Self-consistent 3D radiative transfer for kilonovae

Directional spectra from merger simulations

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ARTIS radiative transfer code

- ARTIS is a 3D Monte Carlo radiative transfer code (method of Lucy 2002)
- Source code at https://github.com/artis-mcrt/artis/
- Radioactive decay energy released during simulation time range is discretised into uniform-energy packets
- Pellets of radioactive energy co-move with the ejecta until their decay time, then can make several state transitions according to energy flows until they exit the simulation volume as radiation packets with some wavelength (contributing to the synthetic spectra and light curve).
- Simulations always follow time evolution with light travel time accounted for (no single-time snapshots).

Kromer & Sim (2009)

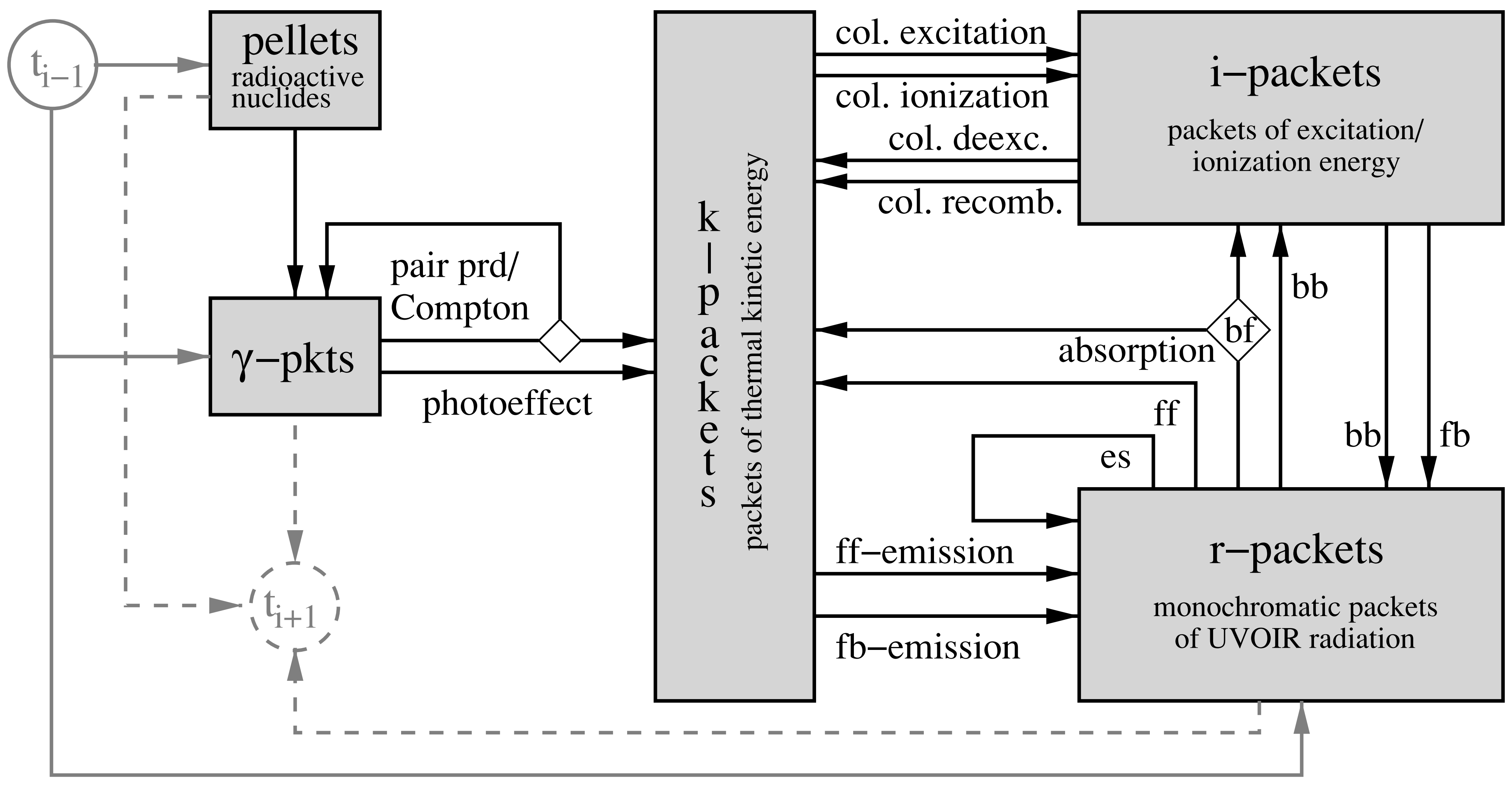

Figure 1. Flow chart outlining the mode of operation of the code. For discussion, see the text.

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ARTIS development for kilonovae

- ARTIS had followed just a few decay chains relevant to SNe Ia (e.g., Ni56->Co56->Fe56) with β^+ and EC only.
- Now needs to handle decays of r-processed material
  - ~2500 nuclides with α and β^- decays from ENDF/B-VII.1 (Chadwick+ 2011 via Hotokezaka's data file on GitHub)
  - Abundances from Bateman equation sum over all ancestor paths from snapshot abundances. No loops allowed (e.g. no n- or p-capture reactions)
  - Gamma-ray decay spectra from NNDC followed by full frequency-dependent transport
  - Particle emission using average kinetic energy of each specific nuclear decay
    - Time-dependent deposition of energy (locally, with assumption of full trapping)
- Input initial energy densities at snapshot from all reactions prior to snapshot time of 0.1d
- Use the relativistic Doppler shift

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Synthetic spectra and light curves from merger models

- 1.35-1.35 $M_\odot$ dynamical ejecta by Vimal Vijayan (SFHO EoS with neutrinos) as presented by Collins et al. (2023). Terminated at ~20 ms after merger with ejecta mass: 0.004 $M_\odot$.

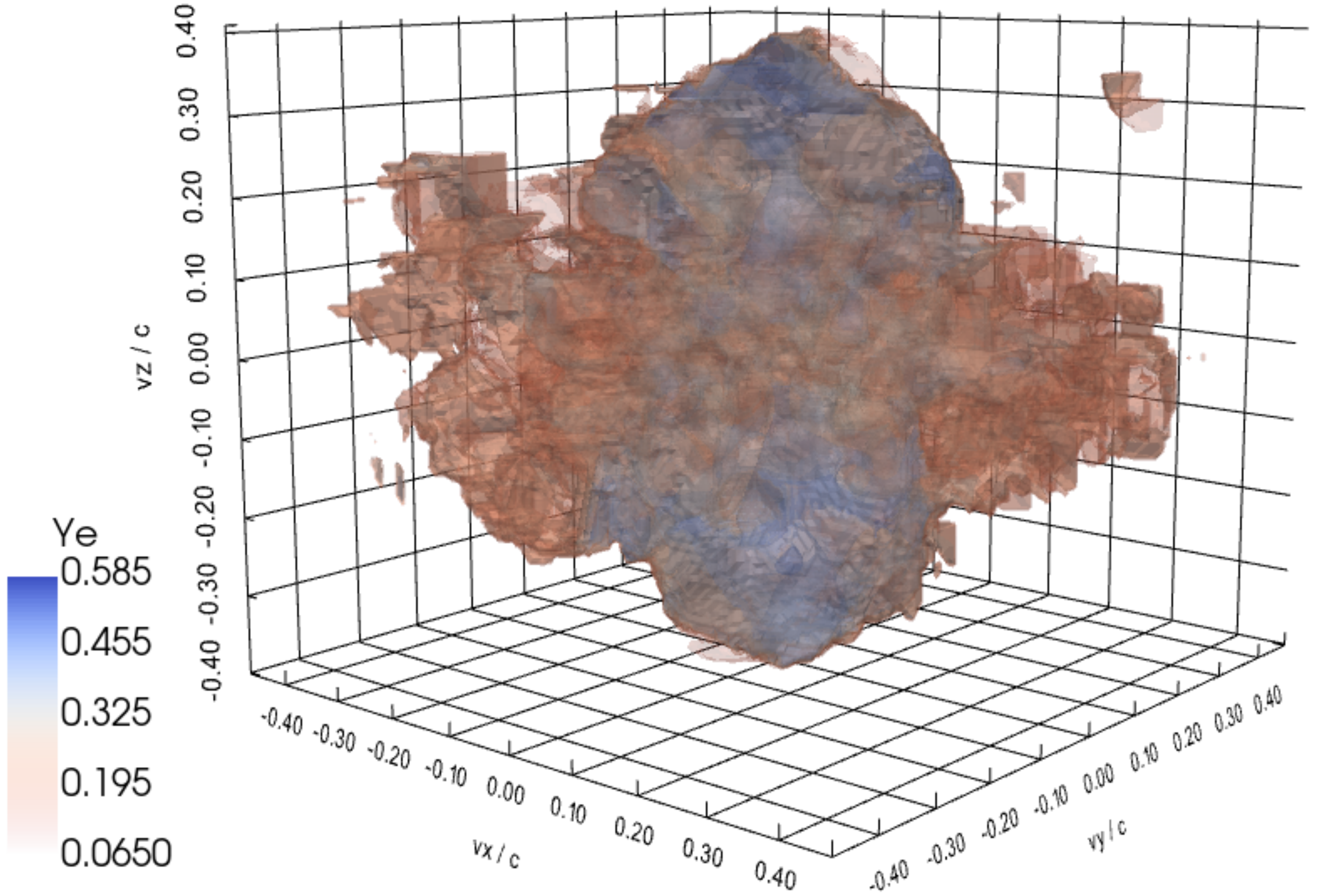
- Detailed r-process nuclear network calculation on ~4000 SPH particles up to 0.1 days with homologous expansion (Martínez-Pinedo)

- ARTIS 50^3 3D radiative transfer from 0.1 days with further homologous expansion and decays with time-dependent thermalisation to 20 days (80d for 3D AD2). Observables predicted until 3.4d (or 13.6d for 3D AD2)

- Opacity is line-by-line Sobolev calculated from the element/ion composition and temperature (LTE Saha/Boltzmann)

    - AD1: Cu to Ra (I to IV) (JP-LT database, Tanaka et al. 2020) and C, O, Ne, Mg, Si, S, Ar, Ca, Fe, Co, Ni from CMFGEN compilation (Hillier 1990). No selection cuts and ~44 million lines included

    - AD2: same as AD1 but with calibrated Kurucz data for Sr, Y, and Zr (I-IV)



Hydro + neutrino model by Vimal Vijayan
Figure from Collins et al. (2023)

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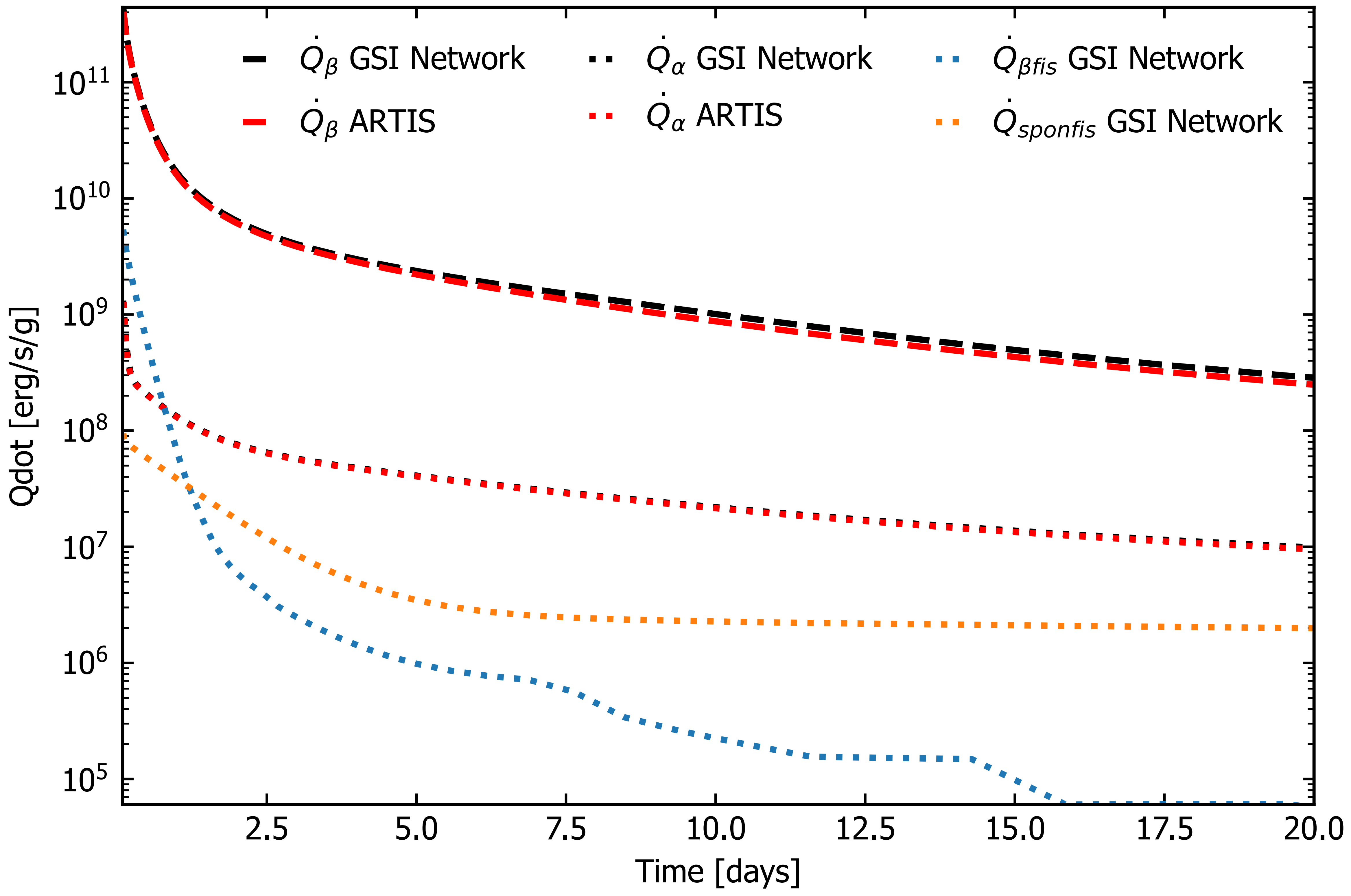
ARTIS decay-only vs full network

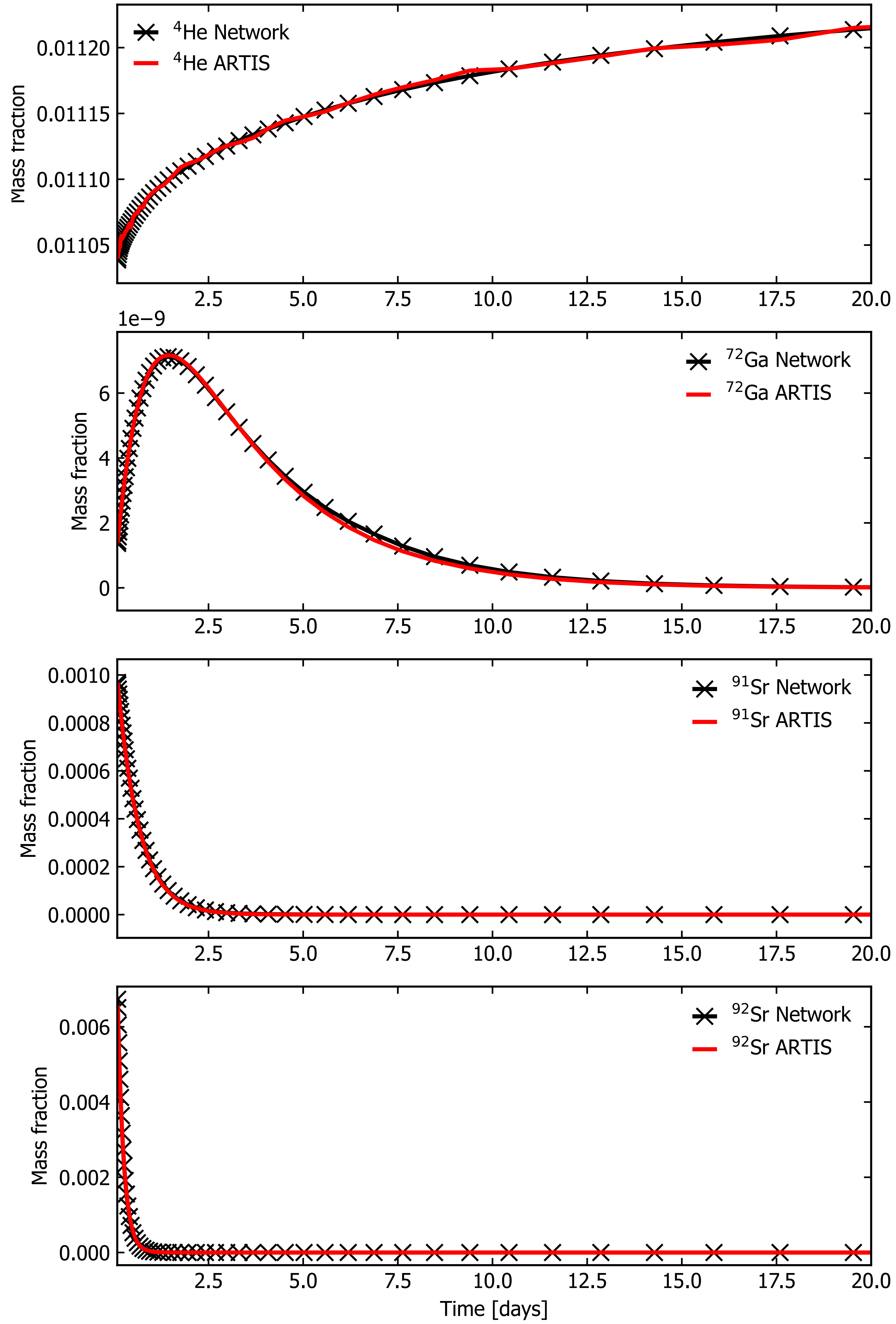
Global



Good tracking of decay power

Fission not included, but contribution is small

One cell



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Luminosity evolution

- Our early dynamical ejecta mass is ~10 times too low to match AT2017gfo emitting mass
- 3D is brighter than 1D, possibly because light can escape through “gaps” in the inhomogeneous ejecta.
- Wavelength calibration has a small effect on luminosity
- Thermalisation break after ~3 days (compare to Collins+23)

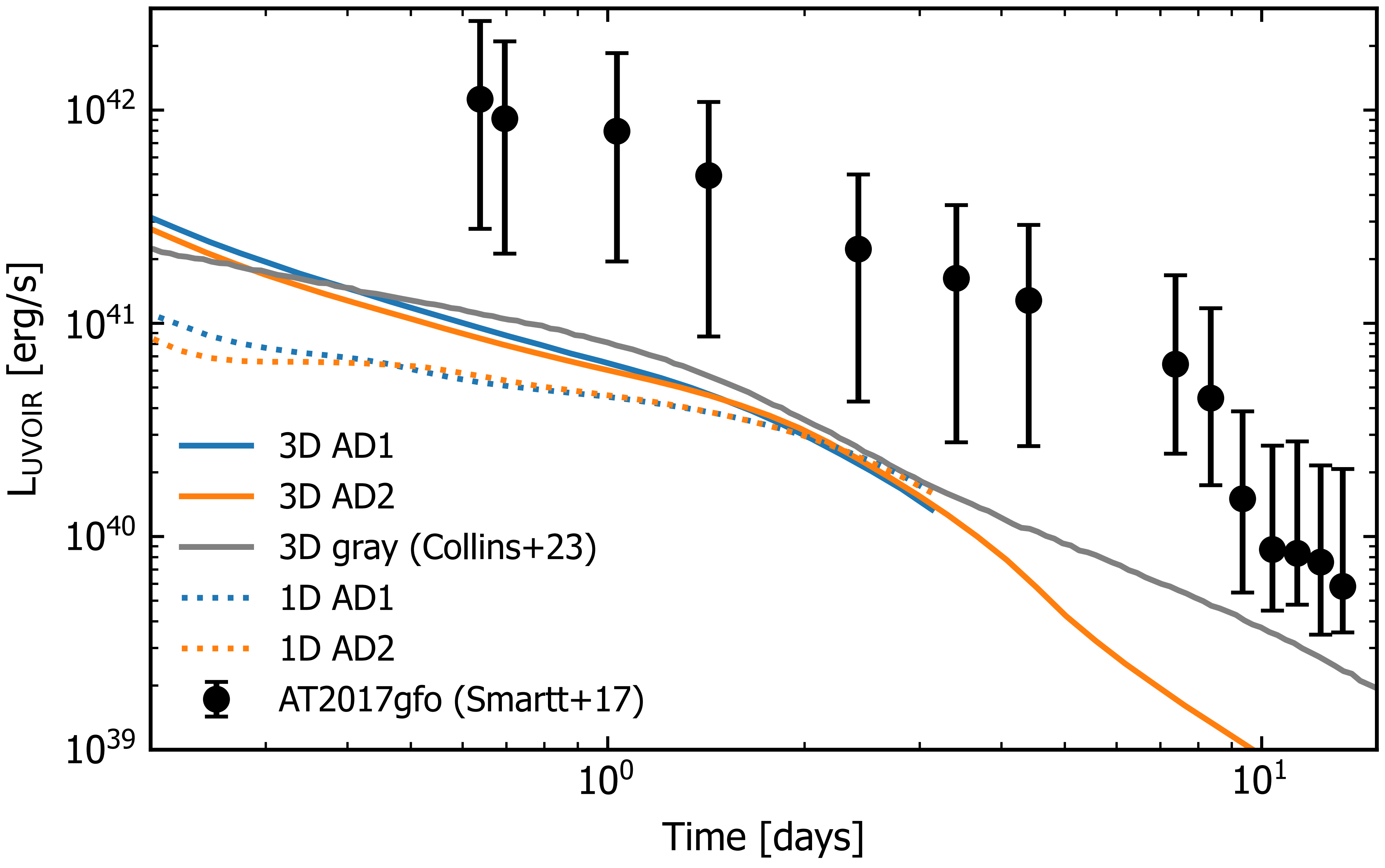

Figure 1. Direction-integrated luminosity versus time for the models 3D AD1, 3D AD2, 1D AD1, 1D AD2, the 3D gray opacity model of Collins et al. (2023), and inferred bolometric luminosity of AT2017gfo (Smartt et al. 2017).

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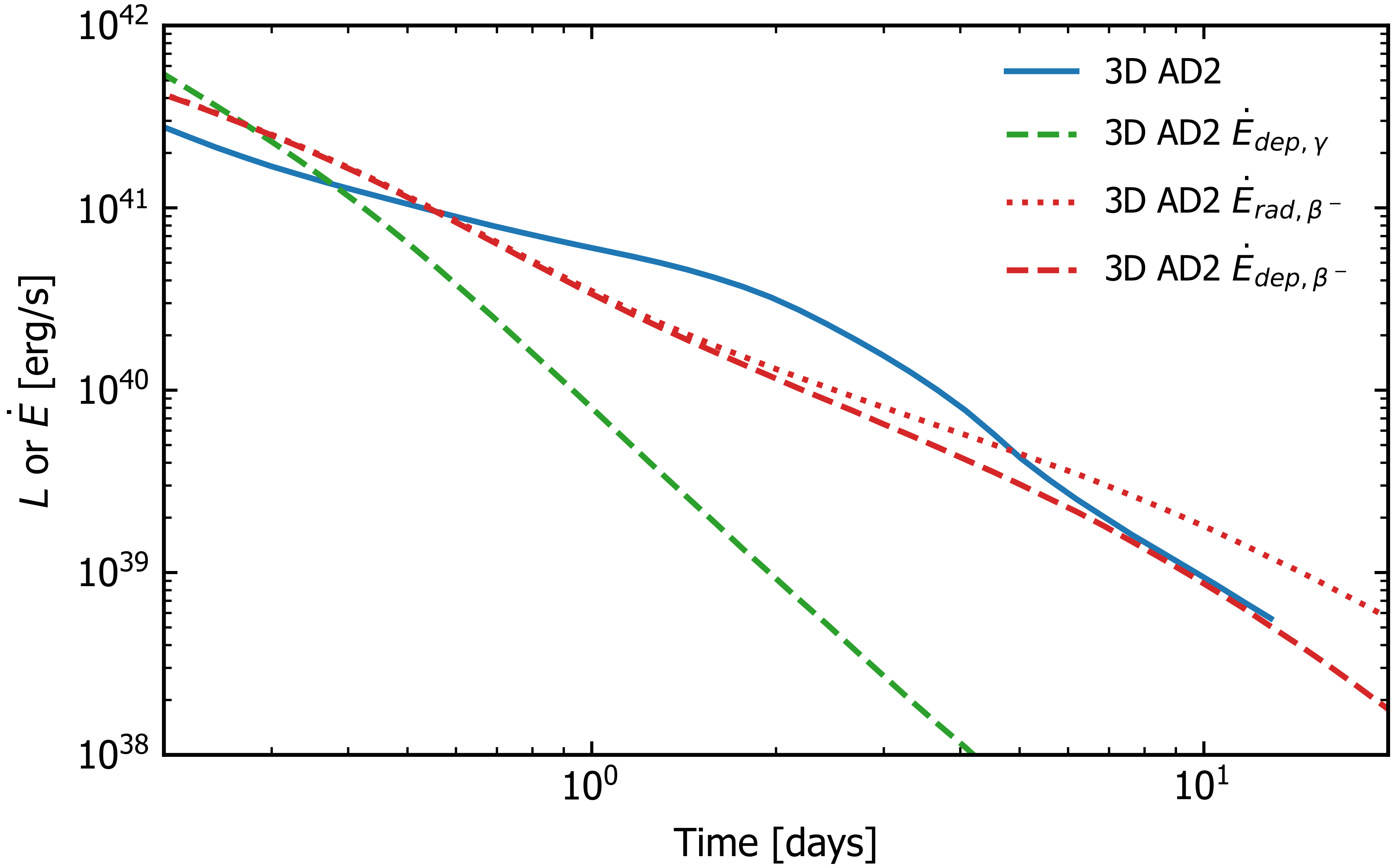
Thermalisation vs. Barnes+ (2016) approximation

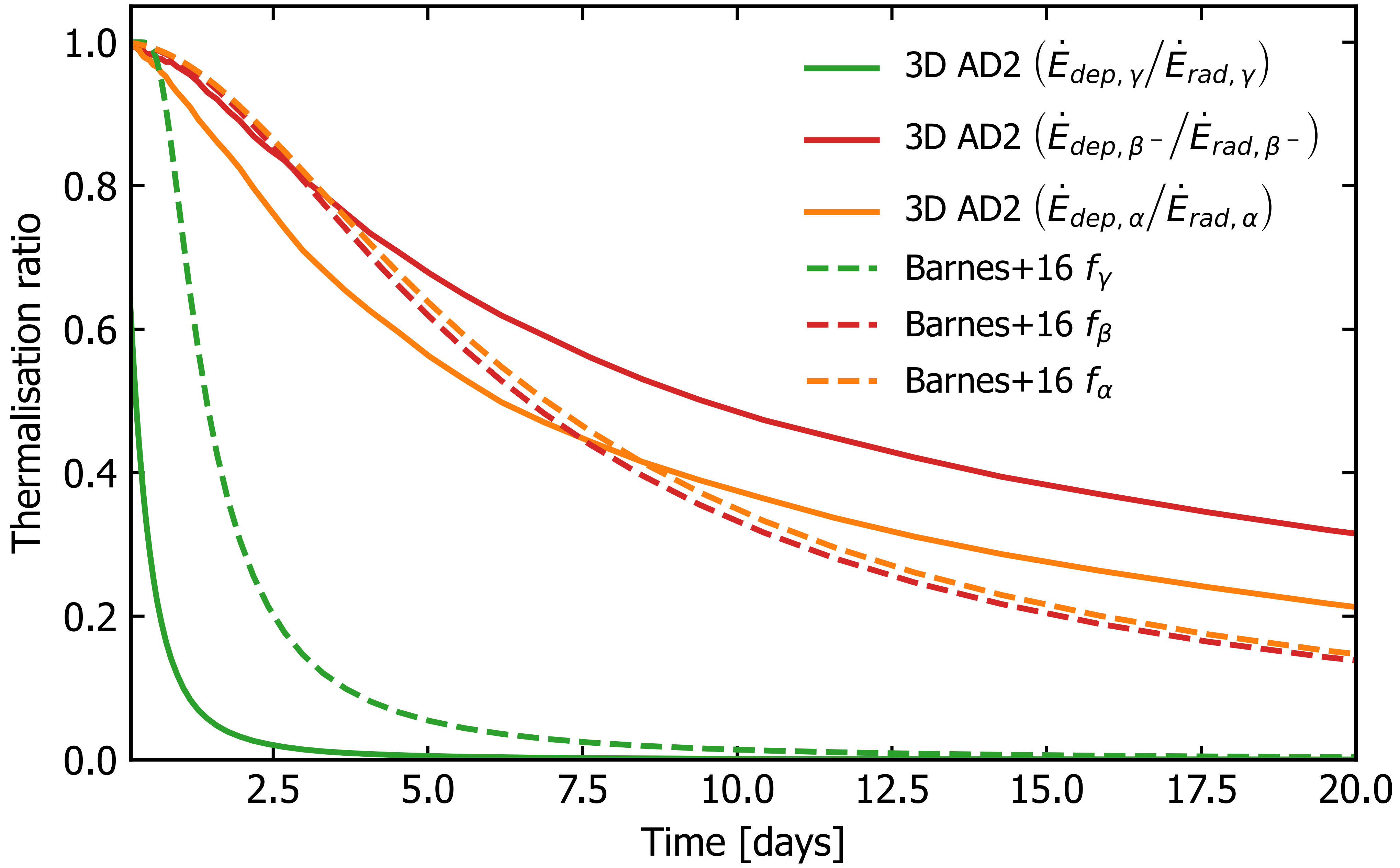
- Deposition rate is calculated per-decay from emitted particle energy and approximate loss rate (4e10 ρ [MeV/s] for β, 5e11 ρ [MeV/s] for α, with ρ in g cm-3)
- Deposition is local (no escape). Assumed to be trapped by magnetic fields.
- Lower right: comparison of our treatment to the Barnes+2016 analytical approximation (mass and ejecta KE params set based on our 3D model)

$$t_{\rm ineff} \approx 7.4 \left(\frac{E_{\beta,0}}{0.5\ {\rm MeV}}\right)^{-1/2} M_5^{1/2}\ v_2^{-3/2}\ {\rm days}.$$

$$f_{\rm p}(t) = \frac{\dot{E}_{\rm th}}{\dot{E}_{\rm rad}} = \frac{\ln\left[1 + 2\left(\frac{t}{t_{\rm ineff,p}}\right)^2\right]}{2\left(\frac{t}{t_{\rm ineff,p}}\right)^2}.$$

Barnes et al. 2016 approximation





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Direction-averaged spectra 3D versus 1D

- For the same NSM model and atomic dataset (AD1 or AD2) using the 1D spherical average of the ejecta density/composition does not recover the spherical average of the spectrum.

- Radiative transfer for multi-D NSM models should be done in multi-D, even when direction-dependence is ignored

- Preliminary: 2D looks different to 3D (lacking blue flux, but without spurious ~12000 Å feature)

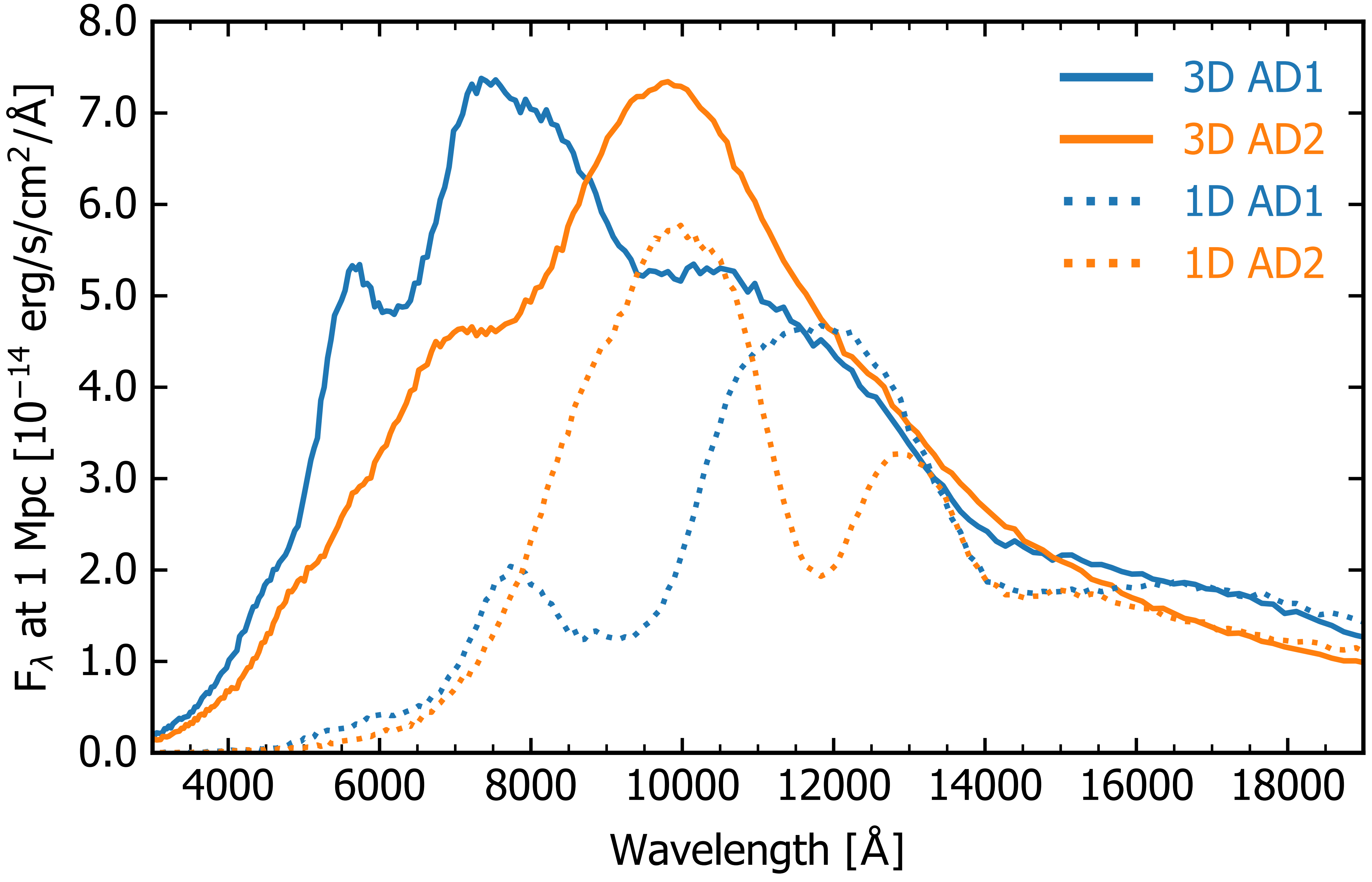

Figure 5. Spherically-averaged spectra at 0.8 days for the 3D AD1 (solid blue), 3D AD2 (solid orange), 1D AD1 (dashed blue), 1D AD2 (dashed orange) models.

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3D direction-dependent observables

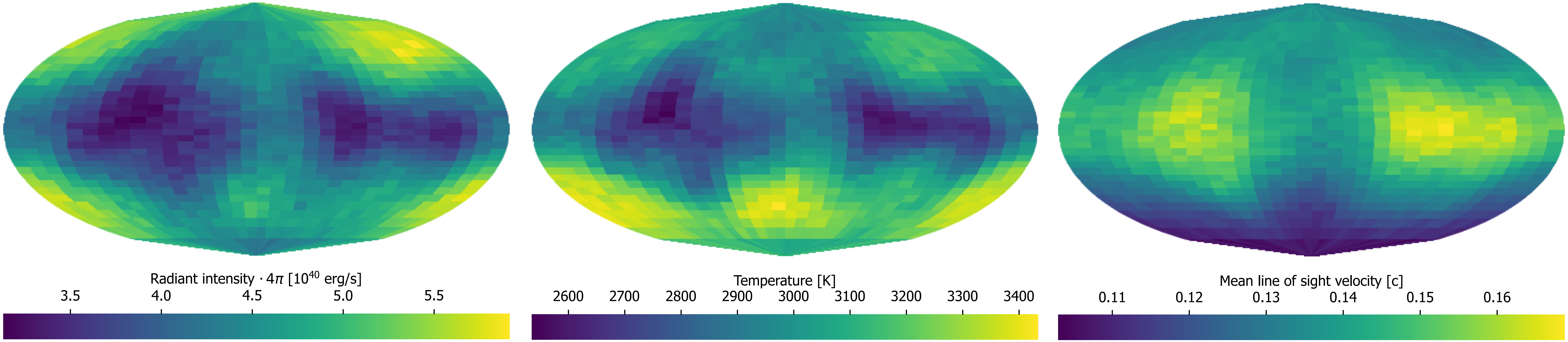

Figure 2. Mollweide projections of direction-dependent quantities for 3D AD2 UVOIR packets arriving at the observer between 1.3 and 1.7d: radiant intensity times 4π solid angle, mean temperature at last interaction, and line of sight velocity at last interaction. For these figures, we use 32x32 direction bins, uniformly spaced in azimuthal angle (horizontal) and cosine of the polar angle (vertical) to give the same solid angle in each bin.

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Spectra at 0.8d

- AD2 with calibrated Sr, Y, Zr (Kurucz) leads to very different spectral peak locations and features.
- Equatorial spectra are relatively featureless compared to polar spectra
- AT2017gfo was observed near the polar inclination, and the two-peaked spectrum looks similar….

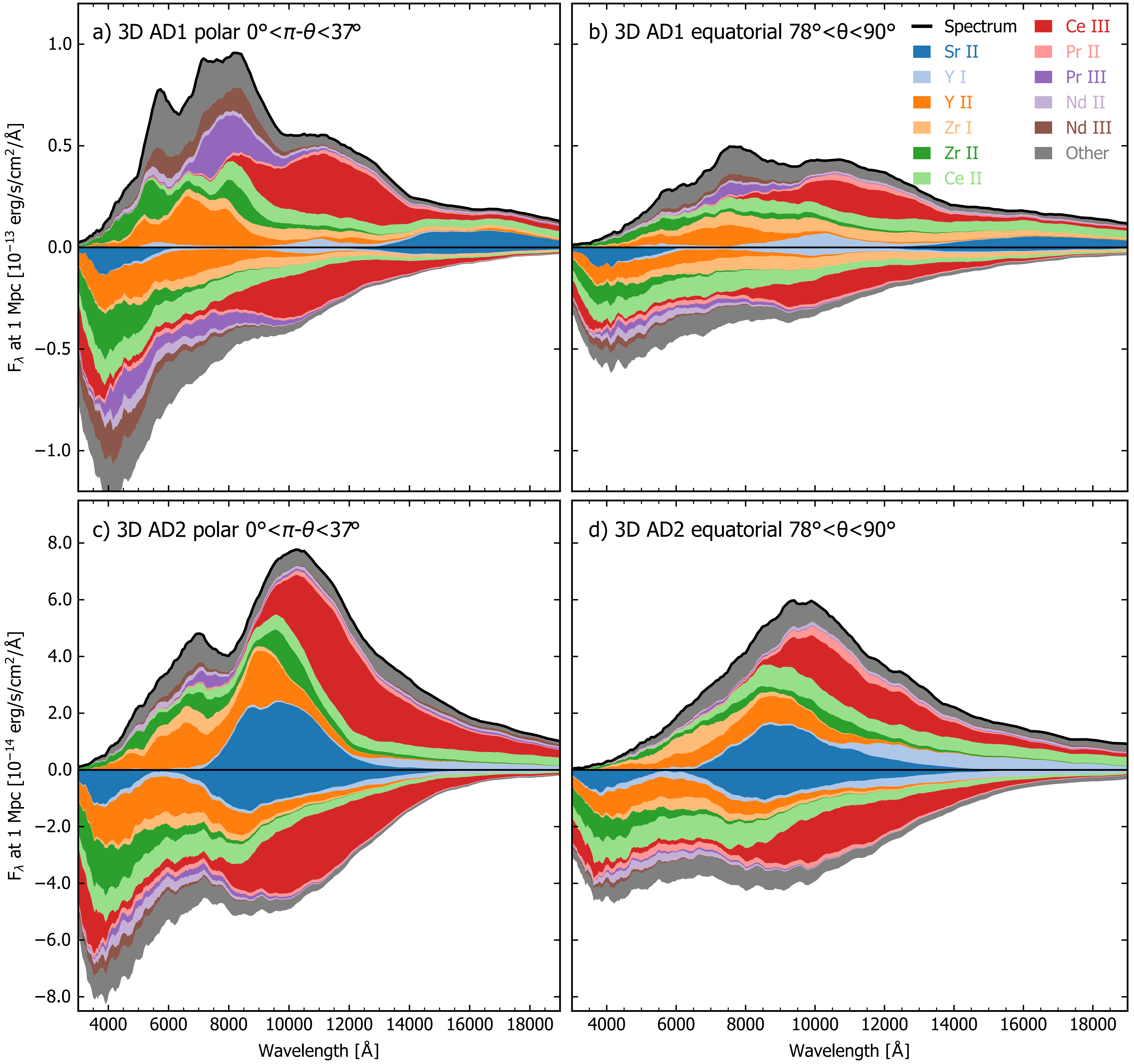

Figure 3. Spectra for polar and equatorial viewing directions for the 3D AD1 and 3D AD2 models at 0.8 days. The height of each wavelength point is colored according to the emitting species of the last interactions of the emerging radiation packets. The area under the horizontal axis shows the distribution of frequencies (colored by absorbing/scattering ion) just prior to the last interactions of the emerging packets. The 11 most-significant ions are separately colored, while the "Other" group combines many smaller contributions from other ions.

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Evolution versus AT2017gfo

- Times don't match and our model evolves too fast but…
- Similar SED sequence of between 3D AD2 (pole) and AT2017gfo
- More mass from later ejecta might slow the spectral evolution, or reduced expansion velocities (features too blueshifted)

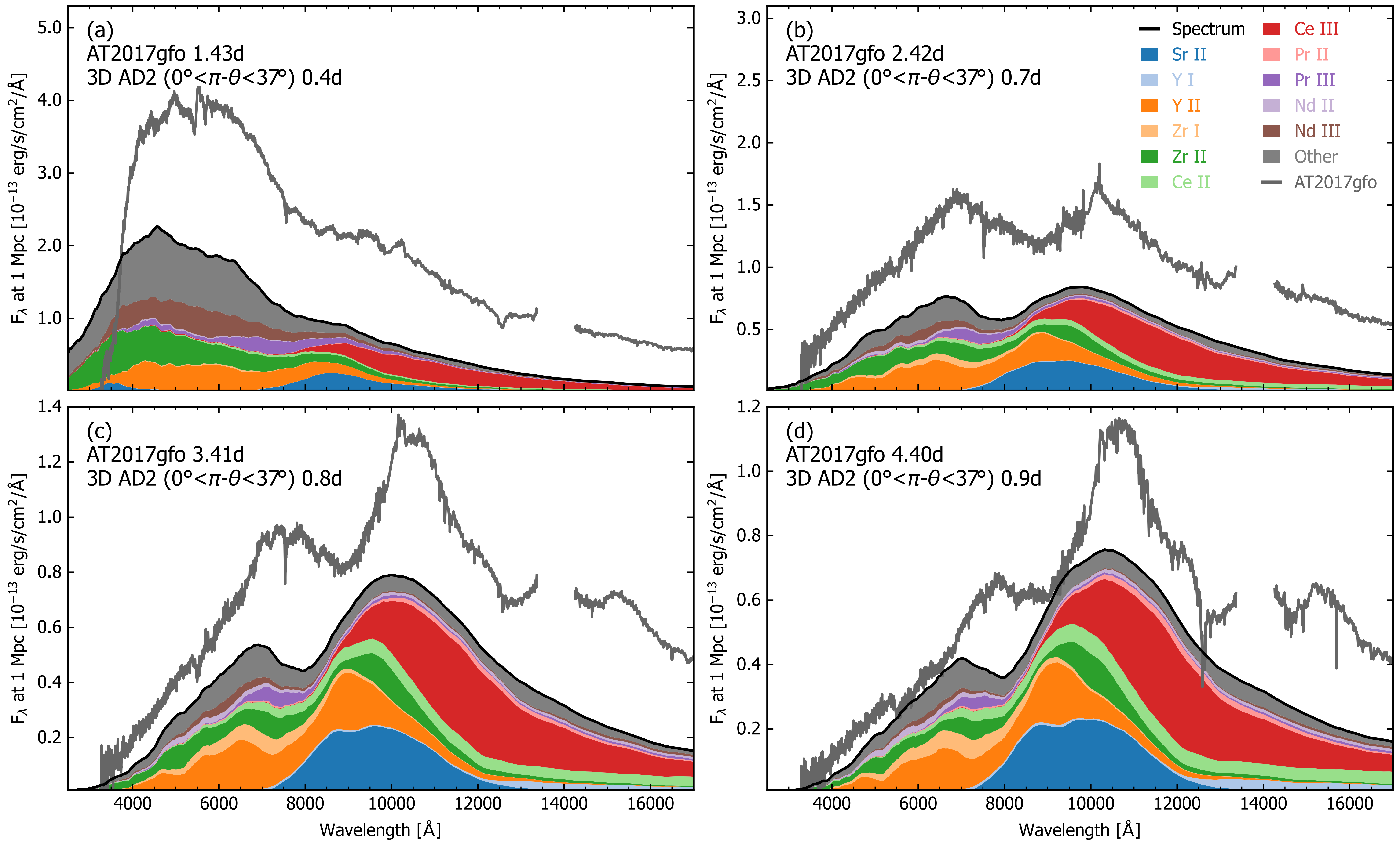

Figure 4. Time series of spectra in the polar direction of the 3D AD2 model compared to reddening and redshift corrected spectra of AT2017gfo (Pian et al. 2017; Smartt et al. 2017). The area under the spectra have been coloured by the emitting species of the last interactions of the emerging packets. The times of the ARTIS and AT2017gfo spectra intentionally do not match.

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Conclusions

- 3D radiative transfer with line-by-line opacities, detailed radioactive decay and thermalisation is practical on a modern cluster (~210 kilo-core-hours for 3D AD2 0.1-80d)
- Angle-average of ejecta does not predict the angle averaged spectra. Multi-D RT is important for forward modelling.
- Wavelength calibration of atomic data is crucially important for producing accurate synthetic spectra, as we show with Sr, Y, Zr
- Forward modelling from an NSM simulation to synthetic polar spectra leads to evolution resembling AT2017gfo
    - Evolves too fast, possibly due to low early ejecta mass of 0.004 $M_\odot$ or deviations from homology at 20ms post-merger
- The relatively featureless spectra for equatorial observers suggests that future observations of edge-on kilonovae could appear substantially different from AT2017gfo.
- Further analysis of the models (e.g. anisotropy vs observations) in Tuesday talk of Christine Collins.

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