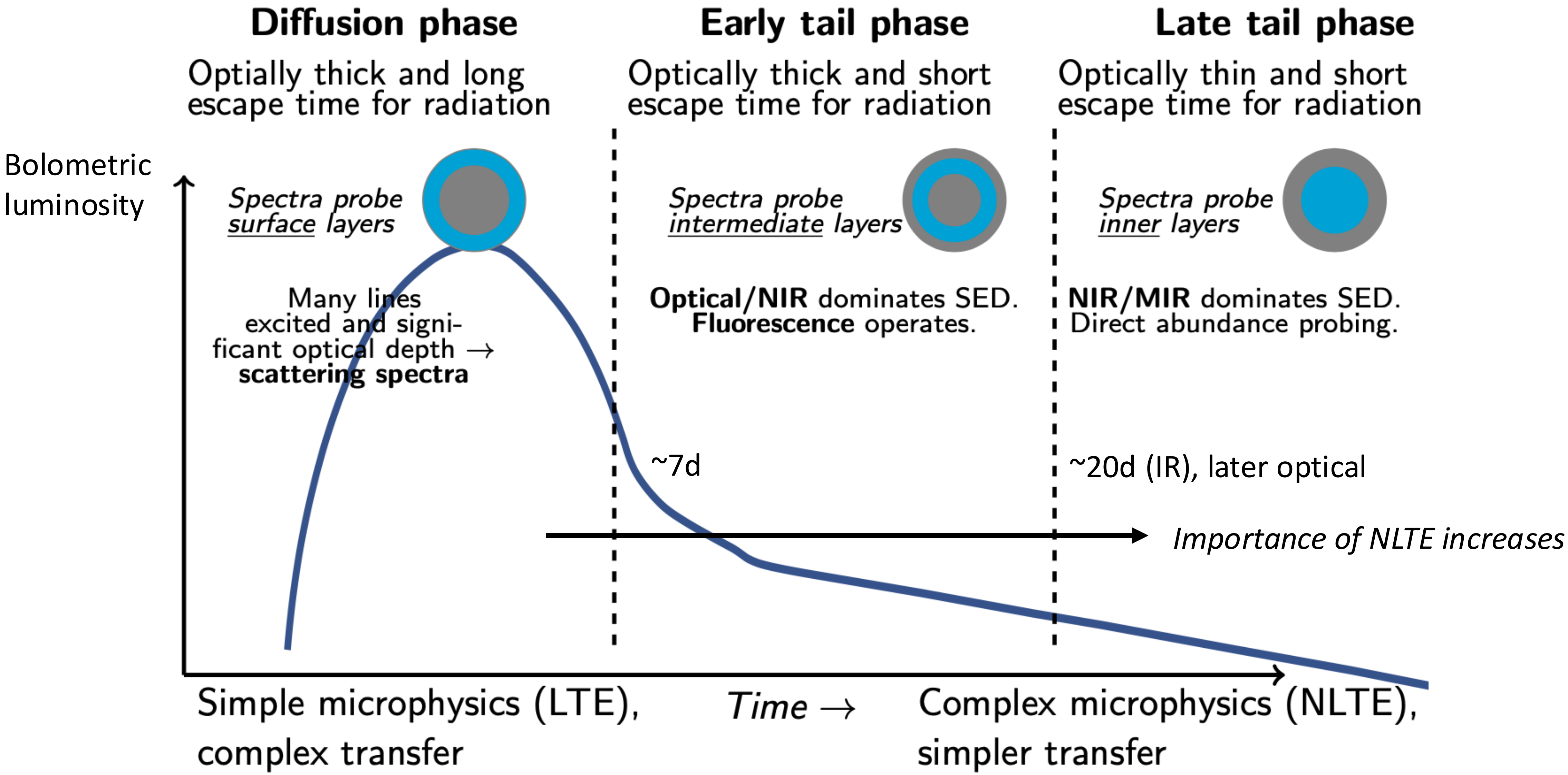
Spectral synthesis modelling of kilonovae

Anders Jerkstrand, Stockholm University

with Quentin Pognan, Smaranika Banerjee, Jon Grumer, Blanka Vilagos, Bart van Baal + more

European Research Council

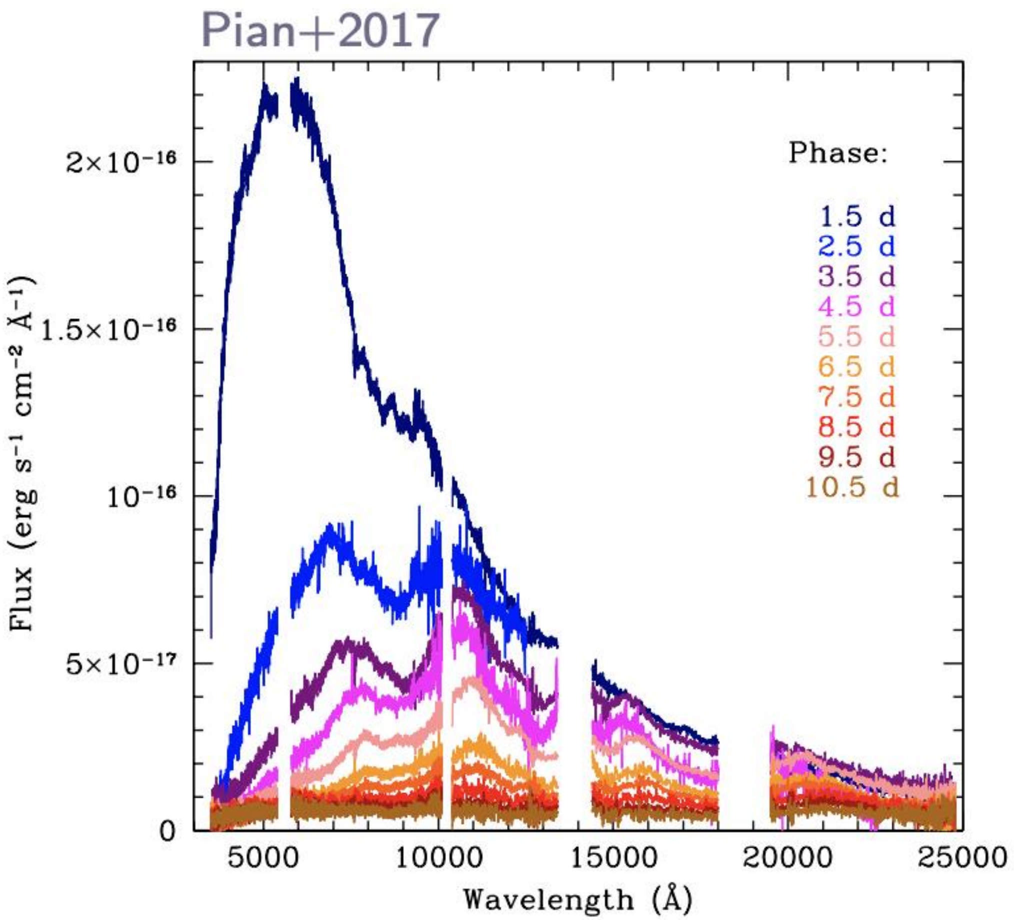
Knut and Alice Wallenberg Foundation



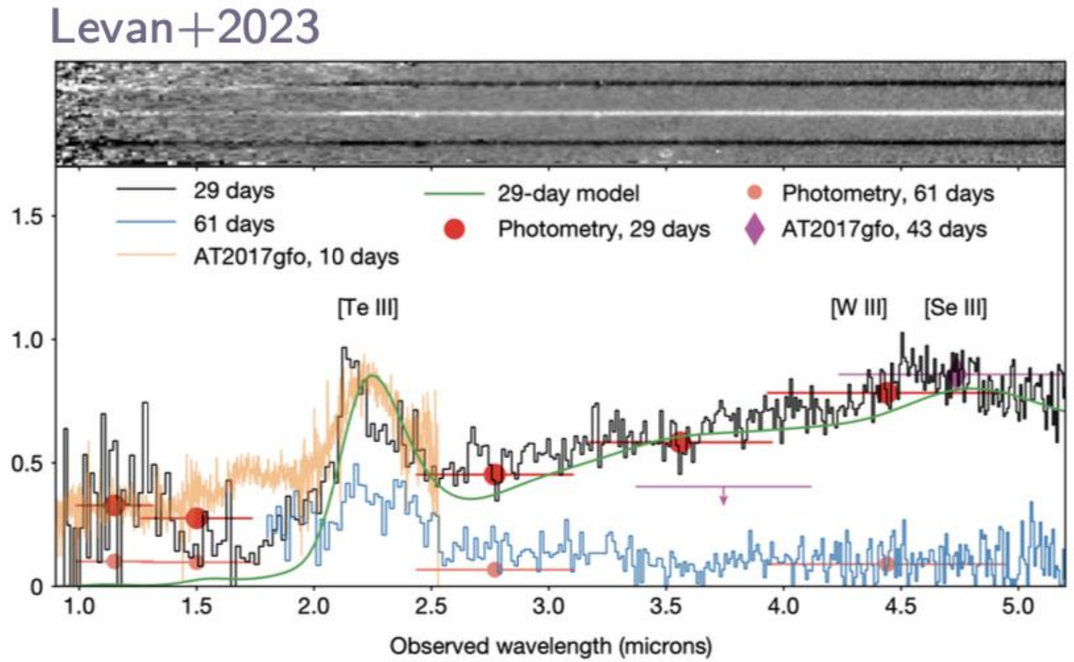
Reviews: Sim 2017 (Handbook of SNe) Jerkstrand 2017 (Handbook of SNe), 2025 (LRCA)

The phases are difficult to discern from spectra due to **many active lines** and **high velocities** → blending.

AT2017gfo



AT2023vfi



LTE assumes excitations/deexcitations and ionization/recombination dominated by

1) Interaction with thermal electrons
2) Interaction with black-body photon field

(1) Breakdown for excitation occurs e.g. when

n_e C_down(T) <~ A --> **n_e <~ 10^7 * (A / Upsilon) cm^{-3}**

Take Upsilon ~ 1 --->

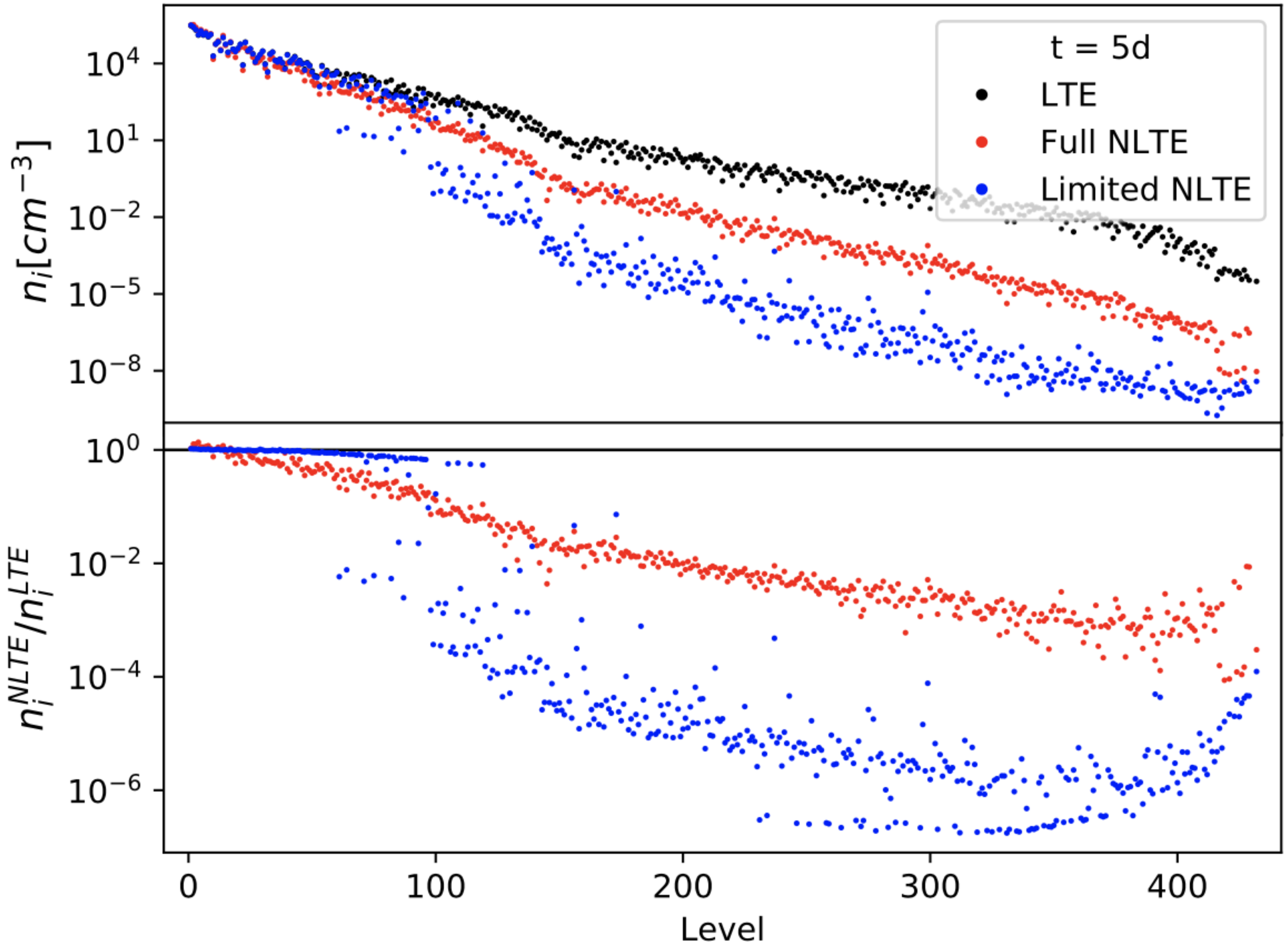
- **Levels with allowed transitions (A ~ 10^8 s^{-1}) are never in LTE.**
- **Levels with forbidden transitions (A <~ 1 s^{-1}) go into NLTE after some time (~days/weeks). (n_e ~ t^{-3})**

LTE assumes excitations/deexcitations and ionization/recombination dominated by

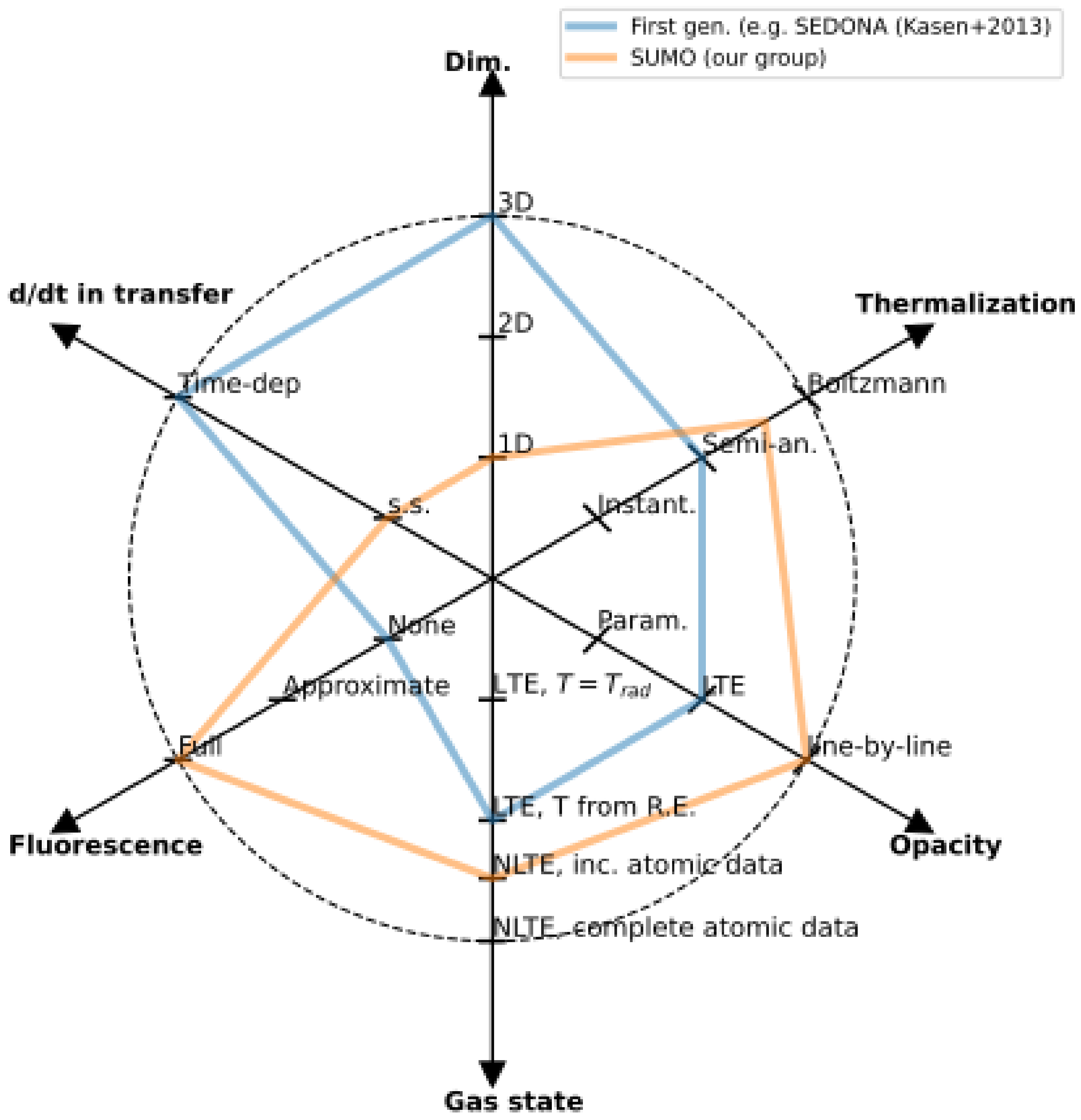
1) Interaction with thermal electrons

2) Interaction with black-body photon field

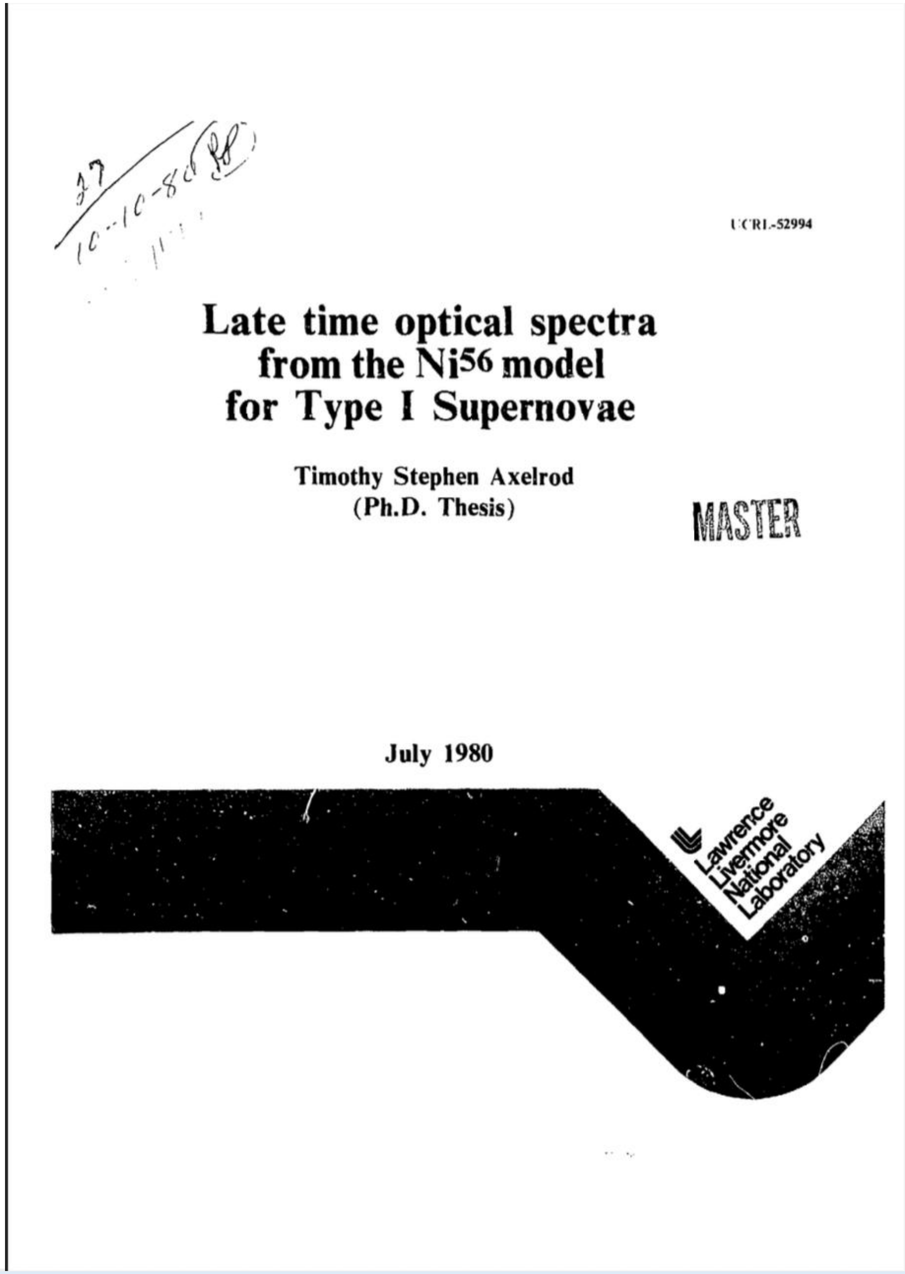
(2) Breakdown needs testing with NLTE + RT modelling



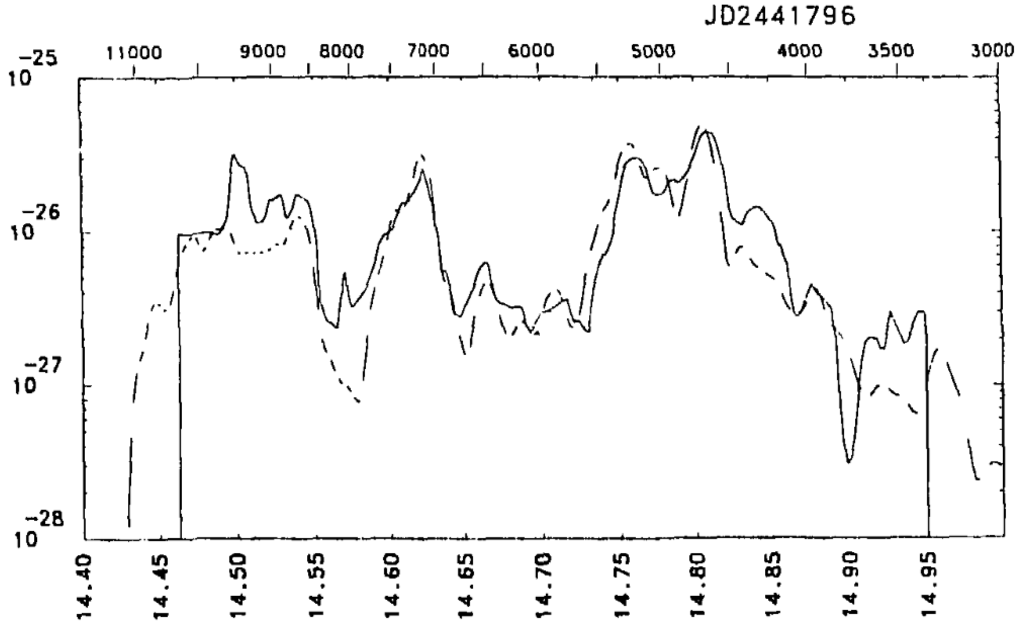
Pognan+ 2022

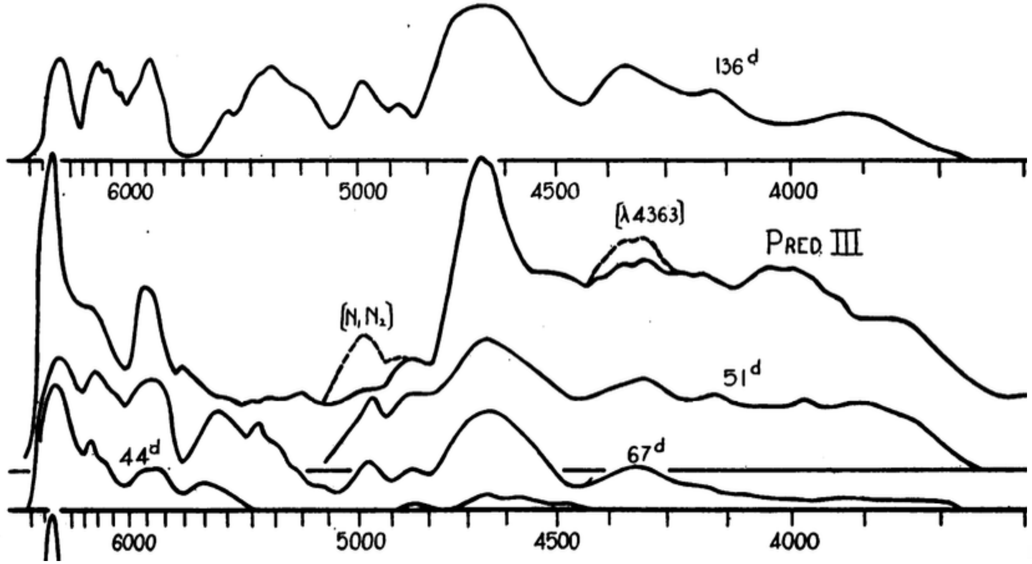


- No code does "all" → match code physics to desired thing to predict, to what accuracy.
- Pioneering LTE light curve models (Tanaka, Kasen,..) now followed by second generation of NLTE models (Hotokezaka, Pognan, AJ, ..)



- **Axelrod 1980** laid groundwork for nebular-phase physics in SNe : how energy flows from MeV radioactive decays to UV/optical/IR photons.





SYNTHETIC SPECTRA FOR SUPERNOVAE

BY CECILIA PAYNE-GAPOSCHKIN AND FRED L. WHIPPLE

HARVARD COLLEGE OBSERVATORY

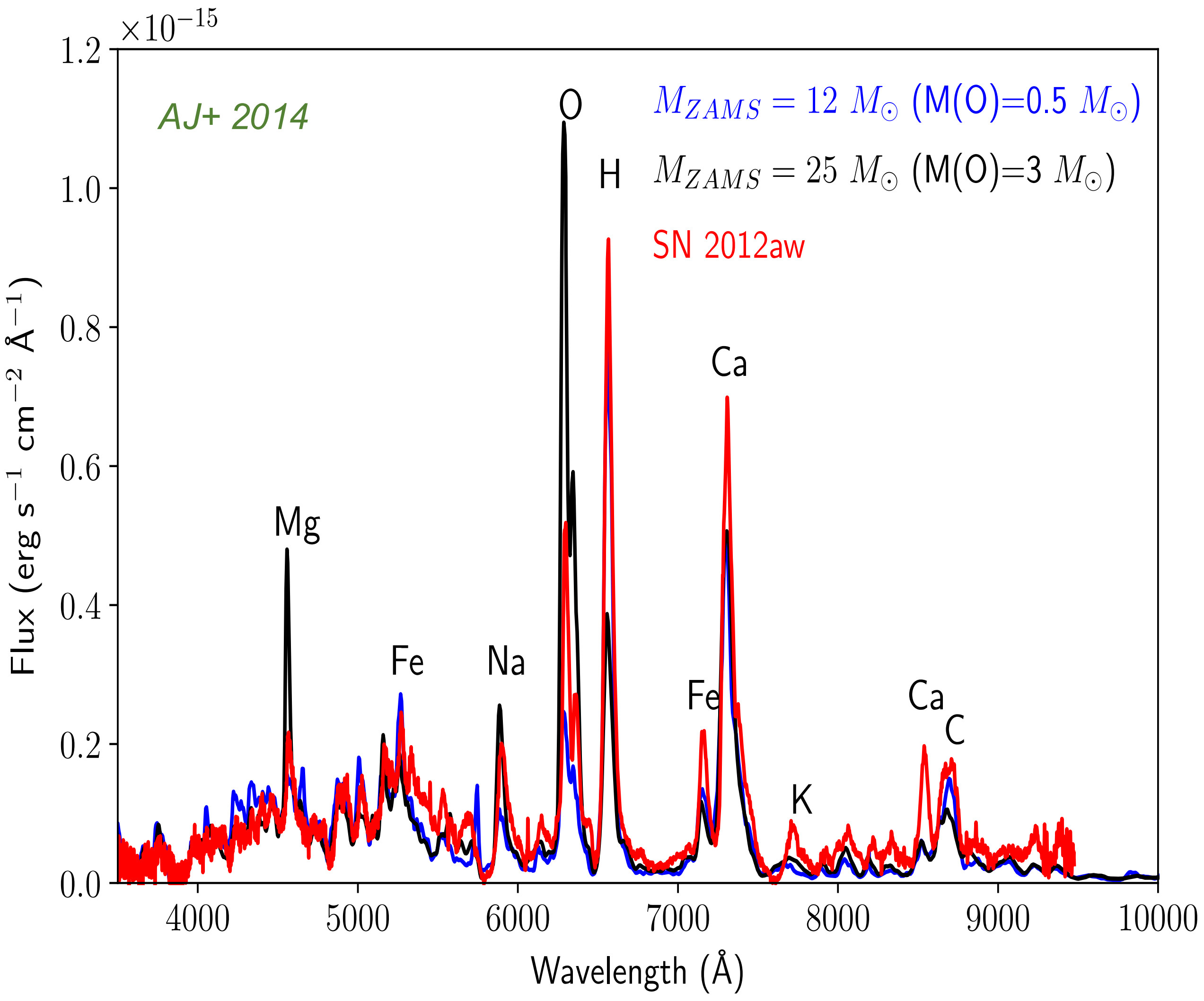
Communicated March 14, 1940

Introduction.—The excellent series of spectra of the supernovae in I. C. 4182 and N. G. C. 1003, published by Minkowski,[1] present for the first time a basis for a quantitative interpretation. Eight typical spectra, showing the major stages of the development during the first two hundred days, are shown in figure 1; they are directly reproduced from Minkowski's microphotometer tracings, with some smoothing for plate grain. The pre-maximum spectra (which show few features in addition to an apparent continuum) and the very late spectra (more than two hundred days after maximum) are not represented. Since all supernovae apparently show nearly identical spectral changes,[2] this series can be considered as representative of all, both with regard to the essential spectral features and to changes with time. The broad features in the blue-violet region appear to shift to the red with time, while the features in the red region show variations but no systematic shift in wave-length.

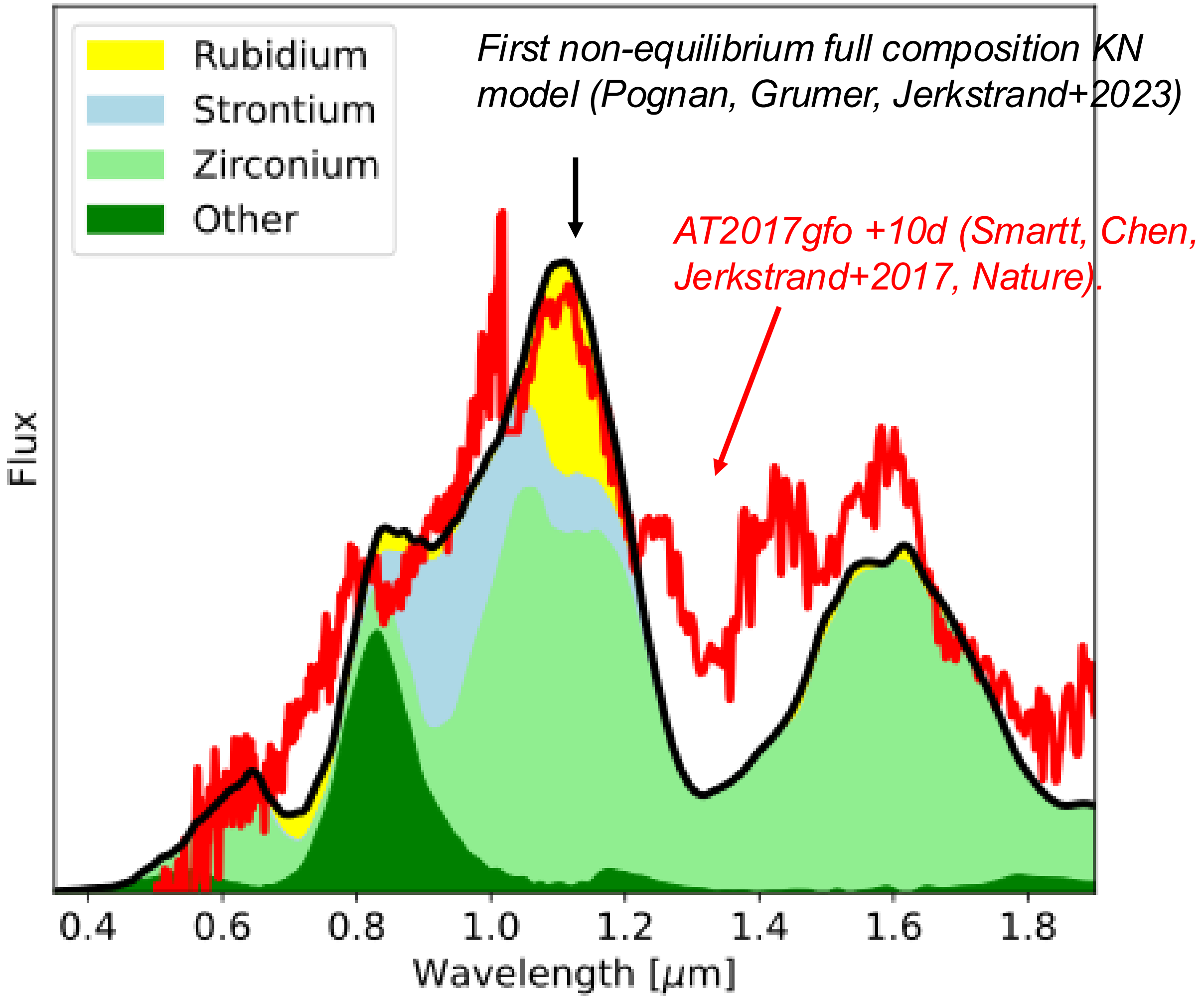
THE SUMO CODE

Non-thermal physics	Full steady-state Boltzmann solver for 1 ev – 3 keV range	Kozma & Fransson 1992, AJ+2012
Radiative transfer	Line-by-line, hybrid ray-tracing/Mont Carlo scheme with full fluorescence	AJ+2011,2012
Rate equations	Full collisional-radiative matrix, Sobolev approximation	AJ+2012, Pognan,AJ+2022 (time-dep.)
Atomic data	For r-process, complete set of FAC model atoms, first 4 ionization stages. Detailed rec. rates for light rp-elements.	Pognan,Grumer,AJ+ 2023 Banerjee,AJ+2025
Chemistry	Full NLTE coupling for 4 molecules, formation by ~100	Liljegren,AJ+2020, 2023
Inner boundary power	Allow X-ray power source (e.g. magnetar/accretion disk)	Omand & AJ 2023

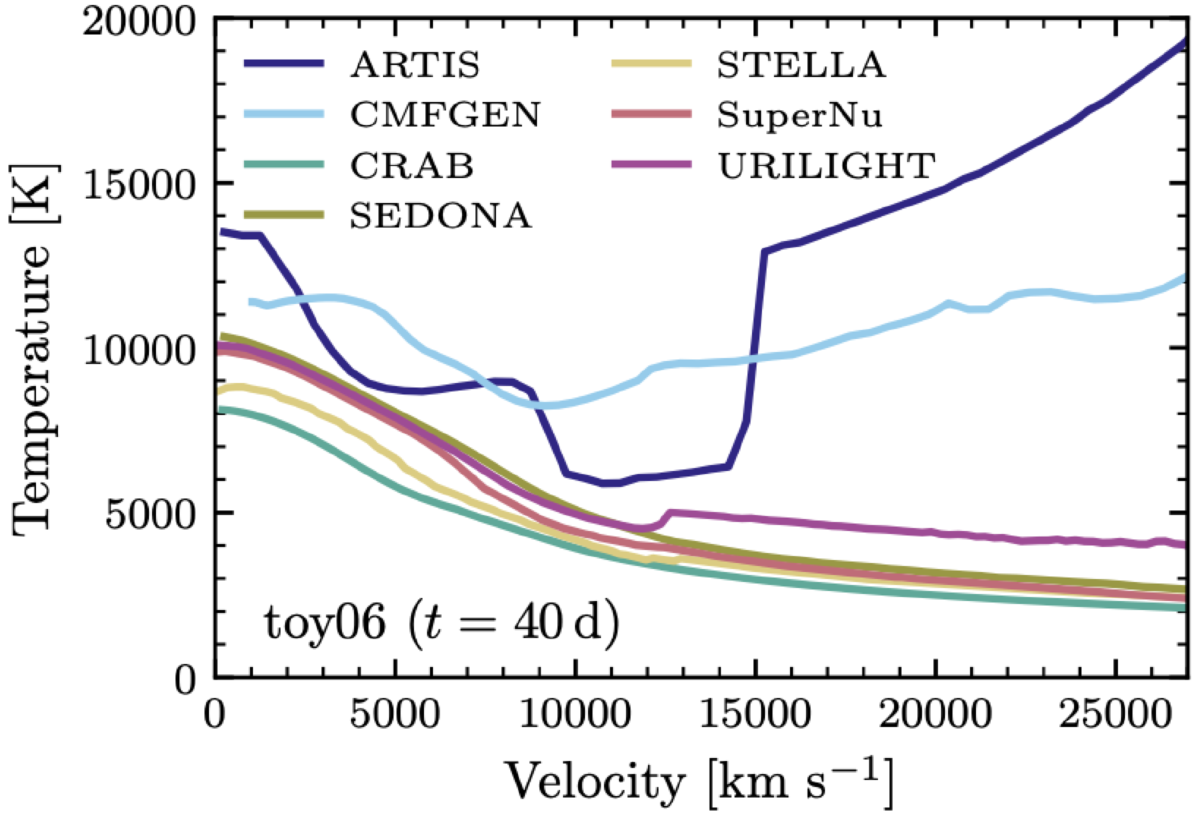
Supernova case

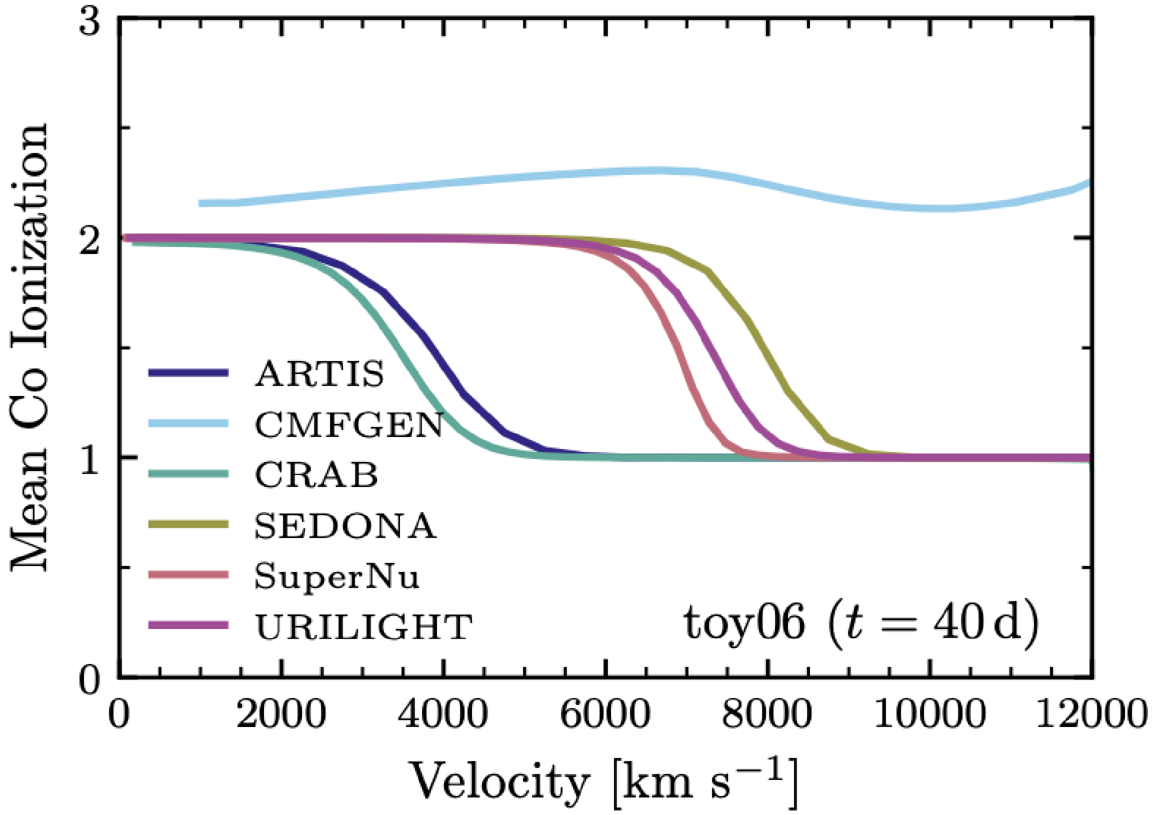


Kilonova case



Even for a “simple” toy model of a Ia SN





Blondin+2022

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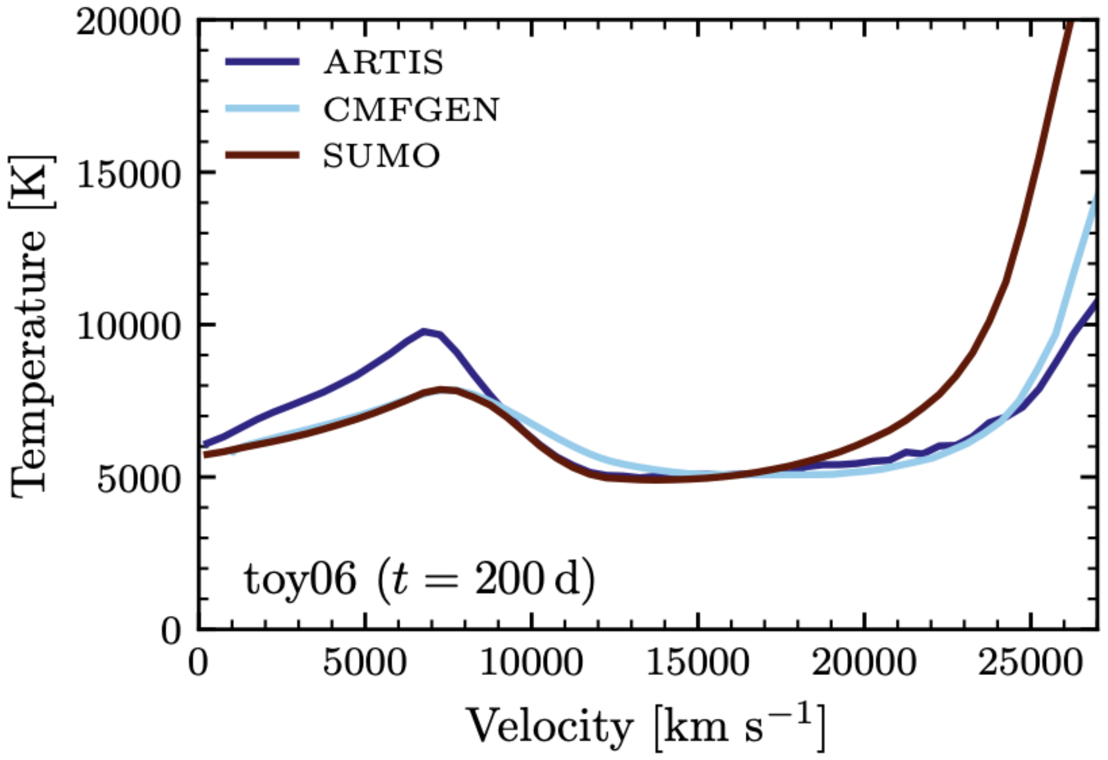
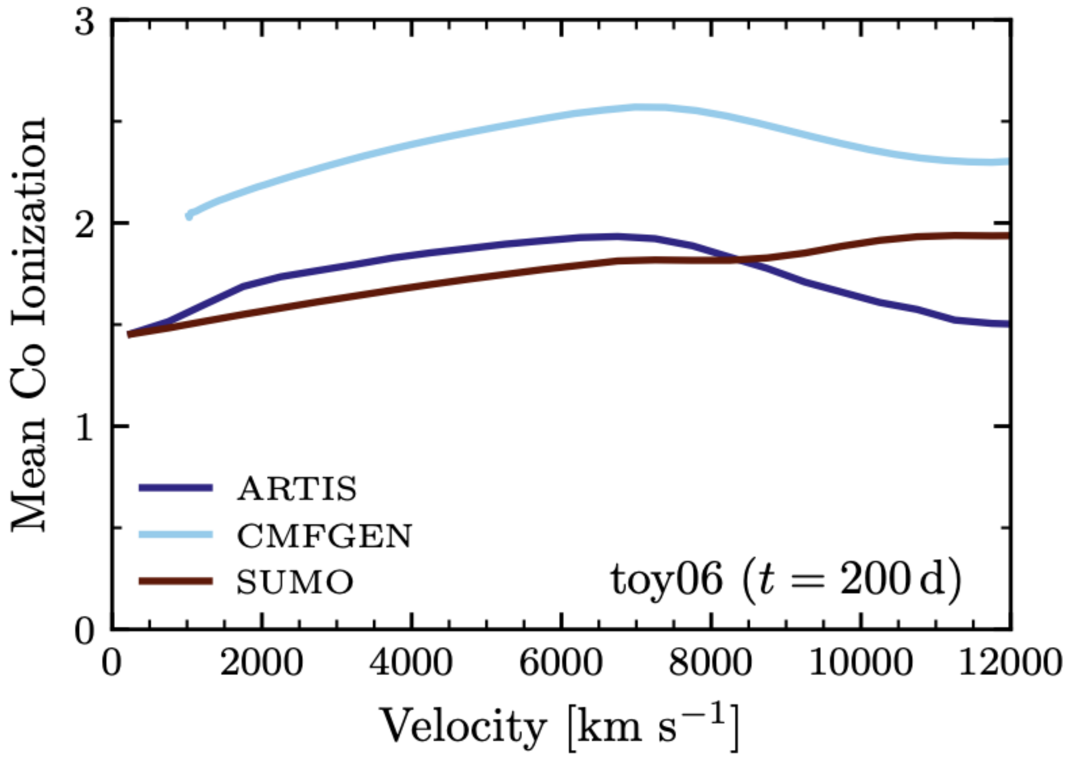




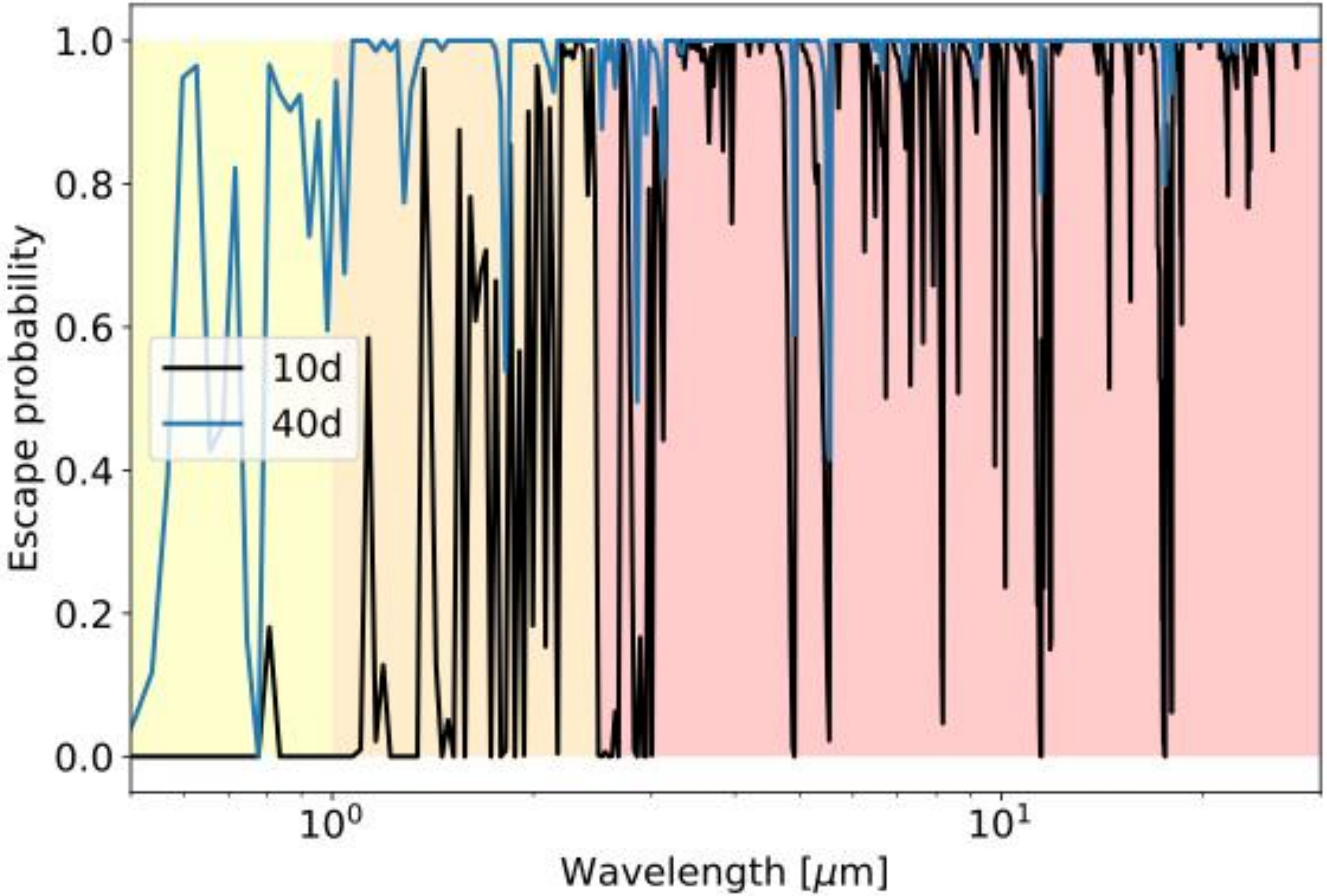
Blondin+2022

→ what’s under the hood matters and field is far from “convergence”

Using mid-infrared emission lines to diagnose KNe

AJ, in prep

1) ONLY LATE EPOCHS AND LONG WAVELENGTHS PROBE THE BULK EJECTA COMPOSITION



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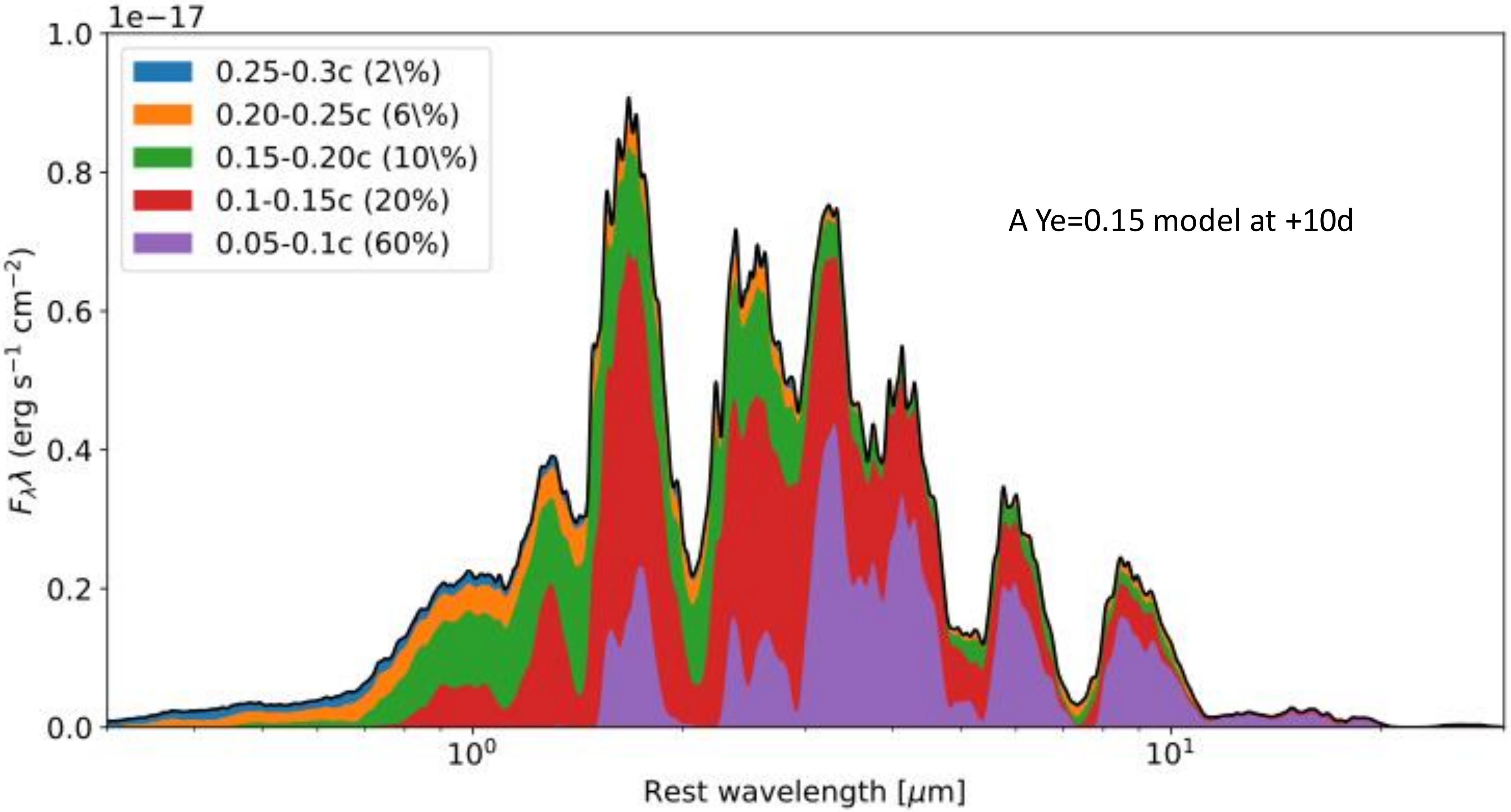
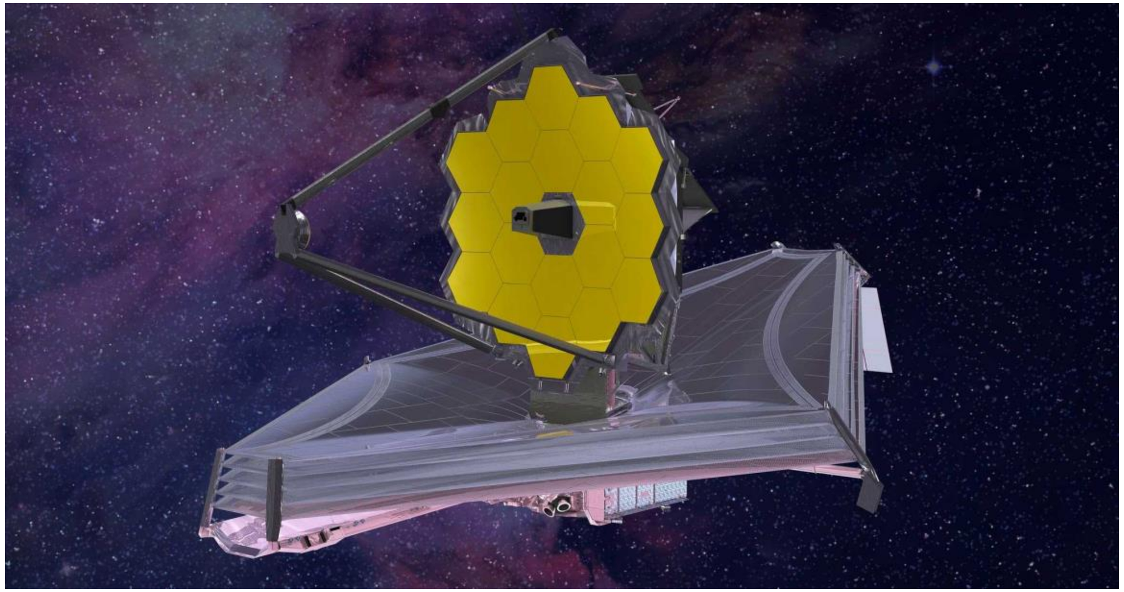


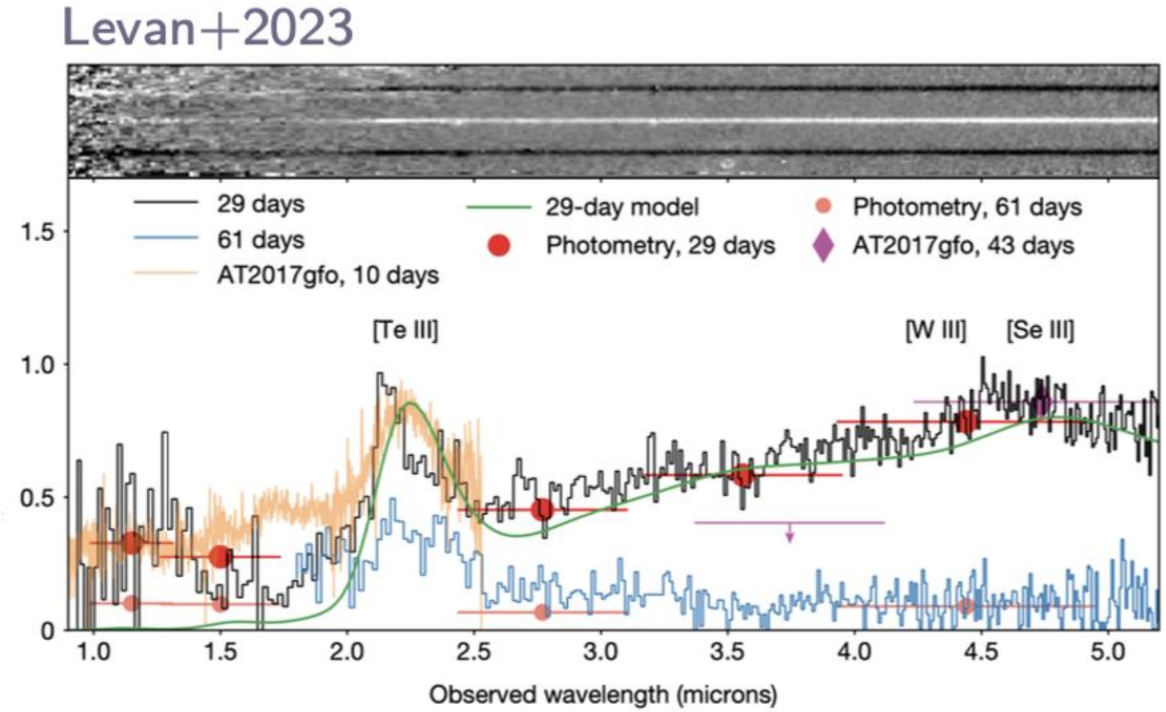
A Ye=0.15 model at +10d

2) MIR LINES REACH THE REGIME hnu <~ kT → LUMINOSITY WEAKLY DEPENDENT ON (POORLY KNOWN) TEMPERATURE

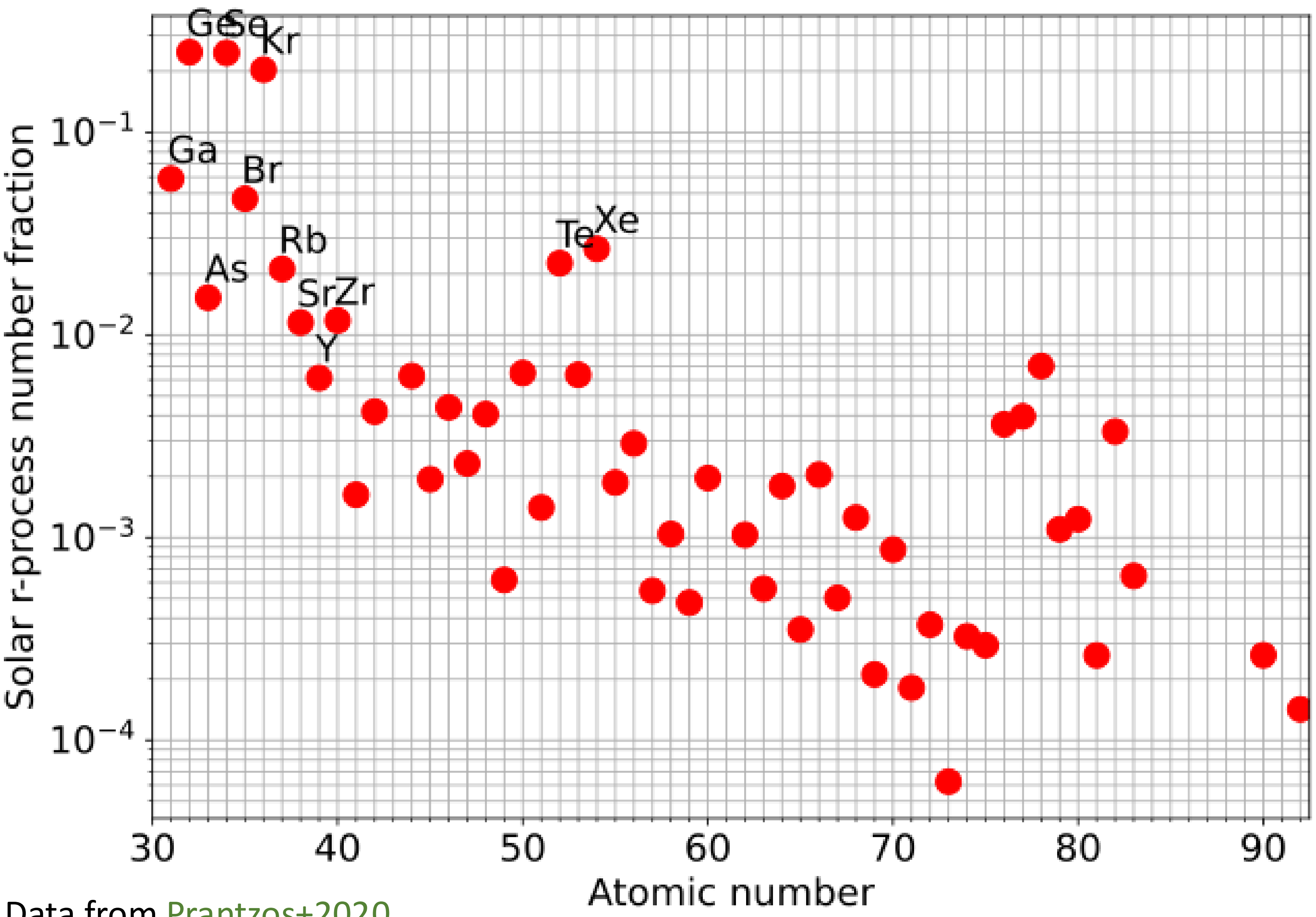
$$e^{-h\upsilon/kT} \rightarrow 1$$

2) JWST HAS VERY GOOD SENSITIVITY, IN PARTICULAR NIRSPEC INSTRUMENT (1-5 micron)



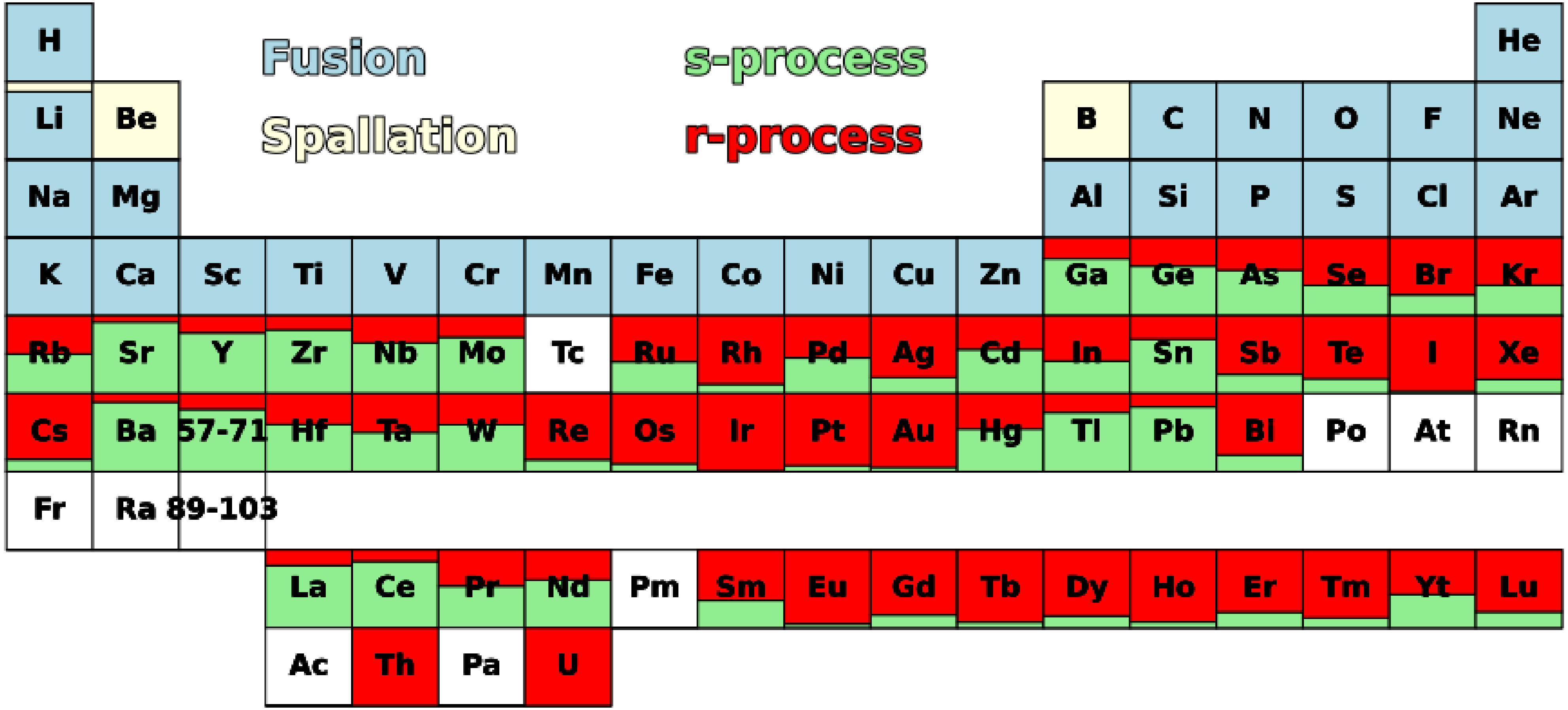


This KN at **300 Mpc** (compare 40 MPc for AT2017gfo)!



Data from Prantzos+2020

- *Do NSM make all the r-p elements?*
- In nebular phase **emission prop. to abundance** → these are good targets.
- We therefore focus our atomic data and detailed modelling efforts on these (**rec. rates**: Banerjee,AJ+2025), **collision strengths**: AJ+, in prep.)



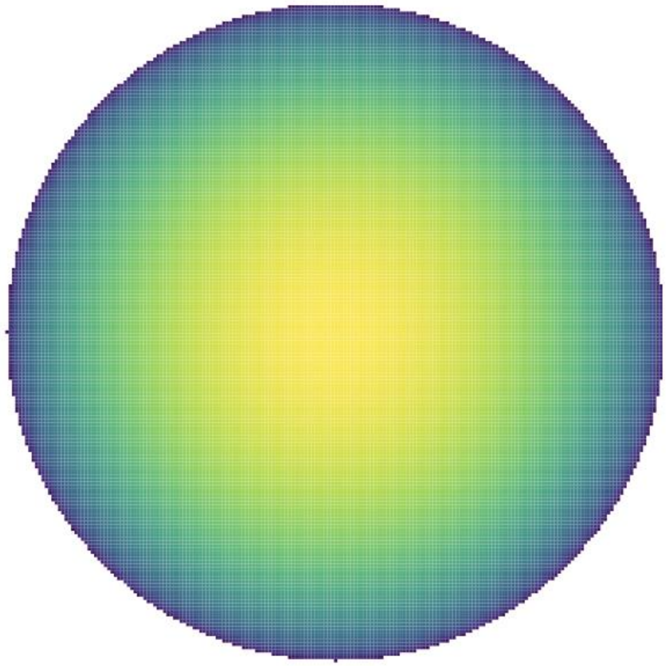
Data from Prantzos+2020

Setup:

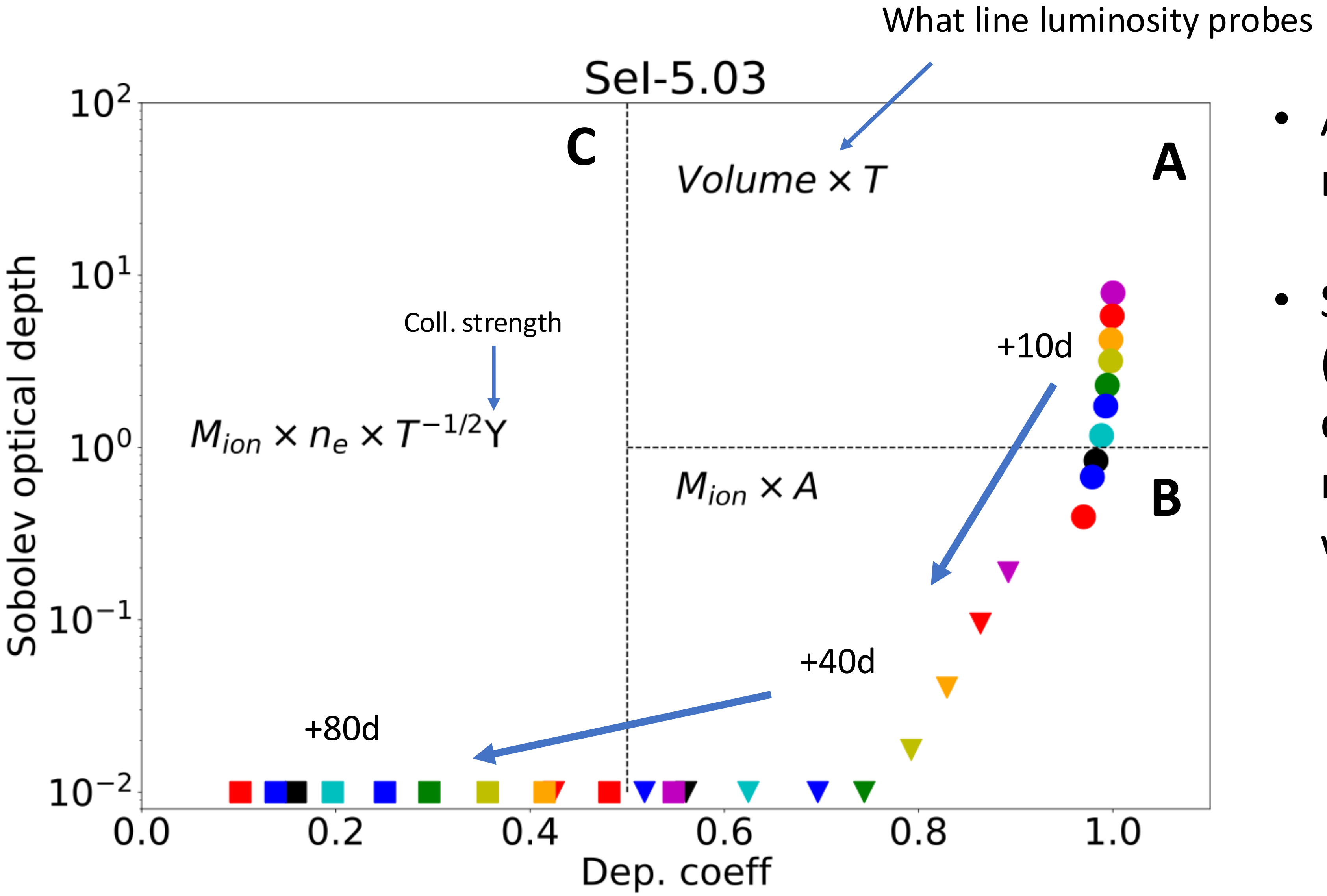
$$M_{ejecta} = 0.05\ M_{\odot}$$

$$\rho(v) \propto v^{-3}$$

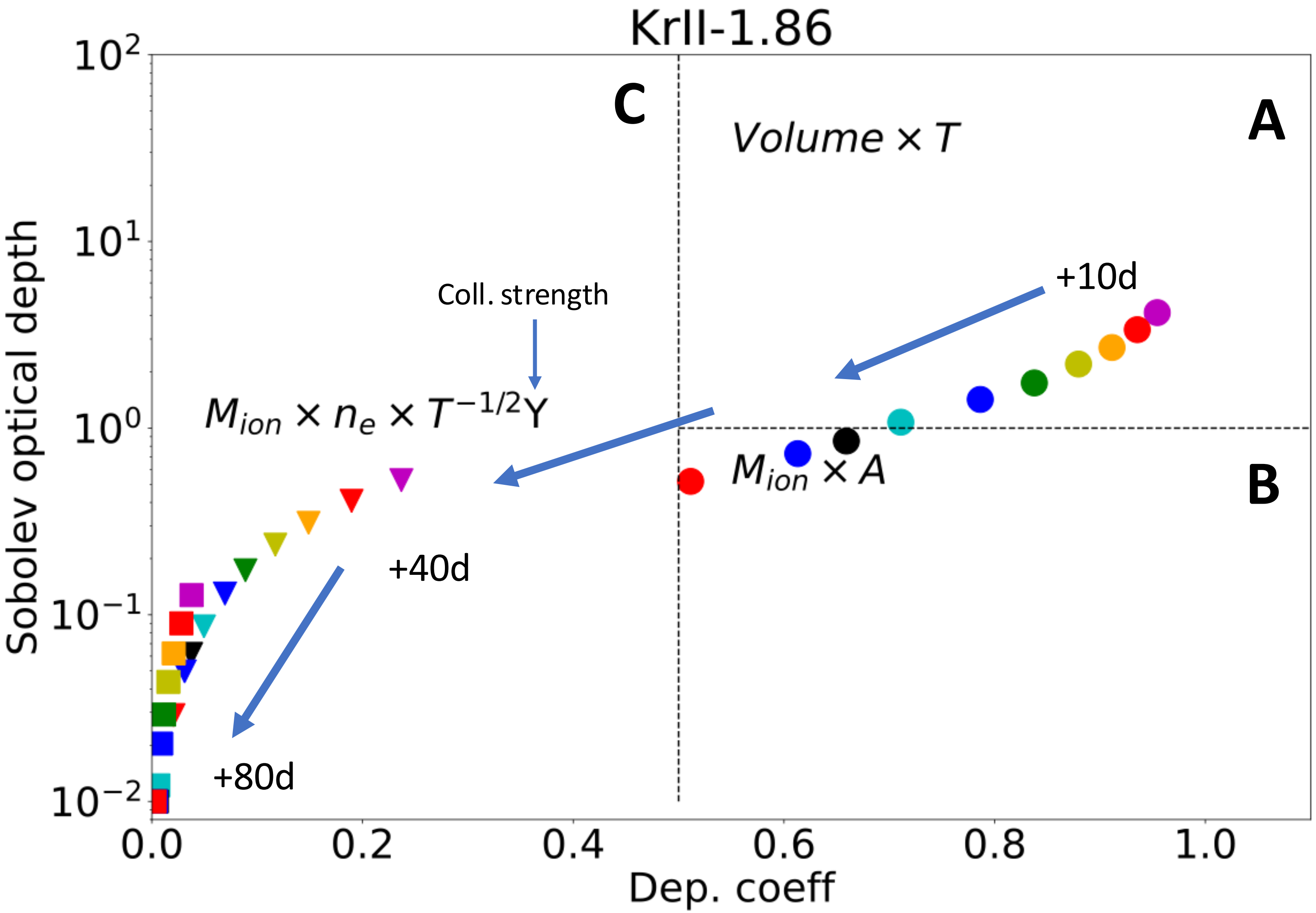
Z=30-40, 52, 54, solar composition.



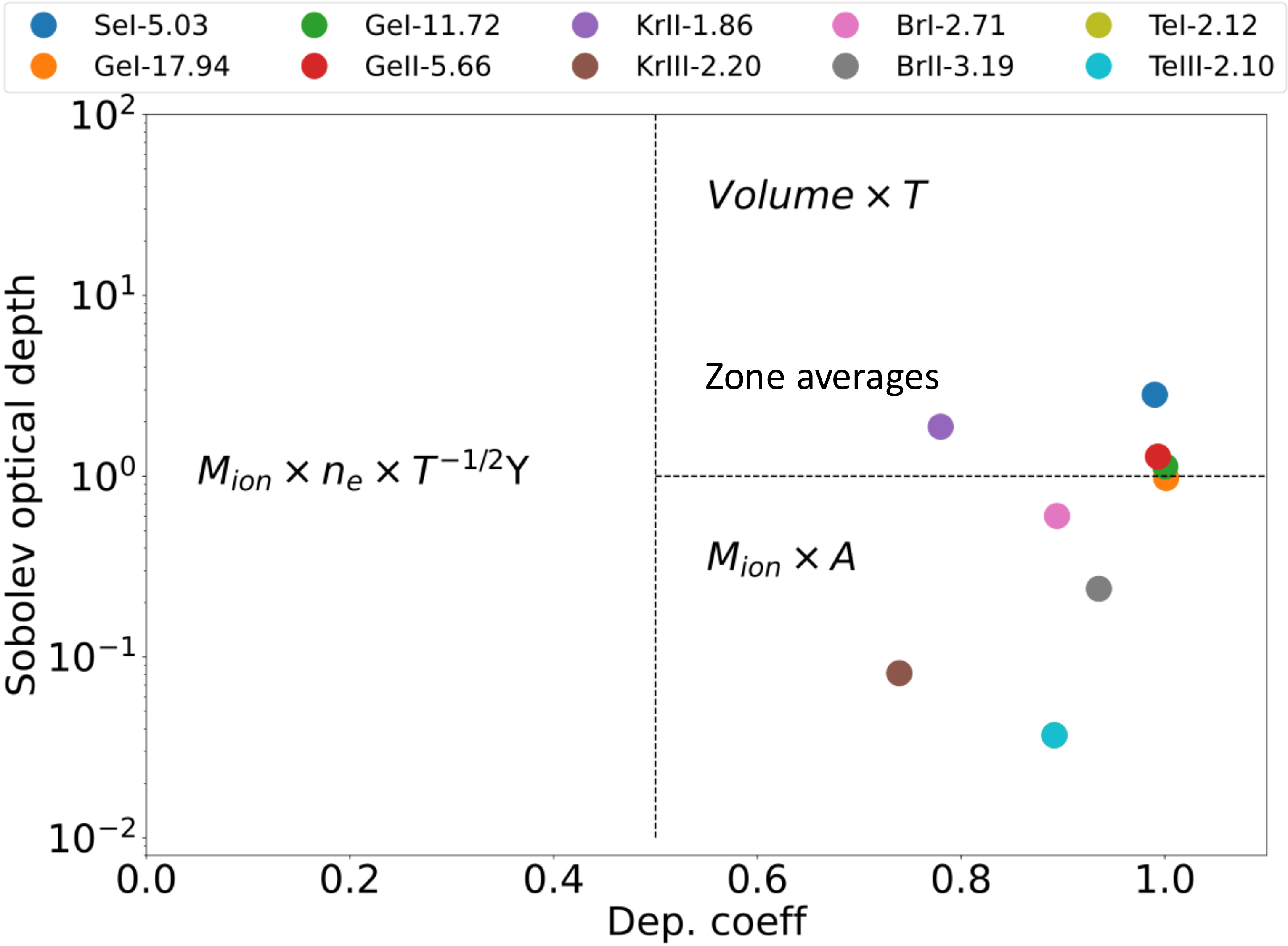
- Vary v_in & decay power



- All lines will move from regime **A** to **C** over time.
- Some will pass through **B** (the best regime to determine ionic mass) : models guide which and when.



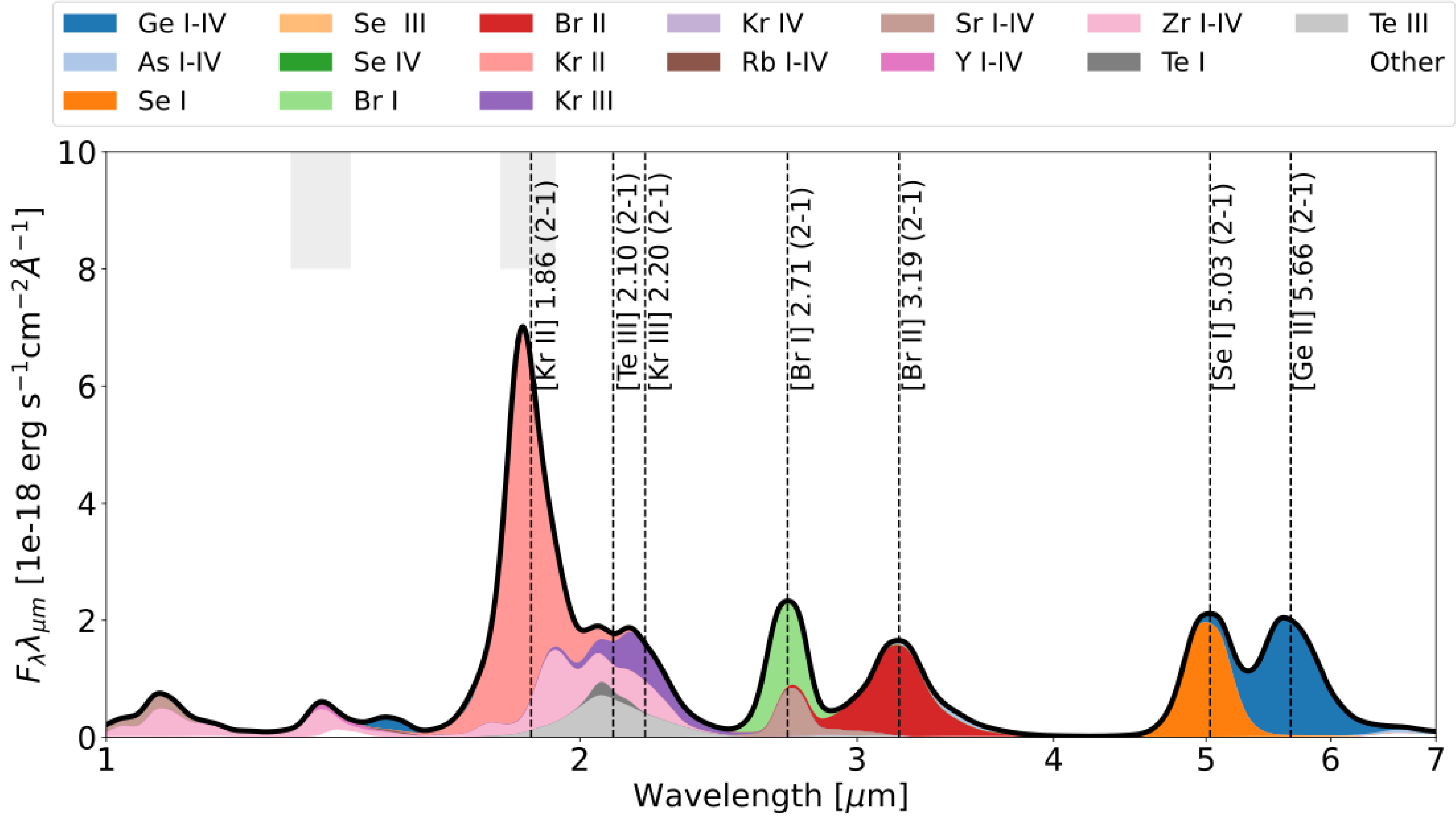
- All lines will move from regime **A** to **C** over time.
- Some will pass through **B** (the best regime to determine ionic mass) : models guide which and when.
- For lines skipping **B**, we are critically dependent on collision strengths.



- For a given epoch, models guide which lines most fruitful to observe in detail.

v_in=0.02c, low power, +10d

Strong lines from Kr, Br, Se, Ge : many non-blended



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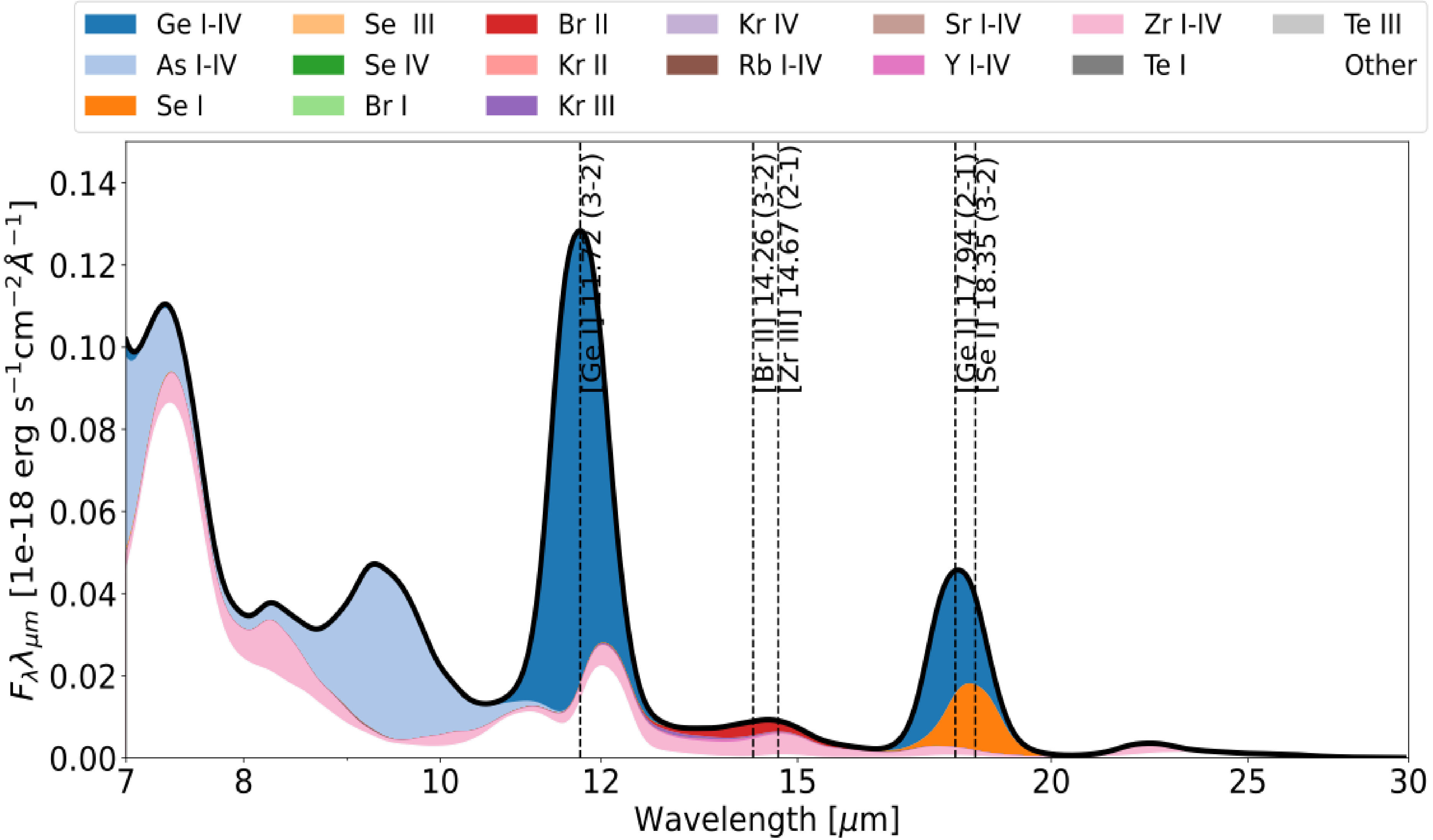
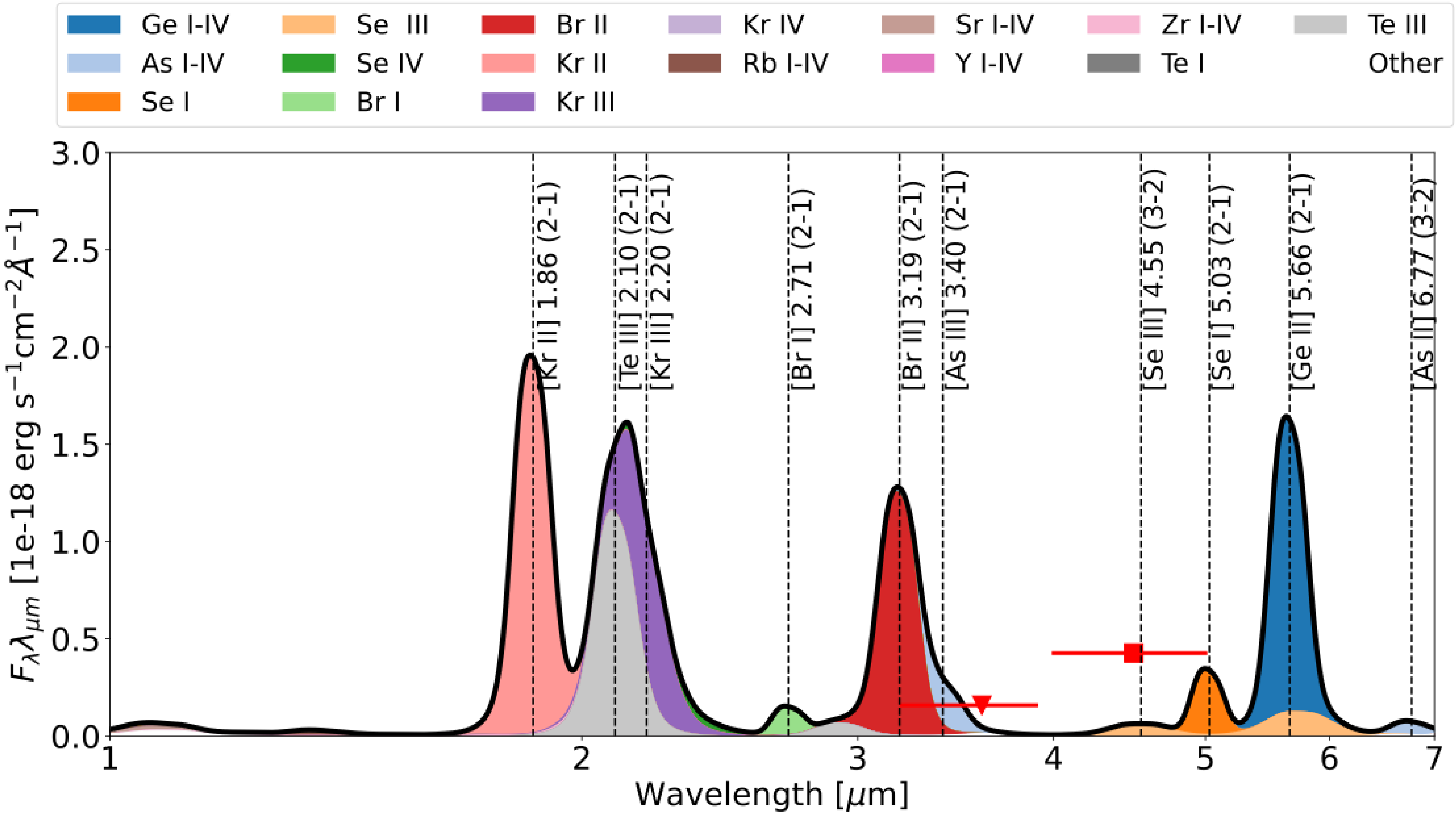


v_in=0.02c, low power, +40d

Later epoch: Same elements, different lines



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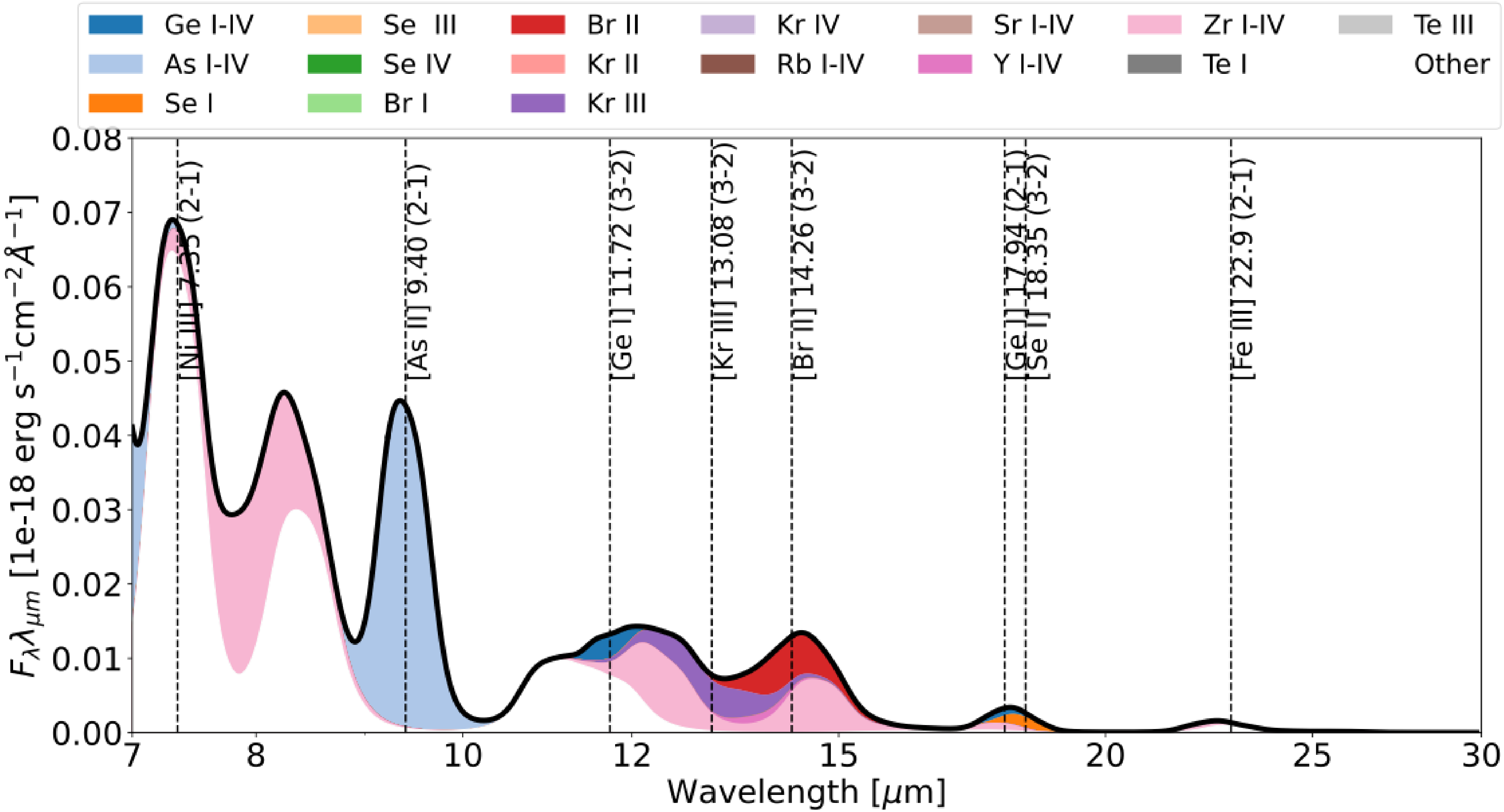
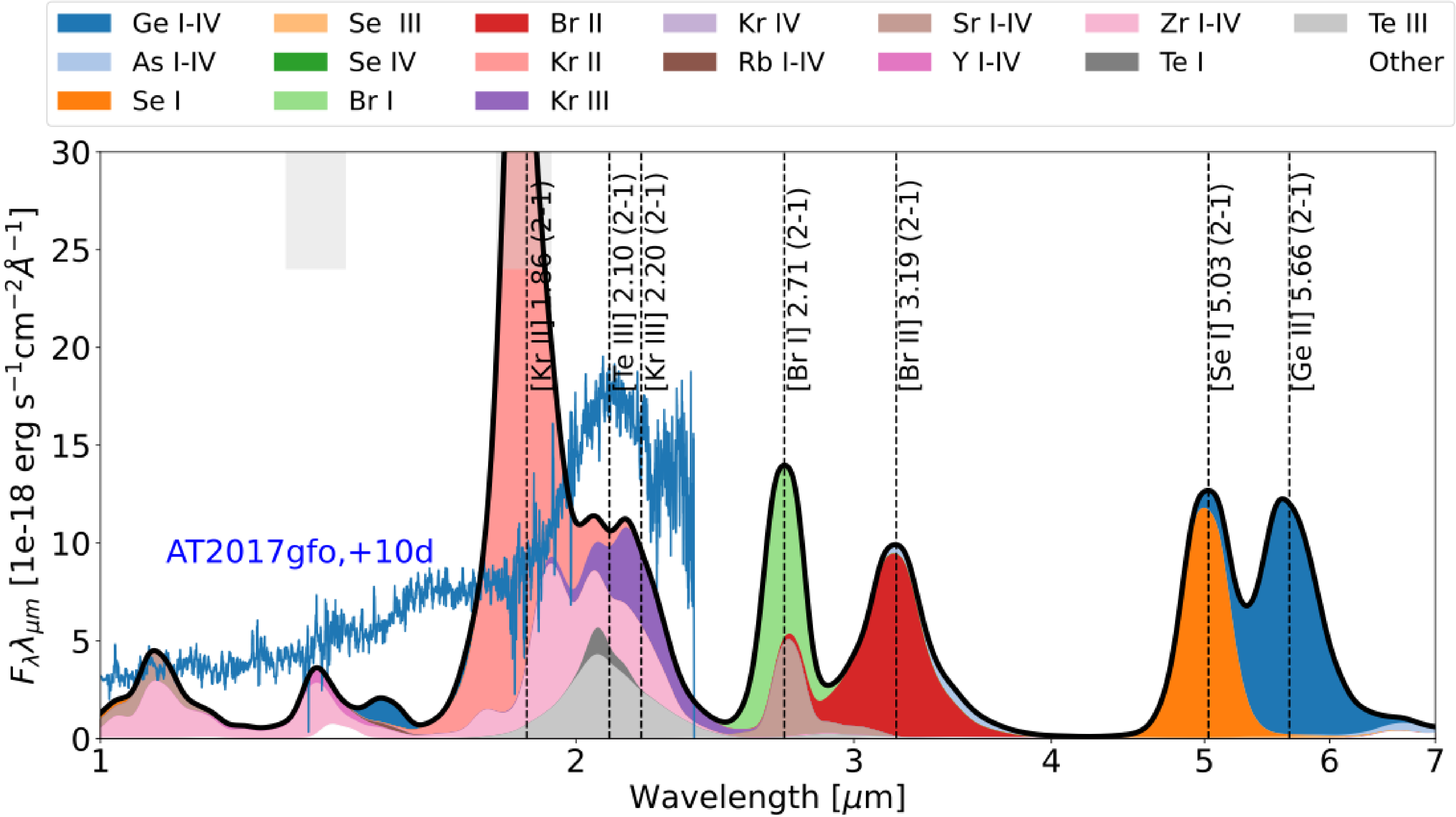


WHAT AT2017GFO DATA IS TELLING US

1) STRONGLY SUBSOLAR KR PRODUCTION 2) KR (II + III) DOMINATES THE 2.1 FEATURE



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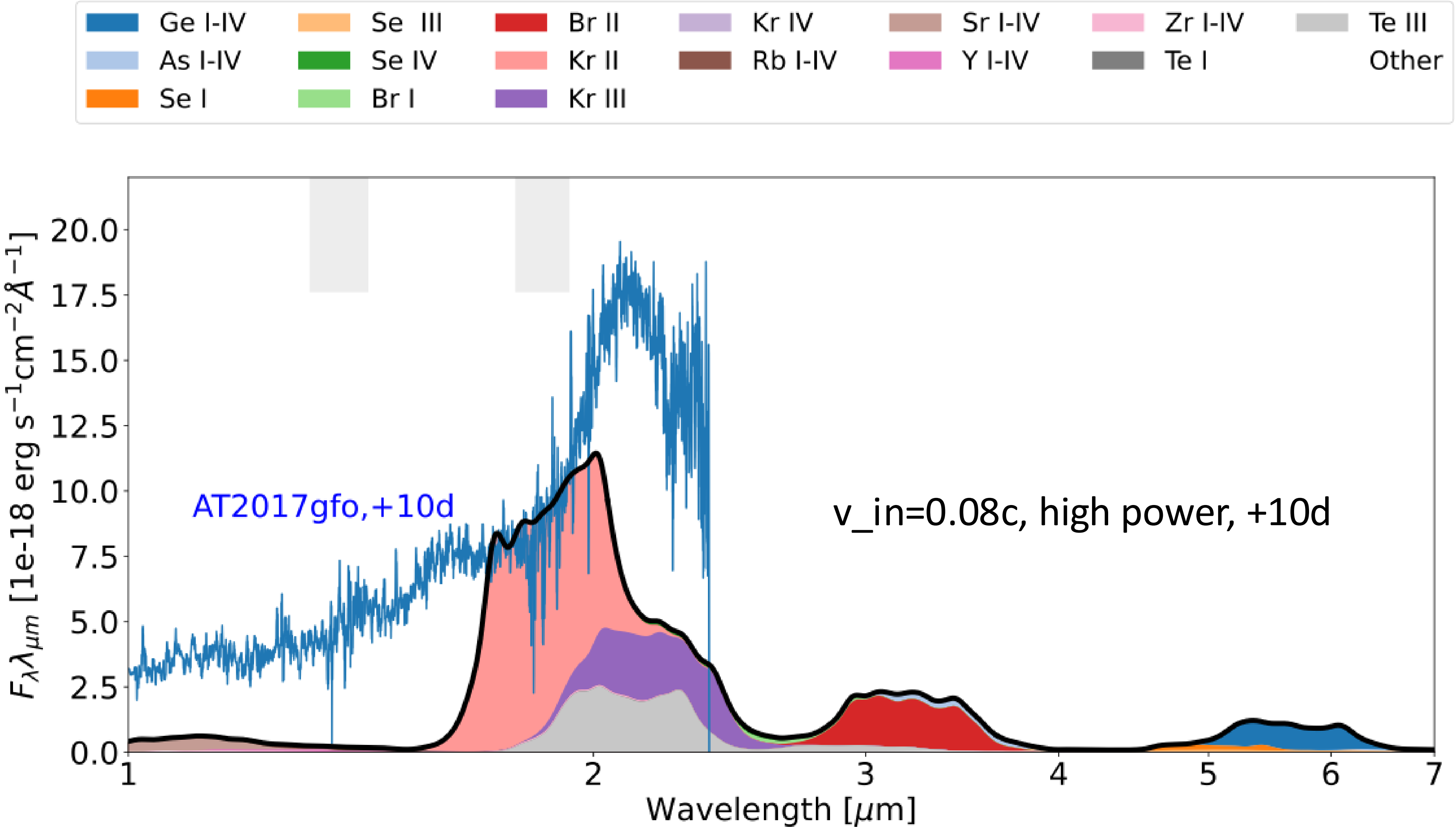

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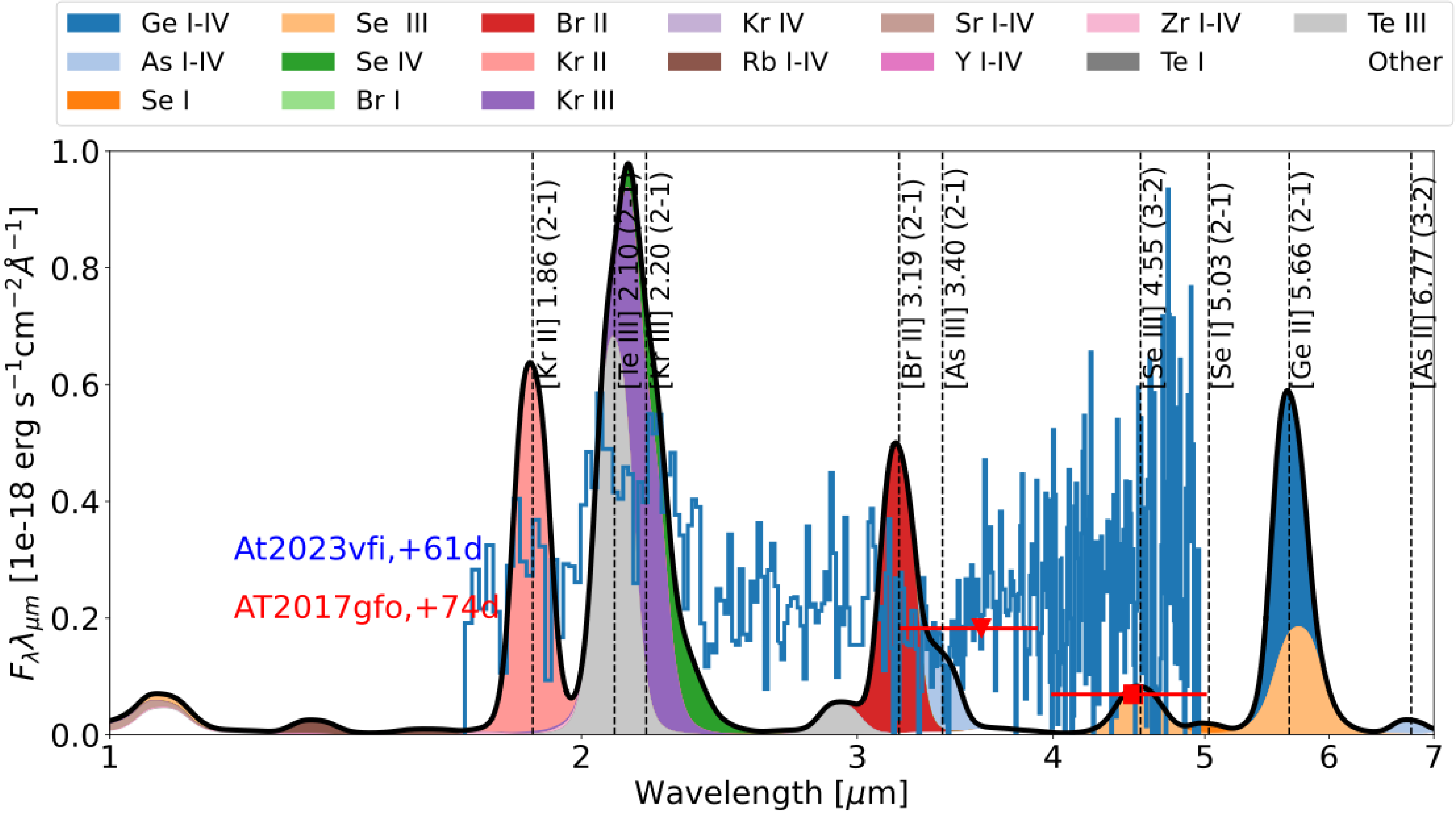
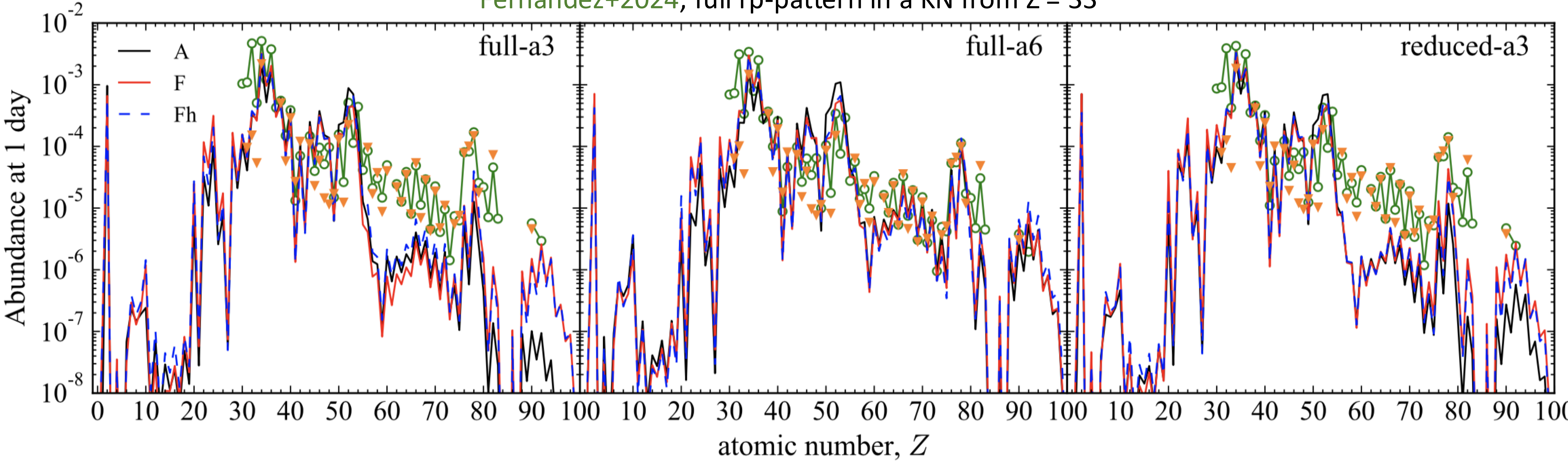
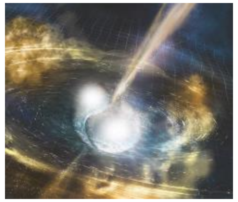
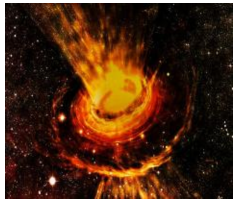


Fernandez+2024, full rp-pattern in a KN from Z = 33



- But also SNe can make the solar pattern up to Z ~ 38 (e.g. Sukhbold+2016, Wanajo+2018).
- Hints from low-metallicity stars : a transition somewhere between Z=32 and Z=38 for main source (Cowan 2005, Roederer+2012,2022).





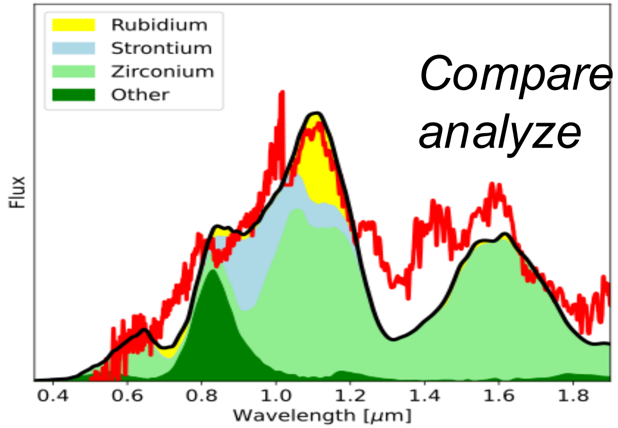
Hydrodynamic models

Toy models

Radiative transfer simulations, SUMO (1D) and EXTRASS (3D) codes

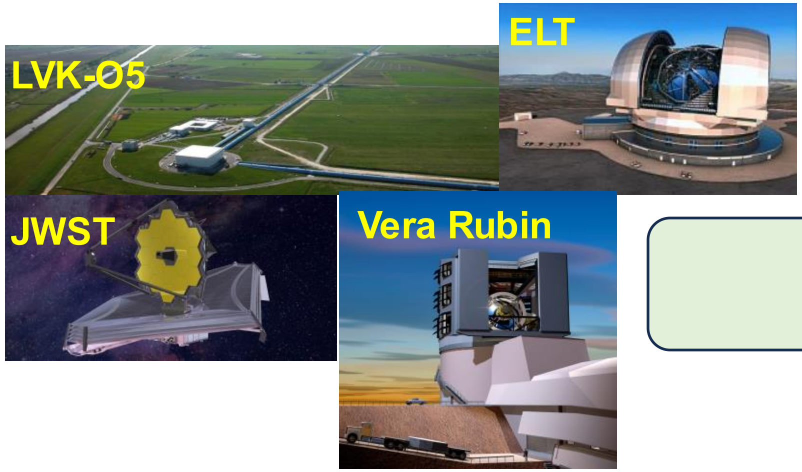
Ideas to test

Light curves and spectra



Compare and analyze

Inform proposals



Data

Results

Abundances

Merger mechanisms

Fundamental physics

SUMMARY

- KNe have **three distinct evolutionary phases** – *diffusion phase*, *early tail phase*, and *late tail phase*.

- Light curve and spectral modelling codes do things along at least **6 axes of accuracy**. Different codes show, for SNe, quite big differences for test inputs.

- New NLTE models show **diagnostic potential of NIR/MIR lines at late times**.
  - Should be able to derive abundances of strong constrains on Ge, Se, Br, Kr, ..
  - AT2017gfo and AT2023vfi data indicate **severely subsolar Kr production** : important piece of puzzle for understanding the origin of 1^{st} peak r-process elements.