

The fireshell equations of motion and the P-GRB observational properties

Carlo Luciano Bianco,

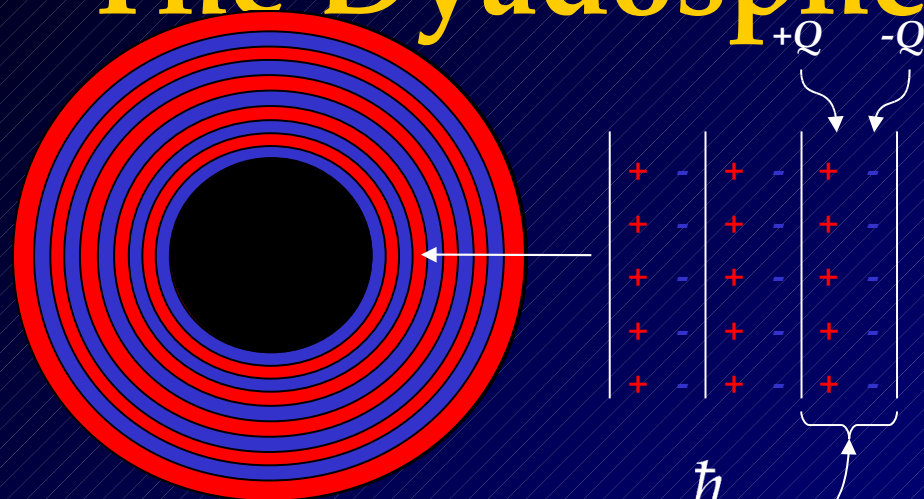
Maria Grazia Bernardini, Letizia Caito, Gustavo De Barros,
Luca Izzo, Barbara Patricelli, Remo Ruffini

2nd Galileo – Xu GuangQi Meeting
Ventimiglia – Italy – July 15th, 2010

(some) Key Features of the Model

- No need for beaming to reduce energy budget (10^{55} ergs allowed).
- Prompt emission made of two different components: the Proper GRB (P-GRB) and the extended afterglow peak.
- (Quasi)-Thermal spectrum in the fireshell co-moving frame for the prompt emission.
- Short and Long GRBs differ only by their different fireshell baryon loading and surrounding medium.
- Need to distinguish “genuine” short and “disguised” short GRBs.

The Dyadosphere

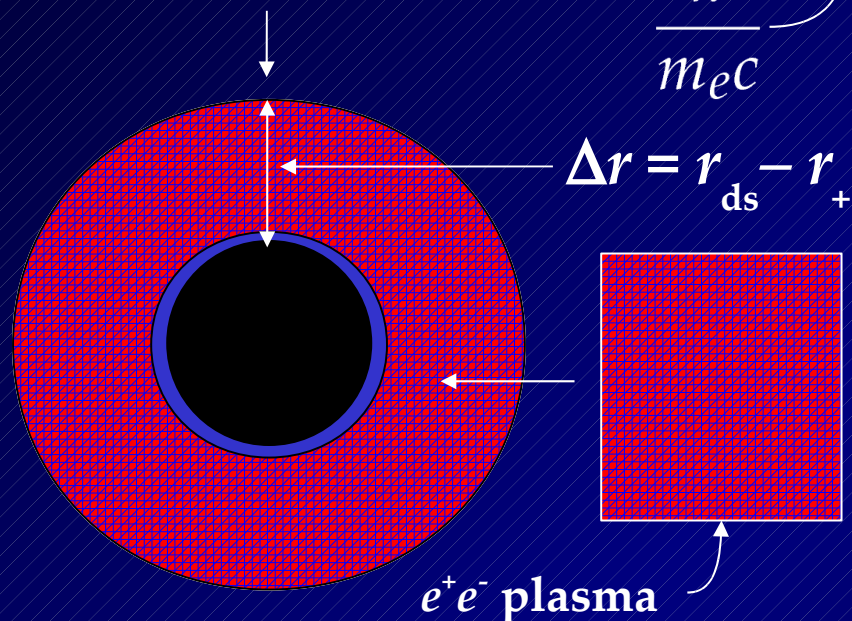


$$\mu = \frac{M}{M_{\odot}}$$

$$\xi = \frac{Q}{M}$$

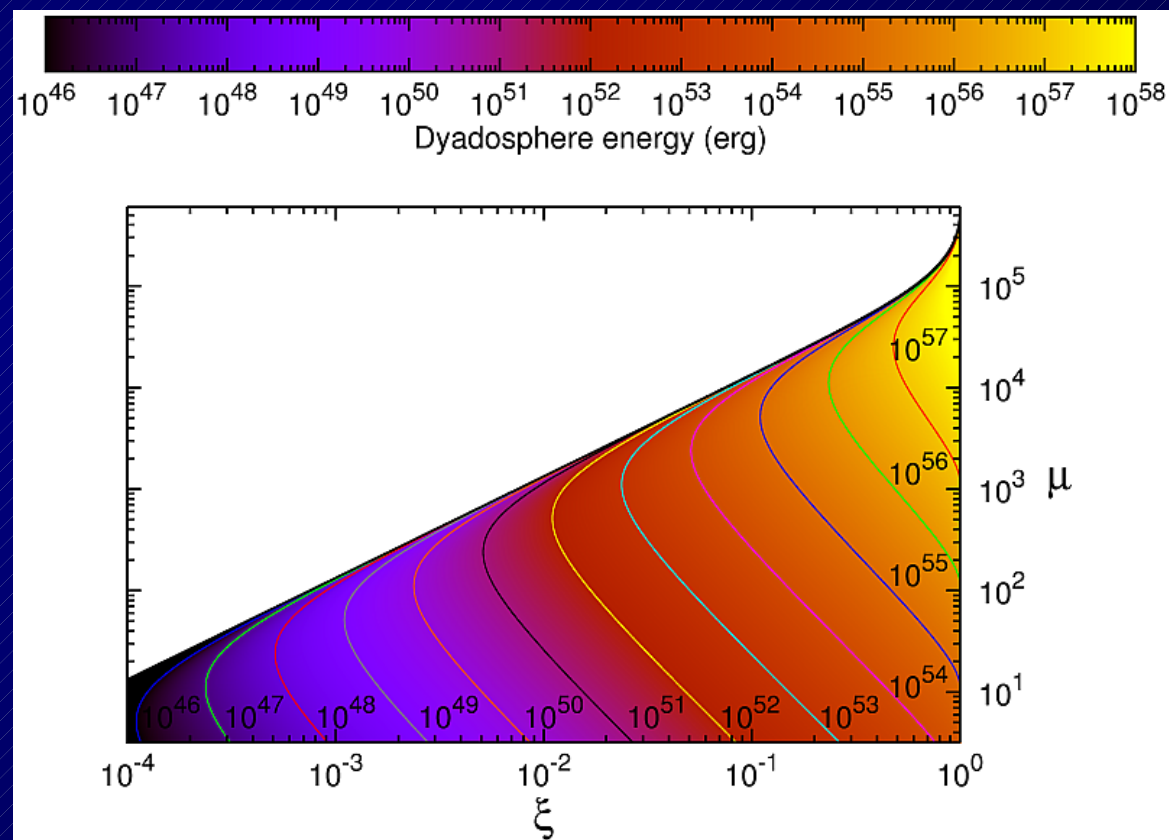
$$r_+ \simeq 1.47 \times 10^5 \mu \left(1 + \sqrt{1 - \xi^2} \right) \text{ cm}$$

$$r_{\text{ds}} \simeq 1.12 \times 10^8 \sqrt{\mu \xi} \text{ cm}$$



e^+e^- plasma

$$E_{\text{dya}} = \frac{1}{2} \frac{Q^2}{r_+} \left(1 - \frac{r_+}{r_{\text{ds}}} \right) \left[1 - \left(\frac{r_+}{r_{\text{ds}}} \right)^4 \right]$$



Preparata, Ruffini, Xue, *A&A*, **338**, L87, (1998)

Ruffini, Bianco, Chardonnet, Frascchetti, Vitagliano, Xue, "Cosmology and Gravitation", AIP, (2003)

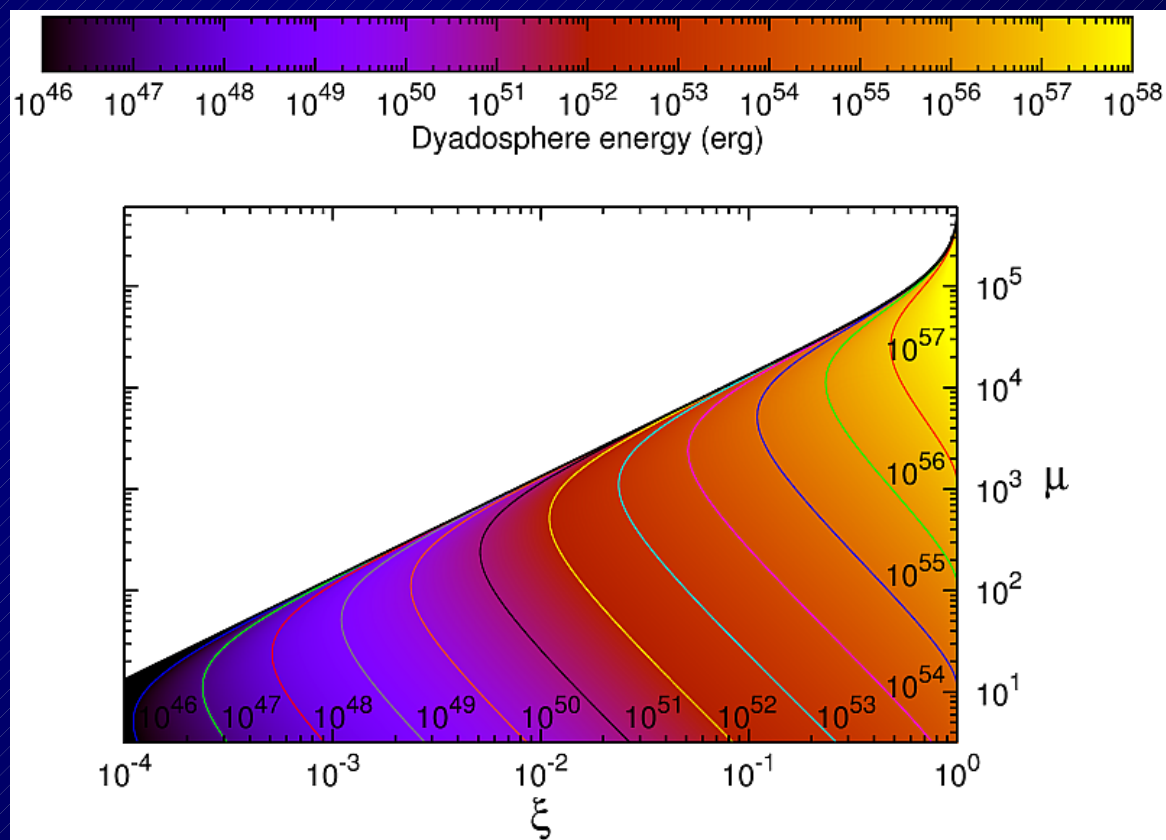
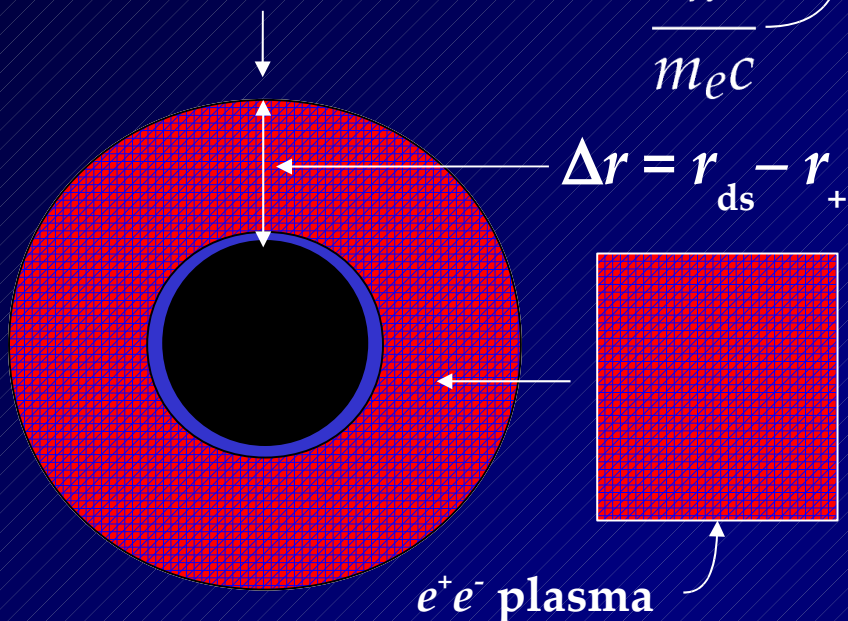
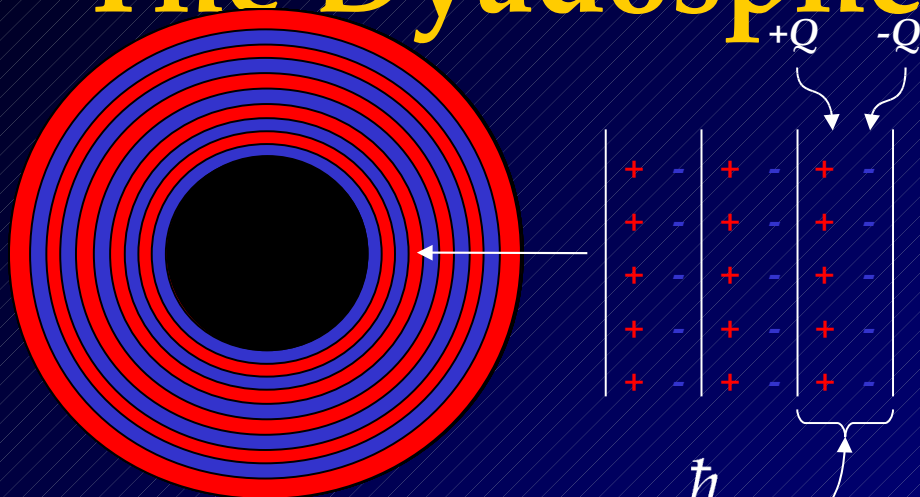
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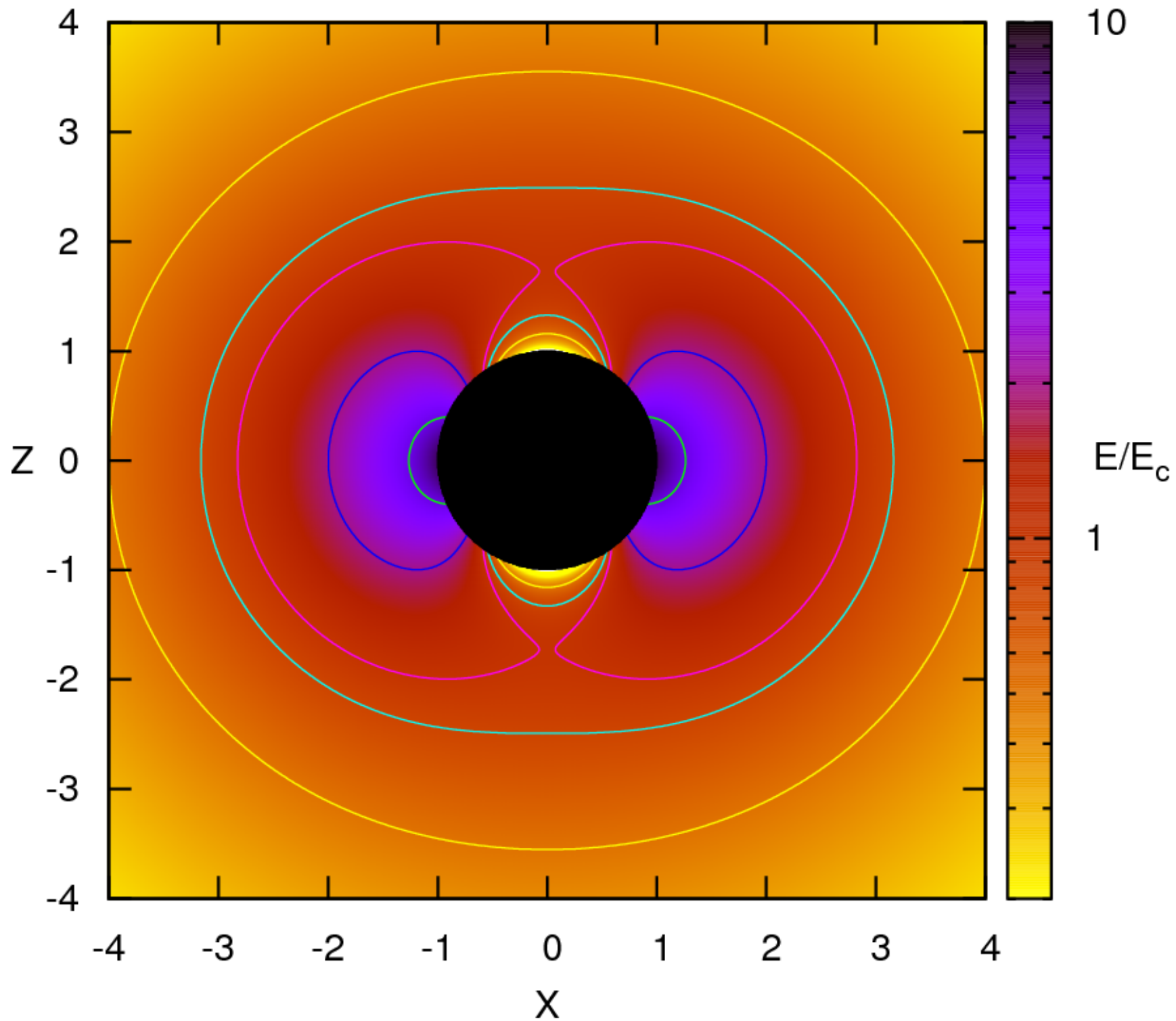


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Preparata, Ruffini, Xue, *A&A*, **338**, L87, (1998)

Ruffini, Bianco, Chardonnet, Fraschetti, Vitagliano, Xue, "Cosmology and Gravitation", AIP, (2003)

The Dyado-torus



Cherubini,
Geralico, Rueda,
Ruffini, *PRD* **79**,
124002 (2009).

Ruffini,
Vereshchagin,
Xue, *Phys.Rep.*
487, 1 (2010).

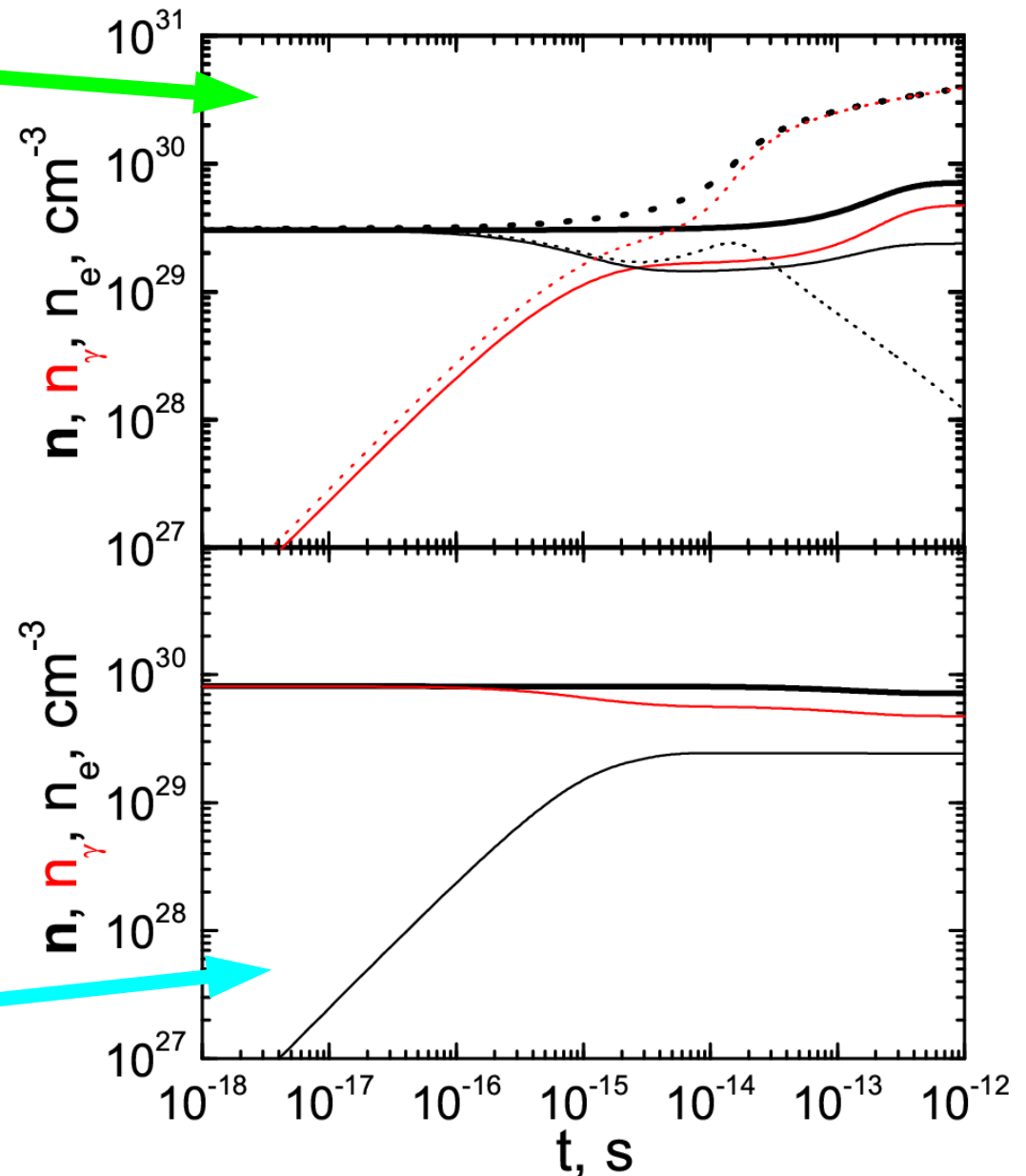
Thermalization of $e^+e^-\gamma$ plasma

Starting with a pure e^+e^- configuration

Dotted lines: *Neglecting* inverse 3-body interactions (Cavallo & Rees, 1978).

Solid lines: *Considering* inverse 3-body interactions (Aksenov, et al., 2007).

Starting with a pure γ configuration



Engulfment of baryonic remnant

$$B \stackrel{def.}{=} \frac{N_B m_p c^2}{E_{dya}} \equiv \frac{M_B c^2}{E_{dya}}$$

Assumptions:

- PEM pulse geometry unchanged;
- Fully inelastic collision;
- Thermal equilibrium between baryons and PEM pulse.

Valid if:

- $B < 10^{-2}$;
- n_{e+e-}/n_B very high (e.g. $> 10^6$);
- PEM pulse γ very high: ($\gamma \geq 100$).

Results:

- Strong decrease in PEM pulse γ Lorentz factor:

$$\gamma_{\text{coll}} = \gamma_0 \frac{1 + B}{\sqrt{\gamma_0^2 (2B + B^2) + 1}};$$

- Rise of the PEM pulse internal energy measured in the co-moving frame:

$$\frac{E_{\text{coll}}}{E_{\text{dya}}} = \frac{1}{\gamma_0} \sqrt{\gamma_0^2 (2B + B^2) + 1} - \left(\frac{1}{\gamma_0} + B \right);$$

- A corresponding re-heating of the plasma in the co-moving frame, but not in the laboratory frame, a rise of $e+e-$ pair number and a grater PEM pulse opacity.

Engulfment of baryonic remnant

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!

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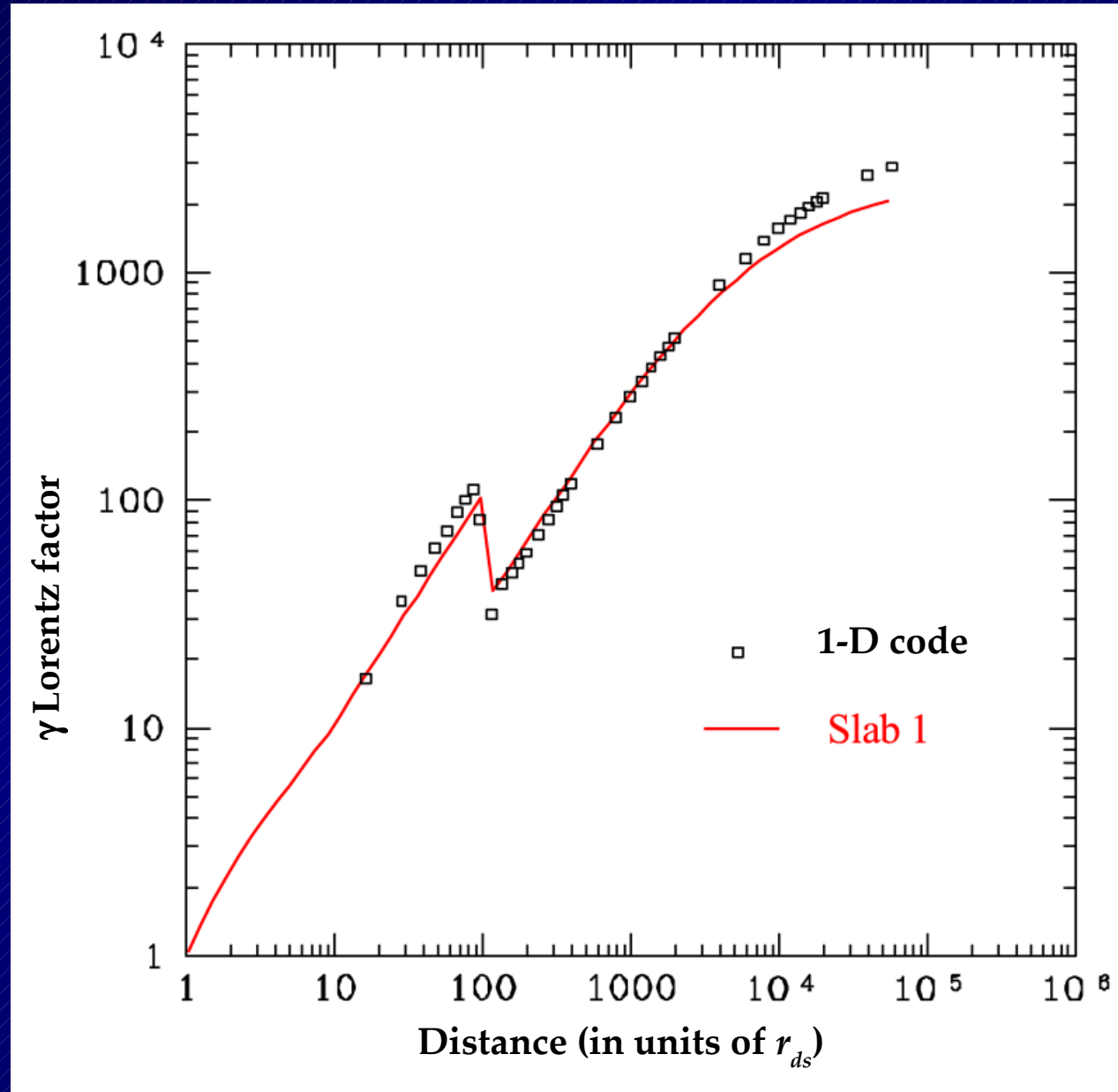
The optically thick *fireshell*: The PEMB Pulse

$$\gamma_{\text{asym}} \stackrel{\text{def.}}{=} \frac{E_{\text{dya}}}{M_B c^2} \equiv \frac{1}{B}$$

At transparency point:

$$\gamma_{\circ} \xrightarrow{B \rightarrow 10^{-2}} \gamma_{\text{asym}}$$

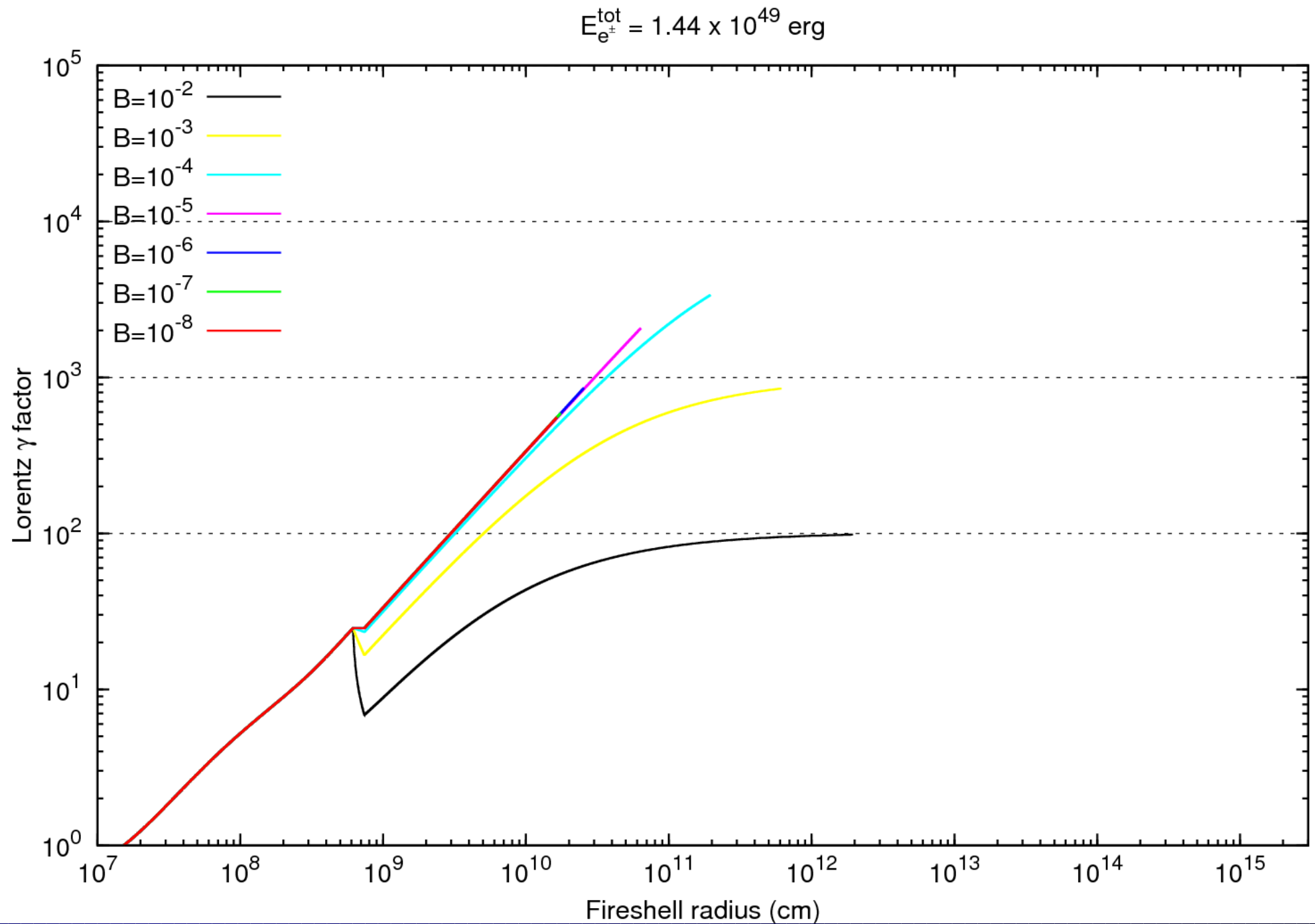
The percentage of PEMB Pulse internal energy converted into baryonic kinetic energy rises with rising B .



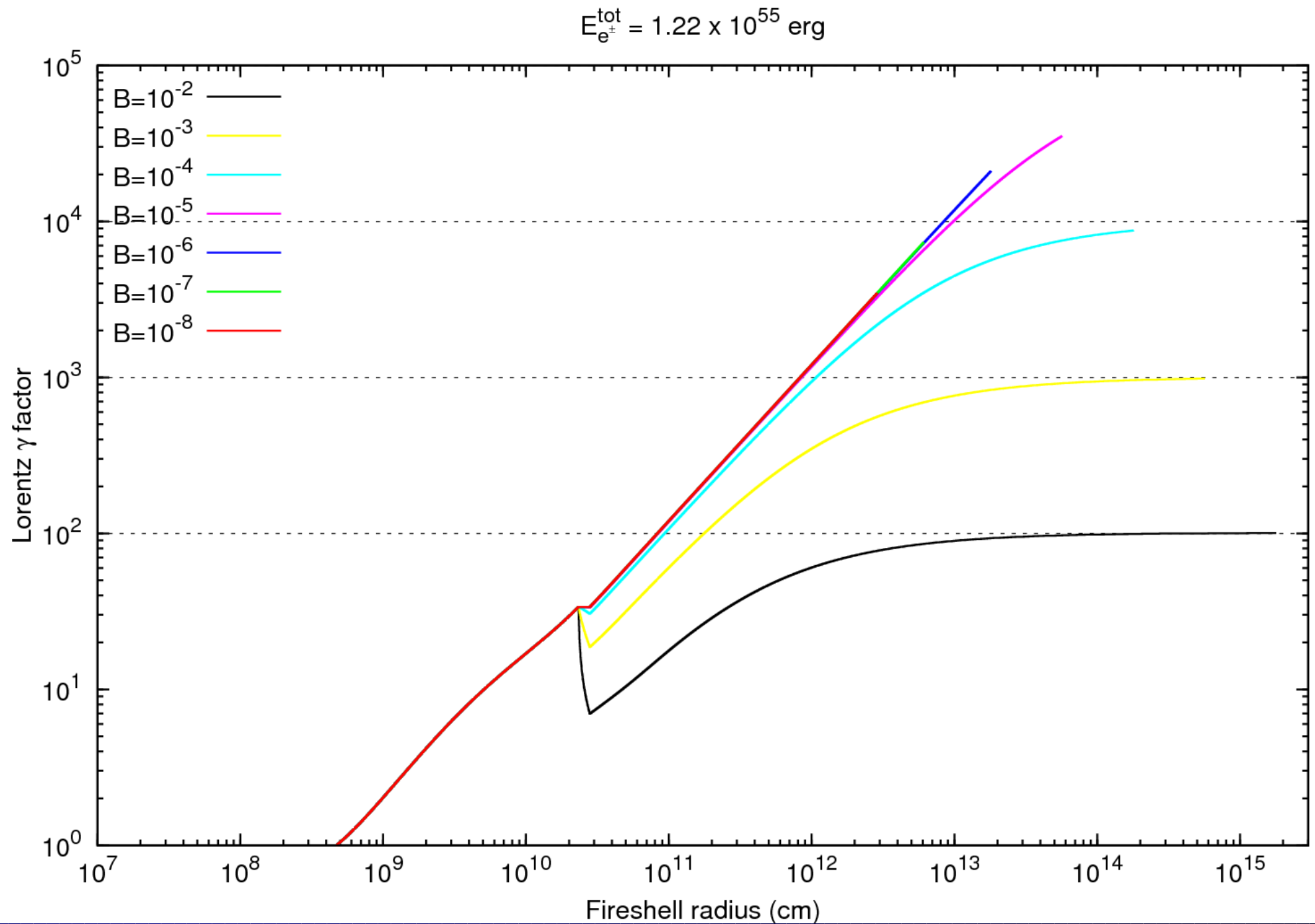
Ruffini, Salmonson, Wilson, Xue, *A&A*, **359**, 855, (2000)

Ruffini, Bianco, Chardonnet, Frascchetti, Vitagliano, Xue, "Cosmology and Gravitation", AIP, (2003)

The optically thick *fireshell*: The PEMB Pulse



The optically thick *fireshell*: The PEMB Pulse



Fireshell dynamics

Baryon conservation:

$$\frac{n_B^0}{n_B} = \frac{V}{V_0} = \frac{\mathcal{V}}{\mathcal{V}_0} \frac{\gamma}{\gamma_0} \quad V = \gamma \mathcal{V}$$

Adiabatic expansion:

$$\frac{\tilde{\epsilon}_0}{\tilde{\epsilon}} = \left(\frac{V}{V_0}\right)^{\tilde{\Gamma}} = \left(\frac{\mathcal{V}}{\mathcal{V}_0}\right)^{\tilde{\Gamma}} \left(\frac{\gamma}{\gamma_0}\right)^{\tilde{\Gamma}},$$

Energy conservation:

$$T^{0\nu}_{,\nu} = 0$$

Rate equation:

$$\frac{\partial}{\partial t} N_{e^\pm} = -N_{e^\pm} \frac{1}{\mathcal{V}} \frac{\partial \mathcal{V}}{\partial t} + \overline{\sigma v} \frac{1}{\gamma^2} (N_{e^\pm}^2(T) - N_{e^\pm}^2)$$

V – comoving volume,

$\mathcal{V}$ – lab volume,

n_B – baryon number density,

$\tilde{\Gamma}$ – thermal index,

$\tilde{\epsilon}$ – internal energy density,

ρ_B – rest mass density,

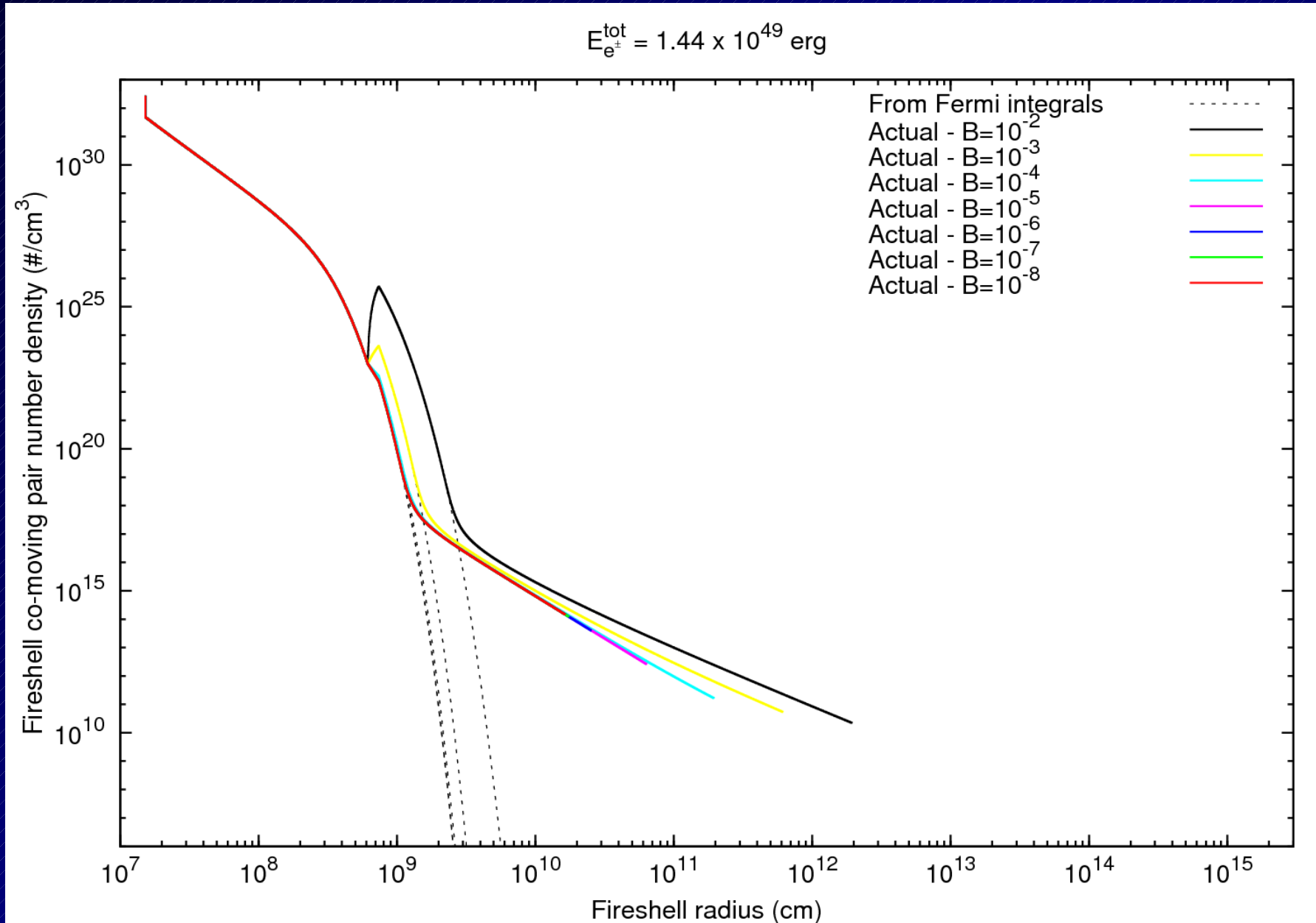
σ – cross section,

v – velocity,

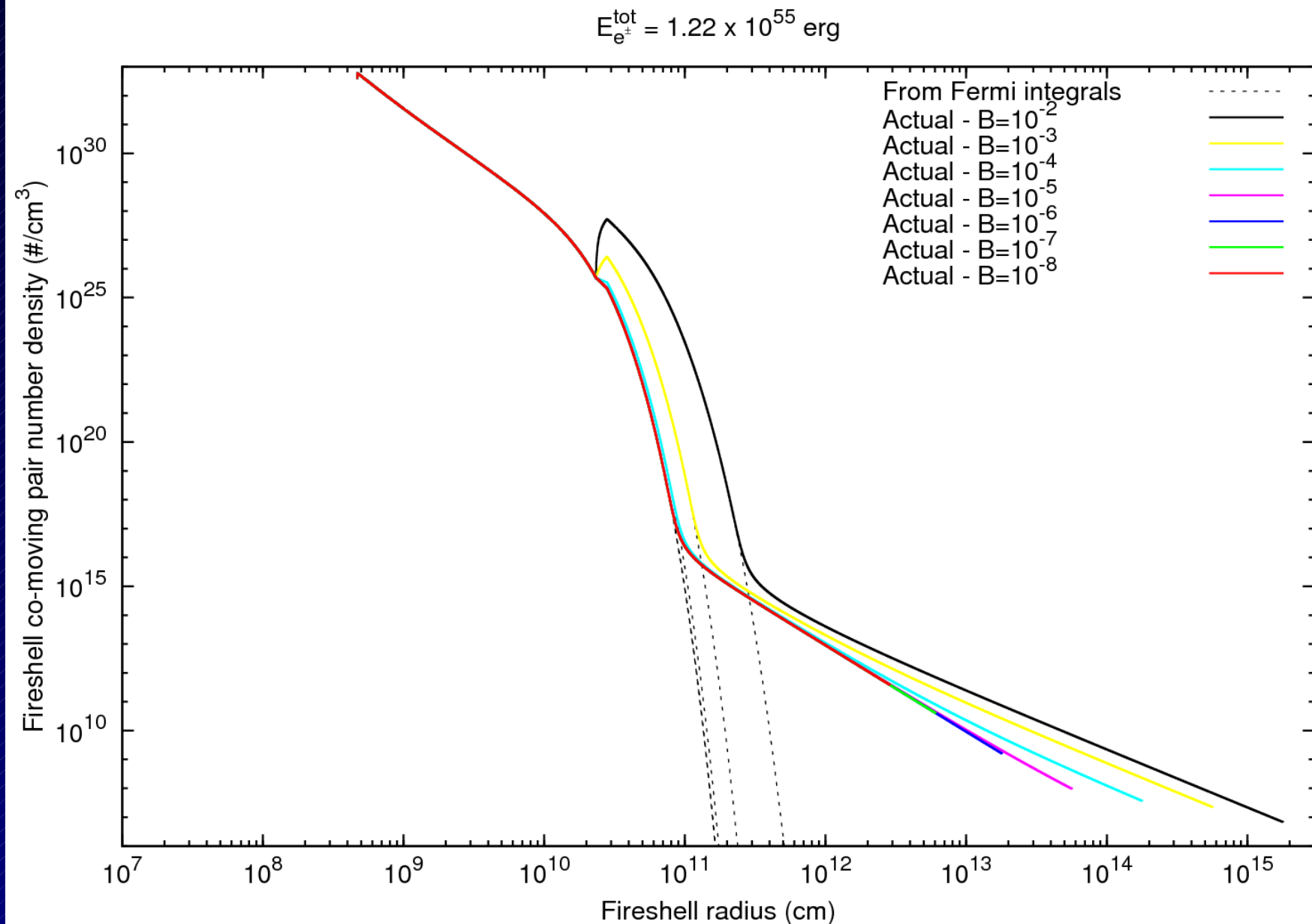
N_{e^+,e^-} – number of pairs,

T – plasma temperature.

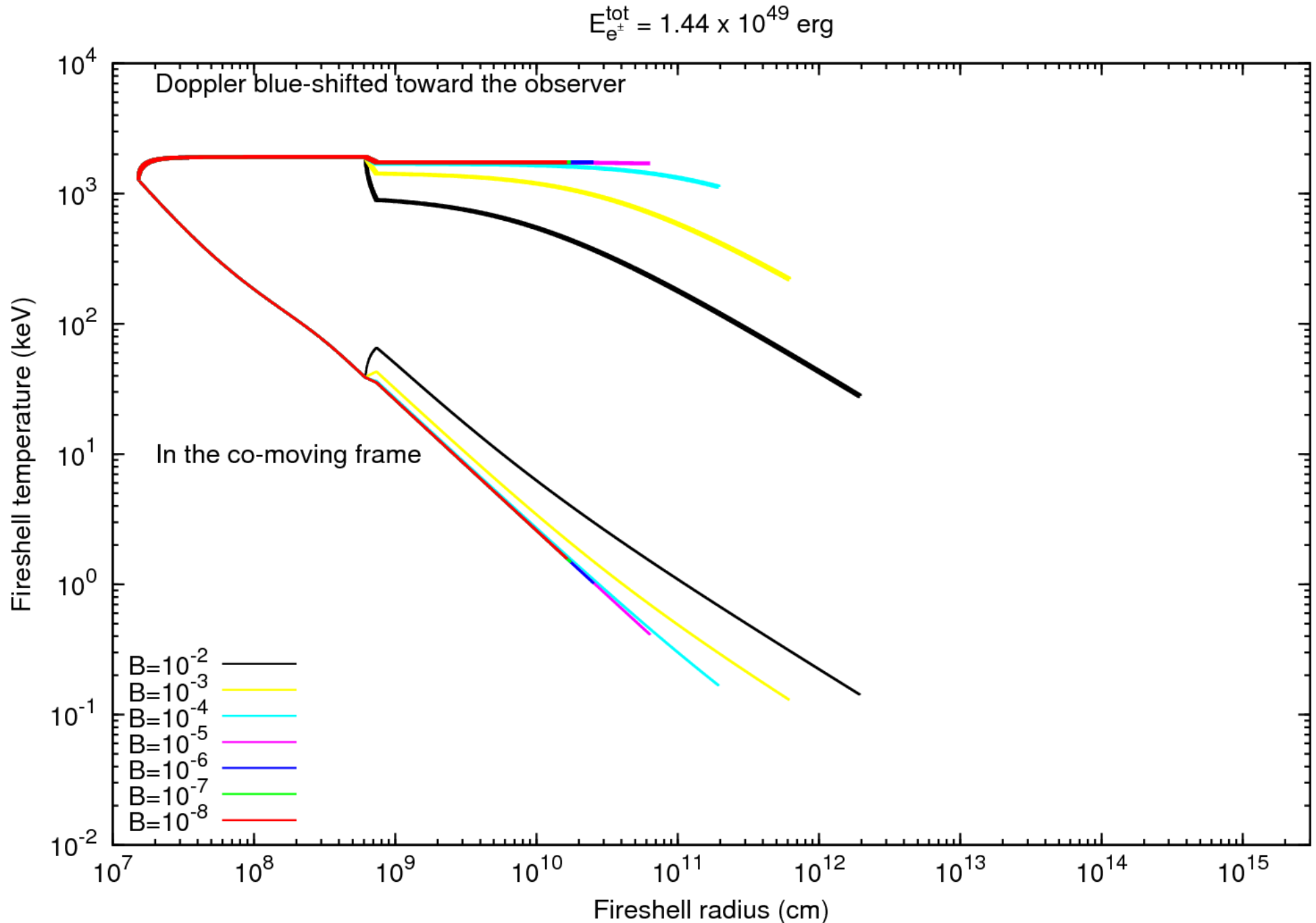
Fireshell pair number density: the role of the rate equation



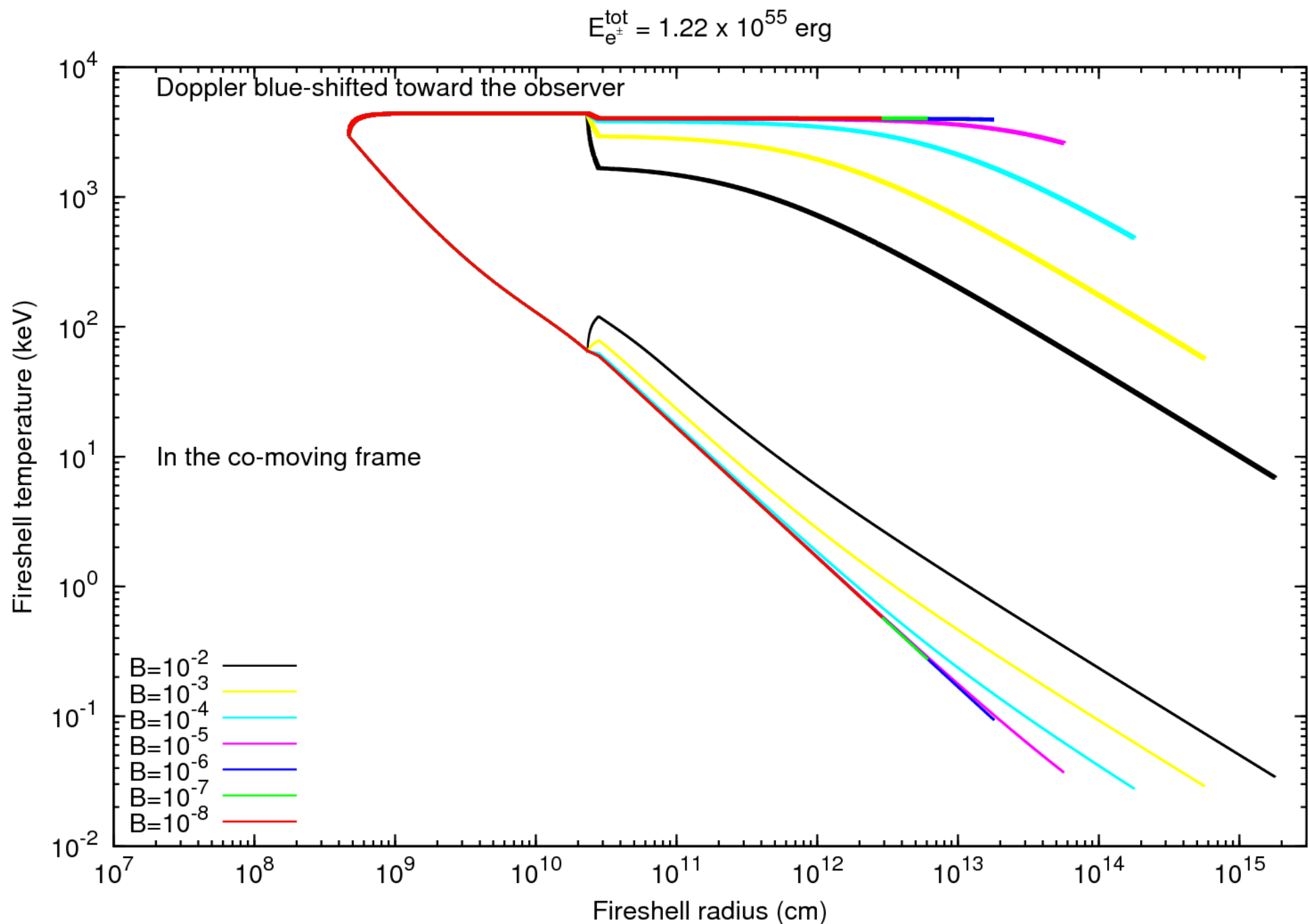
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Fireshell Temperature



Fireshell Temperature

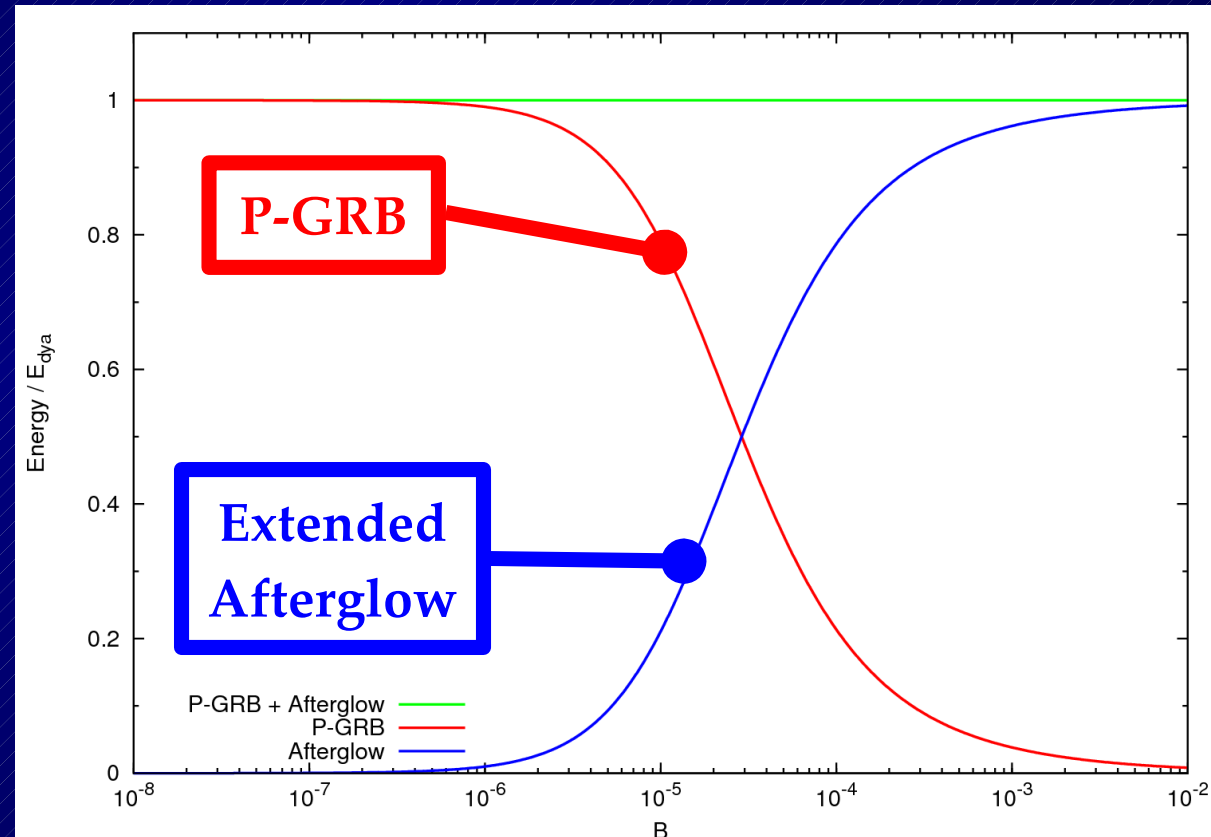


Fireshell transparency:

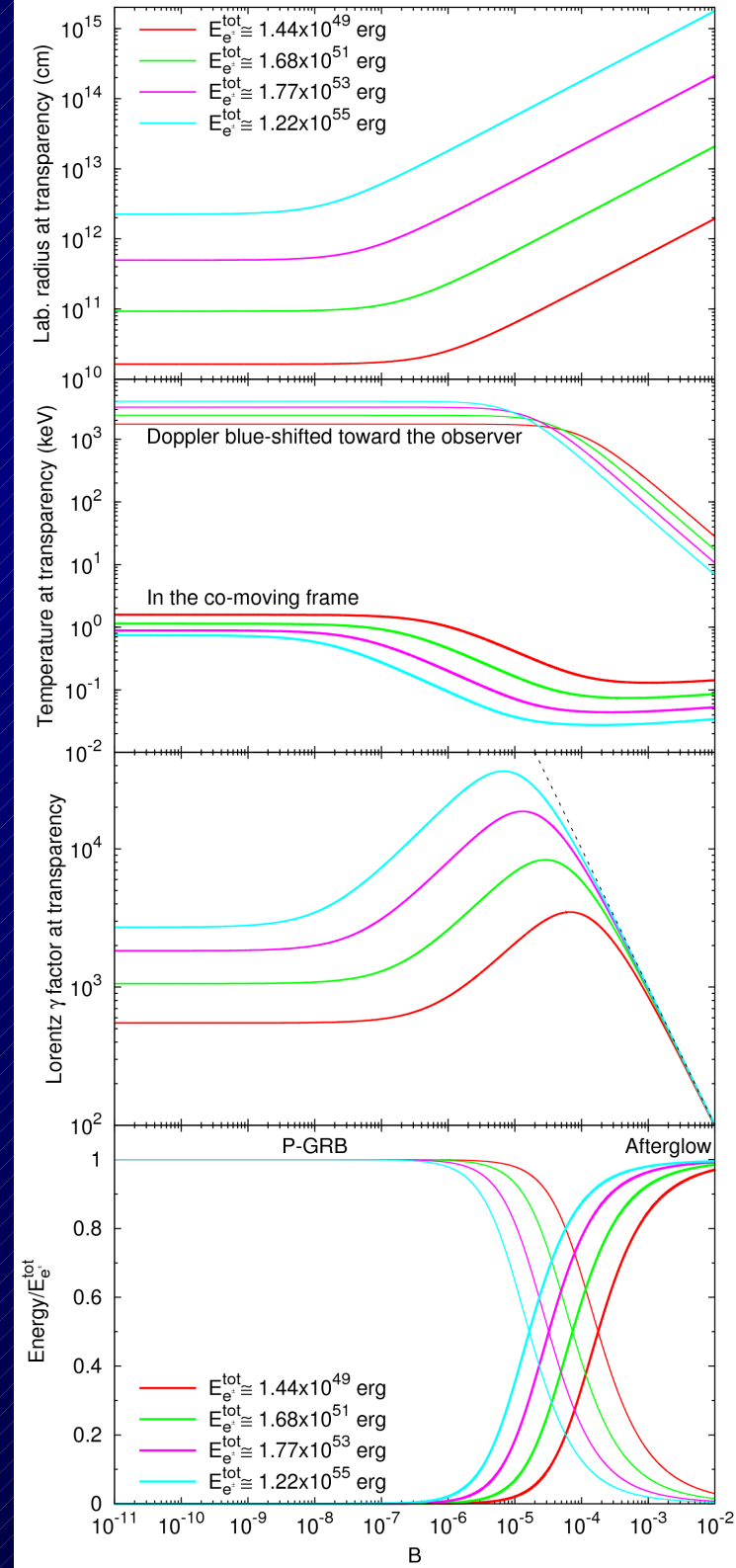
the P-GRB emission and the optically thin *fireshell*

- All photons produced by the electron-positron pair recombination are emitted in a short but strong energy flash: *the P-GRB*
- Out of the PEMB pulse it remains only an optically thin *fireshell* of baryonic matter accelerated at ultra-relativistic velocities: the ABM Pulse, which gives origin to *the extended afterglow*.
- The ratio between the fraction of PEMB Pulse internal energy converted into ABM Pulse kinetic energy and that emitted in the P-GRB depends on the B parameter.

$$B \stackrel{\text{def.}}{=} \frac{N_B m_p c^2}{E_{\text{dya}}} \equiv \frac{M_B c^2}{E_{\text{dya}}}$$



Fireshell transparency



Interaction ABM Pulse – ISM

Assumptions:

- sequence of fully inelastic collisions of the ABM pulse with a great number of ISM concentric spherical shells, thin, cold, at rest in the laboratory frame;
- ABM pulse thickness is constant if measured in the laboratory frame;
- the energy released in the collision is emitted instantaneously (*fully radiative condition*).

$$\gamma_2 = \frac{\gamma_1 + \frac{\Delta M_{\text{ism}} c^2}{\rho_{B_1} V_1}}{\sqrt{1 + 2\gamma_1 \frac{\Delta M_{\text{ism}} c^2}{\rho_{B_1} V_1} + \left(\frac{\Delta M_{\text{ism}} c^2}{\rho_{B_1} V_1} \right)^2}}$$

Energy and momentum conservation

$$\Delta E_{\text{int}} = \rho_{B_1} V_1 \sqrt{1 + 2\gamma_1 \frac{\Delta M_{\text{ism}} c^2}{\rho_{B_1} V_1} + \left(\frac{\Delta M_{\text{ism}} c^2}{\rho_{B_1} V_1} \right)^2} - \rho_{B_1} V_1 \left(1 + \frac{\Delta M_{\text{ism}} c^2}{\rho_{B_1} V_1} \right)$$

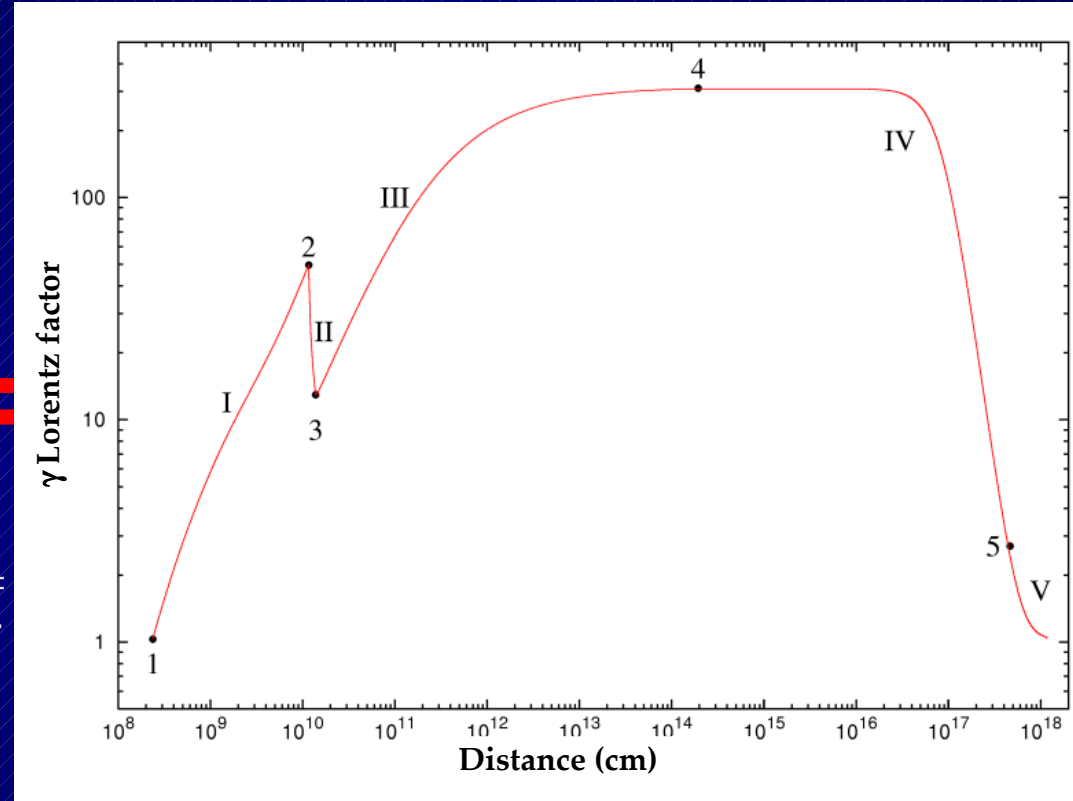
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ABM Pulse – ISM: differential form

$$\begin{cases} dE_{\text{int}} = (\gamma - 1) dM_{\text{ism}} c^2 \\ d\gamma = -\frac{\gamma^2 - 1}{M} dM_{\text{ism}} \\ dM = \frac{1 - \varepsilon}{c^2} dE_{\text{int}} + dM_{\text{ism}} \\ dM_{\text{ism}} = 4\pi m_p n_{\text{ism}} r^2 dr \end{cases}$$

Fully radiative condition: $\varepsilon = 1$

$\gamma_0 \gg \gamma \gg 1$
Blandford – McKee

Analytic integration

Fully adiabatic condition: $\varepsilon = 0$

Analytic integration

$\gamma_0^2 \gg \gamma^2 \gg 1$
Blandford – McKee

$$\gamma \propto r^{-3}$$

$$t = \frac{r}{c} \left(1 + \frac{1}{14\gamma^2} \right)$$

$$\gamma \propto r^{-3/2}$$

$$t = \frac{r}{c} \left[1 + \frac{1}{8\gamma^2(r)} \right]$$

Ruffini, Bianco, Chardonnet, Frascchetti, Vitagliano, Xue, "Cosmology and Gravitation", AIP vol. 668, (2003)

Bianco, Ruffini, *ApJ*, 620, L23, (2005)

Bianco, Ruffini, *ApJ*, 633, L13, (2005)

“Canonical GRB” Bolometric luminosity

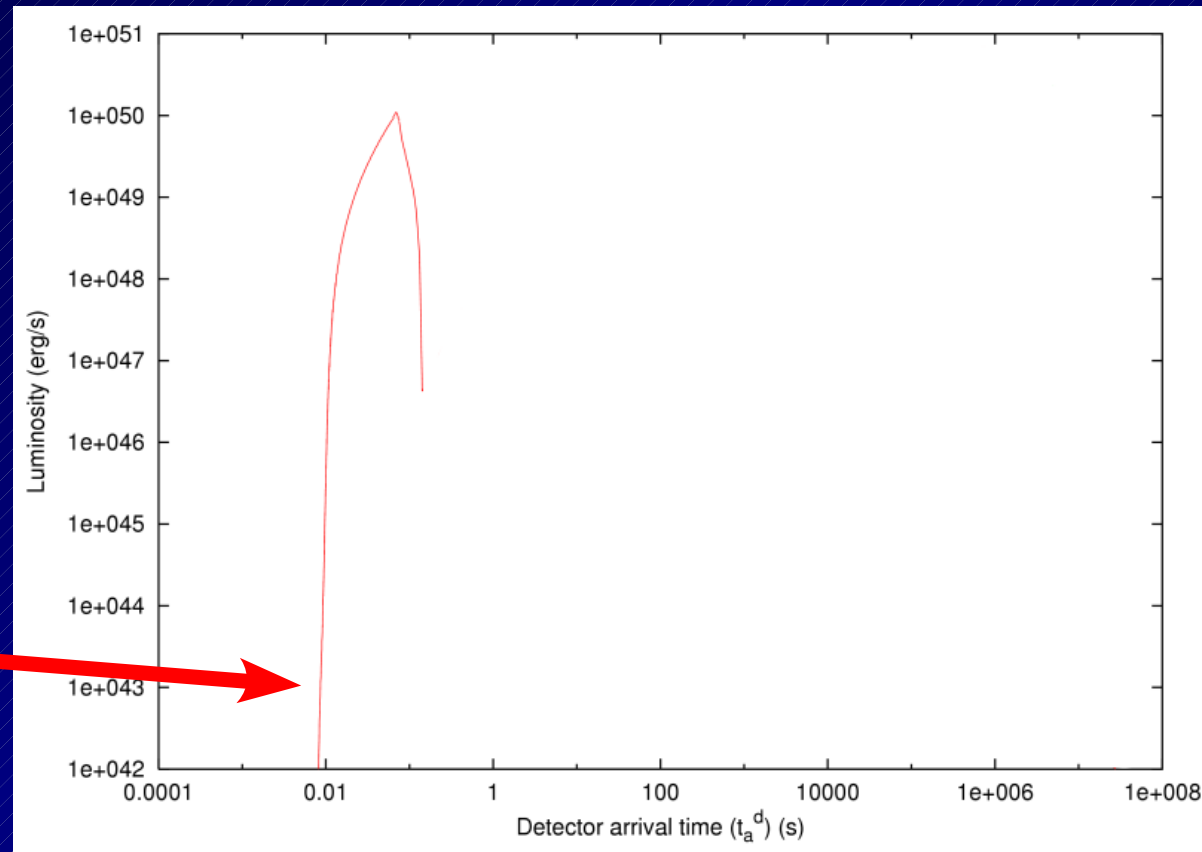
Two different phases:

“Canonical GRB” Bolometric luminosity

Two different phases:

P-GRB: emitted at the PEMB
pulse transparency point.

(still work in progress)



Ruffini, Bianco, Chardonnet, Frascchetti, Xue, *ApJ*, **555**, L113, (2001)

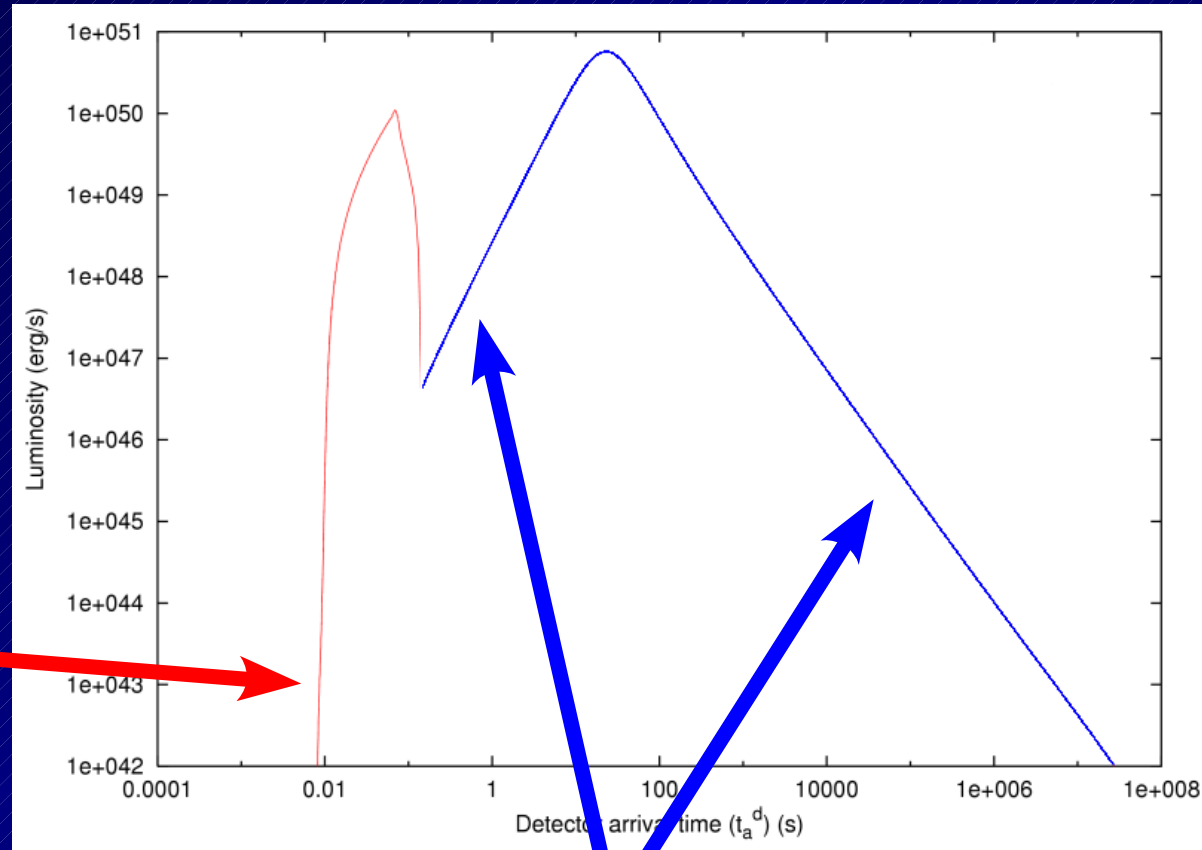
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Extended Afterglow: due to the
interaction between ABM
pulse and ISM. Includes E-APE

$$\frac{dE_\gamma}{dt_a^d d\Omega} = \int_{EQTS(\hat{t}_a^d)} \frac{\Delta\varepsilon}{4\pi} v \cos\vartheta \Lambda^{-4} \frac{dt}{dt_a^d} d\Sigma$$

$$t_a^d = (1+z) \left(t - \frac{\int_0^t v(t') dt' + r_{ds} \cos\vartheta + \frac{r_{ds}}{c}}{c} \right)$$

Ruffini, Bianco, Chardonnet, Frascchetti, Xue, *ApJ*, **555**, L113, (2001)

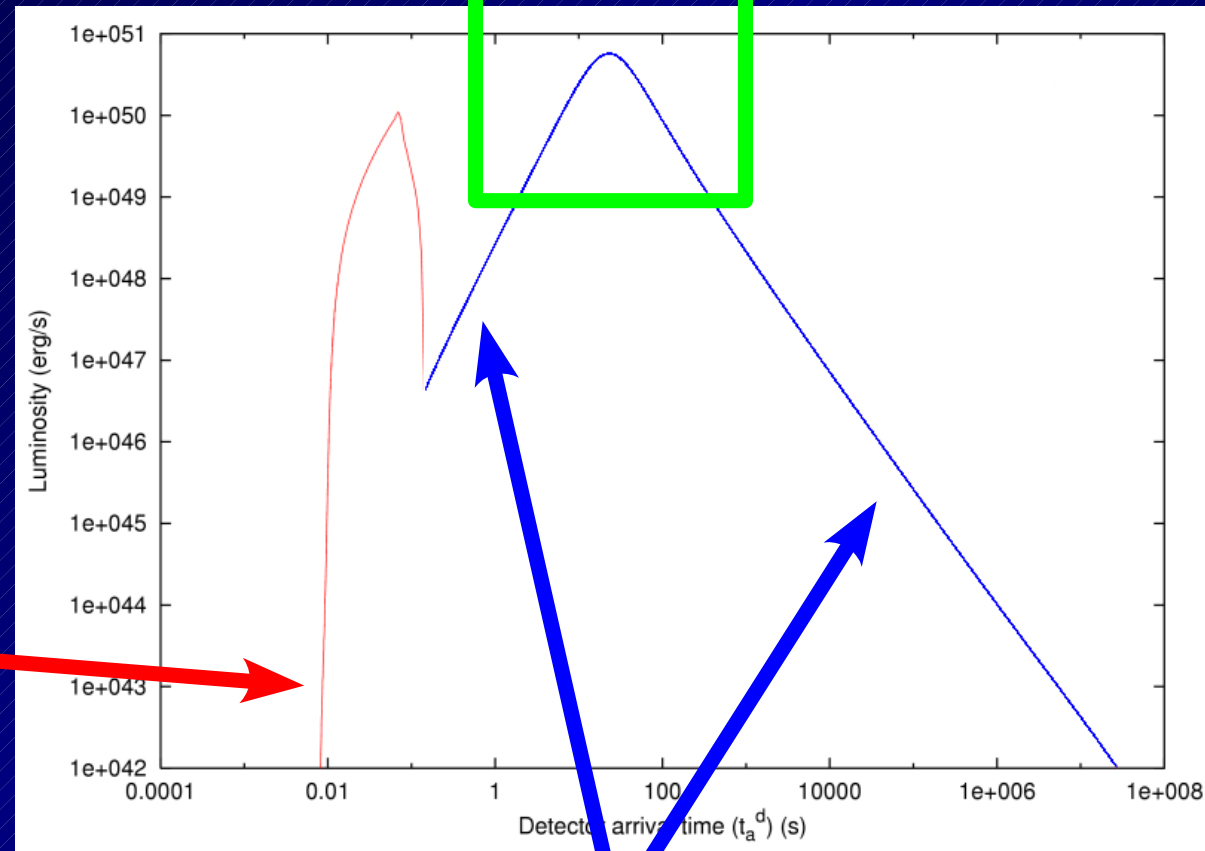
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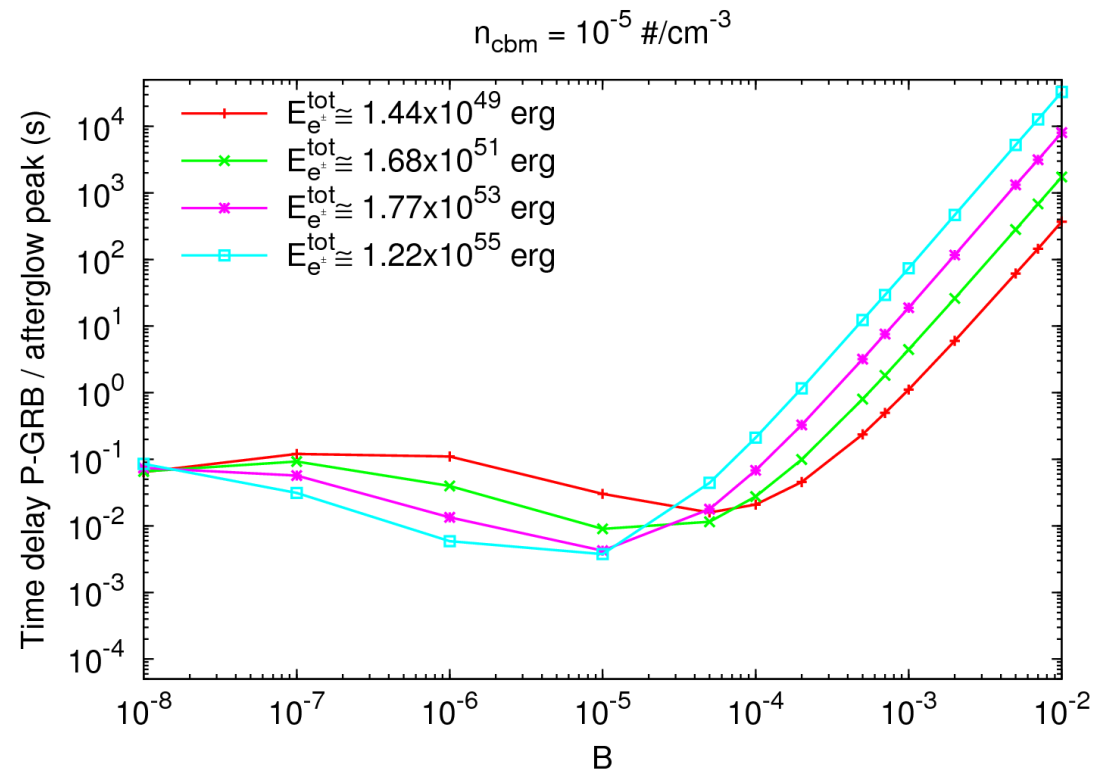
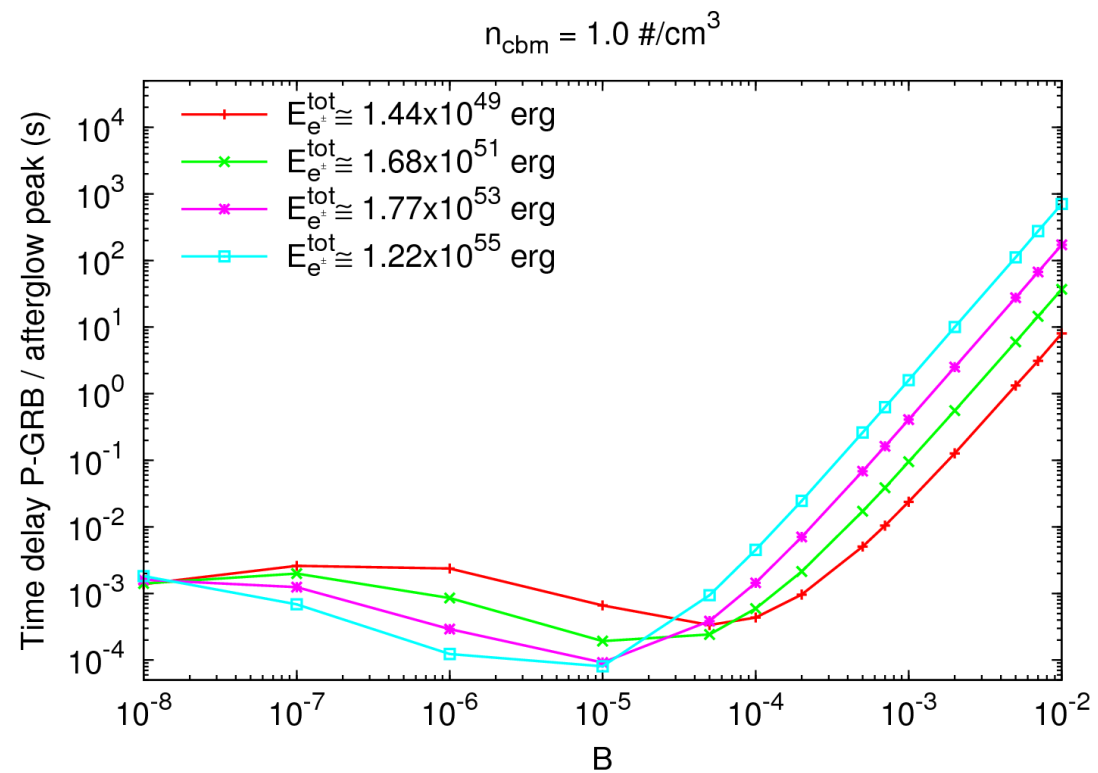
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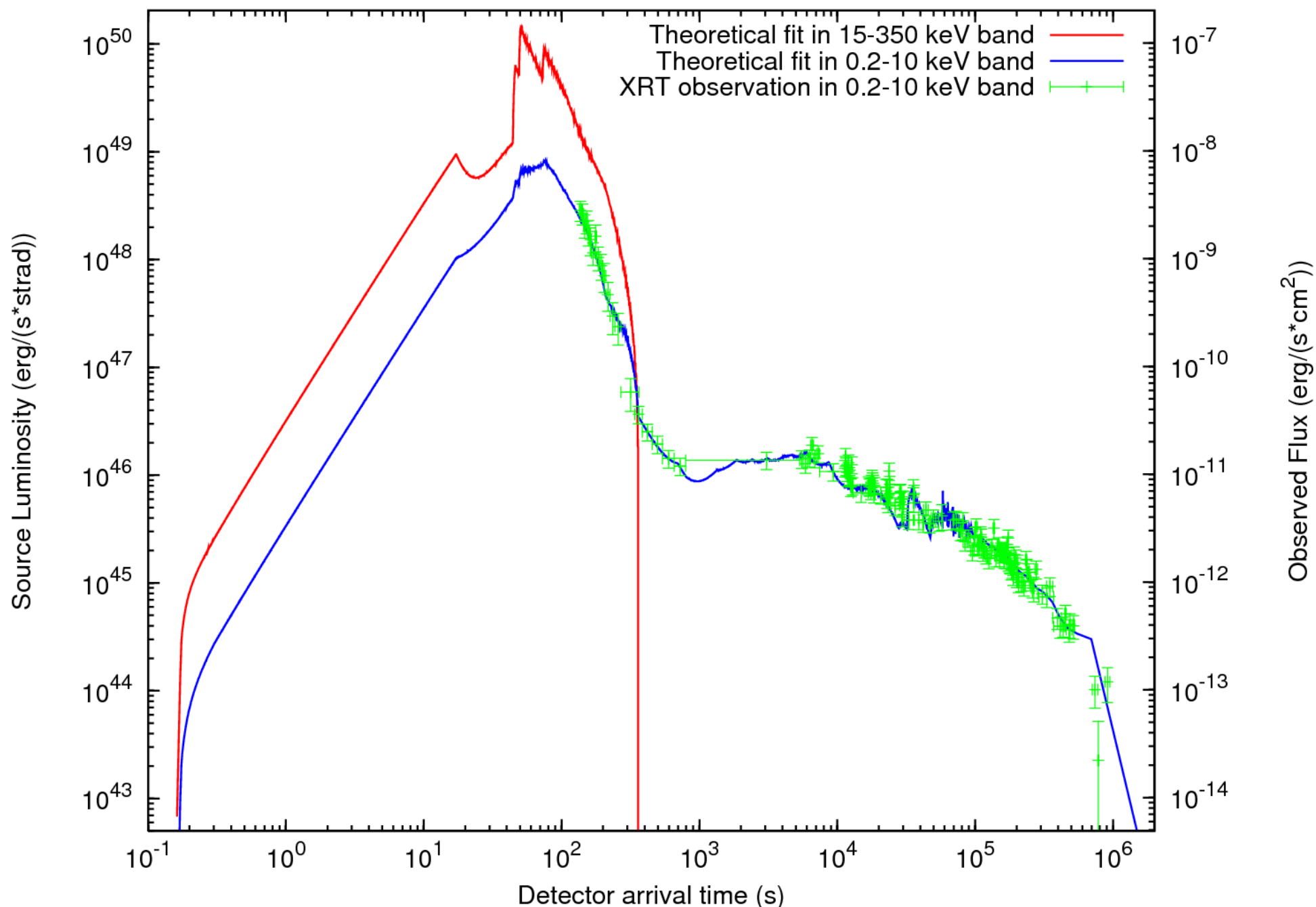
P-GRB

vs.

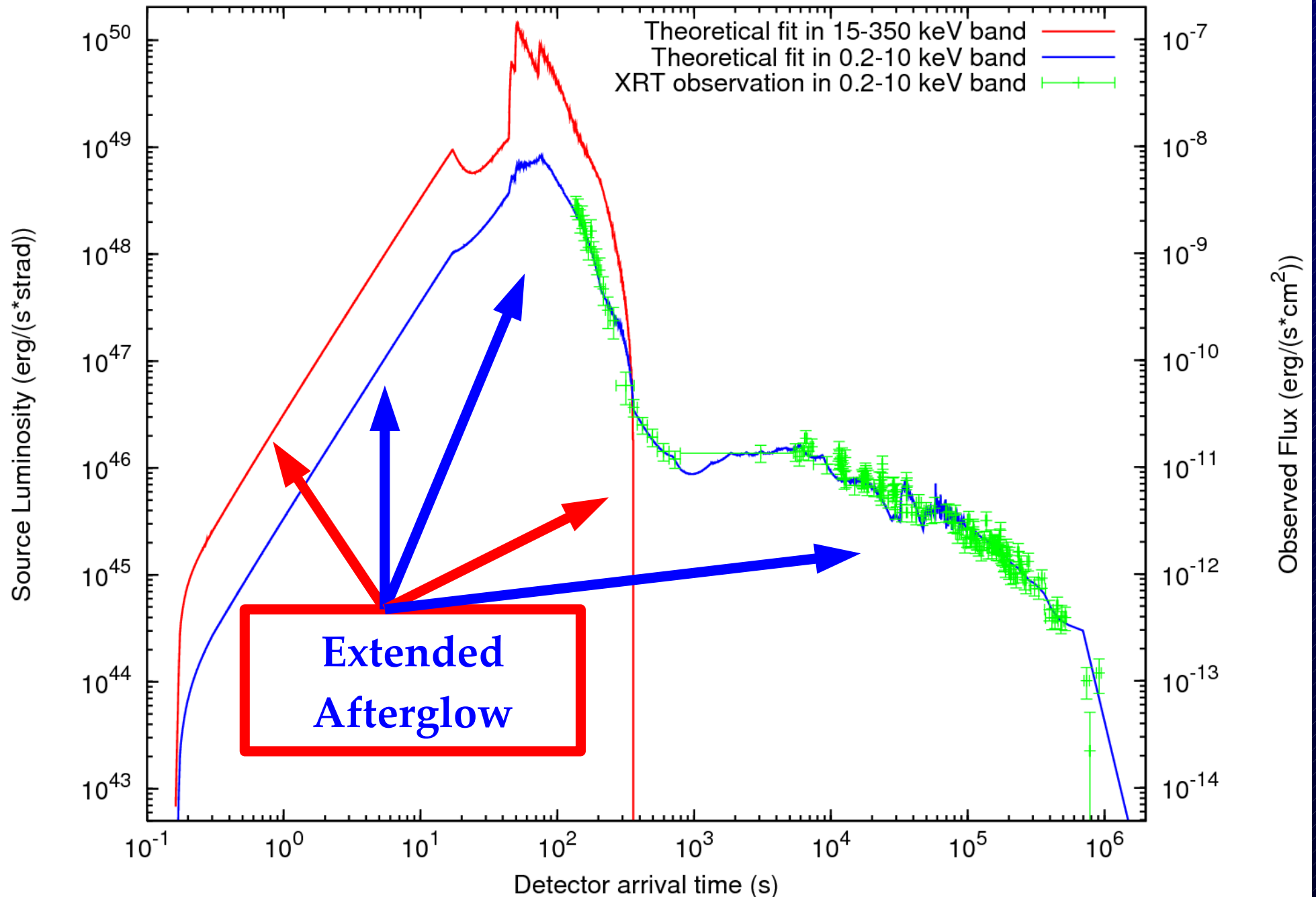
Extended Afterglow



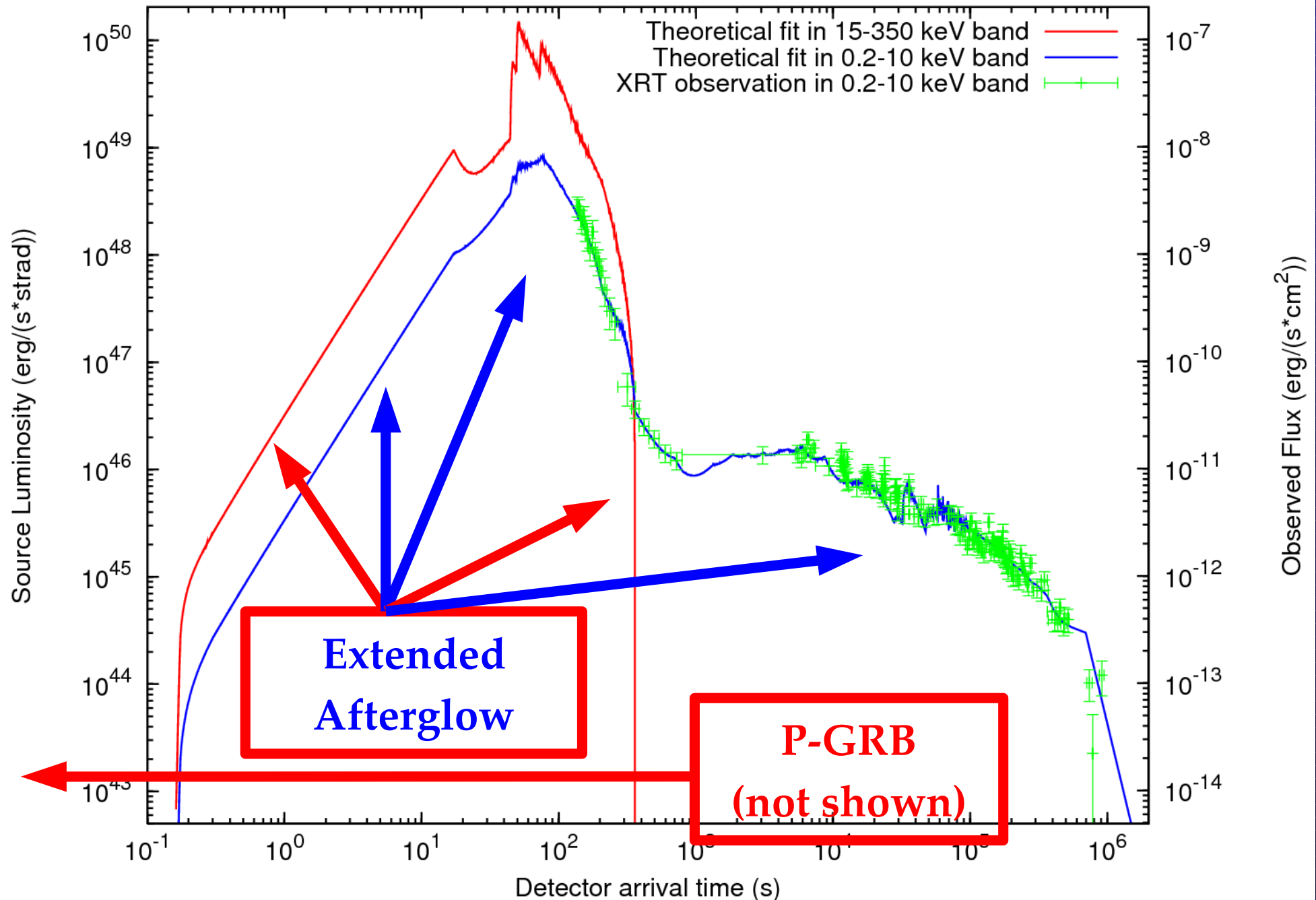
GRB 050315: BAT + XRT Light curve



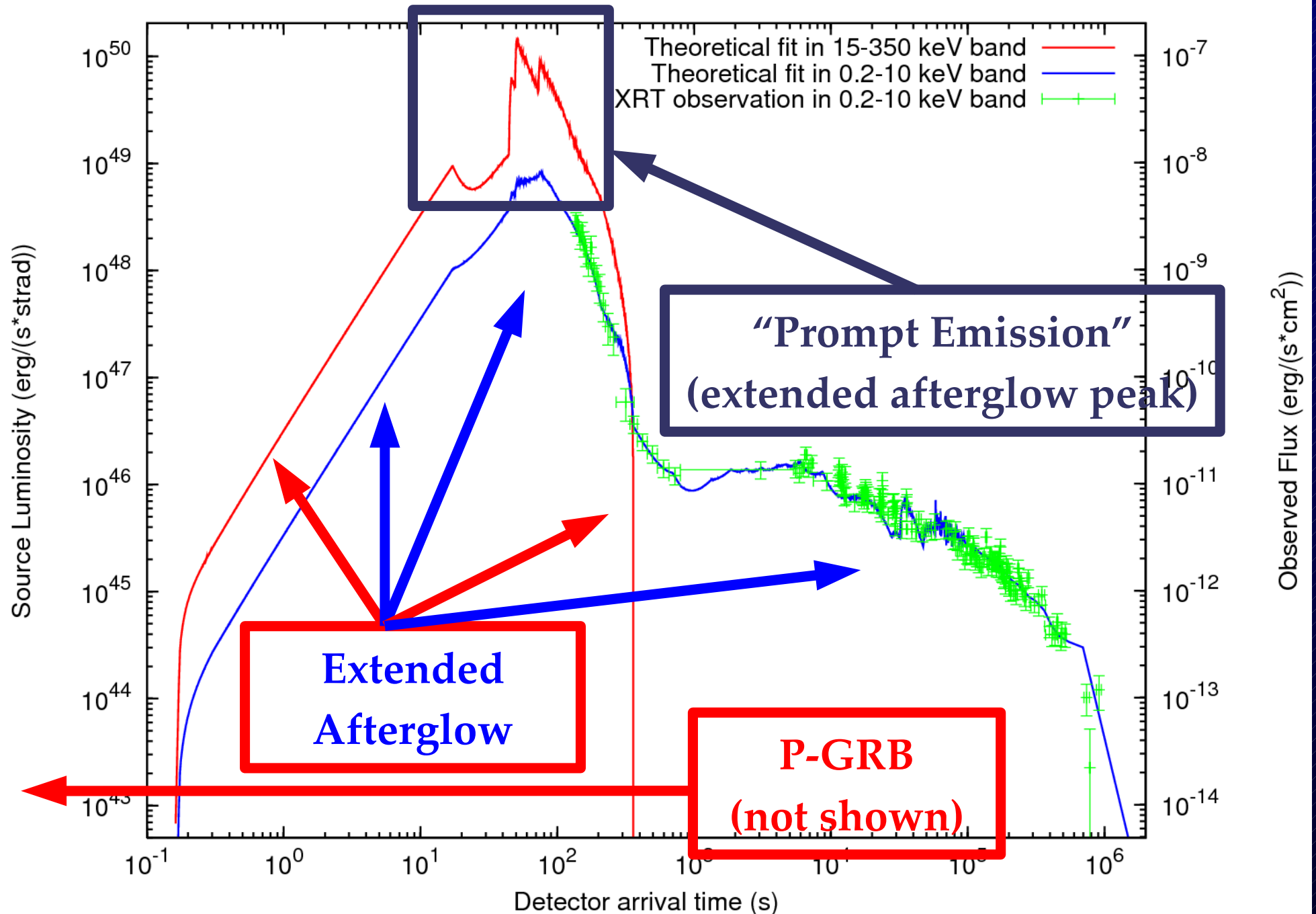
GRB 050315: BAT + XRT Light curve



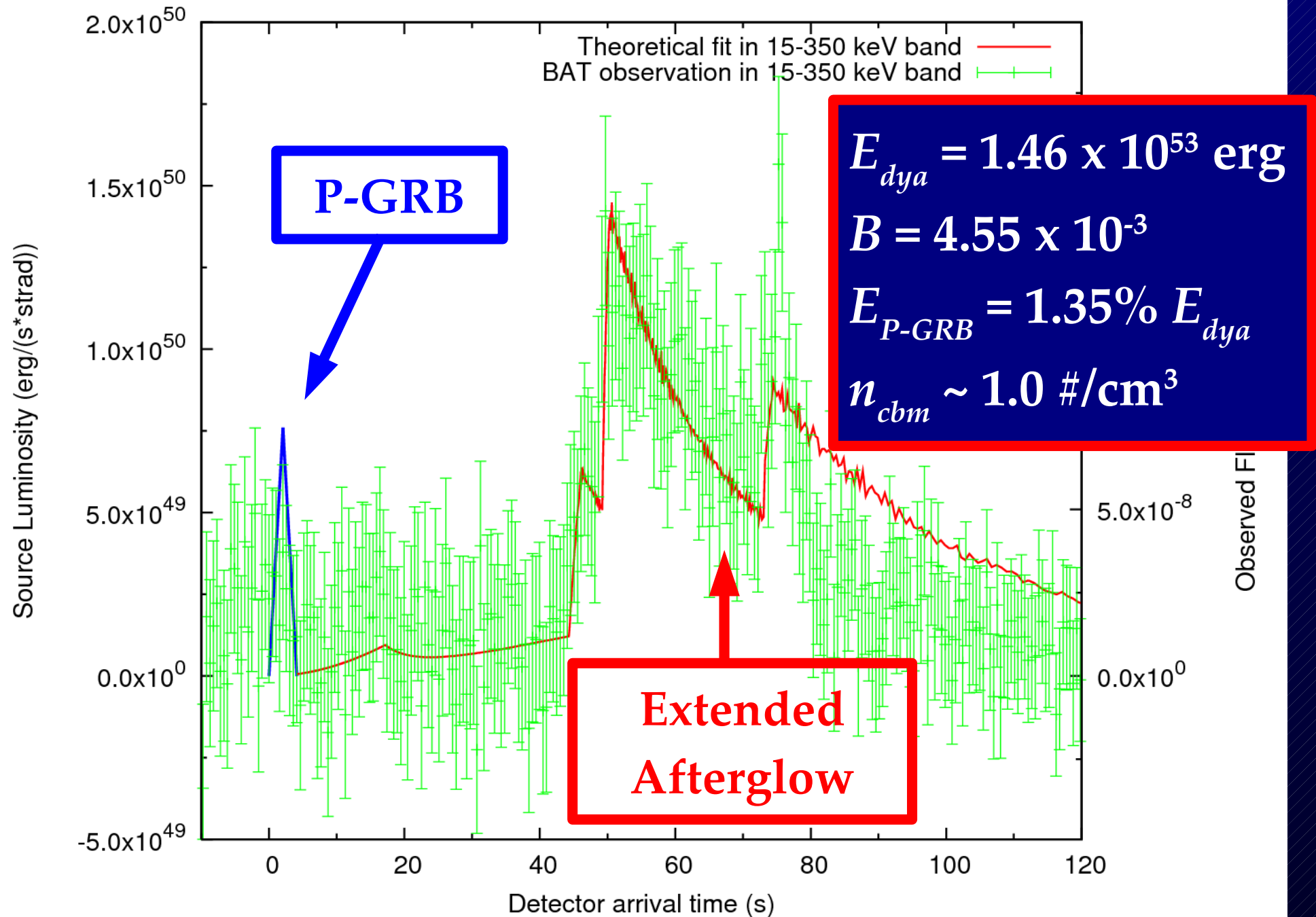
GRB 050315: BAT + XRT Light curve



GRB 050315: BAT + XRT Light curve



GRB 050315: BAT Light curve (15-350 keV)



GRB 970228

prompt emission (*BeppoSAX*)

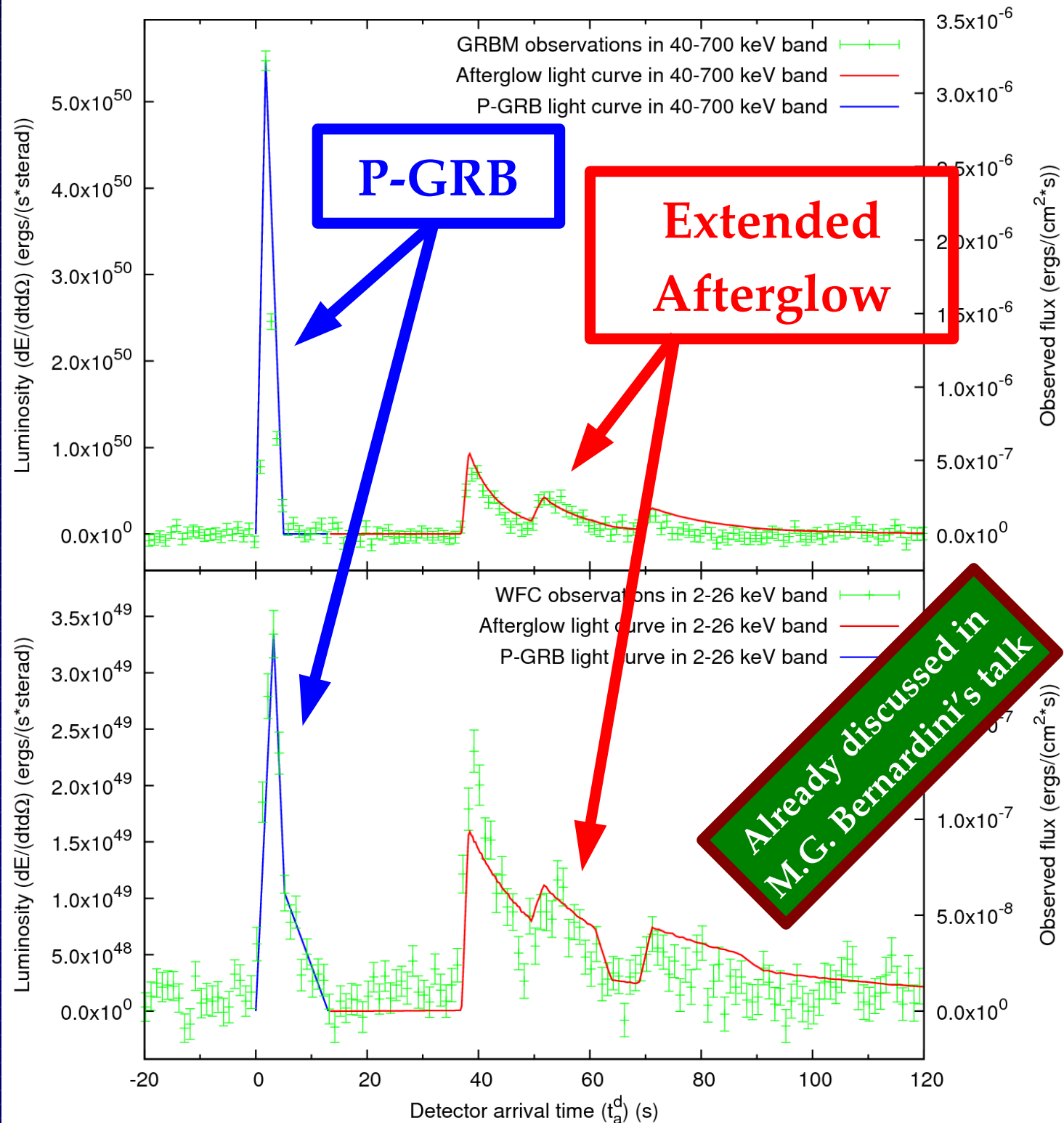
$$E_{dya} = 1.4 \times 10^{54} \text{ erg}$$

$$B = 5.0 \times 10^{-3}$$

$$E_{P-GRB} = 1.1\% E_{dya}$$

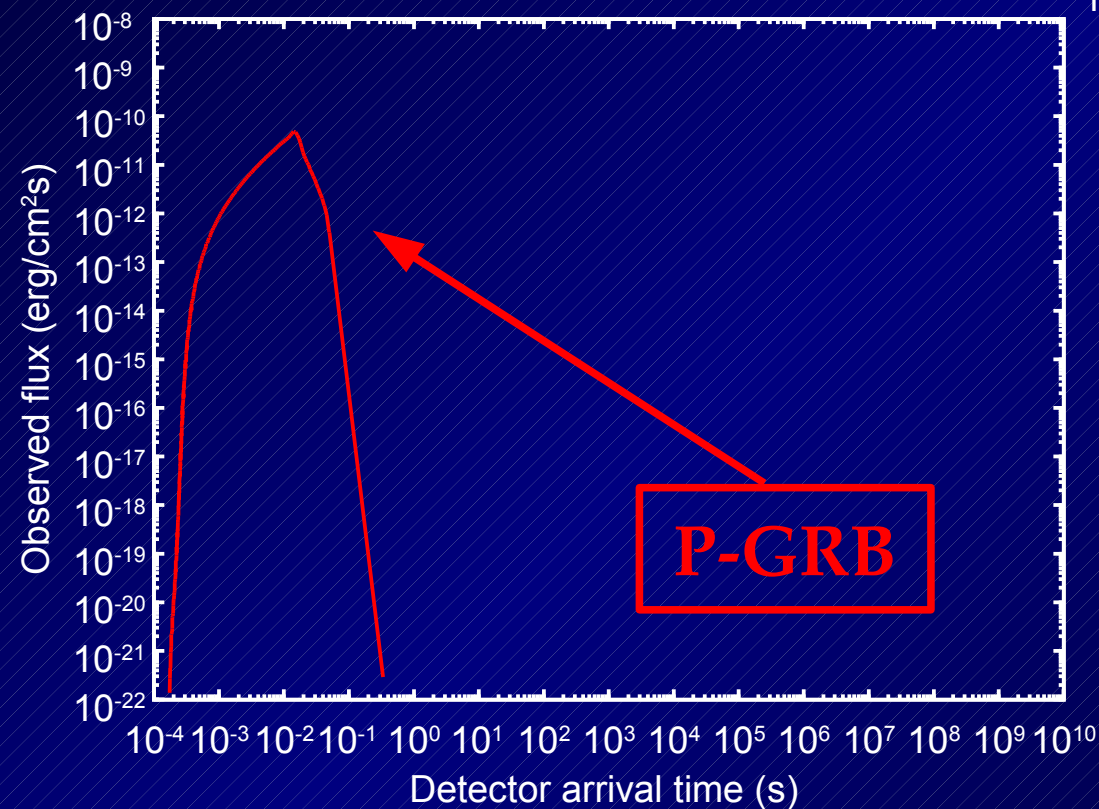
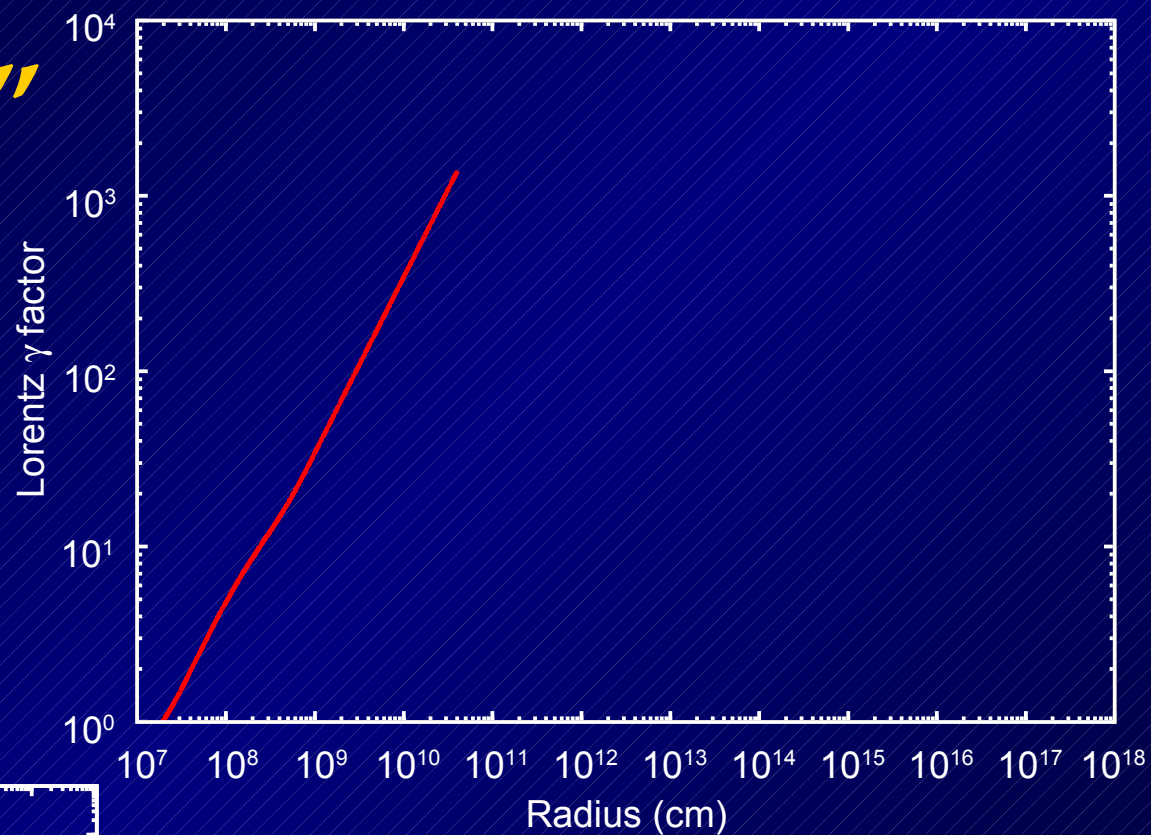
$$n_{ism} \sim 10^{-3} \text{ \#/cm}^3$$

GRB 970228 detected in
the halo of its host galaxy.



"Canonical GRB"

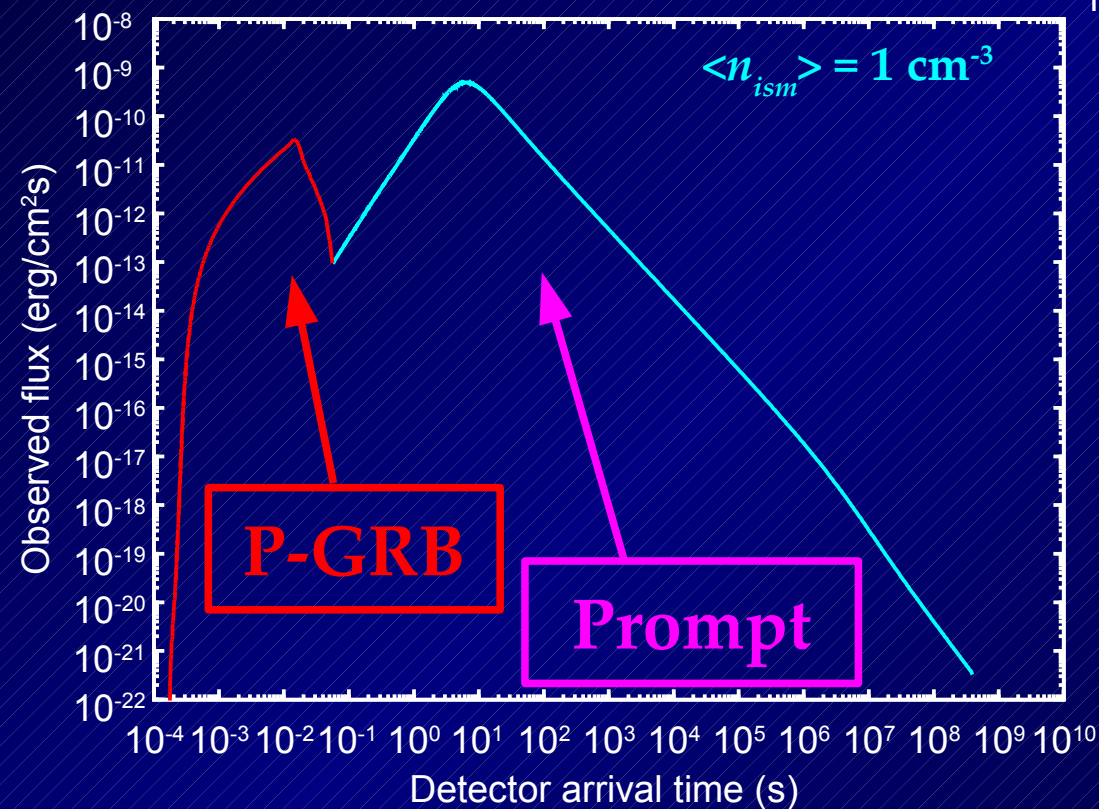
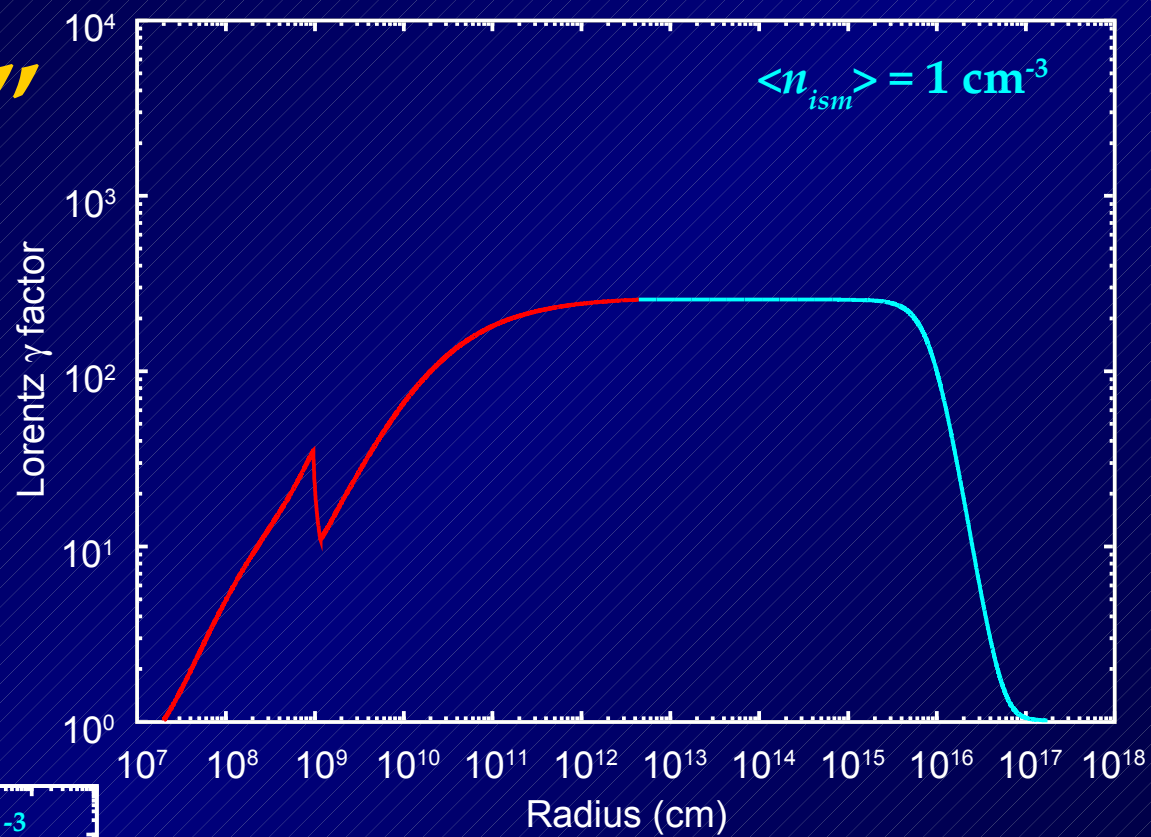
$$B \rightarrow 0$$



"Genuine short"
GRBs

"Canonical GRB"

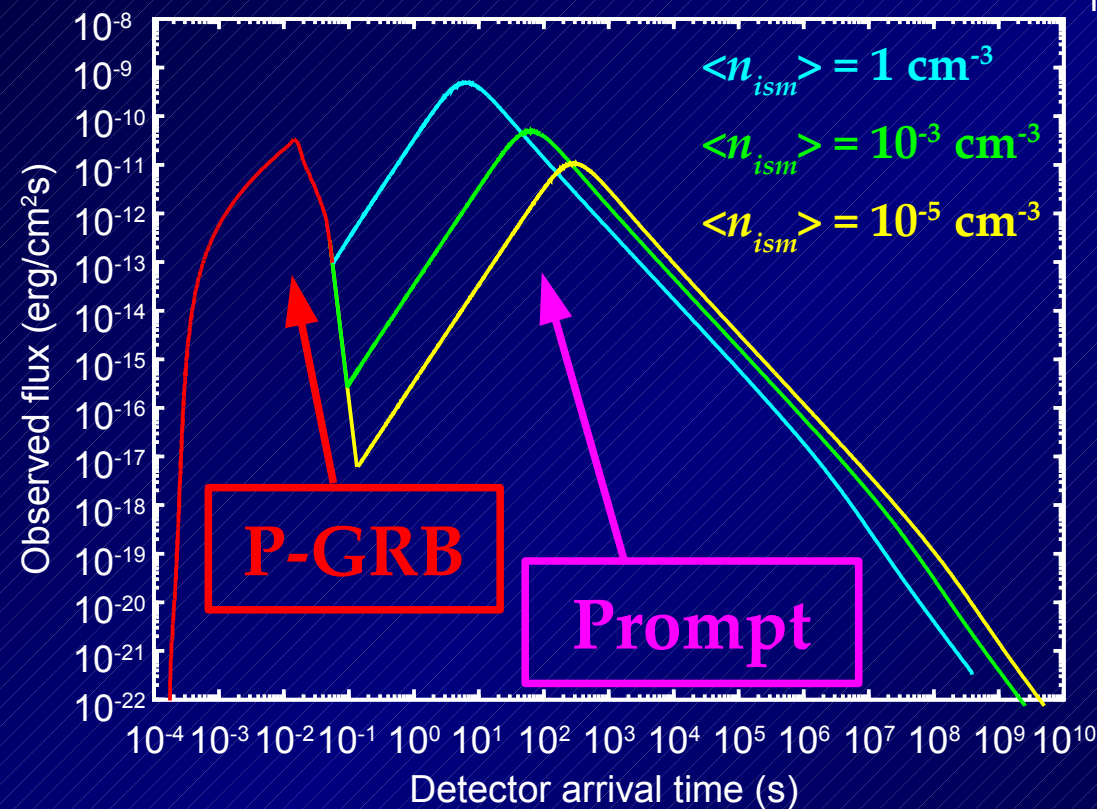
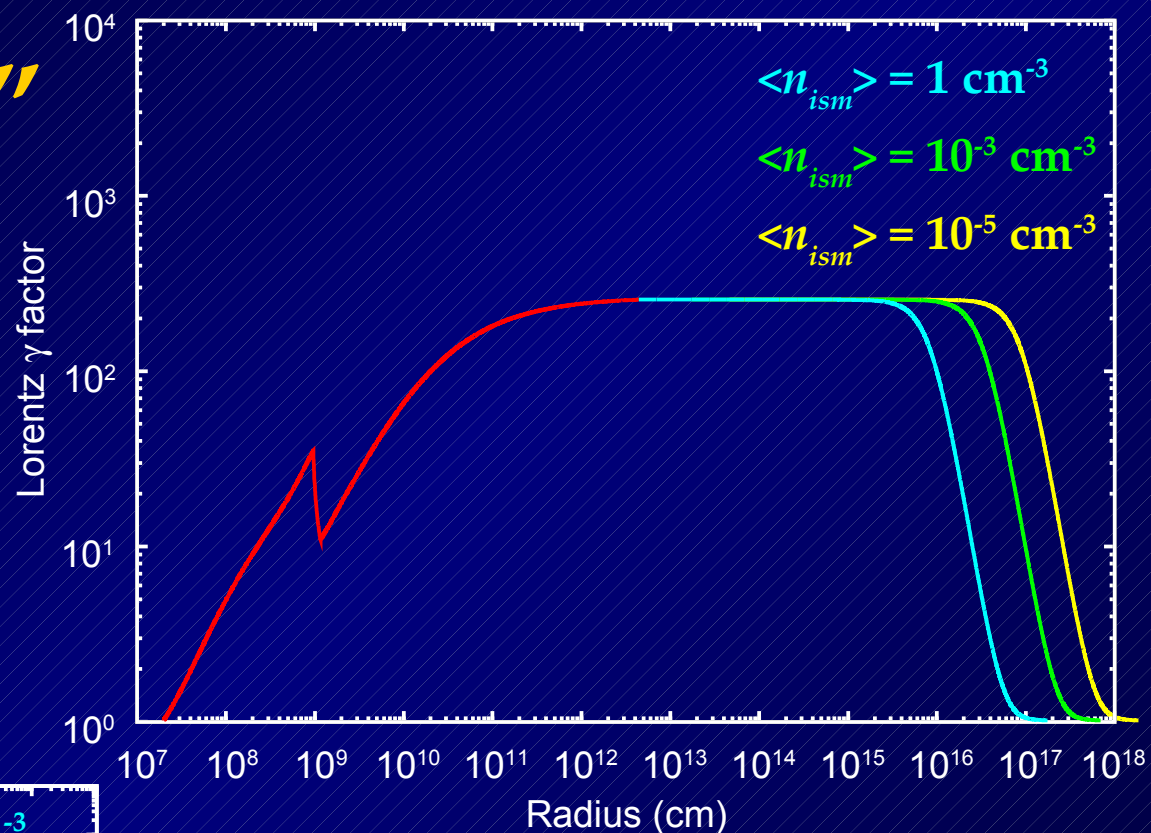
$$B \rightarrow 10^{-2}$$



"Long" GRBs

"Canonical GRB"

$$B \rightarrow 10^{-2}$$



"Long" GRBs
and/or
"Disguised short"
GRBs

Implications for the Amati relation

Bernardini, Bianco, Caito, Dainotti, Guida, Ruffini, *AIP Conf. Proc.*, 966, 7 (2008)

Caito, Amati, Bernardini, Bianco, De Barros, Izzo, Patricelli, Ruffini, *A&A*, in press, arXiv:1006.4842

Implications for the Amati relation

- The usually called “**prompt emission**” actually mixes together both the **P-GRB** and the peak of the **extended afterglow**. Being different physical phenomena, they must be analyzed separately.

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- The **Amati relation** *is fulfilled* only by the so-called “**long**” GRBs, i.e. the canonical GRBs in which the **P-GRB** is negligible and the “**prompt emission**” is dominated by the **extended afterglow**. Instead, *it is not fulfilled* by the “**short**” GRBs, i.e. the canonical GRBs in which the “prompt emission” is dominated by the **P-GRB**.

Implications for the Amati relation

- The usually called “**prompt emission**” actually mixes together both the **P-GRB** and the peak of the **extended afterglow**. Being different physical phenomena, they must be analyzed separately.
- The **Amati relation** *is fulfilled* only by the so-called “**long**” GRBs, i.e. the canonical GRBs in which the **P-GRB** is negligible and the “**prompt emission**” is dominated by the **extended afterglow**. Instead, *it is not fulfilled* by the “**short**” GRBs, i.e. the canonical GRBs in which the “prompt emission” is dominated by the **P-GRB**.
- In “**disguised**” short GRBs, therefore, the **Amati relation** must be fulfilled *only* by the **prolonged soft tail** (which is the **extended afterglow peak**) *alone*, but not by the **initial spikelike emission** (which is the **P-GRB**). This is a *key point* for the **identification** of this novel GRB class.

The “canonical GRB” scenario

Bernardini, Bianco, Caito, Dainotti, Guida, Ruffini, *A&A*, 474, L13 (2007)

Caito, Amati, Bernardini, Bianco, De Barros, Izzo, Patricelli, Ruffini, *A&A*, in press, arXiv:1006.4842

The “canonical GRB” scenario

$$B \leq 10^{-5}$$

The total time-integrated **P-GRB** luminosity is larger than the **extended afterglow** one.

“Genuine” short GRBs:

the **P-GRB** is the leading contribution to the emission and the **extended afterglow** is negligible.

Do not follow the “Amati” relation.

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“Genuine” short GRBs:

the **P-GRB** is the leading contribution to the emission and the **extended afterglow** is negligible.
Do not follow the “Amati” relation.

$$10^{-4} \leq B \leq 10^{-2}$$

The total time-integrated **P-GRB** luminosity is smaller than the **extended afterglow** one.

The “canonical GRB” scenario

$$B \leq 10^{-5}$$

The total time-integrated **P-GRB** luminosity is *larger* than the *extended afterglow* one.

“Genuine” short GRBs:

the **P-GRB** *is* the leading contribution to the emission and the *extended afterglow* is negligible.
Do not follow the “Amati” relation.

$$10^{-4} \leq B \leq 10^{-2}$$

The total time-integrated **P-GRB** luminosity is *smaller* than the *extended afterglow* one.

$$n_{\text{ism}} \sim 1 \text{ \#/cm}^3$$

Normal (“long”) GRBs:

(e.g. GRB 991216, GRB 050315, etc.).
Do follow the “Amati” relation.

The “canonical GRB” scenario

$$B \leq 10^{-5}$$

The total time-integrated **P-GRB** luminosity is *larger* than the *extended afterglow* one.

“Genuine” short GRBs:

the **P-GRB** *is* the leading contribution to the emission and the *extended afterglow* is negligible.
Do not follow the “Amati” relation.

$$n_{\text{ism}} \sim 10^{-3} \text{ \#/cm}^3$$

(compatible with a galactic halo environment)

“Disguised” short GRBs:

the **P-GRB** *appears to be* the leading contribution to the prompt emission because the *extended afterglow* is *deflated* by the small ISM density (e.g. GRB 970228, GRB 060614, etc.).
Only the prolonged soft tail alone follows the “Amati” relation.

$$10^{-4} \leq B \leq 10^{-2}$$

The total time-integrated **P-GRB** luminosity is *smaller* than the *extended afterglow* one.

$$n_{\text{ism}} \sim 1 \text{ \#/cm}^3$$

Normal (“long”) GRBs:

(e.g. GRB 991216, GRB 050315, etc.).
Do follow the “Amati” relation.