The internal shock model for GRB prompt emission

Building a model from numerical simulations

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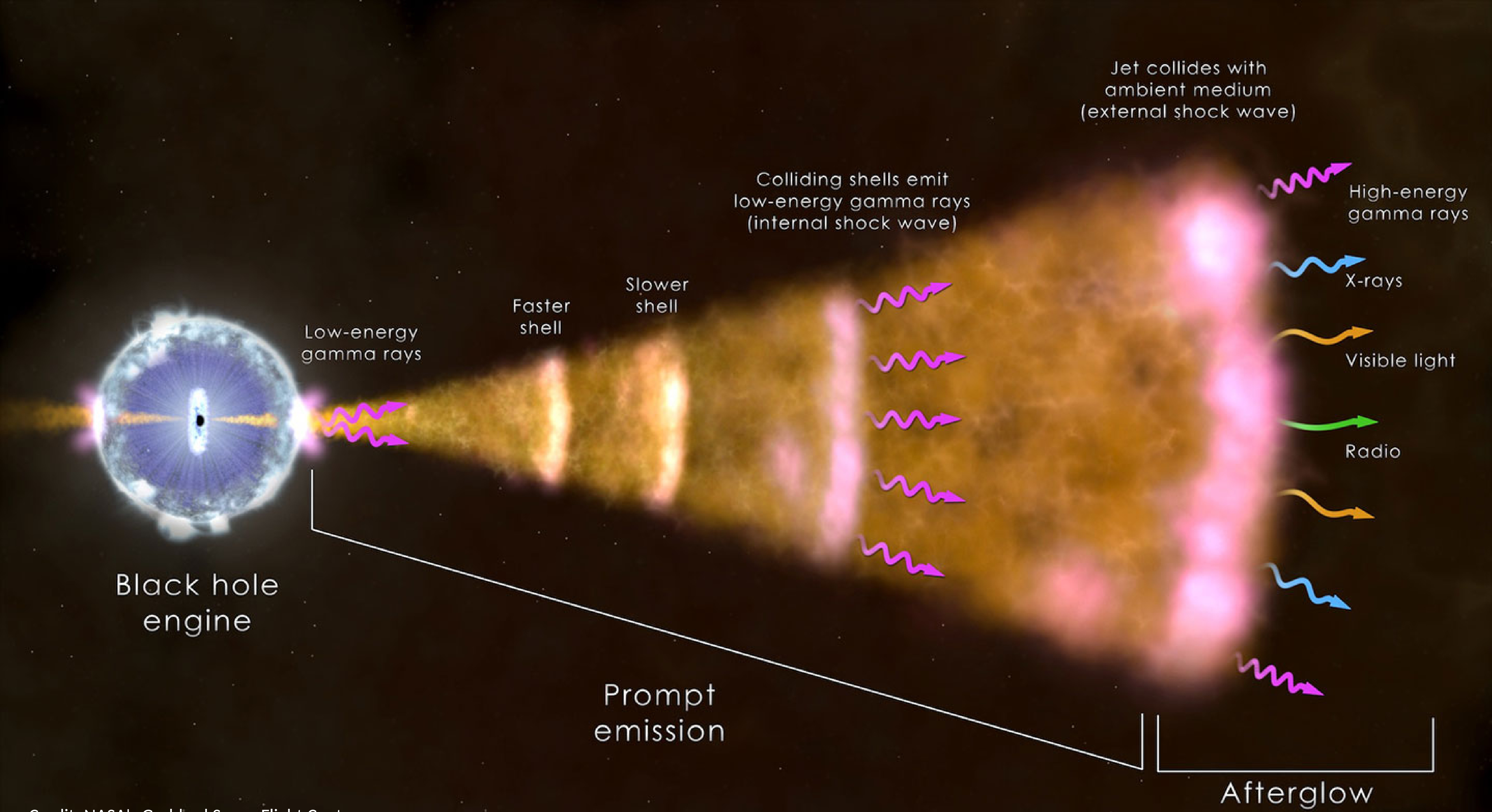
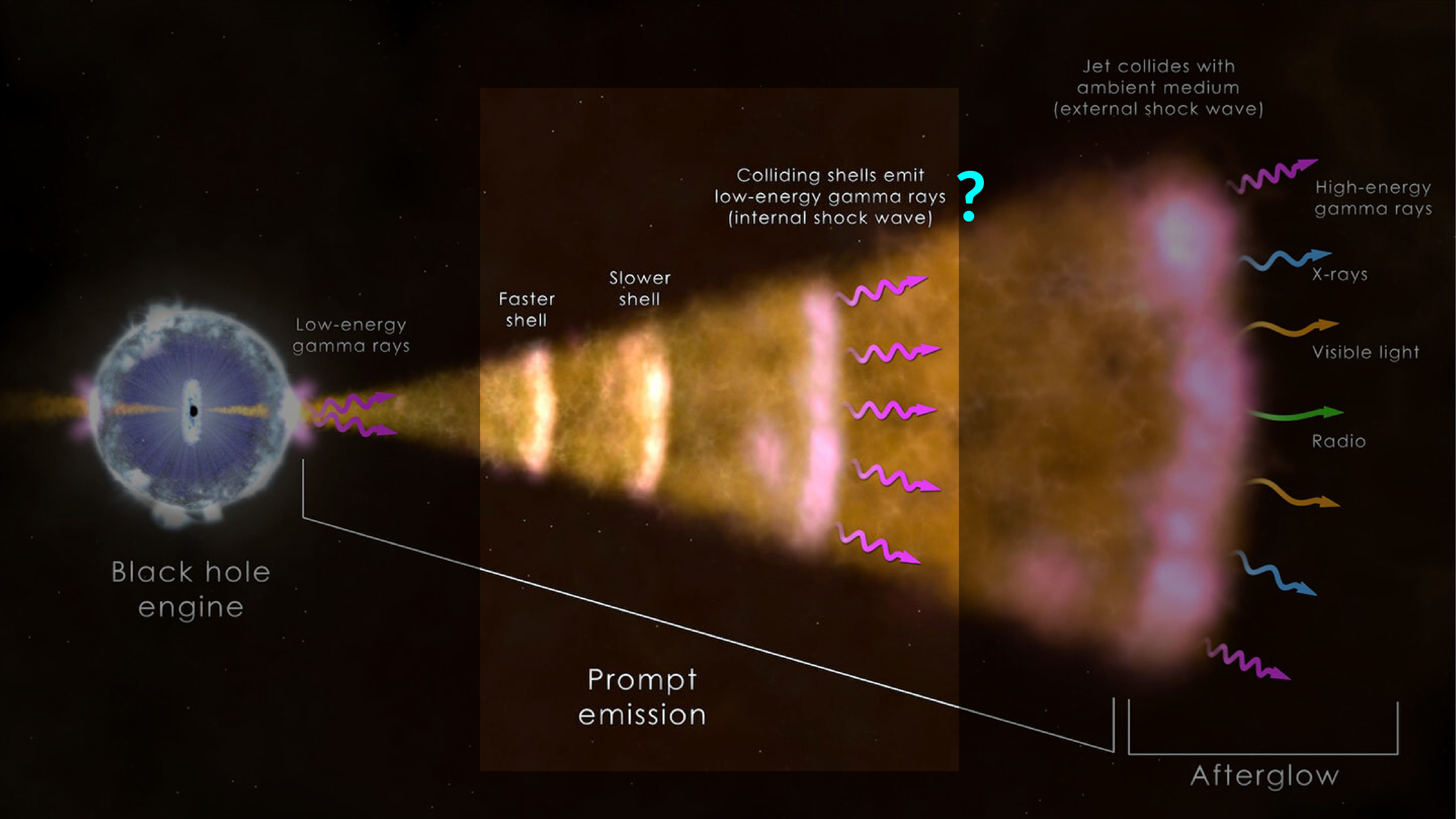
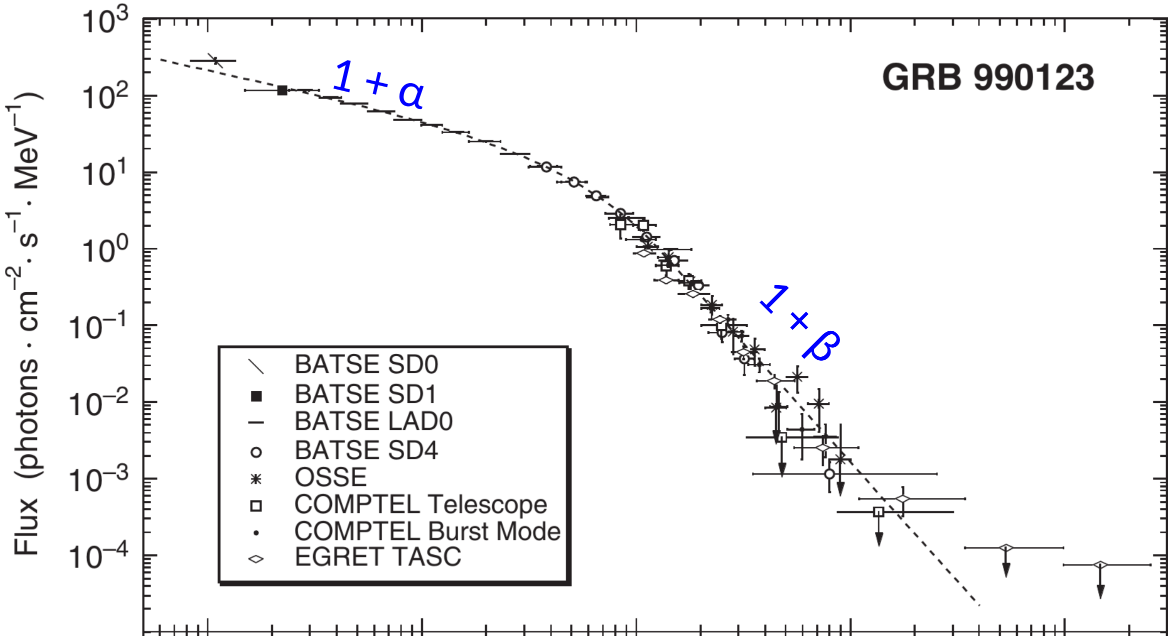


Credit: NASA's Goddard Space Flight Center


Jet collides with
ambient medium
(external shock wave)
Colliding shells emit
low-energy gamma rays
(internal shock wave)
?
High-energy
gamma rays
X-rays
Visible light
Radio
Faster
shell
Slower
shell
Low-energy
gamma rays
Black hole
engine
Prompt
emission
Afterglow

Spectral slopes and efficiencies

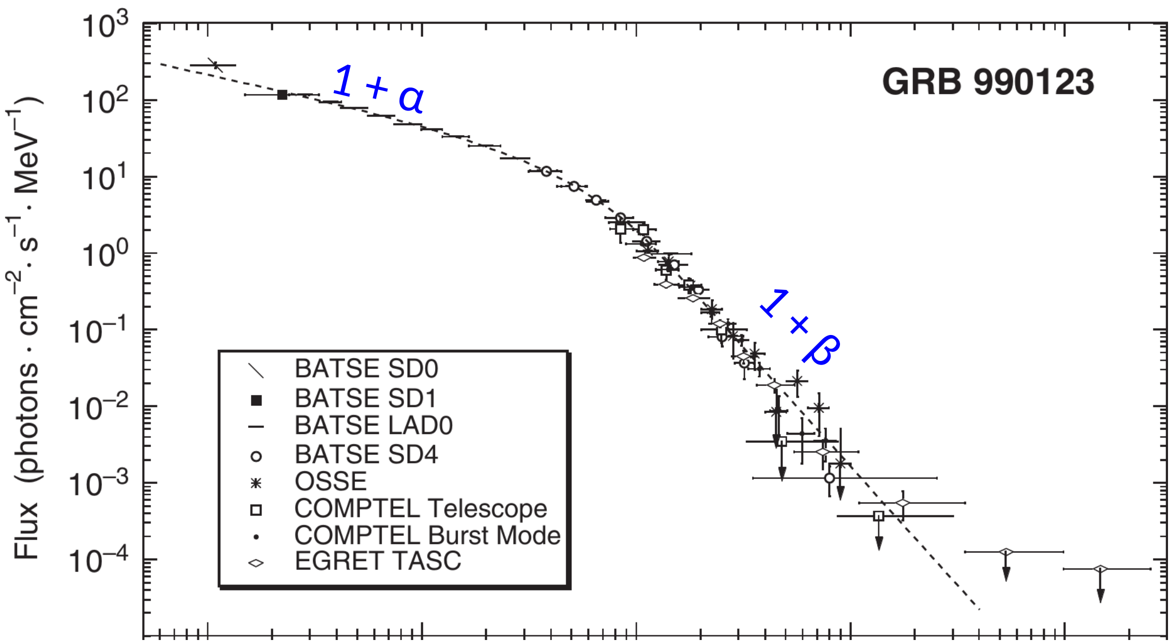


Simplest model: synchrotron emission

→ (α, β) relate to cooling regime

afterglow studies → efficiency ≥ 10-15% → fast cooling

Spectral slopes and efficiencies



Simplest model: synchrotron emission

→ (α, β) relate to cooling regime

afterglow studies → efficiency ≥ 10-15% → fast cooling

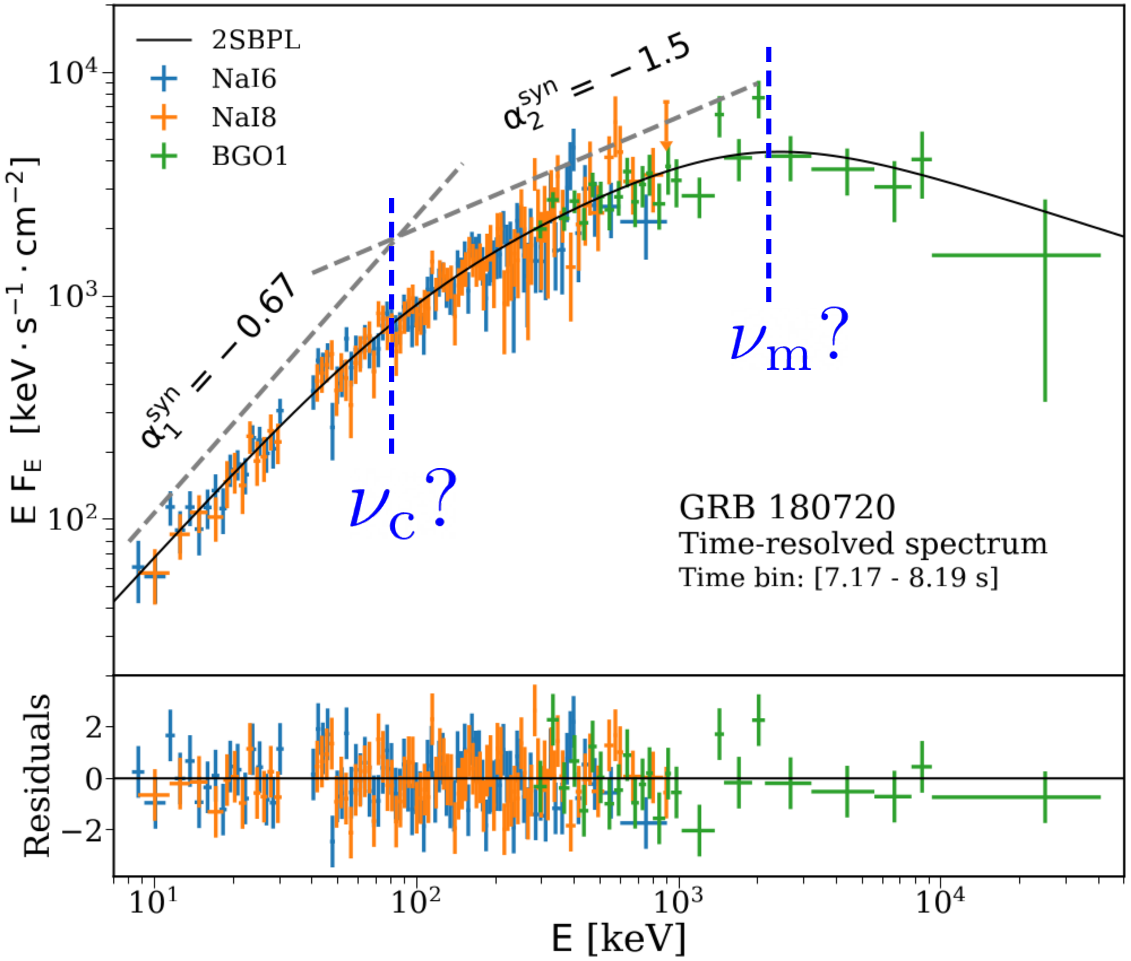
NOT SO FAST

α found in fits disagree with FC, sometimes with synchrotron model itself!

("synchrotron line of death")

Too many photons at low energy, why?

Spectra - a cooling break?



(Ravasio+ 2019)

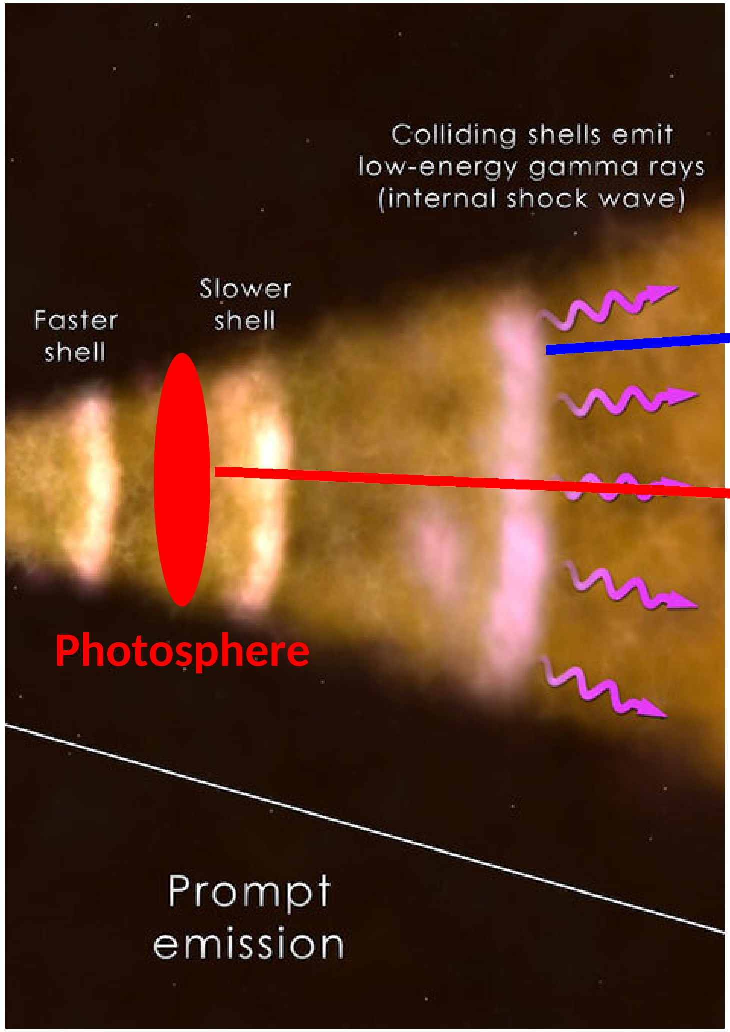
- marginally fast synchrotron cooling?
  - low E slopes of SC + efficiency of FC
  - **highly** dependant on conditions!

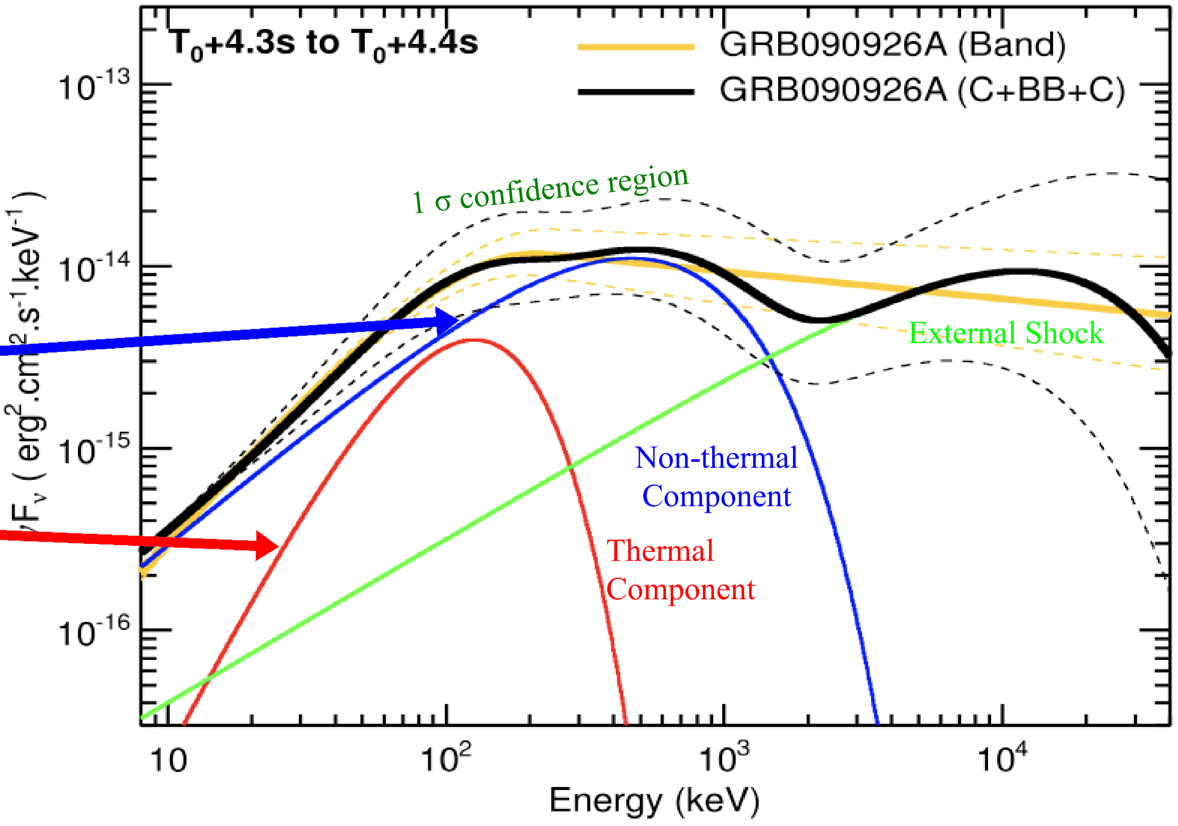
$$\frac{\nu_c}{\nu_m} \propto \Gamma^2 E^6 t_{\mathrm{dyn}}^{-2} \nu_{\mathrm{p}}^{-4}$$

(Beniamini+ 2018)

- inverse Compton cooling?
  - spectra suggests KN regime
  - microphysics at odds with other expectations

Spectra - a thermal component?





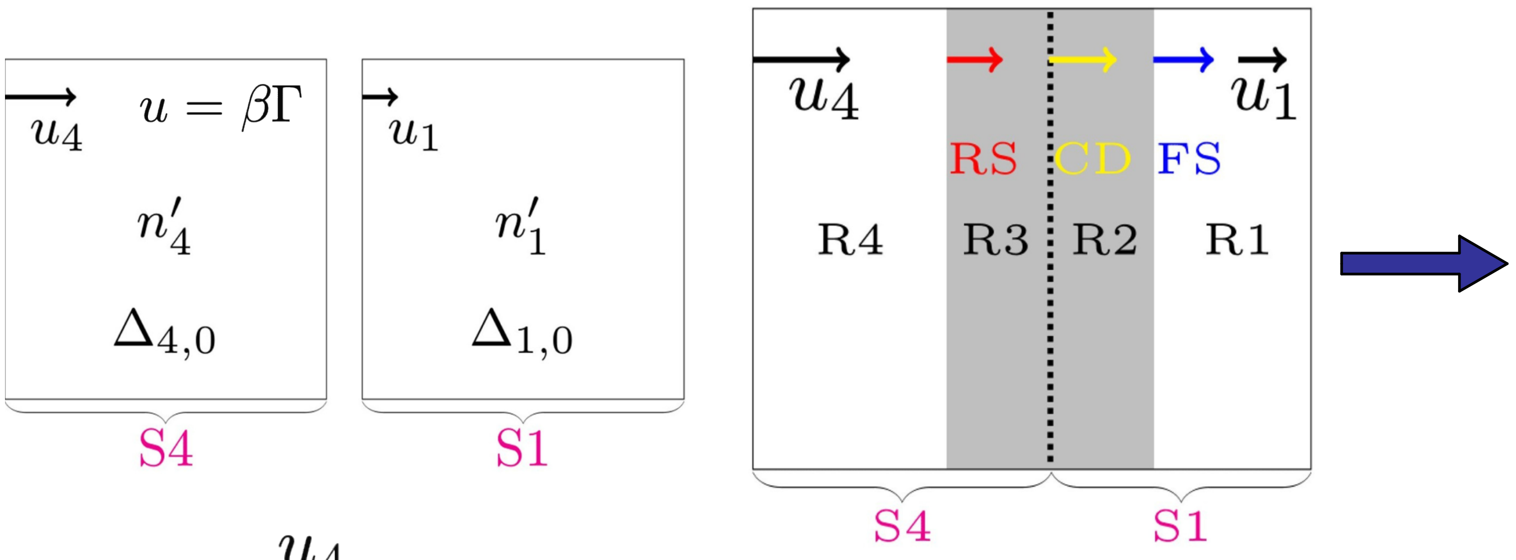
(Guiriec+ 2015)

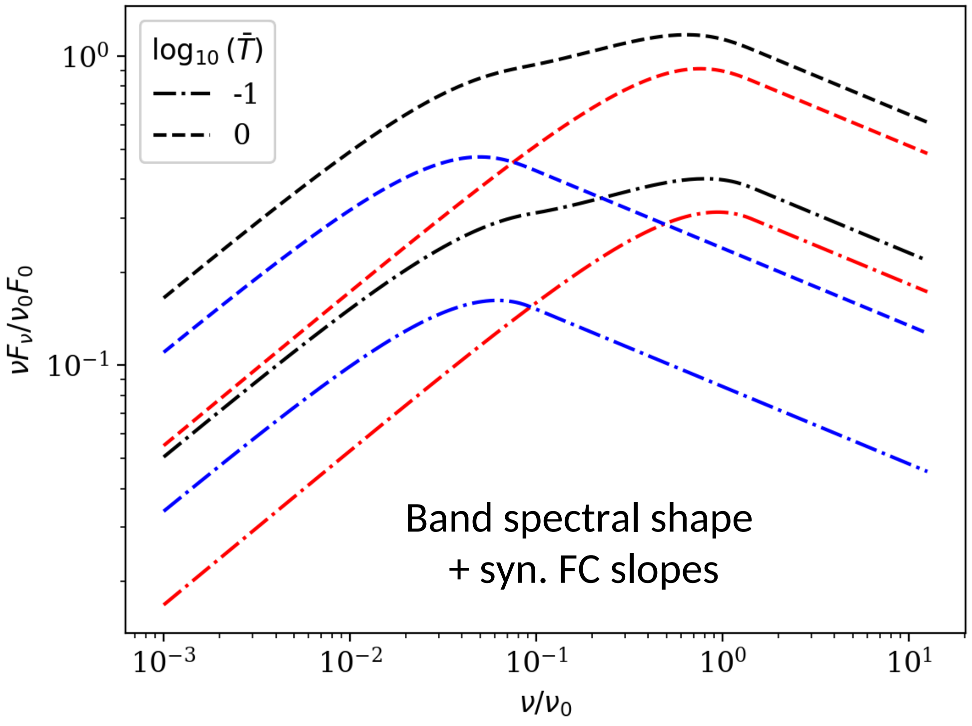
ad hoc component

breaks the simplicity + not always self-consistent

The collision of 2 shells

Context: Rahaman+ 24a,b, collision of two cold shells in planar symmetry





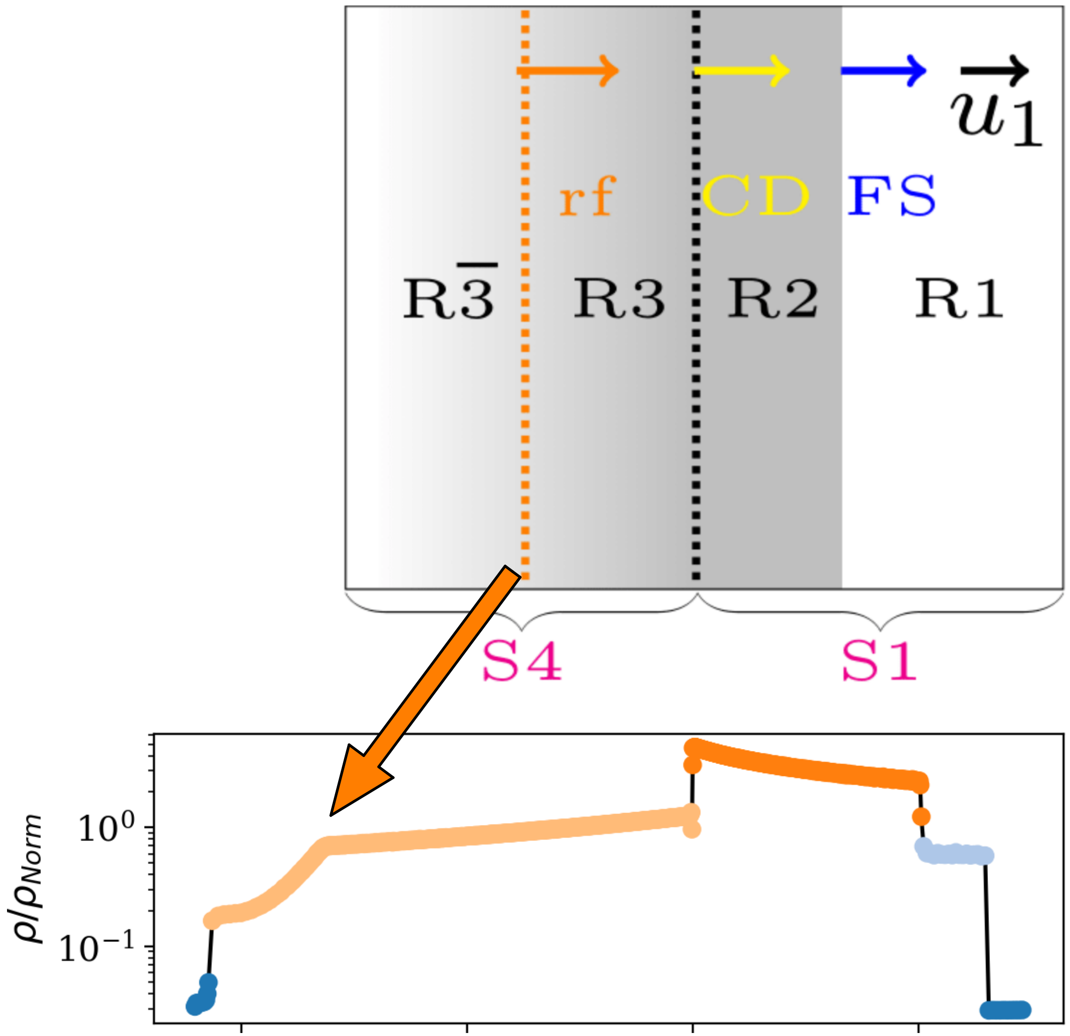
$$a_u = \frac{u_4}{u_1}$$ main physical parameter

$$\rho_i, u_i, \Delta_{i,0}, R_0 \;\rightarrow\; \rho_d, \Gamma_d, e_d, \Gamma_{\rm sh}, \ldots \;\rightarrow\; \nu'_p, L'_{\nu'}$$

Result 1: hydrodynamics of shock fronts fully determined **for any parameters**

Result 2: for typical GRB parameters, **RS and FS dissipate comparable energies**

A hydro constraint: the rarefaction wave



PdV work S4 on S1

→ reprocessed thermal energy can increase efficiency

or

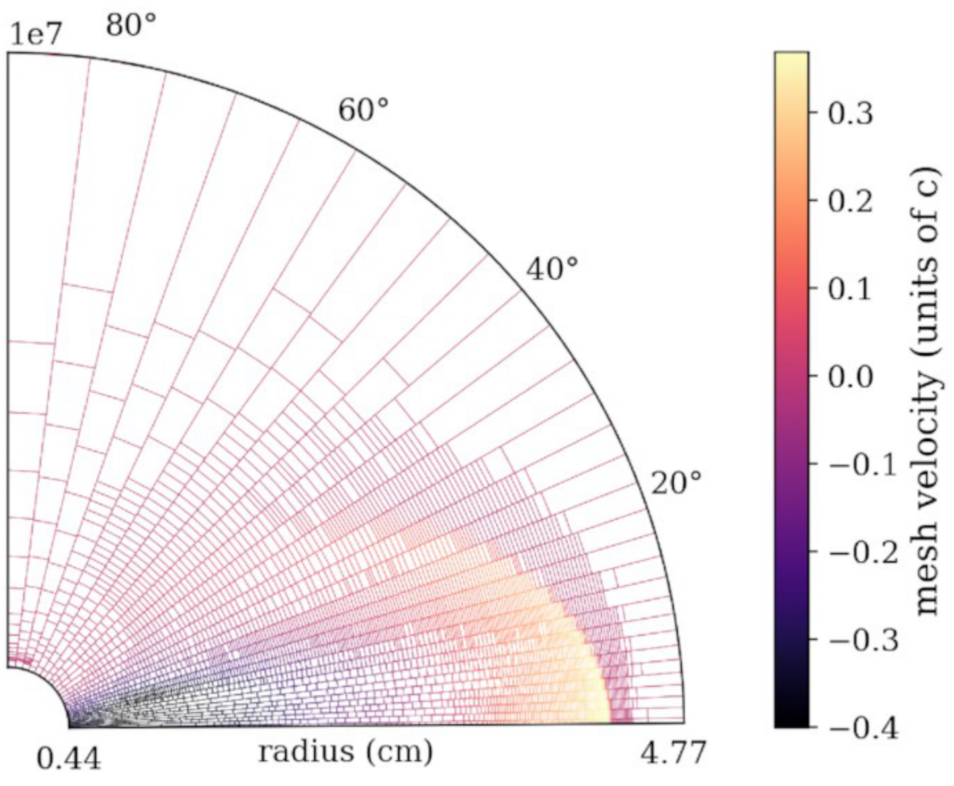
→ **RF wave can halt dissipation**, efficiency imposes

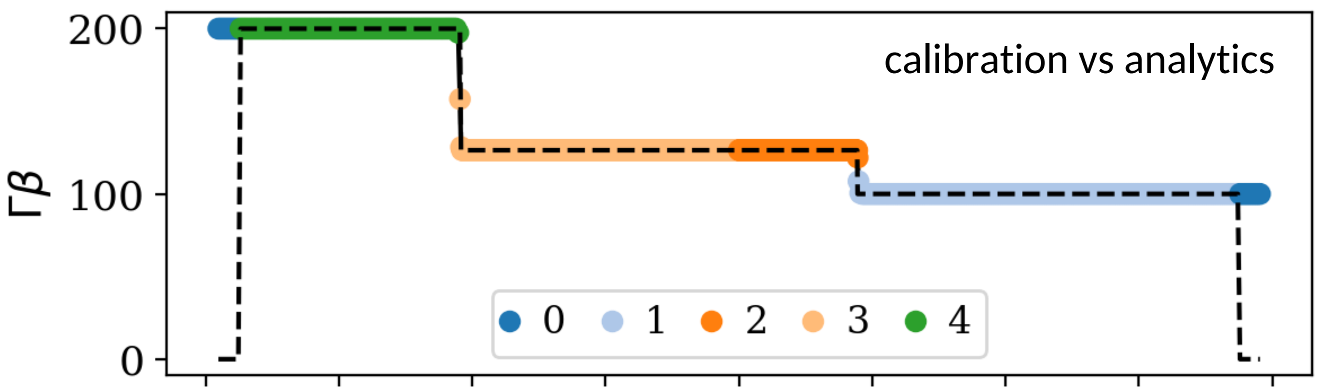
$$0.5 \lesssim \chi = \frac{\Delta_{0,1}}{\Delta_{0,4}} \lesssim 2.5$$

Internal shocks simulations

Hydro : GAMMA (Ayache+ 22) for SRHD

moving mesh suited for propagation over large scales: light, shock capturing, Lagrangian cell behavior

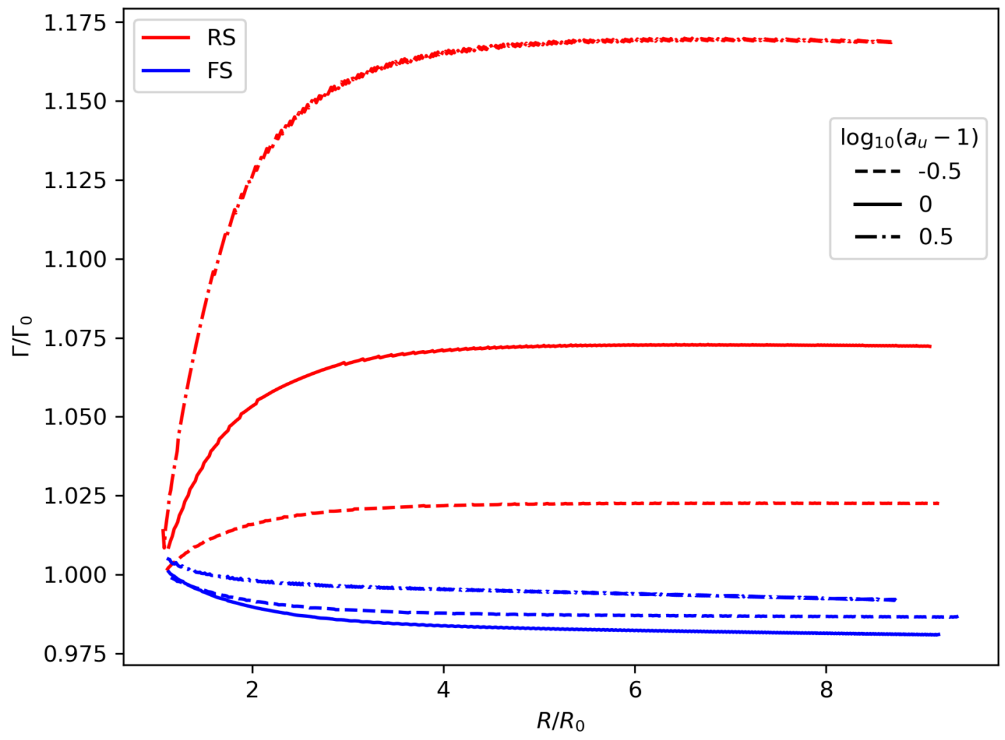


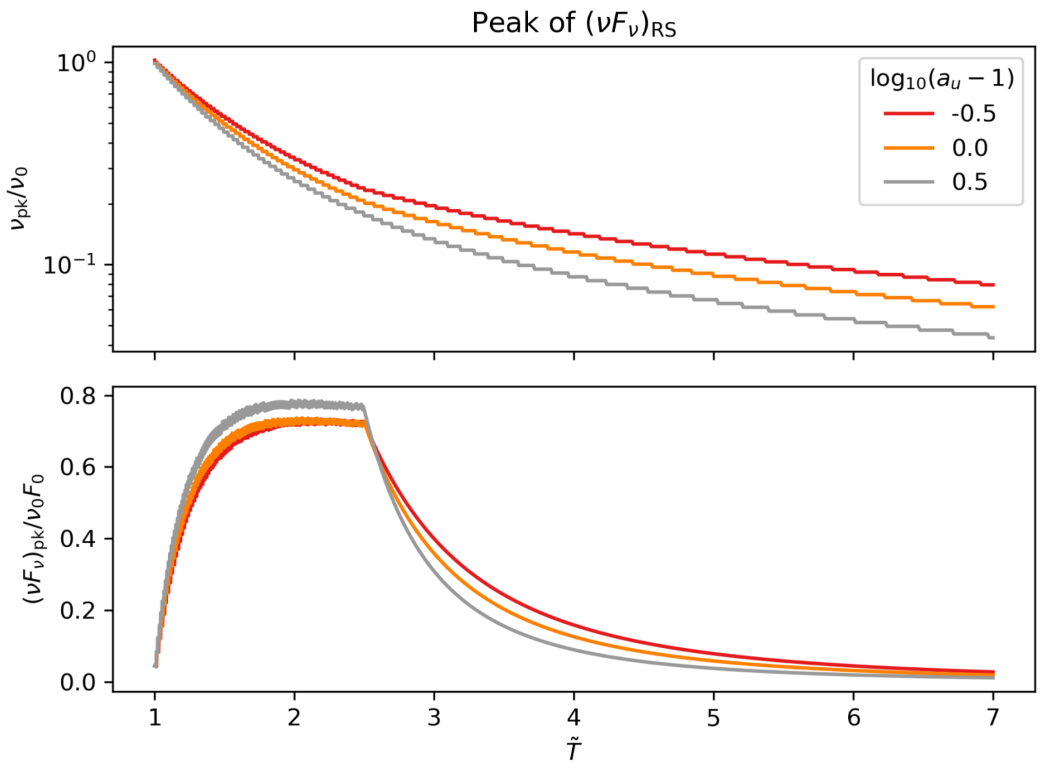


Emission calculation:

1. select contributing cell, derive $\nu_m, \; \tilde{L}_{\nu'_m}$
2. compute flux contribution
$$\Delta F_\nu(T) = \frac{1+z}{4\pi d_L^2} \tilde{L}_{\nu_m} \tau^{-2} S\left[\tau \frac{\nu}{\nu_m}\right]$$
3. add to the total

Spherical effects





RS accelerate, FS decelerate → dissipation rate ↘

→ hard-to-soft evolution depends on proper velocities contrast

Building a surrogate model

constant source power

→ *normalized* peak flux & freq controlled by **only 2 parameters:**

a_u → physics

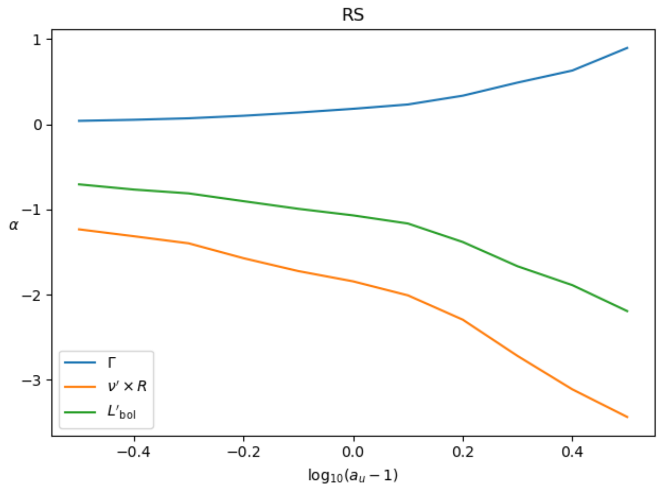
$\frac{t_{\rm on}}{t_{\rm off}}$ → timings (transition to HLE)

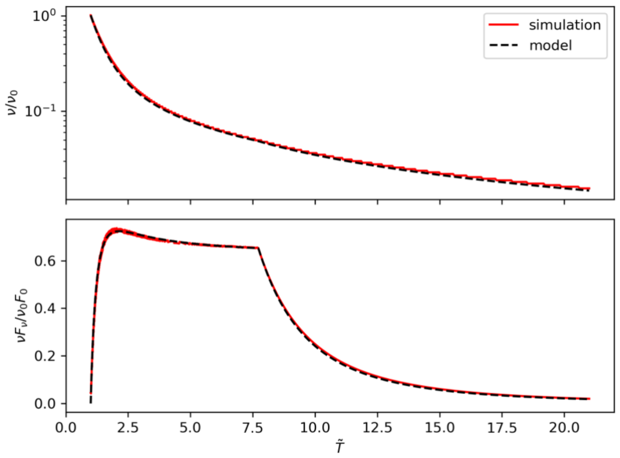
Method:

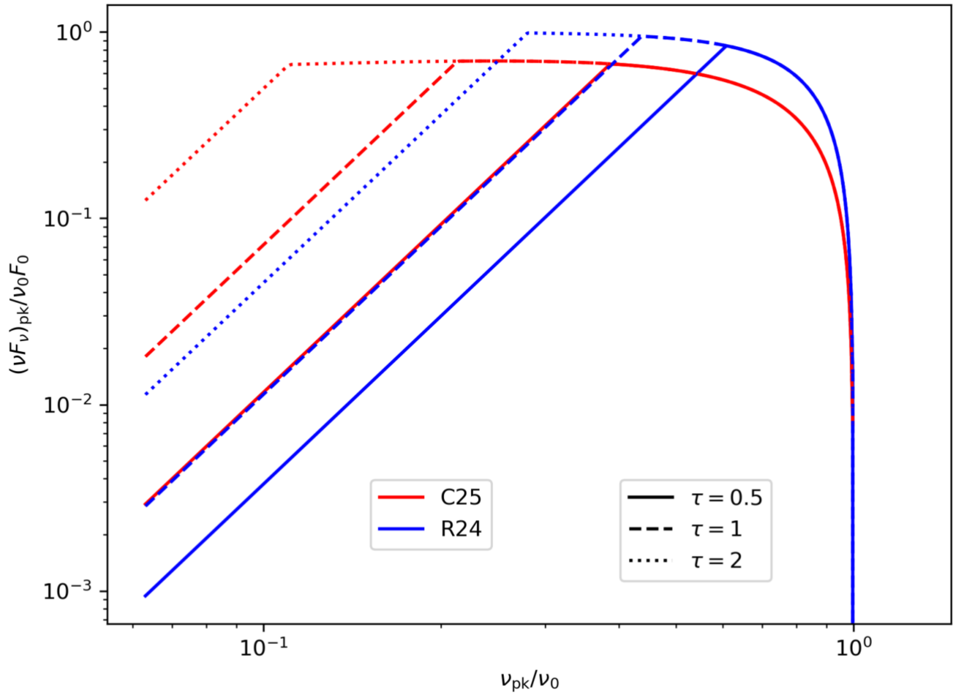
→ sample the $\log(a_u - 1)$ space, set large $t_{\rm on}/t_{\rm off}$

→ fit 'hydro' quantities with a smooth bpl of $x = R/R_0$

→ fit pk flux - pk energy with 'effective angle' $\xi_{\rm eff}(\tilde{T})$





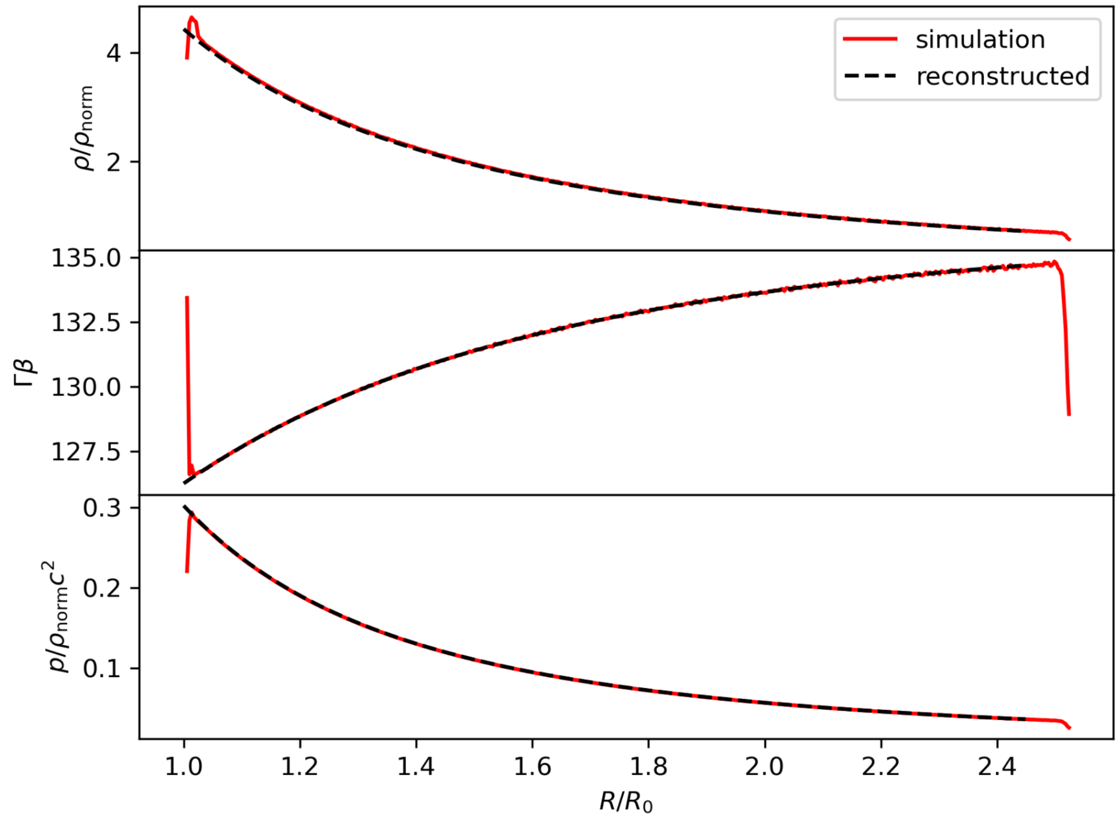


$\nu_p - \nu F_\nu(\nu_p)$ correlation highlights spherical effects

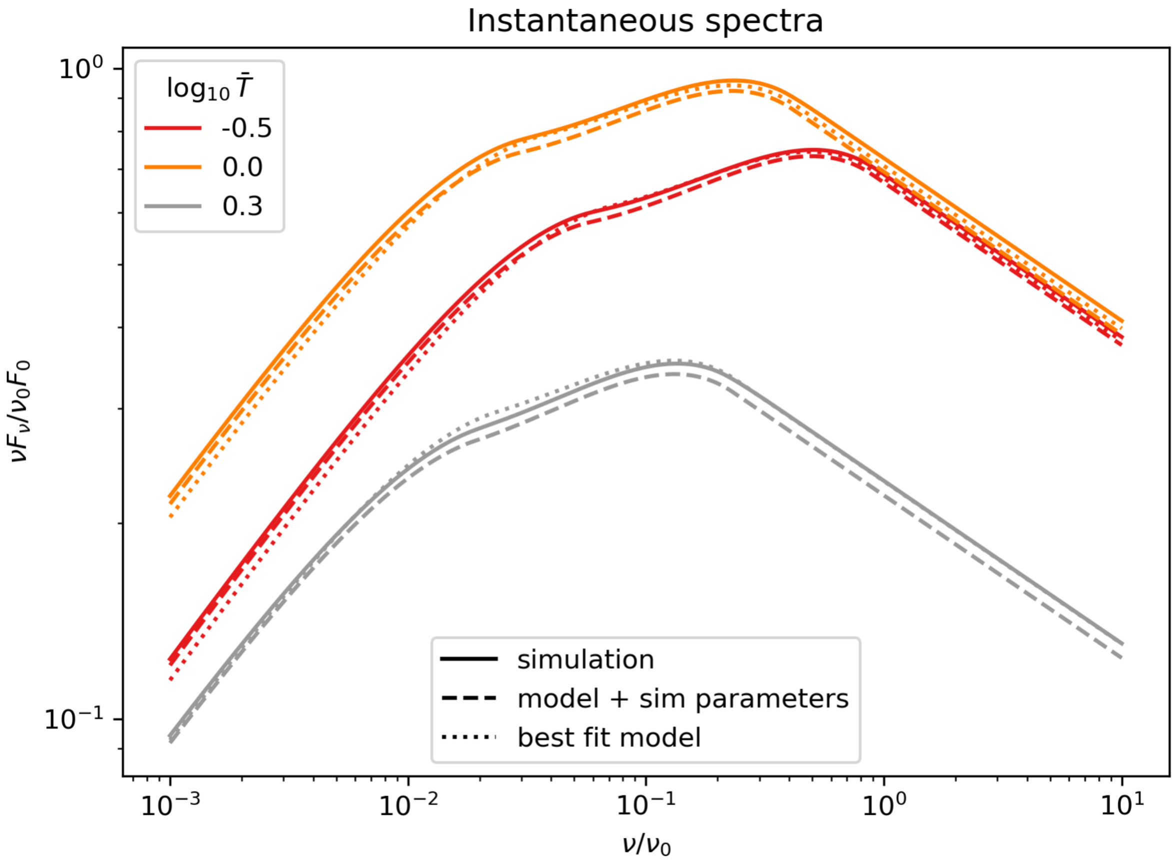
(C25: this study, R24: analytical)

Building a surrogate model (2)

with $\Gamma(x)$, reconstruct hydro downstream:

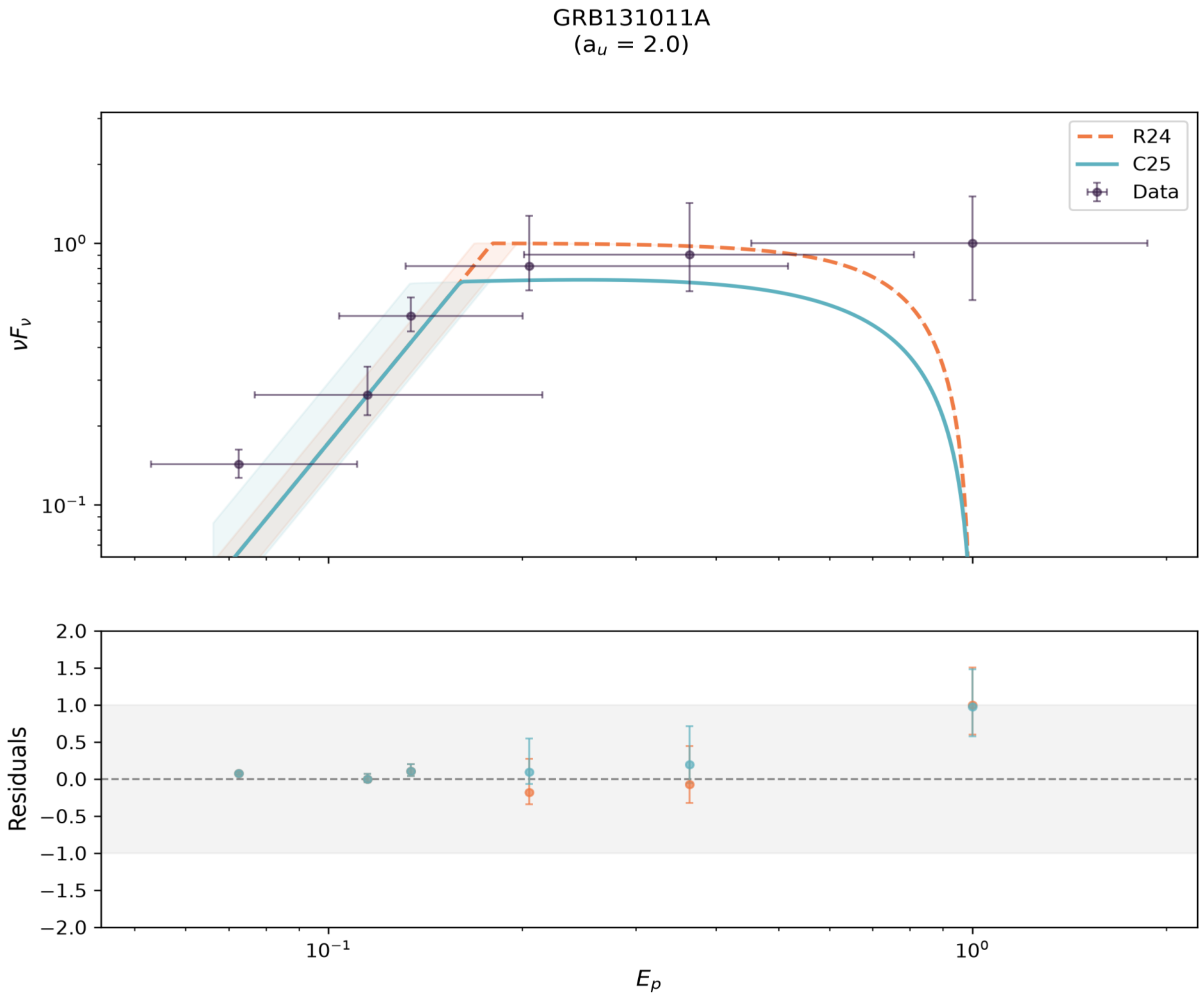


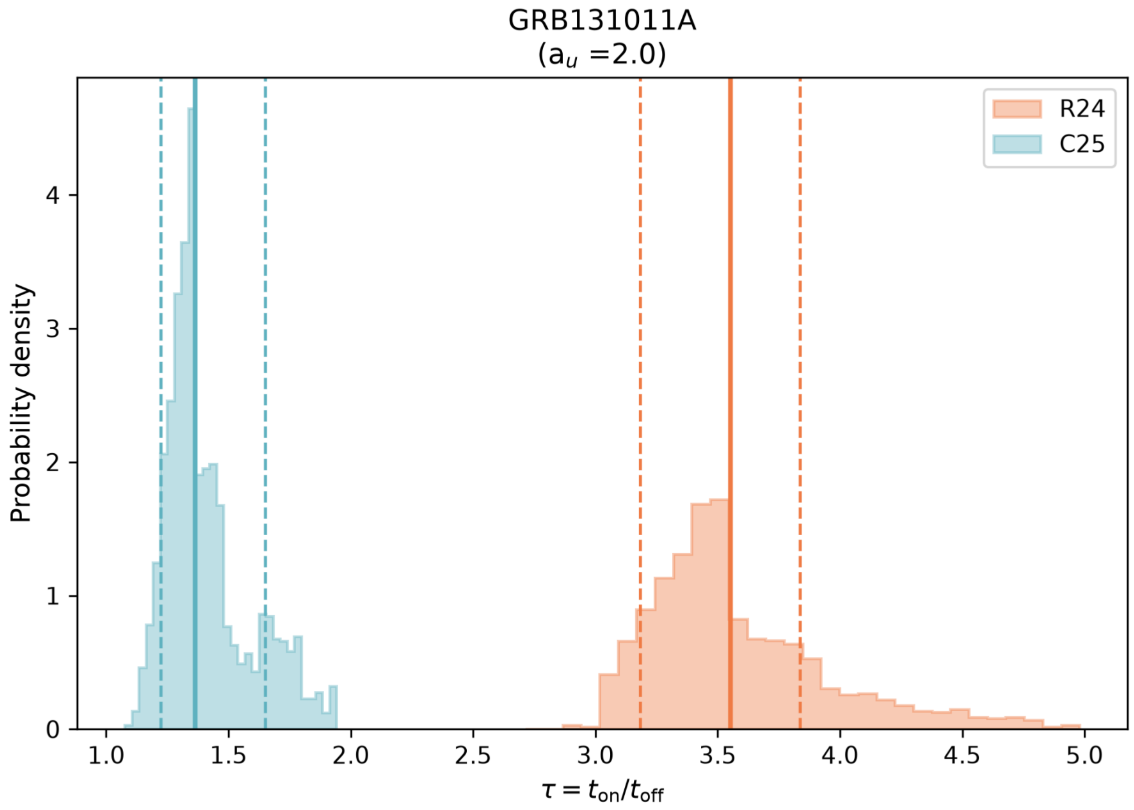
Peaks model + spectral shape = spectral model



Application to data (WIP)

fitting $\nu_p - \nu F_\nu(\nu_p)$ correlation:



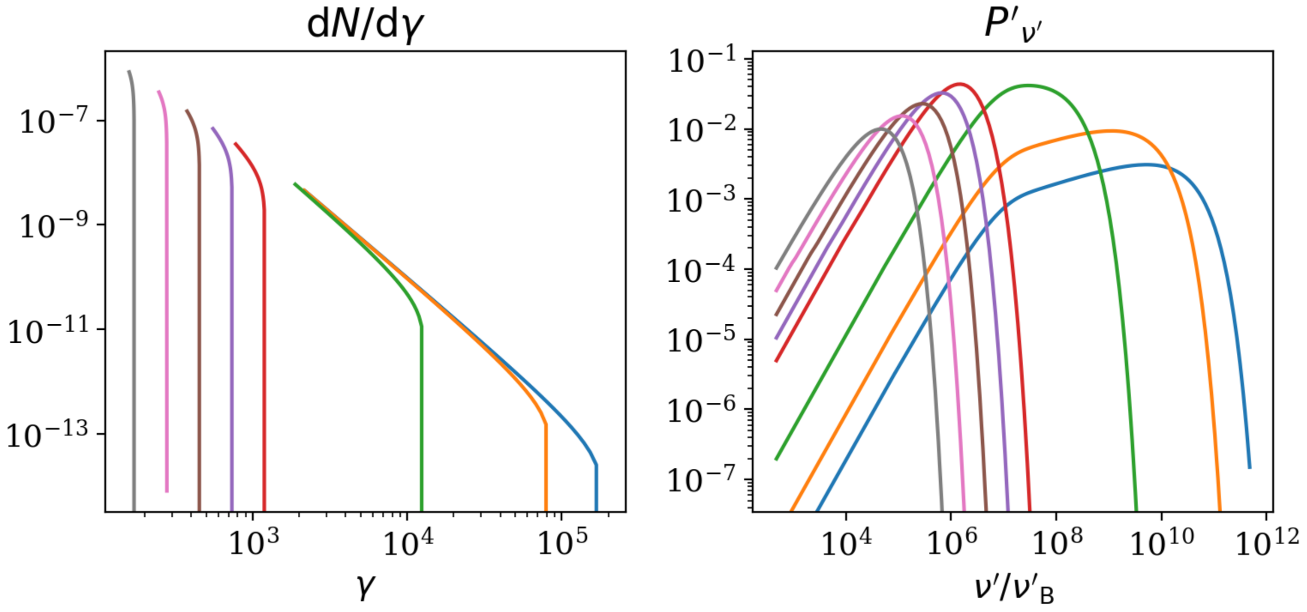


credits: K. Nadaf (Nanjing U.)

Cooling regimes (WIP)

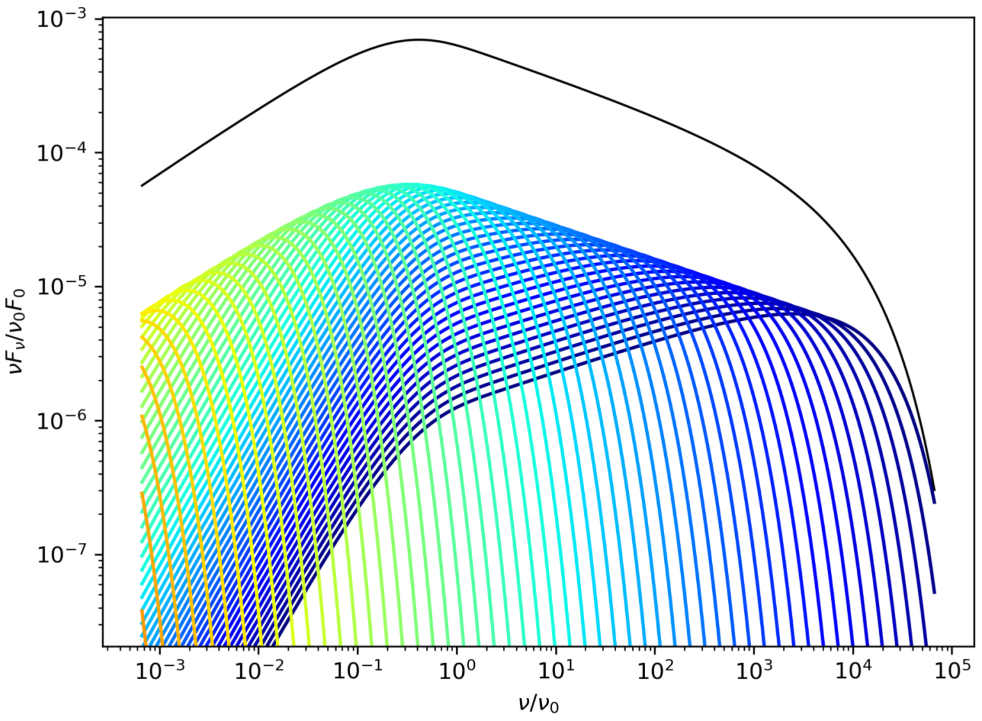
cells are Lagrangian → we can follow e⁻ distribution

$$\frac{\mathrm{d}\gamma_\mathrm{e}}{\mathrm{d}t'} = -\frac{1}{t'_\mathrm{c}}\gamma_\mathrm{e}^2 \rightarrow \frac{\mathrm{d}n}{\mathrm{d}\gamma_\mathrm{e}} = K\gamma_\mathrm{e}^{-p}(1-\gamma_\mathrm{e}\tilde{t})^{p-2}$$



reconstruct hydro over 'cooling' time bins

self-consistent spectral computing of each numerical cell
→ study effects of finite width emission region



Conclusion: the internal shock revisited

- complete theoretical framework for the collision of 2 shells
  → explains low E photon excess in GRB prompt emission
- extension to spherical geometry shows effects on emission
  → modified peak behavior needed for proper data modeling
- a simple model for pulses data fitting
  → $\nu_p - \nu F_\nu(\nu_p)$ correlation, spectral model

From toy model to realistic physics:

- self-consistent synchrotron slopes
- optical counterpart prediction
- realistic initial conditions
- and more!.. (2D effects, variable microphysics, off-axis viewing...)