Spectral synthesis modelling of kilonovae

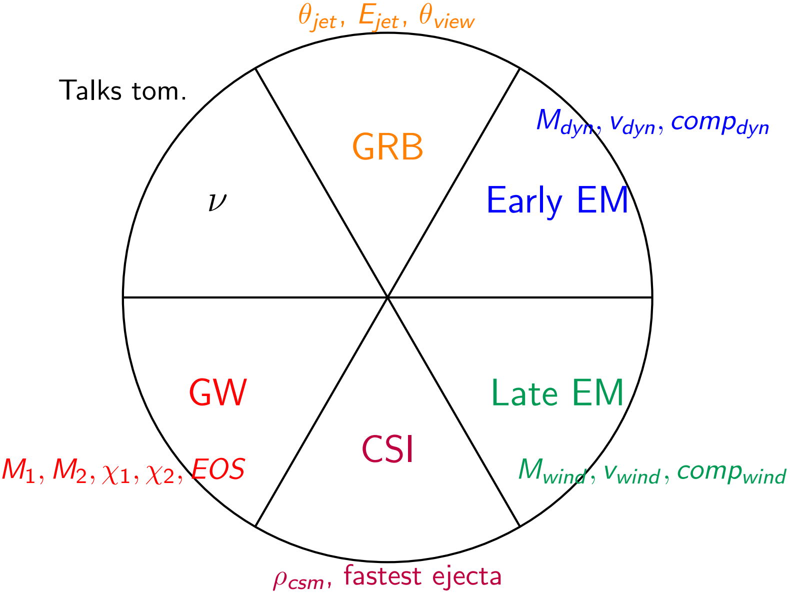
Anders Jerkstrand, with Quentin Pognan, Jon Grumer, Smaranika Banerjee, Eliot Ayache, Blanka Vilagos

Stockholm University

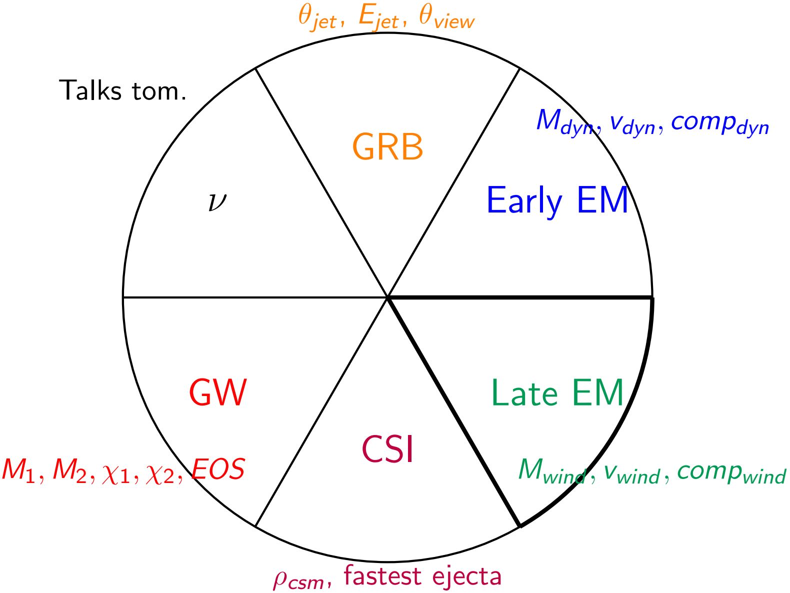
European Research Council

Swedish Research Council

The r-process transient Multi-Messenger Cake



The r-process transient Multi-Messenger Cake



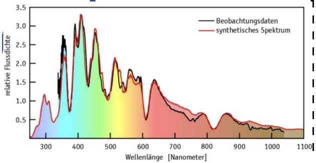
Explosive transient evolution

Diffusion phase

Optially thick and long escape time for radiation

Spectra probe surface layers

Many lines excited and significant optical depth → **scattering spectra**



Early tail phase

Optically thick and short escape time for radiation

Spectra probe intermediate layers

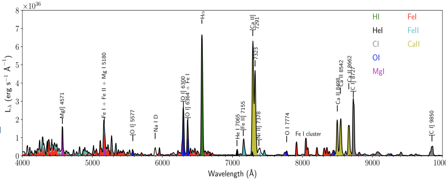
Fluorescence dominates optical and NIR

Late tail phase

Optically thin and short escape time for radiation

Spectra probe inner layers

Few lines excited and reduced optical depth → **emission line spectra**



Simple microphysics (LTE), complex transfer

Time →

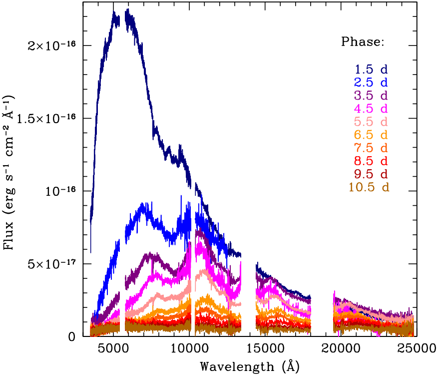
Complex microphysics (NLTE), simpler transfer

Reviews: Sim 2017, Handbook of SNe   Jerkstrand 2017, Handbook of SNe

Higher Doppler broadening and more elements and lines make transition phases less clear in KNe than in SNe

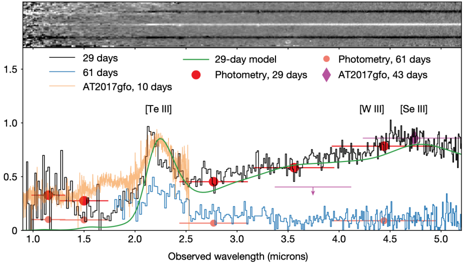
AT2017gfo

Pian+2017



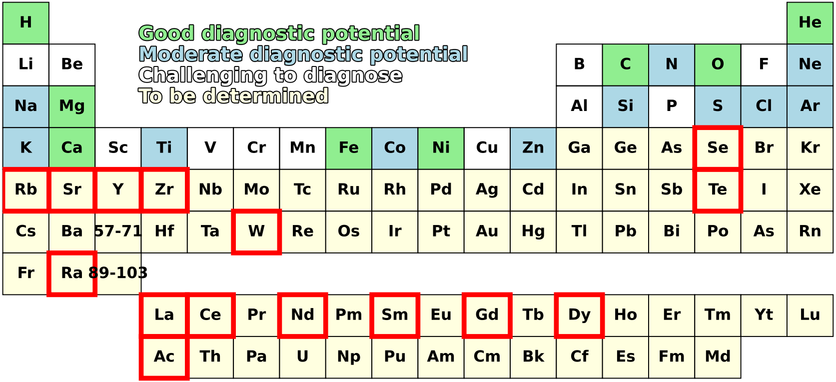
GRB-230307A

Levan+2023



Among the most complex physical objects in cosmos → interpretation needs guidance from **spectral models**.

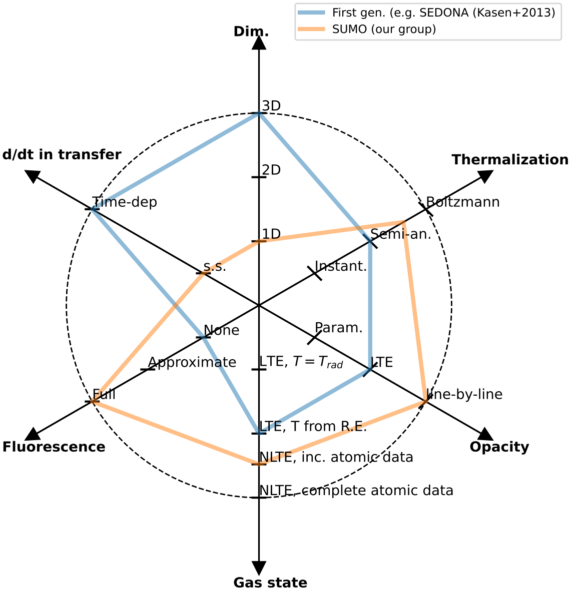
Empirically inferring SN and KN composition



□ =Possible identification in AT2017gfo

Watson+2019,Domoto+2021,2022,Hotokezaka+2022,2023
Sneppen+2023,Pognan+2023,Gillanders+2024

KN spectral synthesis modelling



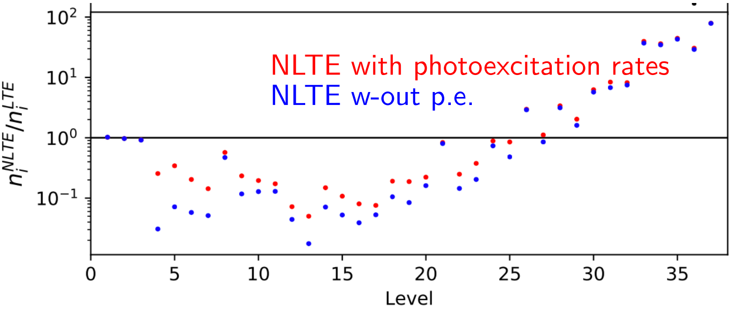
- Can we reach the circle? Each step out can increase the compute time by large factor.

KNe are low-density nebulae already from birth

$$\rho \approx 10^{-13} \left(\frac{M}{0.05\ M_\odot}\right) \left(\frac{V_{char}}{0.1c}\right)^{-3} t_{days}^{-3} \text{ g cm}^{-3} \quad (1)$$

Compare to a stellar atmosphere: $\rho \sim 10^{-9}$ g cm^{-3}.

Example: Pt III in strong NLTE aleady at 5d: Pognan, AJ & Grumer 2022



The SUMO code : 1D NLTE radiative transfer

AJ+2011, 2012

Radioactive decay and γ-ray transport

Non-thermal electron degradation

- Boltzmann equation: downscatter by losses to heating, ionization, excitation.

Radiative transfer

- Monte Carlo with Sobolev approximation.
- Lines: $\sim 10^6$ for SNe, $\sim 10^8$ for KNe.
- Continuum : Free-free, bound-free, e^- scattering.

Temperature

- Heating = cooling, or time-dependent 1st law of thermodynamics.

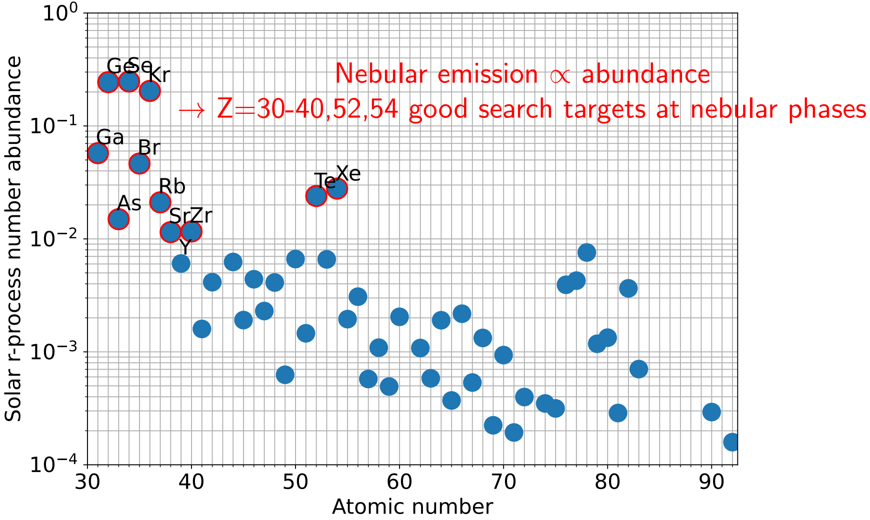
NLTE level populations

- Most of the periodic table included, first 2-4 ionization stages.
- $\sim$10-1000 exc. states each.

R-process atomic data

- **Energy levels and A-values**: Complete set all elements, ions I-IV with FAC (by Jon Grumer).
  - Overall term structure captured but moderate accuracy for energies $\rightarrow$ wavelengths 10-20% uncertainty.
  - Some ions calibrated to NIST.
- **Ionizing collision cross sections**: Lotz 1967 formalism.
- **Excitation collision strengths**: Axelrod 1980, some detailed.
- **Recombination rates**: Constant 10^{-11} cm^{3}s^{-1}, some detailed (Banerjee+,subm.).

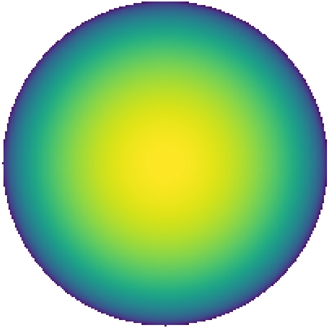
Solar r-process abundances



Data from Prantzos+2020

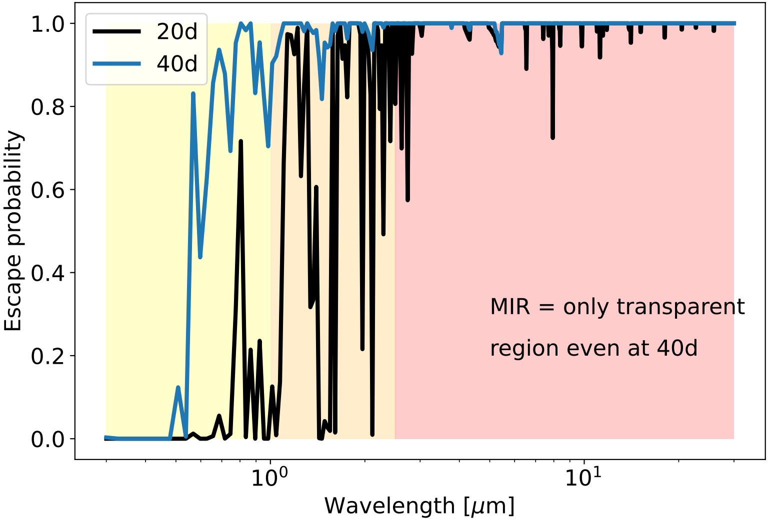
Model illustration, with focus on MIR

$M_{ejecta} = 0.05\ M_{\odot}$, $\rho(v) \propto v^{-3}$, Z=30-40 solar composition.

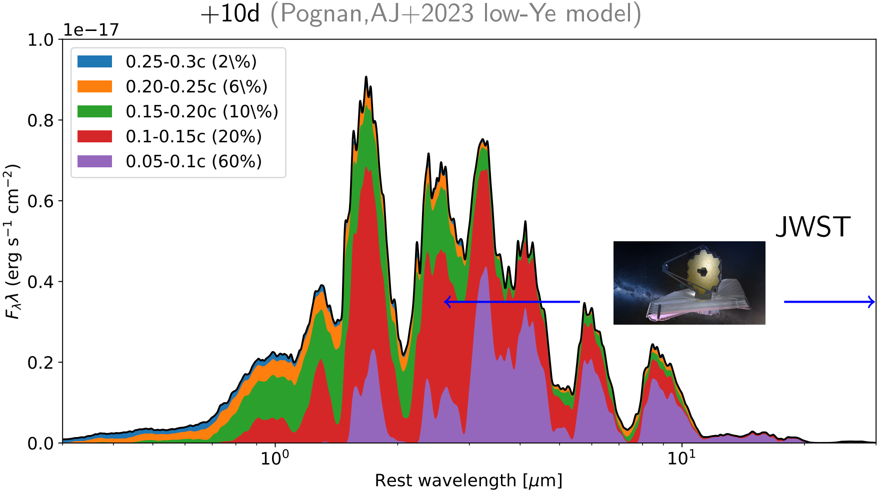


Energy levels and lines in ground multiplets corrected to NIST.
Baseline radioactive decay from Wanajo 2014, analytic thermalization efficiency (Kasen+2019).

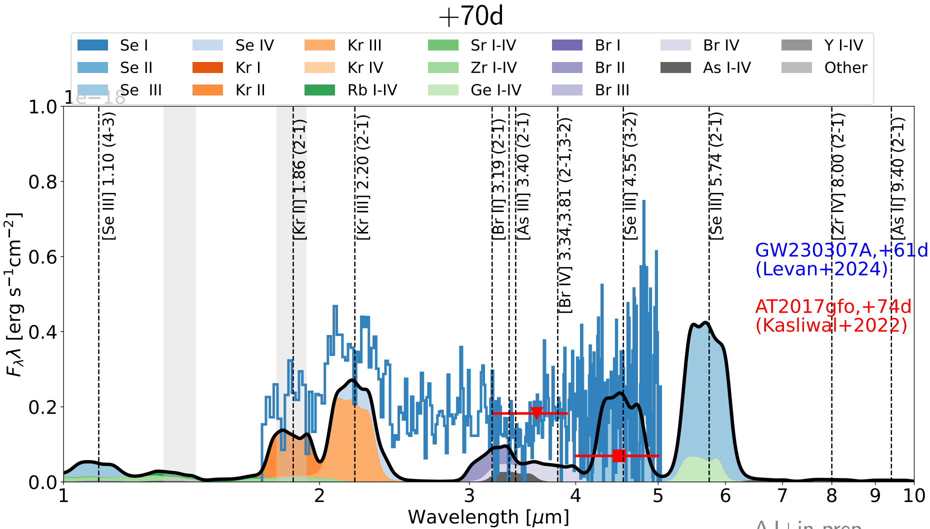
Transparancy vs wavelength



Only long wavelengths probe the bulk ejecta mass

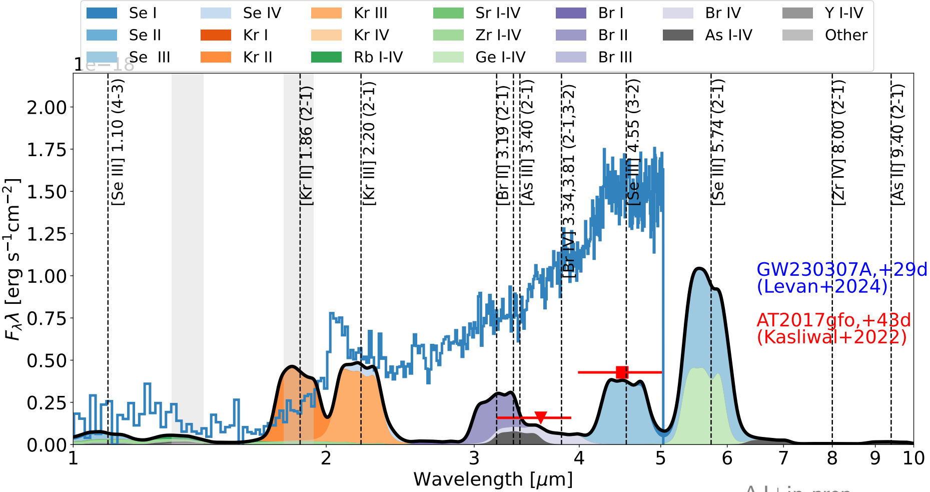


MIR spectra from Z=30-40 elements



AJ+in prep.

MIR spectra from Z=30-40 elements

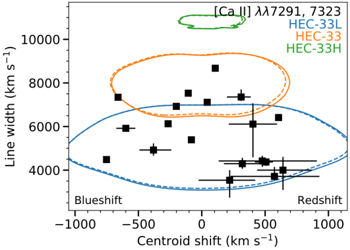


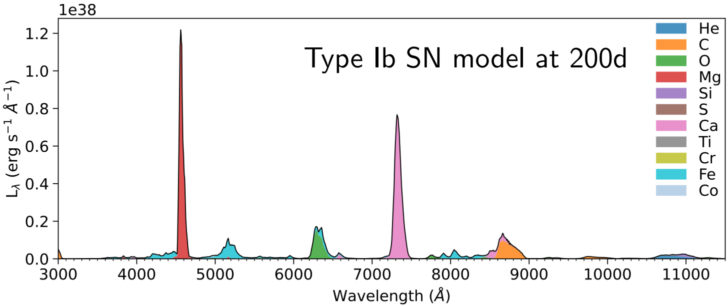
AJ+in prep.

EXTRASS - NLTE spectral synthesis in 3D

AJ+2020,vanBaal+2023,2024

- So far can handle only Z=1-30, and optically thin limit.
- Work to add radiative transfer and r-process elements ongoing.





Summary

- **Second generation of KN spectral models** coming into place considering **NLTE** and **fluorescence**. These effects qualitatively change KN spectra from a few days already and are useful for EM follow-up planning and data analysis.
- Tail-phase EM, particular in IR, gives information on **slow/inner material** constituting the **bulk of KN ejecta**.
- **Z=30-40,52,54** are good primary search targets for nebular IR lines (AJ+in prep.).
    - **[Se III]** 4.55 μm is only good $Z = 30 - 40$ candidate for the 4.5 μm flux in AT2017gfo (see also Hotokezaka+2022) - but new rec. rates make doubtful (Banerjee+,subm).
    - **[Kr III] 2.20** μm is a candidate for the observed 2.1 line in GW230307A and AT2017gfo.
    - Limits can be put on **Br** ($Z = 35$) and **As** ($Z = 33$) to $\lesssim$ solar.