Production de particules de haute énergie dans les sursauts gamma

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1. Le modèle des chocs internes et du choc externe

2. Production de particules de haute énergie

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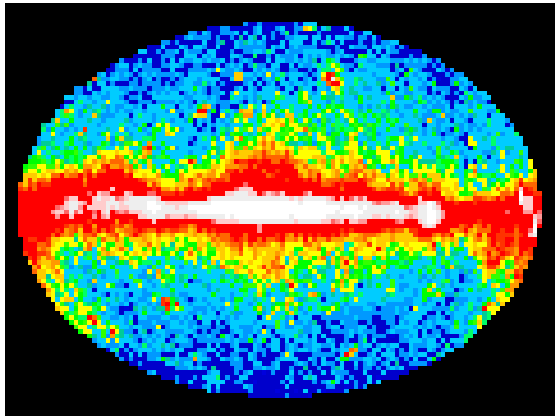
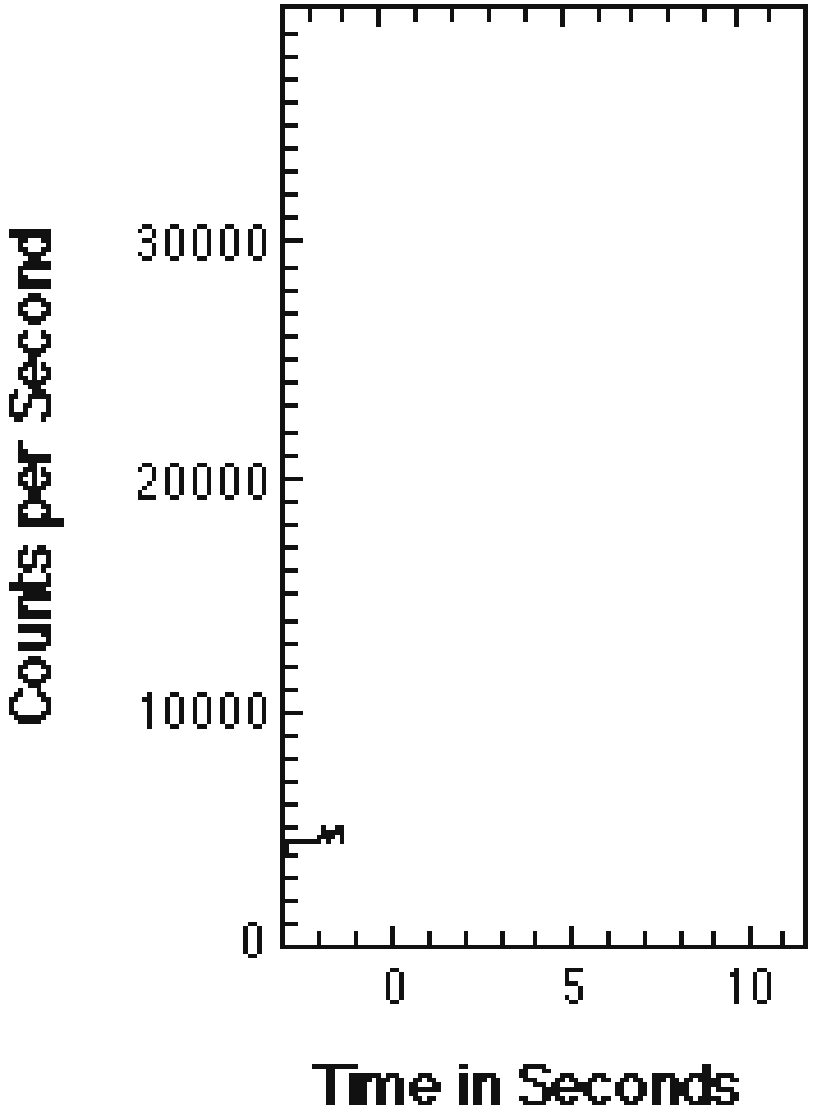
Cours 1
Le modèle des chocs internes et du choc externe

1. Sursauts gamma : principaux faits observationnels
2. Construire un modèle
3. La source centrale et l'éjection relativiste
4. Les chocs internes
5. Le choc externe et le choc en retour
6. Succès et difficultés du modèle

Sursauts gamma : principaux faits observationnels

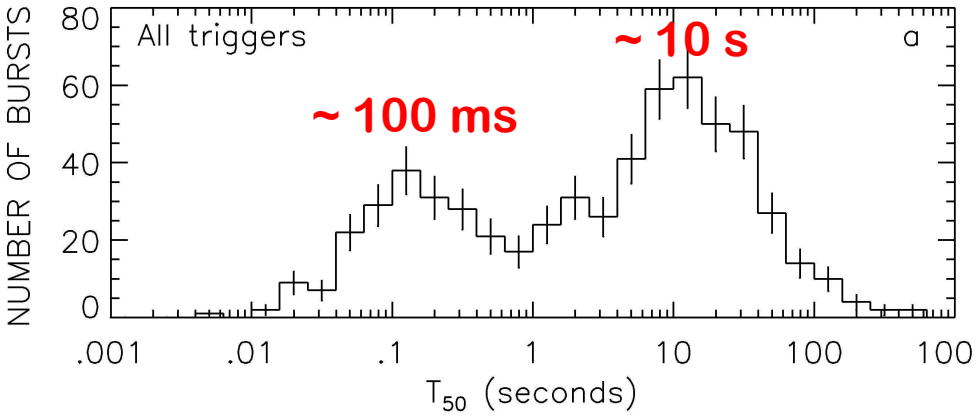




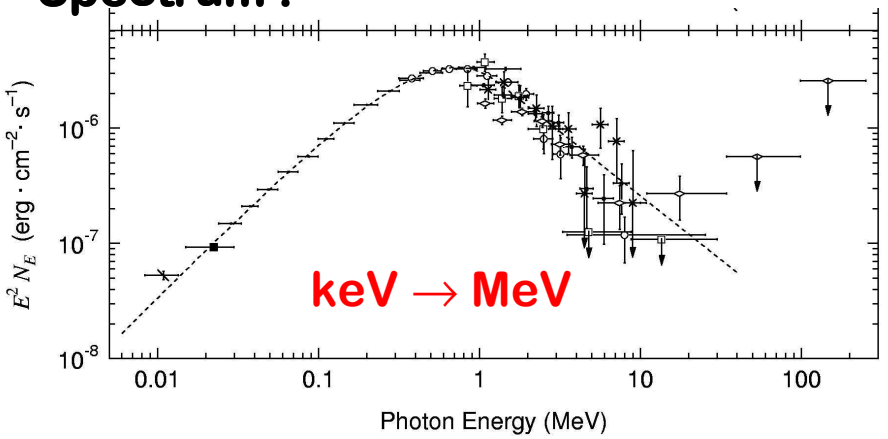
1991-2000 : BATSE ~ 1 GRB per day (total : 2704 GRBs)

Sursauts gamma : principaux faits observationnels

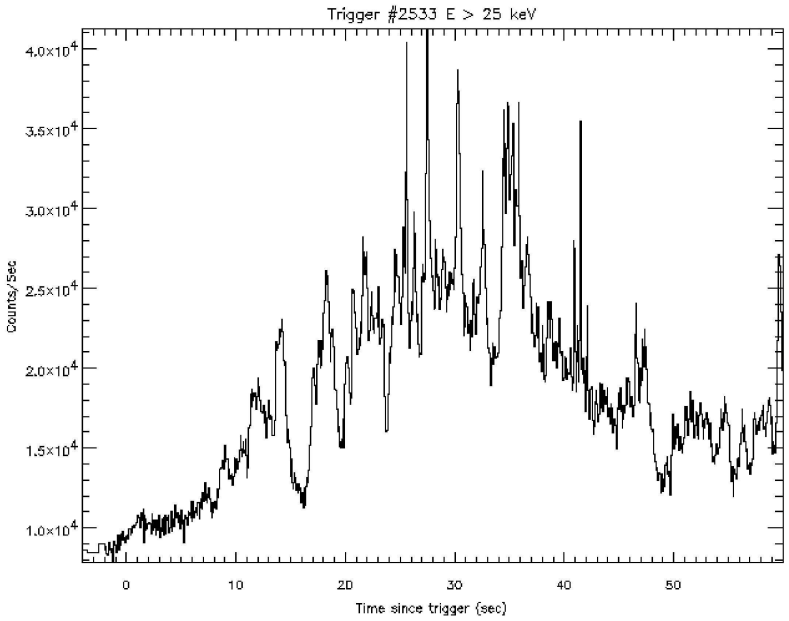
Duration :

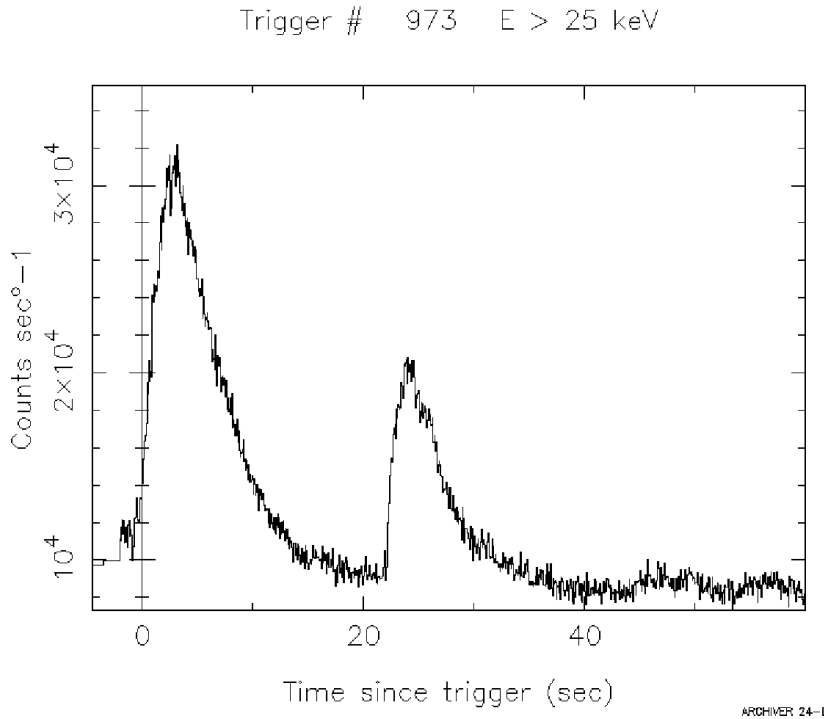


Spectrum :

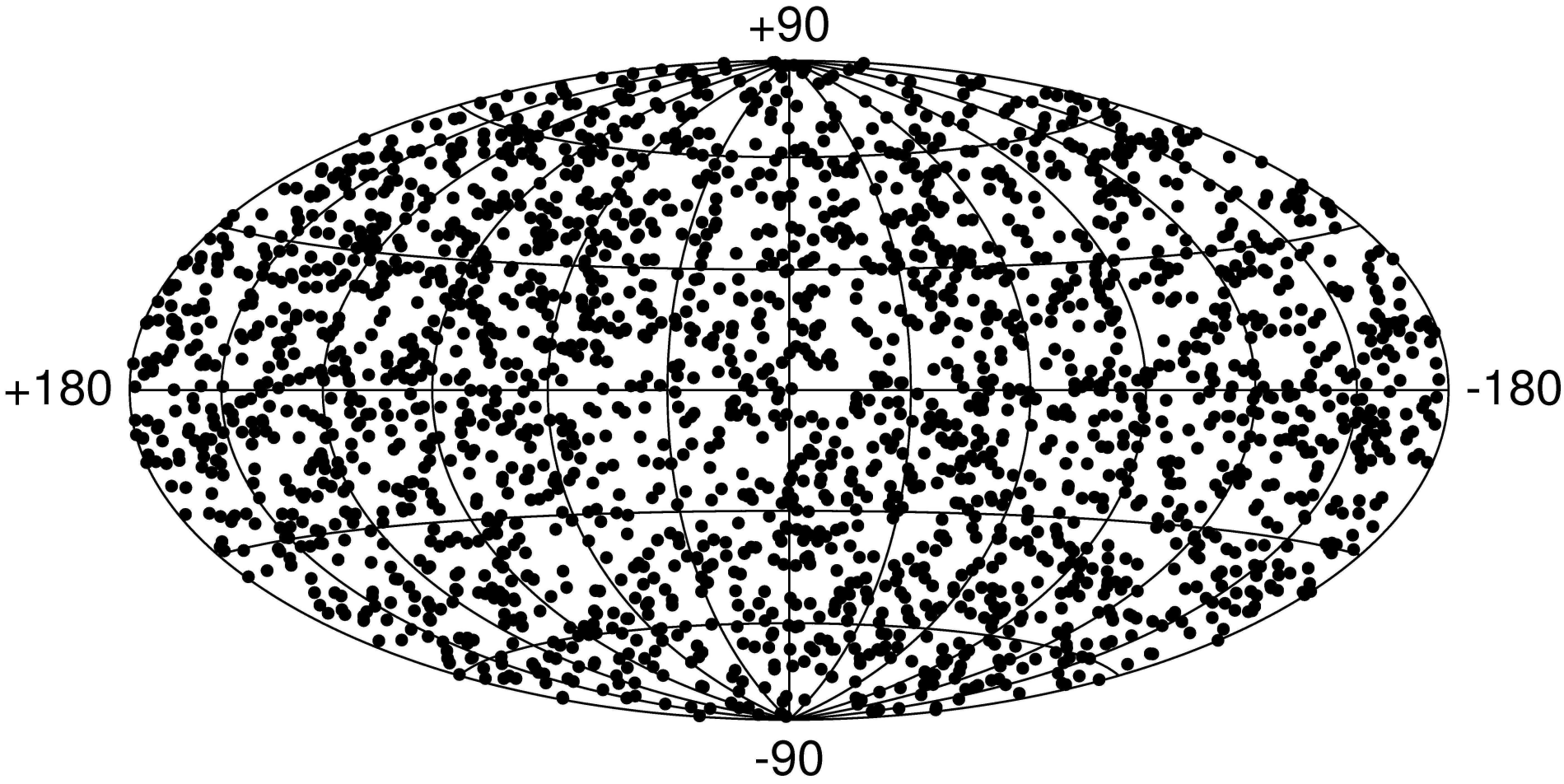


Lightcurves :



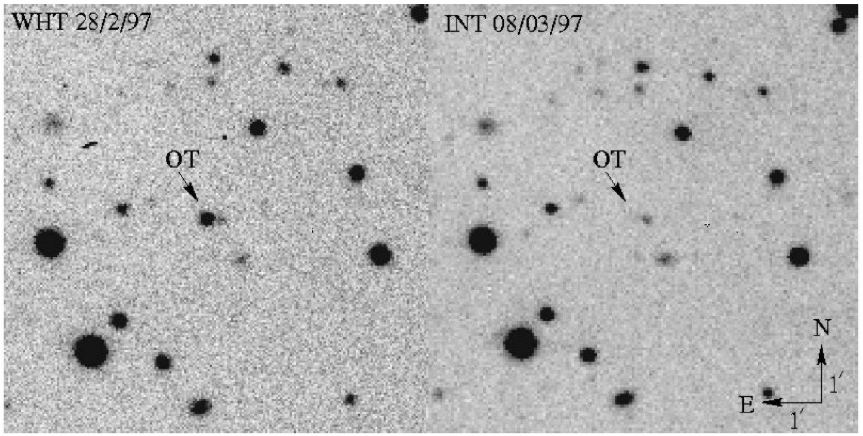


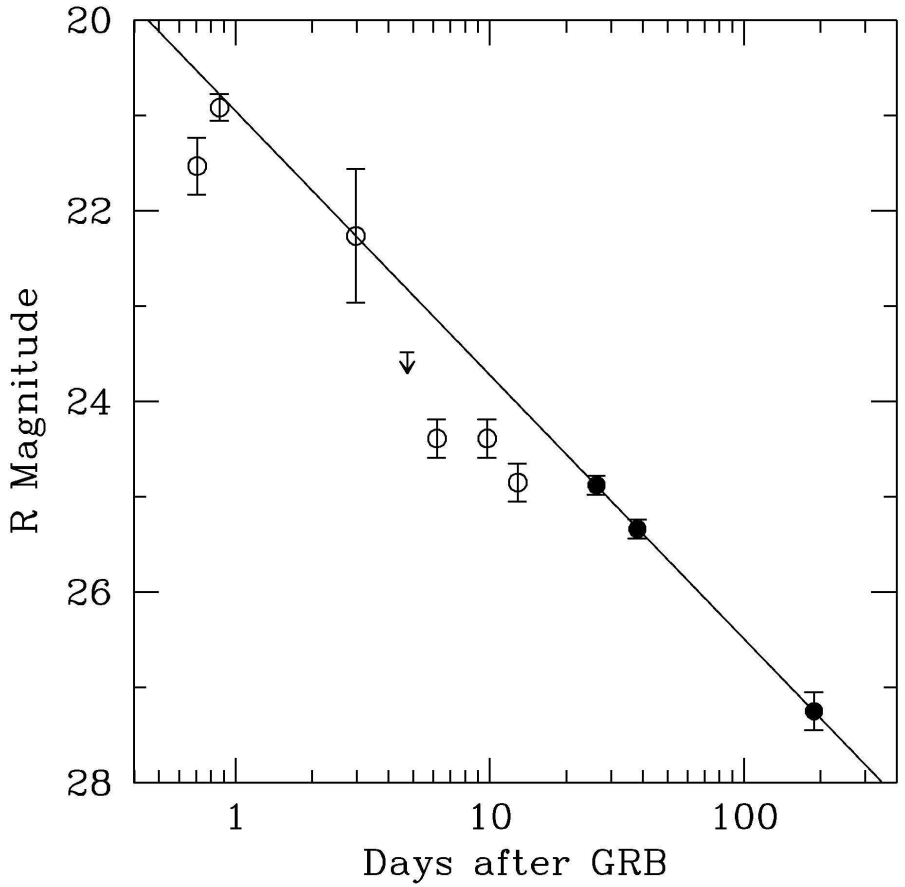
Sursauts gamma : principaux faits observationnels



Sursauts gamma : principaux faits observationnels

GRB 970228 :





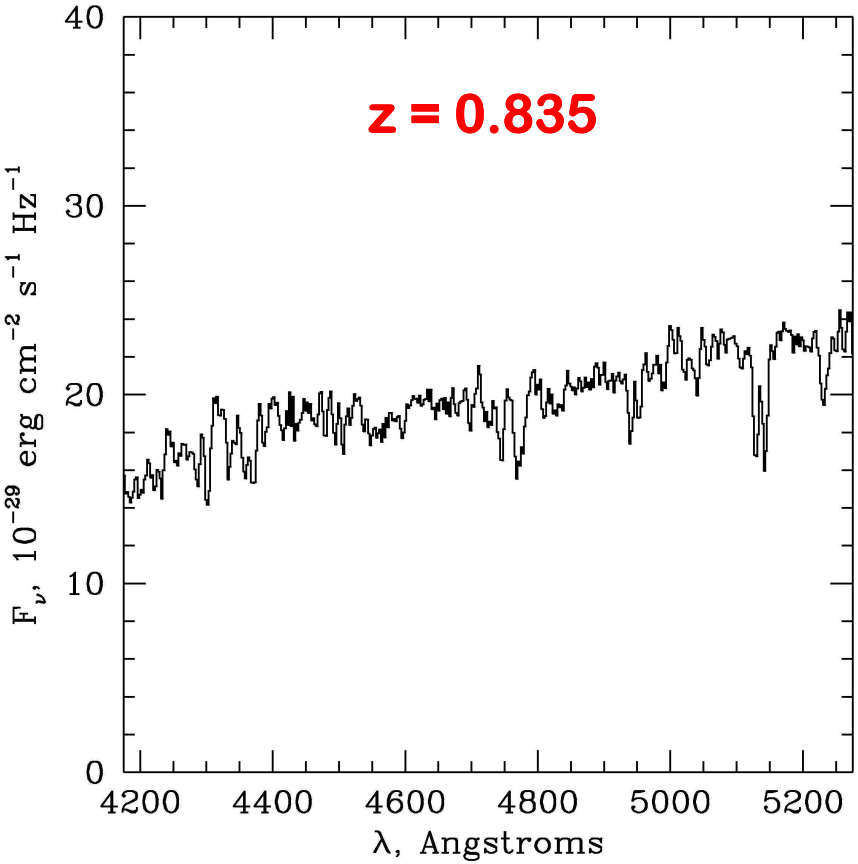
GRB afterglows

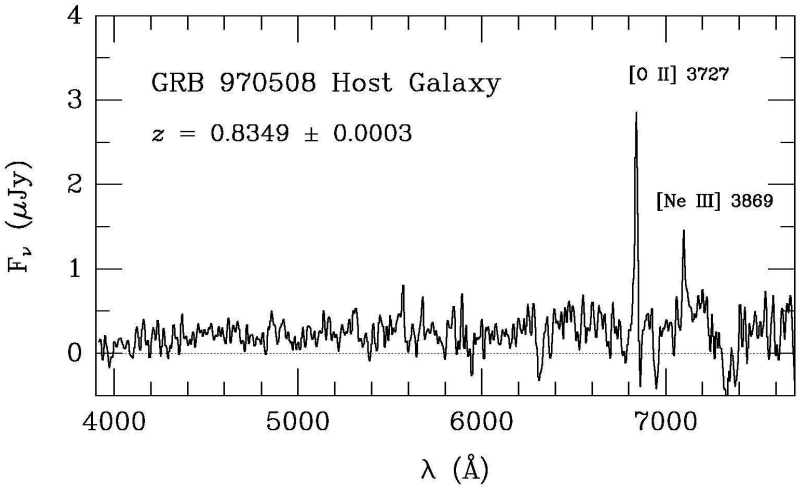
→ temporal decay : hours, days

→ spectral evolution : X,V,radio

Sursauts gamma : principaux faits observationnels

GRB 970508 :

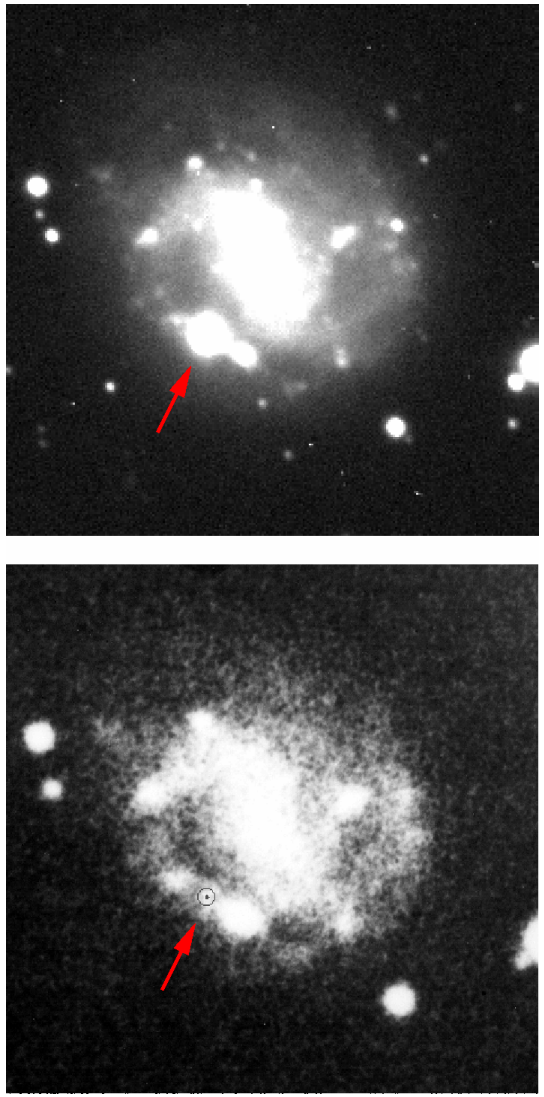




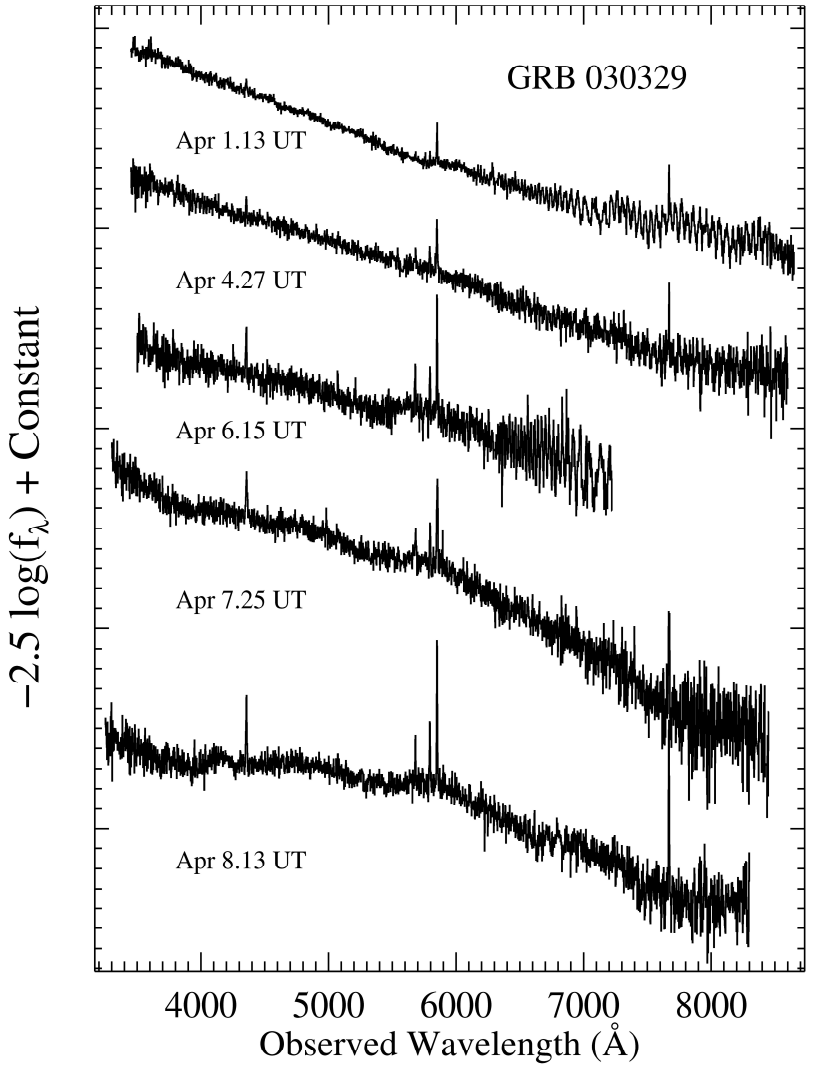
Host galaxy : z = 0.835

Sursauts gamma : principaux faits observationnels

GRB 980425 / SN 1998bw
z=0.008

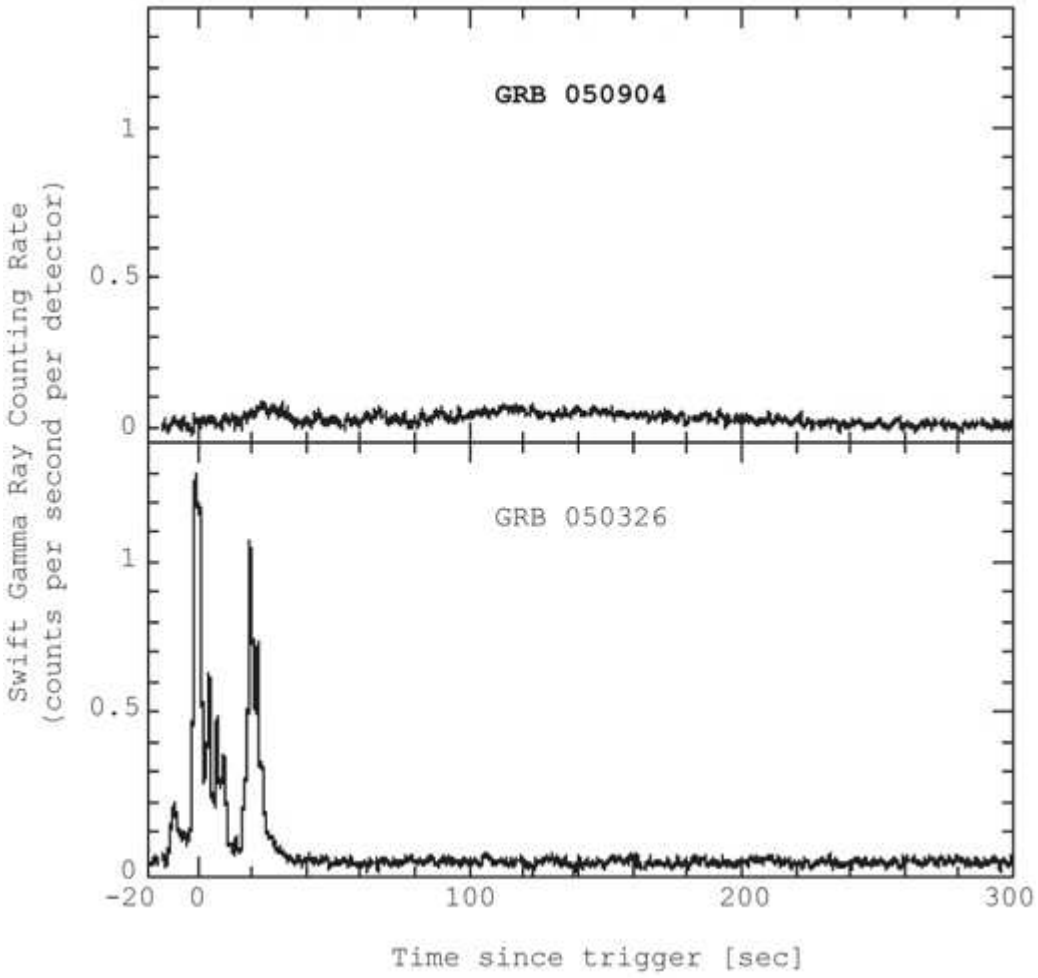


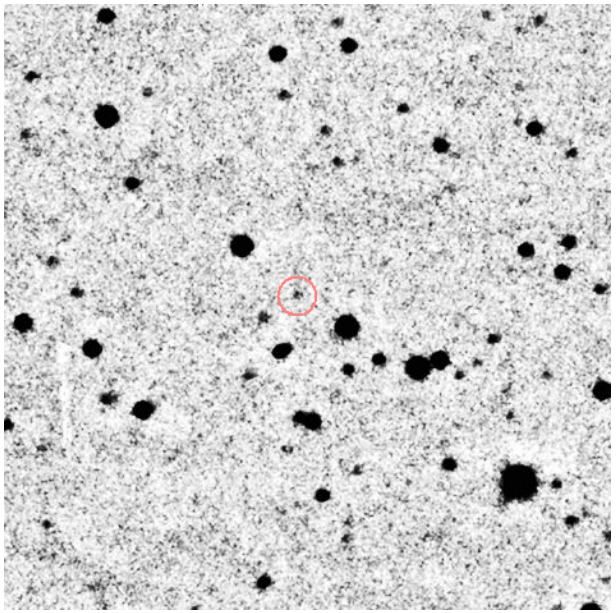
GRB 030329 / SN 2003dhr
z=0.168



Sursauts gamma : principaux faits observationnels

GRB 050904 : z = 6.29 !





TAROT detection @ 86 s

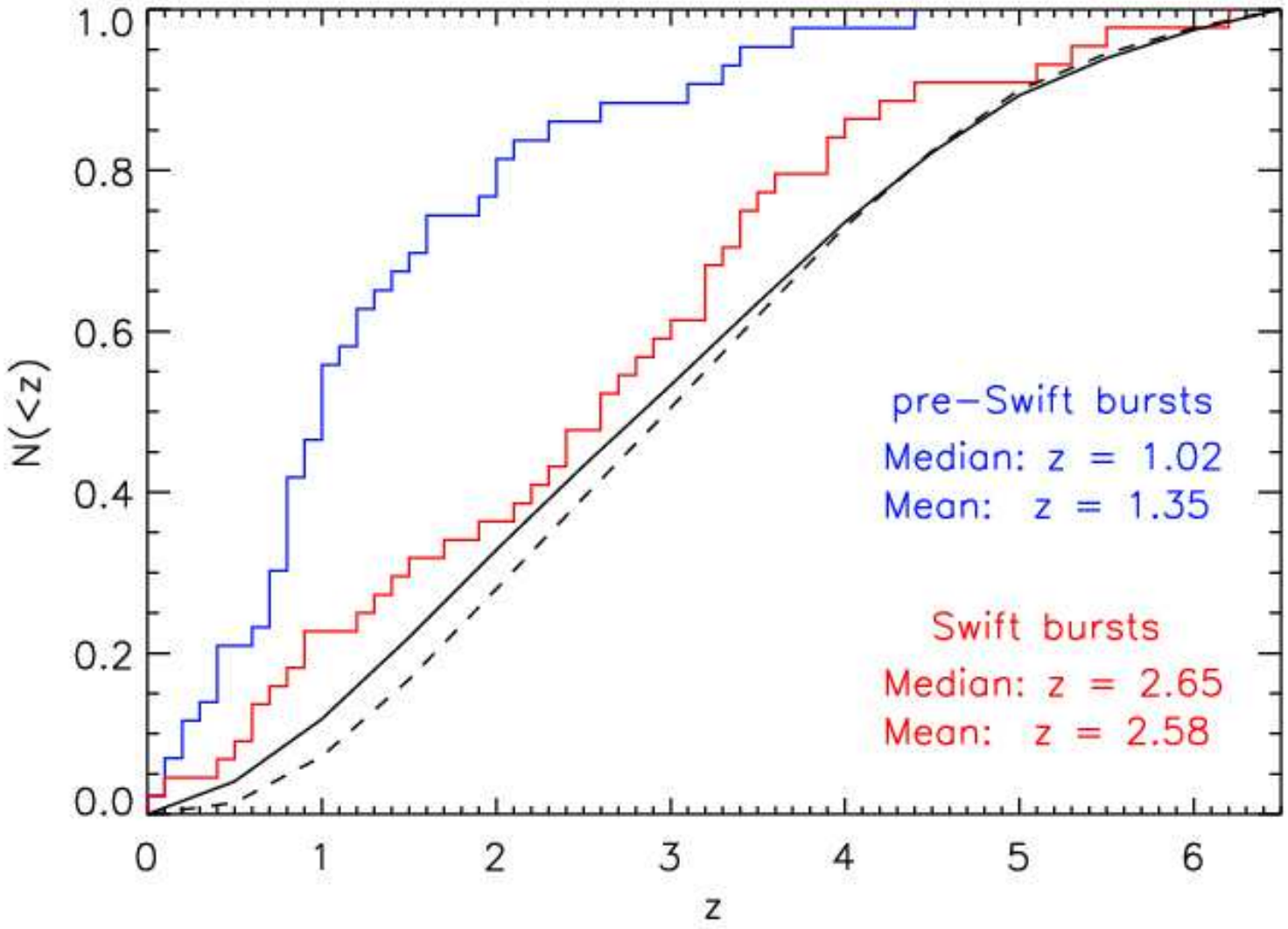
I ~ 16

(Quasar : z = 6.37, I=23.3)

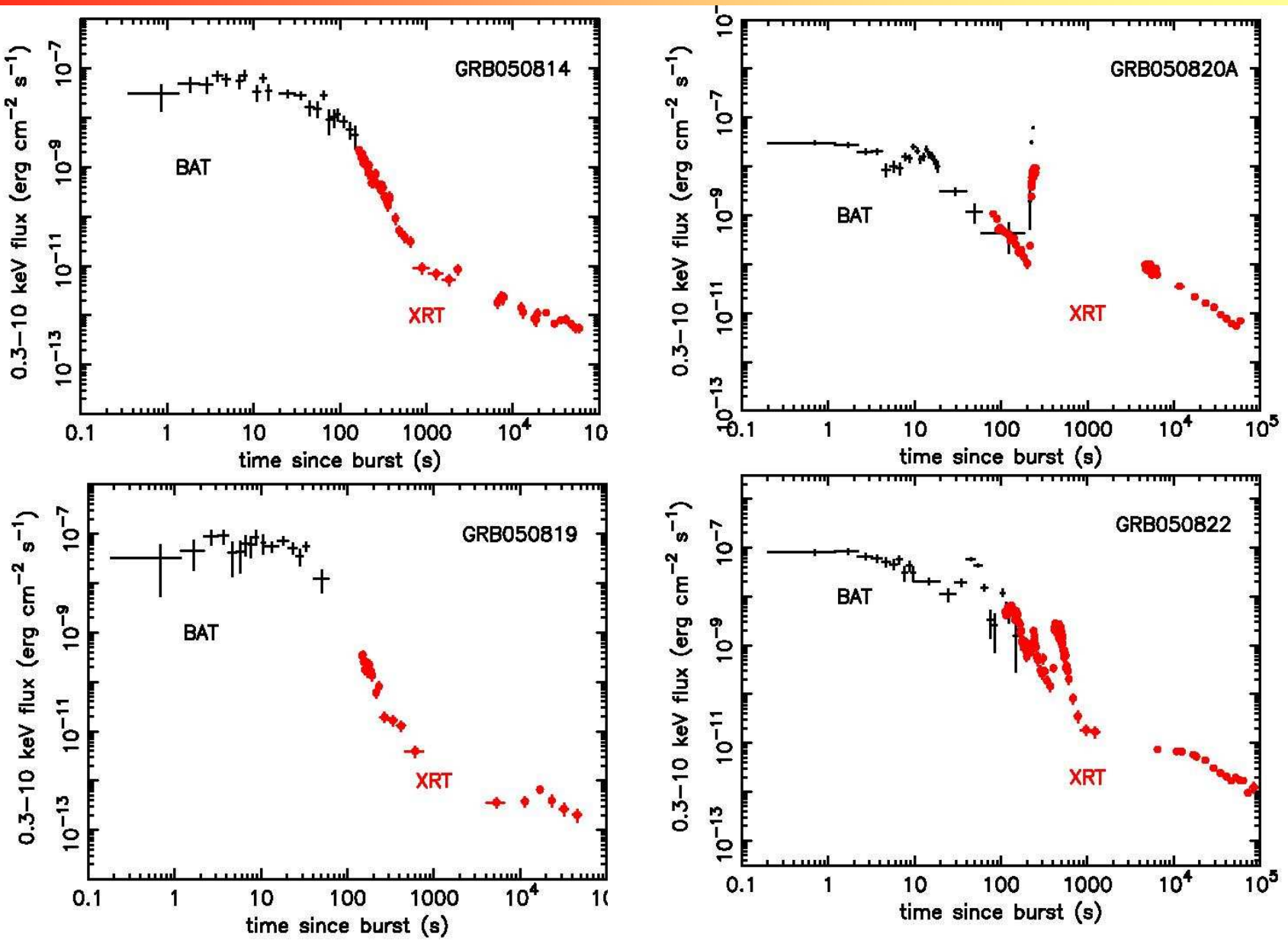
Timescales are multiplied by 1+z = 7.3 (T_{90}>200 s)

Sursauts gamma : principaux faits observationnels

SWIFT : redshift distribution of long GRBs (Jakobsson et al.)



Sursauts gamma : principaux faits observationnels



SWIFT X-ray afterglows O' Brian et al. 2005

Sursauts gamma : principaux faits observationnels

Quelques aspects dont je ne parlerai pas :

- Les XRFs et les XRRs (= sursauts gamma « mous »).
- Les corrélations (Amati, Ghirlanda, …).
- Emission optique simultanée au sursaut gamma (GRB 990123 etc…).
- Les indices observationnels de l'association des sursauts longs avec les étoiles massives (autres que SN associée).
- Rémanences des sursauts courts.
- etc.

Construire un modèle

- **Redshift :** 0.008 → 6.3
- **Energetics :** 10^{51} – 10^{54} erg (isotropic)
  10^{51} erg (after correction for beaming)
- **Timescales :** ms → a few 100 s
- **Spectrum :** non-thermal ; Peak energy : keV - MeV
- **Long GRBs :** association with massive stars

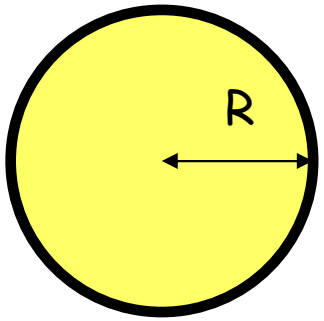
- ▶ Short timescales : compact objects (NS, stellar mass BH)
- ▶ Huge energy : violent event with a large energy release (coalescence, collapse)
- ▶ Short timescales + huge energy : compactness problem ⇒ relativistic motion ($\Gamma \geq 100$)

Construire un modèle

Energy radiated in γ-rays : $E_\gamma = f_\Omega \, 10^{52}$ erg

Variability : $t_{var} \leq 100$ ms

Beaming



Source size : $R \leq c \, t_{var} \leq 30\,000$ km

Opacity $\tau_{\gamma\gamma} \rightarrow e^+e^-$: $\tau_{\gamma\gamma} \approx f_{\gamma\gamma} \, E_\gamma \, \sigma_T / 4\pi \, R^2 \, m_e c^2$

$\tau_{\gamma\gamma} \geq 7 \, 10^{13} \, f_\Omega \, f_{\gamma\gamma}$

Fraction of photons above the pair production threshold (10^{-3} – 10^{-2}).

Problem :

non-thermal spectrum

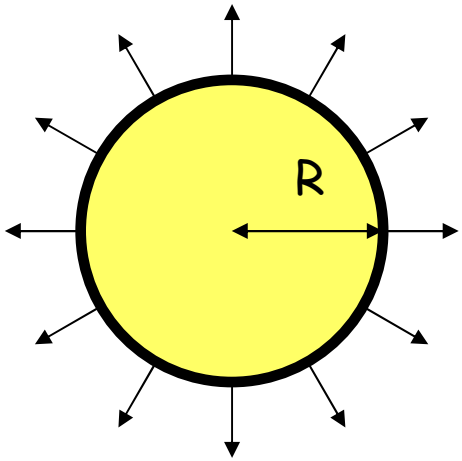
$\Rightarrow$ optically thin medium

Construire un modèle

Energy radiated in γ-rays : $E_\gamma = f_\Omega \, 10^{51}$ erg

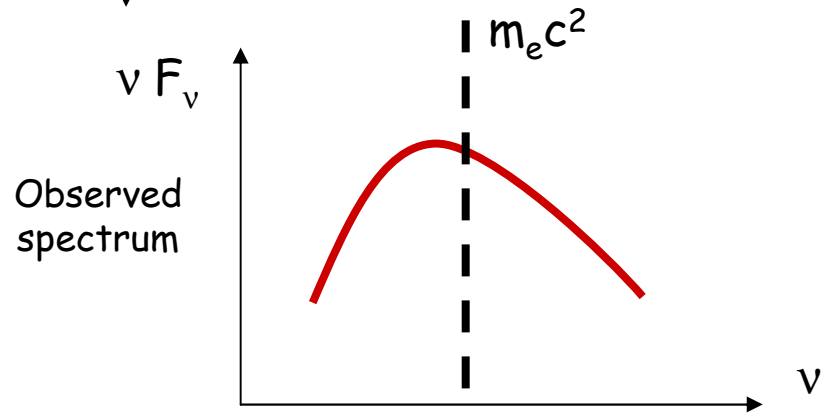
Variability : $t_{var} \leq 100$ ms

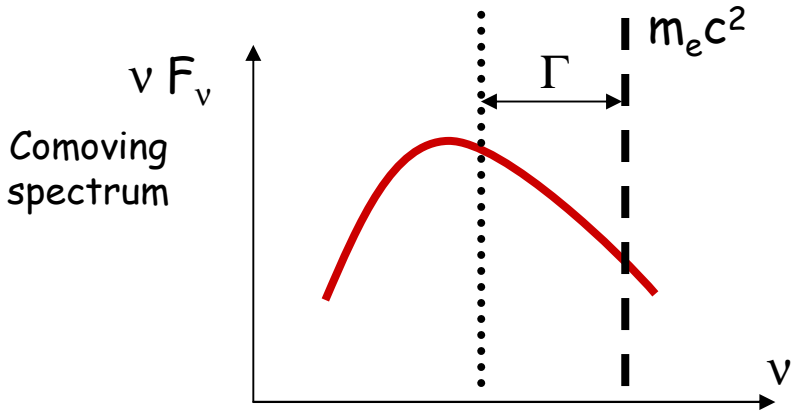
Beaming



Expanding source : Lorentz factor Γ

(i) in the comoving frame of the emitting material, the photon energy is divided by Γ, the fraction $f_{\gamma\gamma}$ is divided by Γ^x (x depends on the high-energy spectral slope).

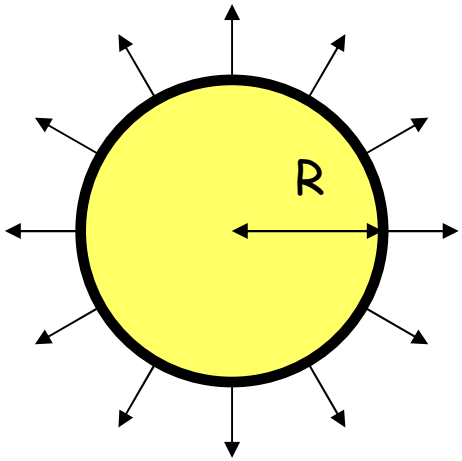




Construire un modèle

Energy radiated in γ-rays : $E_\gamma = f_\Omega \, 10^{51}$ erg

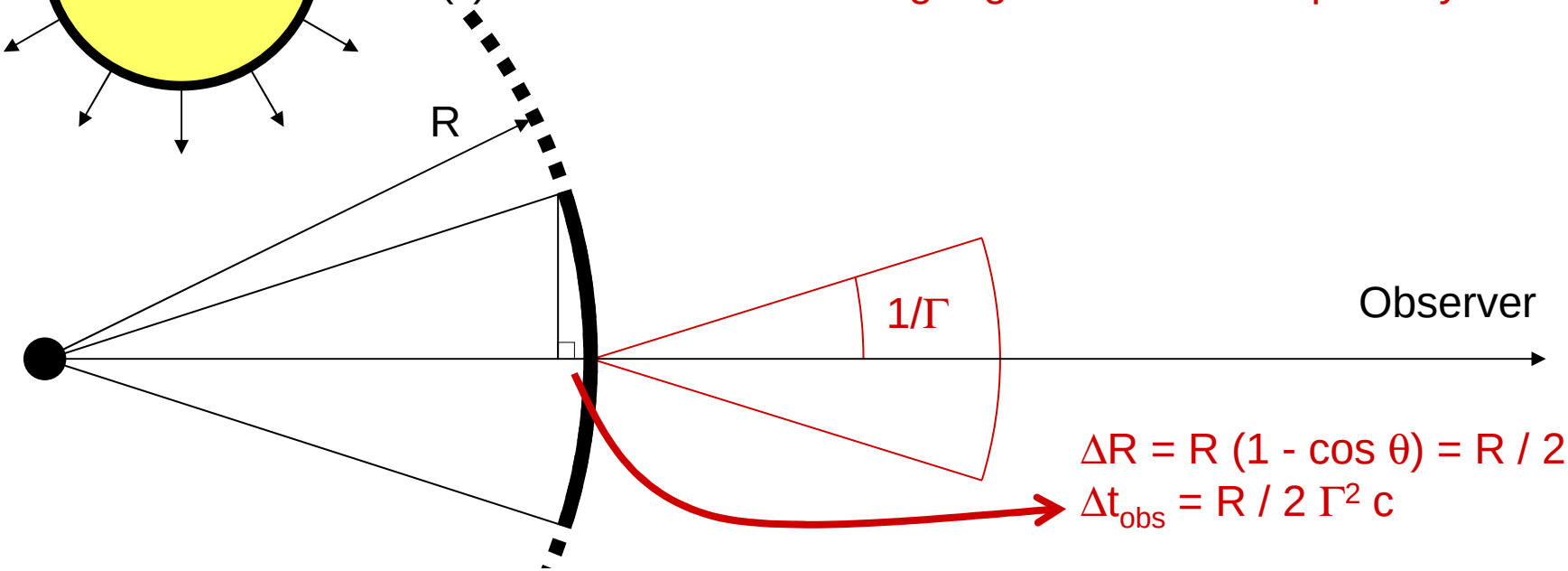
Variability : $t_{var} \leq 100$ ms



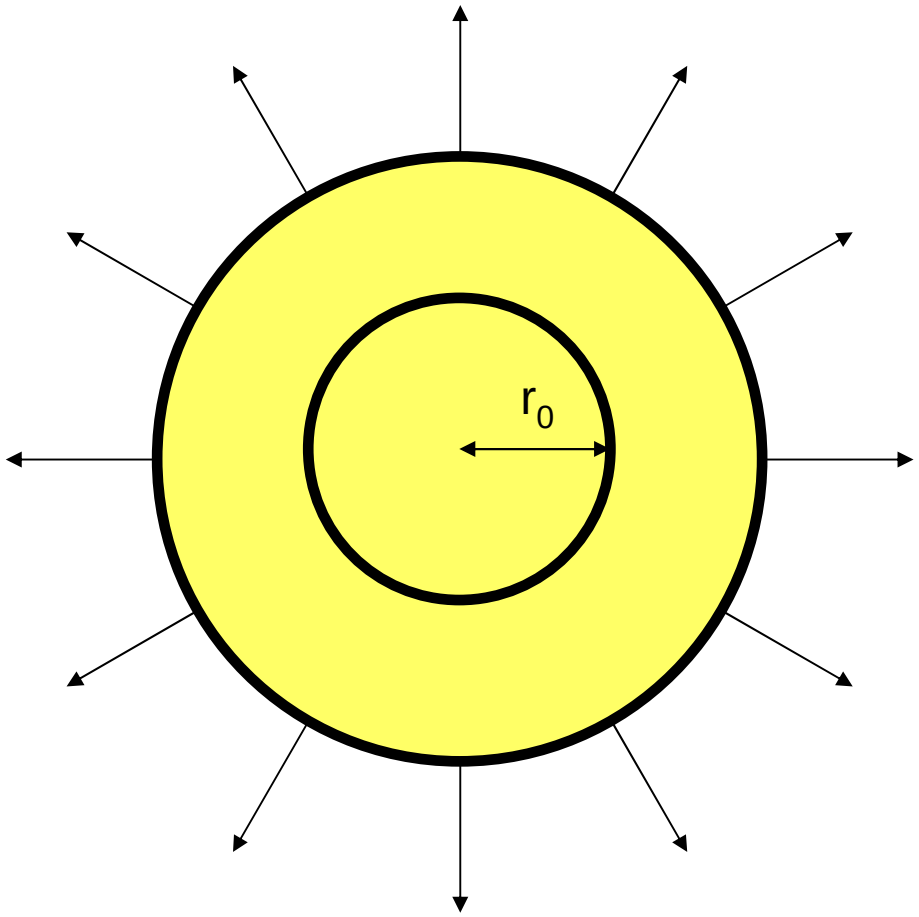
Expanding source : Lorentz factor Γ

(i) in the comoving frame of the emitting material, the photon energy is divided by Γ, the fraction $f_{\gamma\gamma}$ is divided by Γ^x (x depends on the high-energy spectral slope).

(ii) the size of the emitting region can be multiplied by Γ^2.



La source centrale et l'éjection relativiste : (1) fireballs



Energy E released in volume r_0

Mass : $Mc^2 << E$

La source centrale et l'éjection relativiste : (1) fireballs

1D – Spherical symmetry – Adiabatic : Newtonian

Mass conservation :

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial (r^2 \rho v)}{\partial r} = 0$$

Momentum conservation :

$$\frac{\partial (\rho v)}{\partial t} + \frac{1}{r^2}\frac{\partial (r^2 \rho v^2)}{\partial r} = -\frac{\partial P}{\partial r}$$

Energy conservation :

$$\frac{\partial \left(\frac{1}{2}\rho v^2 + \rho\varepsilon\right)}{\partial t} + \frac{1}{r^2}\frac{\partial \left(r^2(\frac{1}{2}\rho v^2 + \rho\varepsilon + P)v\right)}{\partial r} = 0$$

E.O.S. : $\varepsilon = \frac{1}{\gamma - 1}\frac{P}{\rho}$

La source centrale et l'éjection relativiste : (1) fireballs

1D – Spherical symmetry – Adiabatic : Special relativity

Mass conservation :

$$\frac{\partial(\rho\Gamma)}{\partial t}+\frac{1}{r^2}\frac{\partial(r^2\rho\Gamma v)}{\partial r}=0$$

Momentum conservation :

$$\frac{\partial(\rho h\Gamma^2 v)}{\partial t}+\frac{1}{r^2}\frac{\partial(r^2\rho h\Gamma^2 v^2)}{\partial r}=-\frac{\partial P}{\partial r}$$

Energy conservation :

$$\frac{\partial(\rho h\Gamma^2-P-\rho\Gamma)}{\partial t}+\frac{1}{r^2}\frac{\partial\left(r^2(\rho h\Gamma^2-\rho\Gamma)v\right)}{\partial r}=0$$

E.O.S. : $\varepsilon=\frac{1}{\gamma-1}\frac{P}{\rho}$ **Lorentz factor :** $\Gamma=\frac{1}{\sqrt{1-v^2}}$ **Specific enthalpy :** $h=1+\varepsilon+\frac{P}{\rho}$

La source centrale et l'éjection relativiste : (1) fireballs

1D – Spherical symmetry – Adiabatic : Special relativity

Retarded time : $s = t - r$

$$\frac{\partial}{\partial r} \rightarrow \frac{\partial}{\partial r} - \frac{\partial}{\partial s} \qquad \frac{\partial}{\partial t} \rightarrow \frac{\partial}{\partial s}$$

$$\frac{\partial q}{\partial t} + \frac{1}{r^2}\frac{\partial (r^2 q v)}{\partial r} \rightarrow \frac{\partial (q(1-v))}{\partial s} + \frac{1}{r^2}\frac{\partial (r^2 q v)}{\partial r}$$

La source centrale et l'éjection relativiste : (1) fireballs

1D – Spherical symmetry – Adiabatic : Special relativity

Mass conservation :

$$\frac{\partial(\rho\Gamma(1-\mathbf{v}))}{\partial \mathbf{s}} + \frac{1}{\mathbf{r}^2}\frac{\partial(\mathbf{r}^2\rho\Gamma\mathbf{v})}{\partial \mathbf{r}} = 0$$

Momentum conservation :

$$\frac{\partial(\rho\mathbf{h}\Gamma^2\mathbf{v}(1-\mathbf{v}))}{\partial \mathbf{s}} + \frac{1}{\mathbf{r}^2}\frac{\partial(\mathbf{r}^2\rho\mathbf{h}\Gamma^2\mathbf{v}^2)}{\partial \mathbf{r}} = -\frac{\partial \mathbf{P}}{\partial \mathbf{r}} + \frac{\partial \mathbf{P}}{\partial \mathbf{s}}$$

Energy conservation :

$$\frac{\partial\left(\mathbf{P}^{1/\gamma}\Gamma(1-\mathbf{v})\right)}{\partial \mathbf{s}} + \frac{1}{\mathbf{r}^2}\frac{\partial\left(\mathbf{r}^2(\mathbf{P}^{1/\gamma}\Gamma)\mathbf{v}\right)}{\partial \mathbf{r}} = 0$$

E.O.S. : $\varepsilon = \frac{1}{\gamma - 1}\frac{\mathbf{P}}{\rho}$ **Lorentz factor :** $\Gamma = \frac{1}{\sqrt{1-\mathbf{v}^2}}$ **Specific enthalpy :** $\mathbf{h} = 1 + \varepsilon + \frac{\mathbf{P}}{\rho}$

La source centrale et l'éjection relativiste : (1) fireballs

High Lorentz factor : $v \approx 1 - \frac{1}{2\Gamma^2}$

Mass conservation : $\frac{\partial(\rho\Gamma(1-v))}{\partial s} + \frac{1}{r^2}\frac{\partial(r^2\rho\Gamma v)}{\partial r} = 0$

$$\rho\Gamma(1-v) \approx \frac{\rho}{2\Gamma} << \rho\Gamma v \approx \rho\Gamma$$

Therefore : $\frac{1}{r^2}\frac{\partial(r^2\rho\Gamma v)}{\partial r}$ **negligible for small radii.**

Same calculations for energy-momentum conservation.

La source centrale et l'éjection relativiste : (1) fireballs

To check later : width Δ~cst

Then :

$$\Gamma = \frac{1}{\sqrt{1-v^2}}$$

Mass conservation : $\left(4\pi R^2 \Delta\right) \times \Gamma \rho = M = cst$

Energy conservation : $\left(4\pi R^2 \Delta\right) \times (\Gamma \rho) \times \left(h\Gamma - \frac{P}{\rho\Gamma} \right) = E = cst$

$$h = 1 + \varepsilon + \frac{P}{\rho}$$

Adiabatic motion : $\frac{P}{\rho^{\gamma}} = cst$

La source centrale et l'éjection relativiste : (1) fireballs

To check later : width Δ~cst

Mass conservation : $$R^2 \Gamma \rho = \text{cst}$$

Energy conservation : $$h\Gamma = \text{cst}$$

Adiabatic motion : $$\frac{P}{\rho^\gamma} = \text{cst}$$

Energy-dominated phase : $$h \approx \frac{\gamma}{\gamma - 1}\frac{P}{\rho}$$

Then : $$\Gamma \propto R$$

$$\rho \propto R^{-3} \qquad P \propto R^{-4} \qquad \text{(for } \gamma = 4/3 \text{)}$$

La source centrale et l'éjection relativiste : (1) fireballs

To check later : width Δ~cst

Mass conservation : $R^2 \Gamma \rho = cst$

Energy conservation : $h\Gamma = cst$

Adiabatic motion : $\frac{P}{\rho^\gamma} = cst$

Energy-dominated phase : $\Gamma \propto R$ $\rho \propto R^{-3}$ $P \propto R^{-4}$

Matter-dominated phase : $h \approx 1$

Then : $\Gamma = cst$

$\rho \propto R^{-2}$ $P \propto R^{-2\gamma}$

La source centrale et l'éjection relativiste : (1) fireballs

Energy-dominated phase : $\Gamma \propto R \qquad \rho \propto R^{-3} \qquad P \propto R^{-4}$

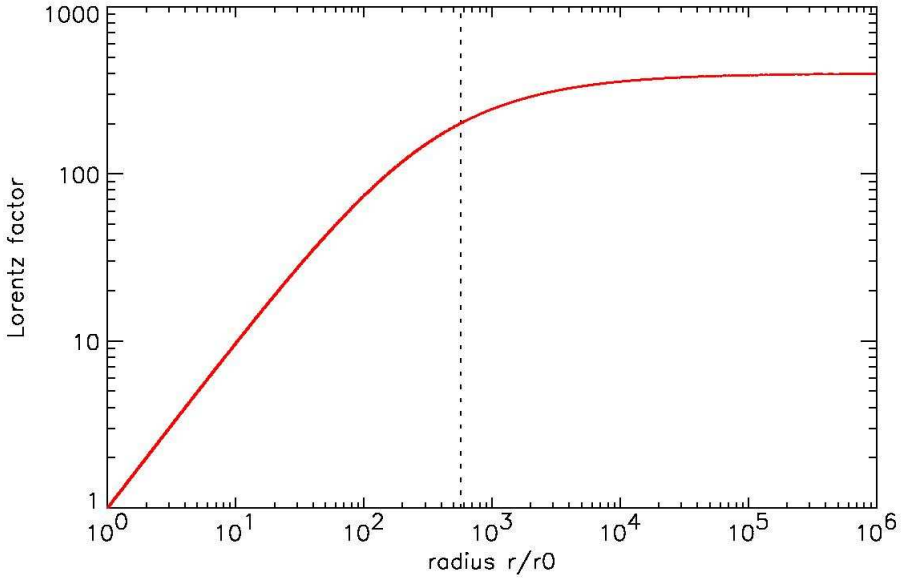
Matter-dominated phase : $\Gamma = cst \qquad \rho \propto R^{-2} \qquad P \propto R^{-2\gamma}$

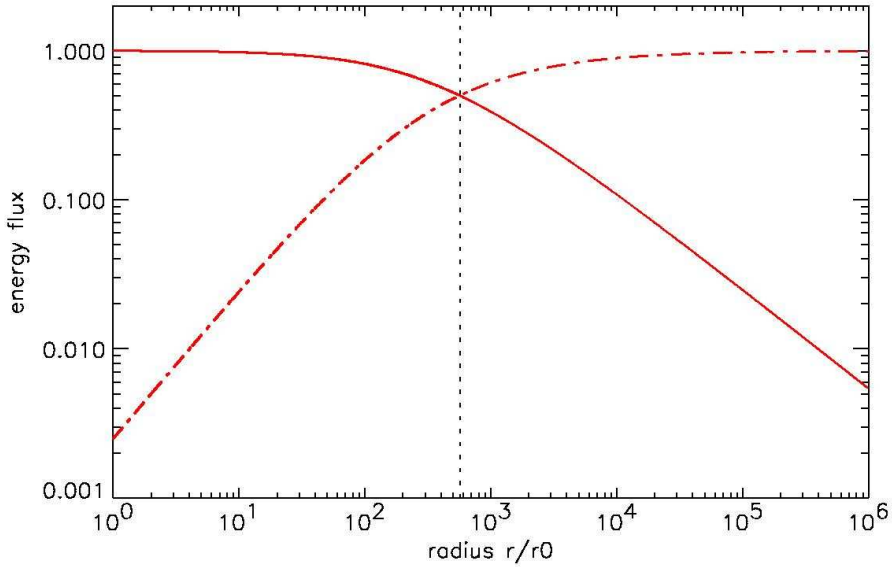
Terminal Lorentz factor : $\Gamma_\infty = h_0 \Gamma_0$

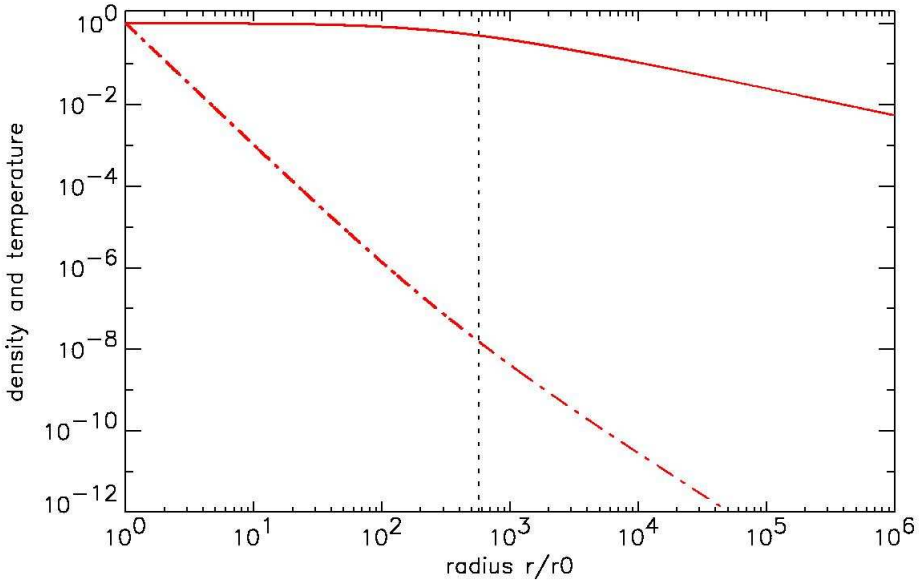
End of acceleration : $R_{acc} = R_0 \dfrac{\Gamma_\infty}{\Gamma_0}$

Constant width : $R << \Delta_0 \dfrac{\Gamma^2_\infty}{\Gamma_0}$

La source centrale et l'éjection relativiste : (1) fireballs







$$R_0 \approx \frac{6GM}{c^2} \approx 9\times10^6 \mu_1 \text{ cm}$$

$$R_{acc} \approx 9\times10^8 \mu_1 \left(\frac{\Gamma_\infty}{100}\right) \text{cm}$$

$$R_{spread} \approx 3\times10^{14} \left(\frac{\Gamma_\infty}{100}\right)^2 \left(\frac{\Delta/c}{1\,s}\right) \text{cm}$$

La source centrale et l'éjection relativiste : (1) fireballs

Initial temperature : $$kT'_0 \approx 1.8 \left(\frac{\dot{E}}{10^{52}\,\mathrm{erg/s}} \right)^{1/4} \left(\frac{R_0}{90\,\mathrm{km}} \right)^{-1/2} \mathrm{MeV}$$

		$R < R_{acc}$	$R > R_{acc}$
Temperature (comoving frame) :	$T' \approx (3P/a)^{1/4}$	$T' \propto R^{-1}$	$T' \propto R^{-\gamma/2}$
Temperature (source frame) :	$T = \Gamma T'$	$T \approx \mathrm{cst}$	$T \propto R^{-\gamma/2}$

Transparent to pairs : $T' < 20\,\mathrm{keV}$ **(usually :** $R < R_{acc}$ **)**

The fireball cannot be purely leptonic (thermal spectrum) : baryonic pollution !

La source centrale et l'éjection relativiste : (1) fireballs

Acceleration :

$$R_{acc} \approx 9\times10^{8}\,\mu_1\left(\frac{\Gamma_\infty}{100}\right)\,\mathrm{cm}$$

Transparency :

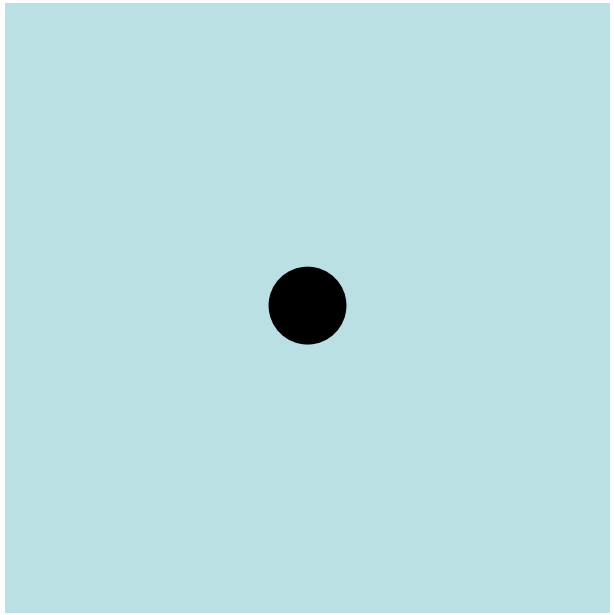
$$R_{ph} \approx 6\times10^{12}\,\mathrm{cm}\left(\frac{\dot{E}}{10^{52}\,\mathrm{erg/s}}\right)\left(\frac{\Gamma_\infty}{100}\right)^{-3}$$

Spreading :

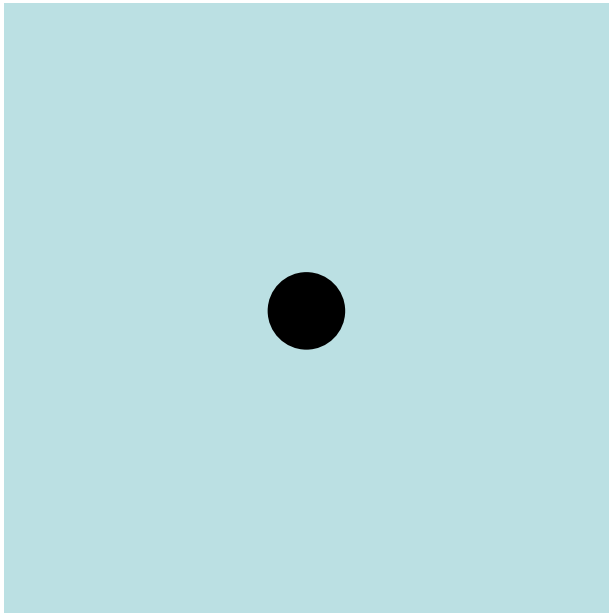
$$R_{spread} \approx 3\times10^{14}\left(\frac{\Gamma_\infty}{100}\right)^{2}\left(\frac{\Delta/c}{1\,\mathrm{s}}\right)\,\mathrm{cm}$$

La source centrale et l'éjection relativiste : (2) « modèles avancés »

Stellar mass black hole formation



Collapsar…



… or NS/BH+NS merger ?

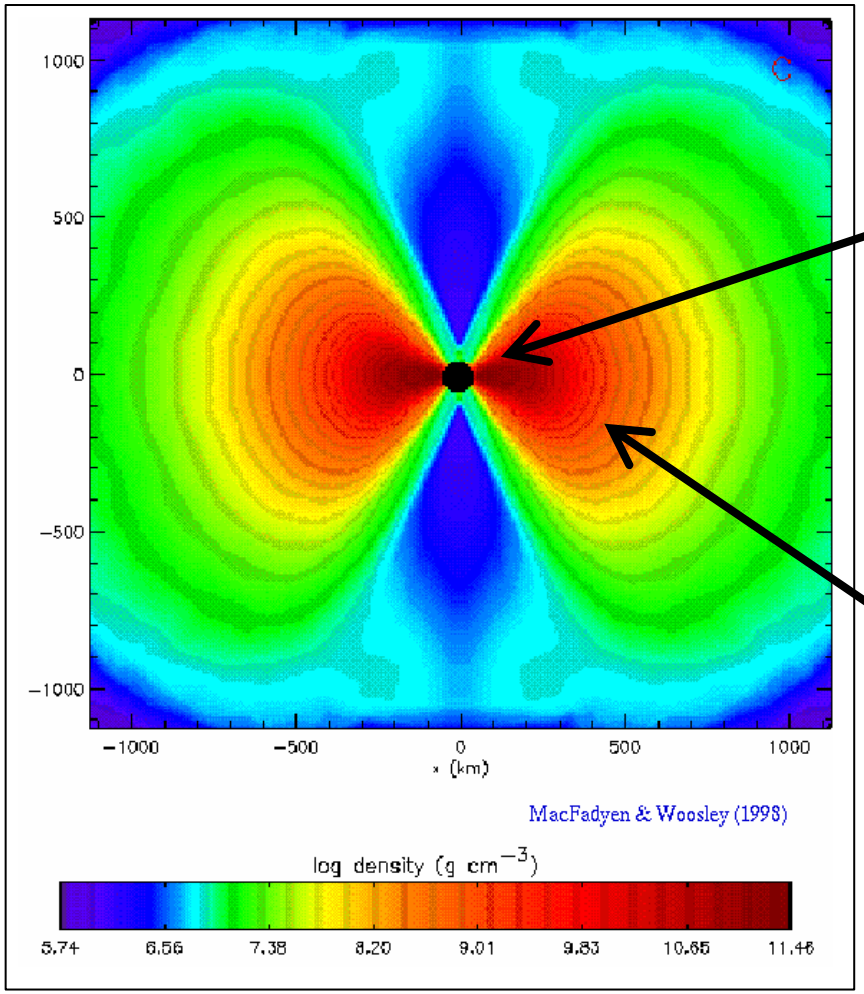
La source centrale et l'éjection relativiste : (2) « modèles avancés »

Collapsars

ex: Progenitor : 35 $M_\odot$

(helium core : 14 $M_\odot$)

(MacFadyen & Woosley 1999)

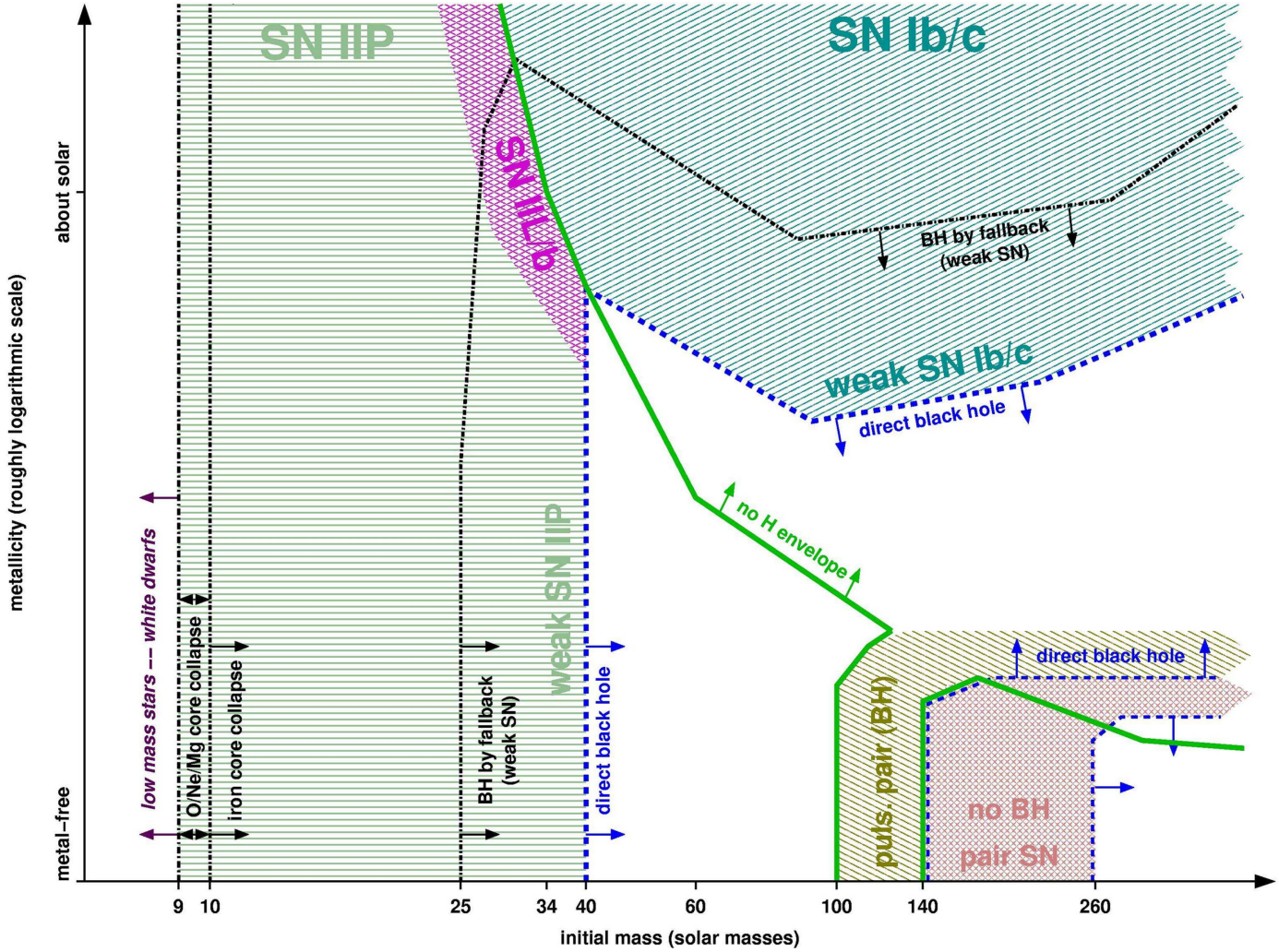


La source centrale et l'éjection relativiste : (2) « modèles avancés »

Many possibilities :

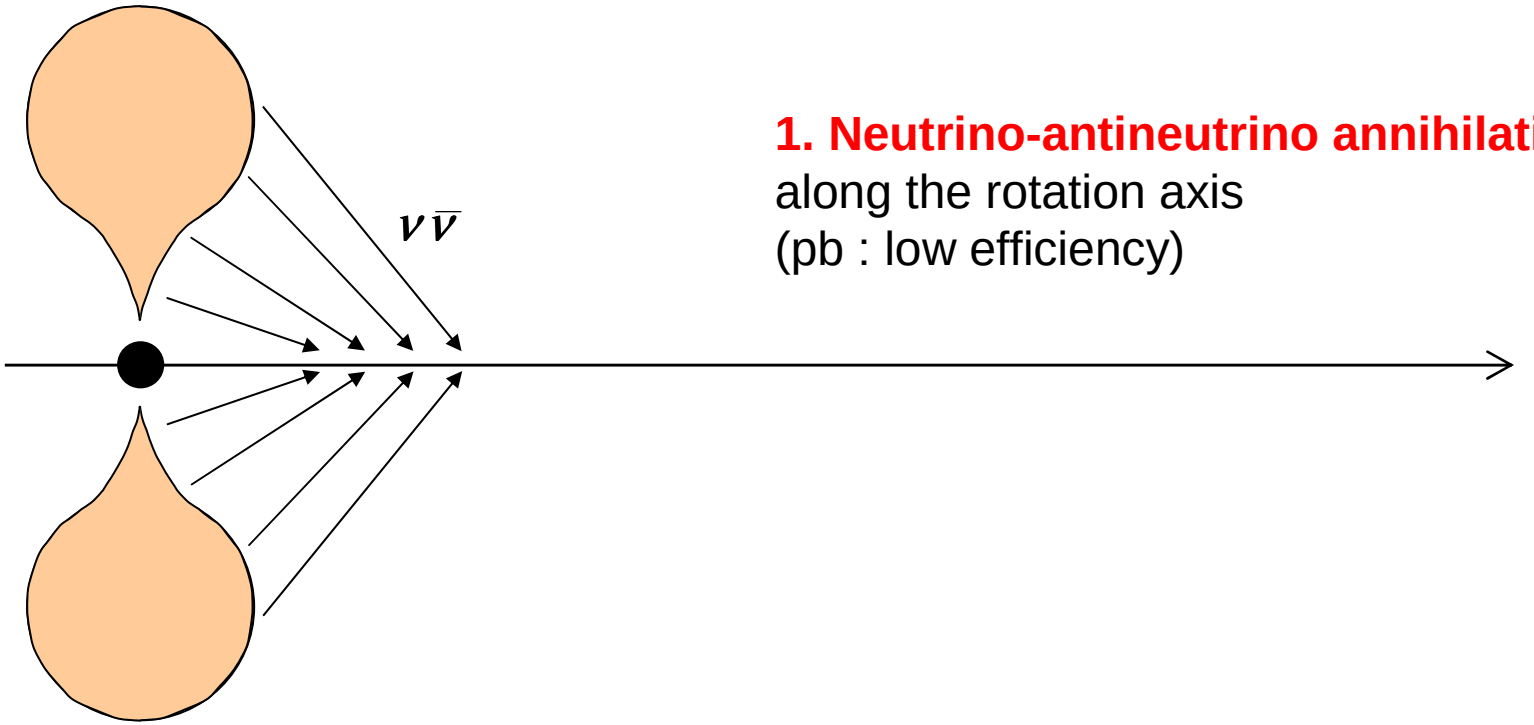
*** Two steps collapse : SN + a possible GRB**

*** Direct collapse : GRB without SN ? (NB: a dense wind could mimic a SN lightcurve)**



Heger et al.

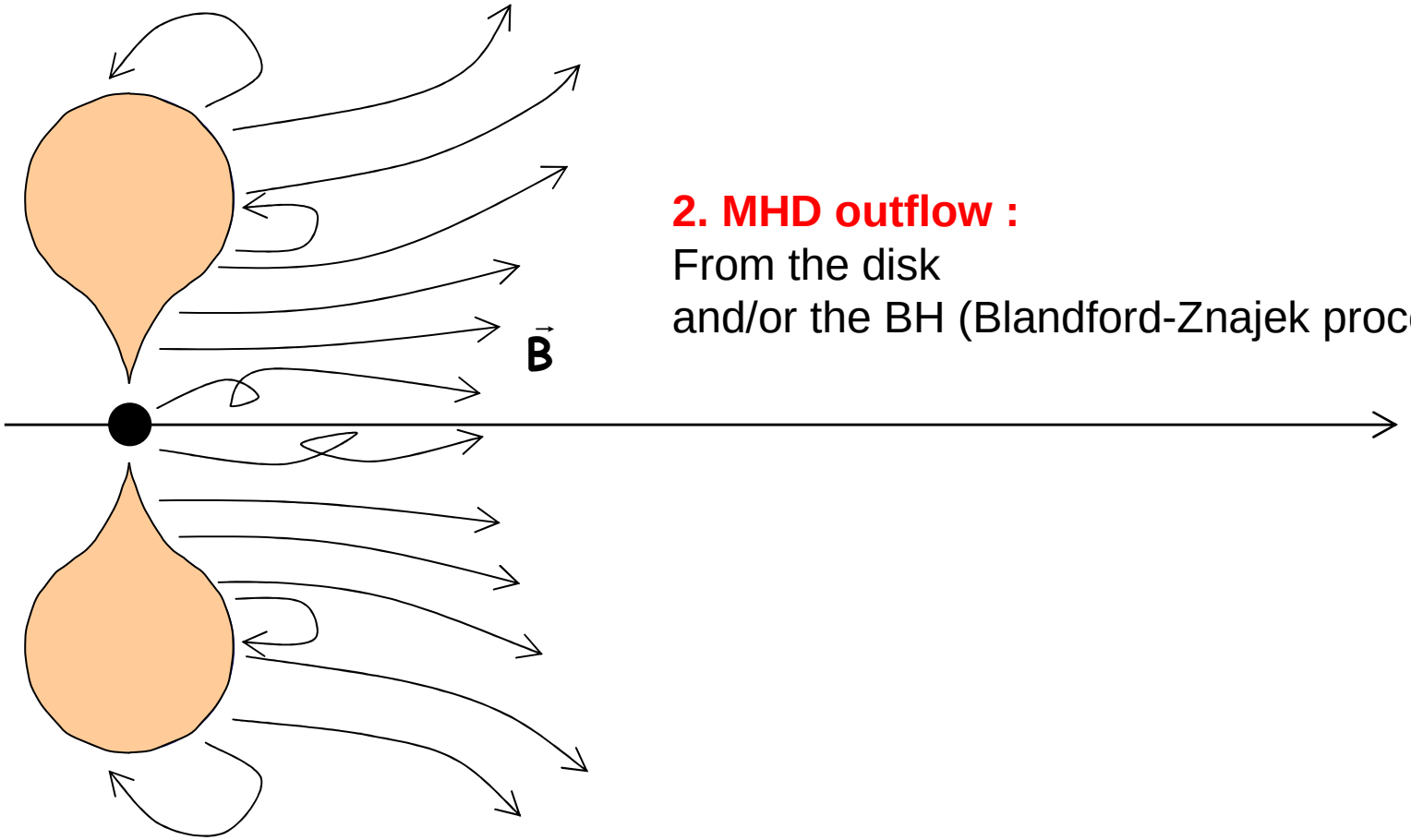
La source centrale et l'éjection relativiste : (2) « modèles avancés »



1. Neutrino-antineutrino annihilation
along the rotation axis
(pb : low efficiency)

Baryonic pollution : must be small.

La source centrale et l'éjection relativiste : (2) « modèles avancés »



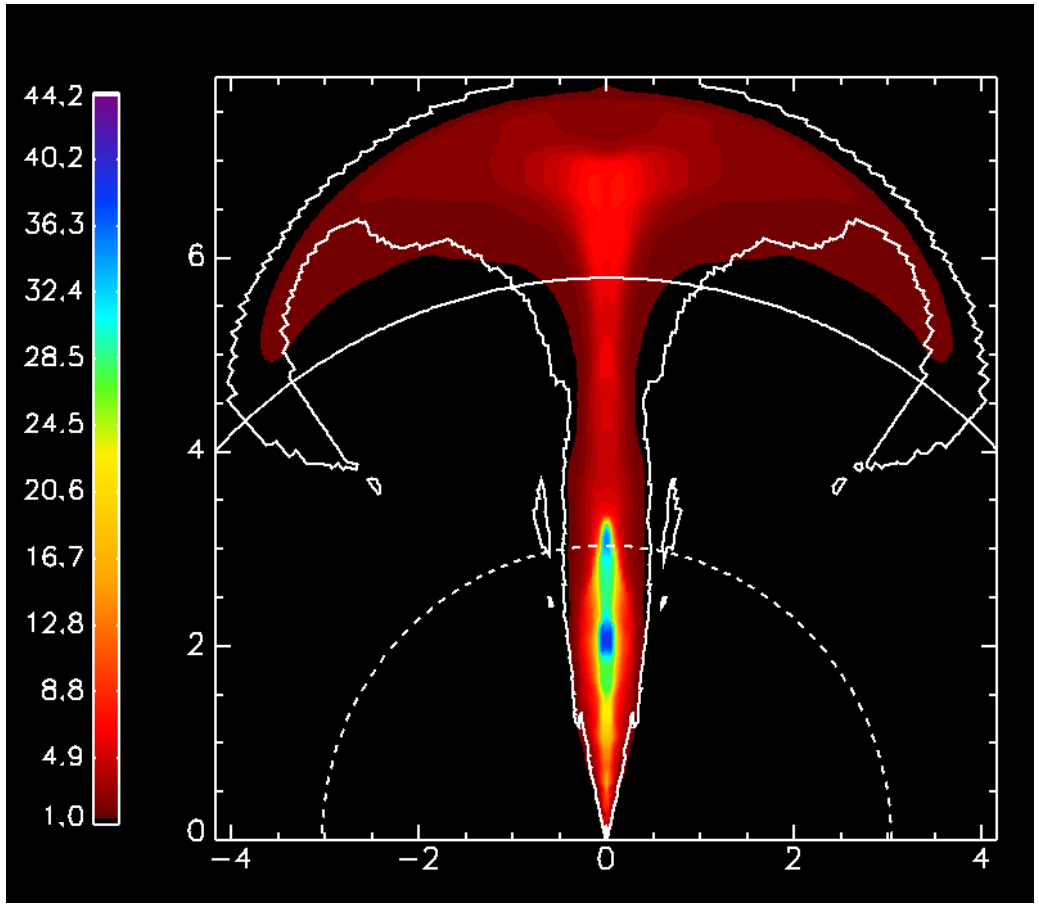
2. MHD outflow :
From the disk
and/or the BH (Blandford-Znajek process)

Baryonic pollution : must be small.

La source centrale et l'éjection relativiste : (2) « modèles avancés »

- Poorly understood process
- Two energy reservoirs : binding energy of the disk (accretion)
  + rotation energy of the black hole (BZ)
- Magnetic field ?
- How to escape the collapsing star ?
- Baryonic pollution ?

Physical conditions to reach an ultra-relativistic (Γ>100) and ultra-energetic (>10^{50} erg) outflow ?

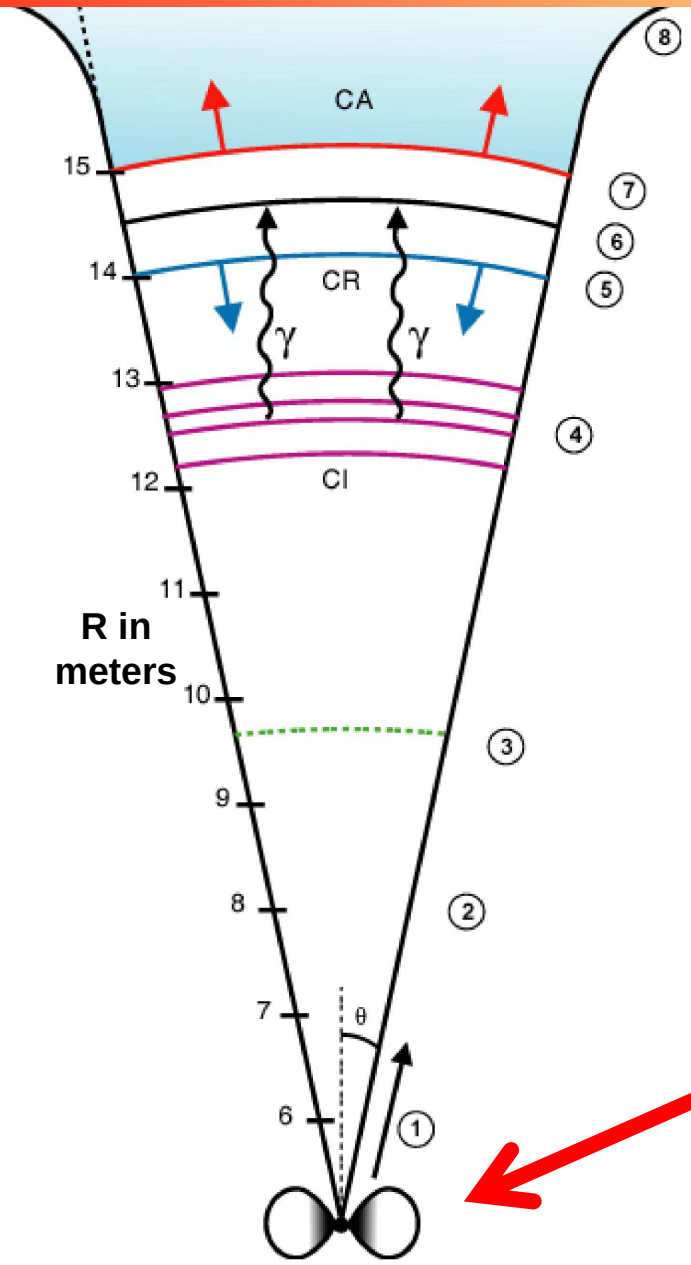


La source centrale et l'éjection relativiste : (2) « modèles avancés »

Ces modèles sont des modèles où le champ magnétique n'est pas dominant.

Je ne parlerai pas des modèles où le flux de Poynting transporte initialement la plus grande fraction de l'énergie (cas extrême : modèle purement électromagnétique de Blandford & Lyutikov).

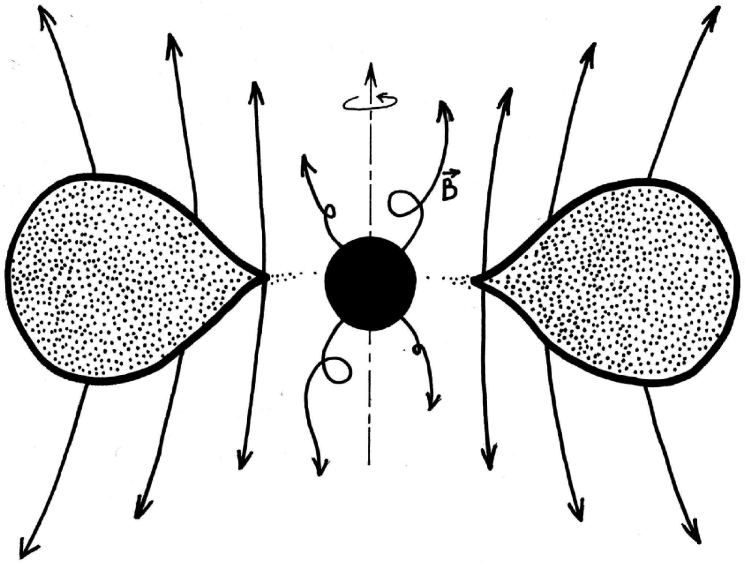
Scénario : les chocs internes – le choc externe



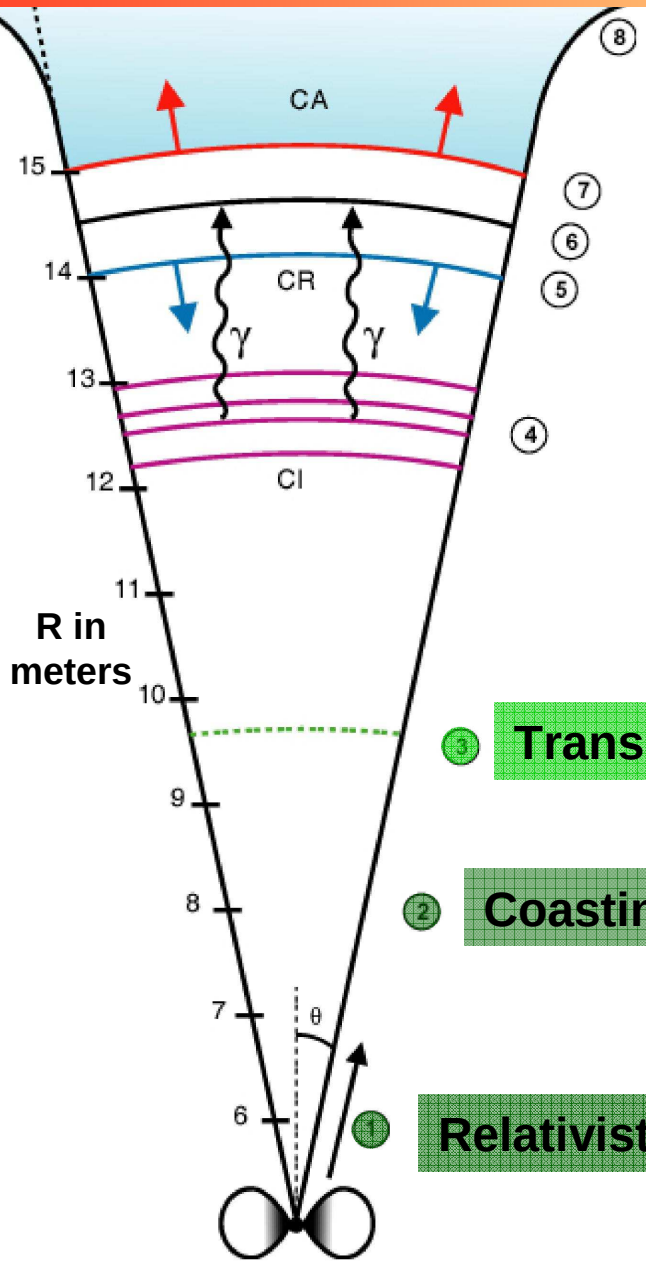
Initial event :

Collapsar (long GRBs)
Mergers (short GRBs ?)

► Stellar black hole + thick disc



Scénario : les chocs internes – le choc externe

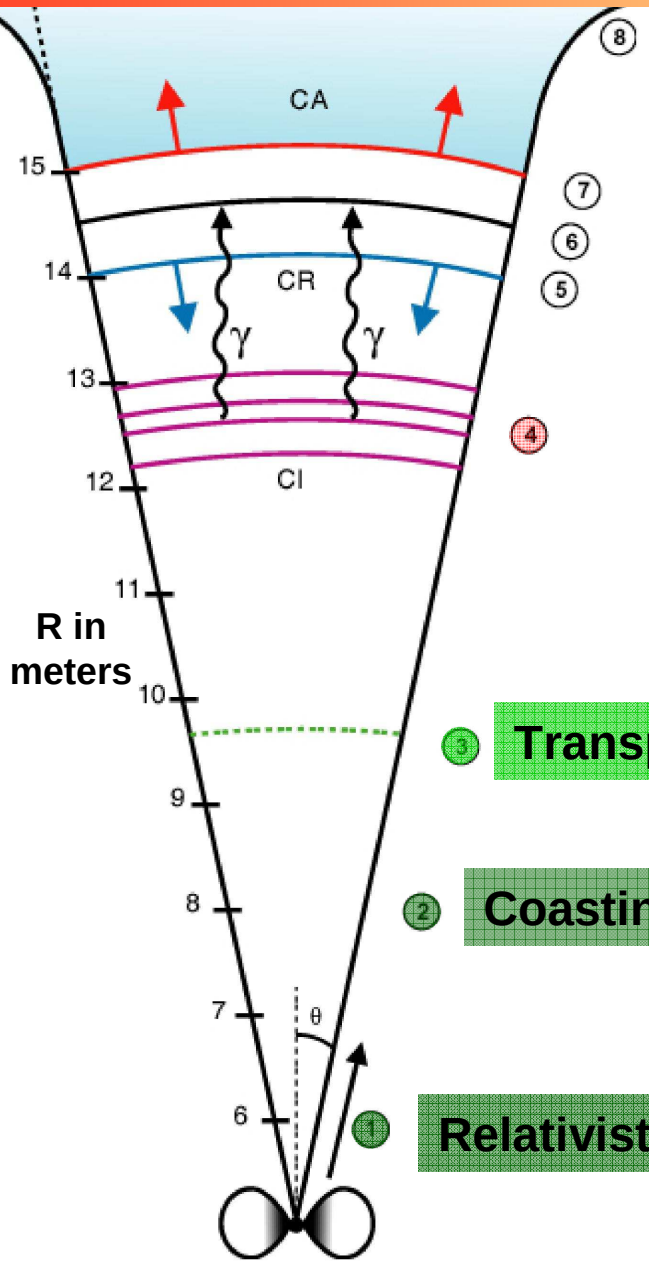


3 **Transparency**

2 **Coasting phase : Final Lorentz factor $\Gamma \geq 100$!**

1 **Relativistic ejection**

Scénario : les chocs internes – le choc externe



④ **Internal shocks :**

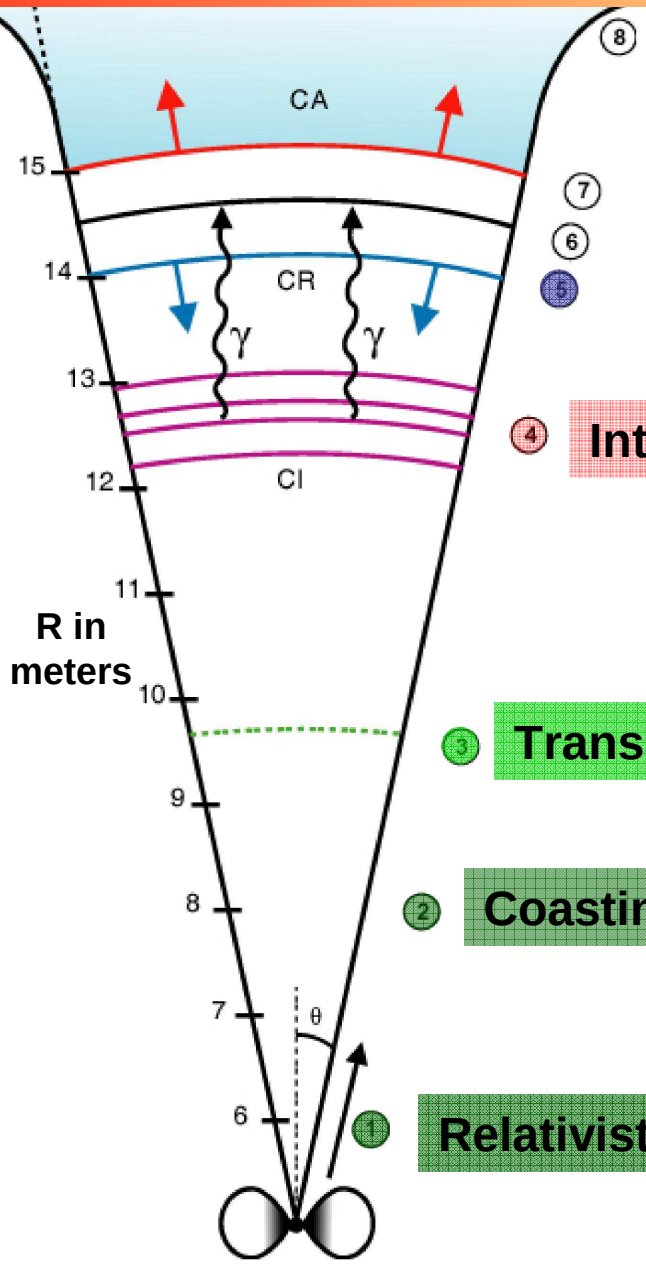
► **Prompt γ/X-rays / optical ?**

③ **Transparency**

② **Coasting phase**

① **Relativistic ejection**

Scénario : les chocs internes – le choc externe



⑤ **Reverse shock :**

► **Optical flash ?**

④ **Internal shocks**

③ **Transparency**

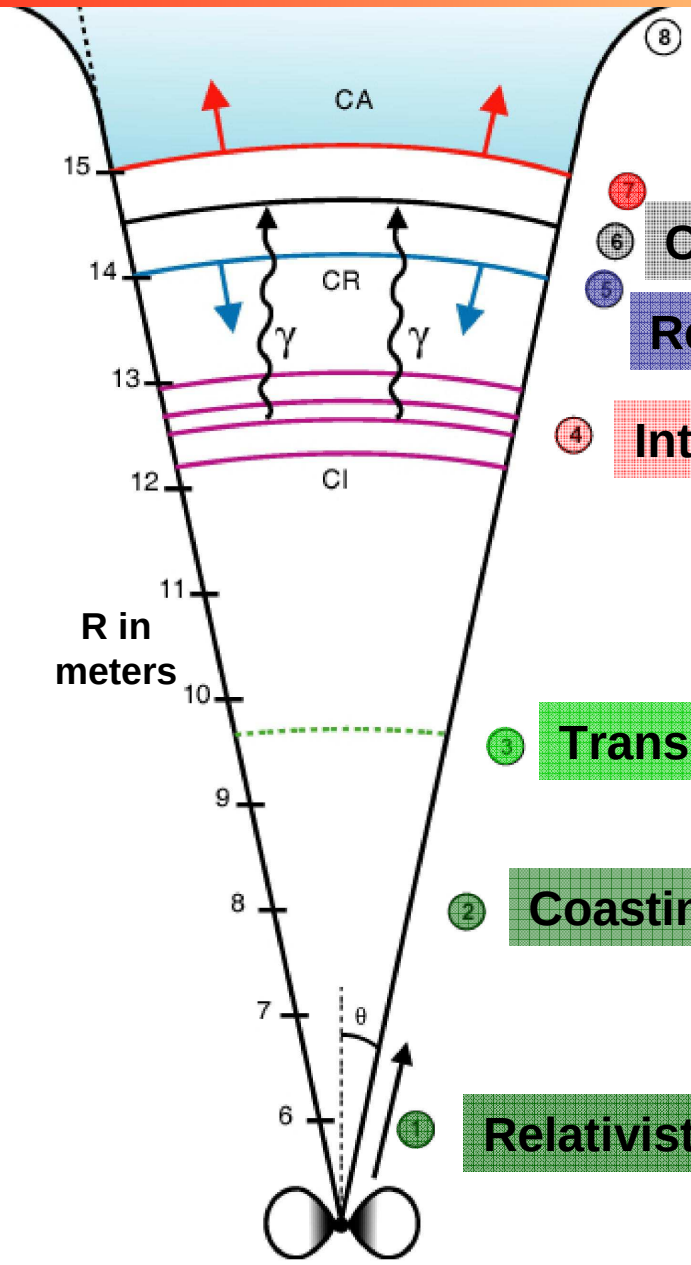
② **Coasting phase**

① **Relativistic ejection**

Scénario : les chocs internes – le choc externe

⑦ **Forward shock :**

► **Afterglow**



⑧

⑦ ⑥ **Contact discontinuity**

⑤ **Reverse shock**

④ **Internal shocks**

③ **Transparency**

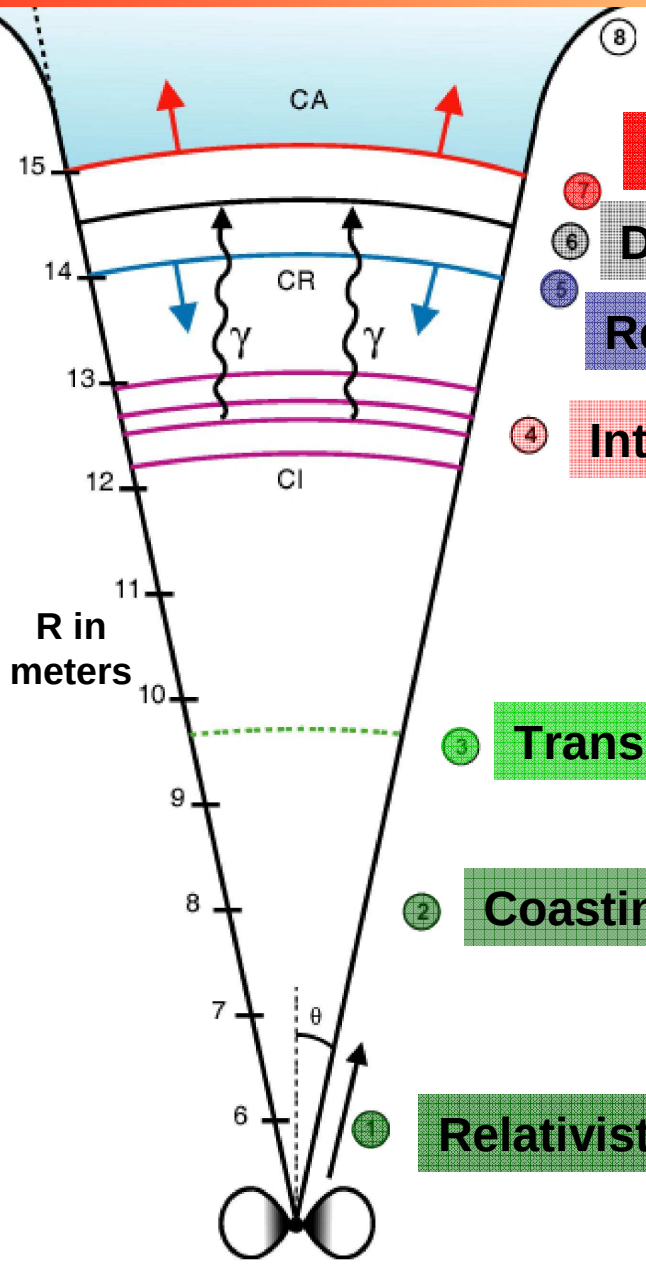
② **Coasting phase**

① **Relativistic ejection**

Scénario : les chocs internes

⑧ Lateral expansion :

Starts at late time.



Les chocs internes

Rees & Meszaros 1997 :

Variability of the lightcurve $\leftrightarrow$ Activity of the central engine

Matter ejection by the central engine :

energy injection rate and/or mass injection rate can vary on a dynamical timescale (ms)

$\Rightarrow$ the final distribution of the Lorentz factor at the end of the acceleration phase can be highly variable

$\Rightarrow$ shock waves propagate within the relativistic ejecta = internal shocks

GRB = emission of the shocked material

Les chocs internes : (1) dynamics

The central source is ejecting relativistic matter from t=0 to $t=t_w$:

*** Shell ejected at t_{ejec} : Lorentz factor $\Gamma_{min} \gg 1$**
*** Shell ejected at $t_{ejec}+t_{var}$: Lorentz factor $\Gamma_{max} \gg 1$**

If contrast $\kappa = \Gamma_{max} / \Gamma_{min} > 1 \Rightarrow$ shock at $R_{shock} = 2 f \Gamma_{min}^2 c t_{var}$

$$t_{shock} = t_{ejec} + 2 f \Gamma_{min}^2 t_{var}$$

with $f \approx \kappa^2/(\kappa^2-1) \approx 1$ for $\kappa > 2$-3

(for simplicity, assume the two shells have same mass M)

two shells merge :

*** new mass 2M**

*** new Lorentz factor $\Gamma_r \approx (\Gamma_{min} \Gamma_{max})^{1/2} = \Gamma_{min} \kappa^{1/2}$**

*** dissipated energy : $e \approx (\Gamma_{min} + \Gamma_{max} - 2 \Gamma_r) Mc^2$**

*** efficiency : $f_d \approx (\kappa^{0.5}-1)^2 / (1+\kappa) \approx$ 10% - 40% for $\kappa =$ 3-10**

Les chocs internes : (1) dynamics

Shock : $R_{shock} = 2 f \Gamma_{min}^2 c t_{var}$ and $t_{shock} = t_{ejec} + 2 f \Gamma_{min}^2 t_{var}$

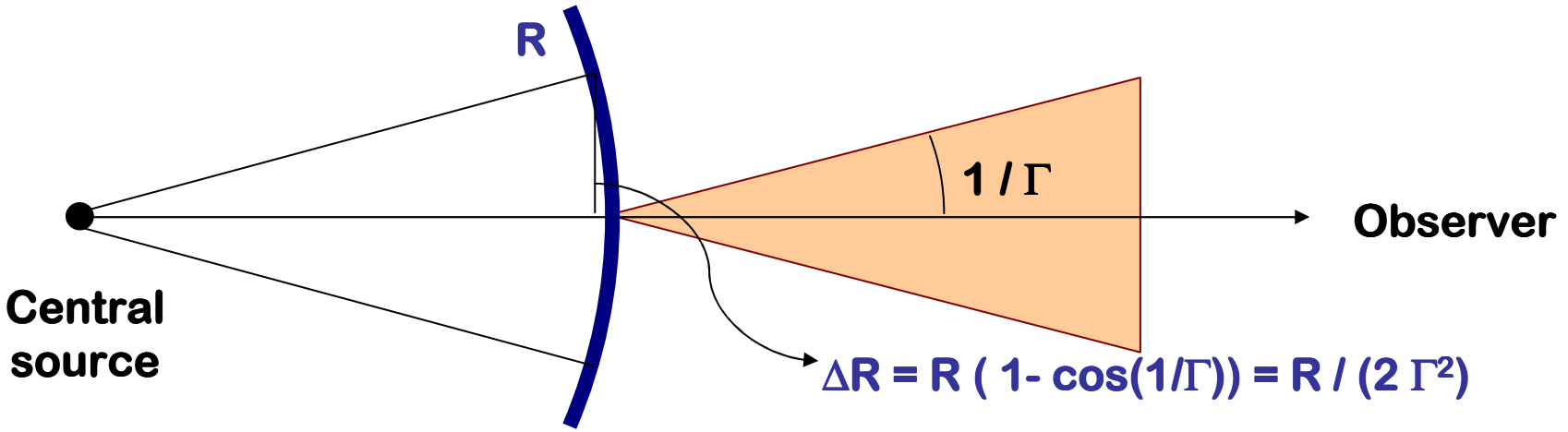
with $f \approx \kappa^2/(\kappa^2-1) \approx 1$ for $\kappa > 2$-3

shocked material : Lorentz factor $\Gamma_r \approx \Gamma_{min} \kappa^{1/2}$

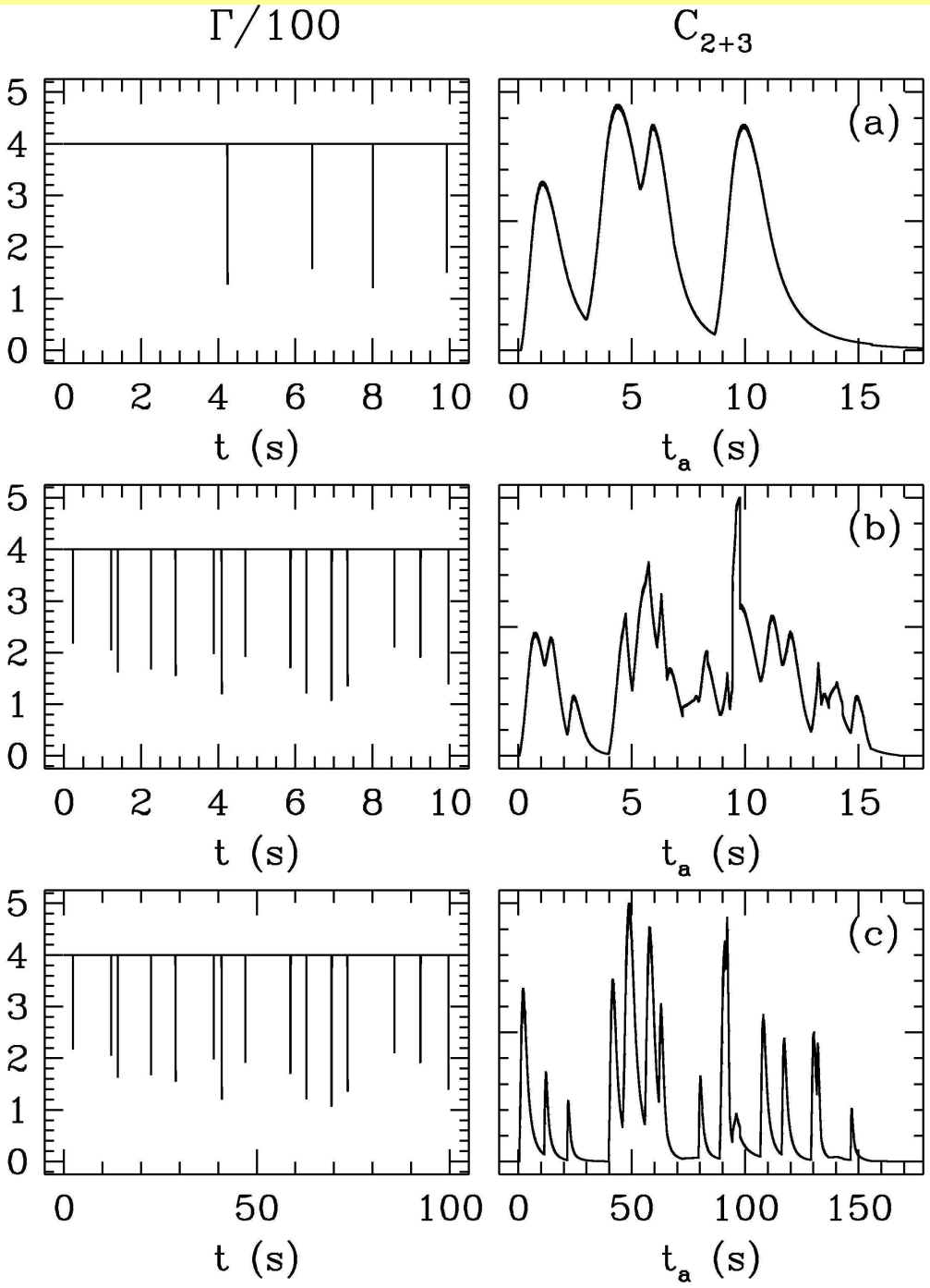
Lightcurve ↔ source activity

Observer time * arrival time of photons $t_a = t - R / c \approx t_{ejec}$

* angular spreading $\Delta t_a = R / (2 \Gamma^2 c) \approx t_{var}$



Les chocs internes



Daigne & Mochkovitch 1998

Les chocs internes : (2) microphysics

Internal shocks : mildly relativistic

Shocked material : density $\rho_* \approx 7\,\rho$

energy density $\varepsilon_* / c^2 \approx (\kappa^{0.5}+\kappa^{-0.5})/2-1 \approx$ 200 MeV/p

Equipartition parameters :

Magnetic field α_B : $B^2/8\pi \approx \alpha_B\,\rho_*\,\varepsilon_*$

Electrons α_e, ζ : Density : $\zeta\,\rho_* / m_p$

Energy density : $\alpha_e\,\rho_*\,\varepsilon_*$

Distribution : $n(\Gamma_e) \propto \Gamma_e^{-p}$ for $\Gamma_e > \Gamma_m$

Lorentz factor : $\Gamma_m \approx (\alpha_e/\zeta)\,(m_P/m_e)\,(\varepsilon_*/c^2)$

Les chocs internes : (3) radiation

Synchrotron / IC :

* if $\zeta \approx 1$: $\Gamma_m \approx$ 100-1000 : GRB = IC
  pb = low efficiency (low B is needed)
* if ζ small : Γ_m is larger : GRB = synchrotron
  efficiency is better

Global efficiency =

	f(dissipation)	(10-40 %…)
x	α_e	(10%-50% ???)
x	f(rad)	(close to 100% fast cooling)
x	f(BATSE)	(close to 100% if syn)

Les chocs internes

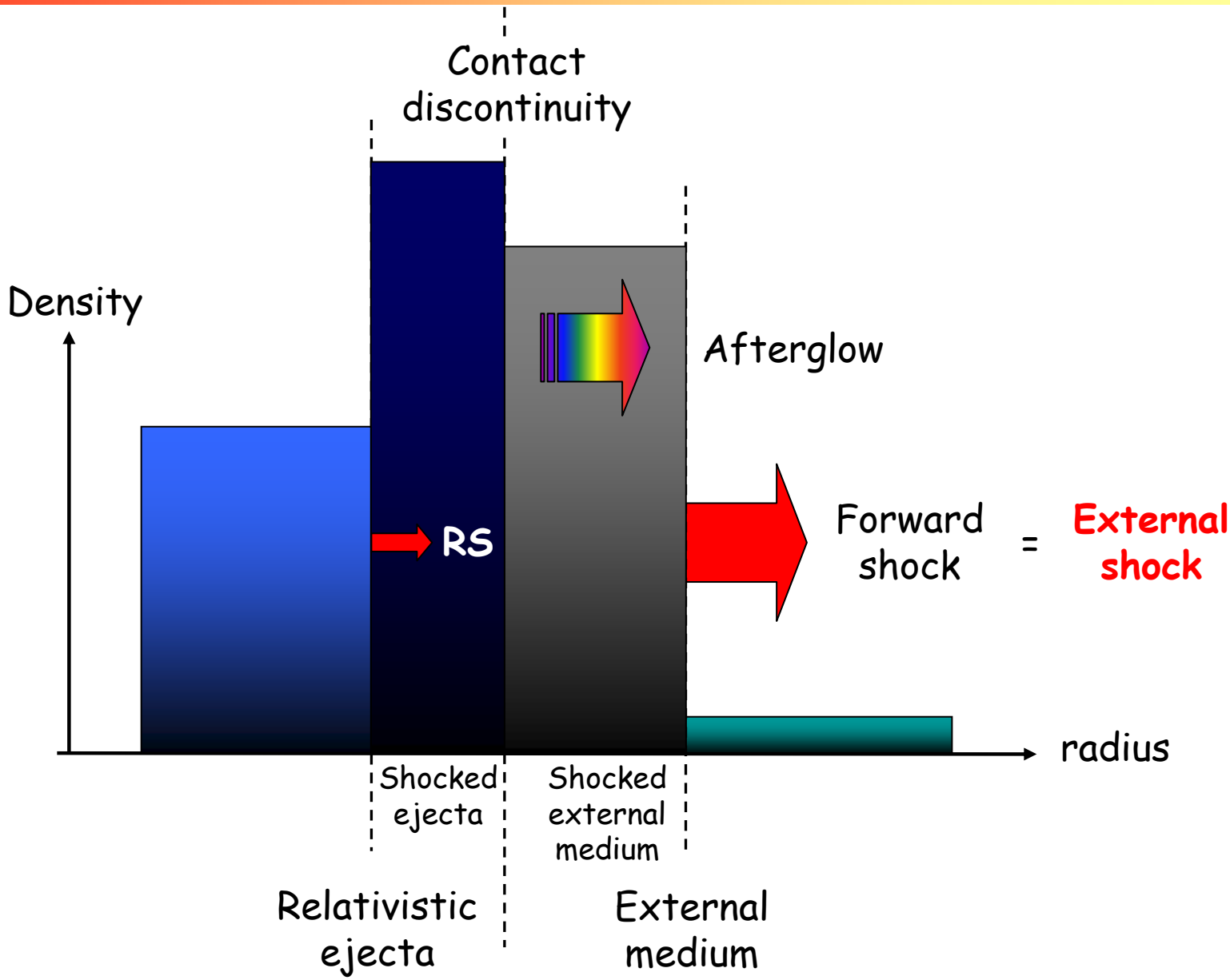
Status : - the hydrodynamics is well understood,
- the radiative processes at work (and the related physics of particle acceleration in midly relativistic shocks) are very poorly understood.

The model : - can reproduce the observed variability
- can explain the hardness-duration correlation
- can reproduce the hard-to-soft evolution
- etc…

Questions : - shape of the spectrum ? (low-energy slope)
- efficiency ?

Observations : -one really needs to extend the spectral range where GRBs are observed (GLAST, SVOM).

Le choc externe et le choc en retour



Le choc externe et le choc en retour

External shock (1) : dynamics

The swept-up mass M_{ext} depends
on the density profile in the external medium :

$$\rho = A / r^s$$

$$M_{ext} = 4\pi/(3-s)\, A\, r^{3-s}$$

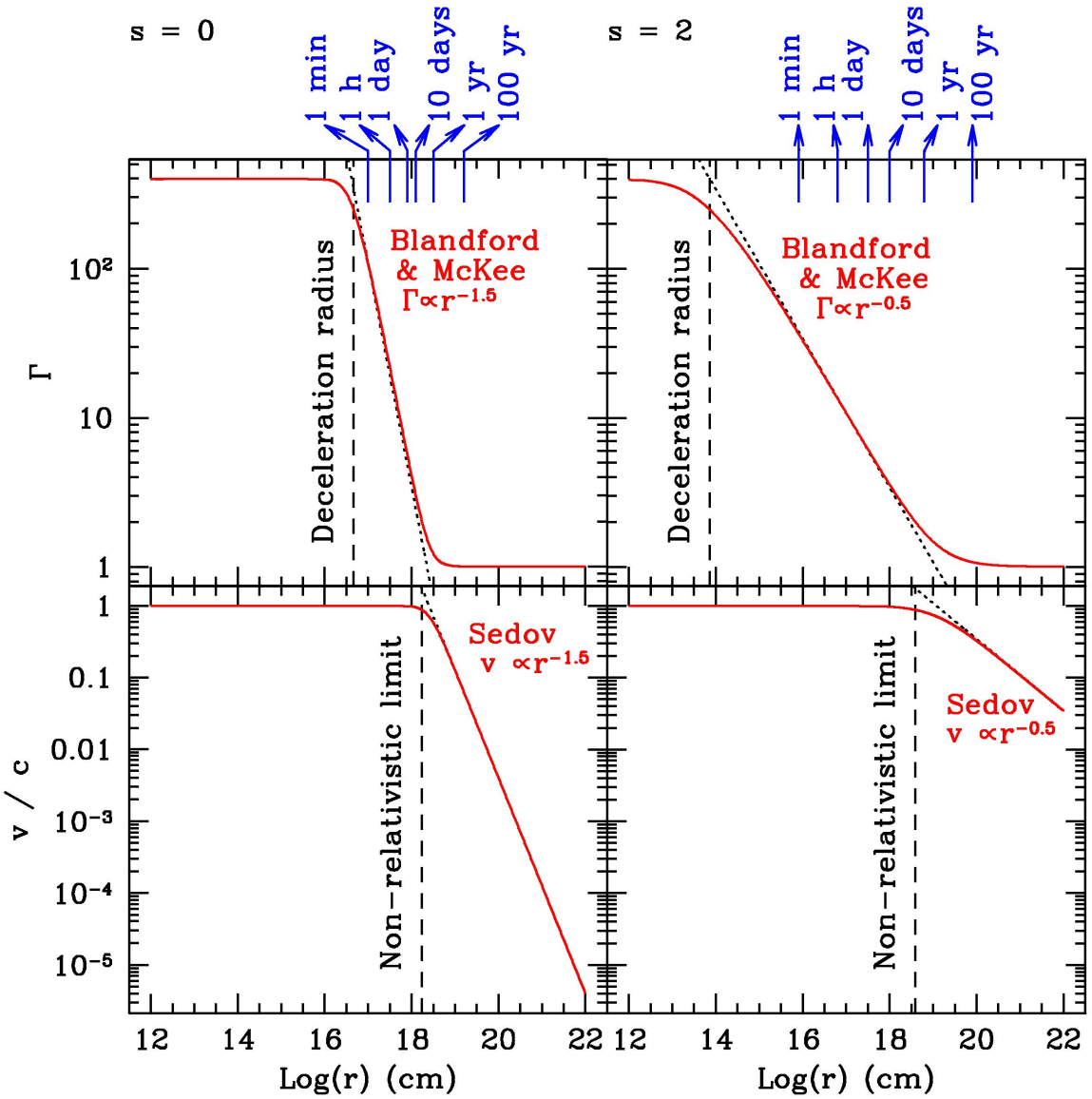
Deceleration radius : $M_{ext} = M_0/\Gamma_0 = E_0 / \Gamma_0^2\, c^2$

$$R_{dec} = [\, (3-s)/4\pi \;\; E_0 / A\, \Gamma_0^2\, c^2 \,]^{1/(3-s)}$$

$$R_{dec} = 1.2\ 10^{17}\ E_{53}^{1/3}\ n_0^{-1/3}\ \Gamma_2^{-2/3}\ \text{cm} \quad \text{for } s = 0 \text{ and } A = n\, m_p$$

$$R_{dec} = 1.8\ 10^{15}\ E_{53}\ A_*^{-1}\ \Gamma_2^{-2}\ \text{cm} \quad \text{for } s = 2 \text{ and } A = 7.6\ 10^{11}\ A_*\ \text{g/cm (WR)}$$

Le choc externe et le choc en retour



Relativistic ejecta :

$\Gamma_0 = 400$

$E_0 = 10^{53}$ erg

$M_0 = E_0/\Gamma_0 c^2 = 1.4\ 10^{-4}\ M_\odot$

External medium :

Uniform (s=0): $n = 1\ cm^{-3}$

Stellar wind (s=2): $A_* = 1$

Le choc externe et le choc en retour

External shock (2) : radiation

(1) Physical conditions in the shocked medium:
given by BM solution.

$$\varepsilon_* = \Gamma\, c^2$$
$$\rho_* = 4\, \Gamma\, \rho_{ext}$$

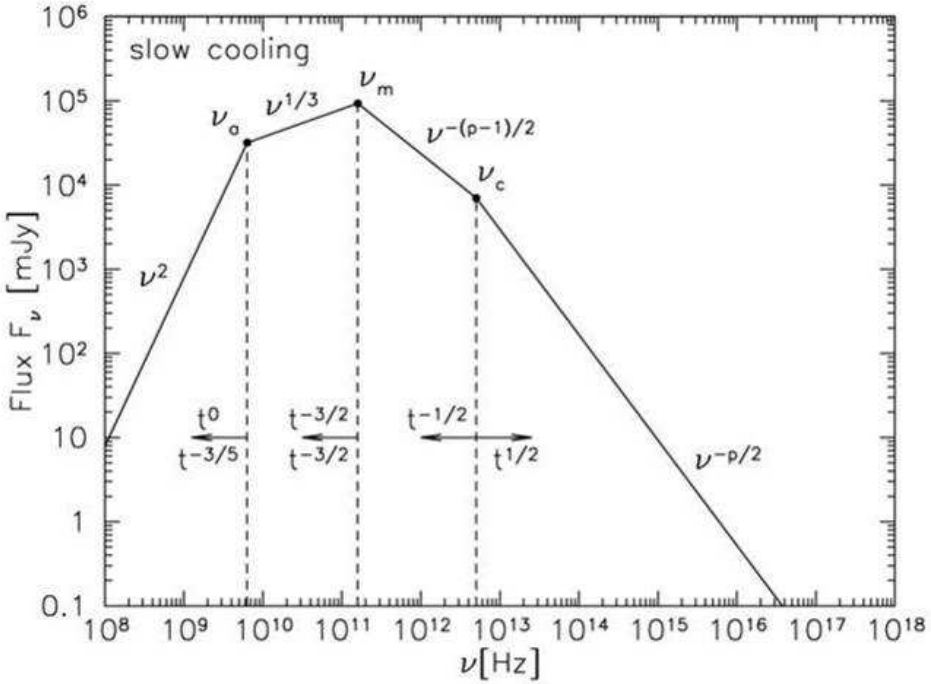
(2) Magnetic field–Relativistic electrons: "equipartition"

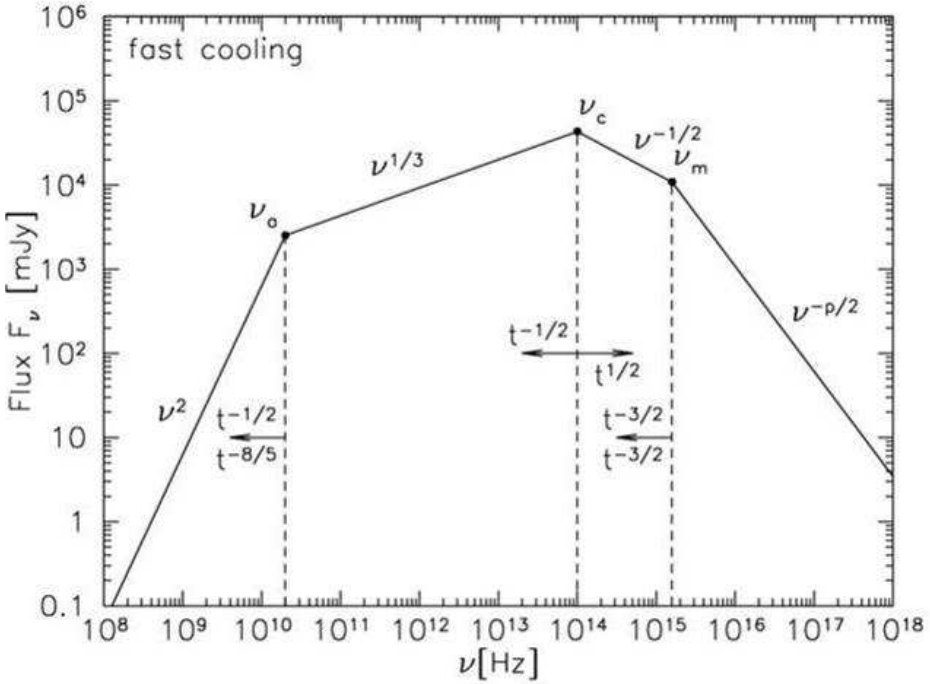
$$B^2 / 8\pi = \alpha_B\, \rho_*\, \varepsilon_* \quad \Rightarrow \quad B = (\, 32\, \pi\, \alpha_B\, \rho_{ext}\,)^{0.5}\, \Gamma\, c$$

$$(\rho_*/m_p)\Gamma_e m_e c^2 = \alpha_e \rho_* \varepsilon_* \quad \Rightarrow \quad \Gamma_e = (m_p / m_e)\, \varepsilon_*/c^2$$

(3) Synchrotron spectrum : fast or slow cooling (Sari et al. 1998)

Le choc externe et le choc en retour





$t'_{ex} = R / \Gamma c$

$t'_{syn} = 6\pi m_e c / \sigma_T / B^2 / \Gamma_e$

$= t'_{ex} (\Gamma_e / \Gamma_c)^{-1}$

$\Gamma_e > \Gamma_c$: efficient radiative cooling

For $\Gamma_{min} > \Gamma_c$: « fast cooling »
all electrons lose radiatively their energy in t'_{ex}.

For $\Gamma_{min} < \Gamma_c$: « slow cooling »
most electrons do not radiate efficiently.

Le choc externe et le choc en retour

External shock (3) : other effects

(1) Opening angle of the "jet" :

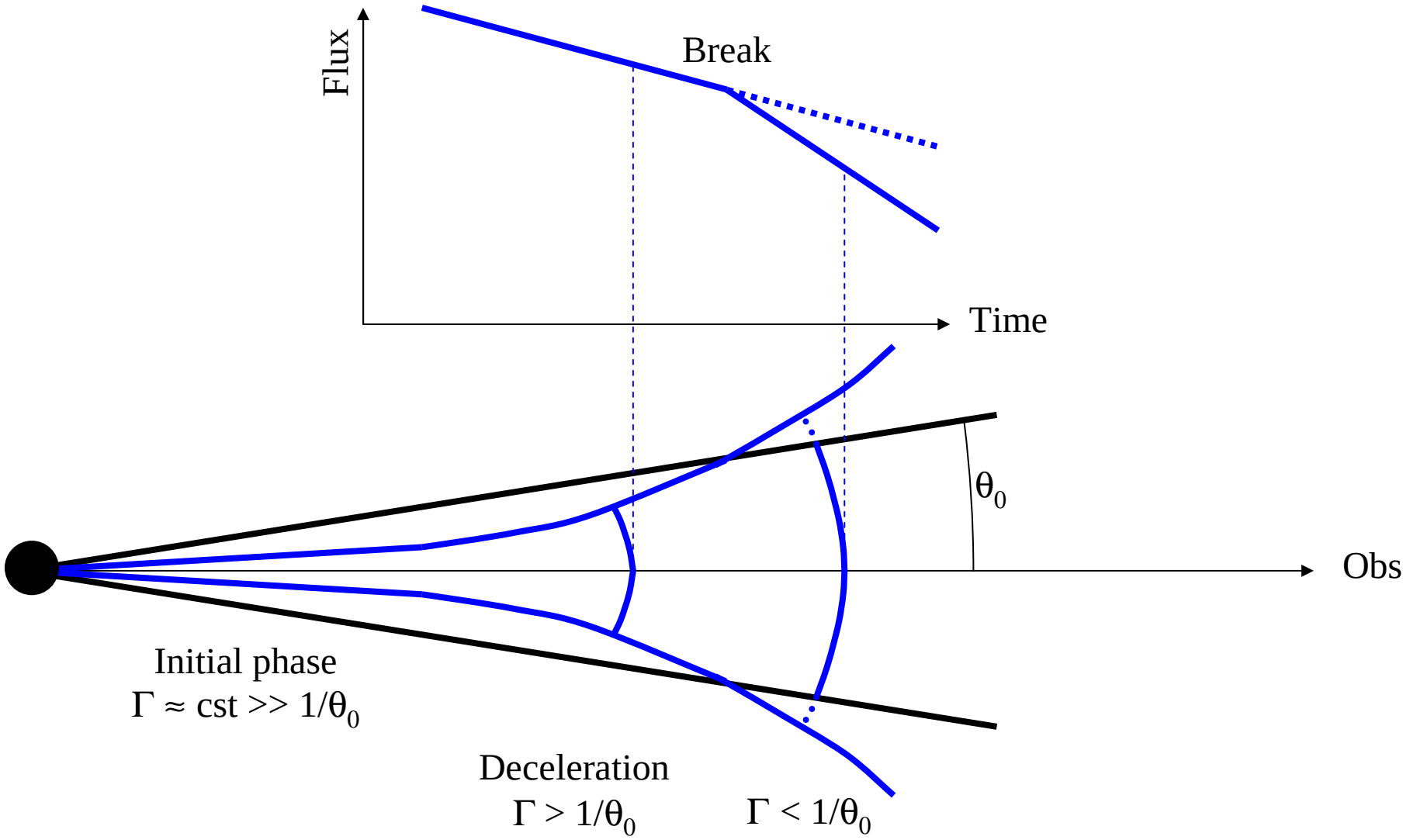
Break in the afterglow lightcurve :

$$< (\Omega/4\pi)^{-1} > \approx 500$$ (Frail et al. 2002)

(2) Modification of the dynamics due to radiative losses

(3) More realistic radiative processes : Compton inverse, etc…

Le choc externe et le choc en retour



Le choc externe et le choc en retour

External shock : results

Multi wavelength late-time (> a few hours) afterglow observations are well reproduced (i.e. Beppo SAX era).

Reverse shock

Dynamics : short-lived shock wave
(observed duration ~ Δ/c + decaying tail)

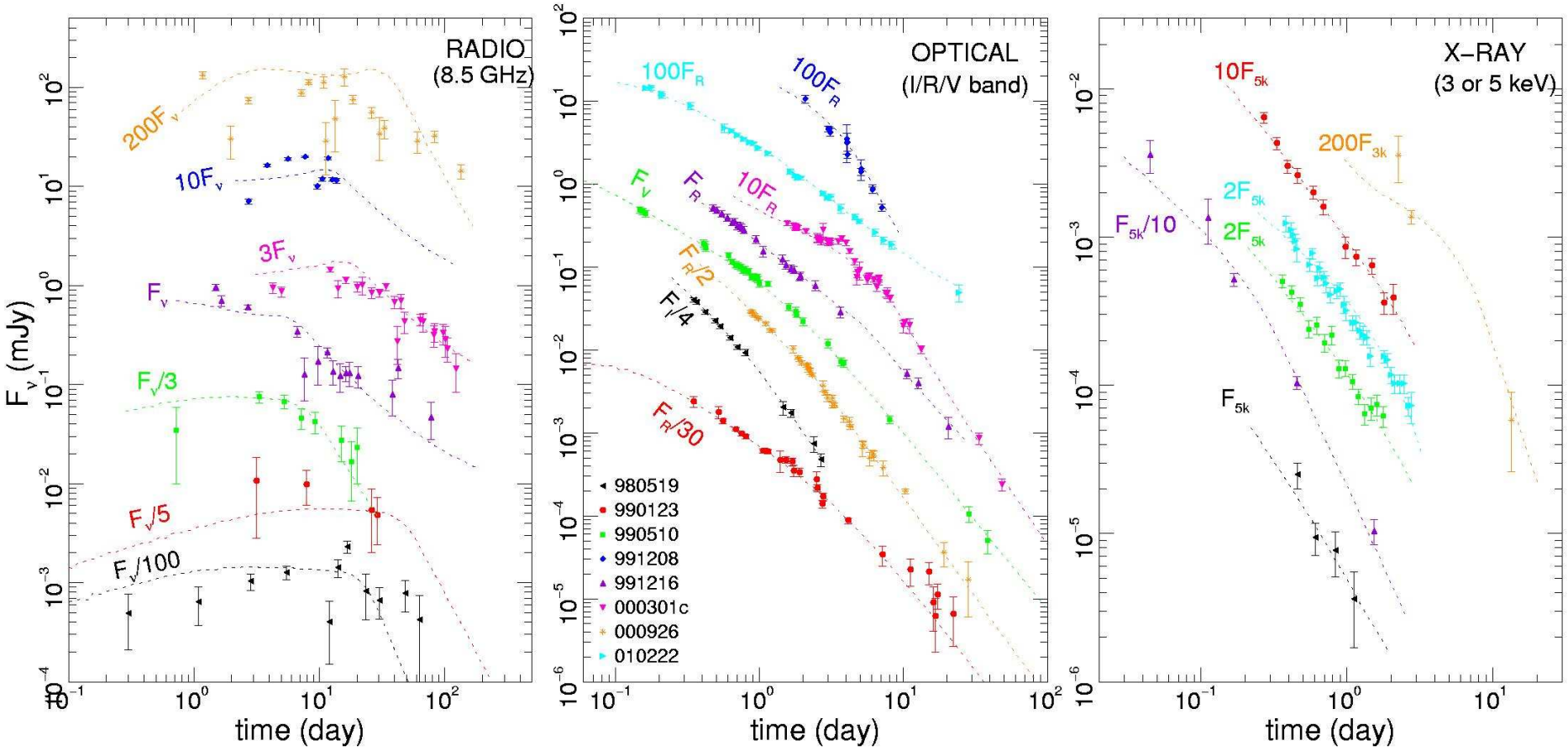
High density medium : RS crosses the relativistic shell before the end of the internal shock phase
Low density medium : RS comes after IS

Radiation : idem external shock
Results : debated (optical flash ?)

Succès et difficultés du modèle

1. Internal shocks : γ-ray prompt emission well reproduced
   but : low efficiency

2. Afterglows in the pre-SWIFT era : nice fits by the FS model…



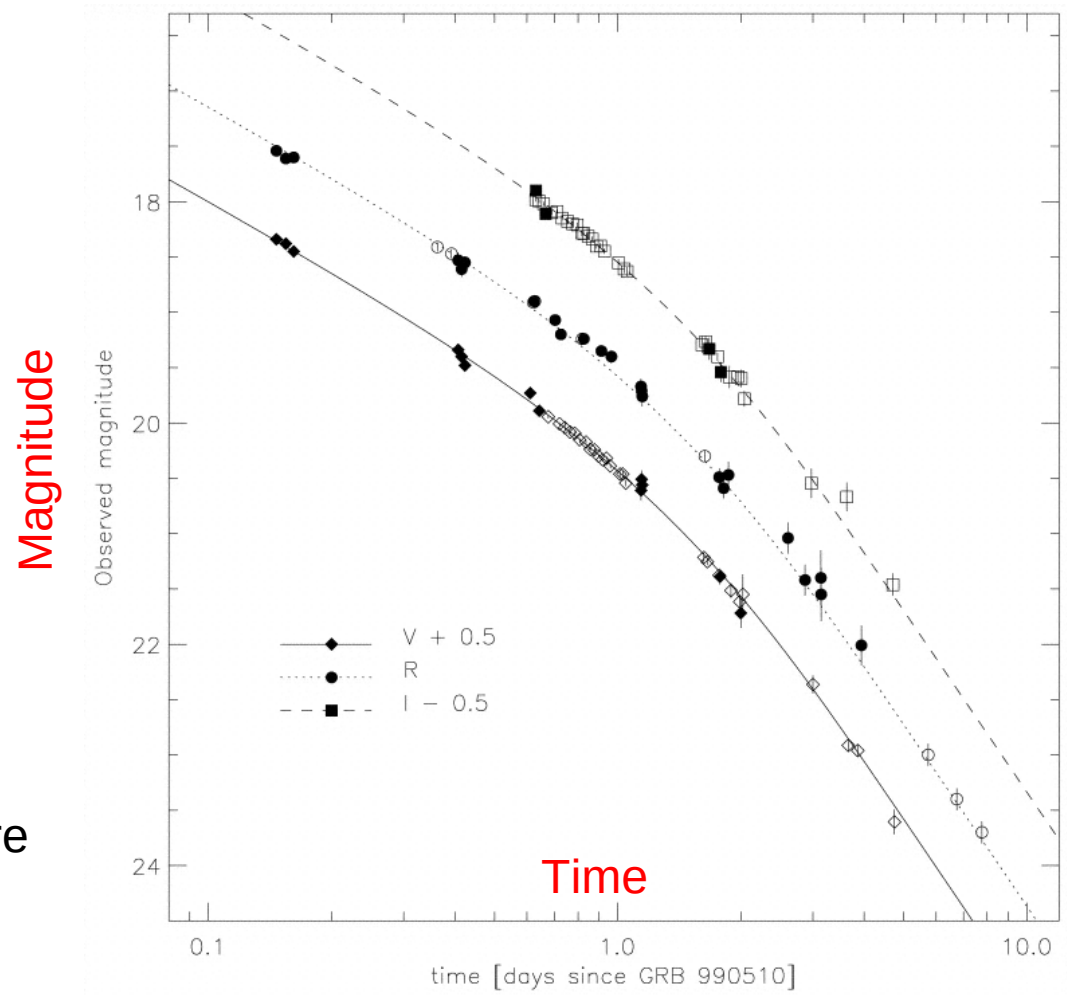
(e.g. Panaitescu & Kumar 2001)

Succès et difficultés du modèle

3. Afterglows in the pre-SWIFT era : jet (achromatic) breaks

(e.g. GRB 990510,

Harrison et al. 1999)

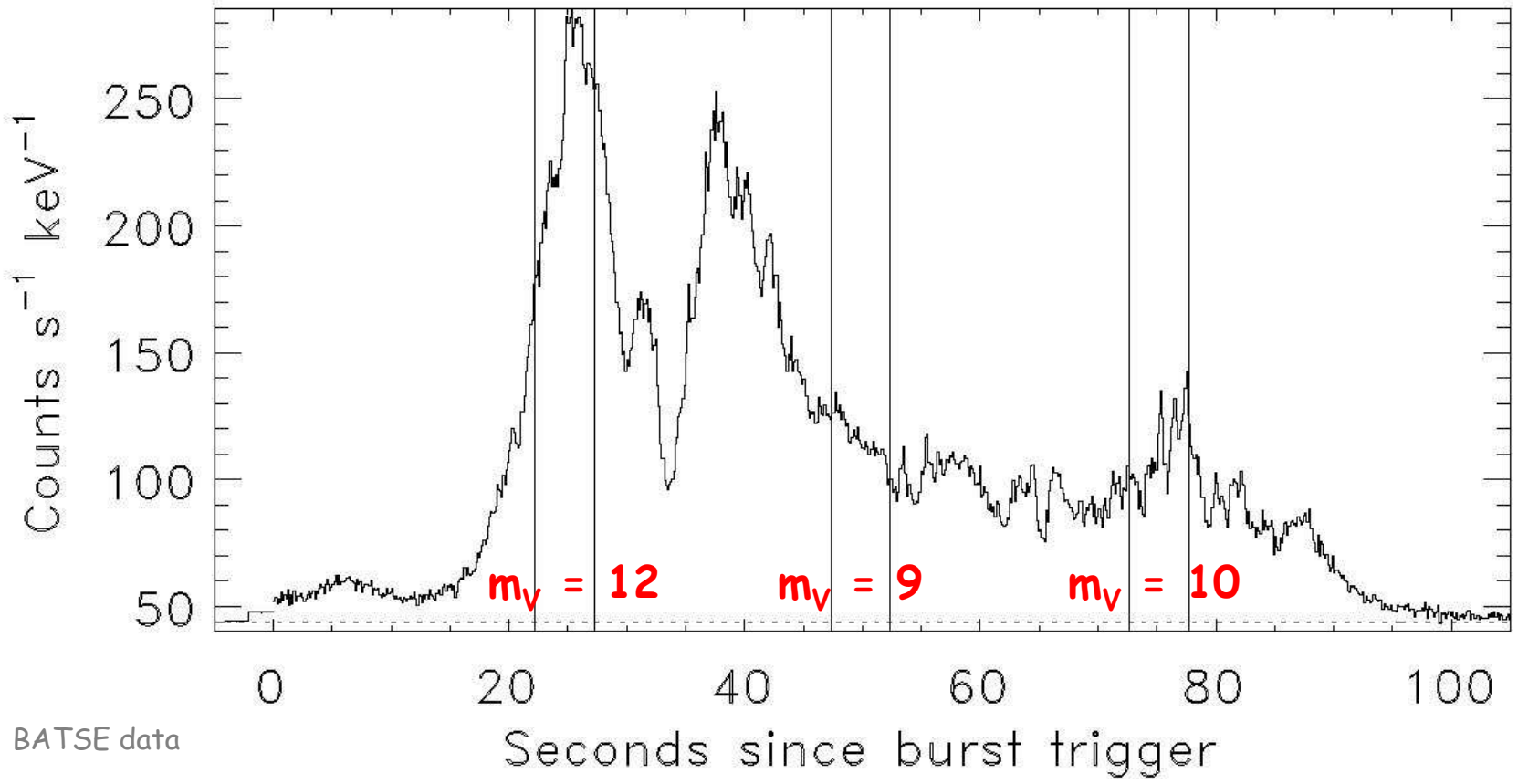


Usually, X-ray observations are not available at break time.

Succès et difficultés du modèle

4. Afterglows in the pre-SWIFT era : one famous optical flash

GRB990123 / ROTSE such cases are very rare



Succès et difficultés du modèle

5. Afterglows in the pre-SWIFT era : first problems…

- Uniform medium when a wind is expected (Chevalier, Li & Fransson 2004)

  Panaitescu & Kumar 2001 : n ~ 0.01 – 10 cm^{-3}

  e.g. GRB030329 (SN Ic) : uniform medium with n ~ 2 cm^{-3} !
  (Berger et al. 2003)

- Slope p of the electron distribution is often found to be p<2

  Panaitescu & Kumar 2001 : p ~ 1.4 – 2.8

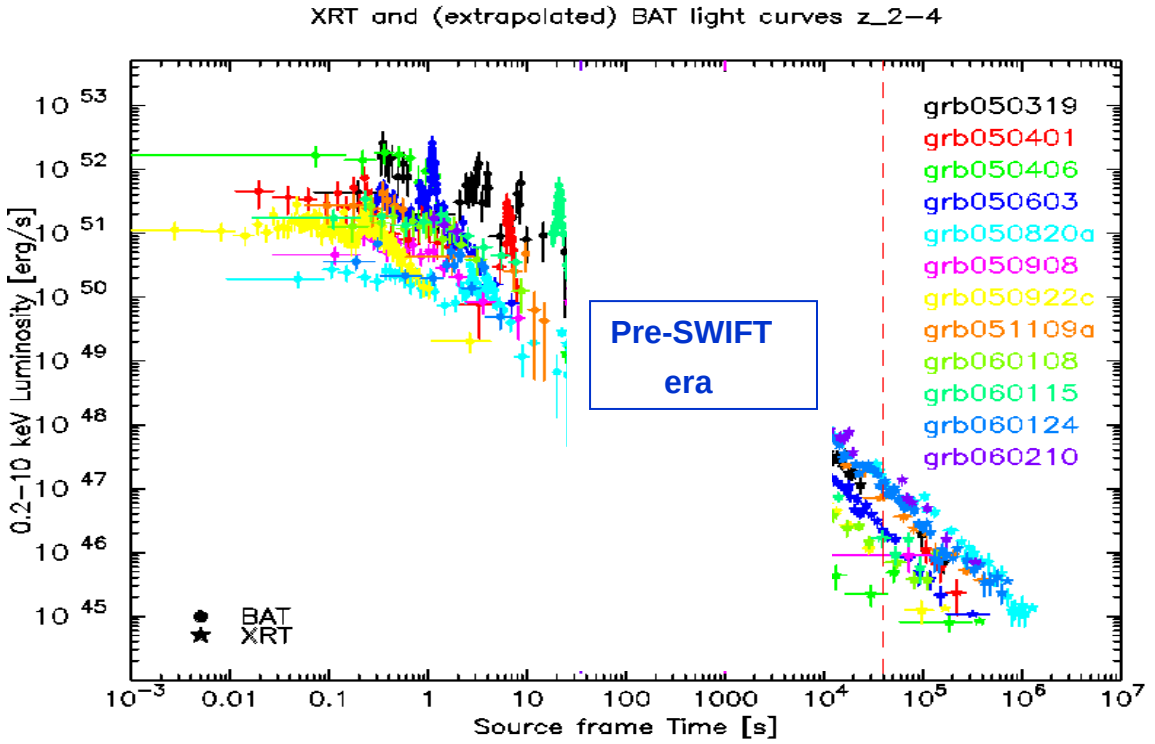
  Acceleration theory : 2 < p < 2.5 ?

- Radio afterglow can be shallower than in the visible, in contradiction with predictions (Panaitescu & Kumar 2004)

Succès et difficultés du modèle

6. Afterglows in the pre-SWIFT era : more problems…

- X-ray plateau

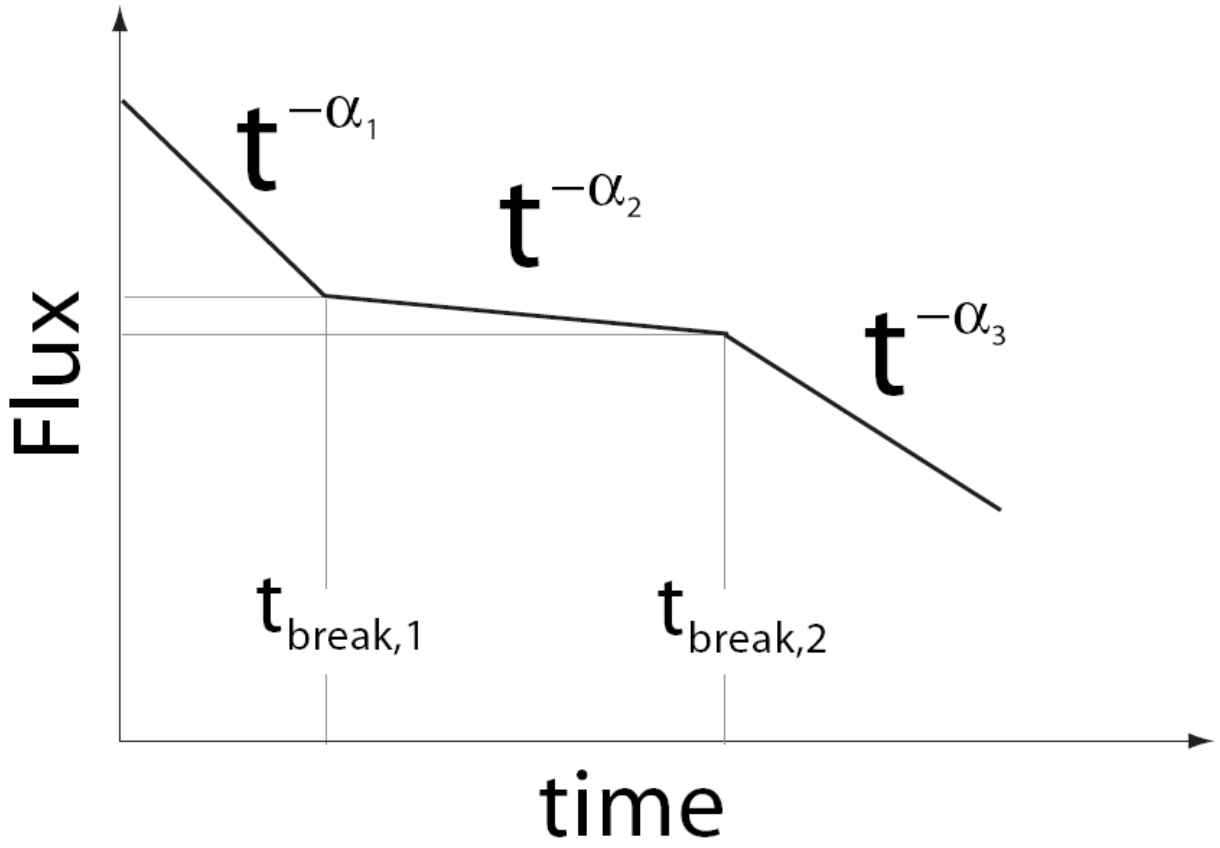


(Mangano et al, 2006)

Succès et difficultés du modèle

6. Afterglows in the pre-SWIFT era : more problems…

- X-ray plateau



Nousek et al. 2006

Succès et difficultés du modèle

6. Afterglows in the pre-SWIFT era : more problems…

- X-ray plateau

This plateau cannot be reproduced by the simplest version of the external shock model.

Most discussed possibility : late energy injection (Sari & Meszaros 2000)

This scenario requires to add a large amount of energy to the FS (Panaitescu et al. 2006)

Succès et difficultés du modèle

6. Afterglows in the pre-SWIFT era : more problems…

- X-ray plateau

Efficiency crisis for the prompt emission

E_{fs}^{0} before the injection ; $E_{fs} = k \times E_{fs}^{0}$ after the injection.

Prompt phase efficiency : apparent = $f = \dfrac{E_\gamma}{E_\gamma + E_{fs}}$

true = $f_0 = \dfrac{E_\gamma}{E_\gamma + E_{fs}^{0}} = \dfrac{kf}{(k-1)f + 1}$

With k = 15 and f = 0.1, **f_0 = 0.625 !**

Probably difficult for most models of the prompt emission (IS : f_0 = a few %)

Succès et difficultés du modèle

6. Afterglows in the pre-SWIFT era : more problems…

- X-ray plateau

  ► Efficiency crisis for the prompt emission

  ► Models of the central engine ?

Succès et difficultés du modèle

6. Afterglows in the pre-SWIFT era : more problems…

- X-ray plateau

- Where are the jet breaks ? (Burrows & Racusin 2007)

  Jet break are expected to be achromatic (same time in X-rays and Optical)

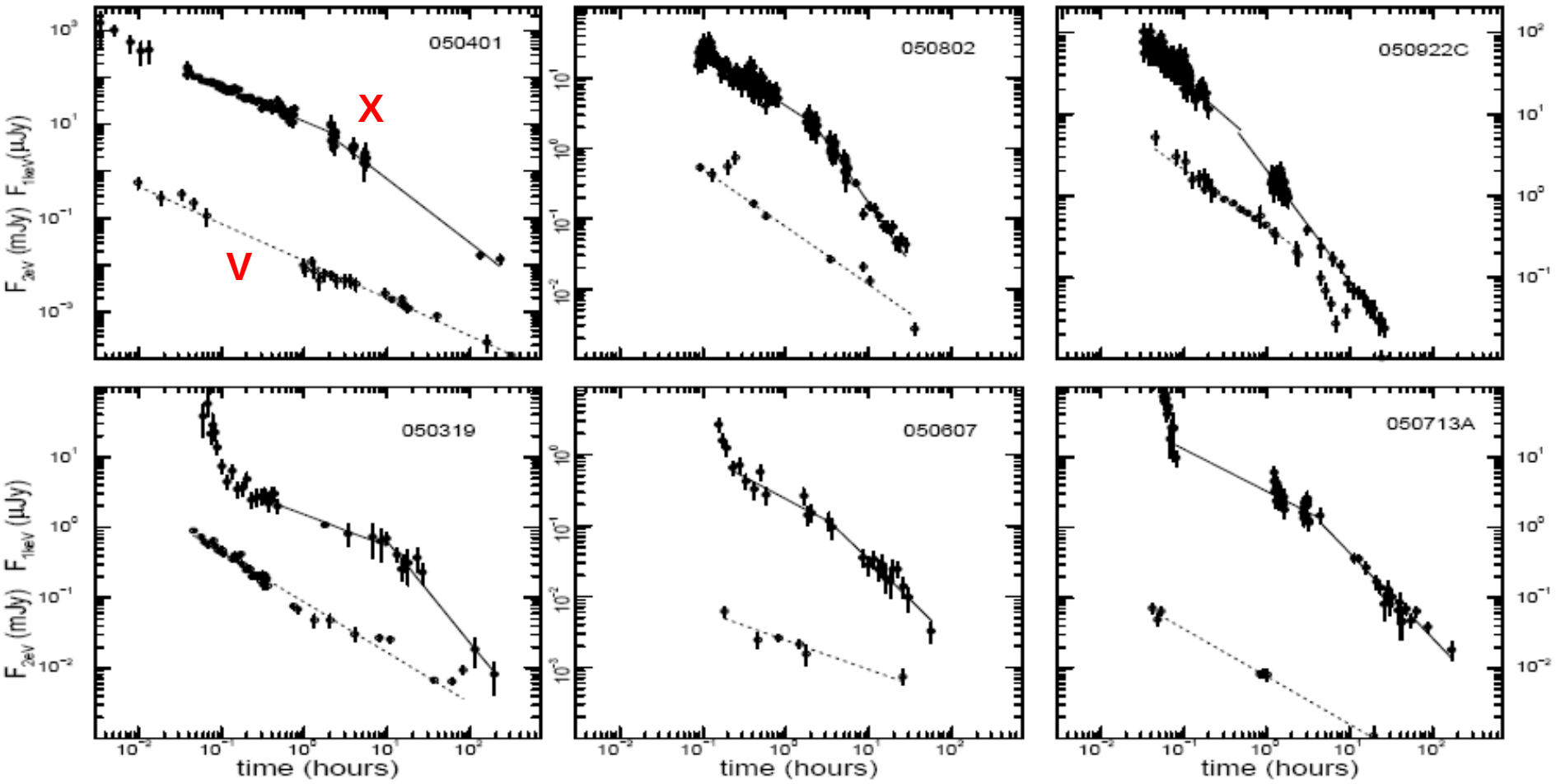
  Such breaks are very rare in the SWIFT era where the X-ray and Optical afterglows are followed simultaneously up to a few days.

- Chromatic breaks (Panaitescu et al. 2006)

  Such breaks cannot be easily explained in the standard FS model.

  ► Chromatic breaks require varying microphysics parameters

Succès et difficultés du modèle



Panaitescu et al. 2006

Succès et difficultés du modèle

6. Afterglows in the pre-SWIFT era : more problems…

- X-ray plateau
- Where are the jet breaks ?
- Chromatic breaks
- X-ray flares (Burrows et al. 2005)

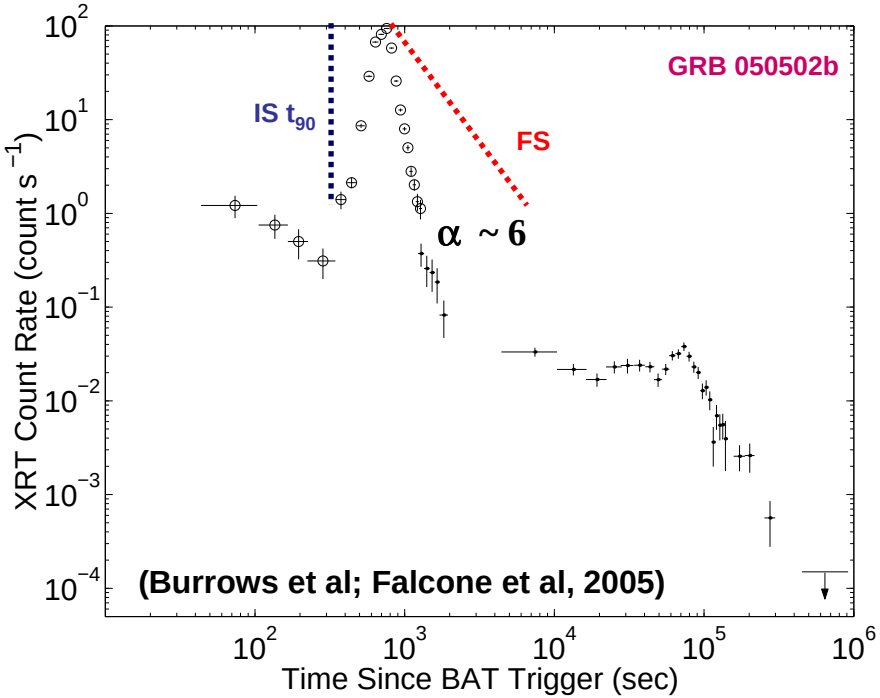
Usually interpreted as a late activity.

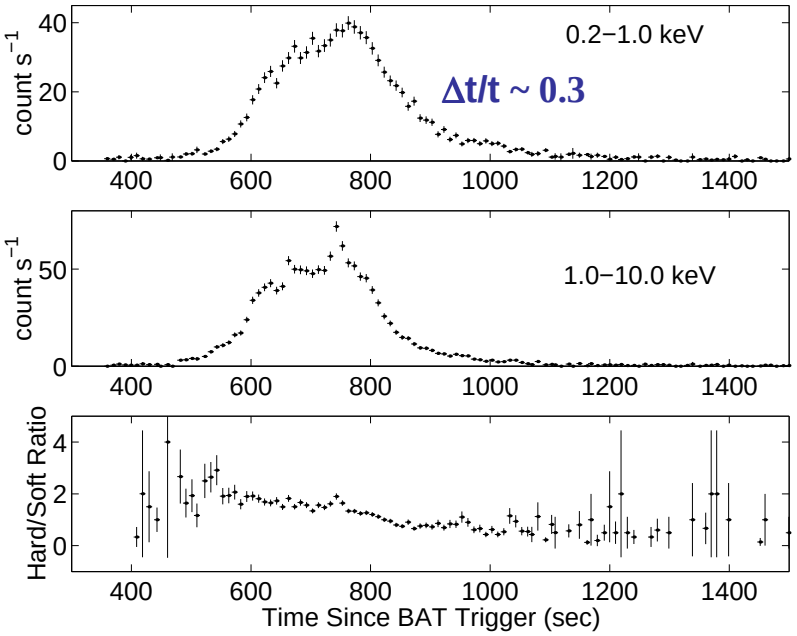
This interpretation is very challenging for the models of the central engine.

Succès et difficultés du modèle

Forward shock : rise and decay are too steep. $t_d \propto t^{-\alpha}$ with $\alpha < 3$

Internal shocks : duration seems very long. $\Delta t/t \lesssim 1$





Flares as late internal shocks :
smoother Lorentz factor at late time, i.e. variability timescale ∝ time

Vers un changement de paradigme ?

Several propositions to solve these problems.

One possibility studied at IAP : should we change our paradigm ?

afterglow = RS instead of FS

Two important changes in the proposed RS scenario :

(1) The forward shock is radiatively inefficient
(at least until late times when Γ_{FS} ~ 1-2)

(2) The reverse shock is long lived and produce the afterglow

(Genet, Daigne & Mochkovitch 2007 – Uhm & Beloborodov 2007)

Vers un changement de paradigme ?

Several propositions to solve these problems.

One possibility studied at IAP : should we change our paradigm ?

afterglow = RS instead of FS

Two important changes in the proposed RS scenario :

(1) The forward shock is radiatively inefficient
(at least until late times when Γ_{FS} ~ 1-2)

Low ε_B and/or ε_e in ultra-relativistic shocks ?

(see e.g. Milosavljevic & Nakar 2006)

Vers un changement de paradigme ?

Several propositions to solve these problems.

One possibility studied at IAP : should we change our paradigm ?

afterglow = RS instead of FS

Two important changes in the scenario :

(1) The forward shock is radiatively inefficient

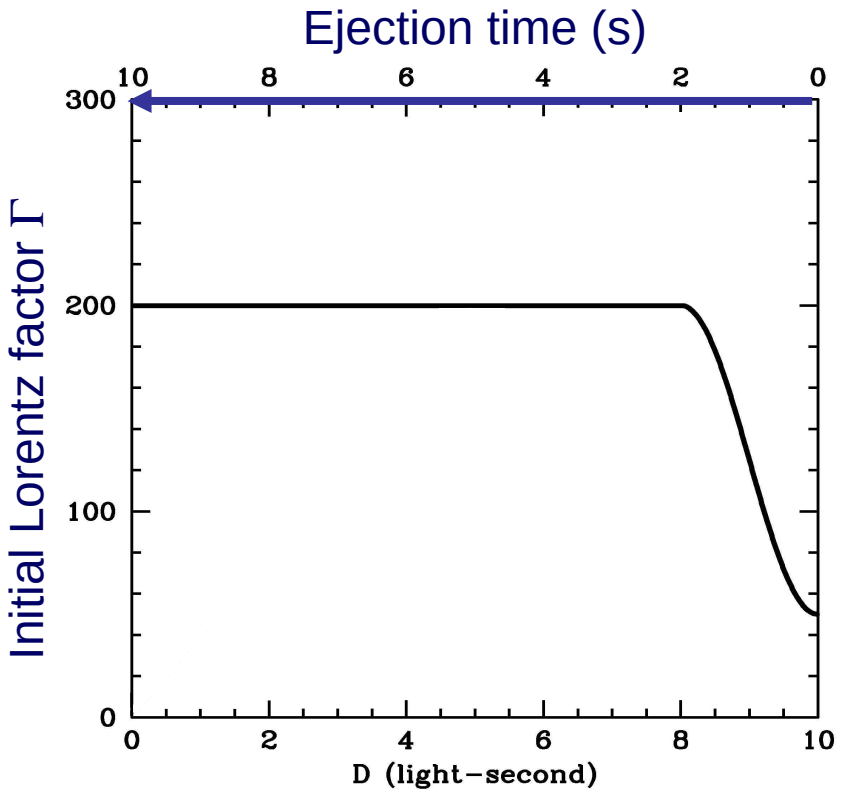
(2) The reverse shock is long lived and produce the afterglow

- **This does not require a late activity**
- **This requires a tail of low-Γ material :**
  Γ varies from a few 100 to ~ 1 during the ejection phase
- **Kinetic energy in the ultra-relativistic part (Γ>100) and the tail are comparable.**

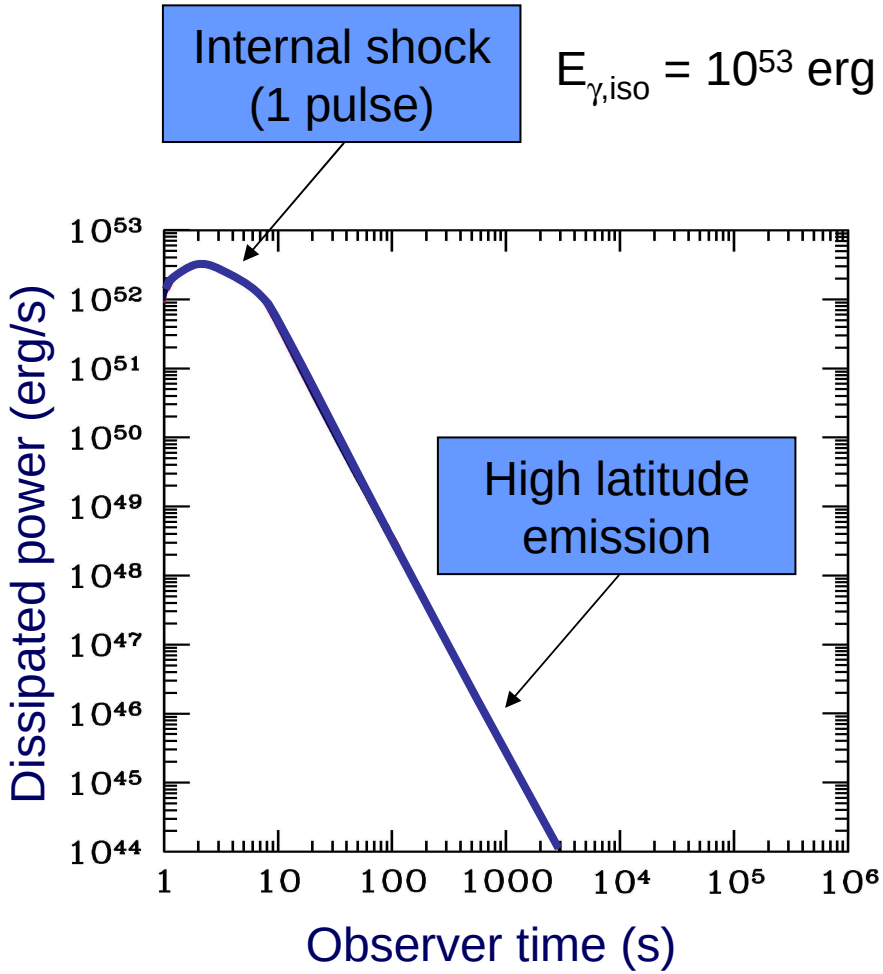
Vers un changement de paradigme ?

Can the afterglow come from the reverse shock ?

Genet, Daigne & Mochkovitch 2007 :



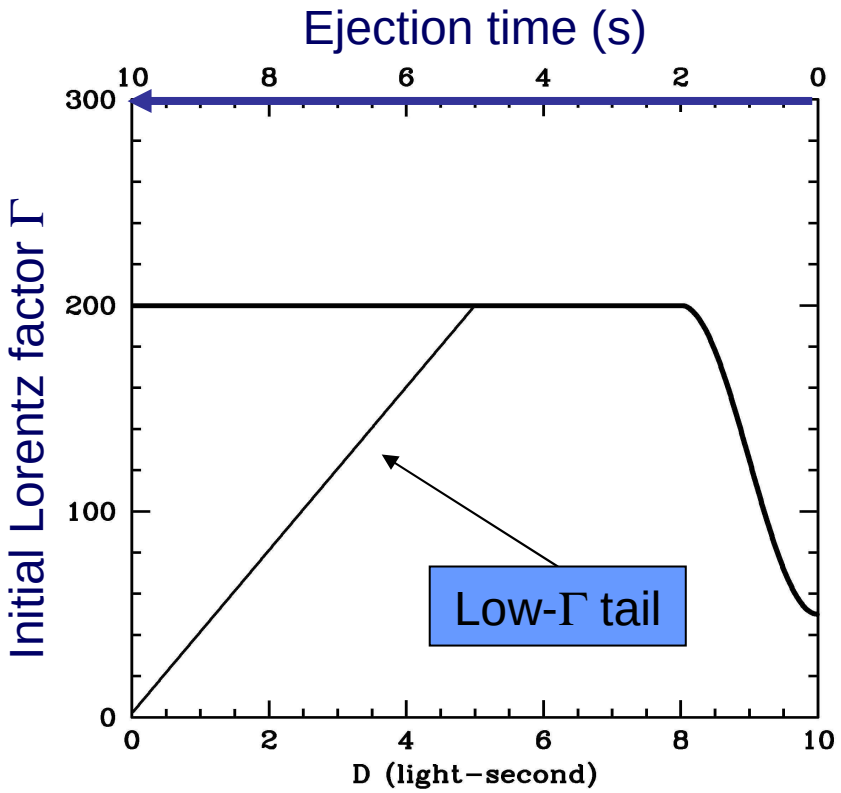
Relativistic ejection
Total duration = 10 s

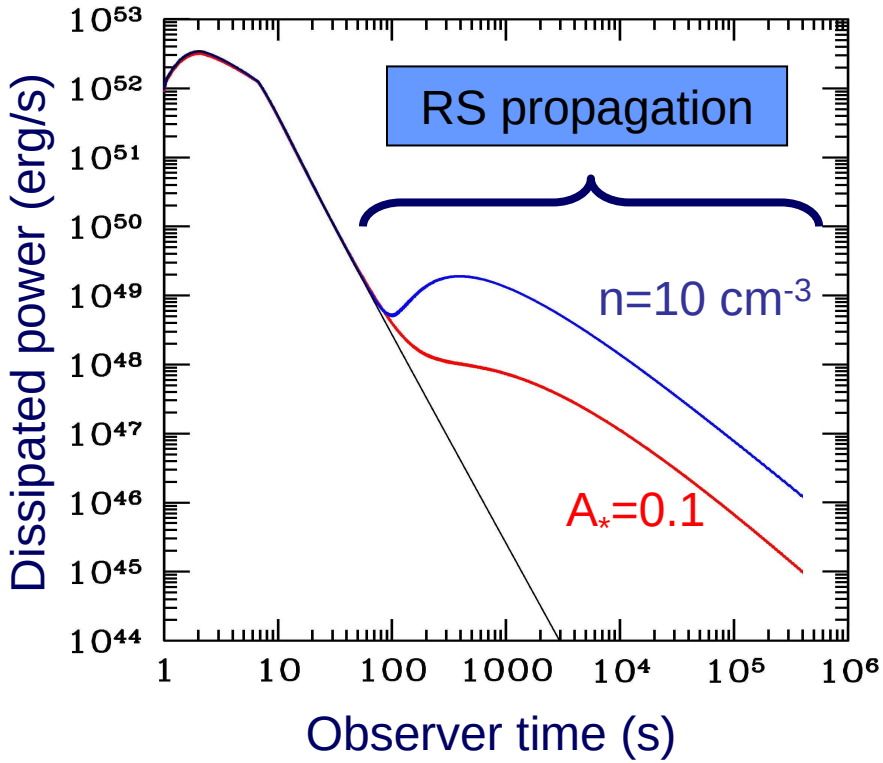


Naked GRB

Vers un changement de paradigme ?

Can the afterglow come from the reverse shock ?

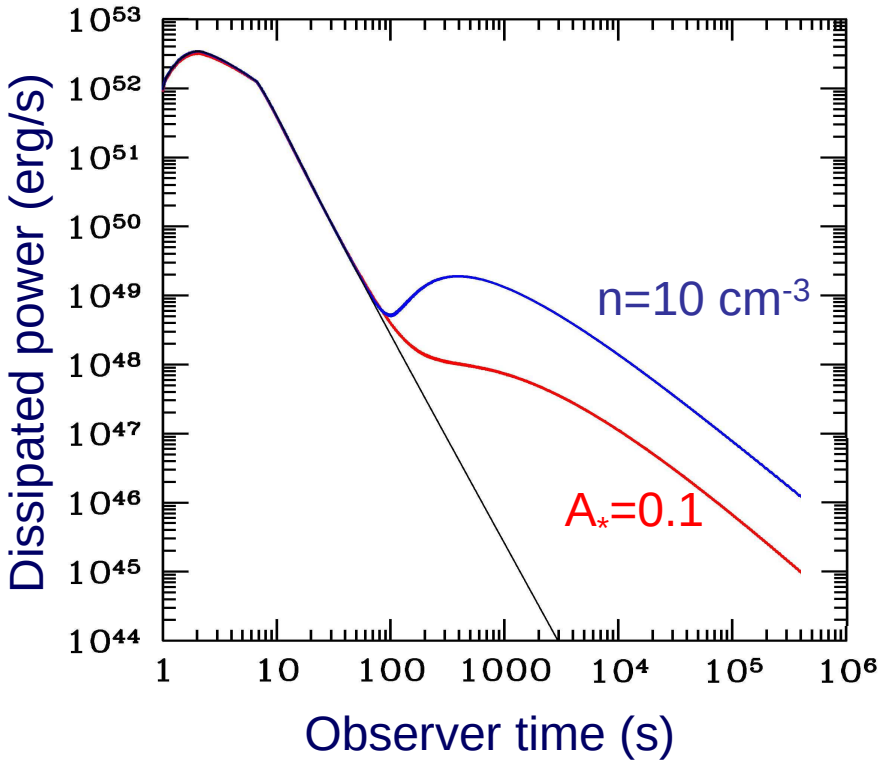




Relativistic ejection
Total duration = 10 s

Vers un changement de paradigme ?

Can the afterglow come from the reverse shock ?



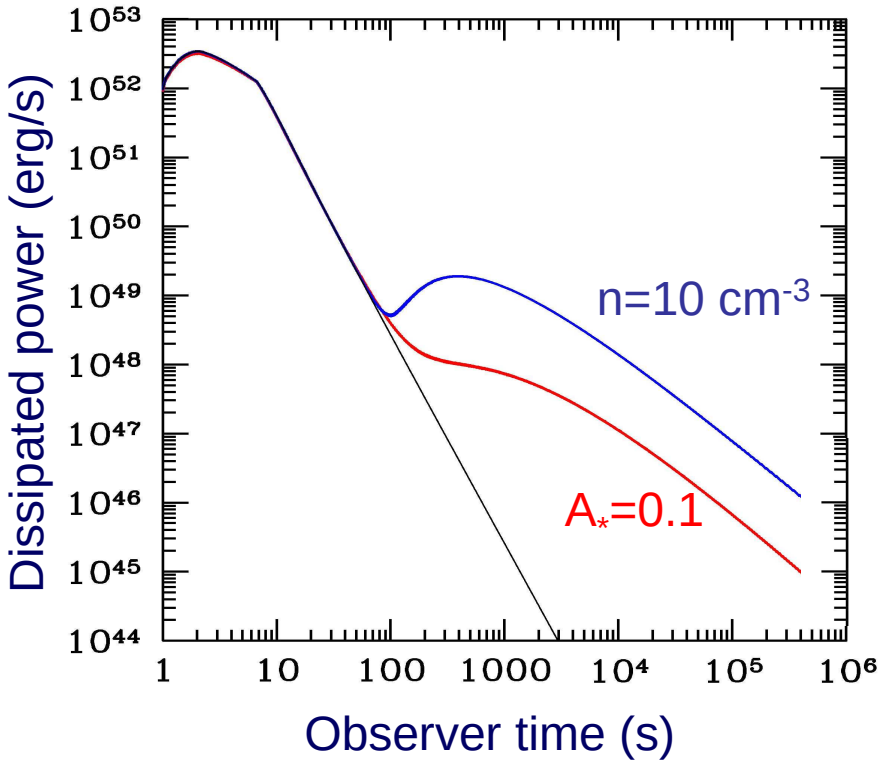
This dissipated power is a robust feature of the model (pure dynamical calculation).

The shape is mainly determined by $d\Gamma/dM$ in the ejecta.

If $d\Gamma/dM$ is irregular, bumps or wiggles car be observed (without any late activity).

Vers un changement de paradigme ?

Can the afterglow come from the reverse shock ?



Microphysics :

Internal shocks and the reverse shock are very similar :

►they propagate in the relativistic ejecta

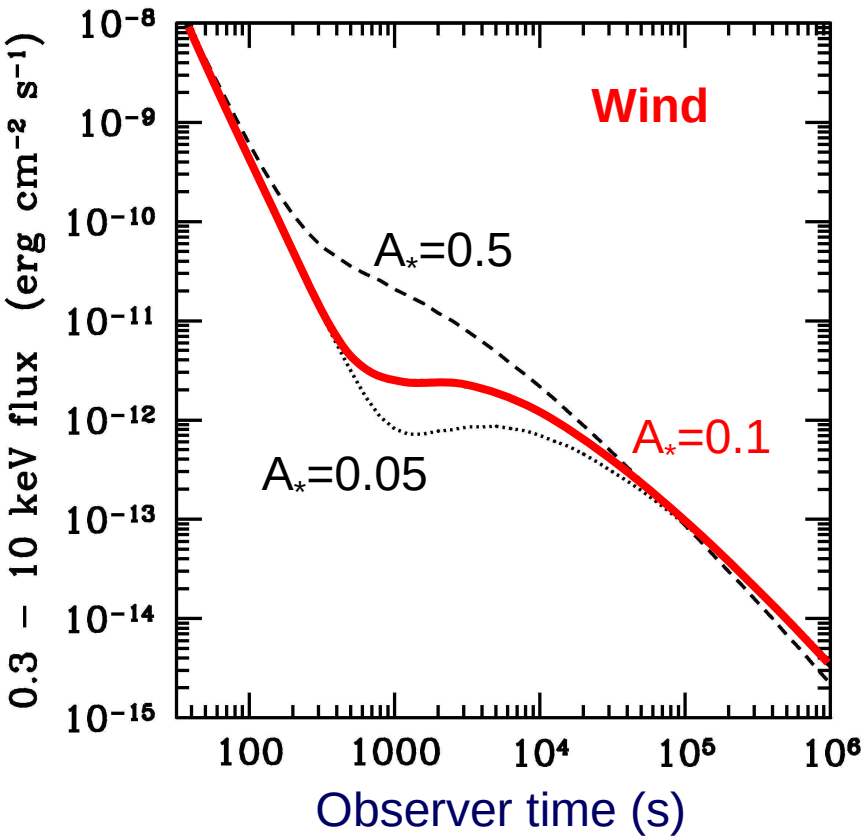
►they are mildly relativistic

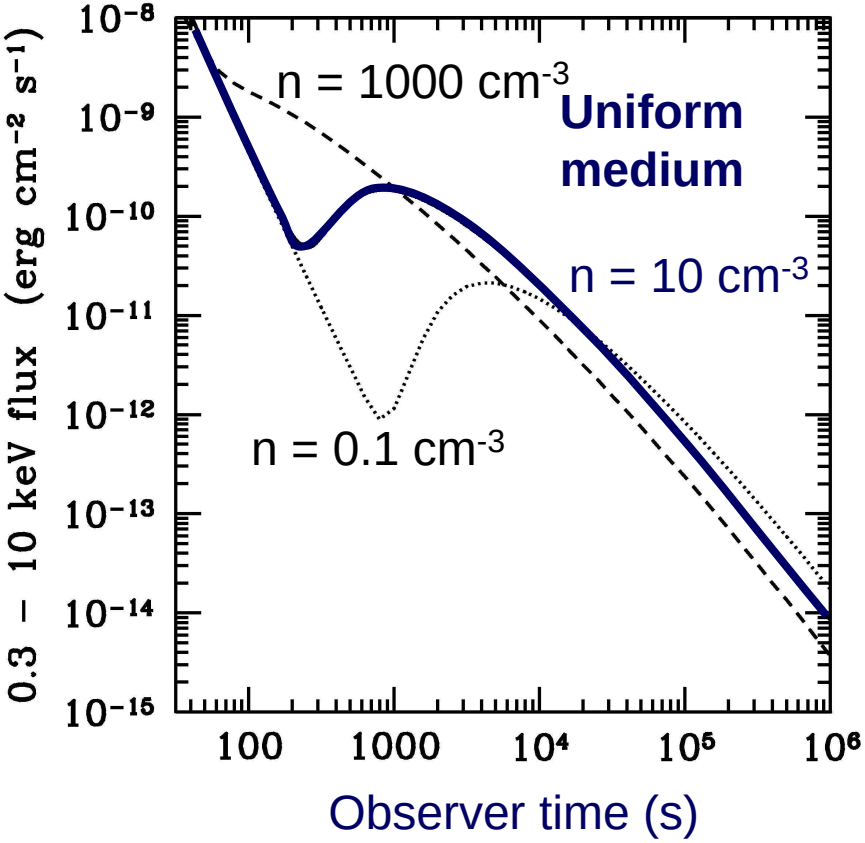
We adopt the same parameters: large ε_e and ε_B, small ζ

$\varepsilon_e=\varepsilon_B=1/3$; $\zeta=0.01$

Vers un changement de paradigme ?

Can the afterglow come from the reverse shock ?

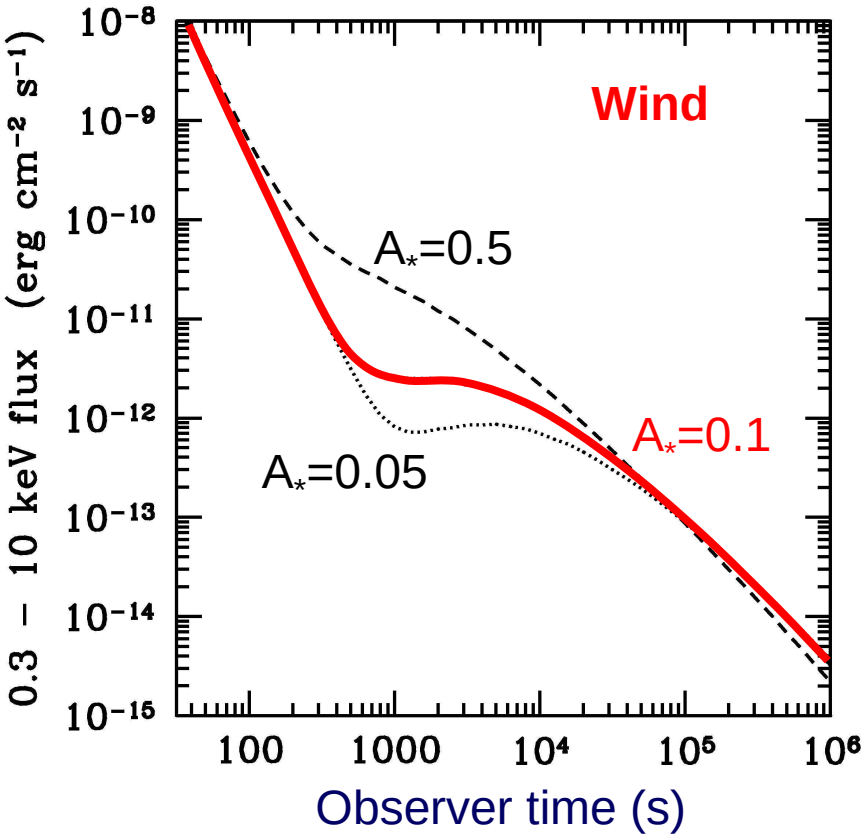




Early X-ray afterglow : XRT flux (0.3-10 keV)

Vers un changement de paradigme ?

Can the afterglow come from the reverse shock ?



The wind environment is preferred, as expected in the collapsar model.

Early X-ray afterglow : XRT flux (0.3-10 keV)

Vers un changement de paradigme ?

Can the afterglow come from the reverse shock ?

This model :
* **reproduces the XRT lightcurves (plateaux)**
* **reproduces the optical / radio lightcurves**
* **can produce flares**
* **can produce chromatic breaks**

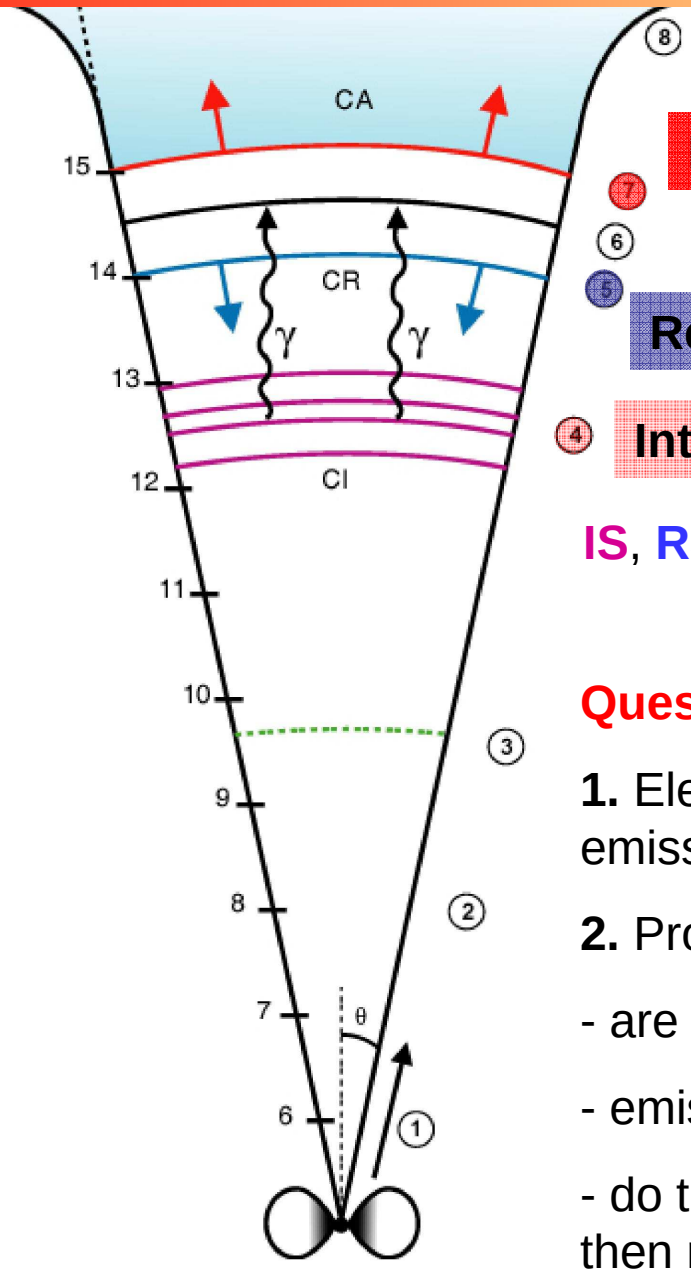
work in progress…

Fin du Cours I

Cours 2
Production de particules de haute énergie

1. Vue d'ensemble
2. L'émission gamma de haute énergie
3. L'accélération des protons
4. L'émission de neutrinos de haute énergie

Les sursauts γ sources de particules de haute énergie ?



Forward shock (afterglow)

Reverse shock (prompt/ early afterglow)

Internal shocks (prompt)

IS, **RS**, **FS** : radiating shock accelerated electrons (protons are also present)

Questions :

1. Electrons :
emission of high-energy γ 's ?

2. Protons :

- are they accelerated ? (E_{max} ?)

- emission of high-energy γ 's ?

- do they interact with γ 's to produce pions (and then muons and HE neutrinos) ?

La question des flux attendus

1. Une première question est de savoir si un certain de type de particules de haute énergie est produit dans les sursauts gamma.

2. Une seconde question est de savoir quel est le flux attendu pour un sursaut gamma donné, connaissant sa distance (il peut y avoir des effets de propagation important : VHE photons or UHECRs).

3. Une troisième question est d'évaluer la contribution globale de la population de sursauts gamma au flux observé sur terre.

L'émission gamma de haute énergie

Peu de sursauts détectés par EGRET (uniquement des très brillants) :

* mauvaise résolution temporelle
* généralement simultané au sursaut « prompt »
* un cas particulier GRB 94???? : un photon à 18 Gev 1 h après le sursaut !

Dans la perspective de GLAST, beaucoup d'articles récents présentent des calculs prédictifs de l'émission gamma de haute énergie attendue.

* cadre dynamique simplifié : un choc interne « typique » ou le choc externe alla Blandford-McKee
* processus pris en compte :
  - acceleration mise à la main
  - pertes adiabatiques
  - electrons : synchrotron (+self abs.), inverse compton, $\gamma\gamma$ annihilation and pair production
  - protons : idem + photomeson interactions

Voir par exemple : chocs internes : Asano & Inoue astroph/0705.2910
choc externe : Fan & Piran astroph/0706.0010

L'émission gamma de haute énergie

Projet ANR « émission gamma des jets relativistes » :
Bosnjak, Daigne (IAP), Dubus (LAOG), Giebels (LLR), Piron (LPTA)

Three steps calculation :

1. Dynamics : « solid shells » model developed at IAP

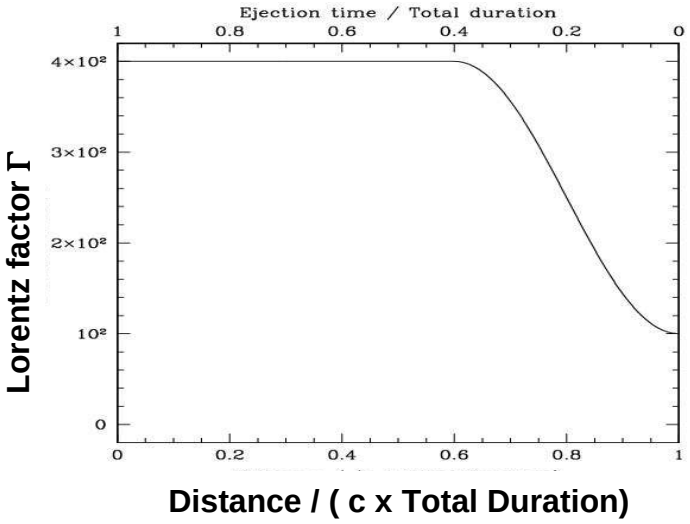
Input parameters : Γ(t) and $\dot{E}$(t) during the relativistic ejection

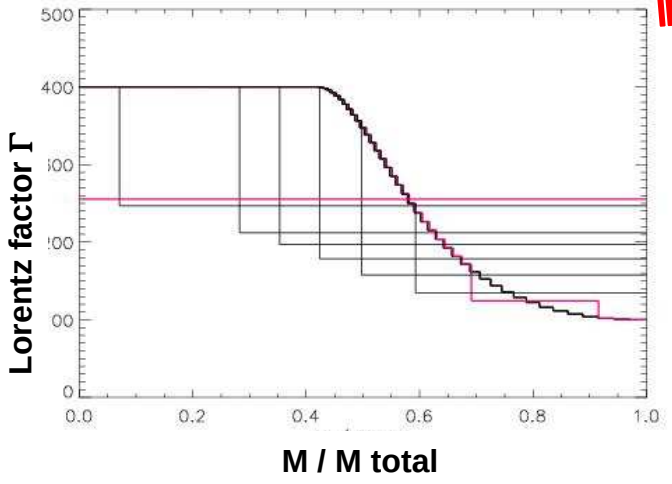
For each shock wave : R, t, density and energy density in the shock medium

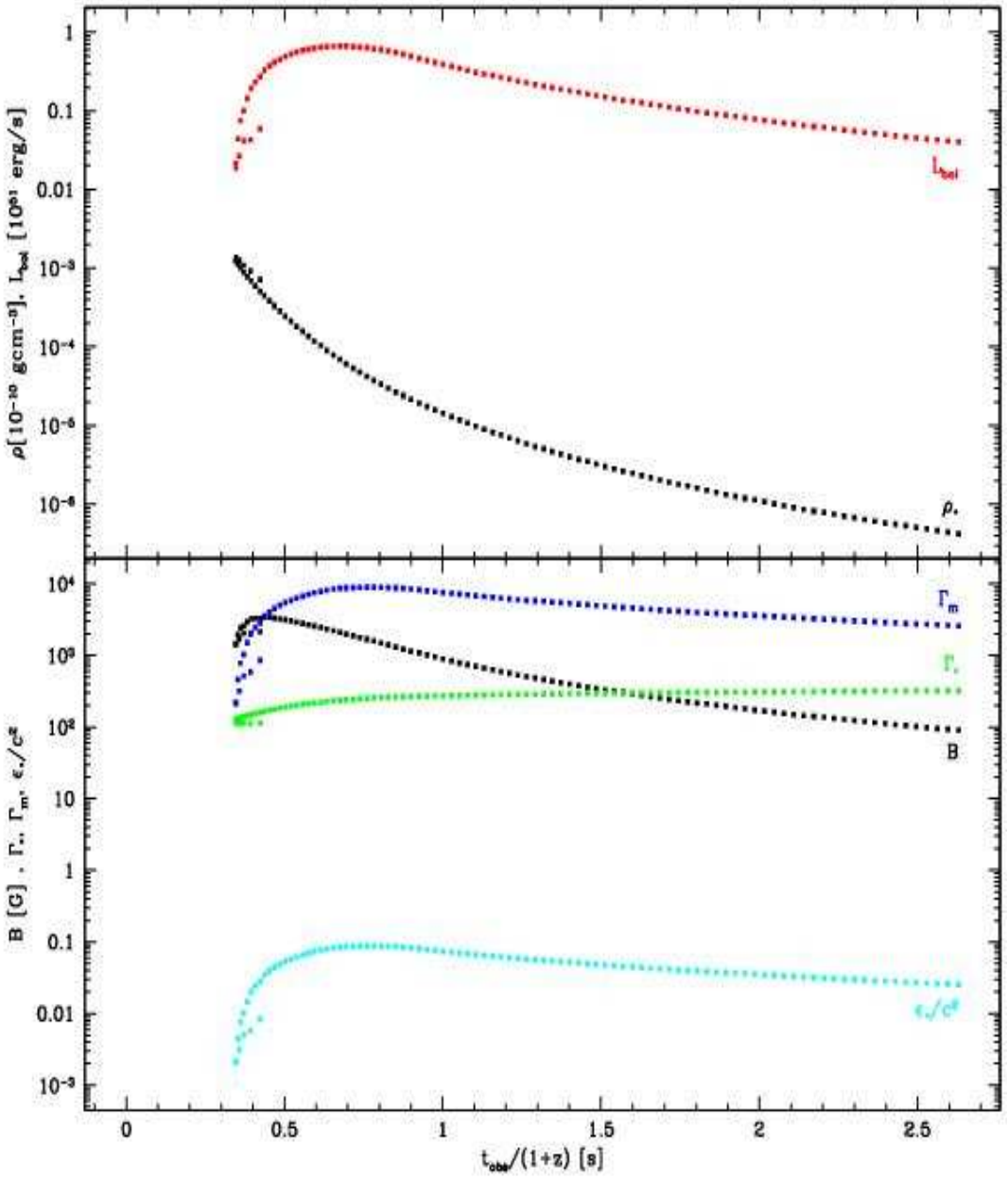
Microphysics : α_B, α_e, ζ, + slope p $\Rightarrow$ **magnetic field, electron distribution**

Present status : e^- only. For protons, needs additional parameters (α_e , ζ_p)

L'émission gamma de haute énergie







L'émission gamma de haute énergie

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Bosnjak, Daigne (IAP), Dubus (LAOG), Giebels (LLR), Piron (LPTA)

Three steps calculation :

1. Dynamics & « Microphysics »

2. Radiation in the comoving frame : for each « collision »

Echelle de temps radiative << échelle de temps dynamique

Electrons :

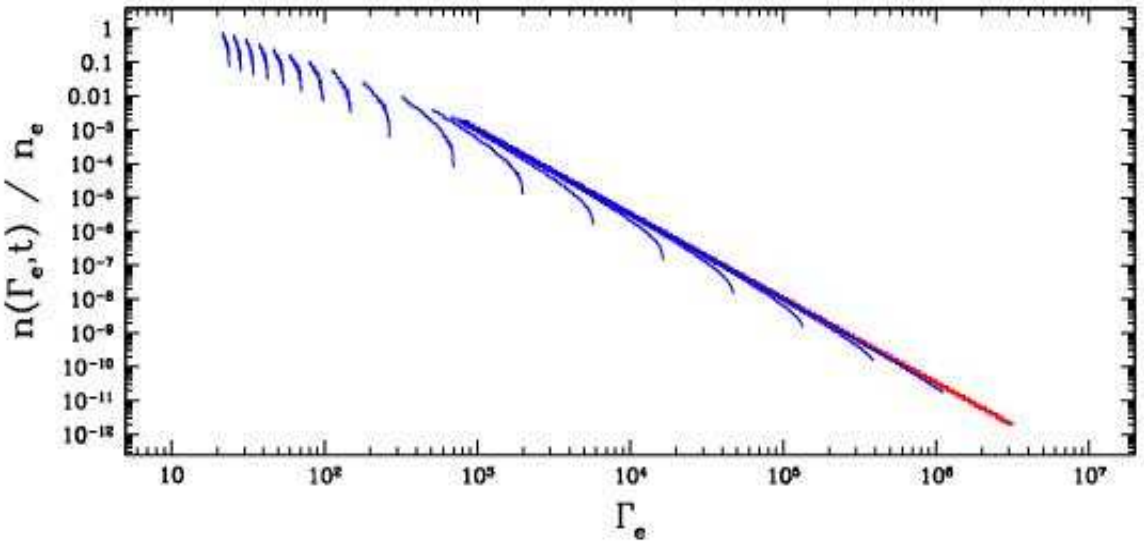
$$\frac{\partial n'}{\partial t'}(\Gamma'_e,t') = -\frac{\partial}{\partial \Gamma'_e}\left[\left(\left.\frac{d\Gamma'_e}{dt'}\right|_{syn+ic} + \left.\frac{d\Gamma'_e}{dt'}\right|_{ad}\right) n'(\Gamma'_e,t')\right]$$

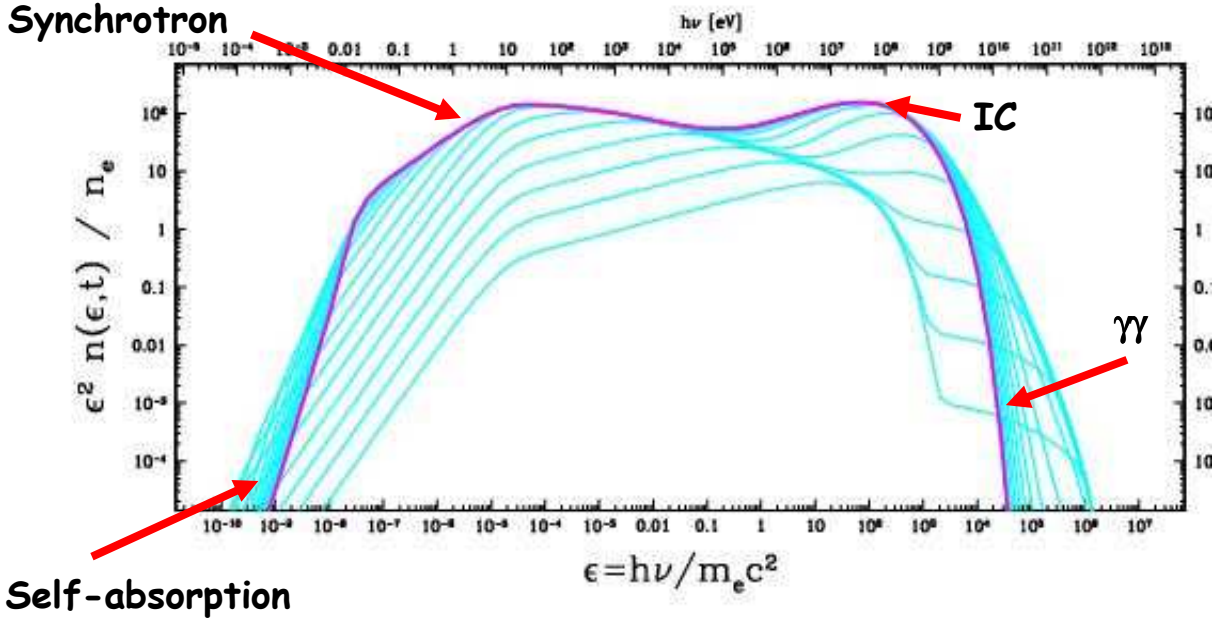
Refroidissement adiabatique
Emission synchrotron
Diffusions Compton inverse
Auto-absorption synchrotron
Annihilation photon-photon

Photons :

$$\frac{\partial n'_\nu}{\partial t'} = \int n'(\Gamma'_e,t') P_{syn+ic}(\Gamma'_e)\, d\Gamma'_e - cn'_\nu \int n'(\Gamma'_e,t')\sigma_{abs}(\Gamma'_e,\nu)\, d\Gamma'_e - cn'_\nu \int_{\nu'>\frac{(m_e c^2)^2}{h^2\nu}} n'_{\nu'}(t')\sigma_{\gamma\gamma}(\nu,\nu')\, d\nu'$$

The density of relativistic electrons $n'(\Gamma'_e,t')$ (initial distribution and distribution evolving in time) and the photon spectrum (final and evolving in time) both in the comoving frame:





Relative importance between the synchrotron and IC emission depends on Comptonization parameter $Y = L_{IC}/L_{syn}$:

$Y(Y+1) = \alpha_e / \alpha_B$ **(Thomson)**

IC dominant:
$Y >> 1$
+ Thomson regime

Synchrotron dominant:
$Y << 1$
+ Klein-Nishina regime

L'émission gamma de haute énergie

Projet ANR « émission gamma des jets relativistes » :
Bosnjak, Daigne (IAP), Dubus (LAOG), Giebels (LLR), Piron (LPTA)

Three steps calculation :

1. Dynamics & « Microphysics »

2. Radiation in the comoving frame

3. Observed quantities

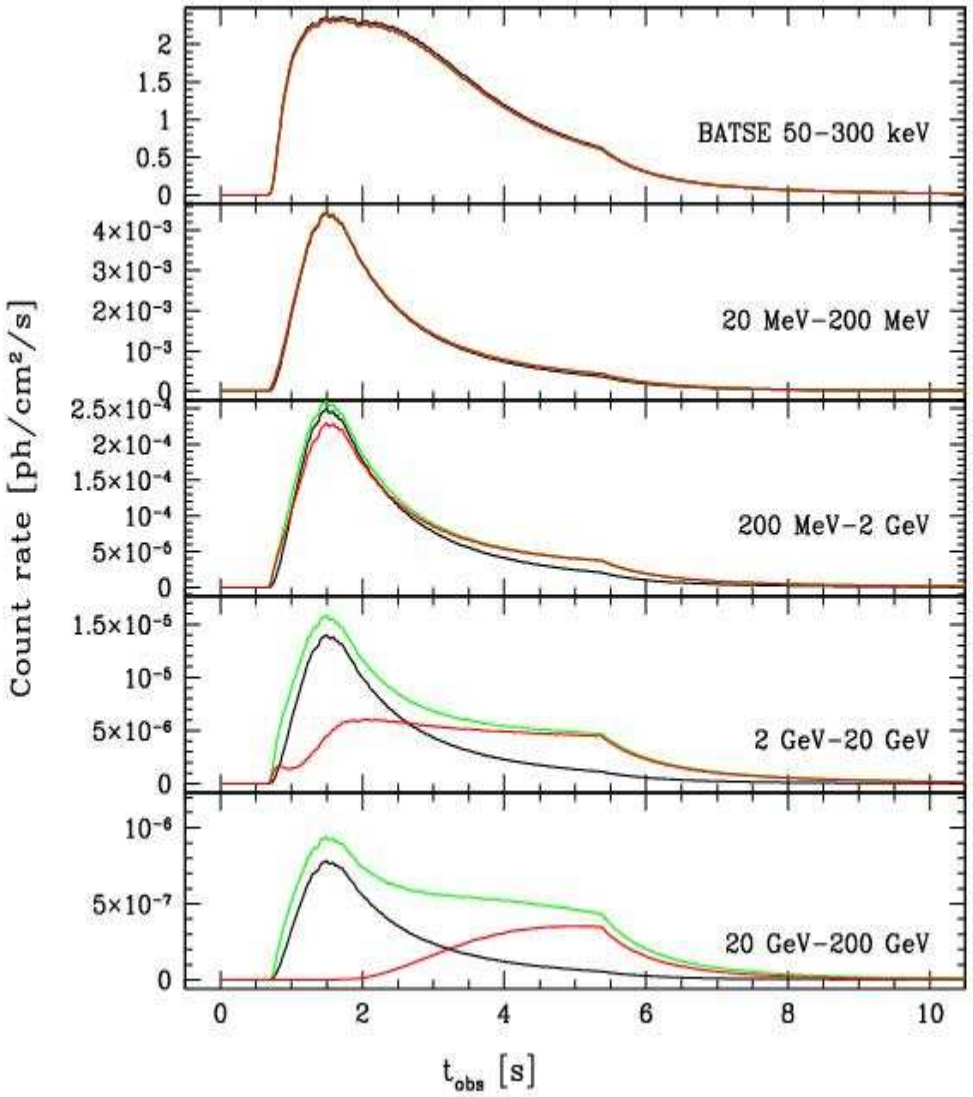
*** for each collision : comoving frame → fixed frame**
(including geometrical effects due to the curvature of the emitting surface)

*** propagation (cosmological effects** + absorption at VHE**)**

*** sum over all contributions : synthetic burst**

(lightcurves in different energy bands + spectra at different times)

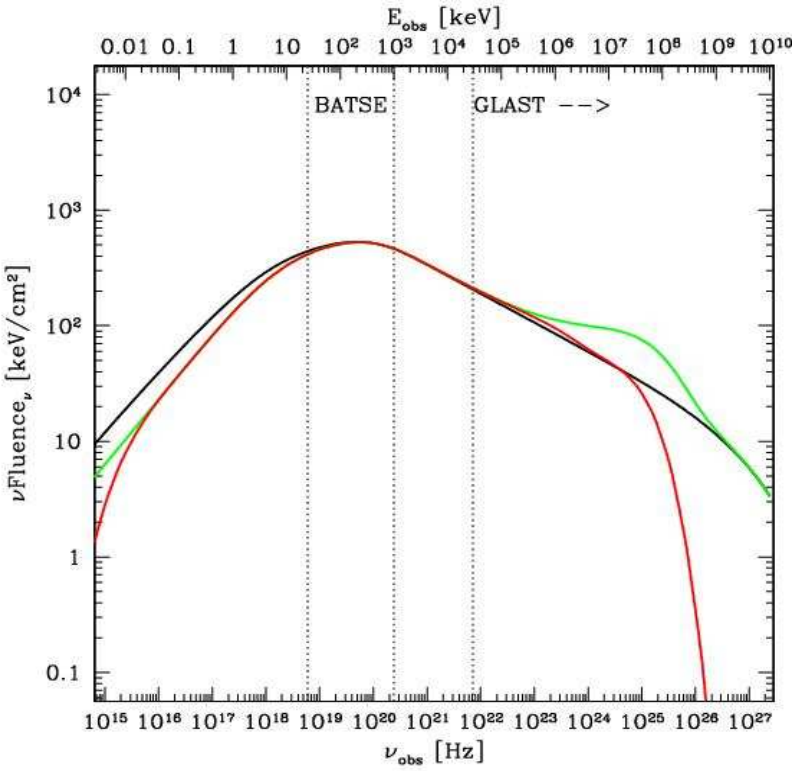
L'émission gamma de haute énergie



Synchrotron only

Synchrotron + IC

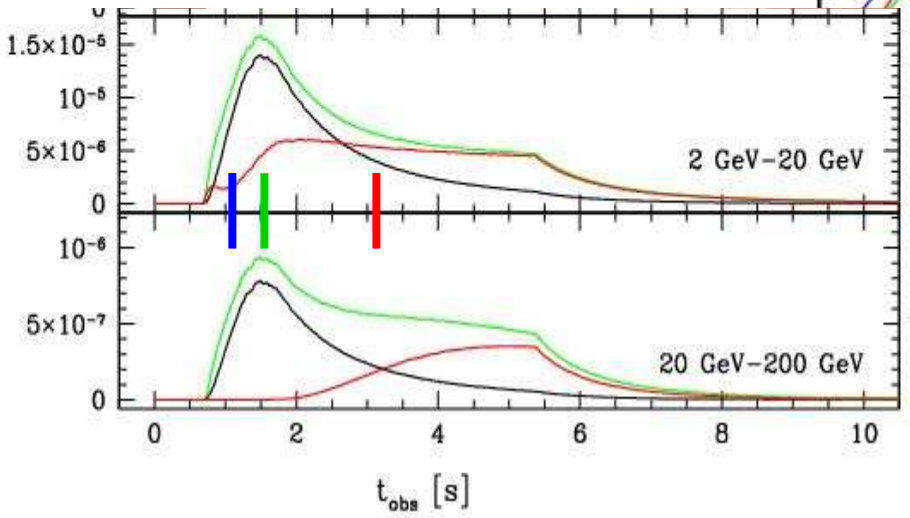
Snychrotron + IC + γγ annihilation + self absorption

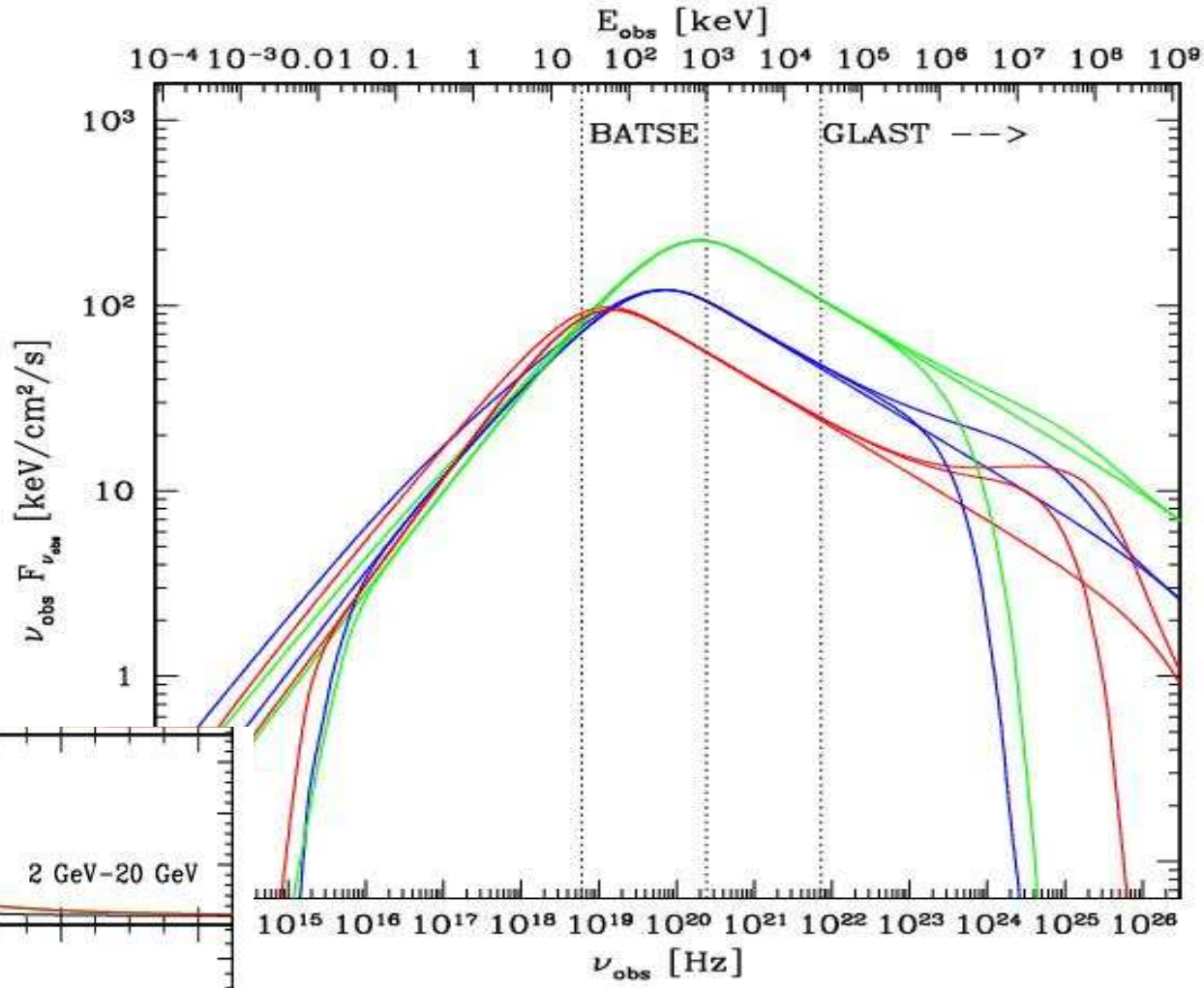


L'émission gamma de haute énergie

Single pulse model
T_{90} ~ 4 sec

- t_{obs} = 1 sec
- t_{obs} = 1.5 sec
  (peak in the light curve 50-300 keV)
- t_{obs} = 3.5 sec
  (rise in the 20 – 200 GeV band LC)





L'émission gamma de haute énergie

Projet ANR « émission gamma des jets relativistes » :
Bosnjak, Daigne (IAP), Dubus (LAOG), Giebels (LLR), Piron (LPTA)

Three steps calculation :

1. Dynamics & « Microphysics »

2. Radiation in the comoving frame

3. Observed quantities

Work in progress : multi-pulses, protons, application to RS and FS.

In the most optimistic case, GLAST observations will allow the determination of several key parameters :

- *** Lorentz factor of the relativistic ejecta**
- *** Radius, density, … of the ejecta during the internal shock phase**
- *** Magnetic field**
- *** Electron Lorentz factor (and slope)**

= some key constraints for the other particles (p, ν)

L'accélération des protons

e.g. Waxman 2003

Three possible sites : IS, RS and FS

WARNING

Maximum energy ? $t_{acc} < \mathrm{Min}(t_{rad} , t_{ex})$

- Acceleration timescale : $t_{acc}(E) \sim R_L(E) / c$
- Radiative timescale : $t_{rad}(E) \sim t_{syn}(E)$ (synchrotron dominant at UHE)
- Hydrodynamical timecale : $t_{ex} \sim R / \Gamma c$
  (=escape time, adiabatic cooling timescale, largest scale over which the magnetic field fluctuates, …)

L'accélération des protons

E = proton energy in the observer frame

Comoving frame : $t_{acc} \sim 56\ s\ (E/\ 10^{20}\ eV)\ (\Gamma\ /\ 200)^{-1}\ (B/\ 1000\ G)^{-1}$

$t_{ex} \sim 170\ s\ (R/\ 10^{15}\ cm)\ (\Gamma\ /\ 200)^{-1}$

$t_{rad} \sim 9000\ s\ (E/\ 10^{20}\ eV)^{-1}\ (\Gamma\ /\ 200)\ (B/\ 1000\ G)^{-2}$

- Limit 1 (acc=ex) : $E = 3.0\ 10^{20}\ eV\ (R/\ 10^{15}\ cm)\ (B\ /\ 1000\ G)$

- Limit 2 (acc=rad) : $E = 1.3\ 10^{21}\ eV\ (\Gamma\ /\ 200)\ (B/\ 1000\ G)^{-1/2}$

Transition limit 1 / limit 2 : $R = 10^{15}\ cm\ (E/\ 8.10^{20}\ eV)^{3}\ (\Gamma\ /\ 200)^{-2}$

L'accélération des protons

First case : external shock

BM : $\Gamma(R) = 200\ (\Gamma_0 / 200)\ \ (R / R_{dec})^{-3/2}$

$B(R) = 25\ G\ (\alpha_B / 0.1)^{0.5}\ (n_{ext} / 1\ cm^{-3})^{0.5}\ (\Gamma_0 / 200)\ \ (R / R_{dec})^{-3/2}$

- Limit 1 (acc=ex) :

$E = 2.5\ 10^{20}\ eV\ (R_{dec} / 10^{17}\ cm)\ (\alpha_B / 0.1)^{0.5}\ (n_{ext} / 1\ cm^{-3})^{0.5}\ (\Gamma_0 / 200)\ \ (R / R_{dec})^{-1/2}$

- Limit 2 (acc=rad) :

$E = 8.3\ 10^{21}\ eV\ (\Gamma_0 / 200)\ (\alpha_B / 0.1)^{-0.25}\ (n_{ext} / 1\ cm^{-3})^{-0.25}\ (\Gamma_0 / 200)^{-0.5}\ \ (R / R_{dec})^{-3/4}$

Most efficient at R_{dec}.

Question : is $\alpha_B = 0.1$ realistic ? (usually $\alpha_B = 0.001$: limit 1 is divided by 10)

L'accélération des protons

Second case : internal shocks

- Limit 1 (acc=ex) : $E = 3.0\ 10^{20}$ eV $(R/\ 10^{15}$ cm$)$ $(B\ /\ 1000$ G$)$
- Limit 2 (acc=rad) : $E = 1.3\ 10^{21}$ eV $(\Gamma\ /\ 200)$ $(B/\ 1000$ G$)^{-1/2}$

$R \sim 2\ \Gamma^2\ c\ (t_{var} \rightarrow t_w) \sim 2\ (10^{12} \rightarrow 10^{16})$ cm for $\Gamma = 200$, $t_{var} = 1$ ms, $t_w = 10$ s

If BATSE = synchrotron radiation : $E_p = 300$ keV $(\Gamma\ /\ 200)$ $(\Gamma_m\ /\ 10^4)$ $(B/\ 1000$ G$)$

If BATSE = inverse Compton : B should be much weaker.

- Reverse shock : comparable (R can be larger, B weaker)
- Two interesting poissibilities :
  (a) B can be domionated by a large scale field anchored in the central source
  (b) multi-shocks acceleration

L'accélération des protons : les GRBs source des UHECRs ?

Flux ?

(1) local GRB rate ?

Many studies (based on log N – log P + other constraints) : ~ 0.5 GRB/yr/Gpc^3

(2) Assume energy(protons) ~ energy (electrons) : flux = OK for UHECRs (Waxman)

(3) how many sources ?

$$N(E) = \frac{4\pi}{3} R_{GRB}^{local} \times [D_{\lim}(E)]^3 \times \tau[E, D_{\lim}(E)]$$

τ: dispersion in arrival time

$E = 10^{20}$ eV : $D_{\lim}(E) \sim 100$ Mpc and $\tau(\mathrm{E}, D_{\lim}) \sim 10^7$ yr $\rightarrow$ $N(E) \sim 4\ 10^4$

$E = 2\ 10^{20}$ eV : $D_{\lim}(E) \sim 30$ Mpc and $\tau(\mathrm{E}, D_{\lim}) \sim 2\ 10^5$ yr $\rightarrow$ $N(E) \sim 20$

As the energy increases by a factor of 2 a uniform « UHECR sky » is replaced by just a few directions of arrival.

L'émission de neutrinos de haute énergie

e.g. Waxman 2003

$p + \gamma \rightarrow$ pions ; then $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \overline{\nu}_\mu + \nu_\mu$ = production of HE neutrinos

■ Threshold of the Δ-resonance : $E'_\gamma E'_p \sim 0.2$ GeV^2

i.e. $(E_g / 200$ keV$)\ (E_p / 10^{16}$ eV$) \sim 4\ (\Gamma / 200)^2$

BATSE photons interact with protons at 10^{16} eV

■ Neutrino energy ? ~ 5 % of proton energy $\rightarrow 10^{14}$ eV

■ Number of neutrinos ? Needs detailed calculation (spectrum shape, …)
Waxman : ~10-30 % of proton energy in pions
~ half of this energy in neutrinos

■ Flux ? Based on these estimates + the assumption that UHECRs are due to GRBs (normalization) : ~ 1-10 neutrinos per year for a km^2 detector

This implies a low number of sources : detailed calculation for a nearby bright GRB would be useful.

Résumé

Gamma-ray bursts

- **Dynamical evolution seems understood (relativistic ejection, IS,RS,FS)**
- Emission sites, radiating processes : still debated

High-energy particles for gamma-ray bursts

- **High-energy gamma-rays : certain (EGRET)**

GLAST results should help in determining some key parameters of the model.

- High-energy protons : acceleration has to be better understood.

UHECRs : present estimates use optimistic acceleration timescales…
Some implications on the number of sources.

- High-energy neutrinos : probable (needs « only » 10^{16} eV protons)

Expected flux is low : detailed calculations are needed for nearby bright GRBs.

- A related question : a better understanding of the local GRB distribution is needed.