Internal hydrodynamical shocks as a mechanism for GRB prompt emission

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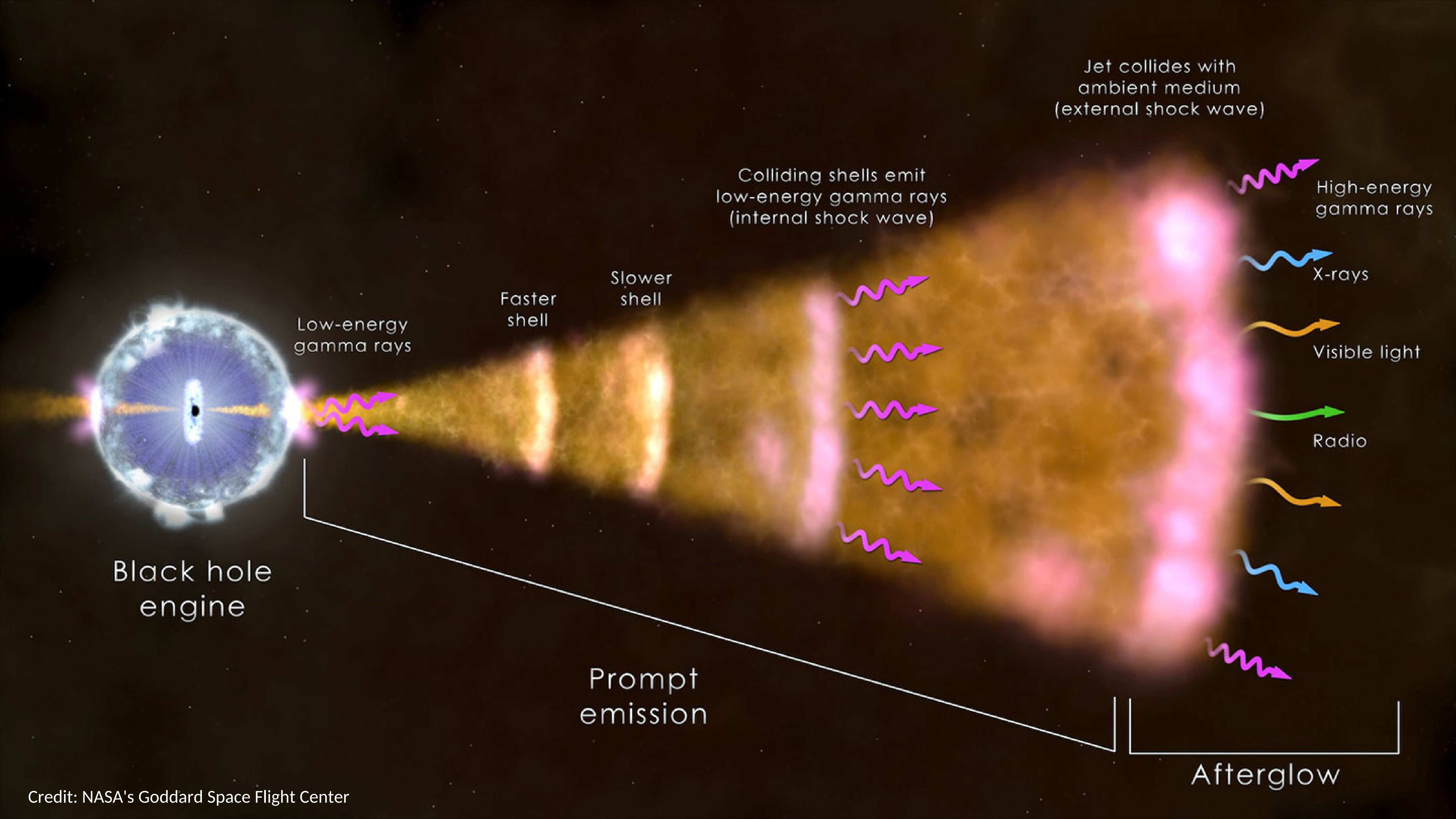
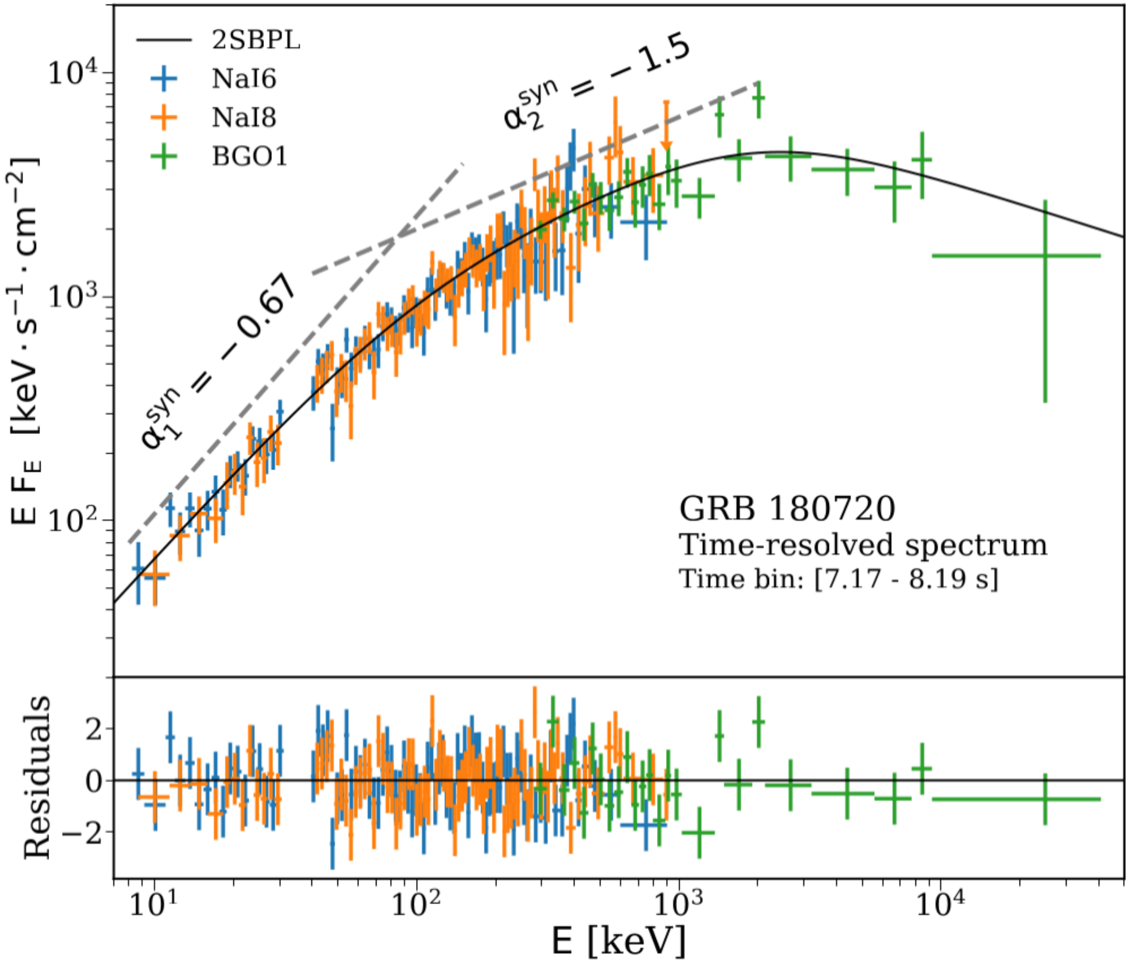


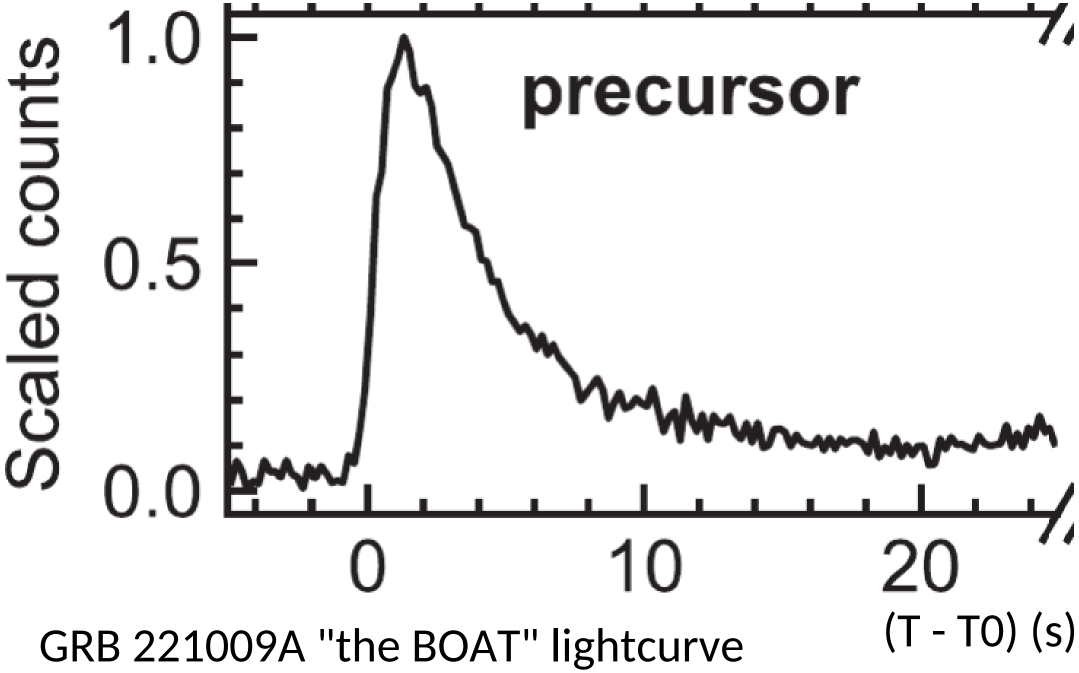
Credit: NASA's Goddard Space Flight Center

GRB properties

- doubly broken power-law spectrum
- Fast Rise Exponential Decay lightcurve



(Ravasio+ 2019)



GRB 221009A "the BOAT" lightcurve

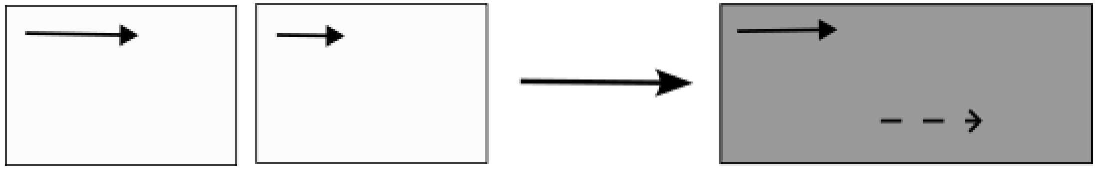
(Yan+ 2023)

The ballistic approach

(Daigne & Mochkovitch 98)

2 shells → 1 shell

$$(\Gamma_1, \Gamma_2) \rightarrow \Gamma_r \approx \sqrt{\Gamma_1 \Gamma_2}$$



internal motion dissipate energy $\epsilon = (\Gamma_{int} - 1) m_p c^2$

→ accelerate electrons → radiation (synchrotron, IC..)

$$\Gamma_{int} = \frac{1}{2}\left[\left(\frac{\Gamma_1}{\Gamma_2}\right)^{1/2} + \left(\frac{\Gamma_2}{\Gamma_1}\right)^{1/2}\right]$$

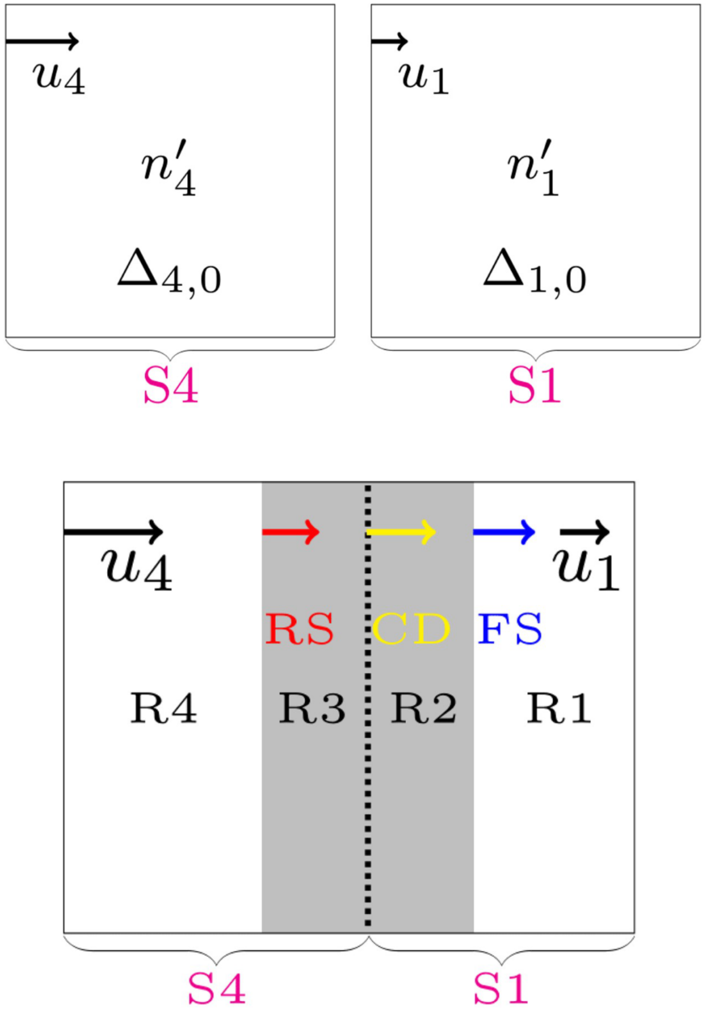
one zone model (single emitting front)

- lot of successes explaining observations
- cannot explain the subdominant component

→ photospheric? other contribution?

Model update: Rahaman+ 24a

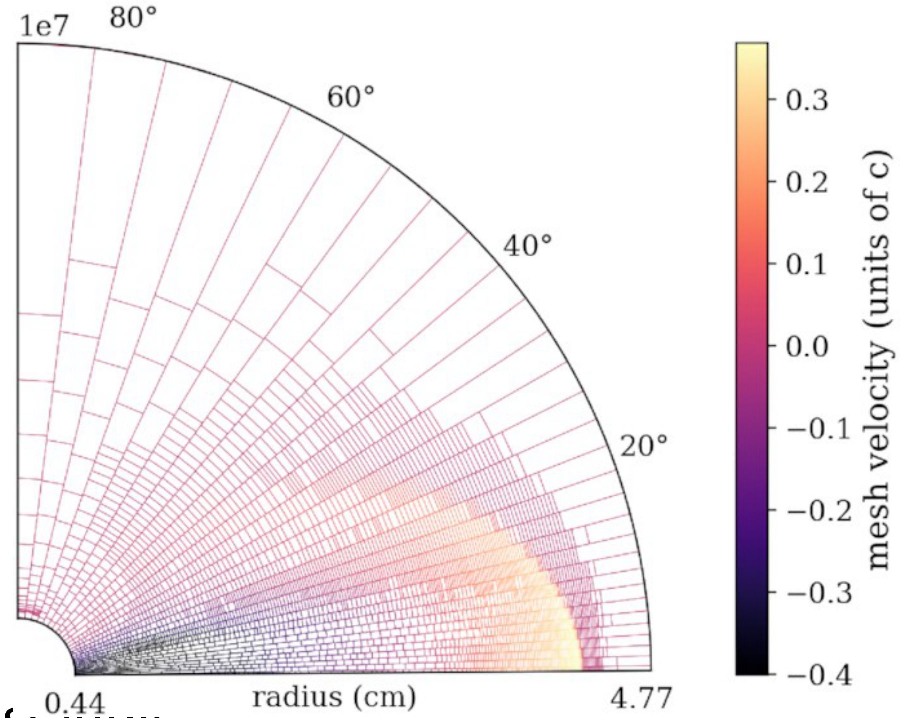
- Buy 1 shock, get 1 free!
  - 1 shock = 1 infinitely thin shell propagating & emitting
  - hydro in planar
  - emission calculated by adding propagation effects
- Explains obs. features without fine-tuning:
  - subdominant low-energy spectral component
  - doubly-broken power law spectrum
- Still some defaults:
  - low velocity ratio imposed to reproduce peak energies ratio
  - assumptions on propagation effects may not hold



Rahaman+ 24a

The methods

- Hydro : GAMMA (Ayache+ 22) for SRHD +
  - moving mesh suited for propagation over large scales
  - good shock capturing
  - can evolve e$^-$ distributions



- Rad : Genet & Granot 09, de Colle et al. 12
  - thin shell approximation: all energy is radiated away 'instantly
  - spectral shapes: Band and synchrotron broken pow. law (syn-BPL)

  - 1 shock front = 1 source of emission

$$\Delta F_\nu(\tau \geq 1) = \frac{1+z}{4\pi d_L^2} \tilde{L}_{\nu_m} \tau^{-2} S\left(\tau \frac{\nu}{\nu_m}\right)$$

Colliding shells hydrodynamics (planar)

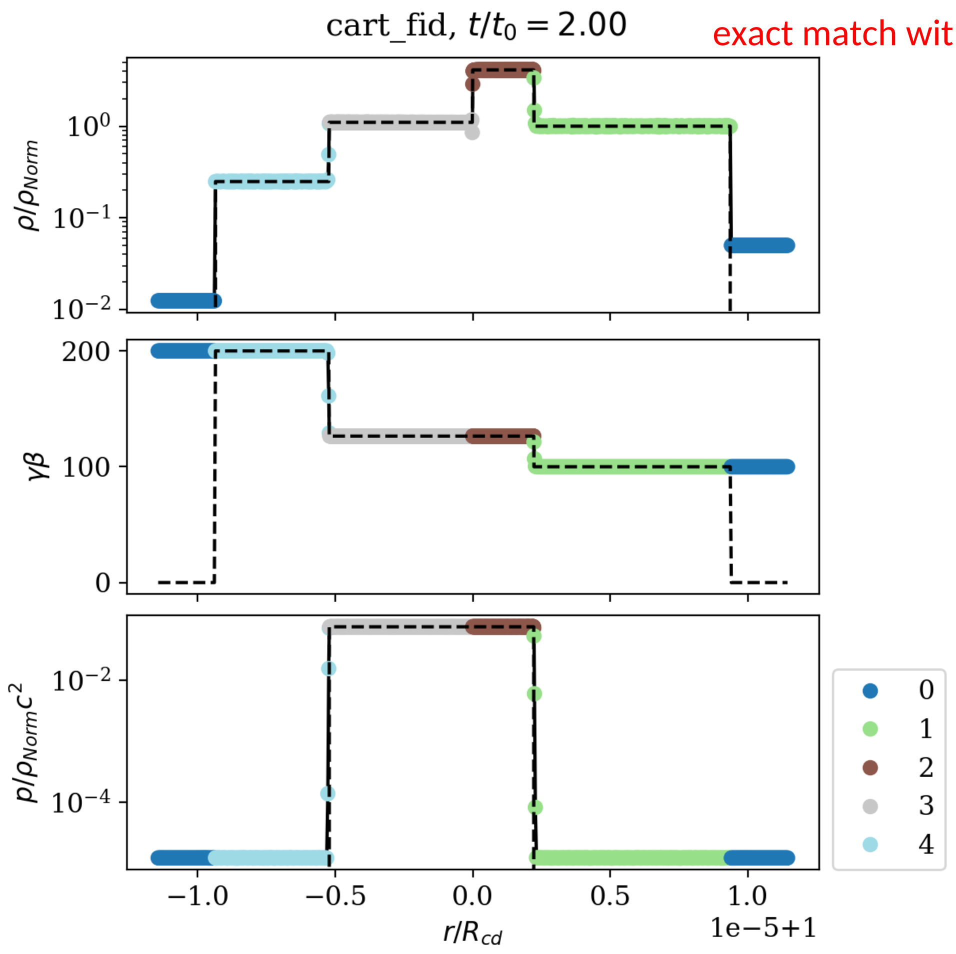
All quantities analytically derivable:

shock fronts propagation → crossing times and radii → pulses peak & width

shock strength → energy conversion → peak frequency and luminosity

$$\gamma_m = \frac{p-2}{p-1}\frac{m_p}{m_e}\frac{\epsilon_e}{\xi_e}(\Gamma_{ud}-1)$$

$$L'_{bol,\gamma} = \epsilon_e(\Gamma_{ud}-1)\frac{\mathrm{d}M}{\mathrm{d}t'}c^2$$



exact match with R24a!

Charlet+ (in prep.)

From hydrodynamics to emission

Analytics:

1. define Equal Arrival Time Surface
2. integrate luminosity over EATS

Numerics:

1. identify shock
2. derive freq. & lum. from hydro
3. add contributions

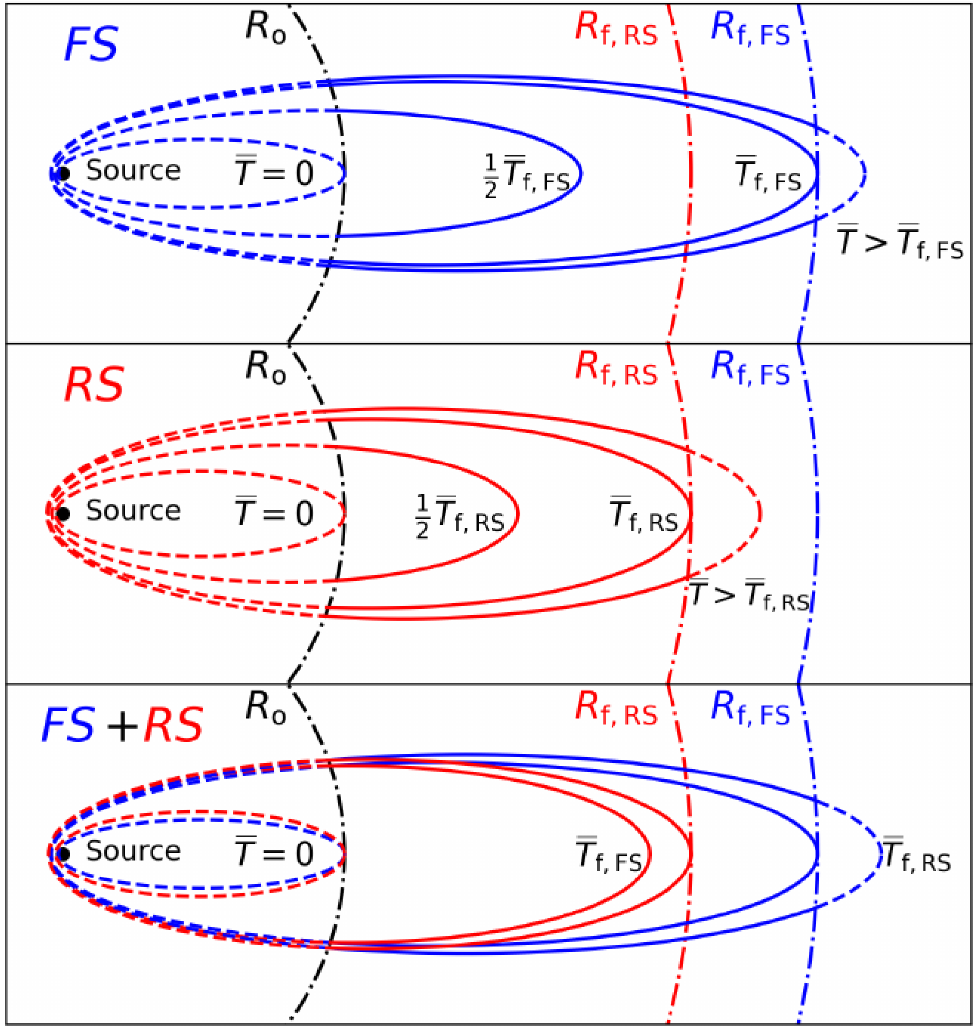
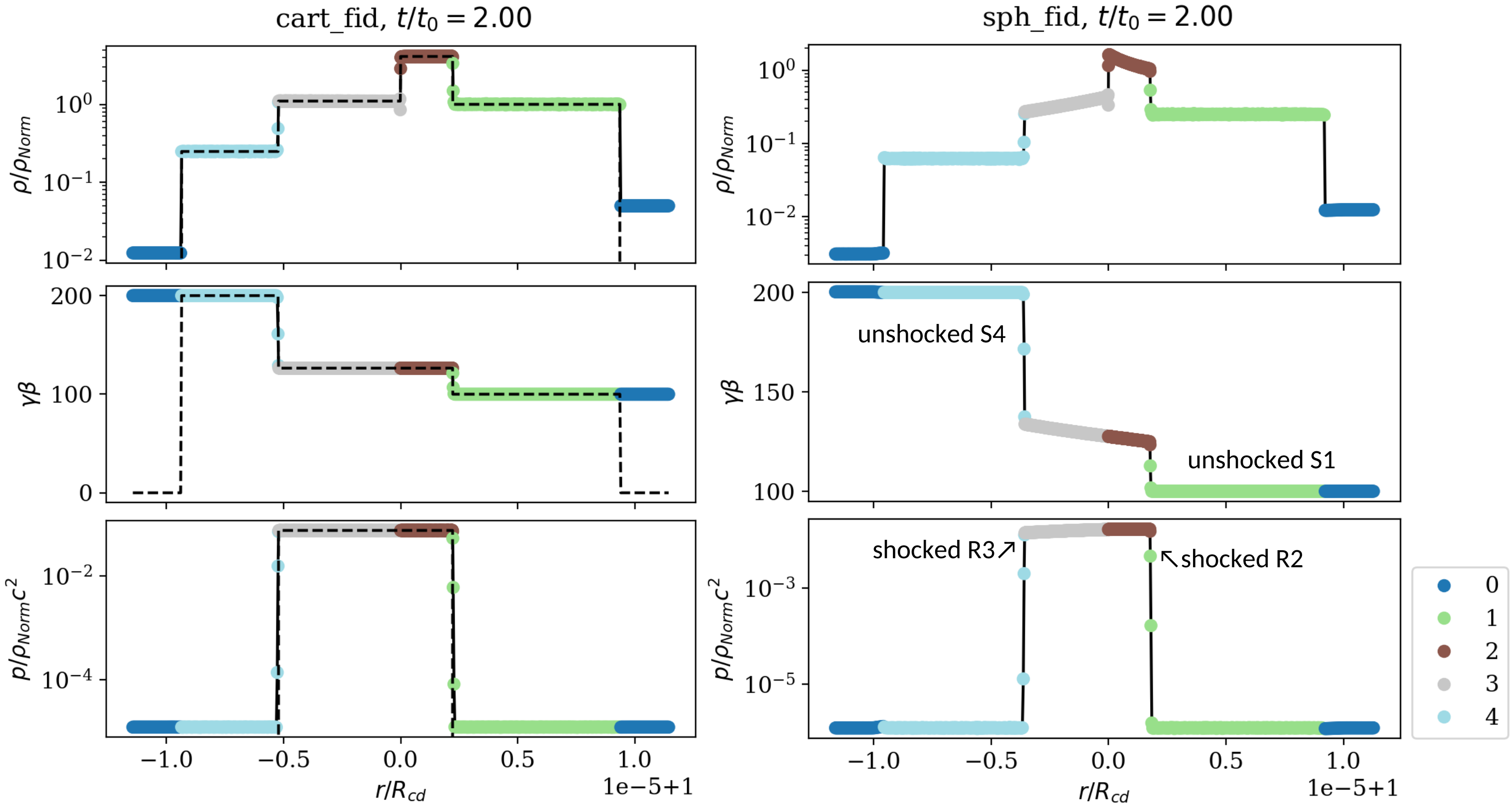


Illustration of EATS (Rahaman+ 24b)

Colliding spherical shells - hydro



planar vs spherical:
everything changes

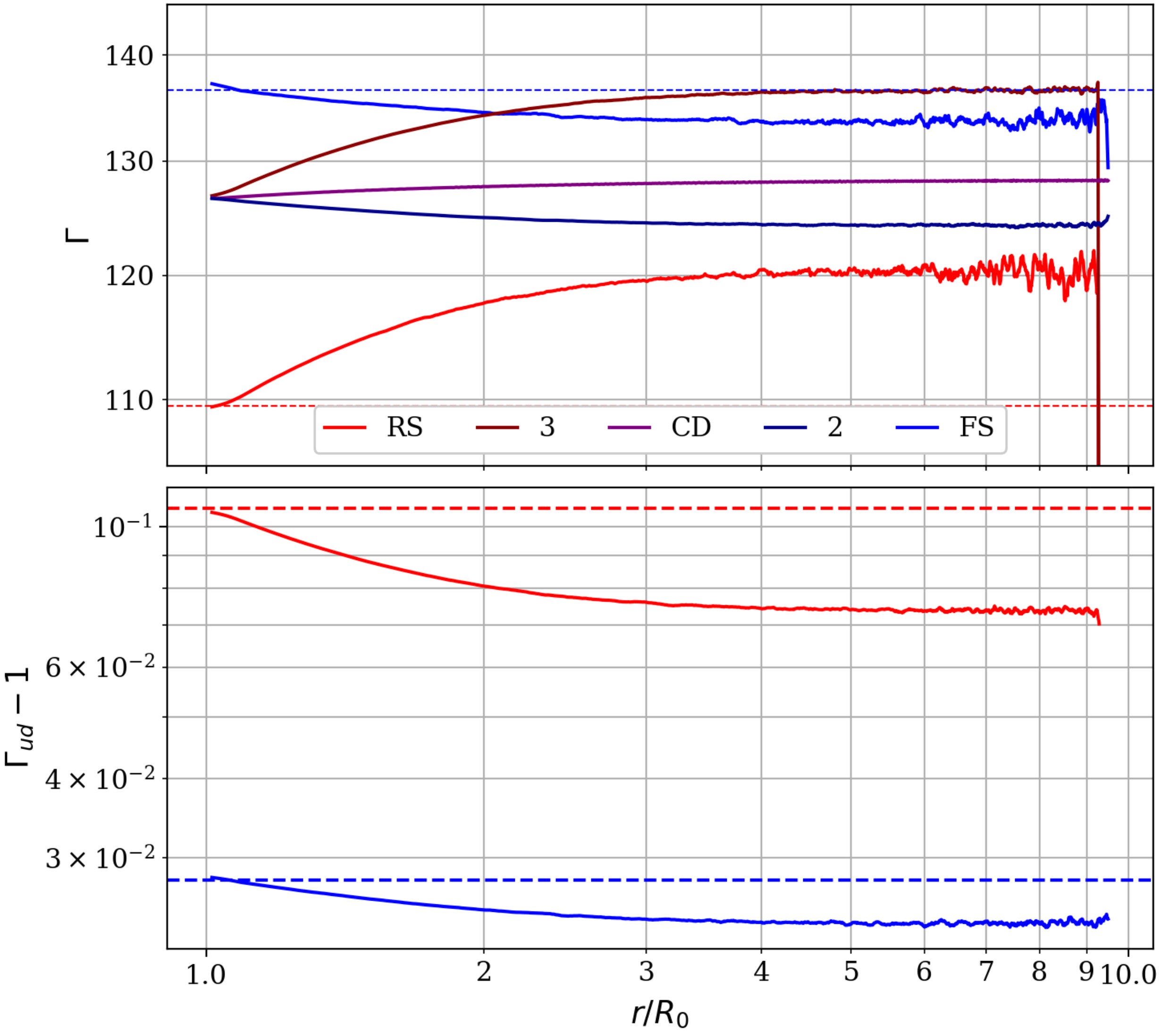
Shocked region structure:

- compression towards center
- velocity profile
- shallow pressure profile

Shock dynamics:

- increase in shocks crossing time and radius
  → shift lightcurve peaks
- variable shock strength!

Spherical effects over doubling radius



- p.law below doubling radius
- converges to constant value

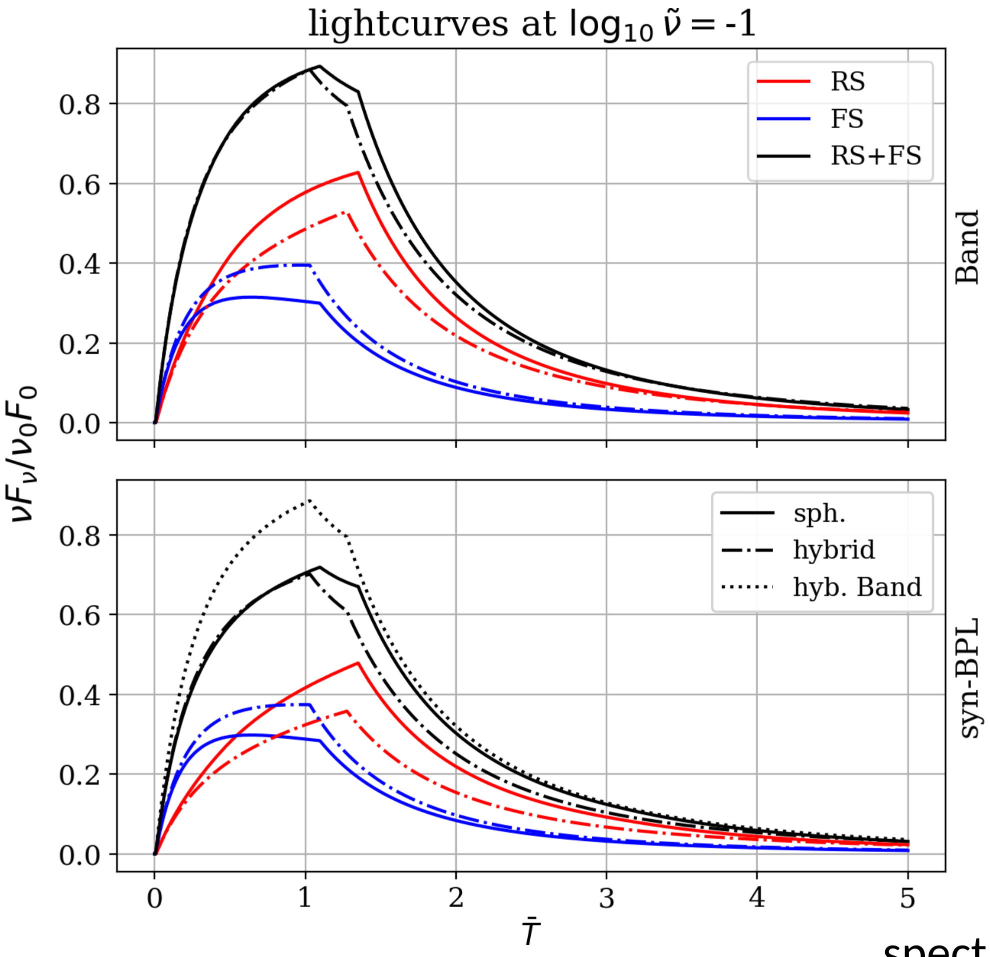
$$X(R) = \left[\left(X_{\rm pl}\left(\frac{R}{R_0}\right)^l\right)^s + (X_{\rm sph})^s\right]^{1/s}$$

for fiducial sim, $\frac{\Delta R_{\rm sph}}{R_0} = 1.52$

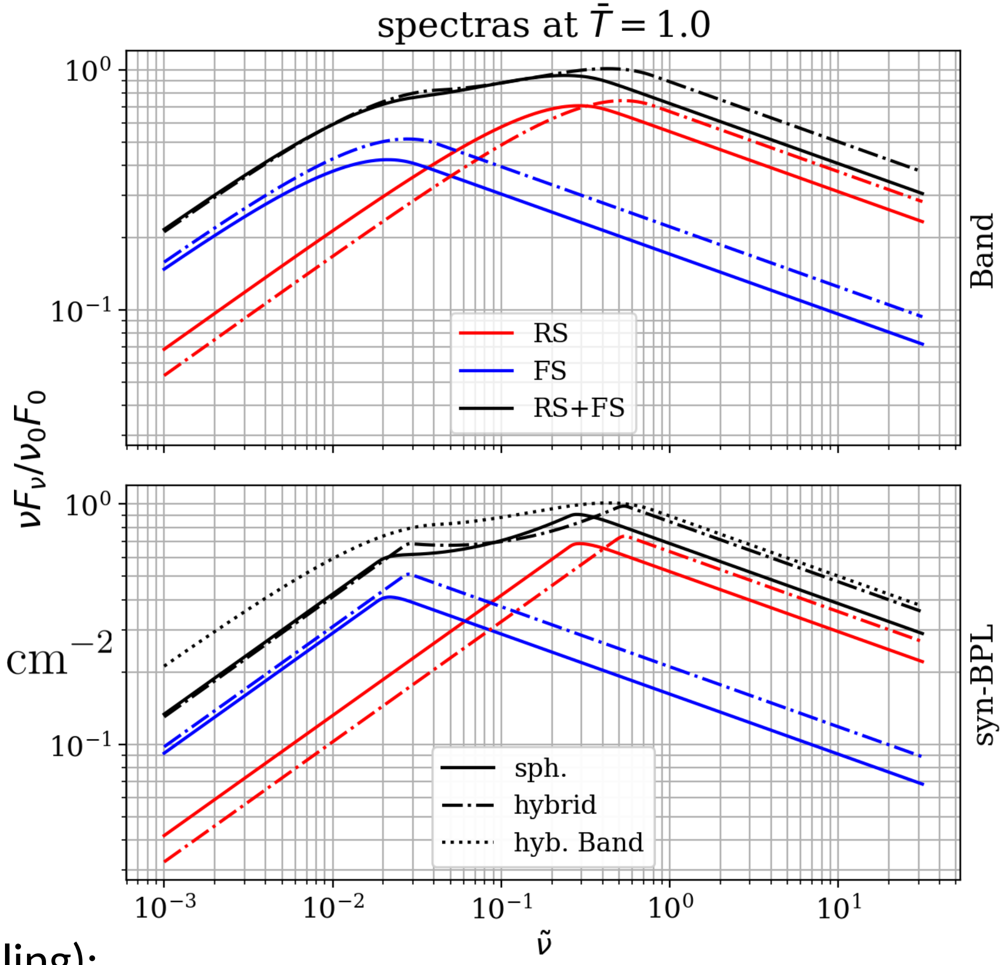
→ p. law approximation won't work to properly describe emission

→ fit hydro to fit flux

Spherical colliding shells - emission



$$\nu_0 = 450\,\mathrm{keV}$$
$$\nu_0 F_0 = 25\,\mathrm{keV}\cdot\mathrm{s}^{-1}\cdot\mathrm{cm}^{-2}$$



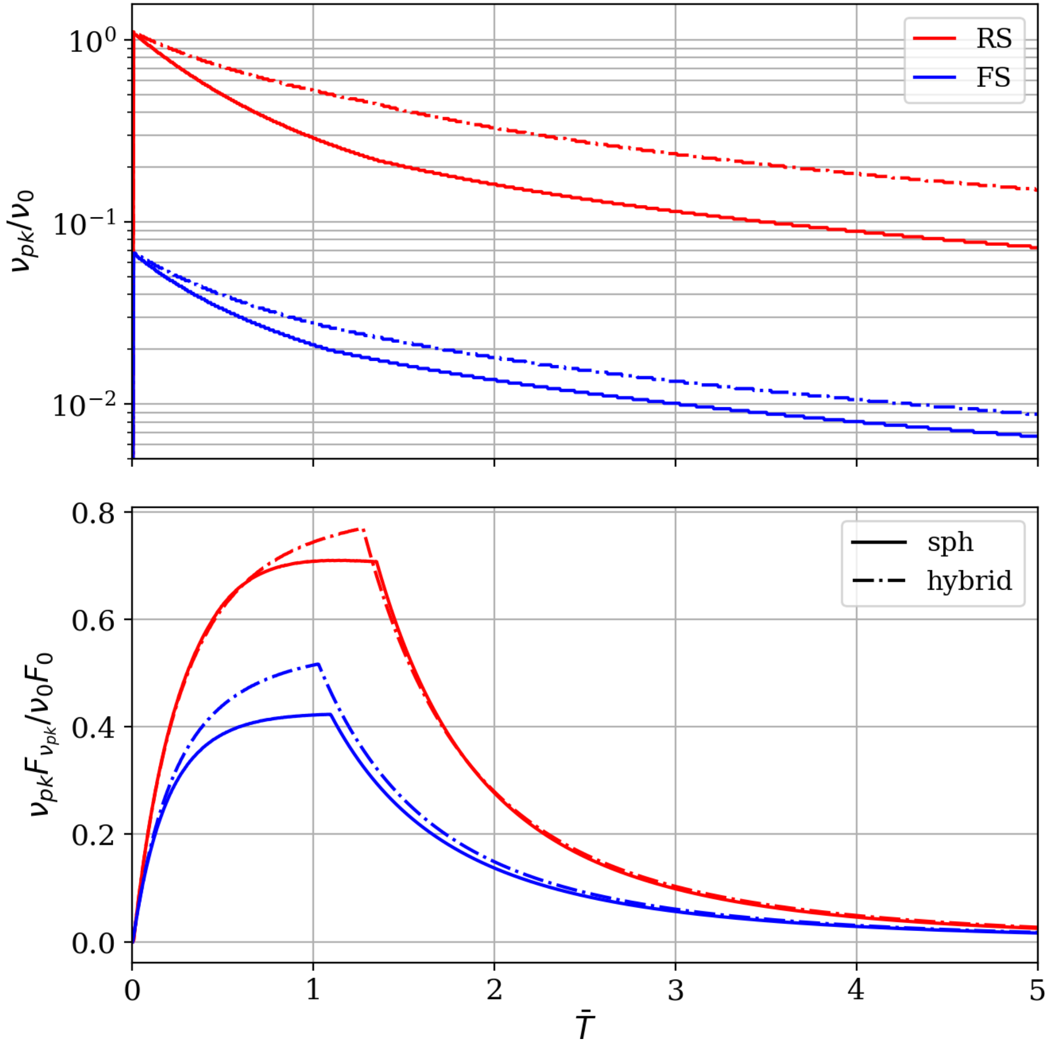
spectral shape (very fast cooling):

$$b_1 = -1/2,\ b_2 = -p/2$$

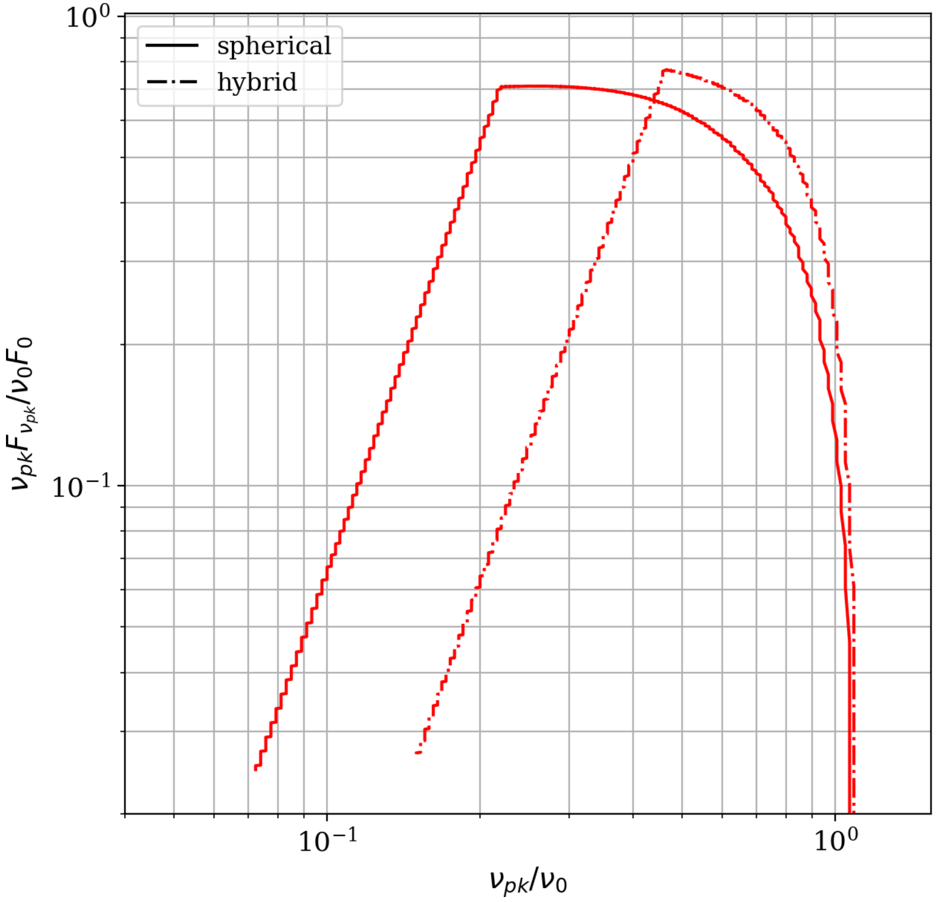
→ ≠ individual shock contributions
→ similar total lightcurve

→ lower frequency peaks

Peak frequency and flux

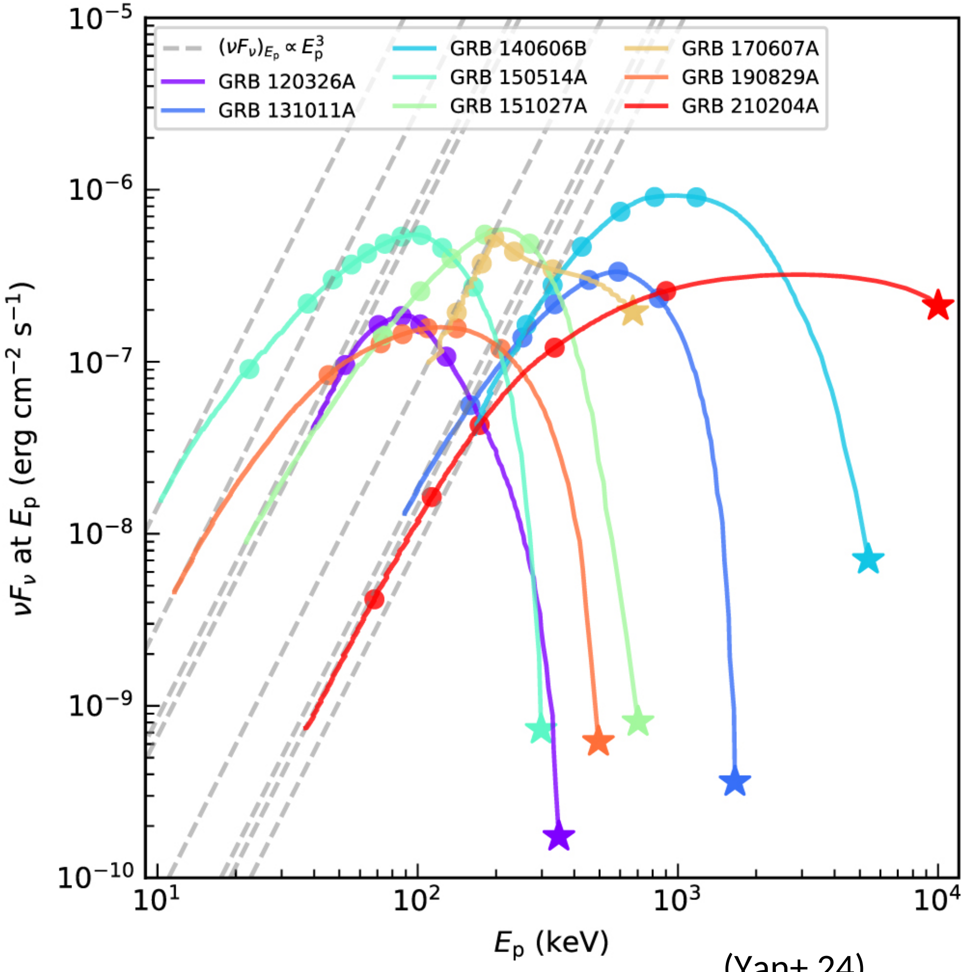


pk freq ↘ faster, peak flux saturates



→ sharp because of assumptions
→ extends to lower freq
→ low freq tail $\nu_{pk}F_{\nu_{pk}} \propto \nu_{pk}^3$

From flux to central engine



(Yan+ 24)

R24: no saturation, derivation of source activity possible

GRB	$\nu_{\max}/\nu_{1/2}$	$\Delta R/R_0$	$t_{\rm on4}/t_{\rm off}$
140606B	0.45	1.66	1.29
131011A	0.59	1.04	0.81
170607A	0.36	2.36	1.85
151027A	0.65	0.84	0.66
150514A	0.60	0.99	0.78
120326A	0.70	0.71	0.56
190829A	0.50	1.40	1.09

→ need more ingredients to fit observations to central engine

Conclusion

- Internal shock model revisited
  - planar hydro model showed success in reproducing some obs. features
  - extension to spherical shells using simulations: p. law before doubling radius then saturates
  - emission from fiducial run precises results, spectral behavior closer to observations
  - exploration of fully spherical behavior for larger scope model

- Some strong assumptions

  very fast cooling, homogeneous shells, no LF drift, constant microphysical parameters..

- More work to do
  - include cooling regimes
  - vary microphysics
  - apply to more complex flows (link with GRMHD simulations results) and/or in 2D

Article coming soon!