EMMI+IReNA Workshop “Remnants of neutron-star mergers
— Connecting hydrodynamics models to nuclear, neutrino, and kilonovae physics”
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# Finding signatures of heavy elements in kilonova photospheric spectra

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Domoto et al. 2021, ApJ, 913, 26
Domoto et al. 2022, ApJ in press, arXiv:2206.04232

# Contents

- Why is studying spectra important?
- How can we study kilonova spectra?
- What can be improved?

# Contents

- Why is studying spectra important?

  It is challenging but needed to understand our Universe

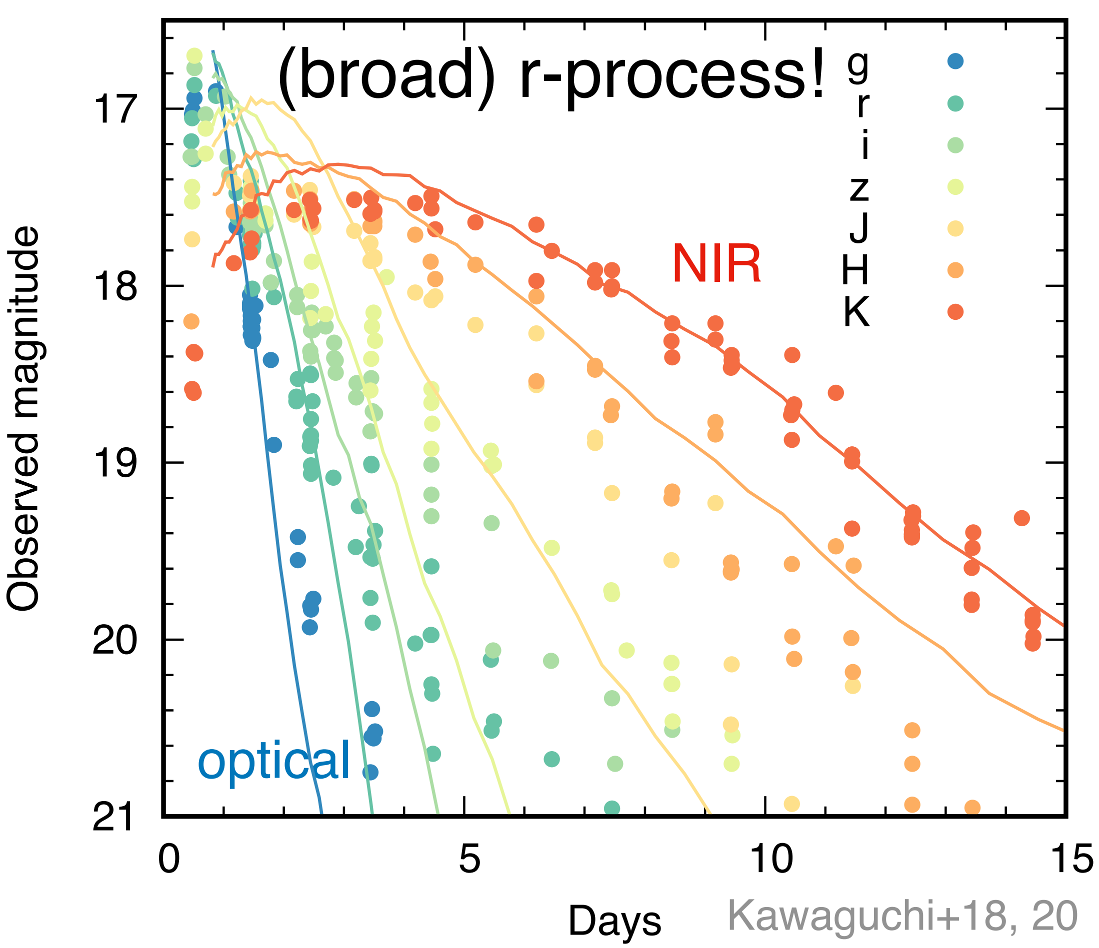
- How can we study kilonova spectra?

- What can be improved?

# Kilonova in GW170817

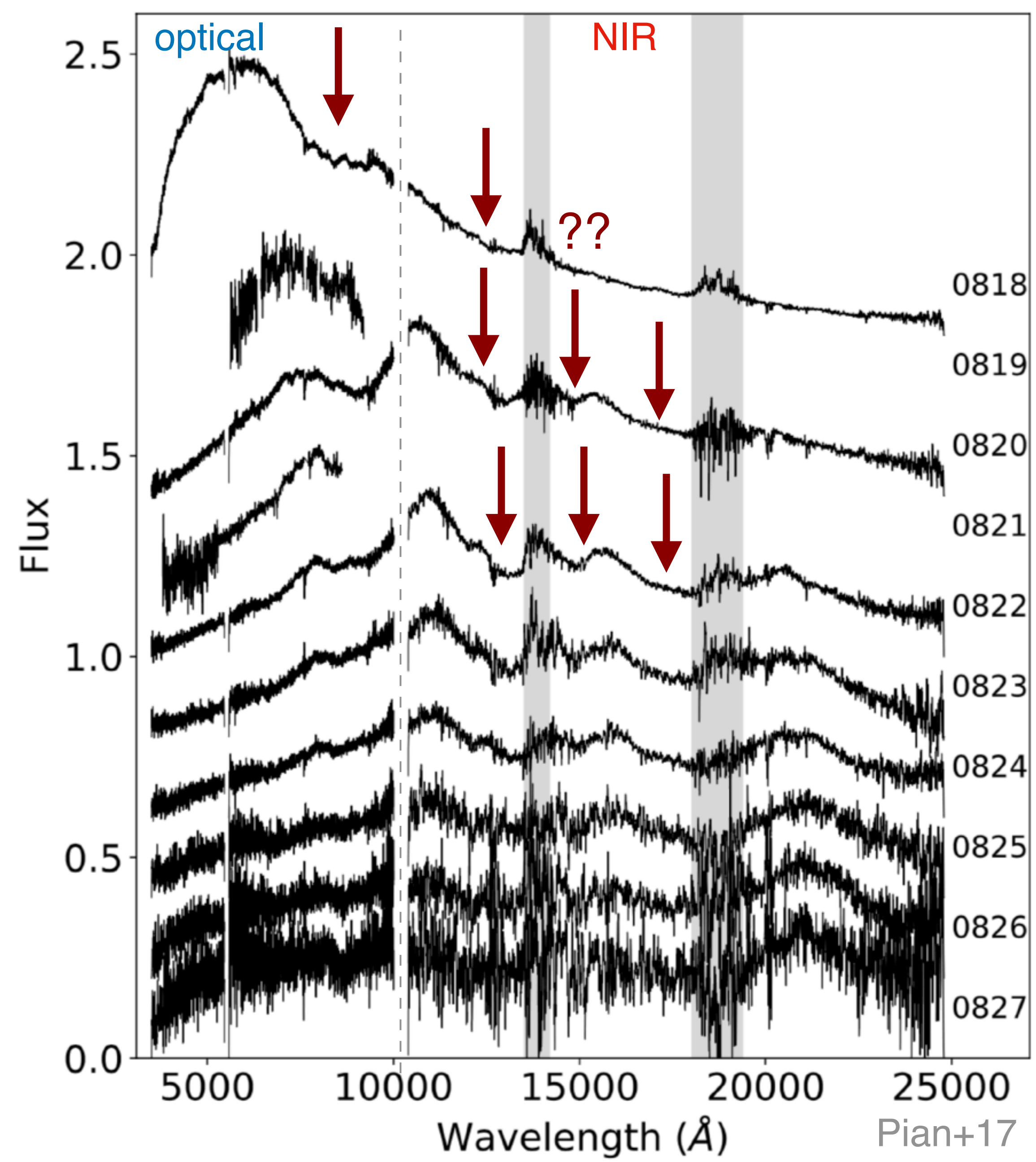
e.g., Arcavi+17, Smartt+17, Kasen+17, Kilpatrick+17, Perego+17, Rosswog+17, Shibata+17, Tanaka+17, Toroja+17, …


Utsumi+17




Kawaguchi+18, 20

## Which and how much elements?

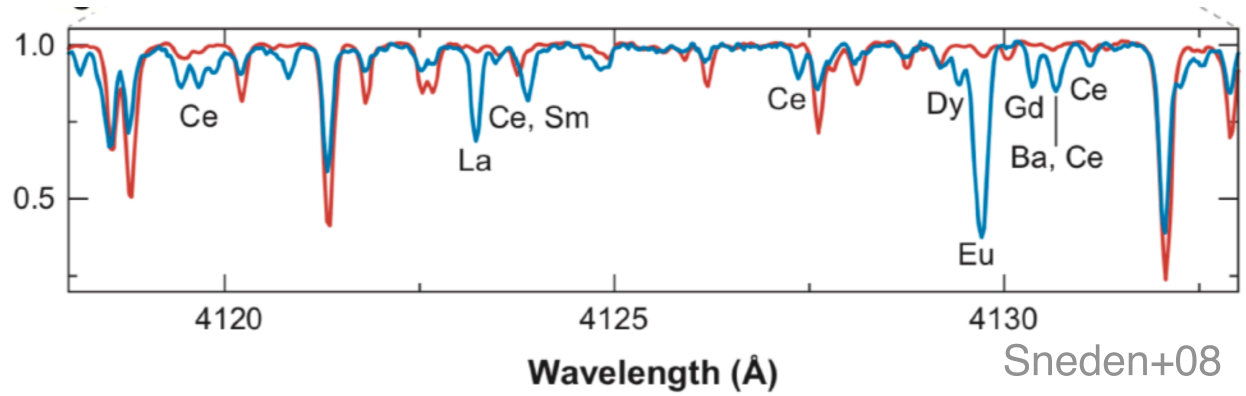



Watson+19, Domoto+21, Gillanders+22

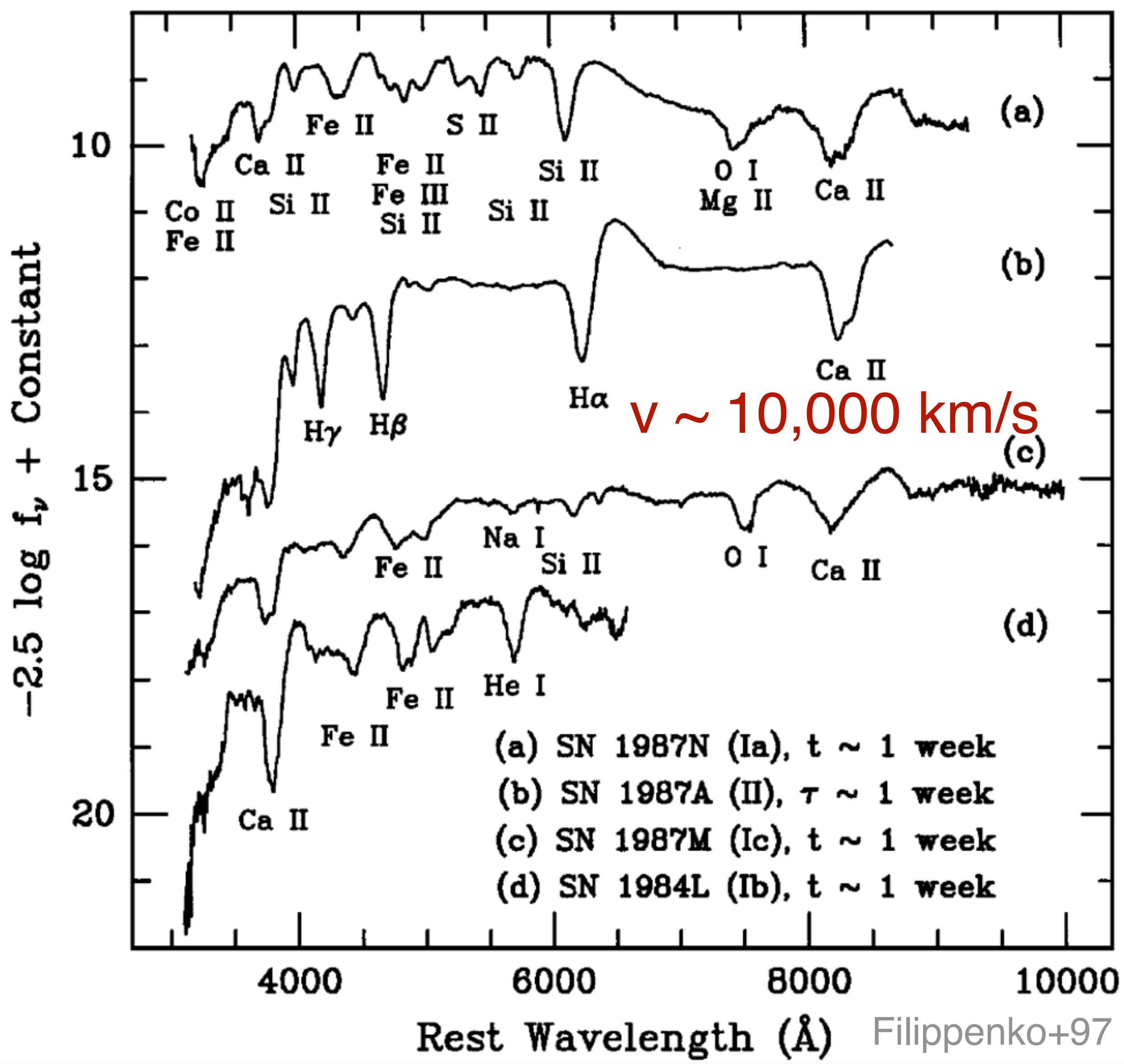
Pian+17

# What is difficult?

Star




Supernova

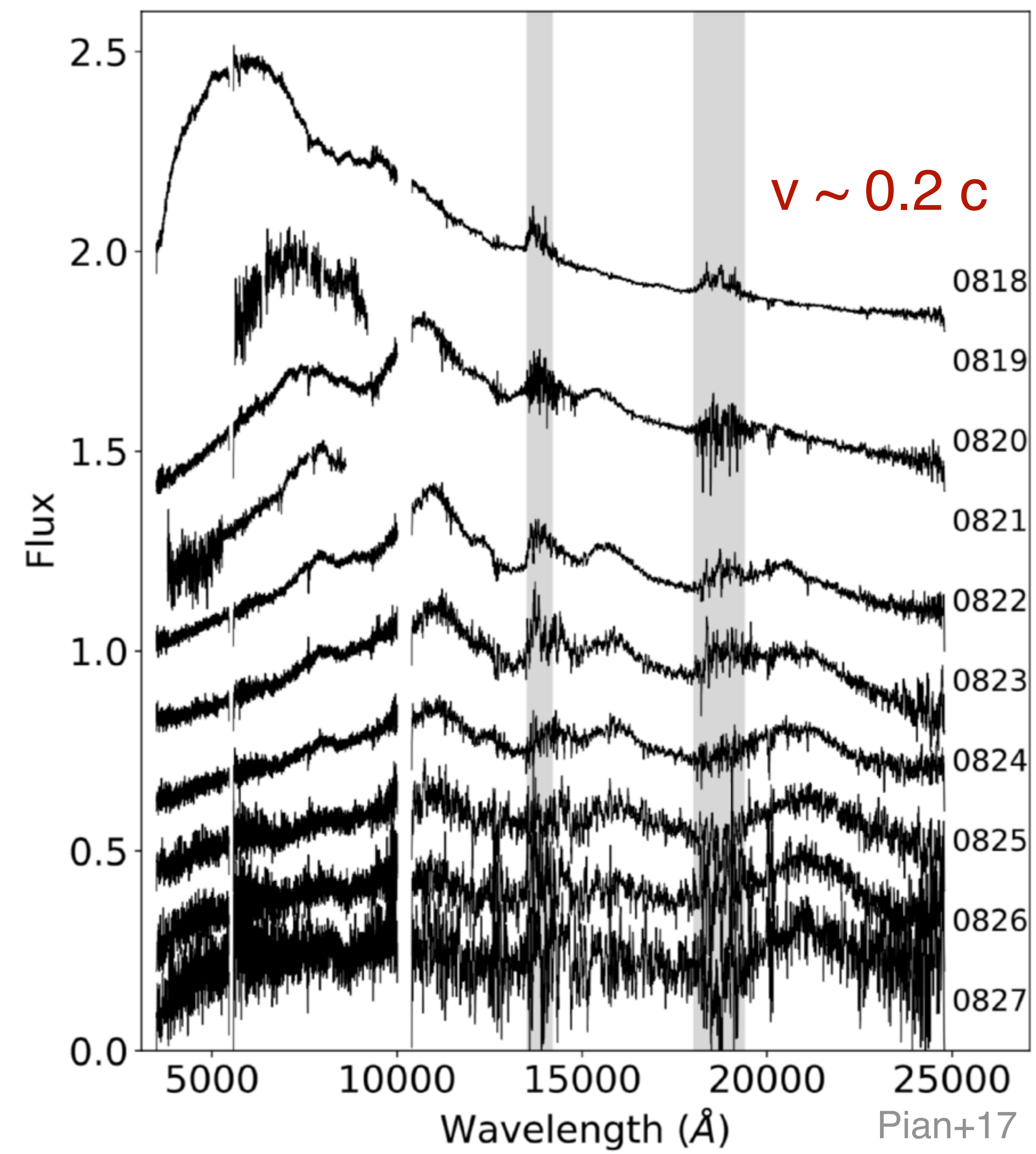



Kilonova:

<u>Fast expansion velocity</u>

<u>Heavy elements</u> (beyond iron)

More luminous <u>in near infrared</u>



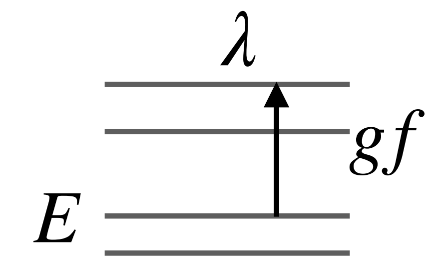
# What is needed: atomic data

## Difficulty on study of kilonova spectra

Line strength: “Sobolev optical depth”

*radial (expanding) v ≫ thermal v

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




| | Experimentally calibrated list<br>*spectroscopically accurate<br>e.g., NIST, VALD, DREAM | Theoretically constructed list<br>*high completeness<br>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 — Light curve calculations

# Contents

- Why is studying spectra important?
- How can we study kilonova spectra?
  Domoto et al. 2021; 2022
- What can be improved?

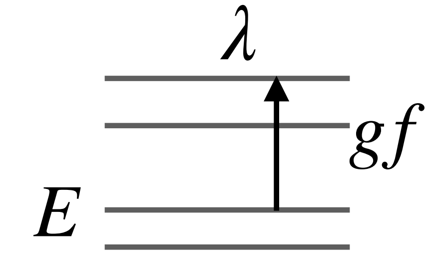
# Strategy

## To overcome the situation on data

Line strength: “Sobolev optical depth”

*radial (expanding) v ≫ thermal v

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

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|---|---|---|
| Transition wavelength | ✔ | low accuracy |
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Combining advantages

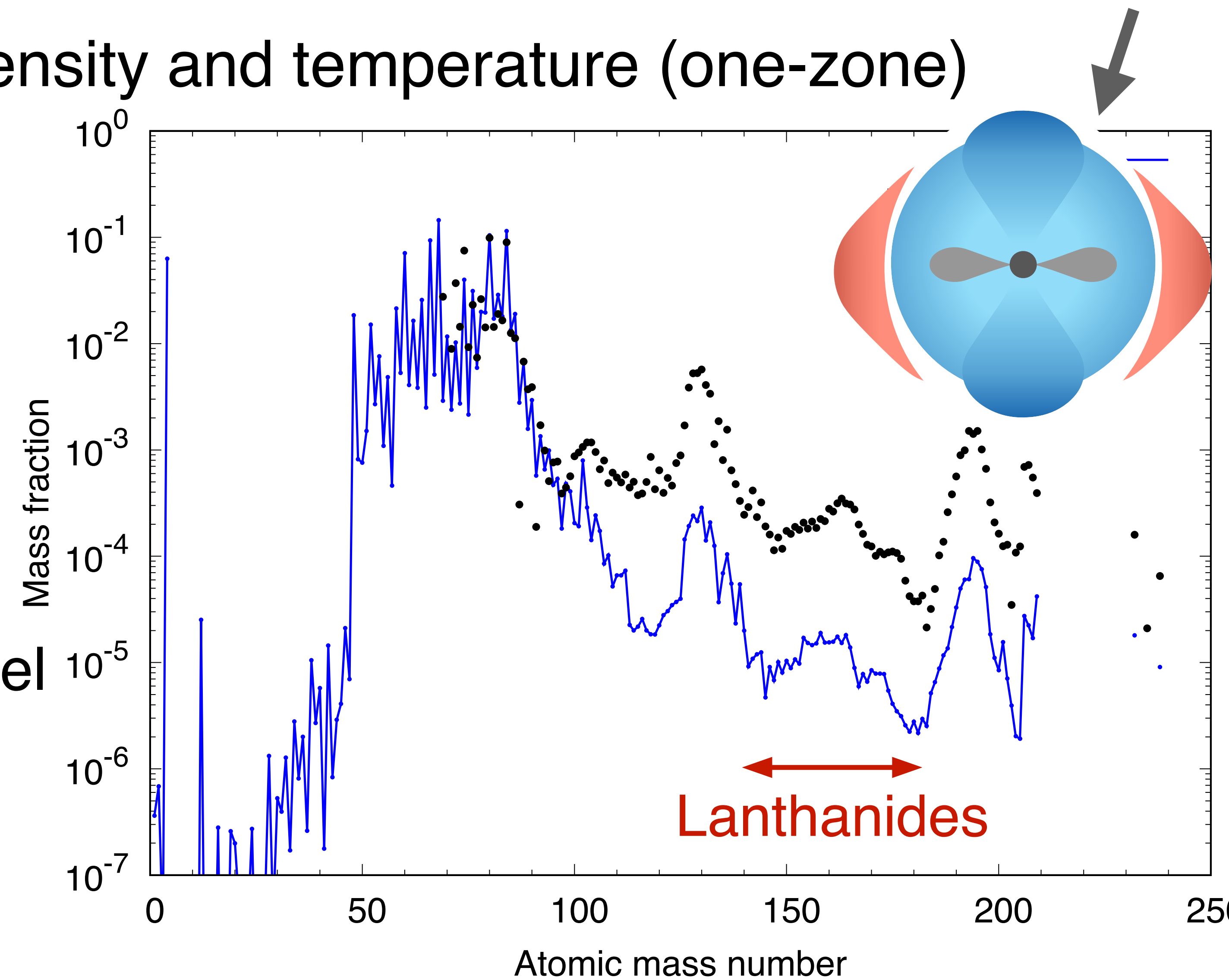
# Systematic calculation of line strength

Find which species produce strong absorption

Calculate line strength at typical density and temperature (one-zone)

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

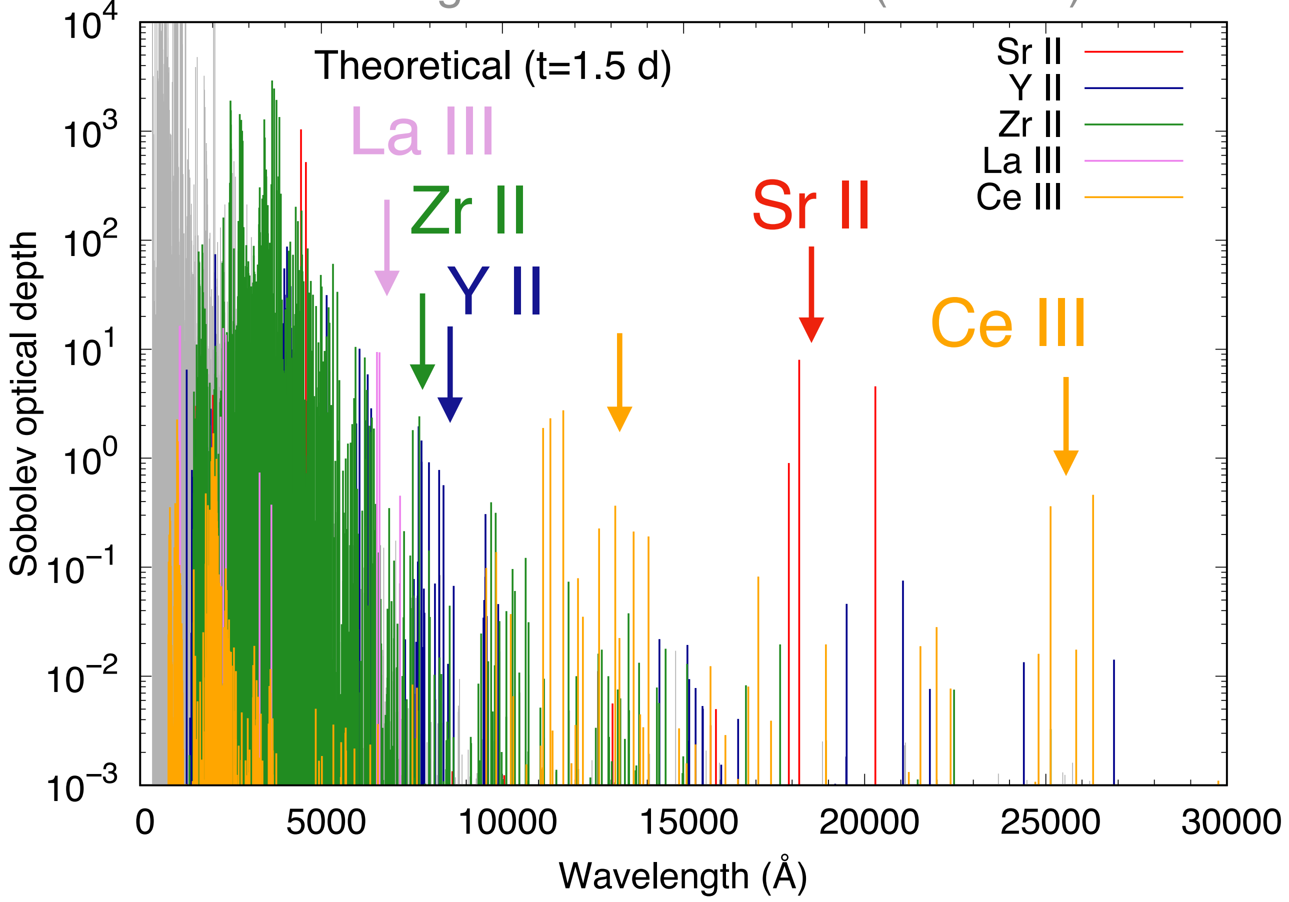
- Atomic data: theoretical line list
  Tanaka+20
- Abundance: solar-r-like pattern model
  Wanajo 18
- Assuming LTE



# Candidate species

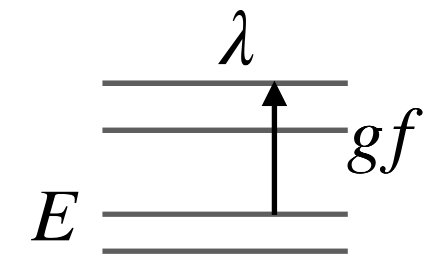
$\rho = 10^{-14}$ g cm$^{-3}$, $T = 5000$ K at t=1.5 d

using theoretical line list (Z=30-88)




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

# Energy level calibration

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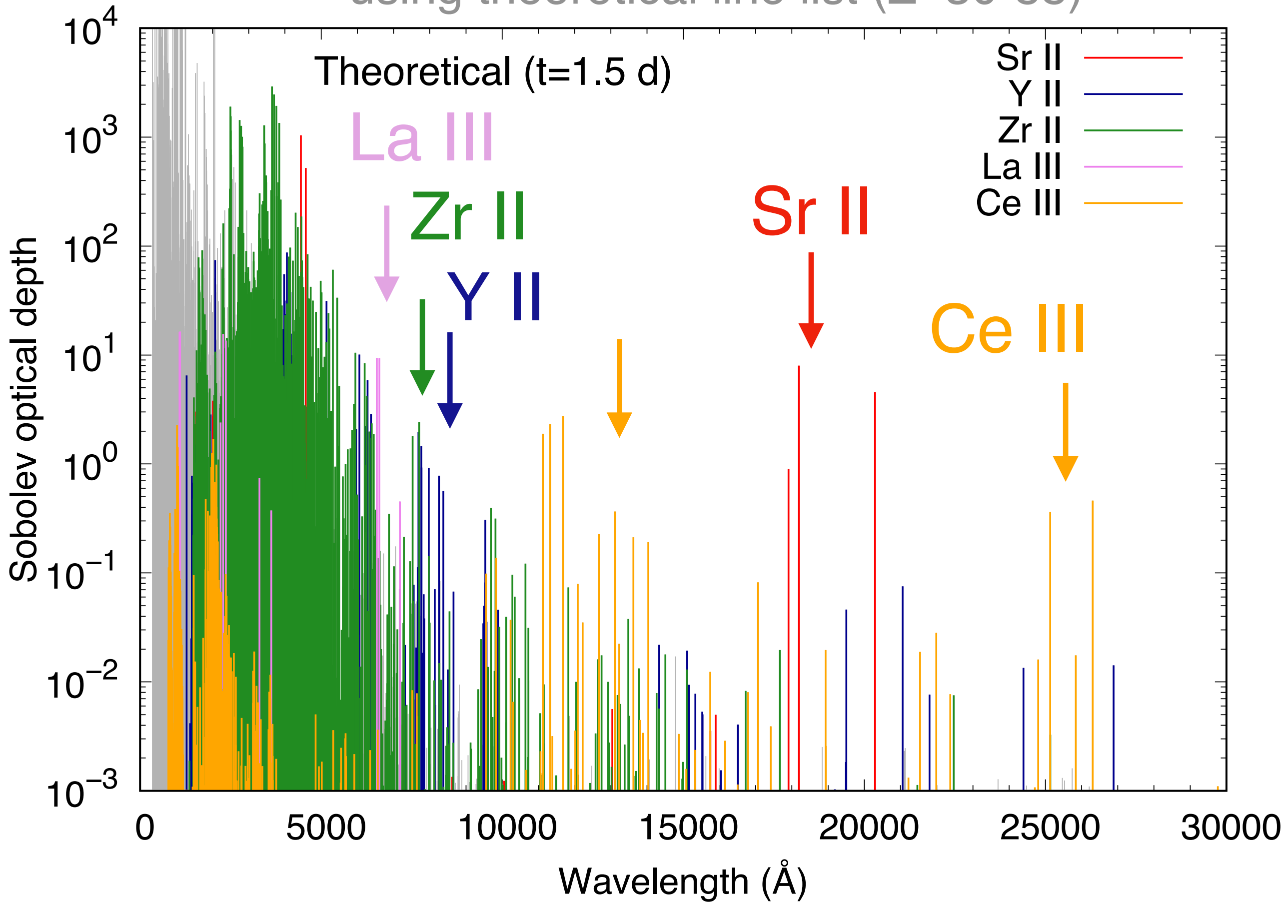
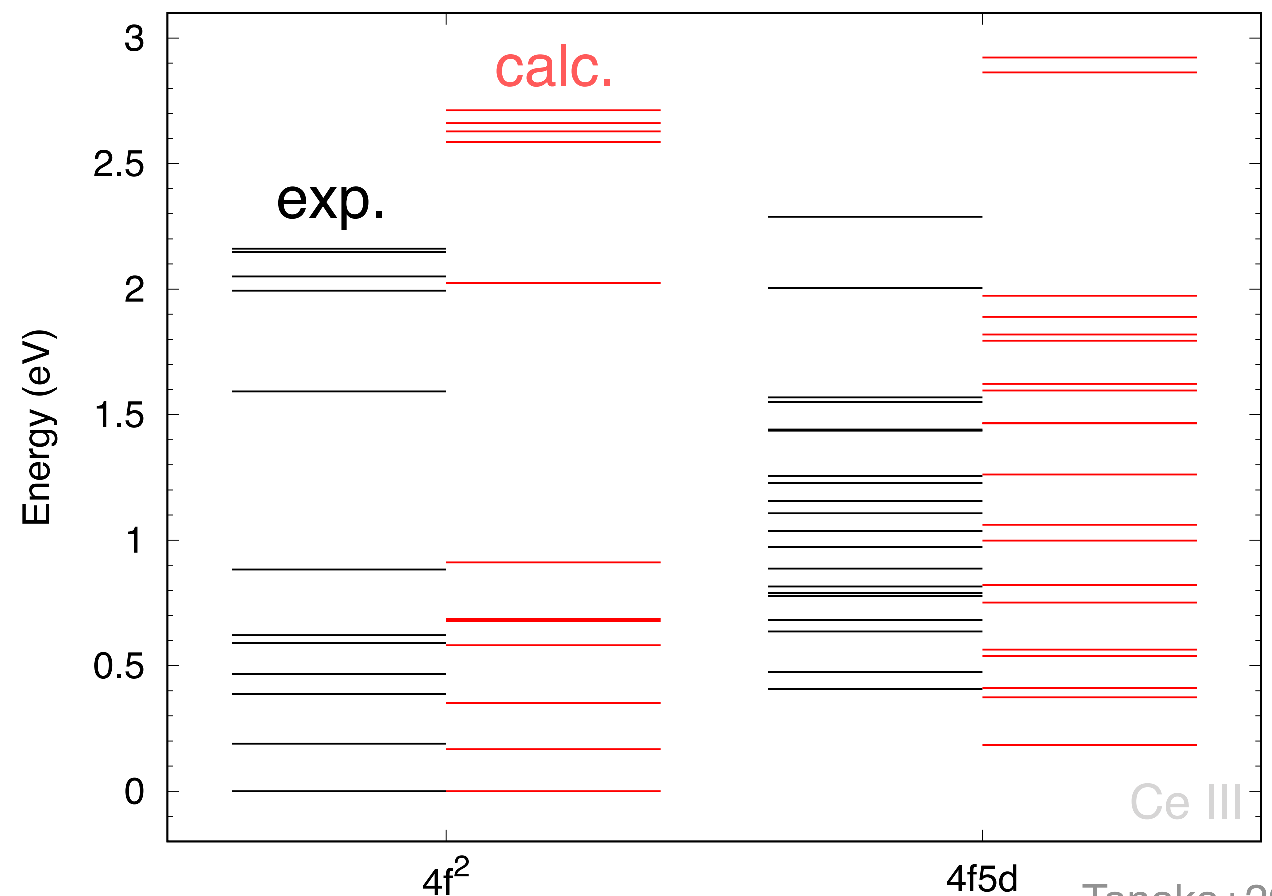



Tanaka+20

Calibrate energy levels with experimental data and find λ

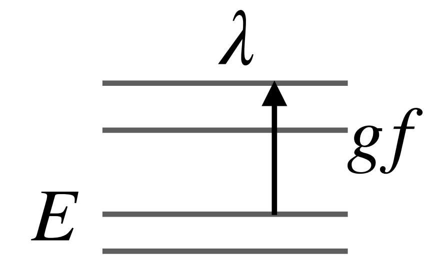
$$\lambda = \frac{hc}{\Delta E}$$

LSJ code (Gaigalas+04), NIST Atomic Spectra Database

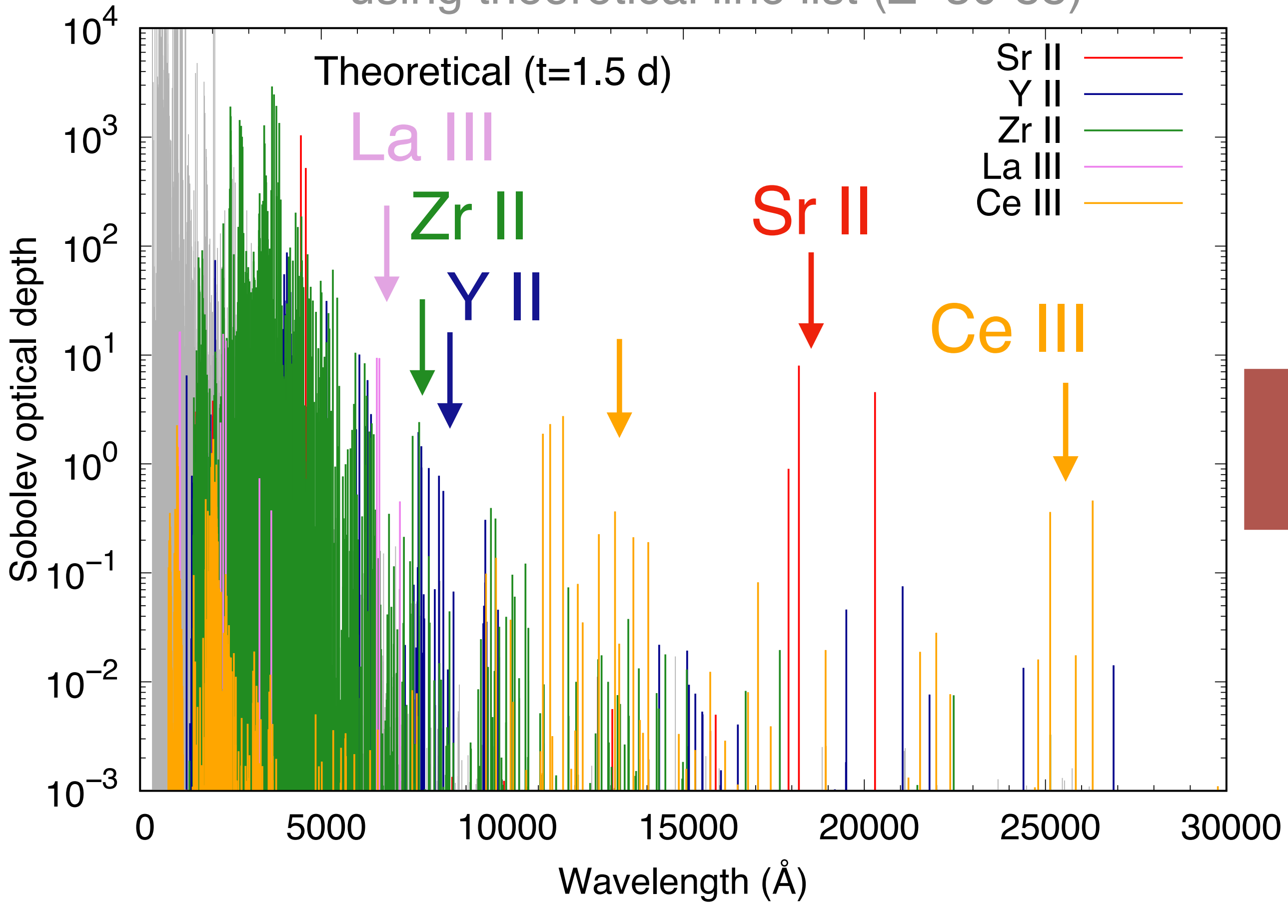
- Adopt theoretical transition probabilities if they are unknown experimentally

# Construction of hybrid line list

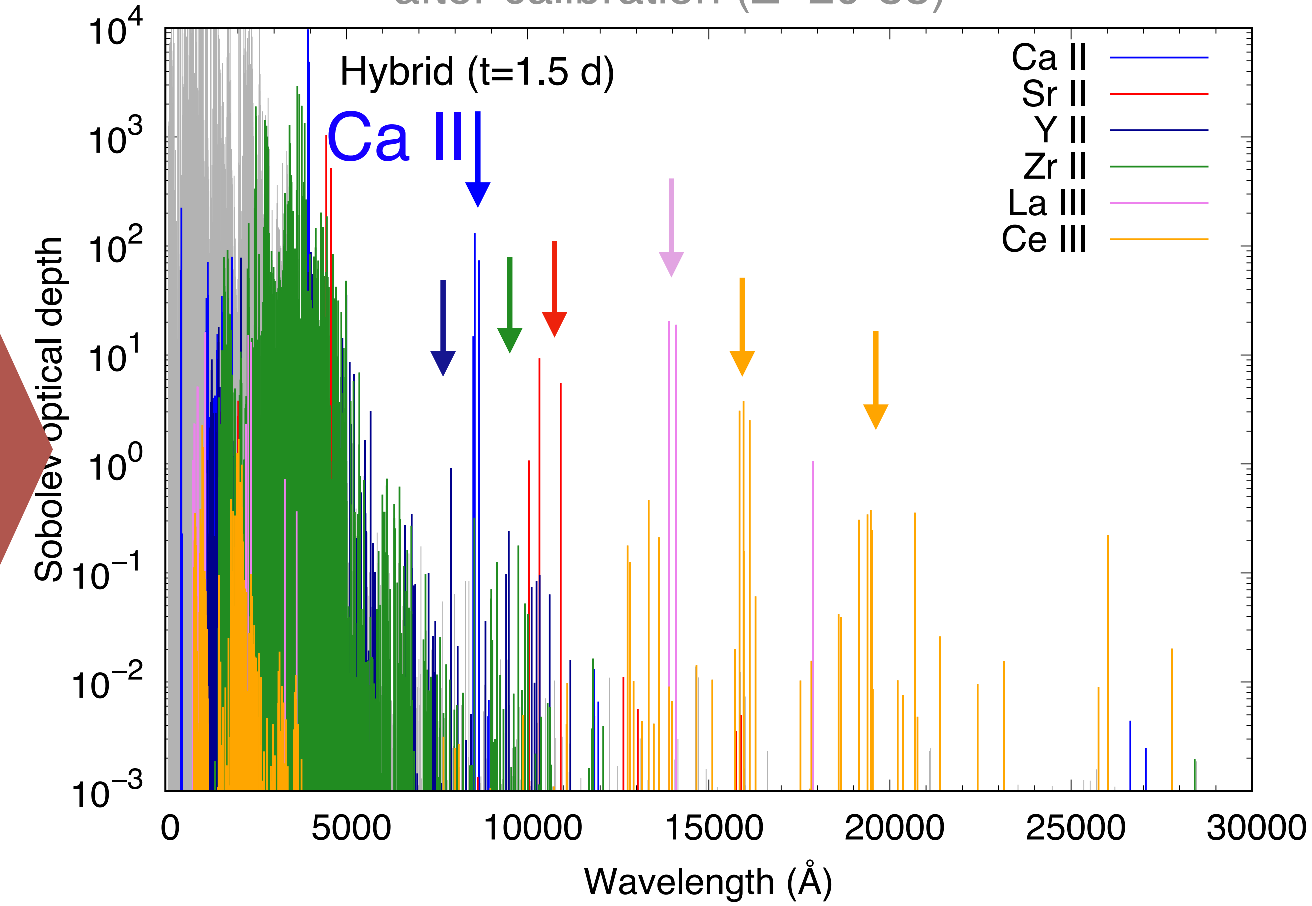
$\rho = 10^{-14}$ g cm$^{-3}$, $T = 5000$ K at t=1.5 d




using theoretical line list (Z=30-88)




after calibration (Z=20-88)




Transition probabilities of La III/Ce III lines are taken from theoretical values

=> "experimentally accurate" strong transitions
+ theoretically constructed weak transitions

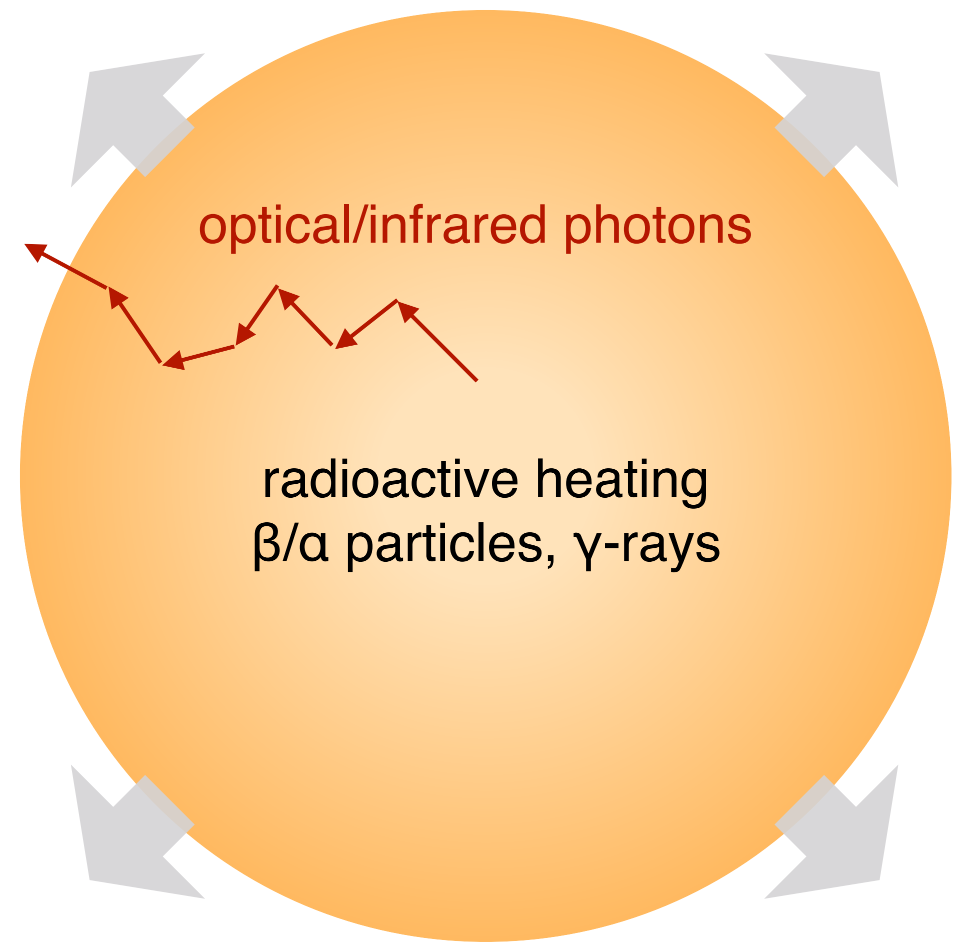
# Radiative transfer simulations

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 (homologous distribution)

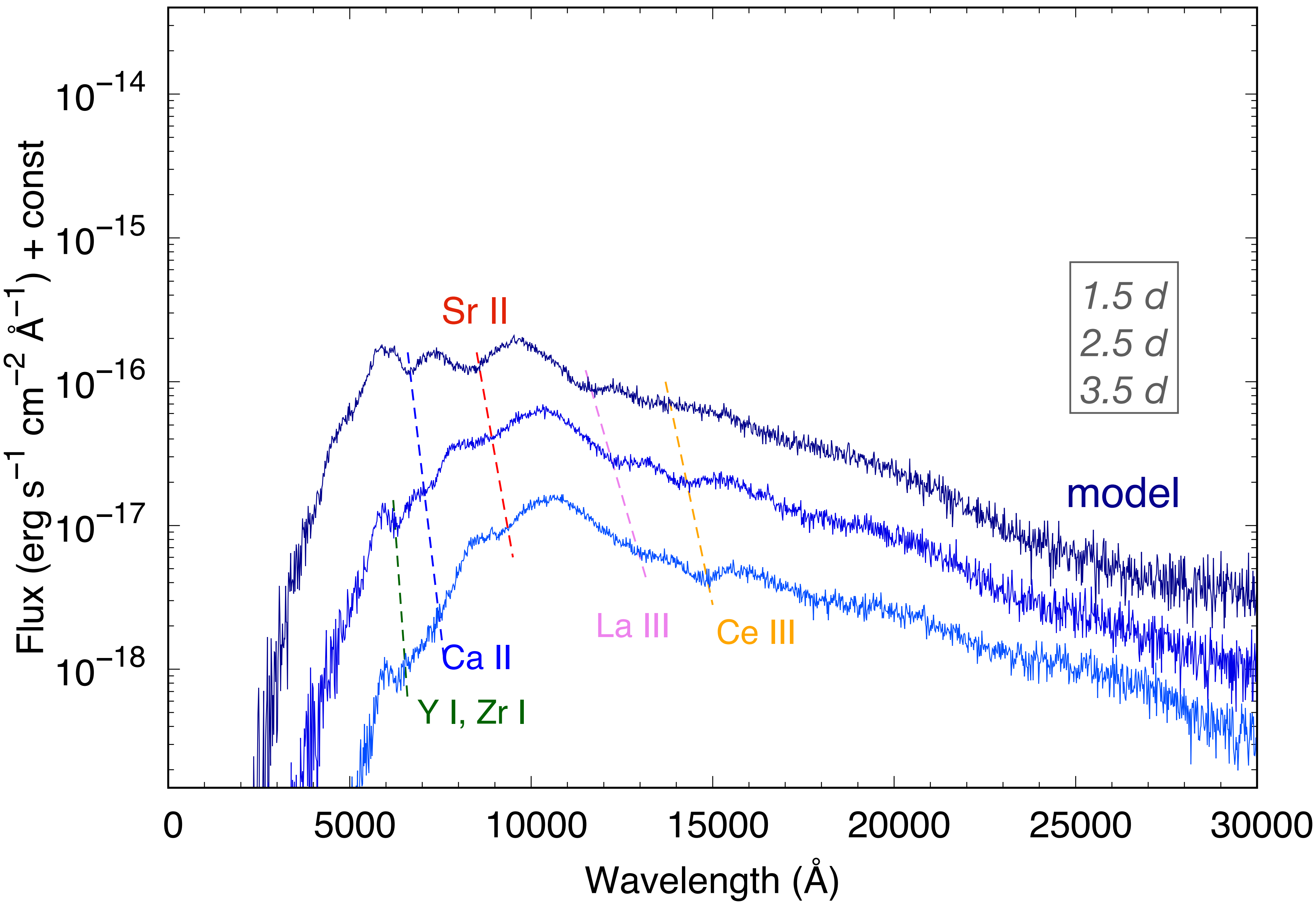



Ionization/population:
LTE (Saha eq. + Boltzmann dist.)

Atomic data: new hybrid line list

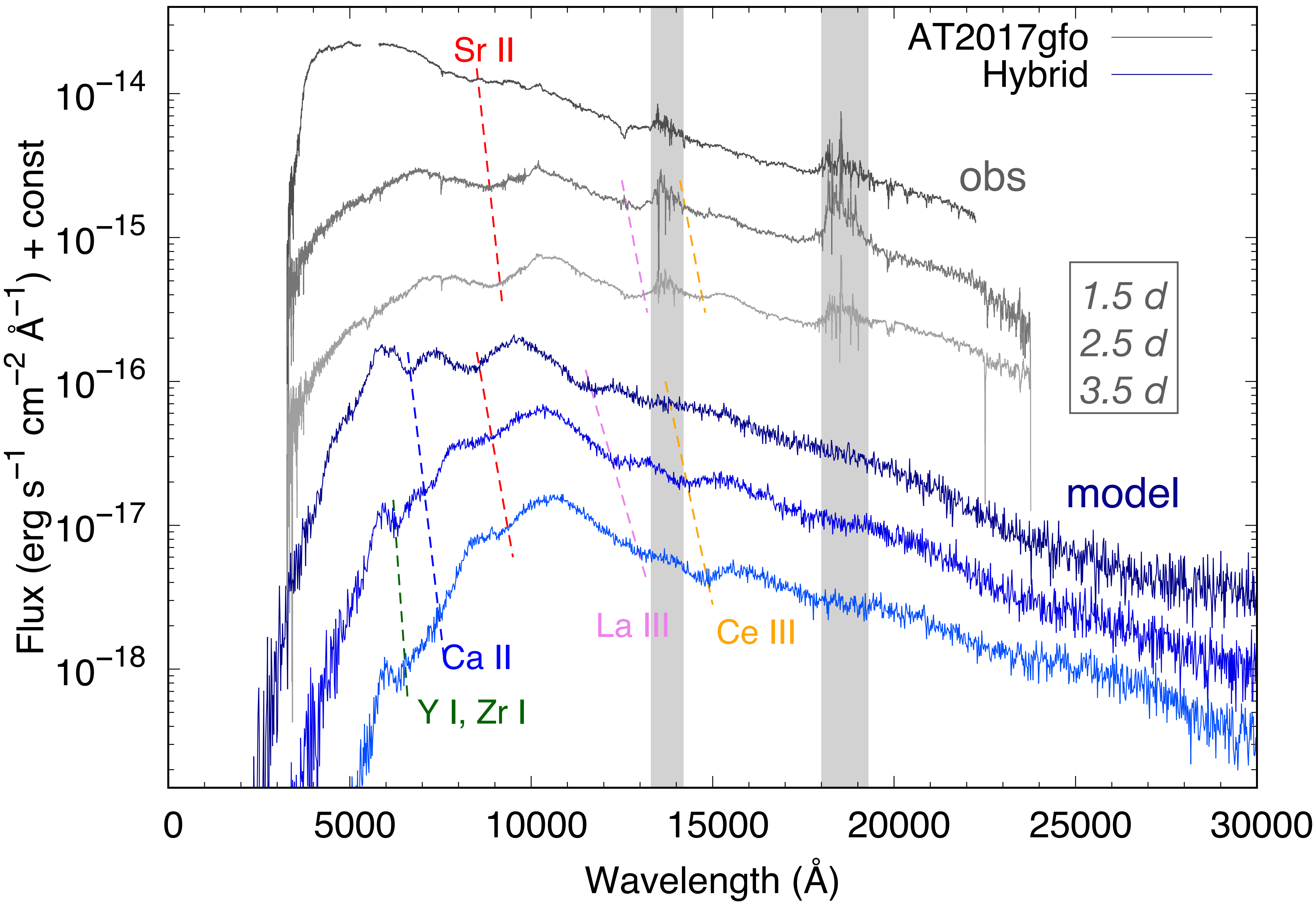
→ Realistic spectral shapes & features

# Results: synthetic spectra




Strong lines of each ion produce absorption lines

# Comparison with observations

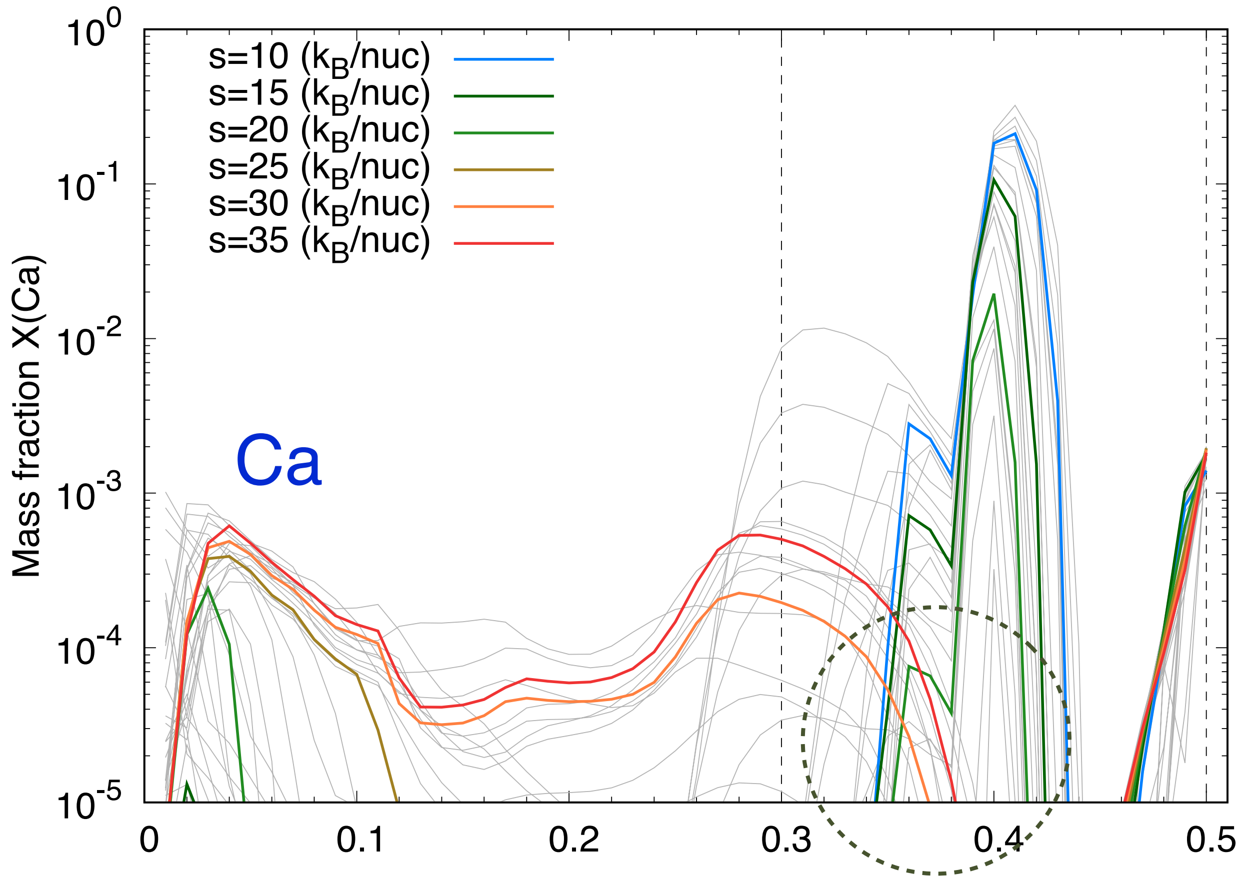


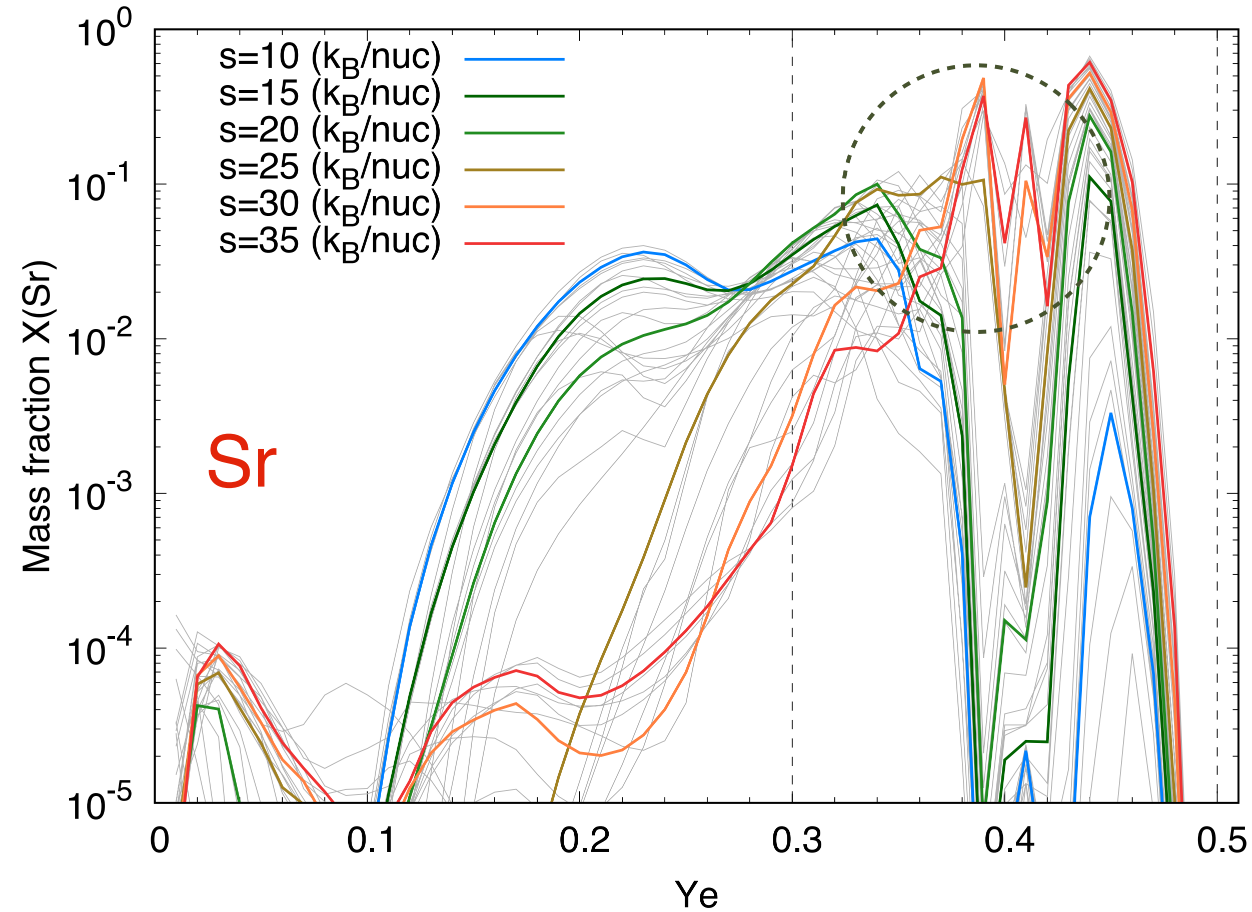

X(Ca)/X(Sr) < 0.002 to explain the optical feature

NIR features can be explained by lanthanides

# Implication from Ca/Sr

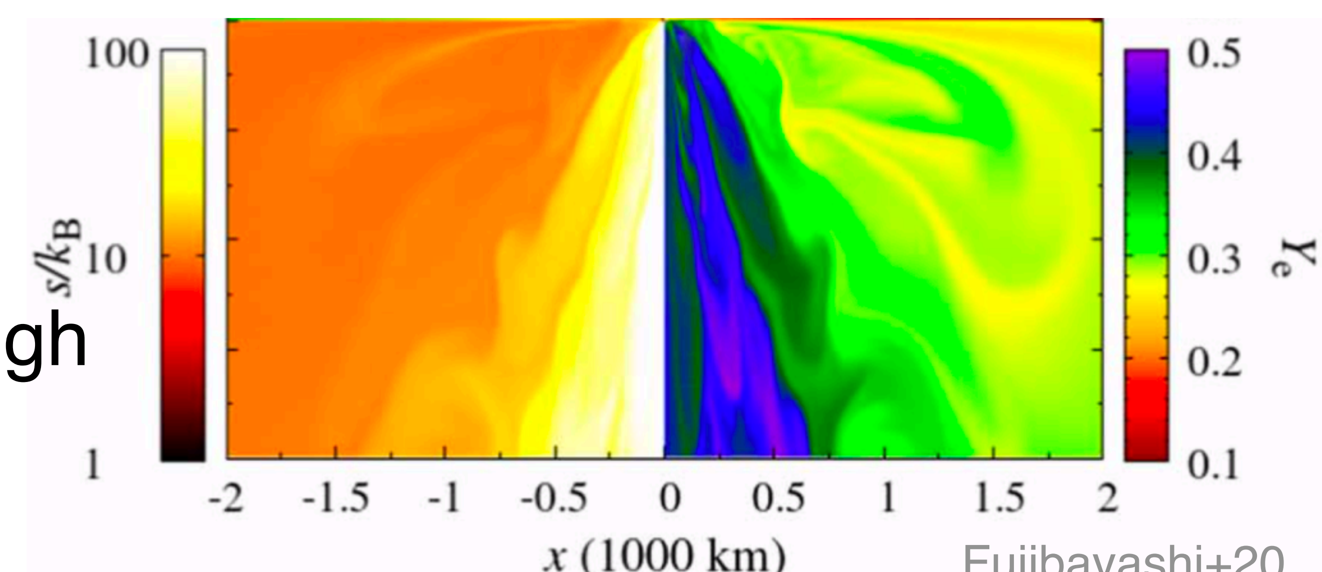
color: v=0.2 c & different entropies



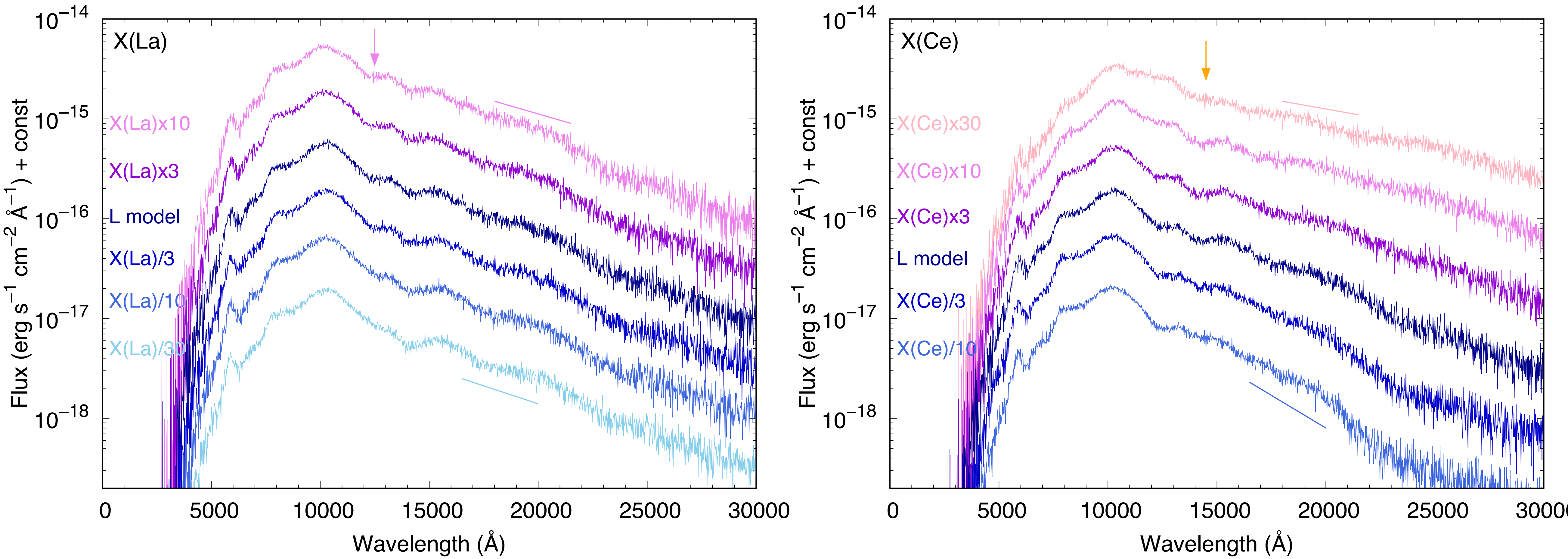

X(Ca)/X(Sr) < 0.002

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




Fujibayashi+20

# Mass fraction of lanthanides




X(La) > 2 x $10^{-6}$

X(Ce) ~$10^{-5}$ - $10^{-3}$

Lanthanide fraction ~ 2 x ($10^{-4}$ ~ $10^{-2}$)
(if abundance pattern is similar to solar pattern)

cf. previous estimation (blue component): ~$10^{-5}$ - $10^{-3}$

Arcavi+17, Kilpatric+17, Nicholl+17, Gillanders+22

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- What can be improved?
  What is done so far and what assumptions remain

# Work on photospheric spectra so far

| | Radiative transfer | Line list | Abundances (key elements) | |
|---|---|---|---|---|
| Watson et al. 2019 | TARDIS code<br>MOOG<br>Single ρ and T | Incomplete<br>VALD, Kurucz | Solar (Sr) | LTE<br>1D calculation |
| Domoto et al. 2021, 2022 | Full<br>Self-consistent for the entire ejecta | Complete<br>(theory + experiment) | Solar-like pattern<br>(Ca, Sr, Y, Zr, La, Ce) | |
| Gillanders et al. 2022 | TARDIS code | Incomplete<br>Kurucz + some + theory | Single Ye results<br>(Sr, Y, Zr) | |
| Vieira et al. 2022 | TARDIS code | Incomplete<br>VALD + some | Inferred by parameter estimate<br>(Sr, Y, Zr) | |

see also Gillanders et al. 2021 (Au and Pt), Perego et al. 2022 (He)

# Summary

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

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

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

- Mass fraction of La and Ce in GW170817 are estimated to be $< 2\times10^{-6}$ and $\sim 10^{-3}$-$10^{-5}$ (direct estimation)

- Theoretical transition probabilities? Multi-dimensional effects? NLTE?