Shocks in Gamma-Ray Bursts: from theory to observations

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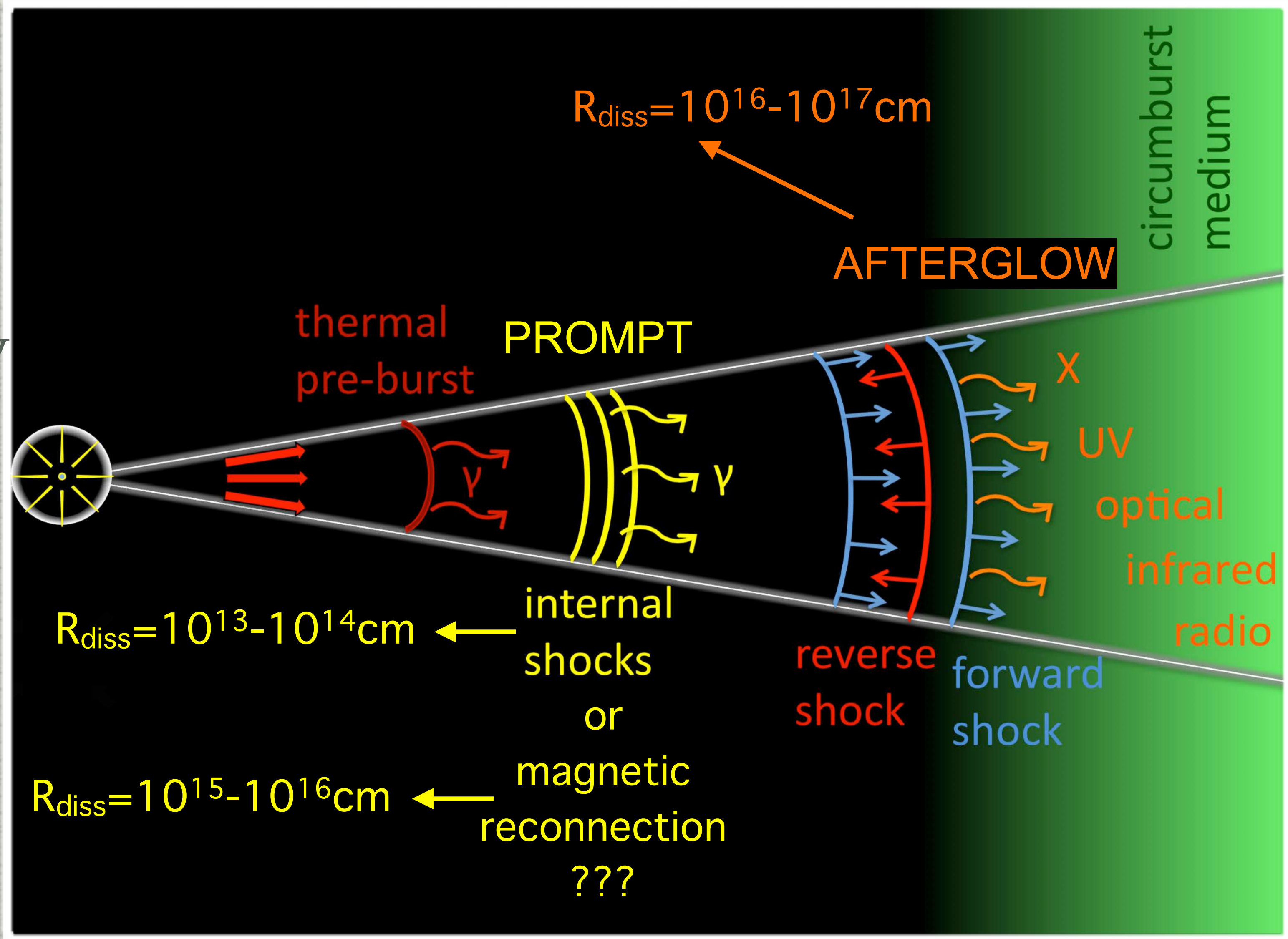
GRBs: the standard model

Shocks take place in two different sites

PROMPT

- 10 keV- 10 MeV
- < 1s to 10^3 s
- non-thermal spectra

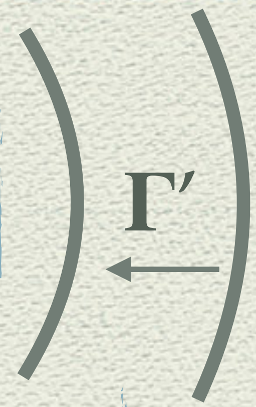


AFTERGLOW

- softX, OT, radio
- weeks, months
- flux PL decay in time

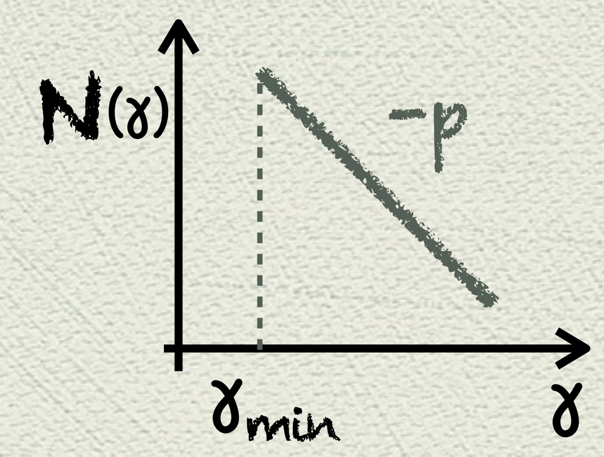
Prompt
— internal shocks —
mildly relativistic

$$U' = 4\,\Gamma'\,(\Gamma' - 1)\,n\,m_p\,c^2$$



electrons

$$U'_e = \epsilon_e\,U'$$



$$\gamma_{e,min} = \frac{\epsilon_e}{\xi_e}\,\frac{p-2}{p-1}\,\frac{m_p}{m_e}\,(\Gamma' - 1)$$

$$\gamma_{e,min} \sim 2 \times 10^3\,\frac{\epsilon_{e,-1}}{\xi_{e,-1}}\,\frac{p-2}{p-1}$$

magnetic field

$$U'_B = \epsilon_B\,U'$$

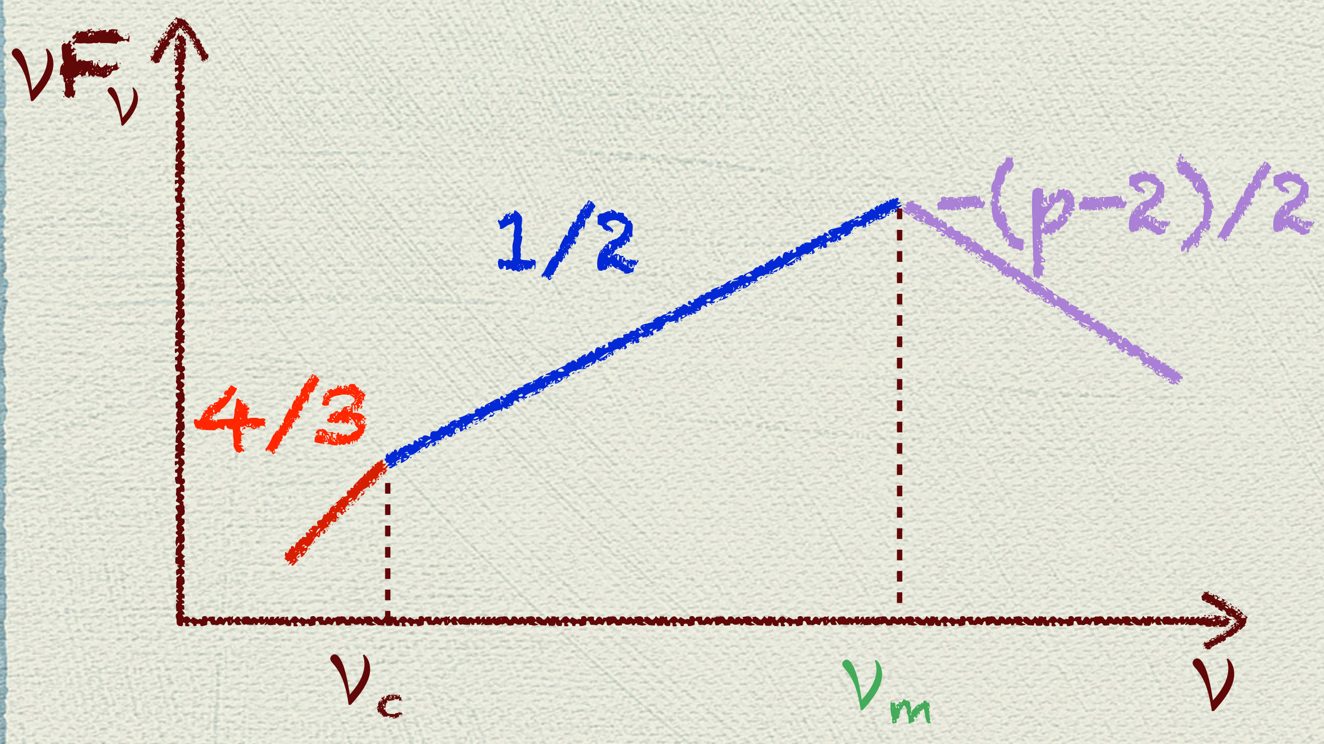
$$U' = \frac{L_{\mathrm{k,jet}}}{4\,\Gamma^2}\,4\,\pi\,R^2\,c$$

$$B' = \left(\frac{2\,\epsilon_B\,L_{\mathrm{k,jet}}}{c}\right)^{1/2}\frac{1}{R\,\Gamma}$$

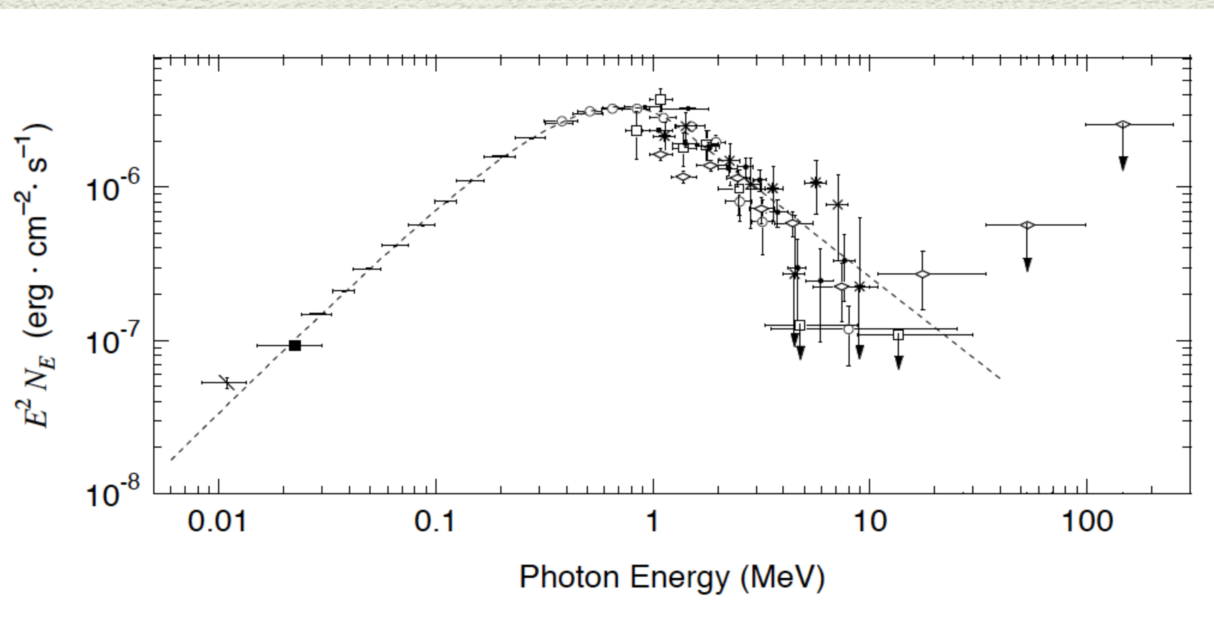
$$B' \sim 2 \times 10^4\,\epsilon_{\mathrm{B}}^{1/2}\,L_{\mathrm{k,jet,52}}^{1/2}\,\frac{1}{R_{14}\,\Gamma_{2.5}}\,\mathrm{G}$$

PROMPT spectra: synchrotron theory vs observations

Theoretical synchro spectrum



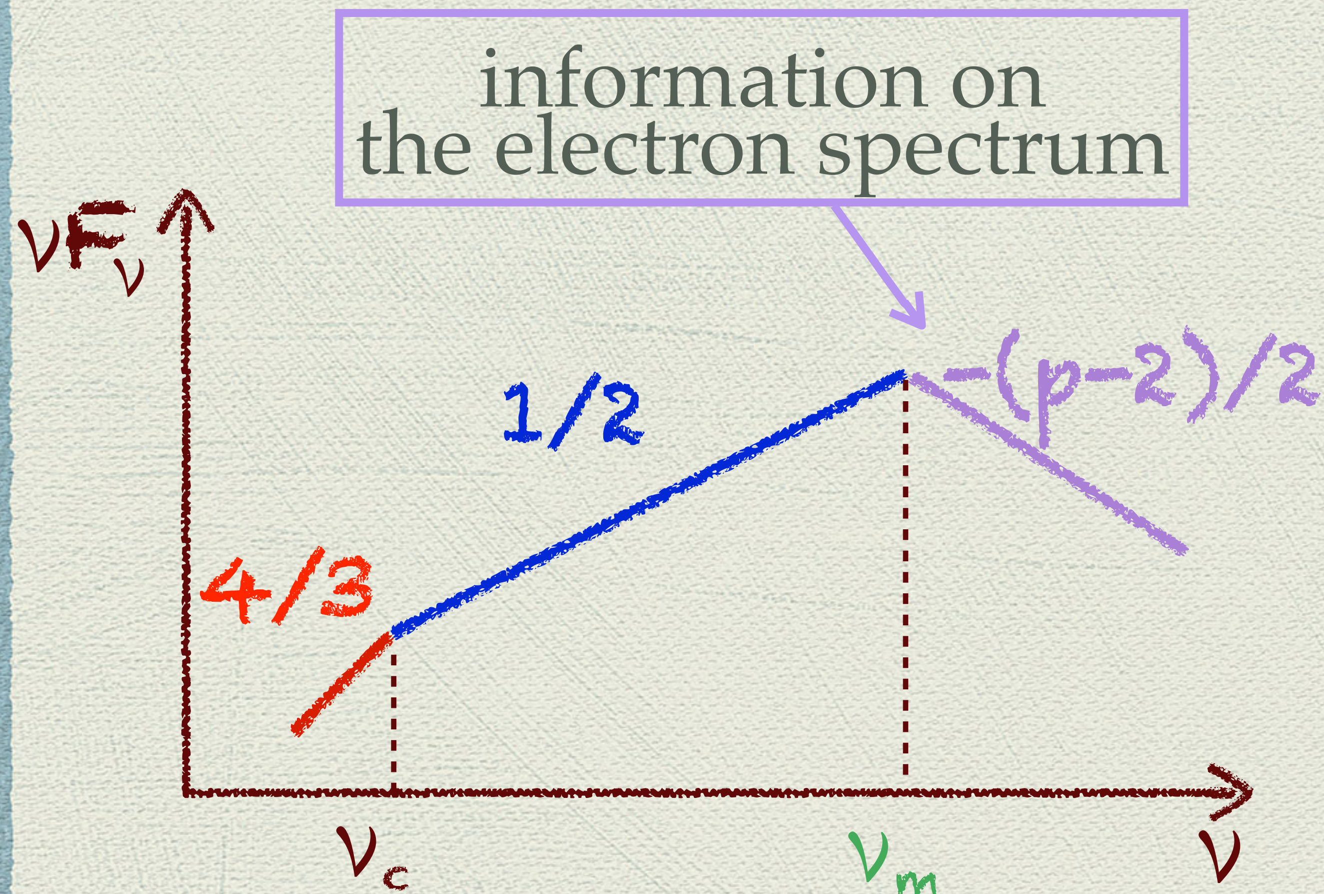
Typical prompt spectrum

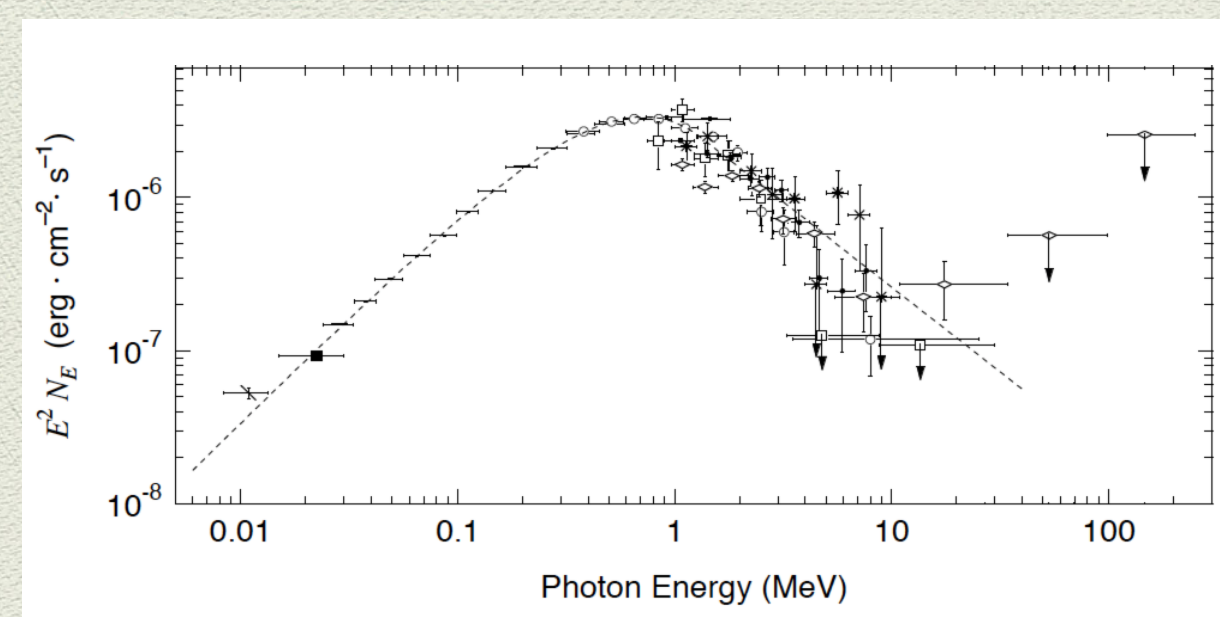


PROMPT spectra: synchrotron theory vs observations

Theoretical synchro spectrum

Typical prompt spectrum



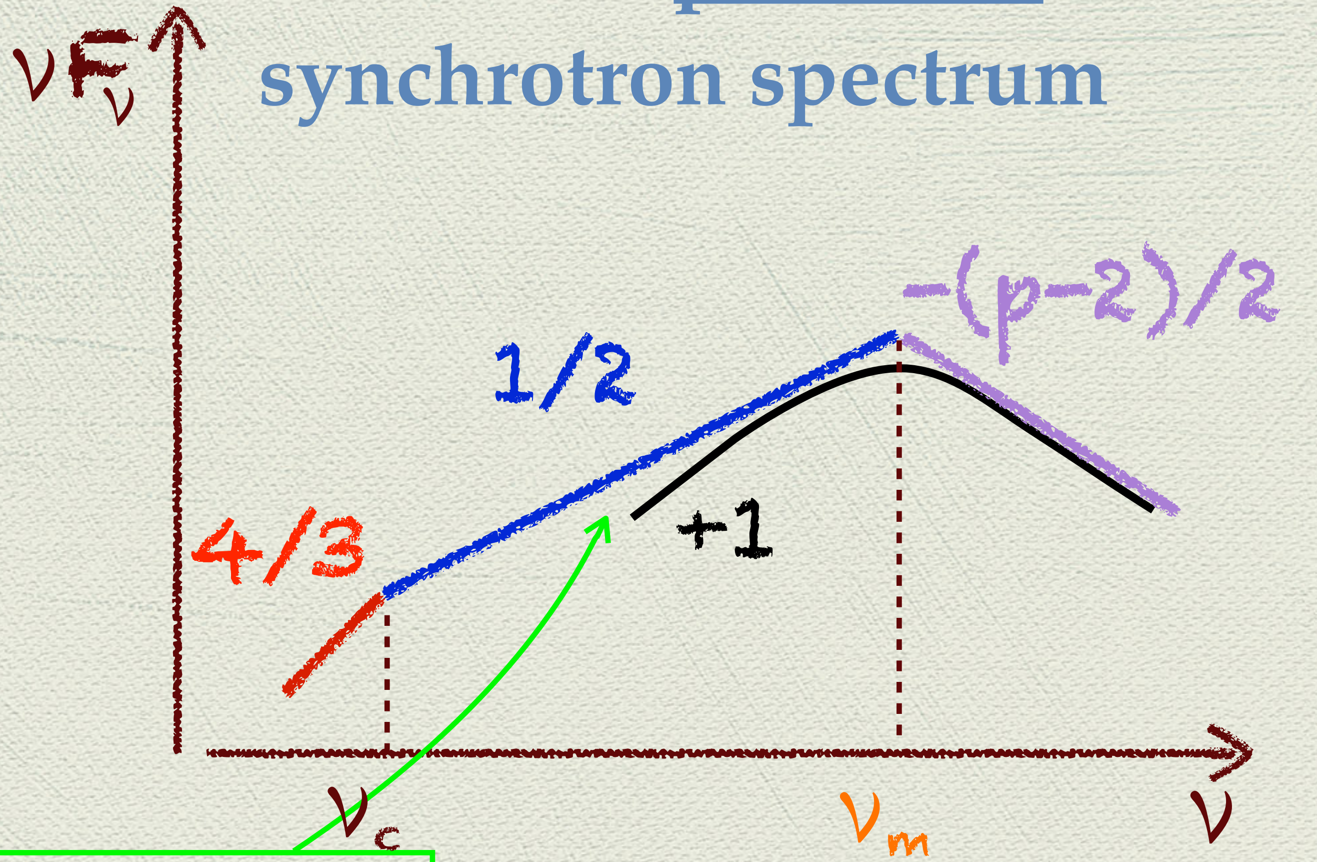


depends on
B, L_k, ε_e, ξ_e

$$E_{\rm peak} = 20 \left(\frac{\epsilon_{e,-1}}{\xi_{e,-1}}\right)^2 \epsilon_B^{1/2}\, L_{\rm k,jet,52}\, R_{14}^{-1}\ {\rm keV}$$

PROMPT spectra: synchrotron theory vs observations

Colours: <u>predicted</u> synchrotron spectrum



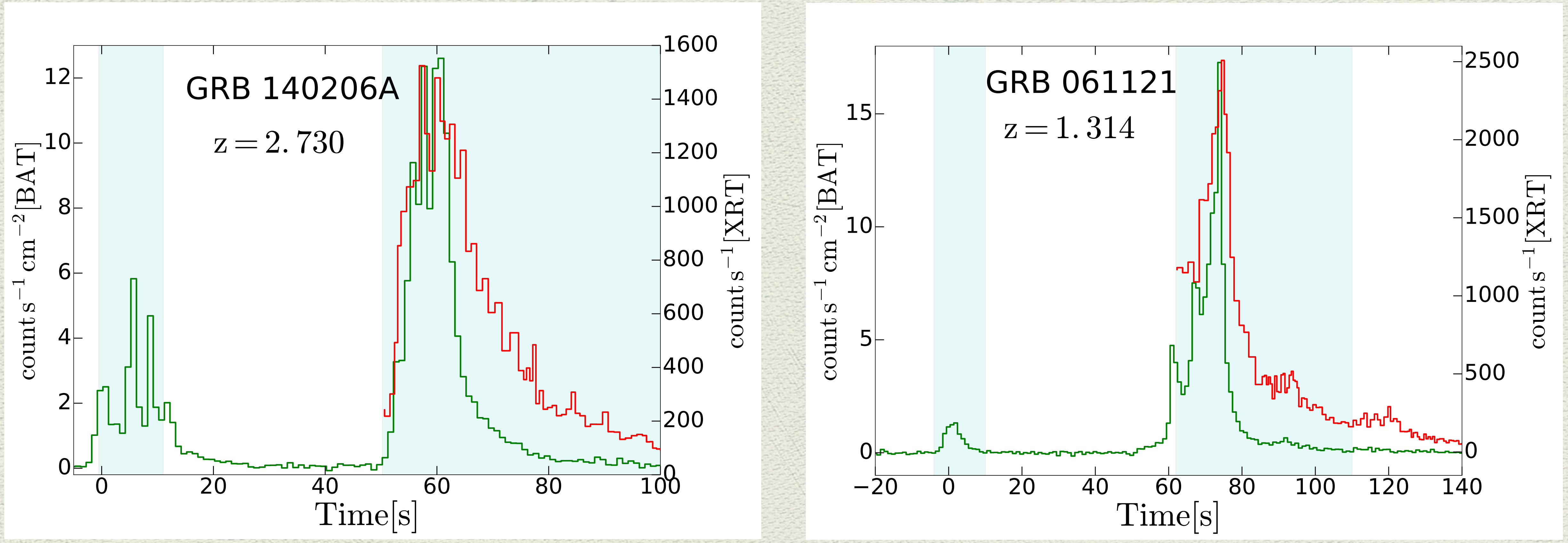
Inconsistency!
Observed spectra are harder than predicted

Black: typical <u>observed</u> prompt spectrum

Prompt emission

Light curves

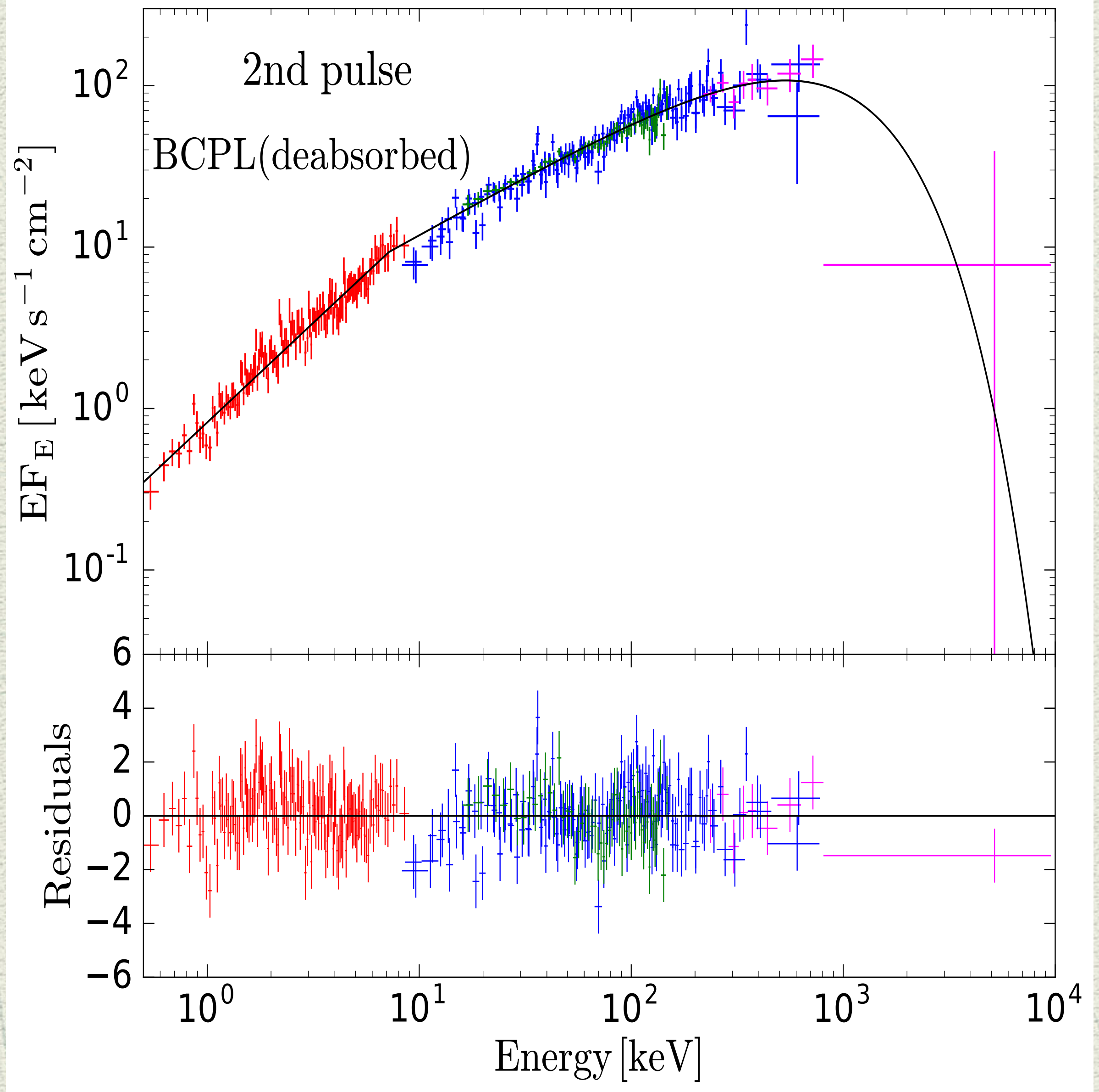
red = XRT 0.3 -10 keV
green = BAT 15 - 150 keV

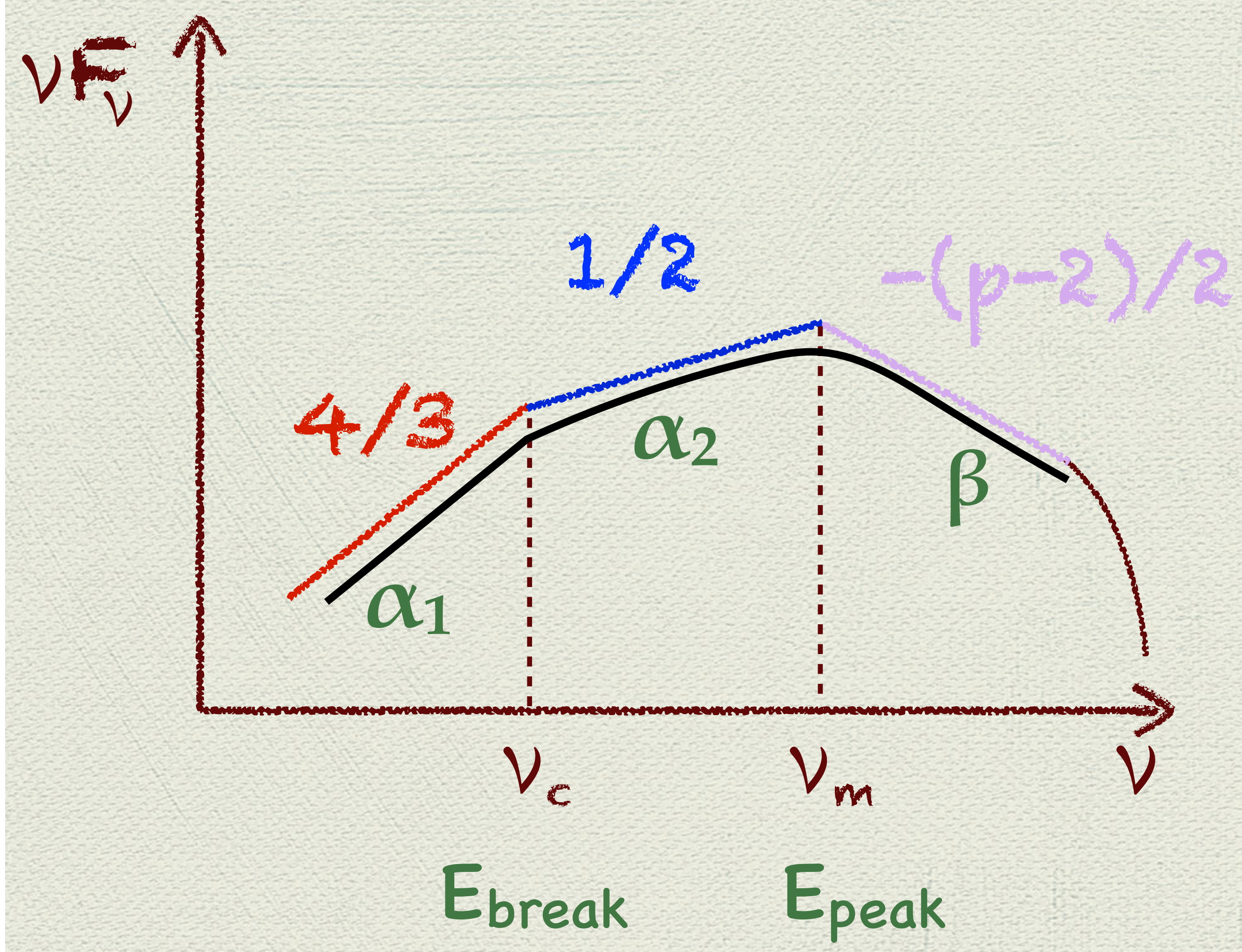


Oganesyan, Nava, Ghirlanda, Celotti, 2017, ApJ

Oganesyan, Nava, Ghirlanda, Celotti, submitted

Comparison between observed spectral shape and synchrotron spectrum

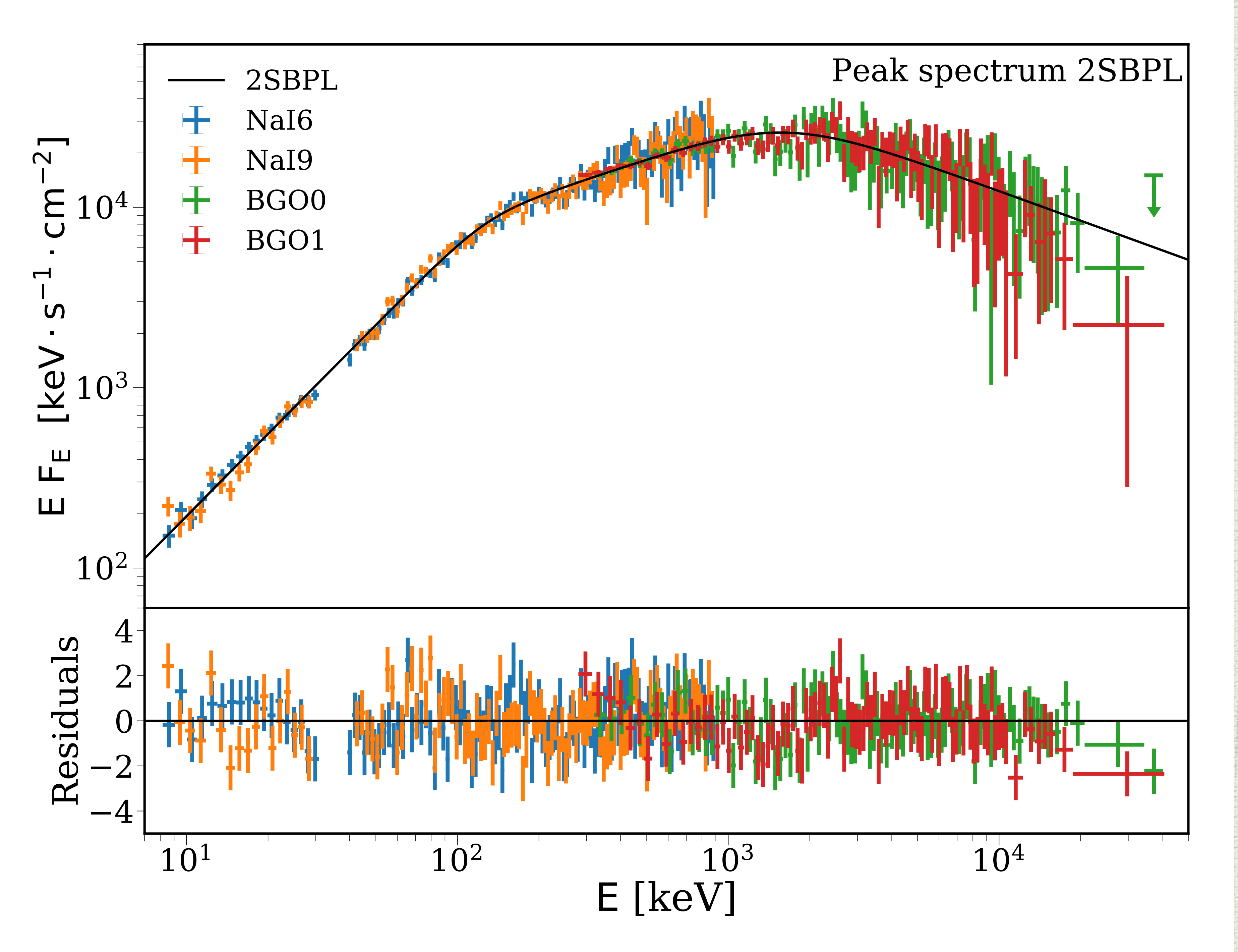




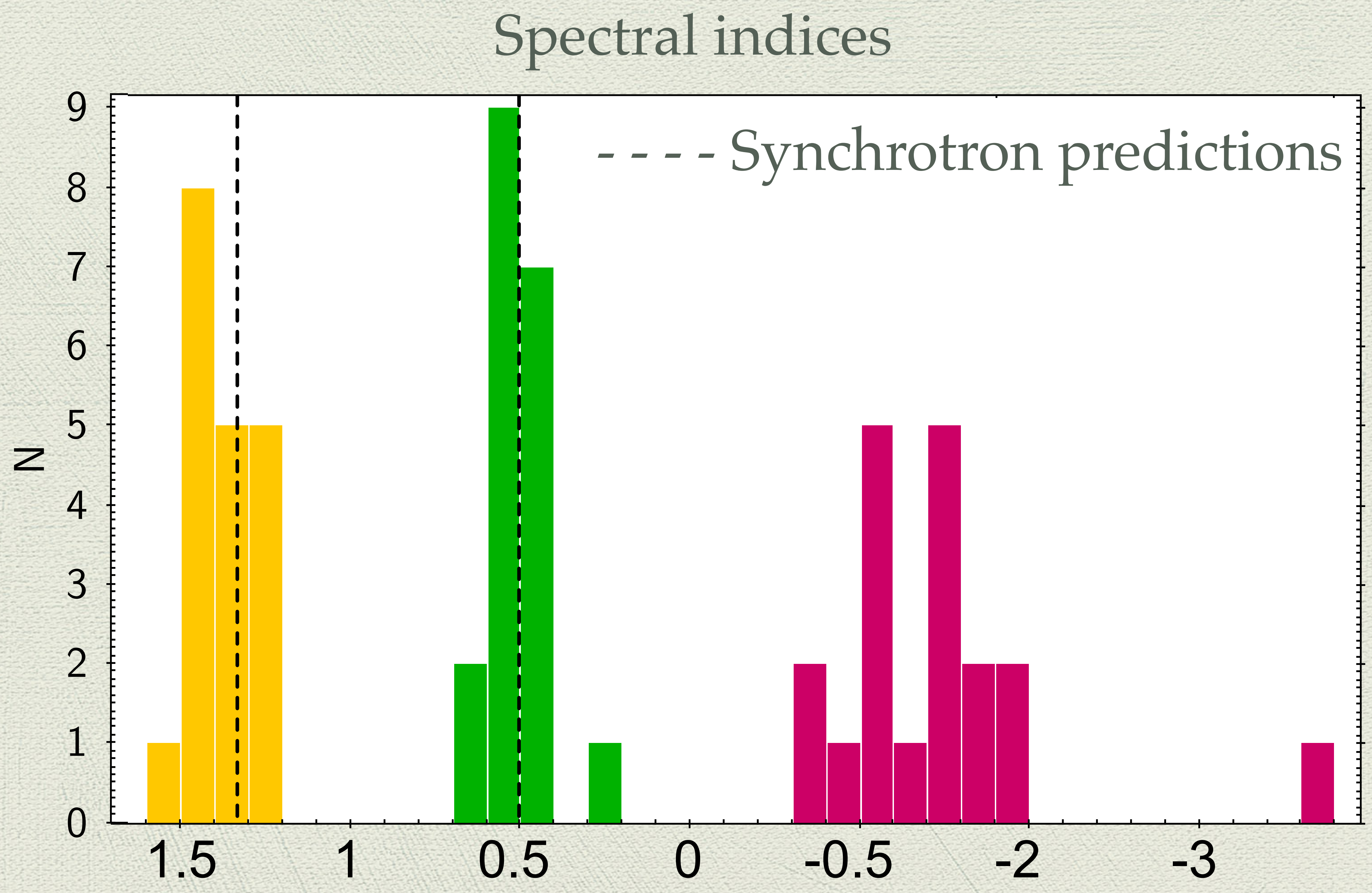
Spectral breaks in Fermi bursts?

Ravasio,…LN et al., 2018, in press

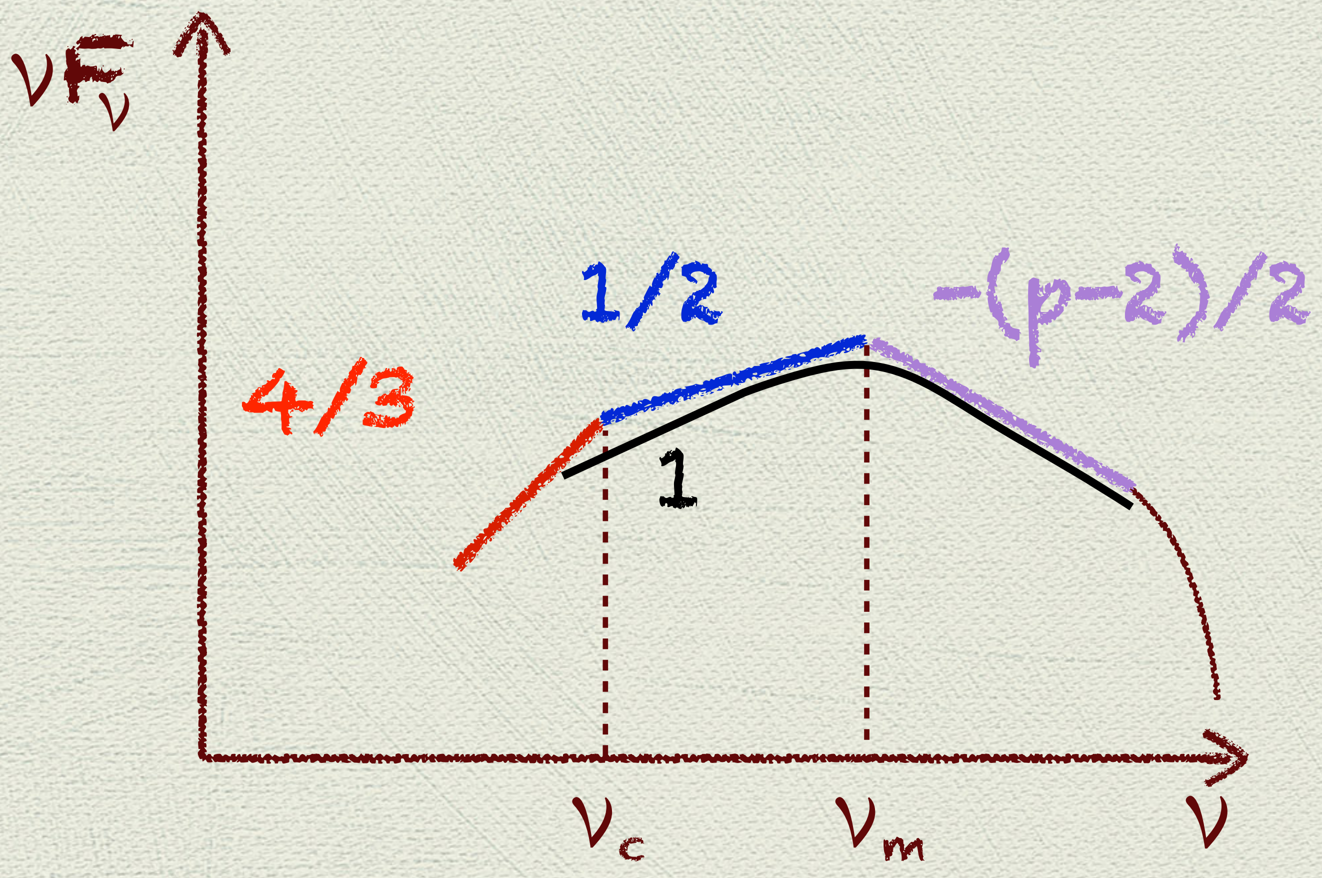
GRB 160625B



GBM GRB 160625B results from time-resolved analysis



Are we observing synchrotron radiation in marginally fast cooling regime?



Theoretical models

marginally fast cooling:

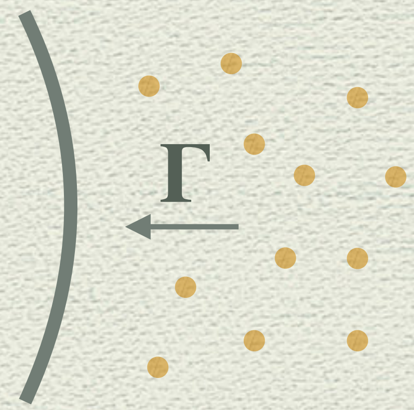
$\nu_c \sim \nu_m$

Derishev 2007
Kumar & McMahon 2008
Daigne et al. 2011
Beniamini & Piran 2013,2014
Uhm & Zhang 2014

Implications:

small $B' \sim 10$ G
large $\Gamma > 500$
large $\gamma_{min} > 10^{4\text{-}5}$

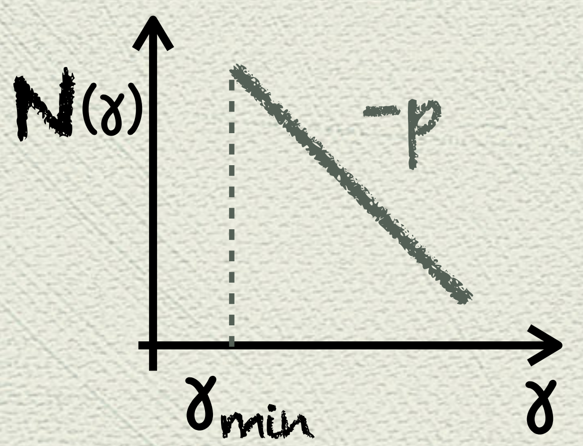
Afterglow
— external shocks —
ultra-relativistic



$$U' = 4\,\Gamma^2\, n\, m_p\, c^2$$

electrons

$$U'_e = \epsilon_e\, U'$$



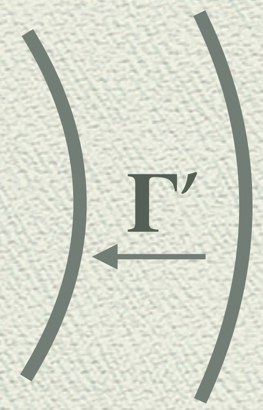
$$\gamma_{e,min} = \epsilon_e \frac{p-2}{p-1} \frac{m_p}{m_e} \Gamma$$

magnetic field

$$U'_B = \epsilon_B\, U'$$

$$B' = \sqrt{32\,\pi\,\epsilon_B\, n\, m_p\, c^2}\,\Gamma$$

Prompt
— internal shocks —
mildly relativistic



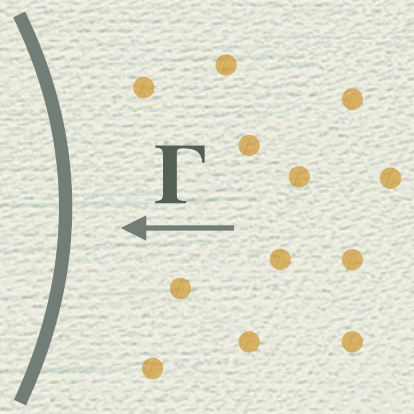
$$\gamma_{e,min} \sim 2 \times 10^3 \, \frac{\epsilon_{e,-1}}{\xi_{e,-1}} \, \frac{p-2}{p-1}$$

$$B' \sim 2 \times 10^4 \, \epsilon_{\rm B}^{1/2} \, L_{\rm k,jet,52}^{1/2} \, \frac{1}{R_{14} \, \Gamma_{2.5}} \, {\rm G}$$

$B' \sim 10^4$ G

$\gamma_e \sim 400$

Afterglow
— external shocks —
ultra-relativistic



$$\gamma_{e,min} \sim 5 \times 10^4 \, \epsilon_{e,-1} \, \frac{p-2}{p-1} \Gamma_{2.5}$$

$$B' \sim 20 \, \epsilon_{\rm B,-2}^{1/2} \, n_0^{1/2} \, \Gamma_{2.5} \, {\rm G}$$

$B' \sim 20$ G

$\gamma_e \sim 10^4$

Afterglow

observations / modeling

- Six (seven) free parameters in the model

  ε_{e}, ε_{B}, (ξ_{e}), p, E_k, $n = n_0 R^{-s}$

- non simultaneous observations at different ν
- radio observations available only for a small sample and at late time
- observed features not included in the model (bumps, plateaus, flares,…)

some of the parameters are fixed to what is believed is their typical value

Afterglow

observations / modeling

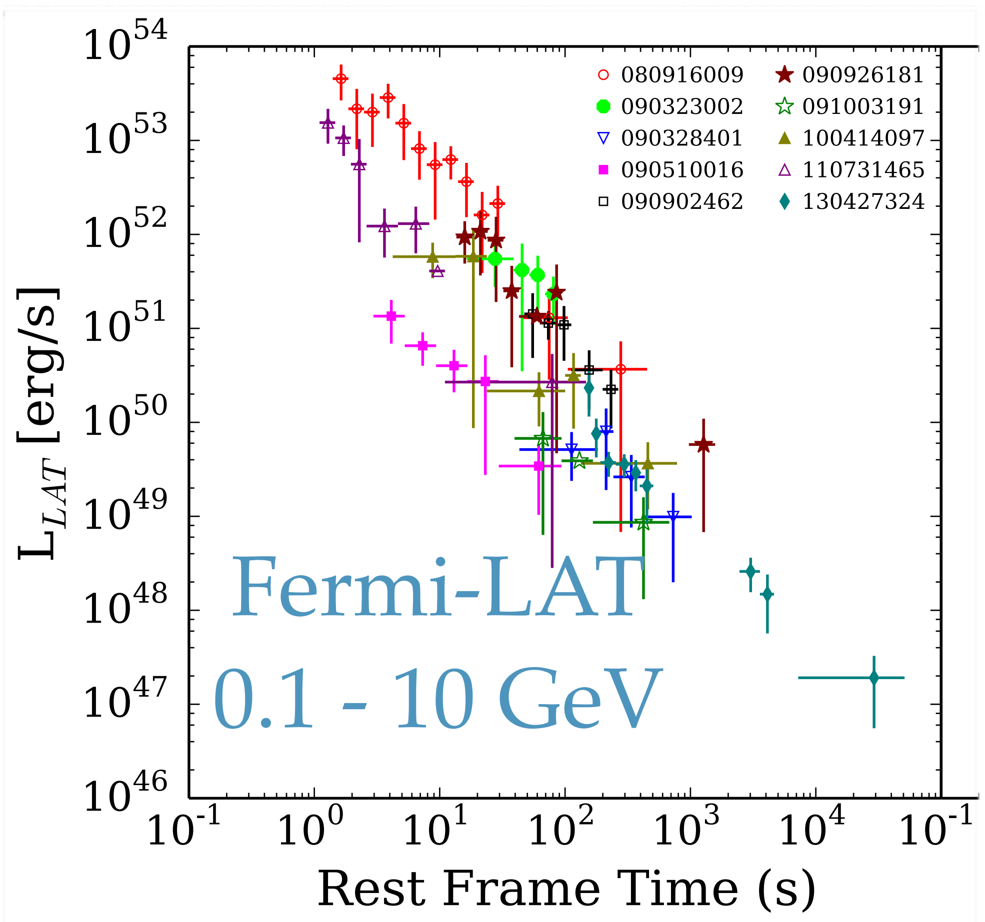
- Six (seven) free parameters in the model

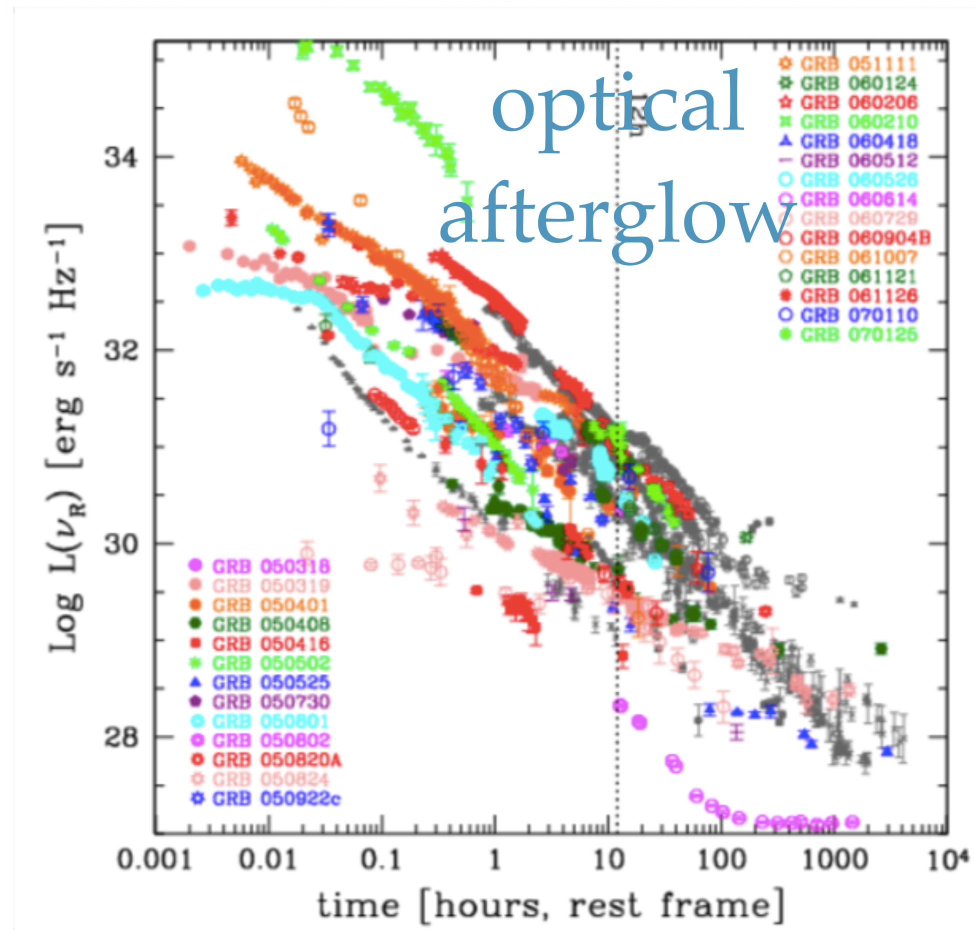
  $\varepsilon_e = 0.1$, $\varepsilon_B = 0.01$ (ξ_e) $p = 2.3$, E_k (from prompt), $n = n_0 R^{-s}$
- non simultaneous observations at different ν
- radio observations available only for a small sample and at late time
- observed features not included in the model (bumps, plateaus, flares,…)

some of the parameters are fixed to what is believed is their typical value

GeV AFTERGLOW

around 50 GRBs with GeV long lasting emission





same origin as the X-ray and Optical afterglow:

-- External Shocks --

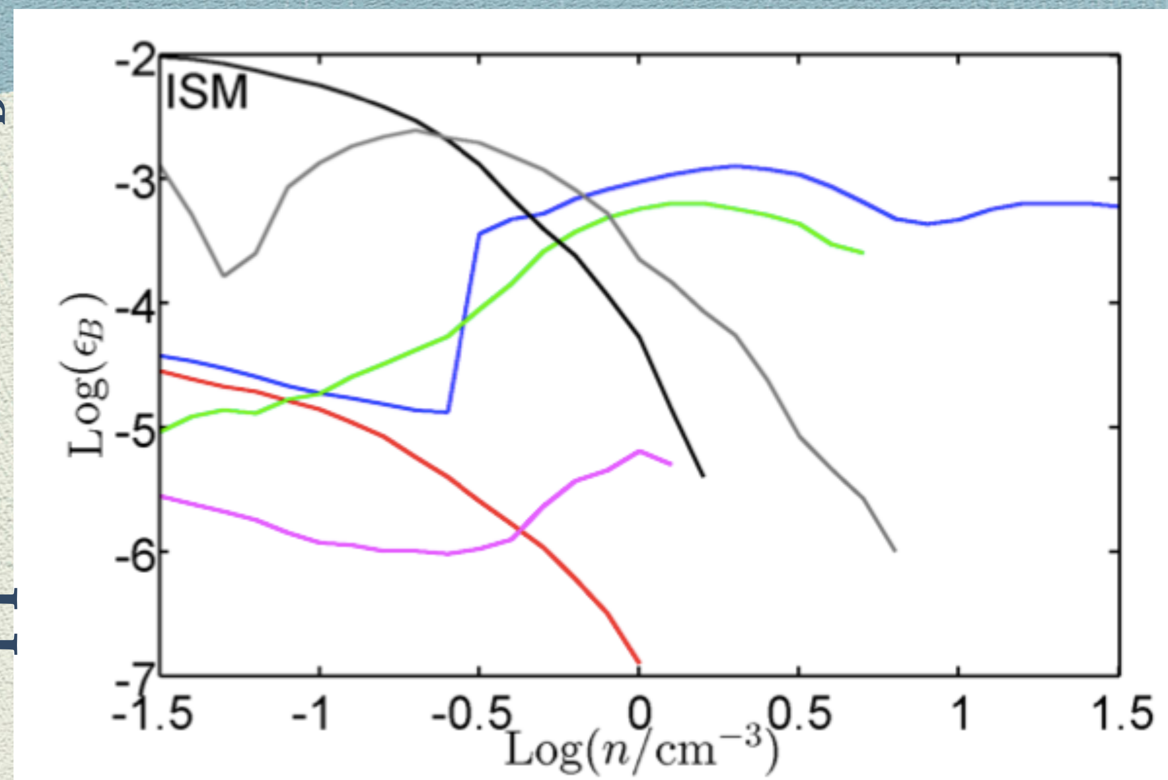
Ghisellini, Ghirlanda, Nava & Celotti 2010 — Ghirlanda, Ghisellini & Nava 2010
Kumar &Barniol Duran 2009, 2010; Gao et al. 2009;
Corsi, Guetta & Piro 2010; De Pasquale et al. 2010

Upper limits on ε_B

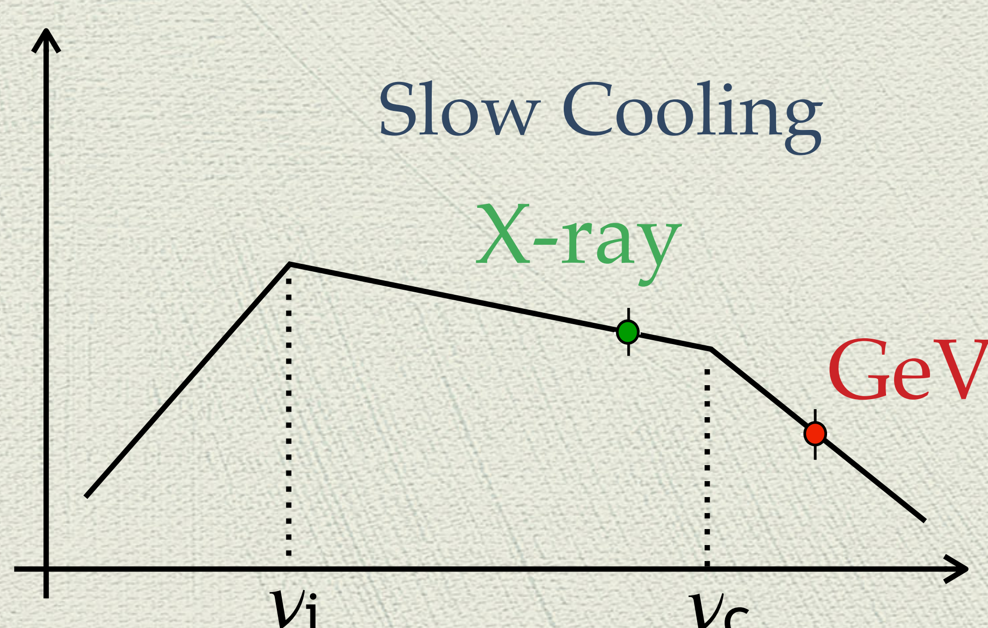
always smaller that the **canonical value ε_B=10^{-1}-10^{-2}**

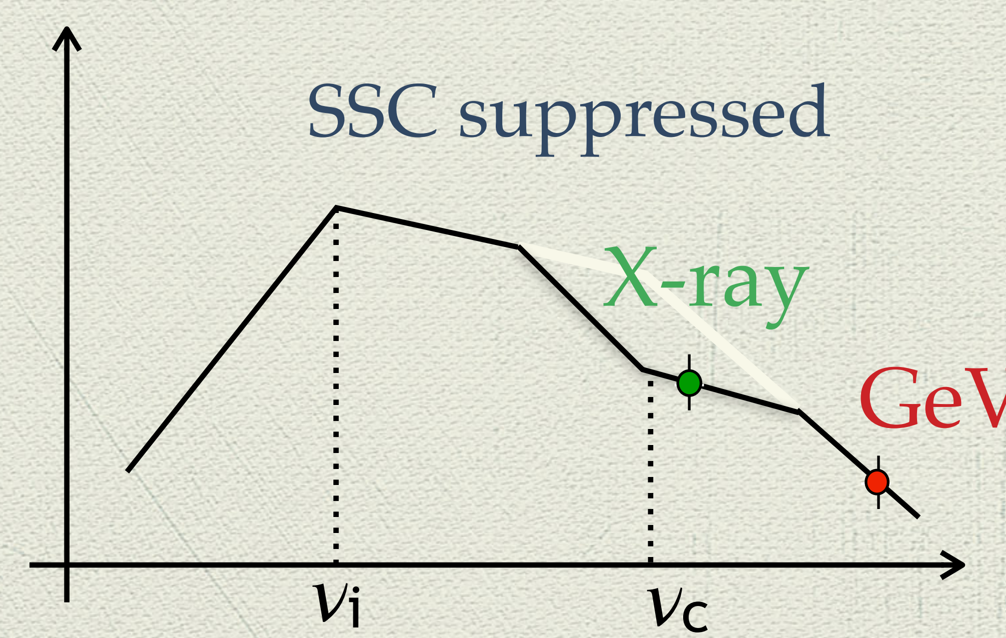
(Kumar & Barniol Duran 2009, Lemoine 2013a/b — Santana et al., 2014)

upper limits to ε_B



Density





Conclusions

- Small B…? What is the value of B relevant for particle cooling?
- Maximum energy of accelerated electrons?
- Efficiency of the acceleration mechanism (= fraction of particles injected in the acceleration process)?

Future

- SKA: radio observations at late time, when fireball isotropic, give direct estimate of the true energy
- CTA: cutoff in the afterglow synchrotron spectrum (=maximal energy of accelerated particles)?
  Inverse Compton component?