Can emission at higher energies provide insight into the physics of shocks and how the GRB inner engine works?

Eduardo do Couto e Silva

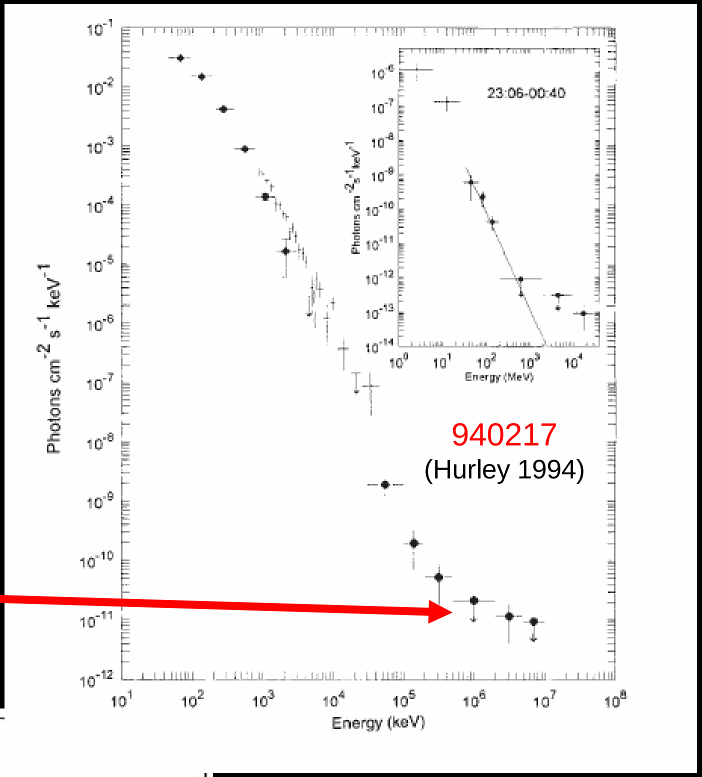
Dec 1 , 2005

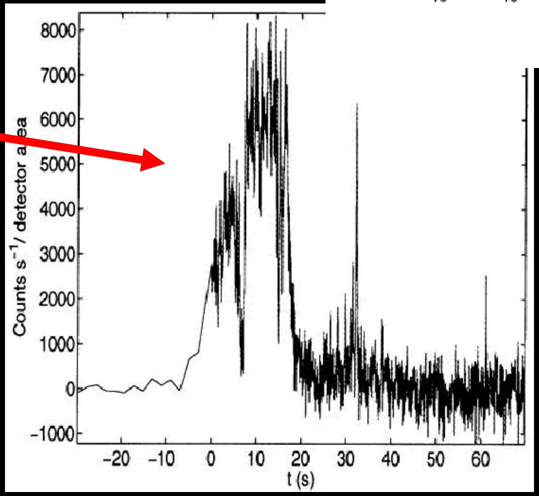
GRB Fundamental Questions

- Origin
  - Where does the energy come from?
    - How can it be so large?
    - How does the inner engine work?
- Evolution
  - How does the GRB evolve?
    - What are the dynamics of the relativistic flow?
    - How does it collimate the flow (in case of jets)?
- Observed Radiation
  - What is behind the emission mechanism?
    - How can we explain the radiation we observe?

Some GRB Experimental Facts

- Intensity, location, rate
  - Typical fluences
    - $10^{-4 \text{ to } -7}$ ergs cm^{-2}
  - Cosmological distances
    - z ~ 1
  - Rate
    - 1 /Myrs/galaxy
- Energy Spectrum
  - Non-thermal emission
    - up to γ rays (3 GeV)
- Temporal properties
  - Rapid flux variations
    - miliseconds
  - Range of burst durations
    - few seconds to hours



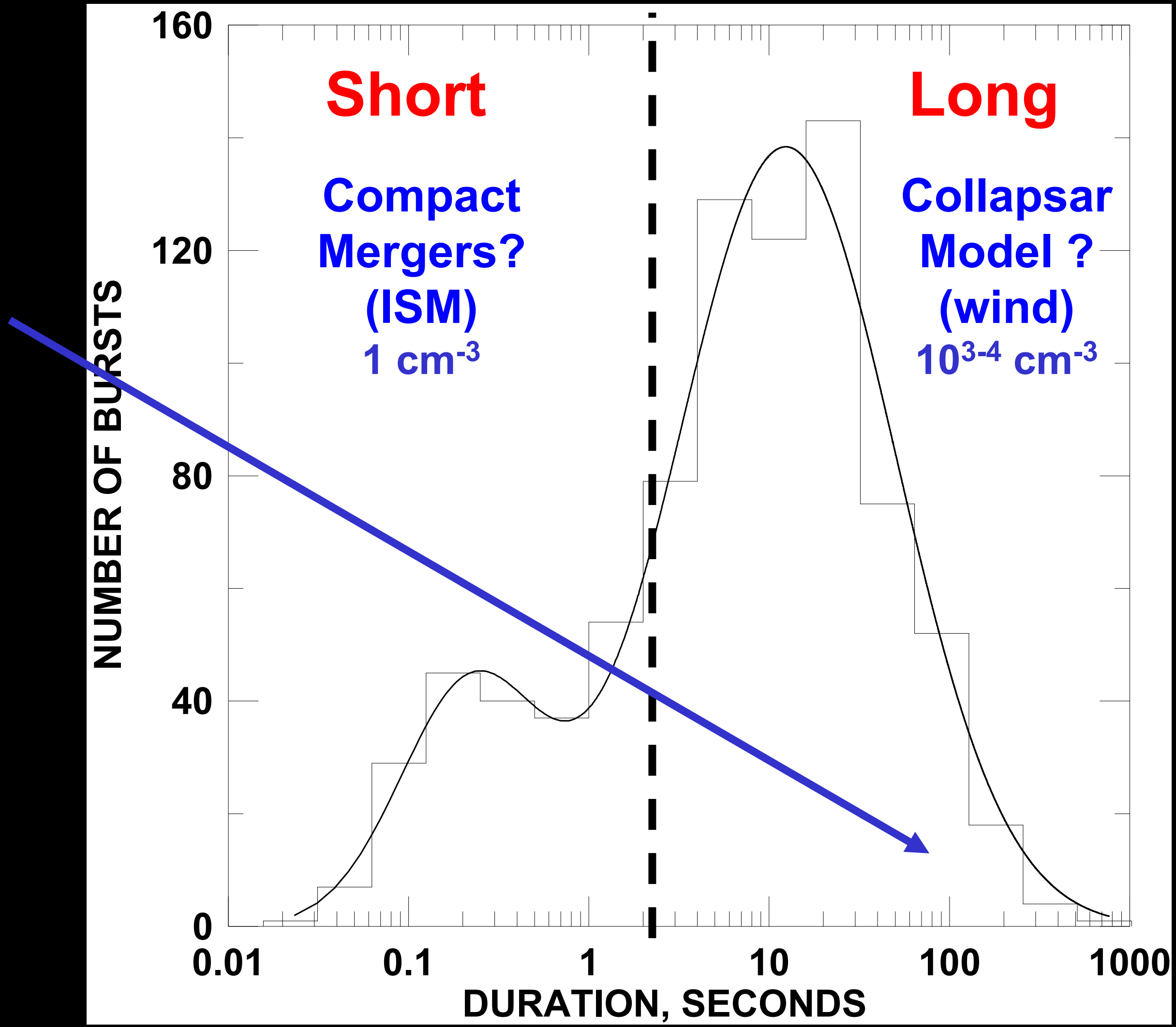


Transients are hard to catch!

Duration of GRBs

If there is a compact object at the inner engine, the source must also be active for a long time

(e.g stellar mass BH accreting from a massive disk, rotating NS driving Poynting flux)



Introduction to the Fireball Model

Catastrophic event:
merger or hypernova
(rapid and energetic)

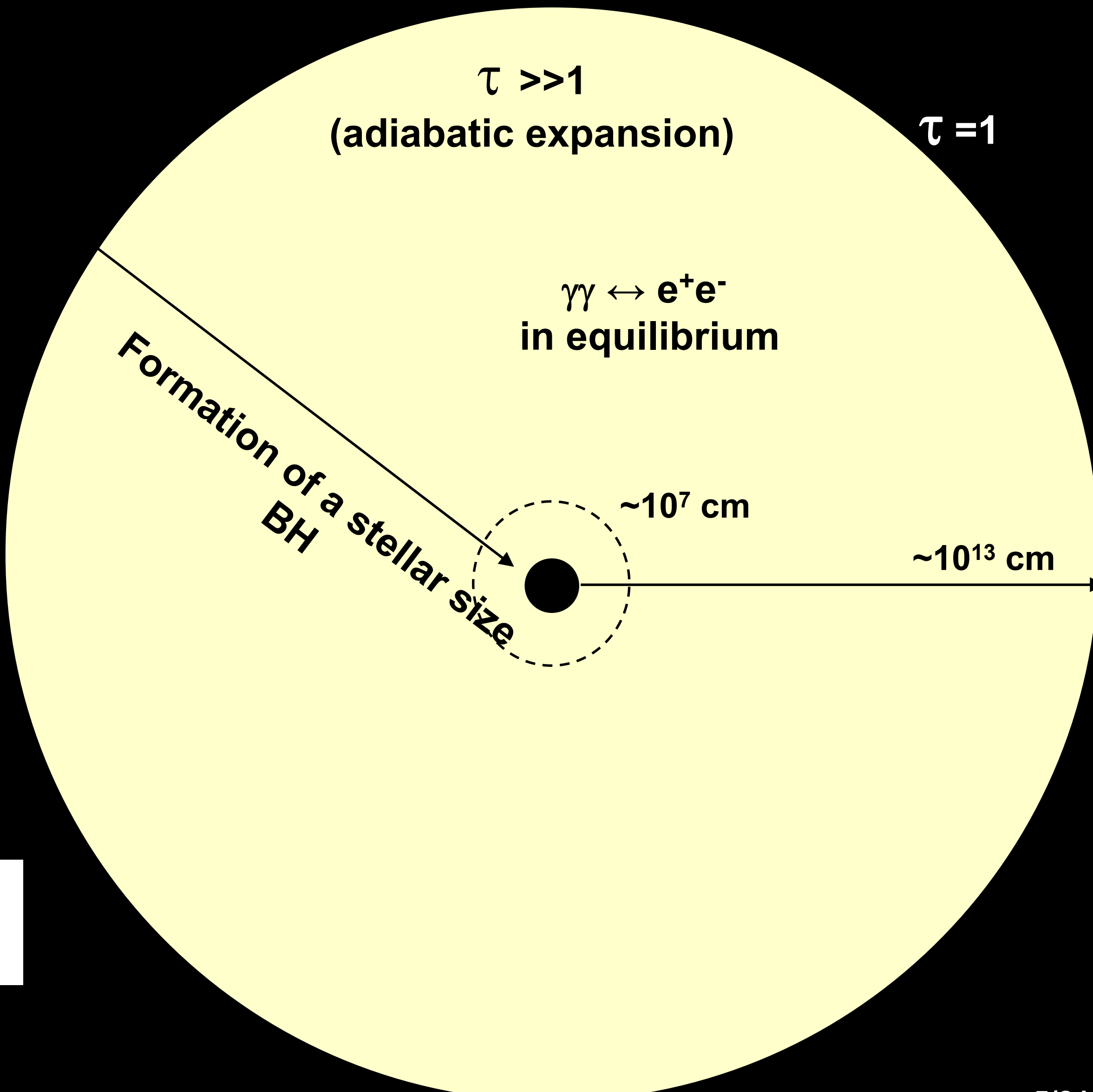
Energy release within gravitational radius of BH

($\gamma\gamma \leftrightarrow e^+e^-$ in equilibrium, radiation can not escape)

Little rest mass energy

(mostly relativistic flow)

Can it explain non-thermal emission in γ rays?

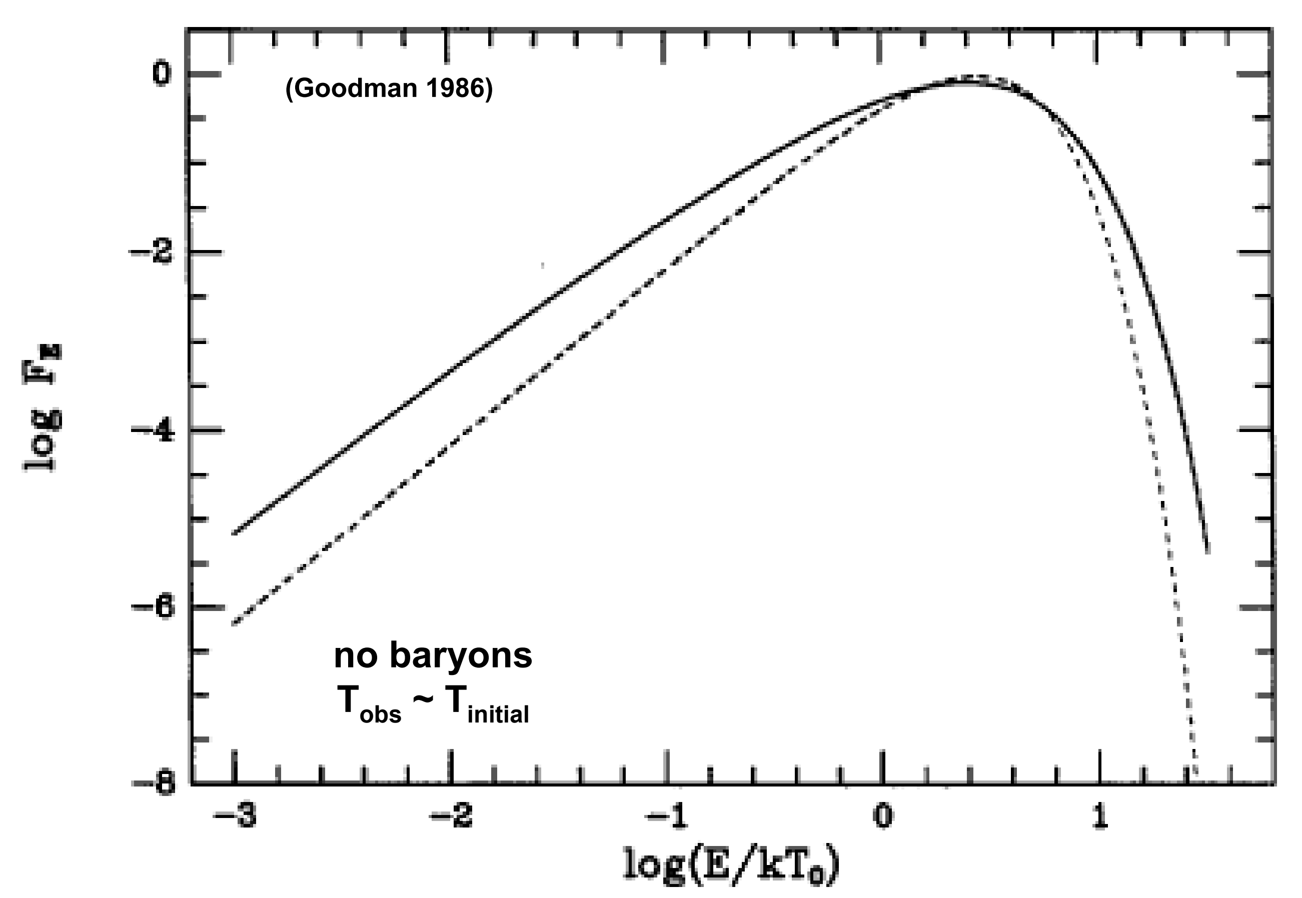


Fireball Model: quasi thermal spectrum

$$\tau_{\gamma\gamma} = \frac{f_p \sigma_T F D^2}{R_i^2 m_e c^2}$$

Fireball
(Piran 1999)

opaque radiation plasma whose initial energy is significantly greater than its rest mass



Large opacity means γ rays can't escape !

$$\tau_{\gamma\gamma} = 10^{13} f_p \left(\frac{F}{10^{-7}\, erg/cm^2}\right)\left(\frac{D}{3000 Mpc}\right)^2 \left(\frac{\delta T}{10 ms}\right)^{-2}$$

Burst variability

~10^{28} cm : cosmological distances

BATSE fluences

GRB Fundamental Questions

- Origin
  - Where does the energy come from?
    - How can it be so large?
    - How does the inner engine work?
- Evolution
  - How does the GRB evolve?
    - What are the dynamics of the relativistic flow?
    - How does it collimate the flow (in case of jets)?
- Observed Radiation
  - What is behind the emission mechanism?
    - How can we explain the radiation we observe?

Baryonic Load in the Fireball Model

Entropy per baryon $\eta = E_0 / M_0 c^2$

(model dependent)

High: $M_0 > 10^{-9} M_{sun}$, $\eta < 10^{-5}$

Low: $M_0 < 10^{-9} M_{sun}$, $\eta > 10^{-5}$

Internal Energy is converted into kinetic energy of baryons

(Baryons limit increase in Γ)

Competing processes:

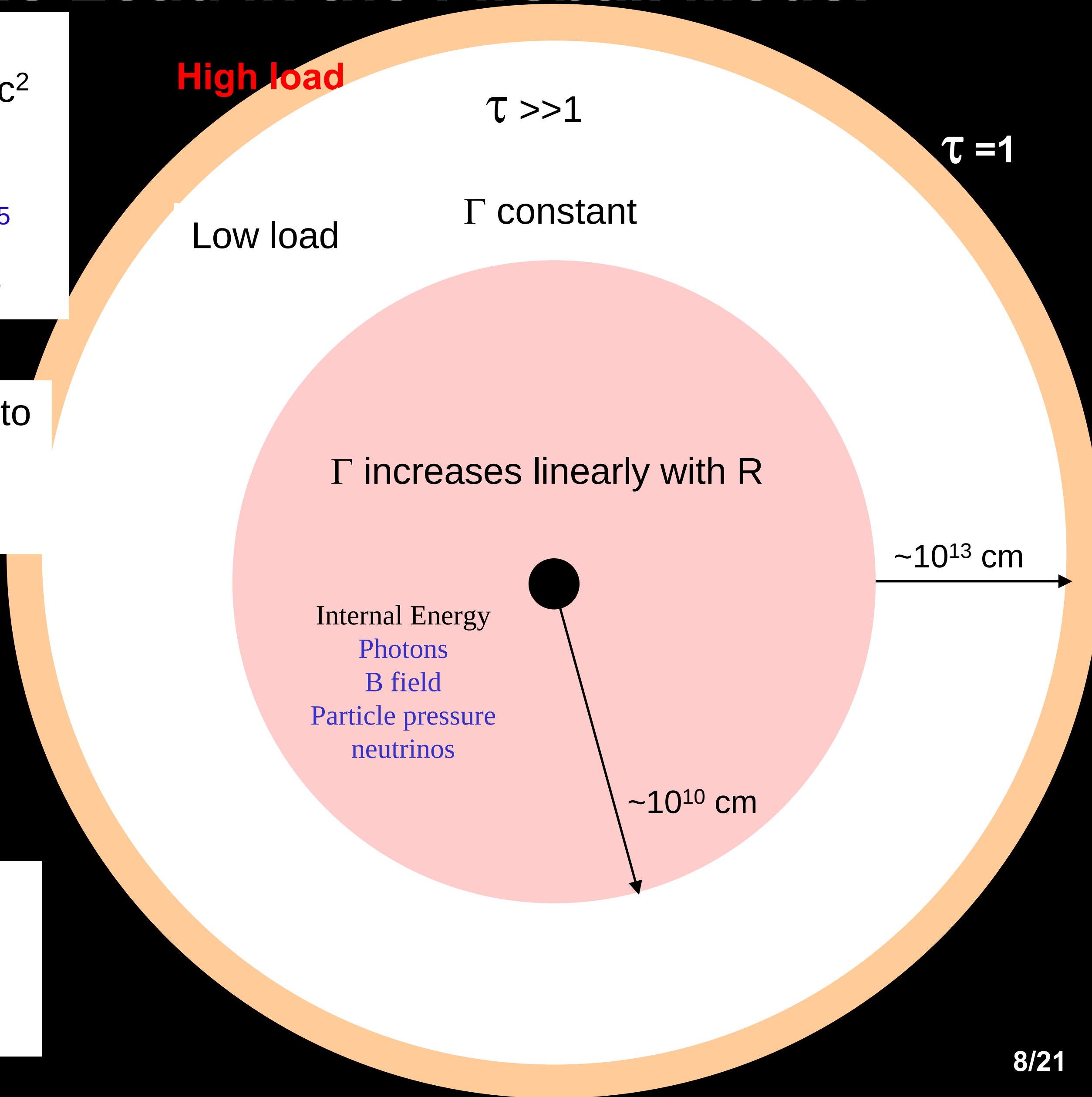
Bulk acceleration

relativistic flows of large Γ

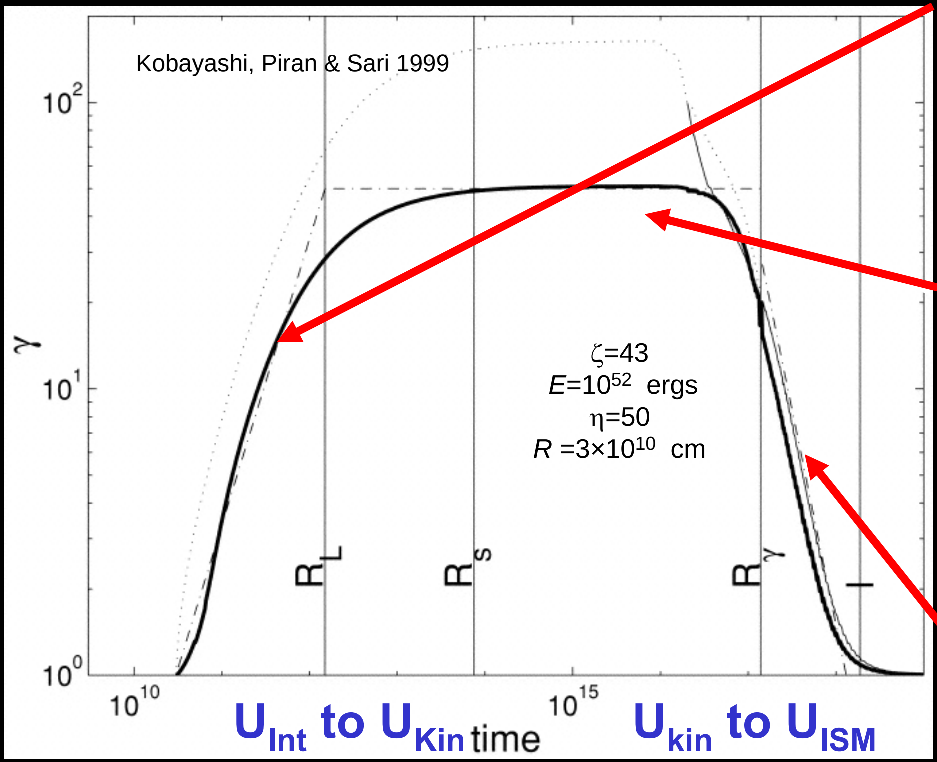
Cooling Losses

synchrotron or IC ~ Γ^2

Amount of baryons is determined by the original environment in which the fireball was created



Fireball Evolution



- **Expansion phase ($\Gamma \sim r$)**
  - **limited by the rest mass of baryons**
- **Coasting phase ($\Gamma \sim$ constant)**
  - **form shells of comparable size of the fireball at rest (Blandford and Mckee 1976)**
    - **Newtonian for large load**
    - **Relativistic for small load**
- **Decelerating phase ($\Gamma \sim r^{-2}$)**
  - **limited by inertia of external medium**

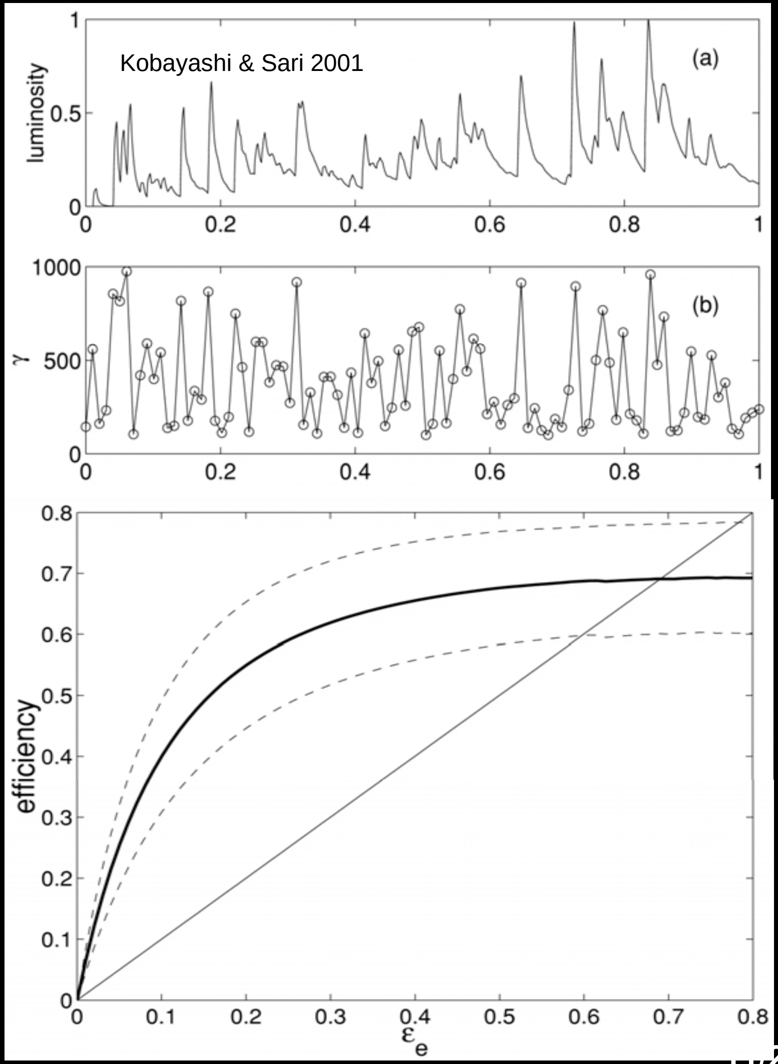
GRB Fundamental Questions

- Origin
  - Where does the energy come from?
    - How can it be so large?
    - How does the inner engine work?
- Evolution
  - How does the GRB evolve?
    - What are the dynamics of the relativistic flow?
    - How does it collimate the flow (in case of jets)?
- Observed Radiation
  - What is behind the emission mechanism?
    - How can we explain the radiation we observe?

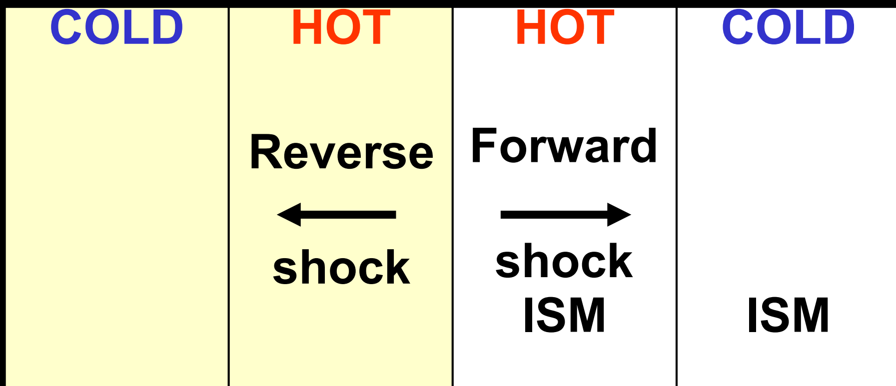
Dissipation Phase: Internal Shocks

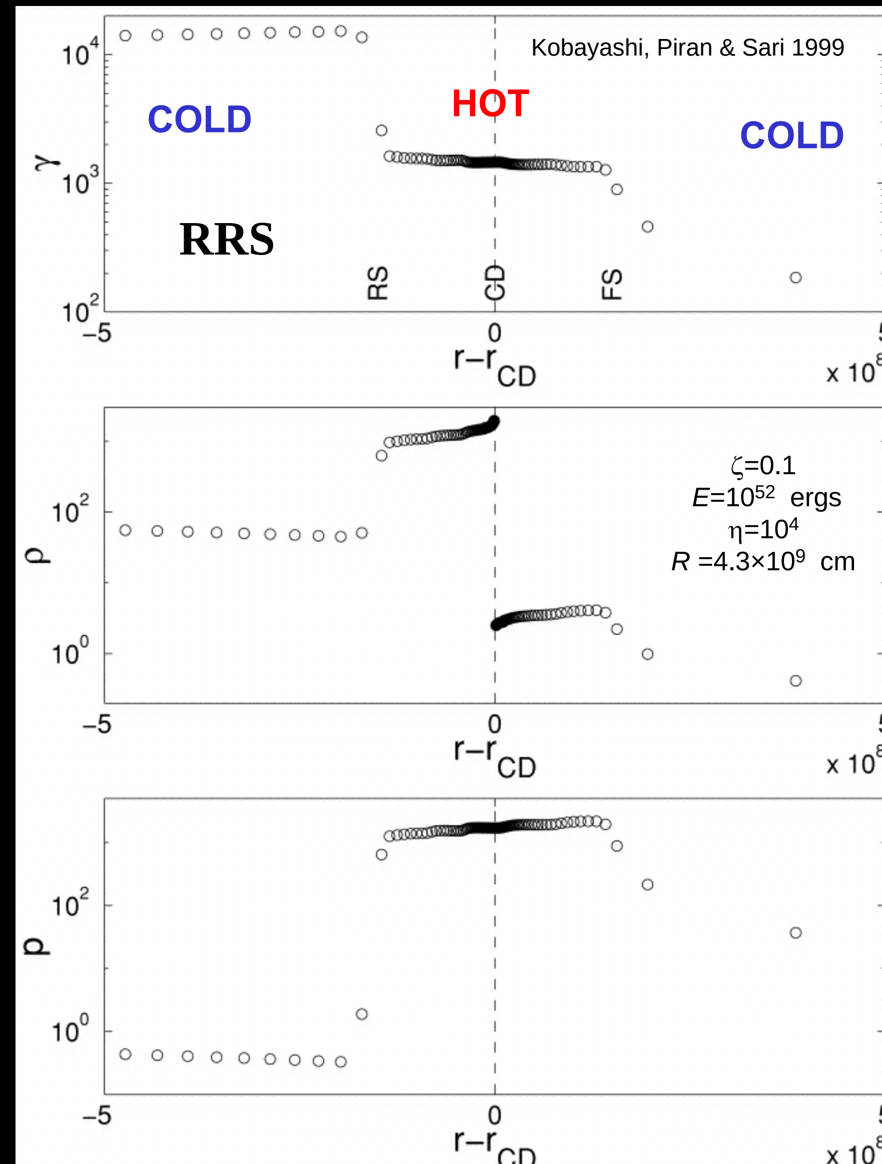
- Engine creates an outflow wind
  - Shells are produced
    - Fast ones catch slow ones
    - Fluctuations in the distribution Γ is responsible for time structure
- Efficiency Problem
  - Conversion of U_{kin} to radiation ~ few % (Kumar 1999)
  - can't transfer heat into radiation from Coulomb ep collisions
    - Hydrodynamic (1/10)
    - Radiation by e- (1/3)
    - Observed energy band (1/3)
- Variability depends on distance from inner engine (Zhang & Meszaros 2003)
  - Is shell's B local or from inner engine?

- Improve efficiency
  - multiple collisions



Dissipation Phase: External Shocks





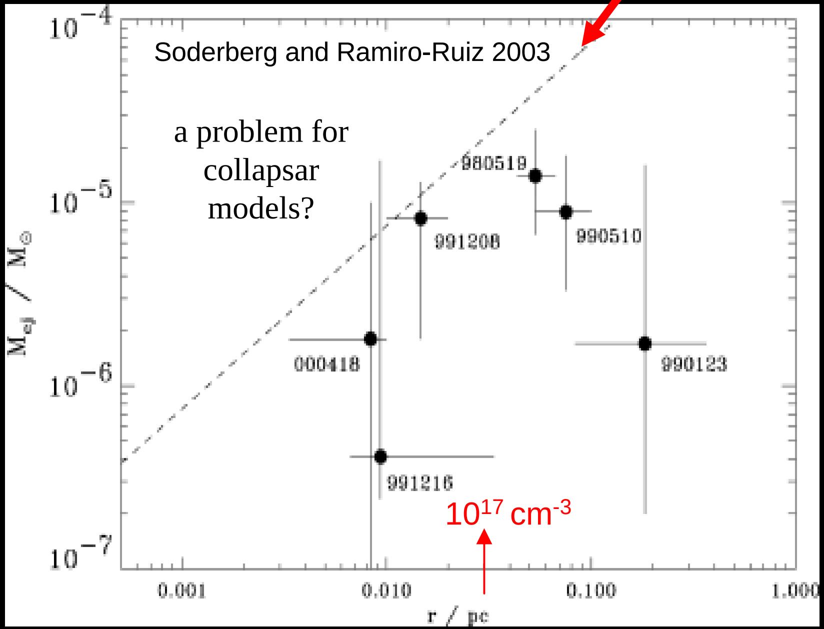
- Plethora of models
  - Shells
    - thin or thick
  - Shocks
    - Relativistic or Newtonian
  - External Medium
    - ISM or wind like

What is the ambient density?

$$\frac{dM}{dt} = 10^{-6} M_{\odot} . yr^{-1}$$
$$v_{wind} = 10^{3} km . s^{-1}$$

SNR > 1 M_{Θ}

- Deceleration Phase (~ 10^{17} cm)
  - Stellar wind in massive progenitor
    - Medium is not homogeneous
    - n ~ $1/r^2$
    - Wind sweeps ~ 1/ Γ x its rest mass
    - Typically ~ 10^{-6} M_{Θ}
  - Dense ISM as in early galaxies?
    - Constant medium density
    - ISM now ~ 1 cm^{-3}
    - Molecular clouds > 10^3 cm^{-3}
    - Clumpy ISM?
- Need initial Lorentz factor to put constraints on the swept-up matter versus radius
  - Timescale is days
    - relativistic effect

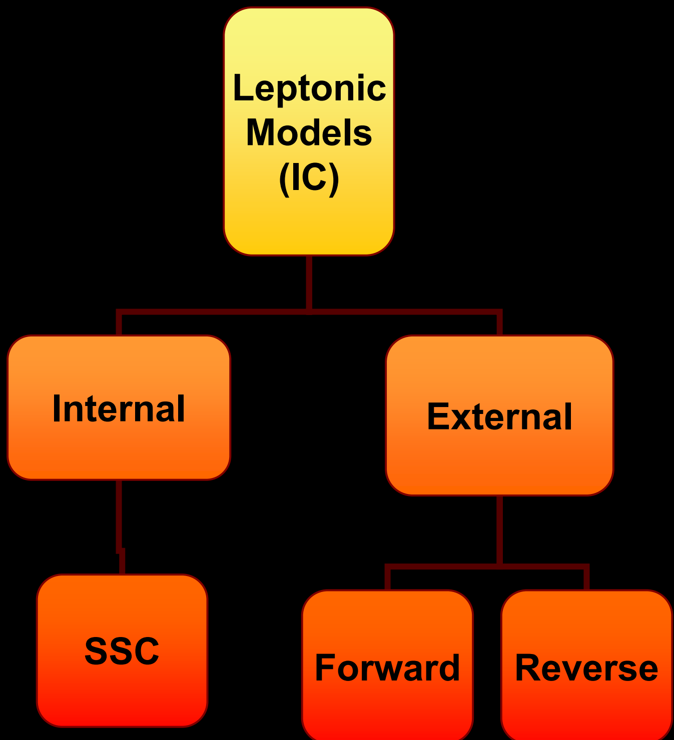


SNR ~ many pc

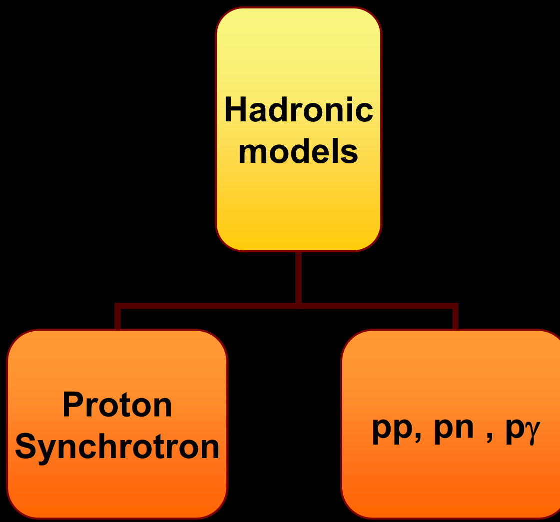
GRB	v_w (1000 km s^{-1})	$\dot{M}$ (10^{-6} $M_{\odot}$ yr^{-1})	n_0 (cm^{-3})
980519	0.58	0.3	100.0
990123	0.50	0.015	3.4
990510	1.4	0.2	55.0
991208	1.0	0.7	> 10^4
991216	1.8	0.08	> 10^4
000418	1.4	0.9	> 10^4

Fit parameters

High Energy Emission Models



- Controversial
- Hard to model IC
  (Pe'er Waxman 2005)
  - KN regime
  - HE EM cascades
  - Large τ from e+-



- Internal
  - 100 keV + γ_e^3 = 100 GeV
- External Forward
  - 10 keV + γ_e^5 = 100 TeV
- External Reverse
  - 100 eV + γ_e^3 = 100 MeV

Shock Plasma Parameters

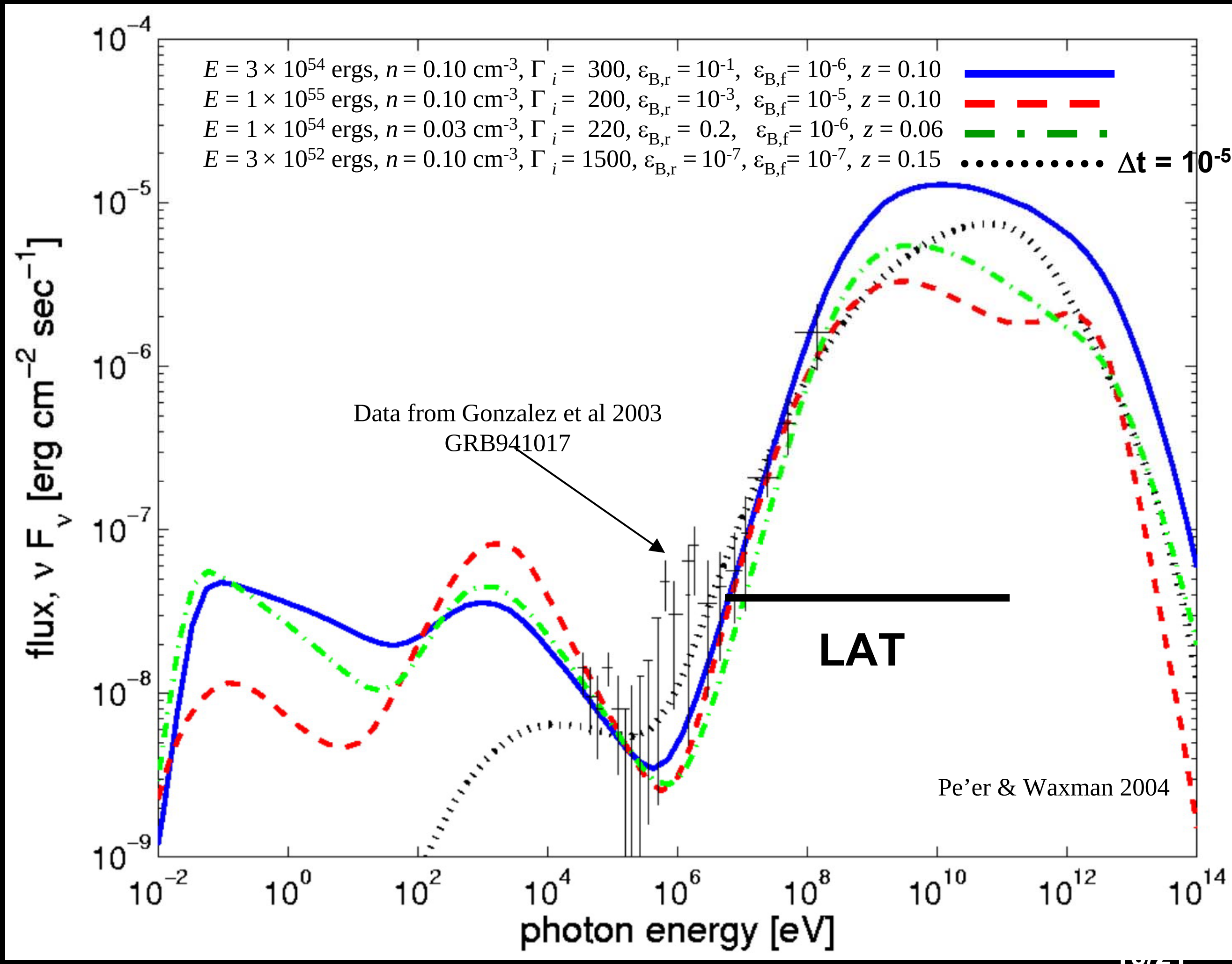
- Luminosity of the Source
  - $L \sim 10^{52}$ ergs s^{-1}
    - too hard for GLAST
- Lorentz Factor of Bulk Plasma
  - $\Gamma \sim 10^2$ to 10^3
    - cut-offs at the energy spectrum (GLAST)
- Time Variability
  - $\Delta T \sim 10^{-4}$ to 10^{-3} s
    - ~30 μs with GLAST
- Fraction of Thermal Magnetic Energy Density behind the shock
  - $\varepsilon_B \sim 1$ to 10^{-5}
    - Ratio of peaks in SED (GLAST+?)
- Fraction of Thermal Electron Energy Density behind the shock
  - $\varepsilon_e \sim 1$ to 10^{-5}
    - Ratio of peaks in SED (GLAST+?)
- Energy distribution of accelerated electrons
  - p (power law index) ~ 2 to 3
    - SED fits (GLAST+?)

Can we use GLAST measurements to constrain these parameters?

Are p, ε_B ε_e time independent?
(Paitanescu and Kumar 2001)

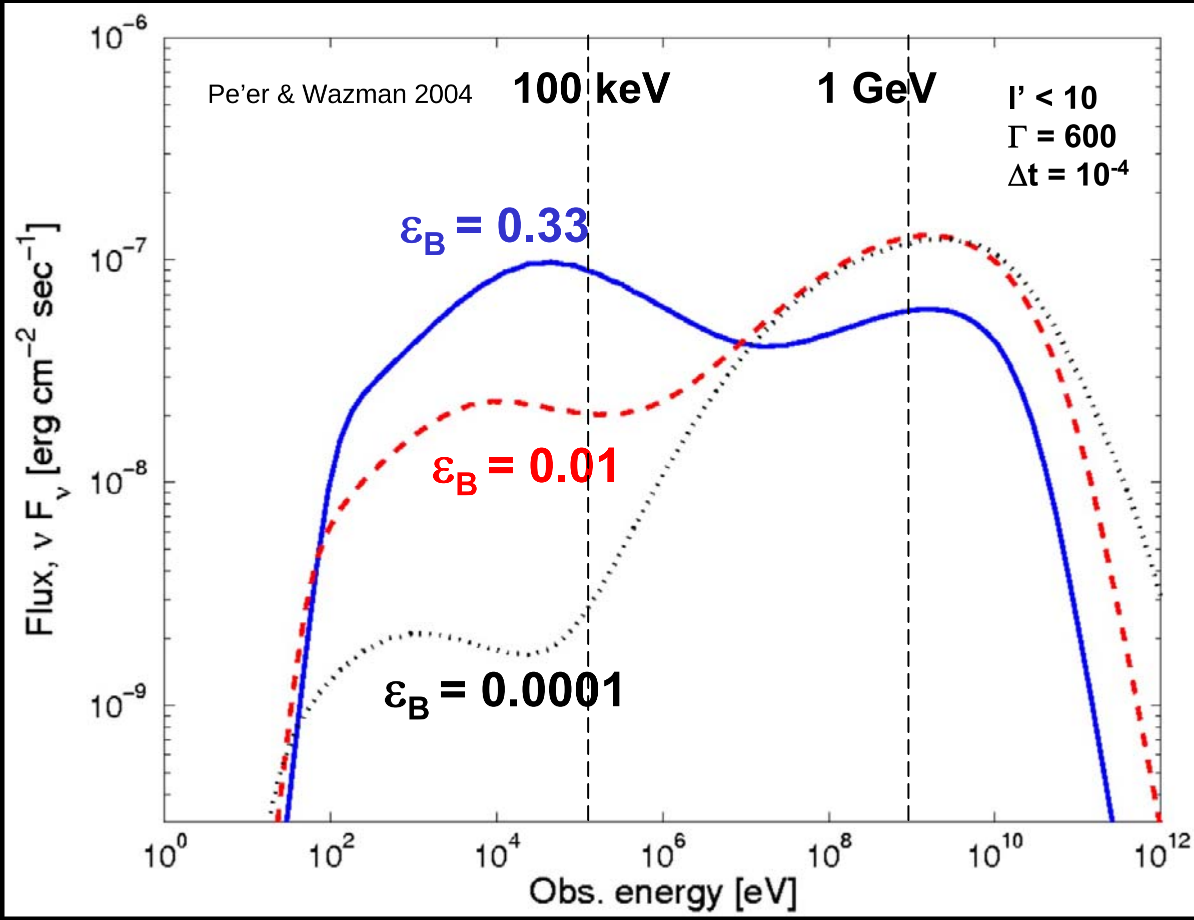
Modeling Delayed Emission for GRB941017

- High Energy data constrains
  - Total Energy
  - Lorentz factor
  - Ambient density
- Two models used
  - External shock
    - e- from FS IC scatters γ from RS
    - SSA is important
  - Internal Shock
    - $\Delta t = 10^{-5}$



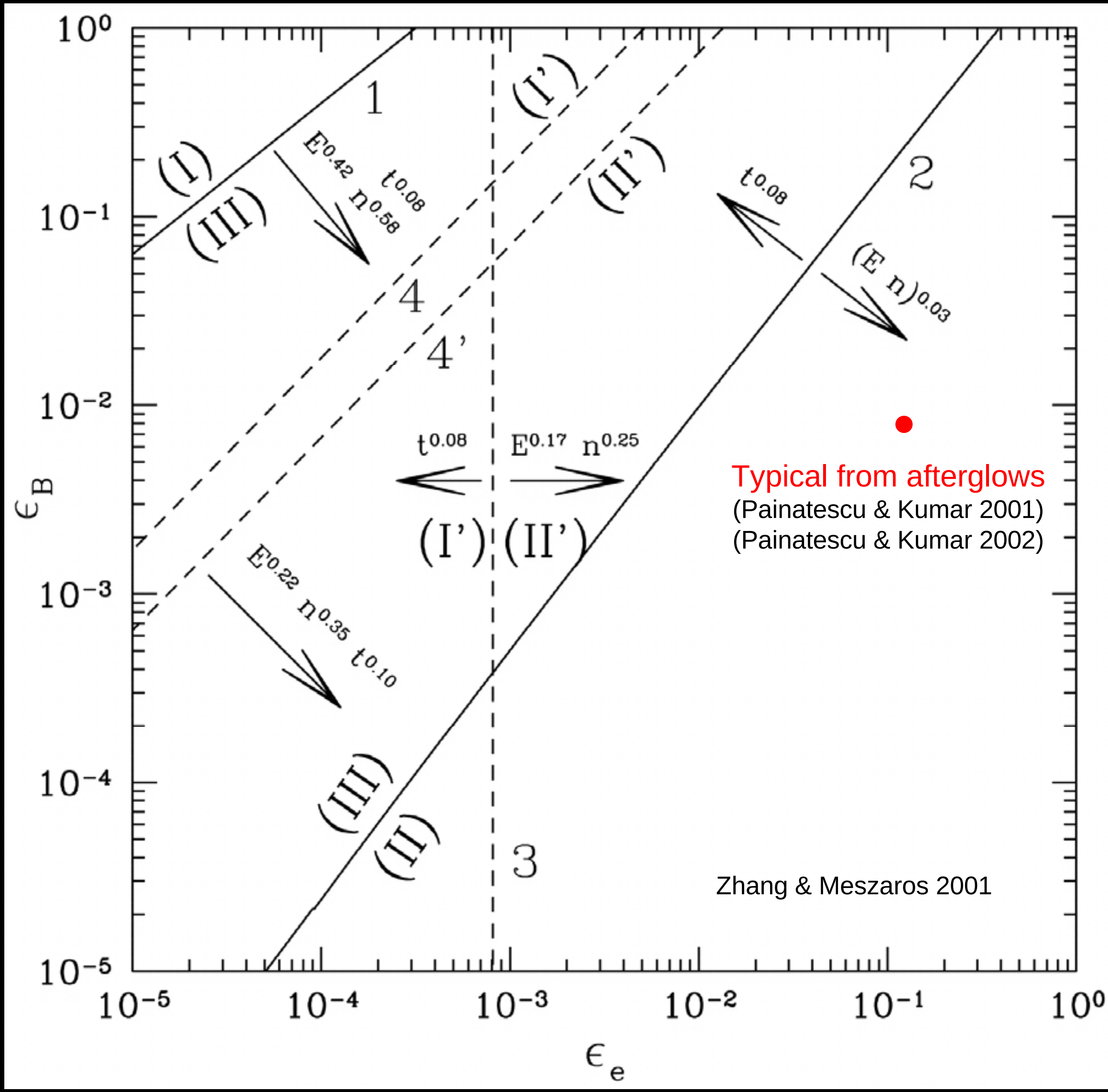
Multiwavelength Observations to Constrain Models

- Model
  - Prompt emission from internal shocks
    - in relativistic wind
  - Spectra as high as 10 GeV
    - Flux has a strong dependence on Γ
    - Measure cut-offs with GLAST!
- Ratio of peaks in kev/GeV can be used to constrain ratio of $\varepsilon_B / \varepsilon_e$
    - LAT + GBM?
    - Swift + GLAST?
- Caveat:
  - single shell collisions



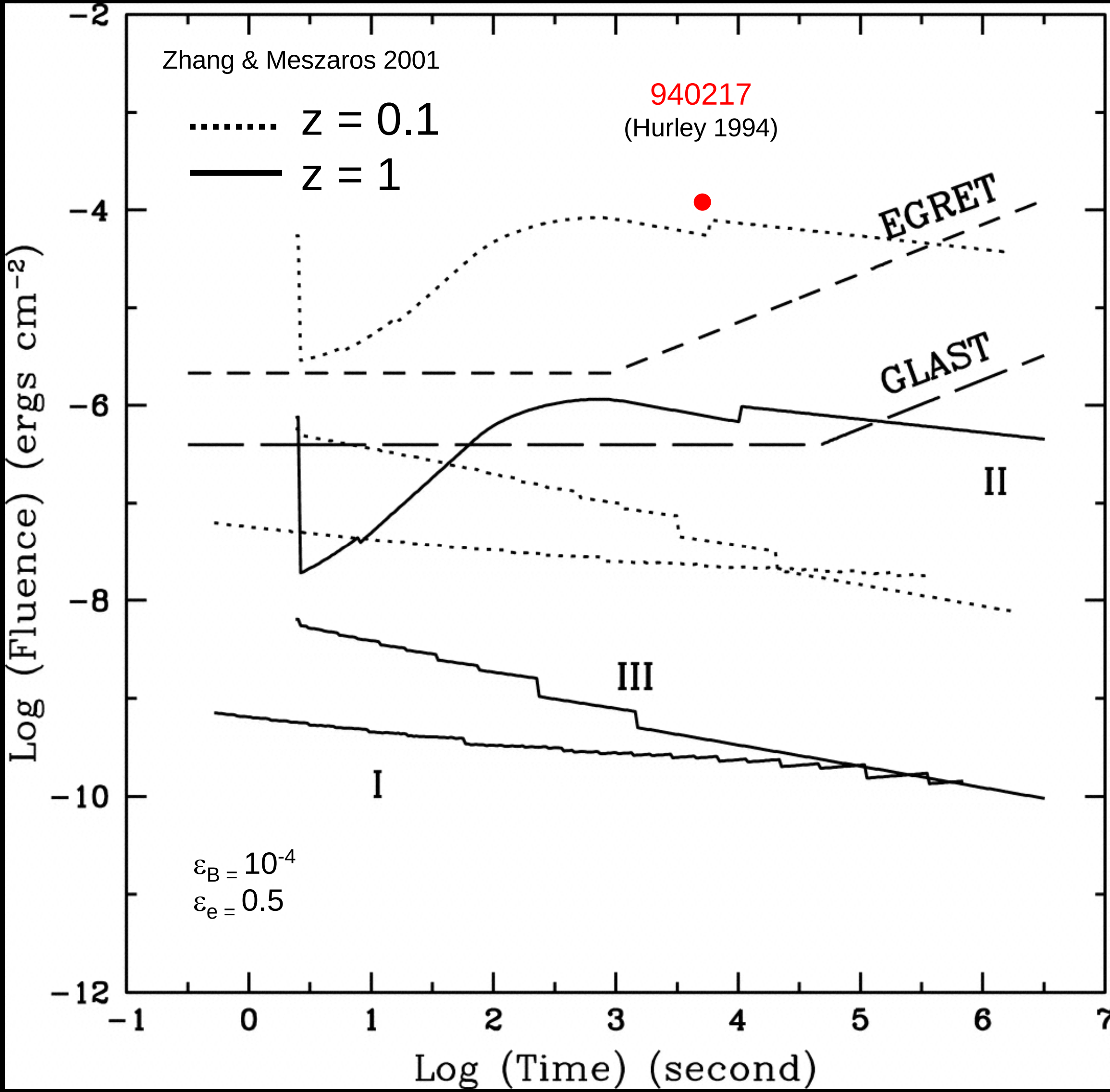
Which Model do we Choose?

- Region I
  - Proton synchroton
    - hard with GLAST
    - large ε_B
- Region II
  - Inverse Compton
    - good for GLAST
    - denser medium helps
    - small ε_B :internal shocks
- Region III
  - Electron synchroton
    - not in GLAST range



We need DATA !

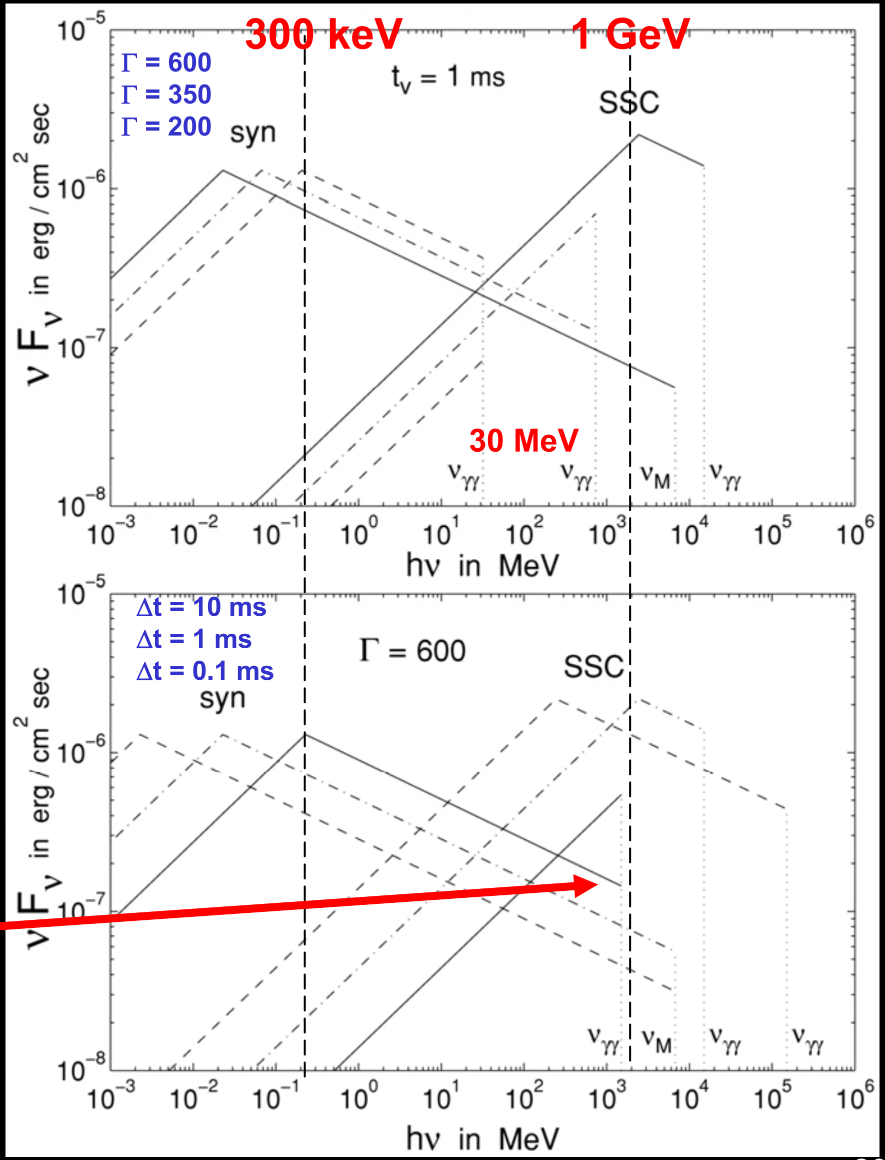
- **Region I**
  - Proton synchroton
    - hard with GLAST
    - large ε_B
- **Region II**
  - Inverse Compton
    - good for GLAST
    - denser medium helps
- **Region III**
  - Electron synchroton
    - not in GLAST range



Can we constrain p and Γ?

Guetta & Granot 2003

- **Model**
  - **Prompt emission from internal shocks**
    - **in relativistic wind**
  - **To escape the system photons must have**
    - **opacity of HE γ to pair production with LE γ < 1**
    - **opacity to pair production < 1**
  - **SSC dominates above 100 MeV**
    - **Power law index > 2**
    - **GLAST can constrain p**
- **GRB940217:**
  - **Γ= 600, Δt = 0.1 ms, E_p = 200 KeV**
  - **Should we expect variability smaller that 0.1 ms?**



To B or Not to B….

- Magnetic Fields may play a key role in GRB formation
  - Magnetic Poynting flux dominates instead of radiation pressure
  - Easier to transport energy
    - No need of baryons (good for internal models)
  - Narrower Peak Energy distribution
  - Energy components
    - Electromagnetic
    - Internal
    - Kinetic (bulk)

$$\sigma = \frac{EM}{U_{\mathrm{int}} + U_{kin}}$$

Large value makes it hard to develop strong external shocks

(Paitanescu and Kumar 2001)

- This will be my next talk…