Gamma Ray Bursts

Theory and observations

Dafne Guetta OAR

Useful reviews:

Waxman astro-ph/0103186
Ghisellini astro-ph/0111584
Piran astro-ph/0405503
Meszaros astro-ph/0605208

GRBs most luminous objects in the Universe!!

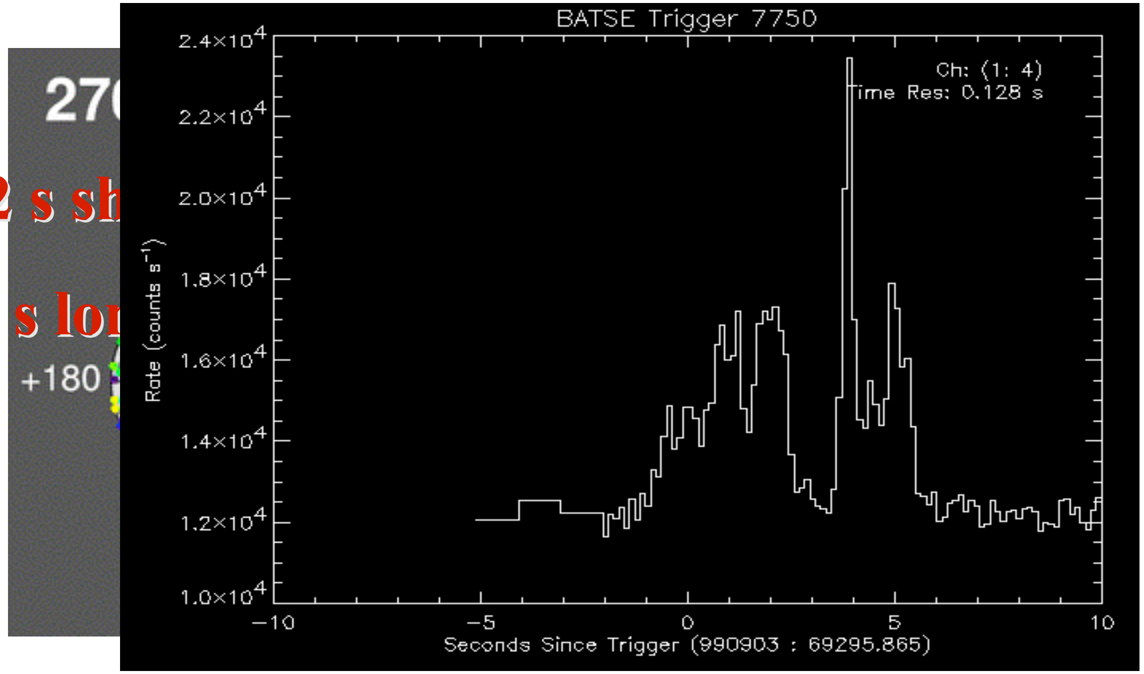
- Sun Luminosity $L_{\odot} \sim 4 * 10^{33}$ erg/s
- Supernova $L \sim 10^{51}$ erg/s
- Galaxies with nuclei $L \sim 10^{48}$ erg/s
- **GRB luminosity $L \sim 10^{52}$ erg/s**
- **Also Most distant objects in the universe! $z_{max} \sim 9$**

GRBs: flashes of 0.1 MeV gamma rays that last 1-100 s

γ-ray observations summary

- Isotropy in the sky

- Duration: $T_{90} \approx$ { 0.2 s sh / 20 s lo



- Variability: Most show $\Delta t \sim 64$ ms
  Some $\Delta t \sim 1$ ms

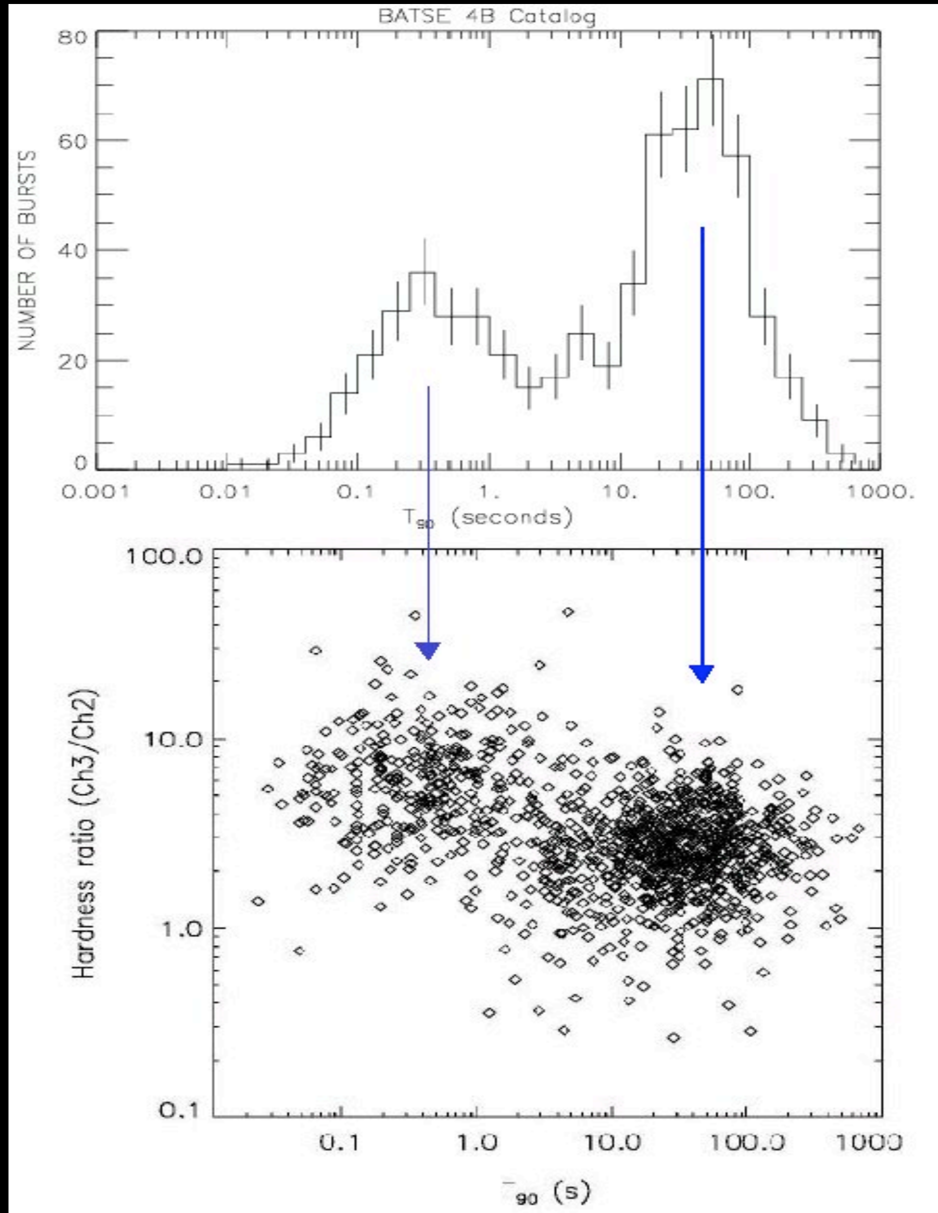
- Flux: $f = 10^{-4}$ - 10^{-7} erg/cm^2 s

- Rate R ≈ 300/yr BATSE and 100/yr Swift

Two different classes of Gamma-Ray Bursts

- GRBs duration distribution is bimodal (e.g. Briggs et al. 2002)
  - 0.1-1 s -> Short bursts
  - 10-100 s -> Long bursts

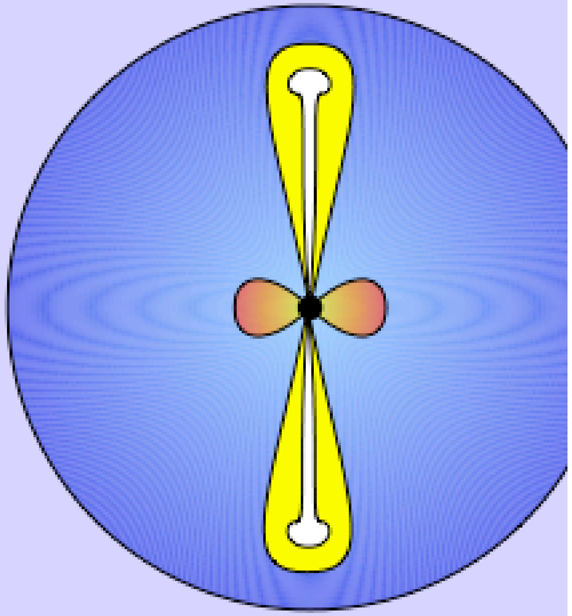
- Short GRBs are harder than long GRBs (e.g. Fishman & Meegan, 1995;Tavani 1996).



Progenitor Long GRBs: Collapsar model $M>30\ M_{\odot}$

Very rough overview

- The core of a rotating massive star collapses to a black hole.
- Material far from the axis does not fall straight in, but forms an accretion disk first.
- Dissipative effects in the disk convert kinetic energy into heat.
- Energy deposited over the poles of the disk powers jets.

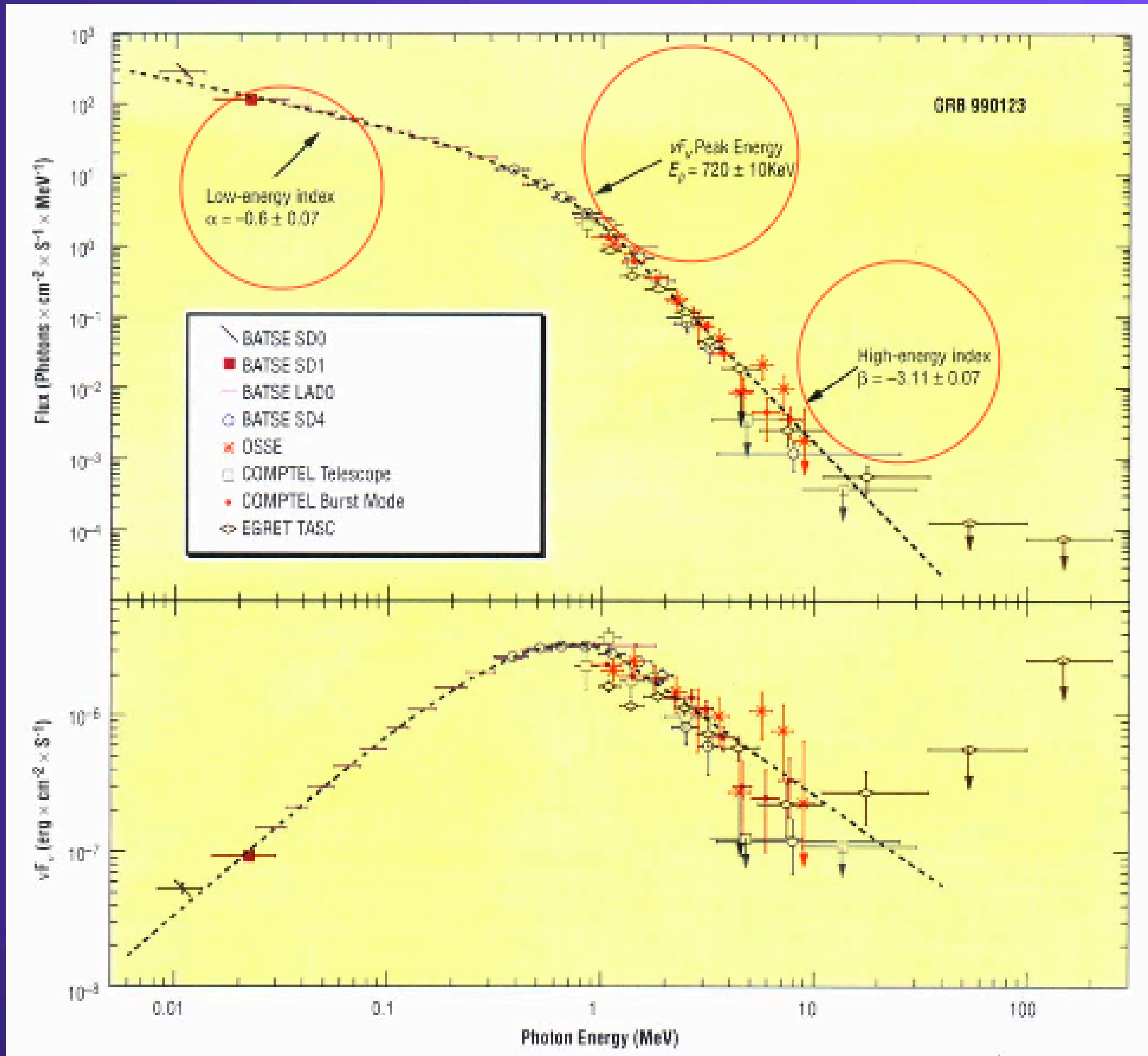


The progenitor star

- Mass: > 30 $M_\odot$
  - Lifetime: 4 – 7 million years
  - It will lose its hydrogen envelope through stellar winds, forming a Wolf-Rayet star, ≈ 300000 km in radius
  - Helium core > 12 $M_\odot$
  - Iron core > 2 $M_\odot$
- Rapidly rotating, ≈ 200 km/s at the surface

Leading model for short GRBs Progenitors
NS-NS merging primordial DNS

Common GRB spectrum of all CGRO instruments



Spectrum well described by a broken power law
Band approximation

•**Non-thermal Spectrum** $N(E) \propto \begin{cases} E^{\alpha} & E<E_0 \\ E^{\beta} & E>E_0 \end{cases}$

BATSE (20 keV-1 MeV)

0.1 MeV < E_0< 1 MeV

$\beta \approx -2$, $\alpha \sim [-1, -0.5]$

The compactness problem

- $\Delta t \sim$ 1-10 ms ➡ Compact sources $R_0 \leq c\,\Delta t \sim 3\ 10^7$ cm

- Cosmological sources (D~3 Gpc) ➡ $L_\gamma \sim fD^2 \sim 10^{52}$ erg/s

  R of our galaxy ~ 30 kpc: extragalactic objects

$$\varepsilon_{\gamma 1}\,\varepsilon_{\gamma 2} \geq (m_e c^2)^2 \qquad \gamma\gamma \rightarrow e^+e^-$$

$$\tau_{\gamma\gamma} \sim \zeta_p R_0 n_\gamma \sigma_T \sim \sigma_T L_\gamma / 4\pi R_0 c\,\varepsilon_\gamma \sim 10^{15}$$

ζ_p fraction of photons above the thereshold of pair production

σ_T=6.25x10^{-25}cm^2

$\varepsilon_\gamma \sim$ 1 MeV

Optical depth $\tau_{\gamma\gamma}$ $(\gamma\gamma \rightarrow e^+e^-)$ >>1

Implications: The fireball

How can the photons escape the source?

Relativistic motion: A plasma of $e^+ e^- \gamma$, a Fireball, which expands and accelerate to relativistic velocities, optical depth reduced by relativistic expansion with Lorentz factor Γ

The reasons:

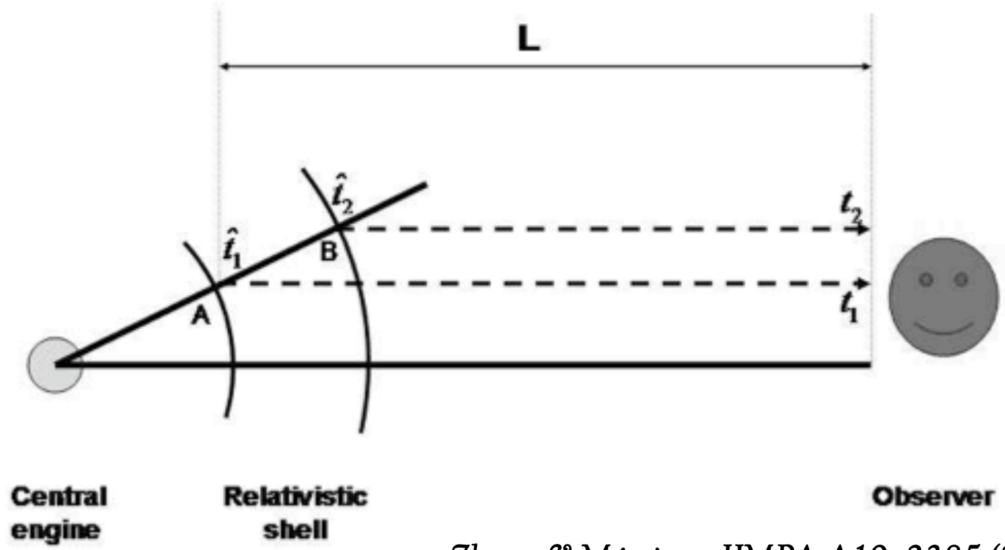
1. In the comoving frame γ below the thereshold for pair production $\varepsilon'_\gamma = \varepsilon_\gamma / \Gamma$ ⇨ $\varepsilon'_{\gamma 1} \varepsilon'_{\gamma 2} \leq (m_e c^2)^2$
2. Number of photons above the threshold reduced by $\Gamma^{2(\alpha - 1)}$ ($\alpha \sim 2$ high-energy photon index);
3. Emitting region has a size of $\Gamma^2 R_0$

$$\Gamma = \sqrt{\frac{1}{1-(v/c)^2}} = \sqrt{\frac{1}{1-\beta^2}}$$

→ $\tau_{\gamma\gamma}$ reduced by a factor $\Gamma^{2+2\alpha} \sim \Gamma^6$.

$\tau_{\gamma\gamma} < 1$ for $\Gamma \geq 100$

Propagation effect



Zhang & Mészàros, IJMPA A19, 2385 (2004)

$$d\hat{t} = \hat{t}_2 - \hat{t}_1 \cong dr/c$$

$$t_1 = \hat{t}_1 + L/c$$

$$t_2 = \hat{t}_2 + (L/c - \beta\cos\vartheta d\hat{t})$$

$$dt = (1-\beta\cos\vartheta)d\hat{t} \cong d\hat{t}/2\Gamma^2$$

Finally,

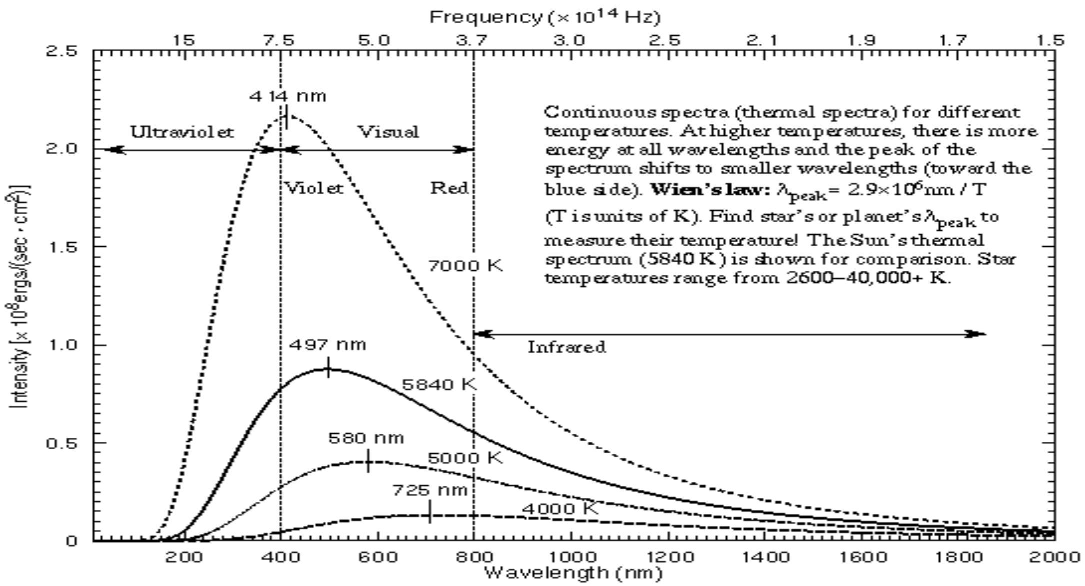
- *dt', comoving time of the shell*

$$dt' = d\hat{t}\,/\Gamma = dt\,/\Gamma(1-\beta\cos\vartheta) = Ddt \cong 2\Gamma dt$$

where D is the Doppler factor.

Fireball evolution

- Fireball expands and cools pairs annihilate and photons may escape, quasi-thermal emission against observations!!!
- Therefore a small barion loading (≥$10^{-8}M_{\odot}$) is needed and the radiation energy is converted to kinetic energy



The Lorentz factor

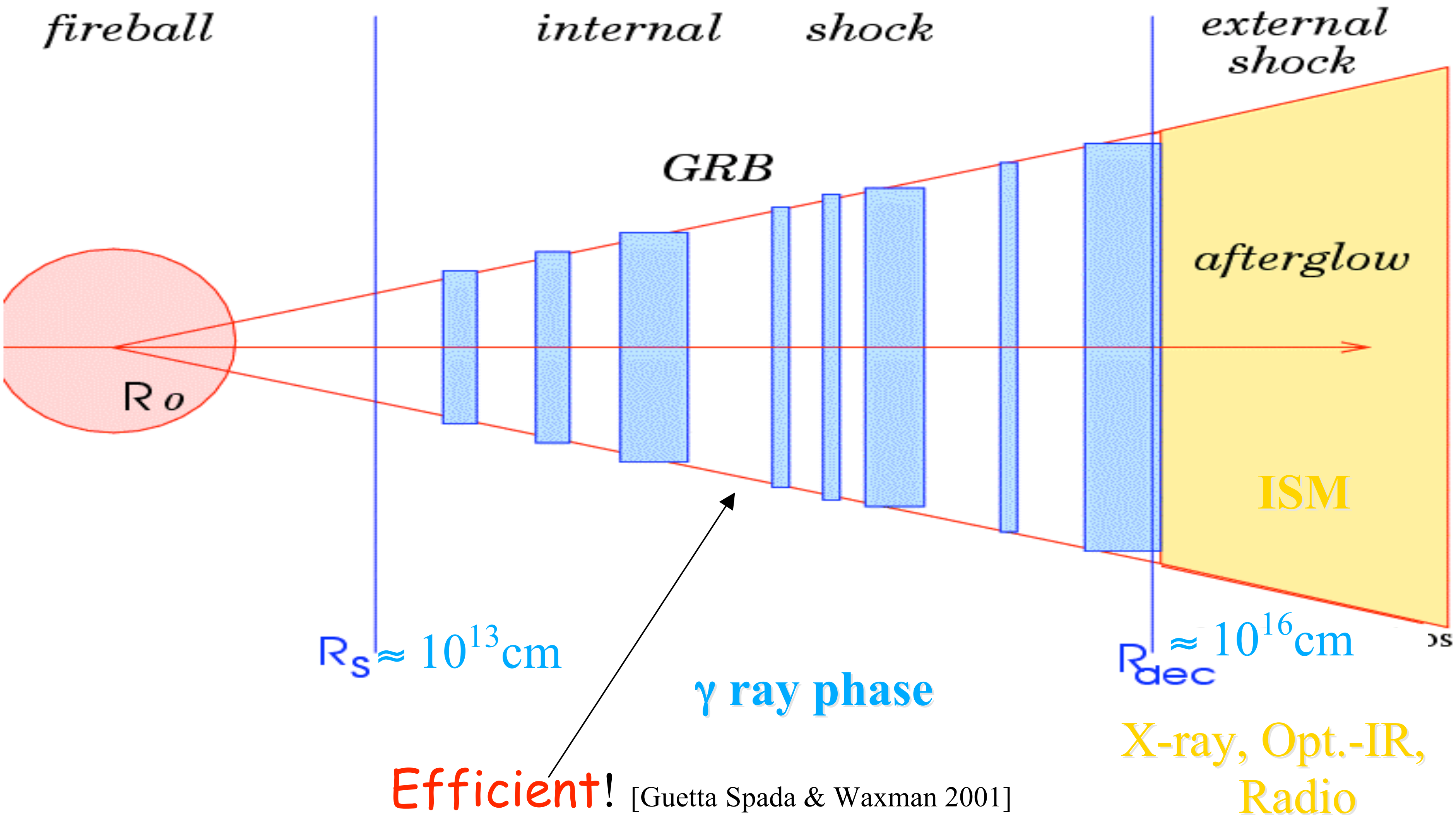
- *As the fireball shell expands, the baryons will be accelerated by radiation pressure.*
- *The fireball bulk Lorentz factor increases linearly with radius.*
- $\Gamma_0 \sim \eta \equiv E/M_0c^2$, M_0 *total baryon mass of the fireball*

How the energy is dissipated

- In order to have some emission from the firebal the energy must be dissipated somehow.
- Observed GRB produced by dissipation of the kinetic energy of this relativistic expanding fireball regardless the nature of the underlying source.
- Possible dissipation mechanism **Internal shocks: collisions between different parts of the plasma**

The internal/external shock scenario

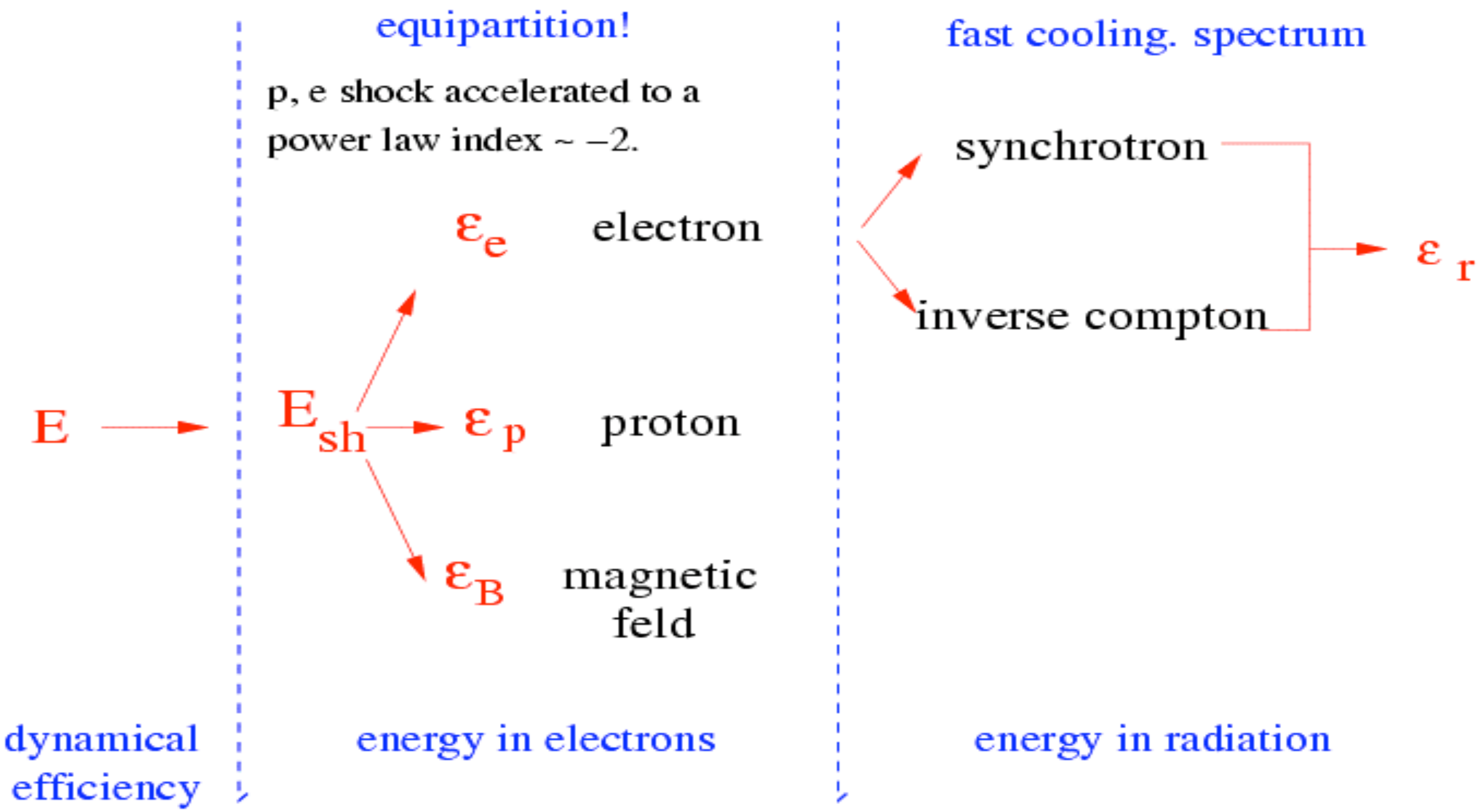
[Rees & Meszaros 1992, '94]



[Guetta Spada & Waxman 2001]

The radiation mechanisms

For each collision:



The efficiency of internal shocks

Shells collide and merge in a single shell with

$$\Gamma = \left(\frac{M_1\Gamma_1 + M_2\Gamma_2}{M_1/\Gamma_1 + M_2/\Gamma_2} \right)$$

$$E_{in} = \left[M_1\Gamma_1 + M_2\Gamma_2 - (M_1 + M_2)\Gamma \right] c^2$$

The conversion efficiency of kinetic energy into internal energy

$$\eta = 1 - \left(\frac{(M_1 + M_2)\Gamma}{M_1\Gamma_1 + M_2\Gamma_2} \right)$$

To get high efficiency $\Gamma_1 >> \Gamma_2$ and $M_1 = M_2$ only a fraction ε_e radiated max 20% can be radiated *(Guetta et al. 2001)* **But the total afterglow energy ~ burst energy!** *(Freedman and Waxman 2001)*

Problem 1: Low efficiency of internal shocks

Internal shock radius

Let's assume that a faster shell (2) impacts on a slower the leading shell (1);

If $\Delta t = t_v$ is the average interval between two pulses (interval between shells ejection)

$$d = ct_v$$

$$\Gamma_2 >> \Gamma_1 \approx \Gamma_0$$

$$r_{is} = cd/(v_2 - v_1) \cong 2\Gamma_1^2 d = 2\Gamma_1^2 ct_v$$

$$r_{is} \cong 10^{13} cm(\Gamma_0/100)^2 (t_v/0.1s)$$

$$\Gamma = \sqrt{\frac{1}{1-(v/c)^2}}$$

Emission properties determined by r_{is}

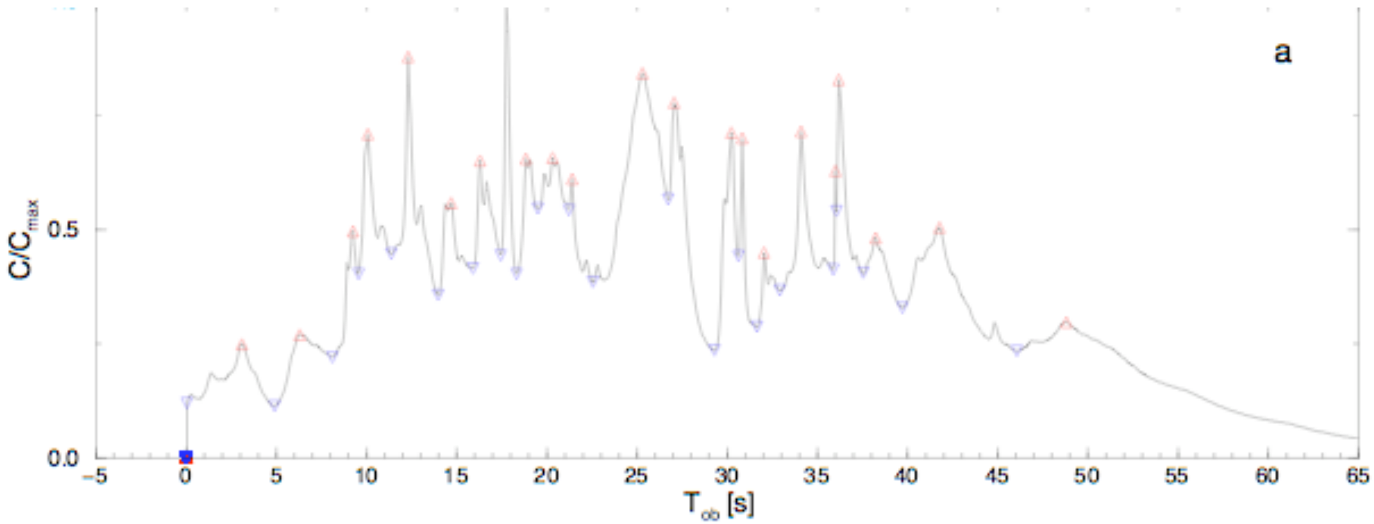
Light curves from internal shocks

Rapid variability and complexity of GRB lightcurves result of emission from multiple shocks in a relativistic wind

Δt (interval between ejected shells) determines the pulse duration and sepration:

IS reproduce the observed correlation between the duration of the pulse (t_p) and the subsequent interval (Δt_p)

Numerical simulations reproduce the observed light curves



(Spada et al. 2000)

Spectrum of the prompt emission

Prompt emission observed has most of energy in 0.1-2 MeV
Generic phenomenological photon spectrum a broken power law

- Internal shocks are mildly relativistic, Γ_{sh}~a few, particle acceleration in subrelativistic shocks. Electrons are accelerated to a power law with energy distribution

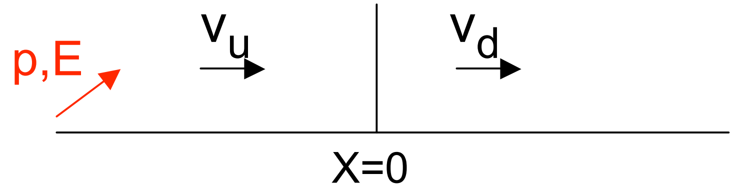
$$\frac{dn_e}{d\gamma_e} = \gamma_e^{-p}$$

with p~2 and $\gamma_e > \gamma_m$

Electrons accelerated in magnetic field: **synchrotron emission**?
i.e. emission from relativistic electrons gyrating in random magnetic fields

Fermi acceleration at shock

1 Pre-shock 2 Post-shock



V=vu-vd velocity of shocked material in the particle frame

In 2 $E' = \gamma(E + pV\cos\theta)$ $p' = \gamma(p\cos\theta + VE/c^2)$

In 1 $E'' = \gamma^2(E + 2\, vV\cos\theta/c^2 + V^2/c^2)$

Energy gain $\langle \Delta E/E \rangle \propto V/c$

Energy distribution $dN/dE = k\, E^{-p}$ $p \sim 2$

N dominated by low energy particles but E_{tot} dominated by high energy particles.

Synchrotron emission

Prompt emission is clearly non-thermal, and most natural process is synchrotron emission, i.e. emission from relativistic electrons gyrating in random magnetic fields.

For an electron with comoving energy $\gamma_e m_e c^2$ and bulk Lorentz factor Γ the observed emission frequency is:

$$\nu = \Gamma \gamma_e^2 (eB/2\pi\, m_e c)$$

Spectrum of the prompt emission

$$N(E) = \begin{cases} E^{-3/2} & E < E_b \\ E^{-1-p/2} & E > E_b \end{cases}$$

Characteristic frequency of synchrotron emission is determined by γ_m and B, $E_b = h\nu_m = h\Gamma\gamma_m 2eB/m_e c$

The strength of the magnetic field is unknown, but its energy density $B^2/8\pi$ is a fraction ε_B of the internal energy.

$$U_B = 4\pi R^2 c\Gamma^2 B^2/8\pi = \varepsilon_B L_{in} = \frac{\varepsilon_B}{\varepsilon_e} L_\gamma$$

B~10^{16-17} G more than a magnetar

$$E_b \approx 1\varepsilon_B^{1/2}\varepsilon_e^{3/2}\frac{L_{\gamma,52}^{1/2}}{\Gamma_{2.5}^2 t_{v,-2}} MeV$$

r_{is}

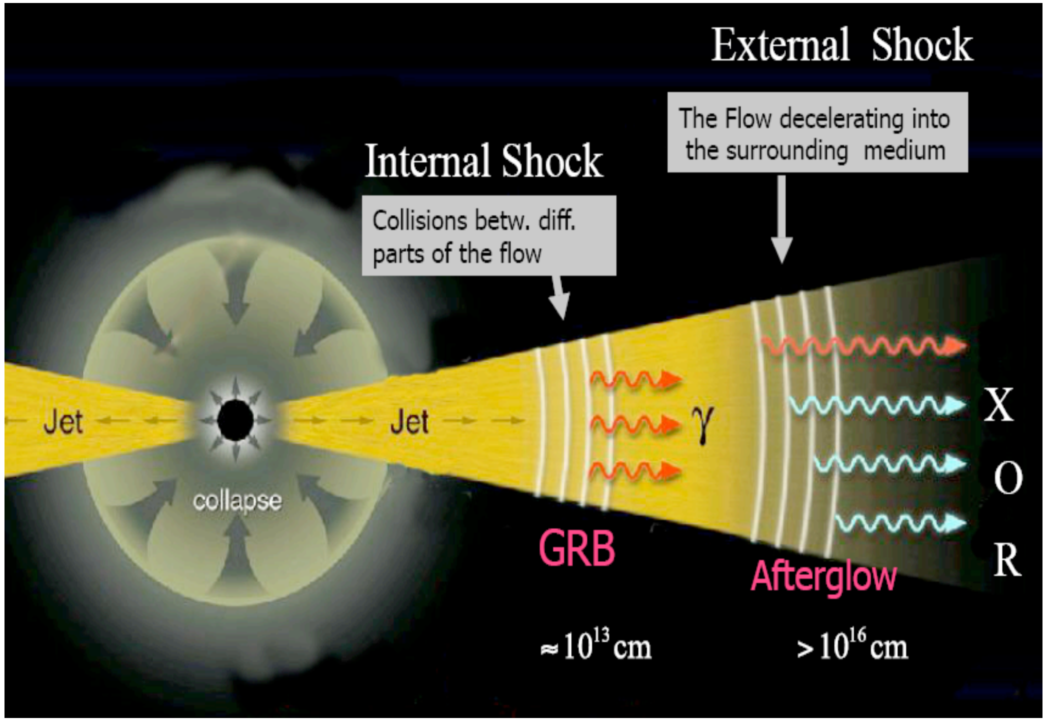
As observed!

Conclusions on the prompt emission

- Internal Shocks reproduce the prompt γ-ray temporal structure but low efficiency problem
- Theoretical open questions on the process of the behaviour of the shocks, particle acceleration and generation of strong B
- Determination of ε_b,ε_e, ε_p that are free parameters of the model, still not clear the physics that determines these parameters.

GRB Theoretical Framework:

- **Progenitors**:
  - Long: massive stars
  - Short: binary merger?
- **Acceleration**: fireball or magnetic?
- **Prompt γ-rays**: internal shocks? magnetic plasma?



- **Deceleration**: the outflow decelerates as it sweeps-up the external medium
- **Afterglow**: from the long lived **forward** shock going into the external medium; as the shock decelerates the typical frequency decreases: X-ray → optical → radio

Afterglow observations

•Delayed low energy (X-ray to radio) emission of GRBs detected for long and short bursts.

•Complicated light curve ending with a power law decay (t^{-1} - t^{-2}) in all bands

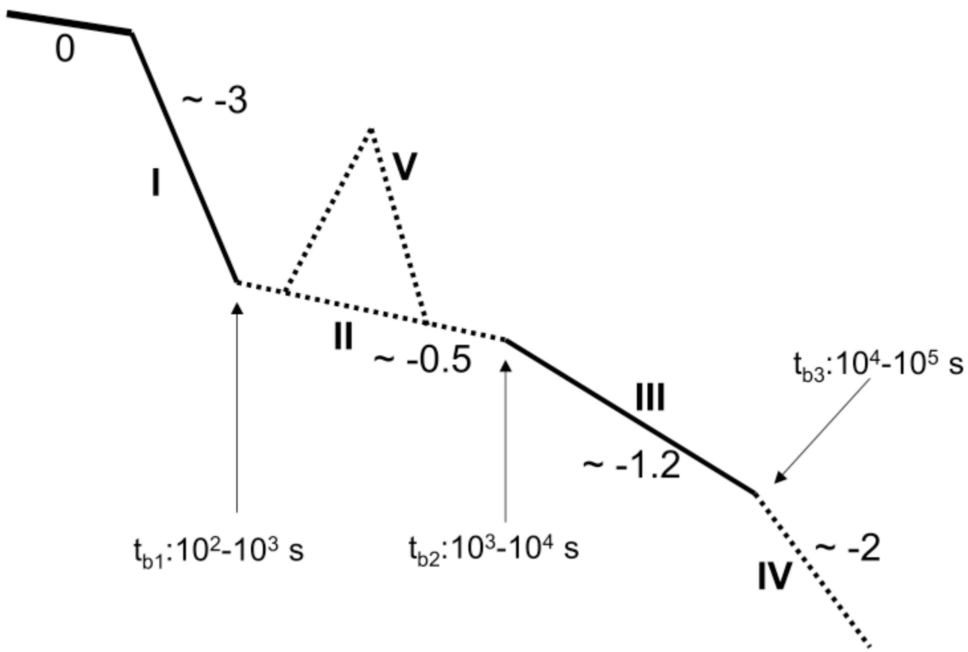
•Synchrotron radiation

•Optical afterglow allowed the determination of the redshift ⇒ **GRBs are cosmological**

Canonical X-ray afterglow light curve:

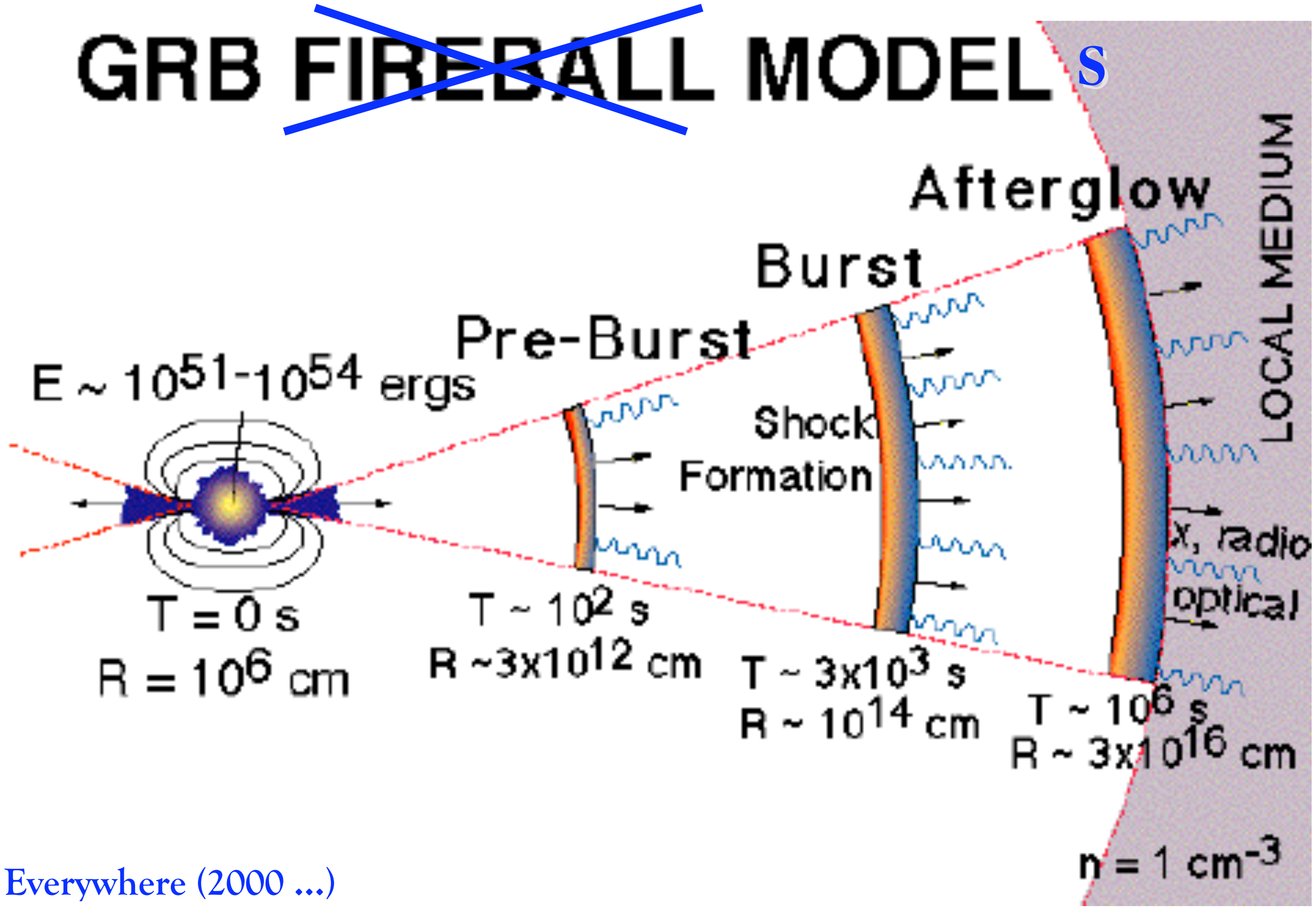
- Steep decay phase (I)
- Shallow decay phase (II)
- Normal decay phase (III)
- Post jet-break phase (IV)
- X-ray flares (V)

Nousek et al., ApJ 642, 389 (2006)



Characteristic radii and times

One of the possible



Everywhere (2000 ...)

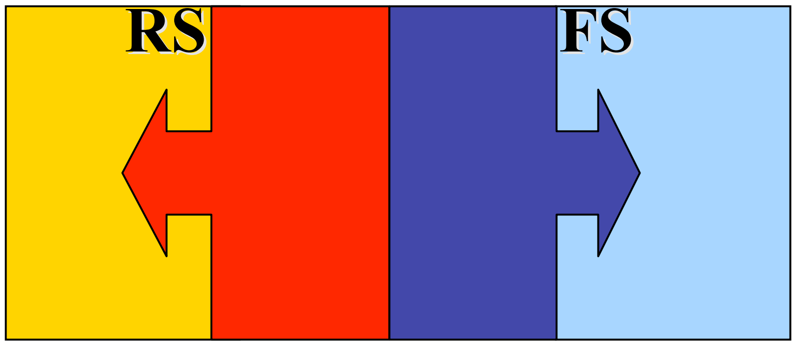
Deceleration (external shock) radius:

- *Eventually the fireball is decelerated by the ambient medium.*
- *During the initial fireball-medium interaction a reverse shock propagates into the fireball.*
- *The deceleration radius is the radius where the reverse shock crosses the fireball shell.*
- $r_\Gamma \approx 10^{16}$ cm *is where the mass collected by the fireball is equal to* $(1/\Gamma_0)$ *of the fireball rest mass.* $M_{ISM} \approx M_0/\Gamma_0$, M_0 = *baryon loading of the fireball.*

As the fireball starts to decelerate a strong external shock also forms and propagate into the medium

Fireball interaction with the surrounding medium

- *There are four regions:*
  - *Unshocked ISM (1), shocked ISM (2), shocked shell (3), unshocked shell (4). Shock jump conditions hold for both shocks.*



Unshocked fluid **Shocked fluid** **Shocked ISM** **Unshocked ISM**

Synchrotron Emission:

Fermi, Phys. Rev. 75, 1169 (1949)

Rybicki & Lightman, Radiative processes in astrophysics

- *Afterglow emission is clearly non-thermal, and most natural process is synchrotron emission, i.e. emission from relativistic electrons gyrating in random magnetic fields.*
- *For GRB prompt, synchrotron hypothesis is still under debate.*

There are three major assumptions:

1. *Electrons are "Fermi" accelerated at the relativistic shocks with a power-law distribution* $N(E) \propto E^{-p}$.
2. *A fraction* ξ_e *of electrons associated to ISM baryons are accelerated, and total electron energy is a fraction* ε_e *of the total internal energy of the shocked region.*
3. *The strength of the magnetic field is unknown, but its energy density* $B^2/8\pi$ *is a fraction* ε_B *of the internal energy.*

The afterglow spectrum is characterised by critical frequencies: ν_m the injection frequency, ν_c the cooling frequency, and ν_M the maximum synchrotron frequency. Moreover, there is also ν_a, the synchrotron self-absorption at lower frequency.

The final GRB afterglow spectrum is then a four-segment broken power-law. If $\nu_m < \nu_c$ we have the "slow cooling case", else if $\nu_m > \nu_c$ we are in the "fast cooling case".

Sari, Piran, Narayan, ApJ 497, L1 (1998)
Meszaros, Rees, Wijers, ApJ 499, 301 (1998)

slow cooling

$$F = F_{\nu,m} \begin{cases} (\nu_a/\nu_m)^{1/3}(\nu/\nu_a)^2 & \nu < \nu_a \\ (\nu/\nu_m)^{1/3} & \nu_a \le \nu < \nu_m \\ (\nu/\nu_m)^{-(p-1)/2} & \nu_m \le \nu < \nu_c \\ (\nu_c/\nu_m)^{-(p-1)/2}(\nu/\nu_c)^{-p/2} & \nu_c \le \nu \le \nu_M \end{cases}$$

fast cooling

$$F = F_{\nu,m} \begin{cases} (\nu_a/\nu_c)^{1/3}(\nu/\nu_a)^2 & \nu < \nu_a \\ (\nu/\nu_c)^{1/3} & \nu_a \le \nu < \nu_c \\ (\nu/\nu_c)^{-1/2} & \nu_c \le \nu < \nu_m \\ (\nu_m/\nu_c)^{-1/2}(\nu/\nu_m)^{-p/2} & \nu_m \le \nu \le \nu_M \end{cases}$$

Conclusions on Afterglow model:

- *There are a few simplifying assumptions. (1) Isotropic fireball, (2) constant ambient density, (3) impulsive injection in the fireball, (4) relativistic fireball, (5) synchrotron emission and (6) no evolution for the microphysics parameters.*

  - *Of course some of these assumptions can be relaxed for more realistic afterglow models.*

Meszaros & Rees, ApJ 476, 232 (1997) - Wijers, Rees, Meszaros, MNRAS 288, L51 (1997) - Waxman, ApJ 485, L5 (1997) - Waxman, ApJ 489, L33 (1997) - Meszaros, Rees, Wijers, ApJ 499, 301 (1998) - Sari, Piran, Narayan, ApJ 497, L1 (1998)

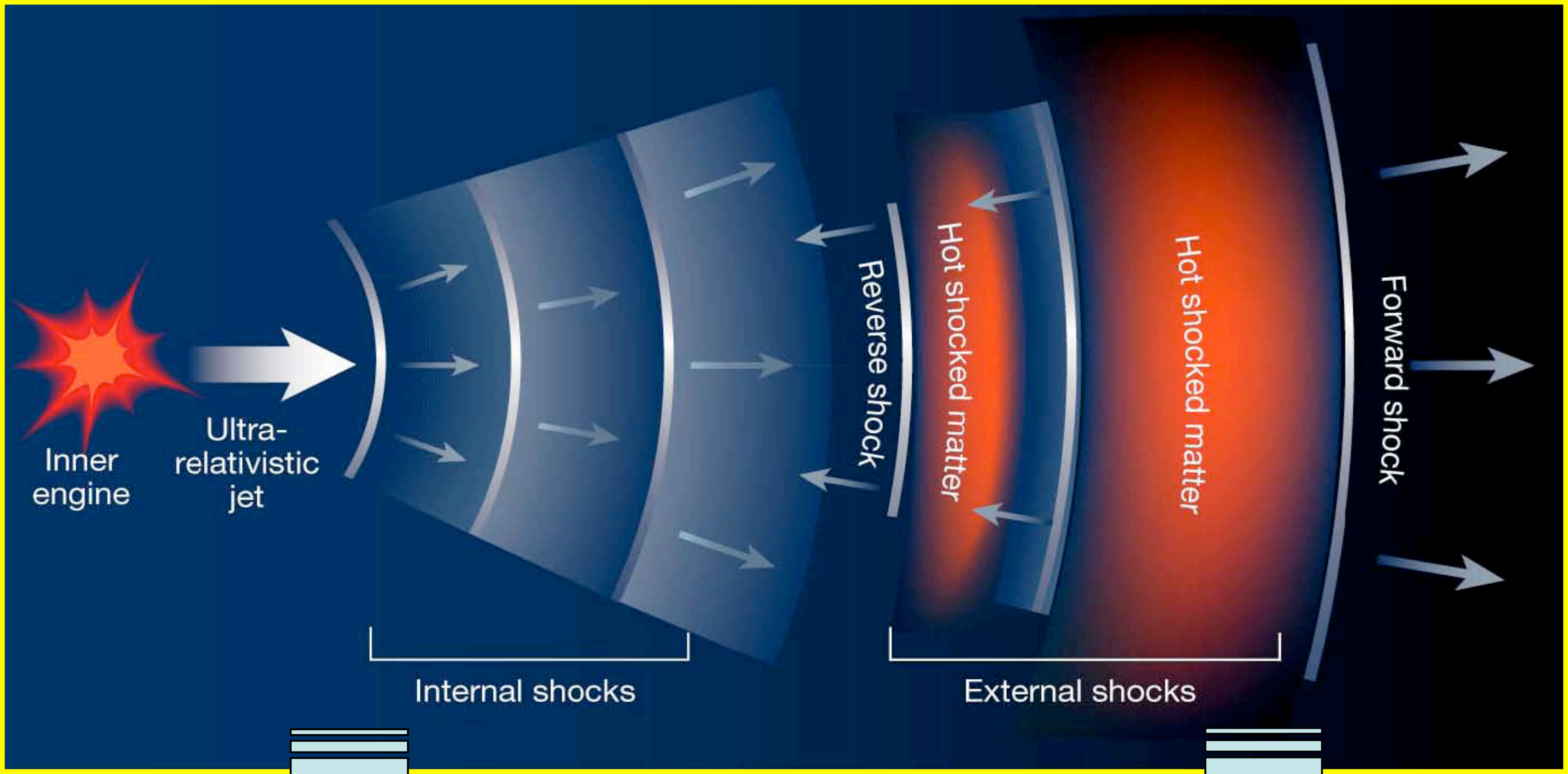
Summary: What do we think to know about GRBs?

- Cosmological distance:Typical observed z>1
- Relativistic expansion: high $\Gamma \sim 100$ required by observation
- Energy released is up to few times the rest mass of Sun (if isotropic) in a few seconds => narrow beam
- Two populations of GRBs: short ($T_{90}<2$ s) and long
- Spectrum non-thermal
- Central Engine
  - Collapse of massive, rotating star? (long GRBs)
  - Coalescence of binary neutron stars? (short GRBs)
- Final Product is Black Hole (probably)

Open questions

- Nature of the progenitor?
- The dynamics of GRB jet why Γ so high, fireball?
- What is the dissipation mechanism that lead to the emission of γ-rays? Internal shocks?
- Jet composition, there are hadron in the jet?
- Radiative processes and physical explanation to the broad band spectrum observed
- *Origin of the high energy emission detected by LAT?*

High Energy emission in GRBs: Many Models



- SSC in internal shocks, 1 MeV-10 GeV (Guetta & Granot 2003, Meszaros et al., Galli & Guetta 2007)
- p-γ interaction, MeV – TeV (Gupta & Zhang 2007)

- SSC in RS, keV-GeV (Granot & Guetta 2003 Kobayashi et al. 2007)
- SSC in FS, MeV-TeV (Galli & Piro 2007)
- p-γ interaction in FS, GeV – TeV (Boettcher & Dermer 2003) p-sync. (Razzaque 2010)