What is the emission mechanism in gamma-ray bursts?

What is the role of radiation mediated shocks?

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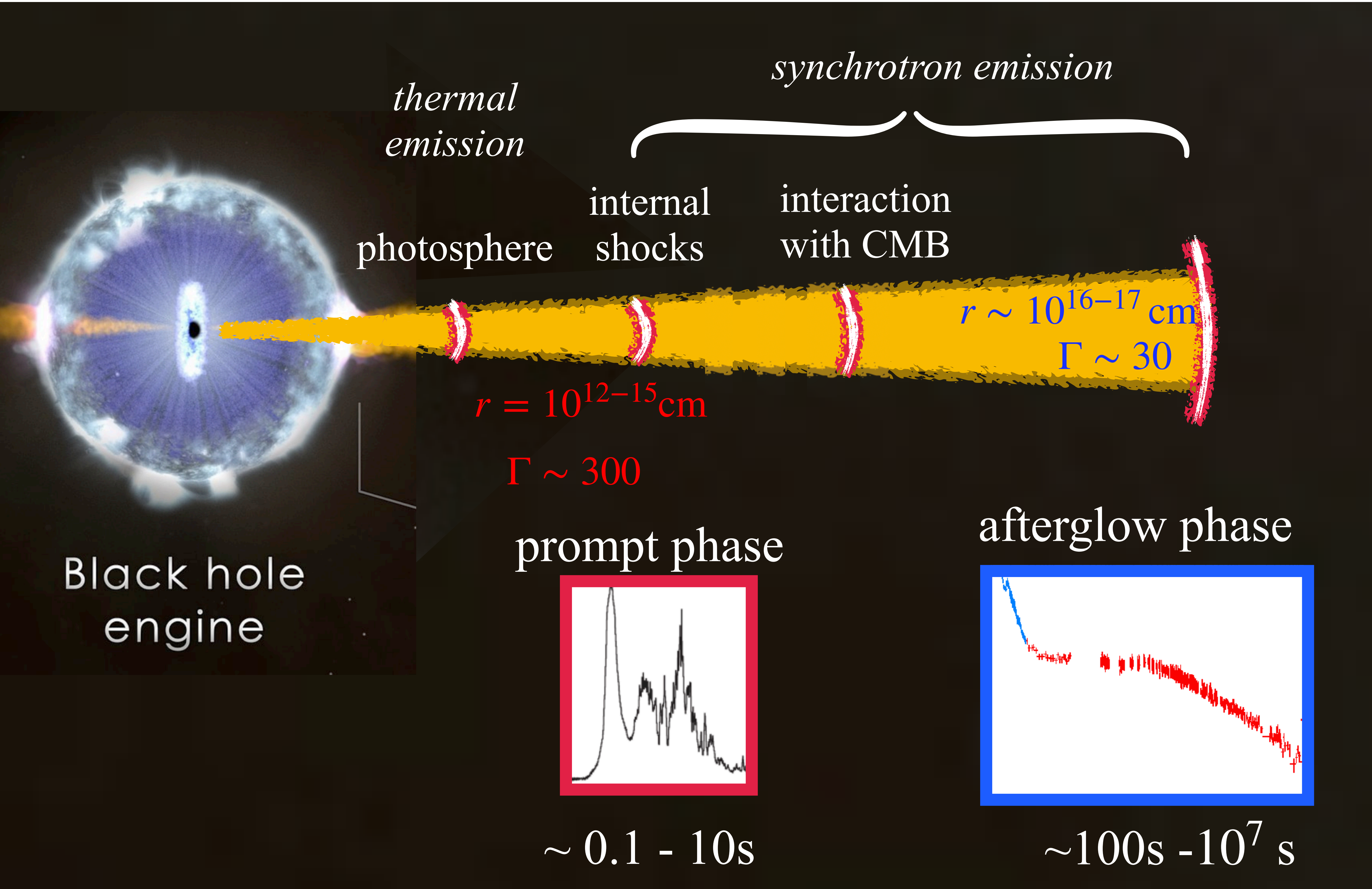
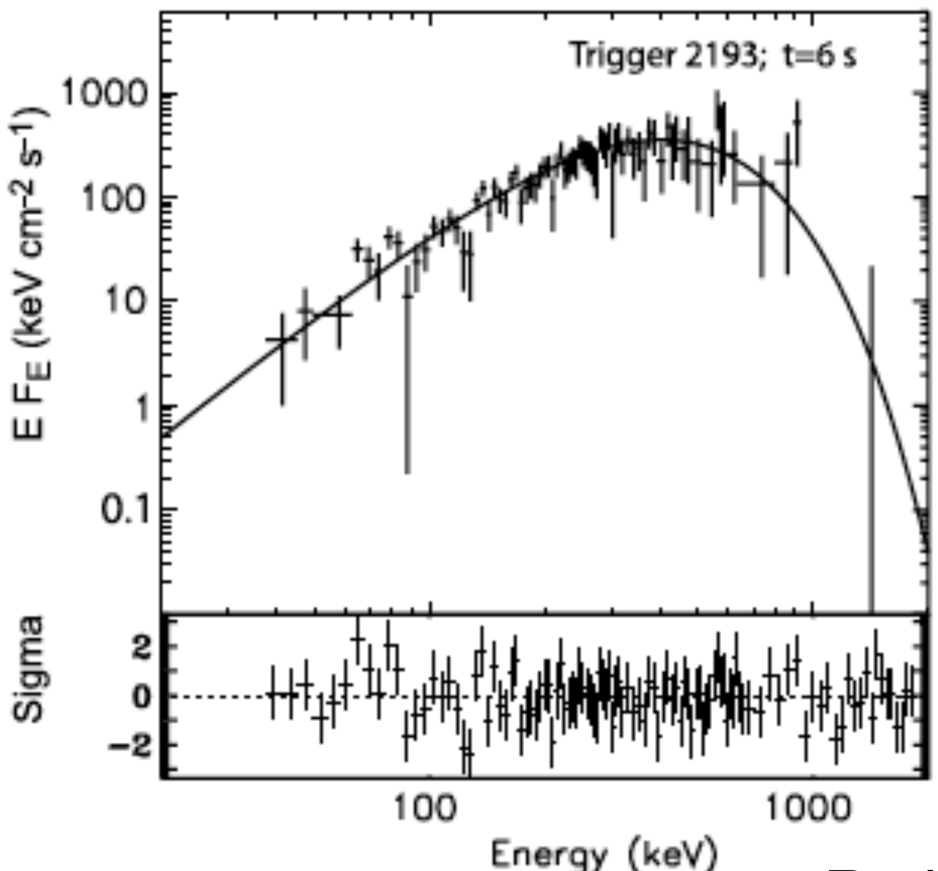
Emission phases of GRBs

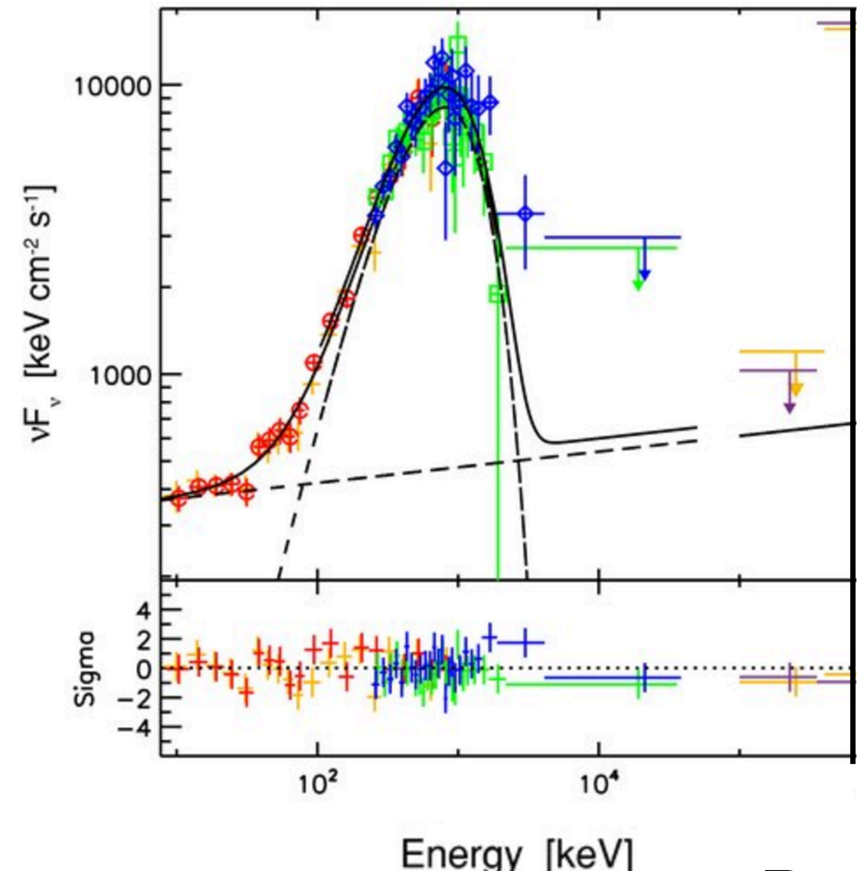


What do the observations show?

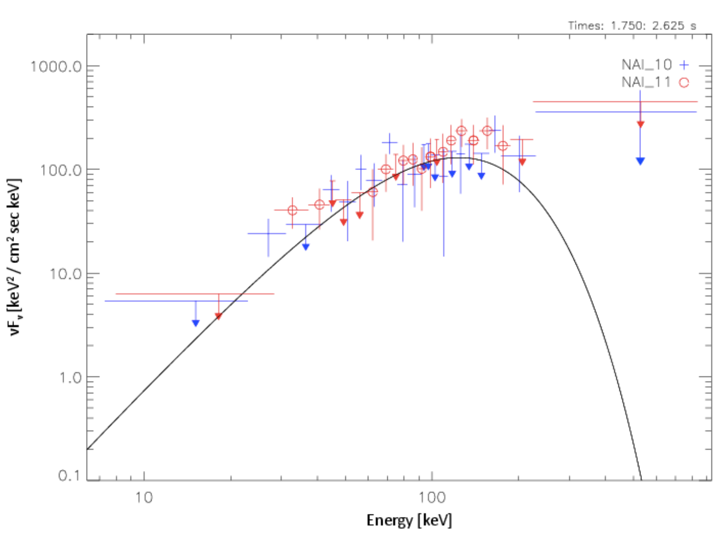
A few per cent of all spectra are quasi-Planckian



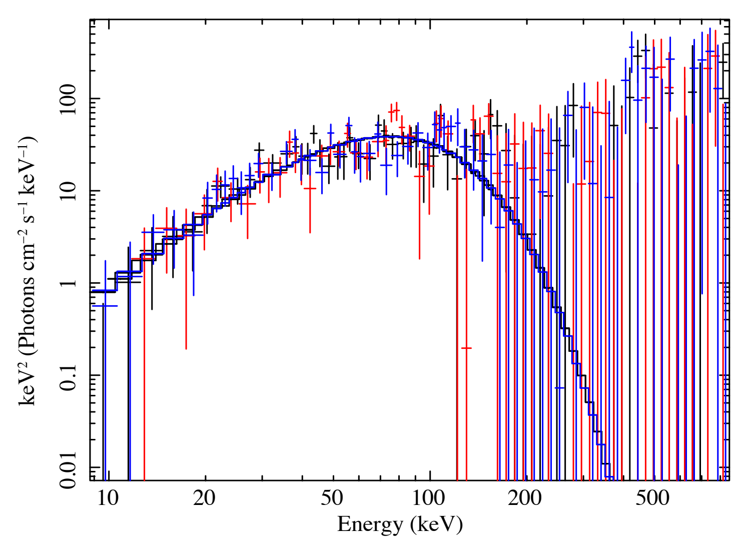
Ryde 2004



Ryde+2010



Ghirlanda+10

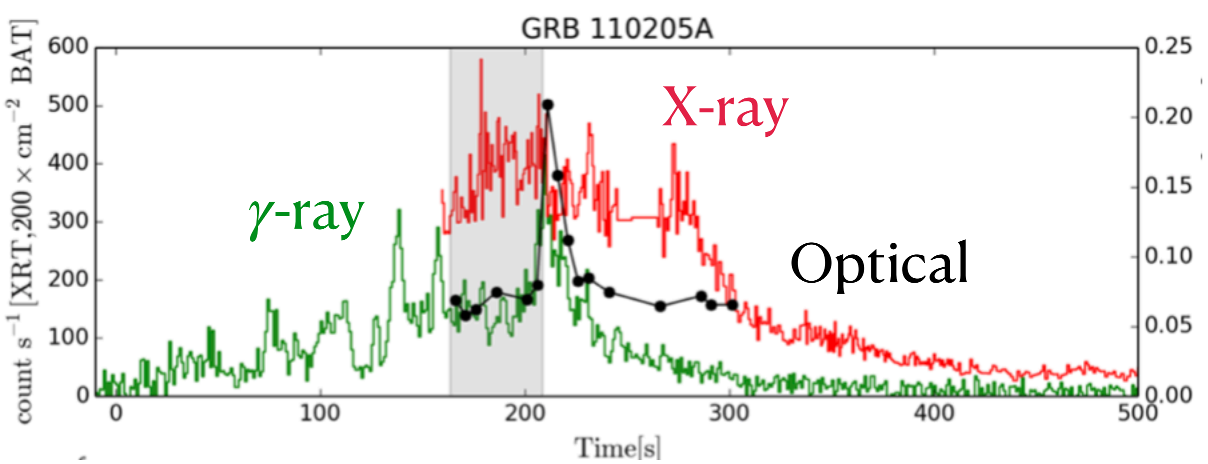


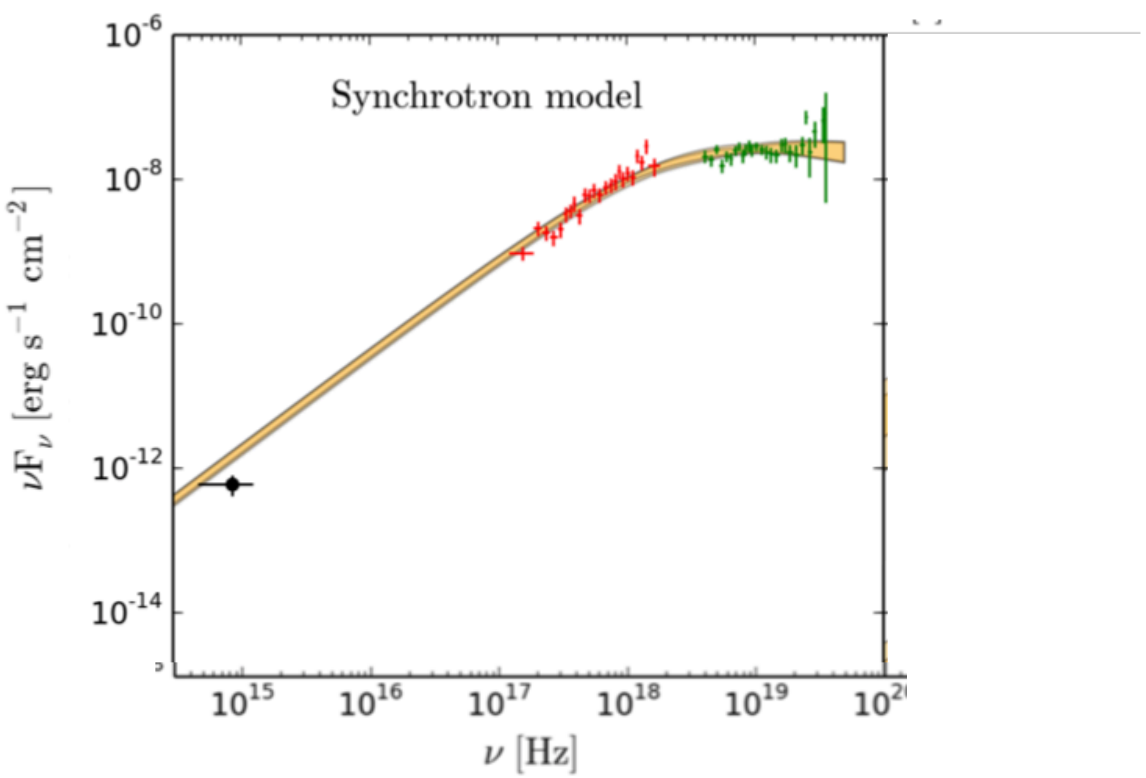
Larsson+15

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

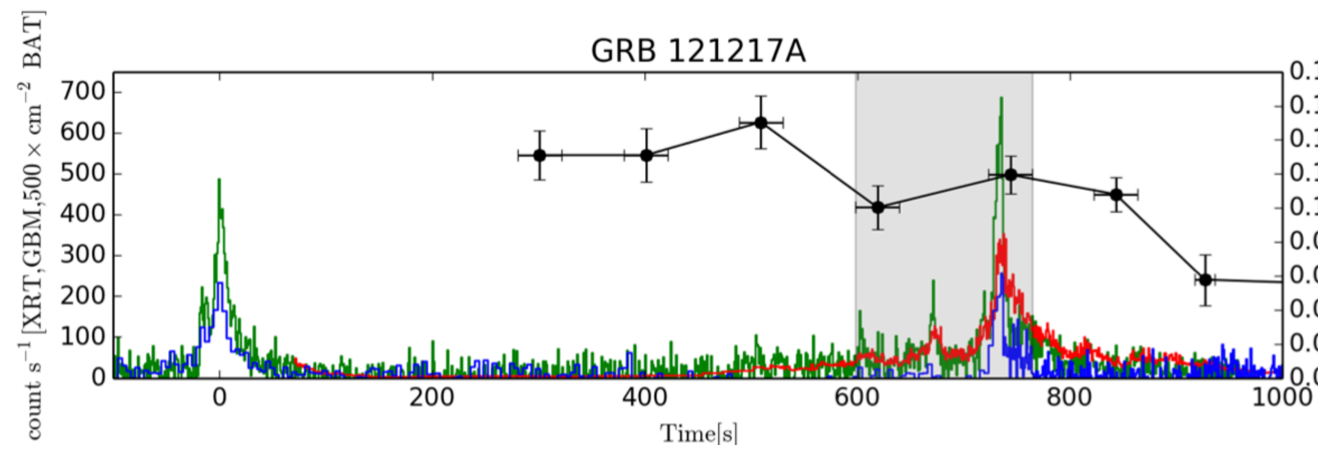
What do the observations show?
Synchrotron emission

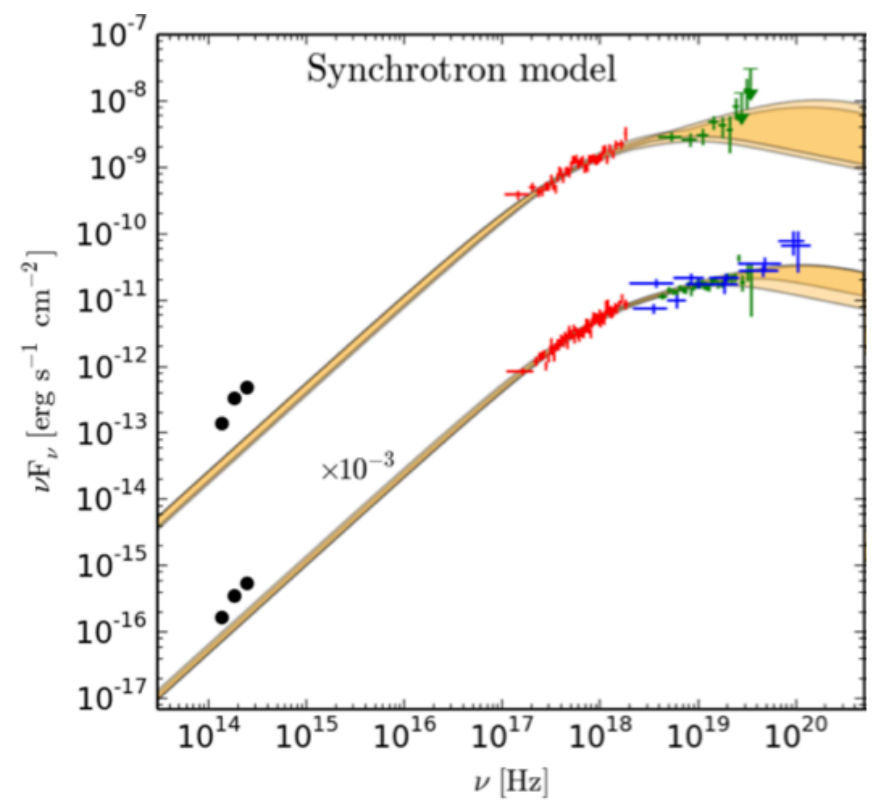
GRB 110205A





GRB 121217A

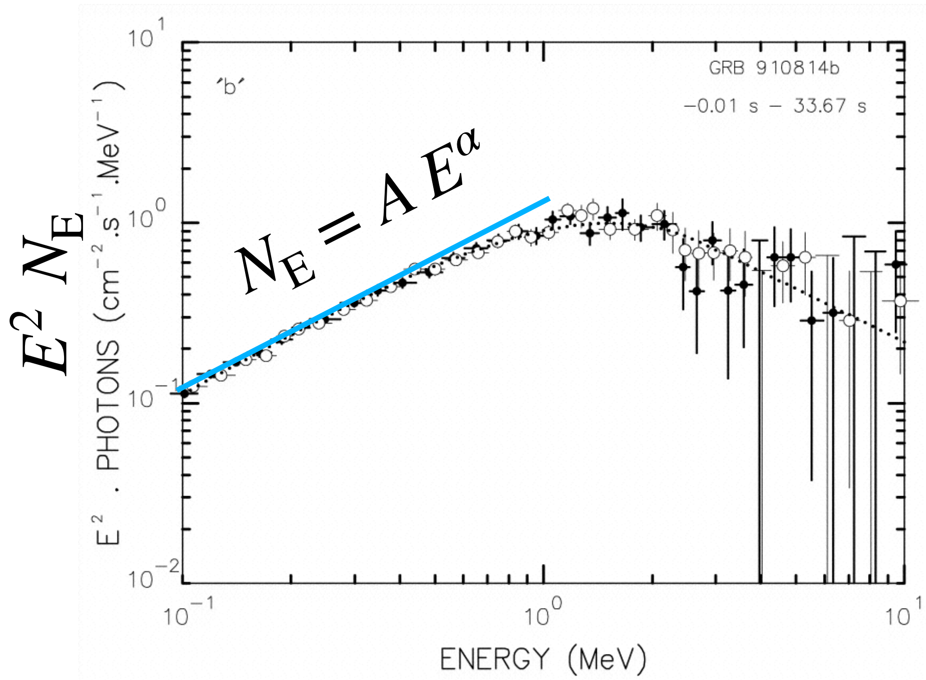




Oganesyan+17, 18, 19; Ravasio+19, 20, 24; Sharma+19; Burgess+20

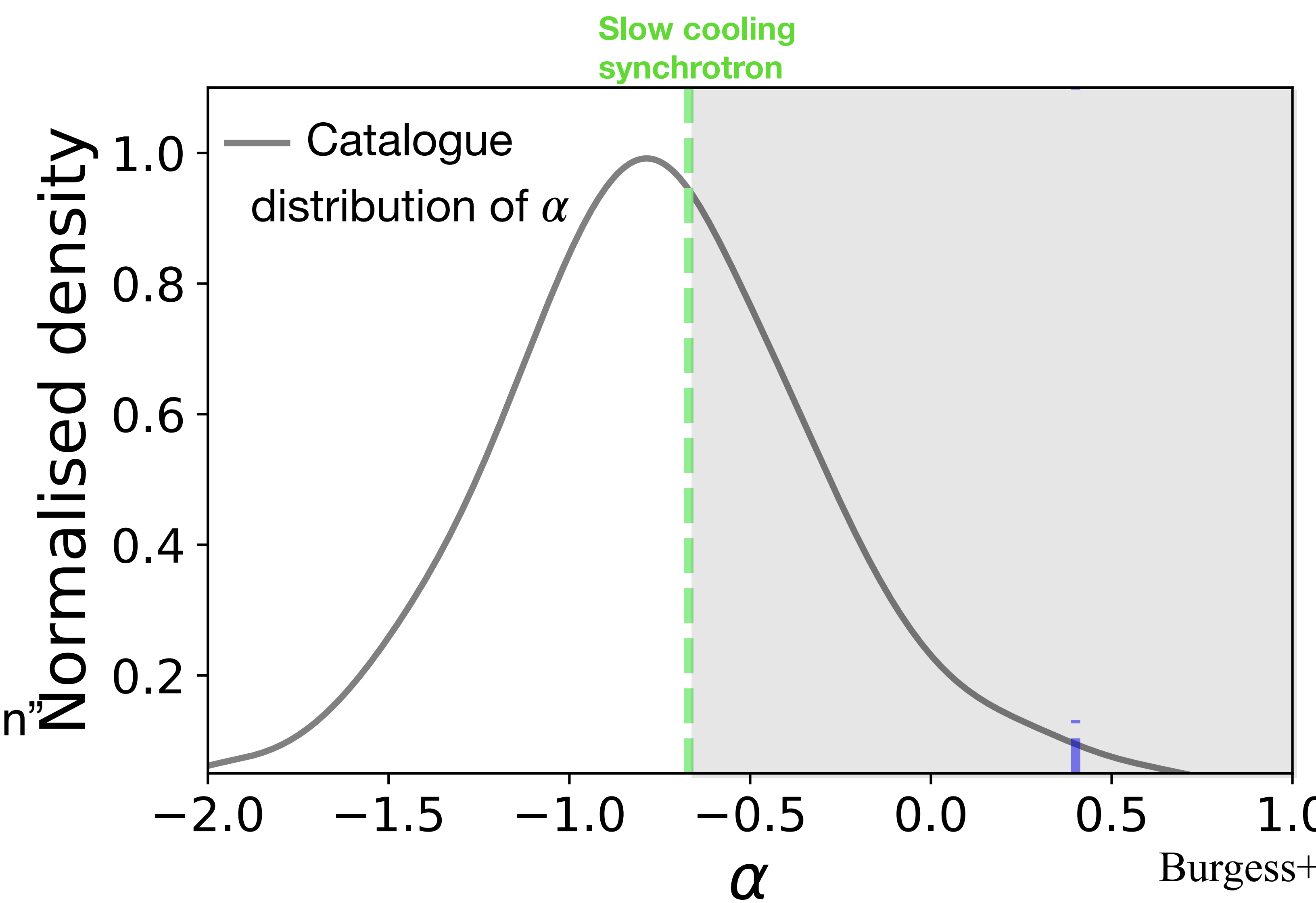
Distribution of prompt emission spectral shapes

Typical gamma-ray spectrum
Empirical Band function



Current α-distribution
2300 GRBs observed
By Fermi/GBM

"line of death for
synchrotron emission"
Preece+98



Burgess+17
Acuner+19

~~What is the emission mechanism in gamma-ray bursts?~~

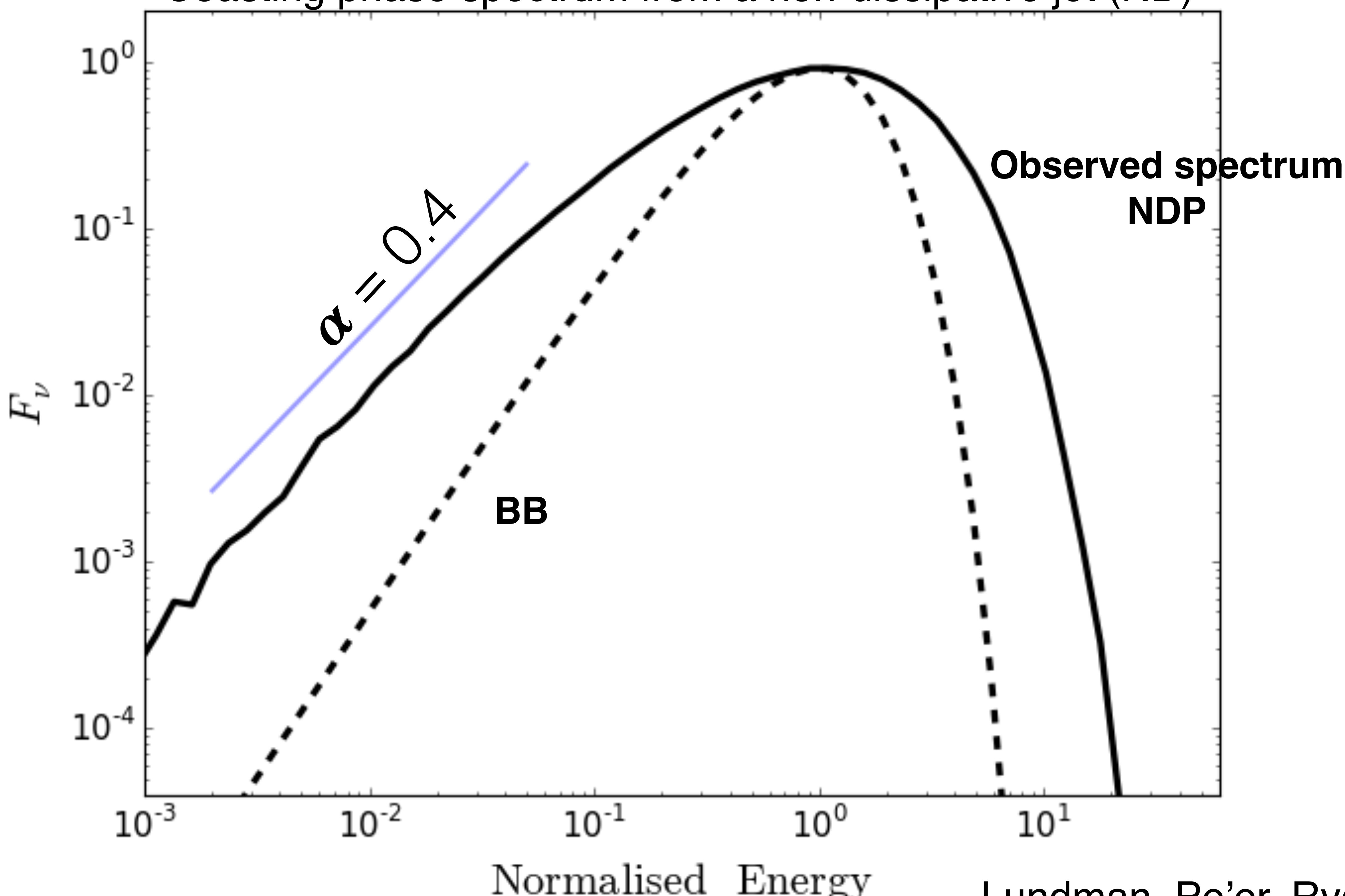
When is the prompt emission dominated by the photosphere? What does its spectrum look like?

When is the prompt emission dominated by the synchrotron emission? What are the conditions for it to be efficient?

Spectrum expected from the photosphere

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

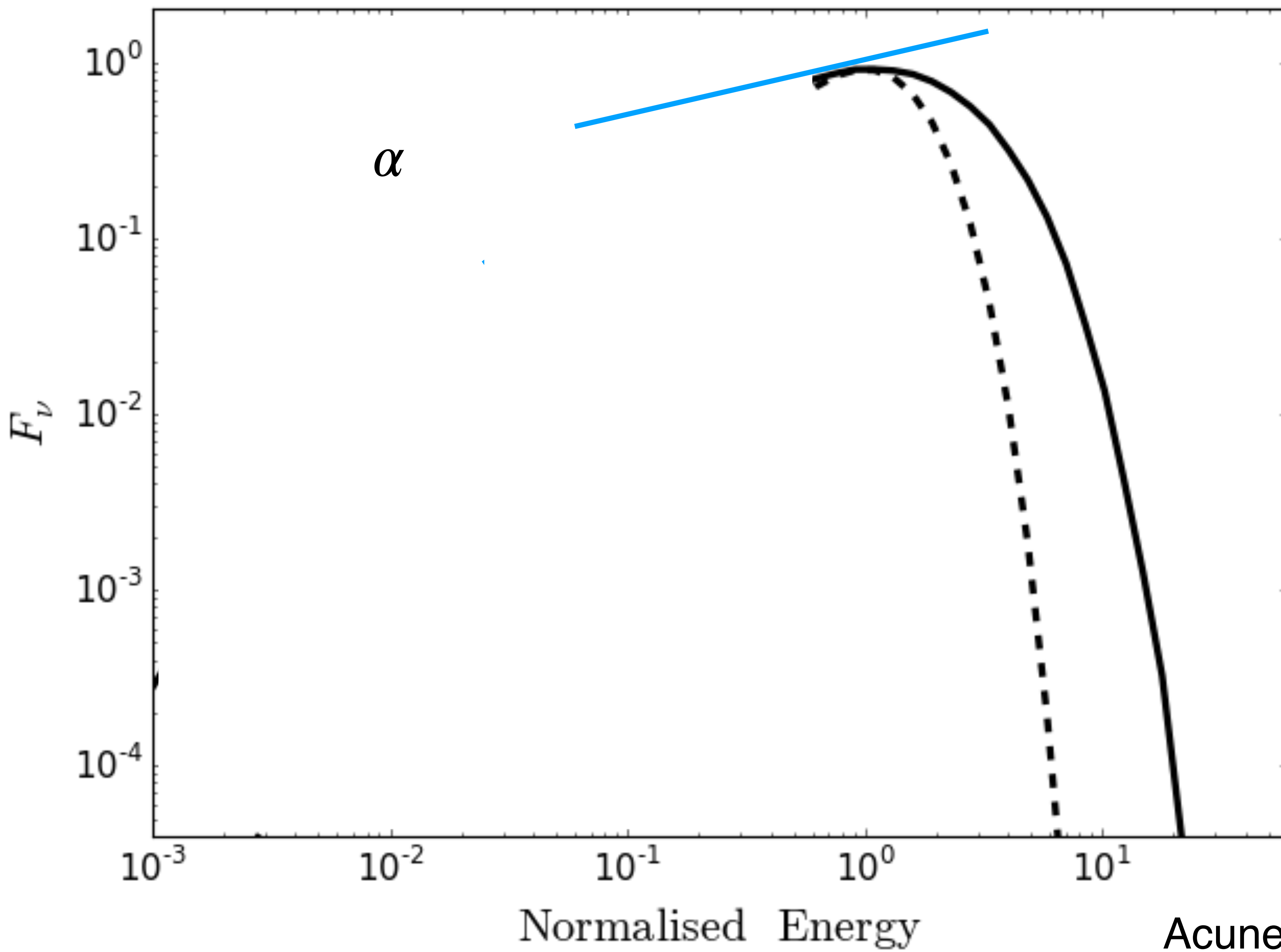
Coasting phase spectrum from a non-dissipative jet (ND)



Lundman, Pe'er, Ryde 2013

Expected photospheric flux in GBM observations

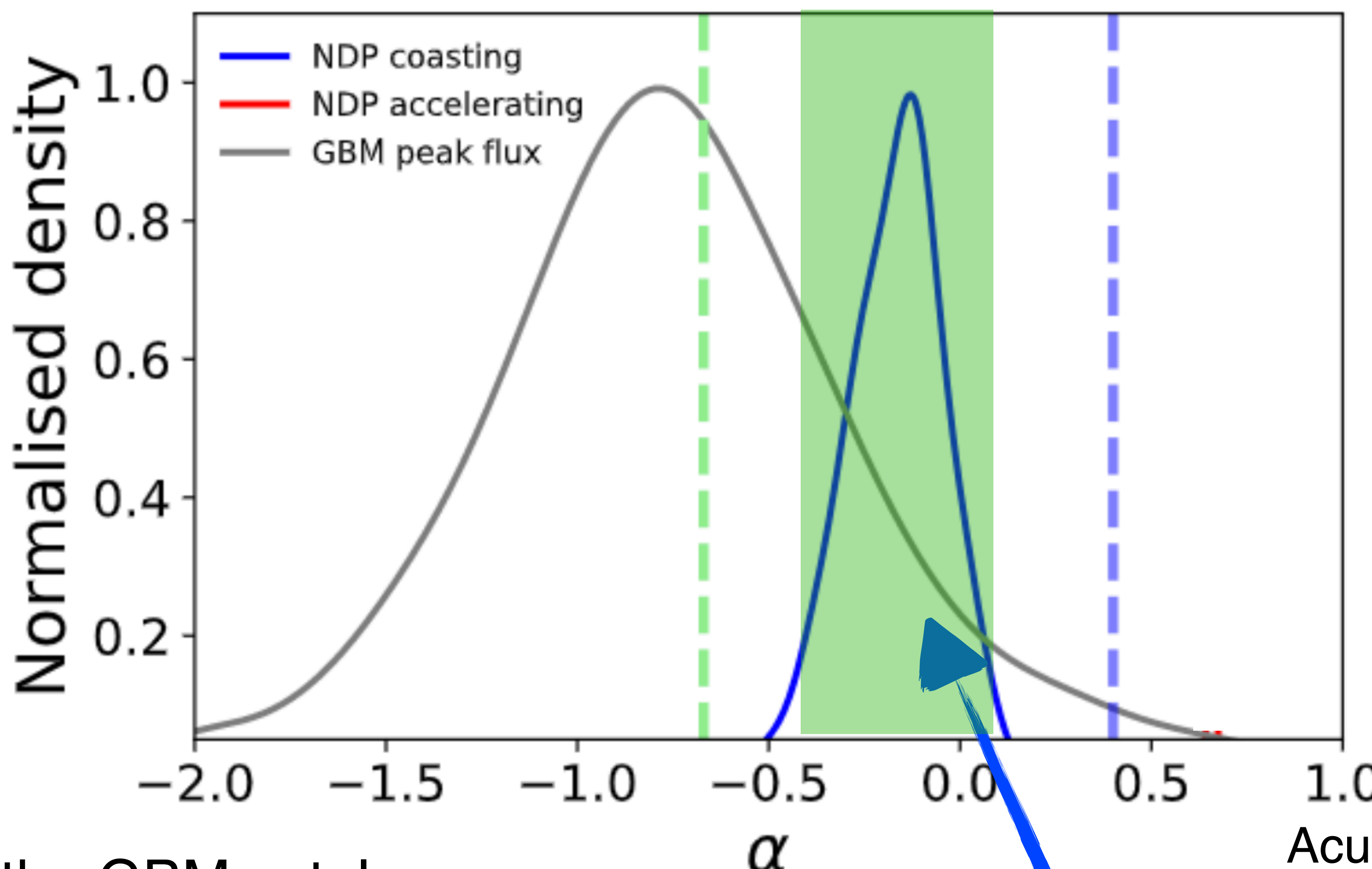
Limited band-width of the gamma-ray detector



Acuner, Ryde &Yu 19

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)

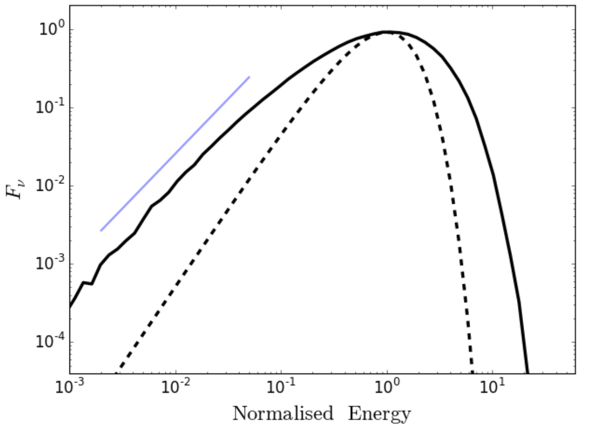
Acuner, Ryde & Pe'er (2020)

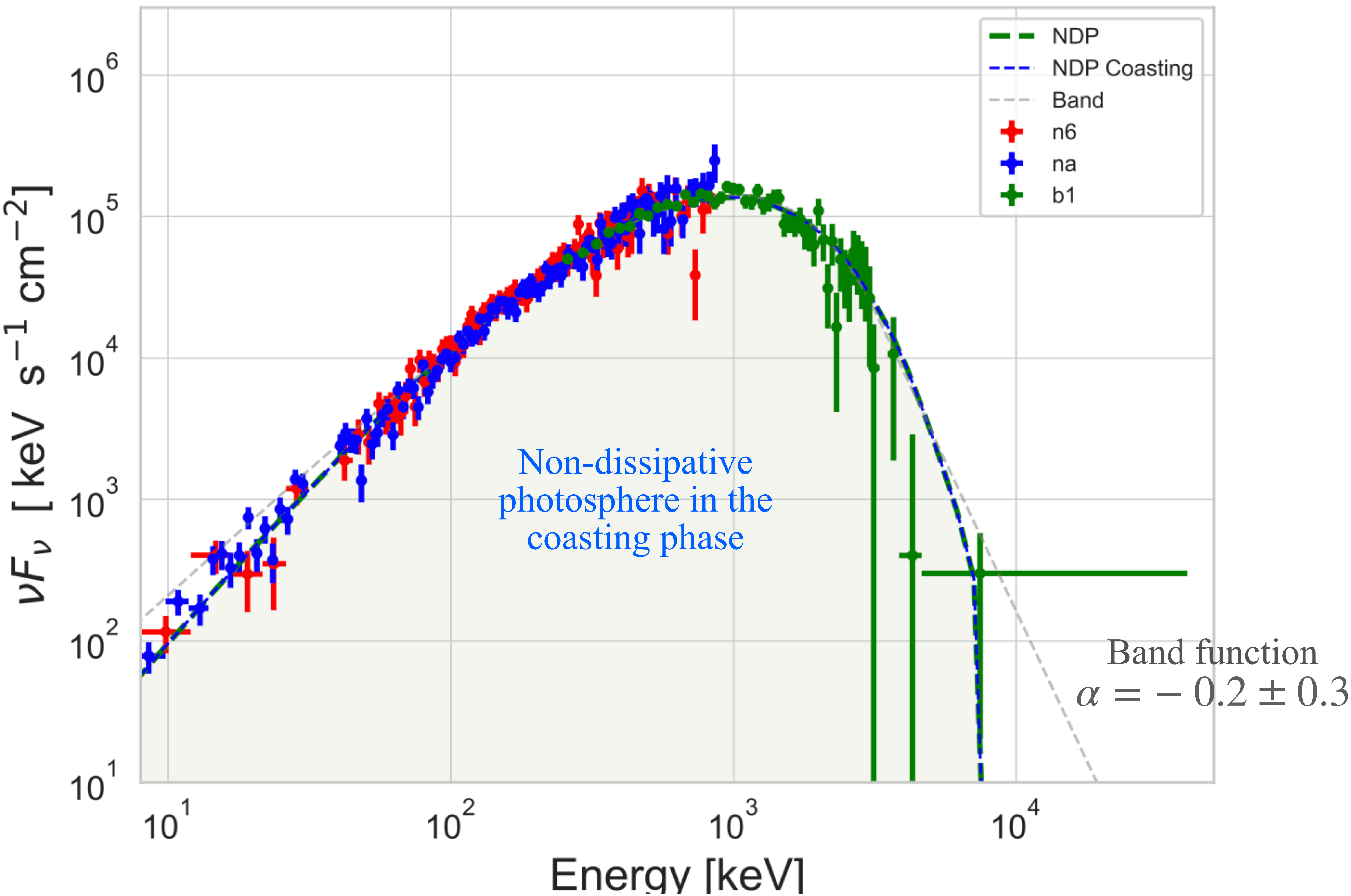
Expected range of α from the photosphere

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

Example: GRB230307

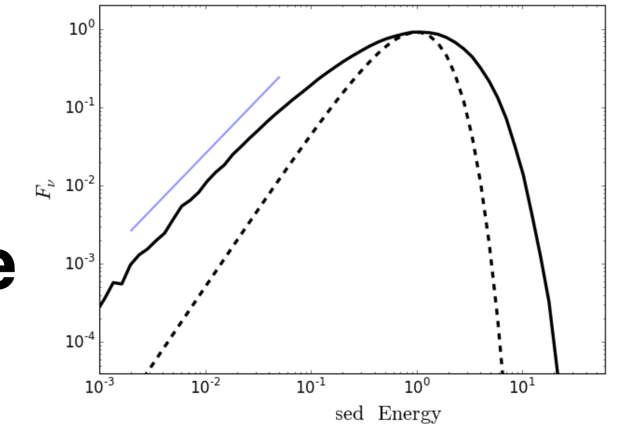
Narrow spectrum: Photosphere in the coasting phase

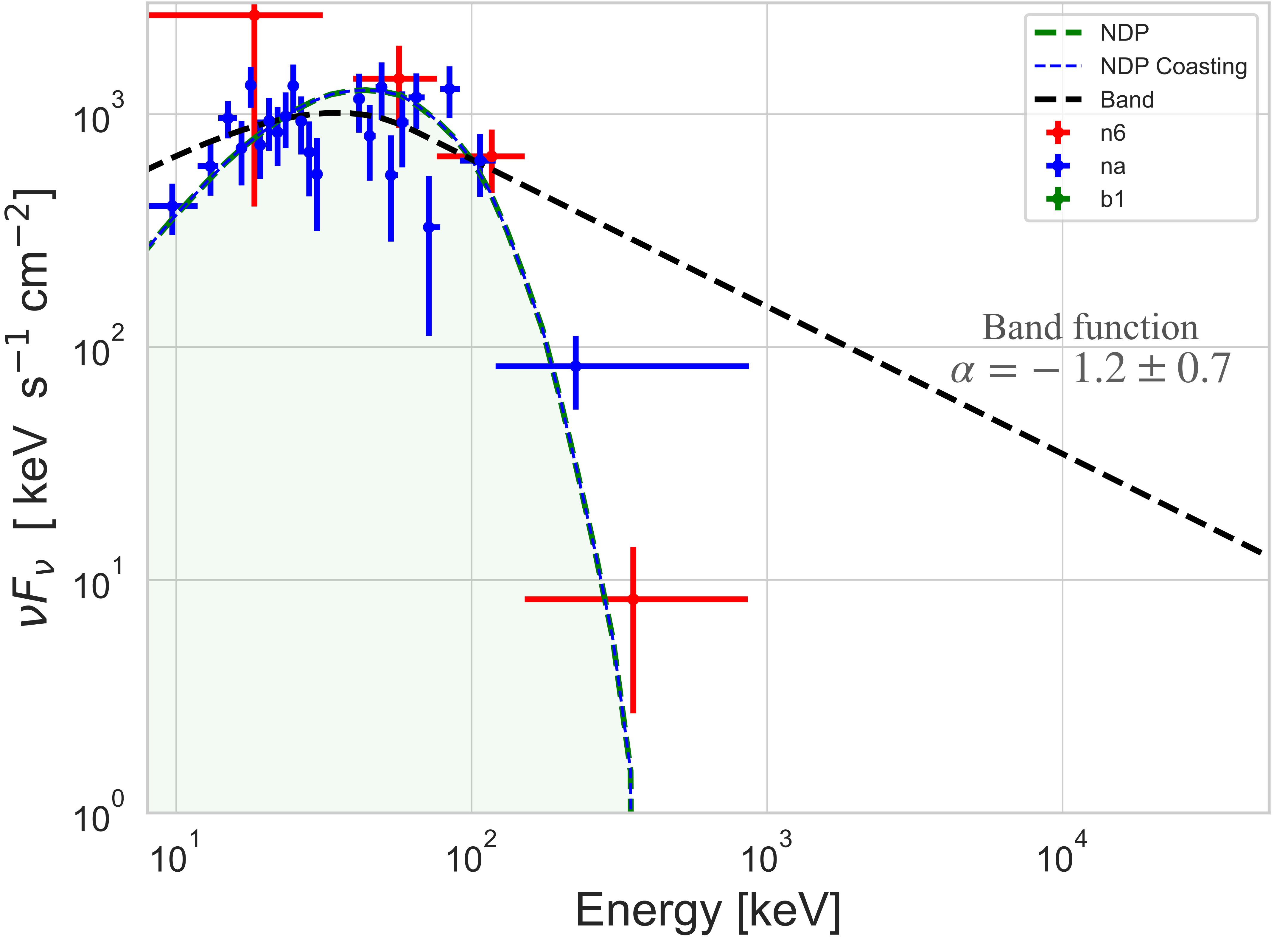




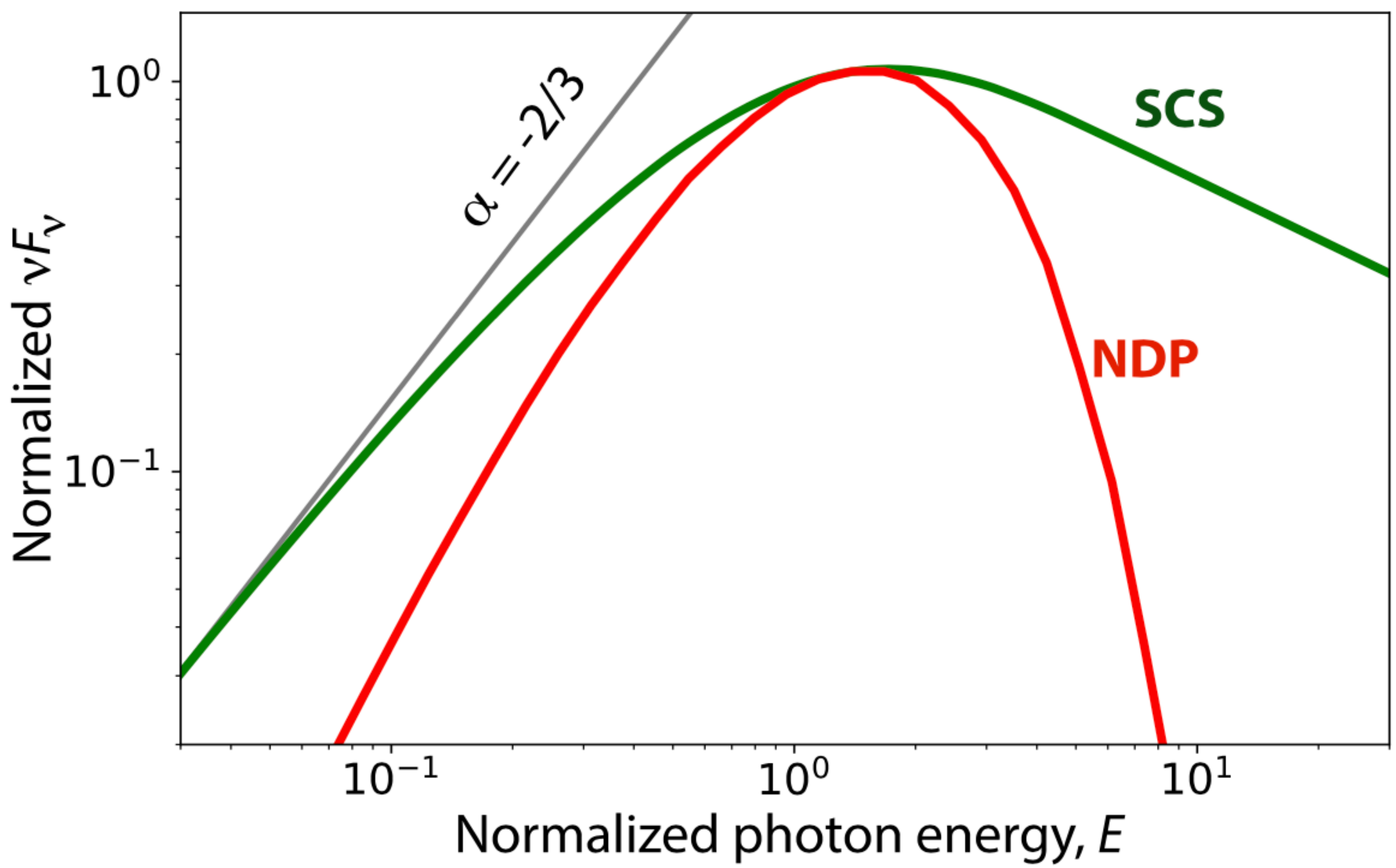
Example: GRB230307

Narrow spectrum: Photosphere in the coasting phase





Model comparison using Bayesian evidences
Synchrotron versus photosphere



Slow cooled synchrotron emission

Non-dissipative photosphere during the coasting phase

For each model we calculate the marginal likelihood or Bayesian evidence $Z_n = \int d\theta \, P(D \mid \theta_n, M_n) P(\theta_n \mid M_n)$

The ratio of the respective evidences, Z_2/Z_1, summarizes the evidence given by the data in favor of one of the models

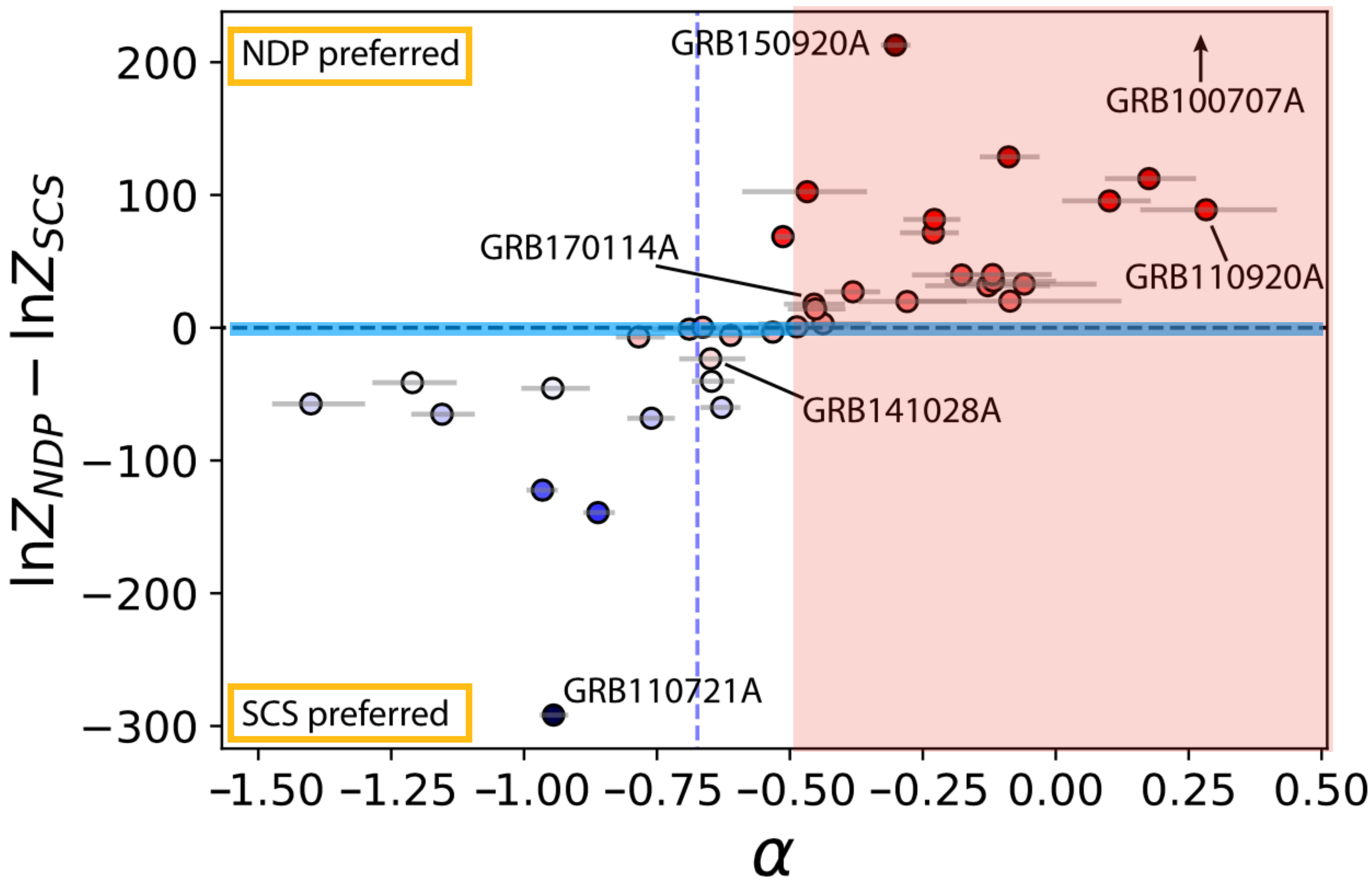
$$\ln \frac{Z_2}{Z_1} = \ln Z_2 - \ln Z_1$$

Acuner, Ryde, Pe'er+20

Model comparison using Bayesian evidences: Results

We do this on the 37 pulses in the catalogue of Yu+19

S > 15 , time resolved, α_{max} bin



The photospheric spectral shape is preferred by 54%±8% of the spectra (20/37),

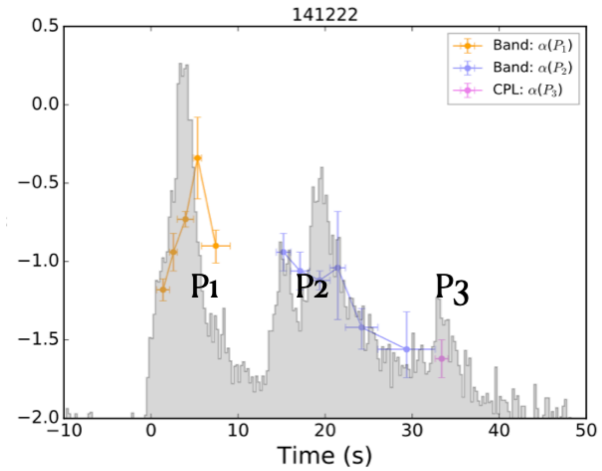
The synchrotron spectral shape is preferred by 38%±8% of the spectra (14/37)

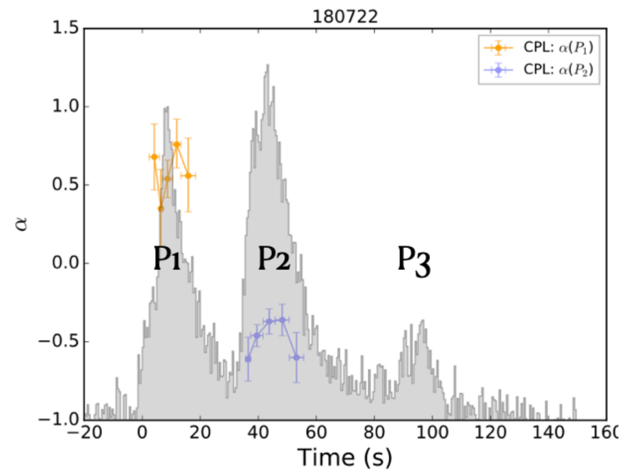
Three spectra are inconclusive

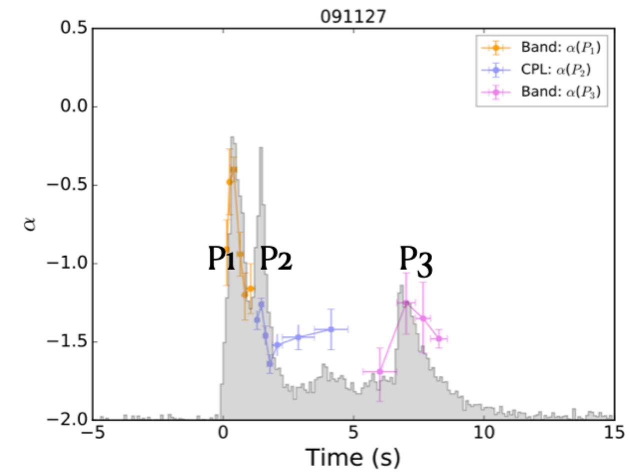
Acuner, Ryde, Pe'er+20

- α good estimator for preferred model: $\alpha \gtrsim -0.5$ prefer NDP
- We also find that information criteria (AIC and DIC) are good approximations of the evidences

How do the spectral properties evolve in multiples bursts?

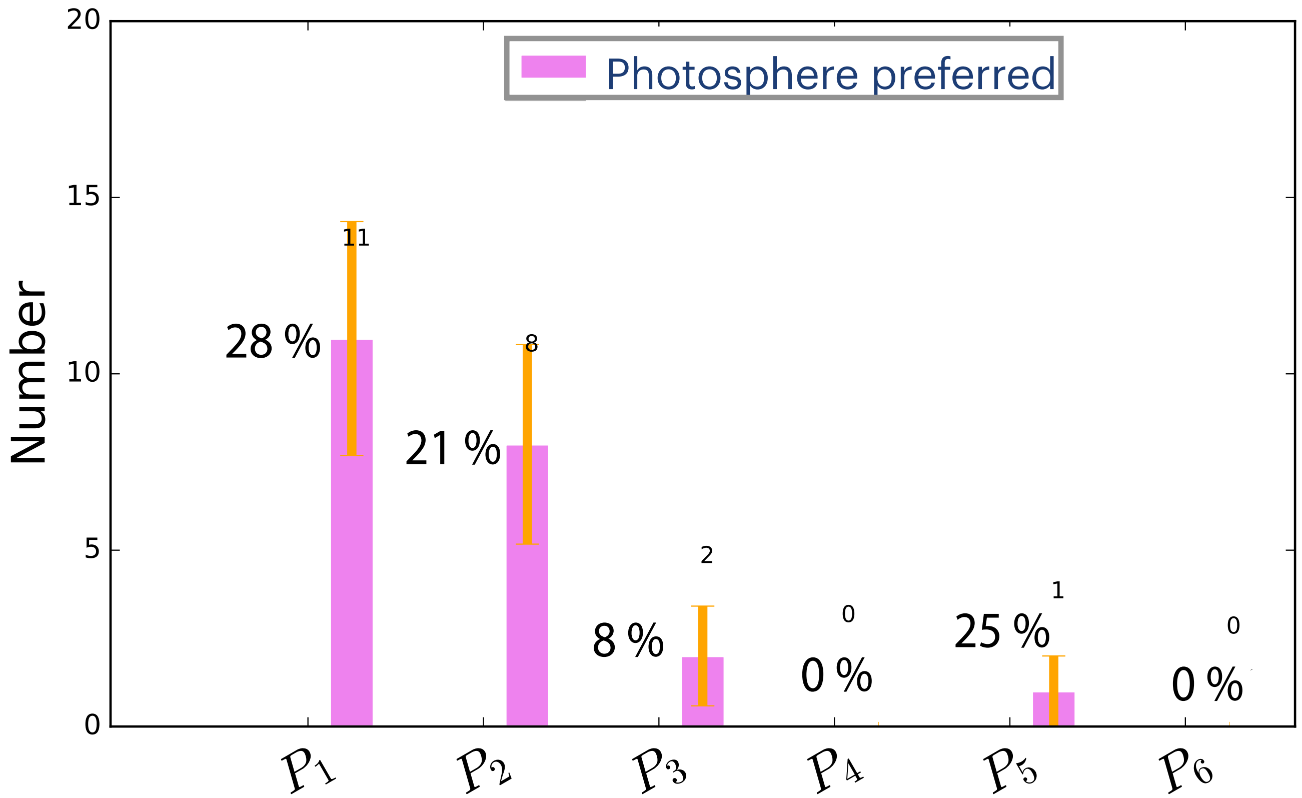


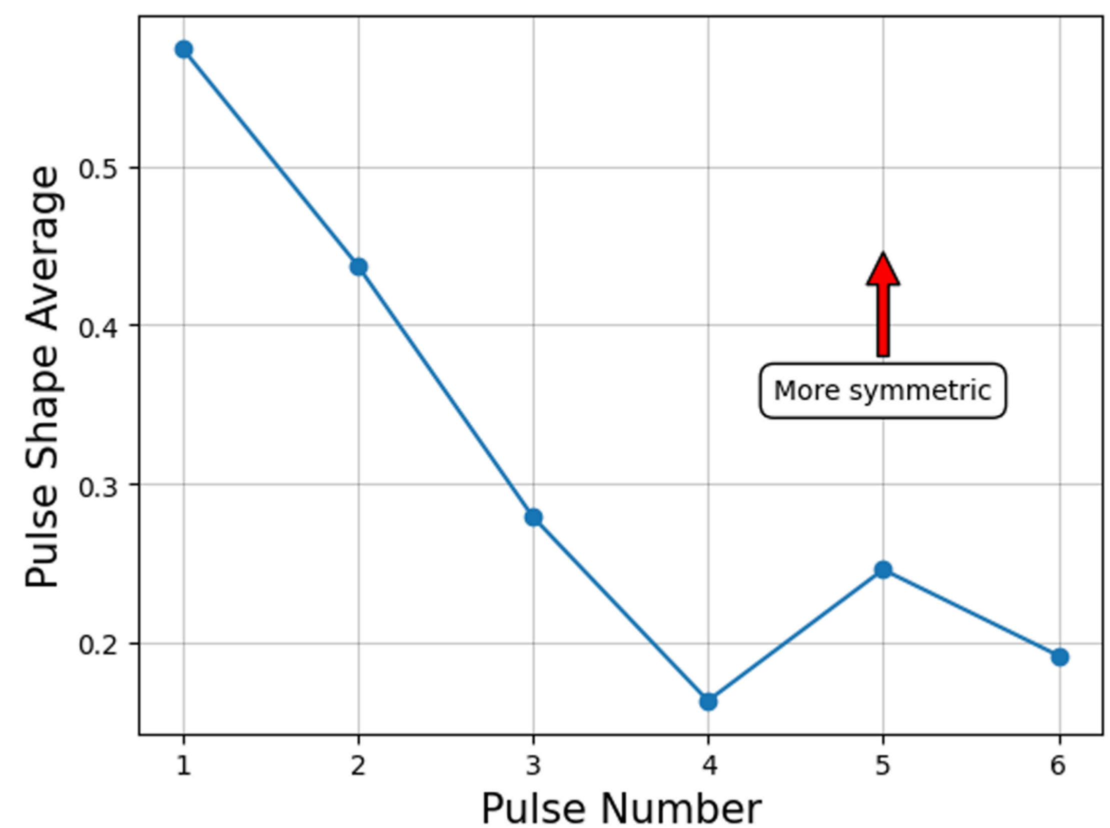




Early pulses have harder spectra

and are more symmetric



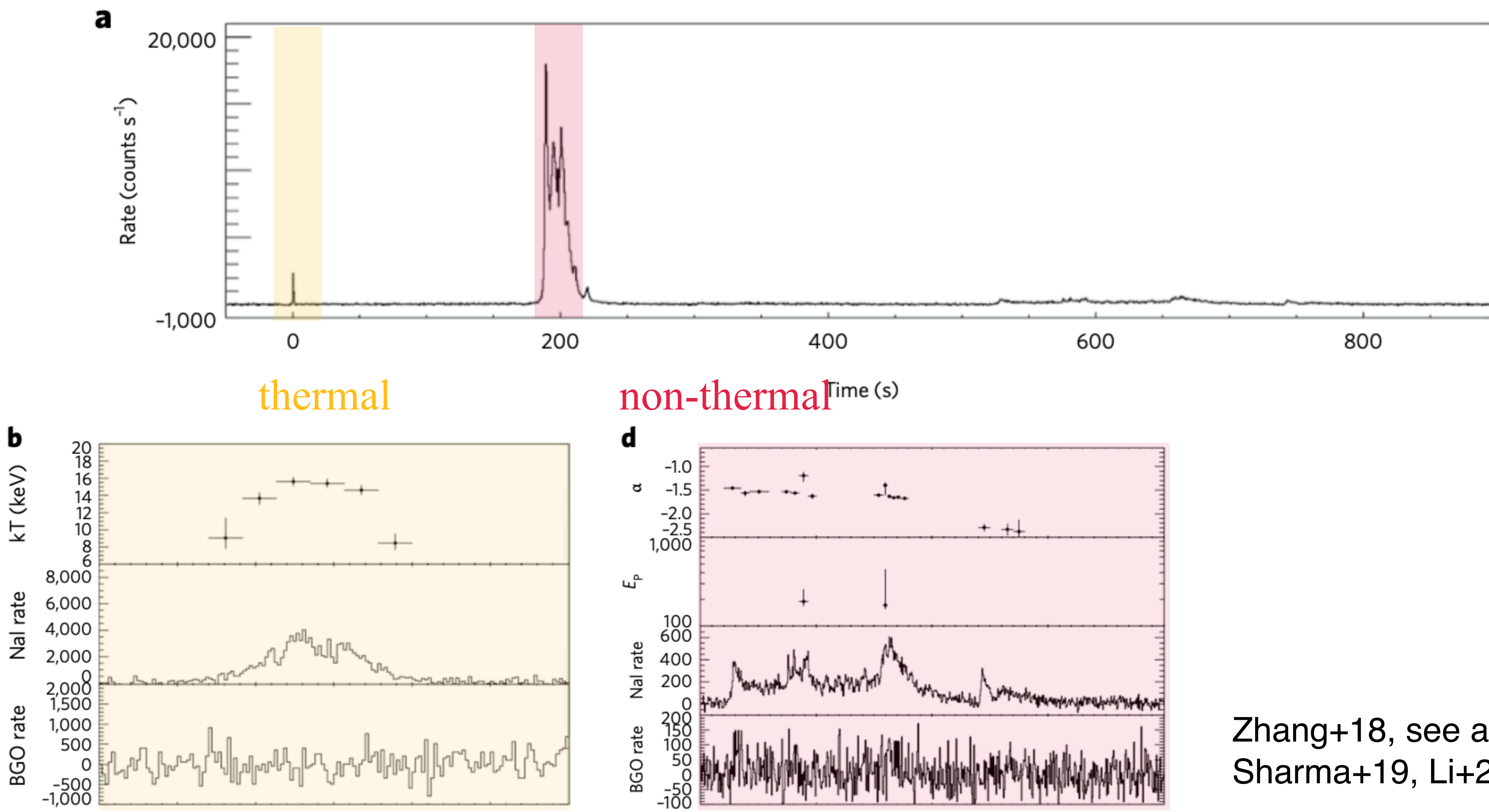


Li, Ryde, Pe’er+21

Gowri, Pe’er, Ryde, Begue-Dereli 25

Earlier pulses are more photosphere-like, while late pulses are more “synchrotron-like”

Transition from thermal to synchrotron emission in GRB 160625B



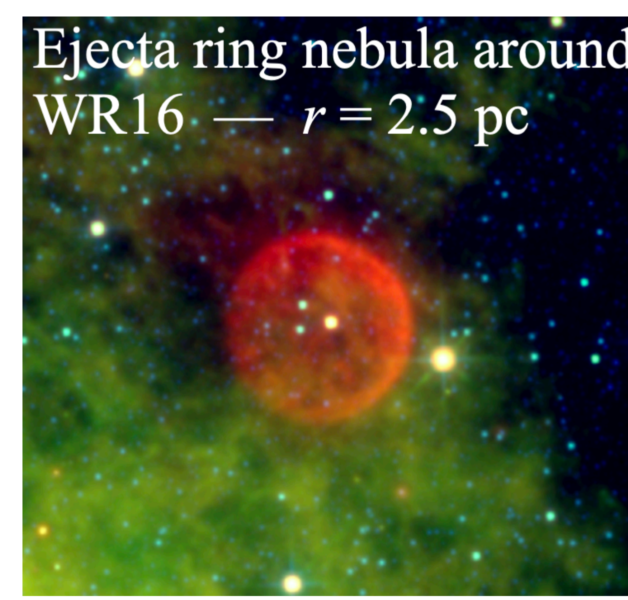
Zhang+18, see also
Sharma+19, Li+23, Gupta+25

Interpretation (Pe’er & Ryde 2024)

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

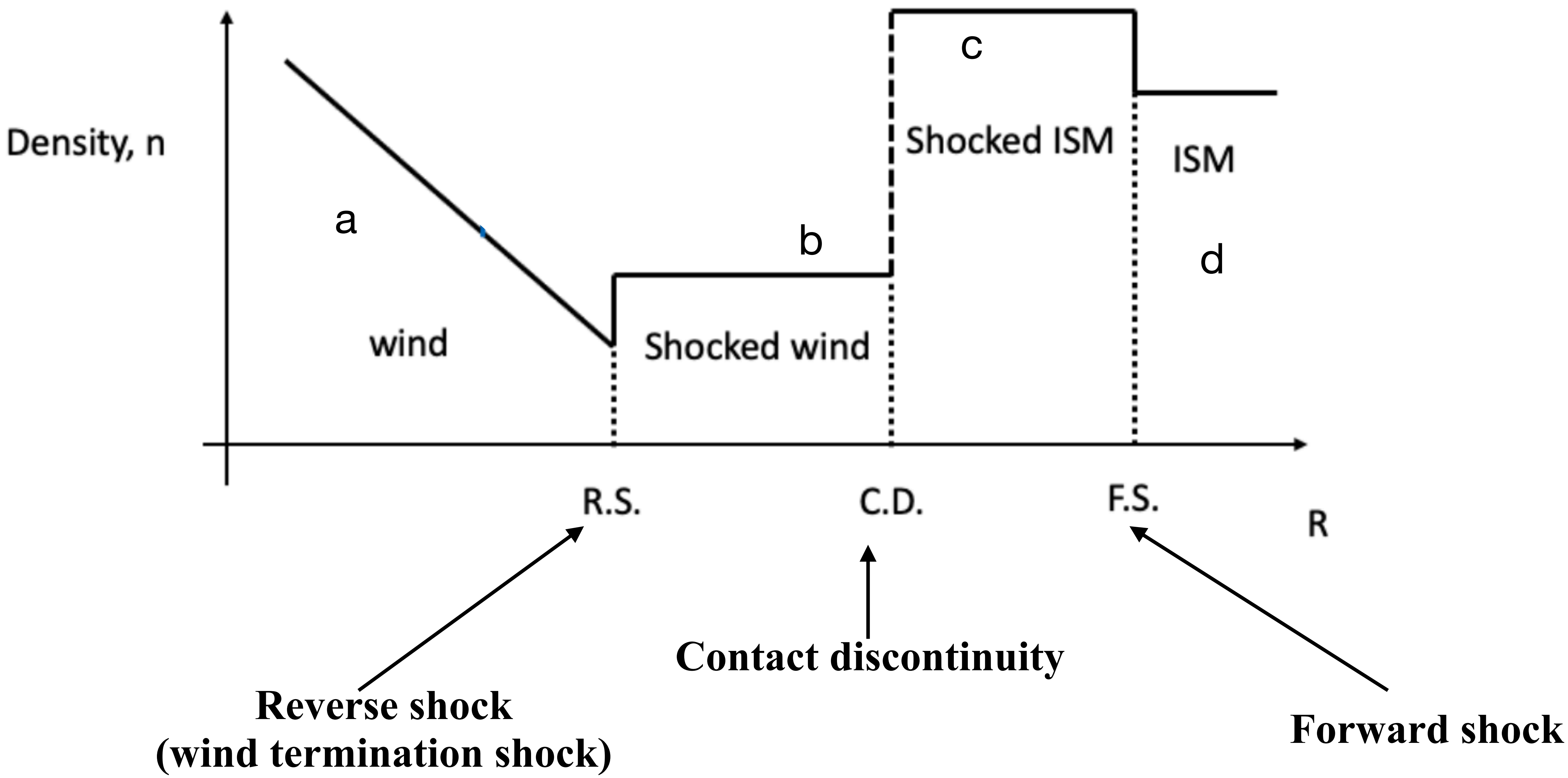
Produces efficient synchrotron emission from the reverse shock, caused by the blast wave, at the contact discontinuity between the shocked wind and the shocked ISM

(Refer to Hamidani’s talk)



Shock structure of the WR wind bubble

(Pe'er & Wijers 2006; Nakar & Granot 2007; van Eerten et al. 2009; Mimica & Giannios 2011)



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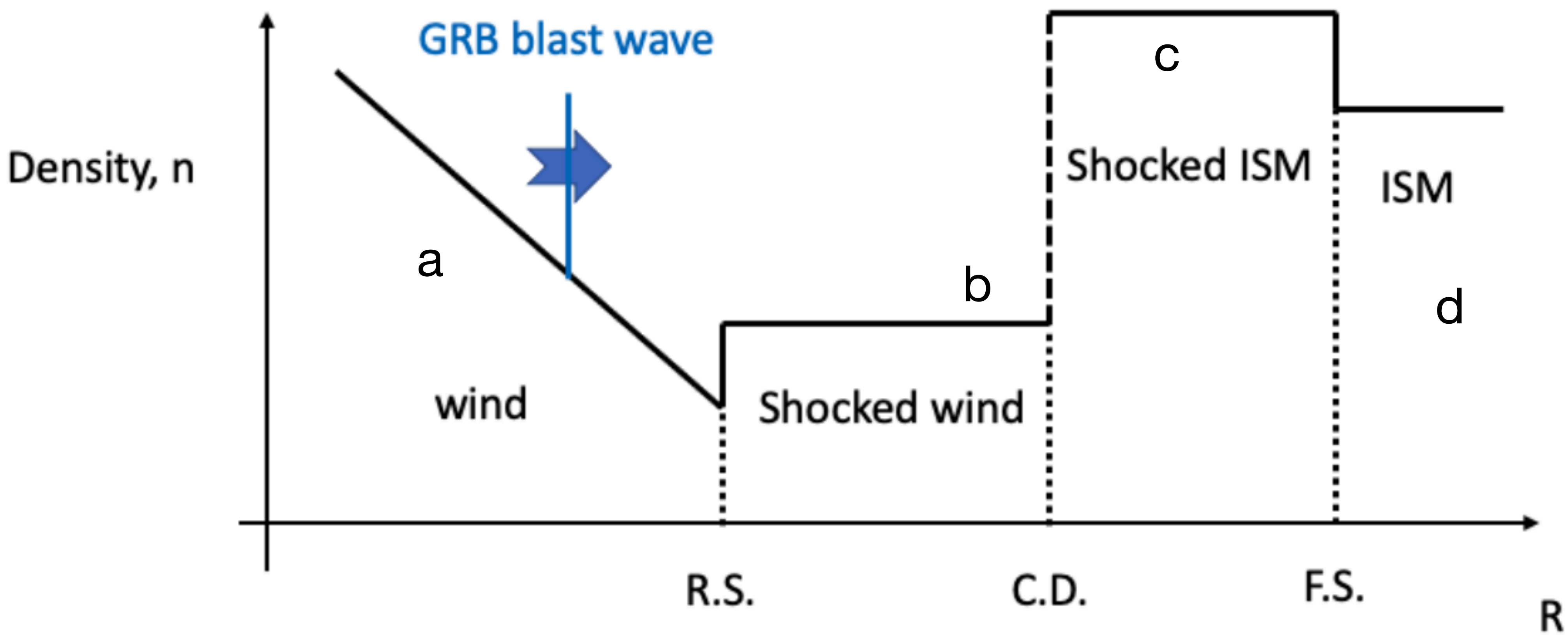


9.2×10^{16}cm

5.5×10^{17}cm

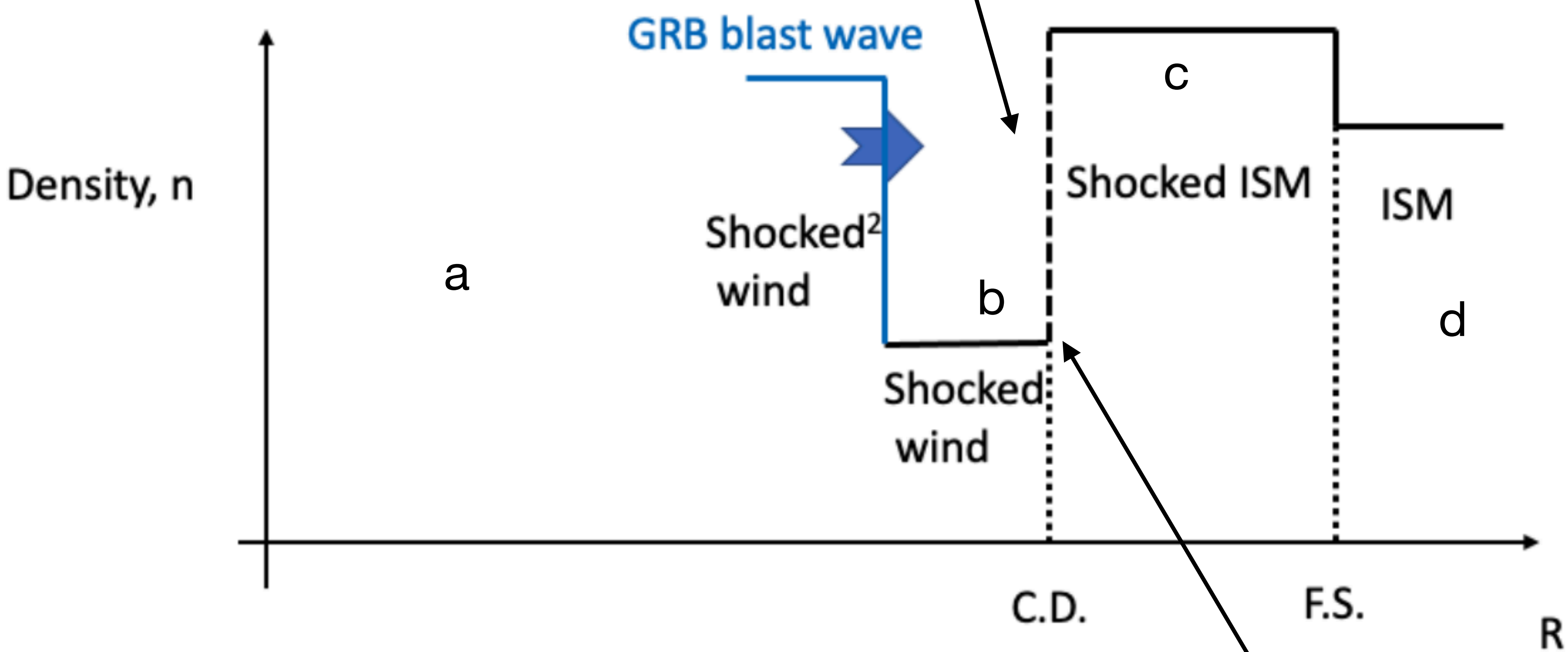
BW reach RS at $t_{\rm R.S.} \sim 1$s

No significant emission

Small effect on jet

1

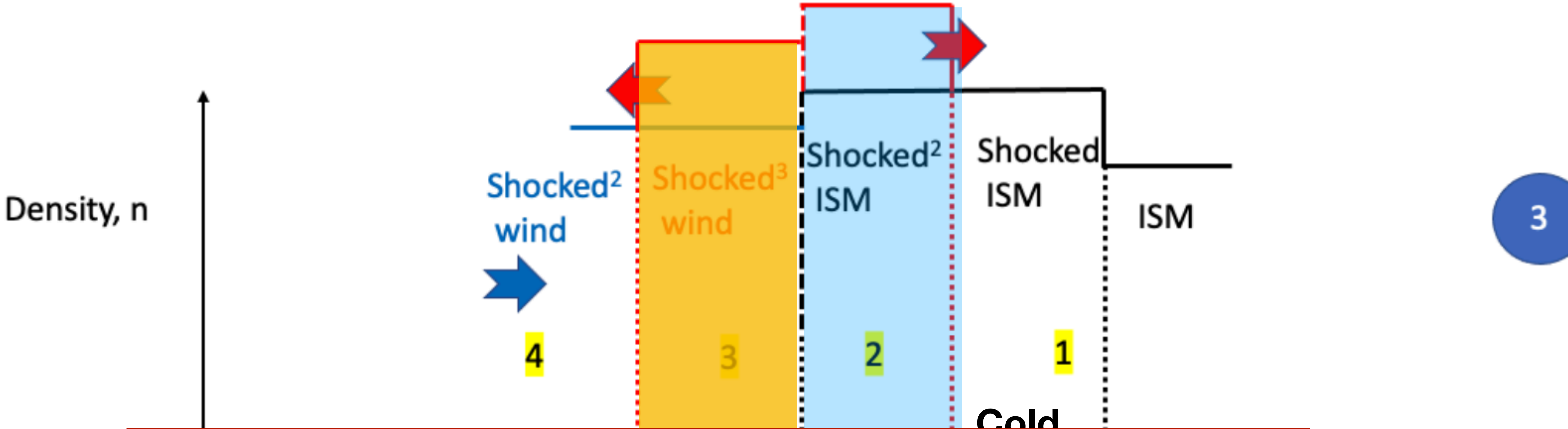
BW reaches CD at $t^{\mathrm{obs}} = 100 - 200\mathrm{s}$



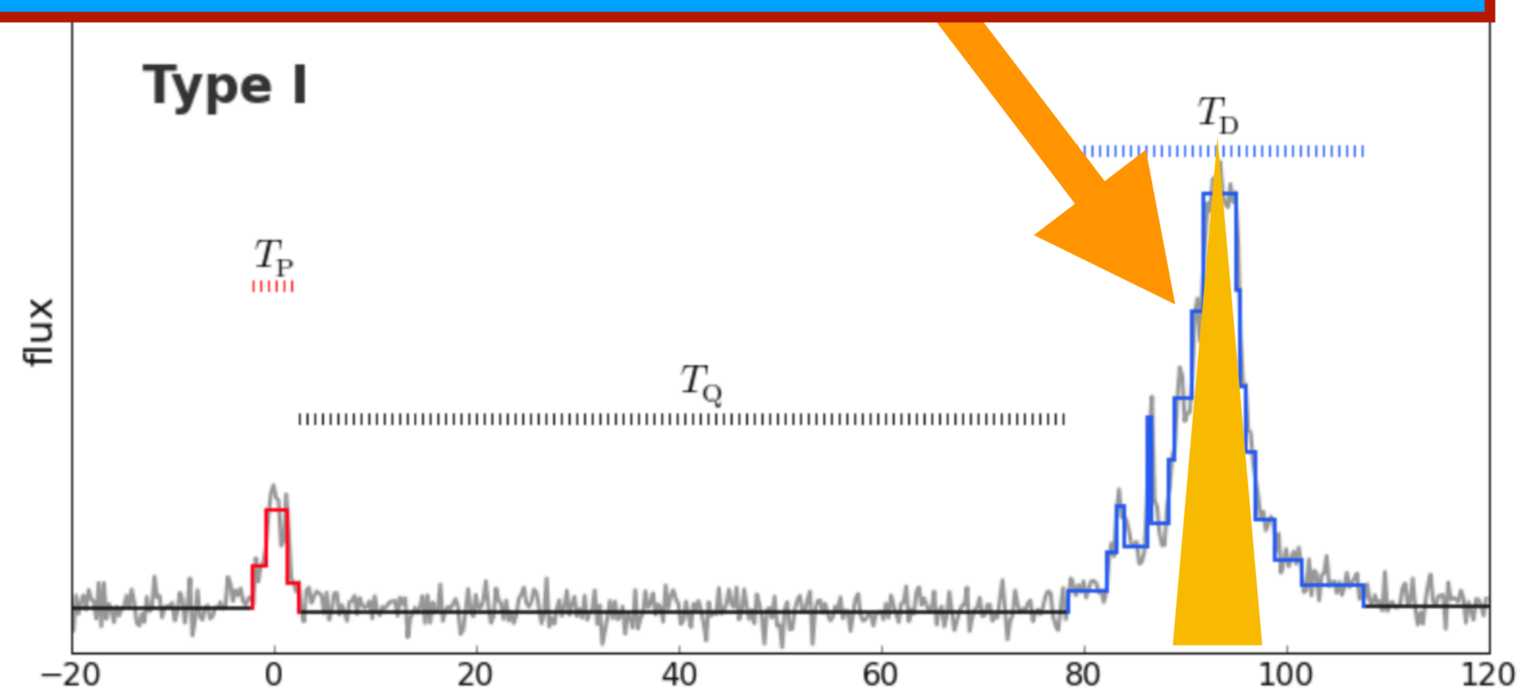
2

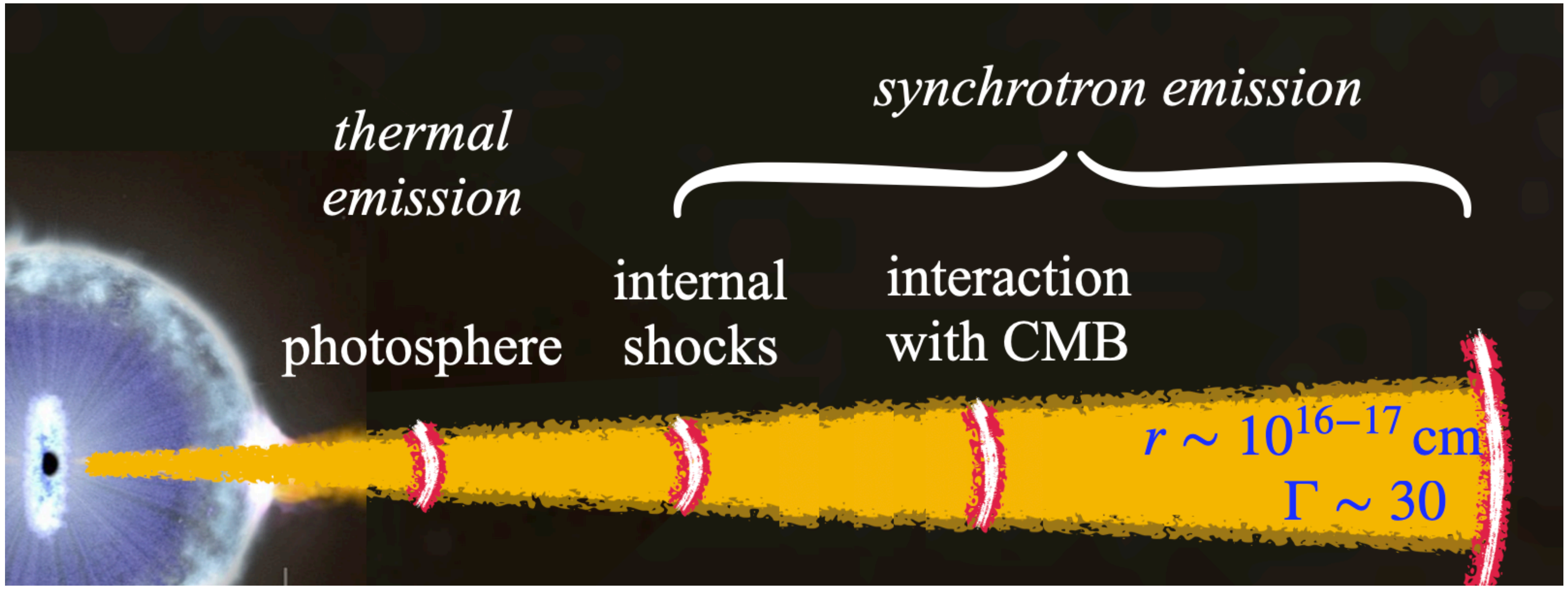
Density jump

$$\frac{n_{\mathrm{c}}}{n_{\mathrm{b}}} \sim 10^4$$



The reverse shock, caused by the blast wave, at the contact discontinuity can emit an intense synchrotron emission at around 100s





When is the prompt emission dominated by the photosphere? ***What does its spectrum look like?***

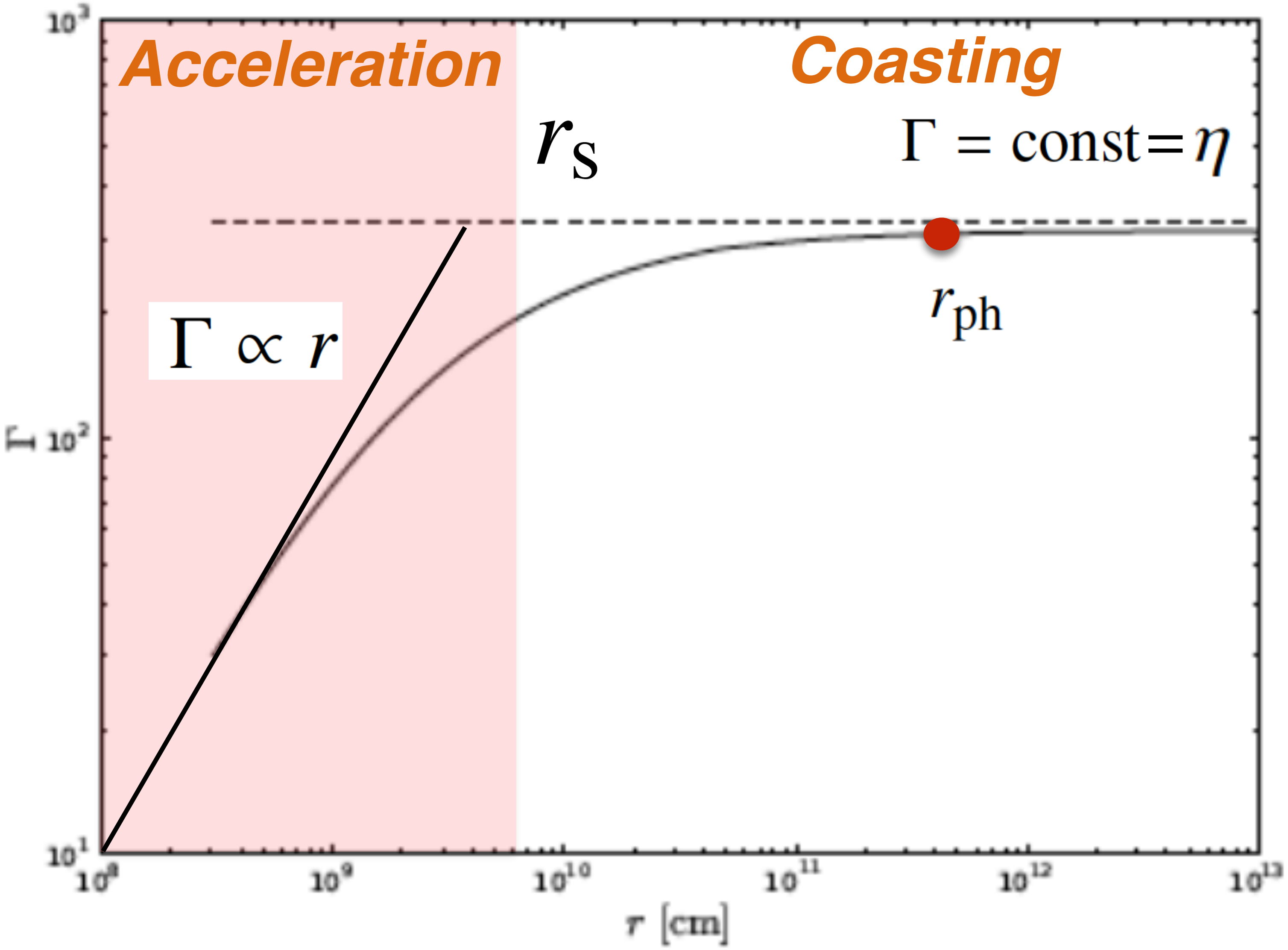
How narrow and how broad can a photospheric spectrum be?

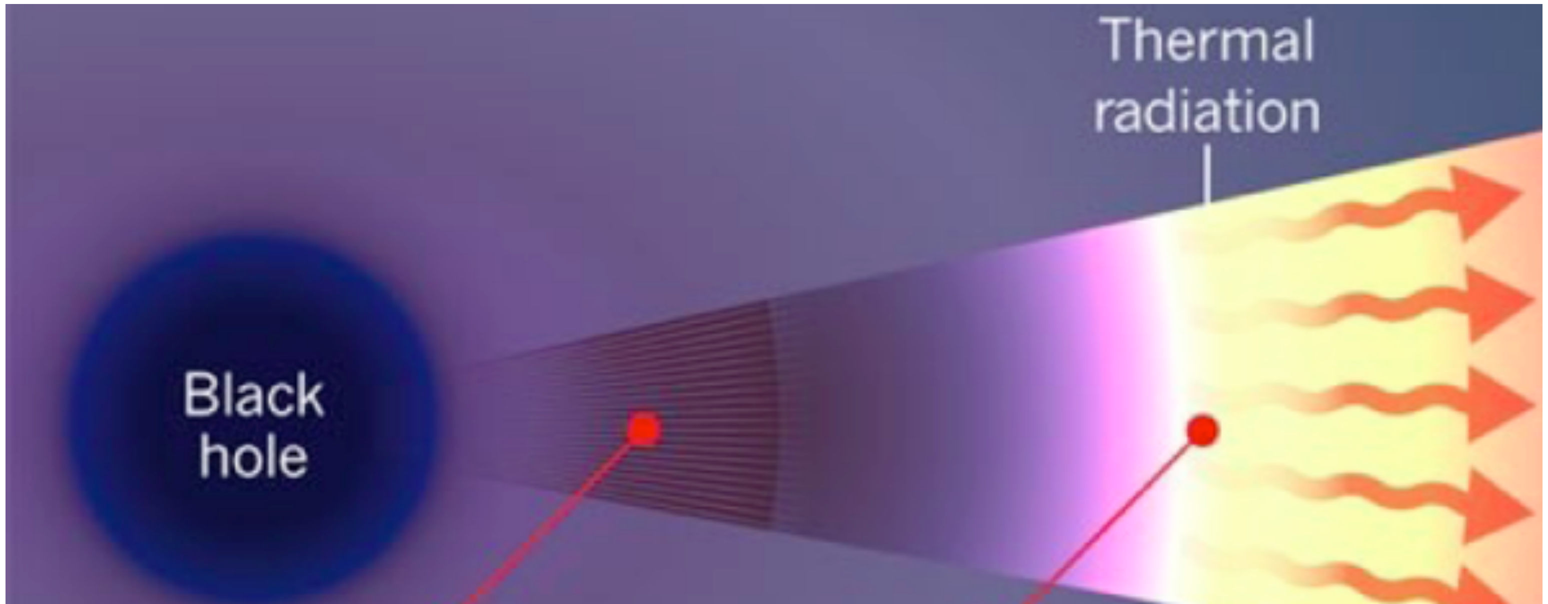
Photospheric emission from an undisruptive jet
What do we expect?

Fireball model:
Lorentz factor

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

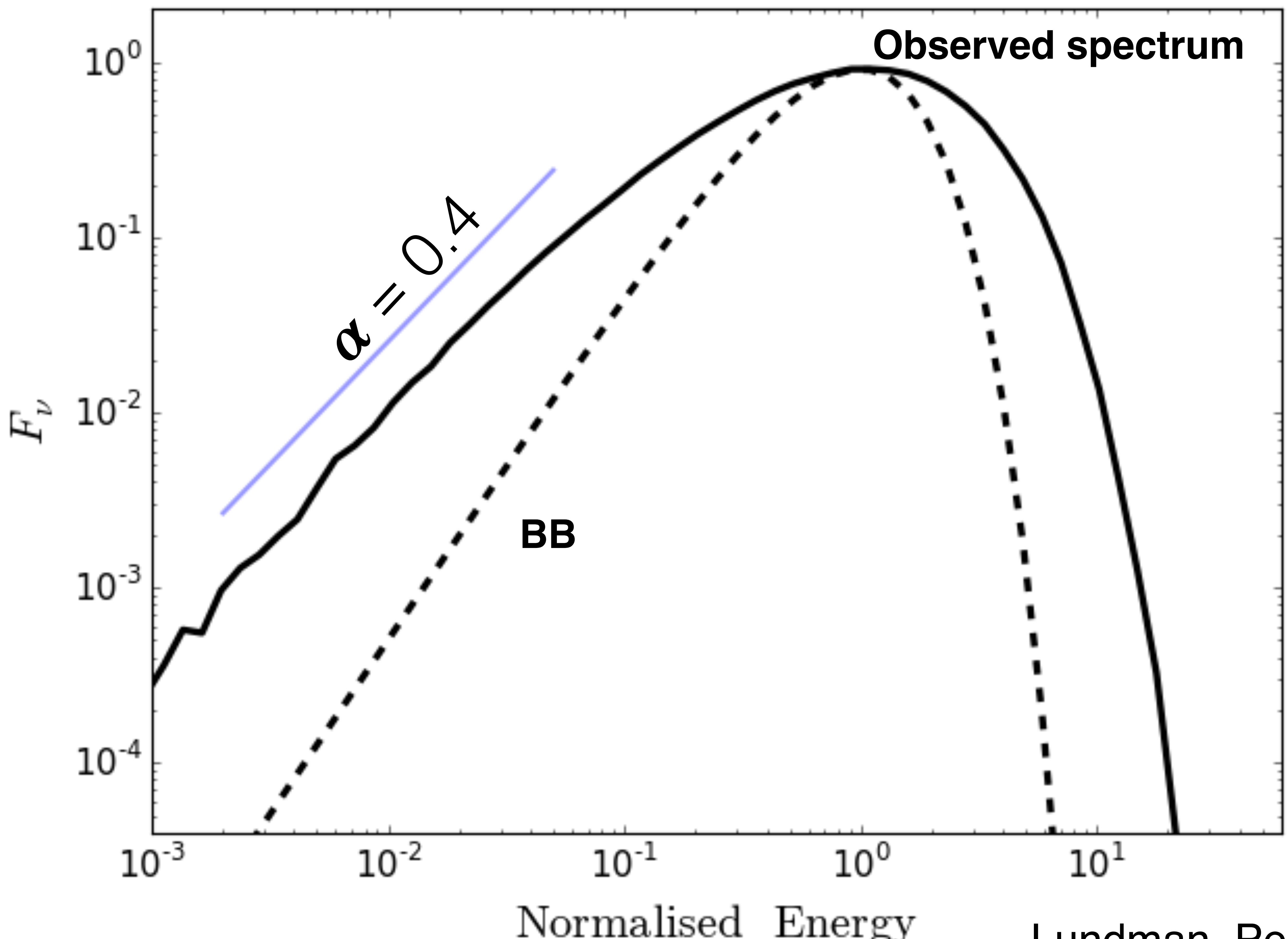
Magnetic dominated flow will have a different dynamics





Coasting phase spectrum from a non-dissipative jet

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



Lundman, Pe'er, Ryde 2013

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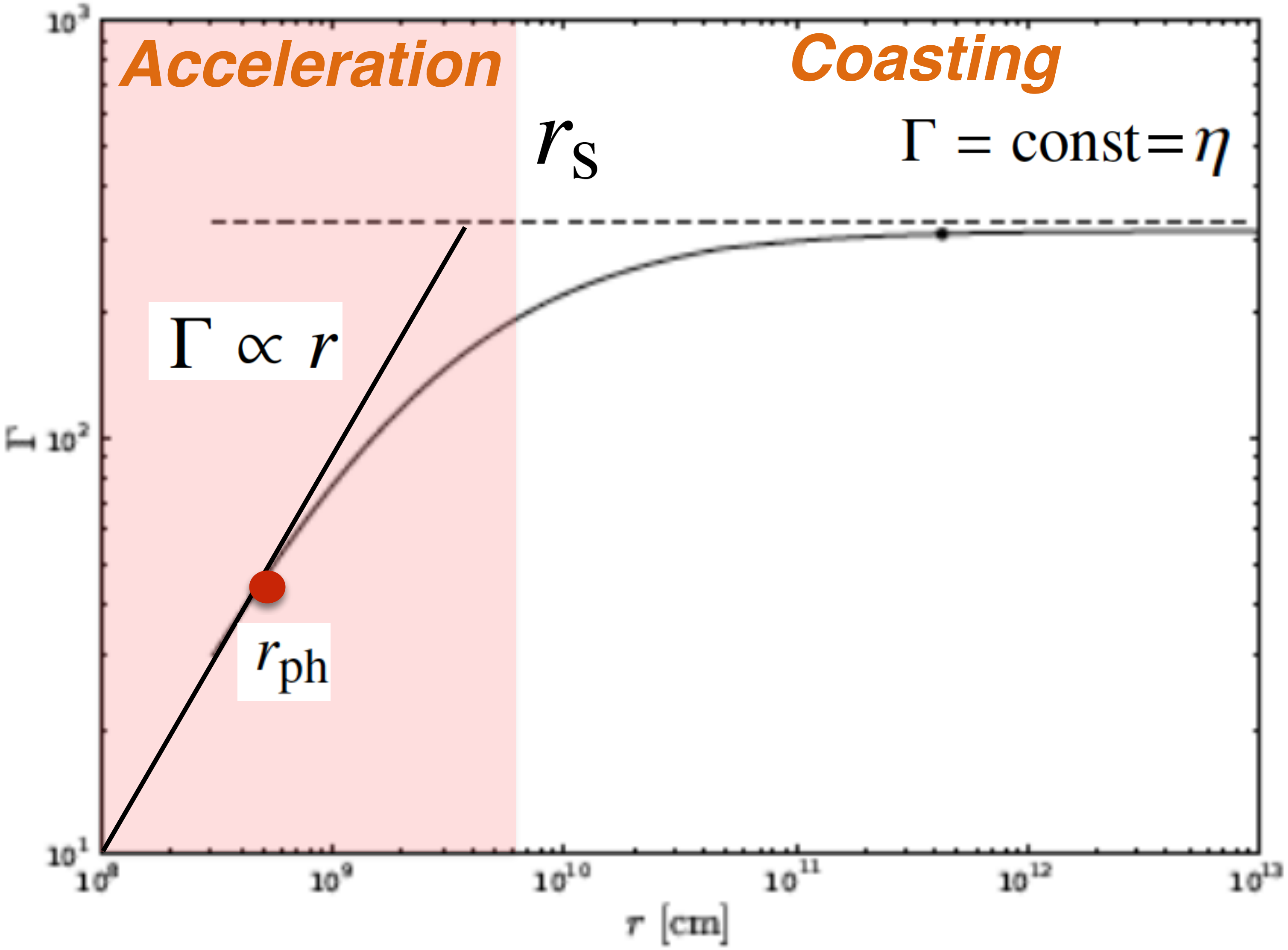
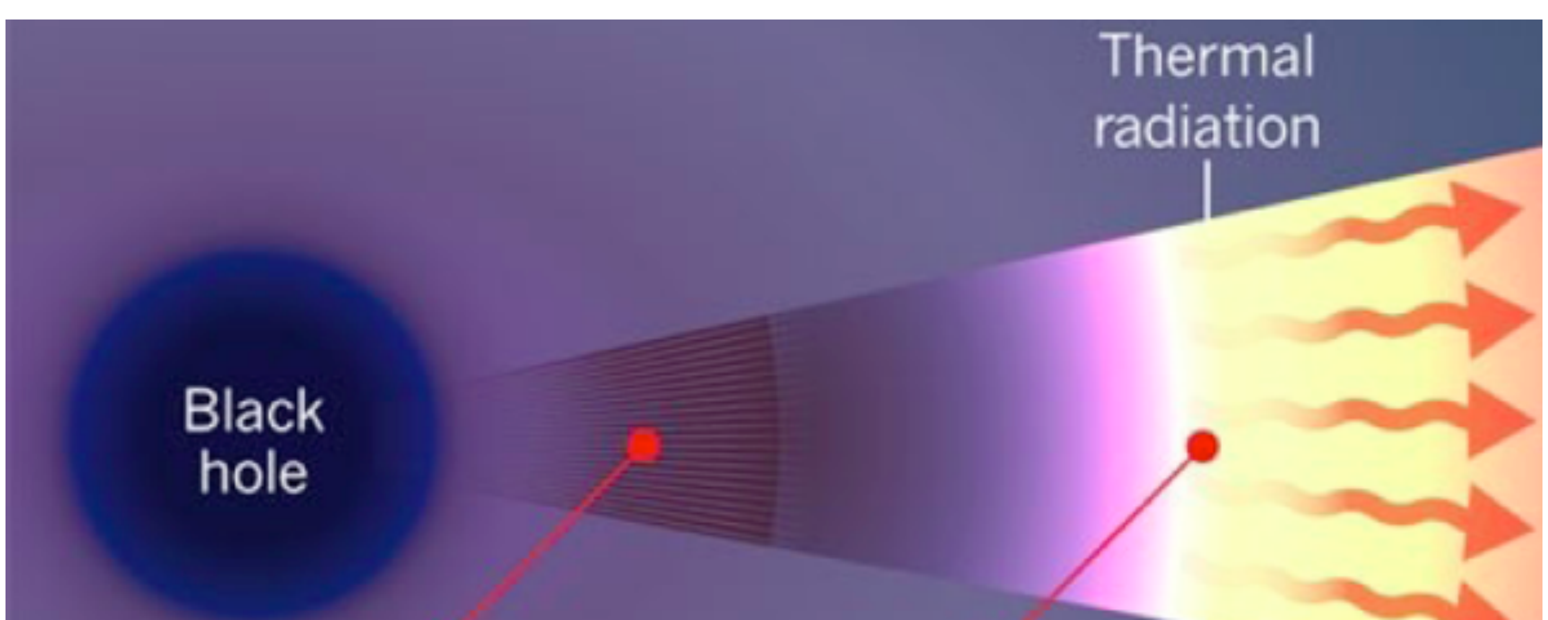
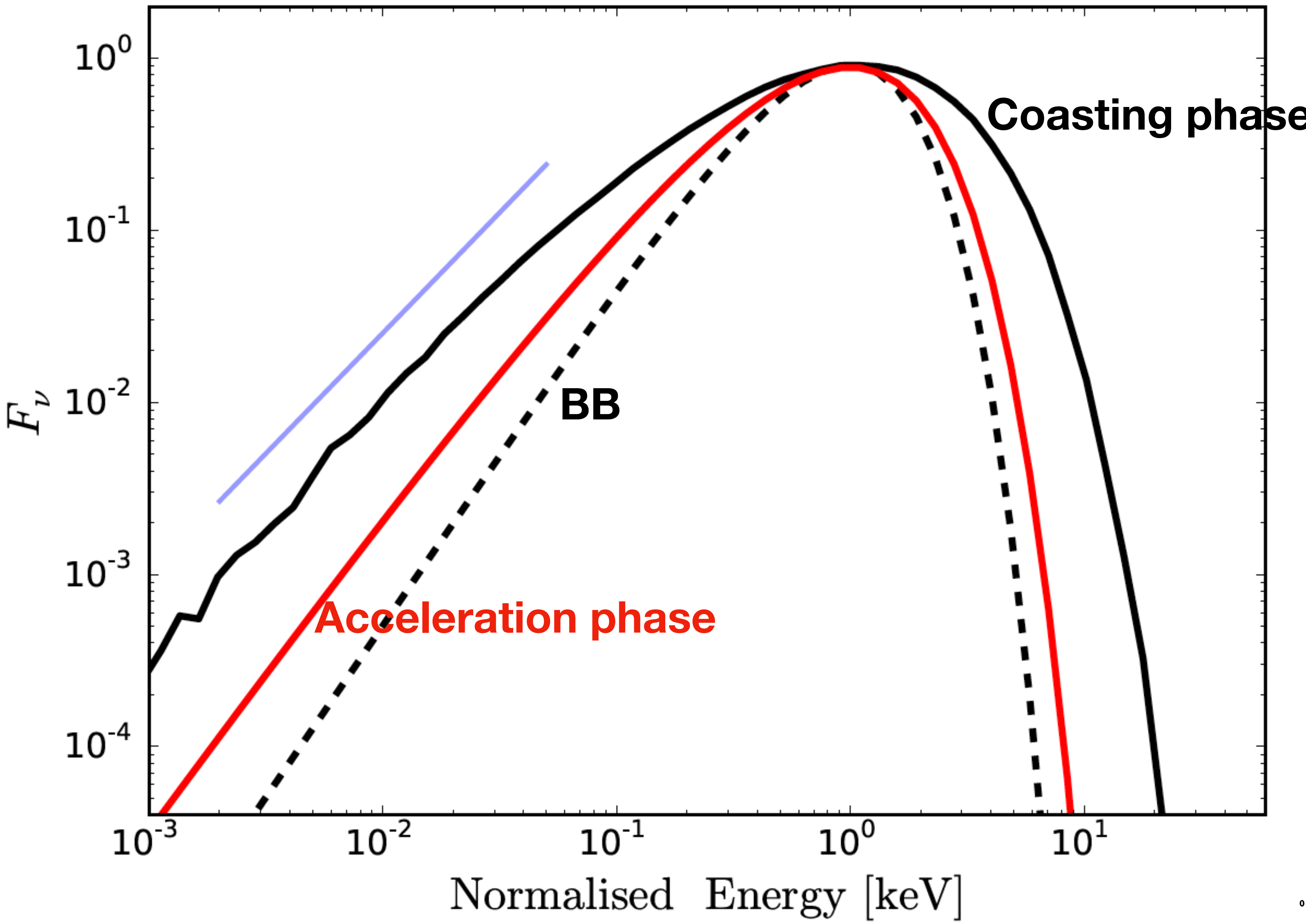
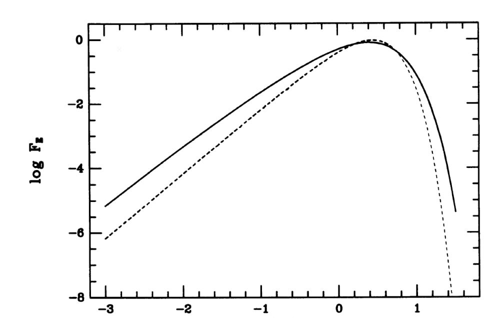




Photosphere in a nondissipative, radiation dominated flow



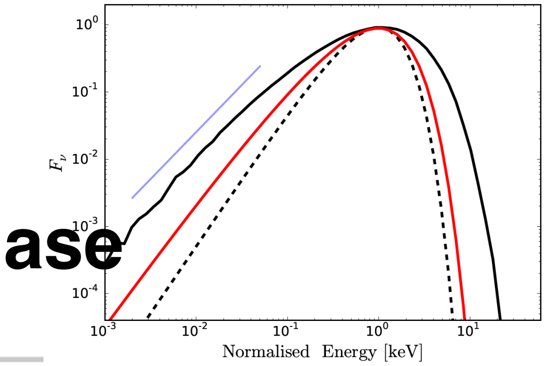
Acceleration phase: $$\frac{\nu L_\nu}{L} = \frac{45}{8\pi^4}\, x^3 \left(\frac{x}{2} - \ln\left[\exp\frac{x}{2} - 1\right]\right)$$

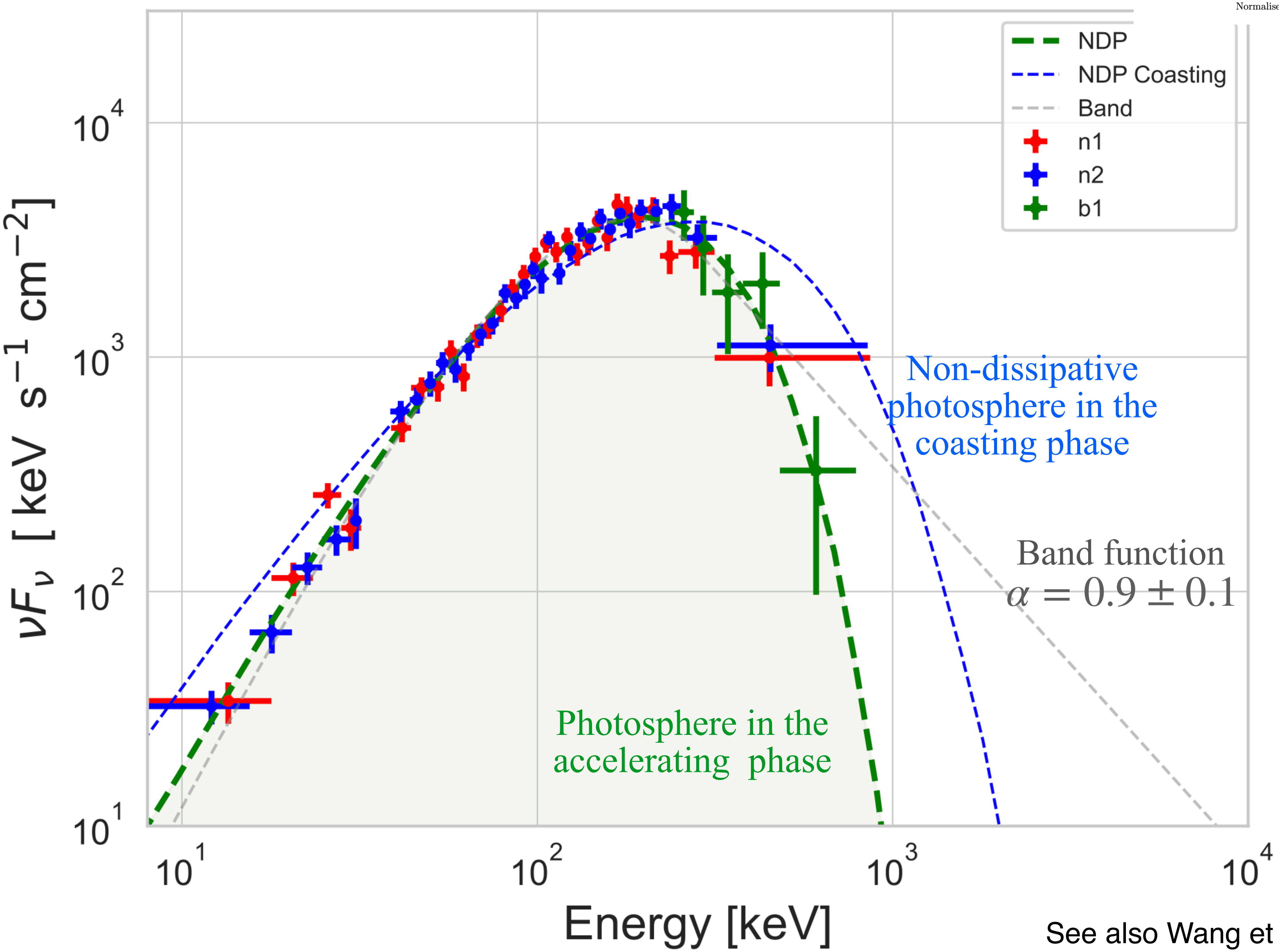


Ryde, Lundman & Acuner (2017)

Example: GRB220426A

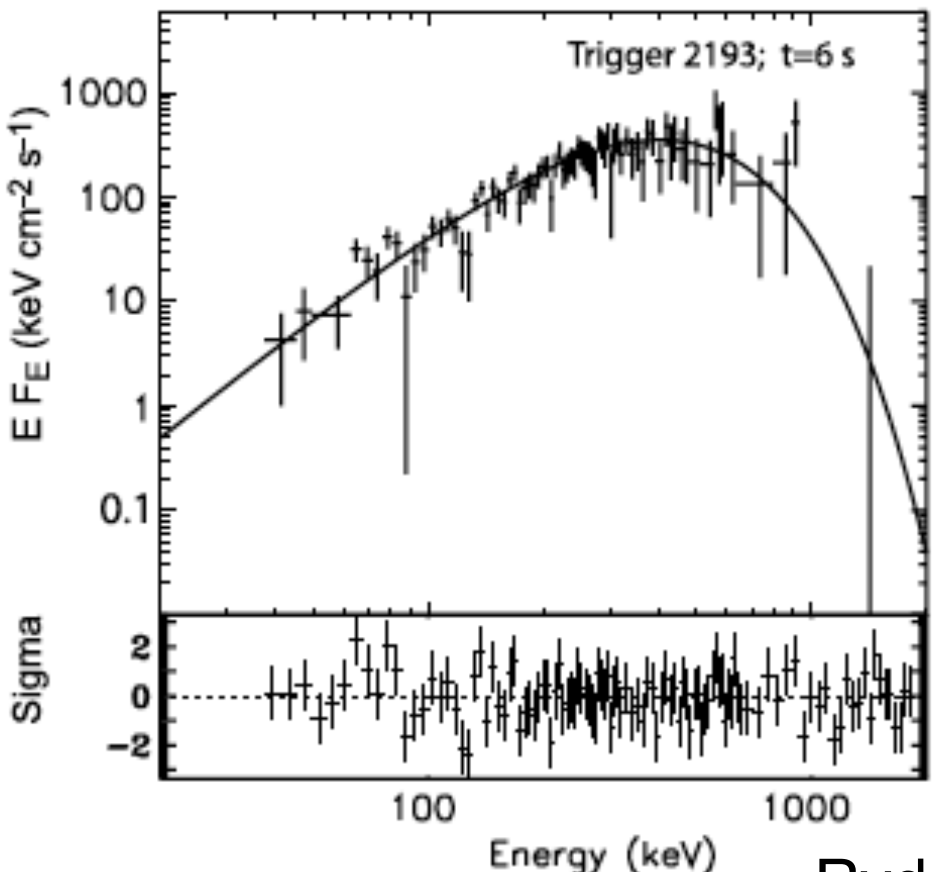
Very narrow spectrum: Photosphere in the accelerating phase



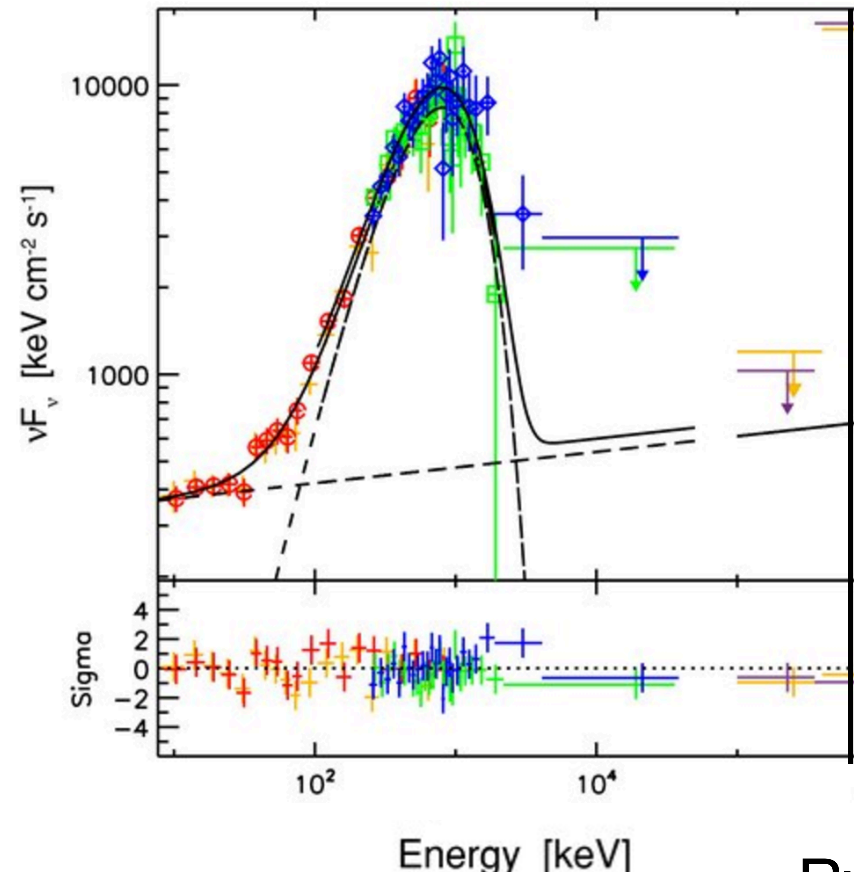


See also Wang et al. (2022)

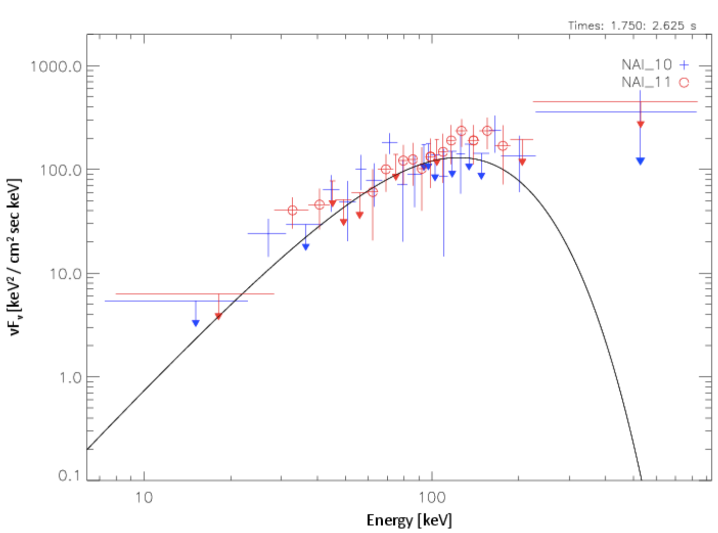
A few per cent of all spectra are quasi-Planckian



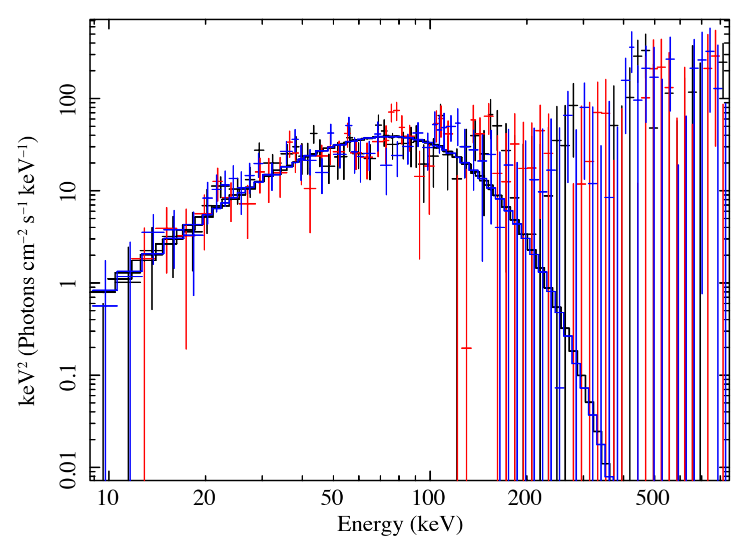
Ryde 2004



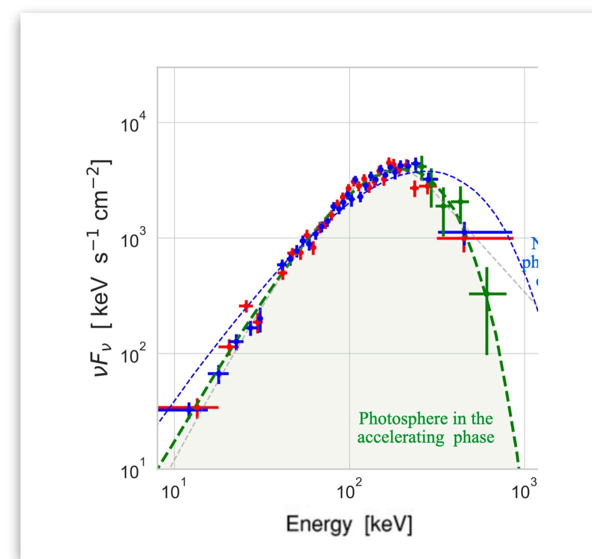
Ryde+2010



Ghirlanda+10



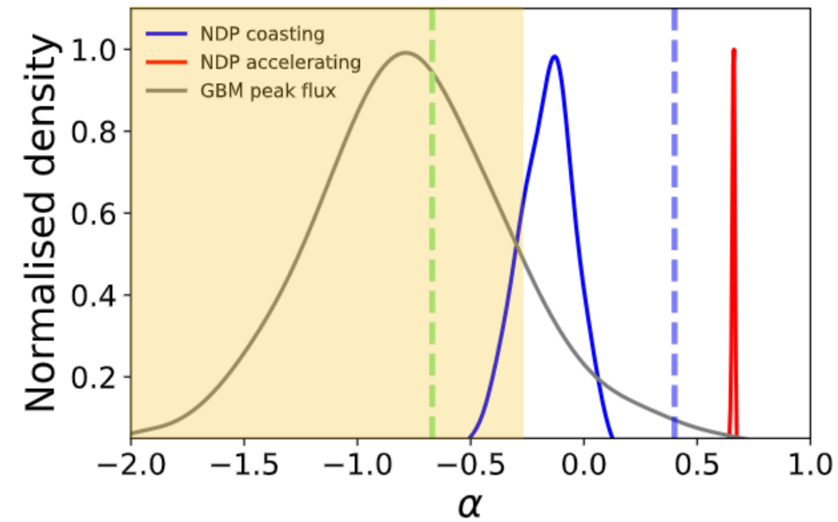
Larsson+15



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

What about the other 3/4 ?

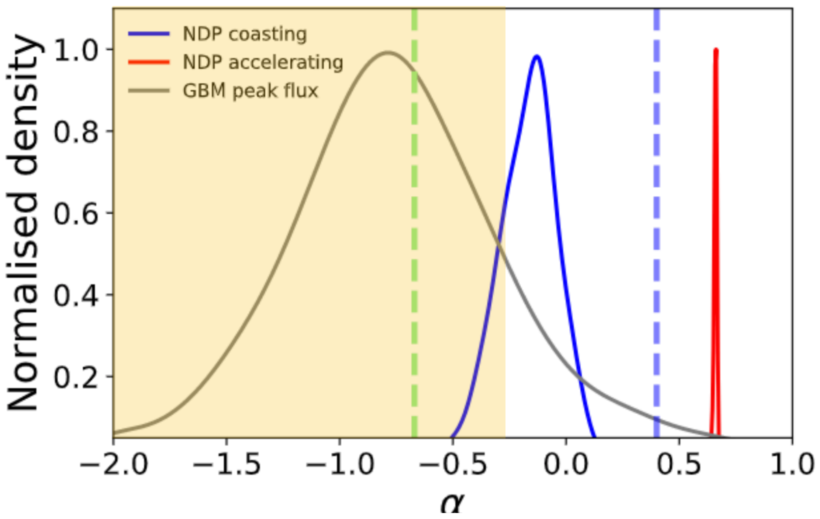
These spectra are broader than ND photospheric spectra



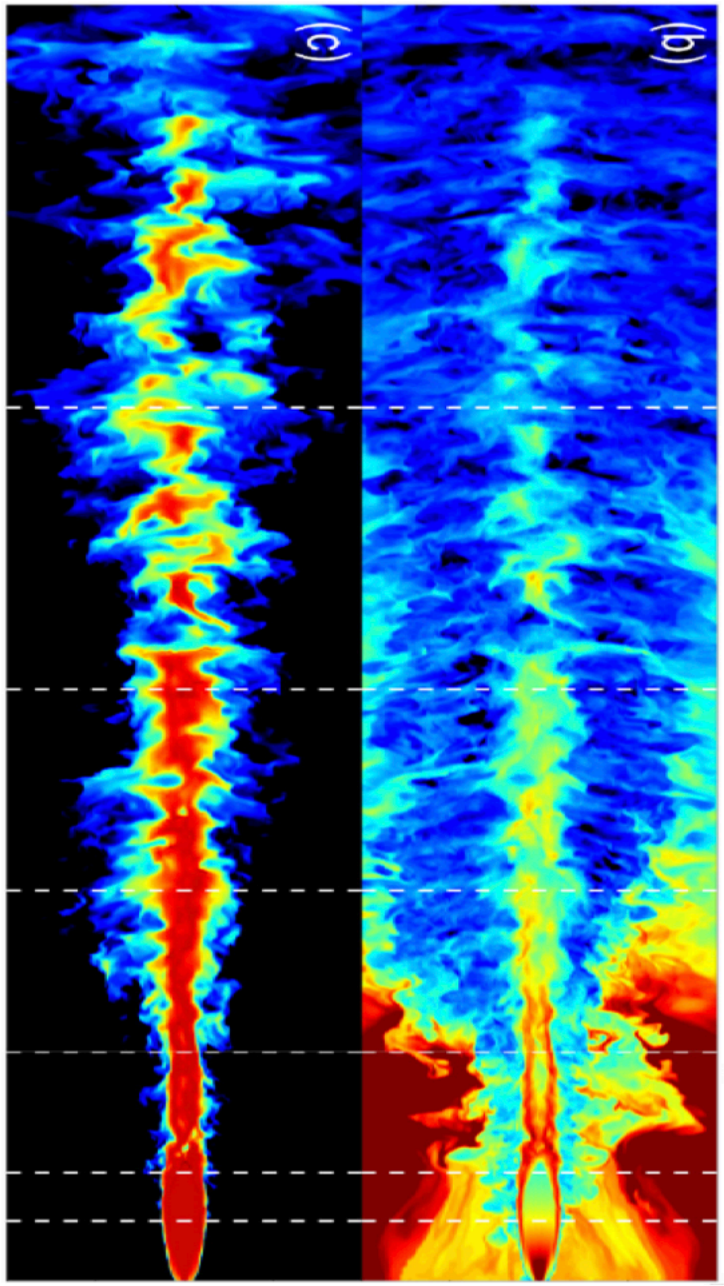
- Additional radiation processes, e.g. optically-thin synchrotron emission
- Multiple emission components, photosphere + synchrotron
- Viewing angle and Lorentz profile
- Smearing in time: enough time resolution?
- Subphotospheric heating (Rees & Meszaros 05, Pe'er+06)

What about the other 3/4 ?

These spectra are broader than ND photospheric spectra



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

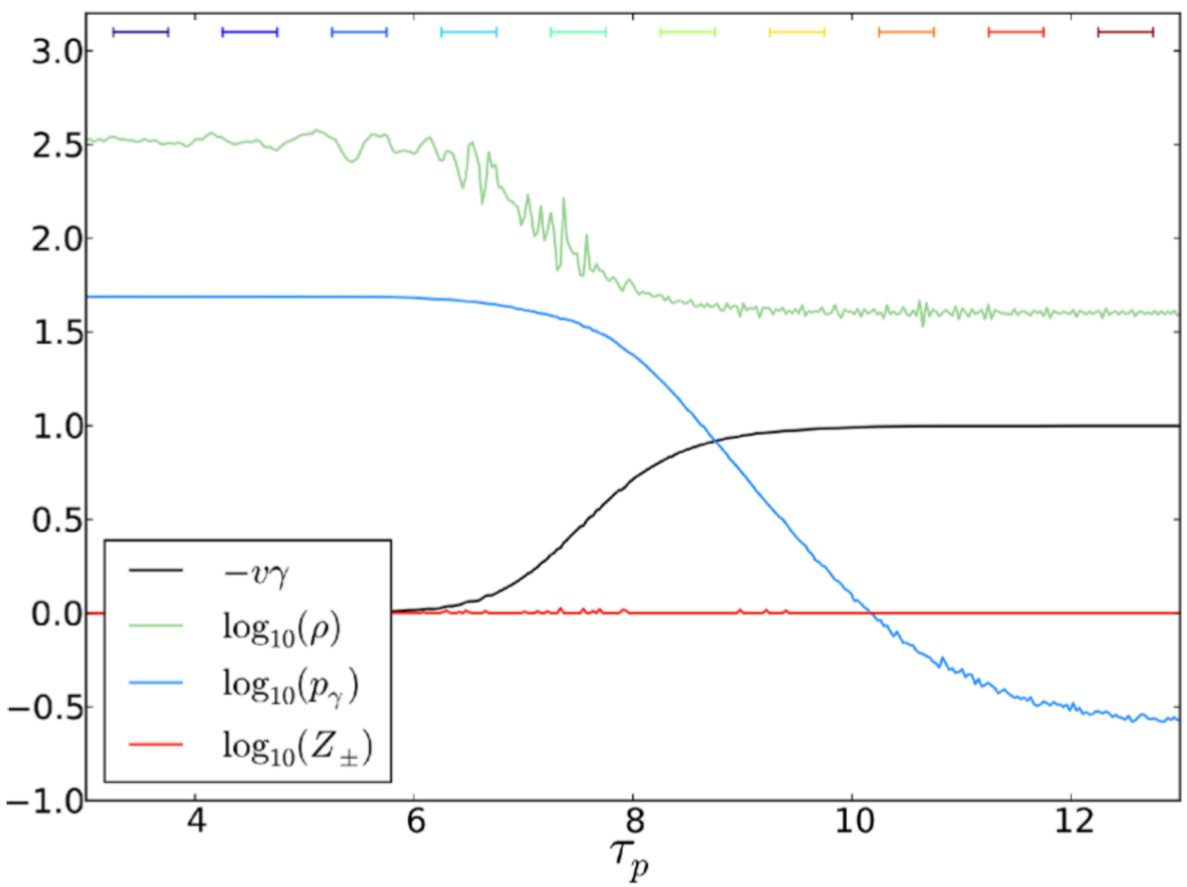


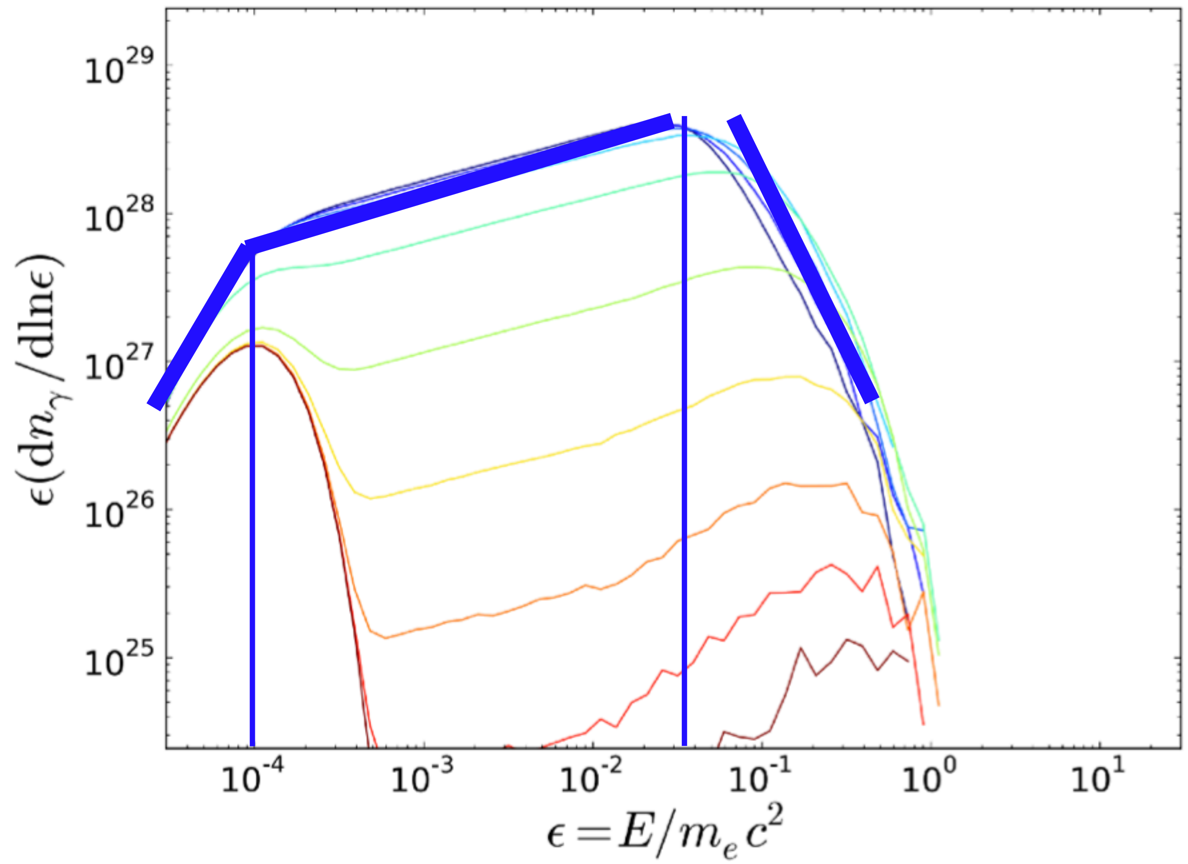
Eichler (1994), Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Katz+ (2010), Budnik+ (2010), Levinson (2012), Beloborodov (2017), Ito+ (2018), Levinson & Nakar (2020)

Gottlieb+ (2020)

Non relativistic photon-rich RMS

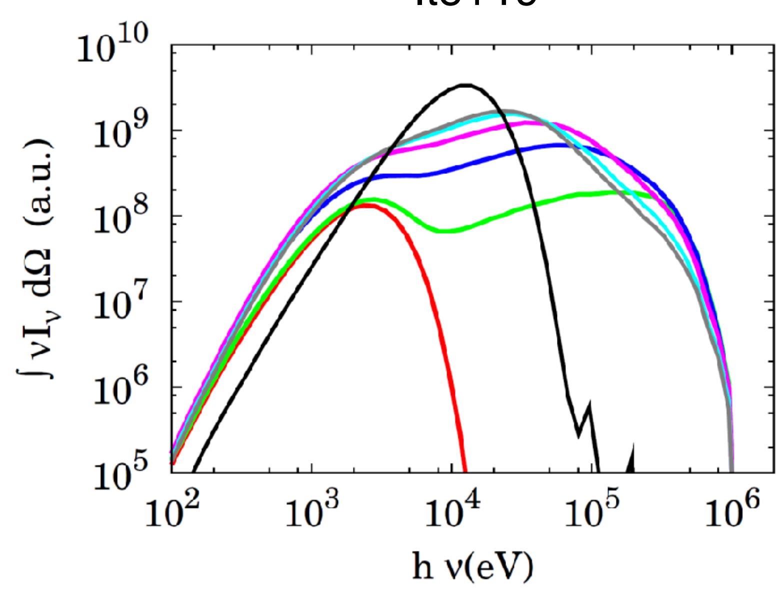
- Smoother, more predictable profile compared to relativistic RMS
- Computationally heavy to run





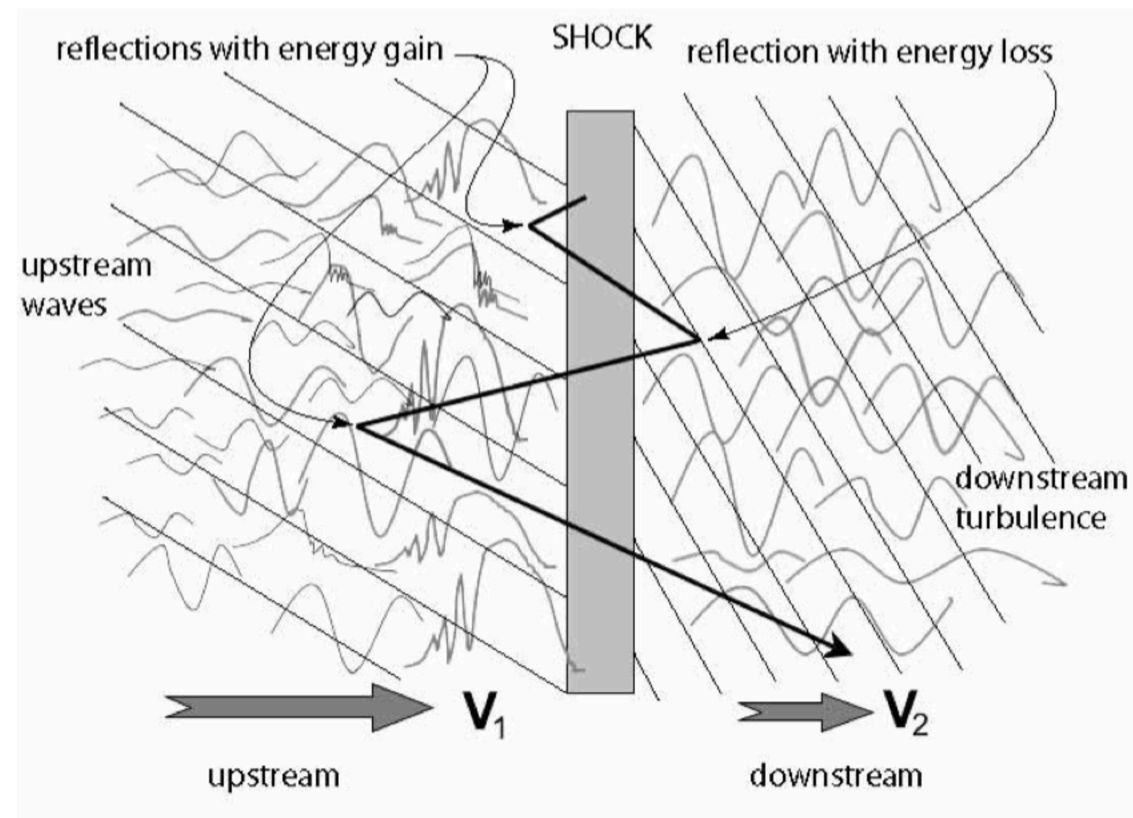
Lundman+ (2018)

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

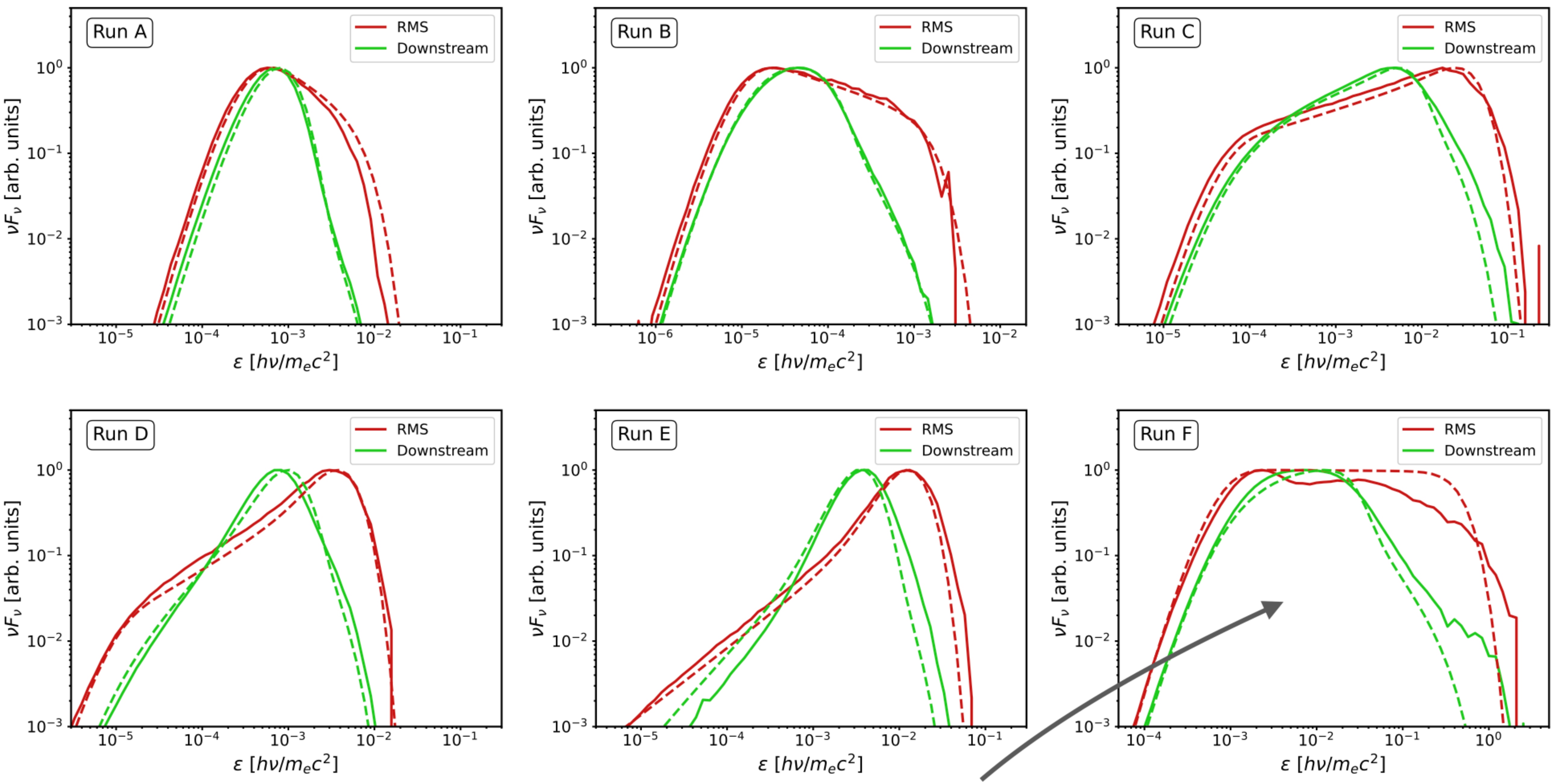


Treumann & Jaroschek (2008)

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

Evolution described by the Kompaneets equation

The KRA (Kompaneets RMS Approximation)

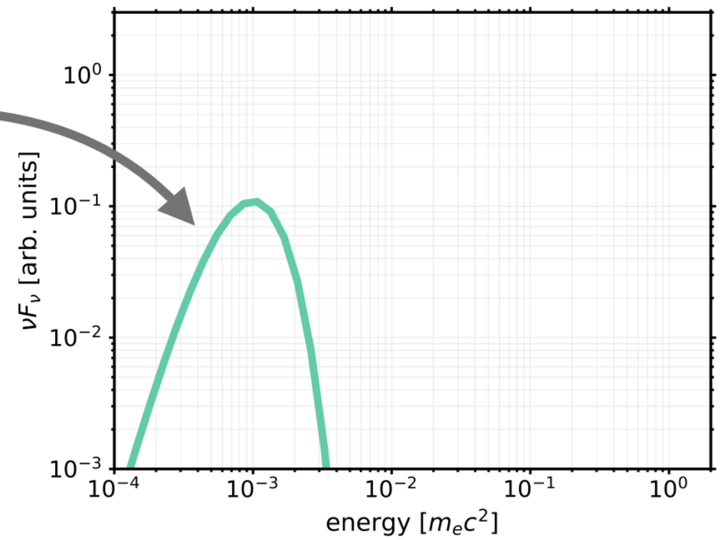


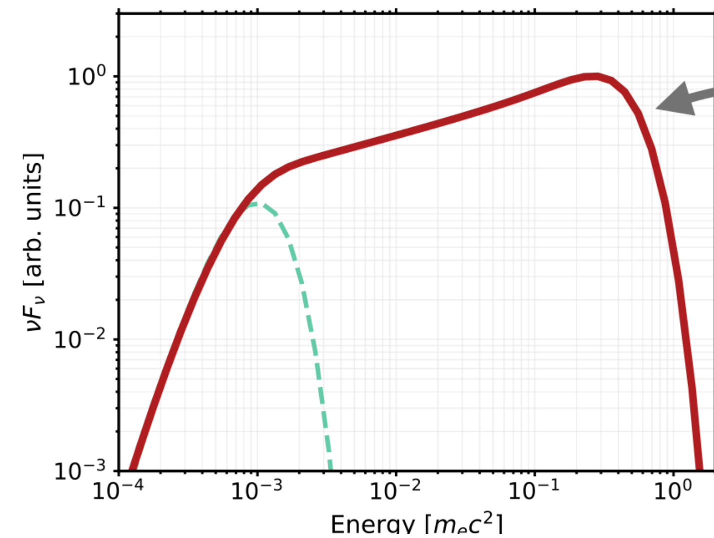
Mildly relativistic shock: $(\beta\gamma)_{\mathrm{u}} = 3$

Samulesson, Lundman & Ryde (2022)

The KRA (Kompaneets RMS Approximation)

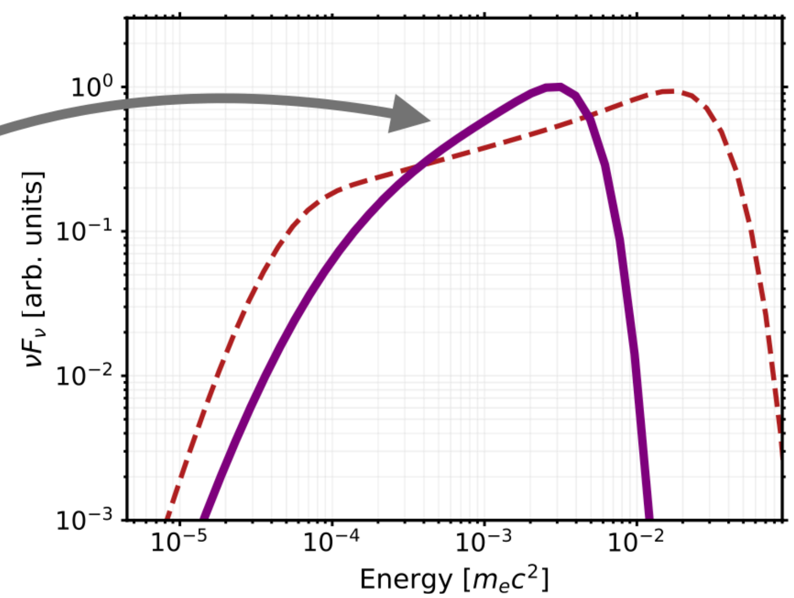
Initial thermal upstream





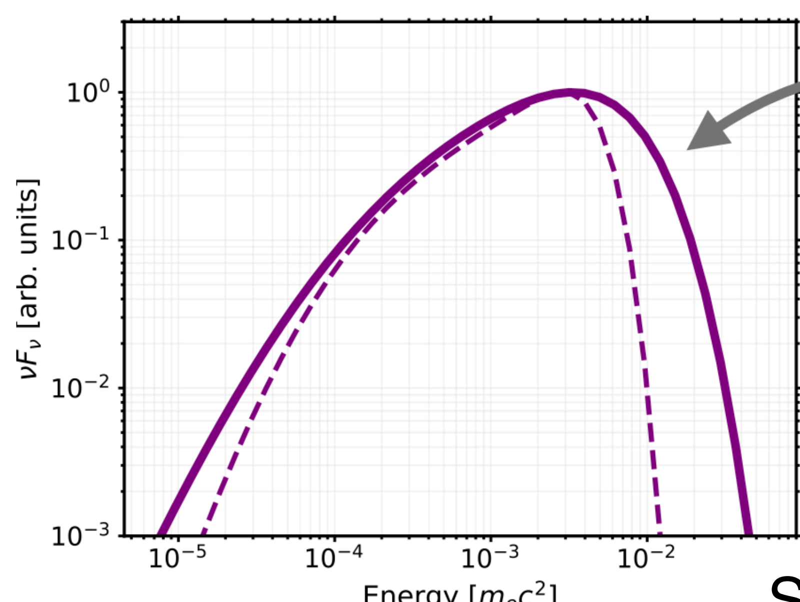
Radiation-mediated shock

Photospheric spectrum



Partially thermalized

Broadened by high-latitude and different radial emission

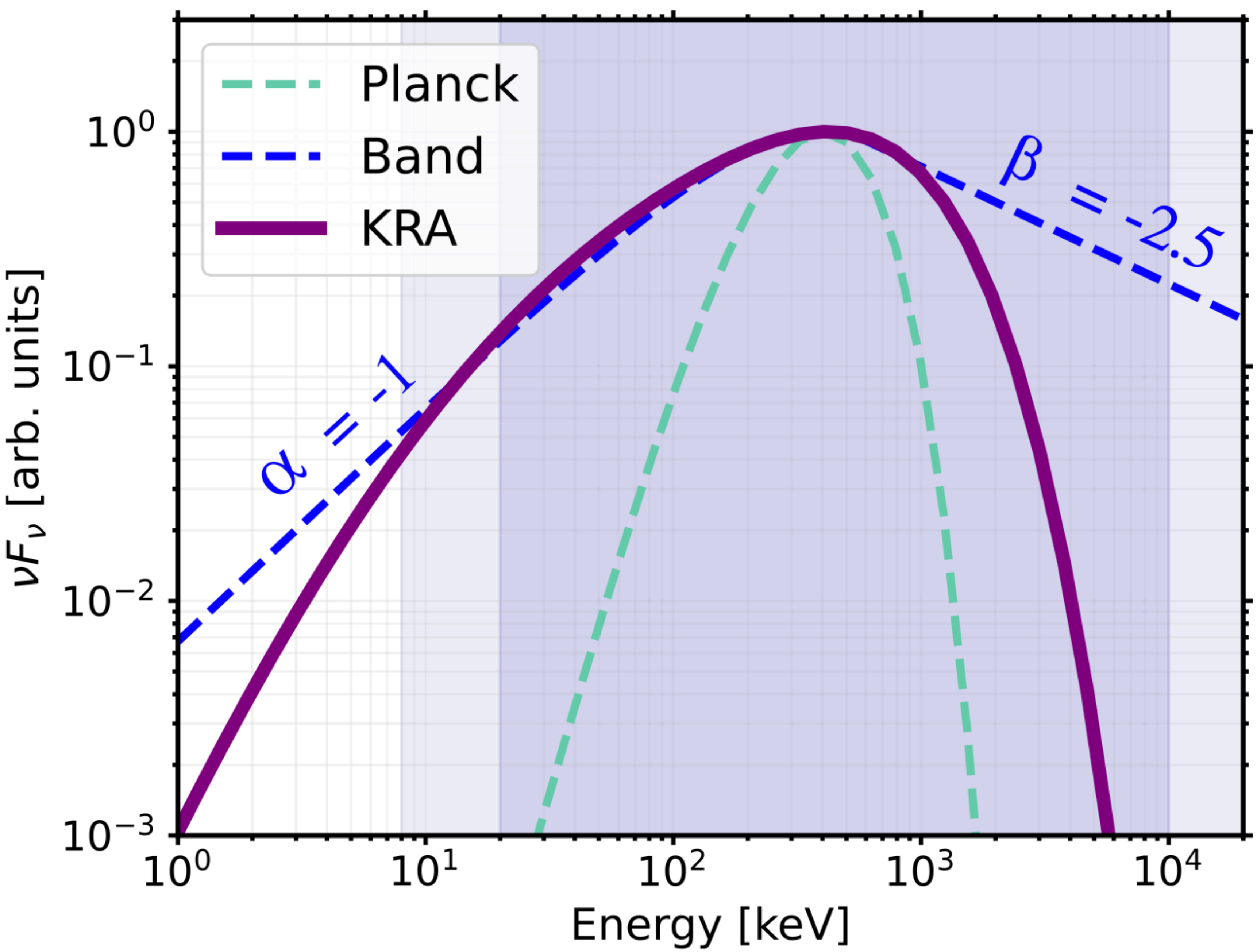


Observed spectrum

Samulesson, Lundman & Ryde (2022)

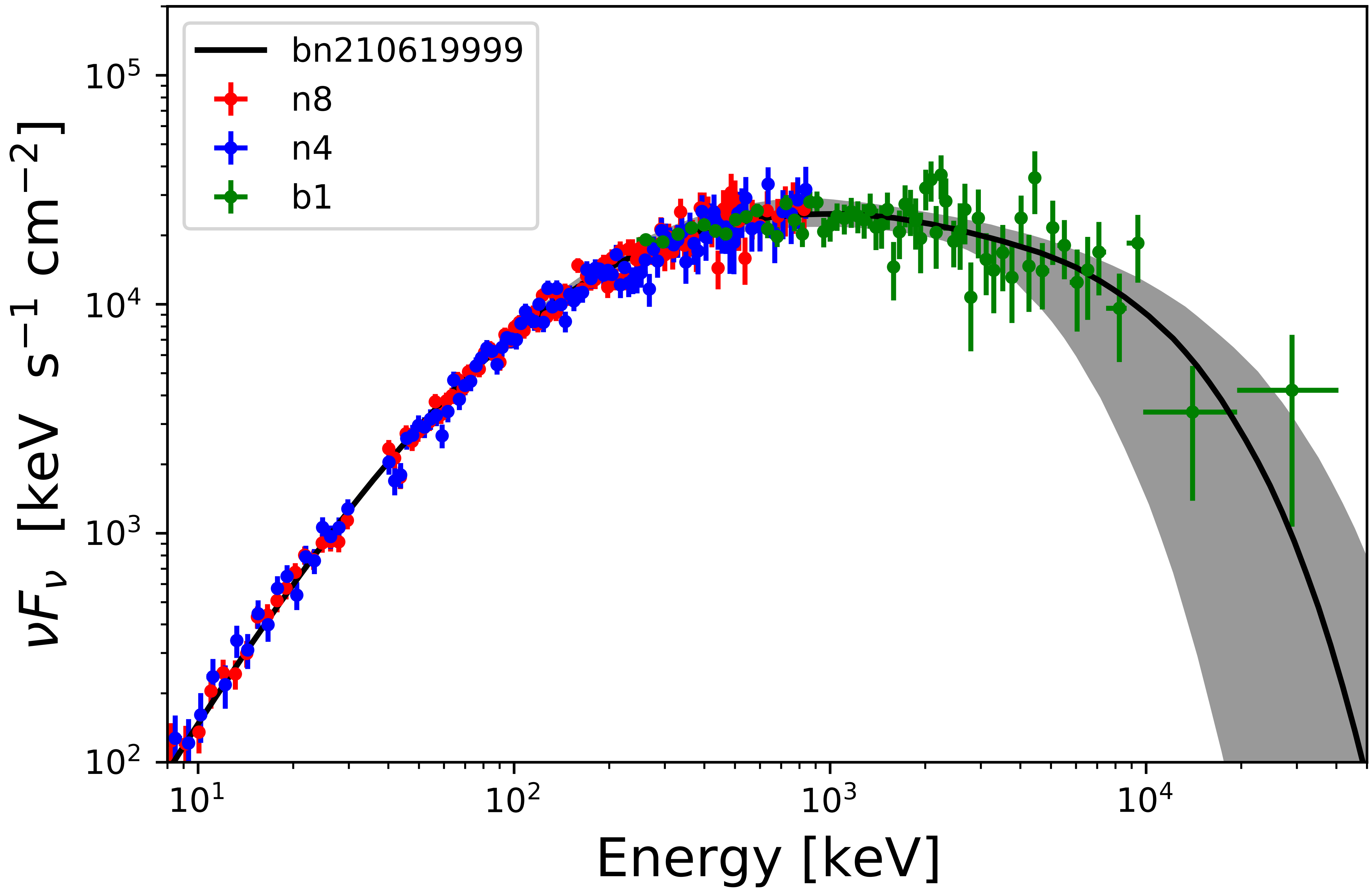
Radiation mediated shocks - observed spectrum

- Broad
- Soft
- Smooth curvature
- Similar to observations



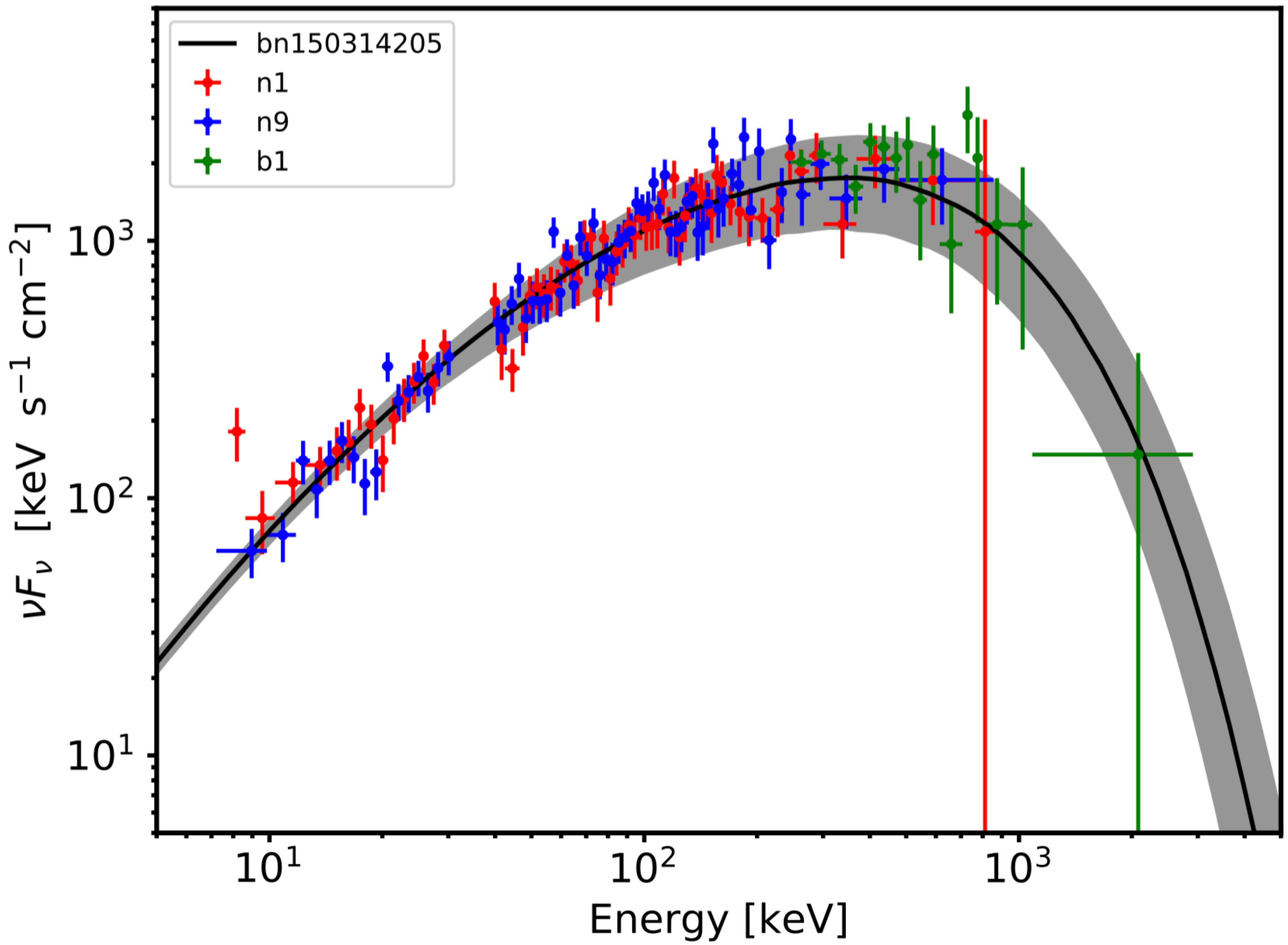
Example: GRB210619

RMS model fit to time resolved data



Example: GRB150314A

RMS model fit to time resolved data



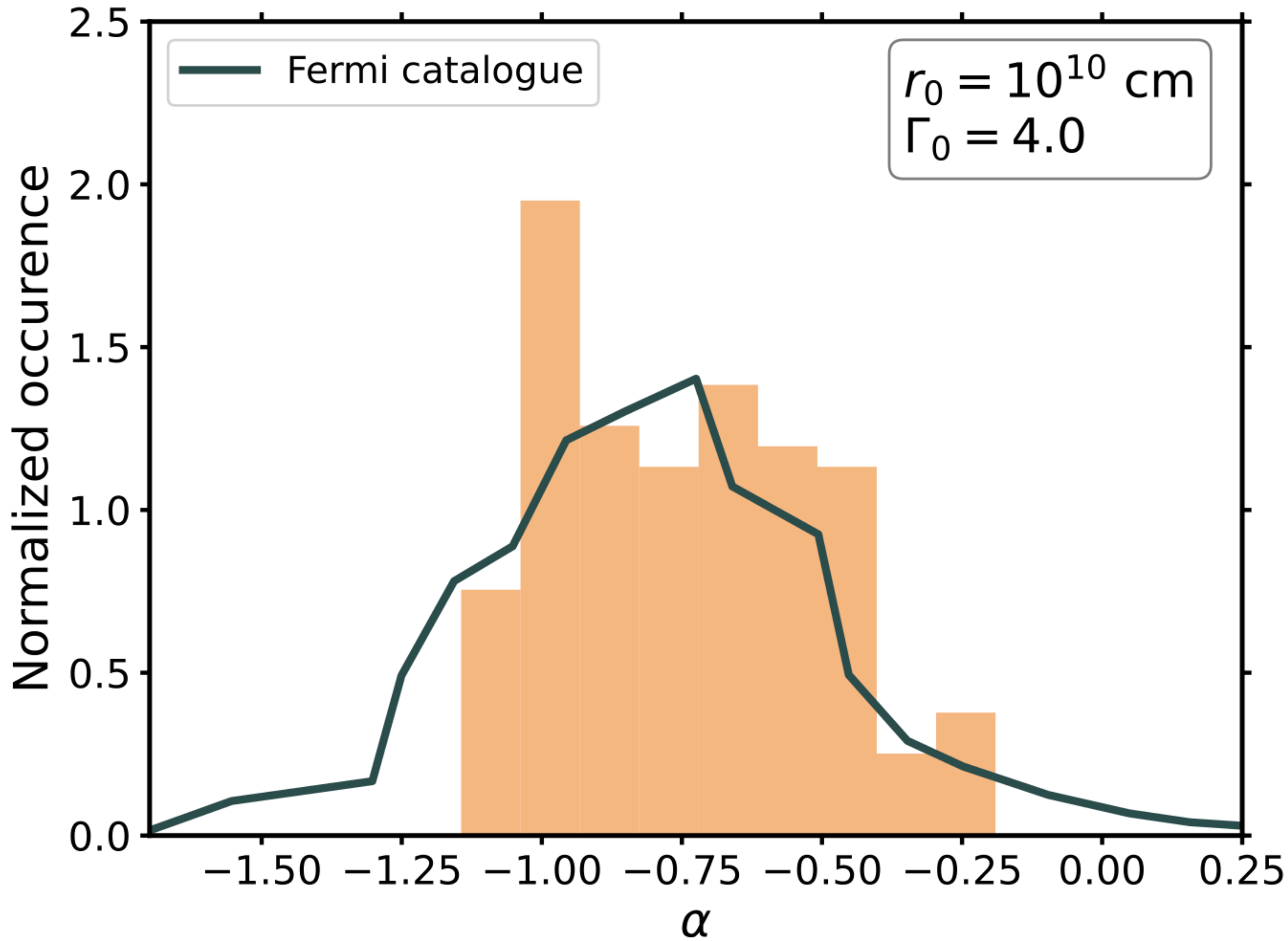
RMS model parameters

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

Samulesson, Lundman & Ryde (2022)

Quantitative comparison against observations

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



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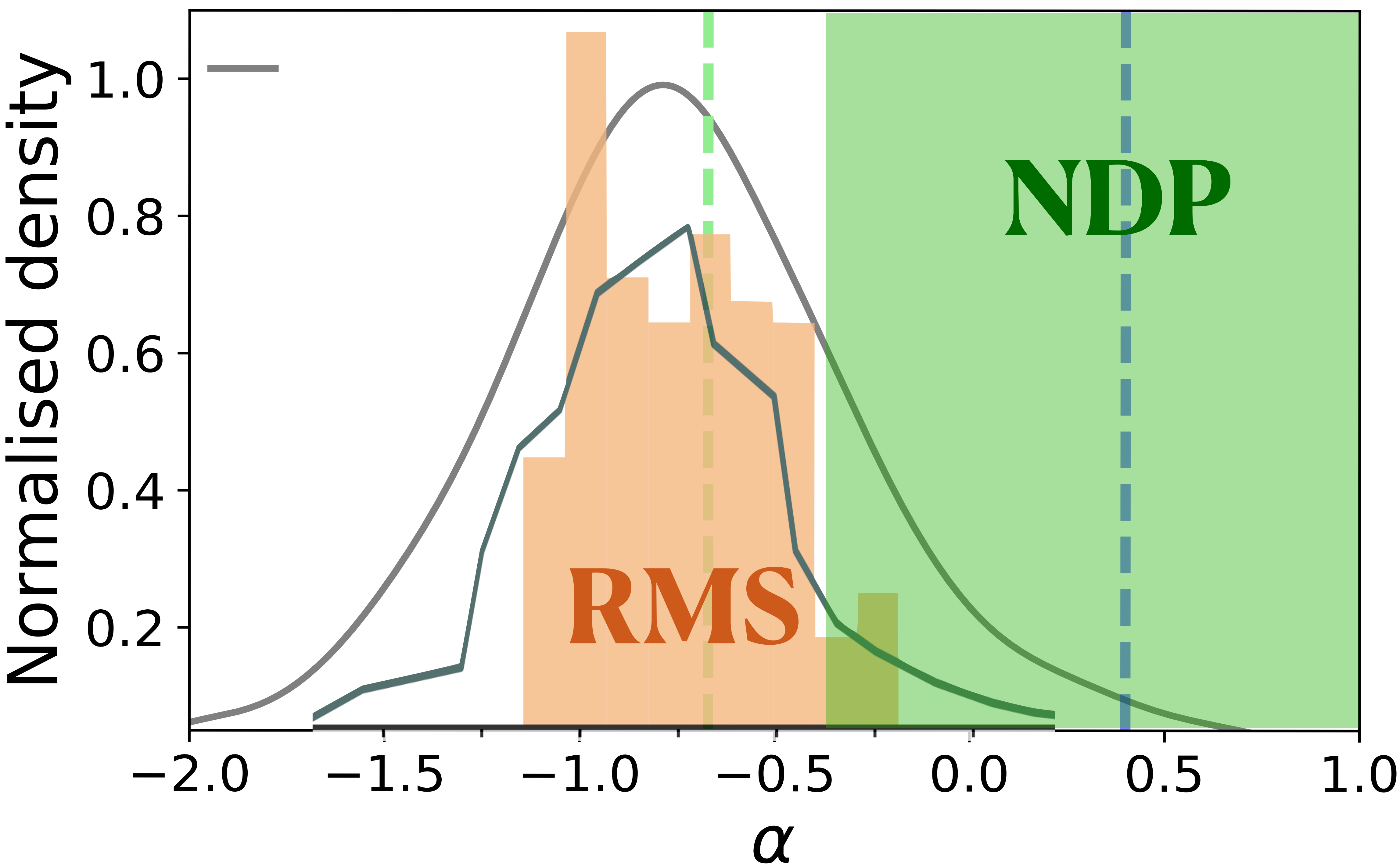
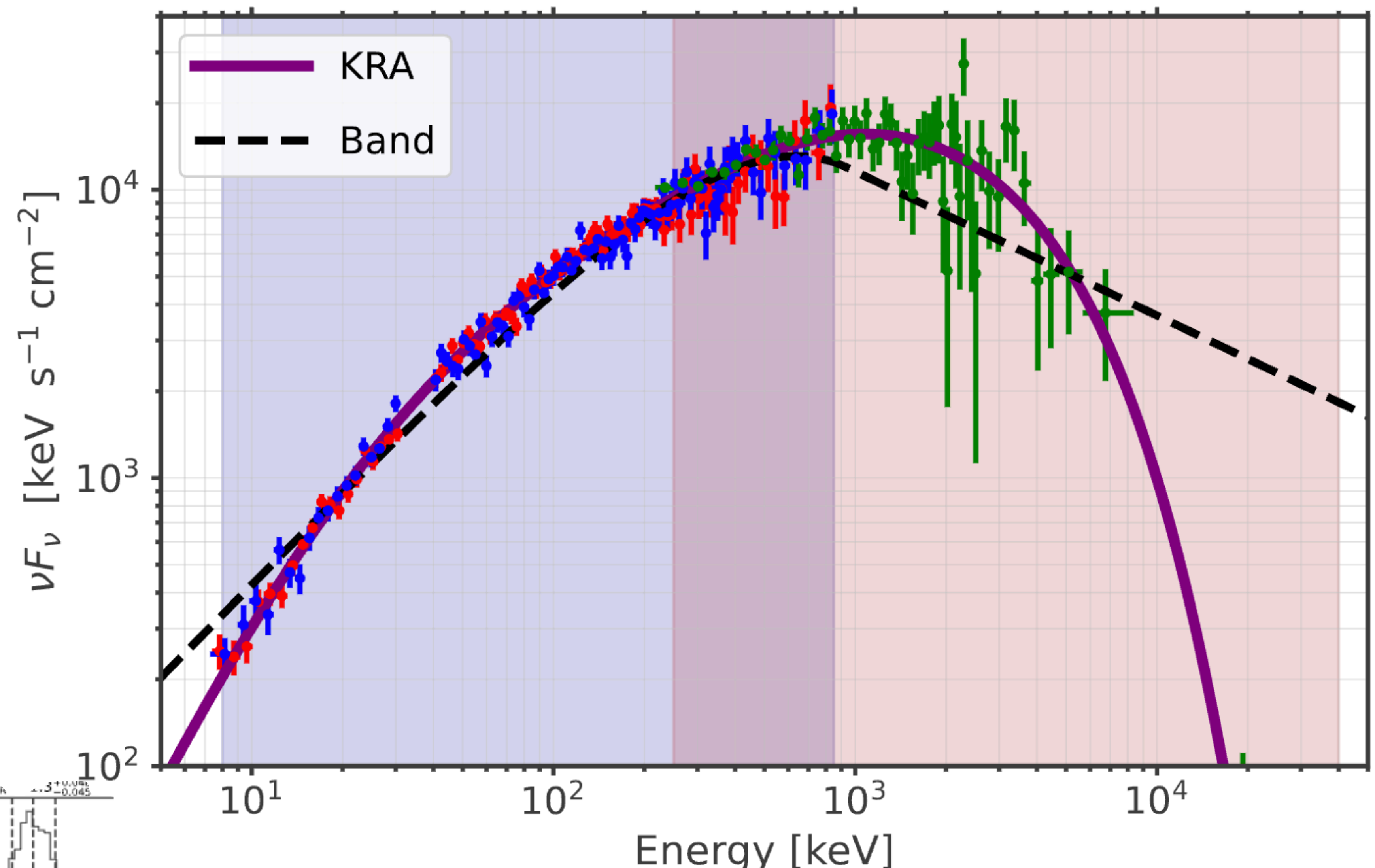
Catalogue distribution of α



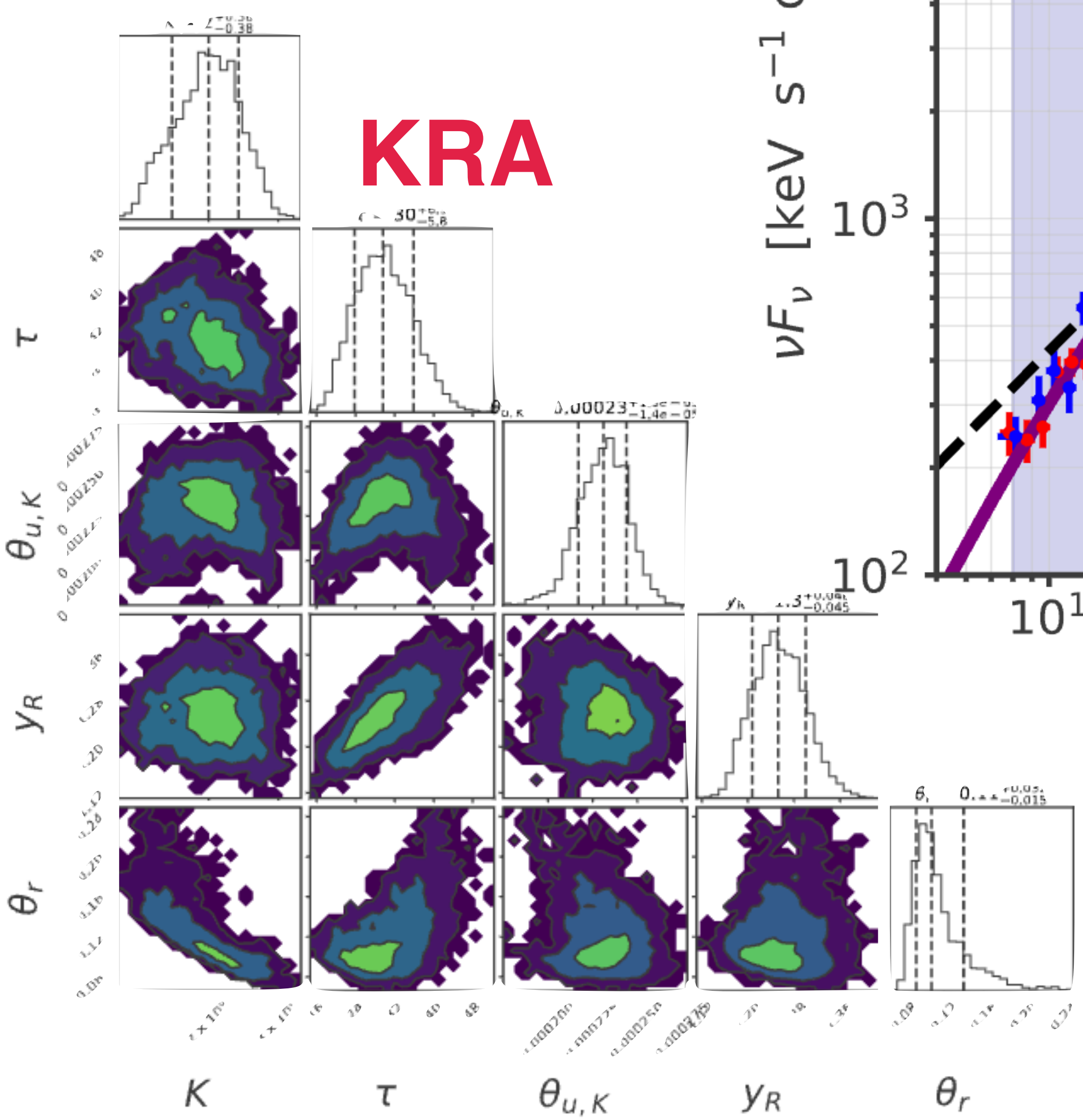
Samulesson & Ryde (2023)

GRB211211A: synchrotron emission?

Two distinct spectral breaks:
Marginally fast cooling synchrotron (Gompertz+23),
Synchrotron + BB (Peng+24)



KRA



RMS

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

Wistemar, Alamaa & Ryde 25

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