The connection between GRB prompt emission physics and high-energy cosmic rays: new constraints using Fermi data

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Samuelsson et. al., 2019, Ap.J., 876, 93
-. 2020, Ap.J., 902, 148

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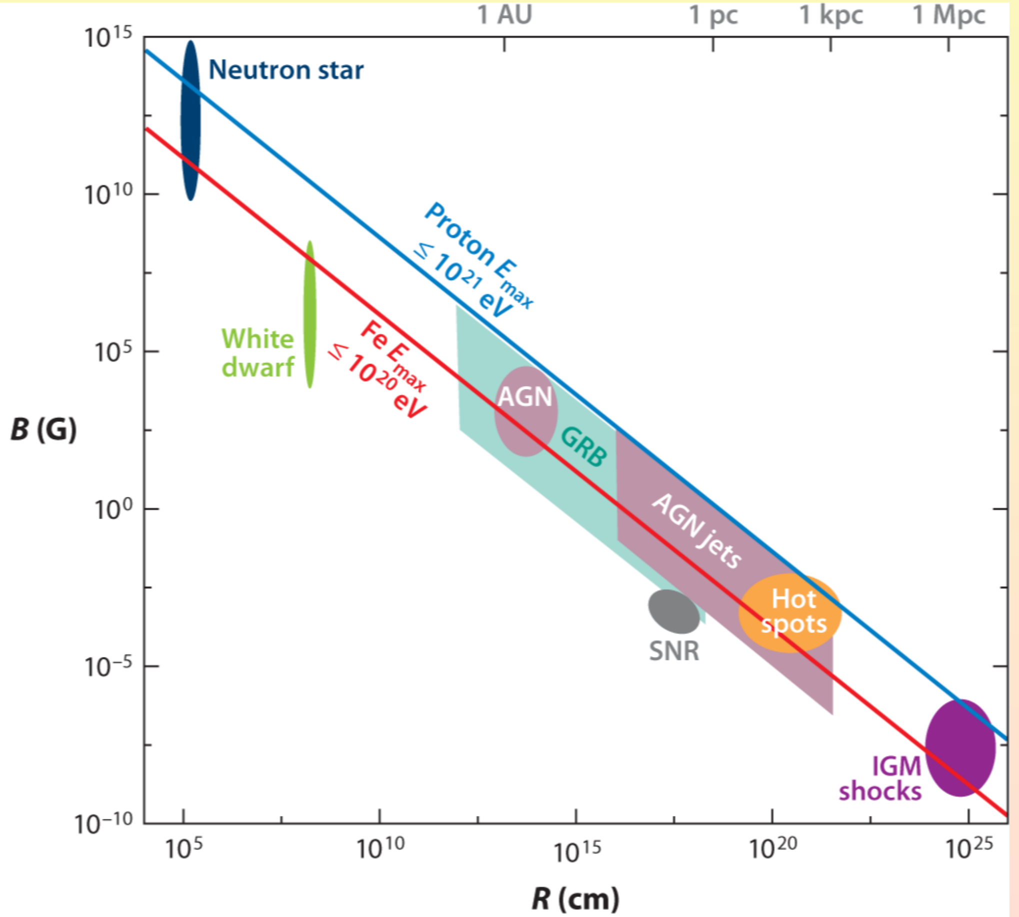
GRB as sources of UHECR ?

Particle acceleration & Hillas condition

General consideration:

During their acceleration, particles need to be confined to the source:



$$r_L = \frac{E}{zqB} <\sim r_{source}$$

(Hillas, 1984;

Fig. from Kotera & Olinto, 2011, ARAA)

Hillas condition in a different way

$$r_{source} B >\sim \frac{E}{zq} \qquad L_B = 4\pi r^2 \Gamma^2 c \frac{B^2}{8\pi} >\sim 10^{45} \Gamma^2 \frac{E_{20}^2}{Z^2} \mathrm{erg/s} = 10^{12} \Gamma^2 \frac{E_{20}^2}{Z^2} L_{sun}$$

Assuming $L_\gamma \sim L_B$, source must be very luminous !

(Lovelace+1976, Norman et. al., 1995)

Main candidates:

- Luminous steady sources (active galactic nuclei) — Γ <=10 , L~ 10^{42}-10^{45} erg/s

  Biermann & Strittmatter 87, Rachen93, Aharonian02, Berezinsky 06,…

- Luminous transient sources (gamma-ray bursts) — Γ ~10^2-10^3 , L~ 10^{51}-10^{53} erg/s

  Levinson & Eichler 93, Milgrom & Usov 95, Waxman 95, 97, 02, 04,…

  External shocks: Vietri95; However, Niemiec +06, Niemiec & Ostrowski06, Lemoine+06, …

  → rel. shocks are ineffective

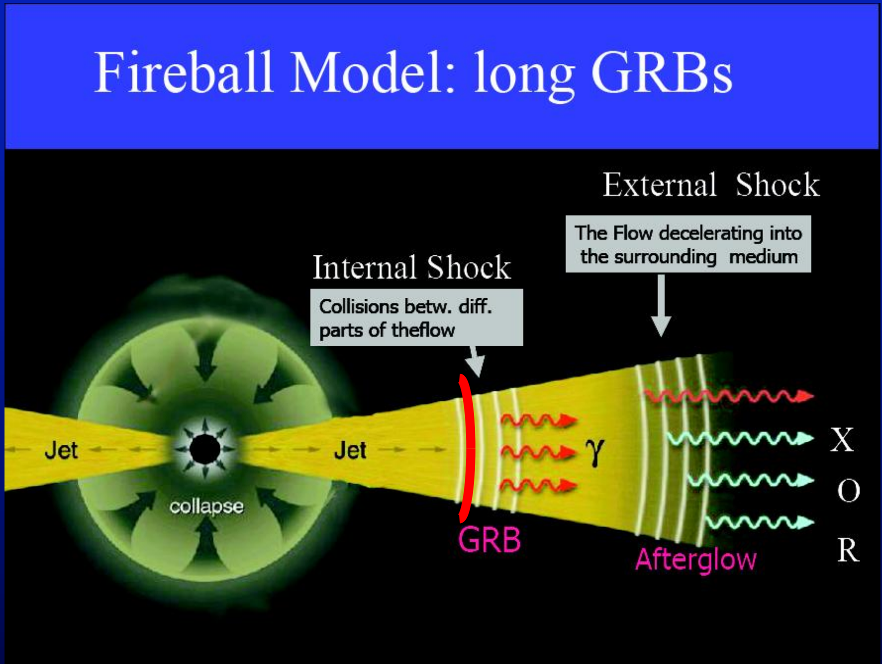
  Internal shocks: Waxman95,… Dermer+98,… Globus+15, 17, … Asano & Meszaros 2016,…

  Reverse shock: Murase+, 2008,…

- Low luminosity GRBs — Γ– ? , L~ 10^{46}-10^{48} erg/s

  Murase+06, 08, Budnik+08, Liu+11,…

A closer look: can GRBs be sources of UHECRs?



Paczynski 1990. Rees & Meszaros 1992, 1994,...
Sari & Piran 1995, ...Daigne & Mochkovich 1998...
Fig. from Meszaros 2001

✓ Luminous transient sources (Hillas condition)

✓ Observed UHECR rate $Q_{UHECR} \sim 10^{44}$ erg/Mpc^3/yr

Local GRB rate: ~1 Gpc^3 yr^{-1}
Wanderman & Piran 2010

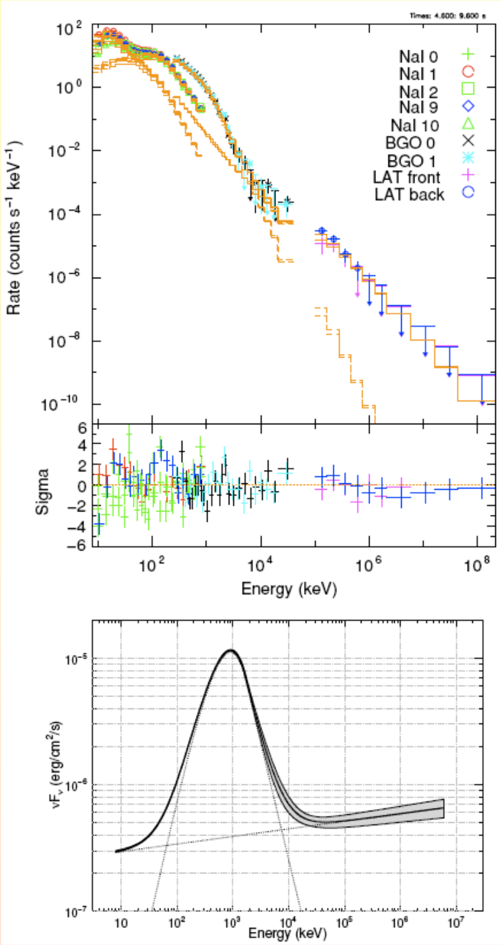
Can work if

$E_{UHECR} \sim E_\gamma \sim 10^{53}$ erg

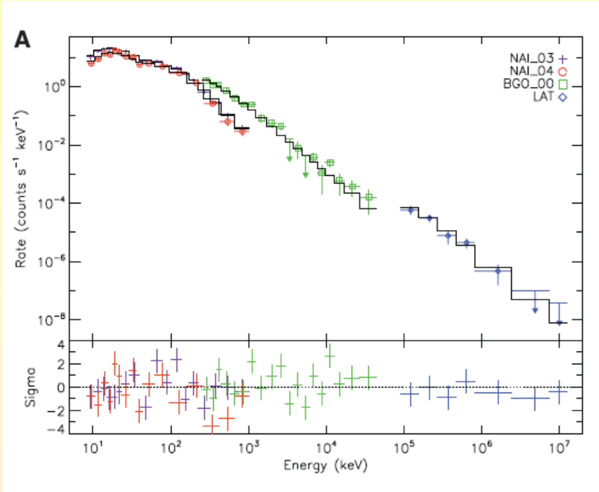
Observational signature??

What produces the observed prompt spectra ?

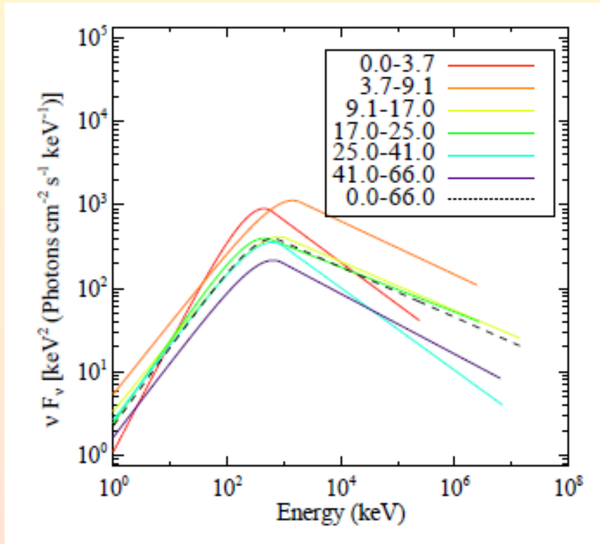
090902B (Abdo+09)



080916C(Abdo+09b)



Sub-MeV peak;



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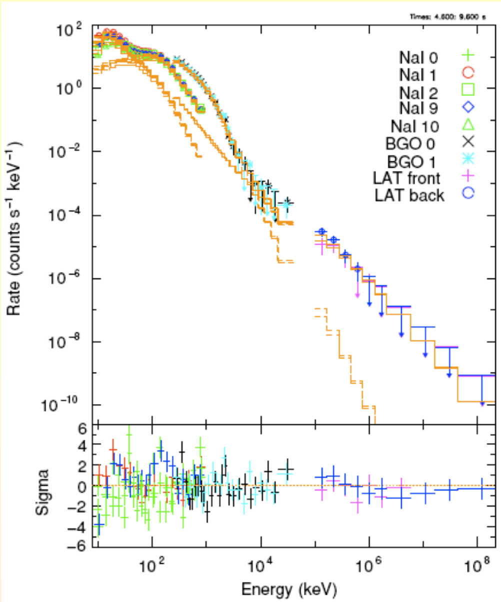

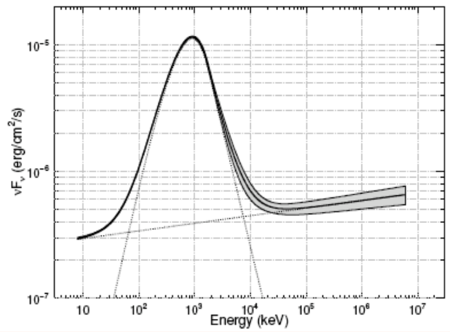

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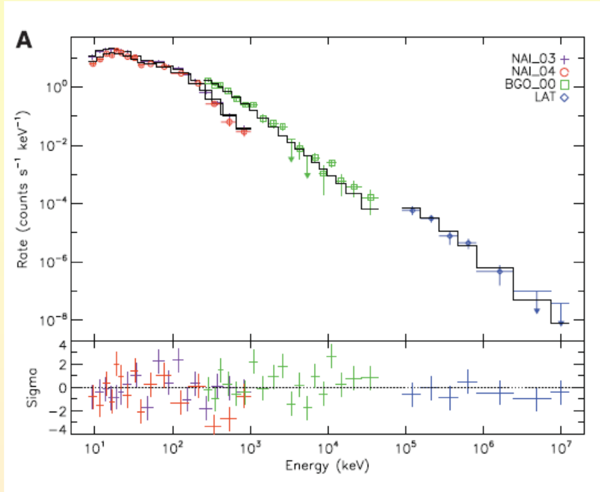
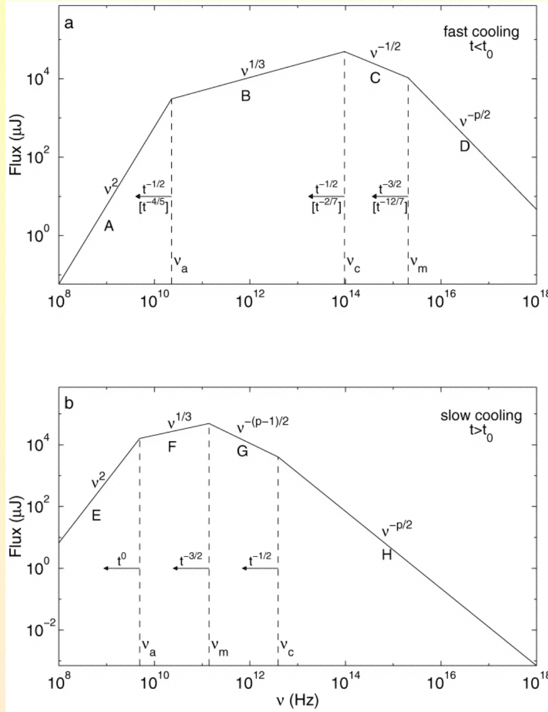




1: Synchrotron

$$\nu_m^{ob} \sim 480\left(\frac{B}{10^5 G}\right)\left(\frac{\gamma_{el}}{10^3}\right)^2\left(\frac{\Gamma}{300}\right) keV$$

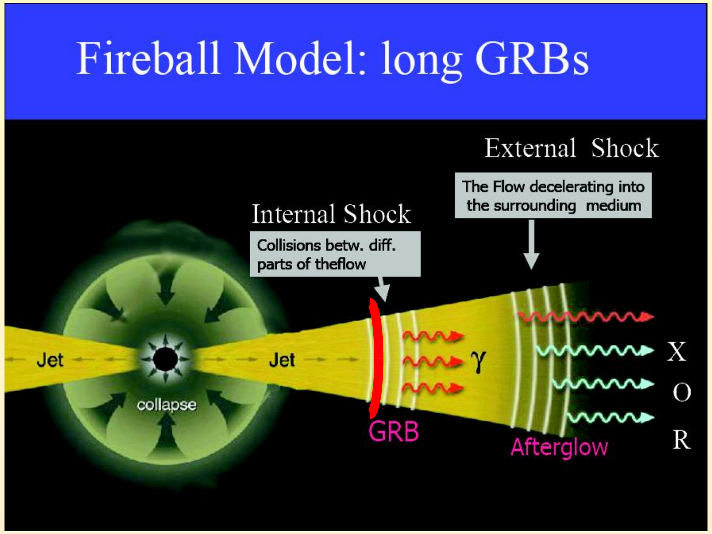
$$\nu_c^{ob} \sim 25\left(\frac{B}{10^5 G}\right)^{-3}\left(\frac{r}{10^{11} cm}\right)^{-2}\left(\frac{\Gamma}{300}\right)^3 eV$$

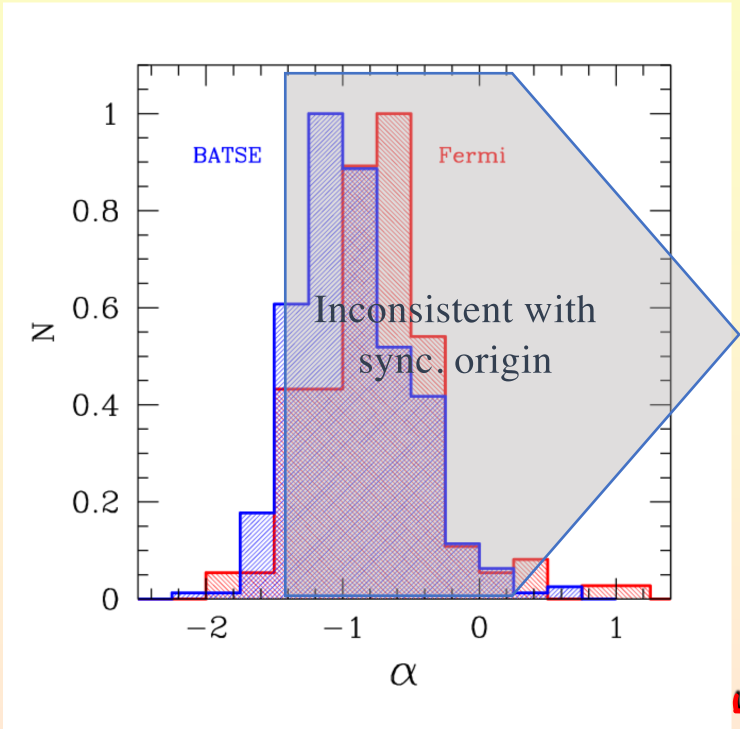
Theory: Rybicki & Lightman 79, Meszaros & Rees 1993, ... Sari+98, ...

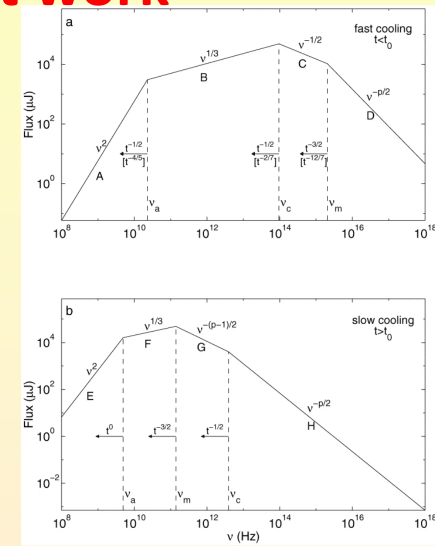
Radiative process – 2: thermal

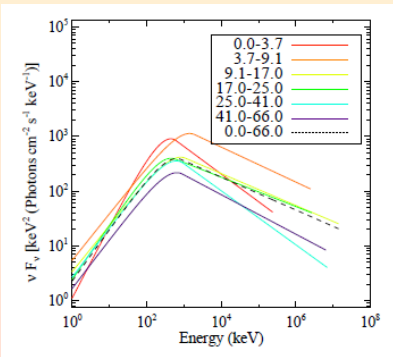
Motivations:

(1) Inherent to model; (2) [simple] synchrotron does not work



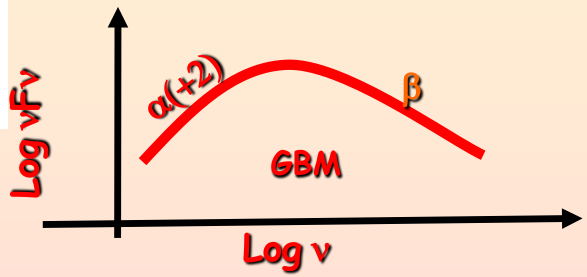






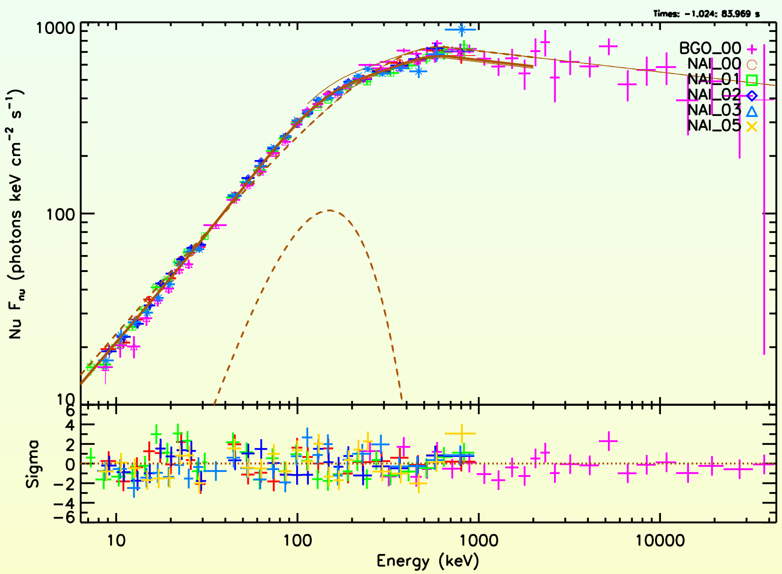
Preece+98: 'Synchrotron line of death':

Nava+11, Goldtein+12, Axelsson+15, Yu+15, …

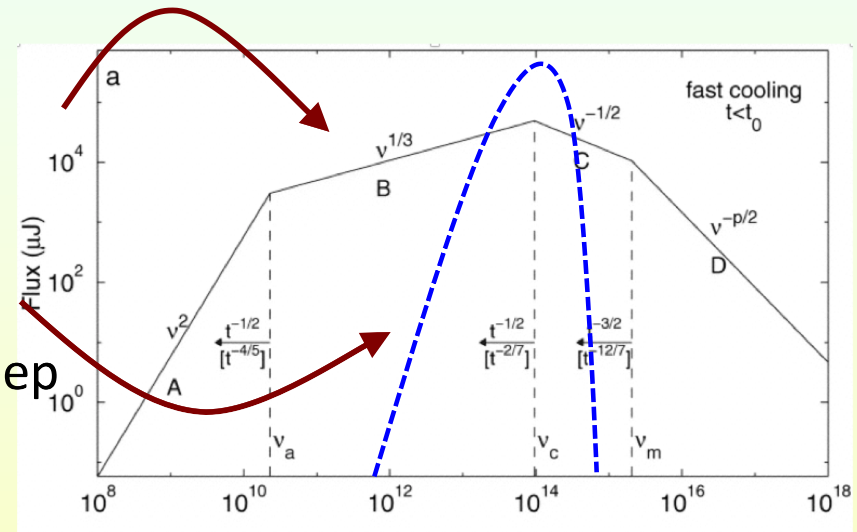


3: Possibly, a "hybrid" model

GRB100724B (Guiriec+11)



Synchrotron – too flat



Planck – too steep

Ryde 2004, 2005, 2010… Ryde & Pe'er 2009,… Pe'er & Ryde 2011, Guiriec+2011, … Iyyani+ 2015,16…

Can GRB accelerate CRs to the highest energies ?

Physical requirements:

1. **Low energy spectral slope**: cannot be too shallow.

Synchrotron dominated

$$\nu_c^{ob} \sim \nu_{peak}^{ob} \sim 300keV$$

(otherwise, slope too shallow)

Thermal dominated

$$F_{\nu,syn}(\varepsilon_{peak}) < 0.2F_\nu^{ob}(\varepsilon_{peak})$$

+upper limits from optical band:

$$F_{\nu,syn}(\varepsilon_{Opt.}) \leq 100mJy$$

2. Physical conditions enable **acceleration of particles to the required energies**

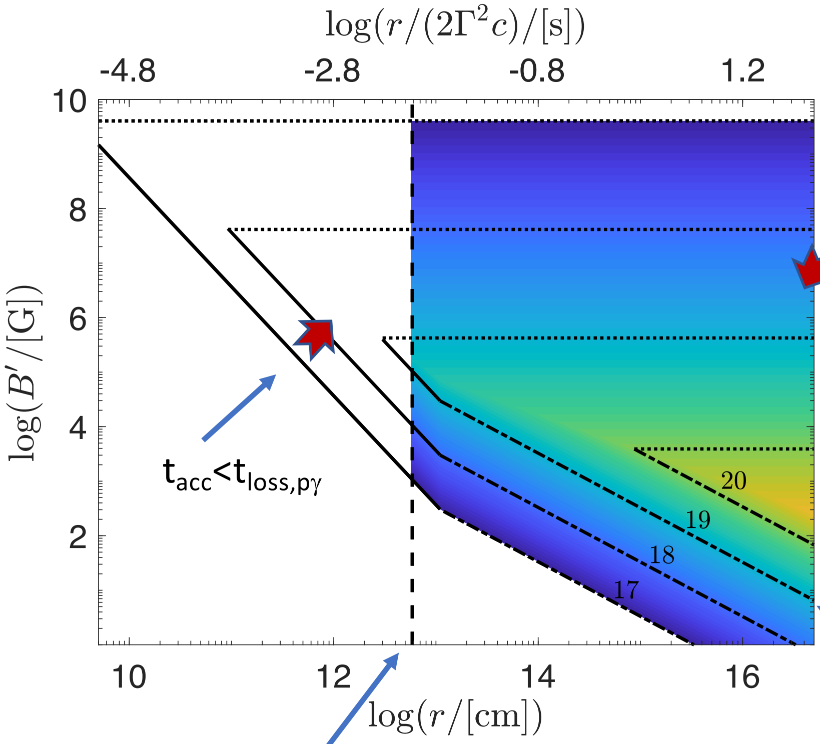
$$t_{acc} < t_{cool}\left\{sync, adiabatic, p-\gamma\right\}$$

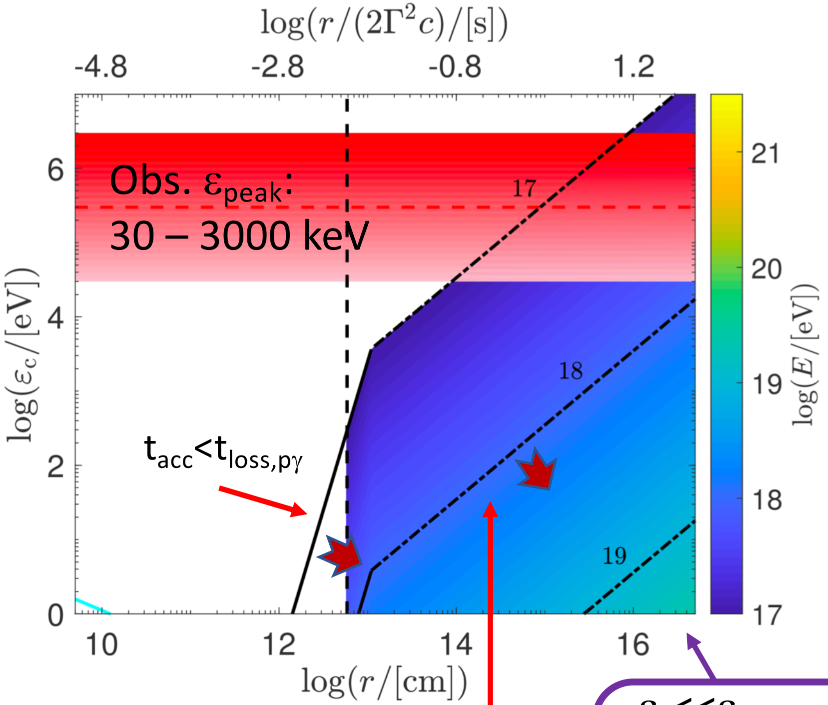
$$t'_{acc} = \frac{E}{\eta czqB'\Gamma}$$

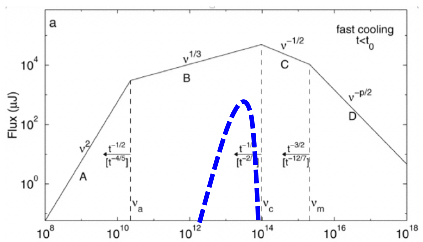
η=efficiency (~0.1)

Results (1): sync. dominated model (Γ=100)

$t_{acc}<t_{cool}$ → limit on B → limit on the cooling frequency





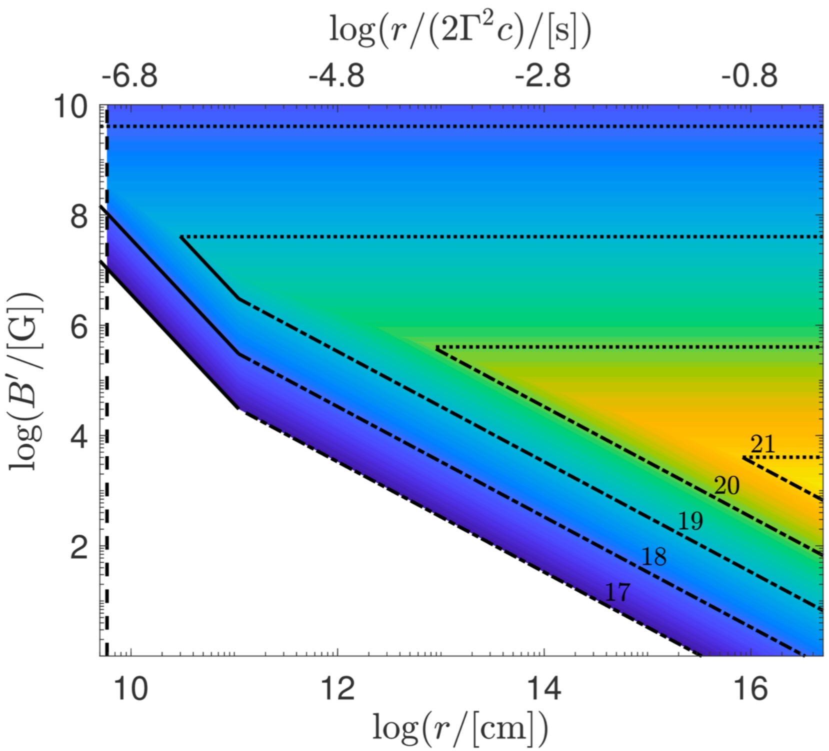


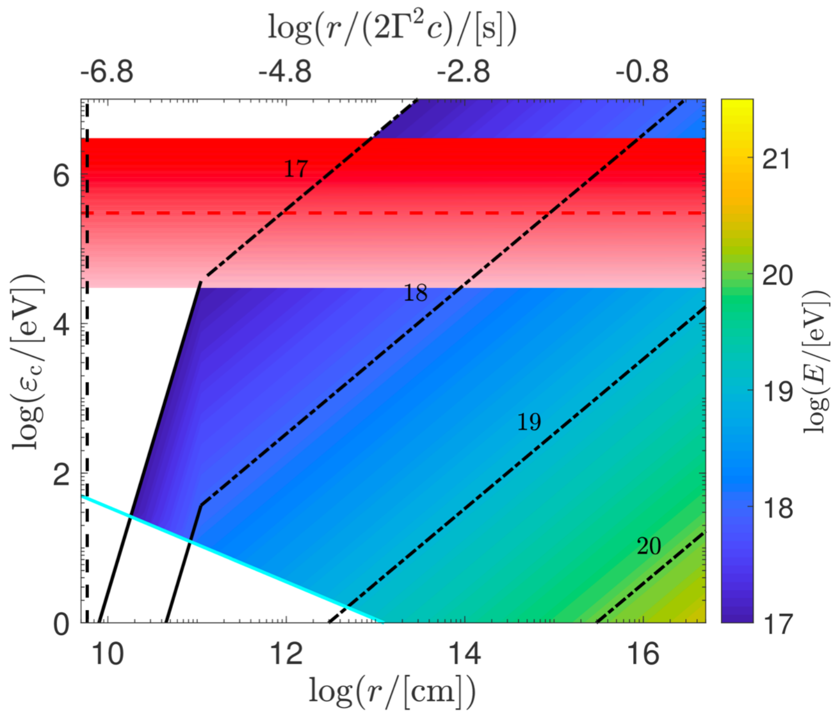
No solution

$\varepsilon_c << \varepsilon_{peak}$
→ Fast cooling
→ Inconsistent Spectral slope

Samuelsson+2019

Results (2): sync. dominated model (Γ=1000)





No solution

Physically: electrons must cool too fast
→ theory does not match obs. spectrum

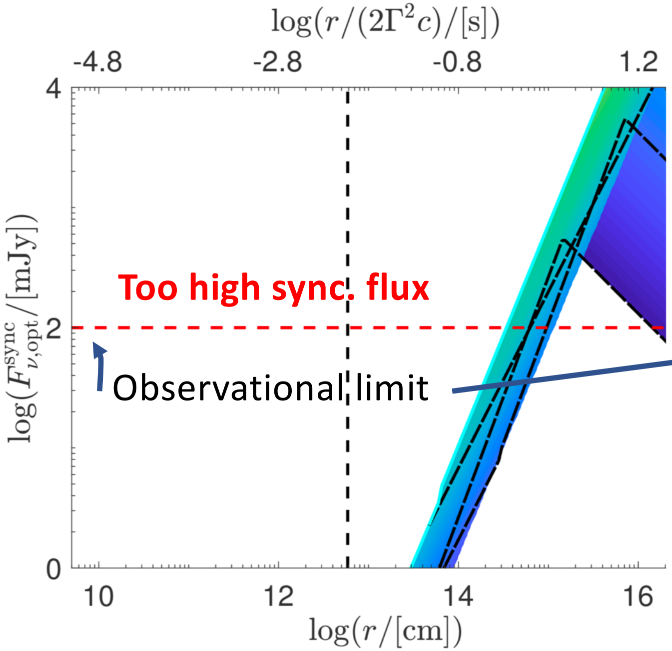
Samuelsson+2019

Results (3): Thermal dominated model (Γ=100)

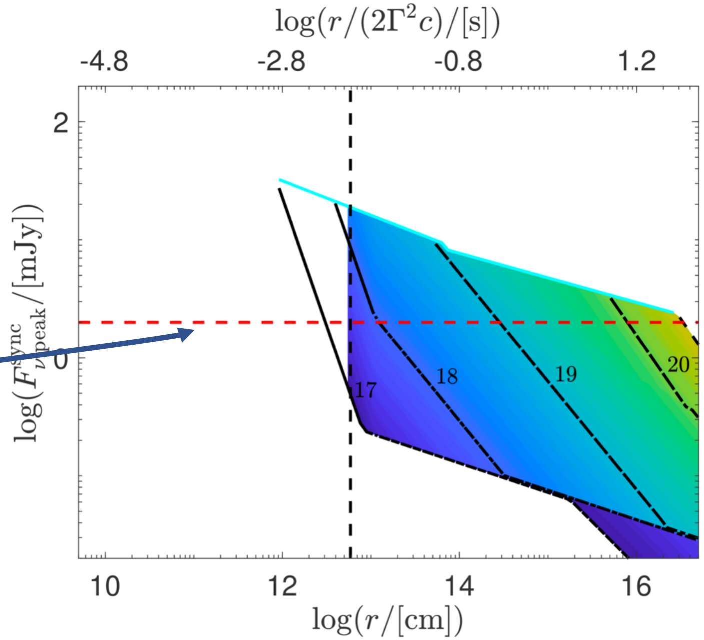
Synchrotron fluxes at

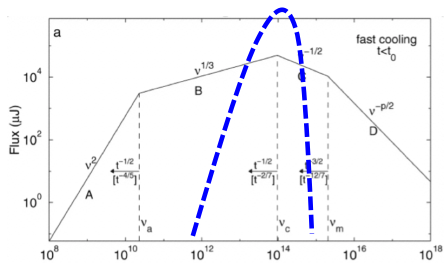
$\{\nu_{ssa}, \nu_m, \nu_c\}$ =
f(E,r,Γ) ←→ f(B,r,Γ)

optical

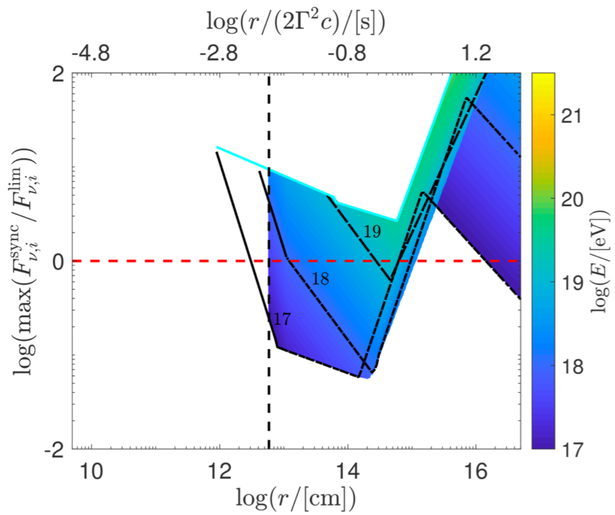


300 keV





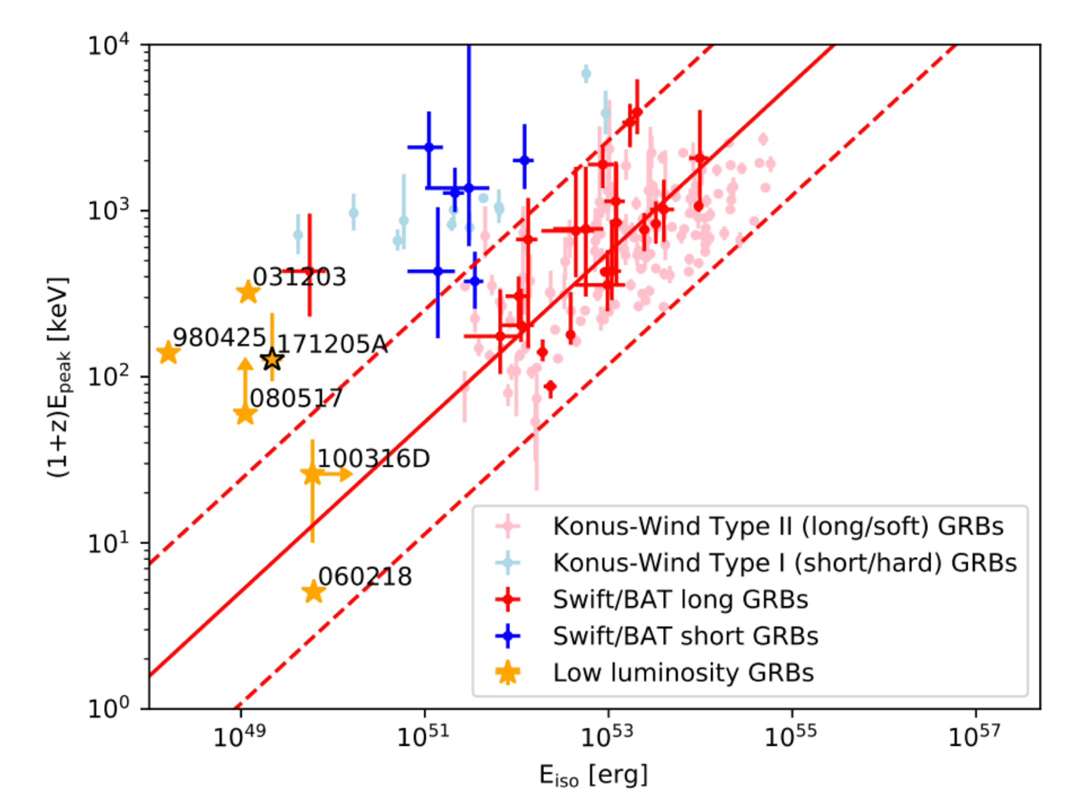
Combined



No solution either

Samuelsson+2019

Low luminosity GRBs: a separate category ?



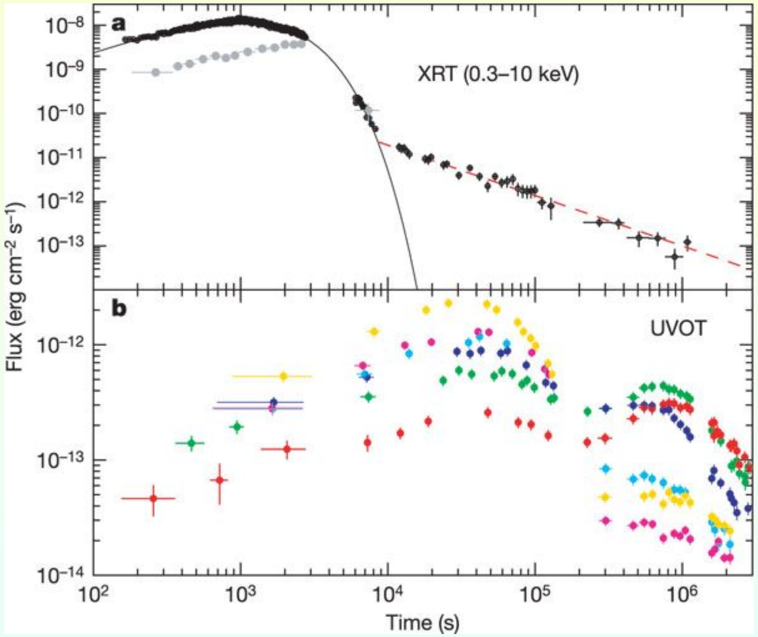
D'Elia+18

- Nearby (z~0.05) (Vs. <z>~2)
- connected to SN
- Very long : t_{90} ~100-1000s
- ~100 times less energetic than regular GRBs
- rate of llGRB ~10-100*rate of GRBs
- Origin: unknown (shock breakout?)
- 060218: L~10^{46}-10^{47} erg/s, E_{iso}~10^{50}-10^{51} erg

Clues from a nearby 'typical' llGRB: 060218

(Very) nearby, z=0.033; Associated with a nearby supernovae SN2006AJ

- **Excellent data during both prompt and AG**



Campana+06

T_{90}~2100 s

L~3*10^{46} erg/s

E_{pk}~5 keV

E_k~10^{48} --10^{50} erg

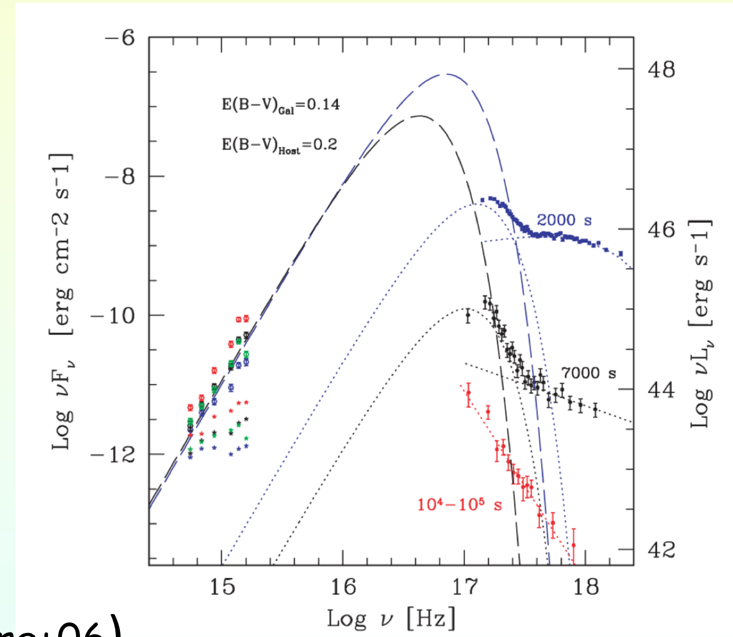
F_ν(op)~0.35 mJy

F_ν(x)~0.1 mJy

$E_{k,SN}$~2*10^{51} erg

Γ_i<~15 (AG; Soderberg+06)

Mazzali+06,



Ghisellini+07

Toma+07: compatible with radio, O, X-ray → N.R. shock (E_k~4*10^{49} erg) → UHECR flux too low

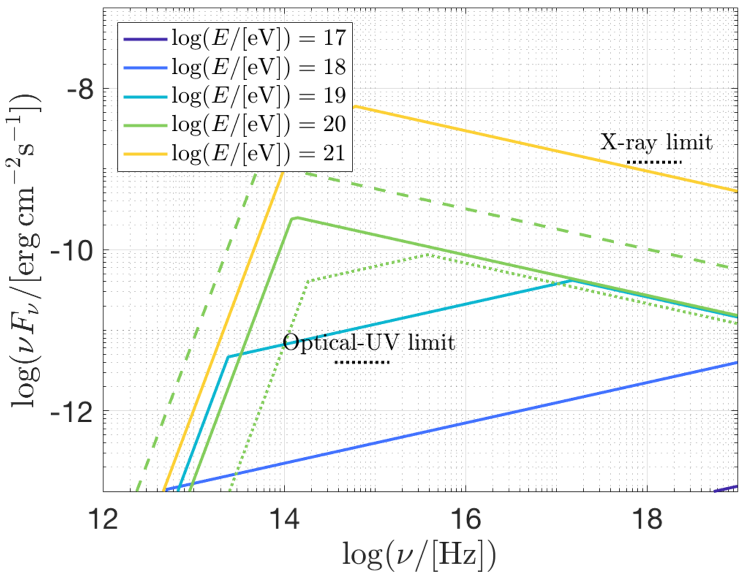
Can llGRB060218 - like be the sources ?

Low energy release (E_k~10^{49} erg), non-relativistic outflow ? (Toma+07)→ UHECR flux too low

-or-

E_k~10^{51} erg, ξ_a<<1; Relativistic outflow ? (Zhang & Murase, 2018) → X/optical too bright

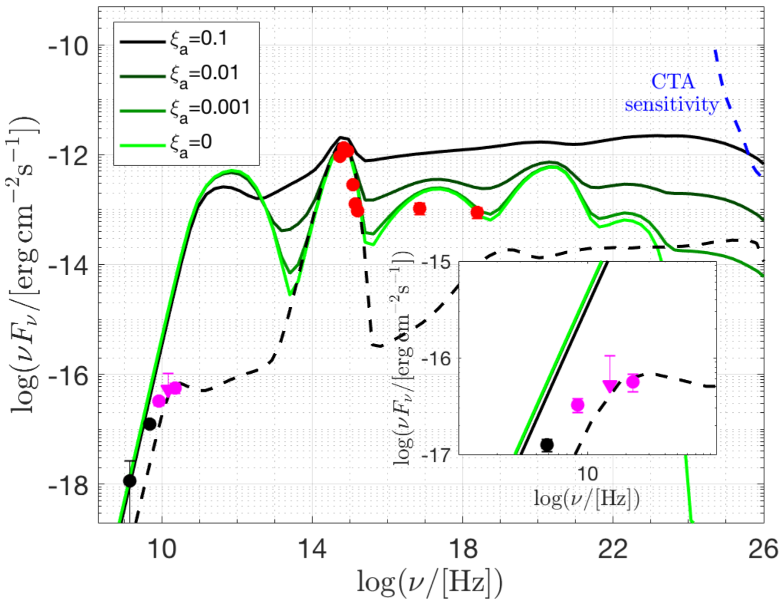
Most favorable (prompt) parameters



R=10^{14} cm,
ξ_a = 10^{-2}

Afterglow (3 days)

ξ_a = fraction of acc. electrons



E_k=10^{51} erg

E_k=10^{49} erg

No solution here as well

Samuelsson+2020

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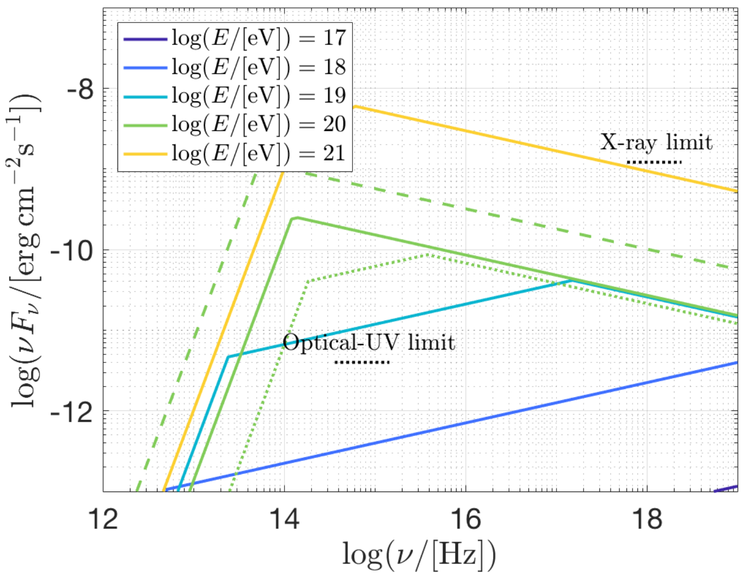

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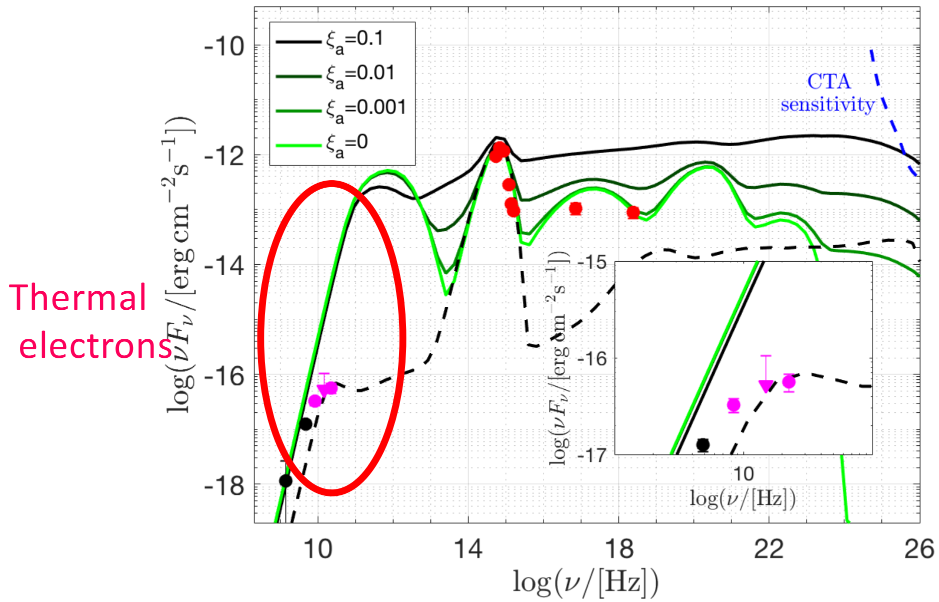


E_k=10^{51} erg

E_k=10^{49} erg

No solution here as well

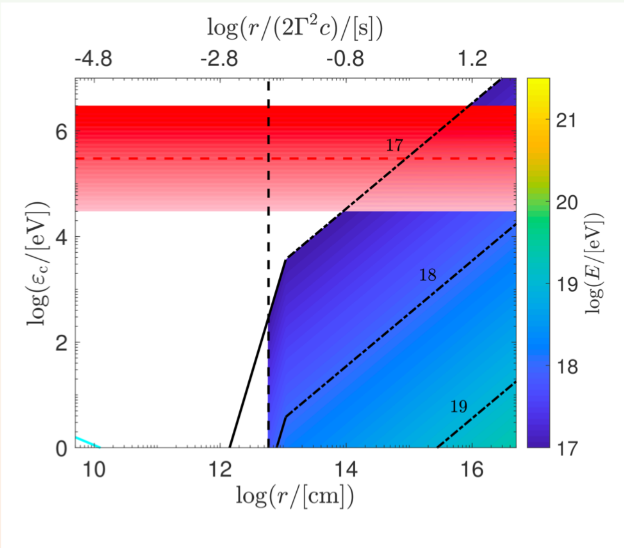
Samuelsson+2020

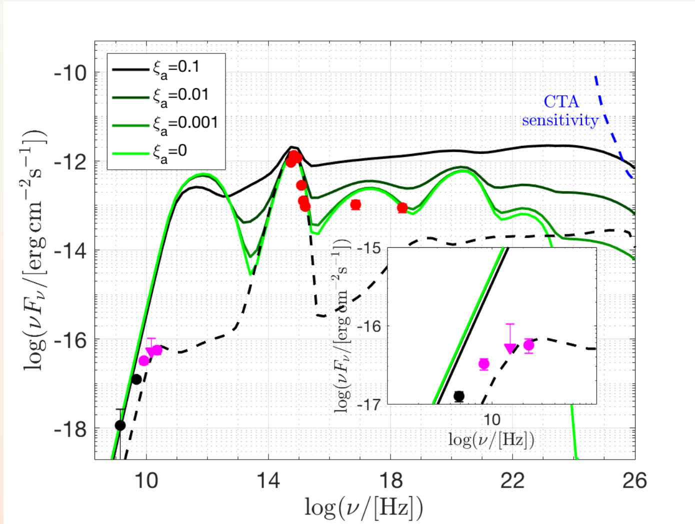
Summary

- **Using standard parameters, GRBs – including llGRBs – cannot be the main sources of UHECRs.**

Either:

- **Fast cooling → inconsistent low energy spectral slope**
- **Small fraction of acc. electrons → bright emission from thermal population**





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