YITP Longterm Workshop

Multi-Messenger Astrophysics in the Dynamic Universe

Red and Slow:

Nebular Phase Kilonovae in the Infra-Red

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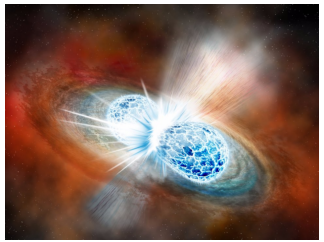
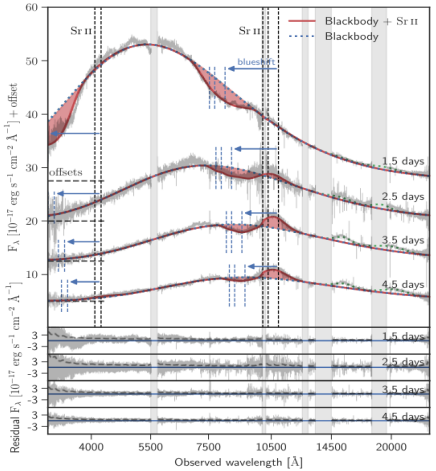
Artist Impression, NASA

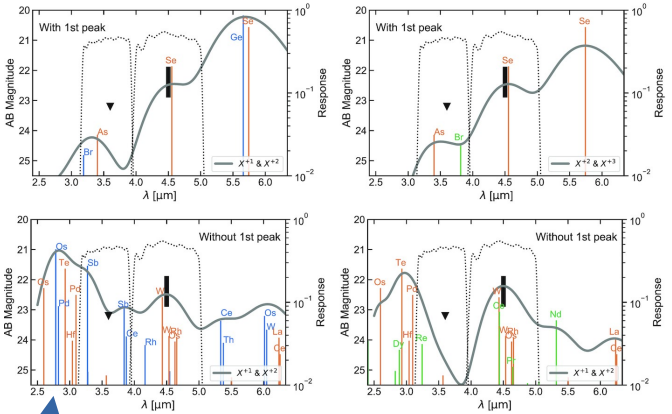


Coalescence, r-process in ejecta

Watson+ 2019



Hotokezaka+ 2022



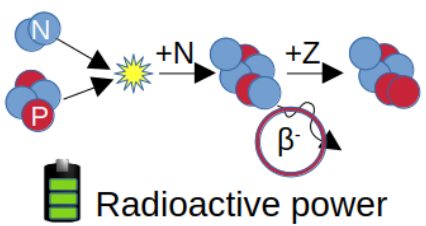
Evolution of a Kilonova

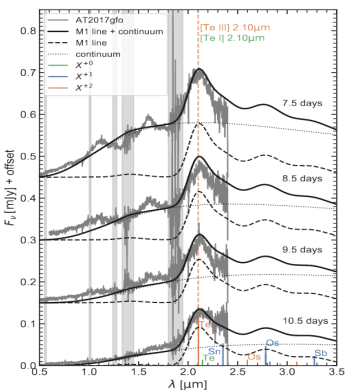
Nebular Phase

0 5 10 20 50 70 100+ Time (days)

Photospheric Phase — Steady-State NLTE — Time-Dependent NLTE

LTE NLTE





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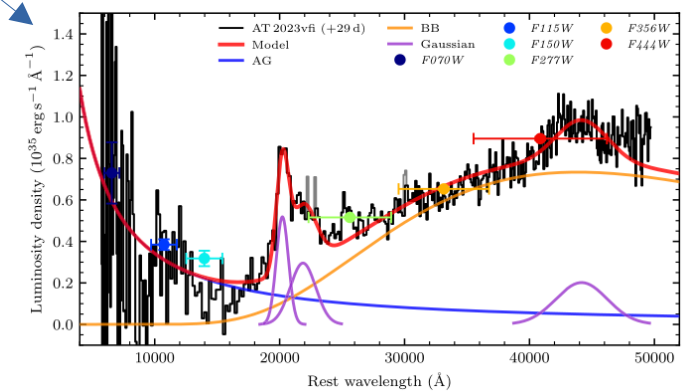


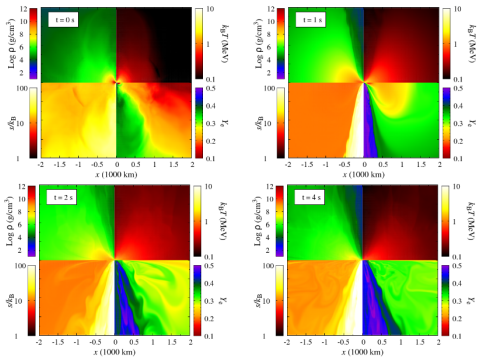
Gillanders & Smartt+ 2025

Nebular phase:

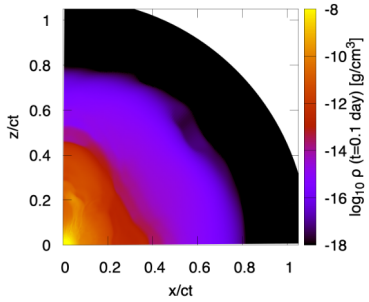
- Optically thin
- NLTE physics
- Slow evolution of T and X_e
- Low energy → NIR-MIR lines

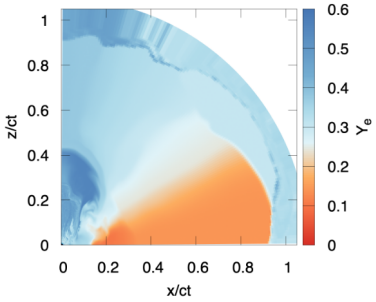
Method and Goals

- Use time-dependent NLTE radiative transfer simulations to explore a parameter space of nebular phase KN spectra in the IR: 1 – 30 μm
  - Input data from end-to-end simulation of symmetric binary NS merger with long-lived remnant, ejecta split into post-merger and dynamical components
- Parameter space of total ejecta mass and fraction of dynamical ejecta
  - M_{ej} = 0.05, 0.01, 0.005 M_{sol}, f_{dyn} = 0, 0.01, 0.05, 0.1, 0.5
- Produce self-consistent nebular phase spectra of KNe
  - Particular focus on the impact of lanthanides in the IR



Numerical Relativity
Fujibayashi+ 2020





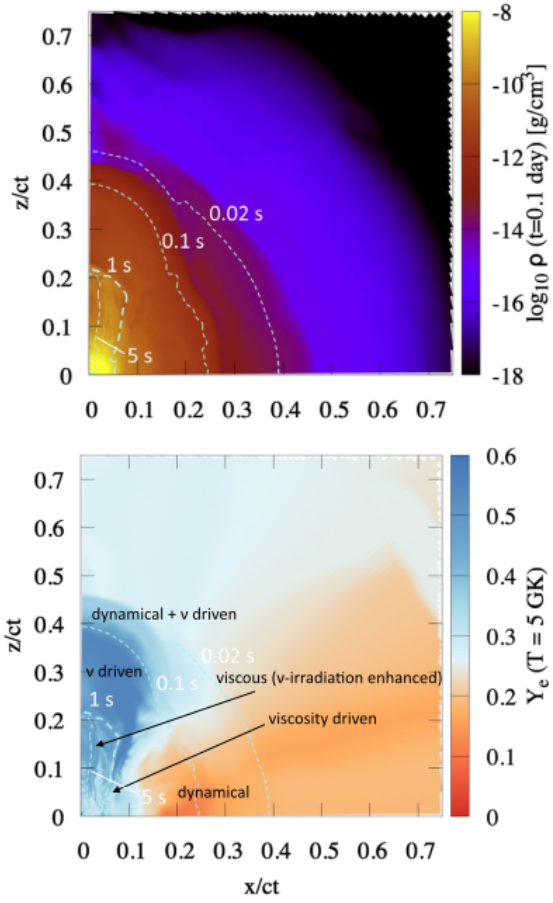
GR Hydrodynamics
Kawaguchi+ 2021

SUMO

NLTE Radiative Transfer
Jerkstrand+ 2011,2012
QP+ 2022

Merger Model

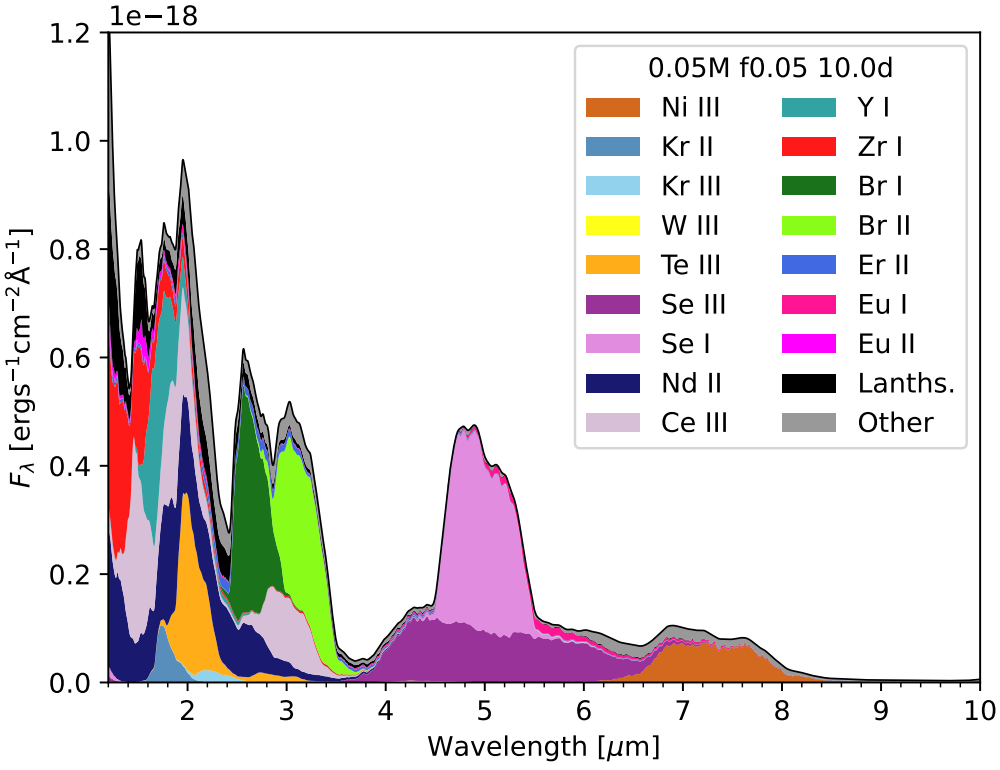
- DD2 EoS, 1.35 M_{sol} symmetric BNS system
  - Long lived remnant scenario
- No lanthanides, 3rd peak or actinides in post-merger ejecta
  - In reality small trace abundances
  - Not impactful in terms of opacity or emission lines
- Post-merger vs dynamical ejecta cutoff at 0.15 s
  - Consistency between 3D NR and 2D HD simulation
- Compositions limited to 30 elements, chosen at 25 days
  - Representative of average composition in 10 – 75 day timespan



Kawaguchi+ 2021

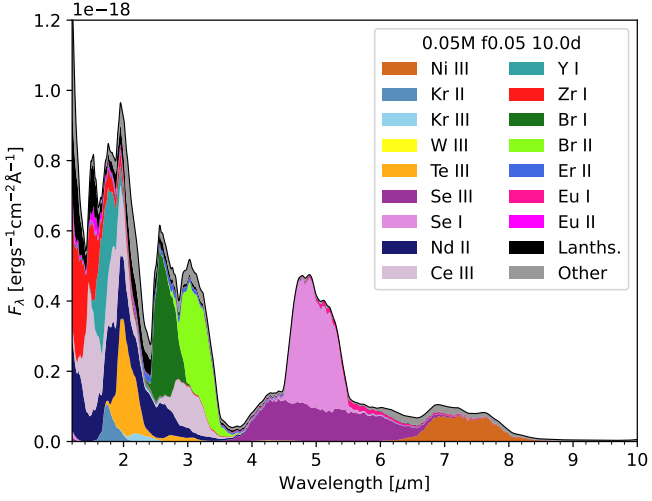
Spectra: Common Features

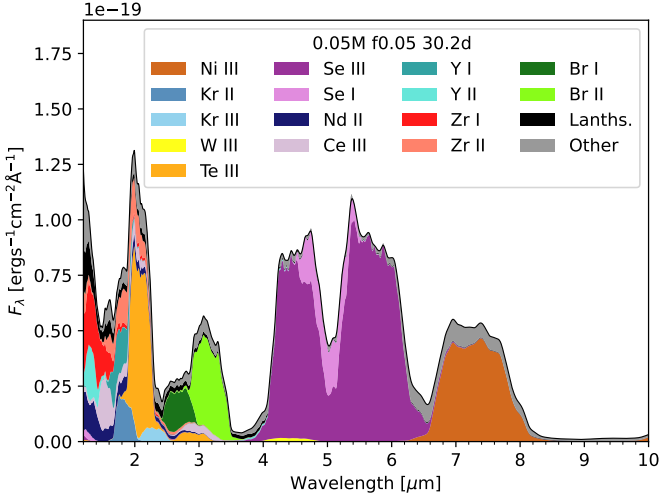
- "Standard" model with $M_{ej} = 0.05 M_{sol}$ and $f_{dyn} = 0.05 \rightarrow X_{La} = 0.0027$
- Key features at 10 days:
  - Very blended emission at ≤ 2 micron
  - Dominant lanthanides are Nd II and Ce III
  - Te III at 2 micron is blended with these
  - Strong Br I/II emission at 3 micron
  - Blend of Se I/III between 4 – 6 micron
  - Some Ni III emission at 7.3 micron (from stable Ni isotopes)

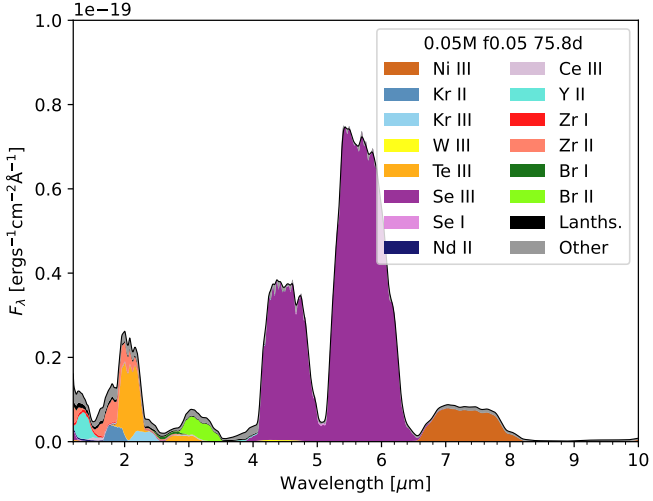


Time Evolution

- The spectra evolve in time, rapidly in the 10 – 30 day range and more slowly after
  - This is linked to the slow evolution of T and X_e
- Initially we have increasing T and X_e
  - Change of dominant ionisation state leads to observable changes
  - Se I → Se III leads to a transition from a single to double peak feature
- At late time, time-dependent effects lead to freeze-out of X_e

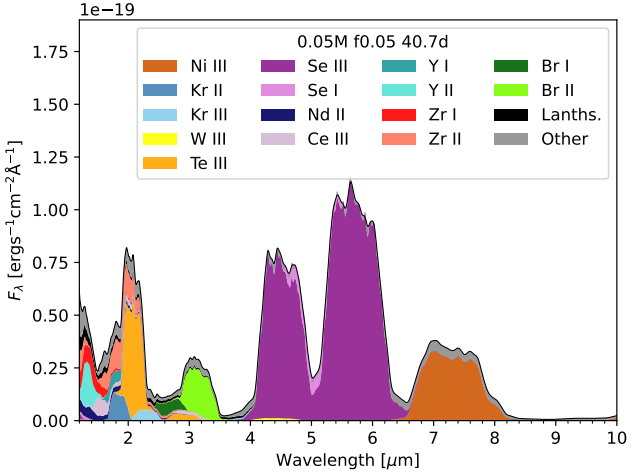


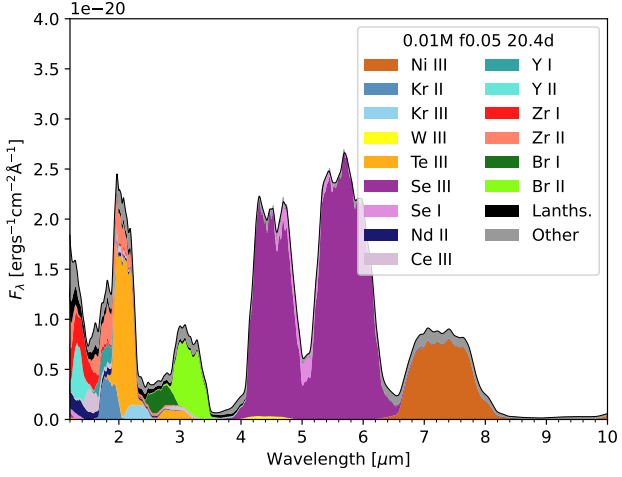




Impact of Ejecta Mass

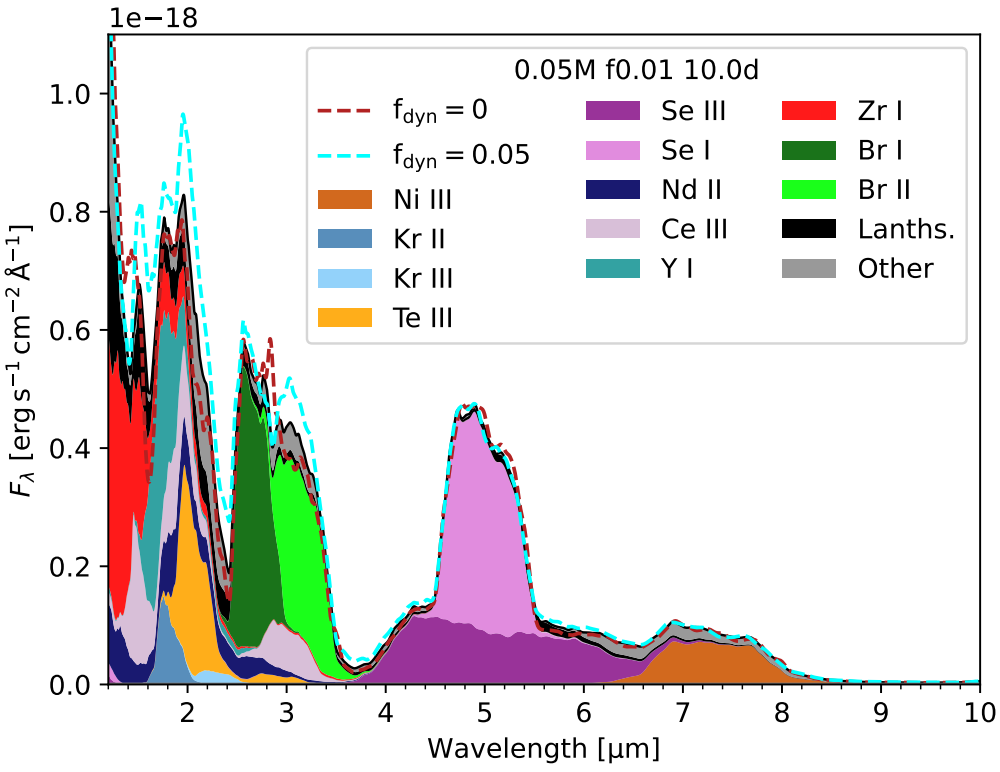
- Smaller ejecta masses yield lower densities at a given time
  - Line cooling is suppressed due to inefficient collisions → typically hotter
  - Both ionisation and recombination are inhibited → similar X_e ~ 0.7-1.5
- Spectral evolution is “compressed” in time
  - E.g. 0.01M_{sol} model at 20 days resembles 0.05M_{sol} model at ~ 40 days
- Freeze-out of X_e occurs earlier
  - SED shape does not evolve much from this point onwards





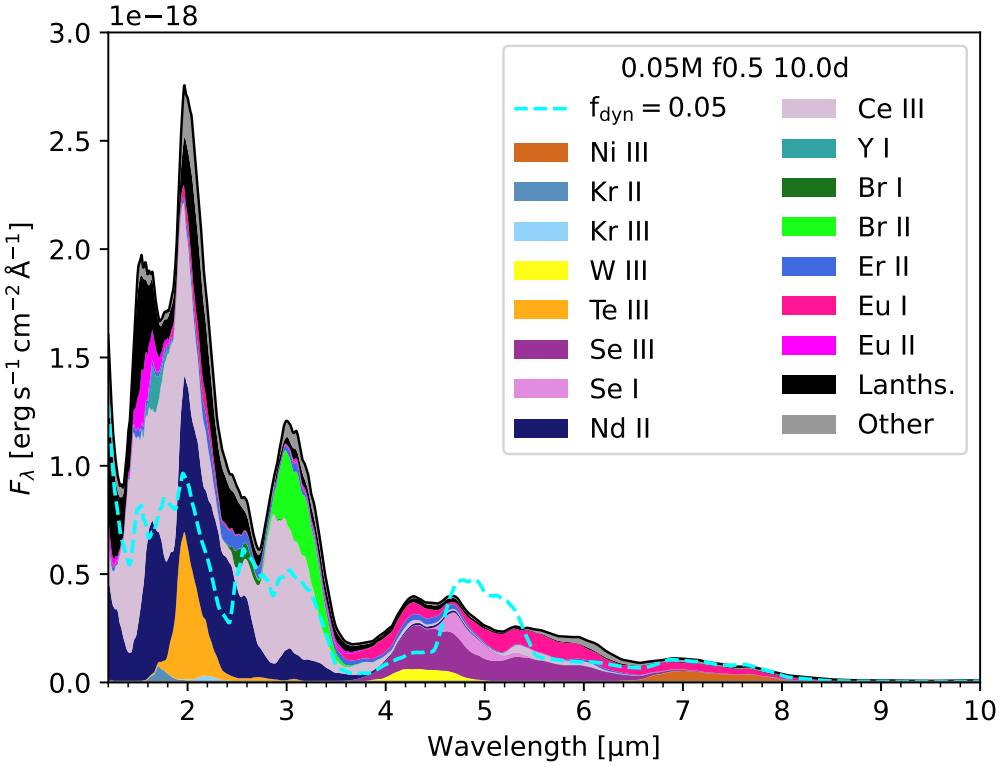
Lanthanide-poor Case

- Consider lanthanide-poor ejecta
  - E.g. f_{dyn} = 0.01 model with X_{La} = 0.001 c.f. f_{dyn} = 0.05 with X_{La} = 0.0027
- Some emission from Ce III and Nd II at ≤ 3 micron
- Compare to fiducial lanthanide-free model f_{dyn} = 0, and f_{dyn} = 0.05
  - Relative contributions are different, e.g. 2 micron blended feature but...
- Overall spectral shape is very similar
  - Unlikely to observationally distinguish cases with $X_{La} \leq 0.0027$ in nebular phase at IR wavelengths



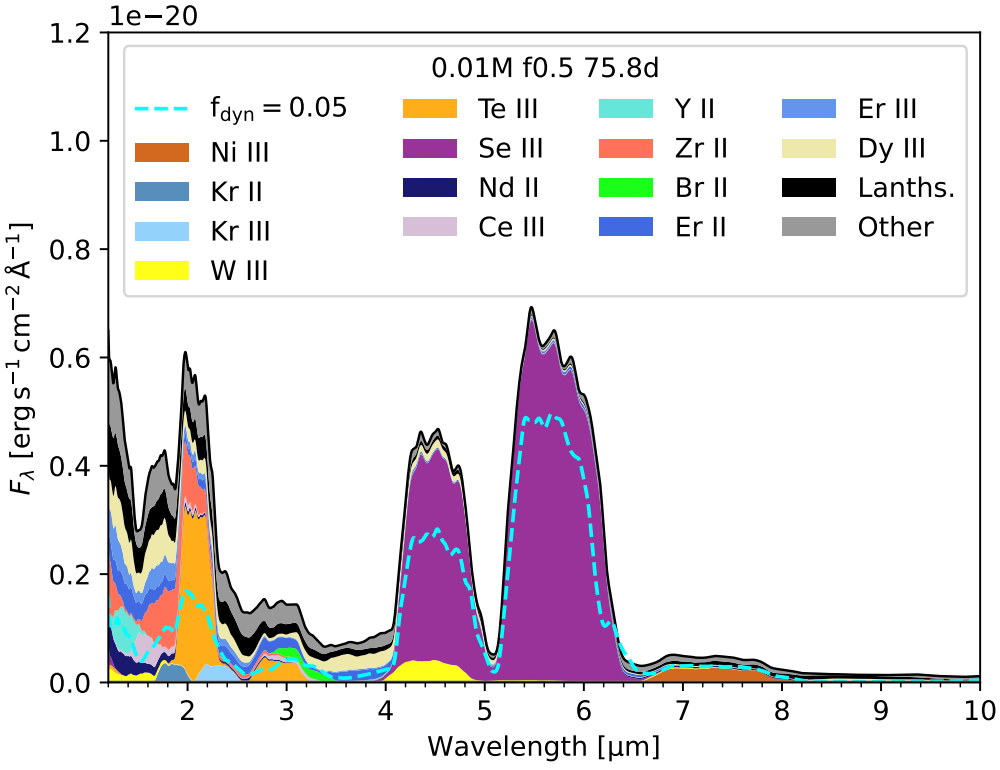
Lanthanide-rich Case

- Consider lanthanide-rich ejecta
  - E.g. f_{dyn} = 0.5 model with X_{La} = 0.0260 c.f. f_{dyn} = 0.05 with X_{La} = 0.0027
- At 10 days, lanthanides completely dominate
  - Te III at 2 micron is largely subdominant
  - No characteristic Se I emission peak at 5 micron
- Due to large f_{dyn}, ejecta has high heating rate → noticeably brighter
  - Combined with an accurate determination of $M_{ej,}$ case should be distinguishable from cases with X_{La} < 0.026

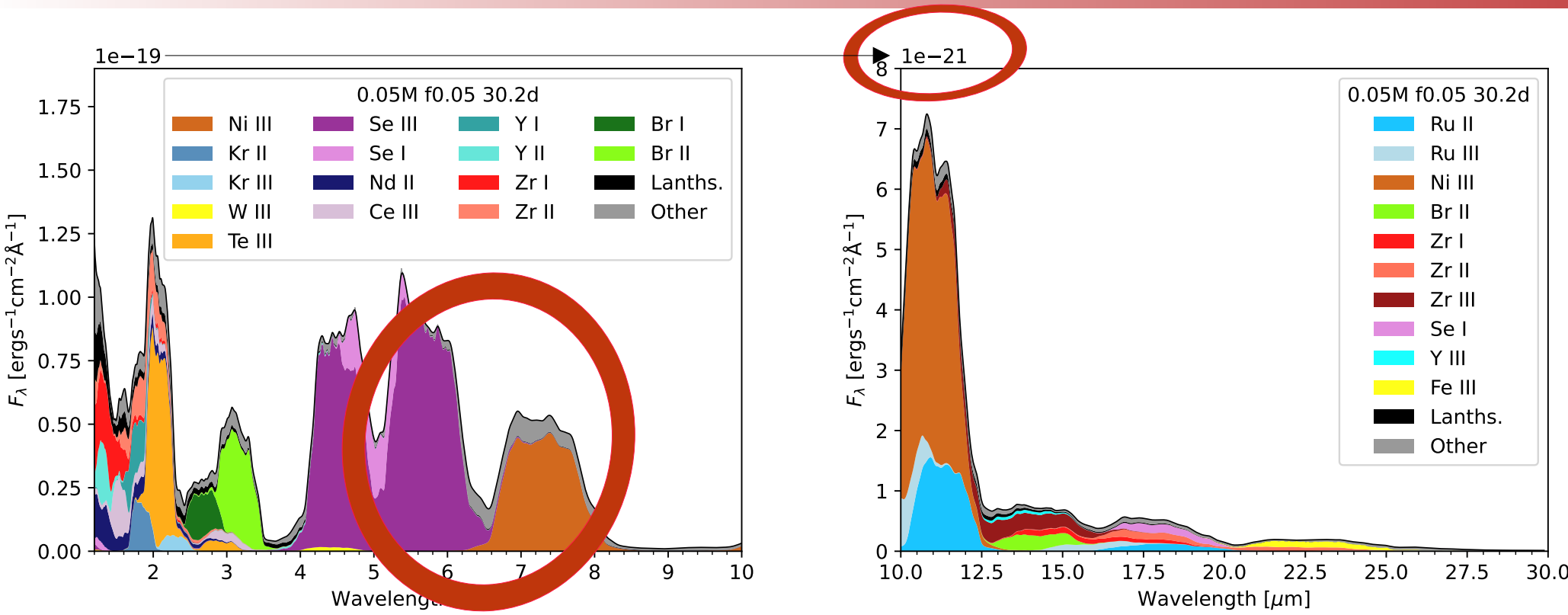


Lanthanide-rich Case

- At high enough X_{La}, lanthanide emission remains significant
  - At late times
  - At smaller masses
- Note that the Se III double peak feature does appear with time
  - Heavier composition → W III contributing up to ~ 20% of emission at 4.5 micron
- Spectral shape past 4 micron is similar to more mildly lanthanide-bearing models
  - Slightly brighter due to higher power, but difficult to distinguish observationally



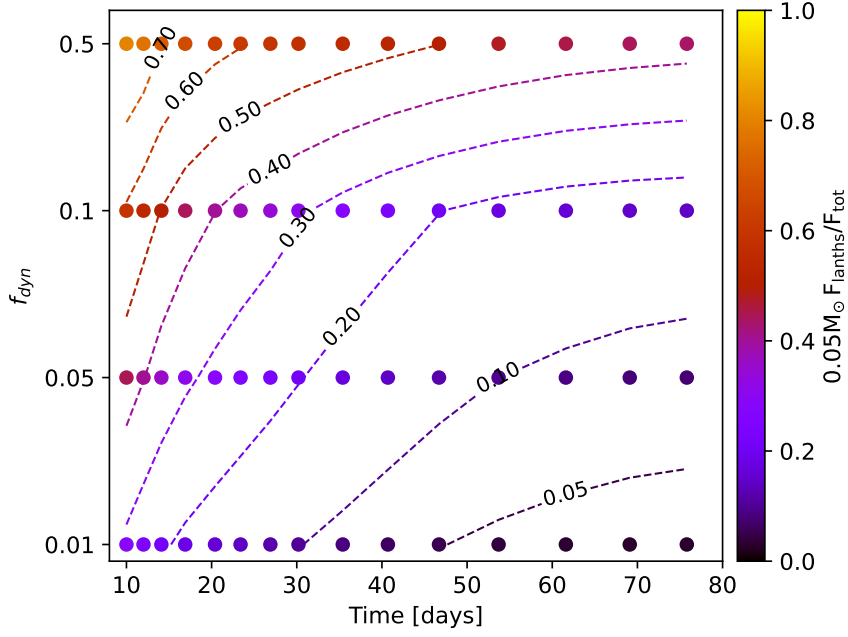
Further into the MIR



- Further into the MIR: mainly 1st, 2nd peak and lighter elements, little to no lanthanides
- Important Ni III line at 11 micron, could be combined with line at 7.3 micron for reliable species ID
  - But luminosity is significantly lower!

Generalising Lanthanide Emission

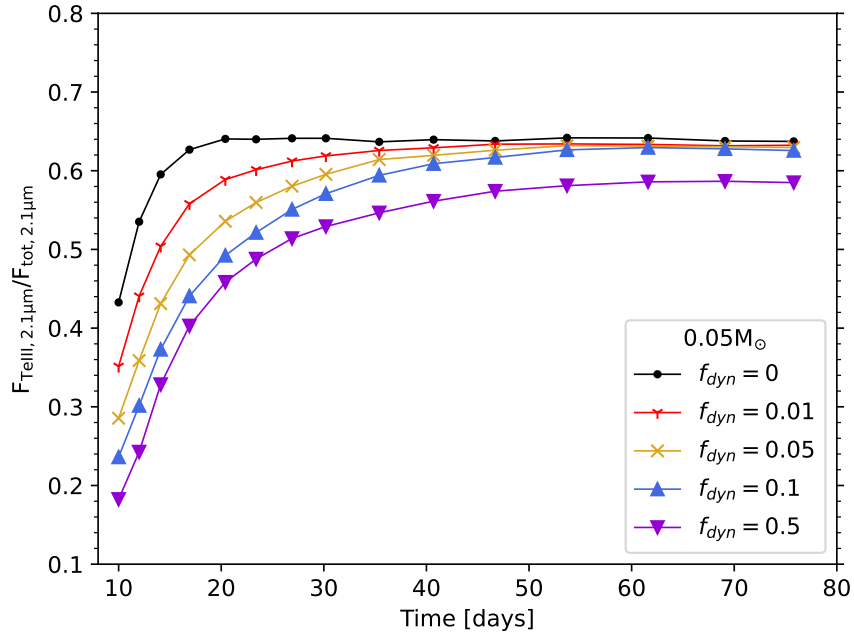
- Where and when does lanthanide emission dominate in the IR in the nebular phase?
  - Typically at wavelengths < 4 micron
  - Earlier times/heavier masses → higher density
- If looking for lanthanides:
  - Earlier is better
  - “Blue” NIR wavelengths ≤ 4 micron
  - But heavy blending is expected…
- If avoiding lanthanides:
  - Wavelengths ≥ 4 micron
  - Later is better
  - But remember luminosity is dropping



Flux fraction coming from lanthanide species in the 1.2 – 3.6 micron range

What about Te?

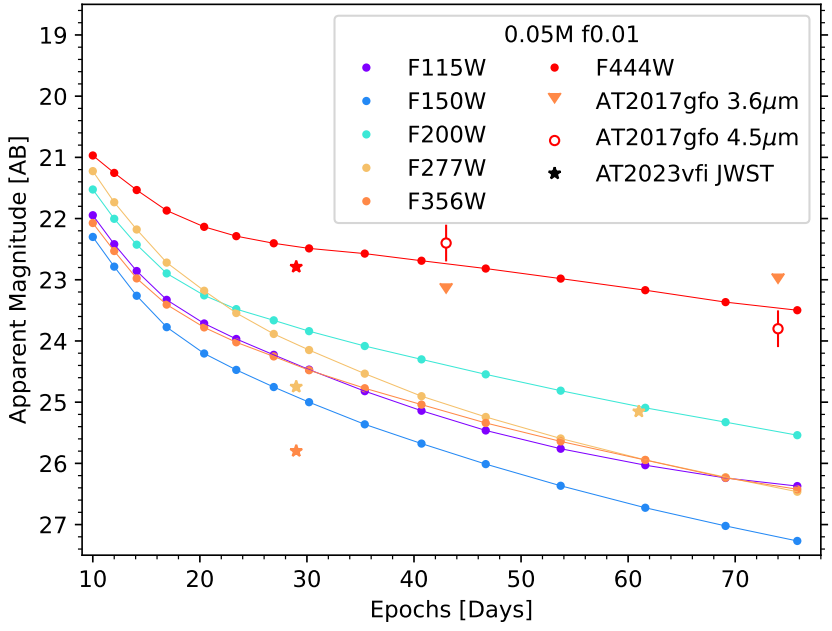
- Te III has been suggested as responsible for emission at 2 micron in AT2017gfo and AT2023vfi
- These models suggest that Te III does indeed play a non-negligible role…
- But it is never the sole emitting species in any model at any epoch
  - In lanthanide-bearing models, blending with Ce III and Nd II occurs
  - In lanthanide-poor models, blending with Zr II, Kr II and Kr III occurs
- Estimating Te mass assuming the emission is fully Te III overestimates (potentially drastically) the value
  - Highlights need for two separate lines from same species for reliable identification and mass calculations



Flux fraction coming Te III at 2.1 micron

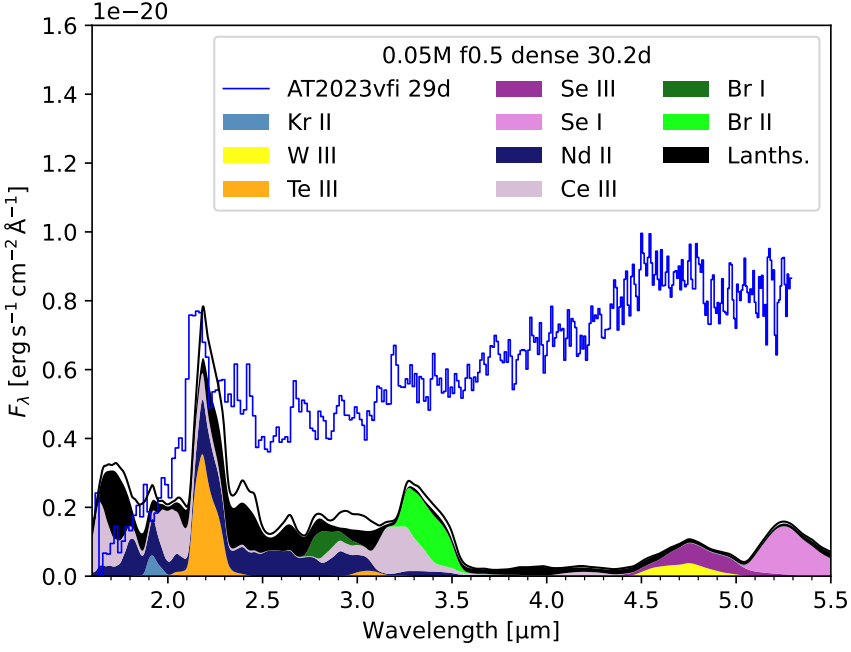
1st or 3rd: Se vs W

- *Spitzer* photometry of AT2017gfo at 43 and 74 days shows emission at 4.5 micron and non-detection at 3.6 micron
- Suggested species for 4.5 micron emission include Se III and W III
  - Our models favour Se III since underlying merger model is long-lived remnant case
  - Dominance of W III requires significantly more neutron rich conditions
- Our f_{dyn} = 0.01 model (X_{La} = 0.001) most closely matches the observed photometry
  - Exploration of short-lived remnant cases and possibly BHNS mergers should be explored



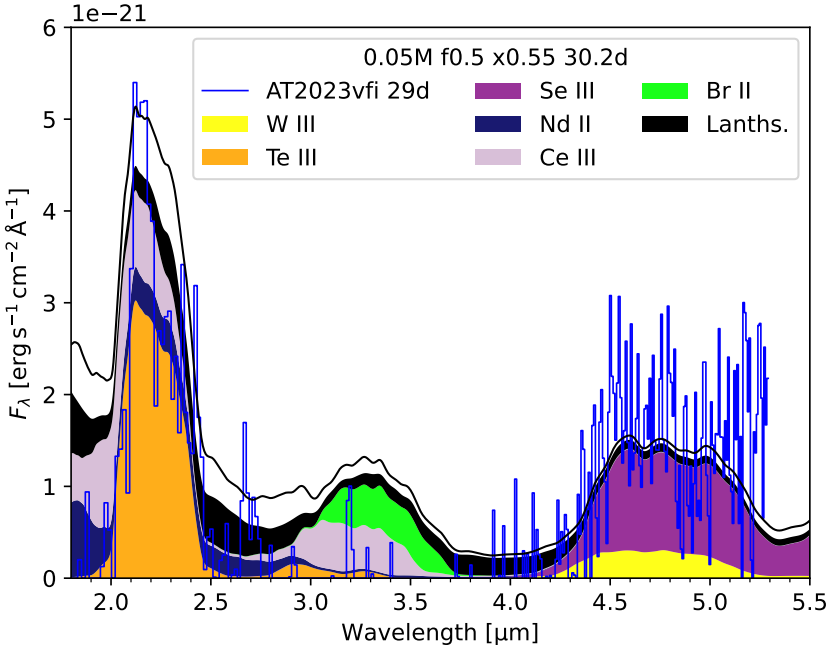
Cool and Mysterious: AT2023vfi

- AT2023vfi spectra at 29 and 61d showed cool, Blackbody like continuua
  - E.g. 29d: T ~ 660K, R ~ 6x10^{15} cm (v_{phot} = 0.08c)
- Origin of this continuum is unclear
  - Photosphere? Dust? Something else?
- Can expansion line opacity make an optically thick BB continuum?
  - Our models are optically thin in NIR at these times
  - Take most lanthanide-rich f_{dyn} = 0.5 model and make a “dense” variation with v_{in} = 0.02c → no continuum formed
- Expansion line opacity cannot form an optically thick NIR continuum at these times in reasonable ejecta conditions



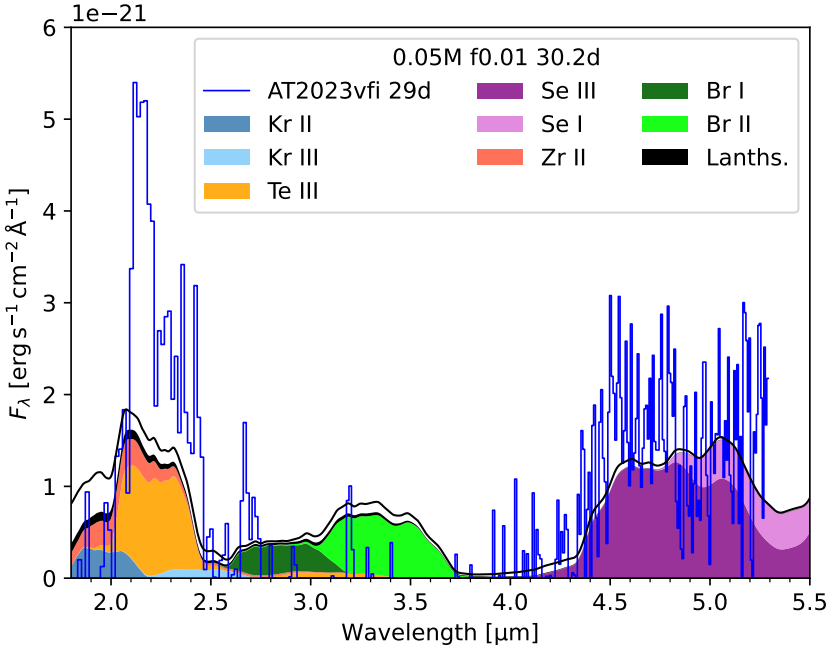
AT2023vfi: Lines

- AT2023vfi also had GRB afterglow and emission line components
  - For comparison to models, subtract best-fit afterglow and BB components
- Case A: BB component is a real “photosphere” with v_{phot} = 0.08c
  - Scale down model spectra corresponding to mass between v_{in} = 0.05 - v_{phot} = 0.08c
- Closest match is f_{dyn} = 0.5 model
  - 4.5 micron emission is mix of Se III and W III
  - 2 micron emission does not reproduce observed line shape
  - Excess flux between 2.5 – 4.0 micron



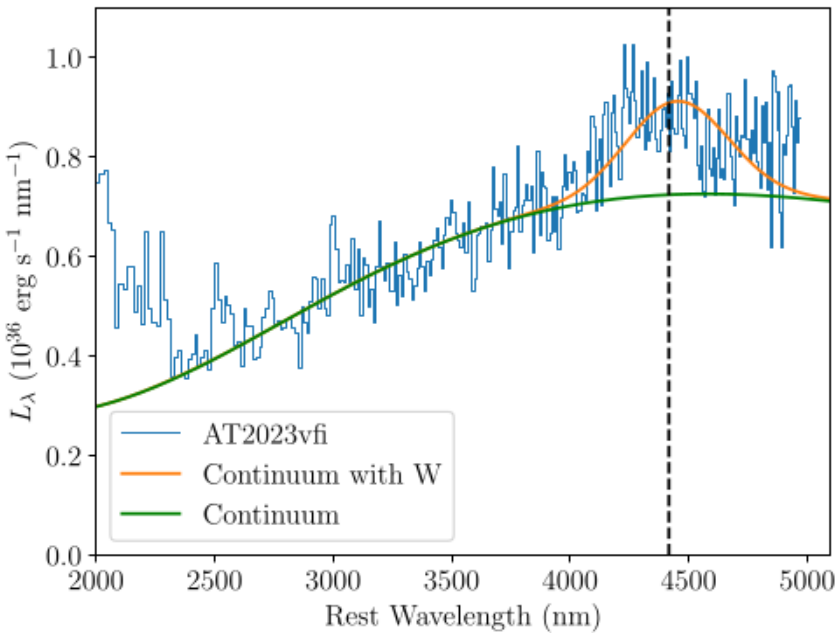
AT2023vfi: Lines

- Case B: Assume BB continuum comes from something other than a photosphere
  - In this case don't scale down model spectra, simply compare to continuum-subtracted spectrum
- Closest match is f_{dyn} = 0.01 model
  - 4.5 micron emission is mainly Se III
  - Te III at 2.1 micron, but not luminous enough
  - Again flux excess between 2.5 – 3.6 micron
- No model reproduces the 29d spectrum of AT2023vfi...



AT2023vfi: Remnant?

- In all models, we find excess Br I/II flux at ~ 3 micron
  - Is Br absent from line-forming ejecta of AT2023vfi at 29d?
- Suppose it is… let's follow the thread
  - Br is a first peak element → other first peak elements also low abundance?
  - Se may also be absent → 4.5 micron emission is dominated by W III?
- Requisite W III mass is ~ 9 x10^{-4} M_{sol} (McCann+2025)
  - Only 1.4 x10^{-4} M_{sol} in f_{dyn} = 0.5 model at 30d
- Our merger model is for long-lived remnant case, could AT2023vfi instead be a short-lived case?
  - Further work needed… but AT2023vfi likely not a long-lived remnant case



McCann+ 2025

Conclusions

- Want to explore IR spectra of KNe in the nebular phase
- Use time-dependent NLTE radiative transfer simulations to explore a parameter space of ejecta mass and lanthanide fraction
- Find several key results:
  - Lanthanide impact is typically limited to wavelengths ≤ 4 micron
  - Te III at 2.1 micron is always blended: Ce III, Nd II, Zr II, Kr II, Kr III
  - Se III dominates emission at 4.5 micron and 5.7 micron
  - Ni III has important features at 7.3 and 11 micron
  - Observations combining NIR and MIR spectroscopy could provide 2 line IDs for 2 different species!
- Comparing our model to AT2023vfi at 29d:
  - Line opacity alone cannot produce an optically thick thermal continuum
  - No model reproduces the observed line emission → some hints that a long-lived remnant case is in tension with spectra of AT2023vfi

Thank you for your attention!