Kilonova emission from realistic neutron star merger simulations

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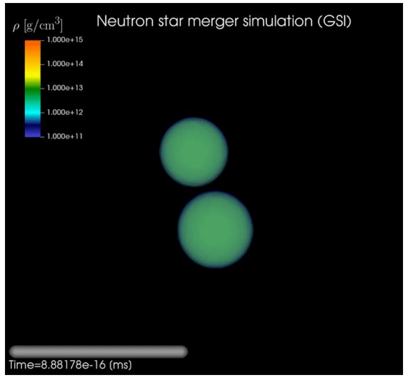
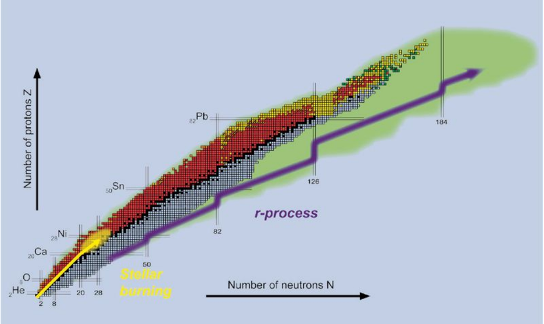
Overview

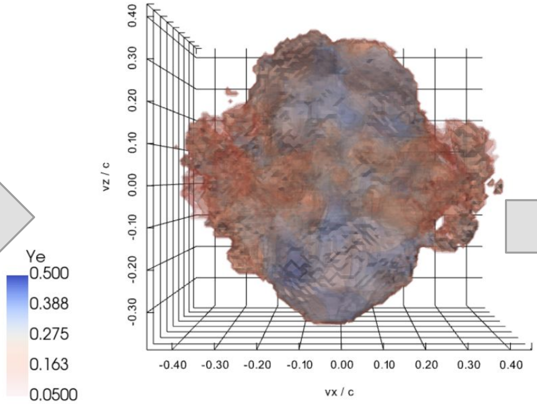
- **Aim**: To predict observables for a realistic neutron star merger simulation
  - Many simulations predicting kilonova have not used real merger data. Most are based on 1D models, or even simplified toy models, while few have carried out 3D simulations.
- **Method**: We use the 3D, Monte Carlo radiative transfer code ARTIS (Kromer + Sim 2009) to predict angle dependent light curves
  - We consider a merger simulation of binary neutron stars (each 1.35 $M_{\odot}$)
  - Merger simulated by a 3D general relativistic smoothed-particle hydrodynamics (SPH) code, and included an advanced neutrino treatment



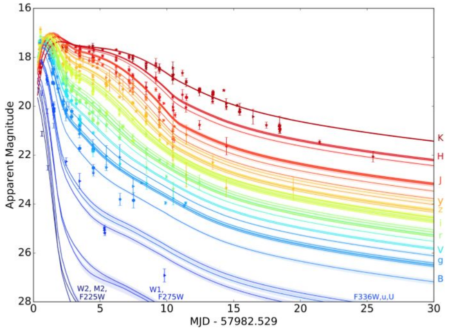
NS-NS merger simulation



Nucleosynthesis calculations provide energy released



Snapshot of dynamical ejecta



Radiative transfer simulations allow direct comparisons with observations

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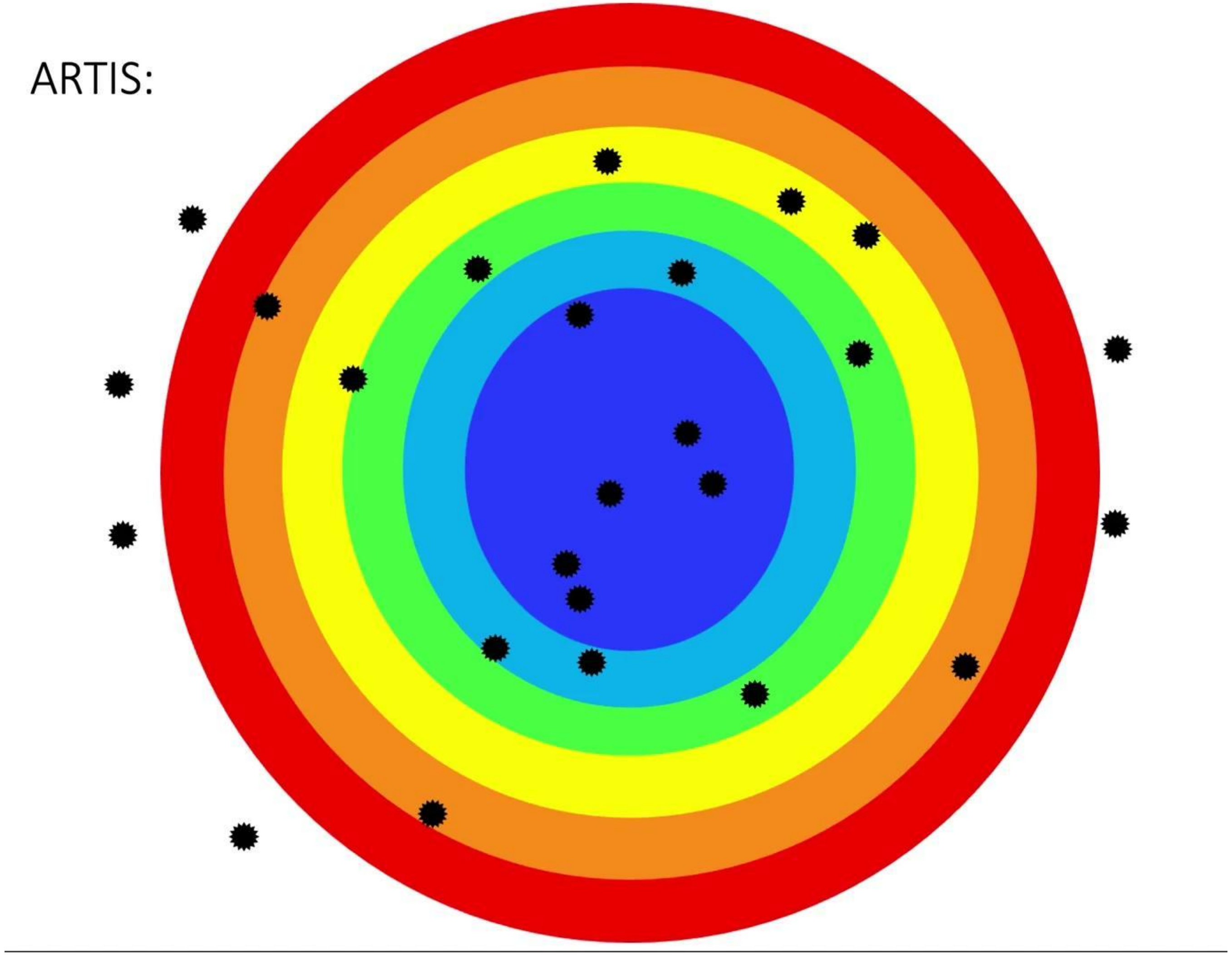
ARTIS Monte Carlo Radiative transfer

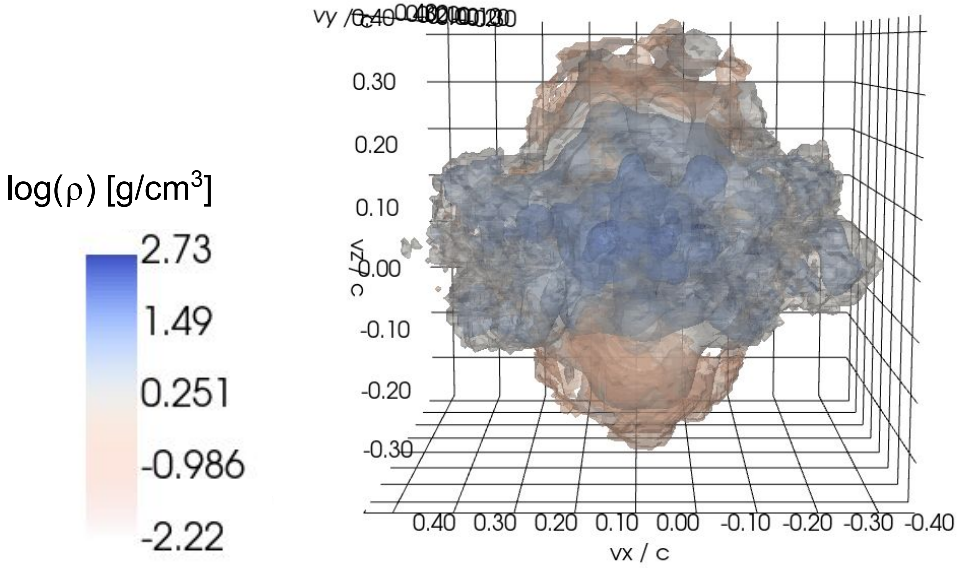
- Monte Carlo 'packets' of photons are placed in the ejecta, according to the distribution of energy produced (obtained from nucleosynthesis)
- Packets follow a random path interacting with homologously expanding ejecta
- Escaping packets are counted and used to produce light curves in different lines of sight



Dynamical ejecta density

- To map SPH particles to the grid, the particles were propagated for 0.5 seconds according to their velocity at the end of the simulation. The positions were mapped to the grid and we then assume homologous expansion

- Merger simulation predicts highly asymmetric ejecta
- Polar directions have much lower central densities than disk
- Total mass of dynamical ejecta mapped to the grid is 0.0028 $M_{\odot}$



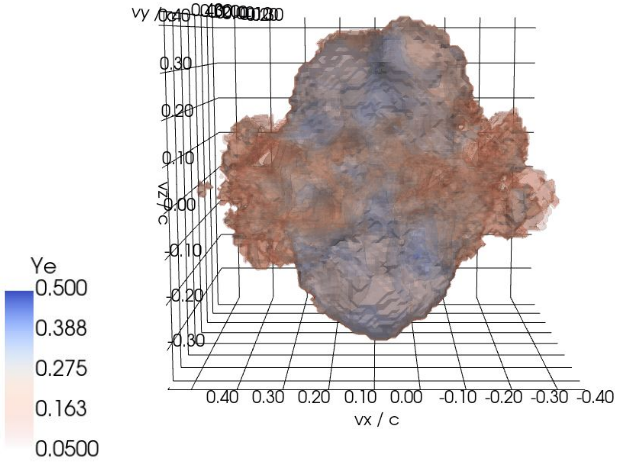
3D rendering of dynamical ejecta, where isosurfaces indicate density

Assume composition dependent opacities

- We assume a grey approximation
- Use Ye dependent opacities
- Ye determines lanthanide fraction
  - Low Ye gives a high lanthanide fraction, leading to high opacities
  - High Ye gives a low lanthanide fraction, leading to lower opacities
- Generally polar directions have higher Ye than the disk

Ye	Grey absorption cross-section $cm^2\ g^{-1}$
$Y_e \leq 0.1$	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

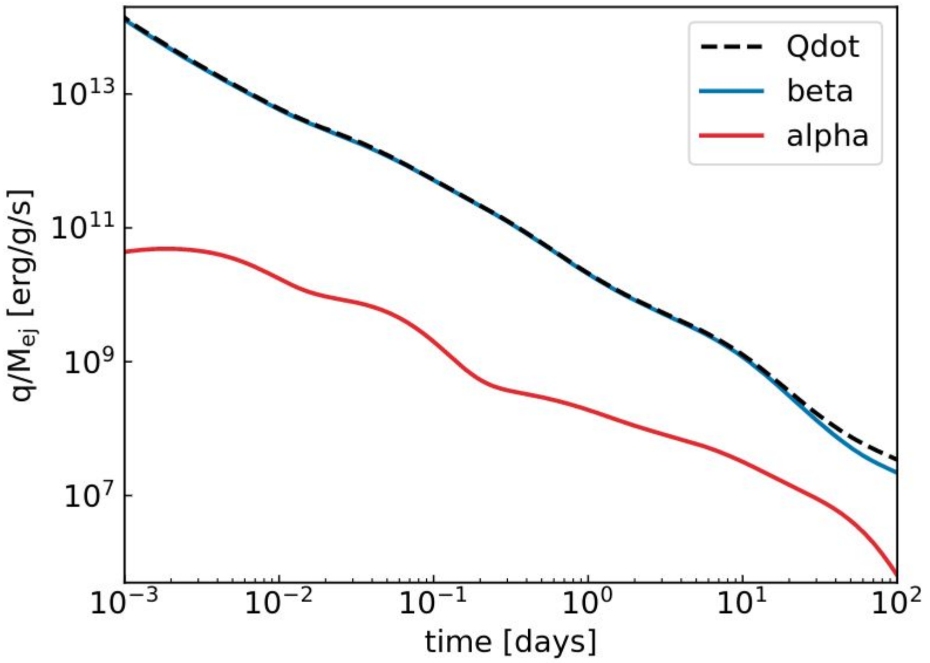
Tanaka et al. 2020



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

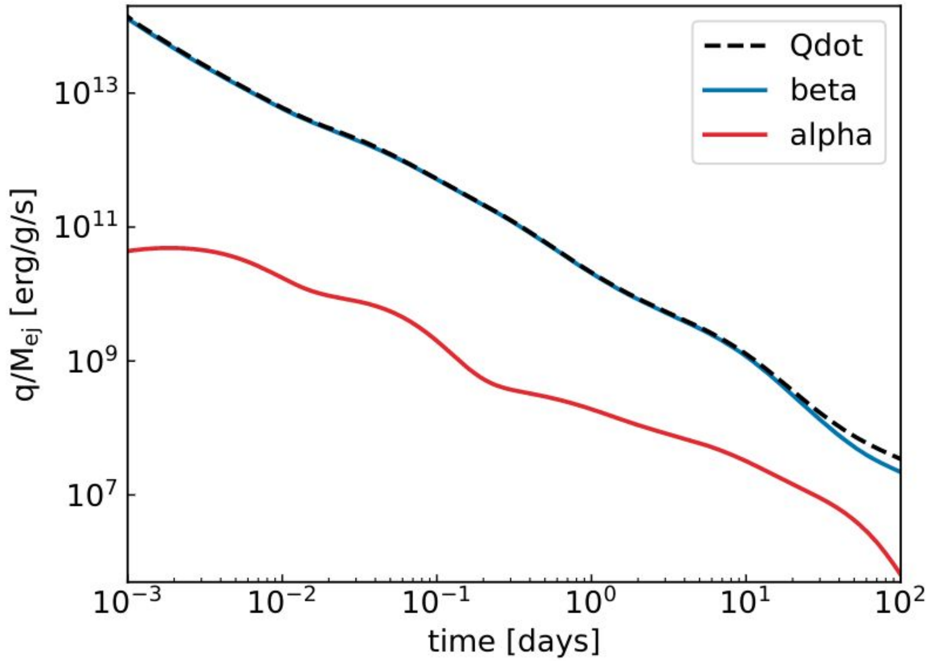
Radioactive heating

- The kilonova is powered by radioactive beta decays, alpha decays and fission
- Nuclear calculations from the SPH trajectories show that in this model most of the heating is from beta decays
- Fission only a small fraction at very early times



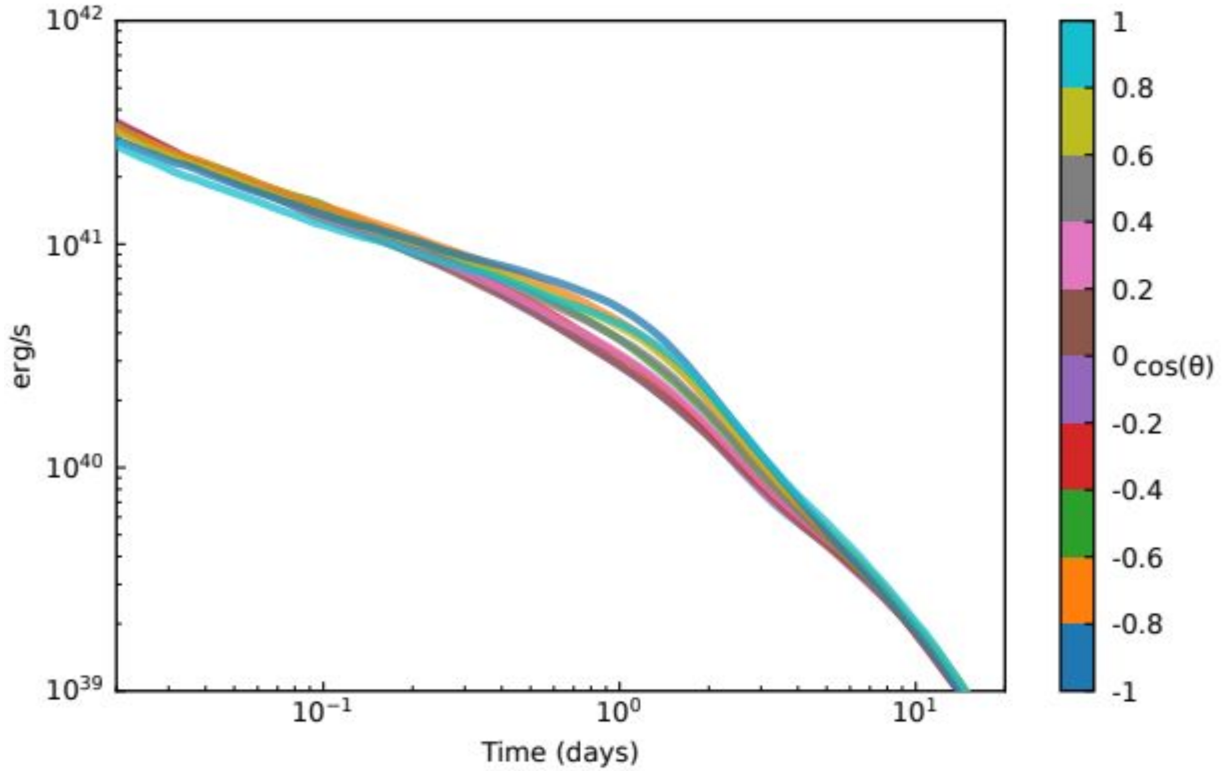
Radioactive heating in ARTIS simulation

- 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



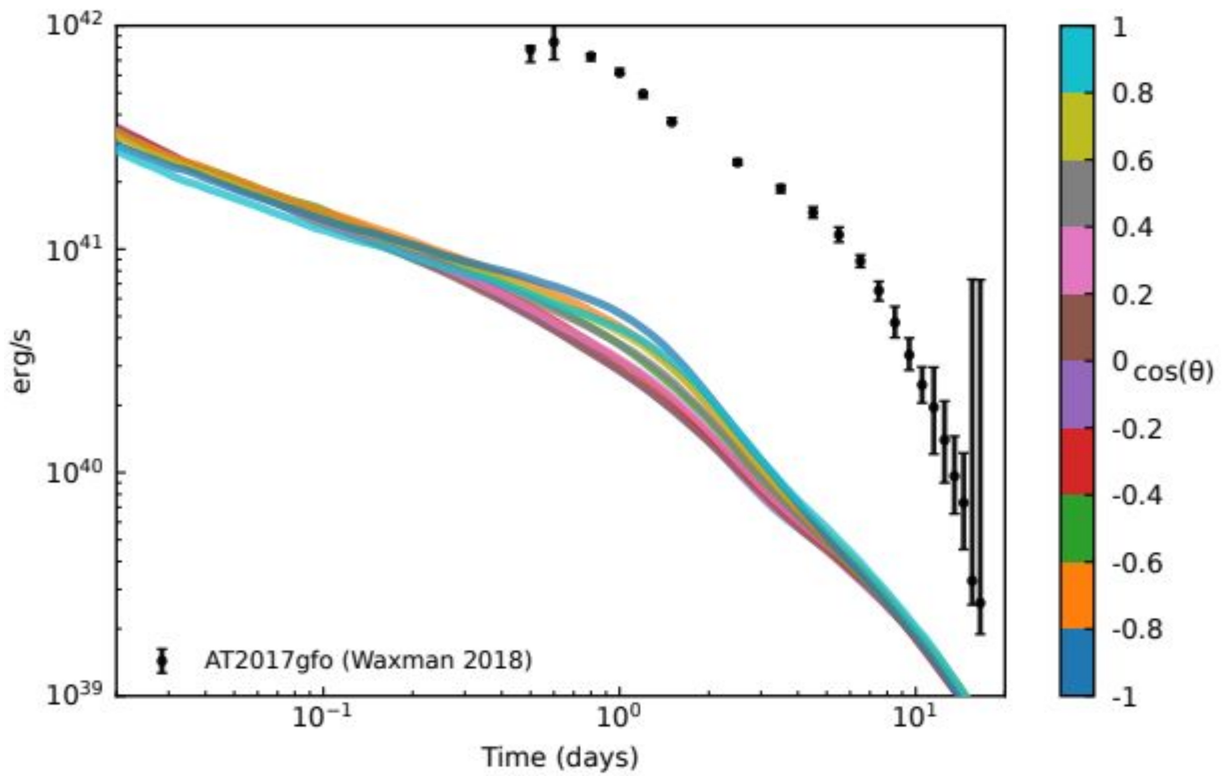
Bolometric light curves

- Despite ejecta asymmetries, we do not find strong viewing angle effects
- Lines of sight in the polar directions are brighter around ‘peak’ due to lower grey opacities and lower densities
- Bolometric light curve does not rise to a peak
    - Energy generated and thermalised in high velocity outer layers with low optical depths



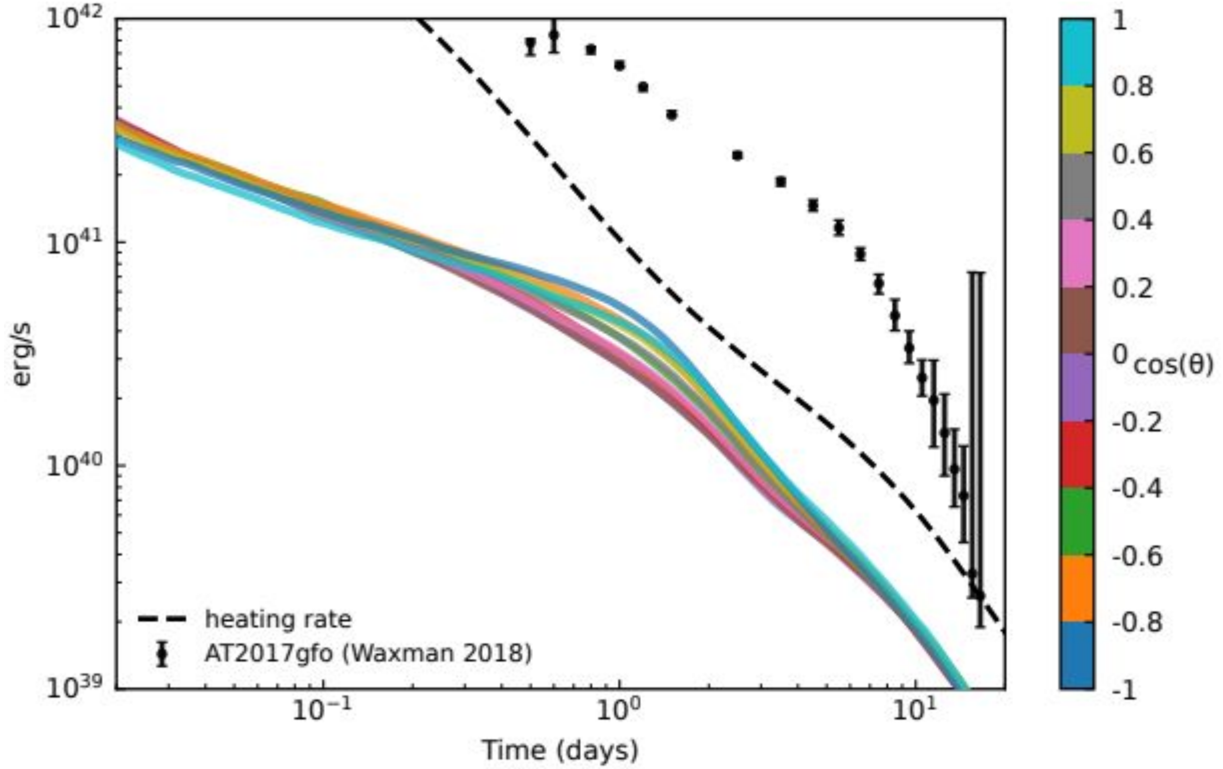
Bolometric light curves

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



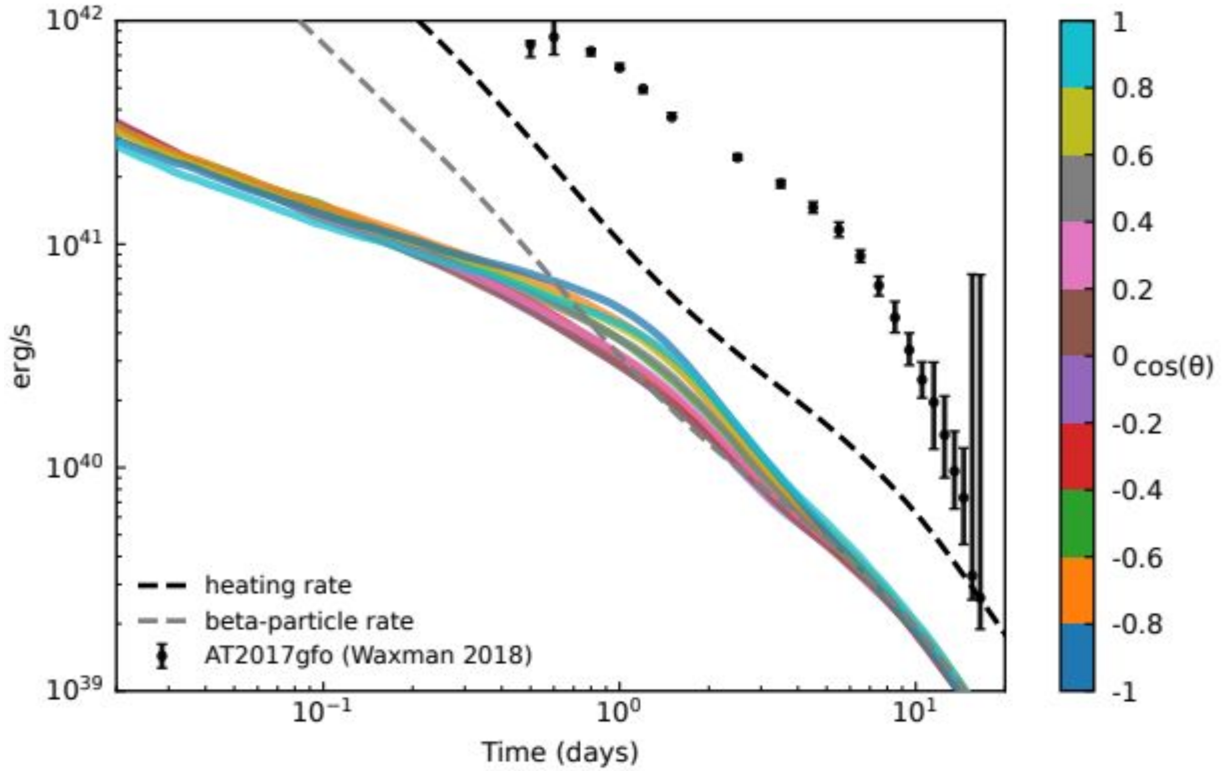
Bolometric light curves

- 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



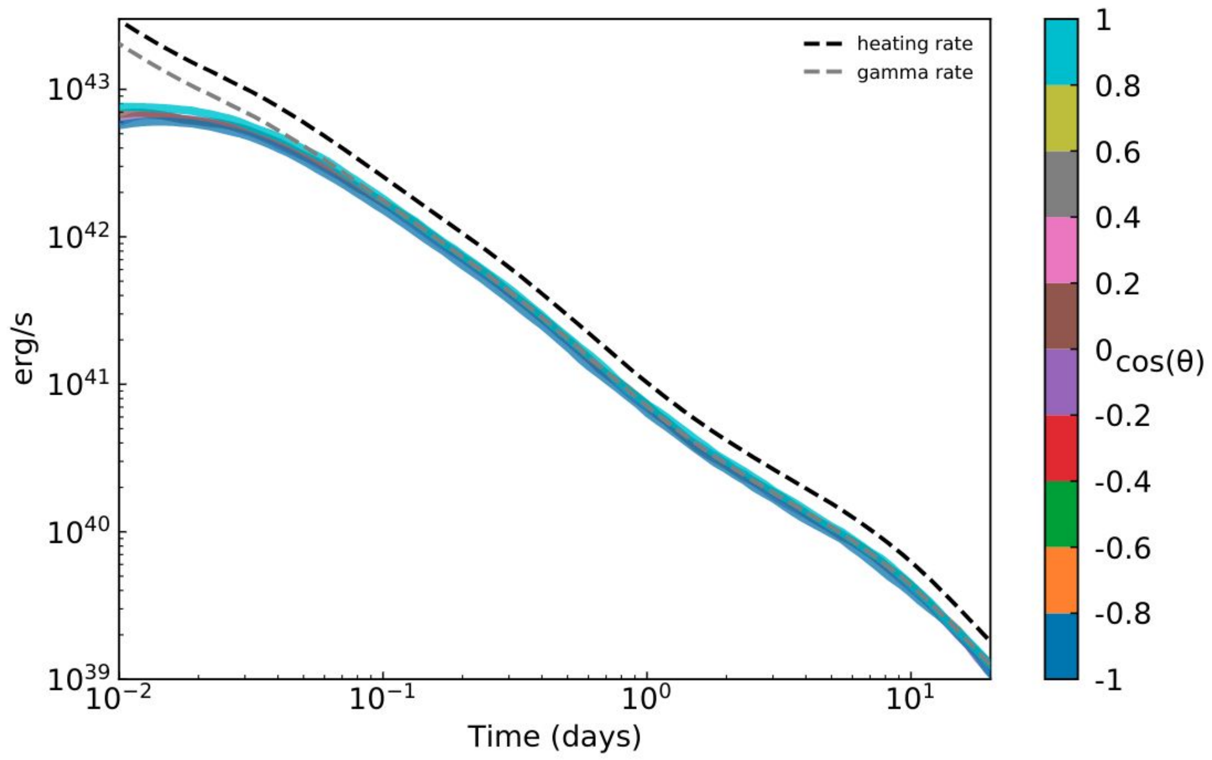
Bolometric light curves

- 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 rate of energy thermalising (in our model entirely on beta-particle rate)
    - For late time light curves, accurately calculating the amount of energy from β-particles will be important



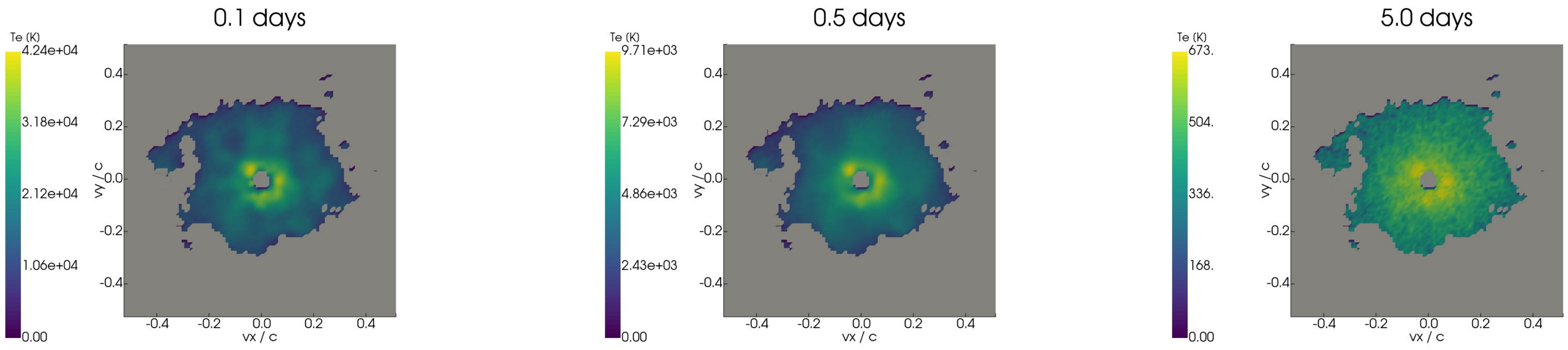
Gamma light curve

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



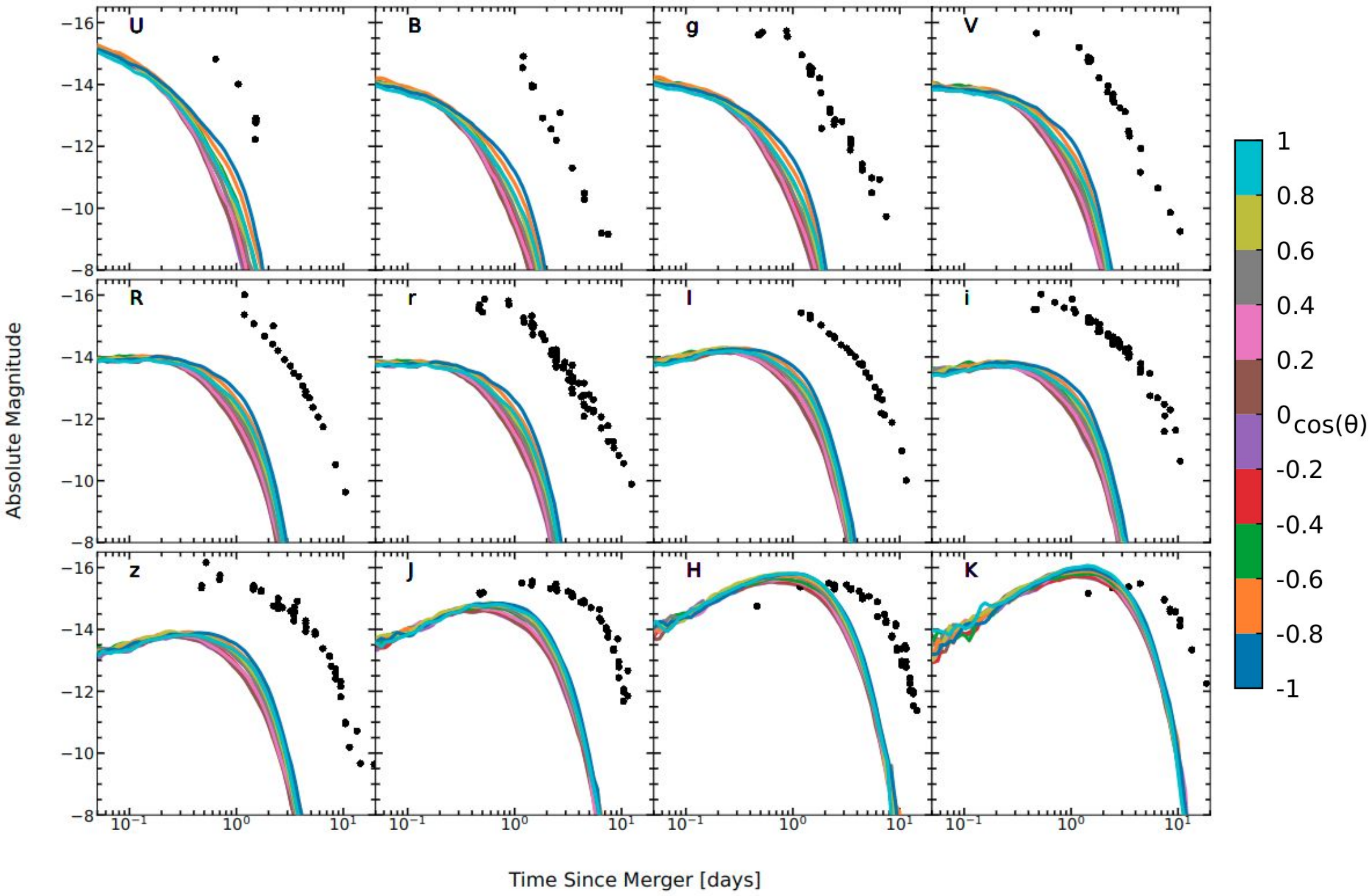
Temperature

- Ejecta temperatures cool rapidly
- At 0.1 days inner ejecta is ~40000 K while outer ejecta > 10000K
- By 0.5 days inner ejecta have cooled to ~9000 K and outer layers are ~2000 K
- By 5 days has cooled to few hundred K
    - However, non-LTE and non-thermal effects may prevent cooling to such low temperatures at later times.



Approximate light curves from black body spectra

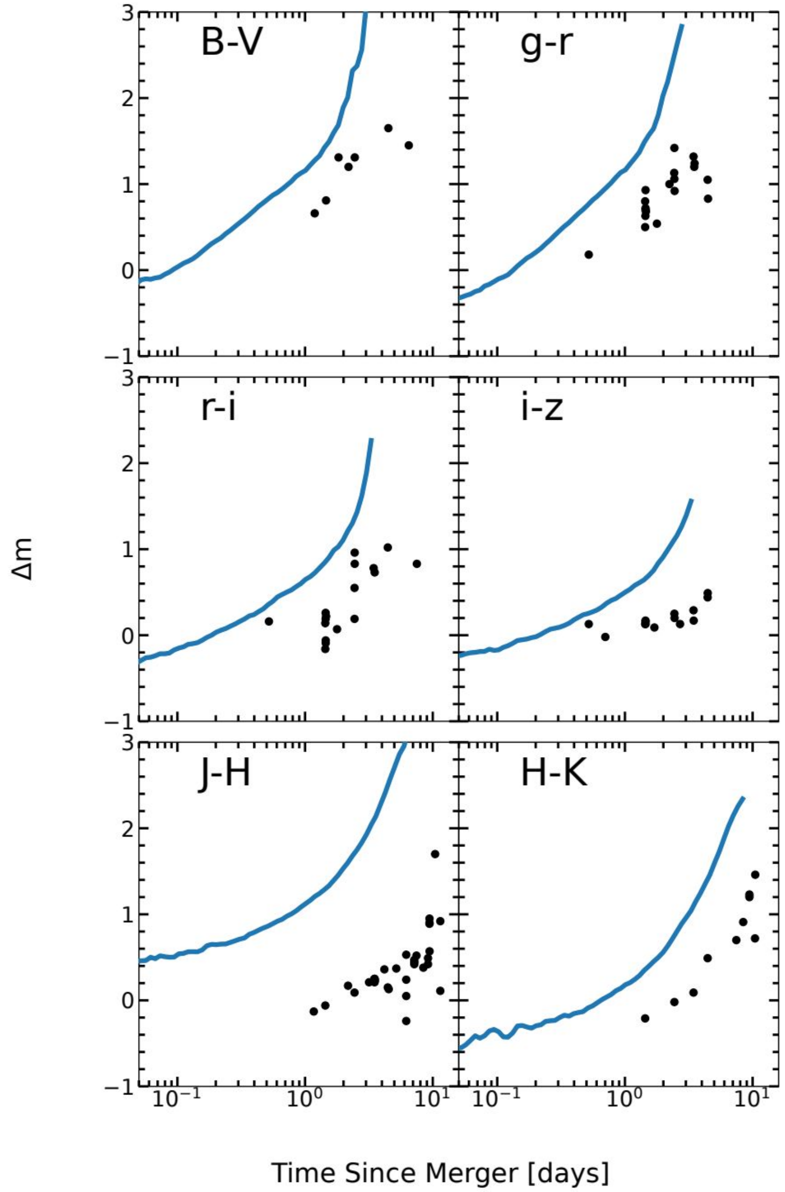
- Since we use a grey approximation we have no frequency dependence
- However, we do have the radiation temperature at the location packets were emitted from
- We can estimate a frequency for the packet from a black body at the radiation temperature
- From this we obtain approximate spectra and can generate band light curves
- Due to temperature evolution alone, we find a rapid blue to red colour evolution, similar to AT2017gfo



AT2017gfo light curves from Villar+2017

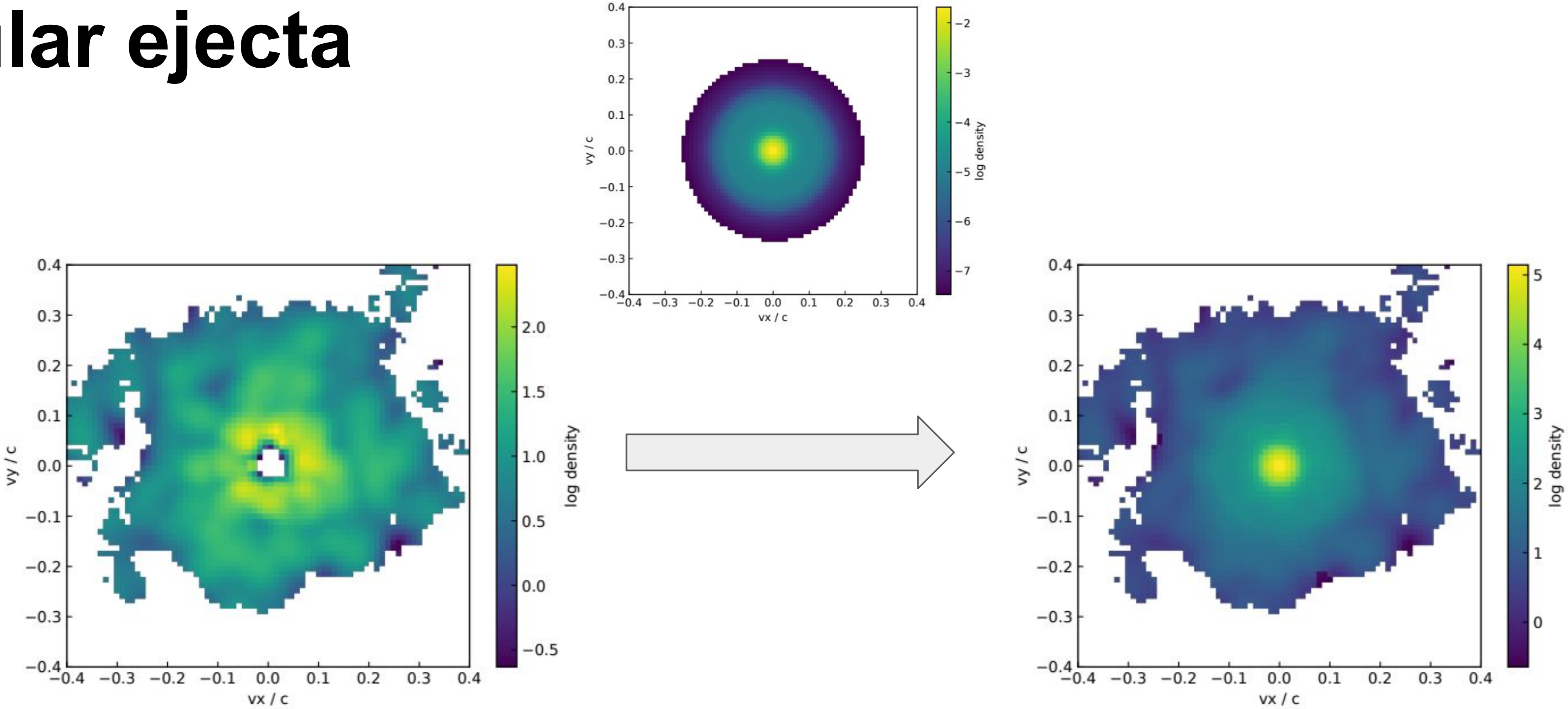
Colour evolution

- 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



AT2017gfo light curves from Villar+2017

Secular ejecta



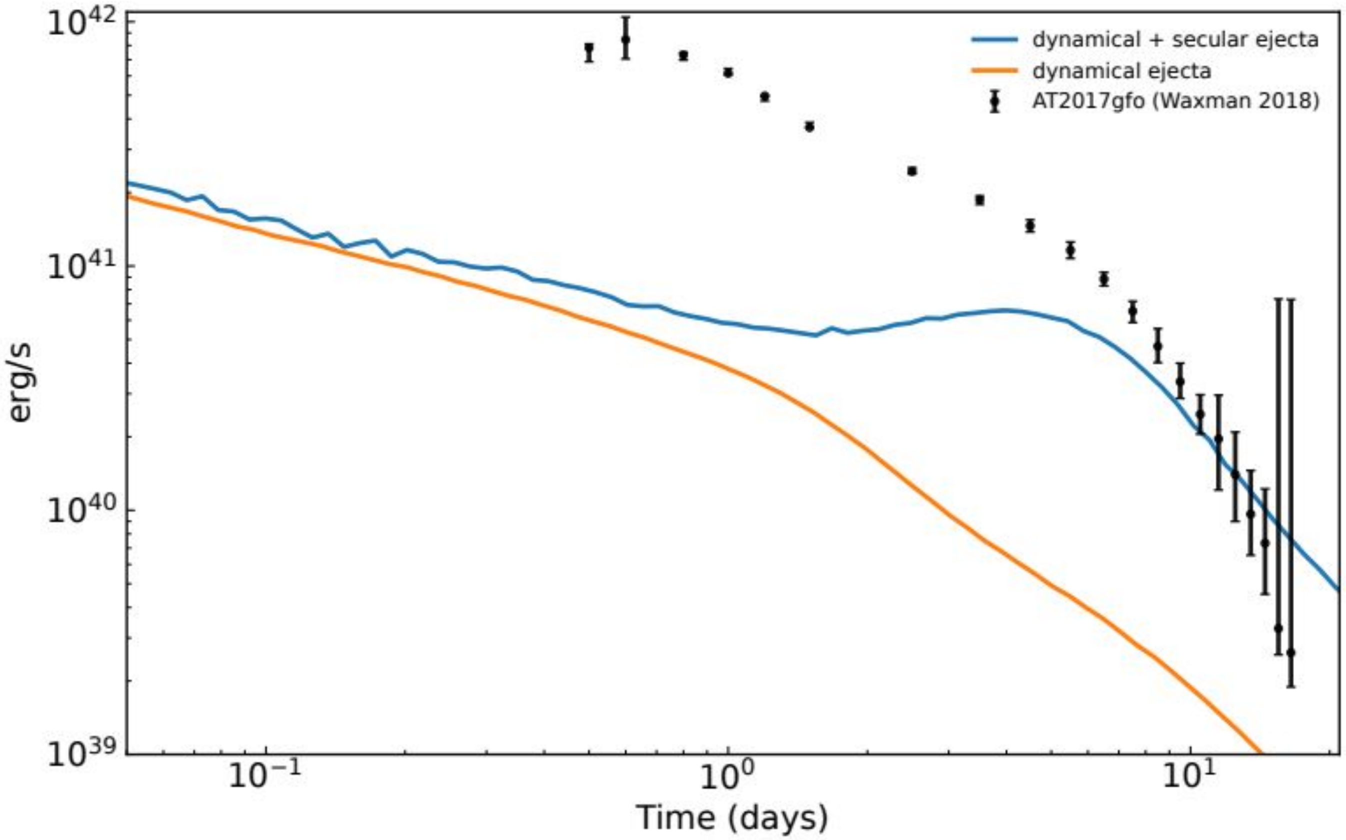
Dynamical ejecta only

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, private communication)
- We angle average the density profile and add this to the dynamical ejecta
- The extra mass is 0.0184 $M_{\odot}$, giving a total ejecta mass of 0.0212 $M_{\odot}$

Secular ejecta

- The additional mass at low velocities increases the energy deposition in the center
- This energy leaves the ejecta after ~2 days
- 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

Conclusions

- Despite asymmetric ejecta, we do not predict strong viewing angle dependencies in the light curves.
- In future, determining the exact energy fractions going into beta-particles, gamma-rays and neutrinos will be important, particularly for the late time light curve.
- 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.