Physics & Astrophysics of Gamma-Ray Bursts

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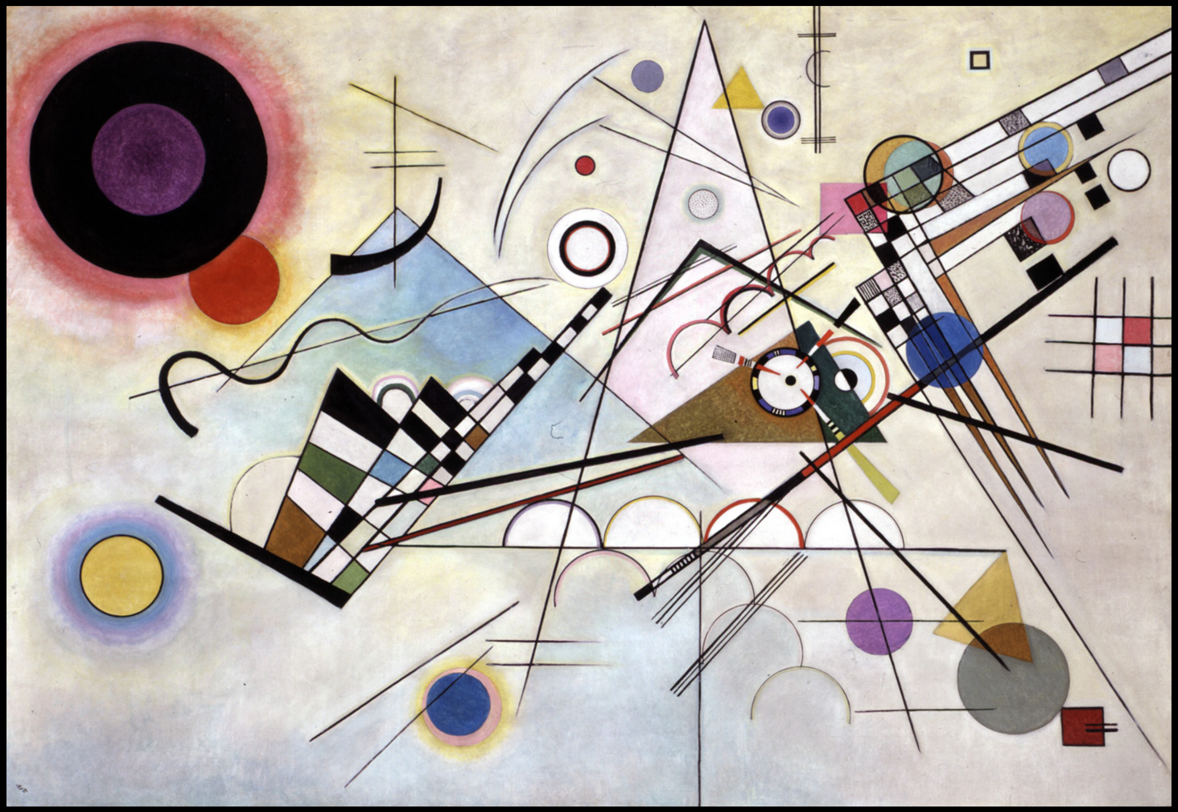
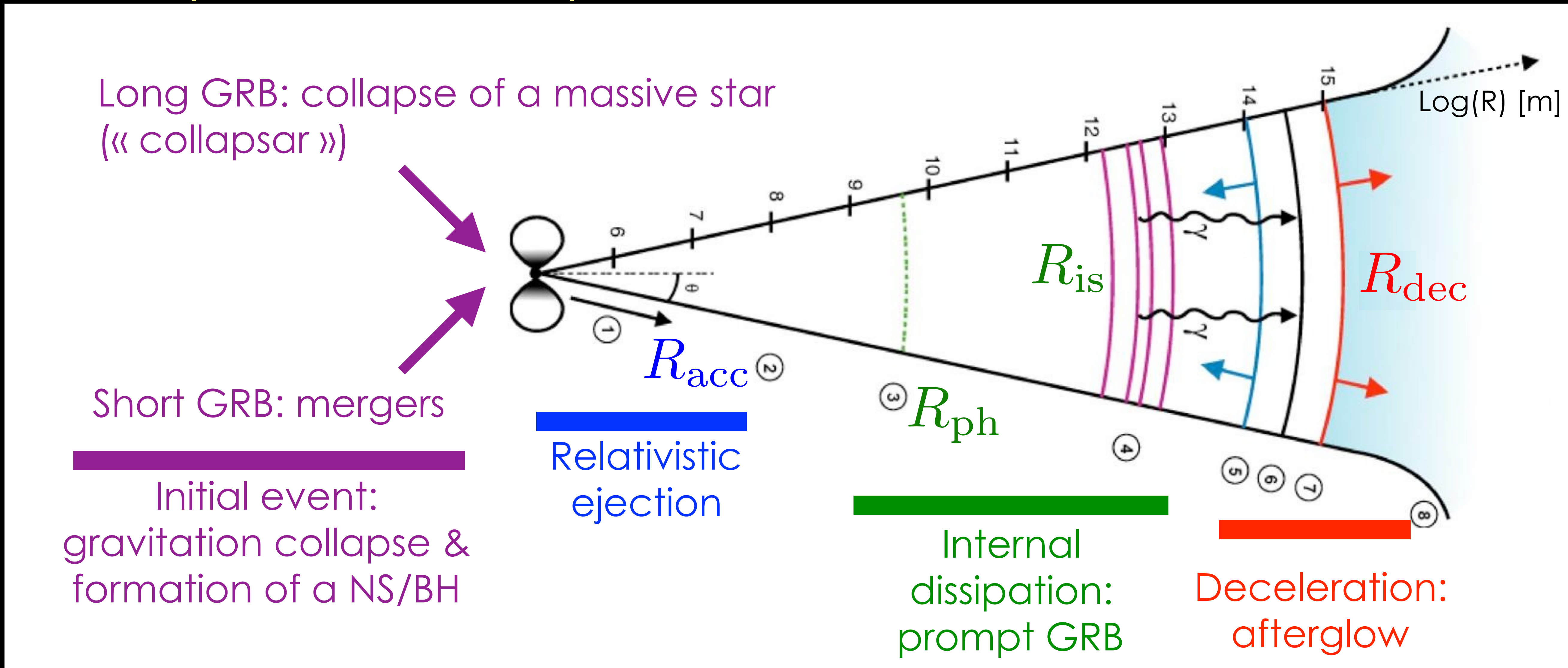


Kandinksy – Composition 8- 1923

Kandinksy – Curves and sharp angles - 1923

GRB Physics: summary



Acceleration

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

Internal dissipation

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

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

Internal dissipation

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

Physics & Astrophysics of Gamma-Ray Bursts

Introduction

A brief history
Observational Facts
Basic Constraints on any GRB model: compact source + relativistic ejecta

Theory

Progenitor - Central Engine
Relativistic Ejection: fireball / open issues
Prompt Emission: internal dissipation in a relativistic ejecta
characteristic radius / lightcurve & spectrum / open issues
Afterglow: interaction of a relativistic ejecta with its environment
characteristic radius & dynamics / lightcurve & spectrum / open issues

Focus on short GRBs: the binary neutron star merger connection - 170817

Afterglow: Constraints on the geometry of the relativistic ejecta
Origin of the prompt emission
Prospects for future associations

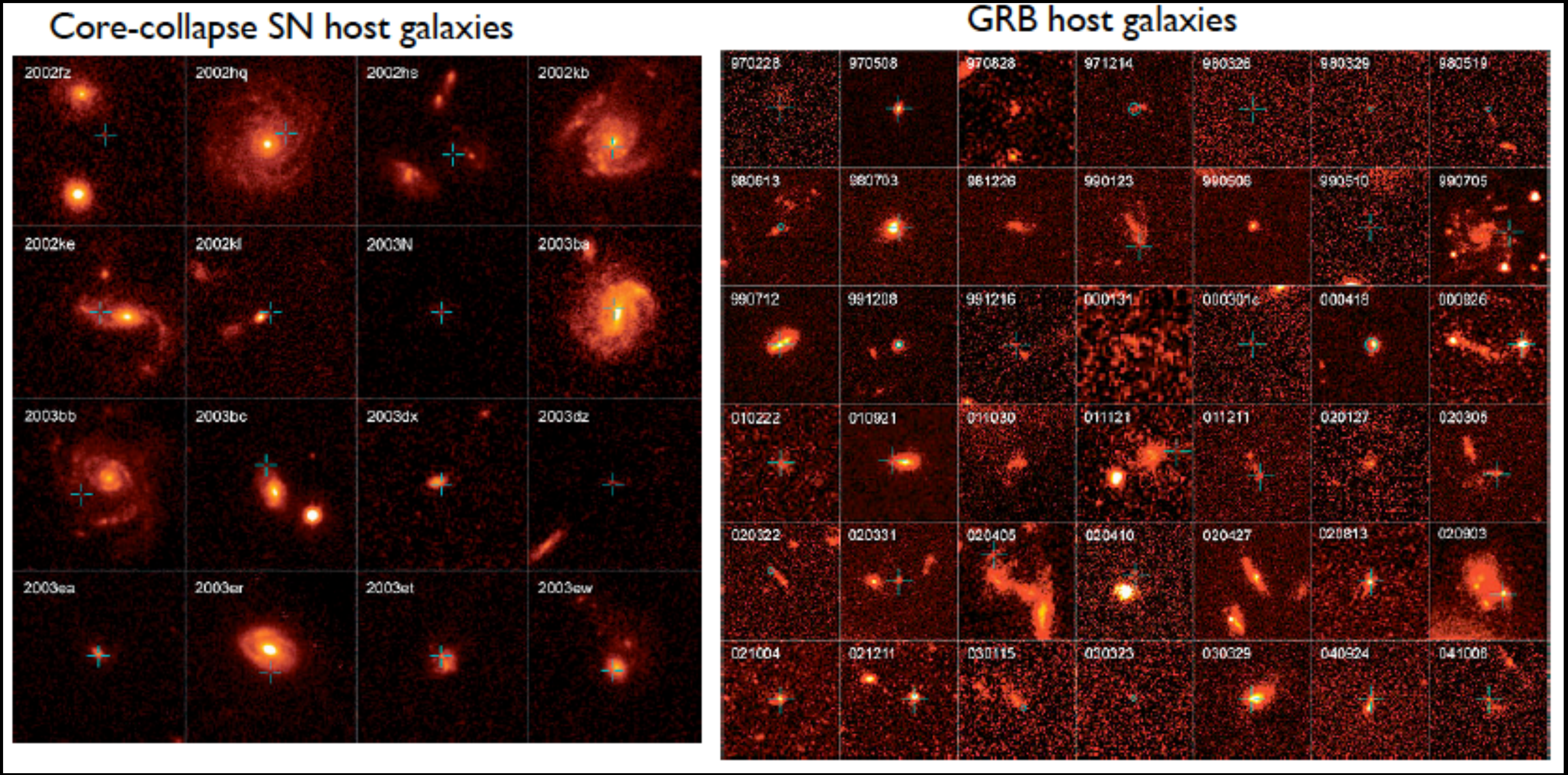
Lecture #1
Lecture #2
Lecture #3

GRB progenitors

Association of long GRBs with massive stars

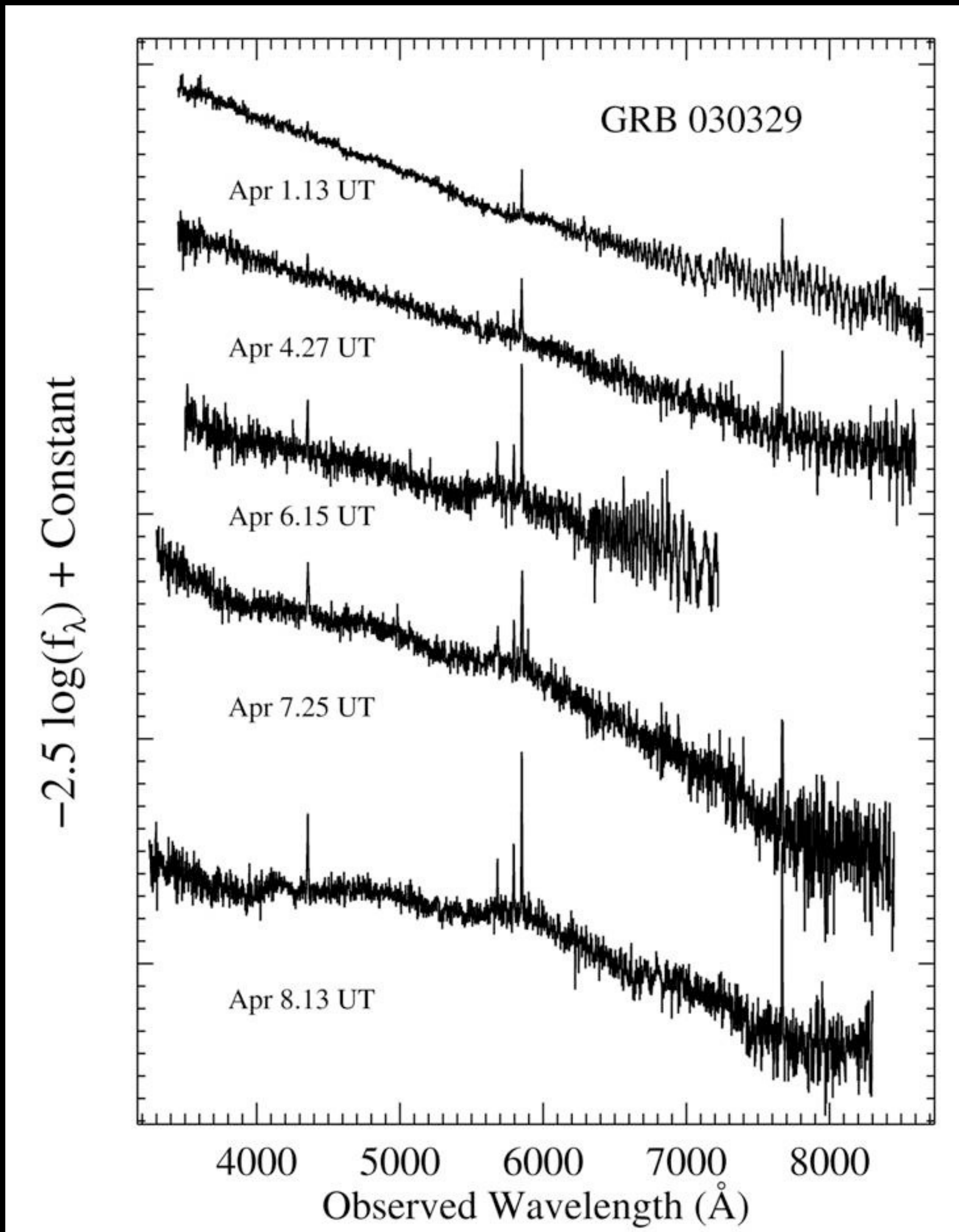
- Star forming host galaxies
- Small offsets
- Association with some core-collapse supernovae (peculiar type Ic)

Furchter+06

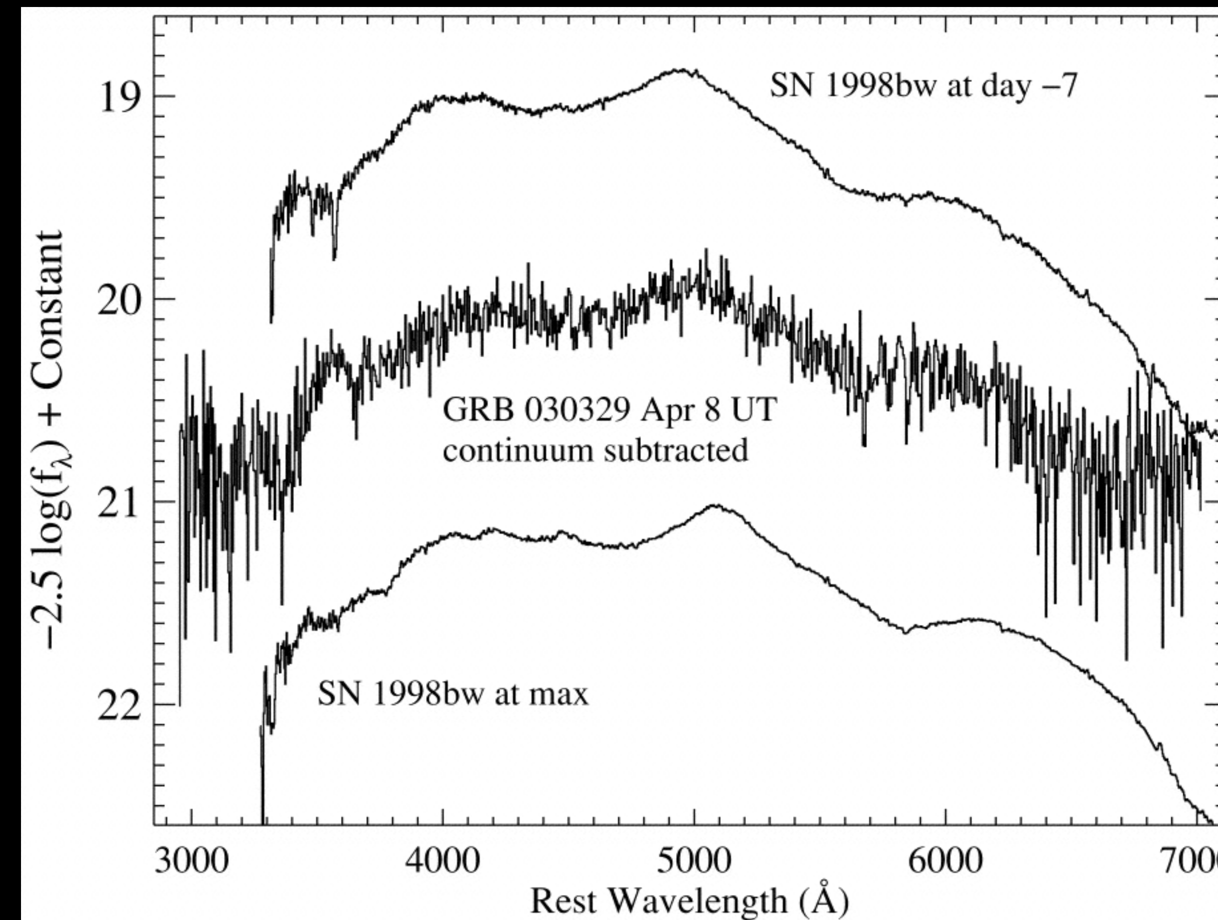


Association of long GRBs with massive stars

GRB 030329 (HETE2) associated with a type Ic supernova
(first association: GRB980425/SN1998bw but under-luminous GRB)



Stanek+03



Several other examples of GRB-SN associations for bursts at low z

A few cases of nearby long GRBs without an associated SN: is it an issue?

Association of long GRBs with massive stars: open issues

- Detailed conditions for a massive star to produce a gamma-ray burst: mass? metallicity? rotation? binarity?

- Origin of GRB diversity (ultra long / low-luminosity / …)

- This complex question can be studied:
  - with observations: host galaxy, GRB environment, etc.

    Clear tendency to favour low-metallicity environment (see e.g. Palmerio+ 19)

  - with population models:

    The GRB com. rate does not strictly follow the star formation rate (Daigne+ 06)
    Evolution with redshift: (a) efficiency of stars to produce GRBs
    and/or (b) GRB luminosity function

    (see Daigne+, Piran & Wanderman, Pescalli, …)

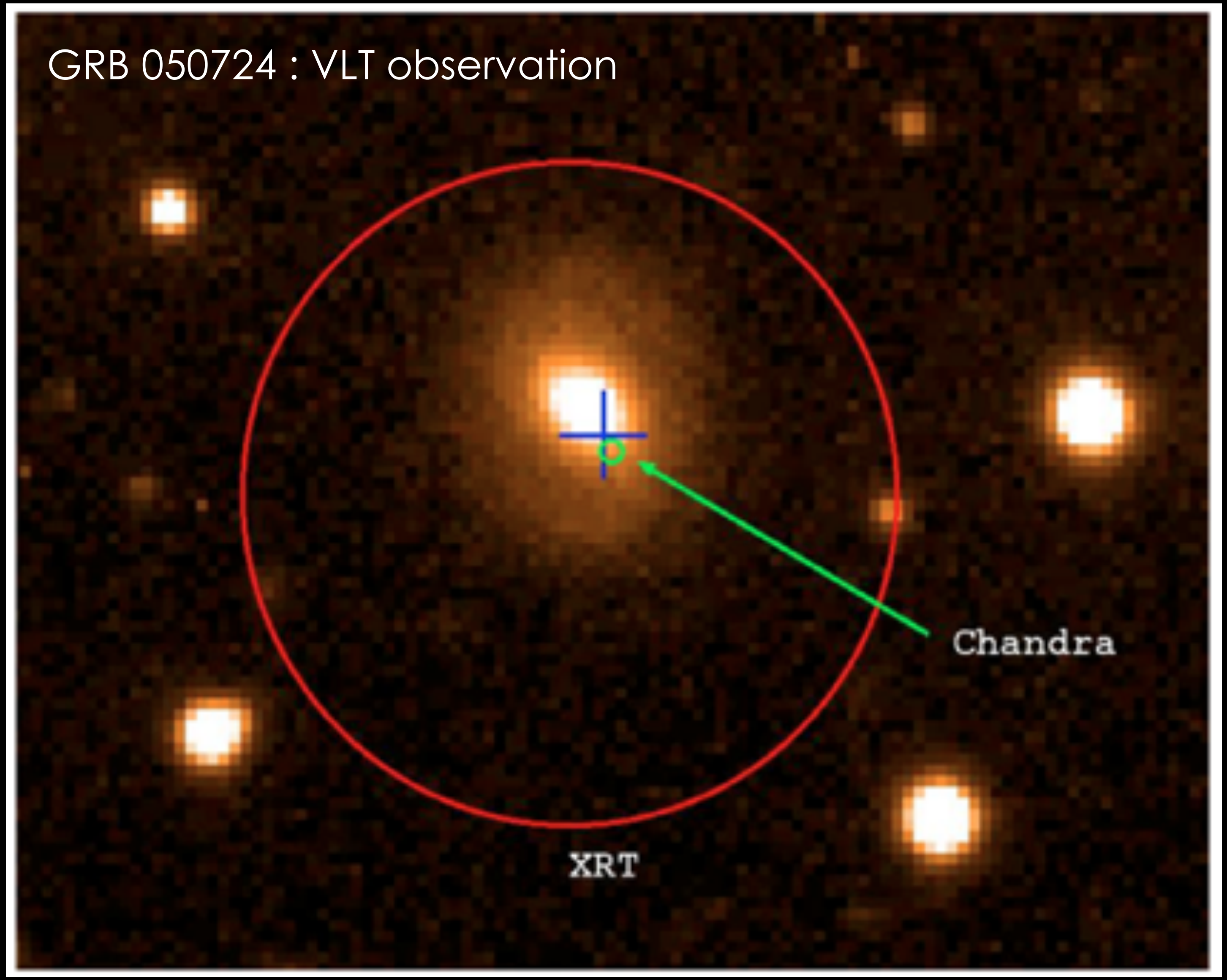
  - with core-collapse theory (difficult: see supernovae)

- GRBs as a tool for cosmology:
  - is it possible to use long GRBs to trace the cosmic SFR?
  - GRBs from first stars (pop III)?

Short GRBs: host galaxy

- All morphologies
- No correlation with star formation
- Large offsets are observed
- No associated supernova

See review by Berger 2014



Barthelemy et al. 2005

Short GRBs: host galaxy

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See review by Berger 2014

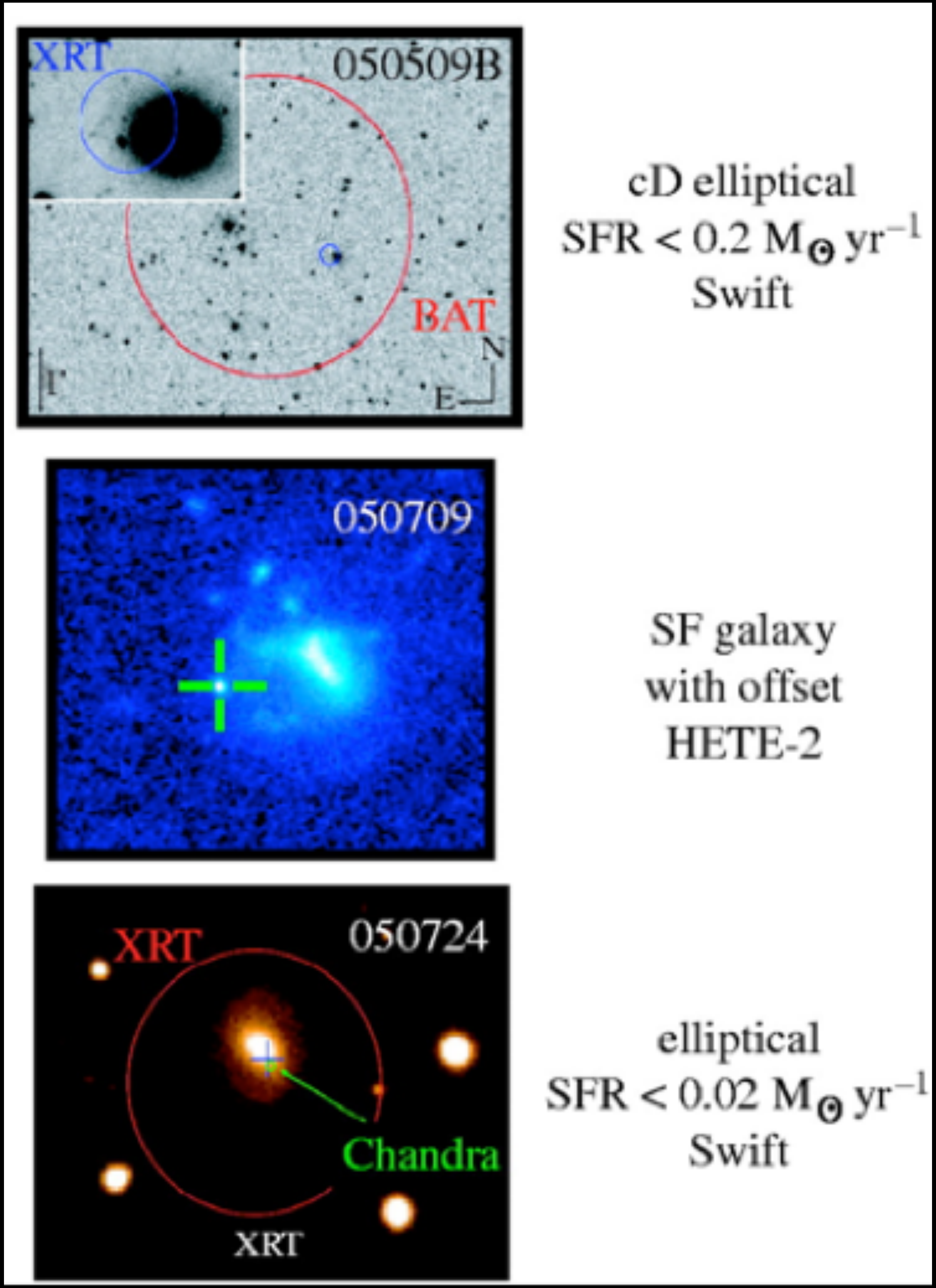
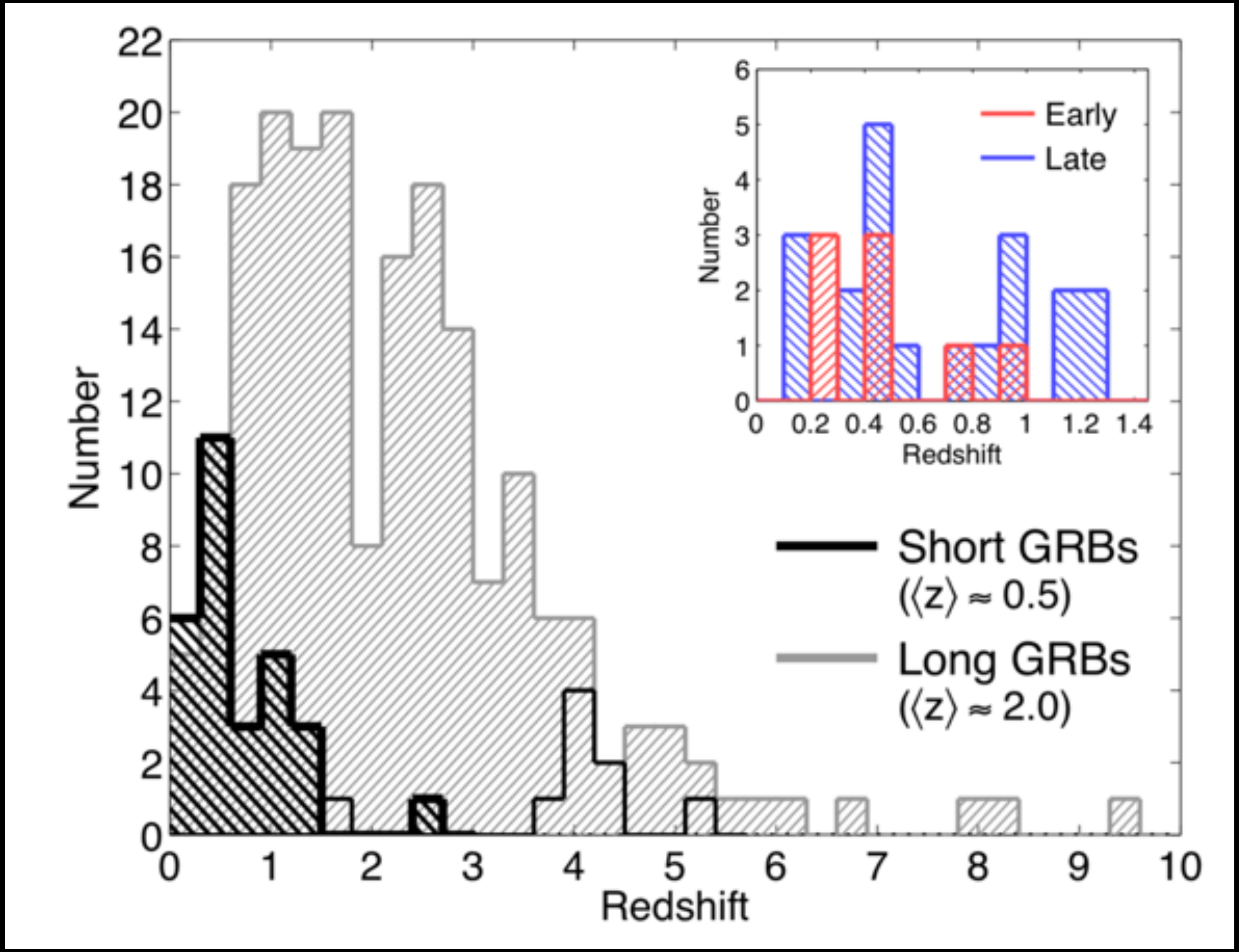


Figure: courtesy of Susanna Vergani

Short GRBs: host galaxy

- All morphologies
- No correlation with star formation
- Large offsets are observed
- No associated supernova

See review by Berger 2014



Association of short GRBs with binary neutron star mergers

- All morphologies
- No correlation with star formation
- Large offsets are observed
- No associated supernova

See review by Berger 2014

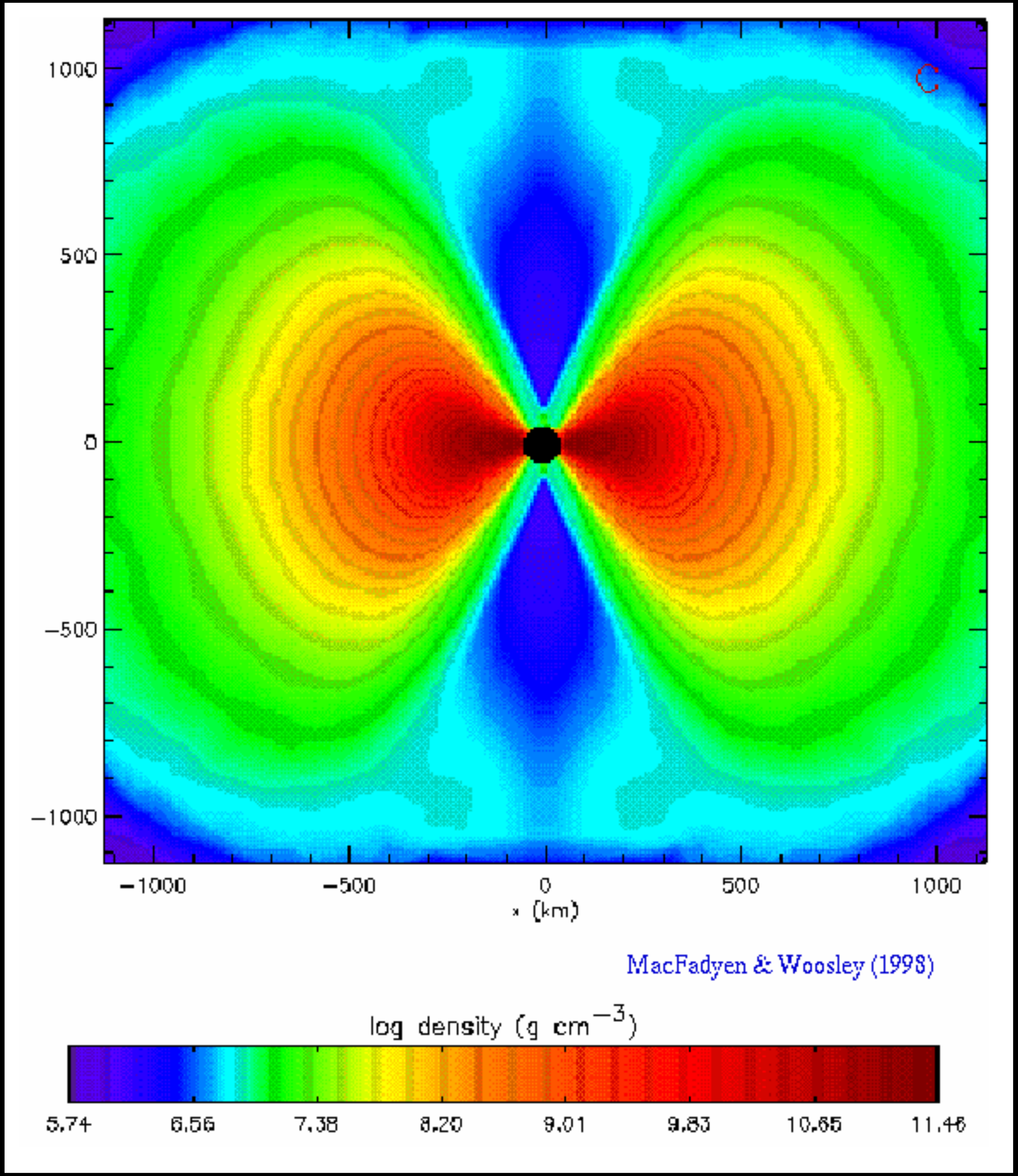
All these observations are consistent with the merger scenario.

In addition: one direct association ! 170817 = GW+short GRB+kilonova+afterglow
However GRB 170817 is peculiar (not just due to an off-axis observation)

GRB Physics:
central engine - relativistic ejection

Central engine: long GRBs

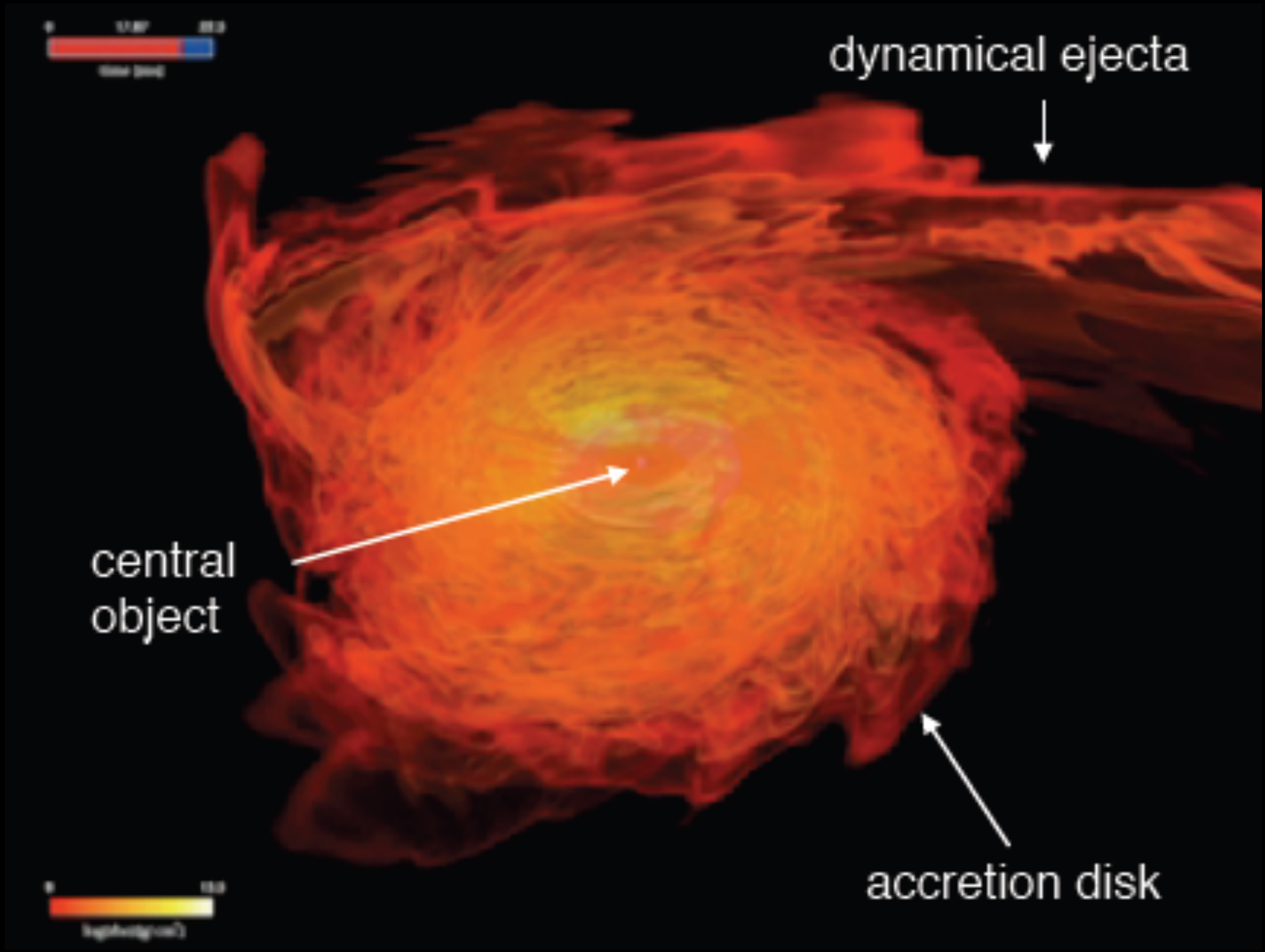
Long GRBs: collapsar (Woosley et al.)



Expected central engine: BH + accreting torus

Central engine: short GRBs

Merger



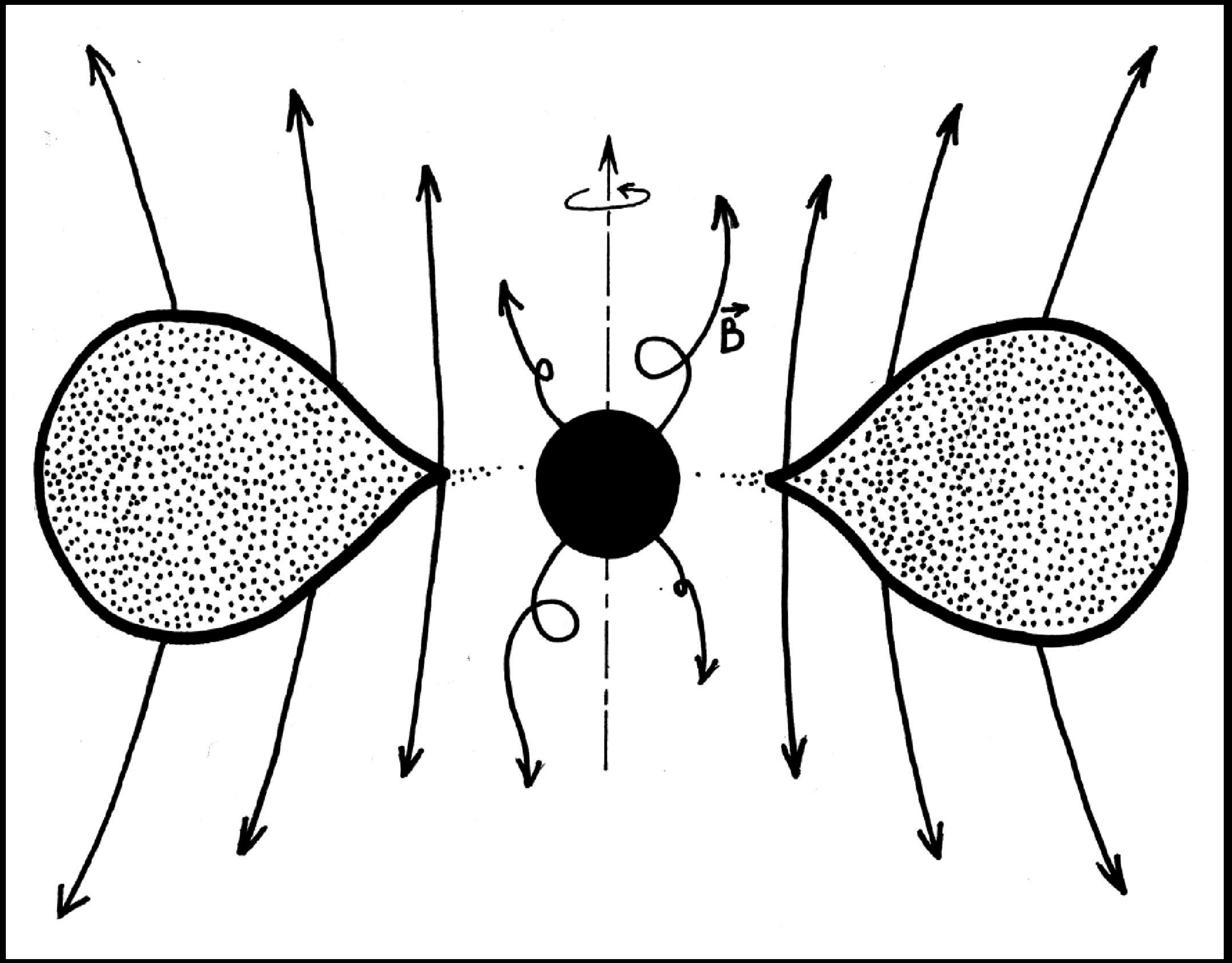
(Rezzolla et al, 2010)

Central object? direct BH / massive NS and collapse to BH / long-lived massive NS

Relativistic ejection: open issues

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

Initial:
thermal
or
magnetic



- At the base of the flow: need a strong limitation of the baryonic pollution

  Detailed calculation is difficult:
  needs to compute precisely all the heating terms (in particular neutrino heating)

  Preferred region: along the rotation axis.

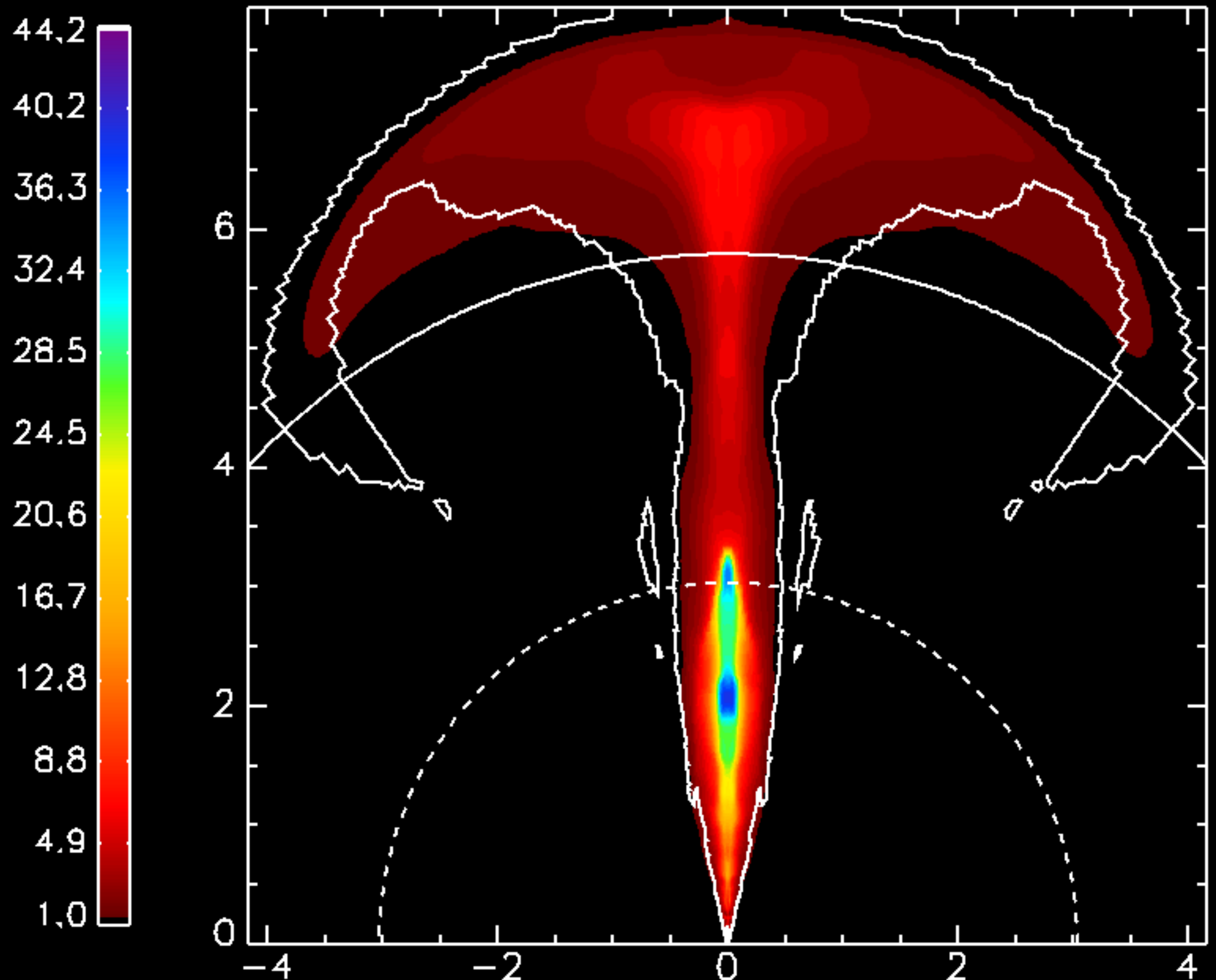
- Origin of the collimation?
  - Hydrodynamic outflow: difficult, no natural nozzle? (stellar enveloppe?)
  - MHD outflow: more natural
  - Role of the propagation within the collapsing star?
    (short GRBs: no collapsing star. Role of the kilonova ejecta?)

- Magnetized outflows:
  - From the disk (alla Blandford & Payne): relativistic outflow? If not: wind?
  - From the BH'ergosphere (alla Blandford & Znajek)

- Do some of these mechanisms work if the central object is a neutron star?

Early propagation of the relativistic ejecta

Escaping from a star…



An early simulation by MacFadyen et al.

Recent developments (e.g. Bromberg et al.): choked jets, impact on the GRB duration, formation of a cocoon, shock breakout, etc.

Early propagation of the relativistic ejecta

Short GRBs: interaction with the kilonova ejecta
(formation of a cocoon? shock breakout? e.g. Nakar et al.)

see discussion of 170817

Late propagation of the relativistic ejecta

What are the properties of the relativistic ejecta at large distance?

(above R_{acc} and below R_{ph})

= initial conditions to understand the prompt and afterglow emission

- Magnetization? (shock do not form and propagate for large magnetization)

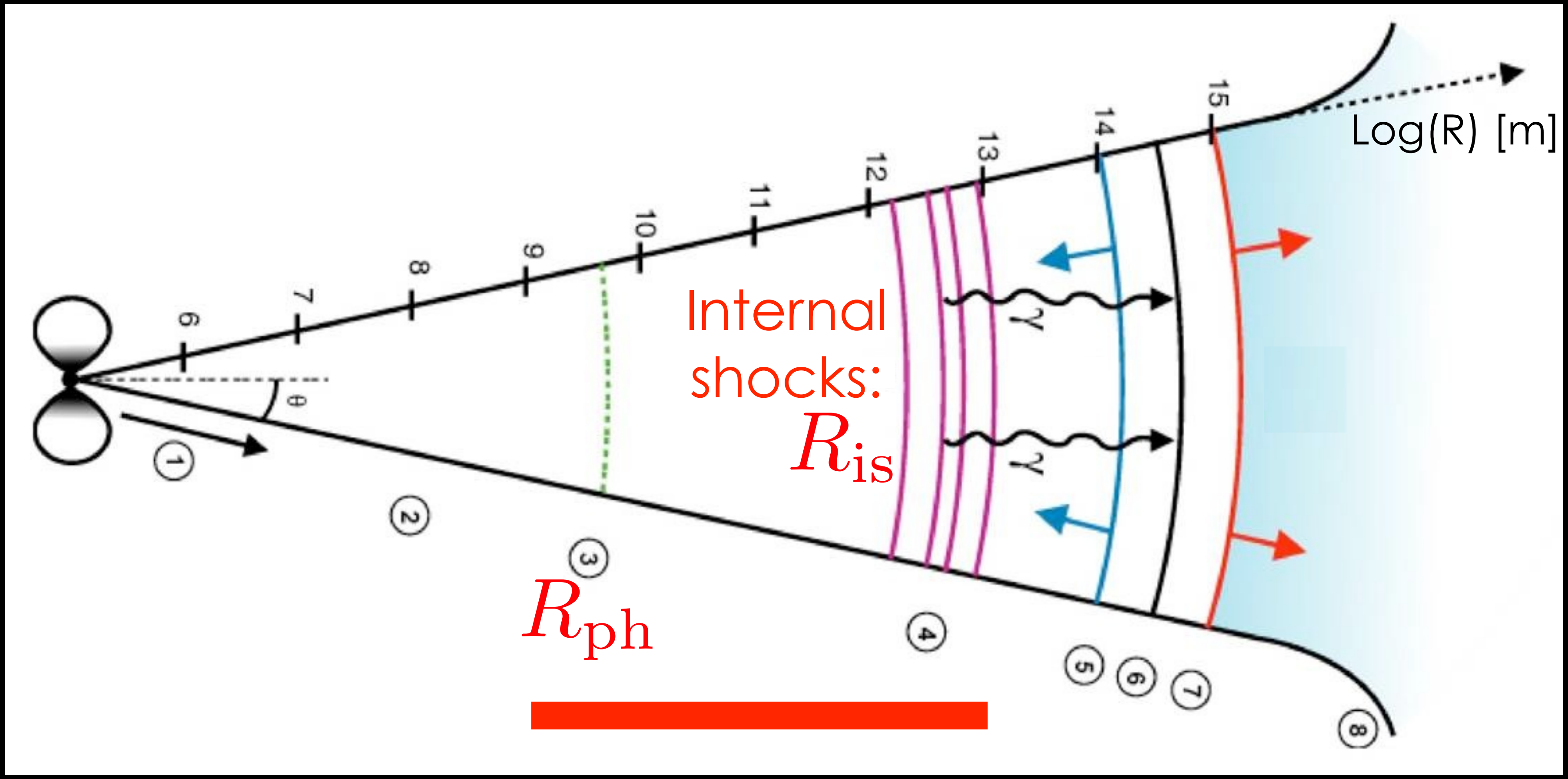
  (efficiency of the magnetic to kinetic energy transfer: see Granot & Komissarov ; Tchekovskoy)

- Radial structure?
- Angular structure?
- etc.

GRB Physics:
prompt emission

Prompt emission

- Short time-scale non-evolving variability: the prompt emission has an internal origin



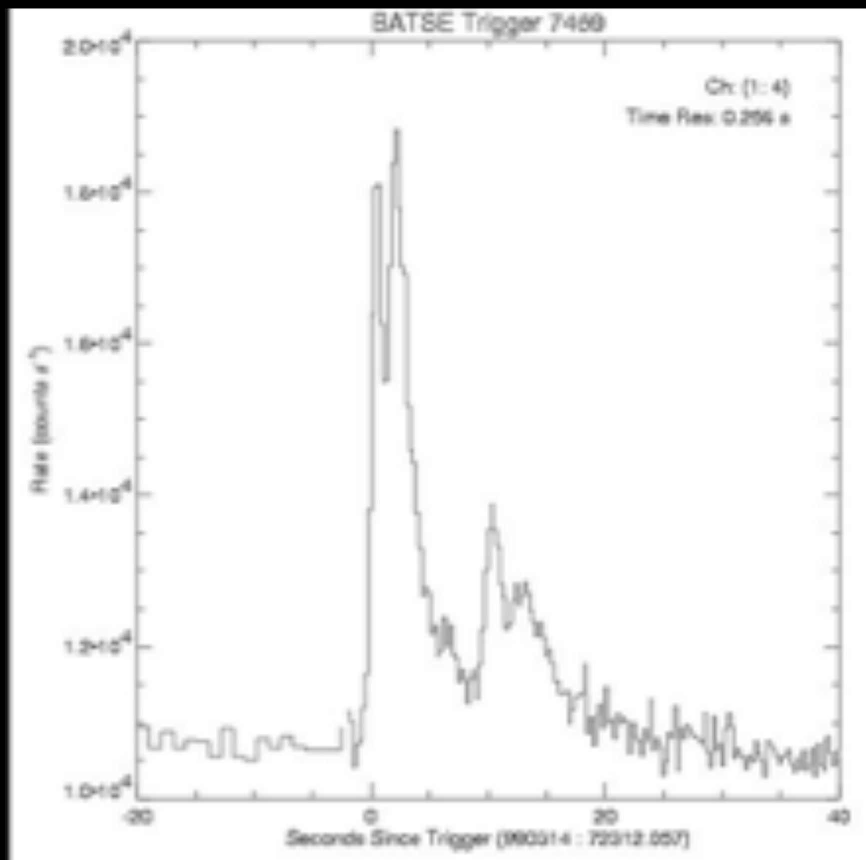
- Main possibilities of internal dissipation:
  (1) dissipative photosphere
  (2) optically-thin synchrotron emission from non-thermal elec. (shocks/reconnection)

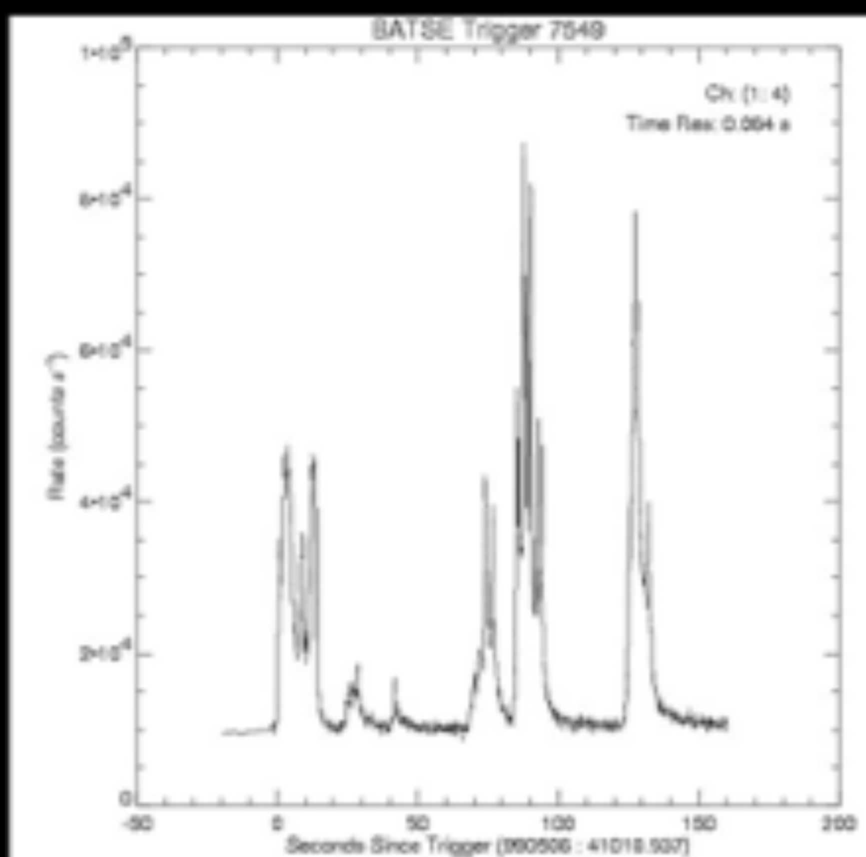
$$R_{\rm ph} \simeq \frac{\dot{E}\kappa_{\rm T}}{8\pi\Gamma^3 c^3} \simeq 6\,10^{12}\,{\rm cm}\left(\frac{\dot{E}}{10^{52}\,{\rm erg/s}}\right)\left(\frac{\Gamma}{100}\right)^{-3}$$

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

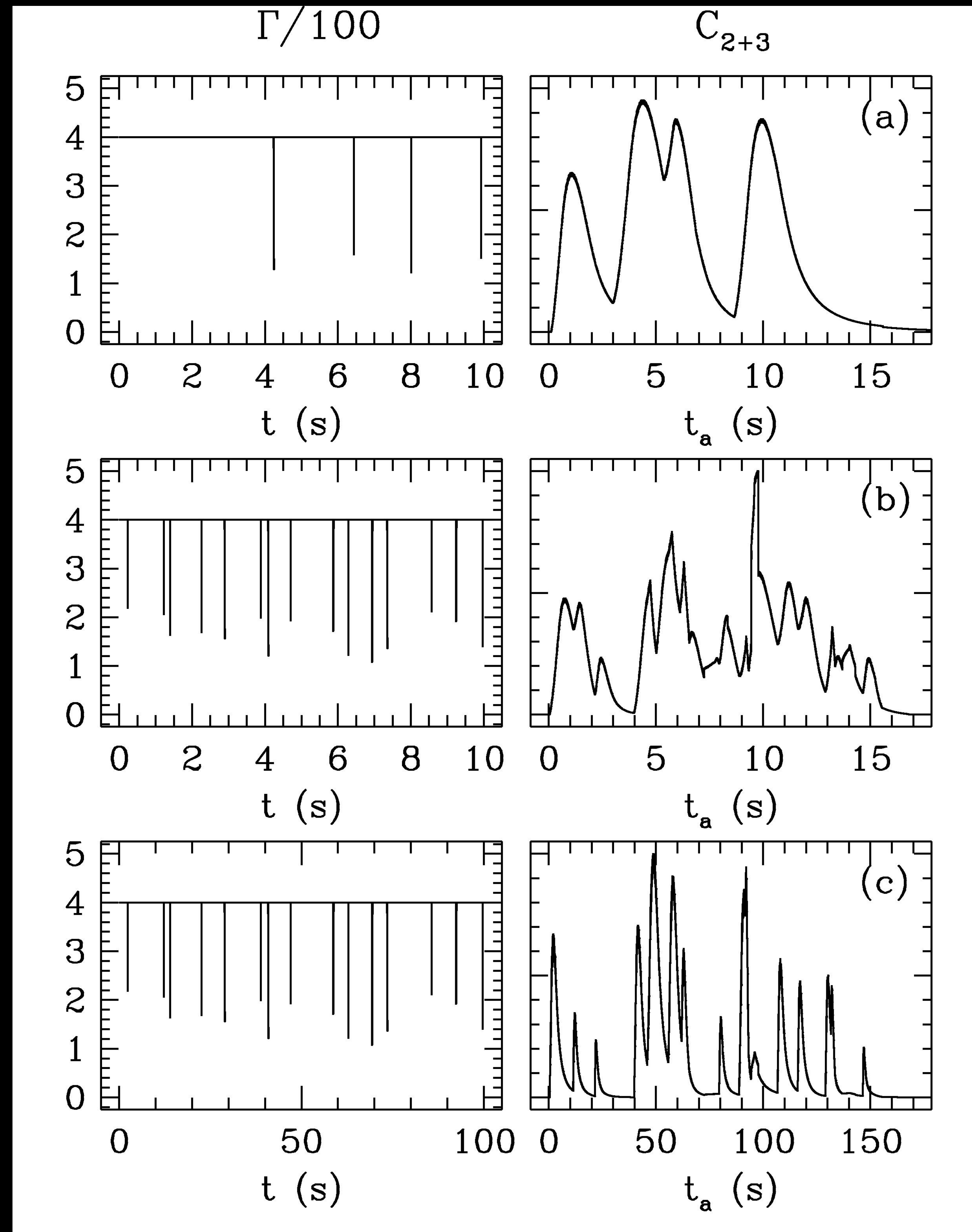
Internal shocks: light curve

Internal shocks: Rees&Meszaros, Sari&Piran, Kobayashi, Daigne & Mochkovitch, …

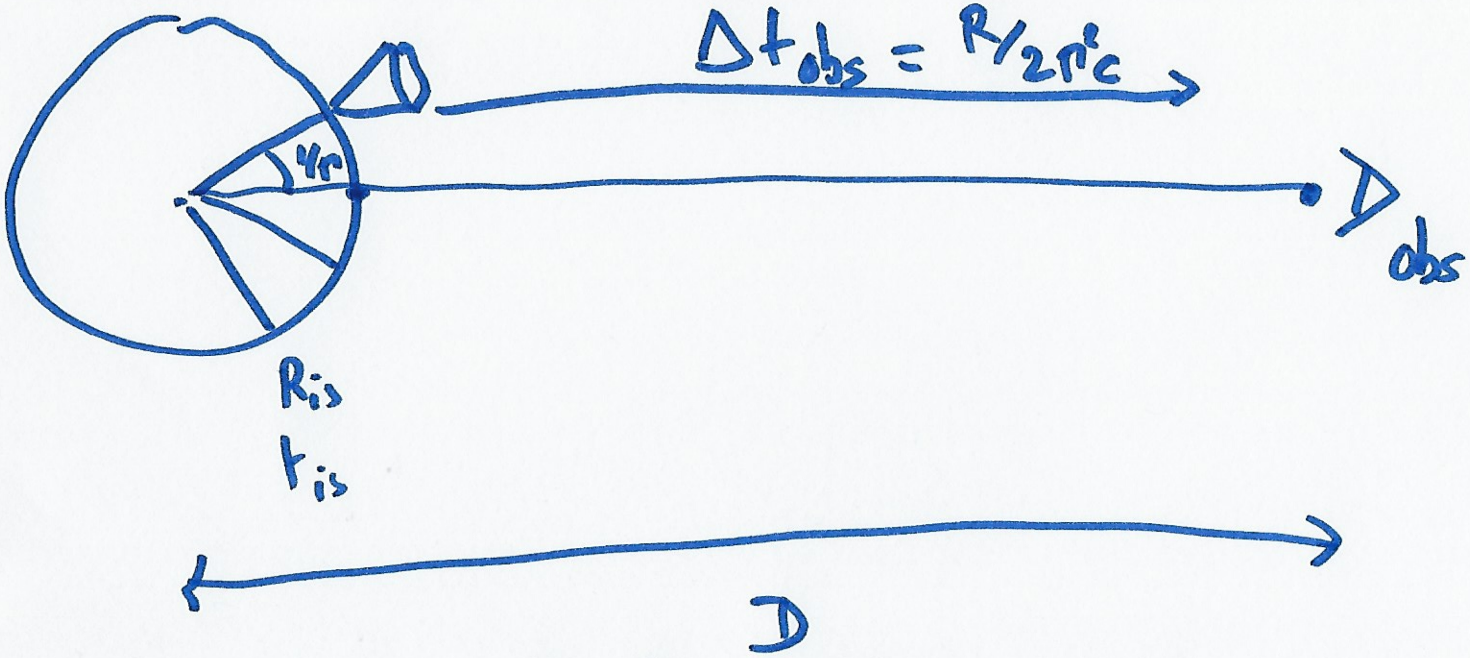




BATSE catalog



Daigne & Mochkovitch 1998



$$t_{obs} = t_{is} + \frac{D - R_{is}}{c} = \left(\frac{D}{c}\right) + (1-\beta_2)\, t_{is}$$

$$= \frac{D}{c} + t_e + \frac{(1-\beta_1)\beta_2}{\beta_2 - \beta_1}\, t_{vm}$$

$$\xrightarrow{UR} \approx \frac{D}{c} + t_e + \frac{1}{\cancel{2\Gamma_1^2}} \, \frac{\cancel{2}\Gamma_2^2 \cancel{\Gamma_1^2}}{\Gamma_2^2 - \Gamma_1^2}\, t_{vm}$$

$$\Gamma_2 \gg \Gamma_1 \rightarrow \approx \frac{D}{c} + t_e + t_{vm}$$

layer 1 $\quad t_e \qquad R = \beta_1 c (t - t_e)$

$\beta_1 \sim 1$

$\Gamma_1 \gg 1$

layer 2 $\quad t_e + t_{var} \qquad R = \beta_2 c (t - t_e - t_{var})$

β_2

$\Gamma_2 > \Gamma_1$

internal shock at $R_1 = R_2$ at $t_{is} = t_e + \frac{\beta_2}{\beta_2 - \beta_1} t_{var}$

$$R_{is} = \frac{\beta_1 \beta_2}{\beta_2 - \beta_1} c t_{var}$$

$$\text{UR: } R_{is} \simeq \frac{2 \Gamma_1^2 \Gamma_2^2}{\Gamma_2^2 - \Gamma_1^2} c t_{var}$$

$$\approx 2 \Gamma_1^2 c t_{var}$$

$\uparrow$

$\Gamma_2 \gg \Gamma_1$

$$\Delta t_{obs} = \frac{R_{is}}{2\Gamma^2 c} = \frac{\Gamma_1^{\cancel{2}}\Gamma_2^{\cancel{2}}}{(\Gamma_2^2-\Gamma_1^2)\,\cancel{\Gamma_1\Gamma_2}}\, t_{var}$$

$$\Gamma^2 \rightarrow \sqrt{\Gamma_1\Gamma_2}$$

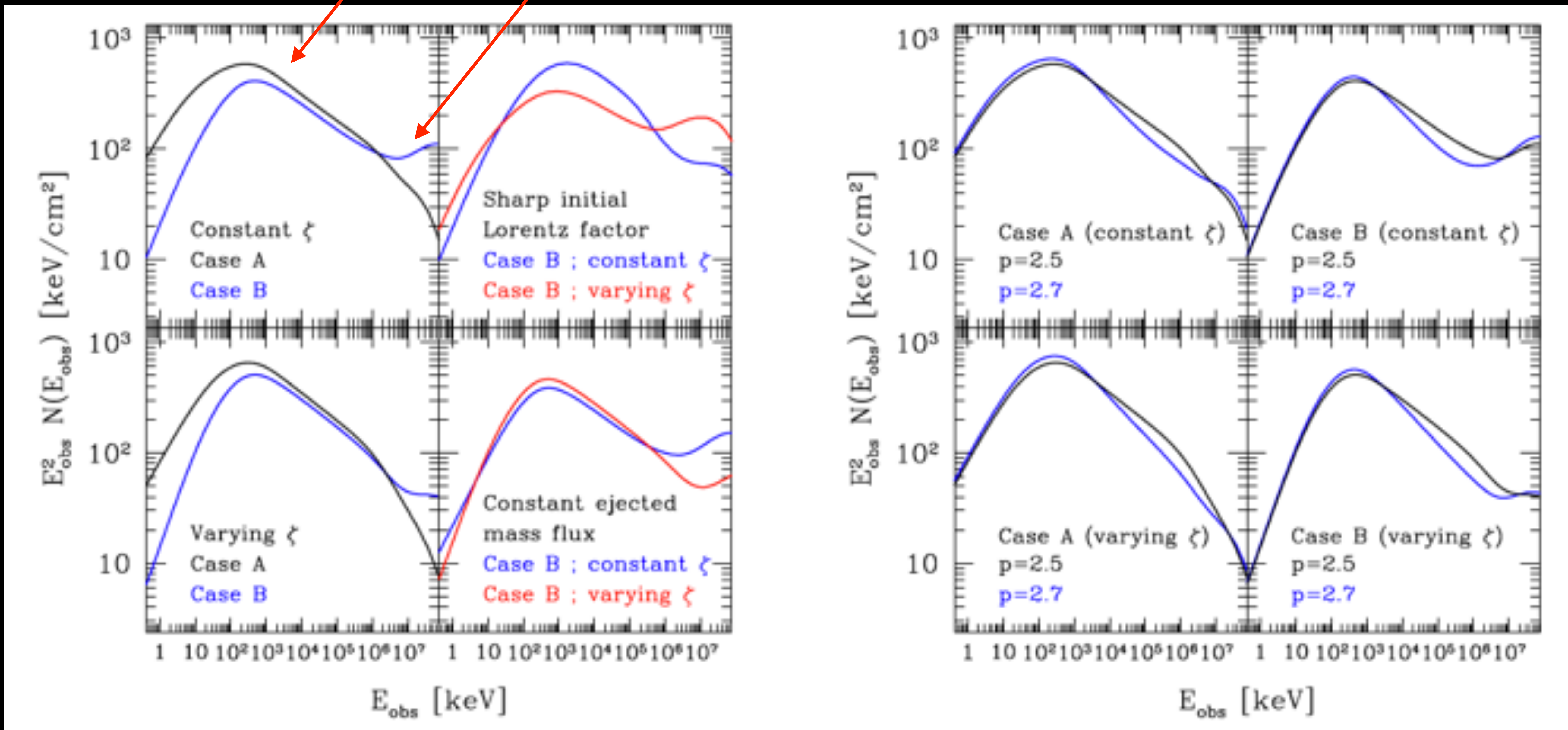
$$\approx \frac{\Gamma_1}{\Gamma_2}\, t_{var} \ll t_{var}$$

$\Gamma_2 \gg \Gamma_1$

Internal shocks: spectrum

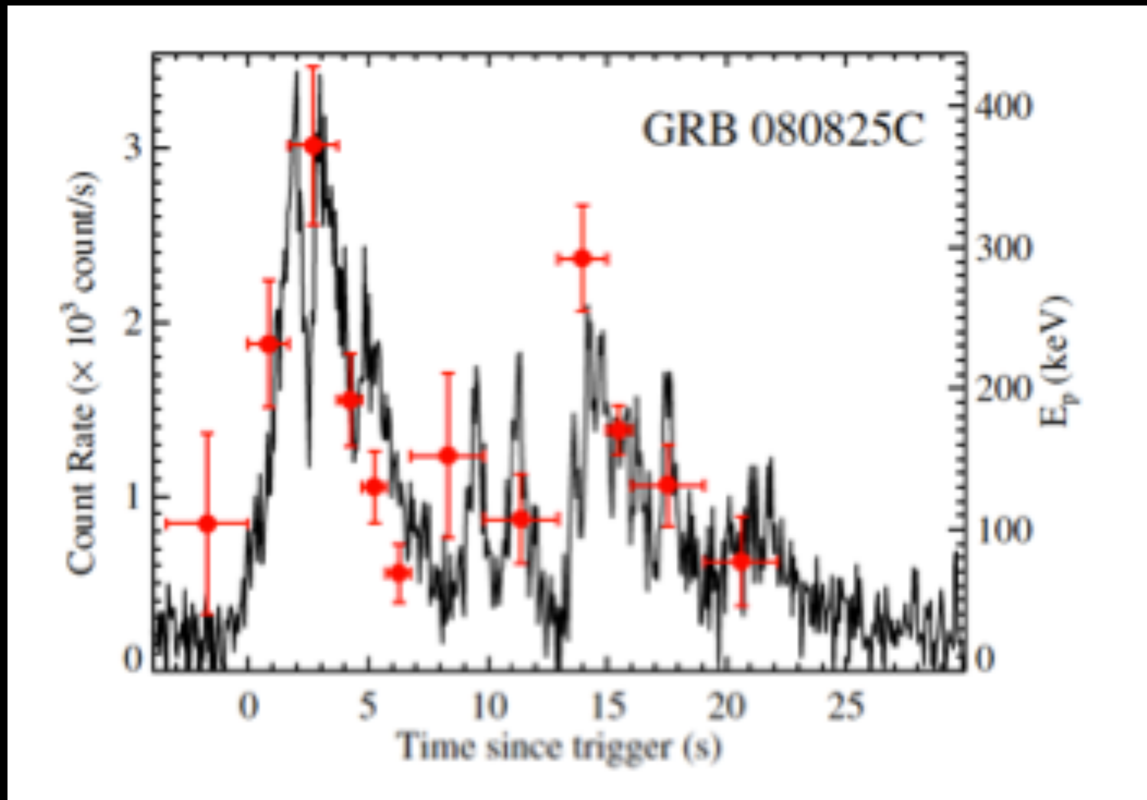
Main component: soft γ-rays (synchrotron)

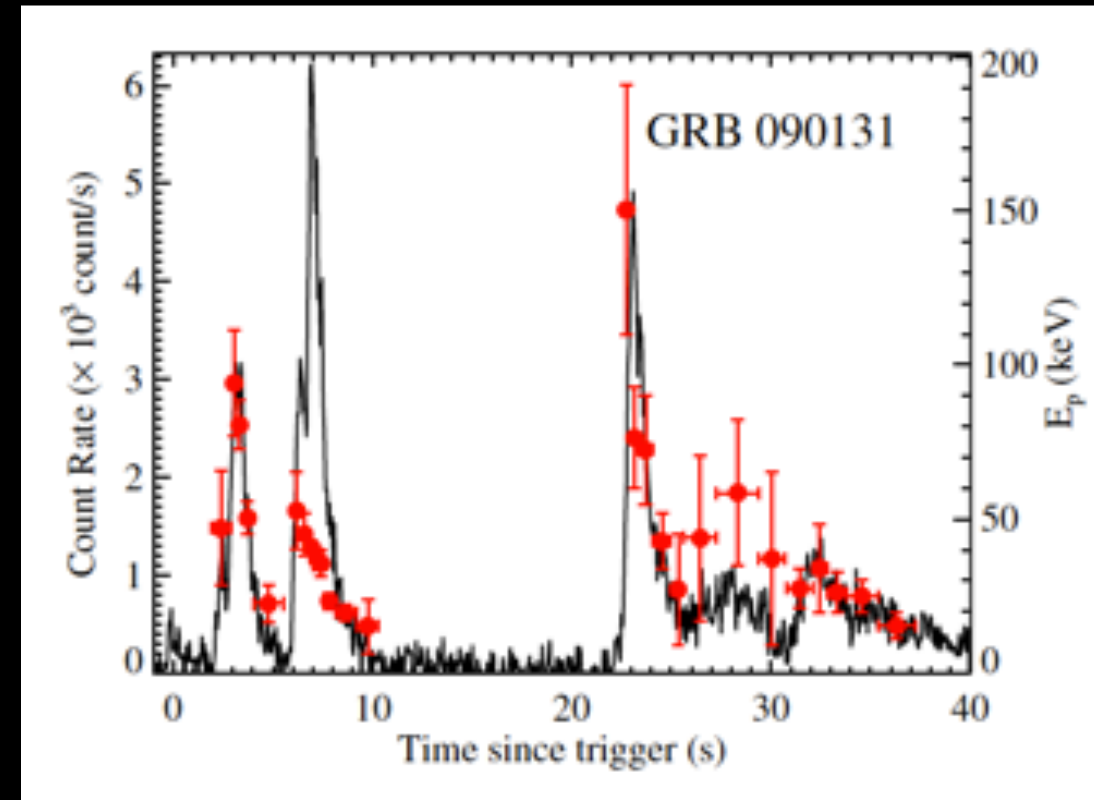
Additional component: high-energy γ-rays (IC)

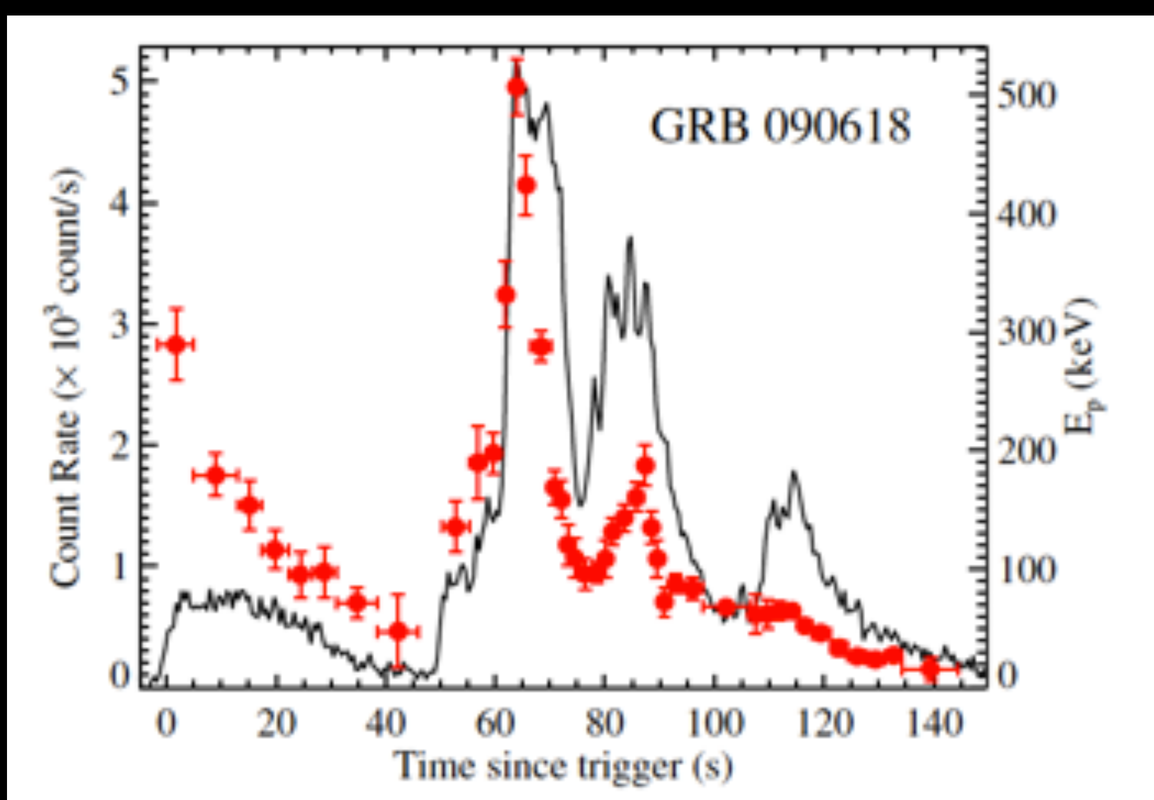


Bosnjak & Daigne 2014 ; see also Asano & Meszaros.

Prompt emission: spectral evolution





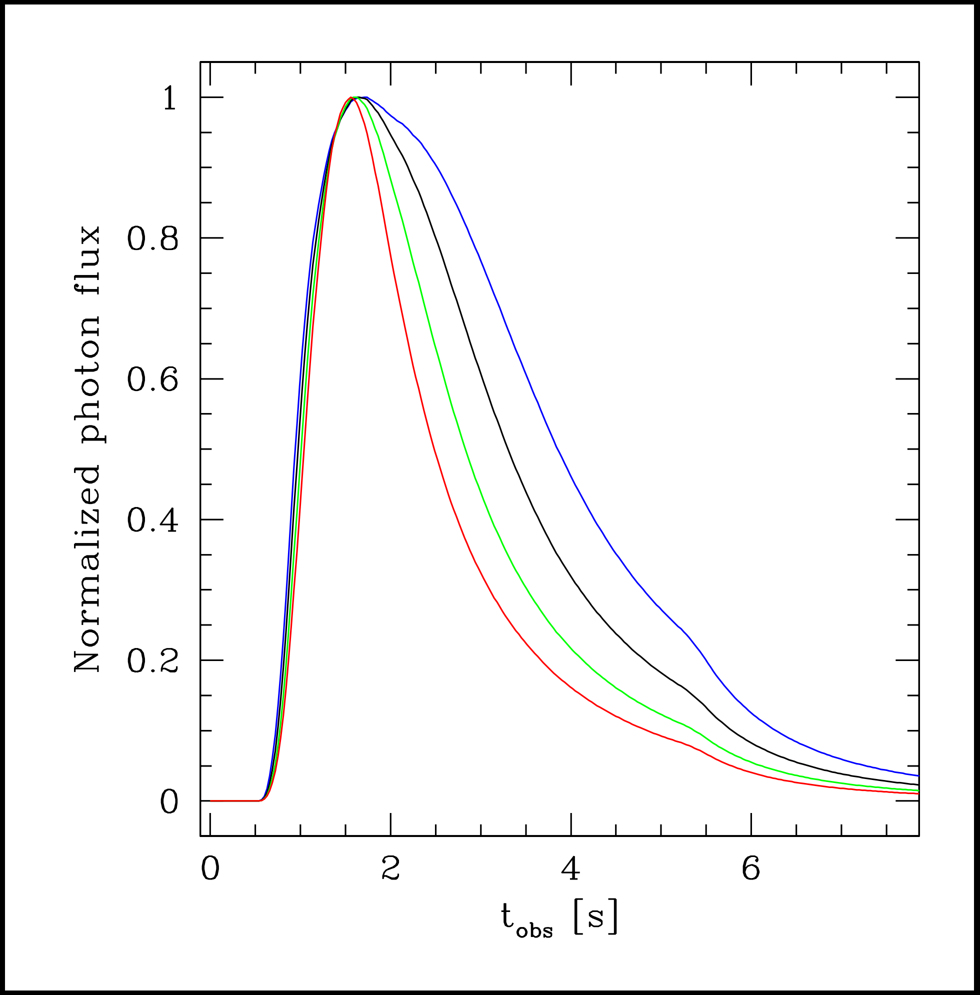


Fermi/GBM observations
(Li et al. 2012)

Black = lightcurve
Red = peak energy

Internal shocks: spectral evolution

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

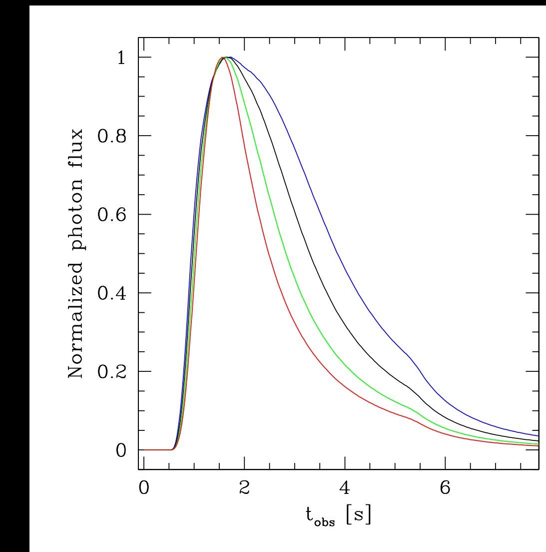


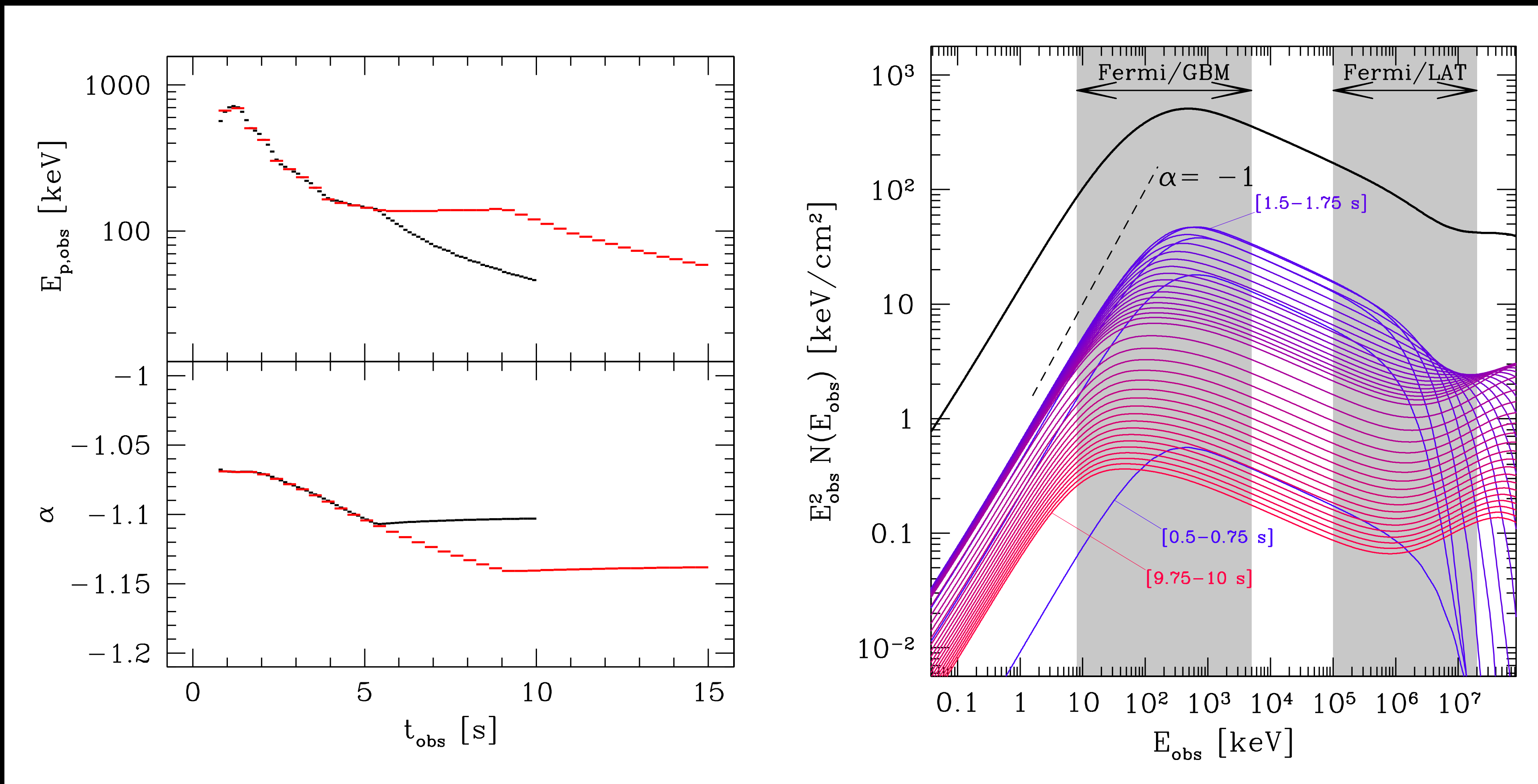
Light curve in BATSE range :
channels 1 (blue) to 4 (red)

Bosnjak & Daigne 2014

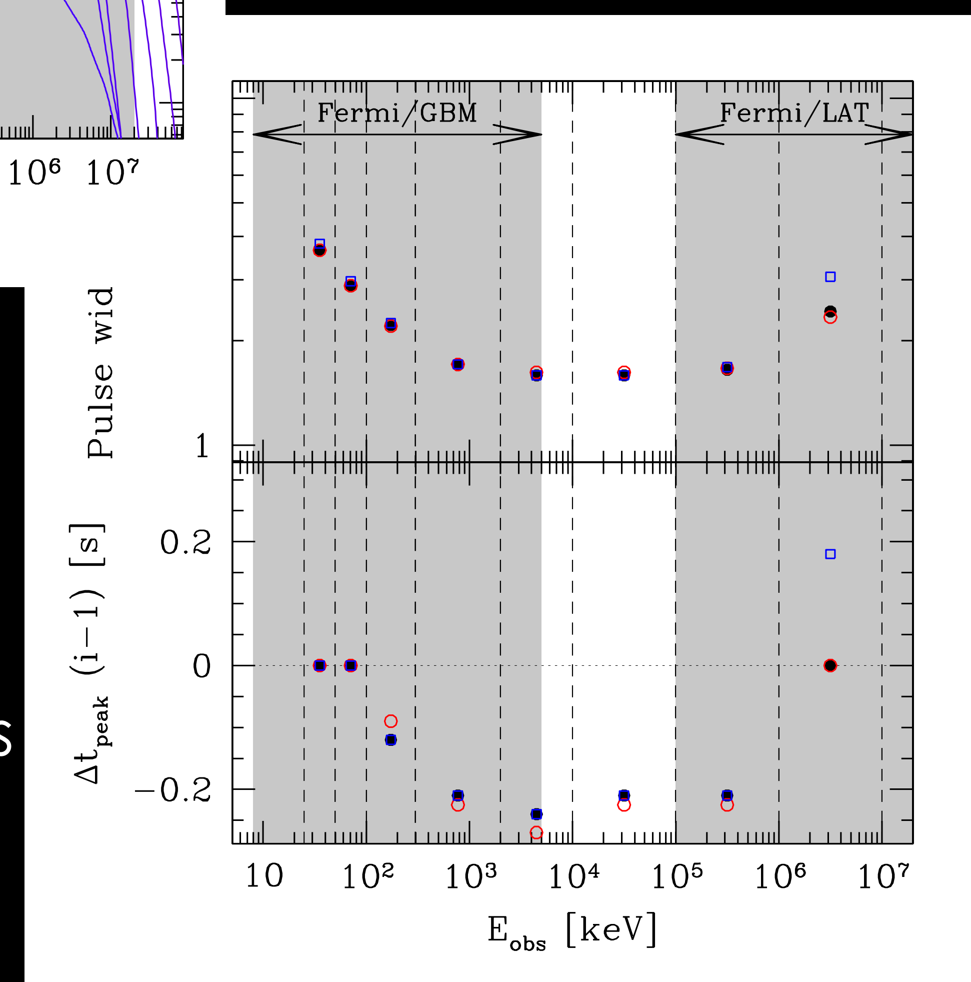
Internal shocks: spectral evolution

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





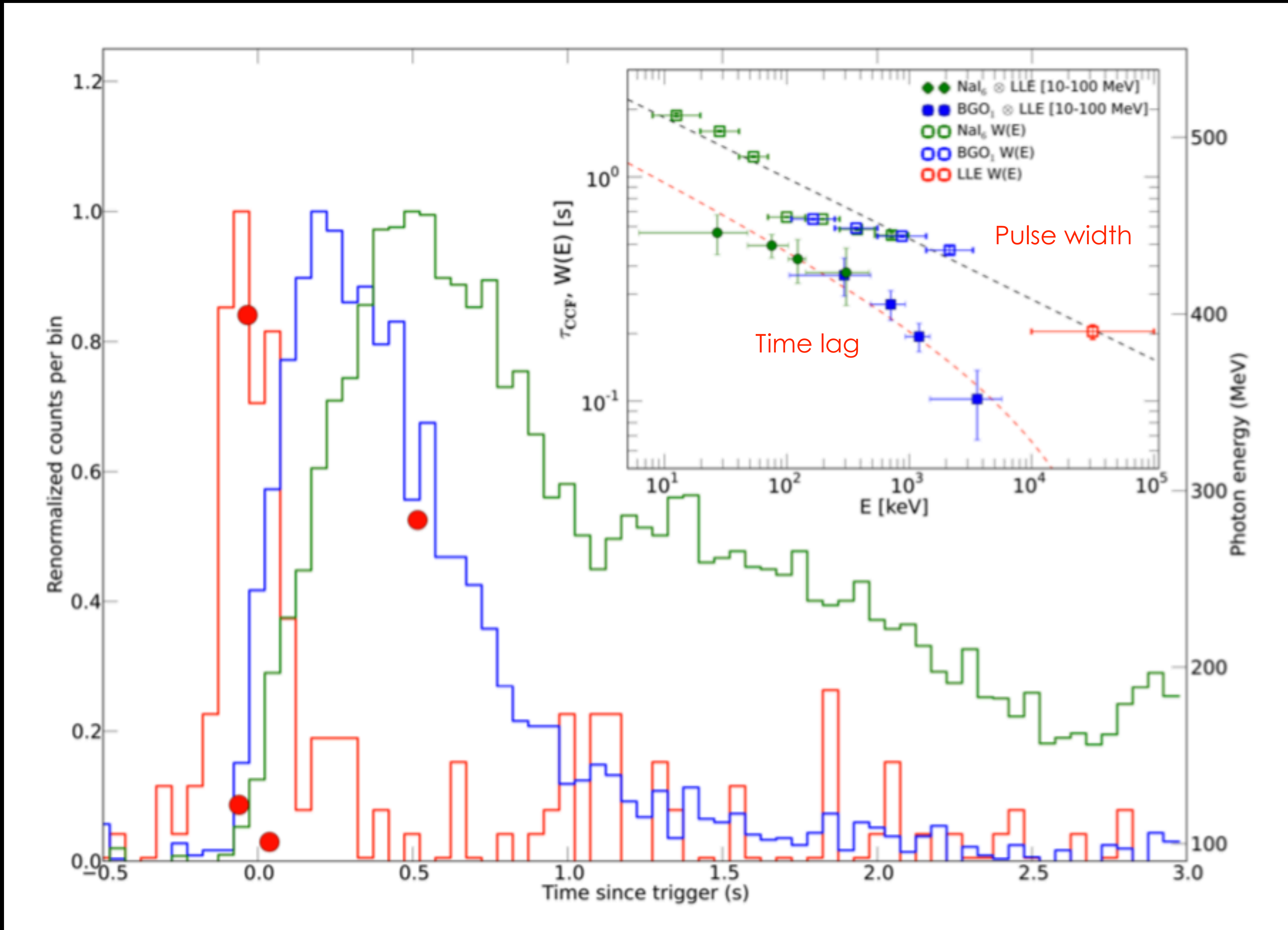
Time evolving spectrum



Pulse width / time lags

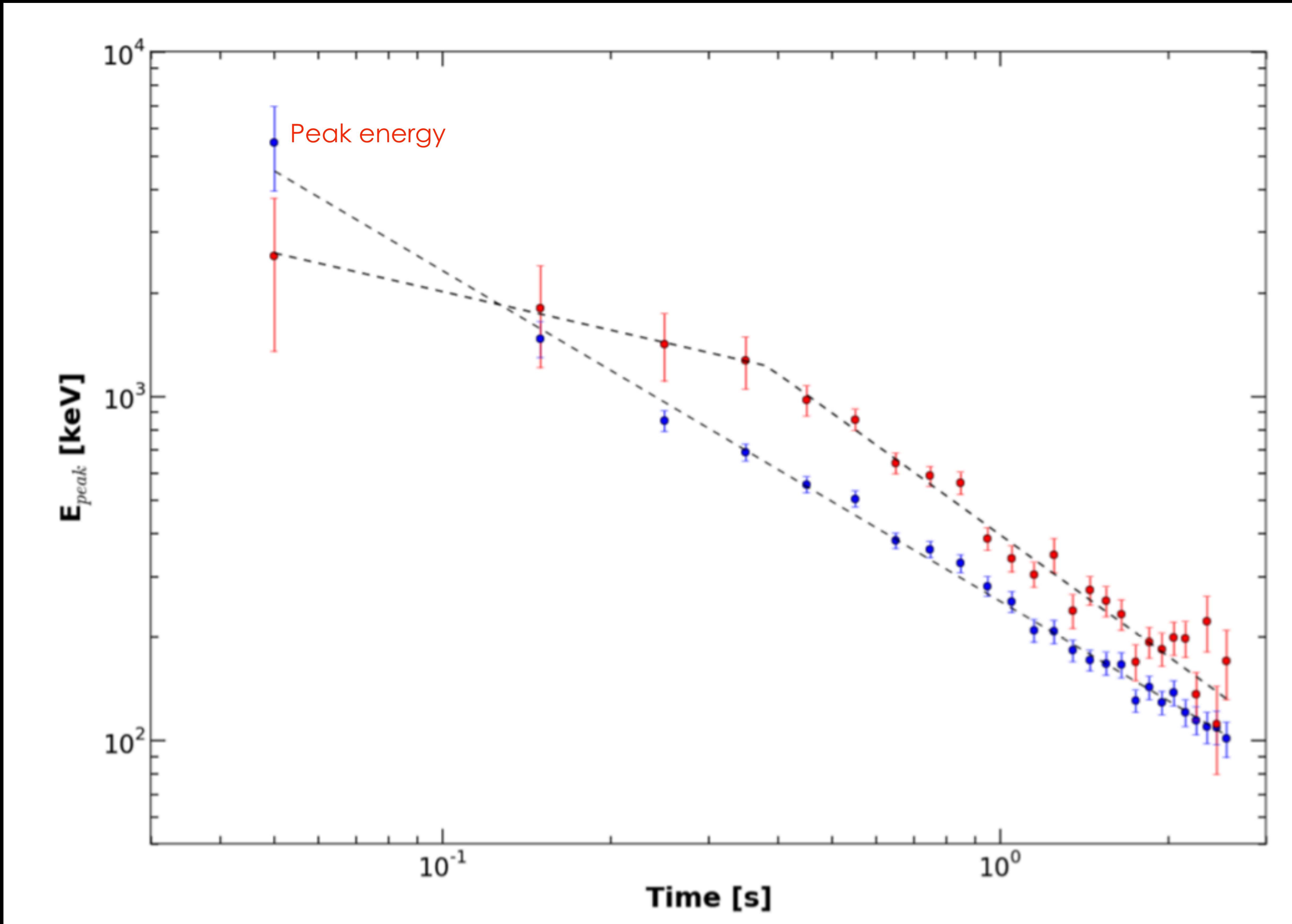
Bosnjak & Daigne 2014

Observations: first pulse of GRB 130427A



Preece et al. 2014

Observations: first pulse of GRB 130427A



Preece et al. 2014

Other possible mechanisms for the prompt emission

- **Synchrotron radiation in optically thin regime (i.e. above the photosphere):**
  - **Low magnetization at large distance: internal shocks**
  - **High magnetization at large distance: reconnection**

  In these scenarios:
  -complex microphysics, not fully understood.
  -synchrotron radiation: spectral shape?
  -large emission radius:
  - prompt HE emission can be produced in the same region (KN-SSC)
  - X-ray early steep decay can be naturally explained (high latitude emission)

Reconnection: Thompson, Spruit, Zhang, Kumar, …

- **Photospheric emission:**
  - Standard photosphere: quasi-thermal
    = cannot explain the main component of the prompt emission
    = may explain some weak quasi-thermal components possibly found by Fermi

  - **Dissipative photosphere**: a non-thermal spectrum can be recovered

  In this scenario
  - dissipative process needs to be identified
  - spectral evolution is not natural
  - low radius: high energy emission ? X-ray early steep decay ?

Photosphere: Rees & Meszaros, Daigne&Mochkovitch, Pe'er, Ryde, …

Dissipative photosphere: Rees&Meszaros, Beloborodov, Vurm, …

Problems with synchrotron radiation?

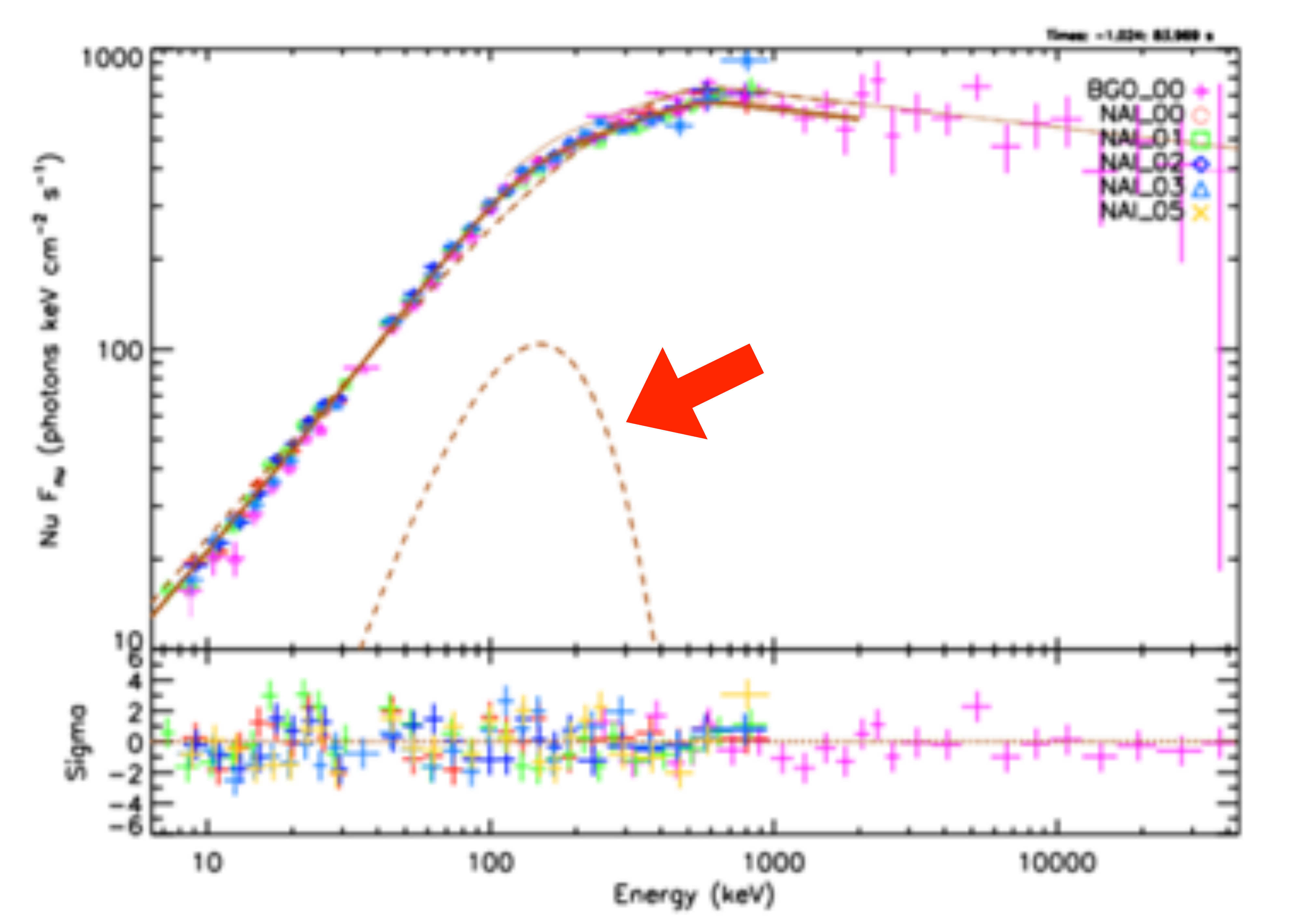
- A long debate: the observed low-energy photon index seems in contradiction with synchrotron radiation
    - Observed: -1 or higher
    - Predicted by standard fast cooling synchrotron radiation: -3/2

- It is not very clear how well this photon index is measured

- Several mechanisms can affect the synchrotron spectrum:
    - marginally fast cooling
    - inverse Compton in Klein-Nishina regime
    - evolving magnetic field in the emission region
    - etc.

Weak quasi-thermal components?

Example: GRB 100724B (Fermi/GBM observations)



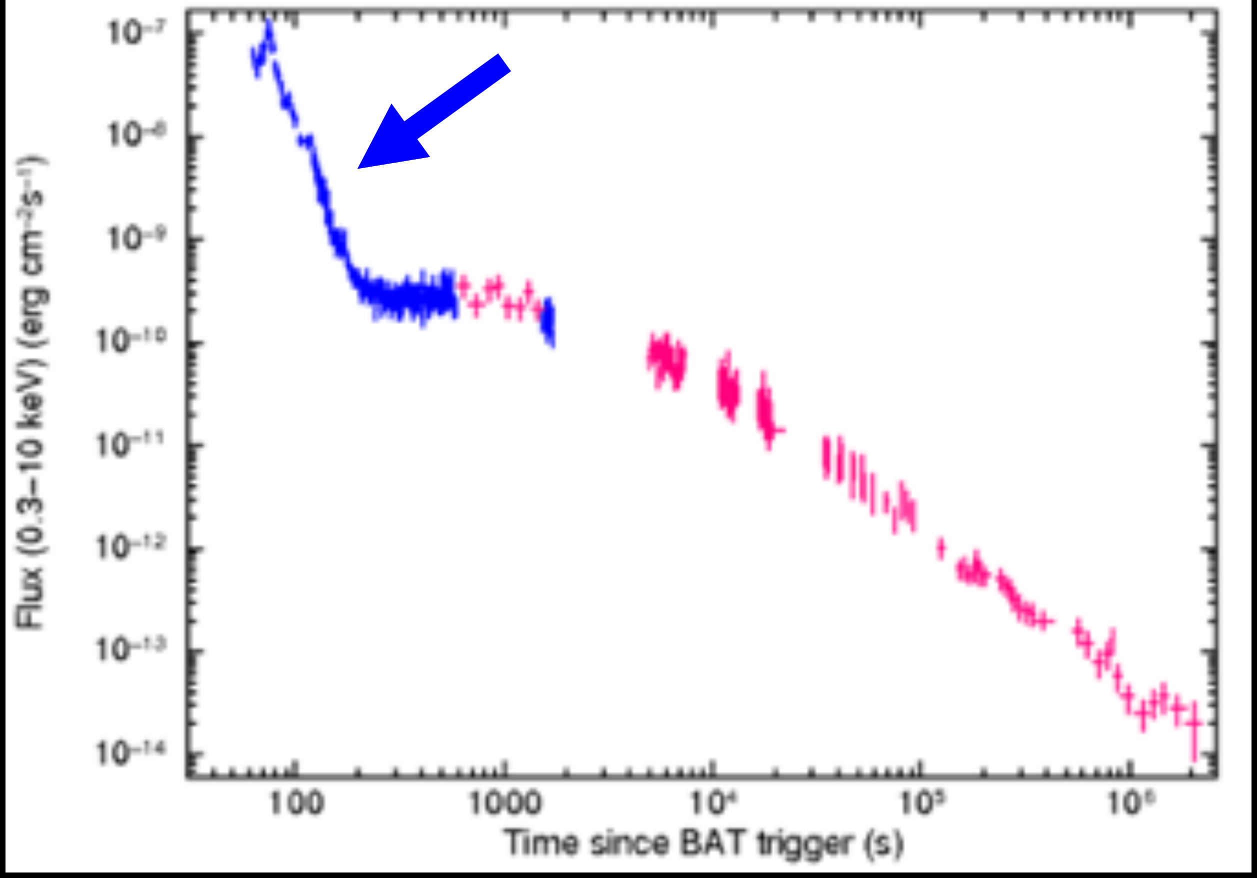
Guiriec et al. [FD] 2011

Prompt to afterglow transition

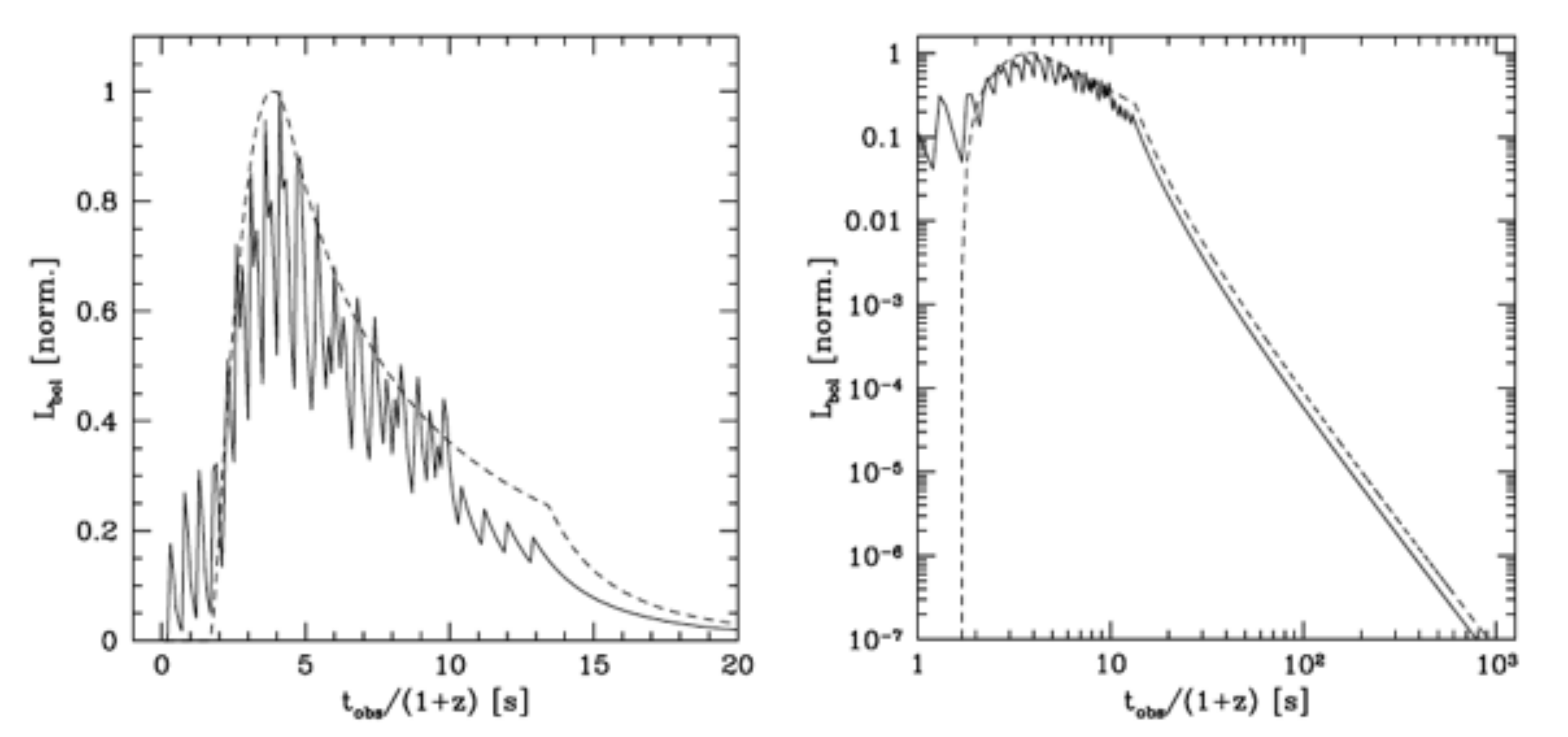
- Early steep-decay (X-rays)
  = high-latitude emission?

  works if $R_{\mathrm{prompt,end}} \simeq \Gamma^2\, c\, t_{\mathrm{burst}}$

  (OK for internal shocks/reconnection)



(Page et al. 2007)



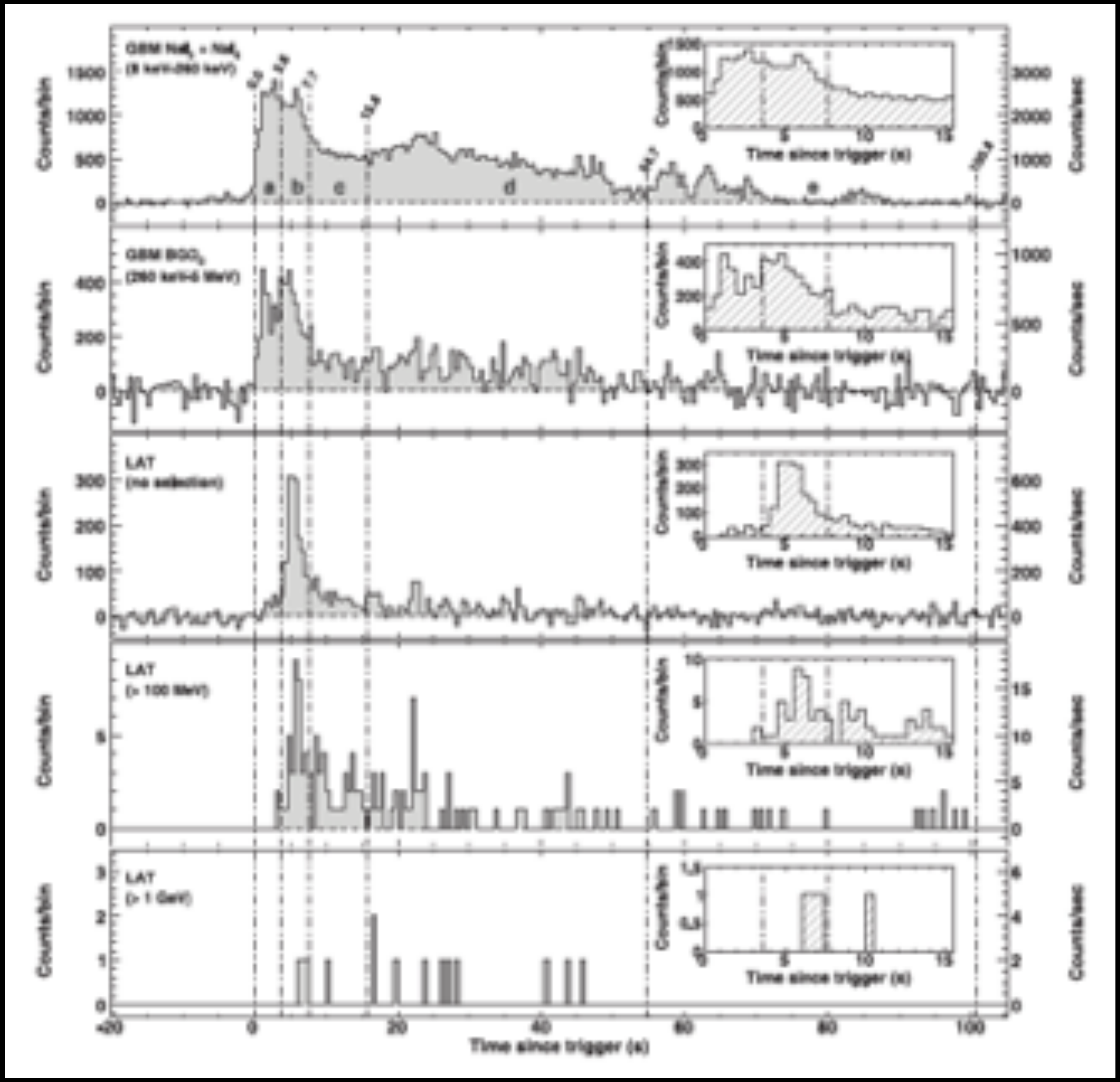
(Hascoët, Daigne & Mochkovitch 2012)

How relativistic are GRB outflows?

- Indirect constraint: high-energy emission and pair production
- Pre-Fermi (MeV range) : Γ_{min} ~ 100-300 (e.g. Lithwick & Sari 2001)
- GeV detection by Fermi: stricter Lorentz factor constraints

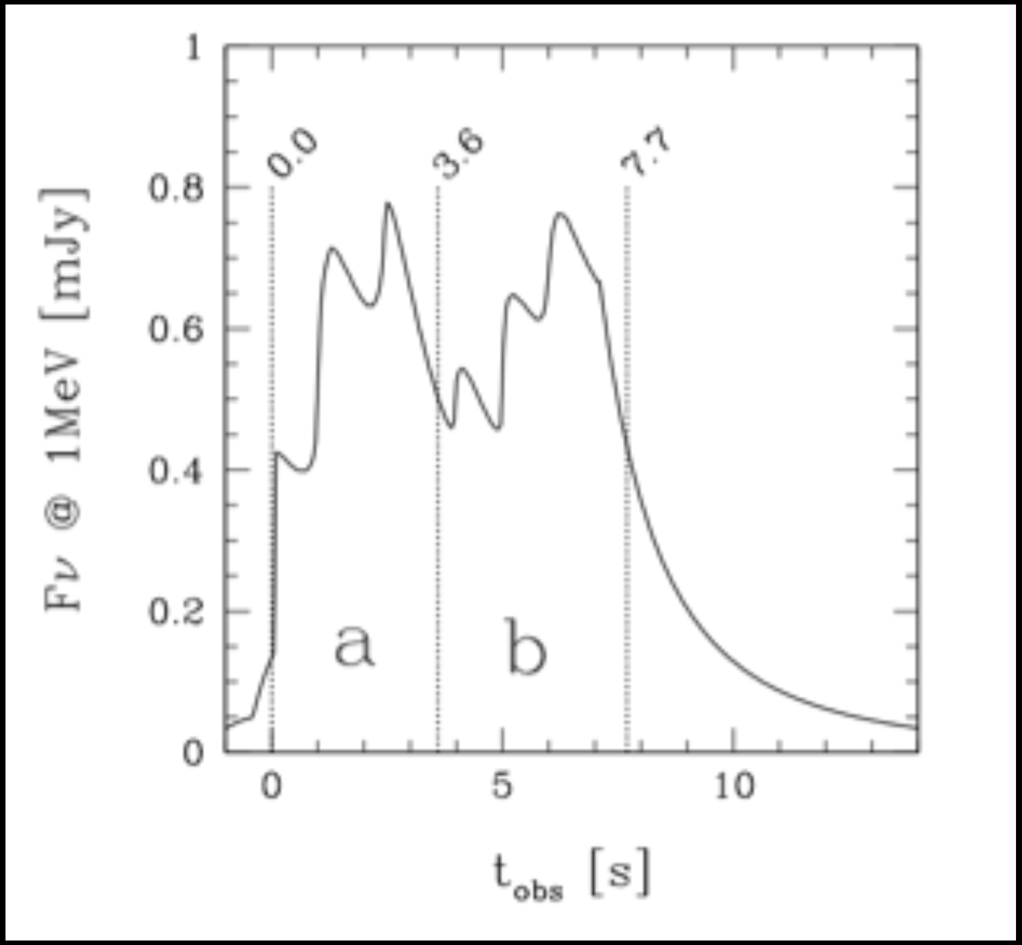
  GRB 080916C: $\Gamma_{min} \geq 887$ (Abdo et al. 09)

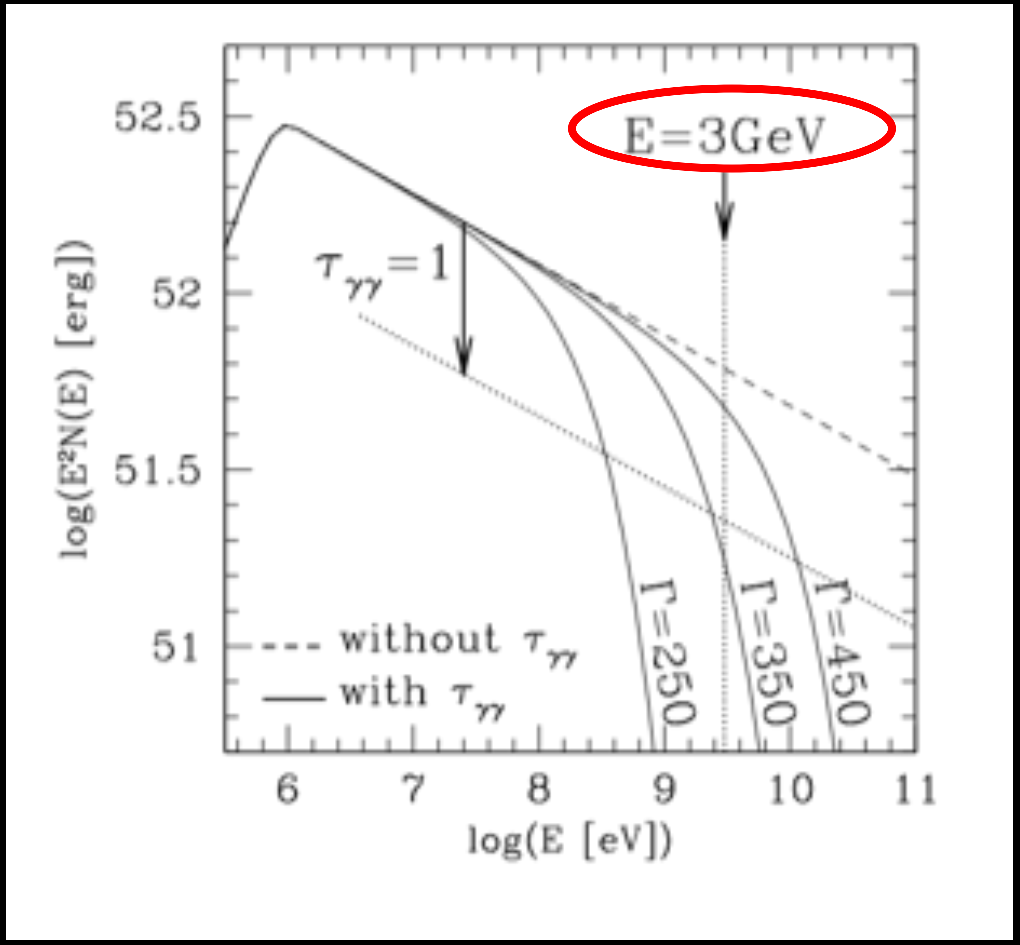
  GRB 090510: $\Gamma_{min} \geq 1200$ (Ackerman et al. 10)



How relativistic are GRB outflows?

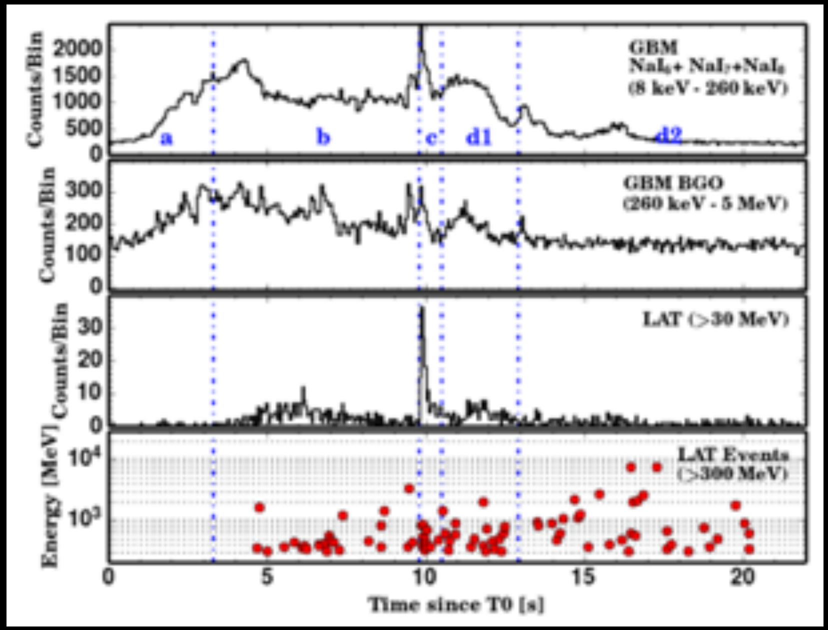
- Detailed calculation: space/time/direction-dependent radiation field
  the estimate of Γ_{min} is reduced by a factor ~ 2-3
  (Granot et al. 2008; Hascoët, Daigne, Mochkovitch & Vennin 2012)
- GRB 080916C :
  Γ_{min} ~ 360 (Hascoët et al. 2012)
  instead of ~900 (Abdo et al. 2009)

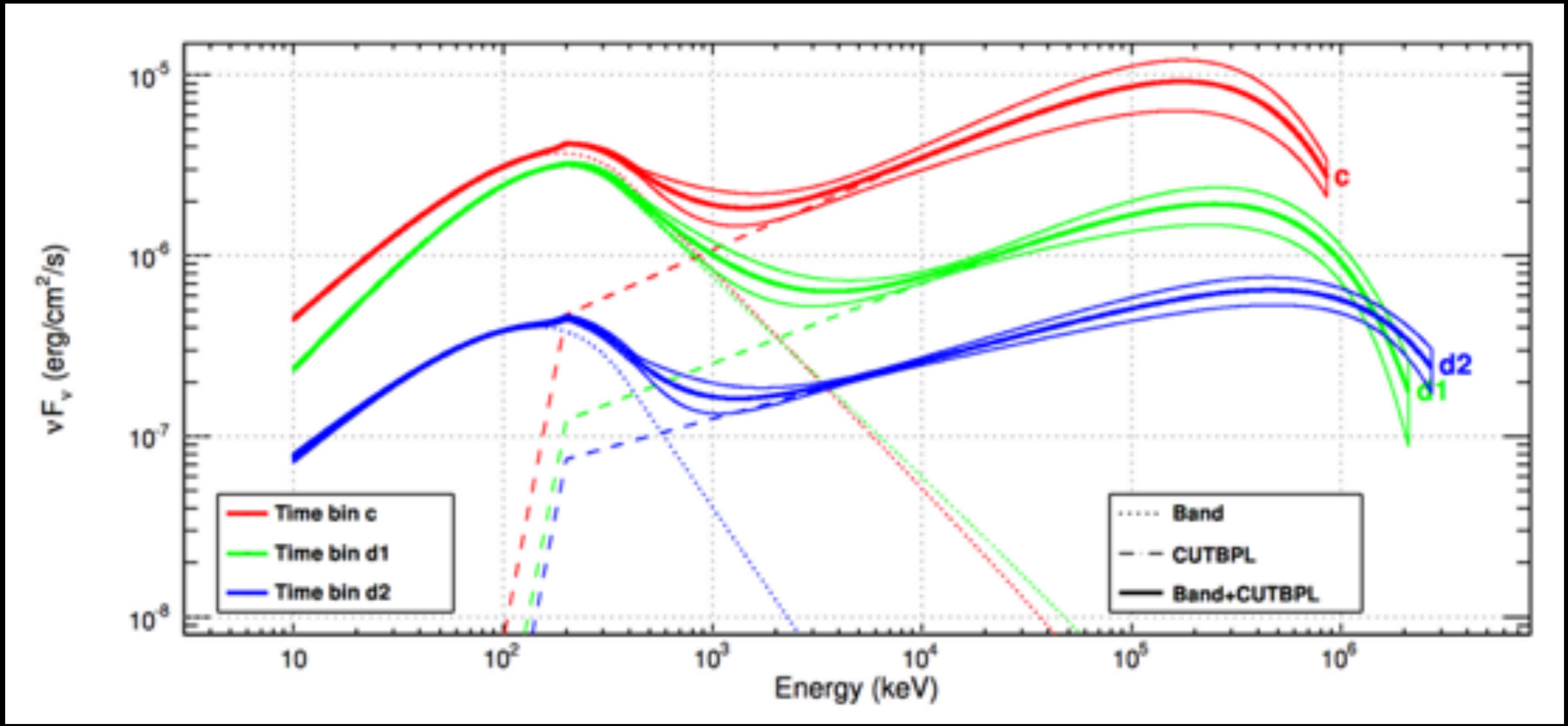




How relativistic are GRB outflows?

- GRB 090926A (Fermi-LAT): first observed cutoff at high-energy (Ackermann et al. 2011)
- New analysis and interpretation:
  - Path 8: 447 → 1088 evts in LAT (× 2.4)
  - cutoff is better detected, in several time bins

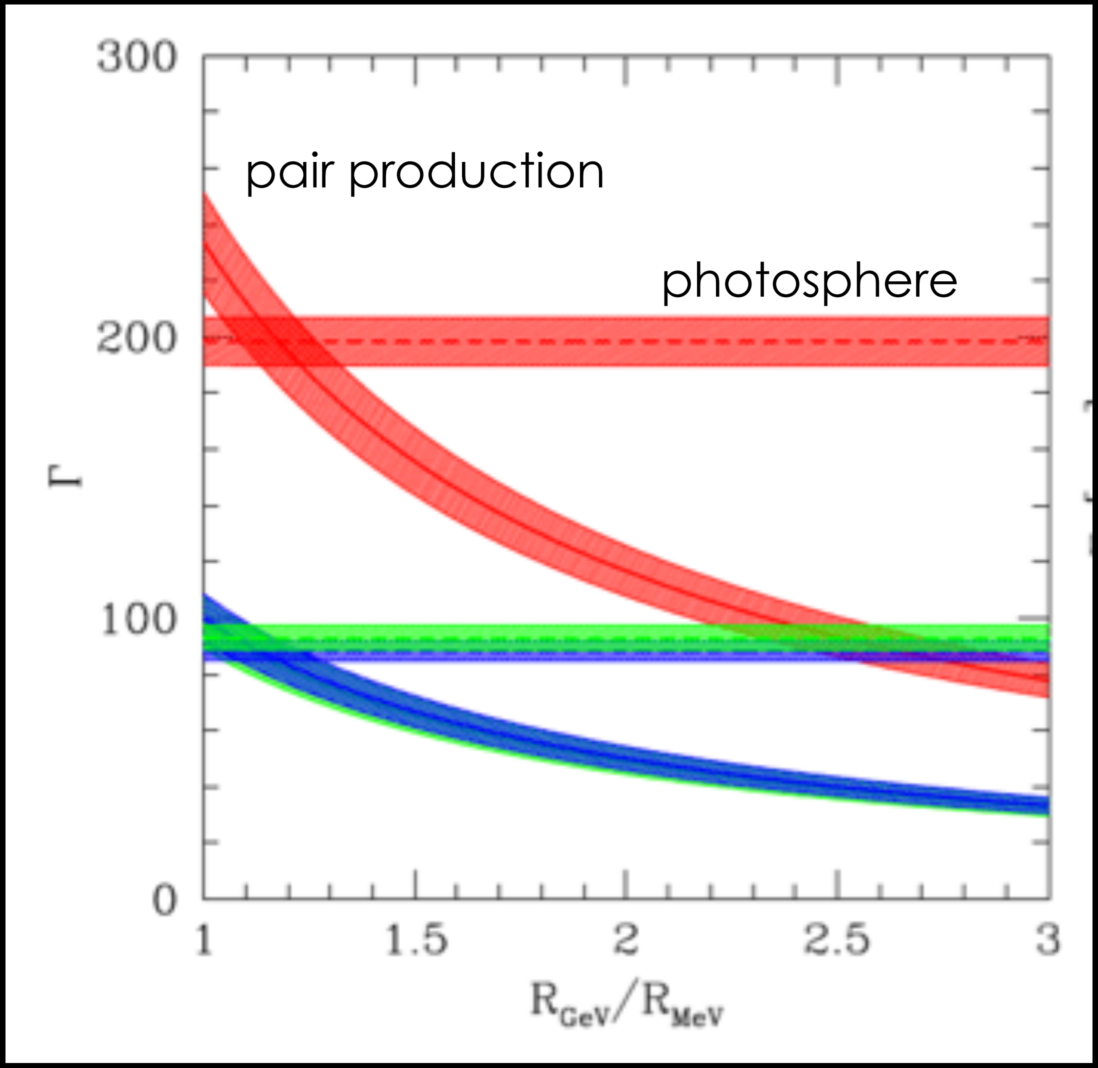


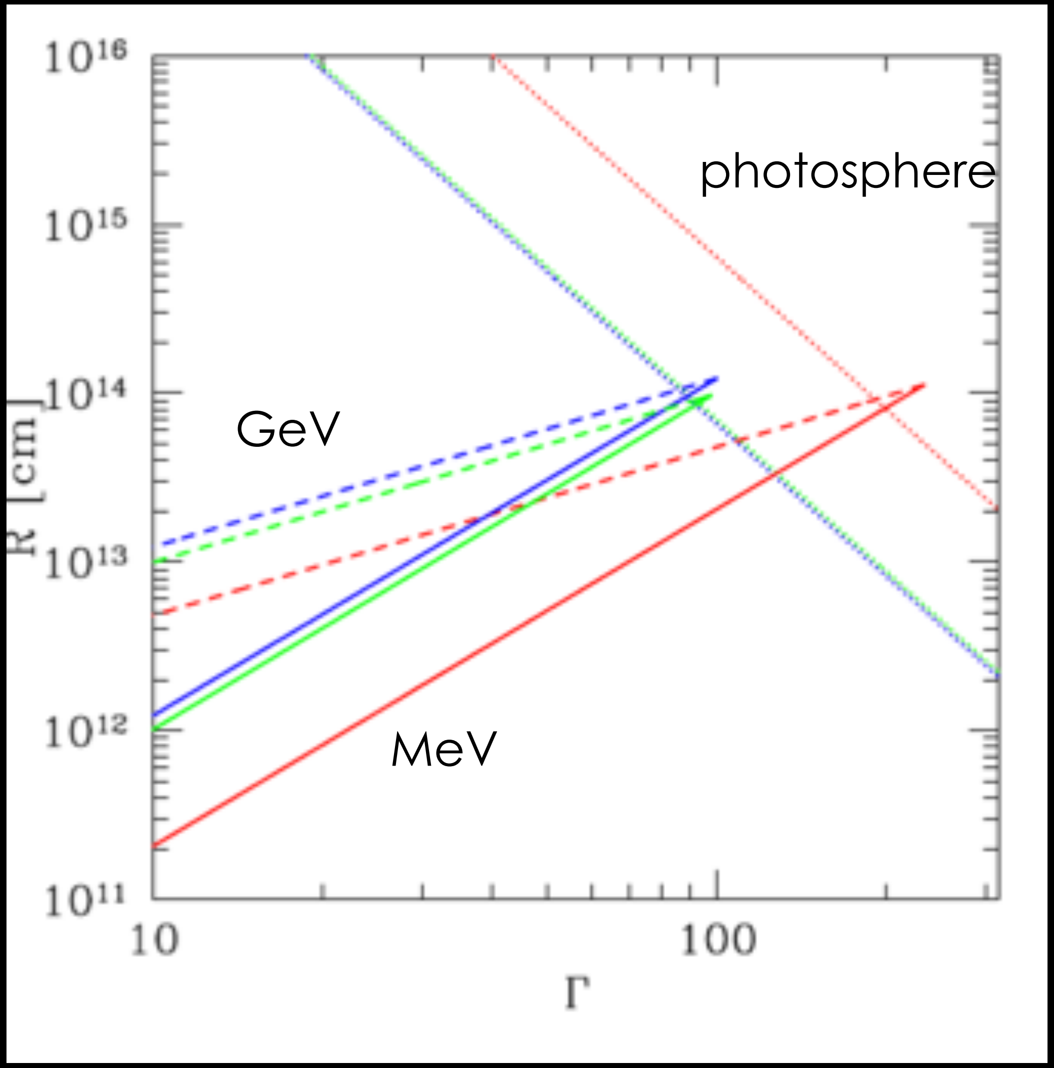


(Yassine, Piron, Mochkovitch & Daigne 2017)

How relativistic are GRB outflows?

- GRB 090926A (Fermi-LAT): first observed cutoff at high-energy (Ackermann et al. 2011)
- Strong constraint on 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 photosphere)





(Yassine, Piron, Mochkovitch & Daigne 2017)

Prompt emission: many open issues

- How to distinguish between these mechanisms?

(note: some combinations are possible, e.g. photosphere+shocks or rec.)

- Microphysics?

- Global efficiency?

- Origin of the prompt optical emission?

- Emission at very high energy?

- Neutrino emission?

- Gamma-ray polarization? see Gill, Granot & Kumar 2019
  Producing a high polarization is difficult, especially for photospheric models.

etc.

Gamma-ray polarization

- In principle, polarization is an efficient tool to probe the physics of the prompt emission:
  sensitive to
  - magnetic field geometry
  - radial/angular structure of the flow
  - radiative process

- However interpretation becomes difficult when the polarization is measured over a long time interval.

GRB	Π (%)	PA (°)	$\sigma_{\rm det}$ ($\Pi > 0\%$)	Instrument	Ref.
021206	80 ± 20	–	> 5.7	*RHESSI*[d]	Coburn & Boggs (2003)
	0		–		Rutledge & Fox (2004)
	41^{+57}_{-44}		–		Wigger et al. (2004)
041219A	98 ± 33		~ 2.3	*INTEGRAL*-SPI[e]	Kalemci et al. (2007)
	$63^{+31\,a}_{-30}$	70^{+14}_{-11}	~ 2		McGlynn et al. (2007)
	43 ± 25^{b}	38 ± 16	< 2	*INTEGRAL*-IBIS	Götz et al. (2009)
061122	> 33 (90% CL)	160 ± 20	–	*INTEGRAL*-IBIS	Götz et al. (2013)
100826A[c]	27 ± 11	–	2.9	*IKAROS*-GAP	Yonetoku et al. (2011b)
100826Ap1[c]	25 ± 15	159 ± 18	2.0		
100826Ap2[c]	31 ± 21	75 ± 20	1.6		
110301A	70 ± 22	73 ± 11	3.7	*IKAROS*-GAP	Yonetoku et al. (2012)
110721A	84^{+16}_{-28}	160 ± 11	3.3	*IKAROS*-GAP	Yonetoku et al. (2012)
140206A	> 28 (90% CL)	80 ± 15	–	*INTEGRAL*-IBIS	Götz et al. (2014)
151006A	< 84	–	–	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160106A	69 ± 24	-23 ± 12	$\gtrsim 3$	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160131A	94 ± 33	41 ± 5	$\gtrsim 3$	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160325A	59 ± 28	11 ± 17	~ 2.2	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160509A	< 92	–	–	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160530A	< 46 (90% CL)	–	–	COSI[g]	Lowell et al. (2017)
160607A	< 77	–	–	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160623A	< 46	–	–	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160703A	< 55	–	–	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160802A	85 ± 30	-36 ± 5	$\gtrsim 3$	*AstroSat*-CZTI	Chattopadhyay et al. (2017); Chand et al. (2018a)
160821A	54 ± 16	-39 ± 4	$\gtrsim 3$	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160821A[h]	66^{+26}_{-27}		~ 5.3	*AstroSat*-CZTI	Sharma et al. (2019)
160821Ap1[h]	71^{+29}_{-41}	110^{+14}_{-15}	3.5	*AstroSat*-CZTI	
160821Ap2[h]	58^{+29}_{-30}	31^{+12}_{-10}	4	*AstroSat*-CZTI	
160821Ap3[h]	61^{+39}_{-46}	110^{+25}_{-26}	3.1	*AstroSat*-CZTI	
160910A	94 ± 32	44 ± 4	$\gtrsim 3$	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
161218A	9	40	~ 1.7	POLAR	Zhang et al. (2019)
	< 41 (99% CL)	–	–		
170101A	8	164	~ 1.5	POLAR	Zhang et al. (2019)
	< 30 (99% CL)	–	–		
170114A	4	164	~ 1.5	POLAR	Zhang et al. (2019); Burgess et al. (2019)
	< 28 (99% CL)	–	–		
170114Ap1[f]	15	122	~ 1.8		
170114Ap2[f]	41	17	~ 2.8		
170127C	11	38	~ 1.9	POLAR	Zhang et al. (2019)
	< 68 (99% CL)	–	–		
170206A	10	106	~ 1.5	POLAR	Zhang et al. (2019)
170206A	< 31 (99% CL)	–	–		
171010A	~ 40	variable	–	*AstroSat*-CZTI	Chand et al. (2018b)

Table 1. Measured degree of linear polarization and position angle in the prompt phase of GRBs. The detection significance $\sigma_{\rm det}$ is the significance of measuring $\Pi > 0\%$. The quoted errors are at the 1σ level. [a] Measured for the brightest pulse of duration 66 s. [b] Measured for the second peak lasting 40 s. [c] The main prompt emission is divided into two time intervals, p1 featuring a 47 s broad flare (line 1), and 53 s long p2 consisting of multiple pulses (line 3). Line 1 jointly fits p1 and p2 assuming they have the same Π but allowing and indeed finding a different PA between them. [d] Reuven Ramaty High Energy Solar Spectroscopic Imager. [e] International Gamma-Ray Astrophysics Laboratory. [f] Π obtained for two equal 2 s time bins within a single pulse, with a significant change in PA between them. [g] Compton Spectrometer and Imager. [h] Average polarization over the single emission episode, with a *Fermi*-GBM (*AstroSat*-CZTI) $T_{90} = 43$ s (42 s), that showed variable polarization levels and PA during three distinct time intervals p1, p2, p3 within the emission episode.

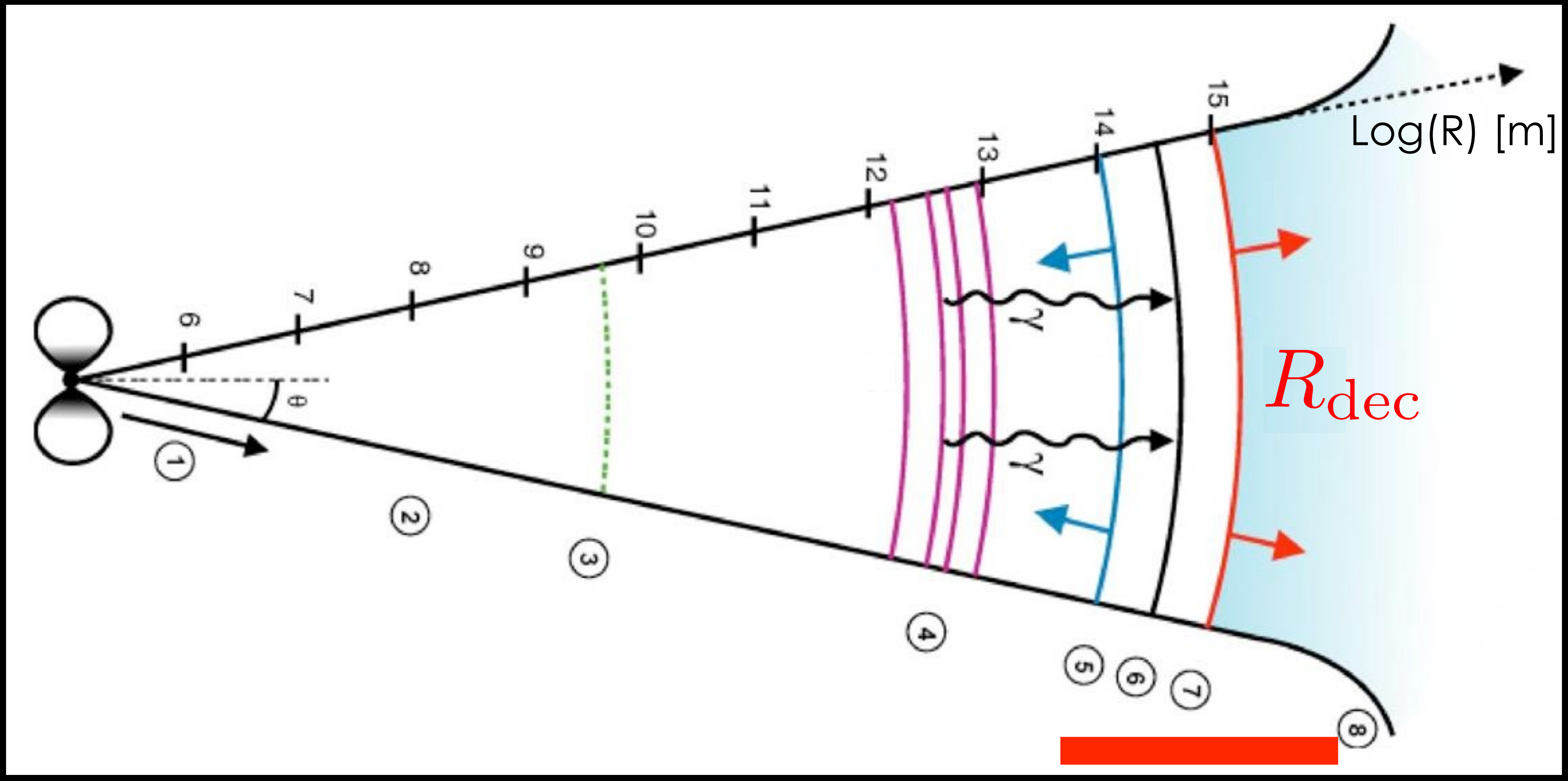
Gill, Granot & Kumar 2019

GRB Physics:
afterglow

Afterglow

Standard afterglow model: Rees & Meszaros ; Sari, Piran, & Narayan

- Long timescales (hours/days/weeks/years): the afterglow has an <u>external</u> origin
- Interaction of the relativistic ejecta with the circus-burst medium: deceleration
- Forward shock: strong ultra-relativistic shock in the external medium = afterglow



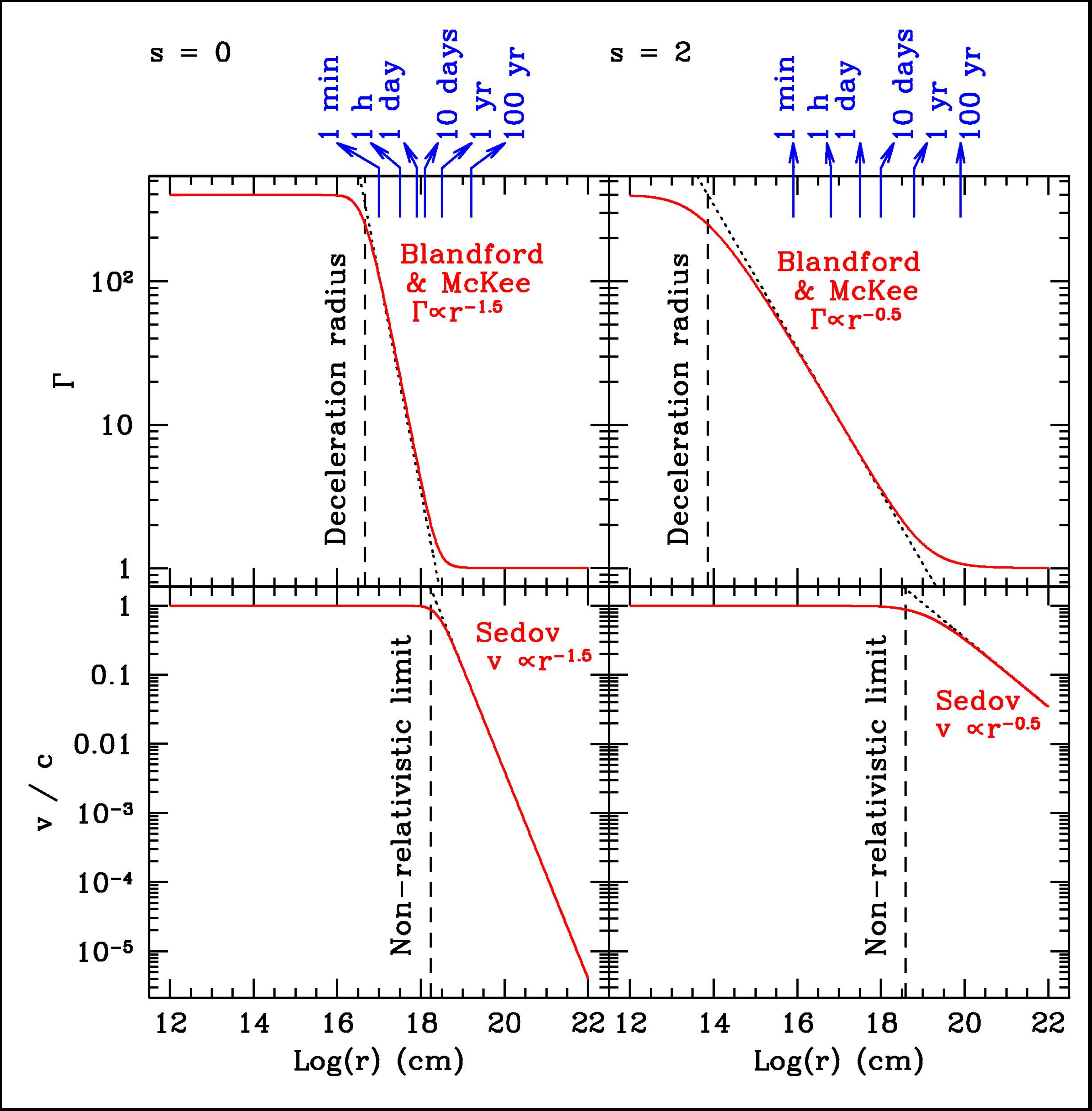
- Reverse shock (if the ejecta has a low magnetization): additional contribution?

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

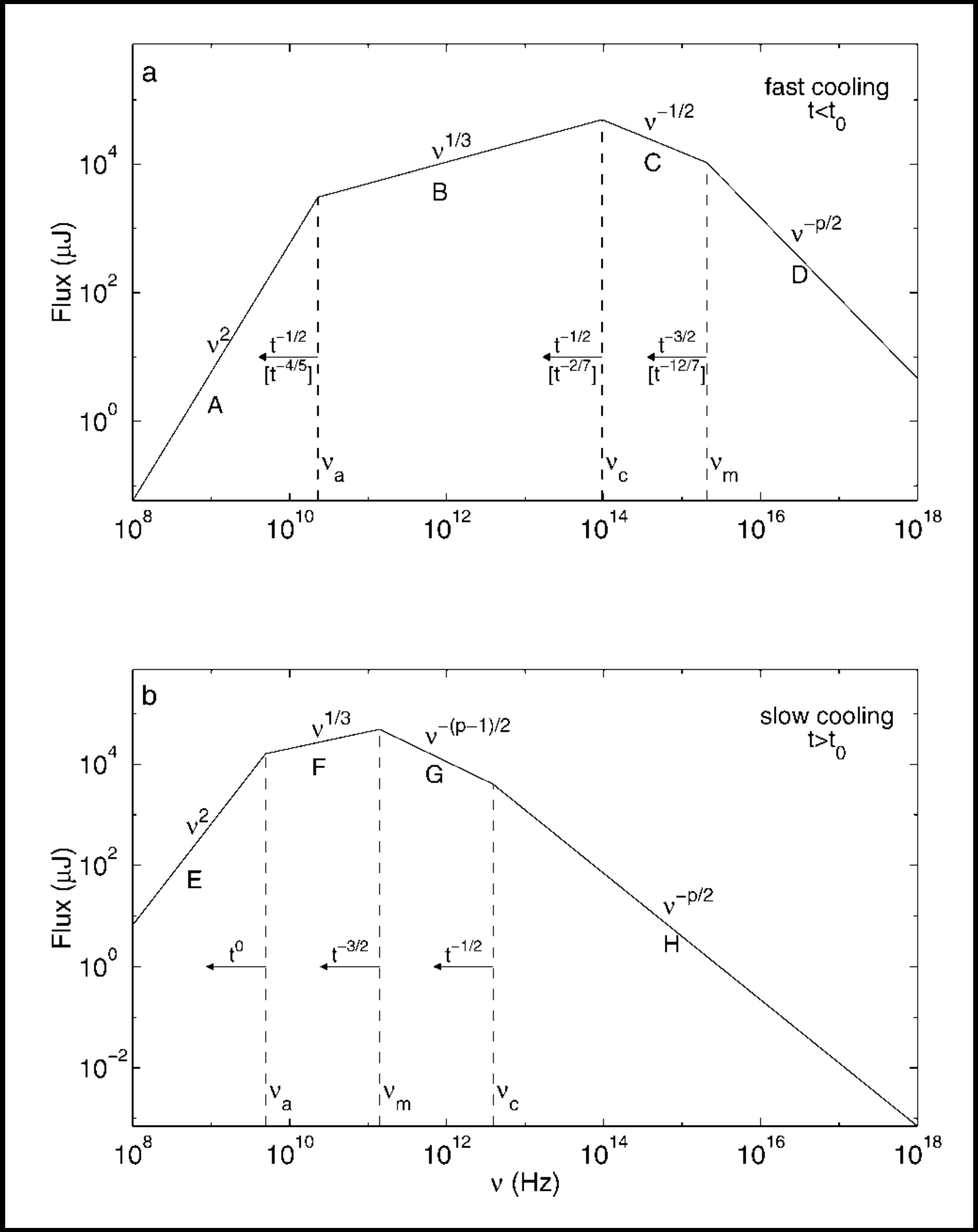
$$R_{\rm Newton} \simeq \left(\frac{3}{4\pi}\frac{\mathcal{E}_{\rm kin,0}}{n_{\rm ext} m_{\rm p} c^2}\right)^{1/3} \simeq 3.2\,10^{18}\,\mathrm{cm}\,\left(\frac{\mathcal{E}_{\rm kin,0}}{10^{53}\,\mathrm{erg}}\right)^{1/3}\left(\frac{n_{\rm ext}}{1\,\mathrm{cm}^{-3}}\right)^{-1/3}$$

Deceleration

Ejecta is decelerated by the external medium



Afterglow theory: synchrotron spectrum



Sari, Piran, Narayan 1998

- Fast cooling regime:

  all electrons have a synchrotron timescale shorter than the dynamical timescale

  = efficient case, where most of the electron energy is radiated

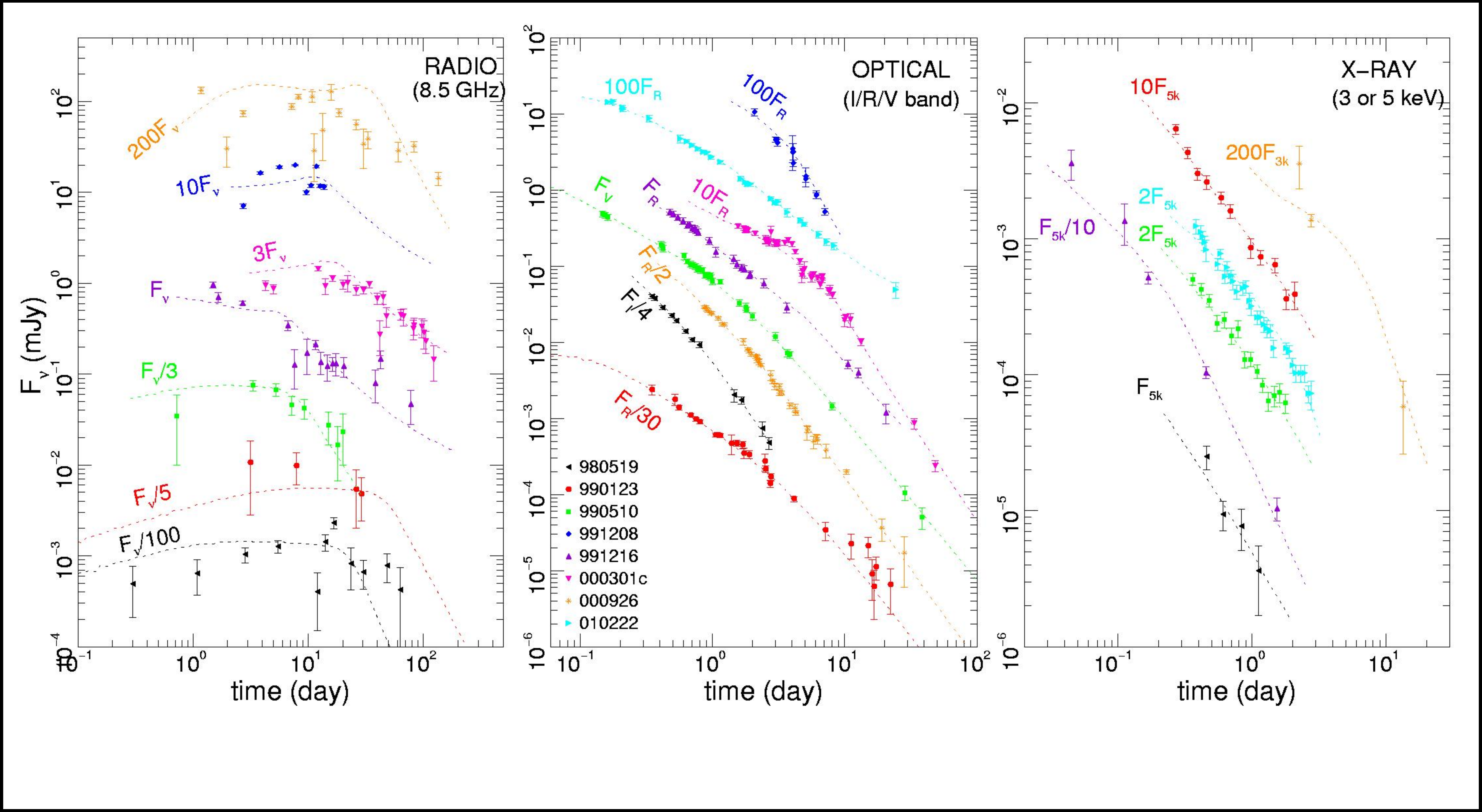
- Slow cooling case:

  only high energy electrons are radiating efficiently. Most electrons have a synchrotron time scale longer than the dynamical timescale

  = inefficient case, where adiabatic cooling becomes dominant

Afterglow theory

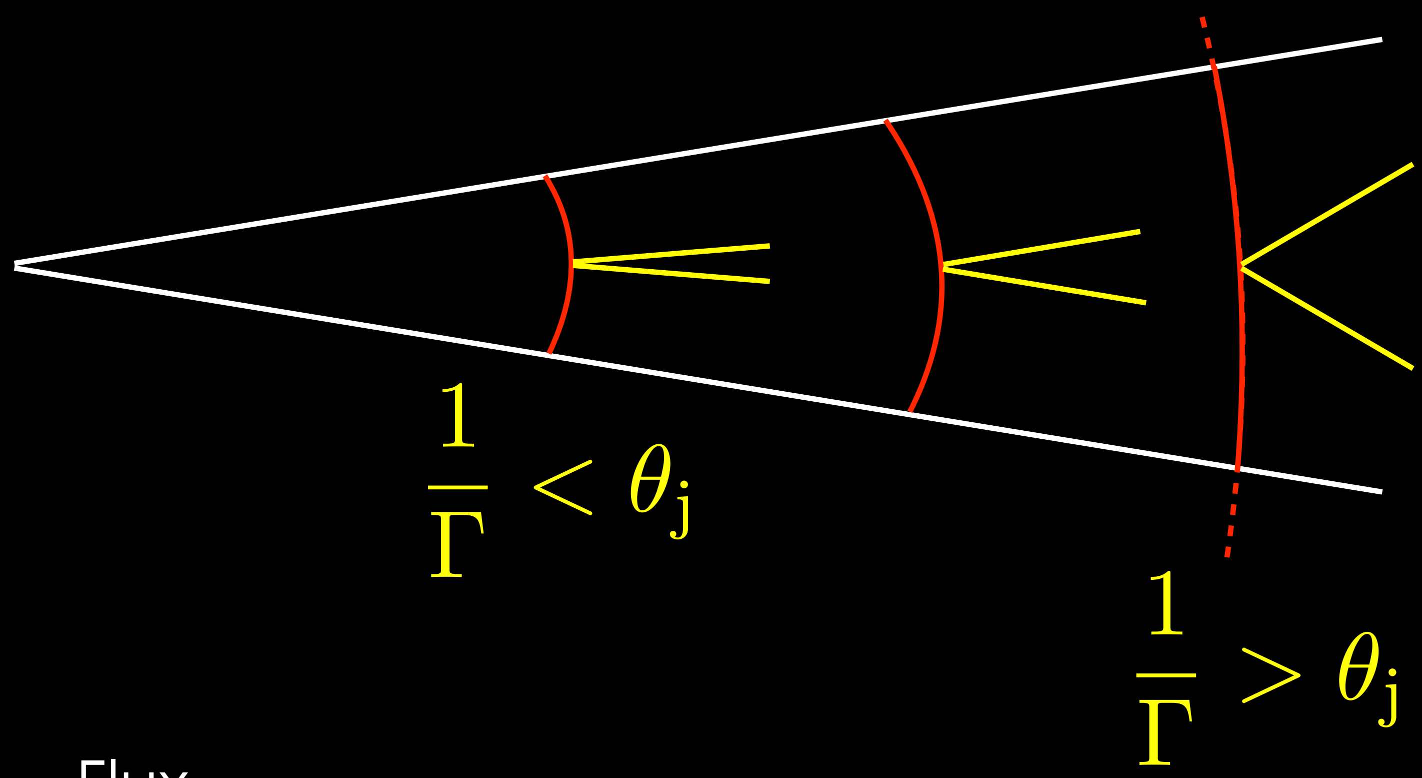
- Synchrotron emission from shocked external medium: good agreement with late afterglow (« normal decay » phase)
- Early afterglow (plateaus/flares): more difficult

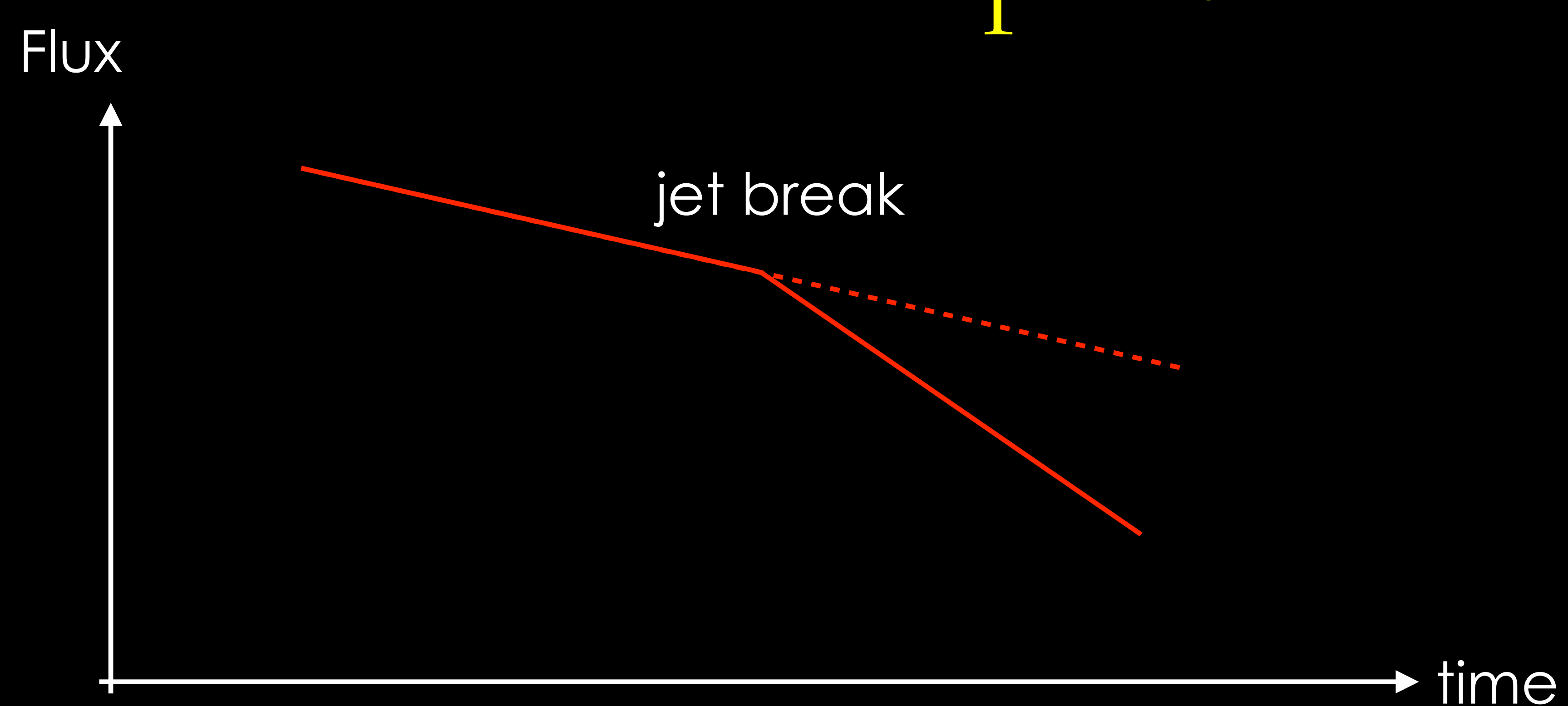


Panaitescu & Kumar 2001

Afterglow theory: jet break

- Achromatic signature

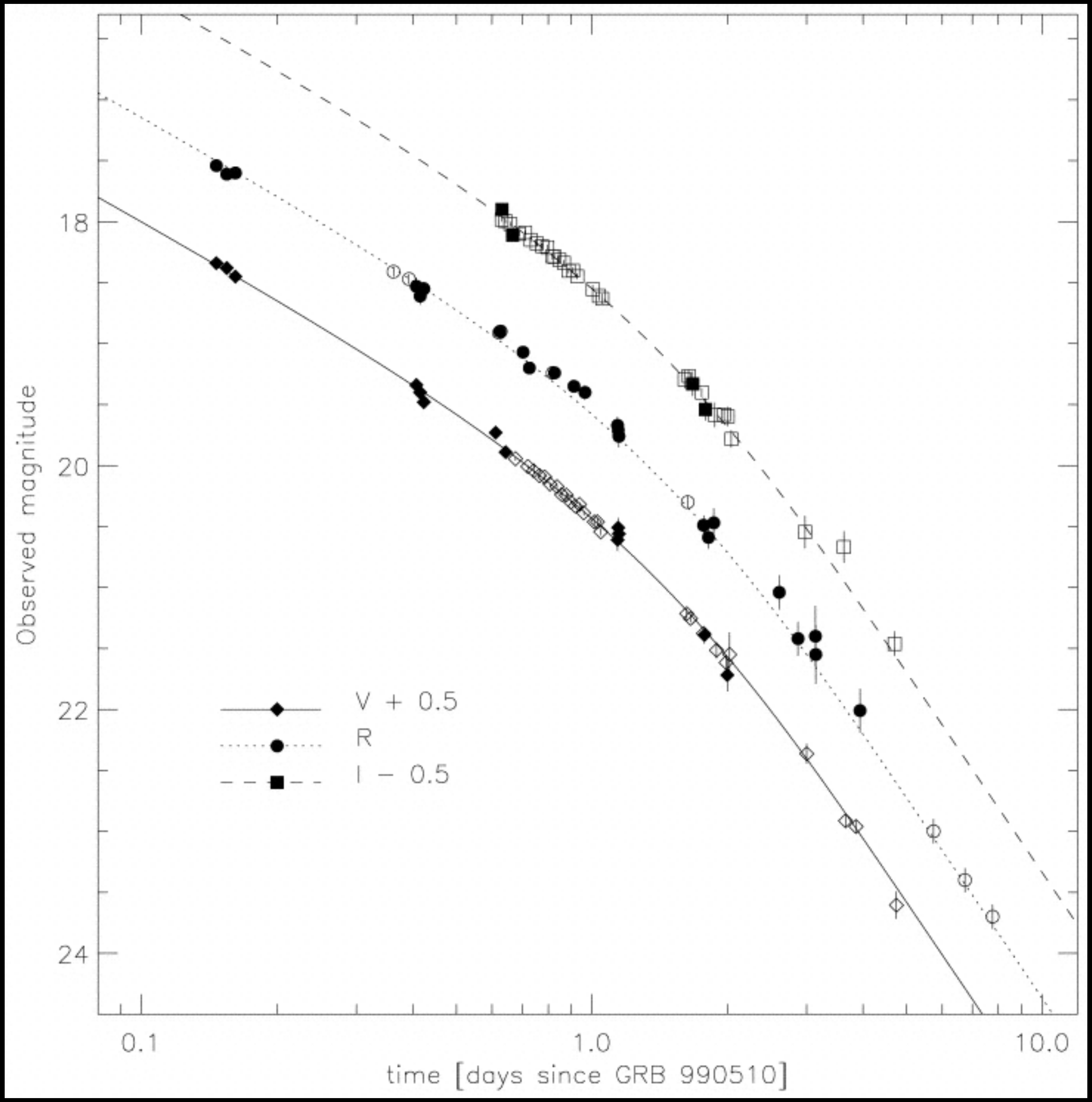




Afterglow theory: jet break

- Achromatic signature
- Breaks are observed: sometimes achromatic, sometimes not…

magnitude



time

GRB 990510
(Harrison et al. 1999)

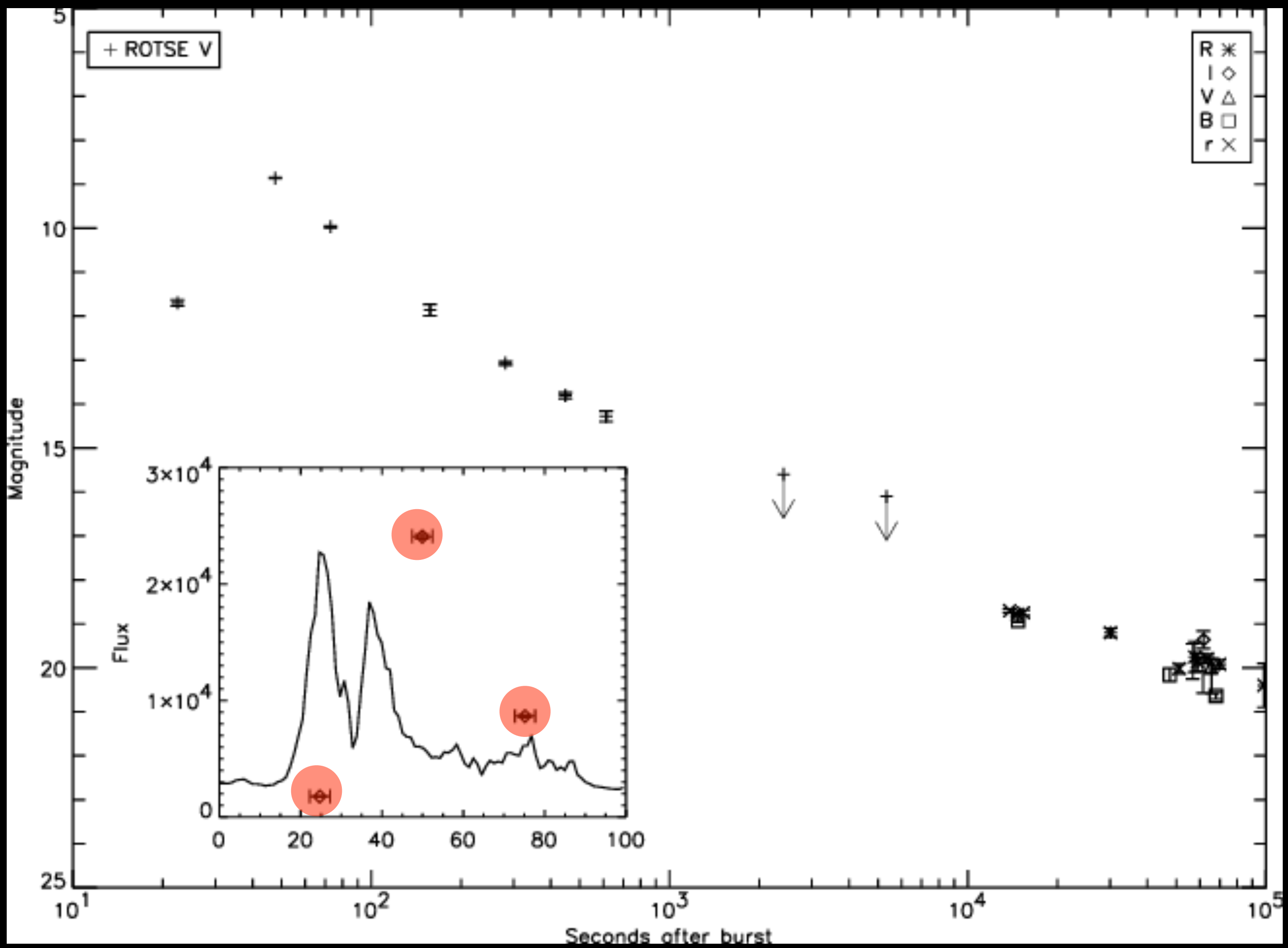
At that time:
no simultaneous X-ray obs.

With Swift:
nice achromatic (X/V) breaks
do not seem to be frequent

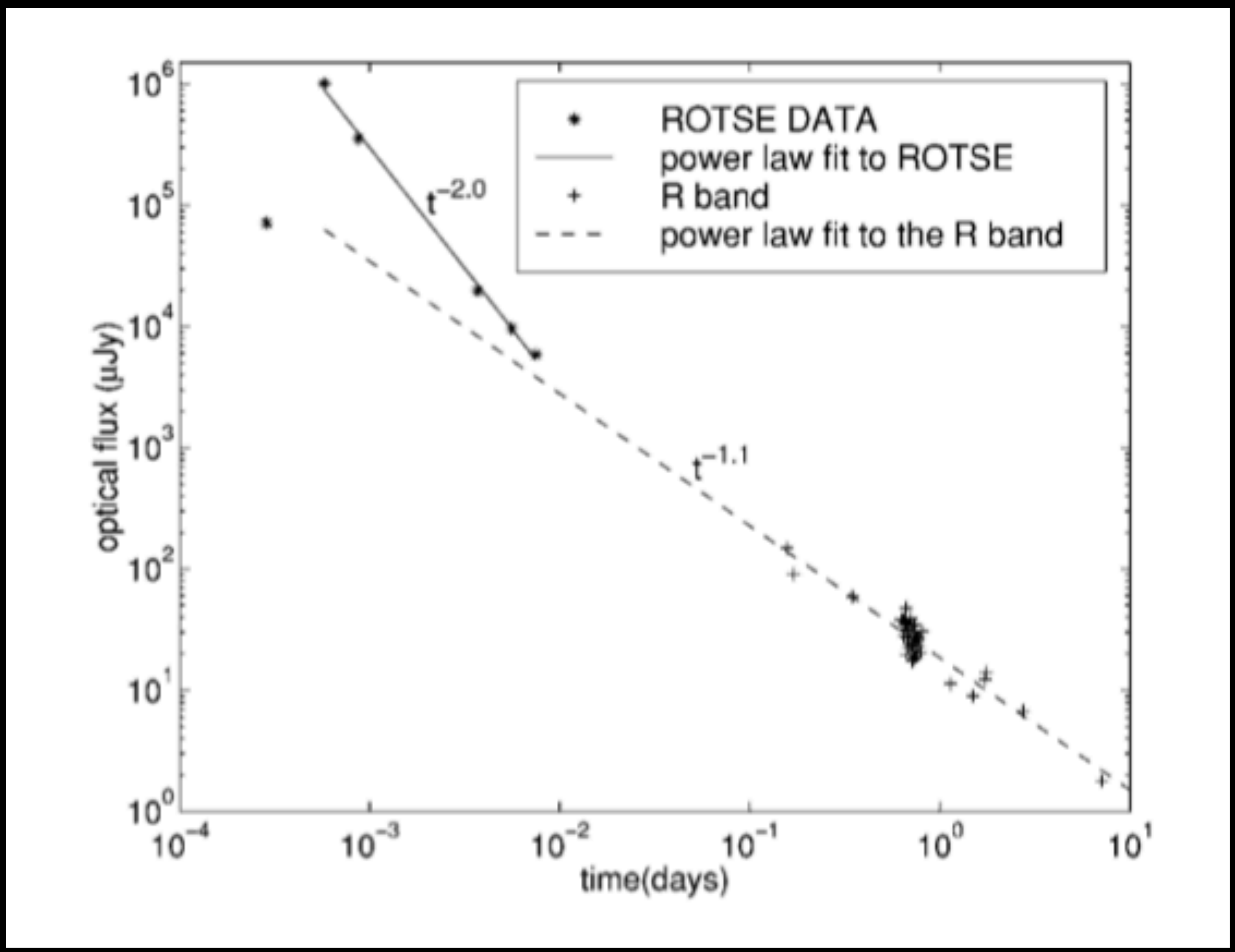
Afterglow: signature of the reverse shock?

- If the magnetization is not too high: a reverse shock propagates within the ejecta when the deceleration starts.

- Contribution of the RS to the emission is debated.
  standard model: RS = early optical flash



GRB990123: ROTSE observations
(Akerlof et al. 1999)



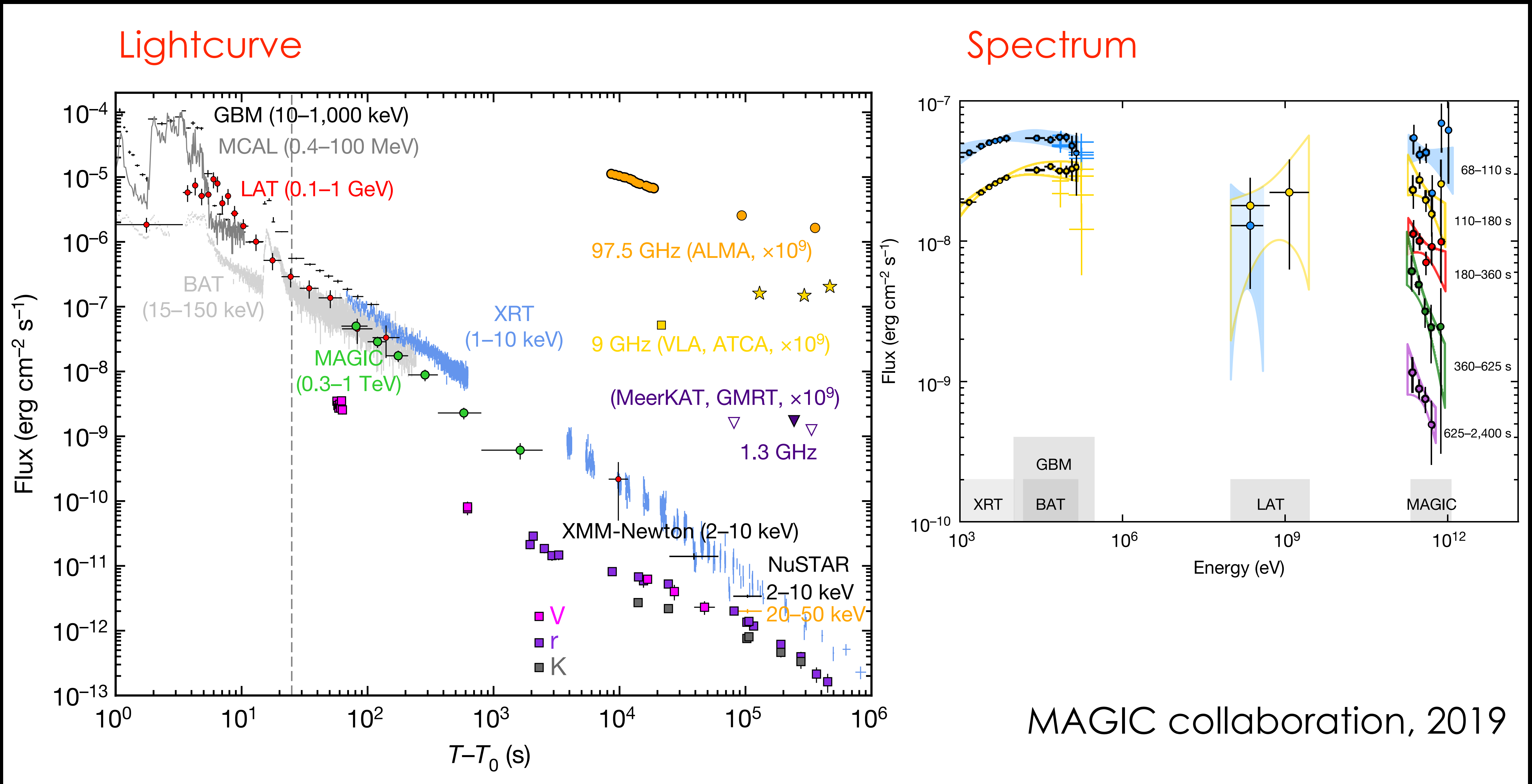
Sari & Piran 1999

- Signature also in radio?
- RS is not necessarily short-lived: contribution in the early afterglow?

Afterglow: some issues with the standard model

- When a good data set is available (good spectral and temporal coverage), it is not easy to obtain a satisfactory fit with the standard afterglow model.

- An example: GRB 190114C (observed by MAGIC)



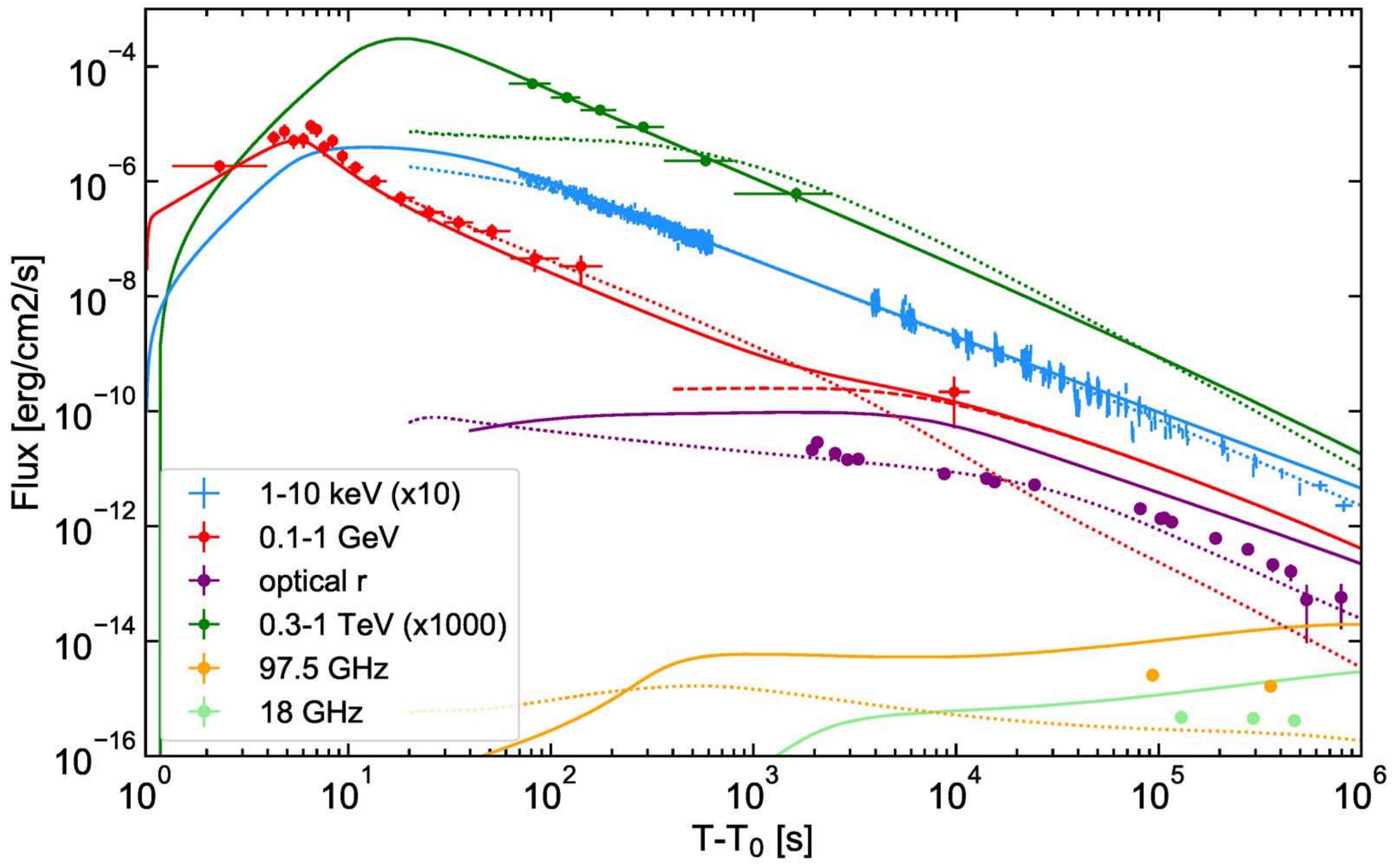
MAGIC collaboration, 2019

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

Afterglow: some issues with the standard model

- When a good data set is available (good spectral and temporal coverage), it is not easy to obtain a satisfactory fit with the standard afterglow model.

- An example: GRB 190114C (observed by MAGIC)
  Detailed modelling by the MAGIC collaboration + multi-λ partners
  (detailed FS dynamics + detailed radiated process = syn+IC with γγ+KN+EBL ; no RS)

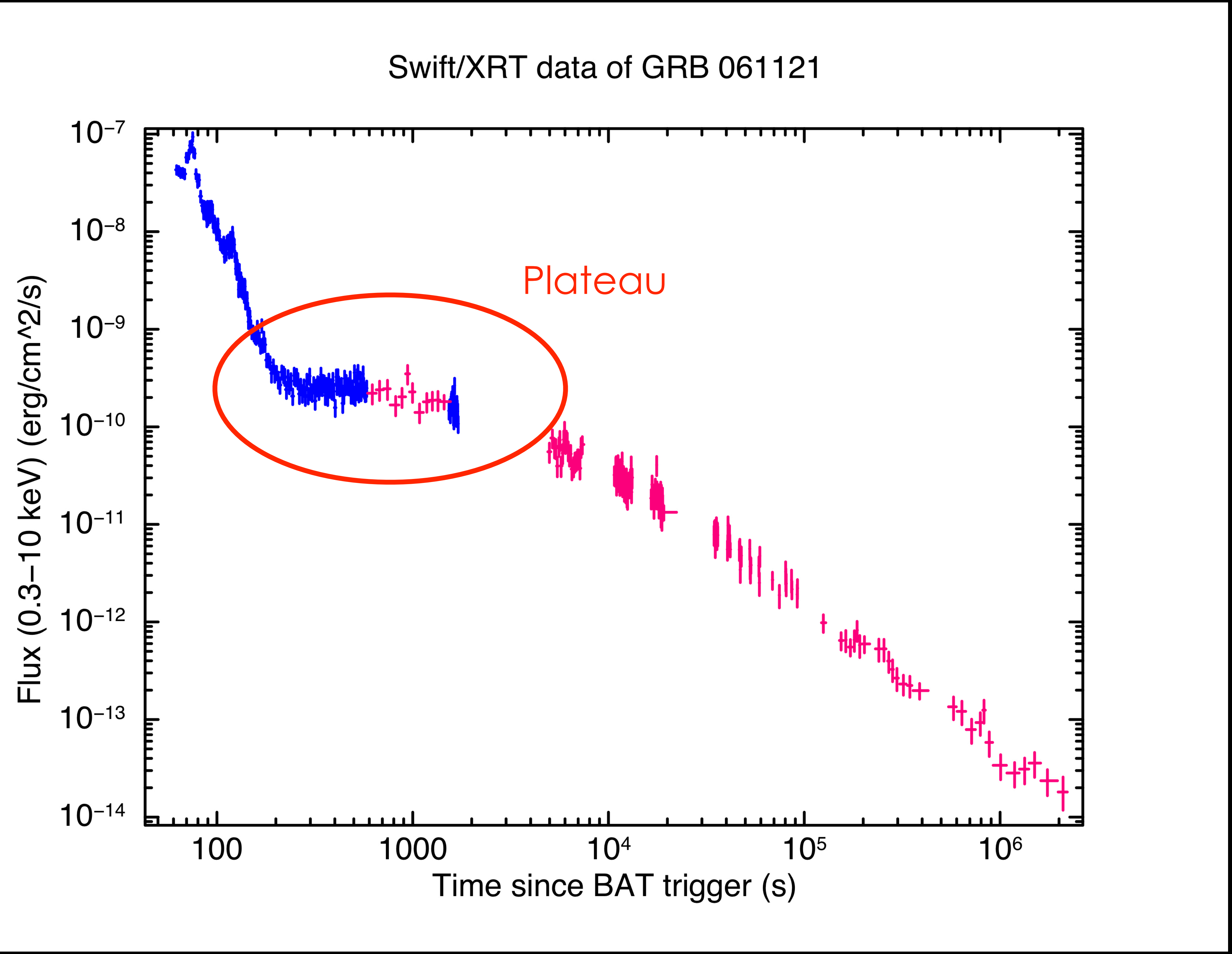


$s=0, \varepsilon_{\mathrm{e}}=0.07, \varepsilon_{\mathrm{B}}=8\times10^{-5}, p=2.6, n_0=0.5$ and $E_{\mathrm{k}}=8\times10^{53}$ erg

- Early NIR-V not modelled (assume RS contribution)
- Model does not fit the radio observations
- Some best fit parameters are puzzling.

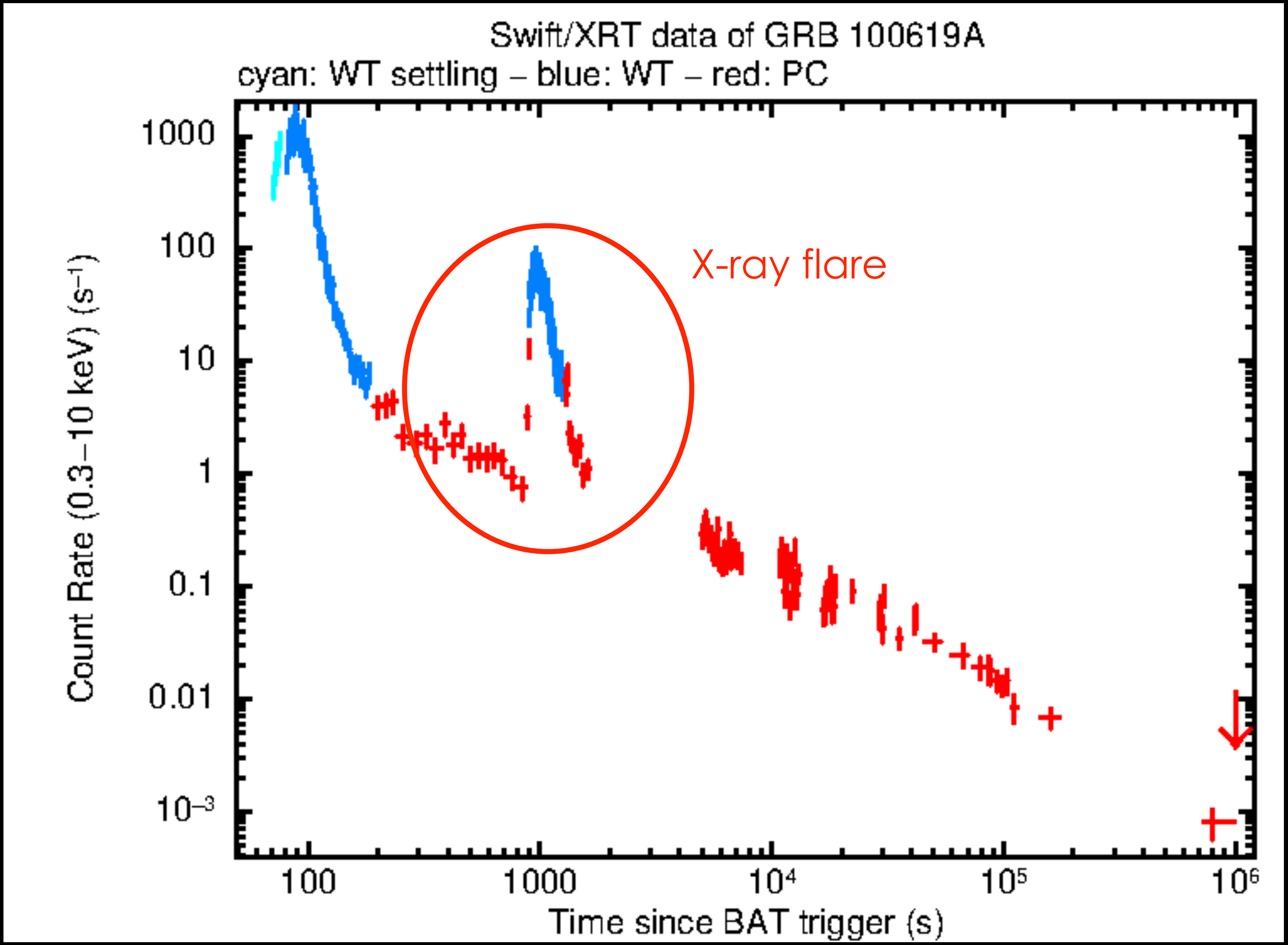
Afterglow: some issues with the standard model

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



Afterglow: some issues with the standard model

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



Afterglow: some issues with the standard model

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

- **The most discussed explanation: late activity of the central engine**

  - plateaus can be produced with a late energy injection
    = deceleration is delayed

    Main problem: efficiency crisis for the prompt

  - X-ray flares can be produced by « prompt GRB » mechanisms associated to a late activity of the central engine

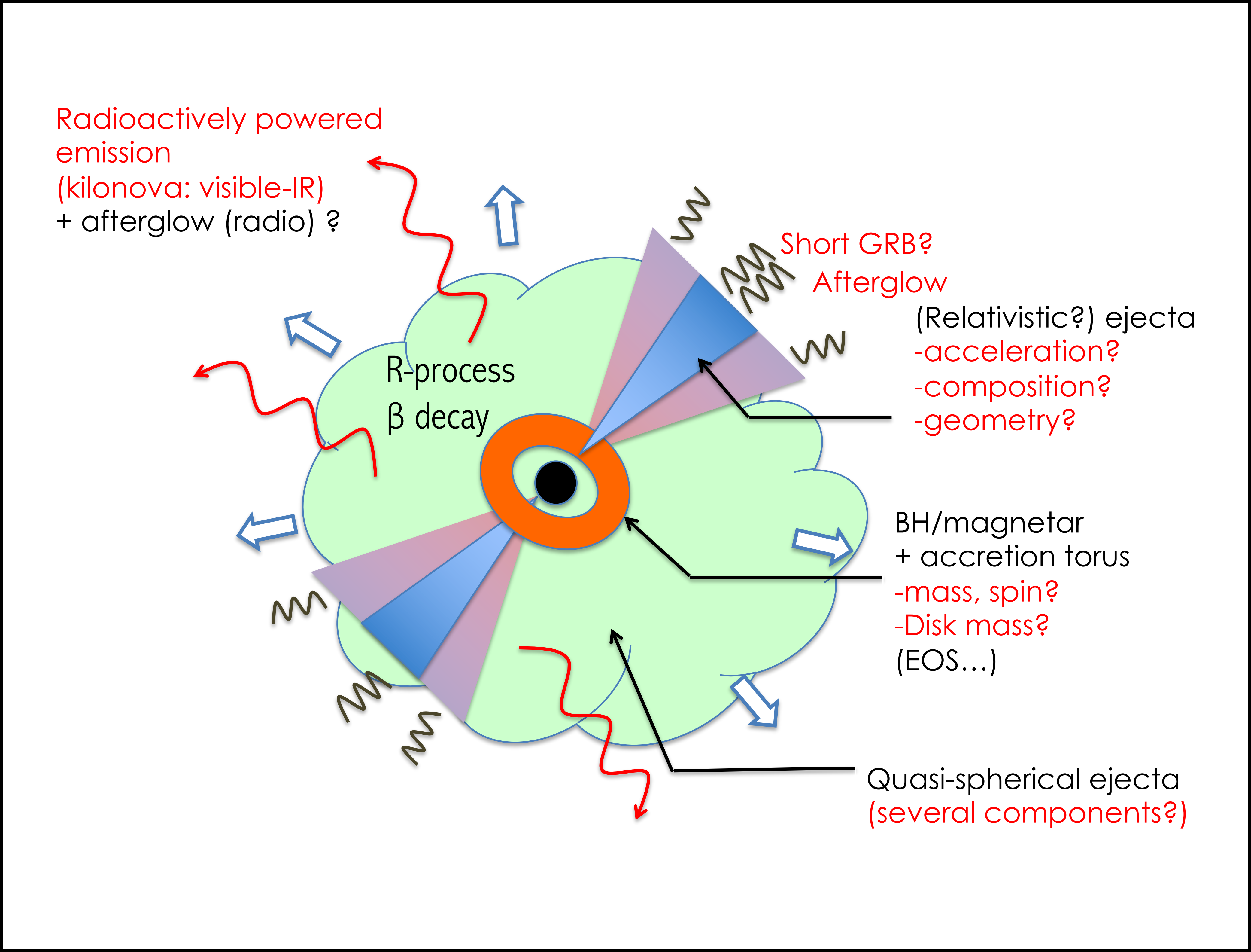
    Main problems:
    (a) some flares are observed at very late time (10^3, 10^4 s) = very late activity

    (b) flares show $\frac{\Delta t_{\mathrm{obs}}}{t_{\mathrm{obs}}} \simeq \mathrm{cst}$: strong evolution of the variability timescale of the central engine!

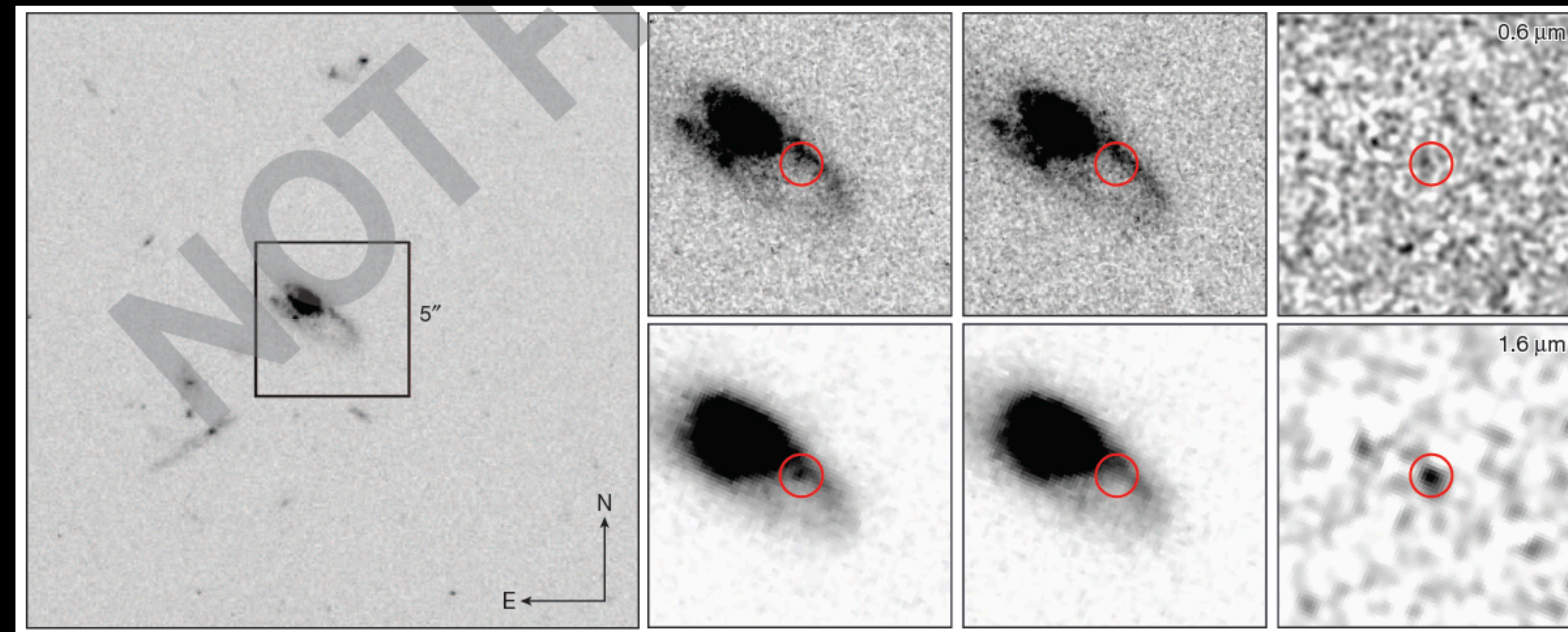
- A lot of other ideas are discussed!
  Among them, IAP's contributions:
  - long-lived reverse shock (with Beloborodov+)
  - slightly off-axis observations (with Beniamini)

Focus on the short GRB-merger connection
The 170817 event

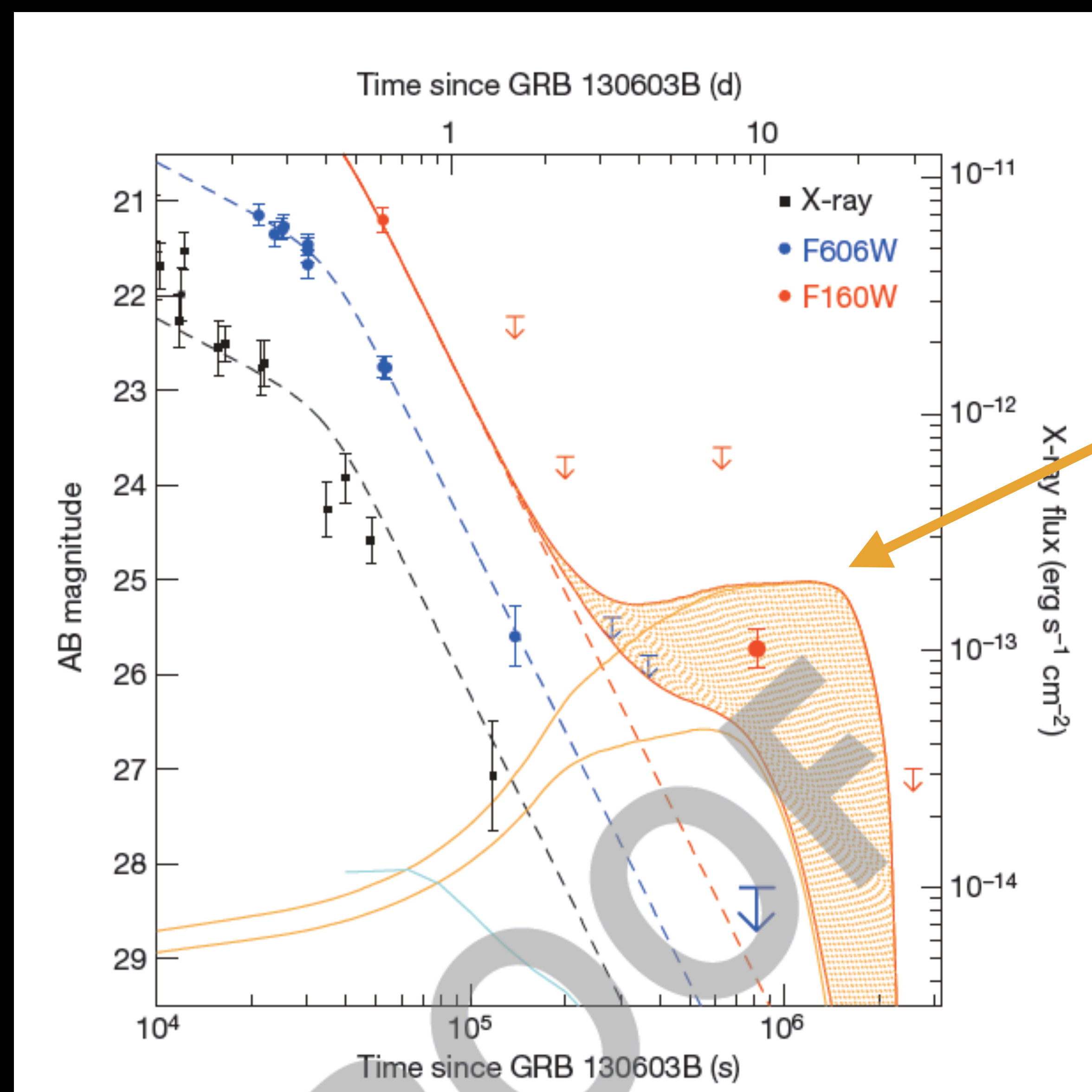
BNS merger: electromagnetic counterparts
Pre-2017 predictions



Kilonova detection?



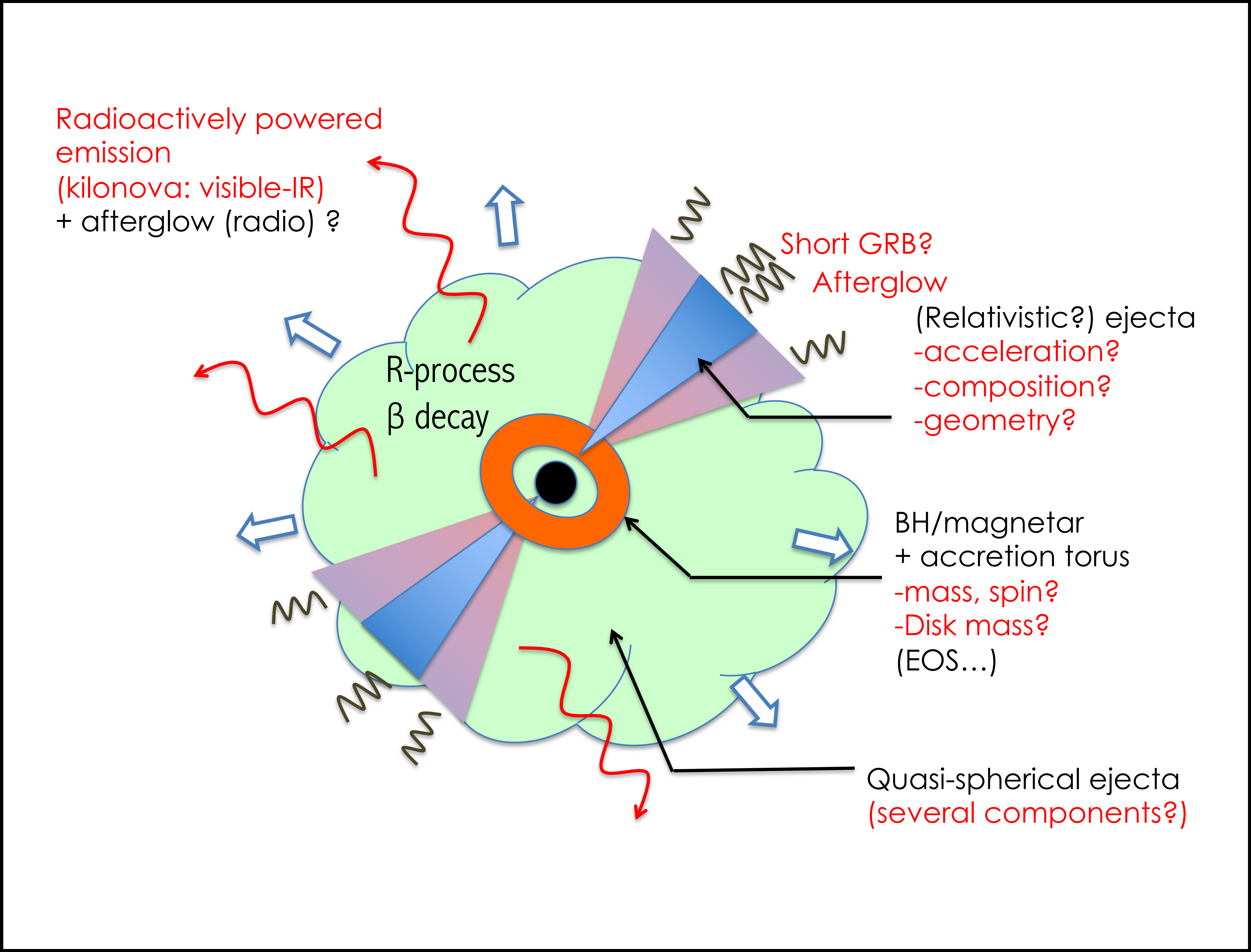
GRB 130603B
(short GRB)



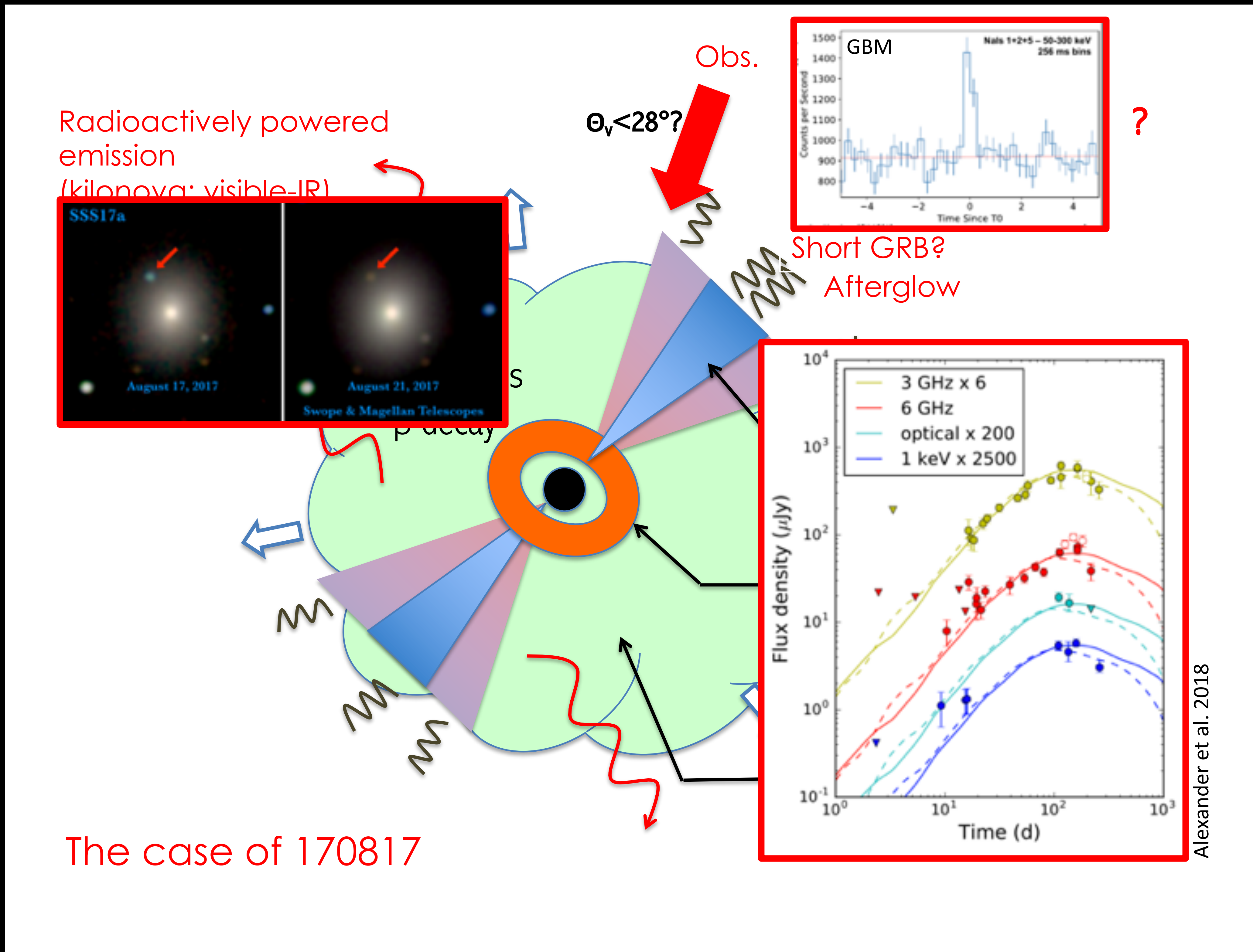
Kilonova?

Tanvir et al. 2013

BNS merger: electromagnetic counterparts
Pre-2017 predictions

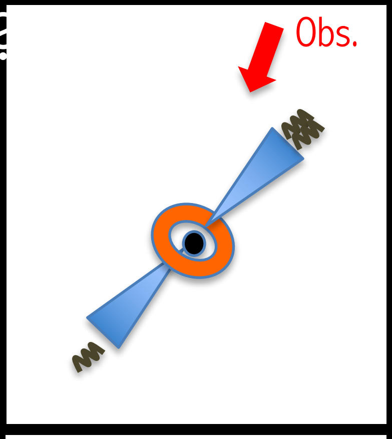


BNS merger: electromagnetic counterparts
The case of 170817

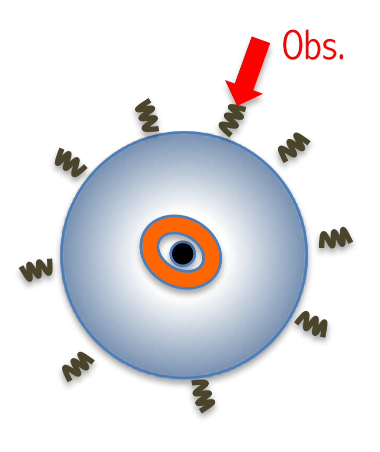


Afterglow

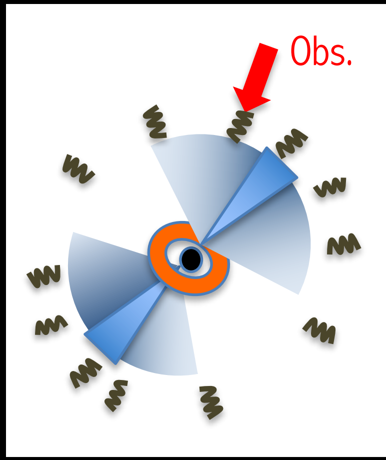
- slow rise, maximum at ~150 days
- a top-hat relativistic jet seen off-axis? ruled-out (slow rise)

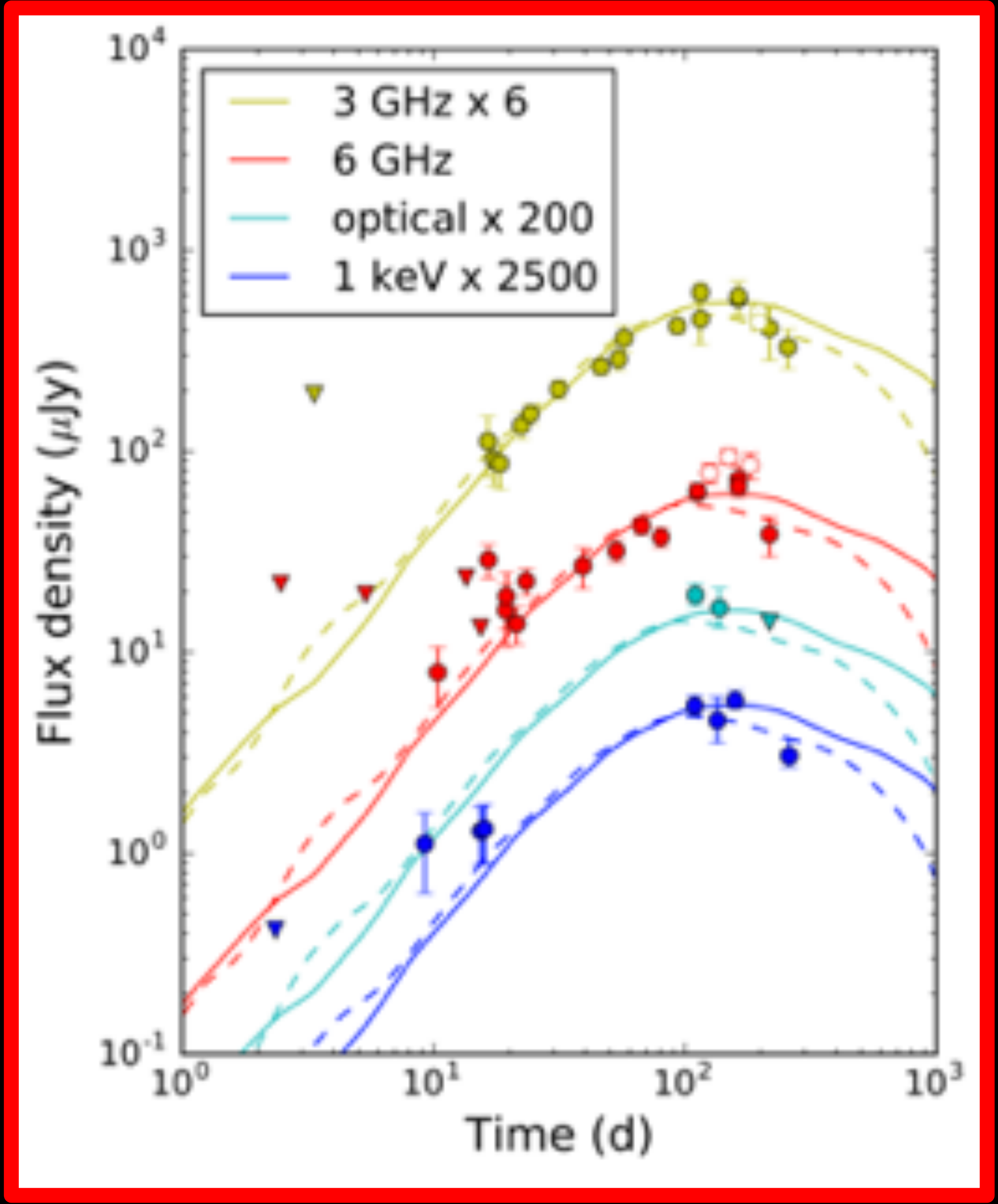


- a quasi-spherical outflow with a radial structure? ruled-out (VLBI)



- a core jet + lateral structure seen off-axis? OK for LC + VLBI

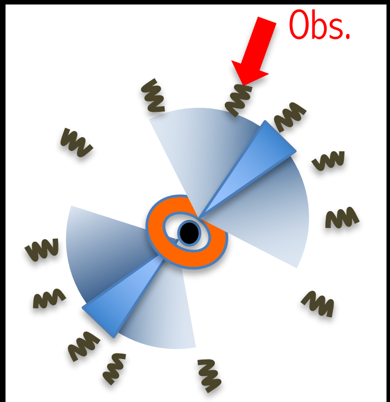


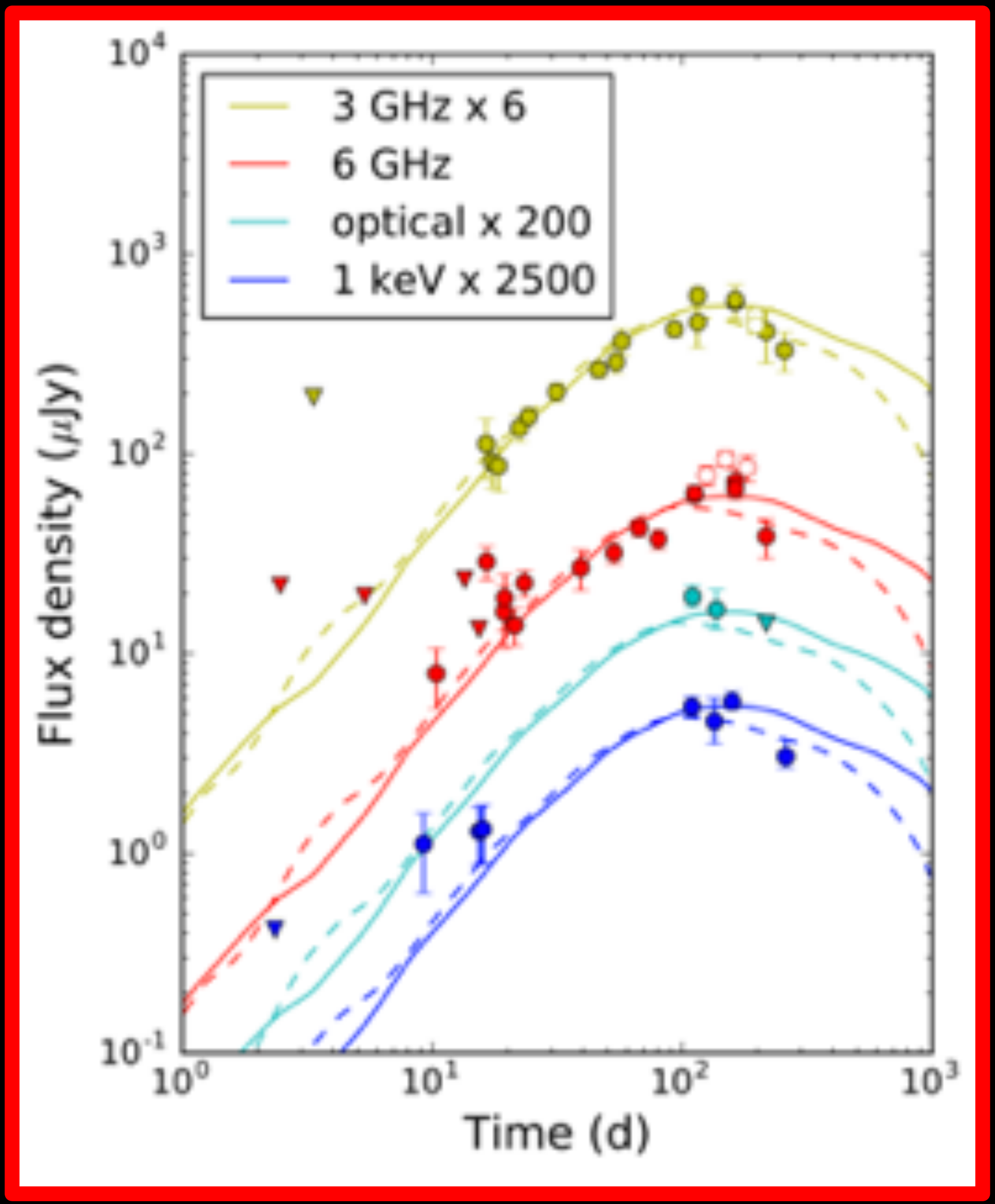


Alexander et al. 2018

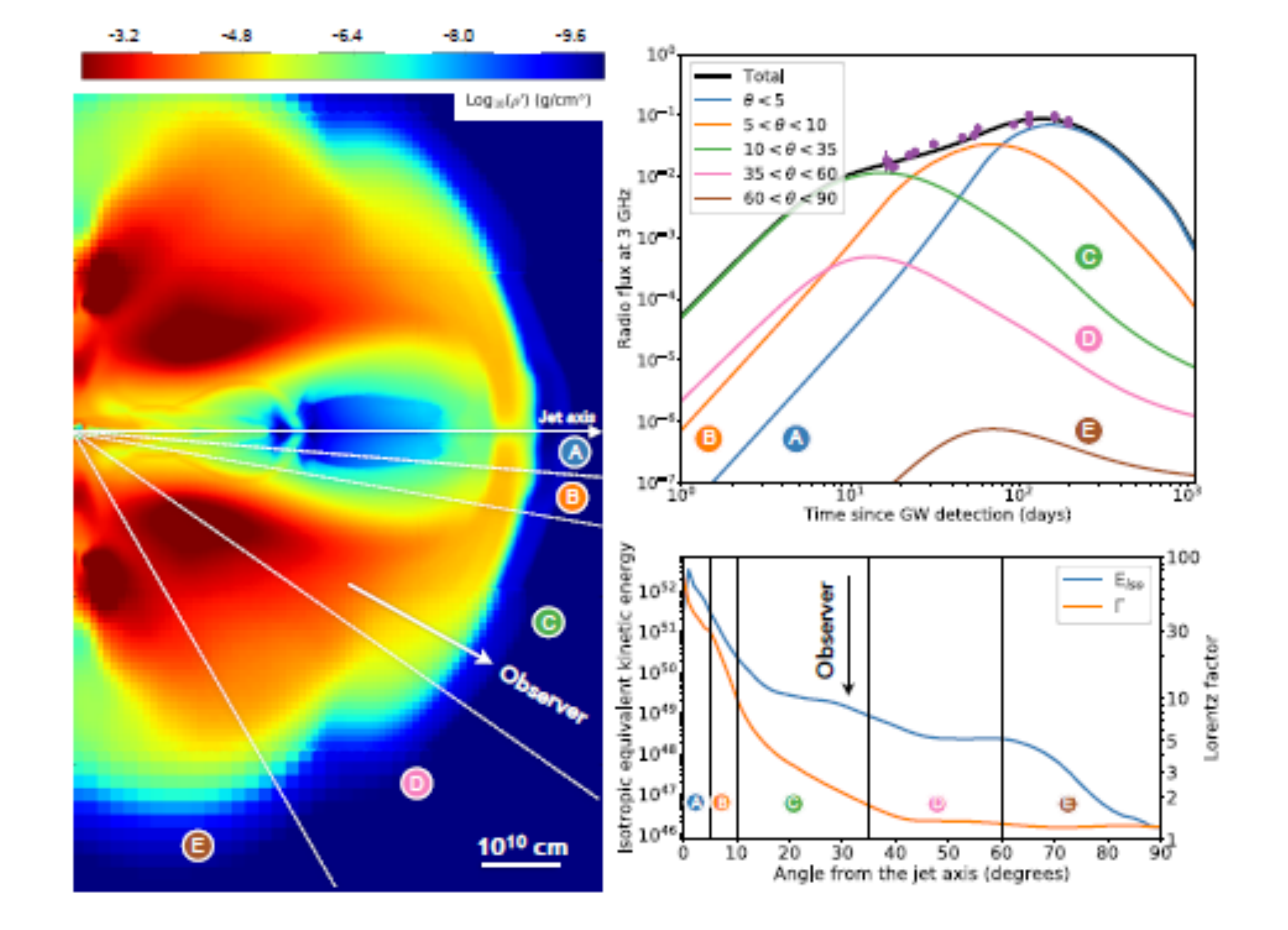
Afterglow

- a core jet + lateral structure seen off-axis?
  OK for LC + VLBI





Alexander et al. 2018

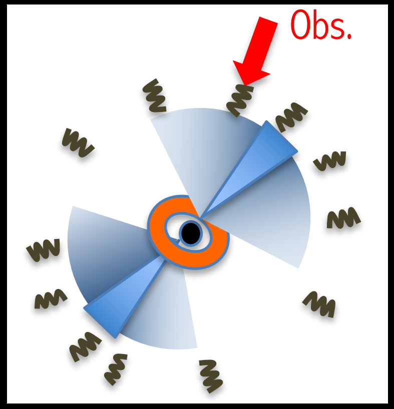


Lazzati et al. 2018

Here: the central jet ($E_{iso,on} \sim 10^{52}$ erg) contributes at 100 days

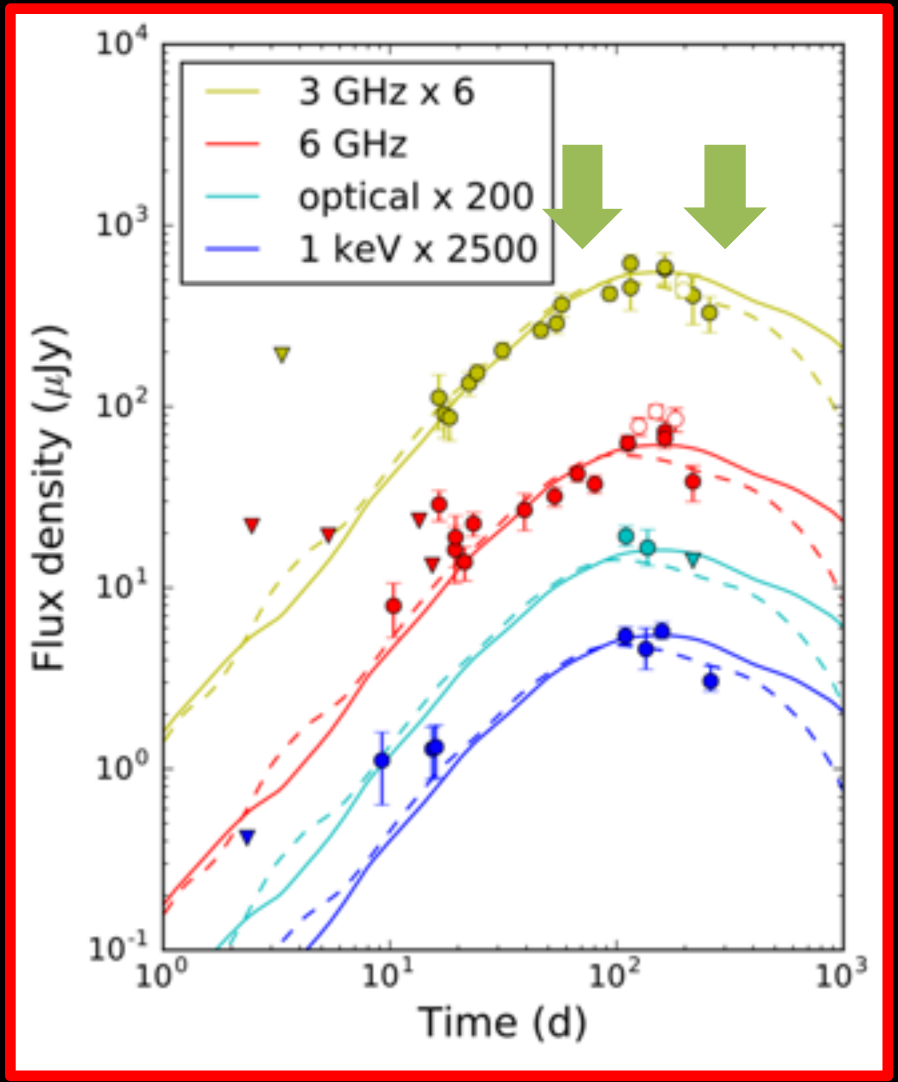
Core jet emerges at late time!
A unique opportunity to study the full geometry of a GRB outflow!

Afterglow



- a core jet + lateral structure seen off-axis?
  OK for LC + VLBI

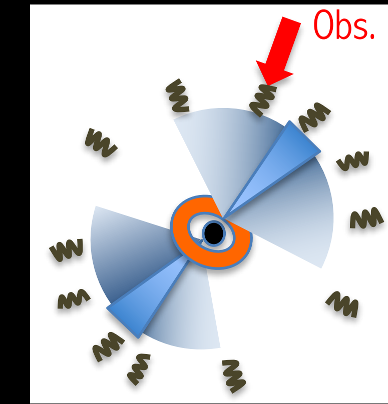
- VLBI: motion of the centroid (Mooley+18) between
  75 and 230 days
  +
  high resolution images: source still very compact at late times (Ghirlanda+19)



Alexander et al. 2018

Afterglow

- a core jet + lateral structure seen off-axis?
  OK for LC + VLBI



- VLBI: motion of the centroid (Mooley+18) between
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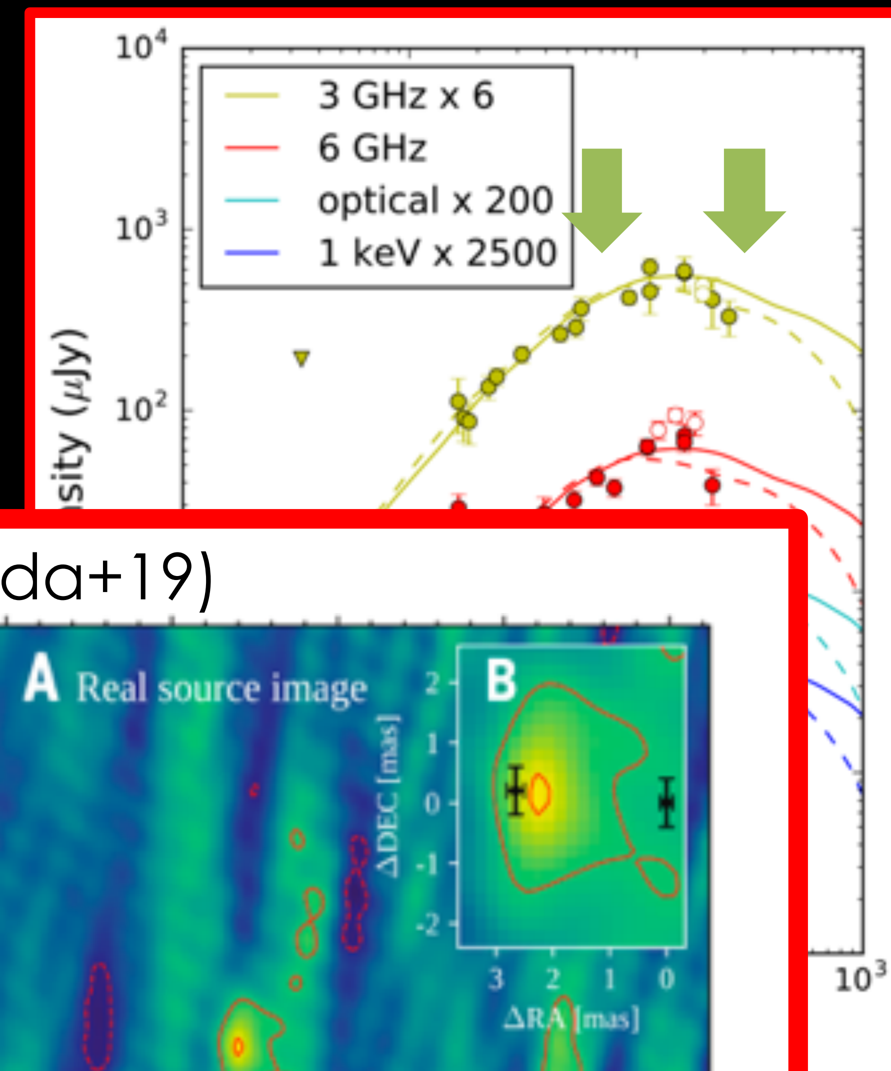
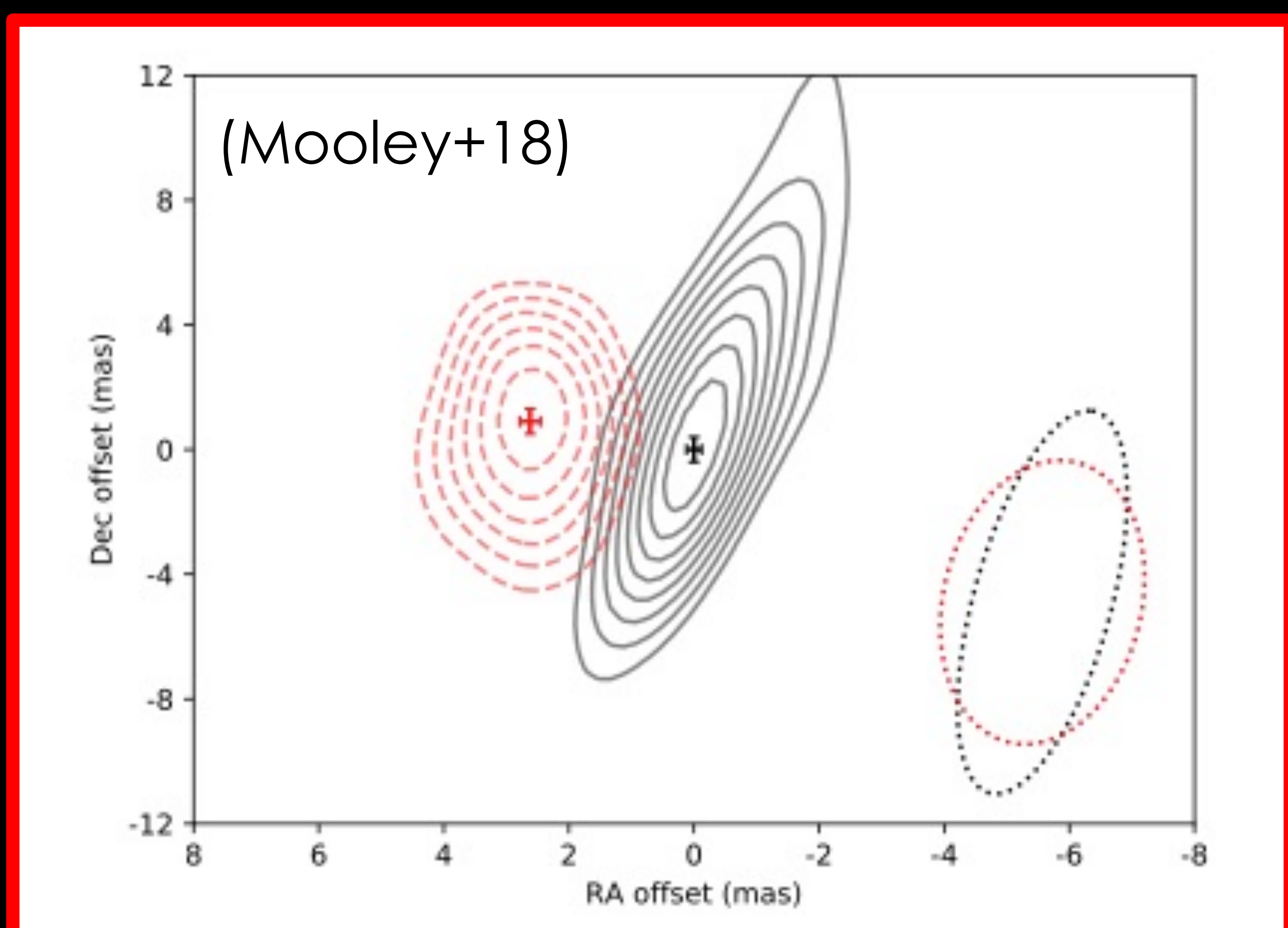
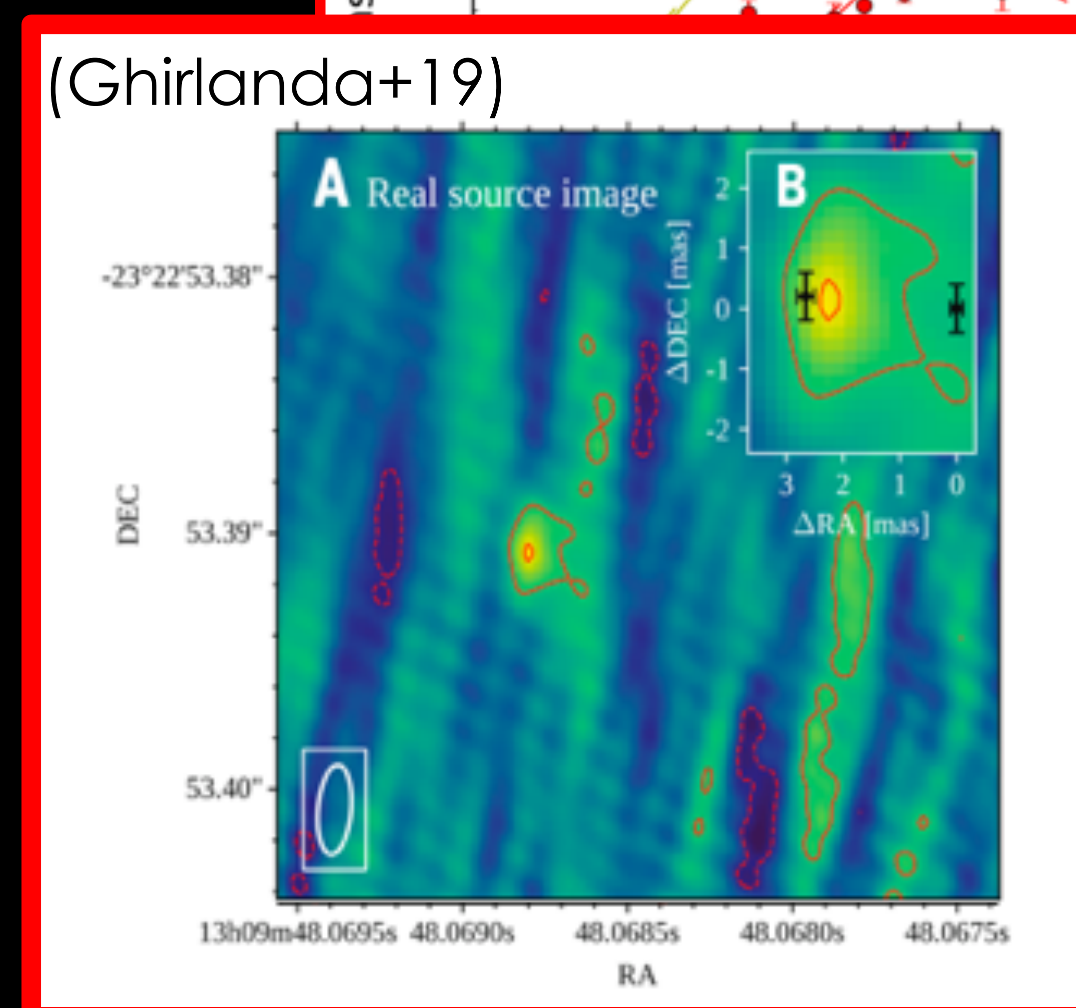
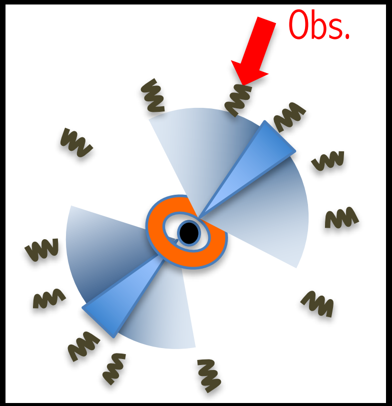


2018





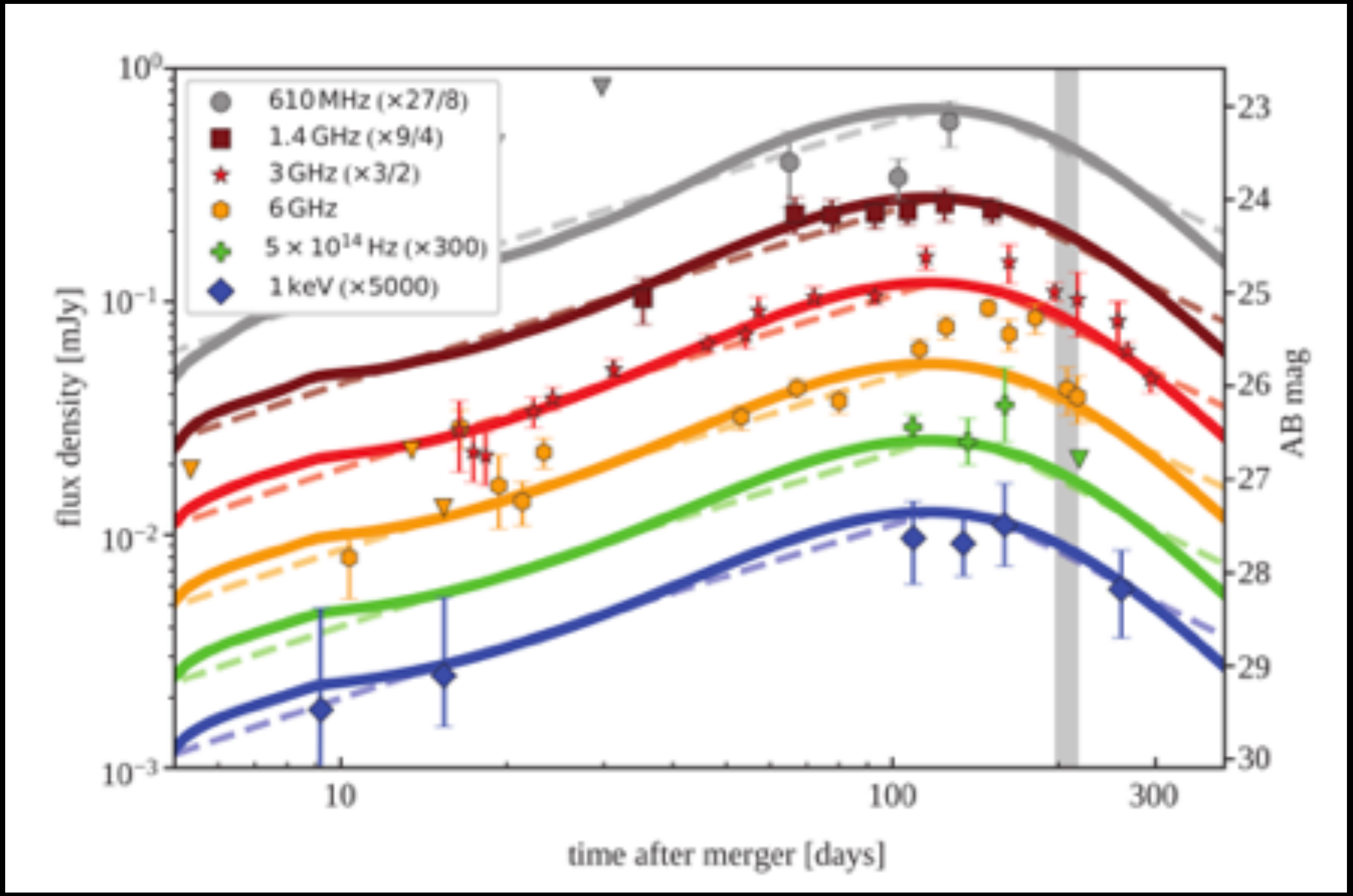
Afterglow



- a core jet + lateral structure seen off-axis?
  OK for LC + VLBI

- VLBI: motion of the centroid (Mooley+18) between 75 and 230 days
  +
  high resolution images: source still very compact at late times (Ghirlanda+19)

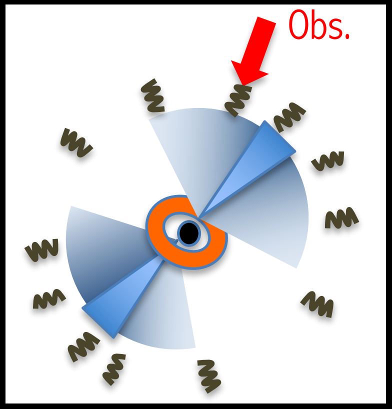
- Superluminic apparentmotion: relativistic jet at ~20°



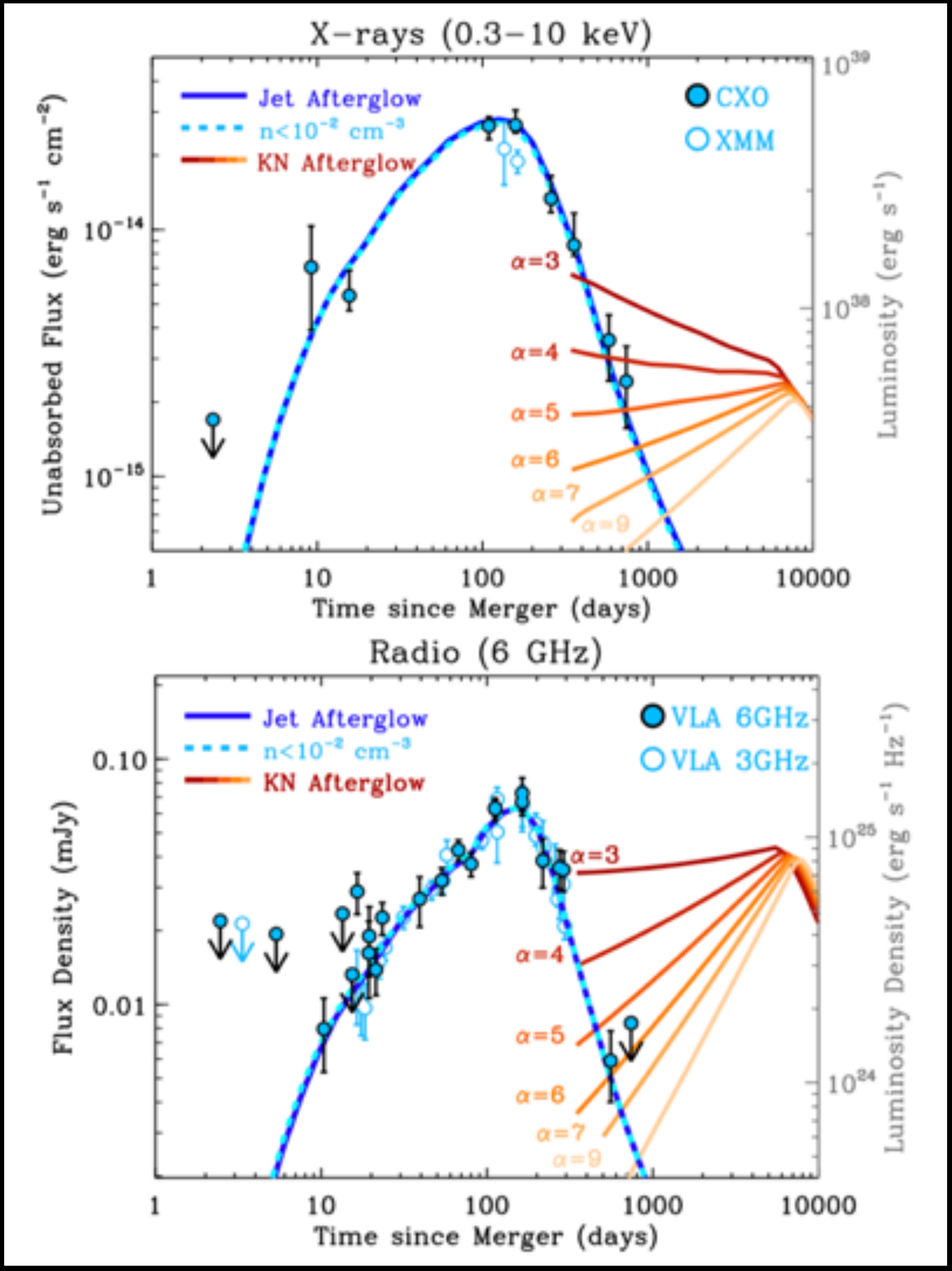
Best fit model:
- lateral structure
- core jet emerges at the peak of the lightcurve
- off-axis observer at 15-20°
- external density ~0.001 cm^{-3}
- central jet ~2-3 10^{54} erg and ~3-4°
  (Mooley+18, Ghirlanda+19, Troja+18, Granot+18, …)

Ghirlanda+19

Afterglow: very late afterglow



- Radio (VLA): detected at 588 days after merger
- X-rays (Chandra): detected at 743 days after merger



- lateral expansion?
- newtonian transition?
- counter-jet?

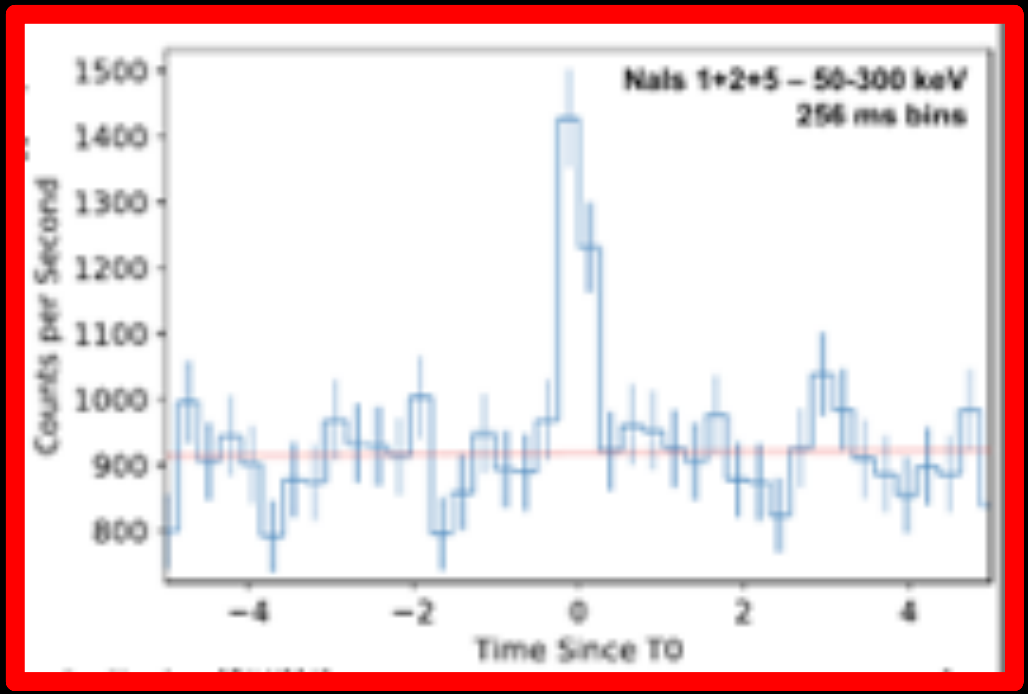
- kilonova-afterglow?

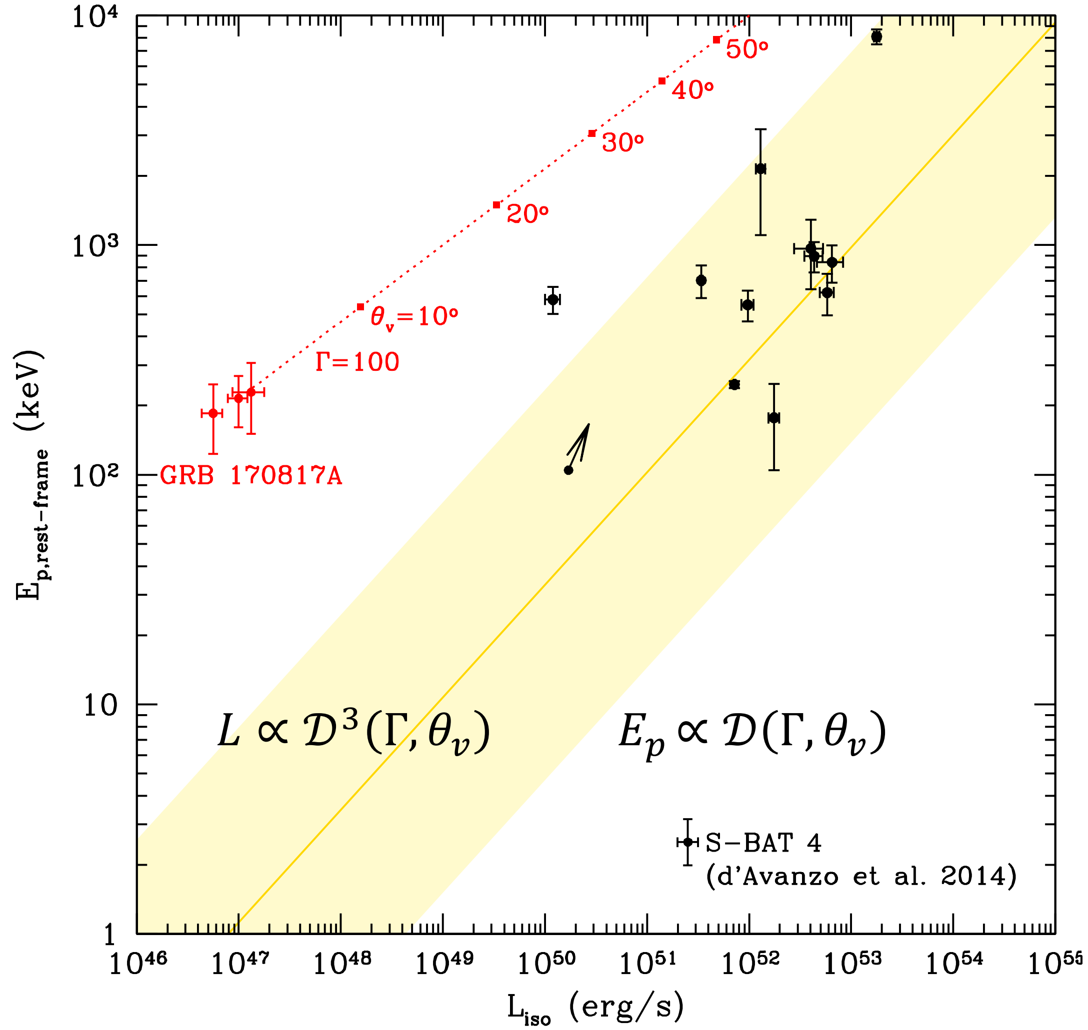
Hajela+19

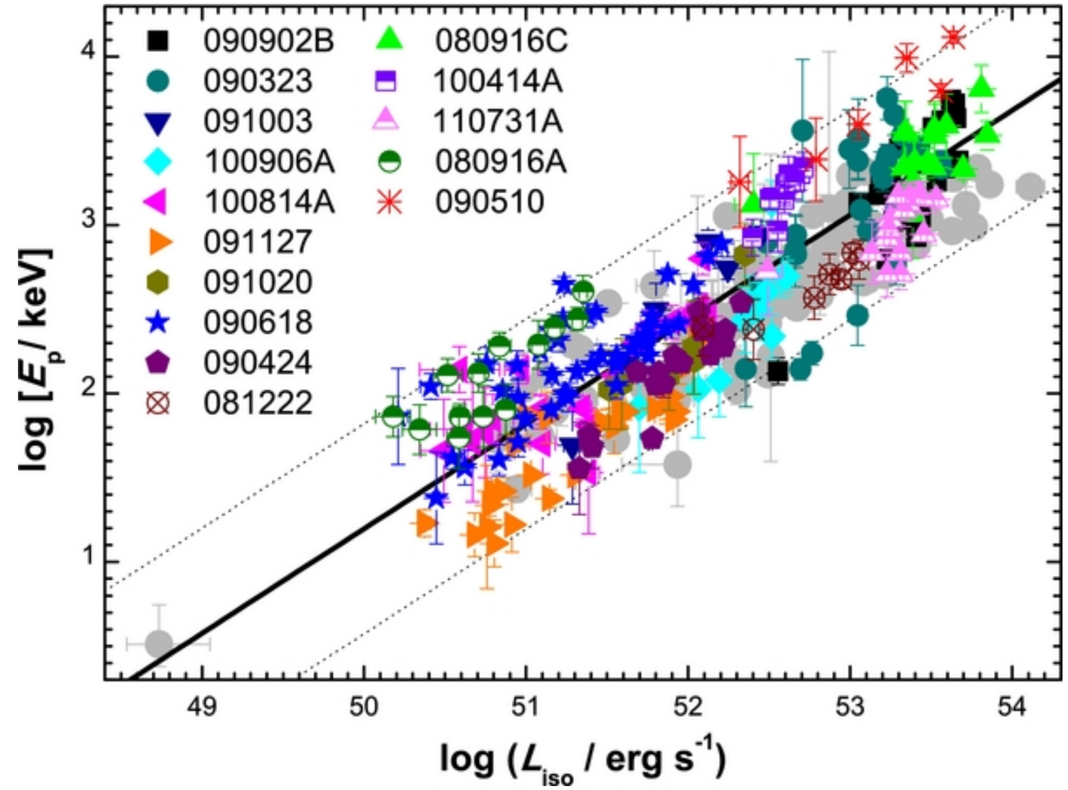
GRB170817A is puzzling

- Very under-luminous
- Still emits well above 200 keV

- Delay 1.7s ; Duration 1.5 s
  L ~ 10^{47} erg/s ; E_{iso} ~ 4×10^{46} erg







Lu et al. 2012

- Standard GRB seen off-axis unlikely
  (Ep would be very high if seen on-axis)

\+

offaxis γ γ opacity (Matsumoto+ 19)

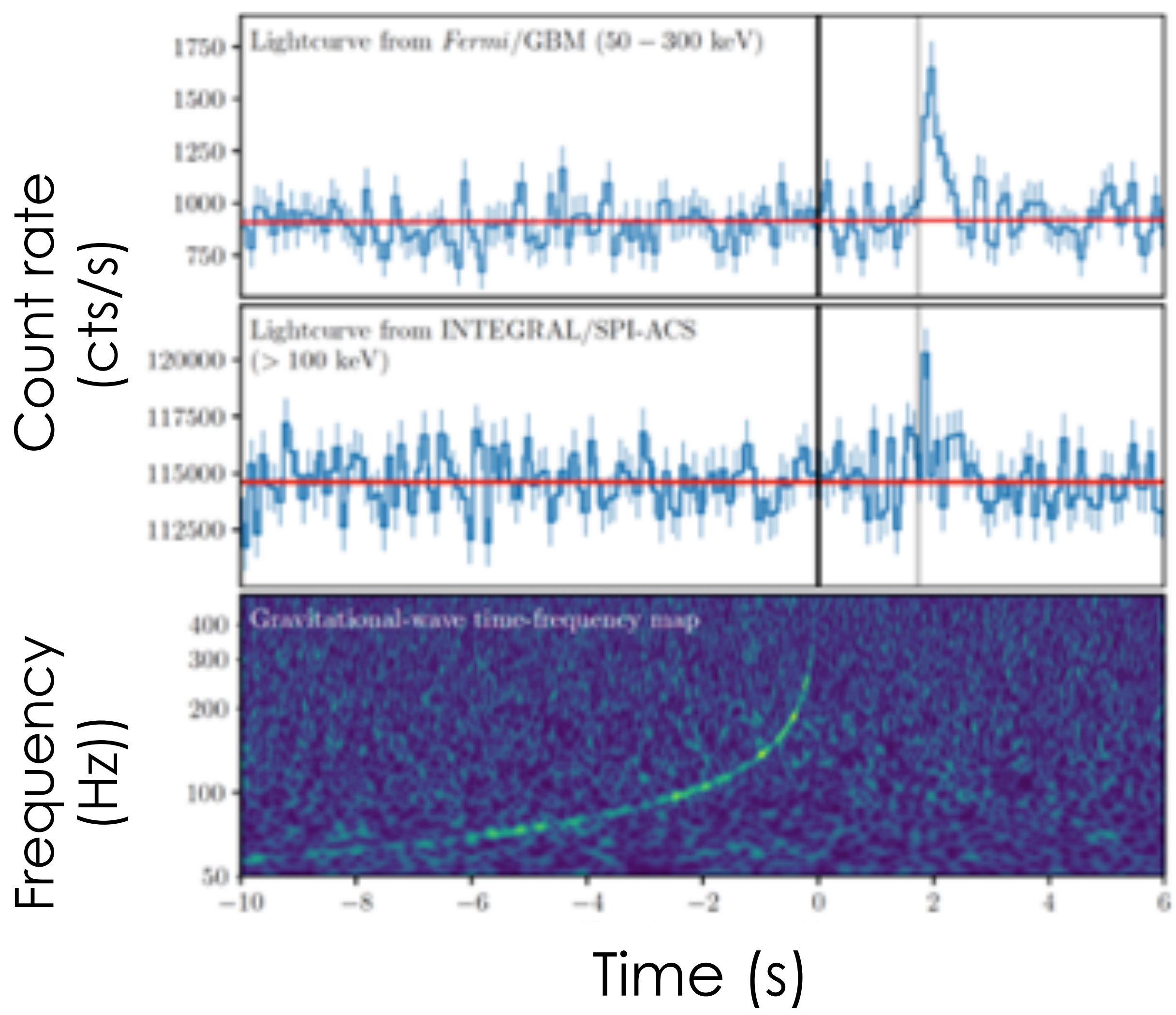
Origin of the lateral structure?

- Jet + kilonova ejecta interaction: formation of a cocoon? (e.g. Gotlieb et al. 18)

- Pro: natural mechanism?
  Possible solution for the short GRB: shock breakout

- Con: fine tuning for the delay between the merger and the relativistic ejecta?
  Short GRB-Merger connection?

$$\Delta t_{\mathrm{GW-GRB}} = \Delta t_{\mathrm{ejection}} + \frac{1-\beta}{\beta}\frac{R_{\mathrm{emission}}}{c}$$



170817: open issues

- Origin of the lateral structure? Which post-merger behaviour? (propagation through the KN ejecta?)

- Origin of the prompt emission?
  - core jet seen off-axis: unlikely
  - less energetic/less relativistic material pointing towards us:
    standard mechanism (e.g. internal shocks, …)
    or
    new mechanism (e.g. shock breakout)

- Connection to the standard short GRB population?
  - GW+short GRB: local population seen off-axis
  - standard short GRBs: distant population seen on-axis or slightly off-axis

    Intersection?
    - more GRB-GW associations in the future?
    - search for weak local short GRBs with gamma-ray satellites?

- Consequences of the emerging geometry for GRB physics: signature of the lateral structure in observations? (e.g. Beniamini+20)

Conclusion

Conclusion

- Gamma-ray bursts are the brightest electromagnetic phenomena in the Universe
- As such, they can be used for cosmology

- A complex physics is at work: a stellar-mass compact source, a relativistic ejection, particle acceleration, non-thermal radiation, …
  =difficult to model

- A standard scenario is well established
  but there are many open questions at each step

- The question of progenitors is especially difficult:
  - core-collapse of some massive stars for long GRBs (detailed conditions?)
  - NS+NS(/BH ?) mergers for short GRBs? (can we already conclude?)

- GRBs are multi messenger events (GW, probably neutrinos): new constraints are coming and will lead to a more realistic physical scenario
  (e.g. evidence for a structured jet in 170817)

- GRB studies in 2020+
  - new space missions following Swift & Fermi (e.g. SVOM)
  - GW: improved sensitivity and localization
  - Neutrinos: larger detection volumes
  - CTA, new generation of radio-telescopes, …
  - Large surveys: orphan afterglows?