GAMMA-RAY BURSTS

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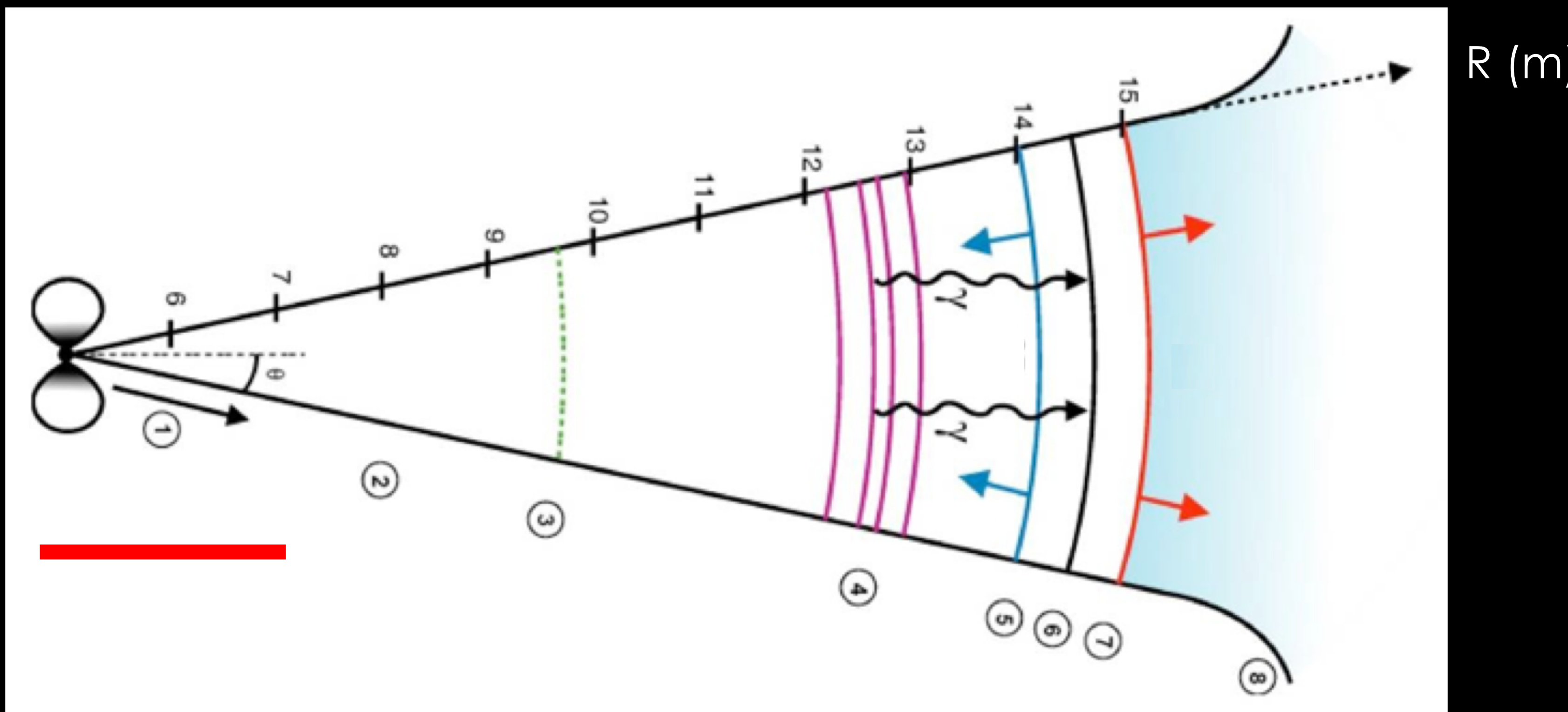
Introduction	A brief history Observational Facts Basic Constraints on any GRB model: compact source + relativistic ejecta
Theory: Basic Elements	Progenitor / Central Engine / Relativistic Ejection Prompt GRB Emission: internal dissipation in a relativistic ejecta Afterglow: interaction Ejecta / External Medium (deceleration)

+ a selection of Modern Topics

The Transient Universe 2023 - Cargèse - June 5, 2023

Initial event & central engine

Huge radiated energy ($E_{iso,\gamma}$~10^{50}-10^{55} erg) + short time scale variability (<100 ms): cataclysmic event leading to the formation of a stellar-mass compact object (accreting BH ?, magnetar ?)

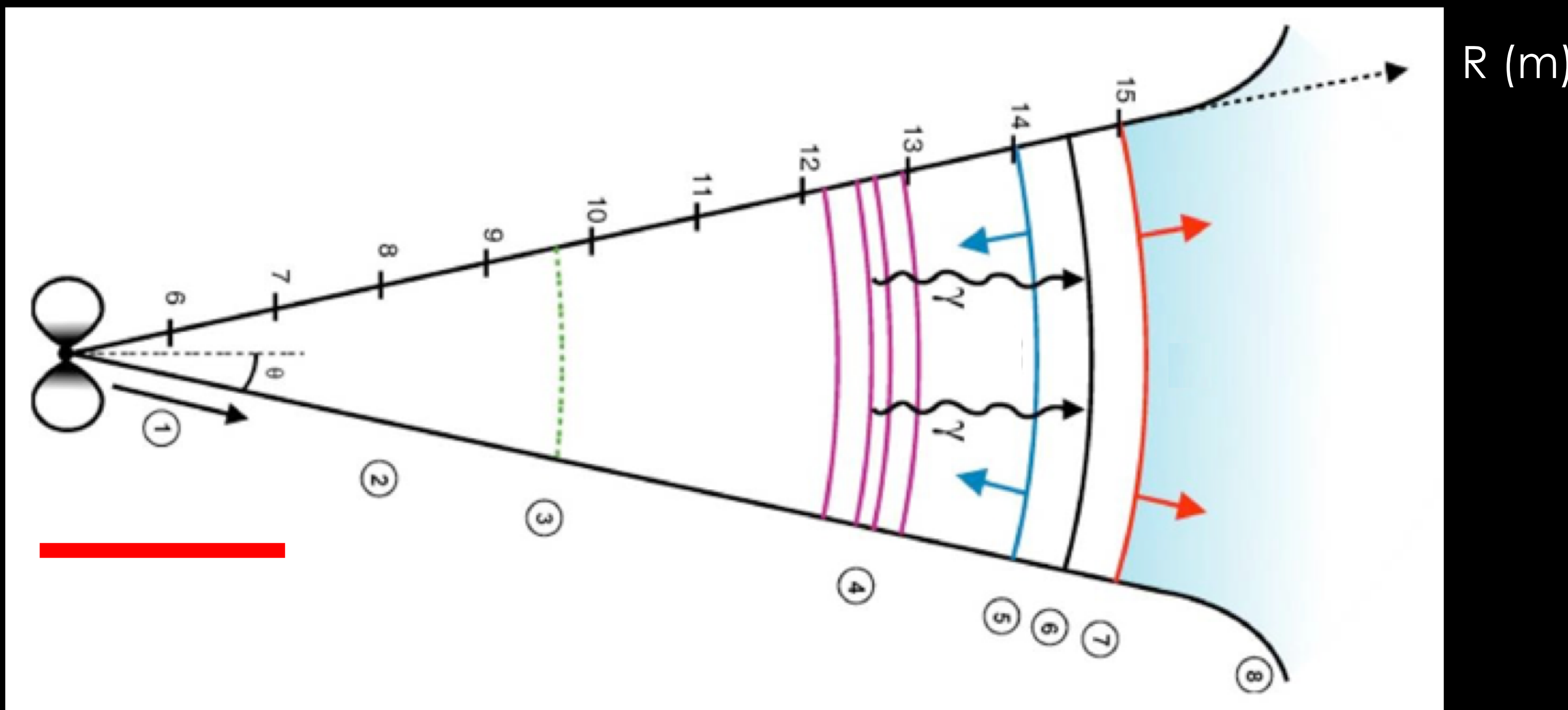


Progenitors:

- **Long GRBs: core-collapse of massive star (collapsar model)**
- **Short GRBs: merger of binary neutron star system (or NSBH)**

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: again a long list of difficult questions

Questions:

- How to limit the baryonic pollution?

$$\Gamma_\infty \leq \frac{\dot{E}}{\dot{M} c^2}$$

Initial: thermal or magnetic

Detailed calculation complicated (heating term includes neutrino heating)

Preferred region: along the rotation axis.

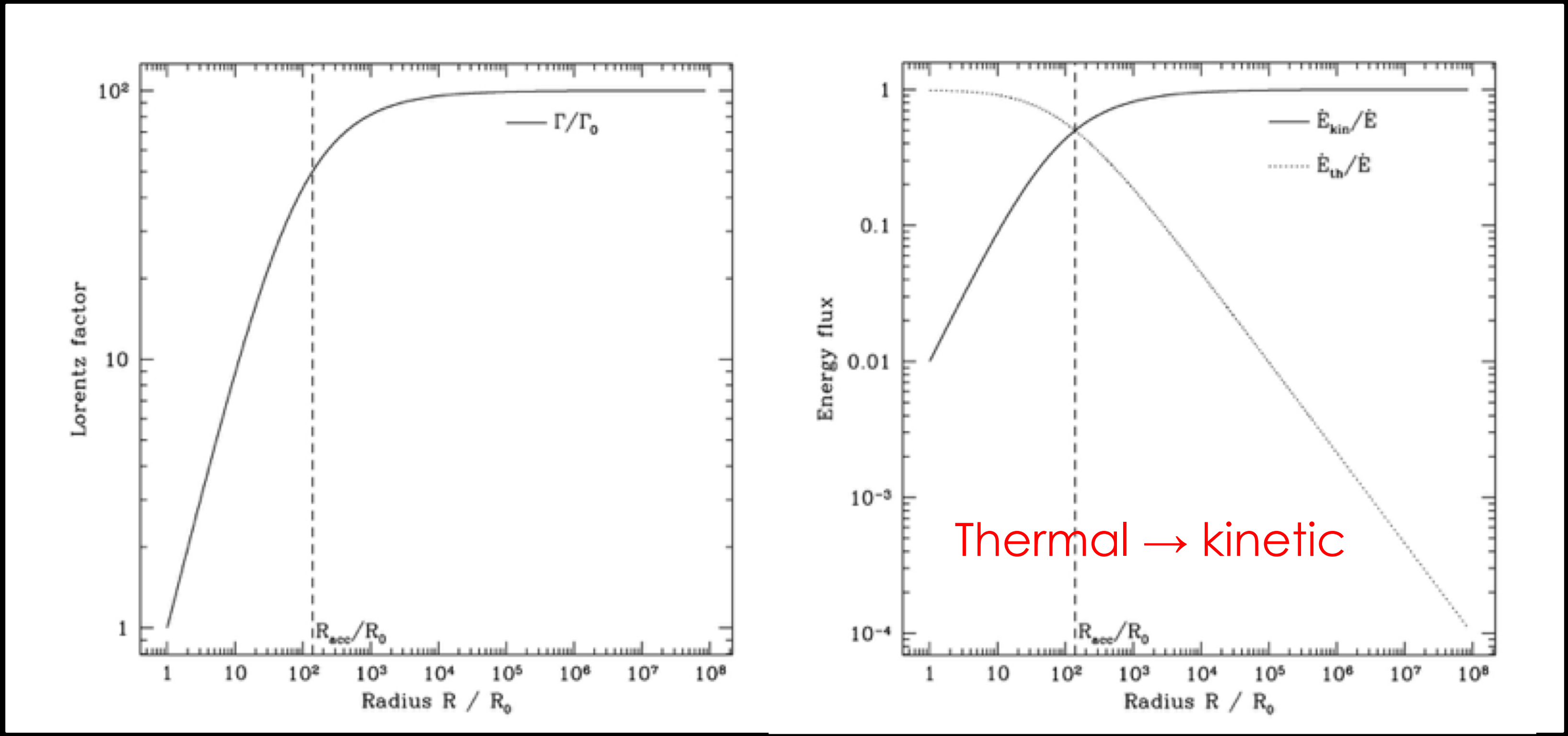
- Origin of the collimation? (hydro: difficult, no natural nuzzle: stellar envelope? MHD: more natural)

- Impact of the early propagation on the jet structure? (see the example of 170817 later) [recent developments: Bromberg et al.]

- Blandford-Znajek or another process?
- What happens if the central object is a neutron star/magnetar?
- Etc.

Relativistic ejection

Reference model: relativistic fireball (unrealistic)



Fireball equations: $4\pi r^2 \rho \Gamma c \simeq \dot{M} = \mathrm{cst}$

$$4\pi r^2 \rho h \Gamma^2 c \simeq \dot{E} = \mathrm{cst}$$

$$\frac{P}{\rho^\gamma} = \mathrm{cst}$$

Valid as along as spreading is negligible:

$$R \ll R_{\mathrm{spread}} \simeq \Gamma^2 \Delta$$

shell width ~ c . ejection duration

Relativistic ejection

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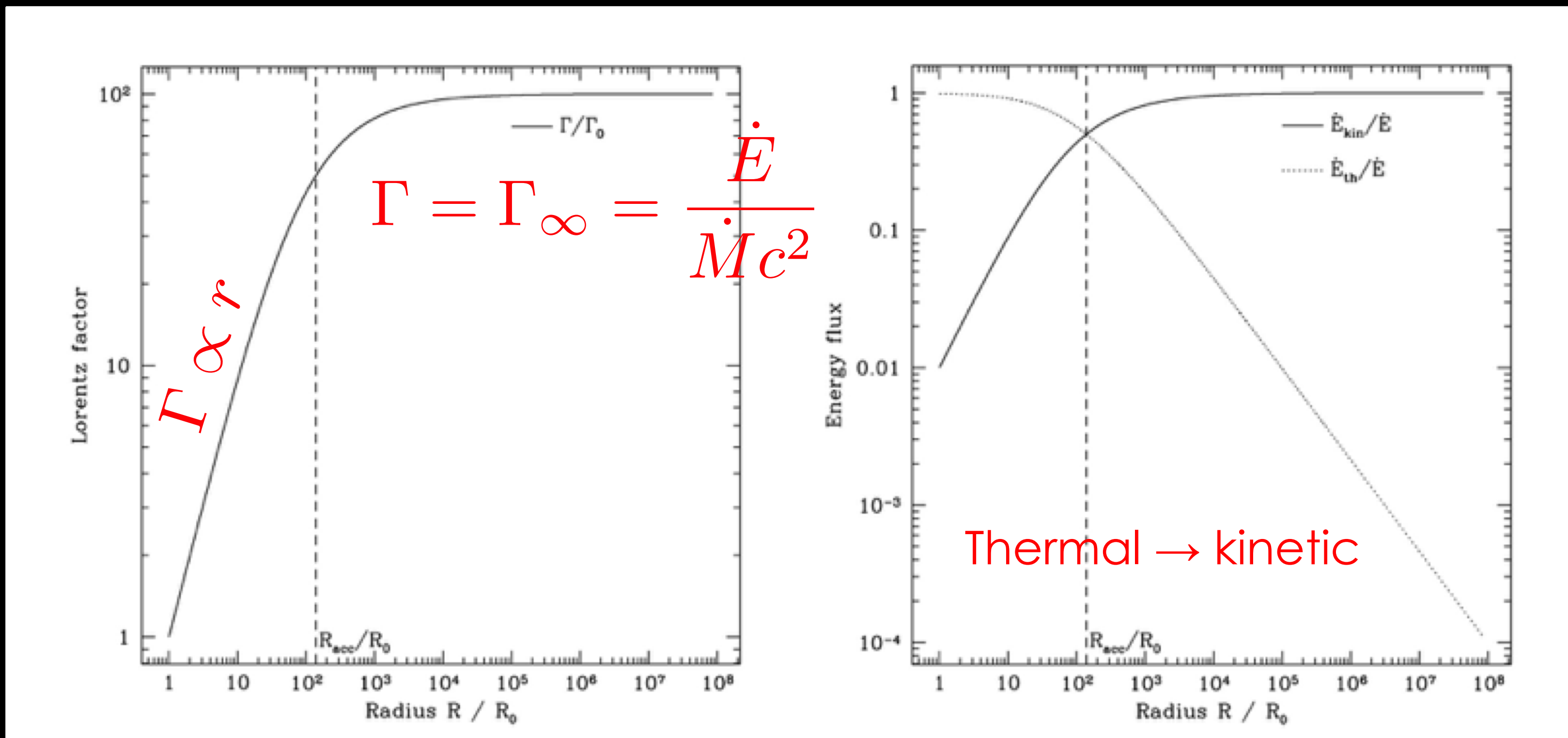


Acceleration (saturation) radius:

$$R_{\rm acc} = \Gamma_\infty R_0 \simeq 10^9\,{\rm cm}\left(\frac{R_0}{100\,{\rm km}}\right)\left(\frac{\Gamma_\infty}{100}\right)$$

Initial size

Relativistic ejection: other difficult questions

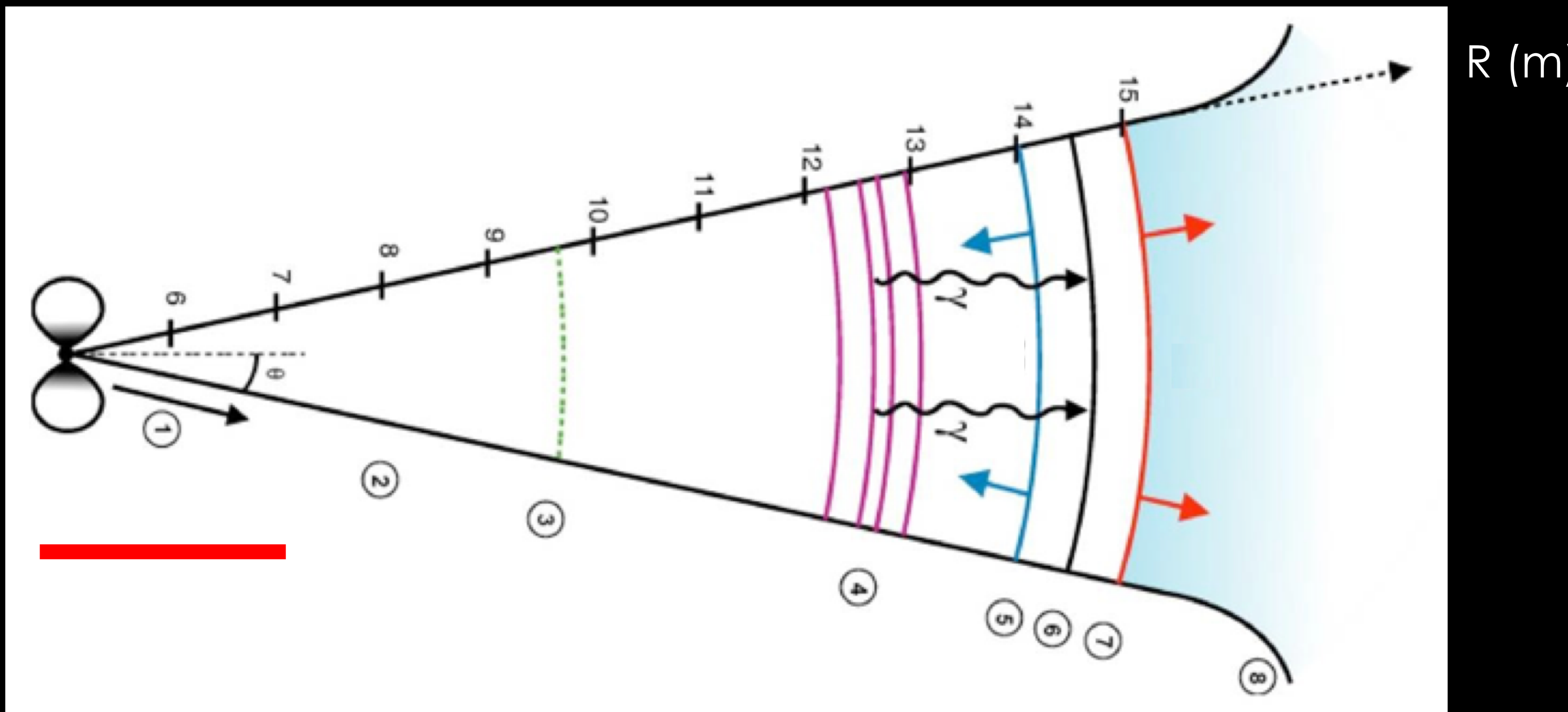
- Realistic ejection models: acceleration radius?
- Final Lorentz factor/Geometry/Magnetization?

  = again an active topic of research

= Initial conditions for the emission phases (prompt, afterglow)

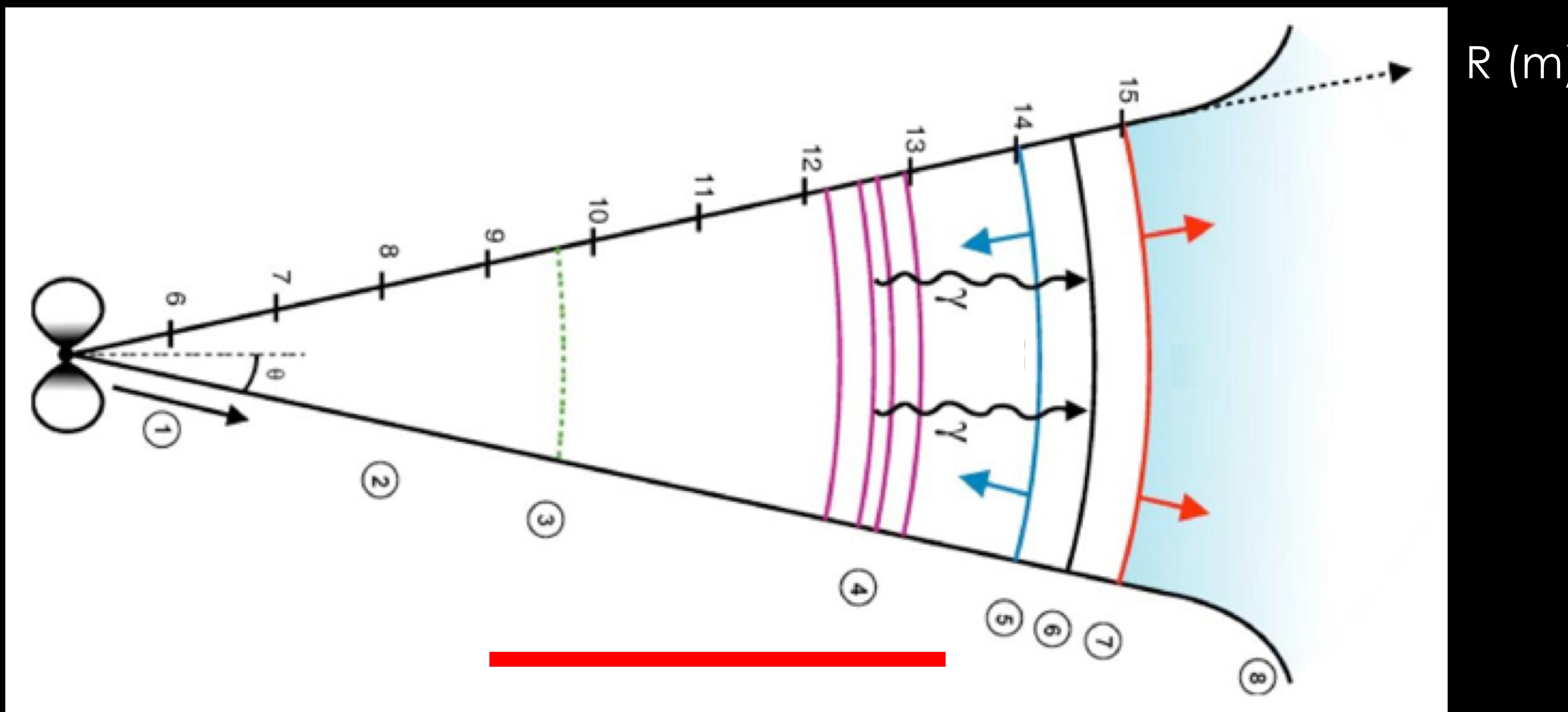
Relativistic ejection

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



Prompt emission

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

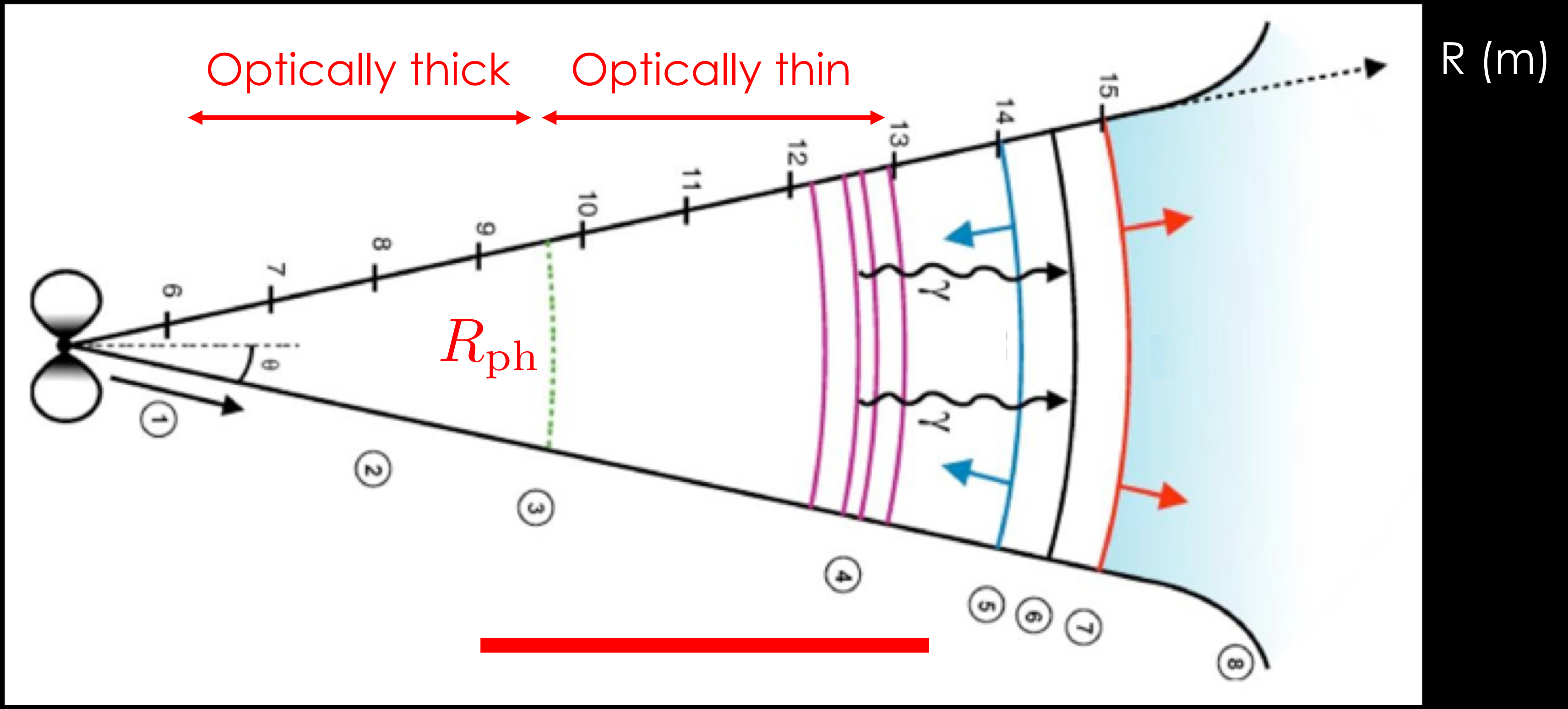


Internal dissipation / radiation processes:
- (Dissipative) Photosphere? (thermal + comptonization)
- Internal shocks? (synchrotron + IC)
- Reconnection? (synchrotron + IC)

Photosphere

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

Relativistic photosphere: angle dependent…



$$R_{\rm ph} \simeq \frac{\dot{E}\kappa_{\rm T}}{8\pi\Gamma^3 c^3} \simeq 6\,10^{12}\,{\rm cm}\left(\frac{\dot{E}}{10^{52}\,{\rm erg/s}}\right)\left(\frac{\Gamma}{100}\right)^{-3}$$

$$R_{\rm ph} \gg R_{\rm acc}$$

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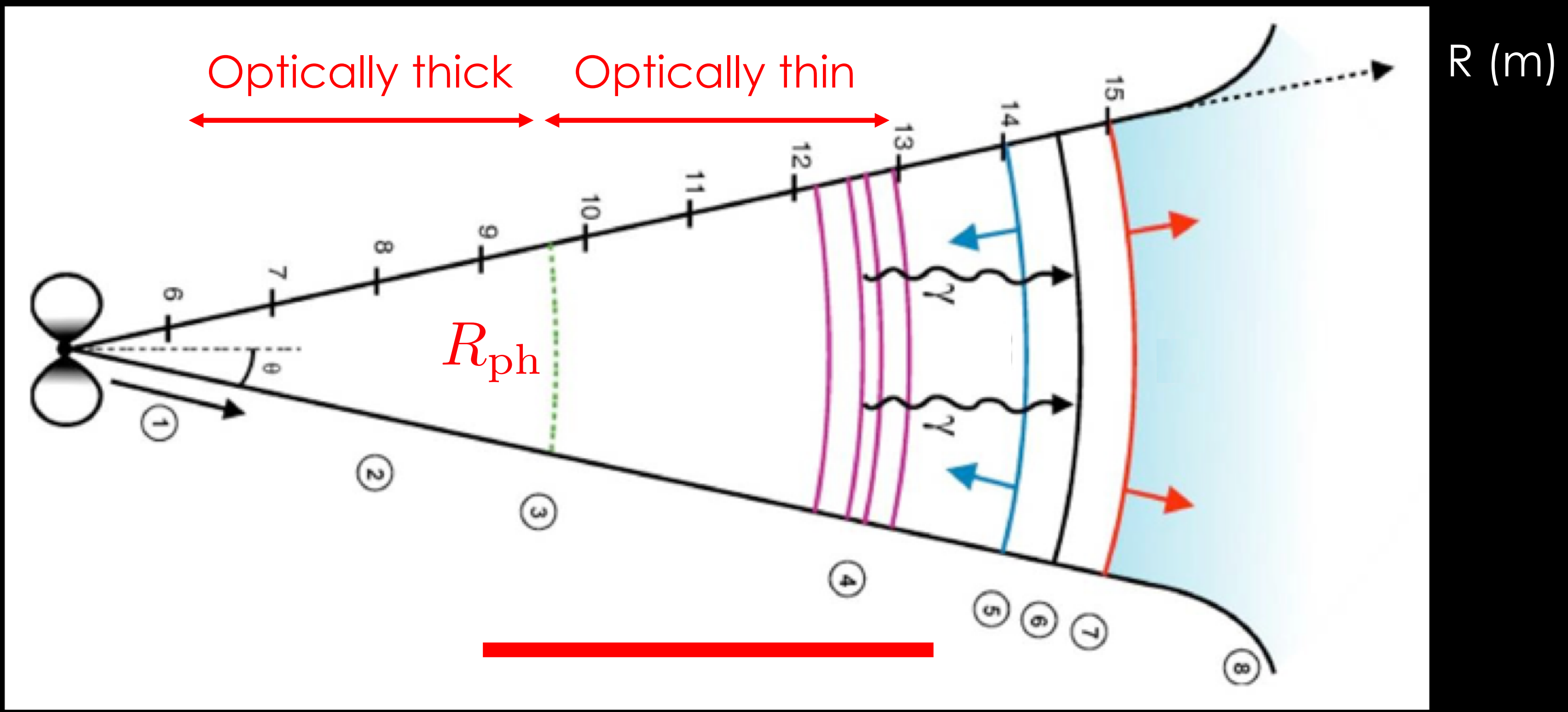
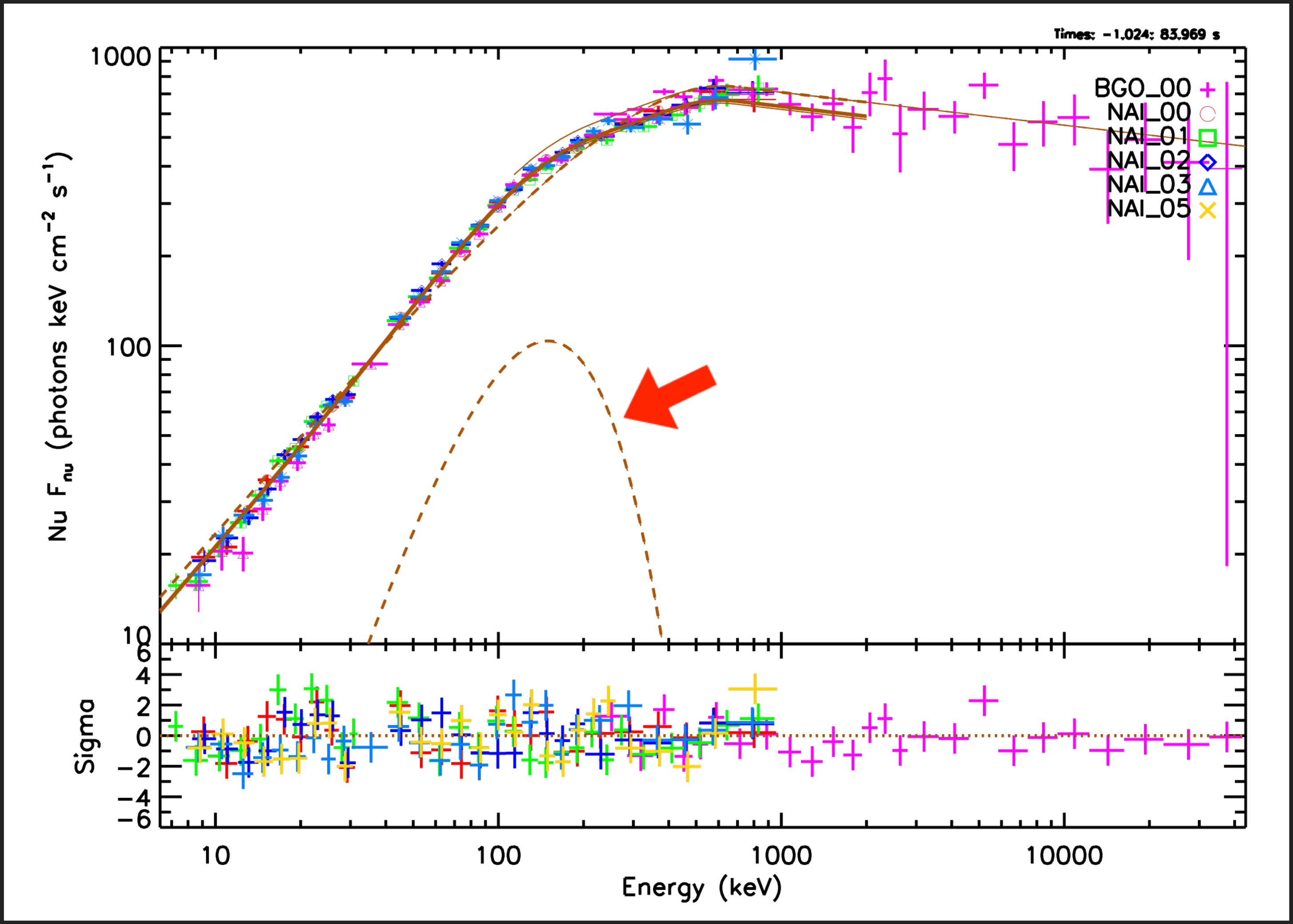


Photospheric emission:

- 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?

Weak thermal components?

Example: GRB 100724B (Fermi/GBM observations)

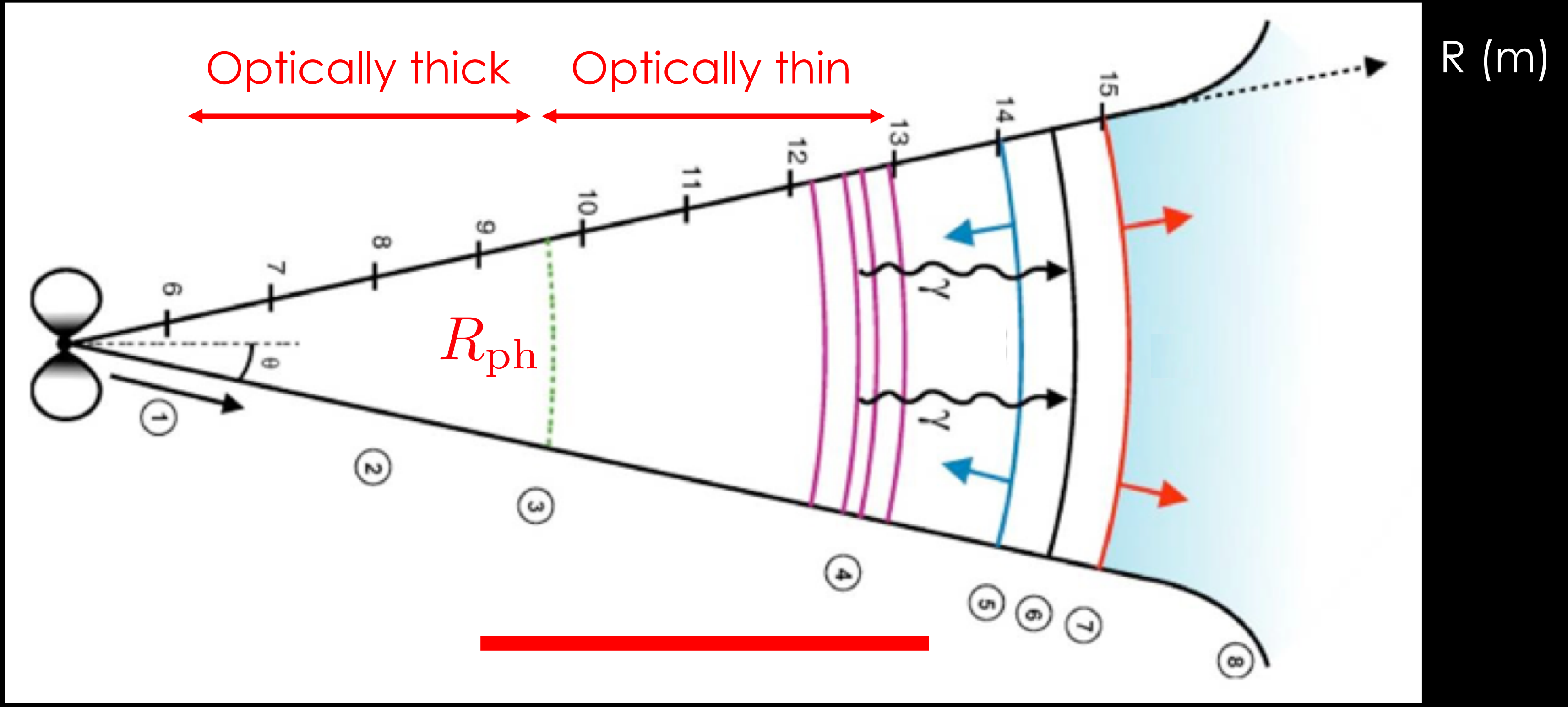


Guiriec et al. [FD] 2011

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

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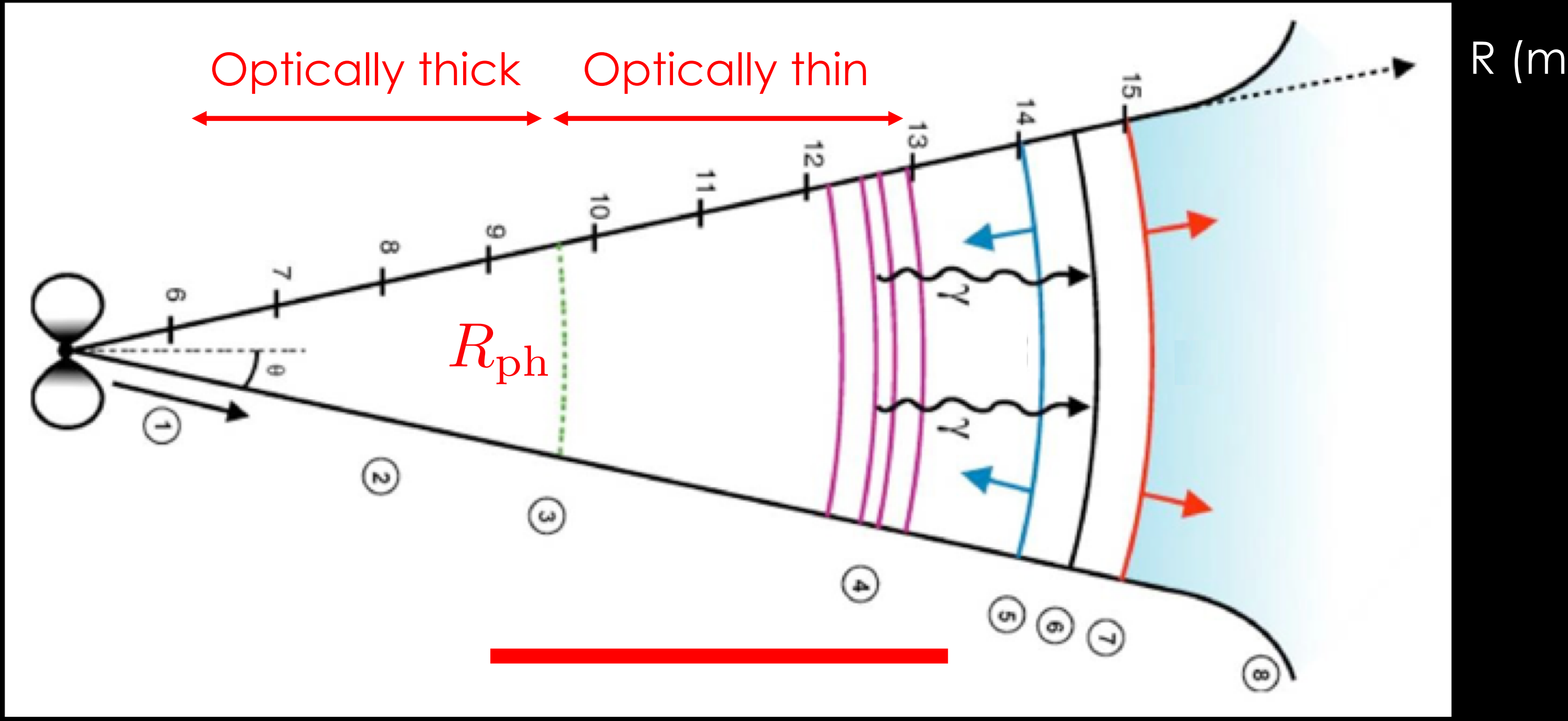

Radius of internal shocks

$$R_{\rm is} \simeq R_{\rm spread} \simeq 2\Gamma^2\Delta \simeq 6\,10^{14}\,{\rm cm}\left(\frac{\Gamma}{100}\right)^2\left(\frac{\Delta/c}{1\,{\rm s}}\right)$$

$R_{\rm is} \gg R_{\rm ph}$ except for the earliest collisions (shortest variability timescale)?

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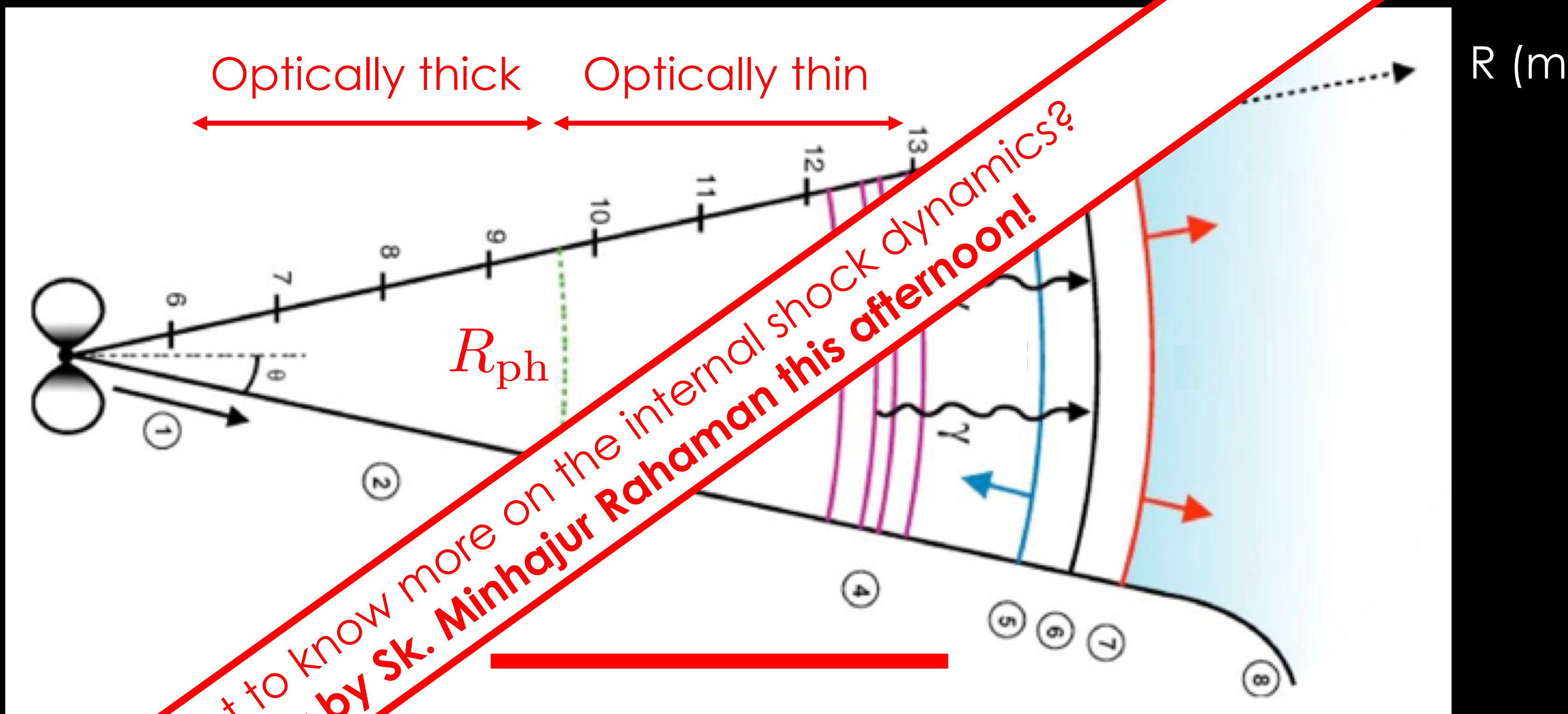

Want to know more on the internal shock dynamics?
see talk by Sk. Minhajur Rahaman this afternoon!

Radius of int… cks

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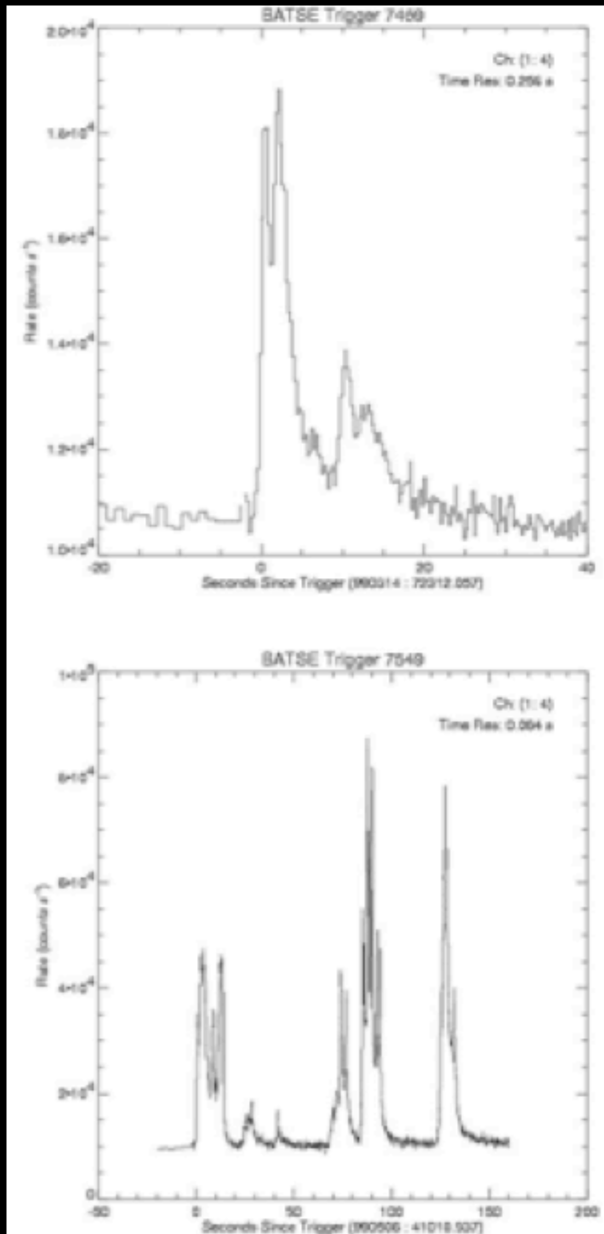
$R_{\rm is} \gg R_{\rm ph}$ except for the earliest collisions (shortest variability timescale)?

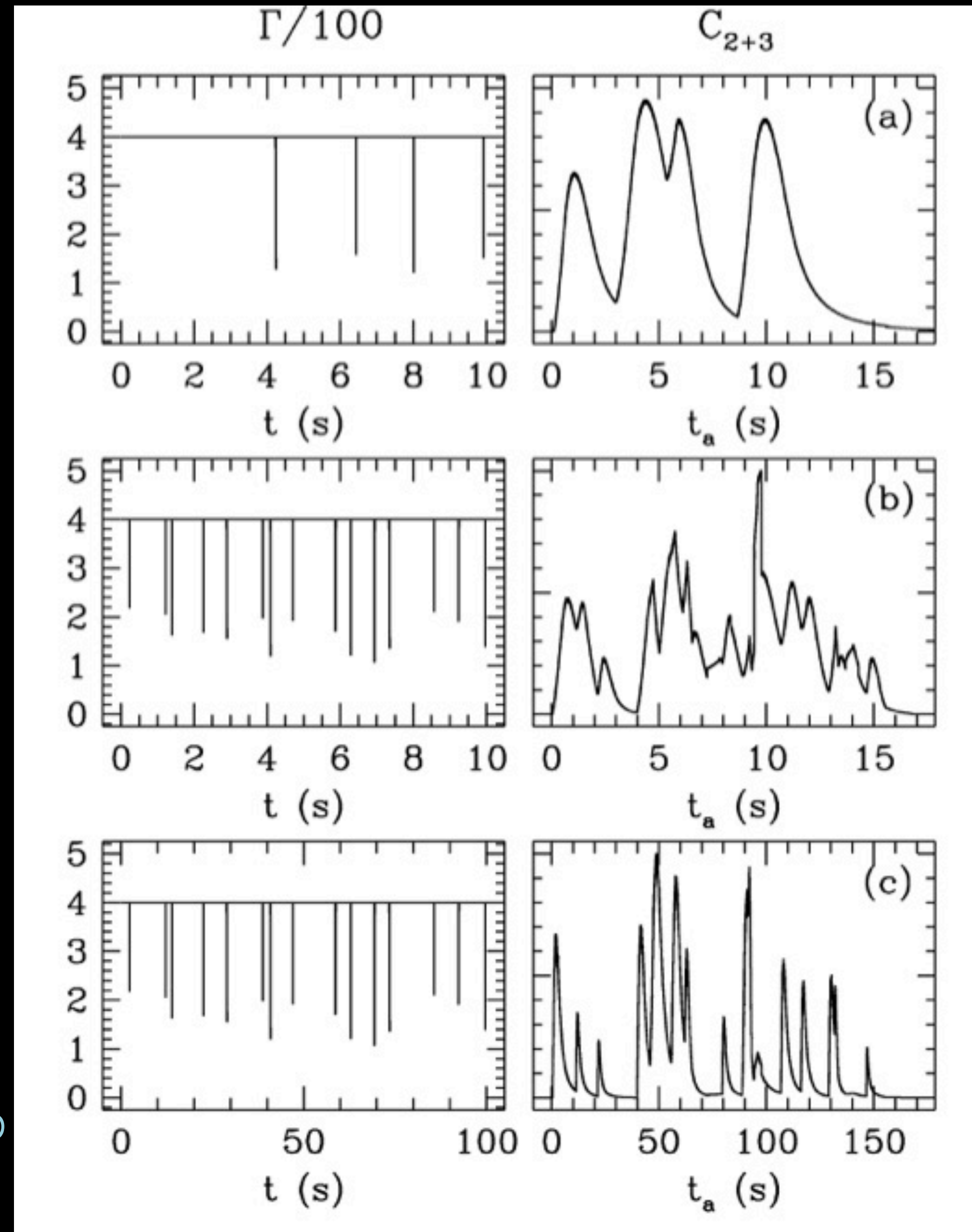
Internal shocks

Rees & Meszaros 94, Kobayashi+ 97, Daigne & Mochkovitch 98, etc.

BATSE catalog

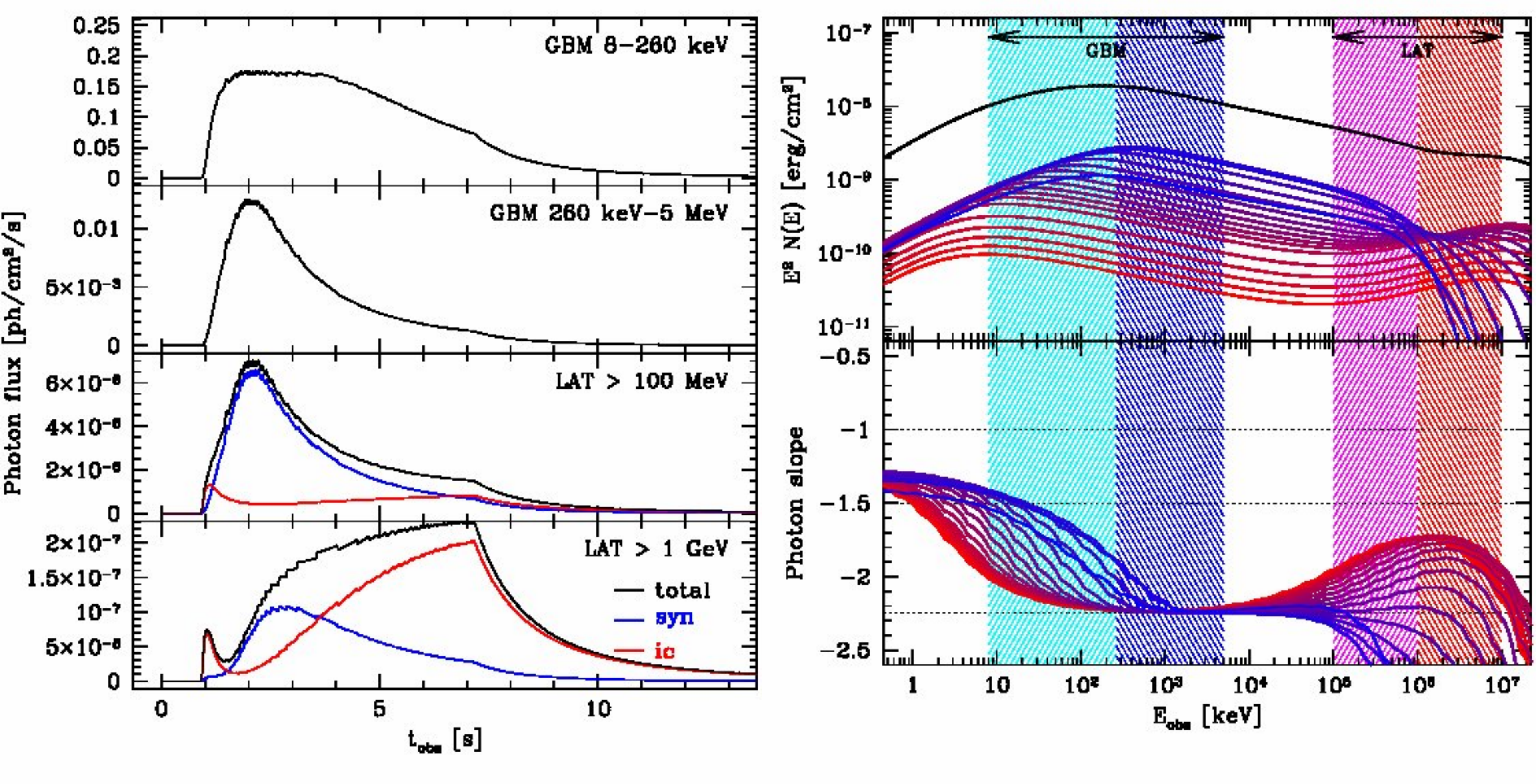


Daigne & Mochkovitch 1998



Internal shocks

Example of a single pulse full simulation (dynamics+radiation)



Bosnjak, Daigne, Dubus 09

Internal shocks

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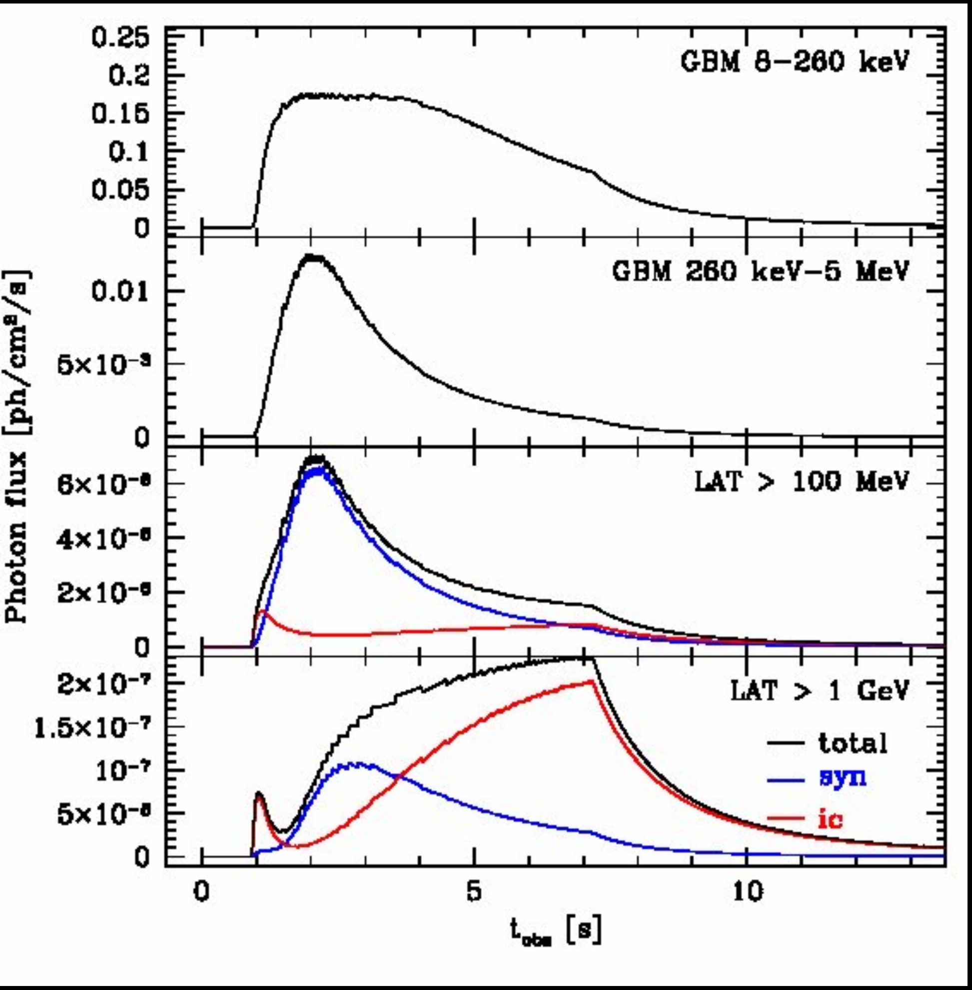
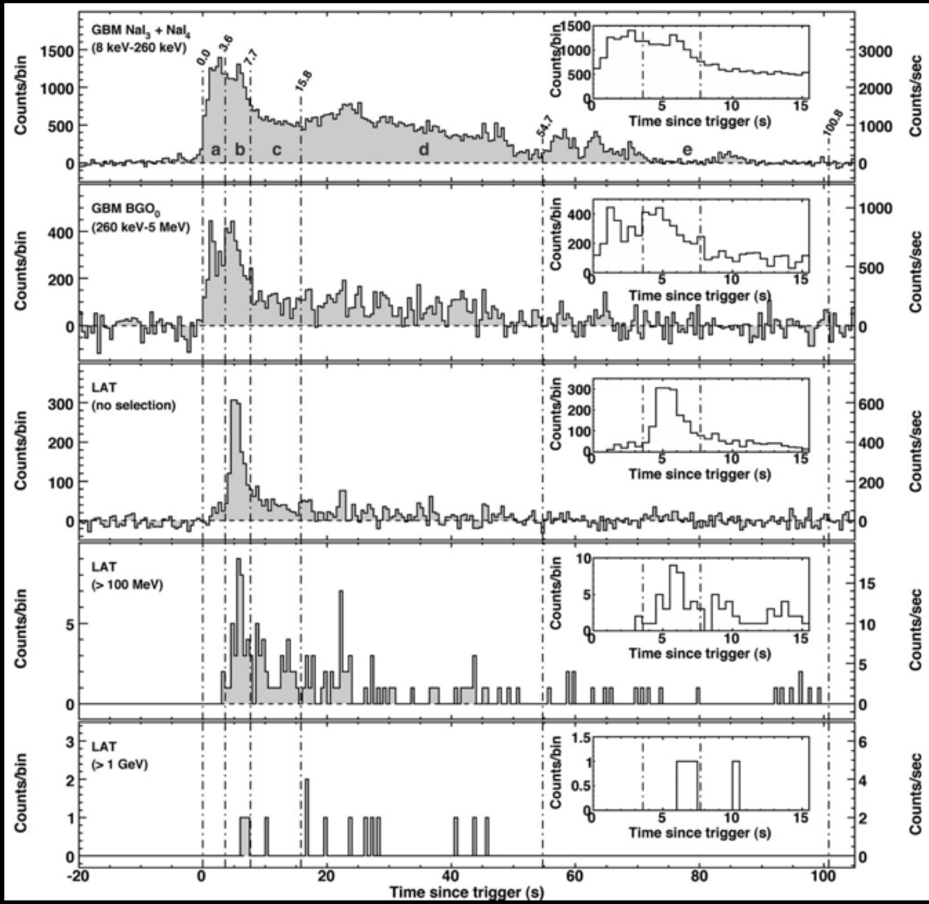




First Fermi GBM+LAT gamma-ray burst GRB 080916C

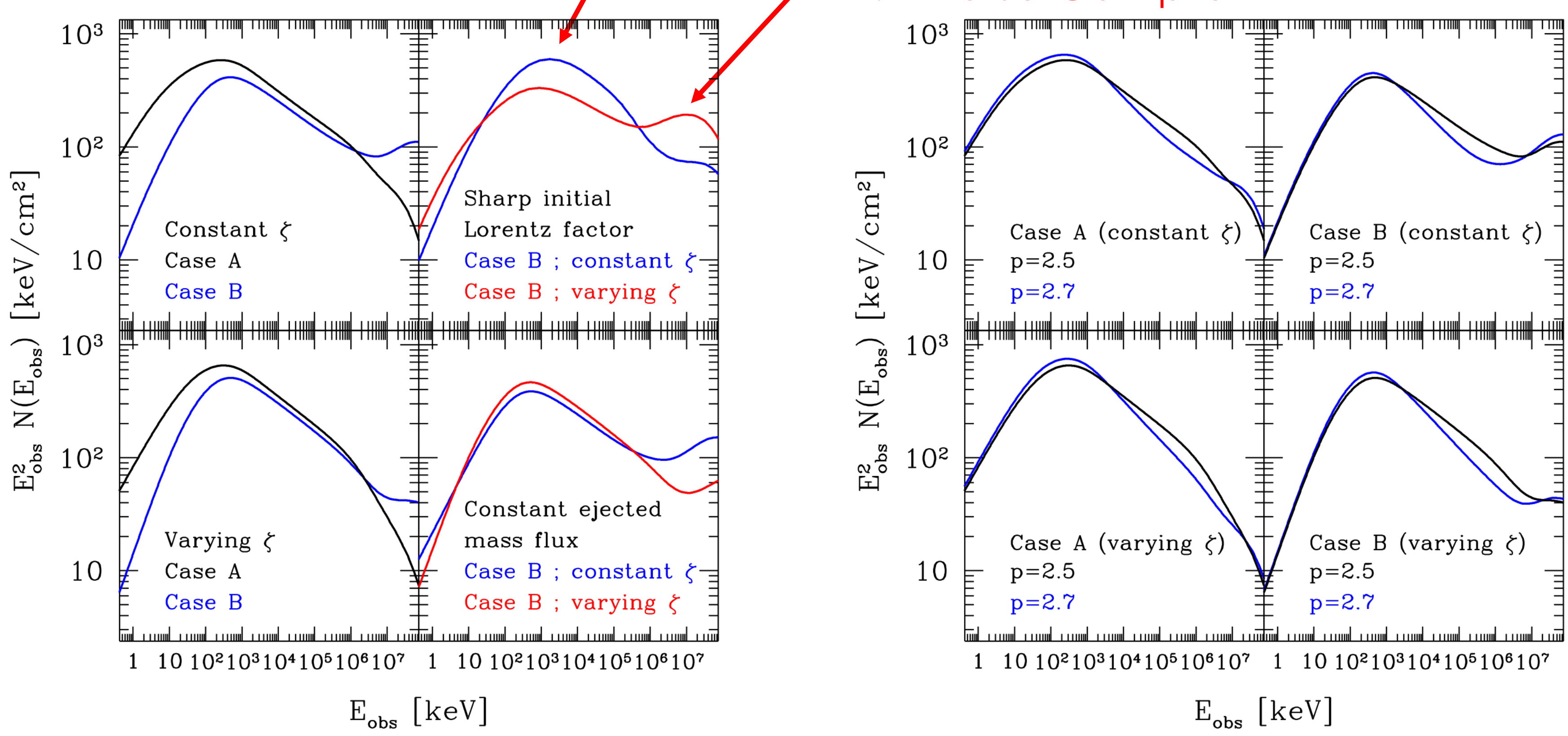
Bosnjak, Daigne, Dubus 09

Internal shocks

Rees & Meszaros 94, Kobayashi+ 97, Daigne & Mochkovitch 98, etc.

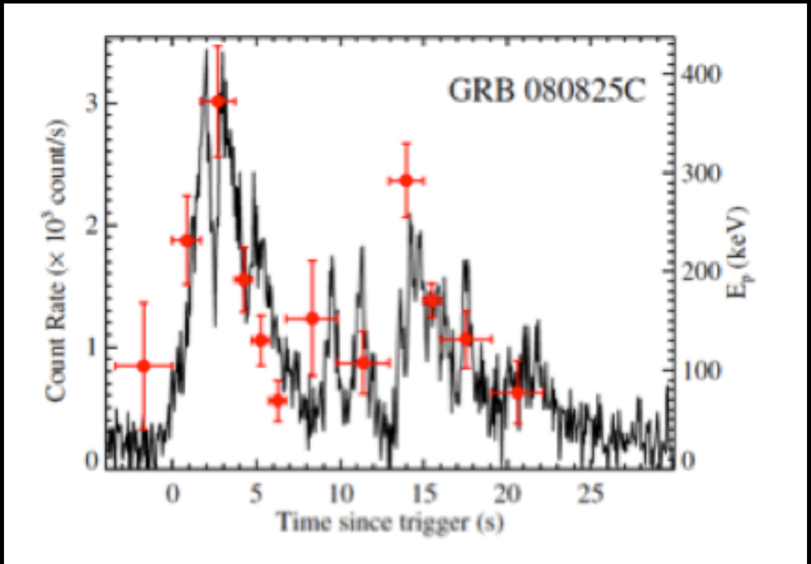
Main component: synchrotron

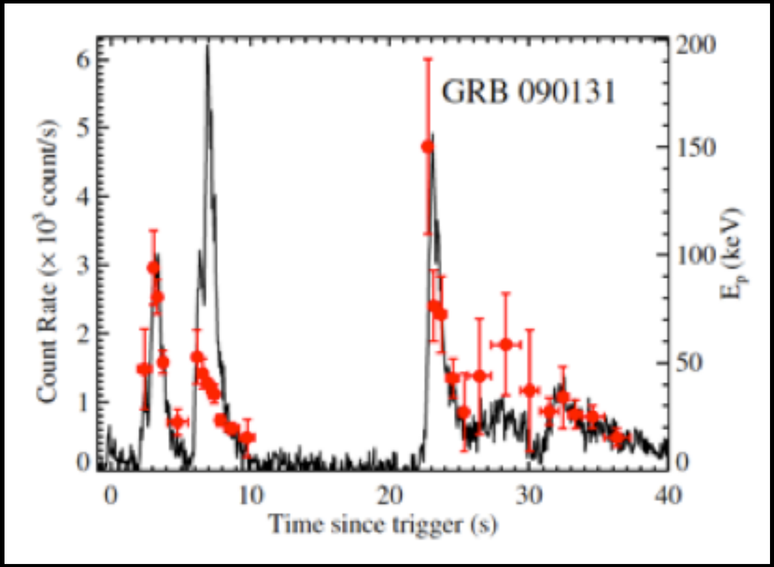
HE: inverse Compton

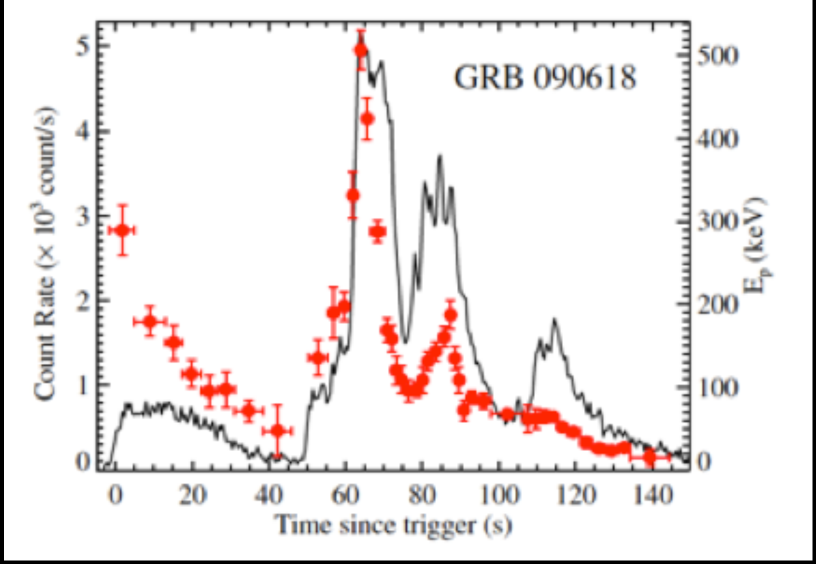


Bosnjak & Daigne 14 ; see also Asano & Meszaros

Spectral evolution





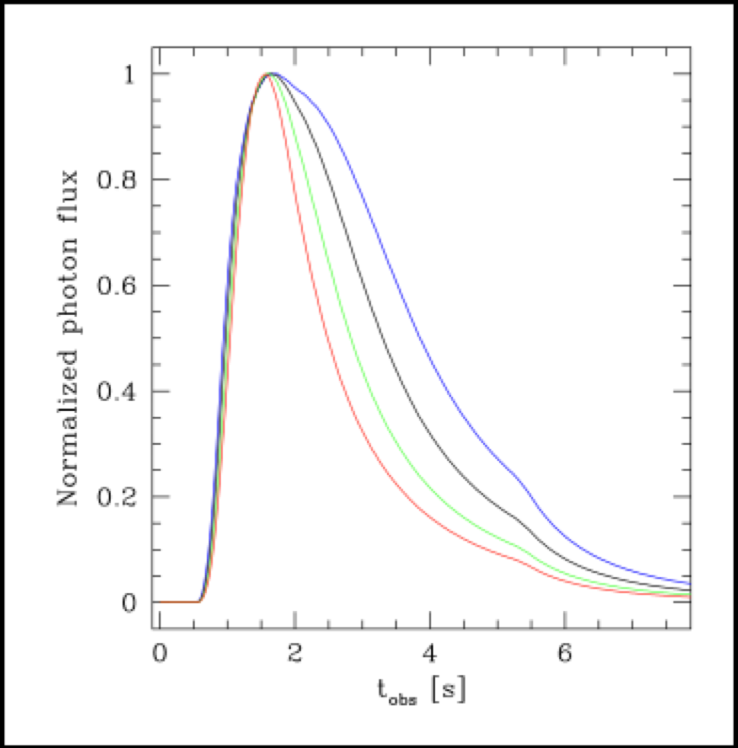


Fermi/GBM observations
(Li et al. 2012)

Black = lightcurve
Red = peak energy

Spectral evolution: internal shocks

A simulated single pulse (dynamics+full radiative calc.):



Light curve in BATSE range : channels 1 (blue) to 4 (red)

Bosnjak & Daigne 14

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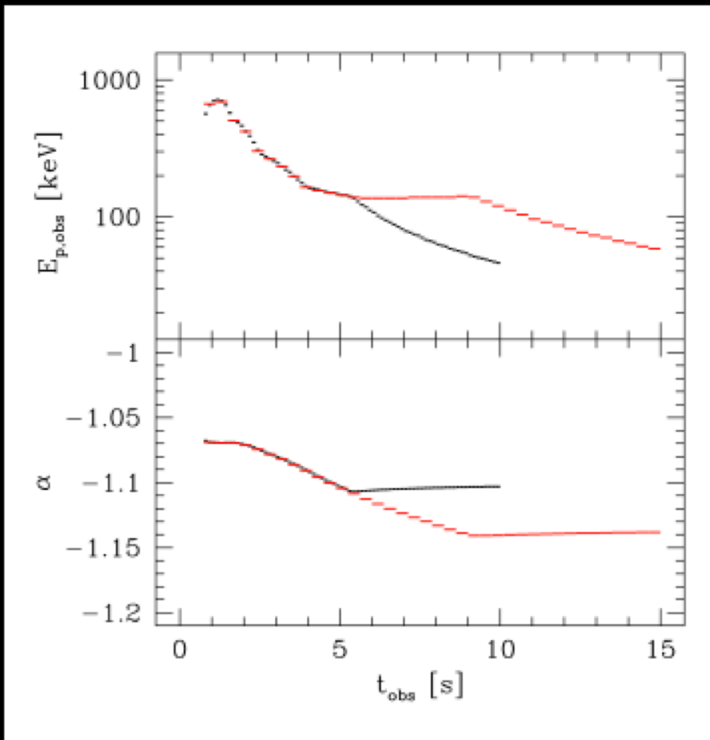
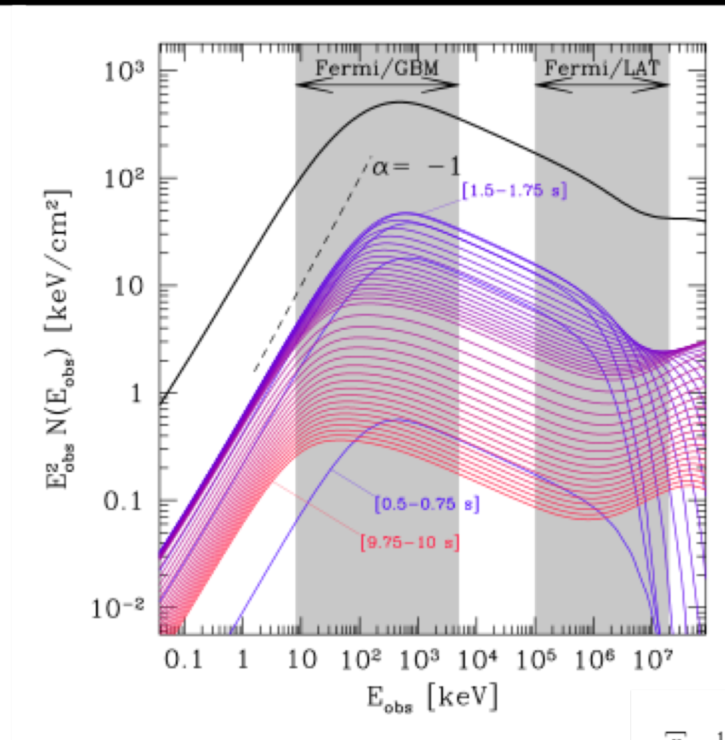
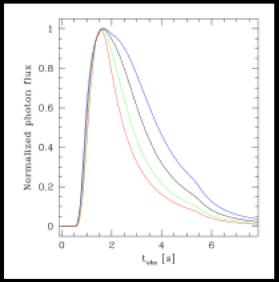
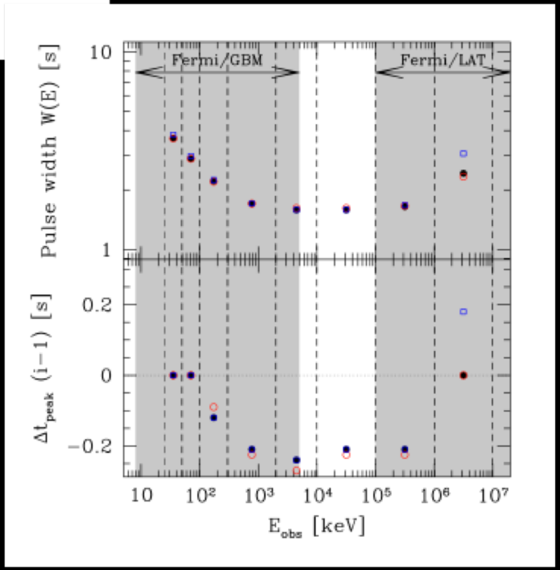






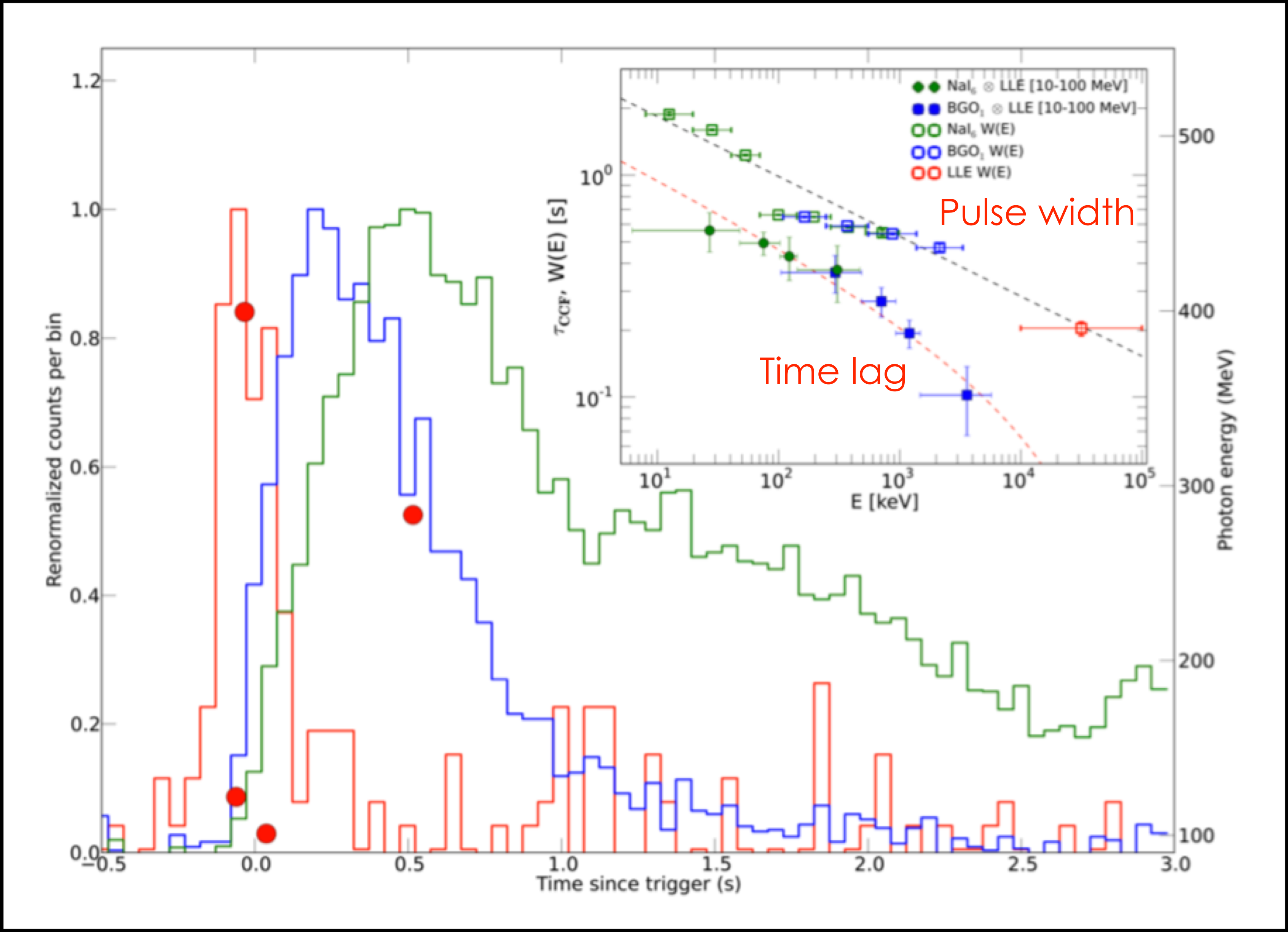
Time evolving spectrum



Bosnjak & Daigne 14

Pulse width / time lags

First pulse of GRB 130427A (« Fermi monster »)



Preece +14

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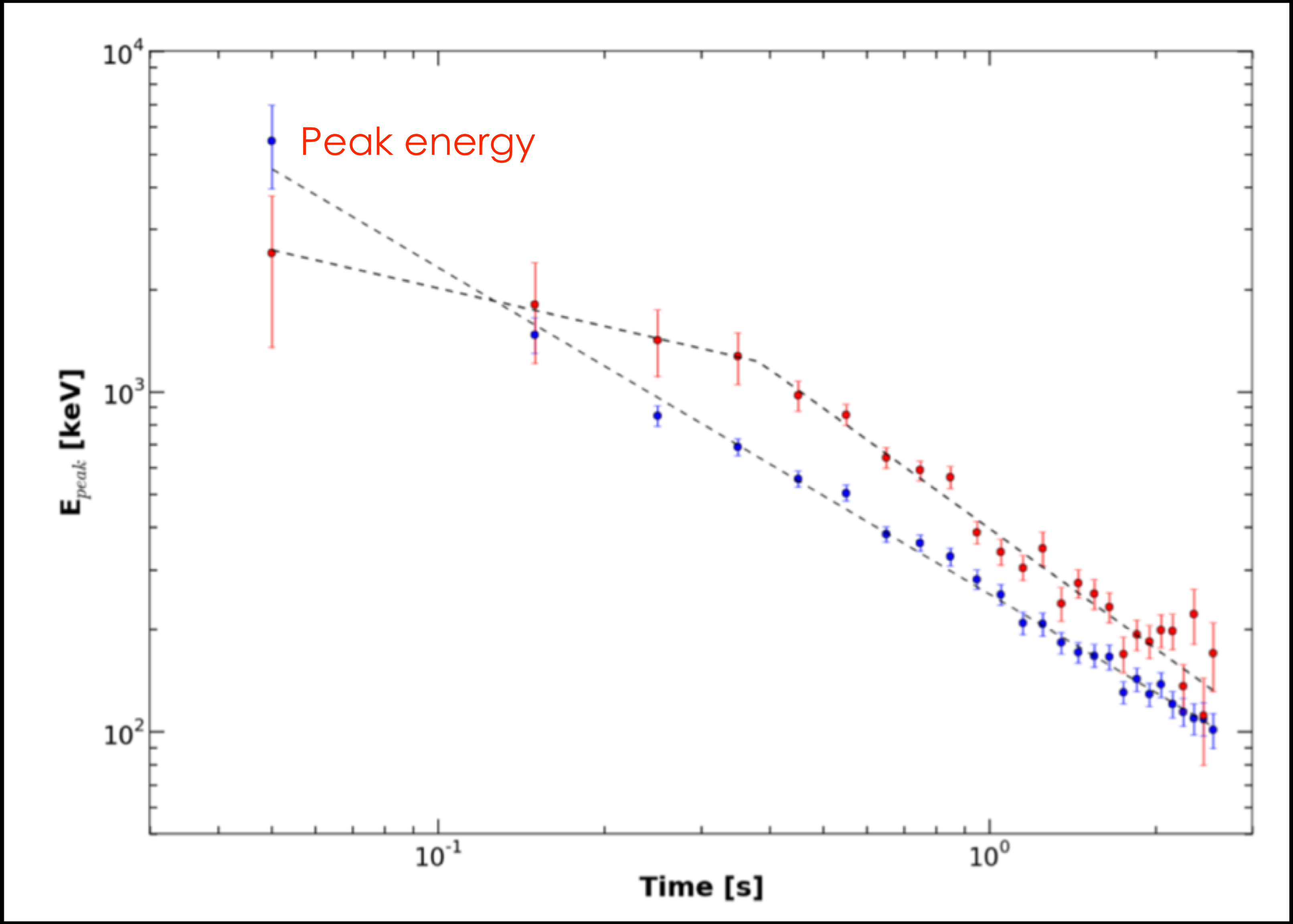

Preece +14

Synchrotron Spectrum

- Evolution an electron: $$\frac{\mathrm{d}\left(\gamma m_{\mathrm{e}} c^2\right)}{\mathrm{d}t} = -P_{\mathrm{syn}}(\gamma) - P_{\mathrm{ad}}(\gamma)$$
- Synchrotron power: $P_{\mathrm{syn}}(\gamma) \propto B^2 \gamma^2$
- Adiabatic cooling: $$P_{\mathrm{ad}}(\gamma) \simeq \frac{\gamma m_{\mathrm{e}} c^2}{t_{\mathrm{dyn}}}$$
- Critical Lorentz factor: $\gamma_{\mathrm{c}} \propto \left(B^2 t_{\mathrm{dyn}}\right)^{-1}$

$\gamma \gg \gamma_{\mathrm{c}}$ Radiatively efficient e$^-$

$\gamma \ll \gamma_{\mathrm{c}}$ Radiatively inefficient e$^-$

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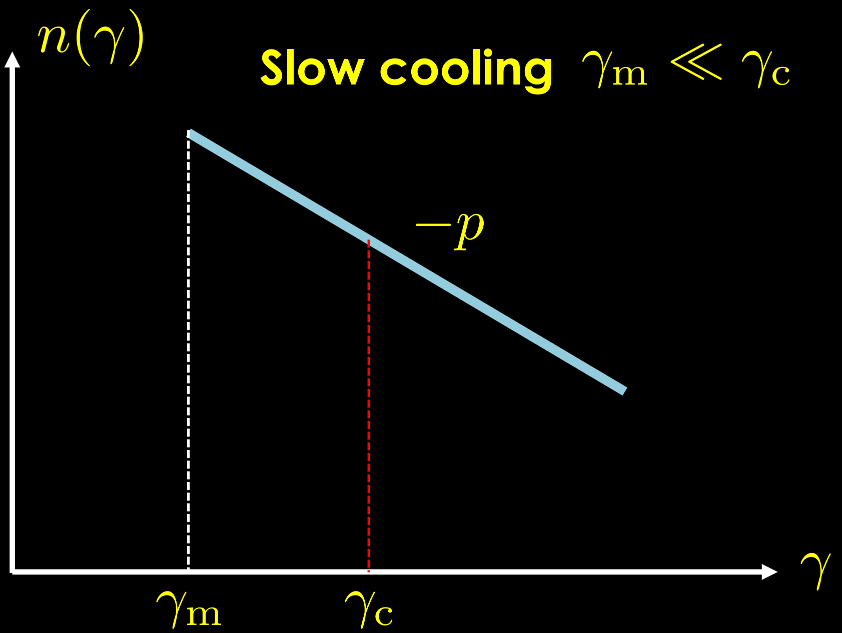
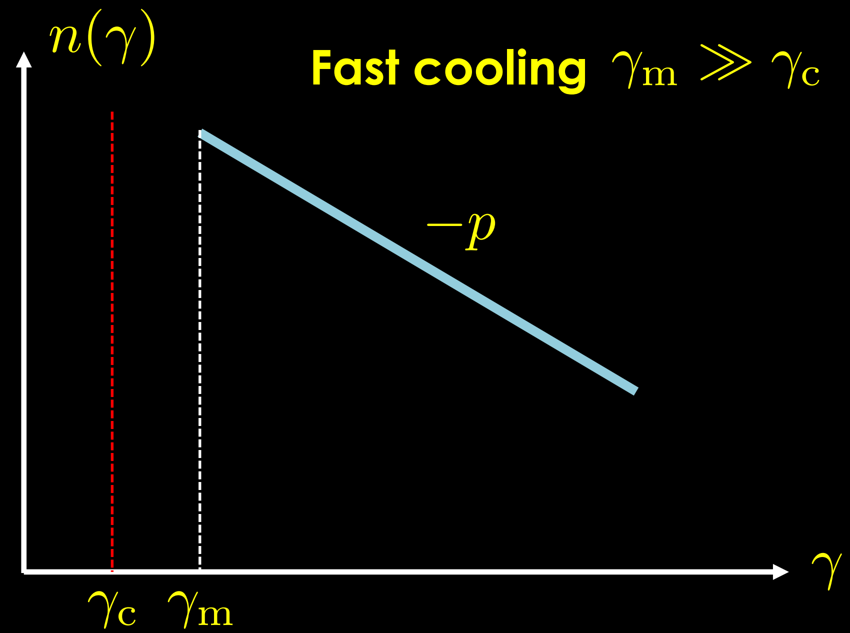
$\gamma \ll \gamma_{\mathrm{c}}$ Radiatively inefficient e$^-$

- **Evolution of a power-law distribution over the dynamical timescale:**

Slow cooling $\gamma_{\mathrm{m}} \ll \gamma_{\mathrm{c}}$



Fast cooling $\gamma_{\mathrm{m}} \gg \gamma_{\mathrm{c}}$



Synchrotron Spectrum

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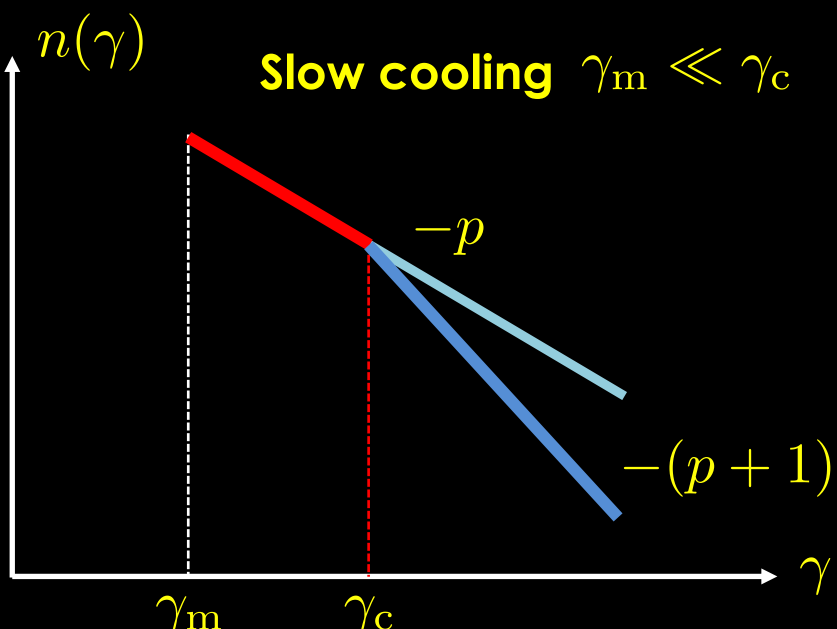
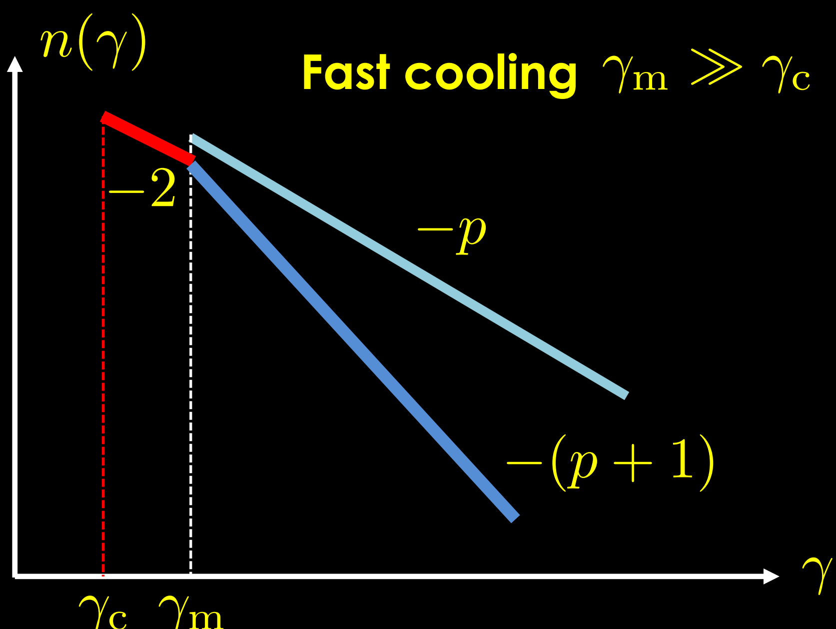
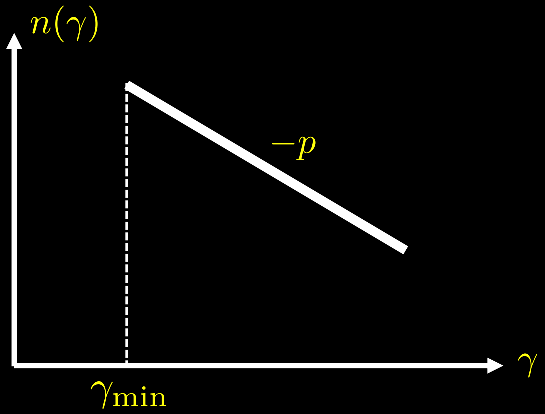


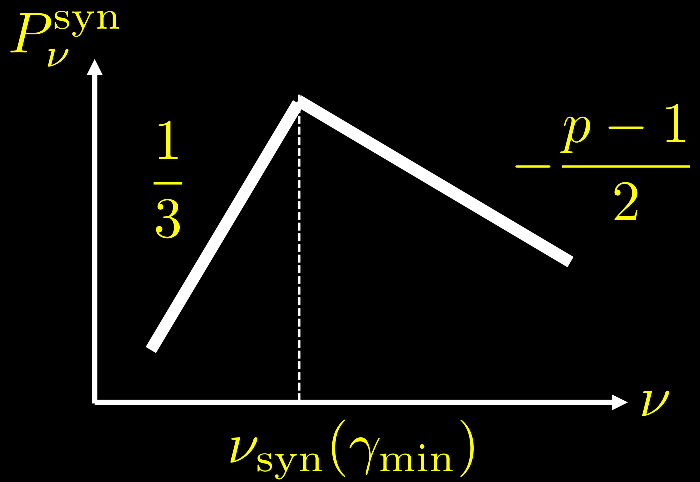


Synchrotron Spectrum

Sari, Piran, Narayan 1998

- **Synchrotron spectral power of a power-law distribution:**





$$\nu_{\rm syn}(\gamma) \propto B\gamma^2$$

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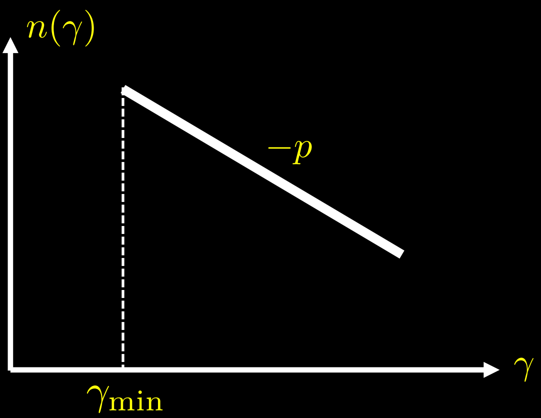
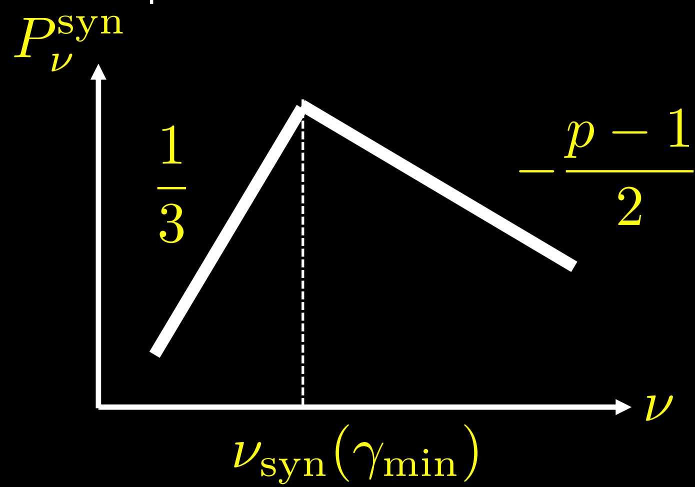
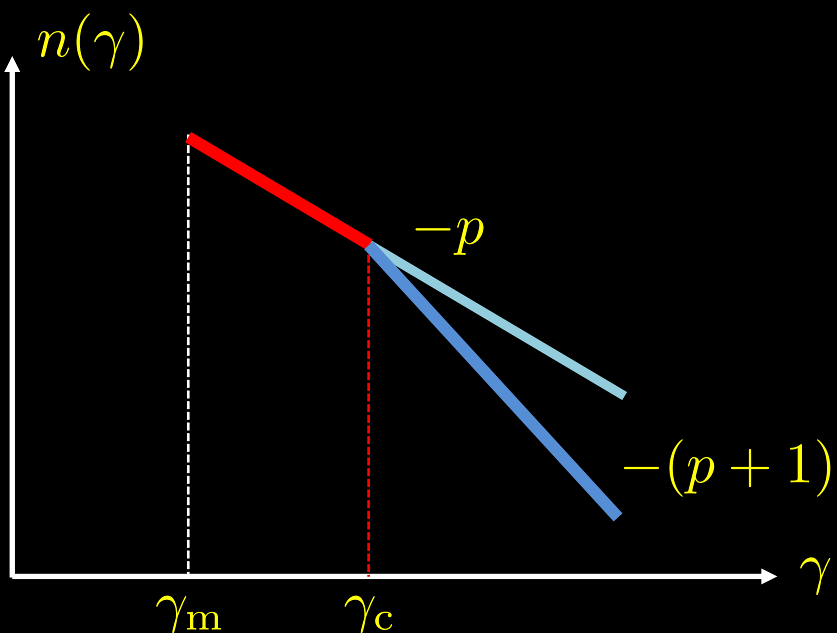


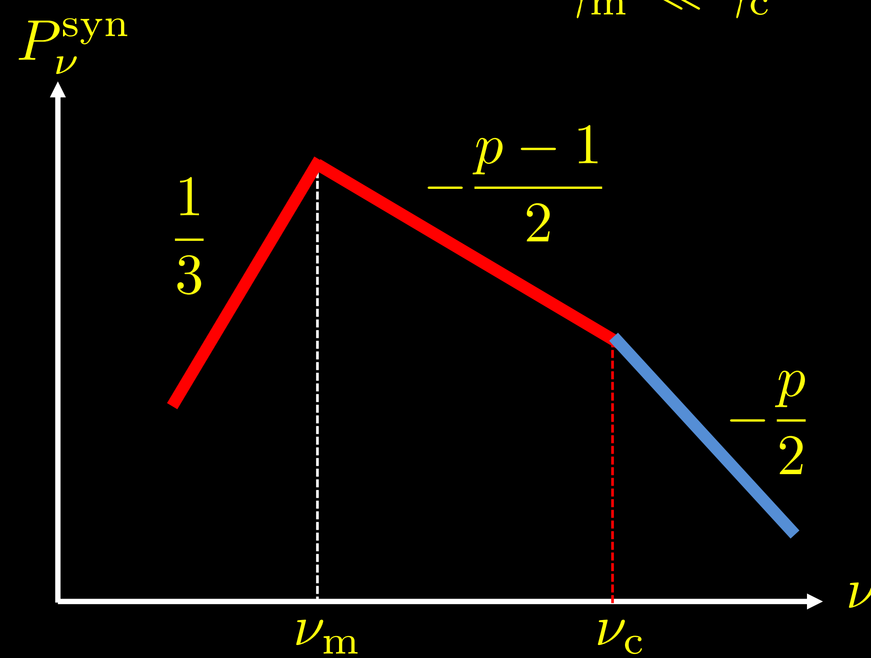


$$\nu_{\rm syn}(\gamma) \propto B\gamma^2$$

- **Synchrotron slow cooling spectrum:**

$$\gamma_{\rm m} \ll \gamma_{\rm c}$$





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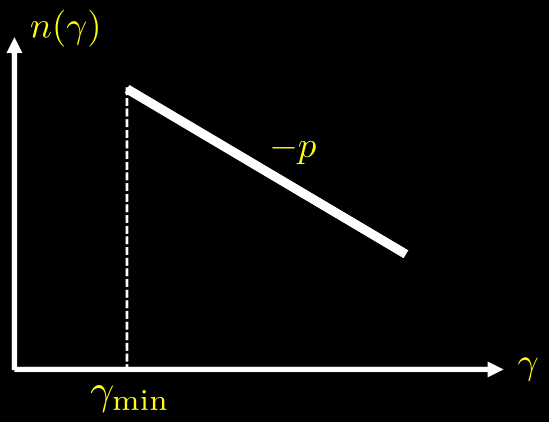
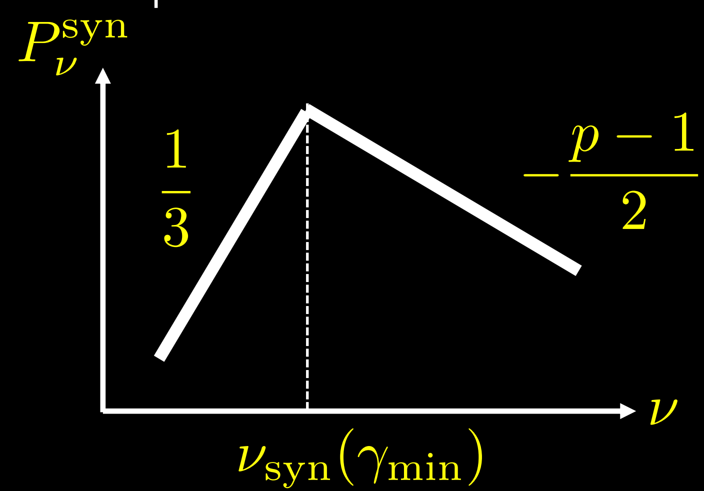
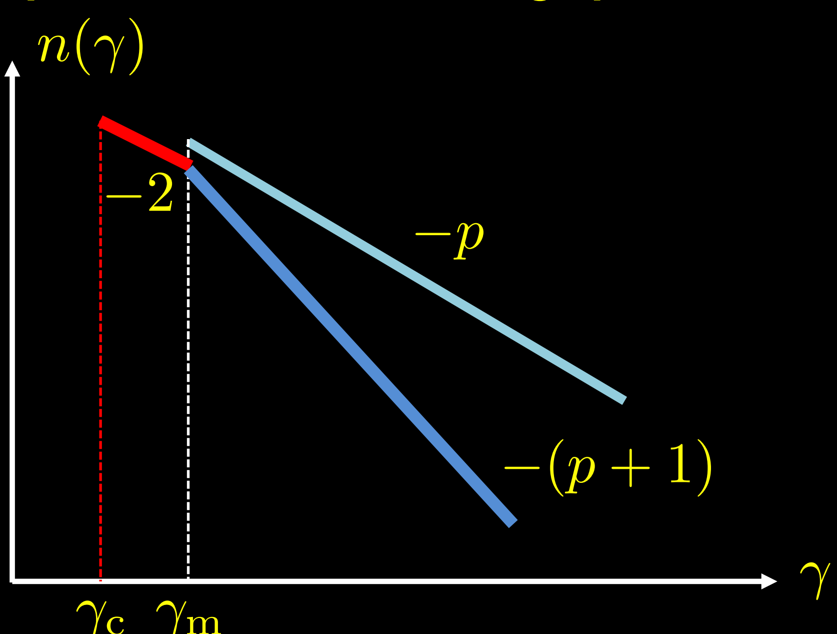


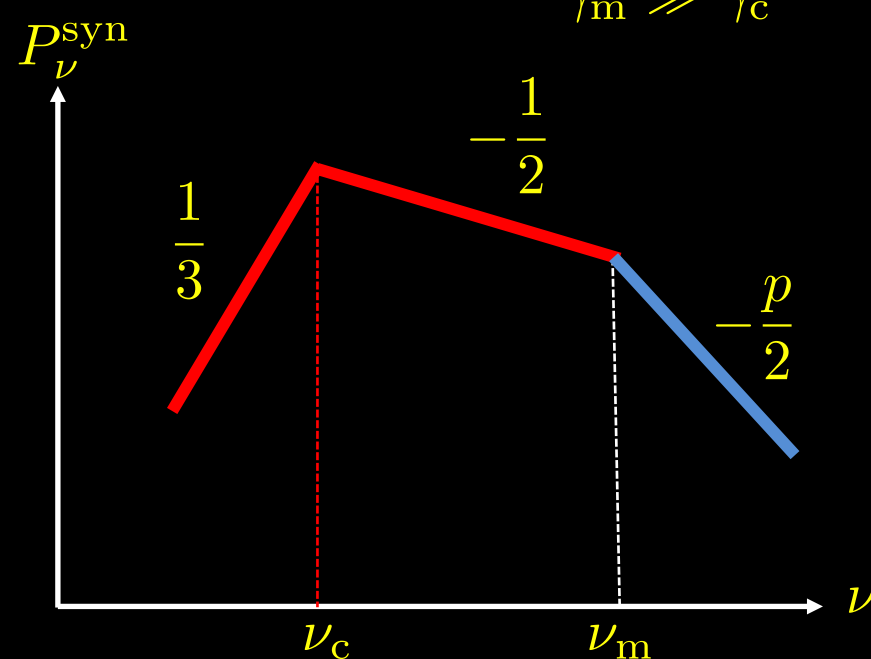


$$\nu_{\rm syn}(\gamma) \propto B\gamma^2$$

- **Synchrotron fast cooling spectrum:**

$$\gamma_{\rm m} \gg \gamma_{\rm c}$$





Prompt emission: many difficult open questions…

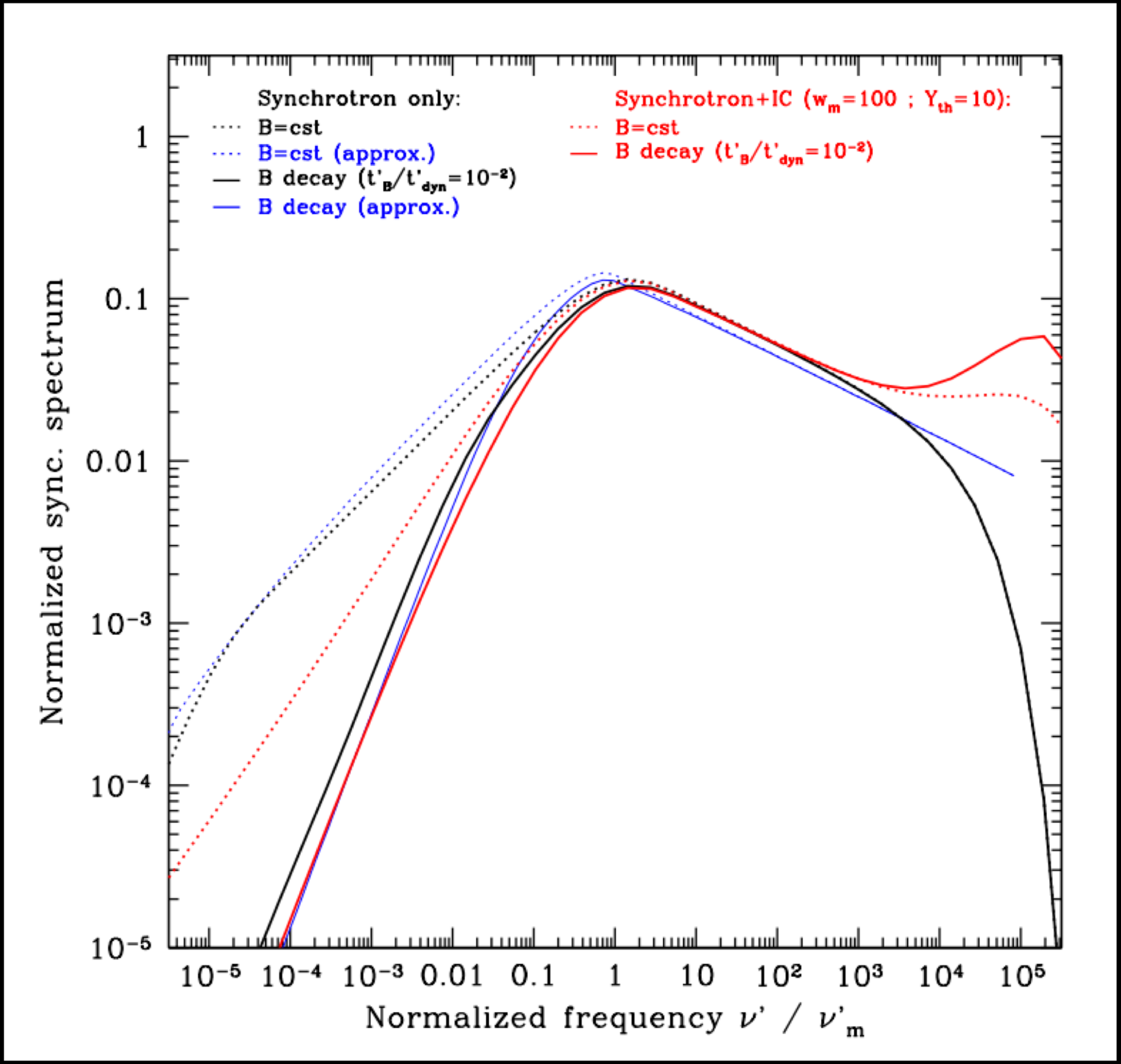
- Spectral shape: observational point of view: unclear
  - fit by phenomenological models: shape is forced: see recent work by Burgess, Yassine & Piron, Ravasio et al., Toffano et al., etc.)
  - How steep is the low-energy photon-index? (Synchrotron: $-\alpha < -2/3$)
- Theoretical point of view: optically thin regime (synchrotron)
  - **Fast cooling:** $\alpha = 3/2$ (Sari, Piran, Narayan 98)
  - Inverse Compton in KN regime: $\alpha \rightarrow 1$ (Derishev, Daigne & Bosnjak)
  - Marginally fast-cooling: $\alpha \rightarrow 2/3$ (Daigne +11 ; Beniamini & Piran 13)
  - (decaying magnetic field ? Daigne & Bosnjak in preparation)

$$t_{\rm plasma} \ll t_{\rm rad}(\gamma_{\rm m}) \ll t_{\rm dyn}$$

Structure of the magnetic field seen by cooling electrons?

- Theoretical point of view: optically thick regime (dissipative photosphere)
  - Nature of the dissipation process?
  - Too steep low-energy photon-index ?
  - Spectral evolution?
  - Lightcurves? Prompt-to-afterglow transition?
  - Etc.

Synchrotron radiation



Daigne & Bosnjak in prep.

Prompt emission

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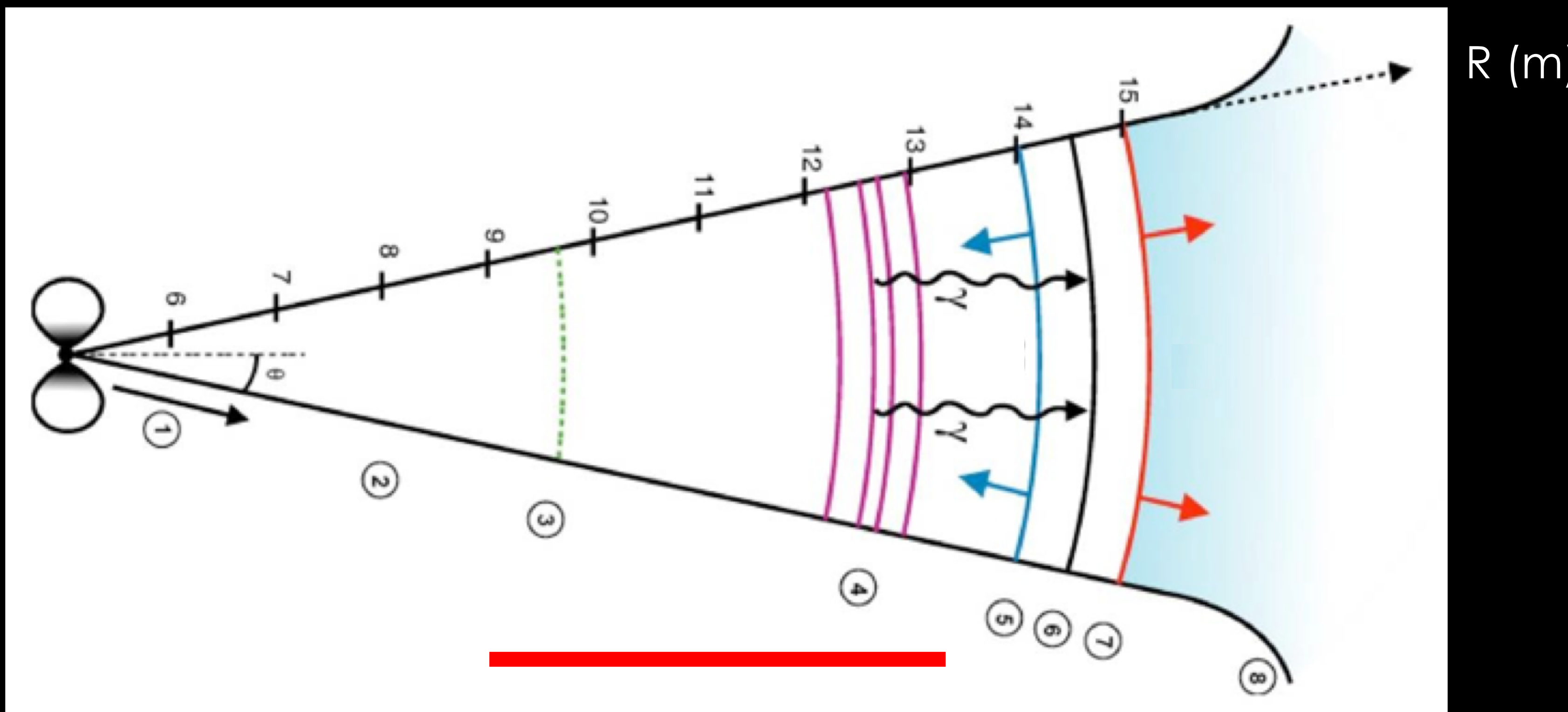
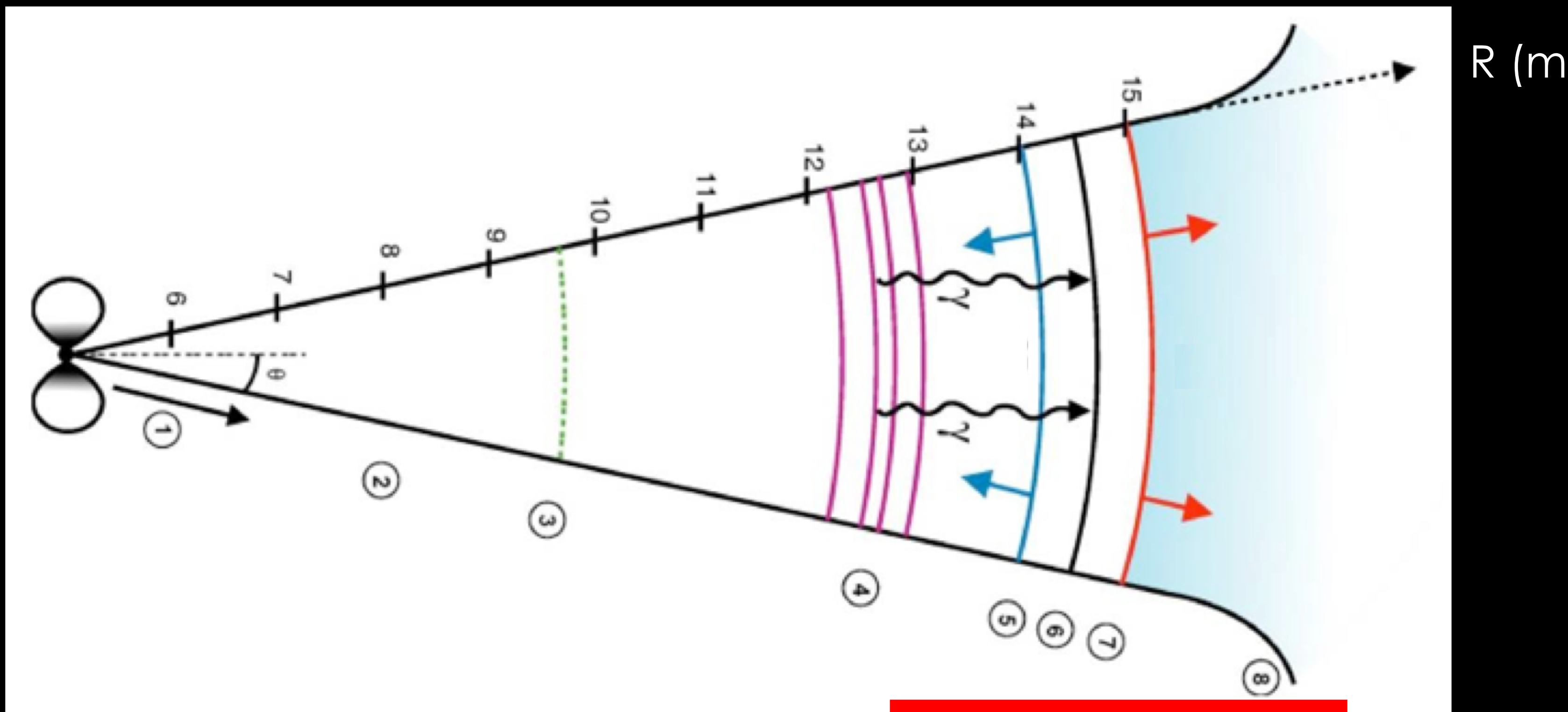


Internal dissipation / radiation processes:
- (Dissipative) Photosphere? (thermal + comptonization)
- Internal shocks? (synchrotron + IC)
- Reconnection? (synchrotron + IC)

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

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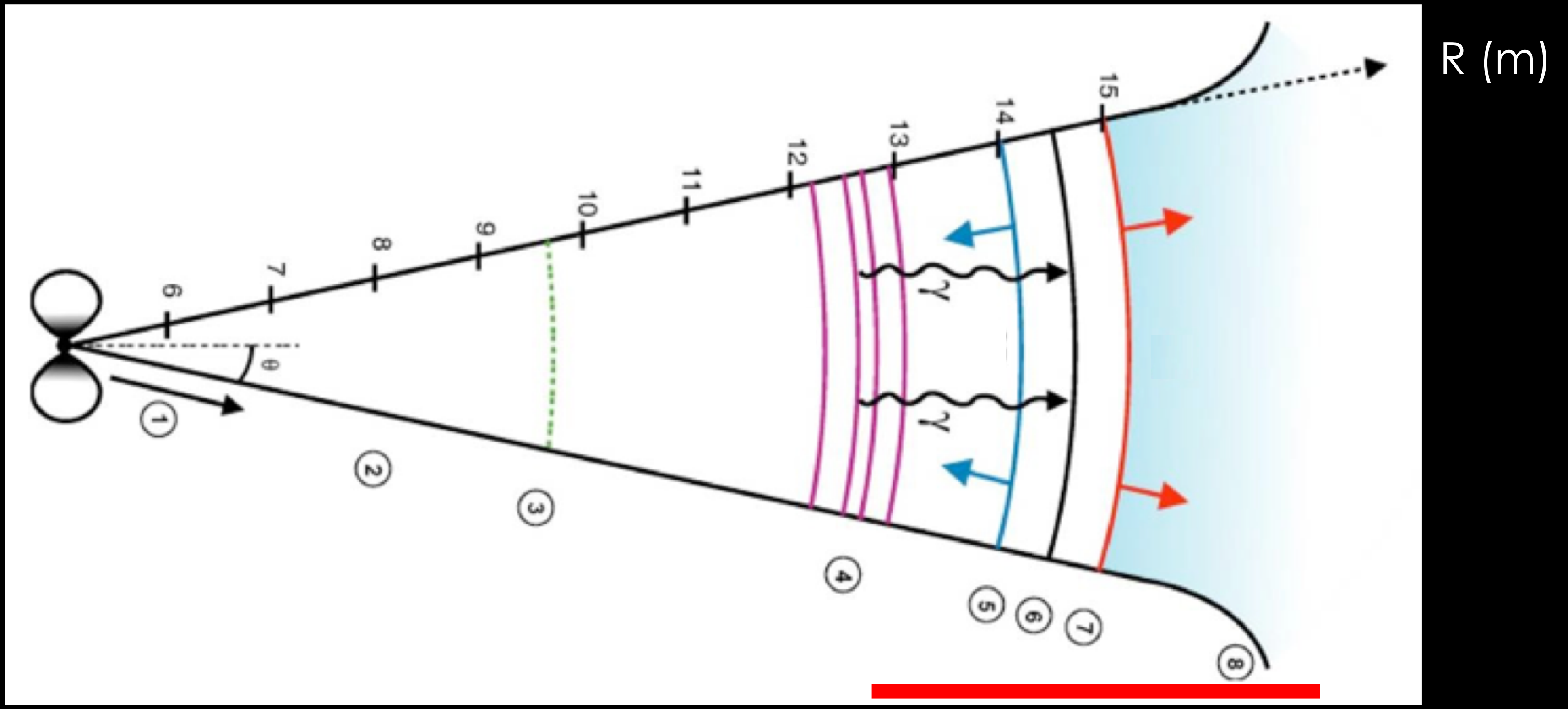


Deceleration radius and transition to the non-relativistic regime:

$$R_{\rm dec} \simeq \left(\frac{3}{4\pi}\frac{\mathcal{E}_{\rm kin,0}}{\Gamma_0^2 n_{\rm ext} m_{\rm p} c^2}\right)^{1/3} \simeq 1.5\,10^{17}\,{\rm cm}\left(\frac{\Gamma_0}{100}\right)^{-2/3}\left(\frac{\mathcal{E}_{\rm kin,0}}{10^{53}\,{\rm erg}}\right)^{1/3}\left(\frac{n_{\rm ext}}{1\,{\rm cm}^{-3}}\right)^{-1/3}$$

$$R_{\rm Newton} \simeq \left(\frac{3}{4\pi}\frac{\mathcal{E}_{\rm kin,0}}{n_{\rm ext} m_{\rm p} c^2}\right)^{1/3} \simeq 3.2\,10^{18}\,{\rm cm}\left(\frac{\mathcal{E}_{\rm kin,0}}{10^{53}\,{\rm erg}}\right)^{1/3}\left(\frac{n_{\rm ext}}{1\,{\rm cm}^{-3}}\right)^{-1/3}$$

Afterglow

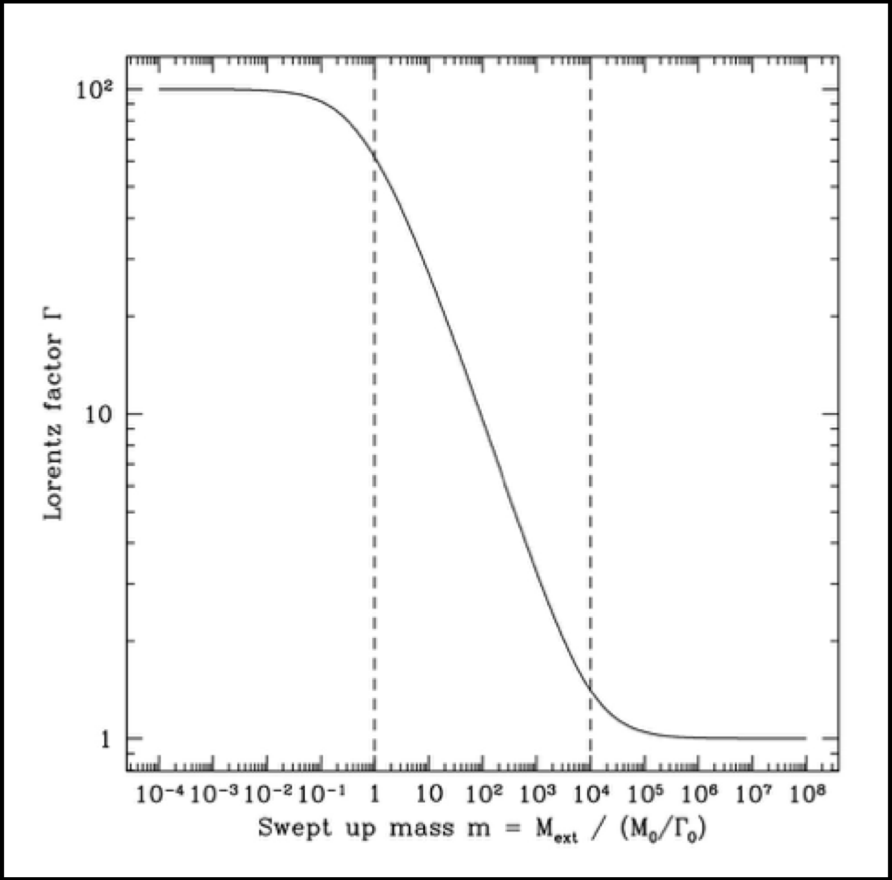
$$R_{\rm dec} \longleftrightarrow M_{\rm ext} \simeq \frac{M_0}{\Gamma_0}$$

Blandford & McKee:

$$\Gamma \simeq \Gamma_0 \quad \text{if} \quad R \ll R_{\rm dec}$$

$$\Gamma \simeq \Gamma_0 \left(\frac{R}{R_{\rm dec}}\right)^{-3/2} \quad \text{if} \quad R_{\rm dec} \ll R \ll R_{\rm Newton}$$

$$\Gamma \simeq 1 \quad \text{if} \quad R \gg R_{\rm Newton}$$ (Sedov: $\beta \propto R^{-3/2}$)



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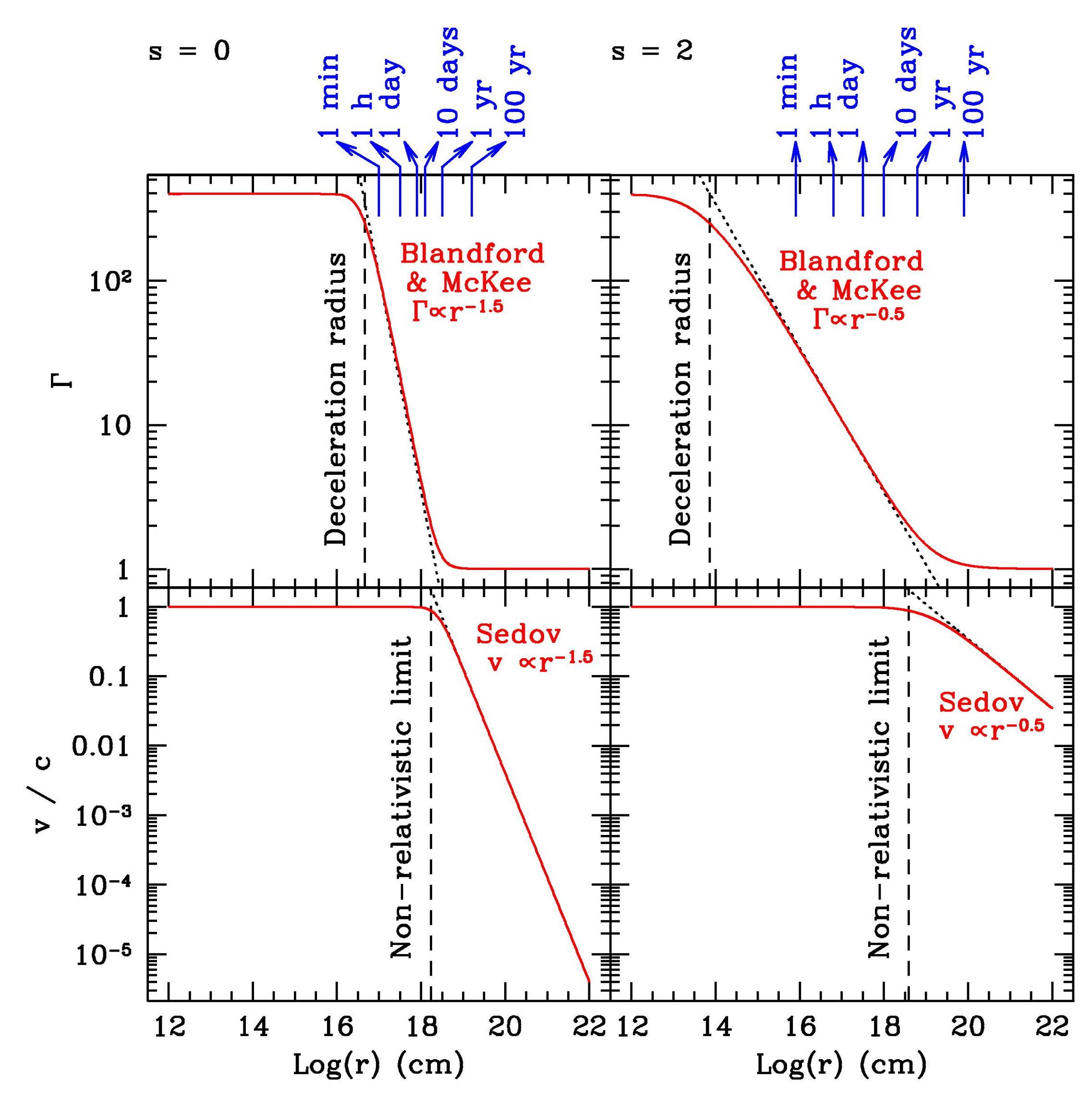
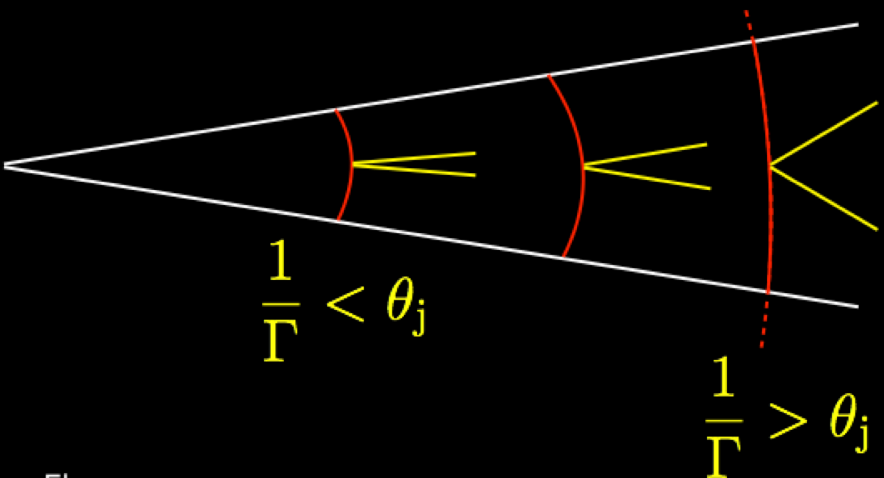
Afterglow

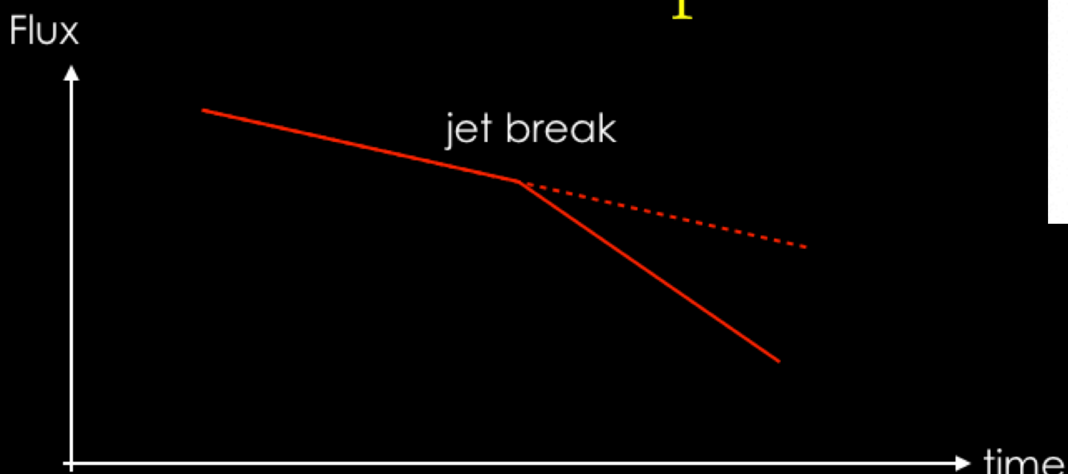


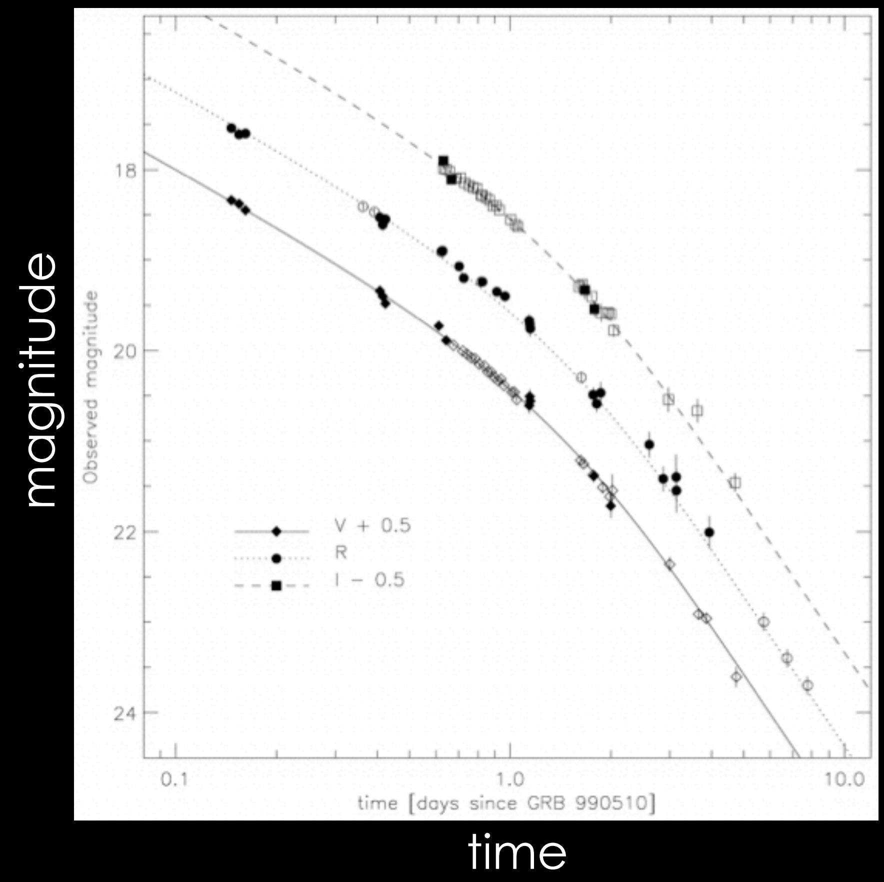
$$t_{\rm obs} = \left(\frac{D}{c}\right) + \int_0^R \frac{{\rm d}R}{2\Gamma^2 c}$$

Afterglow: jet break

Jet break: an achromatic break in the lightcurve which allows to estimate the opening angle of the jet (Rhoads).







GRB 990510
(Harrison et al. 1999)

Afterglow: jet break

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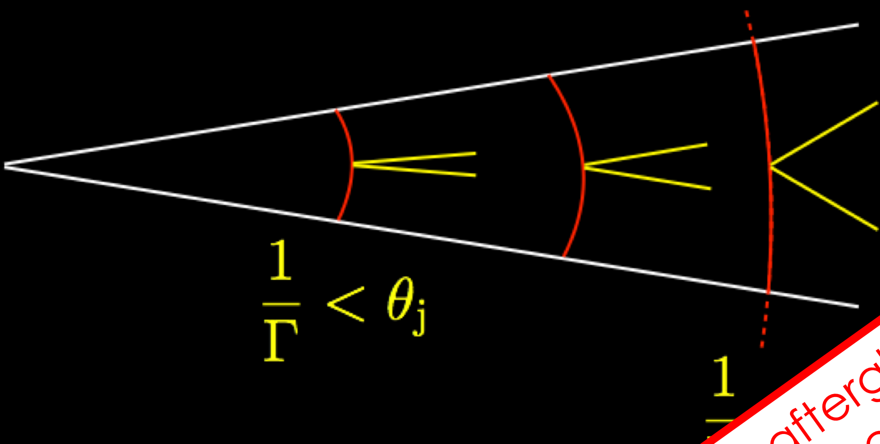
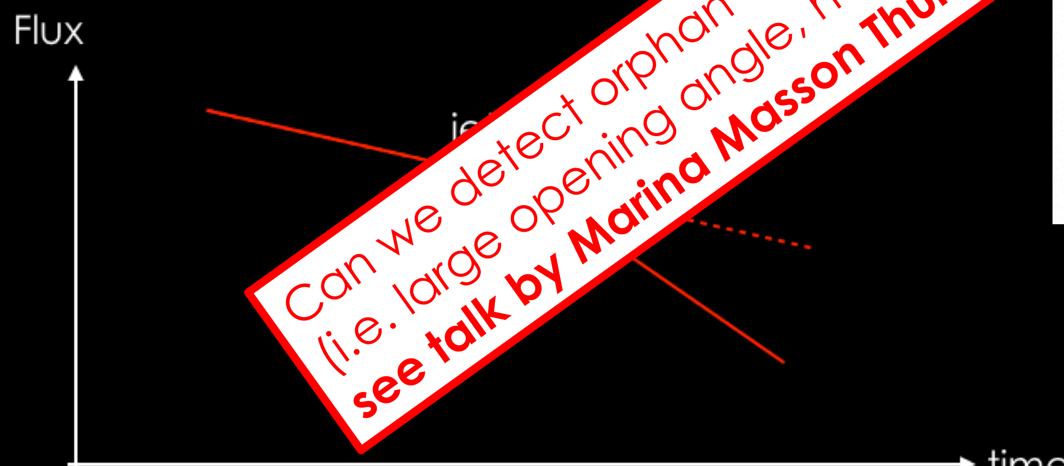
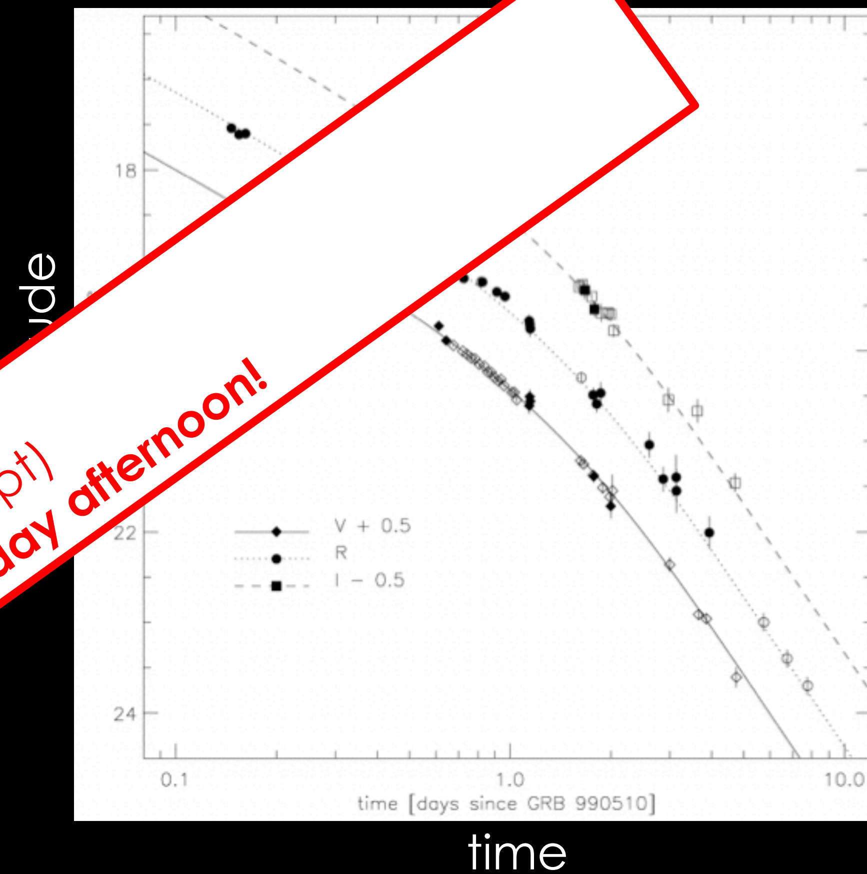




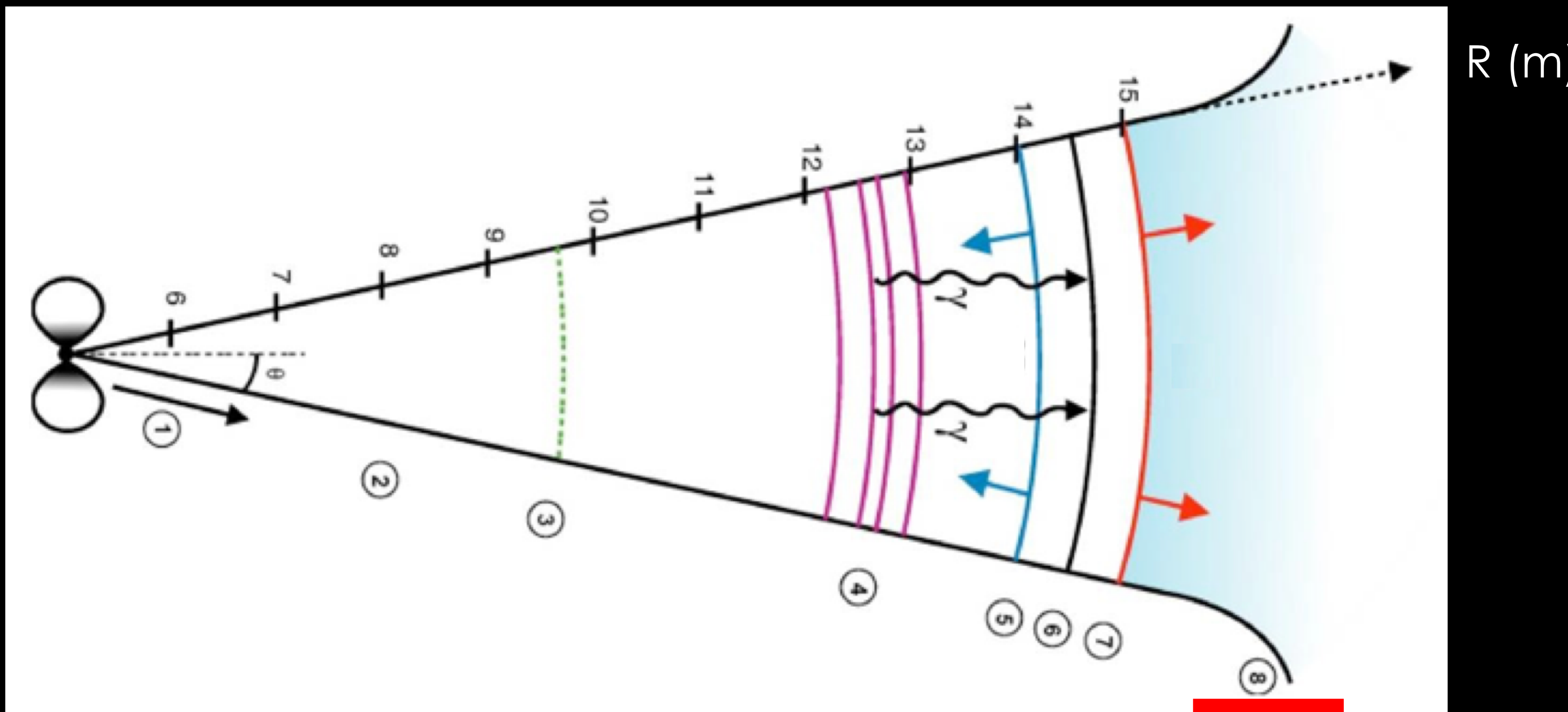
Can we detect orphan afterglows?
(i.e. large opening angle, no prompt)
see talk by Marina Masson Thursday afternoon!



GRB 990510
(Harrison et al. 1999)

Afterglow

Late evolution: lateral spreading? ($\frac{c_s}{\Gamma} \ll c$ in the ultra-relativistic phase)



Afterglow emission

Synchrotron emission from shock-accelerated electrons
Magnetic field?

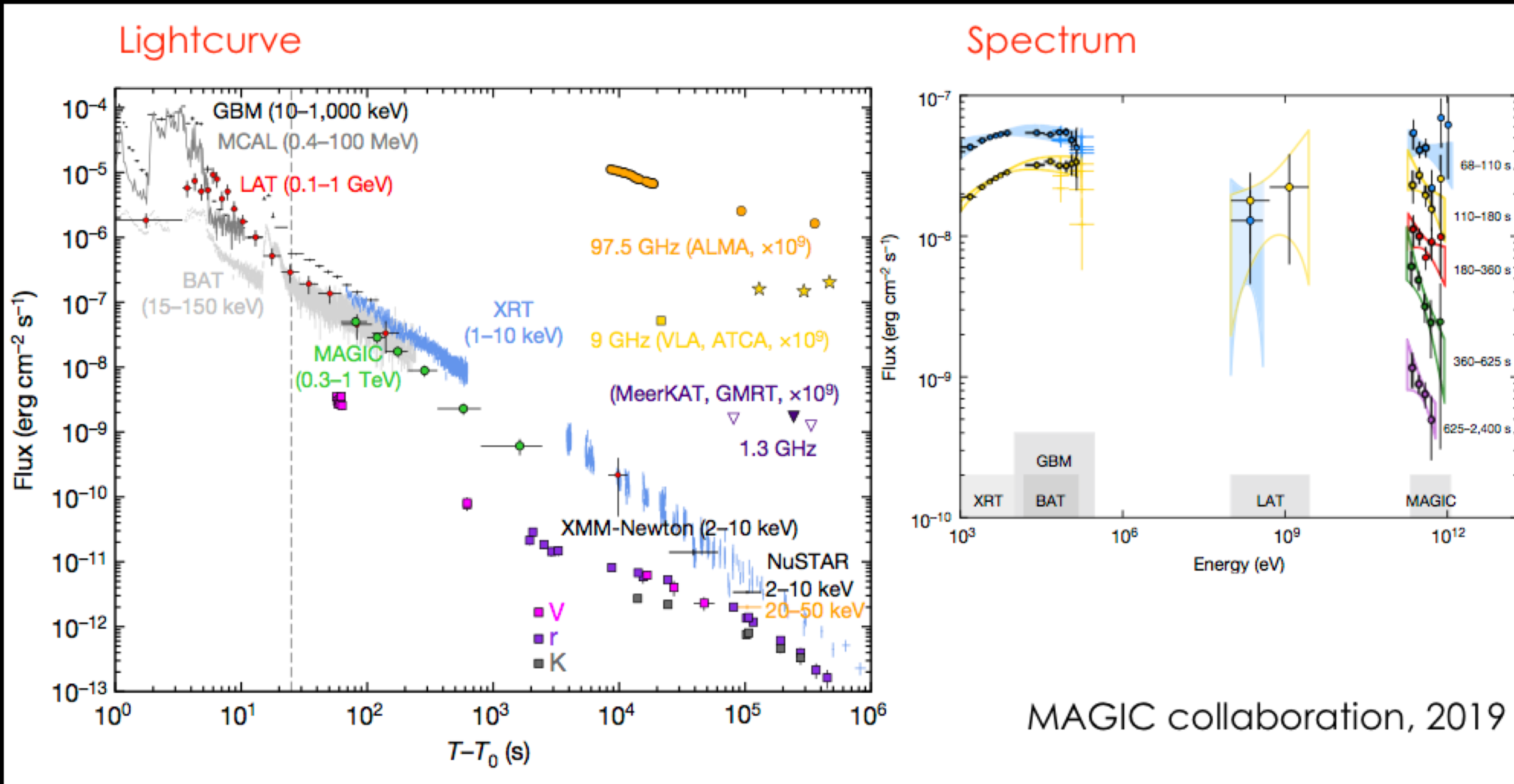
$t_{\rm plasma} \ll t_{\rm dyn} \ll t_{\rm rad}(\gamma_{\rm m})$ (slow cooling)

Microphysics usually parametrized in a very simple way: constant fraction of accelerated electrons, constant fraction of energy injected in accelerated electrons, etc…

Radio to X-rays: good fits but high degeneracy among parameters

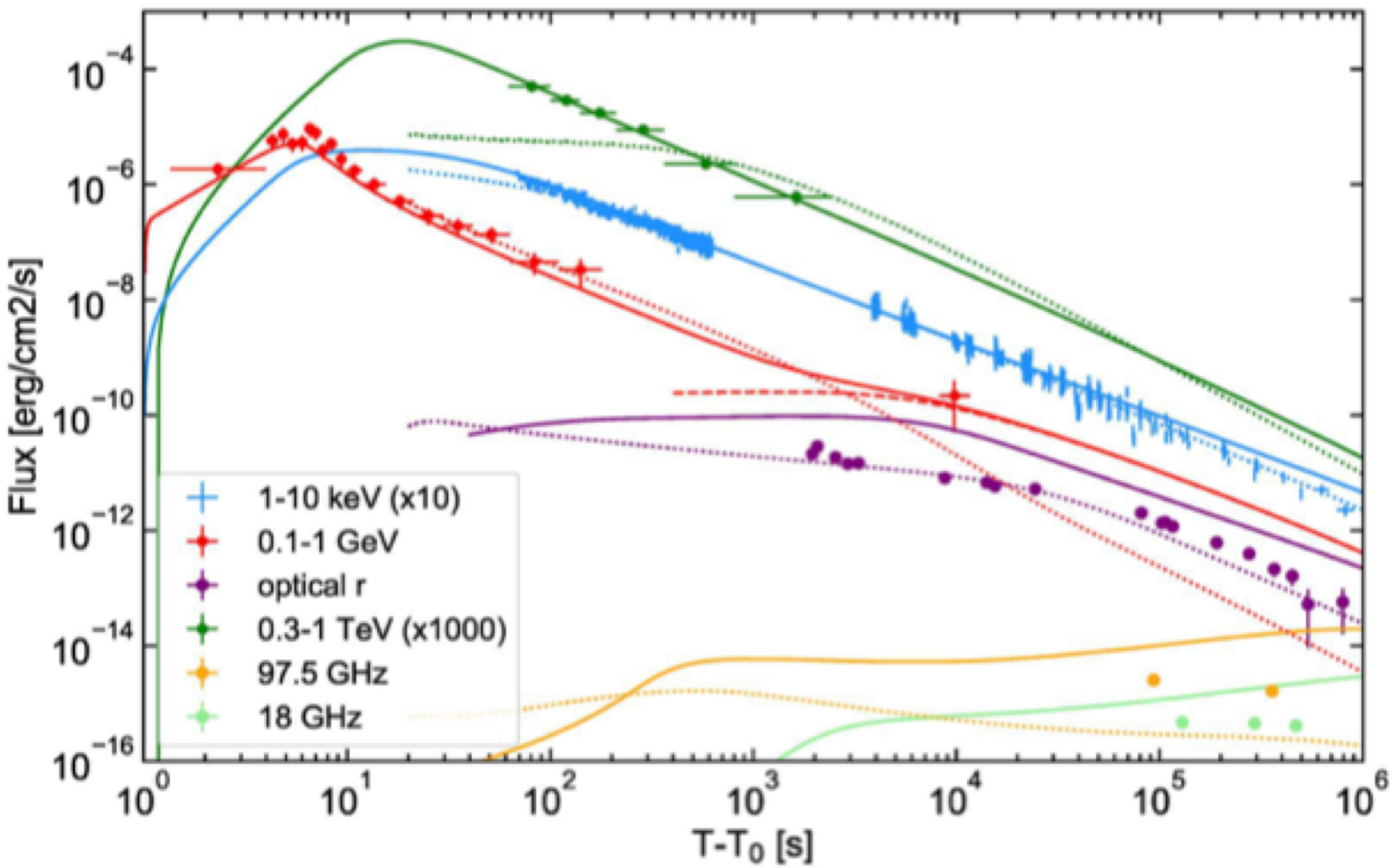
Recent TeV detections: reasonnable fits with synchrotron + IC, better determined parameters

GRB 190114C (MAGIC)



Observations from 1 min to 12 days
radio, NIR, X-rays, Soft γ-rays, HE γ-rays, VHE γ-rays)

GRB 190114C (MAGIC)



$s = 0, \varepsilon_e = 0.07, \varepsilon_B = 8 \times 10^{-5}, p = 2.6, n_0 = 0.5$ and $E_k = 8 \times 10^{53}$ erg

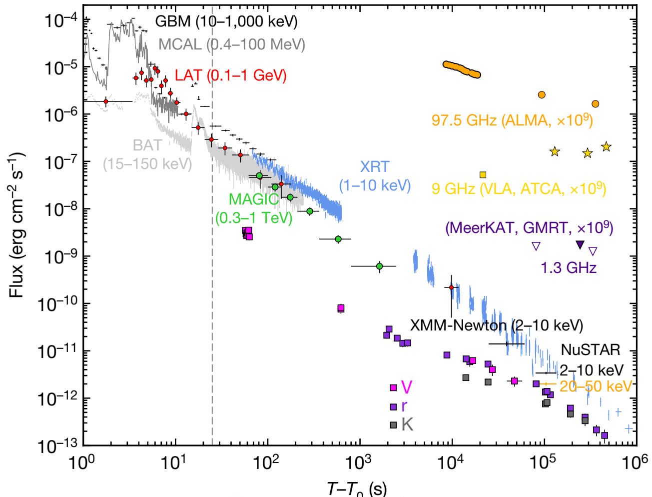
Nava+ 19

GRB afterglows in the TeV range: several detections

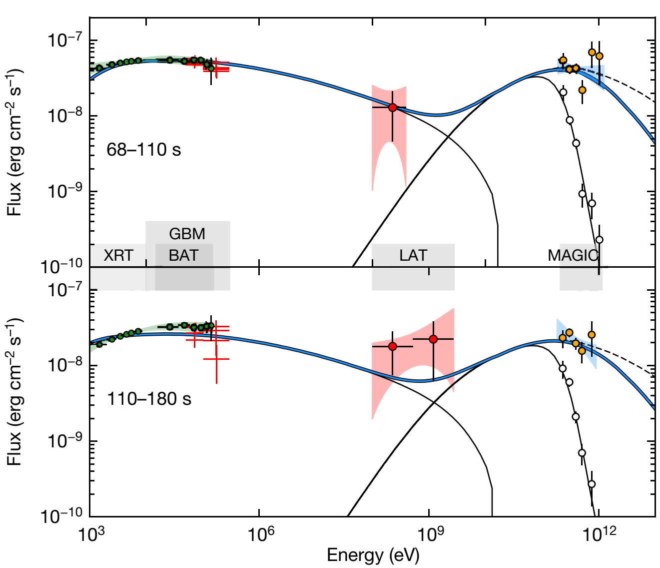
Already at least four GRBs detected at VHE (afterglow):

180720B (HESS) ; 190114C (MAGIC) ; 190829A (HESS) ; 201216C (MAGIC)

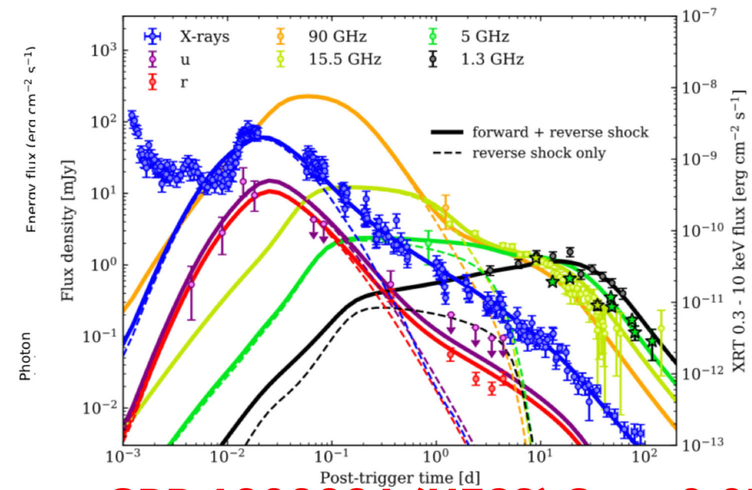
+ GRB 201009A (the BOAT) / LHASSO
+ some other candidates



GRB 190114C (MAGIC) @ z=0.14

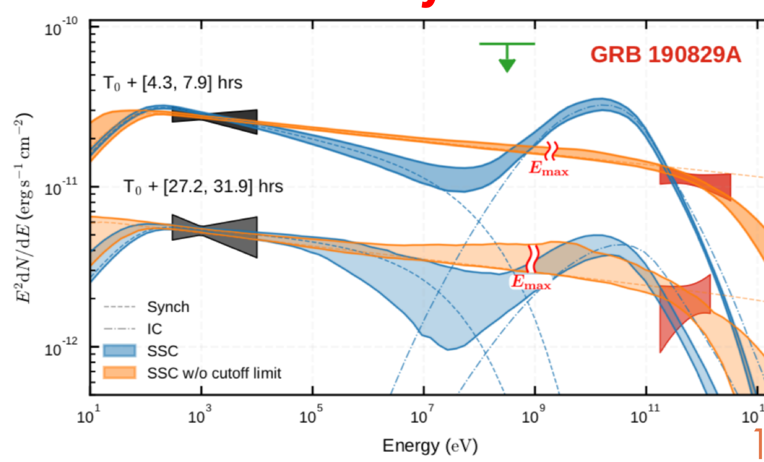


MAGIC collab. 2019a,b



Salafia et al. 2021

GRB 190829A (HESS) @ z = 0.0785
A low-luminosity burst



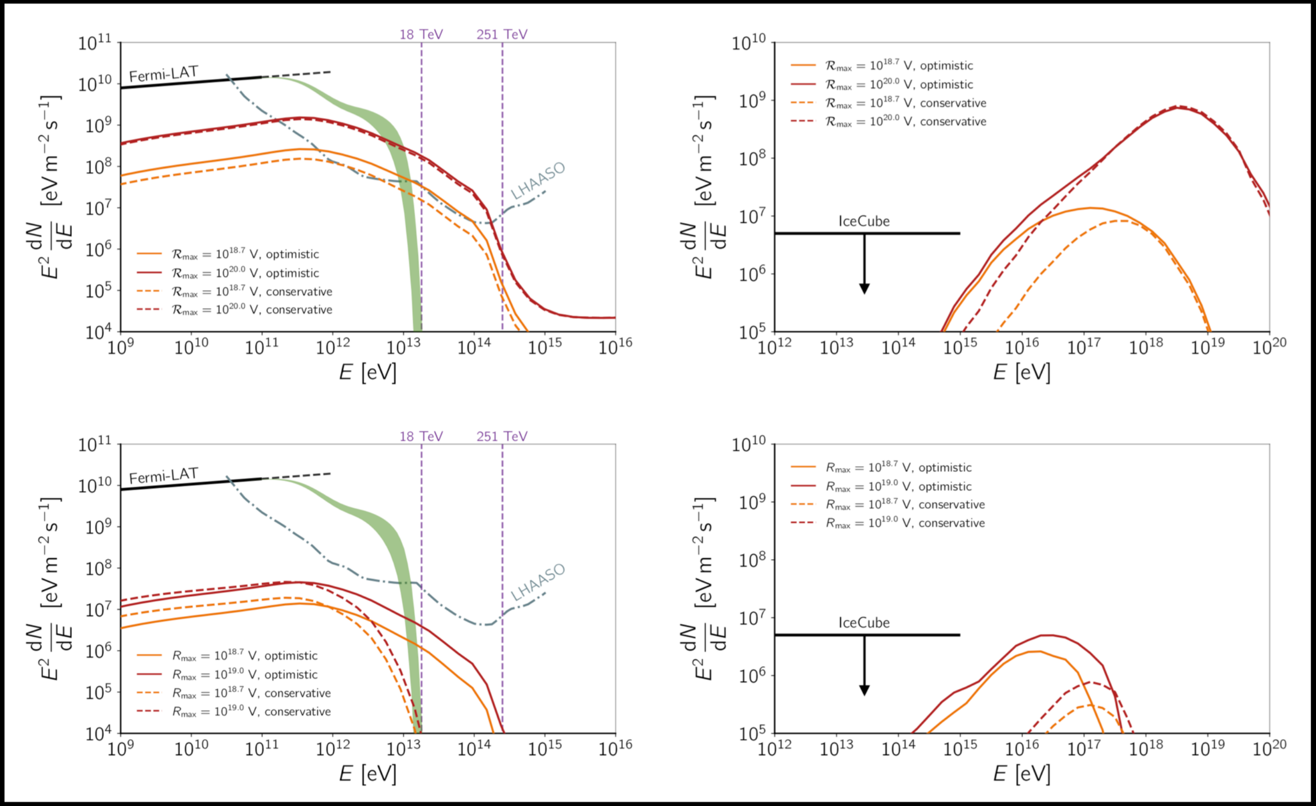
HESS collab. 2021

A 18 TeV photon associated with GRB221009A (the BOAT)?

- Fermi LAT: up to 400 GeV (Xia et al. 2022a,b)
- LHASSO, GCN #32677 (Huang et al. 2022): >5000 VHE photons (>500 GeV)
  - LHASSO detection during the first 2000 s:
    Prompt or early afterglow (prompt in soft γ-rays ~600 s)
  - LHASSO detects VHE photons up to E_{max} ~18 TeV:
    Strong tension with EBL

- **Production of UHCRs+interaction during propagation?** (interaction with CMB/CRB)

Photons | Neutrinos



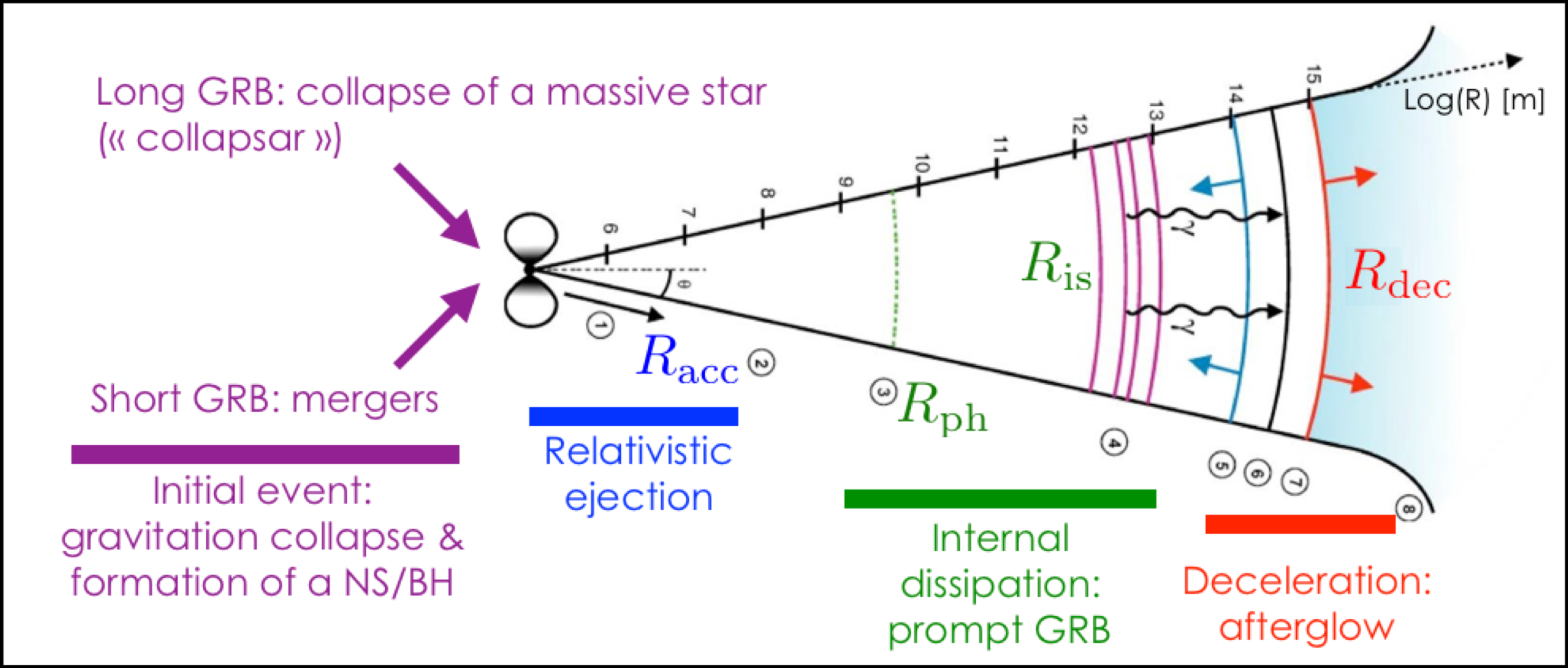
Light UHECRs (p)

Different models: intergalactic B (must be weak)

Heavier UHECRs

Alves Batista 2022

Summary



Acceleration

$$R_{\rm acc} \simeq \Gamma R_0 \simeq 10^9\,\mathrm{cm}\left(\frac{\Gamma}{100}\right)\left(\frac{R_0}{100\,\mathrm{km}}\right)$$

Internal dissipation

$$R_{\rm ph} \simeq \frac{\dot{E}\kappa_{\rm T}}{8\pi\Gamma^3 c^3} \simeq 6\,10^{12}\,\mathrm{cm}\left(\frac{\dot{E}}{10^{52}\,\mathrm{erg/s}}\right)\left(\frac{\Gamma}{100}\right)^{-3}$$

$$R_{\rm is} \simeq 2\Gamma^2\Delta \simeq 6\,10^{14}\,\mathrm{cm}\left(\frac{\Gamma}{100}\right)^2\left(\frac{\Delta/c}{1\,\mathrm{s}}\right)$$

Deceleration

$$R_{\rm dec} \simeq \left(\frac{3}{4\pi}\frac{\mathcal{E}_{\rm kin,0}}{\Gamma_0^2 n_{\rm ext} m_{\rm p} c^2}\right)^{1/3}$$

Complements on Emission

GRB Emission

In addition of already mentioned open questions (spectral shape of the prompt emission, nature of the internal dissipative process, etc.), there are mainy other active topics of research.

- Early afterglow: origin of flares, plateaus, spectral breaks, etc.
- Prompt-to-afterglow transition?
- Contribution of the Reverse Shock?
- Polarization?
- Following the 170817 event: signatures of the lateral structure, role of shock breakout, etc.
- Etc.

- **A very fundamental question: connecting the different scales (plasma, electron cooling, dynamics)**

- **An interesting question:** **CR acceleration?**
  High-energy neutrino emission?
  (photo-hadron interactions)

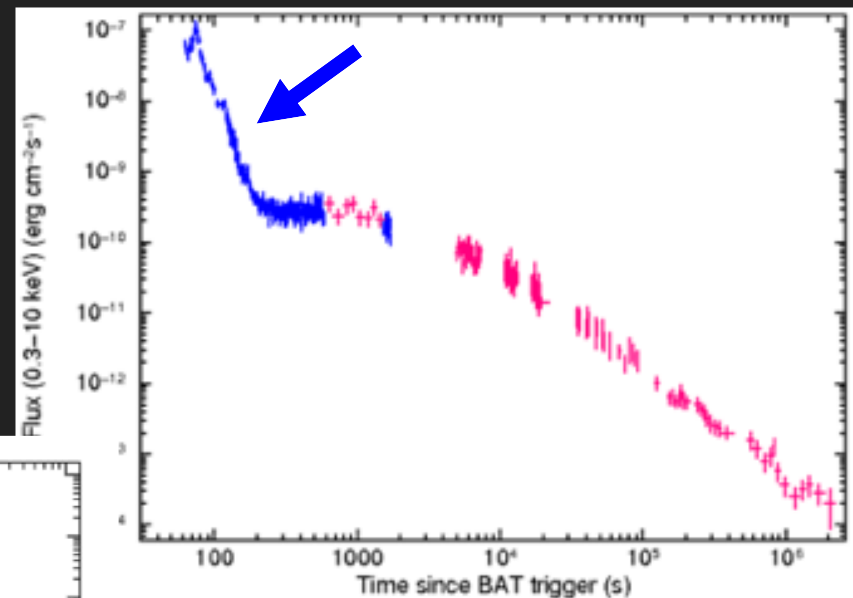
Prompt-to-afterglow transition: high latitude emission

Early steep-decay (X-rays) = high-latitude emission?

See e.g. Genet & Granot 2009

works if $R_{\rm prompt,end} \simeq \Gamma^2\, c\, t_{\rm burst}$ (OK for internal shocks/reconnection)

Photosphere: universal behaviour of the end of the relativistic ejection by the central engine?



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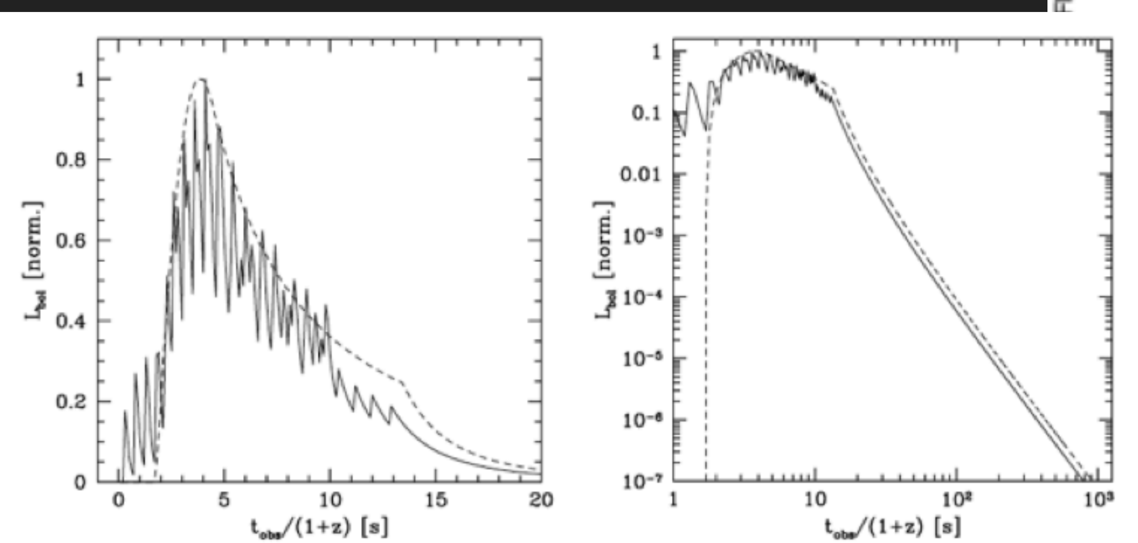


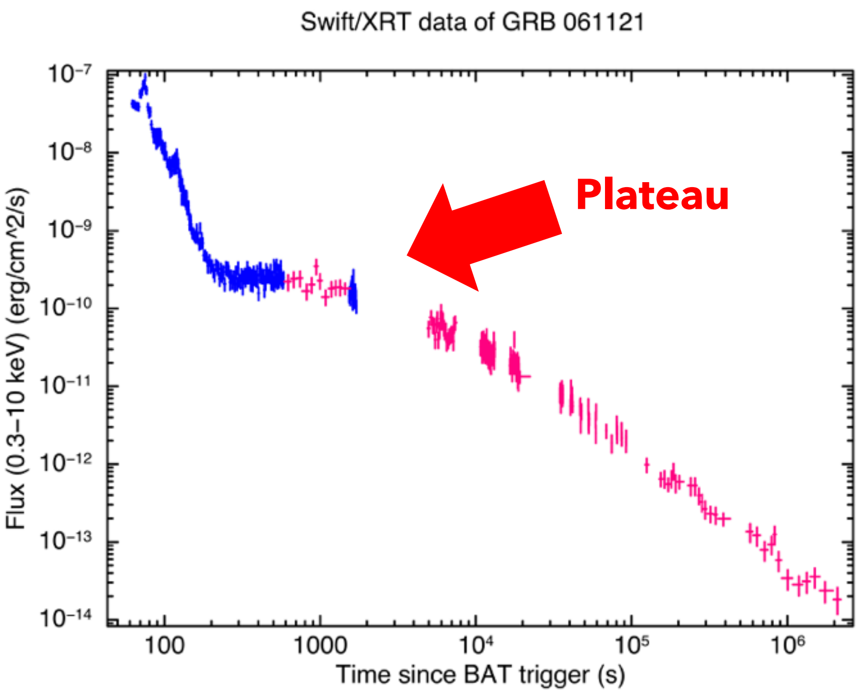
Hascoët, Daigne & Mochkovitch 2012

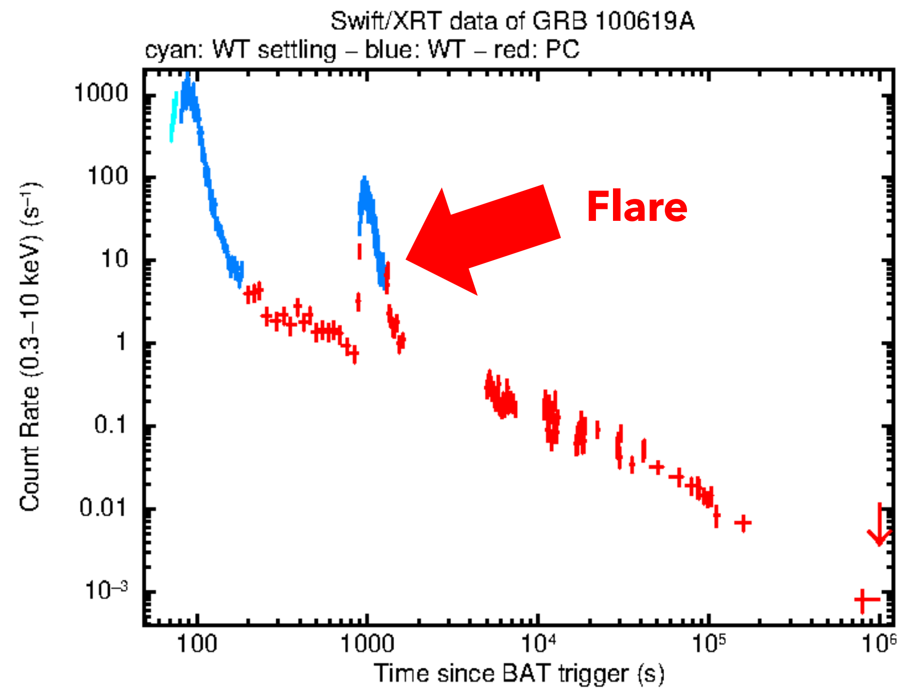
See however Ronchini et al. 2021

Early afterglow: some issues with the standard model

The early afterglow is difficult to model (plateaus, flares)

Puzzling features in the early X-ray afterglow (Swift/XRT)





Early afterglow: some issues with the standard model

The early afterglow is difficult to model (plateaus, flares)

- **Most discussed interpretation: late activity of the central engine**

  - **Plateaus: late energy injection?**
    = deceleration is delayed
    Problems: lifetime of the central engine? Energy crisis for the prompt?

  - **X-ray flares: late internal dissipation?**
    = same mechanism than for the prompt GRB + late ejection
    Problems: (a) some flares at very late times (10^3 s, 10^4 s) ;
    (b) flares show $\Delta t/t \sim cst$ = evolving variability?

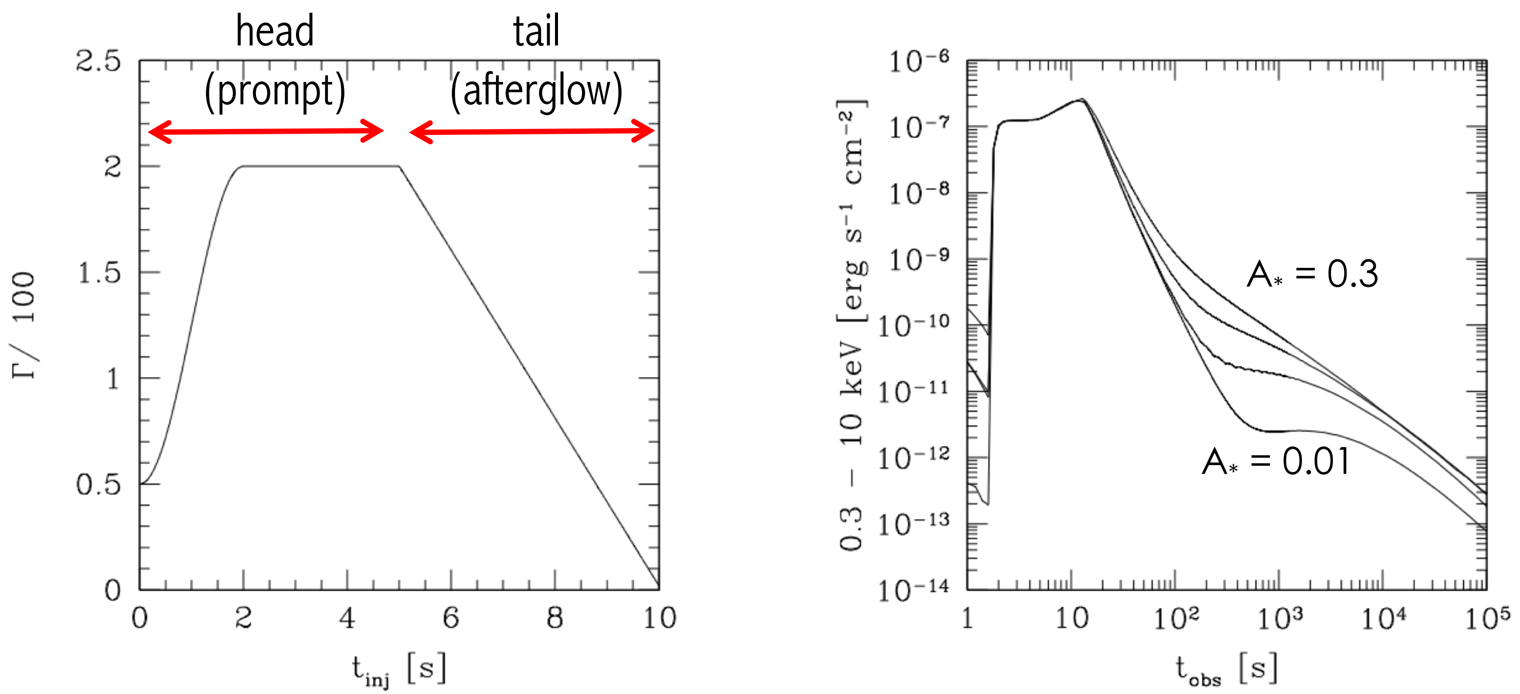
- Alternatives: many ideas

  - Long-lived Reverse Shock?

  - Signature of the lateral structure?

Long-lived Reverse Shocks?

- **Long lived reverse shock: constraint on the initial Lorentz factor in the ejecta** (Rees & Meszaros 98 ; Sari & Meszaros 00 ; Genet [FD] & Mochkovitch 07 ; Uhm & Beloborodov 07)
- **Dominant RS emission: constraint on microphysics RS vs FS (ε_e, ε_B)** (Genet [FD] et al. 07 ; Uhm & Beloborodov 07 ; Uhm [FD] et al. 11)



Initial Lorentz factor distribution

X-ray light-curves

Genet [FD] et al. 2007

$E_{kin,iso} = 2.10^{54}$ ergs ; z = 1

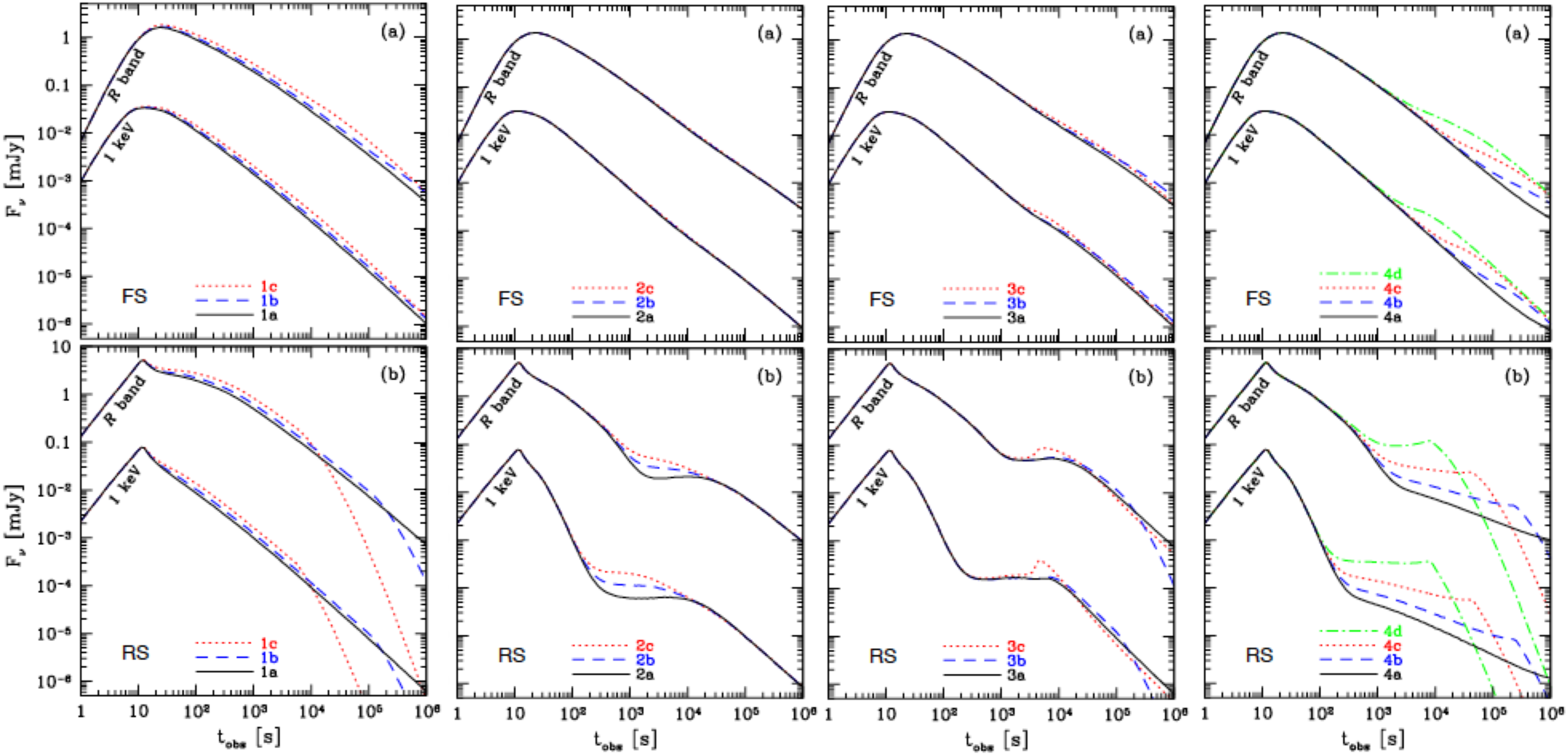
wind density profile $\rho(r) = A_* A_0 r^{-2}$ with $A_0 = 5\ 10^{-11}$ g cm^{-1}

Long-lived Reverse Shocks?

- **Long lived reverse shock: constraint on the initial Lorentz factor in the ejecta** (Rees & Meszaros 98 ; Sari & Meszaros 00 ; Genet [FD] & Mochkovitch 07 ; Uhm & Beloborodov 07)
- **Dominant RS emission: constraint on microphysics RS vs FS (ε_e, ε_B)** (Genet [FD] et al. 07 ; Uhm & Beloborodov 07 ; Uhm [FD] et al. 11)
- **No need for late energy injection**
- **Large diversity of possible lightcurves** (Uhm [FD] et al. 2012)
- Observed correlations between prompt and plateau properties are reproduced (Hascoët [FD] et al. 2013)
- **Flares can be due to overdensities in the low-Lorentz factor tail** (early internal shocks?) (Hascoët, Daigne, Beloborodov & Mochkovitch 2017)
- Hydrodynamical simulations: Lambert & Daigne 2017, Ayache, van Eerten & Daigne 2020)

Long-lived Reverse Shocks: diversity of lightcurves

Top: FS (very low sensitivity to the internal structure of the ejecta)



Bottom: RS

External medium: uniform 1 cm^{-3}

Relativistic ejecta: constant 10^{53} erg/s for 10 s – Source at z = 1

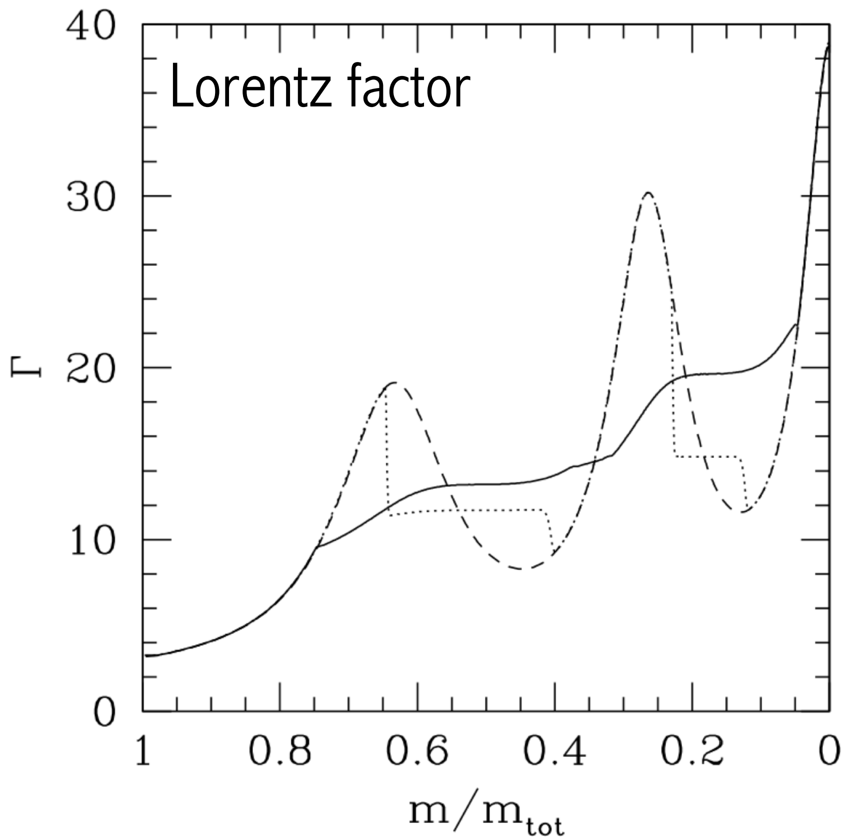
FS: $\epsilon_e = 10^{-2}$; $\epsilon_B = 10^{-4}$; p = 2.3 ; RS: $\epsilon_e = 10^{-1}$; $\epsilon_B = 10^{-2}$; p = 2.3

Uhm [FD] et al. 2011

Each case corresponds to a different initial distribution of the Lorentz factor

Long-lived Reverse Shocks: Flares

- Propagation of the RS in a radially structured ejecta
- Overdensities: signatures of internal shocks?



An exemple of the distribution of Lorentz factor in the ejecta: (relativistic hydro simulation)

- - - - Initial
------- During IS phase
——— End of IS phase (before deceleration)

Hascoët, Beloborodov, Daigne & Mochkovitch, 2017

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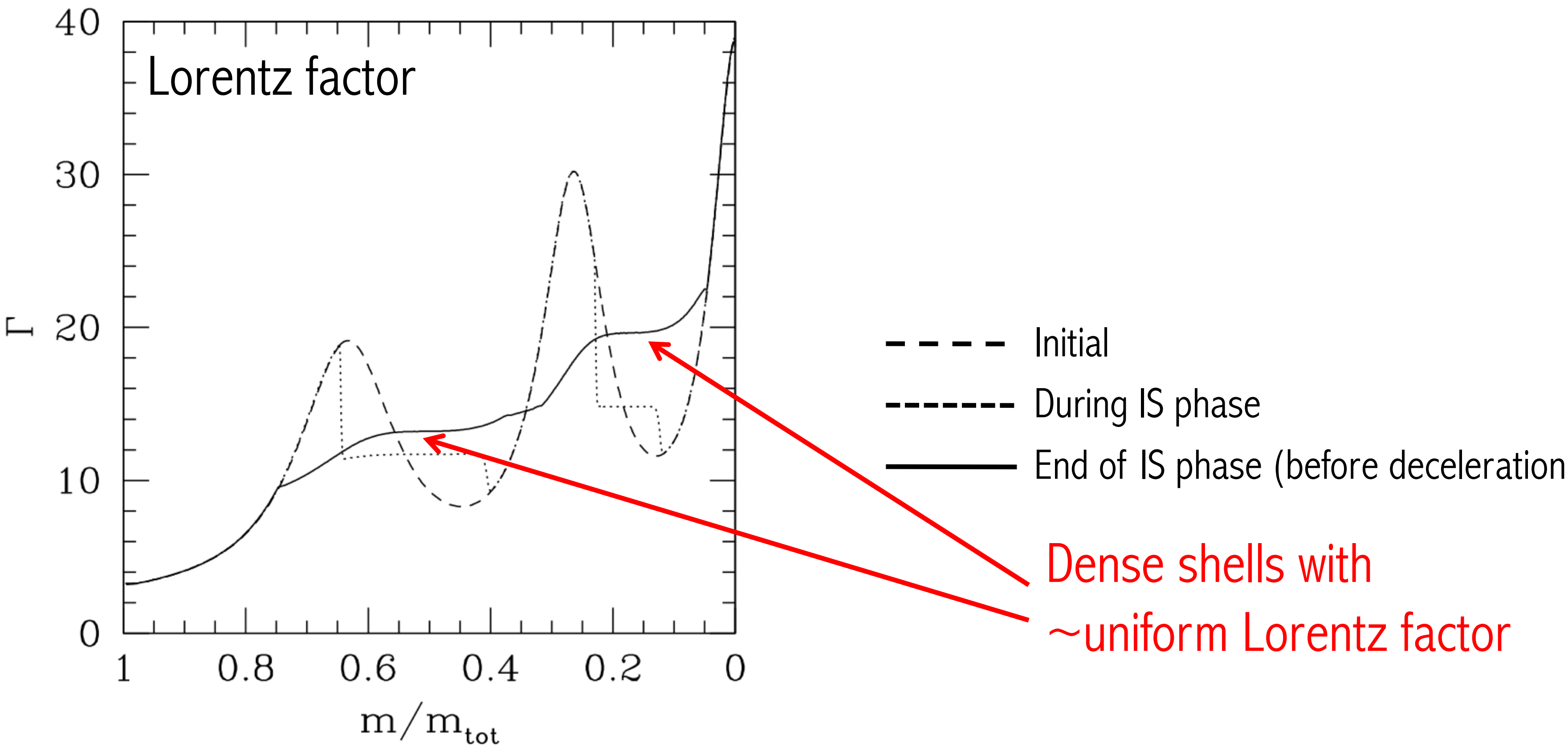

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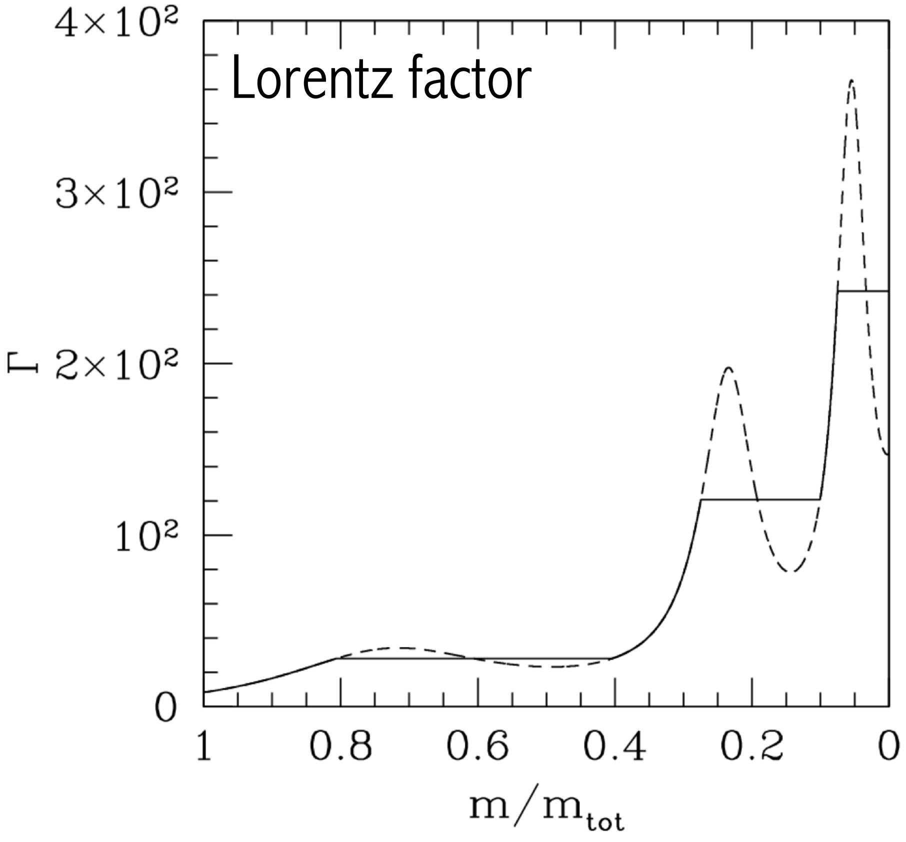

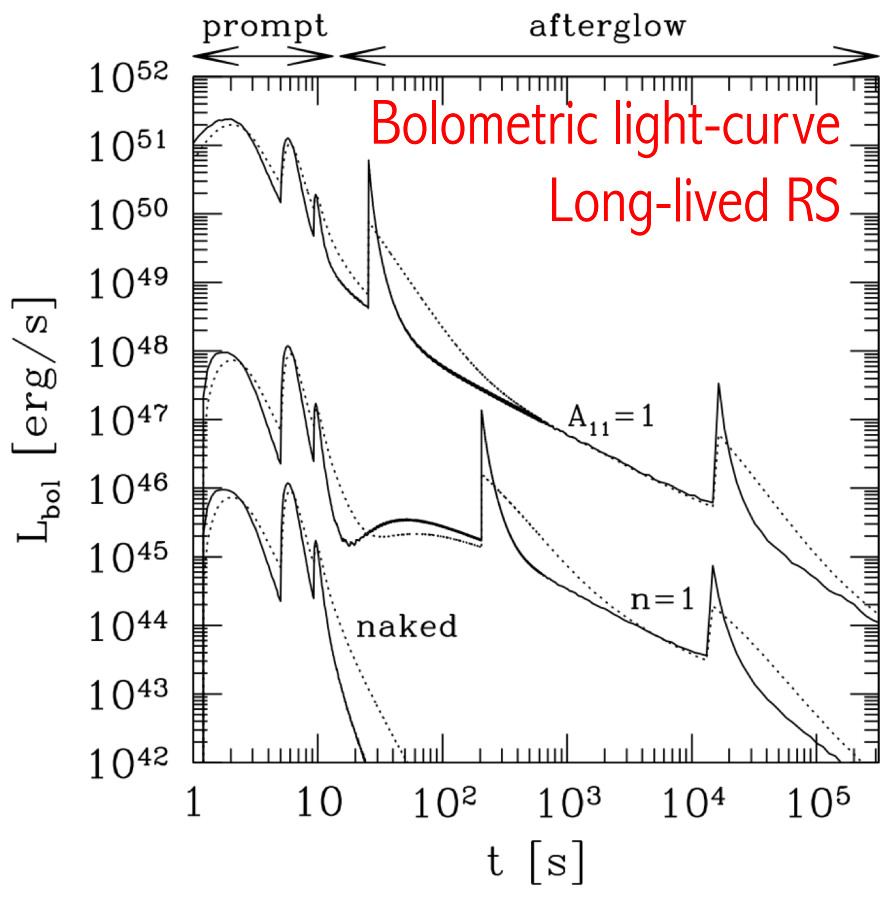

Hascoët, Beloborodov, Daigne & Mochkovitch, 2017

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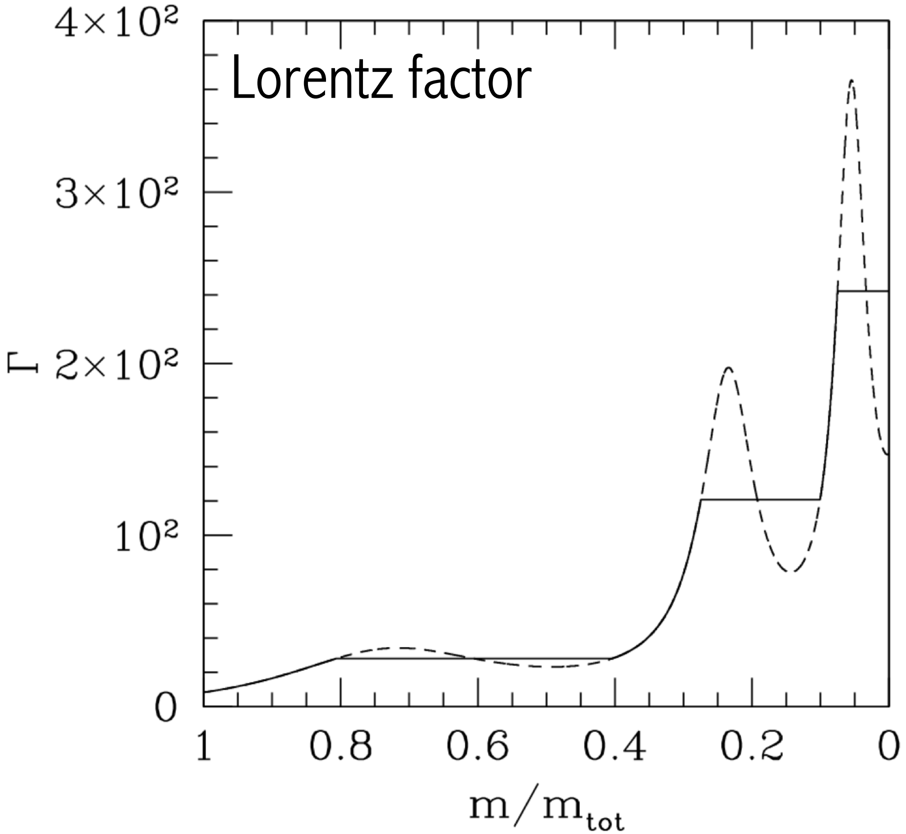
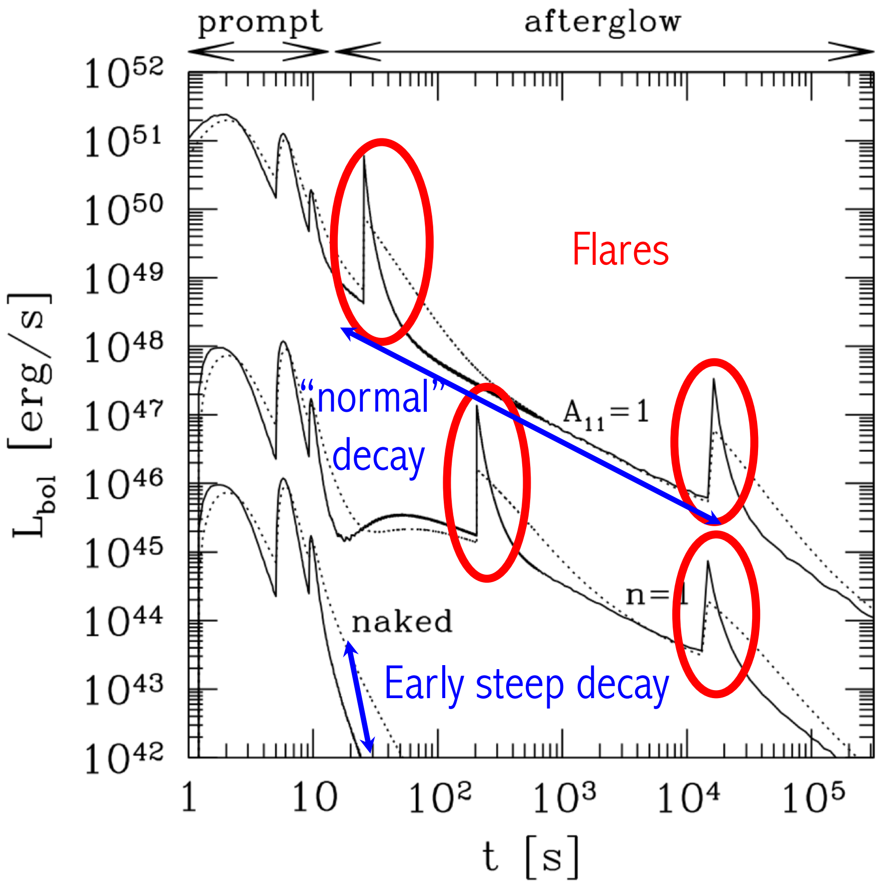




Flares are produced when the RS crosses a dense shell formed in the IS phase

Hascoët, Beloborodov, Daigne & Mochkovitch, 2017

Long-lived Reverse Shocks: Flares

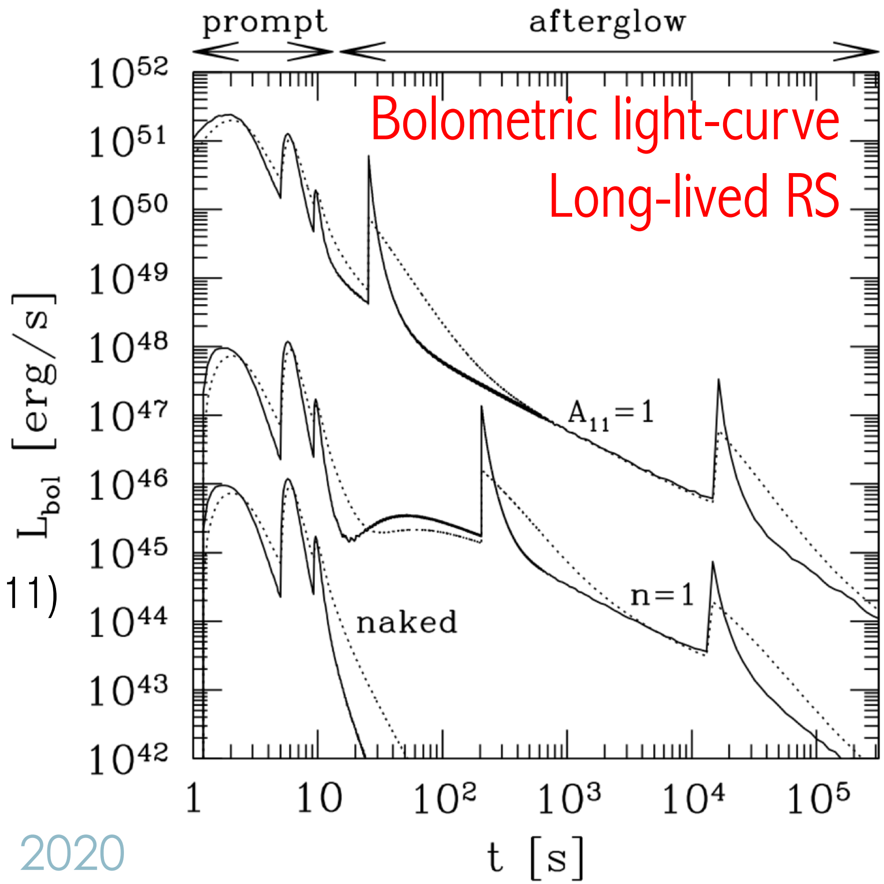
- Propagation of the RS in a radially structured ejecta
- Overdensities: signatures of internal shocks?

Curves: different circumburst medium

Wind	10^{11} g/cm	(L_{bol})
Uniform	1 cm^{-3}	(L_{bol} divided par 10^3)
Naked burst		(L_{bol} divided by 10^5)

------- Isotropic emission

——— Anisotropic synchrotron emission in the comoving frame (Beloborodov [FD] et al. 2011)



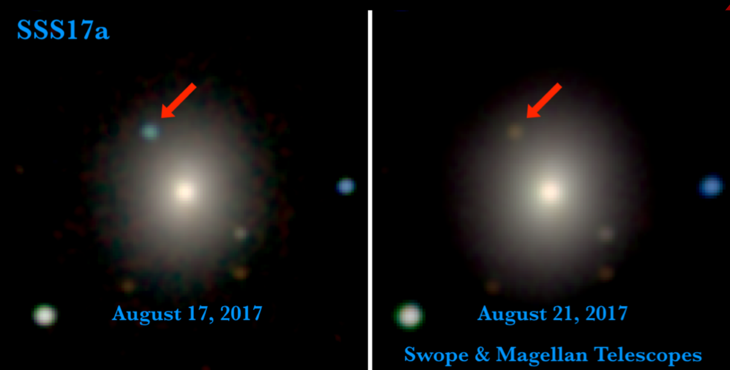
Validation by relativistic hydro simulations:
Lambert & Daigne 2017 ; Ayache et al. [FD] 2020

Flares: Fast rise/Steep decay with Δt/t ~0.1-0.3

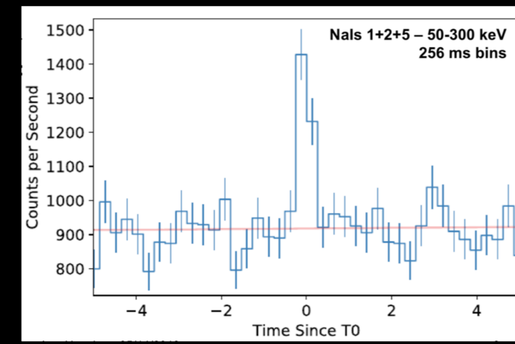
Hascoët, Beloborodov, Daigne & Mochkovitch, 2017

170817

Kilonova: ejecta during the merger
Nucleosynthesis of heavy elements

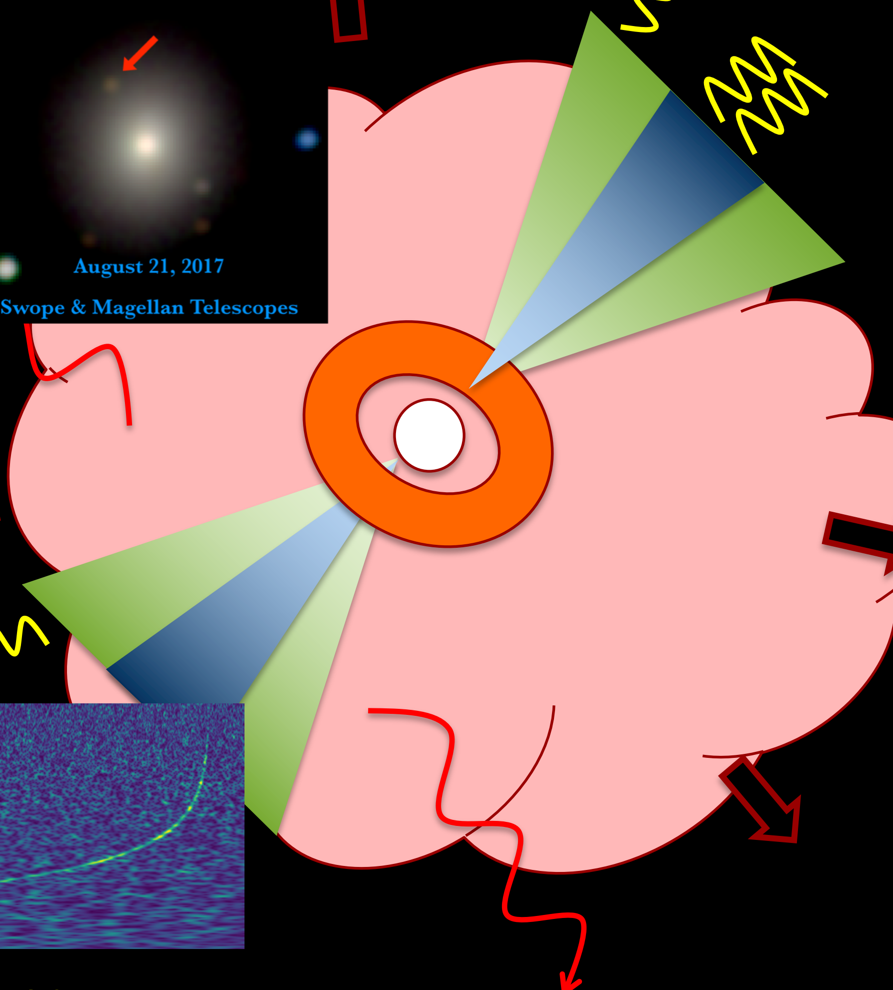


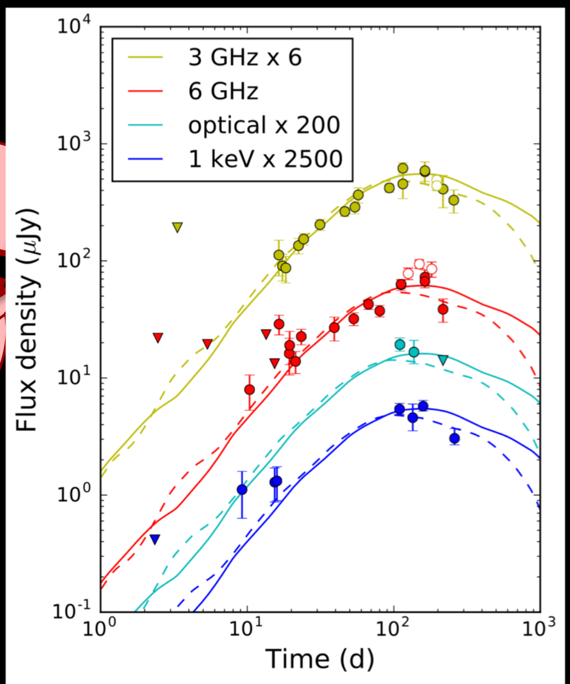
Observer

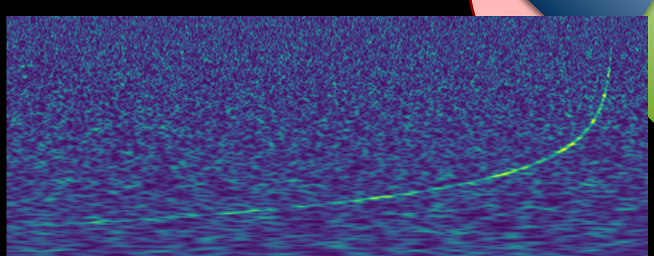


Short GRB: relativistic jet
Shock breakout?

Bright short GRB
for on-axis observer?







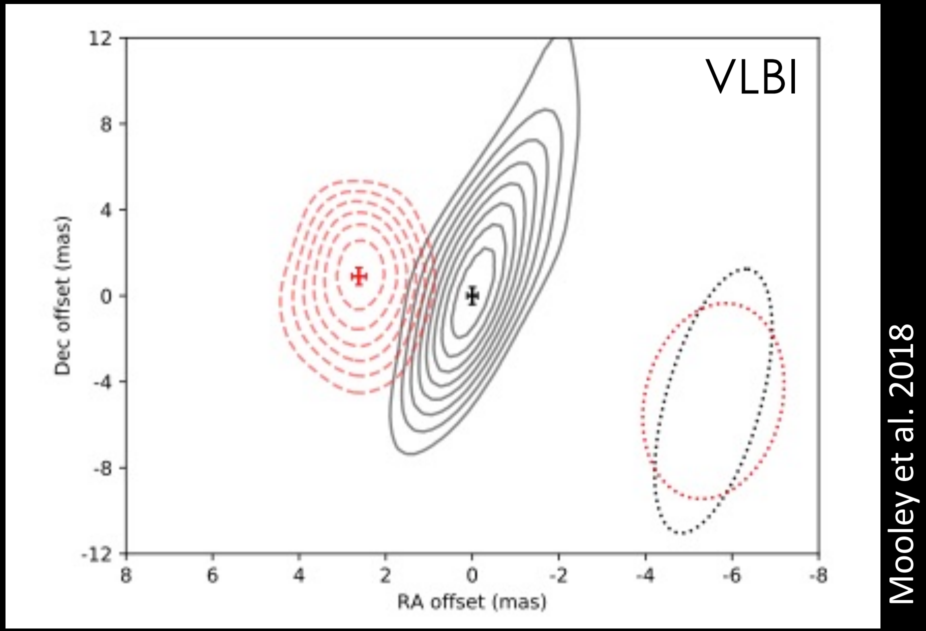
Gravitational Waves
Inspiral phase of a BNS

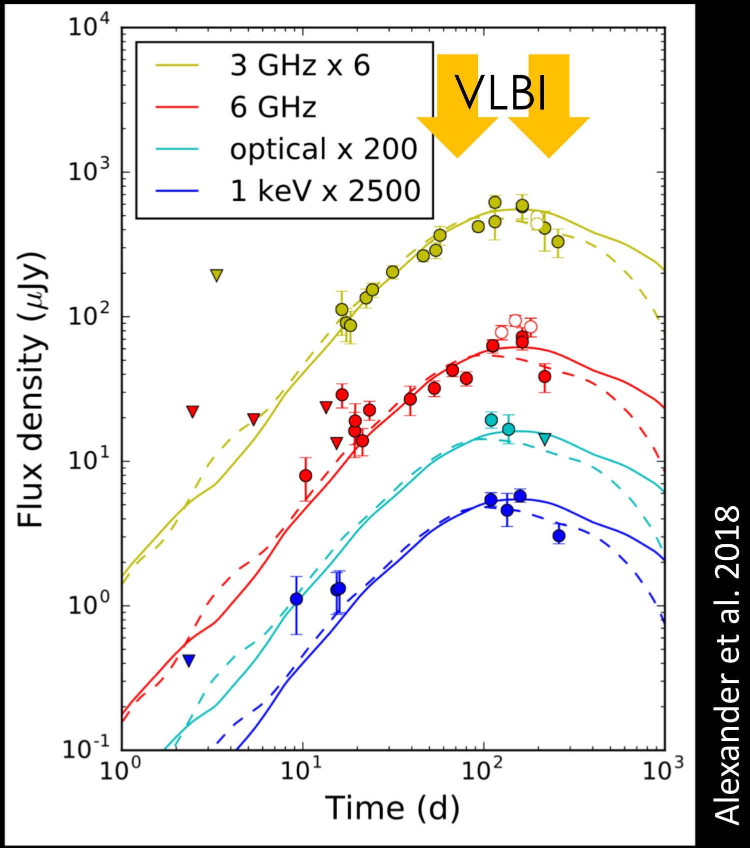
Afterglow: deceleration
of a structred relativistic jet

170817: the afterglow

- Photometry: slow rise for more than 100 days, then decay
- VLBI measurements at peak:
  - superluminal apparent motion
  - compact size
- **LC: lateral structure (due to jet-KN ejecta interaction?)**

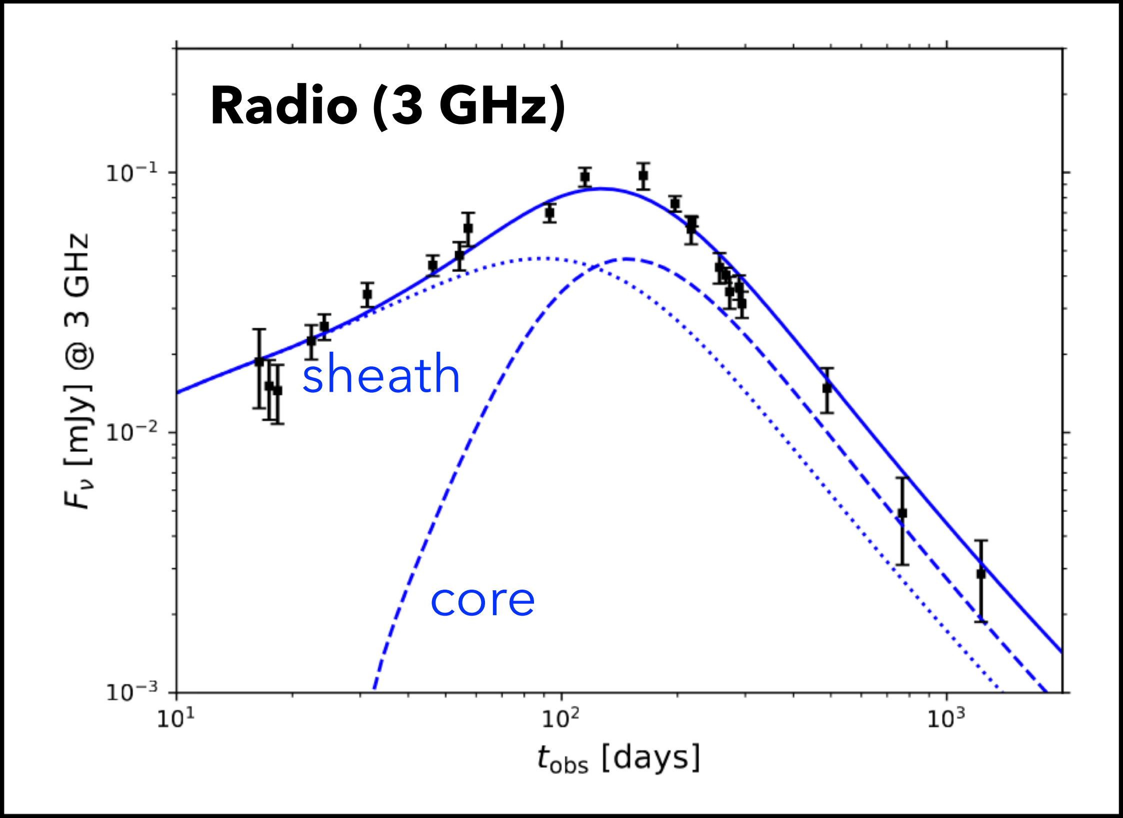
Relativistic jet confirmed !





170817: the afterglow

- Best fit:
  - **High kinetic energy of the core jet (bright SGRB for an on-axis observer)**
  - **Good constraint on viewing angle**

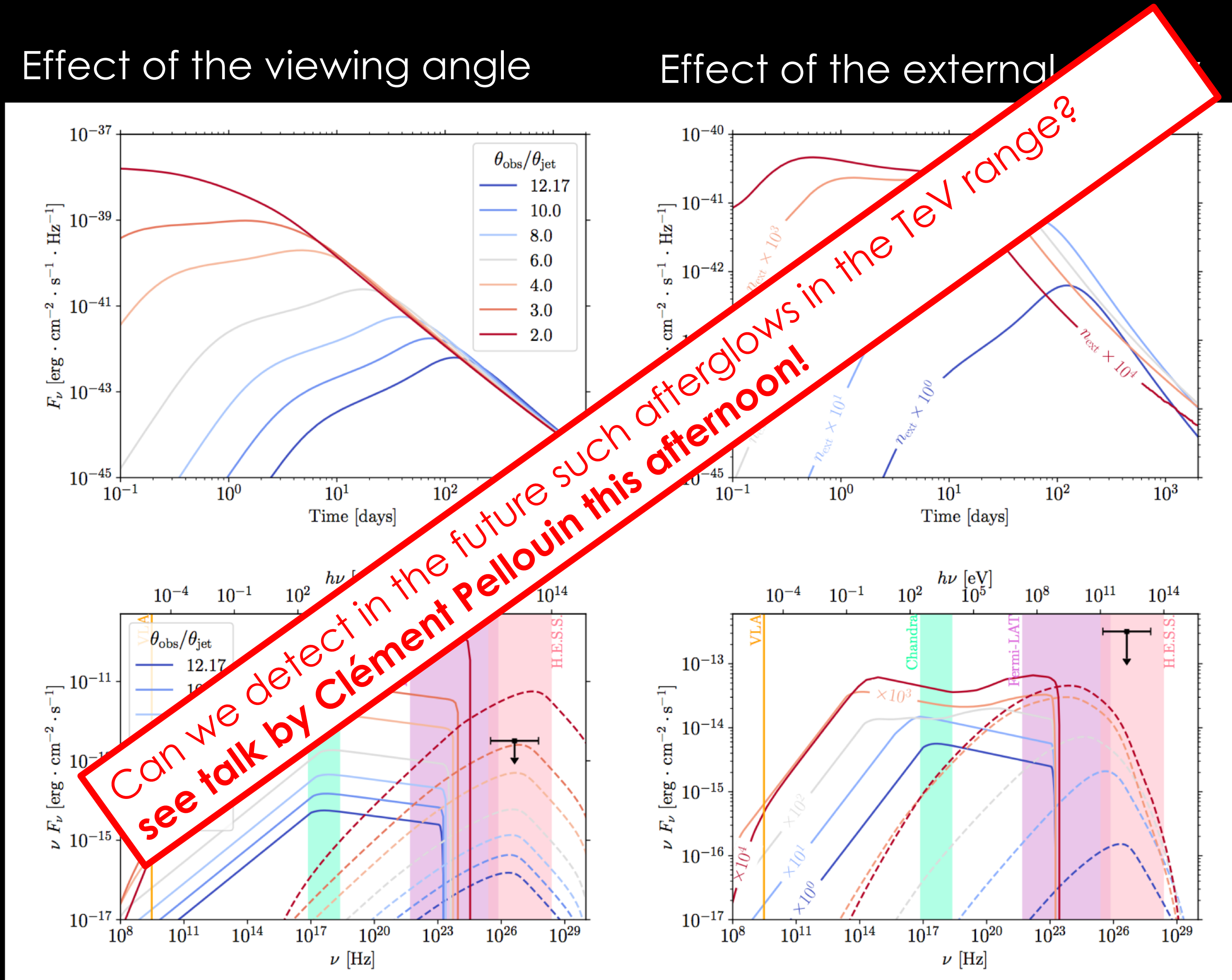


Pellouin & Daigne in preparation

170817: the afterglow

- TeV emission?

Effect of the viewing angle — Effect of the external



Pellouin & Daigne in preparation

Lateral structure: consequences for the early afterglow

- **The lateral structure may be inherited from the early propagation of the ejecta and may be a common features in GRBs.**
  (interaction of the jet with the stellar envelope (collapsar) or the KN ejecta (merger))
- **Can we find signatures of this lateral structure in cosmic GRBs?**
  (Difference compared to 170817: on-axis/slightly off-axis observation)

- **General discussion of the possible lightcurves with a structured jet:**
  Beniamini, Granot & Gill 20202

Lateral structure: consequences for the early afterglow

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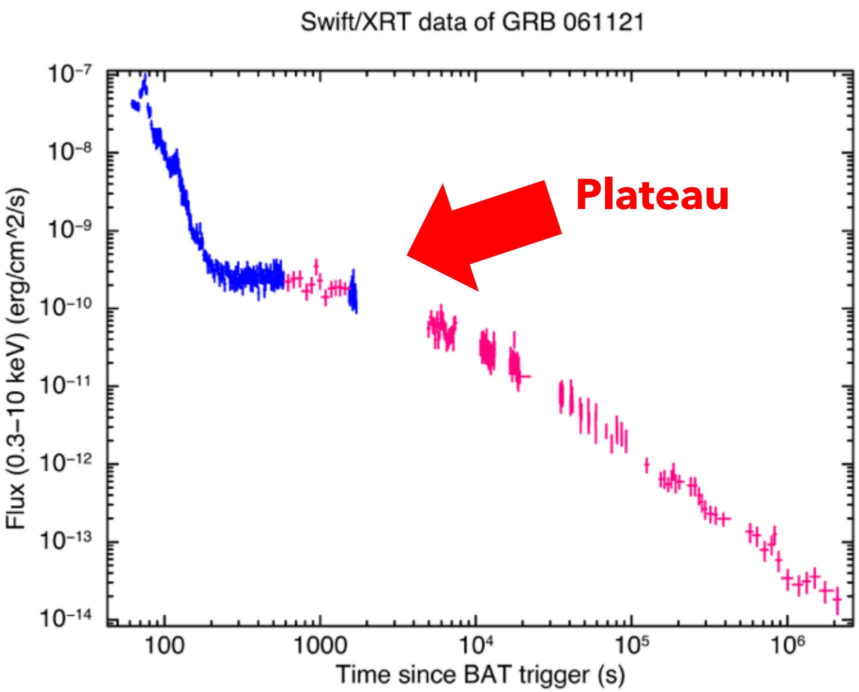
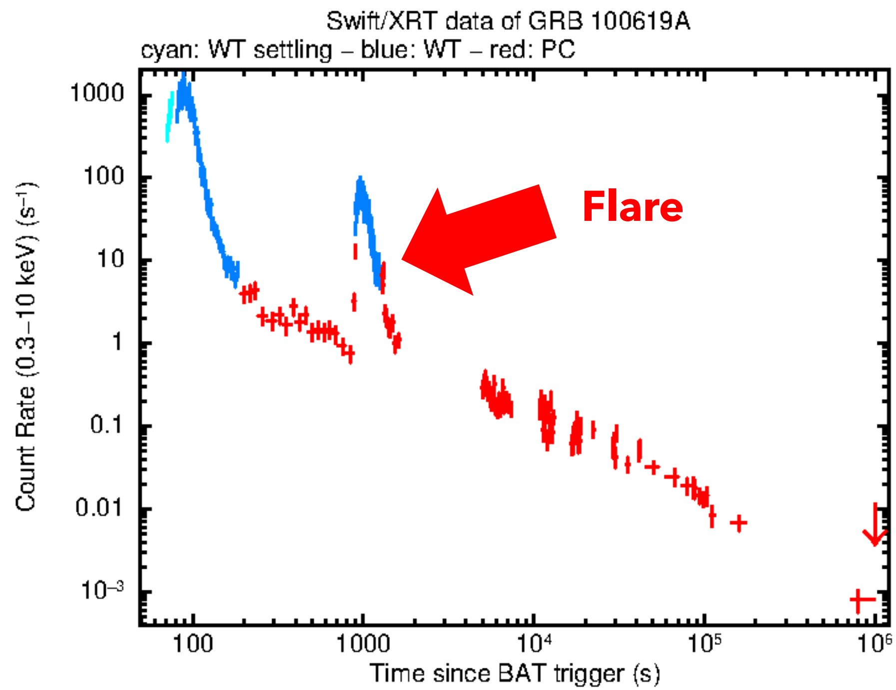
- **Can we find signatures of this lateral structure in cosmic GRBs?**
  (Difference compared to 170817: on-axis/slightly off-axis observation)

Puzzling features in the early X-ray afterglow (Swift/XRT)

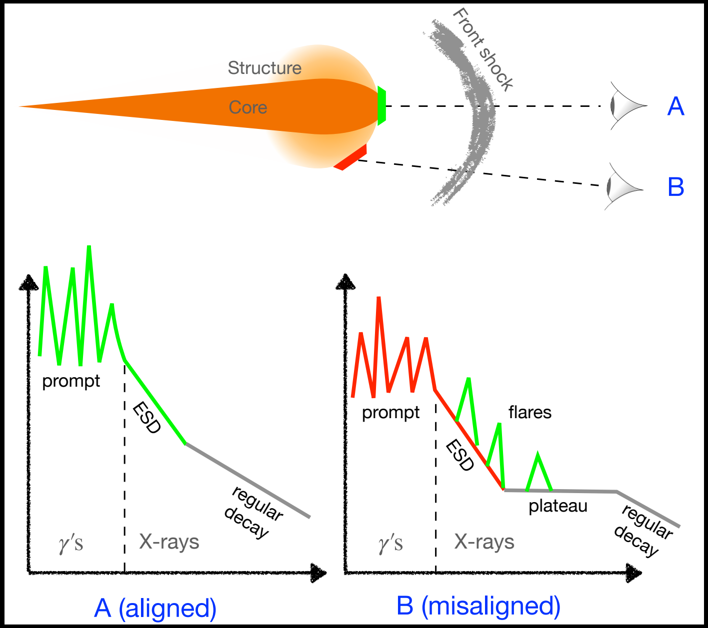




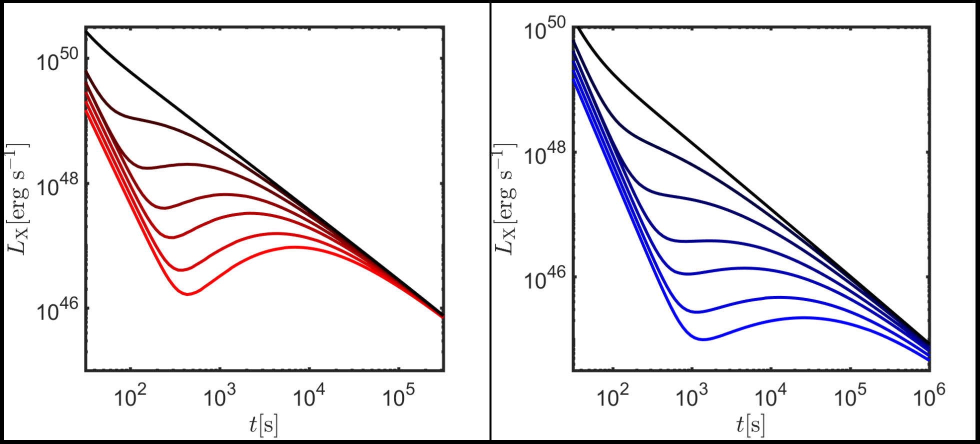
Swift/XRT Catalog

Lateral structure: consequences for the early afterglow

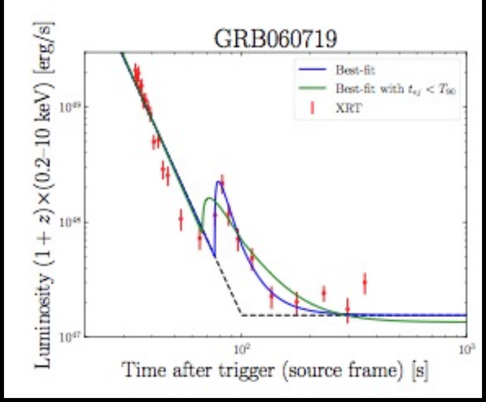
- **Can we find signatures of this lateral structure in cosmic GRBs? Plateaus & Flares?**



Slightly off-axis jets:
X-ray plateaus and flares?



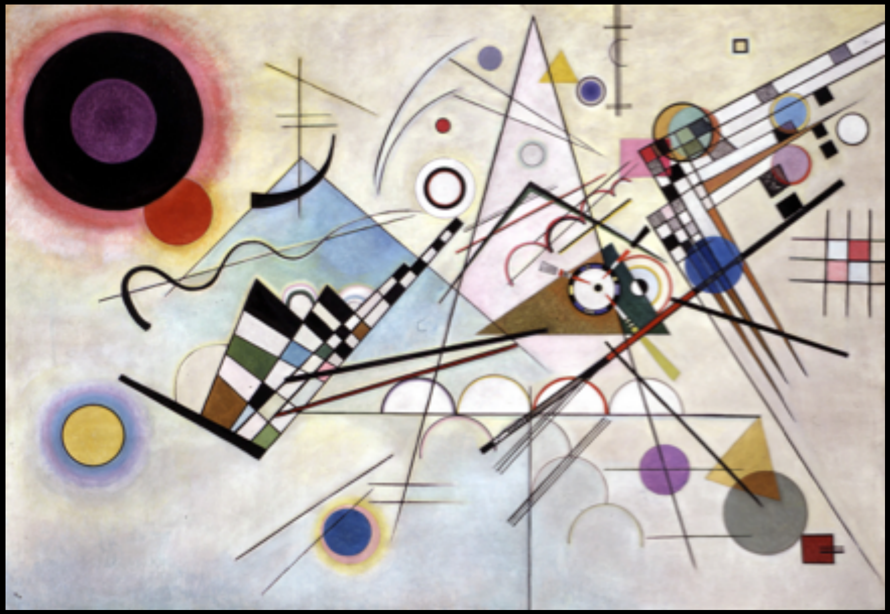
Beniamini et al. [Duque, FD] 2020



Duque et al. [FD] 2022

See also Organesian et al. 2020

GRB Physics: Summary



Kandinksy – Composition 8- 1923
Guggenheim Museum, New-York

Kandinksy – Curves and sharp angles - 1923
Guggenheim Museum, New-York

Questions?