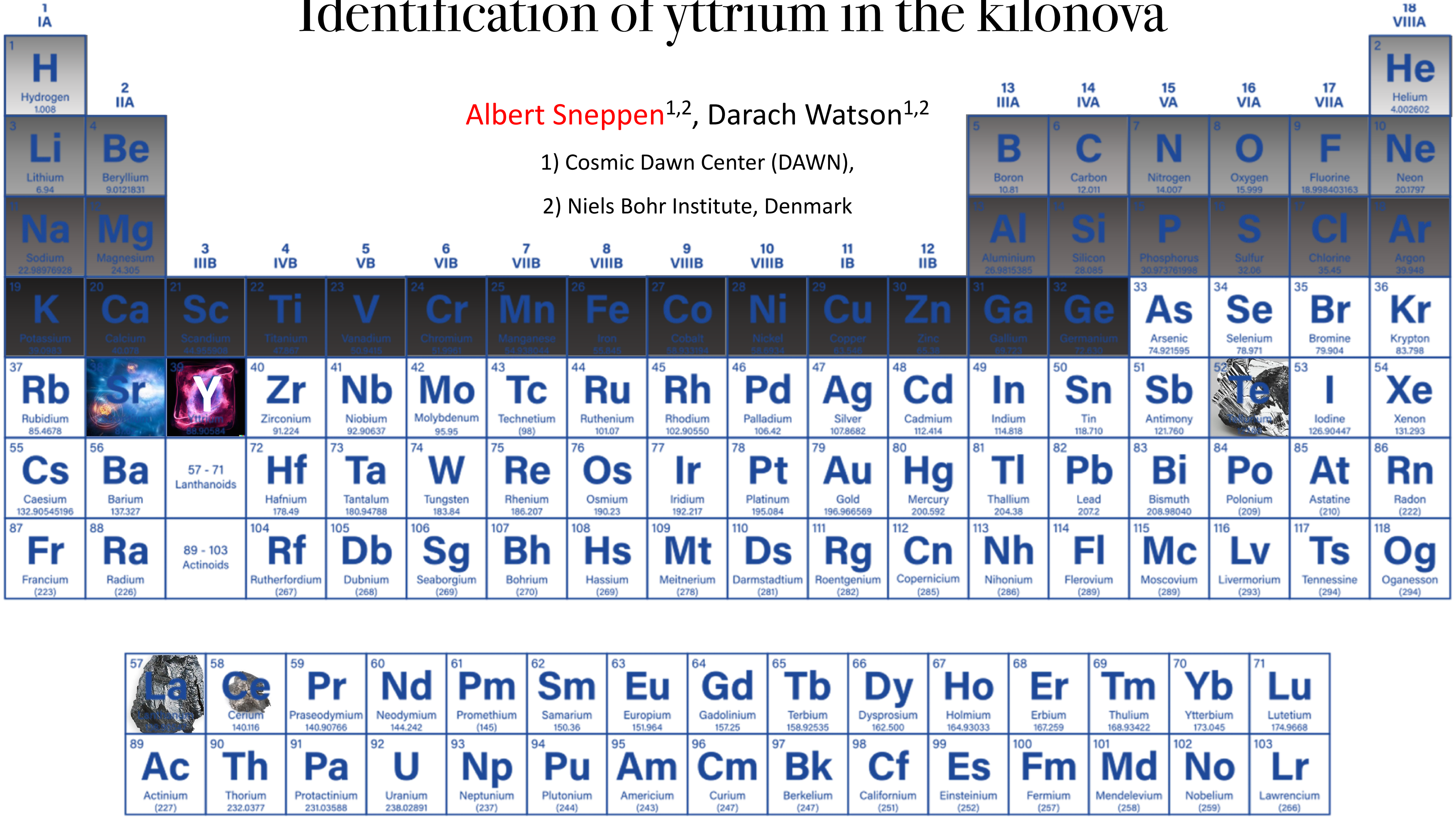
Discovery of a 760 nm P Cygni line in AT2017gfo: Identification of yttrium in the kilonova

Albert Sneppen[1,2], Darach Watson[1,2]

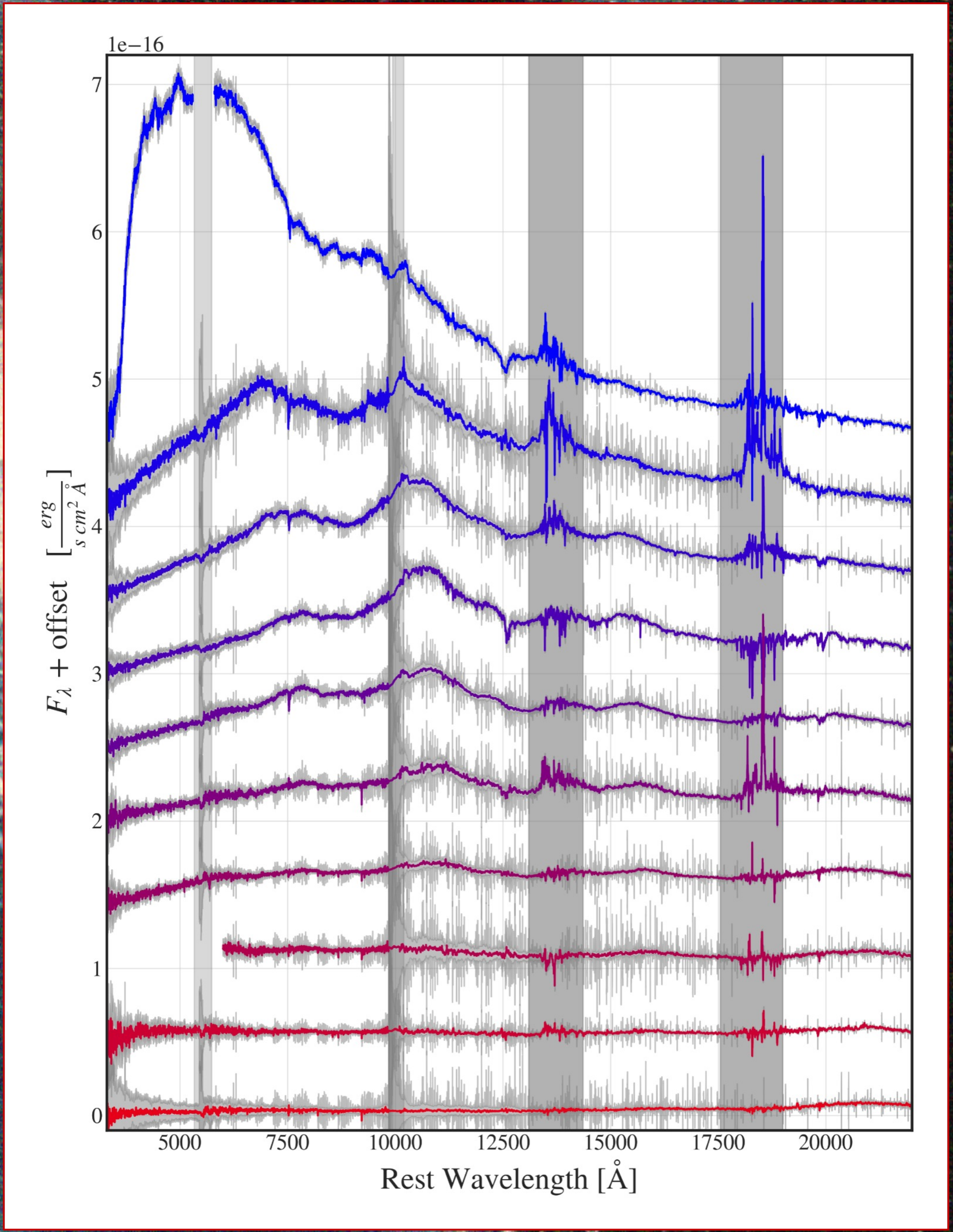
1) Cosmic Dawn Center (DAWN),

2) Niels Bohr Institute, Denmark



The Radiative Transfer and Atomic Physics of Kilonovae - 06-09-2023

The kilonova AT2017gfo



VLT/X-Shooter Spectra,
Smartt et al. (2017) + Pian et al. (2017)

Strontium in the kilonova

For deliberation on the Sr-identification:

Identification of strontium in the merger of two neutron stars

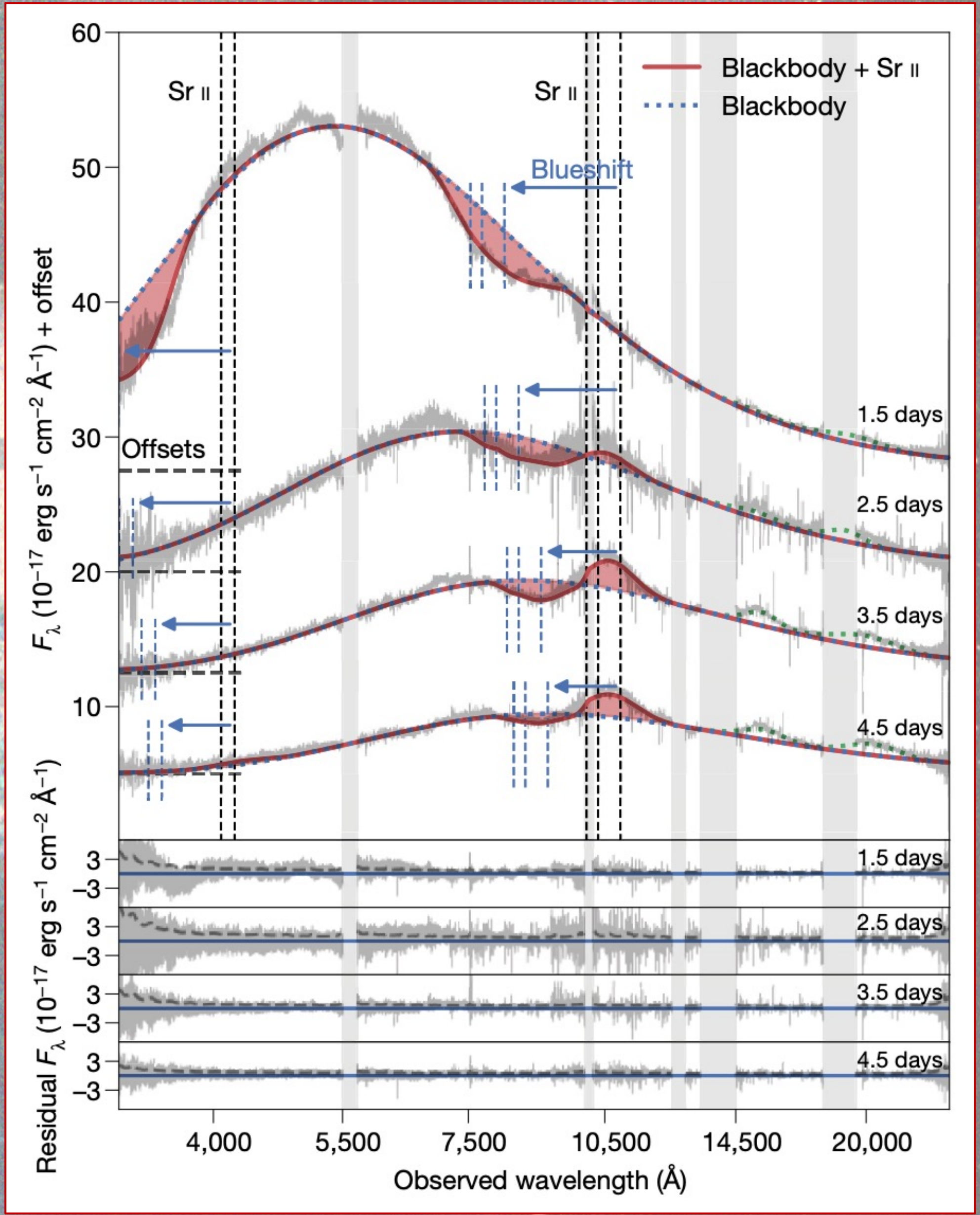
Darach Watson[1,2], Camilla J. Hansen[3,*], Jonatan Selsing[1,2,*], Andreas Koch[4], Daniele B. Malesani[1,2,5], Anja C. Andersen[1], Johan P. U. Fynbo[1,2], Almudena Arcones[6,7], Andreas Bauswein[7,8], Stefano Covino[9], Aniello Grado[10], Kasper E. Heintz[1,2,11], Leslie Hunt[12], Chryssa Kouveliotou[13,14] Giorgos Leloudas[1,5], Andrew Levan[15,16], Paolo Mazzali[17,18], Elena Pian[19] [See end for affiliations]

Reproduced and extended with systematic analyses using radiative transfer codes with more atomic line data:

- Domoto et al. (2021)
- Gillanders et al. (2022)
- Vieira et al. (2023)

Additionally, accounting for the full 3D spatial and time dependence of the density with line-by-line opacity:

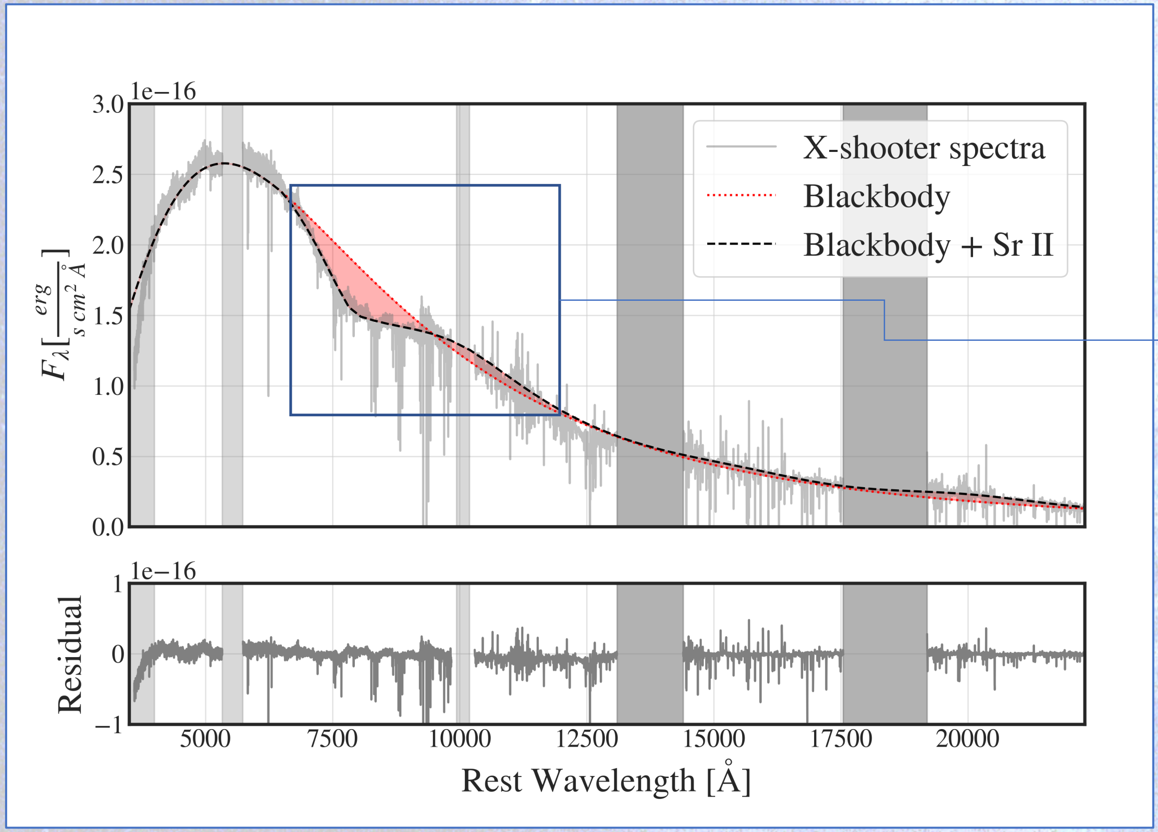
- Shingles et al. (2023)



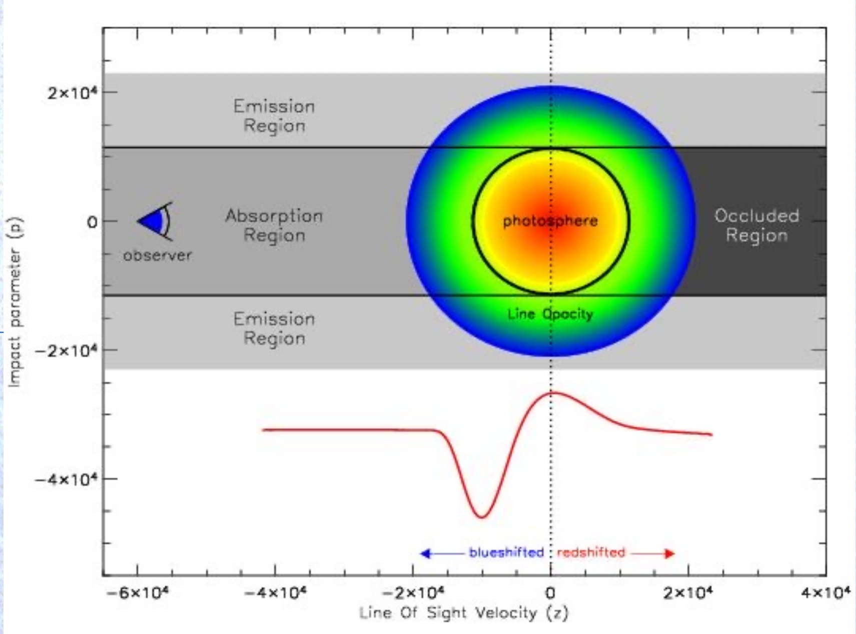
Watson et al. (2019)

The P Cygni information

illustration from Dan Kasen

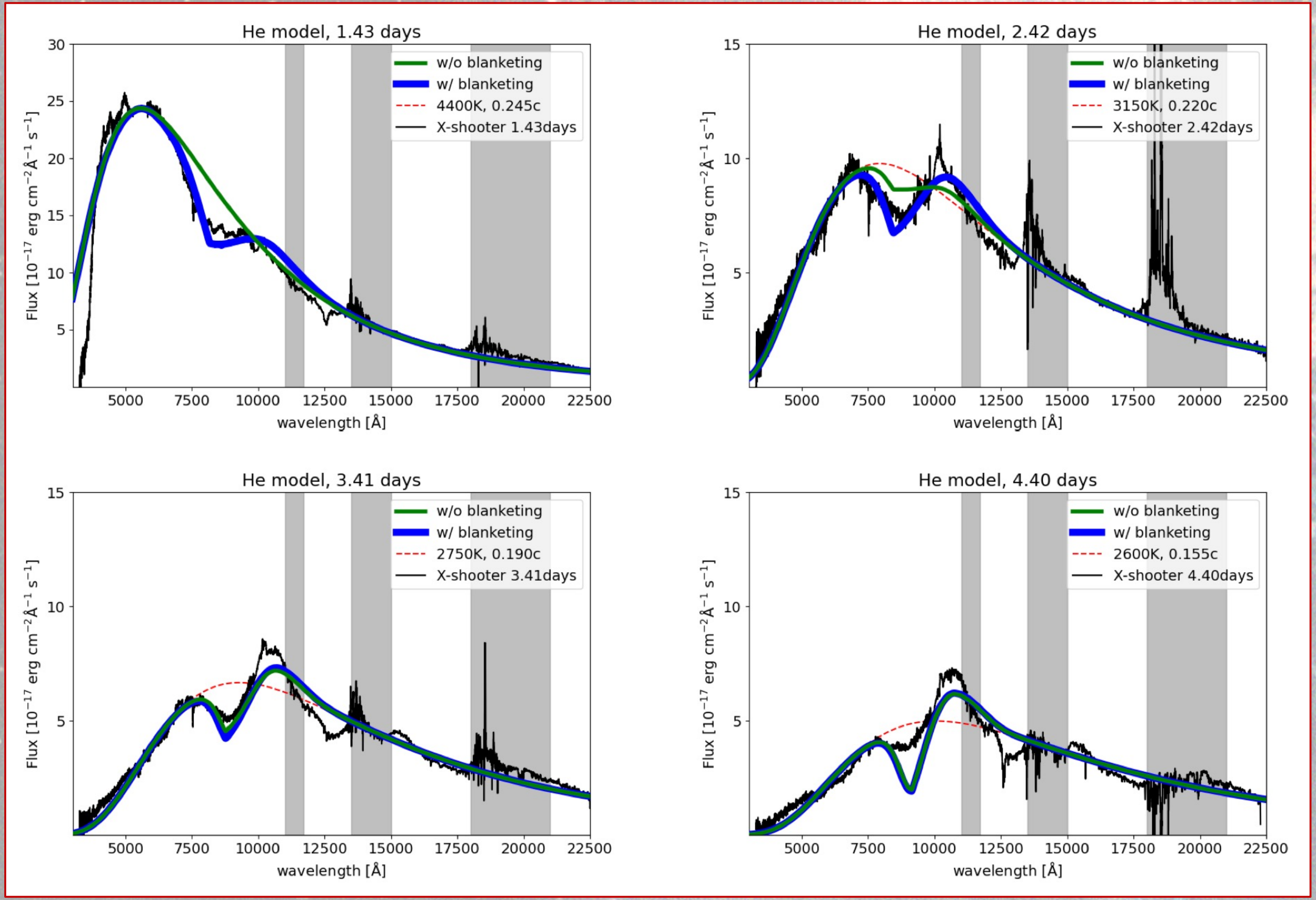


X-shooter spectrum epoch 1



Parameterization of P Cygni profile in the Elementary Supernova from https://github.com/unoebauer/public-astro-tools

Or perhaps 10 833 Å He-line?



Tarumi et al. (2023)

For deliberation on this feature, see:

Perego et al. (2022) & Tarumi et al. (2023)

(Requires NLTE and more helium than previously associated with kilonova-models)

For discussion of the magnitude NLTE effects in KNe, see Pognan et al. (2022)

"This is the first verification for the applicability of LTE expansion opacities for the early KN phase. "

Energy level comparison

Tarumi et al (2023)

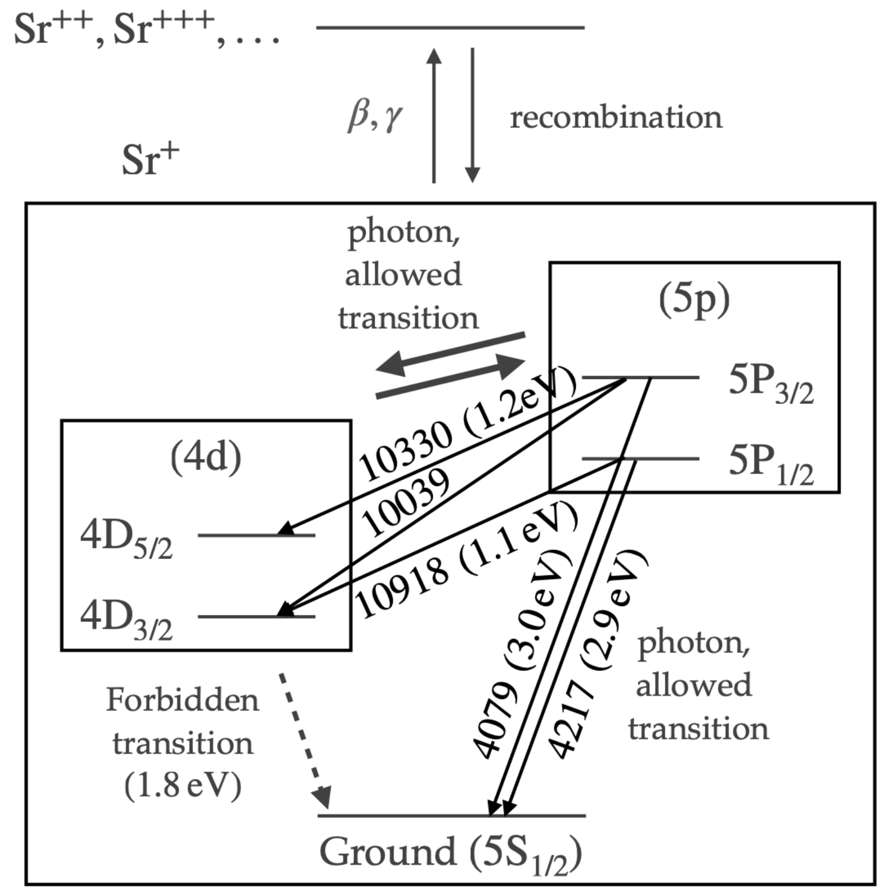


Figure 2. Schematic diagram that shows the populating mechanism of singly ionized Sr.

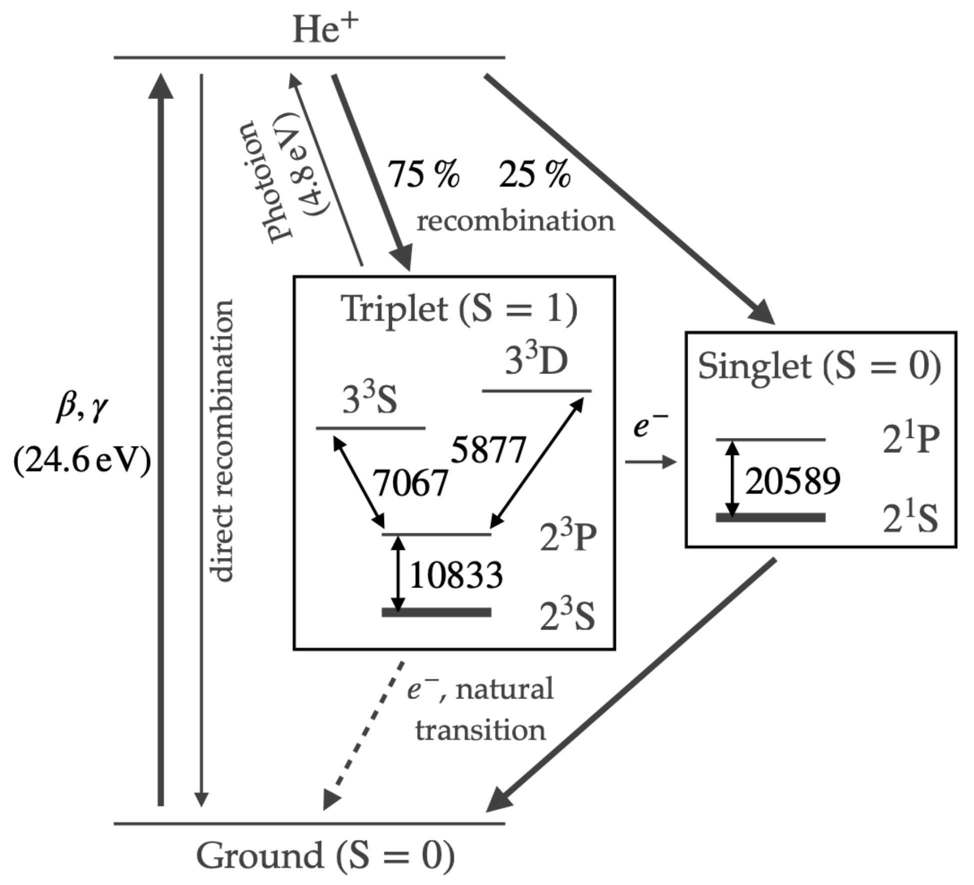
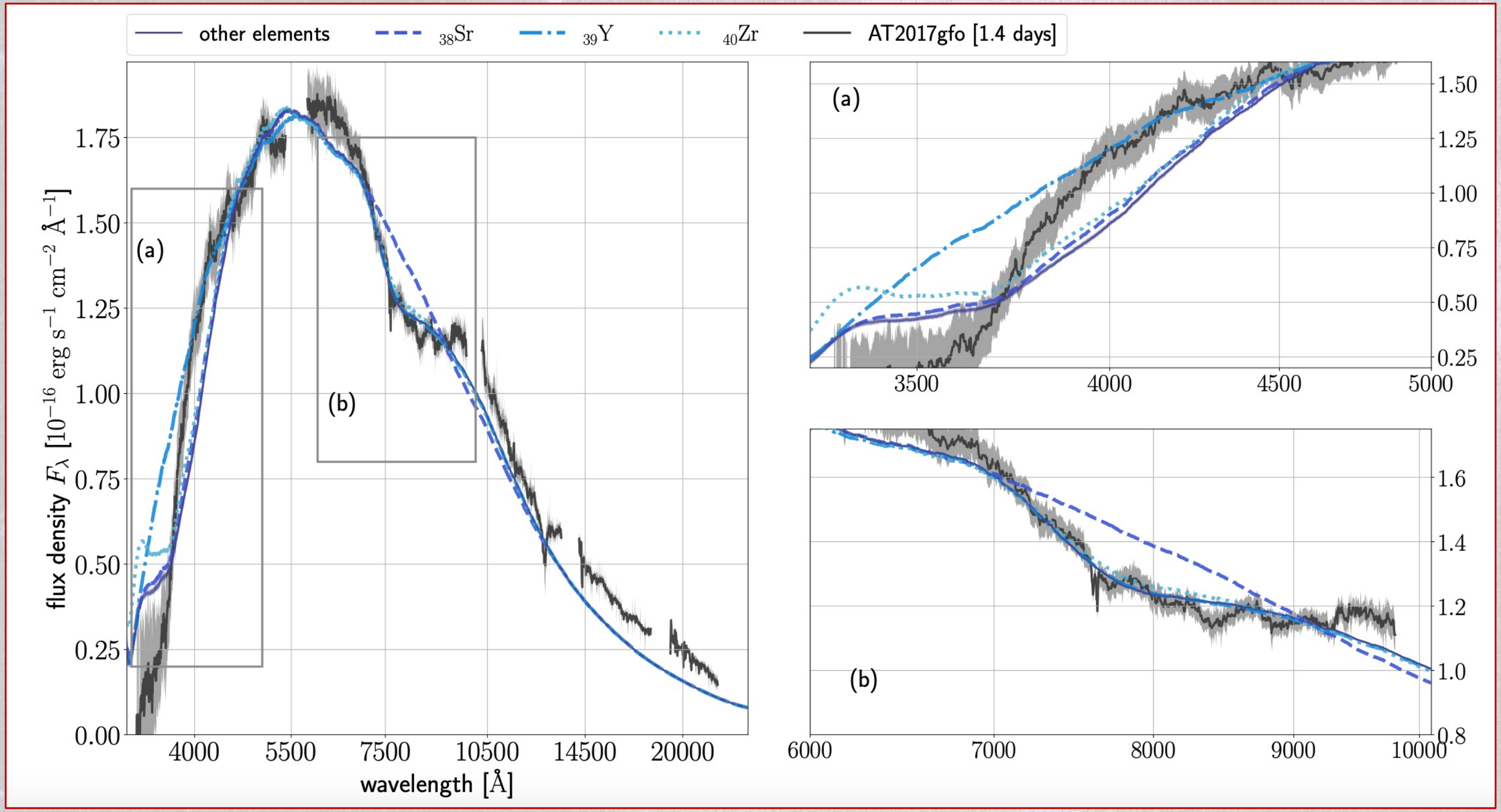


Figure 1. Schematic diagram that shows the populating mechanism of excited He.

Deficit of flux in the UV



Vieira et al. (2023)

Tentative evidence of Y II

- Gillanders et al. (2022)

Tentative evidece of Y II + Zr II

- Vieira et al. (2023)

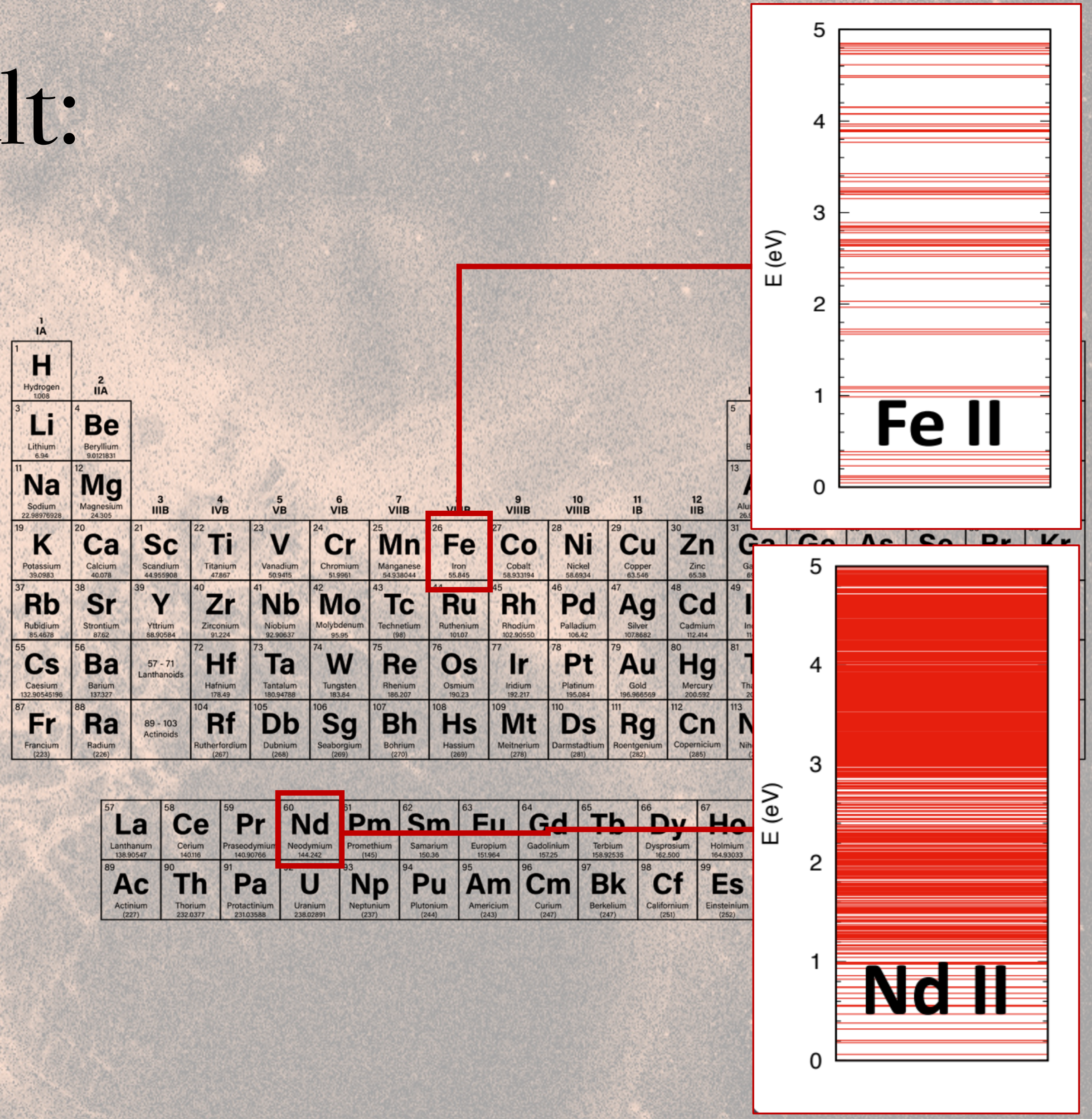
Spectral analysis is difficult:

1) Heavy elements have forest of lines hence strong blending

2) Relativistic velocity makes for extremely broad lines

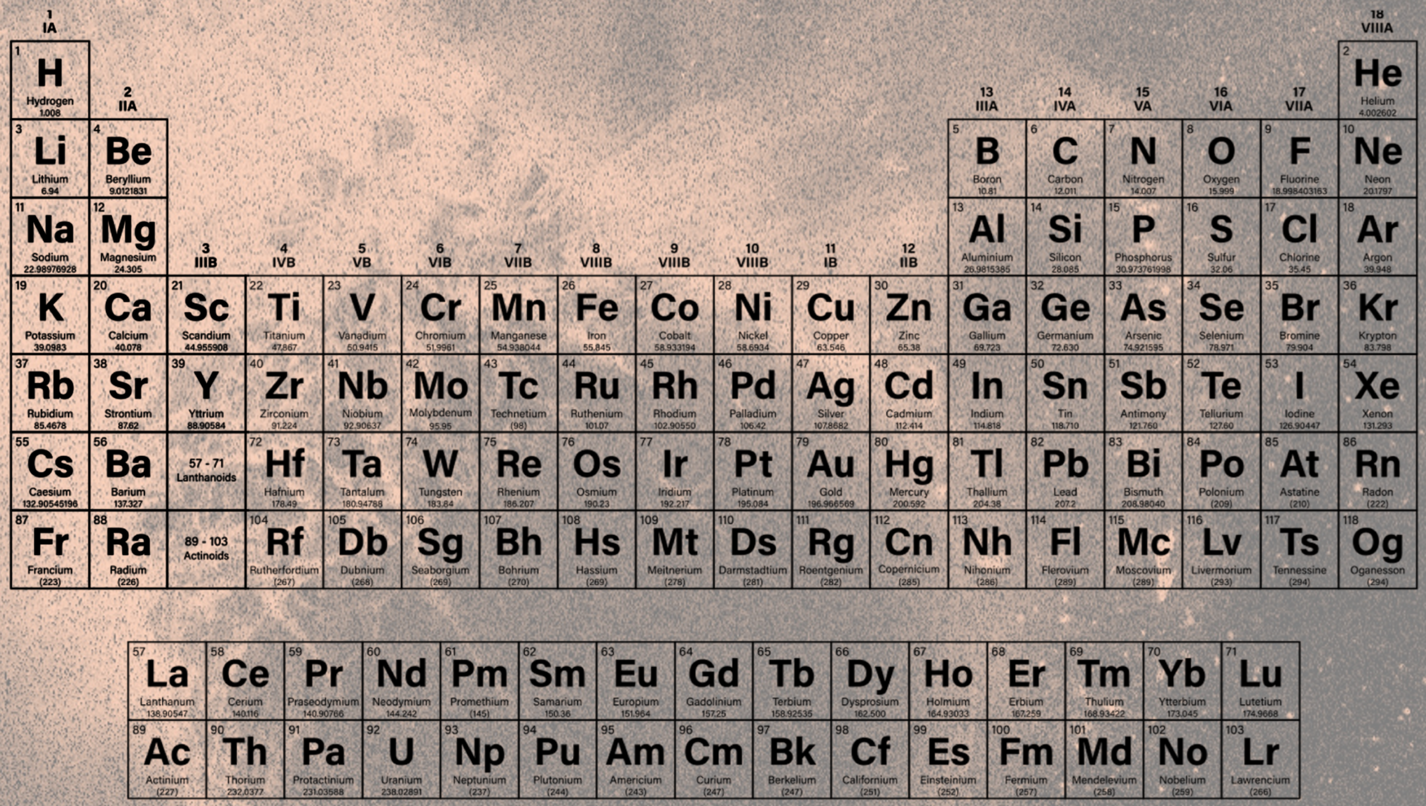
3) Atomic data are incomplete and uncertain - however for recent improvements see:

- Kasen et al (2017), Fontes et al (2020): Lanthanides (I-V)
- Tanaka et al. (2020) $26 \leq Z \leq 88$ (I-IV)
- Banerjee et al. (2020, 2022, 2023) $20 \leq Z \leq 88$ (V-XI)



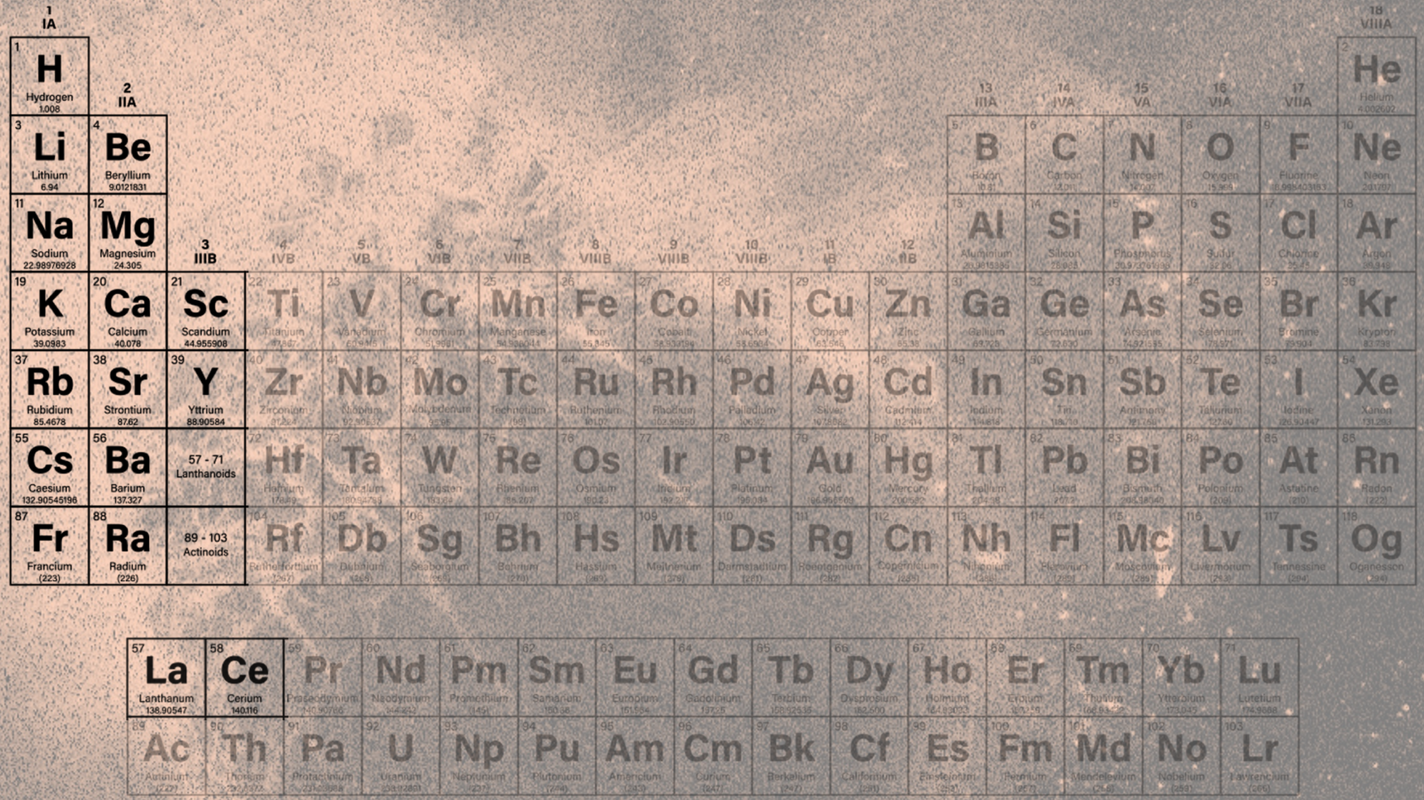
As elaborated in Masaomi's or Nanae's talks

How to make a prominent feature *(in the photospheric epoch)*



How to make a prominent feature *(in the photospheric epoch)*

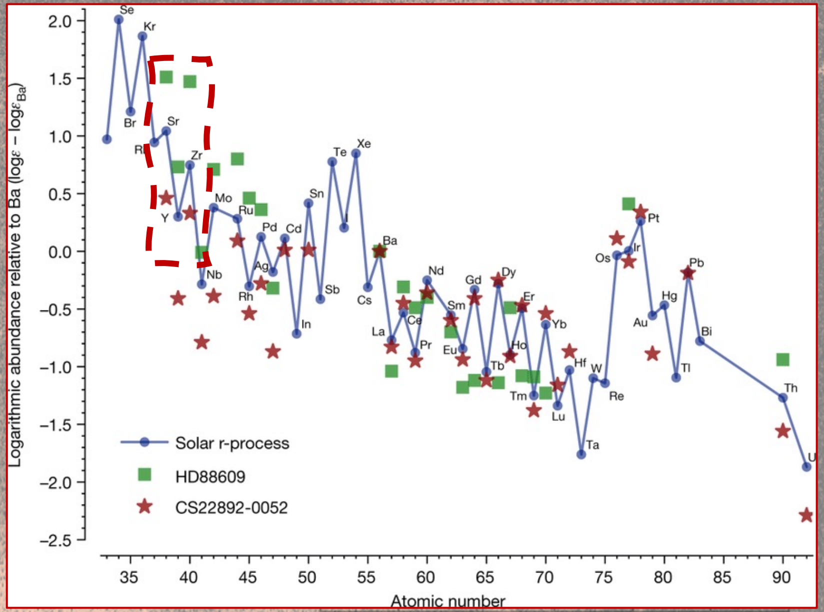
1) Small partition function

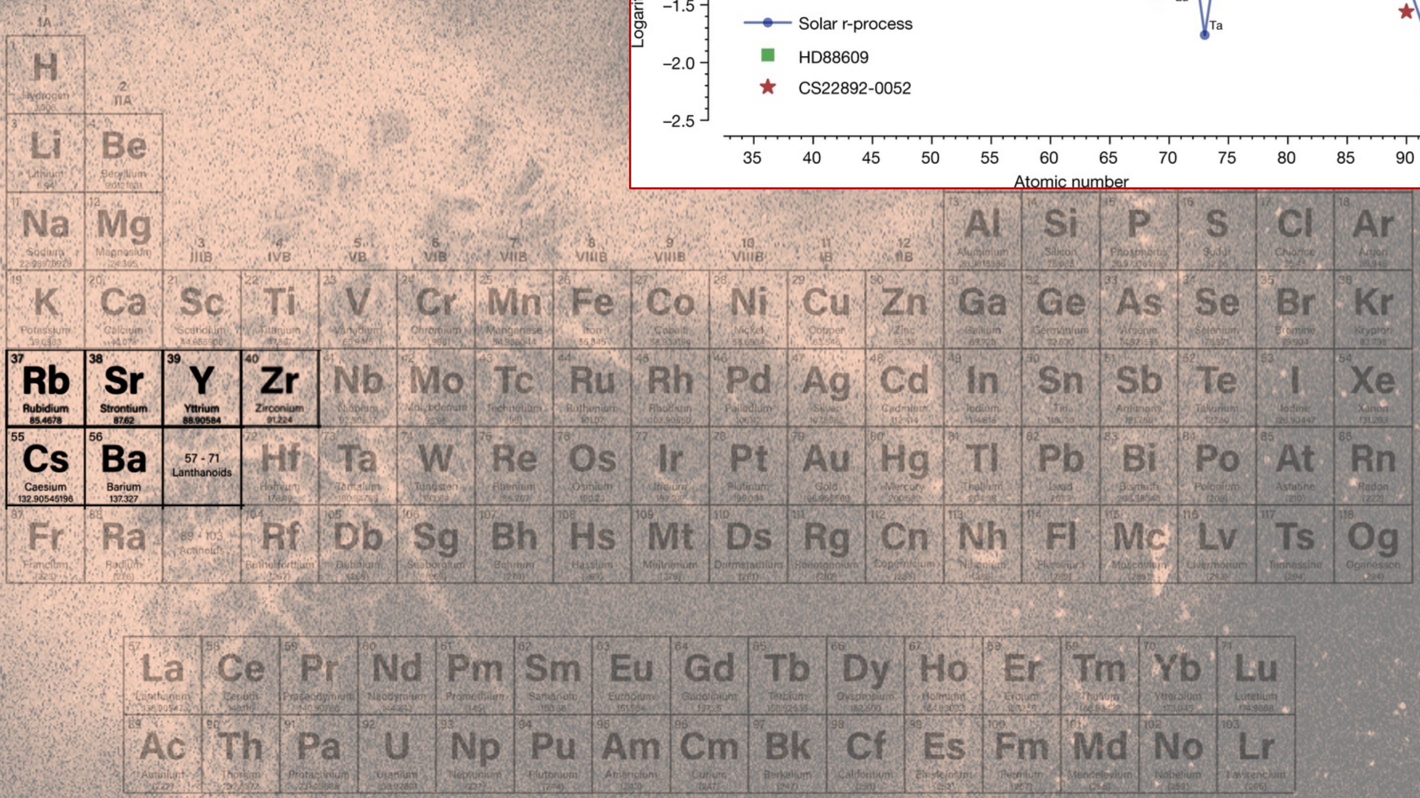


How to make a prominent feature

1) Small partition function

2) High abundance





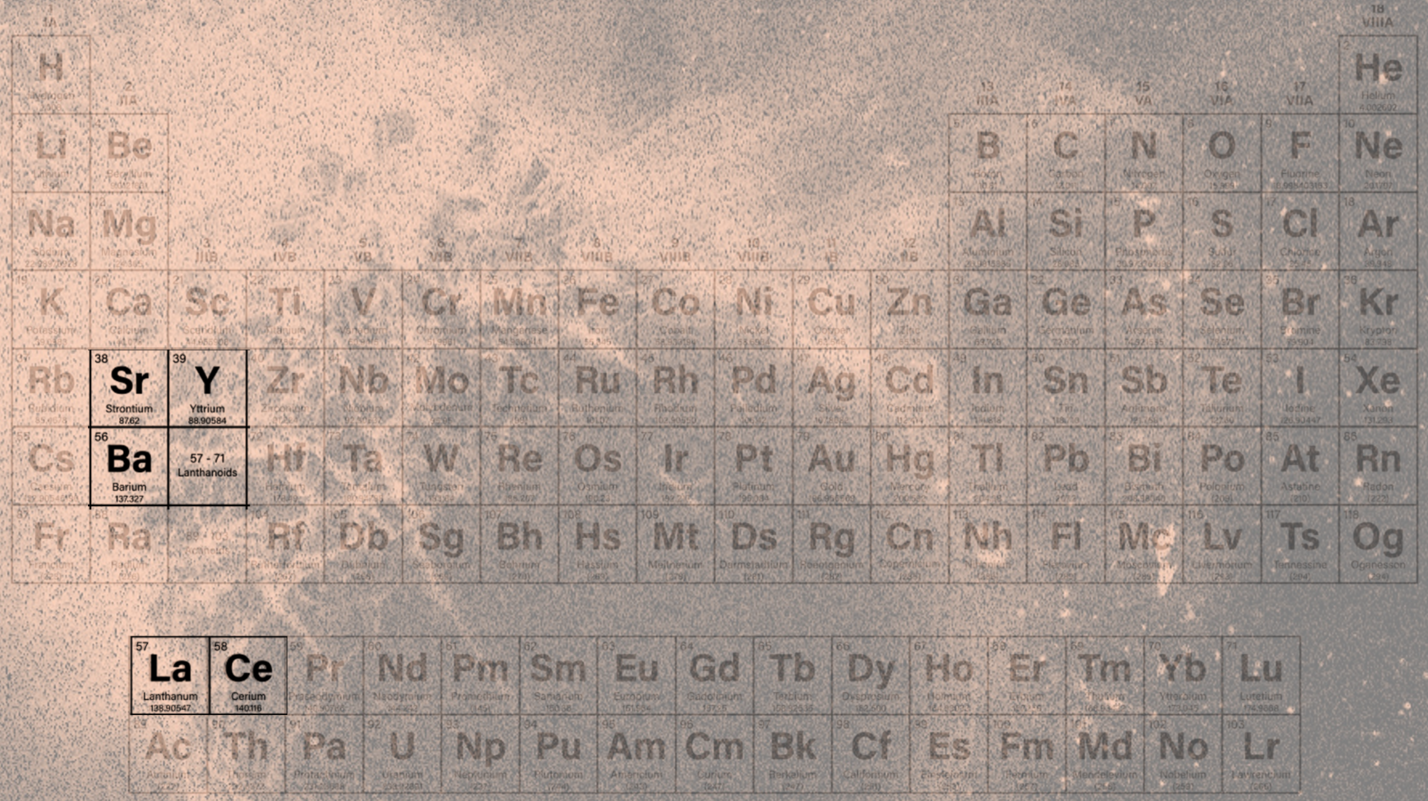
How to make a prominent feature *(in the photospheric epoch)*

1) Small partition function

2) High abundance

3) Transition lines with strong oscillator strength

4) Low-lying energy levels (which are easily accessible for the characteristic temperatures in the kilonova atmosphere)



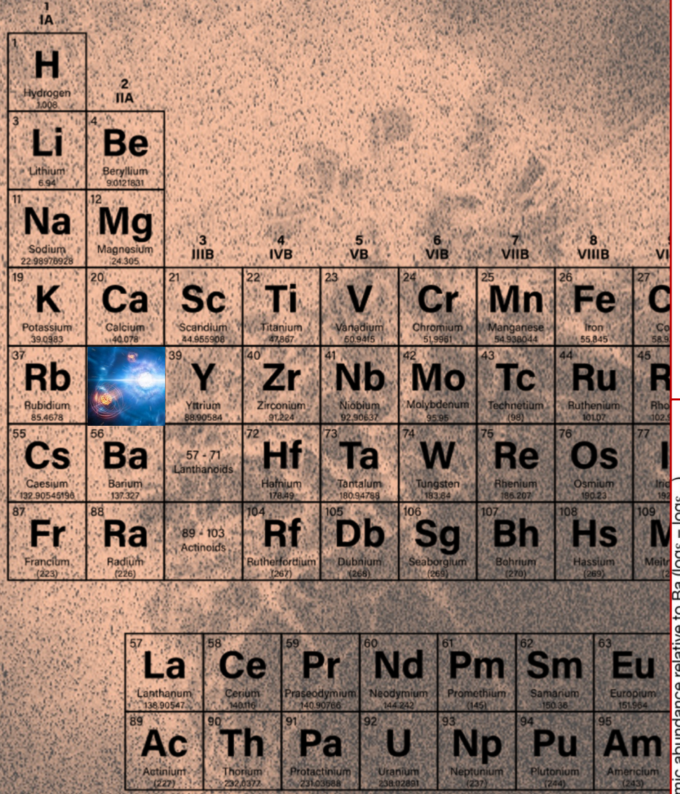
Strontium

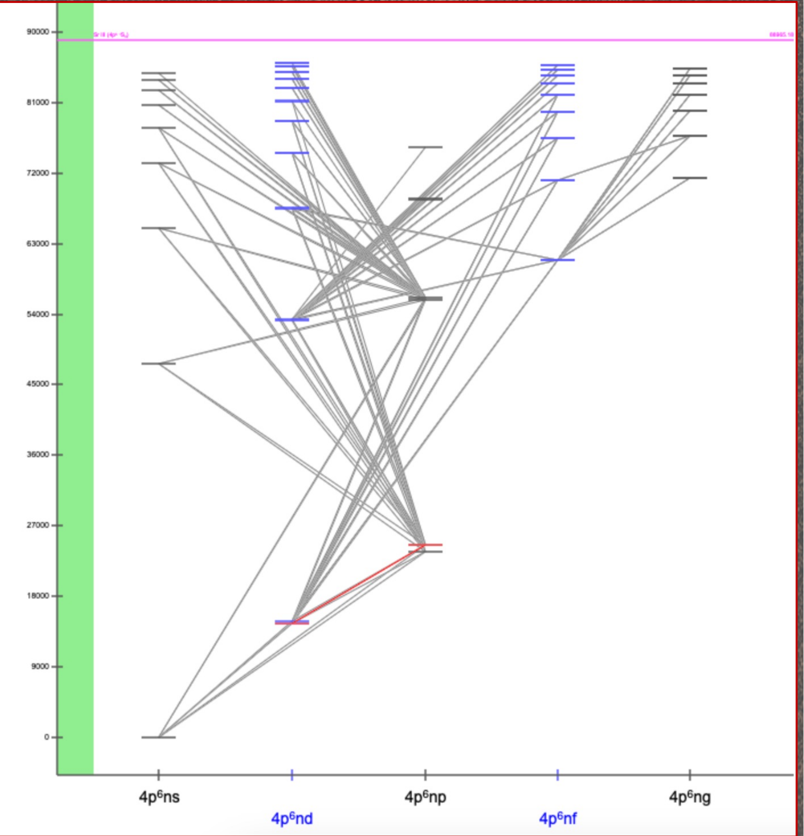
1) Small partition function

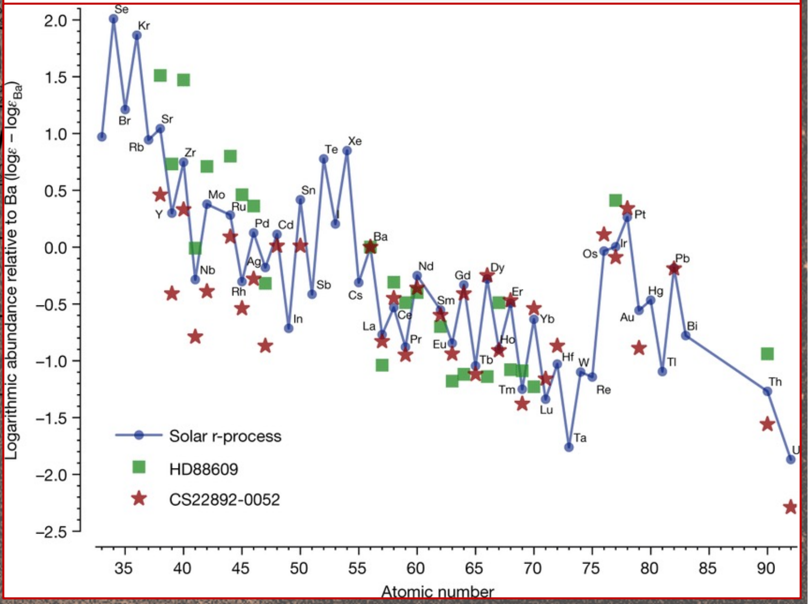
2) High abundance

3) Transition lines with strong oscillator strength

4) Low-lying energy levels
(which are easily accessible for the characteristic temperatures in the kilonova atmosphere)







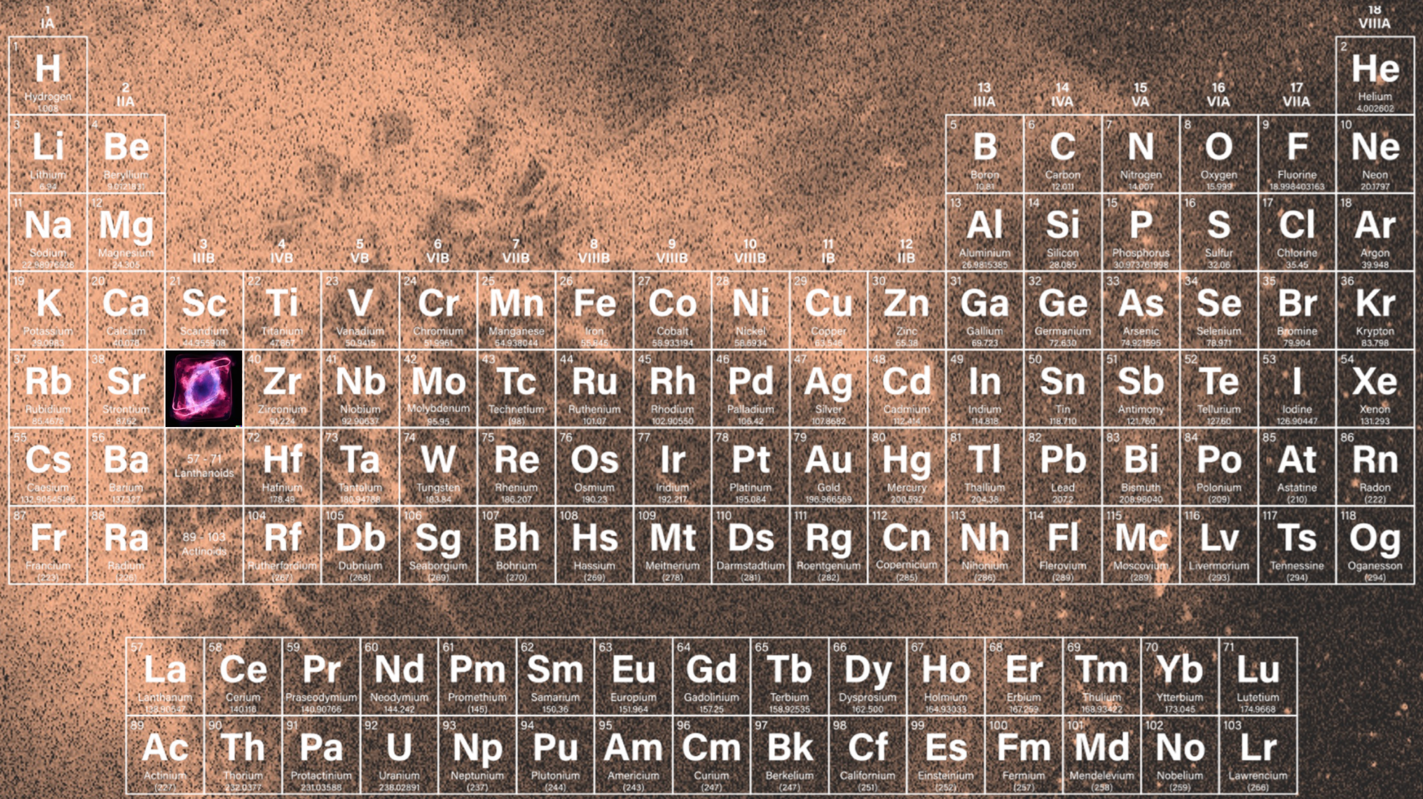
Yttrium

1) Small partition function

2) High abundance

3) Transition lines with strong oscillator strength

4) Low-lying energy levels
(which are easily accessible for the characteristic temperatures in the kilonova atmosphere)



Yttrium

1) Small partition function

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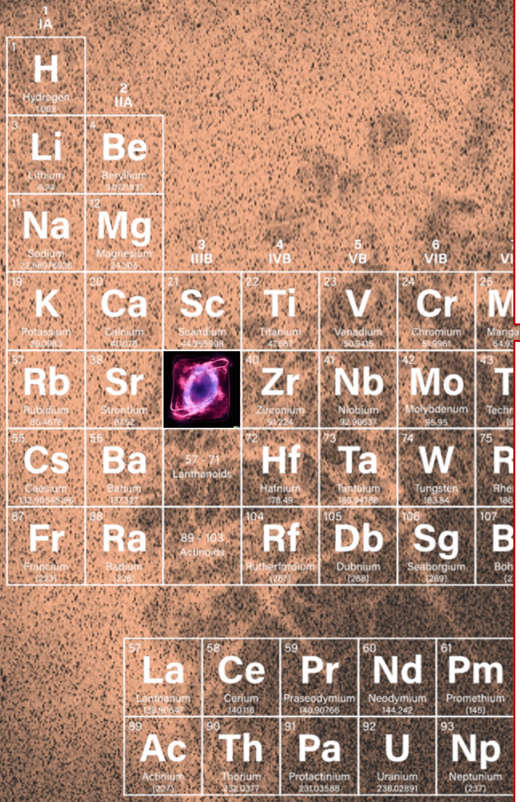
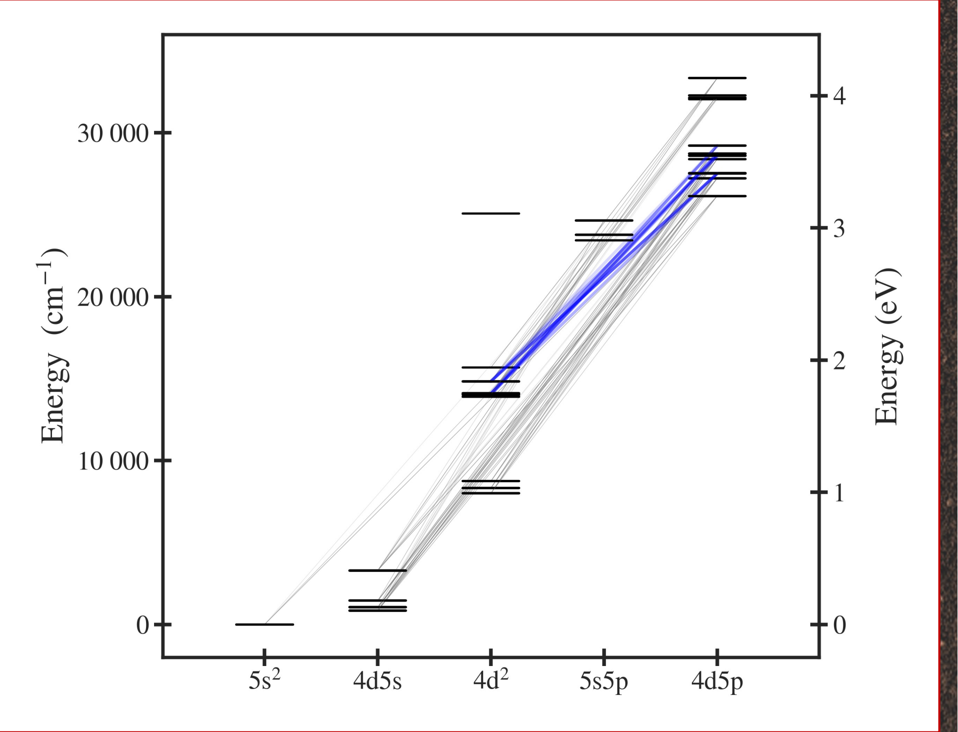
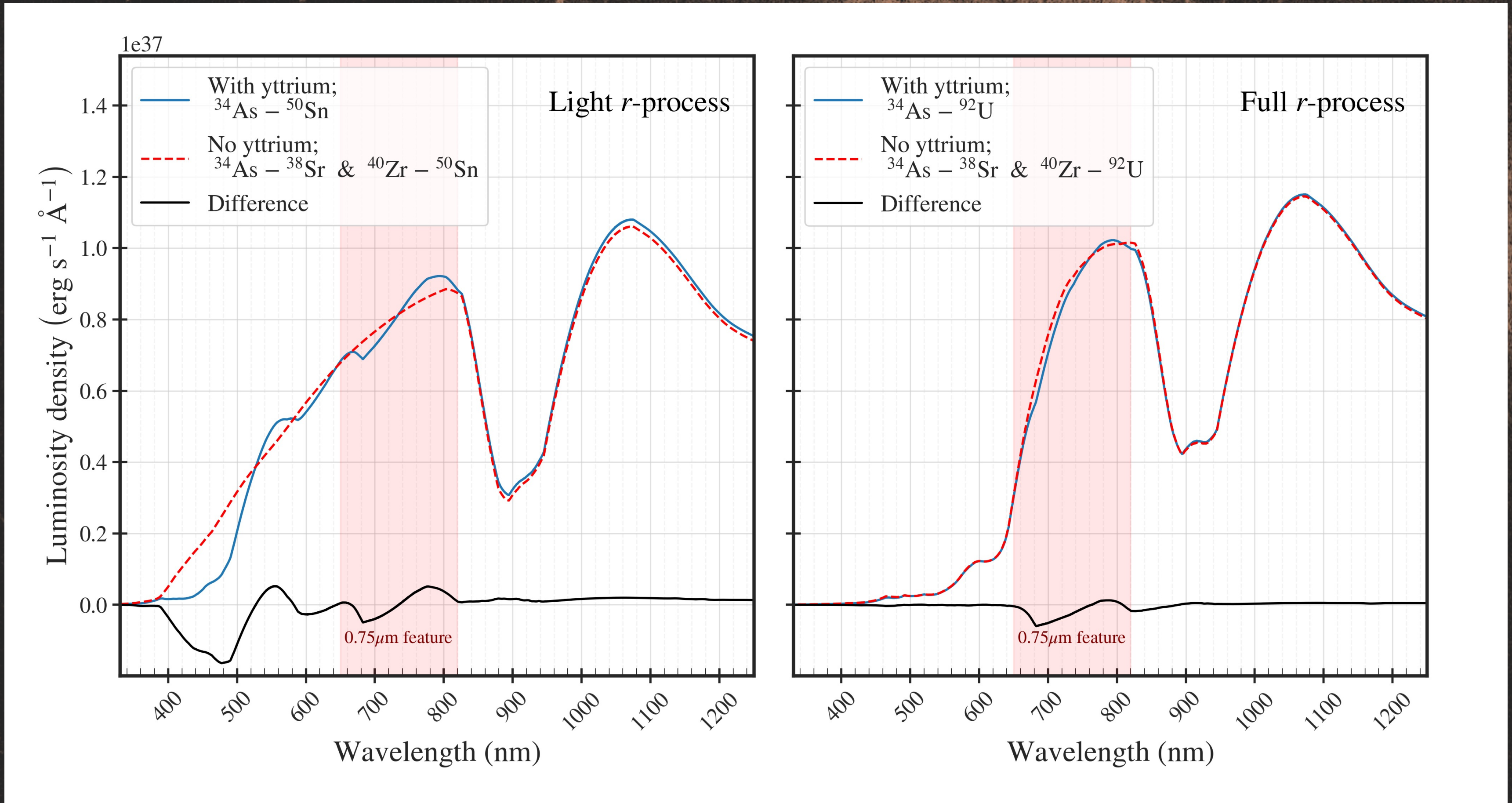




λ (nm)	Lower level 4d^2	E (cm^{-1})	Upper level 4d5p	E (cm^{-1})	log gf
788.19	b^1D_2	14 832	$z^1P^\circ_1$	27 517	−0.60
745.03	a^3P_2	14 098	$z^1P^\circ_1$	27 517	−1.44
733.29	a^3P_0	13 883	$z^1P^\circ_1$	27 517	−1.98
726.42	b^1D_2	14 832	$z^3D^\circ_1$	28 595	−1.11
689.60	a^3P_2	14 098	$z^3D^\circ_1$	28 595	−1.67
685.82	a^3P_1	14 018	$z^3D^\circ_1$	28 595	−1.69
683.24	a^3P_2	14 098	$z^3D^\circ_2$	28 730	−1.86
679.54	a^3P_0	13 883	$z^3D^\circ_1$	28 595	−1.54
679.53	a^3P_1	14 018	$z^3D^\circ_2$	28 730	−1.03
661.37	a^3P_2	14 098	$z^3D^\circ_3$	29 213	−0.83

TARDIS Model

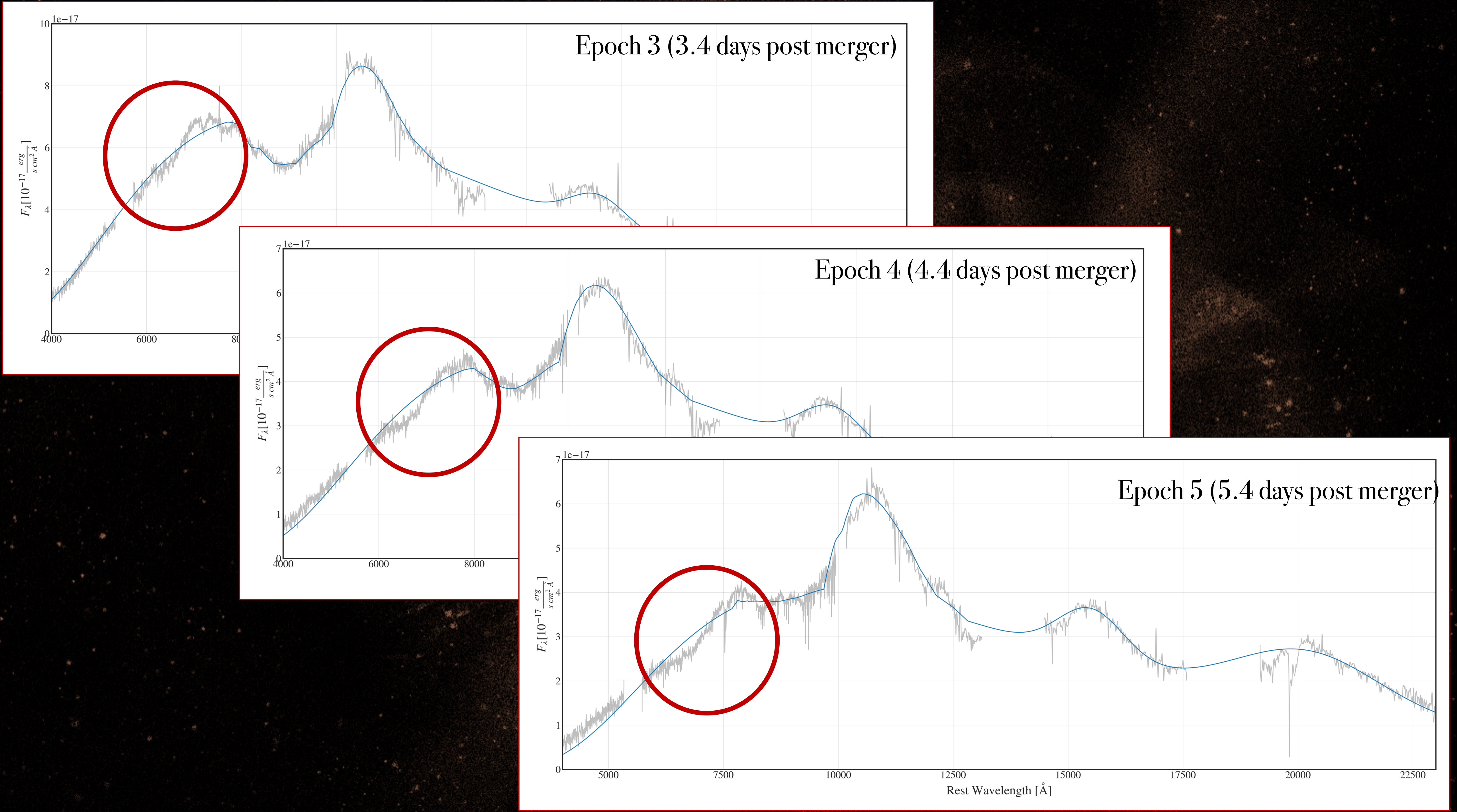


Sneppen & Watson (2023), A&A

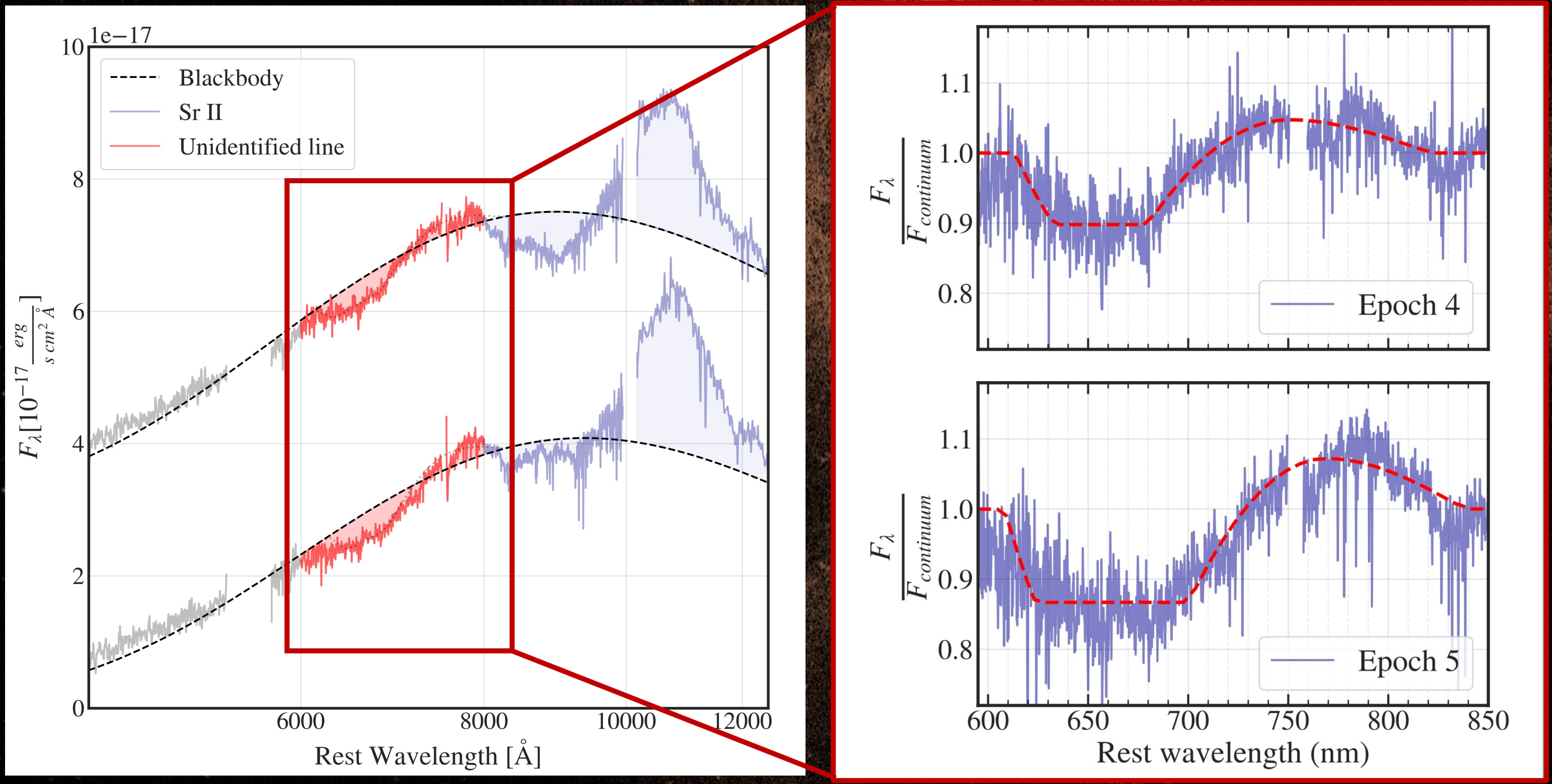
1) The presence of Sr II requires Y II to be present

2) If Y II is present the line transitions *4d5p-4d*^{2} will produce a P Cygni around 760 nm

Thus, a P Cygni at 760 nm is a prediction of the Sr II identification


Epoch 3 (3.4 days post merger)
Epoch 4 (4.4 days post merger)
Epoch 5 (5.4 days post merger)
$F_\lambda [10^{-17} \frac{erg}{s\,cm^2\,\AA}]$
1e−17
Rest Wavelength [Å]

Significant feature…



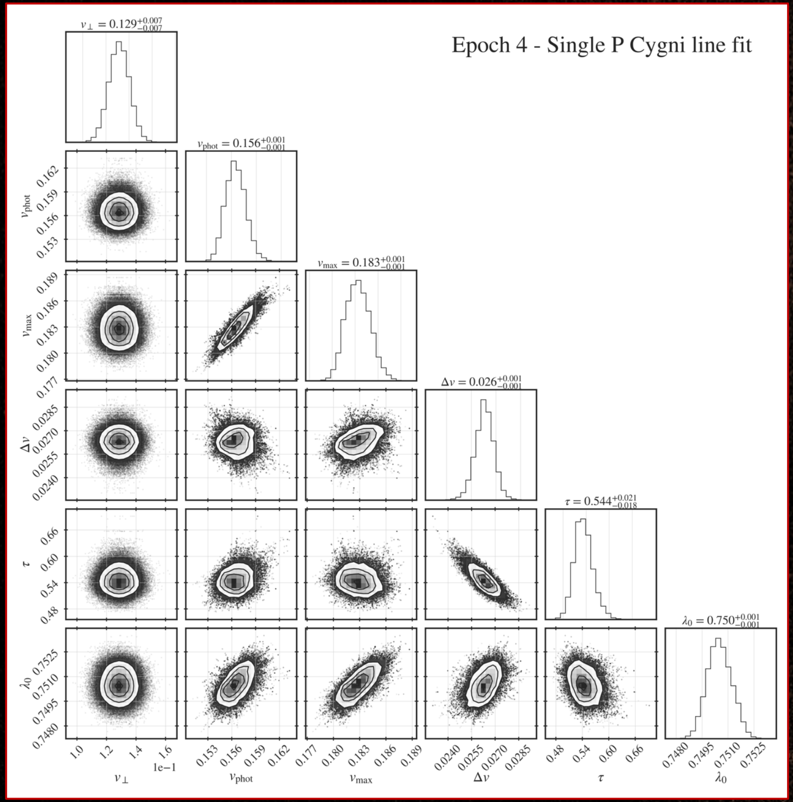
$\Delta\chi^2$ = 4219 and 5590

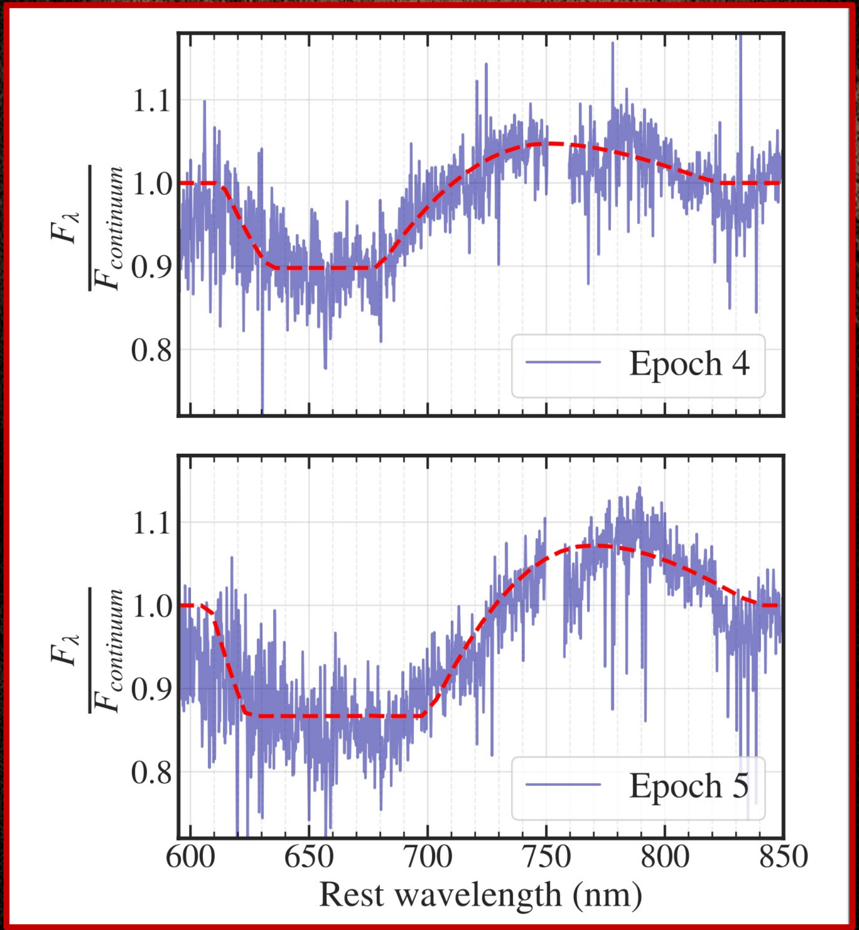
for epochs 4 & 5 respectively

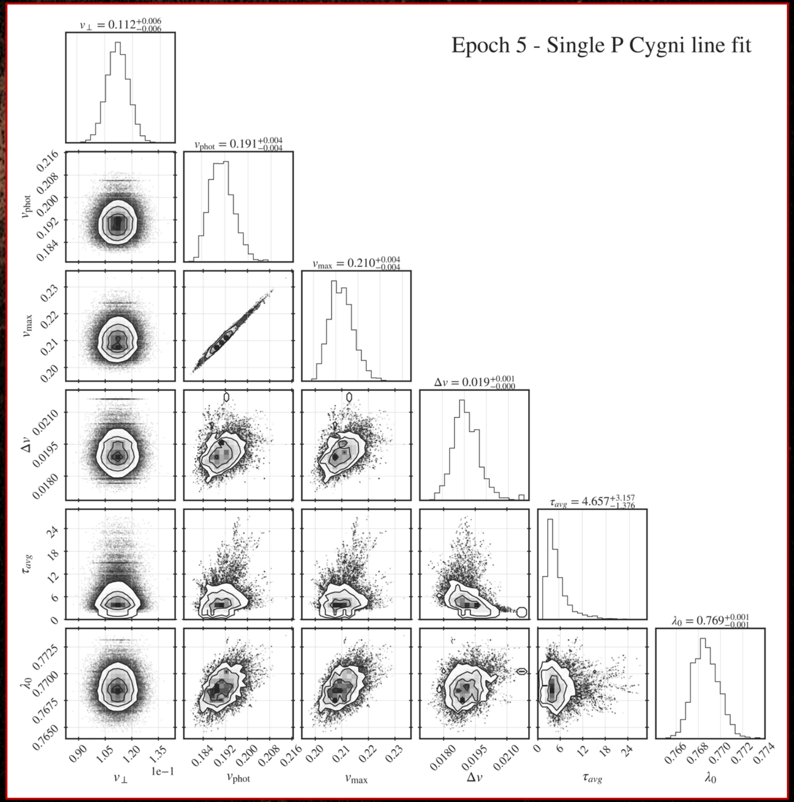
for 5 additional degrees of freedom

Sneppen & Watson (2023), A&A

… with a "correct" central wavelength

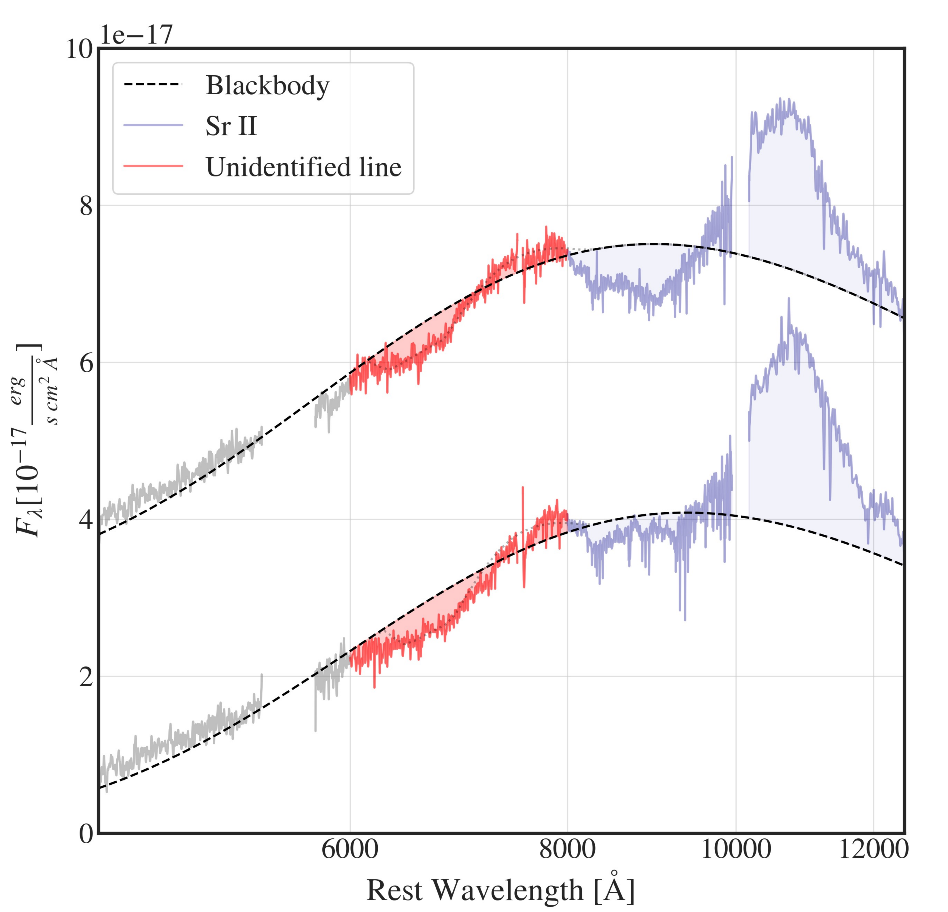






Sneppen & Watson (2023), A&A

… and a consistent expansion velocity with Sr



Sneppen & Watson (2023), A&A

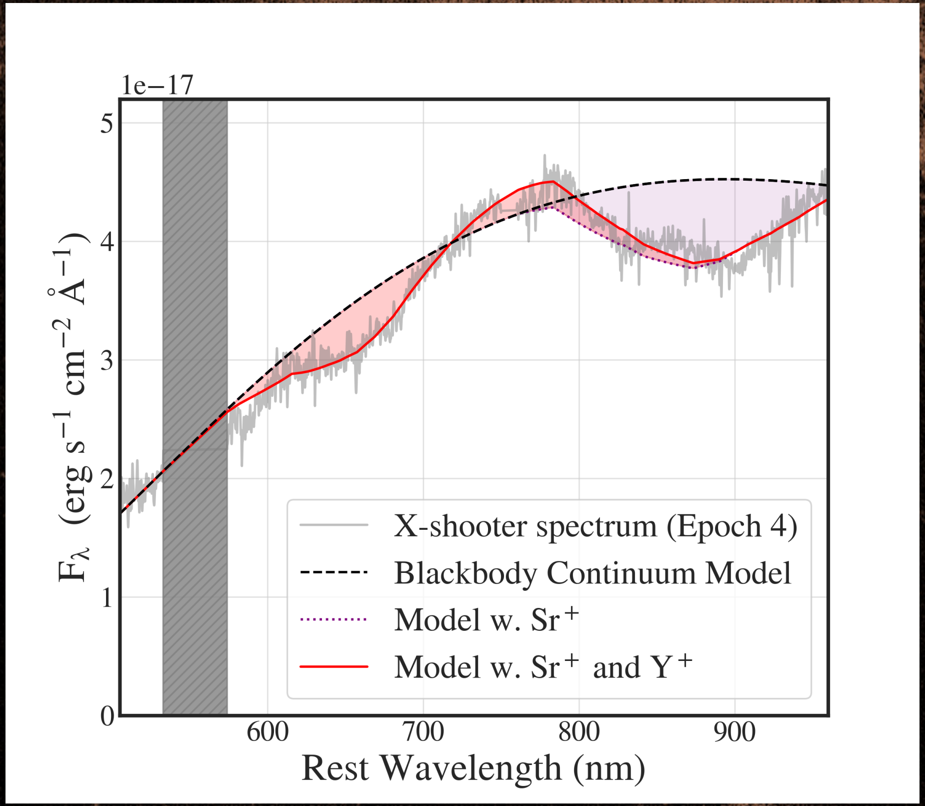
… and a reasonable prominence

Inferred mass:

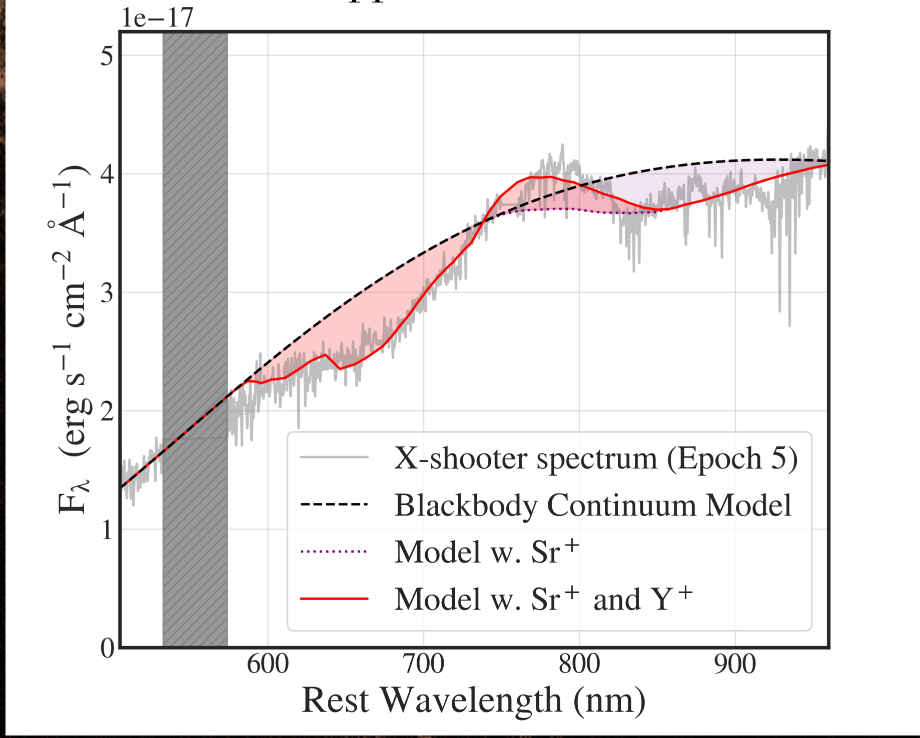
$M_Y \approx 2 \cdot 10^{-4} M_\odot$

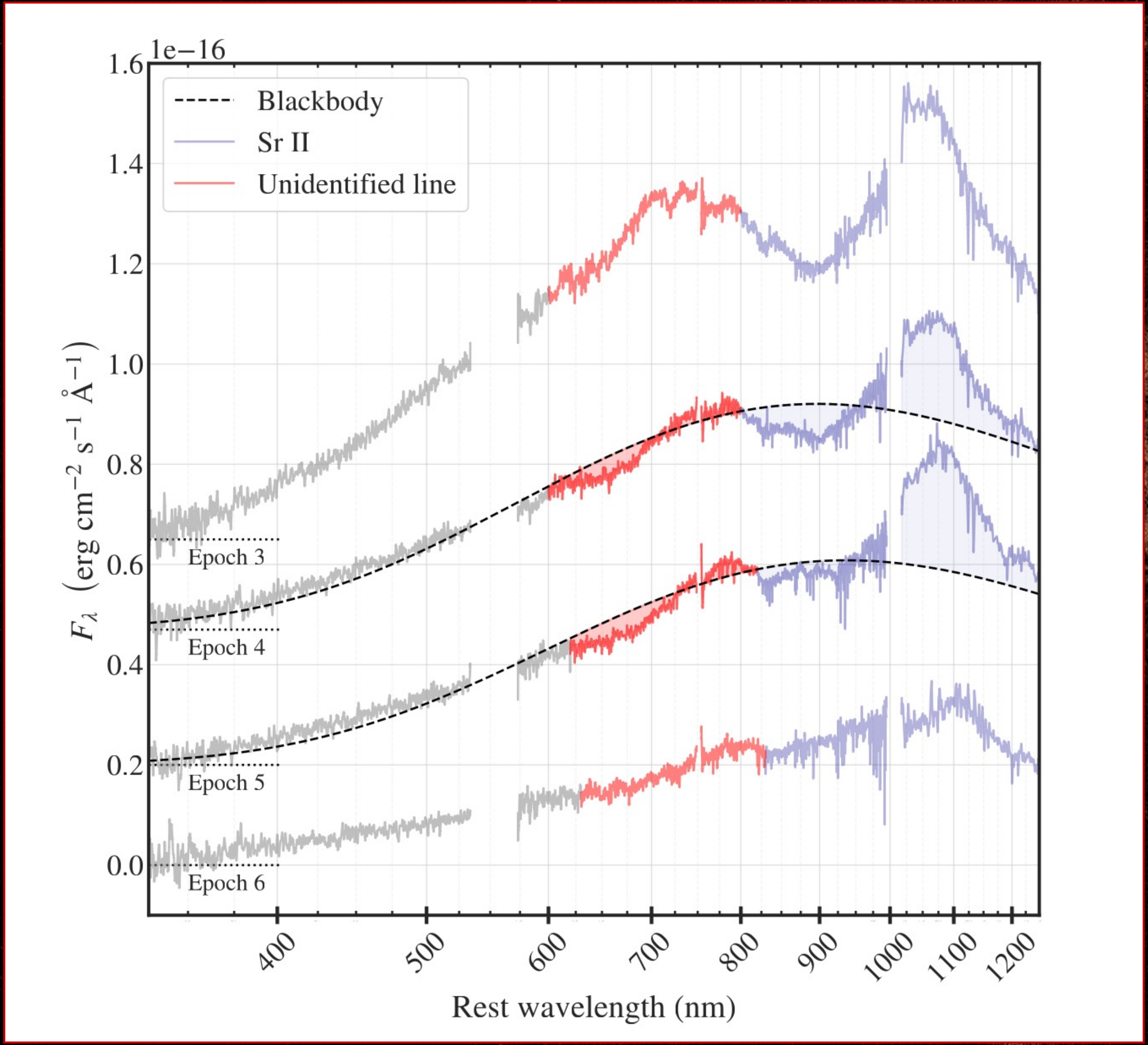
(that is around 0.5 to 0.8 %

of ejected mass is Yttrium)

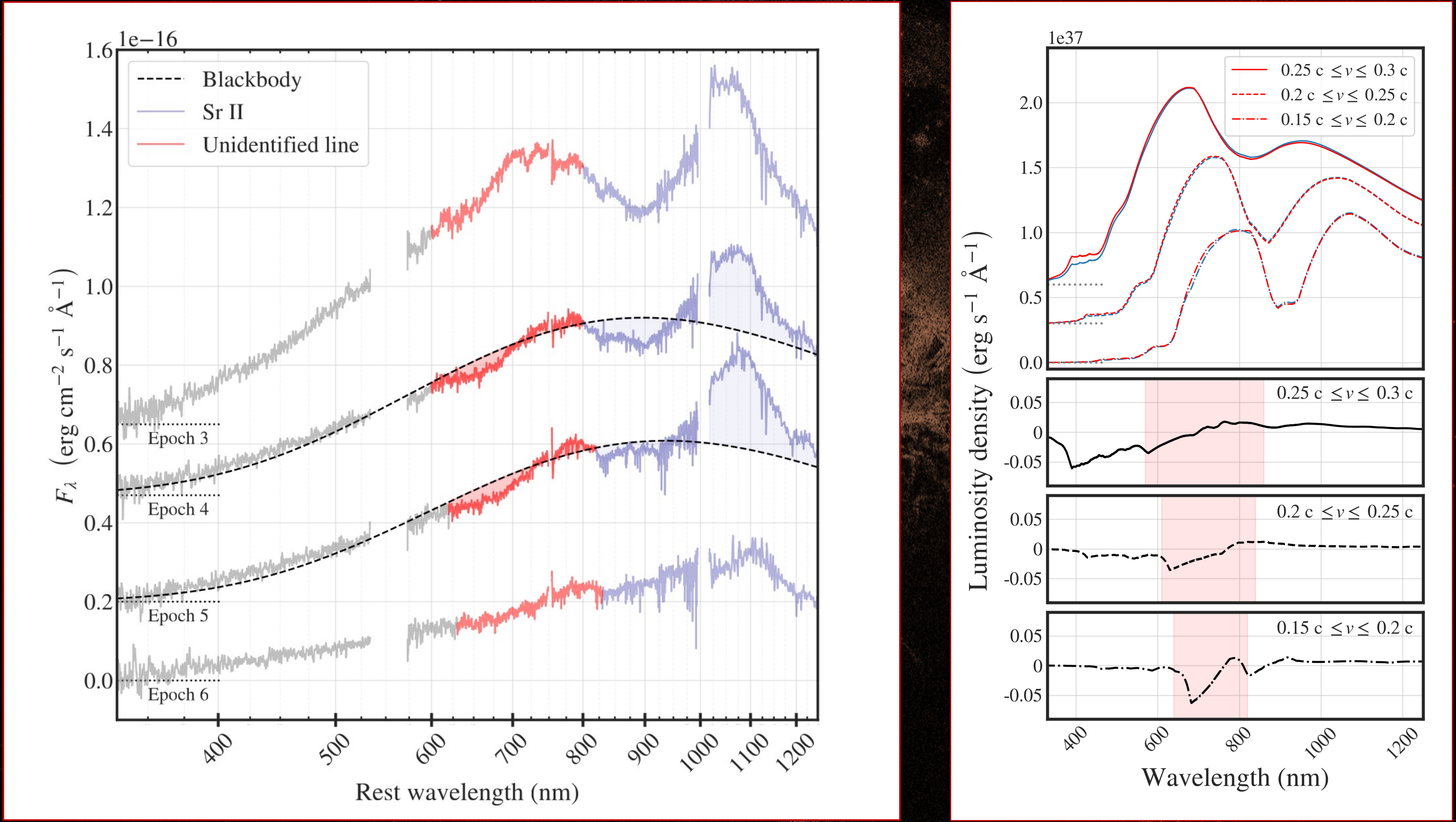


Sneppen & Watson (2023), A&A

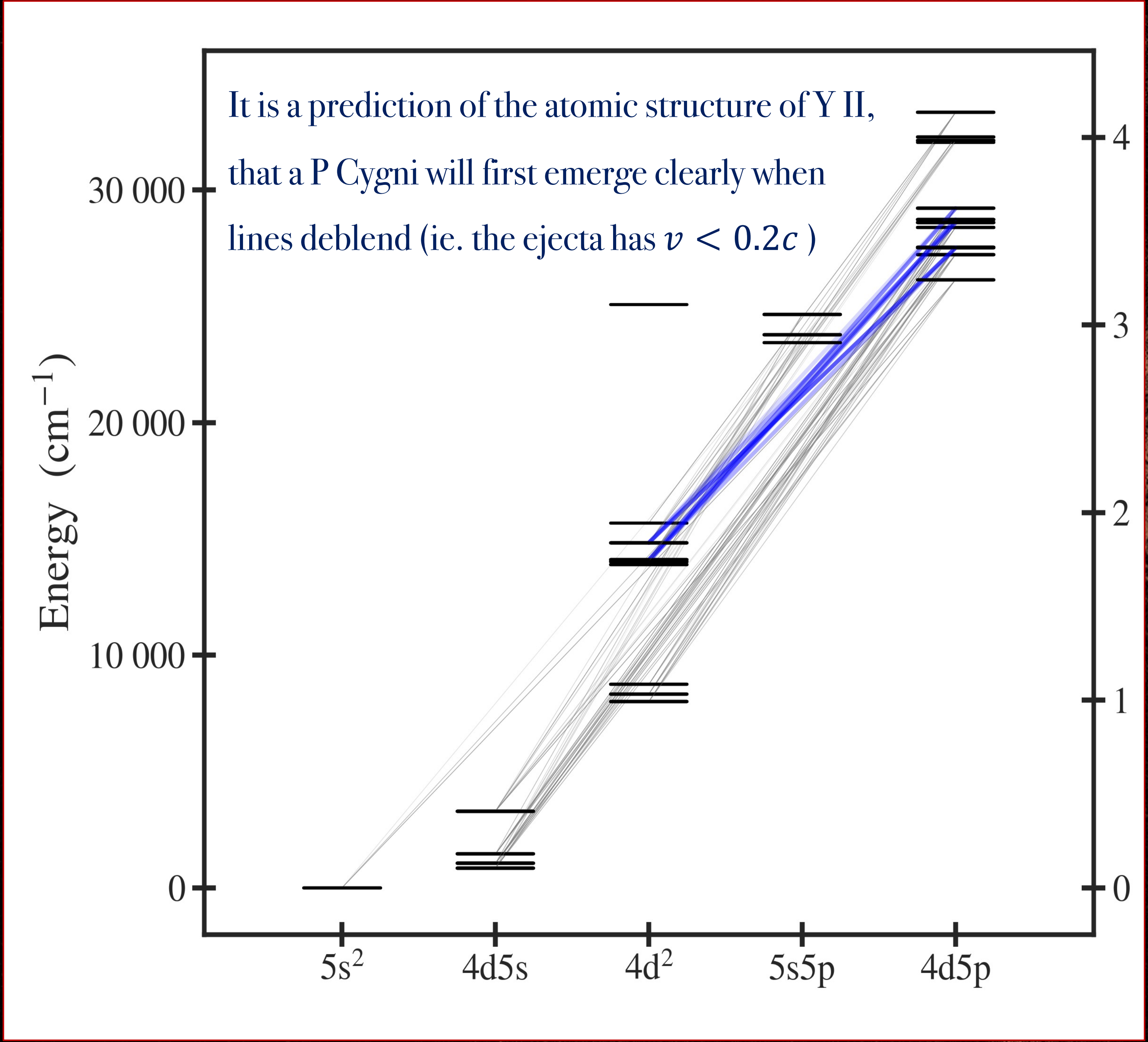


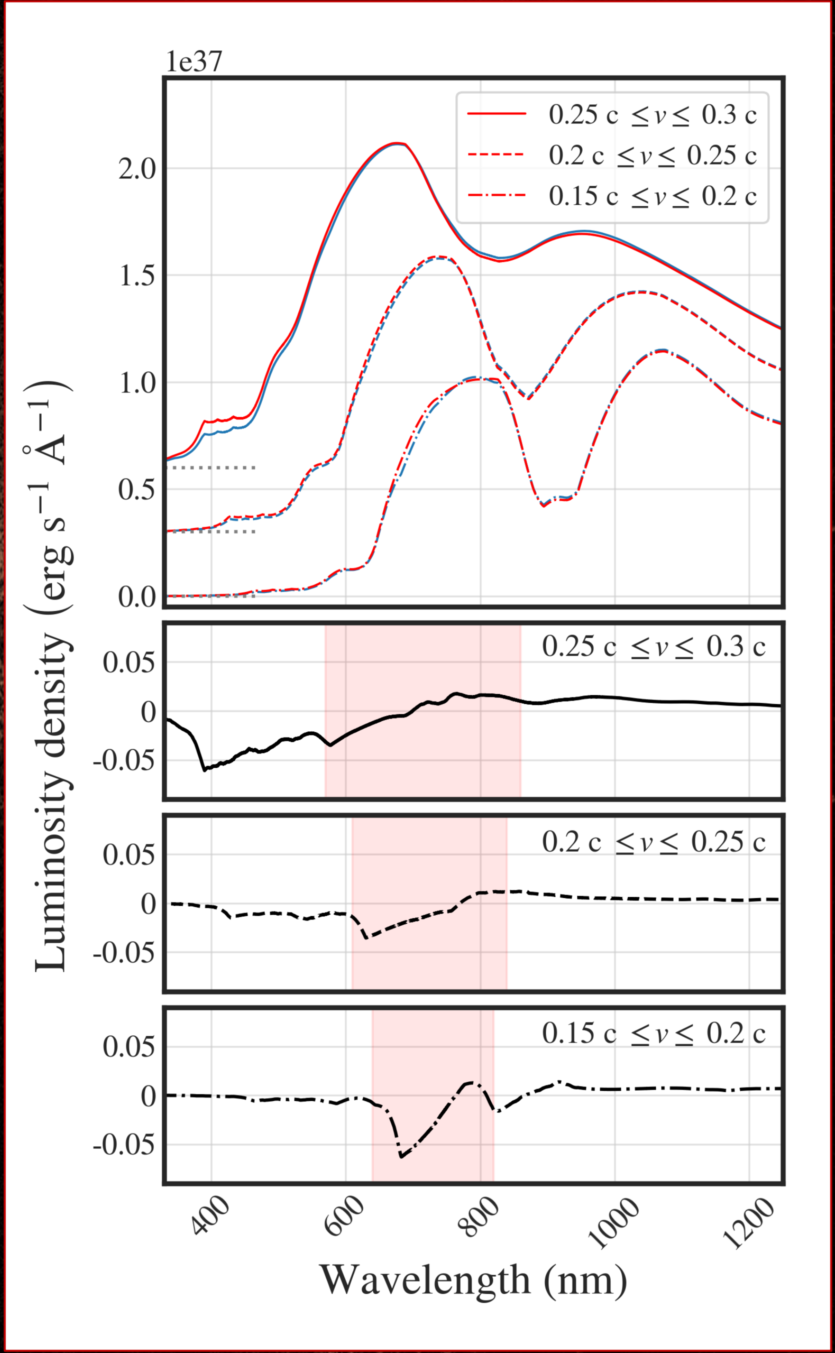


… but appears later than the Sr^{+} feature?

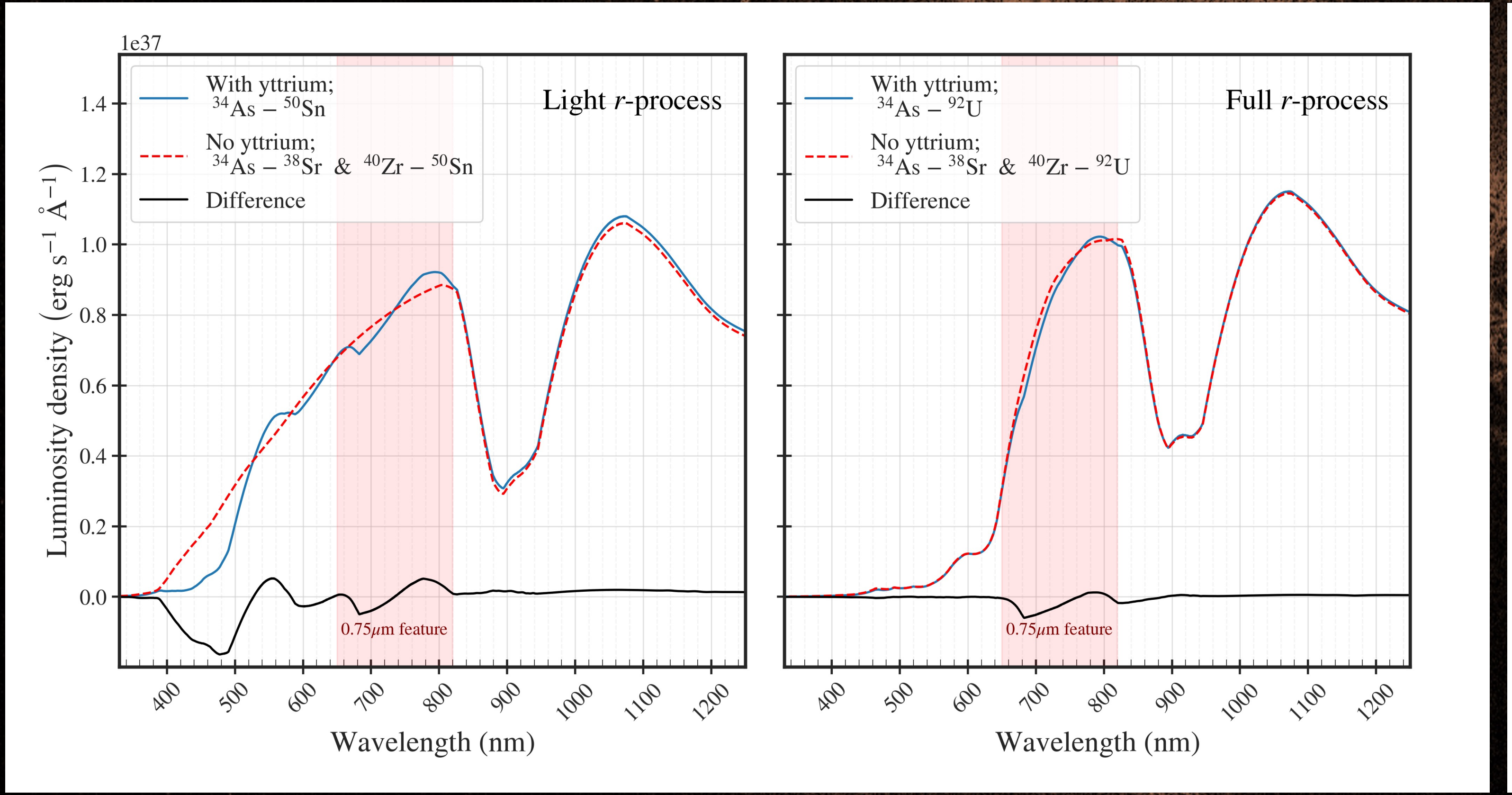


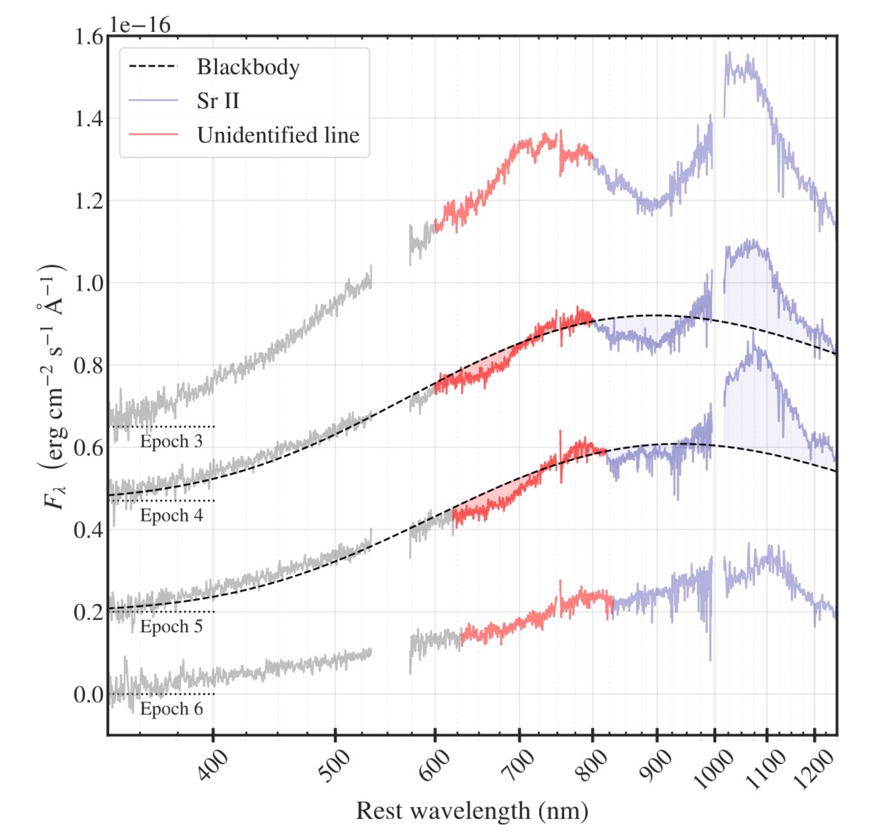
1e−16
Blackbody
Sr II
Unidentified line
Epoch 3
Epoch 4
Epoch 5
Epoch 6
F_λ (erg cm^{-2} s^{-1} Å^{-1})
Rest wavelength (nm)
1e37
0.25 c ≤ v ≤ 0.3 c
0.2 c ≤ v ≤ 0.25 c
0.15 c ≤ v ≤ 0.2 c
Luminosity density (erg s^{-1} Å^{-1})
Wavelength (nm)


It is a prediction of the atomic structure of Y II,
that a P Cygni will first emerge clearly when
lines deblend (ie. the ejecta has $v < 0.2c$)
Energy (cm^{-1})
30 000
20 000
10 000
0
4
3
2
1
0
5s^2
4d5s
4d^2
5s5p
4d5p


1e37
0.25 c ≤ v ≤ 0.3 c
0.2 c ≤ v ≤ 0.25 c
0.15 c ≤ v ≤ 0.2 c
2.0
1.5
1.0
0.5
0.0
0.05
0
-0.05
Luminosity density (erg s^{-1} Å^{-1})
400
600
800
1000
1200
Wavelength (nm)

Y II constraining the line-blanketing?





Sneppen & Watson (2023)

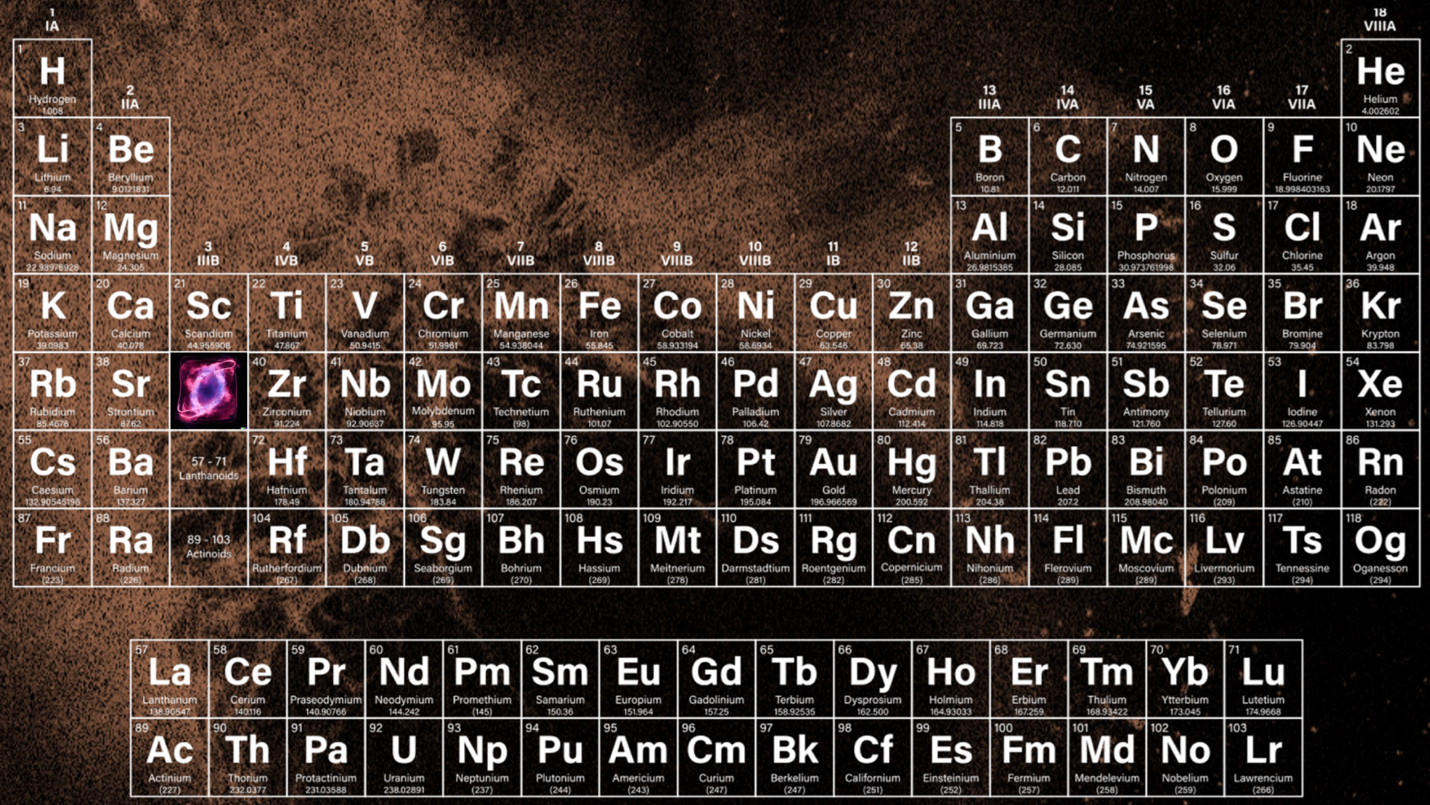
Takeaway messages

1) P Cygni signature observed in KN photosphere, which is $\approx 30\sigma$ significant .

2) The 2nd *"clear"* identification of an r-process element (Yttrium)

Consistent with Y II in terms of:

- Central wavelength
- Prominence (abundance)
- Velocity
- Timing of emergence



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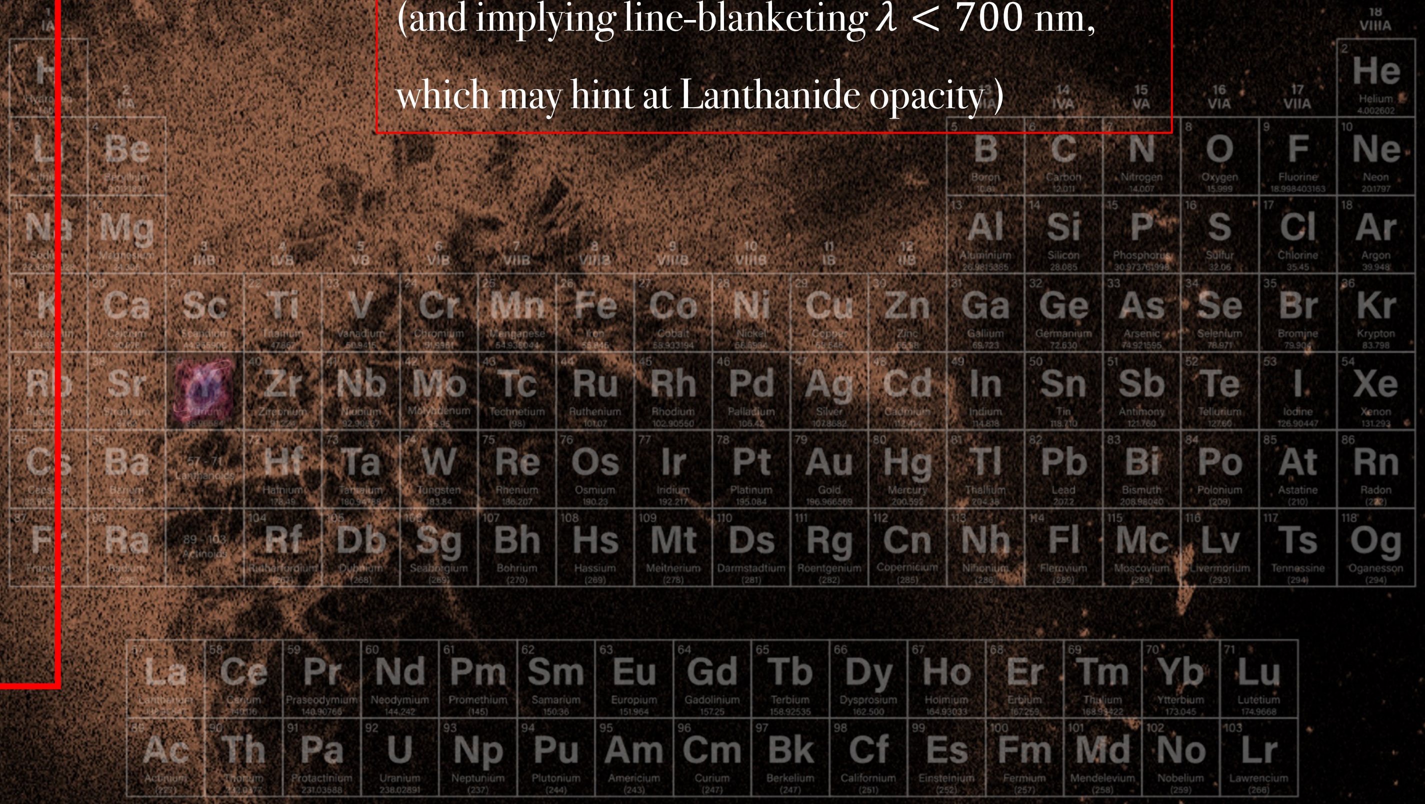
Explicitly revealing information on the KN **composition**,
(and implying line-blanketing $\lambda < 700$ nm, which may hint at Lanthanide opacity)



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Explicitly revealing information on the KN **composition**, (and implying line-blanketing $\lambda < 700$ nm, which may hint at Lanthanide opacity)

Providing new probes of the **velocity stratification** (consistent with the $1\mu m$ P Cygni)

Takeaway messages

1) P Cygni signature observed in KN photosphere, which is ≈30σ significant .

2) The 2nd *"clear"* identification of an r-process element (Yttrium)

Consistent with Y II in terms of:

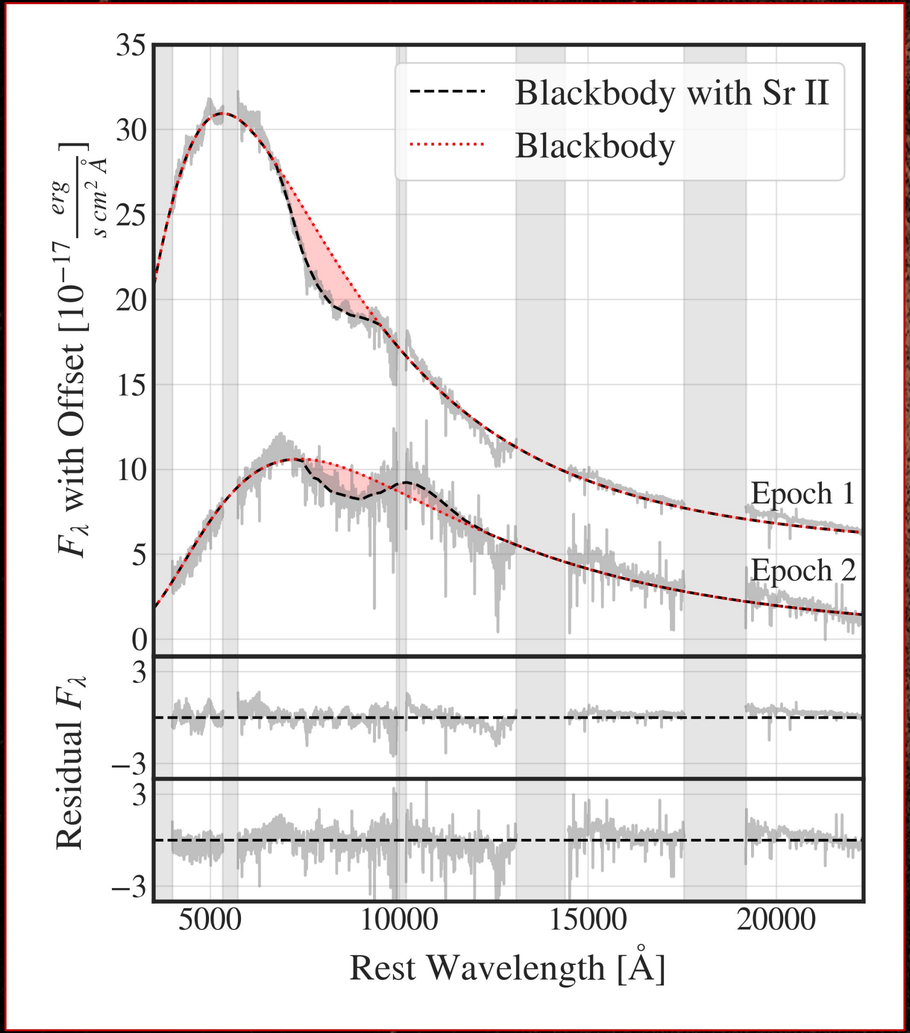
- Central wavelength
- Prominence (abundance)
- Velocity
- Timing of emergence

Explicitly revealing information on the KN **composition**, (and implying line-blanketing $\lambda < 700$ nm, which may hint at Lanthanide opacity)

Providing new probes of the **velocity stratification** (consistent with the $1\mu m$ P Cygni)

The deblending of Y II lines predicts the feature should first appear (marginally) in epoch 3 and be a fully P Cygni in epoch 4.

One last puzzle…



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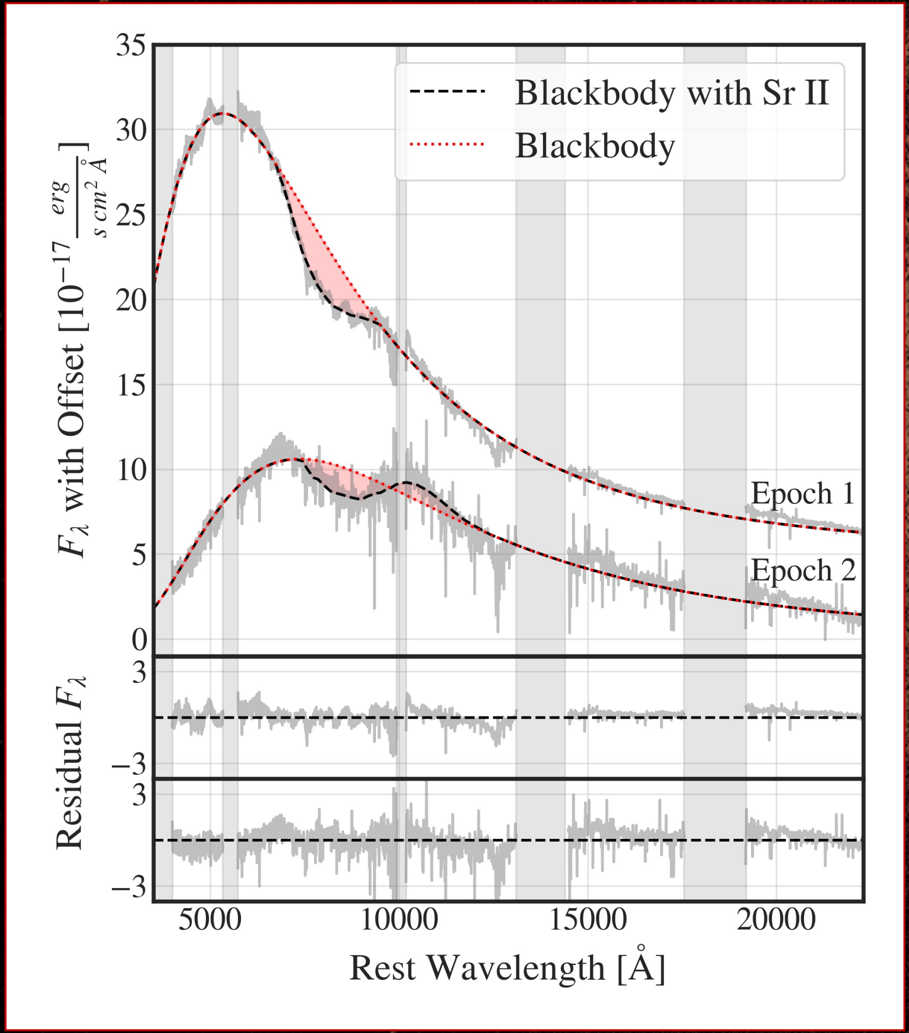
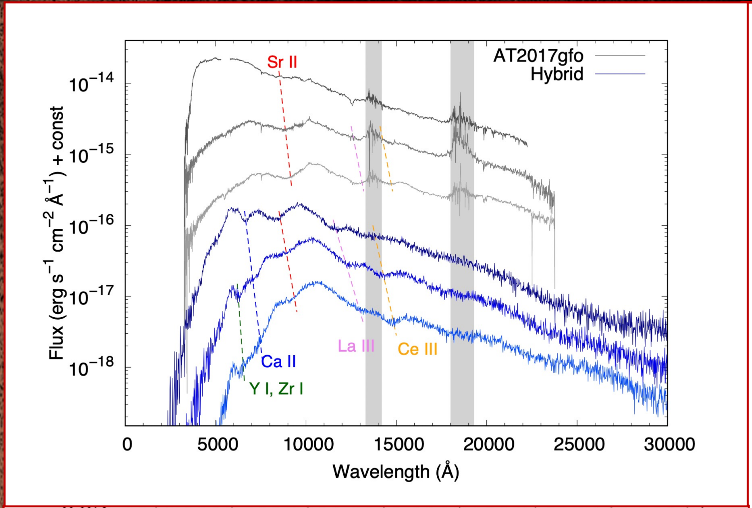
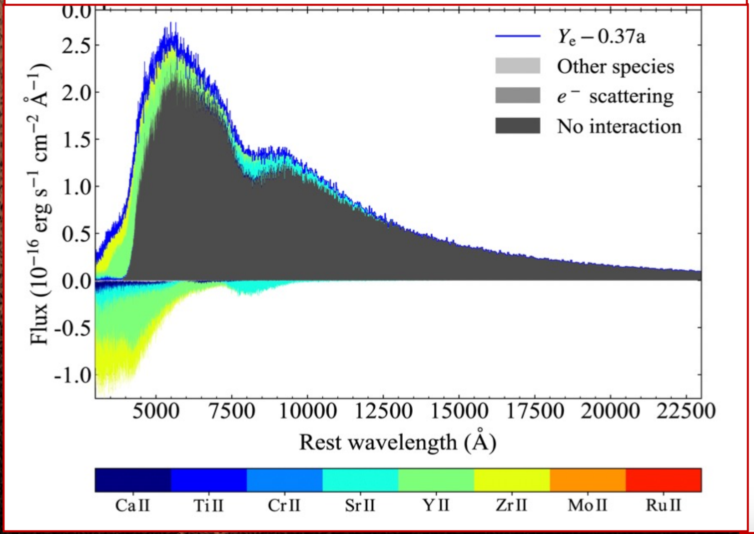
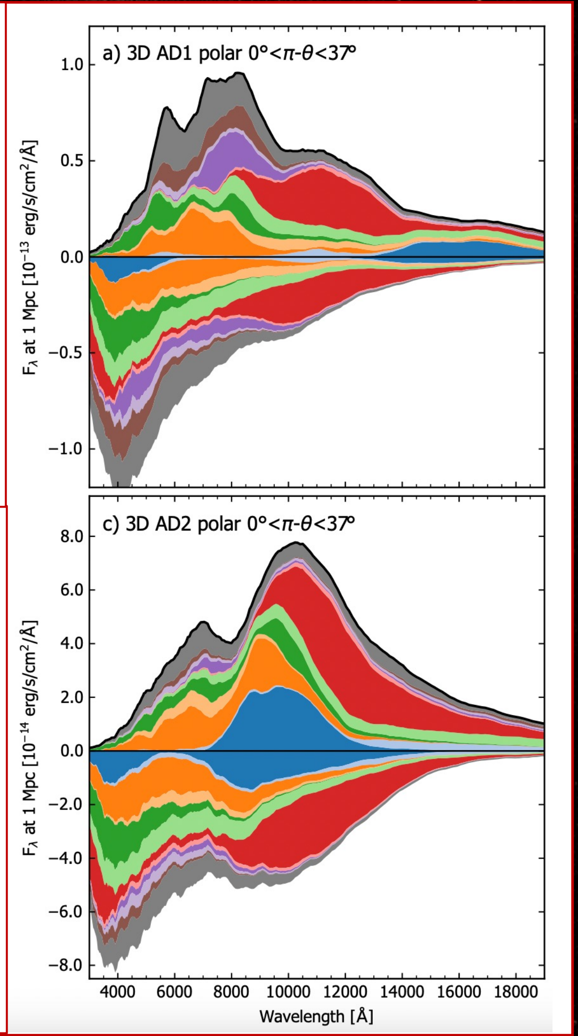


Domoto et al. (2022)





Gillanders et al. (2022)



Shingles et al. (2023)

… On the blackbody spectrum of kilonovae

In press, ApJ

On the Blackbody Spectrum of Kilonovae

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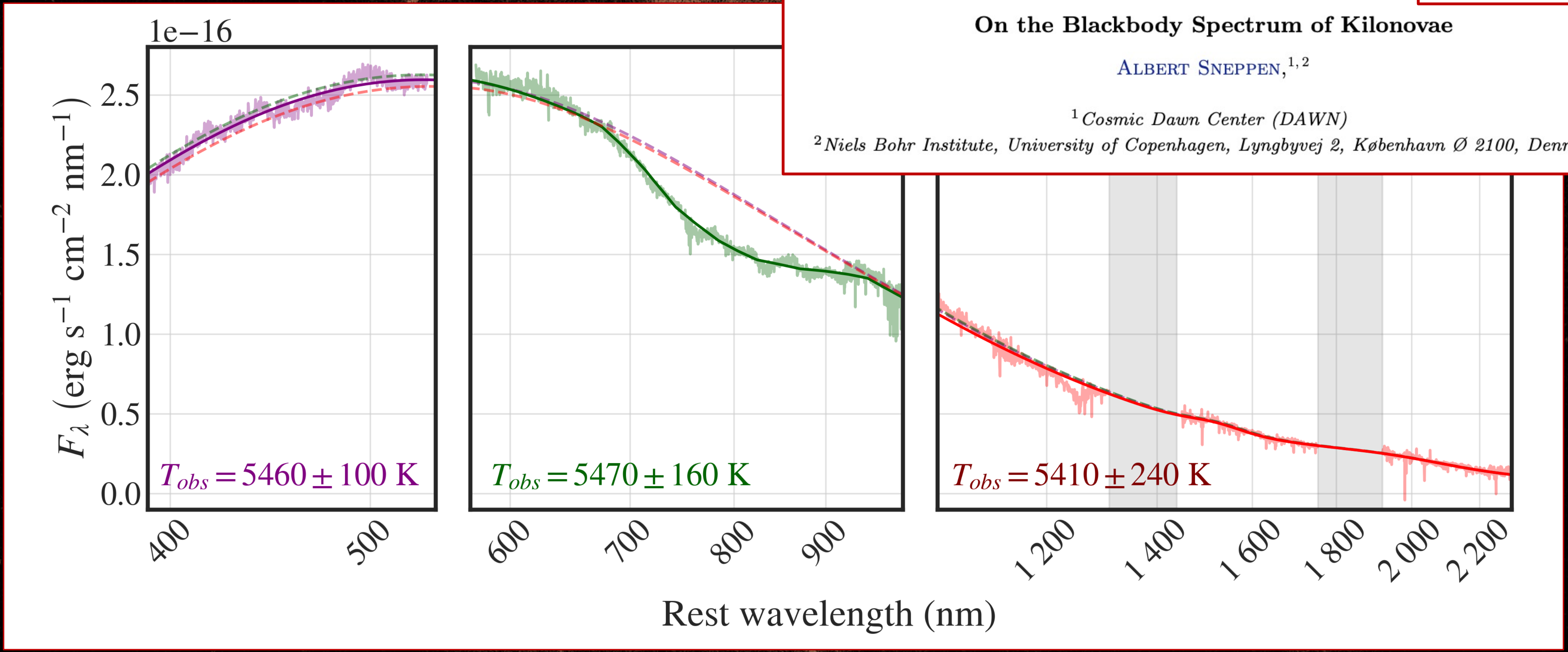
[1] *Cosmic Dawn Center (DAWN)*
[2] *Niels Bohr Institute, University of Copenhagen, Lyngbyvej 2, København Ø 2100, Denmark*



Thank you for listening

Discovery of a 760 nm P Cygni line in AT2017gfo: Identification of yttrium in the kilonova photosphere

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[1] Cosmic Dawn Center (DAWN), Rådmandsgade 62, 2200 København, Denmark
e-mail: a.sneppen@gmail.com
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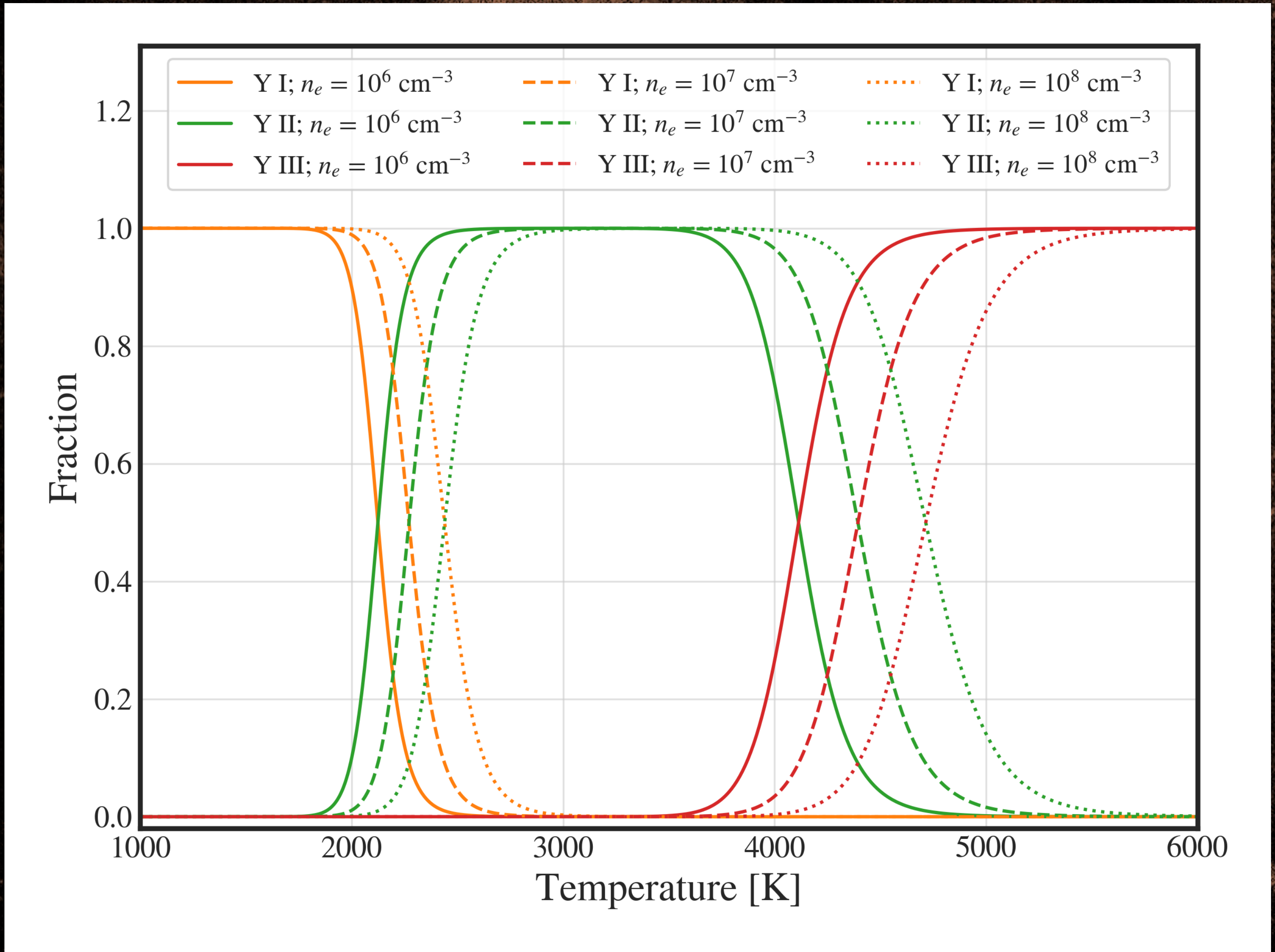
https://arxiv.org/abs/2306.14942

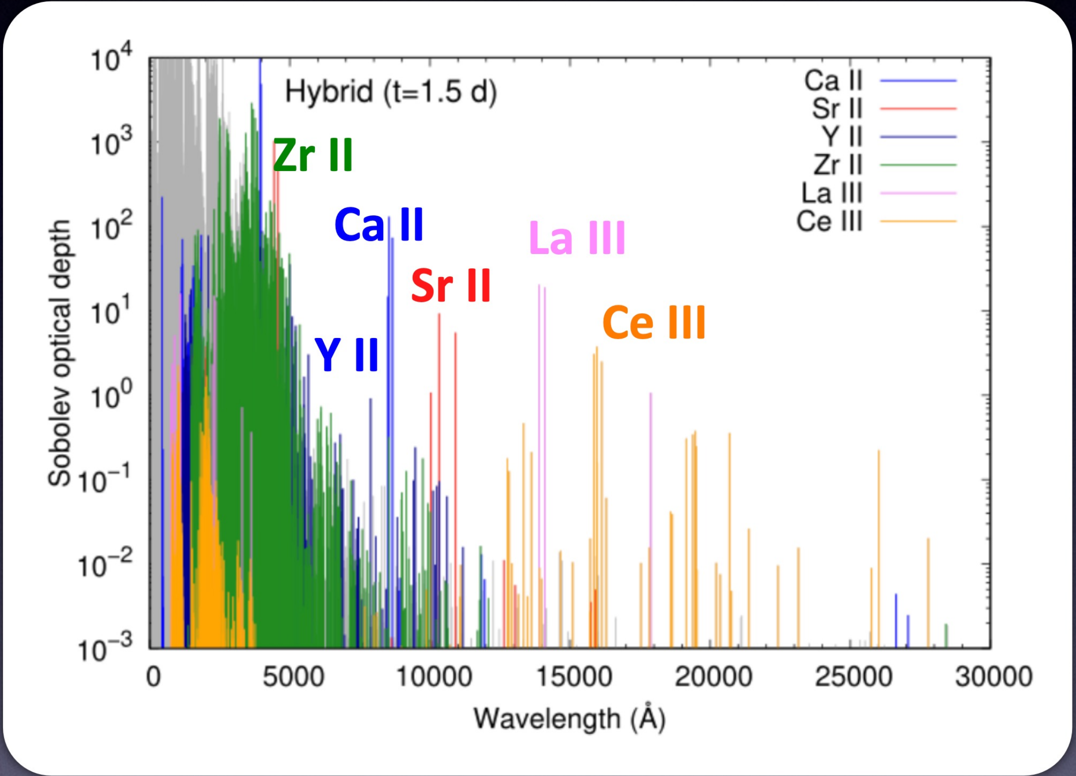
Sneppen & Watson (2023), *A&A, 675*

Extra Slide I: Ionization state

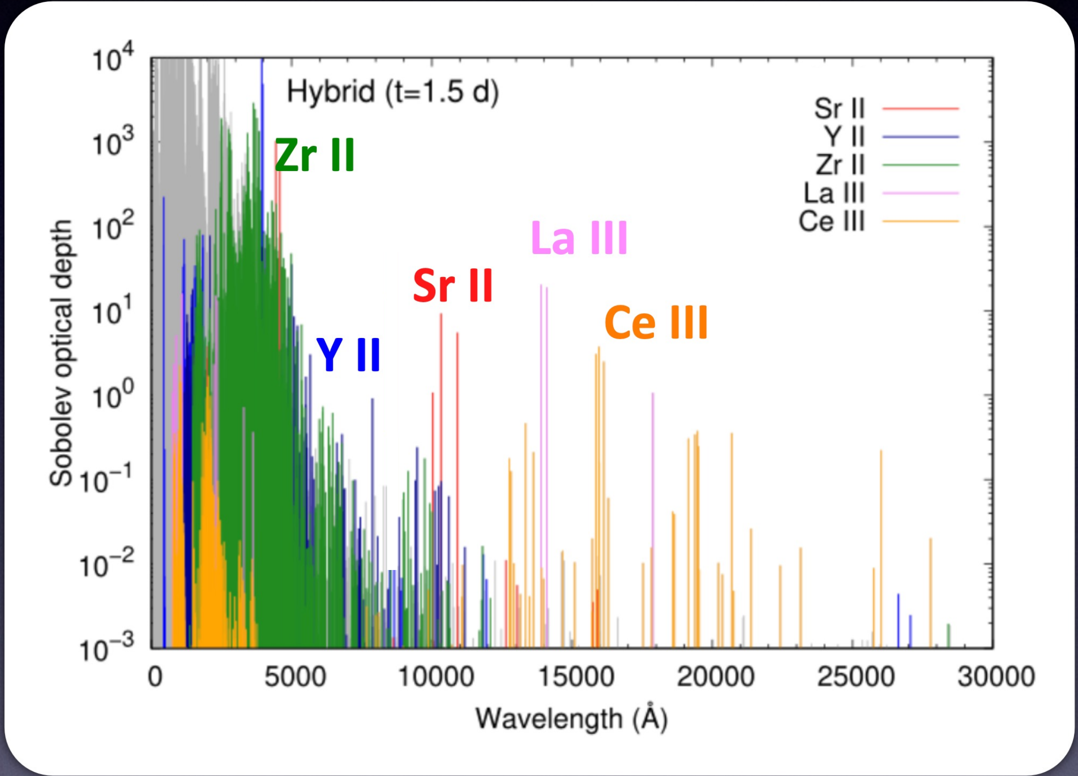


Highest opacity “trees” in Tanaka et al (2020)

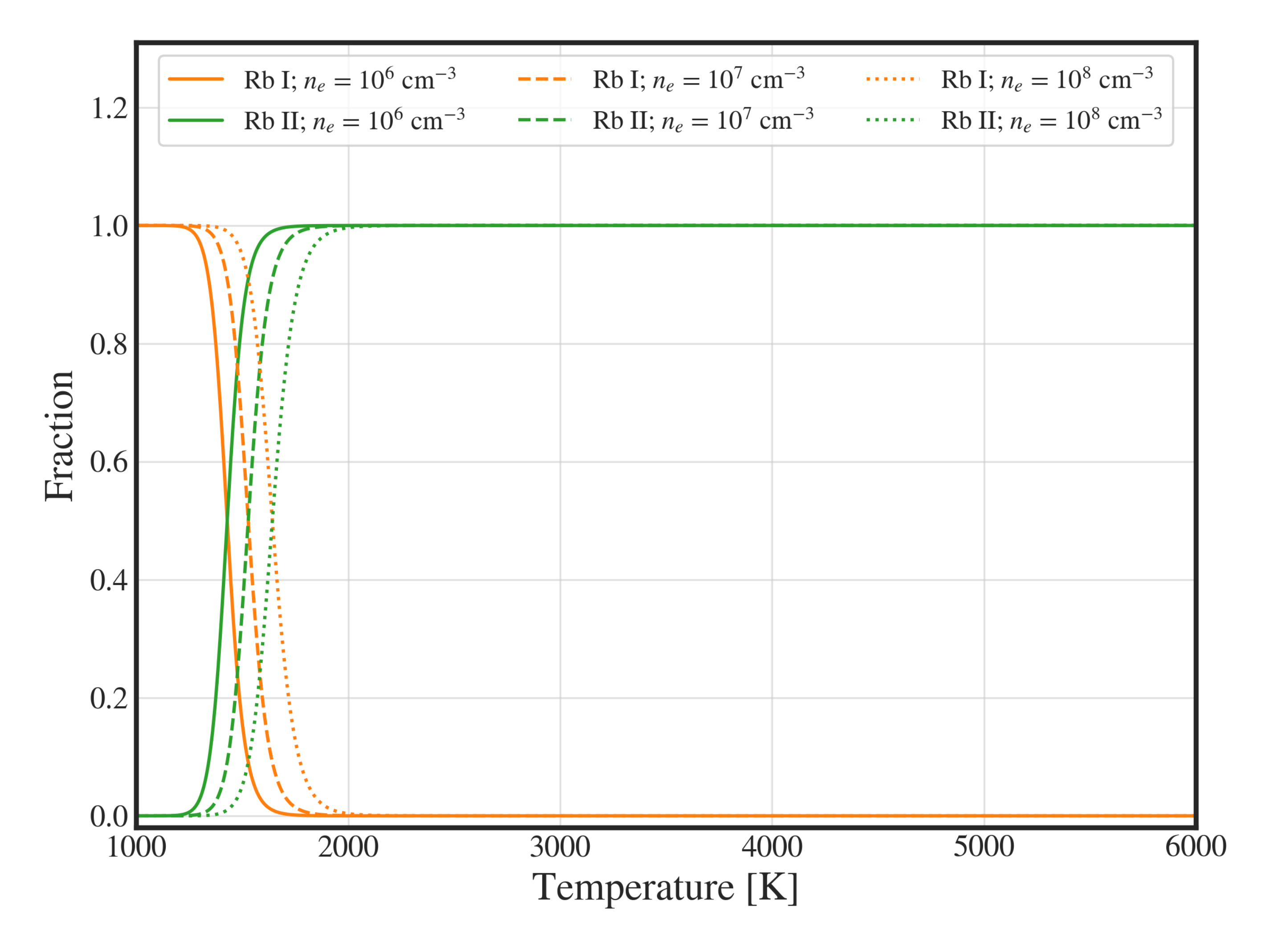
Constructed from complete data (MT+20)



Constructed from complete data (MT+20)



Extra Slide II: Ionization state, Rb I



Rb I could produce a similar feature, but requires NLTE conditions (see recent Pognan et al. (2023)).

Likely not a good fit to the early appearance at 3 days (and the stable prominence derived from 3-5 days), but could dominate such a feature at later times

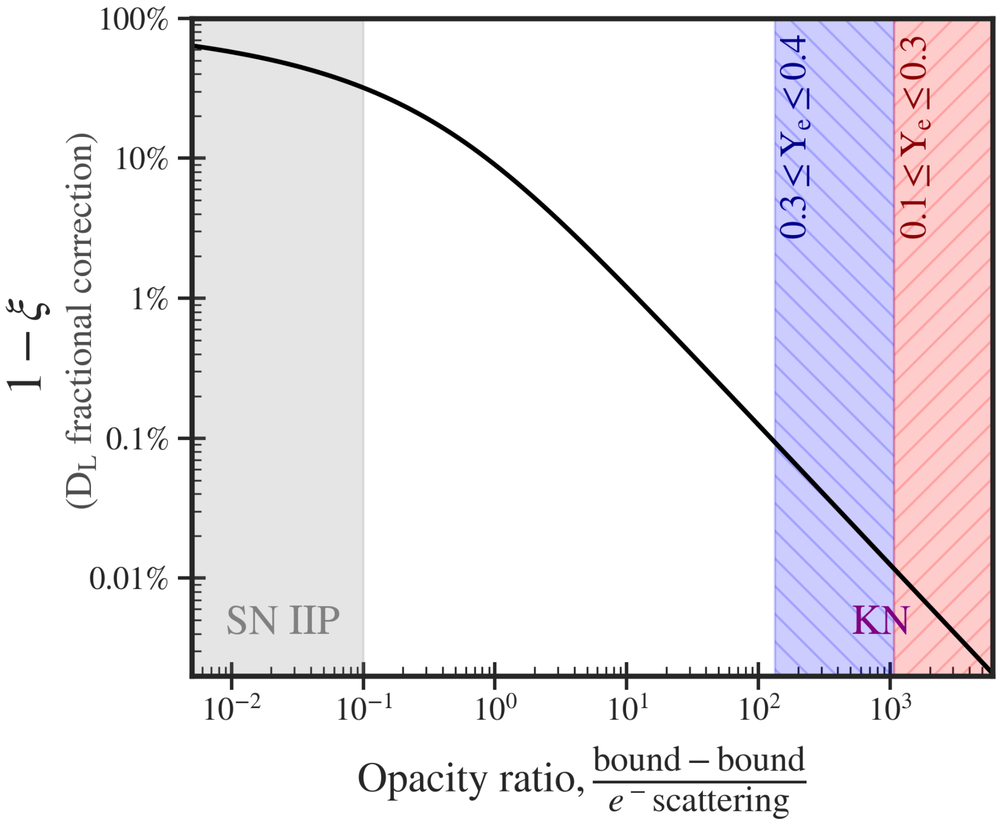


Fig. 3. Fractional correction to the estimated luminosity distance from dilution factors, $1-\xi$, as a function of opacity ratio, $\kappa_{\text{b-b}}/\kappa_{e^-\text{scat}}$. As the opacity ratio is a function of wavelength, we report the integrated Planck mean opacity. When electron-scattering dominates, as in the case of SN IIP (Sim 2017), the photospheric radius inferred from lines will be larger than the thermalisation radius of the blackbody inferred from its flux, thus requiring the introduction of a significant dilution-factor (grey region). However, for neutron-star mergers the bound-bound opacity dominates over electron-scattering, regardless of whether one uses opacities based on lists of known lines (e.g. Tanaka & Hotokezaka 2013) or the higher opacities used in this figure, which are based on more complete theoretically-calculated line-lists (Tanaka et al. 2020). Such dominance of the bound-bound opacity implies negligible corrections to the distance (blue and red hatched region).