Multi-dimensional kilonova radiative transfer from merger simulations

Inferring the geometry of kilonovae

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Overview - Inferring kilonova geometry

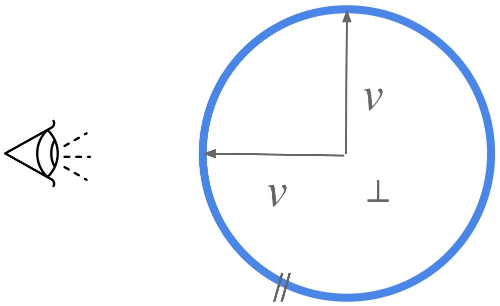
- A high level of sphericity was inferred for the kilonova AT2017gfo (Sneppen+2023)
- Can an asymmetric kilonova simulation appear symmetrical when analysing the synthetic observables in the same way as observations?
    - Methods to infer sphericity from spectra
    - Anisotropy in the ejecta and synthetic observables in a 3D asymmetric kilonova simulation (by Shingles+2023)
    - Inferring sphericity of the simulation
        - Determine whether an asymmetric simulation is compatible with the inferred symmetry constraints

Introduction

- Sneppen+2023 have suggested that the kilonova AT2017gfo was highly spherical
    - They inferred that the photospheric expansion velocity in the line of sight ($v_{//}$) was equal to the expansion perpendicular to the line of sight ($v_{\perp}$)

- This appears to be a challenge for theoretical models.
    - Merger simulations show asymmetries
    - Radiative transfer simulations show viewing angle dependencies

- We apply the same method as Sneppen+2023 to synthetic observables from an asymmetric 3D kilonova simulation (from Shingles+2023)



Sketch of a spherical photosphere where $v_{//} = v_{\perp}$

Methods used to infer symmetry

$v_{//}$ from P-Cygni feature

- Primarily sensitive to expansion in the line of sight

$v_{\perp}$ from expanding photosphere method (EPM)

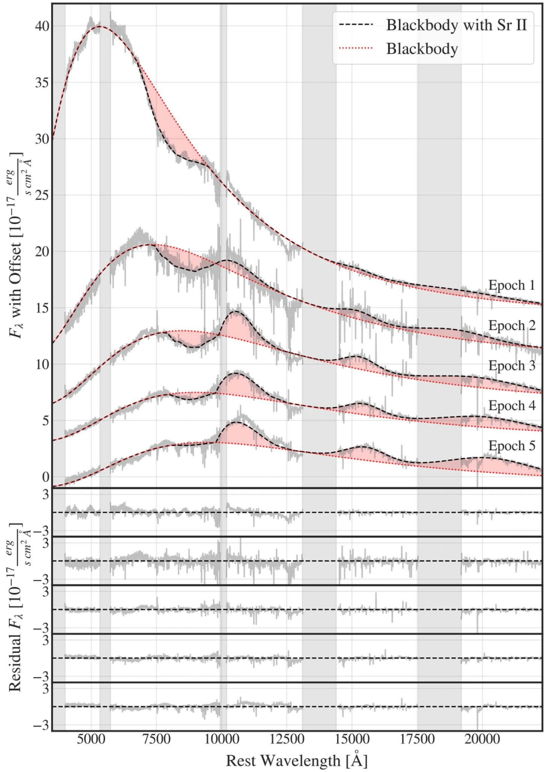
- The EPM assumes the emitting region can be represented by a spherical cross section radiating as a blackbody

$$L = 4\pi R_{\rm ph}^2 \pi B(\lambda, T')$$

$$R_{\rm ph} = v_{\rm ph} t$$

- Primarily sensitive to the photosphere expanding perpendicular to the line of sight

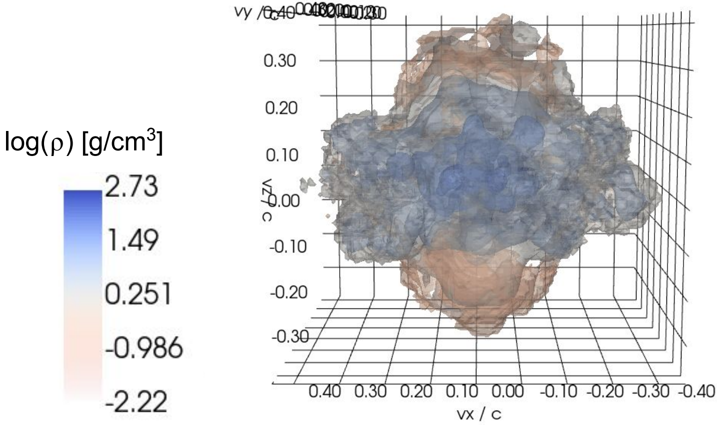
Sphericity quantified by $\Upsilon = \dfrac{v_{\perp} - v_{||}}{v_{\perp} + v_{||}}$ (Y = 0.00 ± 0.02 inferred)



Spectra of AT2017gfo resemble a blackbody, and show a P-Cygni profile (Figure from Sneppen+2023)

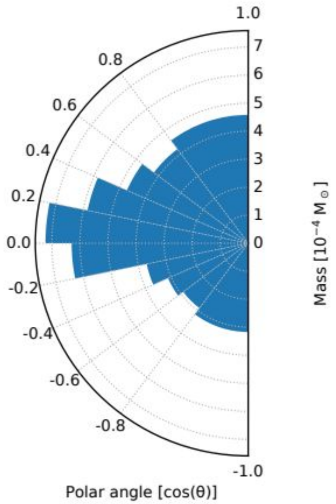
Asymmetric merger ejecta

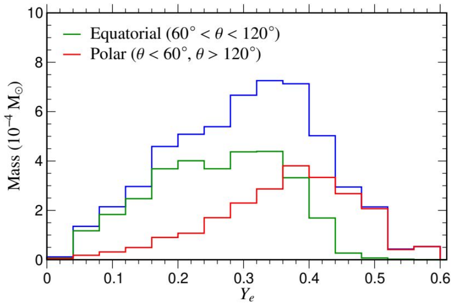
- Merger ejecta from binary neutron star merger simulation input to our radiative transfer calculation (by V. Vijayan)
- More mass ejected at the equator than at the poles
- Higher Y_e at the poles than at the equator



3D rendering of dynamical ejecta, where isosurfaces indicate density

Mass ejected per solid-angle

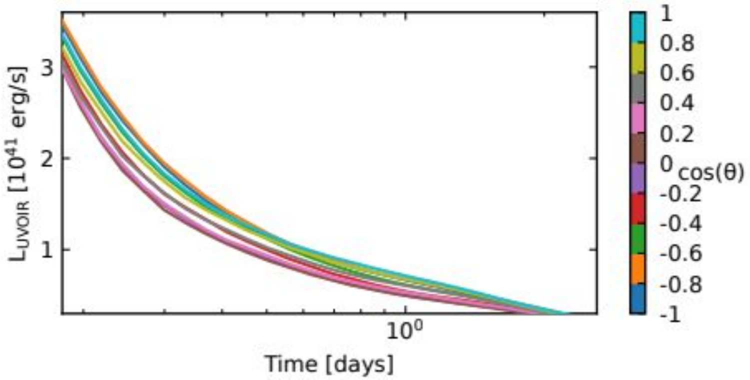




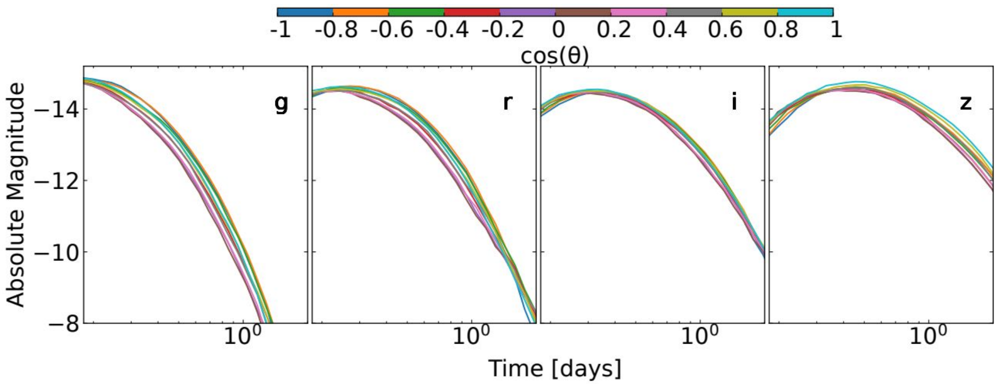
Electron fraction (Y_e) at the poles and equator

Direction dependent Light curves (simulation by Shingles+2023)

- Light curves show viewing angle dependence
  - But not as strong as might be expected from asymmetry of the ejecta

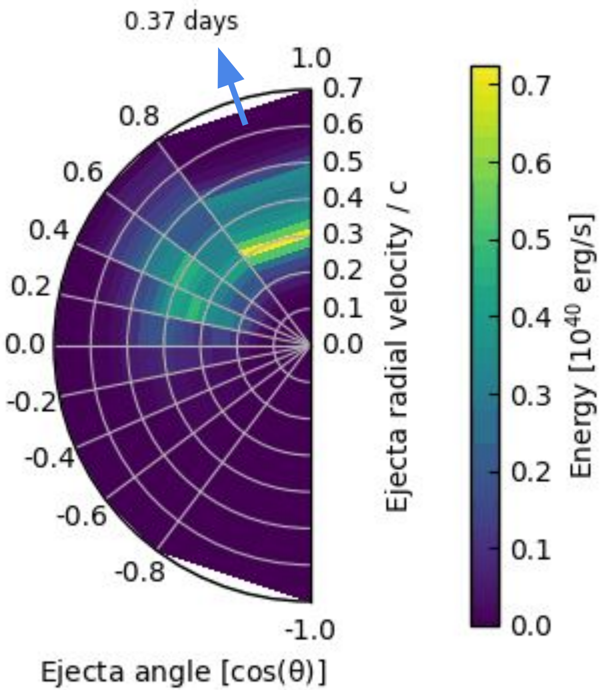


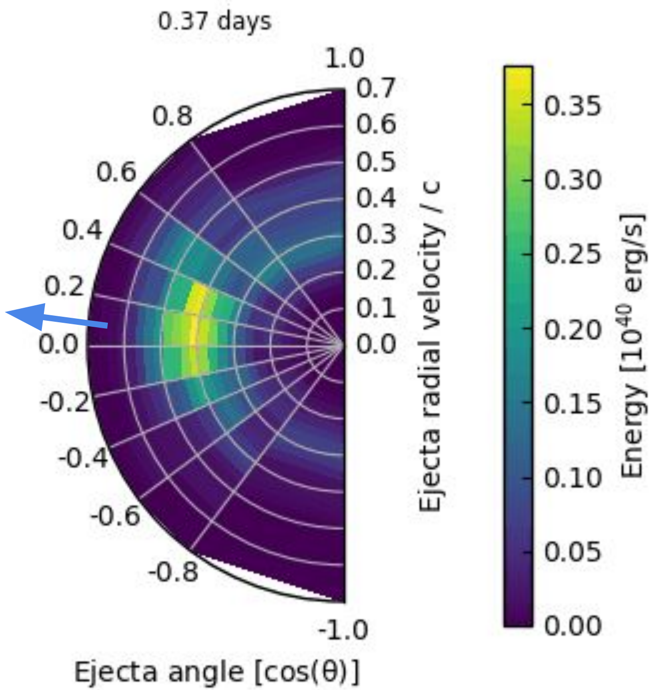
- In all directions light curves initially peak in the bluer bands then evolve to redder colours
  - Despite higher lanthanide fraction at equator



Last-interaction locations

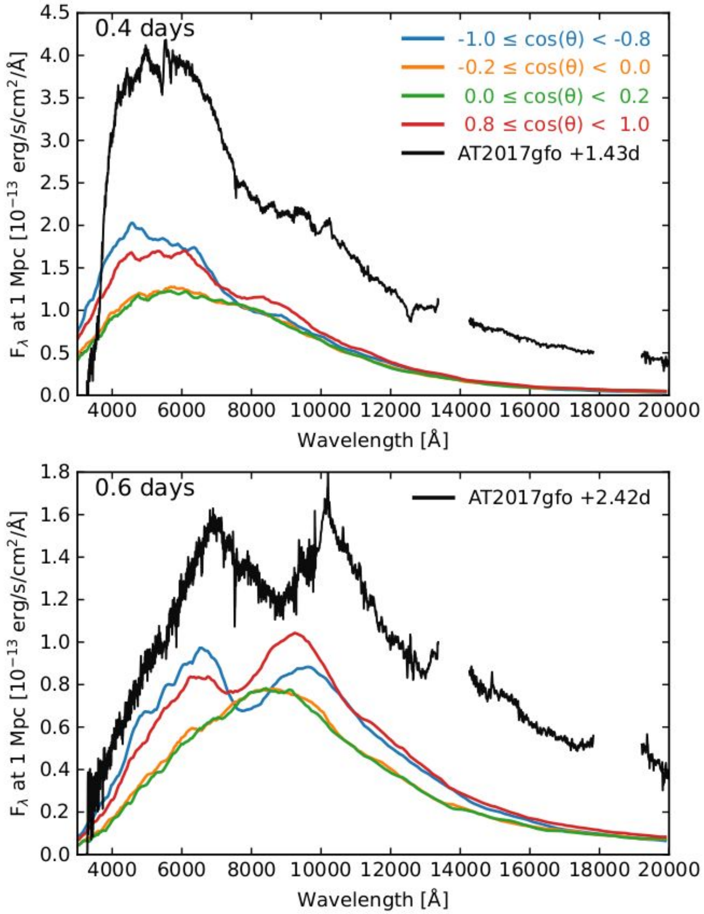
- Ejecta location where radiation last interacted before escaping
- Radiation viewed by an observer is emitted from a broad range of ejecta





Direction dependent spectra

- Spectra at the poles resemble AT2017gfo
- At the equator, spectra are featureless
- The synthetic observables for this simulation are not isotropic
    - We apply the analysis of Sneppen+2023 to determine whether the simulation could appear spherical to an observer
    - We consider synthetic spectra at 0.4 and 0.6 days (since these resemble AT2017gfo)



Inferring photospheric velocities from simulated spectra

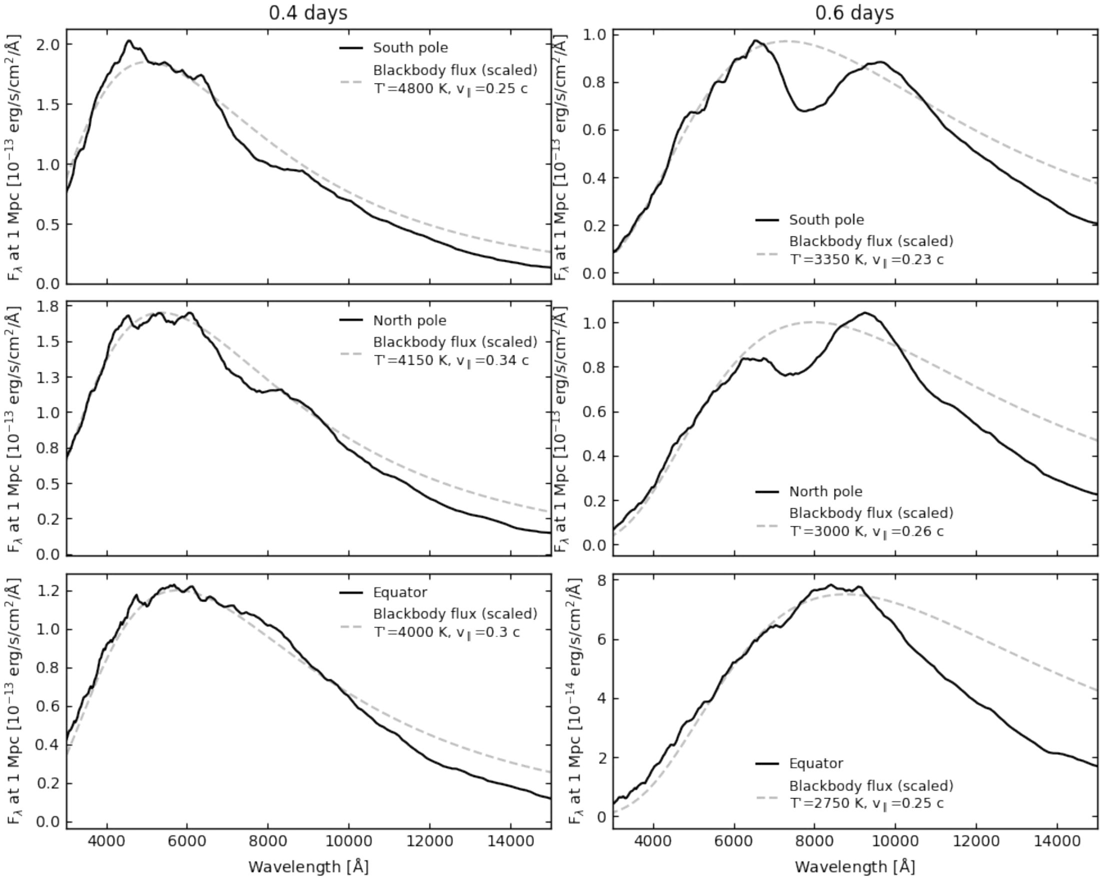
Expanding photosphere method (EPM)

$$L = 4\pi R_{\rm ph}^2 \pi B(\lambda, T')$$

$$R_{\rm ph} = v_{\rm ph} t$$

- Sensitive to photospheric expansion perpendicular to the line of sight ($v_\perp$)

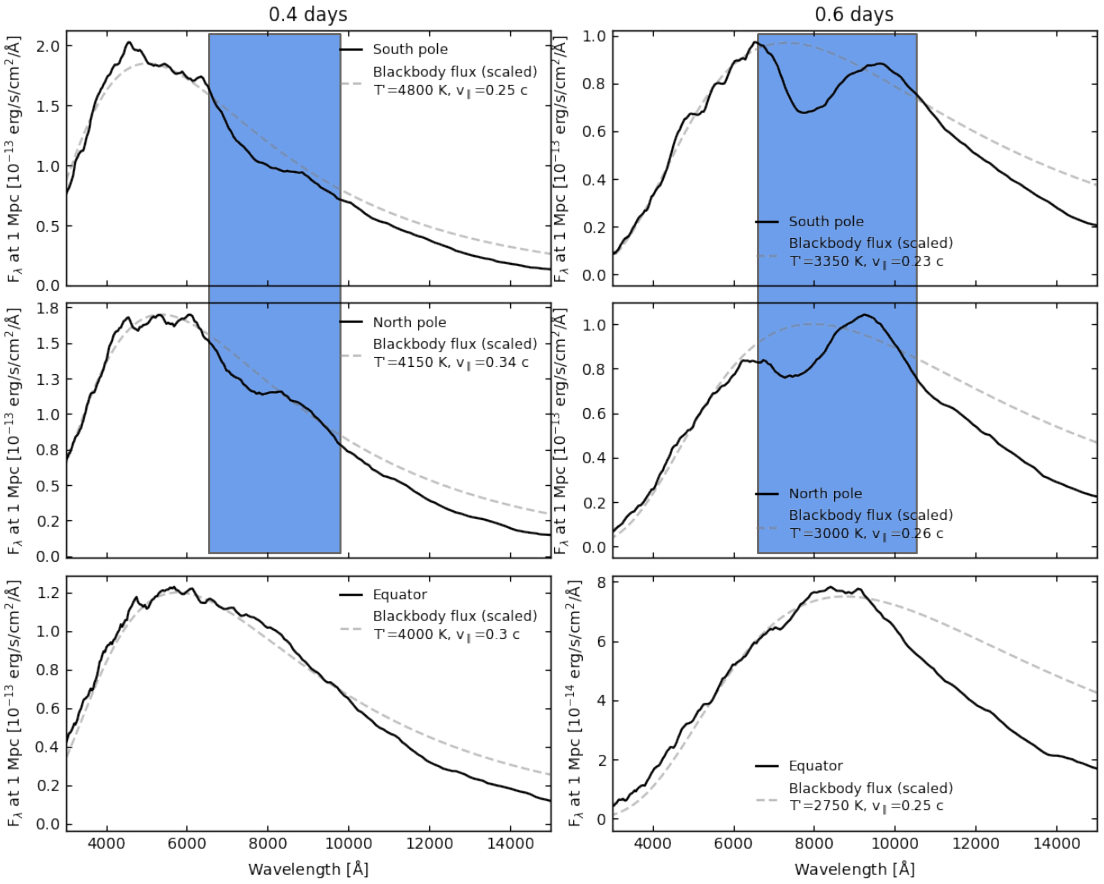
- At 0.4 days, spectra resemble a black body, but by 0.6 days no longer a good match



Inferring photospheric velocities from simulated spectra

Expansion velocity from P-Cygni feature

- Velocity inferred by fitting profile with a simple line profile calculator
- Most sensitive to photospheric expansion in the line of sight ($v_{//}$)
- Spectra at the equator are featureless – $v_{//}$ cannot be measured in the same way



Inferred photospheric velocities and asymmetry

- At 0.4 days the inferred photospheric velocities are very similar
- Implying a high degree of sphericity
  - Within uncertainty of the sphericity inferred for AT2017gfo ($\Upsilon = 0.00 \pm 0.02$)
- At 0.6 days the photospheric velocities from the EPM are too high
  - Spectra no longer resemble blackbody
- Υ is too high
  - Not the case for AT2017gfo

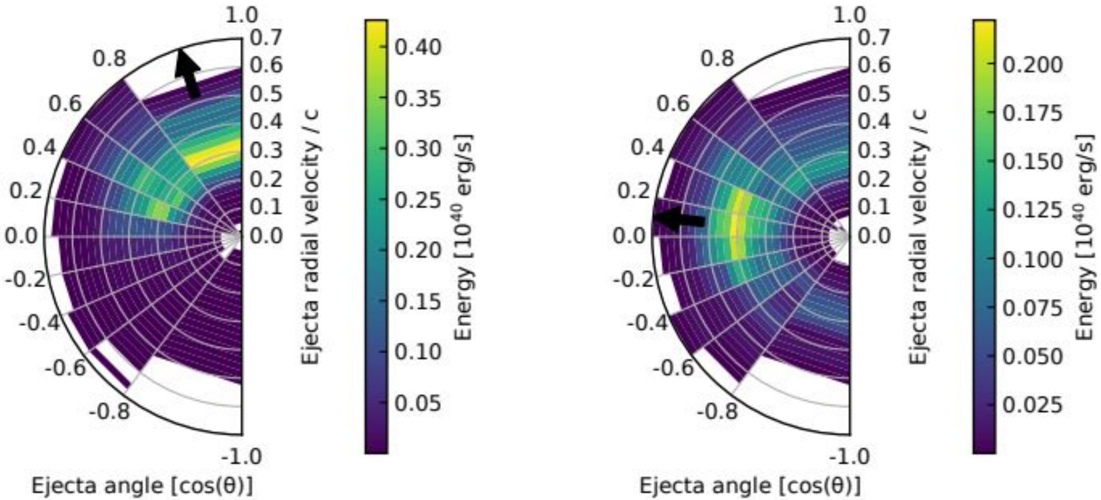
zero-centred asymmetry parameter

$$\Upsilon = \frac{v_\perp - v_\parallel}{v_\perp + v_\parallel}$$

Time [days]	Direction	$v_{//}$ [c] (P-Cygni)	$v_\perp$ [c] (EPM)	Υ (asymmetry)
0.4	South pole	0.25	0.27	0.038
0.4	North pole	0.34	0.33	-0.015
0.6	South pole	0.23	0.31	0.15
0.6	North pole	0.26	0.38	0.19

Sphericity of spectrum forming region

- In ARTIS there is no photosphere defined, but we can investigate the spectrum forming region



Last-interaction location of radiation arriving at an observer at 0.4 days indicating spectrum forming region

Sphericity of spectrum forming region

$$\Upsilon_{\bar{v},i} = \frac{\bar{v}_{i,\mathrm{eq}} - \bar{v}_{i,\mathrm{pole}}}{\bar{v}_{i,\mathrm{eq}} + \bar{v}_{i,\mathrm{pole}}}$$

- Mean last-interaction velocities of radiation travelling towards the poles and the equator
- Indicates a high degree of sphericity at both 0.4 and 0.6 days

Time [days]	Direction	▿,i (mean last-interaction velocity)	Y ▿,i (last-interaction velocity)
0.4	South pole	0.32	0.072
0.4	North pole	0.35	0.028
0.4	Equator	0.37	
0.6	South pole	0.30	0.063
0.6	North pole	0.33	0.015
0.6	Equator	0.34	

Symmetry of mean last-interaction velocities

- Spectrum forming region is slightly less spherical than inferred for the photosphere
- Remains highly spherical over 2 epochs
- The radiation can be highly spherical even when the ejecta are aspherical

Time [days]	Direction	Y (asymmetry)	$Y_{\bar{v},i}$ (last-interaction velocity)
0.4	South pole	0.038	0.072
0.4	North pole	-0.015	0.028
0.6	South pole	0.15	0.063
0.6	North pole	0.19	0.015

Distance estimate

- Using the EPM, we infer the distance to our synthetic spectra
- When the spectra resemble a blackbody distance can be measured (within 4–7%)
  - Underestimated when spectra no longer resemble blackbody
- More accurate distance estimate when a higher sphericity is inferred
  - Could be a test for how accurate a distance estimate can be made

Synthetic spectra at 1Mpc

Time [days]	Direction	Y (EPM+P-Cygni)	D_L [Mpc]
0.4	South pole	0.038	0.93
0.4	North pole	-0.015	1.04
0.6	South pole	0.15	0.74
0.6	North pole	0.19	0.68

Conclusions

- We would infer that our kilonova simulation is highly spherical, even though the ejecta are not
  - In agreement with Sneppen+2023 for AT2017gfo
  - **In some observer directions** – expect that not all future observations will appear spherical (e.g., equator)
- The inferred symmetry constraints of AT2017gfo do not necessarily mean the ejecta are spherical
- The spectrum forming region in the simulation is highly spherical, supporting the level of symmetry inferred from the photospheric velocities
- While a high degree of sphericity is inferred an accurate distance estimate can be made
  - Suggesting sphericity could be a test on the accuracy of the distance estimate