3D radiative transfer kilonova modelling for binary neutron star merger simulations

Christine Collins
GSI

With: Andreas Bauswein, Stuart Sim, Gabriel Martínez-Pinedo,
Vimal Vijayan, Oliver Just, Luke Shingles

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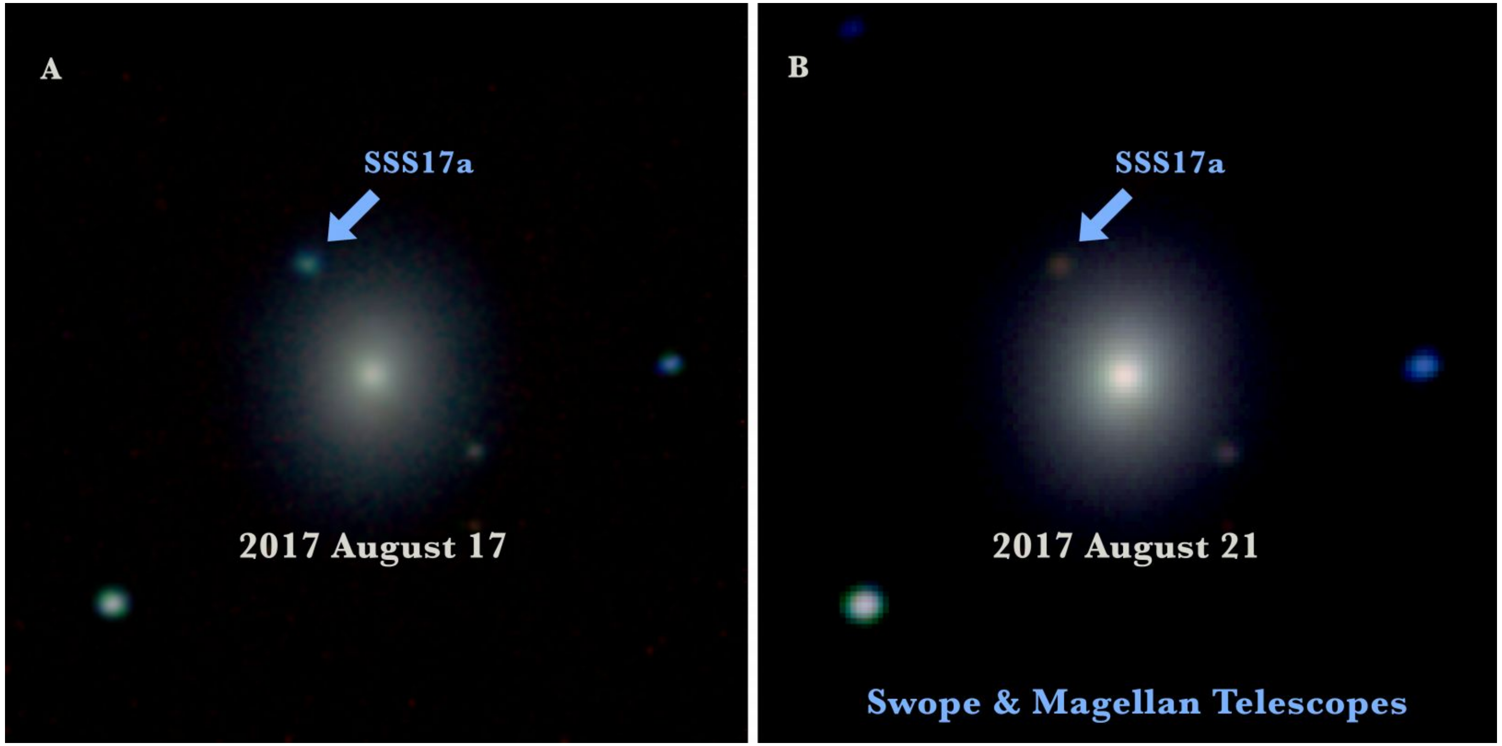
GW170817/AT2017gfo

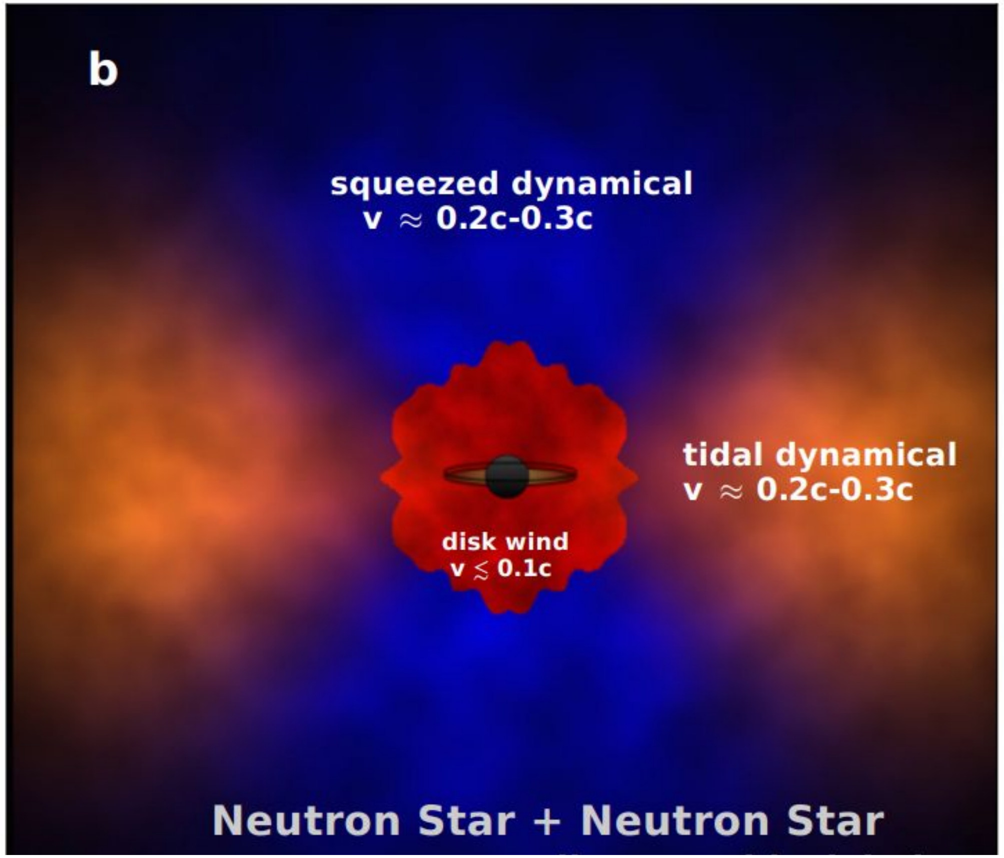
- The kilonova AT2017gfo was observed, coincident with GW170817 from the merging of binary neutron stars
- A bright, blue optical transient was observed which quickly faded and evolved to red colours



Drout et al. 2017

Two component model

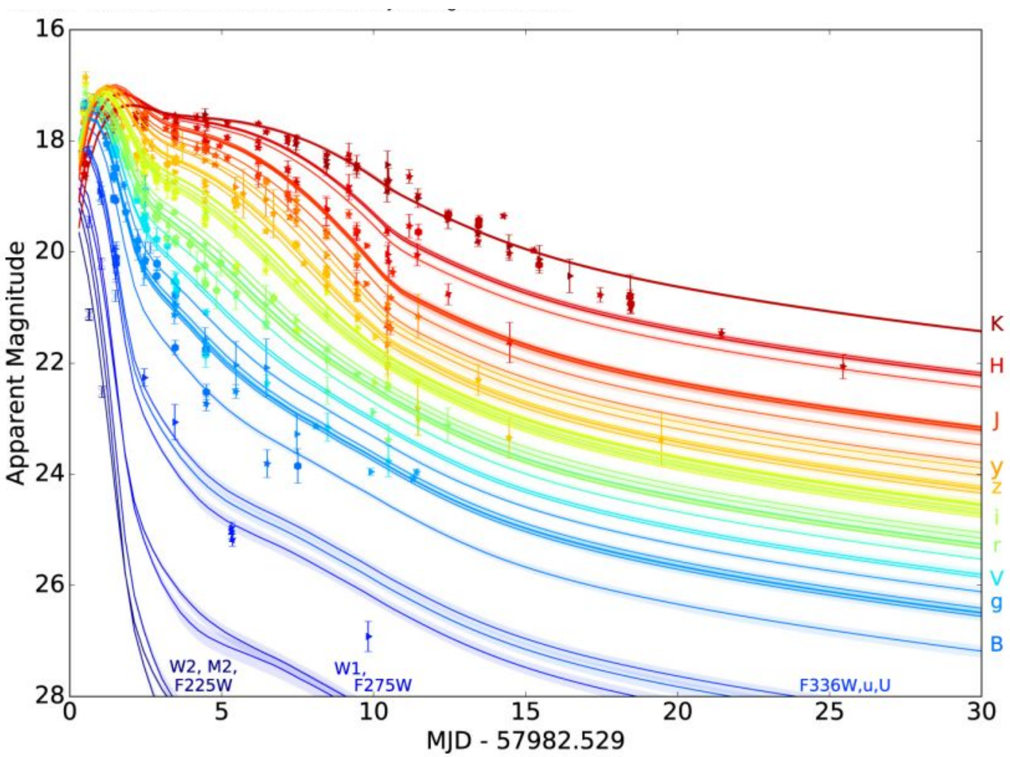
- A two component model has been proposed to explain the blue to red colour evolution
    - high velocity “blue” dynamical ejecta
    - low velocity “red” secular ejecta



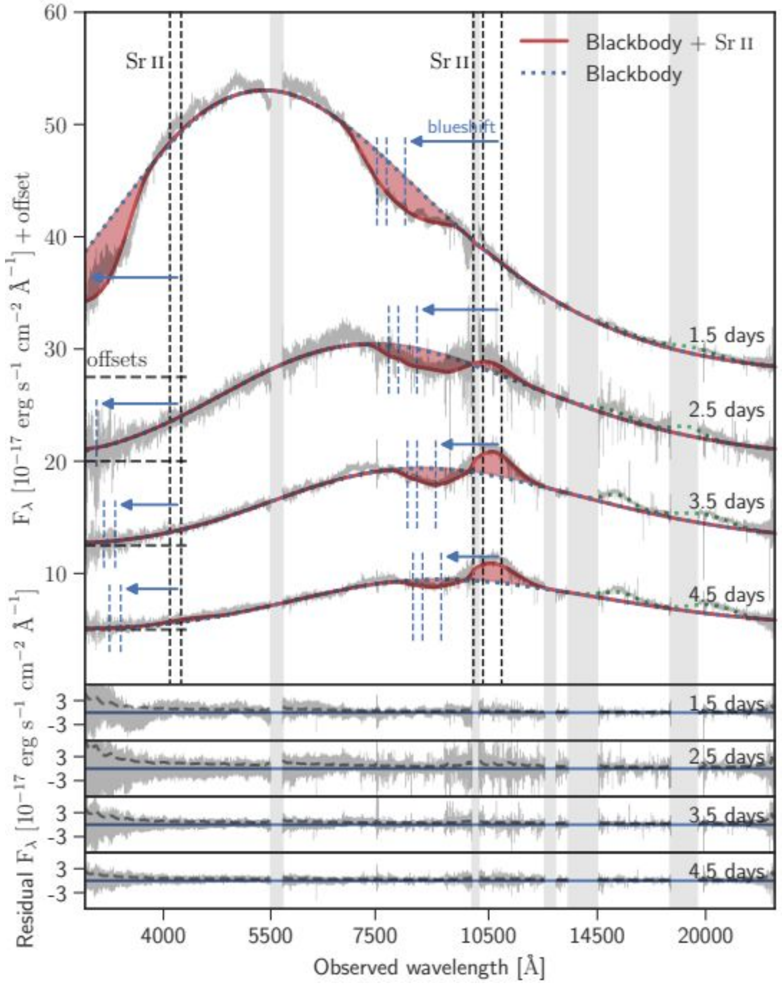
Kasen et al. 2017

Observations of AT2017gfo

- Modelling required to understand observations
- Many approaches have fitted parameters to observations



Villar et al. 2017

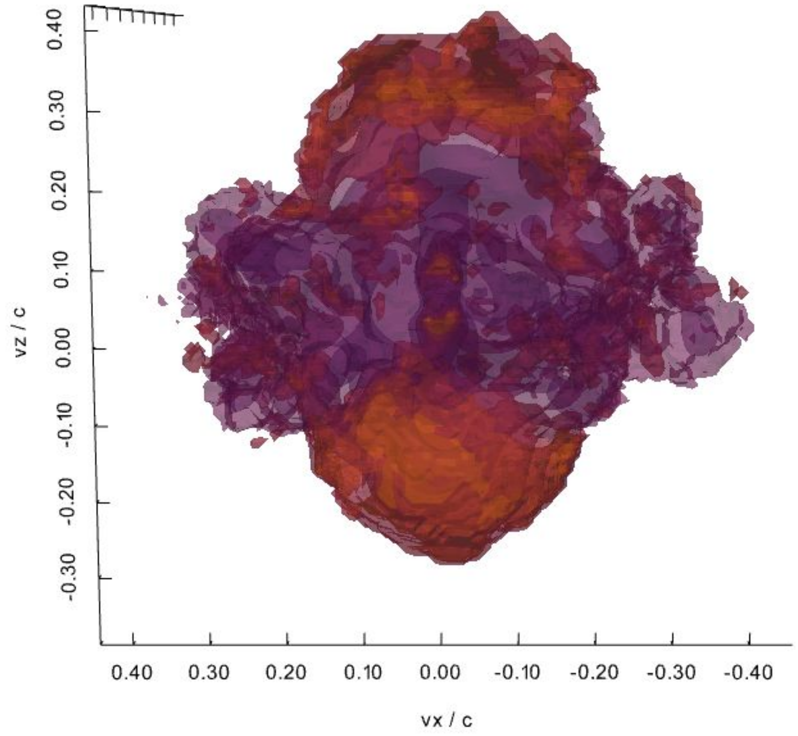


Watson et al. 2019

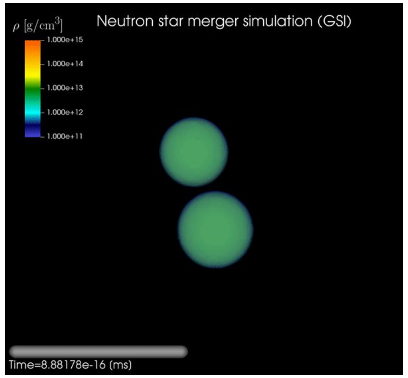
Merger simulations predict asymmetric ejecta

- Dynamical ejecta from binary neutron star merger simulation

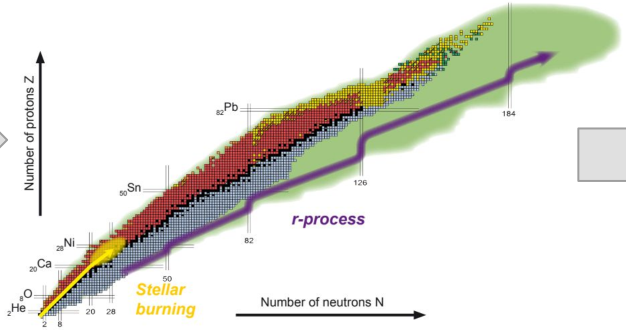
- Need to connect merger simulations to observations



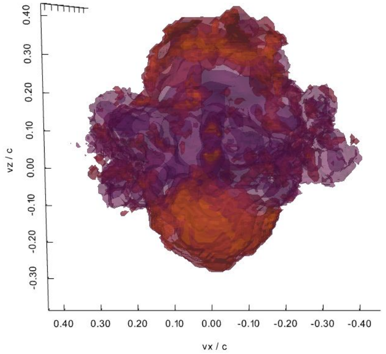
3D kilonova modelling pipeline



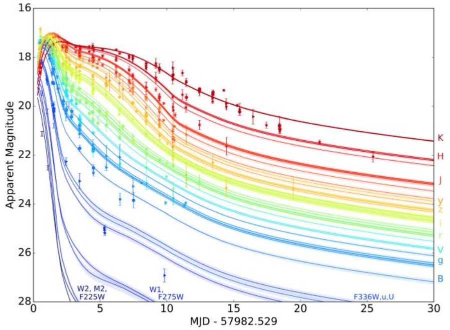
NS-NS merger simulation
credit: S. Blacker



Nucleosynthesis calculations
provide energy released
credit: EMMI, GSI/Different Arts

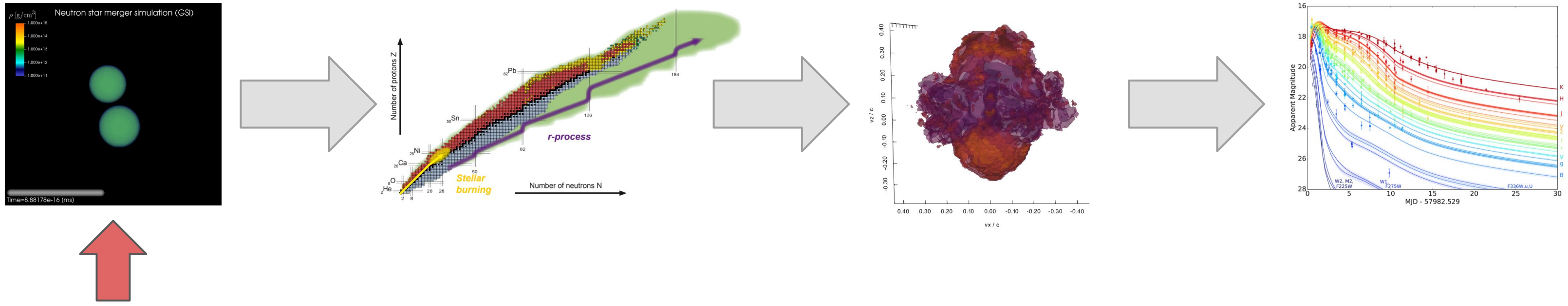


Radiative transfer
calculation based on
ejecta snapshot



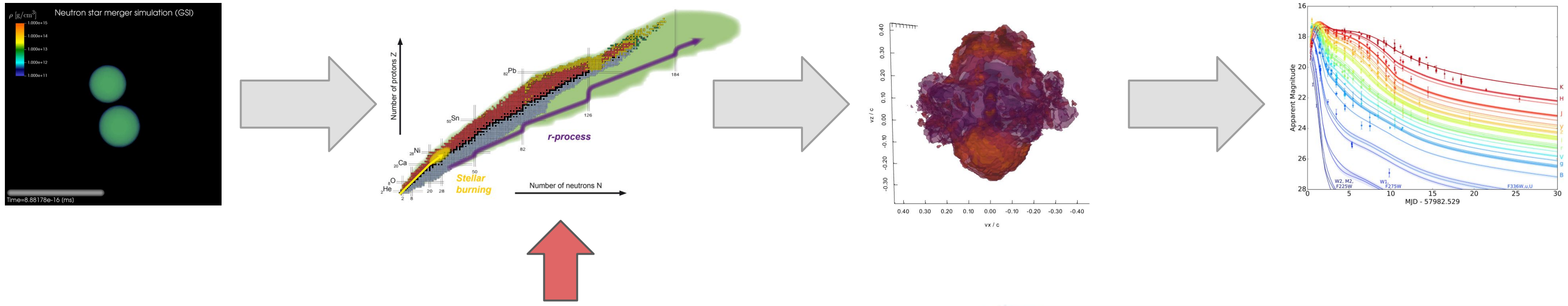
Compare to observations
Image: light curves of
AT2017gfo (Villar et al. 2017)

Merger simulation

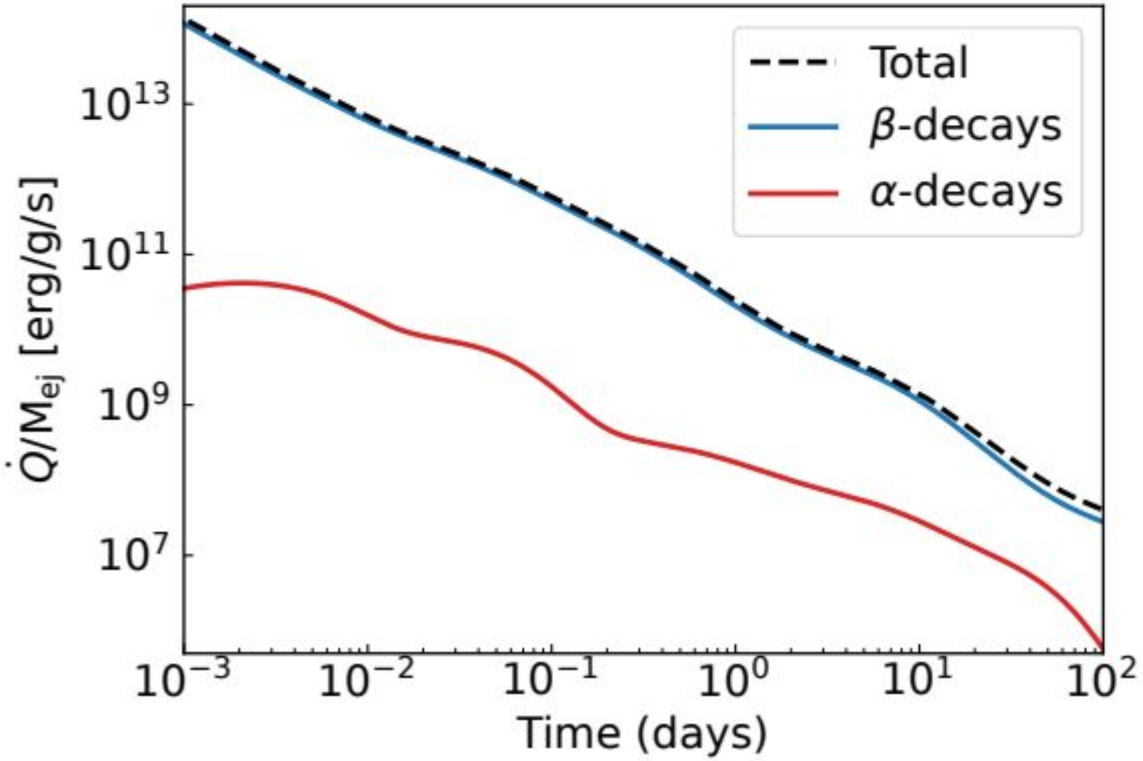


- Merger simulated by a 3D general relativistic smoothed-particle hydrodynamics (SPH) code
  - (Oechslin et al. 2002; Bauswein et al. 2013; carried out by V. Vijayan)
- Used ILEAS scheme for neutrino transport (Ardevol-Pulpillo et al. 2019)
- Equal mass 1.35 $M_\odot$-1.35 $M_\odot$ BNS merger simulated
- We consider only material ejected on dynamical timescales (20s milliseconds after time when both stars touched)

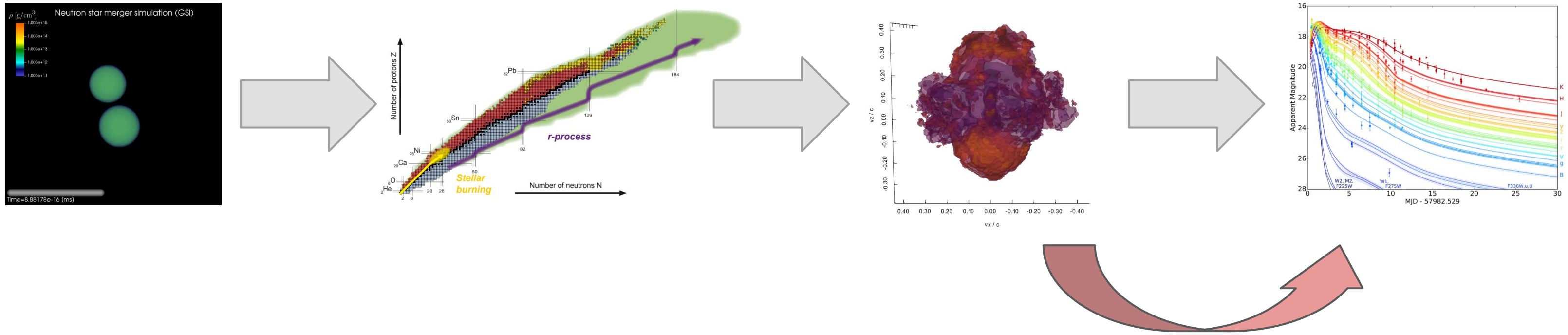
Nuclear calculation



- Nuclear network calculation by G. Martínez-Pinedo
- The energy released by each ejected SPH trajectory is calculated



ARTIS Monte Carlo radiative transfer

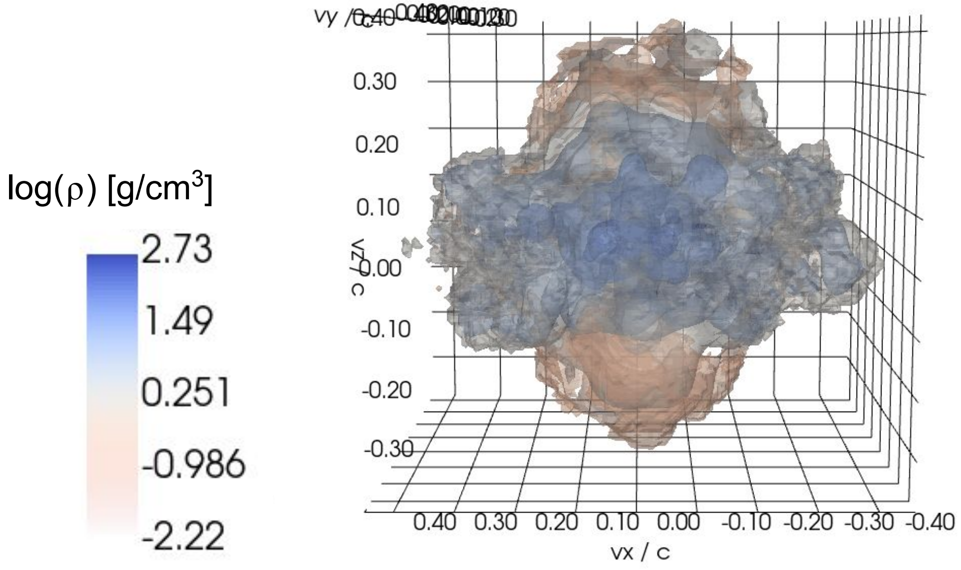


- We carry out 3D radiative transfer simulations to predict line-of-sight dependent light curves
- ARTIS is a time-dependent, 3D, Monte Carlo radiative transfer code (Sim 2007, Kromer & Sim 2009, based on method of Lucy 2002, 2005)
- Radioactive energy is discretised into packets, which are followed until they leave the simulation
- Monte Carlo energy packets are placed in the ejecta, according to the distribution of energy released (obtained from nucleosynthesis)

Mapping SPH particles to radiative transfer grid

- SPH particles were propagated for 0.5 seconds according to their velocity at the end of the simulation.
- Particle densities mapped to a 128^3 cell grid
- Homologous expansion is an assumption made by ARTIS (and most other radiative transfer codes)

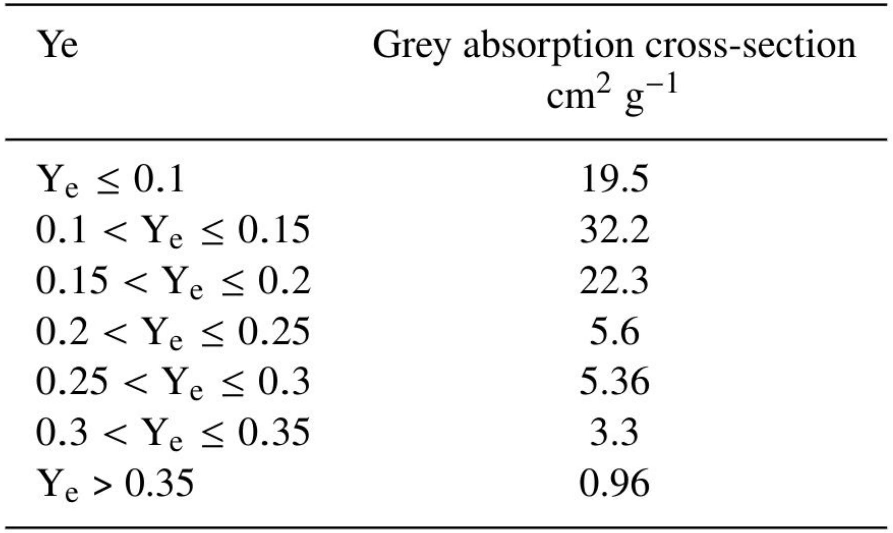
- Polar directions have much lower central densities than disk
- Total mass of dynamical ejecta mapped to the grid is 0.0051 $M_\odot$



3D rendering of dynamical ejecta, where isosurfaces indicate density

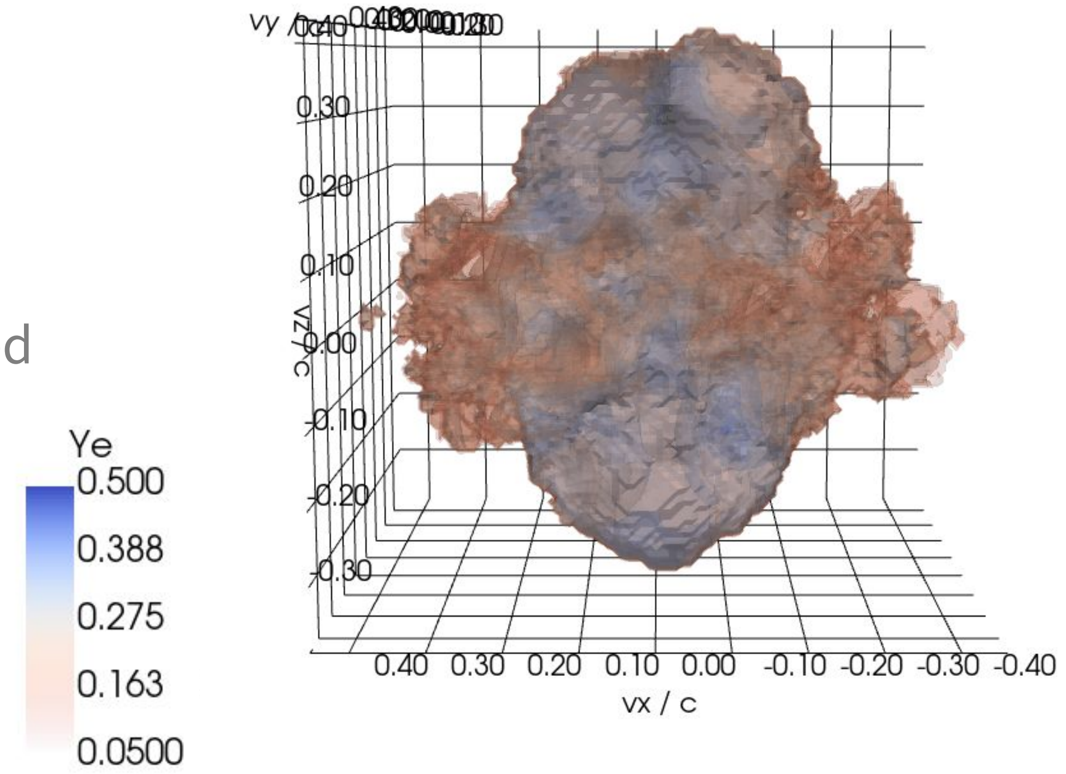
Ye dependent grey opacities

- We assume a grey approximation
- Use Ye dependent opacities (Ye mapped from SPH particles)
- Poles have higher Ye than the equator

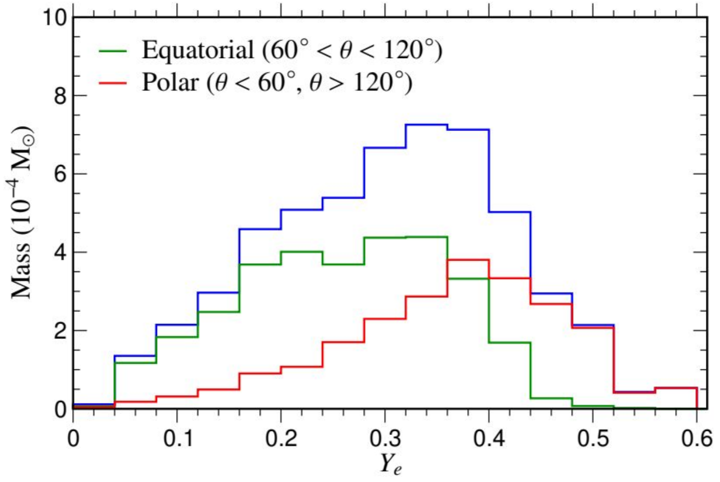


Ye	Grey absorption cross-section $\mathrm{cm^2\,g^{-1}}$
$Y_e \leq 0.1$	19.5
$0.1 < Y_e \leq 0.15$	32.2
$0.15 < Y_e \leq 0.2$	22.3
$0.2 < Y_e \leq 0.25$	5.6
$0.25 < Y_e \leq 0.3$	5.36
$0.3 < Y_e \leq 0.35$	3.3
$Y_e > 0.35$	0.96

Tanaka et al. 2020

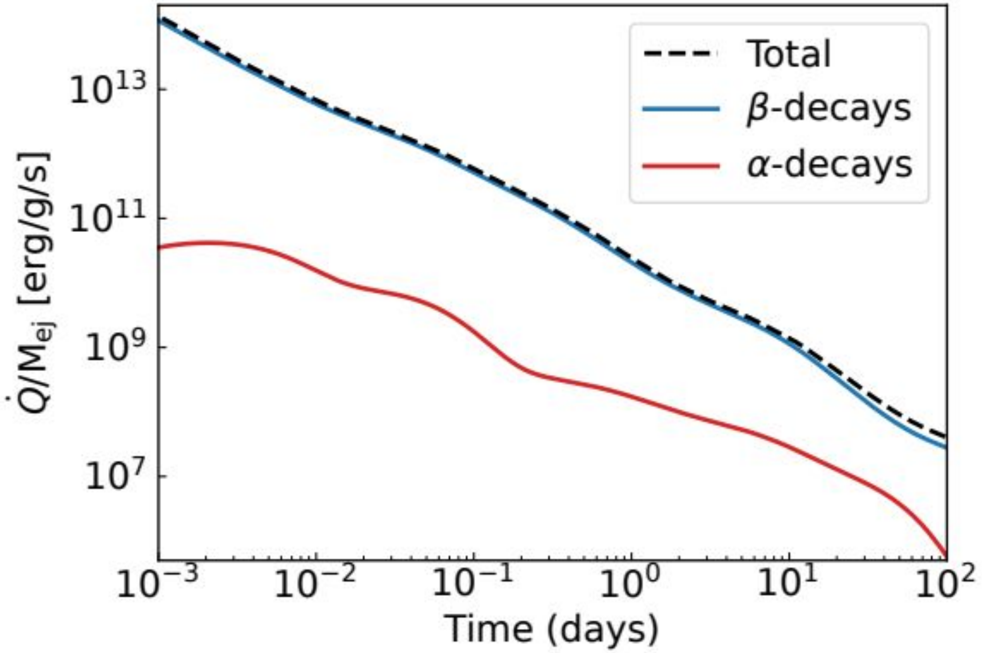


3D rendering of ejecta where colour indicates the electron fraction (Ye) of the material



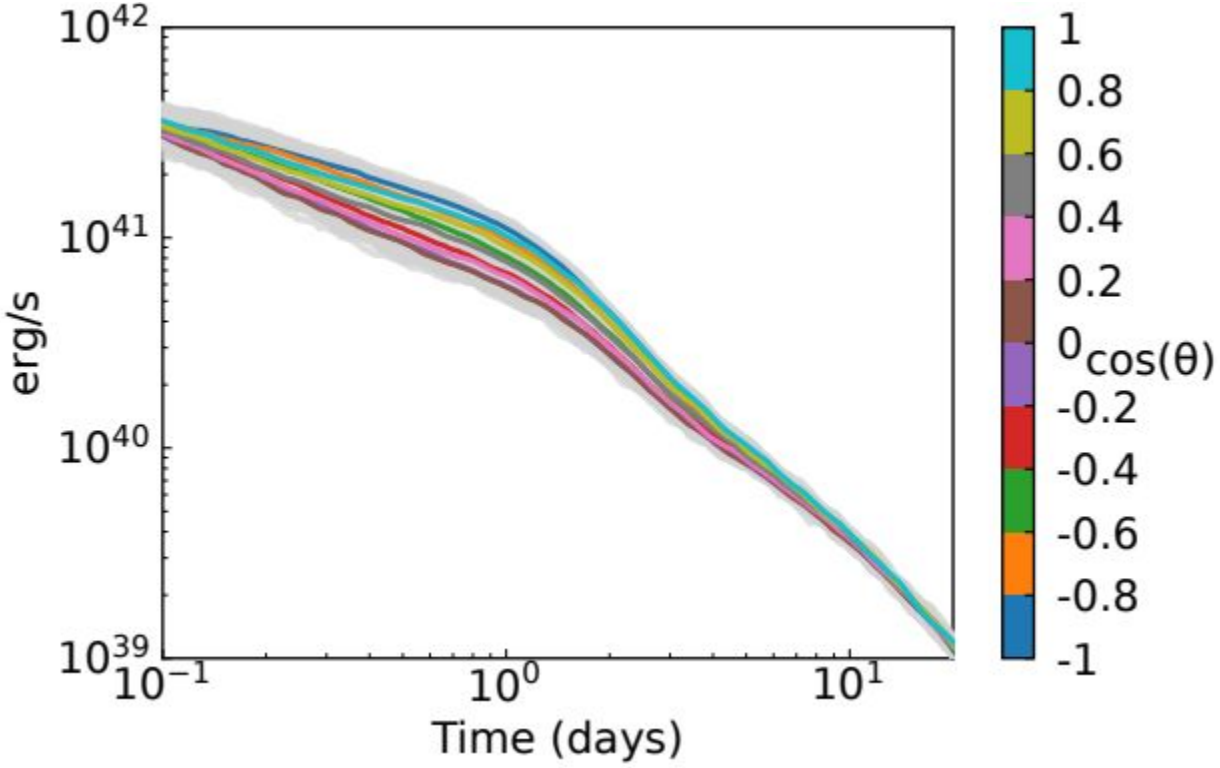
Radioactive heating in ARTIS simulation

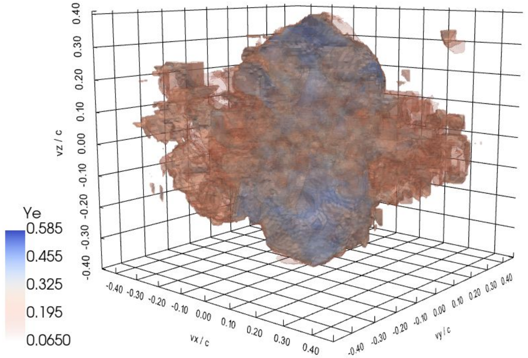
- We assume all heating in our simulation is from beta decays
    - Neutrinos will not thermalise. We assume 35% is lost to neutrinos
    - Assume gamma-rays account for 45% of energy. We include gamma-ray transport (for estimated gamma energies)
    - Assume beta-particles account for 20% of energy, and that these thermalise instantaneously.
        - (Based on Barnes+2016)
- The total energy in a cell is determined from the SPH particle trajectories, but we assume a constant decay rate - the average of all trajectories



Angle-dependent bolometric light curves

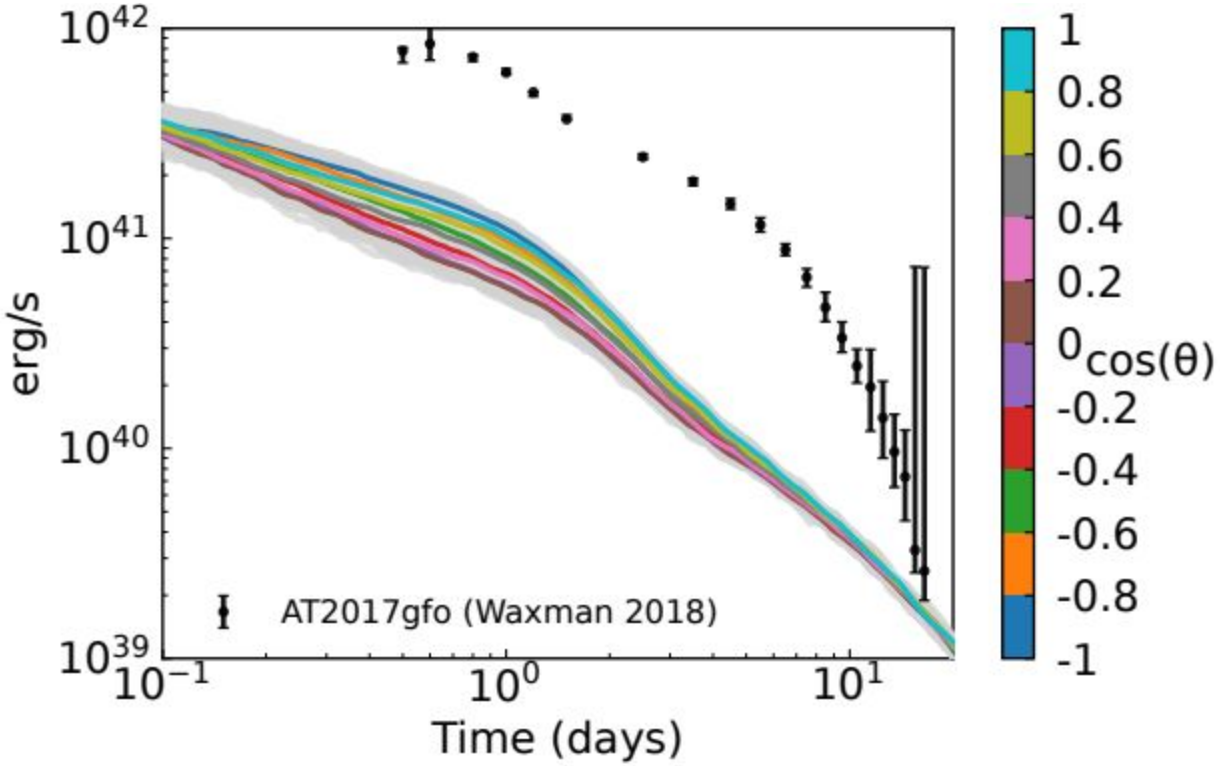
- Bolometric light curves do not rise to a peak, but do show a ‘shoulder’ when the bulk ejecta become optically thin
    - Energy generated and thermalised in high velocity outer layers with low optical depths
- Lines of sight in the polar directions are brighter around ‘peak’ due to lower grey opacities and lower densities





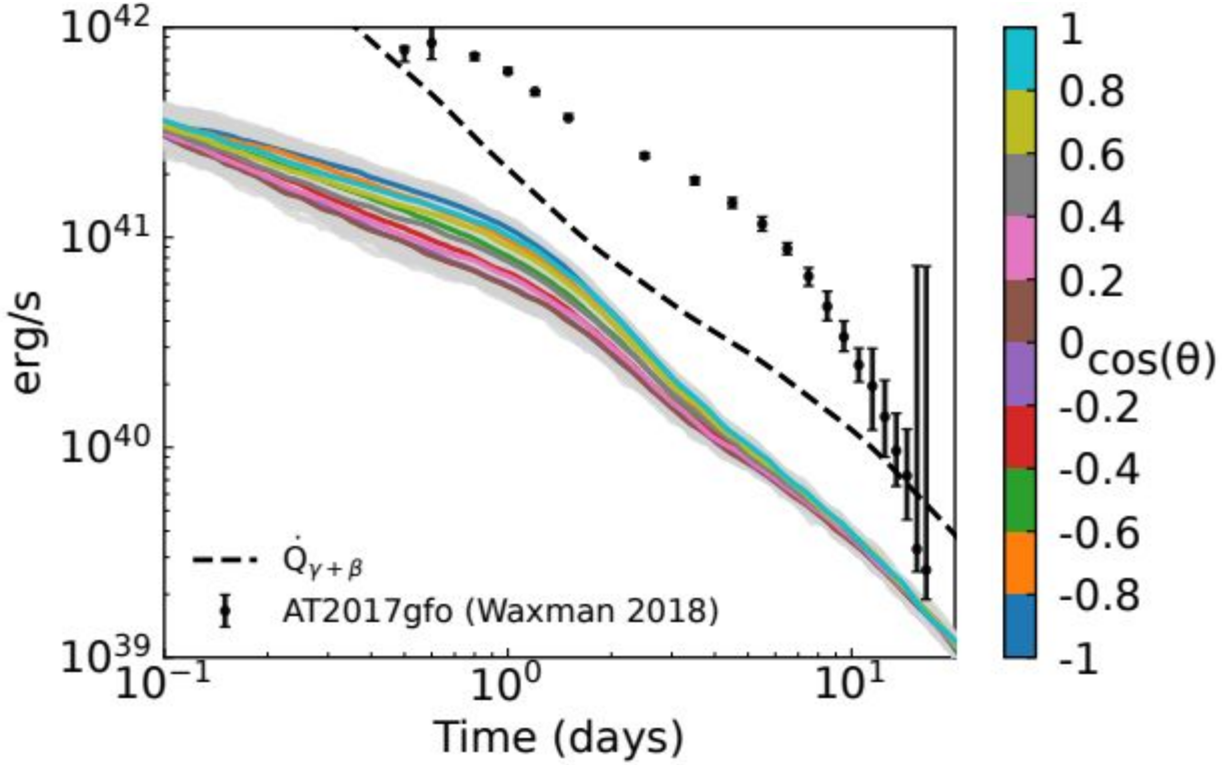
Angle-dependent bolometric light curves

- Dynamical ejecta model is less massive than the total mass inferred for AT2017gfo, and therefore do not expect model to be as bright



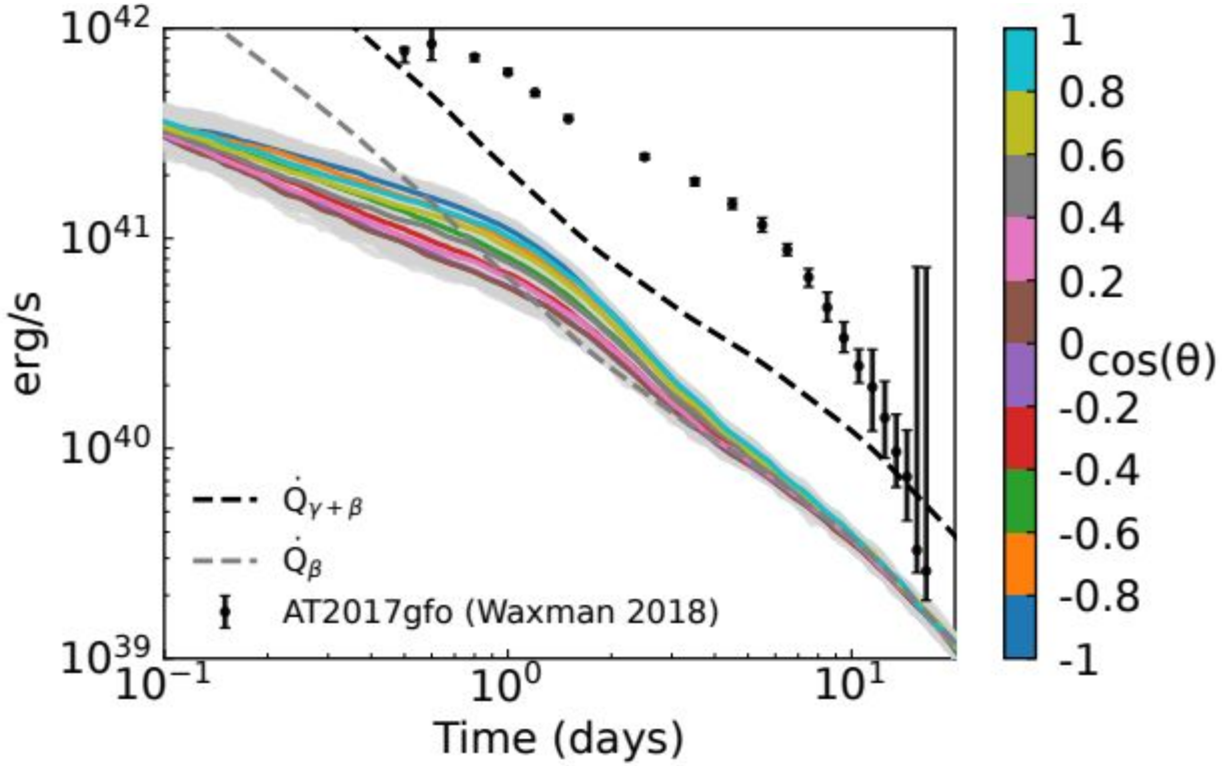
Angle-dependent bolometric light curves

- The total energy available for heating the ejecta is given.
- This excludes the 35% lost to neutrinos
- Remaining energy is ɣ-rays and β-particles



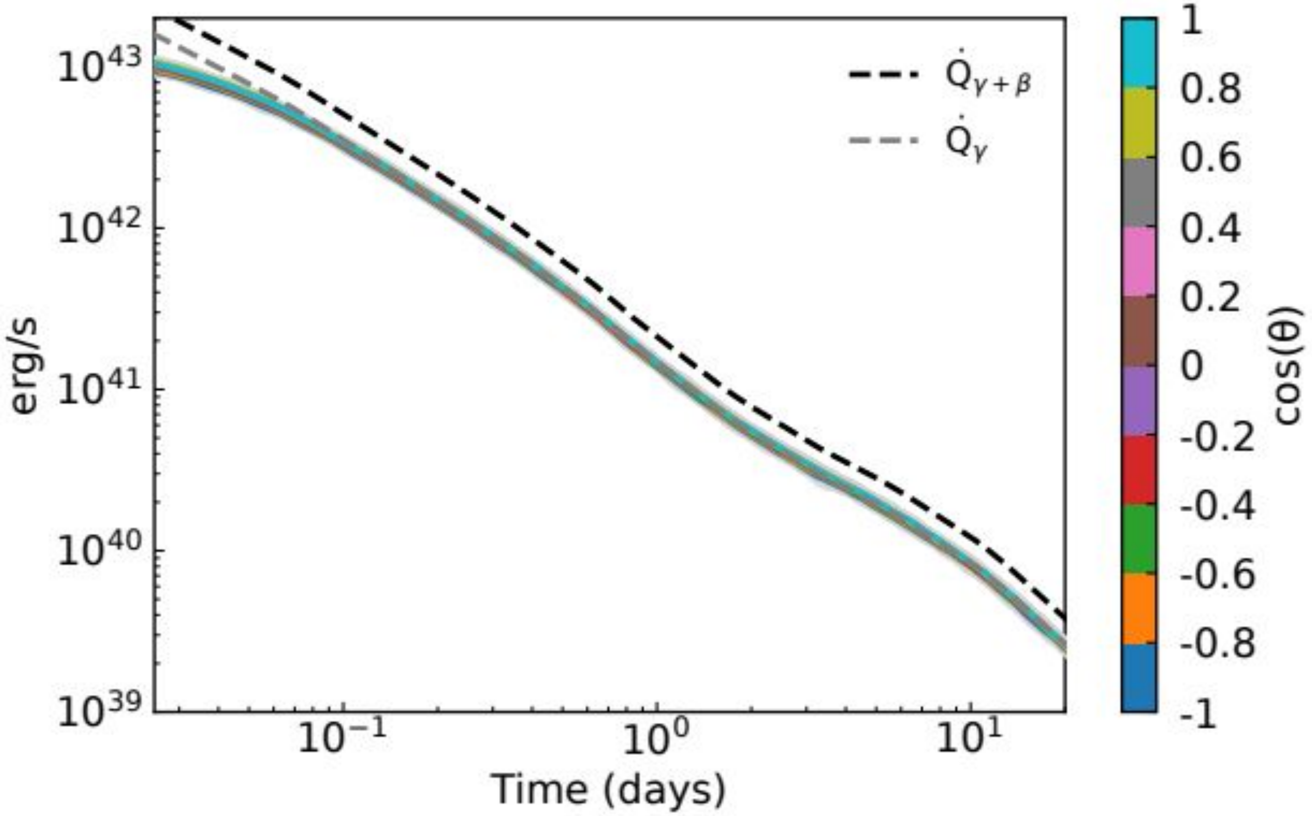
Angle-dependent bolometric light curves

- Also marked is the heating rate by β-particles (20% of total energy)
- We assume all beta particles thermalise instantaneously
- Late time light curve dependent on energy deposition rate (in our model entirely on beta-particle rate)



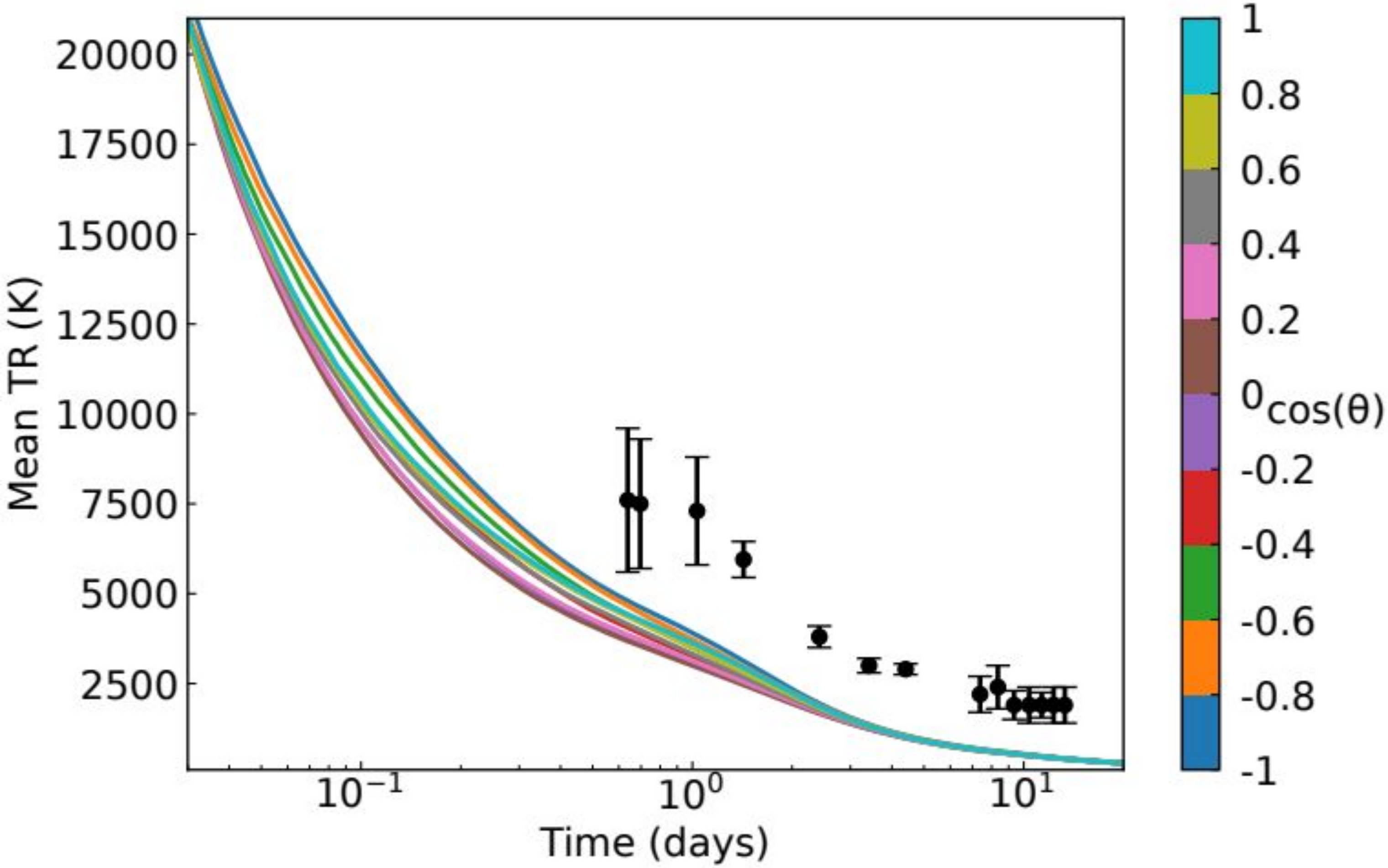
Gamma light curve

- We assume 45% of the total energy to be γ-rays
- γ-rays only thermalise at very early times (< 2 hours), since after this the gamma light curve is the total γ energy
- No viewing angle dependence expected



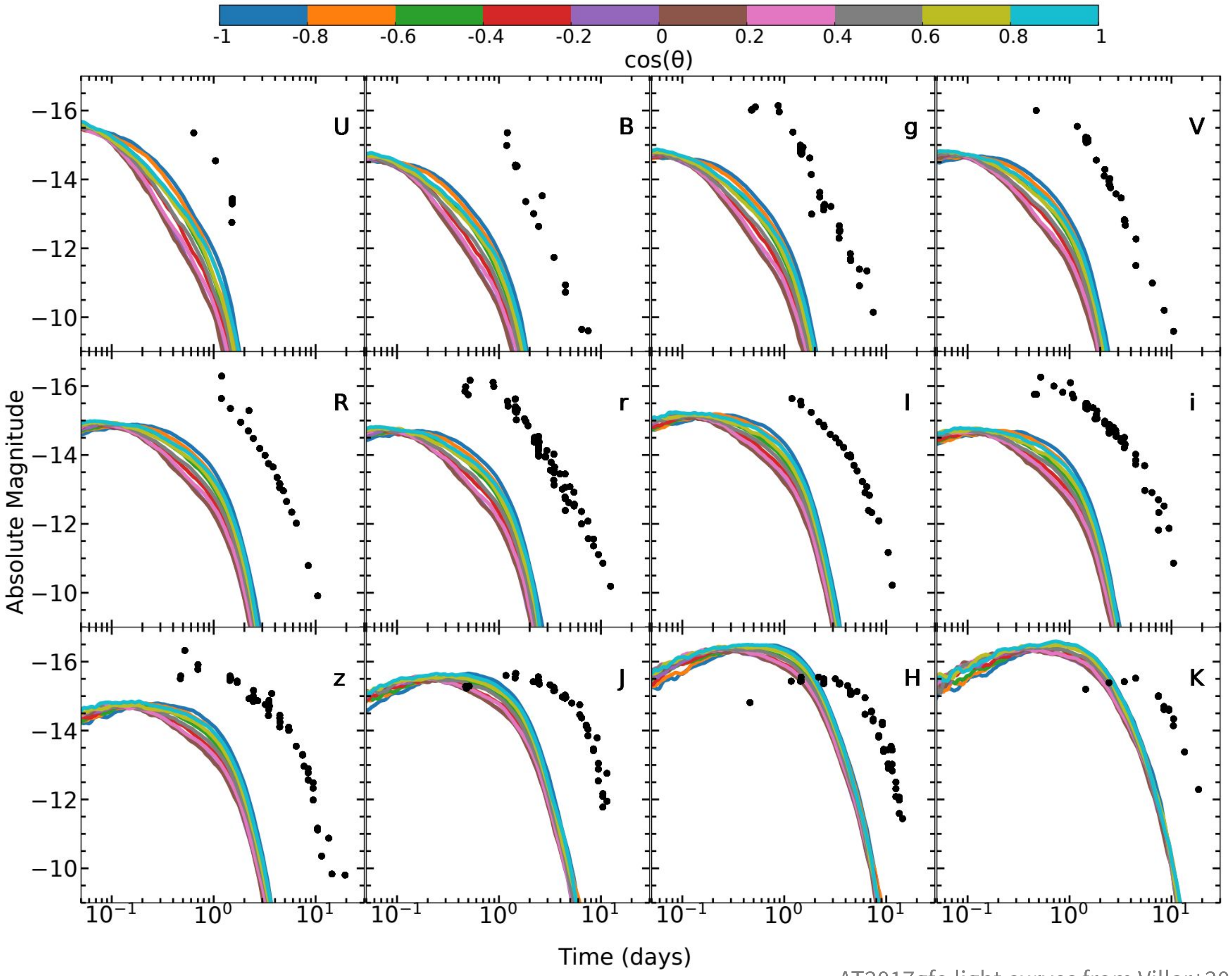
Mean temperature where radiation is escaping

- Ejecta temperatures cool rapidly (due to the high expansion velocities)
- Compared to inferred temperatures from the spectra of AT2017gfo by Smartt et al. (2017)
- Cooler than AT2017gfo, but shows similar decline



Approximate light curves from black body spectra

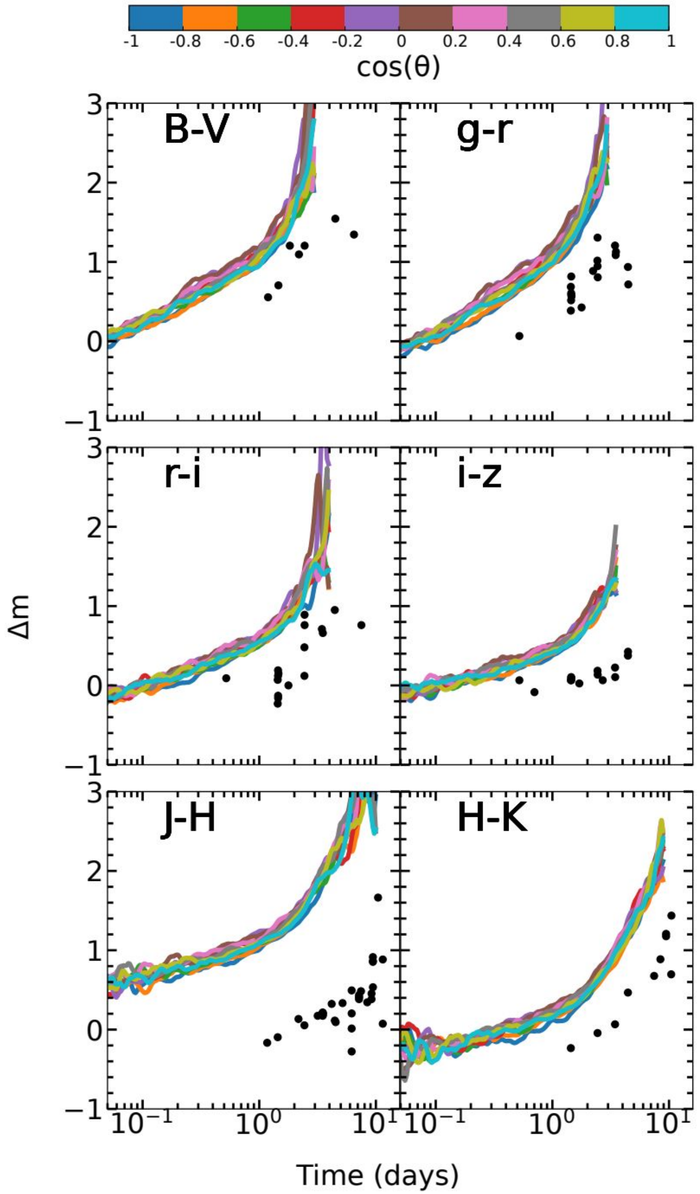
- Since we use a grey approximation we have no frequency dependence
- However, we do have the radiation temperature at the location packets were emitted from
- We can estimate a frequency for the packet from a black body at the radiation temperature
- From this we obtain approximate spectra and can generate band light curves



AT2017gfo light curves from Villar+2017

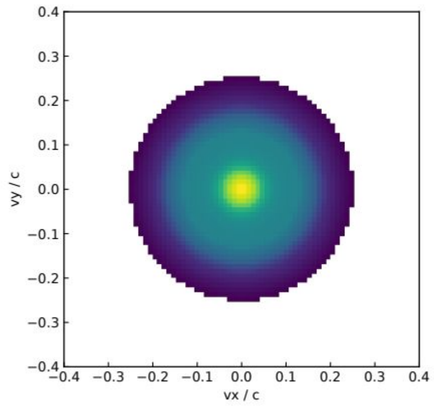
Colour evolution

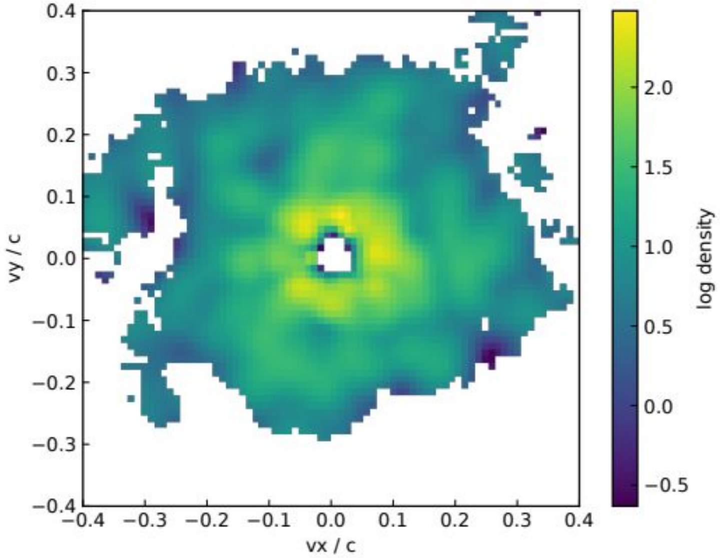
- AT2017gfo showed a rapid colour evolution from blue to red, shown by data points
- From the temperature evolution alone, we find a similarly rapid blue to red colour evolution
- We only include dynamical ejecta
- Suggests colour evolution could be driven by temperature



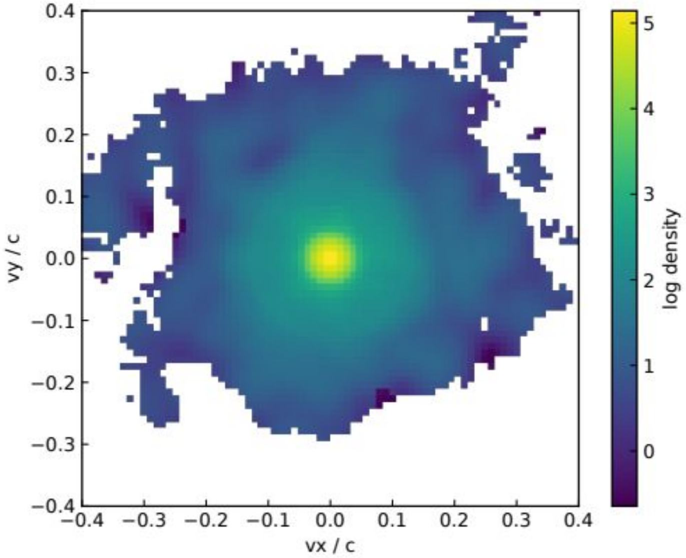
AT2017gfo light curves from Villar+2017

Secular ejecta





Dynamical ejecta only

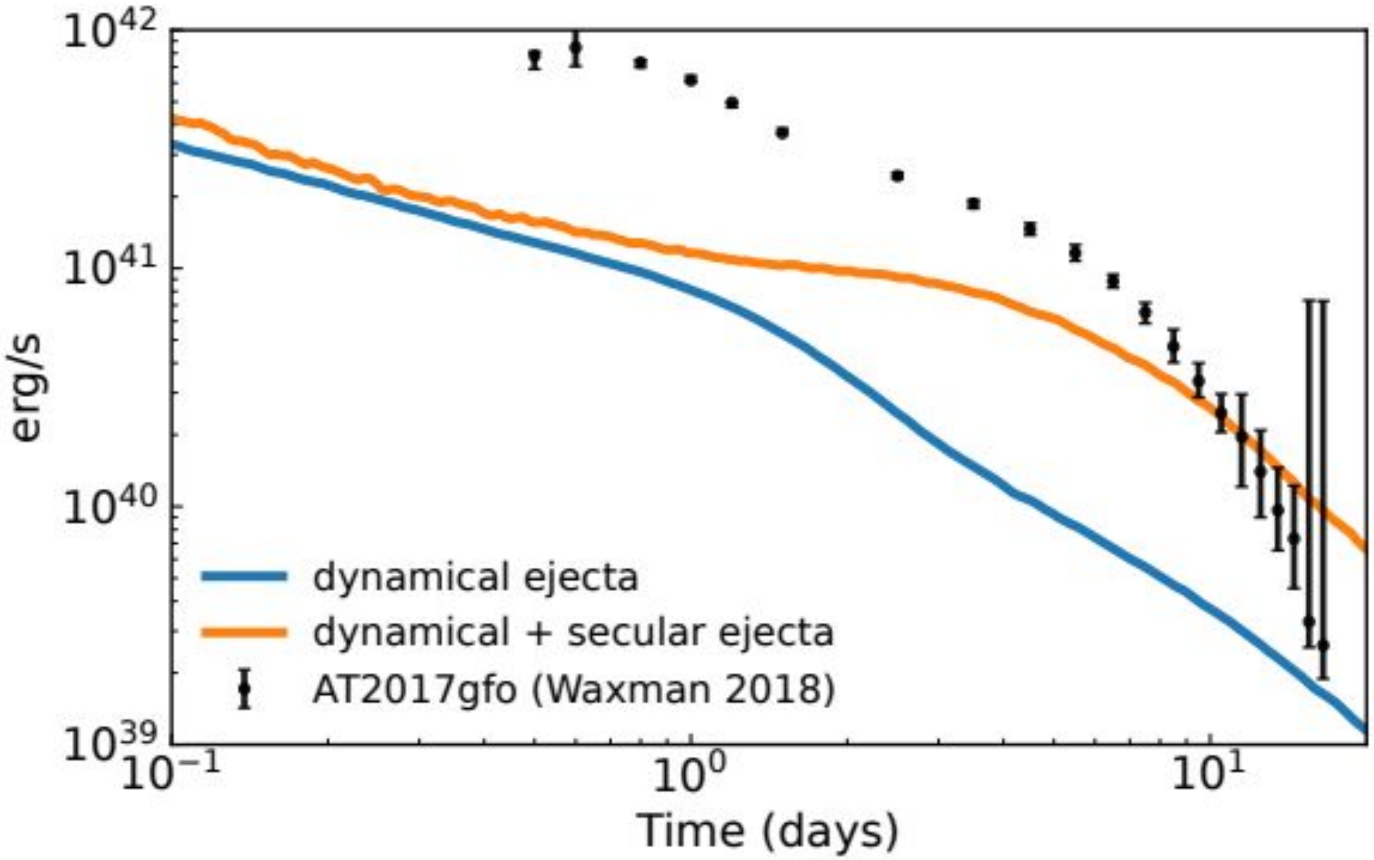


Dynamical plus secular ejetca

- We now include secular ejecta by adding mass from the torus and wind components of a long term evolution simulation (O. Just, similar to models of Just el al. 2015)
- We angle average the density profile and add this to the dynamical ejecta
- We keep the opacity from the dynamical ejecta model, and any empty cells are assumed to have Ye=0.5 (low opacity)
- The extra mass is 0.019 $M_\odot$, giving a total ejecta mass of 0.024 $M_\odot$

Secular ejecta

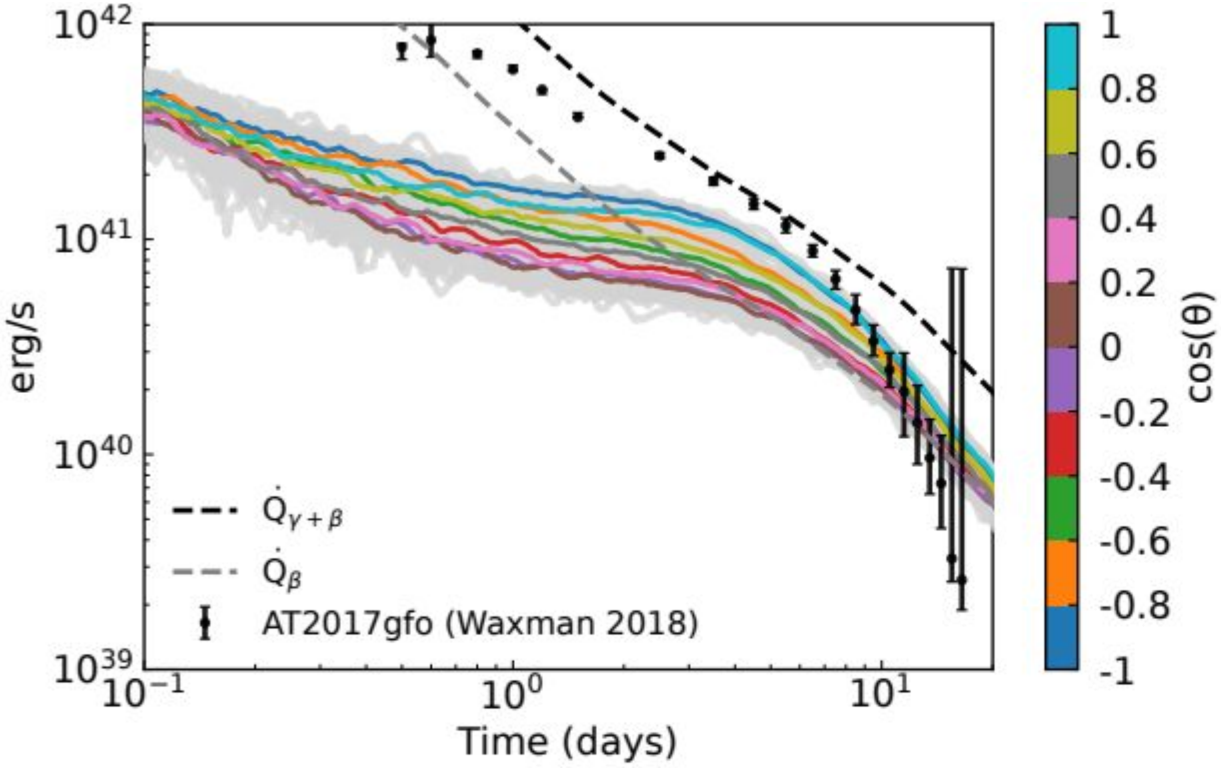
- The additional mass at low velocities increases the energy deposition in the center
- This energy leaves the ejecta after ~ 1 day
- The early light curve brightness only increases slightly
- This suggests that to account for AT2017gfo we would need more mass at higher velocities than is in our model



Angle averaged light curves

Angle-dependent bolometric light curves

- Angle-dependence increases due to secular ejecta



Conclusions

- Since radiation is throughout ejecta, including high-velocity outer ejecta we do not find a rise to peak in bolometric light curves.
- Light curves viewing towards the poles are brighter by factor of ~2 compared to equator.
- Due to the temperature evolution, we find a rapid colour evolution from blue to red, similar to that observed in AT2017gfo. This suggests that the colour evolution could be due to cooling, rather than the composition.
- More mass is required at high velocities to match the observed brightness of AT2017gfo.