Photospheric prompt emission in GRB 211211A from a radiation-mediated shock

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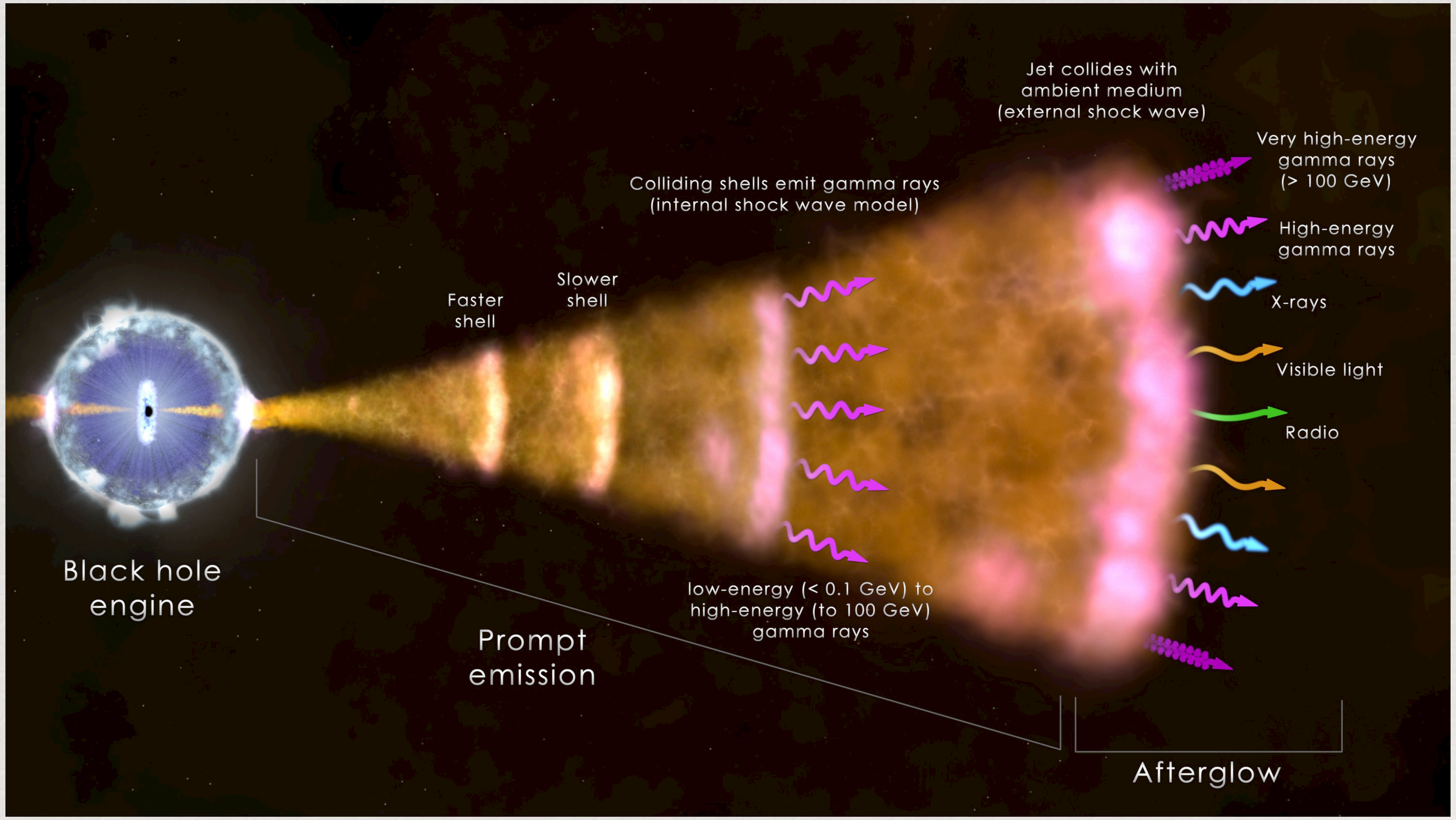
KTH VETENSKAP OCH KONST

Oscar Klein centre

Gamma-Ray Bursts (GRBs)

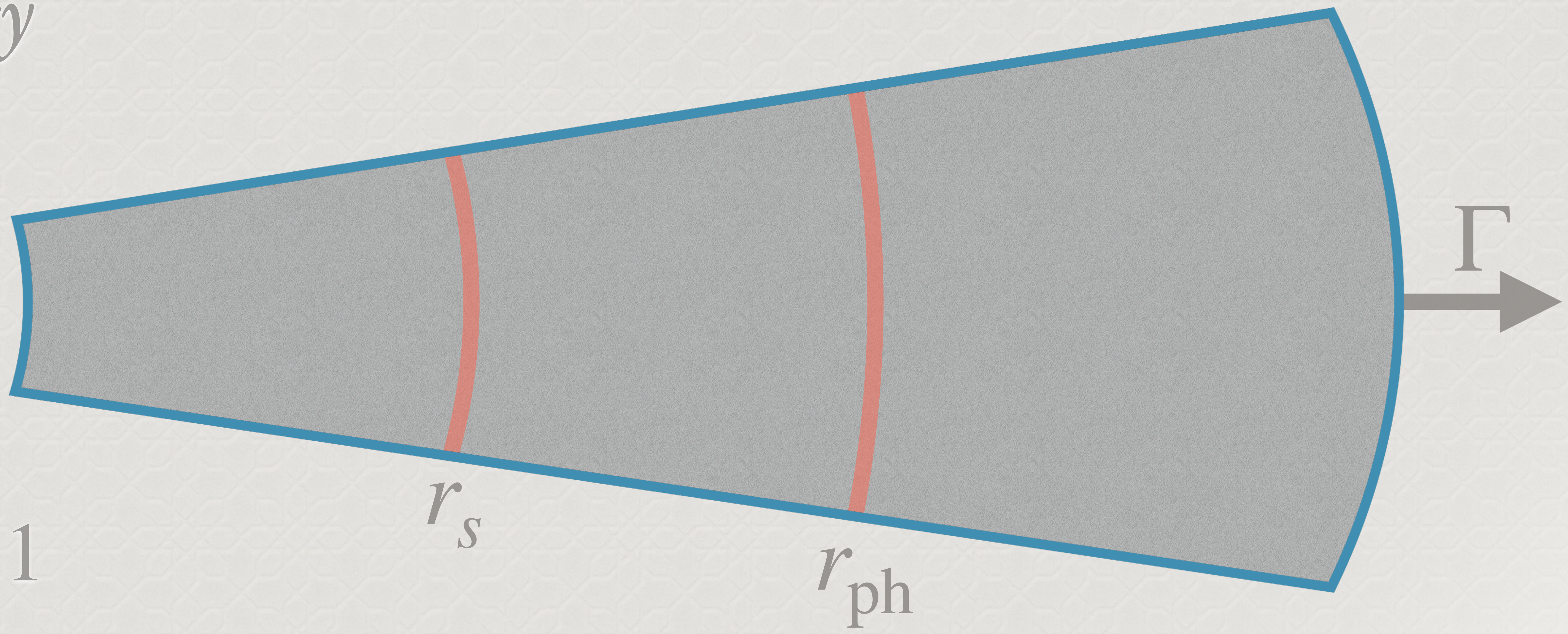
- *Extremely bright flashes of γ-rays at cosmological distances*
- *Highly collimated into ultra-relativistic narrow jet*



Gamma-Ray Bursts (GRBs)

Outflow - fireball model & jet dynamics

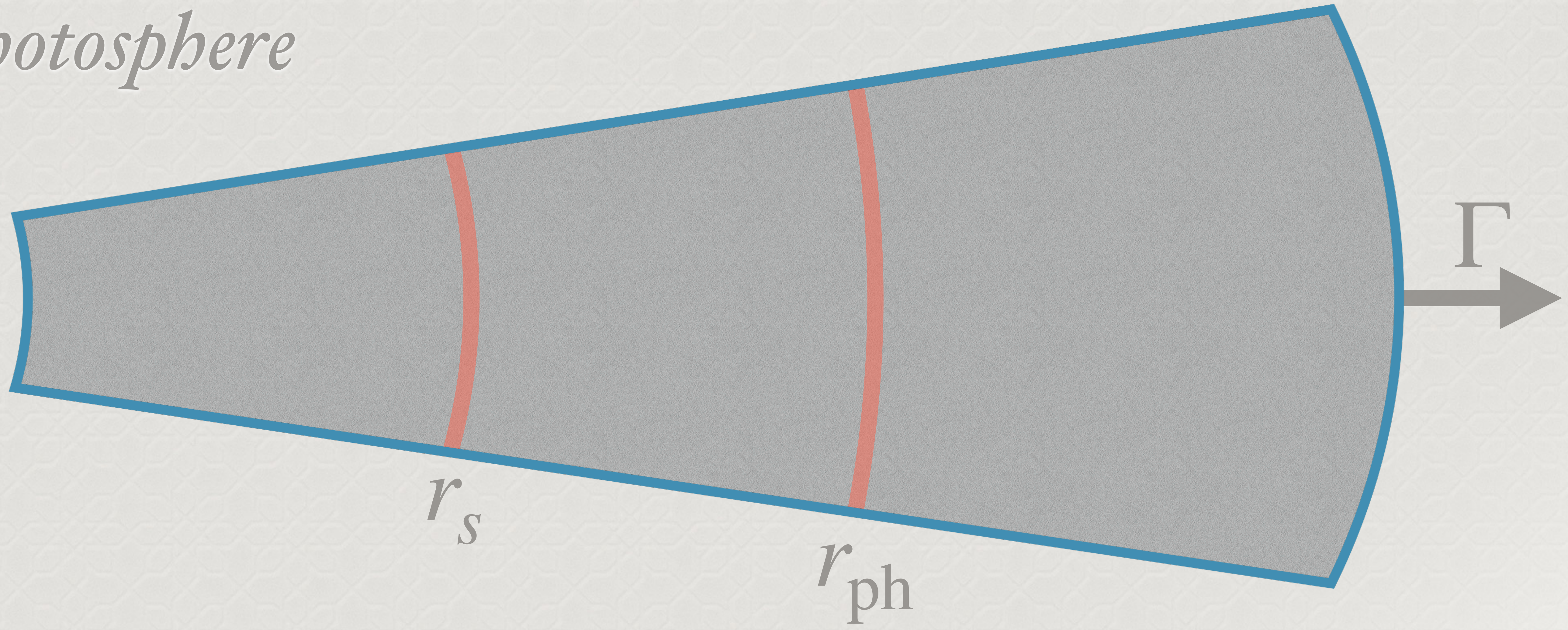
- *Internal energy → Kinetic energy*
- *Acceleration until saturation*
- *Thermal equilibrium*
- *Photosphere: Optical depth, $\tau = 1$*



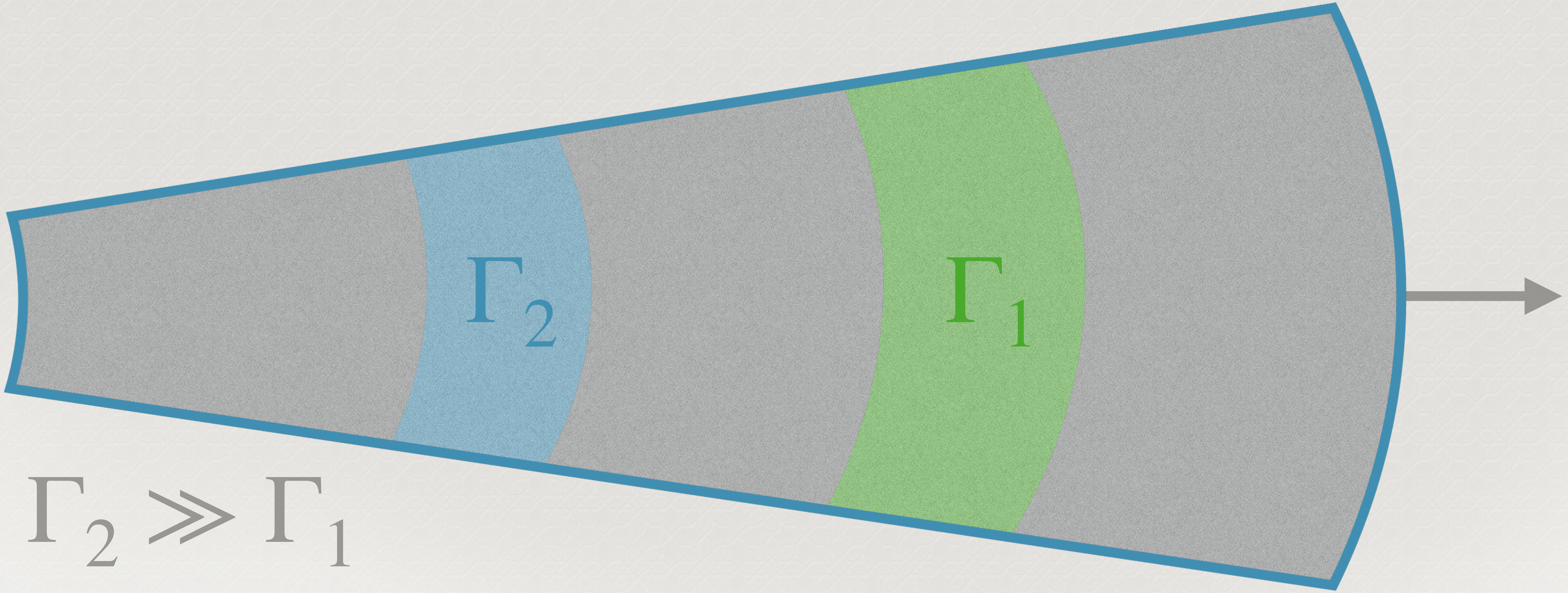
Gamma-Ray Bursts (GRBs)

Prompt emission

- *A dim Planck spectrum at the photosphere*
- *GRB spectra:*
  Typically bright and broader
- *Dissipation can alter spectra*

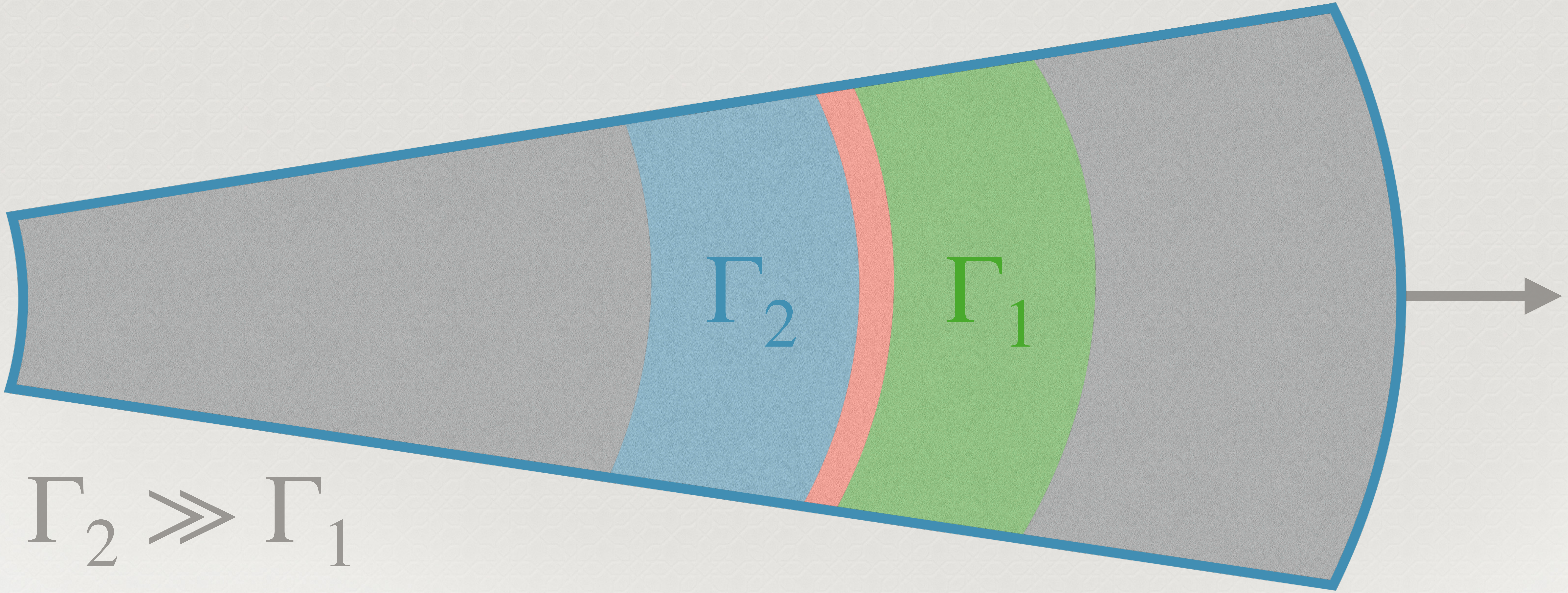


Internal collisions



$$\Gamma_2 \gg \Gamma_1$$

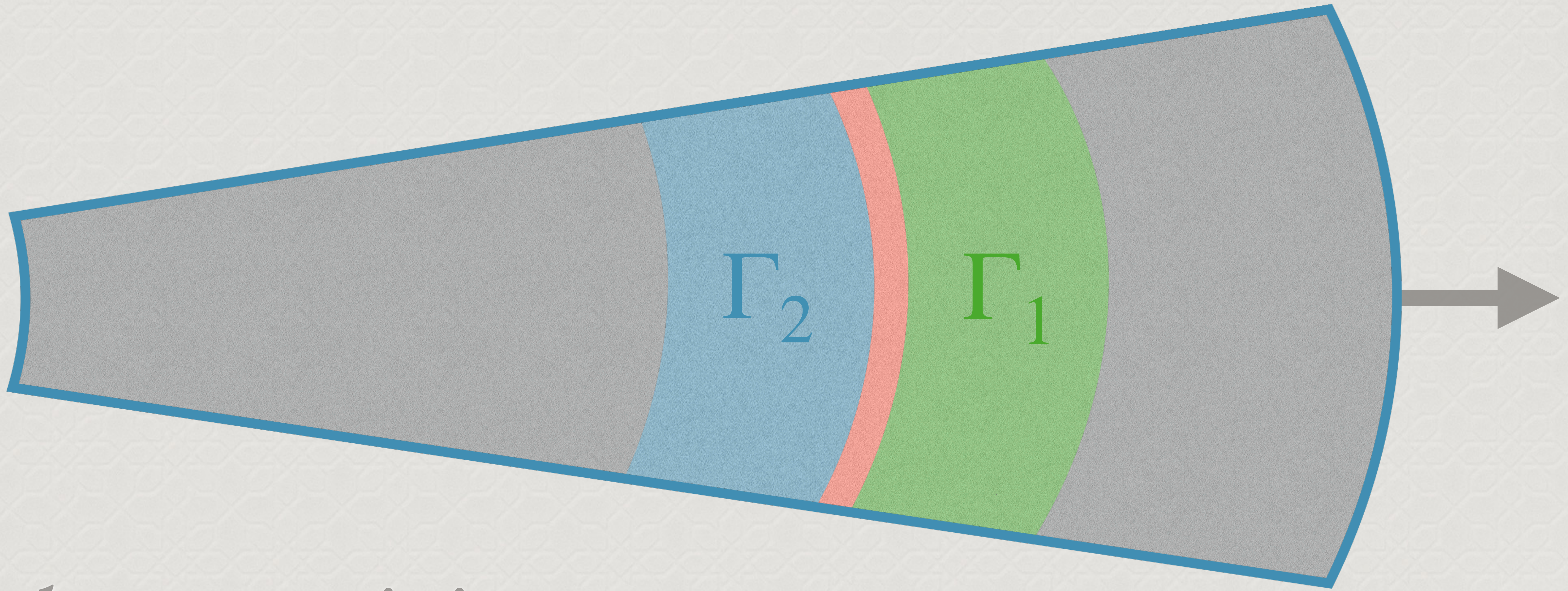
Internal collisions



$$\Gamma_2 \gg \Gamma_1$$

Internal collisions

- *Dissipates kinetic energy*
- *Above or below photosphere*



- *Above: Collisionless shock → Synchrotron emission*
  Relativistic particles gyrate in a magnetic field
- *Below: Radiation-mediated shock (RMS) → Photospheric emission*

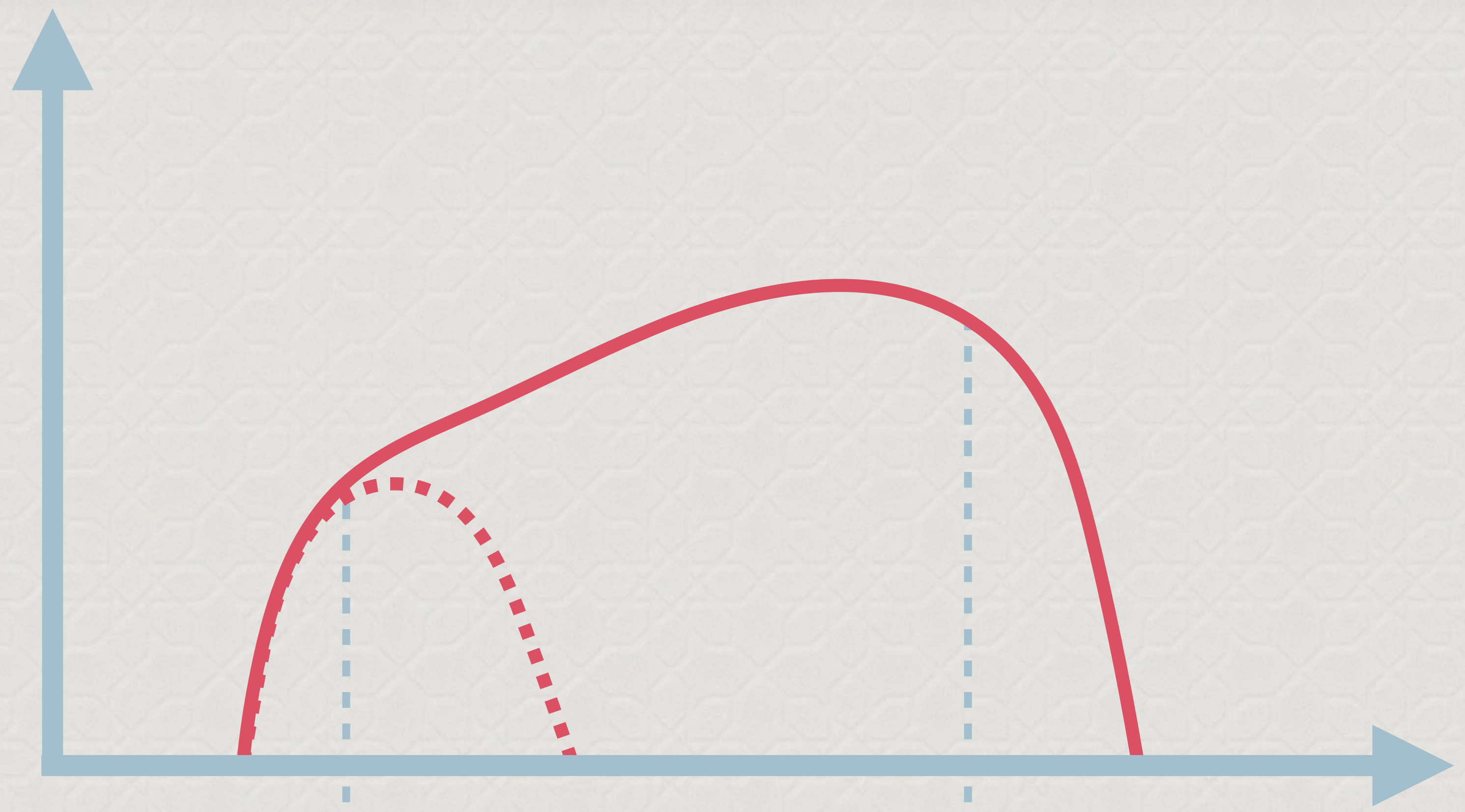
Radiation-mediated shocks

Radiation-mediated shocks

- *Broad, GRB-like spectra*

Radiation-mediated shocks

- *Broad, GRB-like spectra*



RMS

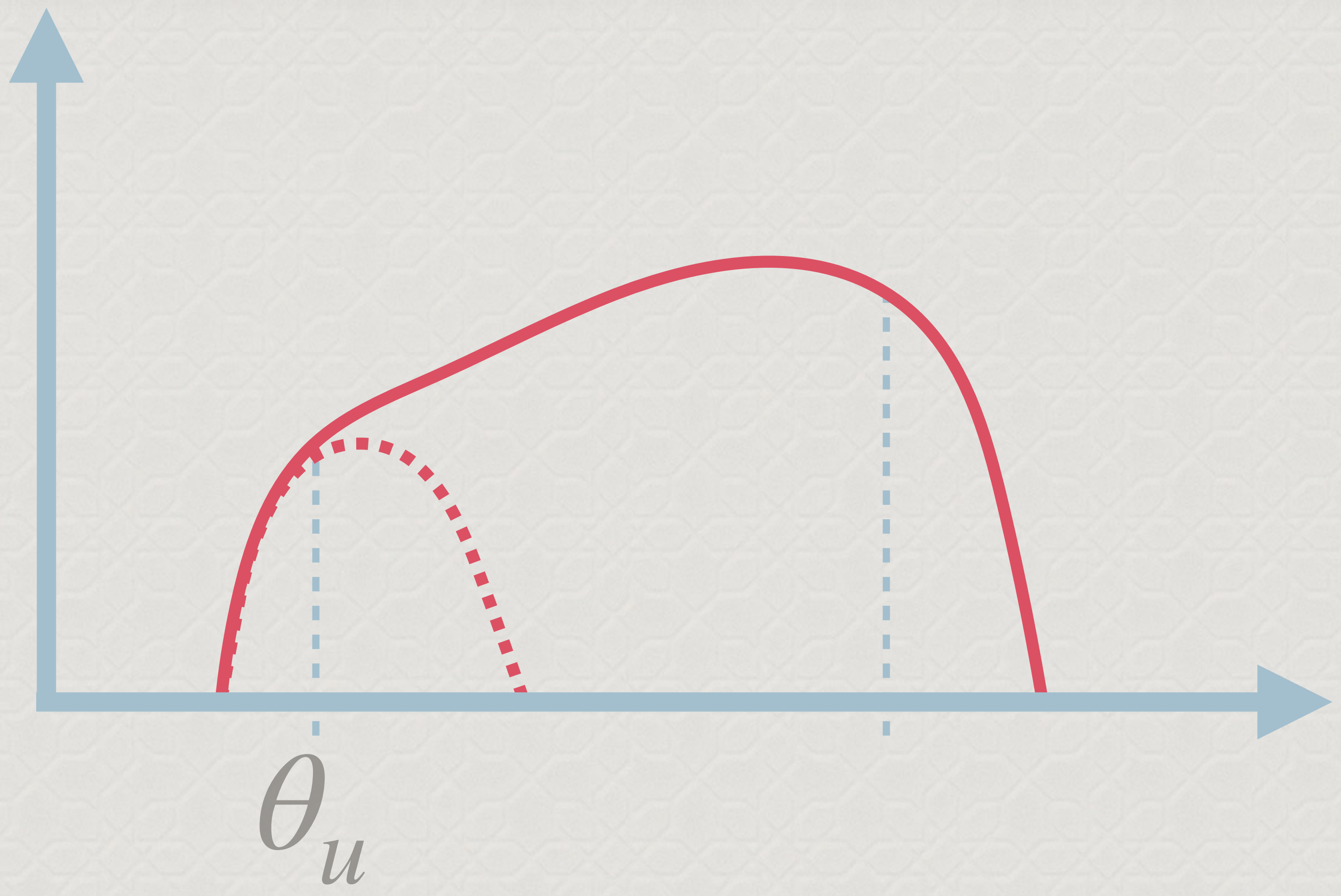
Spectral shape from parameters:

Radiation-mediated shocks

- *Broad, GRB-like spectra*

Spectral shape from parameters:

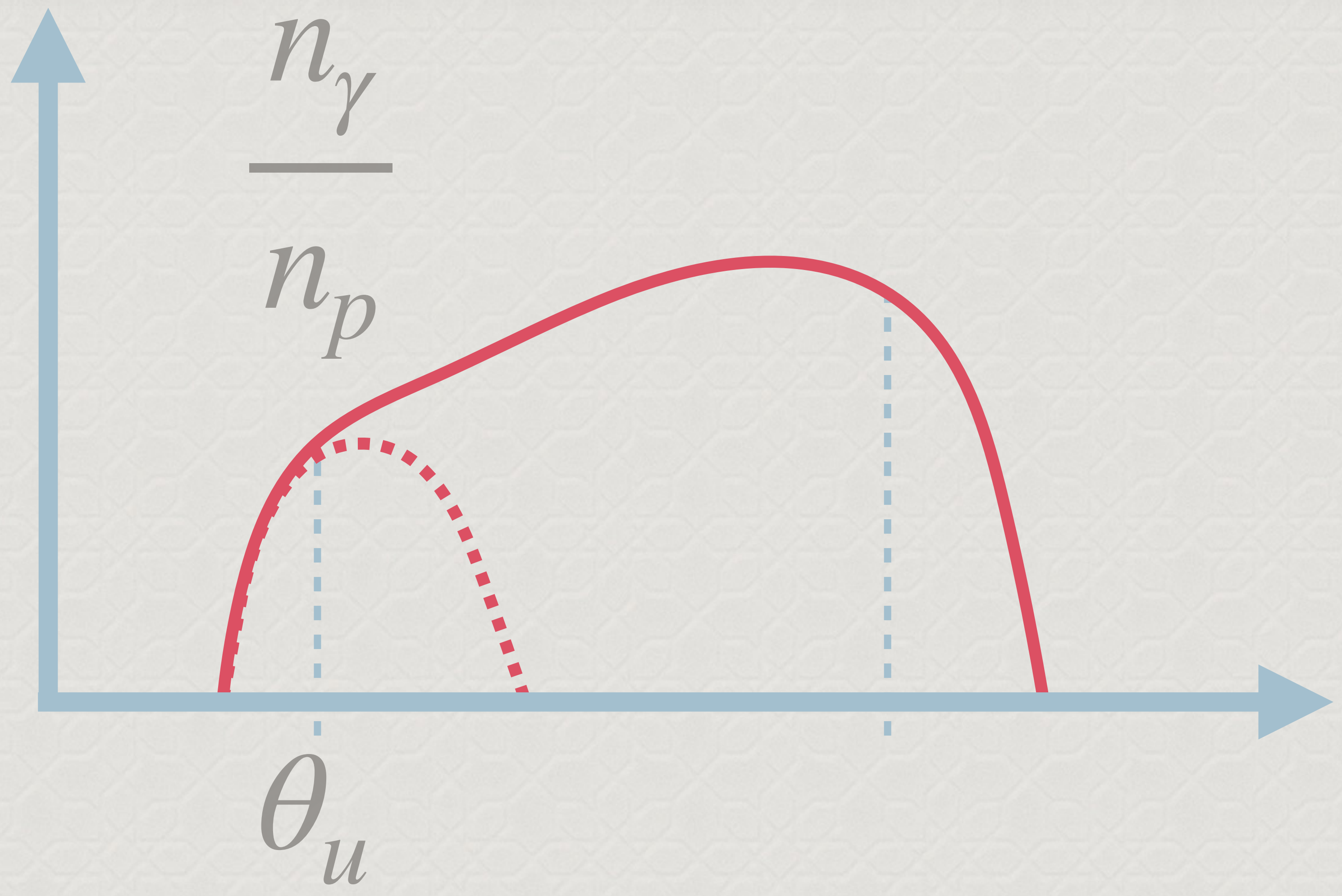
θ_u - upstream temperature



RMS

Radiation-mediated shocks

- *Broad, GRB-like spectra*



RMS

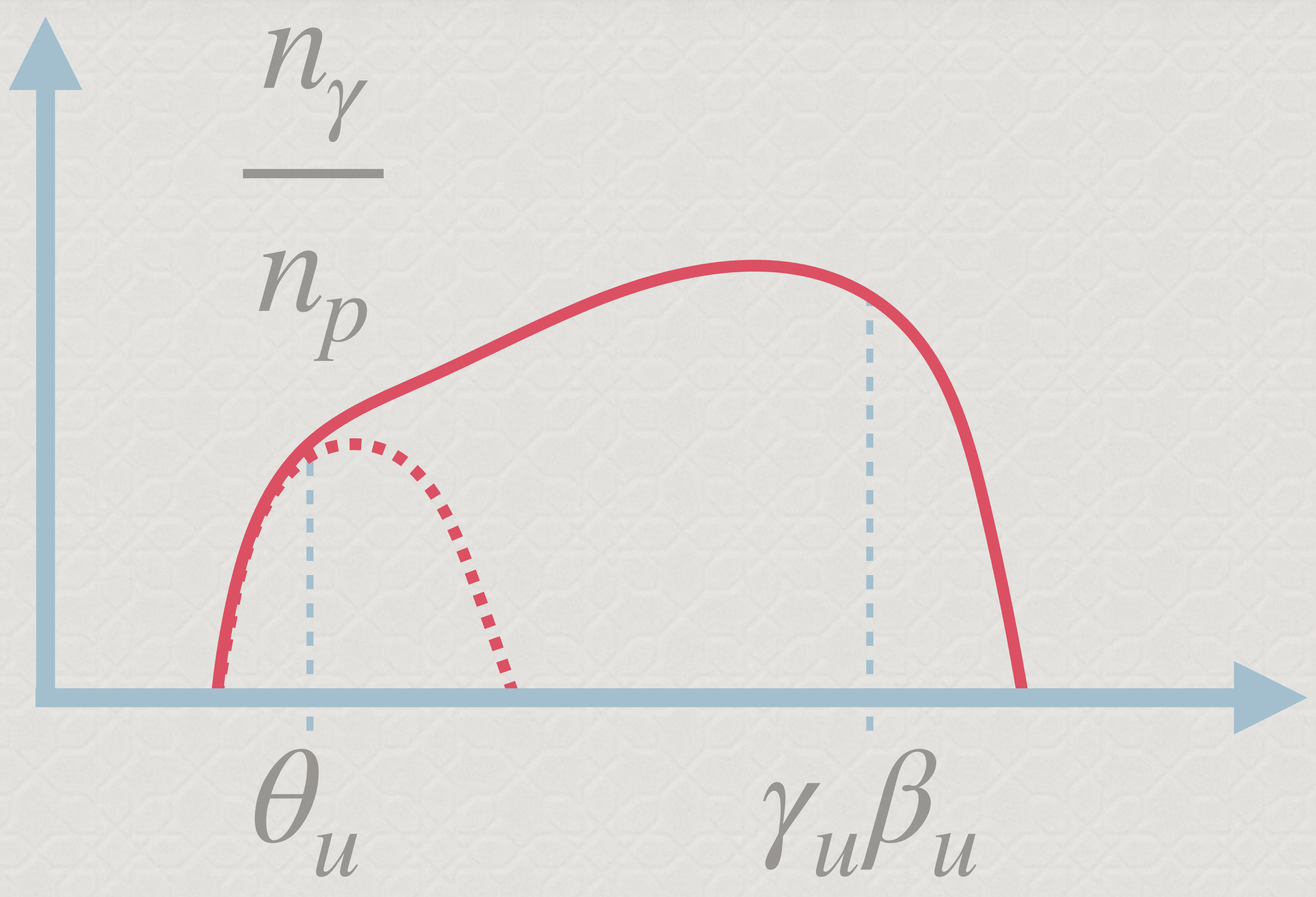
Spectral shape from parameters:

θ_u - *upstream temperature*

n_γ / n_p - *photon to proton ratio*

Radiation-mediated shocks

- *Broad, GRB-like spectra*



RMS

Spectral shape from parameters:

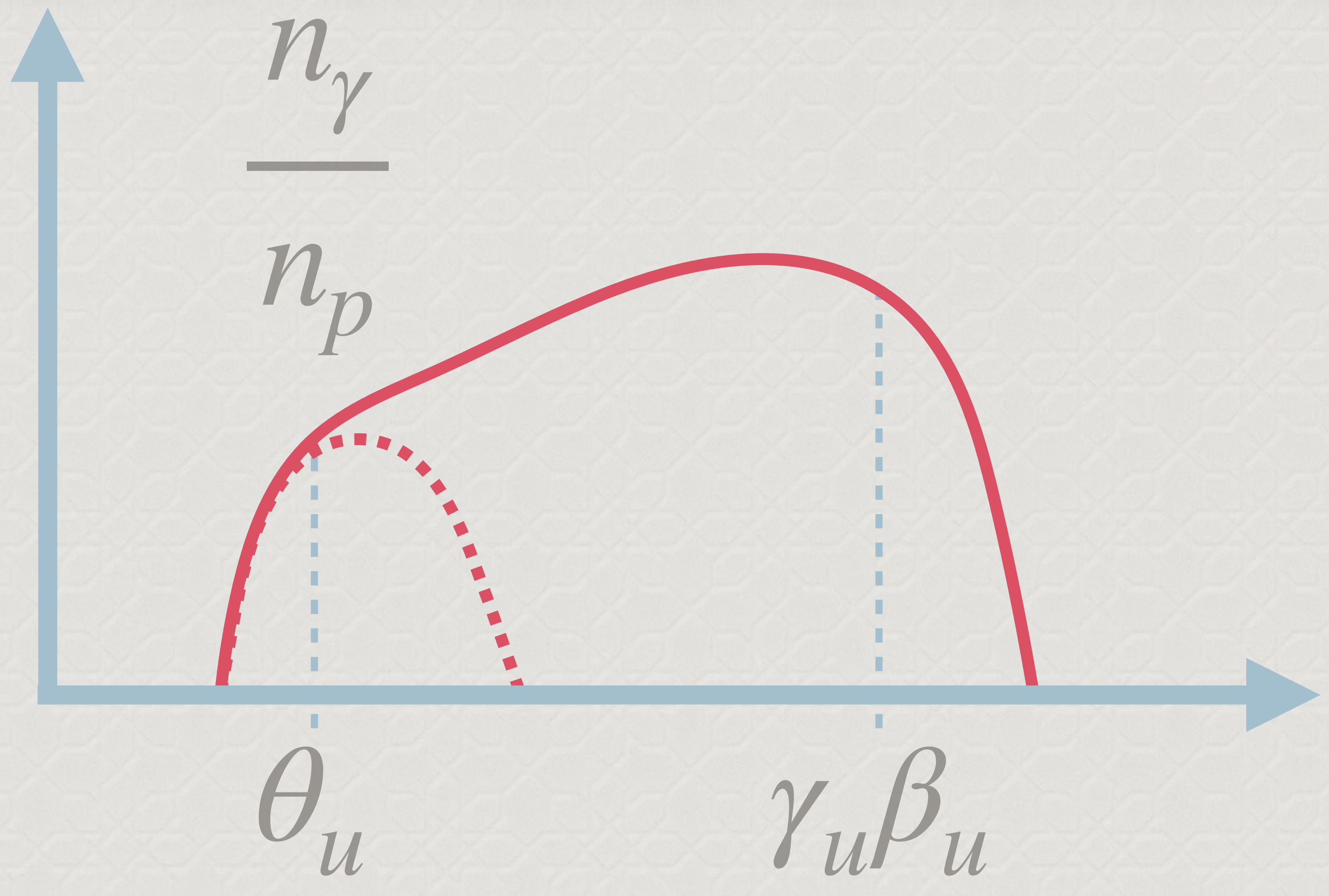
θ_u - *upstream temperature*

n_γ / n_p - *photon to proton ratio*

$\gamma_u \beta_u$ - *upstream momentum*

Radiation-mediated shocks

- *Broad, GRB-like spectra*



RMS

Spectral shape from parameters:

θ_u - *upstream temperature*

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τ - *optical depth*

Radiation-mediated shocks

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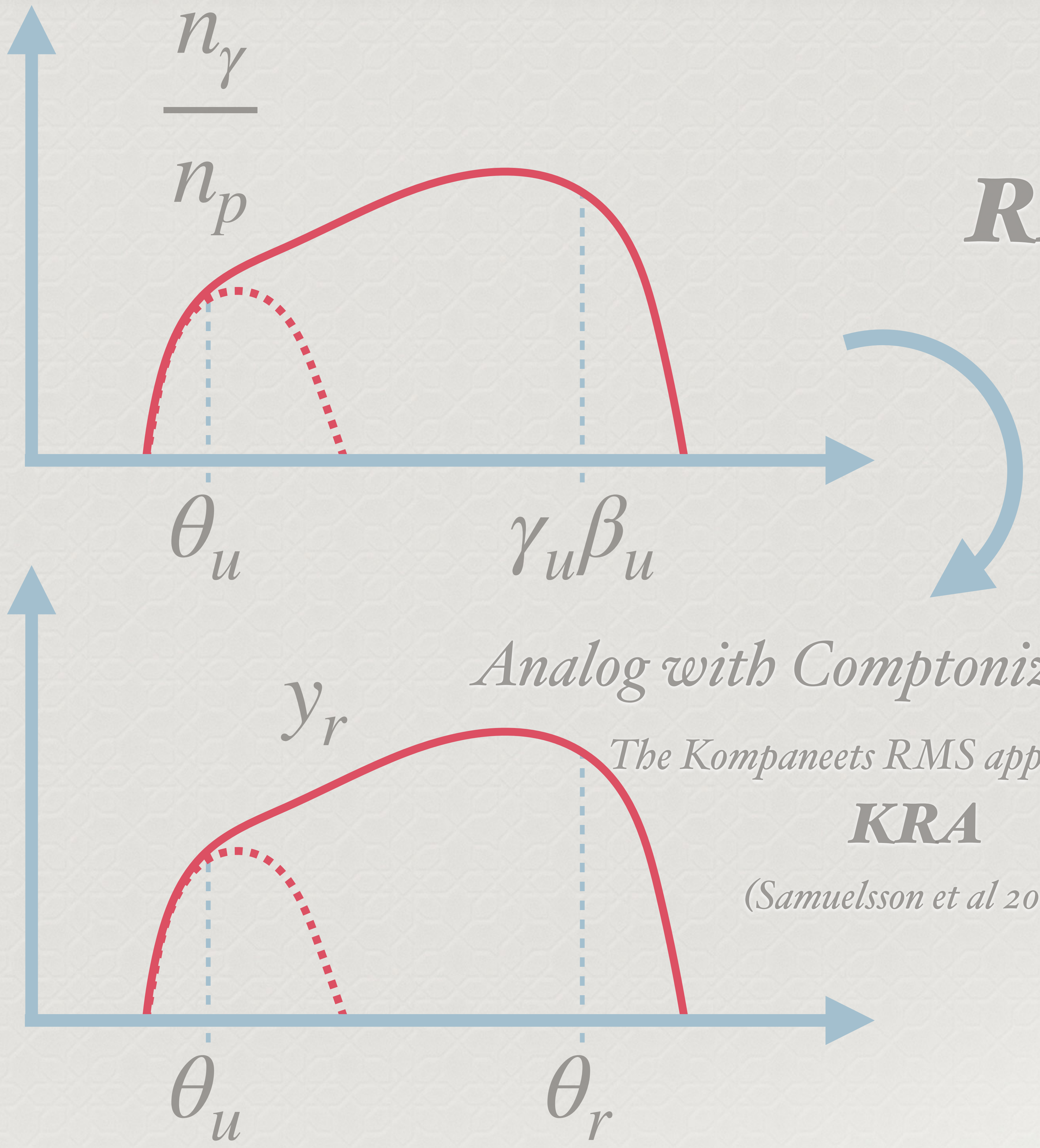


RMS

Analog with Comptonization

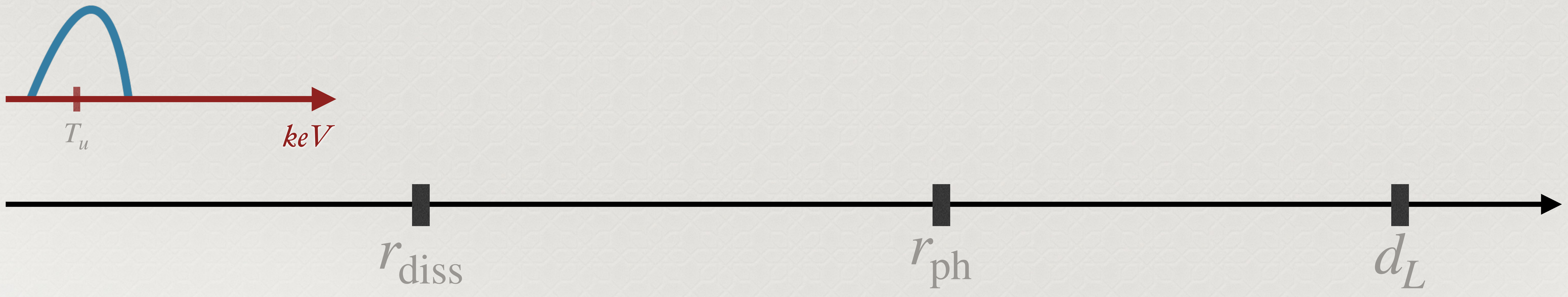
The Kompaneets RMS approximation

KRA

(Samuelsson et al 2022)

Radiation-mediated shocks

Upstream spectrum before the shock



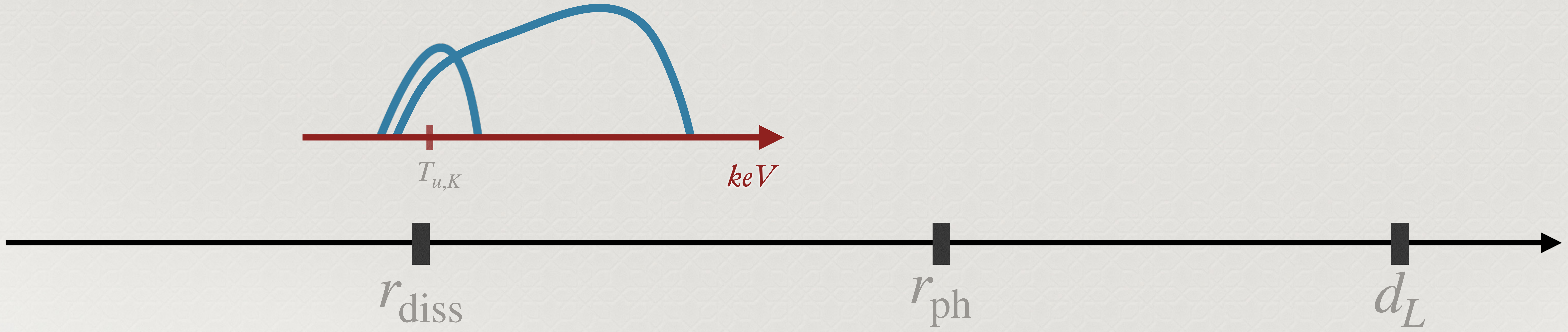
Radiation-mediated shocks

When the collision occurs the plasma is compressed

Radiation-mediated shocks

The dissipation over the shock creates the RMS spectrum

The low-energy break comes from non-scattered photons



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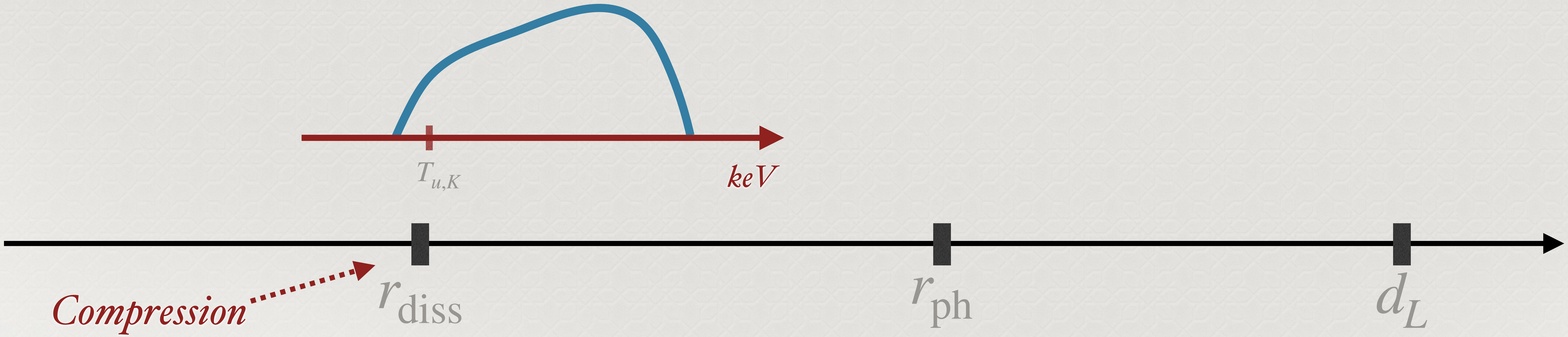

Radiation-mediated shocks

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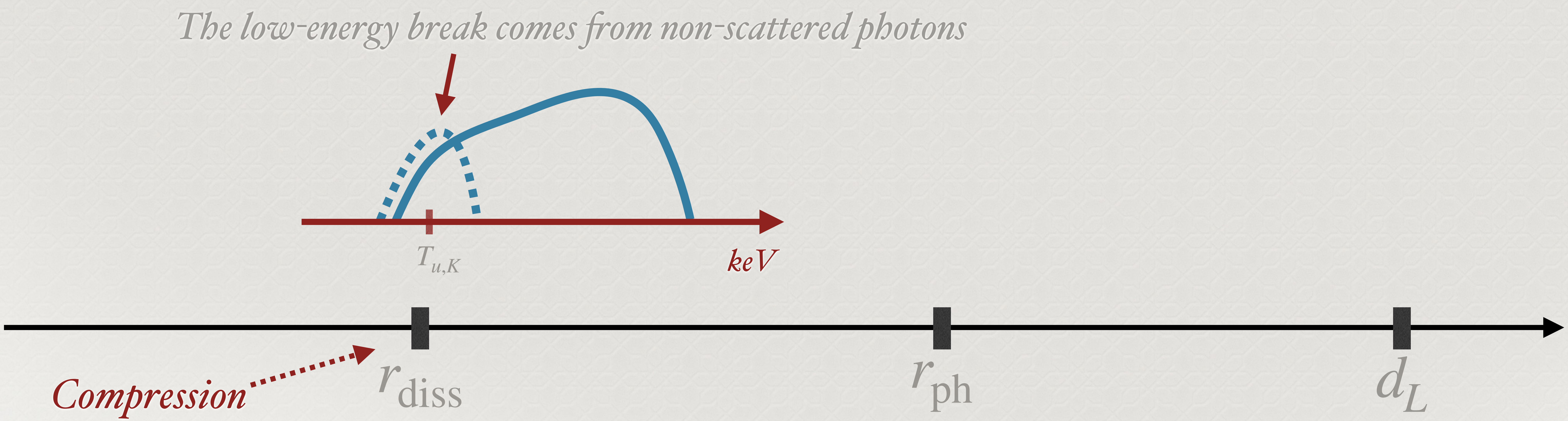
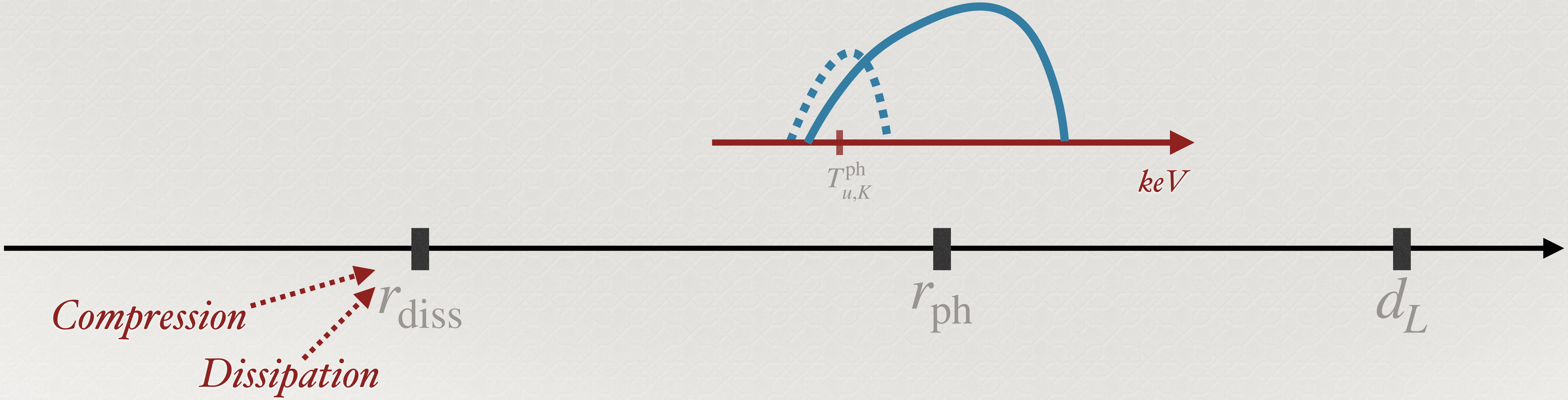


Radiation-mediated shocks

While propagating towards the photosphere, thermalisation occurs



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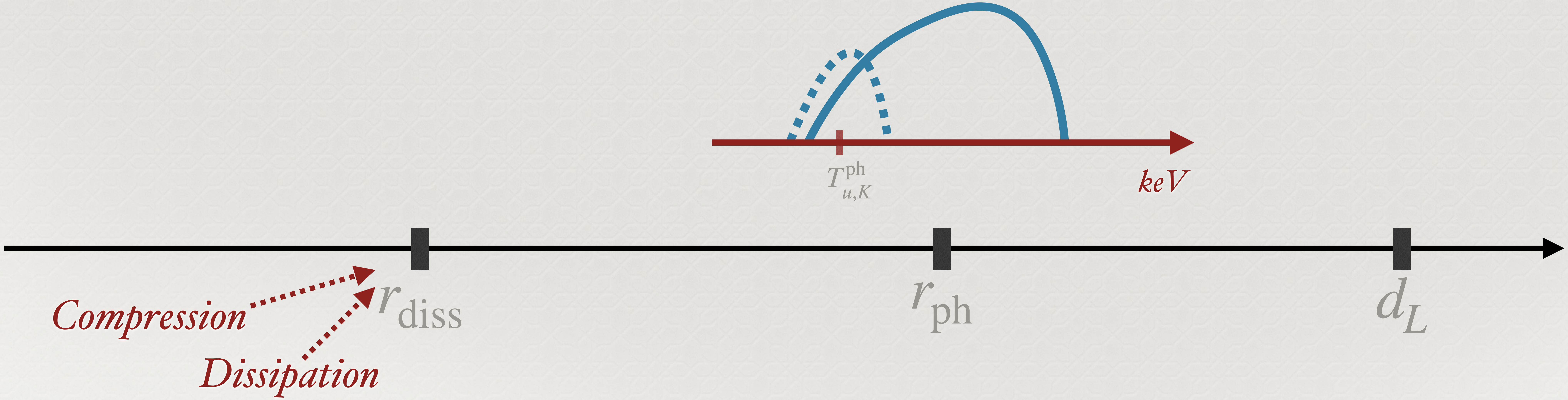
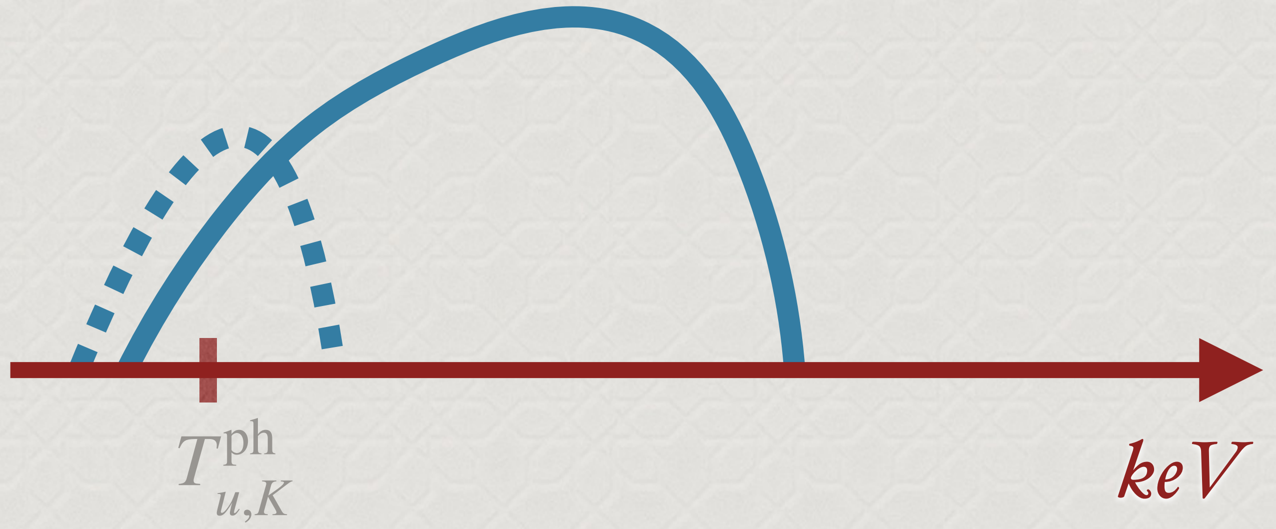
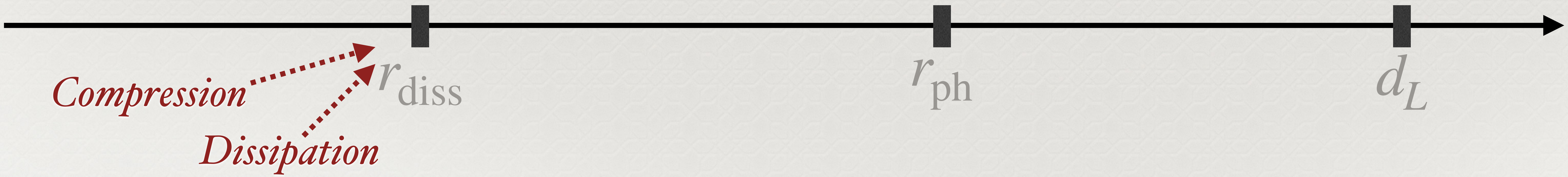


Radiation-mediated shocks

While propagating towards the photosphere, thermalisation occurs

As well as adiabatically cooling as the jet expands





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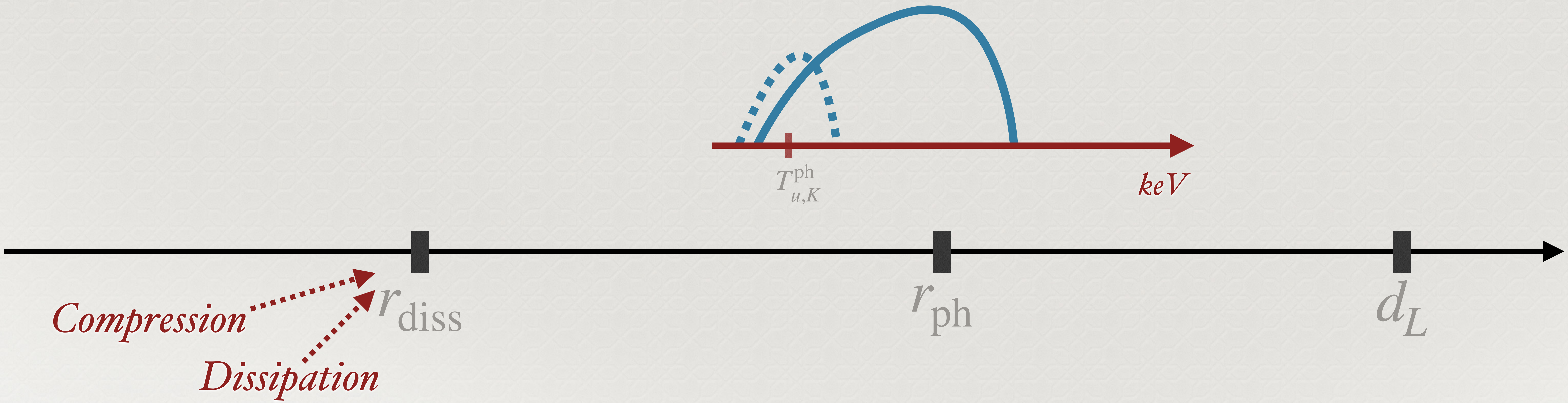
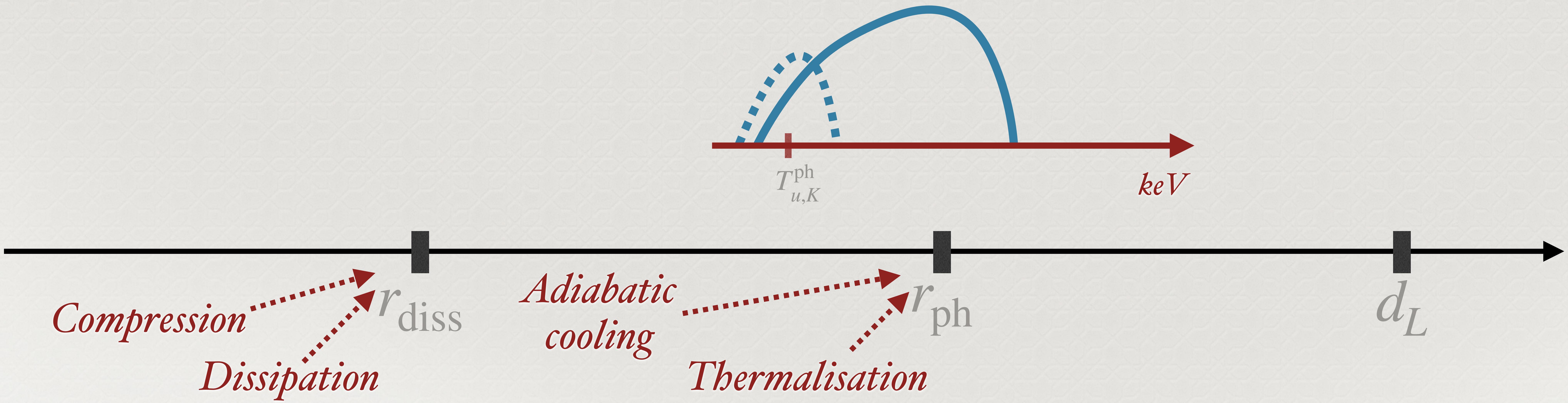


Radiation-mediated shocks



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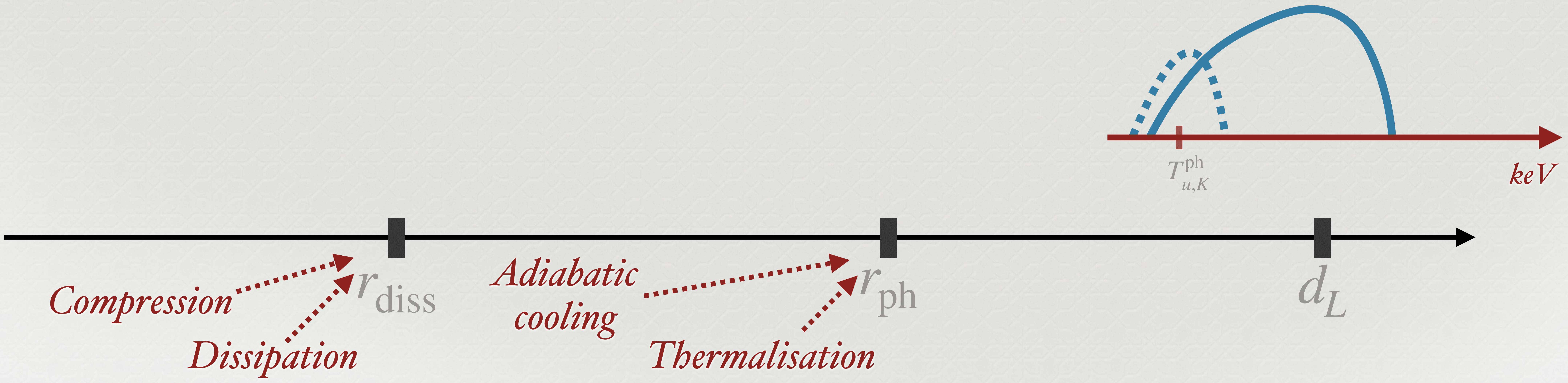
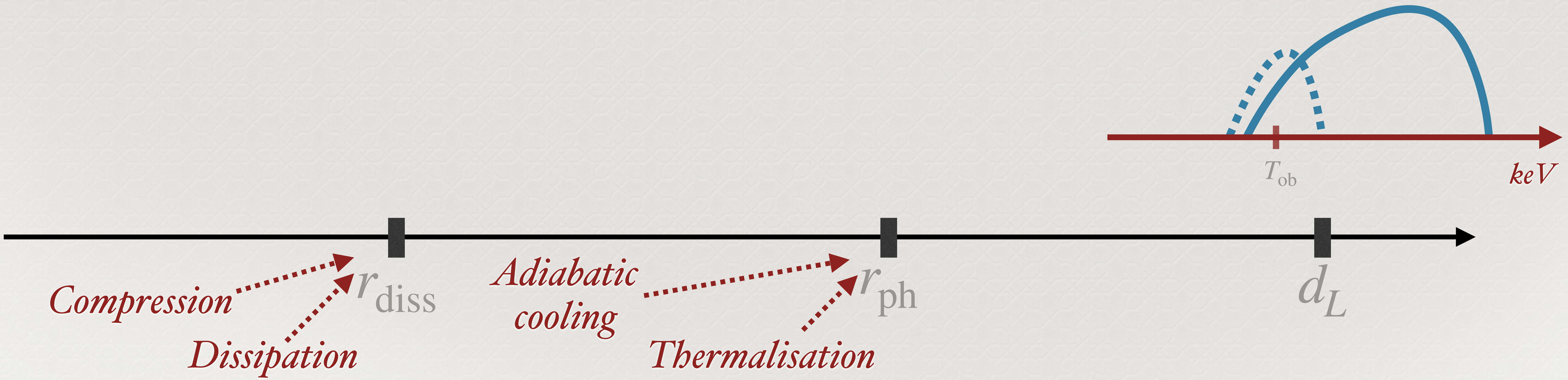


Radiation-mediated shocks

Cosmologically redshifted and doppler boosted



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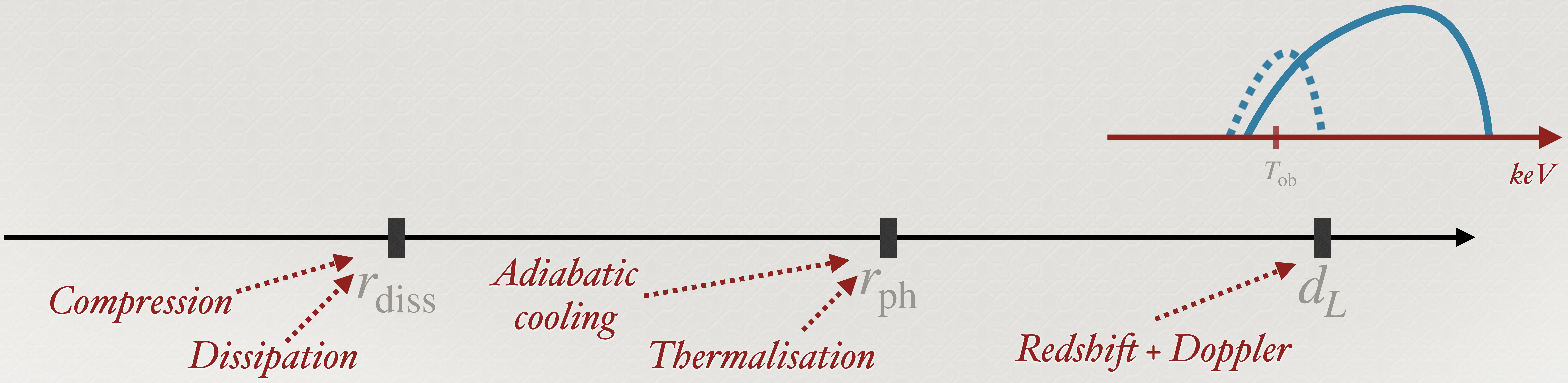
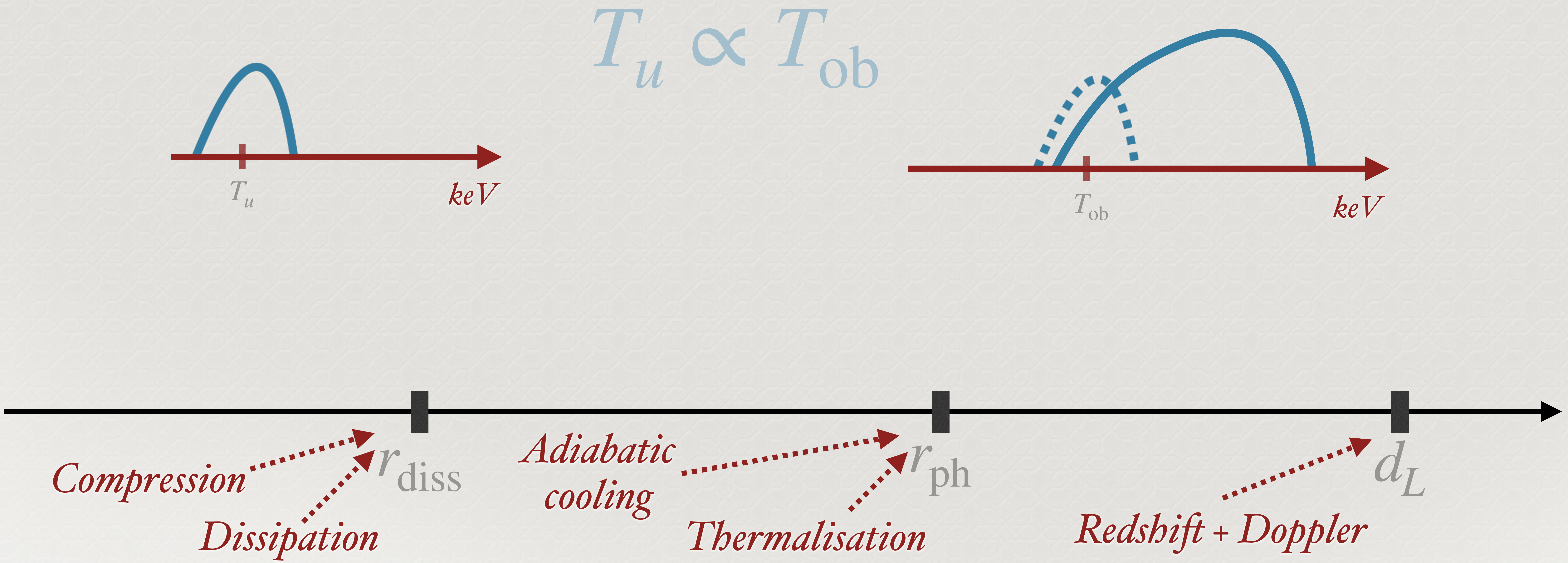


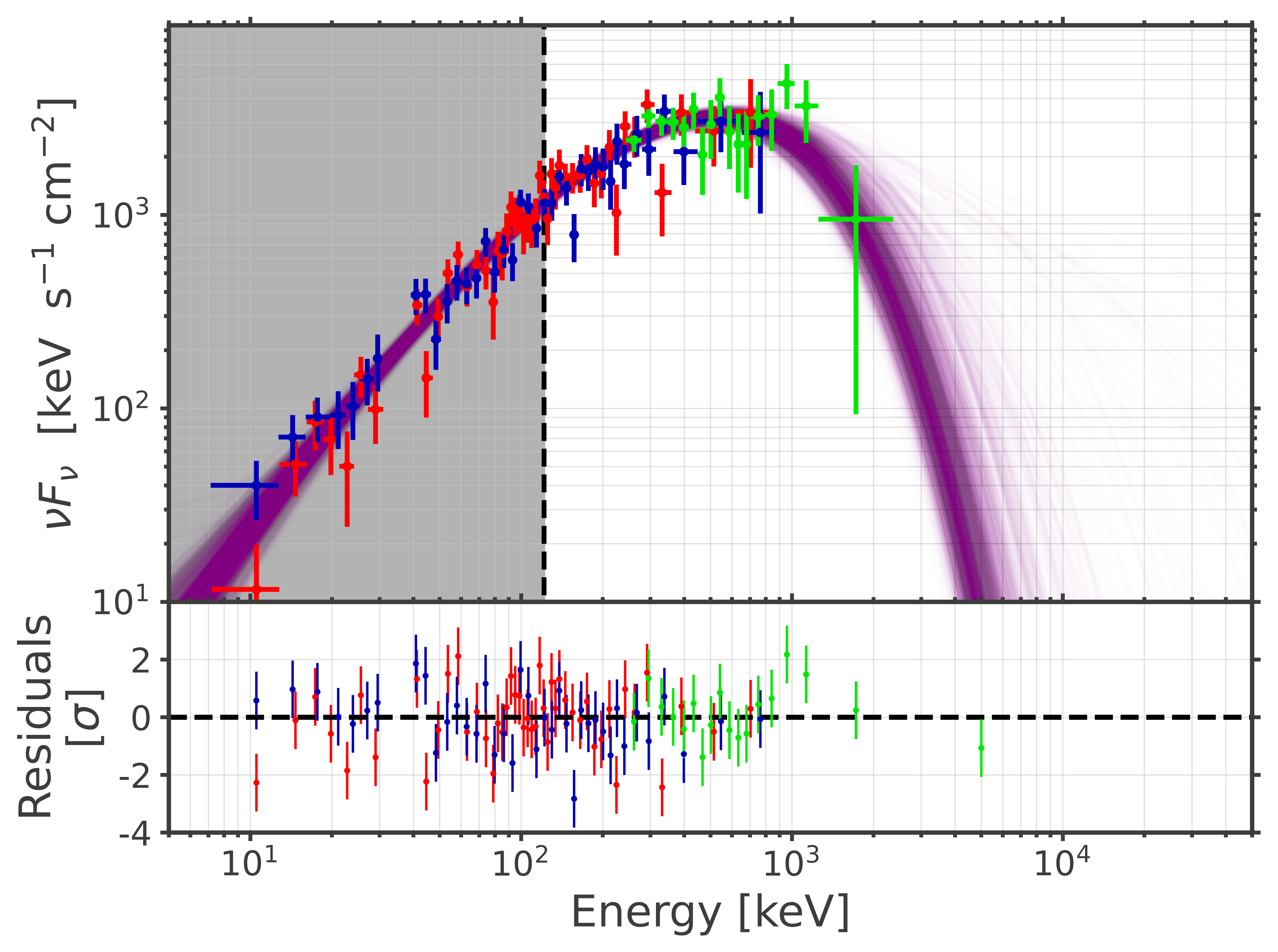
Radiation-mediated shocks

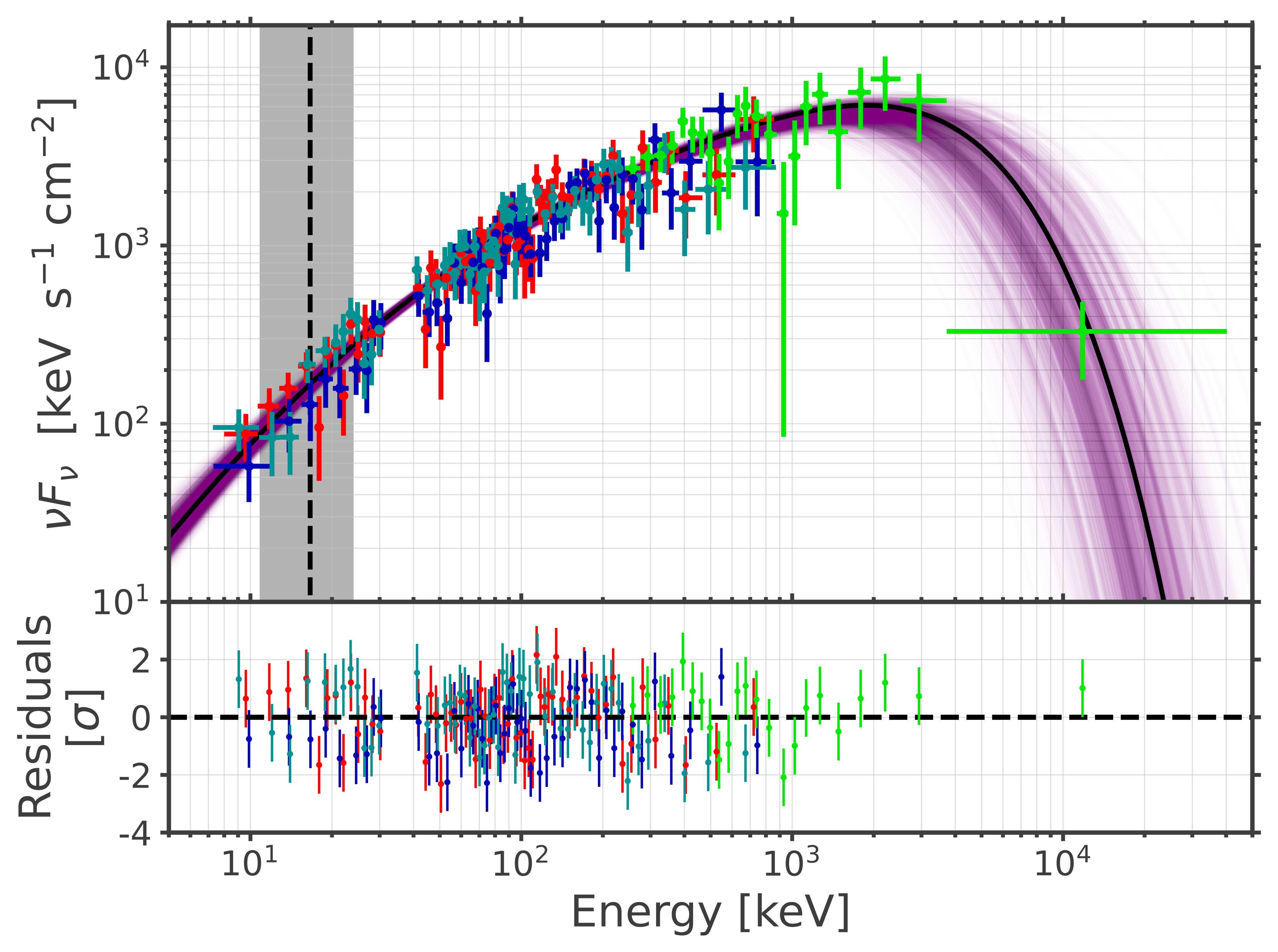


Lorentz factor

$$\Gamma = 34\,(1+z)^2\,\frac{T_{\mathrm{ob},1}^{3/2}\,r_{\mathrm{ph},13}}{d_{L,28}\,N_{\mathrm{ob},2}^{1/2}}$$

Two cases





$\Gamma = < 505^{+35}_{-26}$

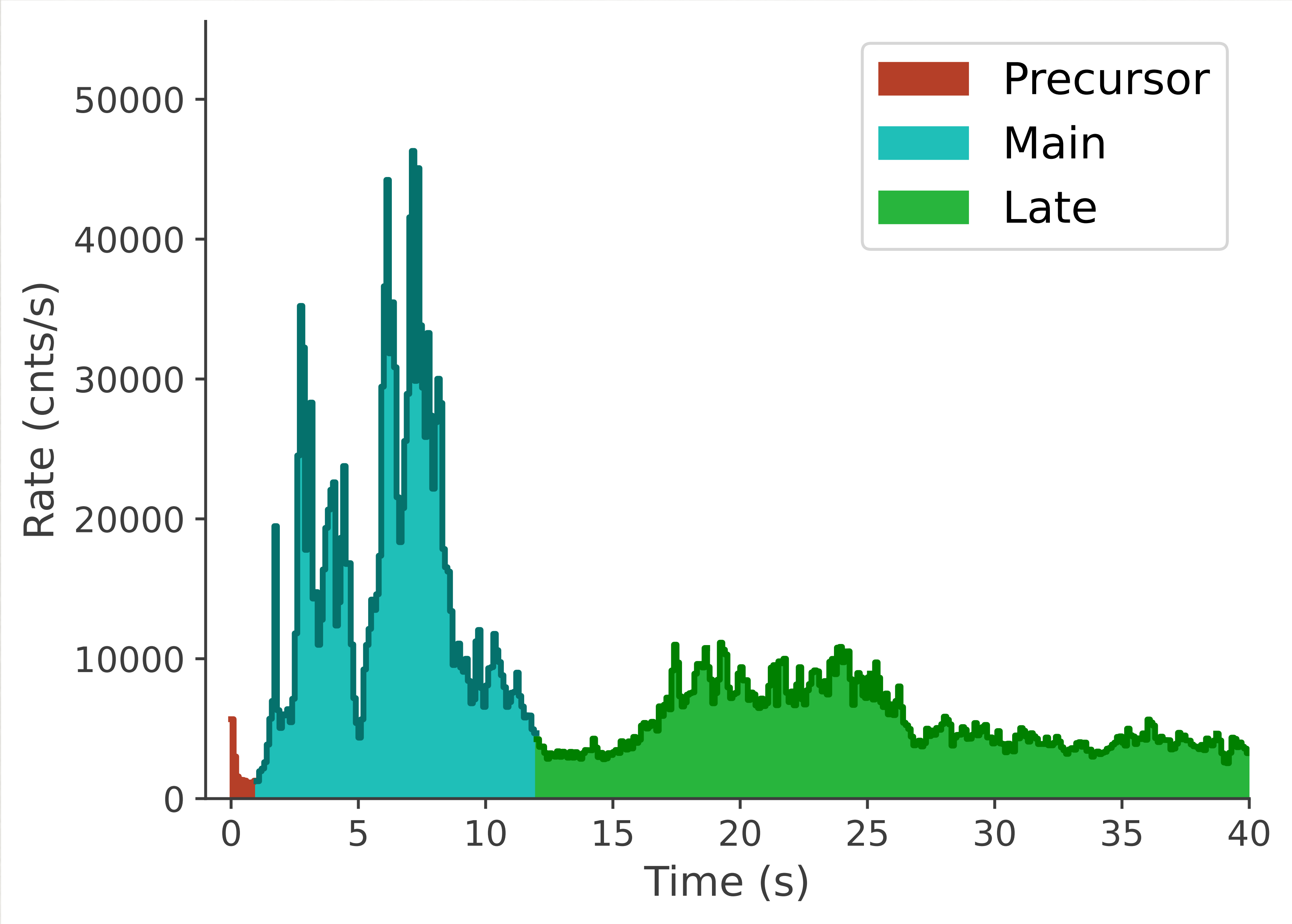
$\Gamma = 443^{+71}_{-70}$

GRB 211211A

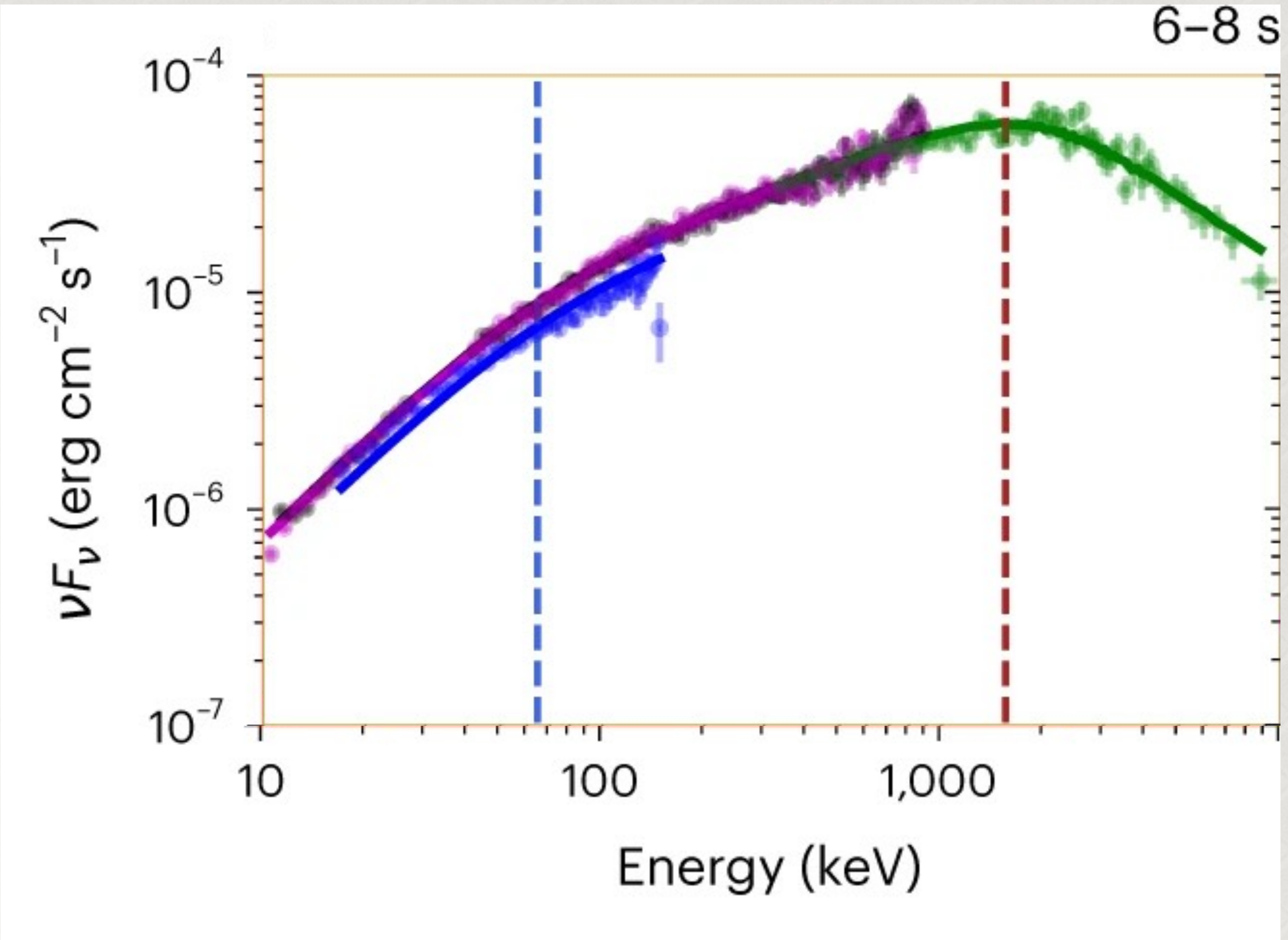
GRB 211211A

- *Long duration - Associated kilonova - Compact merger origin*

(Rastinejad+ 2022, Troja+ 2022, Yang+ 2022, etc.)



Spectrum of GRB 211211A

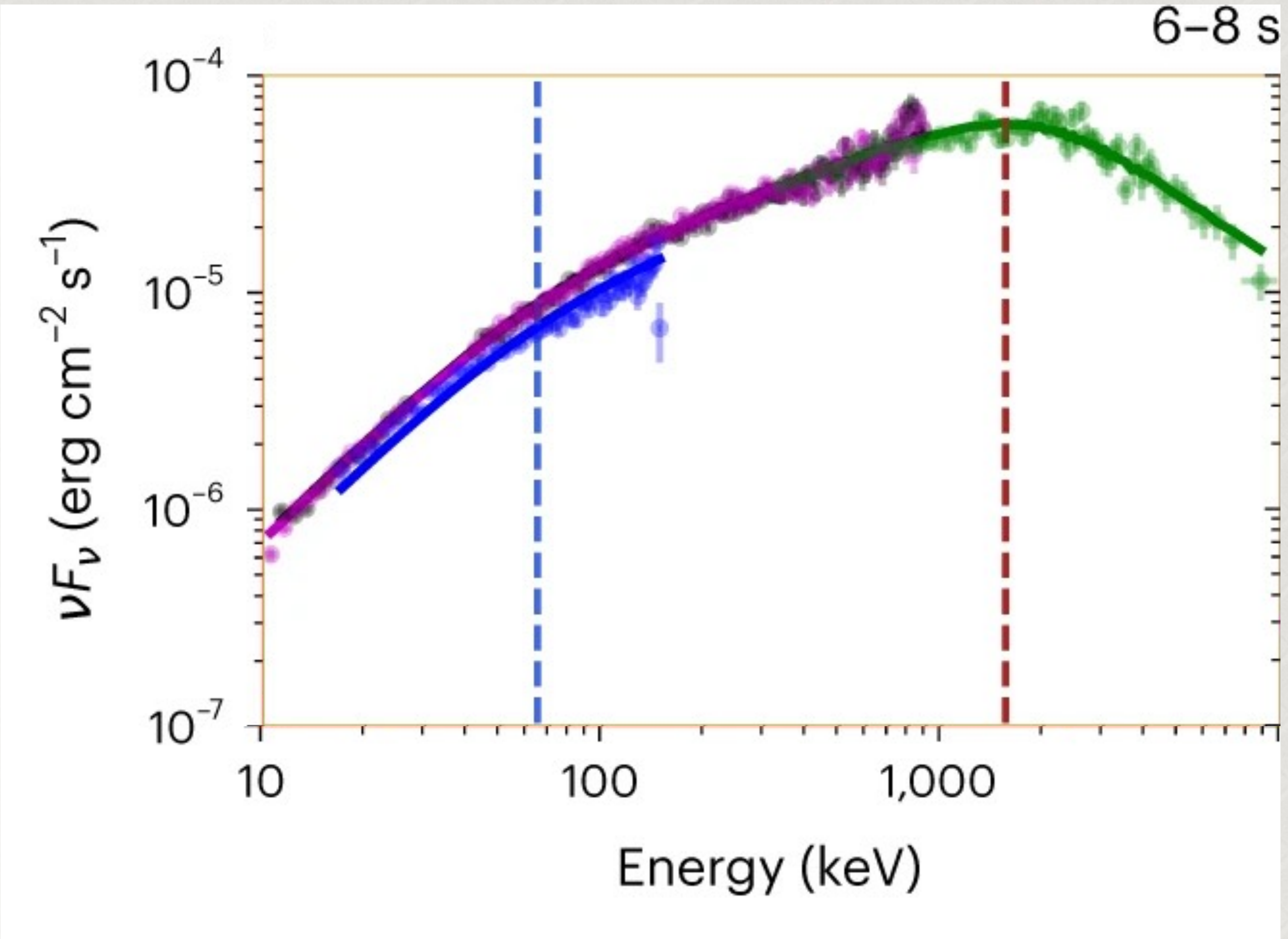


Gompertz+ 2022

Spectrum of GRB 211211A

Synchrotron framework (Gompertz+ 2022, Mei+ 2025)

Band + BB component (Peng+ 2024)



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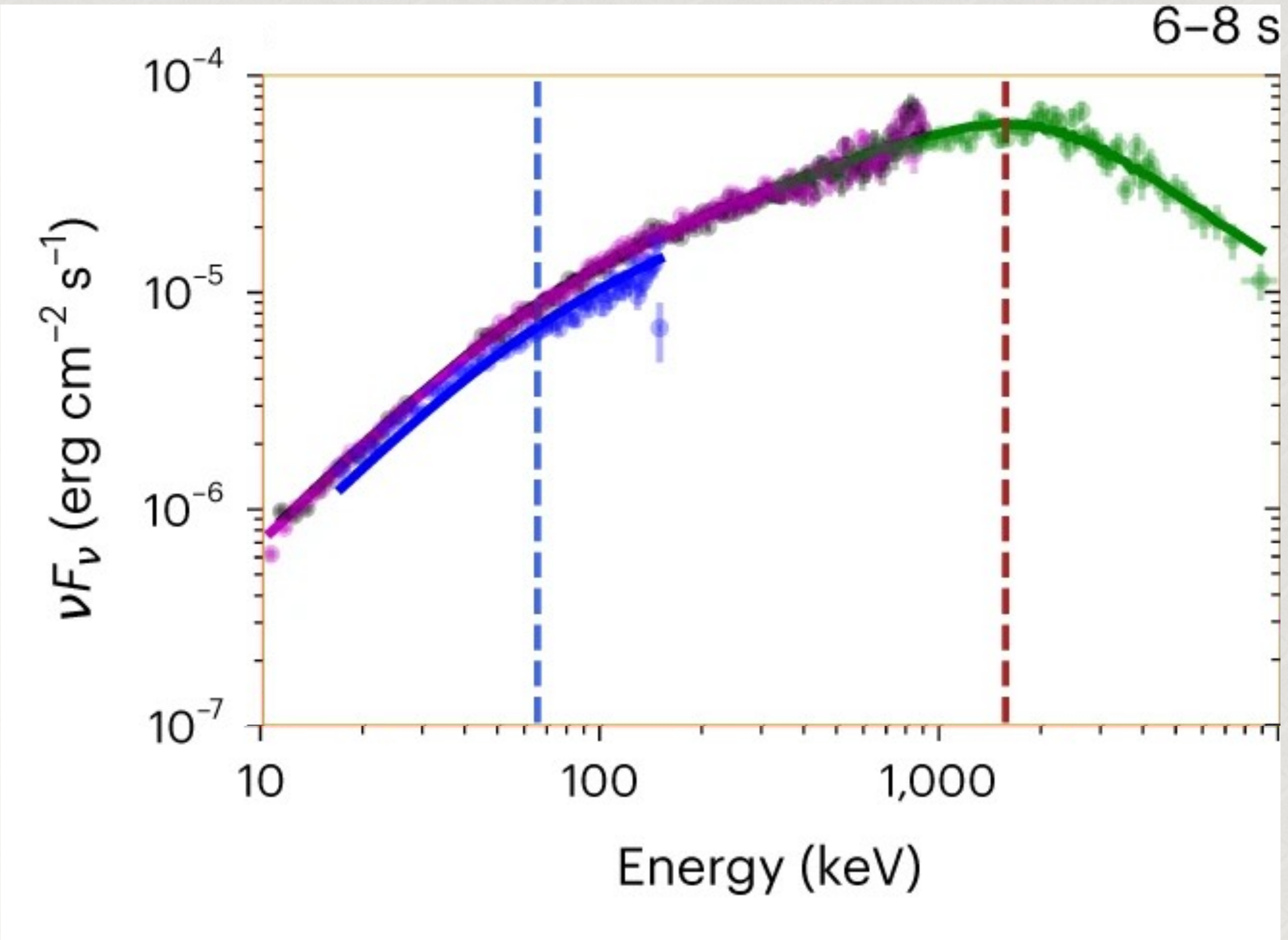
↓

Additional low-energy curvature



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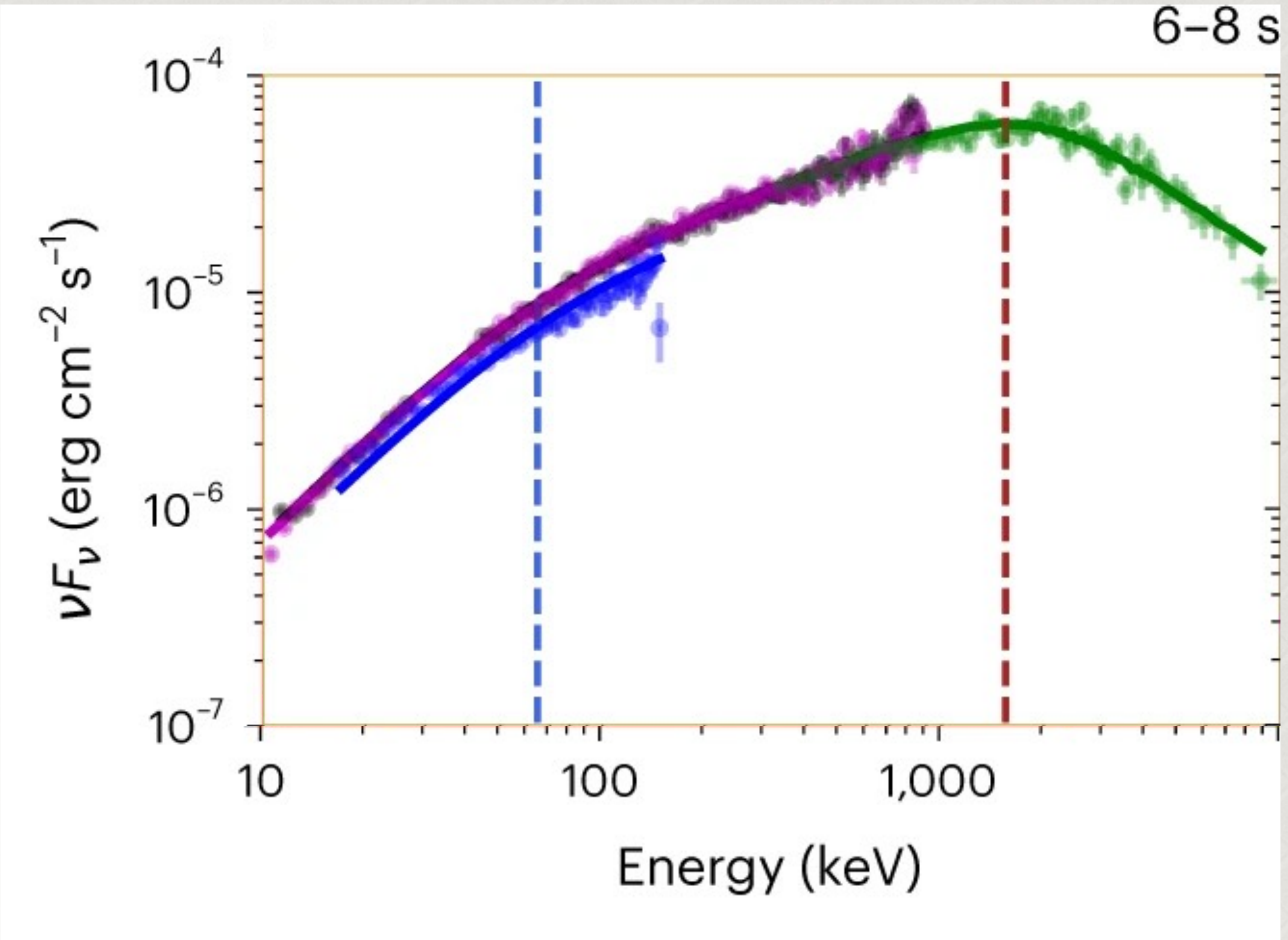
Additional low-energy curvature

We use a photospheric model with RMSs



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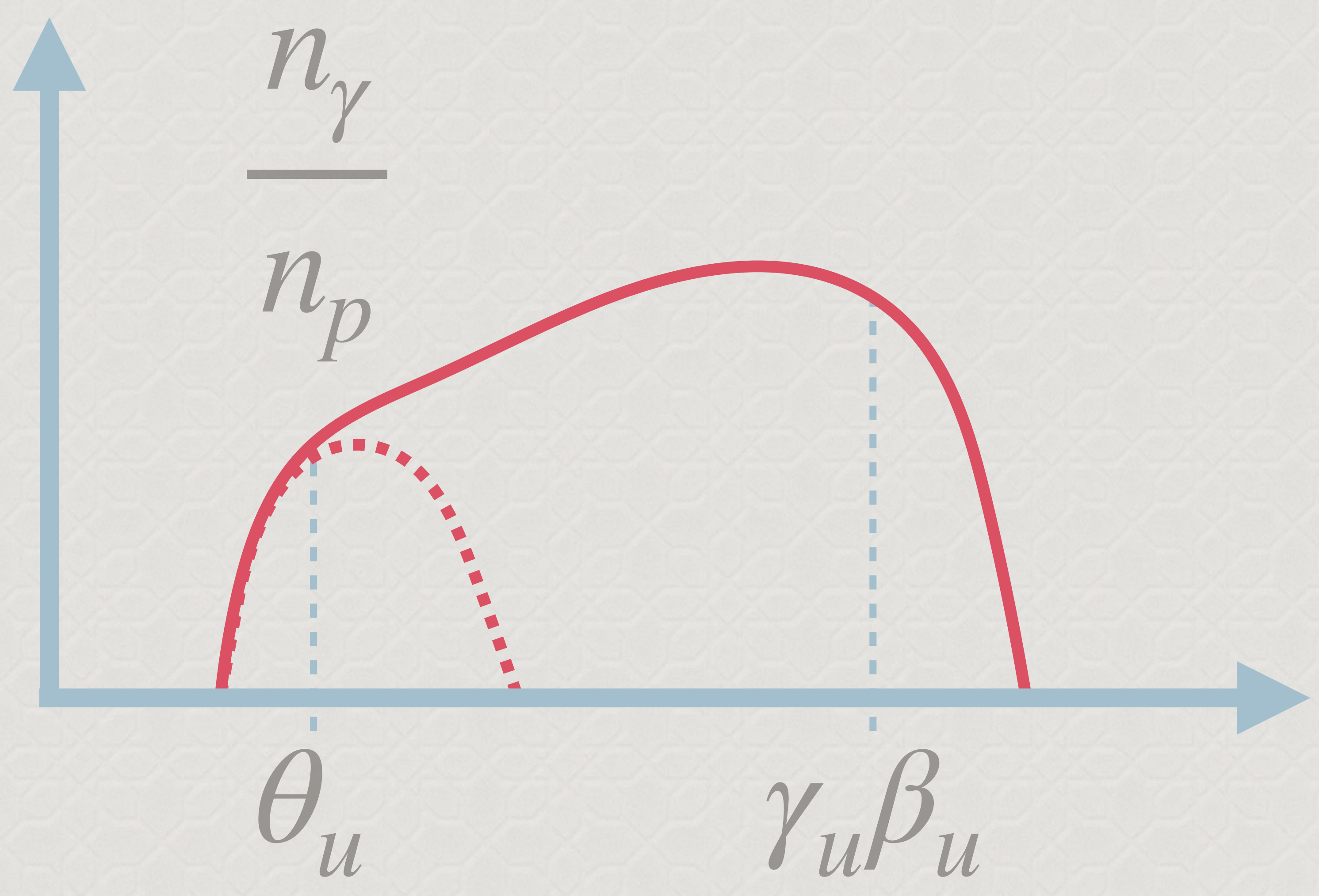
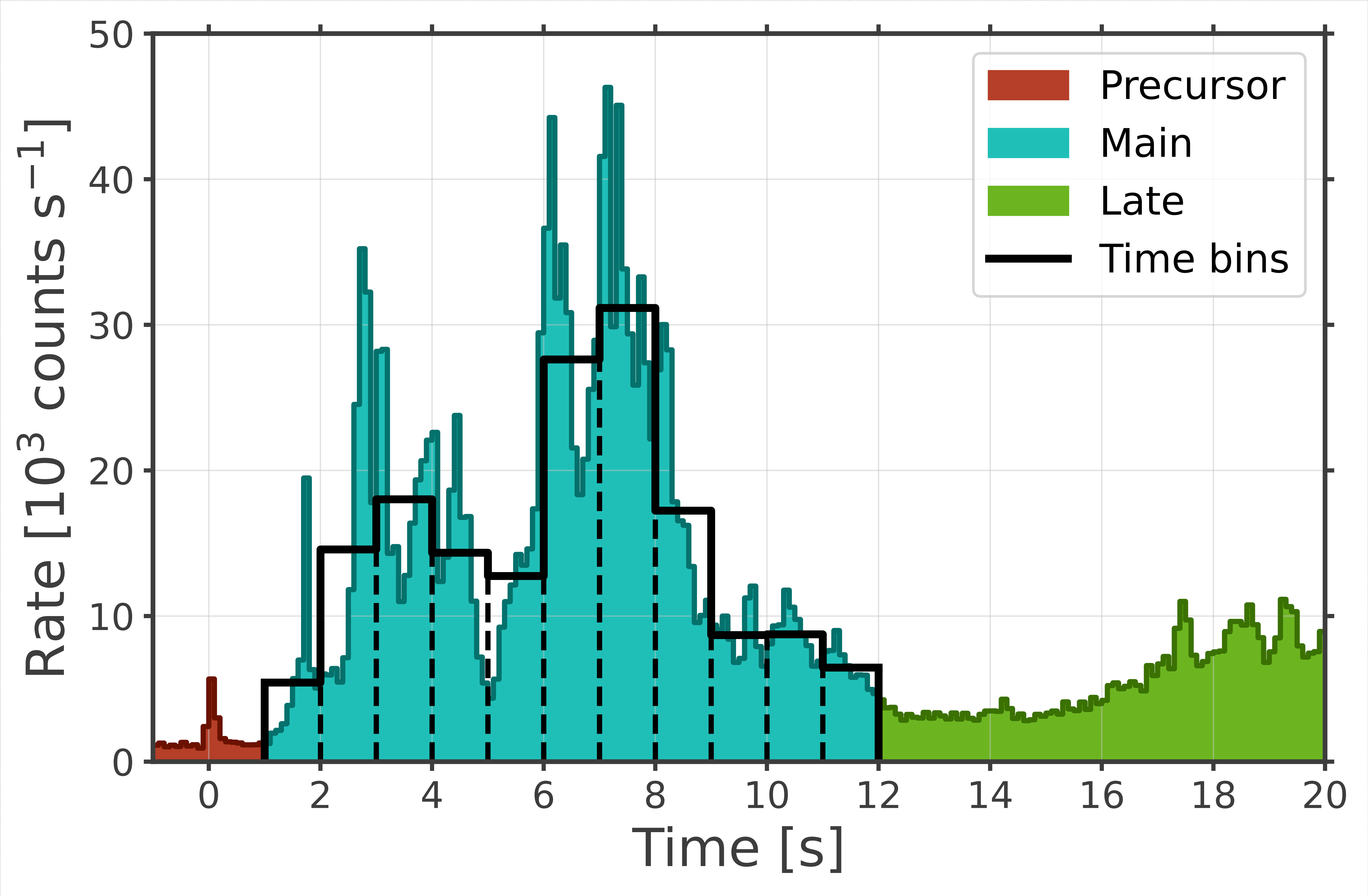


Analysis of the prompt emission

We study the main emission



Analysis of the prompt emission

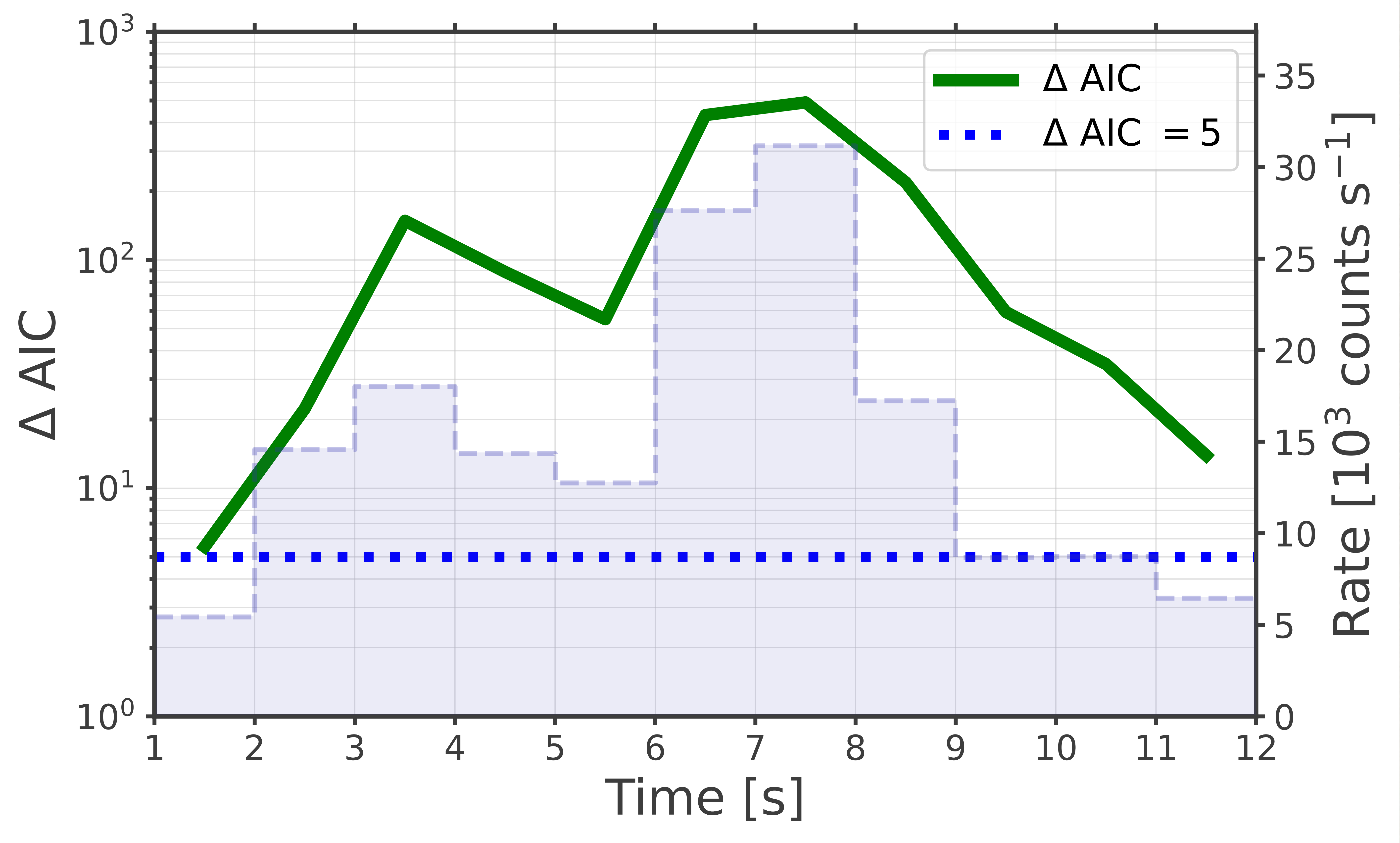
KRA fits significantly better than the Band function

↓

Additional Curvature

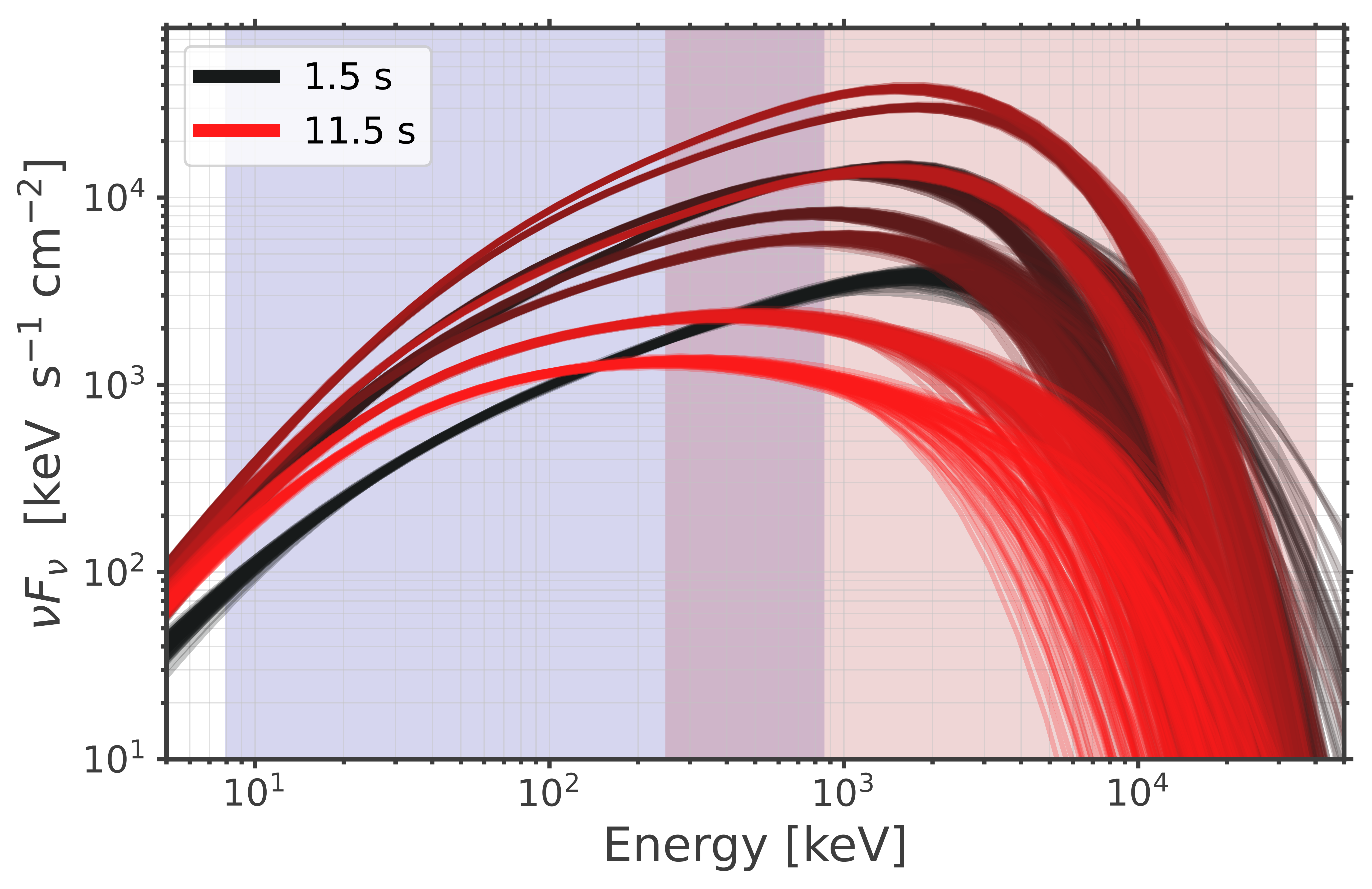
↑

Similar to previous work



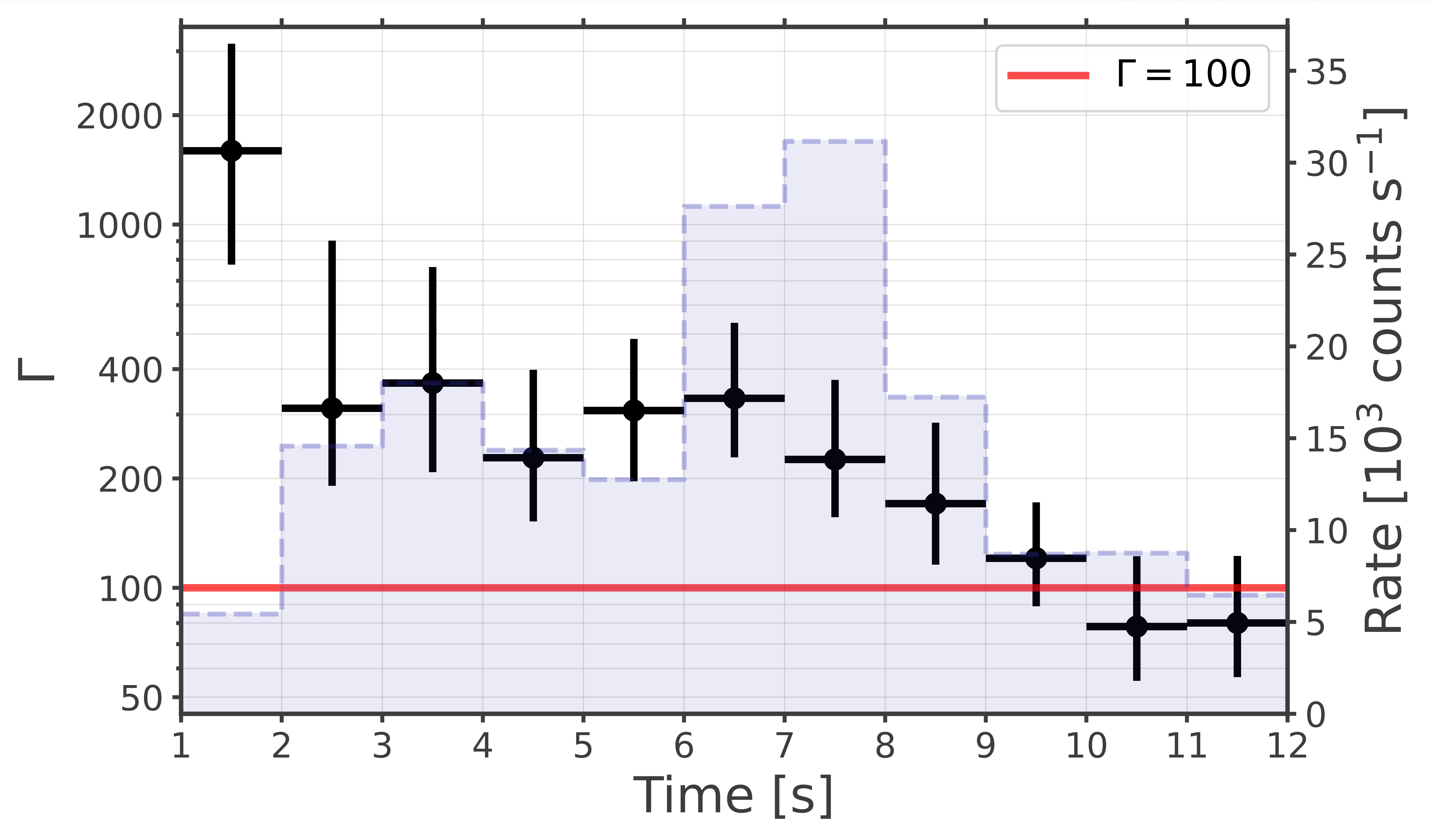
Analysis of the prompt emission

Spectral shape evolution



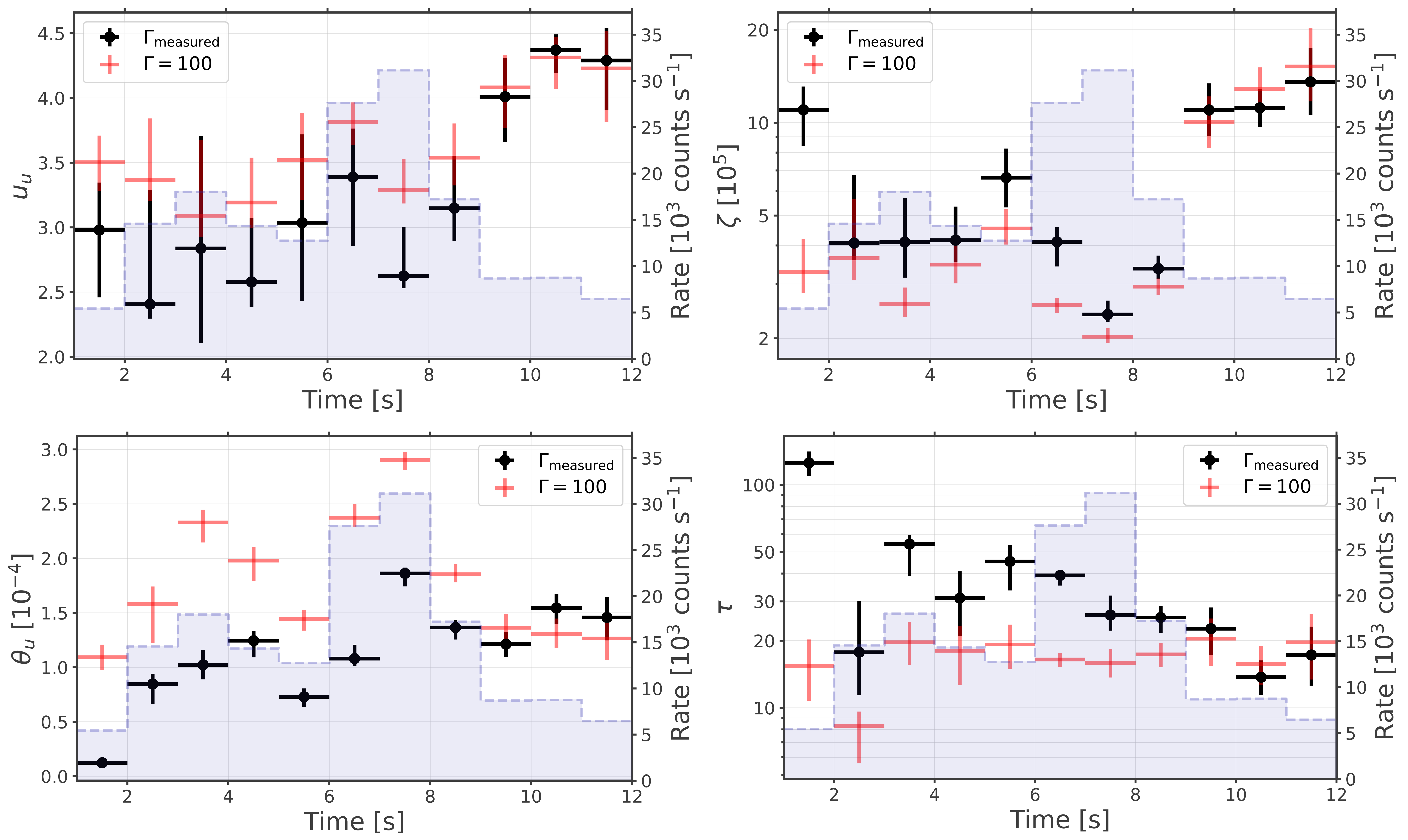
Analysis of the prompt emission

Measured Lorentz factor



Analysis of the prompt emission

RMS parameter evolution



Analysis of the prompt emission

RMS parameters

$\tau \sim 30$

$\theta_u \sim 10^{-4}$

$\gamma_u \beta_u \sim 2.75$

$n_\gamma / n_p \sim 5 \times 10^5$

All derived from the fitted KRA-parameters

Burst parameters

$\Gamma \sim 300$

$r_{\rm ph} \sim 2 \times 10^{13}$ cm

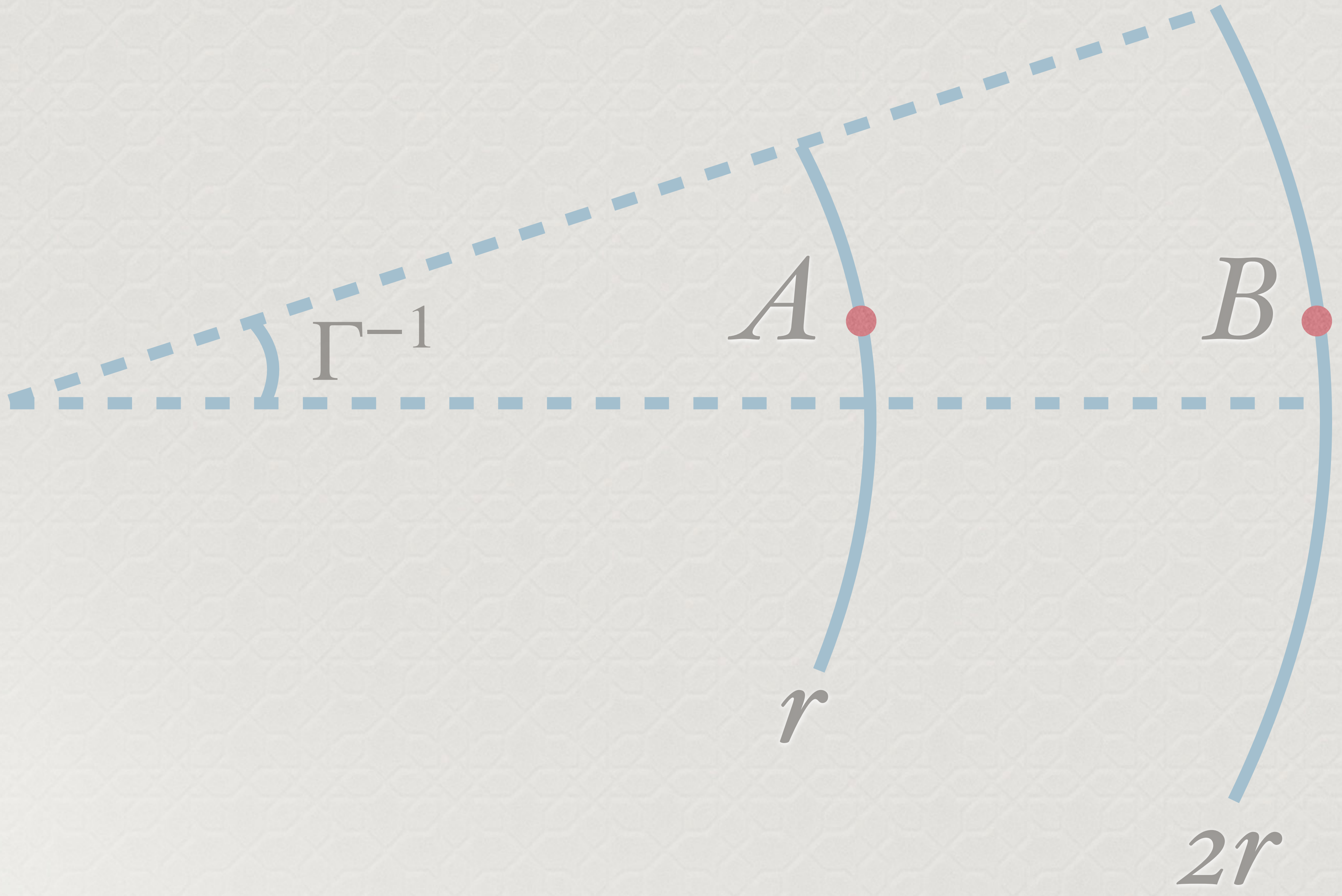
$r_{\rm diss} \sim 6 \times 10^{11}$ cm

Conclusions

- *Photospheric GRB prompt emission is typically broader than a Planck spectrum*
- *Photospheric emission with dissipation from RMSs can reproduce GRB spectra (Samuelsson+ 2023)*
- *The bulk outflow Lorentz factor can be measured from observed spectral properties (Wistemar+ 2025)*
- *Even very broad, typical synchrotron-like spectra can be fitted by photospheric emission e.g. GRB211211A (Wistemar+ in prep. Soon!)*

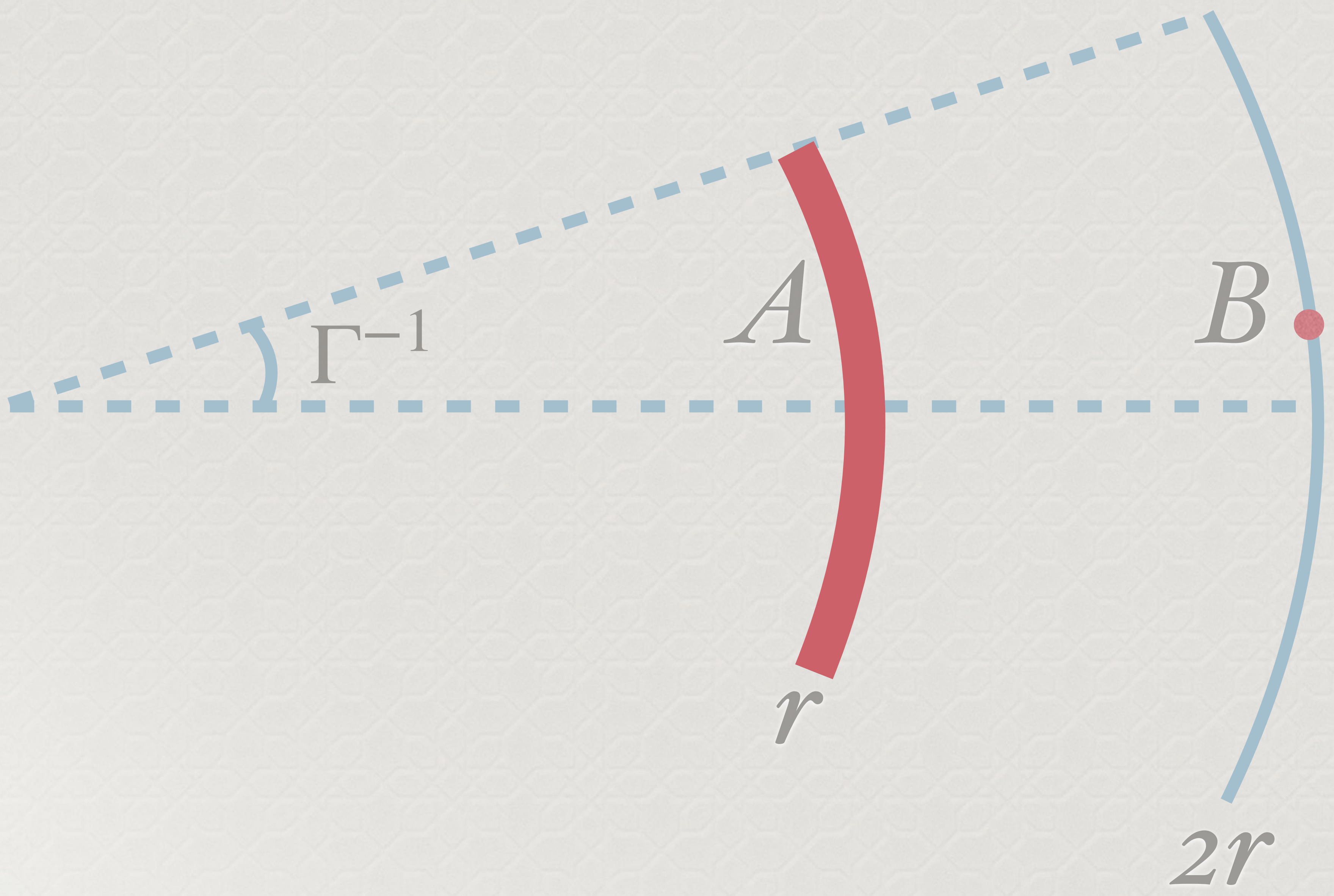
Extra slides

Radial timescale



$$t_B - t_A = t_{\text{rad}} = \frac{r_{\text{ph}}}{2c\Gamma^2}(1+z)$$

Radial timescale



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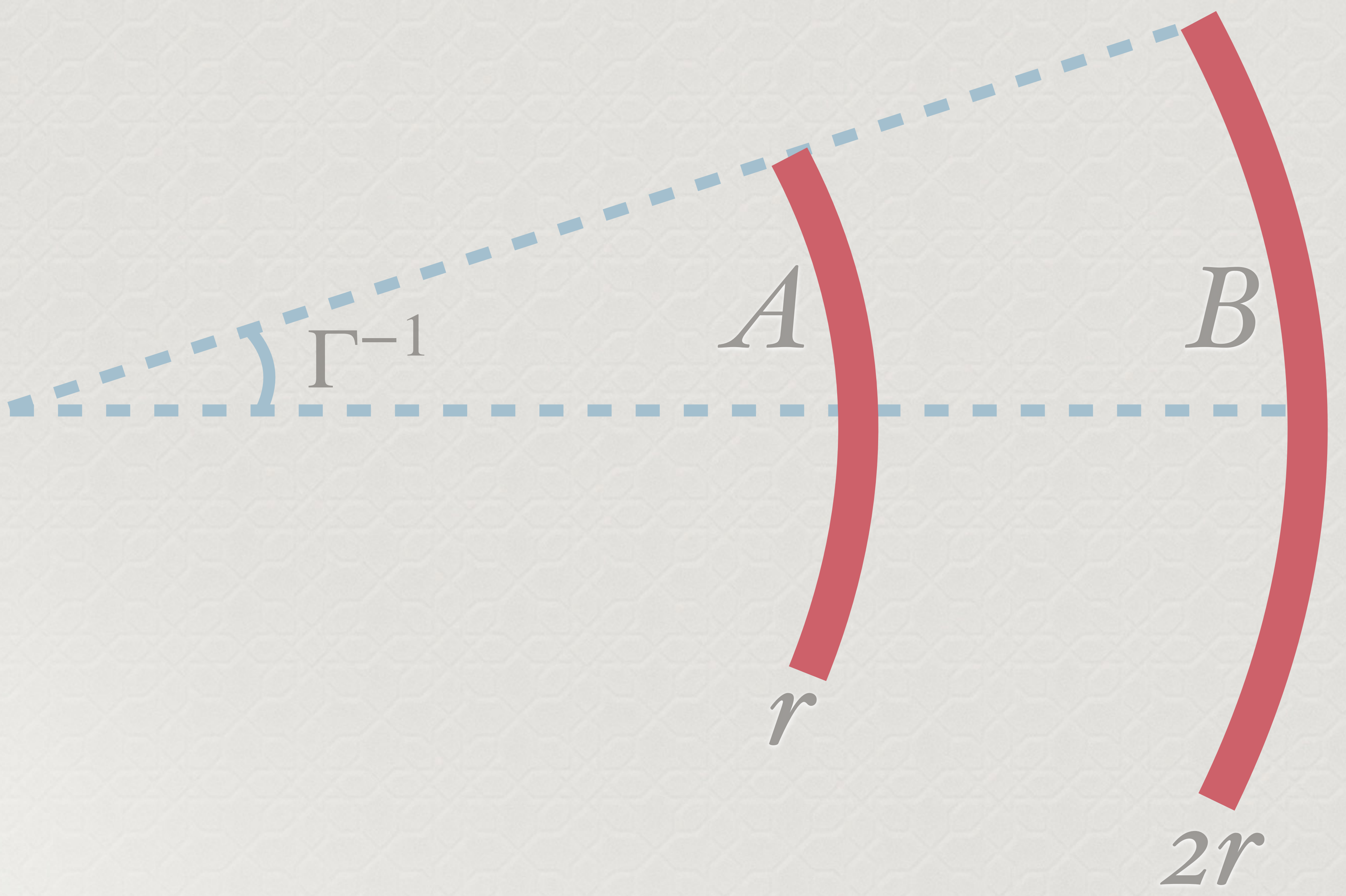
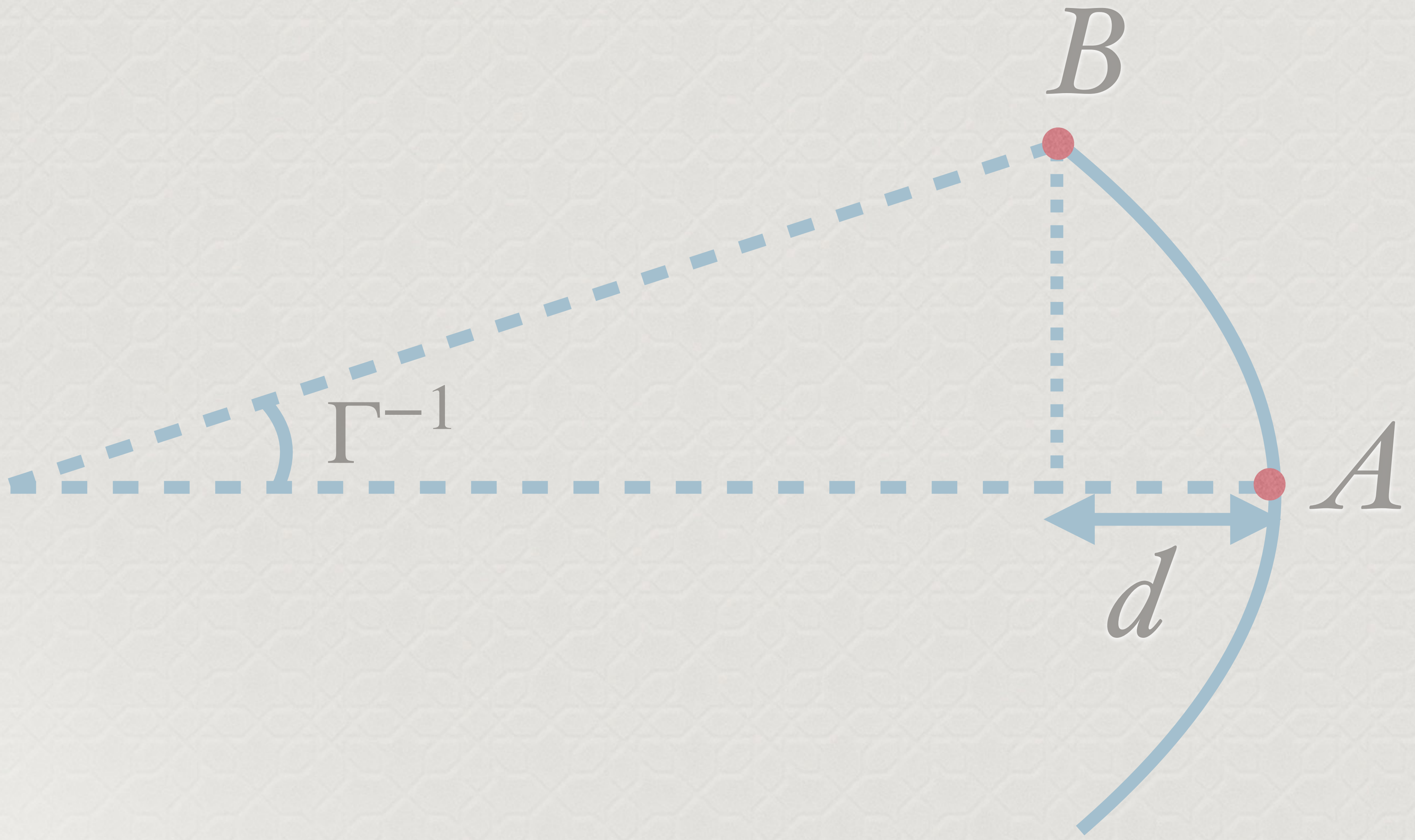


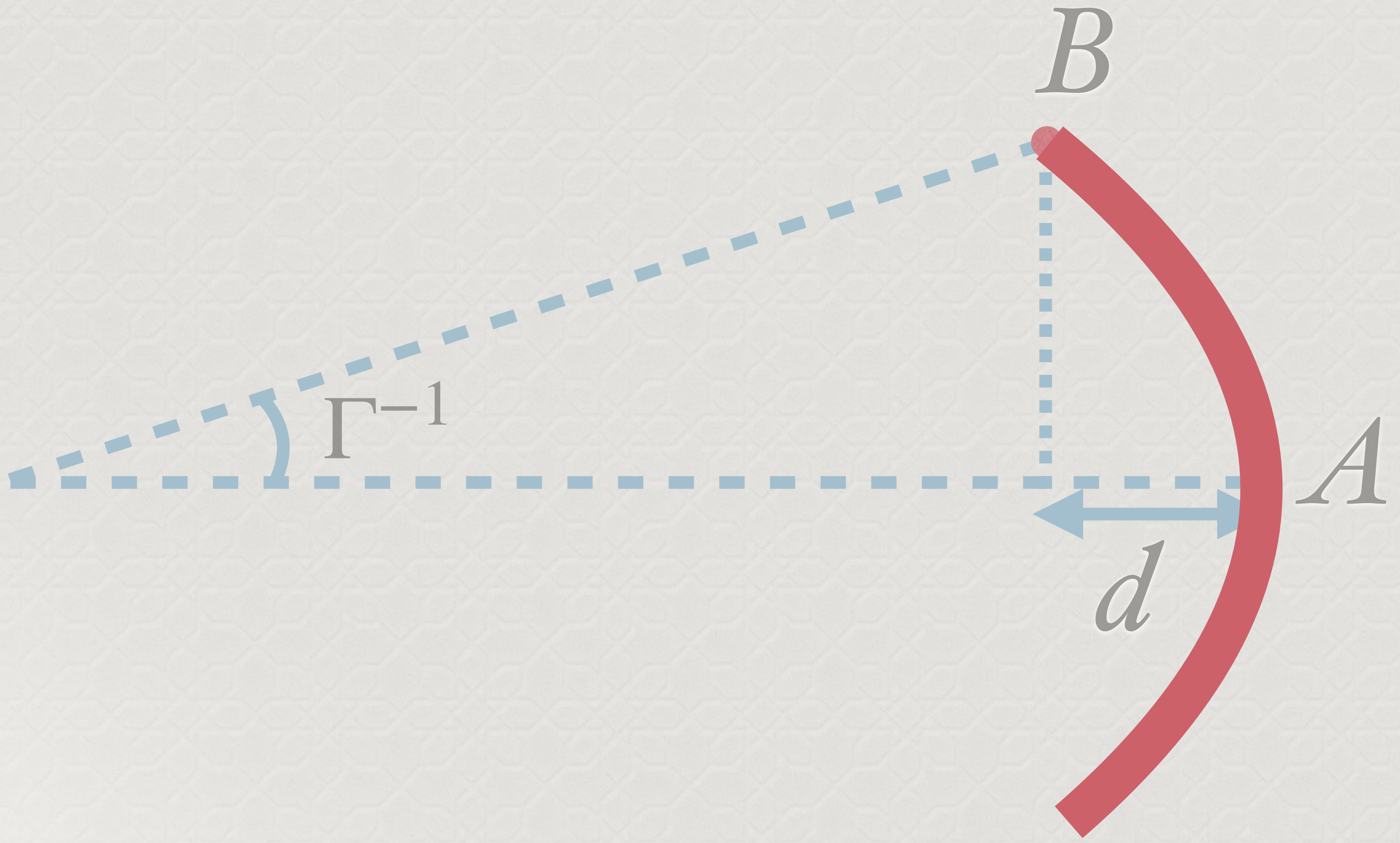
$$t_B - t_A = t_{\rm rad} = \frac{r_{\rm ph}}{2c\Gamma^2}(1+z)$$

Curvature timescale



$$t_B - t_A = t_{\rm curv} = \frac{r_{\rm ph}}{2c\Gamma^2}(1+z)$$

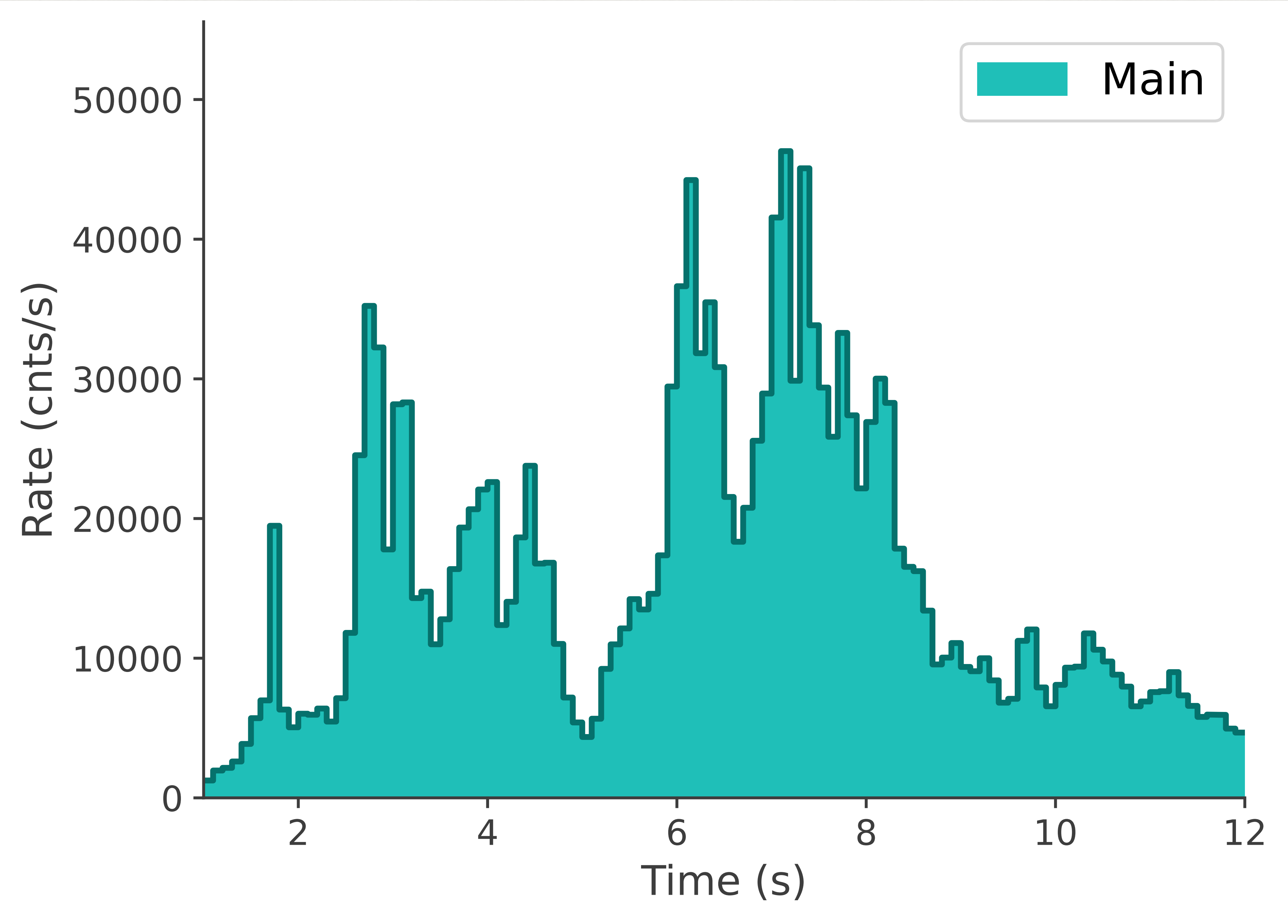
Curvature timescale



$$t_B - t_A = t_{\rm curv} = \frac{r_{\rm ph}}{2c\Gamma^2}(1+z)$$

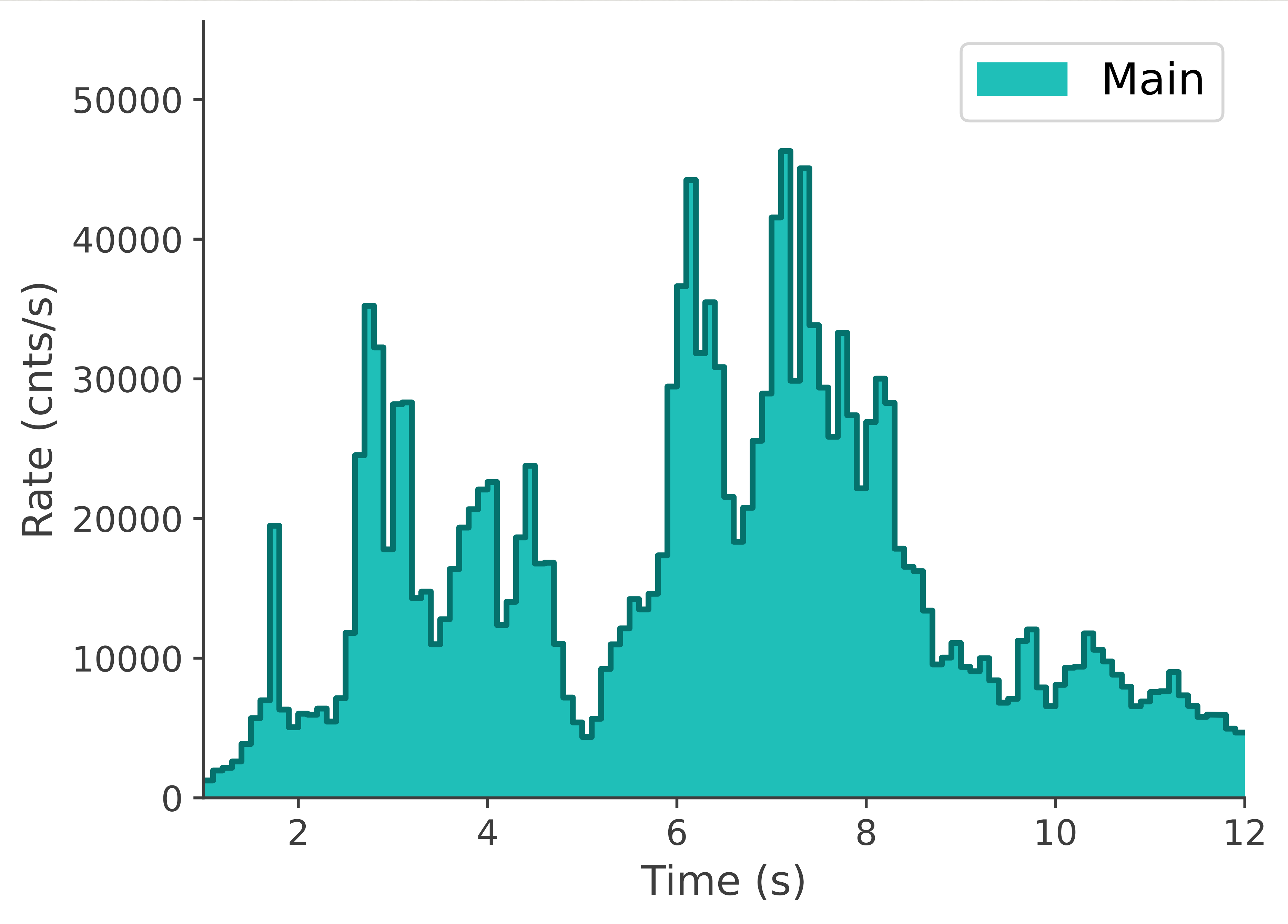
Variability time

Ligt curve variability



Variability time

Ligt curve variability

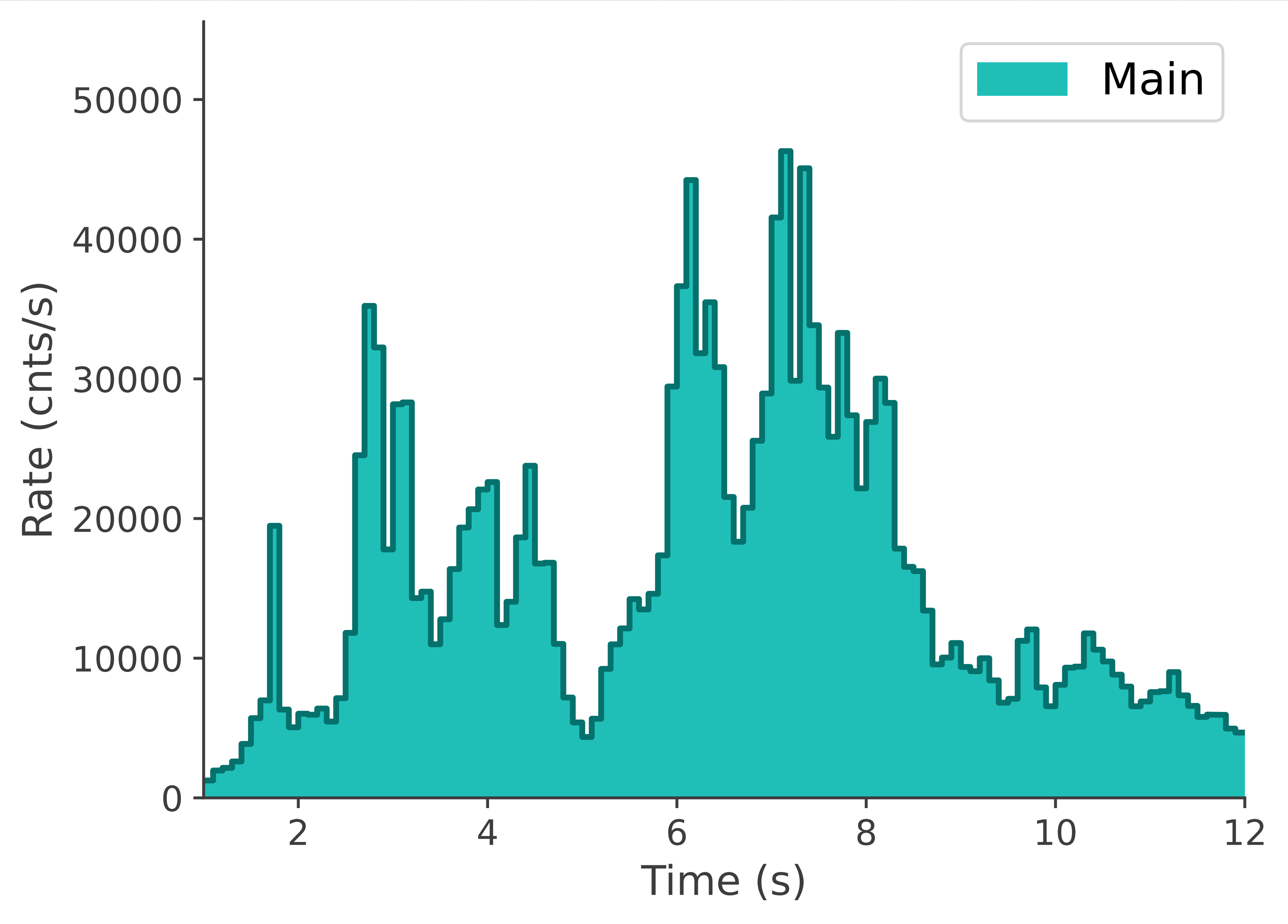


Assuming the variability comes from the curvature or the radial timescale

$$t_{\mathrm{var}} = t_{\mathrm{rad}} = t_{\mathrm{curv}}$$

Variability time

Ligt curve variability



Assuming the variability comes from the curvature or the radial timescale

$$t_{\rm var} = t_{\rm rad} = t_{\rm curv}$$

$$r_{\rm ph} = \frac{2c\Gamma^2 t_{\rm var}}{1+z}$$

Variability time

$$\Gamma = 48\,\frac{1}{1+z}\,\frac{d_{L,28}\,N_{\mathrm{ob},2}^{1/2}}{T_{\mathrm{ob},1}^{3/2}\,t_{\mathrm{var},-1}}$$

Lorentz factor

Observed flux

The photospheric radius can be found from energy conservation and opacity considerations

Pairs

$$r_{\rm ph} = \frac{L\sigma_{\rm T}\kappa_{\pm}}{4\pi m_p c^3\Gamma^3}$$

Lorentz factor

Observed flux

The luminosity is related to the observed flux

Radiation efficiency

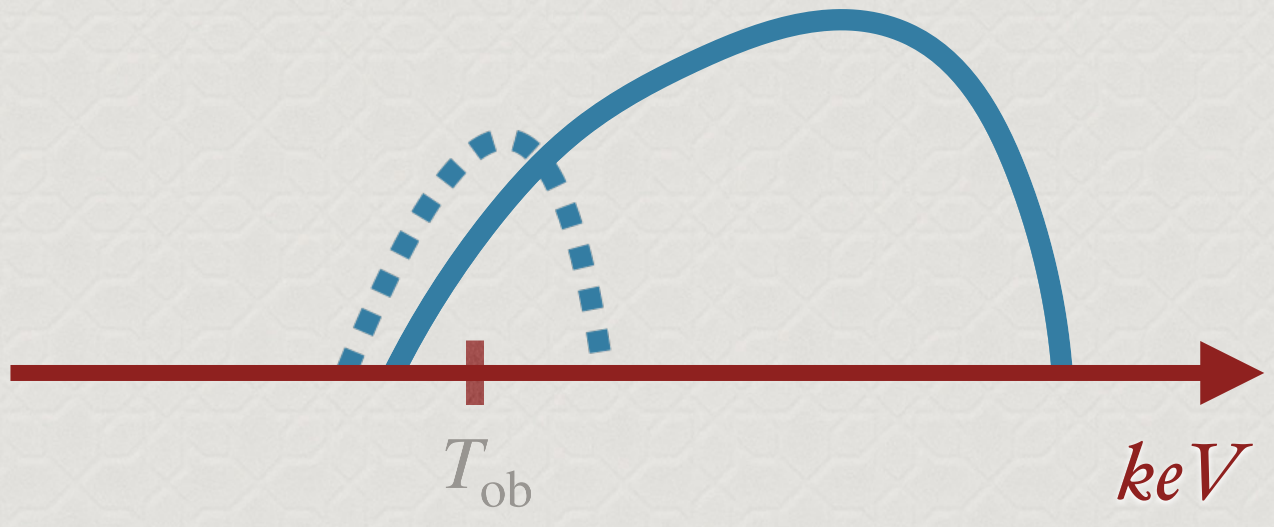
$$L = 4\pi d_L^2 F_{\rm ob}/\epsilon_\gamma$$

Now we get

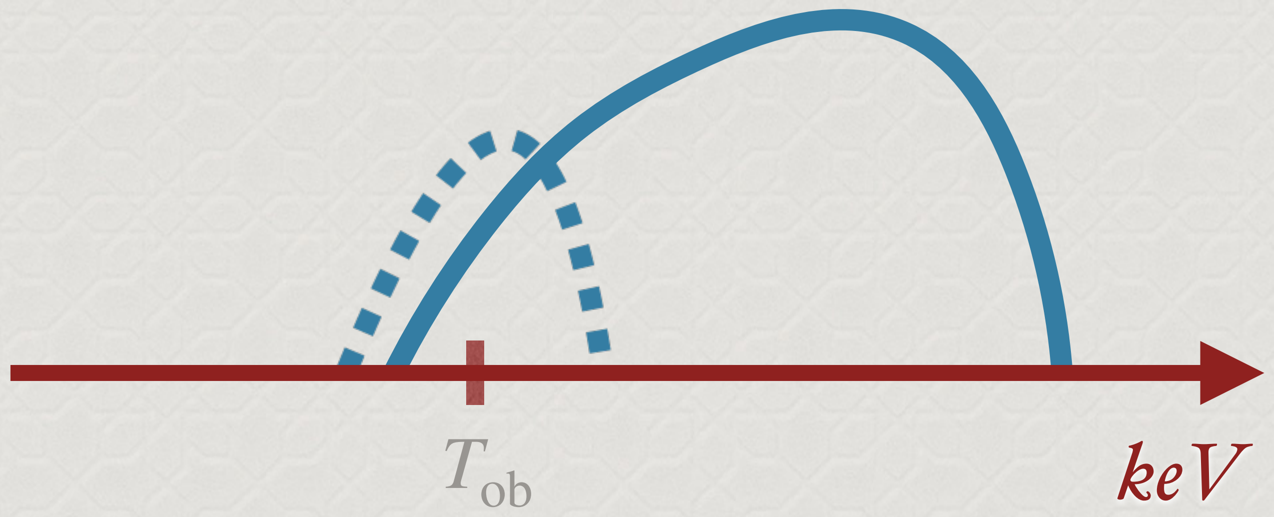
Observed flux

$$\Gamma = 47\,(1+z)^{1/2}\kappa_{\pm}^{1/4}\,\frac{d_{L,28}^{1/4}\,T_{\mathrm{ob},1}^{3/8}\,F_{\mathrm{ob},-7}^{1/4}}{\epsilon_{\gamma,-1}^{1/4}\,N_{\mathrm{ob},2}^{1/8}}$$

Low-energy break



Low-energy break



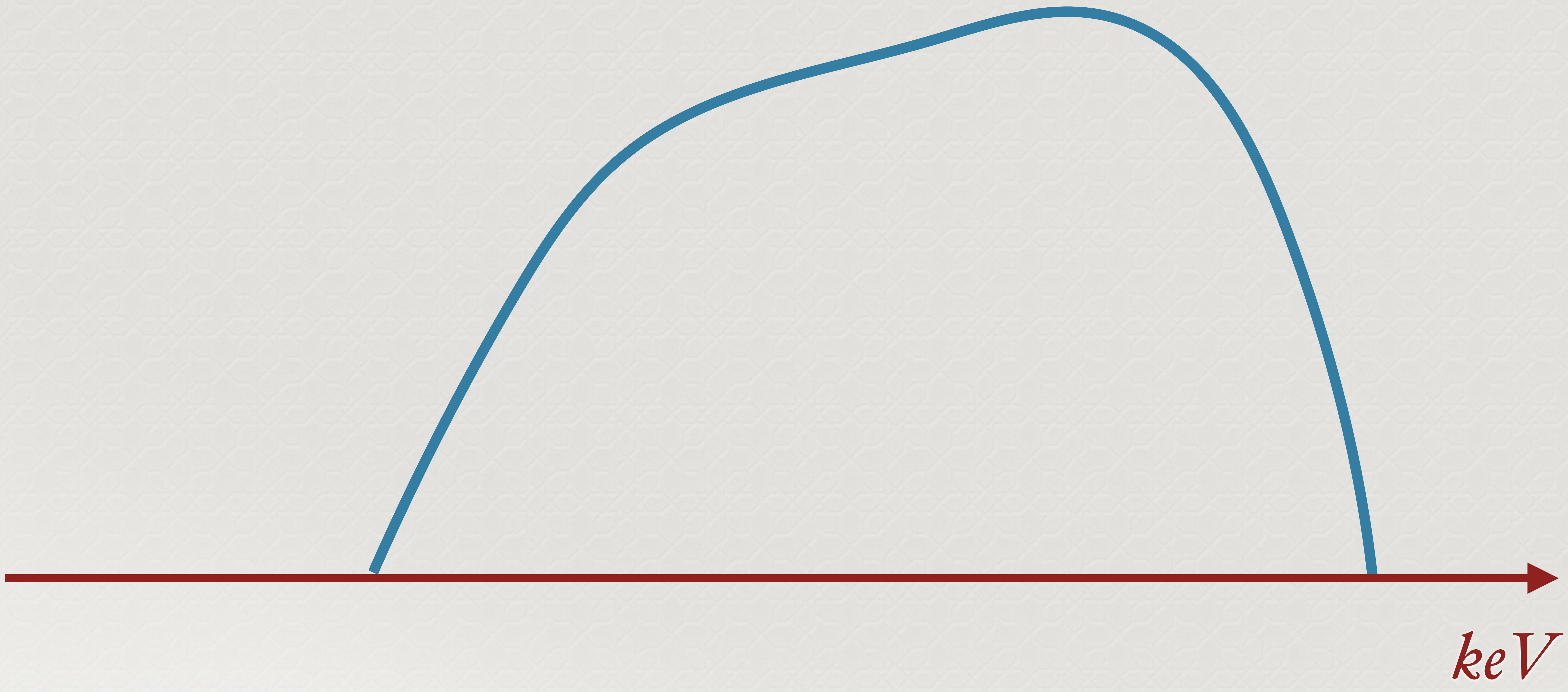
- *RMS models give T_{ob} without thermalisation*
- *Thermalisation or up-scattering increases the break*
- *A discrepancy between T_{ob} and E_b*

Low-energy break

- *A discrepancy between* T_{ob} *and* E_b

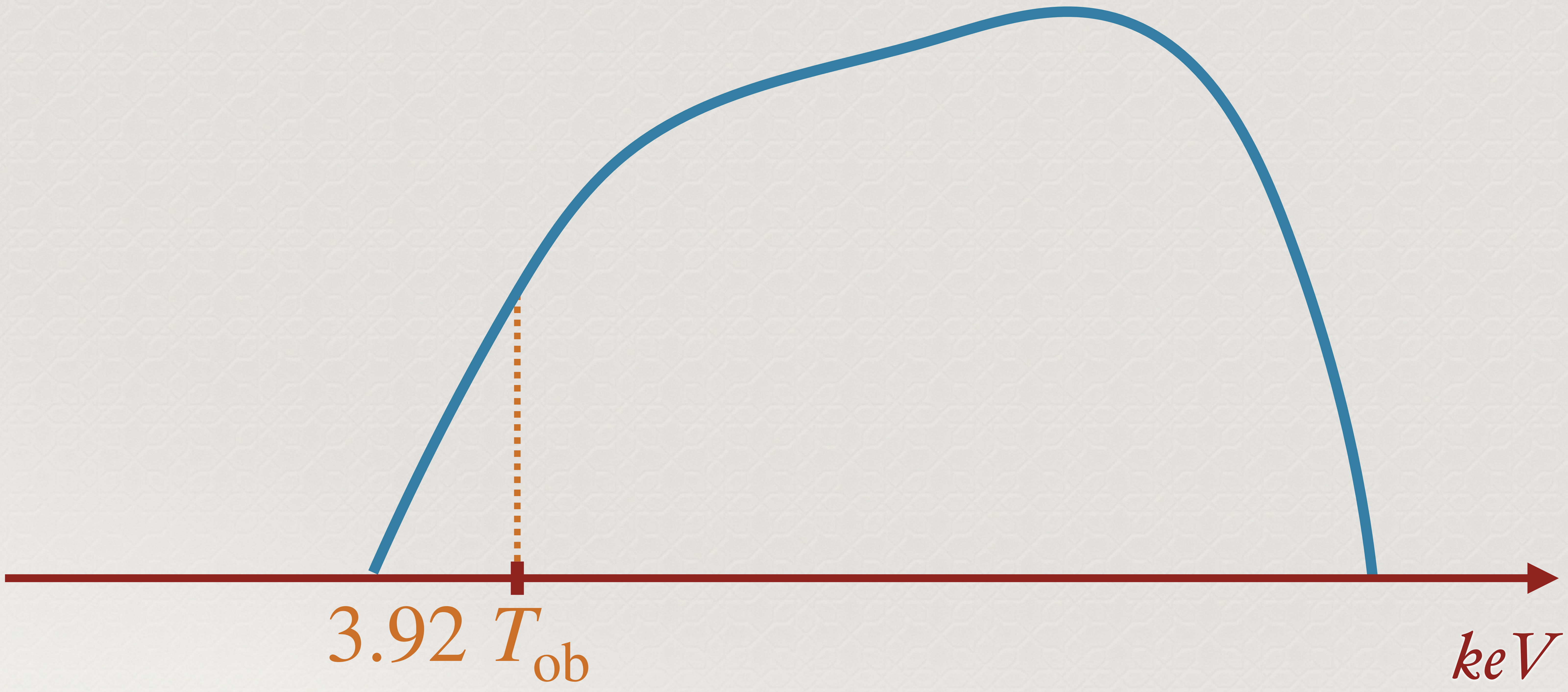
Low-energy break

- *A discrepancy between* $T_{\rm ob}$ *and* E_b



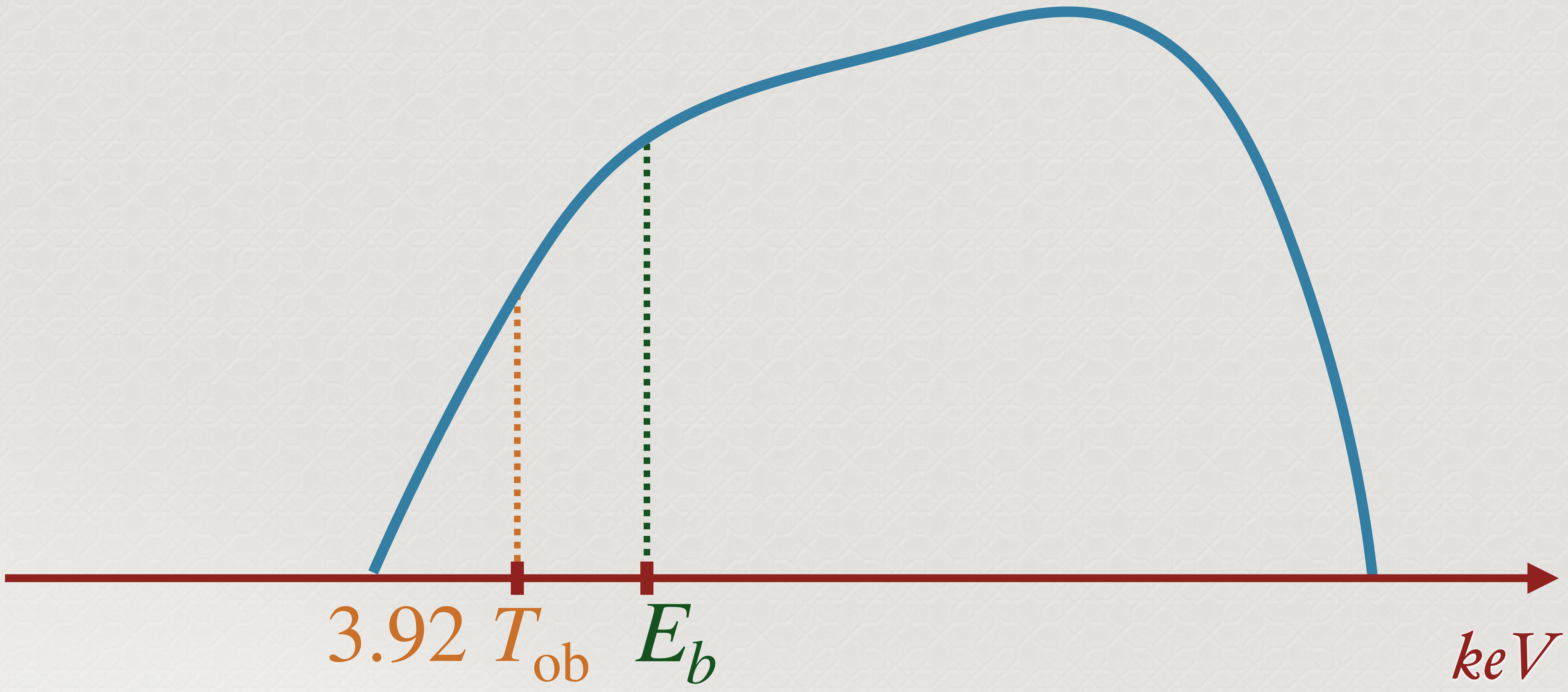
Low-energy break

- *A discrepancy between T_{ob} and E_b*



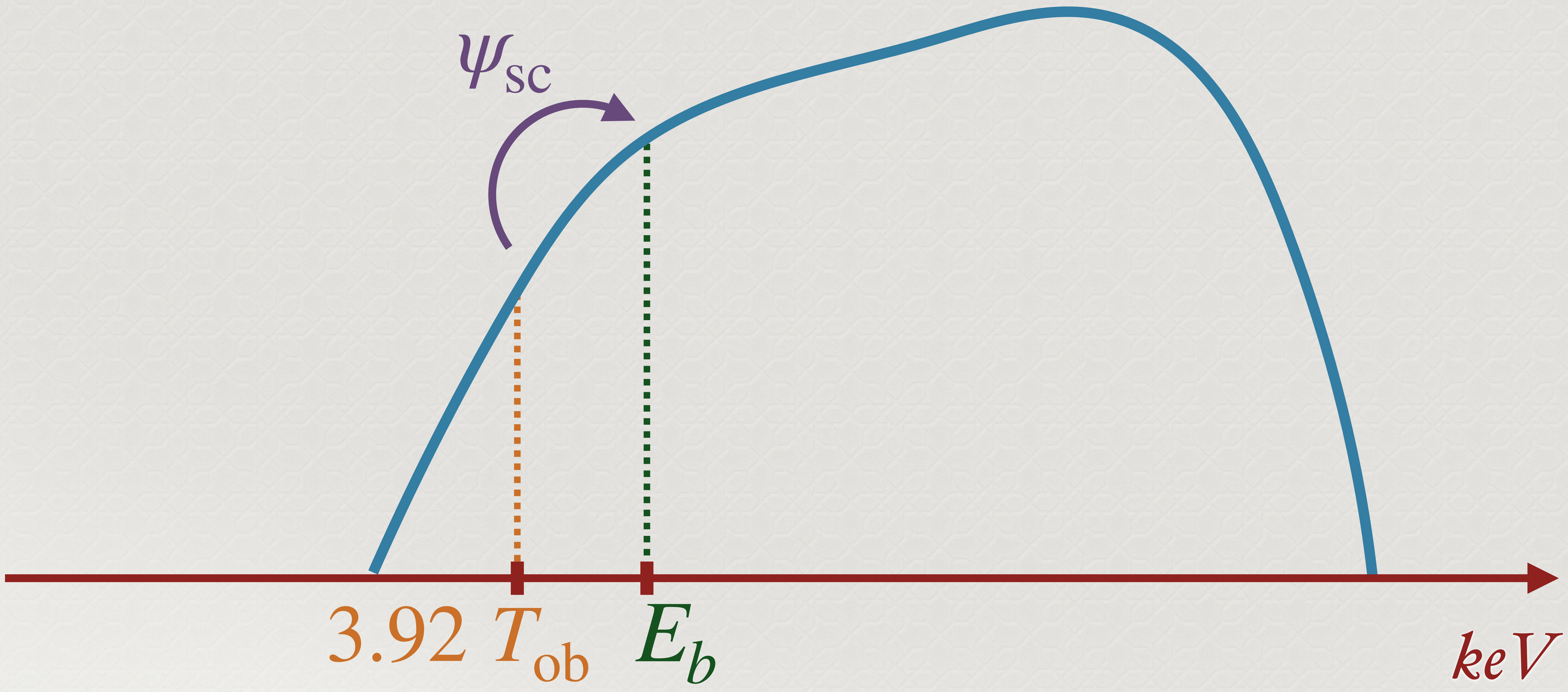
Low-energy break

- *A discrepancy between* $T_{\rm ob}$ *and* E_b



Low-energy break

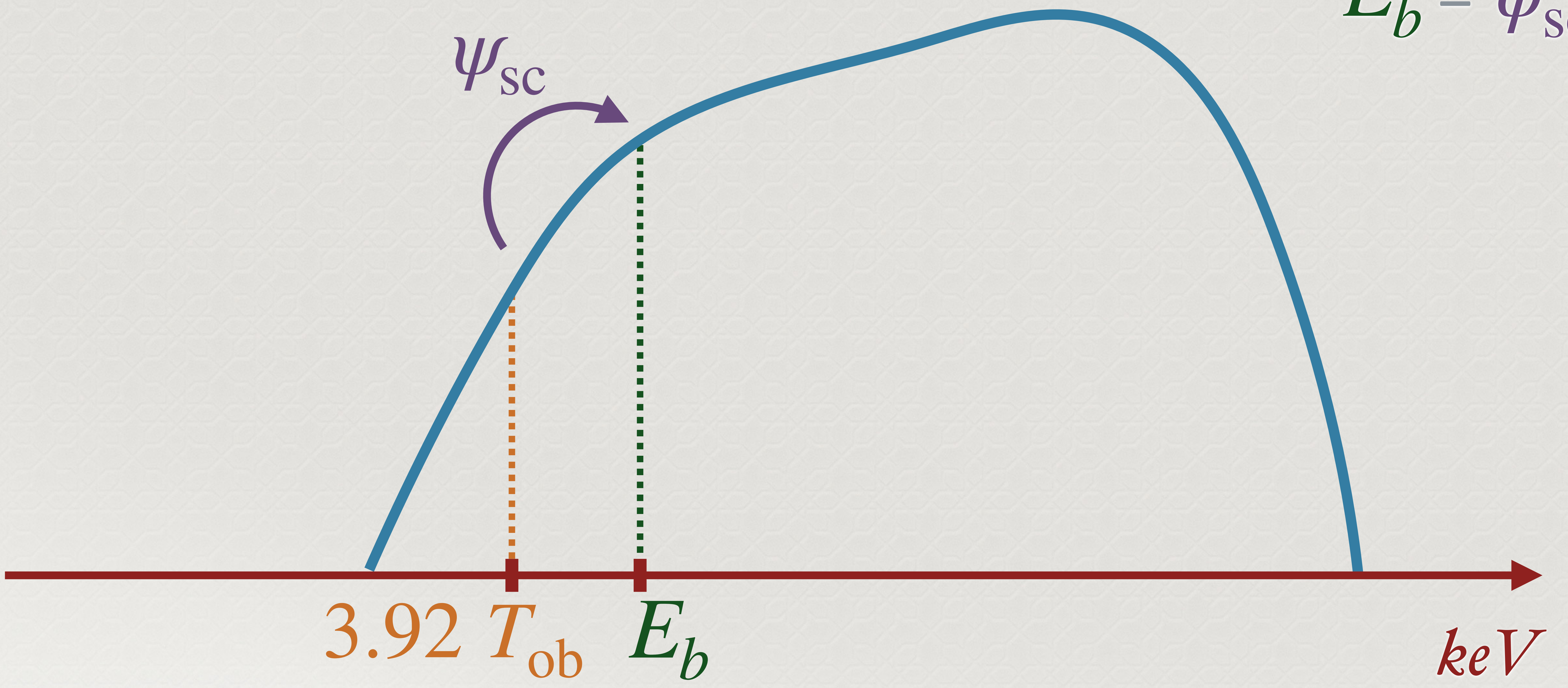
- *A discrepancy between T_{ob} and E_b*



Low-energy break

- *A discrepancy between T_{ob} and E_b*

$$E_b = \psi_{\mathrm{sc}} k_B T_{\mathrm{ob}}$$



Using Γ

What we know

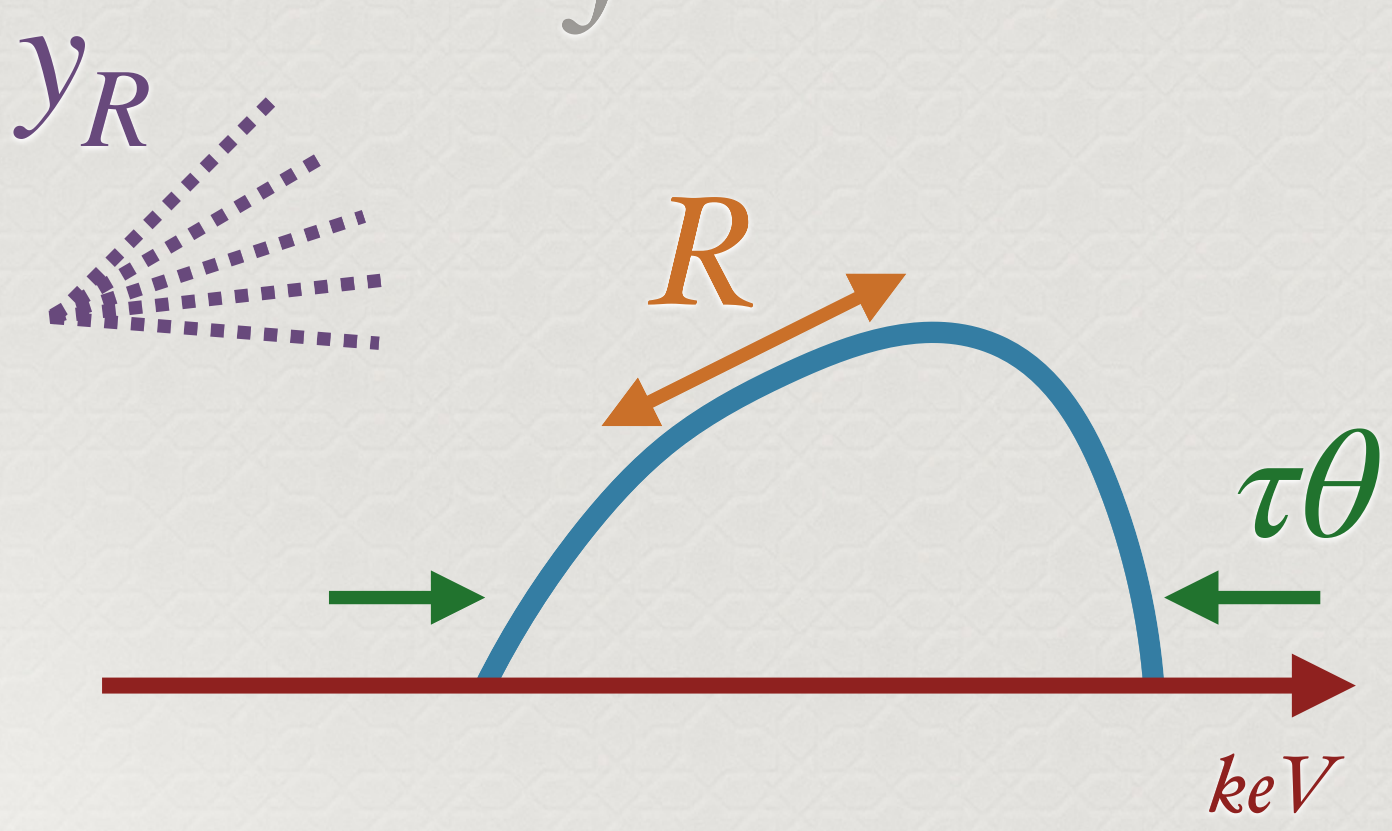
Before Γ

After Γ

Using Γ

What we know

Before Γ



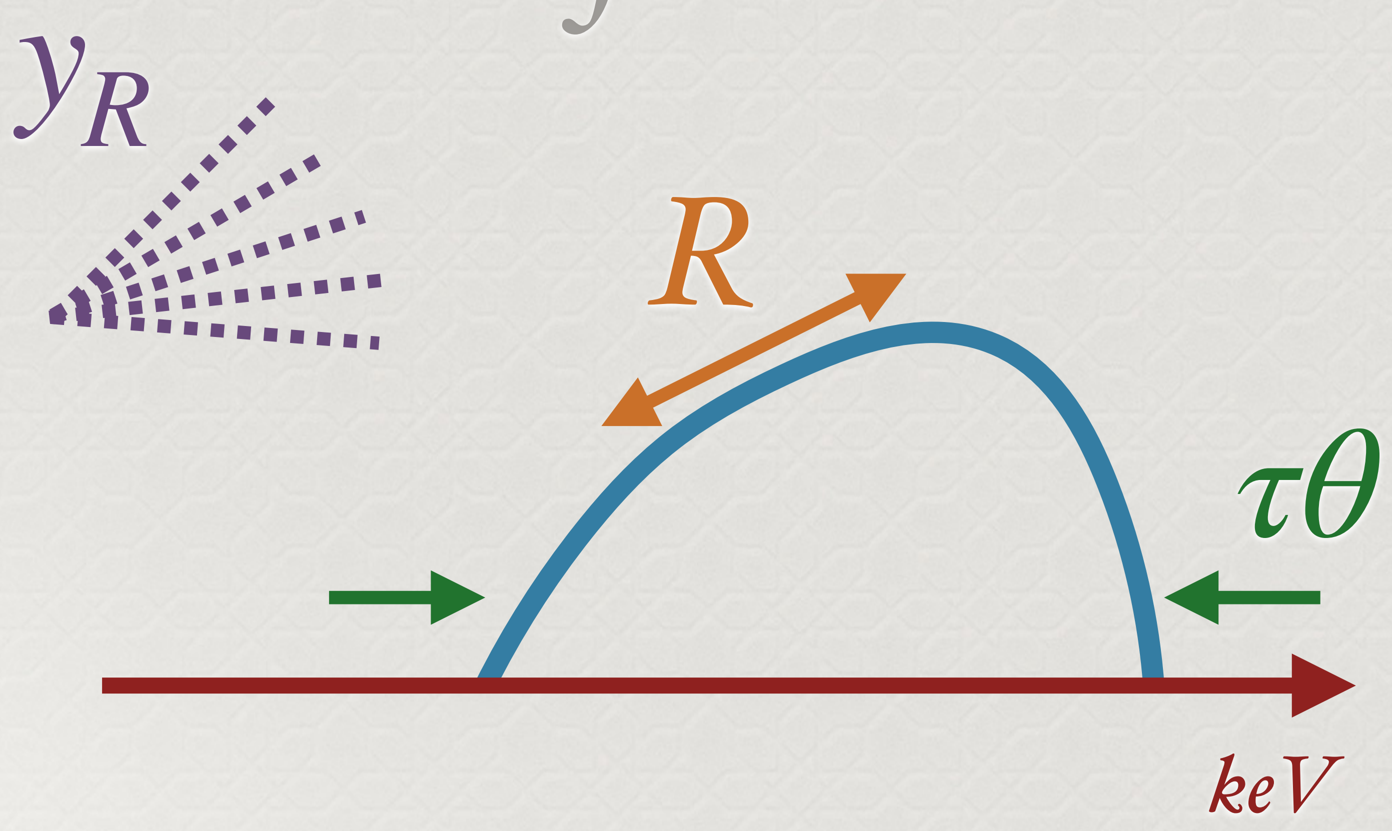
We know the shape and the observer spectral position but not the co-moving spectral position

After Γ

Using Γ

What we know

Before Γ



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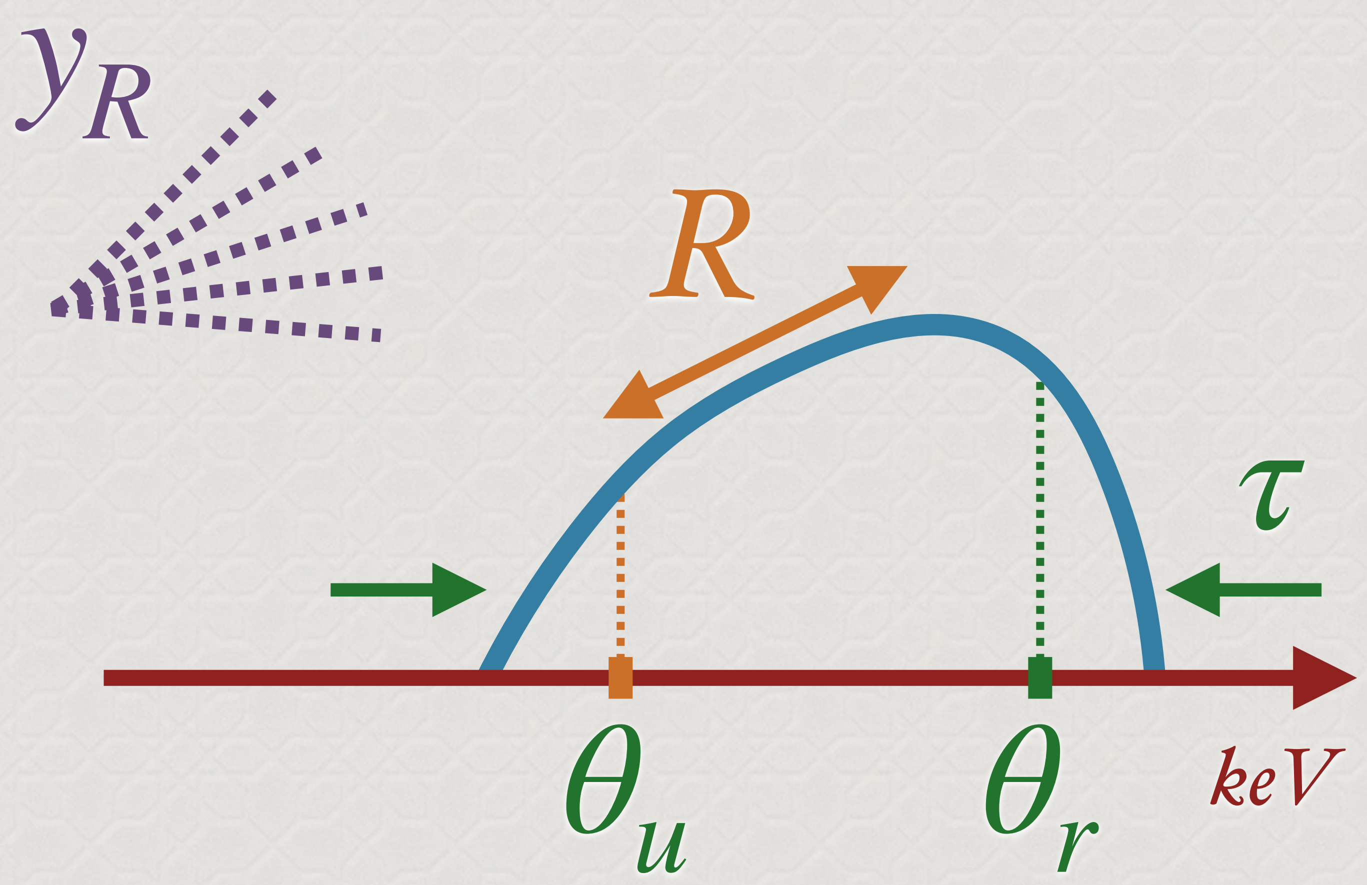
After Γ



We now know the co-moving spectral position