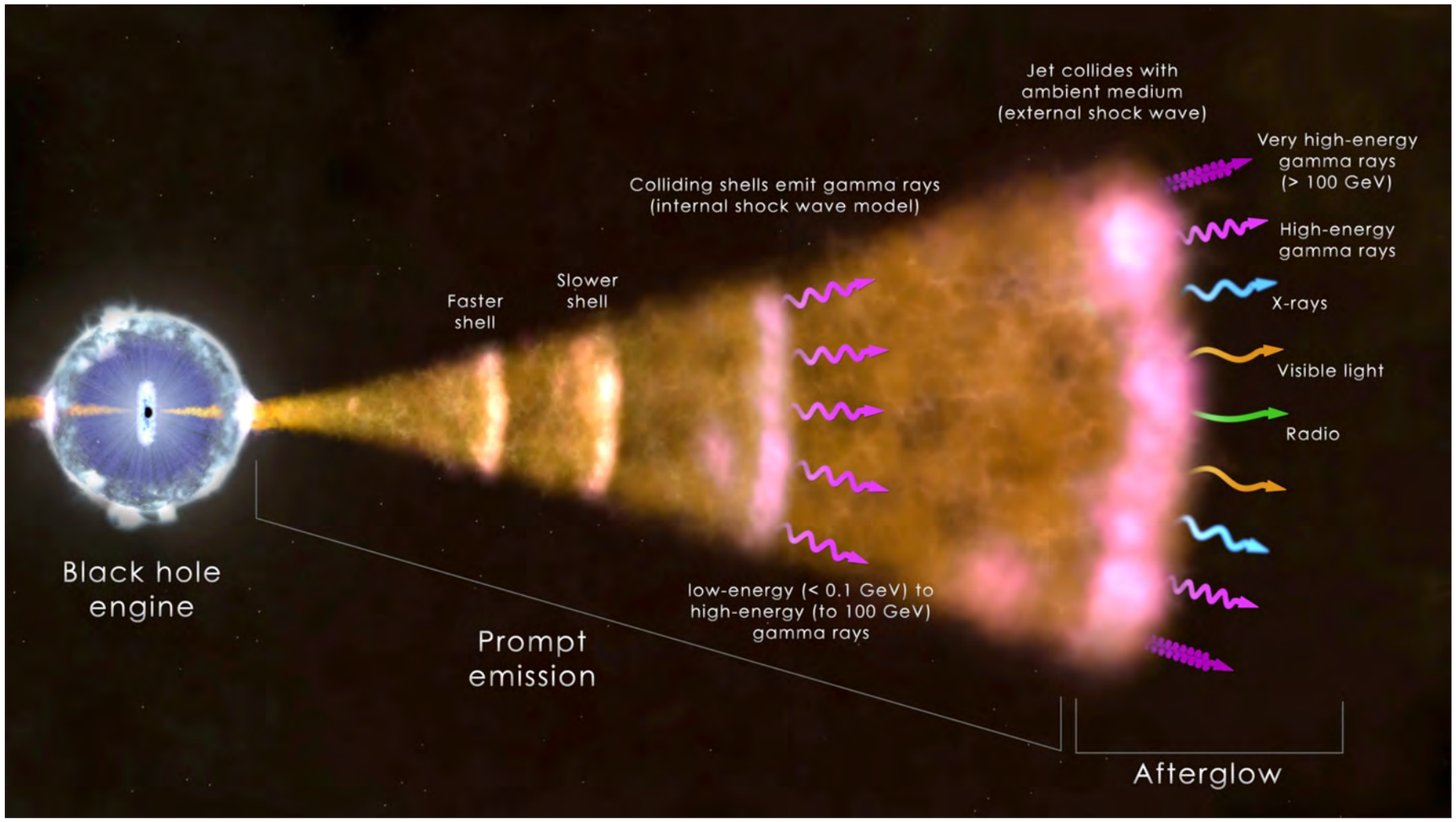
Forward and Reverse Shock Emission from Relativistic Jets with Arbitrary Angular and Stratified Radial Profiles

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2025.12.11

Gamma-ray Bursts (GRB) Afterglow



Synchrotron emission from blastwaves

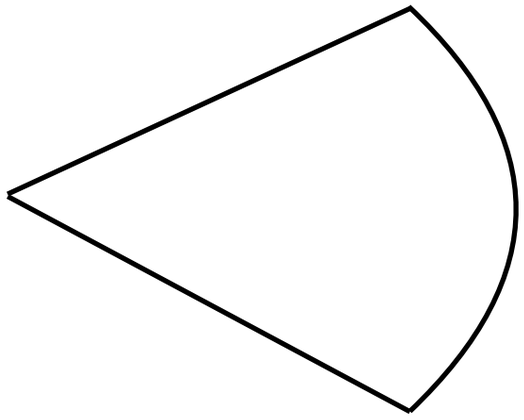
GRB afterglows is important in studying…

- The diversity of GRB afterglow lightcurves.
- How black holes lauch relativistic jets.
- Particle acceleration in relativistic blastwaves.
- Multimesseneger astrophysics: GW-GRB association.
- …

A sophisticated afterglow model is required!

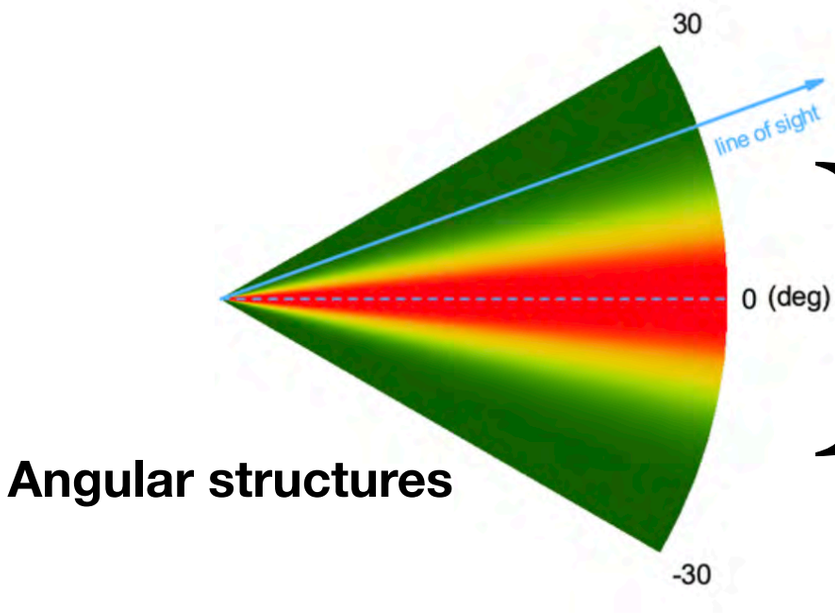
GRB jets

The “standard GRB afterglow model” assumes jets are…



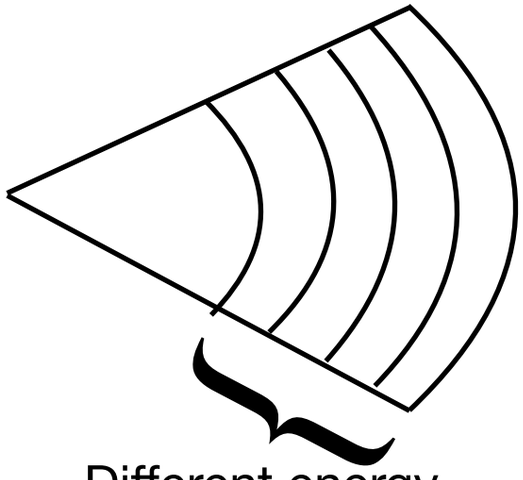
~50% GRB afterglow events **can’t** be explained by the standard model

In practice, numerical simulations show jets are…



Different energy & velocity

Angular structures

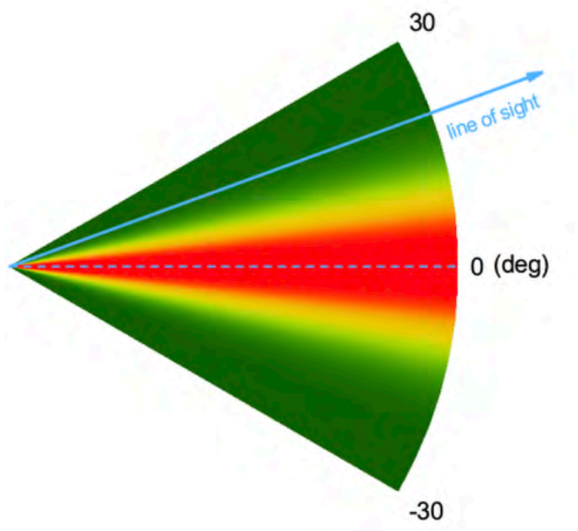


Radial structures

Different energy & velocity

Angular structures

- First proposed in 1998 (Meszaros et al. 1998).



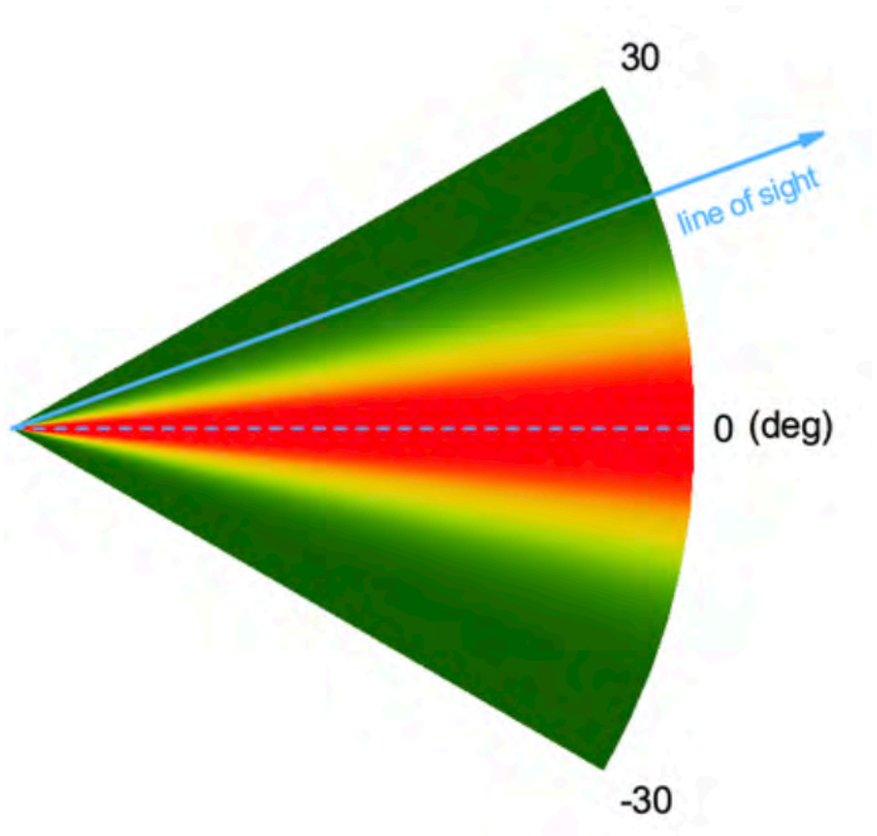
The angular structure is important only for “misaglined” observers.

- Widely adopted in 2018 (GW170817 afterglow).

GRB 170817A: The first evidently misaligned GRB.

Angular structures

- The major difficulty in modeling the dynamics of structured jets: the spreading phase: $\beta\Gamma \sim 1$.



- **Internal pressure causes sideway expansion.**
- **Spreading is non-linear.**
- **Hydro simulations are generally needed.**

We need an idea tool:

As fast as semi-analytic methods.
As accurate as hydro simulations.

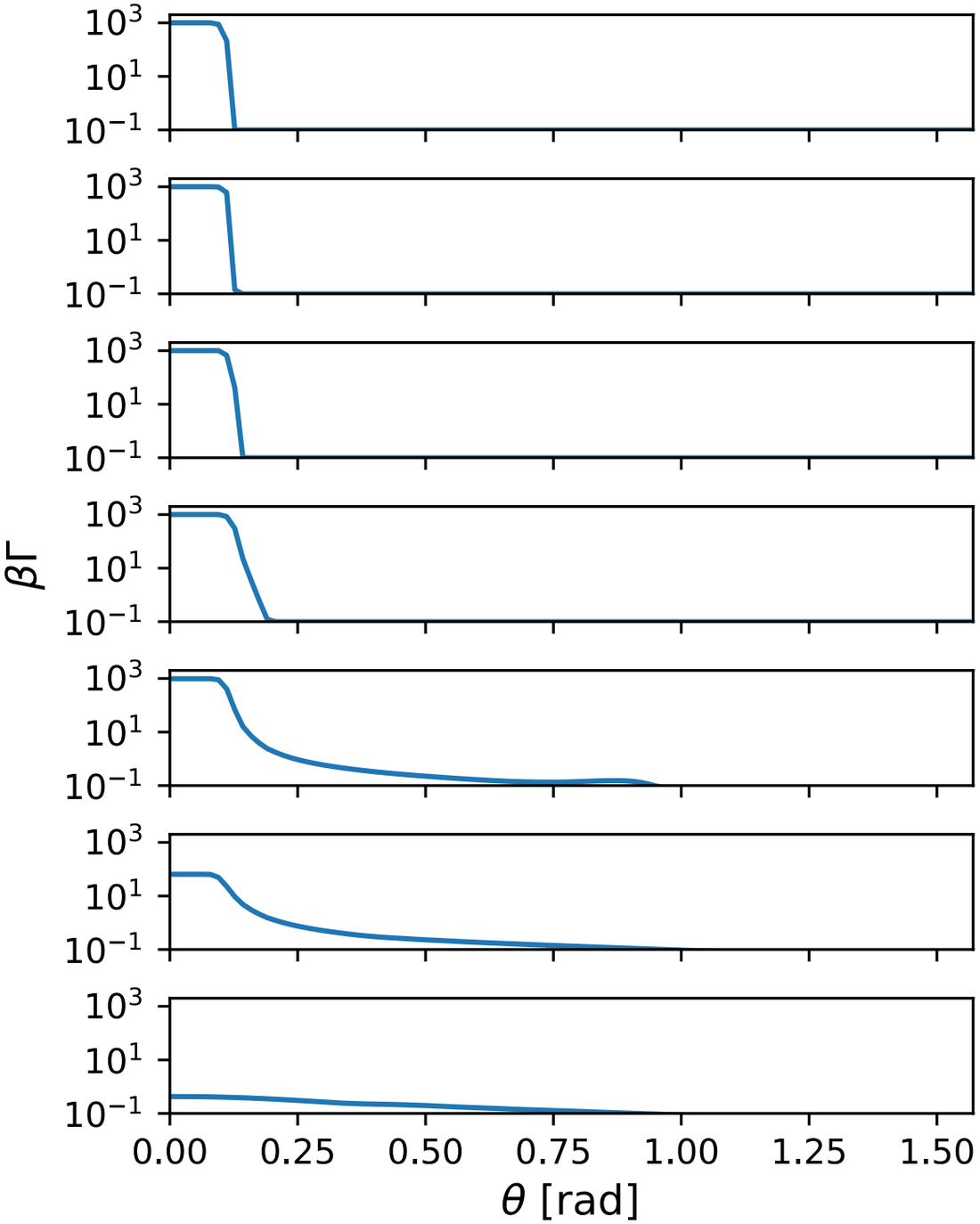
jetsimpy: a new GRB afterglow modeling tool

- Designed for jets with arbitrary angular structures.
- **Key idea**: post-shock region is extremely thin ($\Delta R \sim R/\Gamma^2$): a 2D surface.
- **Method**: Approximate $\rho(r)$ by Delta function $\delta(r)$, and integrate Euler equations along r.

The simulation becomes 1D!

Wang et al. ApJS 2024 (arXiv:2402.19359)

simulation snapshots

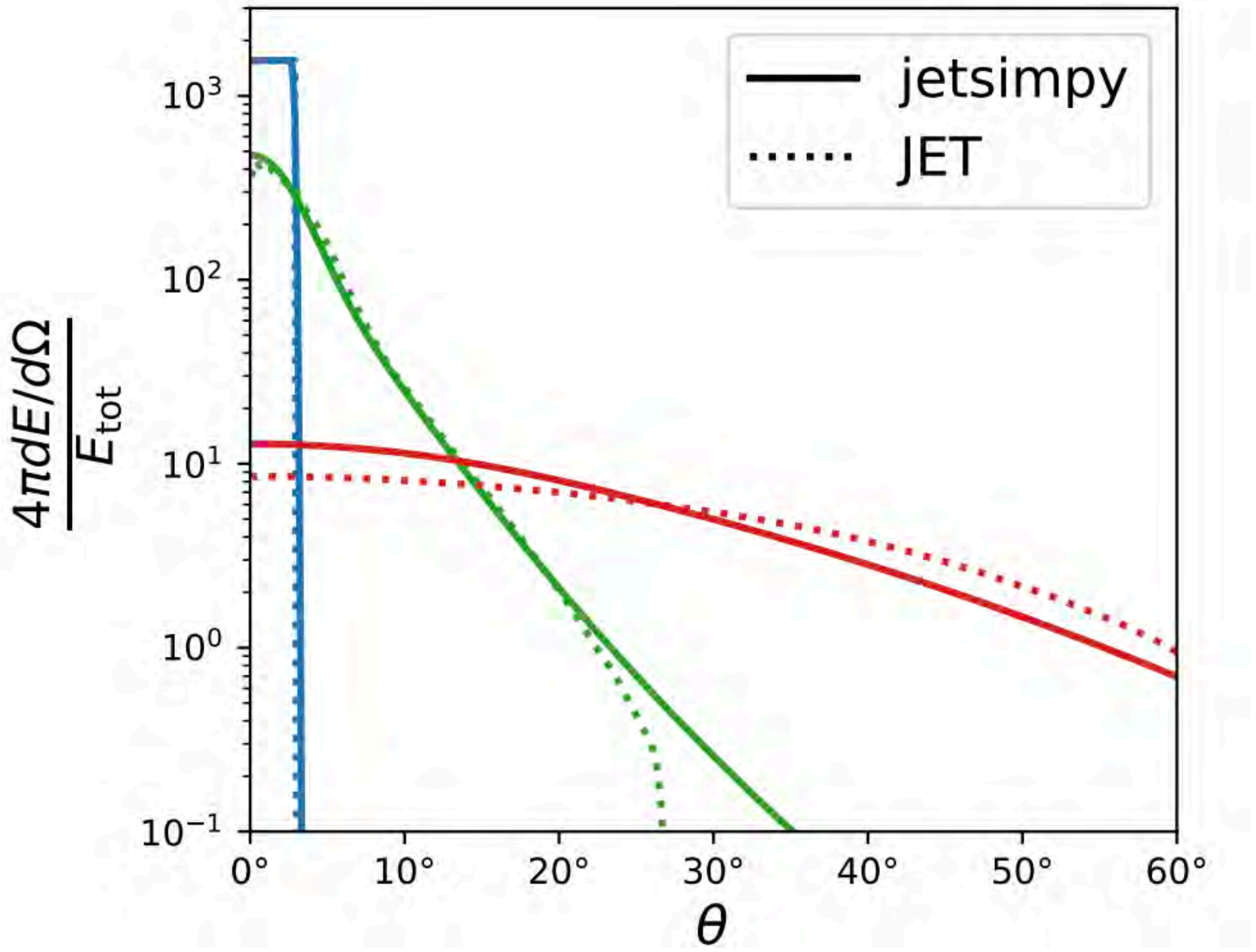


- **Resolution**: 128 polar cells.
- **Efficiency**: 0.1s on a laptop.

  Hydro simulation: 4 hours
- **Accuracy**: Almost same to full hydro (see next page).

***jetsimpy* is the only tool that can do this simulation!**

Accuracy of *jetsimpy*



Radial structures

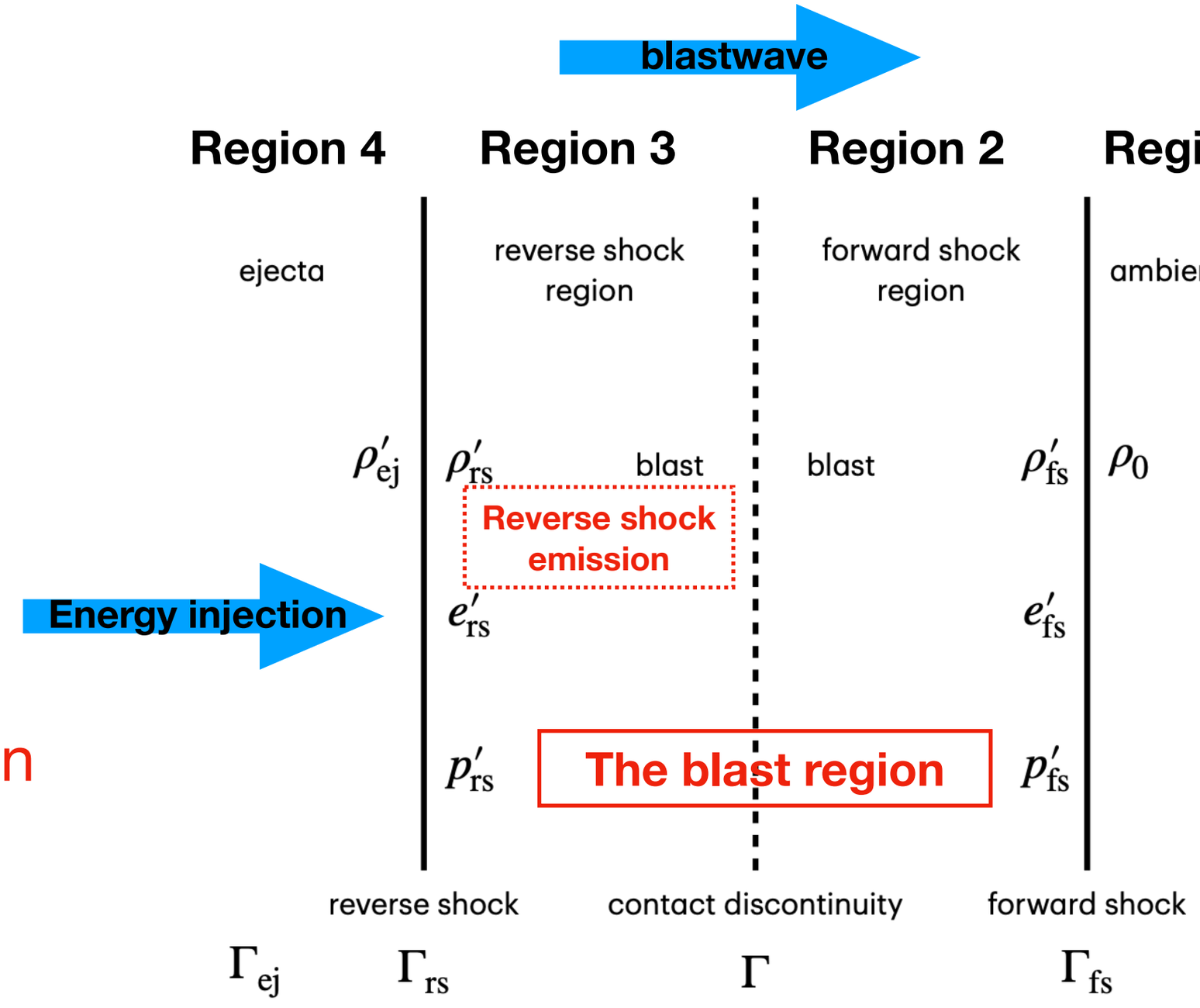
- Reverse shock emission (e.g., Meszaros & Rees 1997)
    - Reverse shock: a shock propagating “backward” to the jet.
- Energy injection (e.g., Rees & Meszaros 1998)
    - Slow shells will catch up with the blastwaves as it decelerates.
- We upgraded *jetsimpy* to study radial structures.

Wang et al. ApJ 2025 (arXiv:2507.15311)

Radial structures

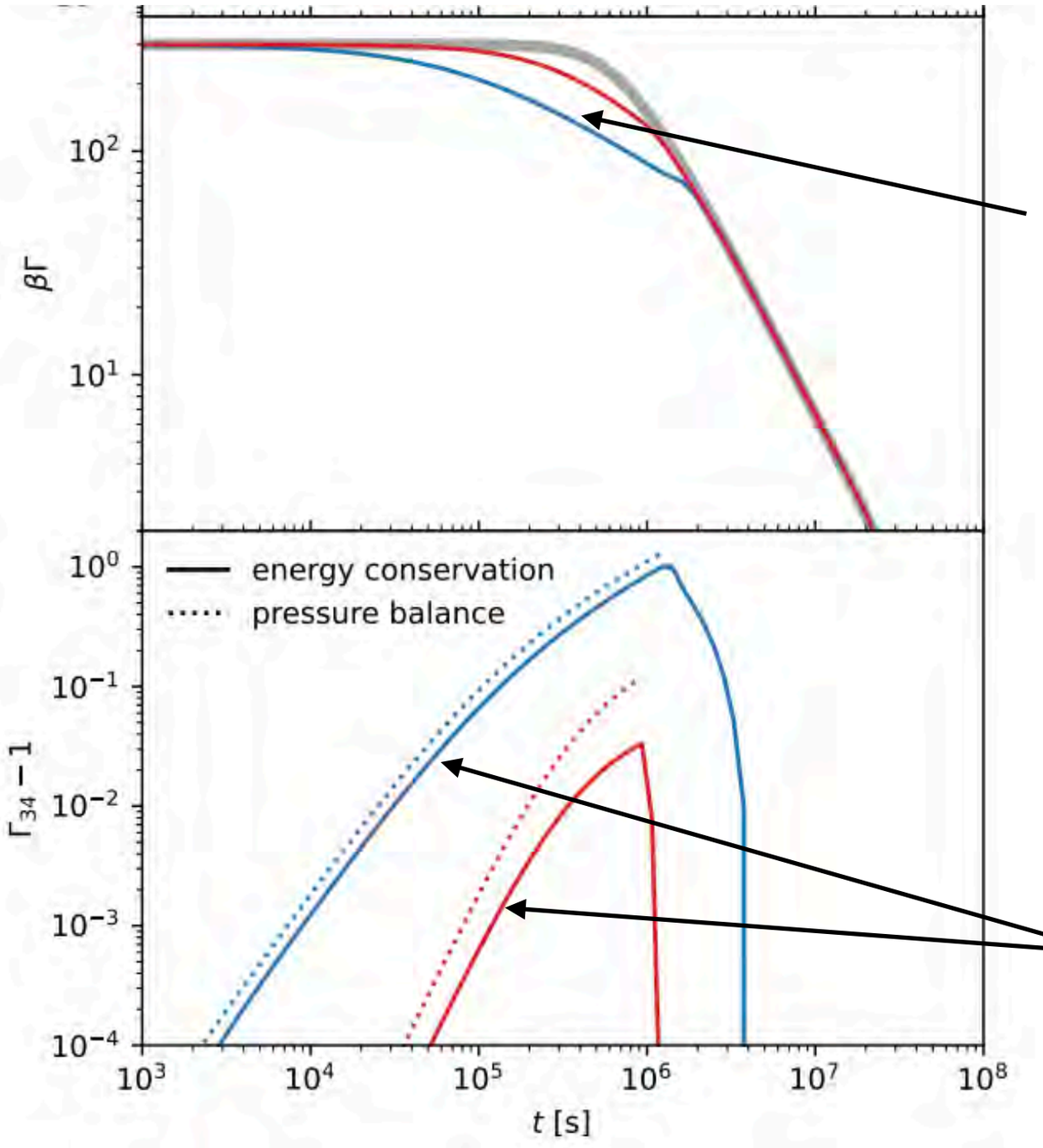
- Analytic method:
  pressure balance

- Our method:
  energy conservation



Uhm 2011 finds pressure balance assumption violates energy conservation.

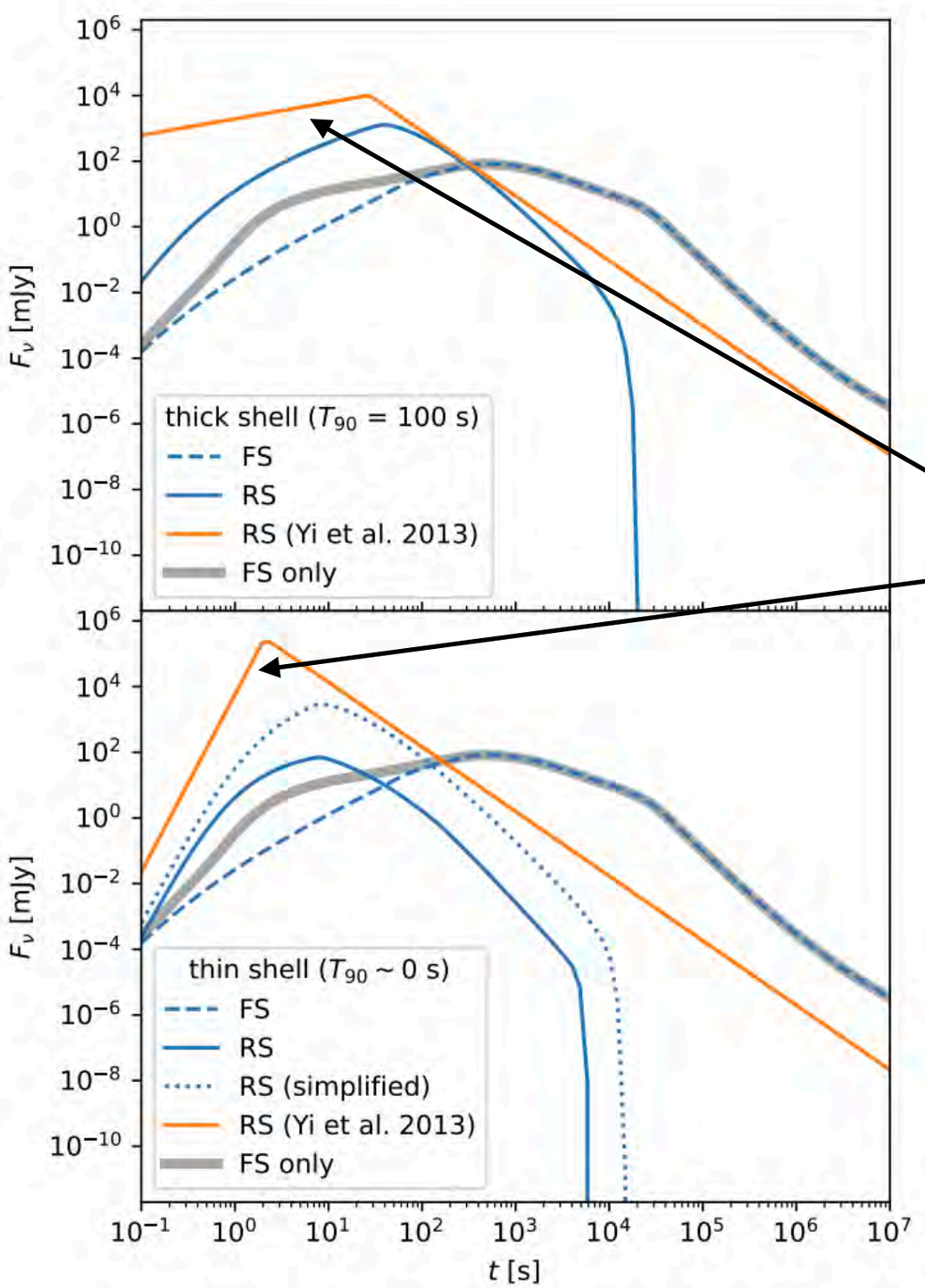
Numerical results



- Analytic: The blastwave decelerates **after** the RS passes through the jet.
- Our: The blastwave decelerates **before** the RS passes through the jet.

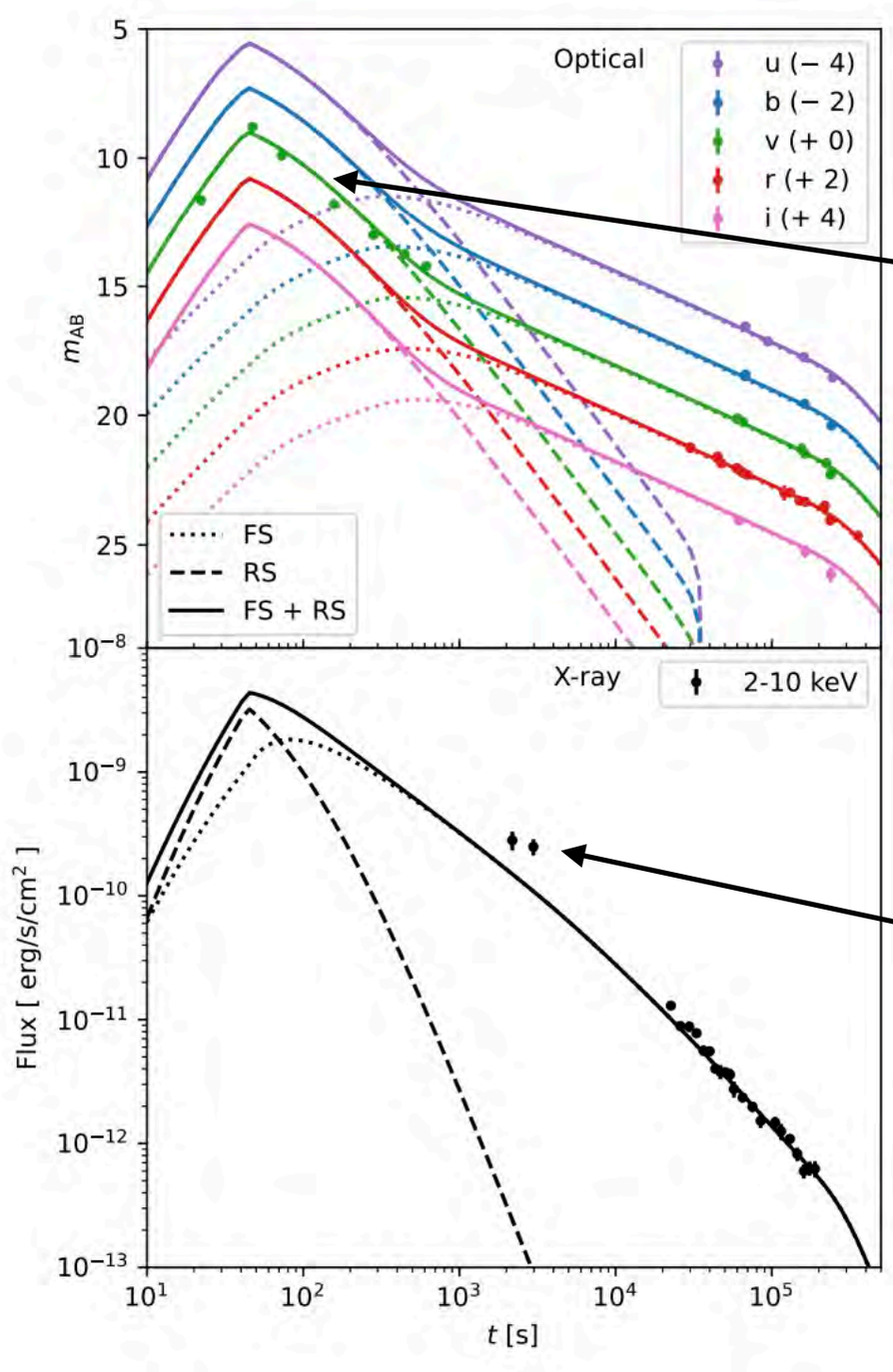
Pressure balance method significantly overestimats the energy density in the blast region.

Reverse shock emission: peak luminosity



Reverse shock emission is overestimated by analytic methods

Real world data: GRB 990123



The optical flash is well fitted.

X-ray emission lies above cooling break.

jetsimpy can also do…

- Jetted TDE
- kilonova afterglow: refreshed shock models.
- off-axis reverse shock emission.
- Arbitrary ambient density profiles.
- Energy injection.
- …

jetsimpy avalibility

- Angular structure: publicly available.
- Radial structure: in development.
- https://github.com/haowang-astro/jetsimpy

The importance of this tool: connecting GRMHD with afterglow modeling







Thank you!