Radiation-mediated shocks in GRB emission

HEPRO VIII, October 26

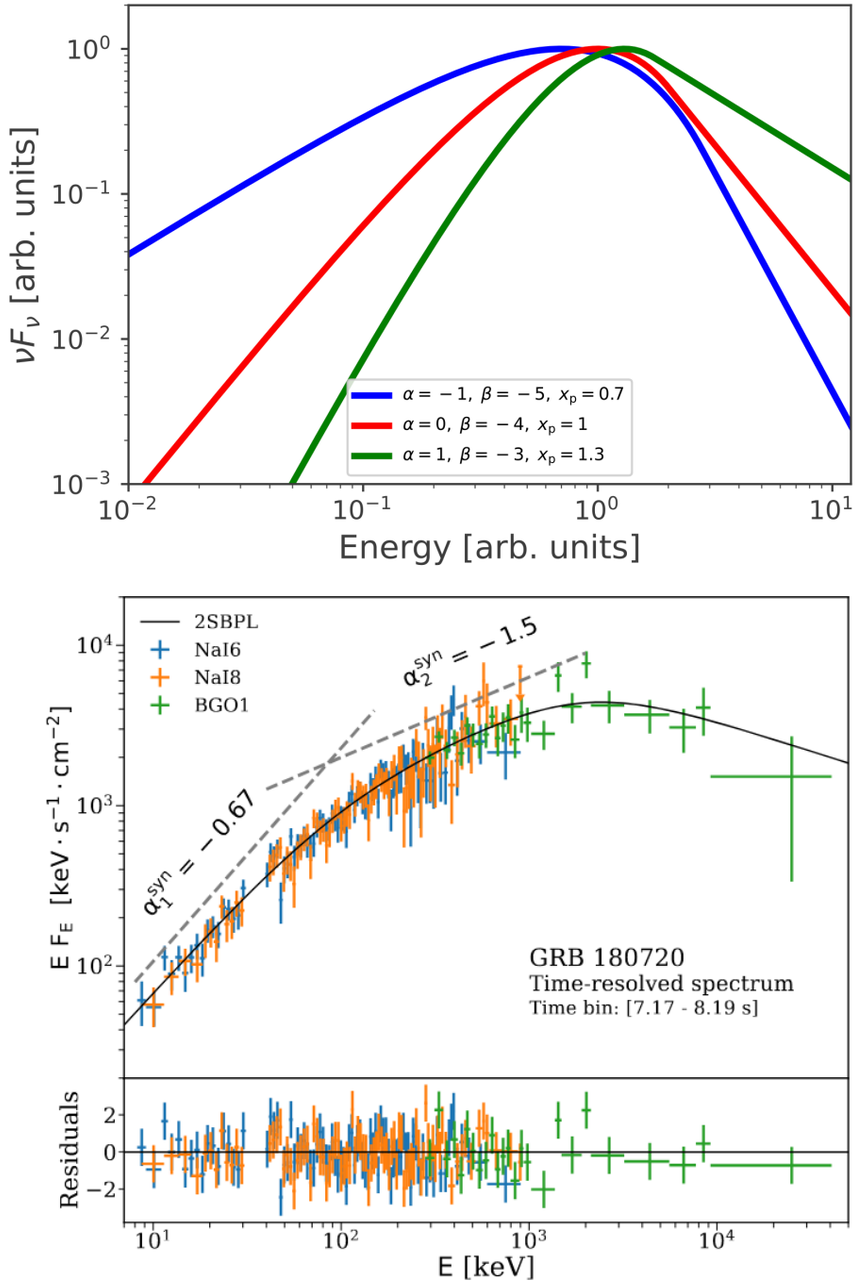
Filip Alamaa (aka Filip Samuelsson)

Collaborators: Felix Ryde, Oscar Wistemar, Frédéric Daigne, Robert Mochkovitch, Christoffer Lundman

Observed spectra

GRB prompt emission spectra

- The origin of the GRB prompt emission remains elusive
- Fitted with phenomenological functions, such as Band-function
- Best statistics at low energy: most weight put on the low-energy index α
- Band-function insufficient in growing number of GRBs

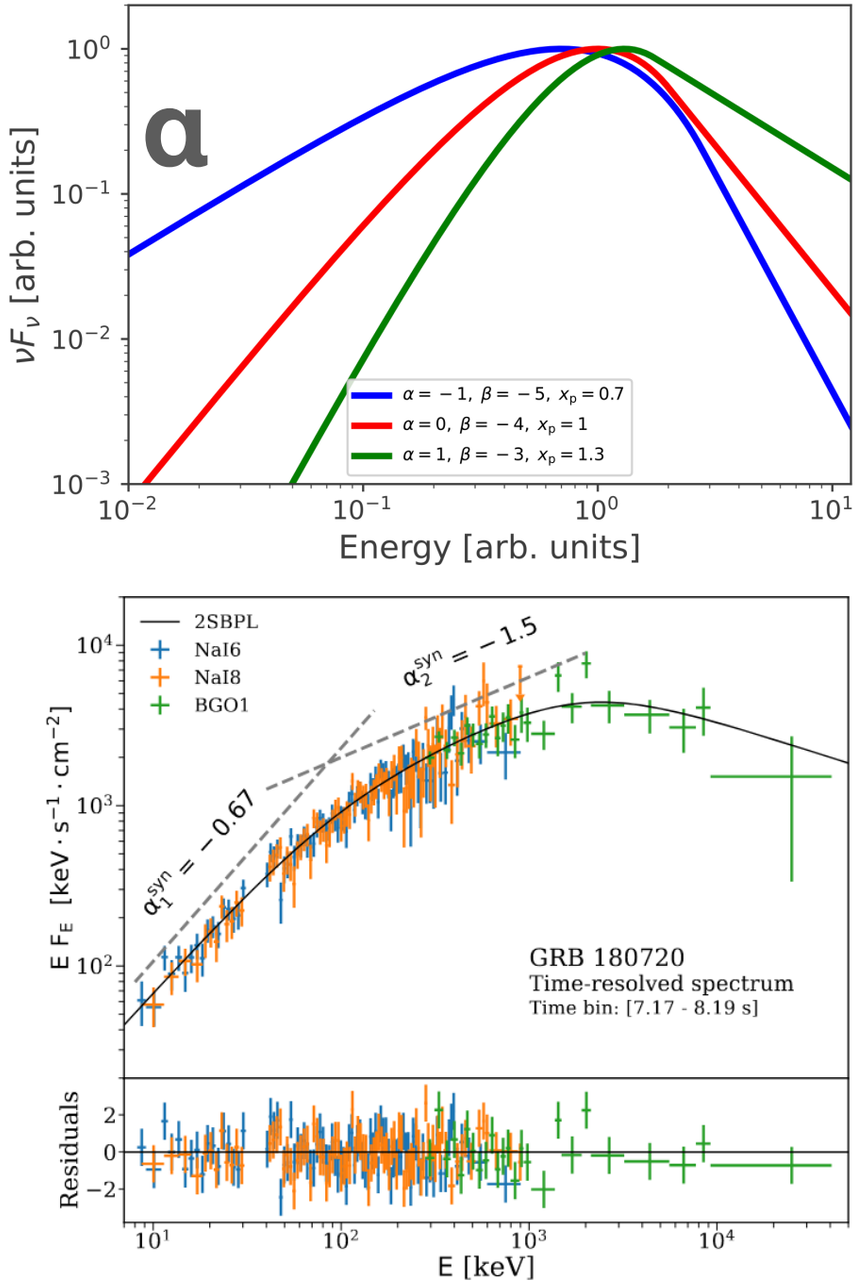


Band+ (1993)

Ravasio+ (2019)

GRB prompt emission spectra

- The origin of the GRB prompt emission remains elusive
- Fitted with phenomenological functions, such as Band-function
- Best statistics at low energy: most weight put on the low-energy index α
- Band-function insufficient in growing number of GRBs

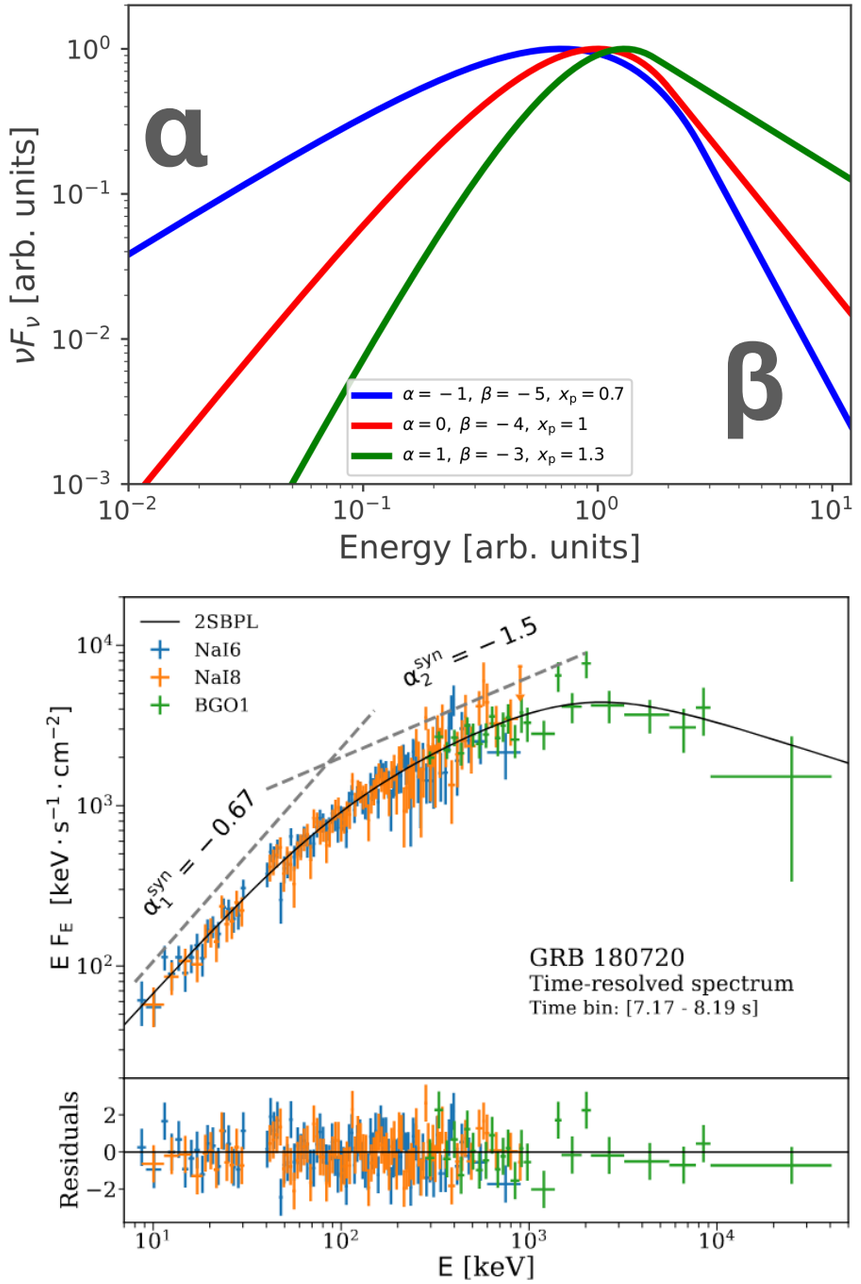


Band+ (1993)

Ravasio+ (2019)

GRB prompt emission spectra

- The origin of the GRB prompt emission remains elusive
- Fitted with phenomenological functions, such as Band-function
- Best statistics at low energy: most weight put on the low-energy index α
- Band-function insufficient in growing number of GRBs

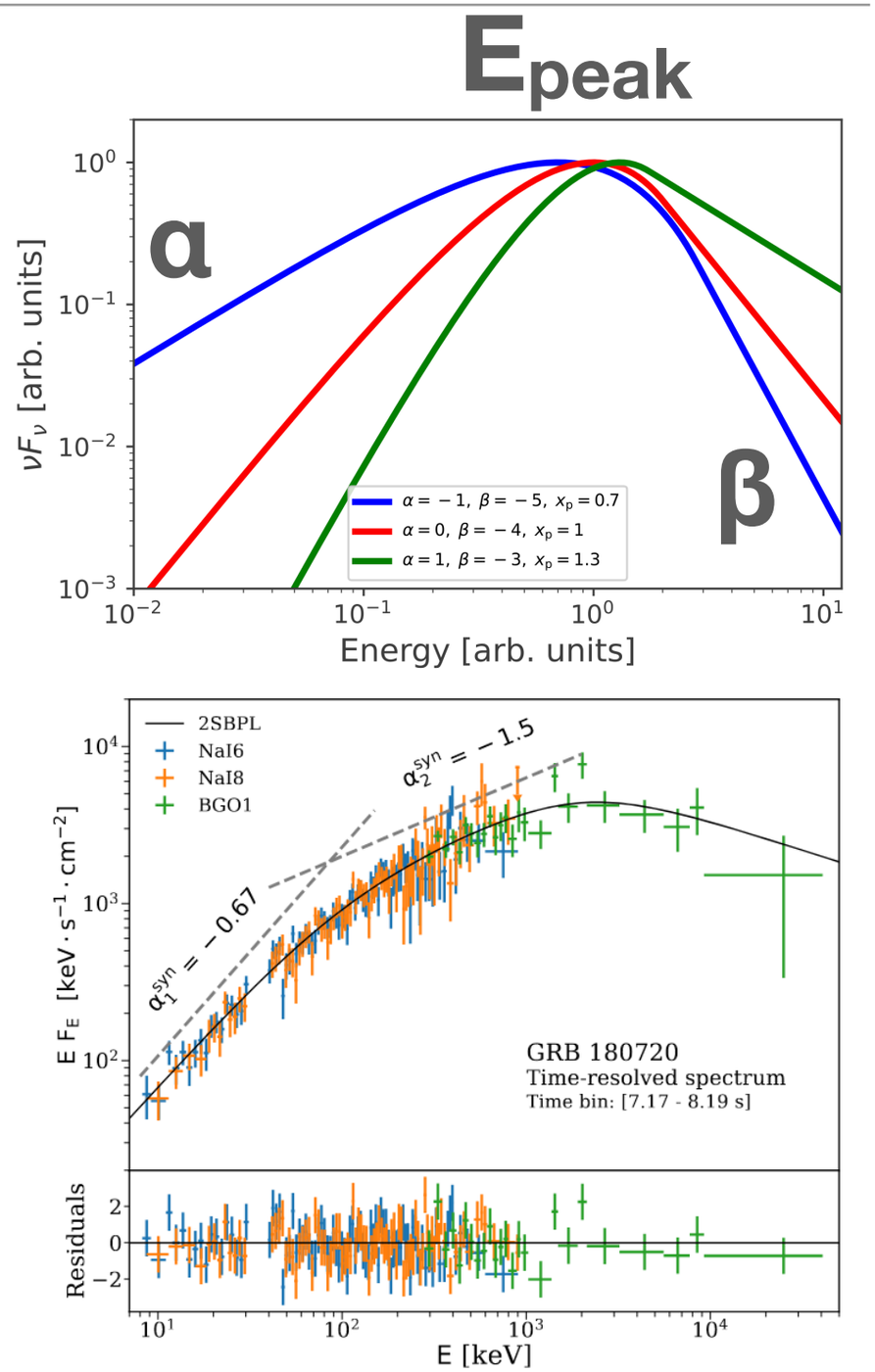


Band+ (1993)

Ravasio+ (2019)

GRB prompt emission spectra

- The origin of the GRB prompt emission remains elusive
- Fitted with phenomenological functions, such as Band-function
- Best statistics at low energy: most weight put on the low-energy index α
- Band-function insufficient in growing number of GRBs

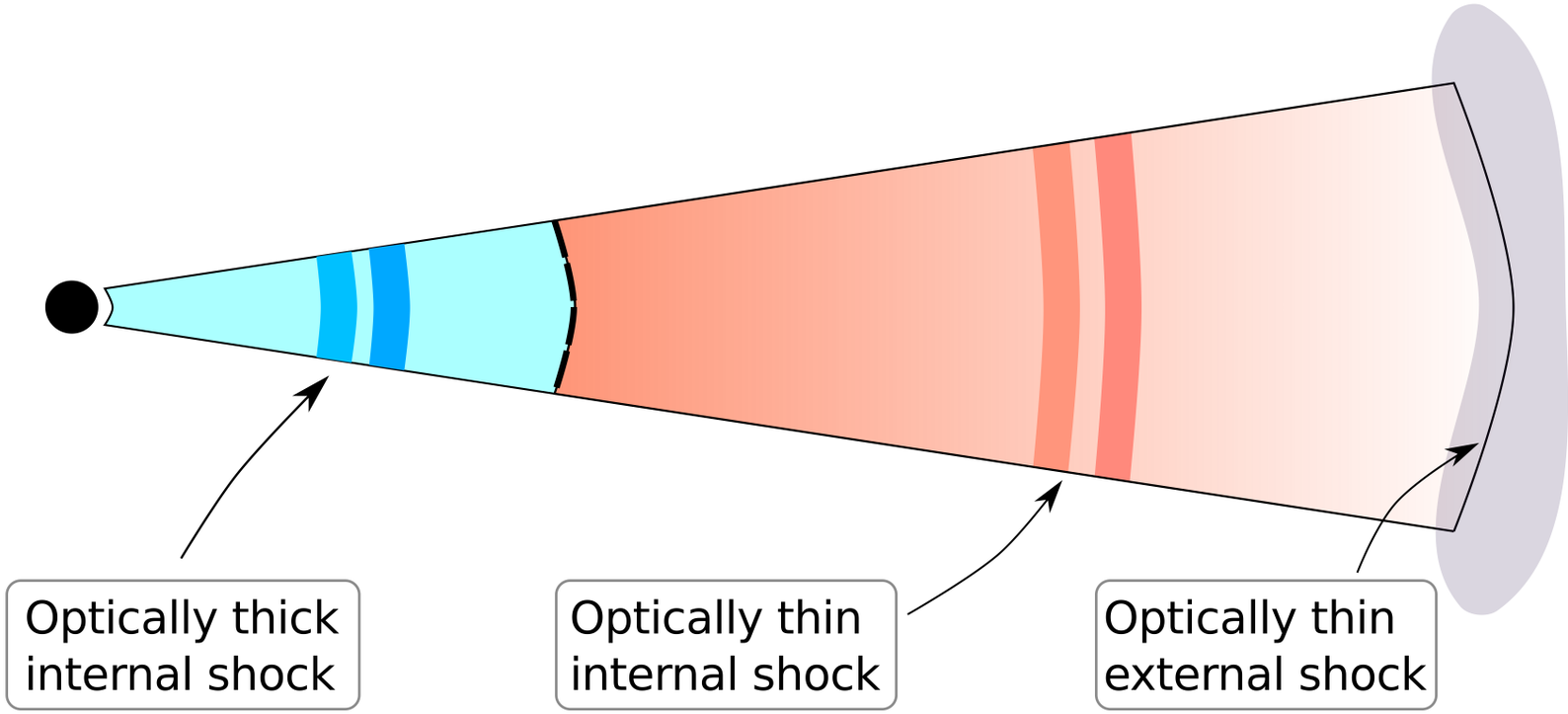


Band+ (1993)

Ravasio+ (2019)

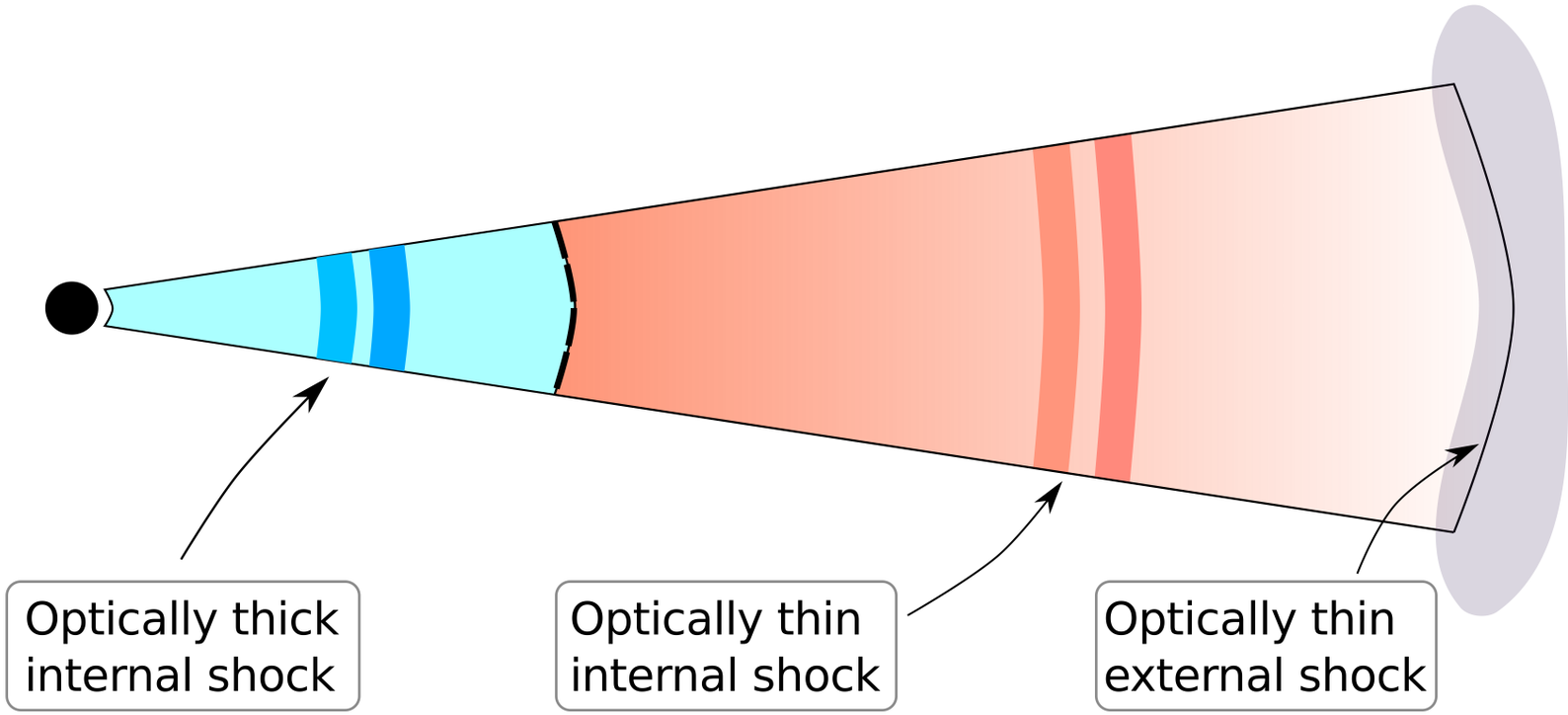
Photospheric emission and radiation-mediated shocks

Non-dissipative photosphere



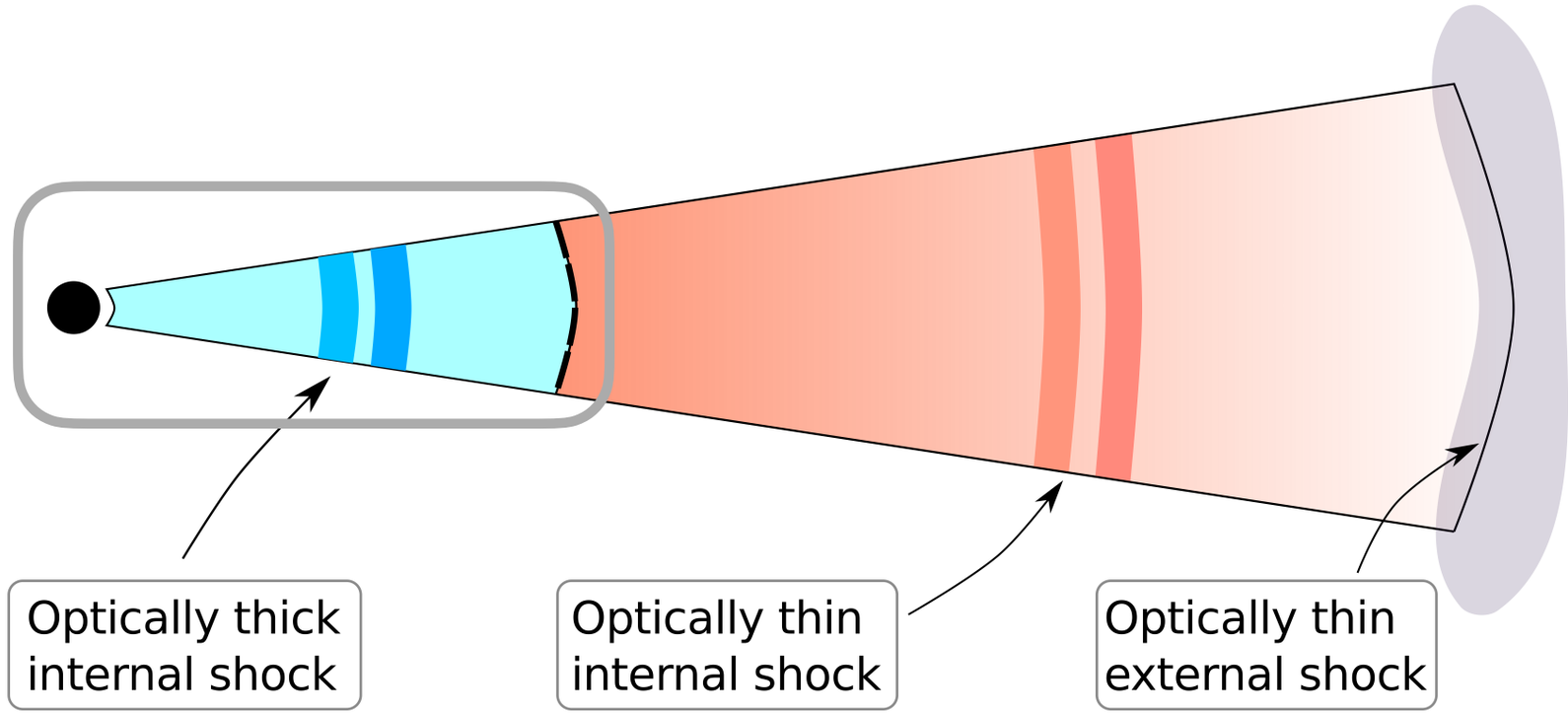
Non-dissipative photosphere

- Optically thick and optically thin models



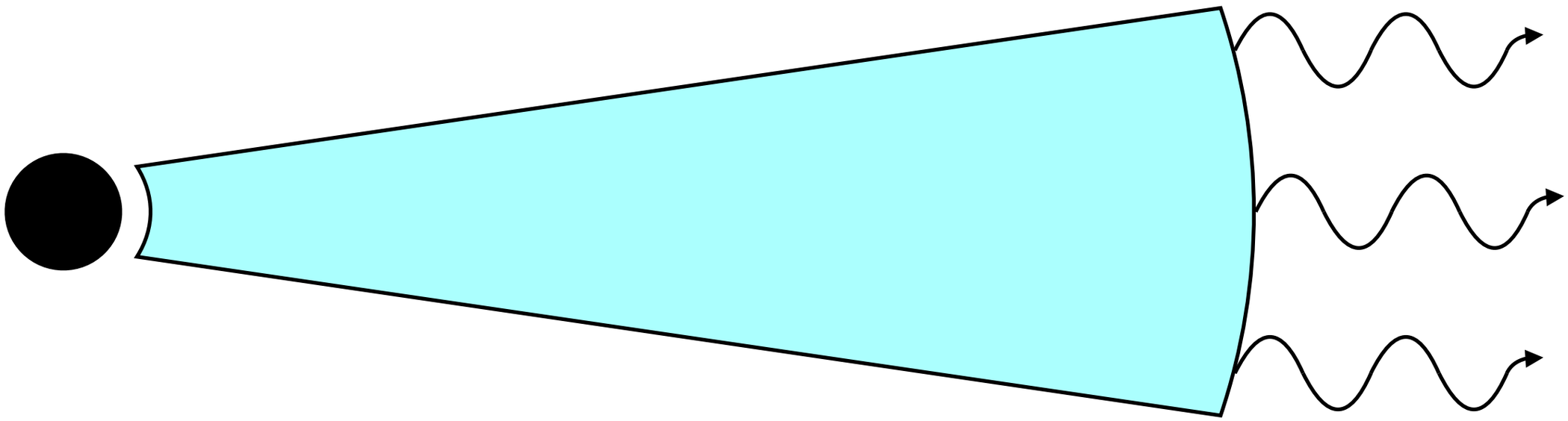
Non-dissipative photosphere

- Optically thick and optically thin models



Non-dissipative photosphere

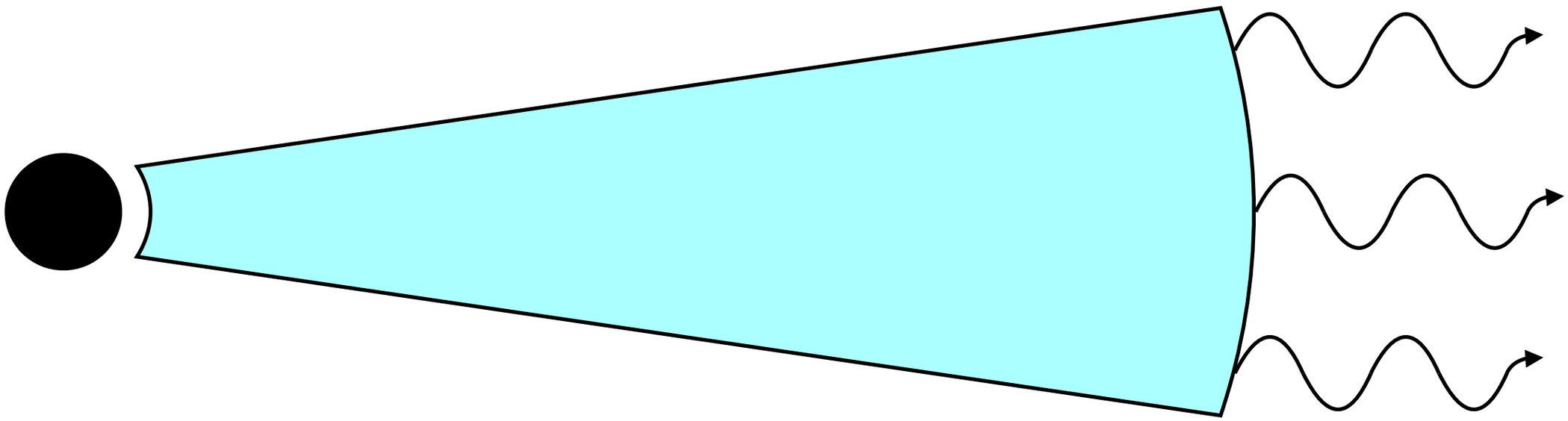
- Optically thick and optically thin models
- Initially trapped radiation released at the photosphere



Cavallo & Rees (1978), Paczyński (1986), Goodman (1986)

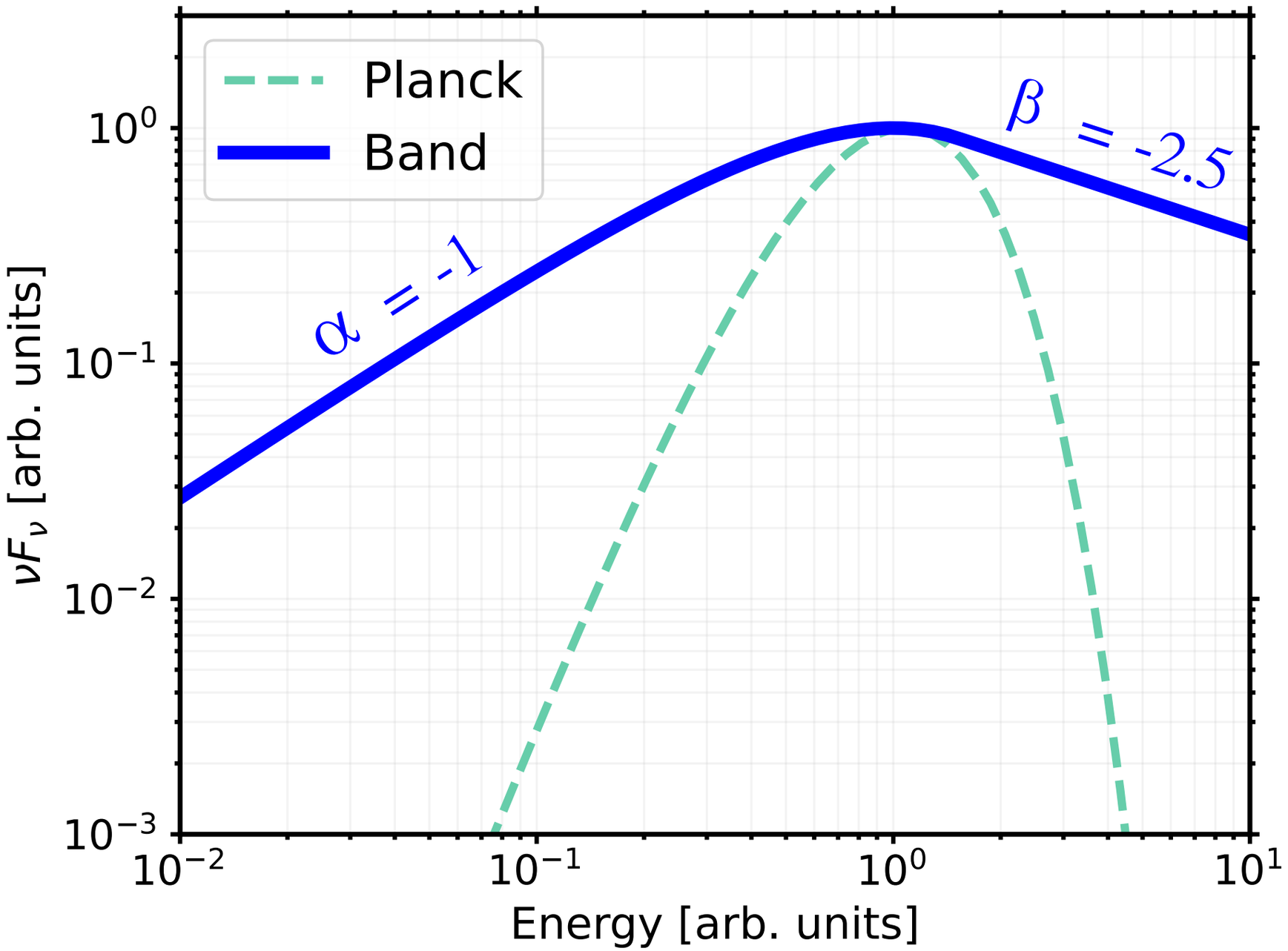
Non-dissipative photosphere

- Optically thick and optically thin models
- Initially trapped radiation released at the photosphere
- Quasi-blackbody radiation expected



Cavallo & Rees (1978), Paczyński (1986), Goodman (1986)

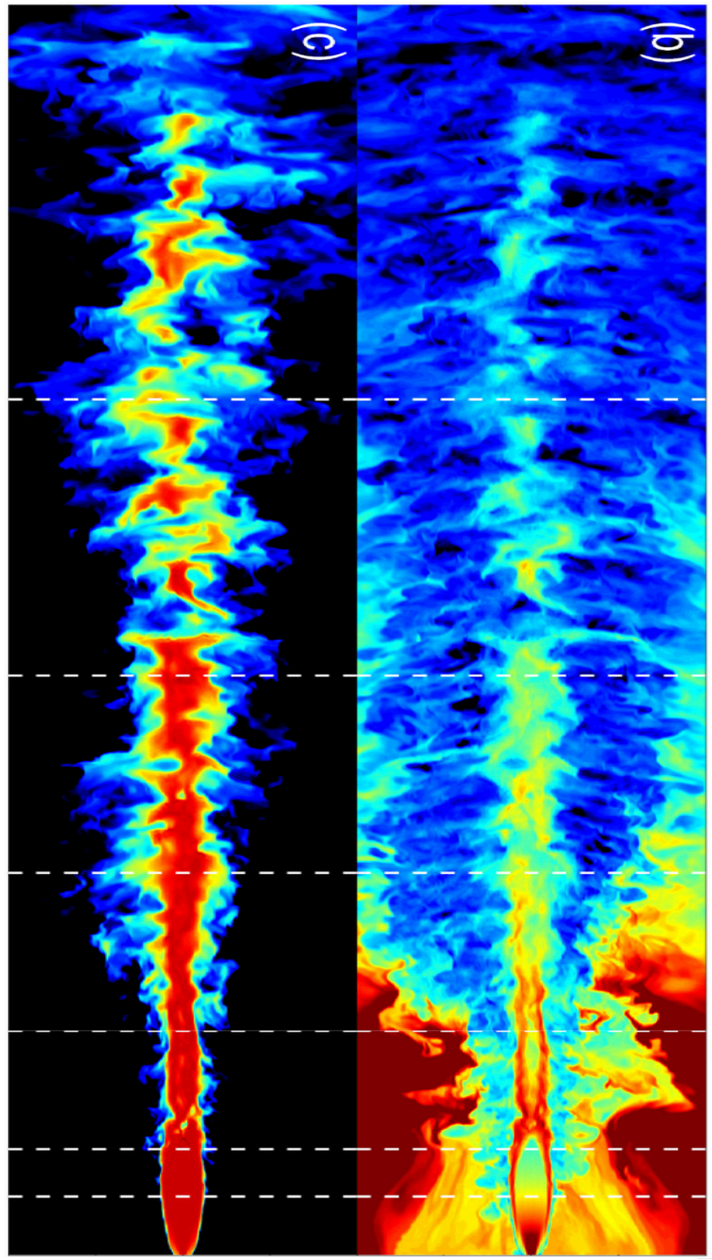
Quasi-blackbody spectra



Subphotospheric dissipation

- Dissipation alters the spectrum
- Shocks are radiation mediated
- Separation in interaction scales makes simulations expensive and no RMS model had been fitted to GRB data
- We aimed to bridge that gap

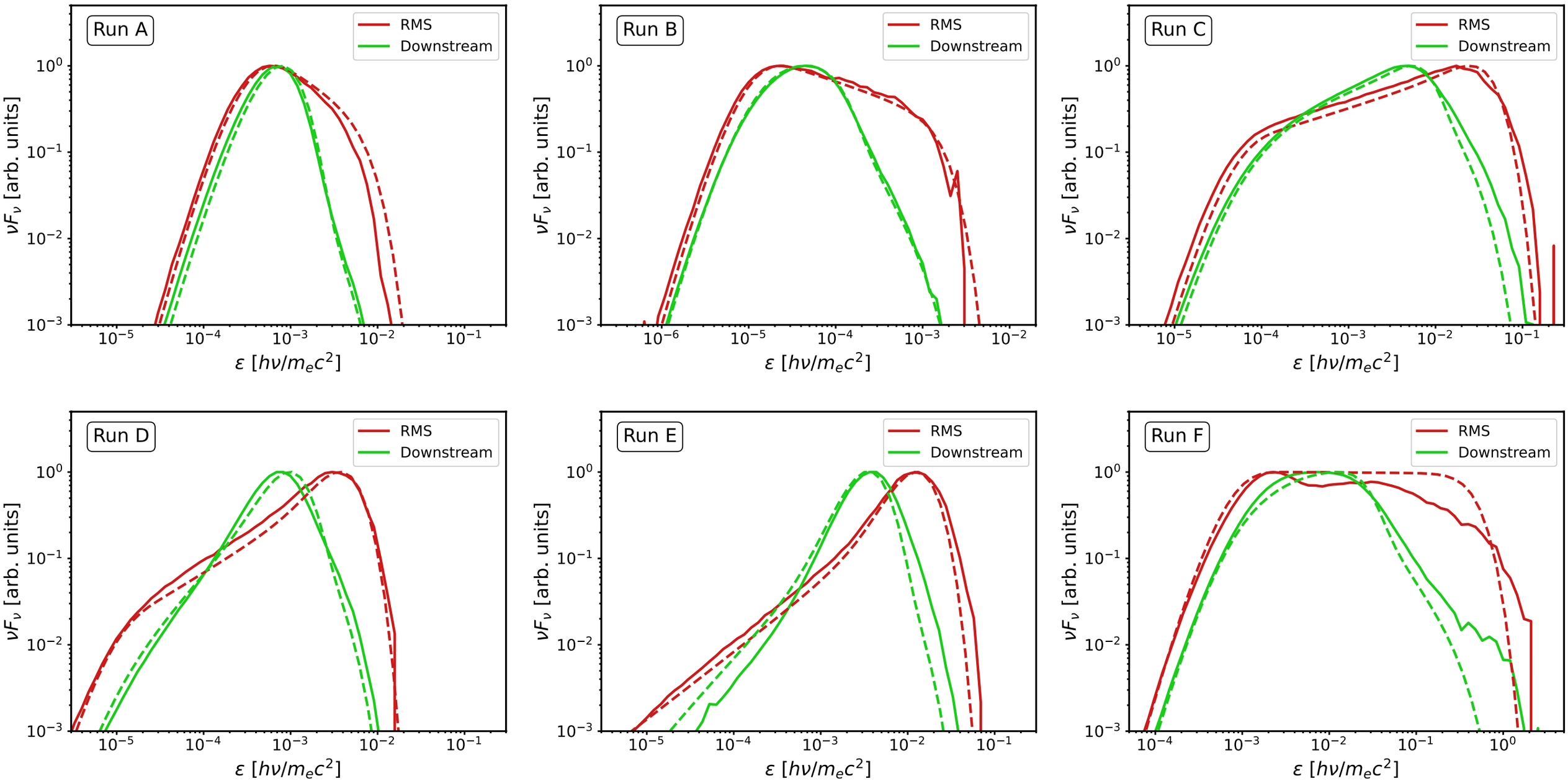
Eichler (1994), Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Katz+ (2010), Budnik+ (2010), Levinson (2012), Beloborodov (2017), Ito+ (2018), Lundman+ (2018), Levinson & Nakar (2020)



Gottlieb+ (2021)

My work

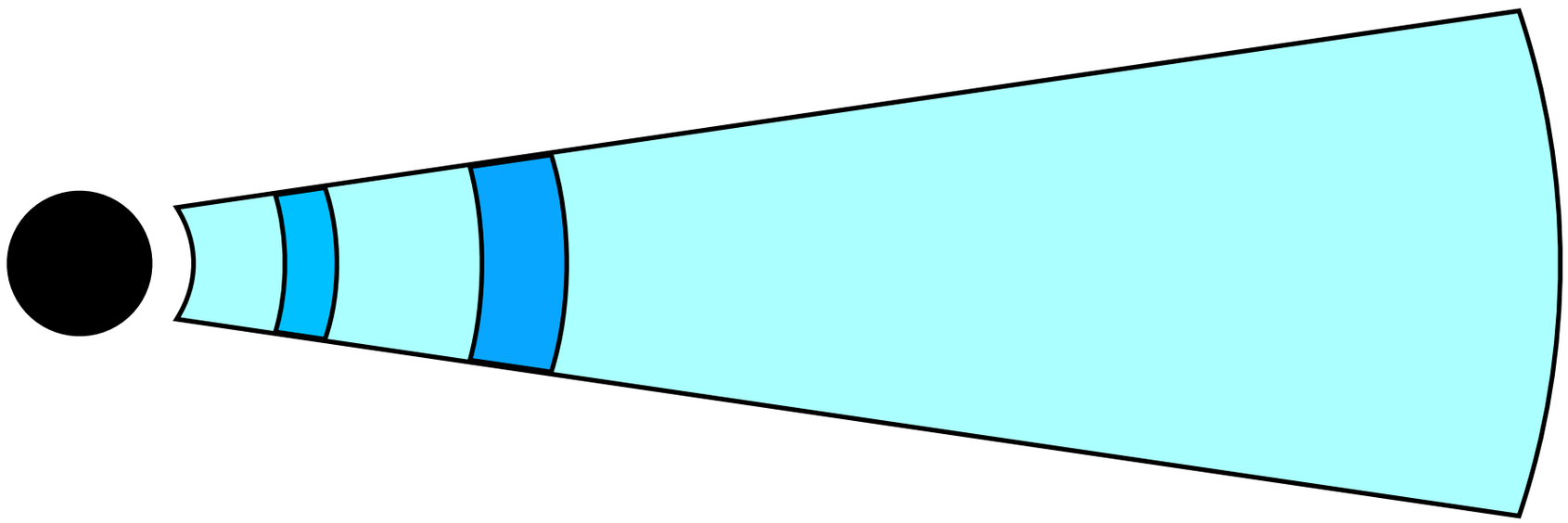
The KRA (Kompaneets RMS Approximation)



Samuelsson+ (2022)

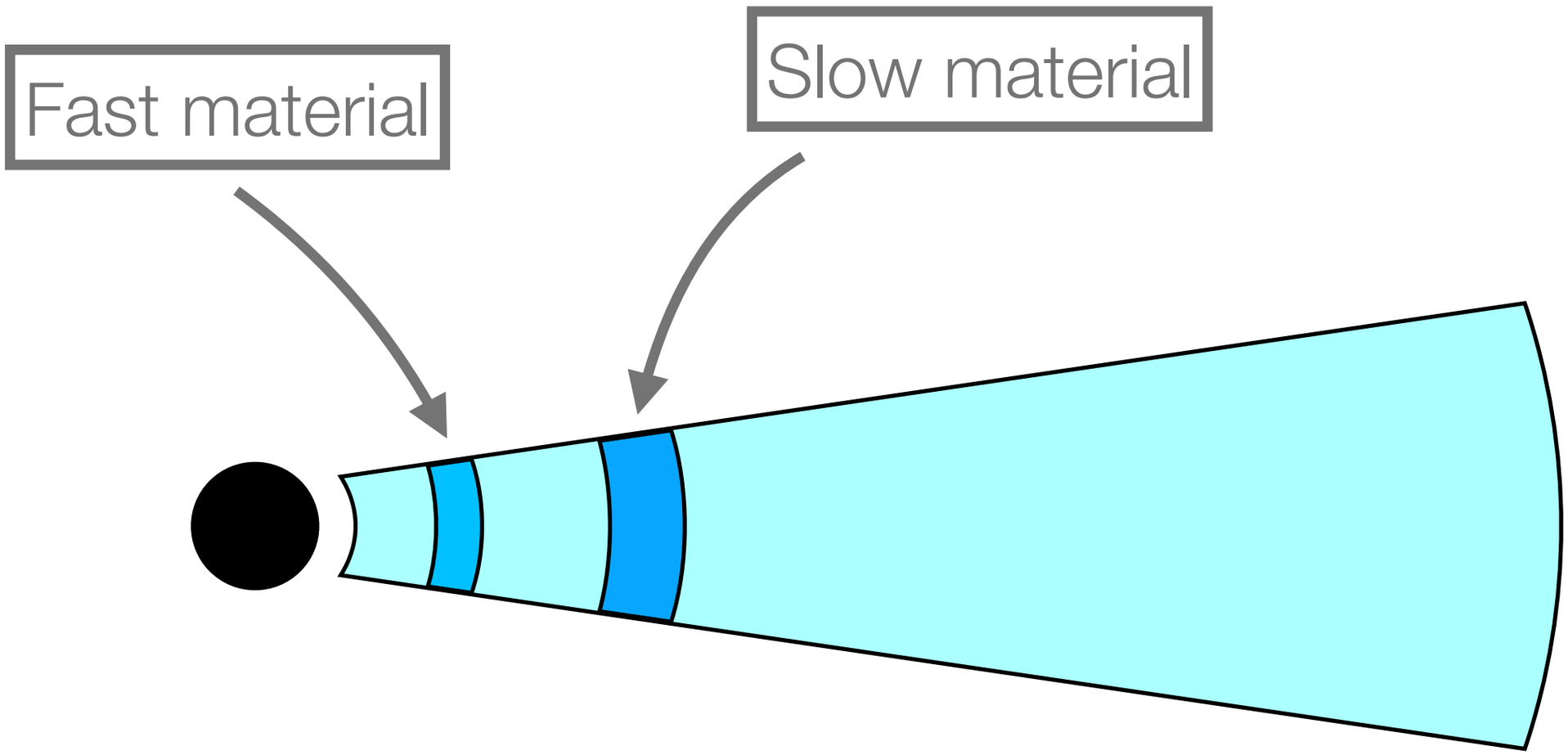
The spectral shape

Radiation-mediated shocks - the general idea



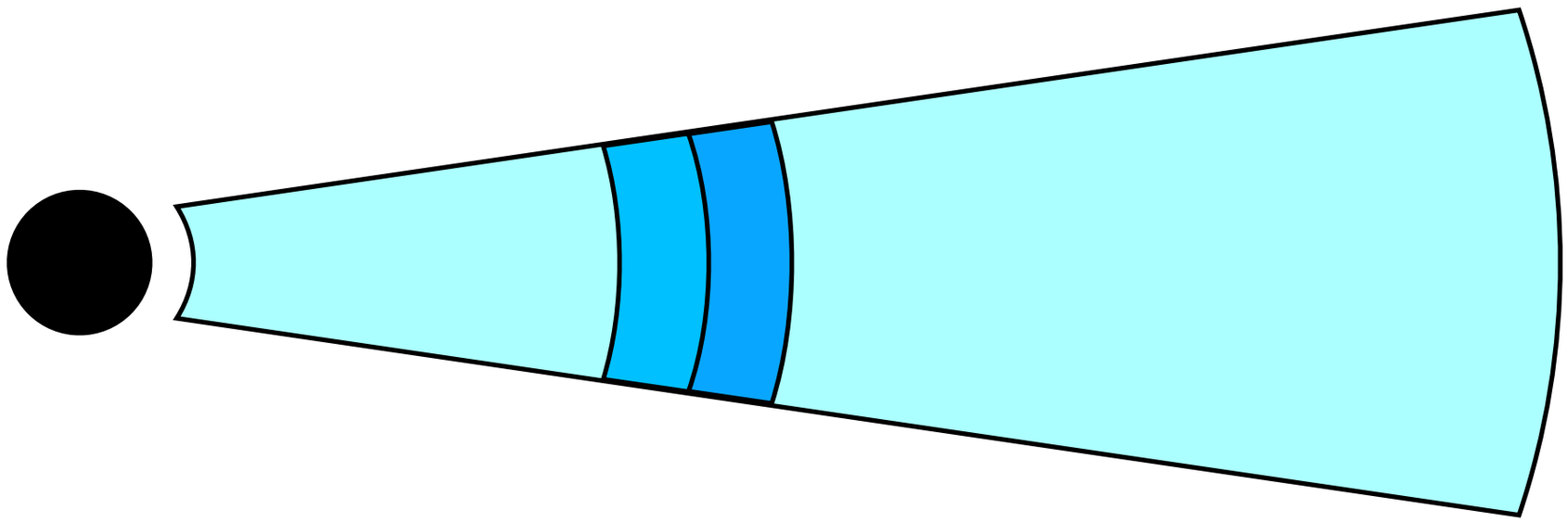
Rees & Mészáros (2005), Pe’er+ (2006), Levinson & Bromberg (2008), Samuelsson+ (2022)

Radiation-mediated shocks - the general idea



Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Samuelsson+ (2022)

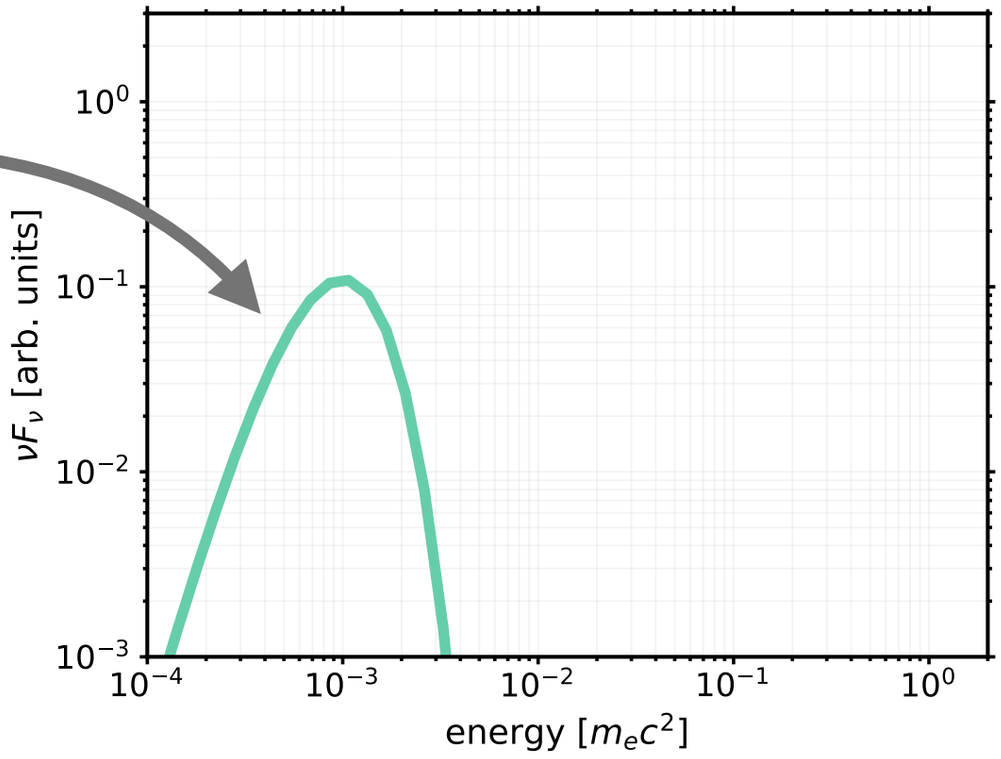
Radiation-mediated shocks - the general idea

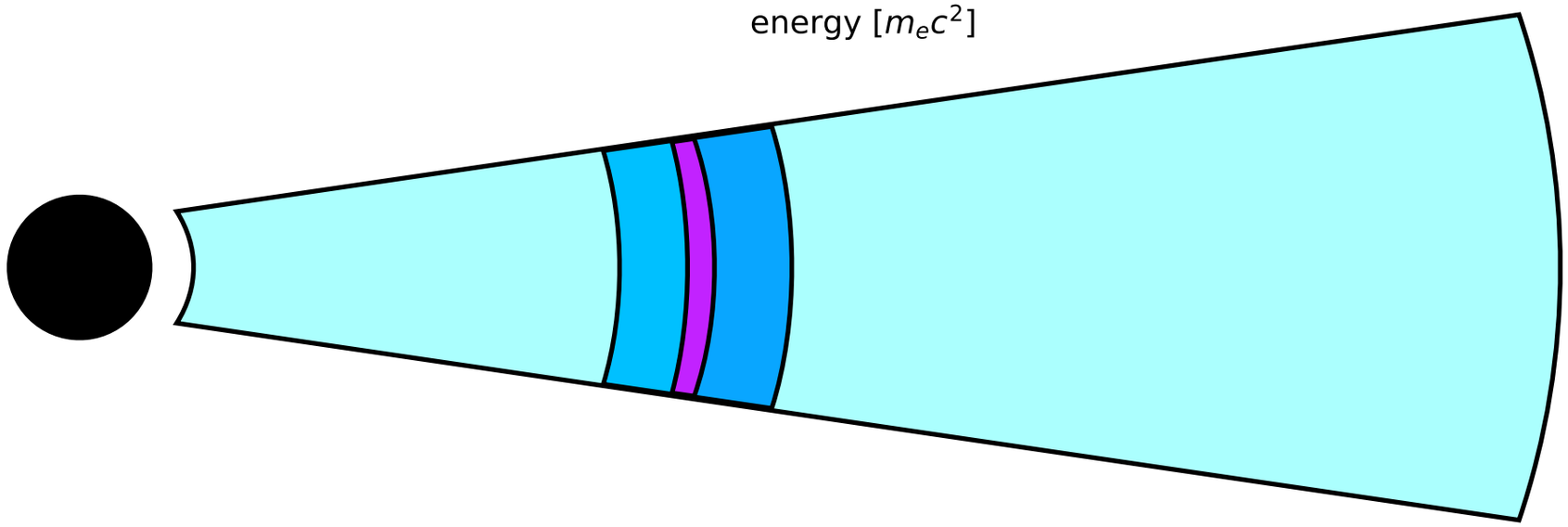


Rees & Mészáros (2005), Pe’er+ (2006), Levinson & Bromberg (2008), Samuelsson+ (2022)

Radiation-mediated shocks - the general idea

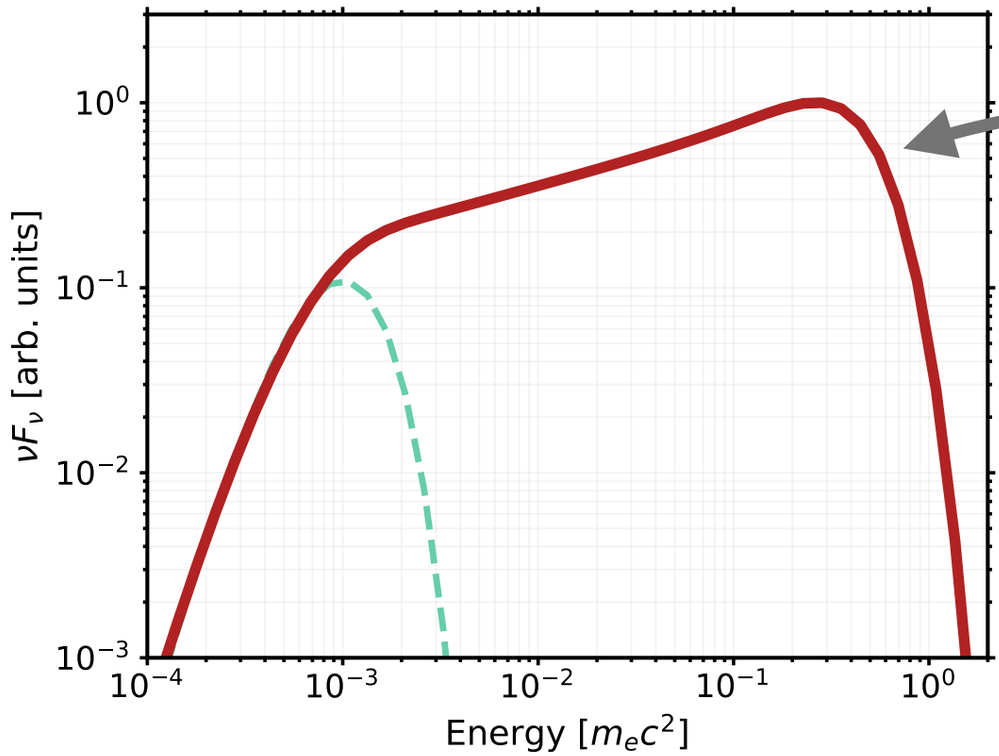
Initial thermal upstream



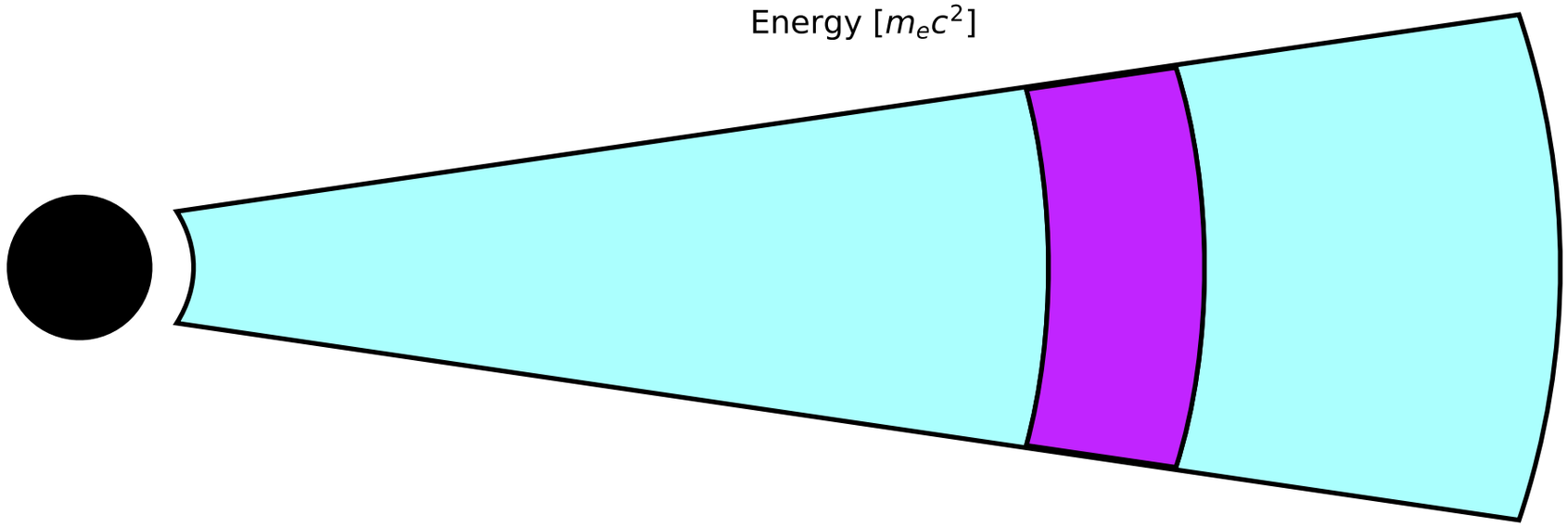


Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Samuelsson+ (2022)

Radiation-mediated shocks - the general idea

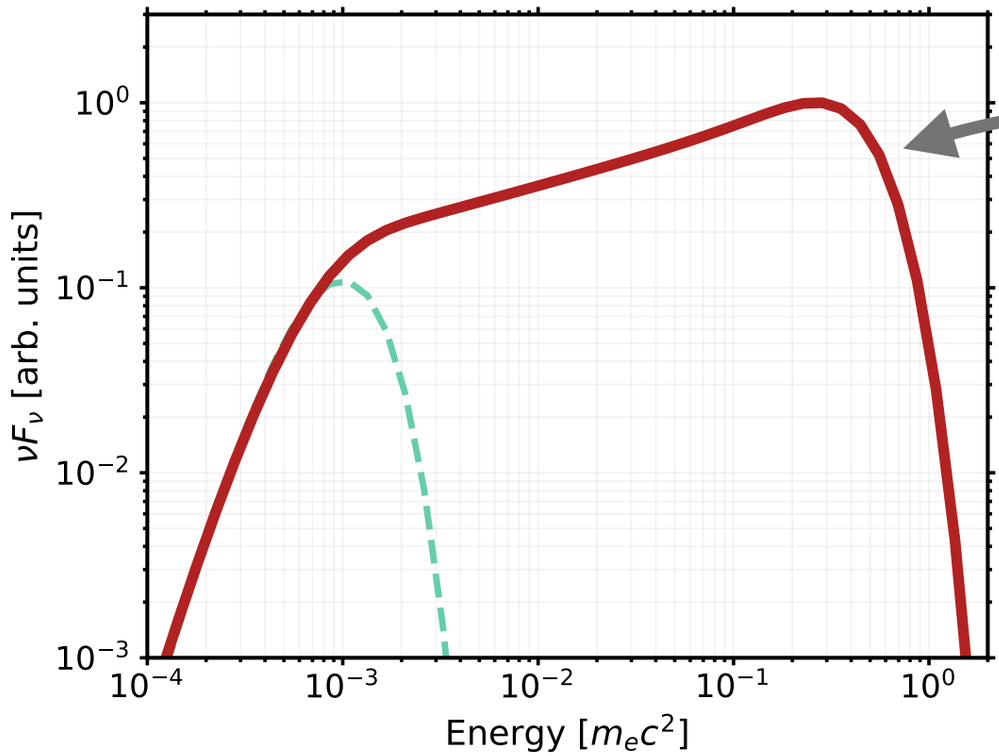


Radiation-mediated shock

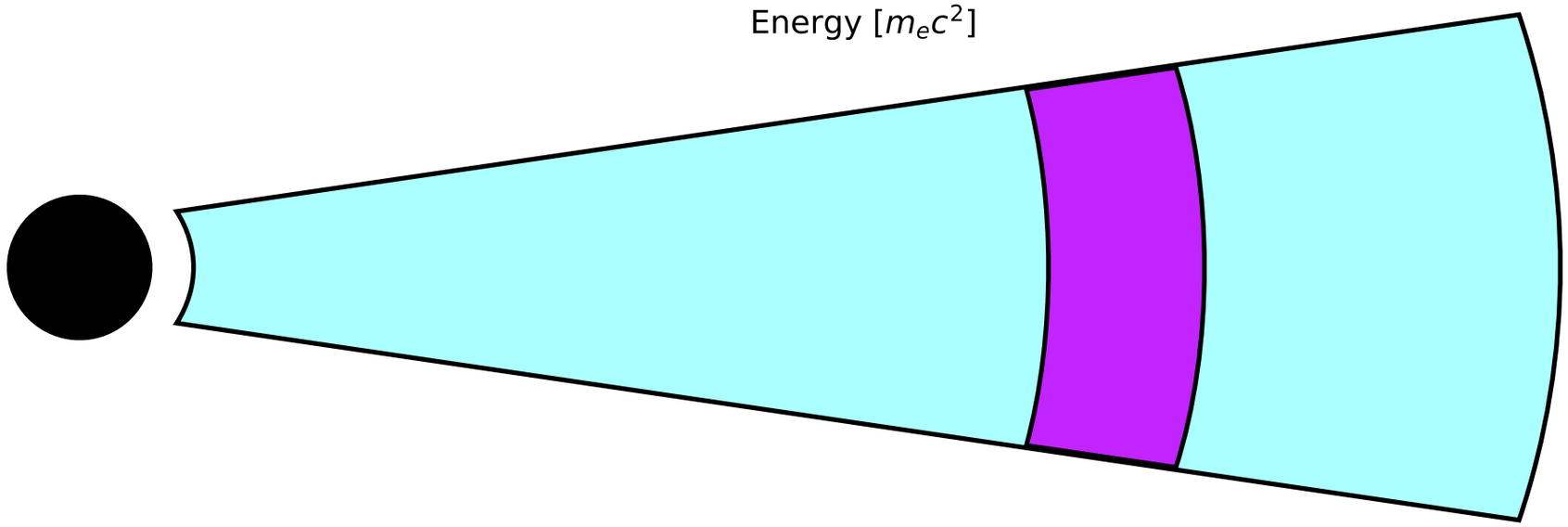


Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Samuelsson+ (2022)

Radiation-mediated shocks - the general idea



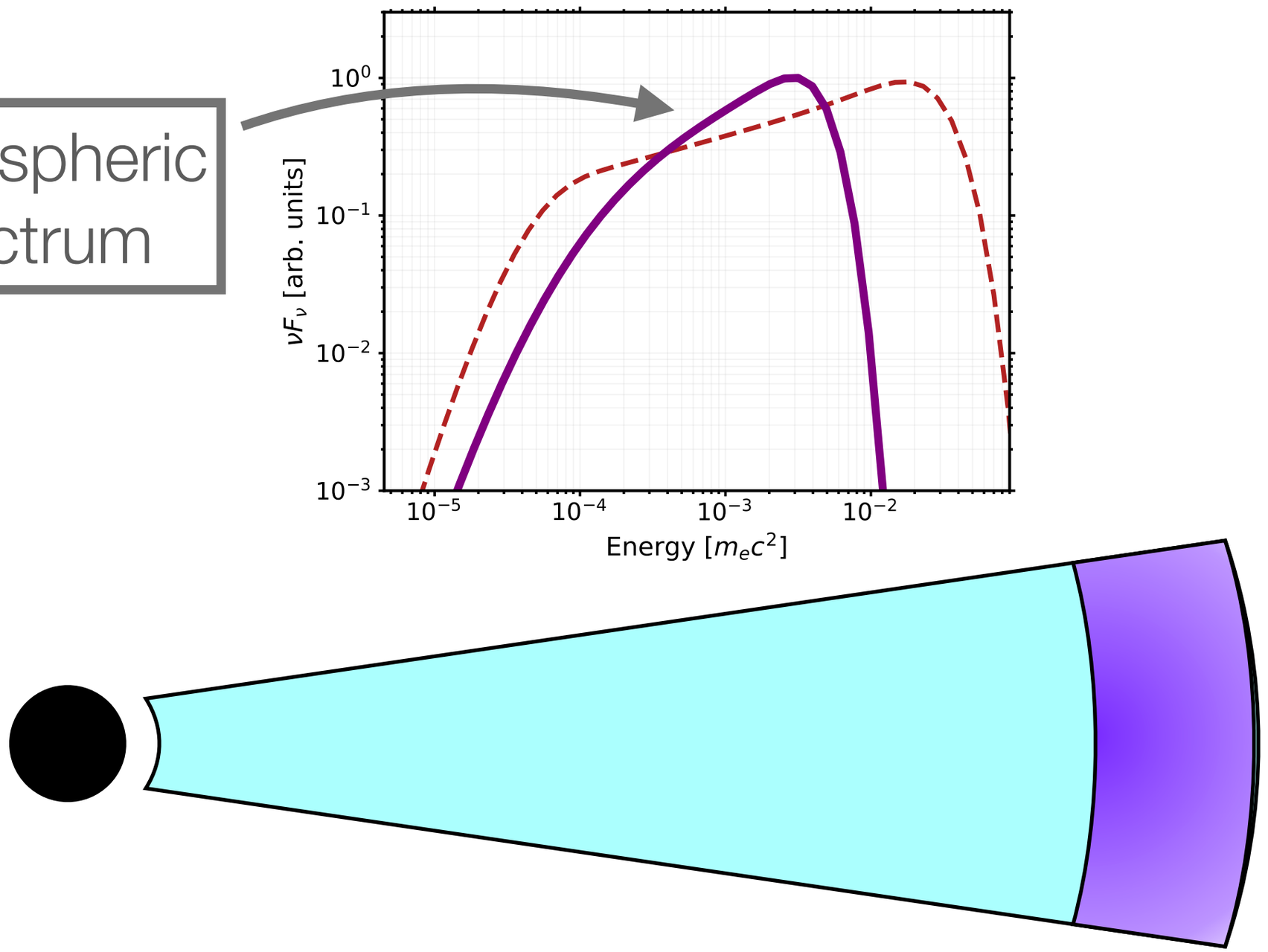
Radiation-mediated shock



Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Samuelsson+ (2022)

Radiation-mediated shocks - the general idea

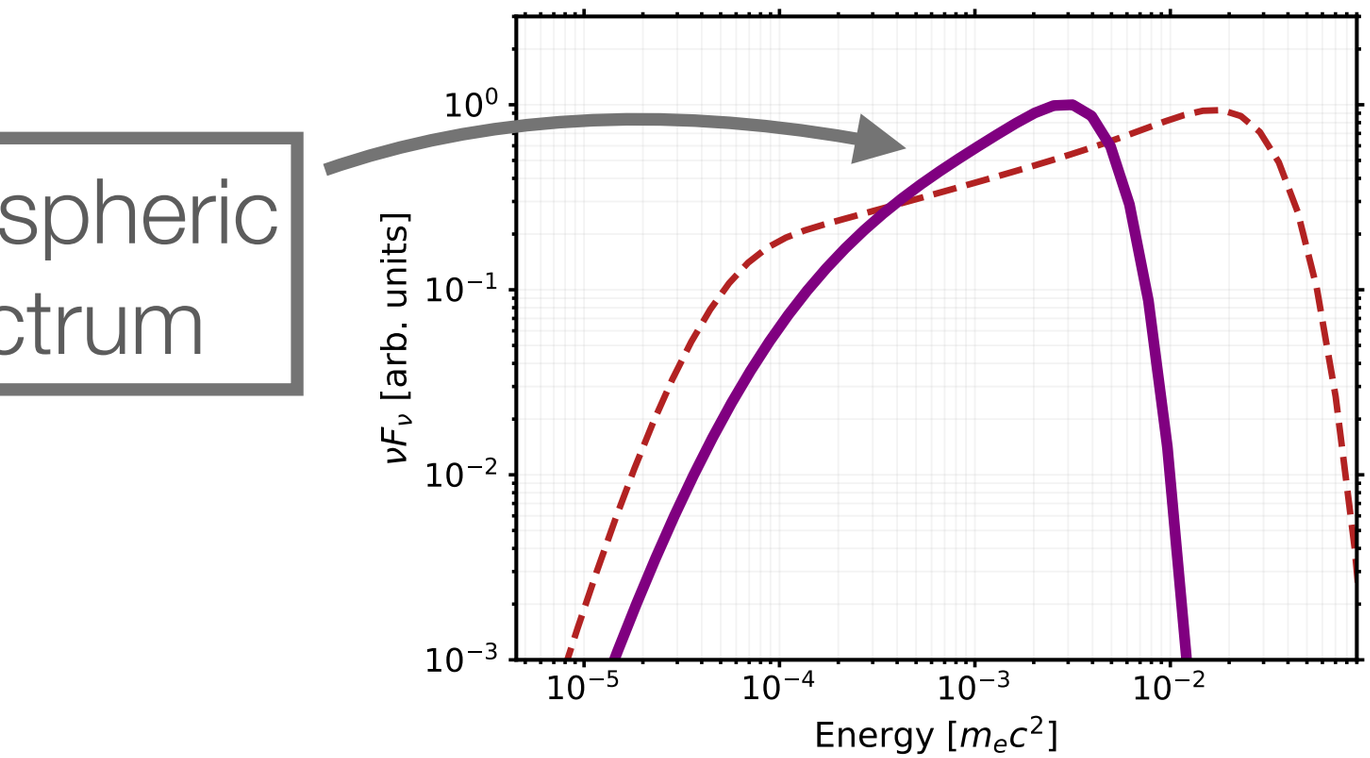
Photospheric spectrum



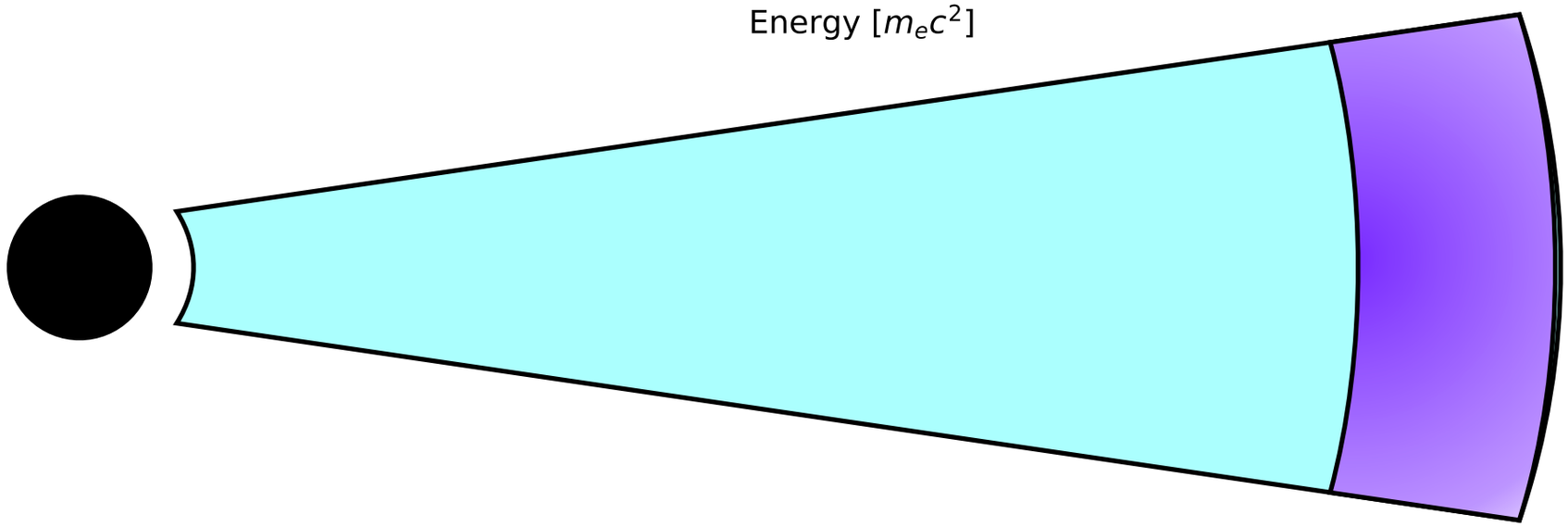
Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Samuelsson+ (2022)

Radiation-mediated shocks - the general idea

Photospheric spectrum

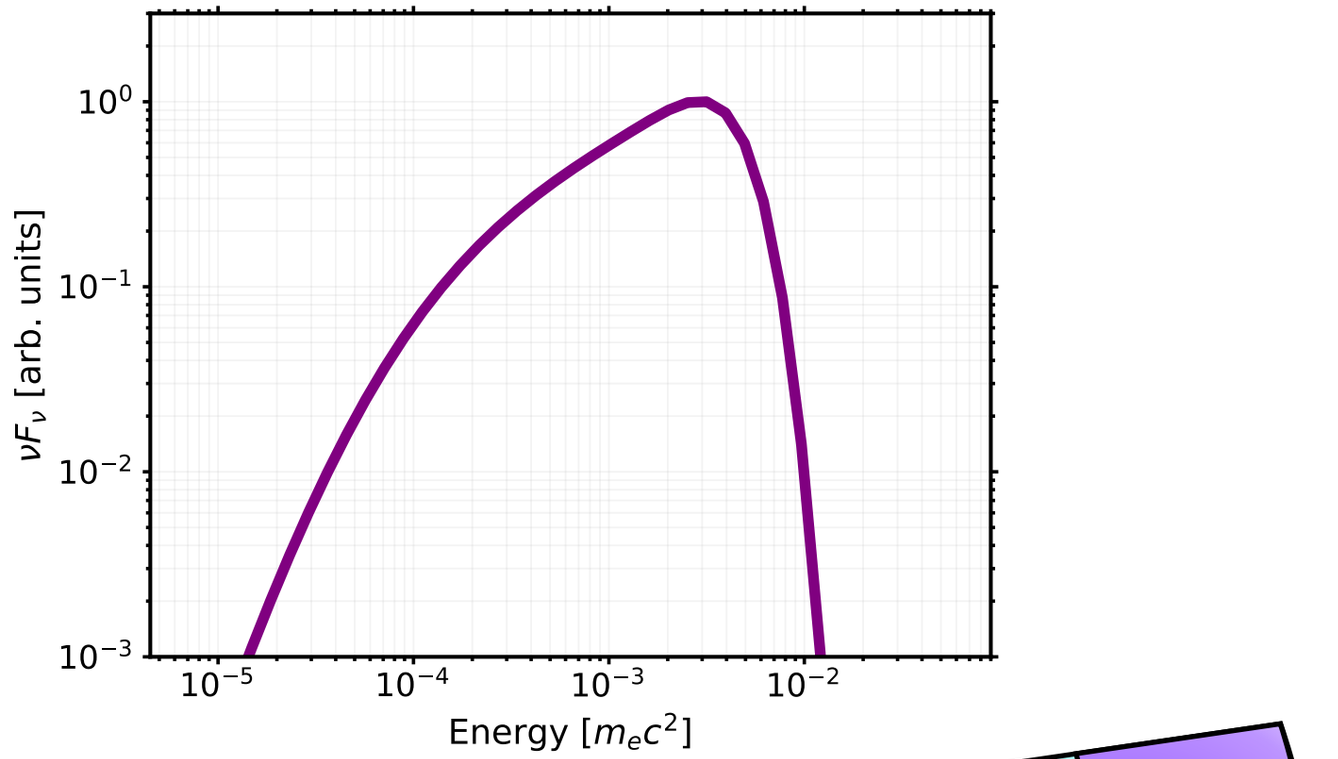


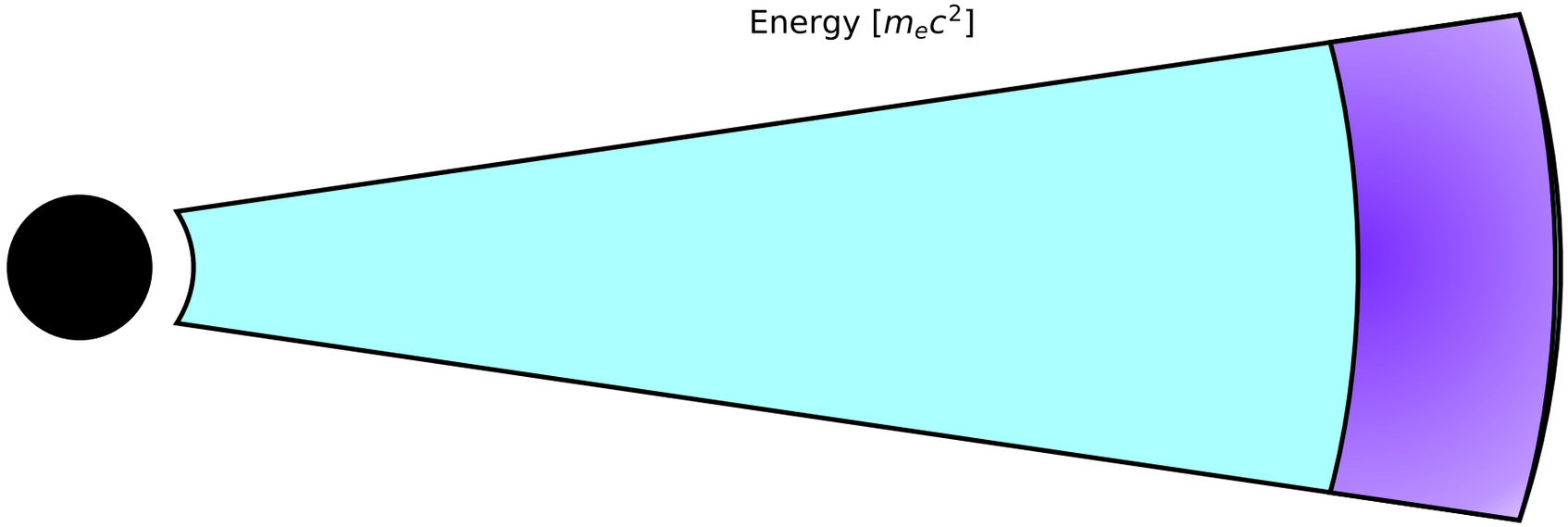
Partially thermalized



Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Samuelsson+ (2022)

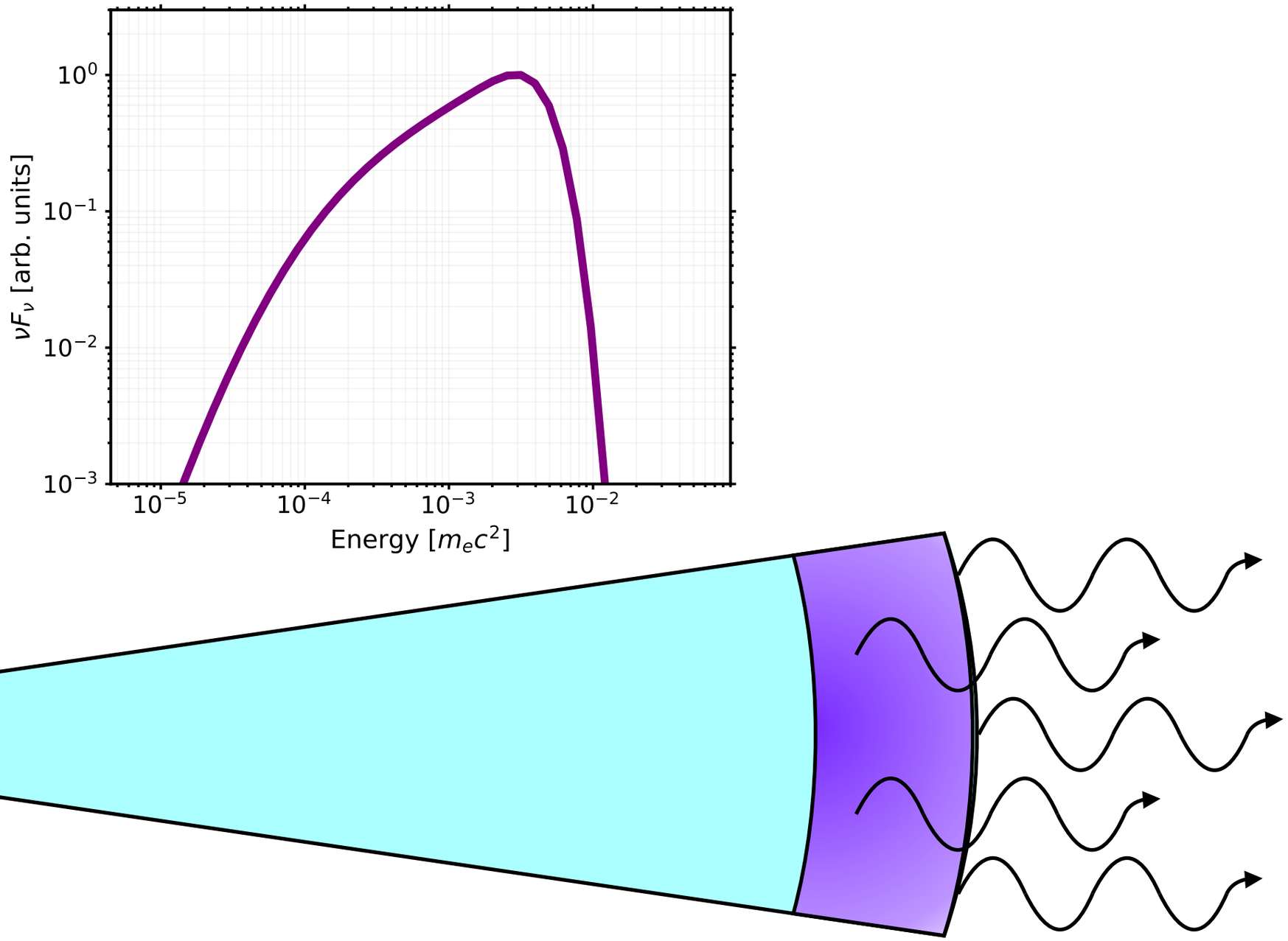
Radiation-mediated shocks - the general idea





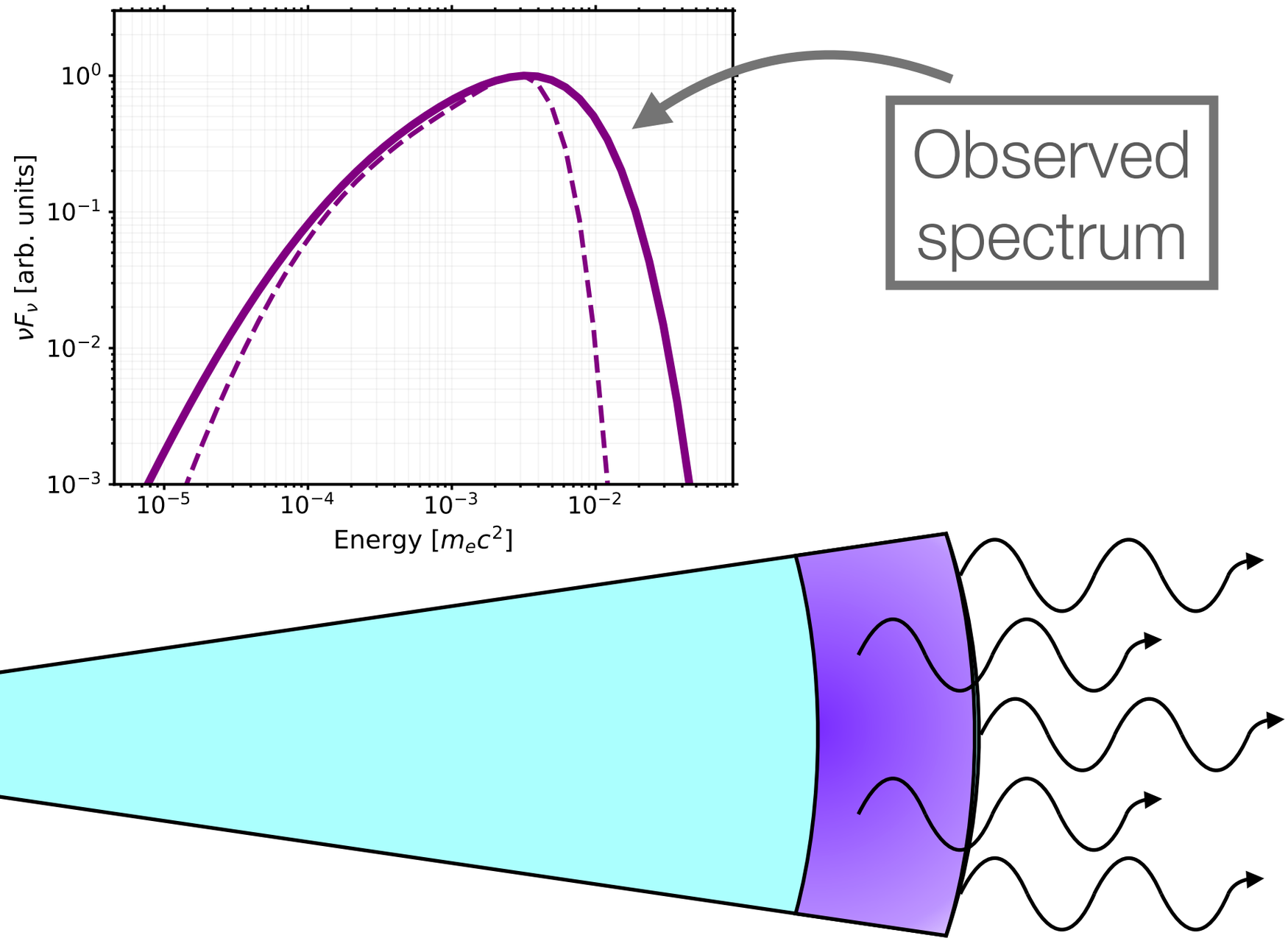
Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Samuelsson+ (2022)

Radiation-mediated shocks - the general idea



Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Samuelsson+ (2022)

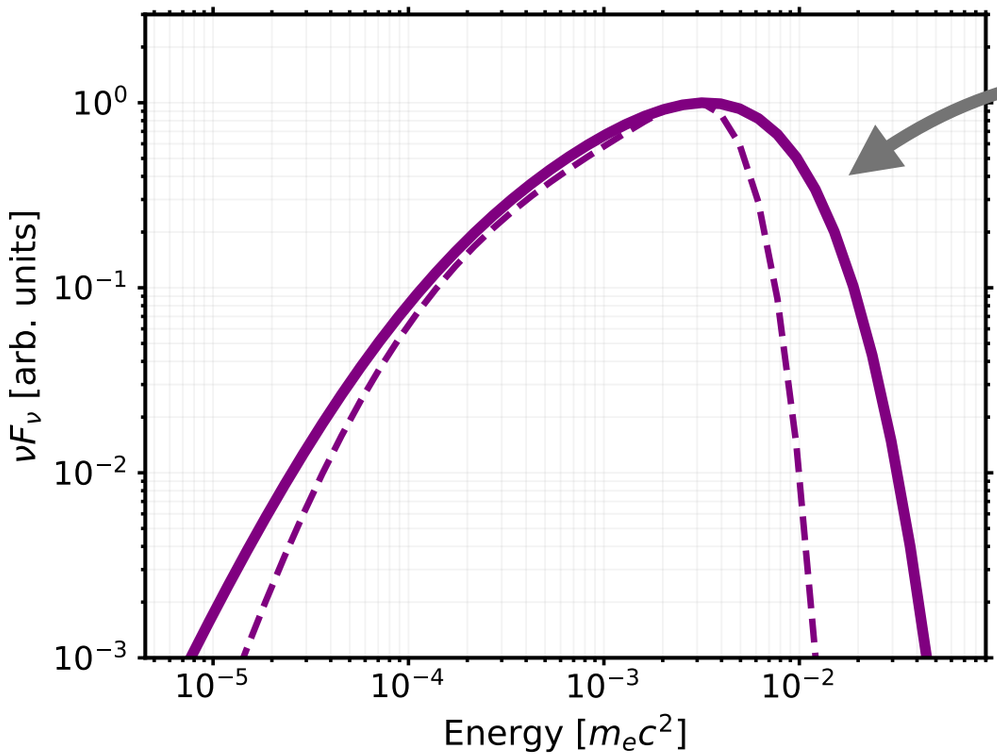
Radiation-mediated shocks - the general idea



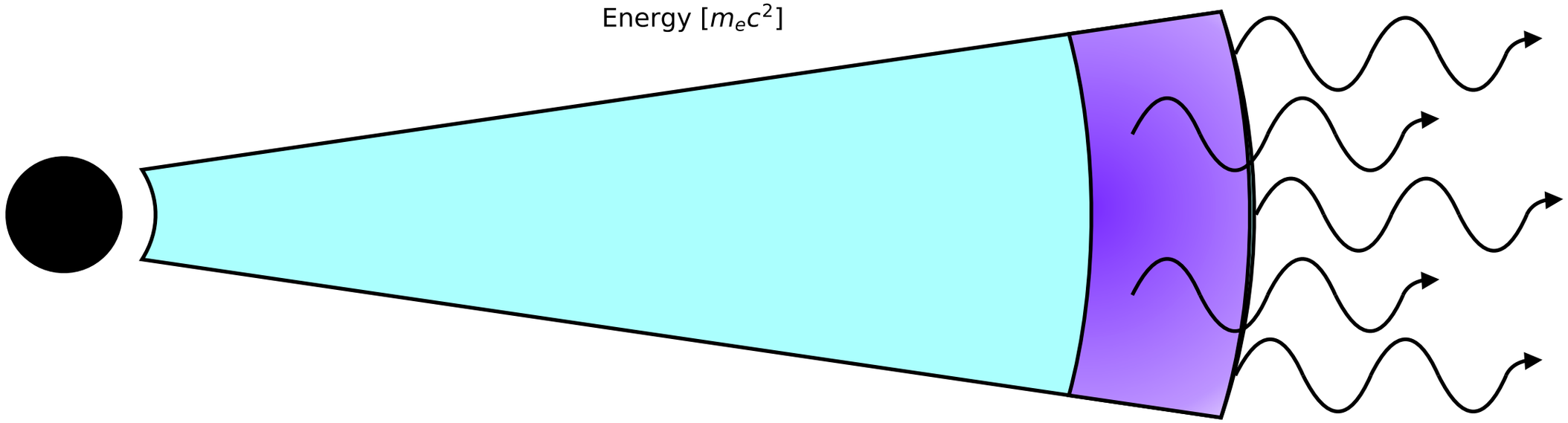
Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Samuelsson+ (2022)

Radiation-mediated shocks - the general idea

Broadened by high-latitude and different radial emission

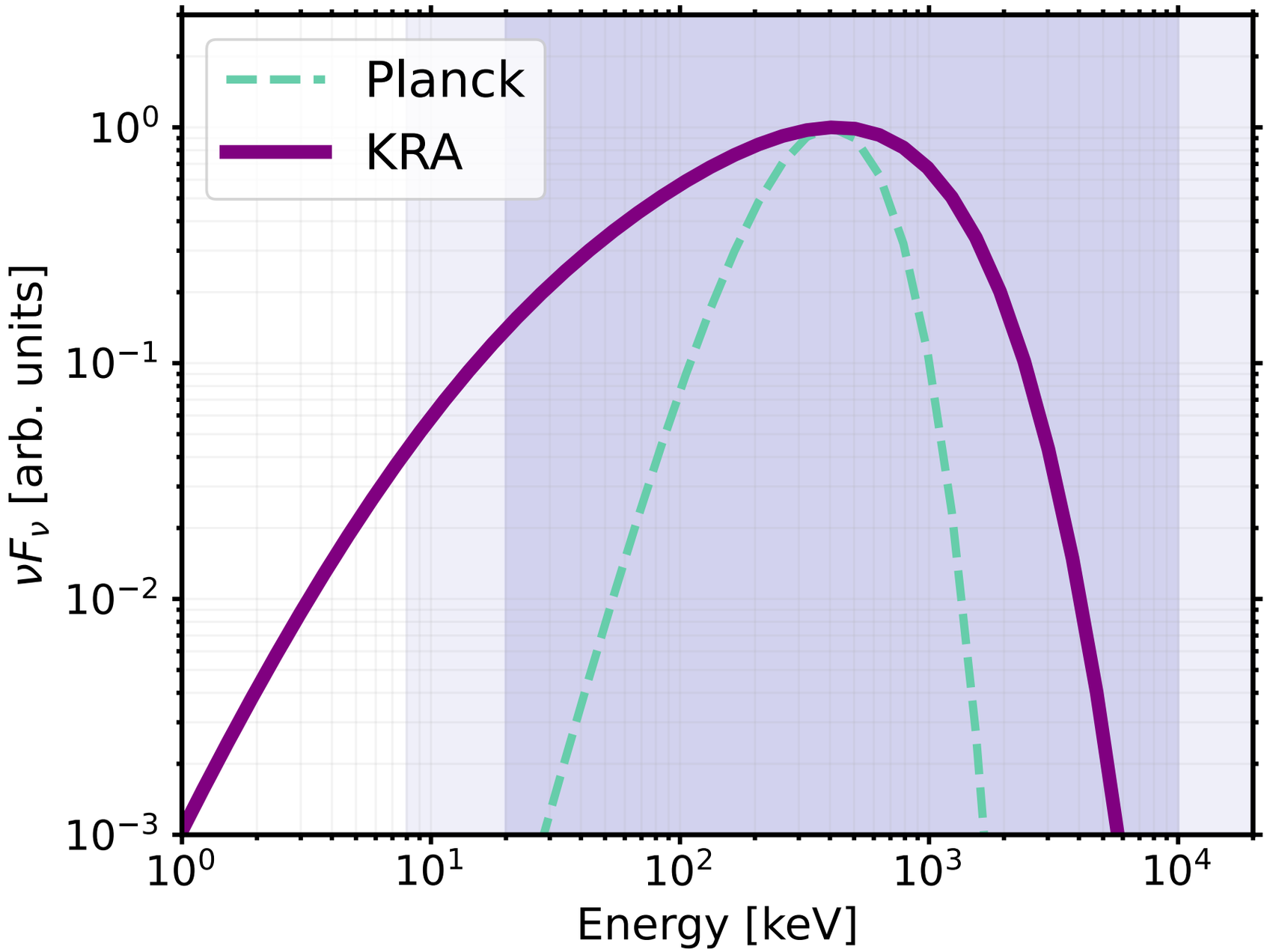


Observed spectrum



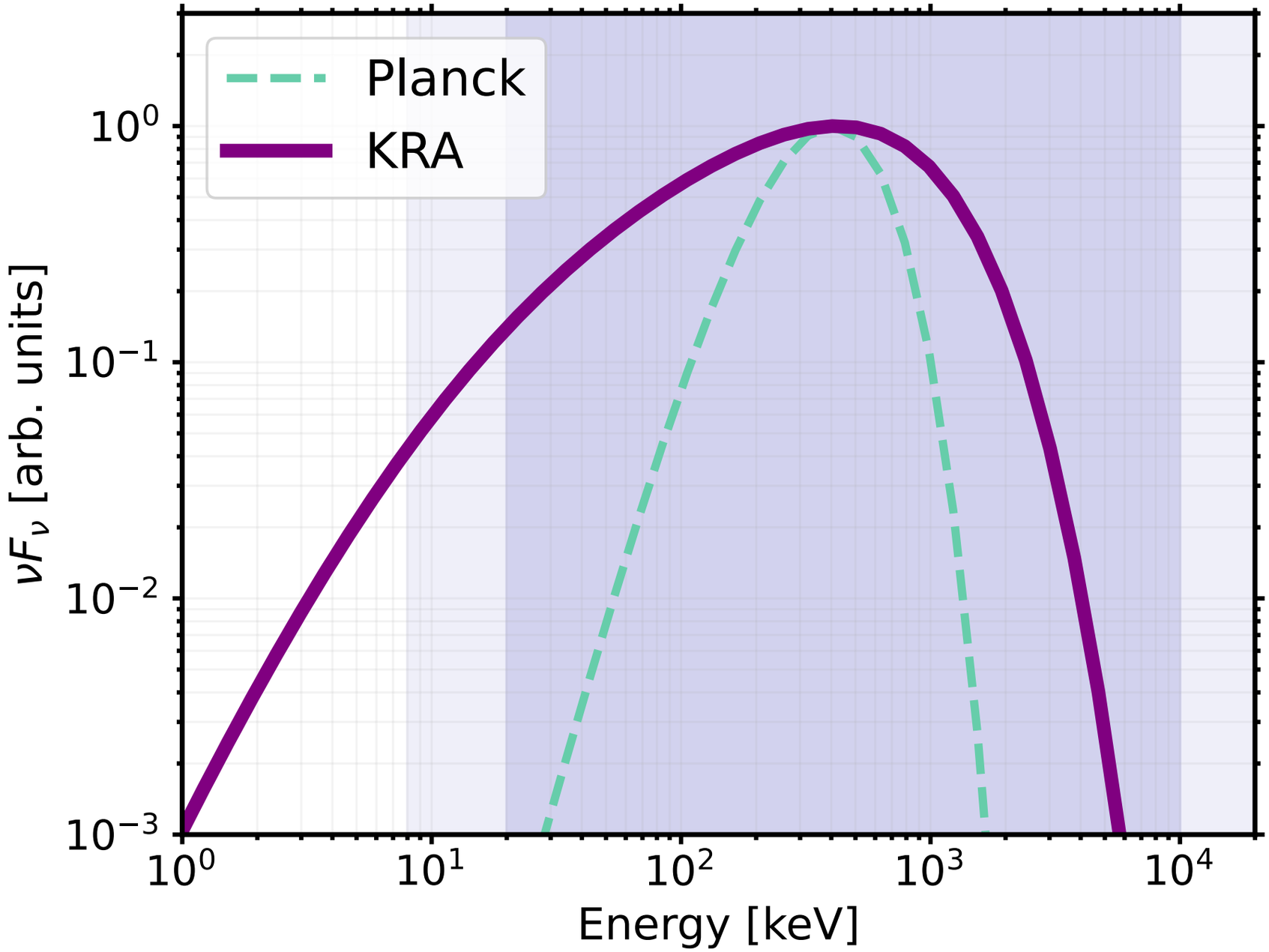
Rees & Mészáros (2005), Pe'er+ (2006), Levinson & Bromberg (2008), Samuelsson+ (2022)

Radiation-mediated shocks - Observed spectrum



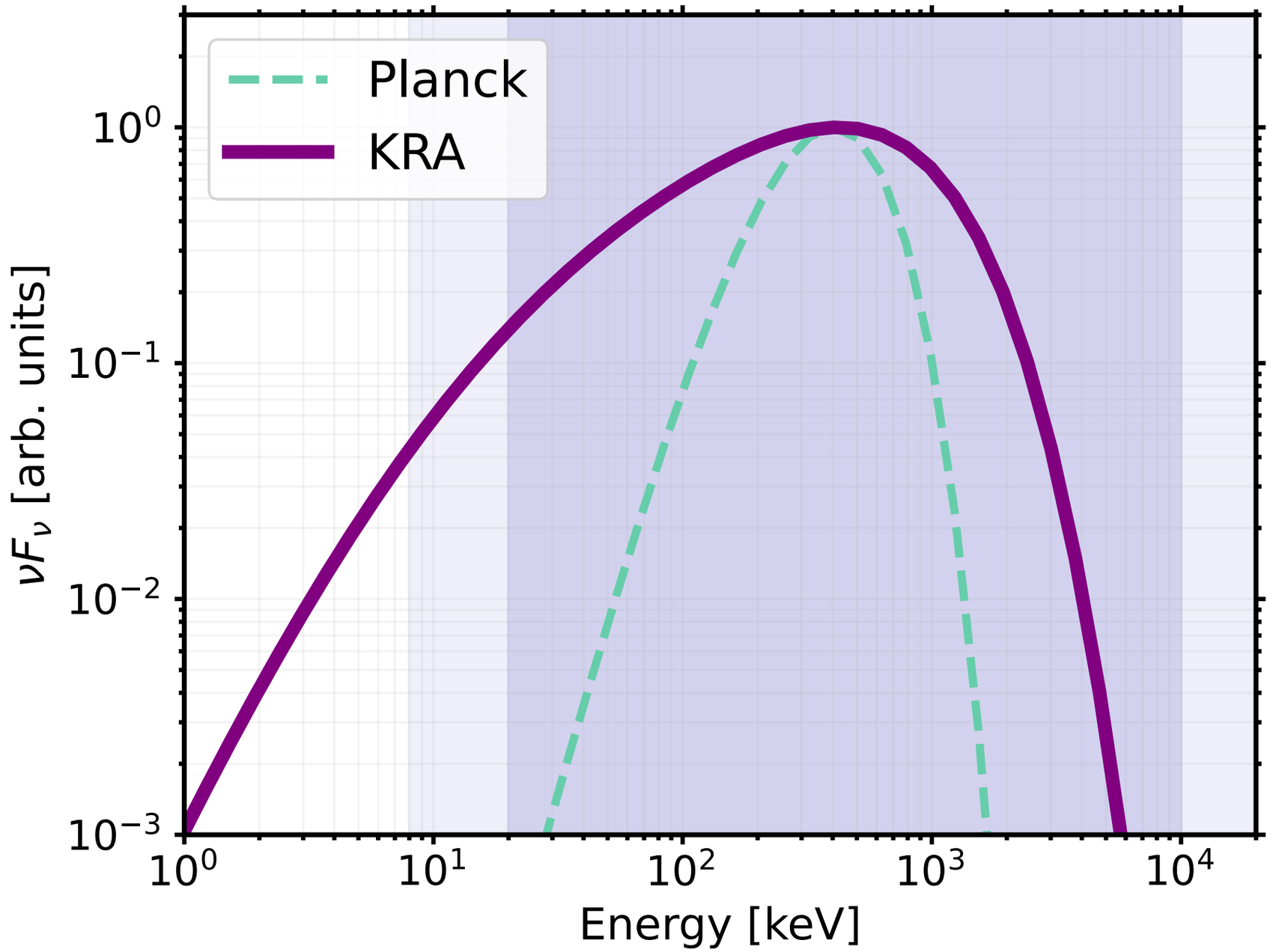
Radiation-mediated shocks - Observed spectrum

- Broad



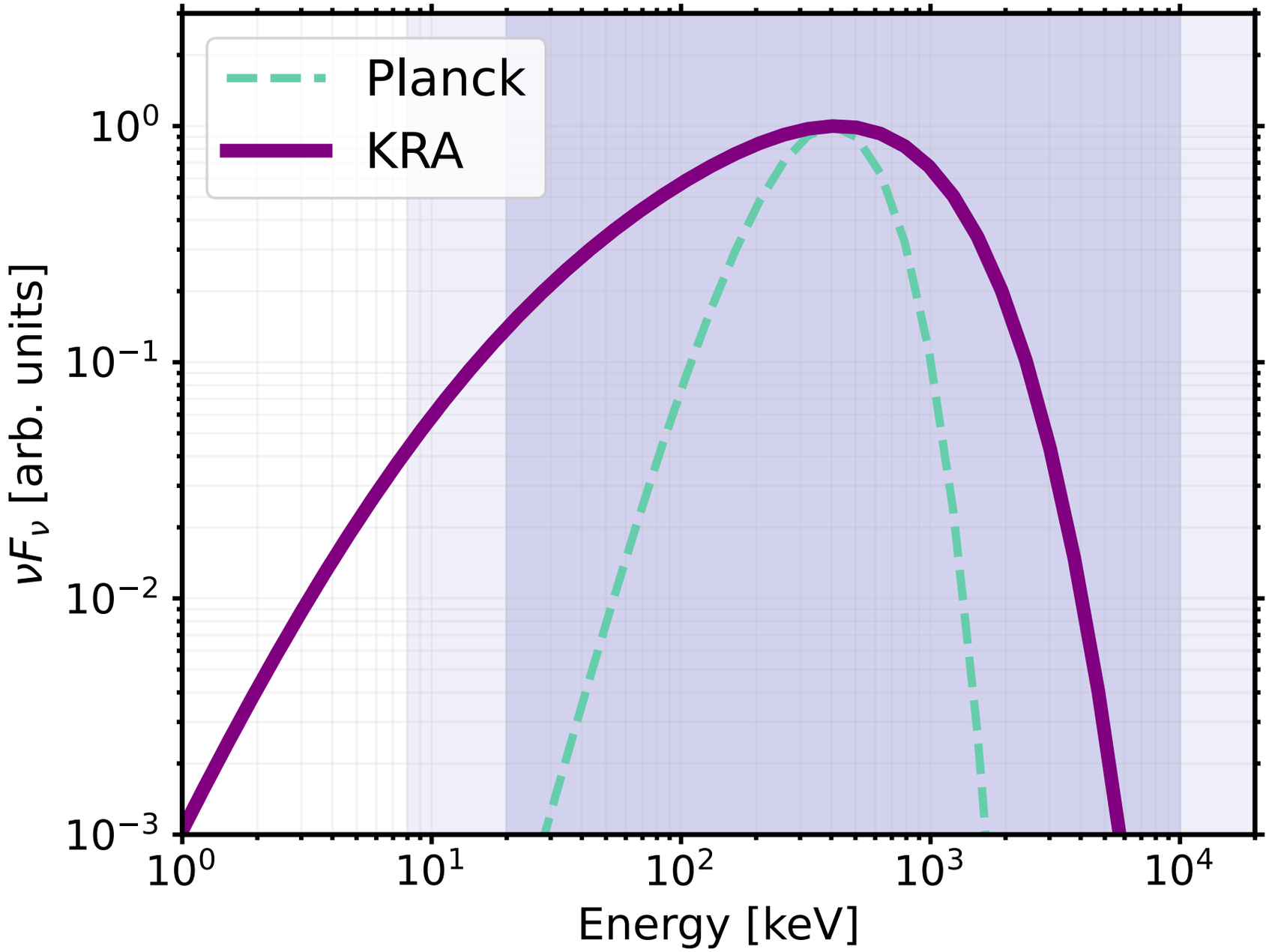
Radiation-mediated shocks - Observed spectrum

- Broad
- Soft



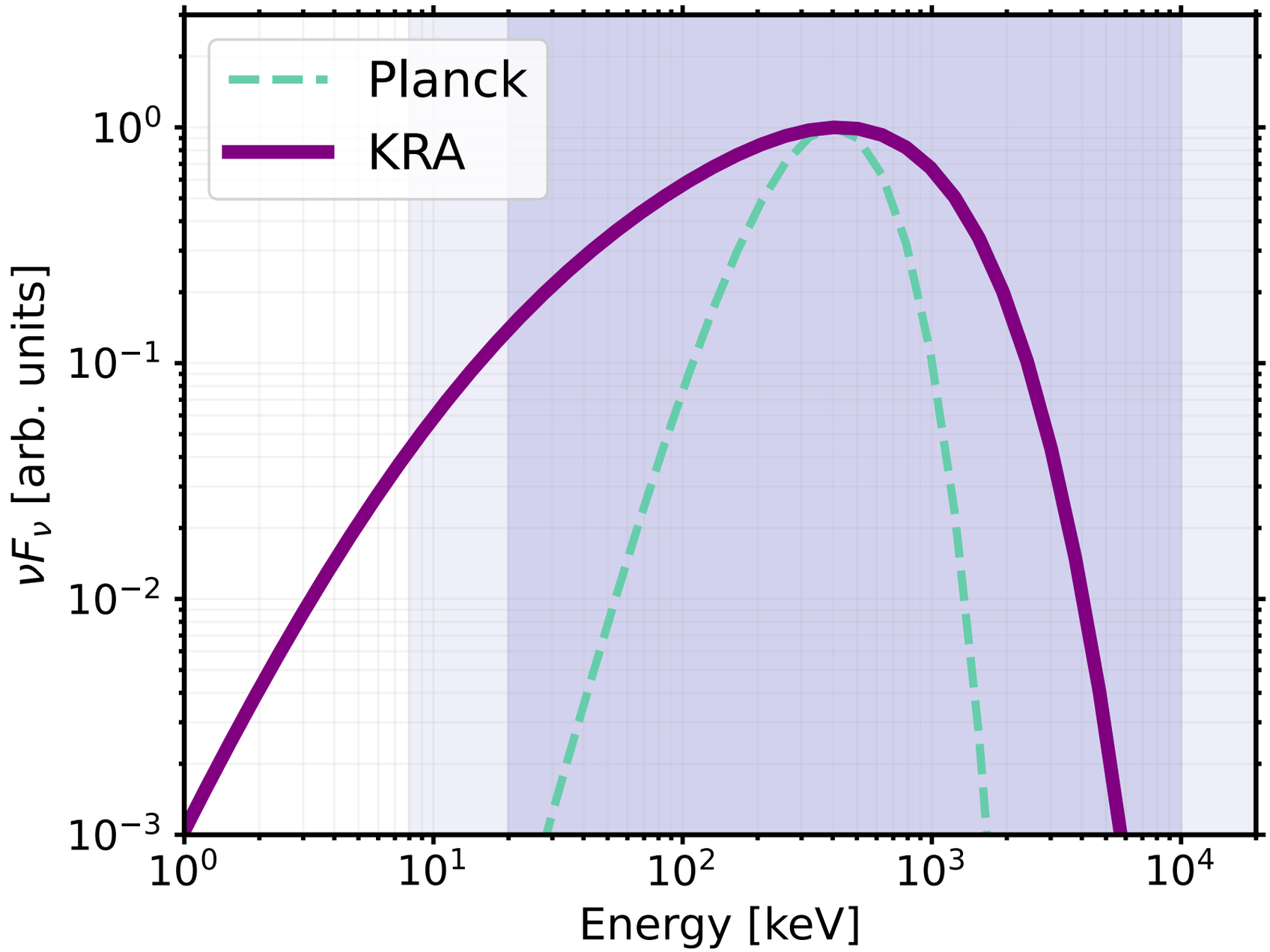
Radiation-mediated shocks - Observed spectrum

- Broad
- Soft
- Smooth curvature



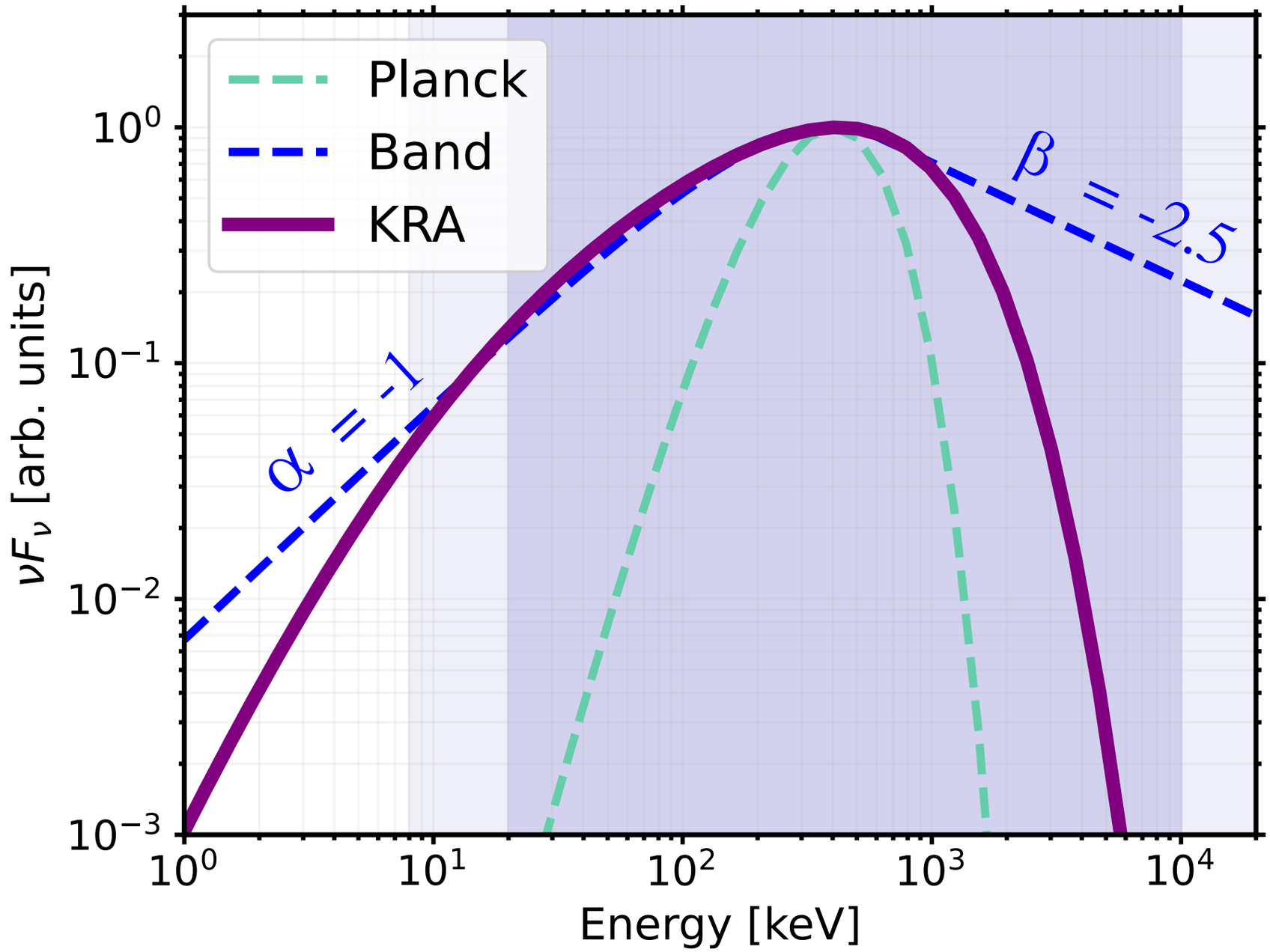
Radiation-mediated shocks - Observed spectrum

- Broad
- Soft
- Smooth curvature
- Similar to observations



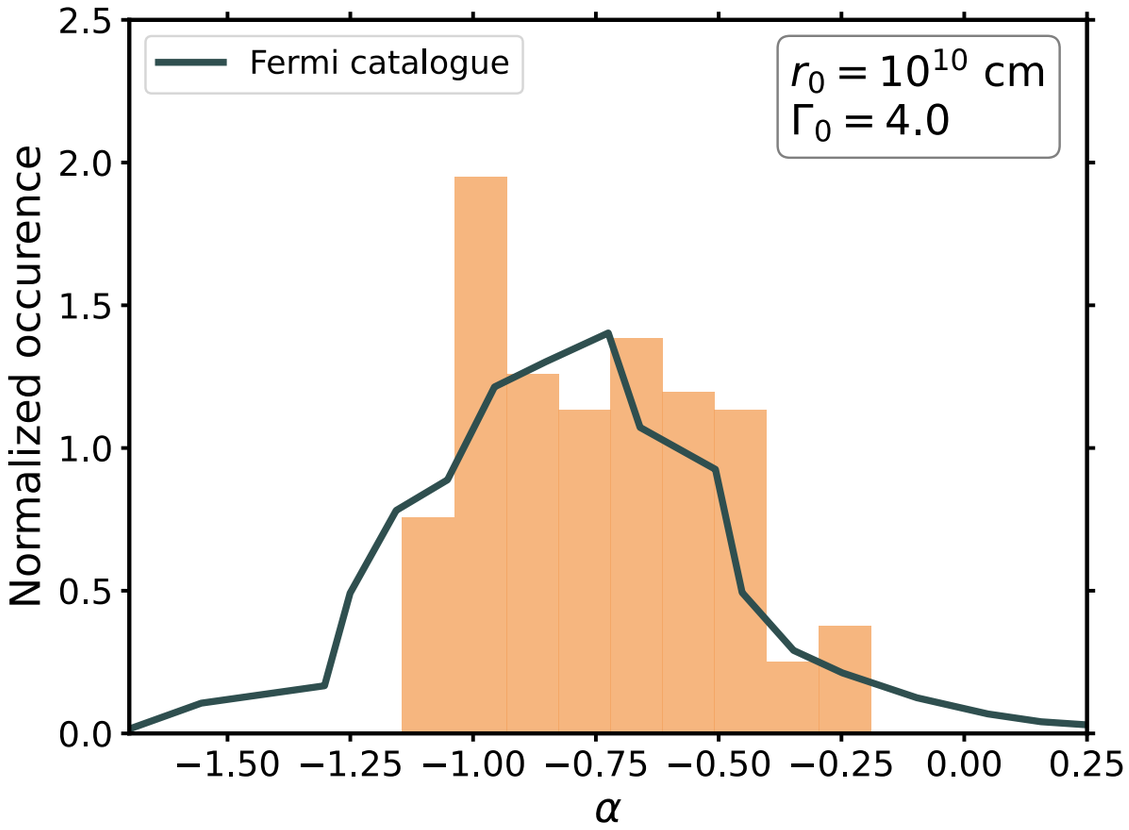
Radiation-mediated shocks - Observed spectrum

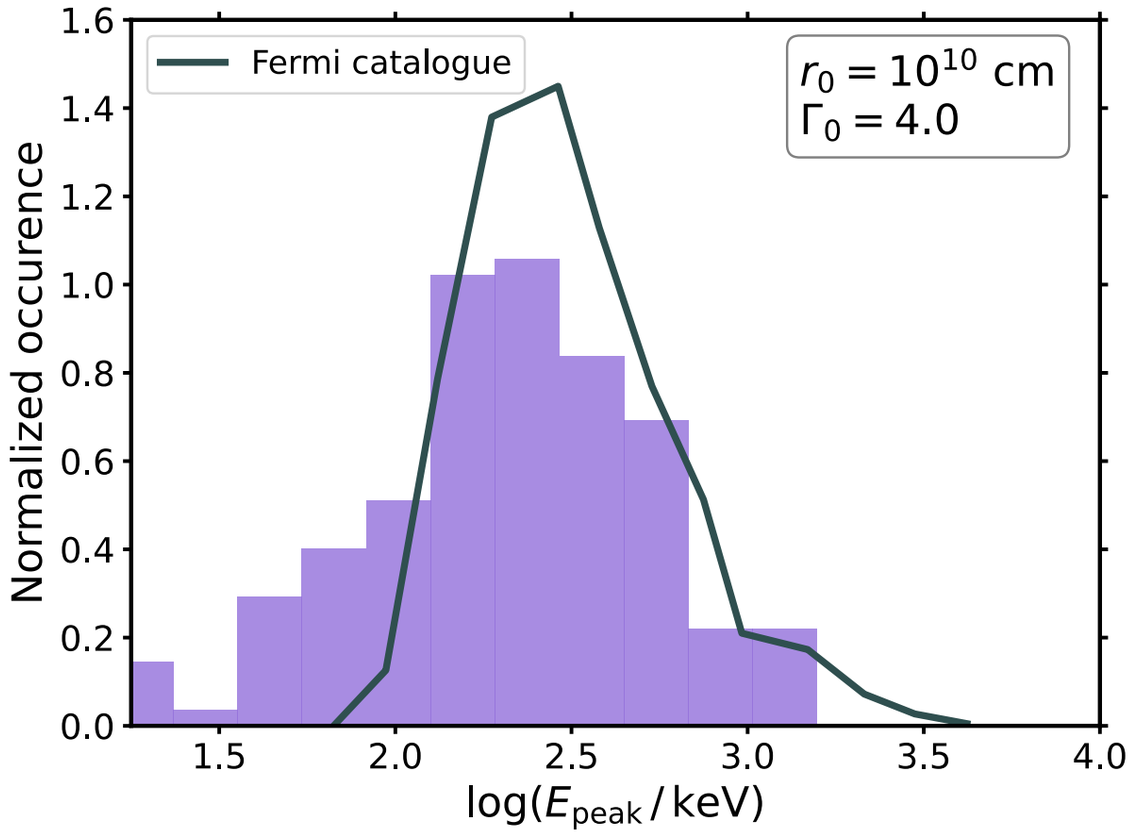
- Broad
- Soft
- Smooth curvature
- Similar to observations



Quantitative comparison against observations

- 150 fits to mock spectra
- Comparison with catalogued values are promising





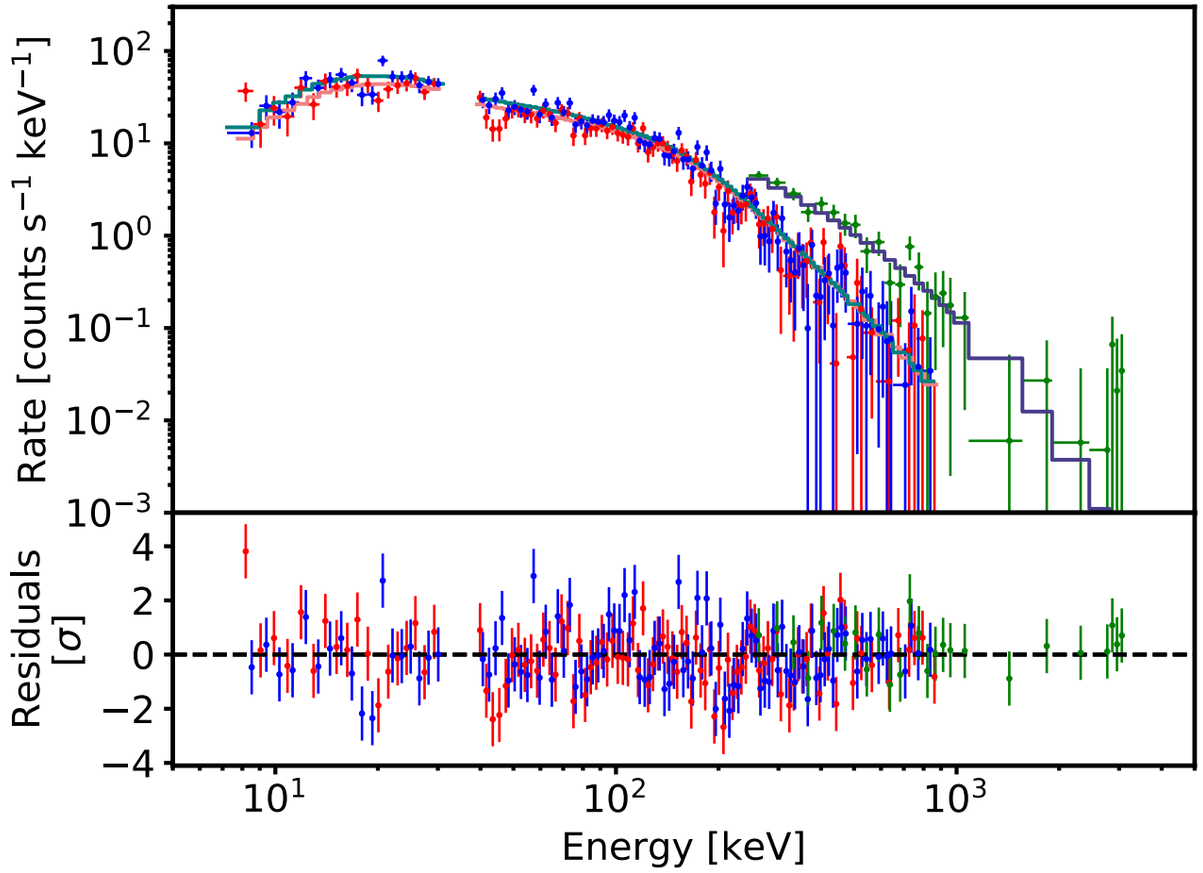
Samuelsson & Ryde (2023)

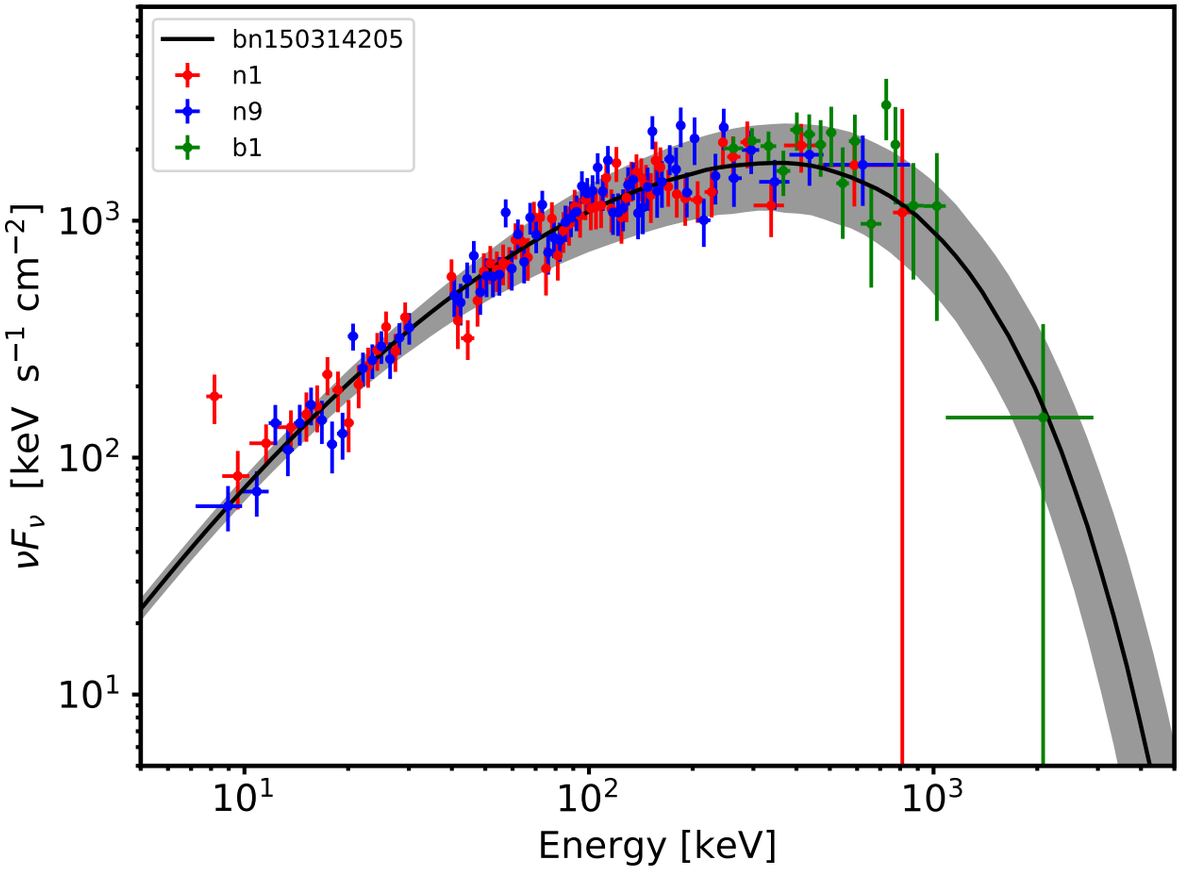
Fitting the data

First RMS-model fit to data

- Time resolved spectrum in GRB 150314A

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



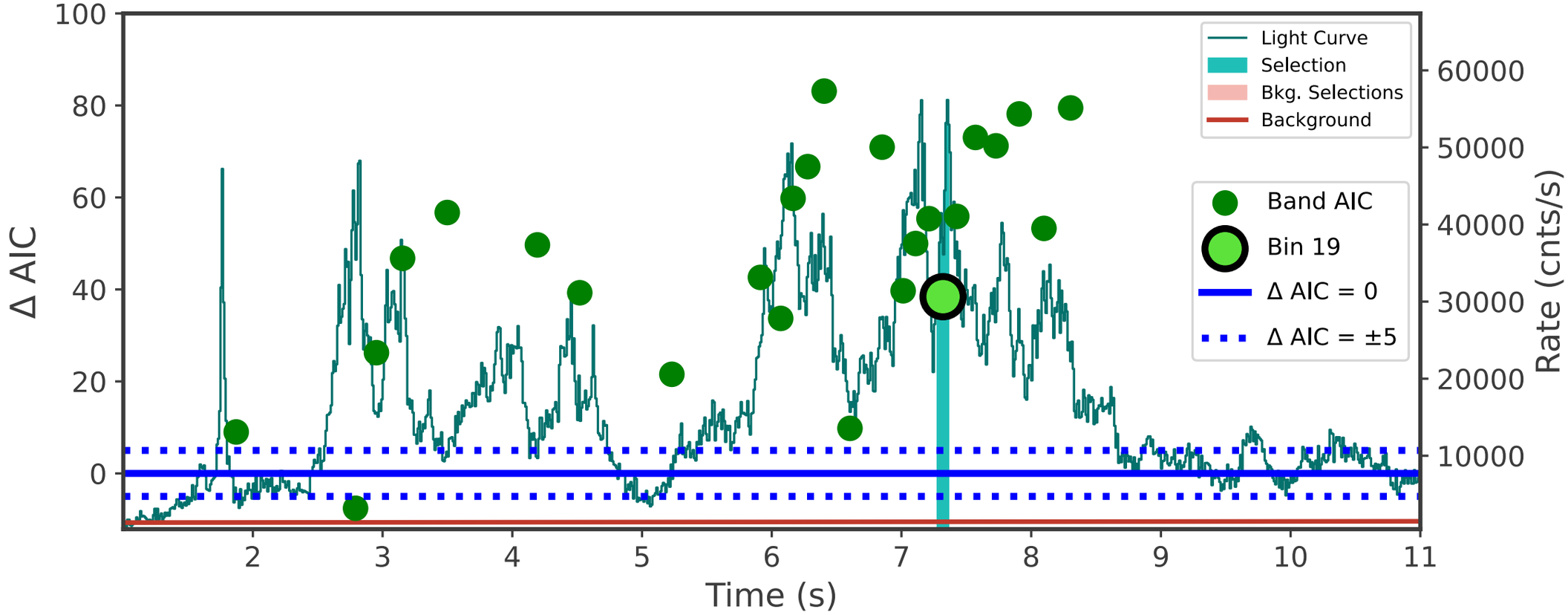


Samuelsson+ (2022)

Work in progress: GRB 211211A

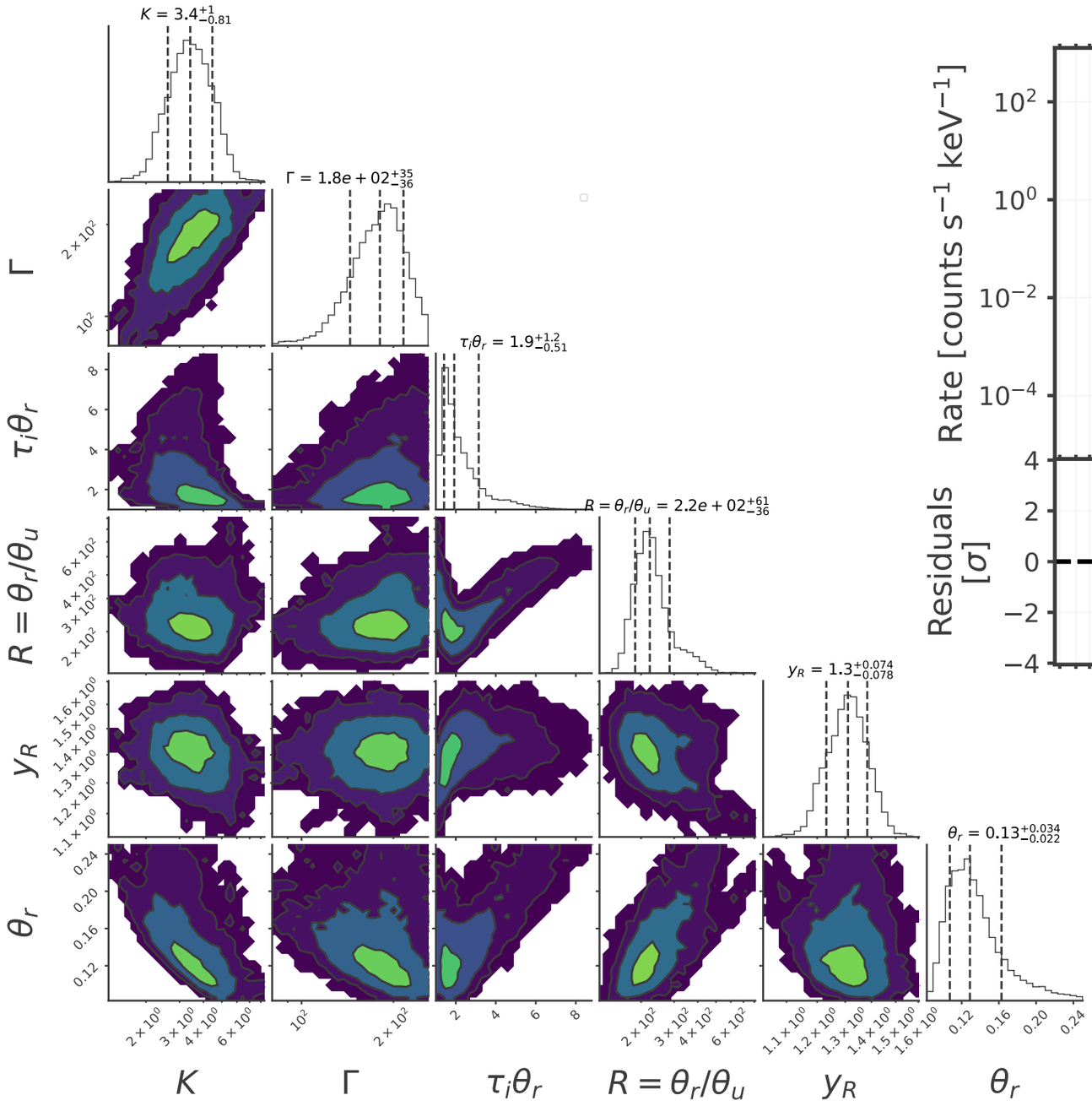
- Interesting burst, long duration but with a kilonova, shown to have more spectral complexity

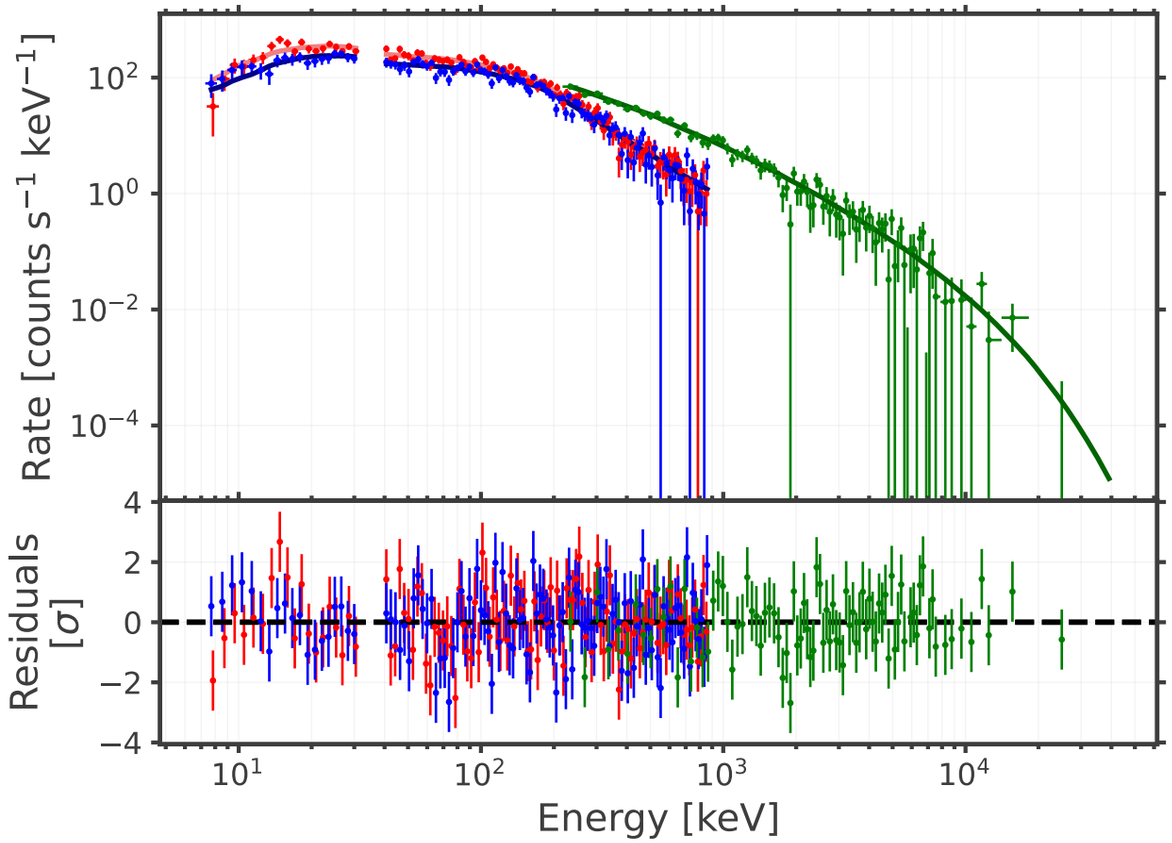
- KRA fits are much preferred over Band



See Oscar Wistemars poster. Rastinejad+ (2022), Gompertz+ (2023)

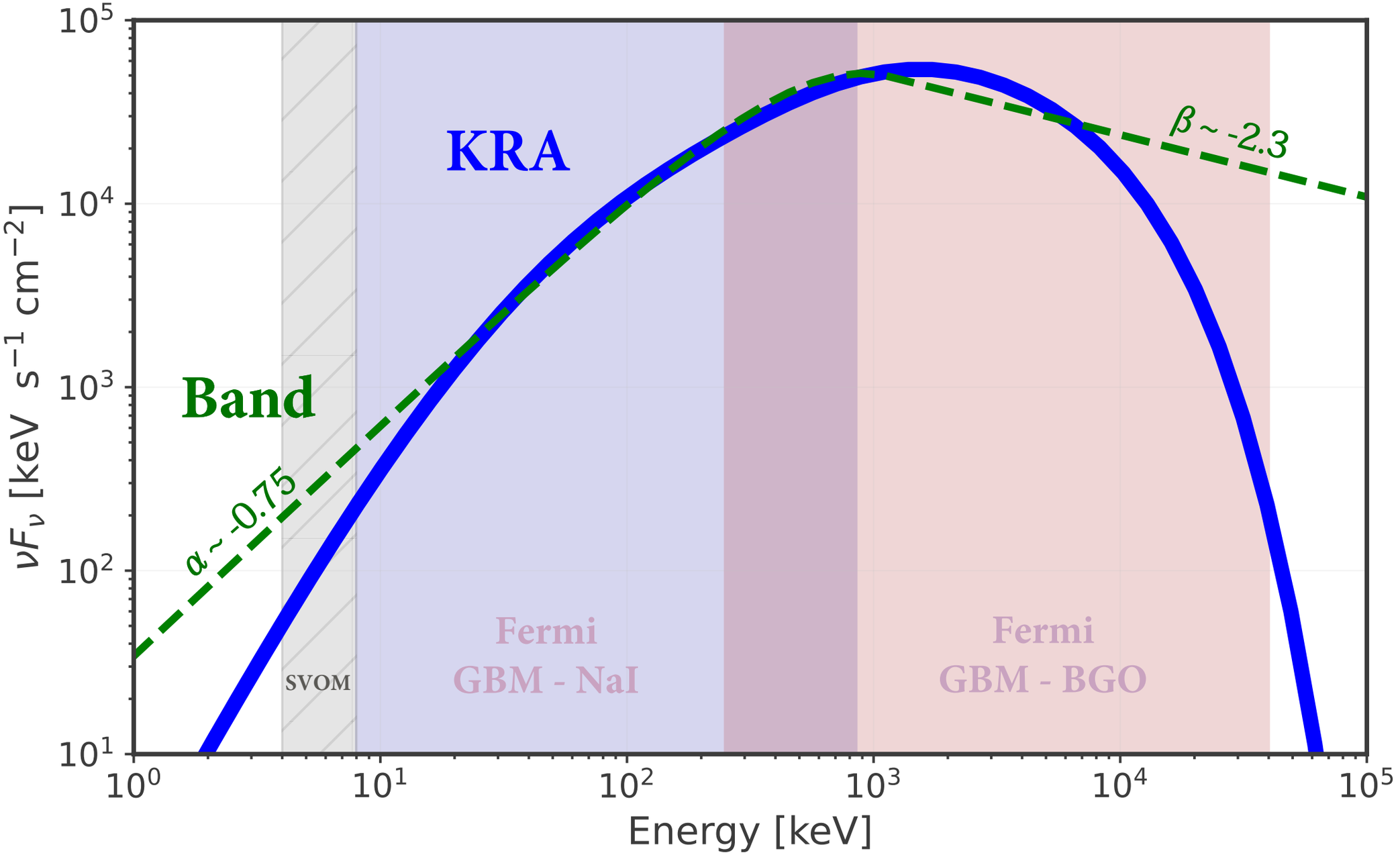
Work in progress: GRB 211211A





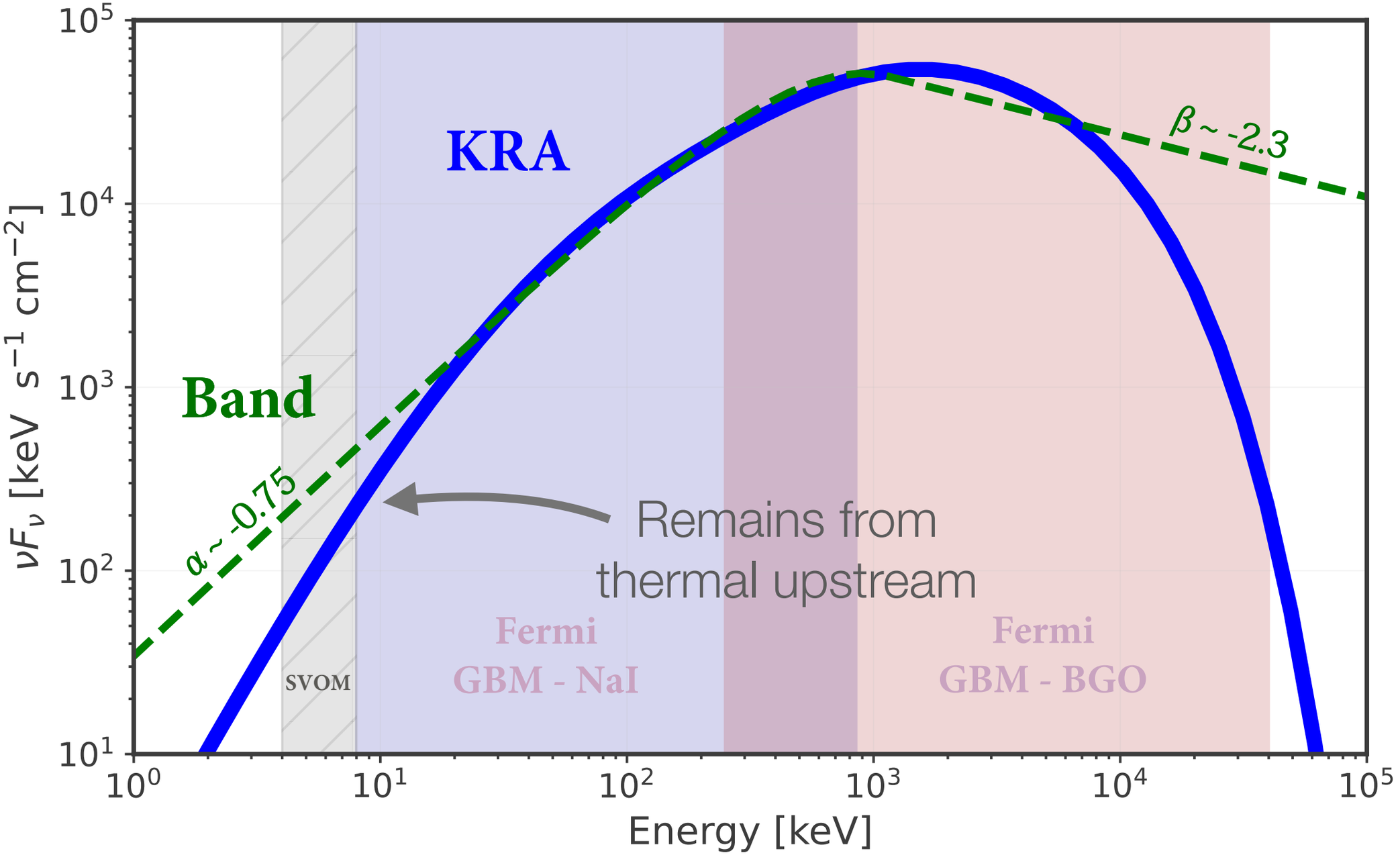
See Oscar Wistemars poster

Work in progress: GRB 211211A



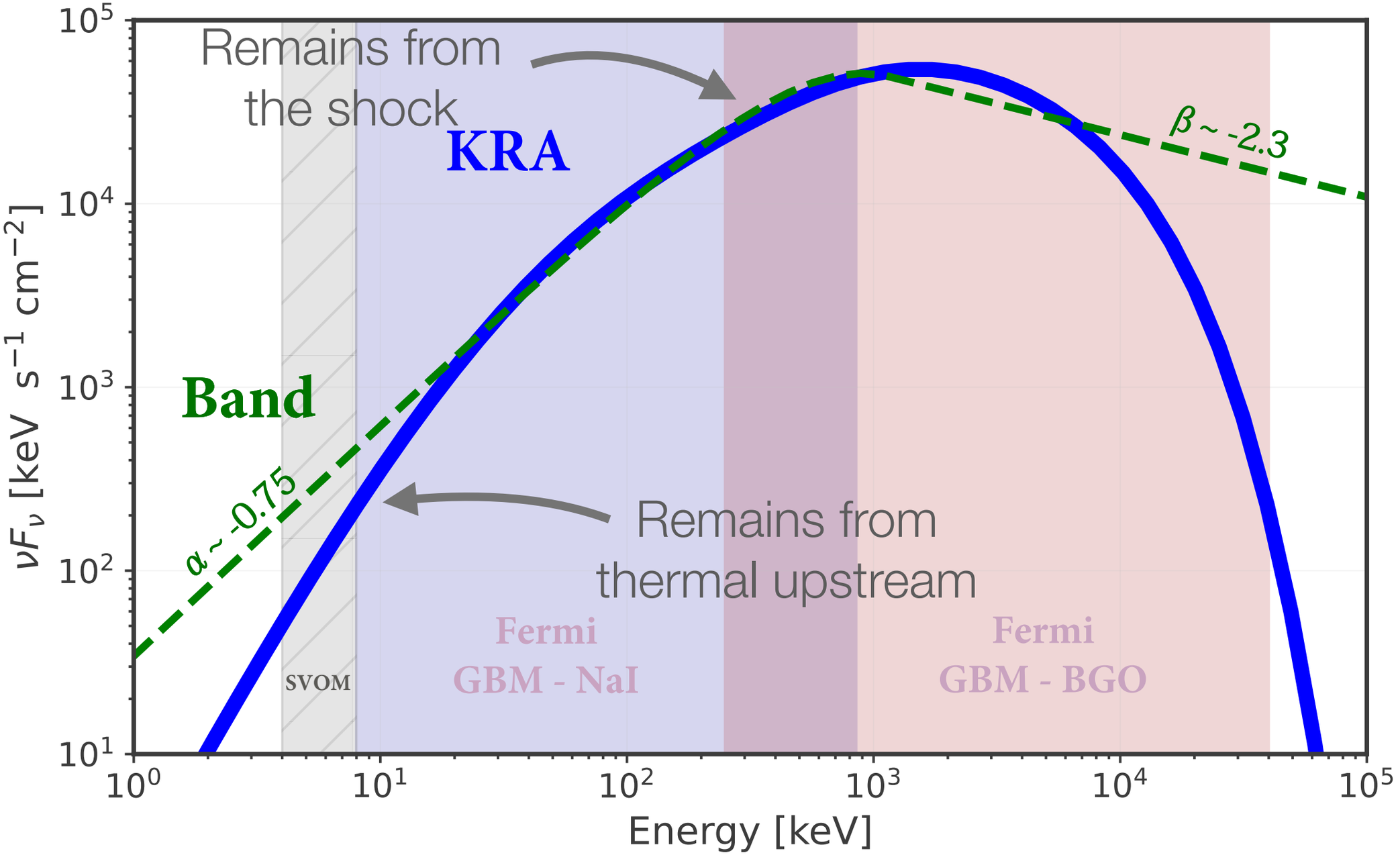
See Oscar Wistemars poster

Work in progress: GRB 211211A



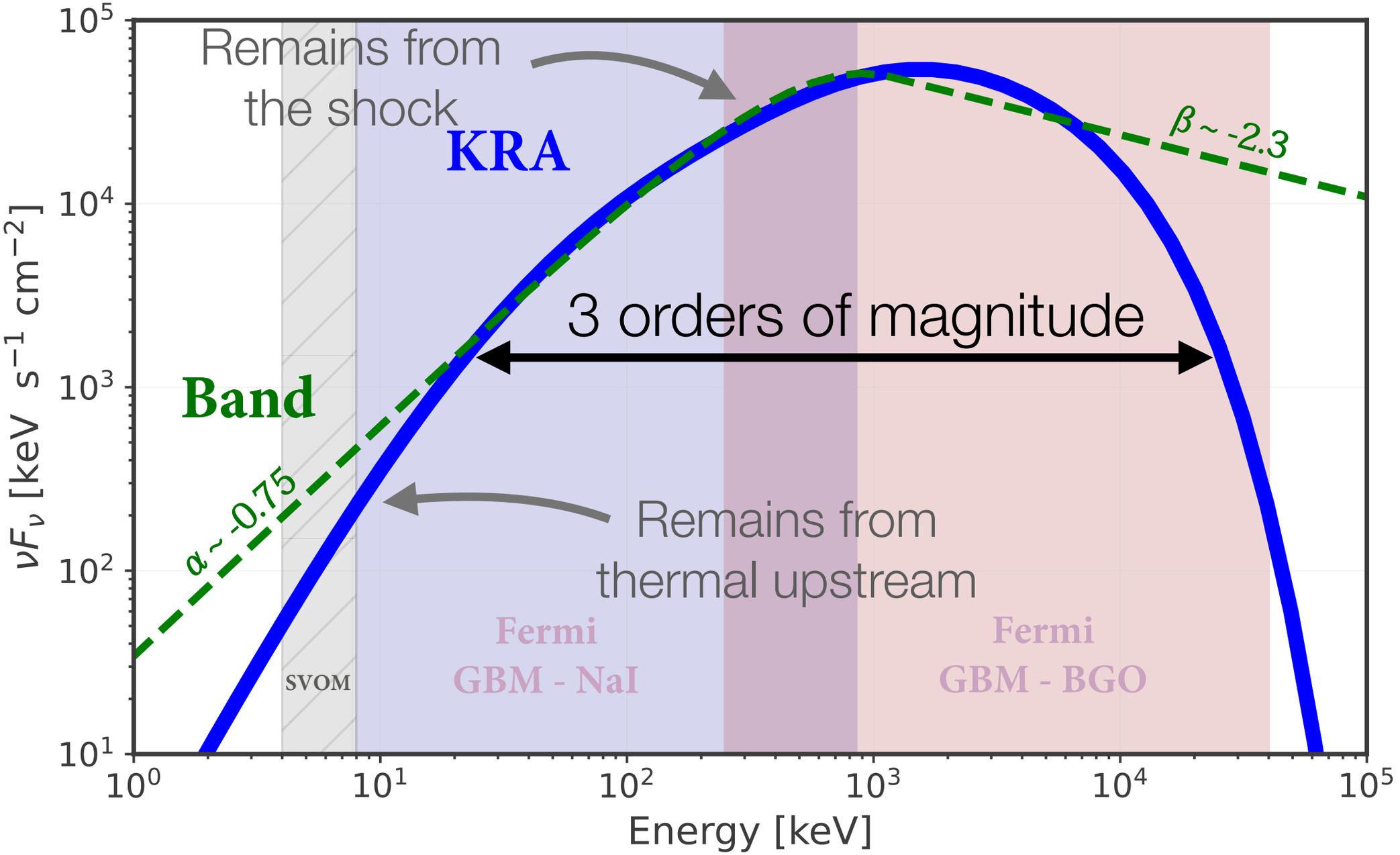
See Oscar Wistemars poster

Work in progress: GRB 211211A



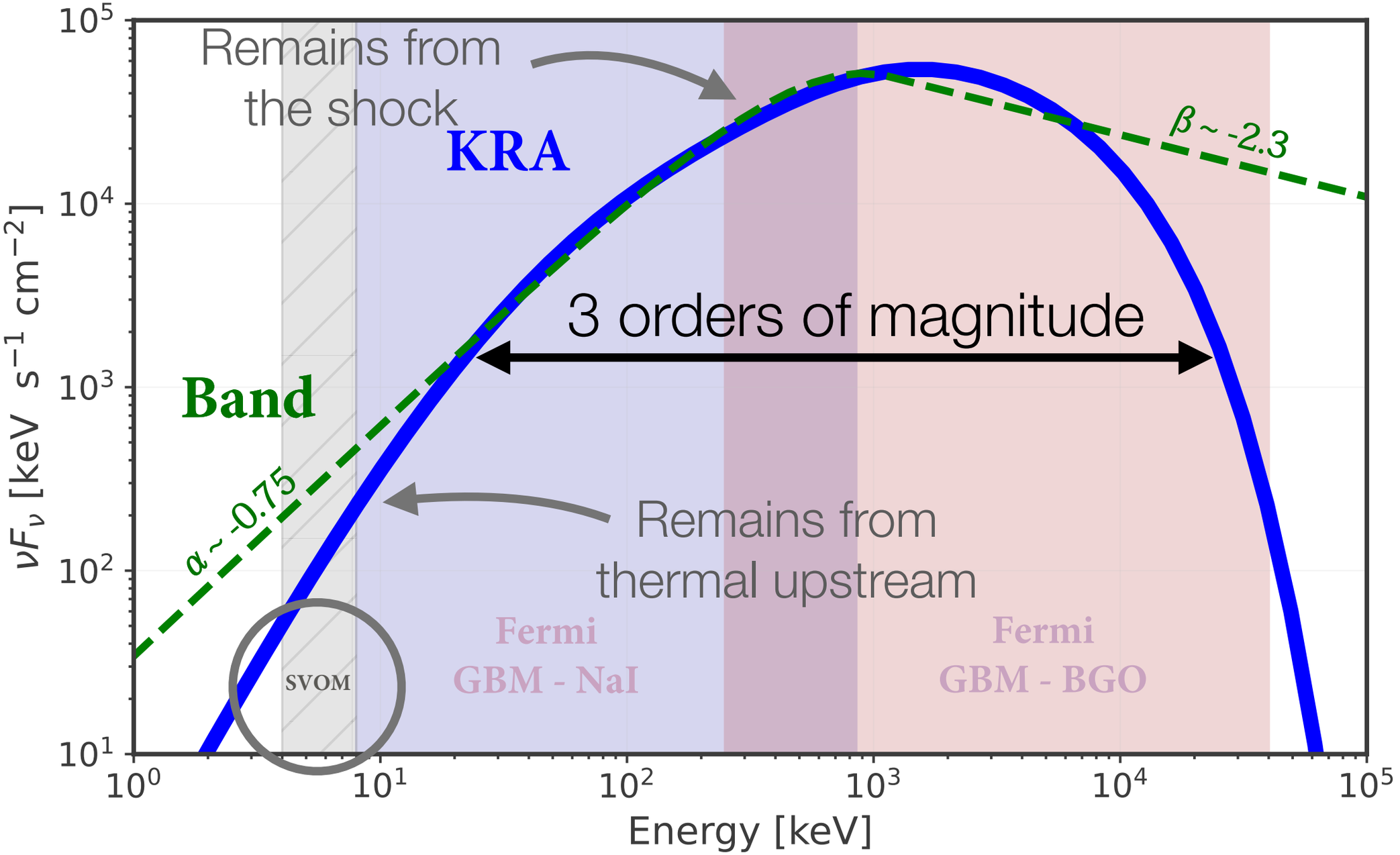
See Oscar Wistemars poster

Work in progress: GRB 211211A



See Oscar Wistemars poster

Work in progress: GRB 211211A



See Oscar Wistemars poster

Early steep decay in photospheric GRBs

Astronomy & Astrophysics manuscript no. output
October 23, 2023

Ending the prompt phase in photospheric models of gamma-ray bursts

Filip Alamaa[1,2], Frédéric Daigne[1,3], and Robert Mochkovitch[1]

[1]Sorbonne Université, CNRS, UMR 7095, Institut d'Astrophysique de Paris (IAP), 98 bis boulevard Arago, 75014 Paris, France
[2]Department of Physics, KTH Royal Institute of Technology, and The Oskar Klein Centre, SE-10691 Stockholm, Sweden
[3]Institut Universitaire de France, Ministère de l'Enseignement Supérieur et de la Recherche, 1 rue Descartes, 75231 Paris Cedex F-05, France

October 23, 2023

ABSTRACT

The early steep decay, a rapid decrease in X-ray flux as a function of time following the prompt emission, is a robust feature seen in almost all gamma-ray bursts with early enough X-ray observations. This peculiar phenomenon has often been explained as emission from high latitudes of the last flashing shell. However, in photospheric models of gamma-ray bursts, the time scale of high-latitude emission is generally short compared to the duration of the steep decay phase, and hence an alternative explanation is needed. In this paper, we show that the early steep decay can directly result from the final activity of the dying central engine. We find that the corresponding photospheric emission can reproduce both the temporal and spectral evolution observed. This requires a late-time behaviour that should be common to

Conclusions

- Interesting period in GRB physics (Launch of SVOM scheduled next year)

- Additional spectral complexity observed in bright GRBs at low energies plausibly universal

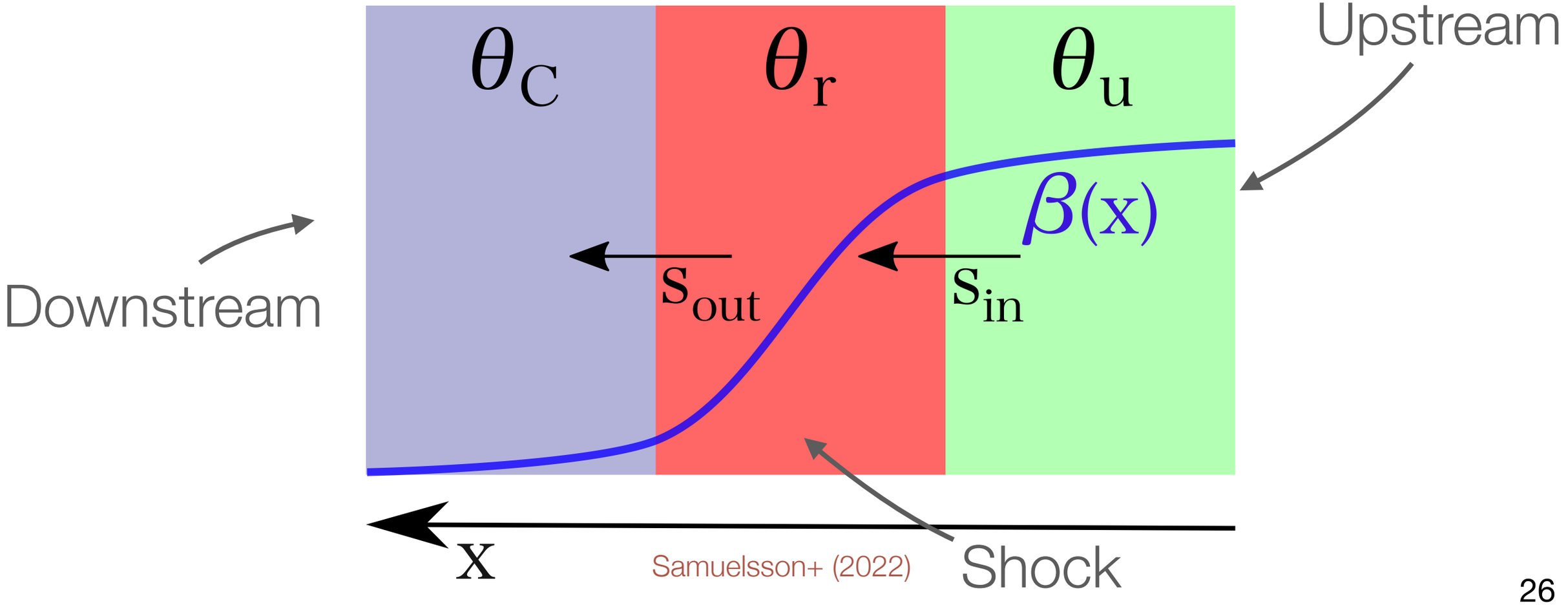
- Photospheric spectra including radiation-mediated shocks are broad, soft, and seem to fit the data really well

Extra slides

The Kompaneets RMS approximation (KRA)

- Fermi acceleration of photons in RMS converging flow ≈ repeated scatterings with hot electrons

- The Kompaneets RMS approximation (KRA)



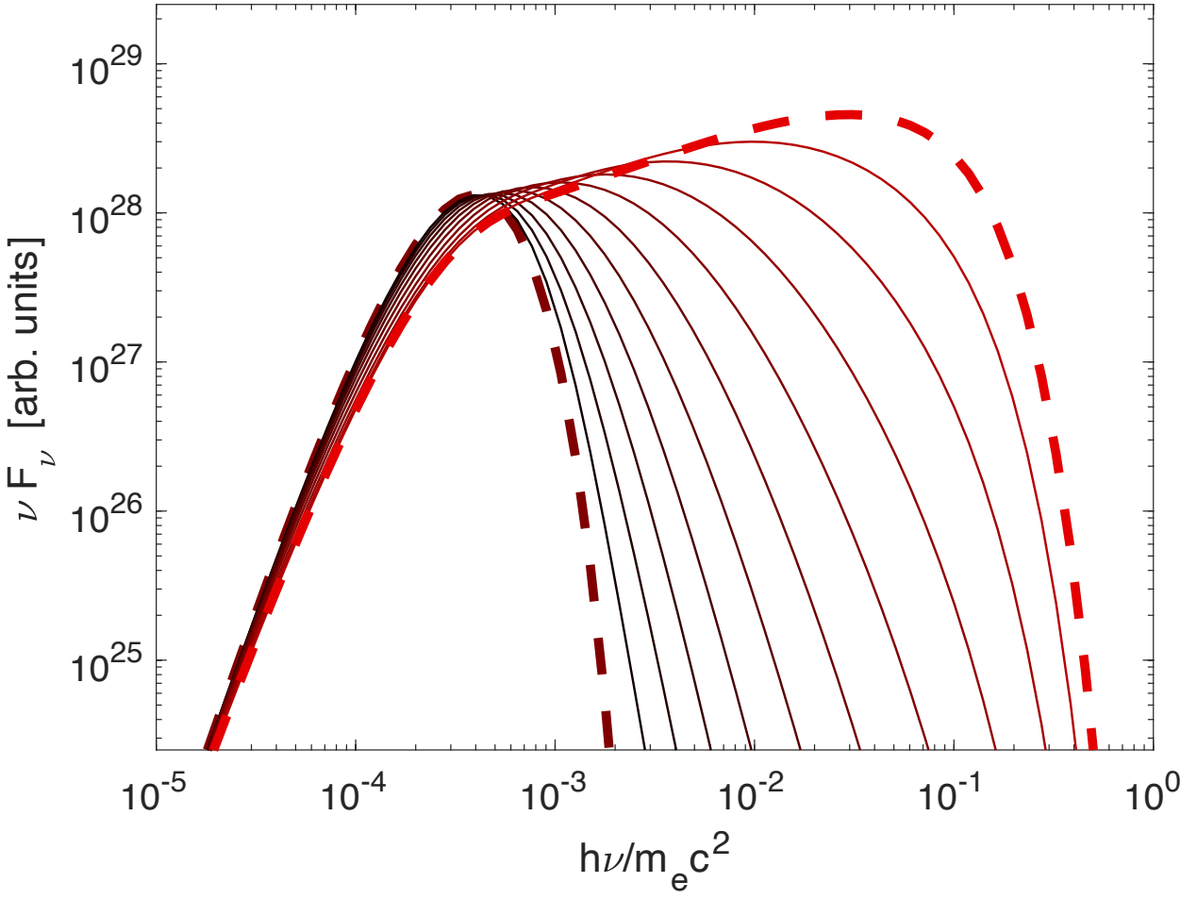
Samuelsson+ (2022)

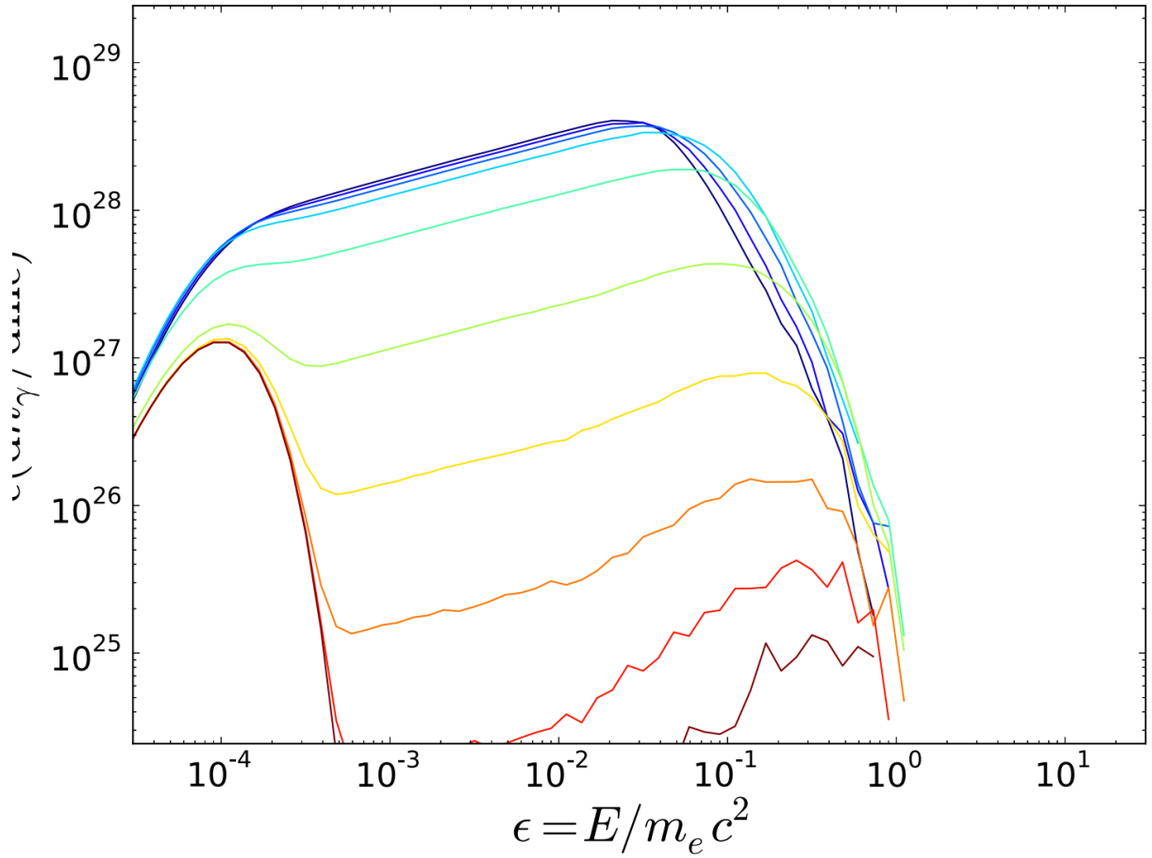
Kompaneet's equation

- Repeated scatterings of non-relativistic thermal electrons

$$\frac{\partial}{\partial \bar{r}}\left(\bar{r}^2 n\right) = \frac{1}{\epsilon^2}\frac{\partial}{\partial \epsilon}\left[\frac{\epsilon^4}{\bar{r}^2}\left(\theta\frac{\partial(\bar{r}^2 n)}{\partial \epsilon} + (\bar{r}^2 n)\right) + \frac{2}{3}\frac{\epsilon^3(\bar{r}^2 n)}{\bar{r}}\right] + s$$

Spectrum — Heating — Cooling — Ad. cooling — Sources

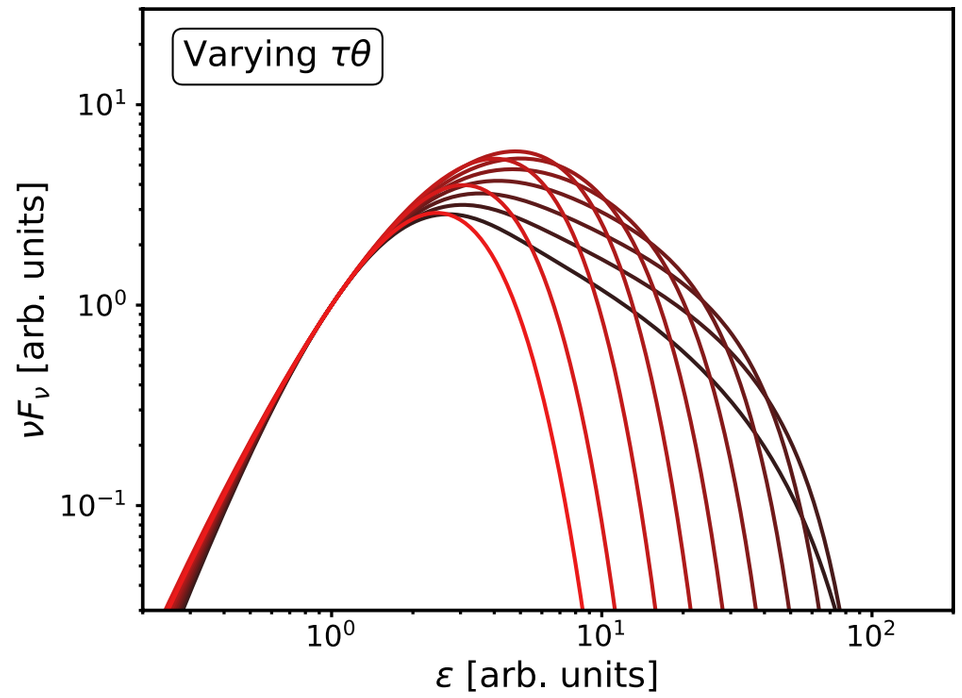


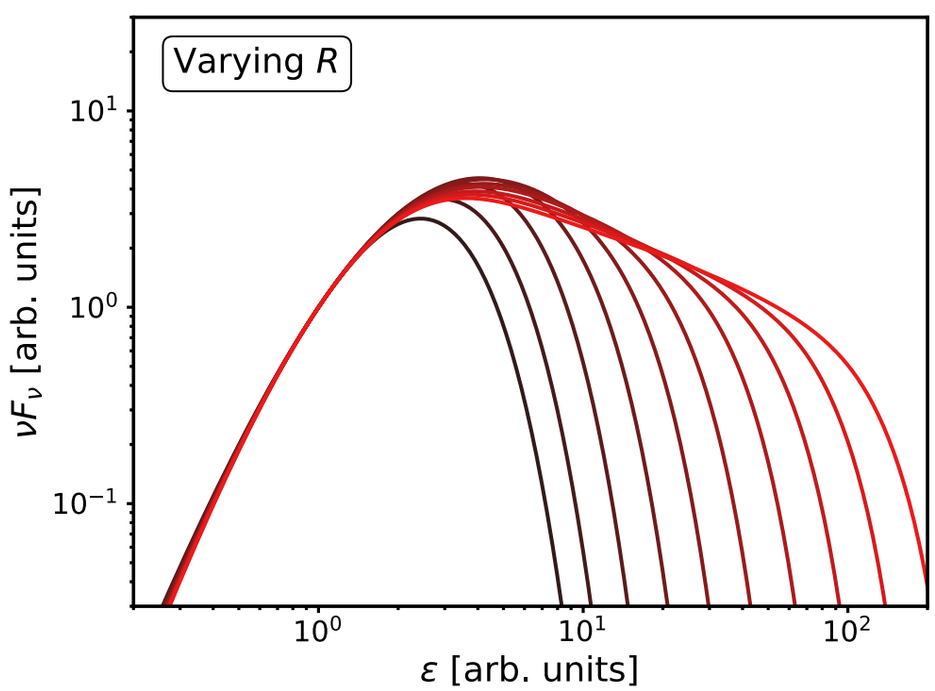


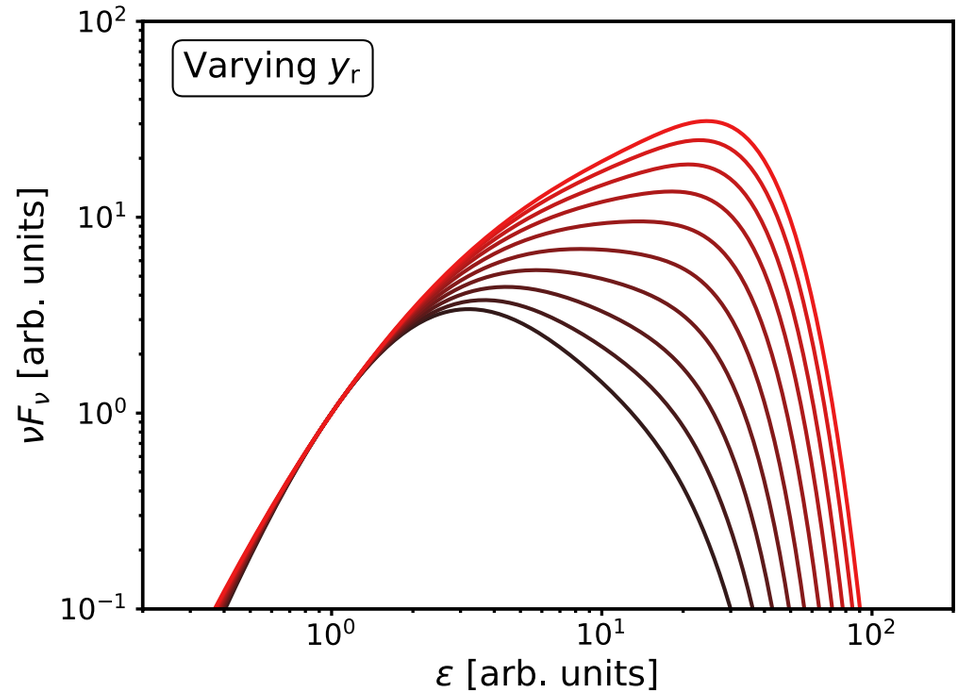
Lundman+ (2018)

Parameters

- Three parameters for the shape

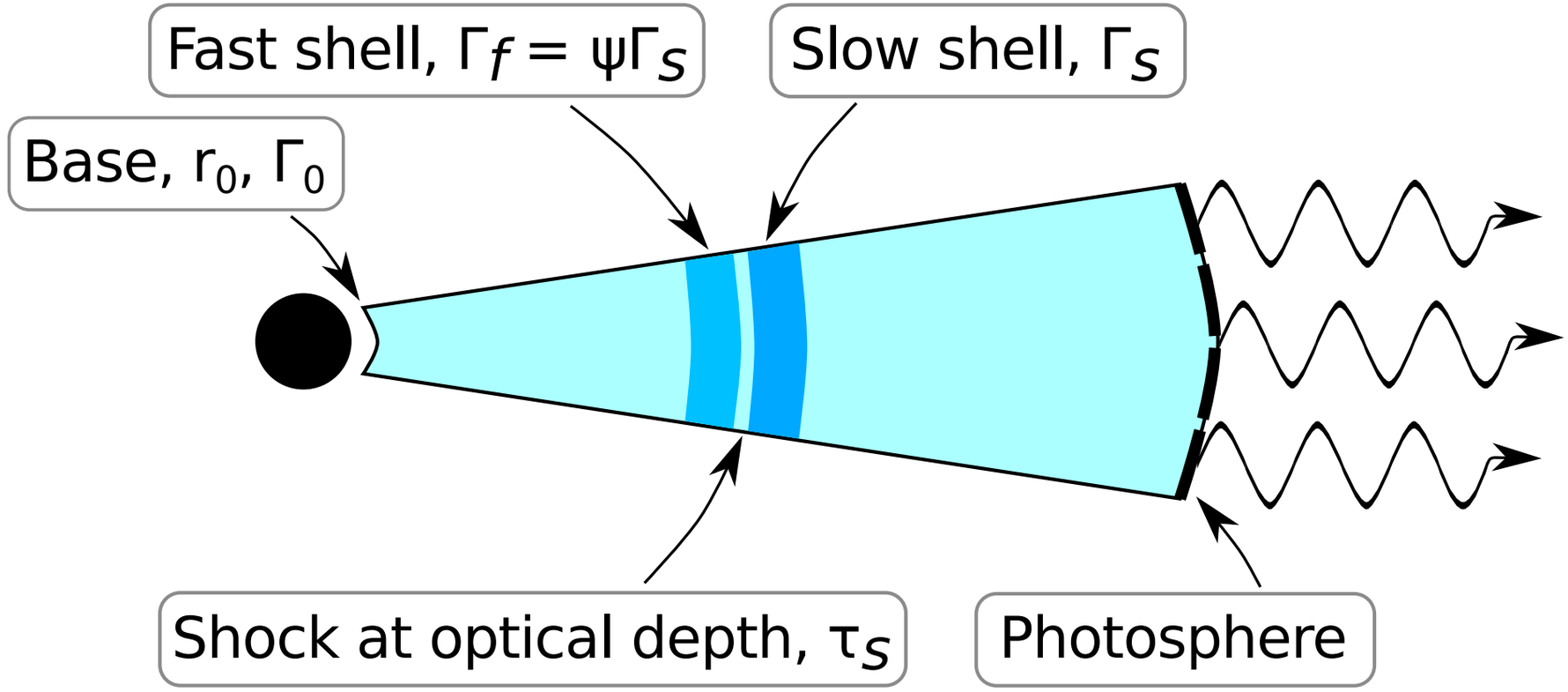






Estimating shock initial conditions

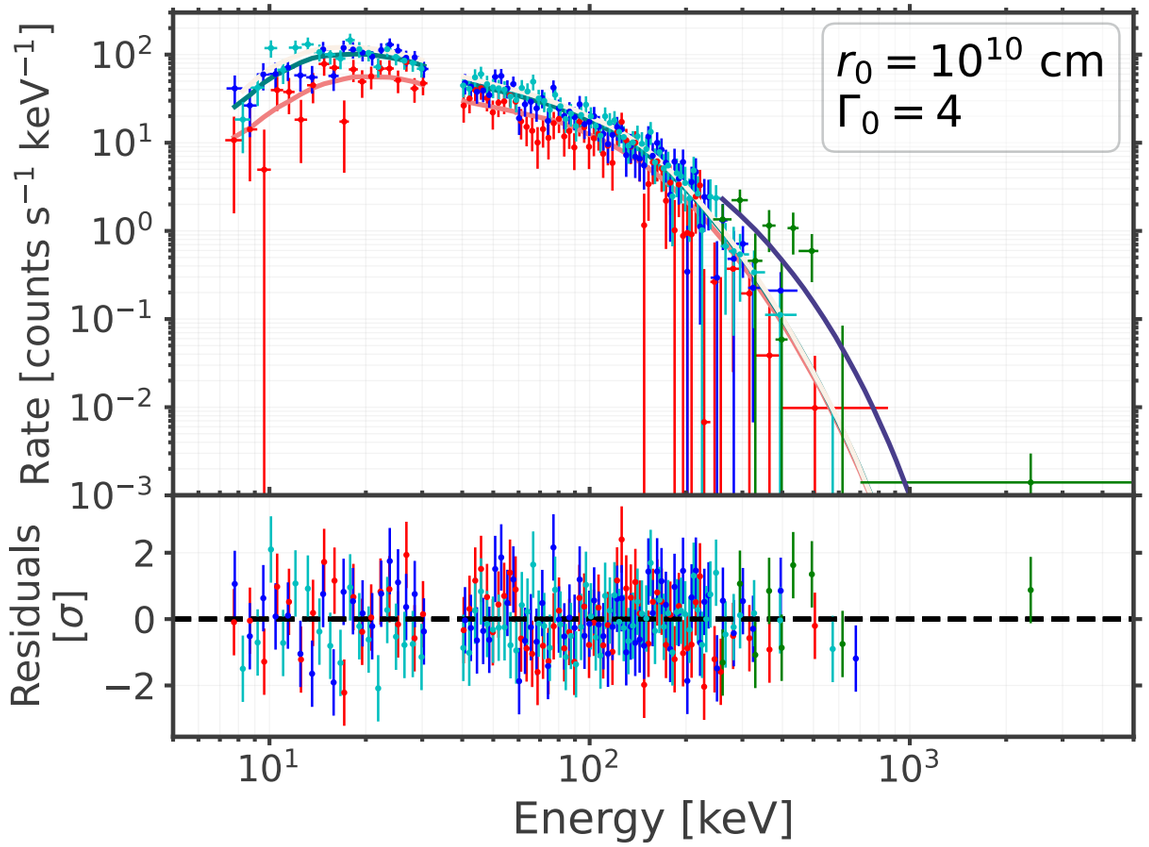
- Without context, shock initial conditions can be anything
- Therefore, we employ a simple internal collision framework

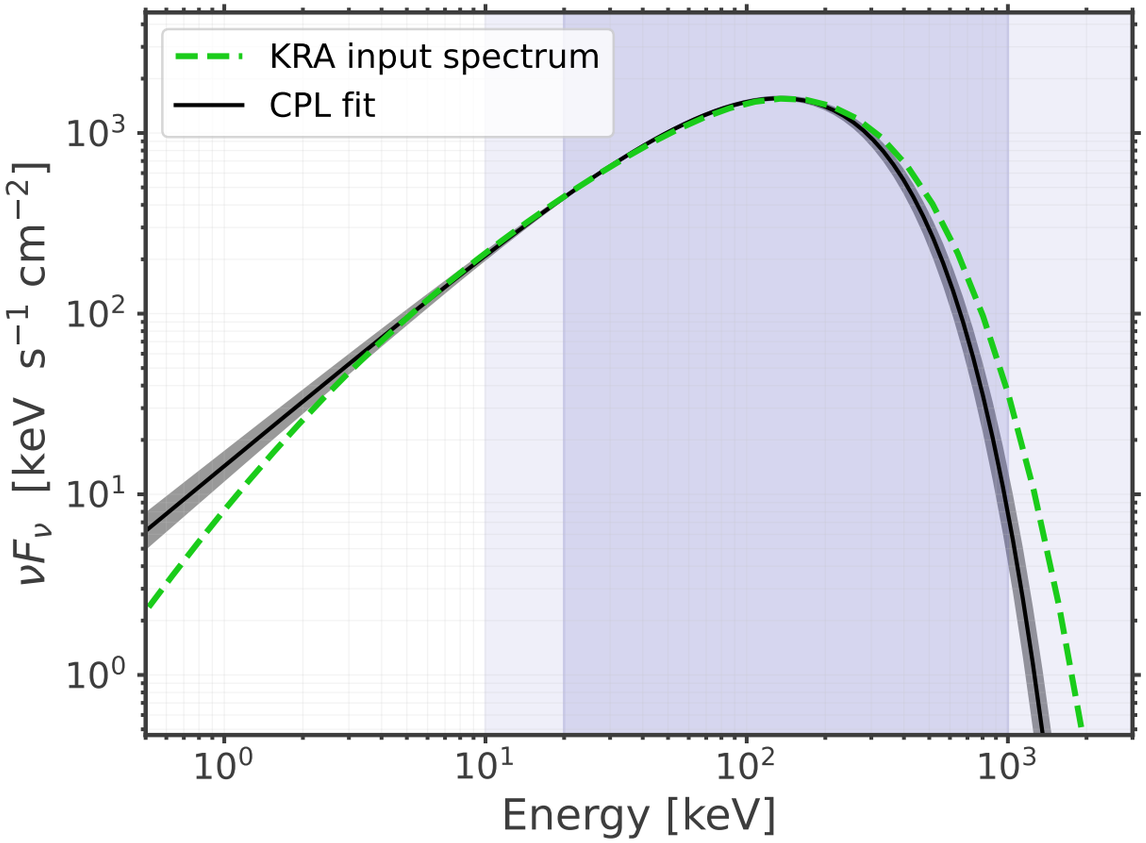


Kobayashi+ (1997), Daigne & Mochkovitch (1998), Rees & Mészáros (2005)

Fit with a cutoff power-law (CPL) function

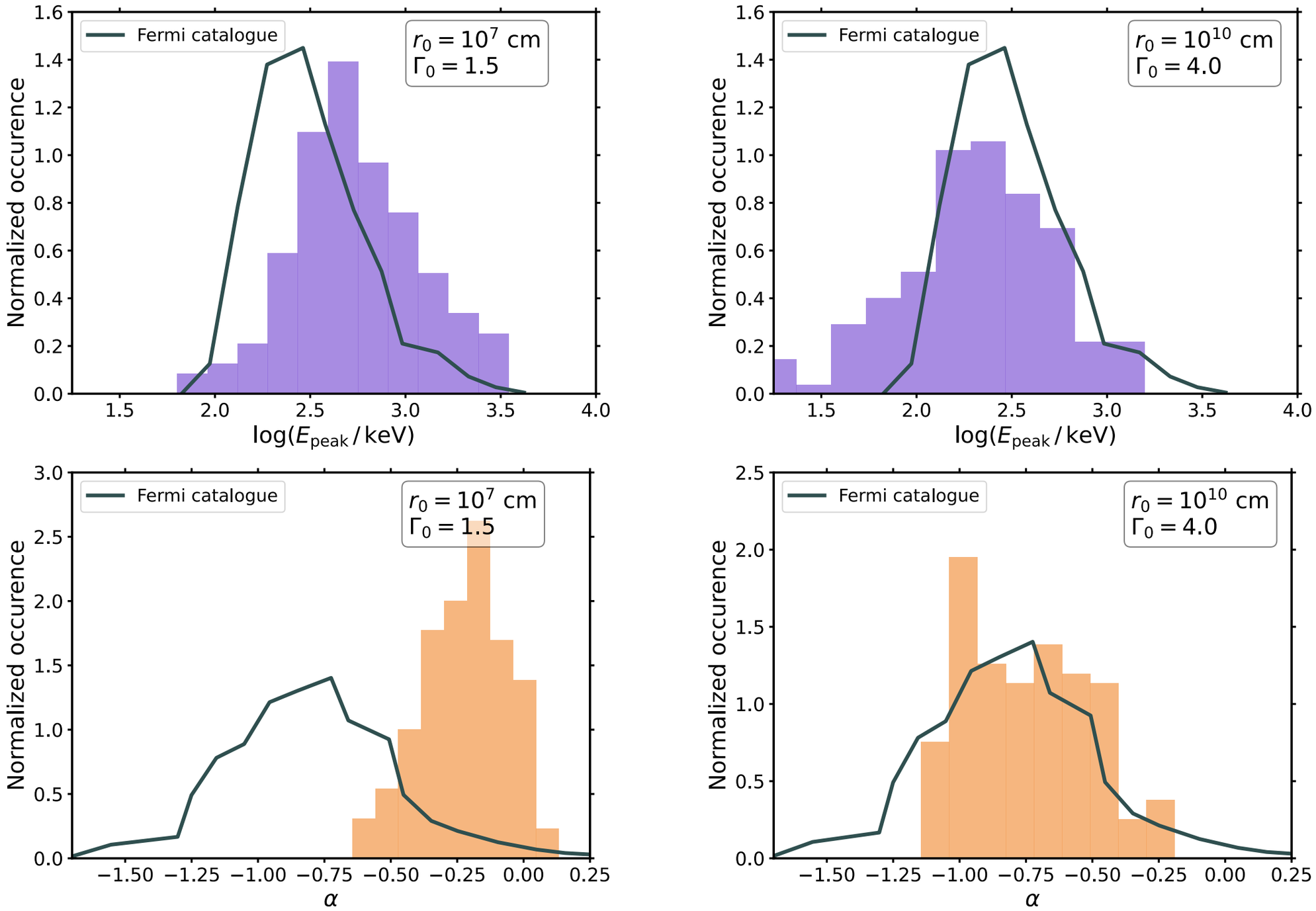
- Forward fold through Fermi GBM response matrix
- Spectra generally well fitted with a CPL; complexity outside detector window





Samuelsson & Ryde (2023)

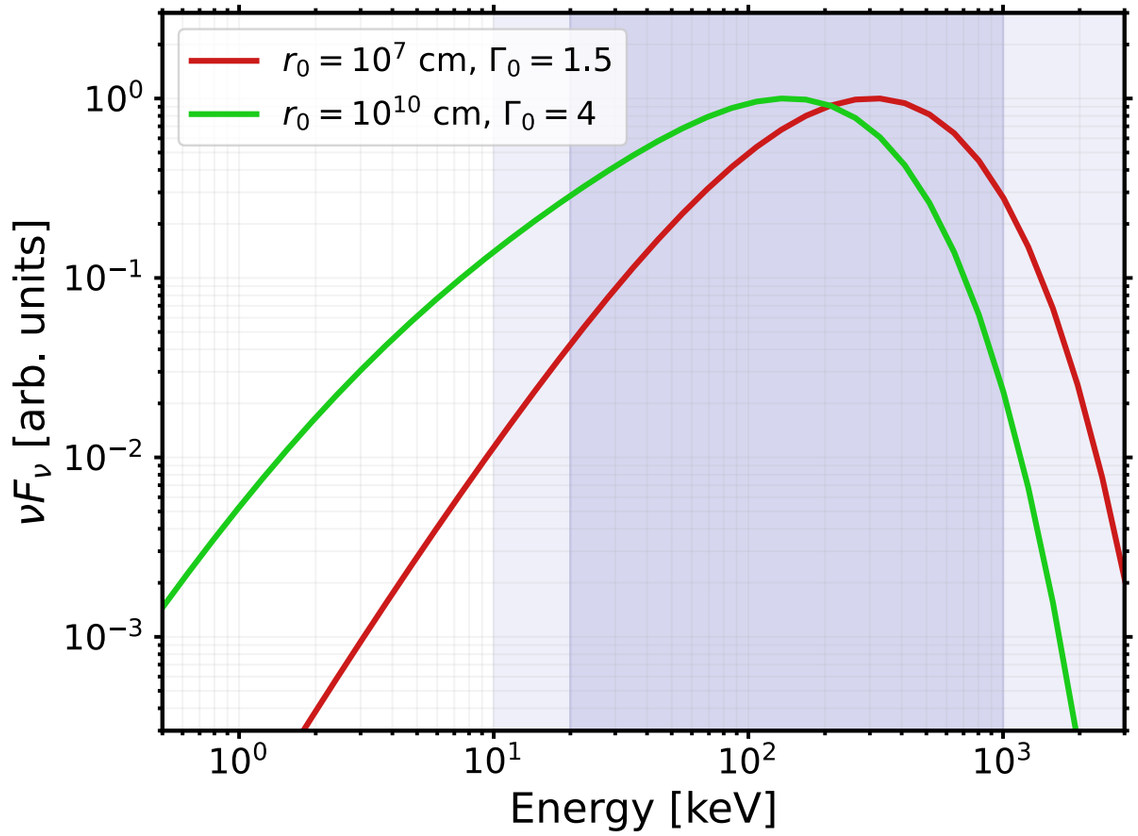
150 fits with a CPL function

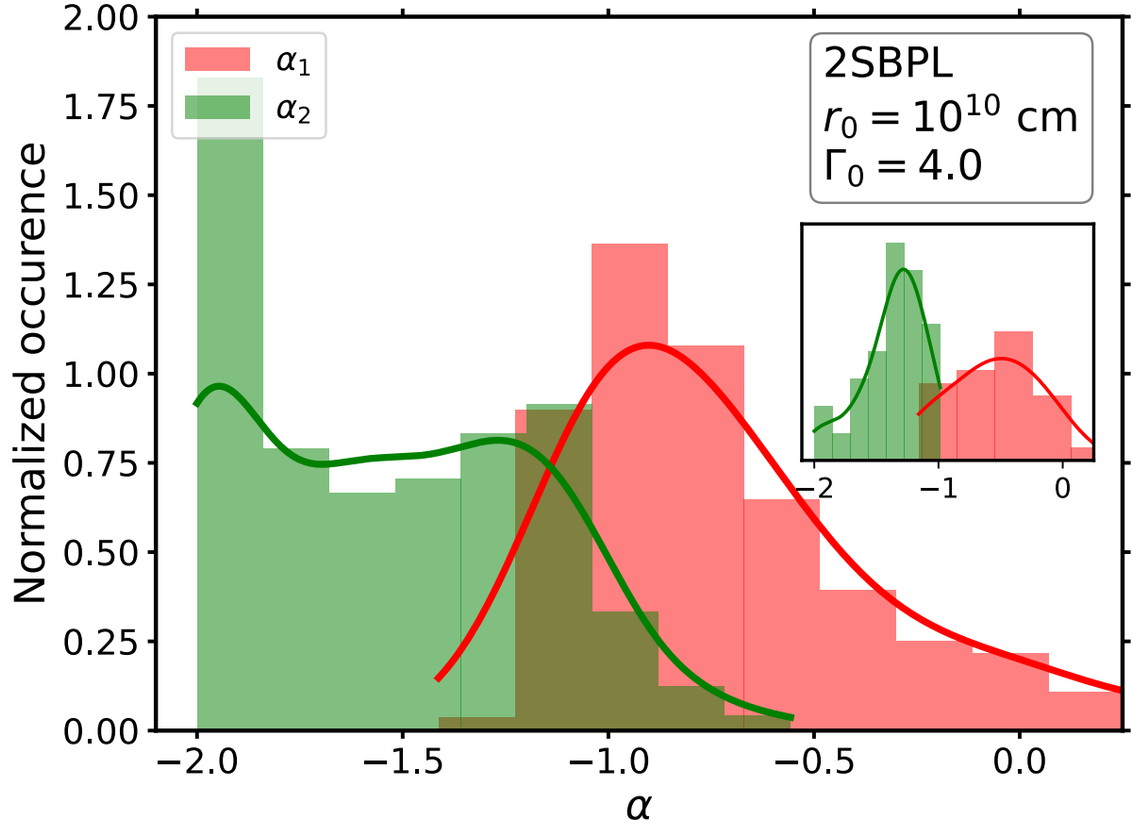


Samuelsson & Ryde (2023)

Additional X-ray break

- Evidence for spectral complexity in GRB fits
- 150 fits allowing for an additional break below the peak-energy

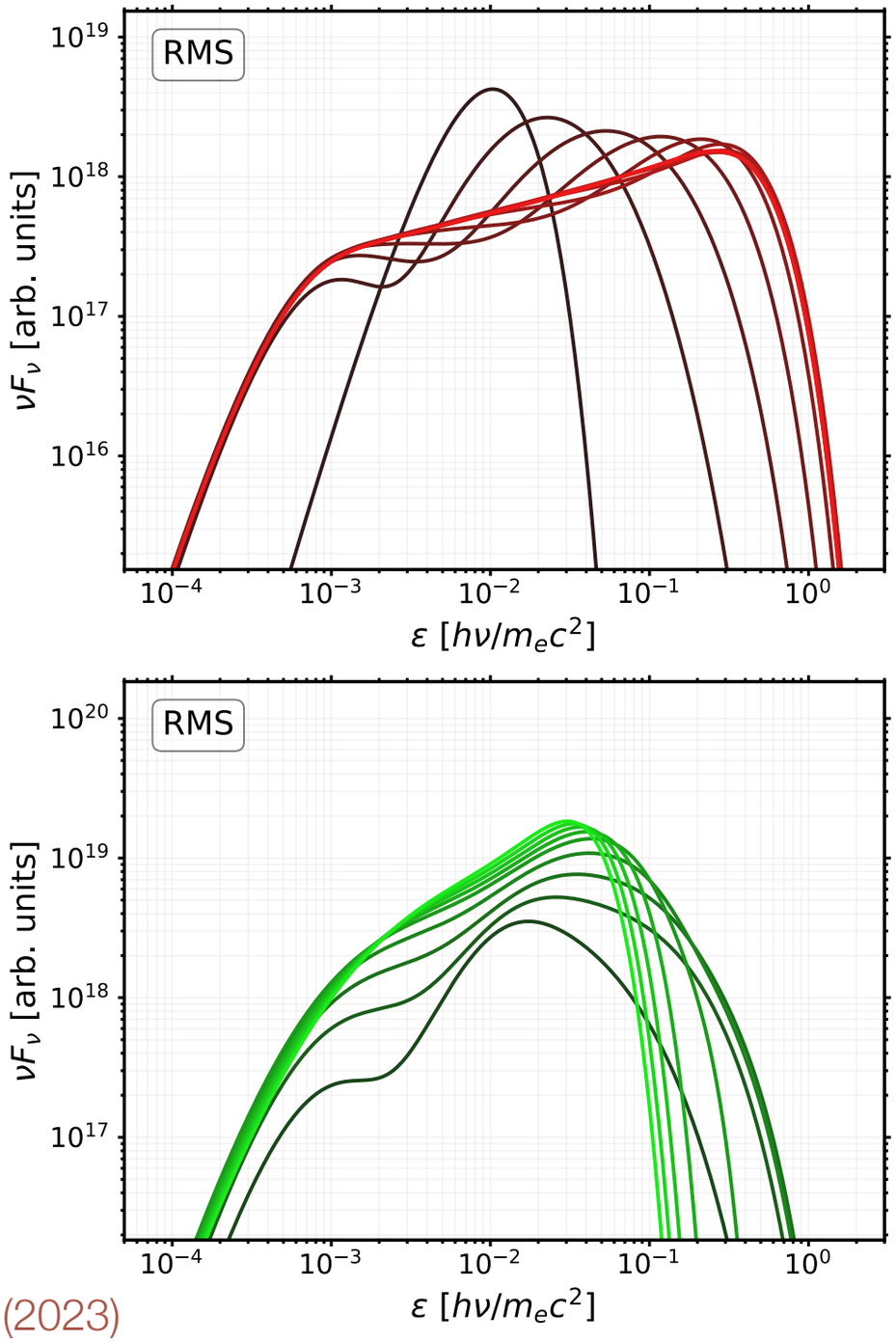




Samuelsson & Ryde (2022). Ryde (2005), Guiriec+ (2011), Axelsson+ (2012), Ravasio+ (2018, 2019), Oganesyan+ (2018, 2019), Gompertz+ (2022)

Optically shallow shocks

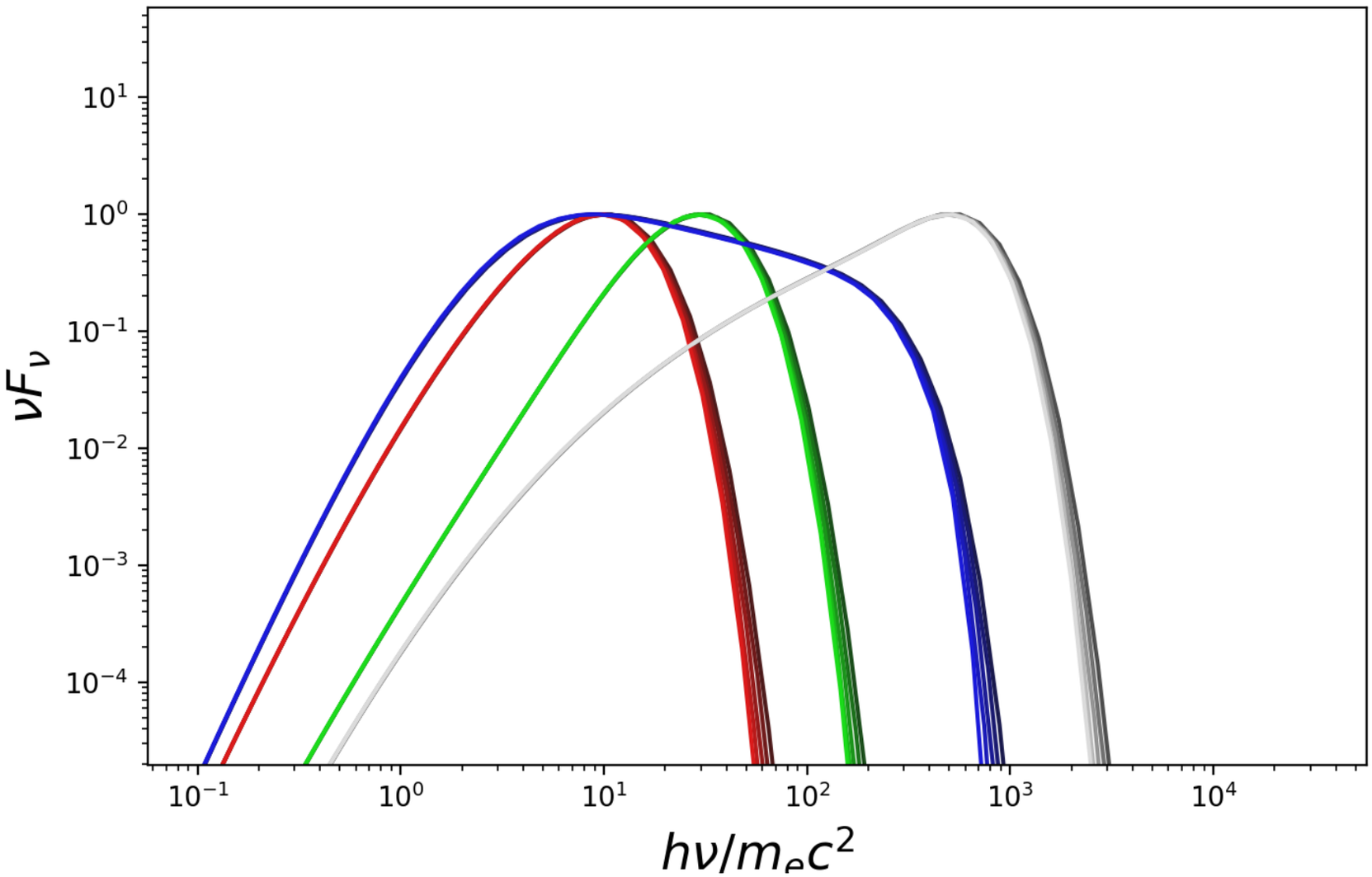
- The radiation takes a long time to reach steady state
- Optically shallow shocks may exist up to $\tau \lesssim 100$
- Optically shallow shocks can show signs of the shock formation in their spectra



Samuelsson & Ryde (2023)

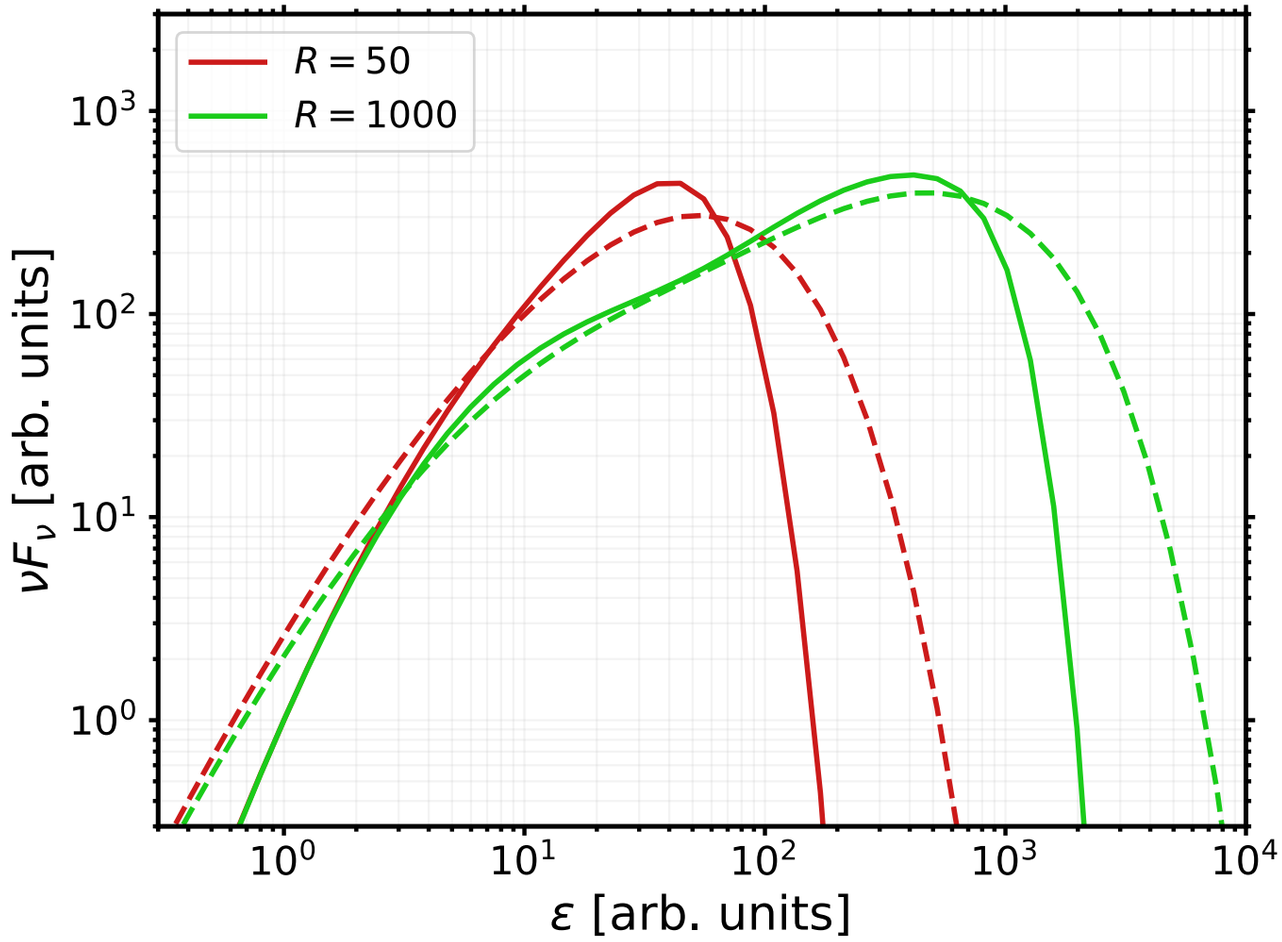
Degeneracy

- Varying tau and theta_r without changing their product



Higher order effects at the photosphere

- We never observe a Planck or Wien spectrum
- High-latitude emission and fuzzy photosphere including angle dependent beaming and adiabatic cooling



Higher order effects at the photosphere

- We never observe a Planck or Wien spectrum
- High-latitude emission and fuzzy photosphere including angle dependent beaming and adiabatic cooling