Kilonovae in the Infra-Red:
Forbidden Emission Lines in NLTE

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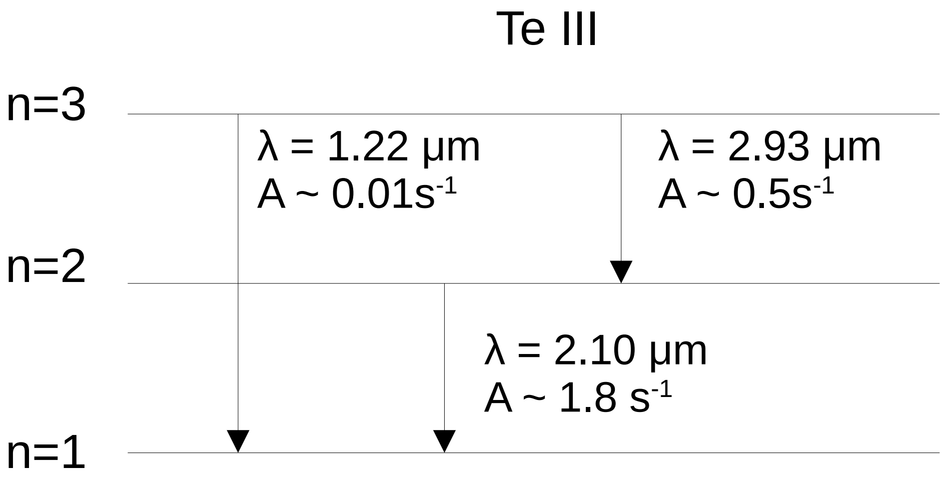
(Albert Einstein Institute)

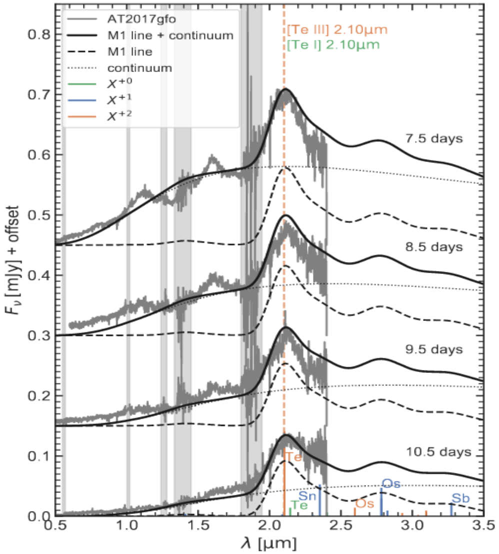
Forbidden Emission Lines

- Emission lines that are not E1 dipoles:
  - M1 dipole, M2 & E2 quadrupoles
- Smaller A-values -> longer radiative lifetimes
- Only occur in low density environments where $t_{rad} < t_{collision}$

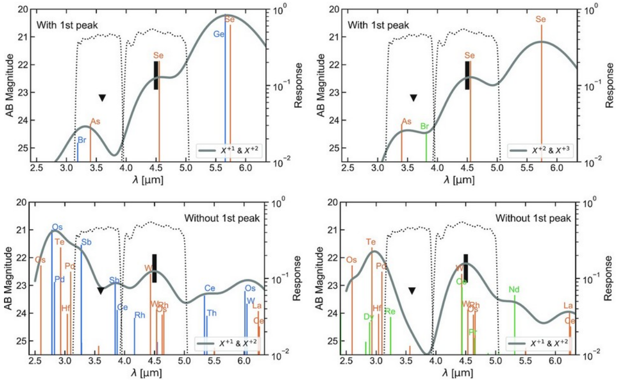


Where and when?

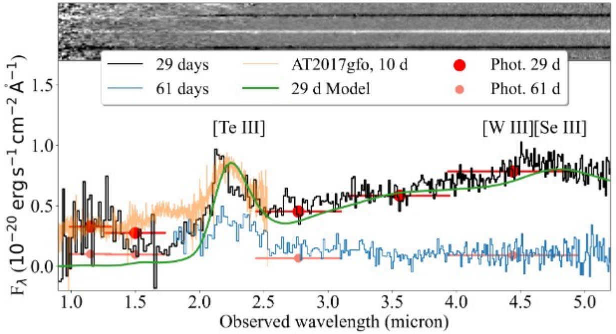
- Forbidden lines typically occur between low lying states
  - E.g. ground multiplets
- Typically small energy differences -> IR emission
- Combined with low density criteria:
  - Should be found in IR wavelengths of nebular phase
  - Low density ejecta layers at earlier times?



7 – 10 days



43 & 75 days



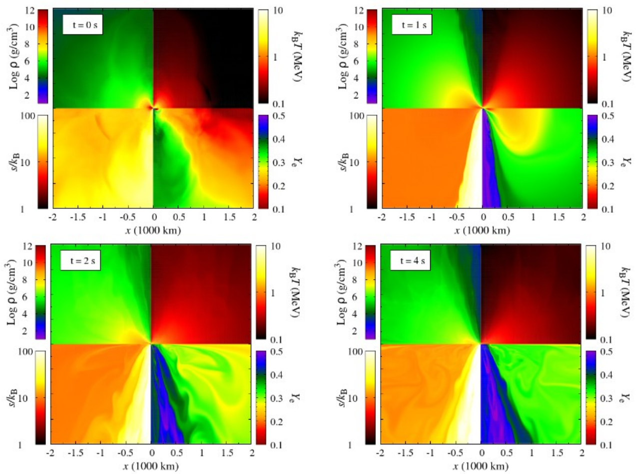
29 & 61 days

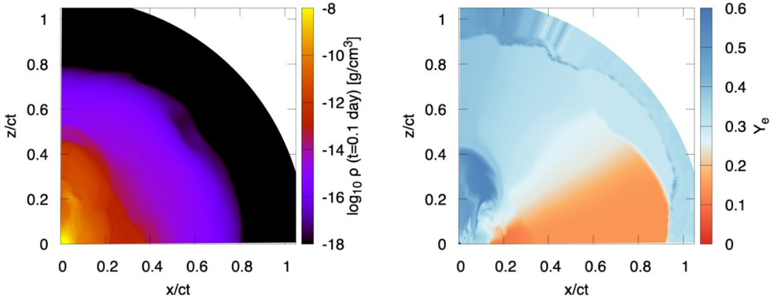
Objectives and Motivation

- Several observations exist of IR emission, attributed to forbbiden emission lines
  - Te III, SeIII/W III
- We need thorough exploration of IR lines across KN parameter space
  - Understand which species can be emitting significantly and in which circumstances
  - Study if or when forbidden emission can be affected by E1 dipole transitions from other species e.g. lanthanides
- Help us understand current observations
- Provide models for future JWST and other IR observations

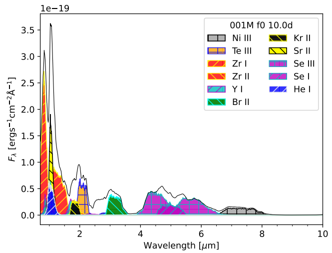
Approach and Methods

- Forbidden IR lines occur in low density media
  - (Time-dependent) Non Local Thermodynamic Equilibrium (NLTE) conditions apply
- Use the NLTE radiative transfer code SUMO to study IR emission line behavior
  - Explore range of sample KN ejecta informed from 3D numerical relativity (NR) and 2D relativistic hydrodynamics (RHD) simulations





SUMO



Fujibayashi+ 2020

Kawaguchi+ 2022

Models and Parameter Space

- Ejecta from RHD simulations split into dynamical (dyn) and post-merger (pm)
  - Based on $t_{cut} = 0.15$ s
  - pm ejecta is taken to be lanthanide free
- Composition is taken to be:

  $f_{dyn}X_{dyn} + (1-f_{dyn})X_{pm}$

- Energy deposition directly from RHD simulation and associated nucleosynthesis calculation

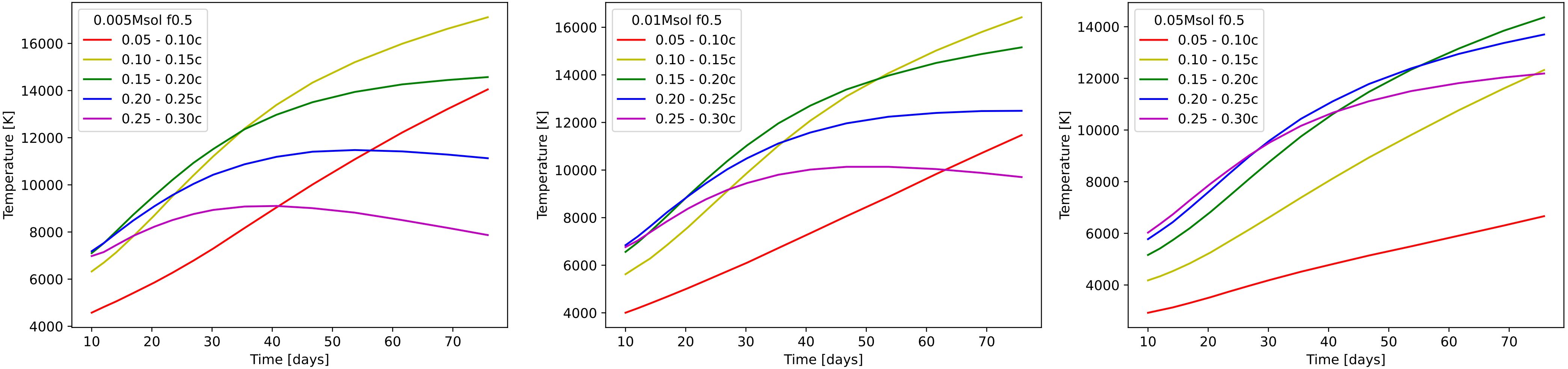
$\rho \sim v^{-4}$
$V_{ej} = 0.05 – 0.3c$

M_{ej} [Msol]
0.05
0.01
0.005

f_{dyn}
0.7, 0.5, 0.1, 0.05

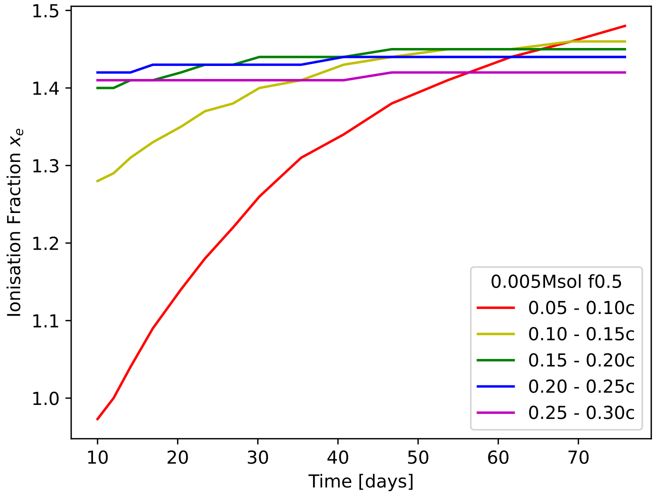
t = 10 - 75d
$X_{pm/dyn}$@ 25 days

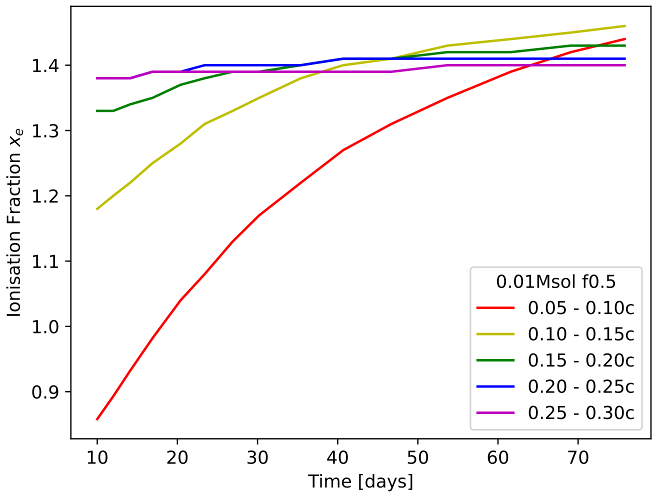
F05: Ejecta Temperatures

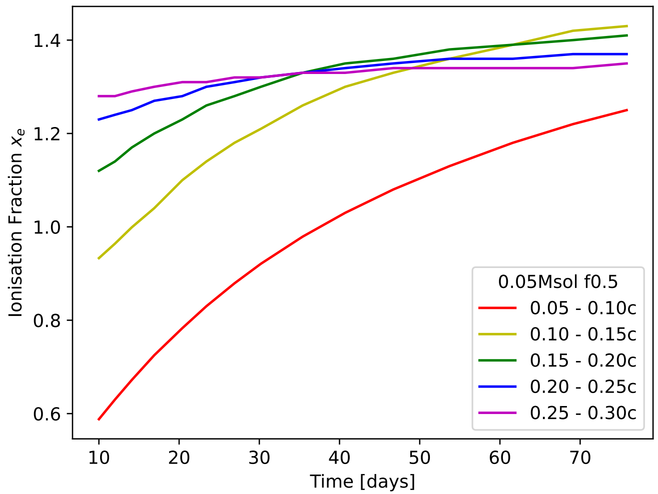


- Typically all masses start with quasi-stratified T structure
- Evolution is different due to different densities
  - Lower density layers experience more time-dependent effects
- This leads to cooling and inversion of the temperature structure

F05: Ejecta Ionisation Structure

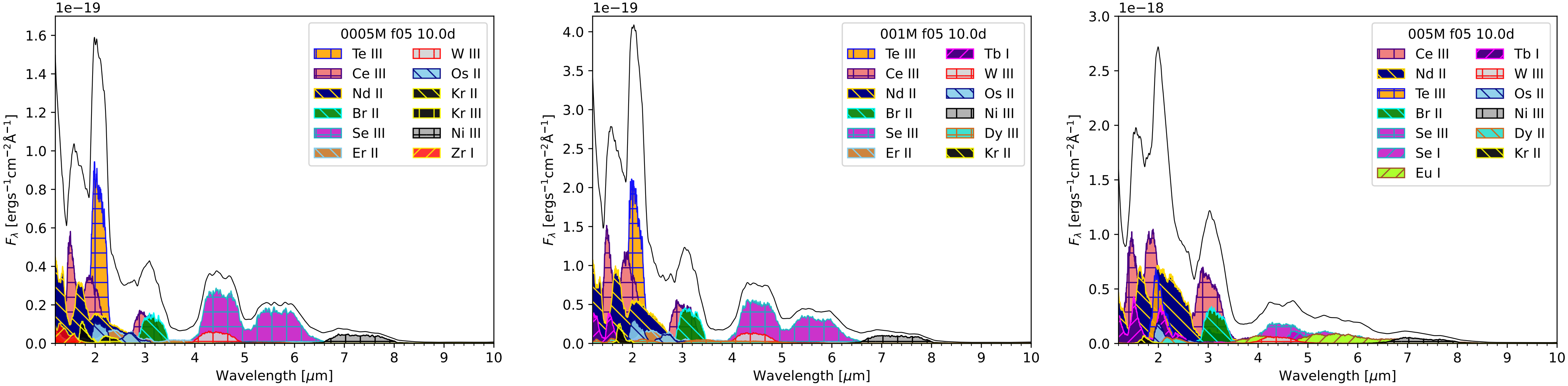






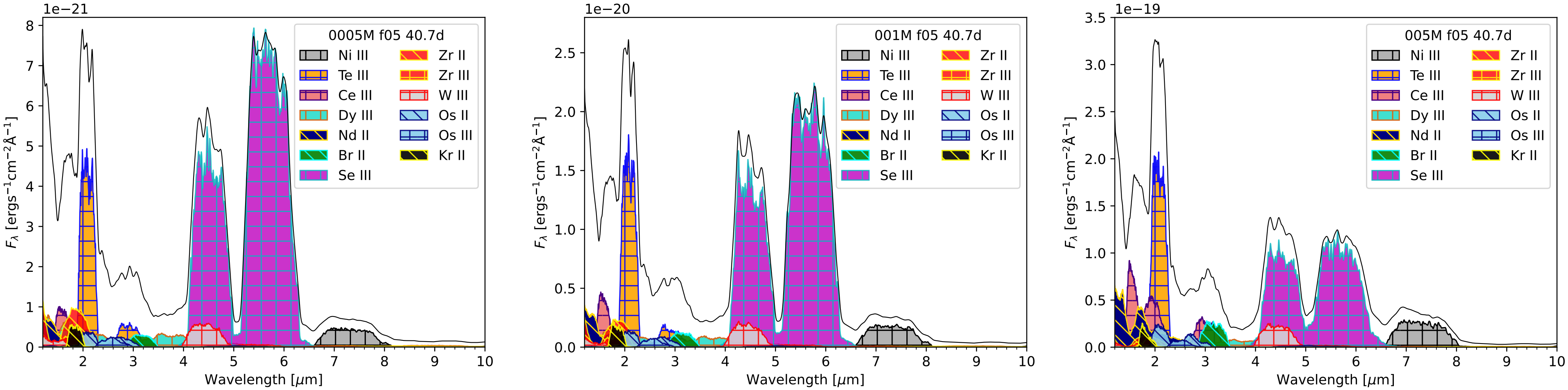
- Similar for all masses
  - Inner layers becoming more ionised
  - Outer layers with frozen structure
- Roughly same degree of ionisation
  - More mass -> more energy -> more ionisation but also more recombination
  - Less mass -> less energy -> less ionisation but also less recombination

F05: Early Spectra 1 – 10μm



- Lanthanide elements make a complicated spectral landscape
- At 10 days, Te III emission at 2.1 micron is significant in most cases, but lost in lanthanide emission for 0.05M_{sol} model
- Se III at 4.5 micron emits more than W III, but:
  - Se is 18% of model mass, W is 1%
- Lanthanide lines are E1 dipoles, but still optically thin (τ < 1) -> they do not absorb other emission

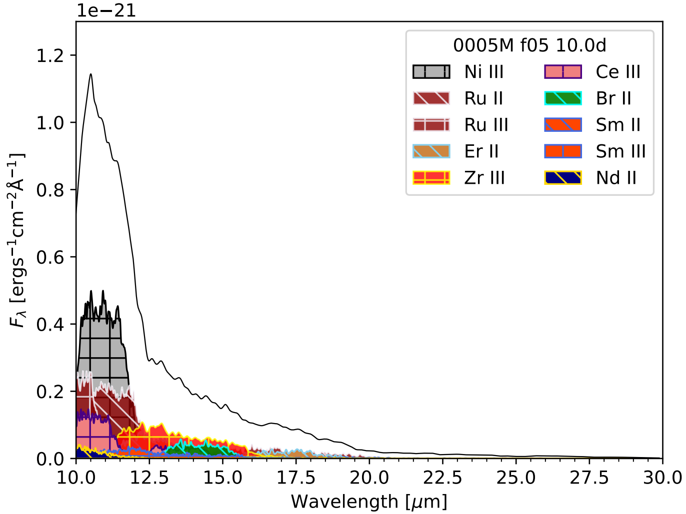
F05: Later Spectra 1 – 10μm

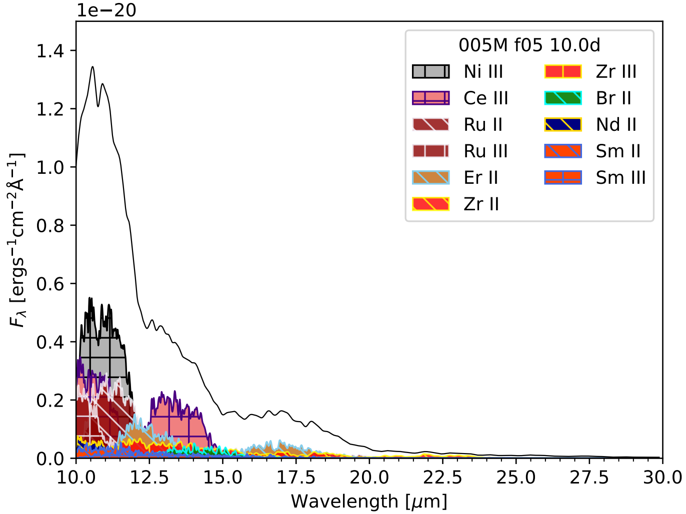


- Se III becomes more significant with time, Te III stands out more in every model
  - W III remains present but subdominant
- More emission at 3.6 micron than in f=0 model, due to Dy III (and others)
- Ni III continues to emit at 7.3 micron mostly by itself

10 - 30μm preview

- Emission past 10μm exists but is relatively faint
- Ni III + Ru II/III at 10 – 12 micron provide most emission
  - Typically little emission past 20 micron
- Also have blending of diverse lanthanides incl. Ce III
  - Details will vary between masses and models (WIP!)

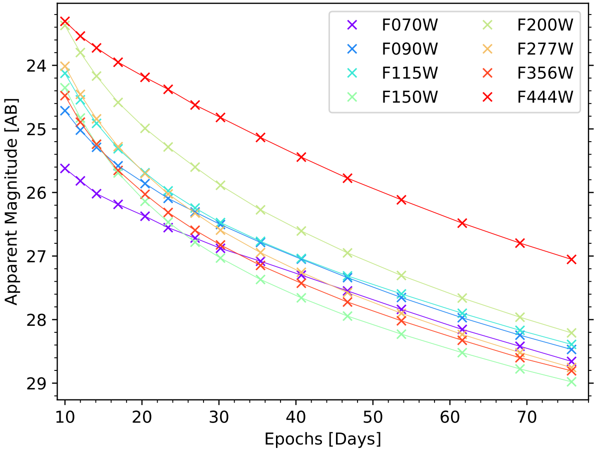


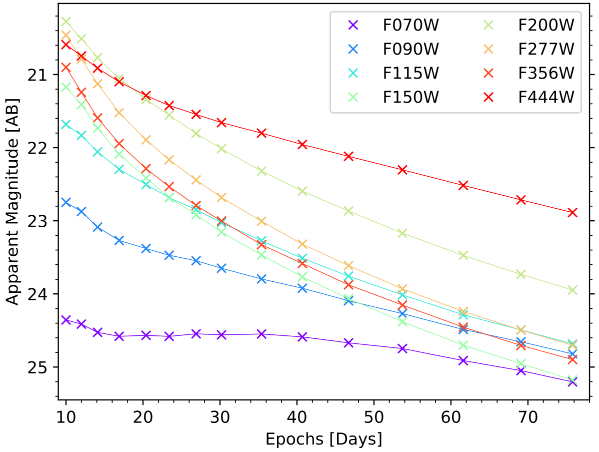


Sample JWST Lightcurves

F0.5, 0.005M_{sol}

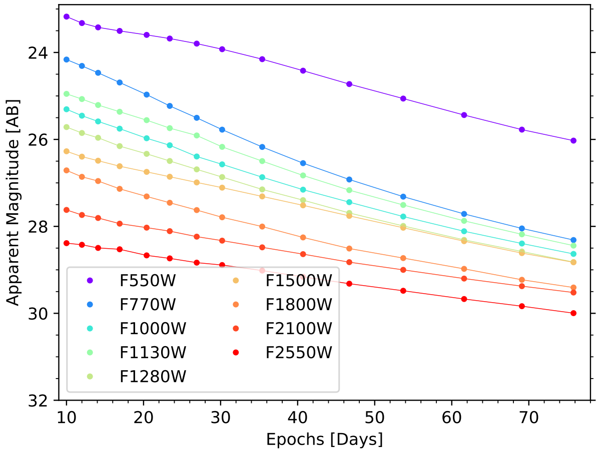
- NIR shows some variation between models
- Brightest bands correspond to 2.1, 4.5, and 5.7 micron features



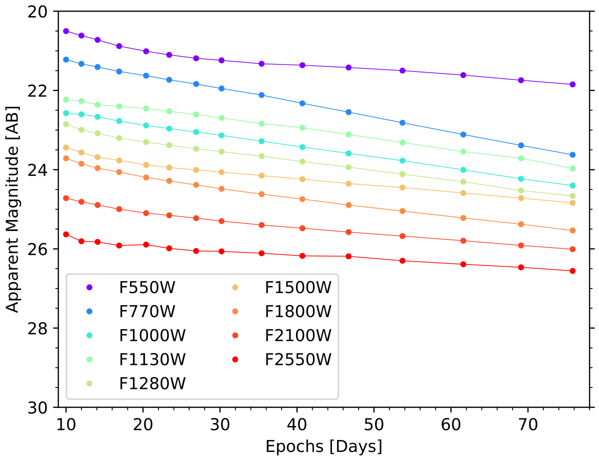


f0.5, 0.05M_{sol}

- Different lanthanide impacts
- 4.44 micron band similar
  - Se III feature evolution is similar in all models



- MIR (> 5 micron) similar between models
- M=0.05M_{sol} brighter
  - More power from greater mass



Summary and Conclusions

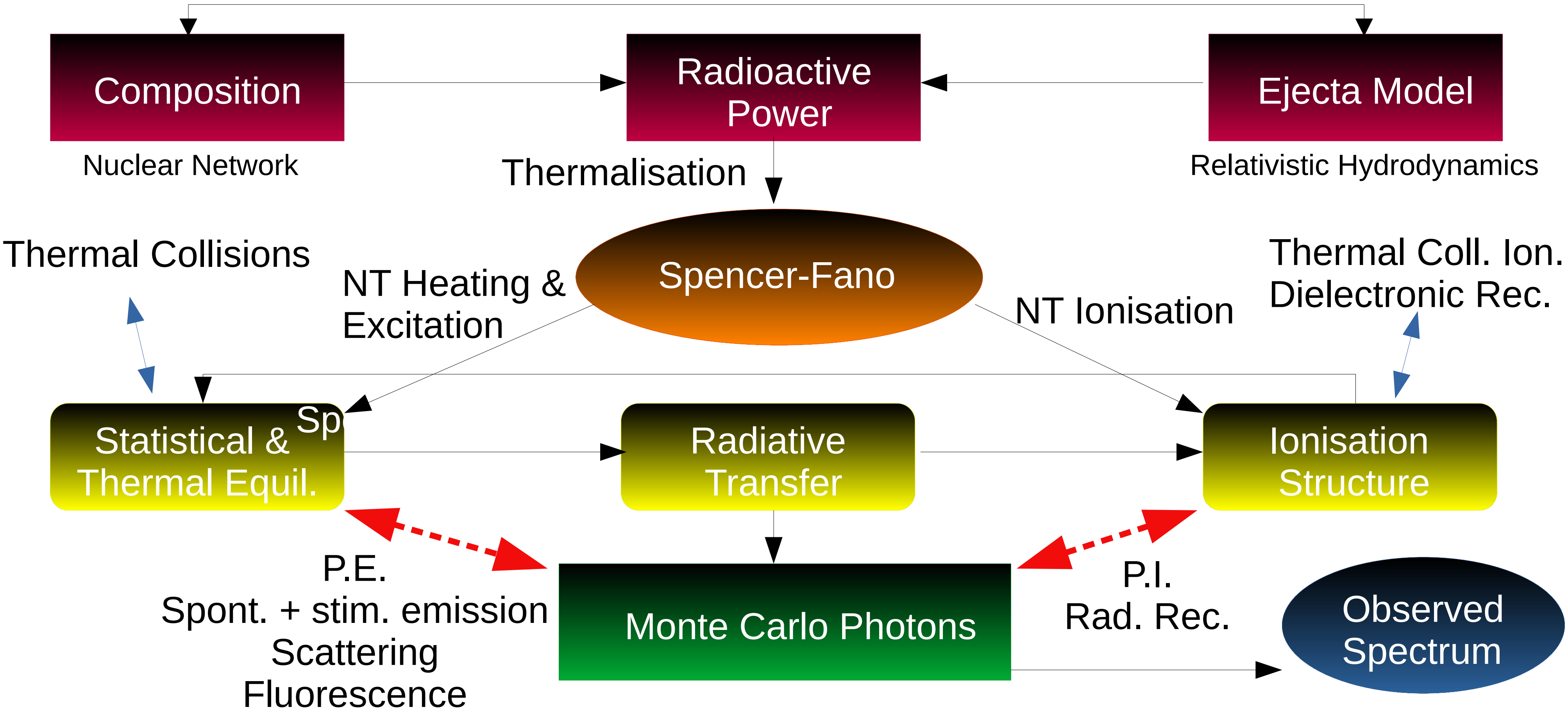
- Good observational and theoretical motivation to study IR emission lines in KNe
  - Due to forbidden nature requiring low density, NLTE physics necessary
- First models covering parts of parameter space generated
  - Te III emission at 2.1 micron significant in most models
  - May blend with lanthanides in parts of parameter space
  - Se III appears to dominate over W III
  - Potentially interesting Ni III feature at 7.3 micron
- Key features impact IR LCs
  - Could provide insight into observed KN if no spectra available

Thank you for listening!

Supplementary Slides

SUMO: (SUpernova MOnte Carlo Code)

Jerkstrand+ 2011
Jerkstrand + 2012



KN Modelling with SUMO (SUpernova MOnte Carlo Code)

Jerkstrand 2011,
Jerkstrand et al. 2012

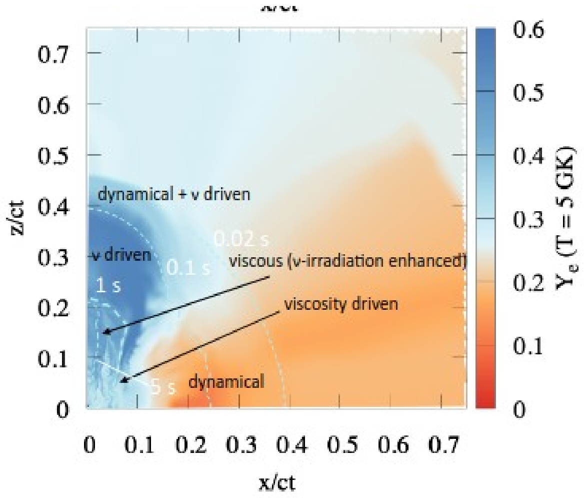
- 1D NLTE Monte Carlo spectral synthesis code
- Line-by-line radiative transfer:
  - Full modelling of resonance scattering and fluorescence
- No assumption of optical thinness
- NLTE physics needs atomic data:
  - Theoretical r-process atomic data (levels and lines) from FAC (Jon Grumer, Uppsala University)
  - Cross sections from various sources, mainly fitting formulae

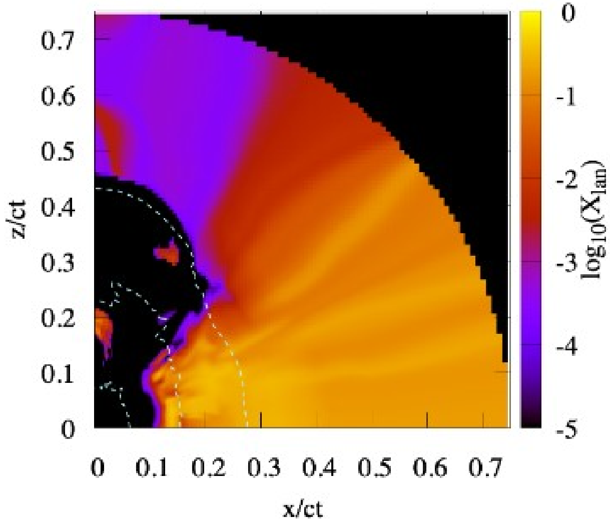
Atomic Data in NLTE

- Energy degradation by Spencer-Fano
  - NT cross-sections -> Lotz 1967 formula
- Excitation: collision strengths
  - Van Regemorter for allowed, $f_{osc} >= 10^{-3}$
  - Axelrod 1980 for forbidden, $f_{osc} < 10^{-3}$
  - Extra scaling based on Bromley+2023
  - Tabulated strengths used where available
- Ionisation:
  - PI cross sections: hydrogenic for first 50 levels
  - Recombination: constant rate 10^{-11} $cm^3 s^{-1}$

Model Details: DD2 1.35M$_{sol}$

- DD2 EoS, 1.35 M$_{sol}$ symmetric BNS system
- No lanthanides in pm ejecta
  - In reality small trace abundances
  - Not impactful in terms of opacity or emission lines
- pm vs dyn ejecta cutoff at 0.15 s
  - Consistency between 3D NR and 2D RHD simulation
- Compositions limited to 30 elements, chosen at 25 days
  - Representative of average composition in 10 – 75 day timespan





Kawaguchi+ 2021

Nebular phase: Steady-state and Time-dependence

- Common assumption in the NLTE regime: steady-state solutions for the gas state
  - Processes like heating/cooling and recombination/ionisation are fast compared to evolutionary time
- Radioactive energy is instantaneously reprocessed, and bolometric luminosity follows energy deposition
- Processes are density dependent -> will become slow and inefficient leading to time-dependent solutions
  - Ionisation structure freeze-out
  - Extra adiabatic cooling in T can lead to temperature turnaround