




Discovery of a 760 nm P Cygni line in AT2017gfo:

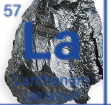
Identification of yttrium in the kilonova

Albert Snepen^{1,2}, Darach Watson^{1,2}

1) Cosmic Dawn Center (DAWN),

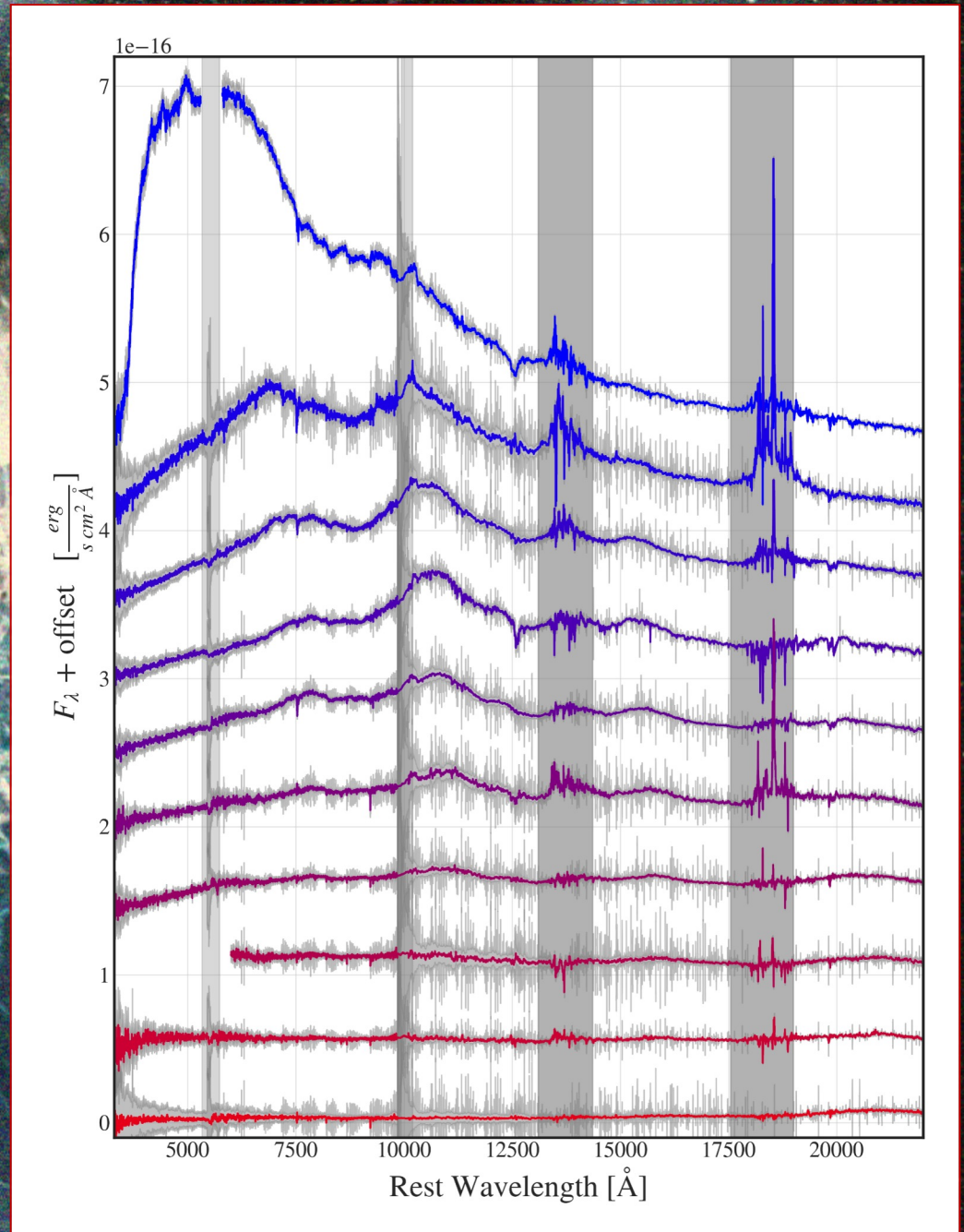
2) Niels Bohr Institute, Denmark

1 IA H Hydrogen 1.008	2 IIA Be Beryllium 9.0121831												18 VIII A He Helium 4.002602					
3 Li Lithium 6.94	4 B Boron 10.81		5 C Carbon 12.011	6 N Nitrogen 14.007	7 O Oxygen 15.999	8 F Fluorine 18.998403163	9 Ne Neon 20.1797											
11 Na Sodium 22.98976928	12 Mg Magnesium 24.305											13 IIIA Al Aluminium 26.9815385	14 IVA Si Silicon 28.085	15 VA P Phosphorus 30.973761998	16 VIA S Sulfur 32.06	17 VIIA Cl Chlorine 35.45	18 VIII A Ar Argon 39.948	
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955908	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938044	26 Fe Iron 55.845	27 Co Cobalt 58.933194	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.63	33 As Arsenic 74.921595	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798	
37 Rb Rubidium 85.4678			40 Zr Zirconium 91.224	41 Nb Niobium 92.90637	42 Mo Molybdenum 95.95	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760		53 I Iodine 126.90447	54 Xe Xenon 131.293	
55 Cs Caesium 132.90545196	56 Ba Barium 137.327	57 - 71 Lanthanoids		72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.592	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 - 103 Actinoids		104 Rf Rutherfordium (267)	105 Db Dubnium (268)	106 Sg Seaborgium (269)	107 Bh Bohrium (270)	108 Hs Hassium (269)	109 Mt Meitnerium (278)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (282)	112 Cn Copernicium (285)	113 Nh Nihonium (286)	114 Fl Flerovium (289)	115 Mc Moscovium (289)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)

57 	58 	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.9668
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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

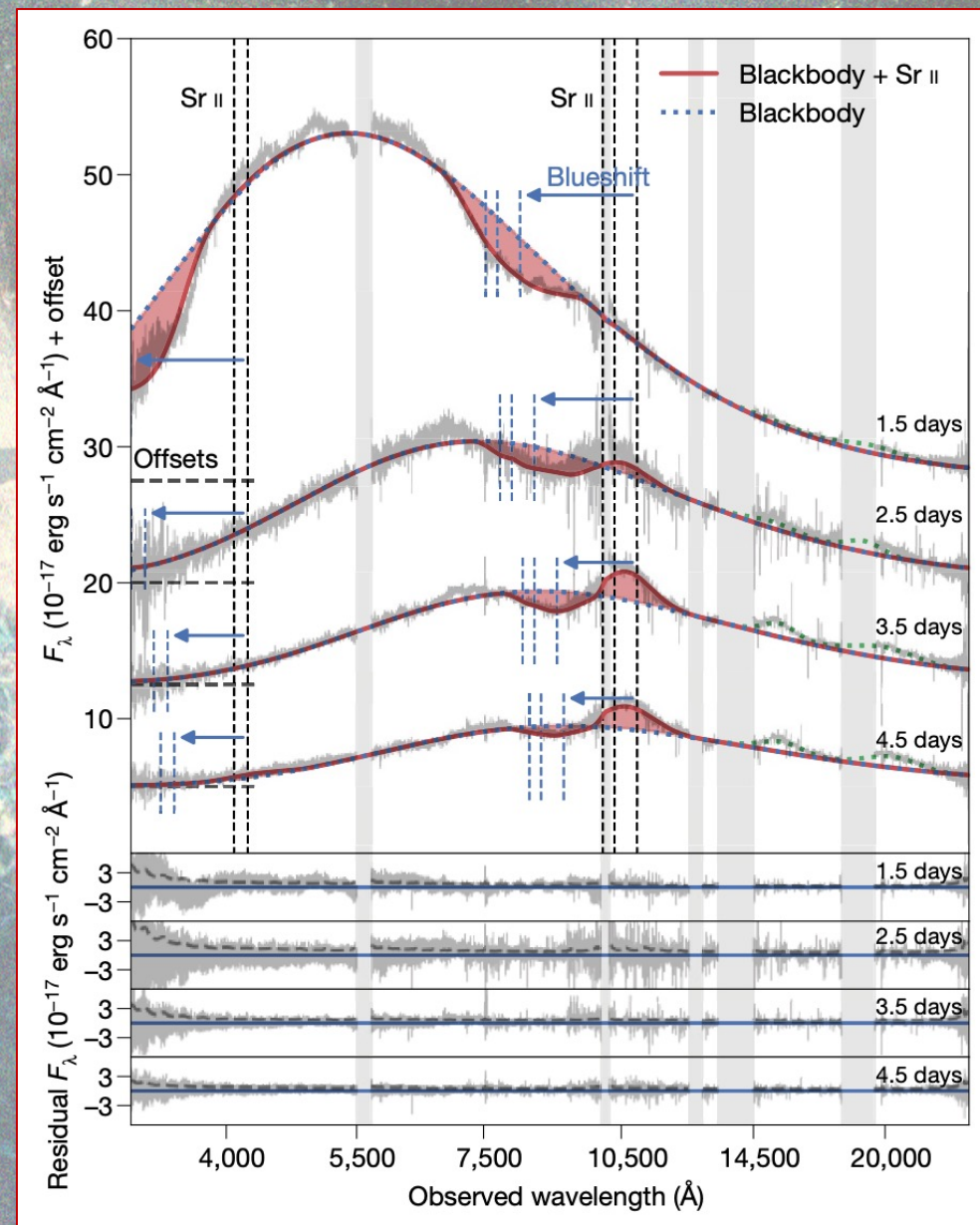
Darach Watson^{1,2}, Camilla J. Hansen^{3,*}, Jonatan Selsing^{1,2,*}, Andreas Koch⁴, Daniele B. Malesani^{1,2,5}, Anja C. Andersen¹, Johan P. U. Fynbo^{1,2}, Almudena Arcones^{6,7}, Andreas Bauswein^{7,8}, Stefano Covino⁹, Aniello Grado¹⁰, Kasper E. Heintz^{1,2,11}, Leslie Hunt¹², Chryssa Kouveliotou^{13,14}, Giorgos Leloudas^{1,5}, Andrew Levan^{15,16}, Paolo Mazzali^{17,18}, Elena Pian¹⁹ [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)

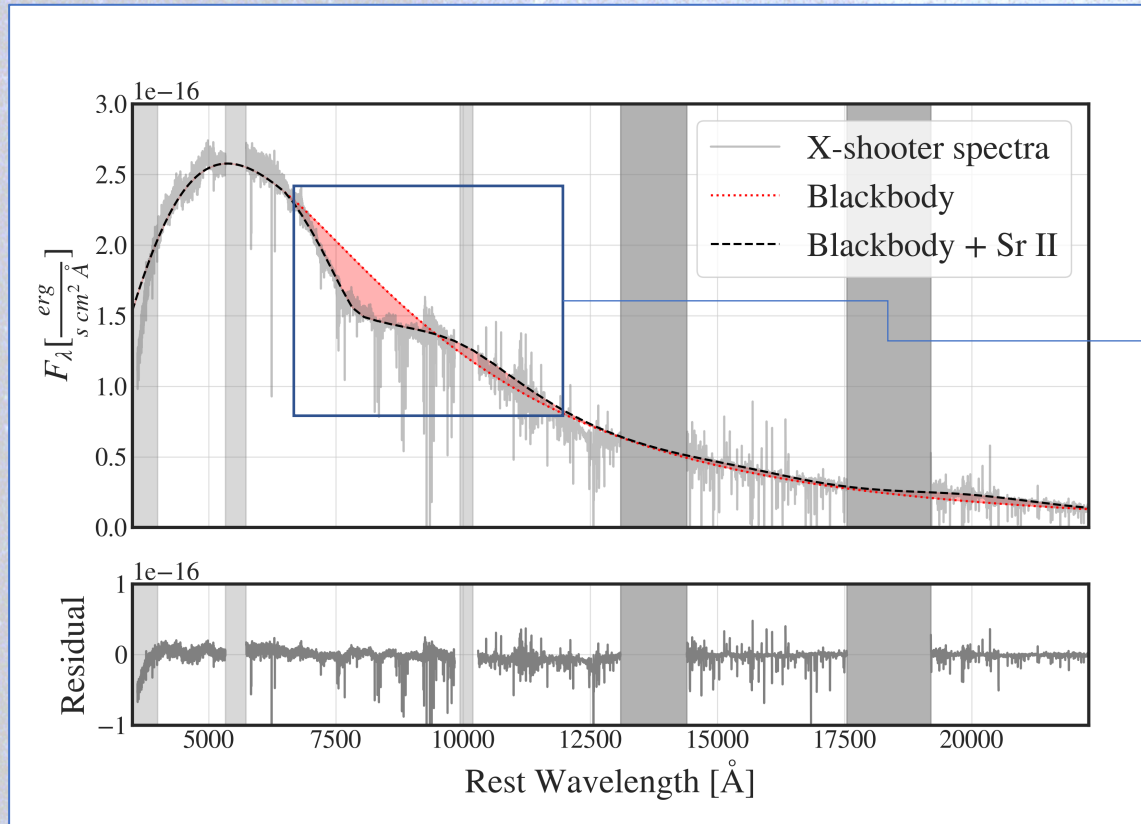
Additionally, accounting for the full 3D spatial and time dependence of the density with line-by-line opacity:

- Shingles et al. (2023)

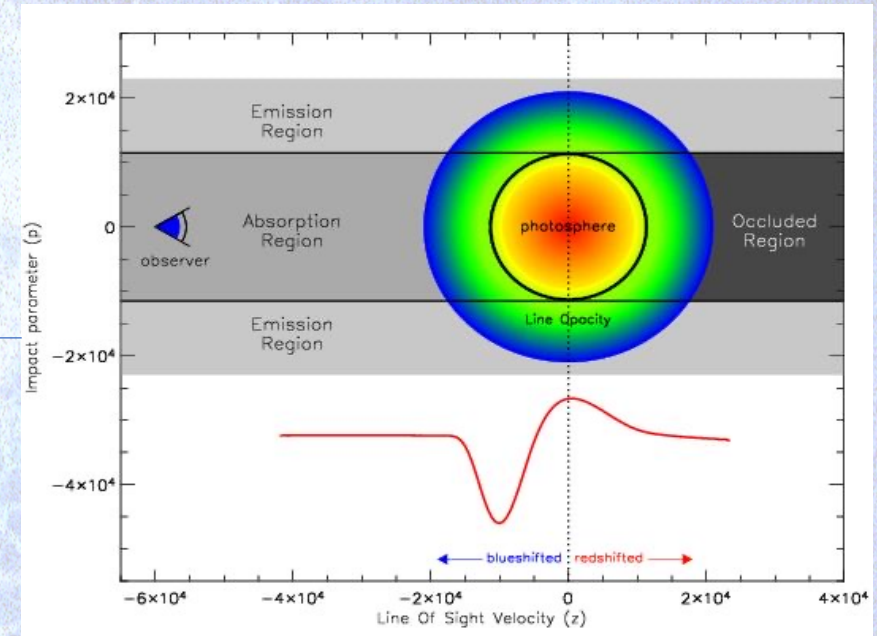


The P Cygni information

illustration from Dan Kasen



X-shooter spectrum epoch 1

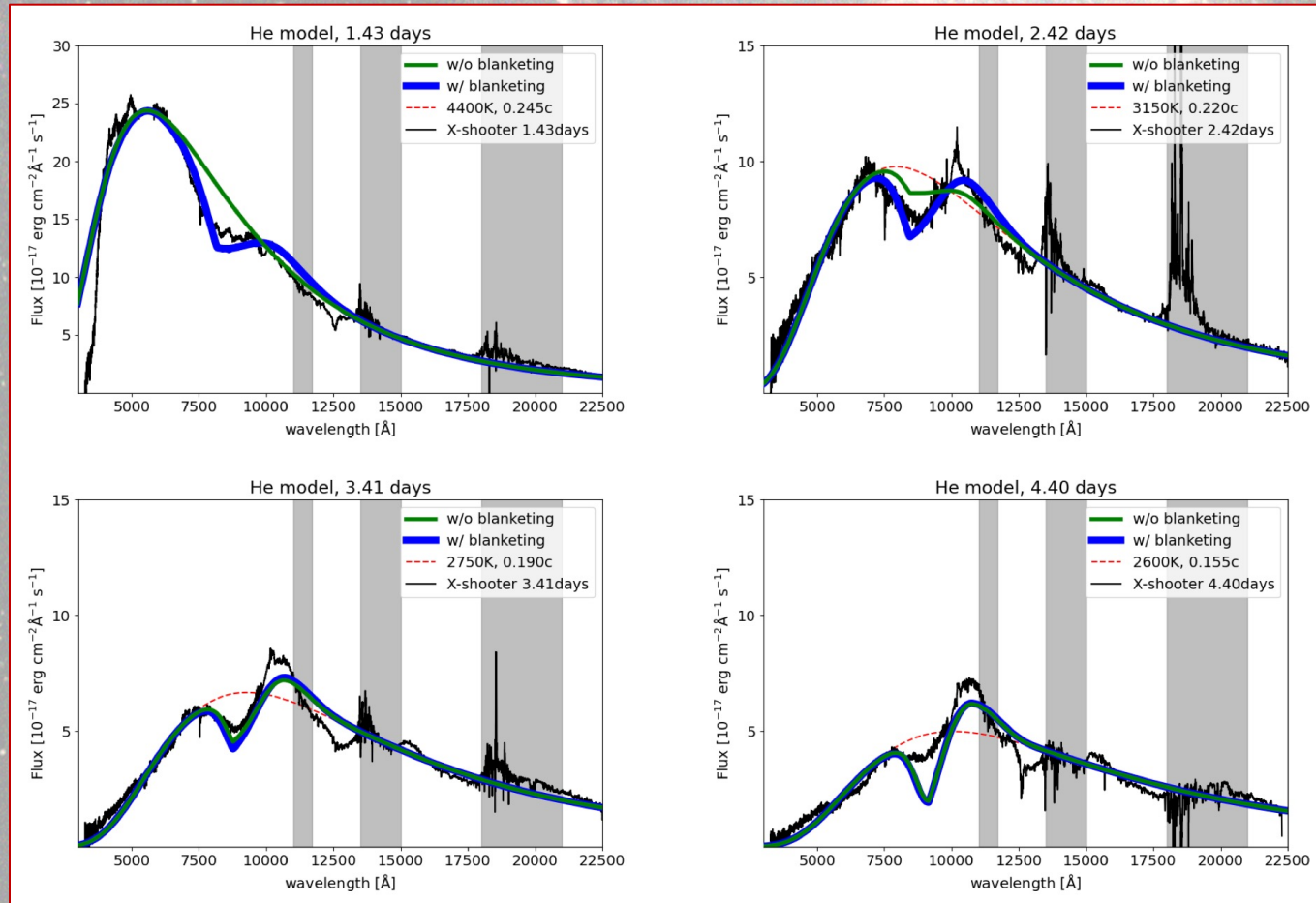


Parameterization of P Cygni profile in the Elementary

Supernova from <https://github.com/unoebauer/>

[public-astro-tools](https://github.com/unoebauer/public-astro-tools)

Or perhaps 10 833 Å He-line?



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."

Tarumi et al. (2023)

Energy level comparison

Tarumi et al (2023)

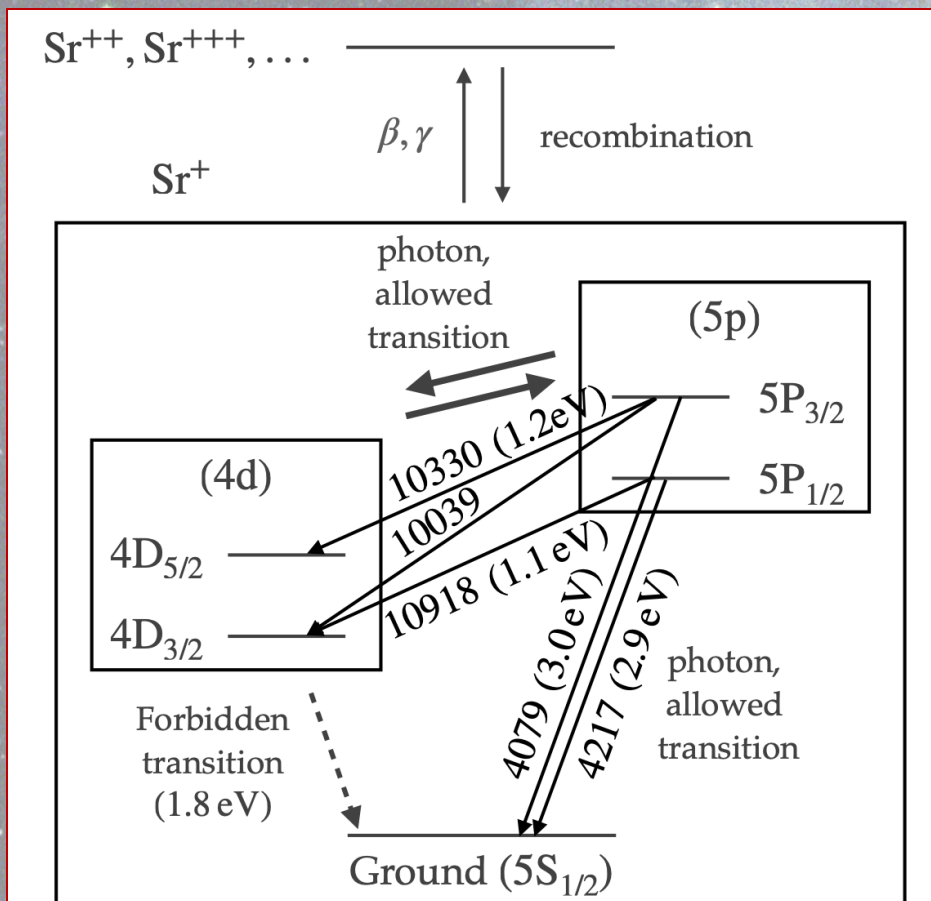


Figure 2. Schematic diagram that shows the populating mechanism of singly ionized Sr.

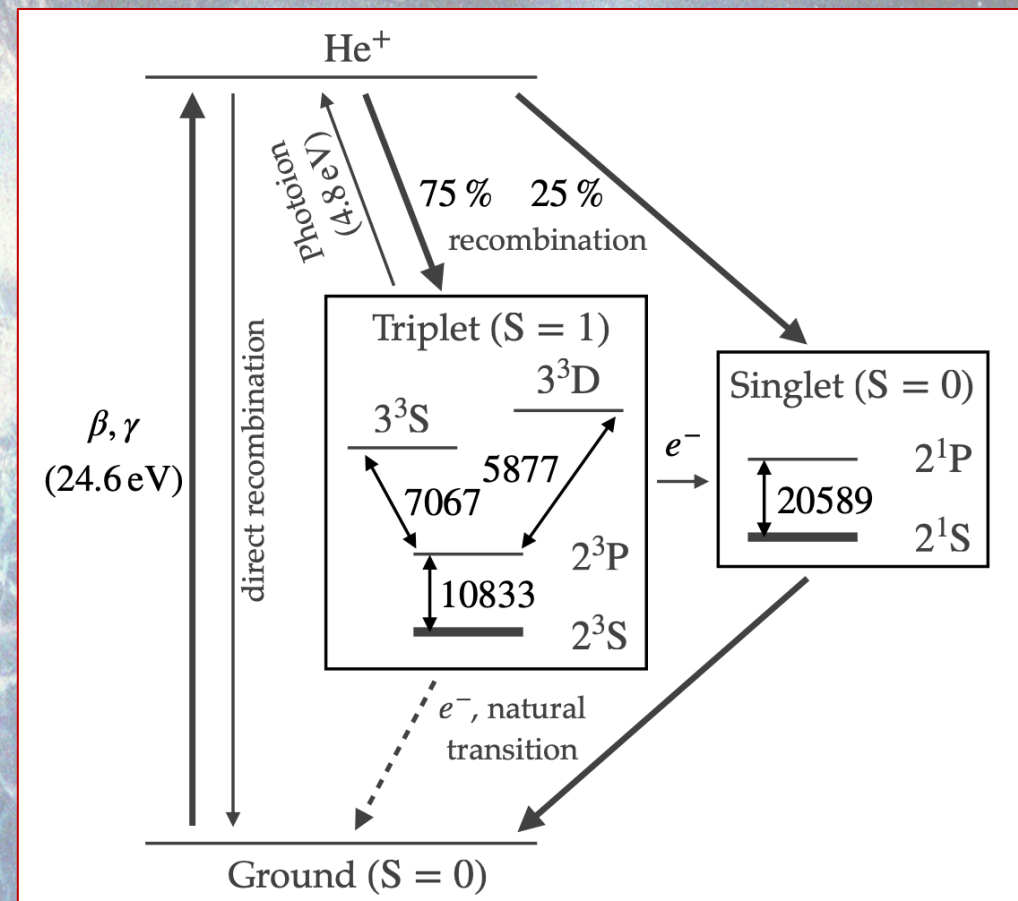
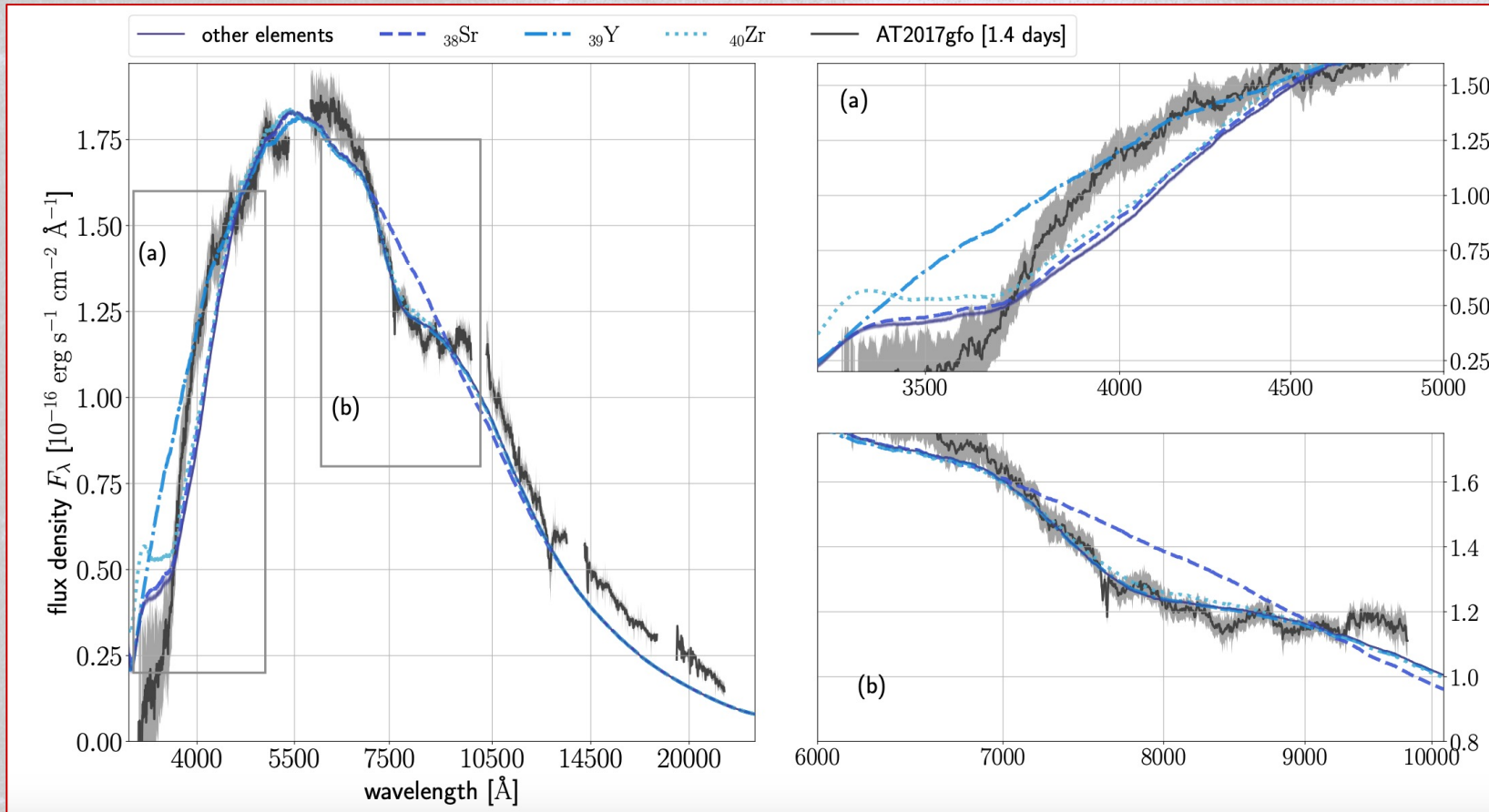


Figure 1. Schematic diagram that shows the populating mechanism of excited He.

Deficit of flux in the UV



Tentative evidence of Y II
- Gillanders et al. (2022)

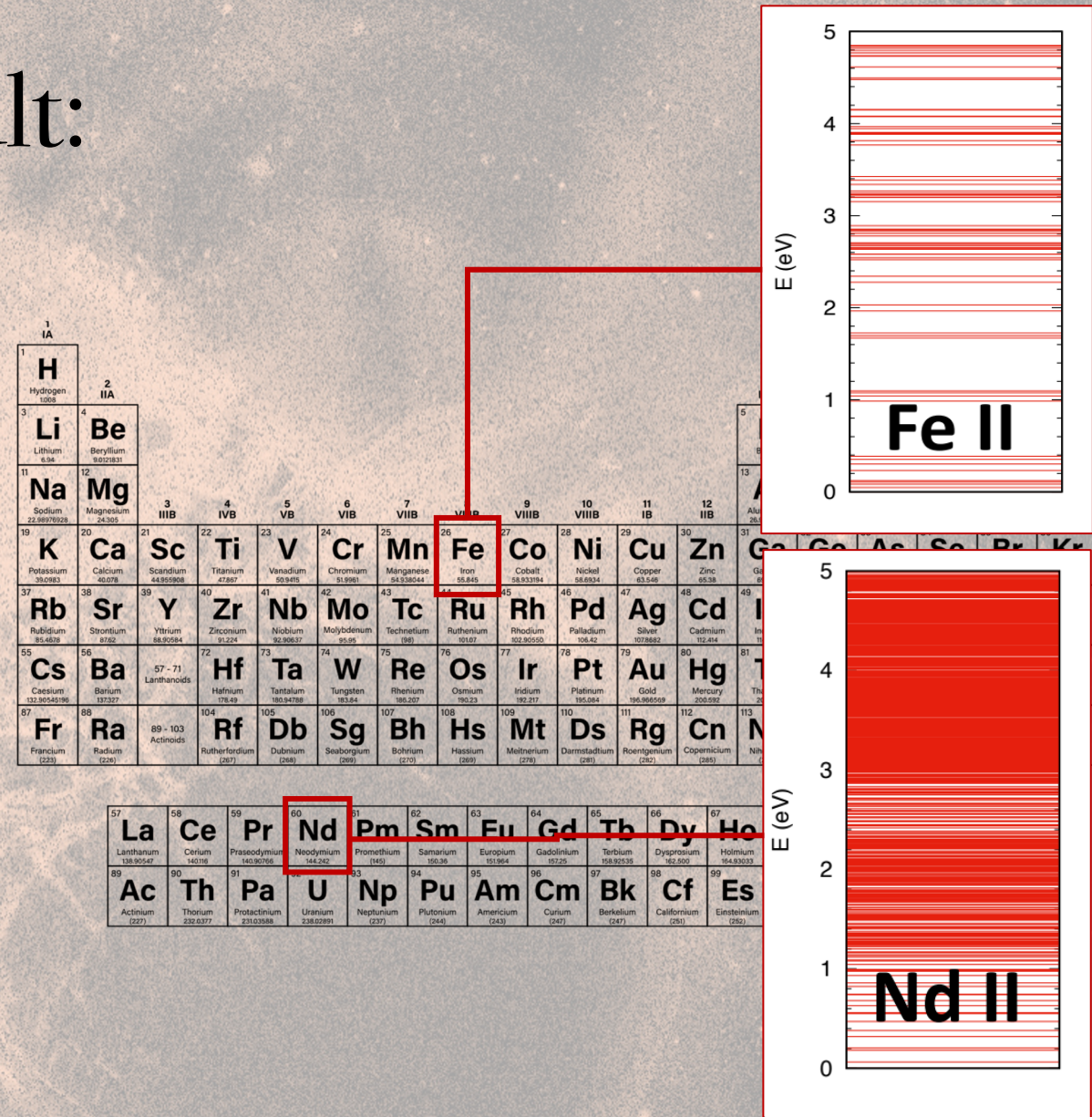
Tentative evidence of Y II + Zr II
- Vieira et al. (2023)

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)*

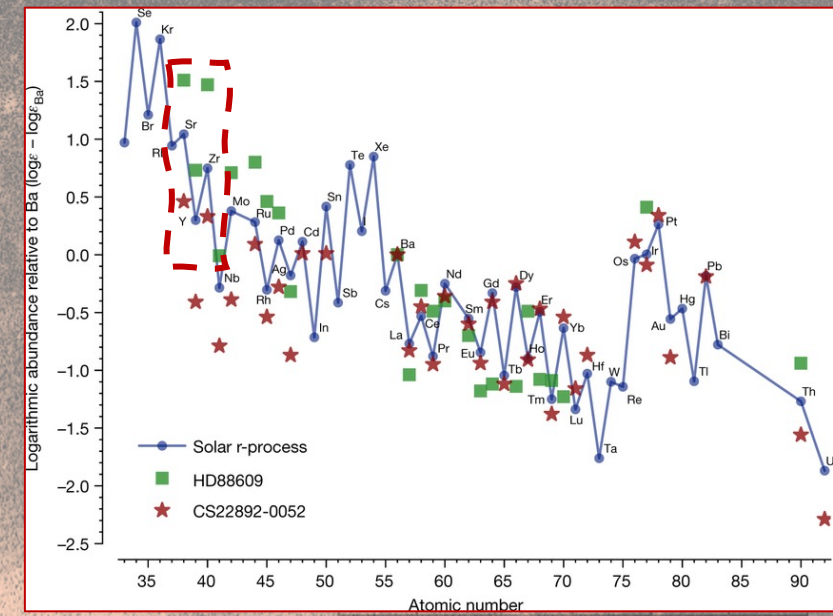
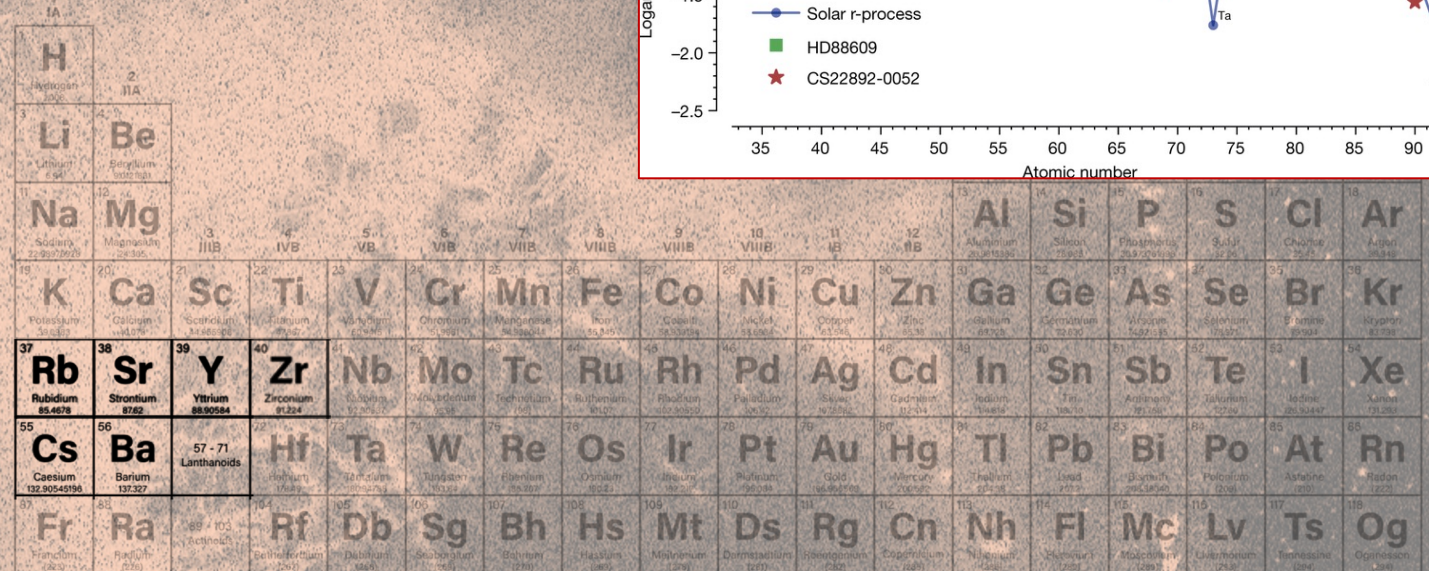
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How to make a prominent feature

1) Small partition function

2) High abundance



57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	Lu
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	Lr
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

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)

1 H Hydrogen	2 He Helium											18 Ar Argon	19 K Potassium	20 Ca Calcium											36 Kr Krypton	37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon	55 Cs Cesium	56 Ba Barium	57-71 Lanthanoids	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon	87 Fr Francium	88 Ra Radium	89-103 Actinoids	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson
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89 Ac Actinium 227	90 Th Thorium 232.0377	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium 237	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 252	100 Fm Fermium 257	101 Md Mendelevium 258	102 No Nobelium 259	103 Lr Lawrencium 260

Strontium

1) Small partition function

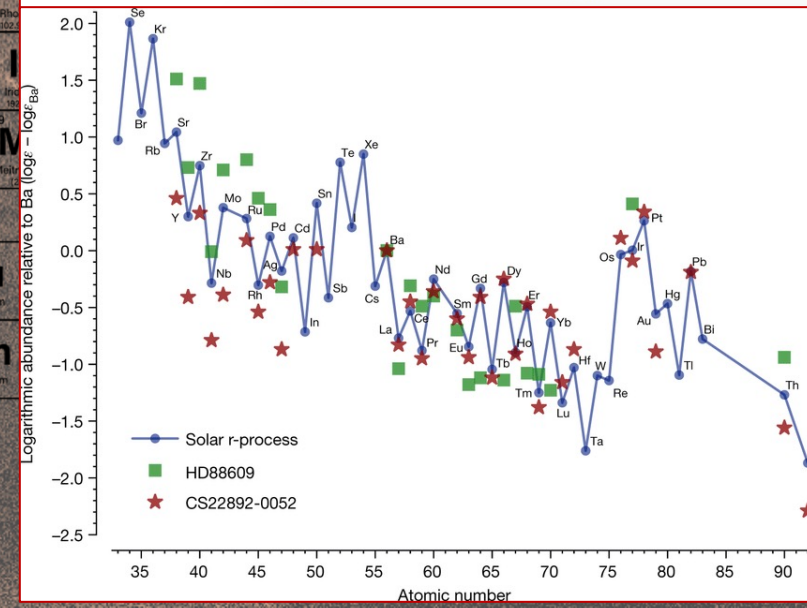
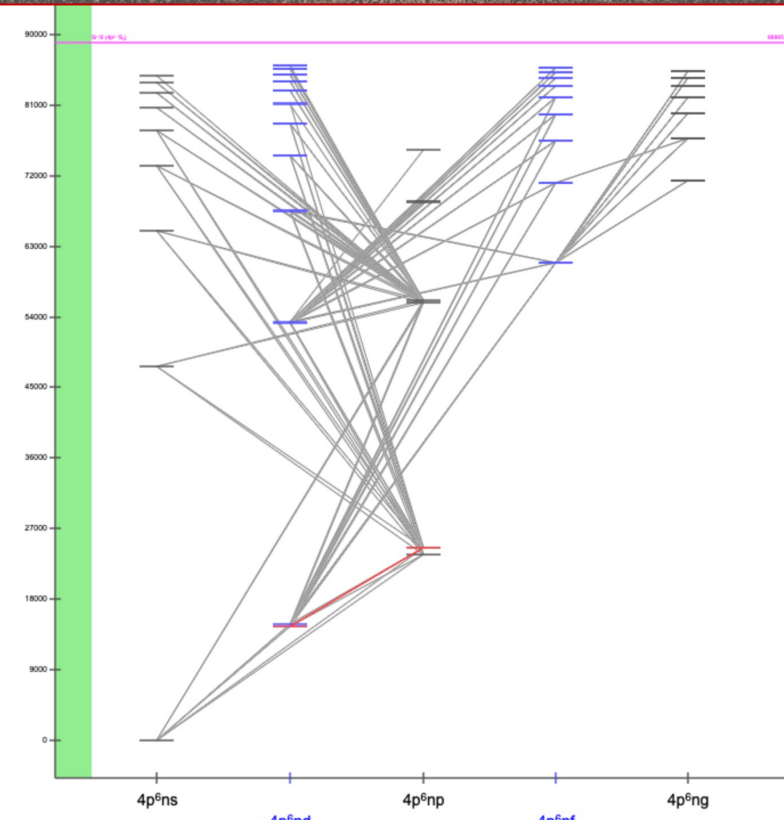
2) High abundance

3) Transition lines with strong oscillator strength

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

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1	H																				
Hydrogen 1.008																					
3	Li	4	Be																		
Lithium 6.94		Beryllium 9.012236																			
11	Na	12	Mg																		
Sodium 22.98976928		Magnesium 24.305																			
19	K	20	Ca	21	Sc	22	Ti	23	V	24	Cr	25	Mn	26	Fe	27	Co				
Potassium 39.0983		Calcium 40.078		Scandium 44.955908		Titanium 47.867		Vanadium 50.9415		Chromium 51.9961		Manganese 54.938044		Iron 55.845		Cobalt 58.9332					
37	Rb	Y		40	Zr	41	Nb	42	Mo	43	Tc	44	Ru	45	Rh						
Rubidium 85.4678		Yttrium 88.90584		Zirconium 91.224		Niobium 92.90637		Molybdenum 95.96		Technetium (98)		Ruthenium 101.07		Rhodium 102.9055							
55	Cs	56	Ba	57 - 71 Lanthanoids		72	Hf	73	Ta	74	W	75	Re	76	Os	77	Ir				
Caesium 132.90545196		Barium 137.327				Hafnium 178.49		Tantalum 180.94788		Tungsten 183.84		Rhenium 186.207		Osmium 190.23		Iridium 192.222					
87	Fr	88	Ra	89 - 103 Actinoids		104	Rf	105	Db	106	Sg	107	Bh	108	Hs	109	Mt				
Francium (223)		Radium (226)				Rutherfordium (261)		Dubnium (268)		Seaborgium (266)		Bohrium (270)		Hassium (285)		Meitnerium (288)					

57	La	58	Ce	59	Pr	60	Nd	61	Pm	62	Sm	63	Eu
Lanthanum 138.90547		Cerium 140.12		Praseodymium 140.90768		Neodymium 144.242		Promethium (145)		Samarium 150.36		Europium 151.964	
89	Ac	90	Th	91	Pa	92	U	93	Np	94	Pu	95	Am
Actinium (227)		Thorium 232.0377		Protactinium 231.03688		Uranium 238.02891		Neptunium (237)		Plutonium (244)		Americium (243)	



Yttrium

1) Small partition function

2) High abundance

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1 H Hydrogen 1.00794																	2 He Helium 4.002602
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Yttrium

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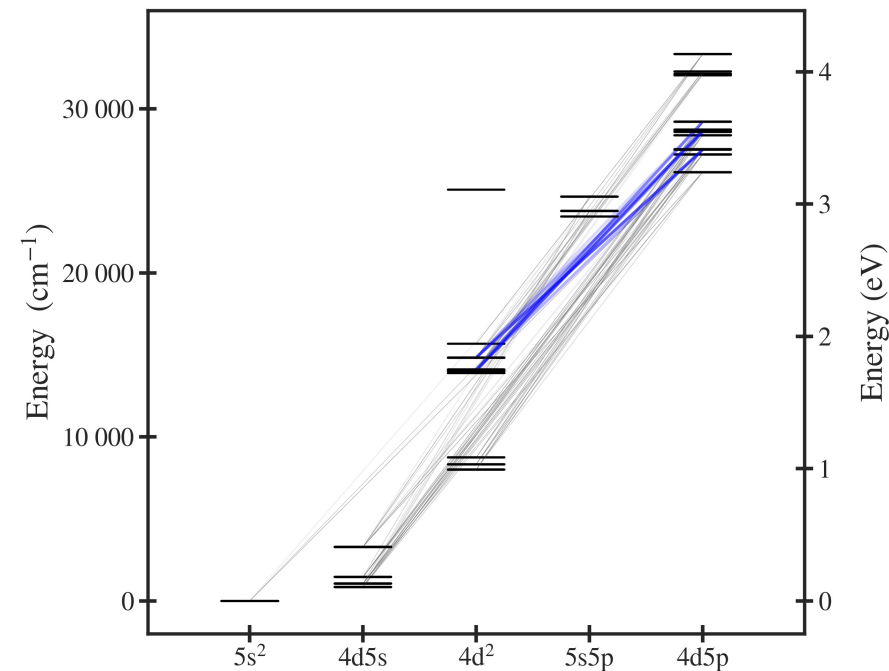
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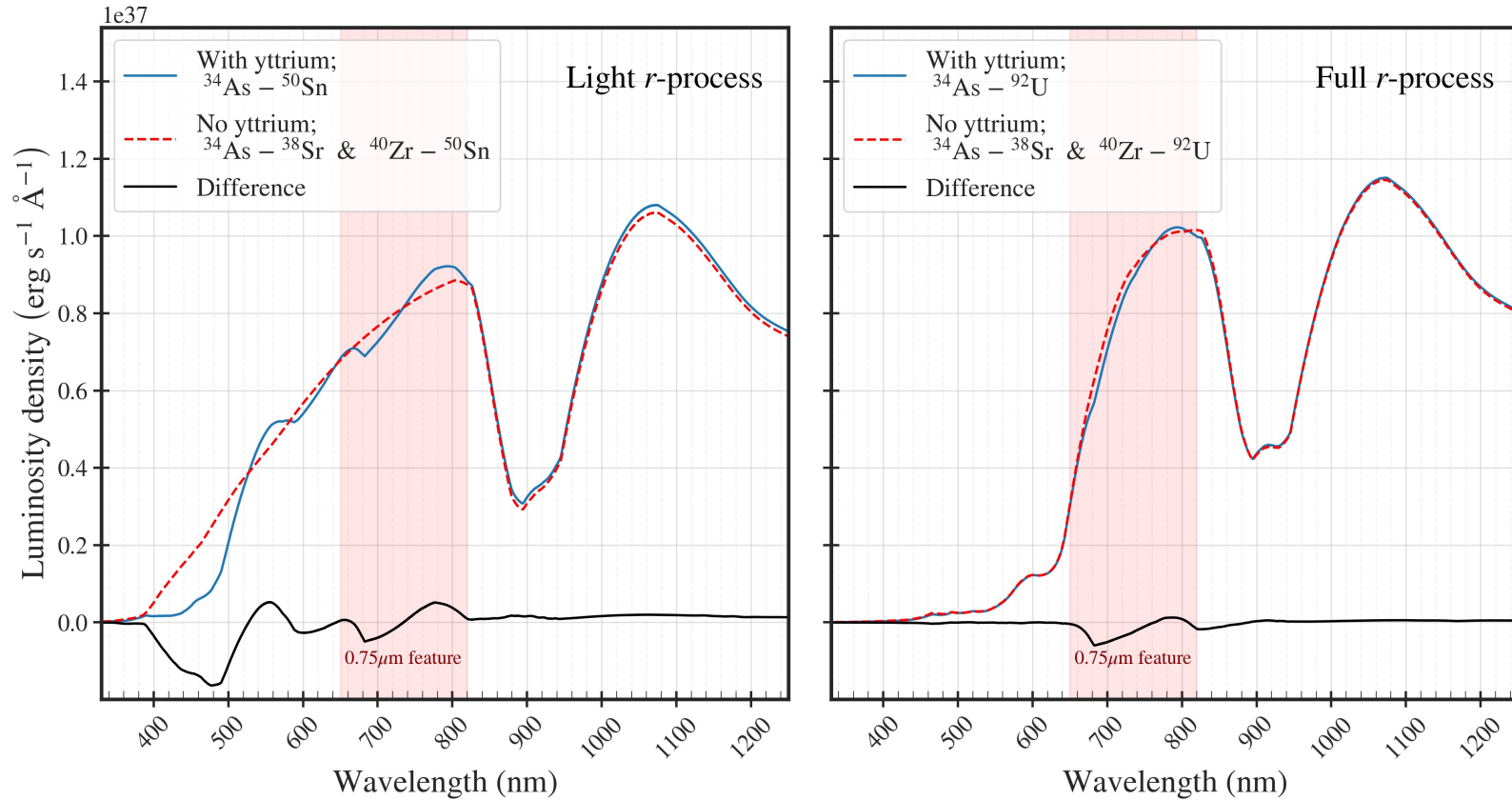
Periodic table showing the position of Yttrium (Y, atomic number 39) in the transition metal series.

Lanthanide and actinide series showing the position of Yttrium (Y, atomic number 39) in the transition metal series.



λ (nm)	Lower level $4d^2$	E (cm^{-1})	Upper level $4d5p$	E (cm^{-1})	$\log gf$
788.19	b^1D_2	14 832	$z^1P_1^o$	27 517	-0.60
745.03	a^3P_2	14 098	$z^1P_1^o$	27 517	-1.44
733.29	a^3P_0	13 883	$z^1P_1^o$	27 517	-1.98
726.42	b^1D_2	14 832	$z^3D_1^o$	28 595	-1.11
689.60	a^3P_2	14 098	$z^3D_1^o$	28 595	-1.67
685.82	a^3P_1	14 018	$z^3D_1^o$	28 595	-1.69
683.24	a^3P_2	14 098	$z^3D_2^o$	28 730	-1.86
679.54	a^3P_0	13 883	$z^3D_1^o$	28 595	-1.54
679.53	a^3P_1	14 018	$z^3D_2^o$	28 730	-1.03
661.37	a^3P_2	14 098	$z^3D_3^o$	29 213	-0.83

TARDIS Model

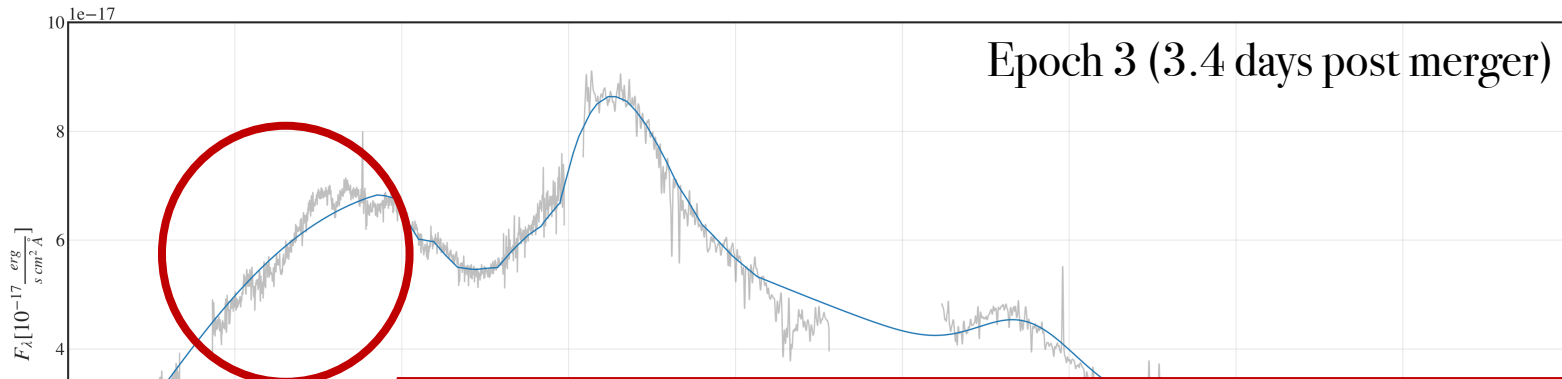


1) The presence of Sr II requires Y II to be present

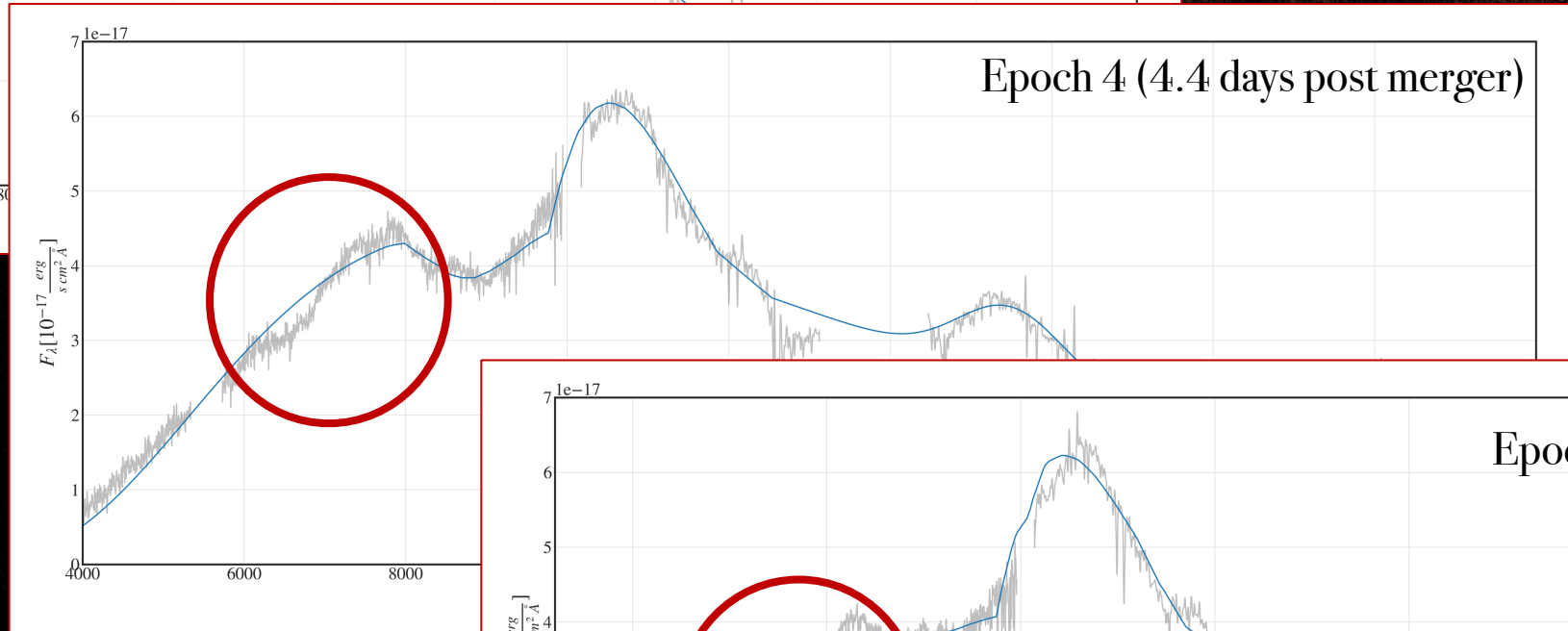
2) If Y II is present the line transitions $4d5p-4d^2$ will produce a P Cygni around 760 nm

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

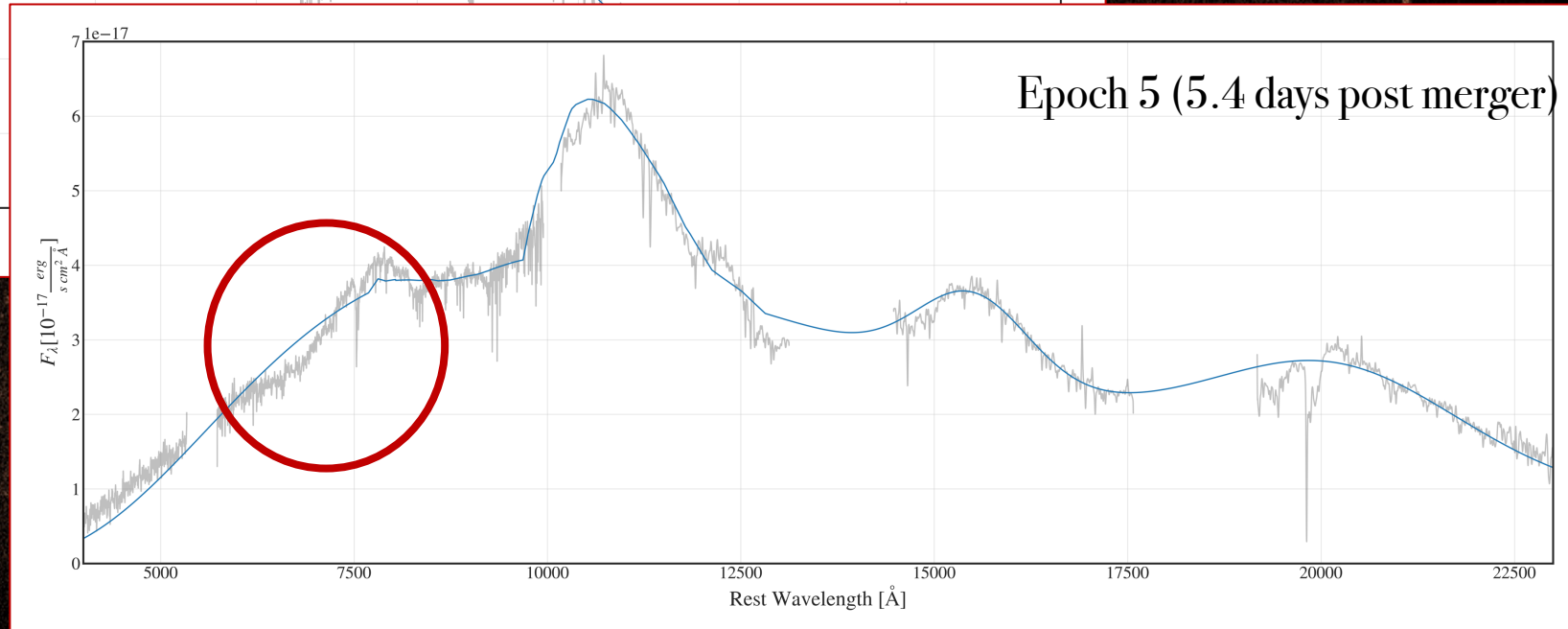
Epoch 3 (3.4 days post merger)



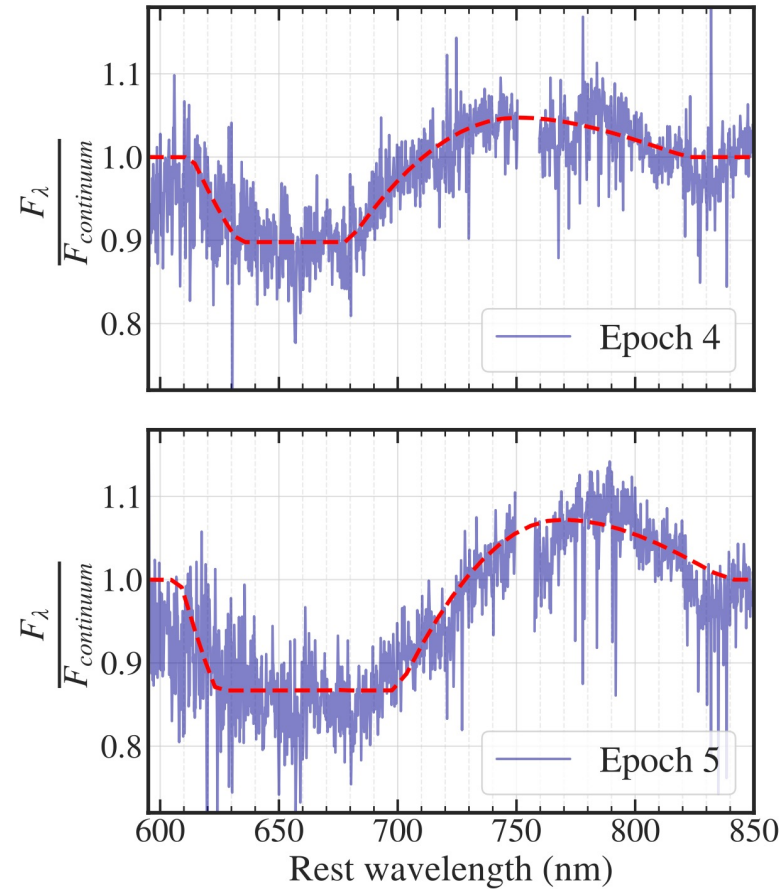
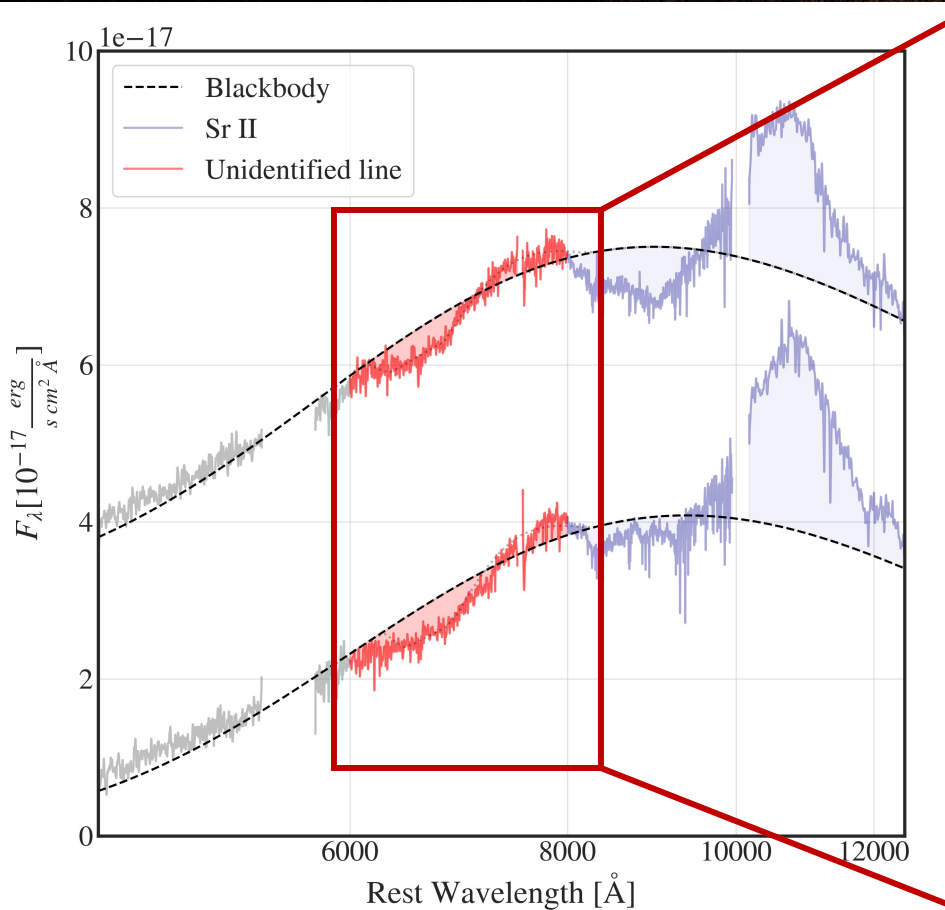
Epoch 4 (4.4 days post merger)



Epoch 5 (5.4 days post merger)

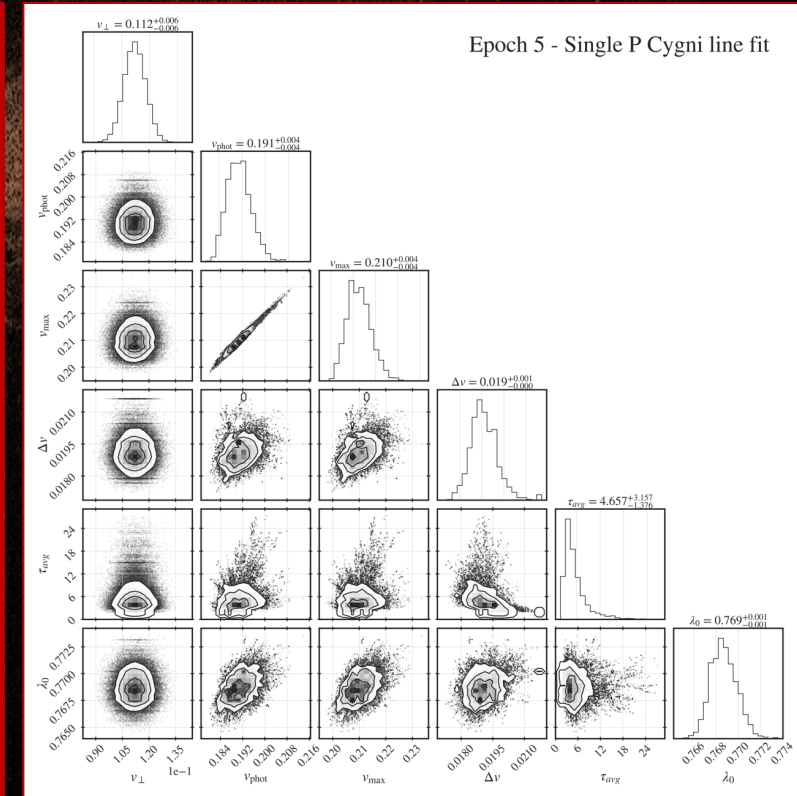
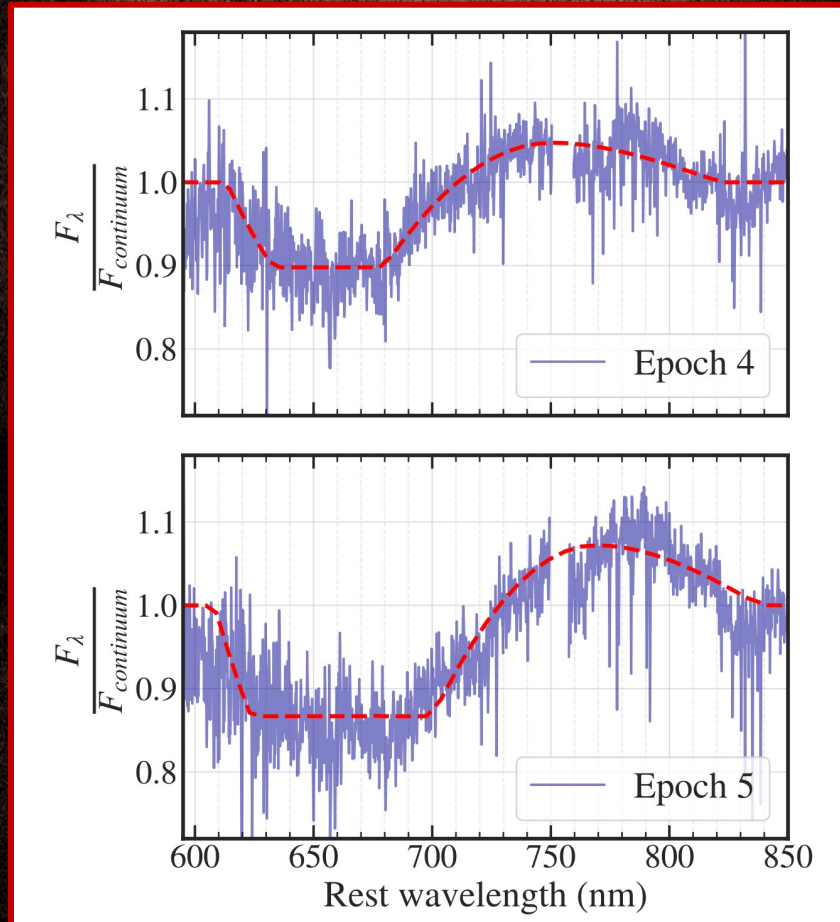
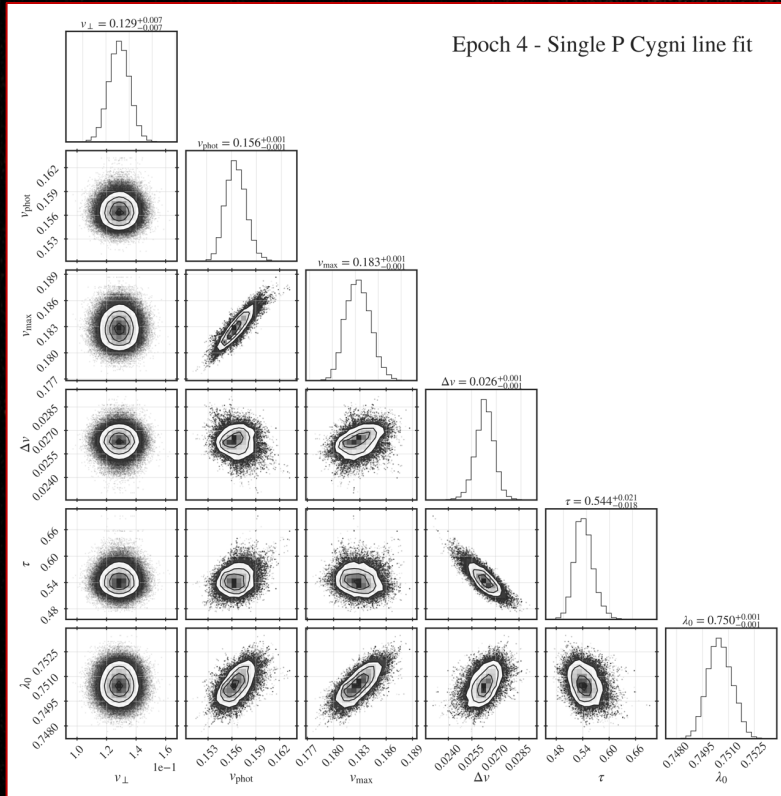


Significant feature...

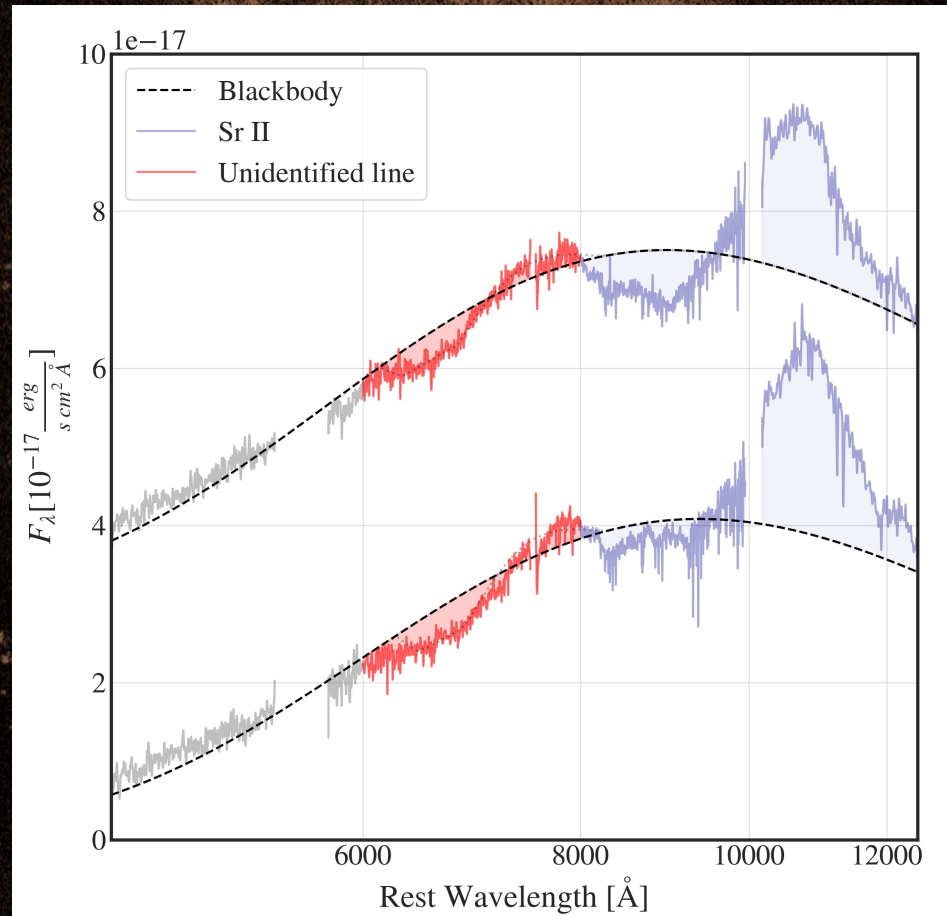


$\Delta\chi^2 = 4219$ and 5590
for epochs 4 & 5 respectively
for 5 additional degrees of
freedom

... with a “correct” central wavelength



... and a consistent expansion velocity with Sr

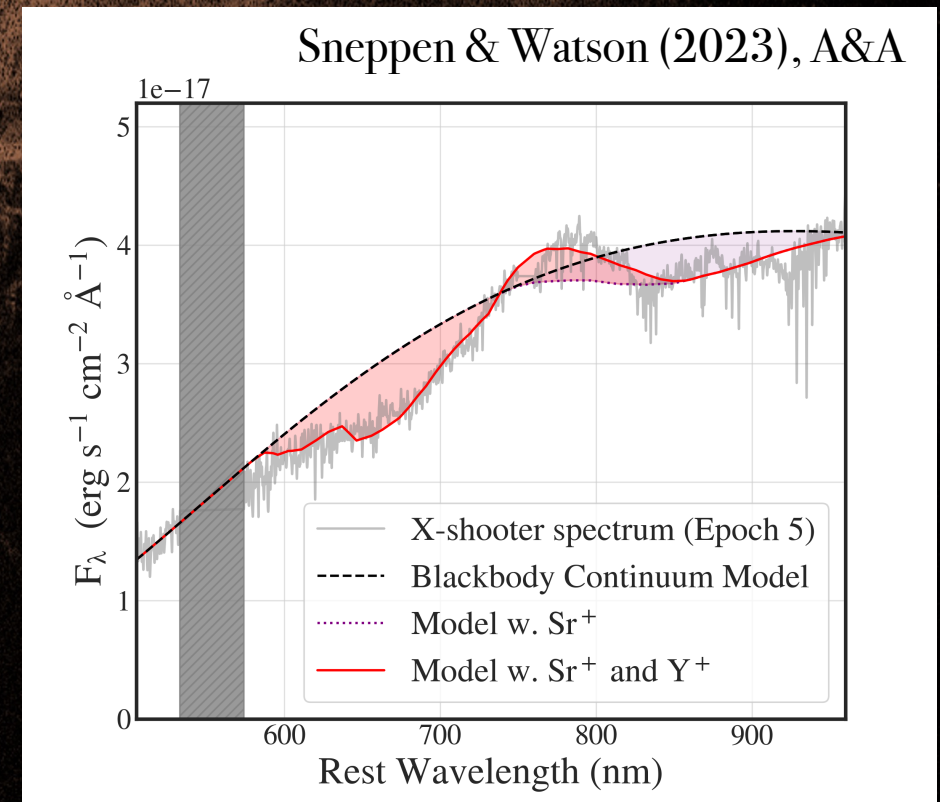
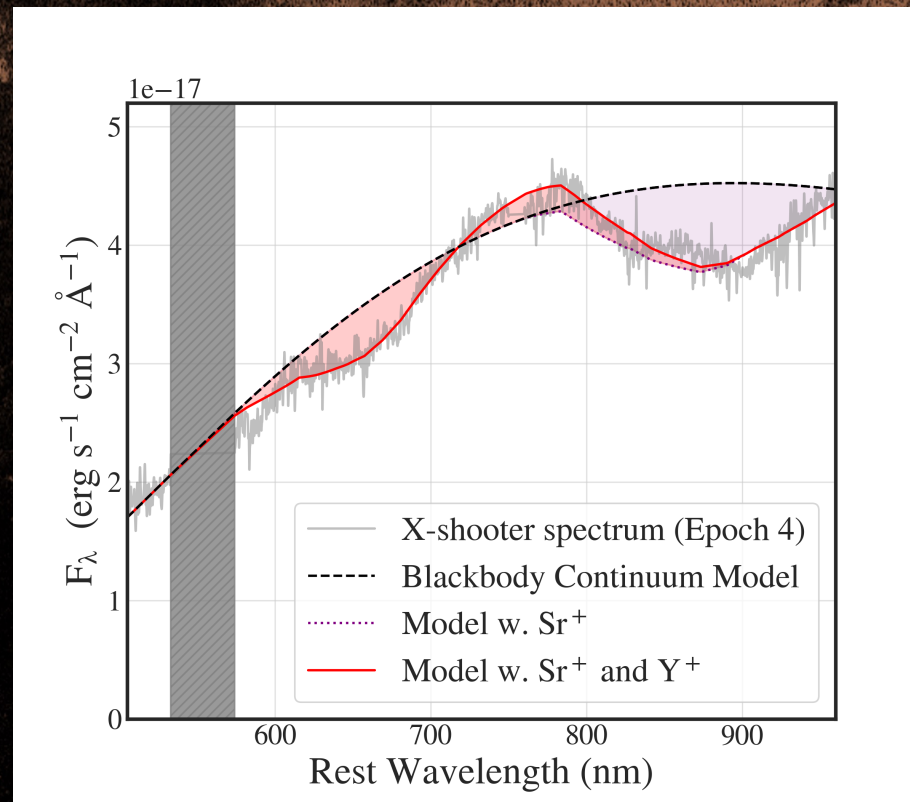


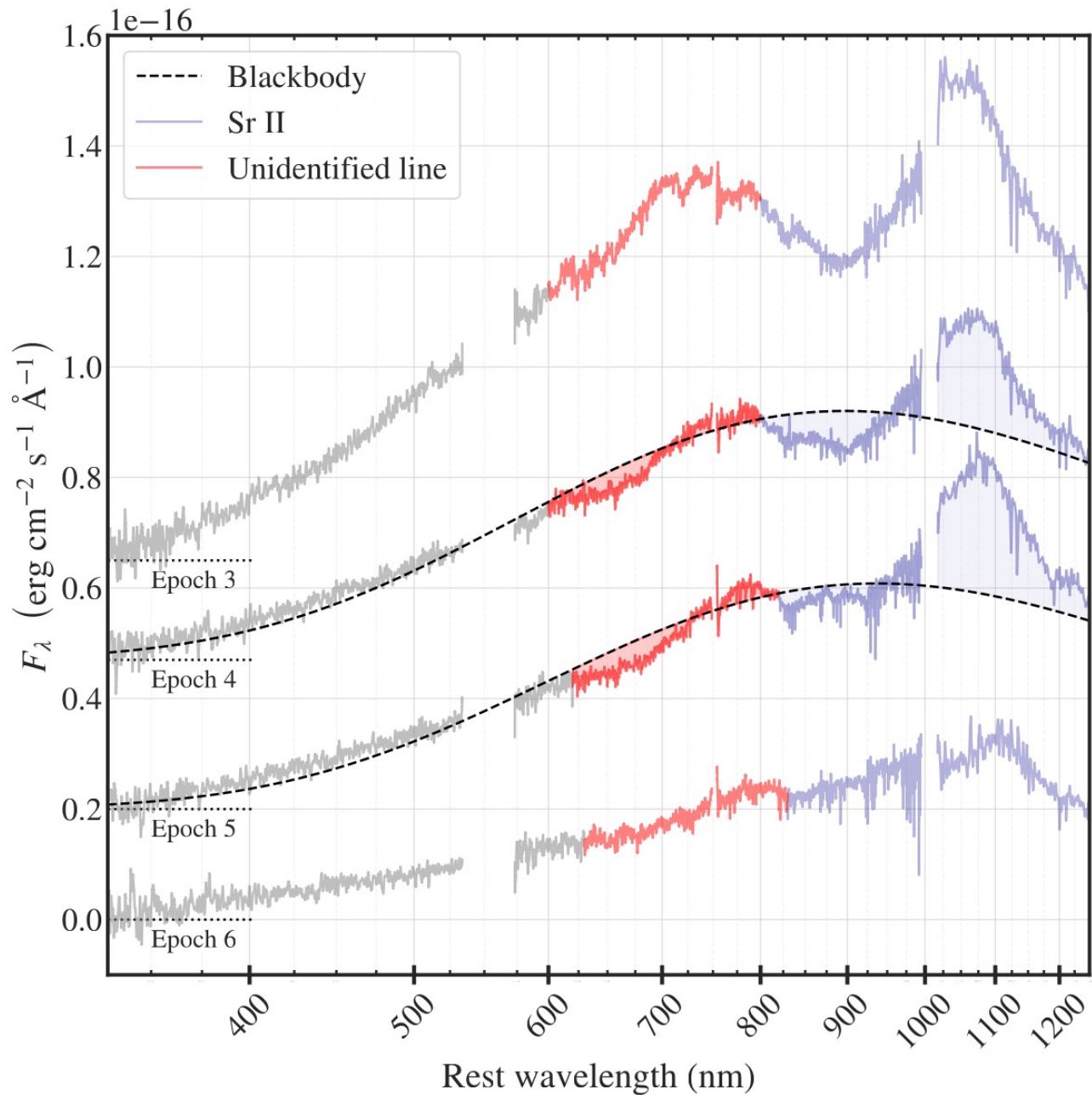
... and a reasonable prominence

Inferred mass:

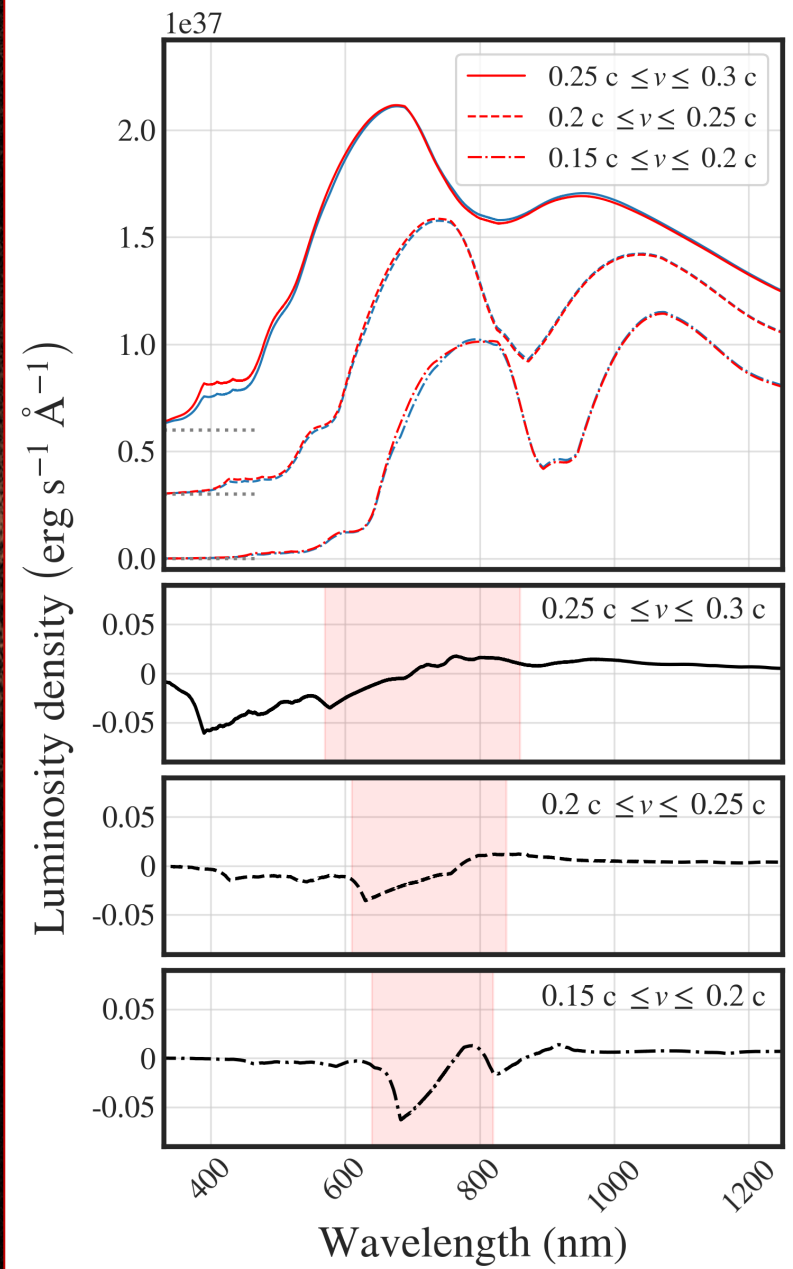
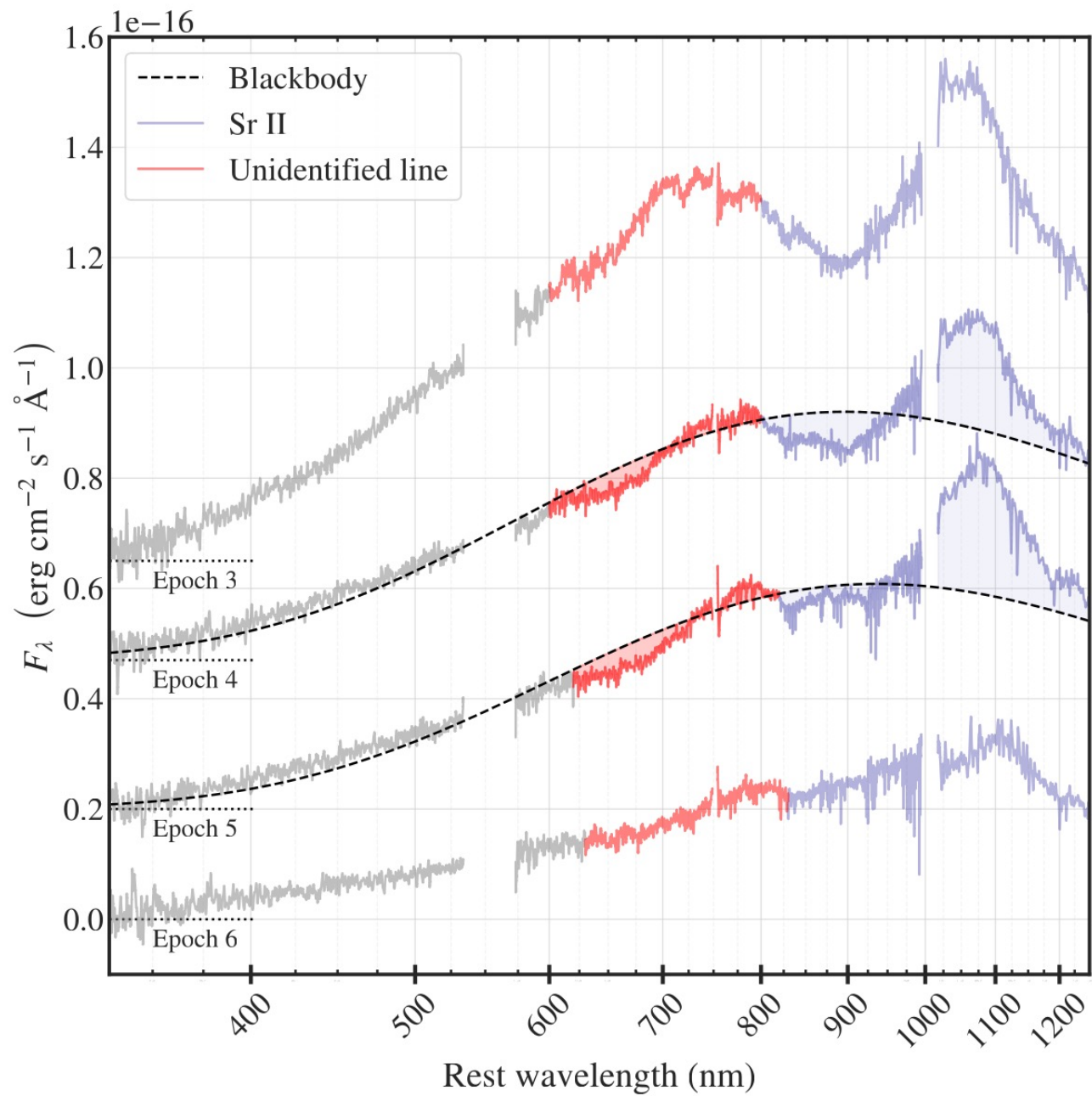
$$M_Y \approx 2 \cdot 10^{-4} M_{\odot}$$

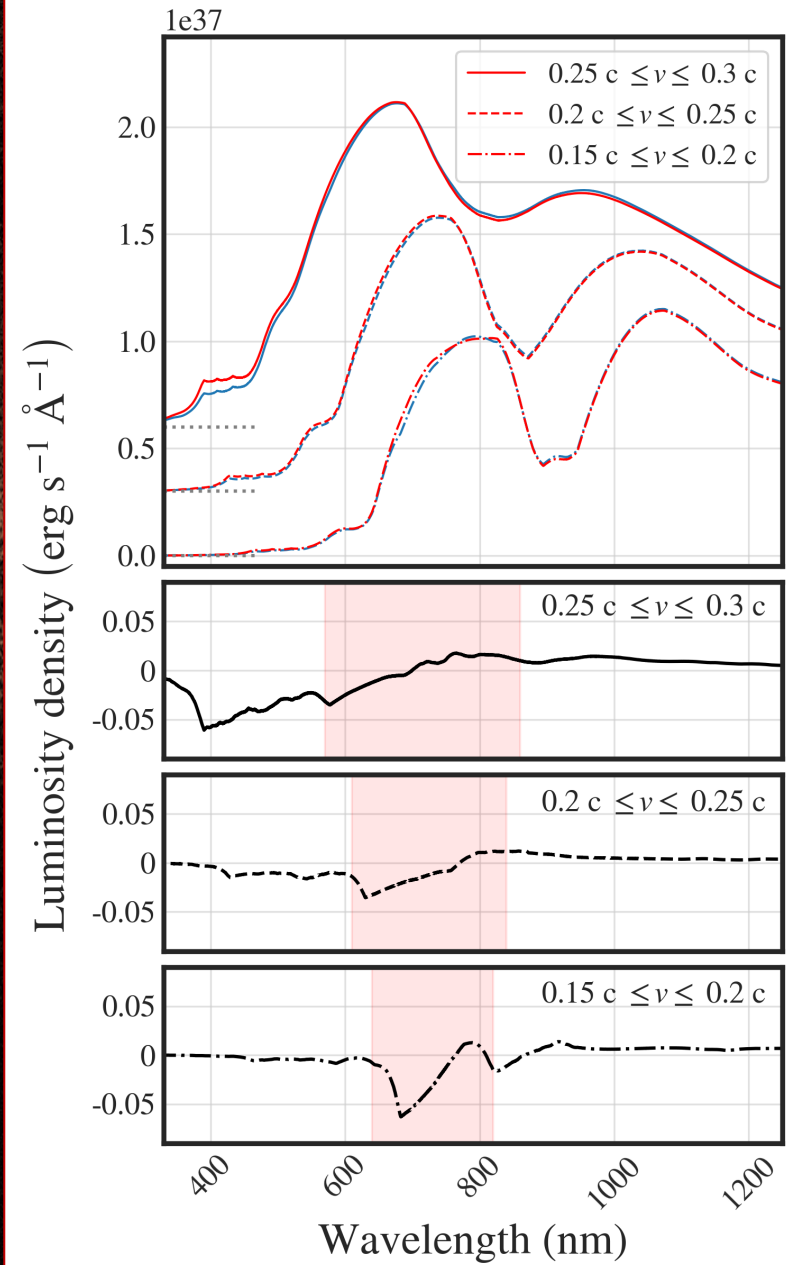
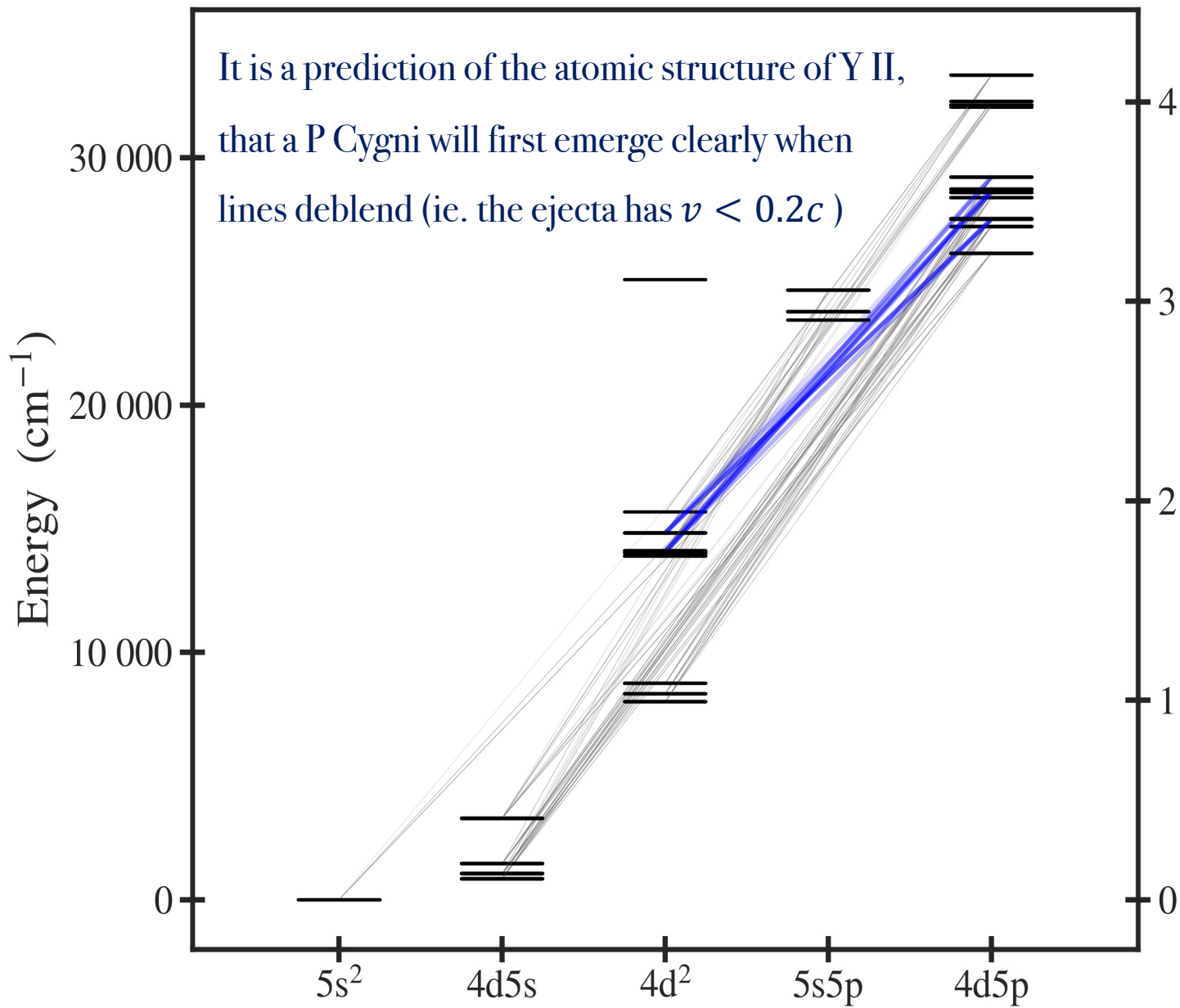
(that is around 0.5 to 0.8 %
of ejected mass is Yttrium)



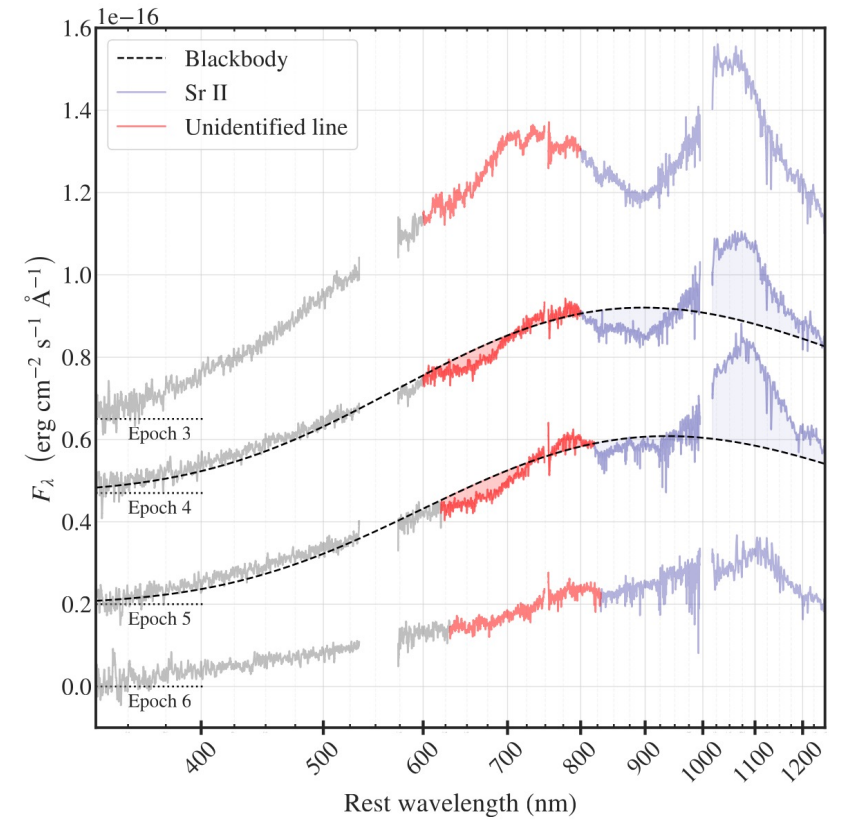
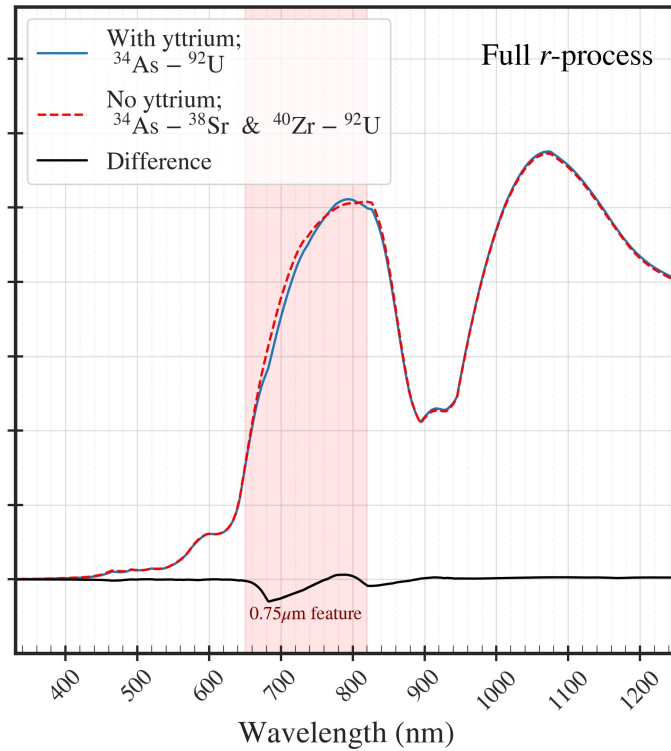
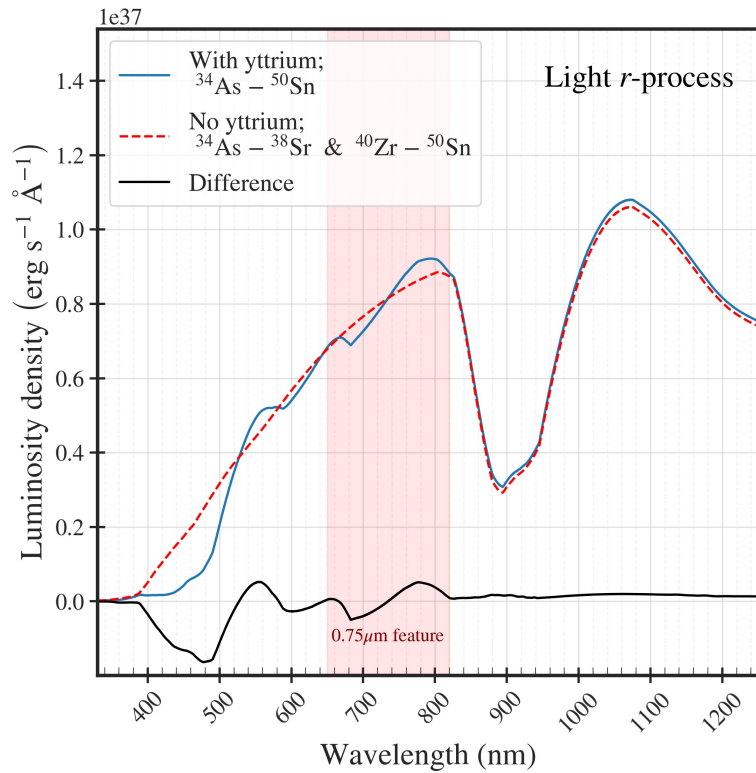


... but appears later than the Sr^+ feature?





Y II constraining the line-blanketing?




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

1 IA																	18 VIIIA	
1 H Hydrogen 1.008																	2 He Helium 4.002602	
3 Li Lithium 6.94	4 Be Beryllium 9.012182											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998403163	10 Ne Neon 20.1797	
11 Na Sodium 22.98976928	12 Mg Magnesium 24.305											13 Al Aluminium 26.9815385	14 Si Silicon 28.085	15 P Phosphorus 30.973761998	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948	
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955908	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938044	26 Fe Iron 55.845	27 Co Cobalt 58.933194	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.921595	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798	
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62		40 Zr Zirconium 91.224	41 Nb Niobium 92.90637	42 Mo Molybdenum 95.95	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293	
55 Cs Caesium 132.90545196	56 Ba Barium 137.327	57 - 71 Lanthanoids		72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.592	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 - 103 Actinoids		104 Rf Rutherfordium (261)	105 Db Dubnium (268)	106 Sg Seaborgium (269)	107 Bh Bohrium (270)	108 Hs Hassium (289)	109 Mt Meitnerium (278)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (282)	112 Cn Copernicium (285)	113 Nh Nihonium (286)	114 Fl Flerovium (289)	115 Mc Moscovium (289)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)

57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.0377	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (266)

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)

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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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56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
Lanthanum	Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium	
138.90547	140.12	140.90766	144.242	144.9128	150.36	151.964	157.25	158.92535	162.50	164.93033	167.258	168.93482	173.045	174.967	
42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	
Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium	
227	232.0377	231.03688	238.02891	237	244	243	247	247	251	252	257	258	259	262	

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

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 $1\ \mu\text{m}$ P Cygni)

1	2											18					
H	He											Ne					
3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
Li	Be	B	C	N	O	F	Ne	Na	Mg	Al	Si	P	S	Cl	Ar		
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
		89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104
		Ba	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
		88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
		Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

Takeaway messages

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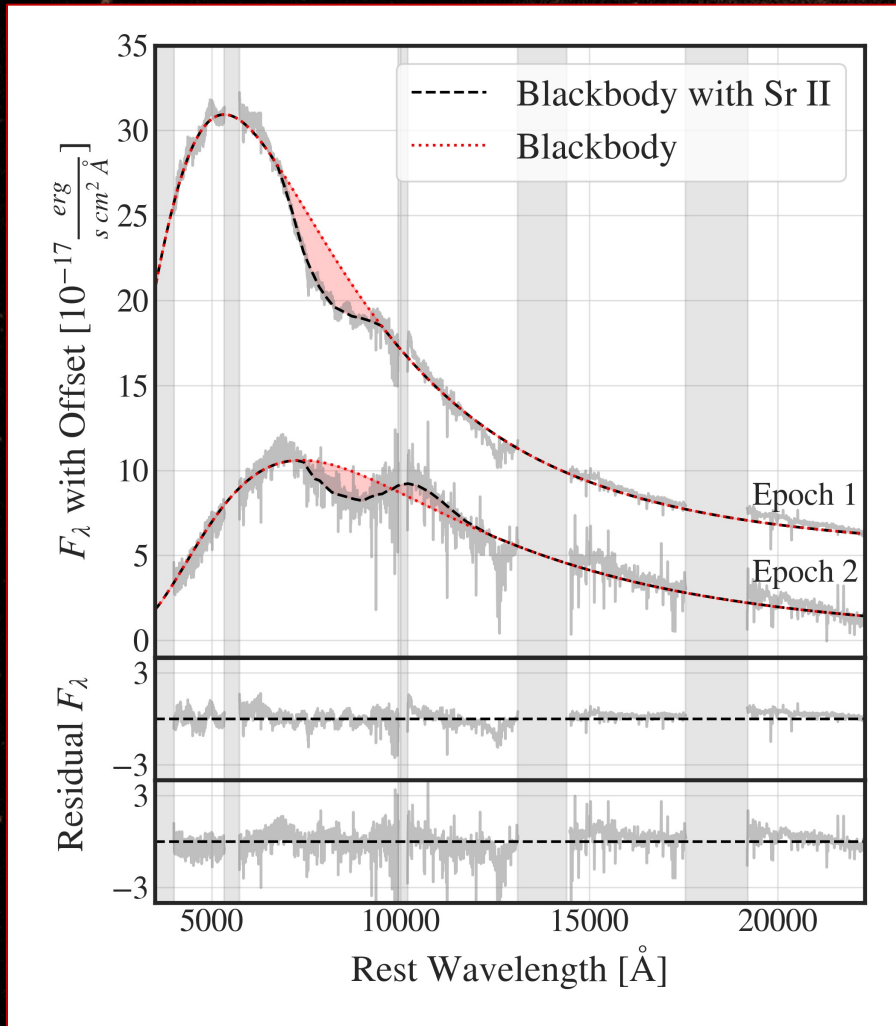
- Central wavelength
- Prominence (abundance)
- Velocity
- Timing of emergence

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)

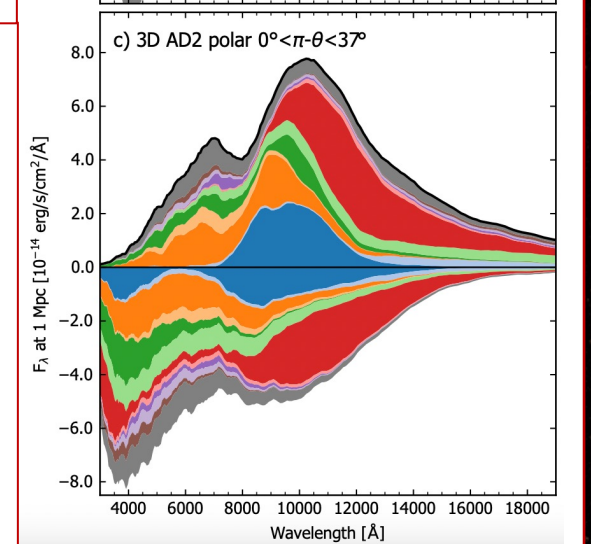
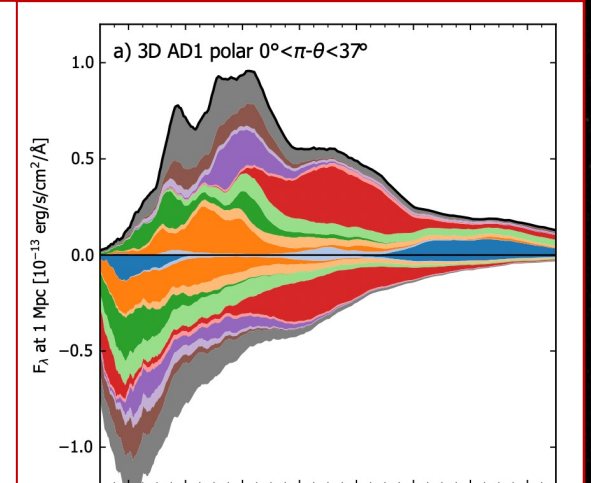
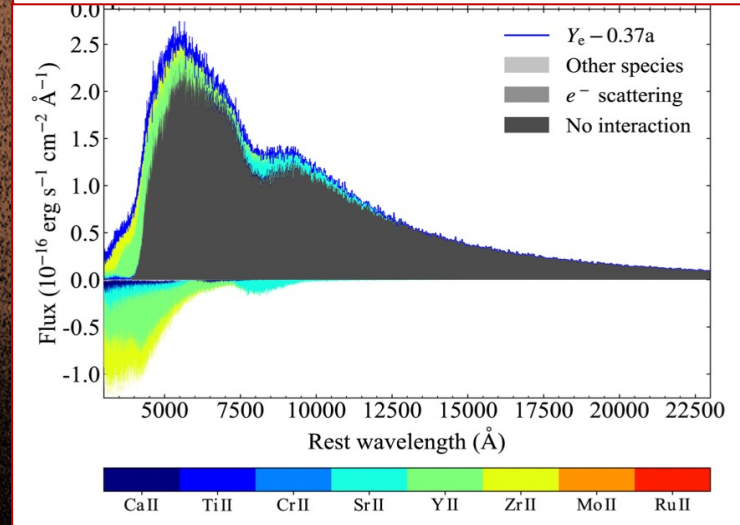
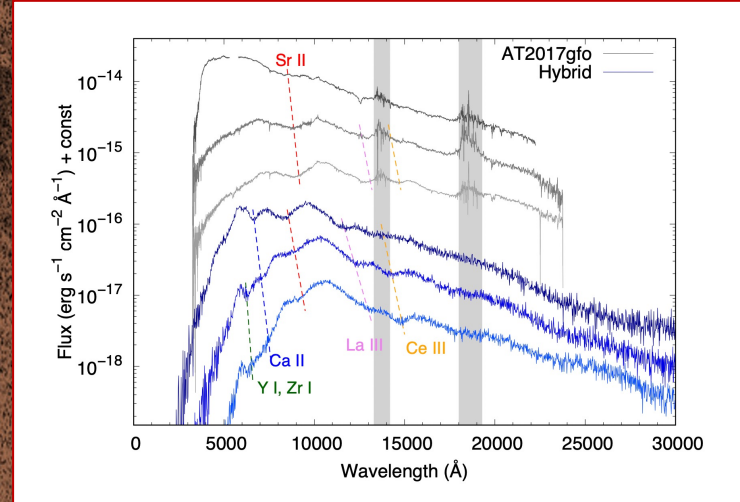
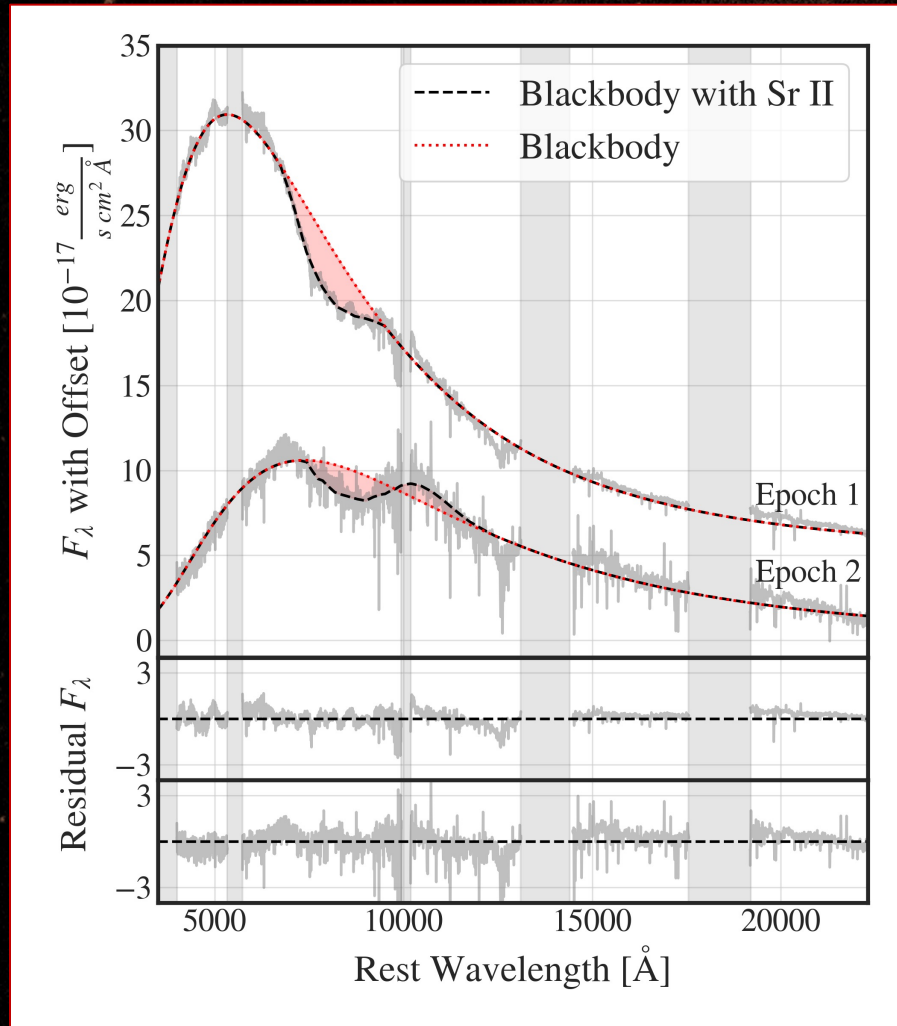
The deblending of Y II lines predicts the feature should first appear (marginally) in epoch 3 and be a fully P Cygni in epoch 4.

One last puzzle...



One last puzzle...

Domoto et al. (2022)



Gillanders et al. (2022)

Shingles et al. (2023)

... On the blackbody spectrum of kilonovae

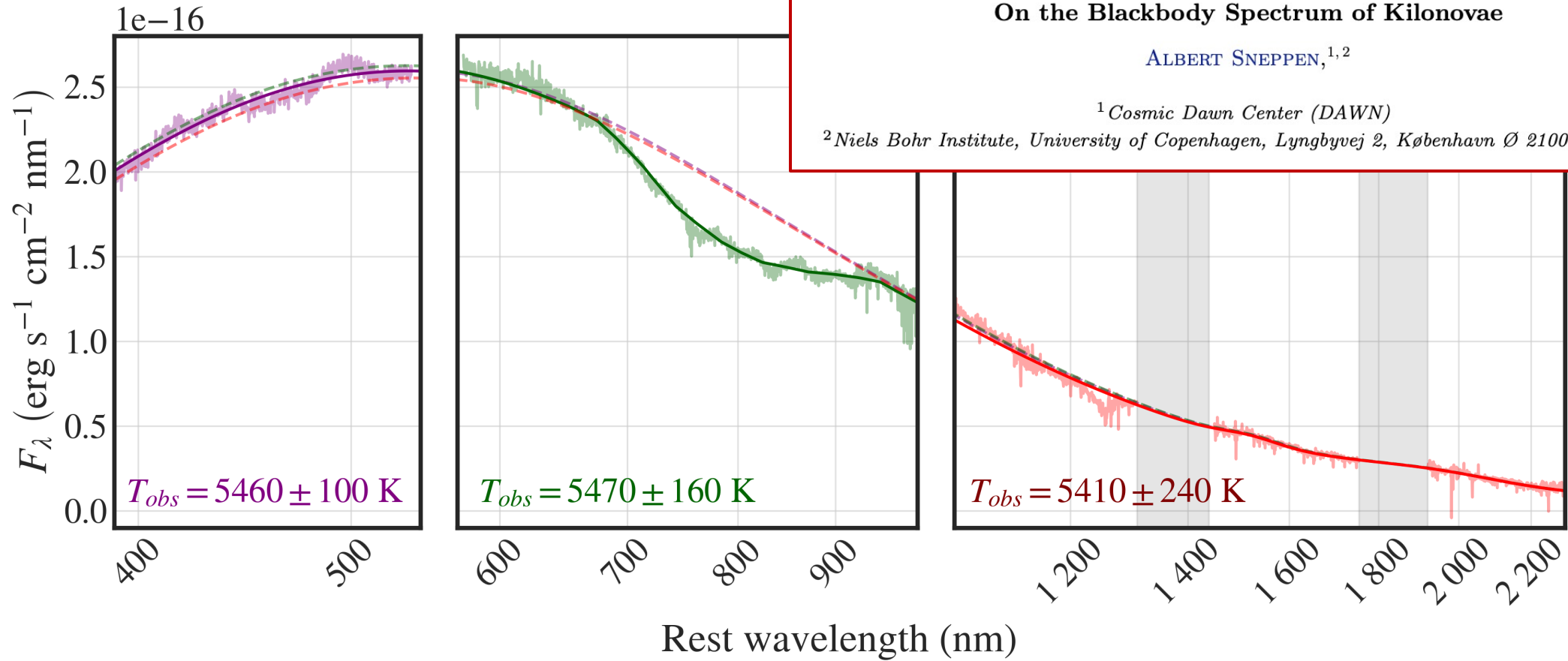
In press, ApJ

On the Blackbody Spectrum of Kilonovae

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²Niels 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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e-mail: a.sneppen@gmail.com

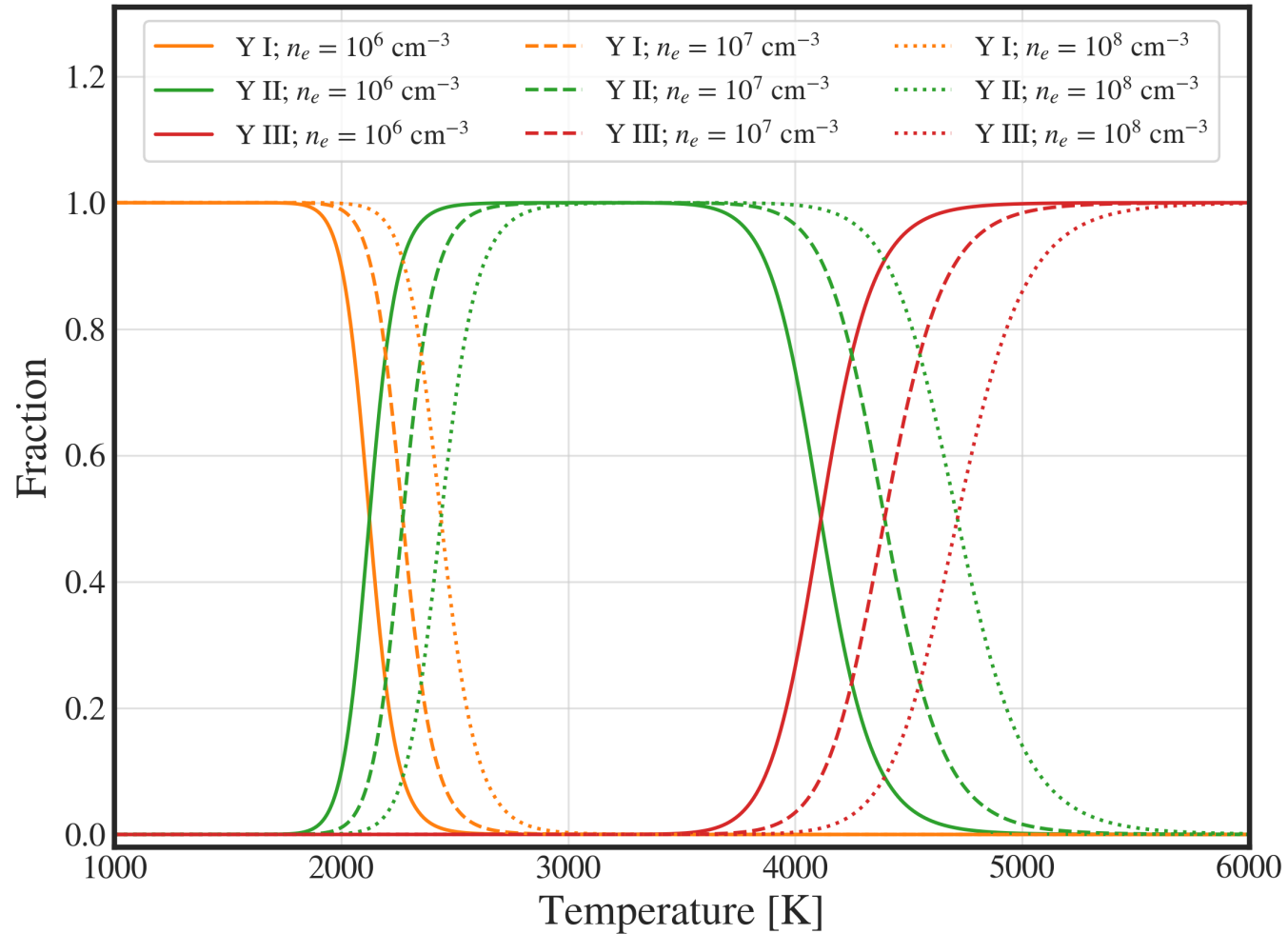
² Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, København 2100, Denmark

Received 15 March 2023 / Accepted 3 June 2023

<https://arxiv.org/abs/2306.14942>

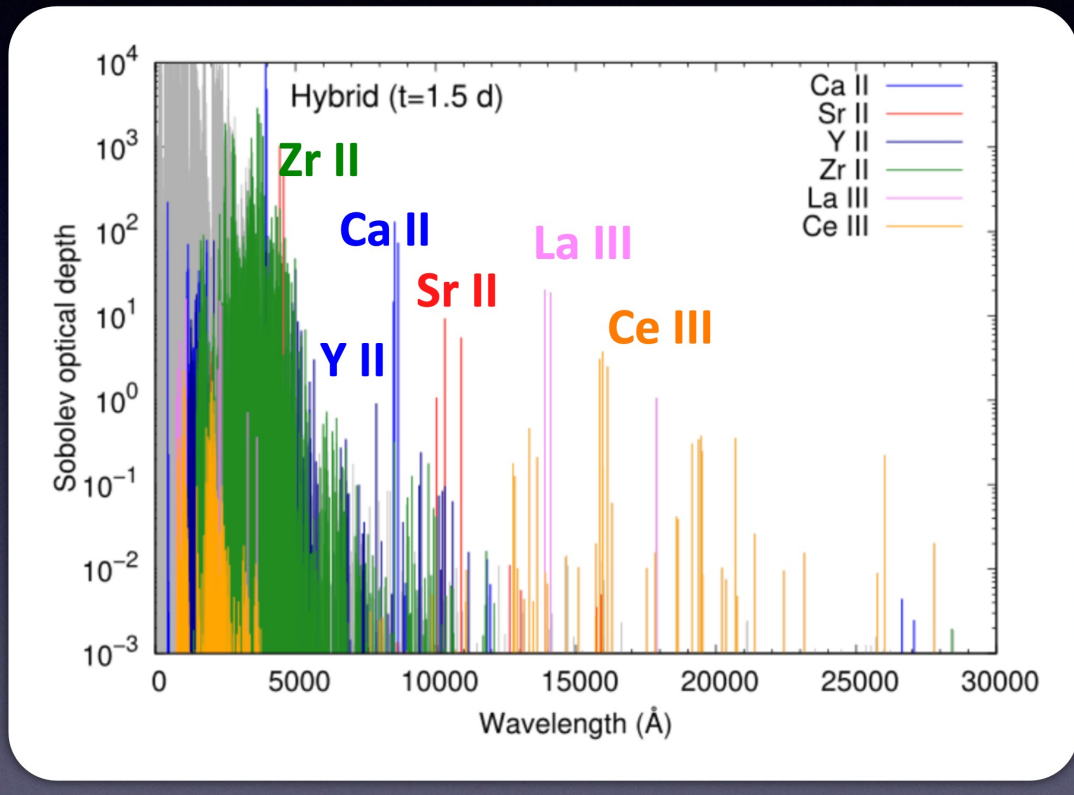
Sneppen & Watson (2023), *A&A*, 675

Extra Slide I: Ionization state

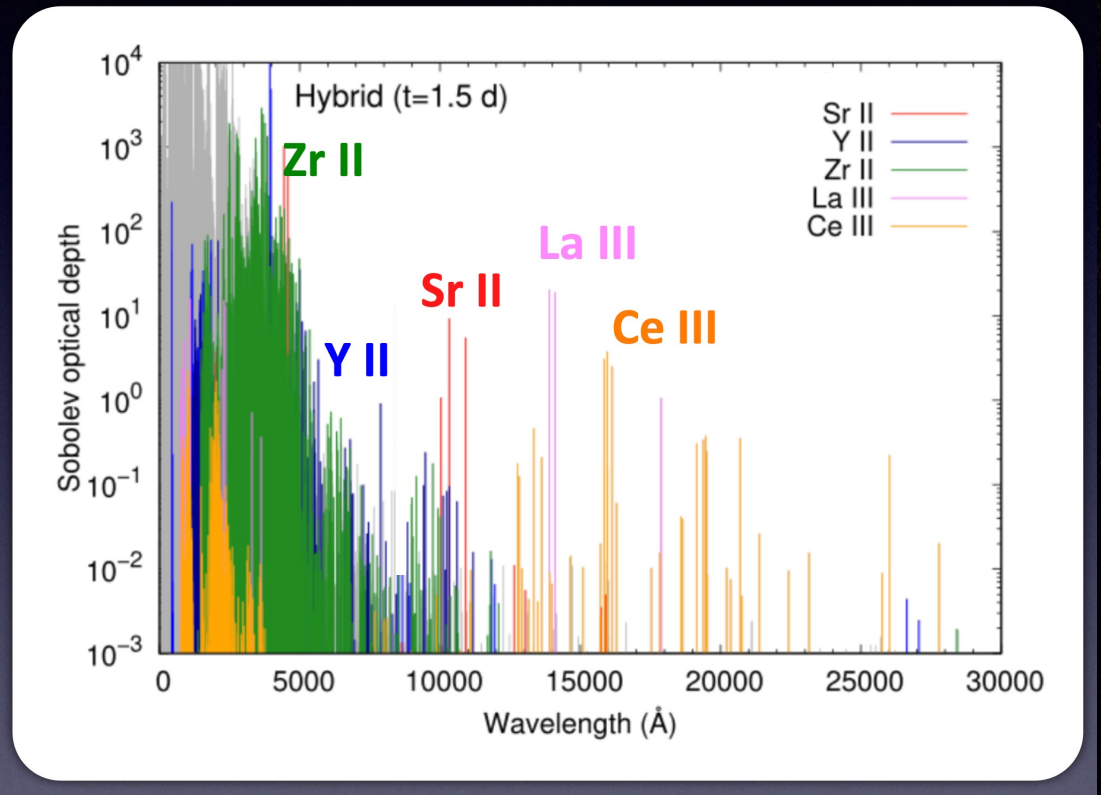


Highest opacity “trees” in Tanaka et al (2020)

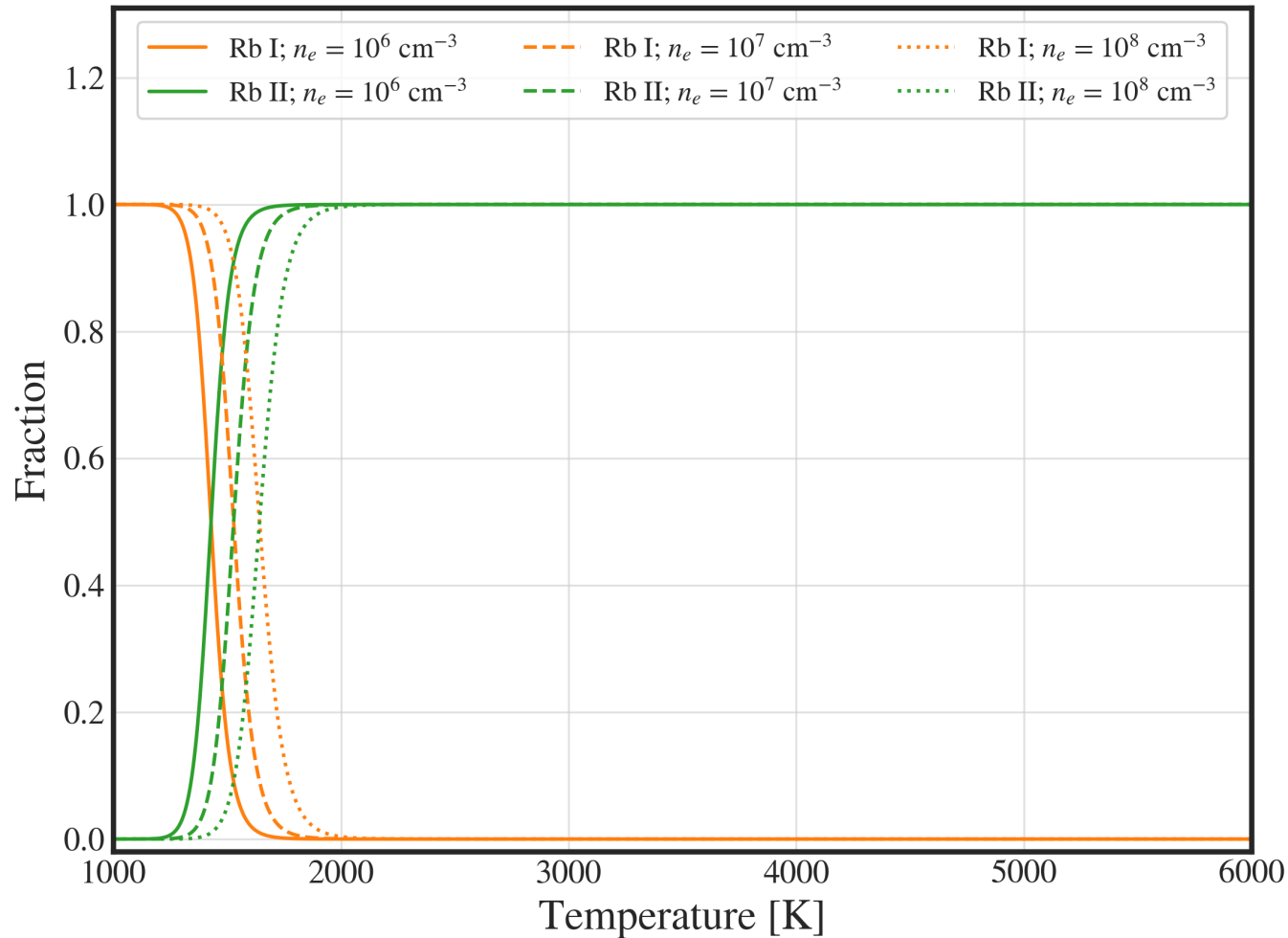
Constructed from **complete** data (MT+20)



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

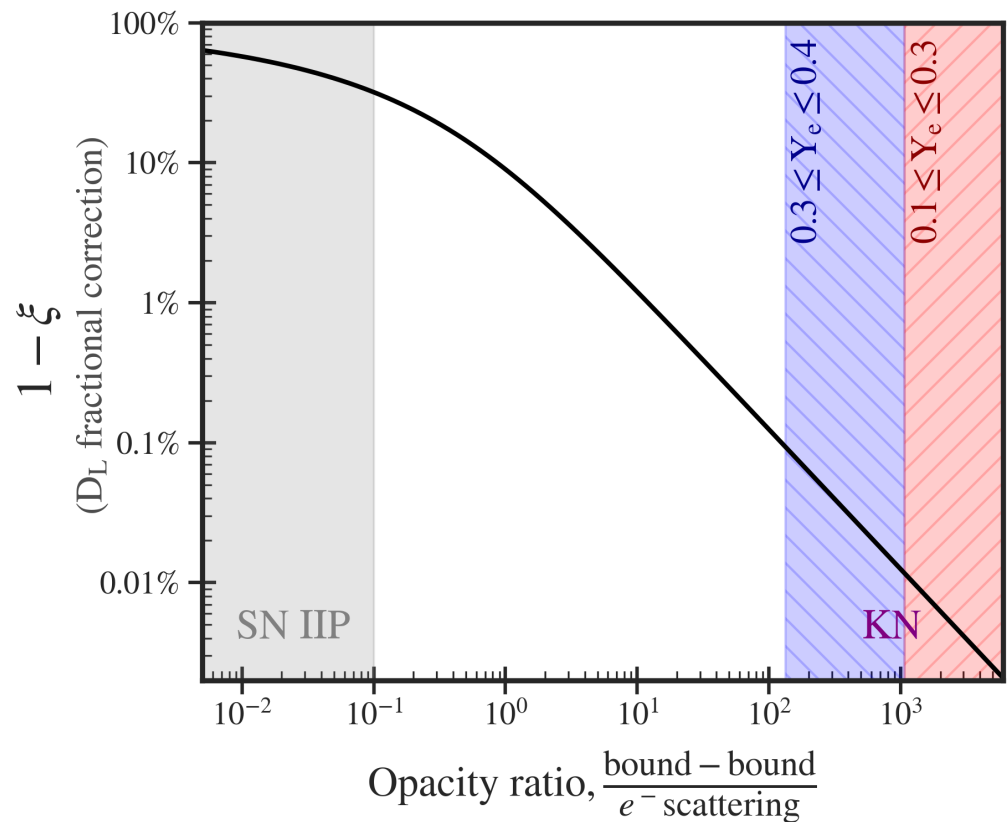


Fig. 3. Fractional correction to the estimated luminosity distance from dilution factors, $1 - \xi$, as a function of opacity ratio, $\kappa_{\text{b-b}}/\kappa_{e^- \text{scat}}$. As the opacity ratio is a function of wavelength, we report the integrated Planck mean opacity. When electron-scattering 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).