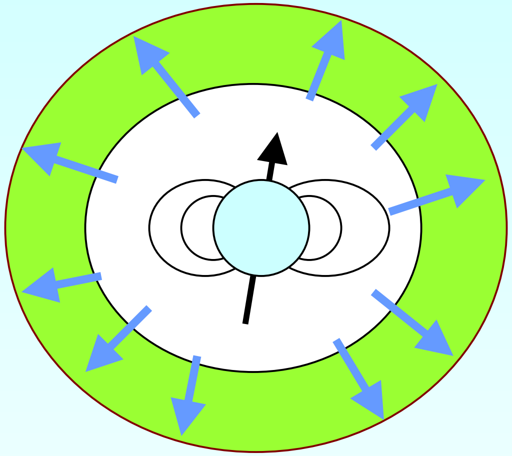
Long Duration GRB Collapsar Model

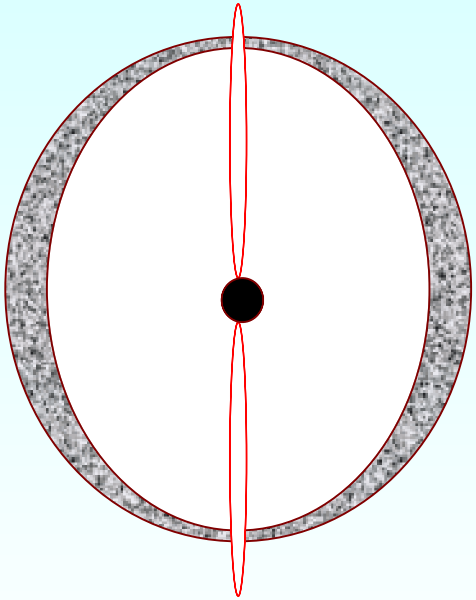


1. Failed Supernova (^{56}Ni production)
2. Emergence of Jet
3. Internal Shocks
4. Standard Energy Reservoir (Upper limit)
5. Blandford-Znajek process to form Jets

Two-Step Collapse (Short-Delay Supranova) Model





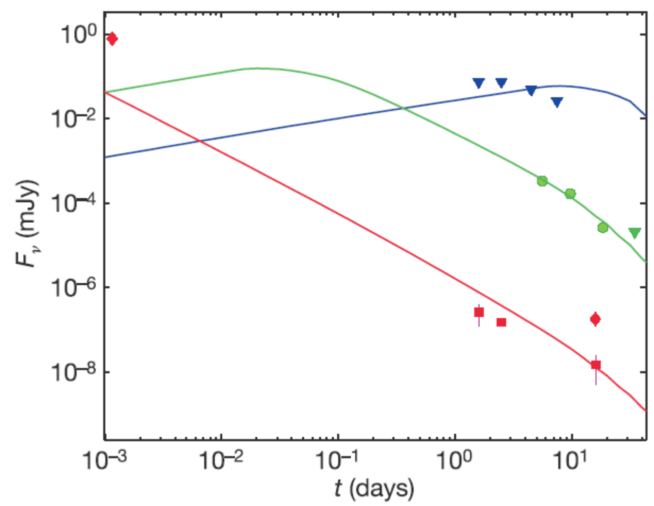


1. Standard SNIb/c (^{56}Ni production)
2. Magnetar Wind Evacuates Poles
3. GRB in collapse of NS to BH
4. Prompt Phase due to External Shocks with Shell/Circumburst Material
5. Standard Energy Reservoir (NS collapse to BH)
6. Beaming from mechanical/B-field collimation
7. Neutron preconditioning of jetway

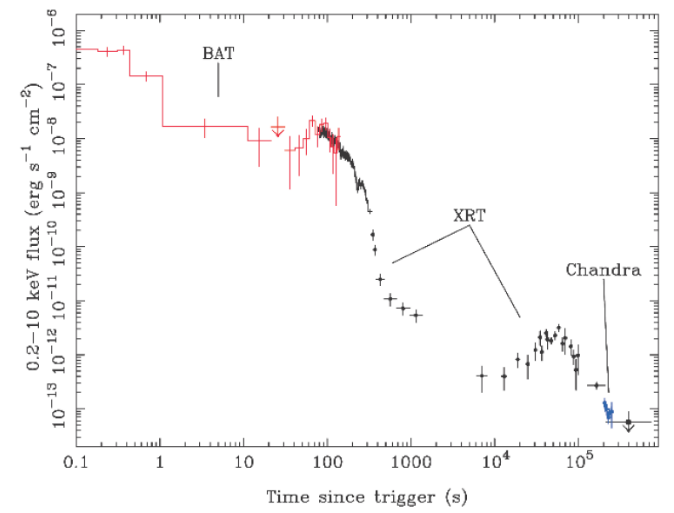
Delay time ~<
1 day (GRB 030329)

Short (Hard) Gamma-Ray Bursts

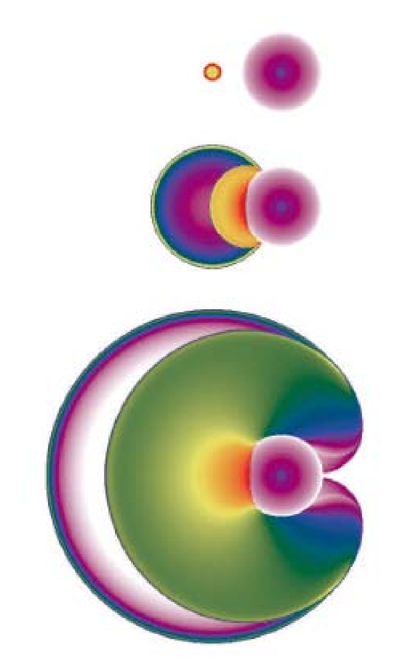
GRB 050709



Fox et al. Nature, 2005



Barthelmy et al. (2005)



MacFadyen, Ramirez-Ruiz, and Zhang (2005)

Leading to

Collapse of Neutron Star to Black Hole **through**

Accretion-Induced Collapse

White Dwarf Coalescence

Dermer & Atoyan, ApJ Letters, submitted (2006)

Summary

Quasi-universal feature of X-ray emission from Swift XRT obs:

constant emission followed by steep decay: curvature relation

How to turn off spherical shell?

1. Internal shell collision gives rising and decaying pulses, with decay phase longer in time than rising phase, contrary to observations

2. Emergence of jet into medium with different properties on size scales ~10^{16} – 10^{17} cm for external shock model provides quantitative explanation of Swift behavior

γ-ray pulses and X-ray flares are due to interactions with clumps of circumburster/stellar wind material

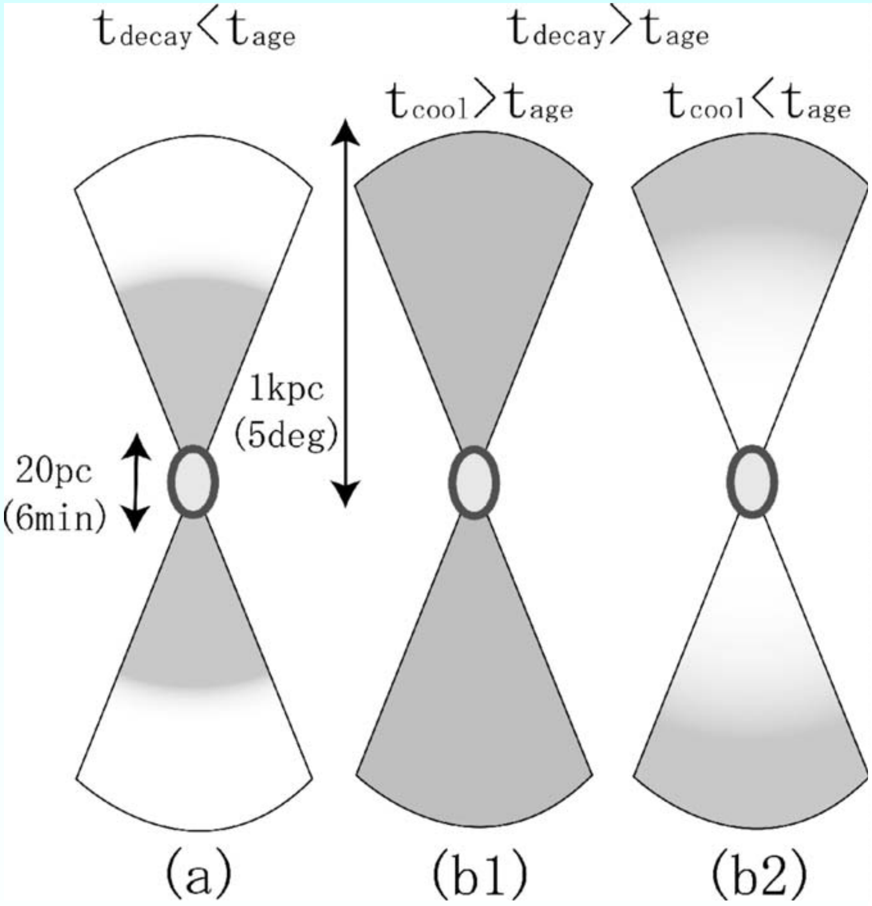
Thermal and nonthermal neutral beams

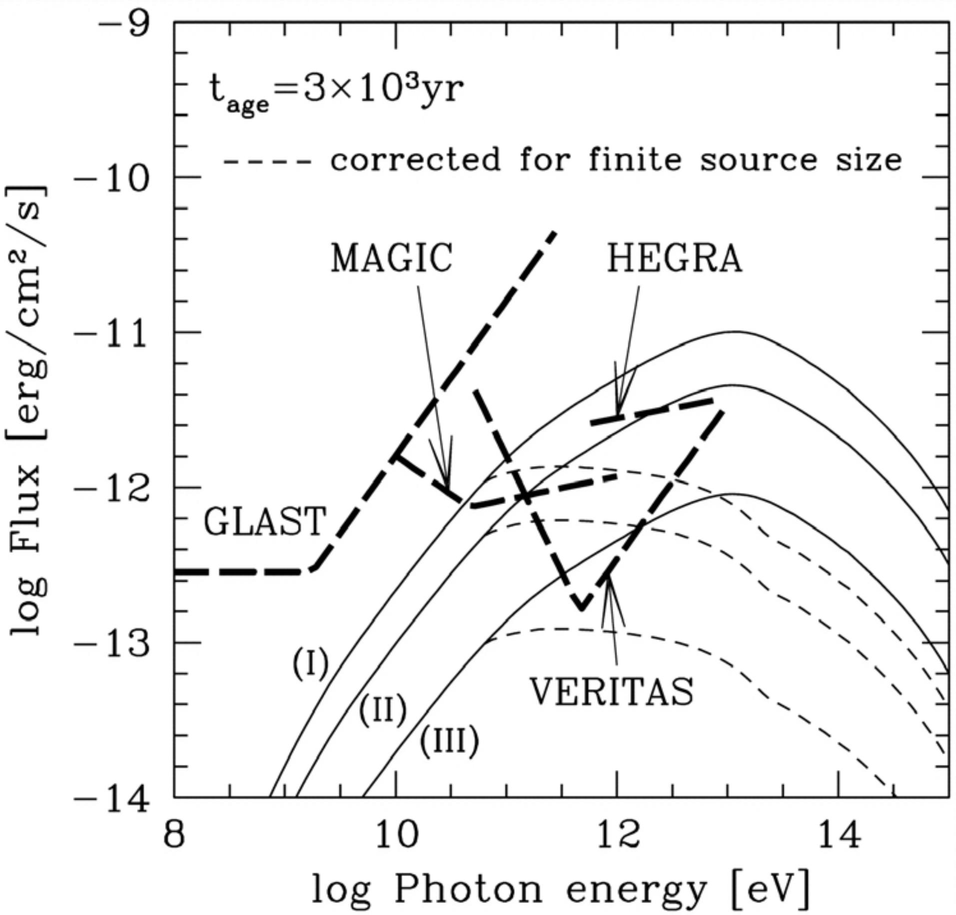
Hadronic and leptonic emission components

1. Two-step collapse (short-delay supranova) model for long-duration GRBs
2. GRB prompt phase could be due to blast wave shell penetrating SN remnant

Neutron Decay Emissions from a Galactic GRB

Compton-scattered CMBR from Neutron-Decay Electrons
formed by GRB associated with W49B





(Ioka, Kobayashi, & Mészáros 2004)

Nonthermal γ-Ray Emission: γγ Transparency Argument for Bulk Relativistic Motion

In comoving frame, avoiding threshold condition for γγ interactions requires

$$\varepsilon'\varepsilon_1' < 1;\ Peak\ \ Flux\ \ :10^{-6} f_{-6}\ ergs\ \ cm^{-2} s^{-1}$$

Requirement that γγ optical depth be less than unity:

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

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

Hi Energy multiwavelength: Swift, GLAST GBM and LAT, IACTs, …