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CENTER FOR ADVANCED STUDIES
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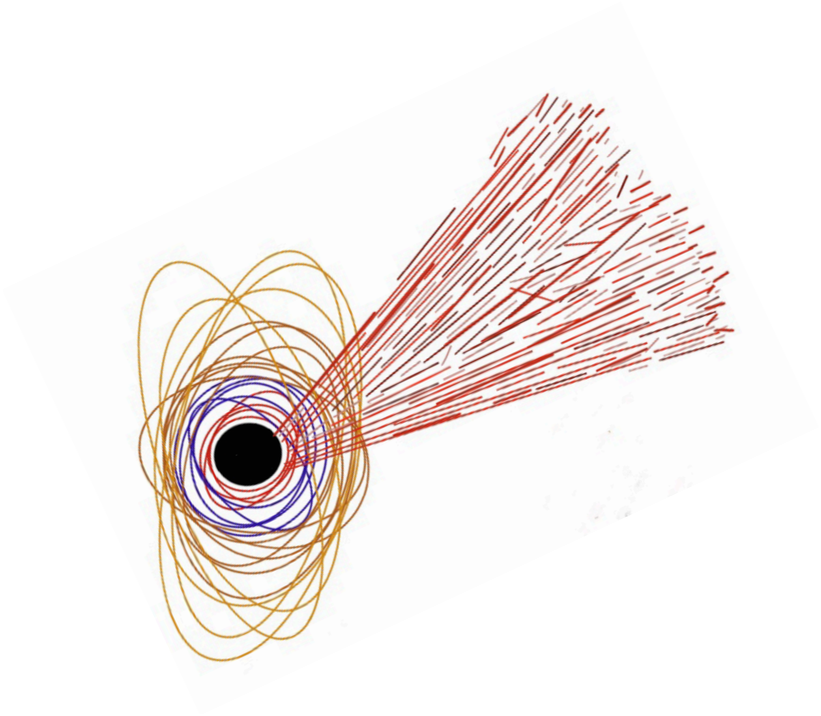
GW group

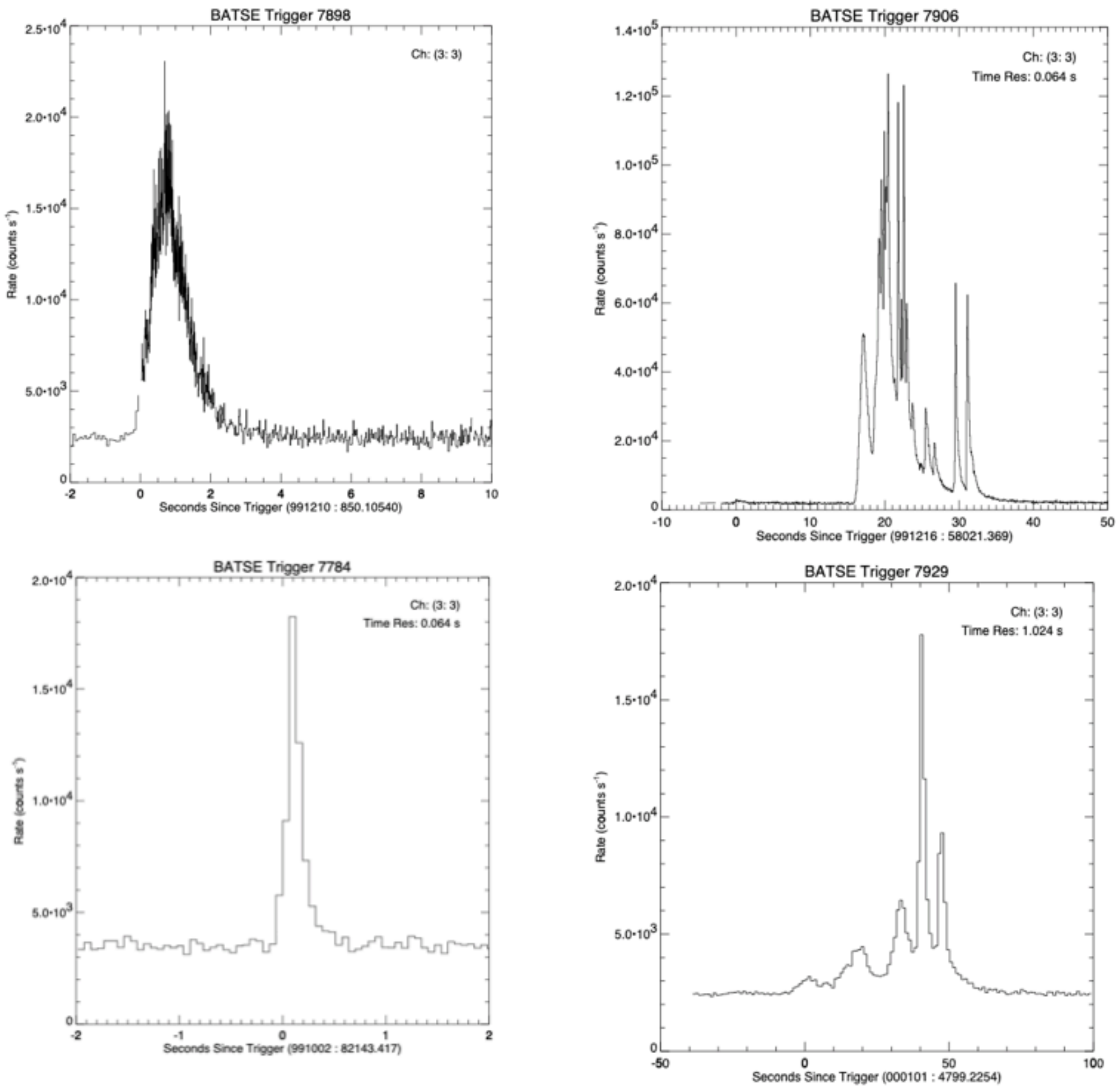
Physics of the GRB prompt emission



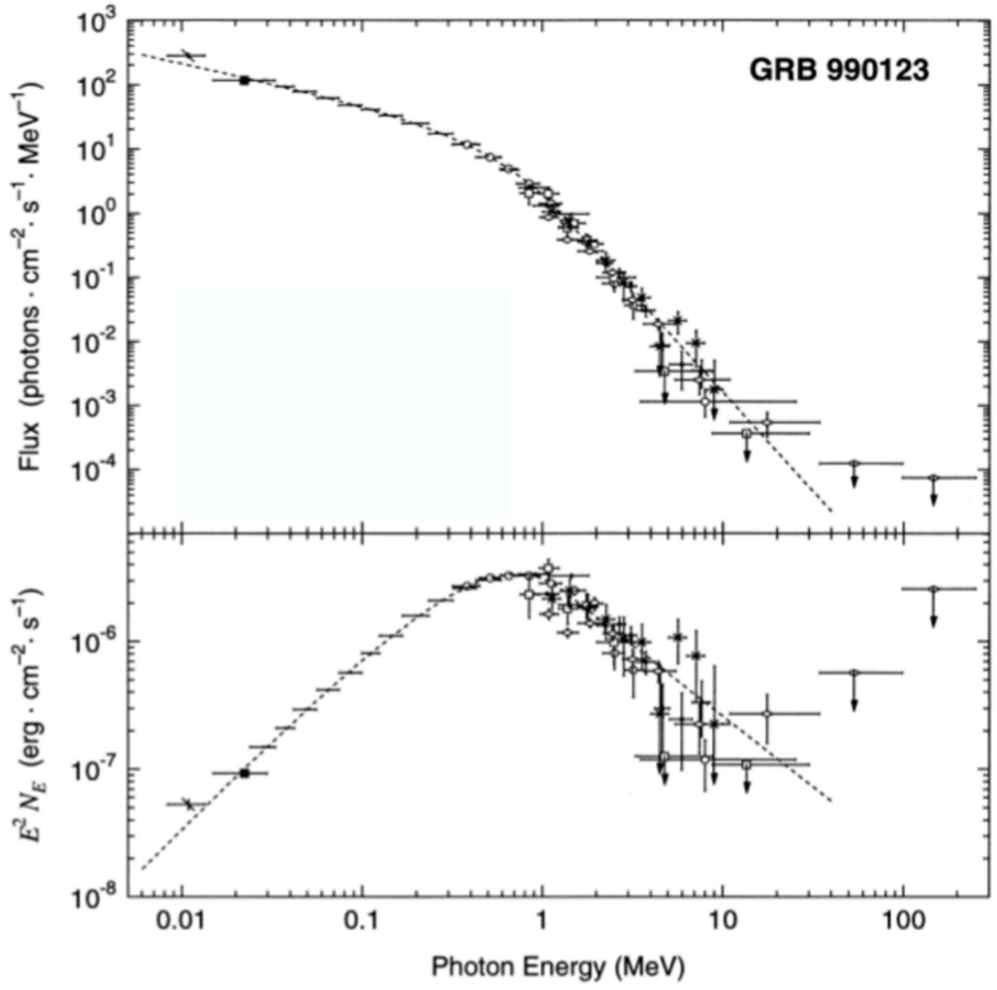
Gor Oganesyan

12 September 2022
V Congresso Nazionale GRB
Trieste

prompt emission



[random BATSE GRBs]



[Briggs et al. 1999]

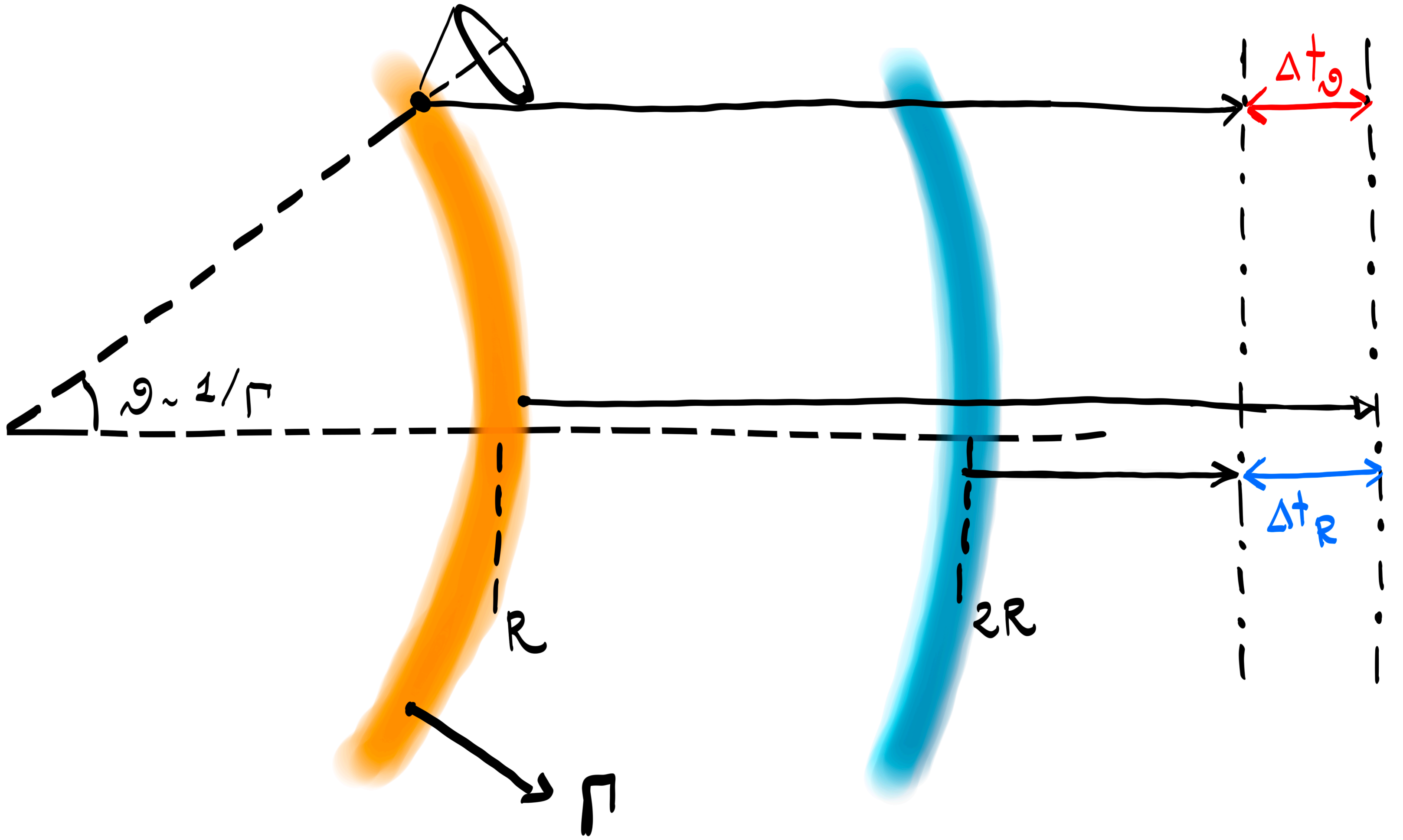
band 10 keV - 10 MeV

total duration 0.1 s - 1000s

variability 0.01-1 s

total energy 1E51-1E54 erg

1st argument : Timing

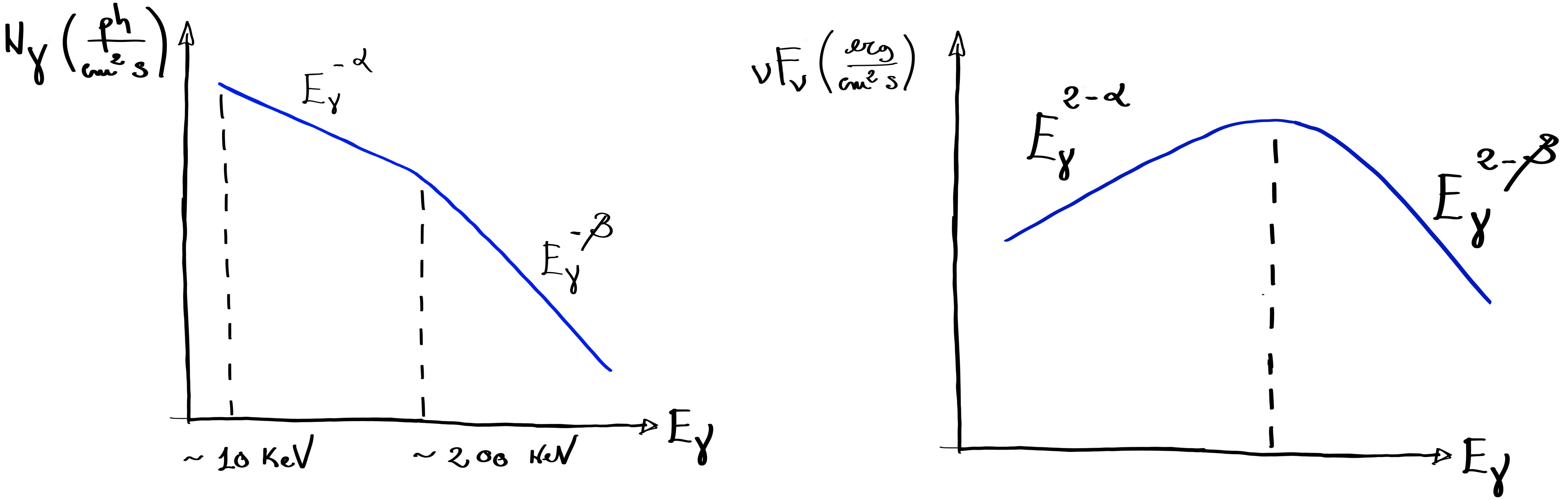


$$\delta T/T << 1$$

[Sari & Piran 1997]

[sketch by S. Ronchini]

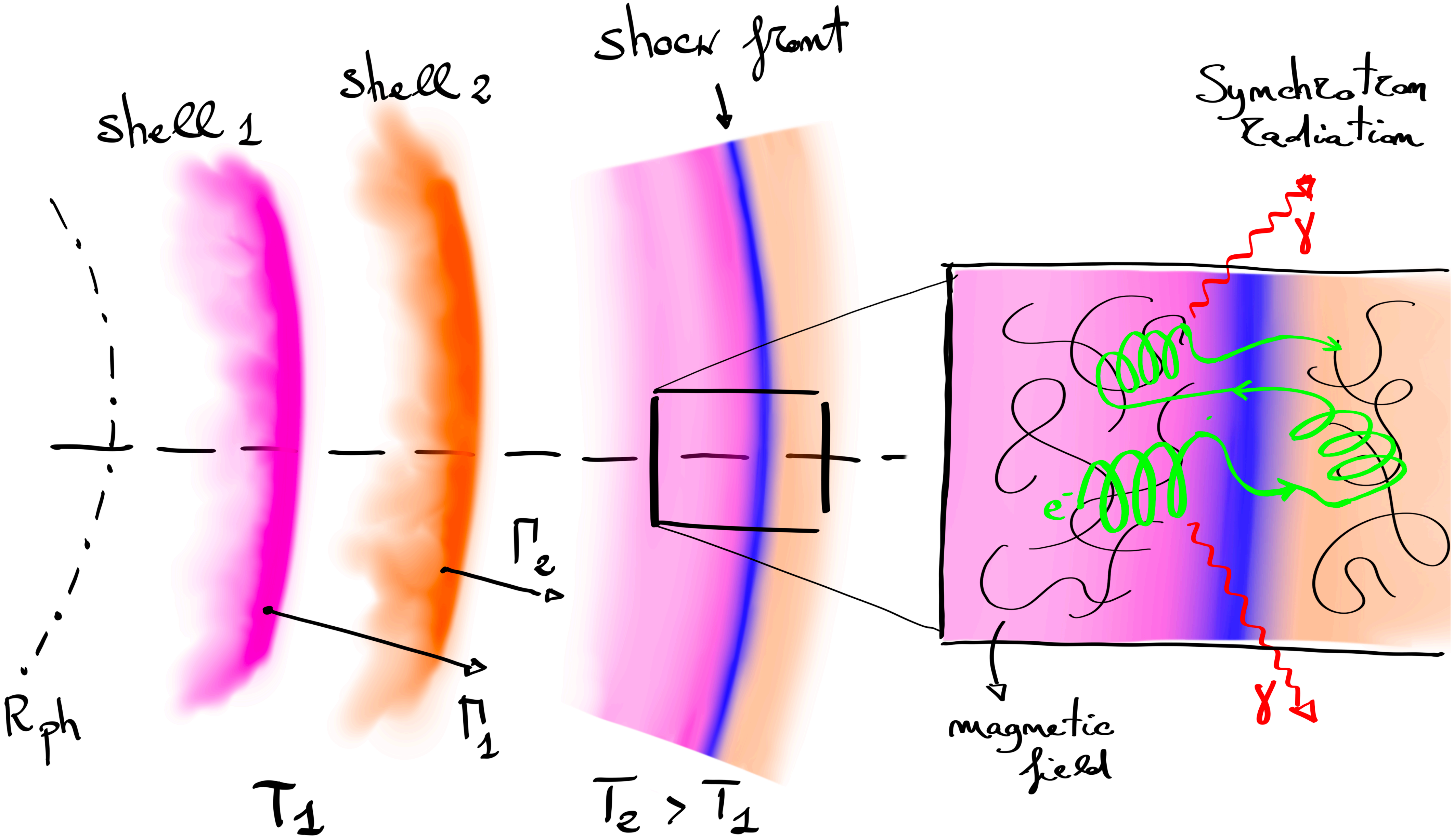
2nd argument : Spectra



Non-thermal spectra

[sketch by S. Ronchini]

The Internal Shocks model



[Narayan et al. 1992, Rees & Mészáros 1994]

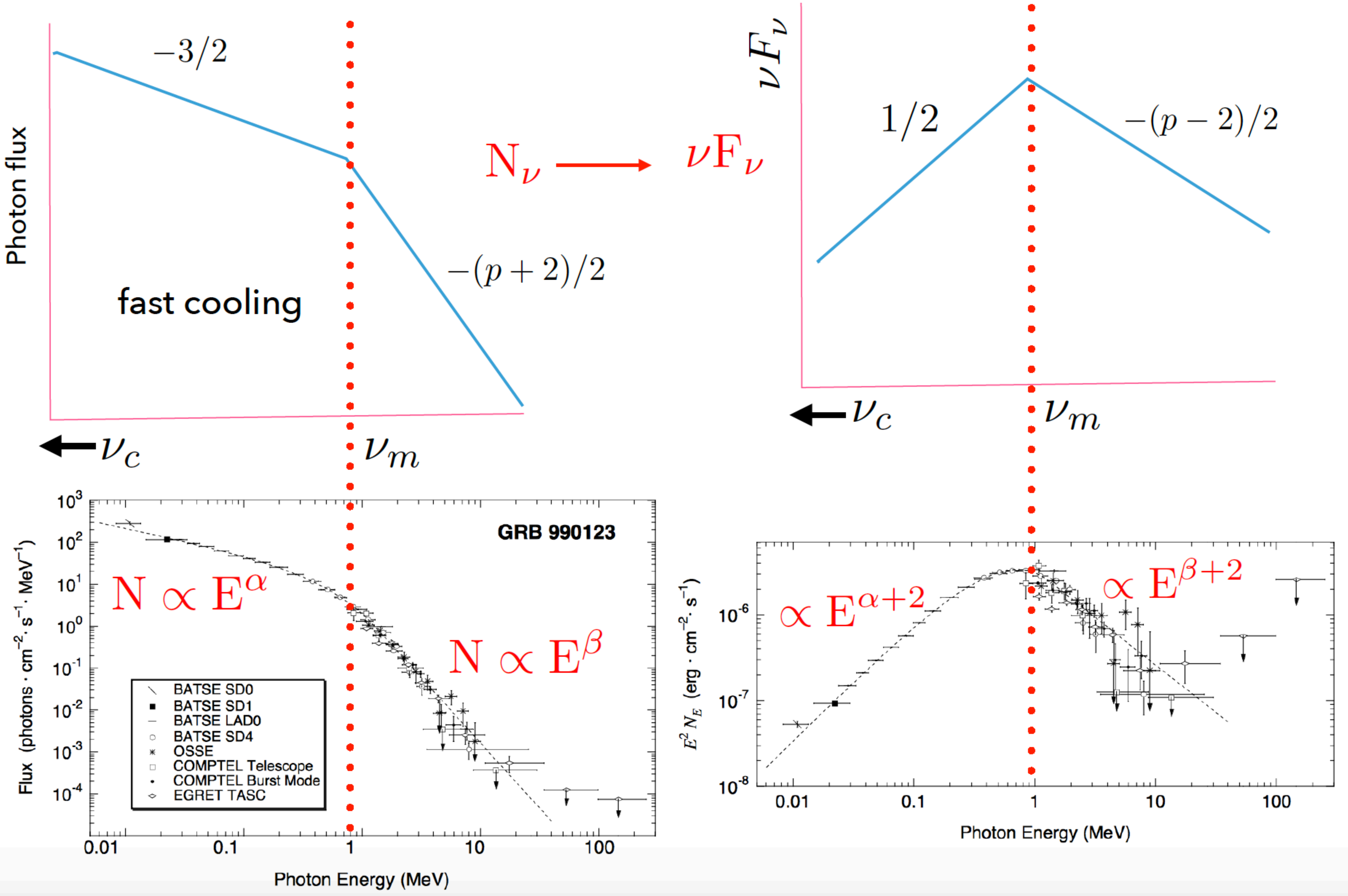
[sketch by S. Ronchini]

The Internal Shocks model

$$t_c = \frac{\gamma m_e c^2}{P_{syn}} \frac{1+z}{\Gamma} \sim 1.1 \times 10^{-5} \frac{\epsilon_B^3 \Gamma_2}{E^2_{2,peak[keV]}(1+z)} s << t_{obs}$$

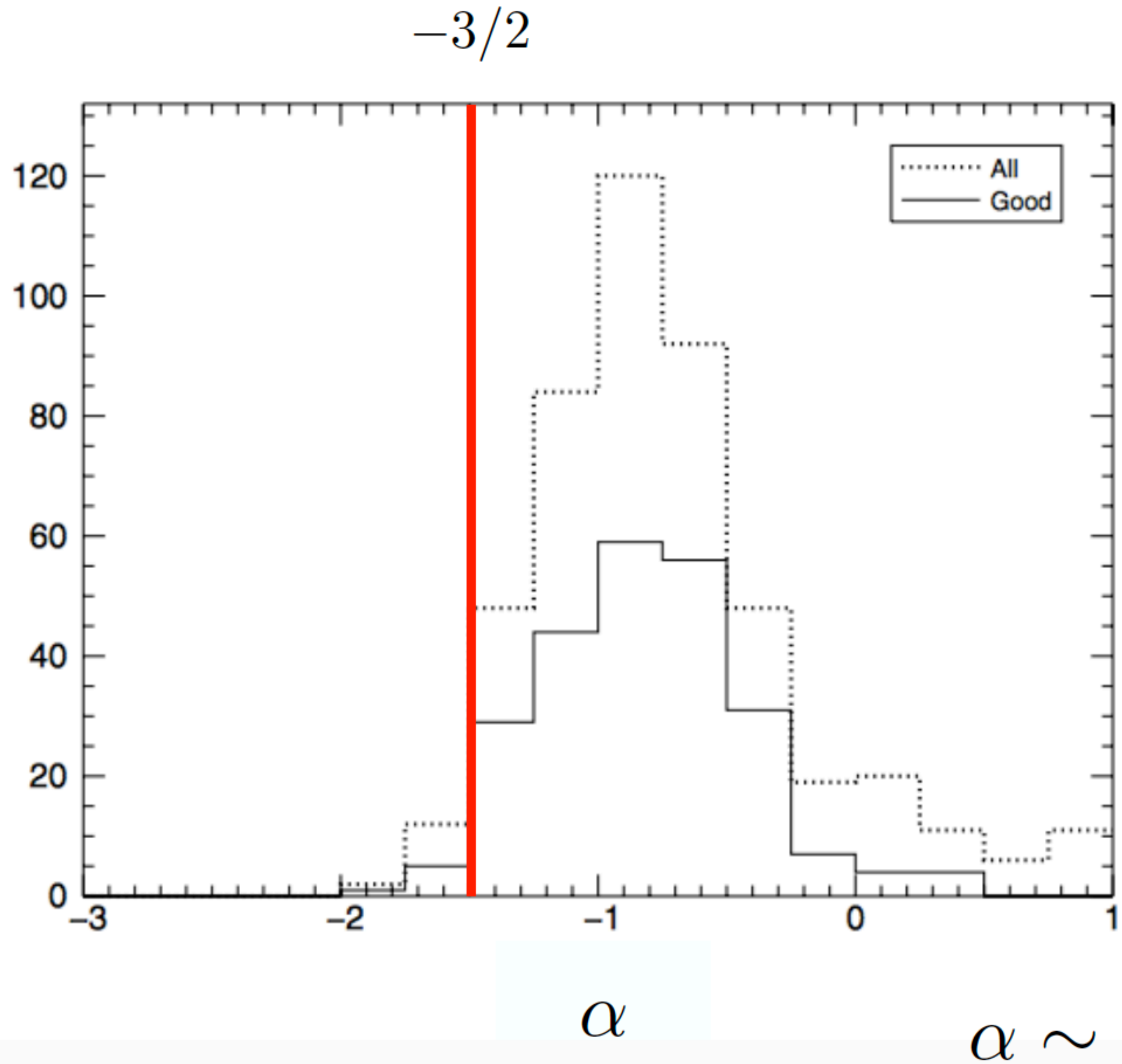
[Ghisellini, Celotti & Lazzati 2000]

Model vs Data



Model vs Data

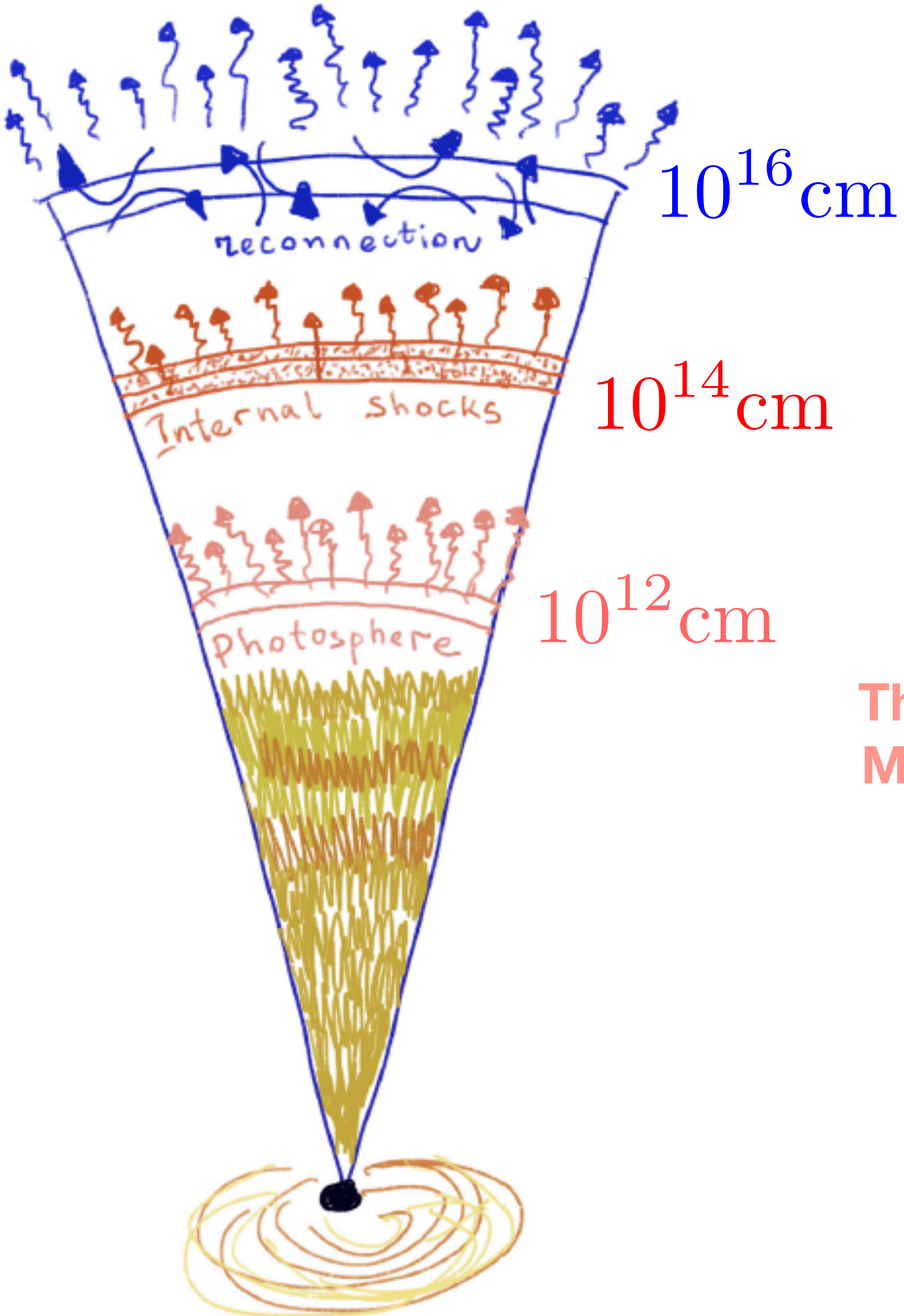
most prompt spectra, in the literature, are not consistent with fast cooling synchrotron spectrum



$\alpha \sim -1$ $\beta \sim -2.5$

2nd Fermi catalog

the GRB production mystery

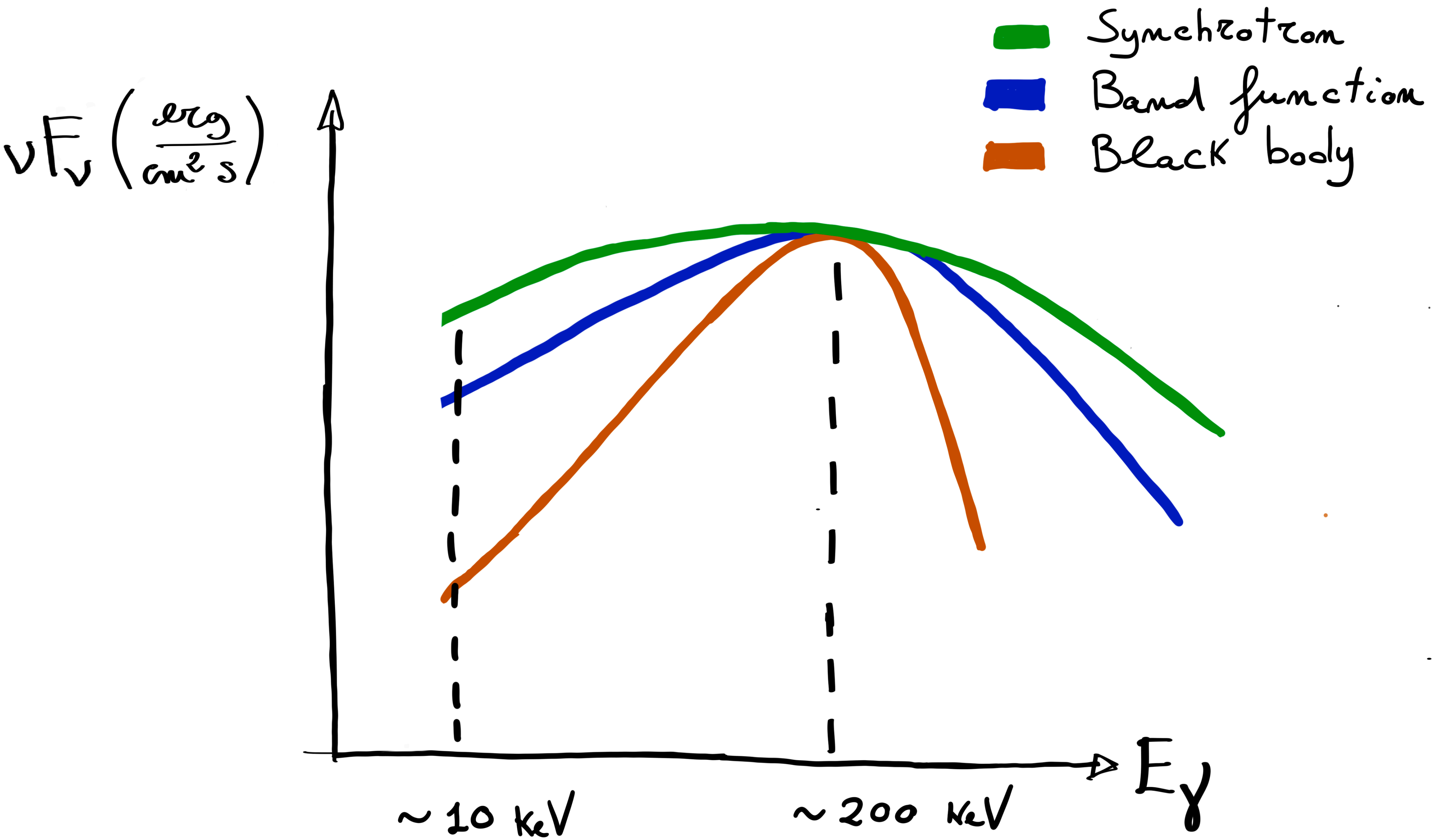


Drenkhahn & Spruit 2002,
Lyutikov & Blandford 2003,
Zhang & Yan 2011

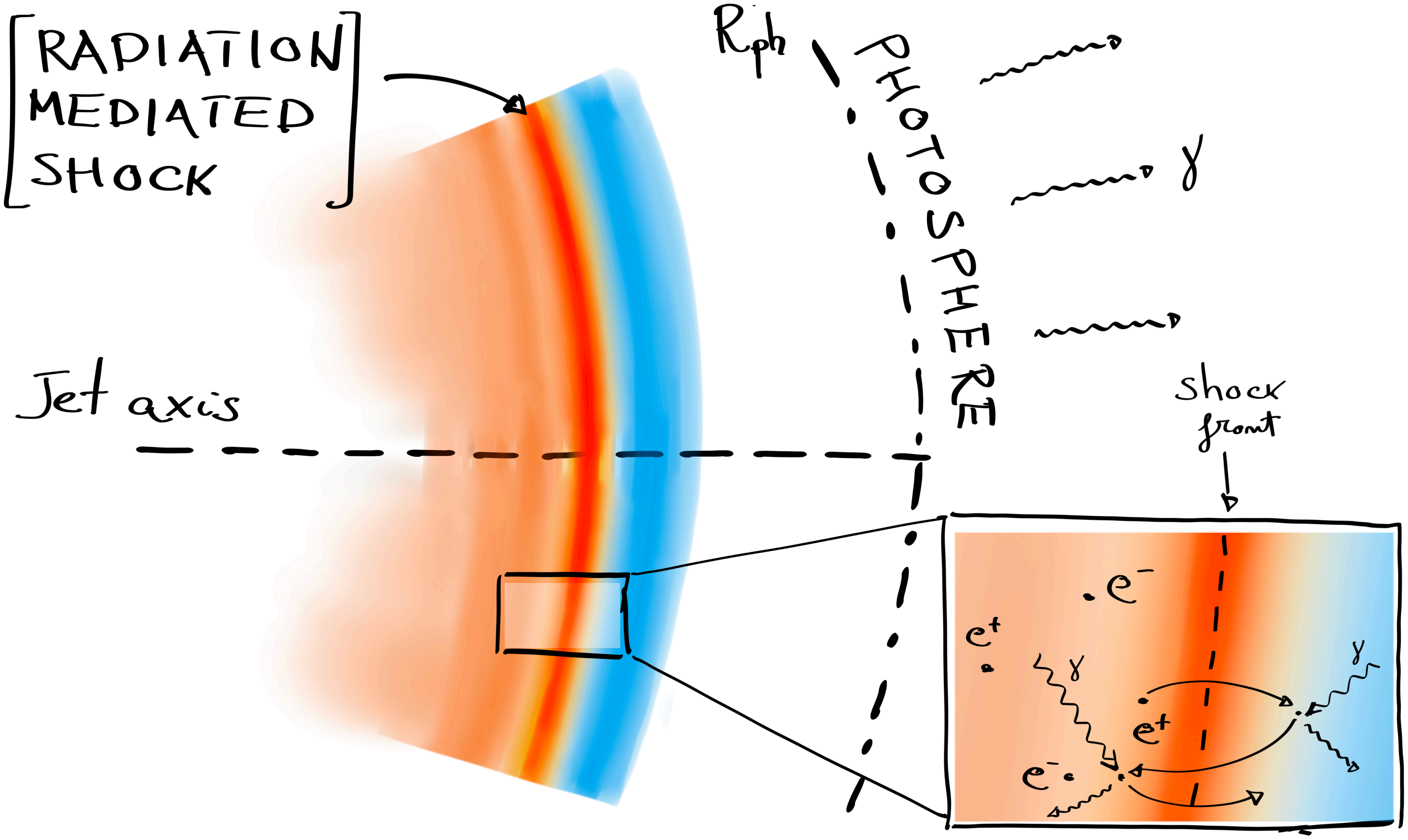
Narayan et al. 1992, Rees & Mészáros 1994

Thomson 1994, Ghisellini & Celotti 1999,
Mészáros & Rees 2000, Pe’er et al. 2006

Make Synchrotron Harder vs Play with the Thermal emission



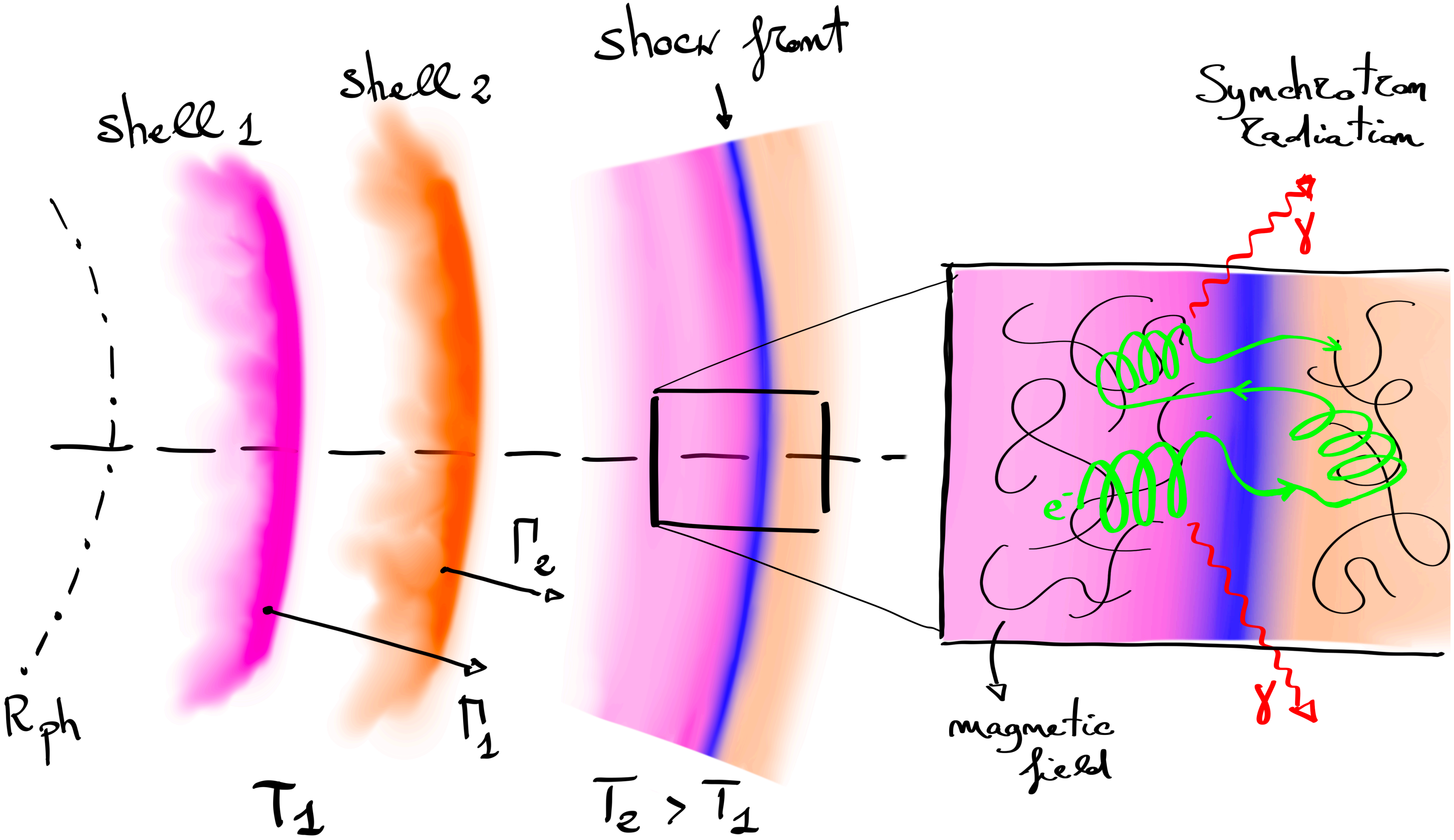
[sketch by S. Ronchini]



[Levinson & Nakar 2020 for a recent review]

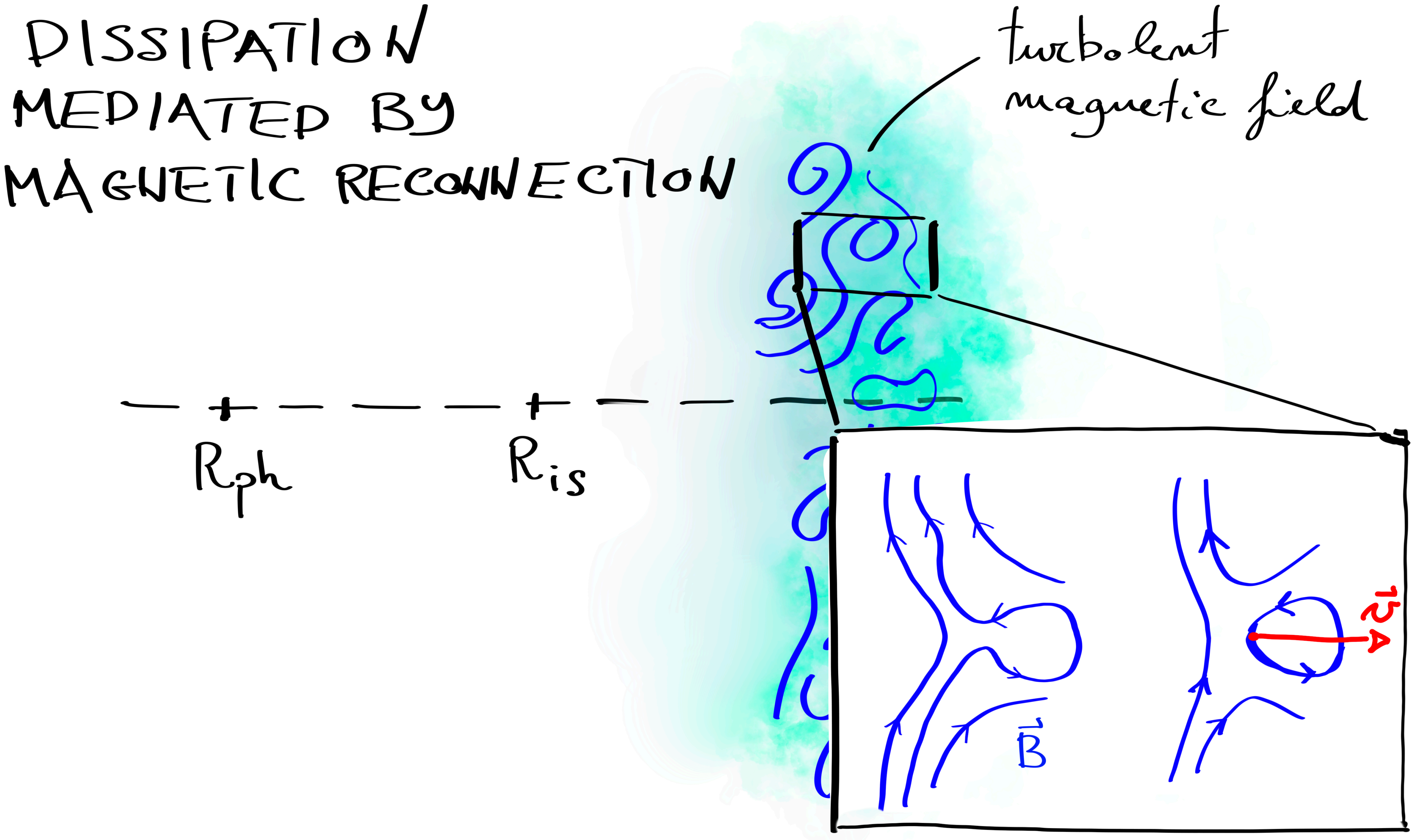
[sketch by S. Ronchini]

The IS model



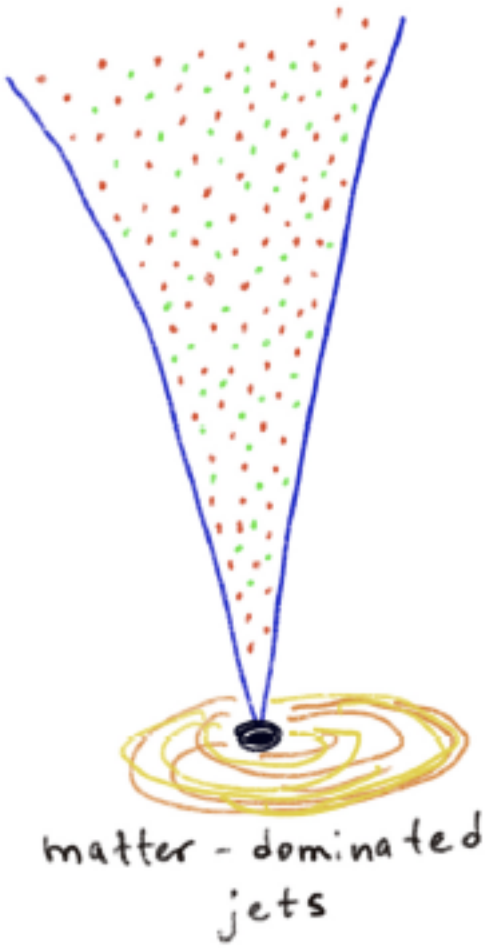
[sketch by S. Ronchini]

Reconnection models

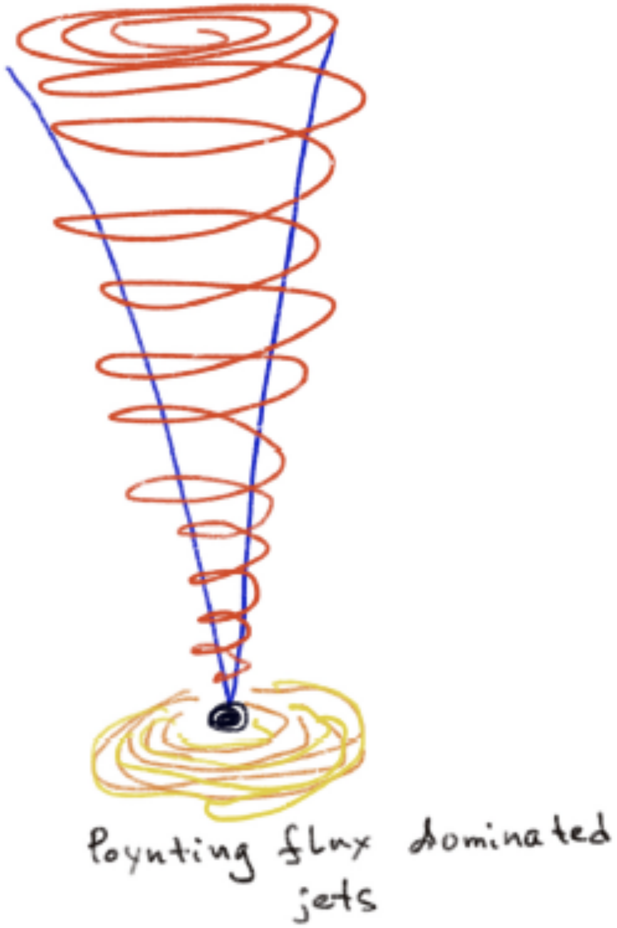


[sketch by S. Ronchini]

the GRB jet mystery

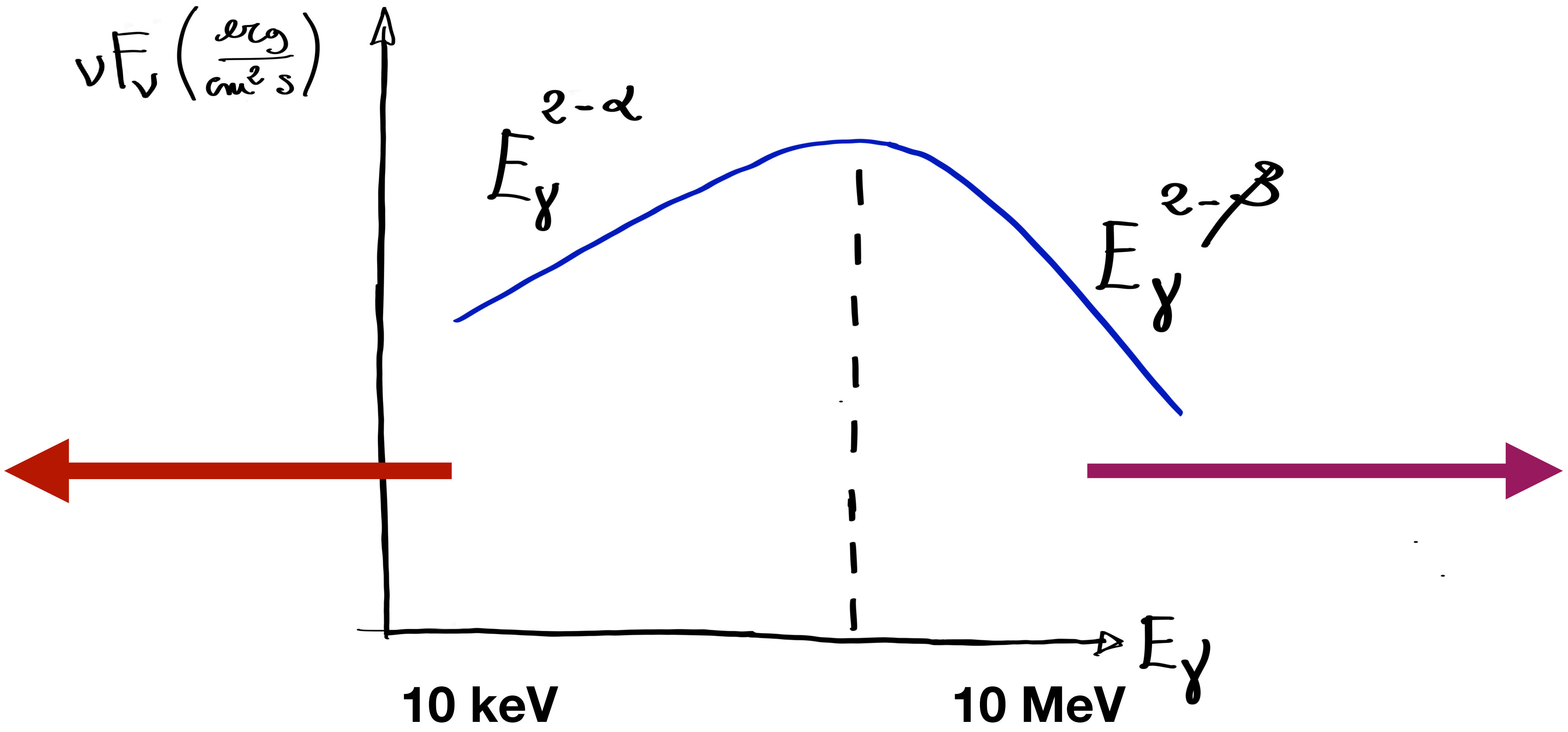


Cavallo & Rees 1978
Paczýnski 1986
Goodman 1986
Shemi & Piran 1990



Usov 1992
Thompson 1994
Mészáros & Rees 1997
Lyutikov & Blandford 2003

Different ways to solve the problem



+ polarisation

[Gill, Kole & Granot 2021 for a recent review]

+ neutrinos

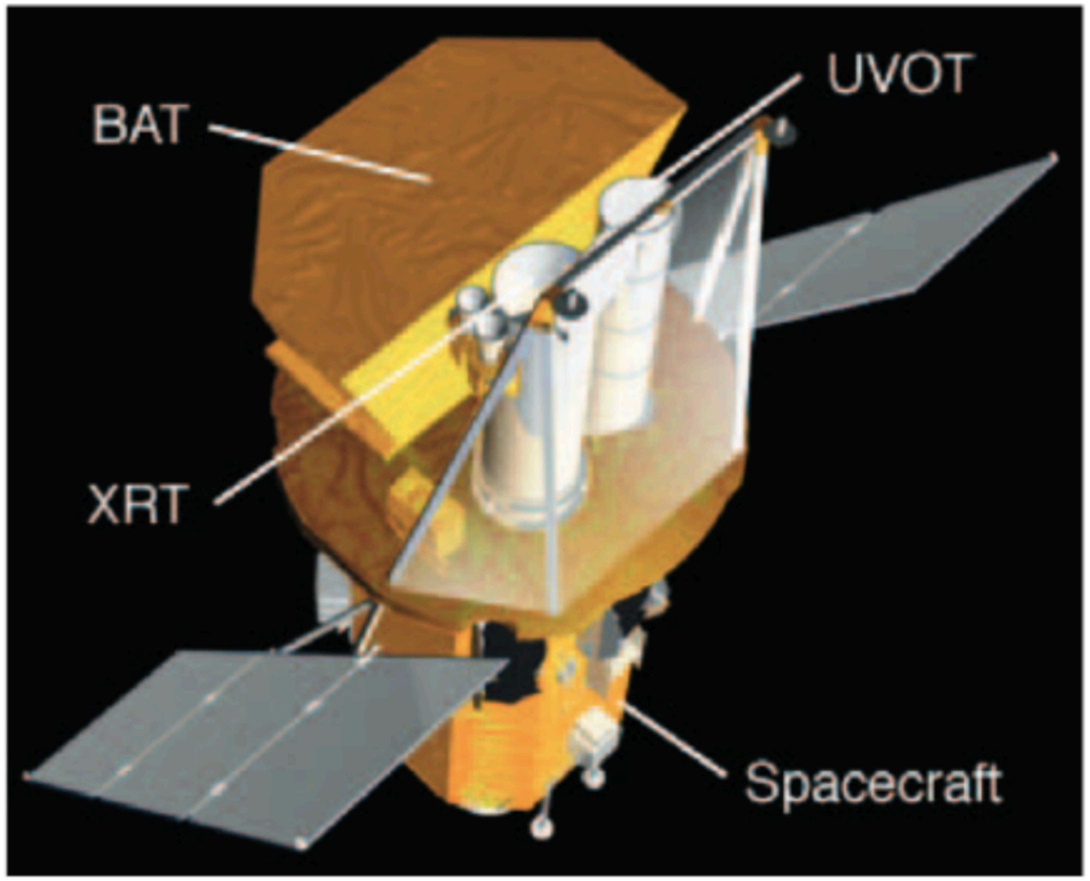
[Pitik, Tamborra & Petropoulou 2021 and Kimura 2022 for recent reviews]

Soft X-rays

15 keV Swift/BAT 150 keV

FOV 1.4 sr

Swift/UVOT



0.5-10 keV

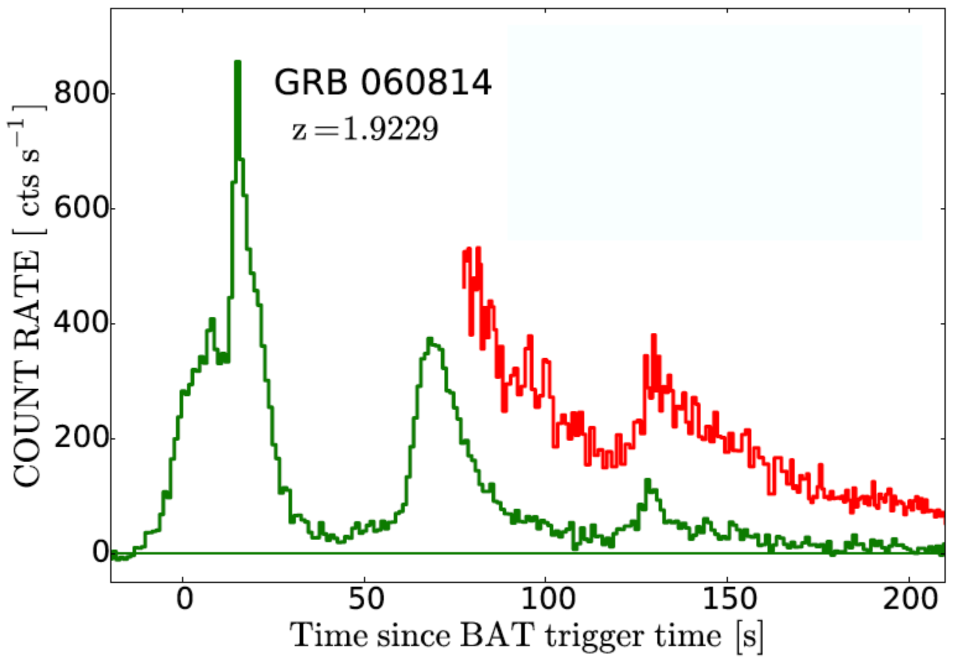
Swift/XRT

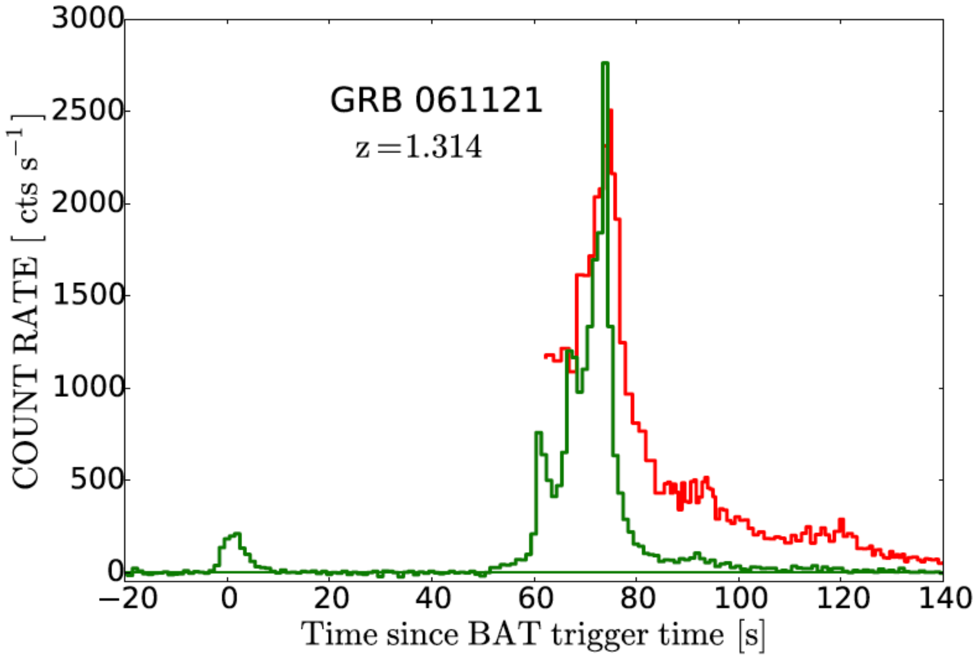
FOV 23.6 arcmin sq

XRT average slewing time ~ 90 s

Soft X-rays

XRT average slewing time ~ 90 s



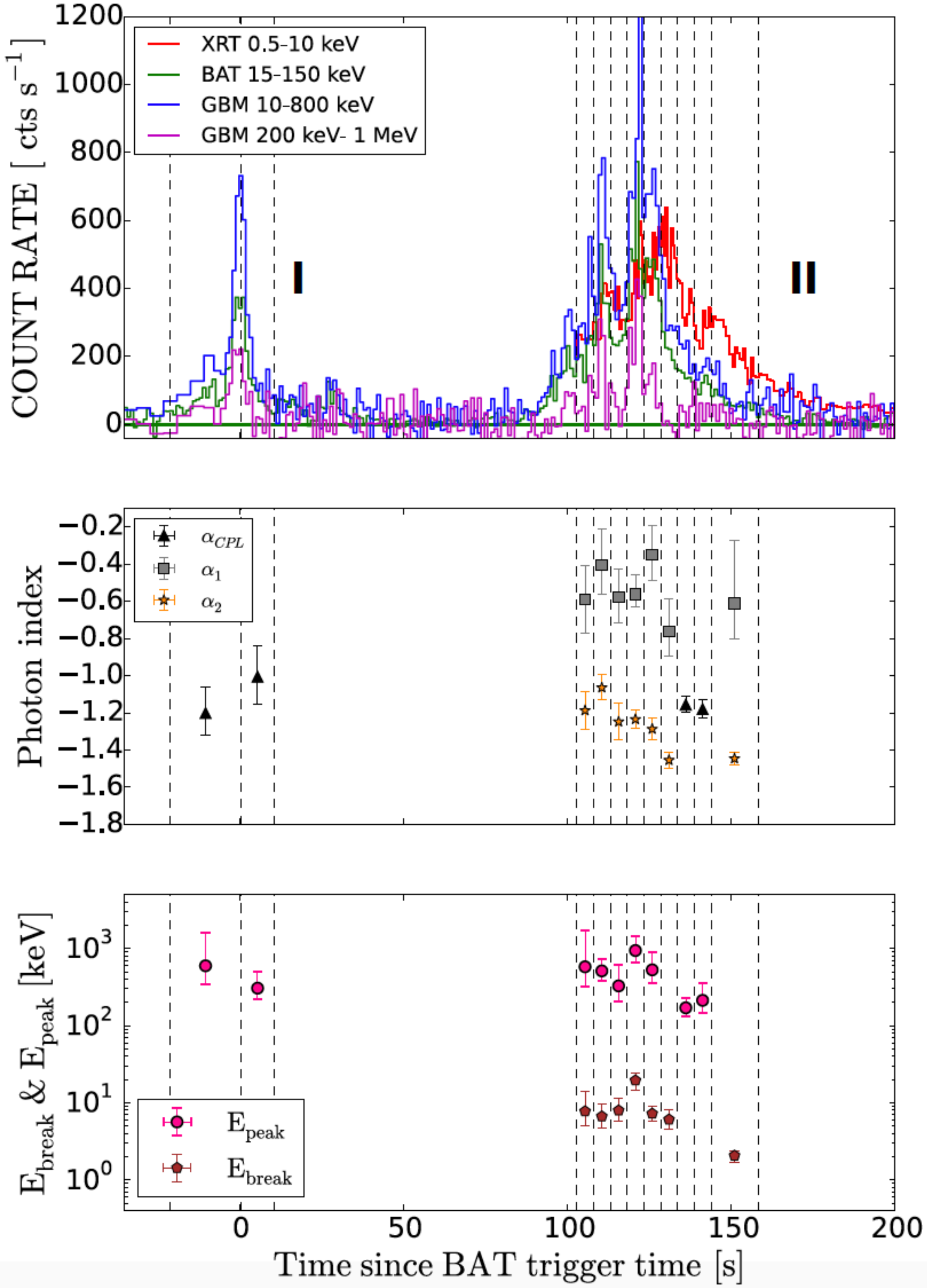


BAT [15-150 keV] + XRT [0.5-10 keV]

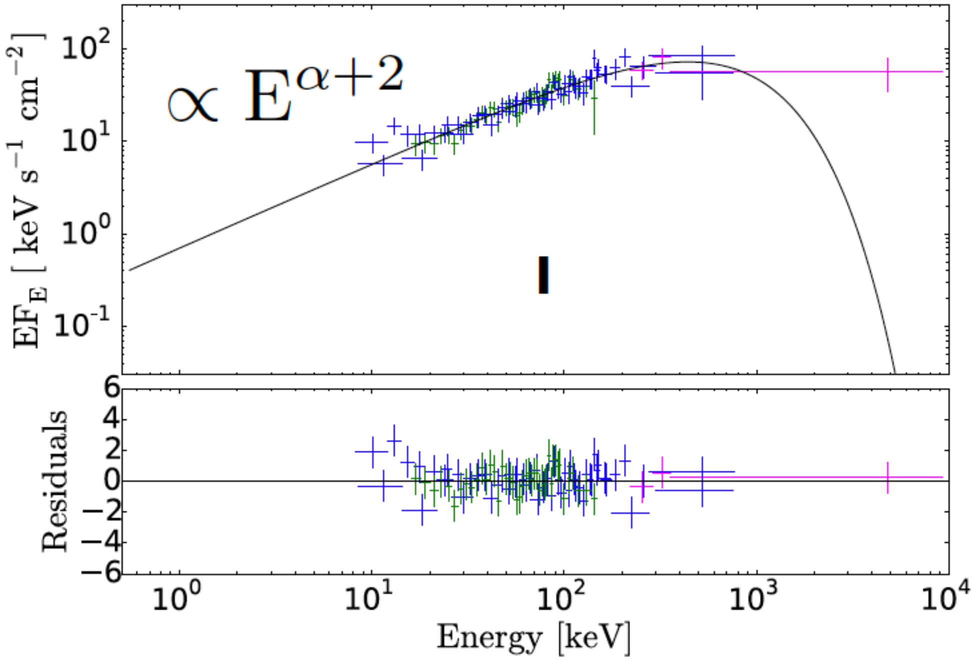
[GO, Nava, Ghirlanda & Celotti 2017; 2018]

Soft X-rays

GRB 140512A

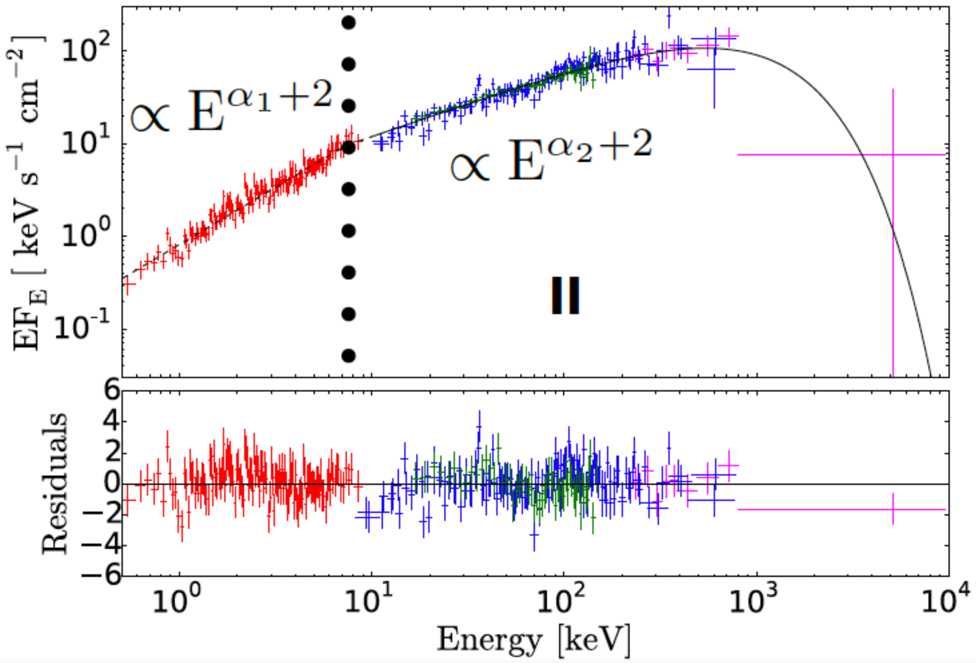


CPL

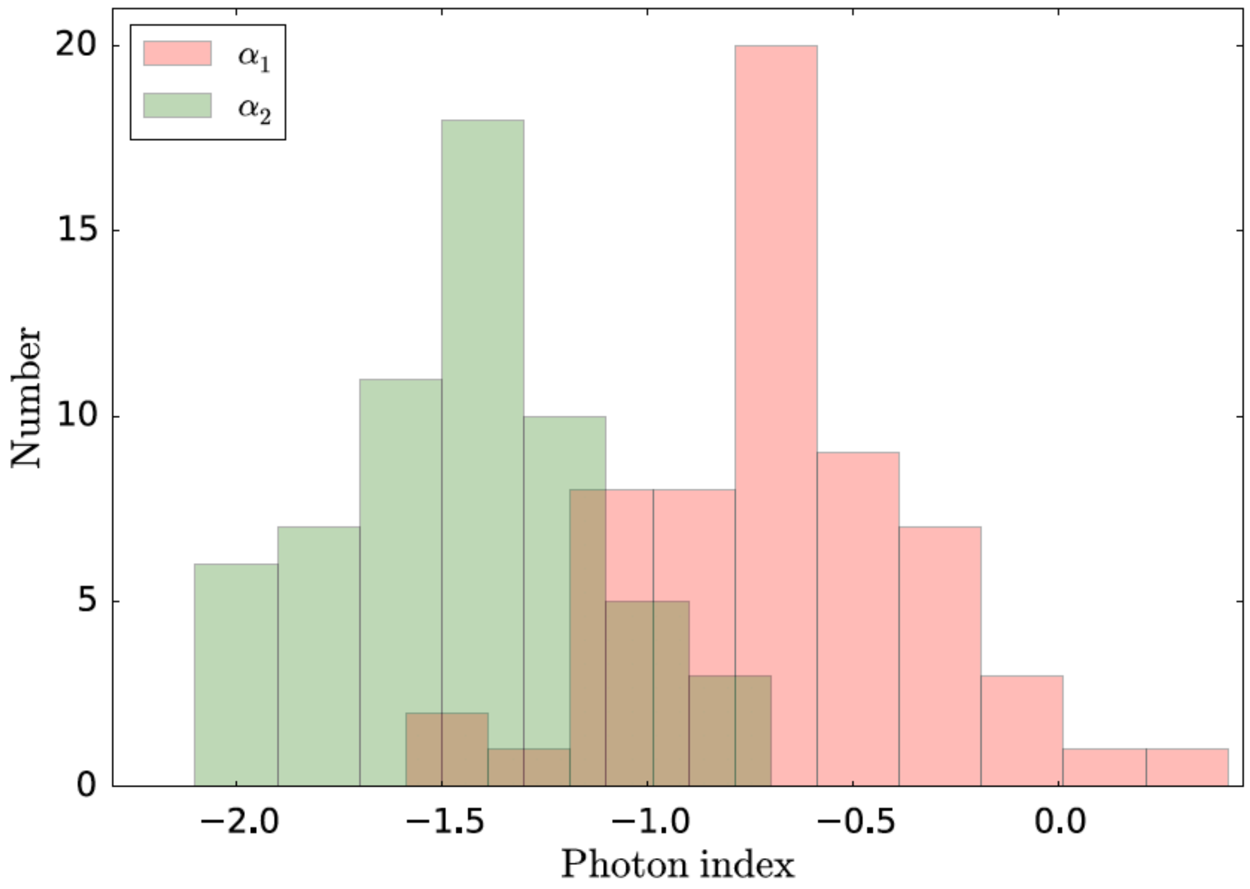


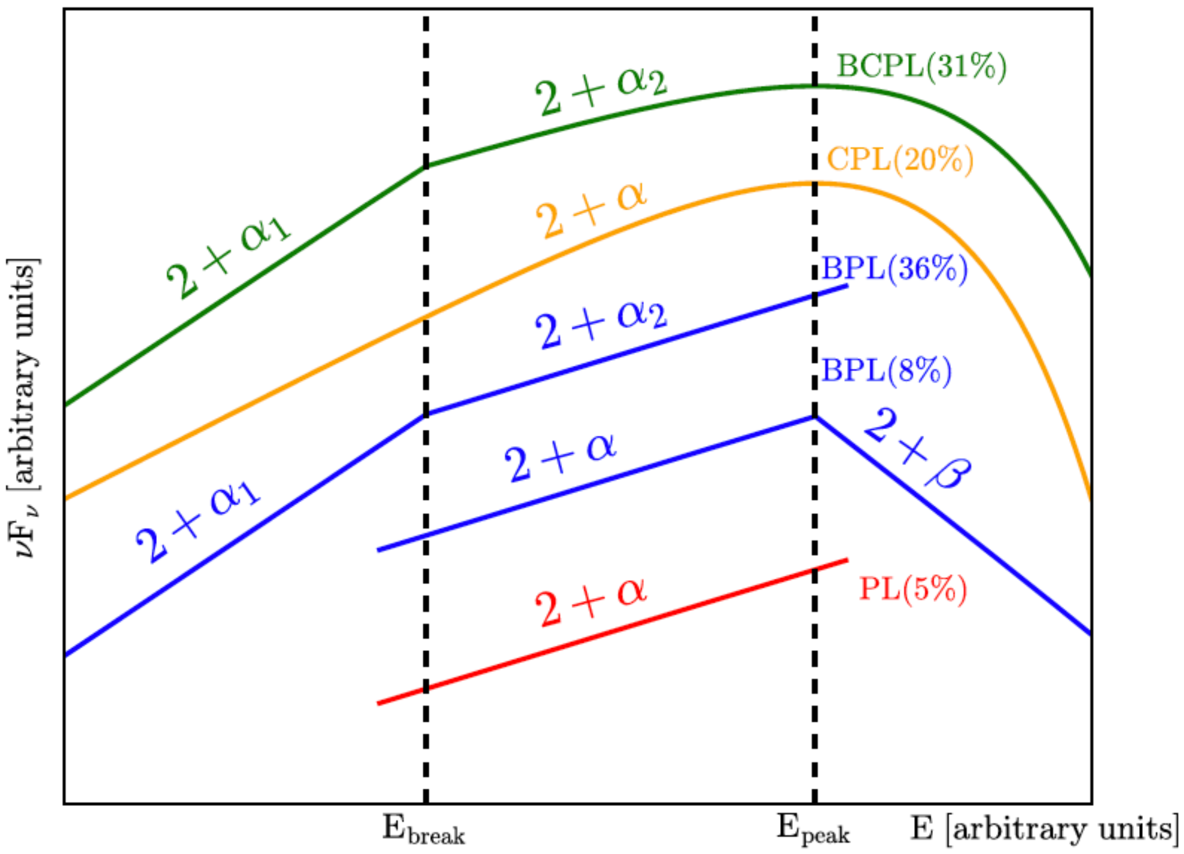
E_{break}

BCPL



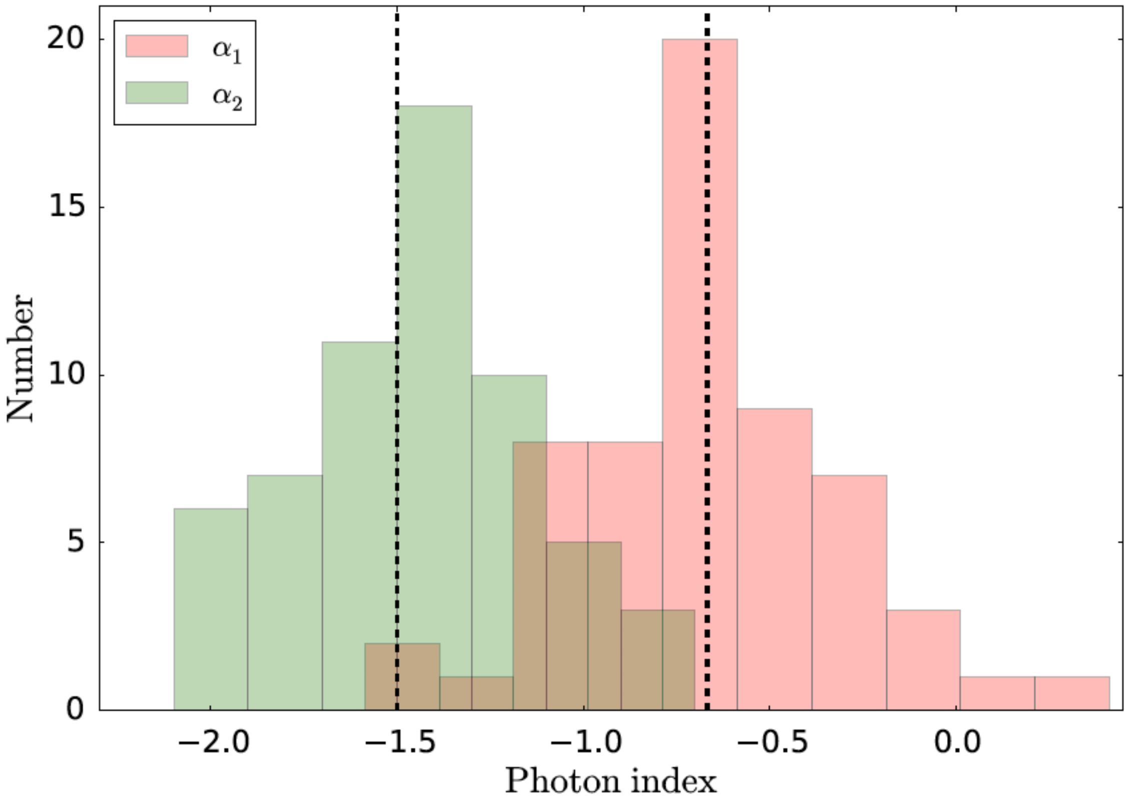
Soft X-rays

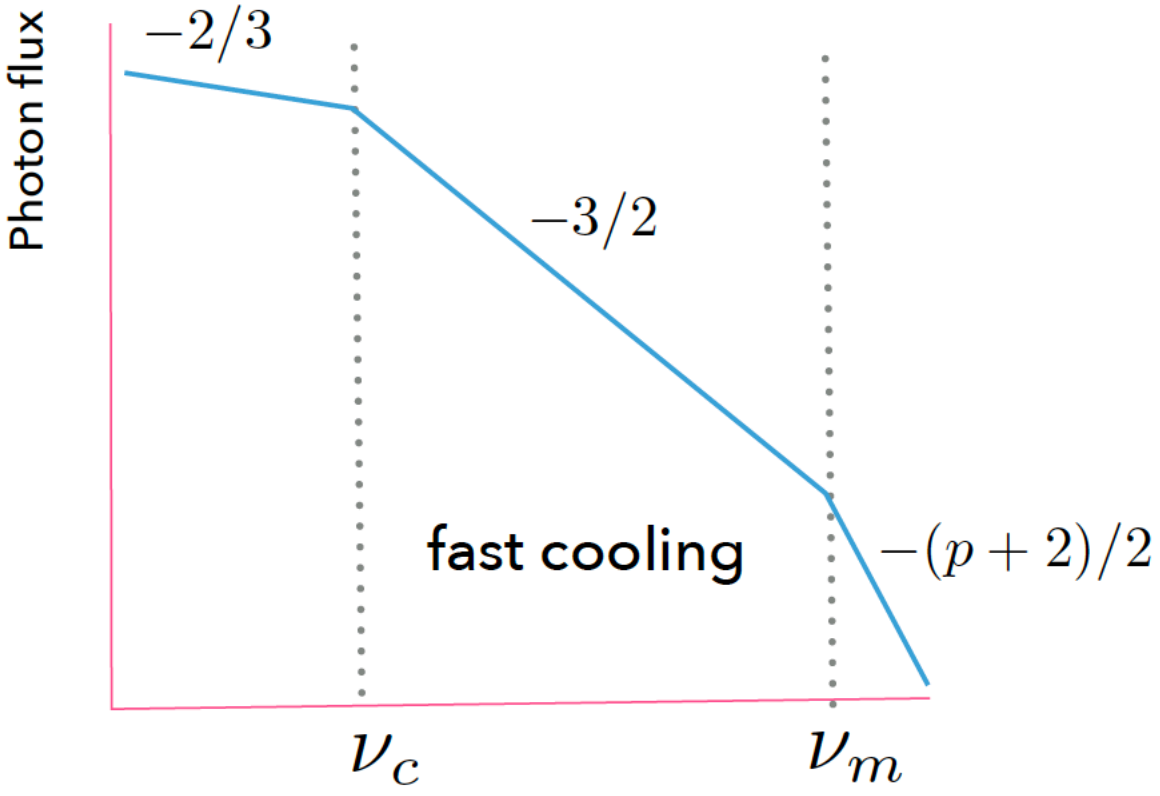




67 % of spectra require a break

Soft X-rays





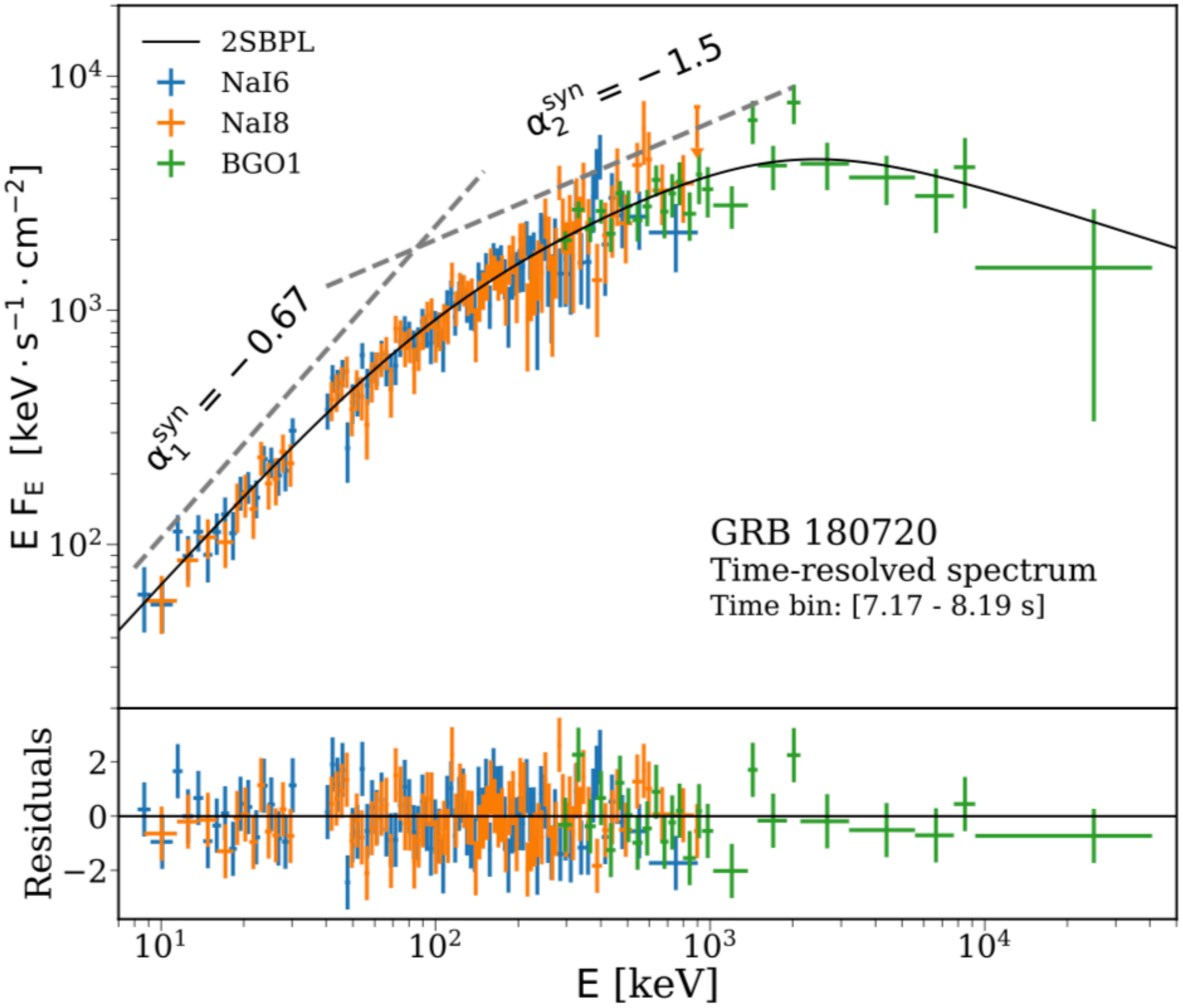
$$\nu_{\rm c} = \nu_{\rm break}$$

consistent with synchrotron spectrum

$$\rm E_{peak}/E_{break} \sim 7 - 175$$

Spectral breaks at hard X-rays

10 short and 10 long GRBs



Fermi GBM

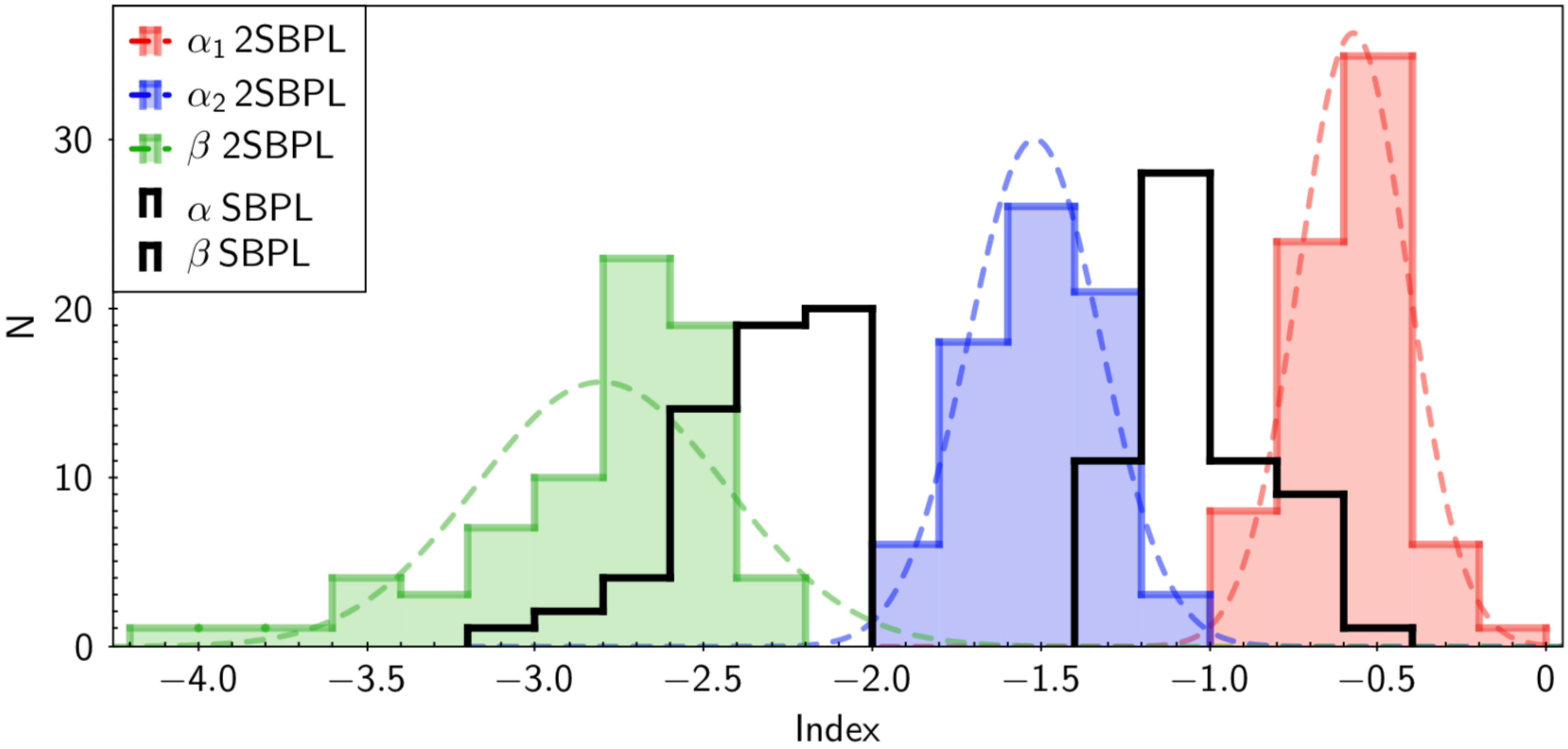
8 keV - 100 MeV

breaks for 8/10 long GRBs

no breaks for short GRBs

[Ravasio et al. 2018; Ravasio, Ghirlanda, Nava & Ghisellini 2019]

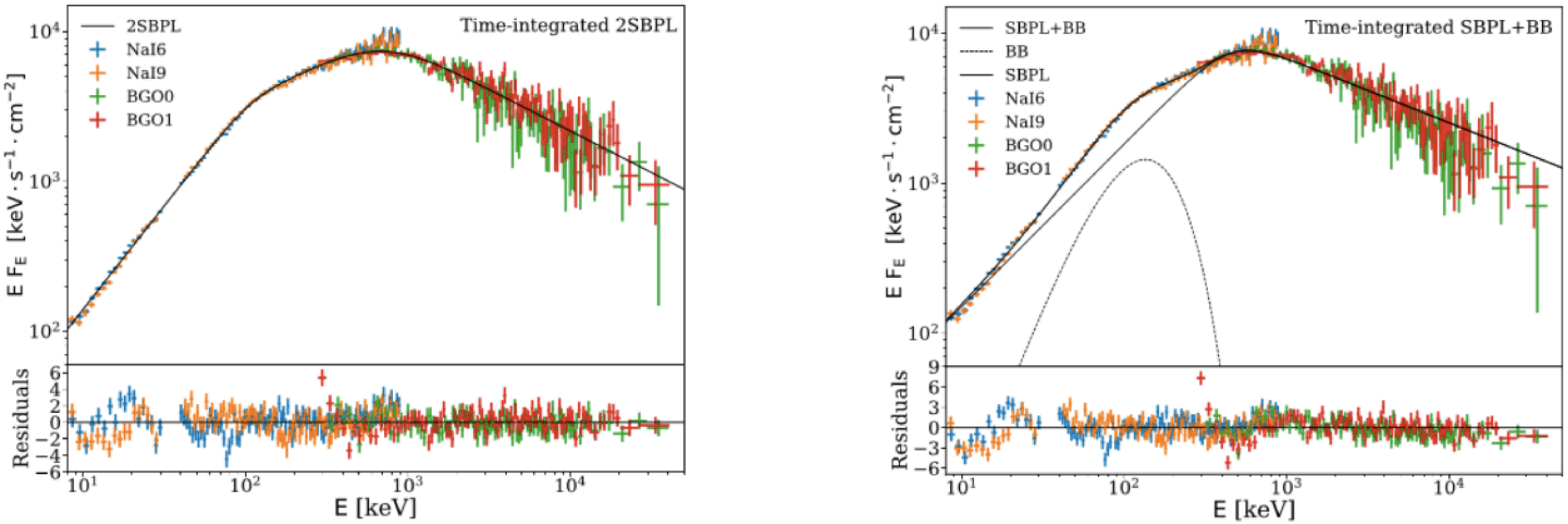
Spectral breaks at hard X-rays



[Ravasio, Ghirlanda, Nava & Ghisellini 2019]

Break vs BB component

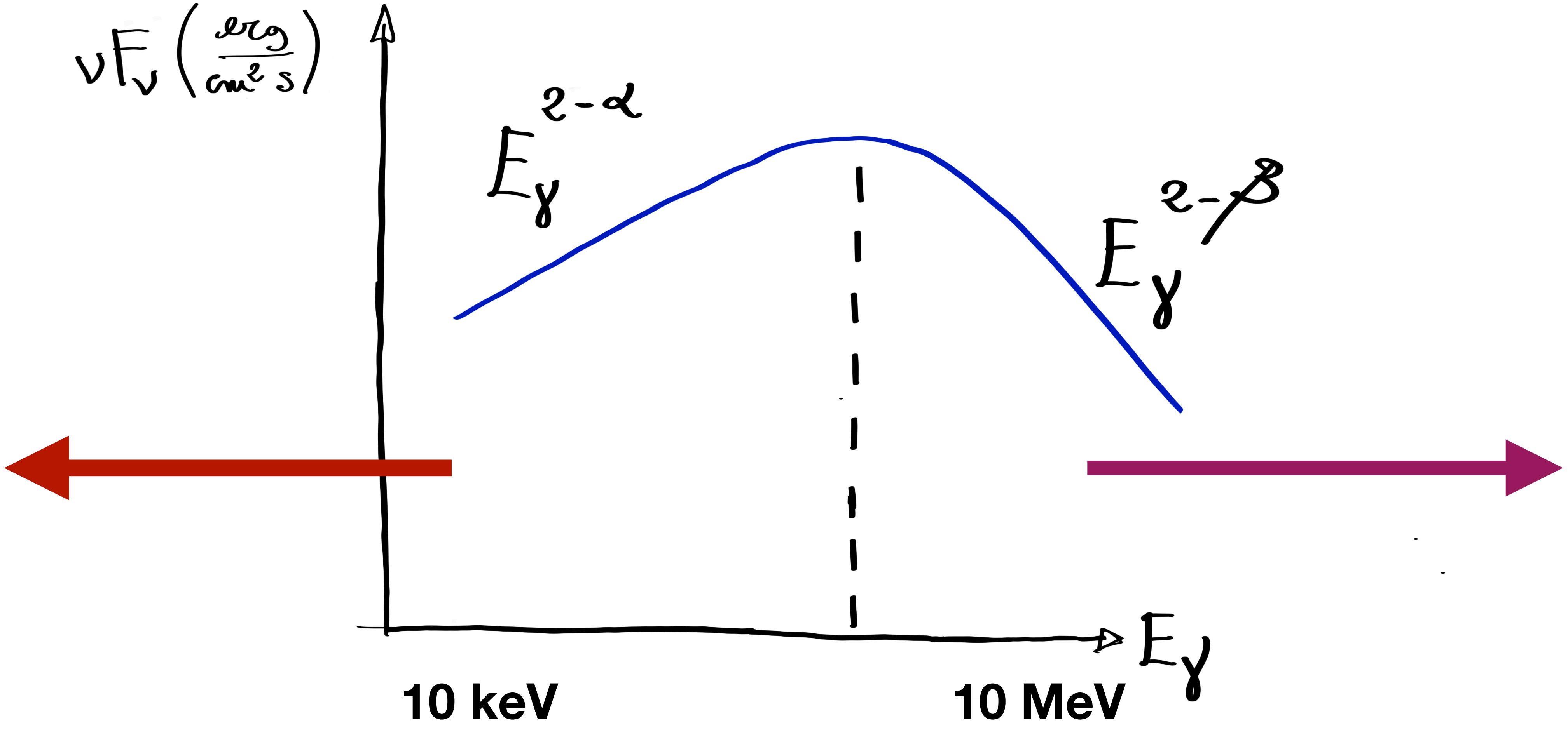
Empirical models vs Physical models



BRIGHT FERMI GRB 160625B

[Ravasio et al. 2018]

Different ways to solve the problem



+ polarisation

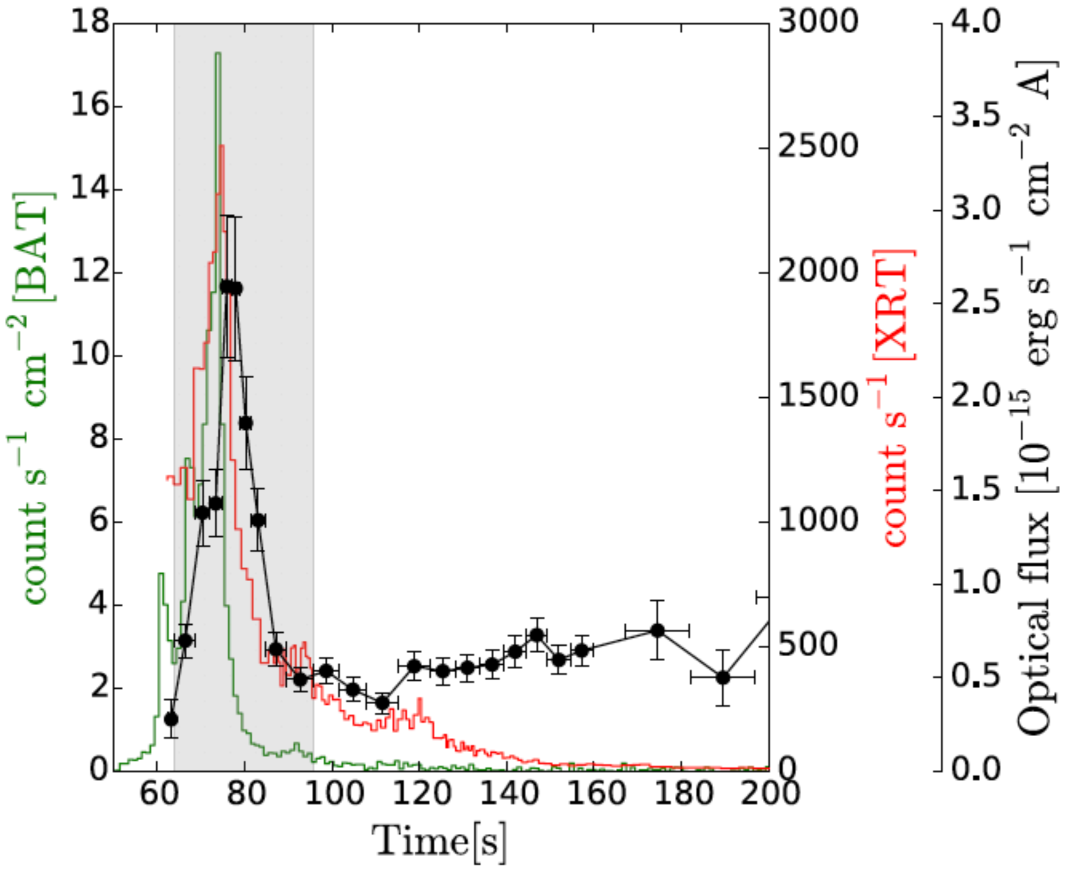
[Gill, Kole & Granot 2021 for a recent review]

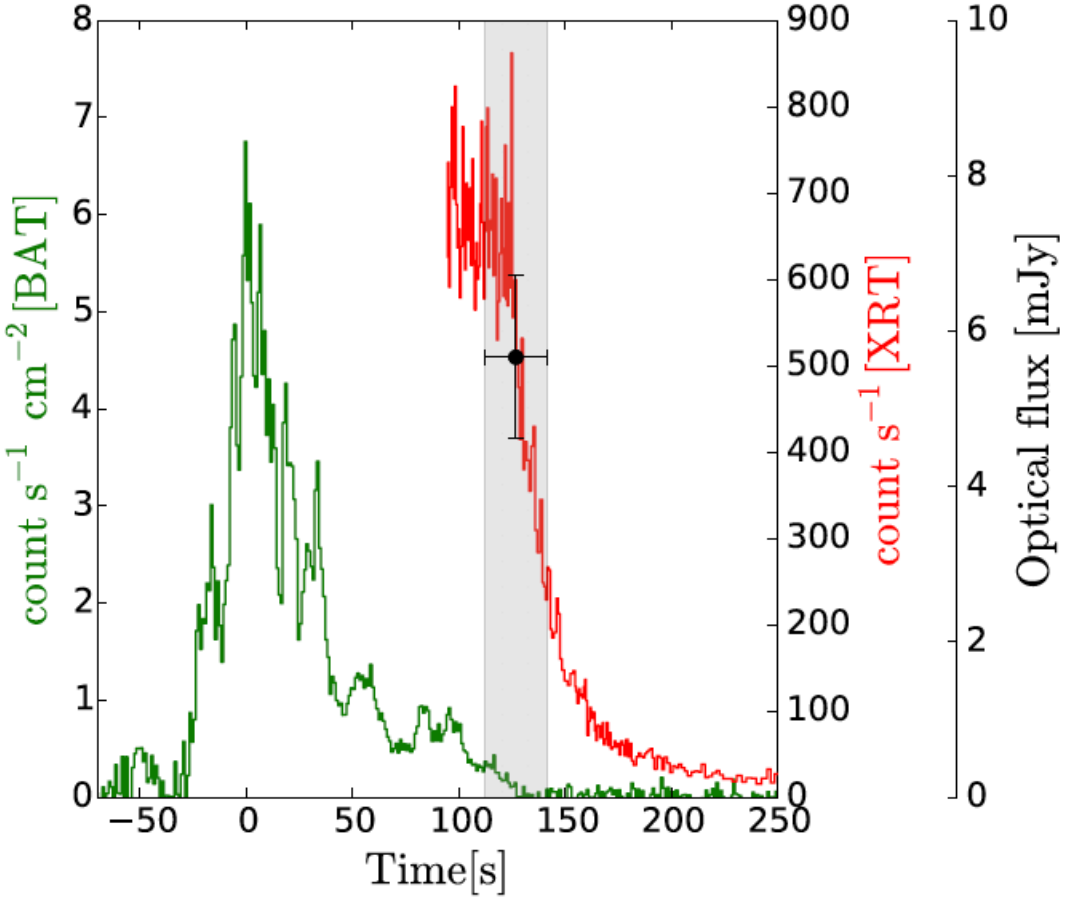
+ neutrinos

[Pitik, Tamborra & Petropoulou 2021 and Kimura 2022 for recent reviews]

Optical emission

21 GRBS (OUT OF 34), 56 TIME-RESOLVED SPECTRA





BAT [15-150 keV] + XRT [0.5-10 keV]+optical data

[Oganesyan et al. 2019]

Optical emission

Synchrotron model for non-thermal distribution of particles
(slow- and fast- cooling)

$$\mathrm{E_c},\ \gamma_\mathrm{m}/\gamma_\mathrm{c},\ \mathrm{norm}$$

↓

Fit to XRT+BAT(+GBM) spectra

(for the time-slices of optical observations)

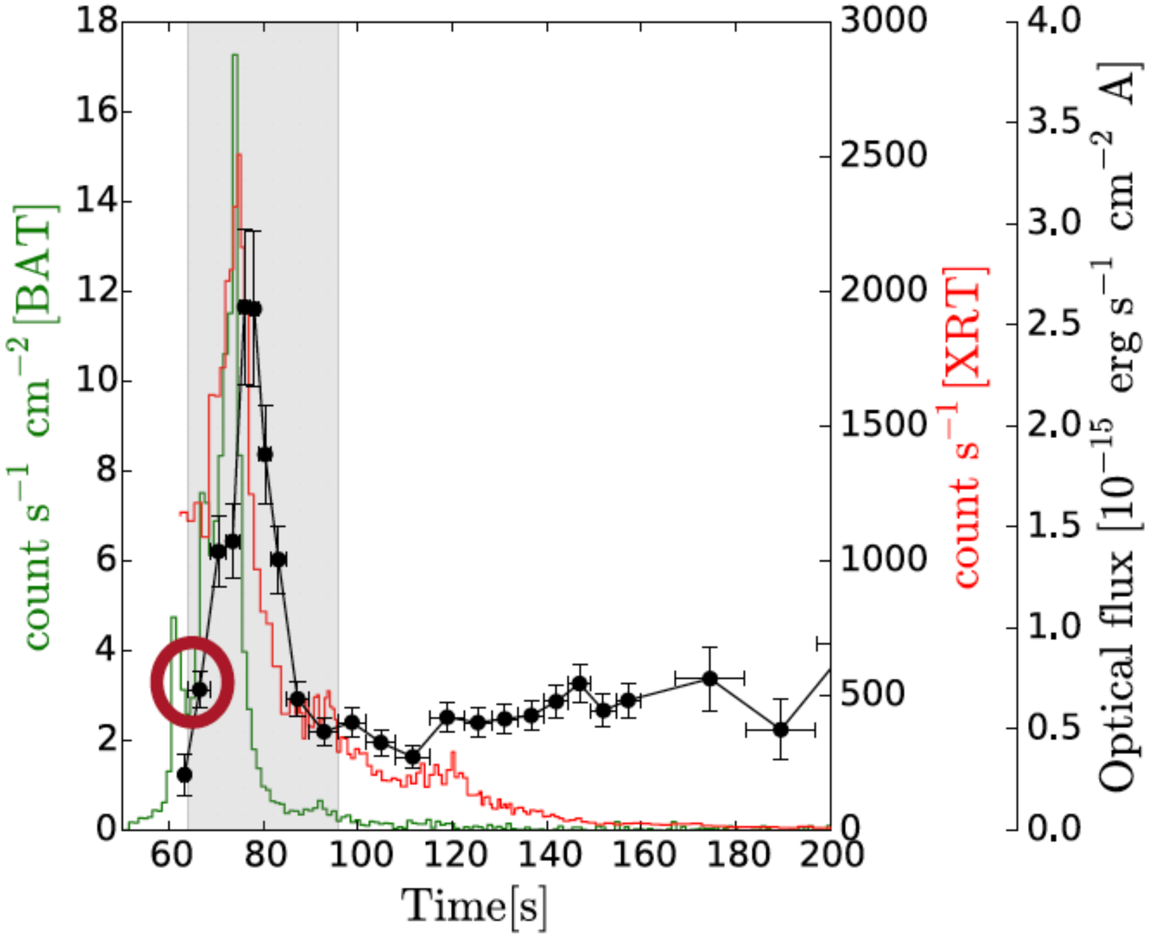
↓

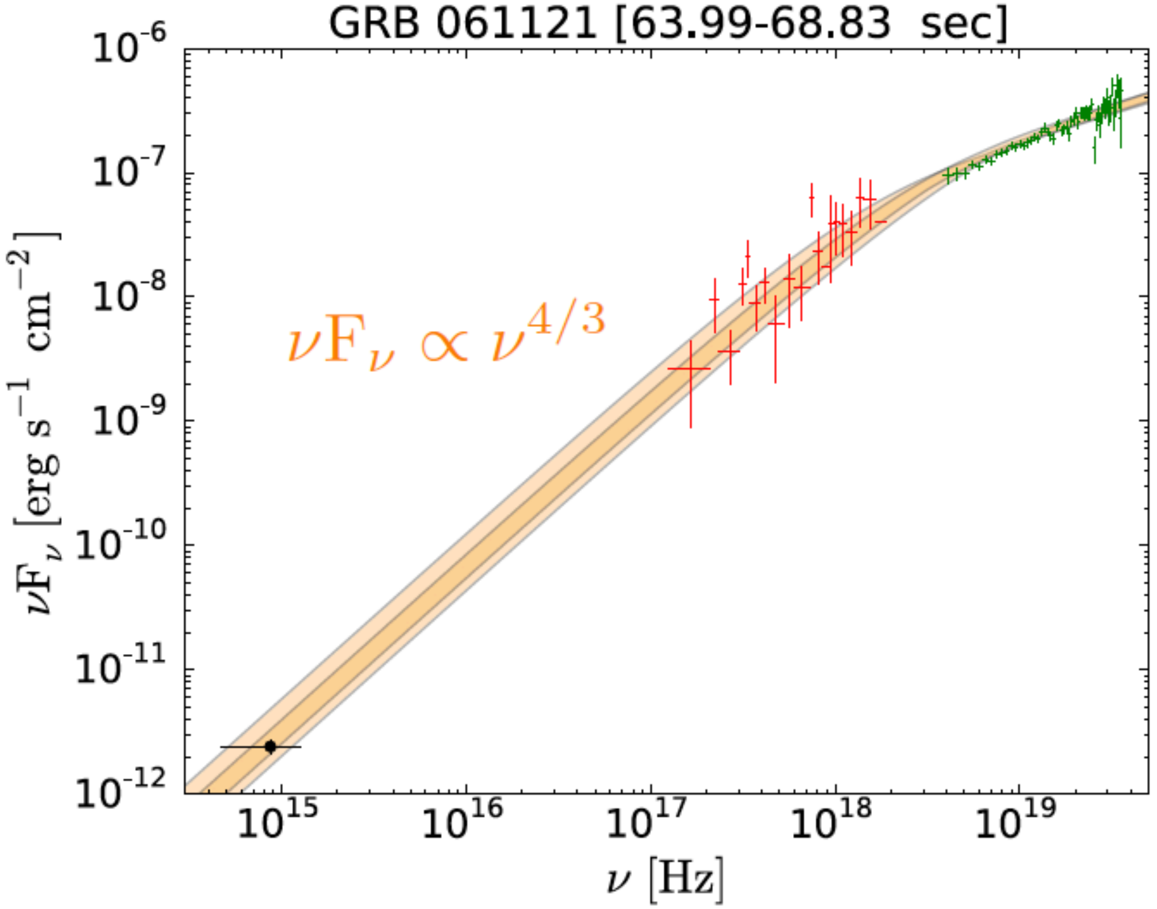
prediction of the optical flux

Optical emission

Case I (3 GRBs, 26 spectra)

TEMPORAL BEHAVIOUR OF OPTICAL EMISSION IS CORRELATED WITH PROMPT



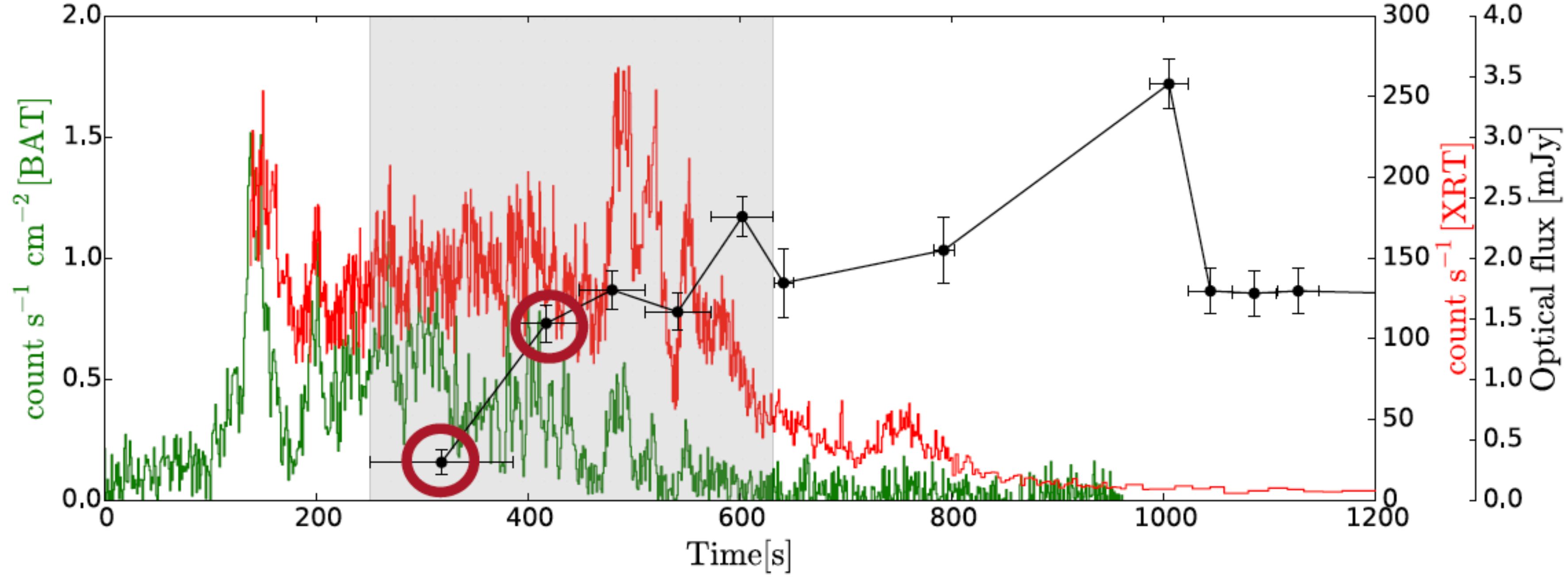


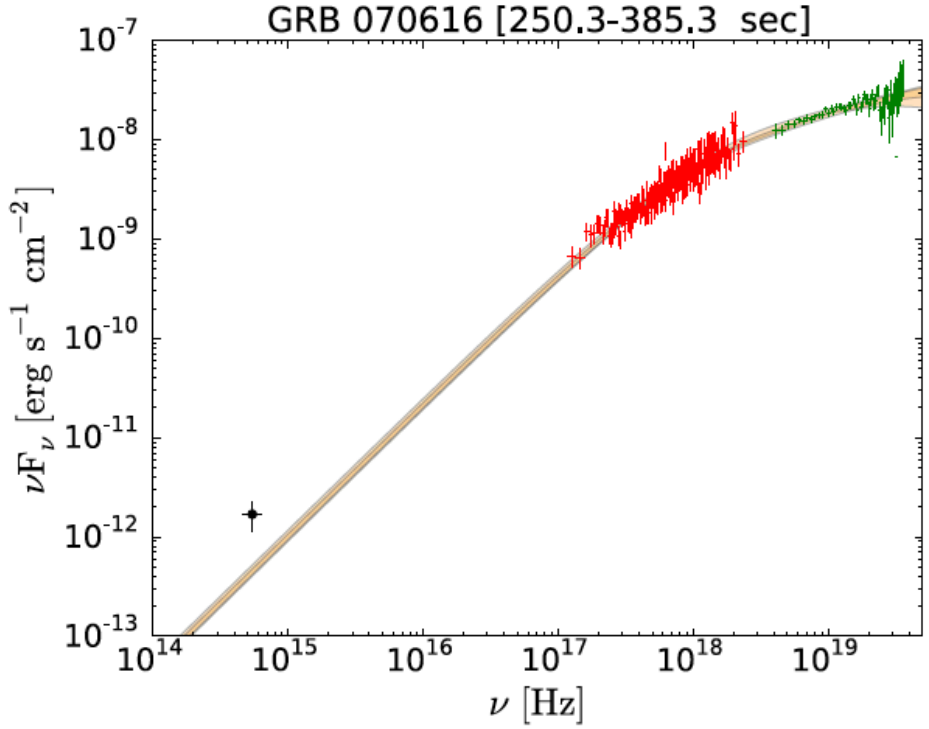
OPTICAL EMISSION IS CONSISTENT WITH SYNCHROTRON FIT

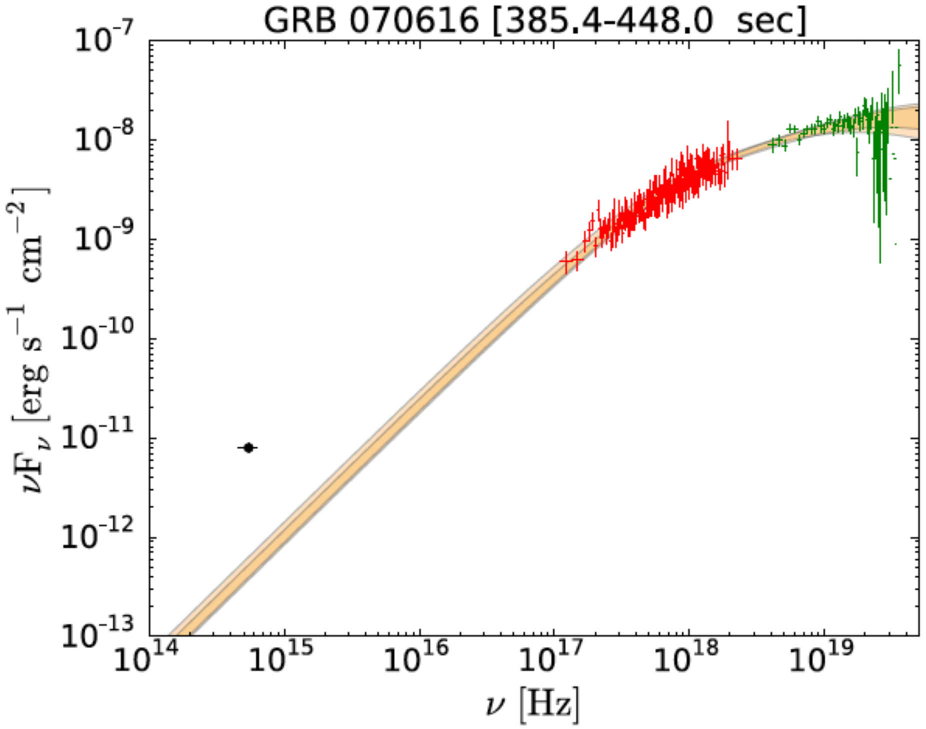
Optical emission

Case II (3 GRBs, 11 spectra)

TEMPORAL BEHAVIOUR OF OPTICAL EMISSION IS NOT CORRELATED WITH PROMPT

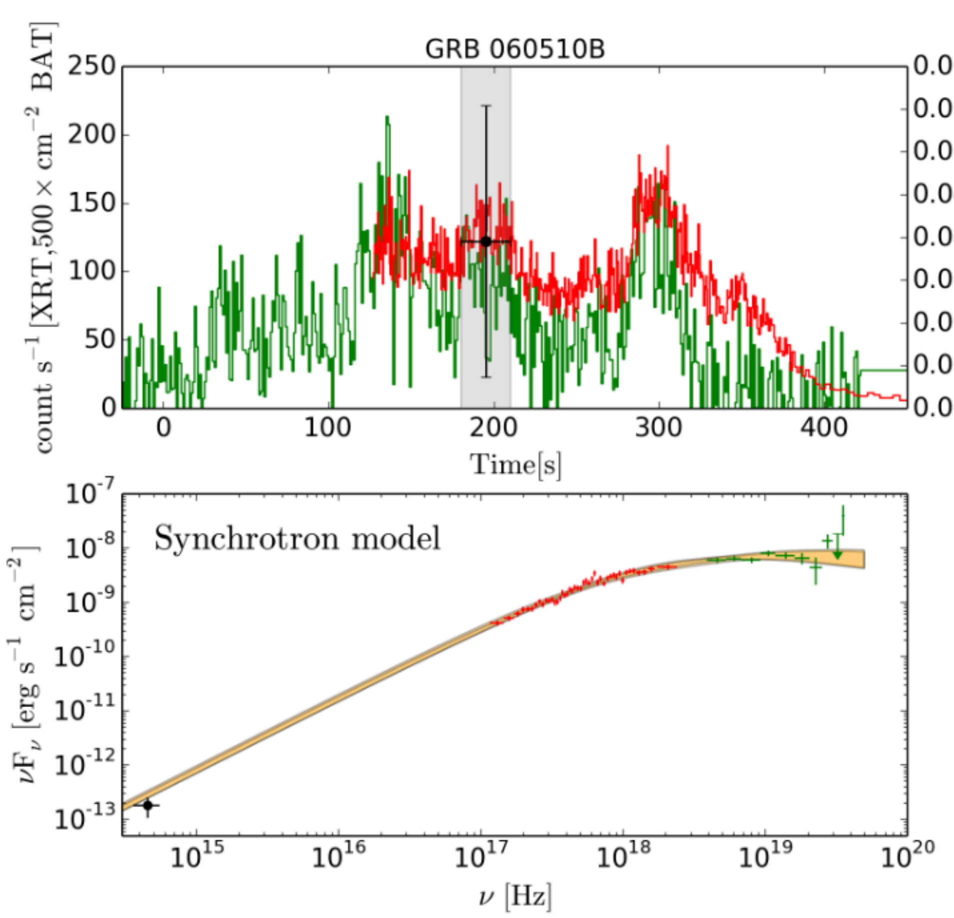


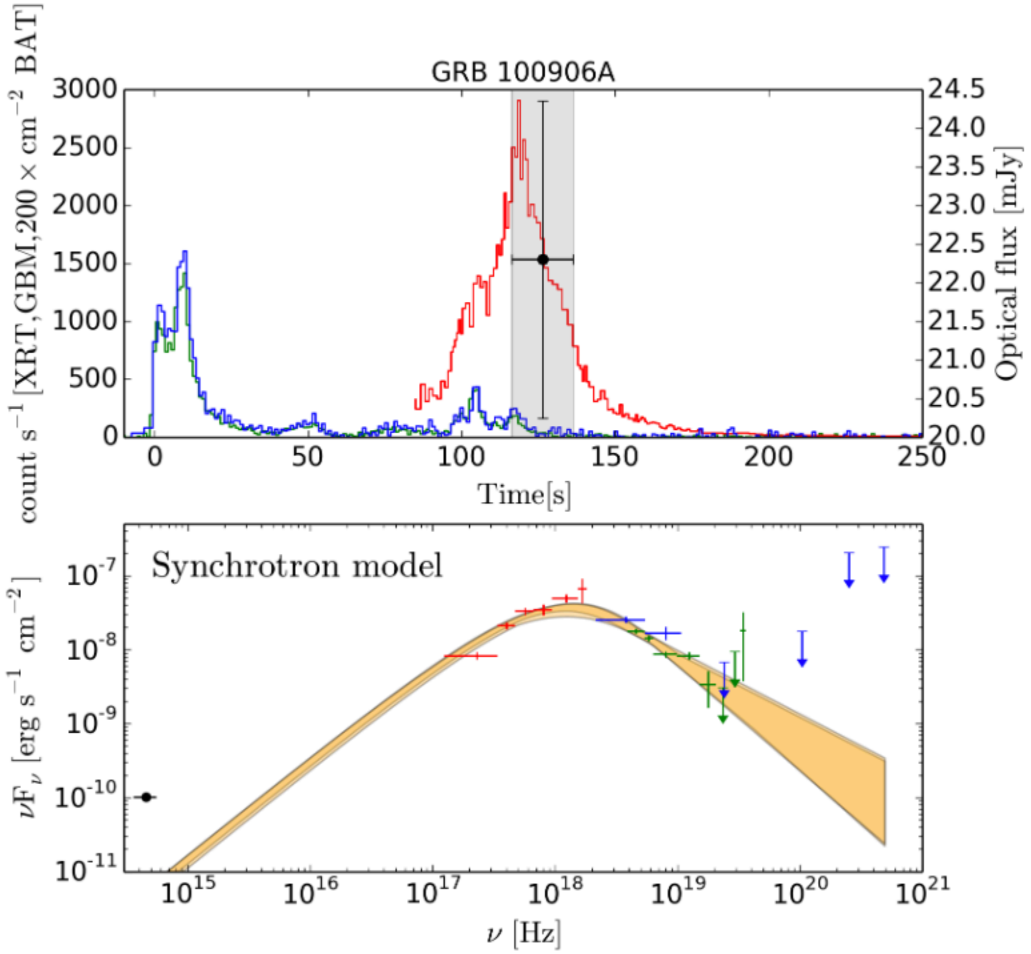




Optical emission

Case III (15 GRBs)
SINGLE OPTICAL OBSERVATION





consistency

6 GRBs

“prompt optical emission”

under-predicted

6 GRBs

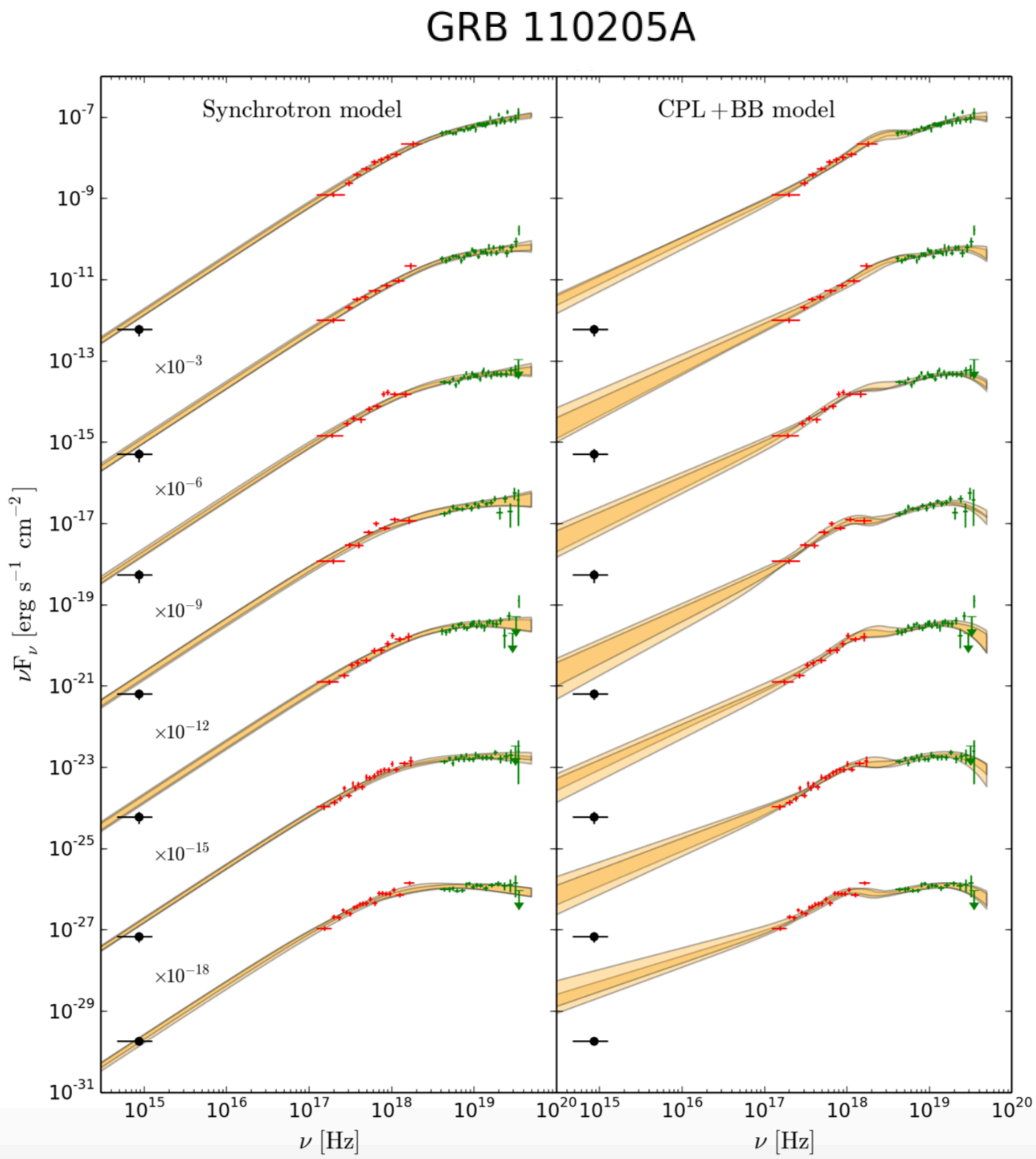
“afterglow emission”

Synchrotron vs 2 component model

~ 90% of spectra are inconsistent with CPL+BB model!

↓

synchrotron model is preferred



What we have learnt

- **There is a low-energy break in the GRB spectra**

- **The break could be the synchrotron cooling frequency**
  Oganesyan et al. 2017,2018; Ravasio et al. 2018,2019

- **Synchrotron model fits the (considered) data**
  Oganesyan et al. 2019; Burgess et al. 2020

see B. Zhang 2020, Nature Astronomy, for a brief discussion

Models that could work

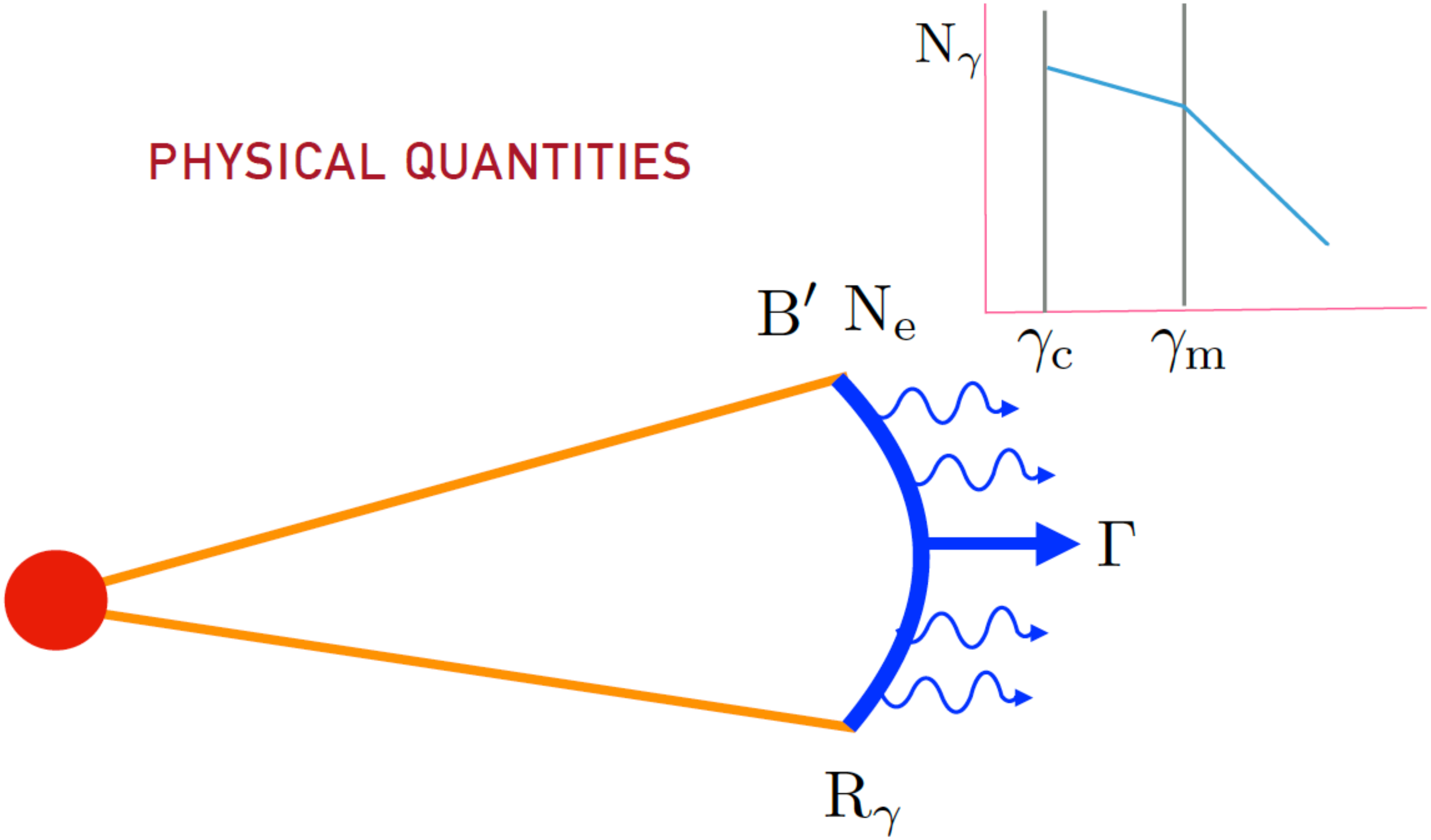
- re-acceleration/heating of electrons
  Kumar & McMahon 2008; Asano & Terasawa 2009; Beniamini & Piran 2014; Beniamini et al. 2018;
- noticeable decay of the magnetic field
  Pe'er & Zhang 2006; Derishev 2007; Zhao et al. 2014; Uhm & Zhang 2014; Zhang et al. 2016
- proton synchrotron model
  Ghisellini et al. 2020

Models that could work

MEASURED PARAMETERS

ν_c $\quad F_\nu(\nu_c) = F_c$ $\quad \gamma_m/\gamma_c$

PHYSICAL QUANTITIES



Models that could work

Kumar & McMahon (2008)　F. Daigne et al (2011)　Beniamini & Piran (2013)

$\Gamma \geq 300$ large bulk Lorentz factors

$\mathrm{B}' \sim 10\,\mathrm{G}$ weak magnetic fields

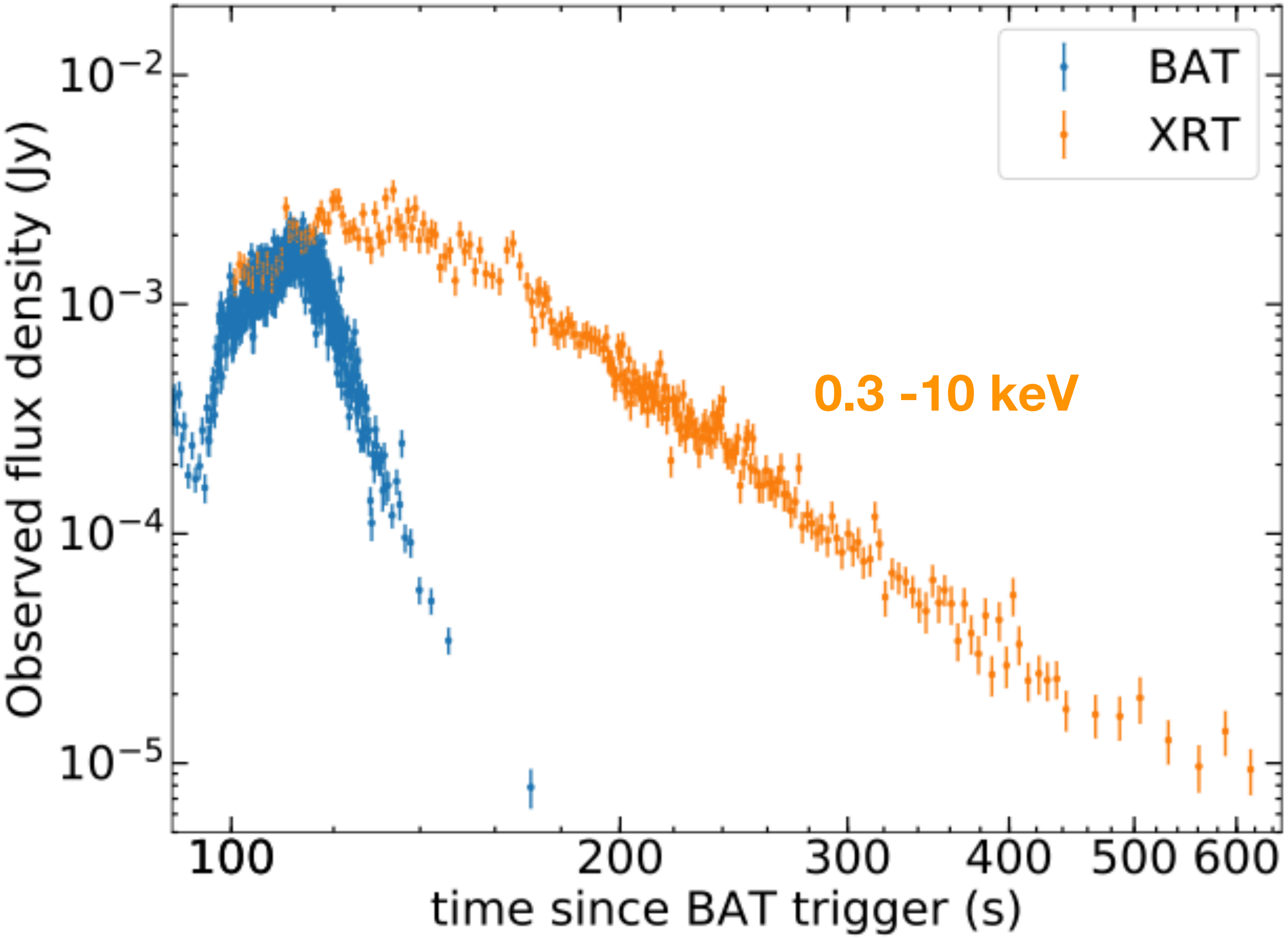
$\nu_c \sim \nu_m$

$R \geq 3 \times 10^{16}\ cm$ large radii

$\gamma_m \sim 10^5$ only small fraction of electrons should be accelerated

which deceleration mechanism can naturally account for this regime?

X-ray steep decay as diagnostics of the GRB emission side



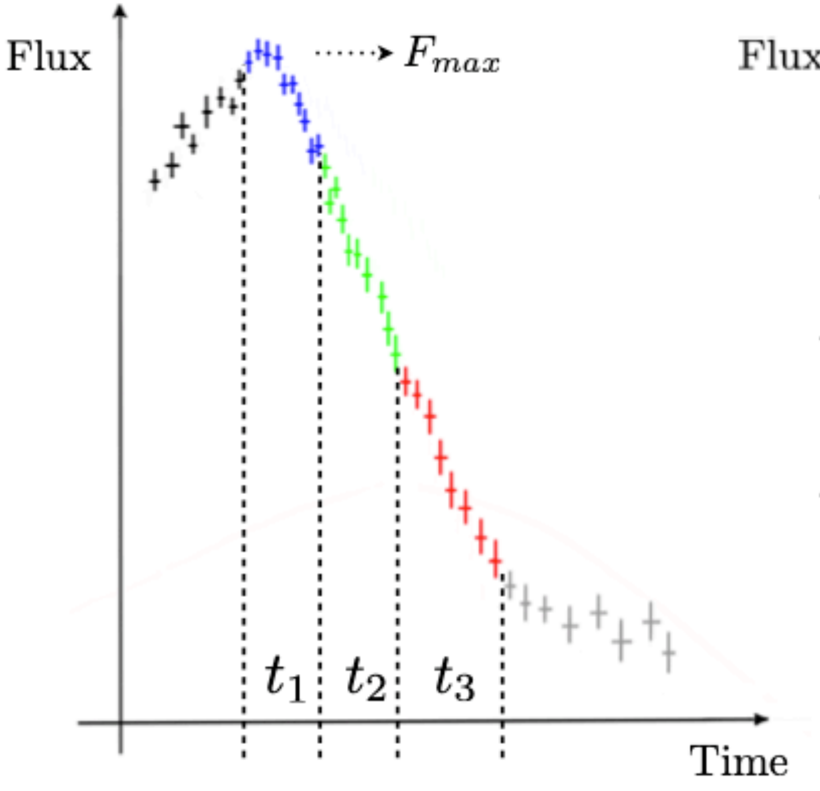
[Ronchini et al. 2021]

Prompt emission

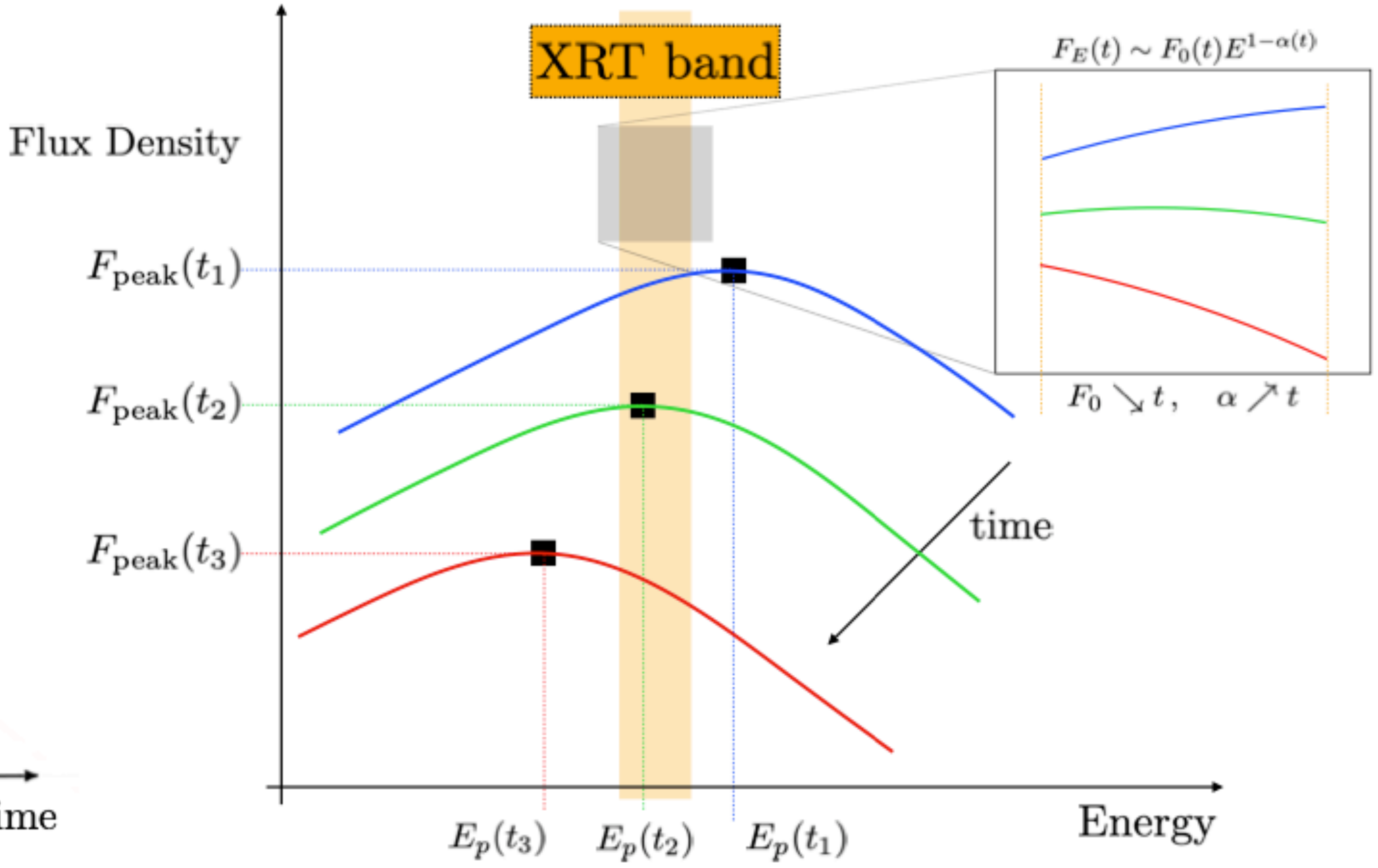
→

Prompt tail

X-ray steep decay as diagnostics of the GRB emission side



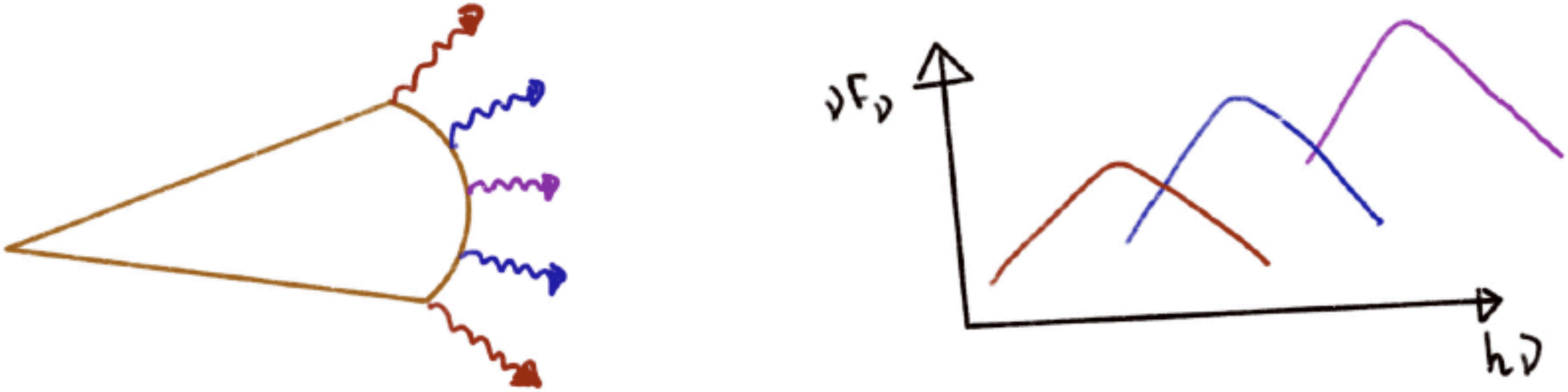
0.3 -10 keV



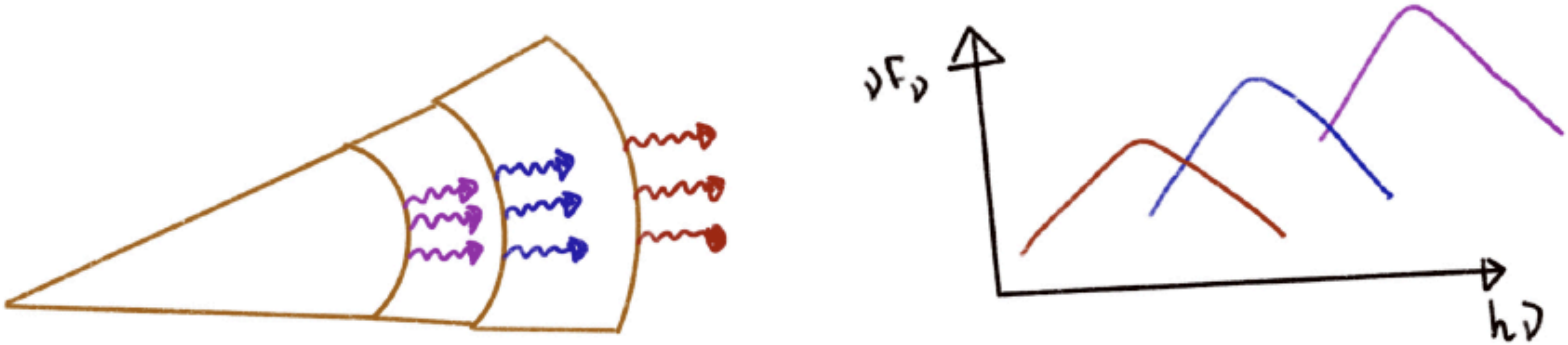
[Ronchini et al. 2021]

X-ray steep decay as diagnostics of the GRB emission side

Efficient cooling —> we observe the high latitude emission

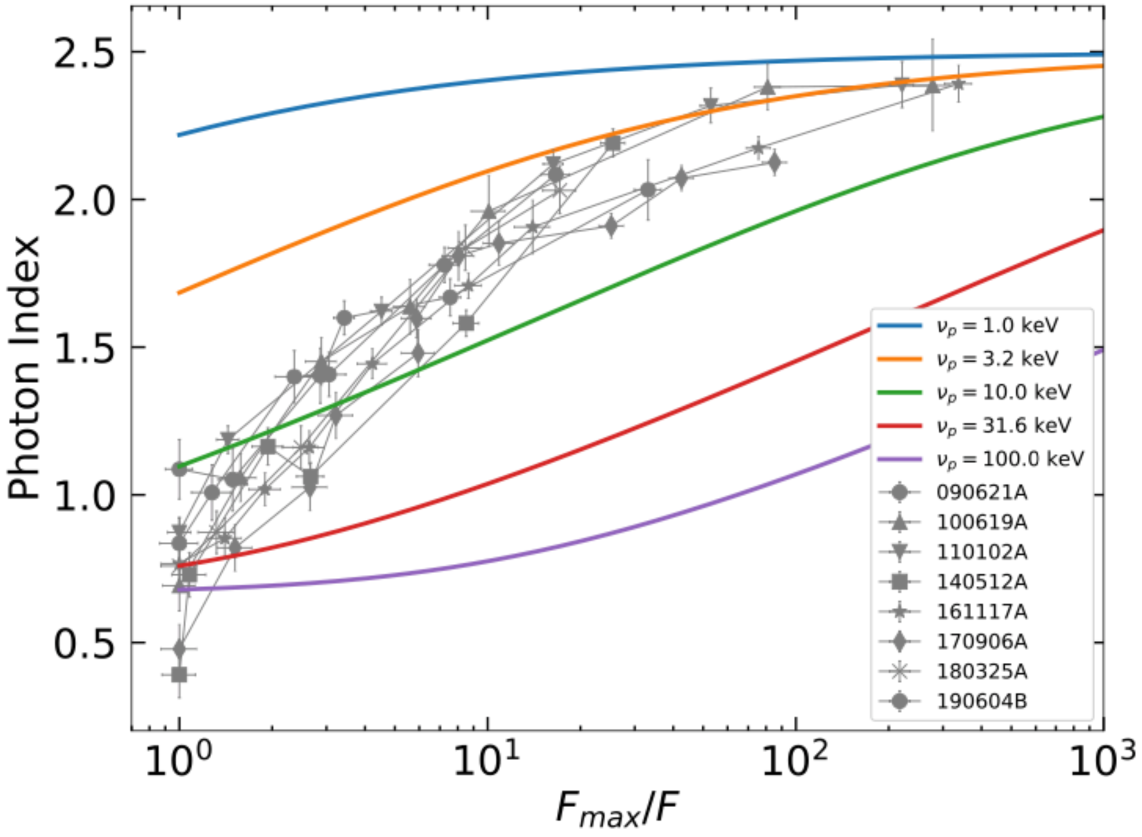


Inefficient cooling —> we observe the adiabatic cooling

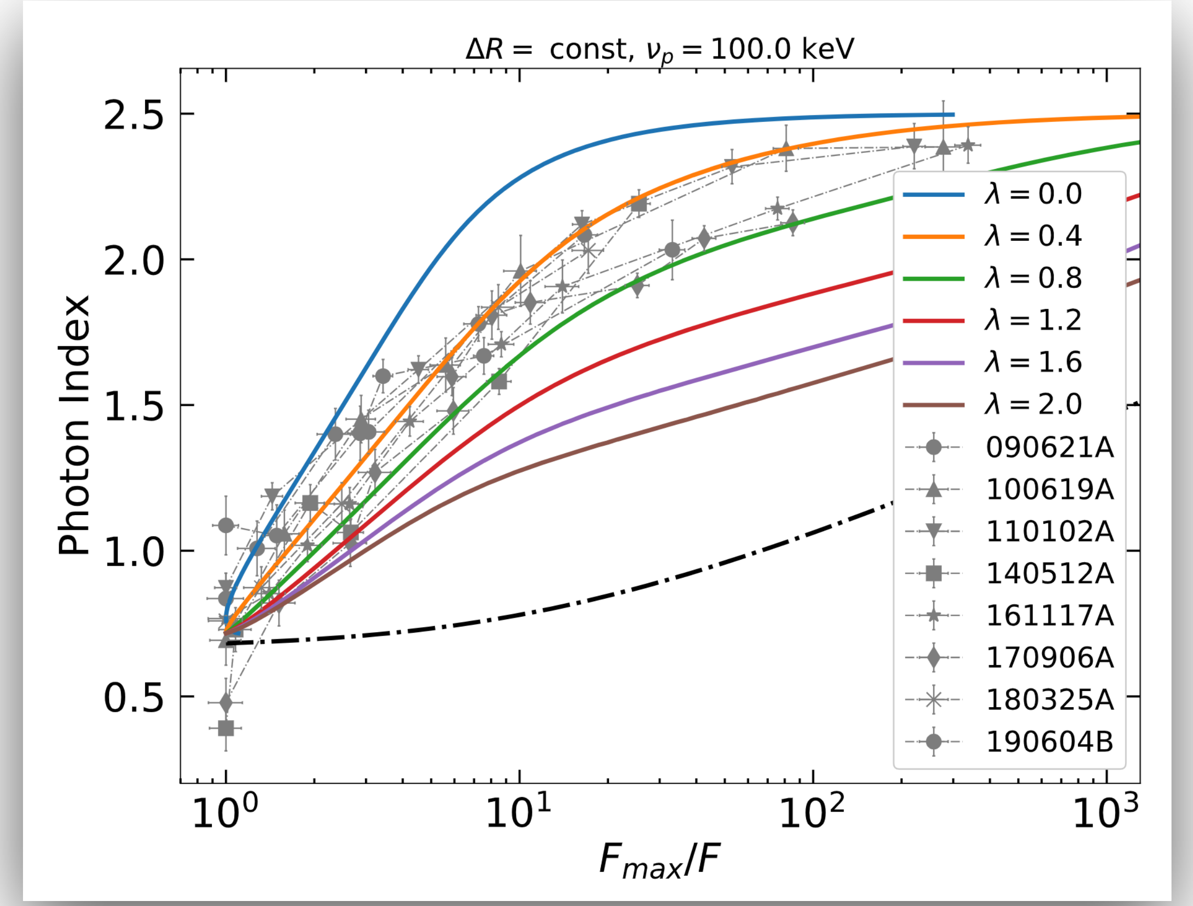


[Ronchini et al. 2021]

Efficient cooling

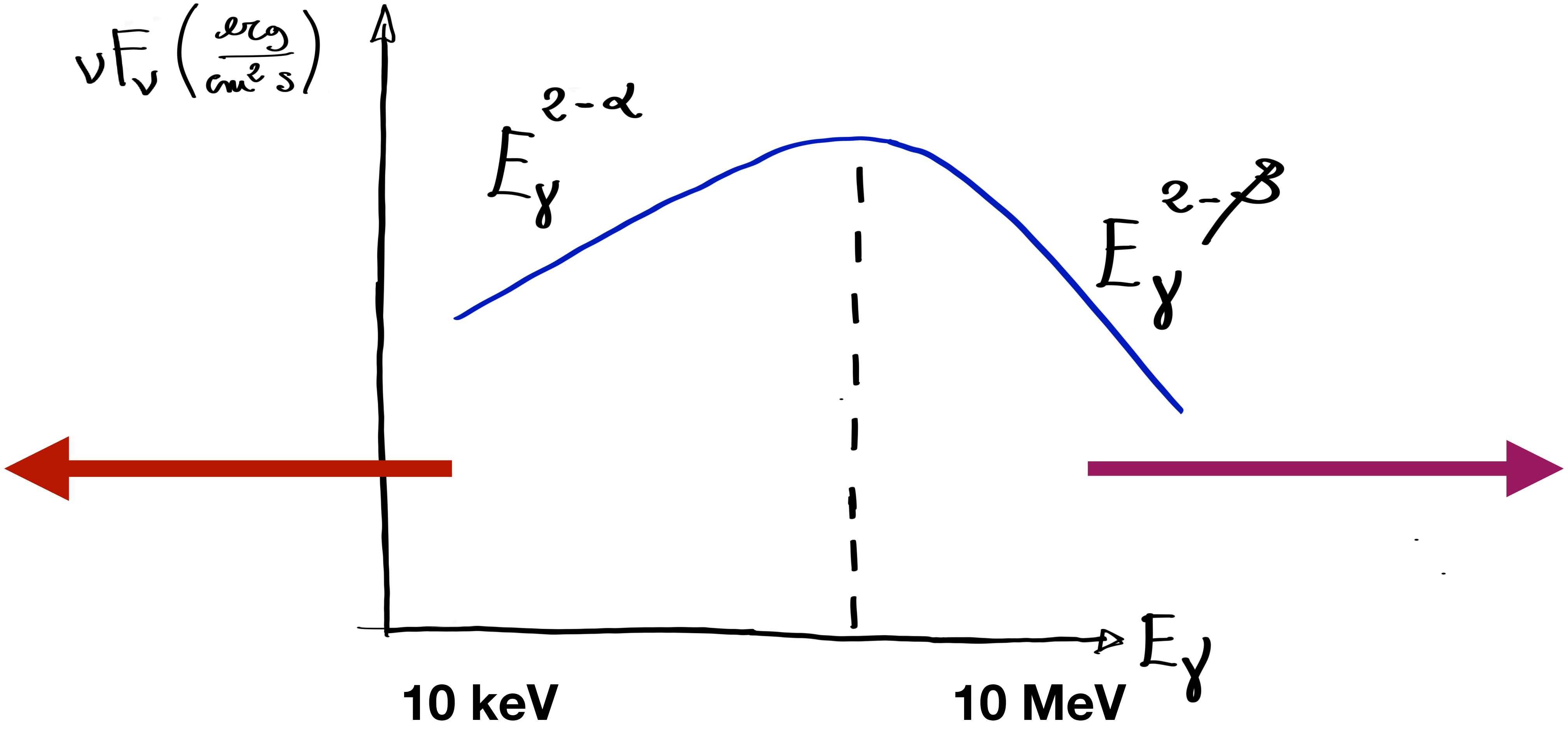


Inefficient cooling



[Ronchini et al. 2021]

Different ways to solve the problem



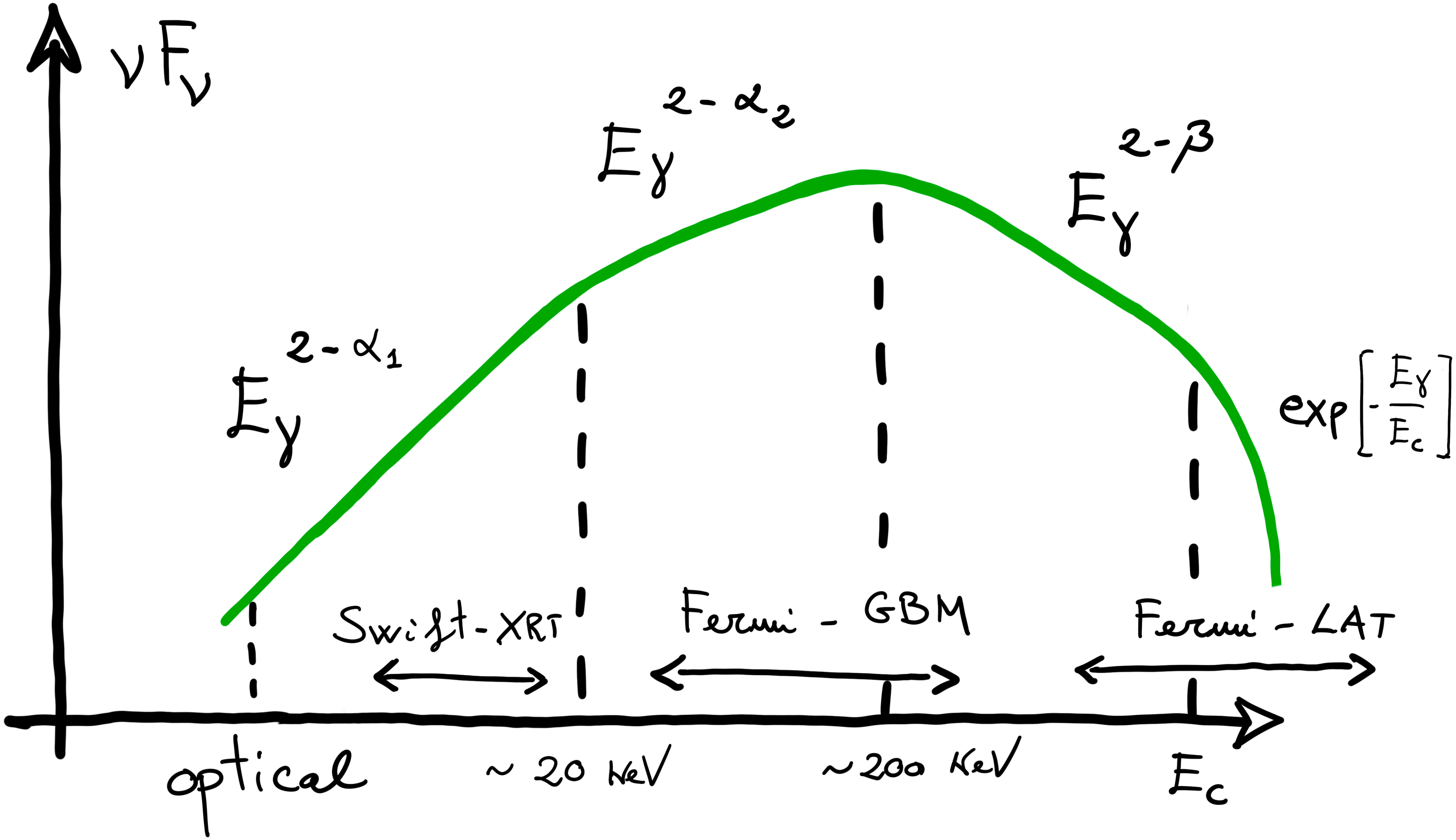
+ polarisation

[Gill, Kole & Granot 2021 for a recent review]

+ neutrinos

[Pitik, Tamborra & Petropoulou 2021 and Kimura 2022 for recent reviews]

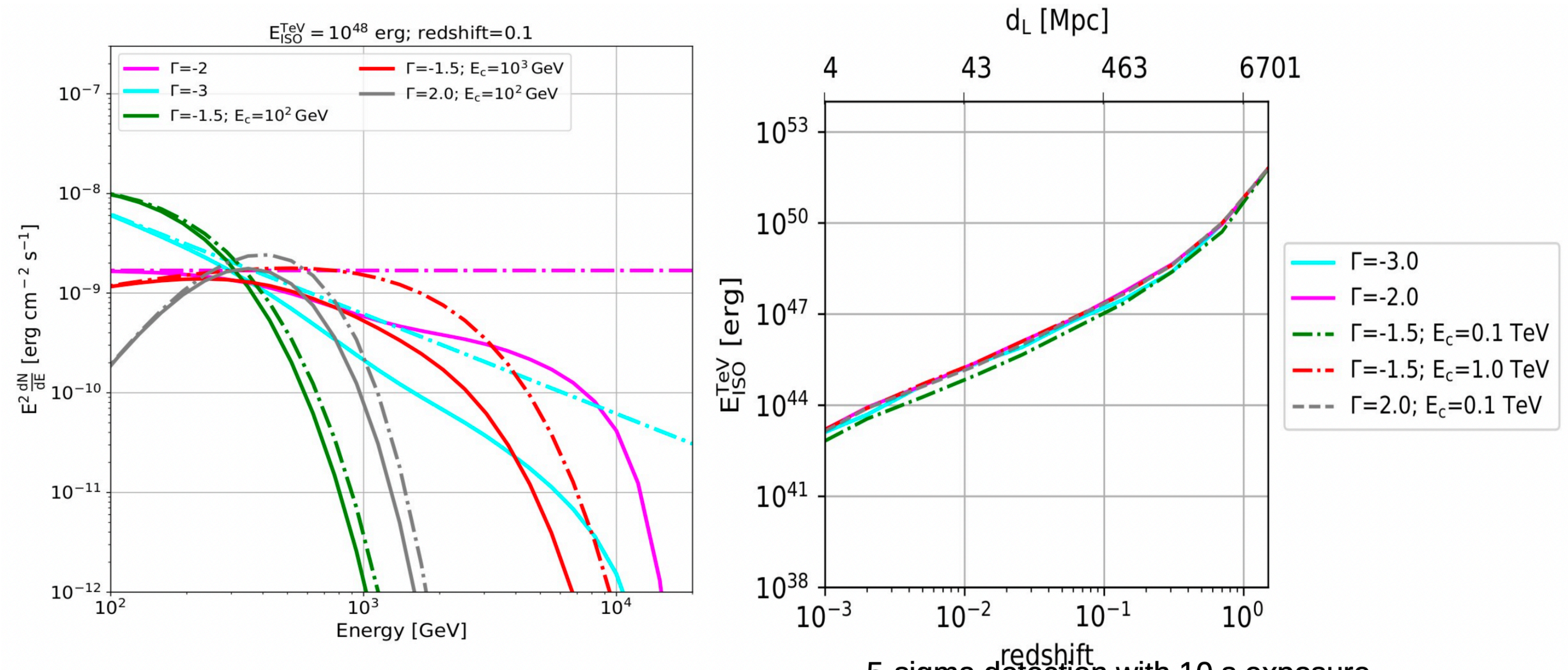
GeV prompt emission



Talk by Maria E. Ravasio

[sketch by S. Ronchini]

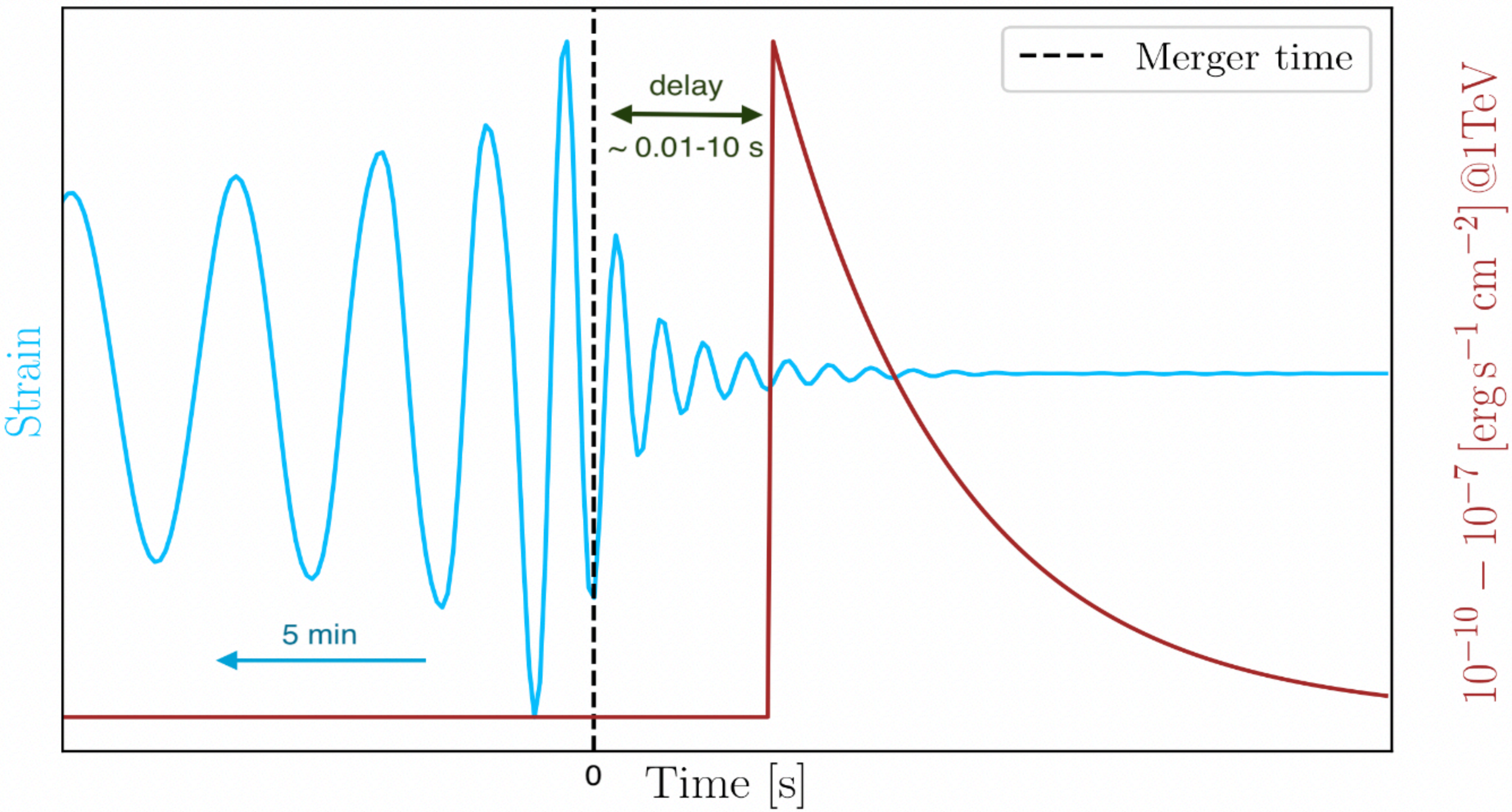
Very High Energy Emission



5-sigma detection with 10 s exposure

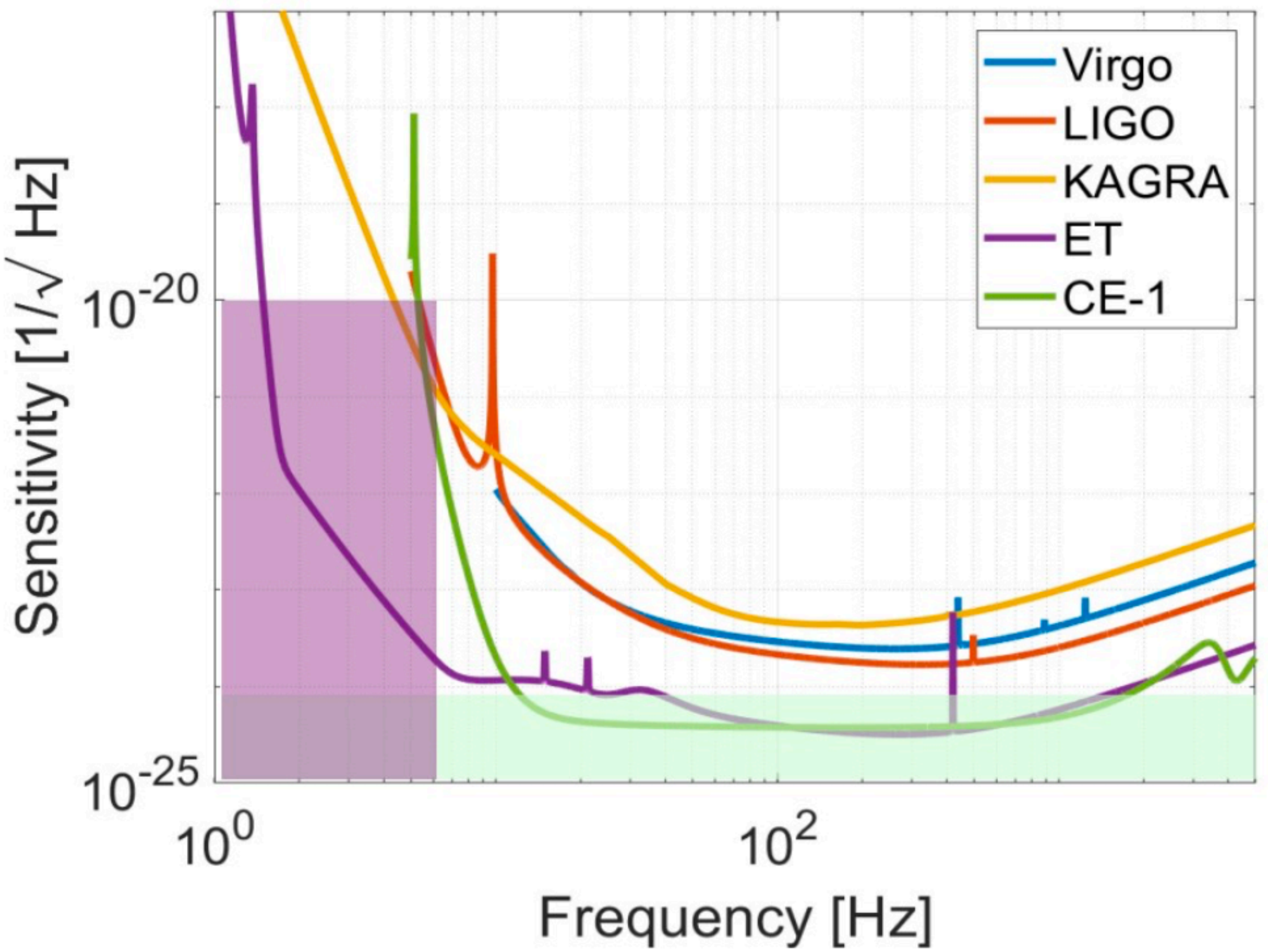
[Banerjee et al., in preparation]

Very High Energy Emission



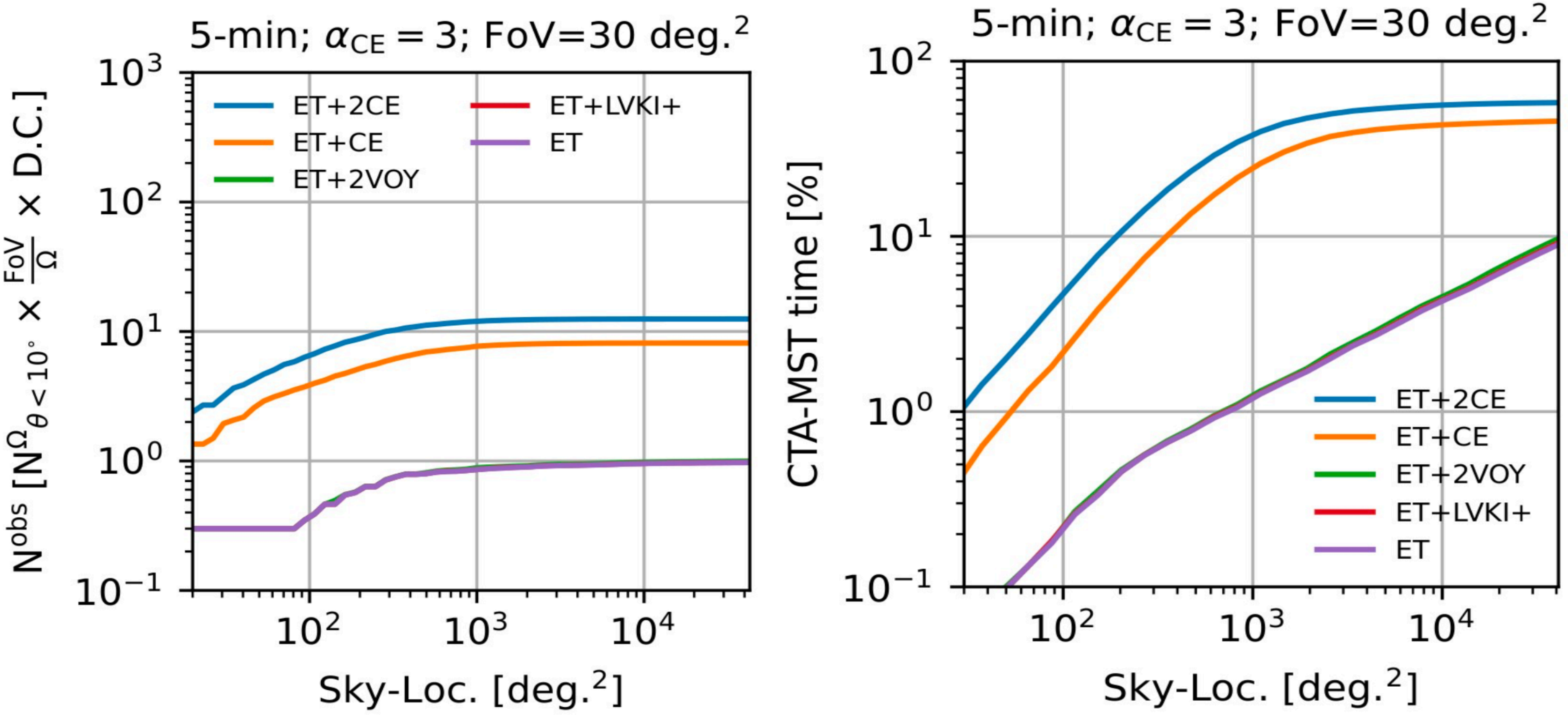
[Banerjee et al., in preparation]

Very High Energy Emission



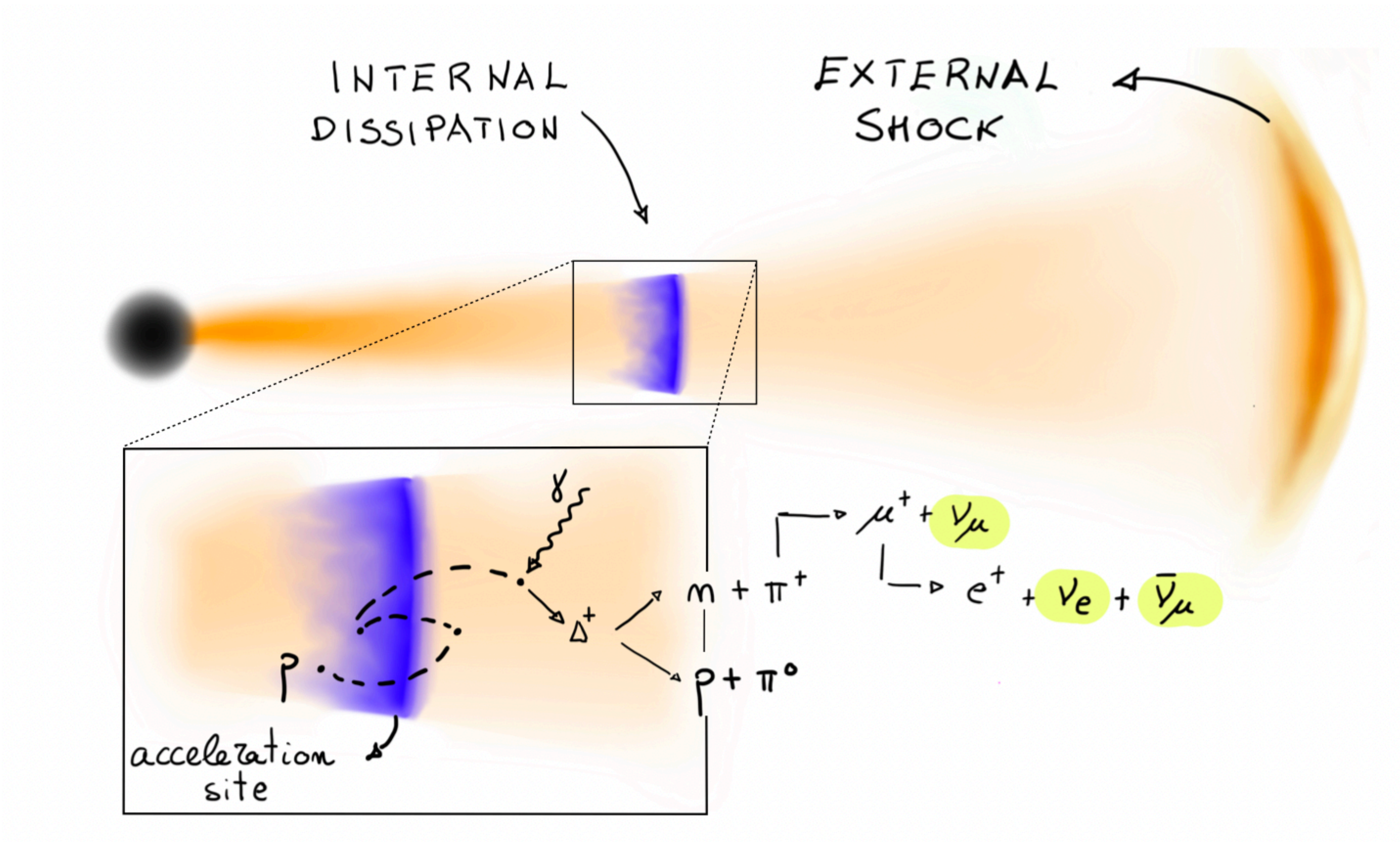
[Banerjee et al., in preparation]

Very High Energy Emission



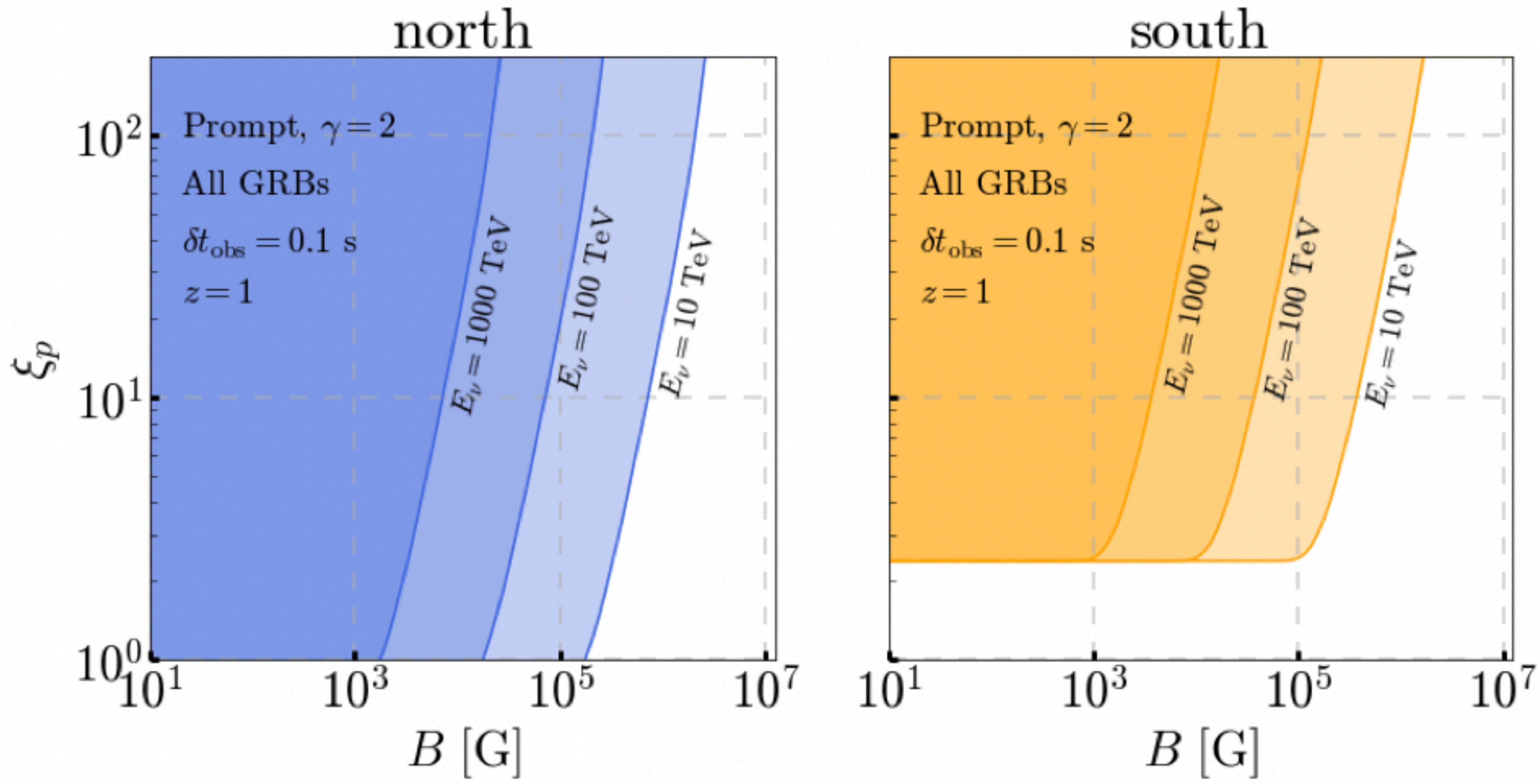
[Banerjee et al., in preparation]

High Energy Neutrinos



[sketch by S. Ronchini]

Search for HE neutrinos



[Lucarelli et al., 2022—> on arXiv]

What we have learnt

X-rays

- low energy spectral breaks
- adiabatic cooling of tails

Optical emission

- consistent with the synchrotron origin
- inconsistent with 2 comp models (Thermal + Non-thermal)

HE emission

next talk by **Maria E. Ravasio**

VHE emission

difficult but possible with 3G GW network and CTA

[Banerjee et al., in preparation]

HE neutrinos

Either few baryons or highly magnetised ejecta
waiting for more photomultipliers in IceCube

[Lucarelli et al., 2022—> on arXiv]

The number of new scenarios grows

Beniamini et al. 2018, MNRAS

Liu et al. 2020, ApJ

Ghisellini et al. 2020, A&A

Gill et al. 2020, MNRAS

Sobacchi et al. 2021, MNRAS

Florou et al. 2021

Bégué et al. 2021

Goto & Asano 2022, ApJ