日本天文学会 2023年秋季年会 Z110a

キロノバのスペクトルで探る
中性子星合体の元素合成

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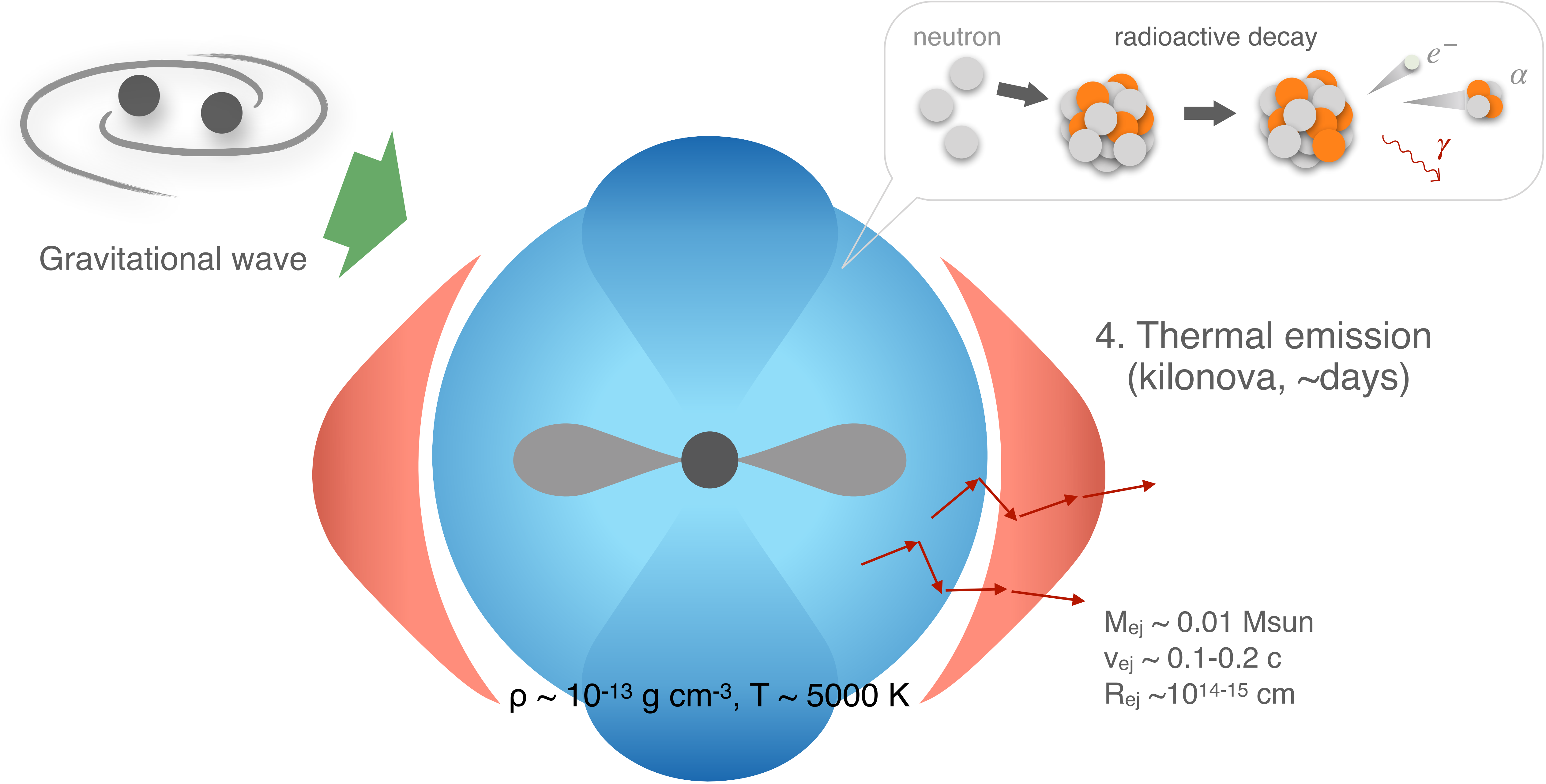
Domoto et al. 2021, ApJ, 913, 26
Domoto et al. 2022, ApJ, 939, 8

“Kilonova”

Radioactively-powered thermal emission from neutron star merger



1. Merger

2. Mass ejection (~ms)

3. Nucleosynthesis (~s)

Gravitational wave

4. Thermal emission (kilonova, ~days)

$\rho \sim 10^{-13}$ g cm^{-3}, T ~ 5000 K

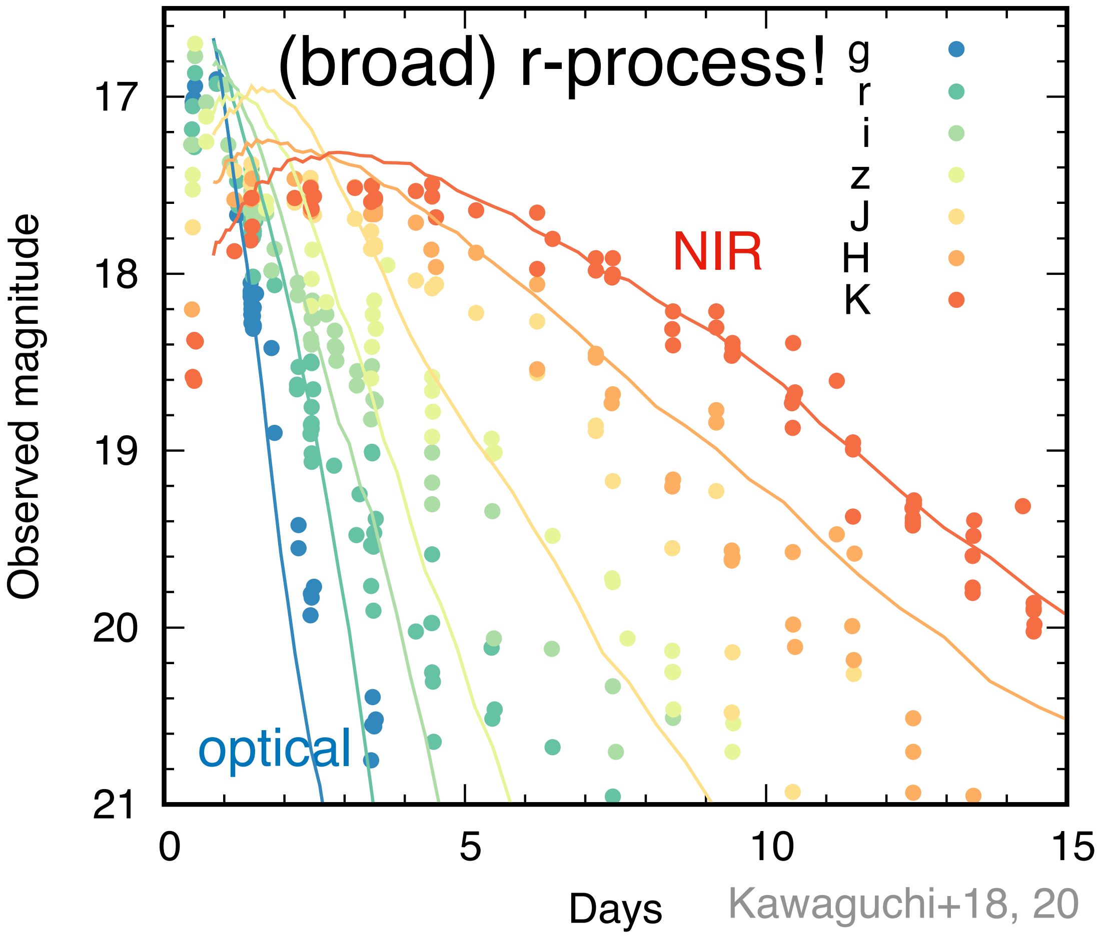
$M_{ej} \sim 0.01$ Msun
$v_{ej} \sim 0.1\text{-}0.2$ c
$R_{ej} \sim 10^{14\text{-}15}$ cm

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

Kilonova in GW170817

e.g., Arcavi+17, Smartt+17, Kasen+17, Kilpatrick+17, Perego+17, Rosswog+17, Shibata+17, Tanaka+17, Toroja+17, …

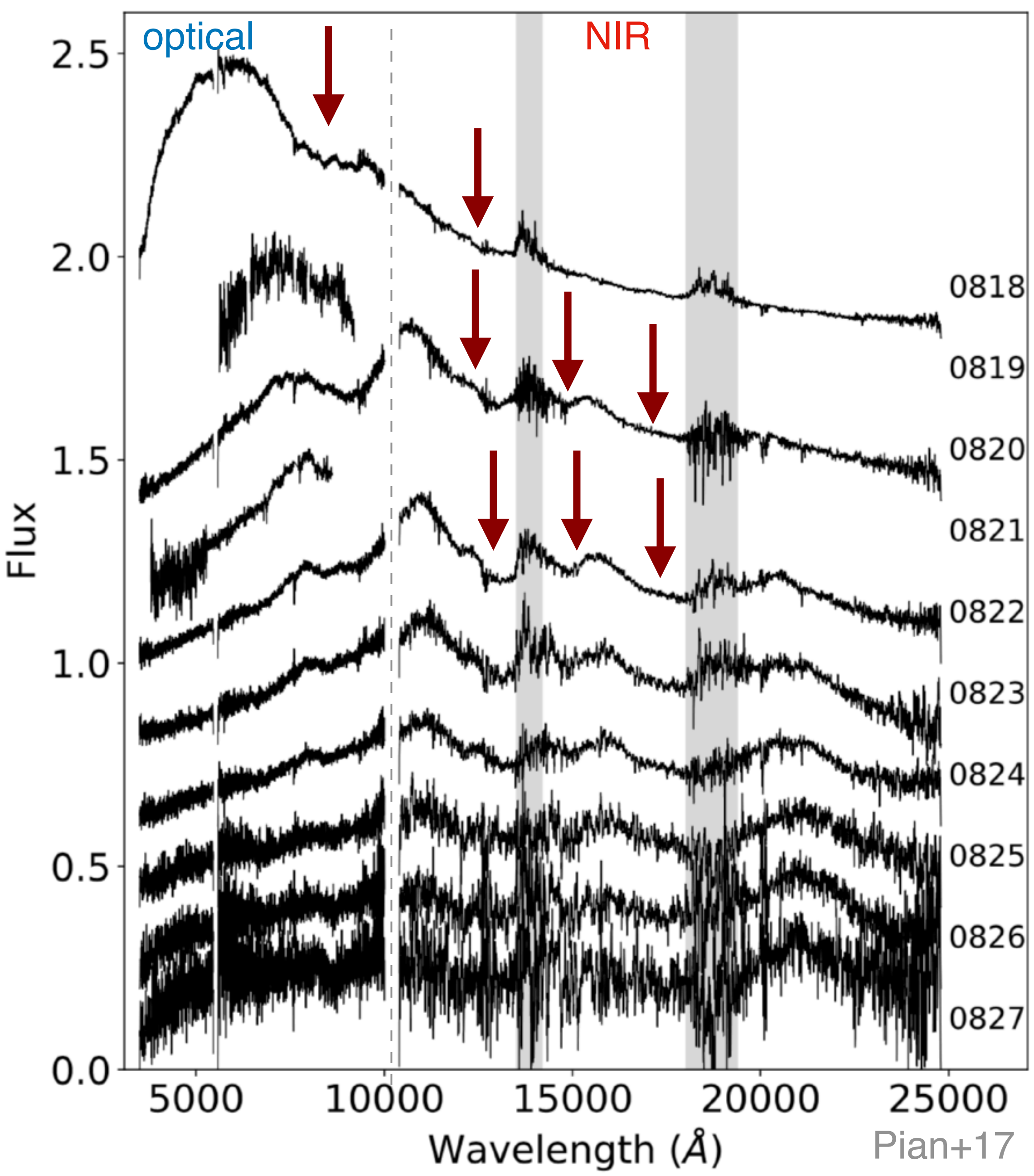
Utsumi+17



Kawaguchi+18, 20

Which and how much elements?

Watson+19, Domoto+21, Gillanders+22
Perego+22, Tarumi+23



Pian+17

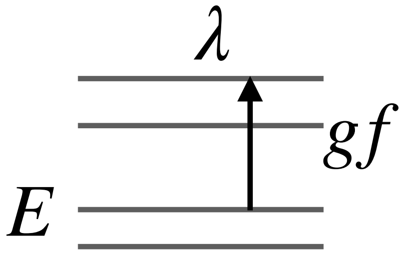
Atomic data

for interaction of photons and matter

Strength of line: “Sobolev optical depth”

*radial (expanding) v ≫ thermal v

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



	Experimentally calibrated data *spectroscopically accurate e.g., NIST, VALD, DREAM	Theoretically constructed data *high completeness e.g., Kasen+17, Tanaka+20, Fontes+20, Banerjee+20, 22
Transition wavelength	✔	low accuracy
Energy level	✔	low accuracy
Transition probability	unavailable (especially for NIR)	available

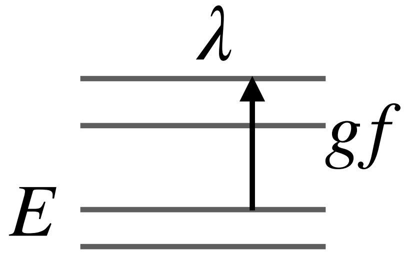
Need for discussion of spectra
(important for strong lines)

Light curve calculations
(even weak lines, ~million)

How can we study spectra?

Strategy: combine two types of datasets

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



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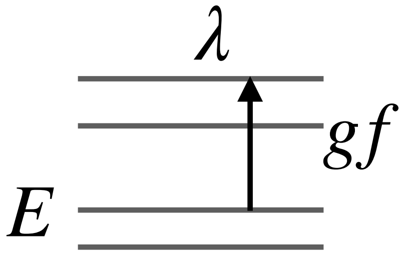
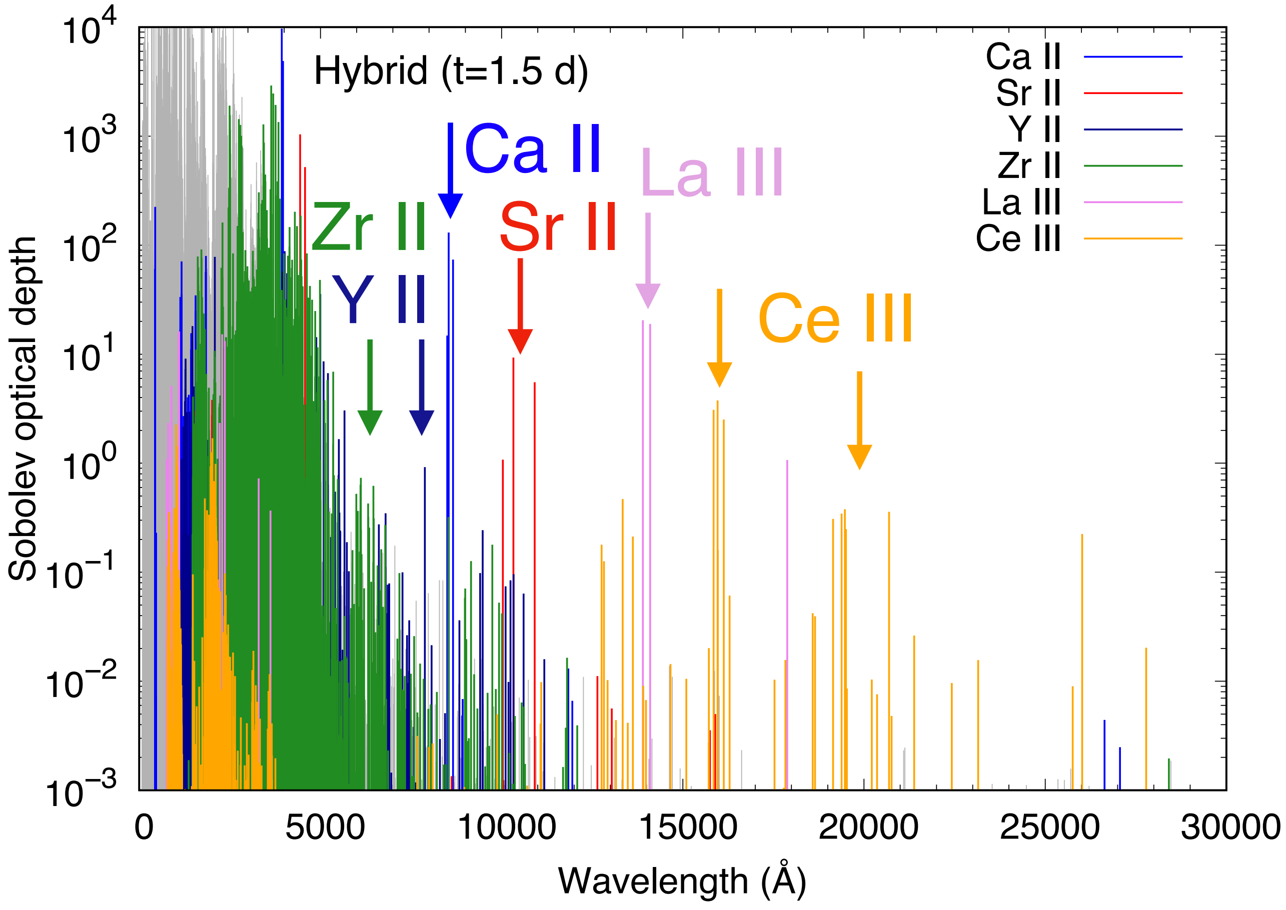
1. Find species having strong transitions (thanks to the complete data)
2. Extend “accurate” data of strong transitions w/ theoretical prob.

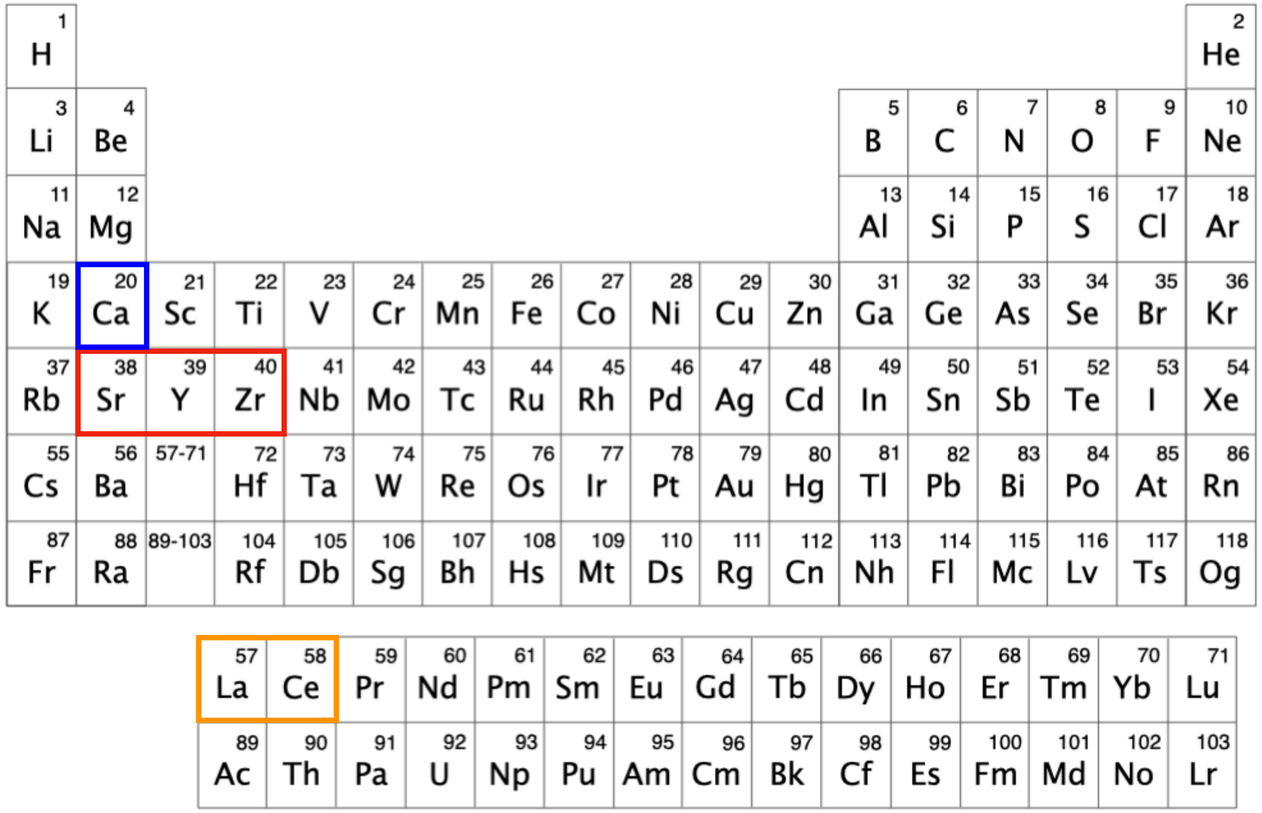
Systematic search of candidate species

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

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







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	57-71	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	89-103	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

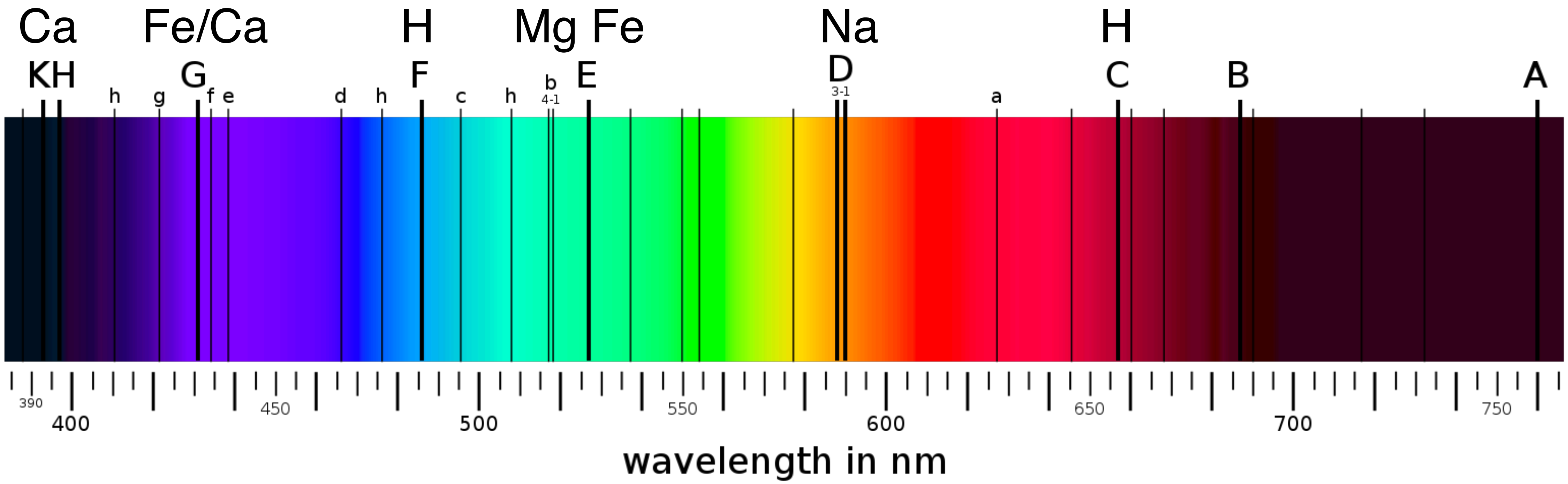
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

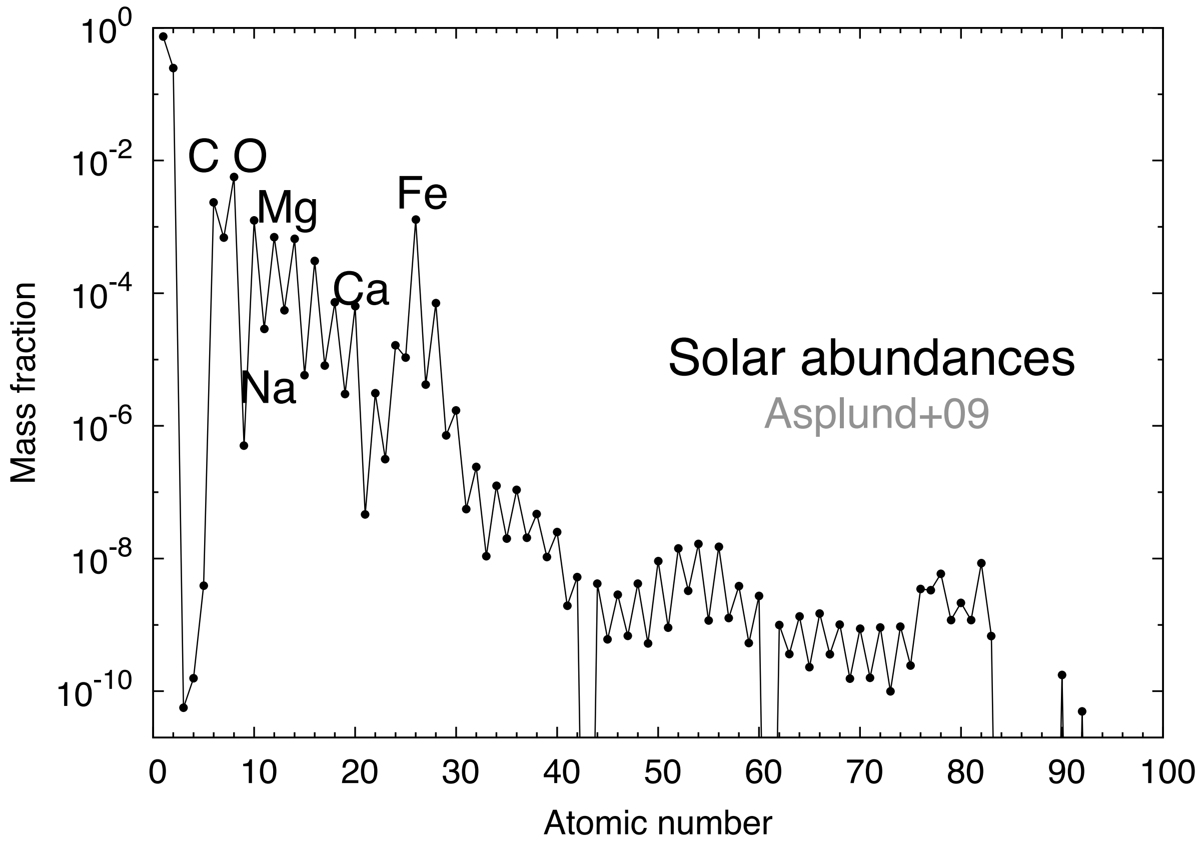
Ca II, Sr II, Y II, Zr II, La III, and Ce III can be strong absorption sources

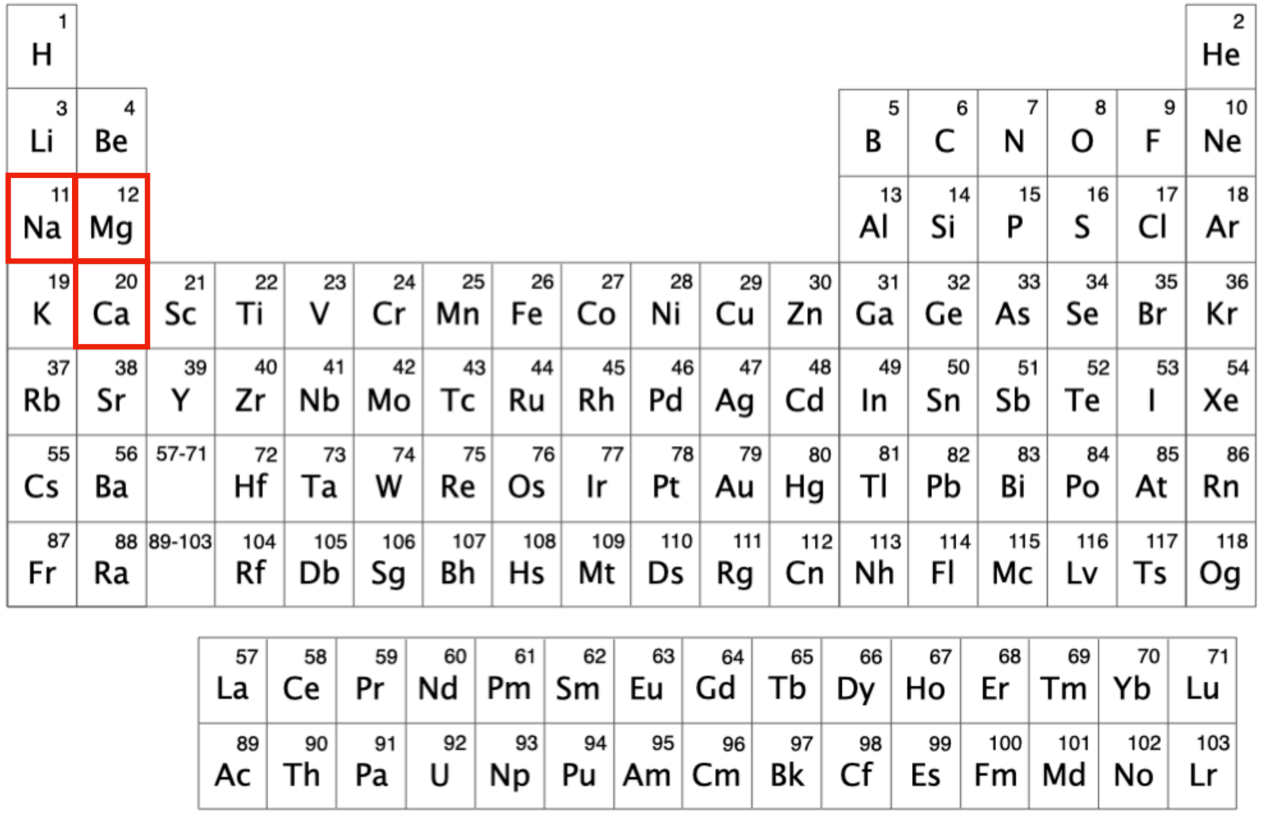
Small number of valence electrons:

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

Same as the Sun!







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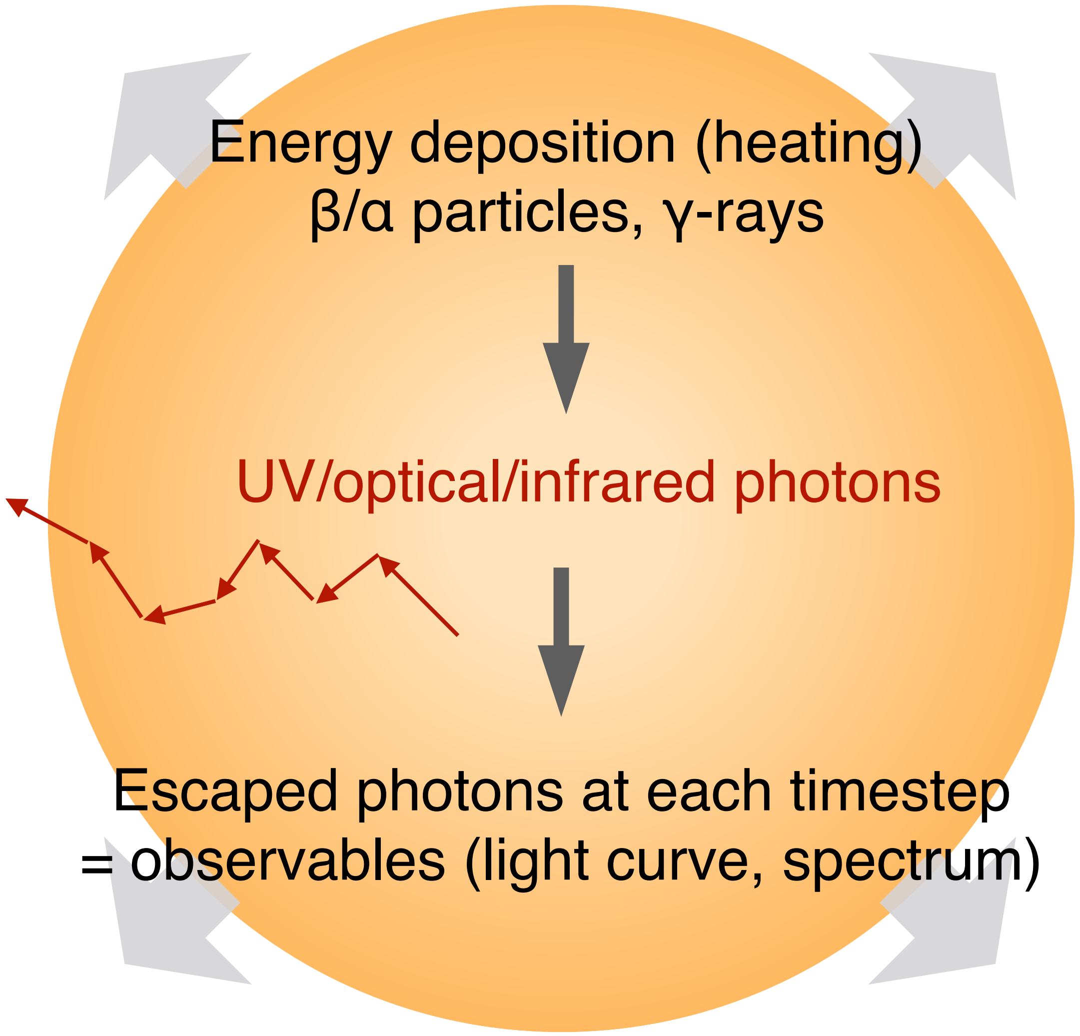
Radiative transfer simulations

Tanaka & Hotokezaka 2013, Tanaka+14, 17, Kawaguchi+18, 20

Calculate realistic synthetic spectra considering ejecta structure

Ejecta model:

- Mass: Mej = 0.03 Msun
- Velocity: v = 0.05-0.3 c
- Density: 1D power law ($\rho \propto r^{-3}$)
- Assume solar-r-like abundance pattern model (homogeneous distribution)



Energy deposition (heating)
β/α particles, γ-rays

UV/optical/infrared photons

Escaped photons at each timestep
= observables (light curve, spectrum)

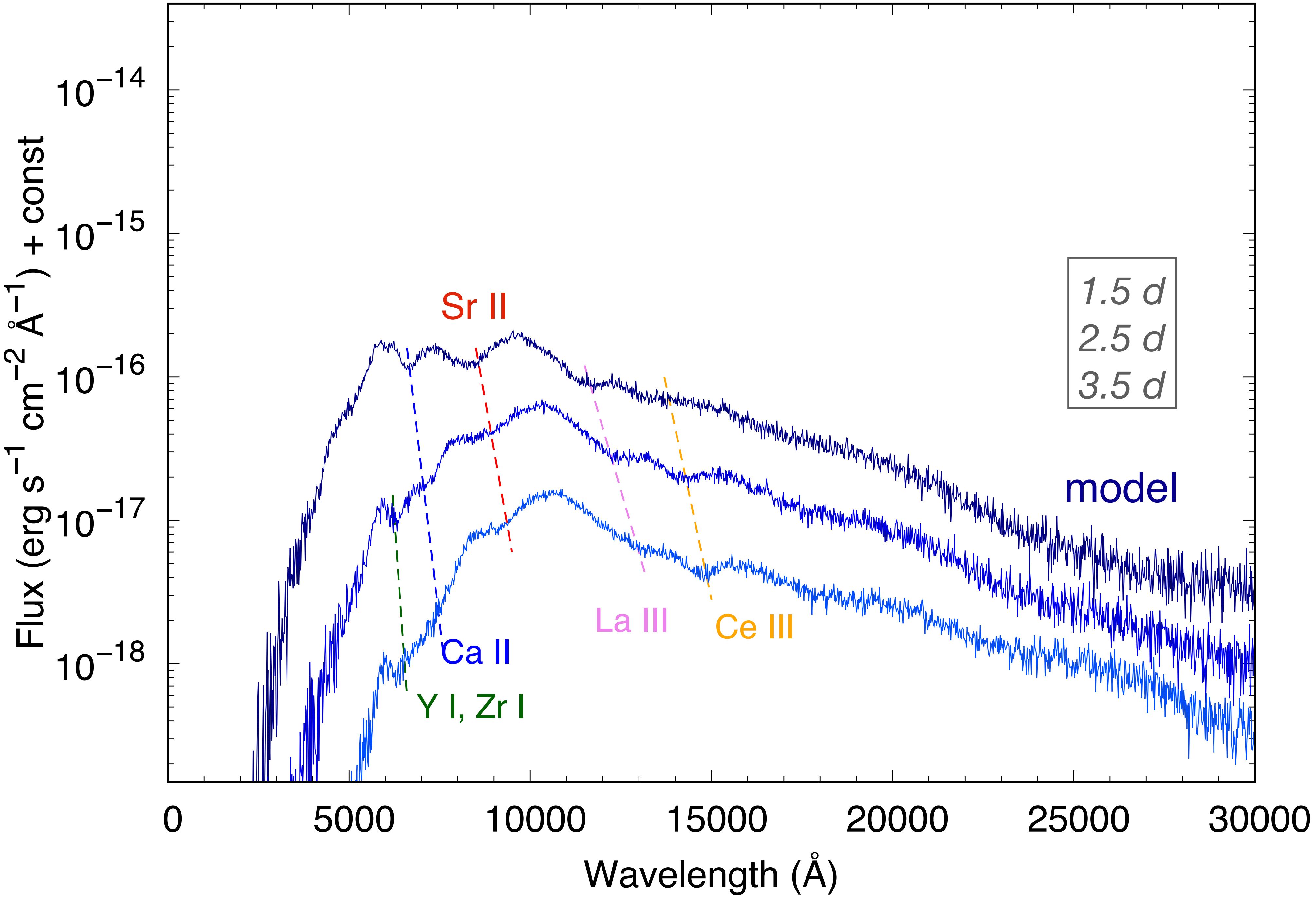
Ionization/population:
LTE (Saha eq. + Boltzmann dist.)

Atomic data: new hybrid atomic data

Monte Carlo radiative transfer

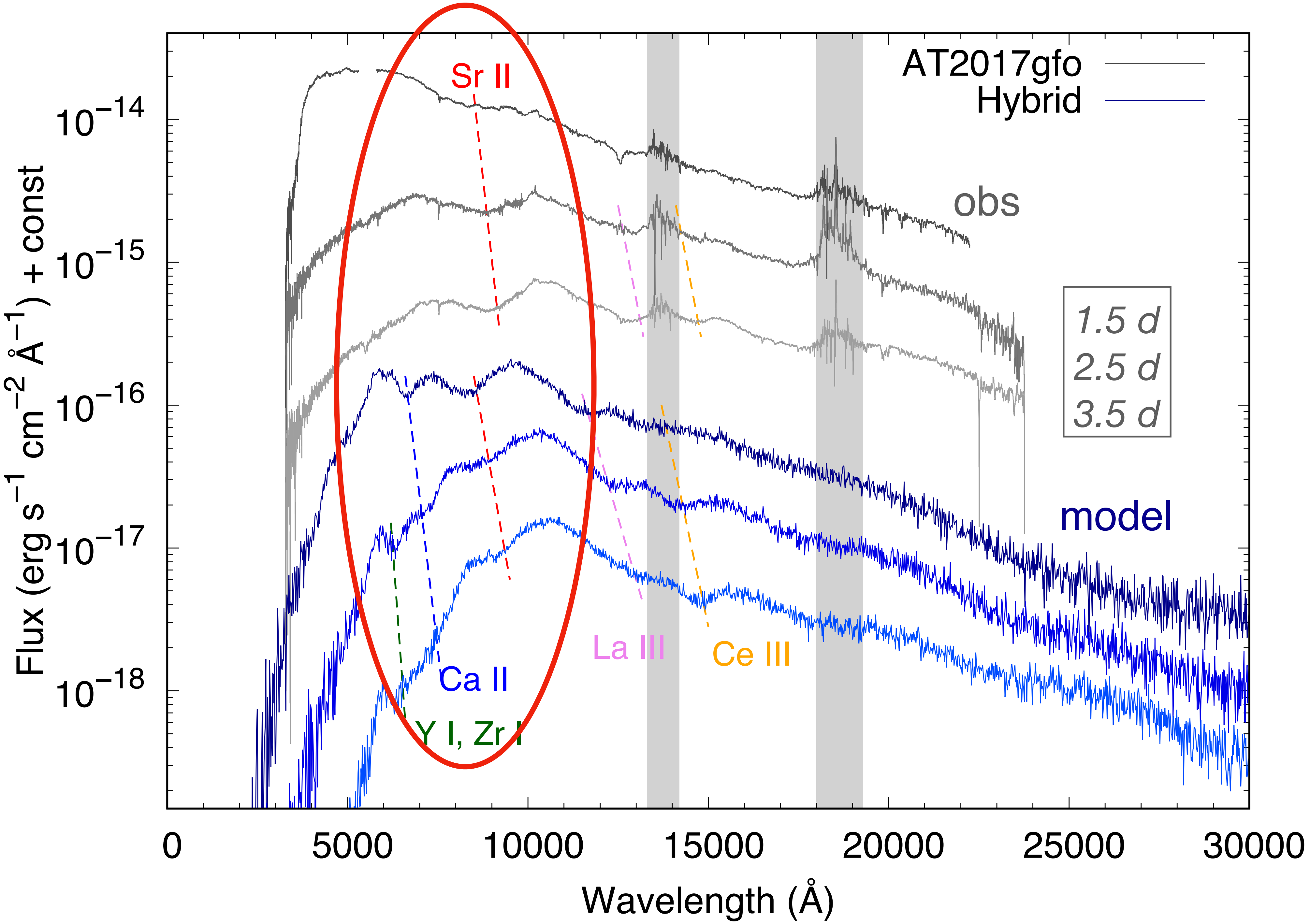
→ Realistic spectral shapes & features

Synthetic spectra



Strong lines of each ion produce absorption lines

Comparison with observations

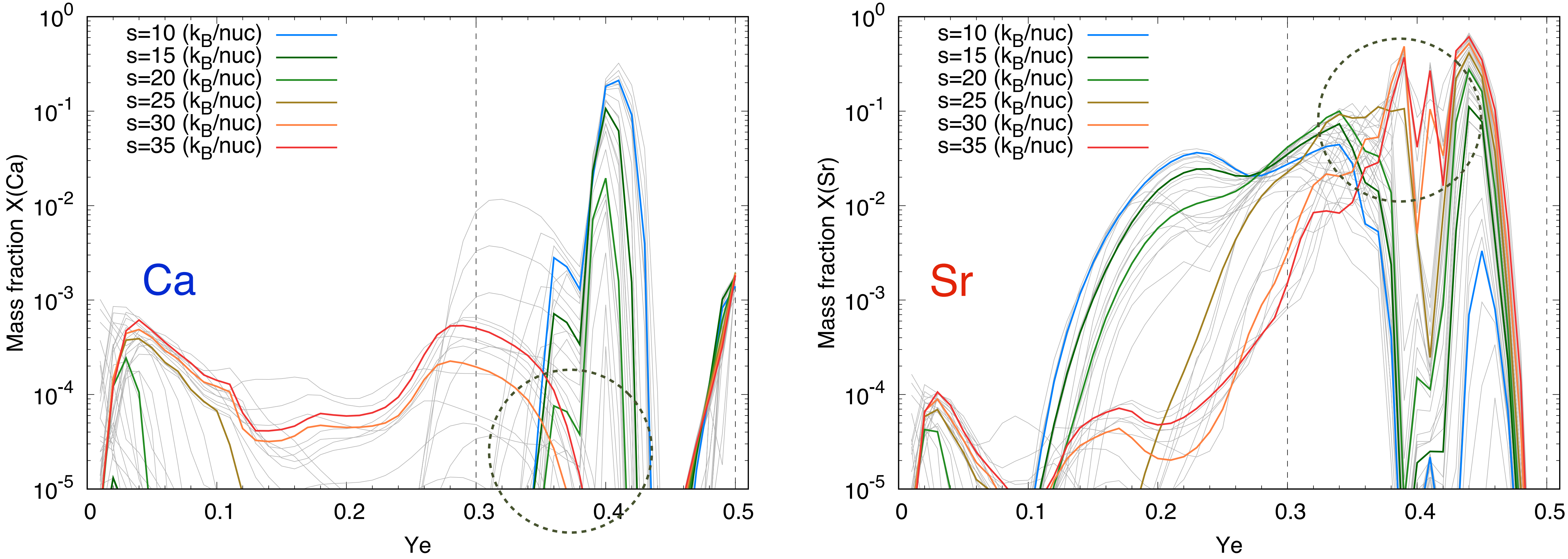


Sr and Ca have similar atomic structures and transitions

X(Ca)/X(Sr) < 0.002 in GW170817

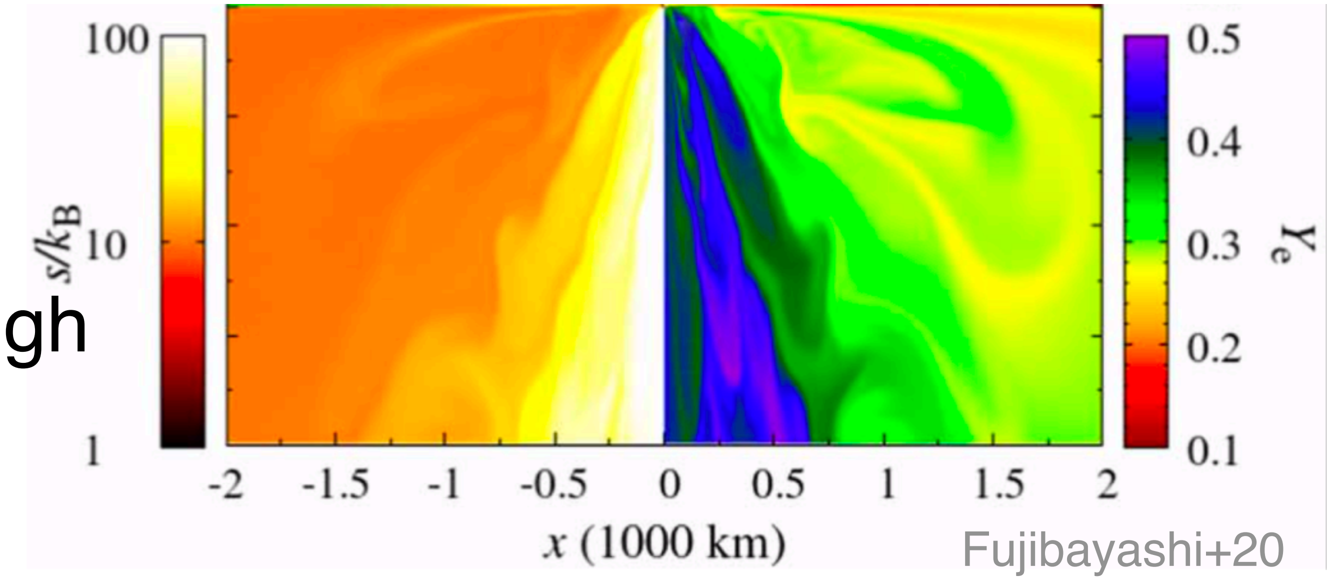
Tracer of physical conditions

color: v=0.2 c & different entropies



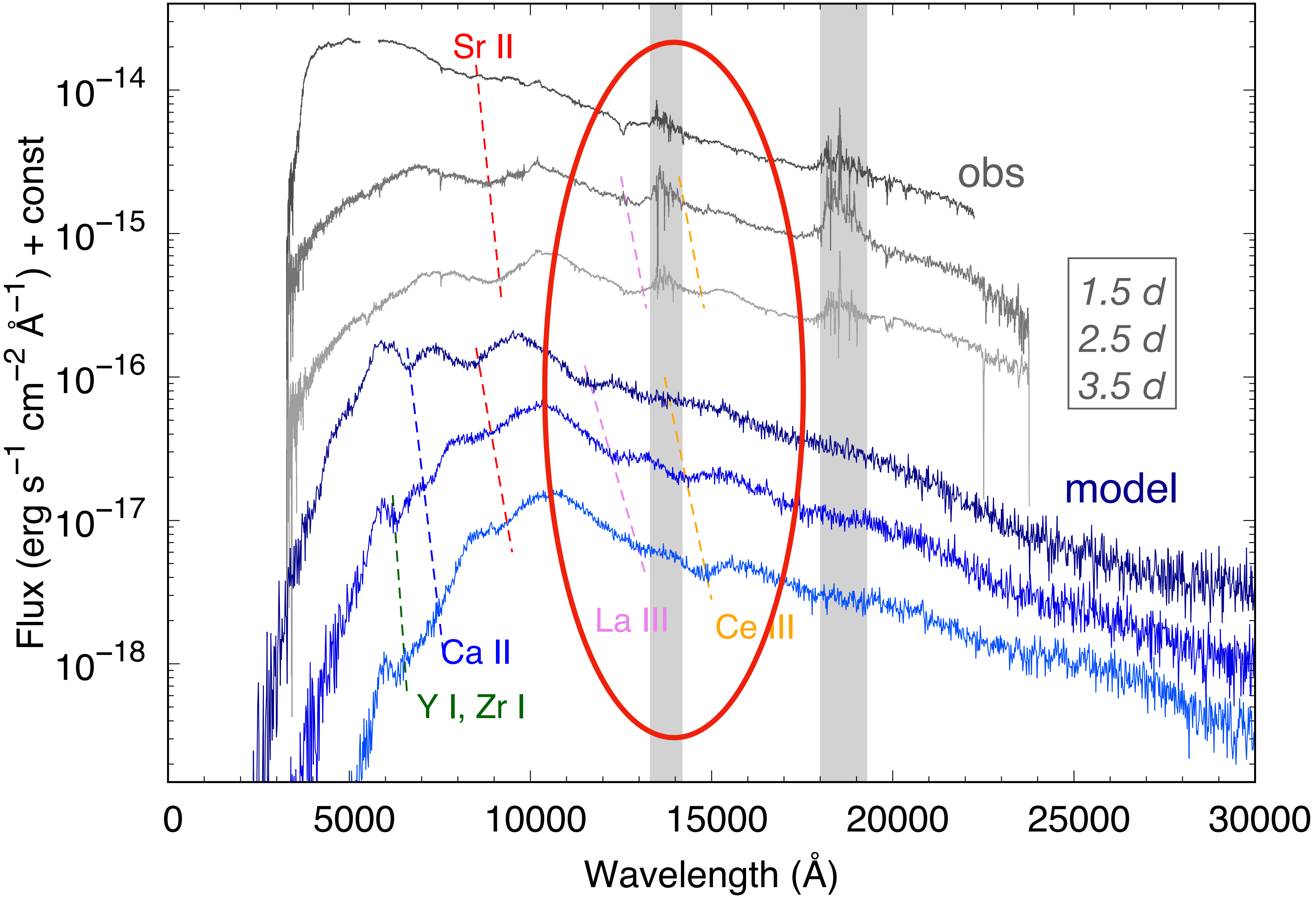
$X(Ca)/X(Sr) < 0.002$

→Velocity and entropy of high-Ye component is relatively high for GW170817



Fujibayashi+20

Comparison with observations

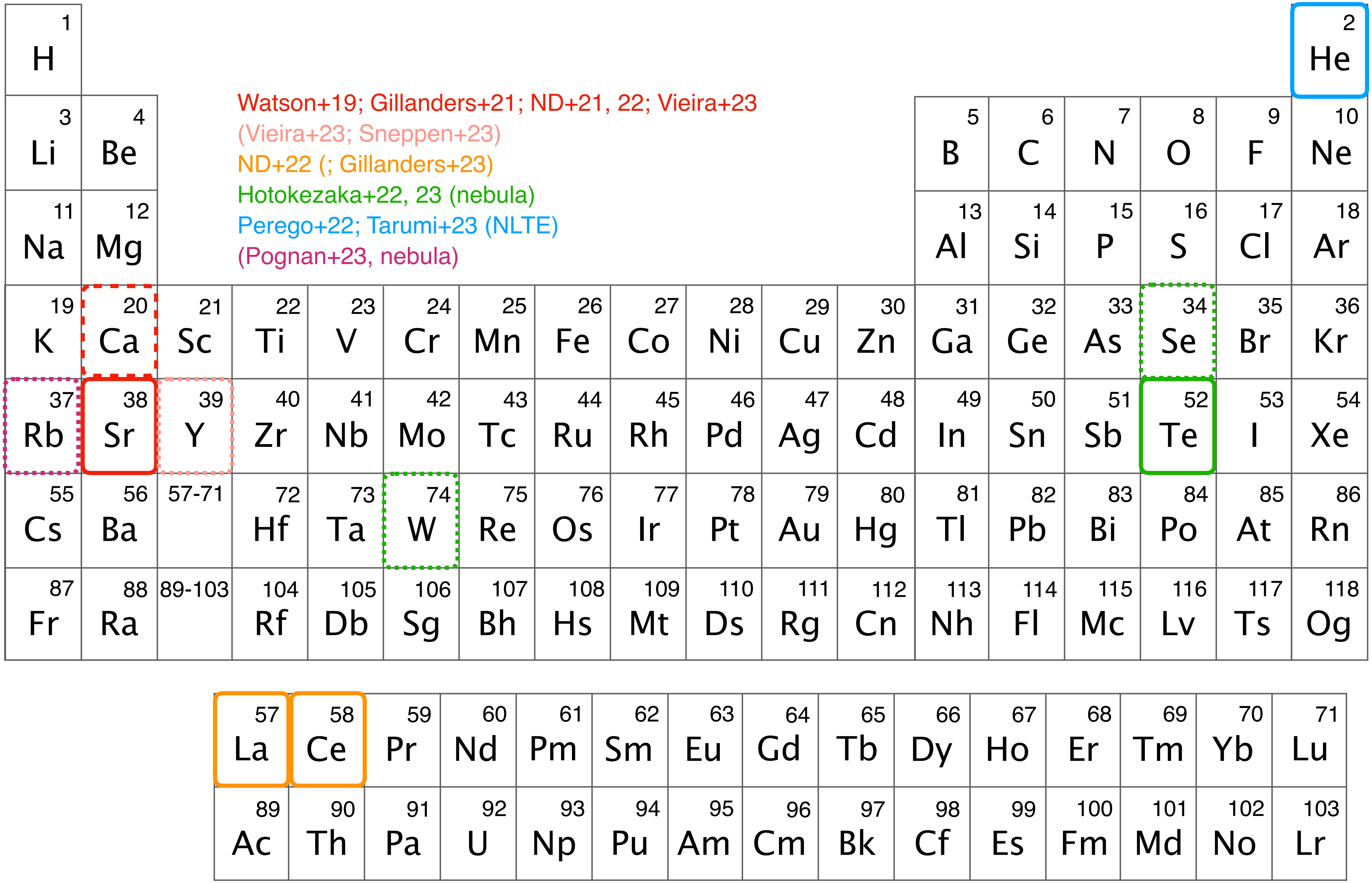


La III and Ce III lines can explain the NIR observed features

$X(La) > 2 \times 10^{-6}$, $X(Ce) \sim 10^{-5} - 10^{-3}$

Implication of elements in GW170817

Further possible constraint? How to reconstruct abundance pattern?



Watson+19; Gillanders+21; ND+21, 22; Vieira+23
(Vieira+23; Sneppen+23)
ND+22 (; Gillanders+23)
Hotokezaka+22, 23 (nebula)
Perego+22; Tarumi+23 (NLTE)
(Pognan+23, nebula)

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Summary

- The origin of elements, physics of NS mergers
  - Identification of elements in spectra is direct way to study synthesized elements
  - Which elements can produce absorption features?
  - What information we can extract from absorption features?

- New atomic data by taking advantages of both experimental (accurate) and theoretical (complete) datasets

- Elements that can appear in spectra: Ca, Sr, Y, Zr, La, and Ce
  - At the left side of the periodic table

- Ca/Sr lines can be used as high-Ye tracer

- Mass fraction of La and Ce in GW170817 are estimated to be $< 2\text{x}10^{-6}$ and $\sim 10^{-3}$-10^{-5} (direct estimation)