Modelling Kilonovae in the Nebular Phase

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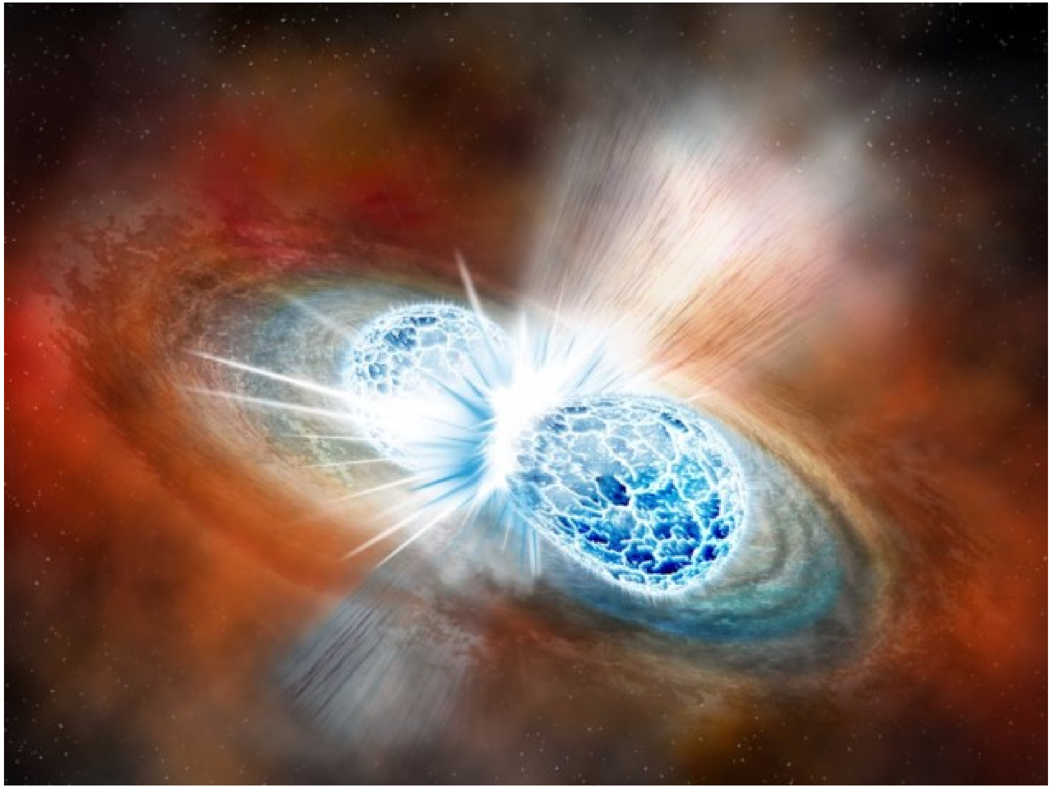
The Basics: What is a Kilonova

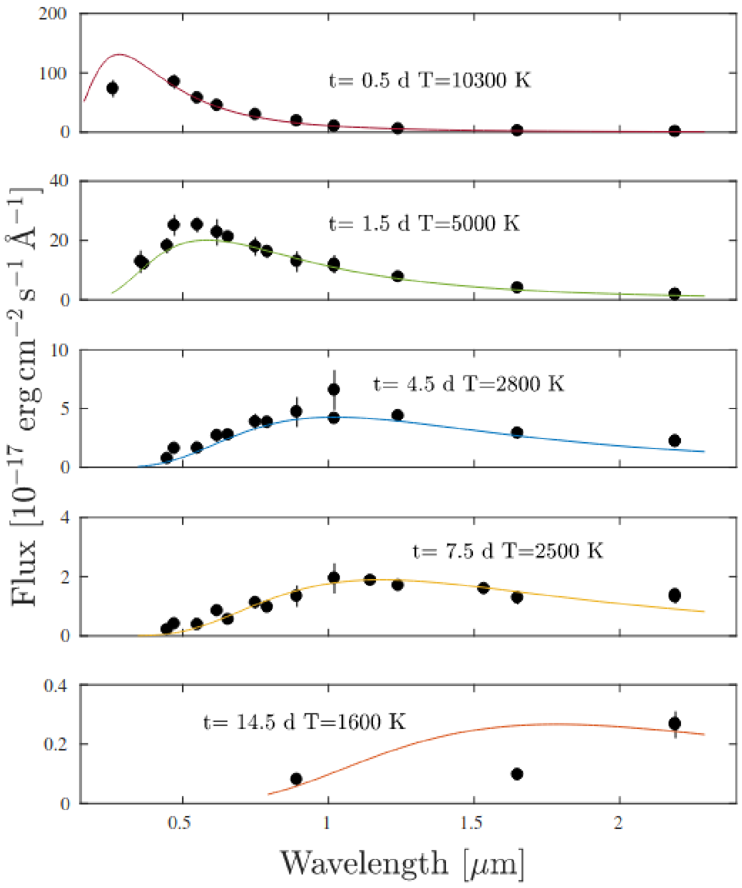
- A kilonova (KN) is a radioactively powered electromagnetic (EM) transient
- Produced from binary neutron star (NS), or neutron star and black hole (BH) mergers
- Evolves rapidly on a timescale of days to weeks



Artist Impression, NASA

The Kilonova: Early Phase

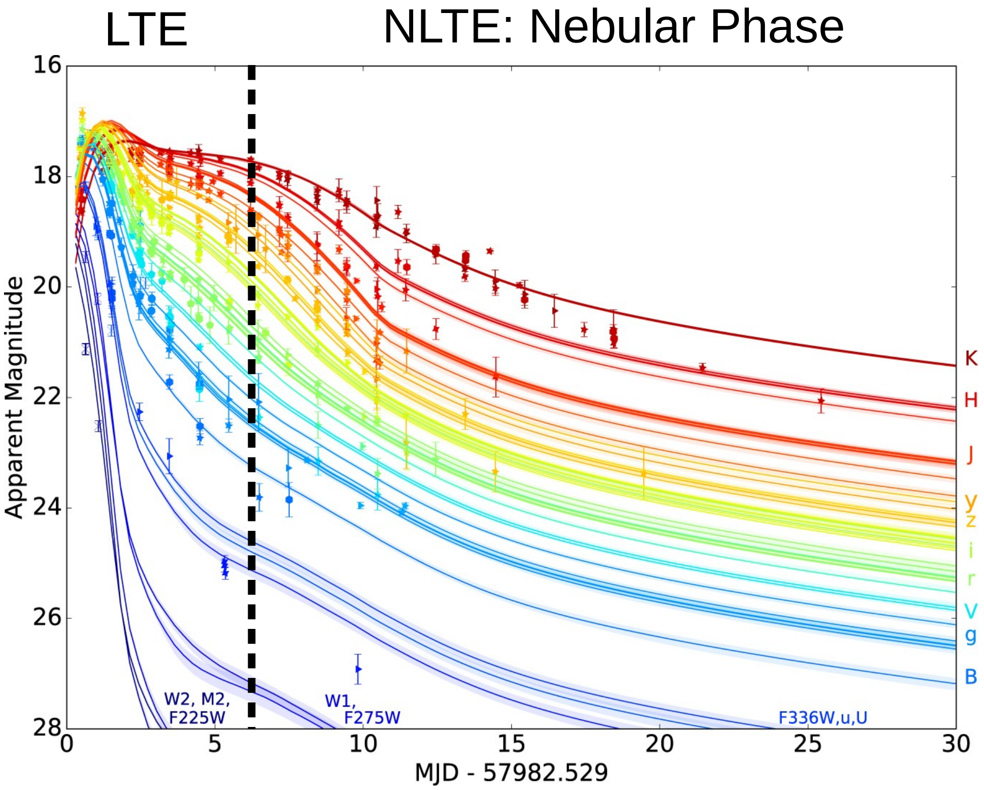
- Initially, the ejecta are extremely hot and dense
  - Ejecta are in local thermodynamic equilibrium (LTE) conditions
- Emission is thermal, and optical depth is high
  - Photons diffuse out of ejecta
  - Only outer ejecta layer probed



Source: Waxman et al. 2018

The Kilonova: Nebular Phase

- As the ejecta expand, dropping densities lead to several effects:
  - Ejecta transition to non-local thermodynamic equilibrium (NLTE) conditions
  - Optical depth drops -> observed emission probes entire ejecta and morphology
  - Spectra are expected to be dominated by emission lines



Source: Villar et al. 2017

Thermodynamics in NLTE

- Temperature determined by balance of cooling (line cooling) and heating (radioactivity)
- Ionisation and excitation by solving rate equations
  - Many processes included: collisional (thermal and non-thermal), radiative processes etc.
- Radiation field coupled to thermodynamic quantities

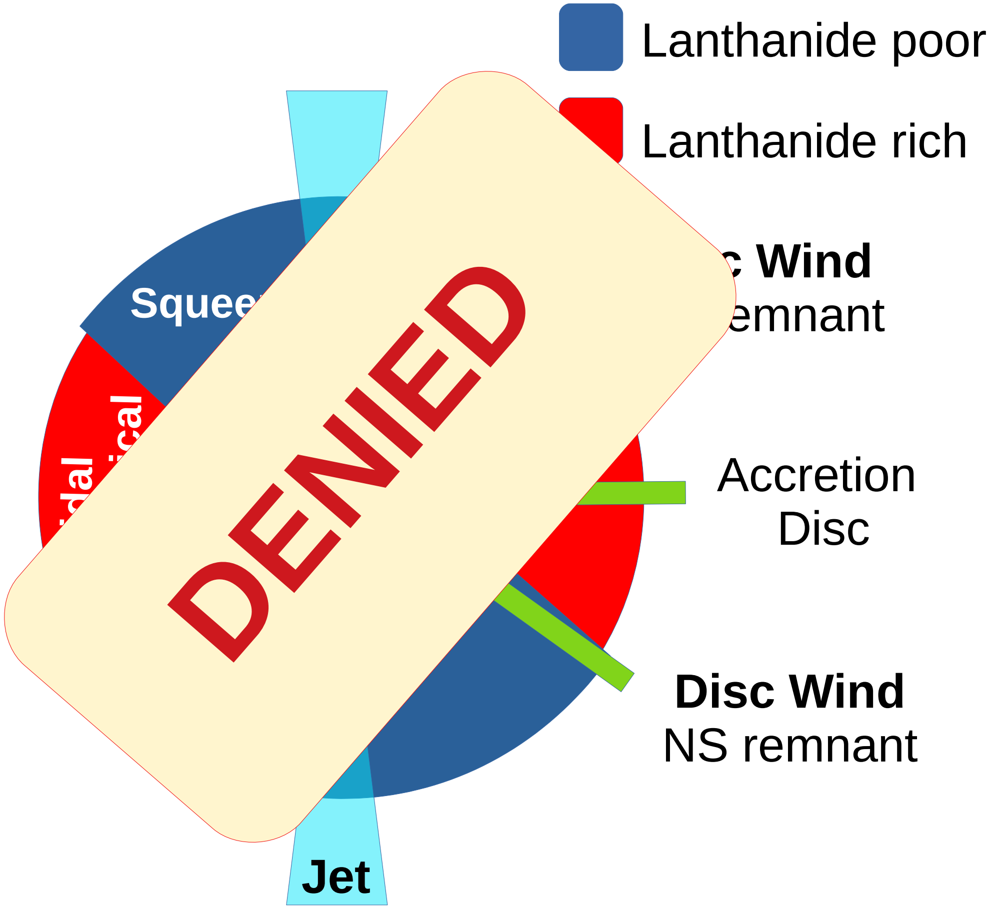
KN Modelling with SUMO (SUpernova MOnte Carlo Code)

Jerkstrand 2011,
Jerkstrand et al. 2012

- 1D NLTE Monte Carlo spectral synthesis code
- Theoretical r-process atomic data (levels and lines) for all r-process elements (Cu - U) up to triply ionised (Jon Grumer, Uppsala University)
- Line by line radiative transfer
- Want to produce high quality spectra in the NLTE regime, ~ 5 days onwards (e.g. Pognan et al. 2022b)

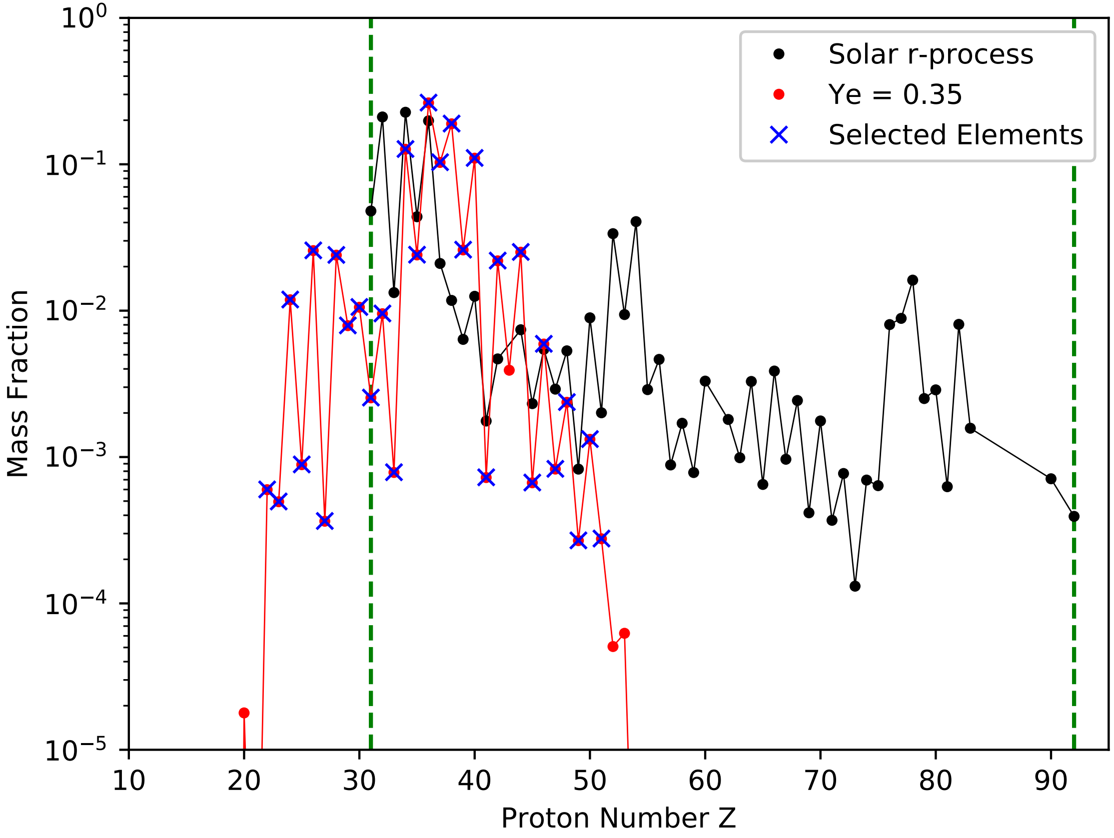
Ejecta Models

- Density profile ~ r^{-3}
  - 1D -> spherically symmetric
- Total ejecta mass: 0.05 M_{sol}
- Ejecta velocity: 0.05 - 0.3 c
- Homologously expanding, from 5 to 20 days after merger



Compositions: $Y_e \sim 0.35$

- Black: solar r-process residuals
- Red: Outputs from nuclear network
- Blue: selected elements modelled in SUMO
  - Max 30 elements
  - Minimum mass fraction 10^{-4}



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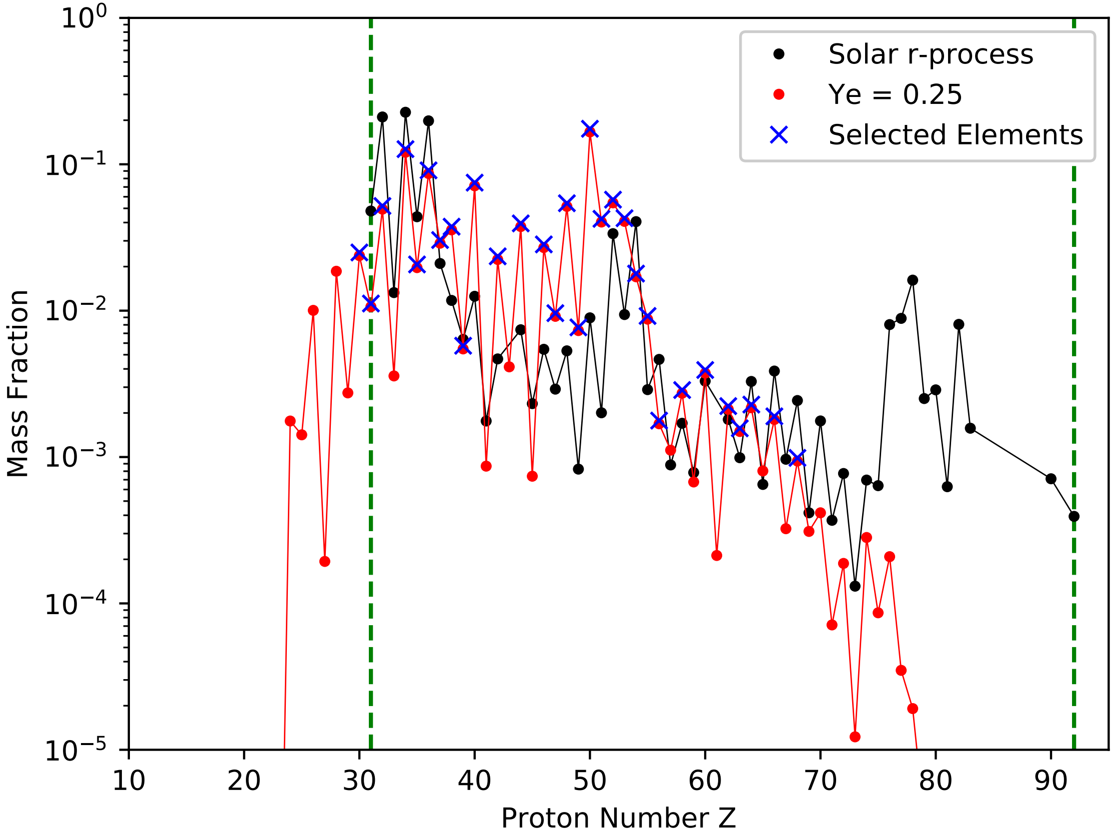

Compositions: $Y_e \sim 0.15$

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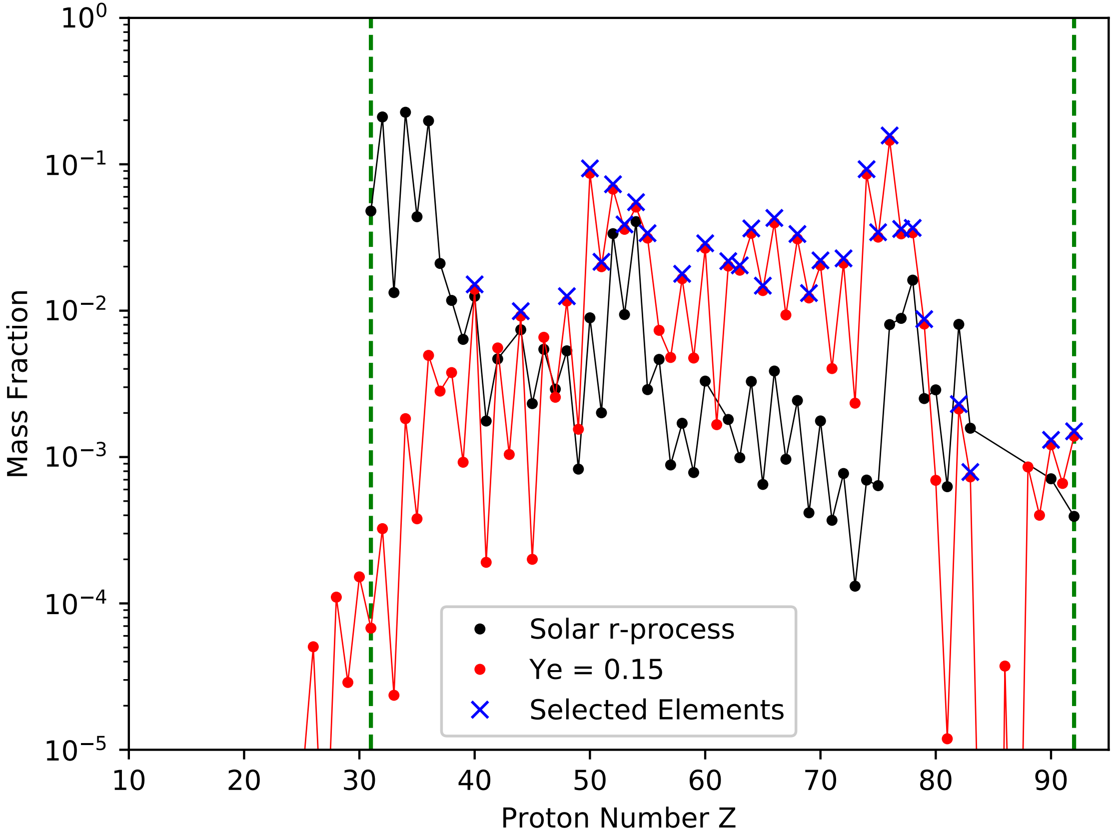
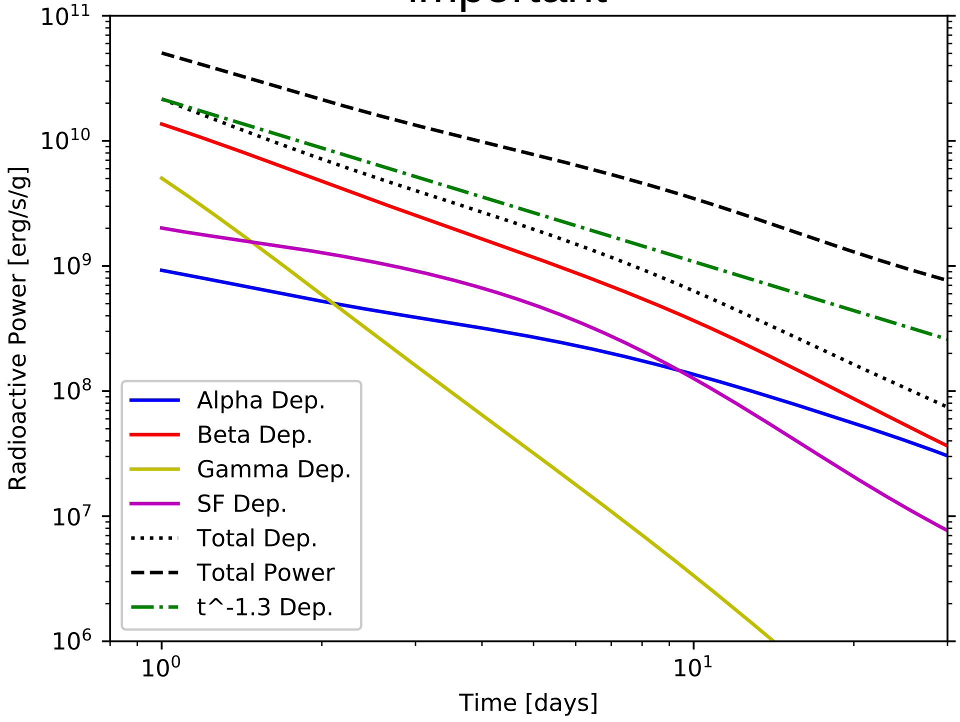


Energy Deposition

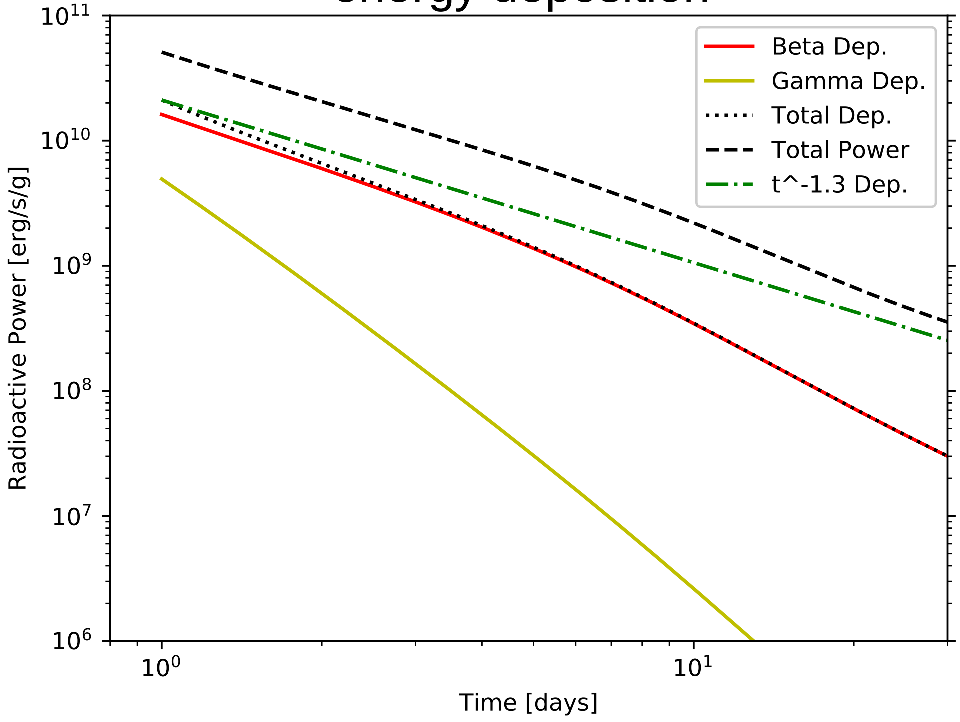
- Raw power from Wanajo et al. 2014 models
  - Power consistent with composition for each model
- Analytical thermalisation fits from Barnes et al. 2016 and Kasen & Barnes 2019
- Inbuilt Spencer-Fano routine splits deposited energy into heating and ionisation channels
  - r-process non-thermal excitation cross sections unknown, but expected to be negligible compared to heating

Energy Deposition: Visualised

Y_e ~ 0.15: fission and alpha decay important

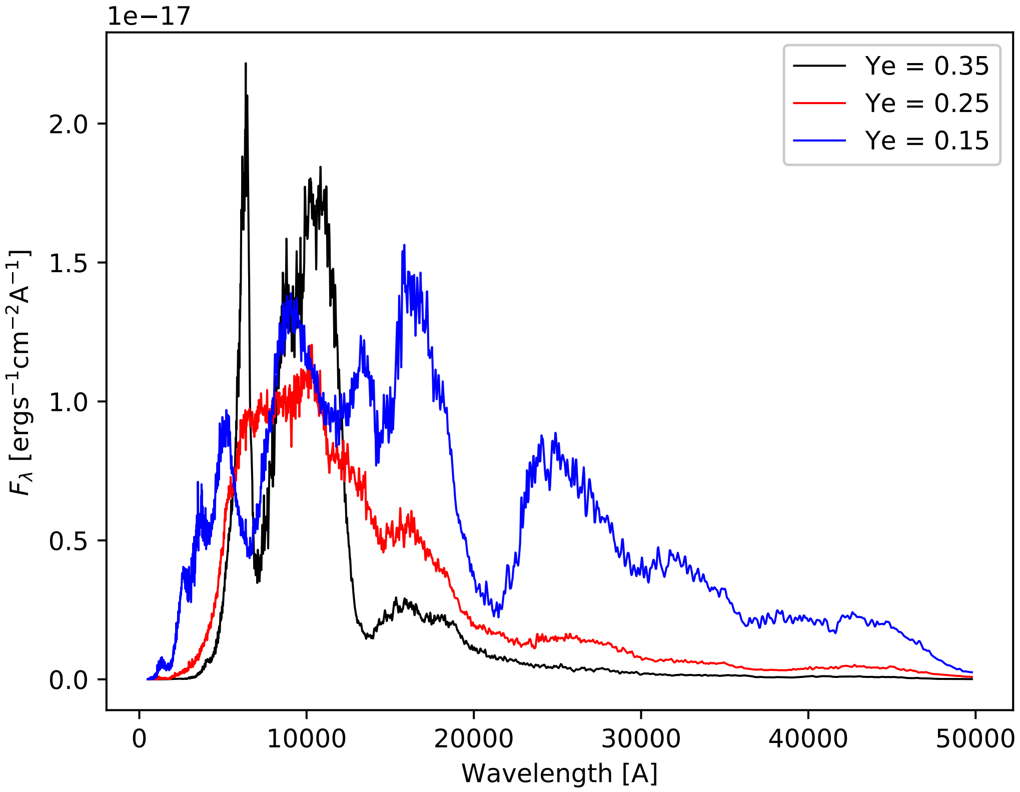


Y_e ~ 0.25: beta decay dominates energy deposition



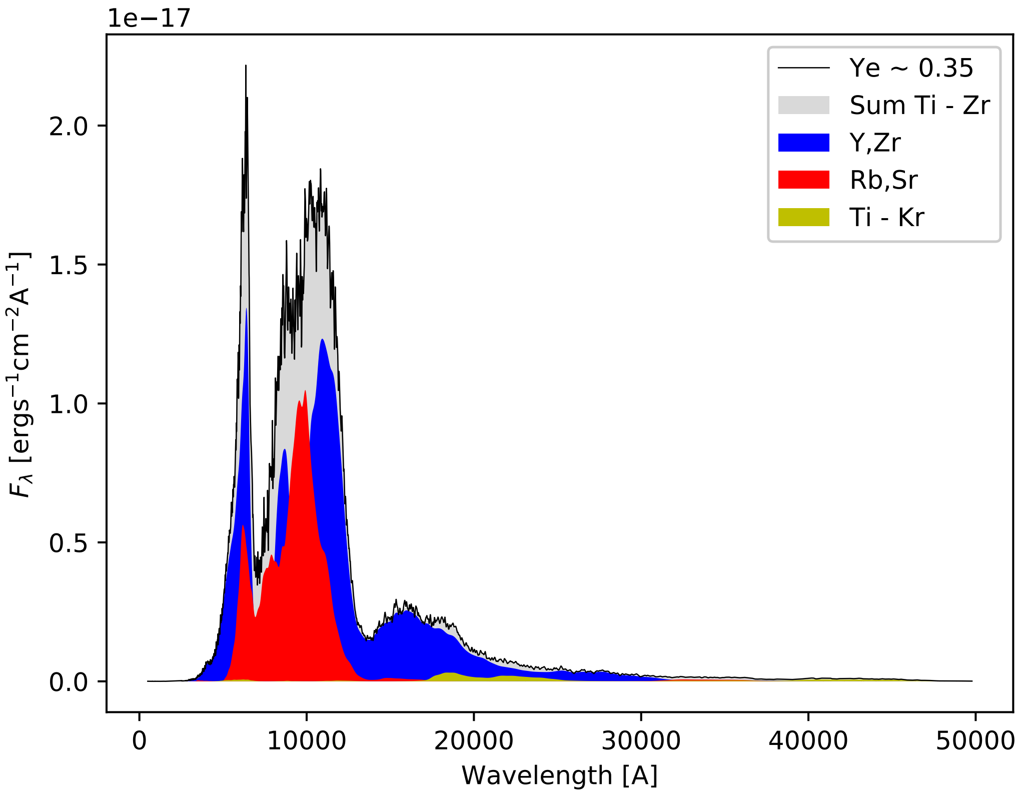
Preliminary Results: 20 days

- Lanthanide rich composition significantly redder
  - Also slightly brighter due to enhanced energy from fission/alpha decay
- Lanthanide free model has almost no IR emission



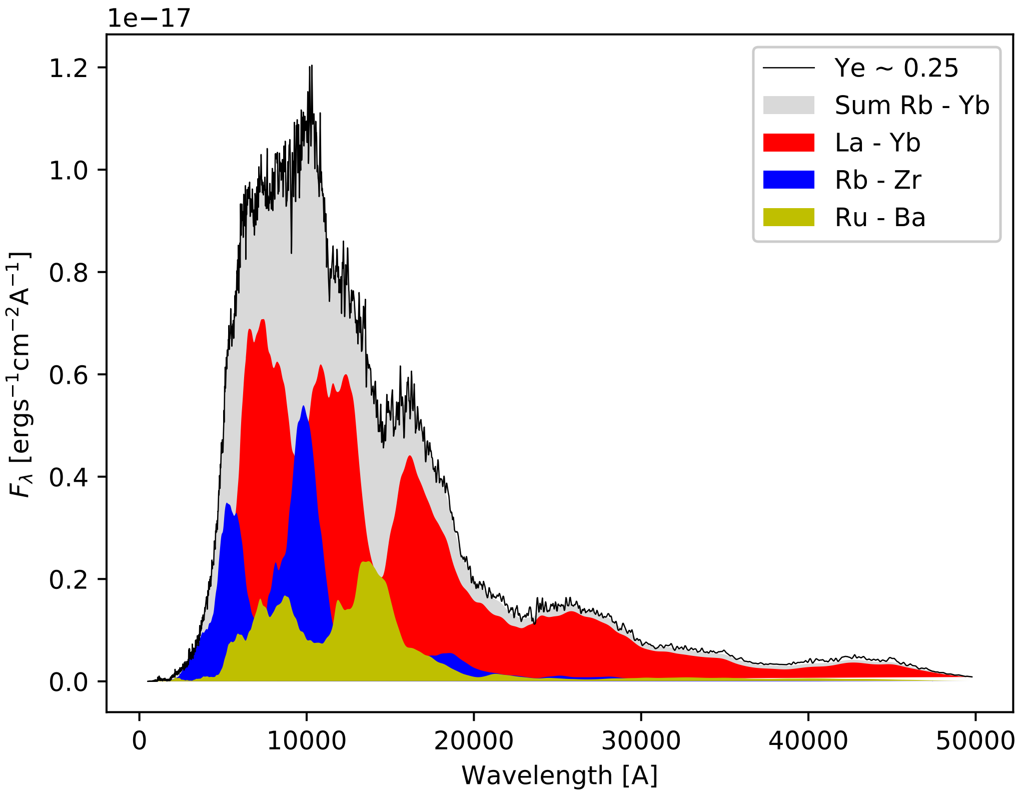
Closer Look: $Y_e \sim 0.35$

- High Y_e model emission dominated by 4 elements at 20 days
  - Groups 1 – 4 elements around 1st r-process peak
- These have few valence electrons, and low lying energy levels -> strong transitions (e.g. Domoto et al. 2022)



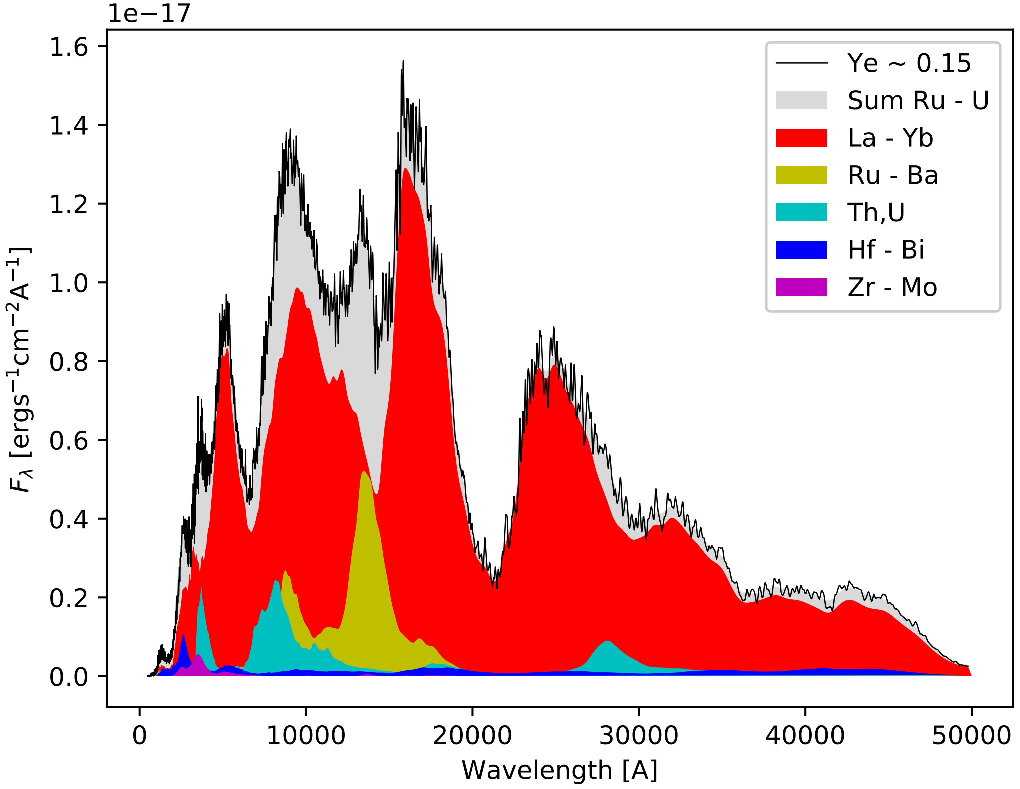
Closer Look: $Y_e \sim 0.25$

- Lanthanides emit strongly in the IR
  - Even at small mass fractions in model $X_{lanth} \sim 0.015$
- 1st and 2nd peak elements still have important contributions



Closer Look: $Y_e \sim 0.15$

- Domination by lanthanides
  - Model is extremely lanthanide rich $X_{lanth} \sim 0.25$
- Some contribution from actinides and 2nd peak elements

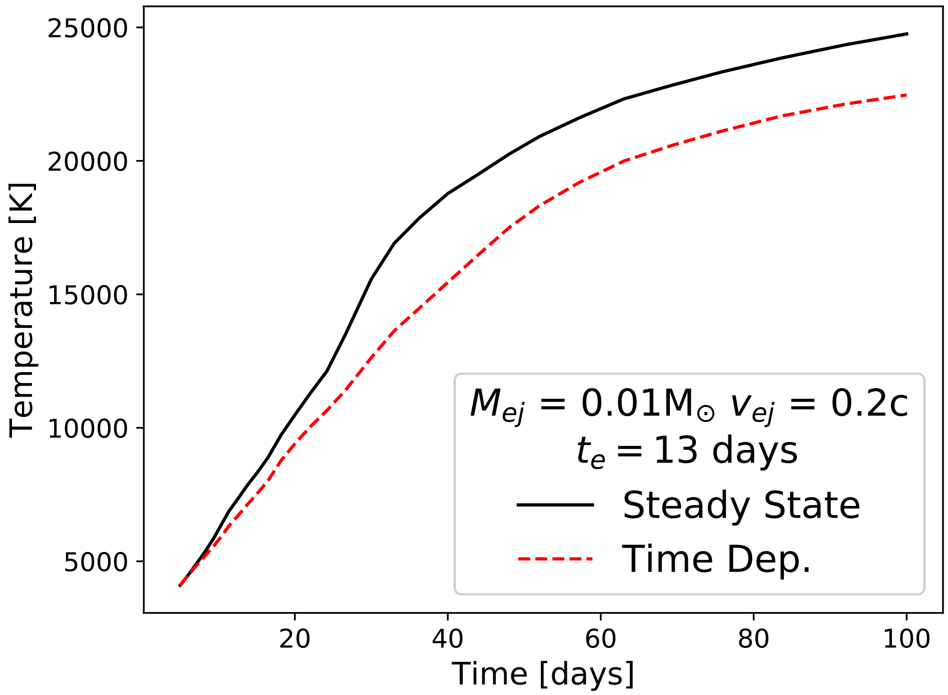


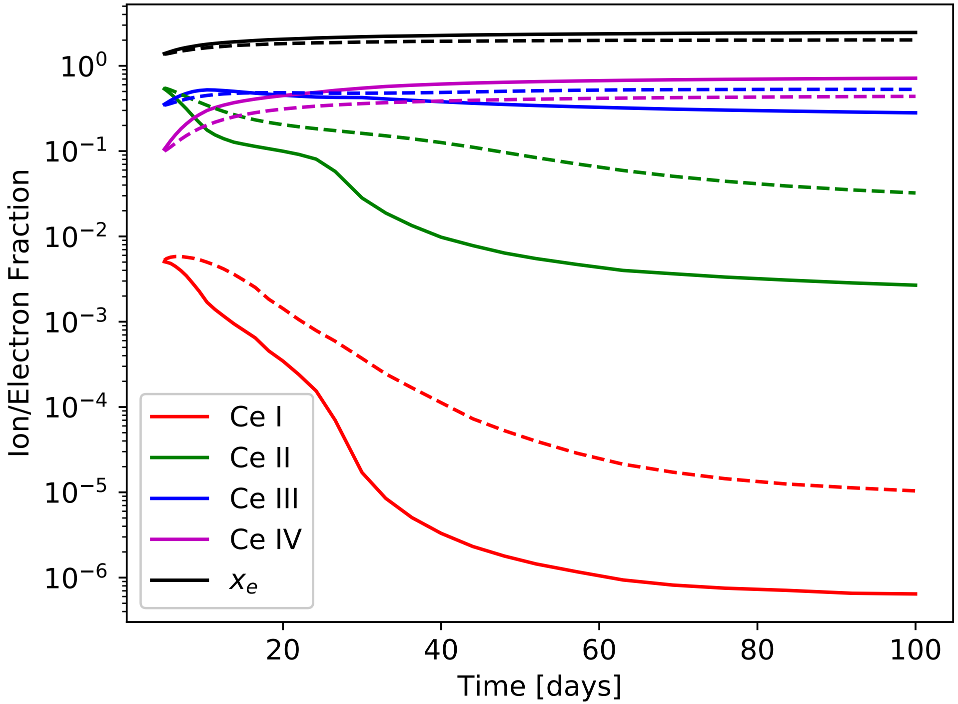
Time-Dependent Effects

- Preliminary results at 20 days are currently in “steady-state” mode
  - Temperature and ionisation equations solved assuming fast cooling/recombination times
- This is not true for the outermost ejecta layers
  - From ~ 10 days onwards, models will be run in time-dependent mode
  - Expect more neutral ionisation structure and cooler temperature

Time-Dependent Effects: Visualised

Different ionisation structures and temperature solutions will affect the emergent spectrum





Source: Pognan et al. 22a

Ongoing/Future Work

- Run models 5 – 20 days after merger:
  - Can a 1D model reproduce AT2017gfo's general evolution?
  - Can we constrain lanthanide masses?
  - Support (or go against?) the Sr II claim for AT2017gfo?
- Include time-dependent effects for T and x_e from 10 days onwards:
  - Changing thermodynamical quantities will affect emergent spectrum
- Make non-homogenous composition model for more "realistic" distribution of elements?

Thank you for listening!