The Radiative Transfer and Atomic Physics of Kilonovae

Spectral features of kilonova in photospheric phase

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September 6th @Stockholm

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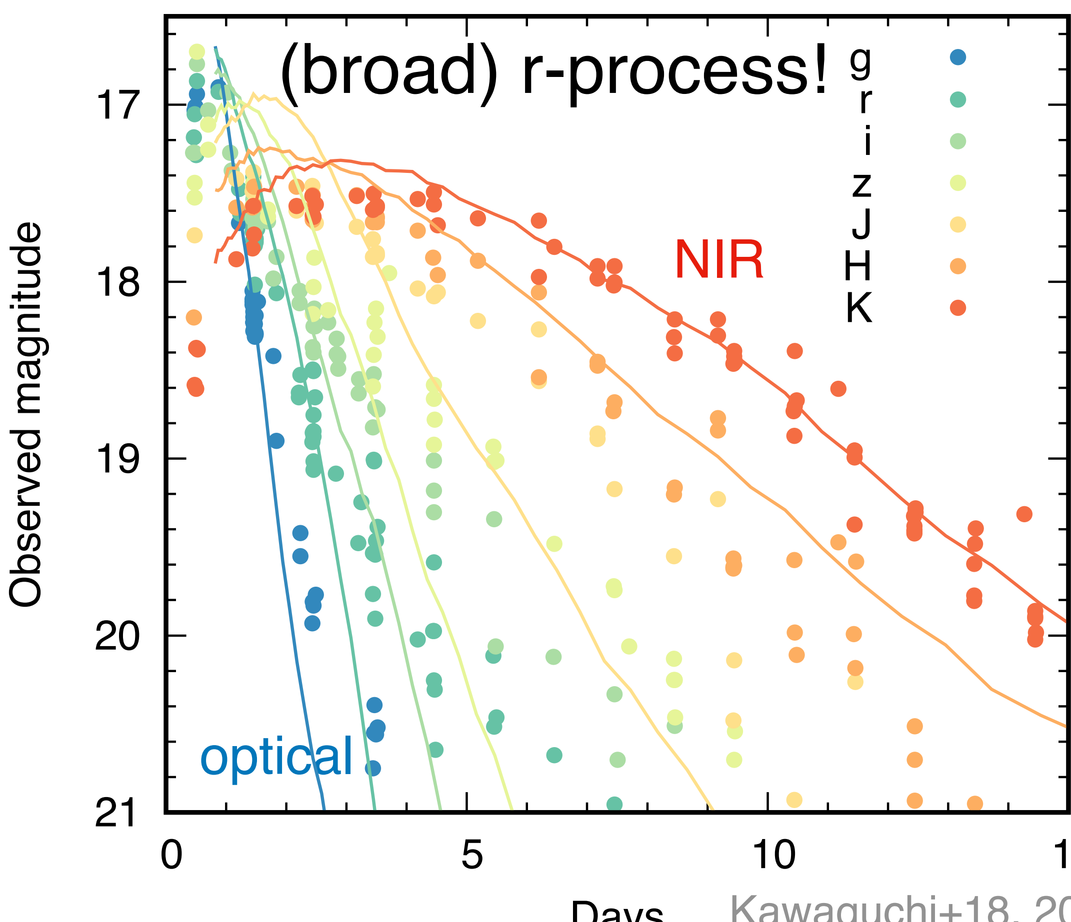
Why spectra?

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

GW170817

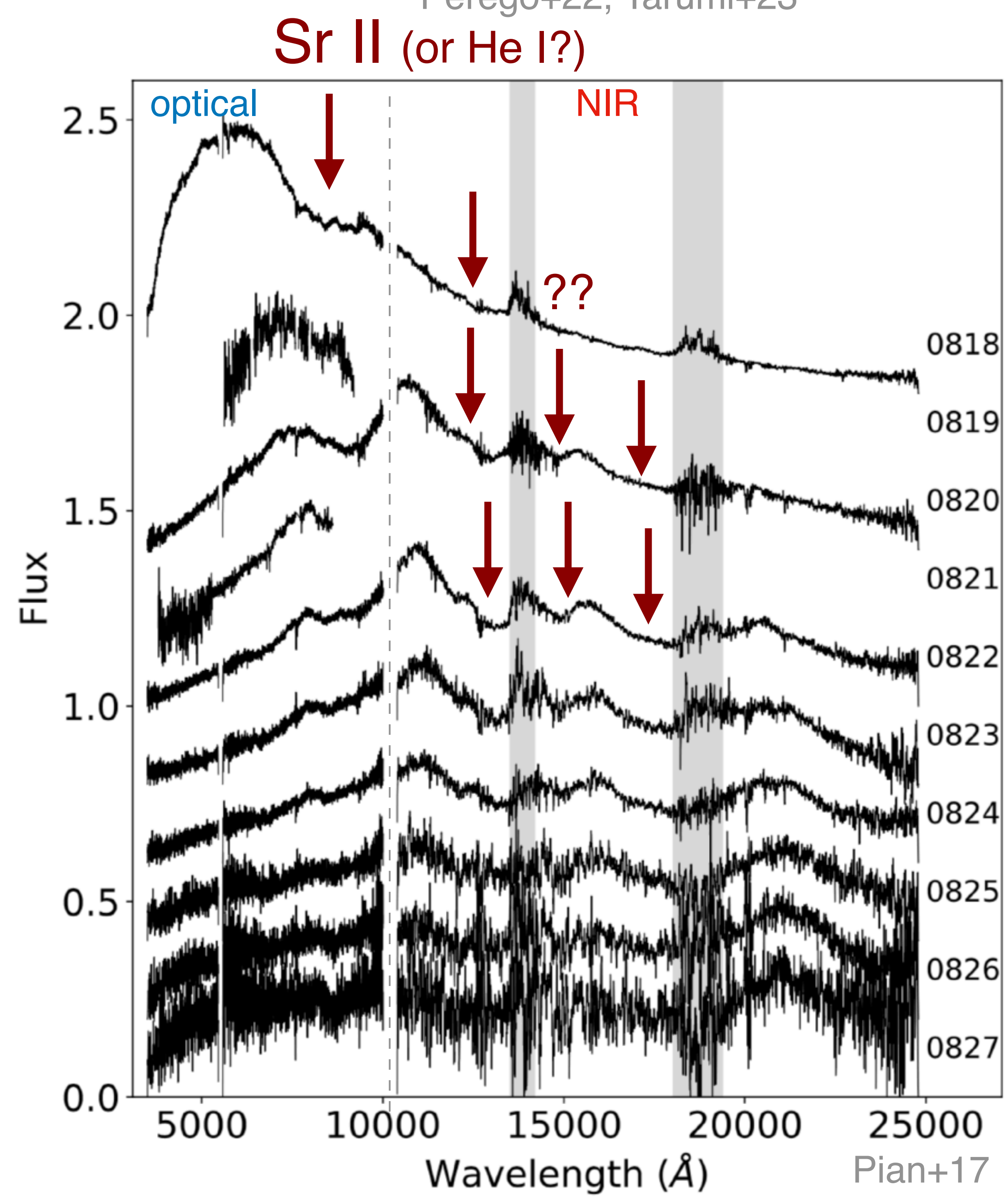
Utsumi+17



Kawaguchi+18, 20

Which and how much elements?

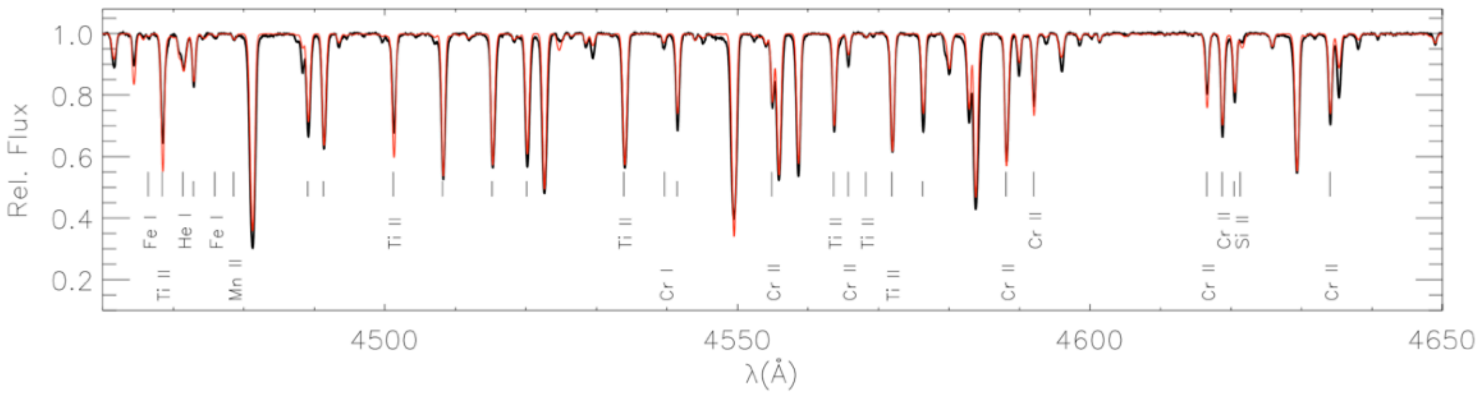
Watson+19, Domoto+21, Gillanders+22
Perego+22, Tarumi+23



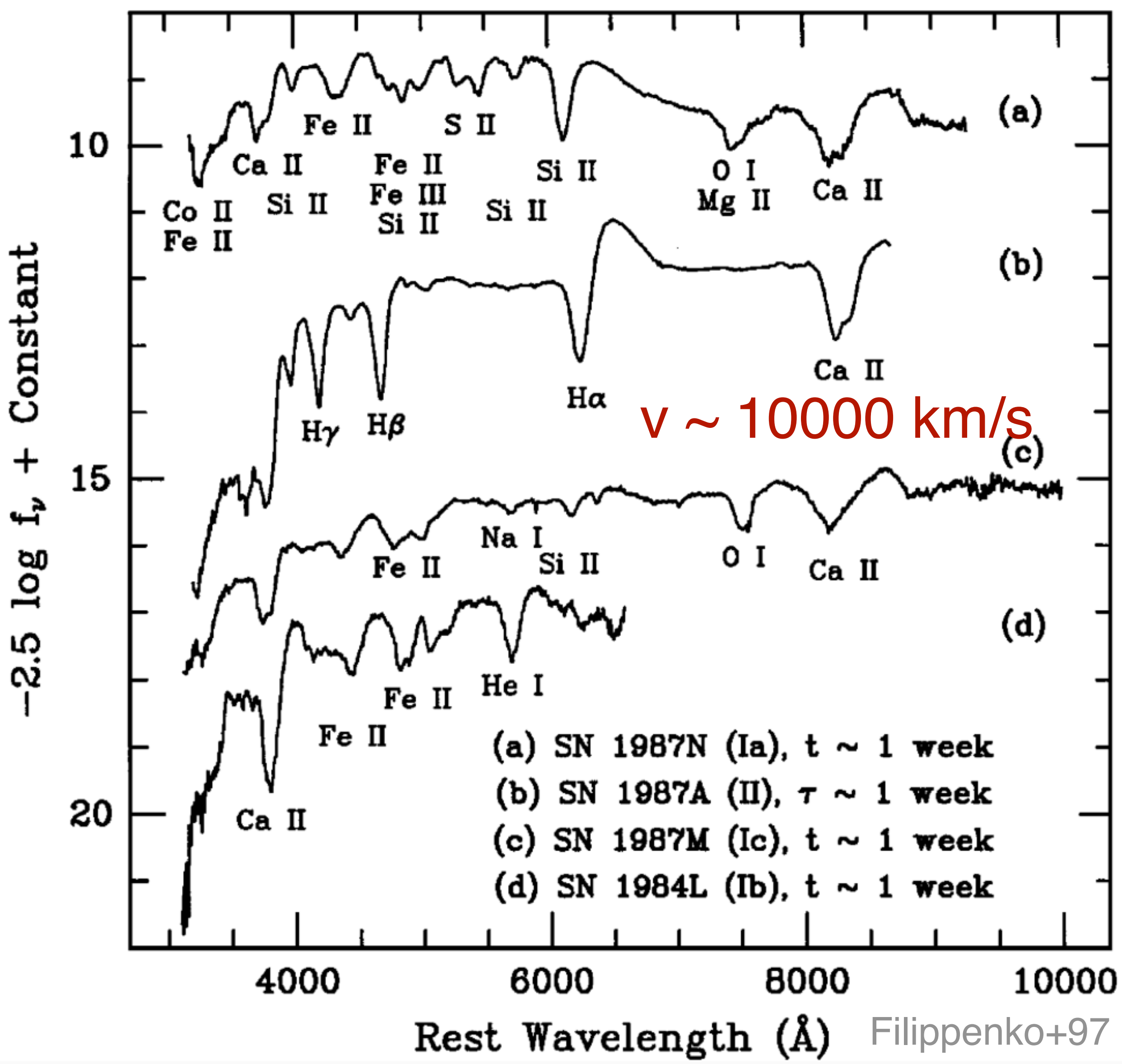
Pian+17

Why difficult?

Star



Supernova



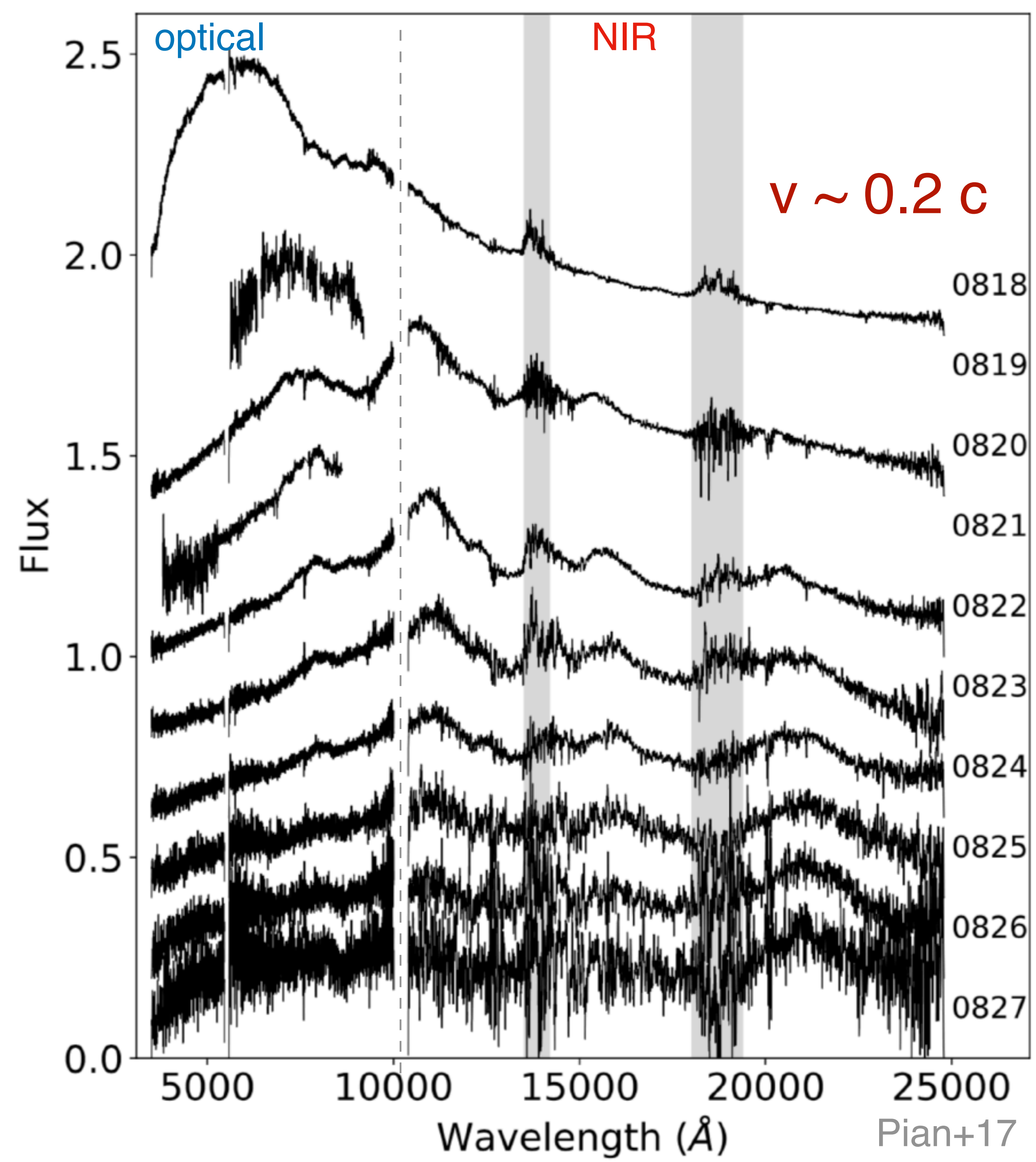
Filippenko+97

Kilonova:

Fast expansion velocity

Heavy elements (beyond iron)

More luminous in near infrared



Pian+17

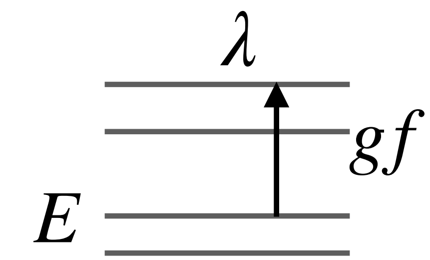
Atomic data from experiments

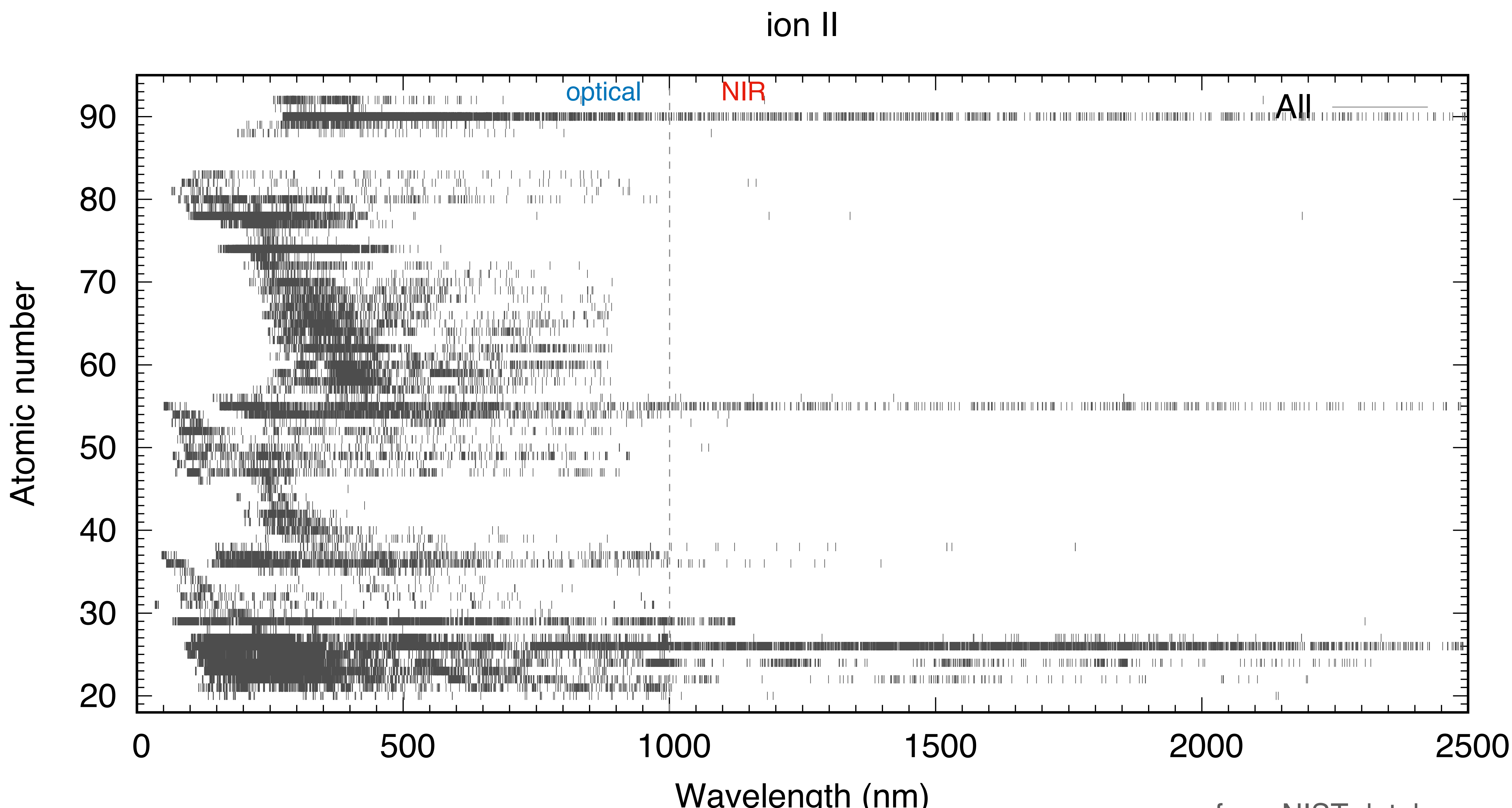
Essential, but lacking data

Strength of line: “Sobolev optical depth”

*radial (expanding) v ≫ thermal v

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





from NIST database

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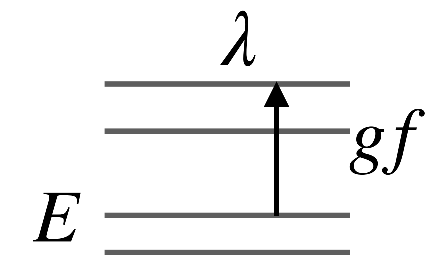

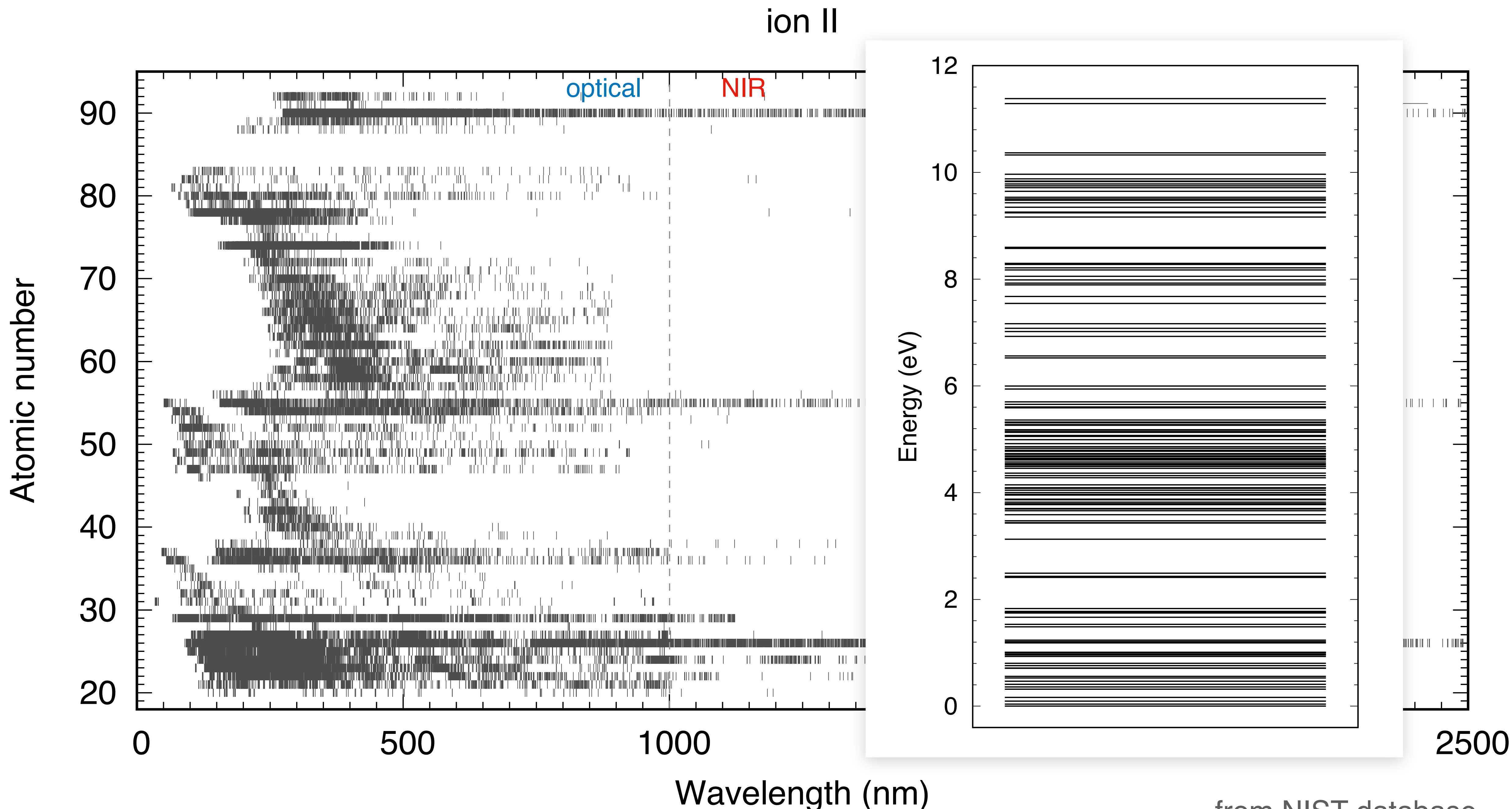

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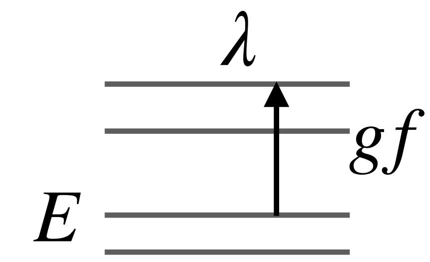
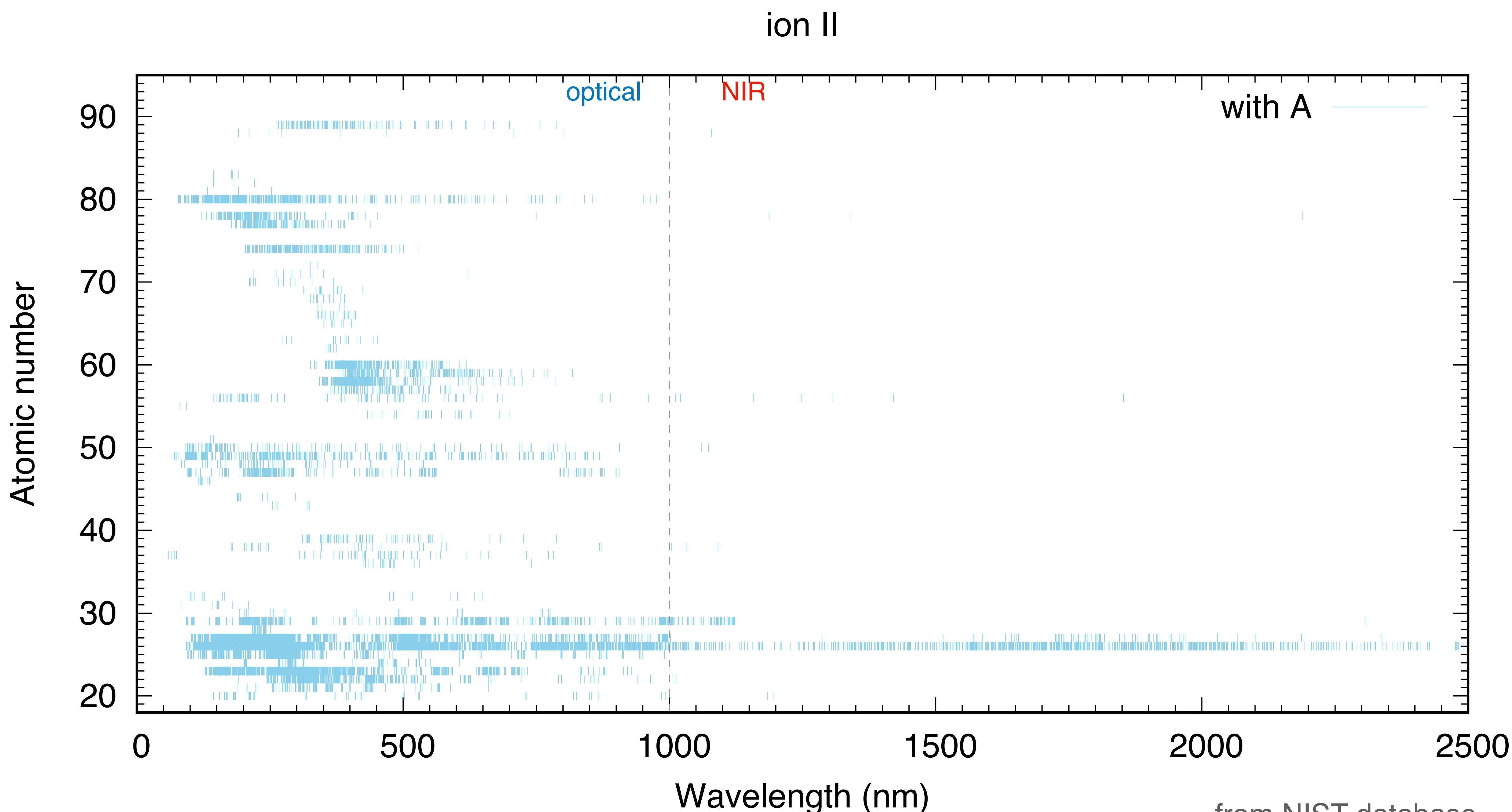
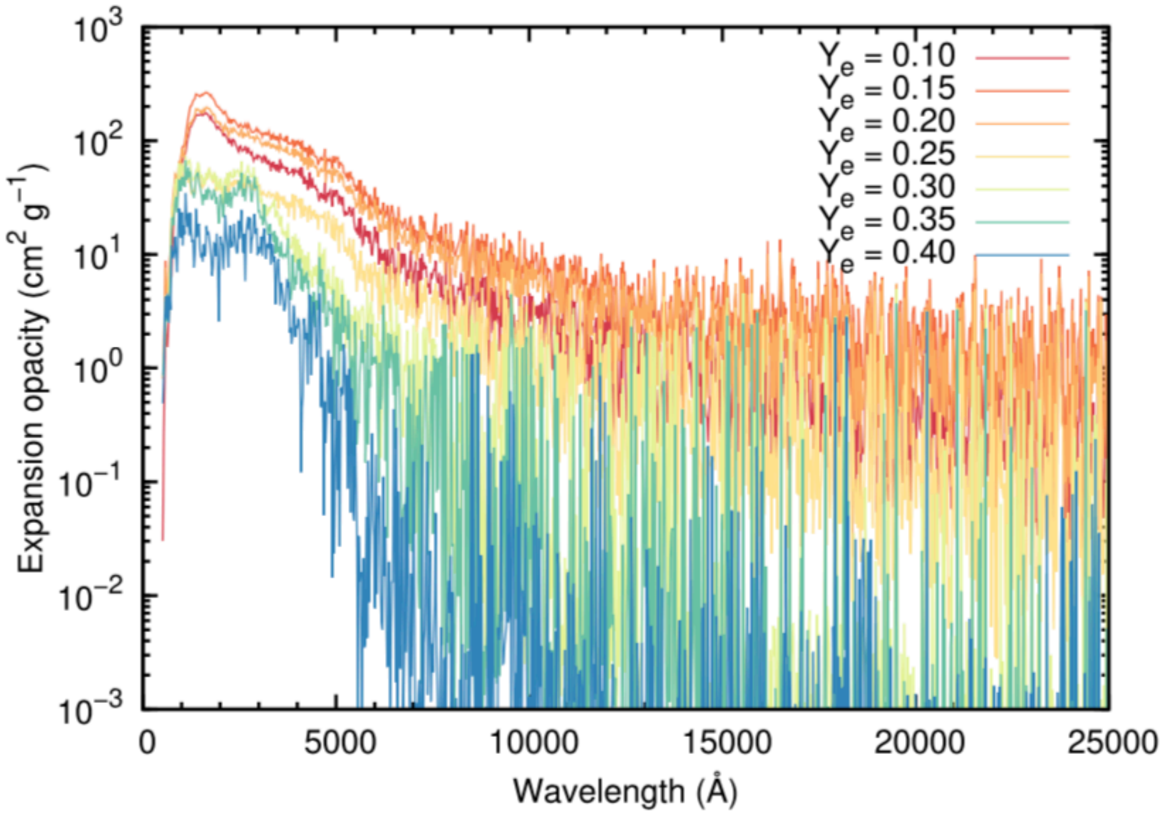


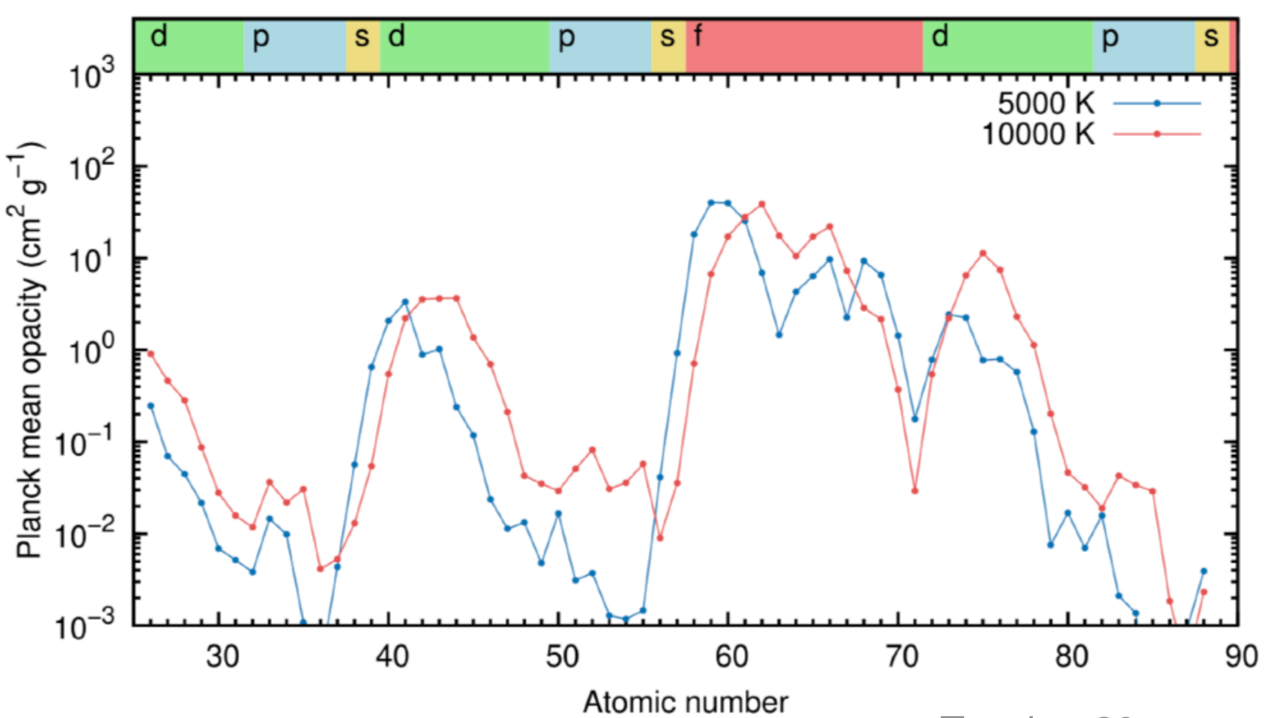


from NIST database

Atomic data from theoretical calculations

<u>Complete, but not much accurate</u>





Tanaka+20

Atomic structure calculations

✔ Statistical properties of elements
(~ 40 million lines)

→ Total opacity can be evaluated

✖ Impossible to discuss spectral features

e.g., Kasen+17, Fontes+20, 23, Banerjee+20, 22, Pognan+22, F. Silva+22, Floers+23, …

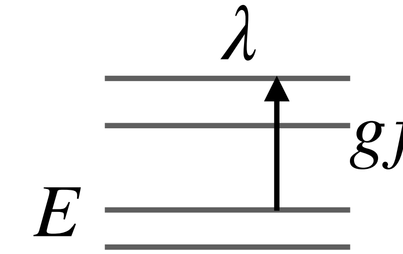
Atomic data

Difficulty on study for kilonova spectra

Strength of line: “Sobolev optical depth”

*radial (expanding) v ≫ thermal v

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



	Experimentally calibrated list *spectroscopically accurate e.g., NIST, VALD, DREAM	Theoretically constructed list *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

Light curve calculations

Spectra study under this situation…

Papers on photospheric spectra for GW170817 (under LTE, 1D)

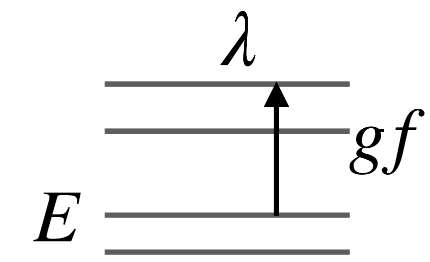
Atomic data	Papers
Only accurate data	Watson et al. (2019), Domoto et al. (2021), Vieira et al. (2023a,b), Sneppen et al. (2023)
Theoretical calc w/ some calib	Gillanders et al. (2021)
accurate data + some calc	Gillanders et al. (2022)
Hybrid data	Domoto et al. (2022)

See Perego et al. (2022) and Tarumi et al. (2023) for NLTE analyses (He I)
Shingles et al. (2023) for 3D calculations

Toward identification

Strategy: combine advantages of line lists

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



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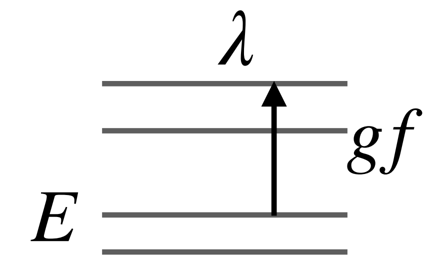
Transition probability	unavailable (especially for NIR)	available

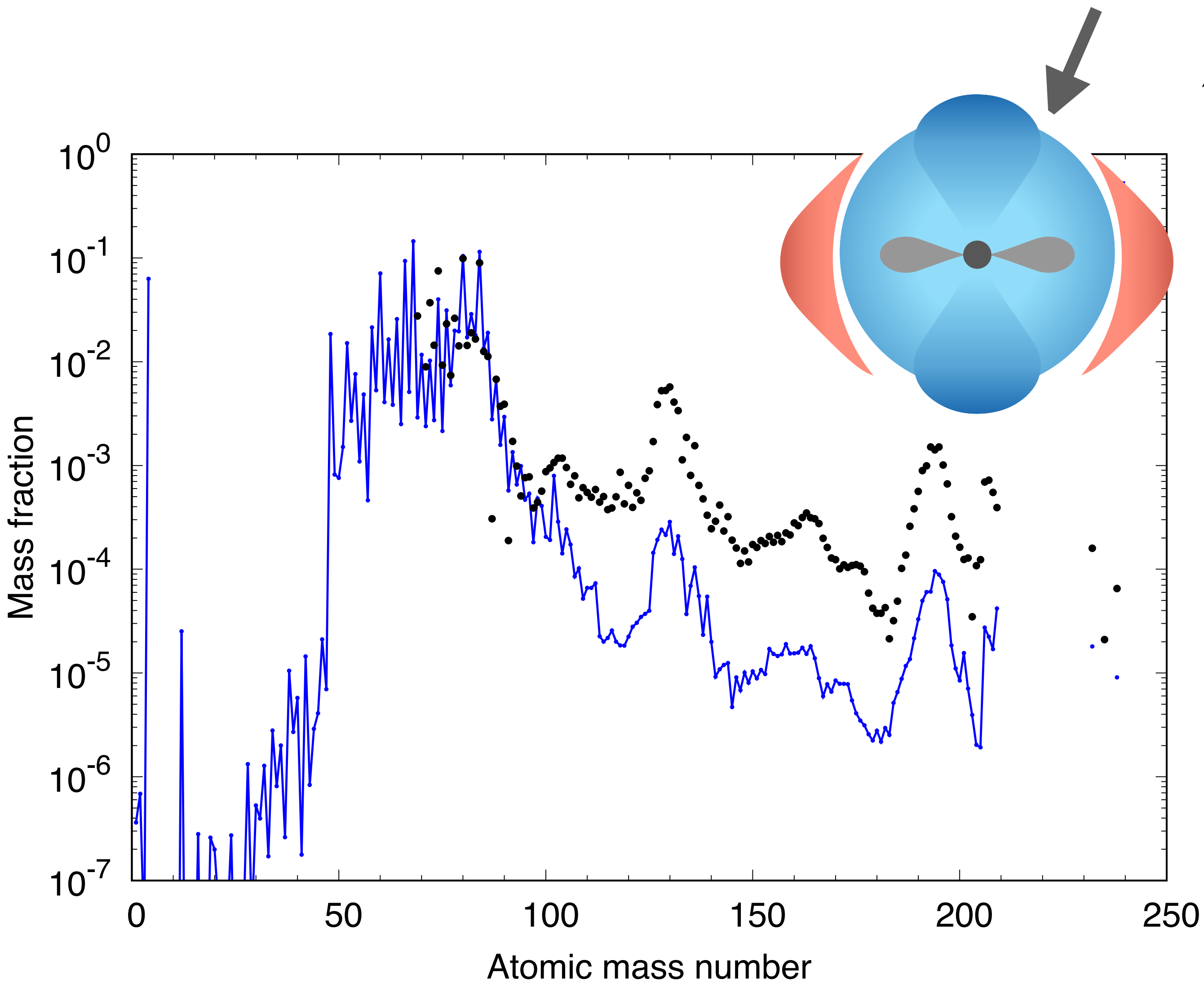
1. Find species having strong transitions (thanks to the complete data)
2. Extend "accurate" data of strong transitions w/ theoretical prob.

Find species having strong transitions

Give density, temperature, abundance + <u>complete</u> atomic data
=> Search the species having strong transitions systematically

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





- Abundance: solar-r-like pattern model

Wanajo 18

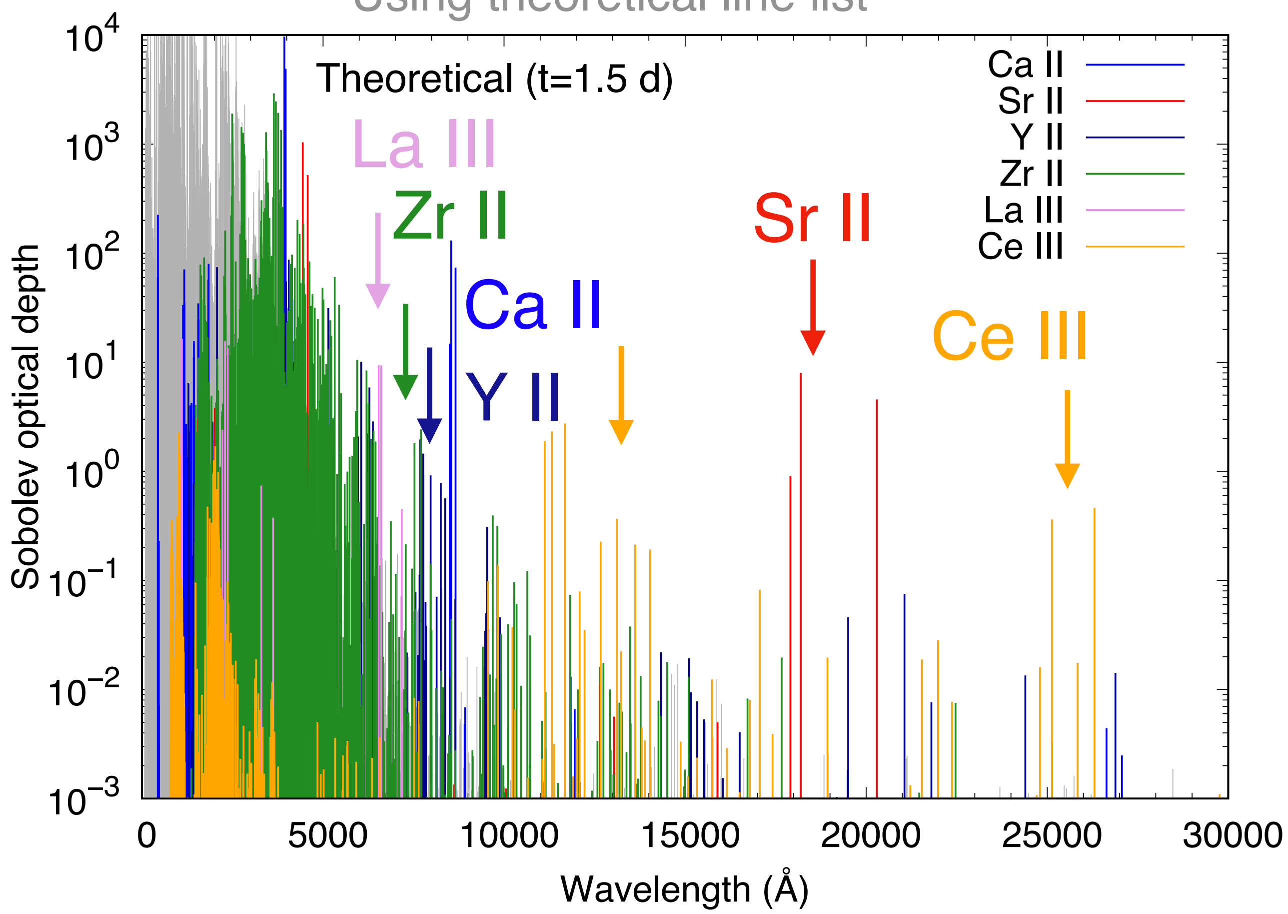
- Ionization/excitation: LTE
  (Saha's eq, Boltzmann distr.)

Find species having strong transitions

Give density, temperature, abundance + <u>complete</u> atomic data
=> Search the species having strong transitions systematically

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

Using theoretical line list



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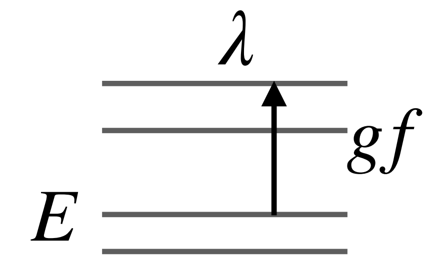
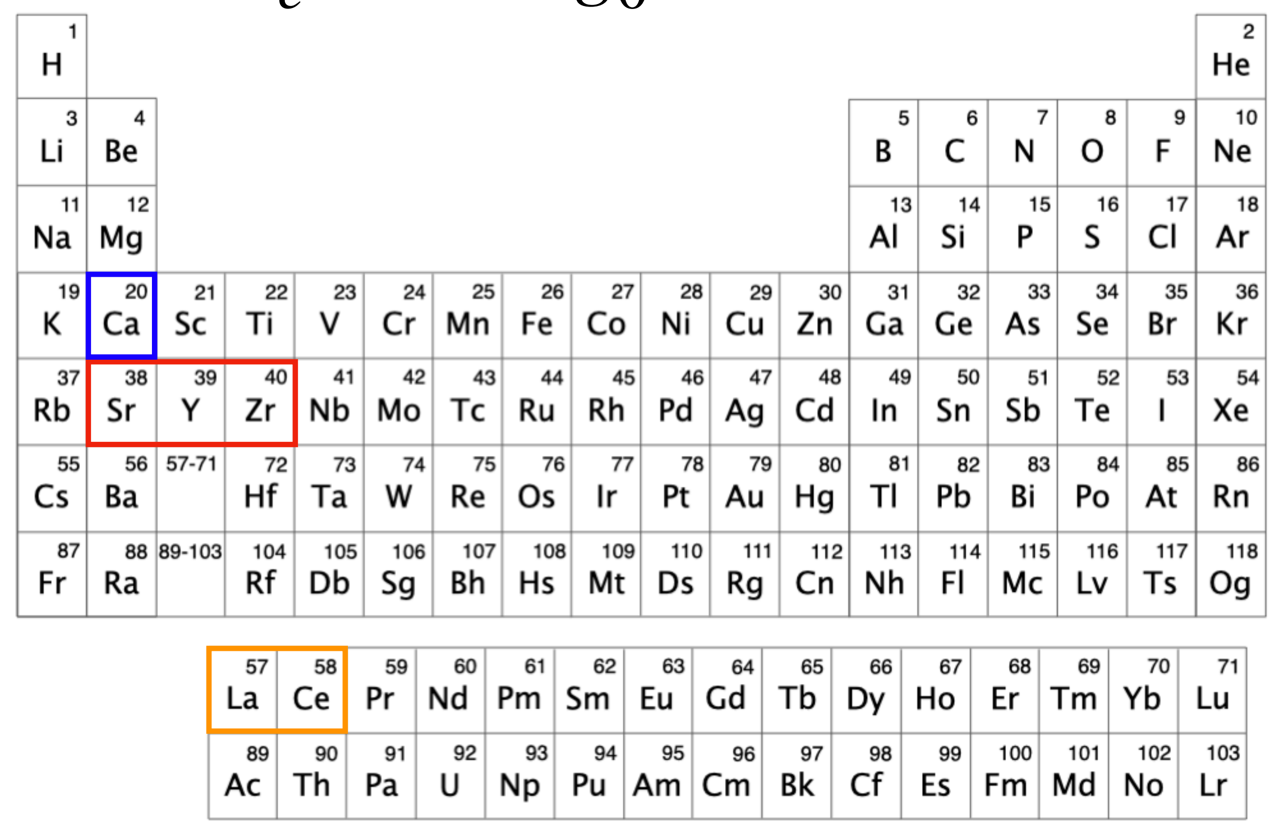
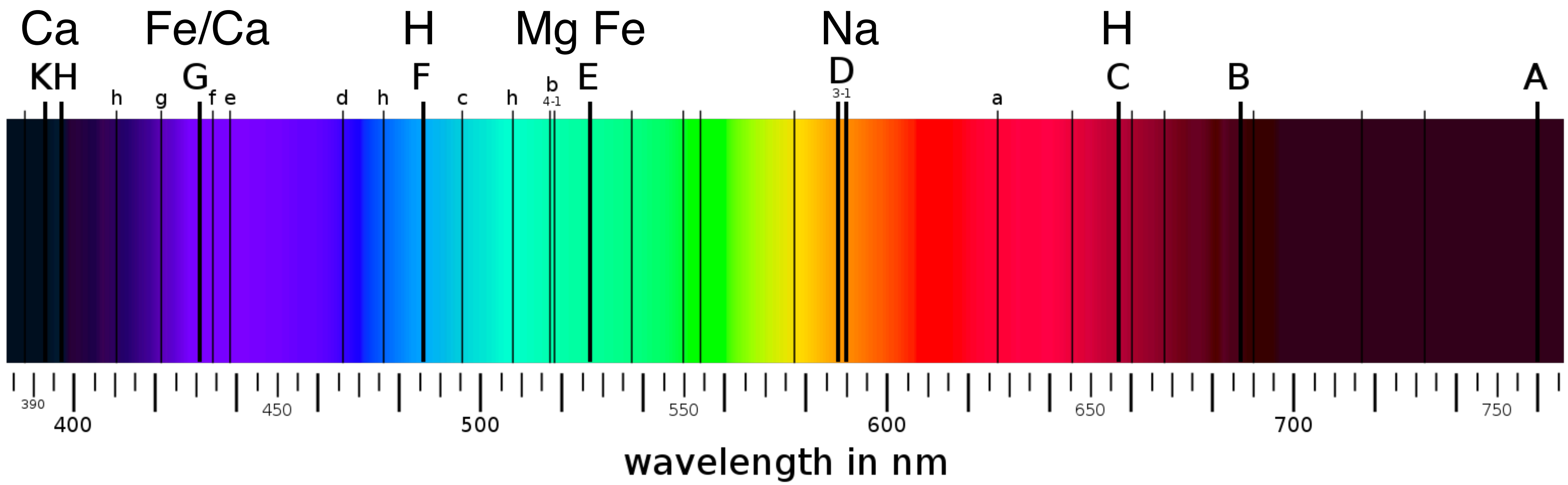


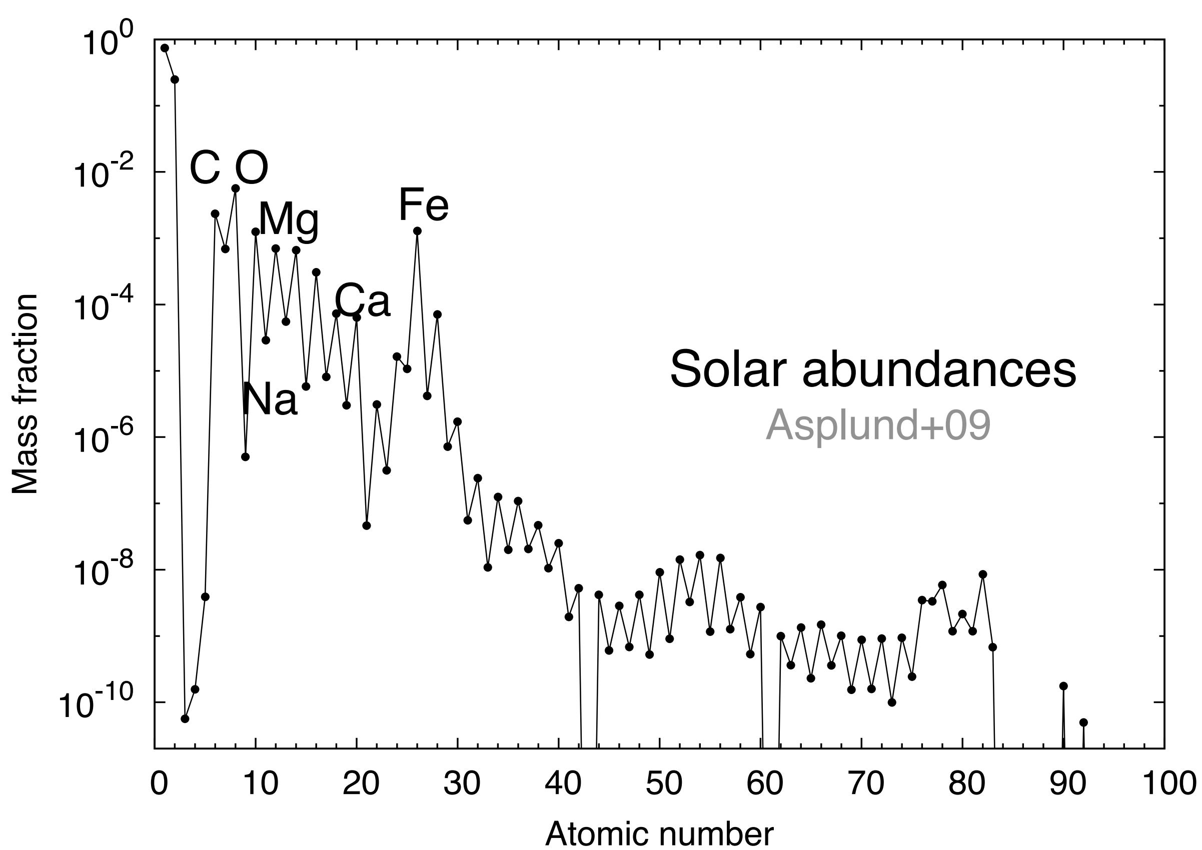


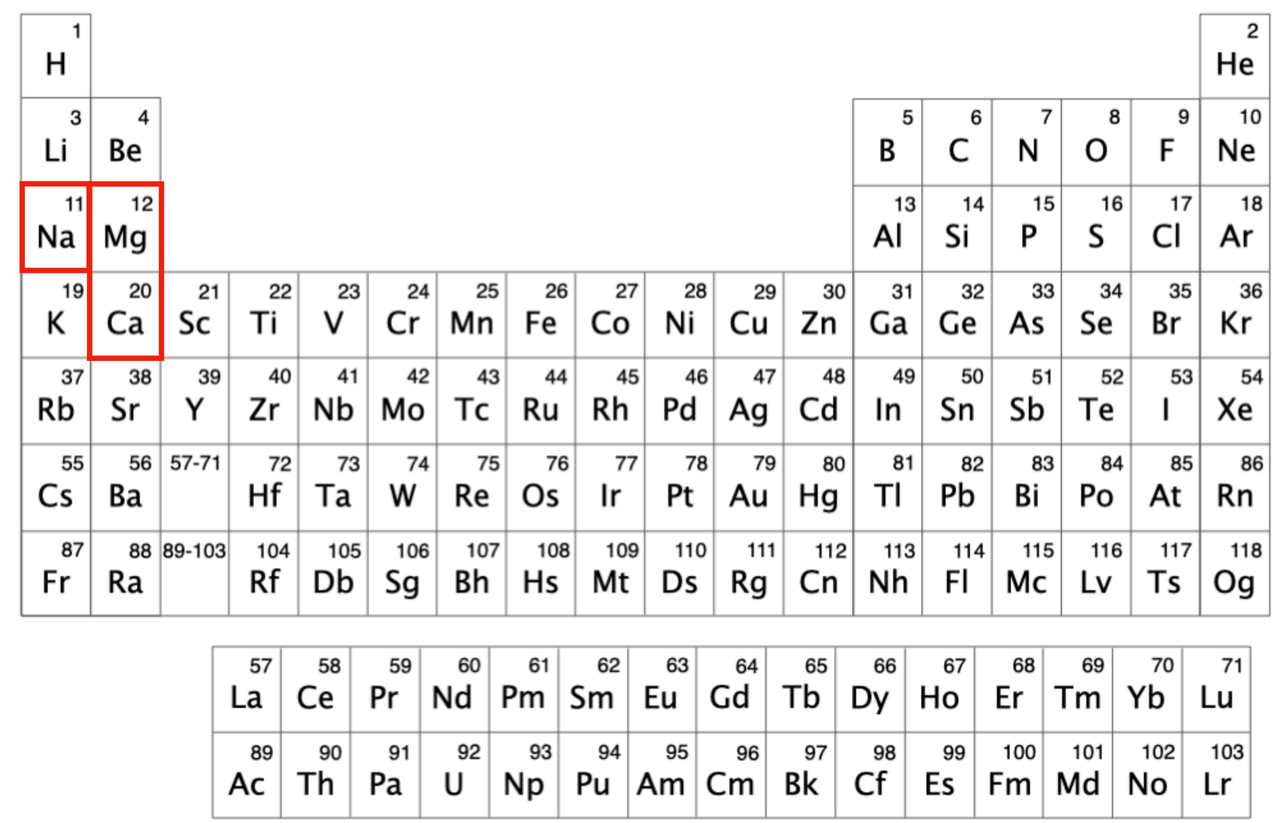
Domoto et al. 2022

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

Same as the Sun!

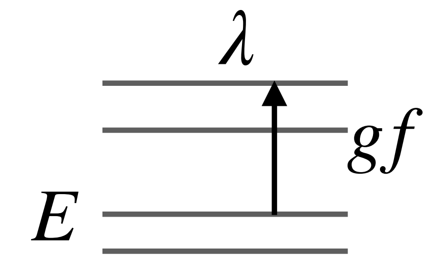






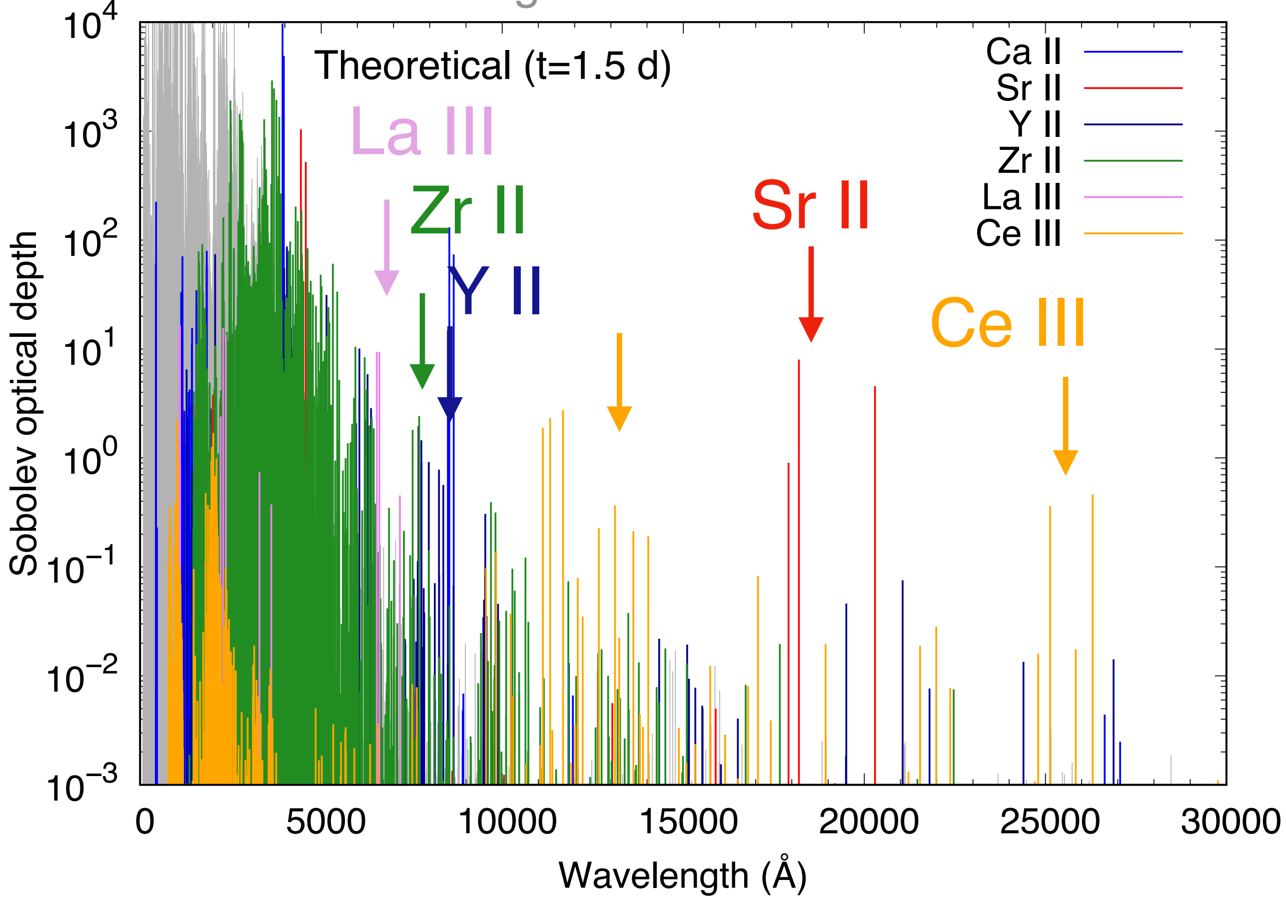
Energy level calibration

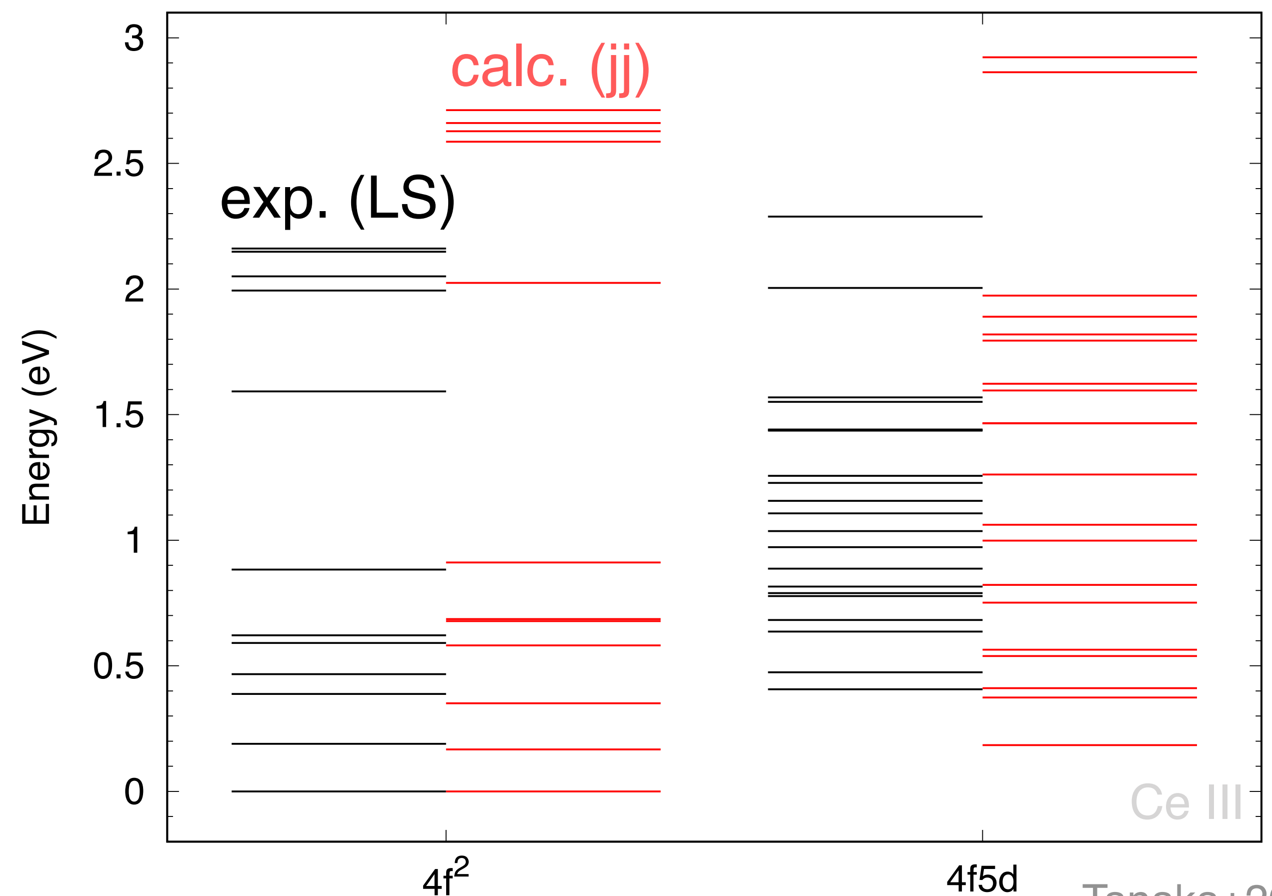
Domoto et al. 2022



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

Using theoretical line list





Tanaka+20

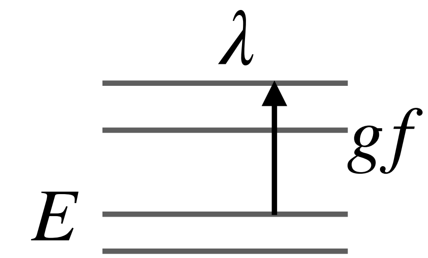
Calibrate energy levels with experimental data, and calibrate λ (only low-lying levels)

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

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

Construction of hybrid line list

Domoto et al. 2022



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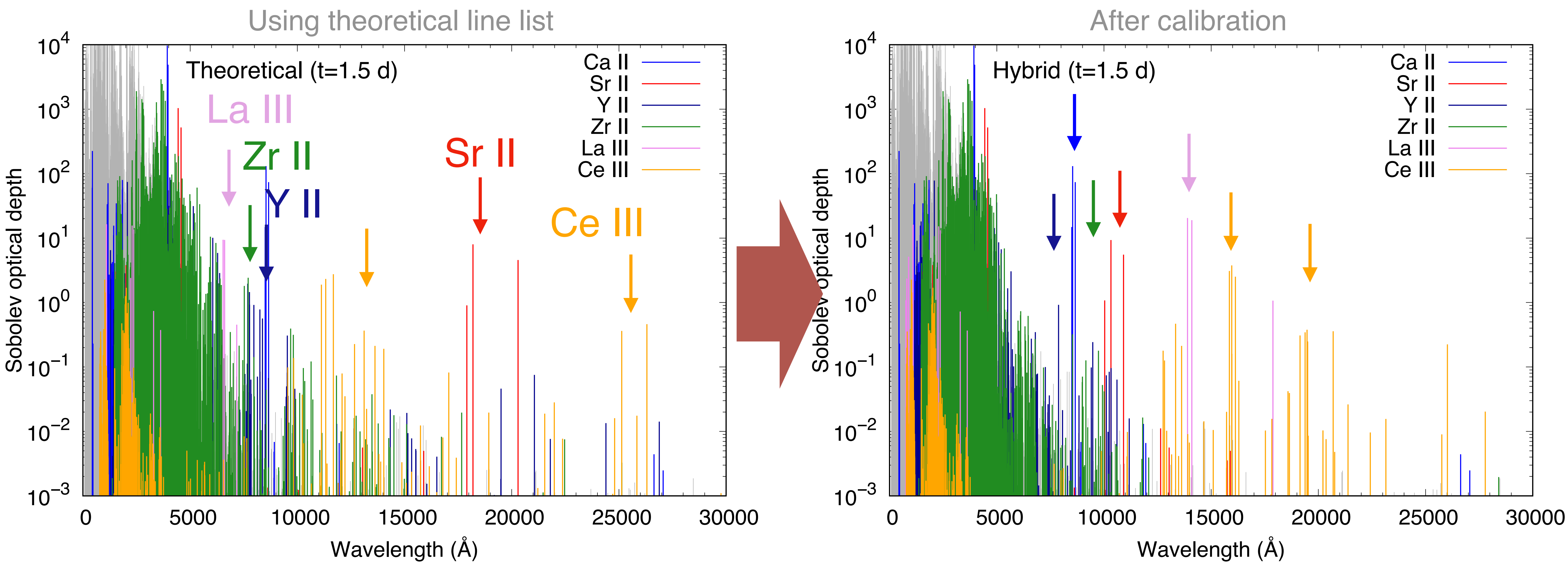


Transition probabilities of La III/Ce III lines are taken from theoretical values

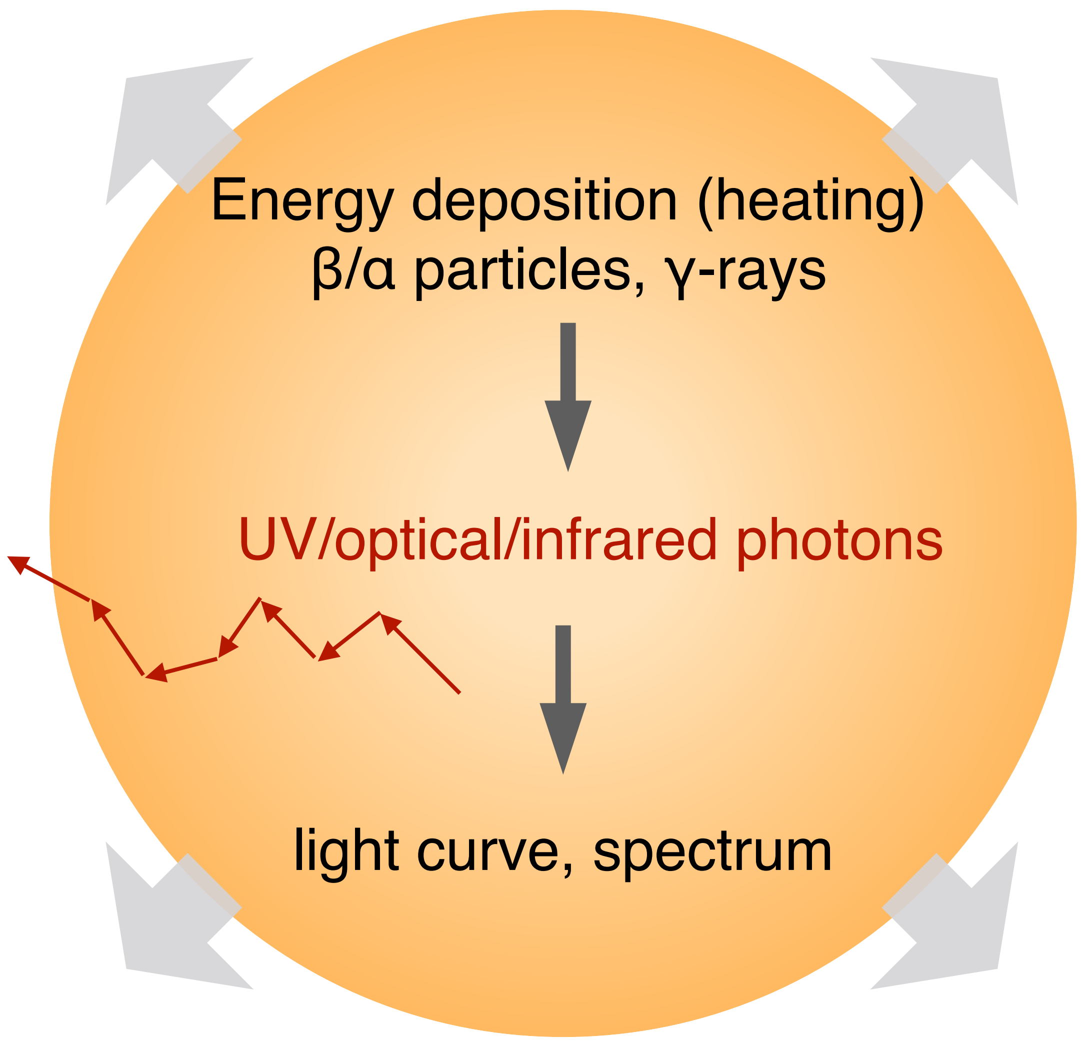
=> "experimentally <u>accurate</u>" strong transitions (for spectral features)

+ theoretically constructed, <u>complete</u> weak transitions (for opacity)

Radiative transfer simulations

Entire ejecta

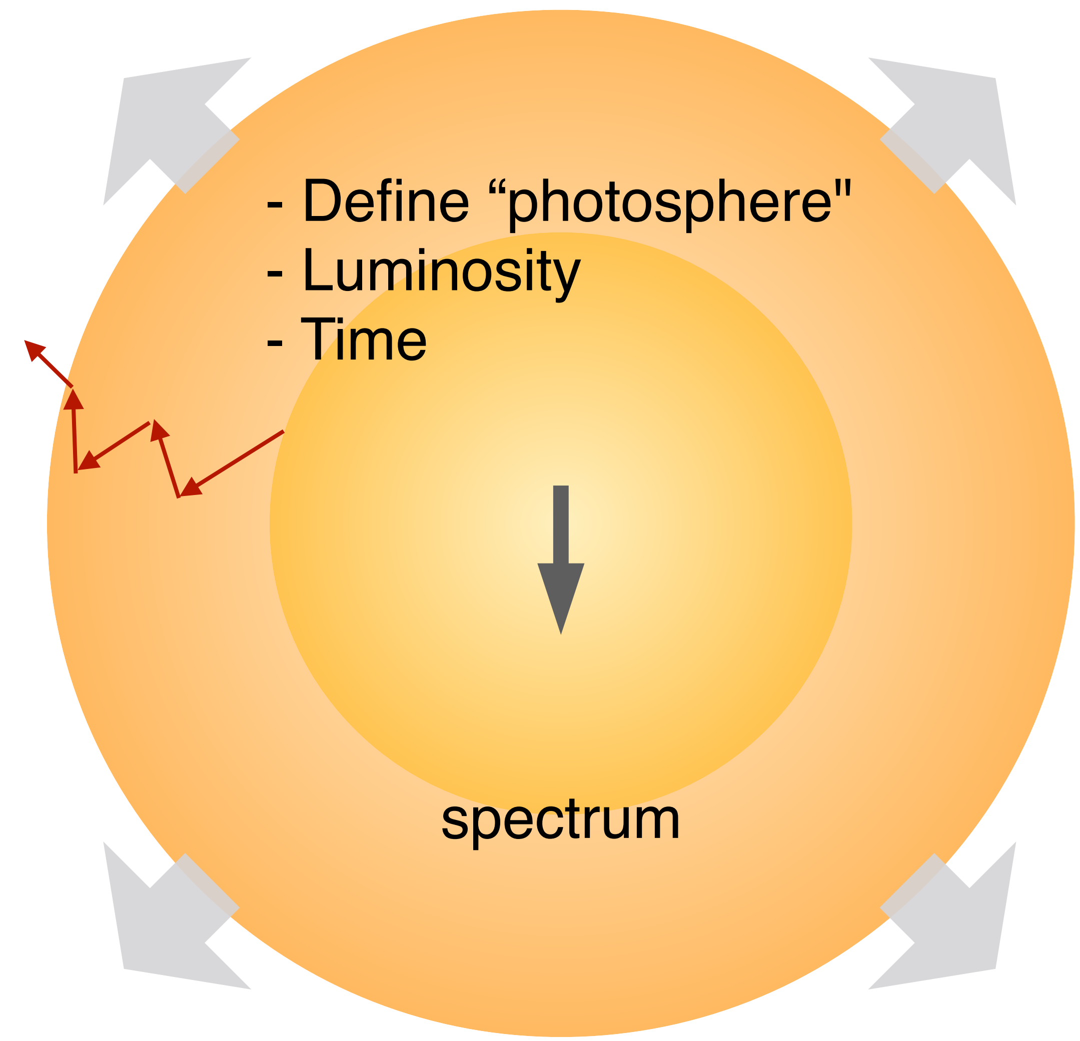
Domoto+21,22



- Self-consistent calculations

Only “atmosphere”

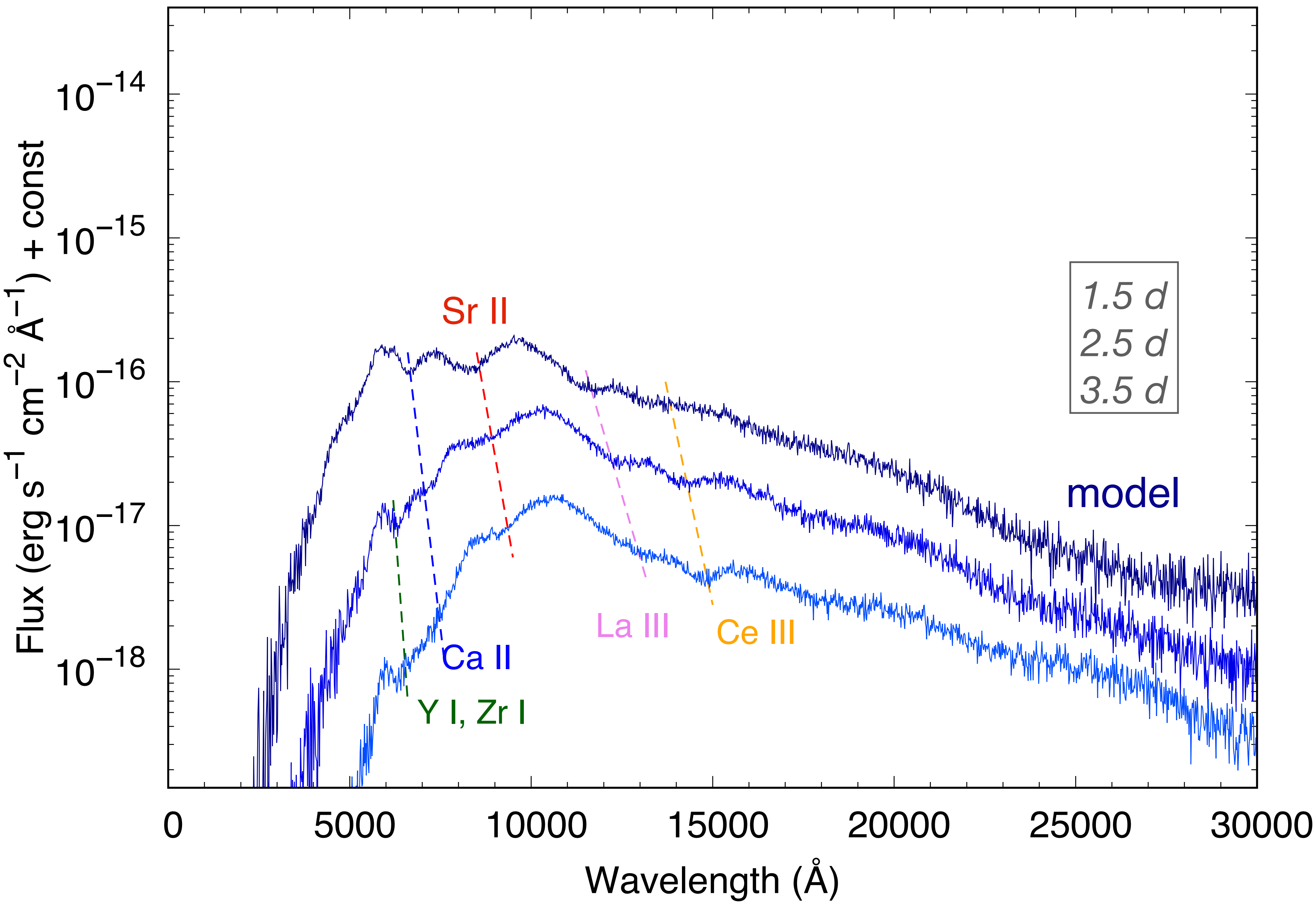
e.g., TARDIS: Gillanders+21,22,23, Vieira+23ab, Sneppen+23



- Get snapshot (for given luminosity)
- Easy to fit to actual data (param inference)

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

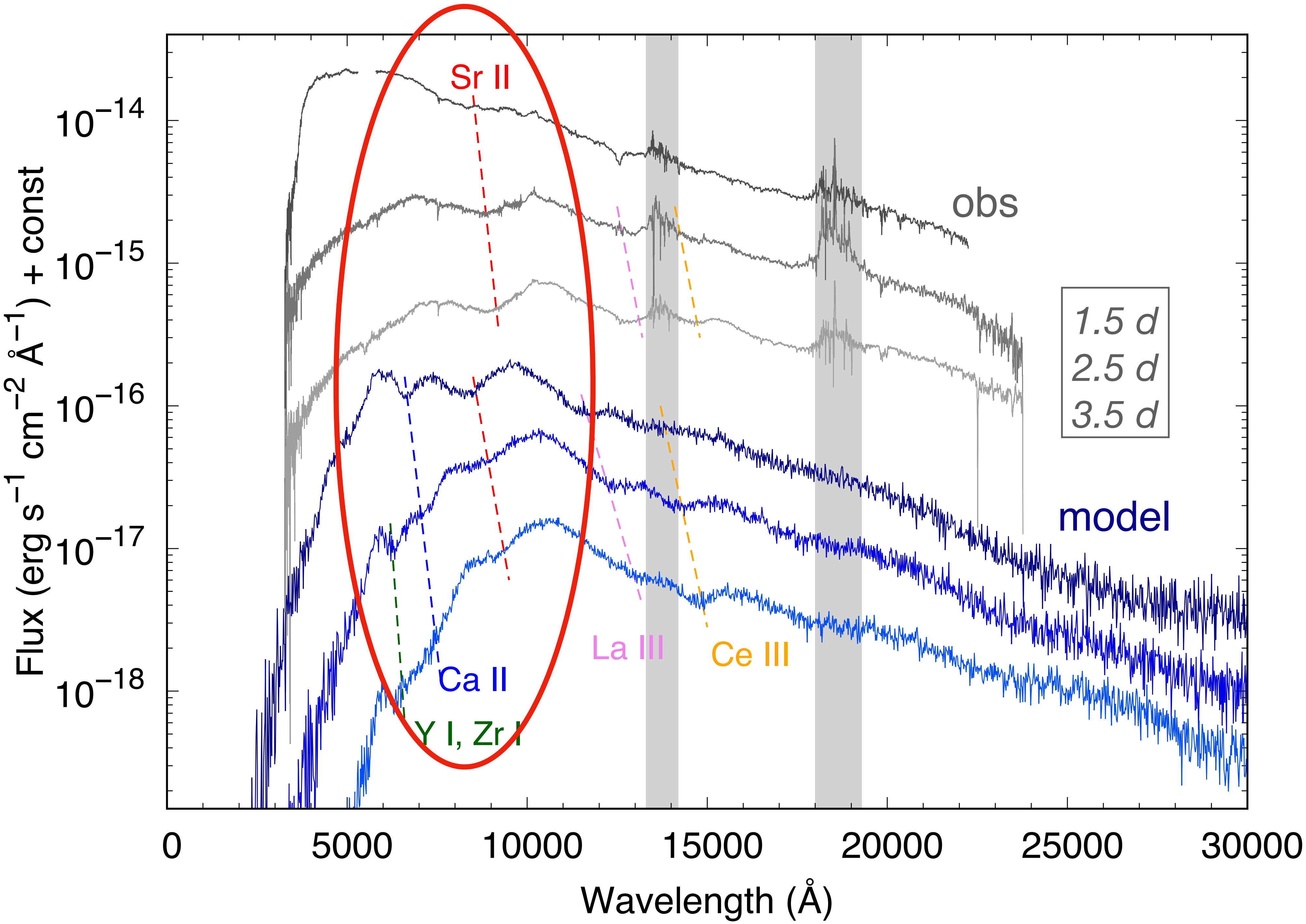
Synthetic spectra



Strong lines of each ion produce absorption lines

Confirmation of Sr, but not Ca

Domoto et al. 2021

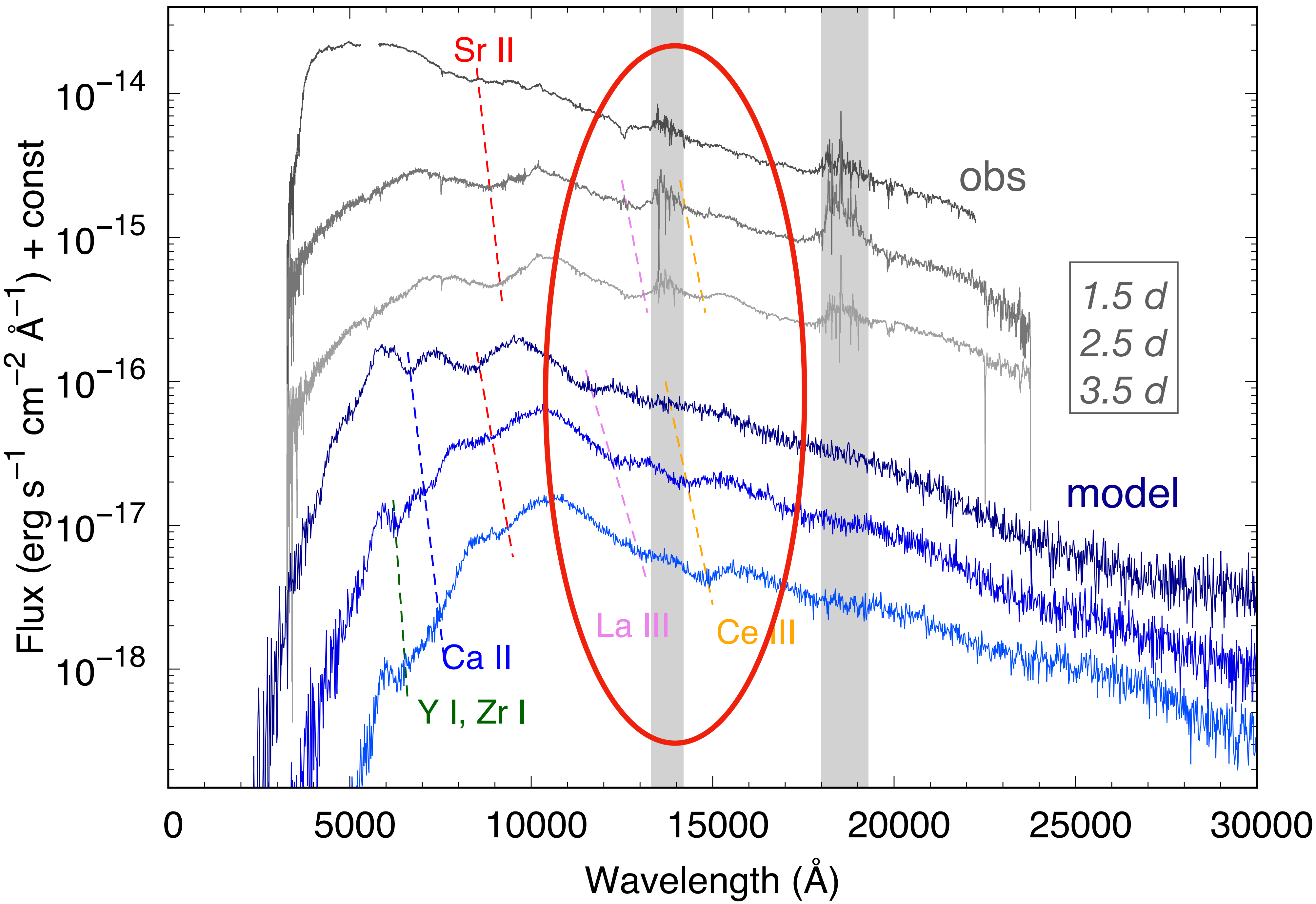


Sr and Ca have similar atomic structures and transitions

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

Identification of La and Ce

Domoto et al. 2022



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

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

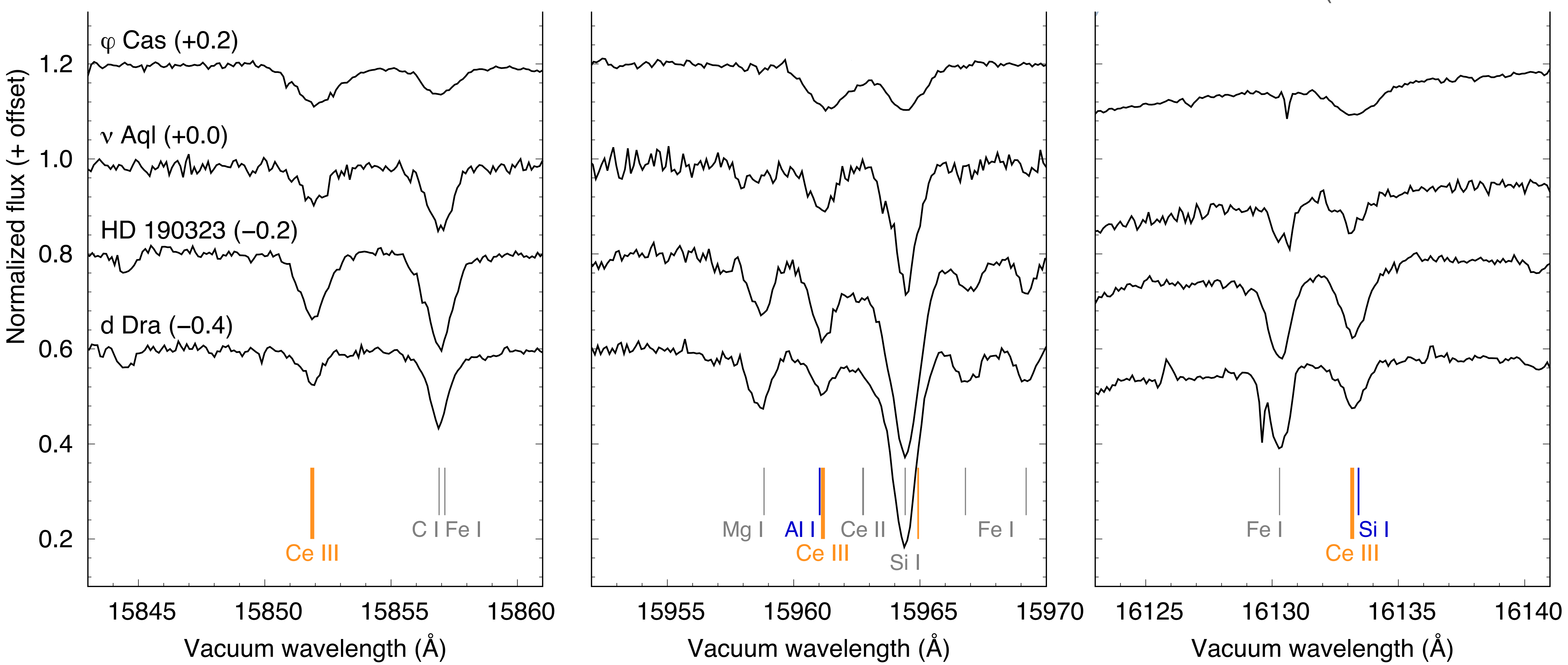
Uncertainty: theoretical gf-values

Transition probabilities should be measured by “experiments”
-> Star can be used as a laboratory

IGRINS (R~45000)

Domoto et al. 2023
(arXiv: 2309.01198)

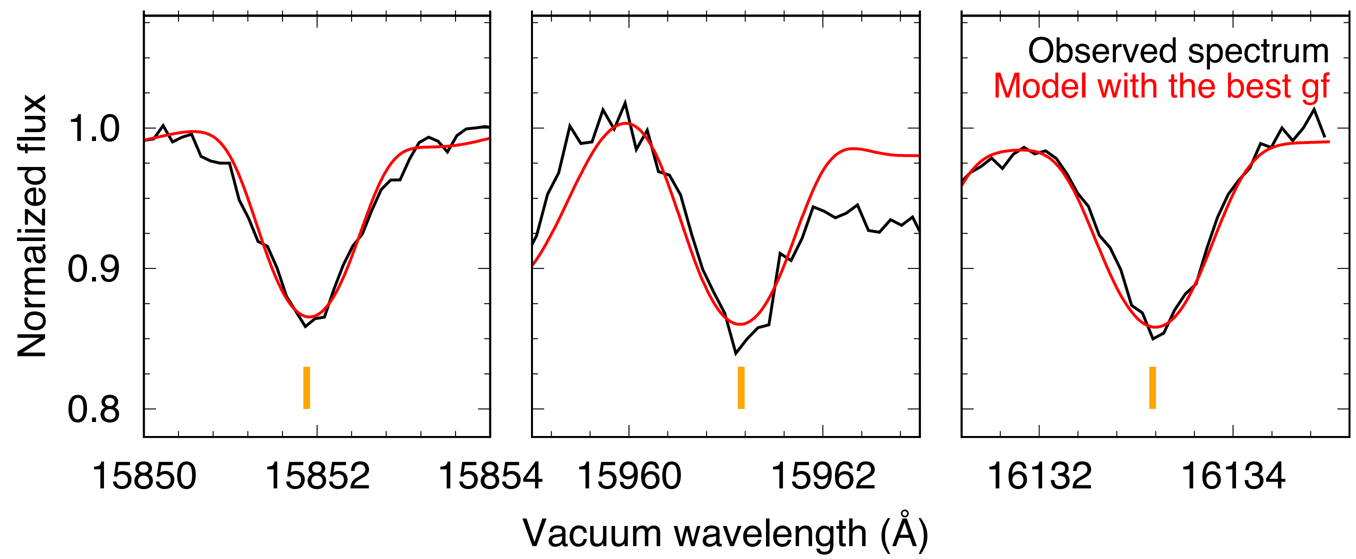
clear absorption of NIR Ce III lines



With known parameters of the stars, gf-value determines absorption depth

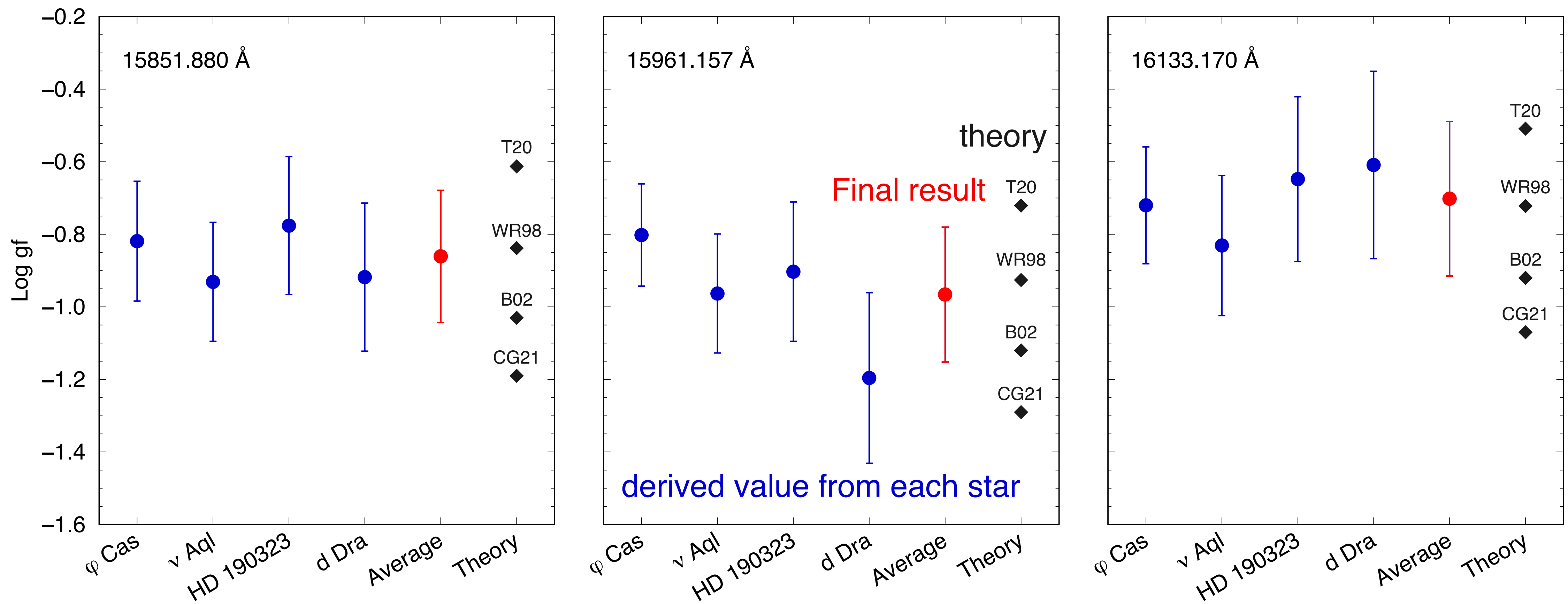
Estimate log(gf) by modeling stellar spectra

Model the spectra under LTE



Use…
- ATLAS/MARCS model
- Turbospectrum
- Params from literatures

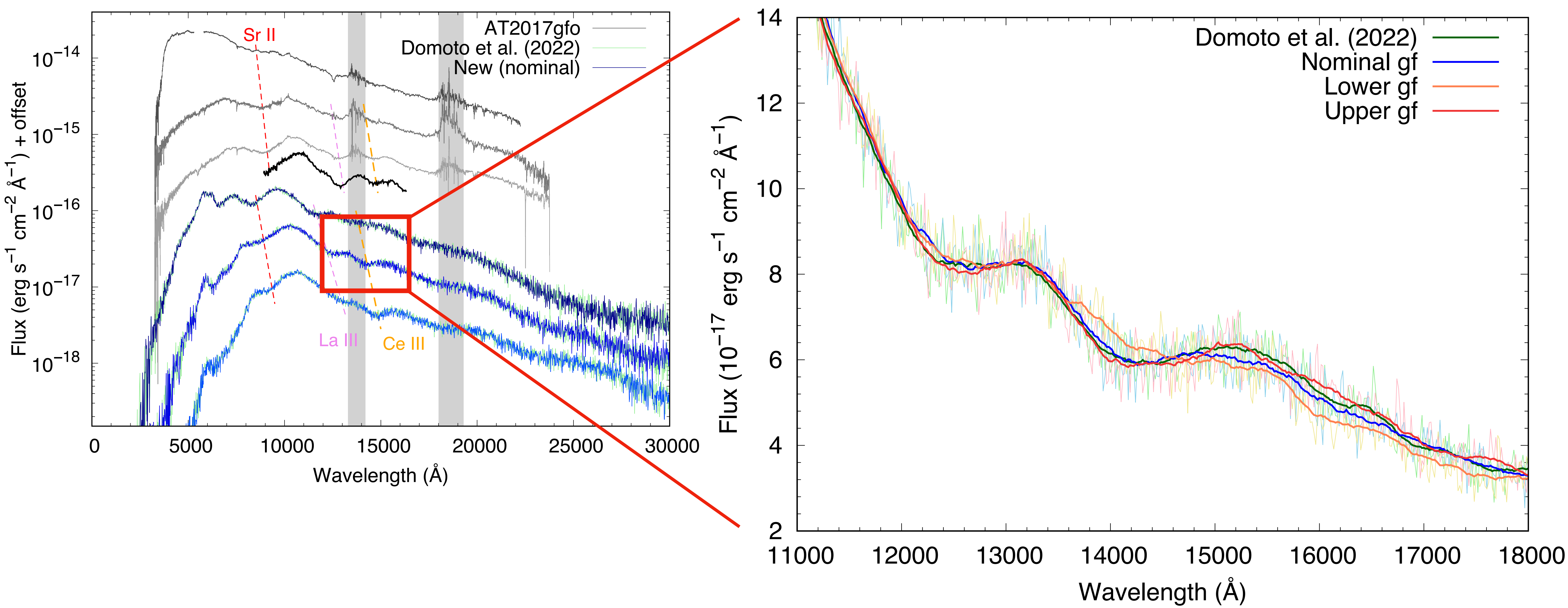
Domoto et al. 2023
(arXiv: 2309.01198)



Support of identification of Ce

Radiative transfer simulations w/ the estimated log(gf)

Domoto et al. 2023
(arXiv: 2309.01198)



Absorption features by Ce III keep produced

How about actinide?

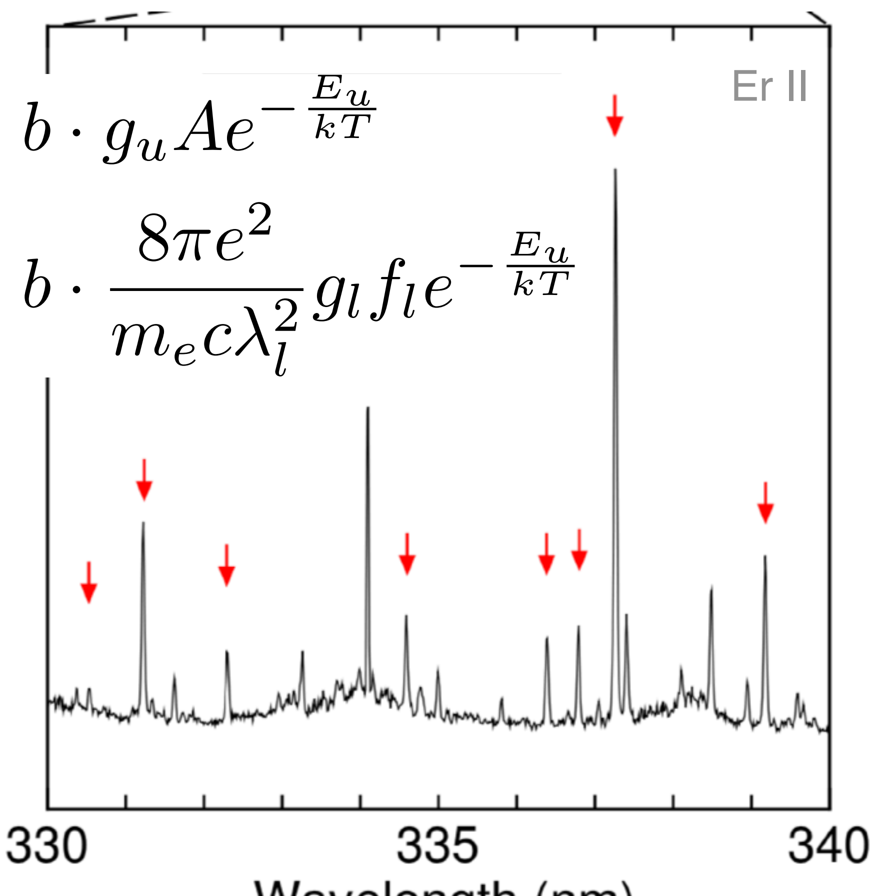
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Th III

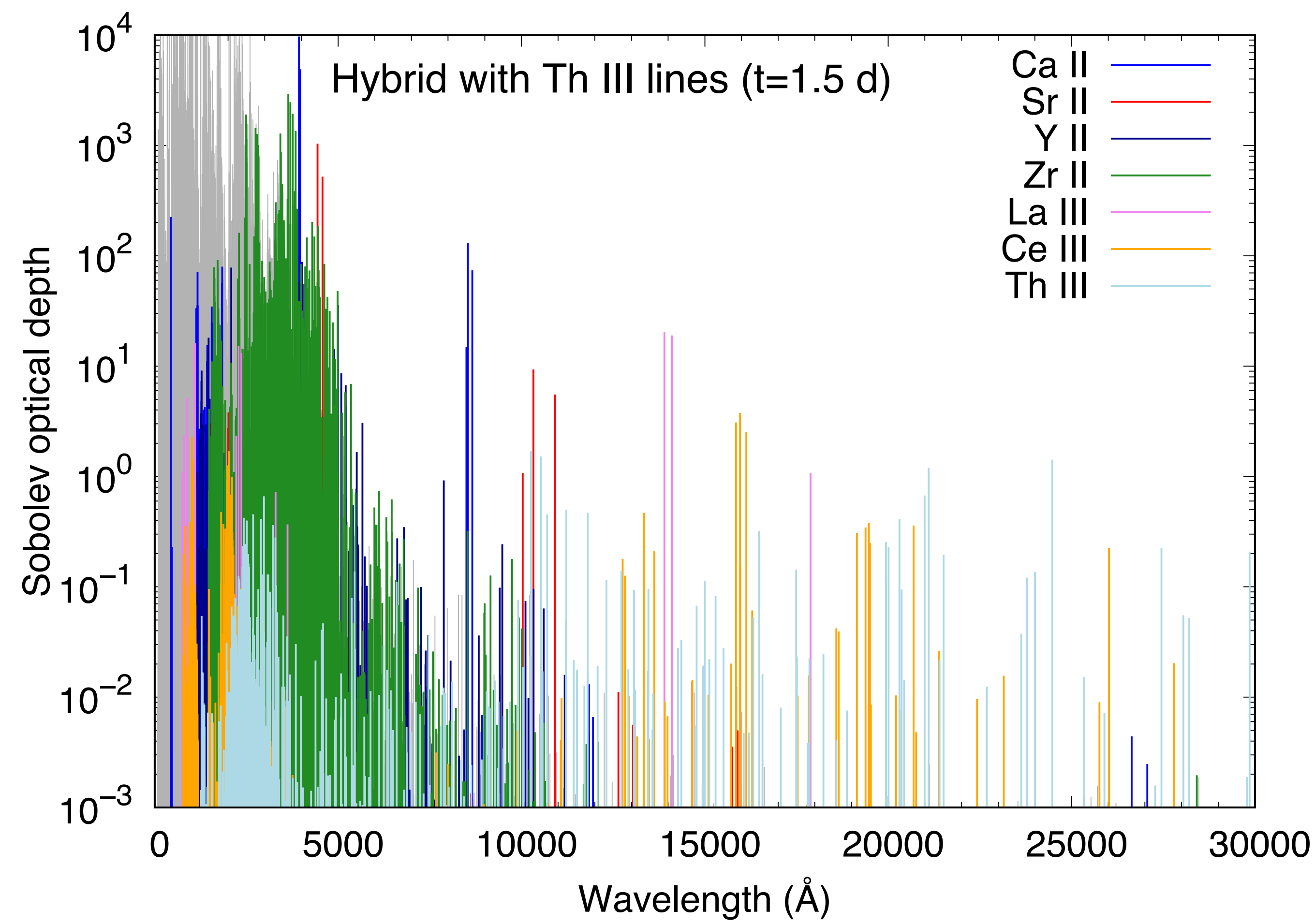
but see Fontes+23, F. Silva+22, Floers+23

- Theoretical data (HULLAC) are available up to Z=88
- Many lines are experimentally known, but gf of NIR lines are unknown

$$I = b \cdot g_u A e^{-\frac{E_u}{kT}}$$
$$= b \cdot \frac{8\pi e^2}{m_e c \lambda_l^2} g_l f_l e^{-\frac{E_u}{kT}}$$

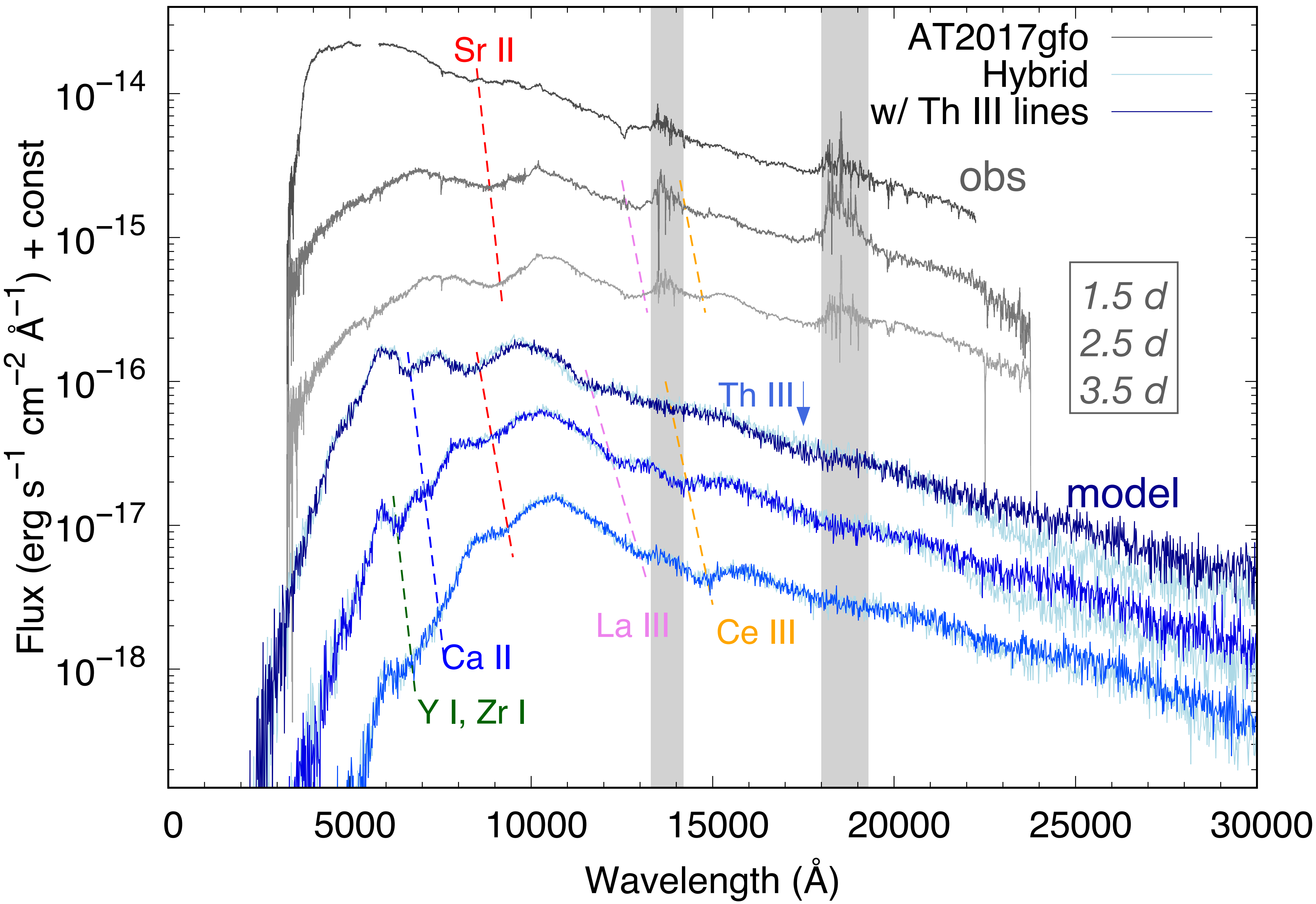


Naoi+22



Can we identify Th III?

Domoto et al. 2022



Th III features are less prominent…

Summary

- Identification of elements in spectra is
  the direct way to study synthesized individual elements

- Which elements can produce absorption features?

- New atomic data by taking advantages:
  - Theoretical (complete) line list -> find candidate species
  - Experimental (accurate) line list -> evaluate actual features

  - 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 high-Ye tracer: constraint on the physical conditions

  - First identification for the NIR features in GW170817: La and Ce
    Mass fractions of La and Ce are $< 2\times10^{-6}$ and $\sim 10^{-3}$-10^{-5} (direct estimate)

- Estimated gf-values from stellar spectra supports the identification of Ce