NLTE spectral synthesis modelling of kilonovae, and opportunities with JWST

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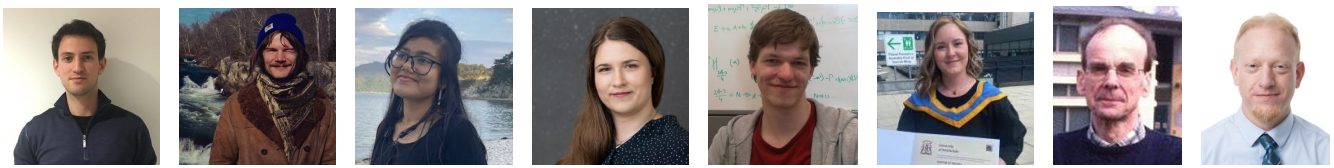

Stockholm University

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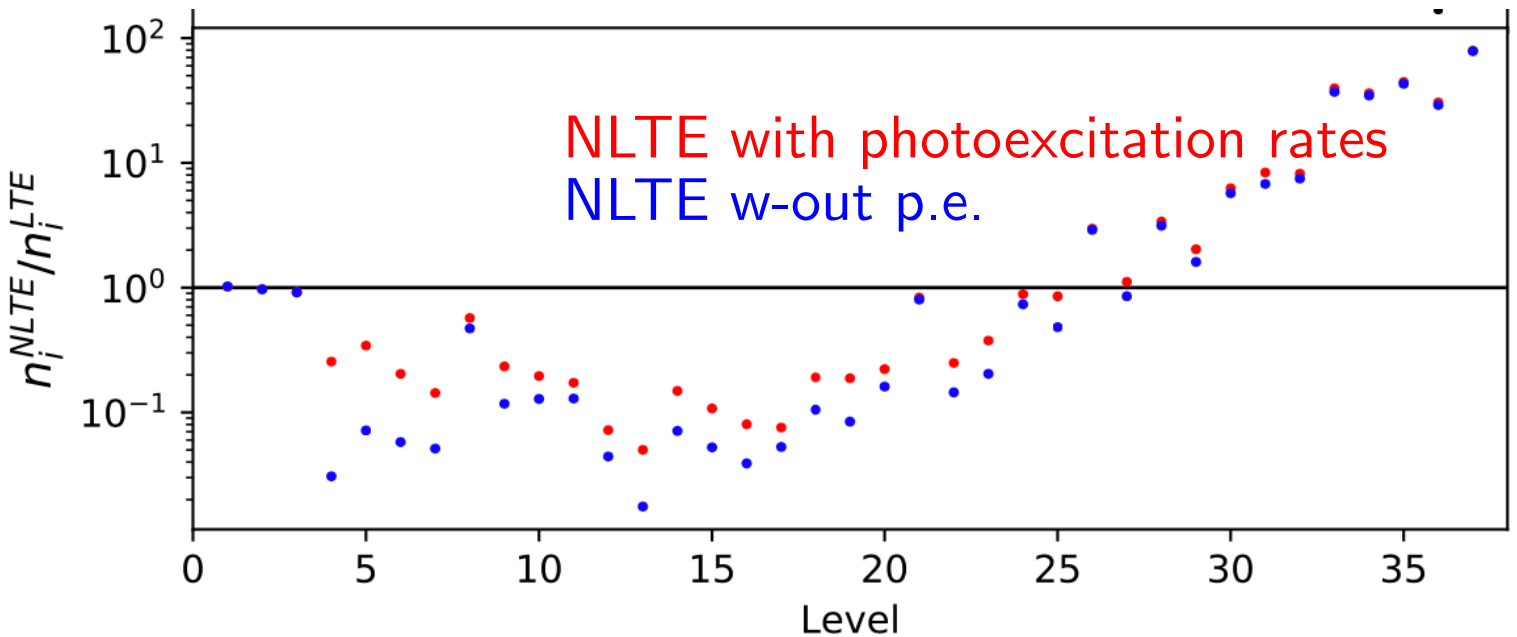
KNe are low-density nebulae already from birth

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

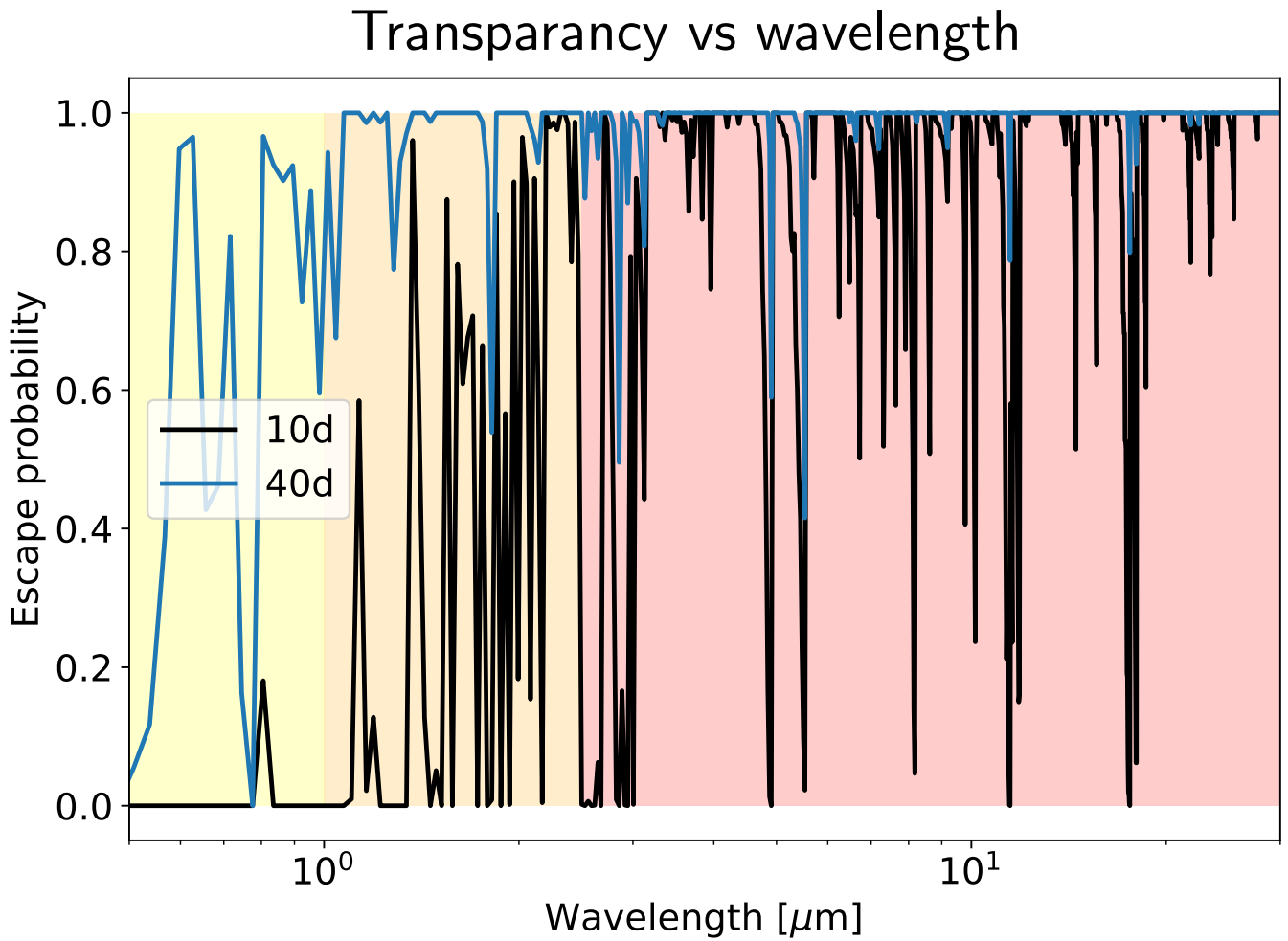
Compare to a stellar atmosphere: $\rho \sim 10^{-9}$ g cm^{-3}.

$\rightarrow$ **NLTE important**.

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

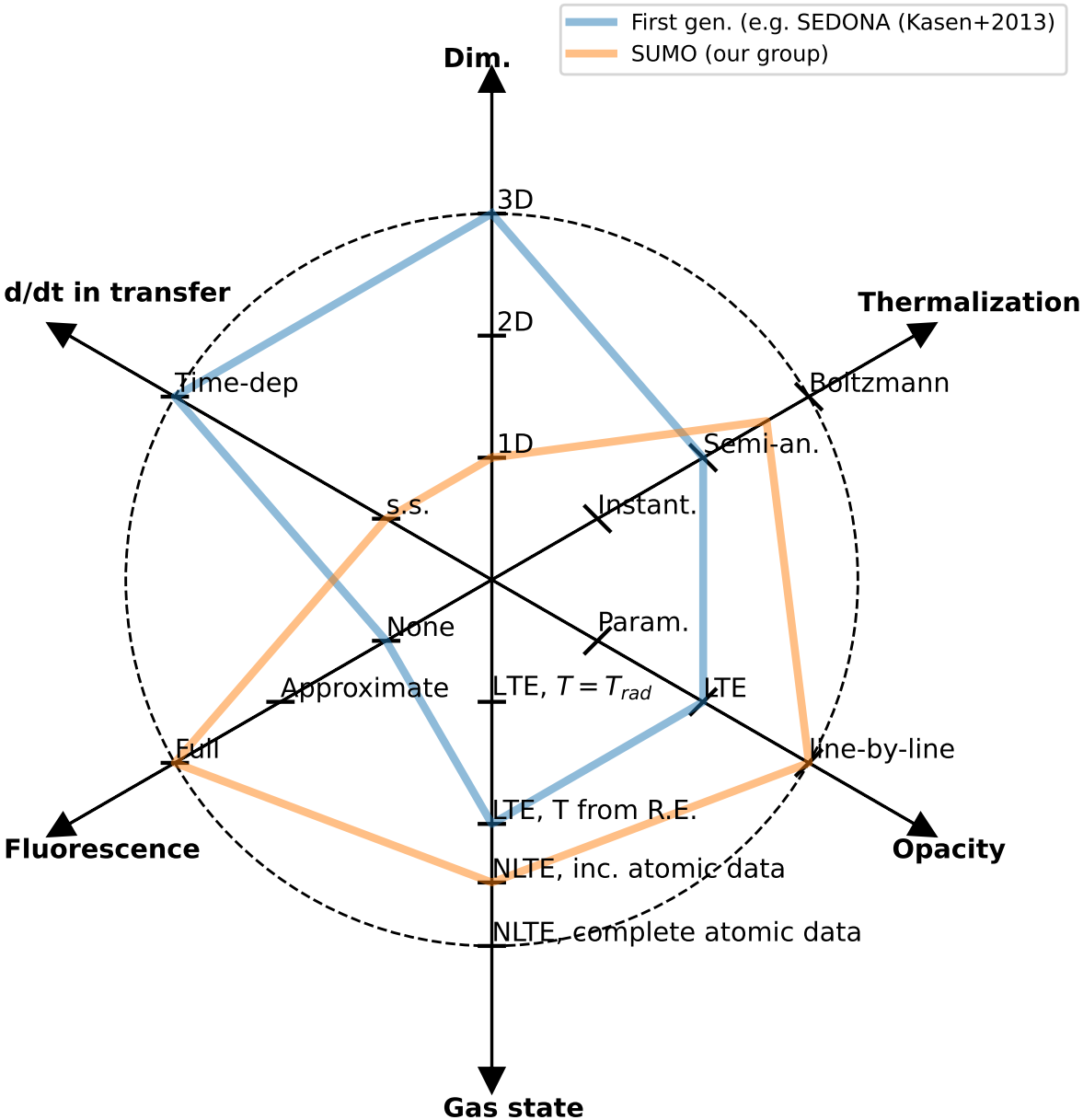


KNe reprocess optical radiation for several months



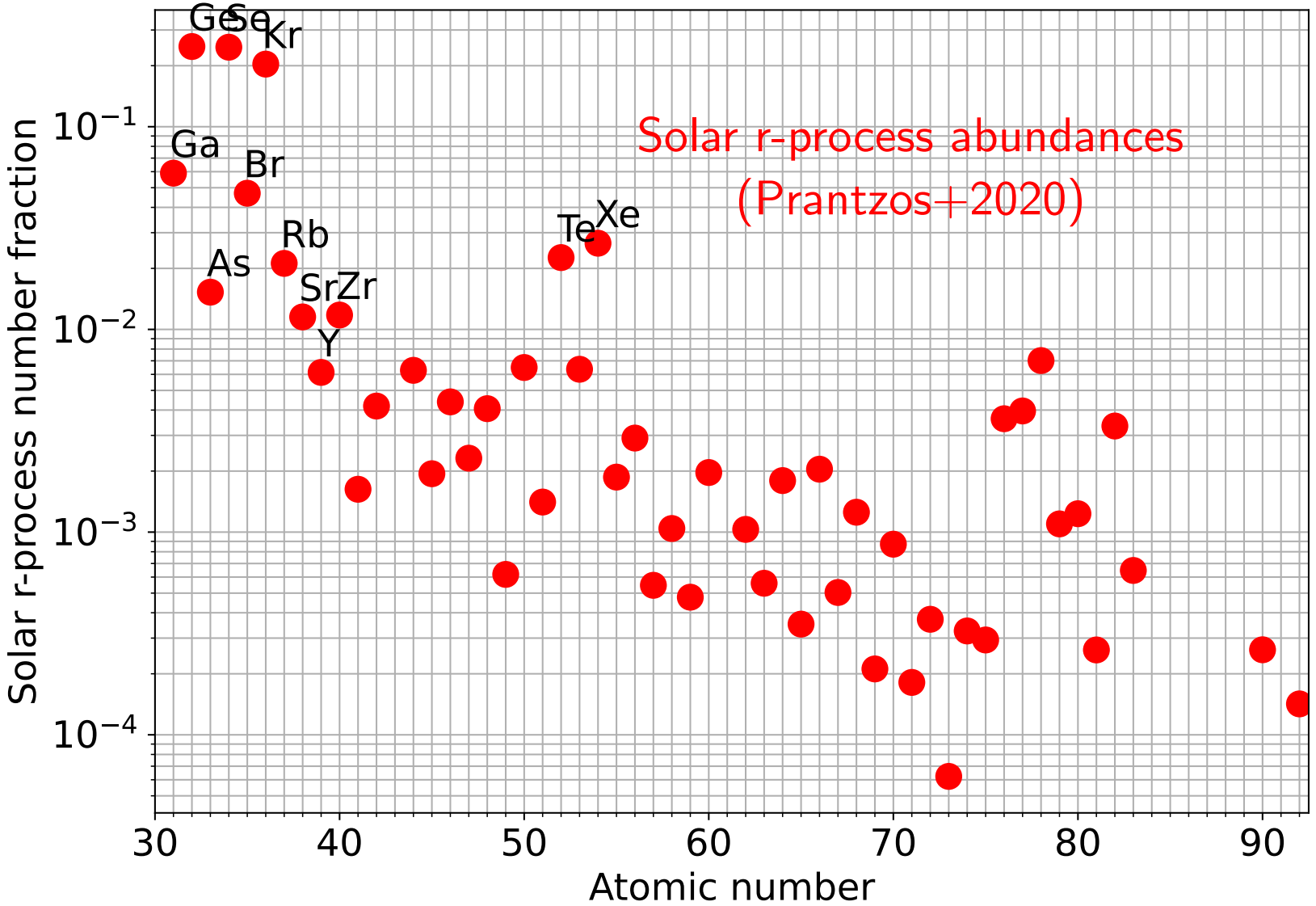
$\rightarrow$ **fluorescence important**.

KN spectral synthesis modelling



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

Nebular emission $\propto$ abundance $\rightarrow Z = 30 - 40, 52, 54$ good search targets



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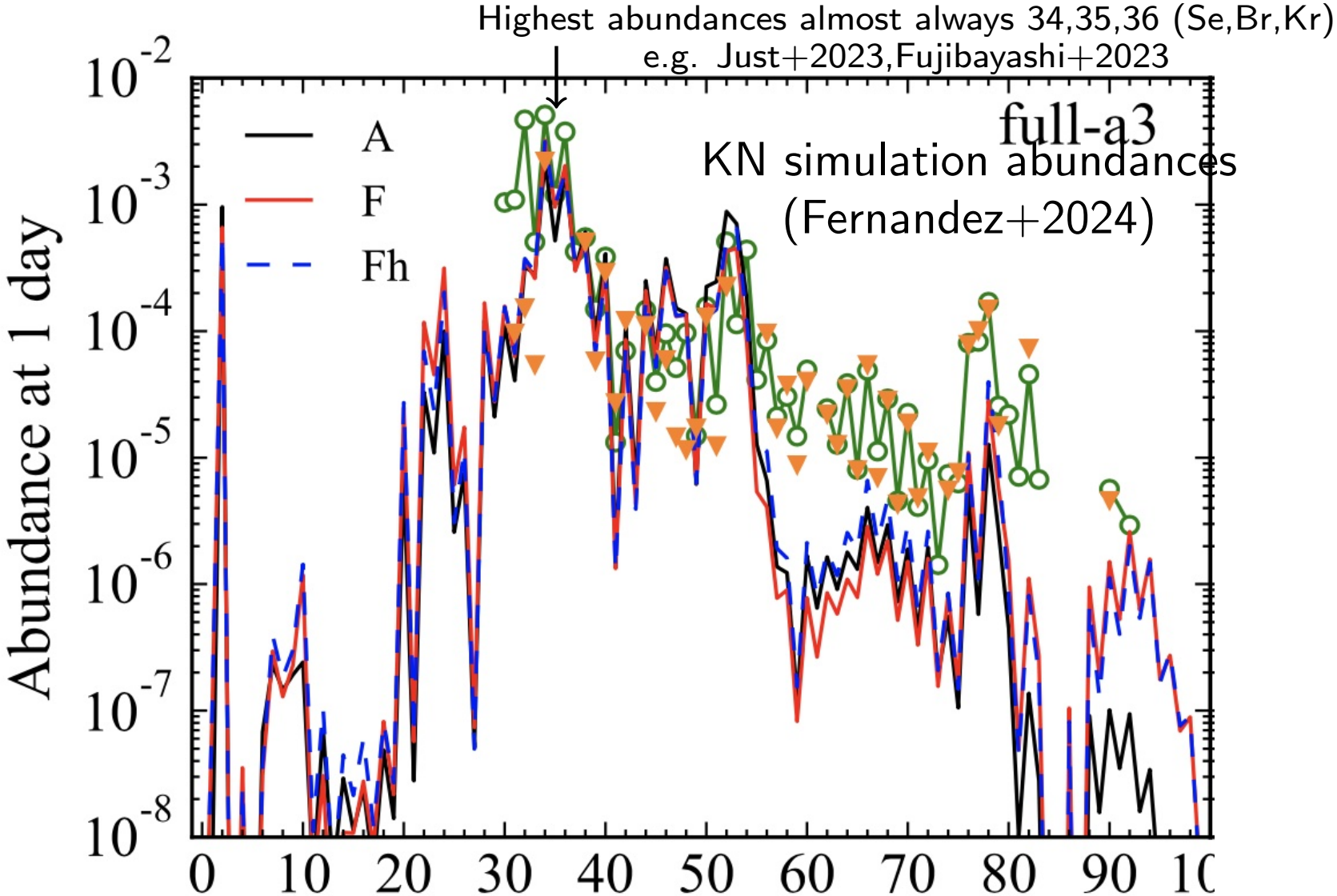
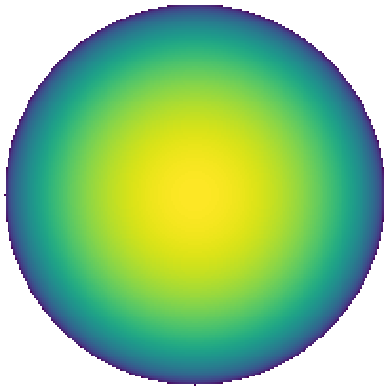


IR line modelling : ejecta model

AJ+ in prep.

Parameters:

$\boldsymbol{M_{ejecta}}$, density power law $\boldsymbol{alpha}$, $\boldsymbol{v_{in}}$, $\boldsymbol{v_{out}}$
(Canonical: $\alpha = -3$, $v_{min} = 0.03$, $v_{max} = 0.3$).

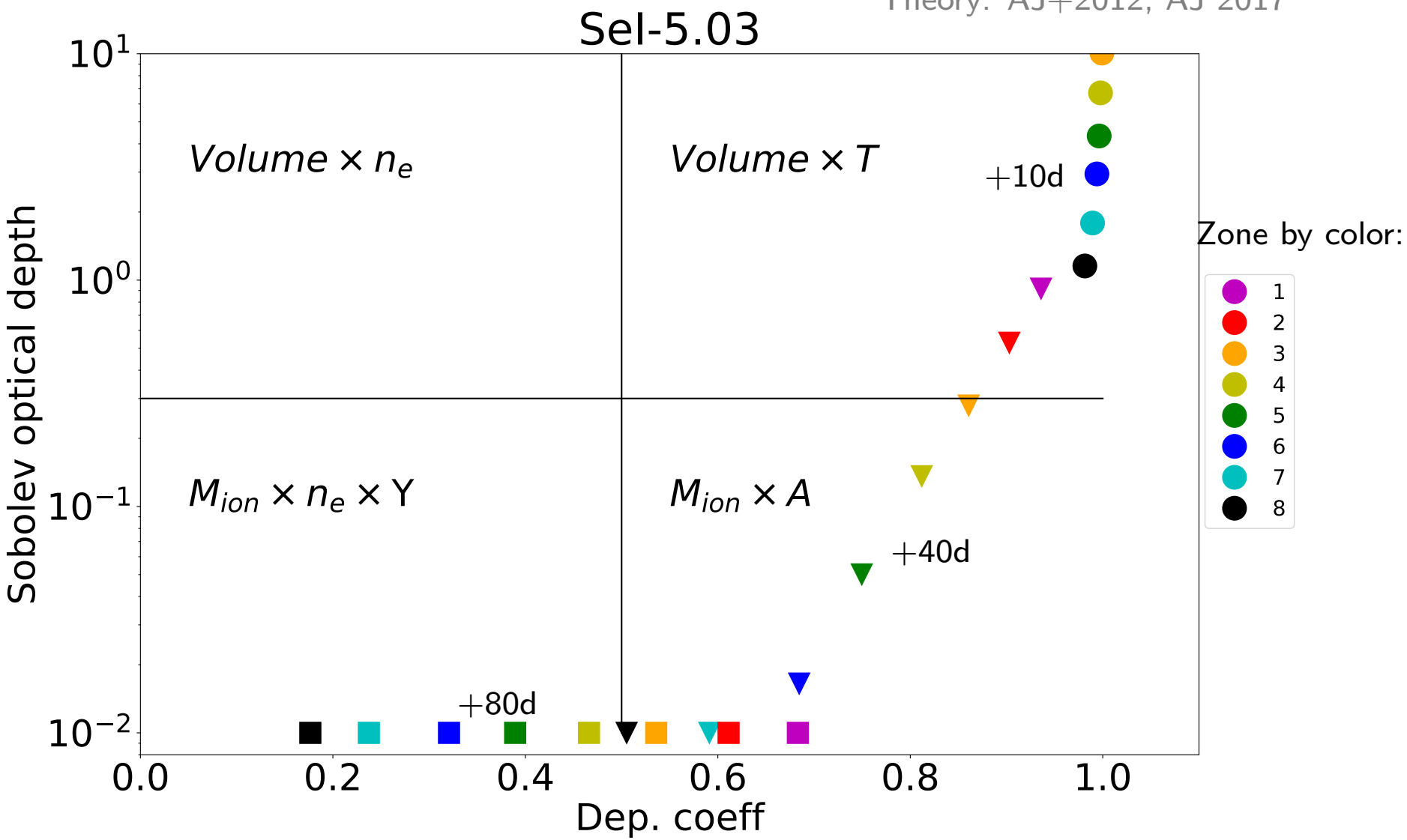


Composition: $Z = 30 - 40$ solar + 1% Fe, Co, Ni.

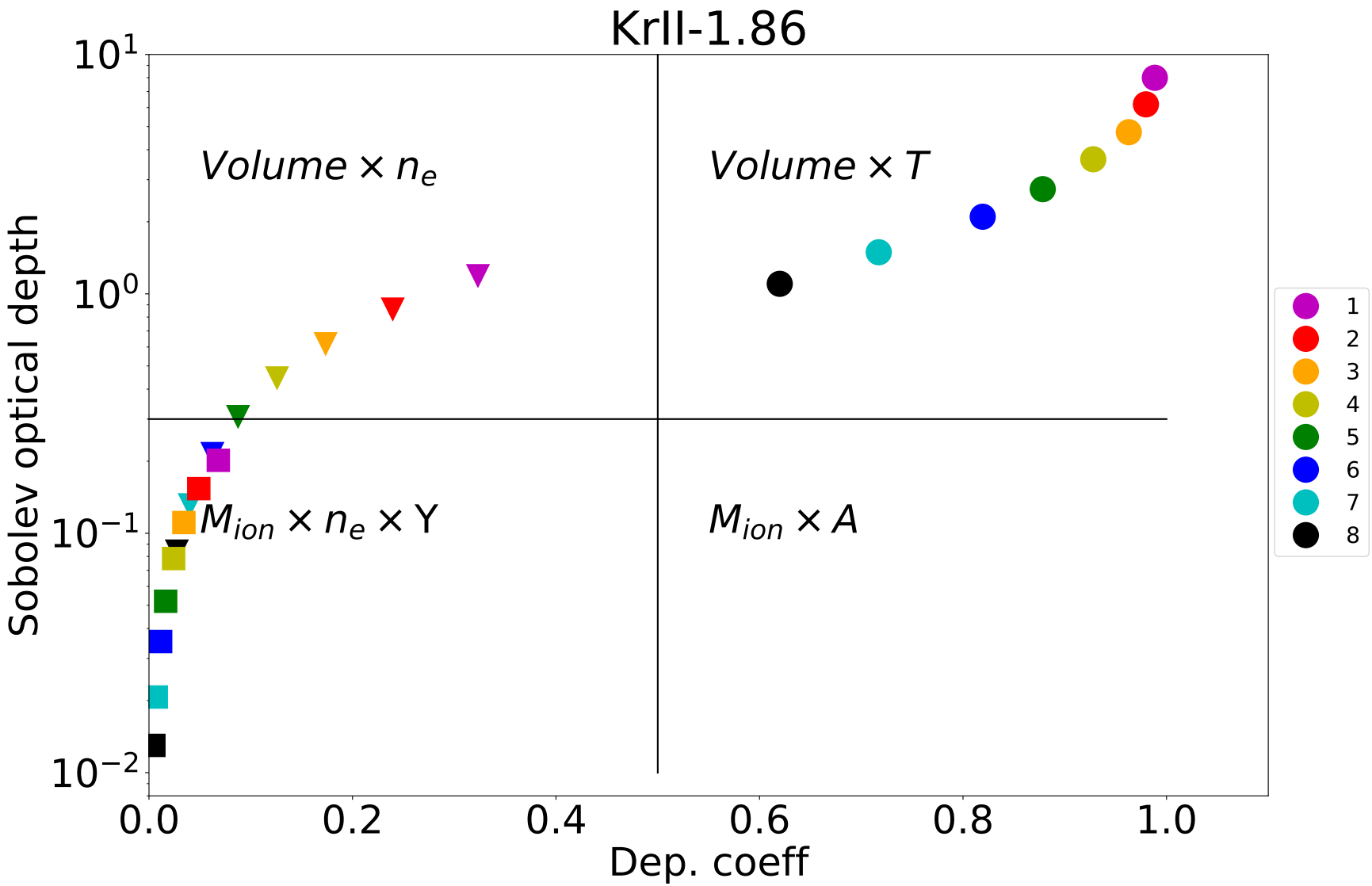
- Energy levels and lines in ground multiplets corrected to NIST.
- Accurate recombination rates for Se, Br, Kr, Rb, Sr, Y, Zr (Sterling 2011, Banerjee,AJ+2024,), lacking 31-33.
- Accurate coll. strengths for Se III, Se IV, Kr III, Kr IV, Rb IV, Sr II, Y II, Zr IV (Schöning+1997, Sterling+2016, Sterling+2017, Mulholland+2024). About 40% completeness for potential IR lines.
- Baseline radioactive decay from Wanajo 2014, analytic time-dependency (Kasen+2019), detailed channels (AJ 2011, Pognan+2022).

IR emission line domains

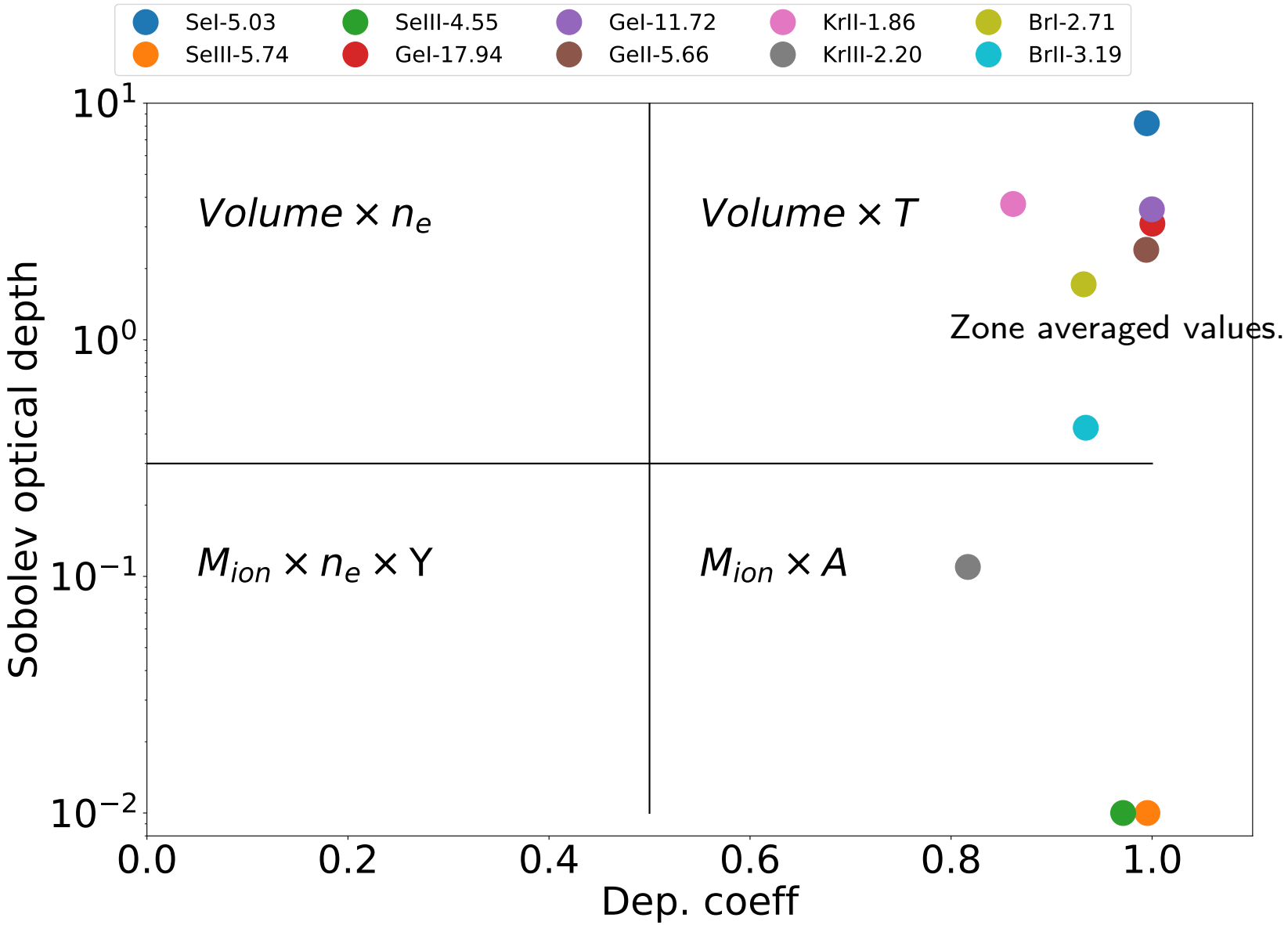
Theory: AJ+2012, AJ 2017



IR emission line domains

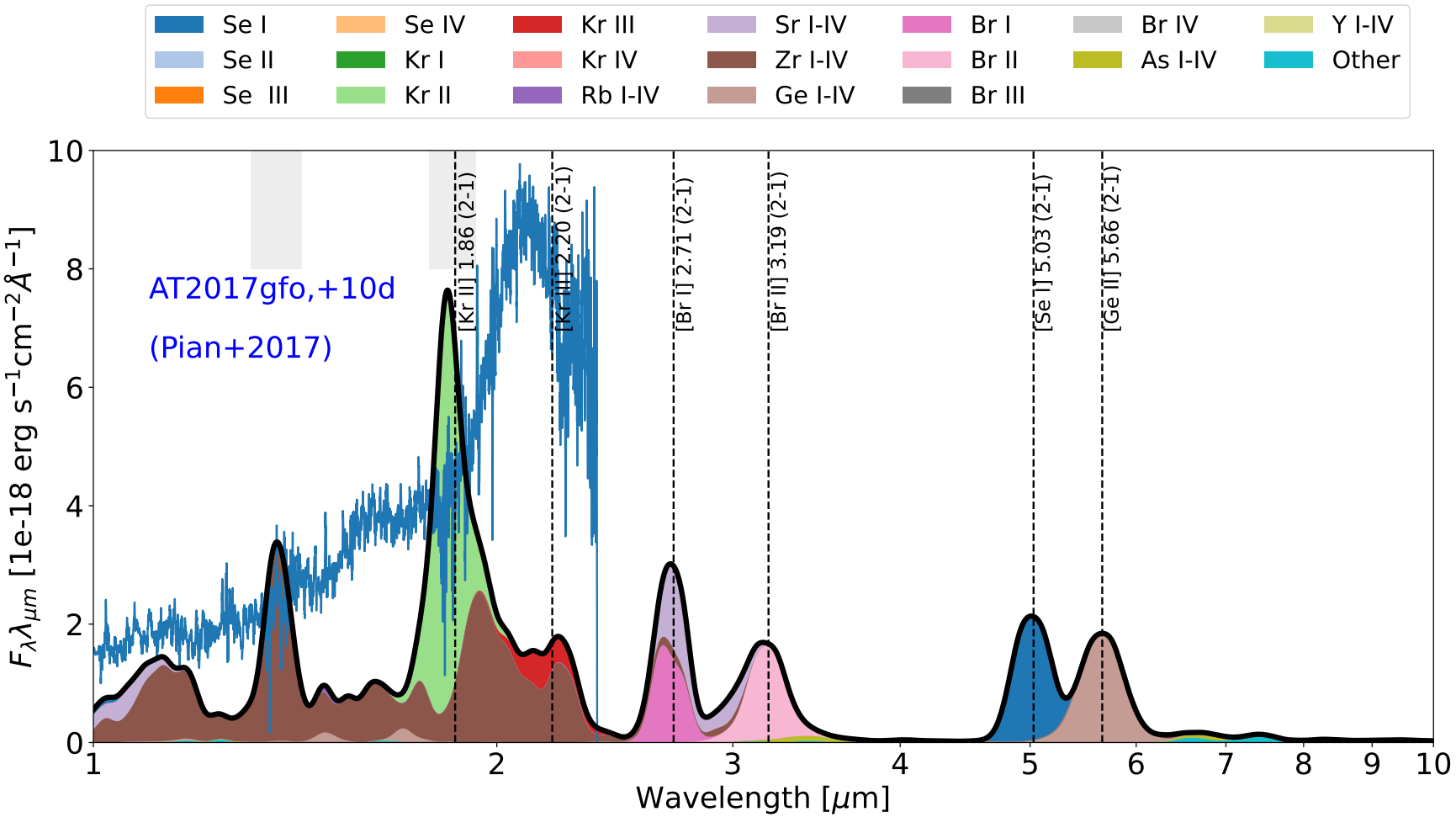


IR emission line domains



IR spectral signatures, $Z \leq 40$

+10d



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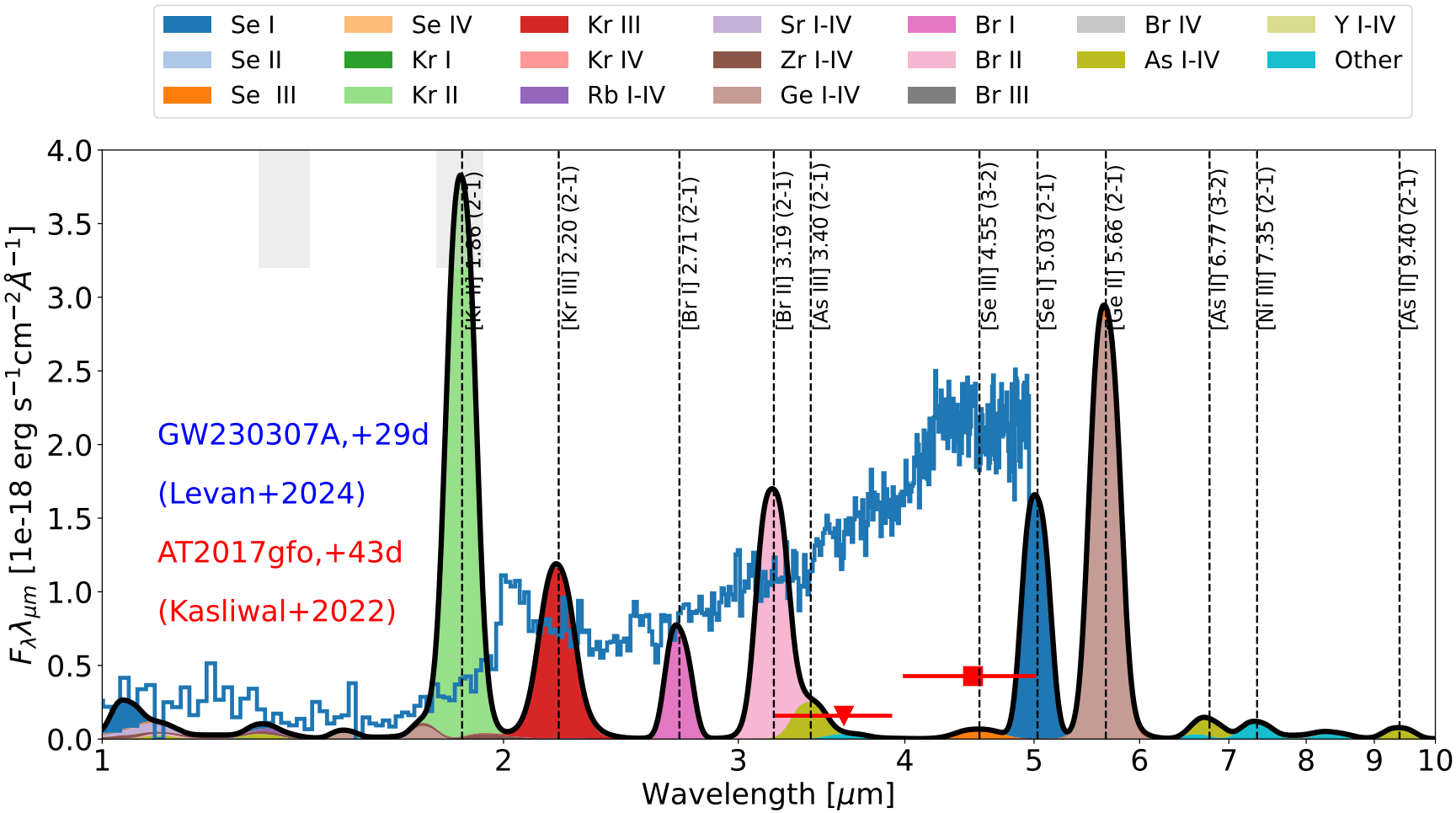
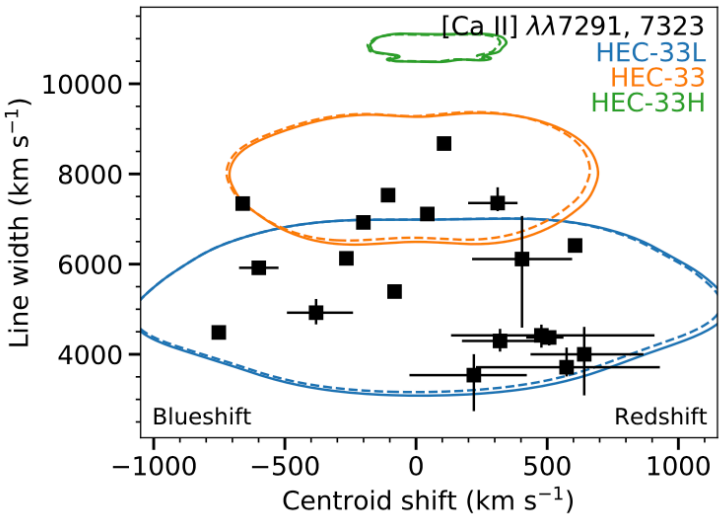
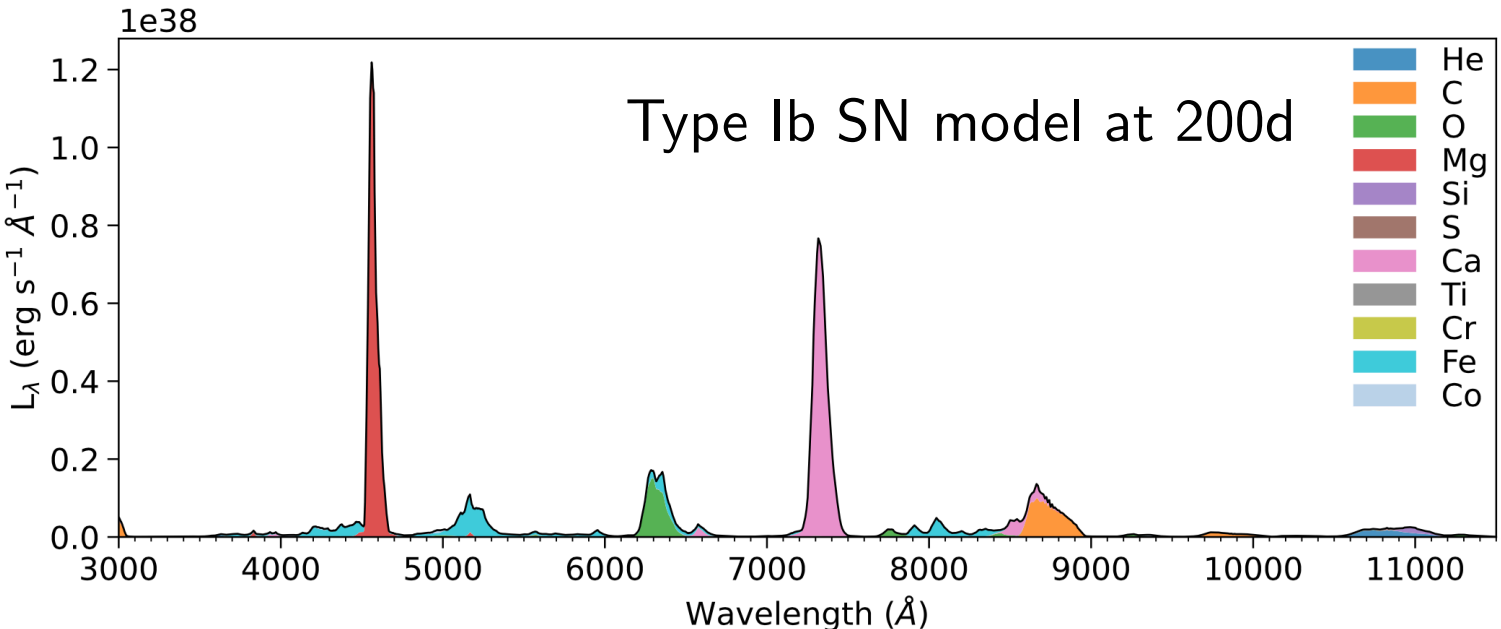


EXTRASS - NLTE spectral synthesis in 3D

AJ+2020,vanBaal+2023,2024, 2025 in prep, Vilagos, in prep.

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





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.).
  - **Selenium** is only good $Z \leq 40$ candidate for the 4.5 μm flux in AT2017gfo - but in NLTE models [Se I] 5.03 μm dominates over [Se III] 4.55 μm (Hotokezaka+2022).
  - **Missing krypton?** Kr has high abundance and makes strong lines not observed in either AT2017gfo or AT2023.
  - Models predict diagnostic MIR signatures of e.g. **Ge**, **As** and **Br**, probable with JWST.

Thank you for listening.