Nucleosynthesis from core-collapse supernovae and kilonovae as inferred from their nebular spectra

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Swedish Research Council

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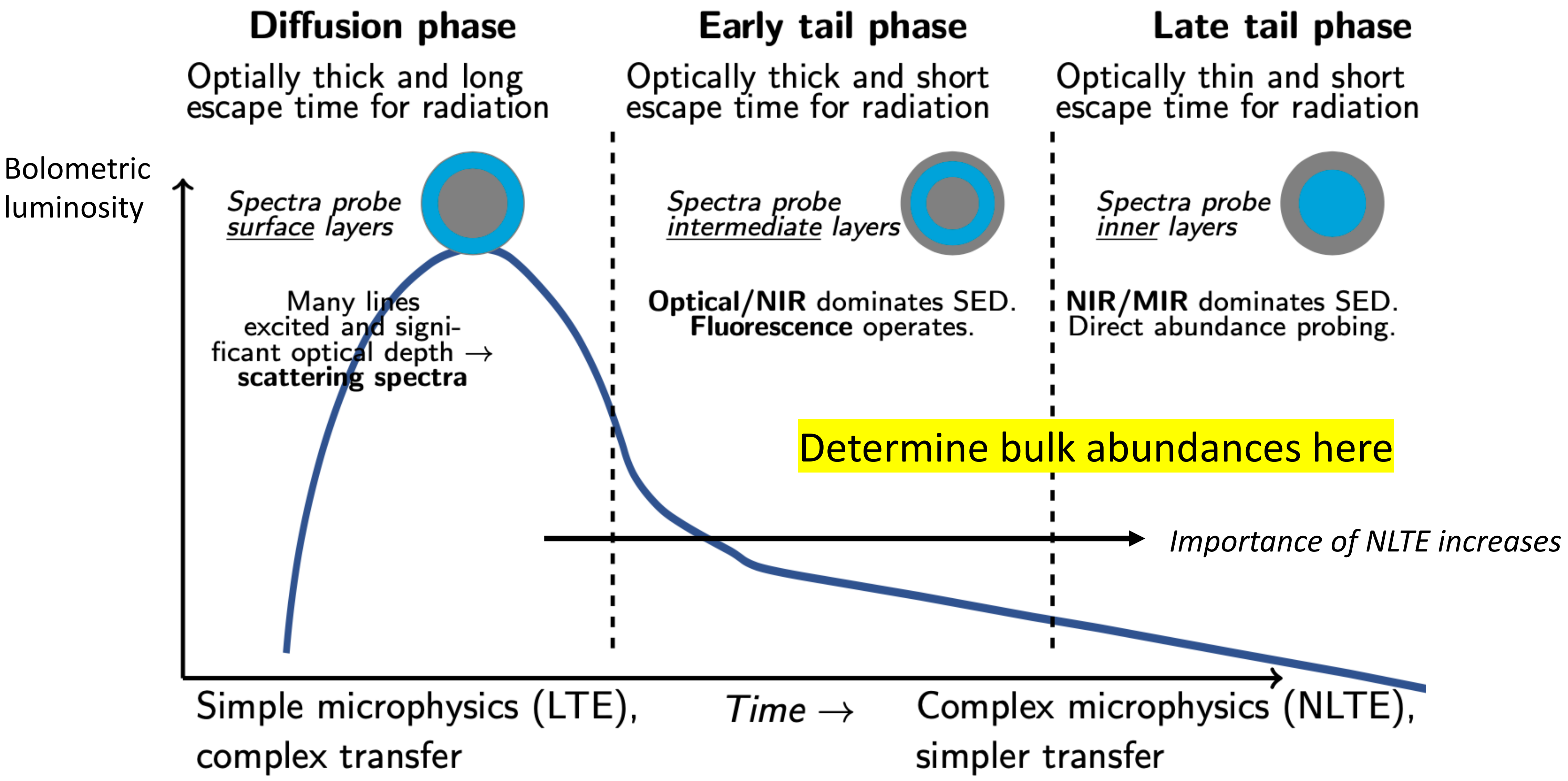
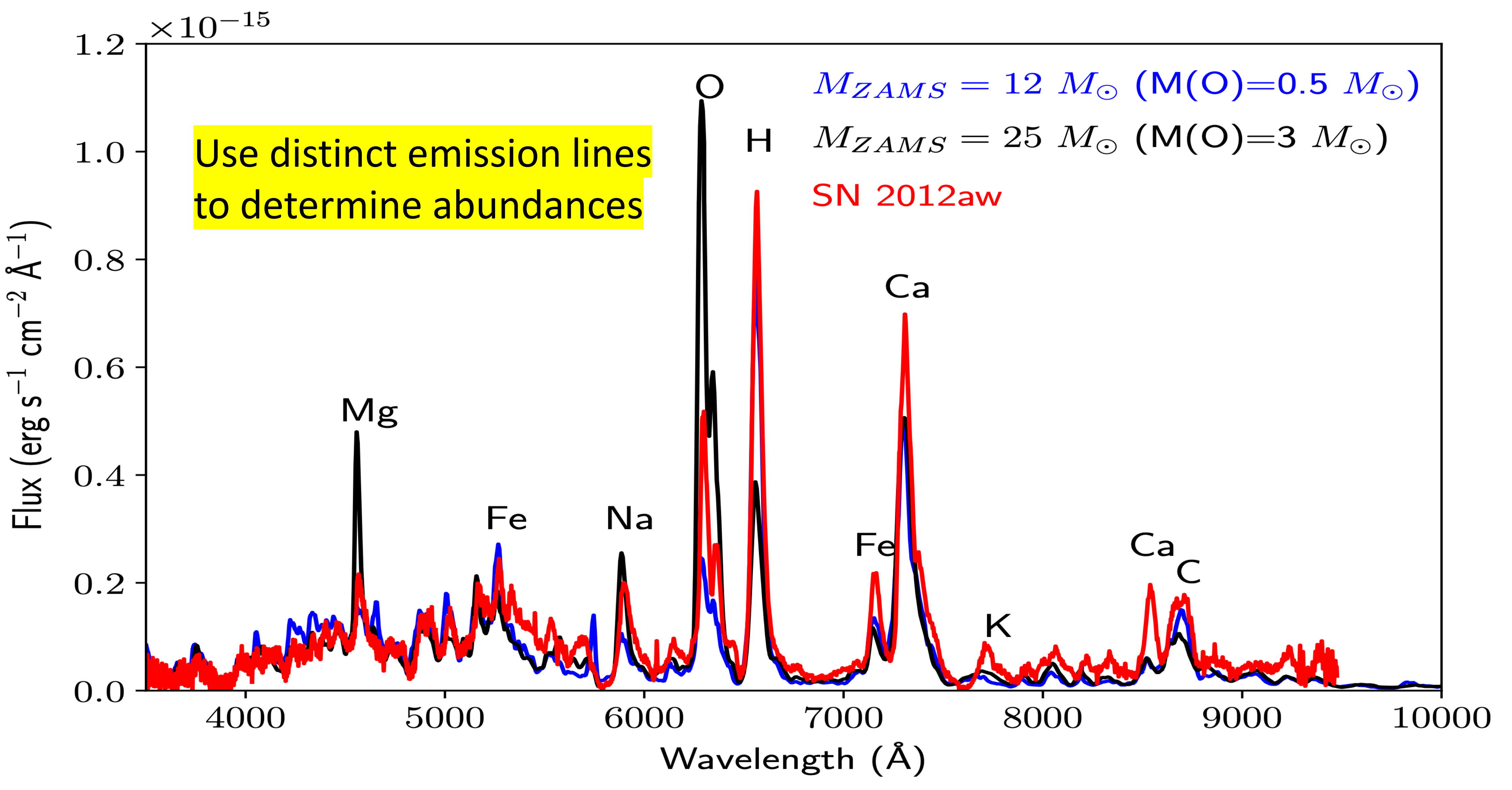
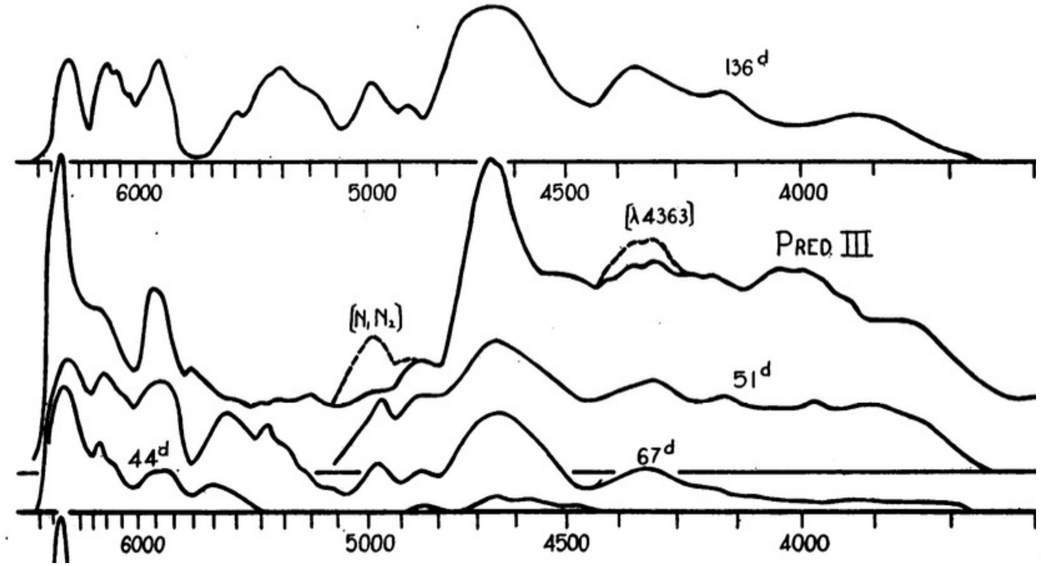


Reviews: Sim 2017 (Handbook of SNe) Jerkstrand 2017 (Handbook of SNe), 2025 (LRCA)


Use distinct emission lines
to determine abundances
$\times 10^{-15}$
Flux (erg s^{-1} cm^{-2} Å^{-1})
Wavelength (Å)
$M_{ZAMS} = 12\ M_\odot$ (M(O)=0.5 $M_\odot$)
$M_{ZAMS} = 25\ M_\odot$ (M(O)=3 $M_\odot$)
SN 2012aw
Mg
Fe
Na
O
H
Fe
Ca
K
Ca
C
0.0
0.2
0.4
0.6
0.8
1.0
1.2
4000
5000
6000
7000
8000
9000
10000



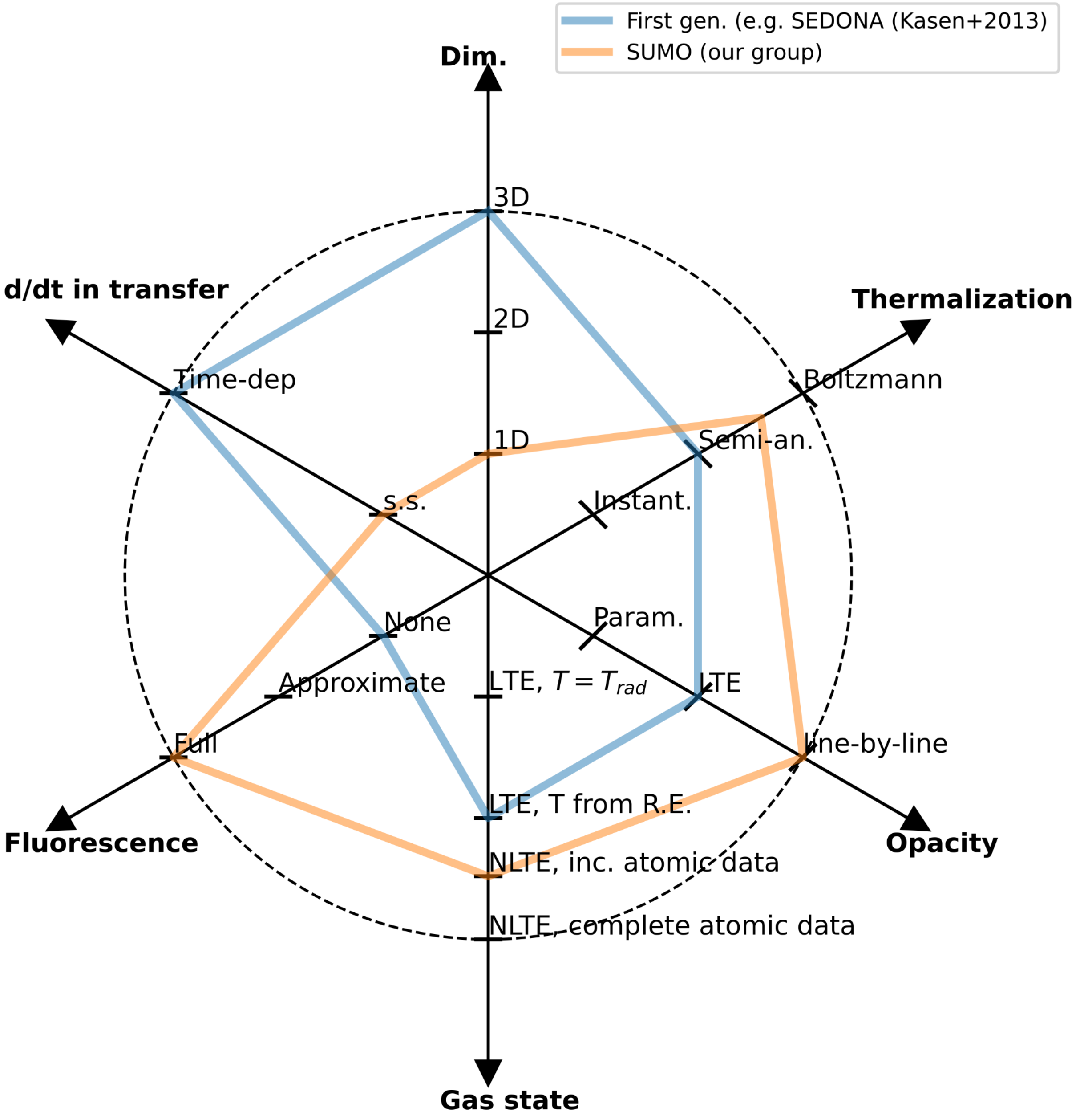
SYNTHETIC SPECTRA FOR SUPERNOVAE

By Cecilia Payne-Gaposchkin and Fred L. Whipple

Harvard College Observatory

Communicated March 14, 1940

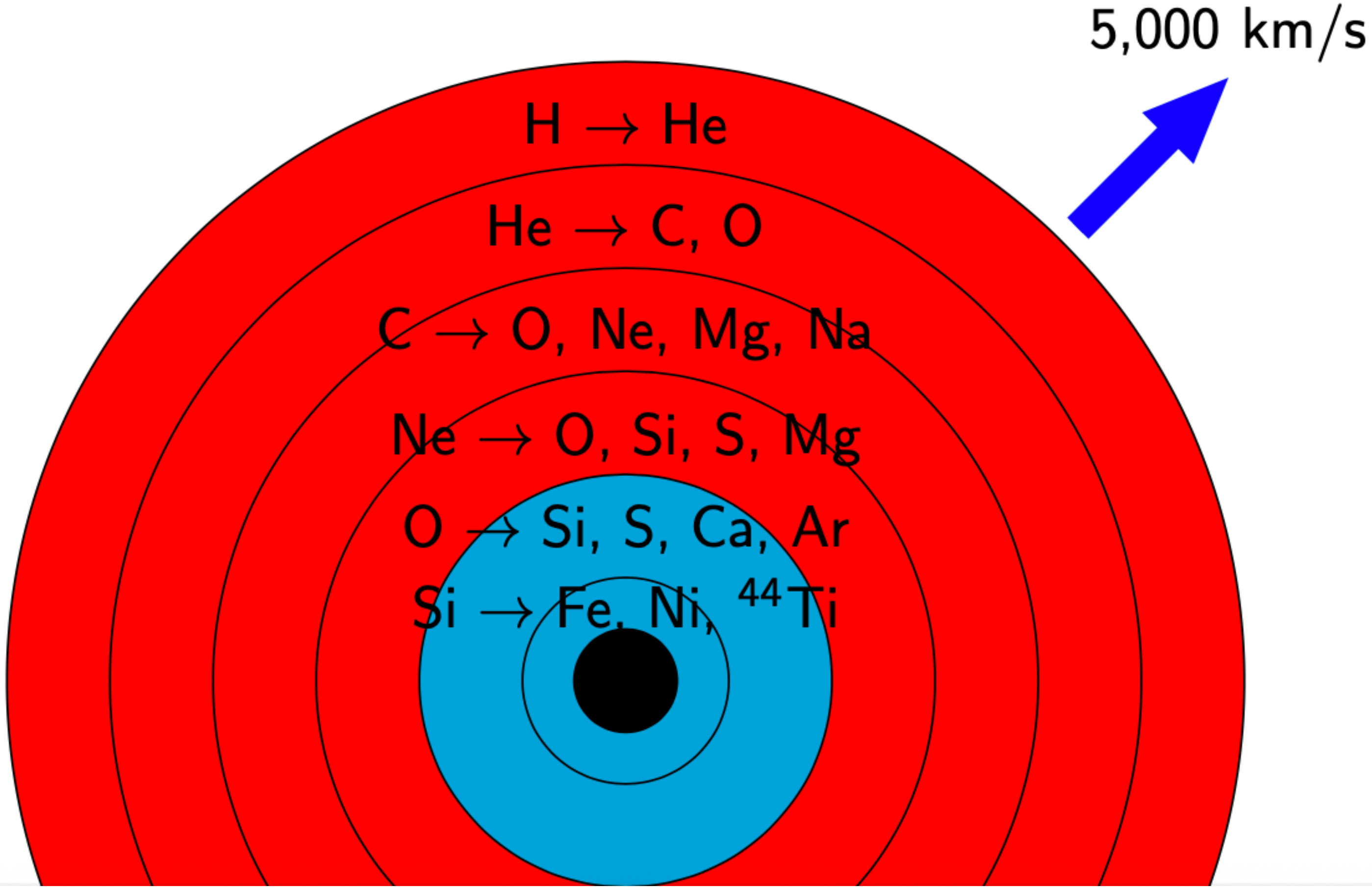
Introduction.—The excellent series of spectra of the supernovae in I. C. 4182 and N. G. C. 1003, published by Minkowski,[1] present for the first time a basis for a quantitative interpretation. Eight typical spectra, showing the major stages of the development during the first two hundred days, are shown 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.

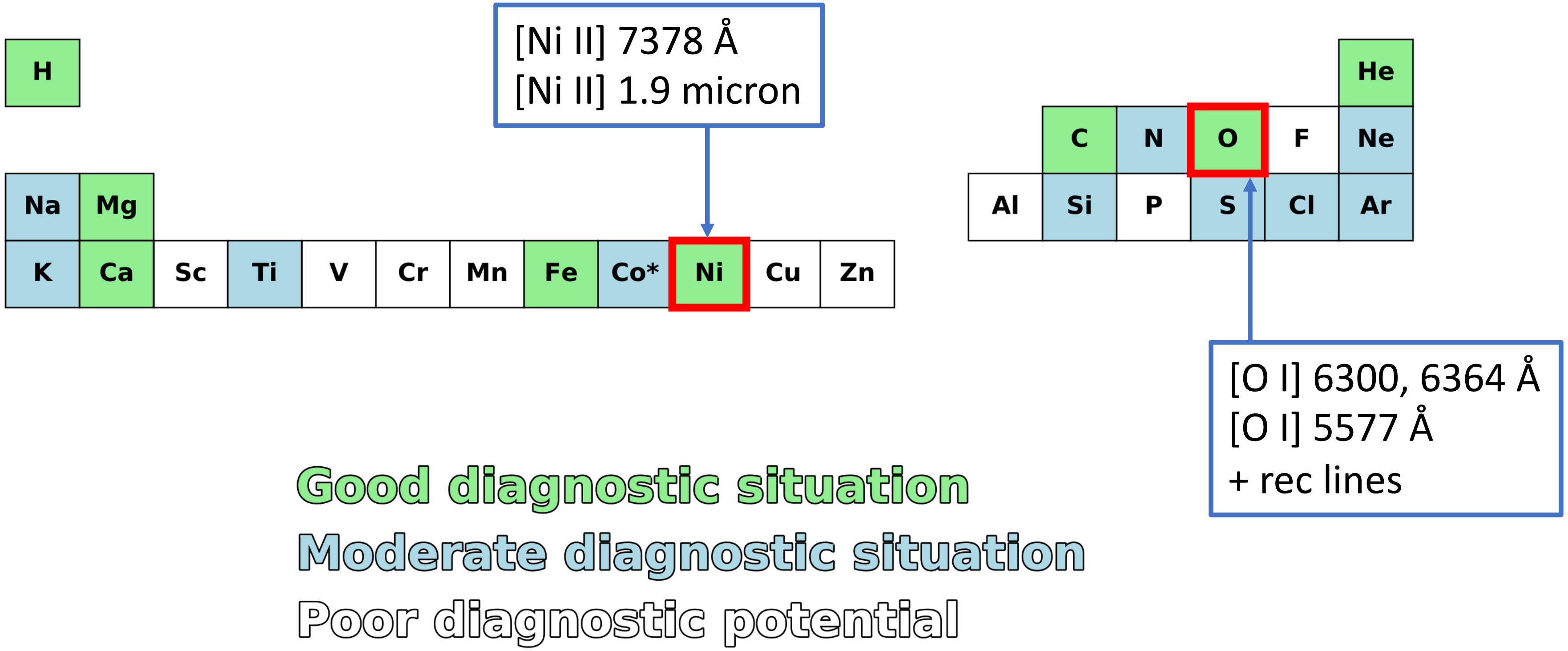


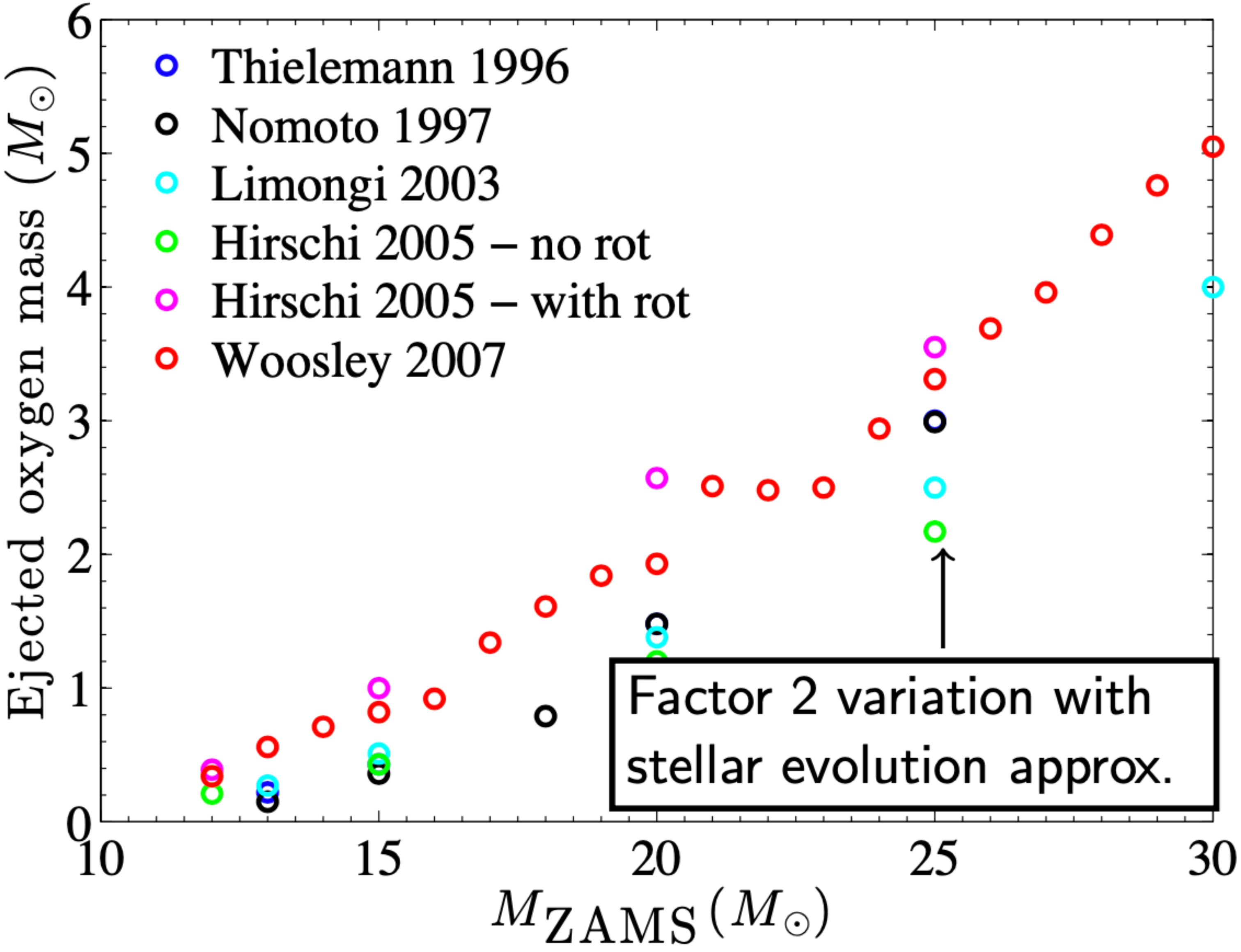
- No code does "all" → match code physics to desired thing to predict, to what accuracy.
- In our group we operate the NLTE codes **SUMO** (1D) and **EXTRASS** (3D)
  AJ+2011,2012,2015,2020
  Liljegren, AJ+ 2020, 2022
  Pognan, AJ+ 2023
  Van Baal & AJ 2026

SUPERNOVAE

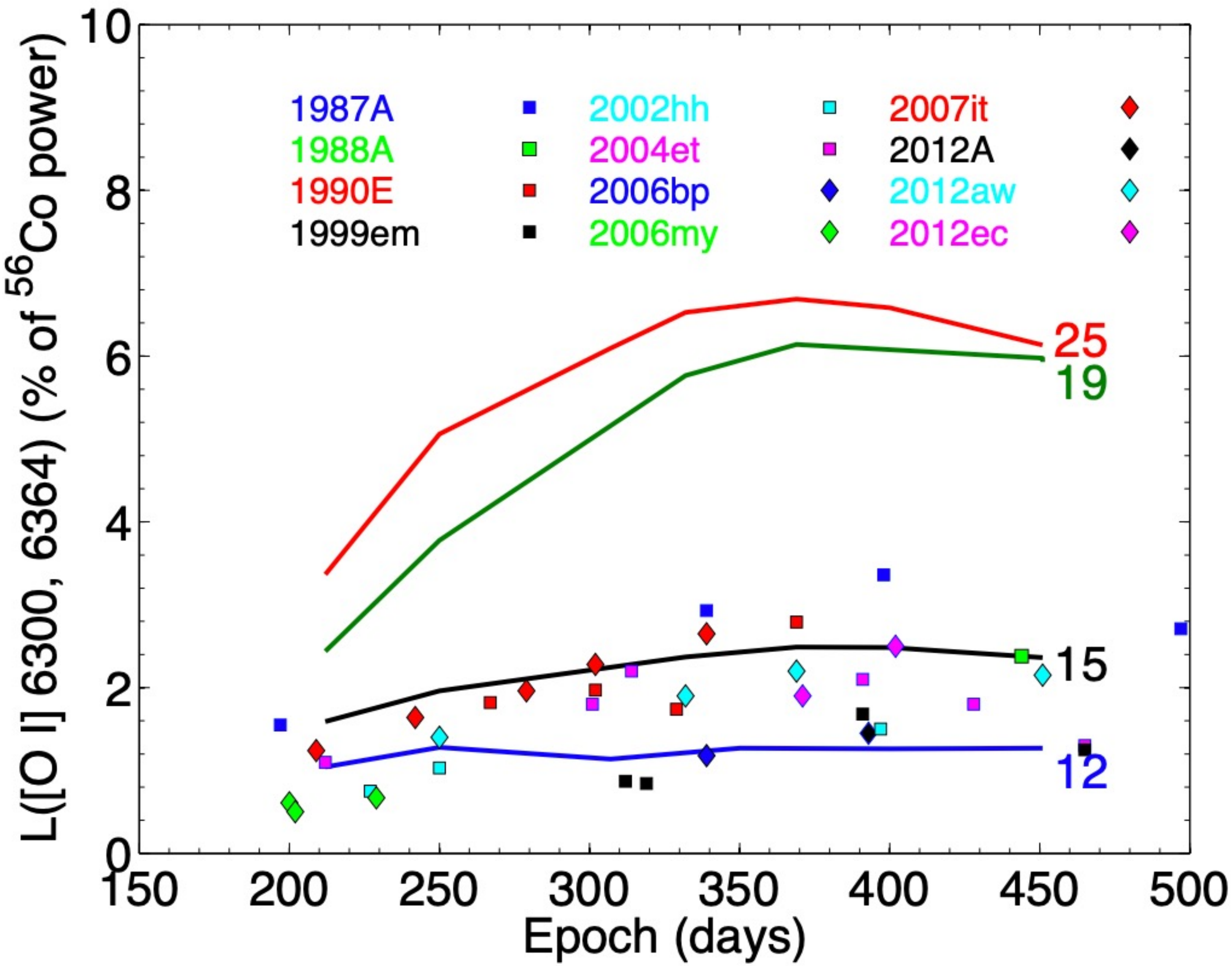
- Hydrostatic (pre-SN) burning: main source of C, O, F, Ne, Na, Mg, Al, P in Universe
- Explosive SN burning: main source of Si, S, Ar, Ca, Fe, Ni in the Universe




H
He
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co*
Ni
Cu
Zn
[Ni II] 7378 Å
[Ni II] 1.9 micron
[O I] 6300, 6364 Å
[O I] 5577 Å
+ rec lines
Good diagnostic situation
Moderate diagnostic situation
Poor diagnostic potential



Thielemann 1996
Nomoto 1997
Limongi 2003
Hirschi 2005 – no rot
Hirschi 2005 – with rot
Woosley 2007
Ejected oxygen mass ($M_\odot$)
0
1
2
3
4
5
6
10
15
20
25
30
M_{ZAMS} ($M_\odot$)
Factor 2 variation with stellar evolution approx.



From direct inference from SN nebular spectra: Average inferred O-yield in a Type II supernova is ~0.5 Msun.

Relatively “low” hydrostatic yields supported by analysis of C, Na, Mg

Similar picture in Type I SNe.

AJ+ 2012, 2014, 2015a, 2018
Barmentloo & AJ 2024
Silverman+ 2017

Stellar evolution/GCE side:

- GCE models using binaries?

- Shell mergers?

- Nuclear rates (e.g. C(alpha,gamma)O)?

Nebular inferrence side:

- Most massive stars shroud their ejecta?

- Some effect not accounted for in models affecting mainly massive star SNe?

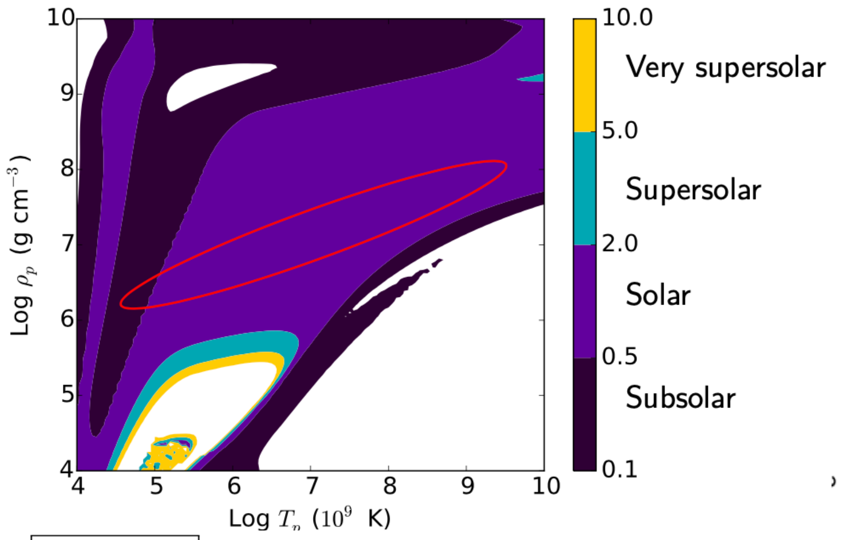
Ni/Fe ratios in 7 CCSNe

SN	Ni/Fe (times solar)	Reference
Crab	60 – 75	Macalpine1989, Macalpine2007
SN 1987A	0.5 – 1.5	Rank1988, Wooden1993, AJ+2015
SN 2004et	$\sim$1	AJ+2012
SN 2006aj	2 – 5	Maeda+2007, Mazzali+2007
SN 2012A	$\sim$ 0.5	AJ+2015b
SN 2012aw	$\sim$ 1.5	AJ+2015b
SN 2012ec	2.2 – 4.6	AJ+2015b

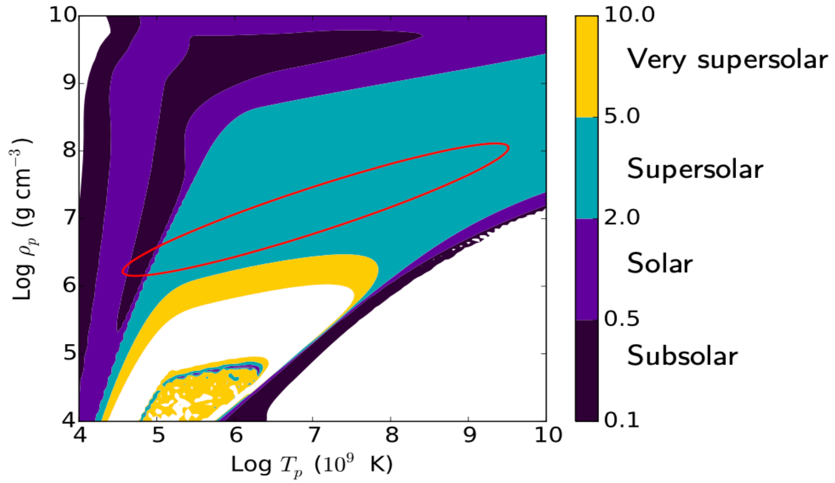
Two main groups: ~solar and ~2-5 times solar

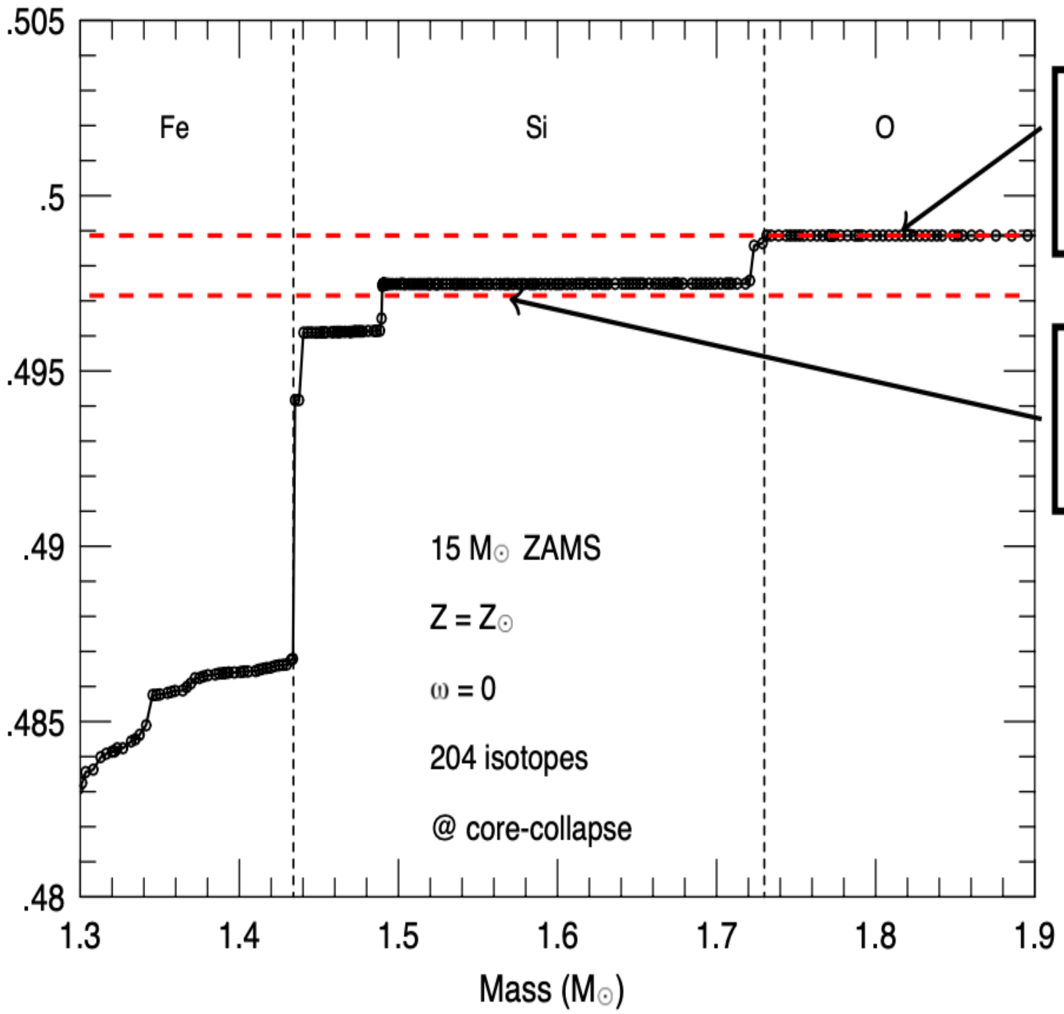
Ni/Fe ratio is a tracer of which progenitor layer was explosively burnt

$Y_e = 0.499$: Only good solutions for Ni/Fe ~ solar



$Y_e = 0.497$: Large allowed region opens up for supersolar





Ye = 0.499 (solar Ni/Fe): Oxygen layer

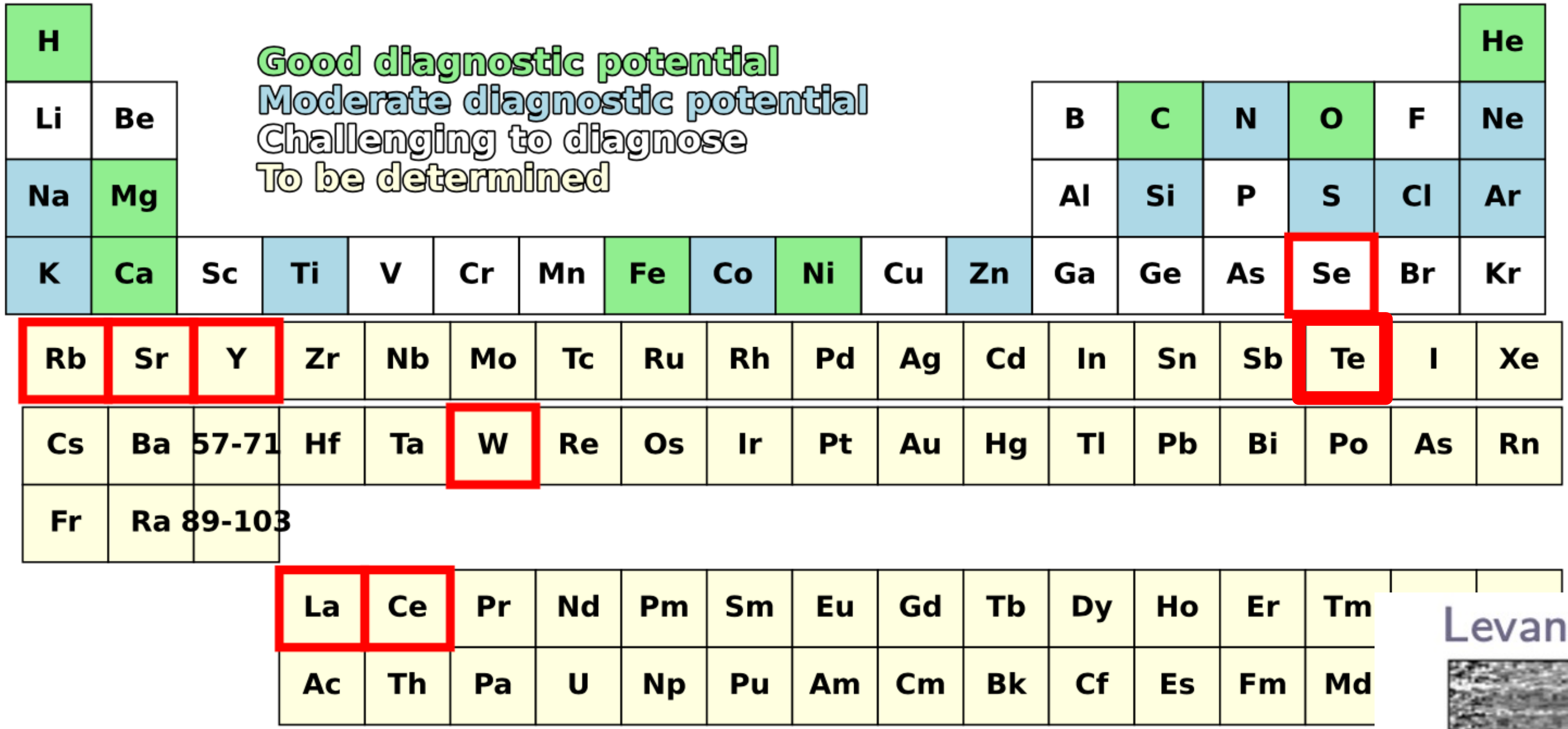
Ye = 0.497 (supersolar Ni/Fe): Silicon layer

AJ, Timmes, Magkotsios+ 2015 ApJ

Some other important results:

- ^{56}**Ni** : Mean production Type II SNe; 0.037 ± 0.005 $M_\odot$ Rodriguez+2021
- ^{44}**Ti** : (1-2)*10^{-4} $M_\odot$ both in SN 1987A and Cas A   AJ+2011, Boggs+2015
- ^{57}**Fe** : Roughly solar ^{57}Fe/^{56}Fe in SN 1987A   Kurfess+1992

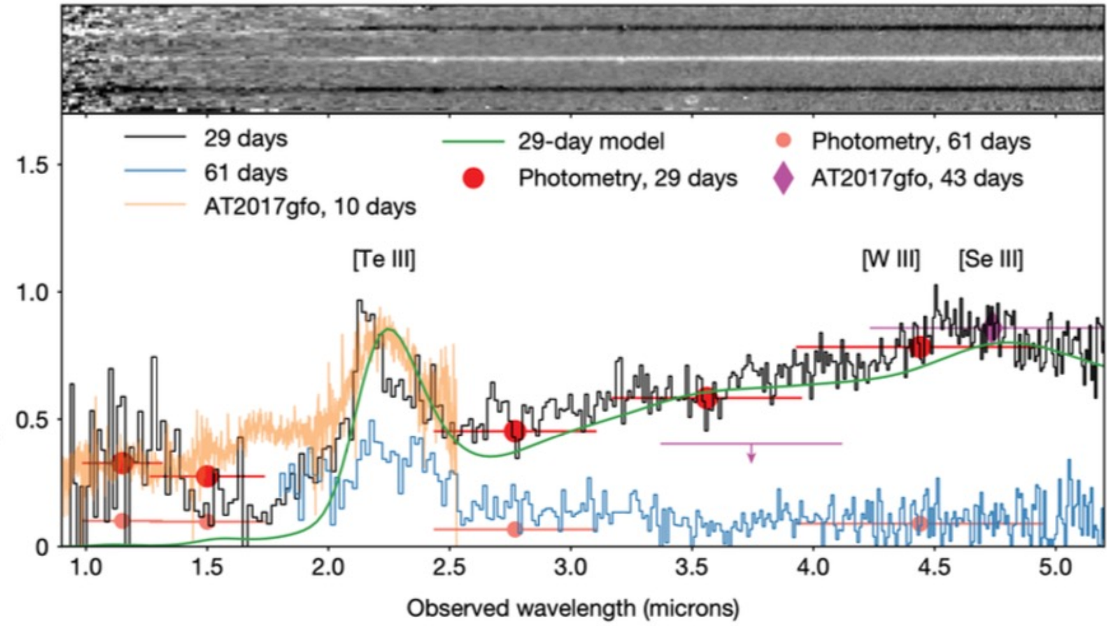
KILONOVAE

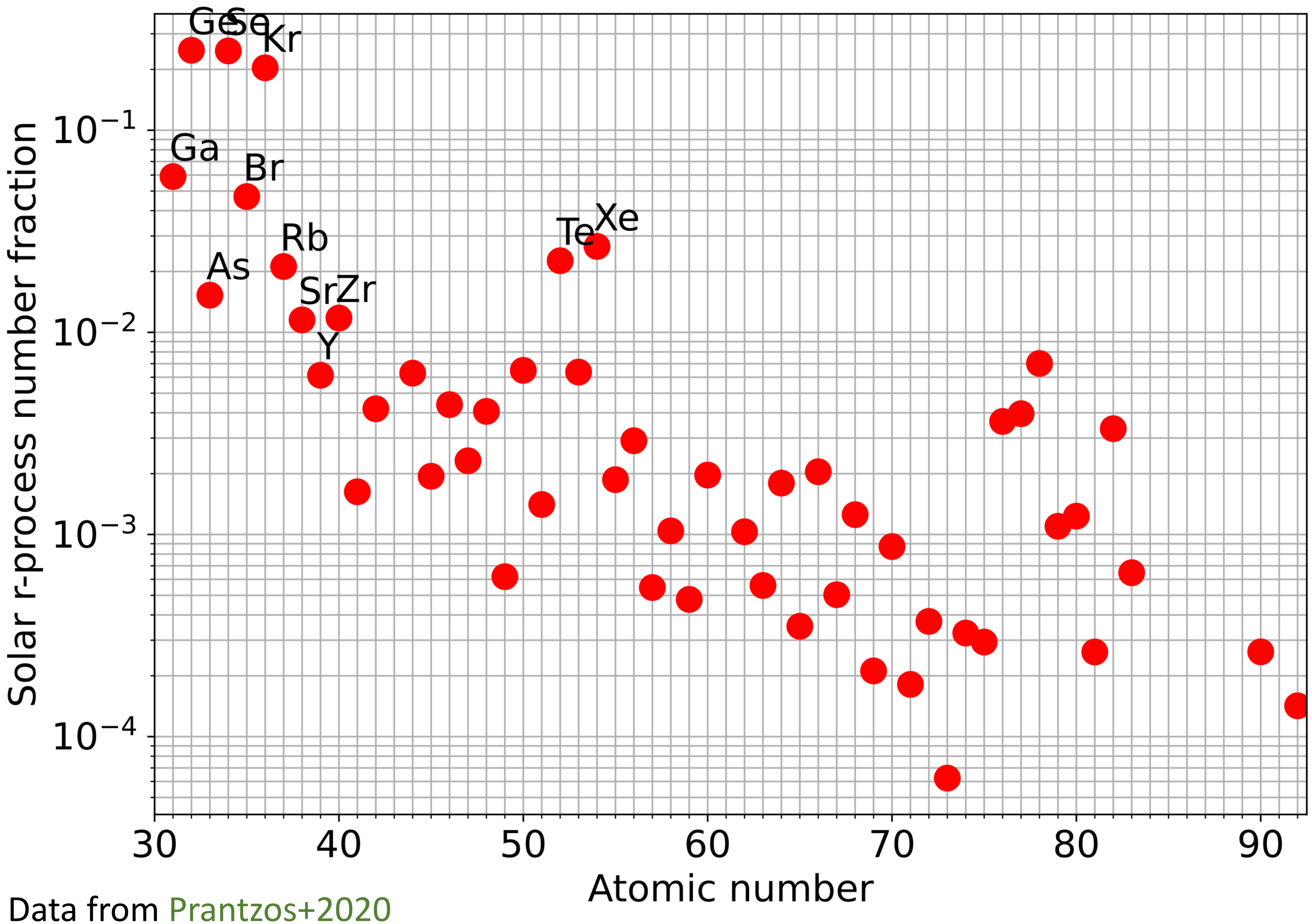


= Possible detection in AT2017gfo

Watson+2019, Sneppen+2023, Gillanders+2024, Vieira+2023, Hotokezaka+2024
Pognan,AJ+ 2023, AJ+2026

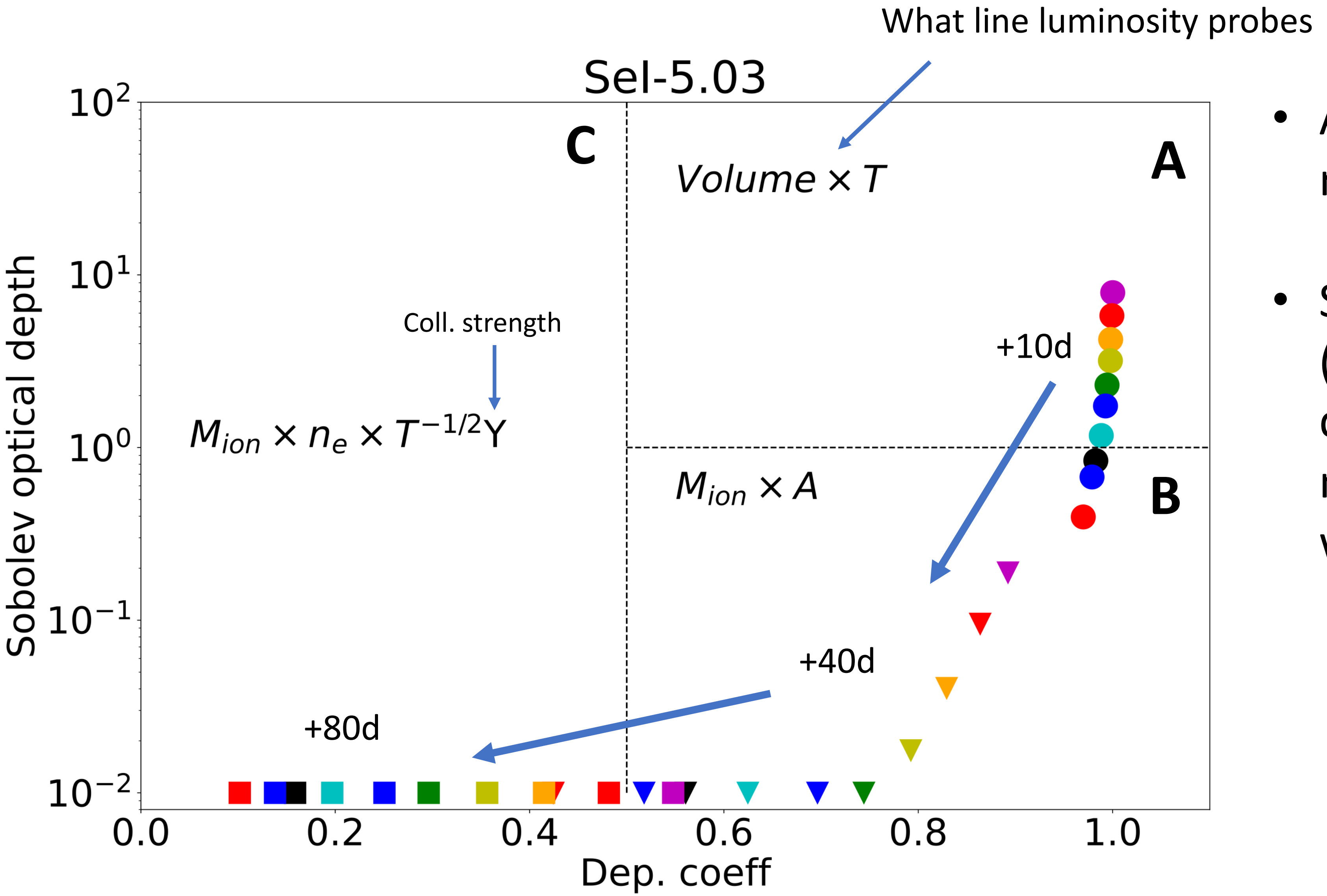
Levan+2023





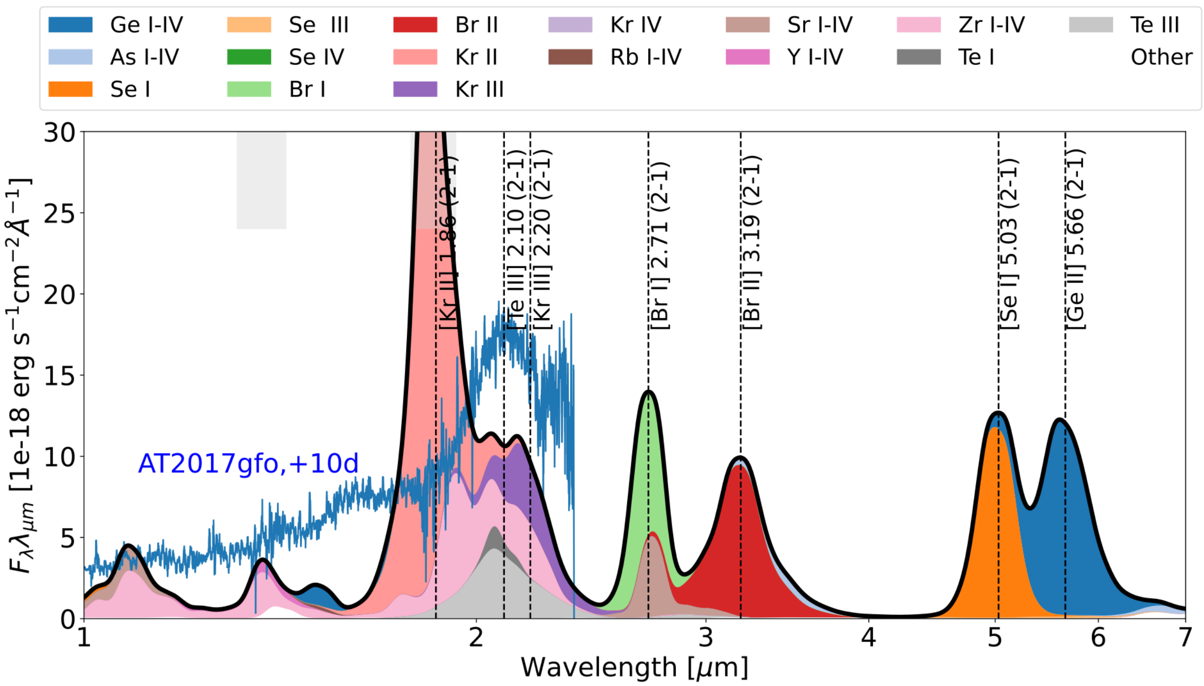
Data from Prantzos+2020

- *Do NSM make all the r-p elements?*
- In nebular phase **emission prop. to abundance** → 1st peak elements are good targets.
- Focus atomic data and modelling efforts on these (**rec. rates**: Banerjee,AJ+2025), **collision strengths**: AJ+2026)

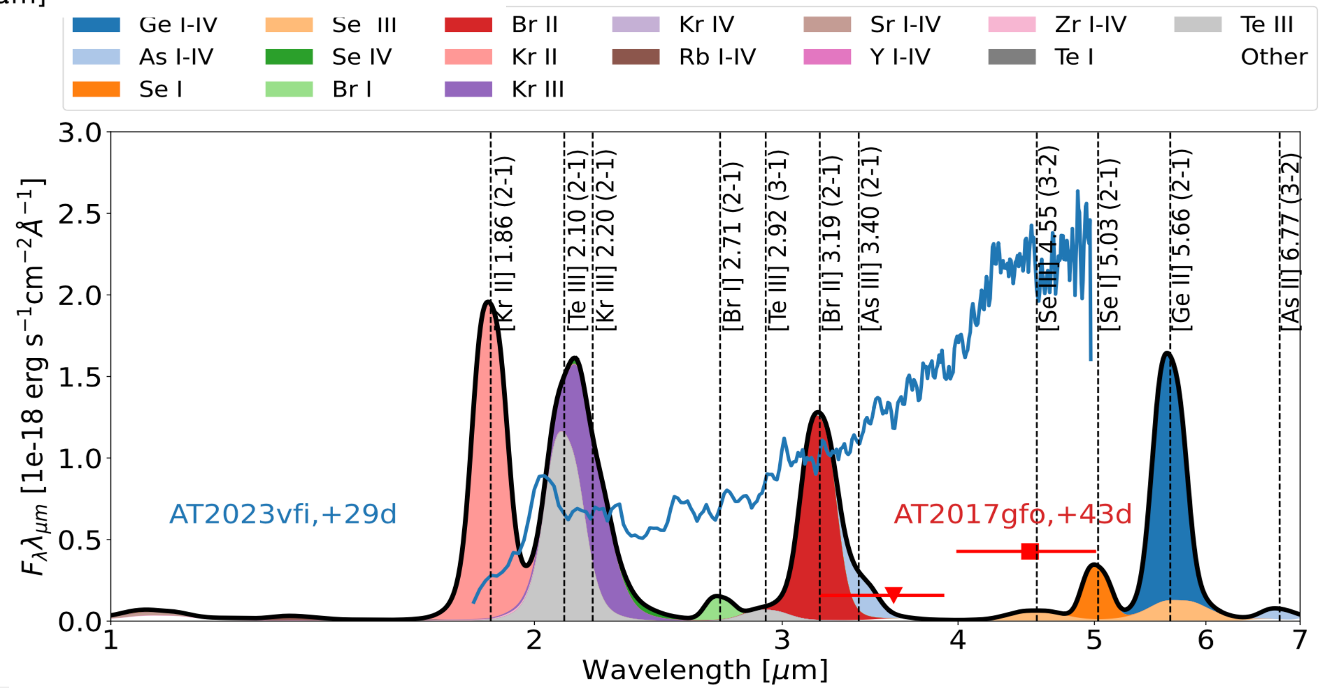


- All lines will move from regime **A** to **C** over time.
- Some will pass through **B** (the best regime to determine ionic mass) : models guide which and when.

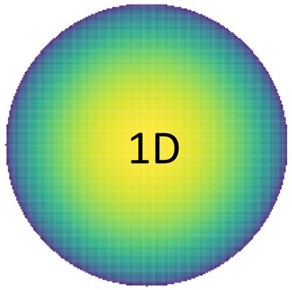
AJ+2026



Indication KNe make subsolar 1st/2nd peak : missing Kr and Br lines



Model:



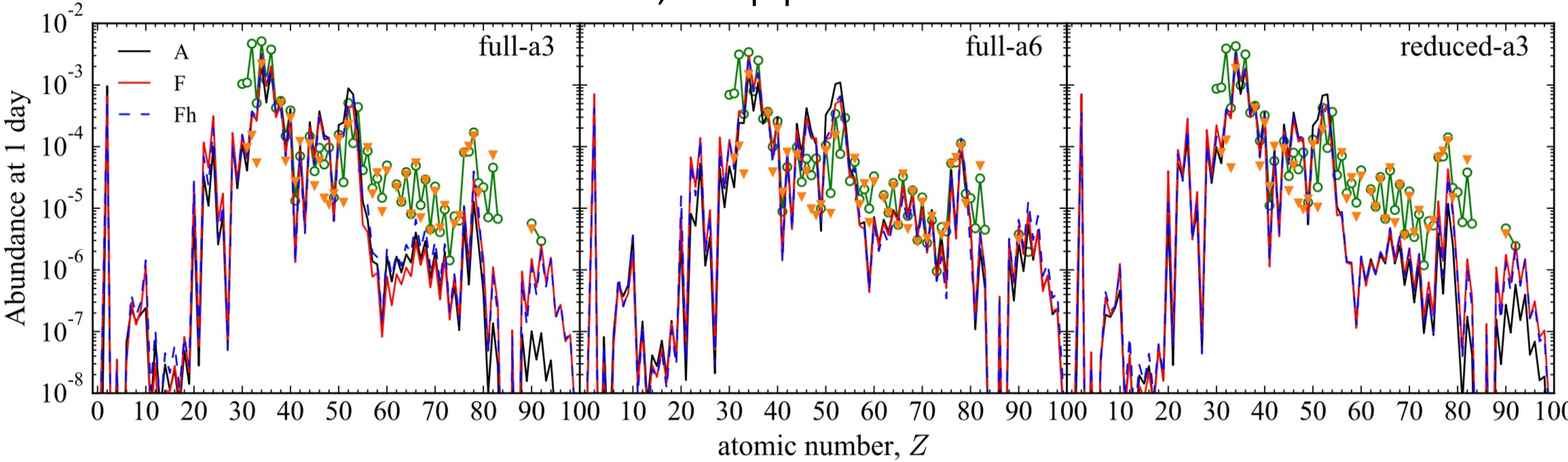
$M_{ejecta} = 0.05\ M_\odot$

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

Z=30-40, 52, 54

solar composition

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



- 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).

KEY TAKEAWAYS

- Supernovae and kilonovae reveal their abundances in the **nebular phase**. Modelling and interpretation with NLTE codes like SUMO.

- Well-determined yields of e.g. **C, N, O, Mg, Fe, Ni** : some tension with standard GCE models (we don’t see enough SNe with high yields).

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

Thank you for listening!