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ウムの同定可能性

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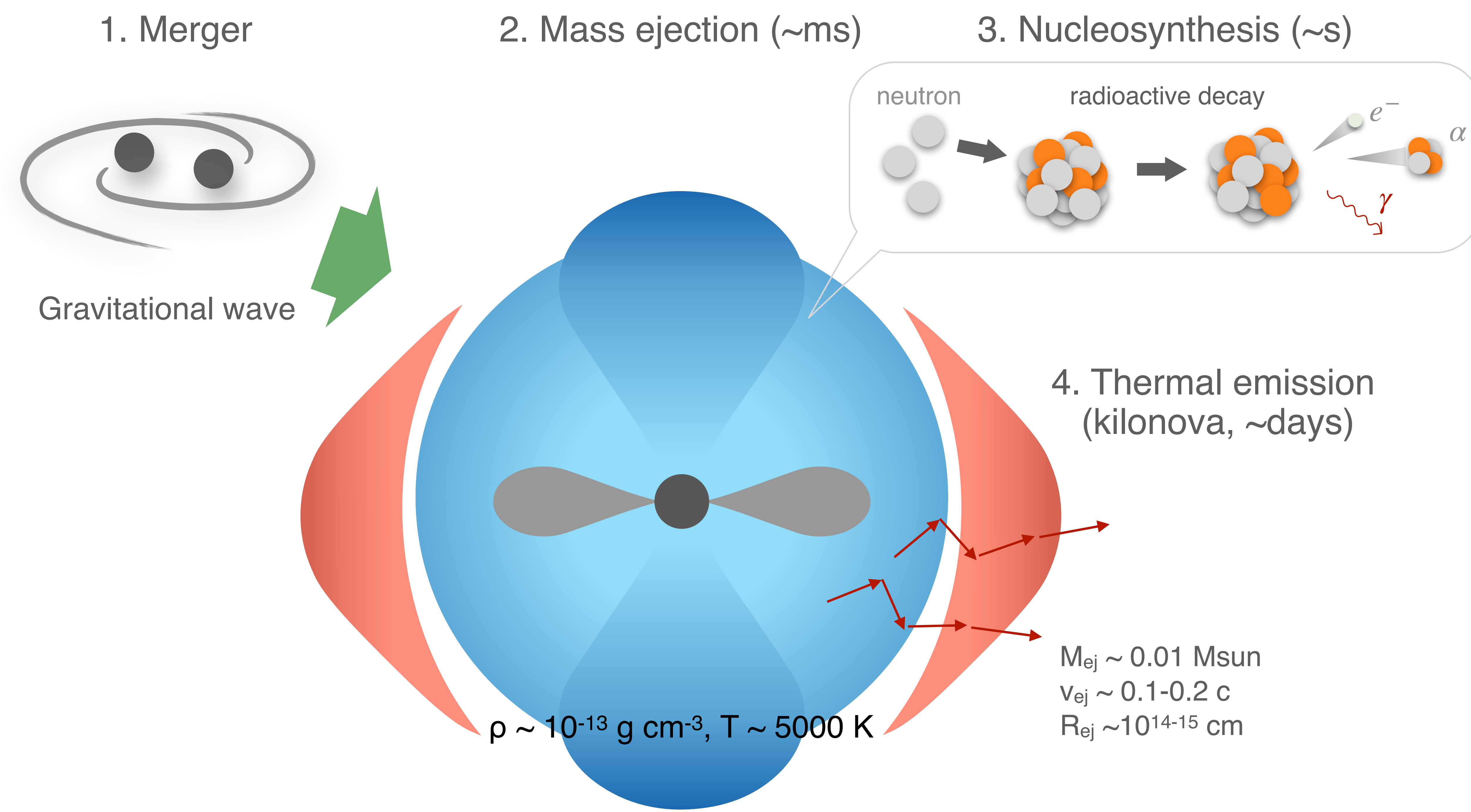
2024/08/09
Domoto et al., submitted

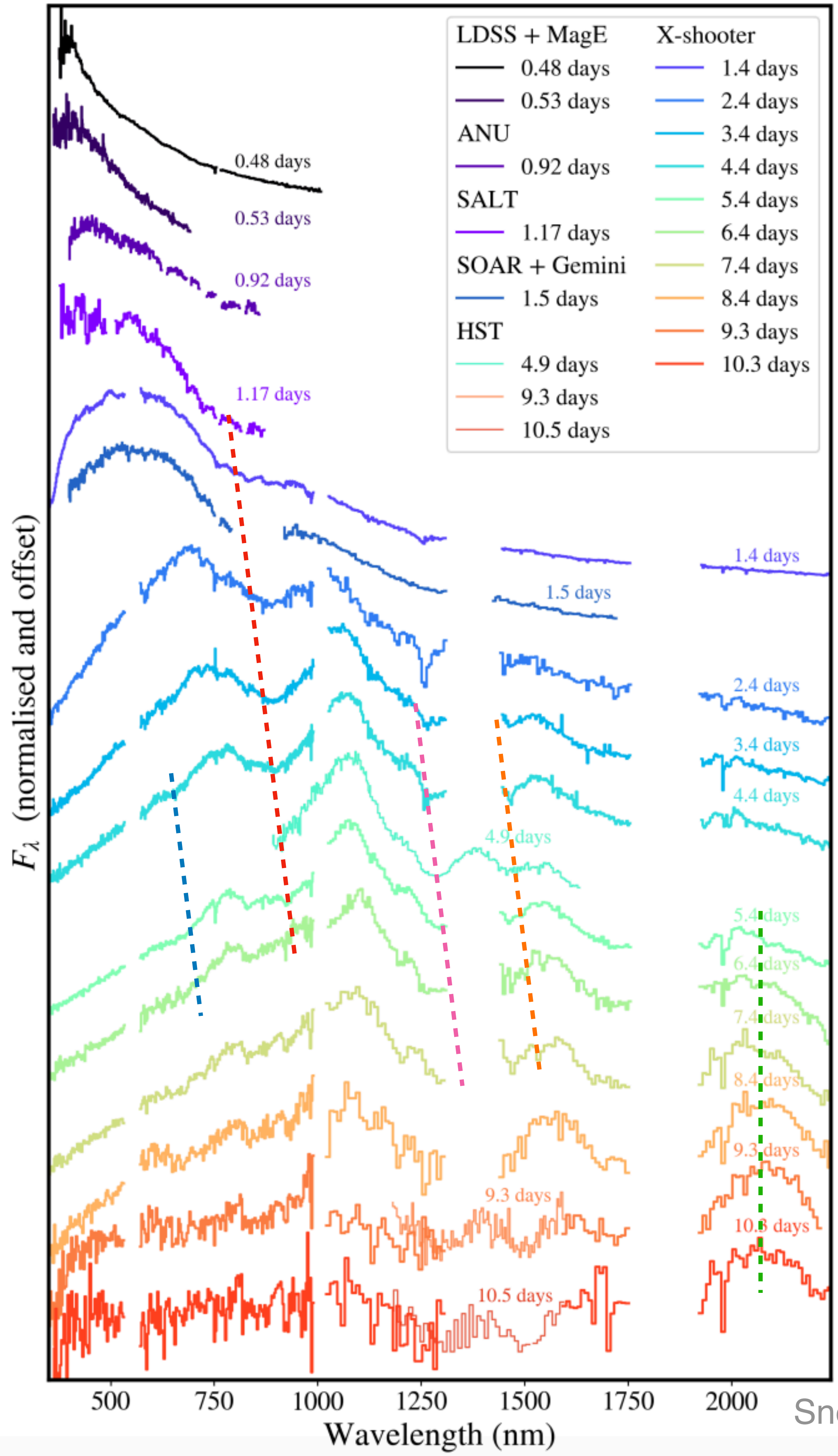
Kilonova

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



Sneppen+24

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

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

<u>Small number of valence electrons</u>

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

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
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
			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

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37 Rb	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54 Xe
55 Cs	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	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
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Can we identify further heavier elements???

Simple expectation

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

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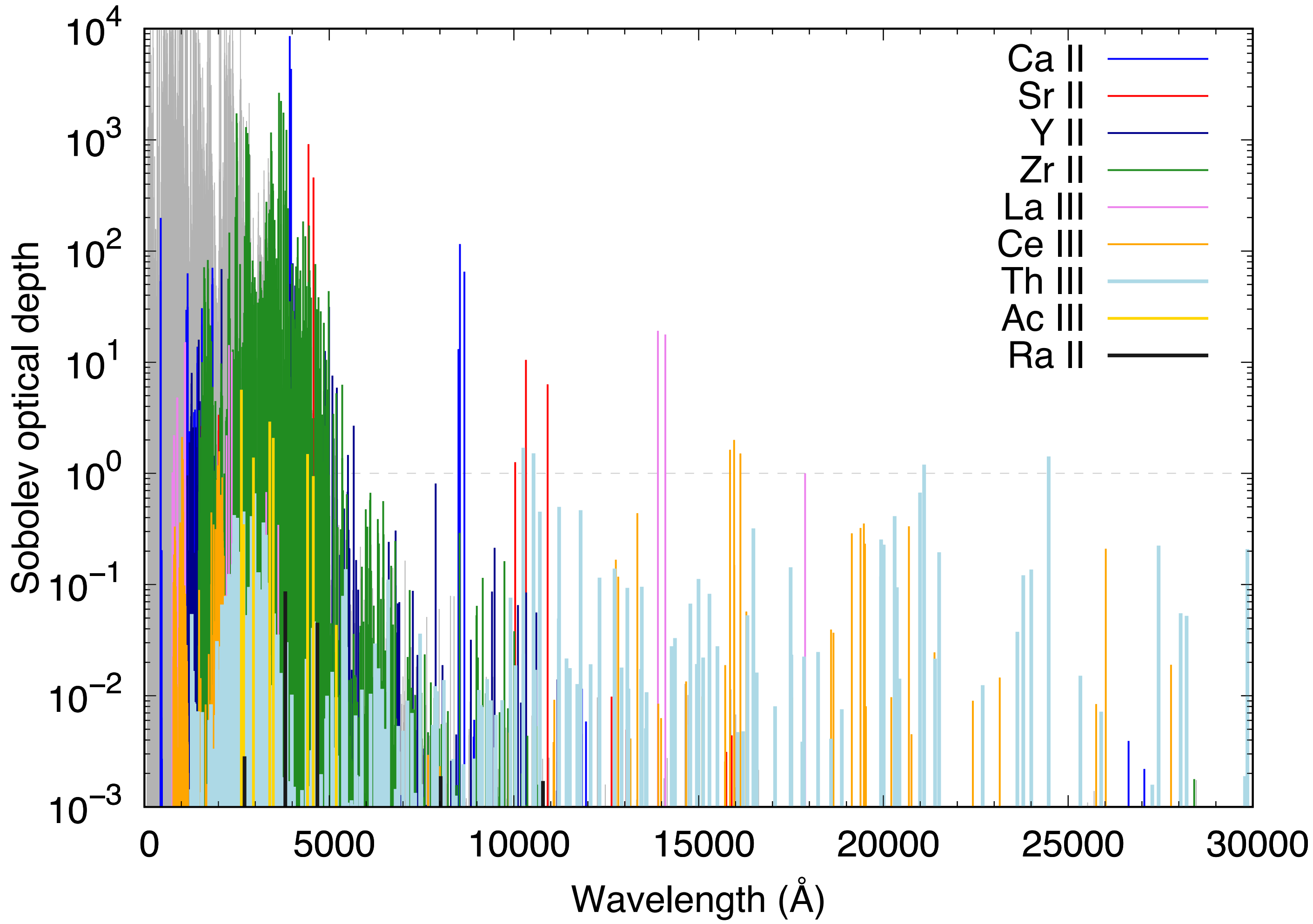
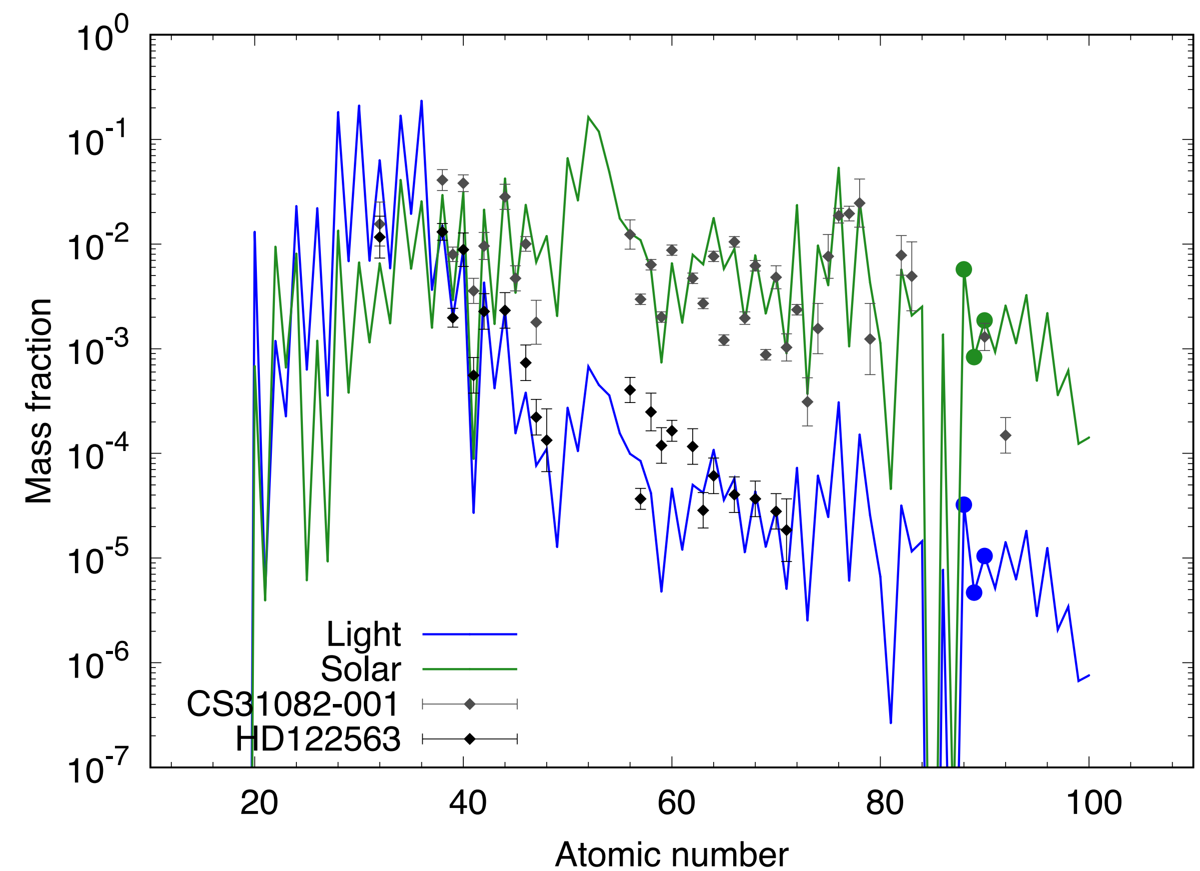
Systematic investigation of strength of lines

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

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

$\rho = 10^{-14}$ g cm^{-3}, $T = 5000$ K at t=1.5 d

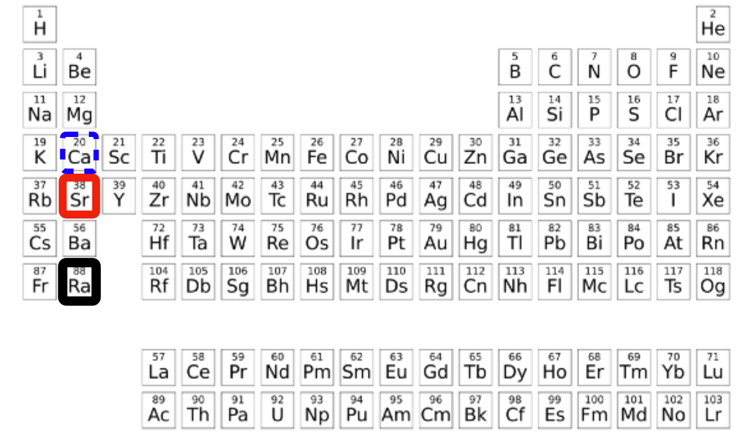


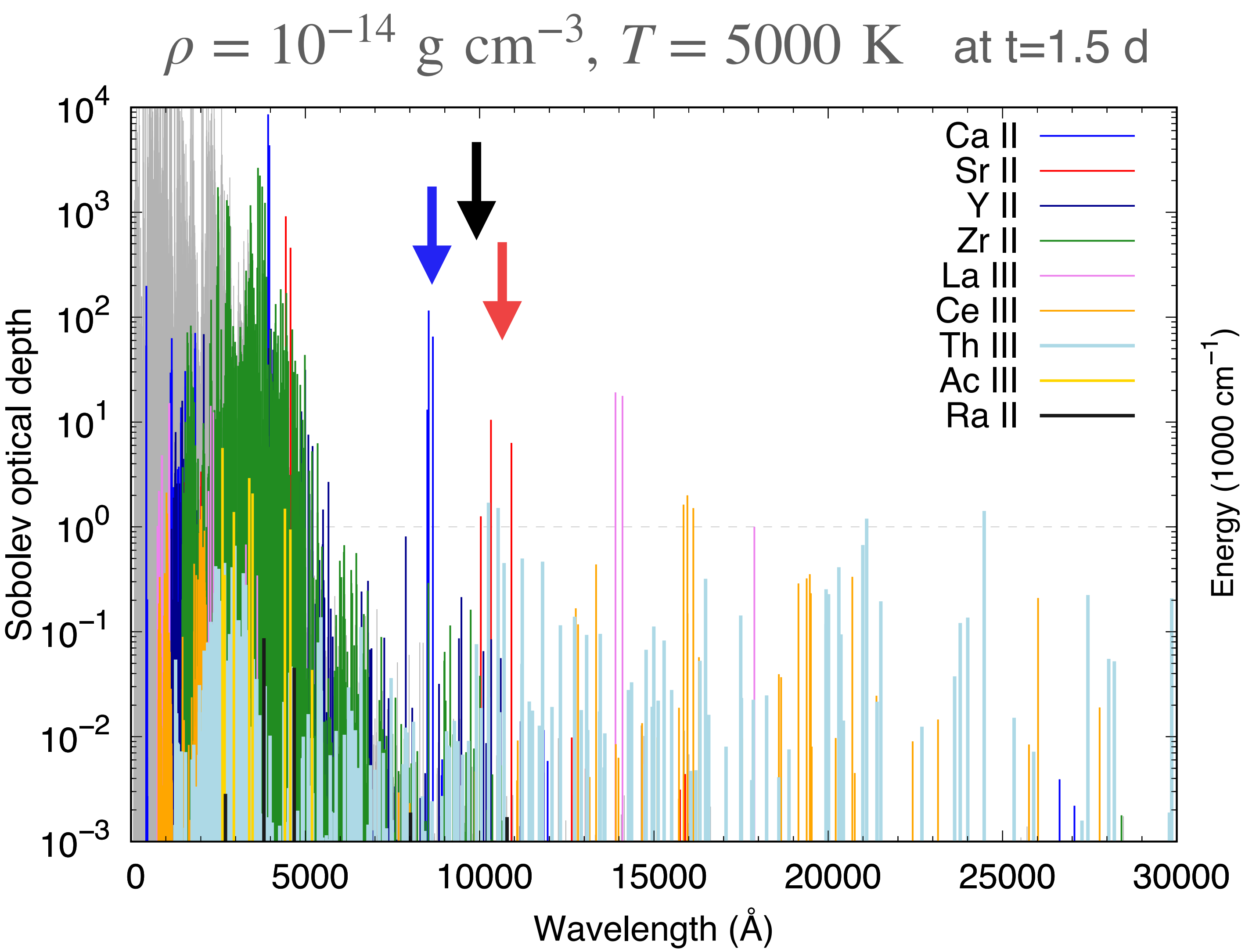


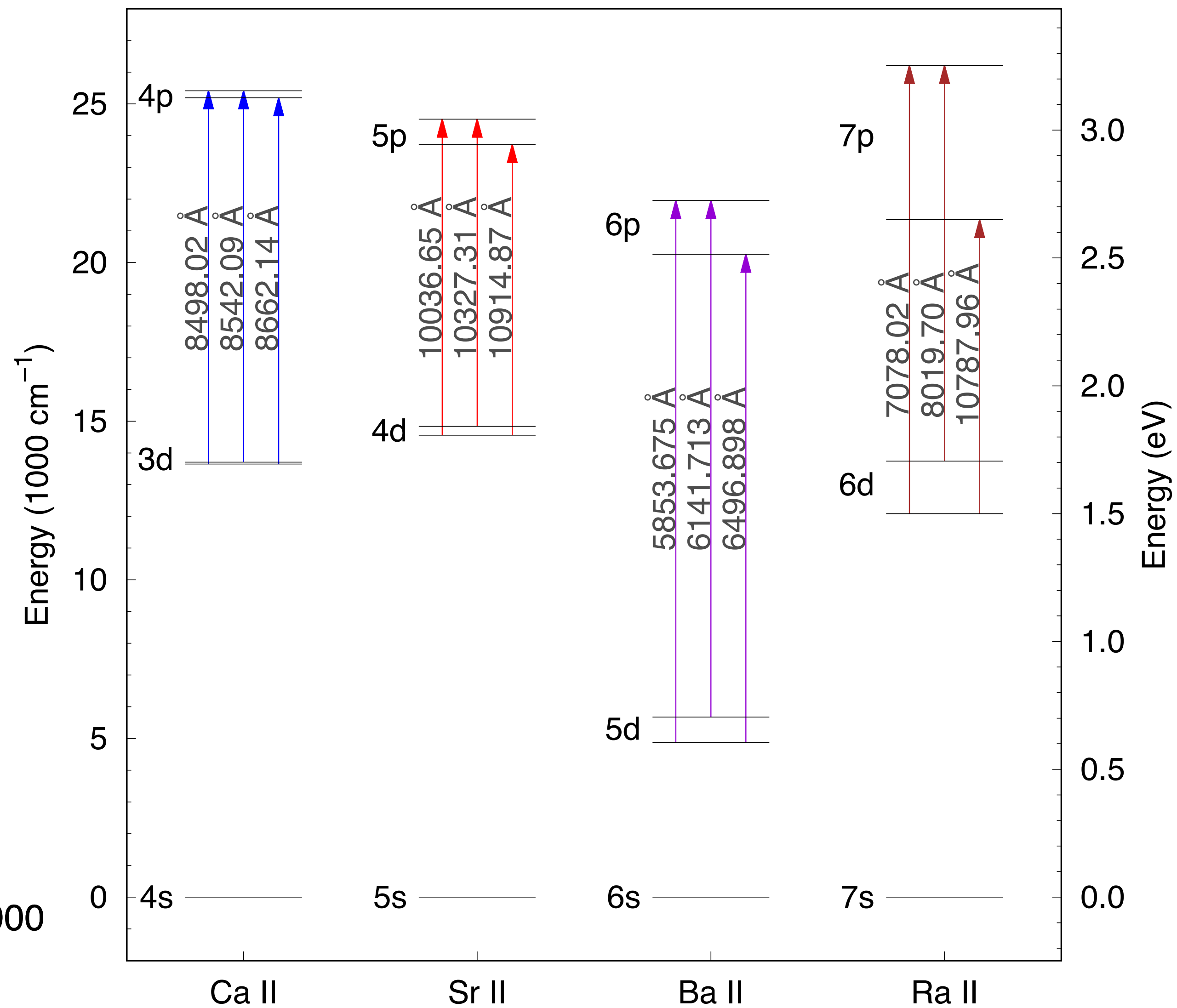
※Blue model reasonably explains La III/Ce III features in AT2017gfo

Ra II (Z=88) is not promising

Analogous atomic structure/transitions to Ca II, Sr II





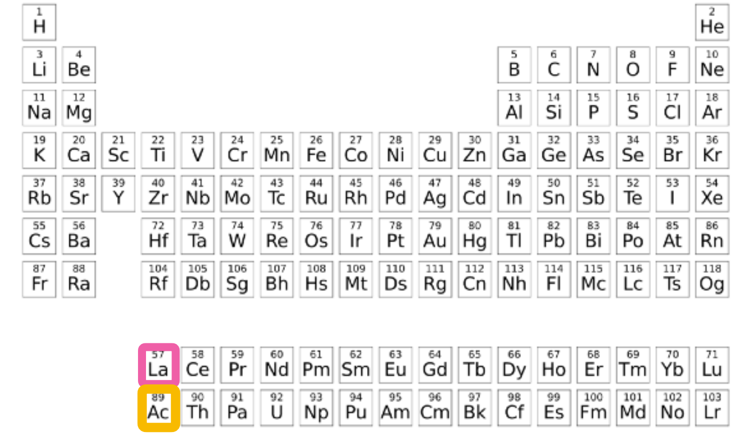


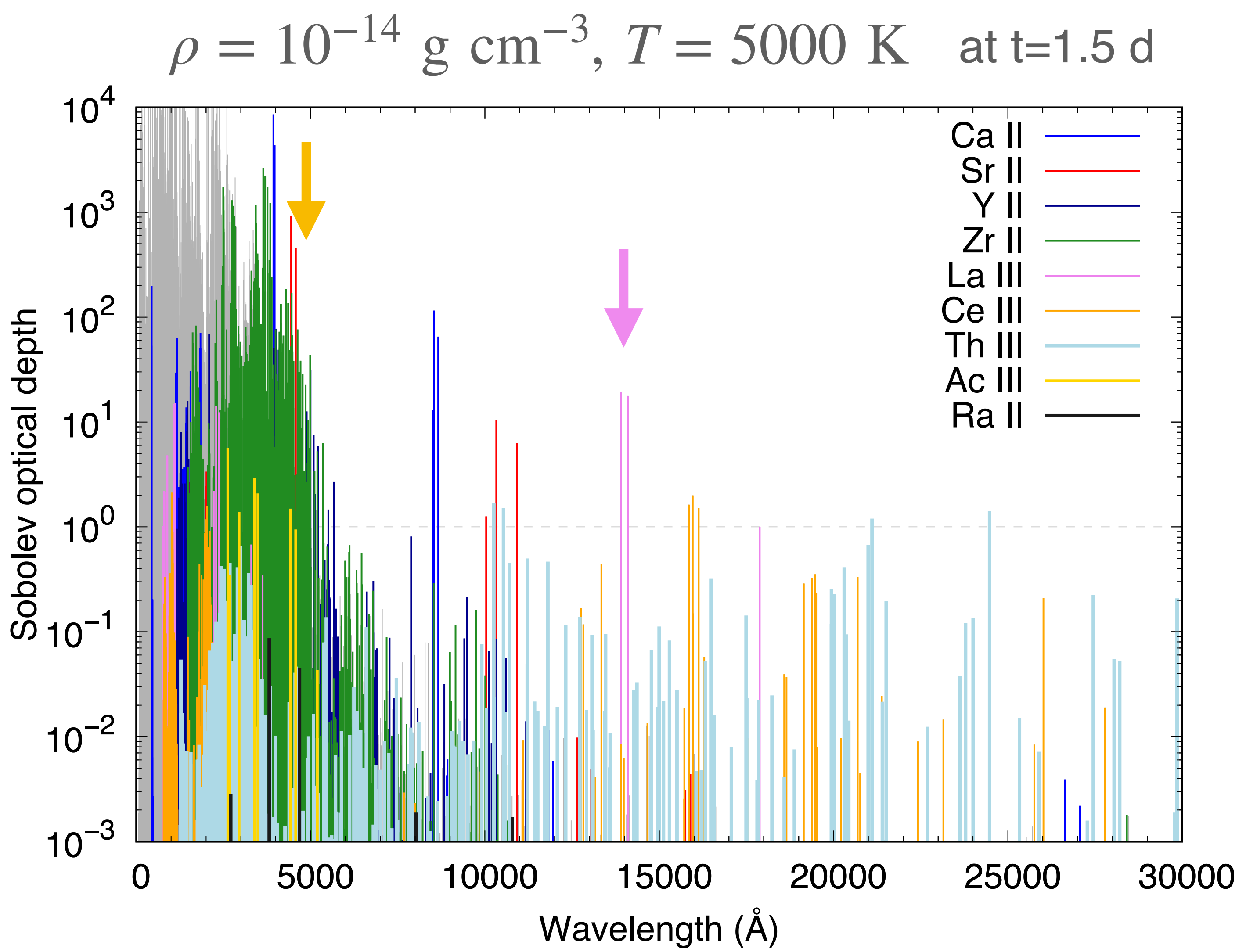
Mass fraction of Ra ~10^{-5} ↔ Ca, Sr ~ 10^{-2}

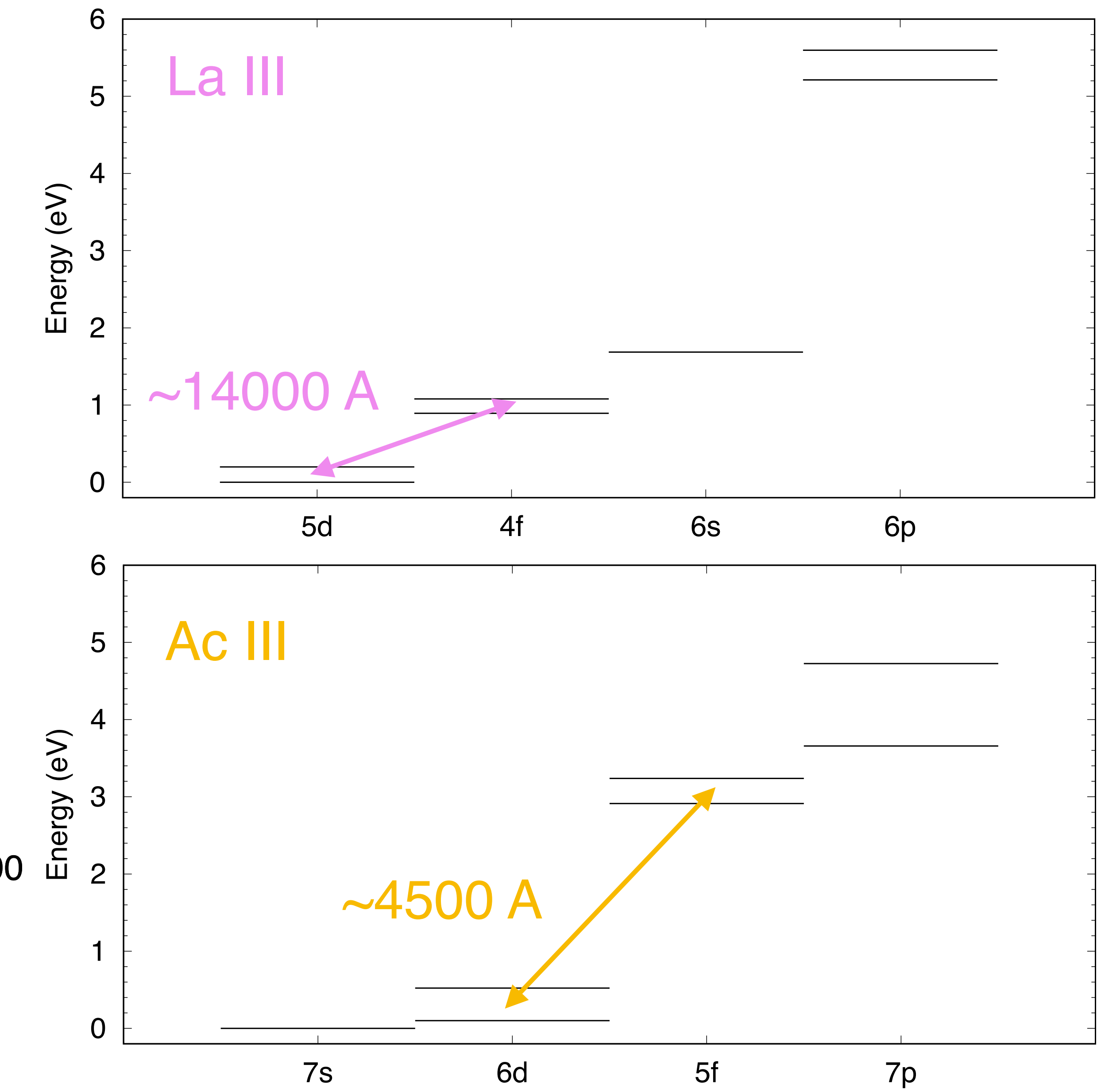
Ra II lines cannot compete with lines of lanthanides w/ similar mass fractions

Ac III (Z=89) is not promising

NOT analogous atomic structure/transitions to La III



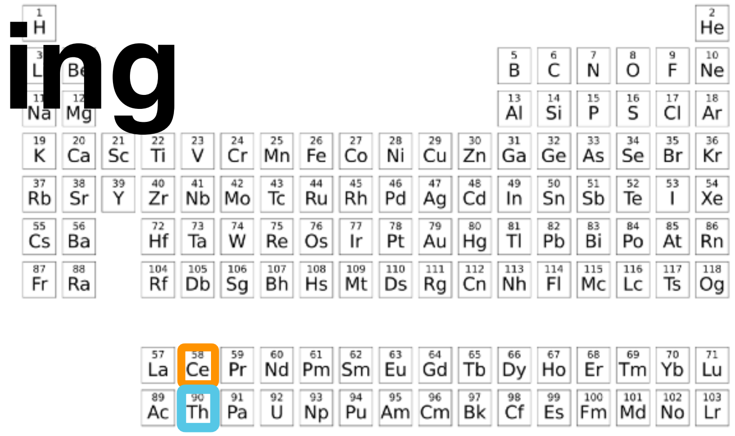




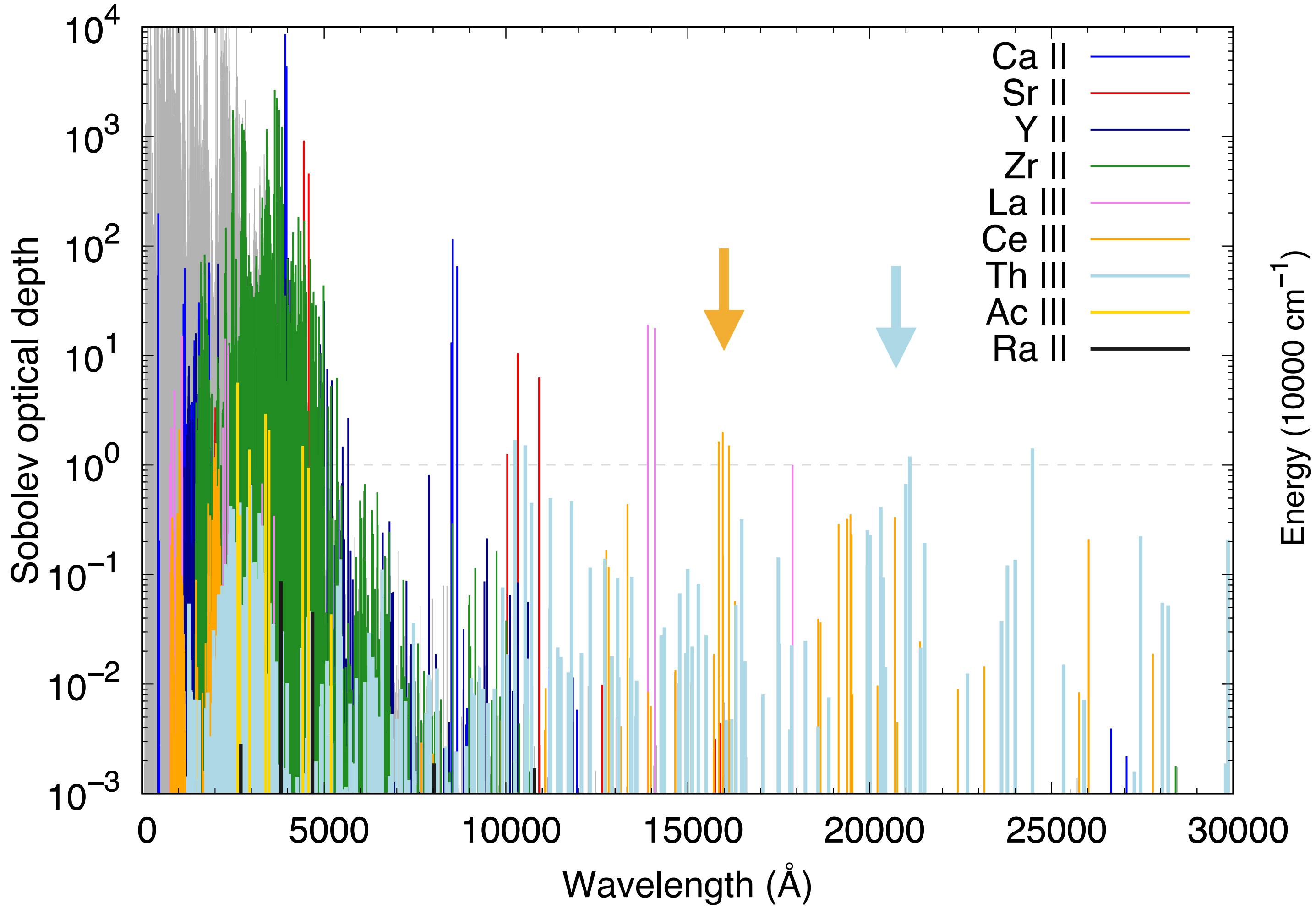
Ac III does not have NIR (E1) lines from low energy levels

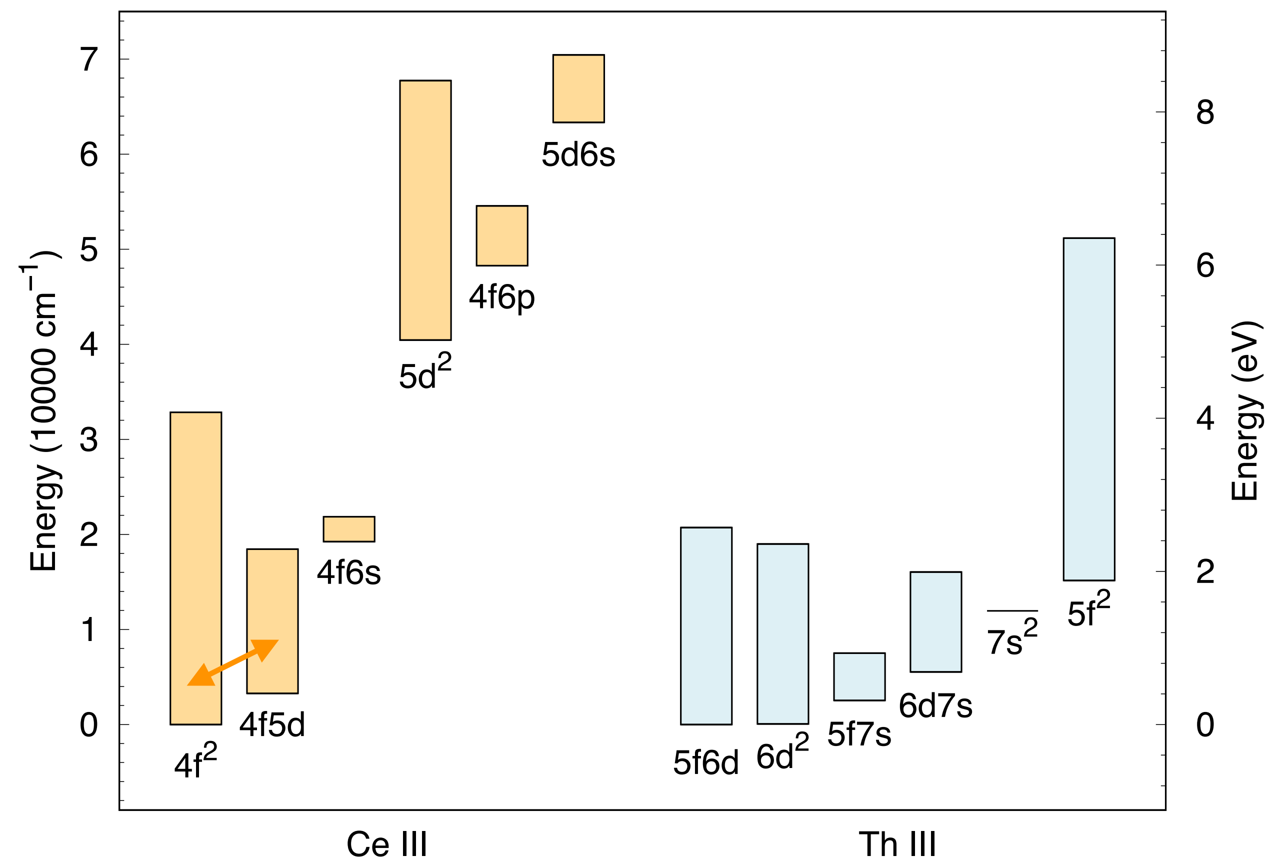
Th III (Z=90) is the most promising

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



$\rho = 10^{-14}$ g cm^{-3}, $T = 5000$ K at t=1.5 d



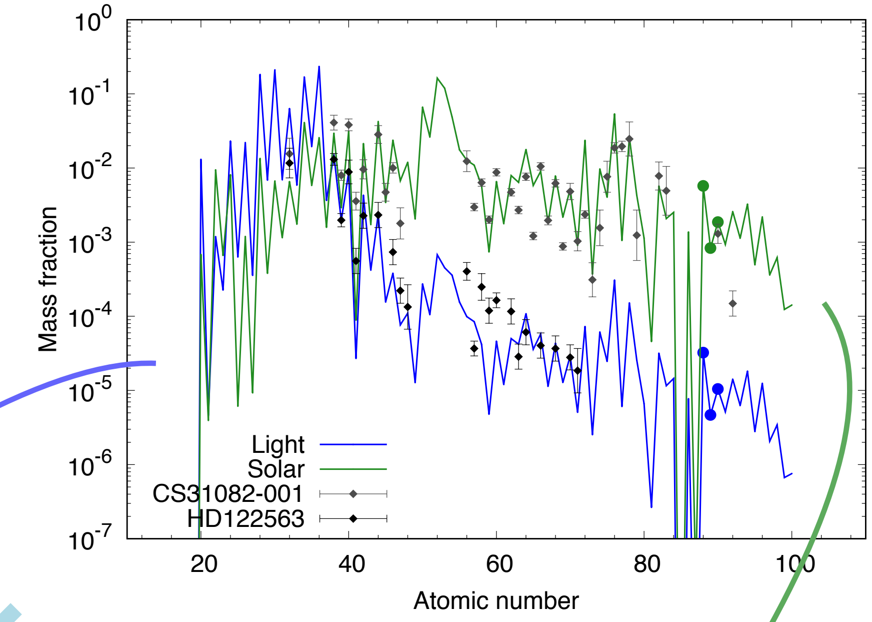


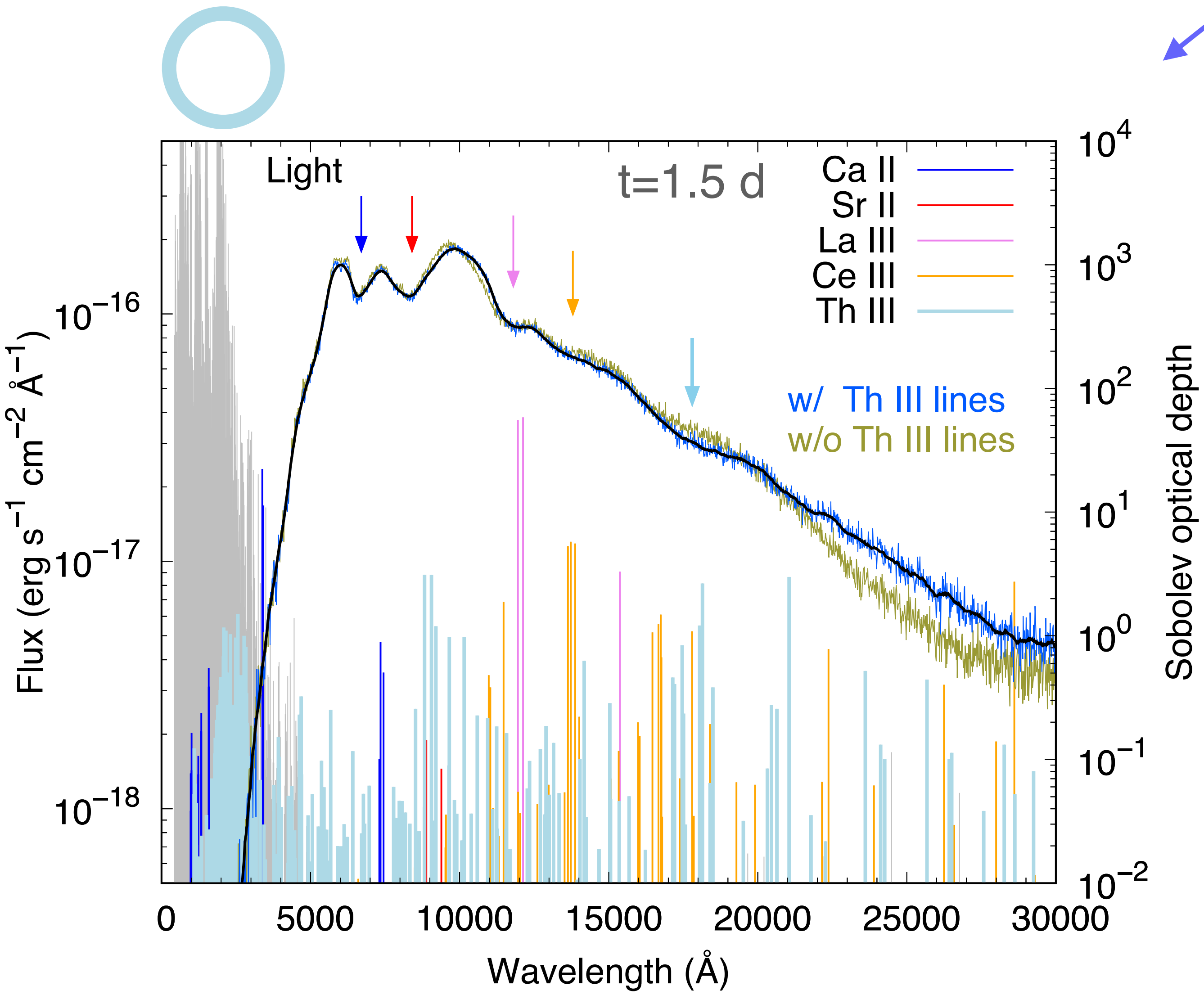
Th III can produce strong transitions (comparable to e.g., Ce III)

Synthetic spectra

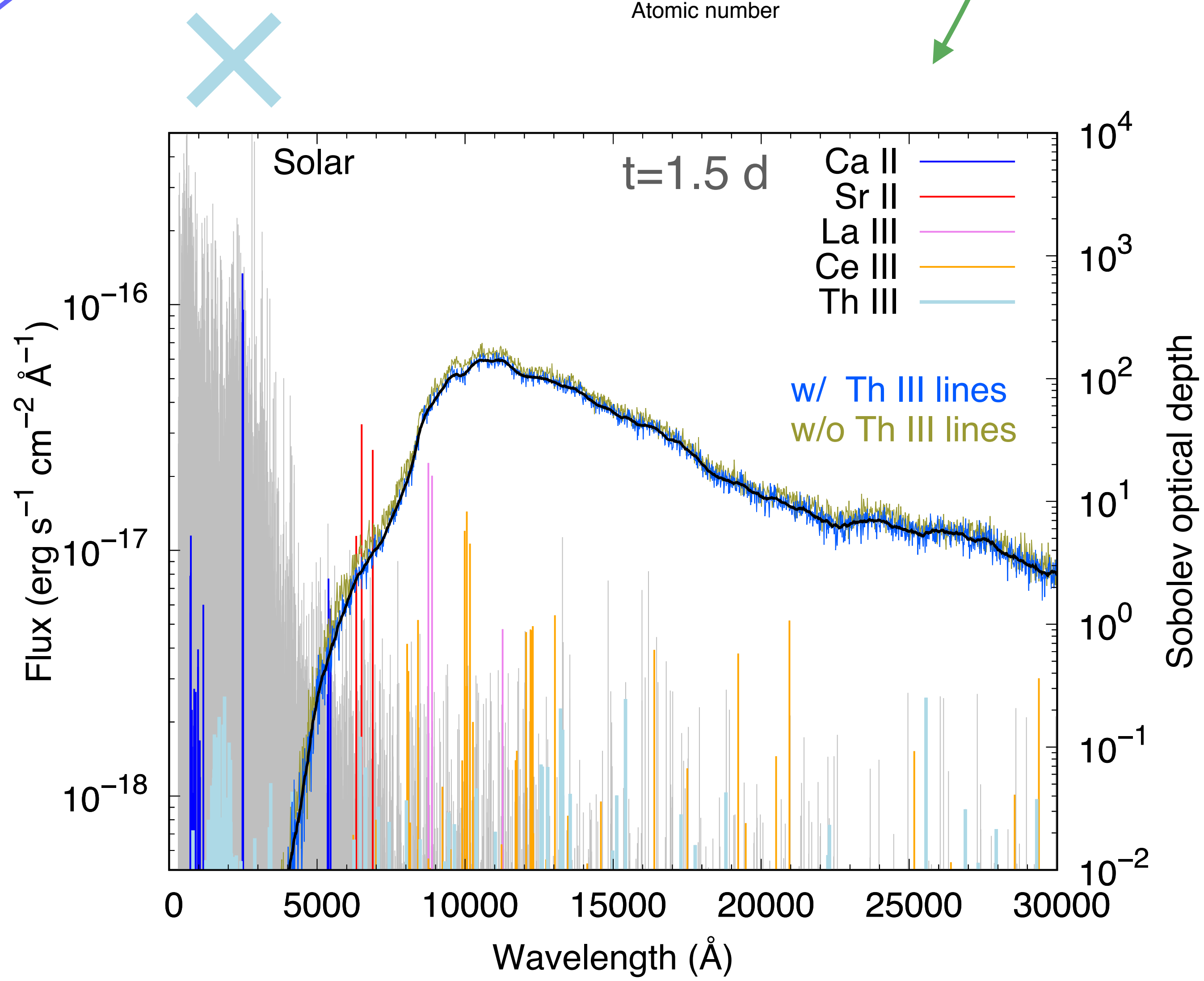
Perform radiative transfer simulations

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



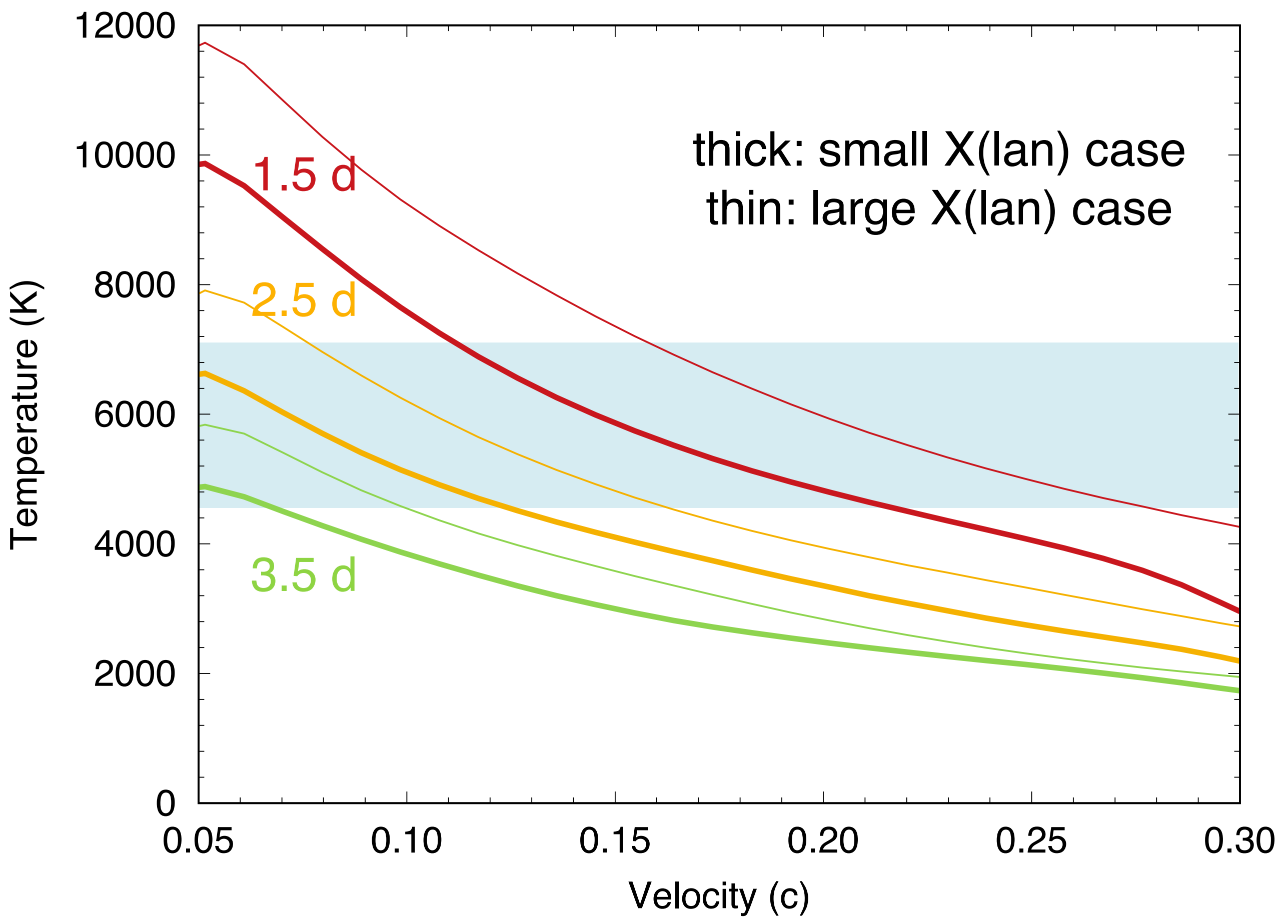


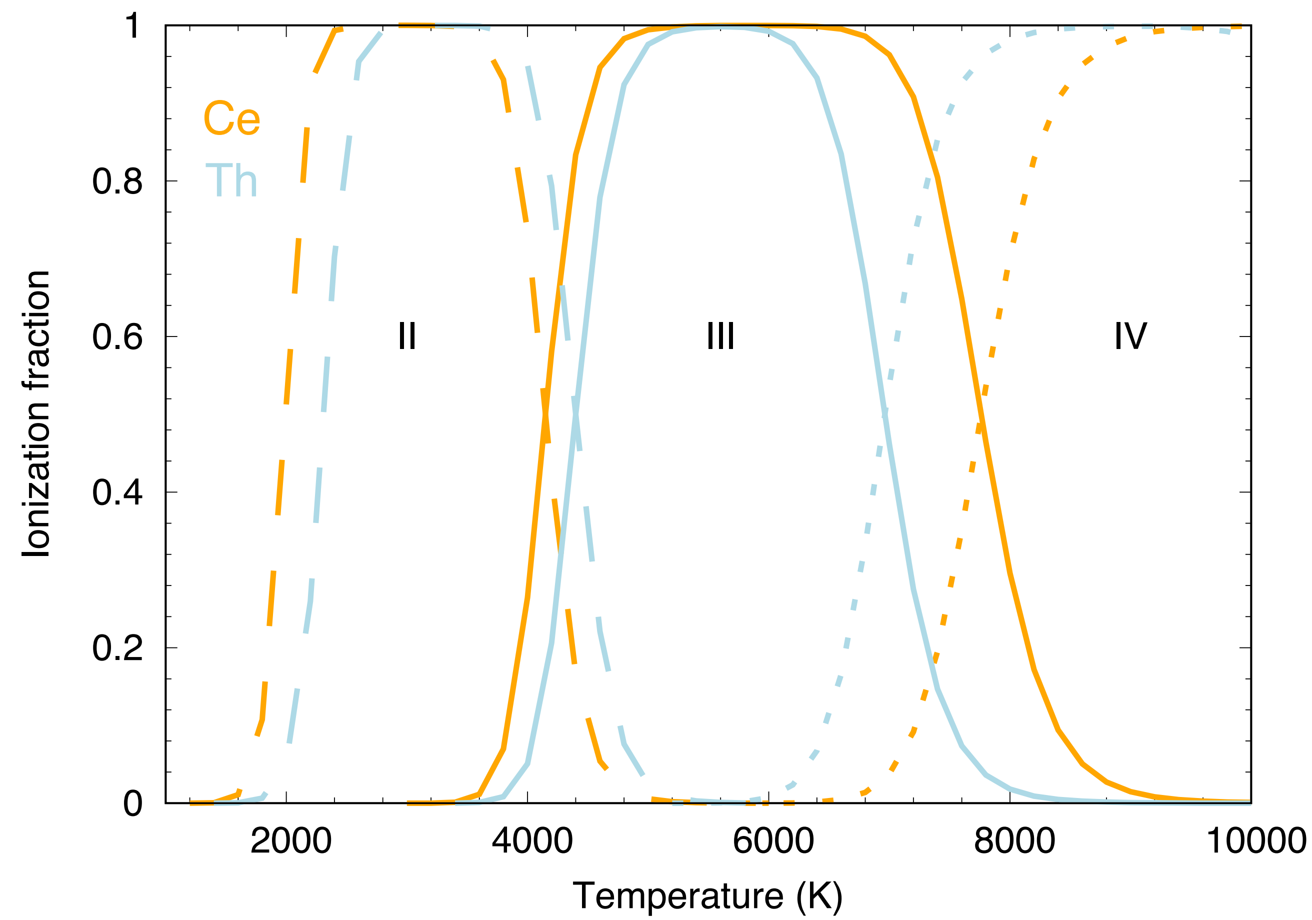
line forming region: T ~ 7000 K (v=0.13c)



T ~ 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

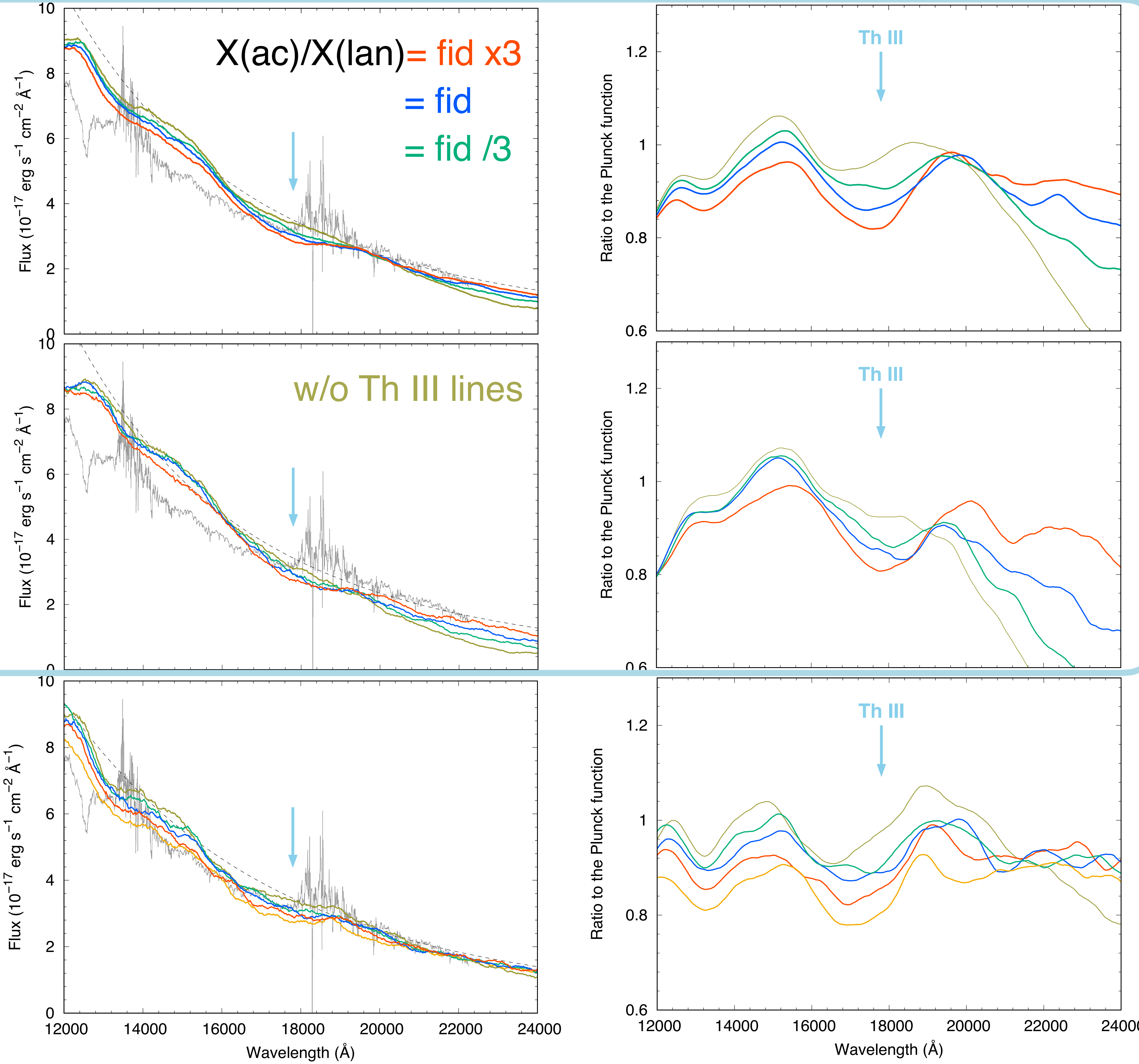
Conditions to find Th features

*homogeneous abundance distribution

X(lan) = fiducial
~ 6 x 10^{-4}

X(lan) = fid /3

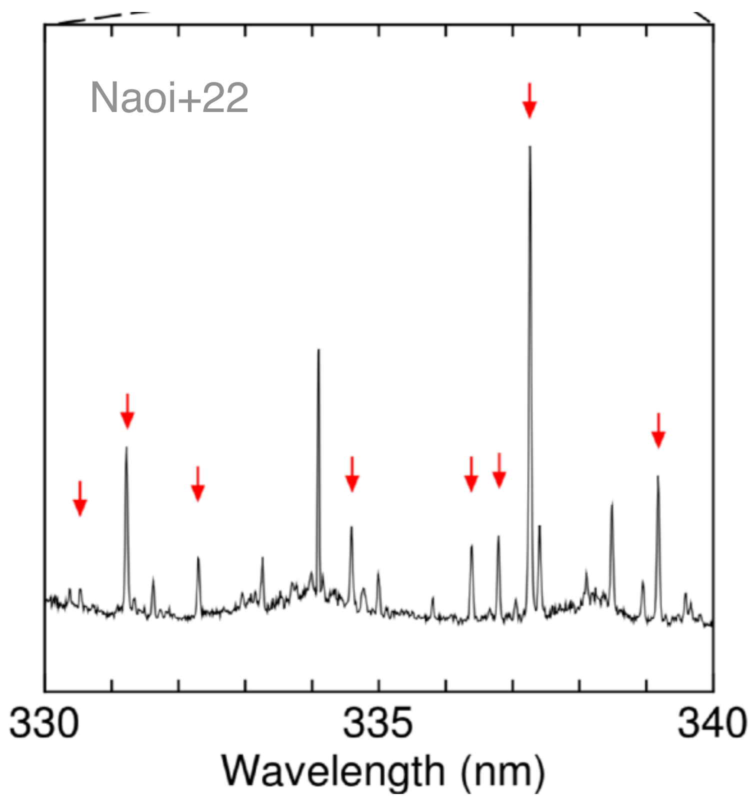
X(lan) = fid x3

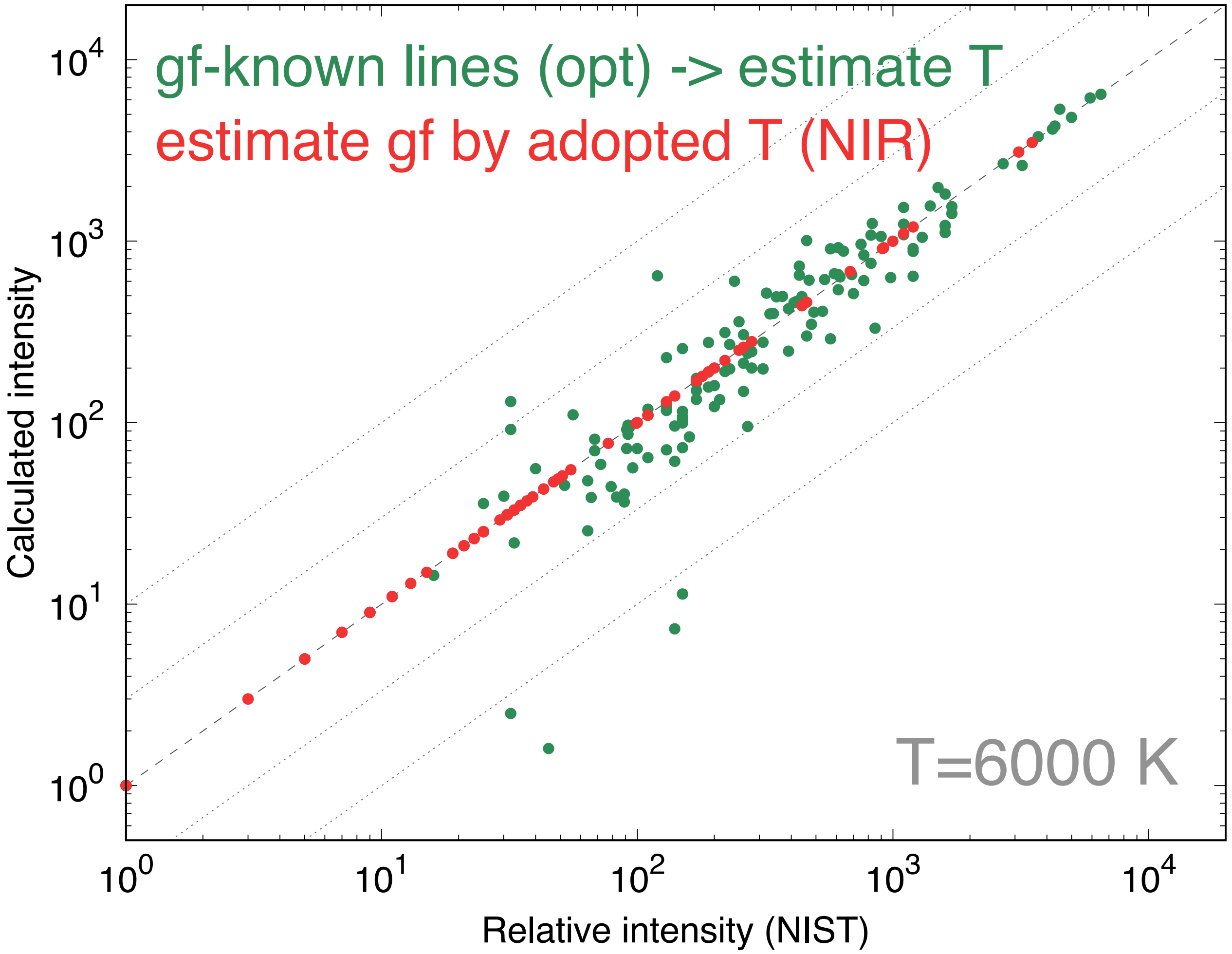


Uncertainties in Th features

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

$$I \propto \frac{8\pi e^2}{m_e c \lambda^2} \, gf \, e^{-\frac{E_u}{kT}}$$





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

Summary

Th is the most promising candidate to find in the kilonova spectra (~1.8 um)

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

<u>Condition</u>

- X(lan) <~ 6 x 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?

<u>Observation</u>

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

<u>Uncertainties</u>

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