

YITP Workshop

“Exploring Extreme Transients: Emerging Frontiers and Challenges”

キロノバのスペクトルにおけるトリアウムの同定可能性

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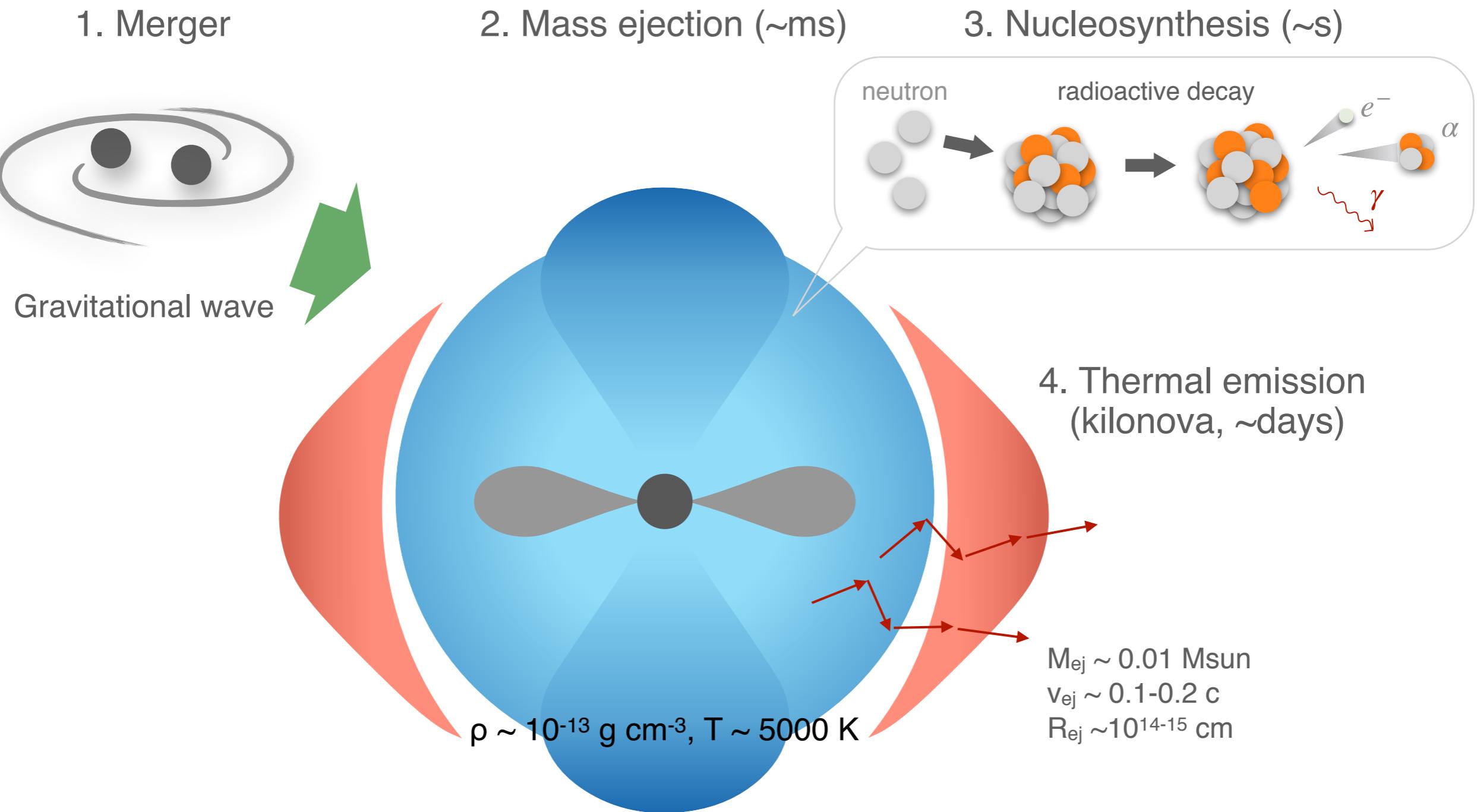
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2024/08/09

Domoto et al., submitted

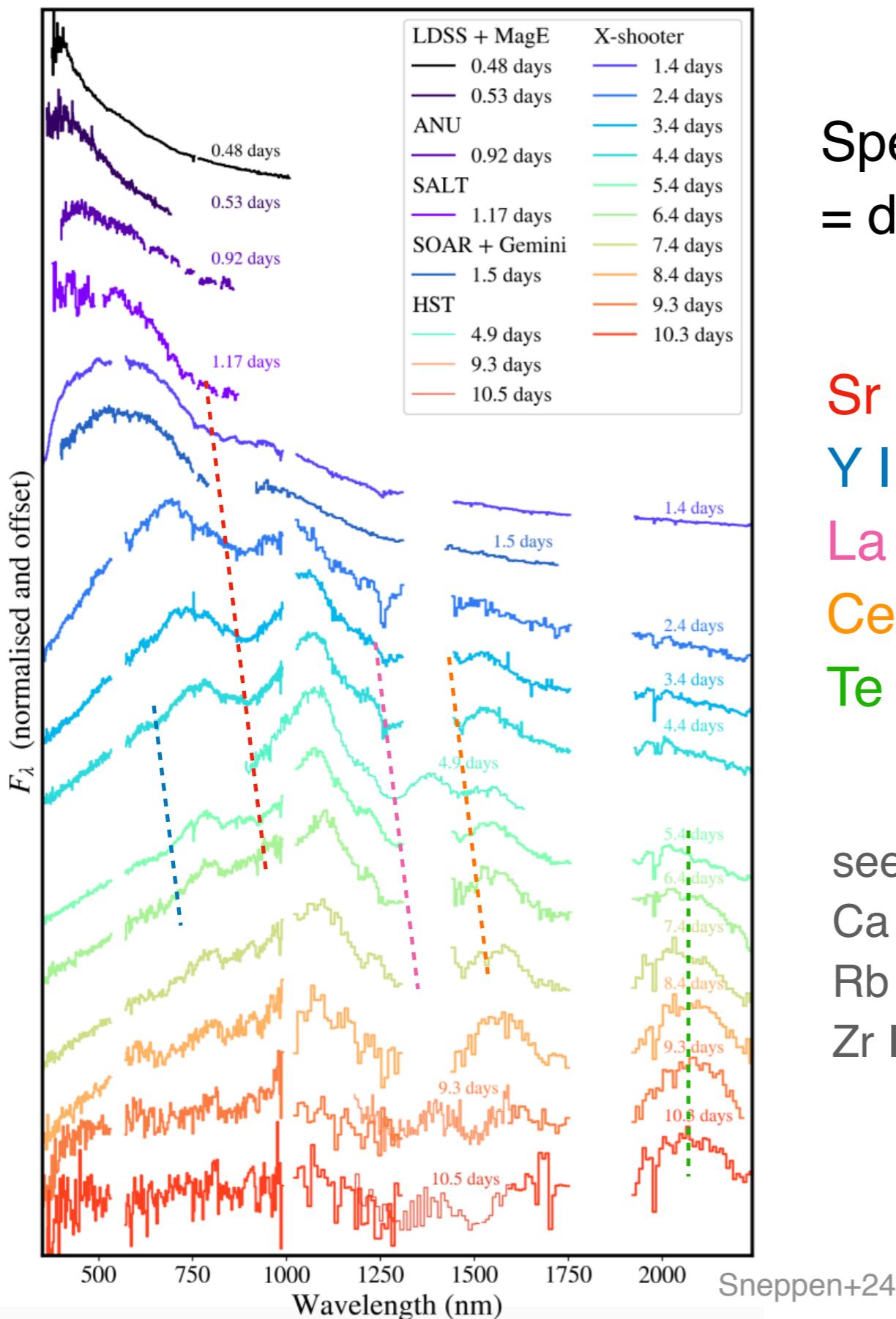
Kilonova

Radioactively-powered thermal emission from neutron star merger



e.g., Lattimer & Schramm 74, Eichler+89, Li & Paczynski 98, Freiburghaus+99,
Metzger+10, Goriely+11, Roberts+11, Tanaka & Hotokezaka 13...

Implications of elements in GW170817



Spectral features
= direct evidence of individual elements

Sr II Watson+19, Gillanders+21, Domoto+21, 22, Vieira+23

Y II Sneppen & Watson 23

La III Domoto+22, Gillanders+23

Ce III Domoto+22, 23, Tanaka+23, Gillanders+23

Te III Hotokezaka+23

see also...

Ca II Domoto+21

Rb I Pognan+23

Zr II Domoto+22, Gillanders+22, Vieira+23

Important elements and atomic properties

¹H

³Li ⁴Be

¹¹Na ¹²Mg

¹⁹K ²⁰Ca

³⁷Rb ³⁸Sr

⁵⁵Cs ⁵⁶Ba

⁸⁷Fr ⁸⁸Ra

Small number of valence electrons

- Small number of transitions
→ higher transition probability (sum rule)
- Low-lying energy levels
→ higher electron population

$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l \frac{g_k f_l}{g_0} e^{-\frac{E_k}{kT}}$$

²He

⁵B ⁶C ⁷N ⁸O ⁹F ¹⁰Ne

¹³Al ¹⁴Si ¹⁵P ¹⁶S ¹⁷Cl ¹⁸Ar

³¹Ga ³²Ge ³³As ³⁴Se ³⁵Br ³⁶Kr

⁴⁹In ⁵⁰Sn ⁵¹Sb ⁵²Te ⁵³I ⁵⁴Xe

⁸¹Tl ⁸²Pb ⁸³Bi ⁸⁴Po ⁸⁵At ⁸⁶Rn

¹¹³Nh ¹¹⁴Fl ¹¹⁵Mc ¹¹⁶Lv ¹¹⁷Ts ¹¹⁸Og

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

Motivation of this work

Small number of valence electrons

- Small number of transitions
→ higher transition probability (sum rule)
- Low-lying energy levels
→ higher electron population

A standard periodic table of elements is shown, highlighting specific groups. The first group (H, He) is at the top left. The second group (Li, Be, Na, Mg) is highlighted in grey. The third group (B, C, N, O, F, Ne) is at the top right. The fourth group (Al, Si, P, S, Cl, Ar) is also highlighted in grey. The fifth group (K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr) is in the middle. The sixth group (Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe) is partially visible. The seventh group (Cs, Ba, Hg, Tl, Pb, Bi, Po, At, Rn) is at the bottom left. The eighth group (Fr, Ra, Rf, Db, Sg, Bh, Hs, Mt, Ds, Rg, Cn, Nh, Fl, Mc, Lv, Ts, Og) is at the bottom right. A red dashed box highlights the second group (Li, Be, Na, Mg), and a blue dashed box highlights the fifth group (K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr). A large orange box covers the entire row of the fifth group.

Can we identify further heavier elements???

An extended periodic table showing elements from atomic number 57 to 103. The lanthanides (La to Lu) are grouped together in pink boxes. The actinides (Ac to Lr) are grouped together in blue boxes. Individual elements are shown in their respective boxes.

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

$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l \frac{g_k f_l}{g_0} e^{-\frac{E_k}{kT}}$$

Simple expectation

Small number of valence electrons

- Small number of transitions
→ higher transition probability (sum rule)
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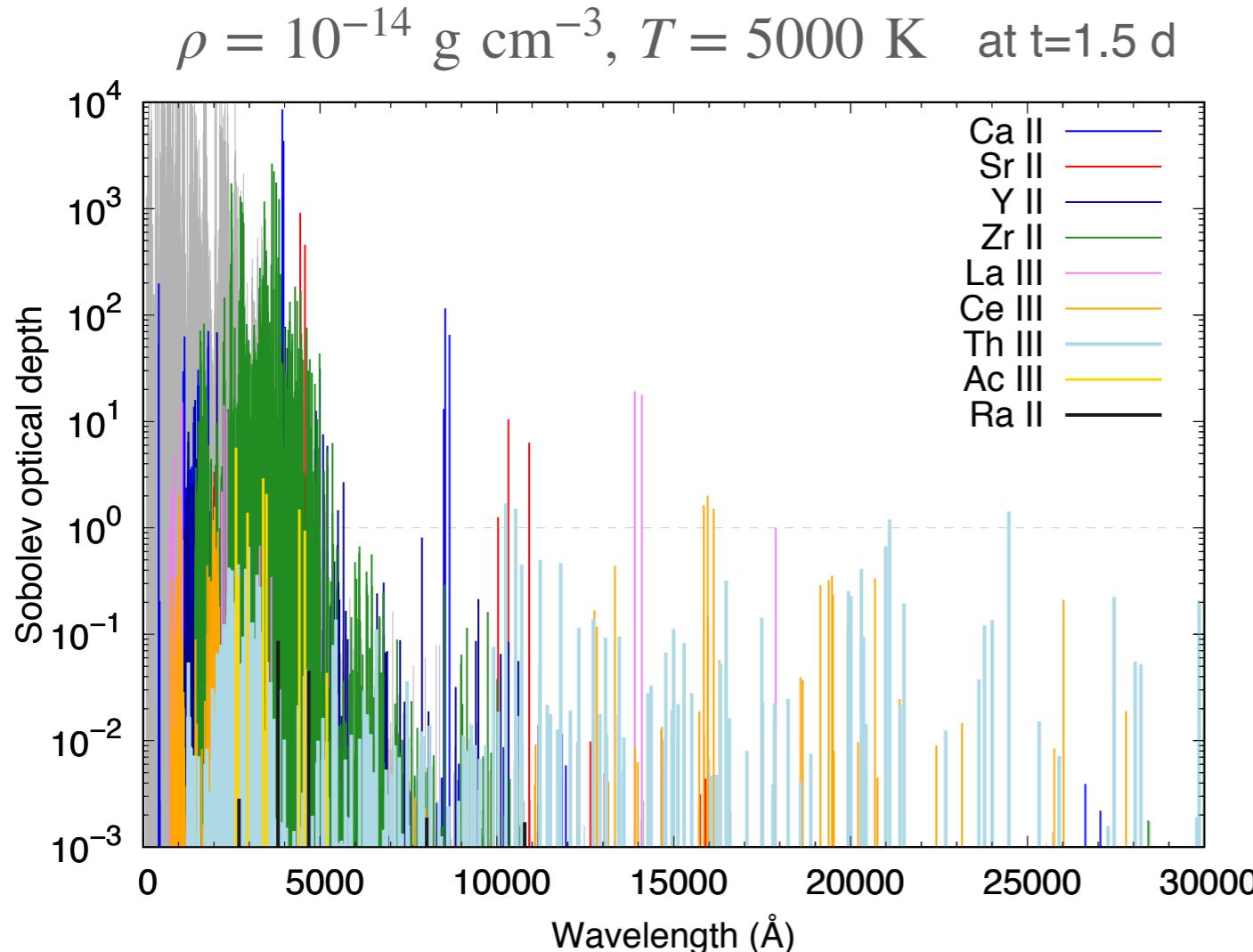
¹ H																				² He
3 Li	4 Be																			
11 Na	12 Mg																			
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr			
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe			
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn			
87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og			

$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l \frac{g_k f_l}{g_0} e^{-\frac{E_k}{kT}}$$

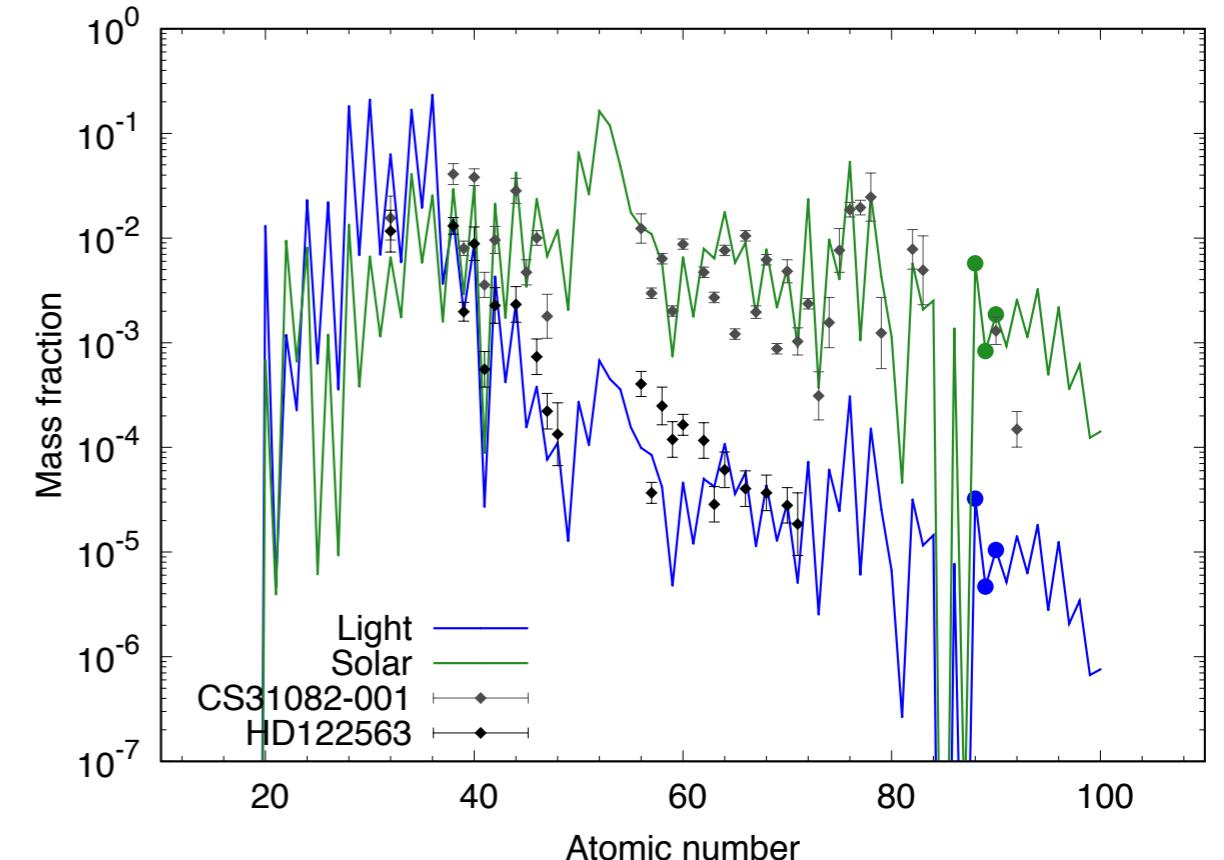
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Systematic investigation of strength of lines

1. Collect the data of bound transitions for Ra II, Ac III, Th III
2. Calculate Sobolev optical depths (under LTE)



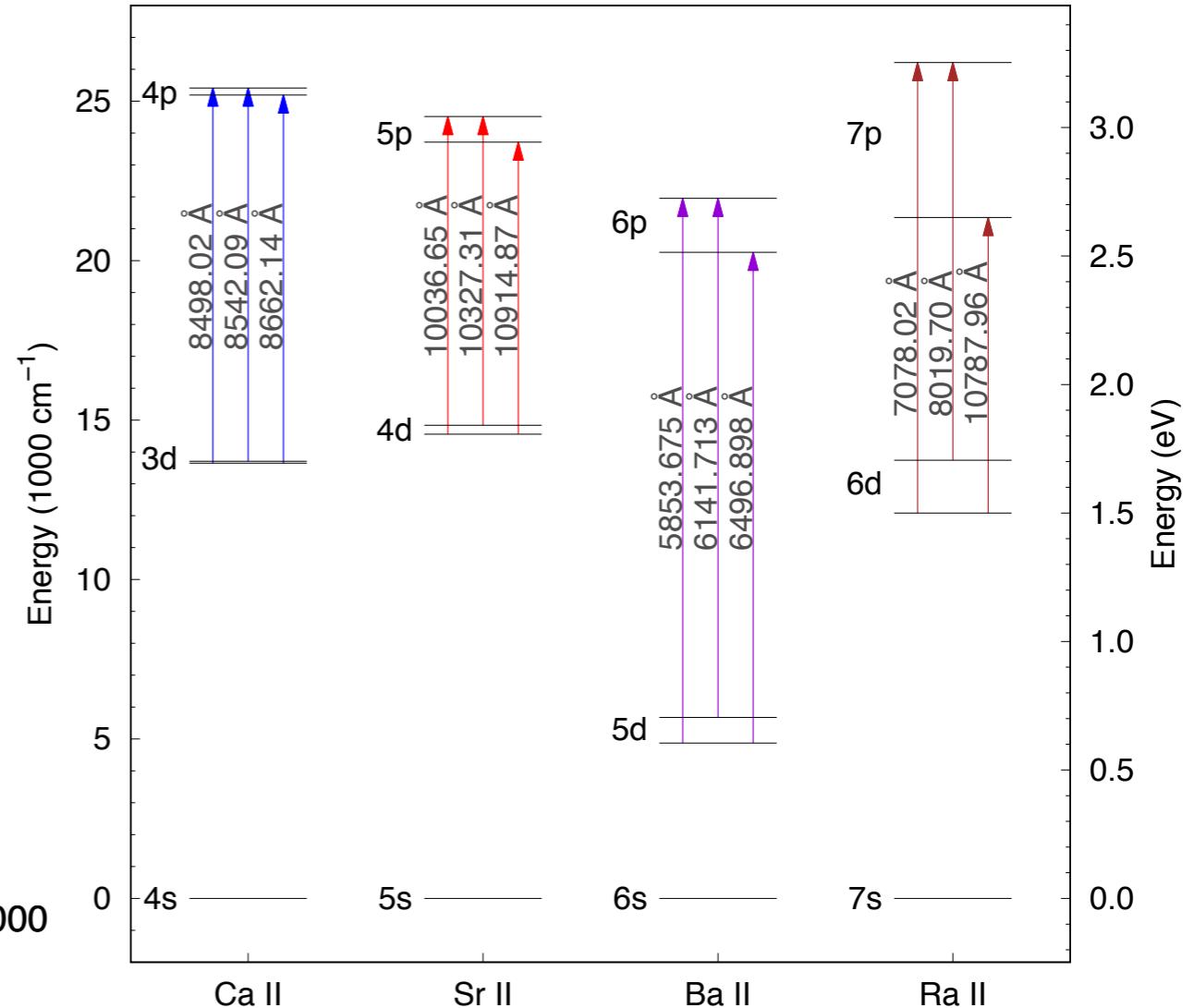
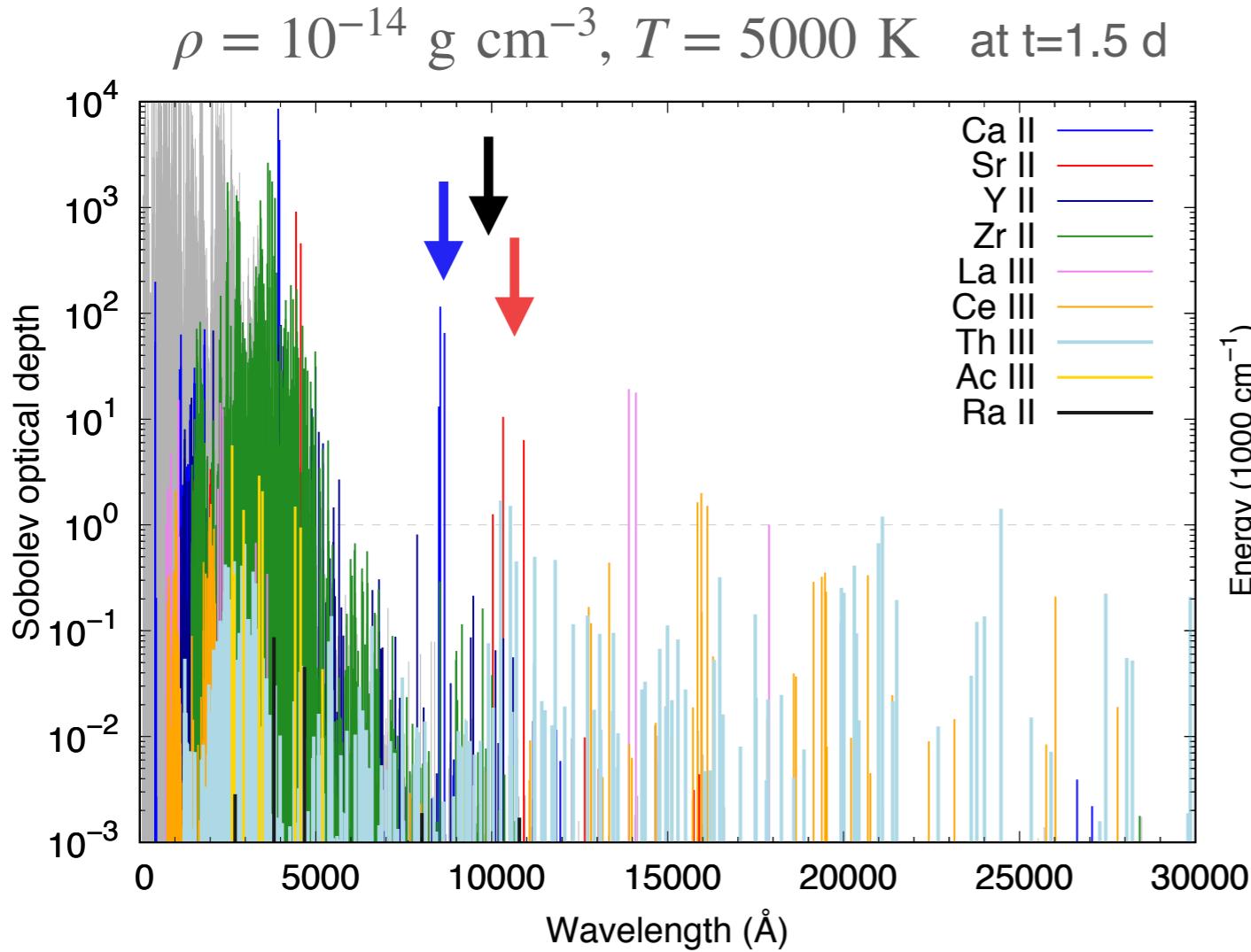
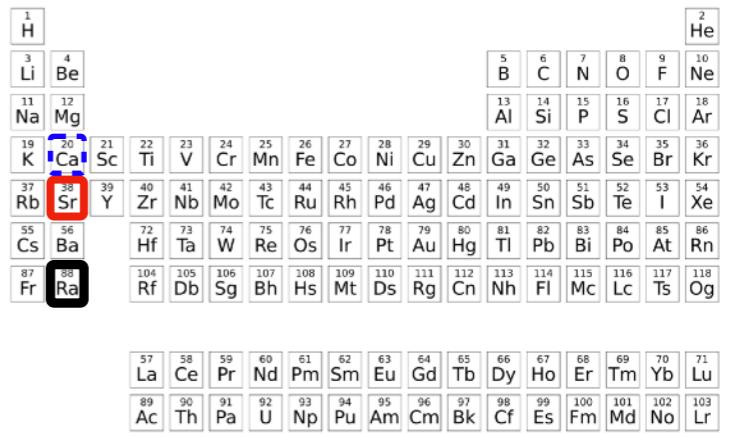
$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l \frac{g_k f_l}{g_0} e^{-\frac{E_k}{kT}}$$



*Blue model reasonably explains
La III/Ce III features in AT2017gfo

Ra II (Z=88) is not promising

Analogous atomic structure/transitions to Ca II, Sr II

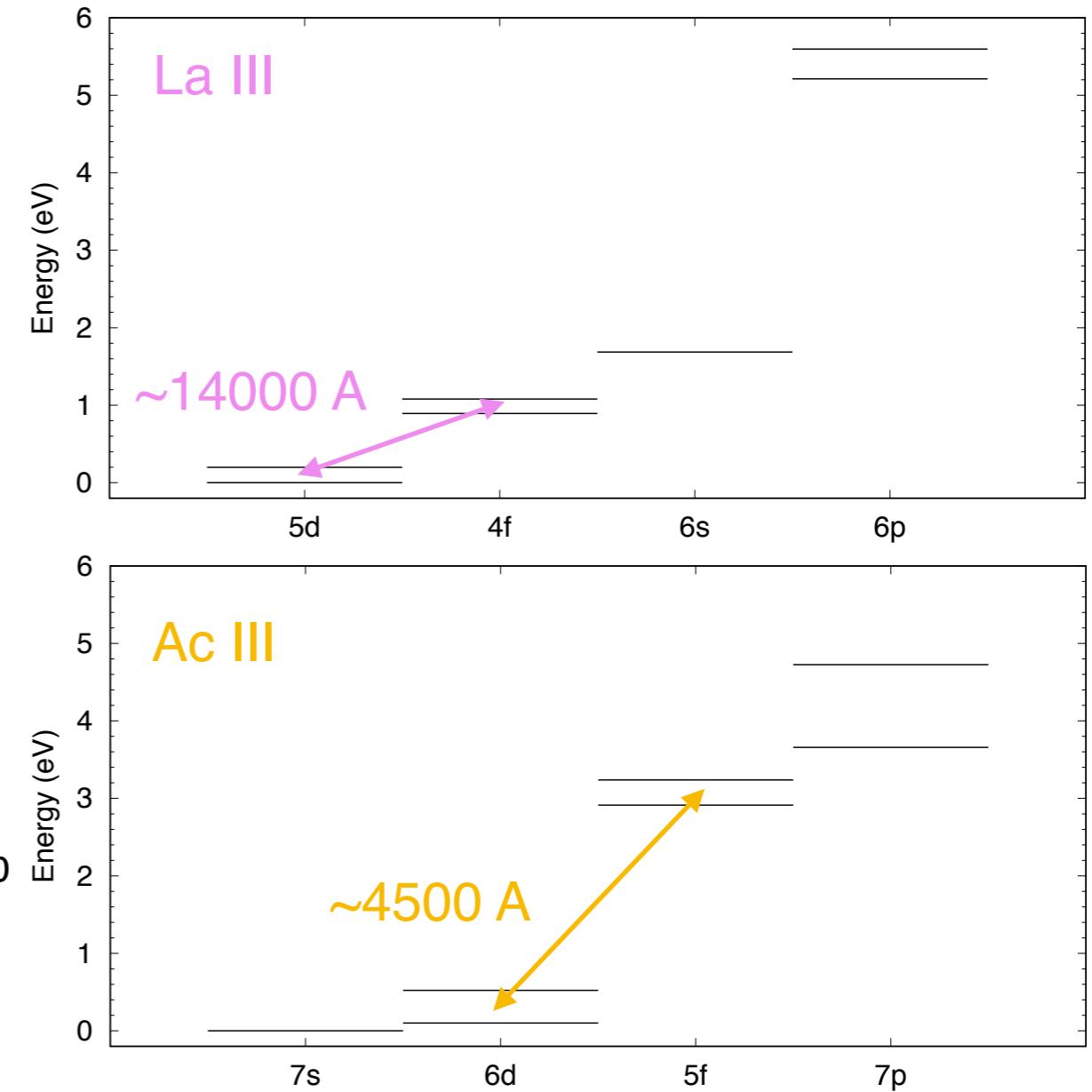
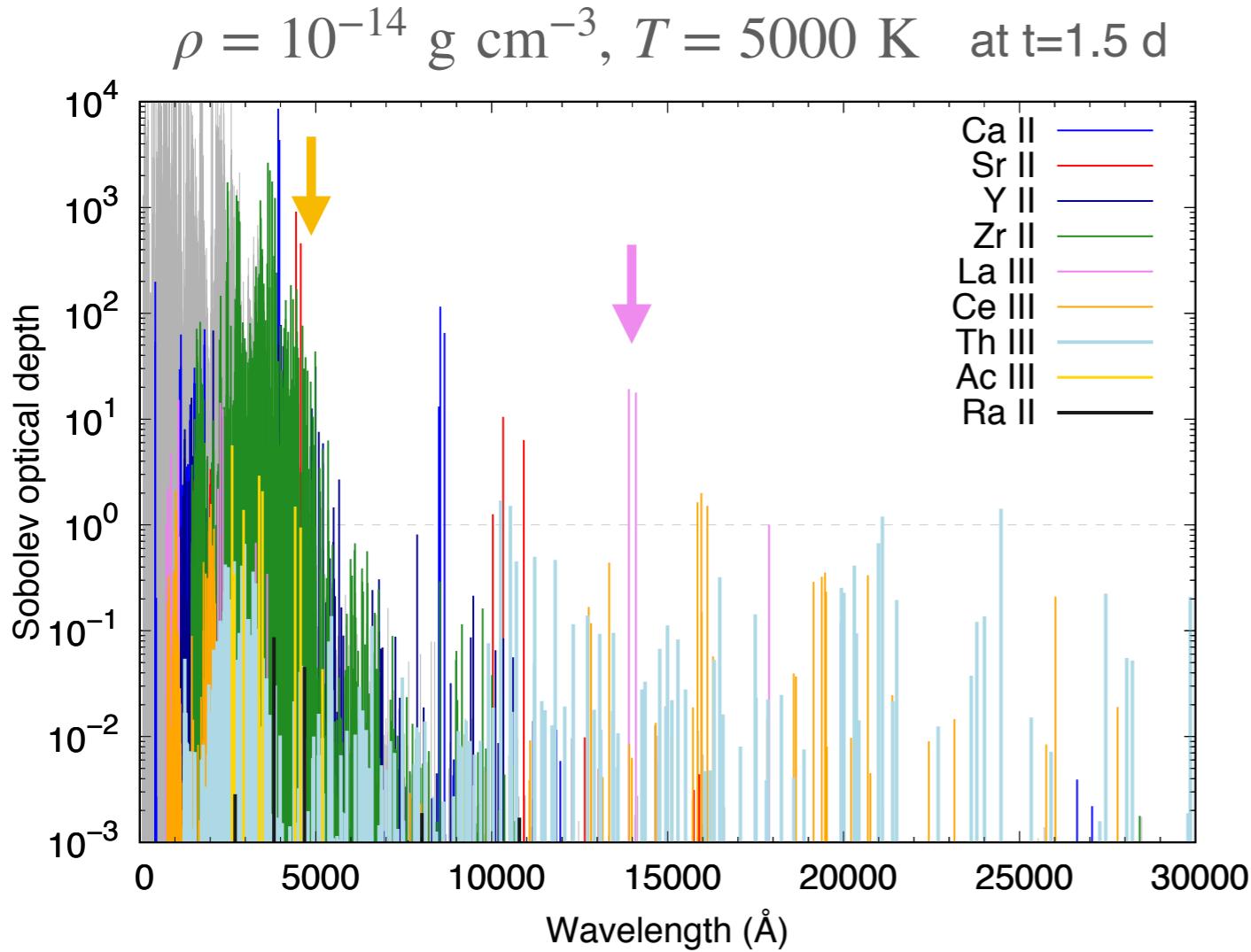


Mass fraction of Ra $\sim 10^{-5} \leftrightarrow$ Ca, Sr $\sim 10^{-2}$
Ra II lines cannot compete with lines of lanthanides w/ similar mass fractions

Ac III (Z=89) is not promising

NOT analogous atomic structure/transitions to La III

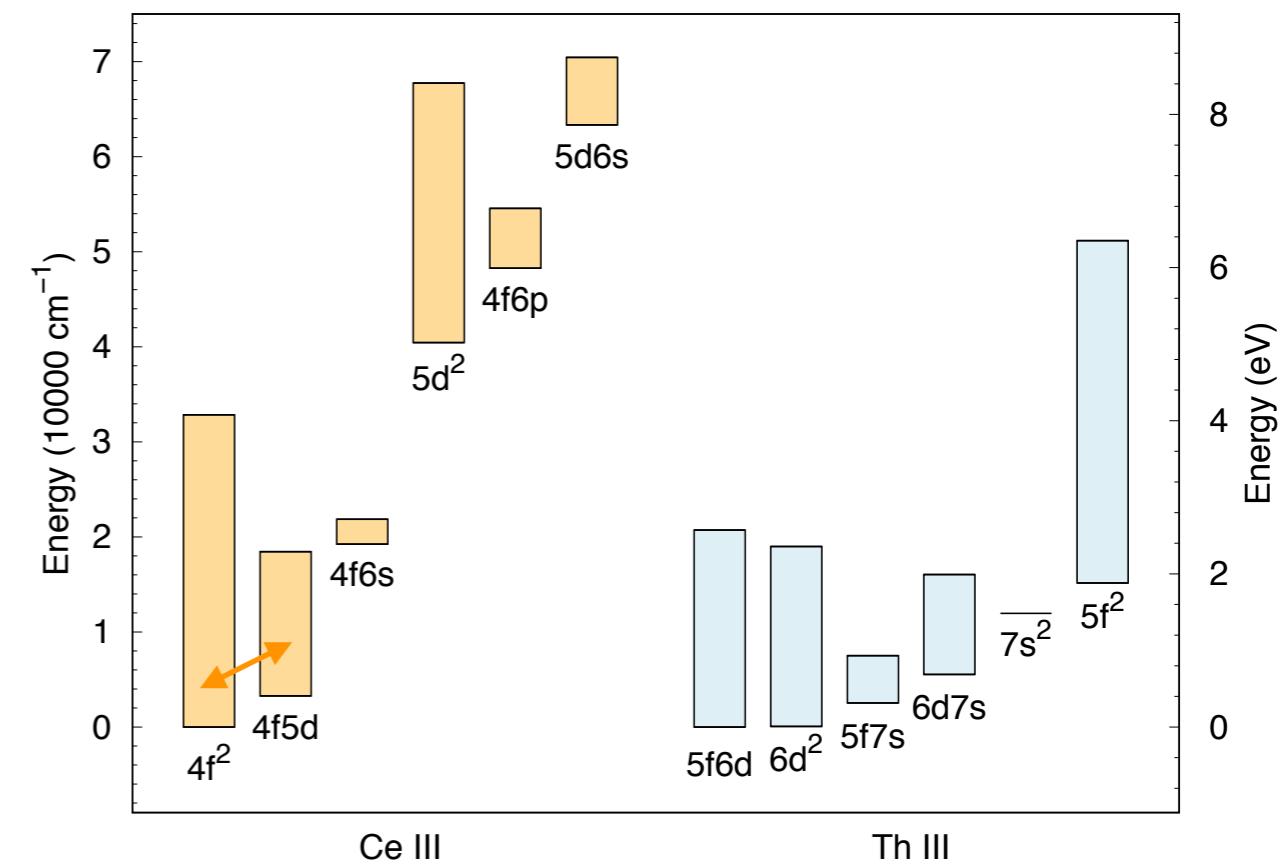
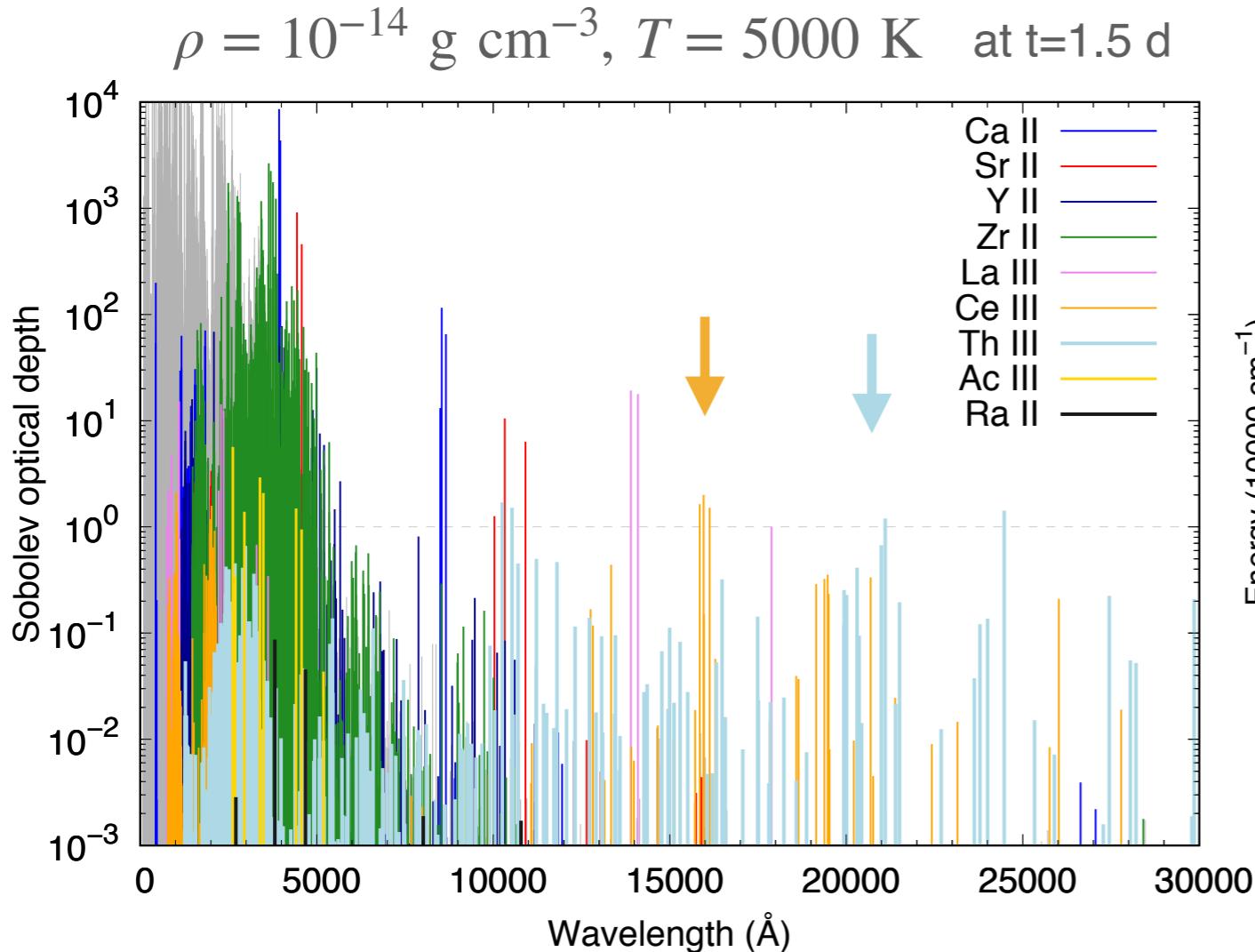
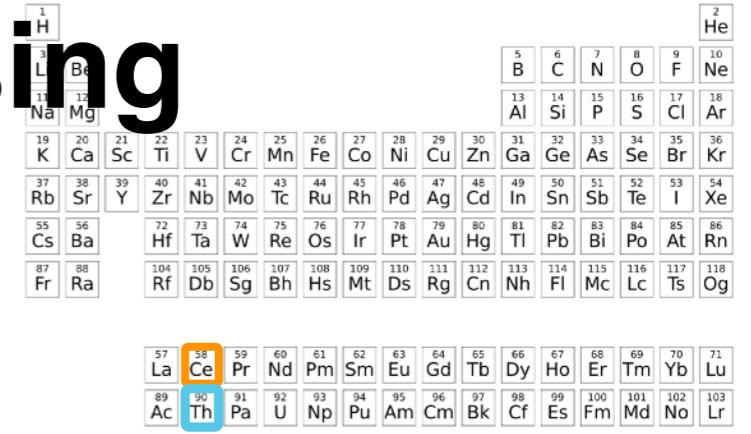
The periodic table shows the element Ac III (Atomic Number 89) highlighted in yellow, and La III (Atomic Number 57) highlighted in pink. The table includes elements from Hydrogen (H) to Oganesson (Og), organized by group and period.



Ac III does not have NIR (E1) lines from low energy levels

Th III (Z=90) is the most promising

Dense low-lying energy levels (compared to Ce III)

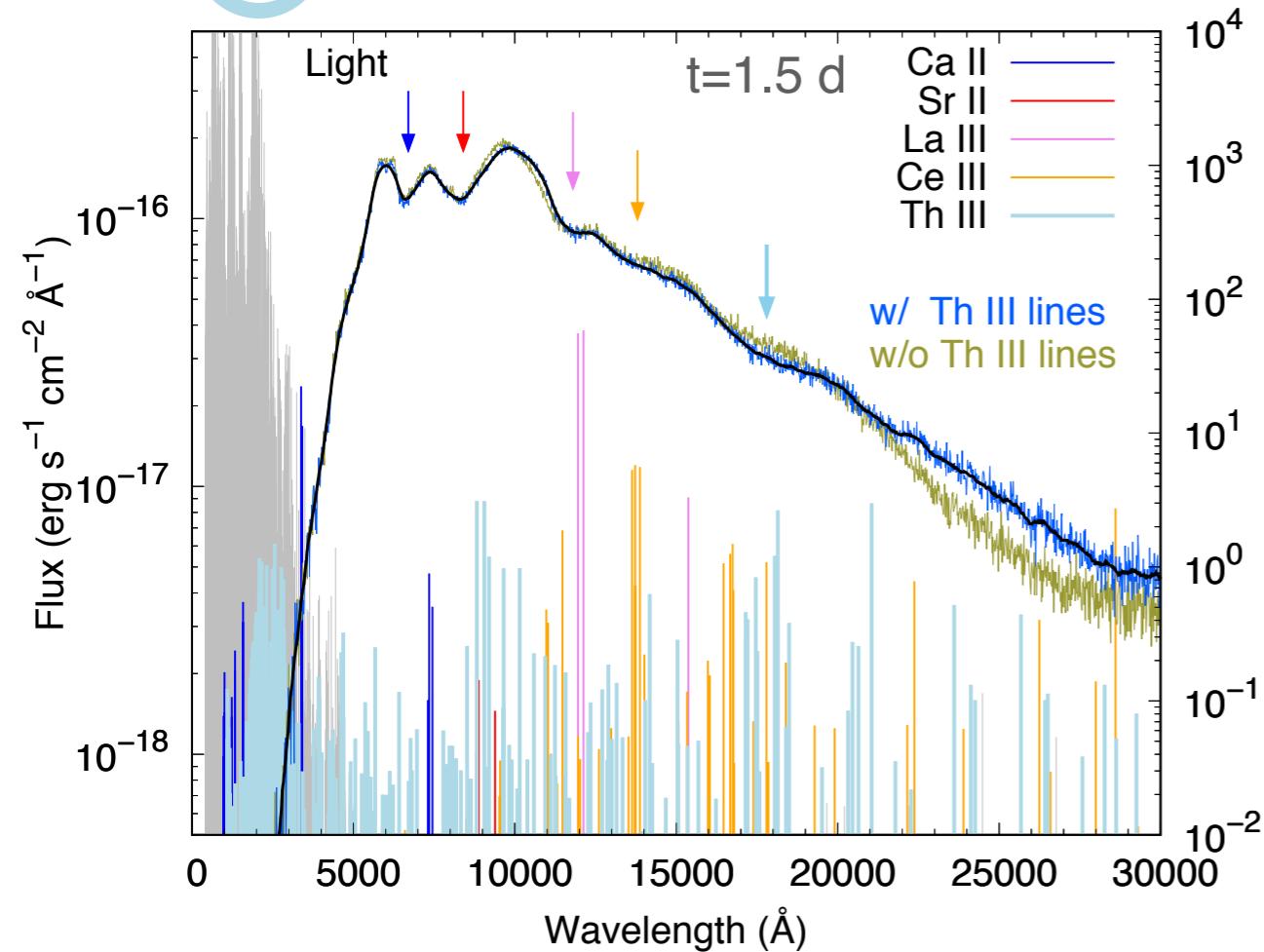
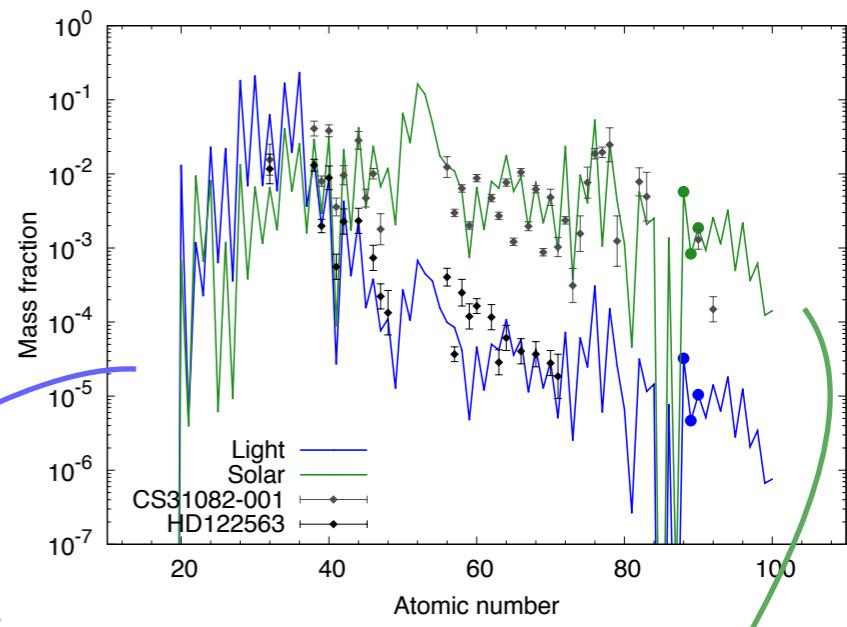


Th III can produce strong transitions (comparable to e.g., Ce III)

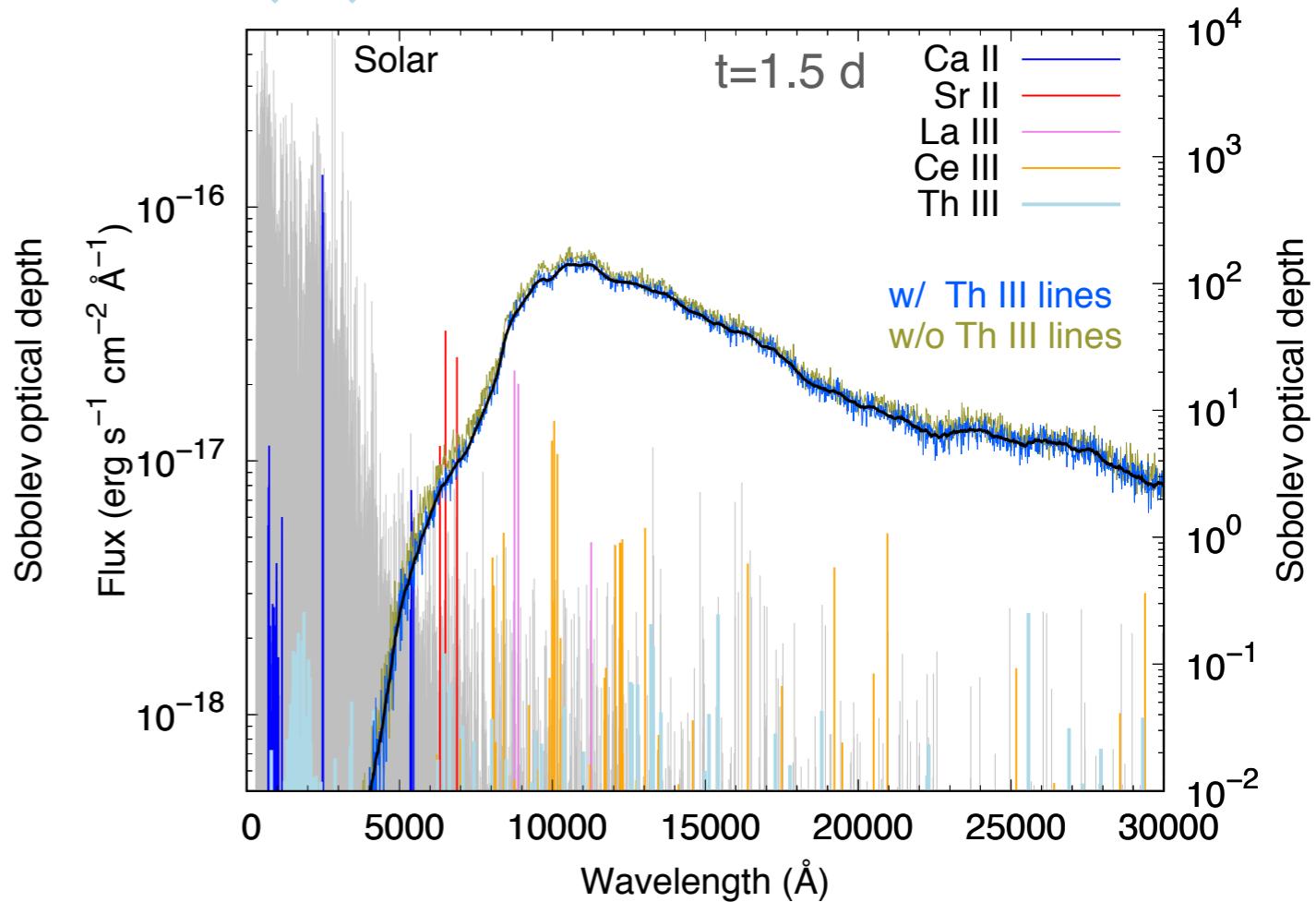
Synthetic spectra

Perform radiative transfer simulations

*1D density structure ($\rho \propto r^{-3}$)

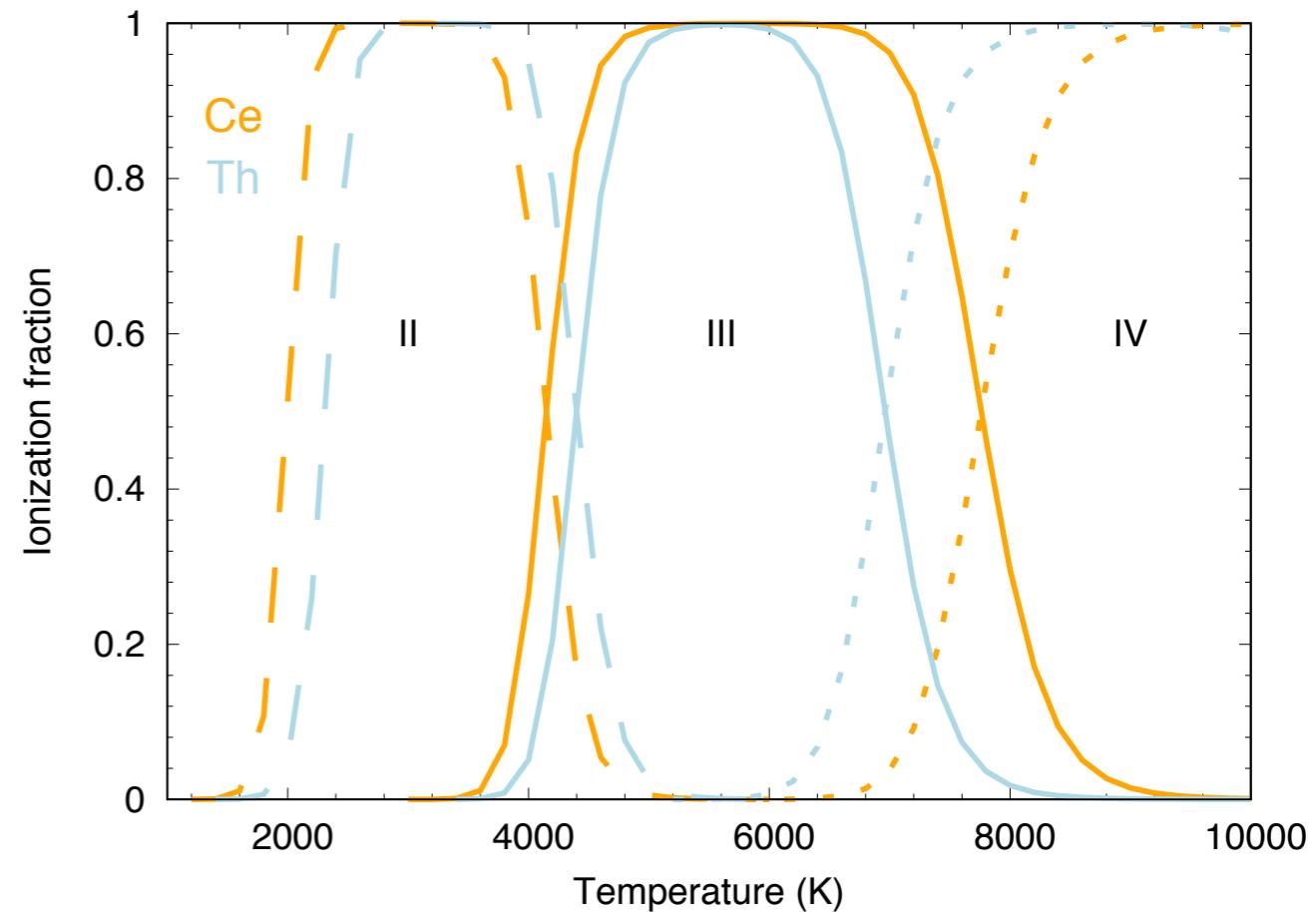
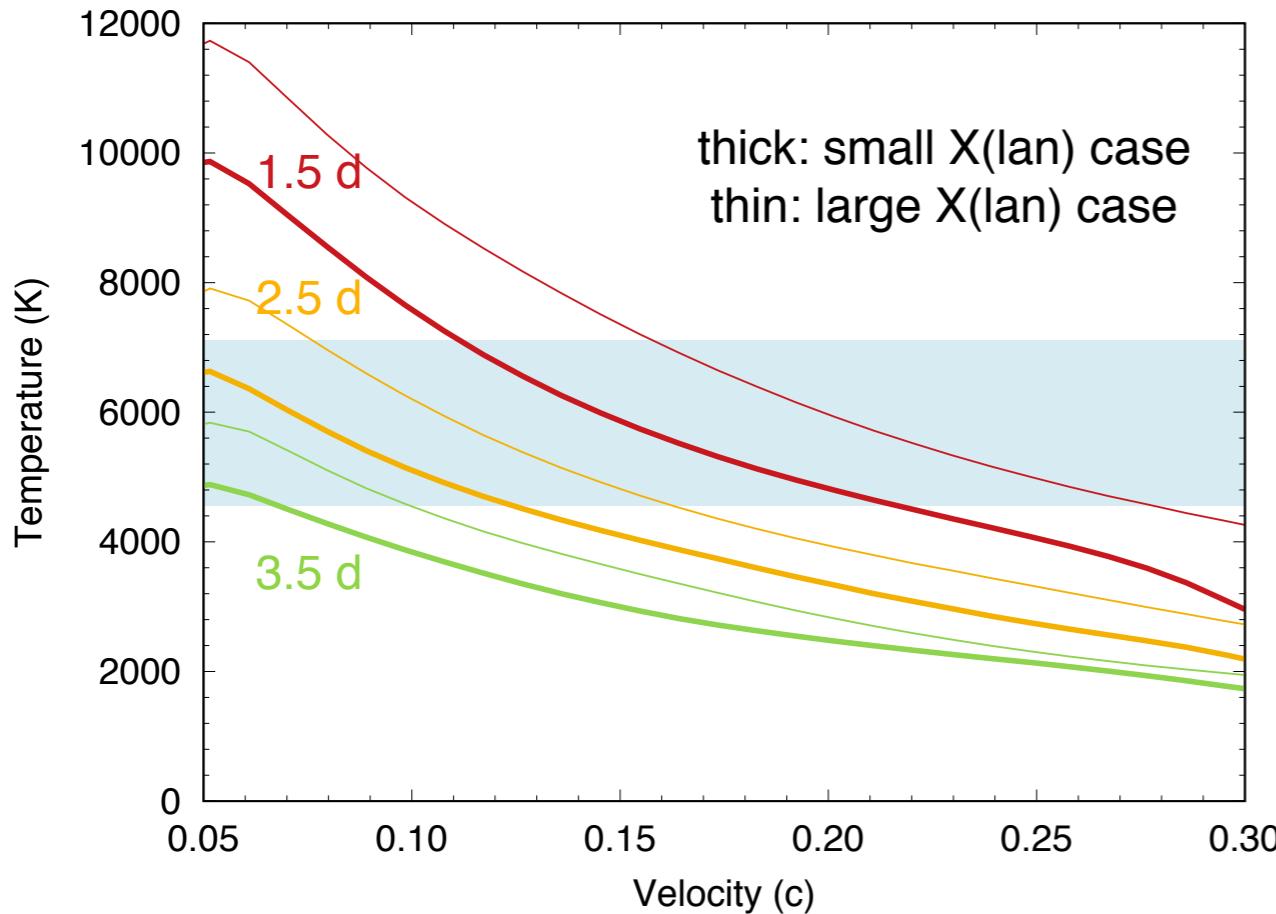


line forming region: $T \sim 7000$ K ($v=0.13c$)



$T \sim 3700$ K ($v=0.37c$)

Temperature dependence of Th III lines



Larger amount of lanthanides (w/ homogeneous abundance distribution)
→ high opacity
→ photosphere goes outward where T is lower

* The feature would be even stronger if the condition that photospheric
T=5000-7000 K w/ a larger mass fraction of lanthanides and Th were realized

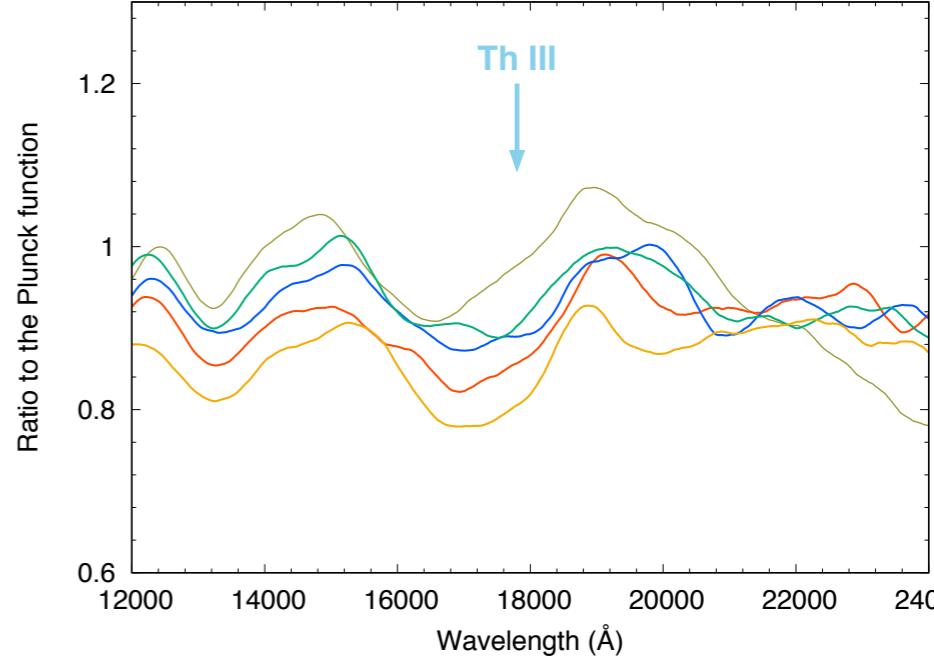
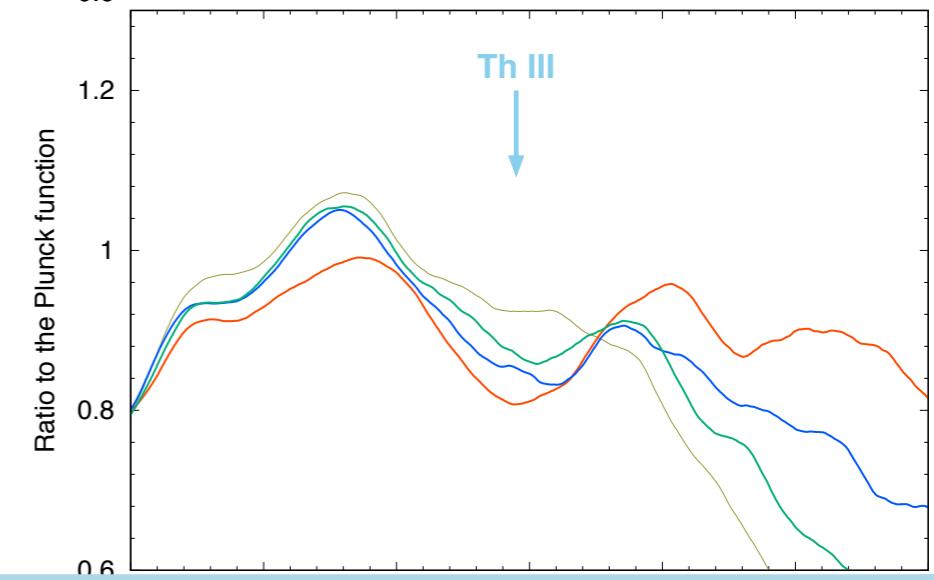
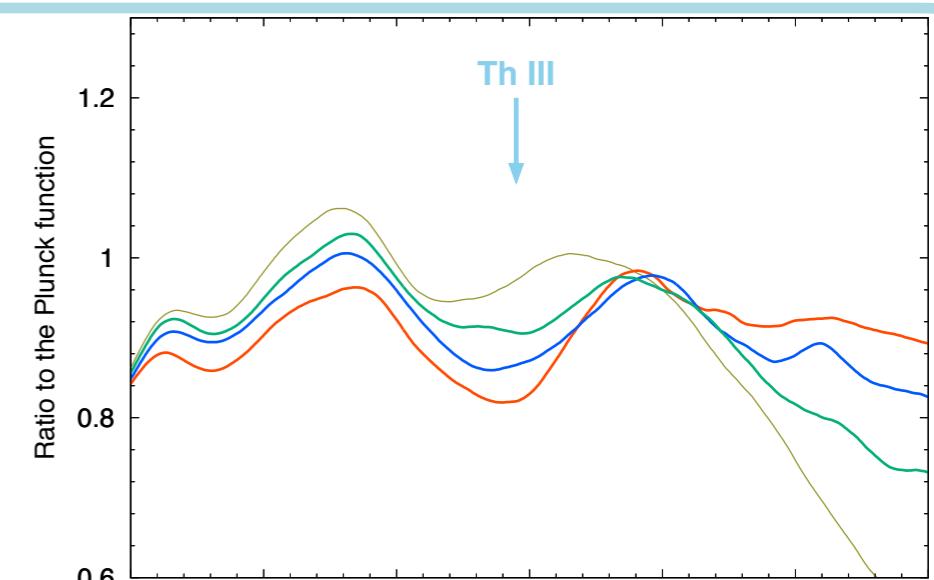
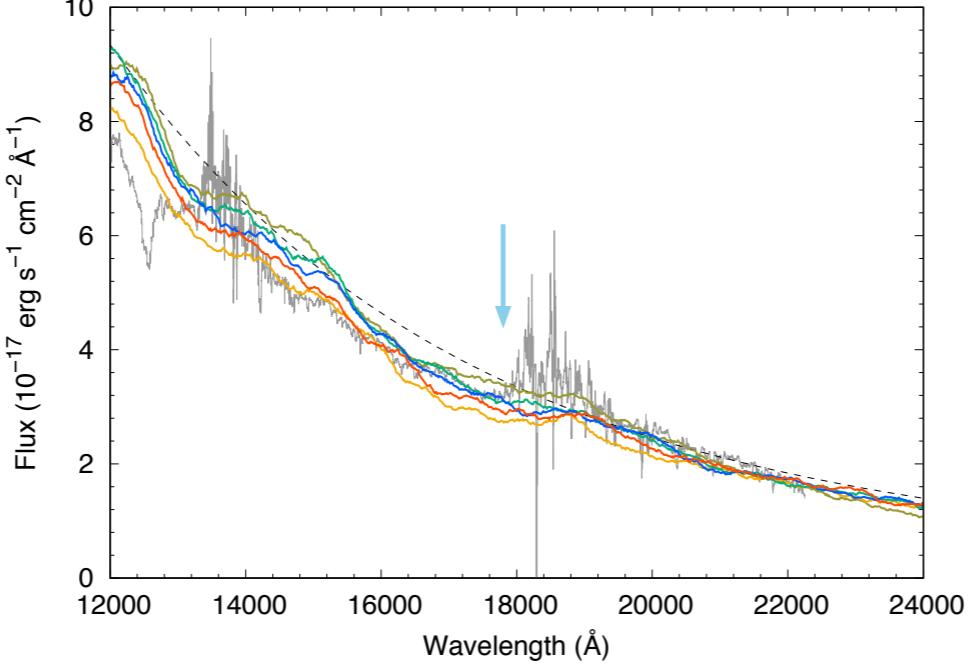
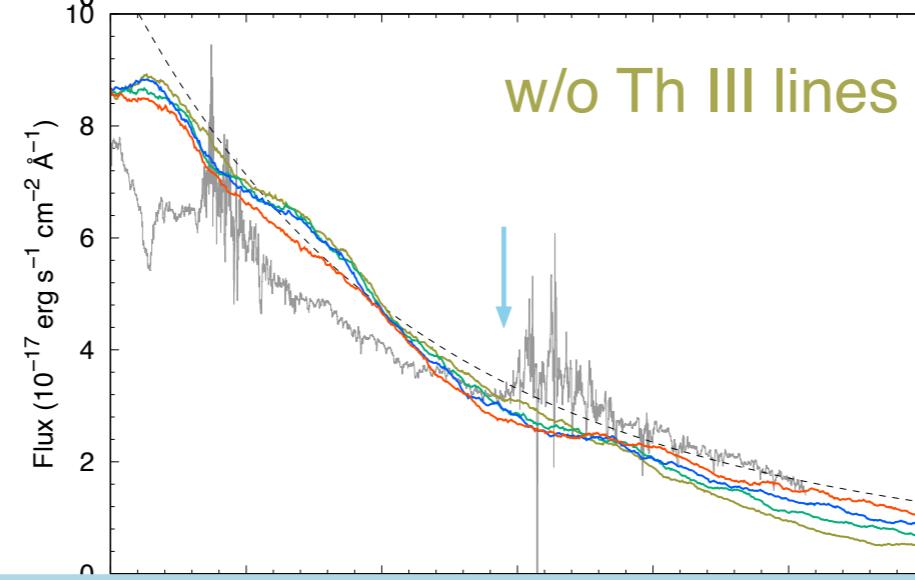
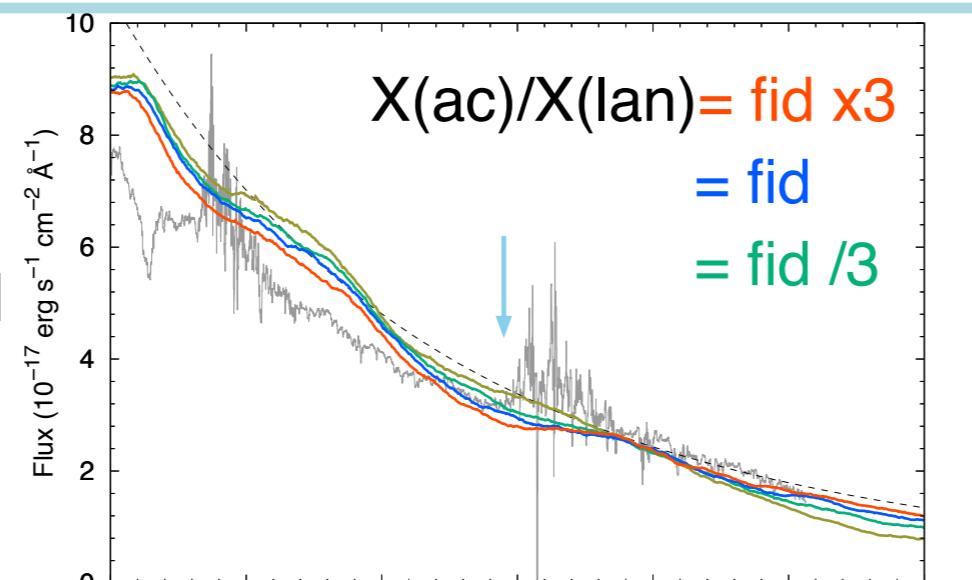
Conditions to find Th features

*homogeneous abundance distribution

$X(\text{lan}) = \text{fiducial}$
 $\sim 6 \times 10^{-4}$

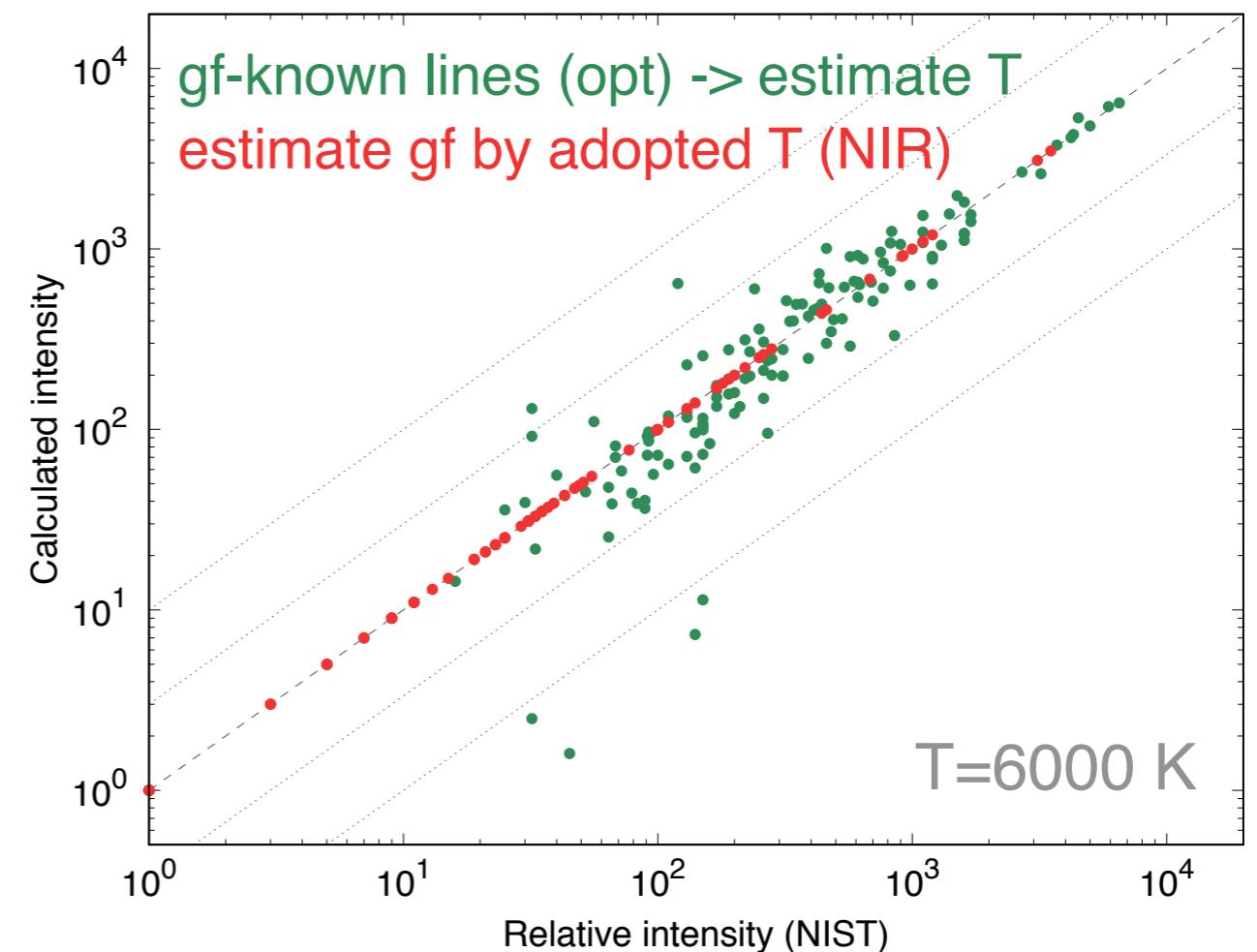
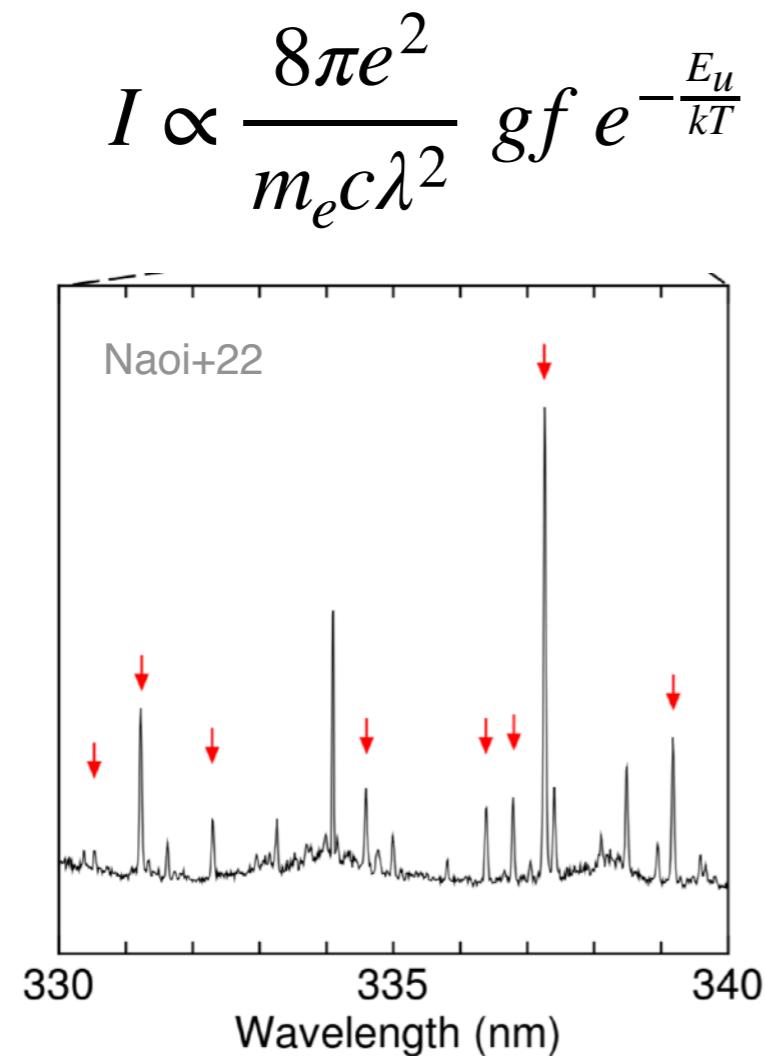
$X(\text{lan}) = \text{fid} / 3$

$X(\text{lan}) = \text{fid} \times 3$



Uncertainties in Th features

Transition probabilities of NIR lines are estimated by “relative intensities”



Should be derived by experiments, or provided by serious theoretical calculations

Summary

Th is the most promising candidate to find in the kilonova spectra ($\sim 1.8 \text{ um}$)

- Dense energy levels and relatively large transition probabilities
- Could be indirect evidence of production of Pt, Au

Condition

- $X(\text{Ia}) < \sim 6 \times 10^{-4}$: bulk of high-Ye (> 0.3) ejecta
w/ a small fraction of neutron-rich component in the line-forming region
- BH-NS or unequal mass BNS?

Observation

- Should be done with no or little atmosphere... from space or high-altitude sites

Uncertainties

- Transition probabilities of NIR Th III lines should be determined by experiments