Photospheres in GRBs
Role of radiation mediated shocks

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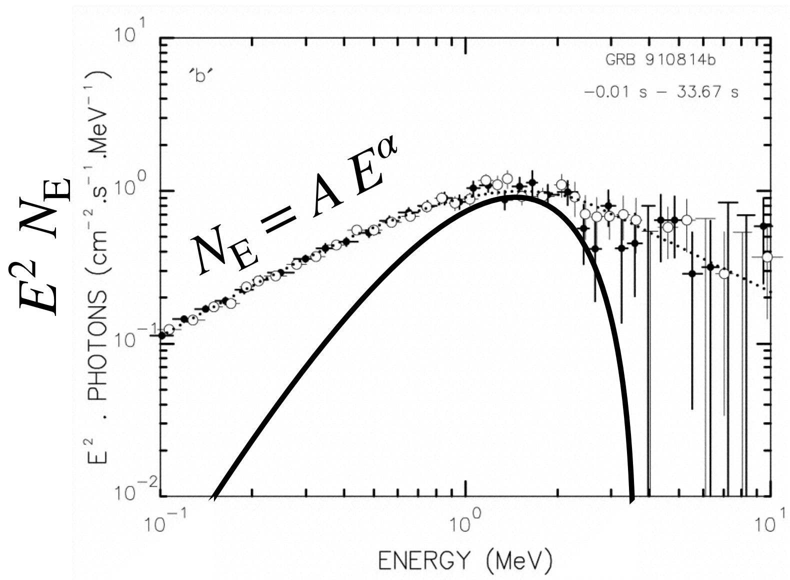
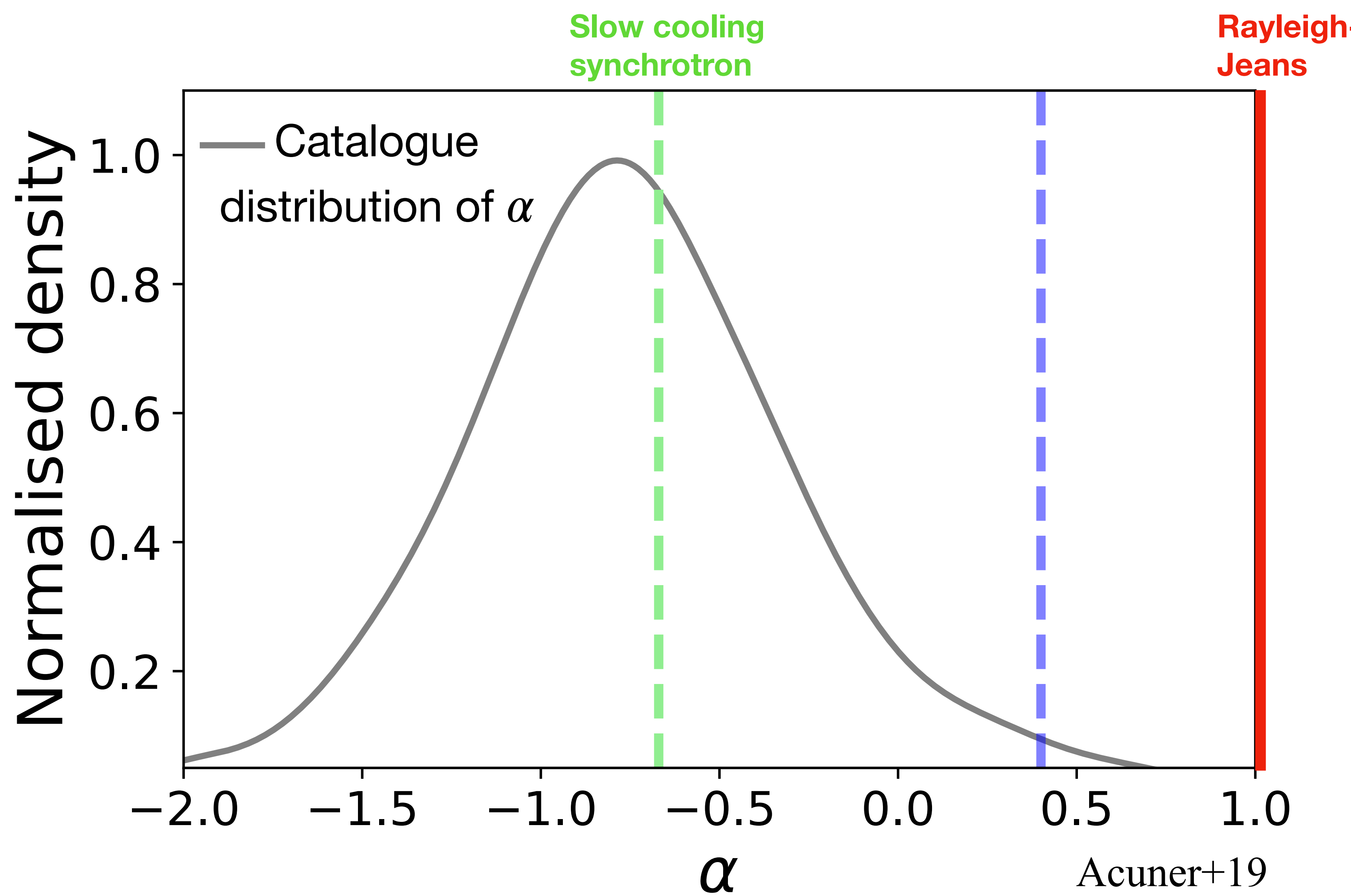
Distribution of prompt emission spectral shapes

Typical gamma-ray spectrum



Current α-distribution

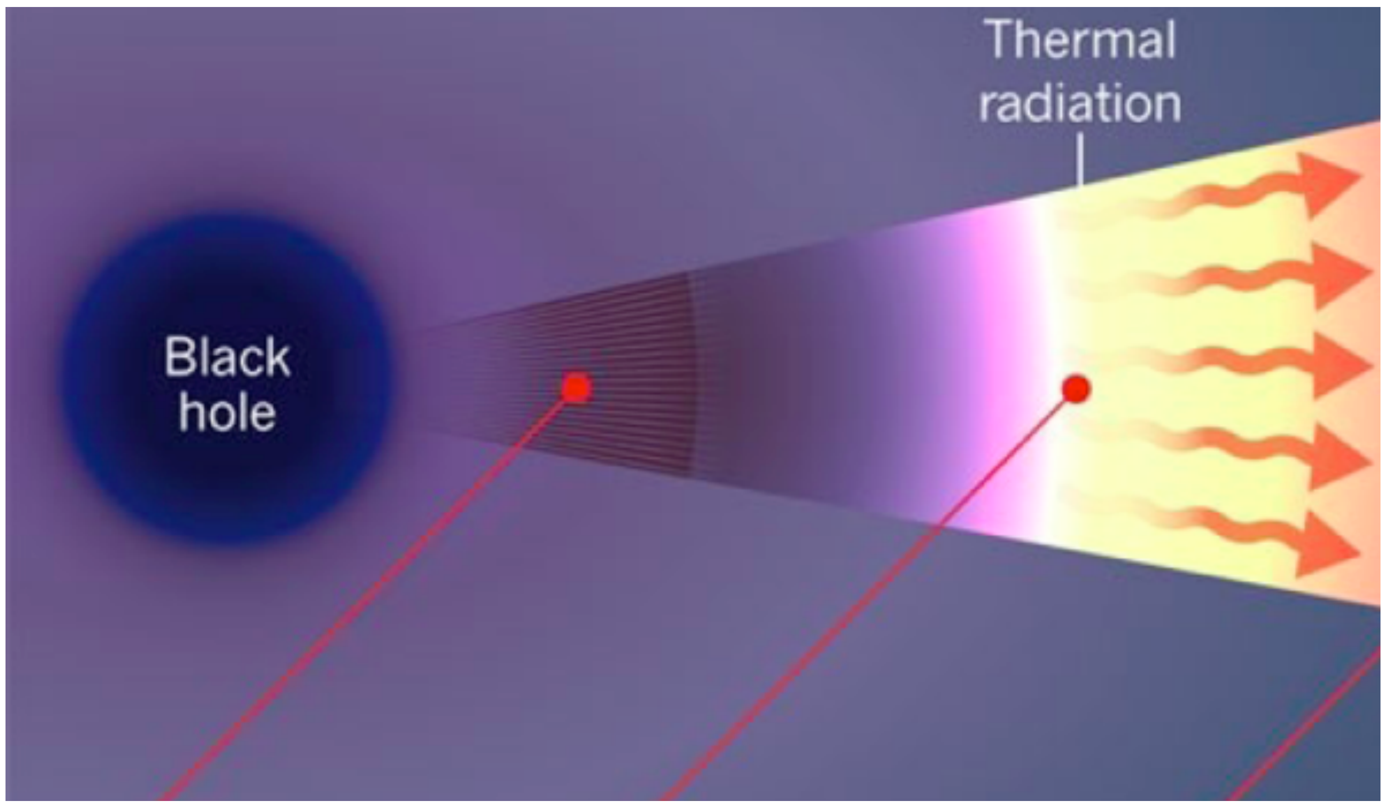
2300 GRBs observed
By Fermi/GBM



Acuner+19
Burgess+17

Photospheric emission in GRBs

Natural ingredient in the fireball model

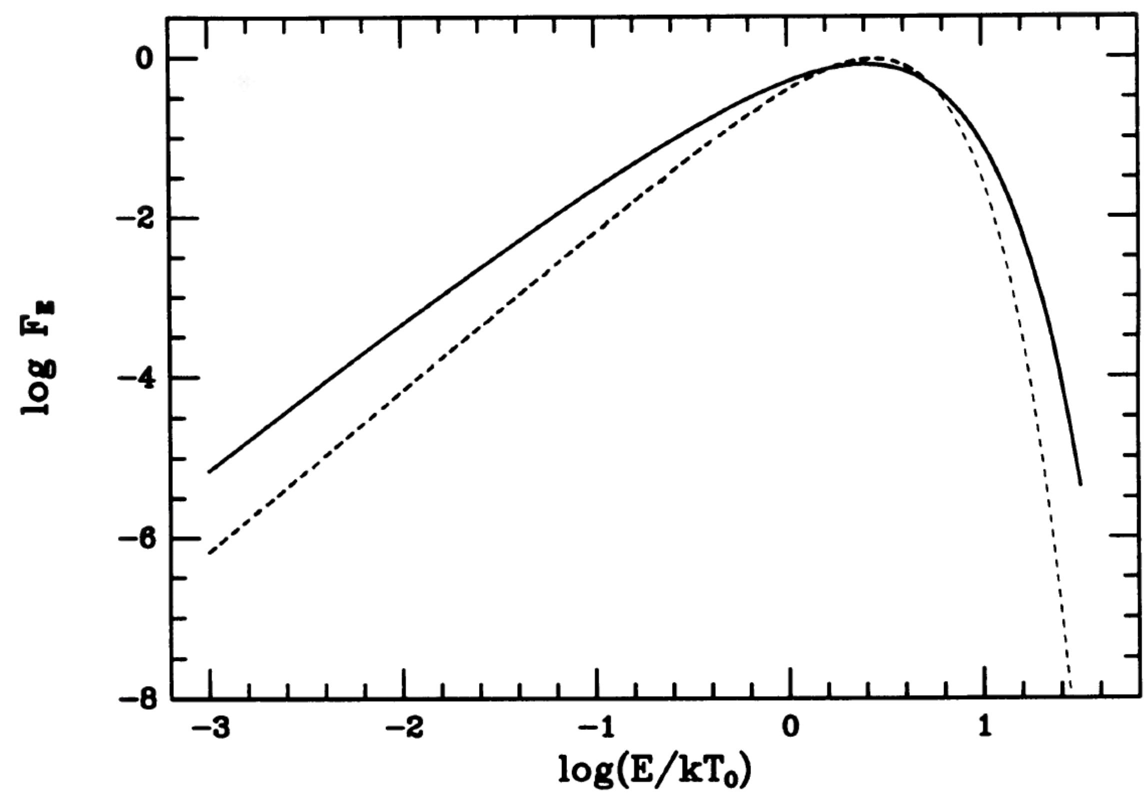


Flow is opaque

Flow becomes transparent: Photospheric flash

Photosphere without shocks and energy dissipation

Goodman 1986

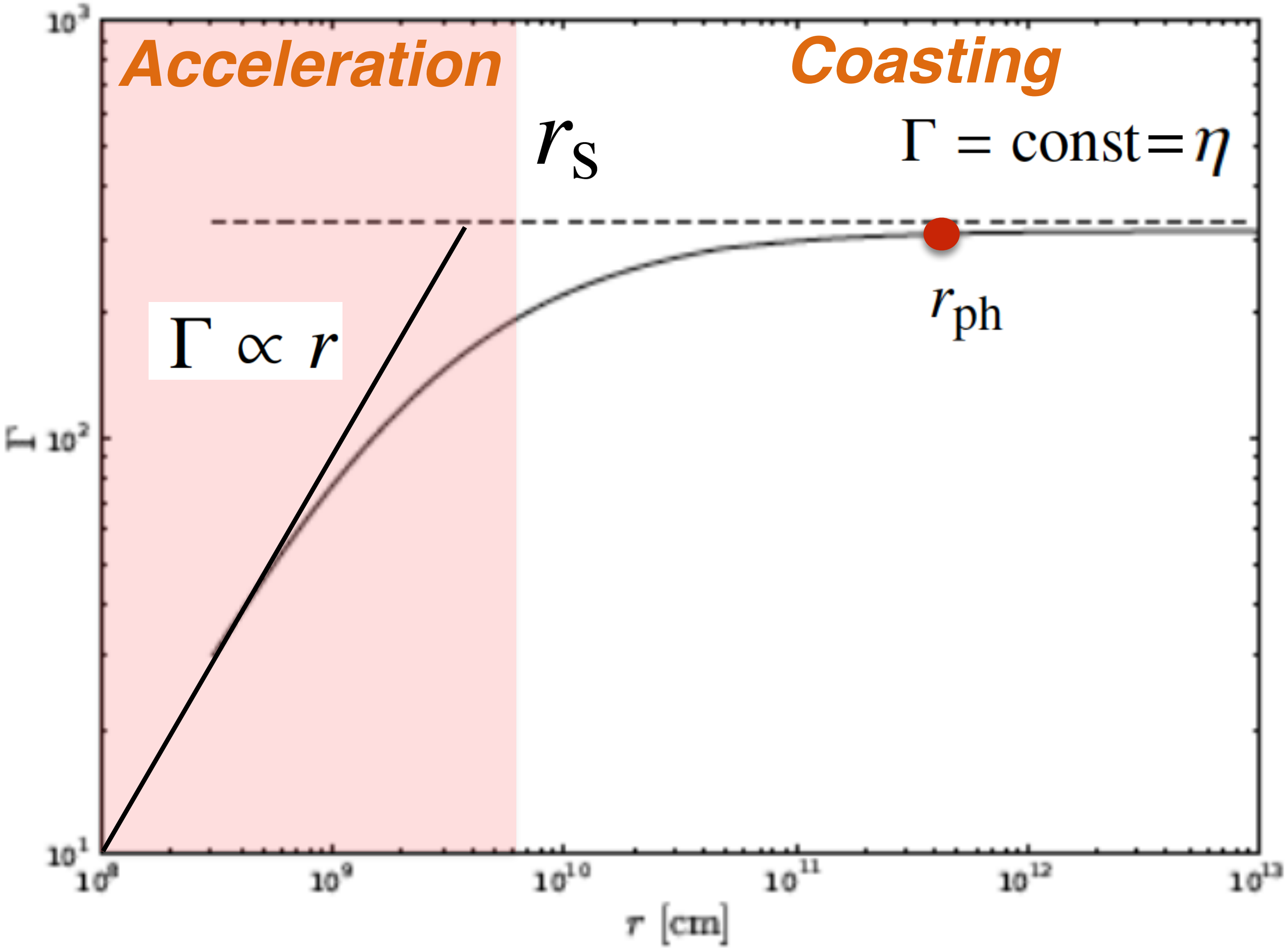


Spectral shape
Not a Planck function!

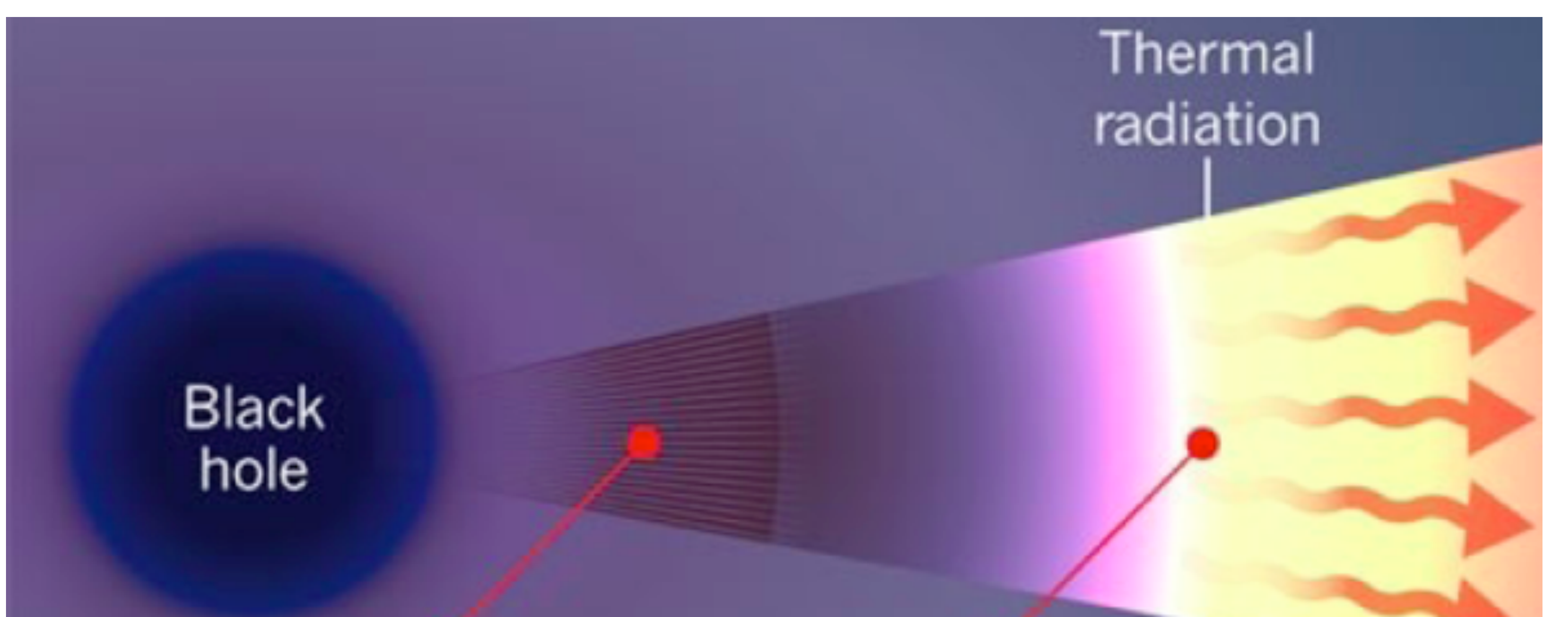
Photospheric emission from an undisruptive jet
What do we expect?

Fireball model:
Lorentz factor

$$\eta = L/\dot{M}c^2$$

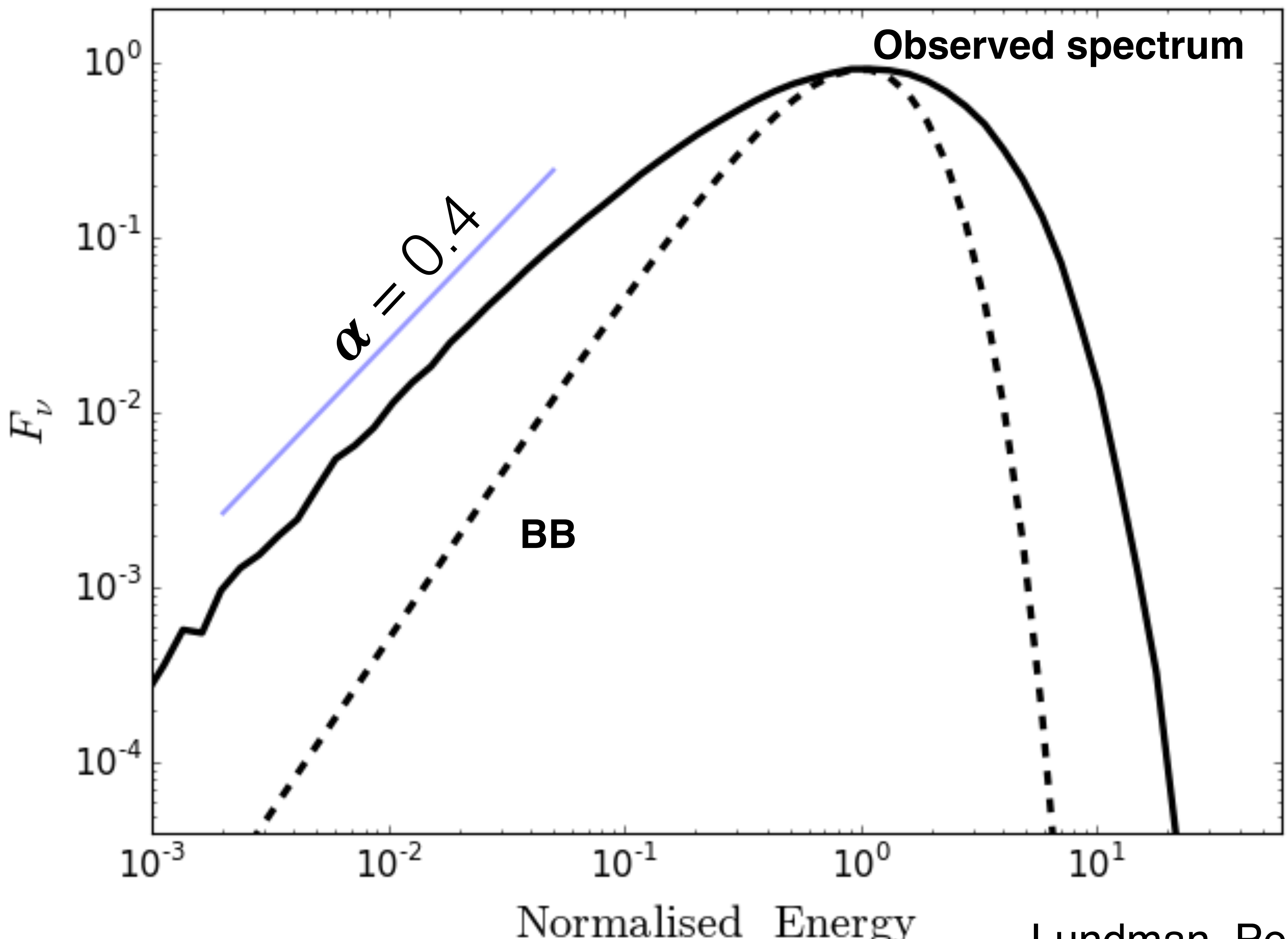


Magnetic dominated flow will have a different dynamics



Coasting phase spectrum from a non-dissipative jet

Pe’er 2008, Beloborodov 2011, Lundman, Pe’er, & Ryde 2013



Lundman, Pe’er, Ryde 2013

Photospheric emission from an undisruptive jet
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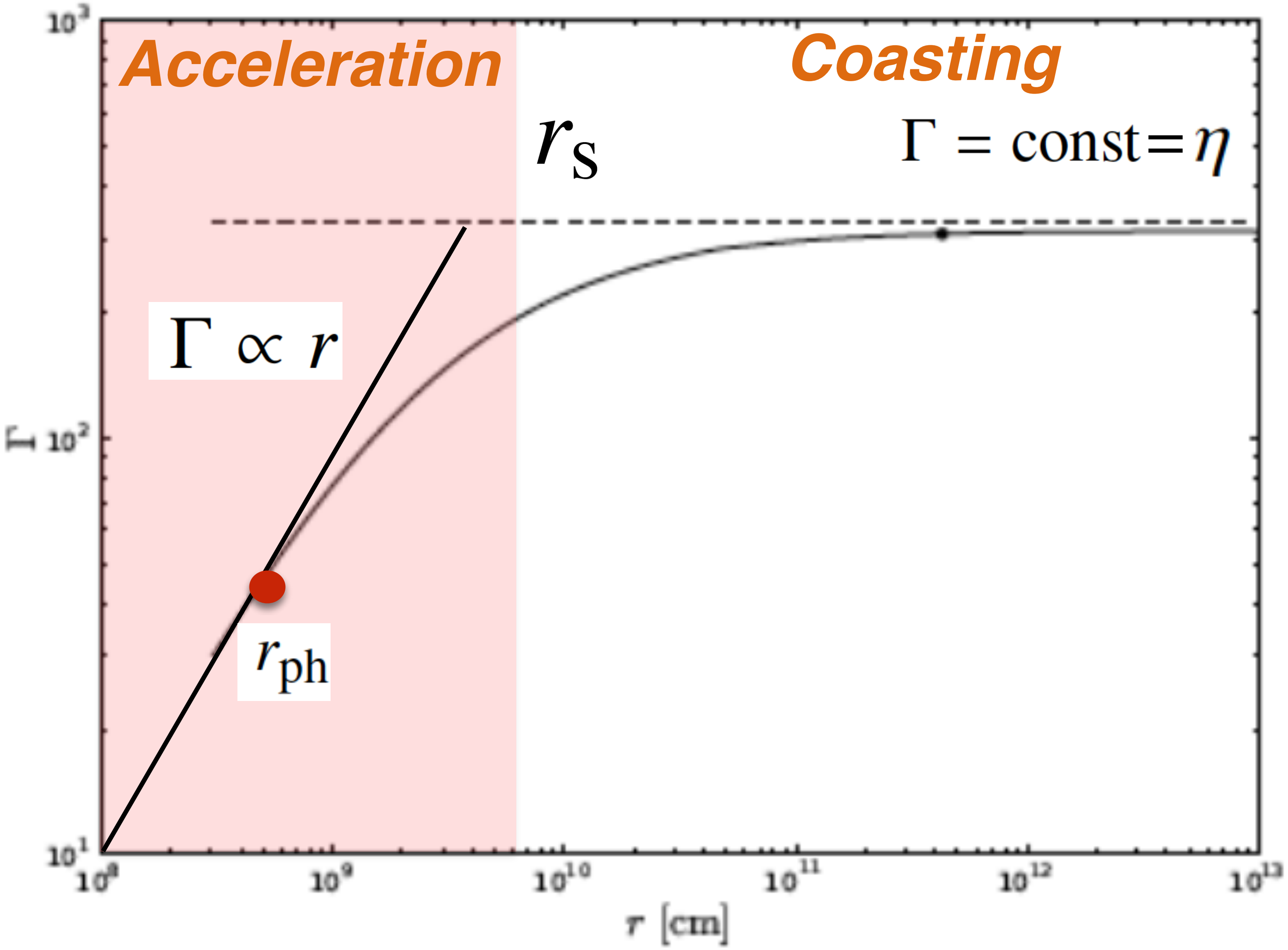
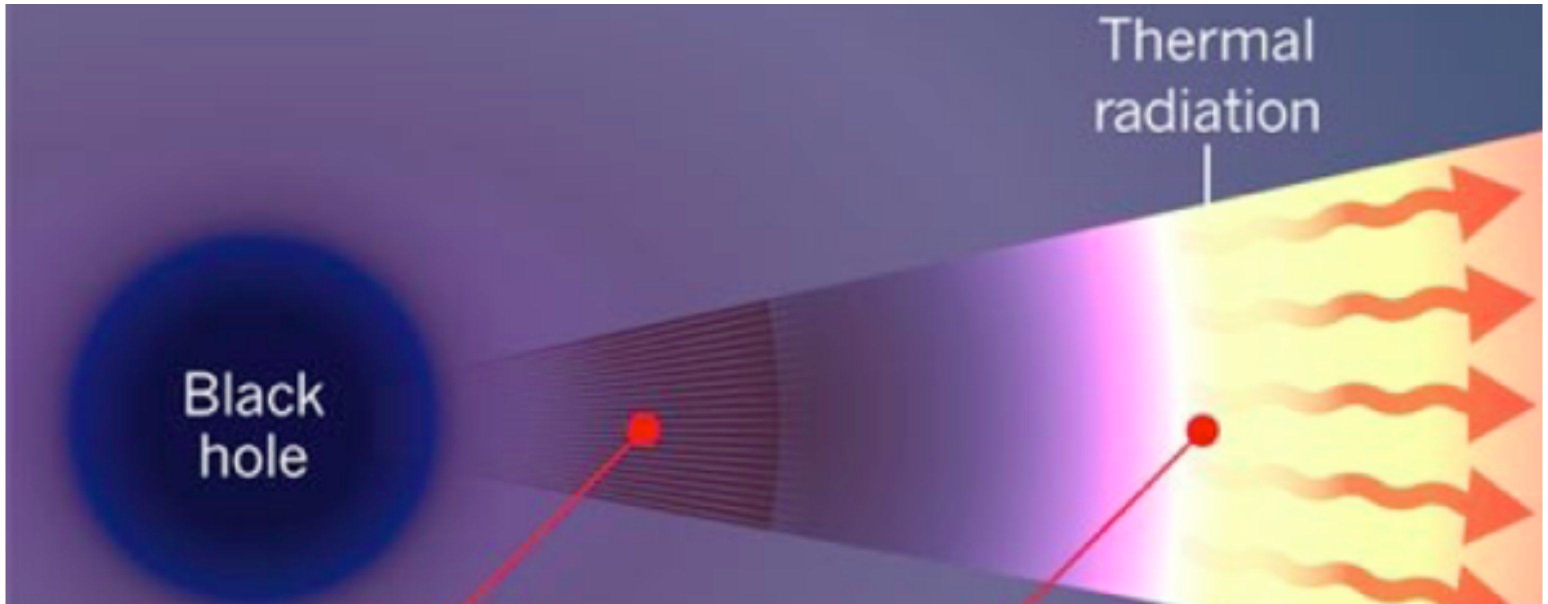
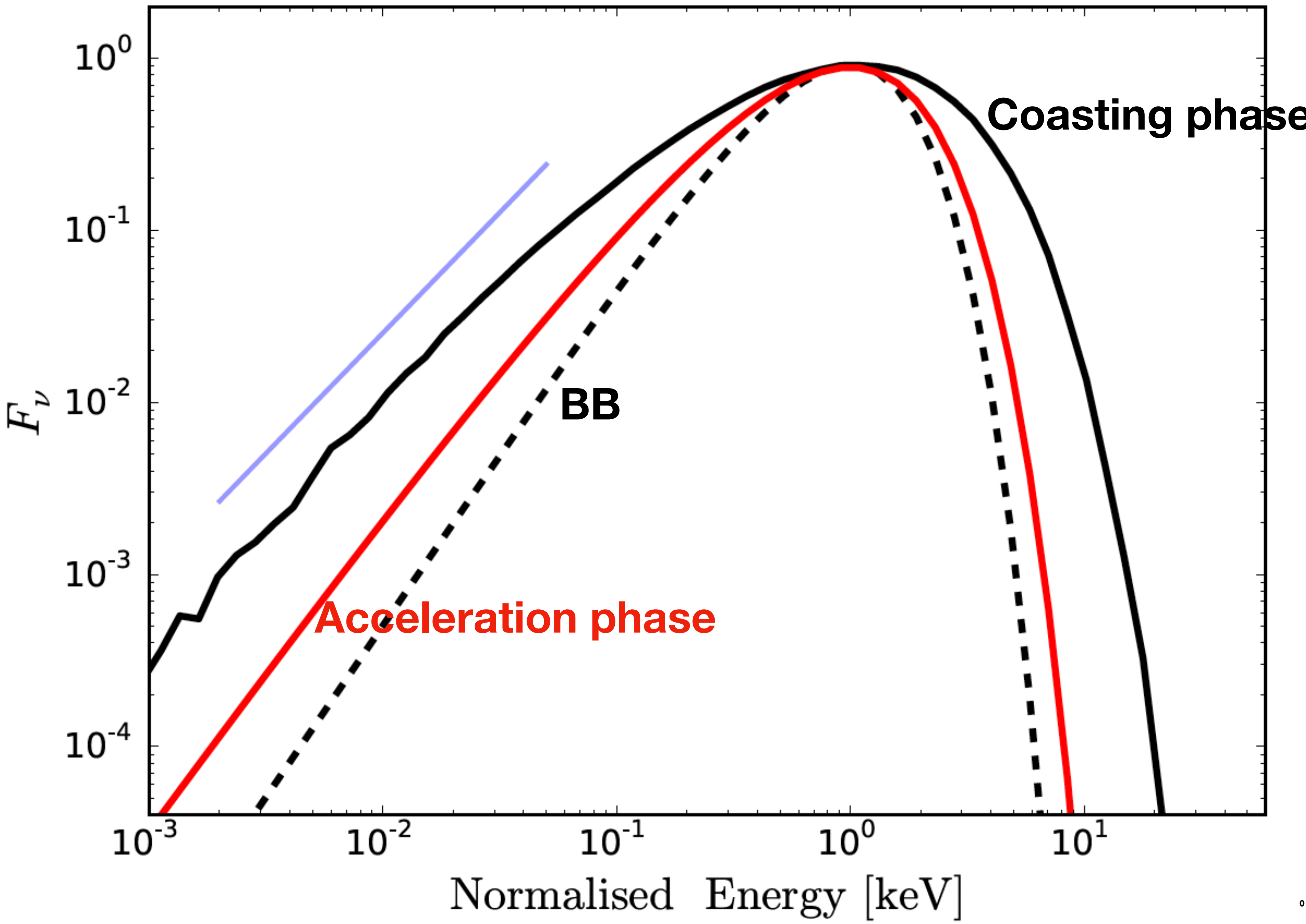
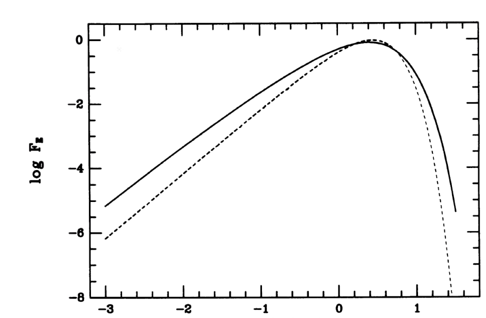




Photosphere in a nondissipative, radiation dominated flow



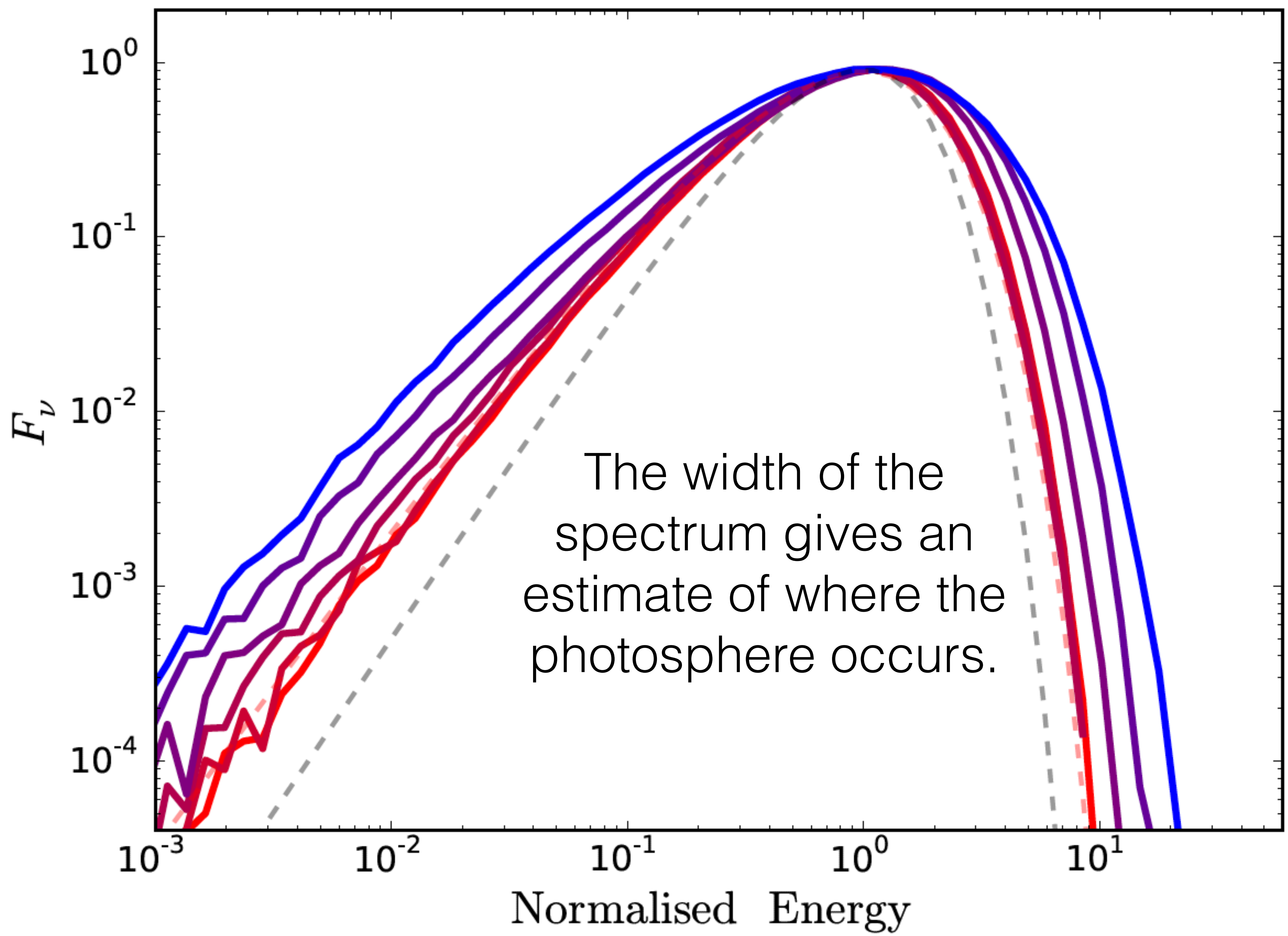
Acceleration phase: $$\frac{\nu L_\nu}{L} = \frac{45}{8\pi^4}\, x^3 \left(\frac{x}{2} - \ln\left[\exp\frac{x}{2} - 1\right]\right)$$



Ryde, Lundman & Acuner (2017)

Nondissipative jet, photospheres in the transition phase

Different values of r_{ph}/r_s



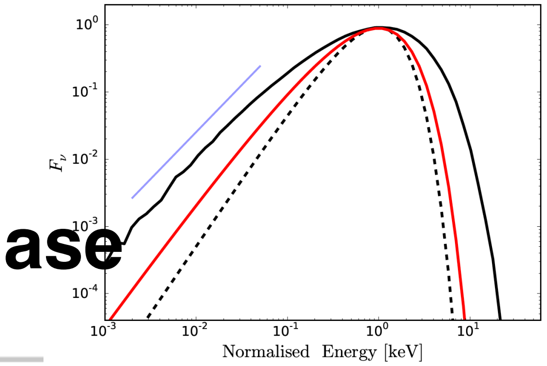
$\eta/\eta_\star = 10^{2.0}$
$\eta/\eta_\star = 10^{1.5}$
$\eta/\eta_\star = 10^{1.0}$
$\eta/\eta_\star = 10^{0.5}$
$\eta/\eta_\star = 10^{0.0}$
$\eta/\eta_\star = 10^{-0.5}$

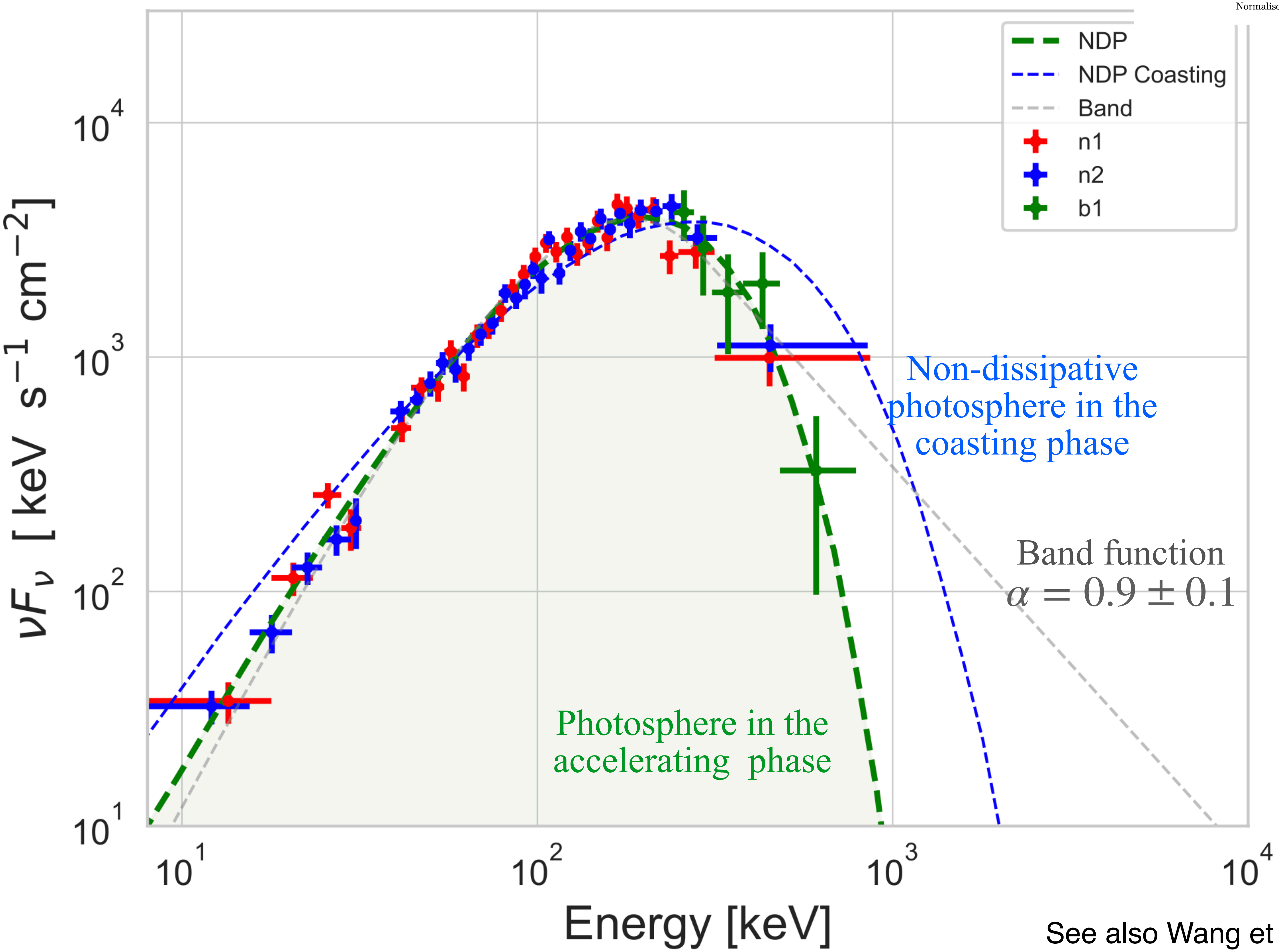
$$\eta_\star \equiv \left(\frac{L\sigma_{\rm T}}{4\pi m_p c^3 r_0}\right)^{1/4}$$

Ryde, Lundman & Acuner (2017)

Example: GRB220426A

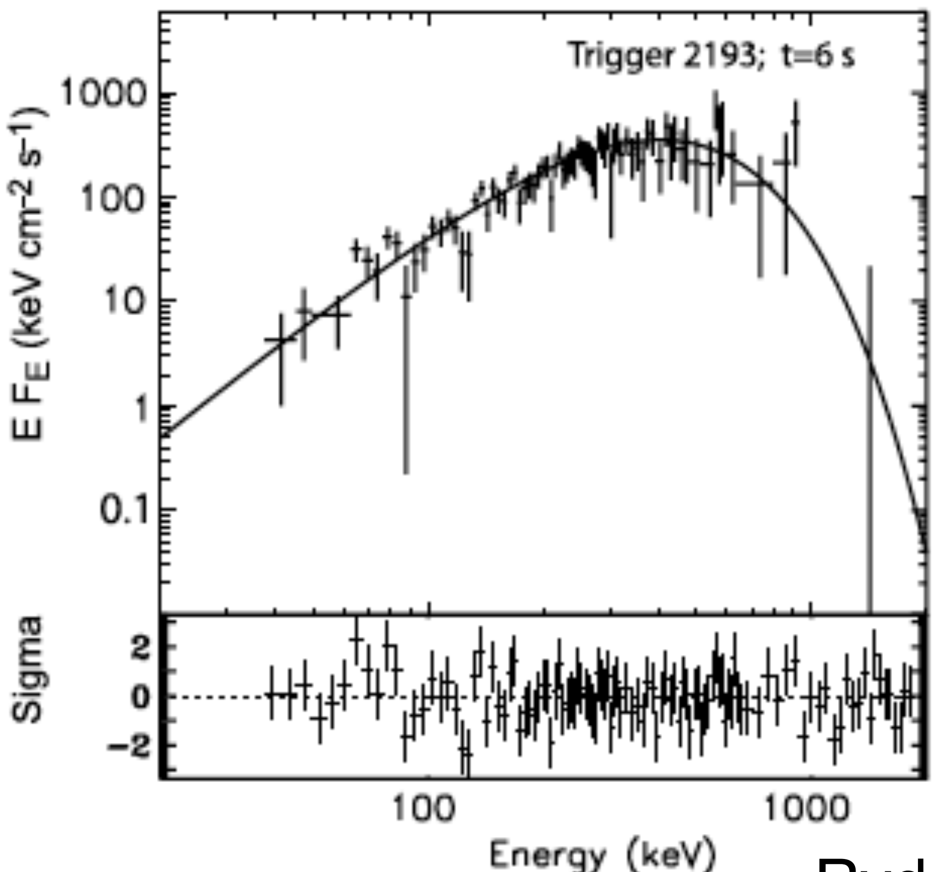
Very narrow spectrum: Photosphere in the accelerating phase



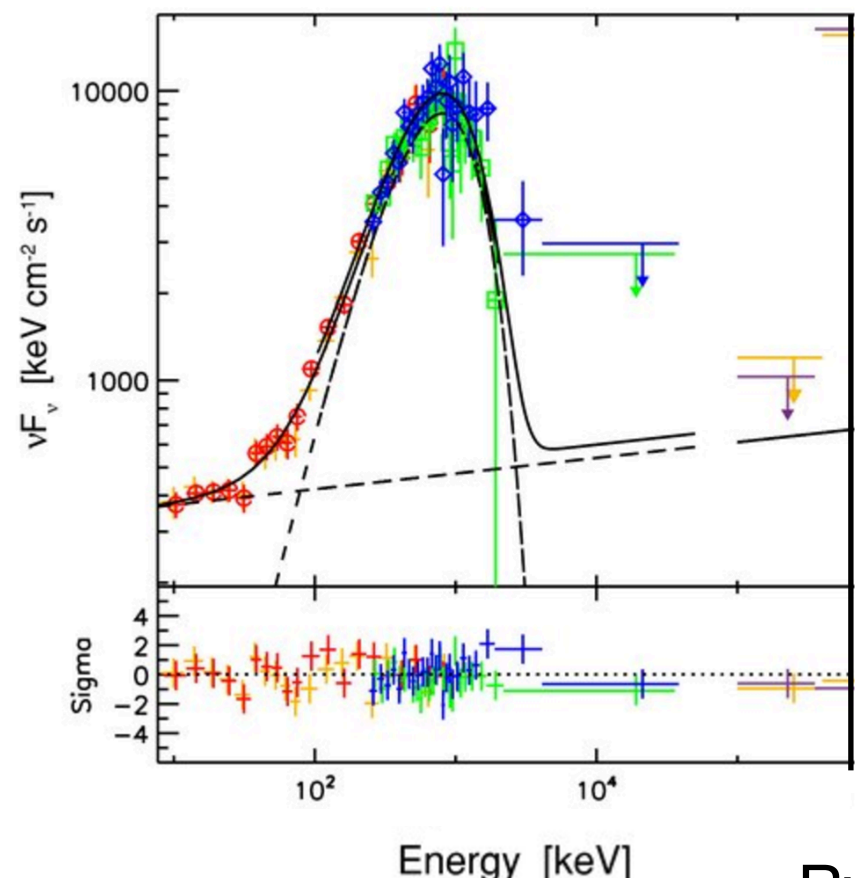


See also Wang et al. (2022)

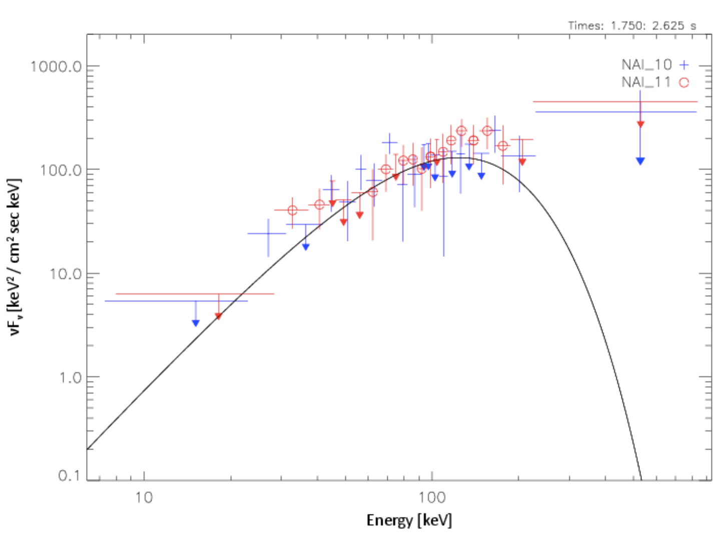
A few per cent of all spectra are quasi-Planckian



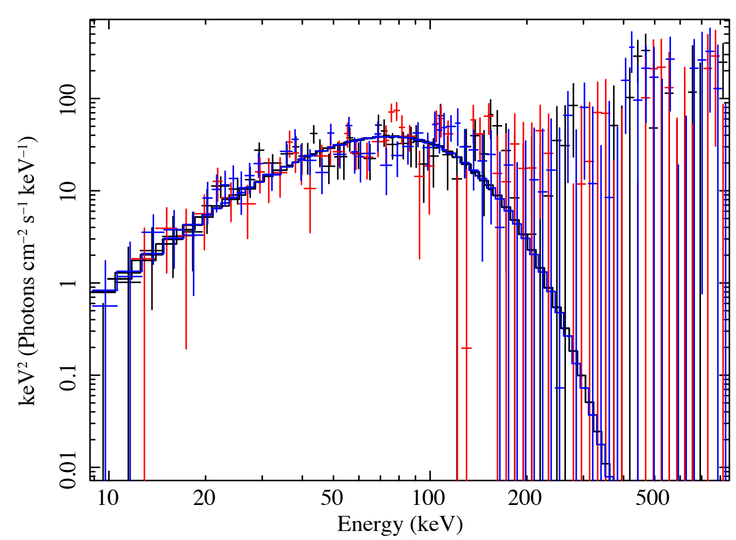
Ryde 2004



Ryde+2010



Ghirlanda+10

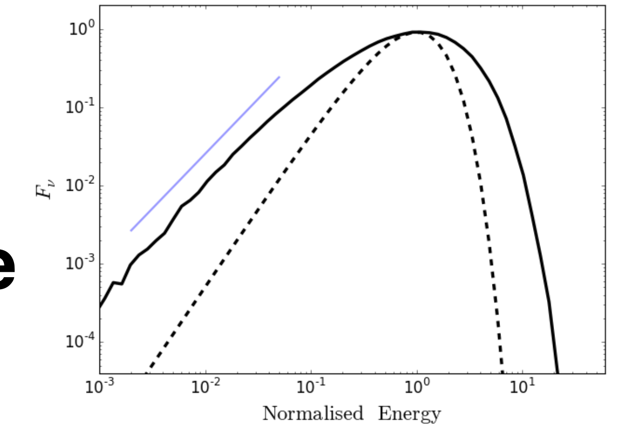


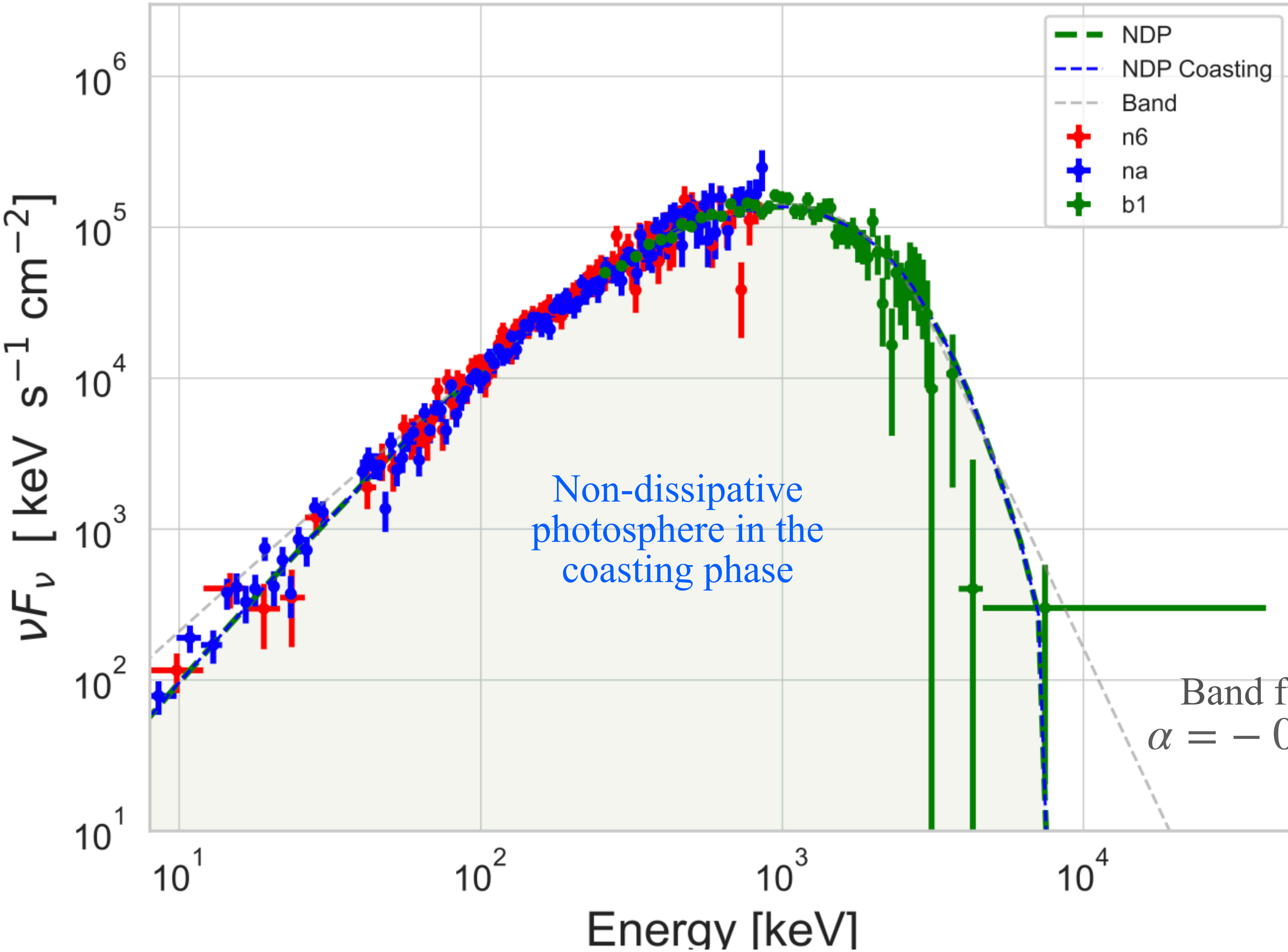
Larsson+15

e.g., Deng+22, Meng+22, Chen+24

Example: GRB230307

Narrow spectrum: Photosphere in the coasting phase

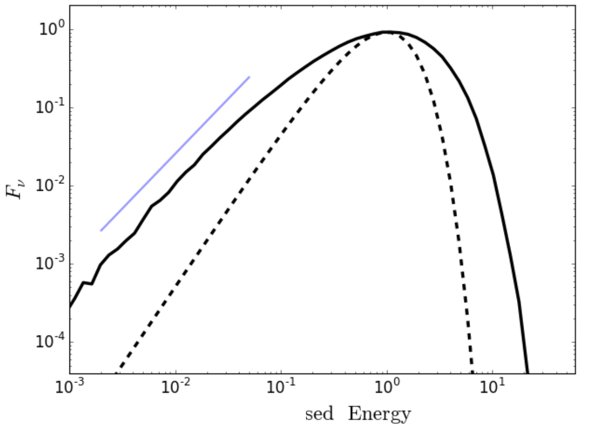


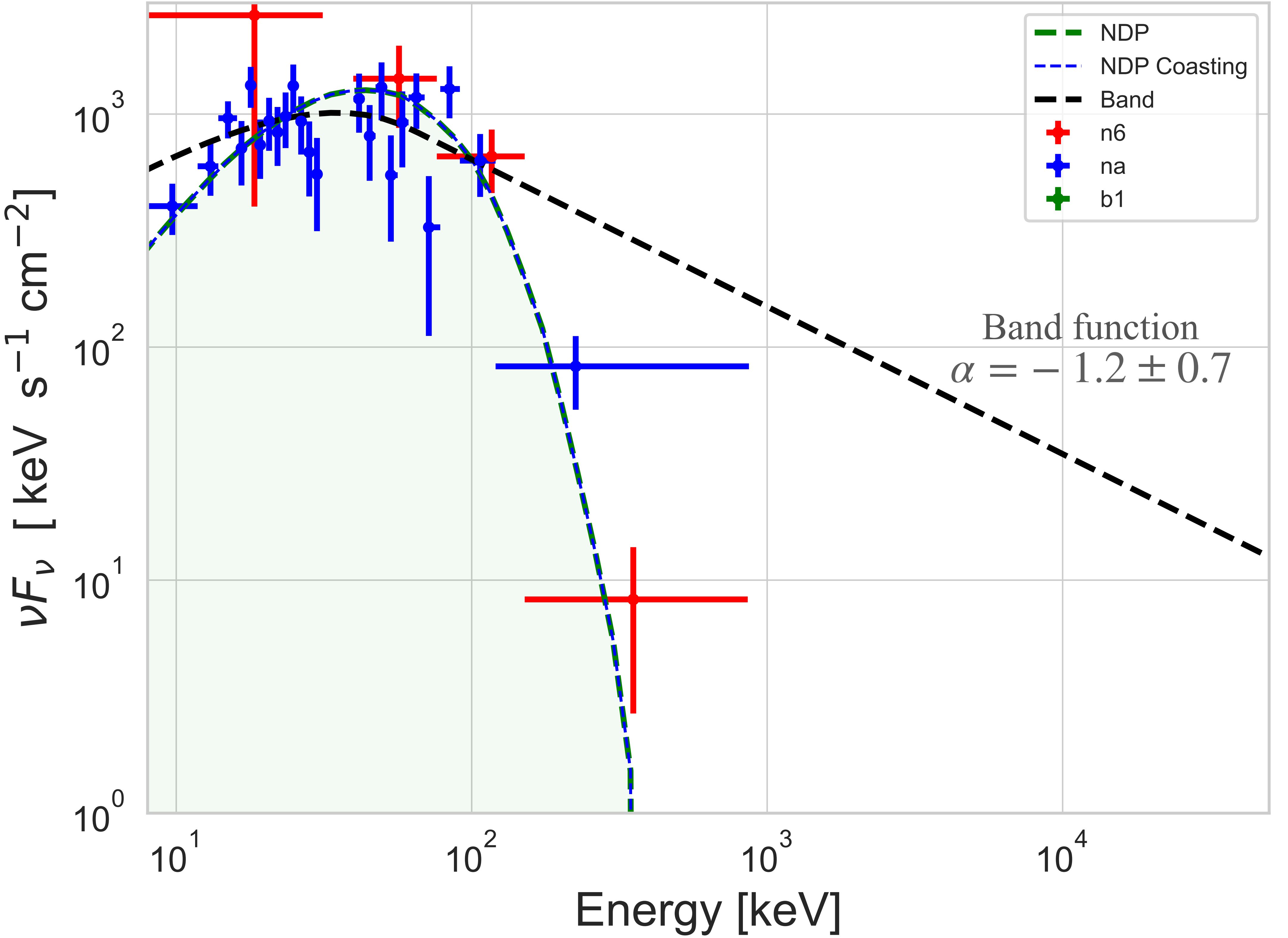


Band function
$\alpha = -0.2 \pm 0.3$

Example: GRB230307

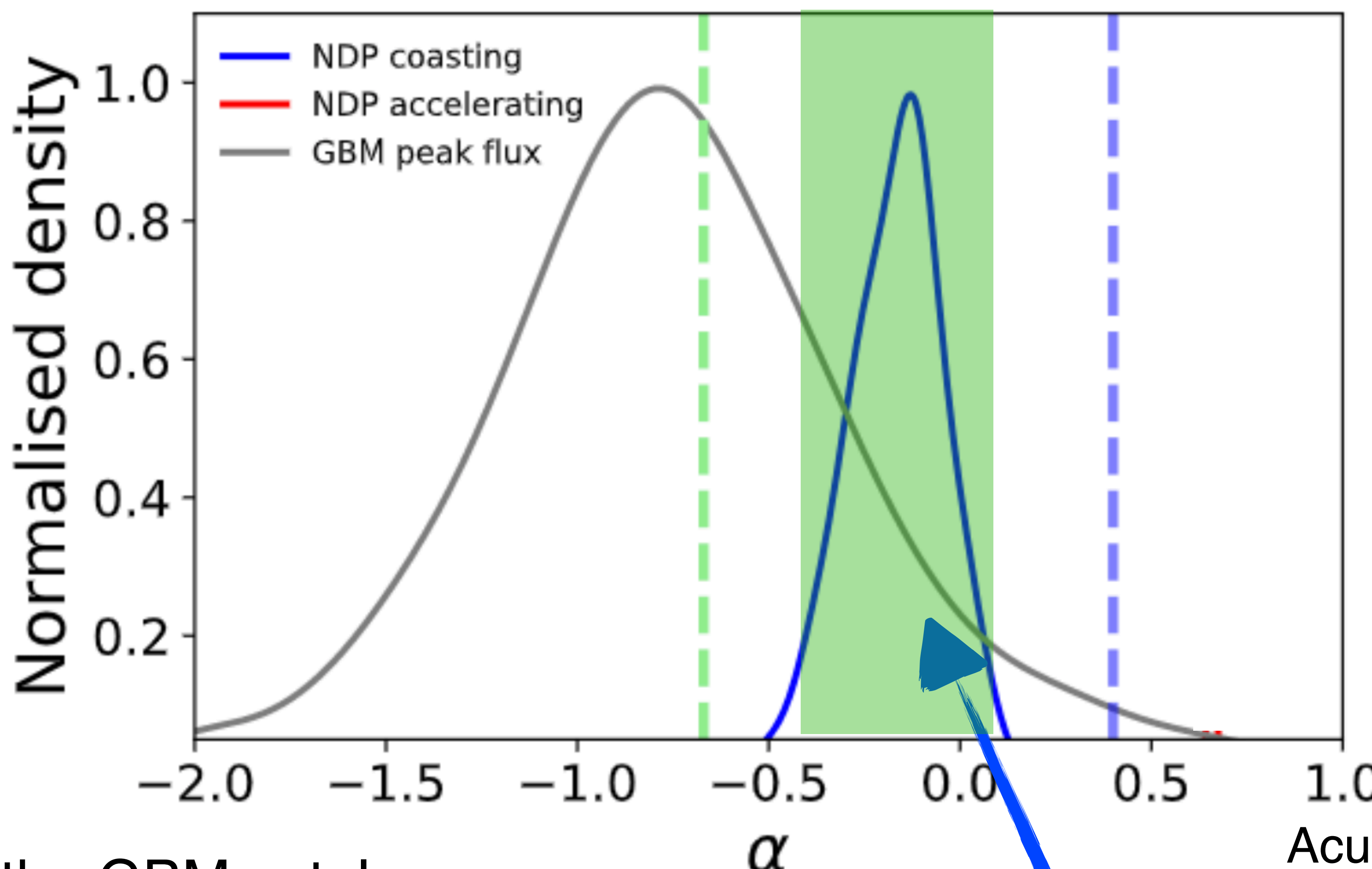
Narrow spectrum: Photosphere in the coasting phase





A quarter of all α-values are consistent with NDP

Distribution of α in the GBM catalogue



E_{pk} from the GBM catalogue

Acuner, Ryde &Yu (2019)

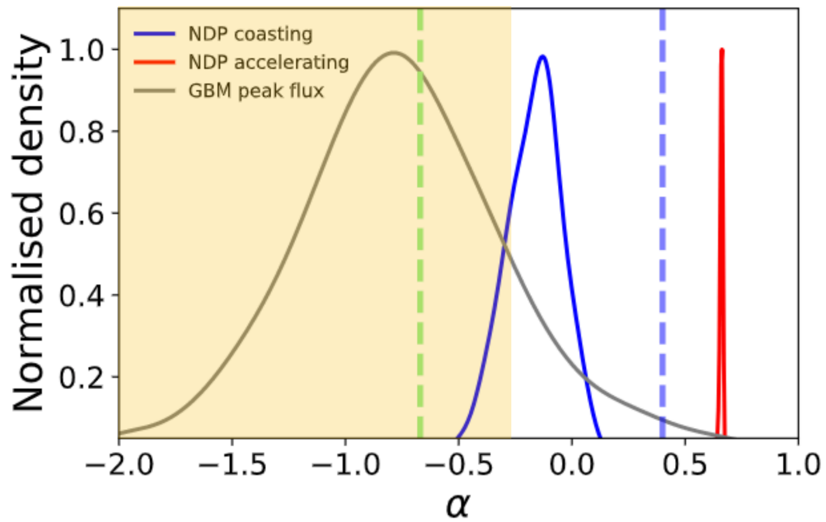
Acuner, Ryde & Pe'er (2020)

Expected range of α from the photosphere

1/4 of all burst have α-values consistent with non-dissipative photospheres

What about the other 3/4 ?

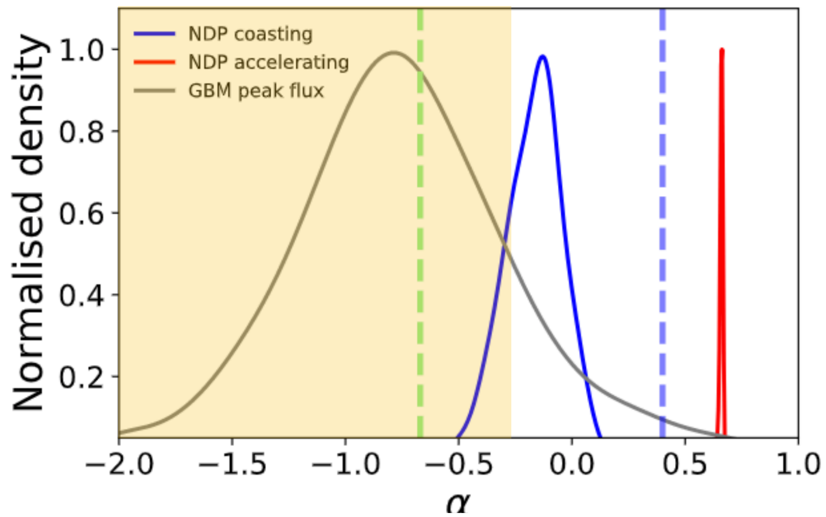
These spectra are broader than photospheric spectra



- Additional radiation processes, e.g. optically-thin synchrotron emission
- Multiple emission components, photosphere + synchrotron
- Viewing angle and Lorentz profile
- Smearing in time: enough time resolution?
- Subphotospheric heating (Rees & Meszaros 05, Pe’er+06)

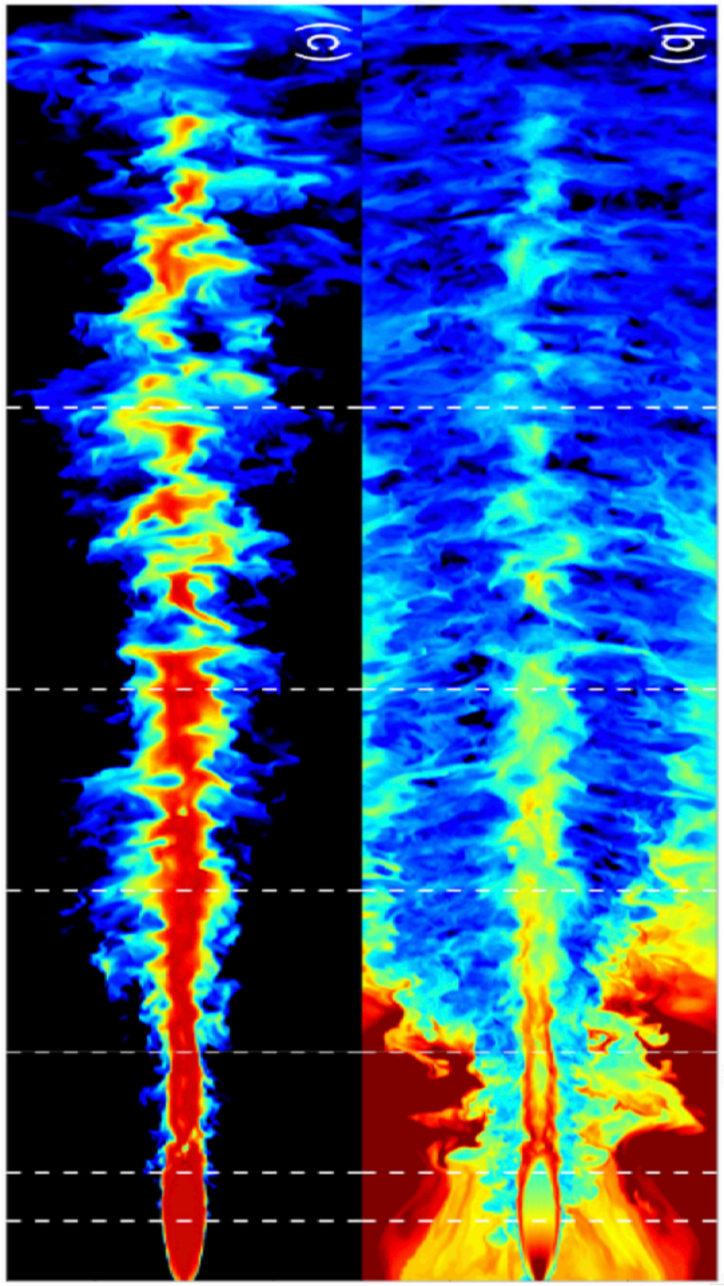
What about the other 3/4 ?

These spectra are broader than photospheric spectra



- Subphotospheric heating
- Alters the spectrum
- Shocks are radiation mediated
- Previously no radiation mediated shock (RMS) model has been fitted to data

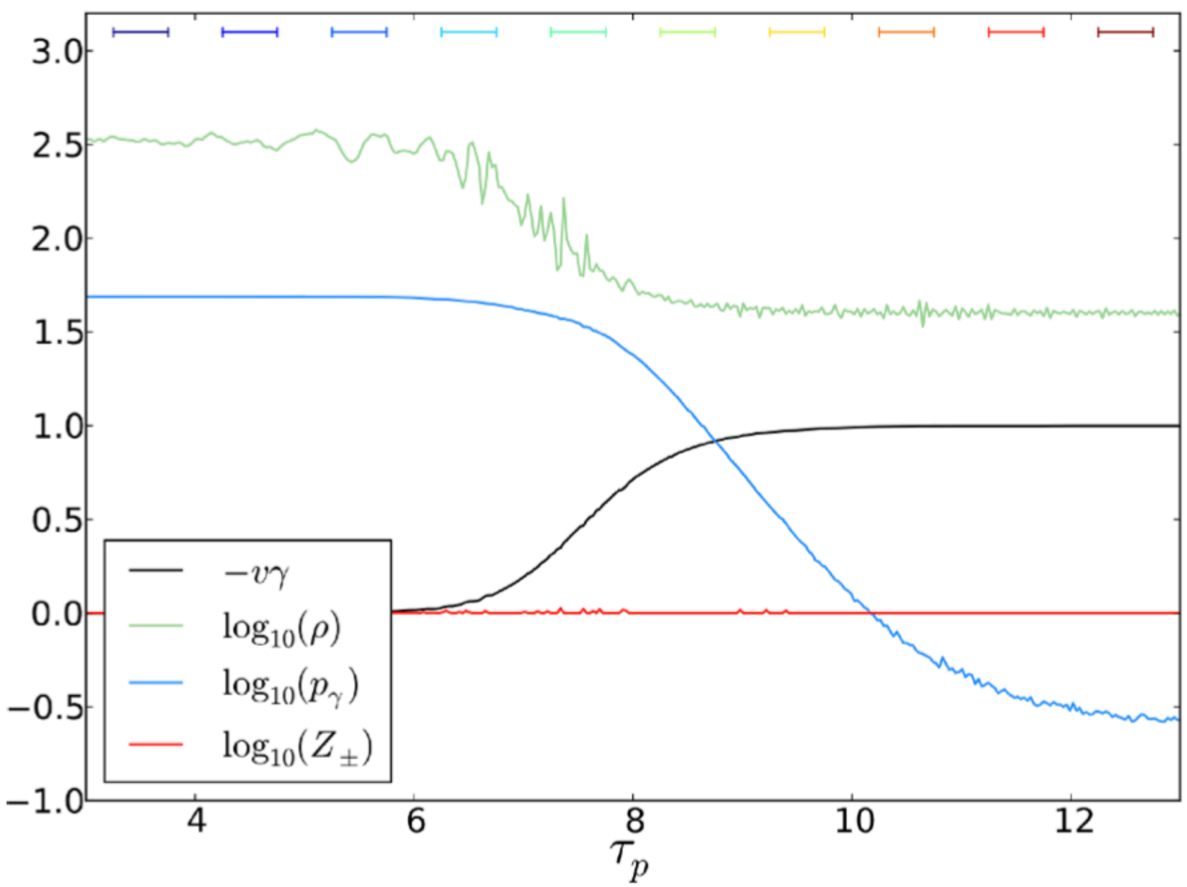
Eichler (1994), Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Katz+ (2010), Budnik+ (2010), Levinson (2012), Beloborodov (2017), Ito+ (2018), Levinson & Nakar (2020)

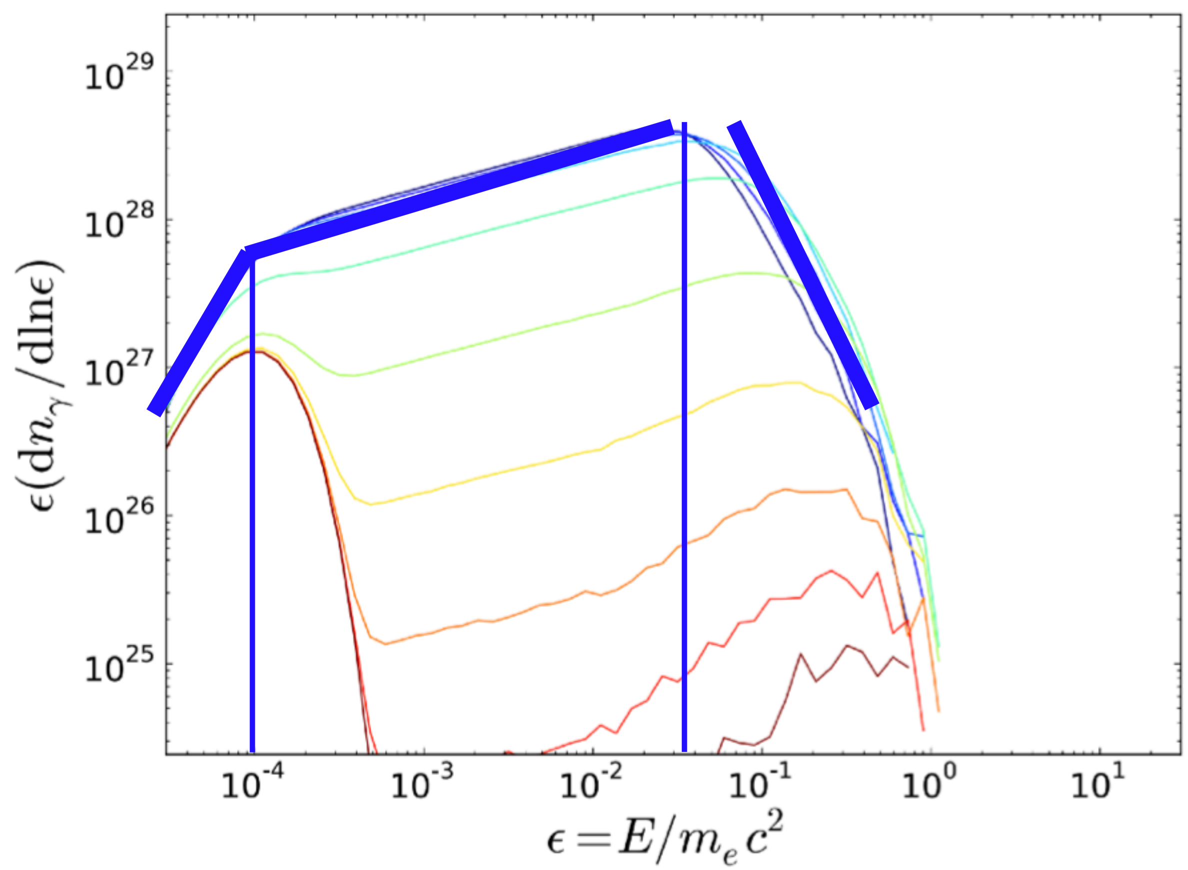


Gottlieb+ (2020)

Non relativistic photon-rich RMS

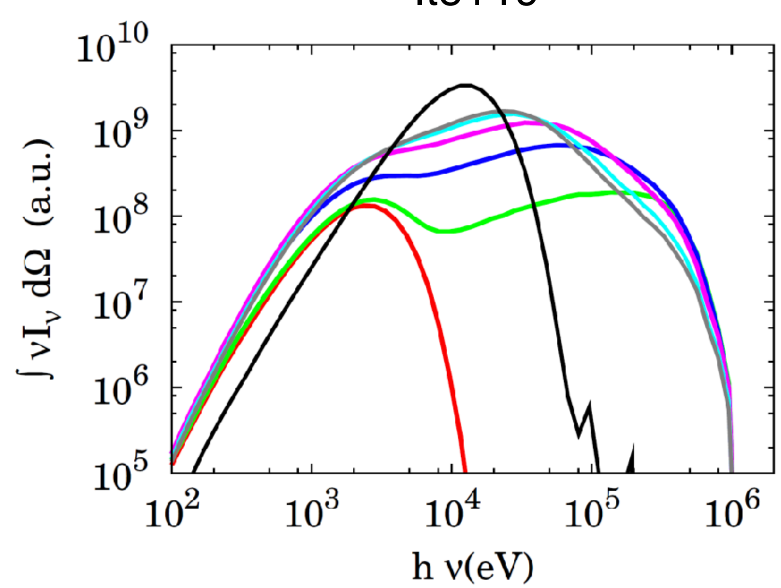
- Smoother, more predictable profile compared to relativistic RMS
- Computationally heavy to run





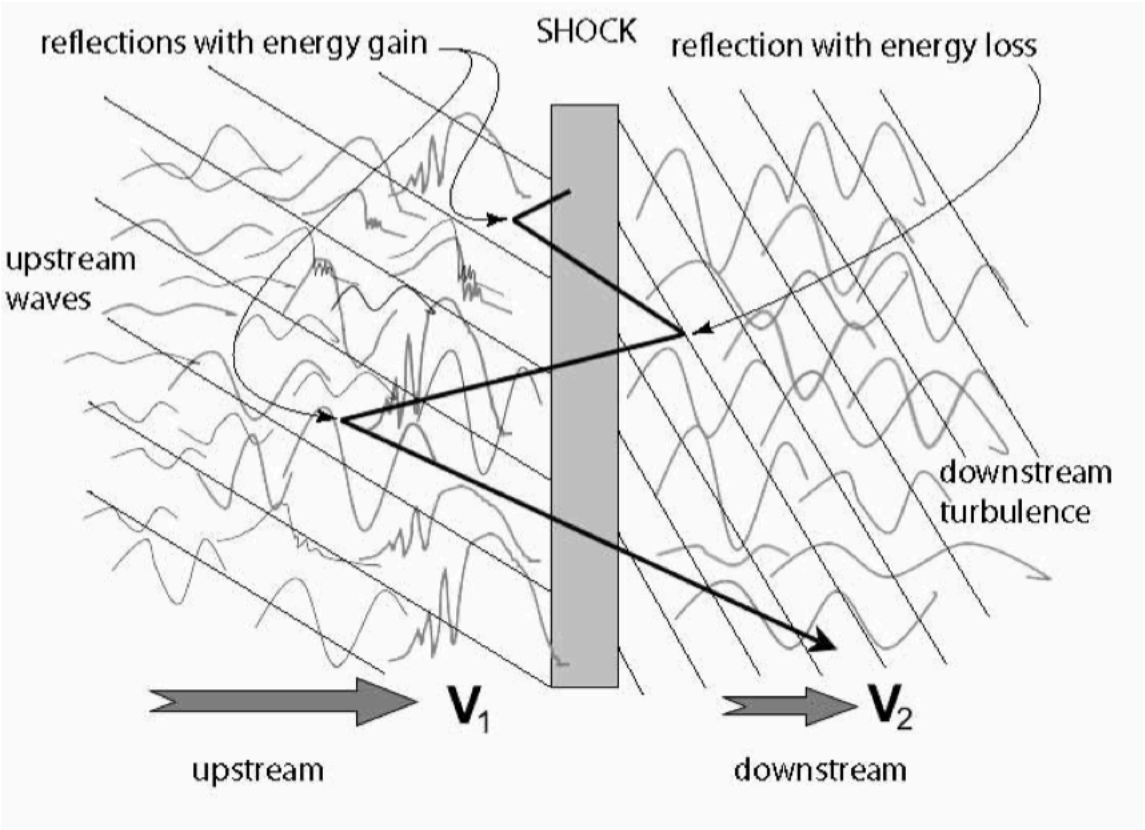
Lundman+ (2018)

Ito+19



Analogous to Fermi type acceleration

- In Fermi shock acceleration, particles scatter back and forth across the shock, gaining energy on average
- An RMS is similar, but it is the photons themselves that scatter and the particles are cold
- A photon-rich RMS forms a power-law spectrum

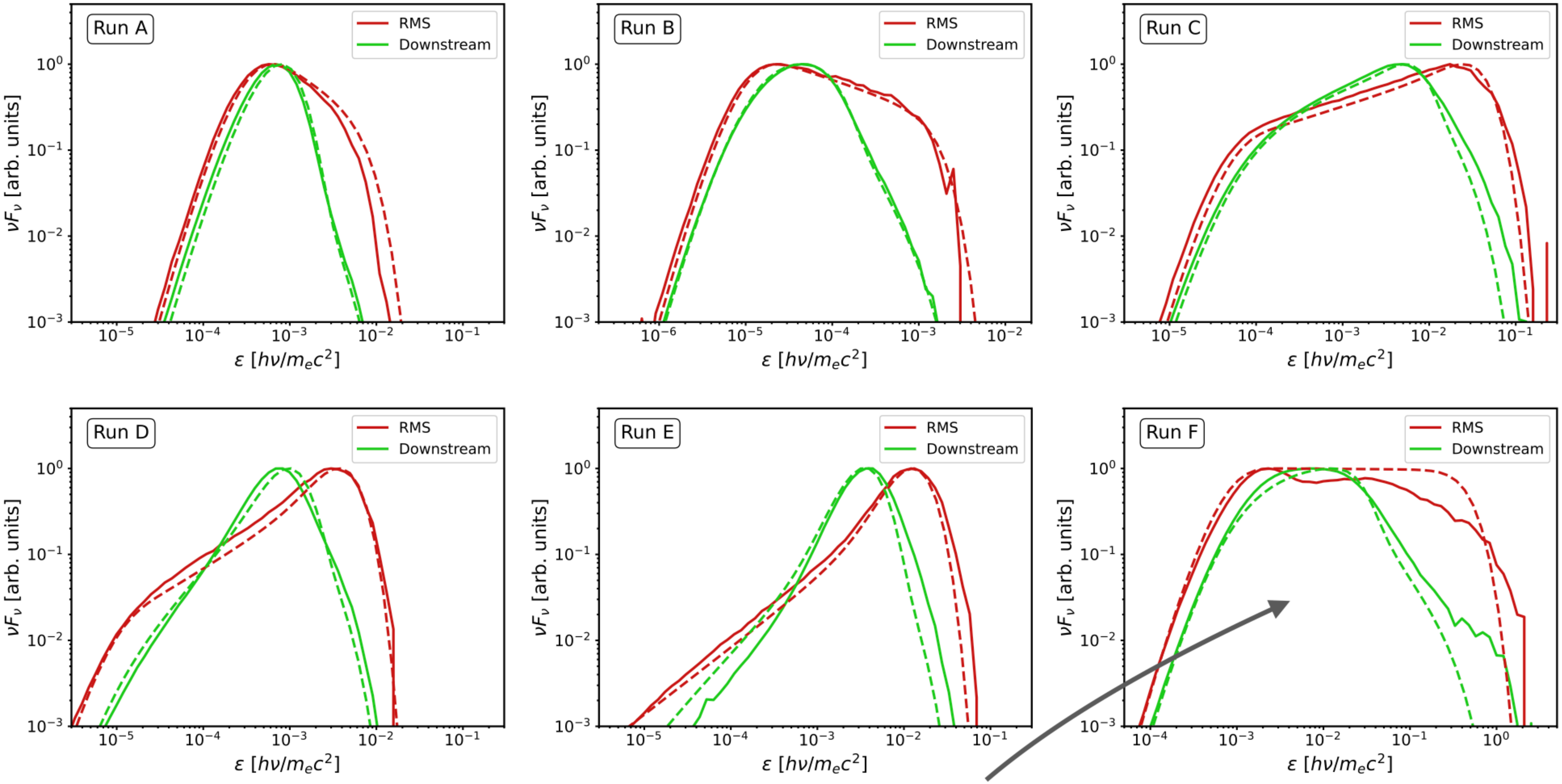


Treumann & Jaroschek (2008)

Fermi-type photon energy gain across RMS ≈ repeated scatterings with hot electrons

Evolution described by the Kompaneets equation

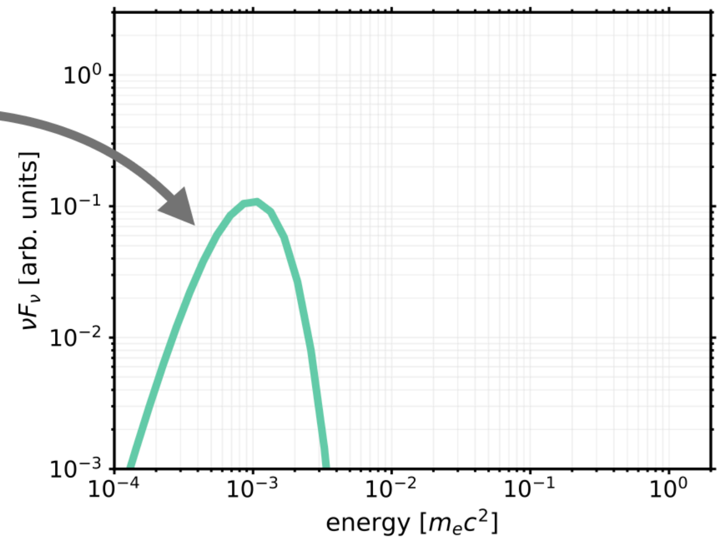
The KRA (Kompaneets RMS Approximation)

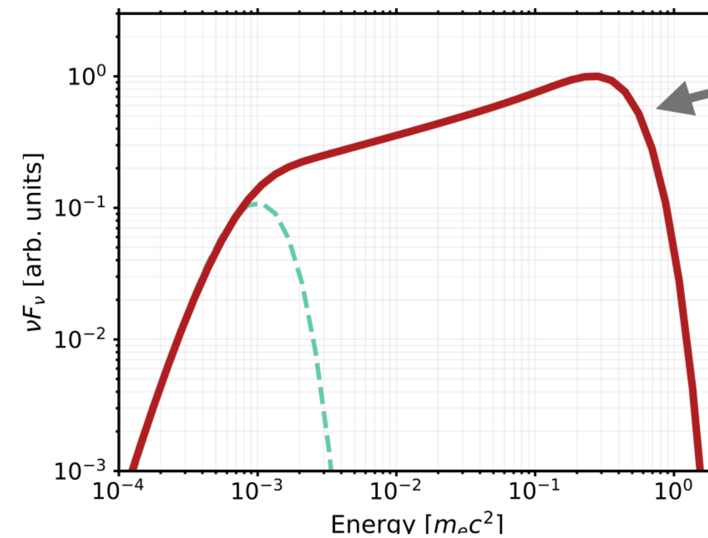


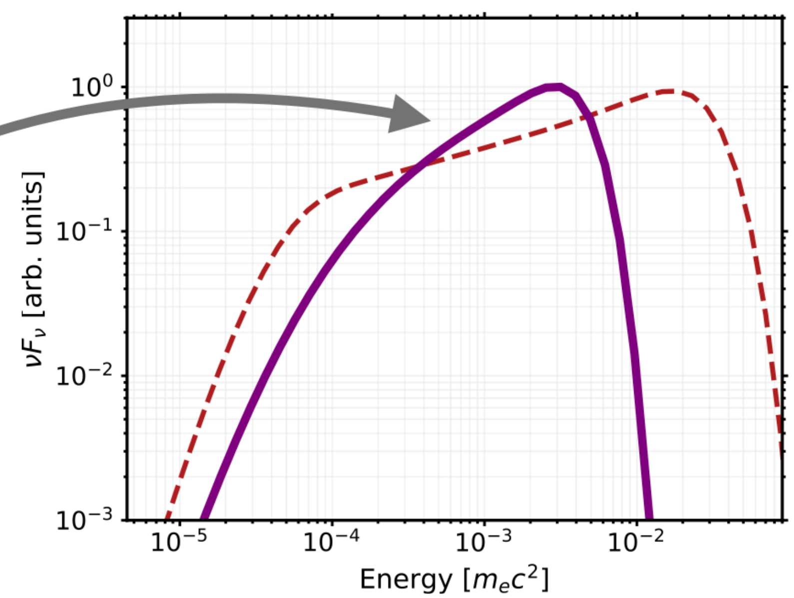
Mildly relativistic shock: $(\beta\gamma)_{\mathrm{u}} = 3$

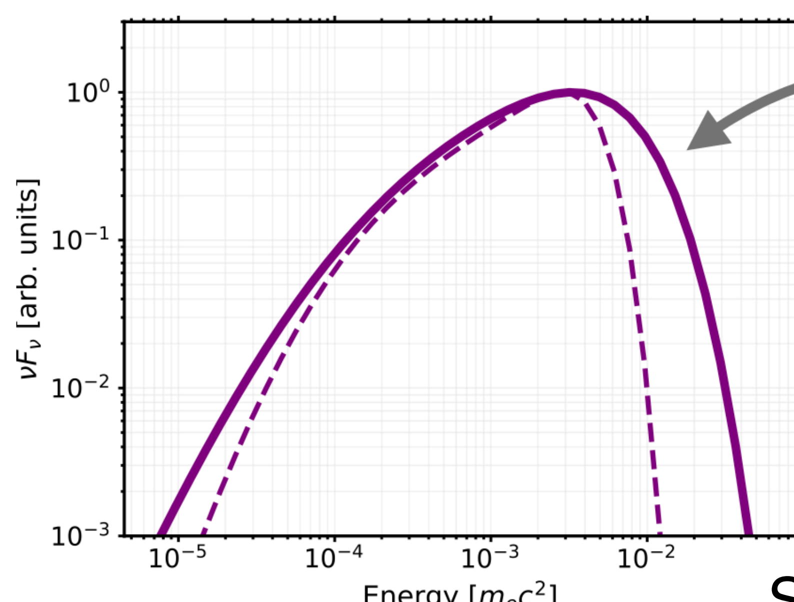
Samulesson, Lundman & Ryde (2022)

The KRA (Kompaneets RMS Approximation)





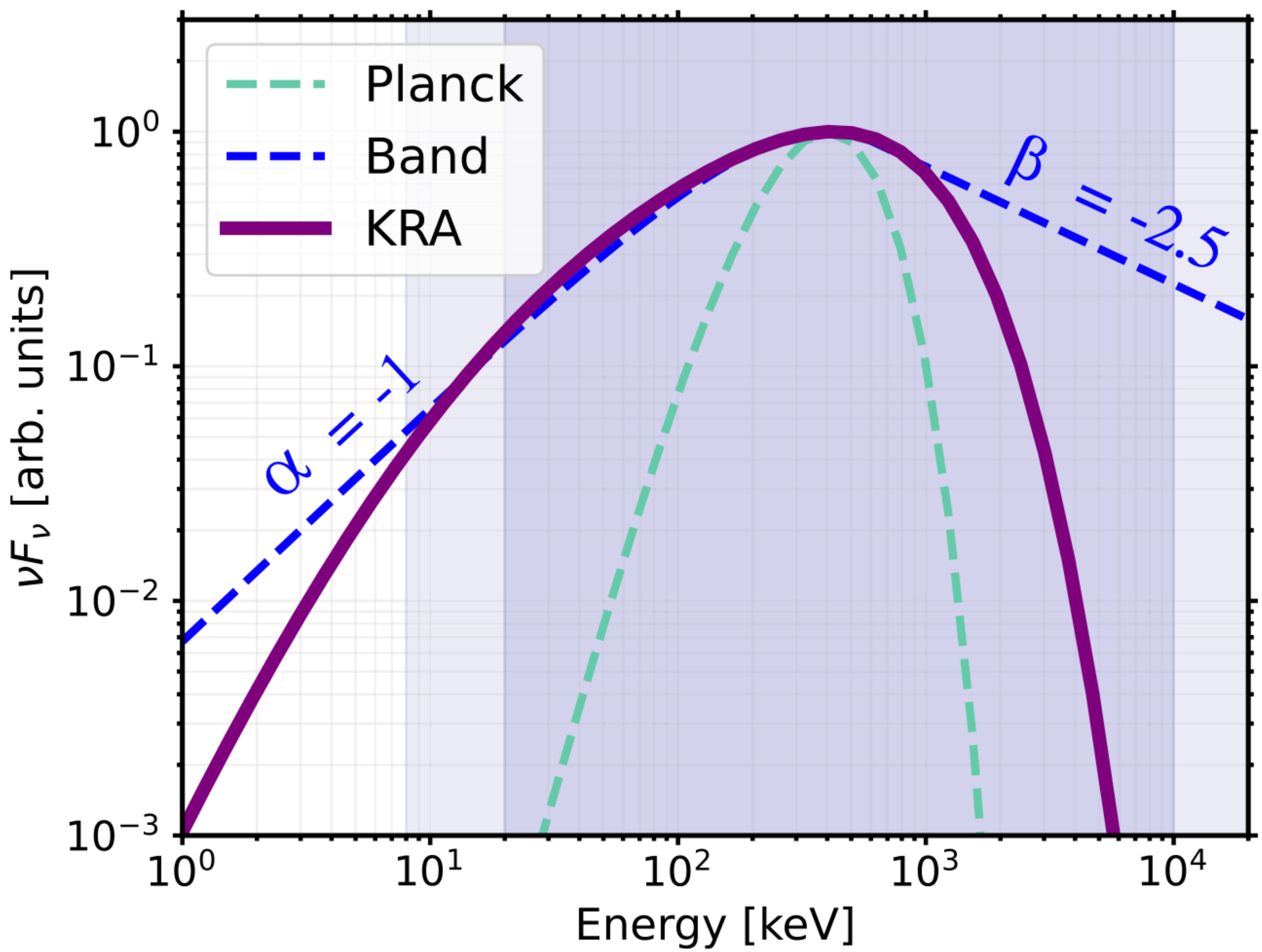




Samulesson, Lundman & Ryde (2022)

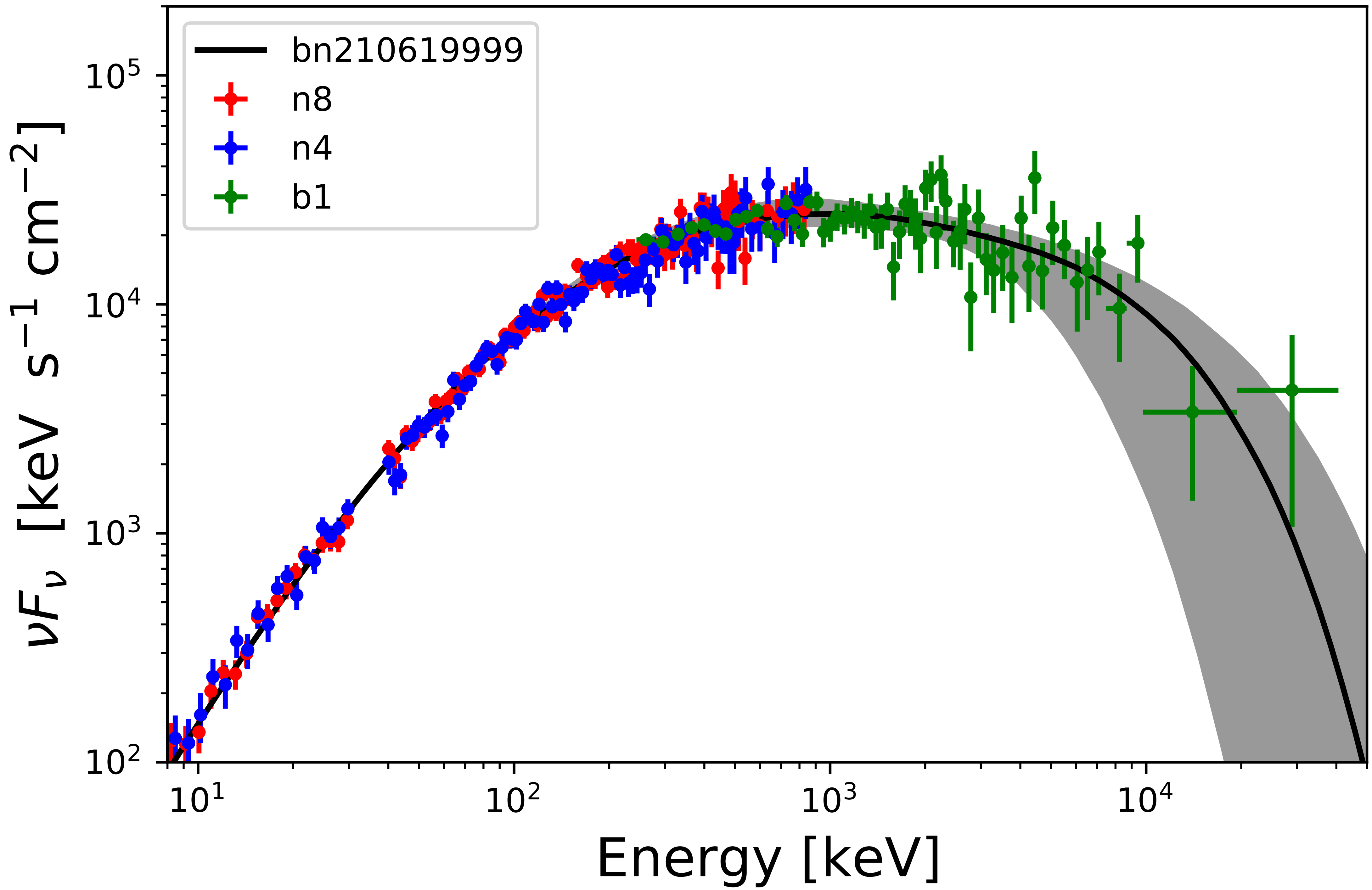
Radiation mediated shocks - observed spectrum

- Broad
- Soft
- Smooth curvature
- Similar to observations



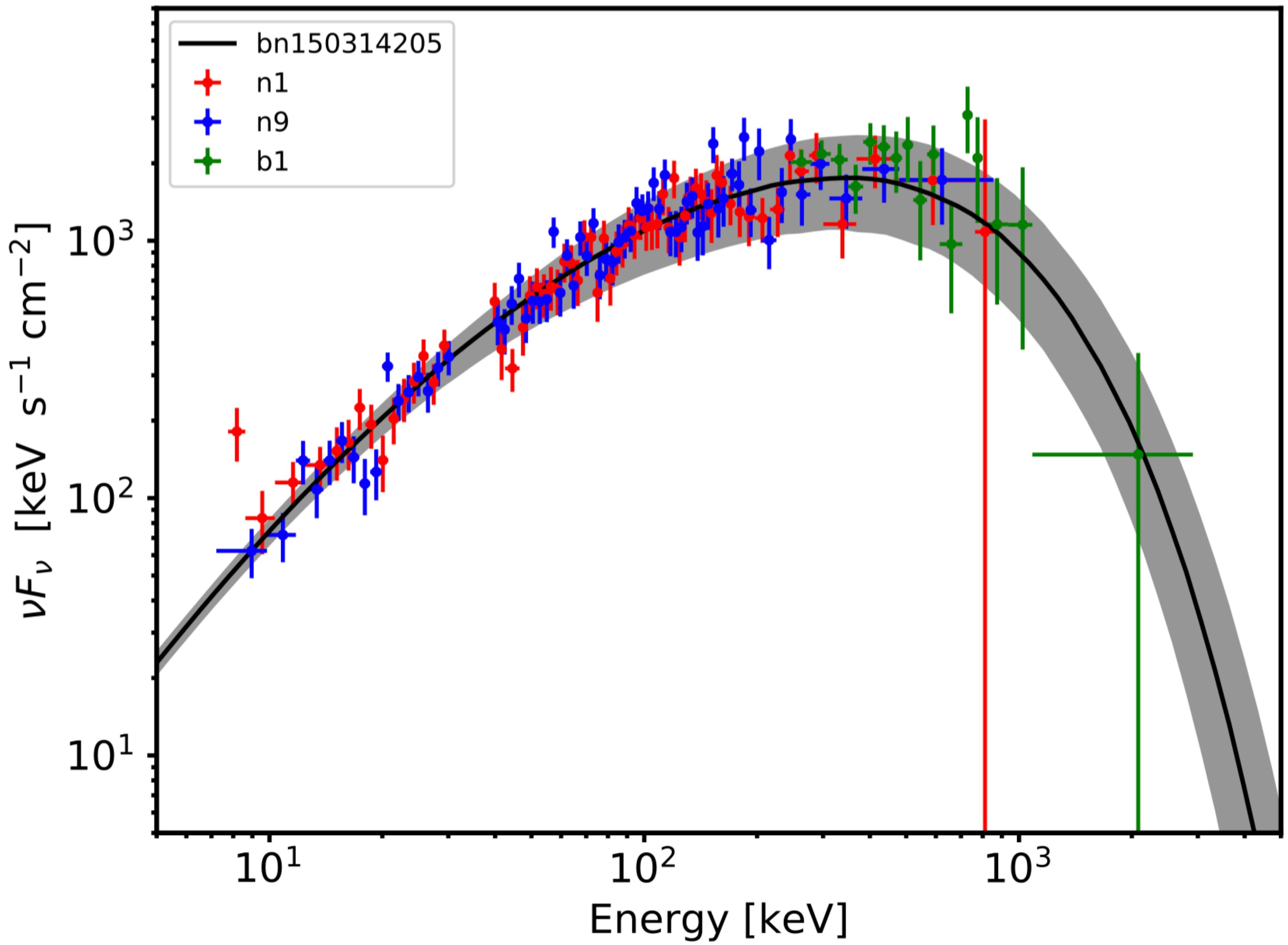
Example: GRB210619

RMS model fit to time resolved data



Example: GRB150314A

RMS model fit to time resolved data



RMS model parameters

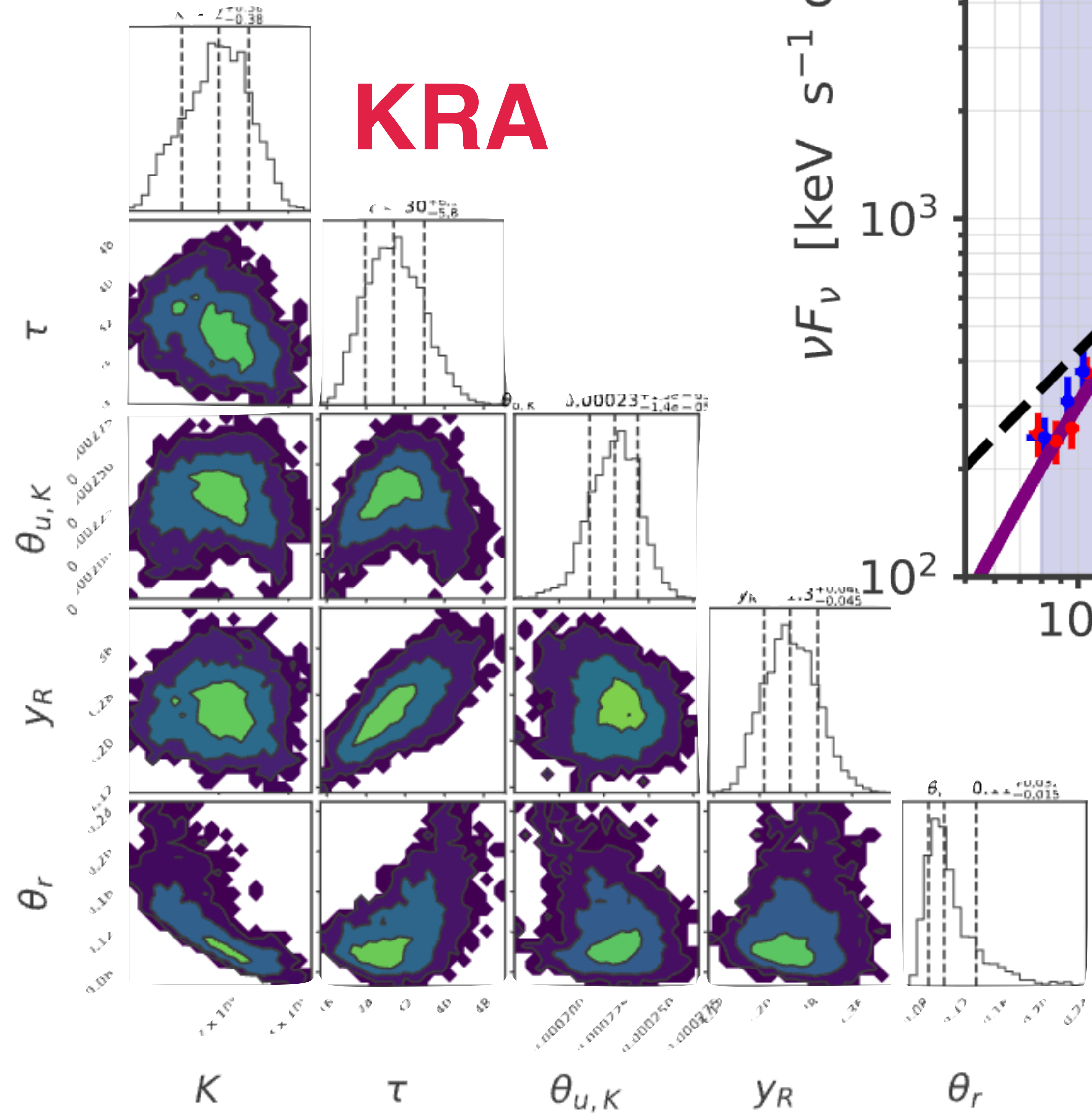
$$(\beta\gamma)_{\rm u} = 1.89, \quad \theta_{\rm u} = 8.8 \times 10^{-5}, \quad \frac{n_\gamma}{n} = 2.0 \times 10^5$$

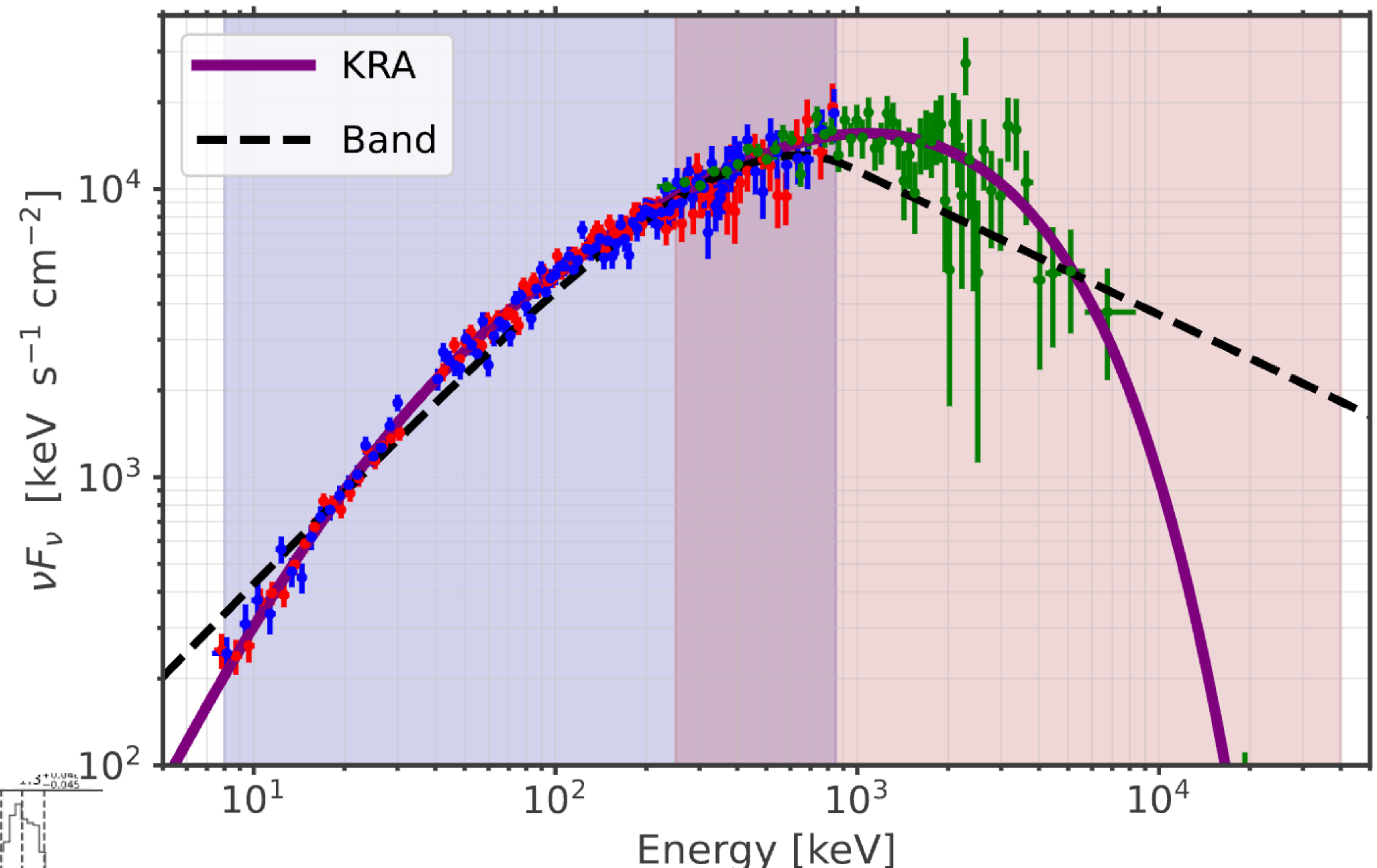
Samulesson, Lundman & Ryde (2022)

Example: GRB211211A

Two distinct spectral breaks:
marginally fast cooling synchrotron (Gompertz+23), multiple components (Peng+24)

KRA





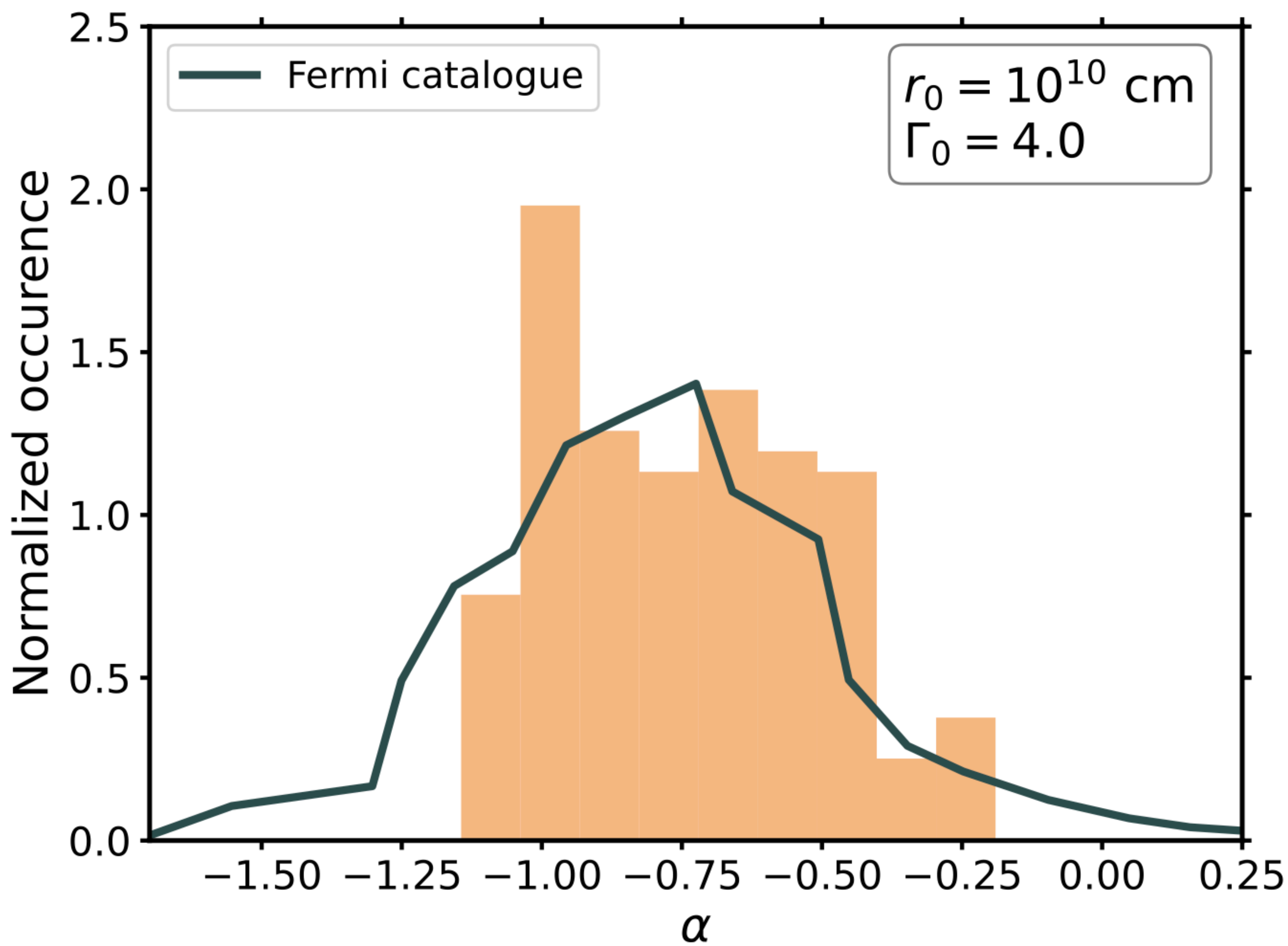
RMS

τ	θ_u	$\gamma_u \beta_u$	ζ	Γ
20	5×10^{-4}	2.3	3×10^5	250

Wistemar, Samulesson & Ryde (in prep)

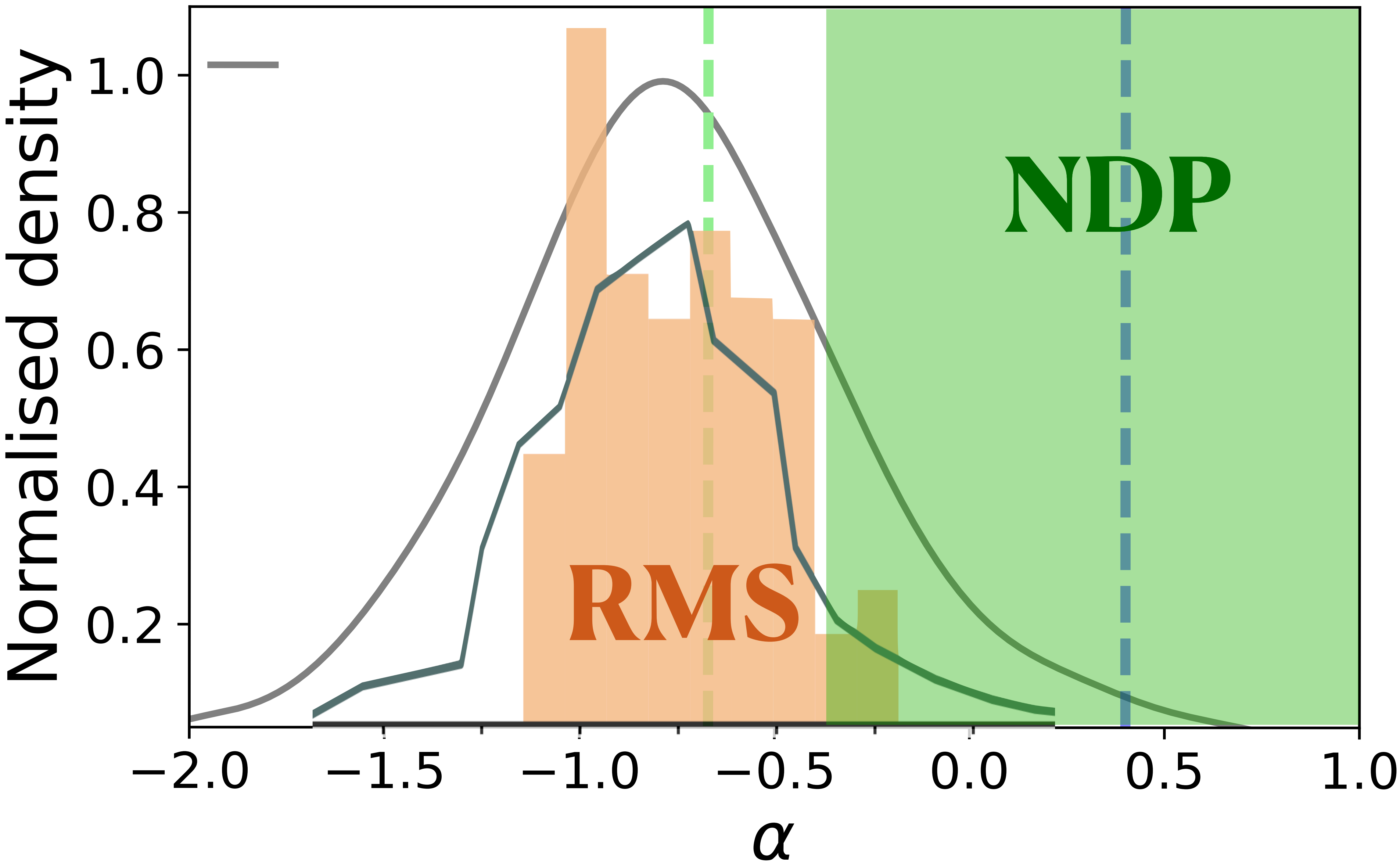
Quantitative comparison against observations

- 150 synthetic RMS spectra
- Fitted with a Band function
- Comparison with catalogued α-values are promising



Samuelsson & Ryde (2023)

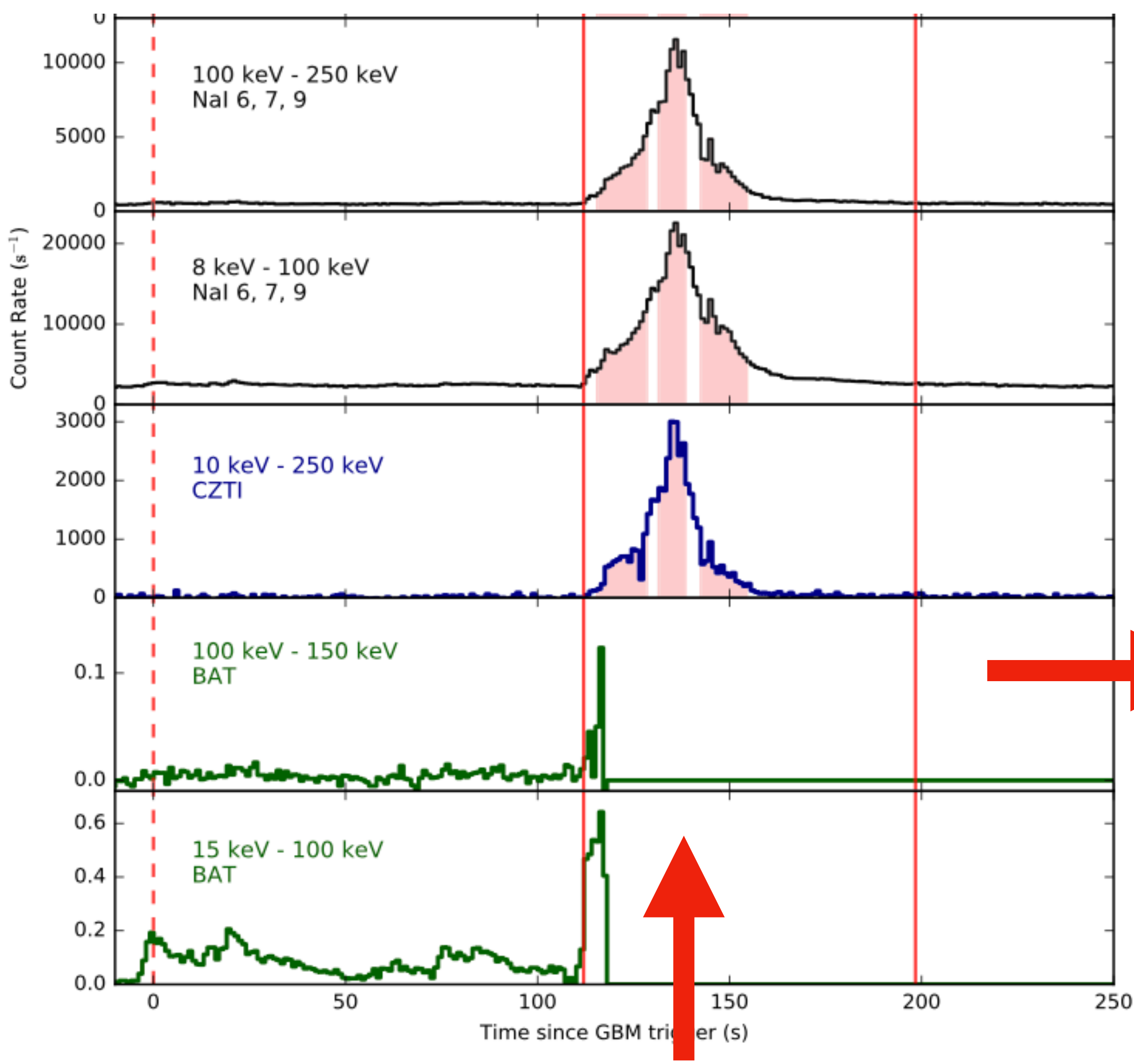
Catalogue distribution of α

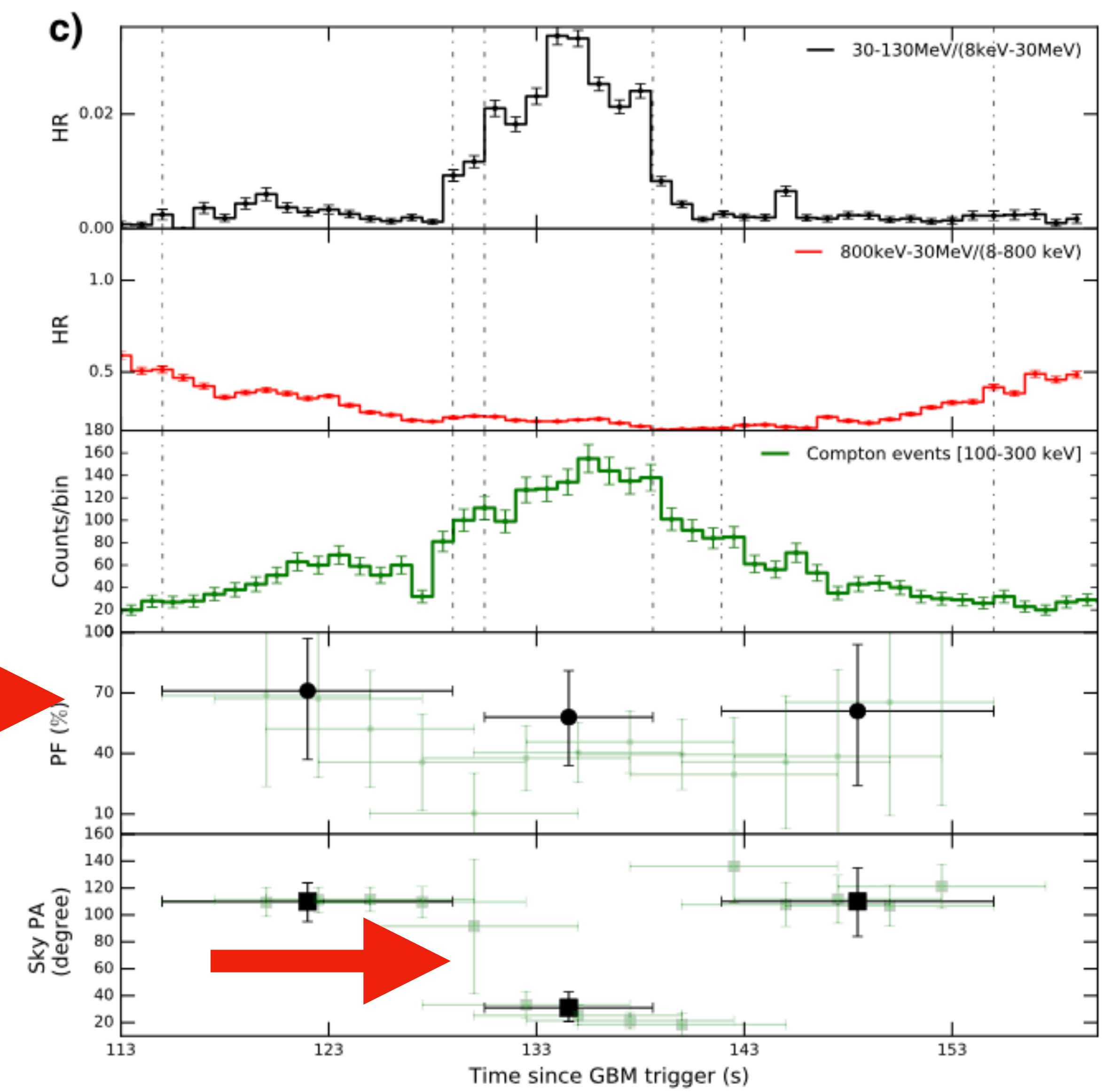


Samuelsson & Ryde (2023)

Example: GRB160821A

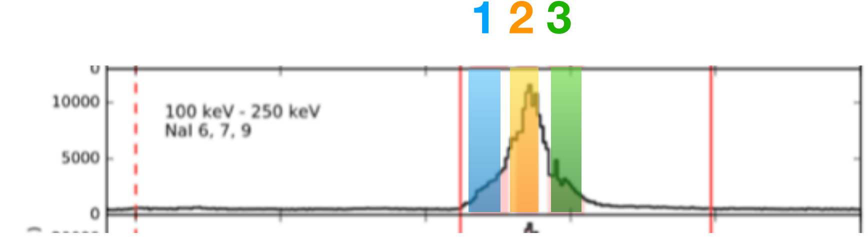
A clear case of synchrotron emission

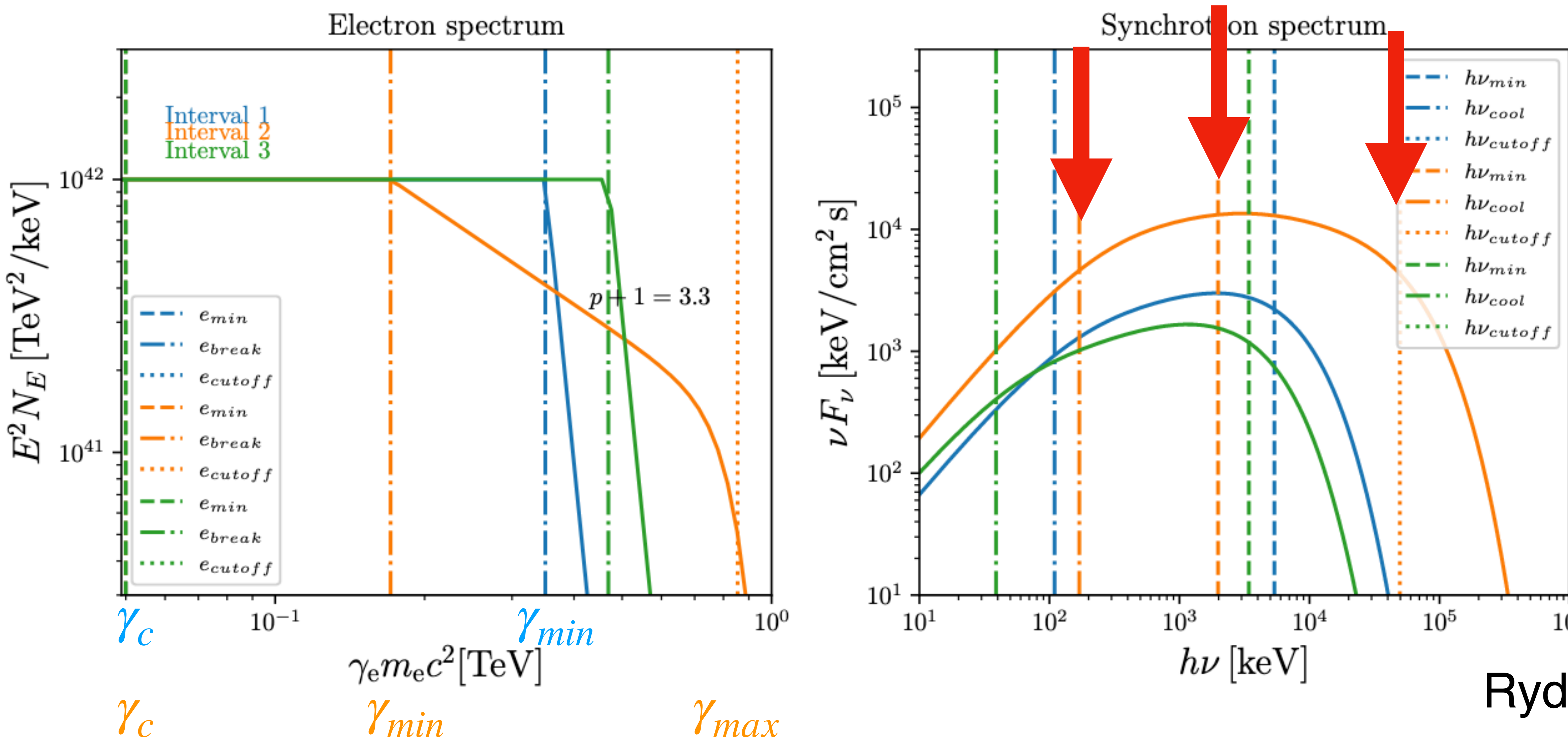




Sharma+19; Ravasio+19; Gill+20

Synchrotron emission in 160821A



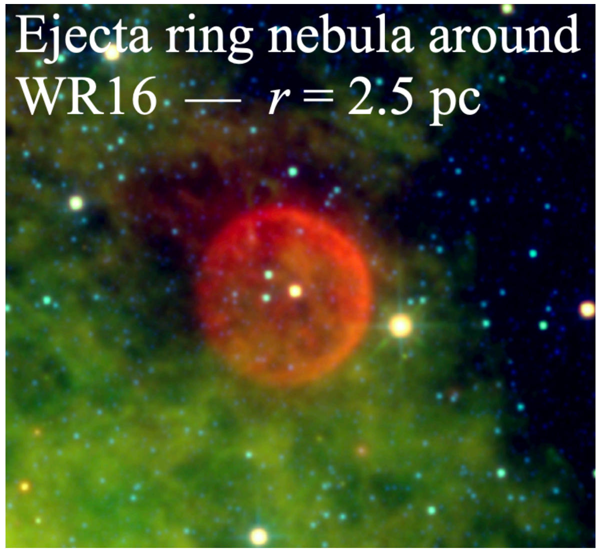


Ryde+22

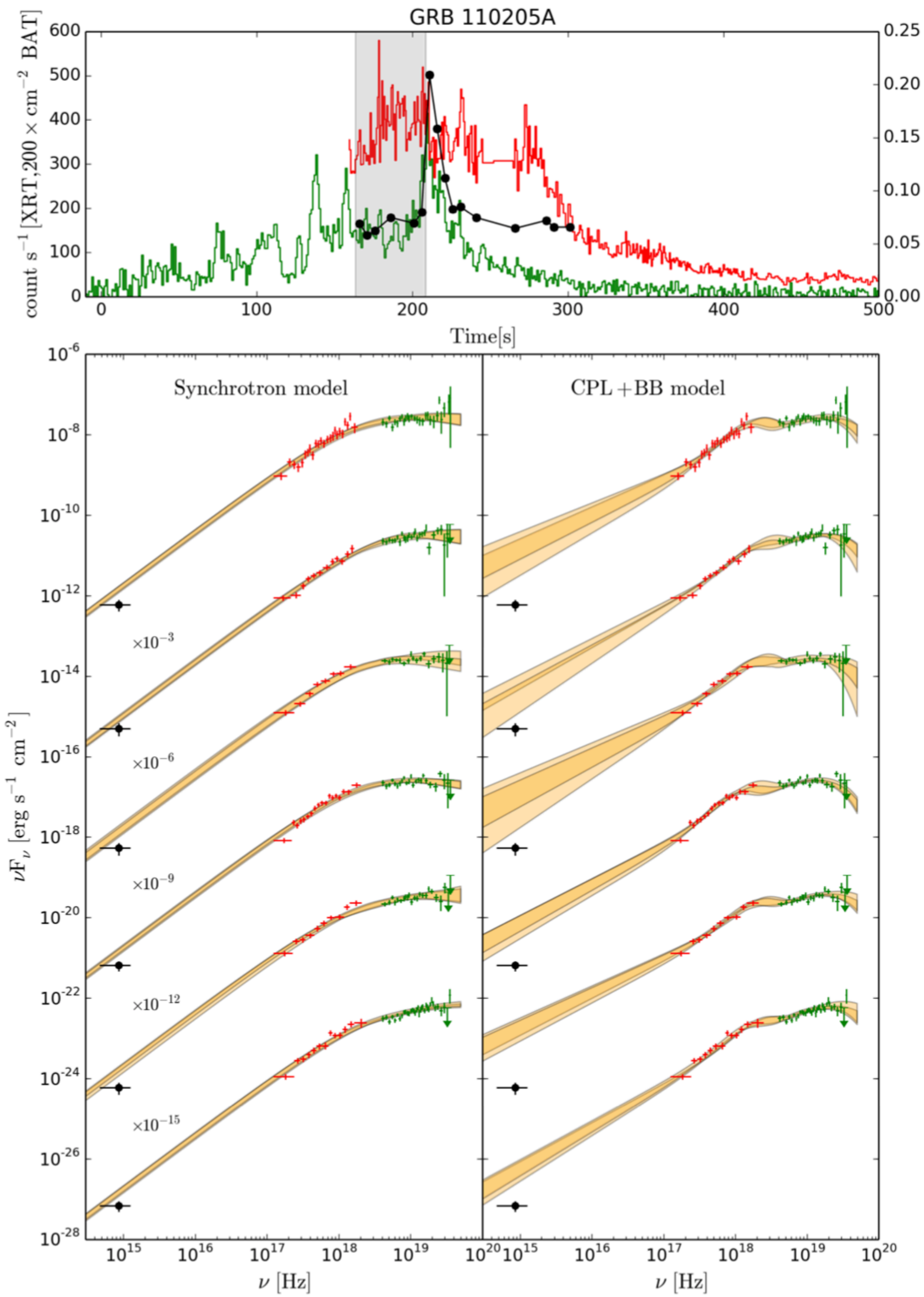
Interpretation (Pe'er & Ryde 2024)

Interaction with the immediate circumburst medium, such as a WR ring nebula.

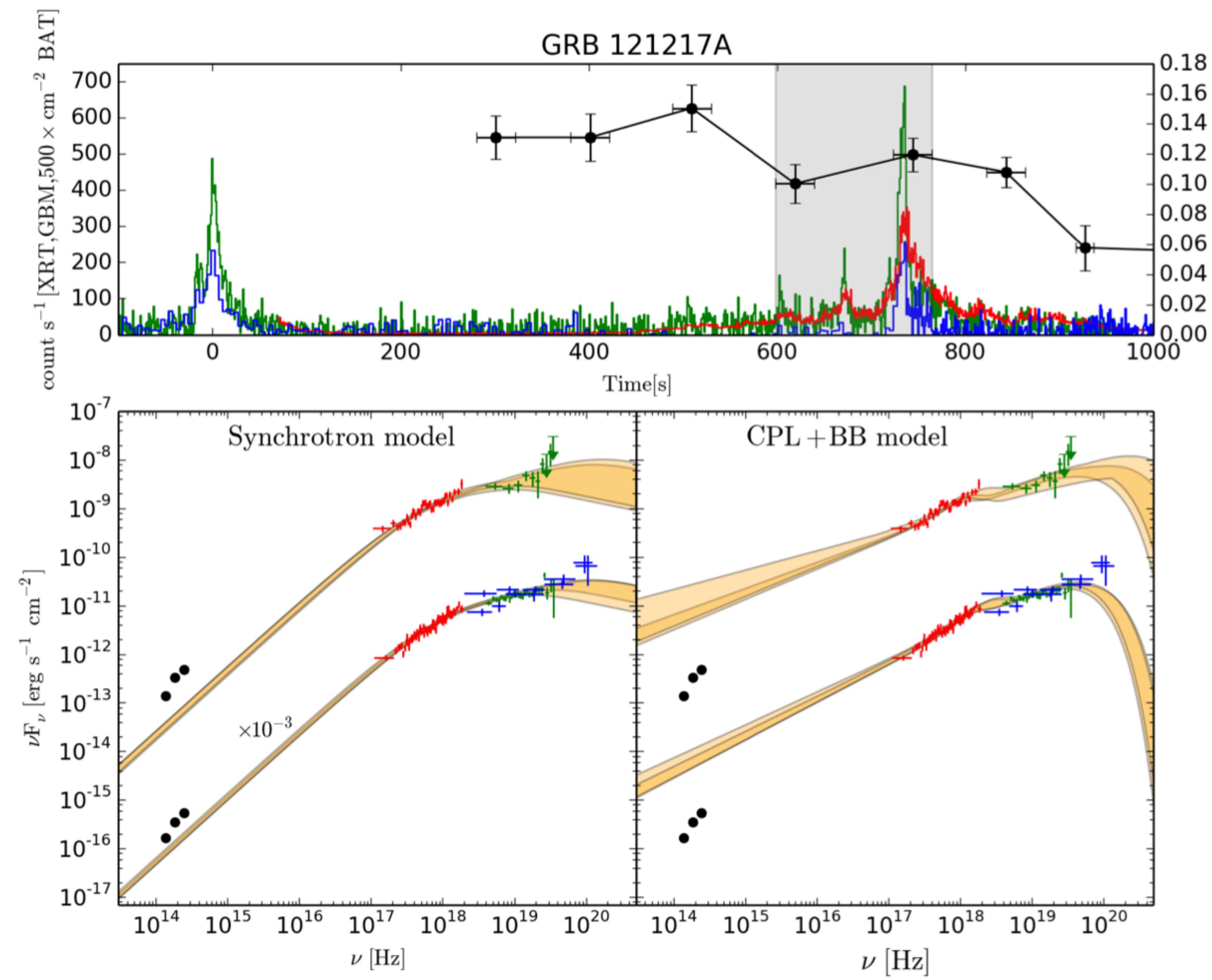
Produces efficient synchrotron emission from the reverse shock, caused by the blast wave, at the contact discontinuity between the shocked wind and the shocked ISM



Synchrotron emission in GRB 110205A and 121217A



Oganesyan+17, 18, 19; Ravasio+19, 20; Burgess+20



Large Lorentz factors and large emission radii

Conclusions

- The GRB photosphere can have a variety of spectral shapes
- Narrowest occur in the acceleration phase
- Shocks below the photosphere are radiation-mediated
- The KRA, which models shock dissipation using hot electrons, can reproduce spectra from detailed RMS simulations
- Dissipative photospheric models can produce broad spectra and reproduce most observed spectral shapes
- To distinguish between RMS and synchrotron spectra one needs additional clues