宇宙線研究所小研究会 高エネルギー現象で探る宇宙の多様性

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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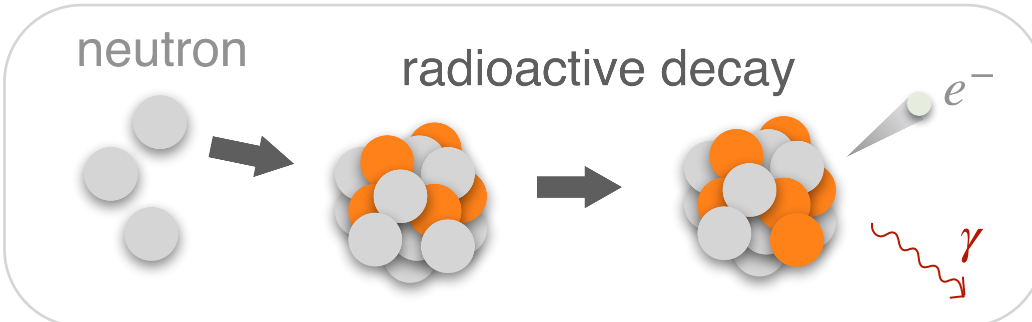
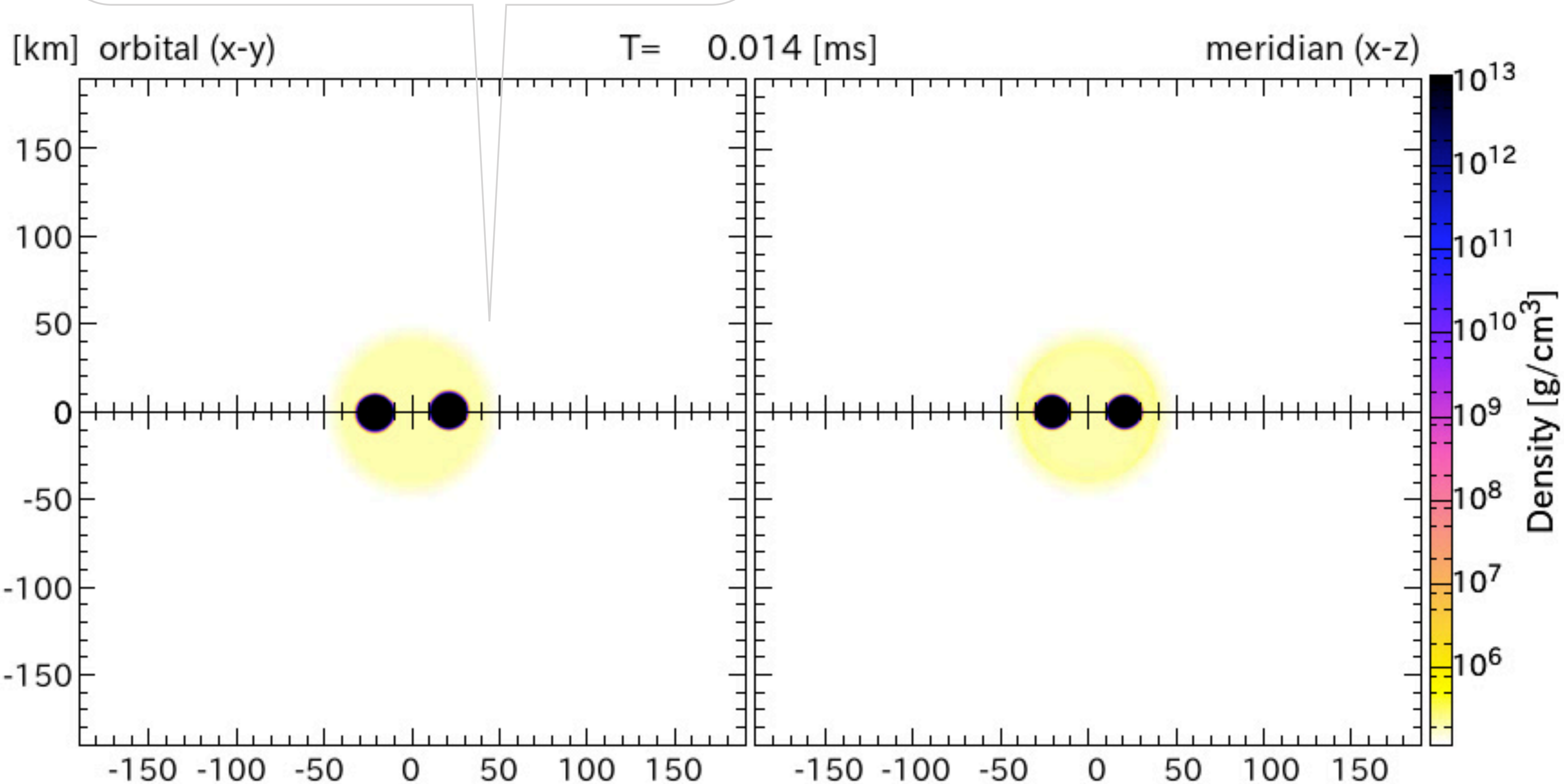
元素の起源


ビッグバン
星の中、超新星爆発
?
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

連星中性子星合体: r-process site



-> Thermal radiation (kilonova)



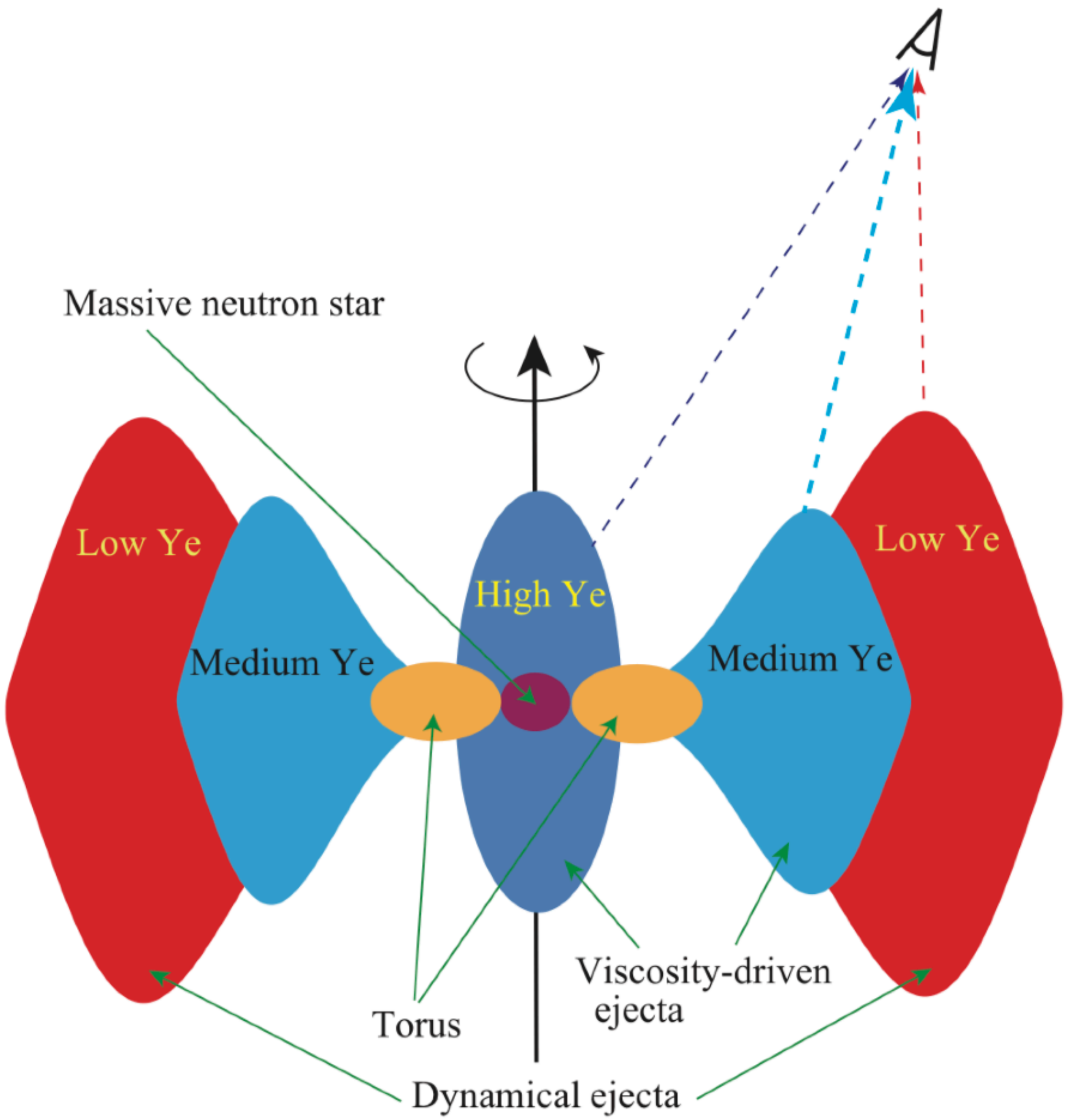
Sekiguchi et al. 2015

元素組成

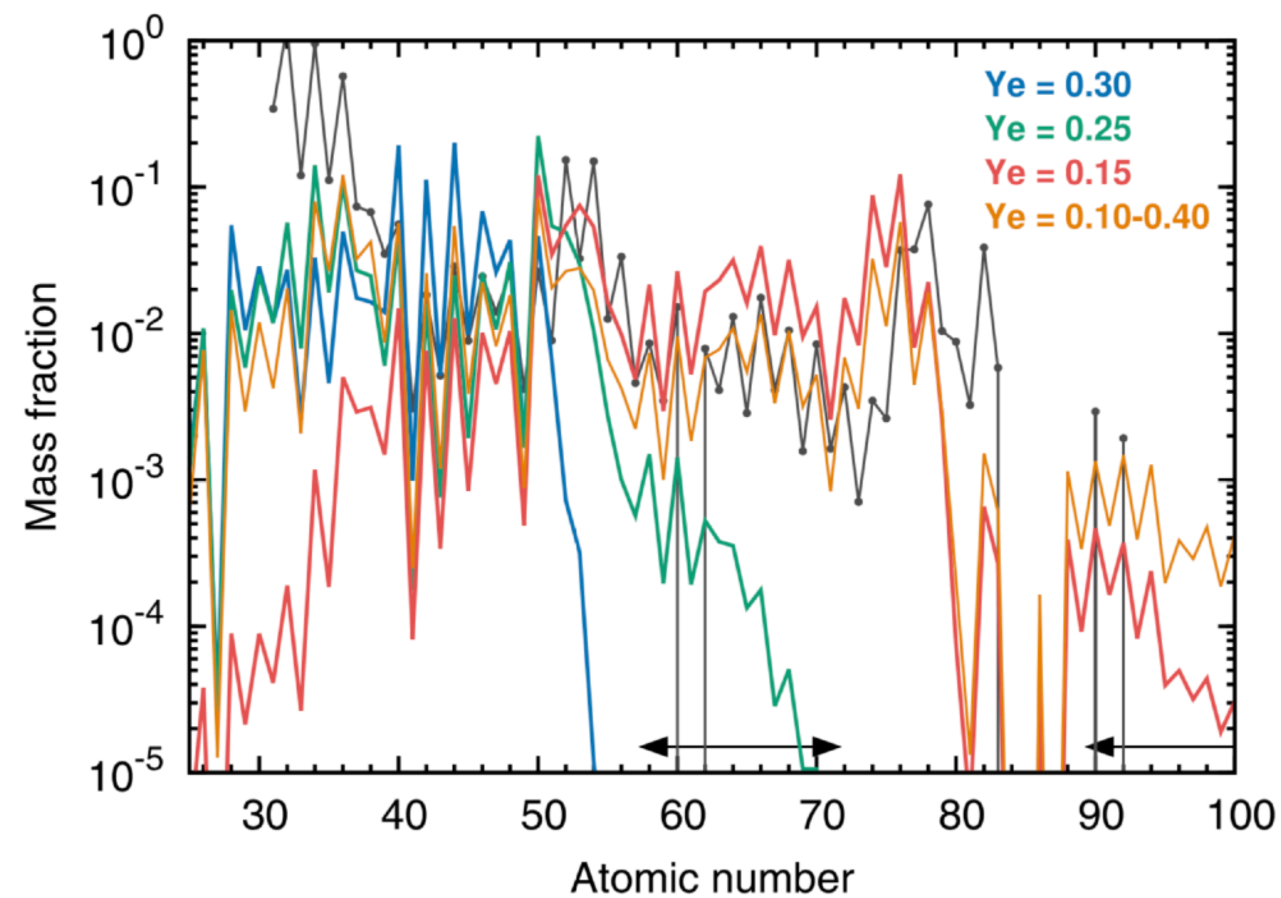
合成される元素の電子割合 (Ye) 依存

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

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



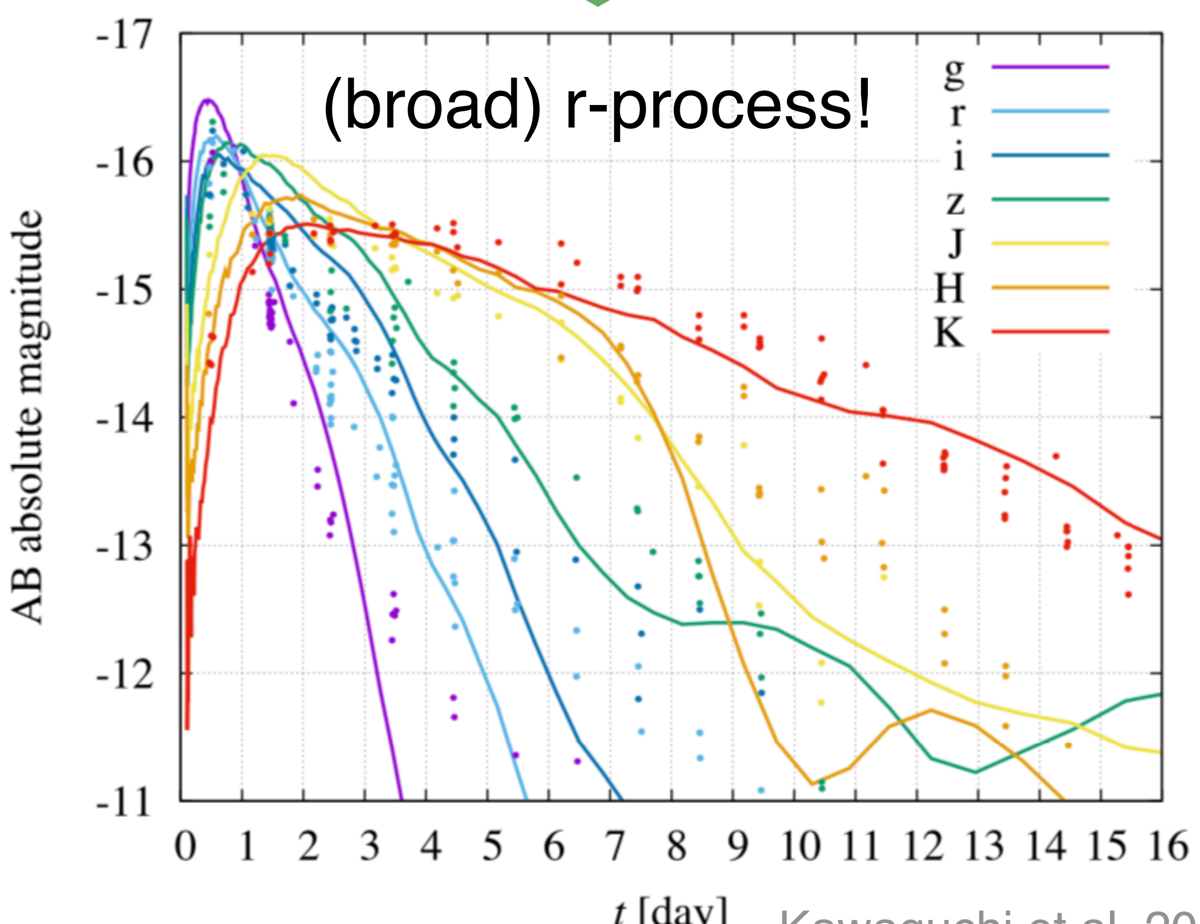
Shibata et al. 2017



Tanaka et al. 2017

GW170817/ Kilonova

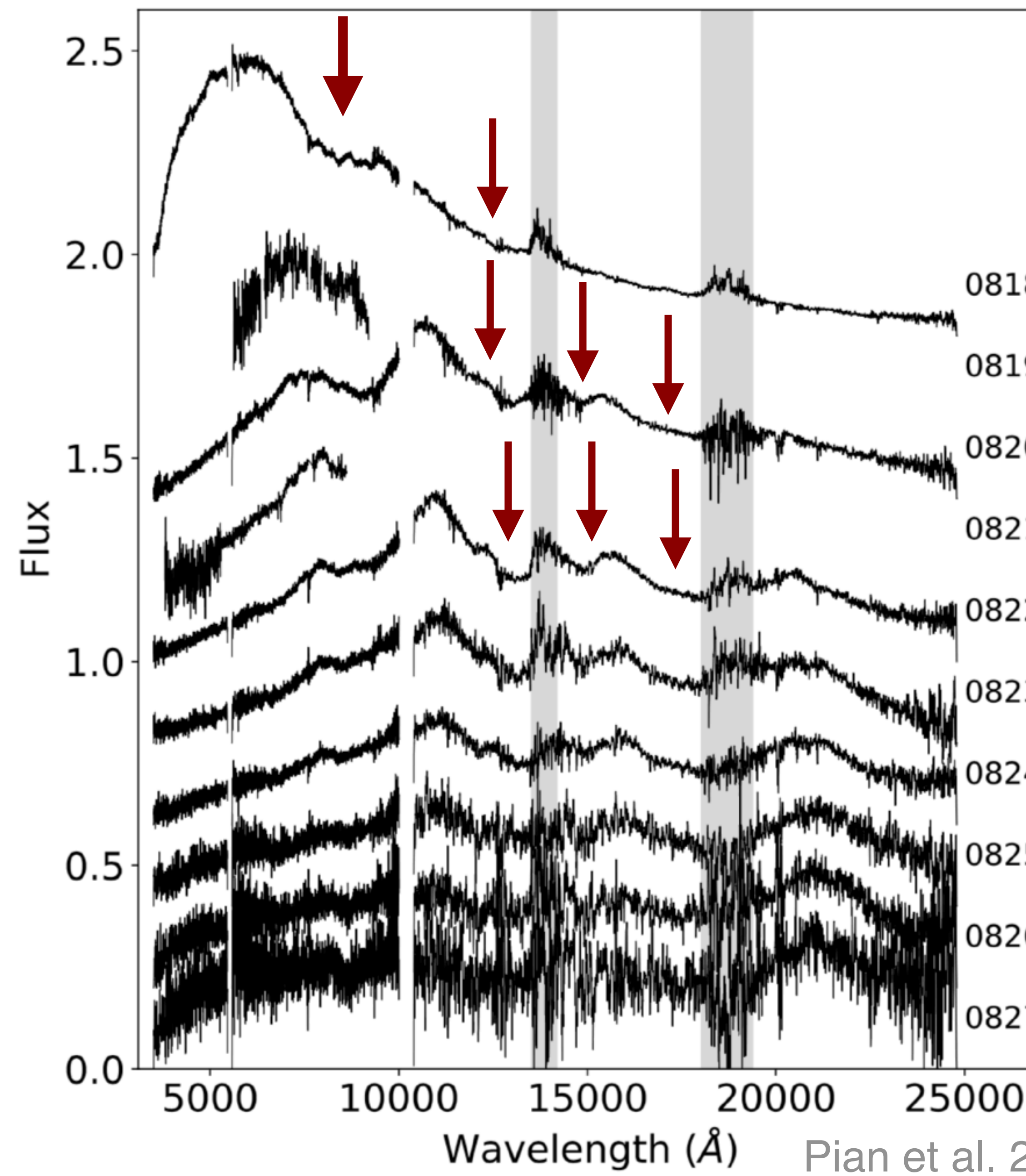
Utsumi et al. 2017



Kawaguchi et al. 2018

Which and how much elements?

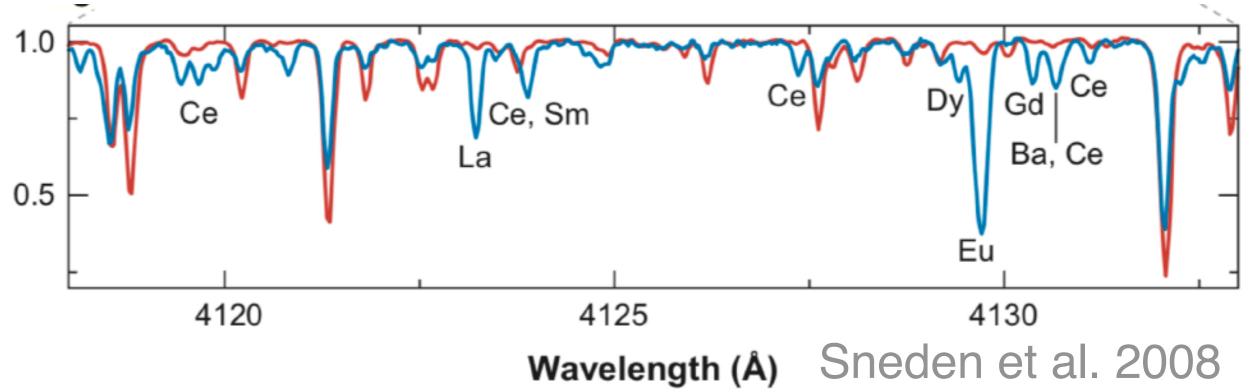
Sr II Watson et al. 2019



Pian et al. 2017

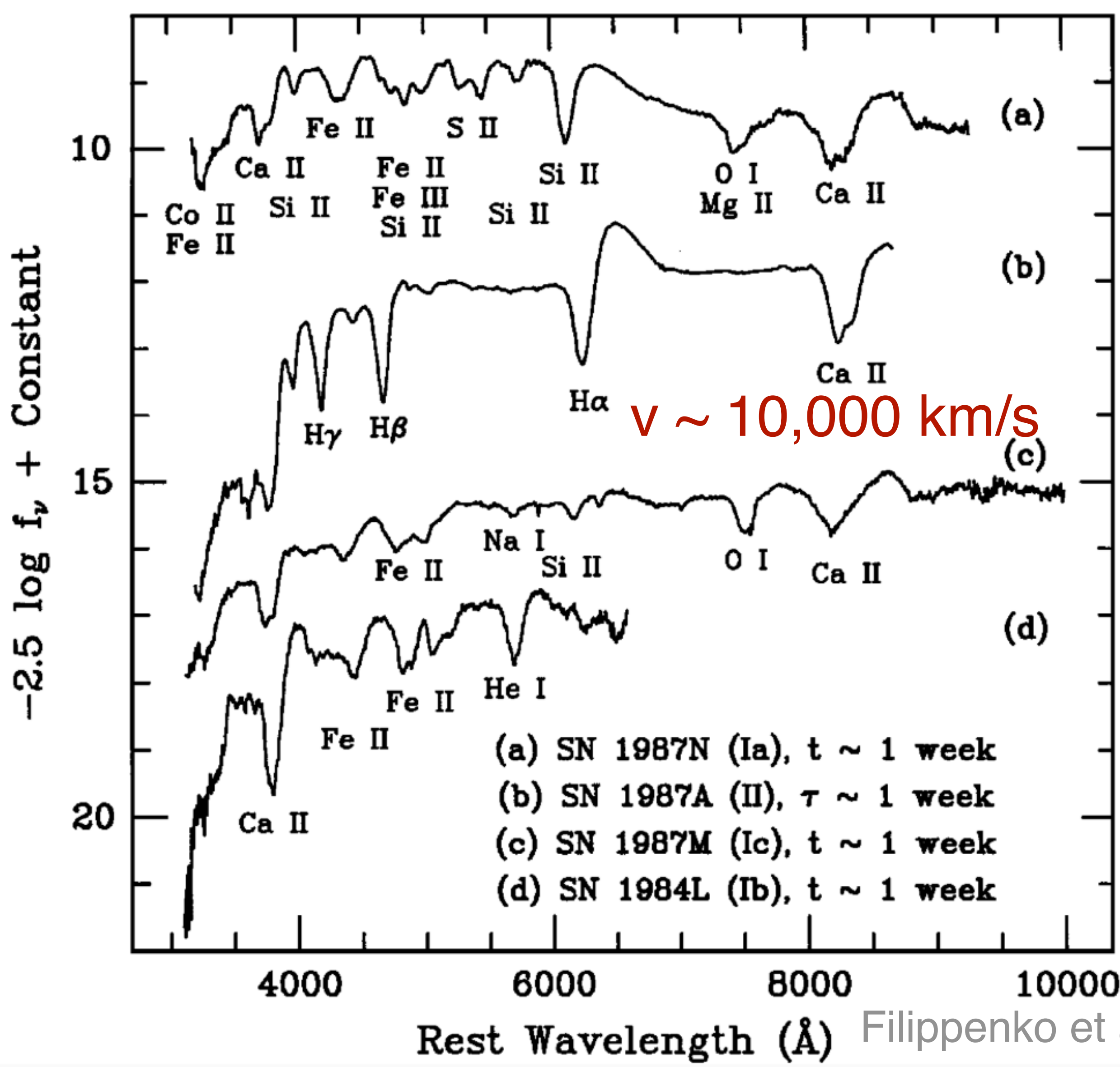
観測スペクトル

恒星



Sneden et al. 2008

超新星爆発



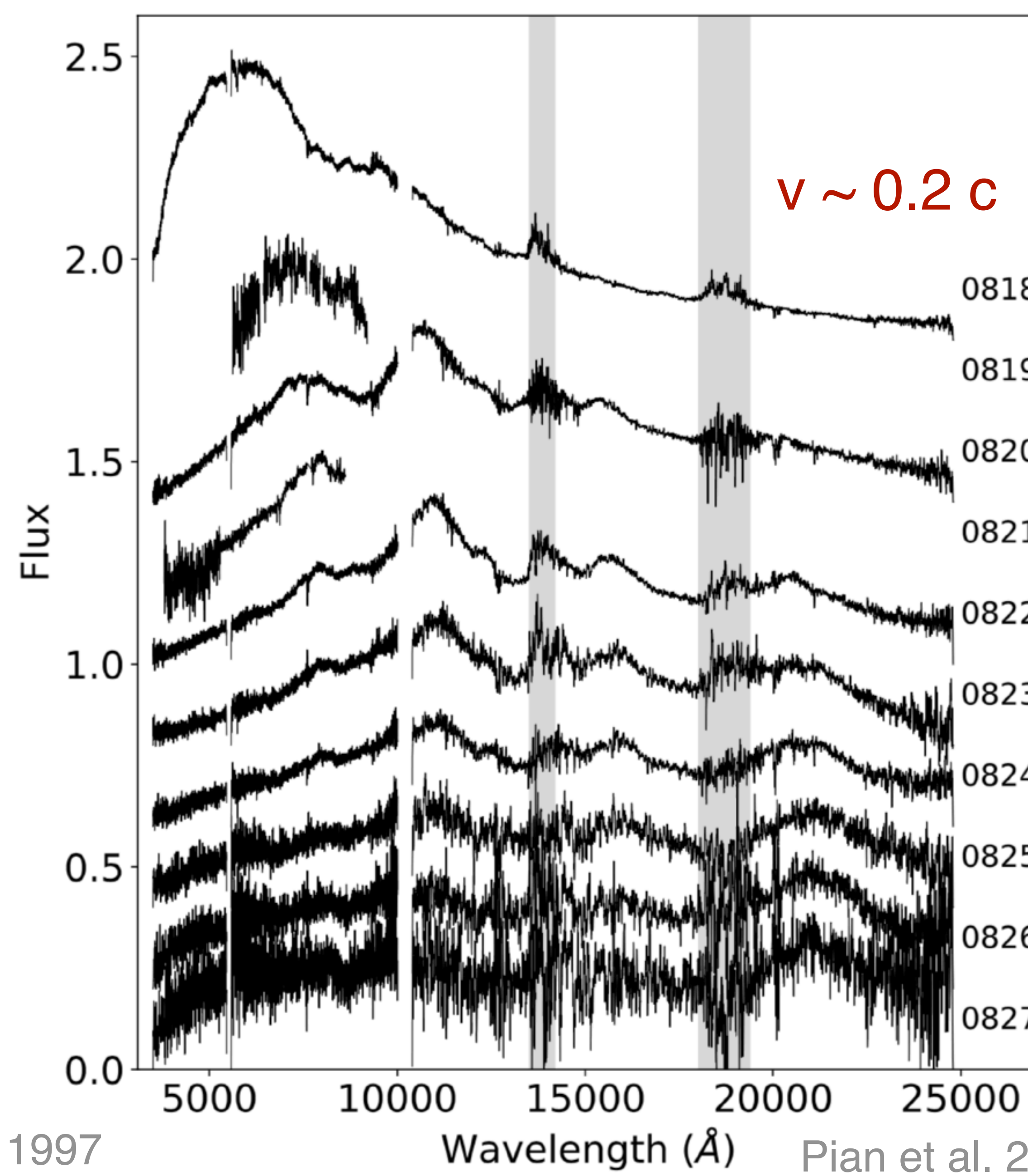
Filippenko et al. 1997

キロノバ:

(鉄より重い) 重元素ばかり

膨張速度が速い

赤外線で長時間光る



Pian et al. 2017

Motivation

元素組成

→ 元素の起源、中性子星合体の物理

スペクトルにおける元素の同定に向けて:

どの元素が強い吸収を作れるのか？

輻射輸送計算

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

- 質量: Mej = 0.03 Msun
- 速度: v = 0.05-0.3 c
- 密度構造: 1D simple power law ($\rho \propto r^{-3}$)
- 元素組成 : a multi-components free expansion model Wanajo 2018

- Line strength of bound-bound transitions

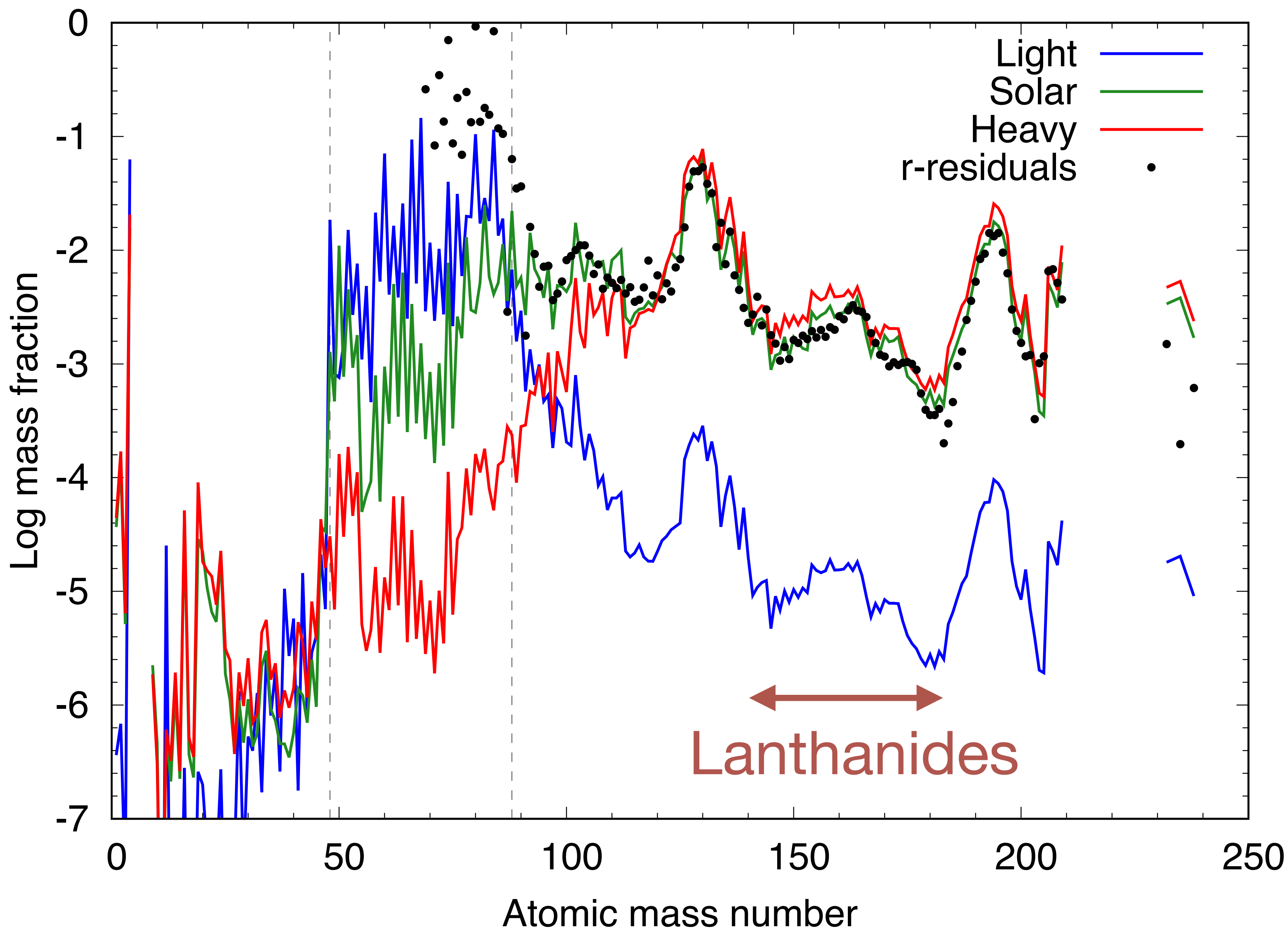
$$\tau_l = \frac{\pi e^2}{m_e c} f_l n_{i,j} t \lambda_l$$

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

*based on atomic experiments

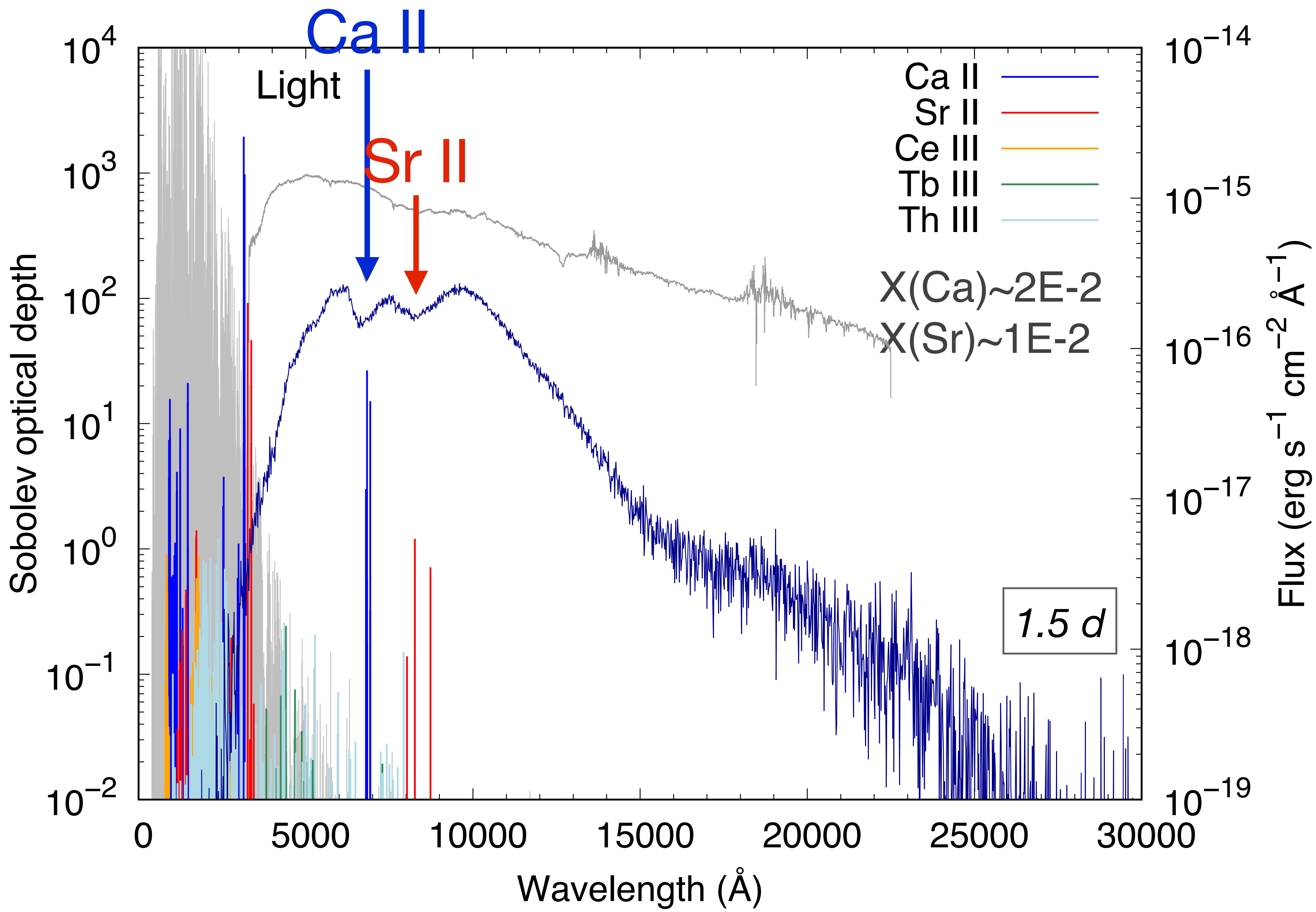
輻射輸送計算

- 元素組成 : a multi-component free expansion model   Wanajo 2018



Results: synthetic spectrum

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

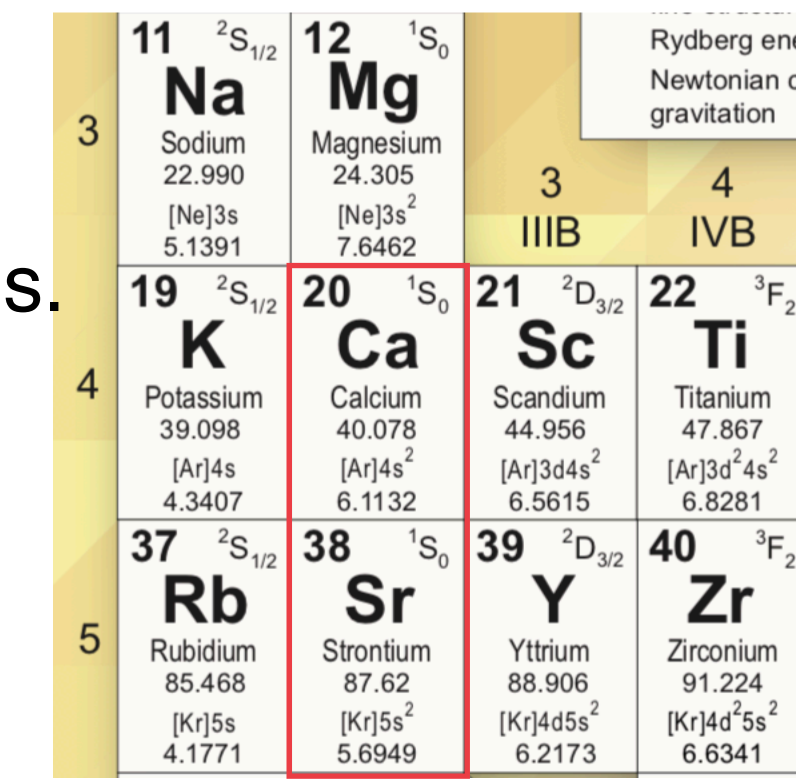


Sr II/Ca II triplet

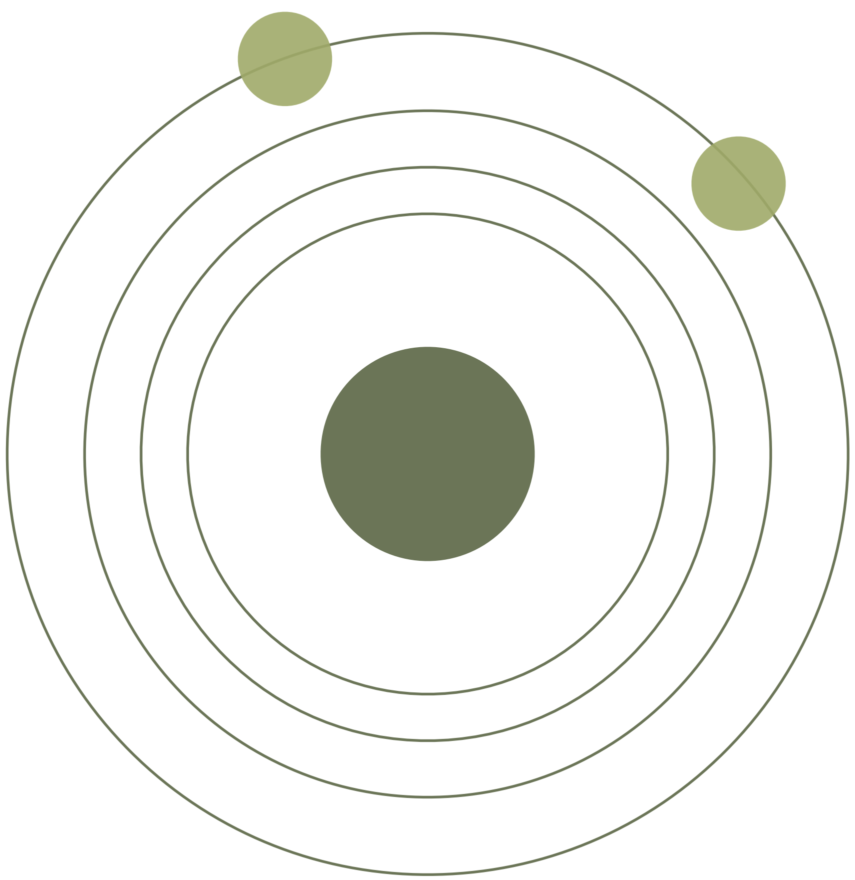
They have a similar atomic structure and transitions.

Ca II triplet $[Ar]3d\ ^2D_{\frac{5}{2},\frac{3}{2}} \longrightarrow [Ar]4p\ ^2P^o_{\frac{3}{2},\frac{1}{2}}$

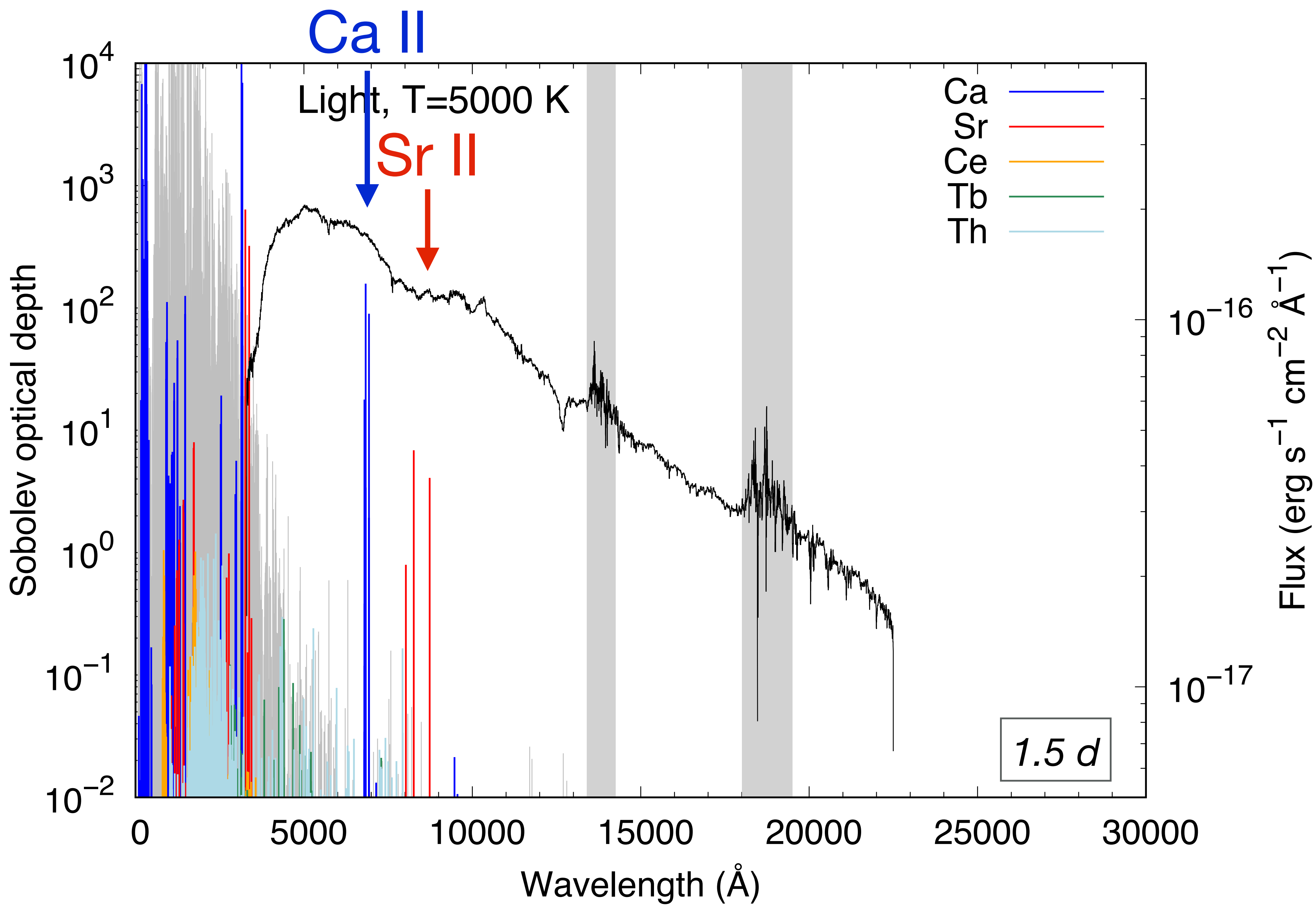
Sr II triplet $[Kr]4d\ ^2D_{\frac{5}{2},\frac{3}{2}} \longrightarrow [Kr]5p\ ^2P^o_{\frac{3}{2},\frac{1}{2}}$



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



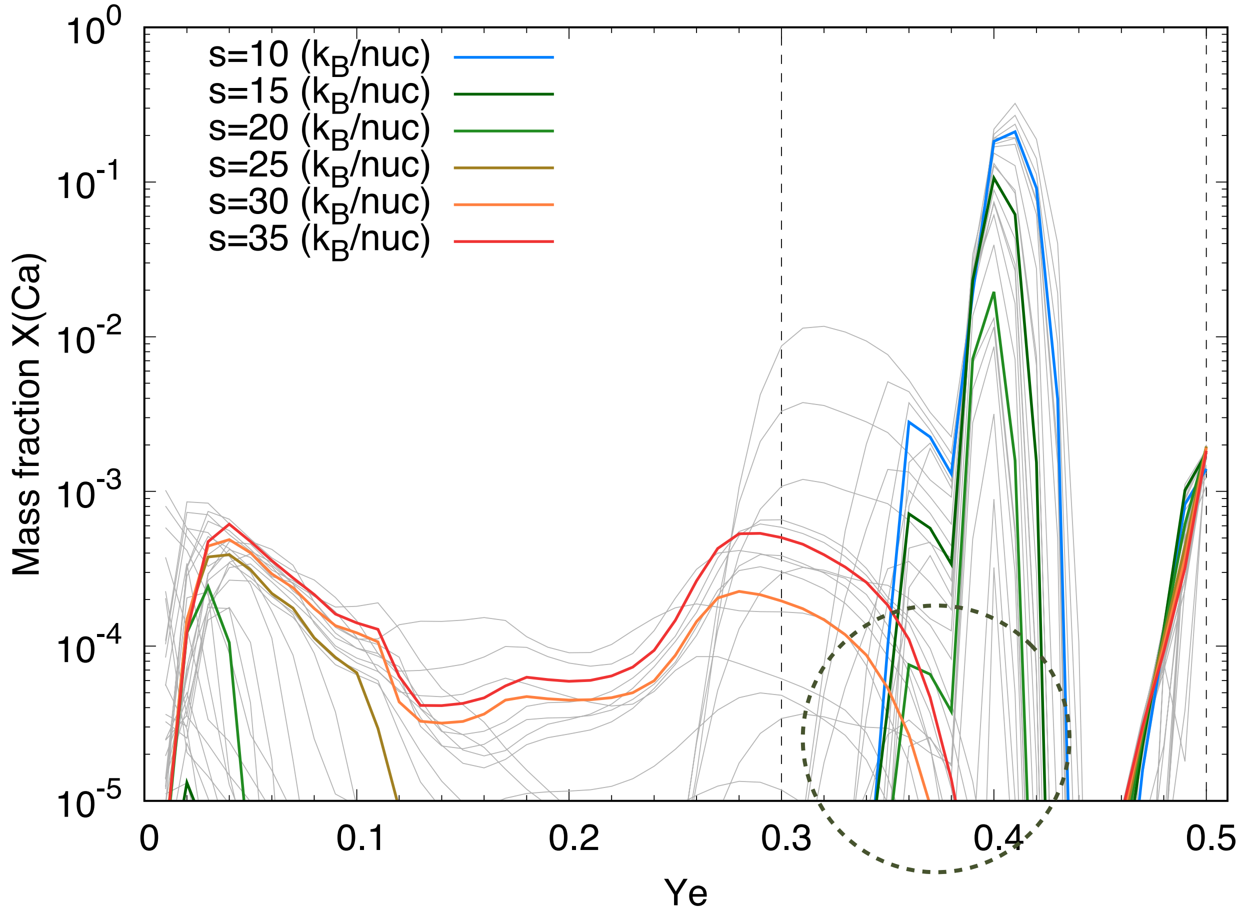
For GW170817

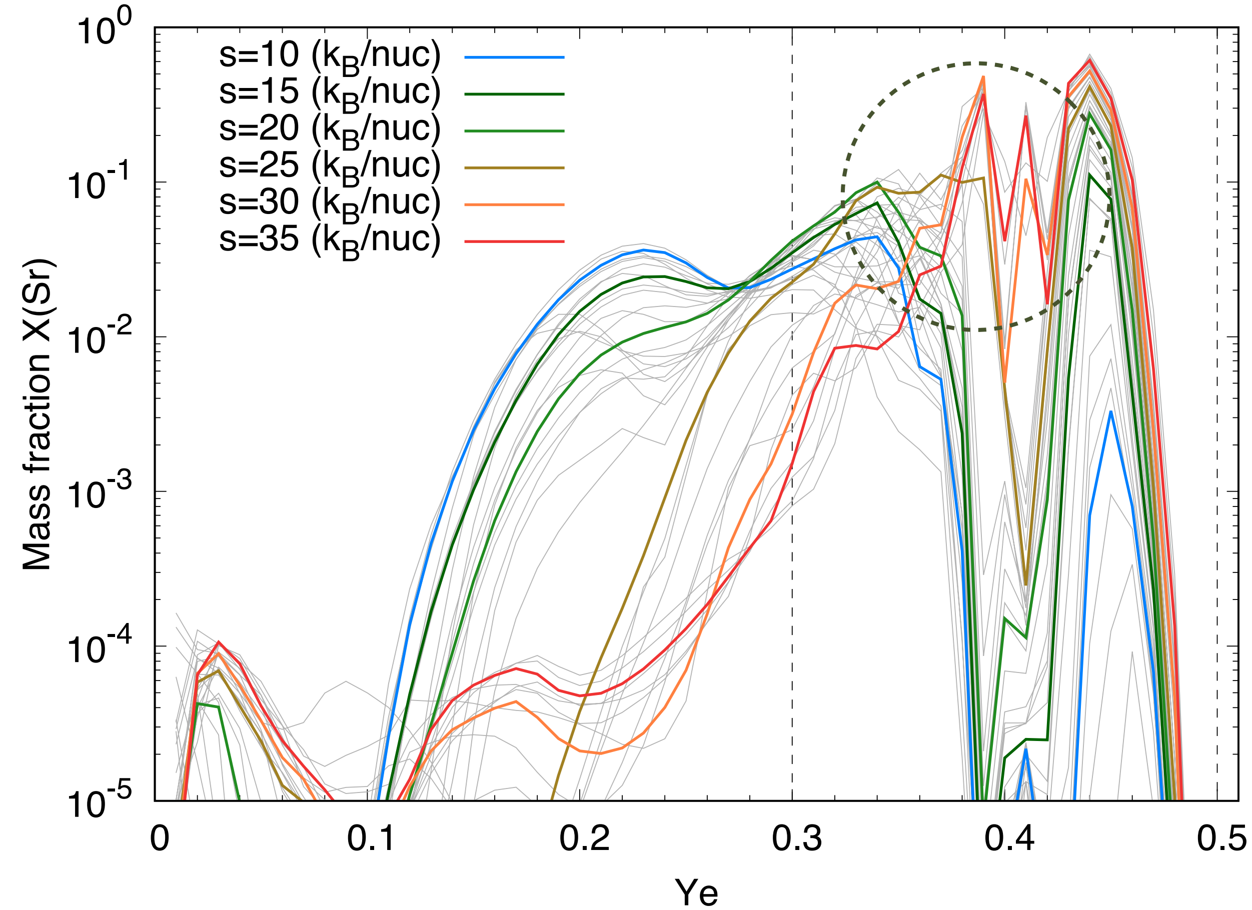


GW170817 → X(Ca)/X(Sr) < 0.002

Physical conditions

color: v=0.2c & different entropies





X(Ca)/X(Sr) < 0.002

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

近赤外線における吸収線

In the λ < 10000 A:

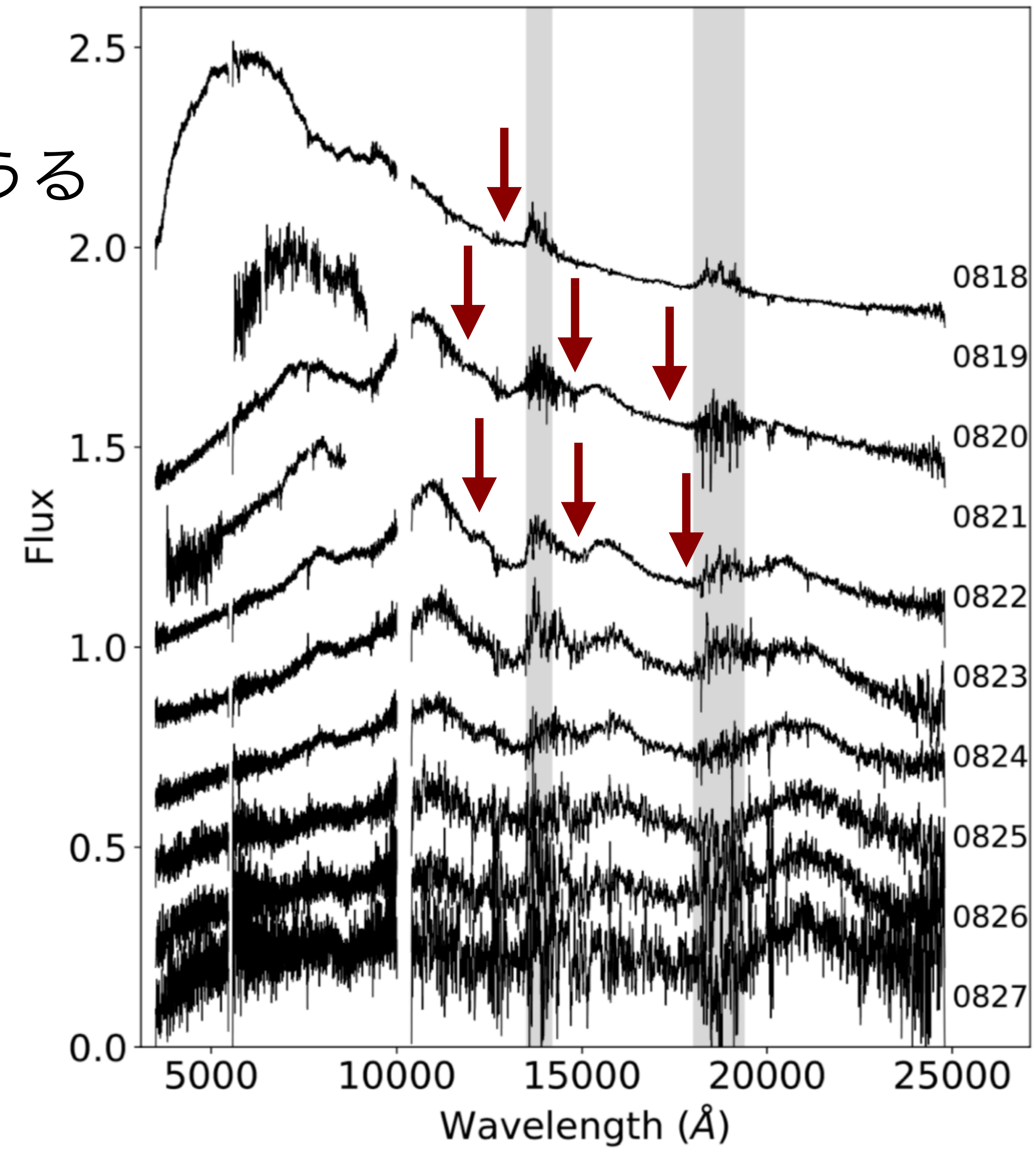
- Sr IIとCa IIが強い吸収線を作りうる
  (high-Ye tracer)

→ GW1701817へ制限

<u>赤外線の吸収線を同定できるか？</u>

*Problem:
lack of accurate atomic data

- Spectral features must be affected
  by accurate atomic data



Pian et al. 2017

Summary

- The origin of elements, physics of NS mergers
  - Identification in spectra is direct way to find synthesized elements.
  - Which elements can produce absorption features?

  - 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 lanthanides.

  - NIR lines are important for understanding of NSM.

- Observational properties of high energy explosion is determined by (micro) atomic physics.