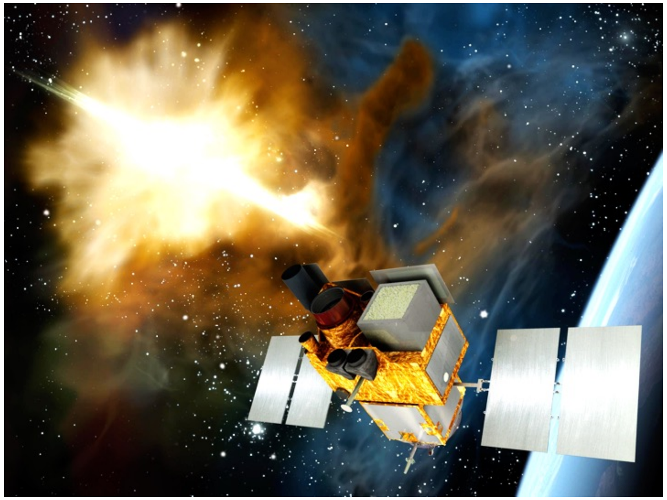
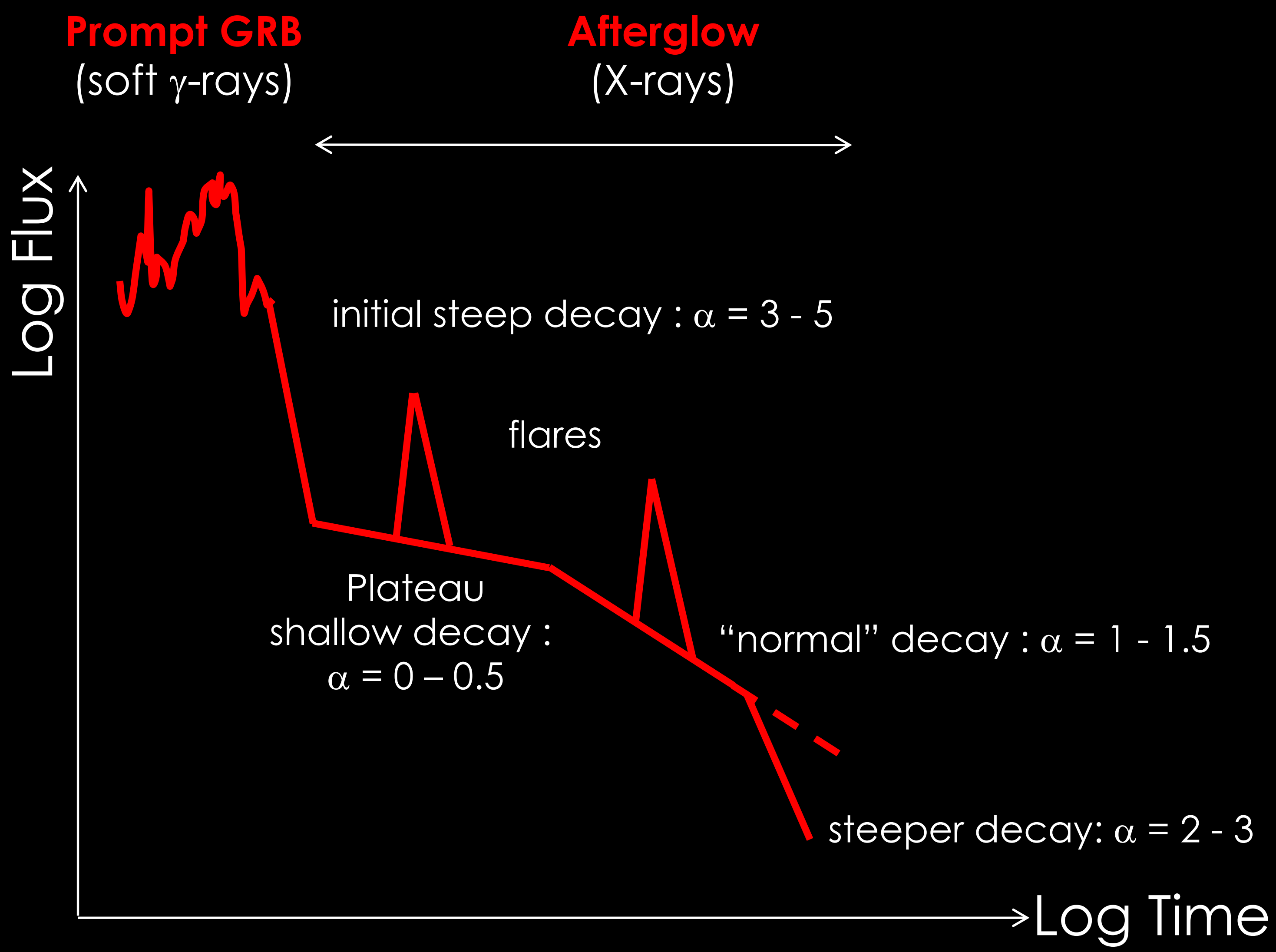
Interpretation/Modeling:
Prompt/afterglow emission / Population models

IAP, 6-7 May, 2024

Frédéric Daigne



GRB Lightcurves: prompt to afterglow



Prompt GRB
(soft γ-rays)

Afterglow
(X-rays)

initial steep decay : α = 3 - 5

flares

Plateau
shallow decay :
α = 0 – 0.5

“normal” decay : α = 1 - 1.5

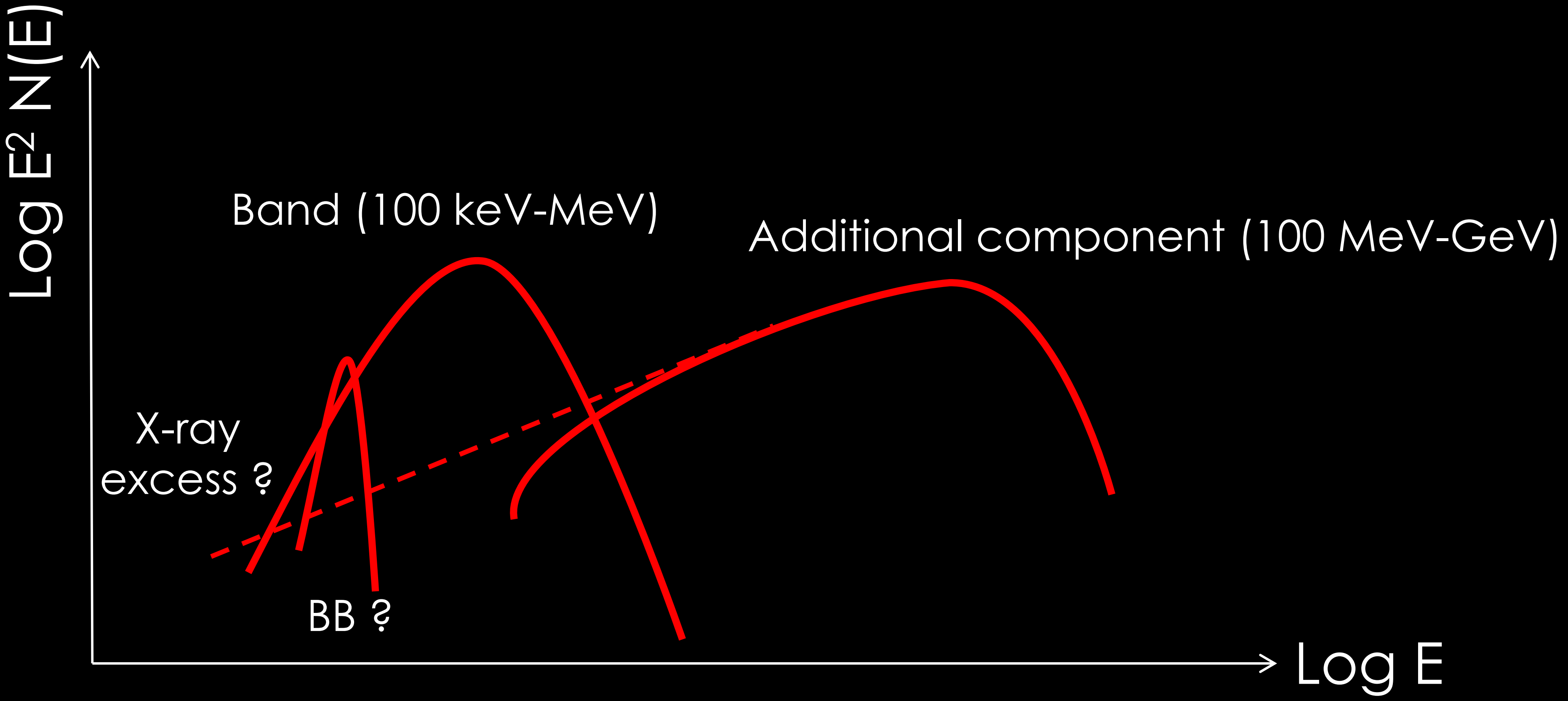
steeper decay: α = 2 - 3

Also: prompt
optical, GeV

Also: optical, radio afterglow
long-lasting Fermi/LAT emission

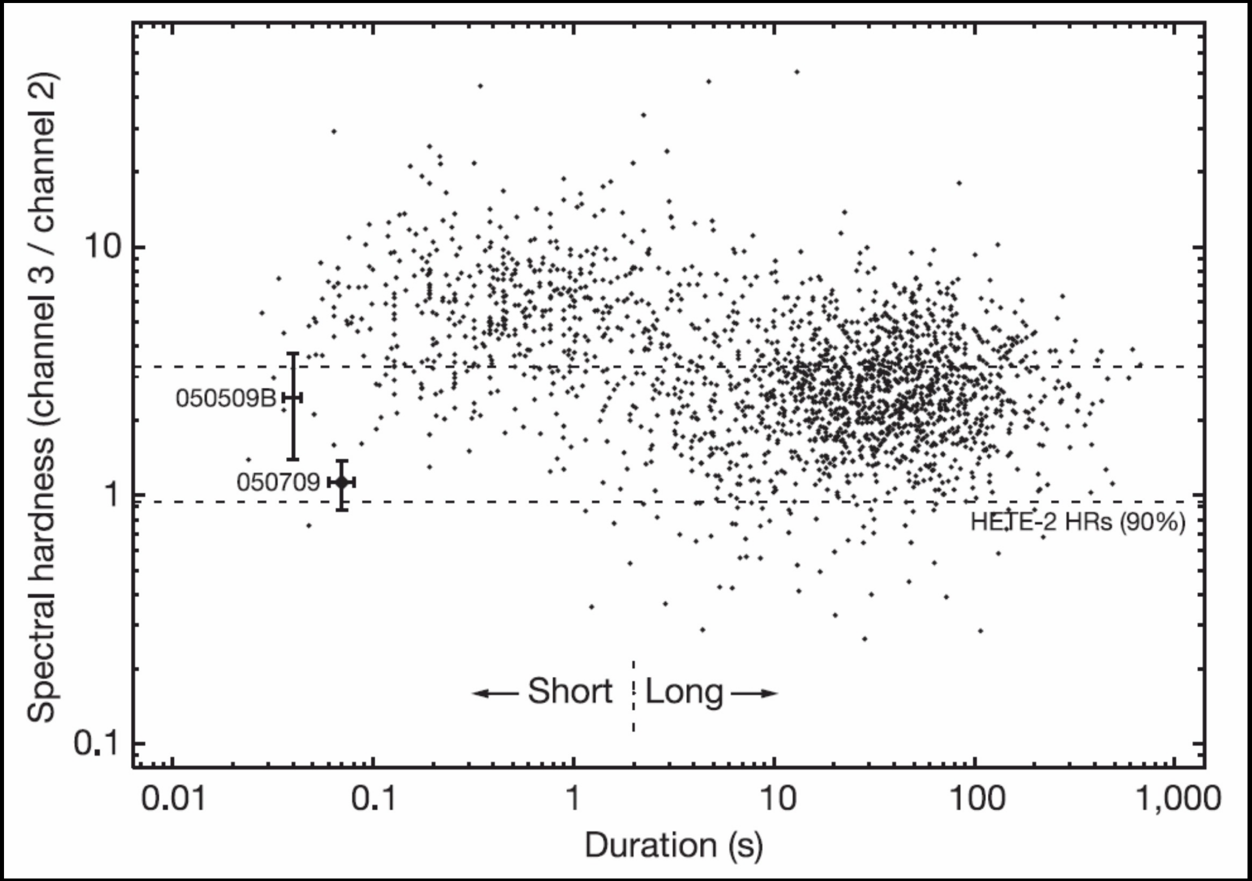
\+ VHE gamma-rays in a few cases (MAGIC, HESS, LHASSO)

GRB Spectrum: Prompt



GRB Spectrum: Afterglow = non-thermal, probably 2 components

GRB diversity: XRR, XRFs, Low-L GRBs, etc.

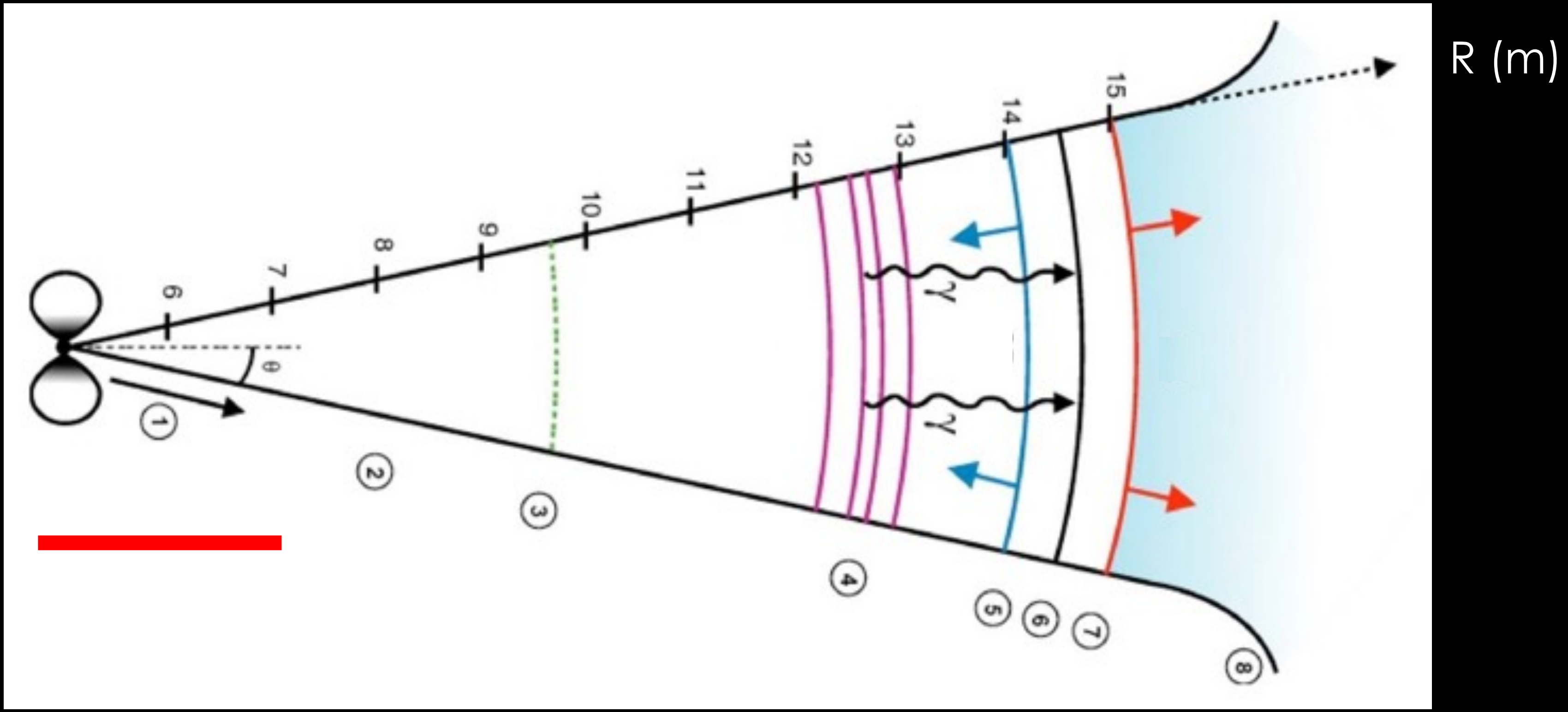


Hjorth et al. 2005

- **Short GRBs tend to be harder**, with some exceptions

- Long GRBs show a lot of diversity, with soft or very soft events, usually also weaker:
  X-ray Rich Bursts, X-Ray Flashes, Low-Luminosity Bursts, etc.
  Same physics/progenitors ? Importance of afterglow/host observations

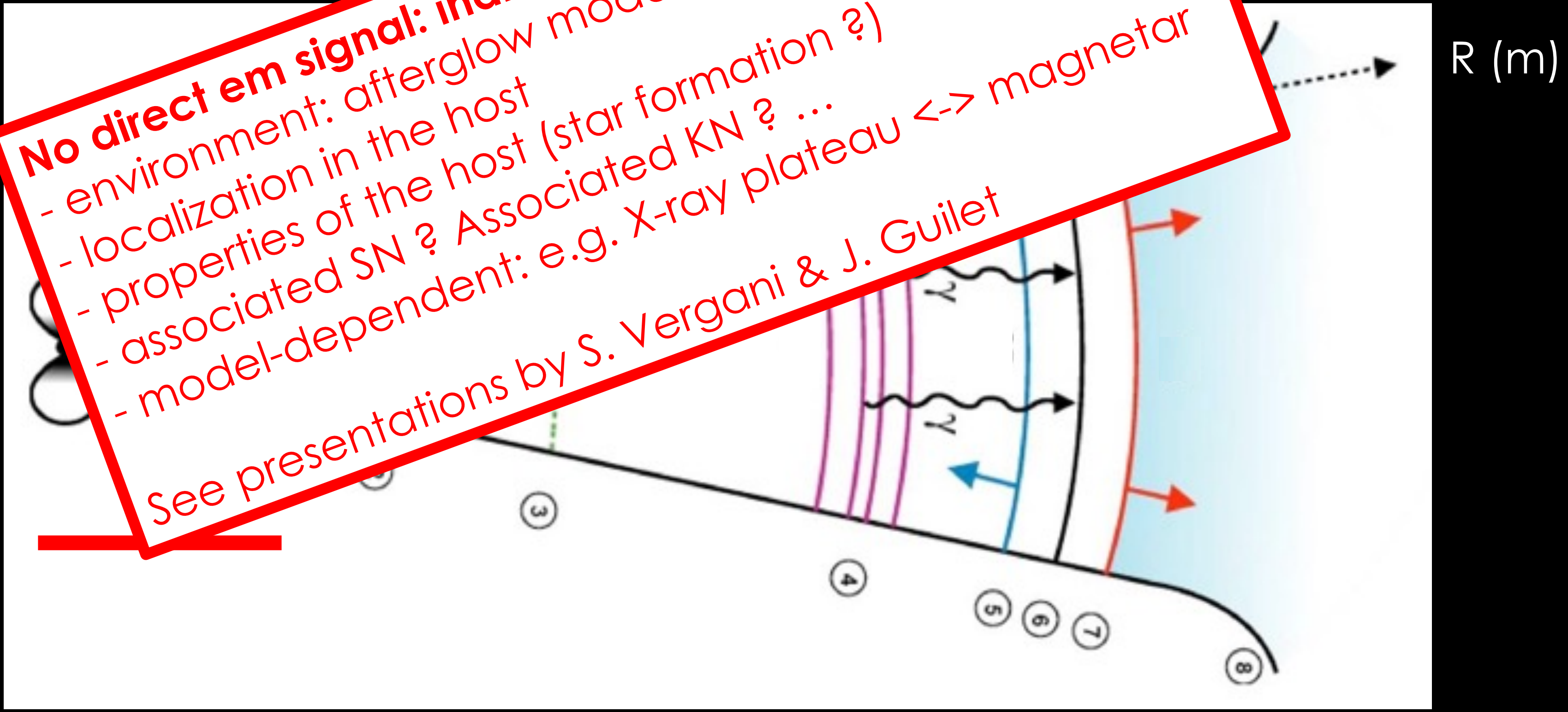
Initial event & central engine



Two main classes of progenitors:

- **Core-collapse of massive star (collapsar model) – « long » GRB**
- **Merger of binary neutron star system (or NSBH ?) – « short » GRB**

Initial event & central engine



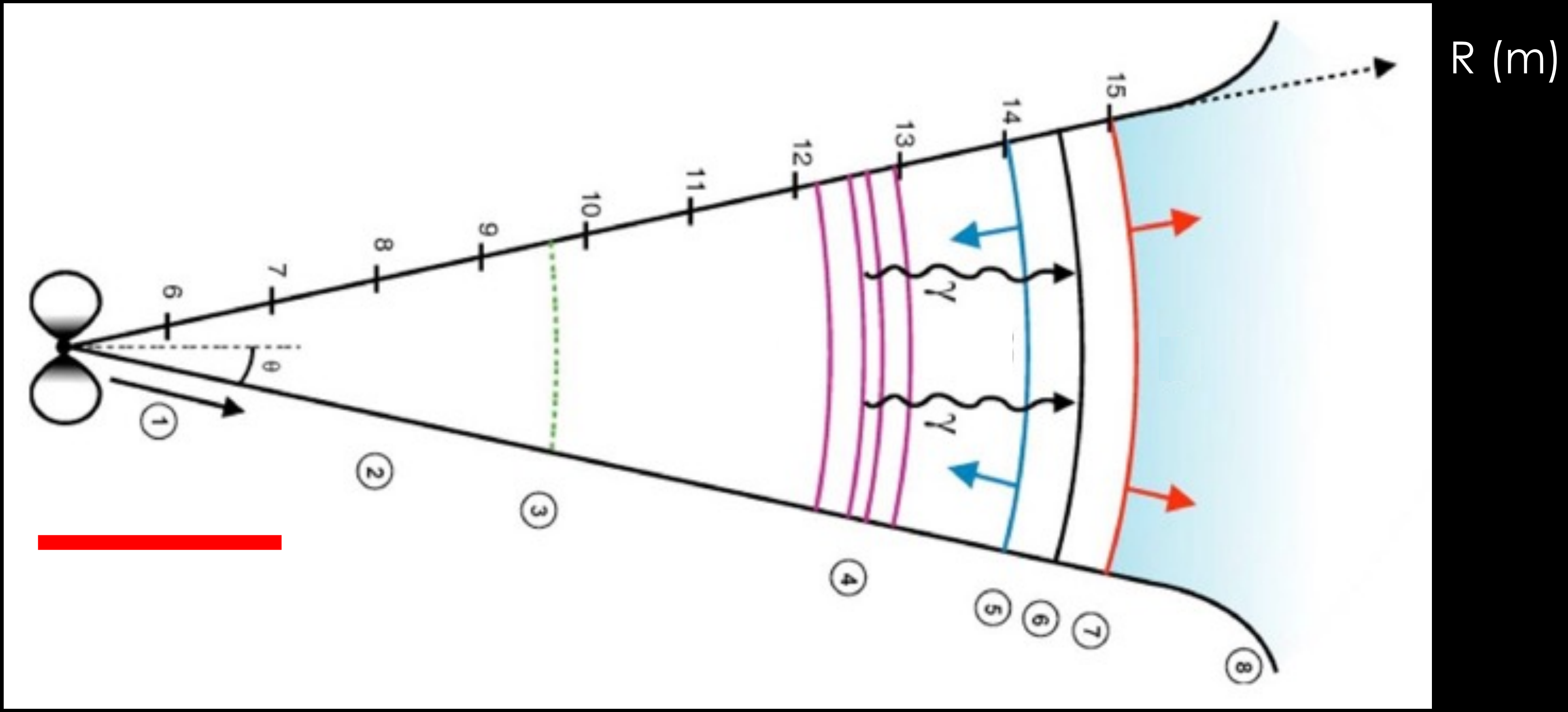
No direct em signal: indirect evidence
- environment: afterglow modelling / host observations
- localization in the host
- properties of the host (star formation ?)
- associated SN ? Associated KN ? …
- model-dependent: e.g. X-ray plateau <-> magnetar

See presentations by S. Vergani & J. Guilet

Two main classes of progenitors:
- Core-collapse of massive star (collapsar model) – « long » GRB
- Merger of binary neutron star system (or NSBH ?) – « short » GRB

Relativistic ejection

The GRB prompt emission has to be produced at large distance in a relativistic ejecta.

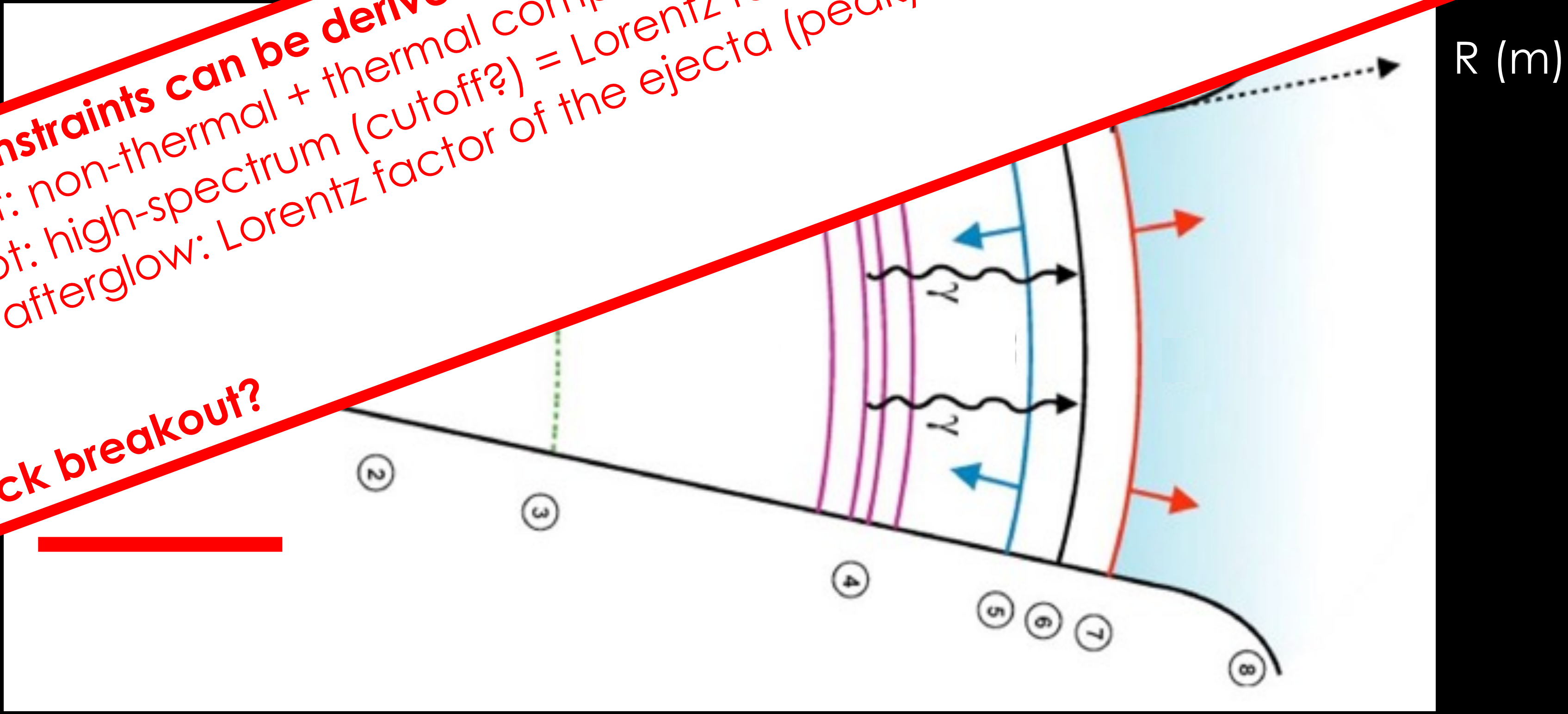


Relativistic ejection:

- Mechanism?
- Properties of the ejecta: Lorentz factor, geometry, magnetization, etc.

Relativistic ejection

The GRB prompt emission has to be prod tivistic ejecta.



Some constraints can be derived from observations:

- prompt: non-thermal + thermal components = composition of the ejecta
- prompt: high-spectrum (cutoff?) = Lorentz factor of the ejecta
- early afterglow: Lorentz factor of the ejecta (peak)
- etc.

Shock breakout?

Relativistic ejection:

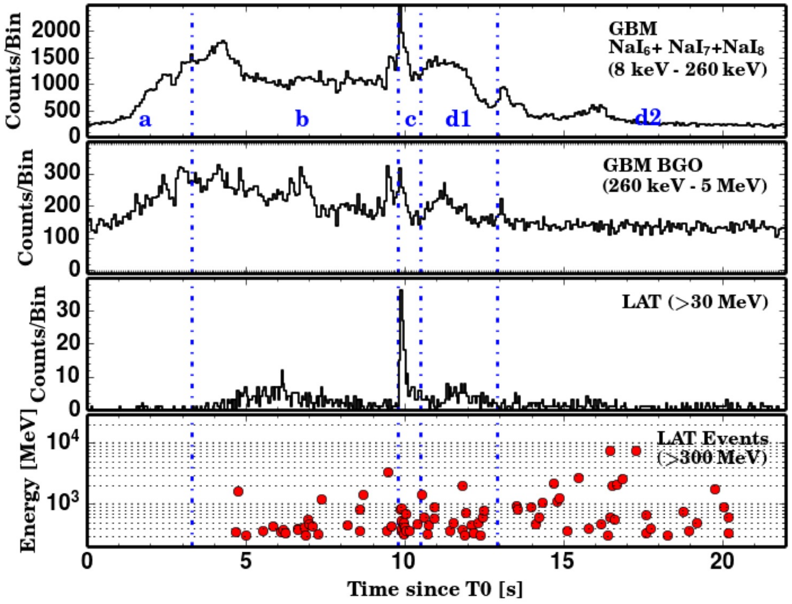
- Mechanism?
- Properties of the ejecta: Lorentz factor, geometry, magnetization, etc.

A few examples of such « simple » diagnostics (not involving a heavy physical modeling)

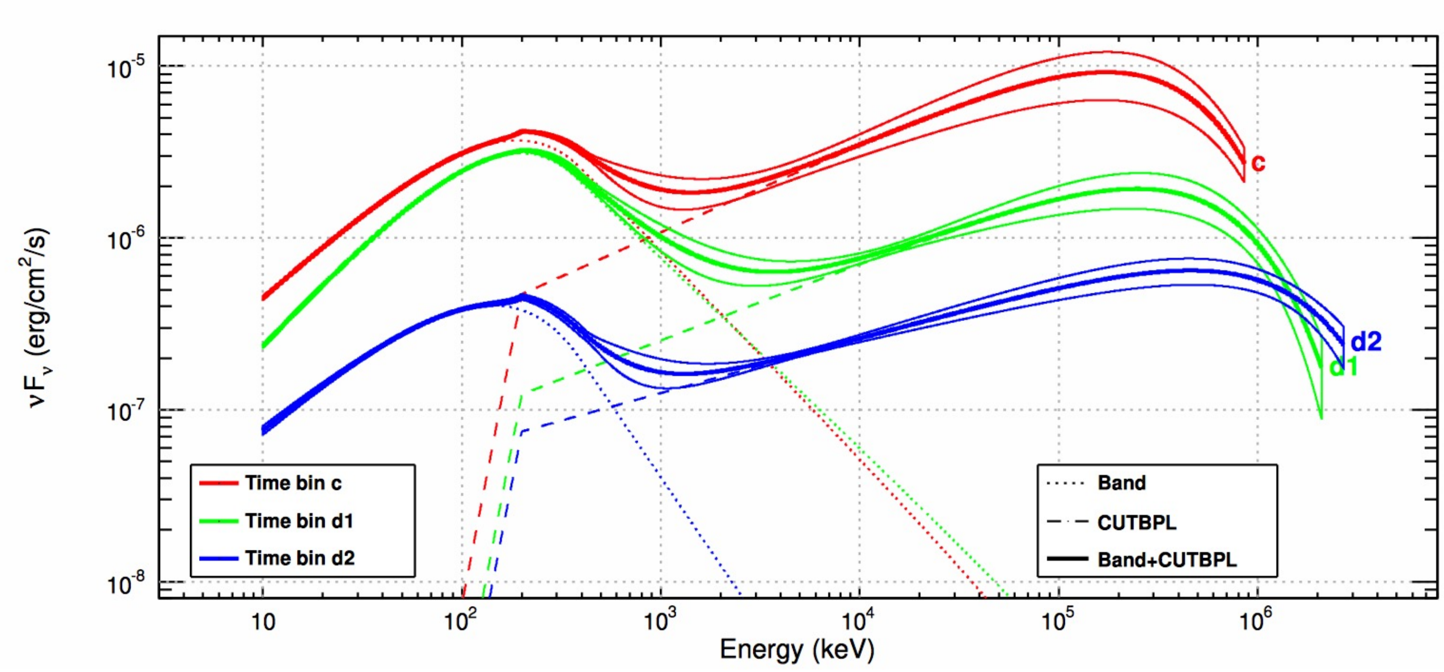
Exemple 1: constraints on the Lorentz factor & emission radius

- Fermi-LAT burst GRB 090926A:
  first observed cutoff at high-energy

- Analysis & interpretation: Yassine et al. [**FD**] 2017
  - time evolution of the cutoff



(Ackermann et al. 2011)



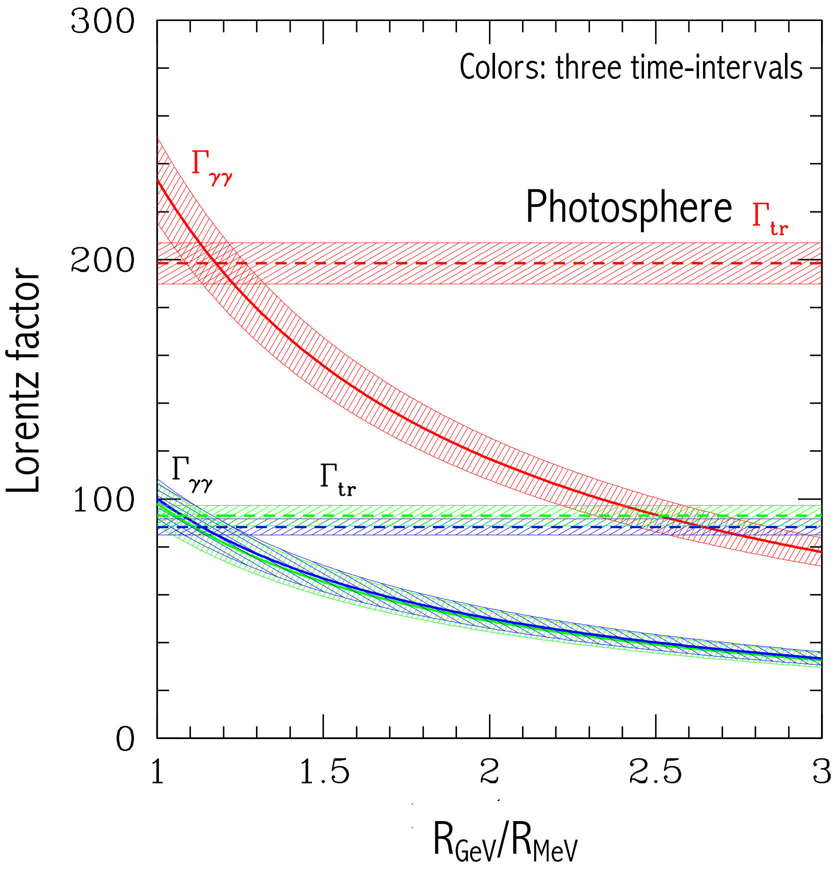
Yassine et al. [**FD**] 2017

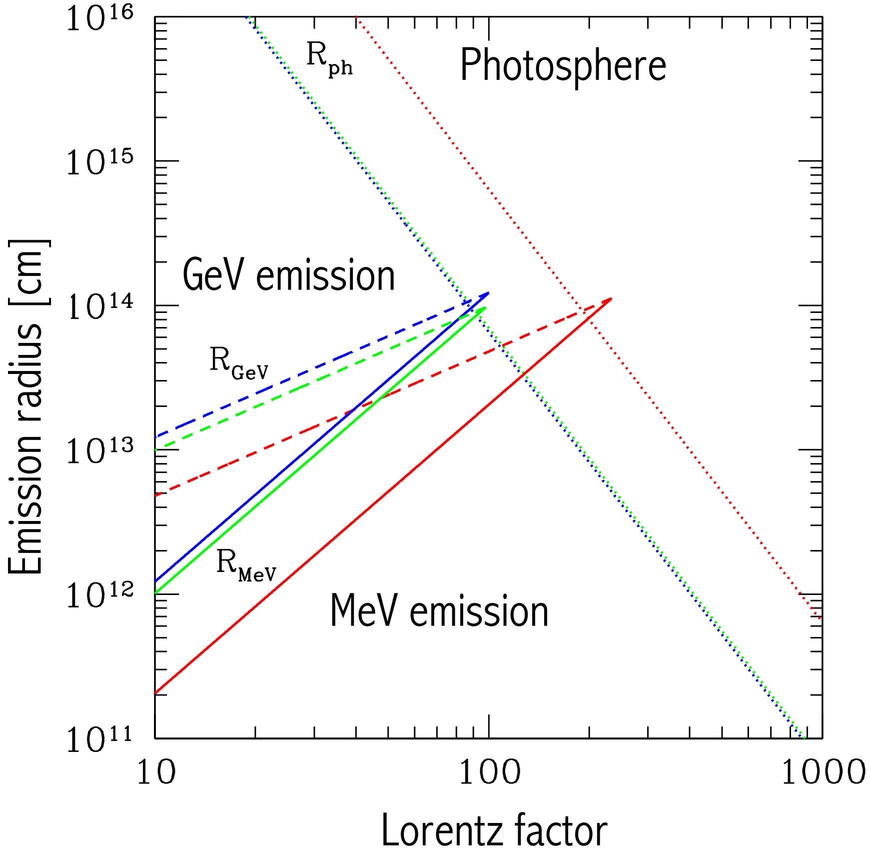
Exemple 1: constraints on the Lorentz factor & emission radius

- GRB 090926A: Analysis & interpretation: Yassine et al. [**FD**] 2017
  - time evolution of the cutoff
  - a natural explanation for the cutoff: $\tau_{\gamma\gamma}(E_{\rm cutoff}) \sim 1$

    detailed calculation: Hascoët et al. [**FD**] 2012

    result: strong constaint on the Lorentz factor and emission radius





Yassine et al. [**FD**] 2017

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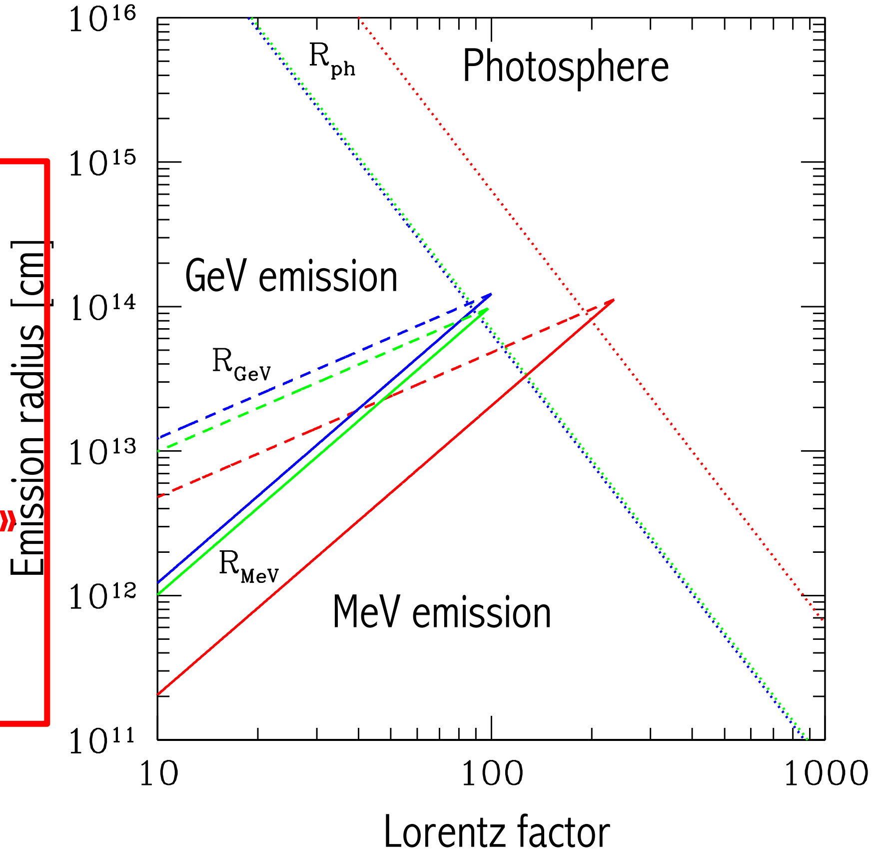
  result: strong constaint on the Lorentz factor and emission radius

Lorentz factor ~ 230 to 100

Emission radius ~ 10^{14} cm

Photospheric radius ~5 10^{13} cm

Compatible with « standard scenario »
(internal shocks/reconnection
above the photosphere)



Yassine et al. [**FD**] 2017

Exemple 1: constraints on the Lorentz factor & emission radius

- **In cases without a detected HE cutoff (usual case):**
  A lower limit on the Lorentz factor of the ejecta can be obtained.

What is needed: Sari & Lithwick 2001, Hascoet et al. [FD] 2012

- Variability timescale
- Spectral shape
- Redshift

$$\Gamma_{\rm min} \simeq \frac{\left[C_1 2^{1+2\beta}\mathcal{I}(\beta)\right]^{1/2(1-\beta)}}{\left[\frac{1}{2}\left(1+\frac{R_{\rm GeV}}{R_{\rm MeV}}\right)\left(\frac{R_{\rm GeV}}{R_{\rm MeV}}\right)\right]^{1/2}}\,(1+z)^{-(1+\beta)/(1-\beta)} \times\left\{\sigma_{\rm T}\left[\frac{D_{\rm L}(z)}{c\Delta t_{\rm var}}\right]^2 E_{\rm c}F(E_{\rm c})\right\}^{1/2(1-\beta)}\left[\frac{E_{\rm max}E_{\rm c}}{(m_{\rm e}c^2)^2}\right]^{(\beta+1)/2(\beta-1)}, \tag{59}$$

Exemple 2: constraints on the ejecta composition

- **A diagnostic can be applied in cases where the soft gamma-ray spectrum shows evidence for two components: a non-thermal component and a quasi-thermal one.**

- Required measurements:
  - flux and temperature of the quasi-thermal component
  - flux ratio non-thermal/thermal

- **Fireball model: leads to a measurement of the Lorentz factor and initial radius**
  Sari & Lithwick 2007 **= strongly model-dependent.**

- **General assumptions:** Hascoët, Daigne & Mochkovitch 2012
  - **When the ejecta is launched: energy = fraction ϵ_{th} thermal**
    fraction $1-\epsilon_{\mathrm{th}}$ magnetic
  - **Large distance: magnetization σ**
    Passive field: $\sigma_{\mathrm{passive}} = (1-\epsilon_{\mathrm{th}})/\epsilon_{\mathrm{th}}$, **efficient magnetic acc.** $\sigma < \sigma_{\mathrm{passive}}$
  - **Non-thermal emission has an efficiency** f_{NTh}

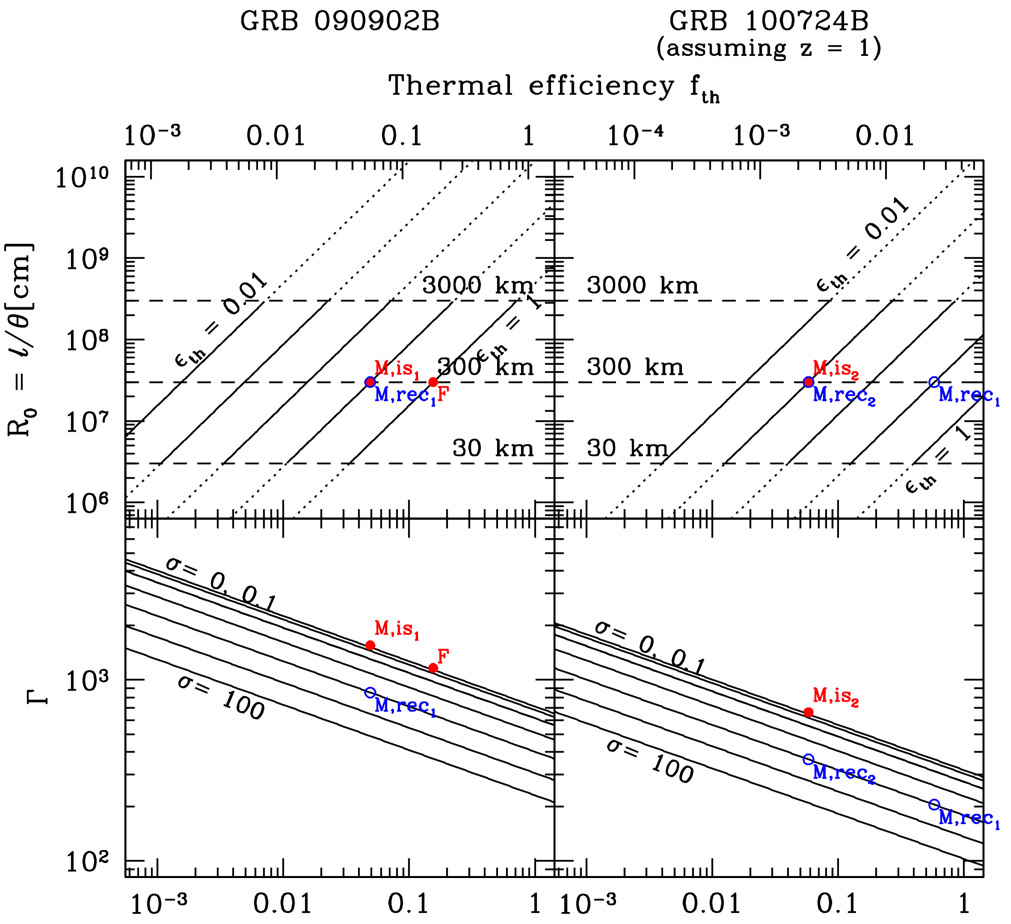
- **Analysis allows to derive a constraint on some of these parameters.**

Ejecta composition from the thermal/non-thermal ratio

Hascoet, Daigne & Mochkovitch 2013

Initial Radius

Lorentz factor



Non-thermal efficiency f_{Nth}

GRB 090902B: a rare case where the quasi-thermal component could be dominant.

GRB100724B: a bright GRB where the presence of a quasi-thermal component can be constrained.

Here: constraints obtained for
- a given non-thermal efficiency (x-axis),
- and a given initial thermal fraction and large-scale magnetization (lines).

F = fireball
M,is = internal shocks (low sigma)
M,rec = reconnection (high sigma)

Fig. 5. Constraints on the thermal and non-thermal emission in GRB 090902B and GRB 100724B. *Top:* for a given thermal fraction $\epsilon_{th} = 10^{-2}$, $10^{-1.5}$, 10^{-1}, $10^{-0.5}$, and 1, the radius $R_0 = \ell/\theta$ at the base of the flow is plotted as a function of the non-thermal efficiency f_{Nth}. The corresponding thermal efficiency f_{th} is also shown (top x-axis). *Bottom:* for a given magnetisation $\sigma = 10^{-1}$, $10^{-0.5}$, 1, $10^{0.5}$, 10^{1}, $10^{1.5}$, and 10^{2} at the end of acceleration phase, the Lorentz factor of the flow is plotted as a function of f_{Nth} (the unmagnetised case $\sigma = 0$ cannot be distinguished from the case $\sigma = 0.1$). Sets of parameters representative of the different classes of scenarios discussed in the paper are indicated: F ($\epsilon_{th} = 1$, $\sigma = 0$) (standard fireball), M,is$_1$ ($\log \epsilon_{th} = -0.5$, $\sigma = 0$,) and M,is$_2$ ($\log \epsilon_{th} = -1.5$, $\sigma = 0$) (efficient magnetic acceleration: magnetisation is low above the photosphere and the dominant non-thermal mechanism is internal shocks), M,rec$_1$ ($\log \epsilon_{th} = -0.5$, $\sigma = 10$), and M,rec$_2$ ($\log \epsilon_{th} = -1.5$, $\sigma = 10$) (magnetised flow at large distance, the dominant non-thermal mechanism is magnetic reconnection). The initial radius is fixed to $R_0 = 300$ km, a typical value for long GRBs. The observational data (thermal flux, temperature, ratio of the thermal over the total flux) used for the calculation (see text) are taken from Abdo et al. (2009); Pe'er et al. (2012) for GRB 090902B (*left column*), and from Guiriec et al. (2011) for GRB 100724B (*right column*).

09092B: $\epsilon_{th} > 0.3 - 0.5$

100724B: is or rec with low $\epsilon_{th} < 0.1$

Exemple 3: Lorentz factor from the peak of the optical afterglow

- Model dependent: standard afterglow model (forward external shock) with some assumptions (efficiency of the prompt emission, ambient density, …)

  peak = deceleration time $T_{\rm p} \simeq T_{\rm dec} \simeq \frac{R_{\rm dec}}{2\Gamma_{\rm bw}^2 c}.$ (OK if $T_{\rm p} \gg T_{\gamma}.$: NR RS)

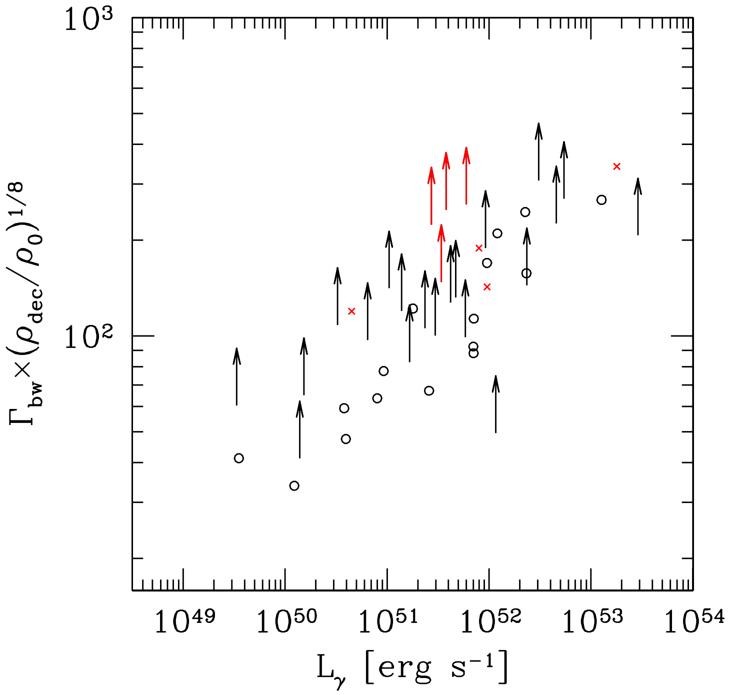
- Early afterglow with a detection of the peak: blast wave Lorentz factor

$$\Gamma_{\rm bw} = \left[\frac{3-s}{32\pi c^5}\,\frac{1-\eta}{\eta}\,\frac{E_\gamma}{\rho_{\rm dec} T_{\rm p}^3}\right]^{\frac{1}{8}}$$

see e.g. Molinari, Vergani et al. 2007, Ghirlanda et al. 2012

- Upper limit on the peak time: lower limit on the Lorentz factor

- With a rich data set starting early, a full AG modelling is possible: constraints on Lorentz factor, density, prompt efficiency = a good science case for SVOM



Hascoët, Beloborodov, Daigne & Mochkovitch 2014

Figure 2. Estimated Lorentz factor of the GRB blast wave, $\Gamma_{\rm bw}$, at the deceleration radius. The product $\Gamma_{\rm bw}\ \rho_{\rm dec}{}^{1/8}$ is estimated using Equation (5) (with $\eta = 0.5$) and shown vs. the burst luminosity L_γ (Equation (2)). The ambient density at the deceleration radius, $\rho_{\rm dec}$, is normalized to $\rho_0/m_{\rm p} = 1\ {\rm cm}^{-3}$. Bursts with $T_{\rm p} < T_\gamma$ are highlighted in red; for these bursts the ejecta Lorentz factor Γ can be substantially higher than $\Gamma_{\rm bw}$ (see text).

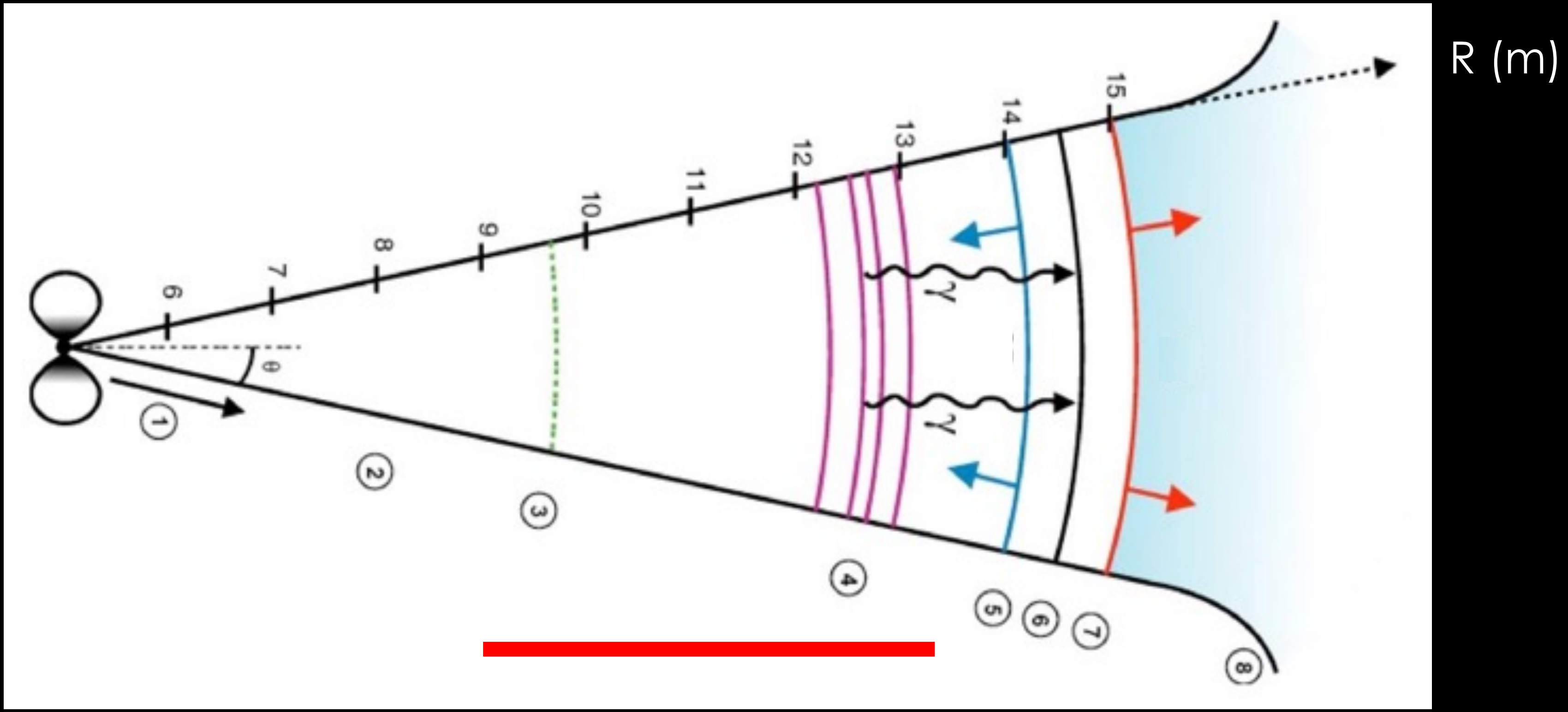
(A color version of this figure is available in the online journal.)

A word of caution:

- **These diagnostics are never 100% model-independent**
- **Lower limit on the Lorentz factor from gamma gamma: robust**
- **Measurement of the Lorentz factor from the HE cutoff: less robust**
  (e.g. the cutoff could be some curvature due to the natural shape of the HE component)
- **Constrain on the initial thermal content of the ejecta: partially model dependent**
  (valid only in scenarios with a non-dissipative photosphere)
- **Measurement of the Lorentz factor from the peak of the early visible afterglow**
  (standard afterglow model + some assumptions on the prompt efficiency,
  the external density)

Prompt emission

Observed short timescale/non-evolving variability in GRB lightcurves imply an internal dissipation in the ejecta (Sari & Piran 1997a,b).

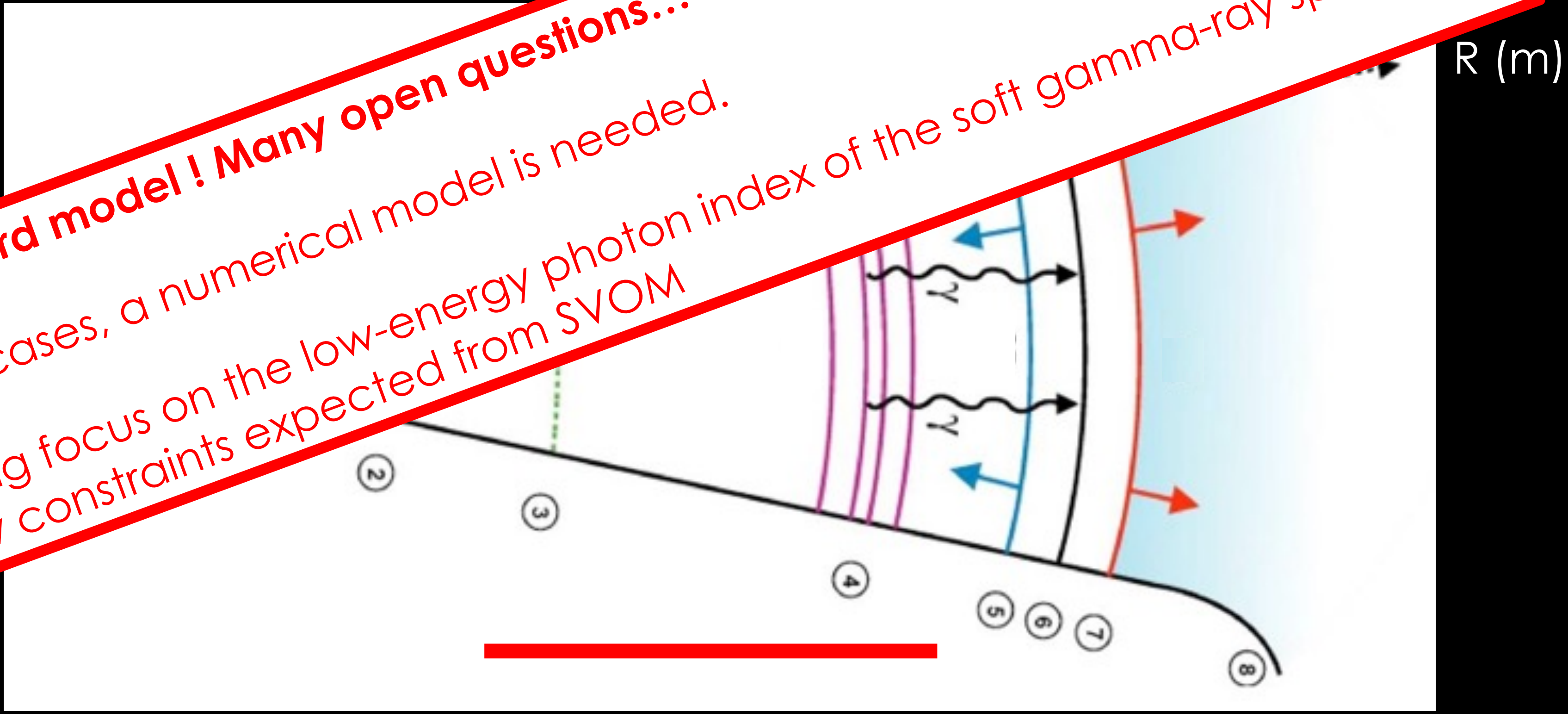


Internal dissipation / radiation processes:

- (Dissipative) Photosphere? (thermal + comptonization)
- Internal shocks? (synchrotron + IC)
- Reconnection? (synchrotron + IC)

Prompt emission

Observed short timescale/non-evolving variability in G… …n internal dissipation in the ejecta (Sari & Piran 1…



No standard model ! Many open questions…

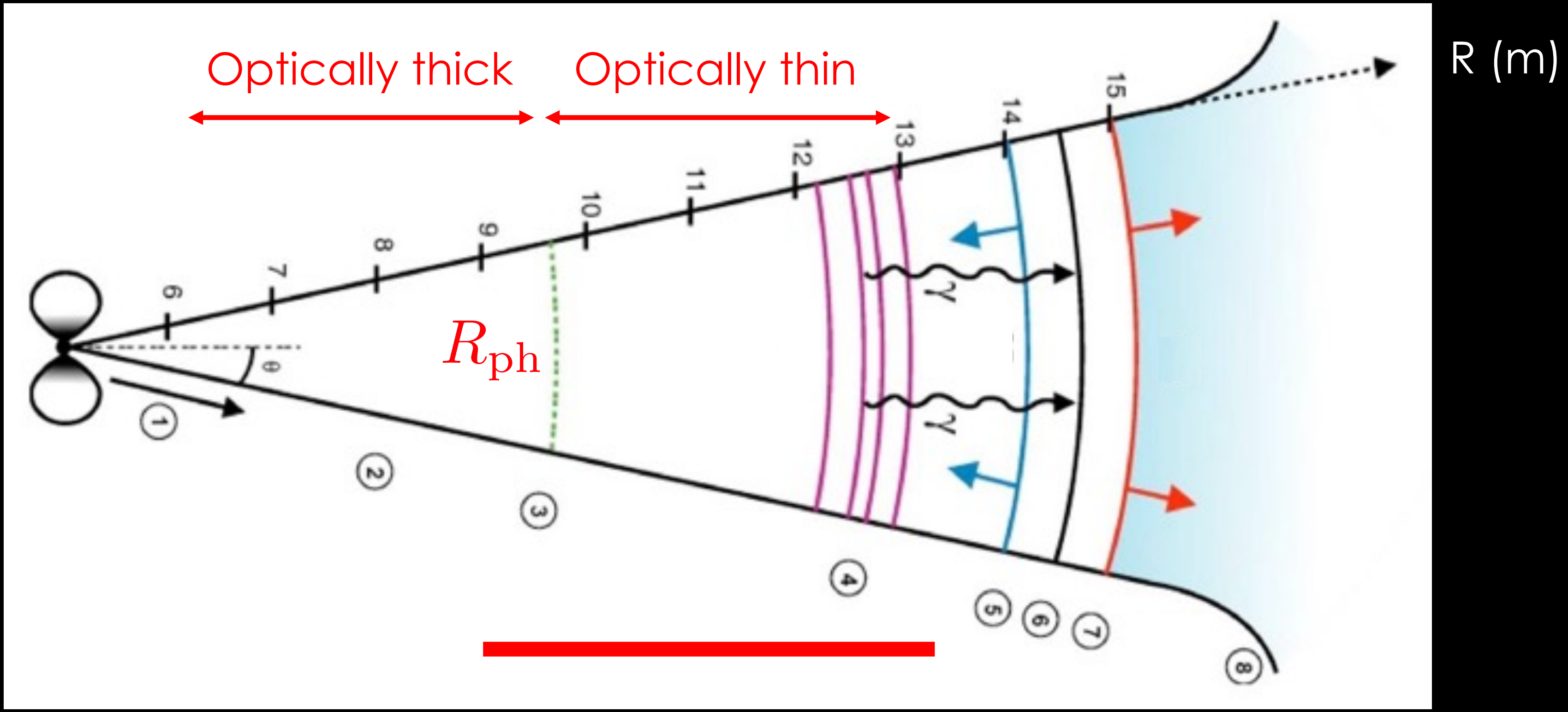
In most cases, a numerical model is needed.

A strong focus on the low-energy photon index of the soft gamma-ray spectrum
= new constraints expected from SVOM

Internal dissipation / radiation processes:
- (Dissipative) Photosphere? (thermal + comptonization)
- Internal shocks? (synchrotron + IC)
- Reconnection? (synchrotron + IC)

Photosphere

At the photospheric radius, the ejecta becomes transparent to its own radiation.



Photospheric emission:

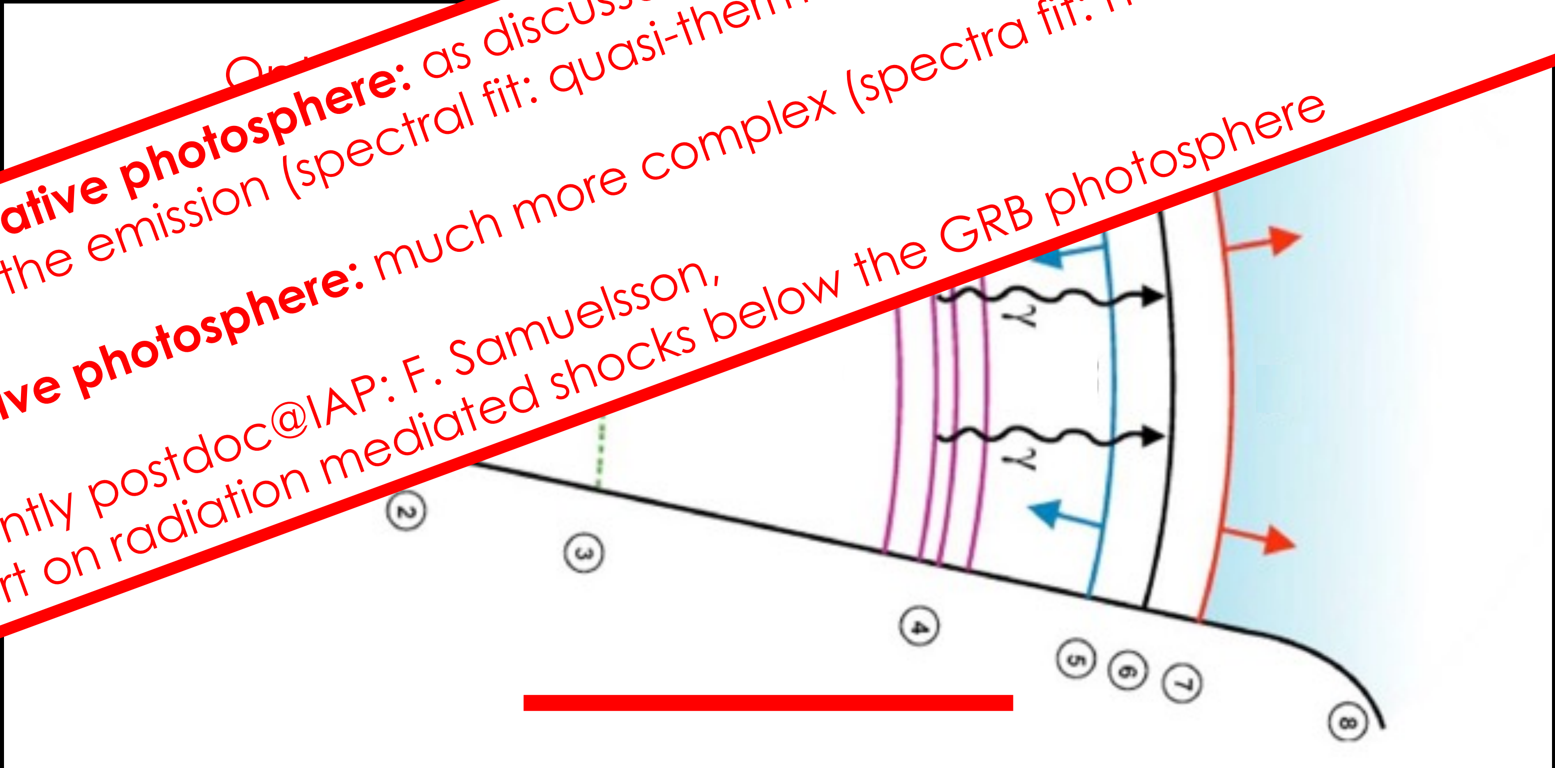
- non-dissipative photosphere: thermal (Paczynski, Peer, Beloborodov, …)
- dissipative photosphere: non-thermal (Rees & Meszaros, Beloborodov, …) dissipation? shocks (radiation mediated shocks, see e.g. Samuelsson), reconnection (see e.g. Giannios), other?

Photosphere

At the photospheric radius, the ejecta become

adiation.

R (m)



Non-dissipative photosphere: as discussed above, simple tools are available to model the emission (spectral fit: quasi-thermal component)

Dissipative photosphere: much more complex (spectra fit: non-thermal)

(currently postdoc@IAP: F. Samuelsson, expert on radiation mediated shocks below the GRB photosphere

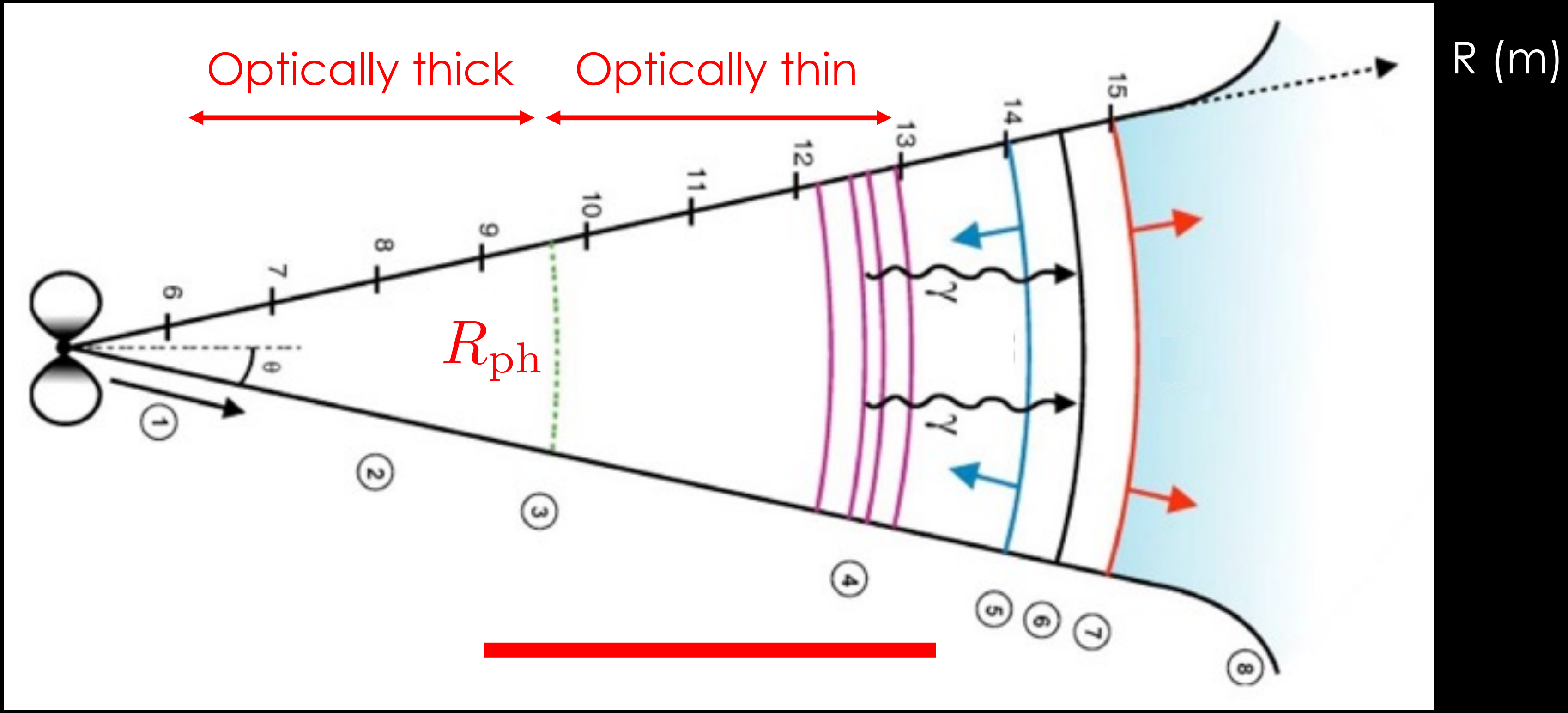
Photospheric emission:

- non-dissipative photosphere: thermal (Paczynski, Peer, Beloborodov, …)
- dissipative photosphere: non-thermal (Rees & Meszaros, Beloborodov, …)
  dissipation? shocks (radiation mediated shocks, see e.g. Samuelsson), reconnection (see e.g. Giannios), other?

Dissipation in the optically thin regime

Reference model: internal shocks (electron acceleration in mildly relativistic collisionless shocks?) [low magnetization at large distance]

Alternative: reconnection (electron acceleration ?) [low magnetization at large distance]



Radiation: synchrotron + Inverse Compton Scatterings in both cases

Dissipation in the optically thin regime

Reference model: internal shocks (electron acceleration in mildl
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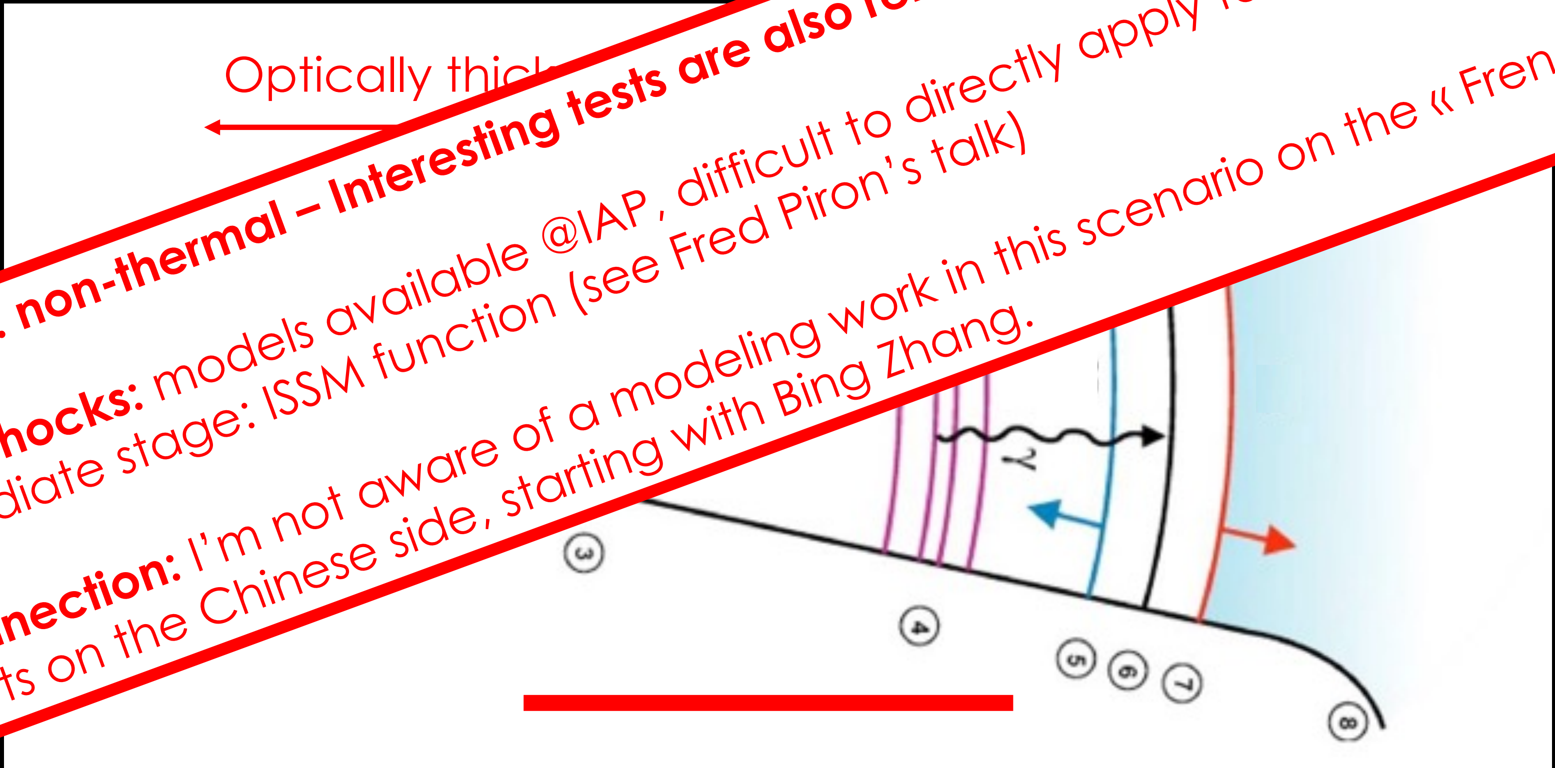
Alternative: reconnection (electron acceleration ?) [
distance]



Spectral fit: non-thermal – Interesting tests are also related to the temporal evolution.

Internal shocks: models available @IAP, difficult to directly apply to fit data
Intermediate stage: ISSM function (see Fred Piron's talk)

Reconnection: I'm not aware of a modeling work in this scenario on the « French » side.
Experts on the Chinese side, starting with Bing Zhang.

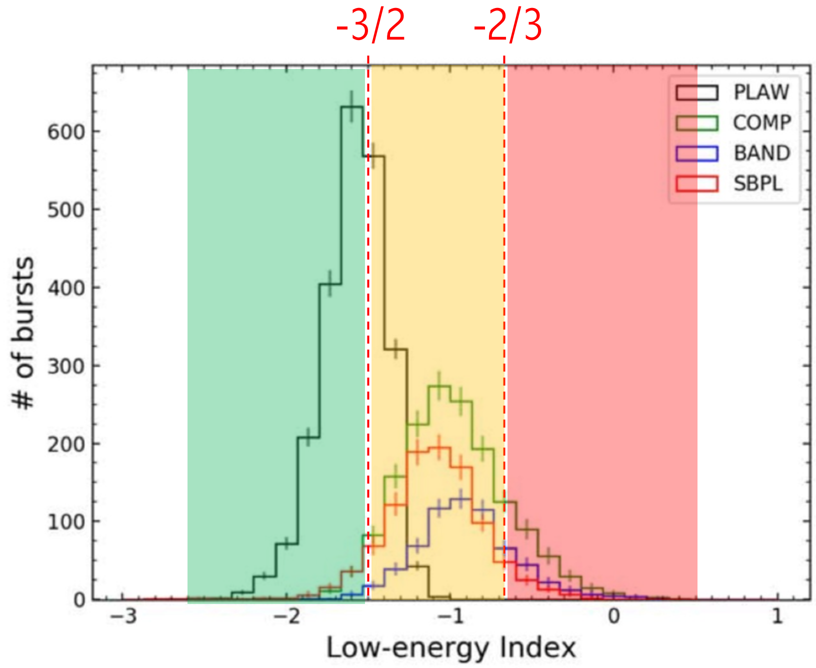
Radiation: synchrotron + Inverse Compton Scatterings in both cases

Just an example: modelling the synchrotron
spectrum in the optically thin regime

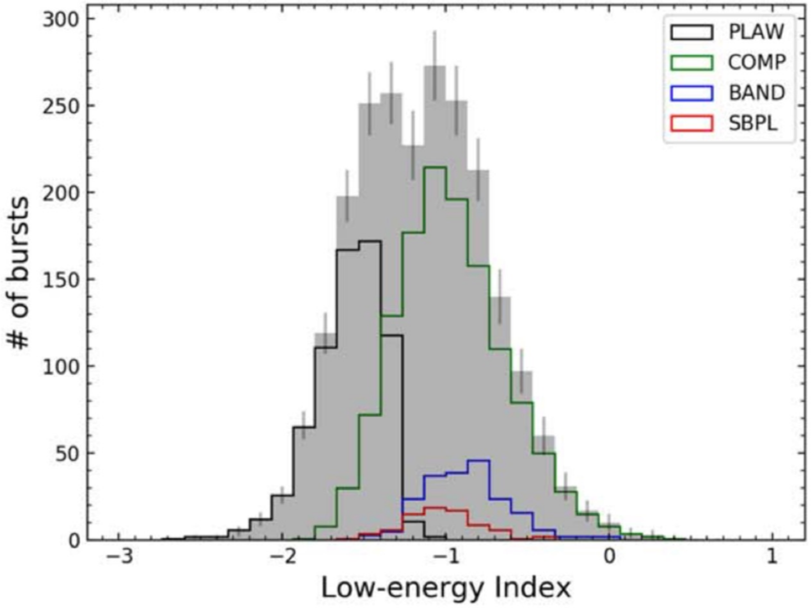
= the dominant process expected above the photosphere
(standard prediction in fast cooling regime: alpha = -3/2)

Band function

- **Fermi/GBM spectral catalog:** (10 years: Poolakkil et al. 2021)
  - 2297 GRBs
  - Time-integrated spectra / Spectrum at peak flux
  - **Low-energy photon index:**



« GOOD » sample:

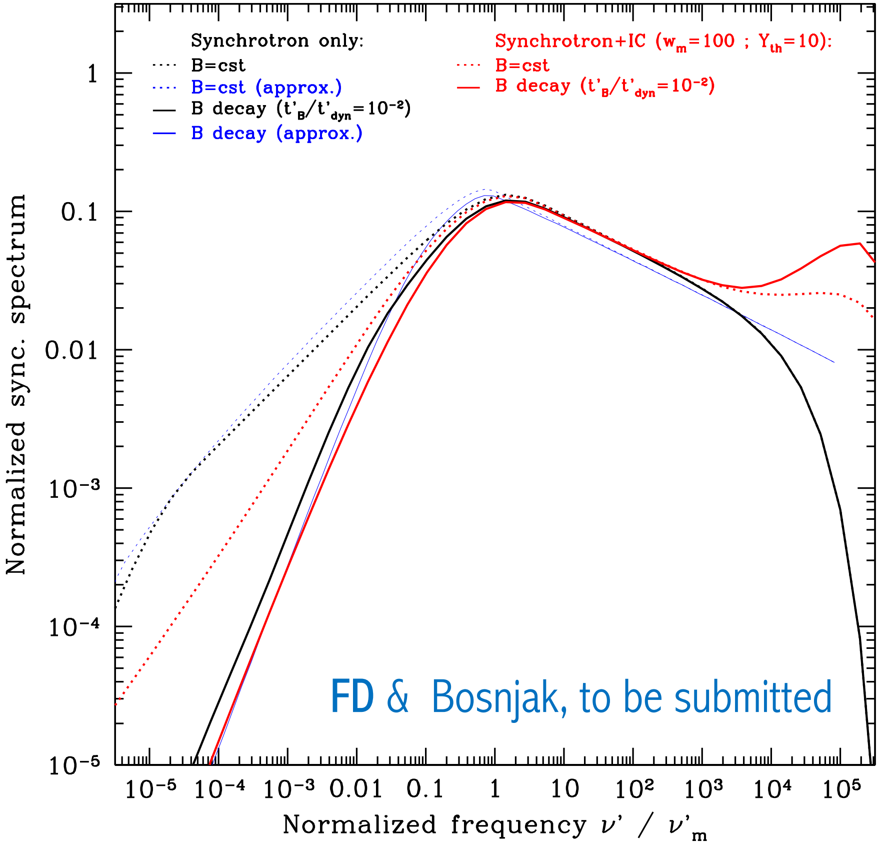


« BEST » sample

- **Robustness of the spectral analysis: see Fred Piron’s presentation…**

Effects of SSC and of a B decay on syn+SSC radiation

- Low-energy photon index of the synchrotron spectrum:
  - SSC in Klein-Nishina regime: $\alpha = -3/2$ to -1
  - B decay on an intermediate scale between the electron radiative timescale and the dynamical timescale: $\alpha = -3/2$ to $-2/3$



FD & Bosnjak, to be submitted

Full modelling: coupling the radiative model to the dynamics of the ejecta

Much more complex: not shown here. Advantage: spectral and temporal properties.

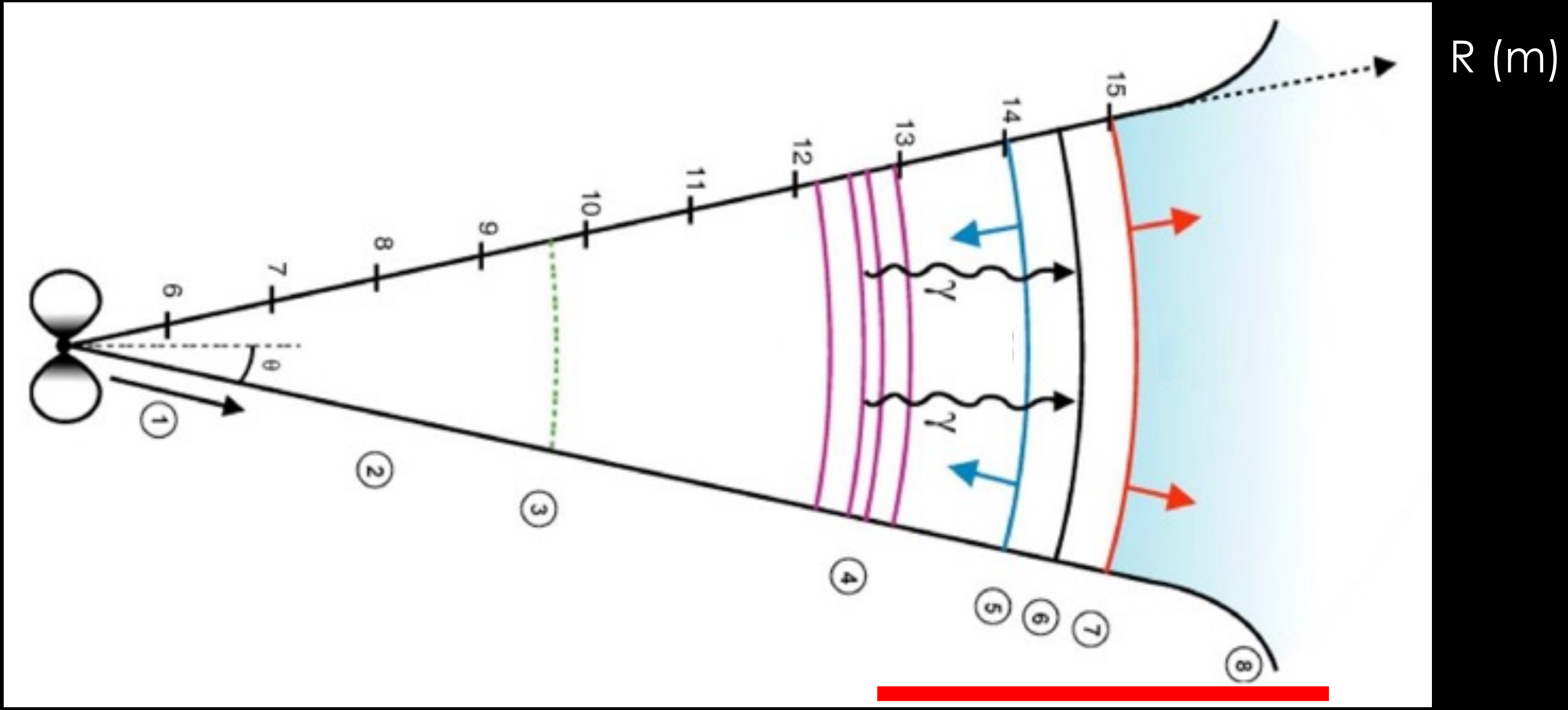
- IAP: tools available for internal shocks, can not be used to directly fit data (too heavy) = intermediate step = ISSM, see Fred Piron's presentation

- IAP: towards a hybrid model, with internal shocks starting below the photosphere (radiation mediated shocks) and still propagating above it (standard internal shocks): long term project with Filip Samuelsson.

- Reconnection models: Bing Zhang et al.
- Shock breakouts? (may be useful to study low-L/soft GRBs)
- Other models?

Afterglow

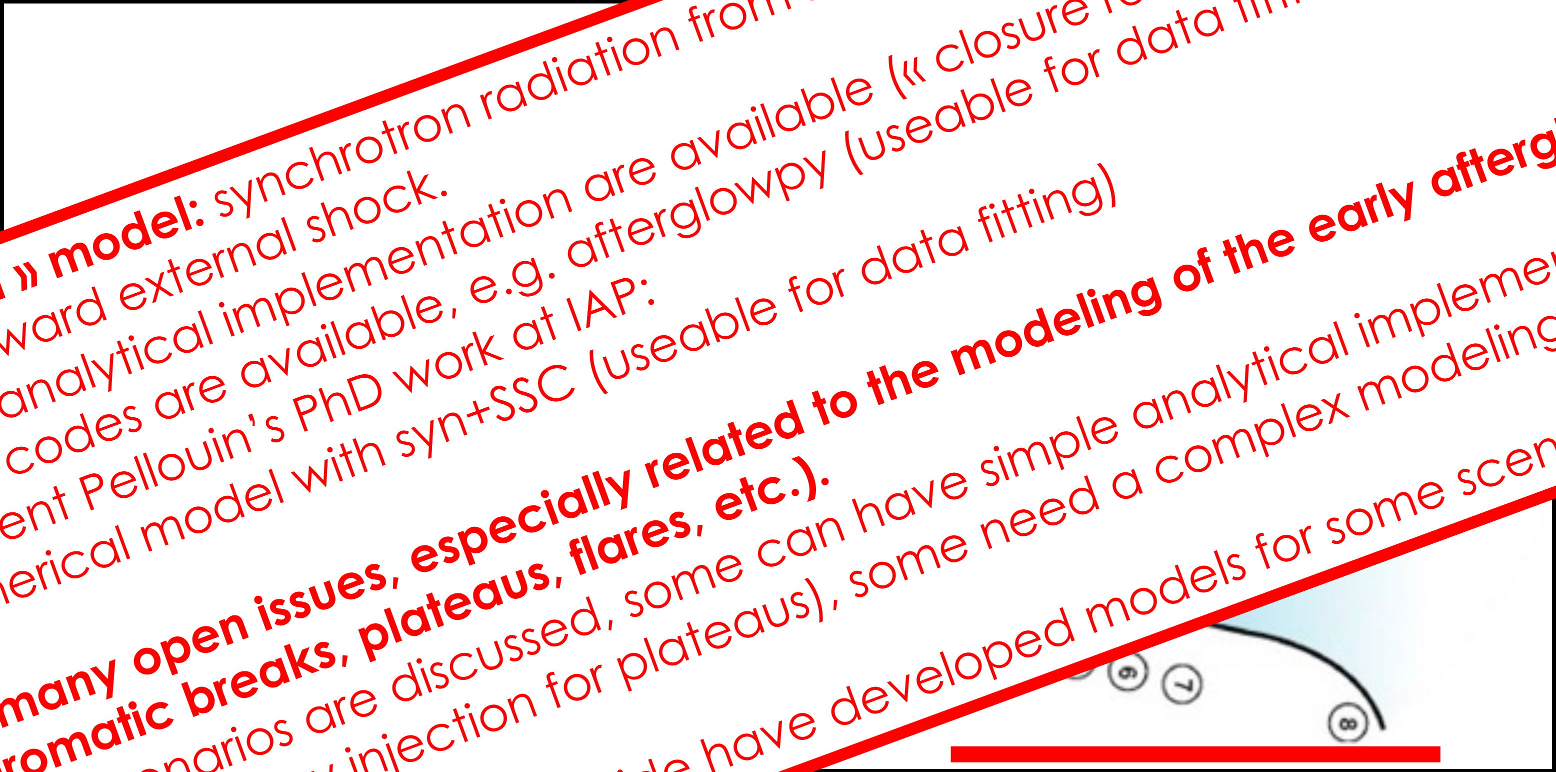
The afterglow is associated to the deceleration of the relativistic ejecta by the external medium. (Rees & Meszaros, Piran & Sari, …)



- Ultra-relativistic forward shock in the external medium (electron acceleration in UR collisionless shocks?)
- Low magnetization: reverse shock in the ejecta (NR / UR)
- Synchrotron + Inverse Compton scatterings

Afterglow

The afterglow is associated to the deceleration of the e
external medium. (Rees & Meszaros, Piran & Sari



« Standard » model: synchrotron radiation from shock-accelerated electrons at the forward external shock.
- Simple analytical implementation are available (« closure relations »).
- Public codes are available, e.g. afterglowpy (useable for data fitting)
- Clement Pellouin's PhD work at IAP: numerical model with syn+SSC (useable for data fitting)

Still many open issues, especially related to the modeling of the early afterglow (chromatic breaks, plateaus, flares, etc.).
Many scenarios are discussed, some can have simple analytical implementation (e.g. late energy injection for plateaus), some need a complex modeling.

Some groups in the French side have developed models for some scenarios.

- ck in the external medium (electron ollisionless shocks?)
- L ation: reverse shock in the ejecta (NR / UR)
- Sy tron + Inverse Compton scatterings

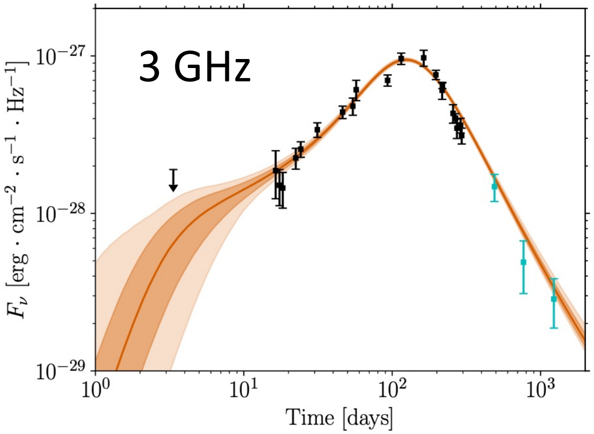
Data fitting with the forward external shock model

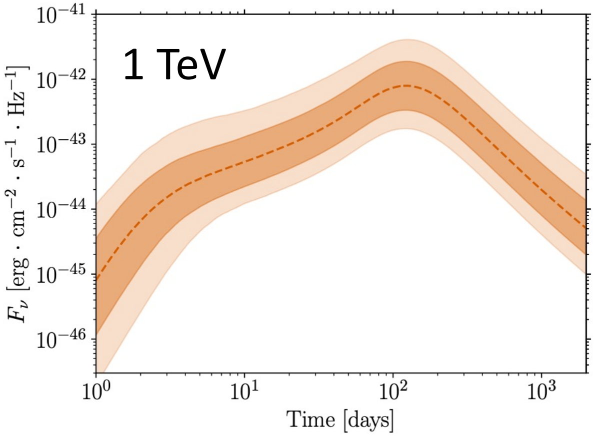
An exemple of an afterglow fit: GW170817

(structured jet, FS: syn+SSC)

Pellouin & Daigne, submitted

Lightcurve:





Posterior distribution on model parameters not shown here: should always be checked (for instance when using afterglowpy).
One can find a good fit with strange parameters: says probably something (note the case here!).

Spectrum at the peak:

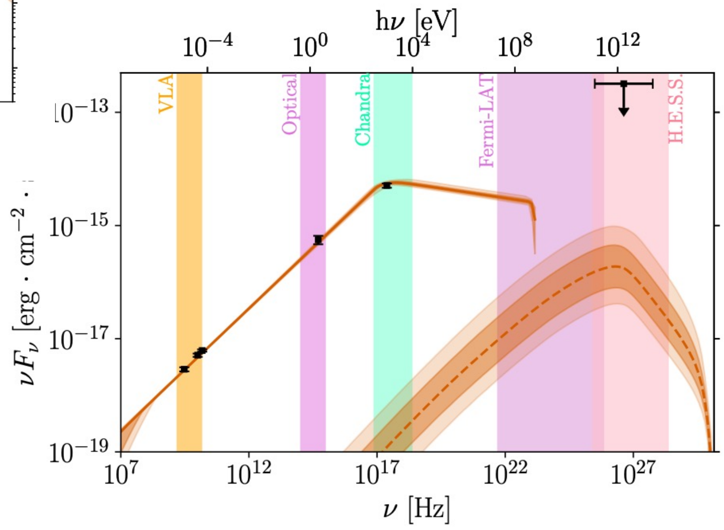


Fig. 9. Posterior distribution of the afterglow spectrum around its peak ($t_{\rm obs} = 110$ days) for the "SSC (with KN)" fit of the afterglow of GW 170817. Data points show the multi-wavelength observations at $t_{\rm obs} \pm 4$ days. The upper limit from *H.E.S.S.* is also indicated (Abdalla et al. 2020). The low-energy component (solid line) is produced by synchrotron radiation, while the high-energy emission (dashed line) is powered by SSC diffusions. Thick lines represent the median value at each observing frequency, dark contours the 68% confidence interval and light contours the 97.5% confidence interval. Some instrument observing spectral ranges are shown in colors.

Code still under development:
- synchrotron self-absorption
- reverse shock
- etc.

One word on population models

- Expertise available: Jesse Palmerio's PhD work (Palmerio & Daigne 2021)

- **Population is described in terms of rate(z), luminosity function, etc.**
- **Main difficulties: correcting for selection effects.**
  = building a large & complete sample (e.g. flux-limited) to apply the model

- Including the afterglow in the model is complex.

- Present status:
  Long GRBs: OK ; Short GRBs : more uncertain ; other kind of events ?

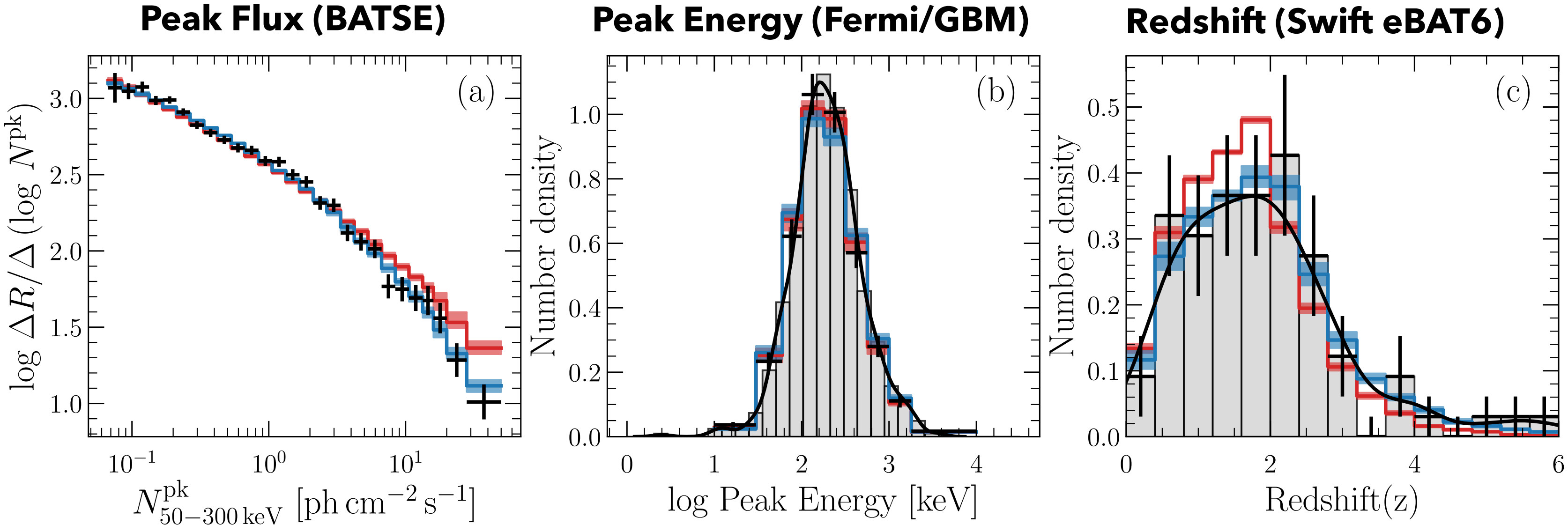
The example of the population of classical long GRBs

Long GRB Population Model

See also Ghirlanda & Salvaterra 2022

Constraints:

Palmerio & Daigne 2021



Red: model without evolution

Blue: model with evolution (here: comoving rate)

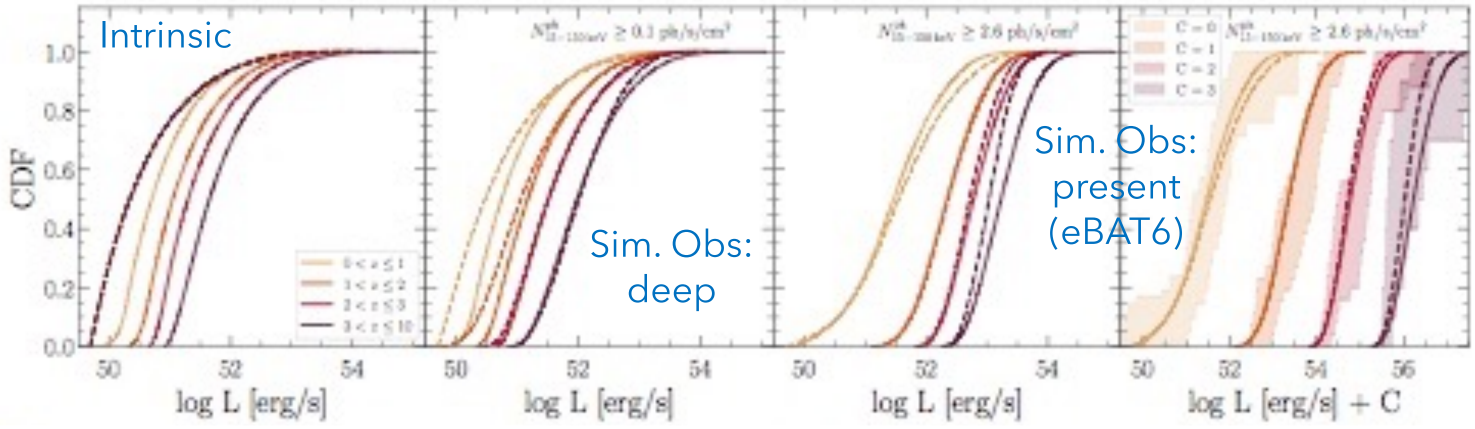
Here we use flux-limited samples to avoid the detailed modeling of the detection efficiency.

Results: an evolution is needed (comoving rate and/or luminosity function)
= a constraint on progenitor models

Long GRB Population Model

Distinguising between rate and luminosity evolution?

Luminosity distribution in four redshift bins



Solid: L evolution

Dashed: Rate evolution

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Would need a sample allowing to build the luminosity distribution in a different redshift bins…

Long GRB Population Model

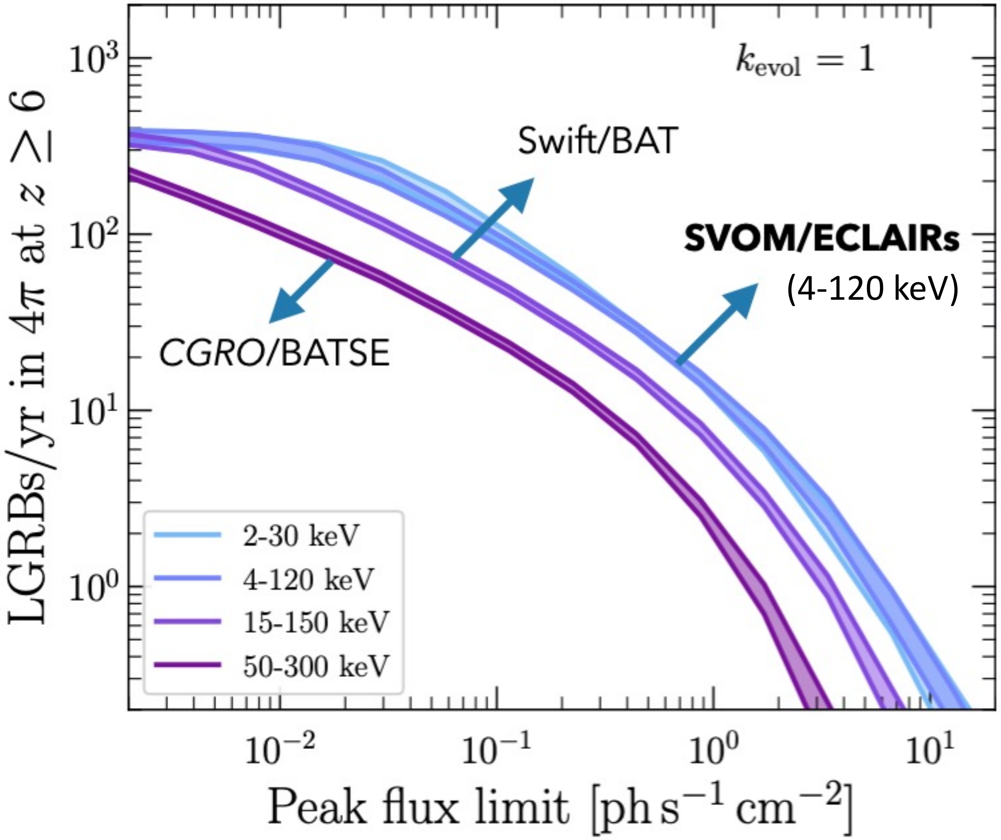
Prediction for high-z GRBs? Interest of low-energy threshold

Pop. model: all-sky rate above z=6 as a function of the peak flux limit

Effect of the energy channel on the detected rate:

Color: energy band

From 50-300 keV (violet)
to 2-30 keV (blue)



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Questions, discussion?