Identification and Abundance Estimate of Heavy Elements in Kilonova Spectra

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Light curves

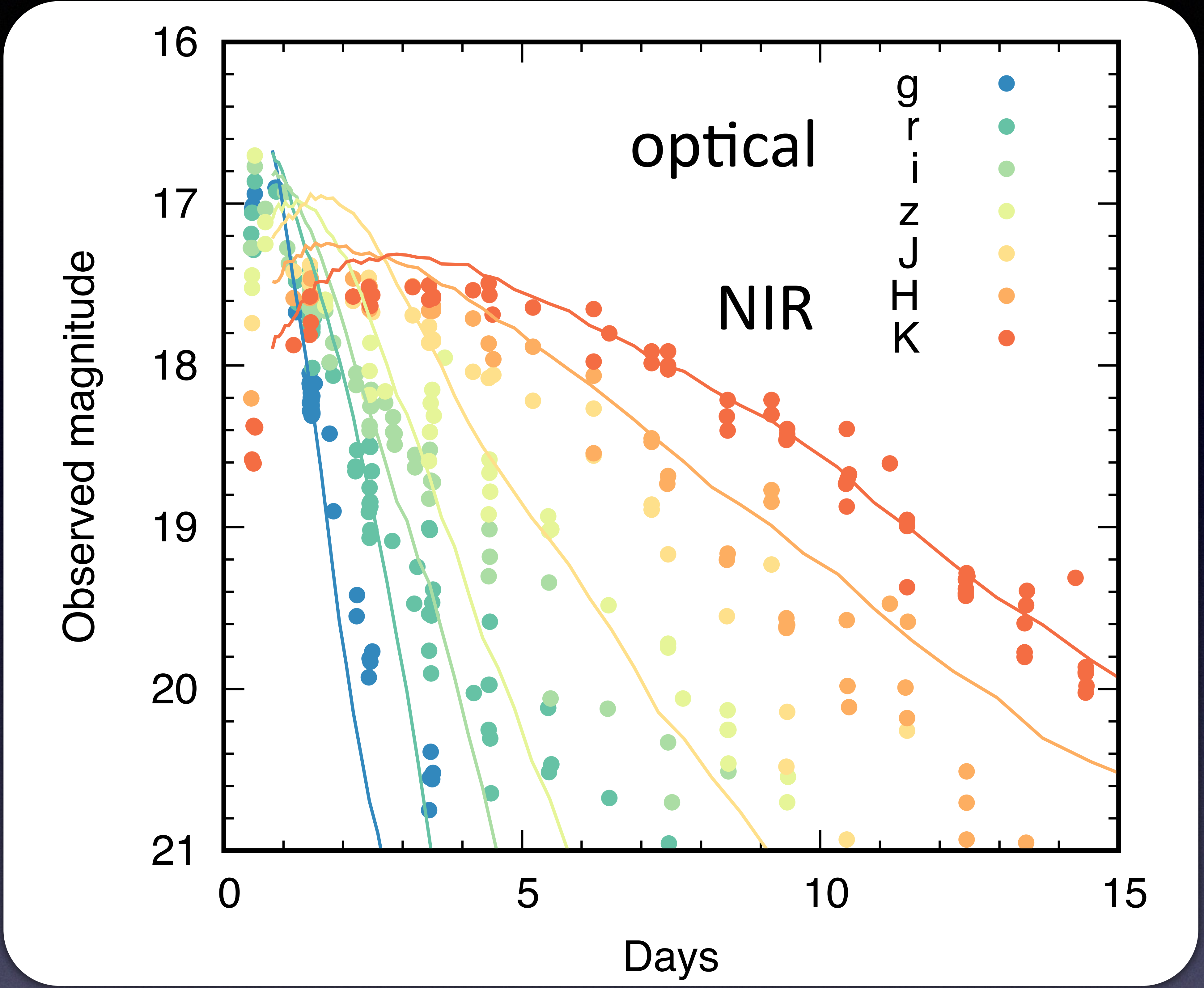


Figure from Kawaguchi+2018, 2020

Spectra

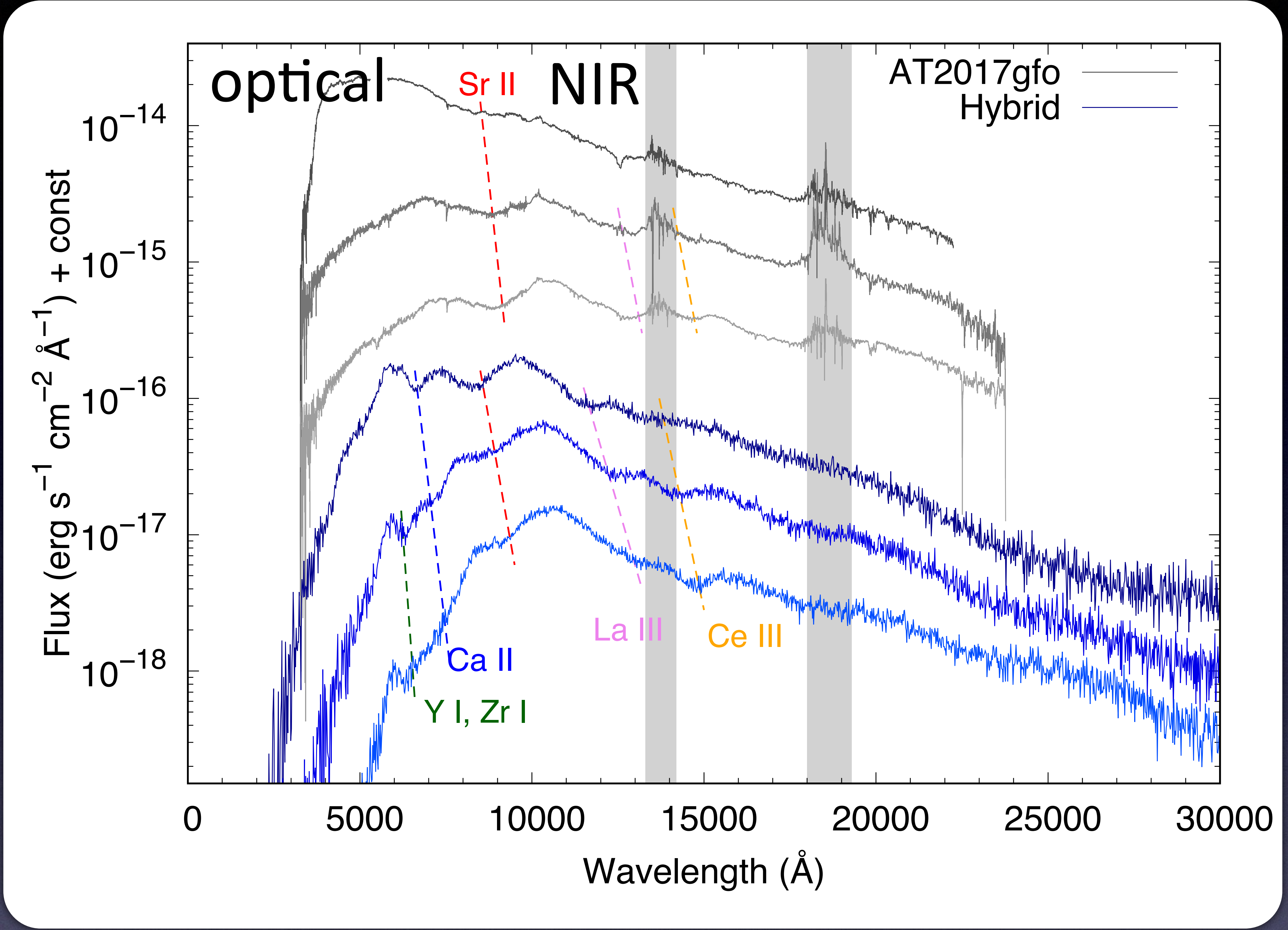


Figure from Domoto+2020,2022

What can we learn?

Ejected mass and (rough) composition

Detailed elemental compositions

Atomic data?

Opacity (statistical properties)

Accurate wavelength and transition probability

Identification and Abundance Estimate of Heavy Elements in Kilonova Spectra

- Element identification in kilonova spectra
- “Experiments” with chemically peculiar stars
- Towards abundance estimates

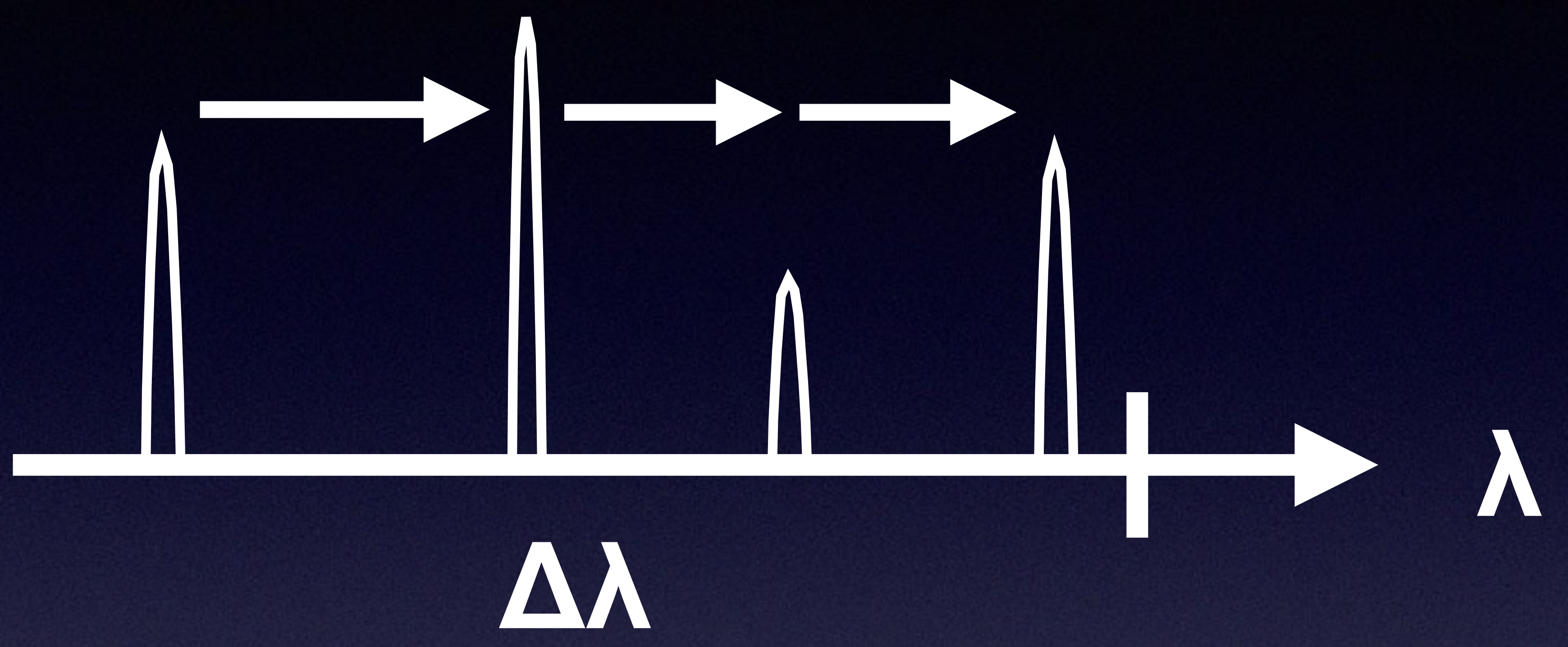
“Minimum” atomic data for kilonovae (LTE)

Bound-bound transitions (“line”)

Friend & Castor 1983 (stellar wind), Pinto & Eastman 1993 (supernova)
Kasen+06, Kasen+13, MT & Hotokezaka 13 (kilonova)

$$\kappa_{\rm exp}(\lambda) = \frac{1}{ct\rho}\sum_l \frac{\lambda_l}{\Delta\lambda}\left(1 - e^{-\tau_l}\right)$$

b-b opacity

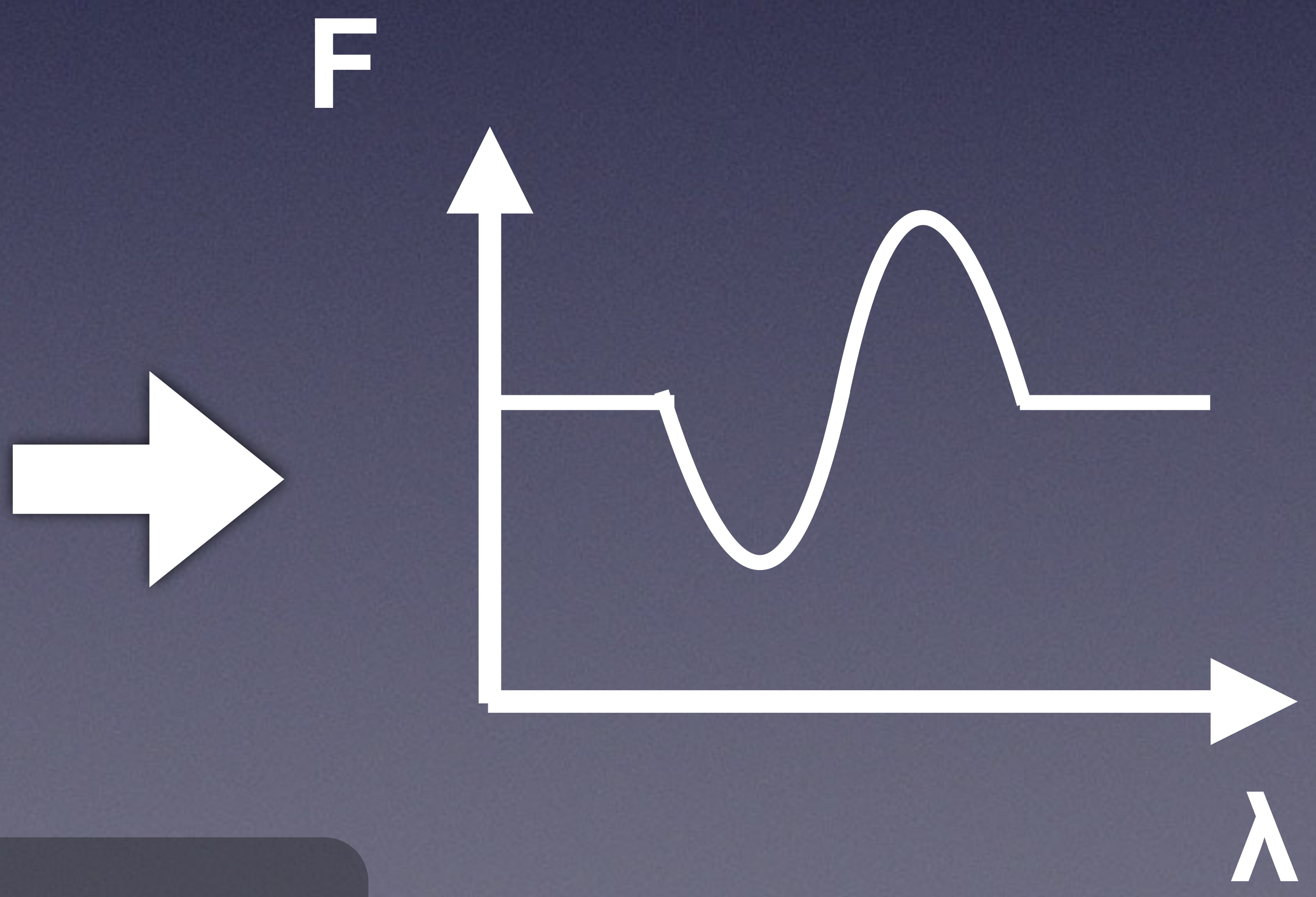


Optical depth of each line (under LTE)

$$\begin{aligned}\tau_l &= \int \alpha dr \\ &= \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l f_l \frac{g_l}{Z_p} e^{-\frac{E_l}{kT}}\end{aligned}$$

Energy levels

Spectrum

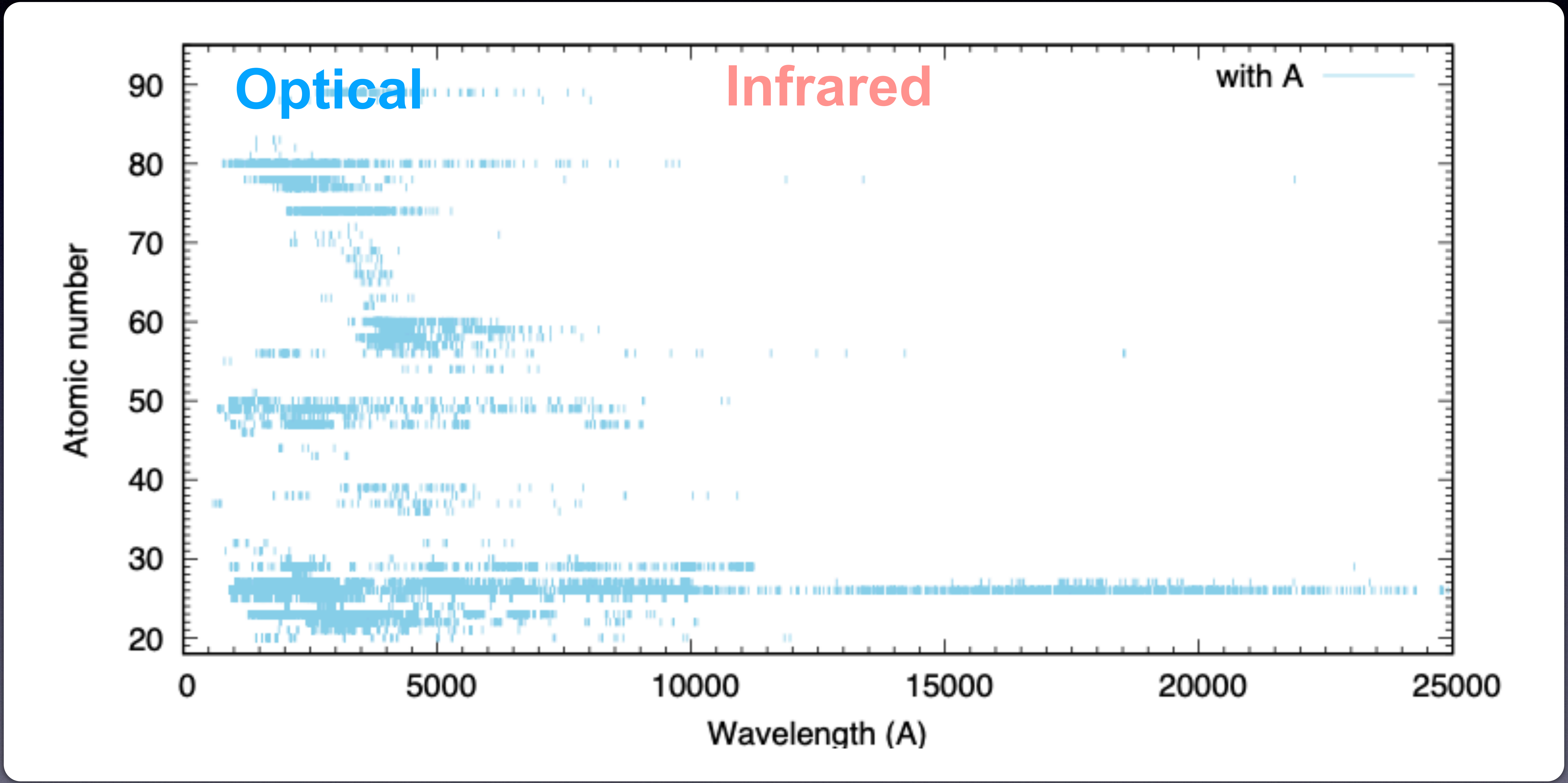


Energy levels + transition probabilities

Available atomic data

Data from the NIST database (singly ionized)

Transitions with known transition probability

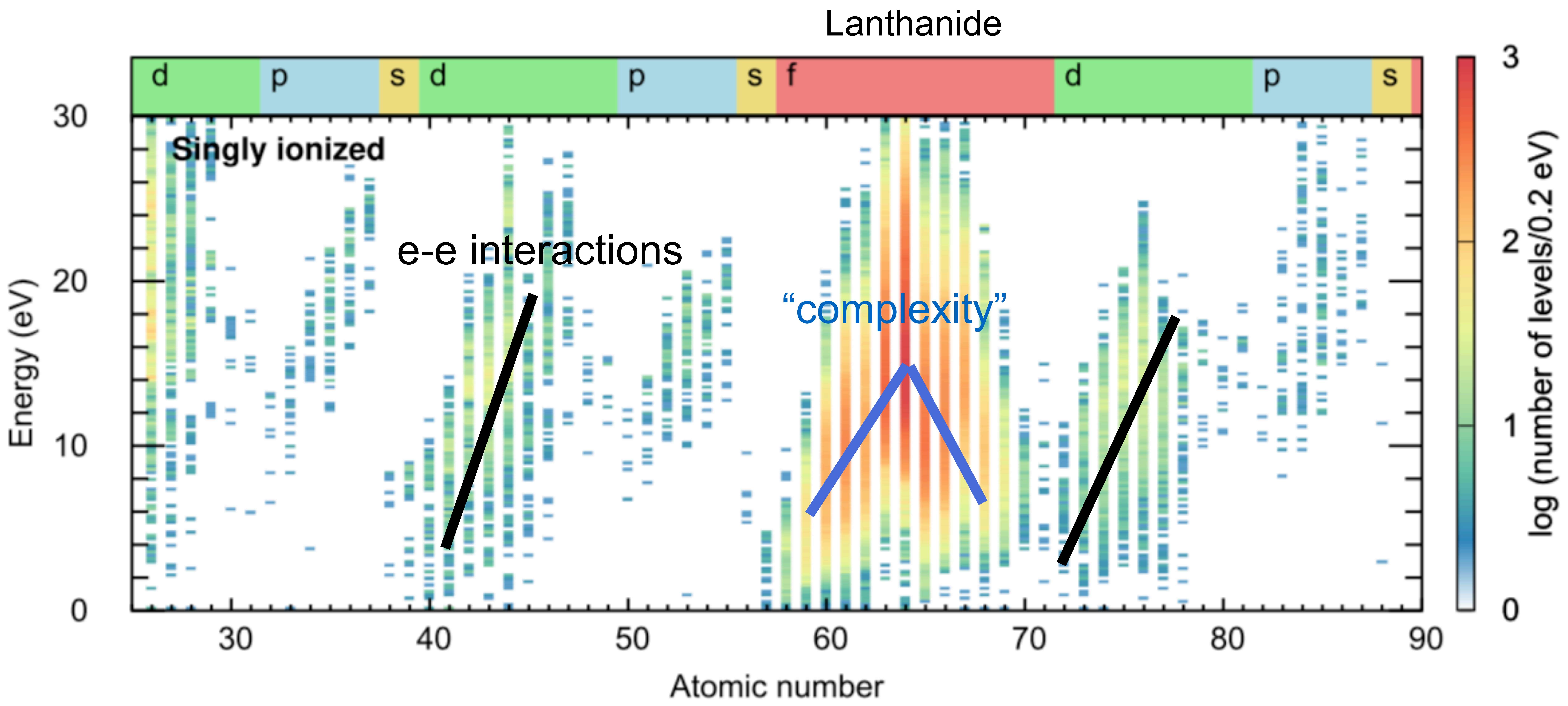


Accurate transition data are highly incomplete (in particular NIR)

Atomic structure calculations

Talks by Chris, Stephane, & Andreas

MT, Kato, Gaigalas, Kawaguchi 20 (HULLAC)
Kato, MT, et al. 24 (ver 2)
see also Fontes+20,21, Deprince+25, Flörs+26

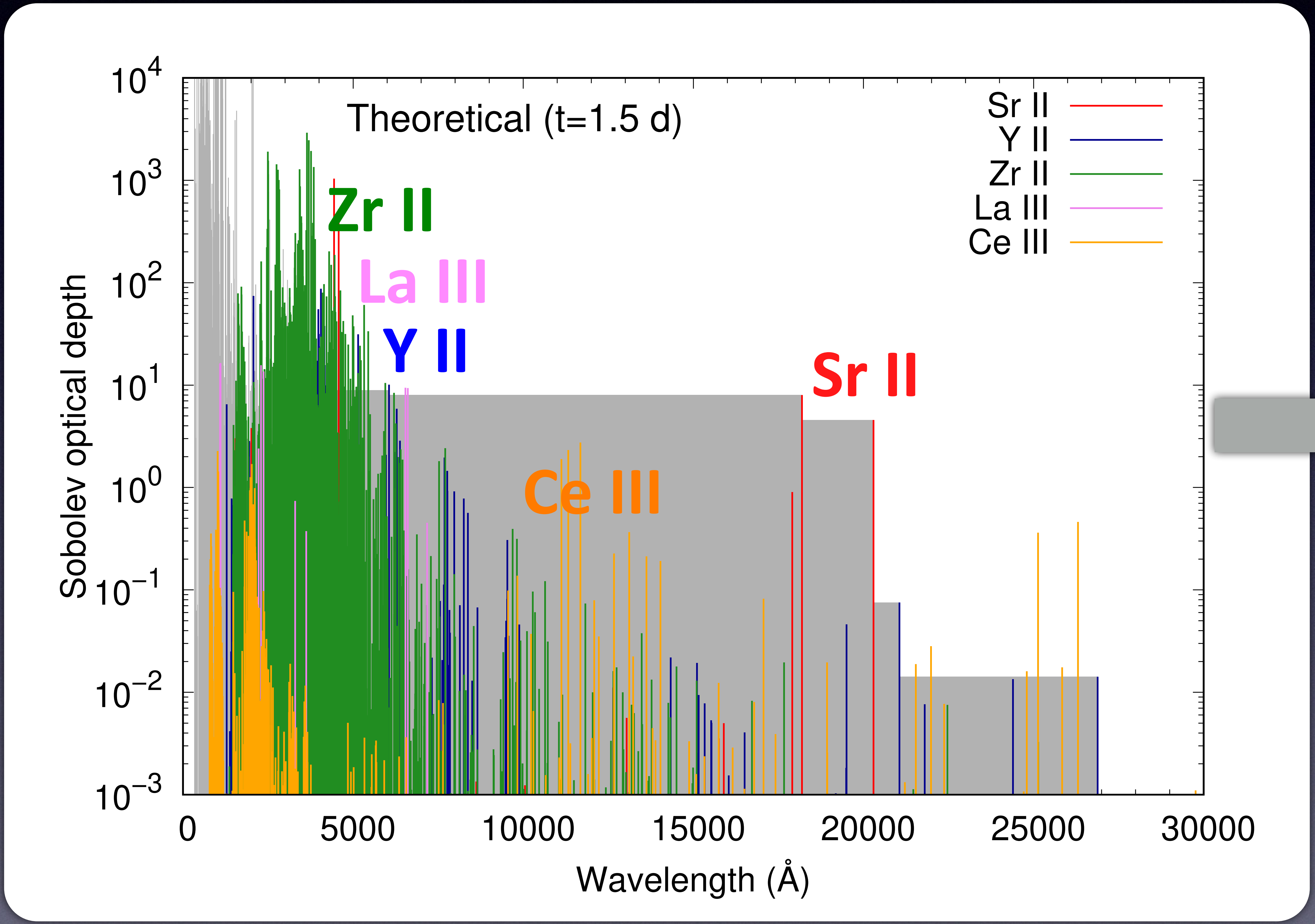


http://dpc.nifs.ac.jp/DB/Opacity-Database/

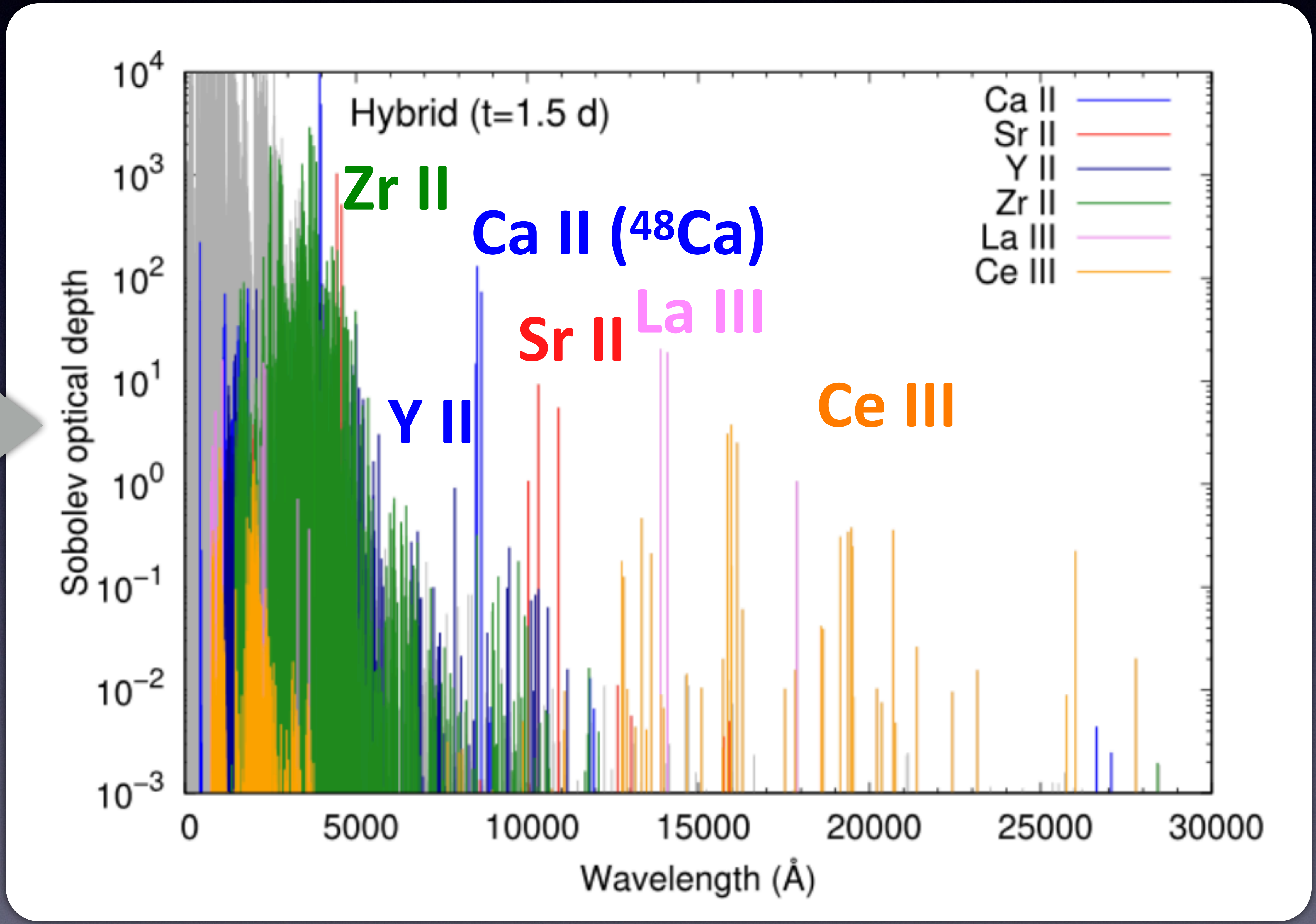
Selection of important elements

Domoto, MT, Kato+22

Theoretical data (MT+20)
(wavelengths are incorrect)



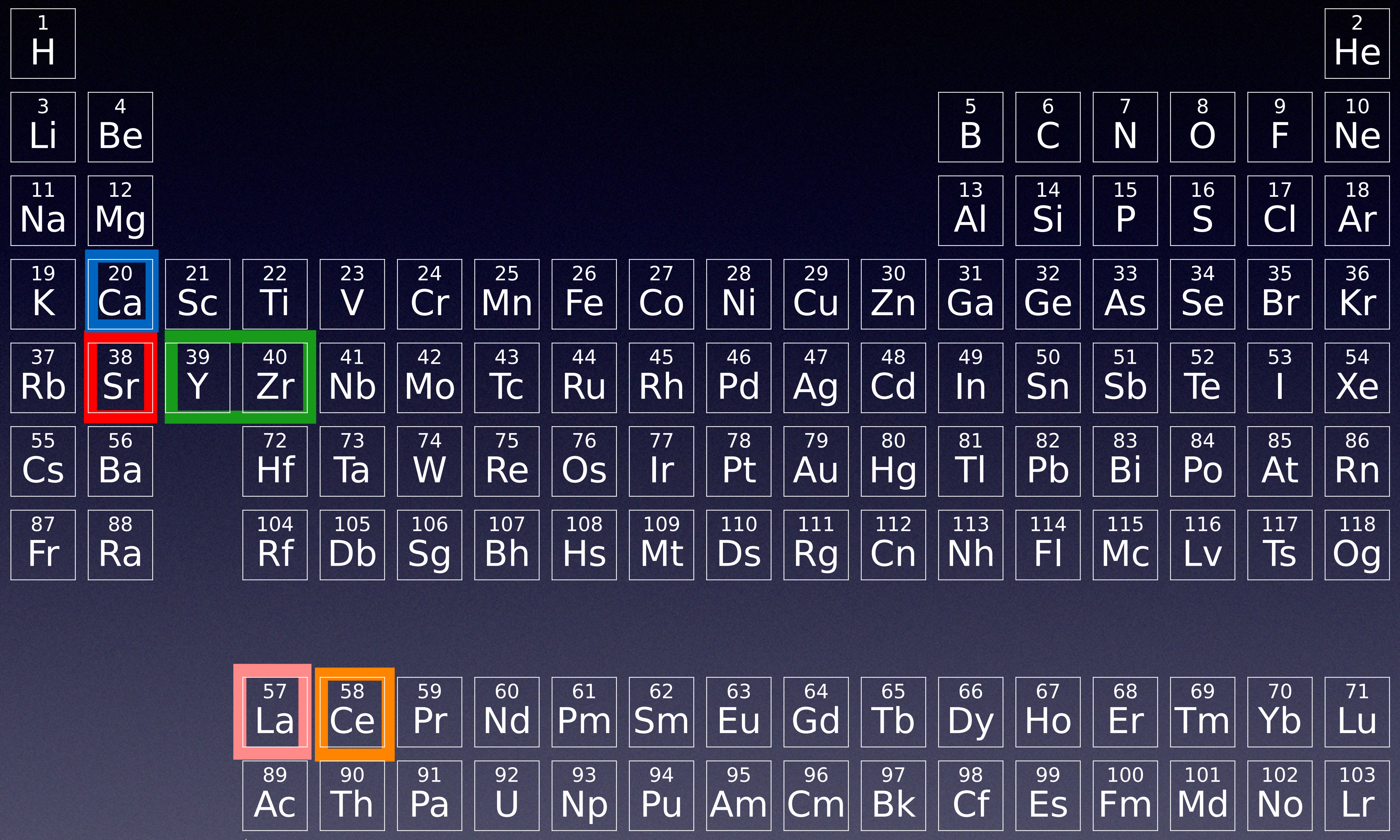
Calibrated for important elements

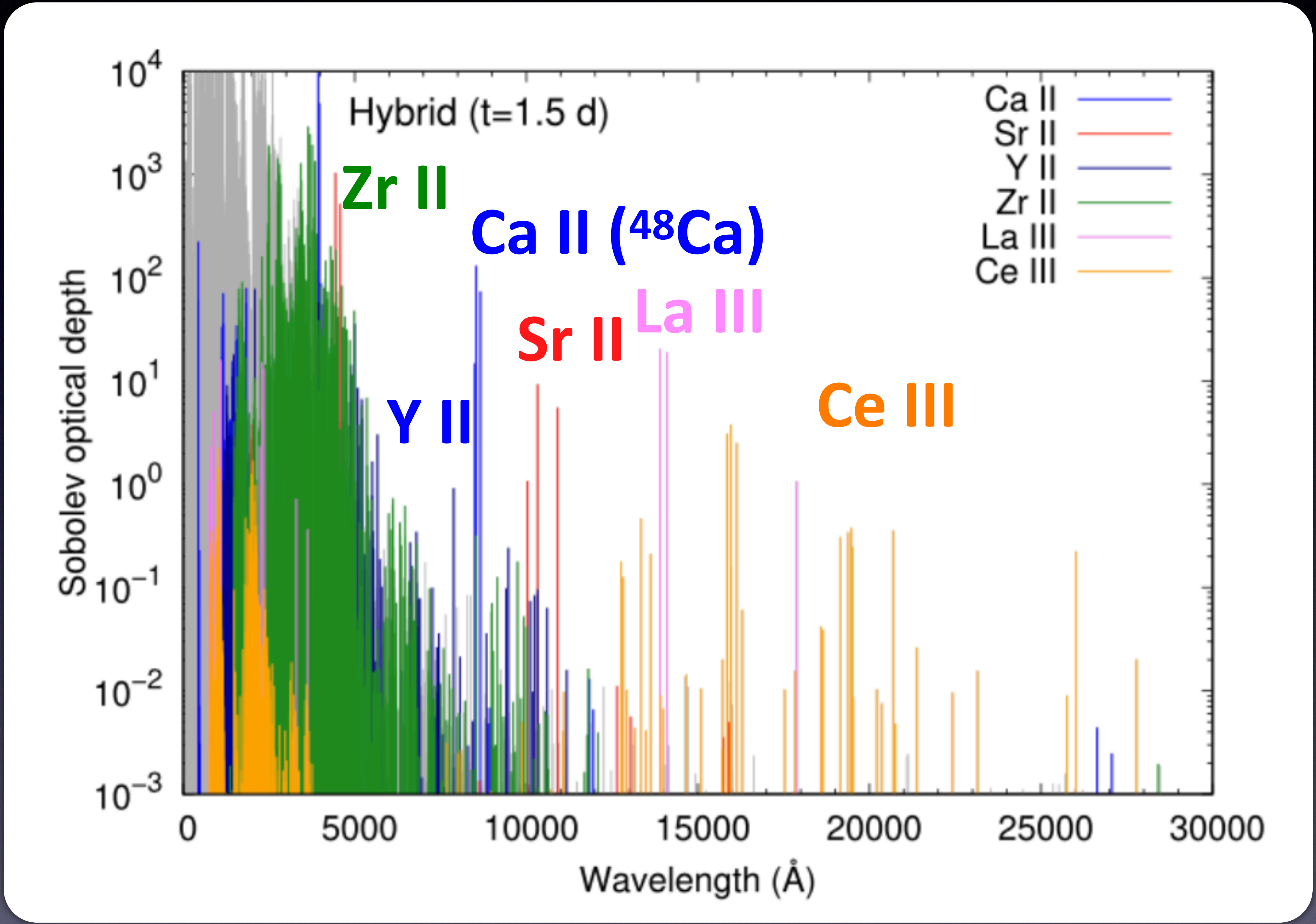


Relatively small number of elements/ions are important

Important elements for kilonova spectra

Watson+19 (Sr)
Domoto, MT, Kato+22 (La, Ce)
Sneppen & Watson 23 (Y)



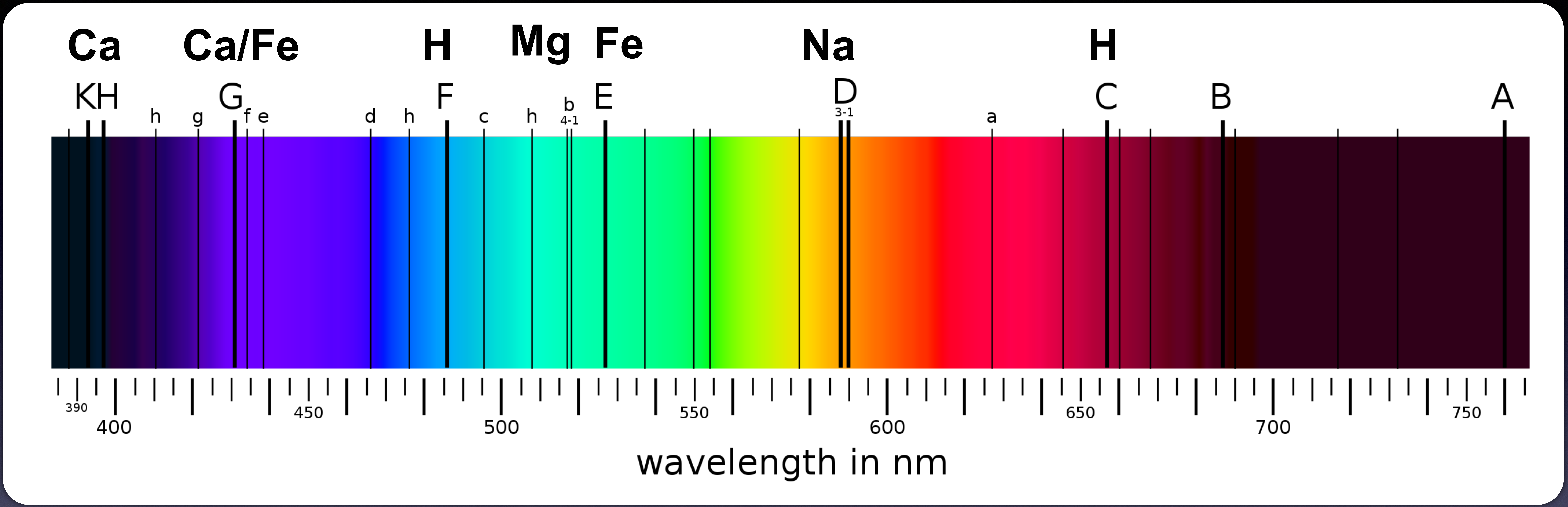


Elements with (1) low-lying energy levels
= higher population
(2) relatively simple structure = small number of transitions
=> high transition probability ("sum rule")

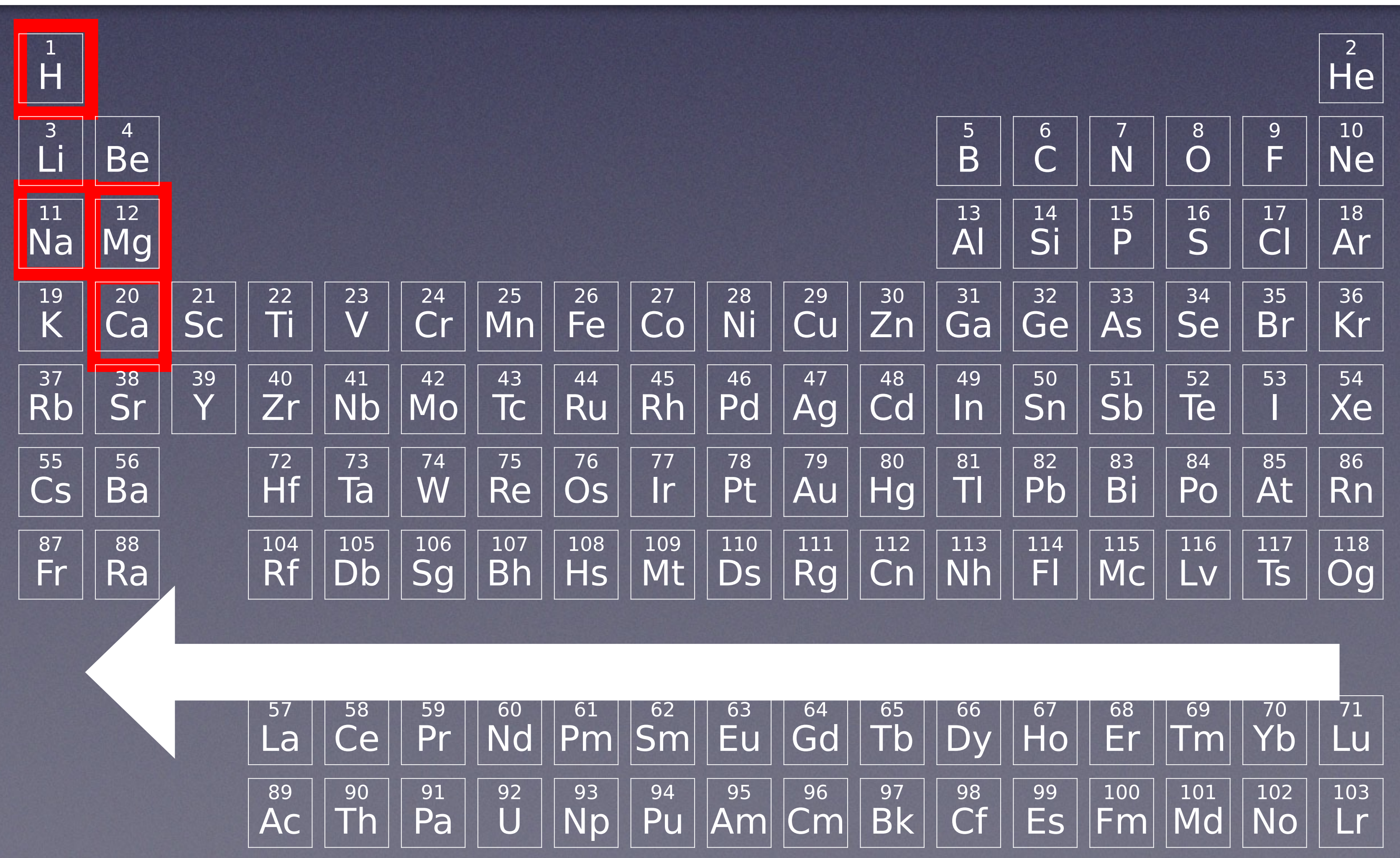
$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l f_l \frac{g_l}{Z_p} e^{-\frac{E_l}{kT}}$$

Solar spectrum

https://en.wikipedia.org/wiki/Fraunhofer_lines



Fraunhofer 1814



Kirchhoff & Bunsen 1860

CHEMICAL ANALYSIS BY SPECTRAL OBSERVATIONS.

BY

G. KIRCHHOFF AND R. BUNSEN.

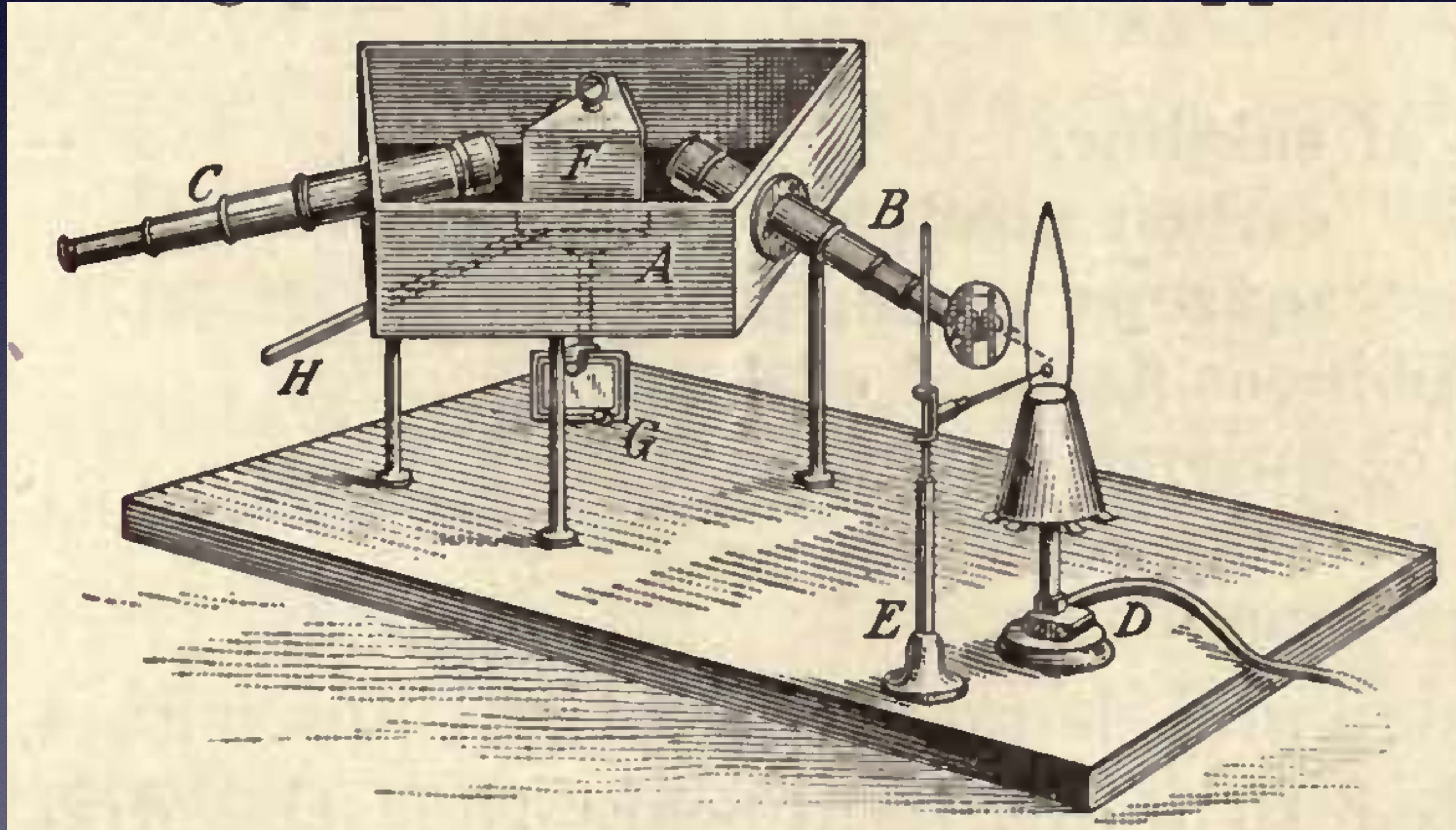
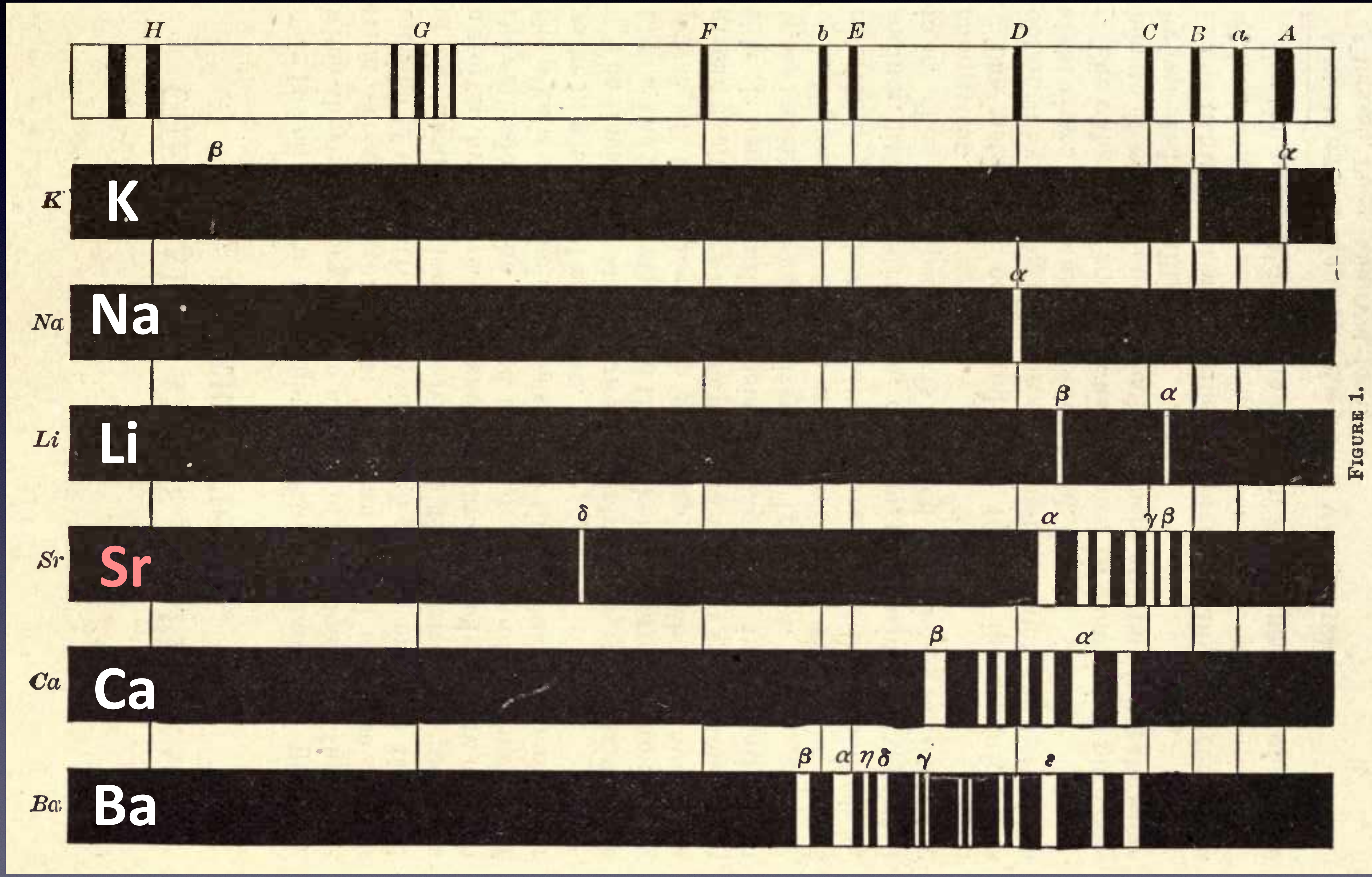


FIG. 2.



Henry Norris Russell 1929

ON THE COMPOSITION OF THE SUN'S ATMOSPHERE[1]

BY HENRY NORRIS RUSSELL[2]

A work after the pioneering work by Cecilia Payne 1925 (first work pointing the H dominance in the Sun)

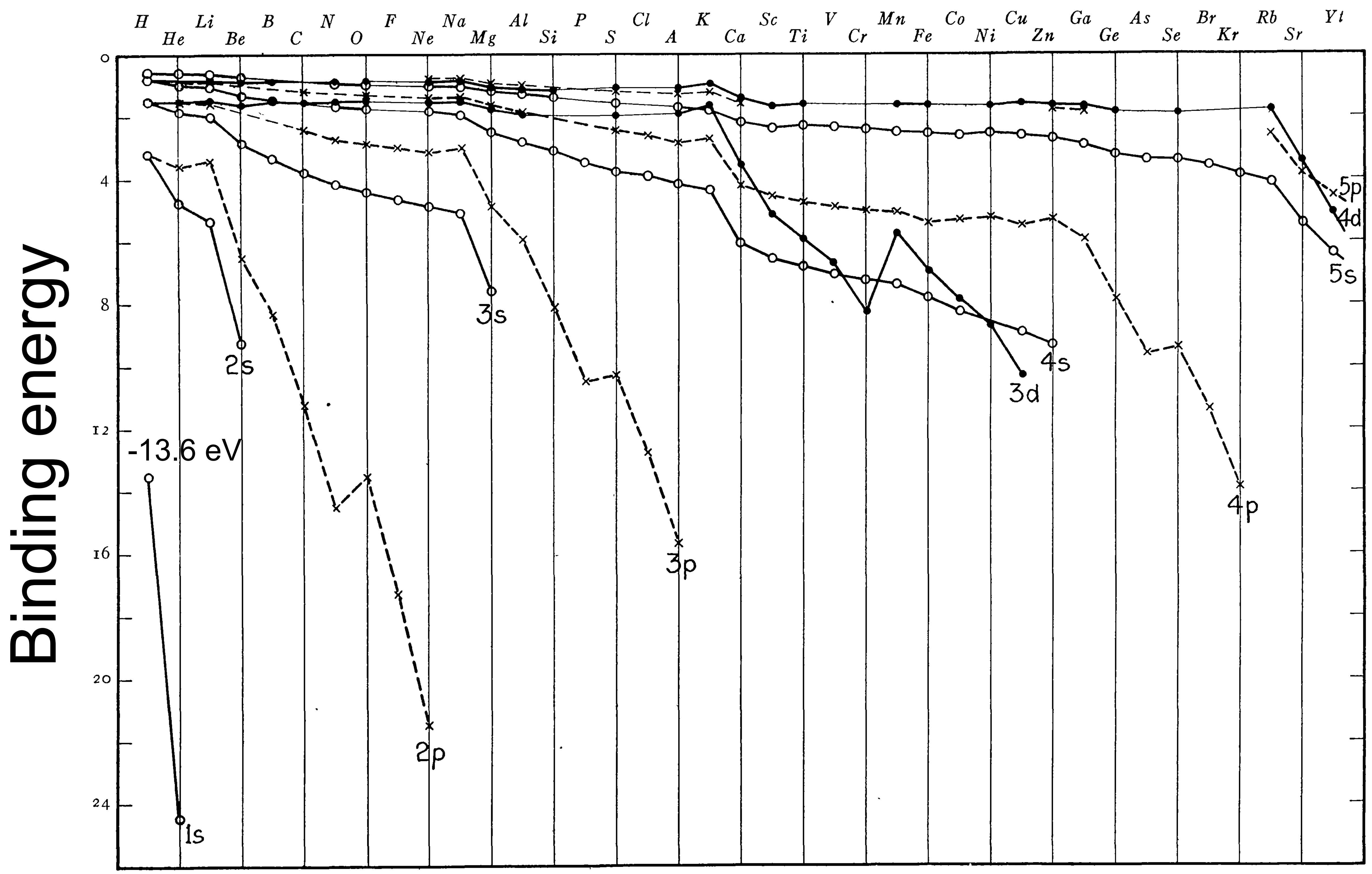


FIG. 1.—Energy of binding of electrons: neutral atoms

Atomic number

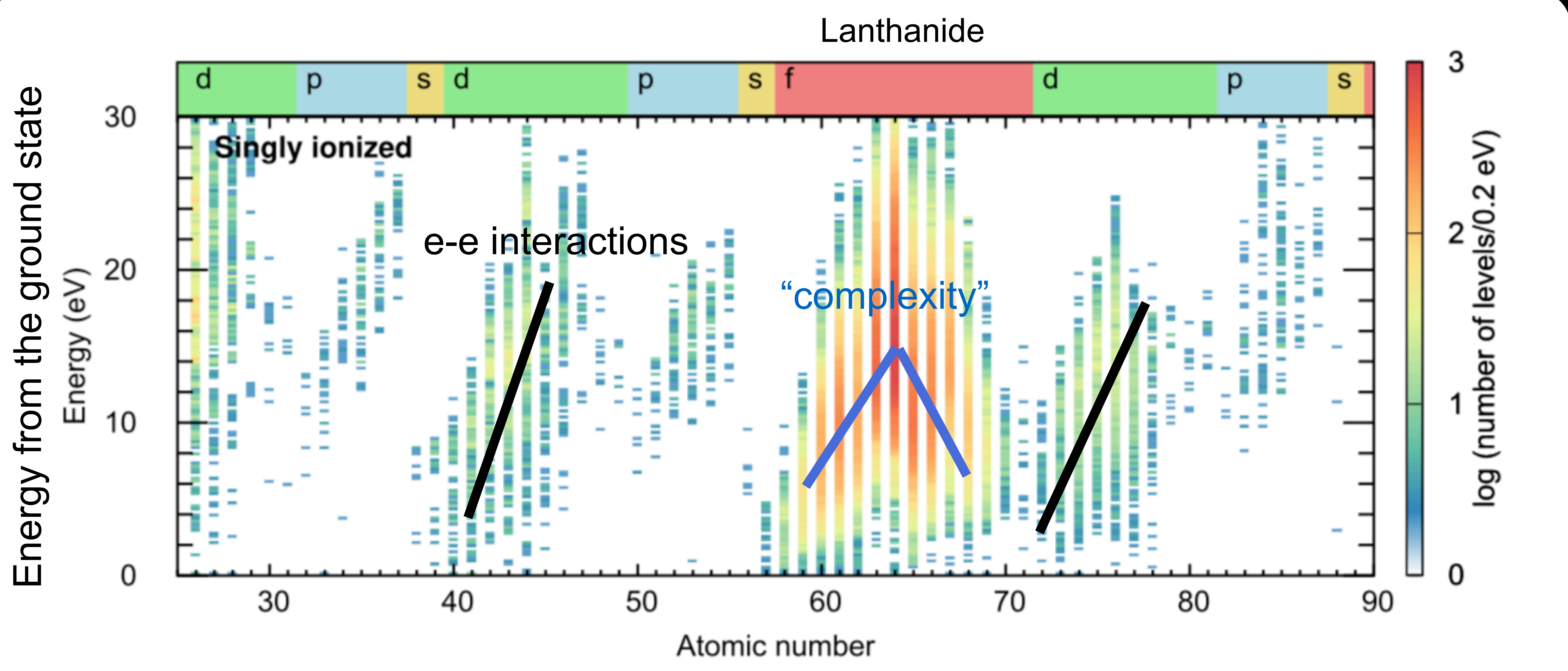
Lists of these lines, in the various arc spectra, are given in Table V. The lines marked with an asterisk have been recorded by De Gramont[2] or Meggers and Kiess[3] as *raies ultimes*, which actually persist in the manner described. Most of the rest are of too short wave-length to have been observed by them, but are undoubtedly of the same nature. Table VI gives similar data for spark spectra. The arrangement for the short periods differs slightly in order to bring spectroscopically similar terms into the same line.

These tables confirm the conclusions which were drawn from the general structure of the spectra. The most persistent arc lines of almost all the metals lie within the region accessible in the sun, while those of the non-metals are without exception out of range. Conditions for detecting the spark lines astrophysically are favorable only for the metals in the earlier parts of the successive periods—for *Be*, *Ca* to *V*, *Sr* to *Cb*, *Ba*, *La*, and probably several of the rare earths, and finally for *Ra*.

"earlier parts of the successive periods" = left side of the periodic table

Atomic structure calculations

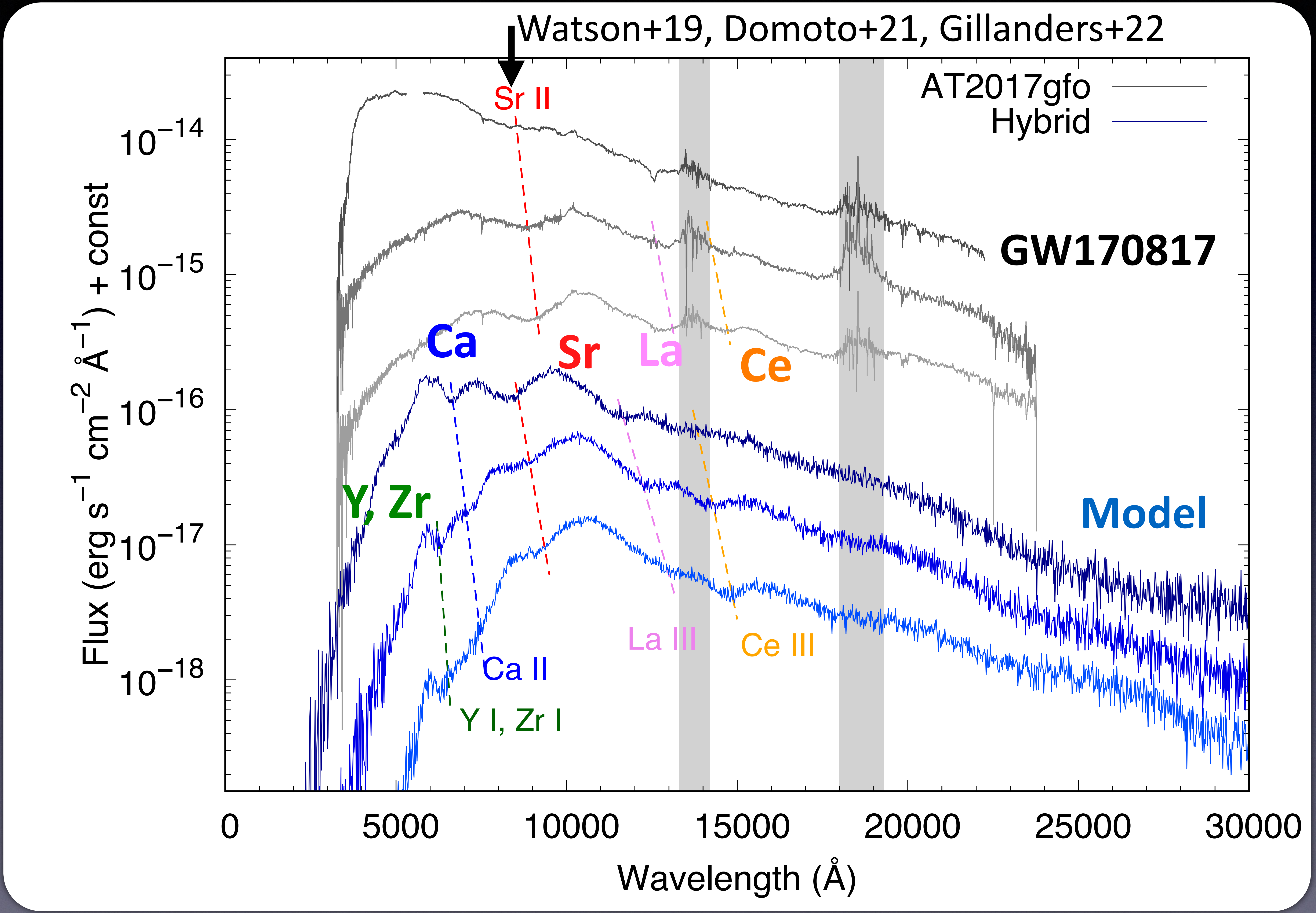
MT, Kato, Gaigalas, Kawaguchi 20 (HULLAC)
Kato, MT, et al. 24 (ver 2)
see also Fontes+20,21, Deprince+25, Flörs+26



http://dpc.nifs.ac.jp/DB/Opacity-Database/

Line identification in NIR wavelength

Domoto+22
see also Gillanders+24

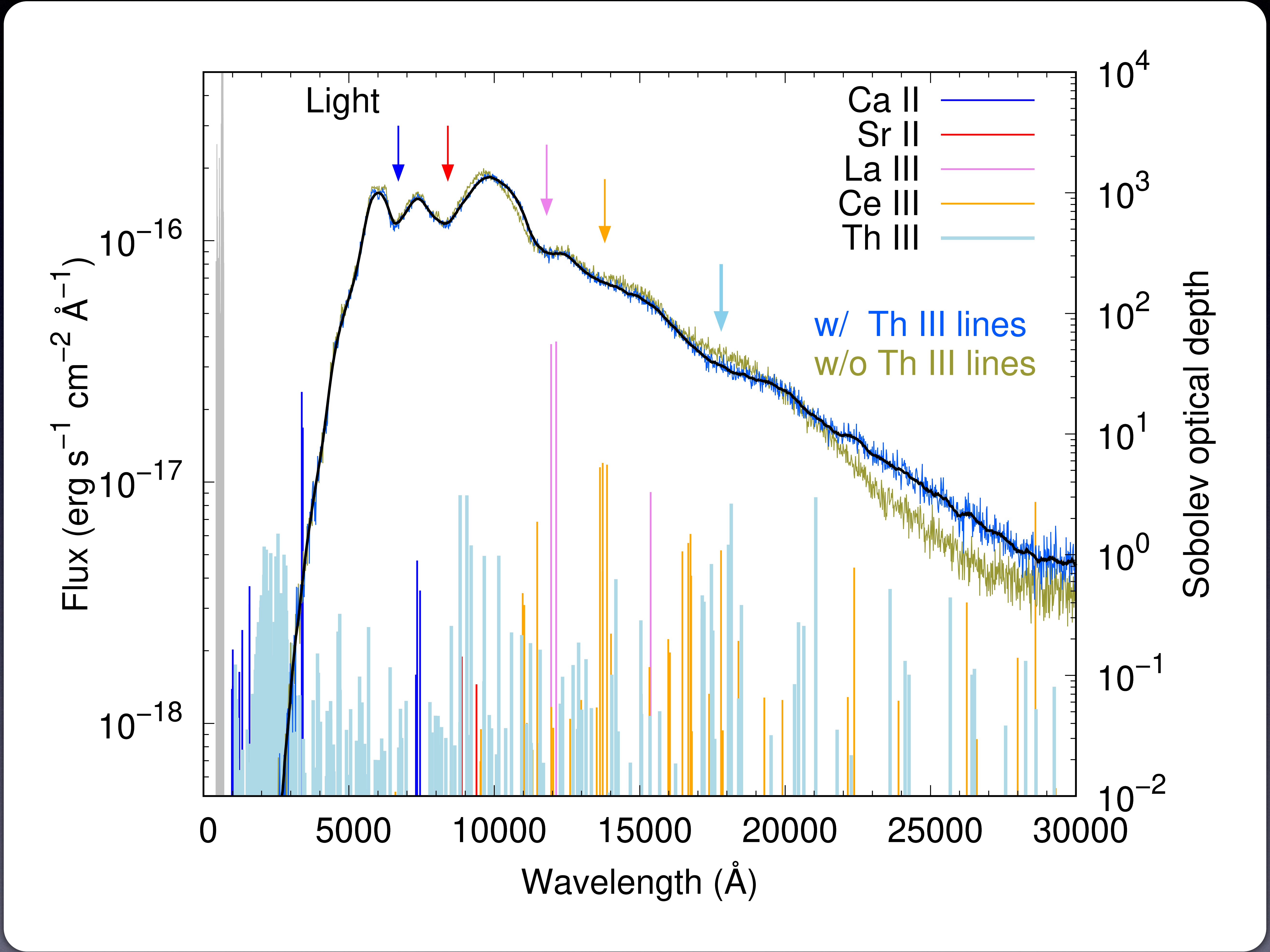


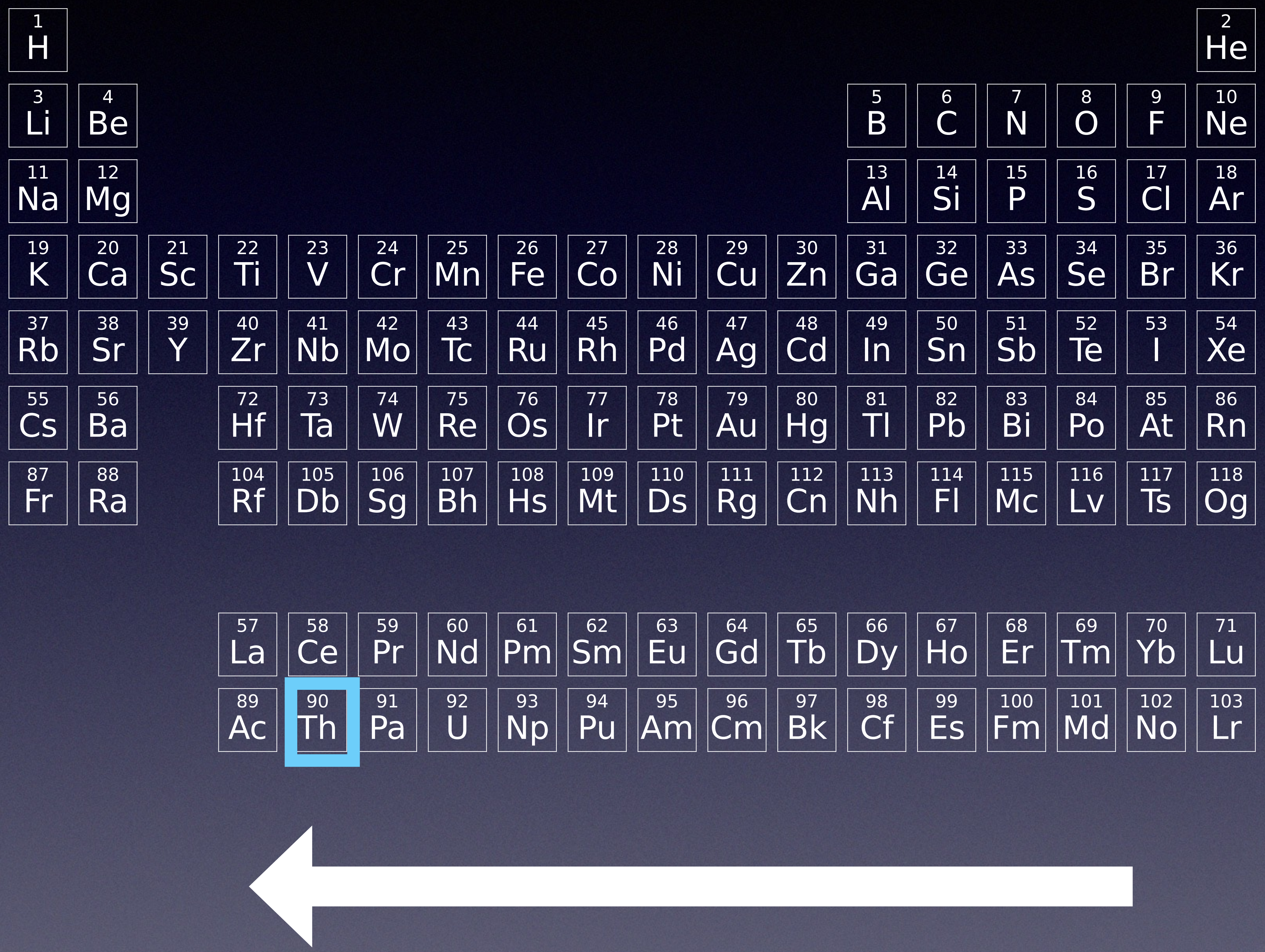
La III (Z=57) and Ce III (Z=58)

Th (Z=90): Heaviest detectable element?

see talks by Camilla and Alex (for metal poor stars)

Domoto+25, see also Pognan+25





Hope for future observations with HST/JWST

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- “Experiments” with chemically peculiar stars
- Towards abundance estimates

Road to the line identification

"Candidate"

(1) Wavelength match

(w/ reasonable Doppler shift)

Need transition wavelengths

(2) Strong lines are expected

(abundances, ionization, excitation, …)

Need transition probabilities

(3) Uniqueness

No other line can produce the same feature

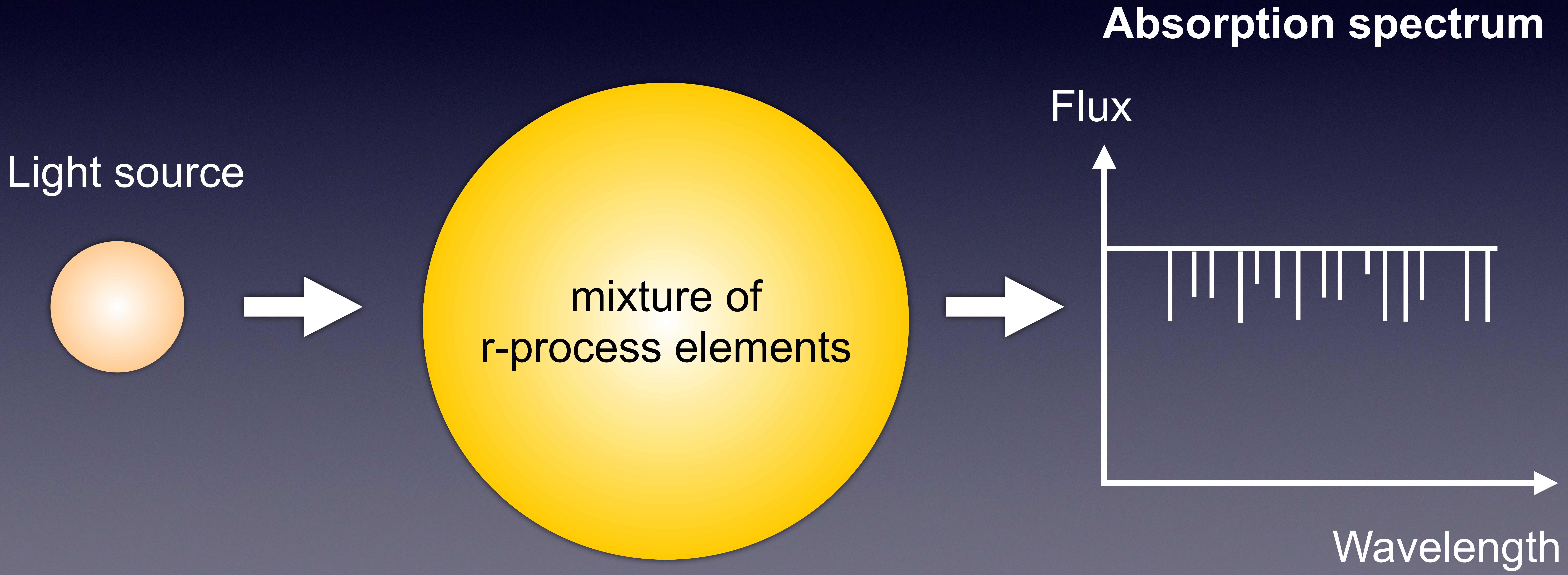
Need data of strong transitions all the elements

"Unique identification"

How to test the uniqueness of the line identification??

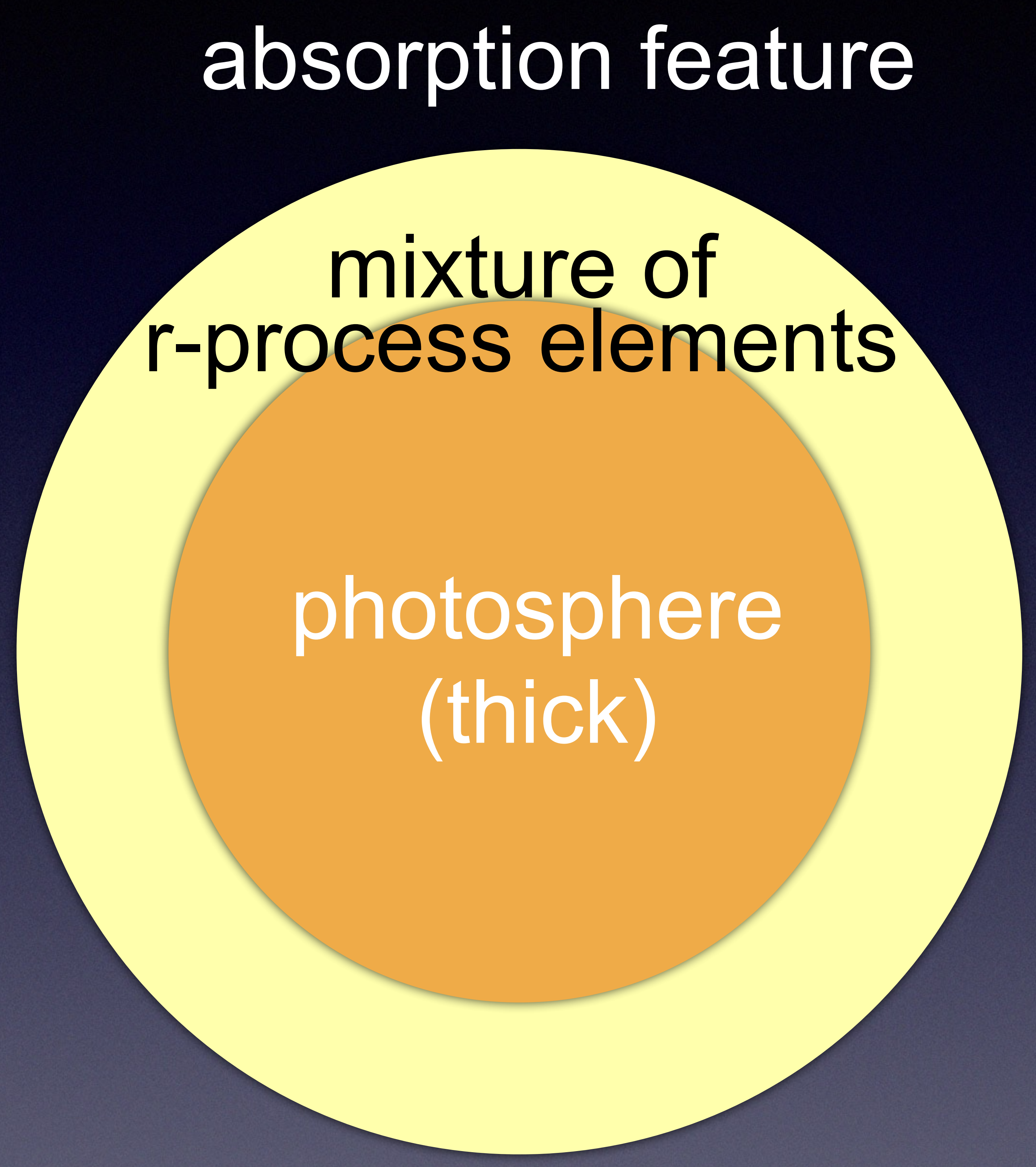
The best spectroscopic experiment…

- $T \sim 5{,}000$ K, $\rho \sim 10^{-15}$ g cm^{-3} ($n \sim \rho / A\, m_p \sim 10^{7}$ cm^{-3})
- Heavy elements dominated plasma

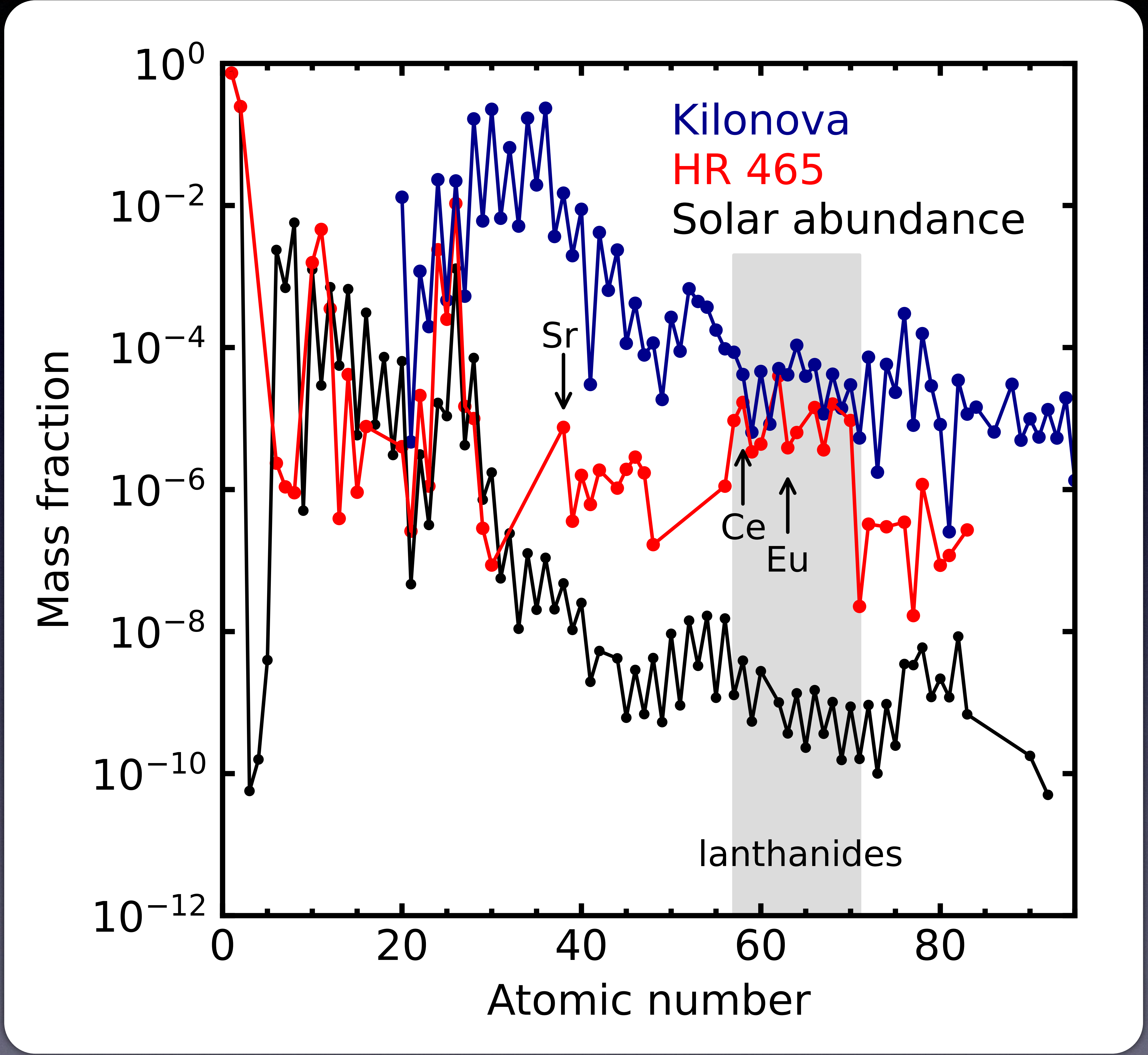


"Experiments" with chemically peculiar stars

MT, Domoto, Aoki et al. 2023



HR 465
[Fe/H] ~ +1.0, [Eu/H] ~ + 4.0

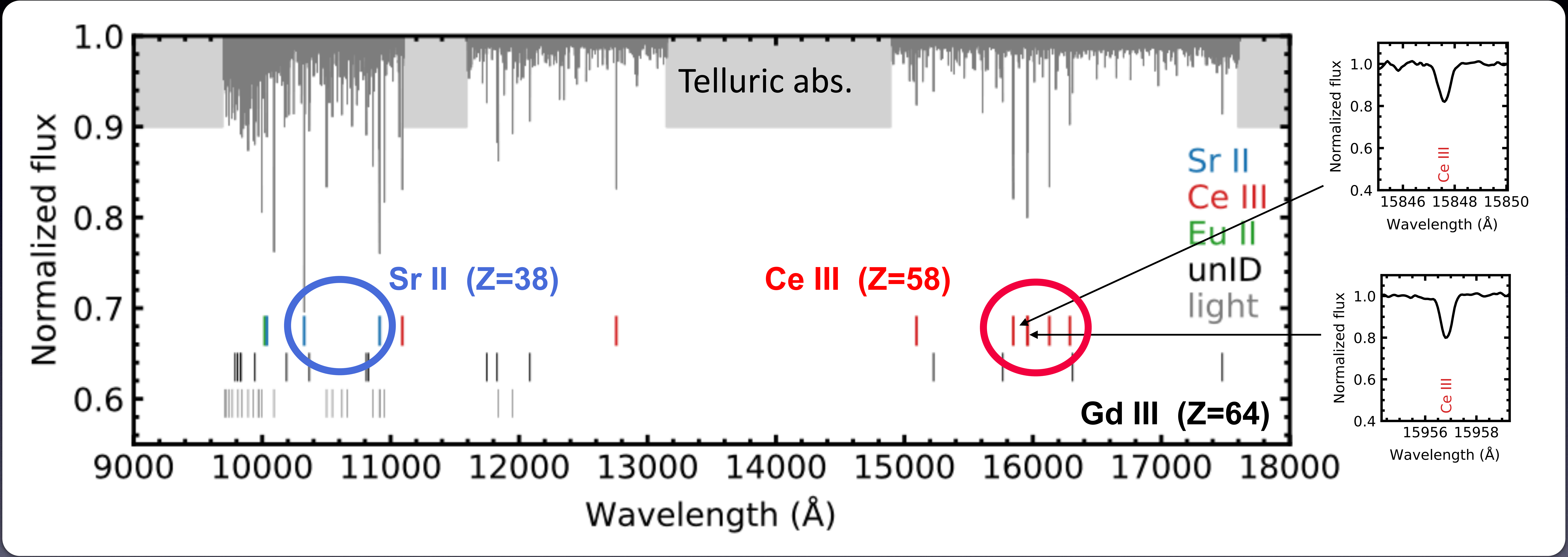


Similar lanthanide abundances (and ionization degrees) with NS merger

NIR spectrum of chemically peculiar star

MT, Domoto, Aoki+23 (Ce)

Subaru/IRD (R ~ 70,000)



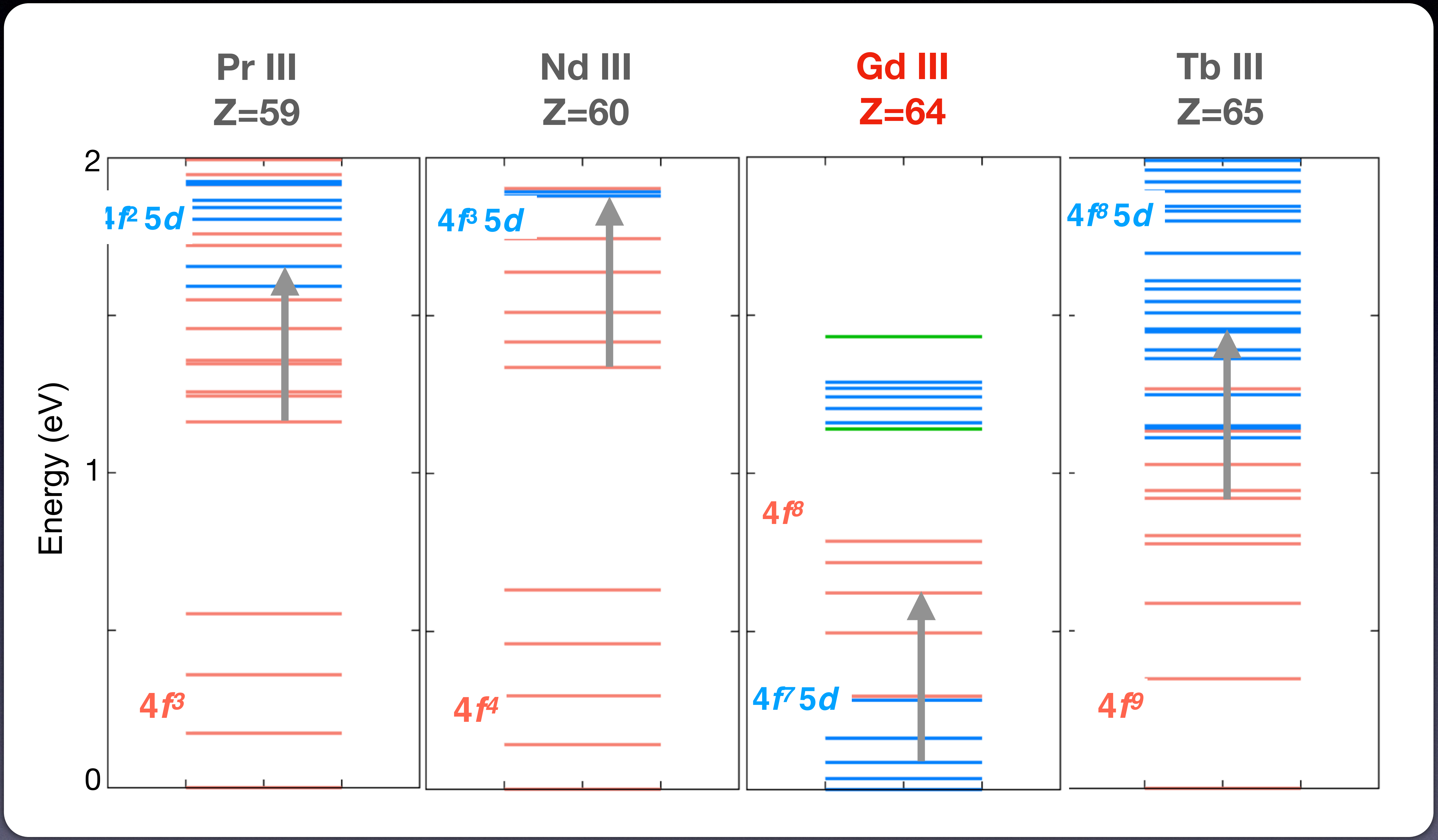
Strongest lines = Sr II, Ce III, and Gd III (La III is not covered)

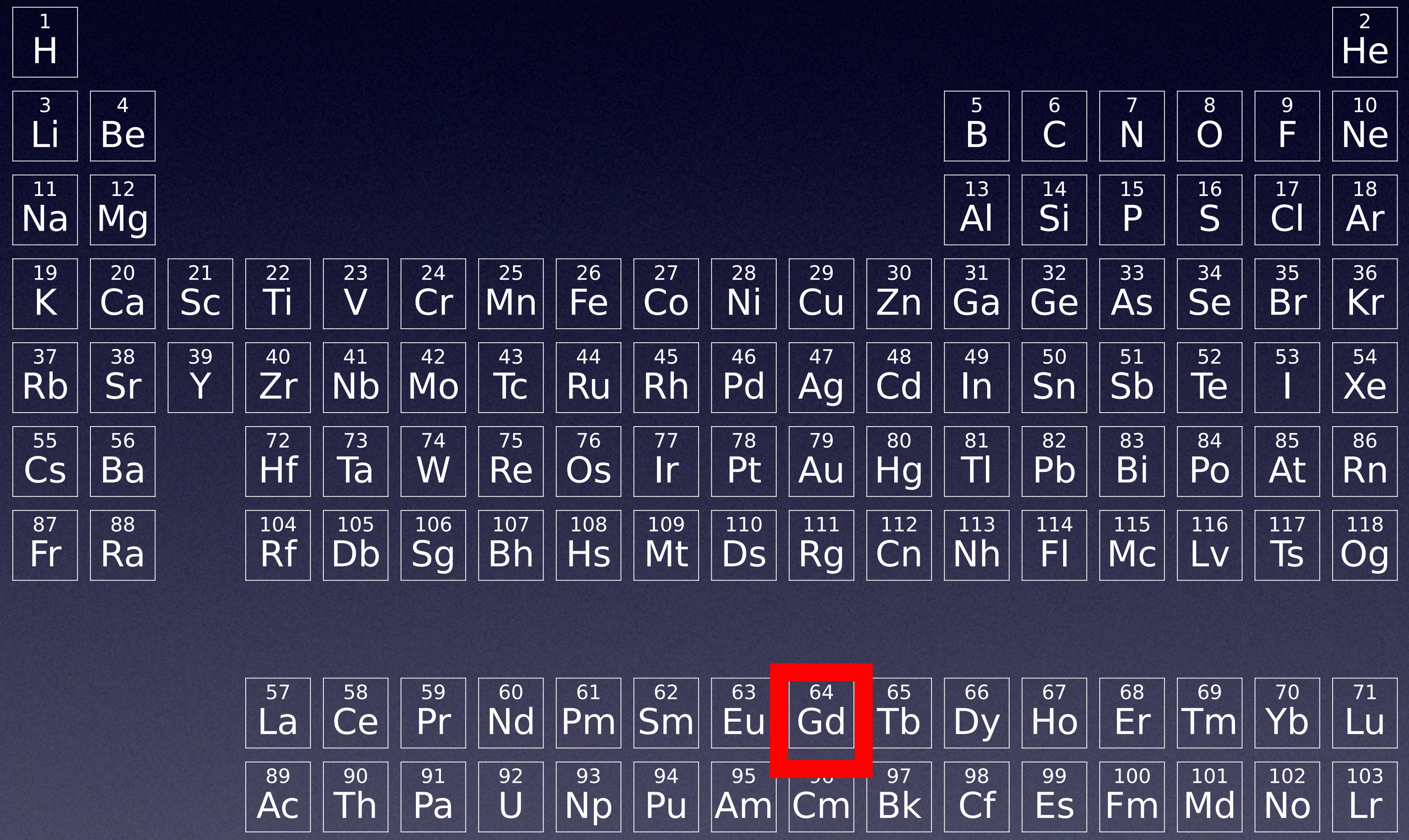
No other comparably strong lines = uniqueness of the identification

An interesting exception: Gd (Z=64)

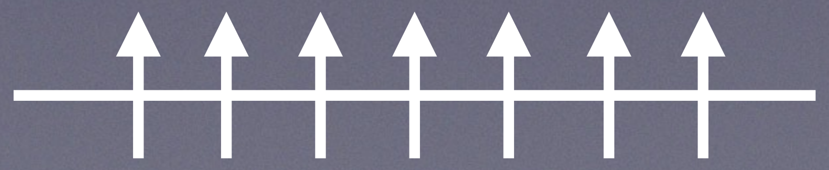
Rahmouni, MT, Domoto+25

see also Gillanders+24, Collins+26 (atomic data by Flörs+26)





$4f^7$ 5d (4f half closed) has lower energy than $4f^8$

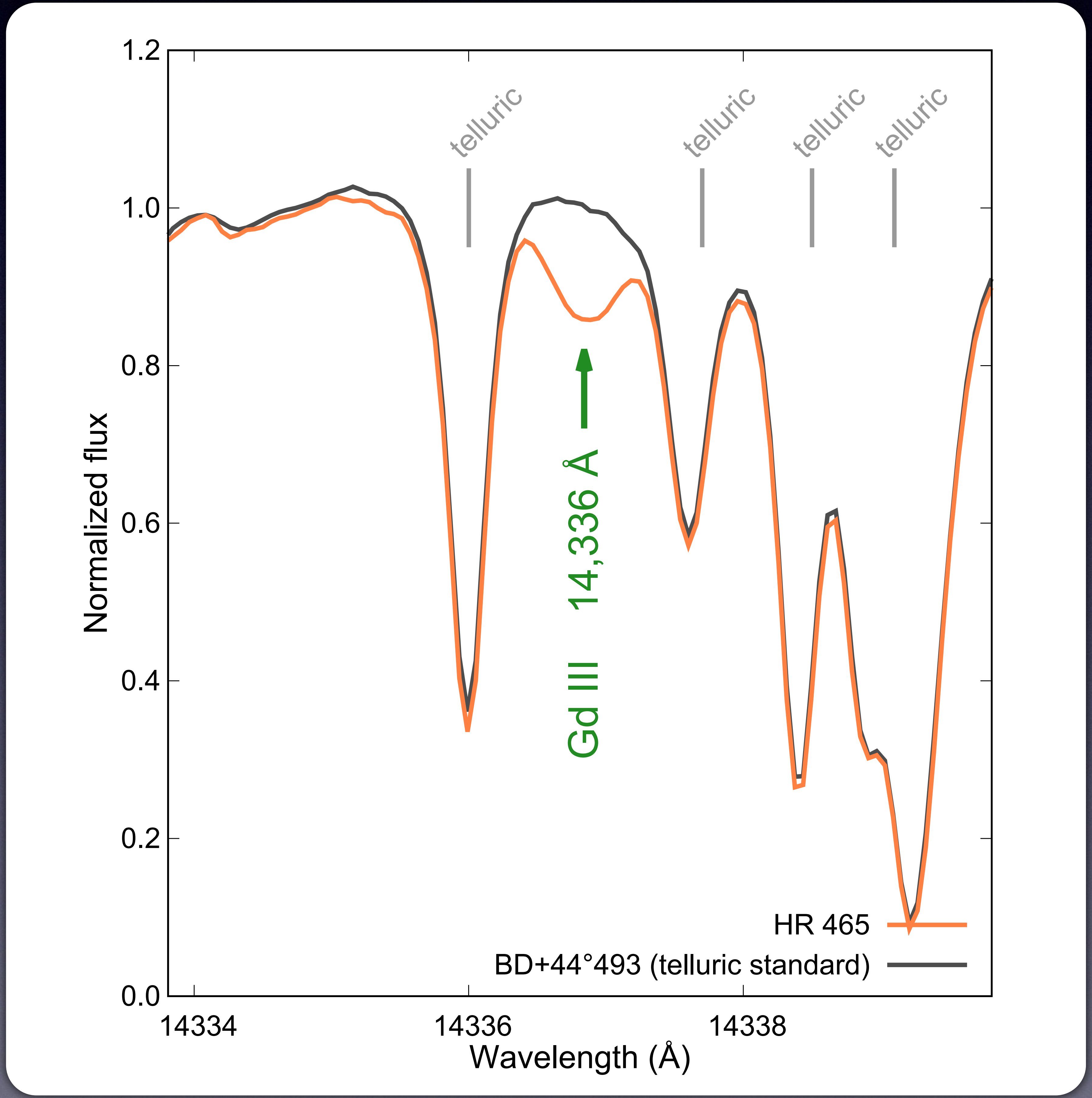


Importance of Gd features (Z=64)

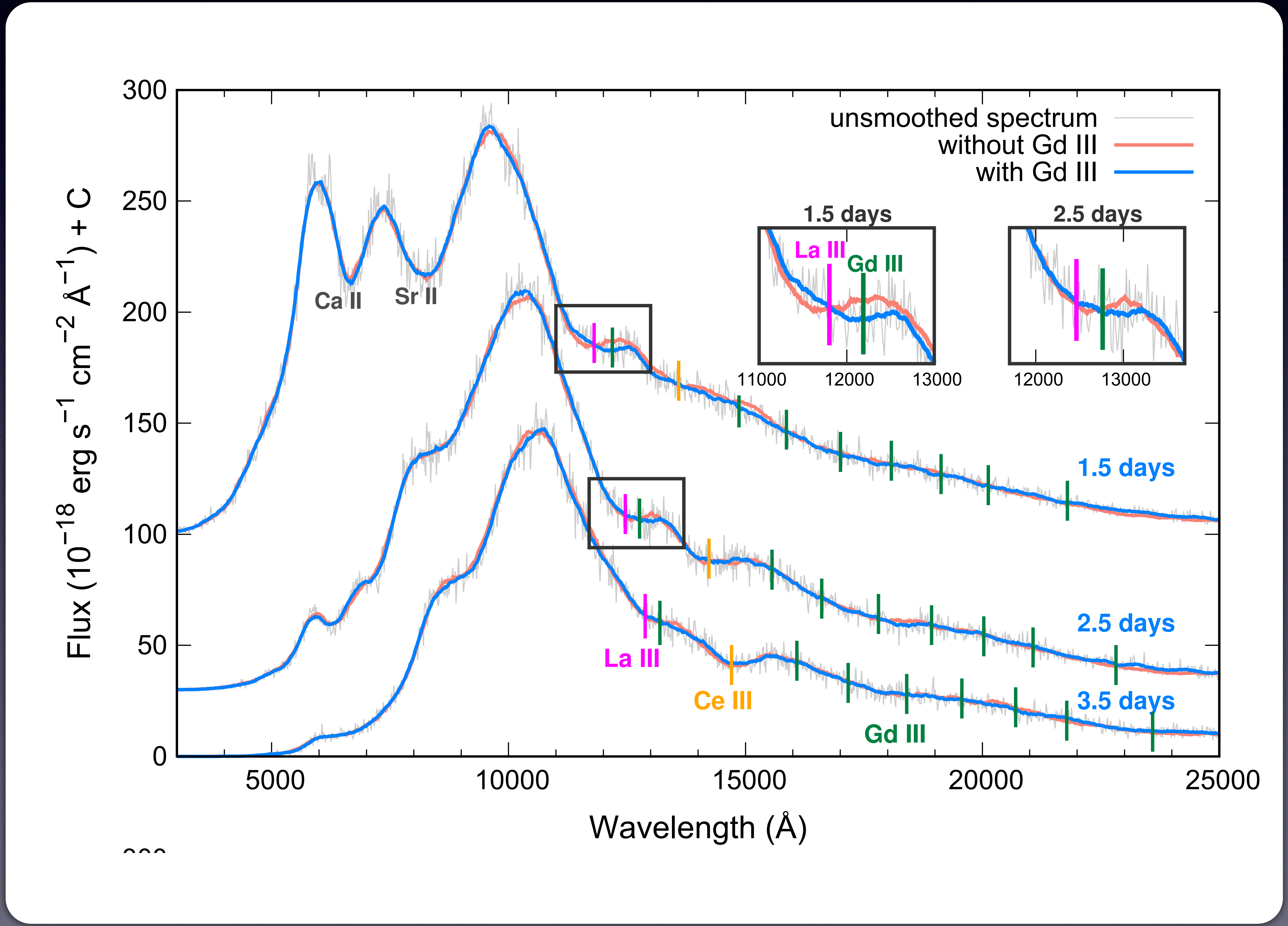
Rahmouni, MT, Domoto+25

see also Gillanders+24, Collins+26 (atomic data by Flörs+26)

Chemically peculiar star

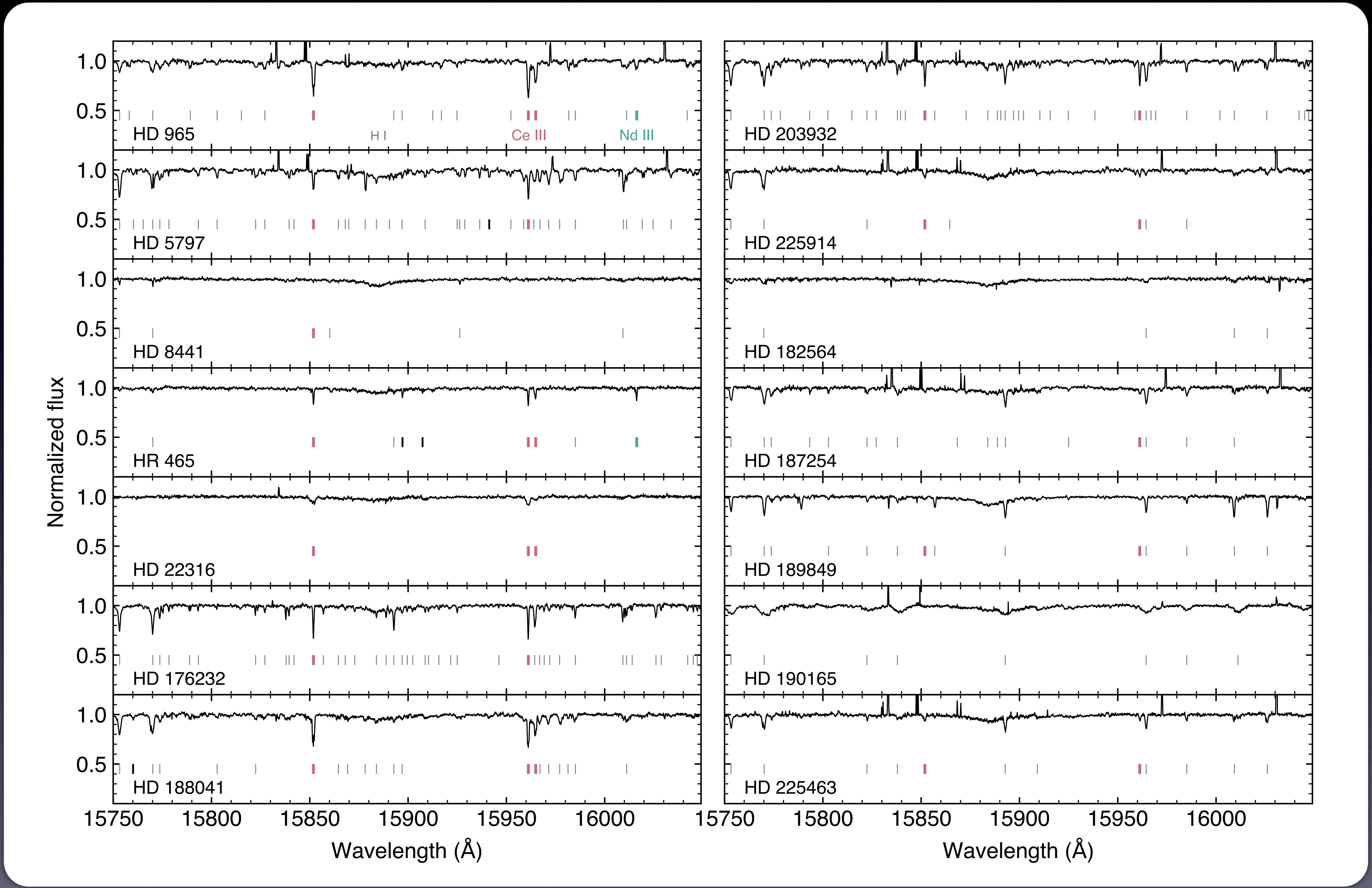


Kilonova



NIR spectra of 13 more chemically peculiar stars

Domoto, MT+ submitted



* Eu II and Gd III
Half-filled 4f + 1 electron

Strongest: Sr II, Ce III, and Gd III

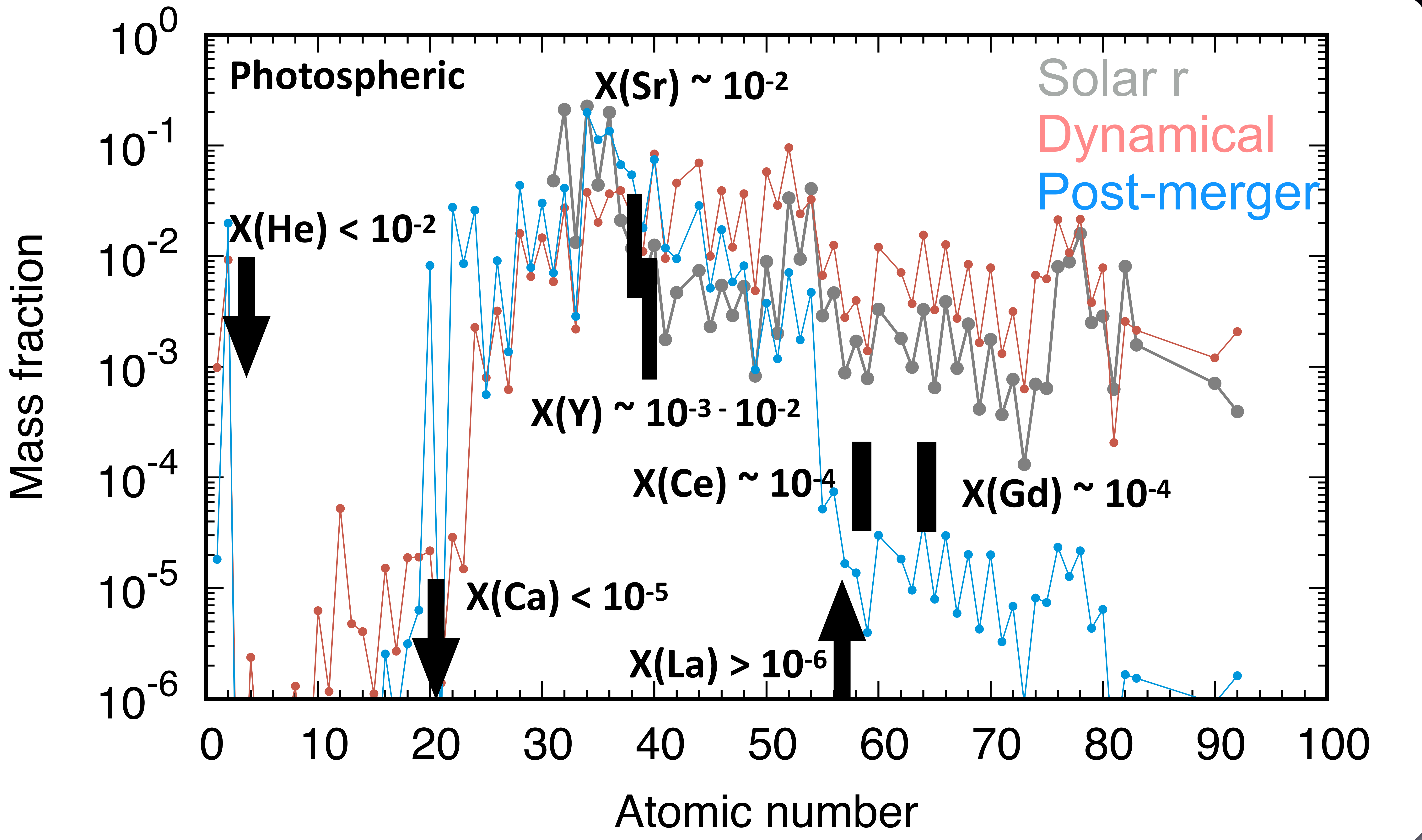
Other (weaker) candidates: Eu II and Nd III

Identification and Abundance Estimate of Heavy Elements in Kilonova Spectra

- Element identification in kilonova spectra
- “Experiments” with chemically peculiar stars
- Towards abundance estimates

Constraints on nucleosynthesis (photospheric spectra)

Photospheric phase: Sr (Watson+19), Sr, Ca (Domoto+21), La, Ce (Domoto+22), Y (Sneppen+23), Gd (Rahmouni+25), He (Sneppen+24, NLTE)



X(lanthanides) ~ 10^{-3} ??

see also Gillanders+26

Model by Fujibayashi+23
SFHo 135-135
(mass fraction is normalized for each component)

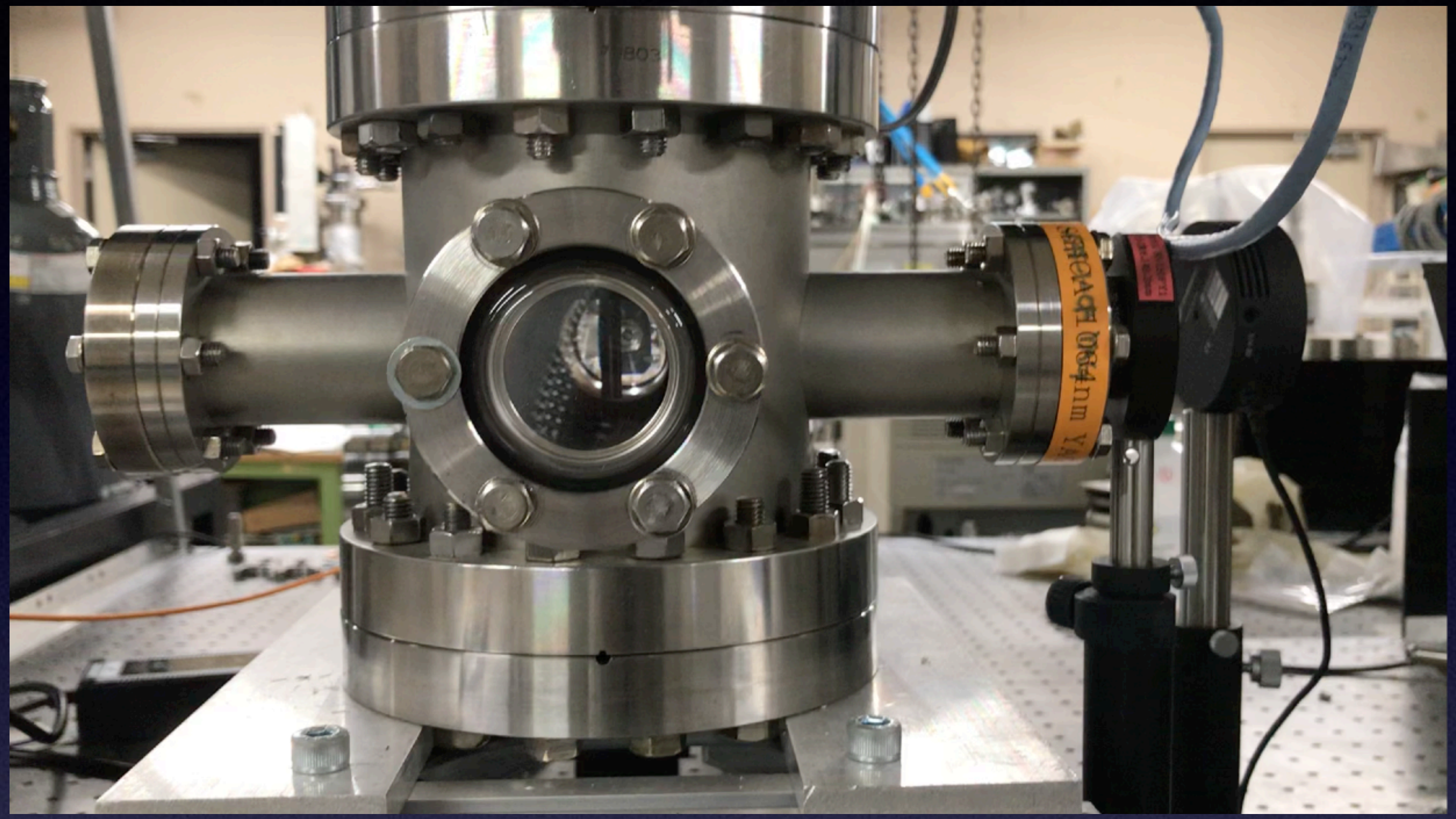
Toward accurate abundance estimate

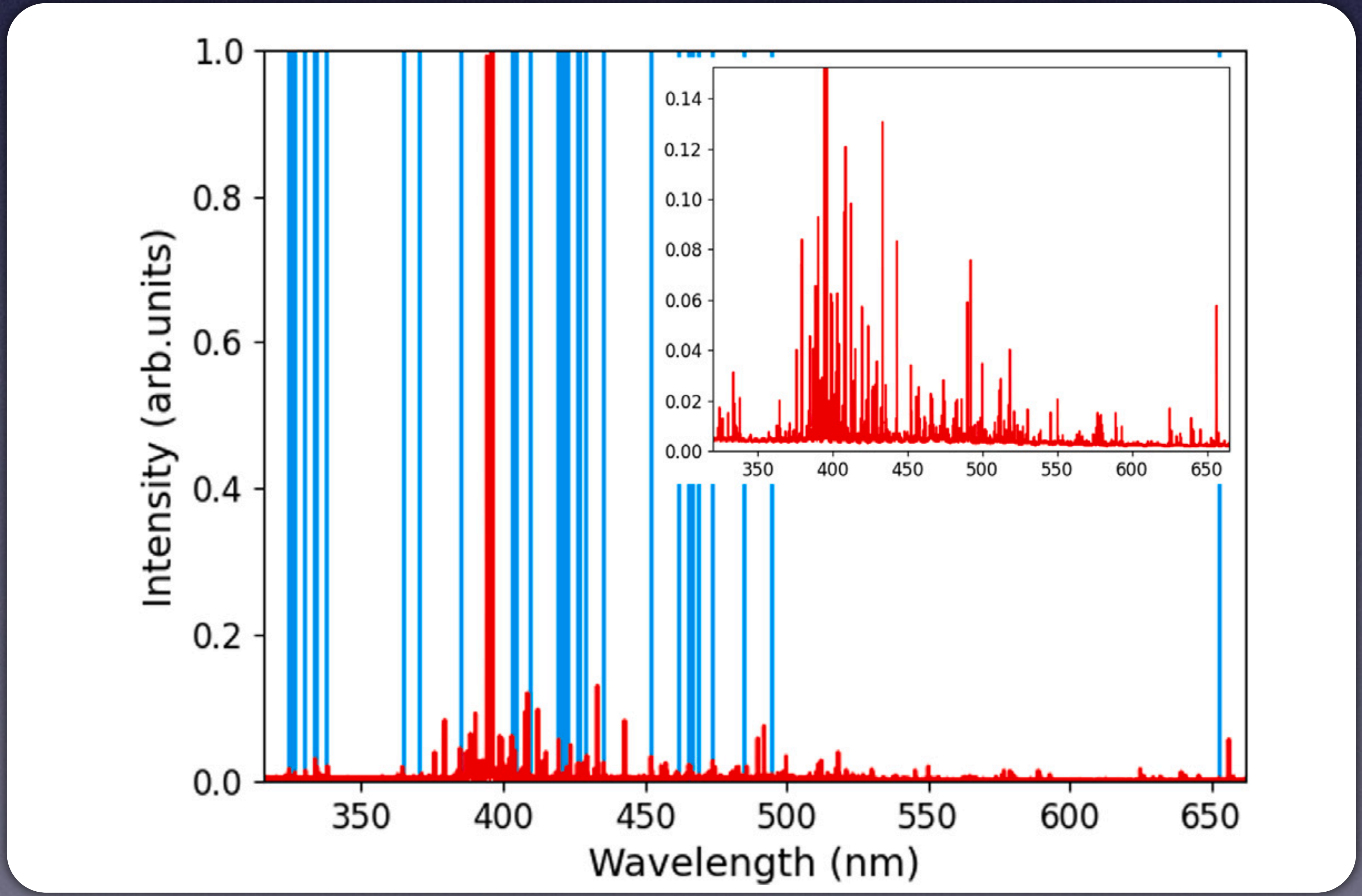
1. (Experimental) atomic data — Talks on Thursday
2. Plasma (non-LTE) modeling — Talks on Wednesday
3. Nebular phase spectra (~ total mass) — Talks in the following session today

1. Spectroscopic experiments

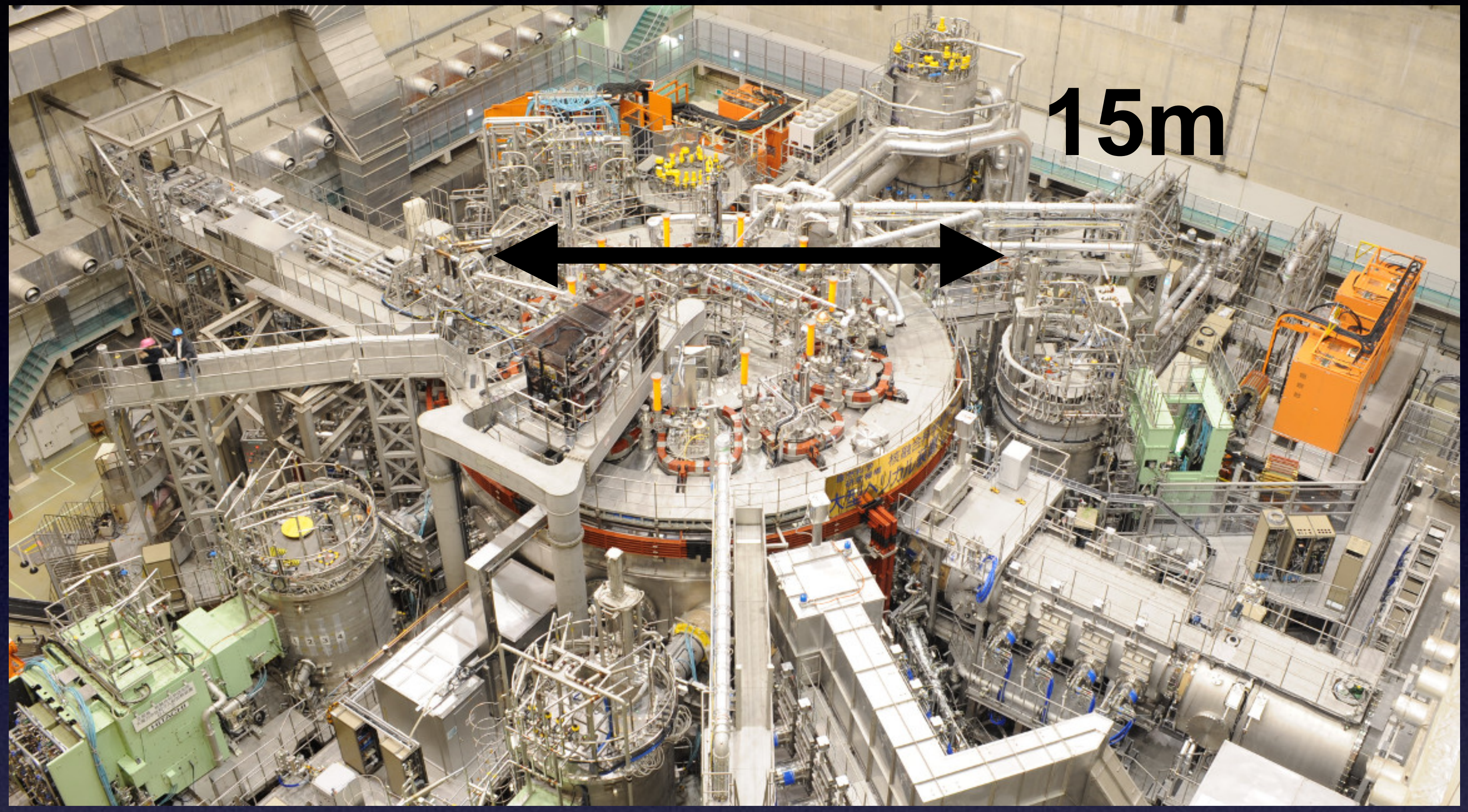
Kodangil, Domoto, MT+2024
Kodangil, MT, Kato+2025

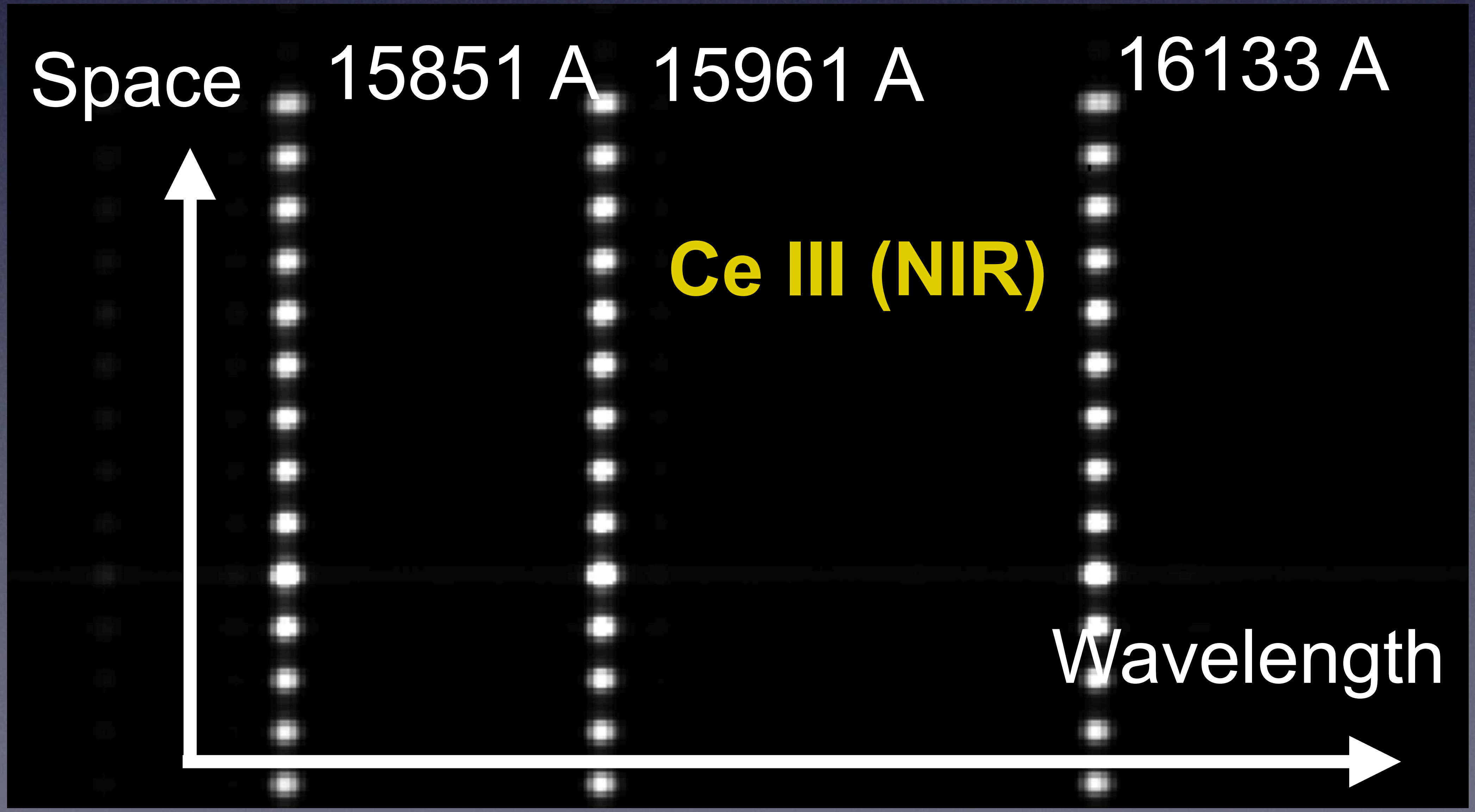
Laser induced breakdown



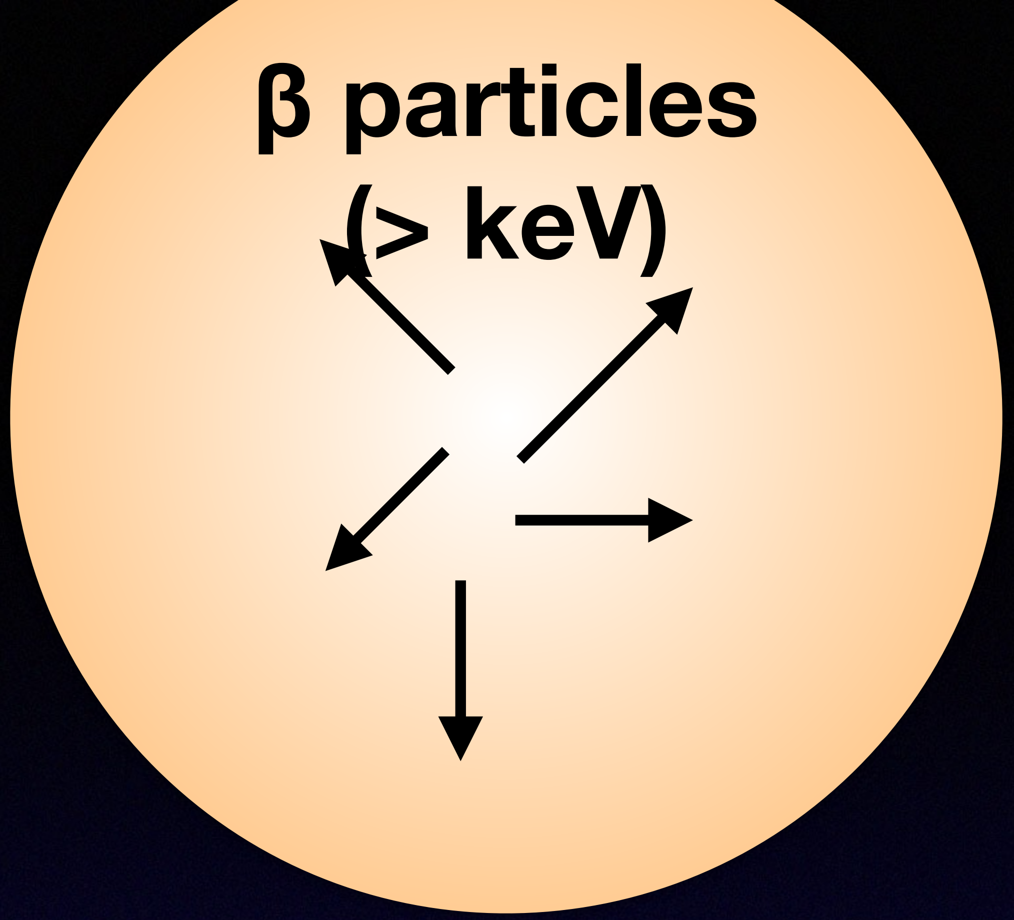


Fusion plasma



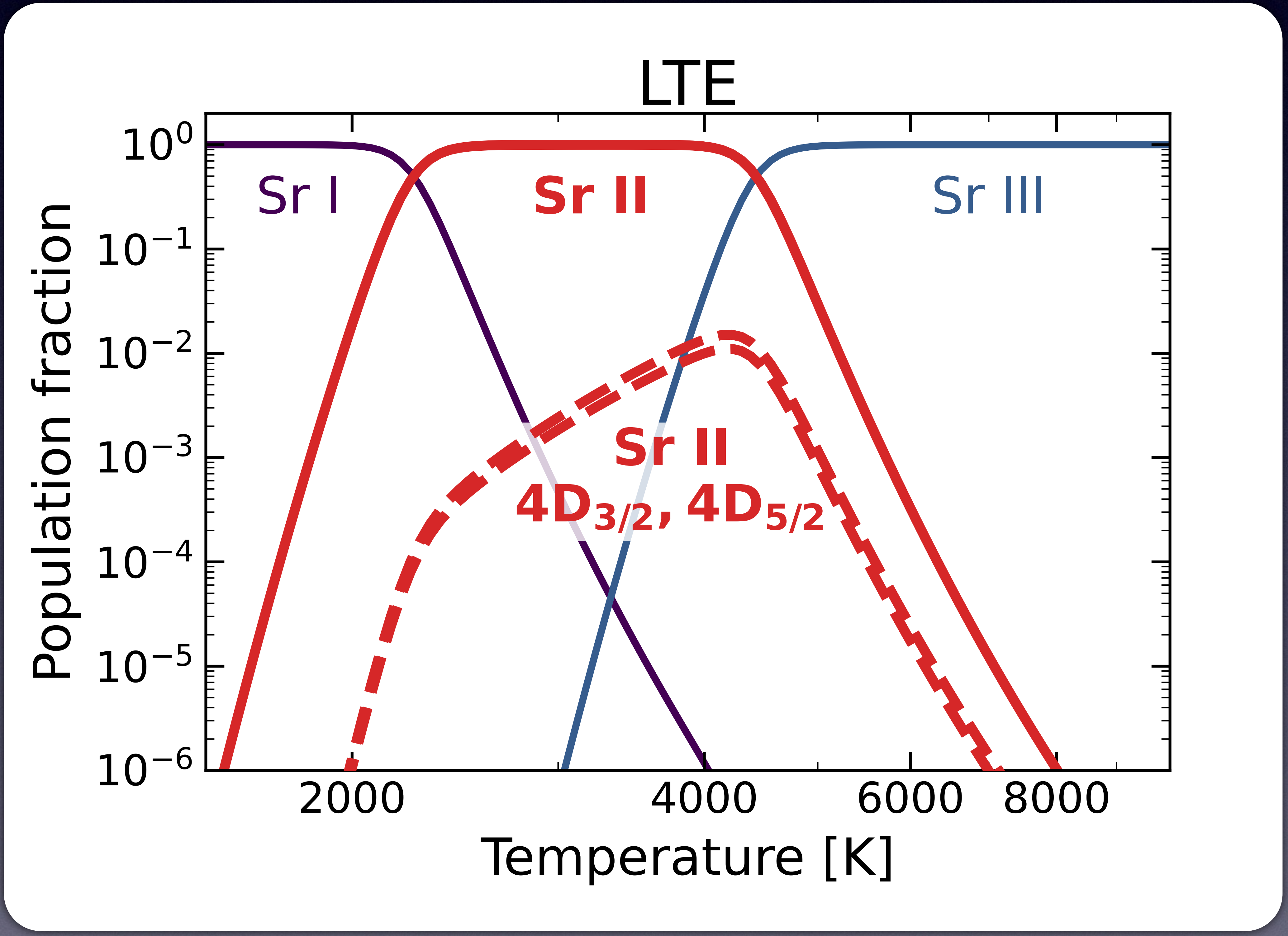


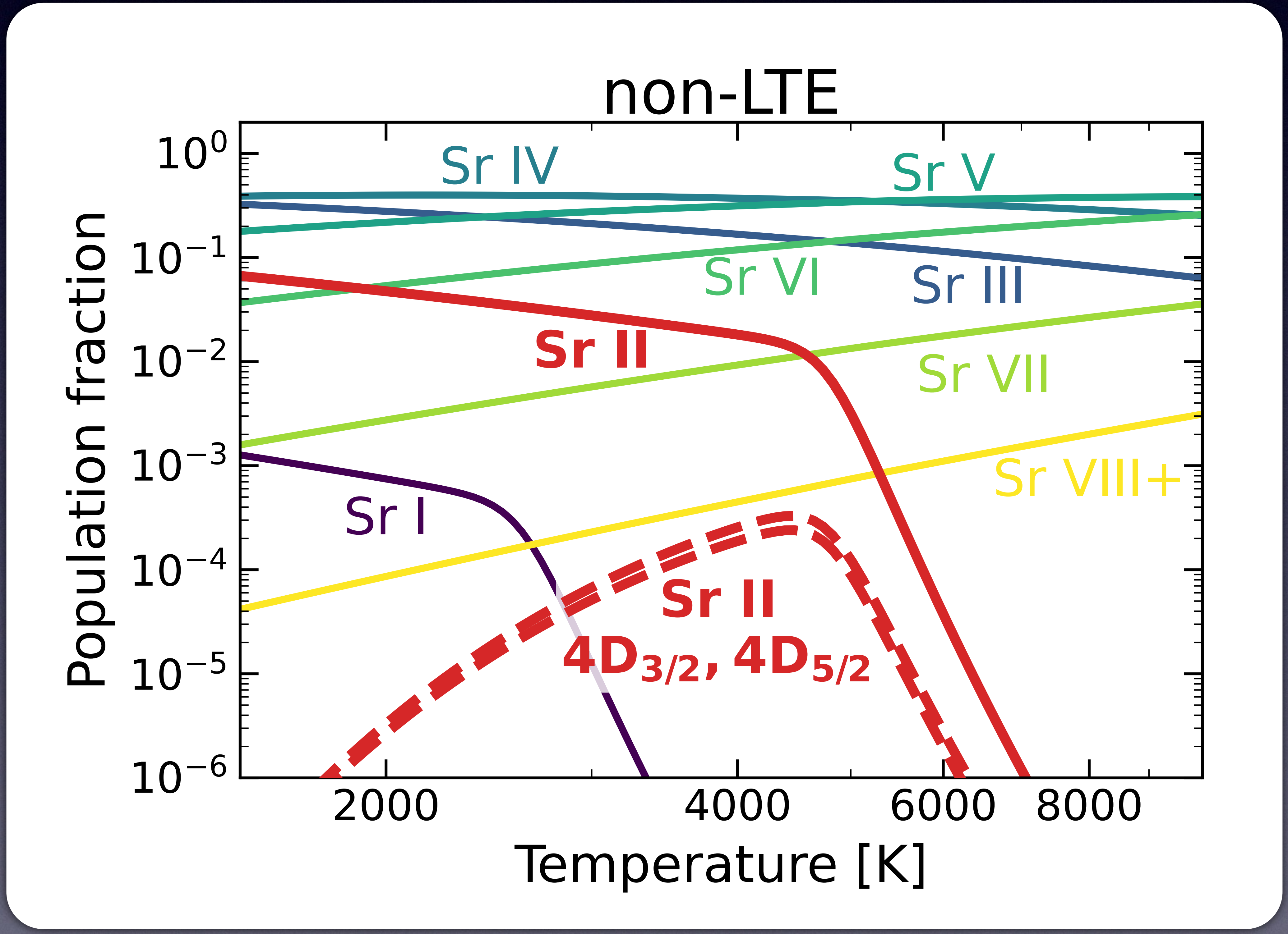
2. Non-LTE plasma modeling



Ionization by non-thermal electrons
Traumi+22, Brethauer+26, Arya+26

Chiba, MT+ 26 (arXiv:2604.05703)





$X(Sr) \sim 10^{-2}$ (consistent with the Solar ratio)

see Aayush's talk

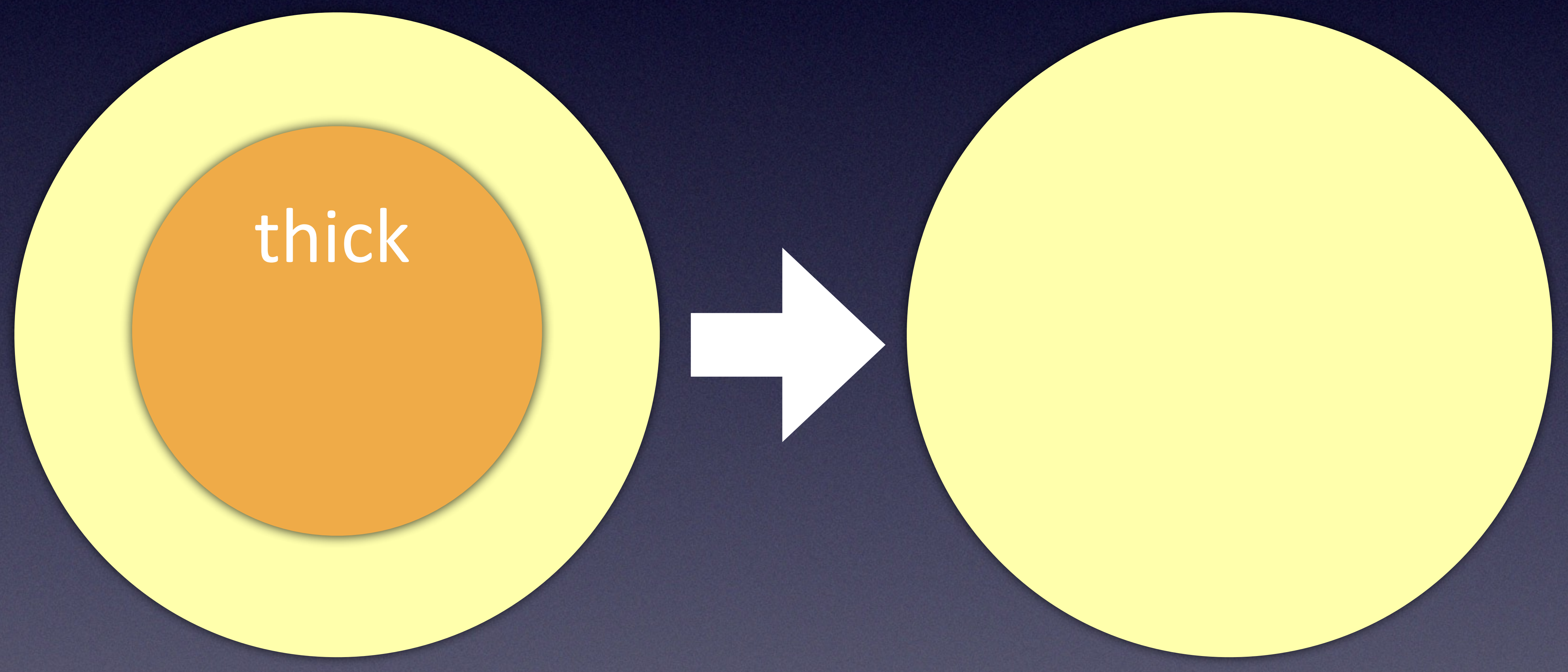
3. Abundance estimates in nebular spectra

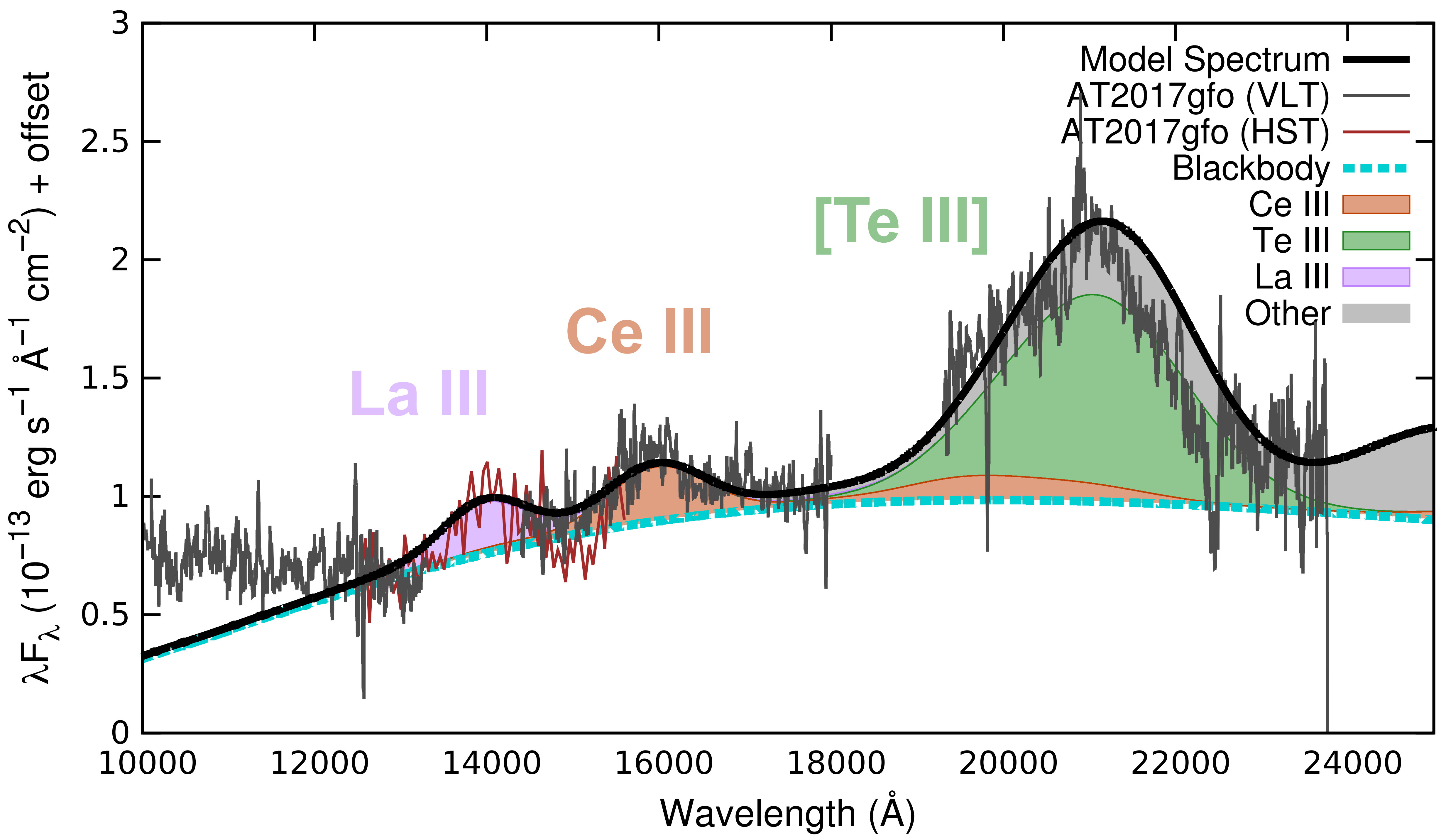
Better probe of total mass

Rahmouni+ in prep.

Early phase
(absorption line)

Late phase
(emission line)





see Andreas's talk

Summary & future

Theory → **Atomic data** ← **Experiments**

Ab-initio calculations
for selected important ions

NIR spectroscopy
Lifetime measurements

Lessons from stars

↓

Radiation transfer

Non-LTE modeling
Nebular spectra

Merger simulations ↔ Radiation transfer

End-to-end
simulations

+ r-process in
core-collapse SNe

Kilonova observations

GW events + GRBs