YITP Workshop
Extreme Outflows in Astrophysical Transients

キロノバのスペクトルで探る r-process元素合成の痕跡

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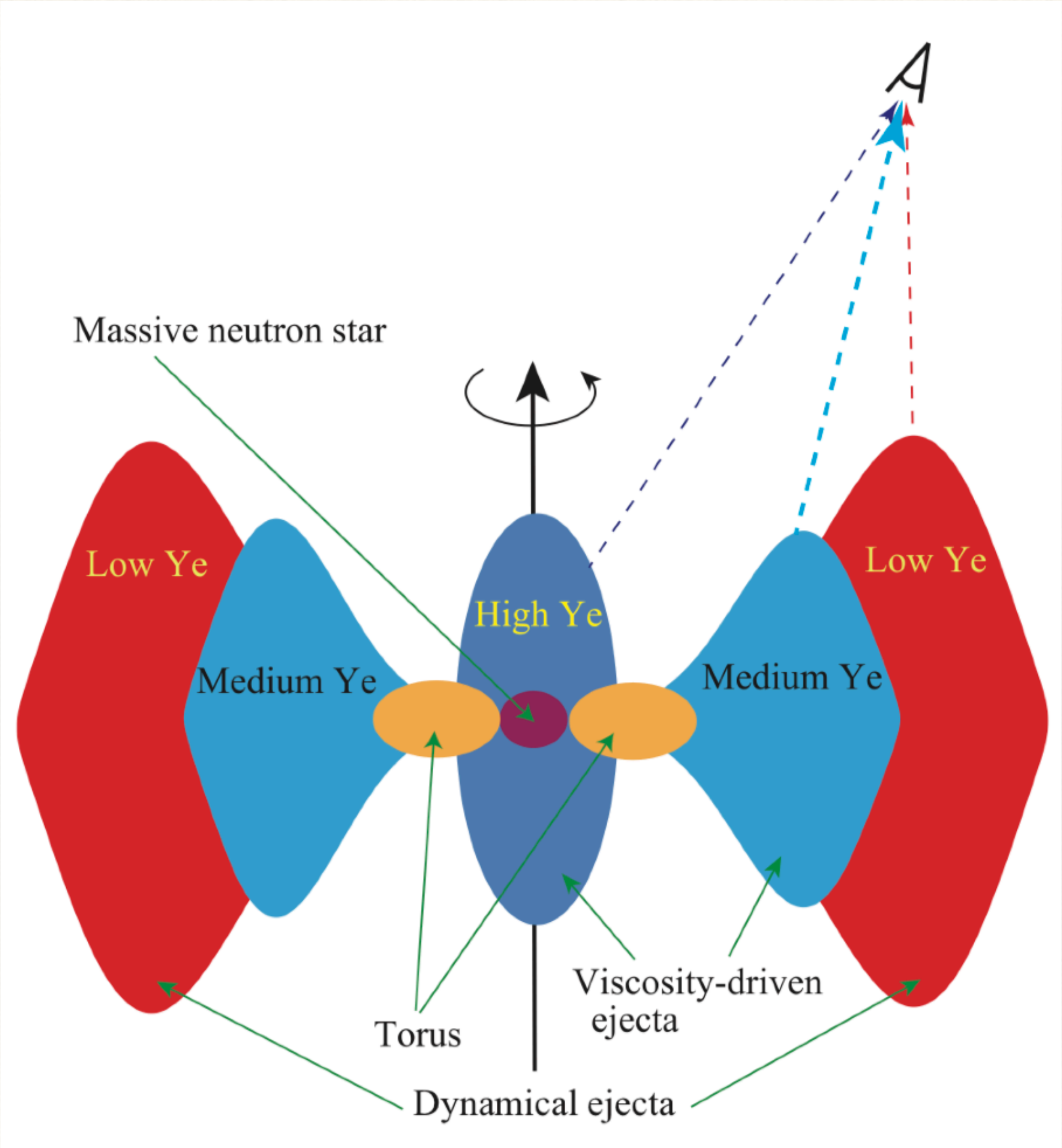
Domoto et al. 2021, ApJ, 913, 26

Kilonova

Ye dependence of synthesized elements

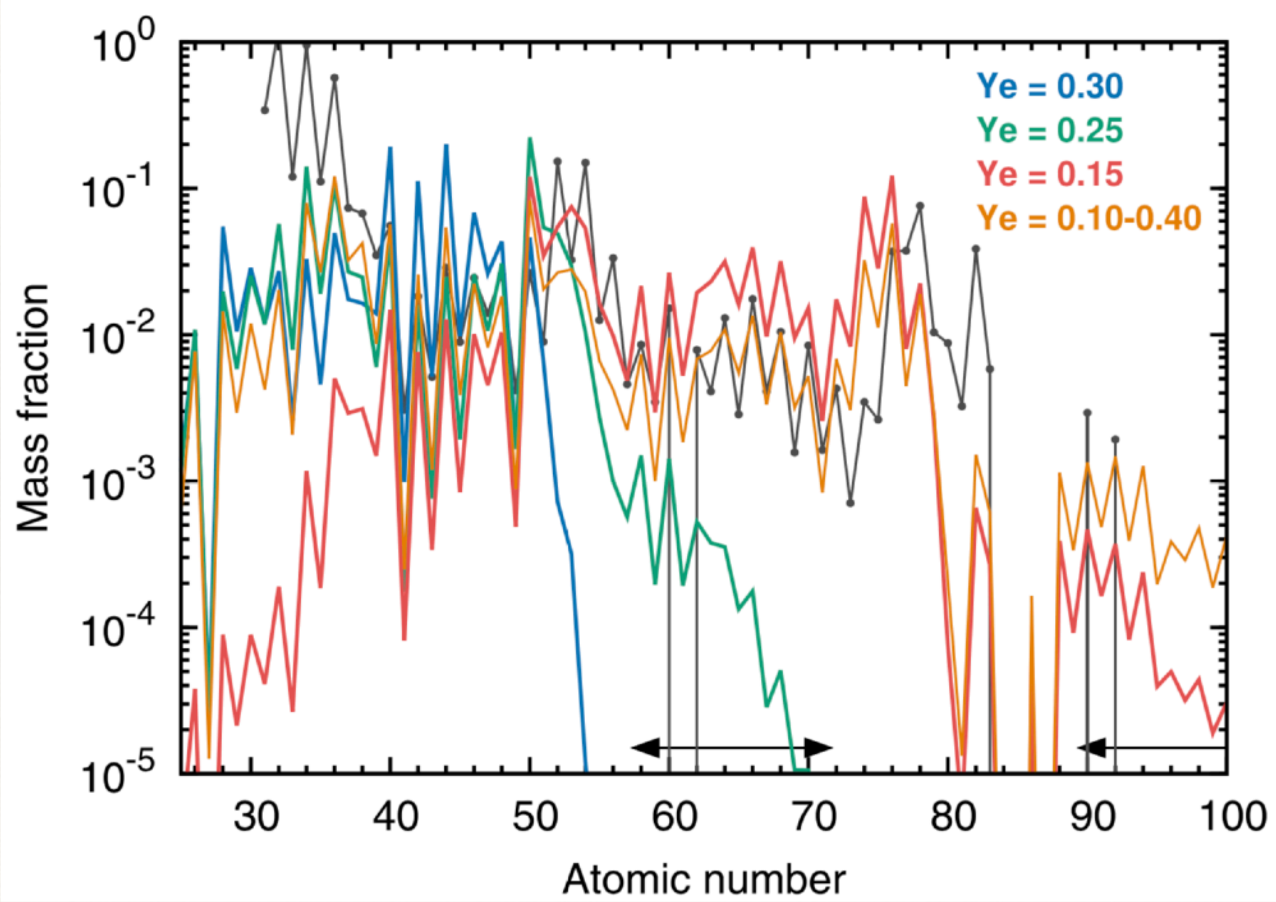
$$Y_e = \frac{n_p}{n_n + n_p}$$



Shibata et al. 2017

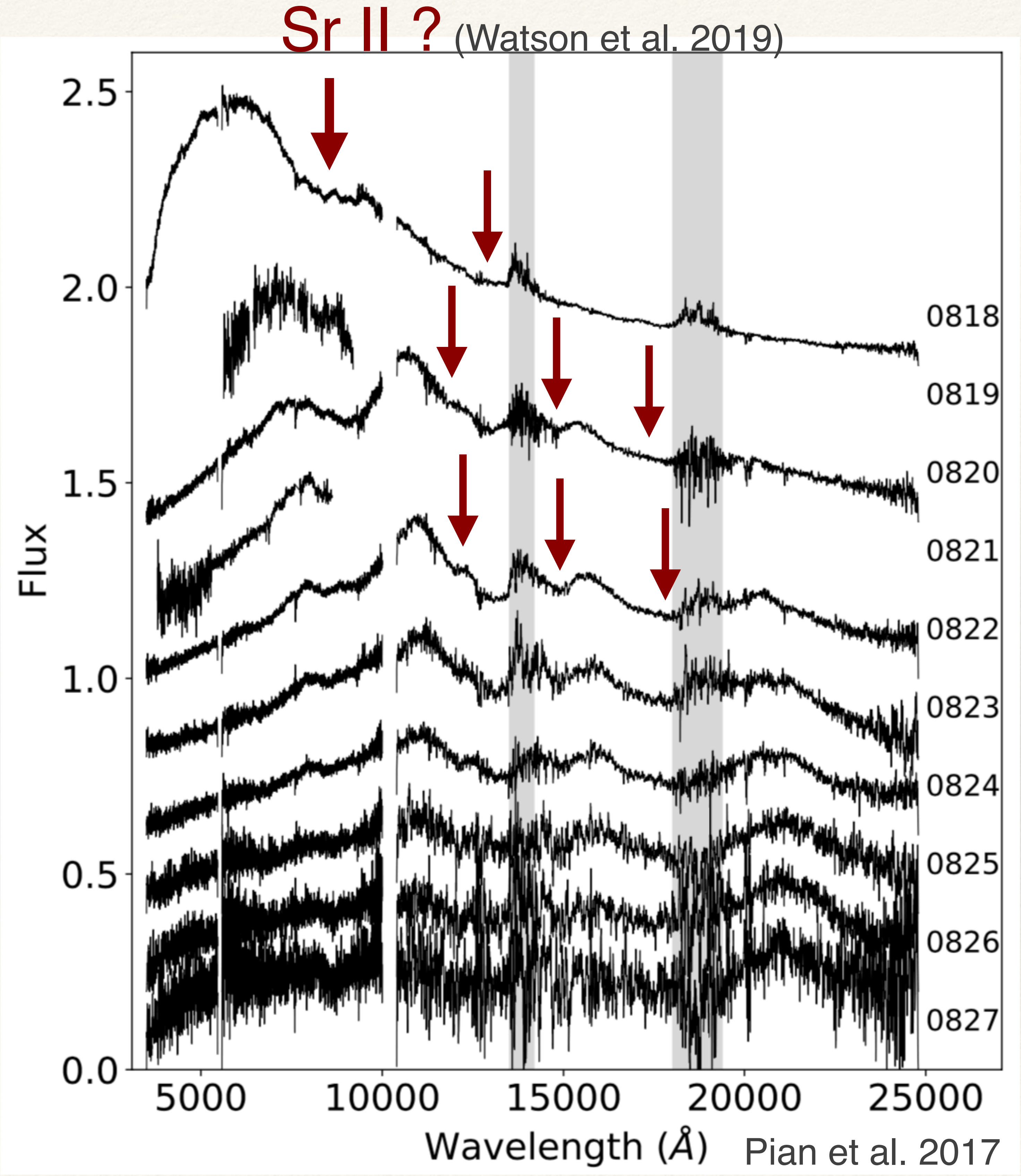
Various Ye

- low Ye: heavy elements
- high Ye: lighter elements



Tanaka et al. 2017

GW170817



Sr II ? (Watson et al. 2019)

Pian et al. 2017

Motivation

Elemental abundance?
→ the origin of heavy elements, physics of NS mergers

Toward identification of elements in spectra:

- Which elements can produce strong absorption line?
- How does abundance affect to kilonova spectra?

Methods

- Radiative transfer simulations

  (Tanaka & Hotokezaka 2013, Tanaka et al. 2014, 2017, Kawaguchi et al. 2018)

  - Mej = 0.03Msun
  - Velocity : v = 0.05-0.3c
  - Density structure: 1D simple power law ($\rho \propto r^{-3}$)
  - Abundance : a multi-components free expansion model (Wanajo 2018)

- Line strength of bound-bound transitions

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

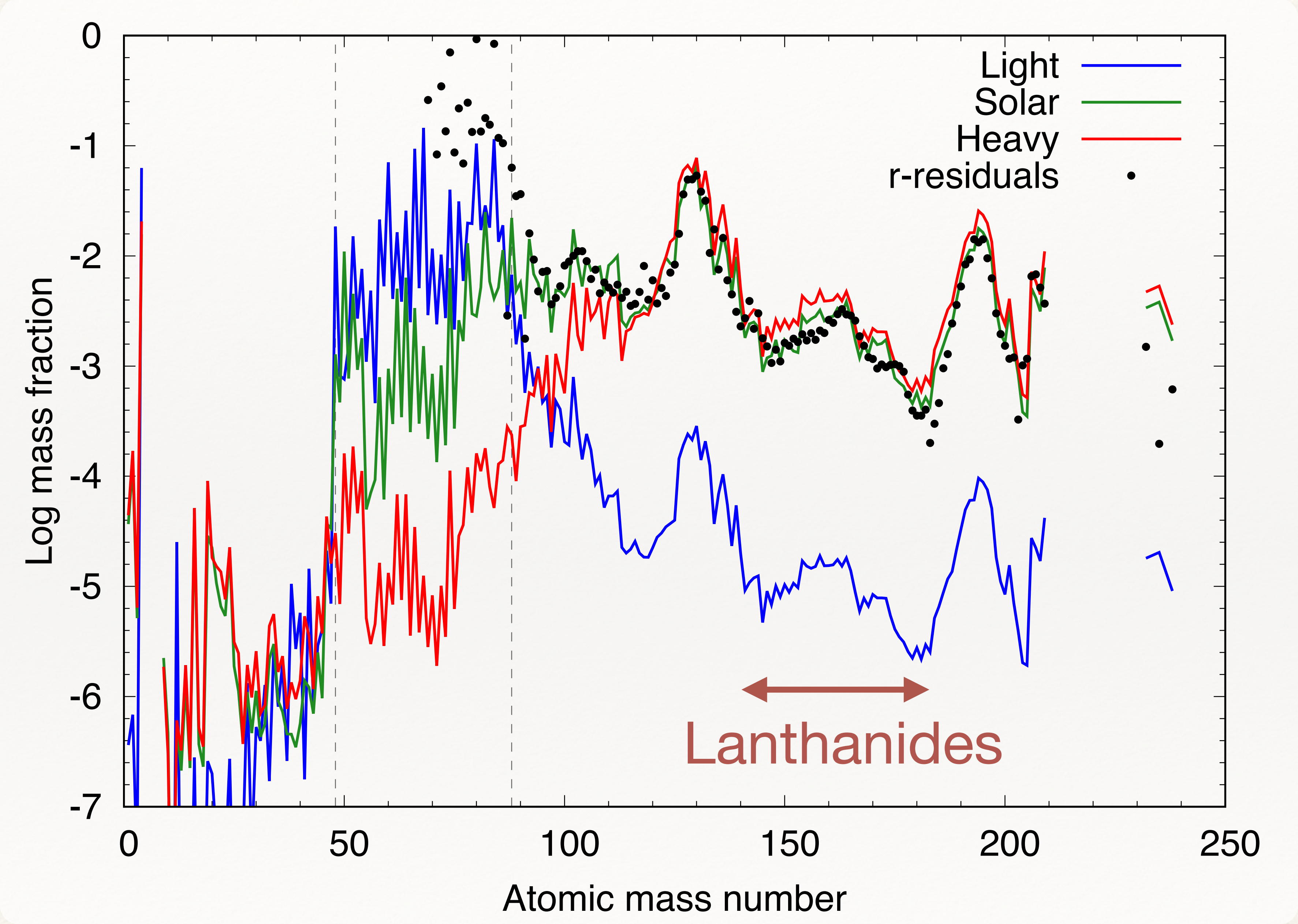
- Line list : VALD (the Vienna Atomic Line Database)

  *based on atomic experiments

Methods

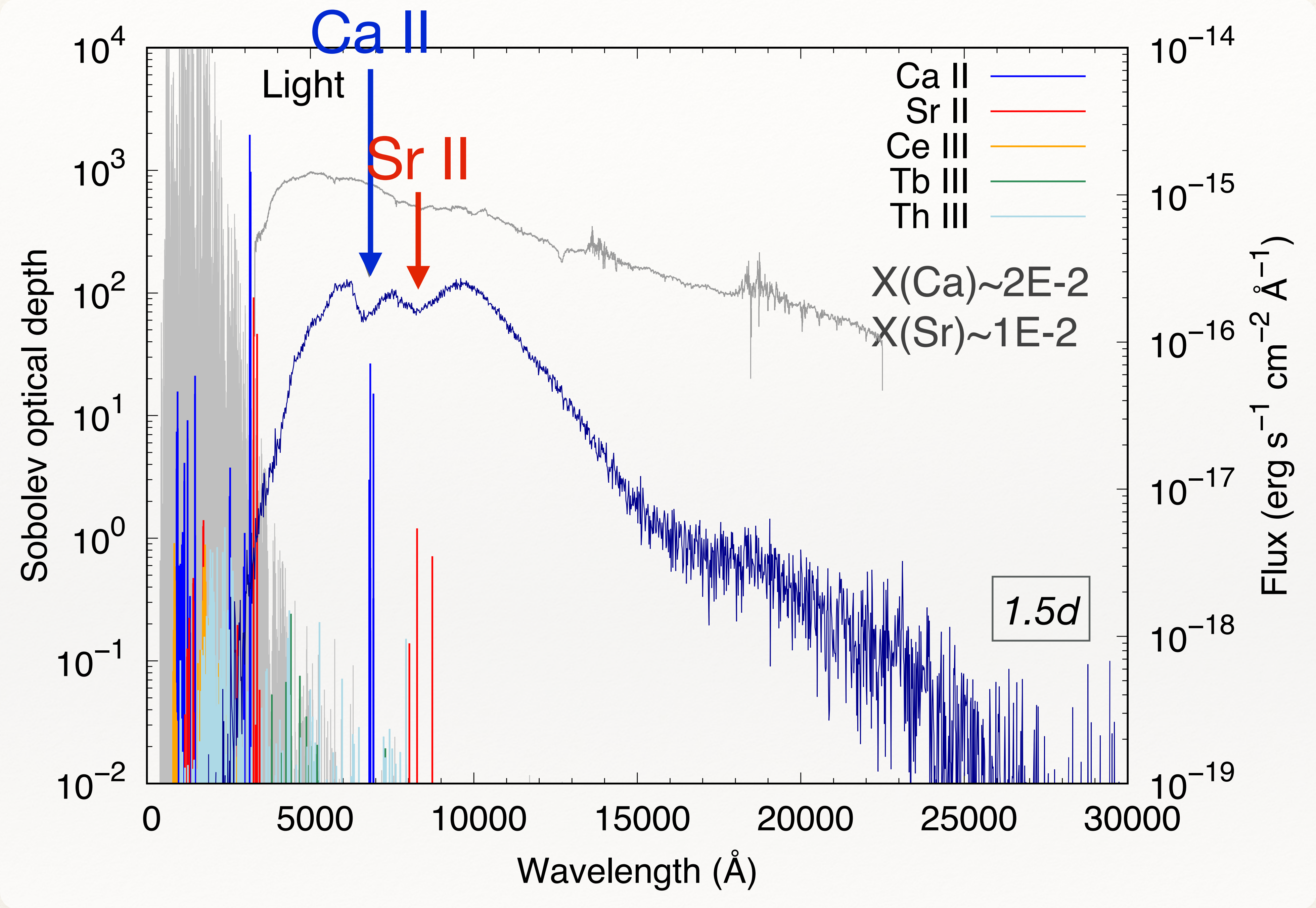
- Abundance : a multi-component free expansion model

(Wanajo 2018)



Lighter elements dominant

$\rho \sim 6 \times 10^{-15}$ g cm^{-3}, $T \sim 5200$ K at $v \sim 0.2c$

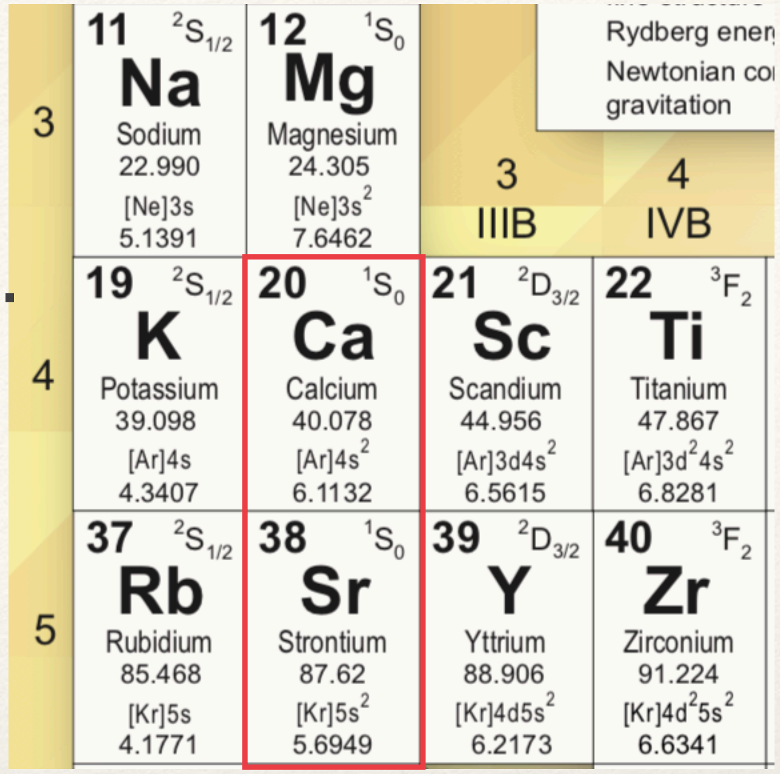


Sr II/Ca II triplet

They have a similar atomic structure and transitions.

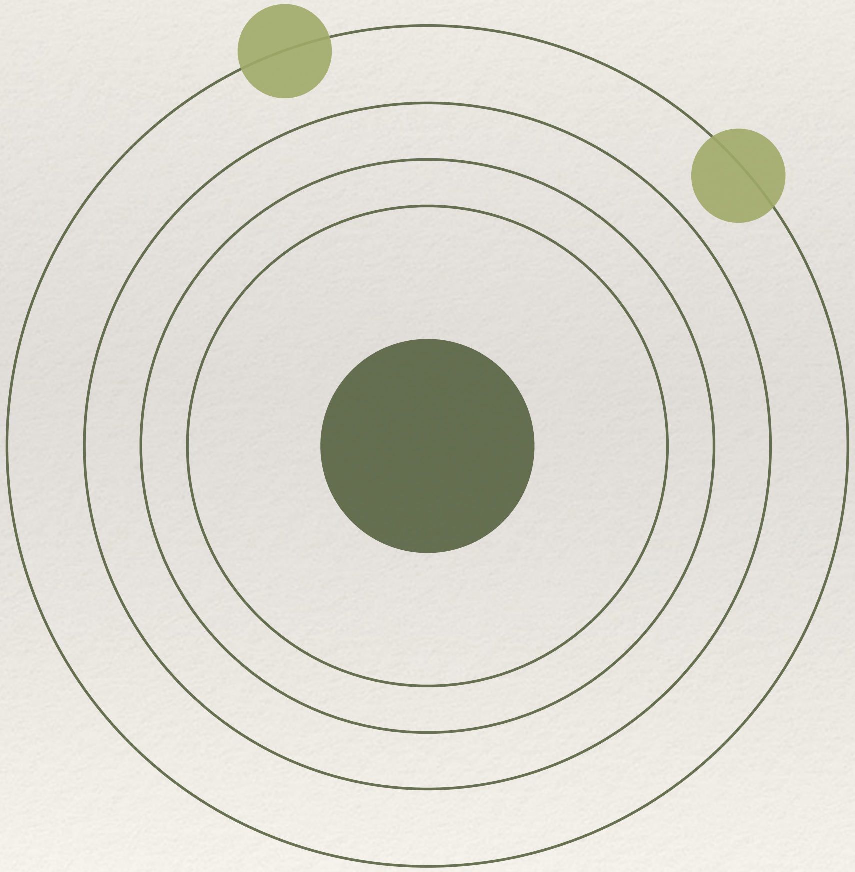
Ca II triplet $[\mathrm{Ar}]3\mathrm{d}\ 3^2\mathrm{D}_{\frac{5}{2},\frac{3}{2}} \longrightarrow [\mathrm{Ar}]4\mathrm{p}\ 4^2\mathrm{P}^{\mathrm{o}}_{\frac{3}{2},\frac{1}{2}}$

Sr II triplet $[\mathrm{Kr}]4\mathrm{d}\ 4^2\mathrm{D}_{\frac{5}{2},\frac{3}{2}} \longrightarrow [\mathrm{Kr}]5\mathrm{p}\ 5^2\mathrm{P}^{\mathrm{o}}_{\frac{3}{2},\frac{1}{2}}$



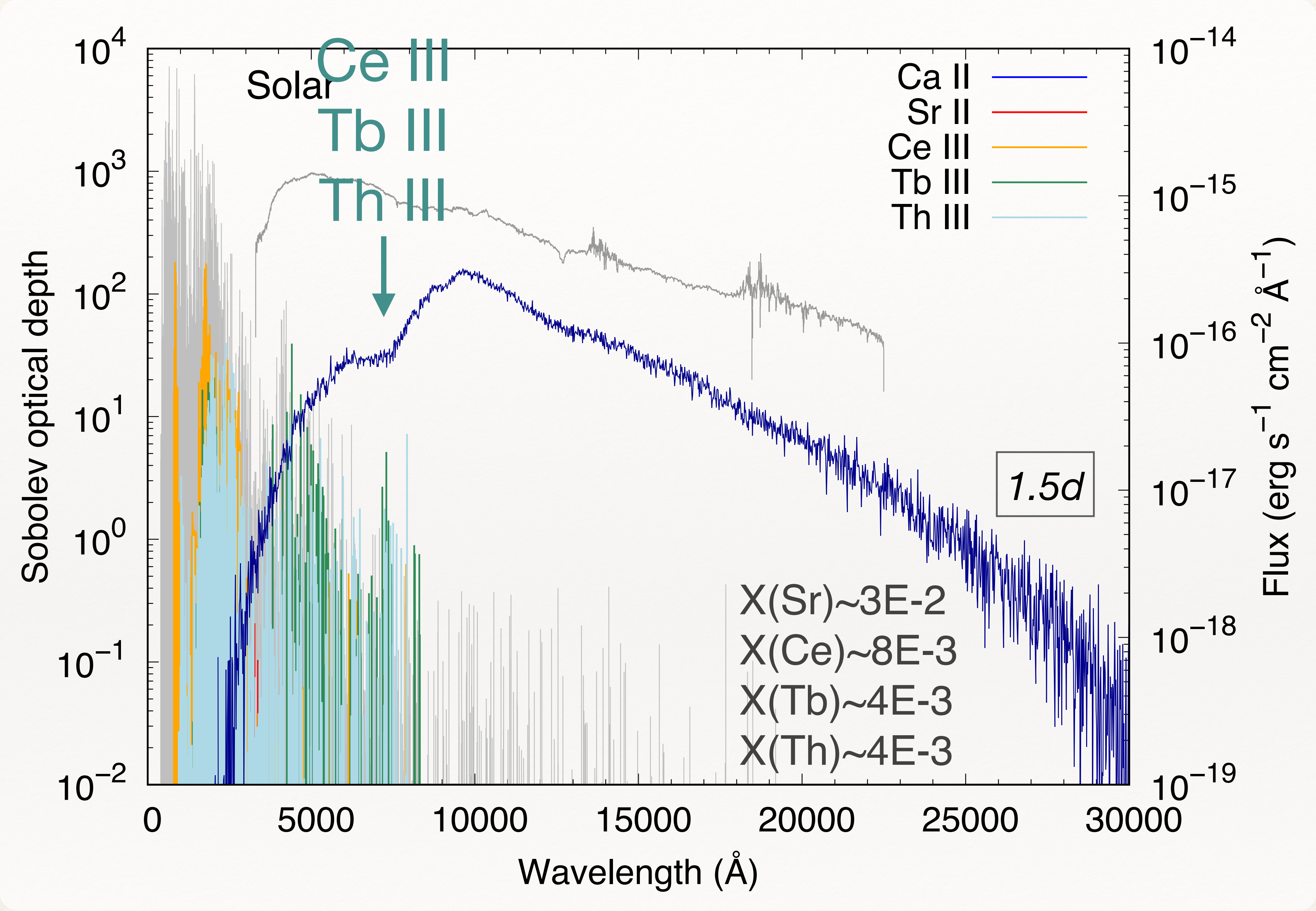
			3 IIIB	4 IVB
3	11 $^2S_{1/2}$ **Na** Sodium 22.990 [Ne]3s 5.1391	12 $^1S_0$ **Mg** Magnesium 24.305 $[\mathrm{Ne}]3s^2$ 7.6462	Rydberg ener Newtonian co gravitation	
4	19 $^2S_{1/2}$ **K** Potassium 39.098 [Ar]4s 4.3407	20 $^1S_0$ **Ca** Calcium 40.078 $[\mathrm{Ar}]4s^2$ 6.1132	21 $^2D_{3/2}$ **Sc** Scandium 44.956 $[\mathrm{Ar}]3d4s^2$ 6.5615	22 $^3F_2$ **Ti** Titanium 47.867 $[\mathrm{Ar}]3d^24s^2$ 6.8281
5	37 $^2S_{1/2}$ **Rb** Rubidium 85.468 [Kr]5s 4.1771	38 $^1S_0$ **Sr** Strontium 87.62 $[\mathrm{Kr}]5s^2$ 5.6949	39 $^2D_{3/2}$ **Y** Yttrium 88.906 $[\mathrm{Kr}]4d5s^2$ 6.2173	40 $^3F_2$ **Zr** Zirconium 91.224 $[\mathrm{Kr}]4d^25s^2$ 6.6341

https://www.nist.gov/pml/periodic-table-elements

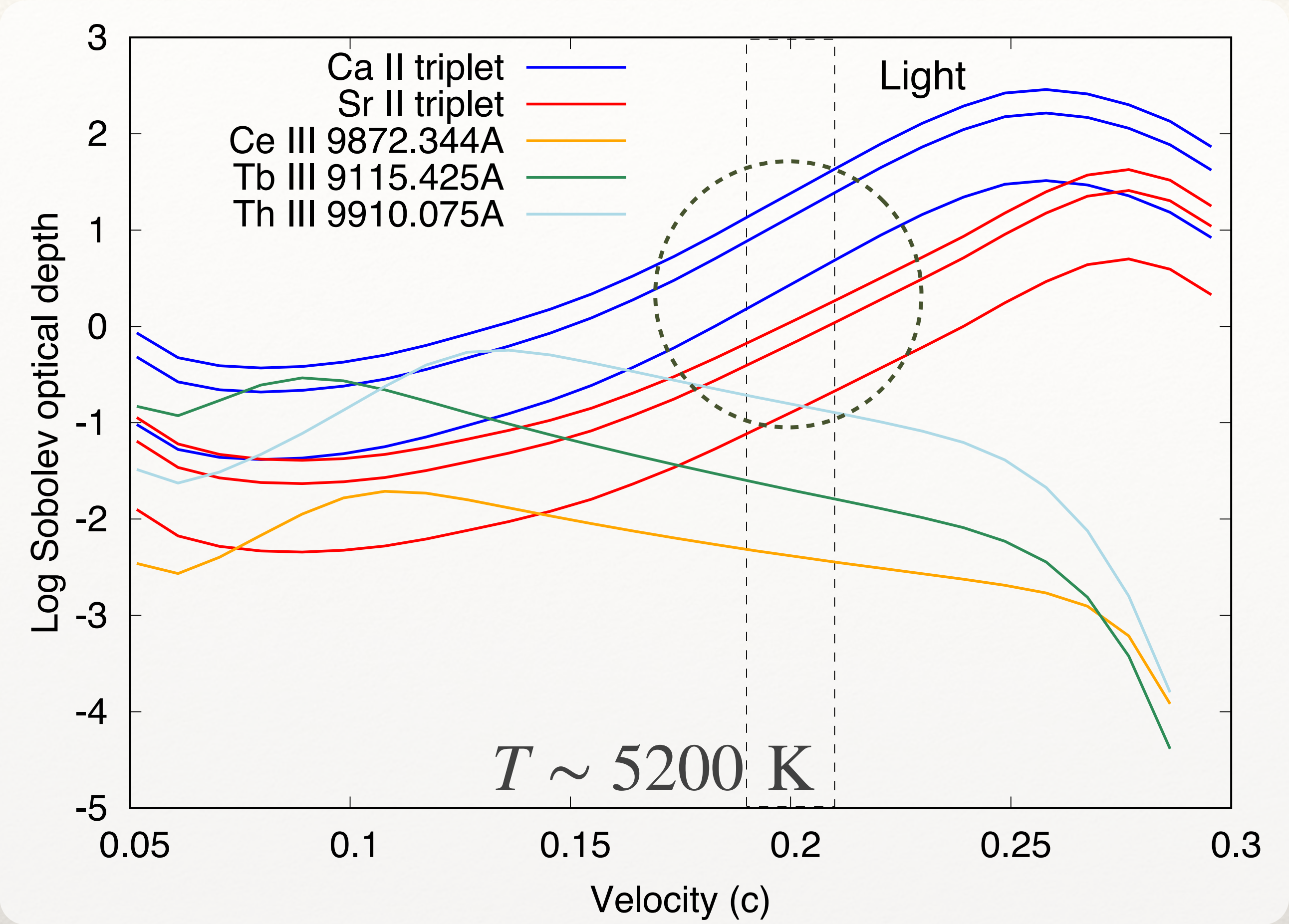


Heavier elements dominant

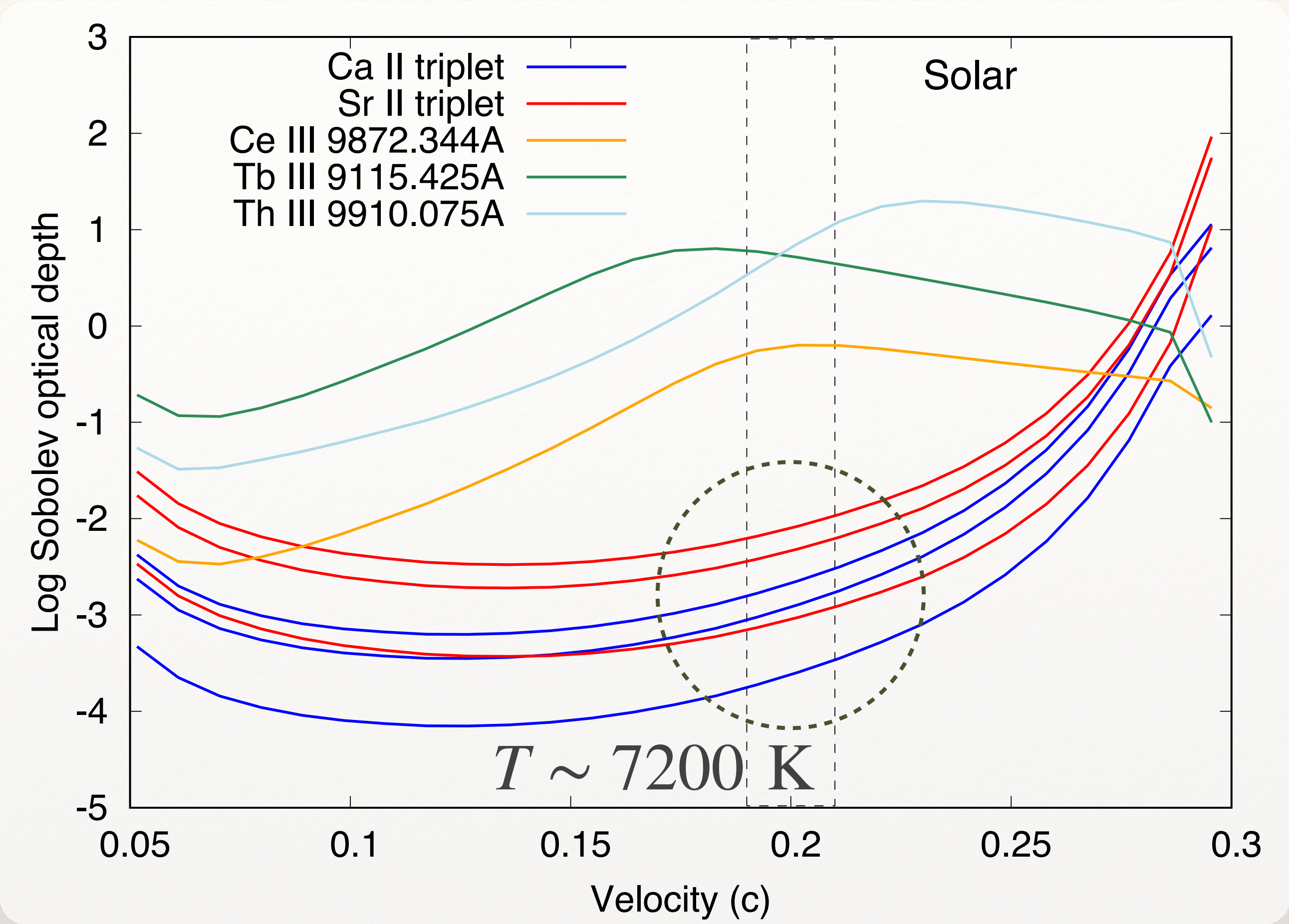
$\rho \sim 6 \times 10^{-15}$ g cm^{-3}, $T \sim 7200$ K at $v \sim 0.2c$



Abundance & temperature dependence



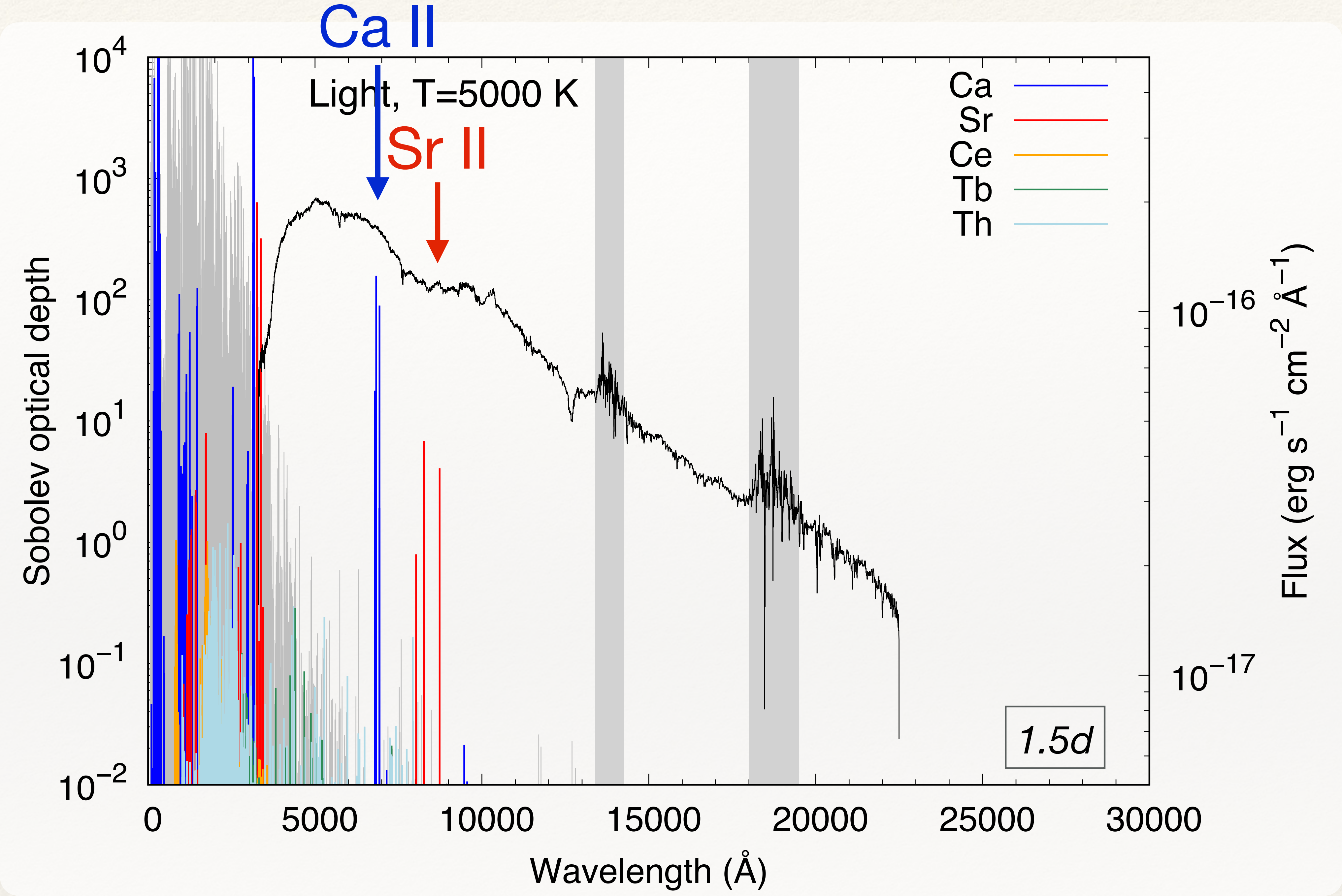
X(Ca, Sr)~1E-2
X(Ce, Tb, Th)~(2-4)E-5



X(Ca, Sr)~3E-2 -1E-3
X(Ce, Tb, Th)~(4-8)E-3

- Temperature difference is due to heating rate taken consistently with abundance.
- Line strength strongly depends on abundance and temperature.

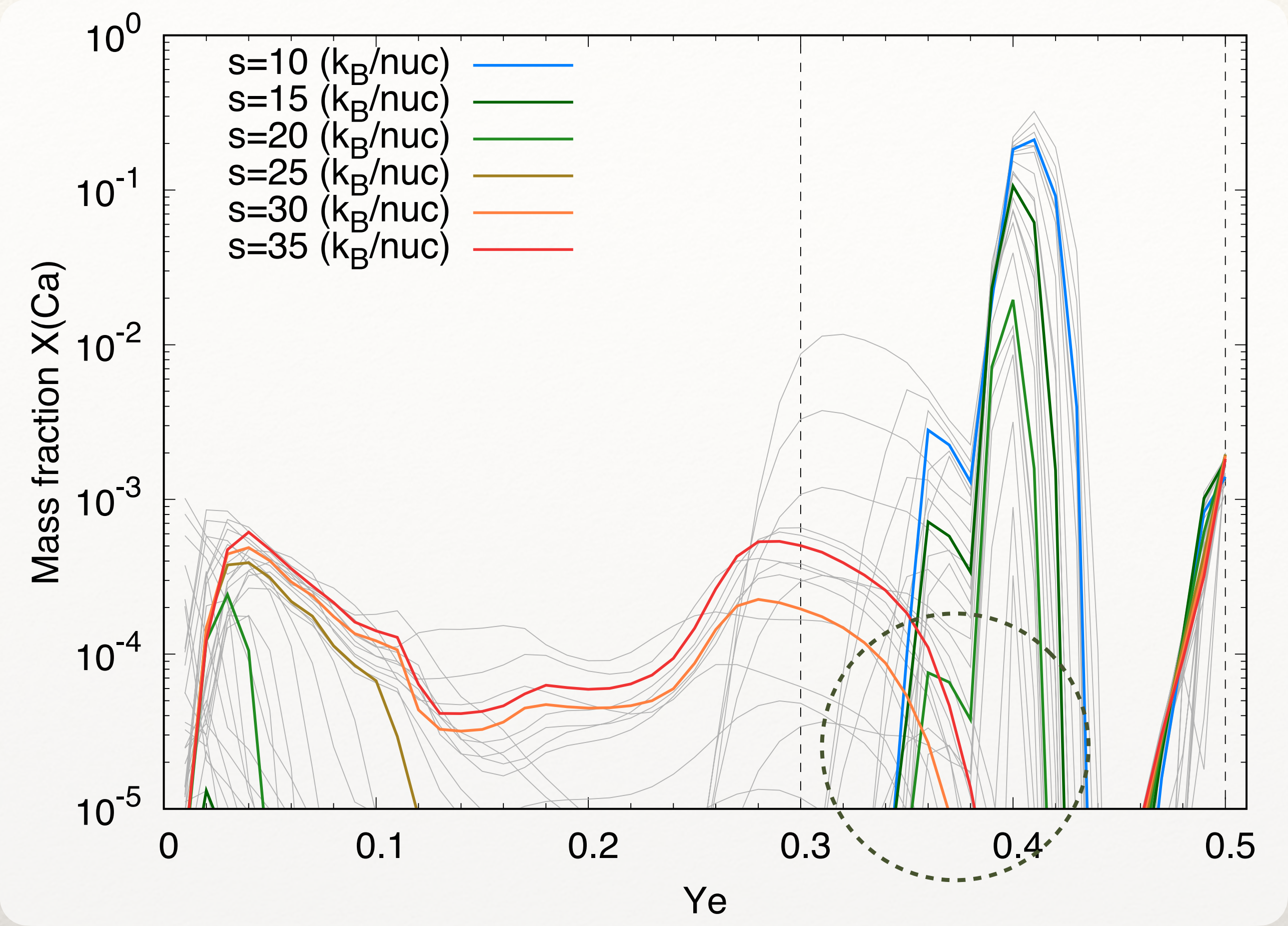
For GW170817

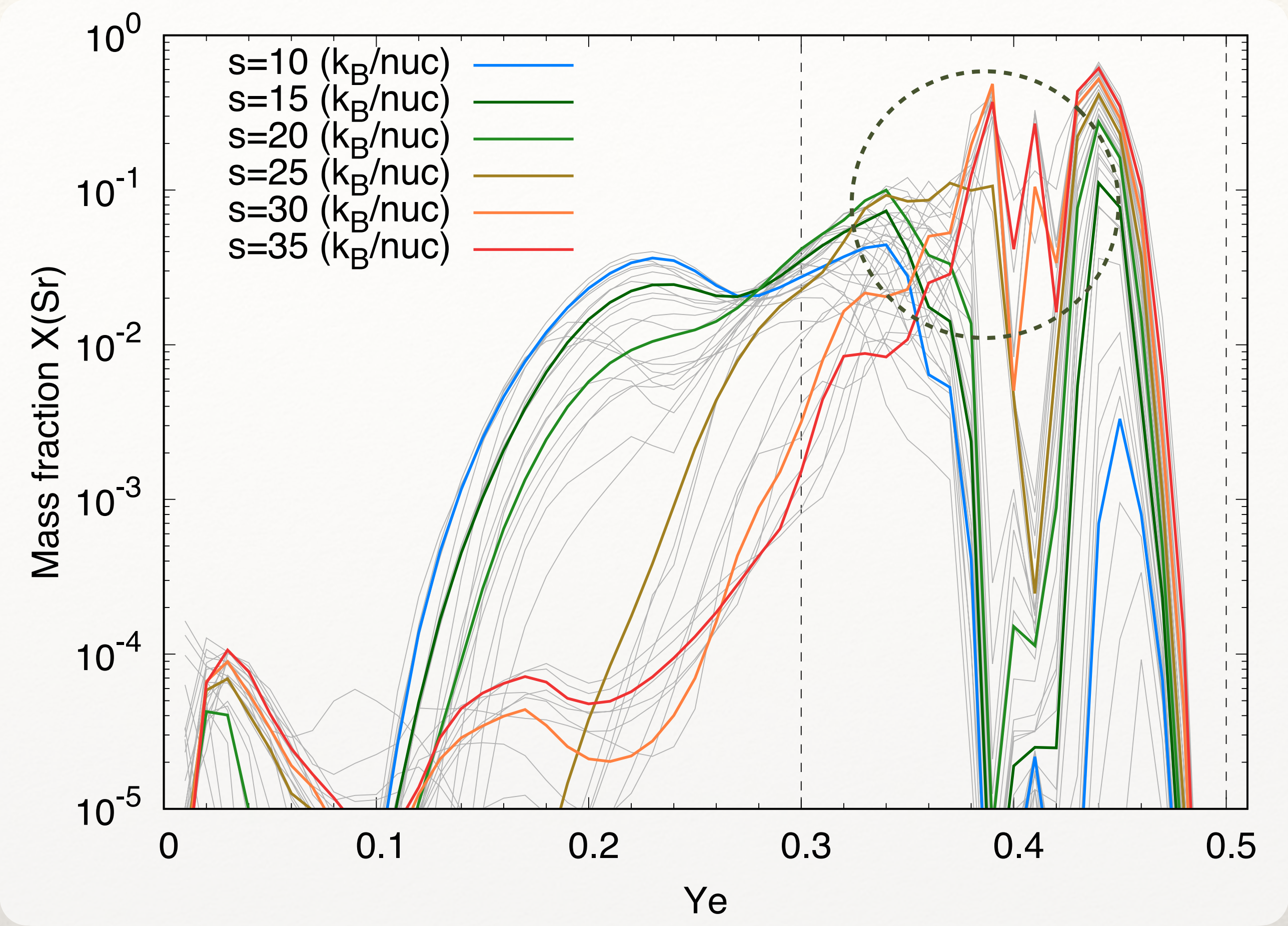


GW170817 → $X(Ca)/X(Sr) < 0.002$

Physical conditions

color: v=0.2c & different s





X(Ca)/X(Sr) < 0.002

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

Summary

- The origin of elements, physics of NS mergers
  - Line strengths of bound-bound transitions
  - Effects of abundance to kilonova spectra

- GW170817: Sr II is consistent, Ca II do not appear.
  => constrains to X(Ca)/X(Sr) and ejecta properties

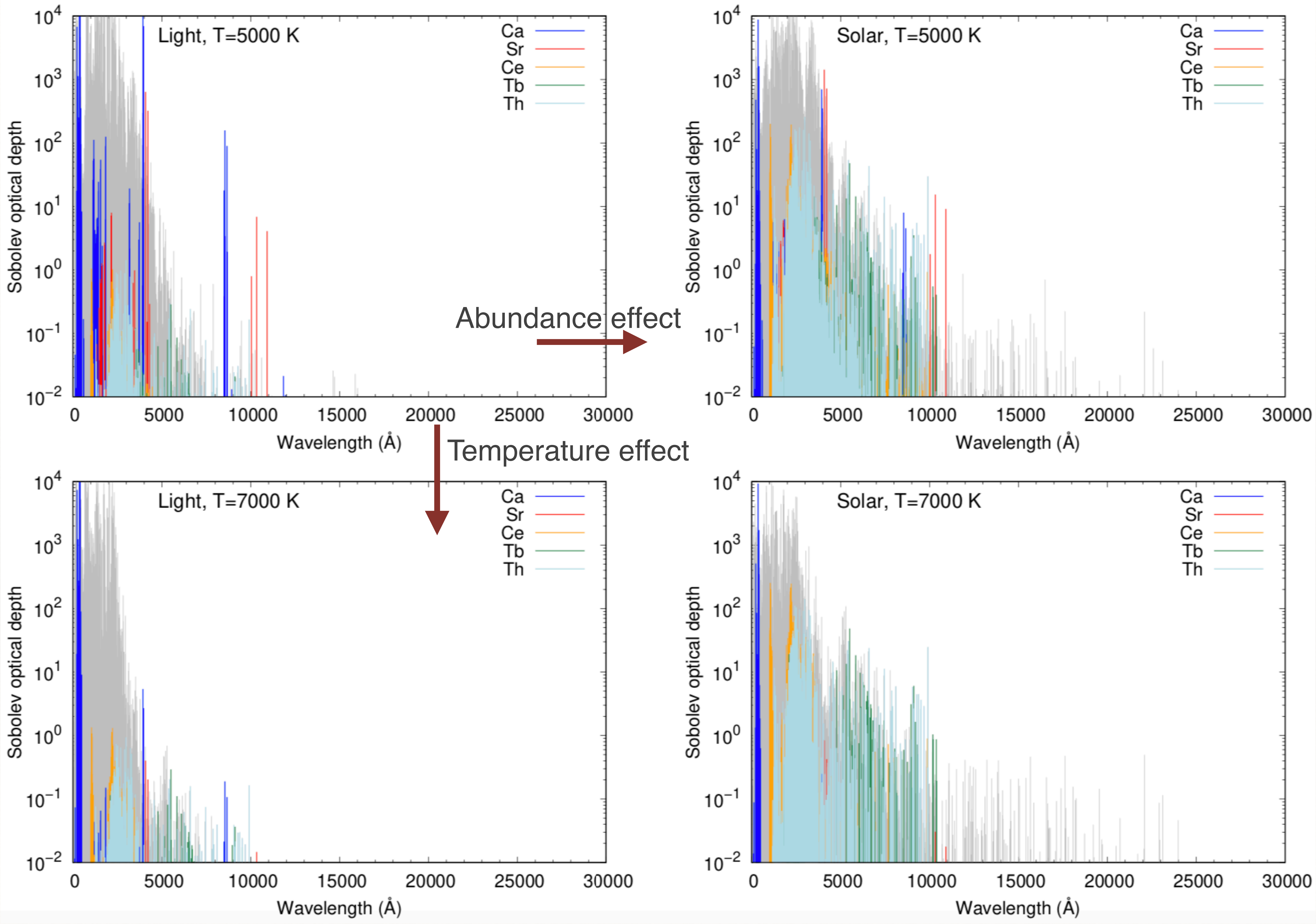
- Not only Sr II but also Ca II lines also appear in the spectra
  if including less heavy elements (high-Ye tracer).

- We can directly obtain the evidence of
  synthesized heavy elements like Ce, Tb and Th.

- NIR lines are important for understanding of NSM.

Line strength for each model with given ρ and T

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



Importance of NIR lines

gf-value from APOGEE: 9 lines of Ce II, 10 lines of Nd II in H-band