Identifying r-process Elements in Kilonova Infrared Spectra

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sirEN (@Giulianova 2025)

Introduction

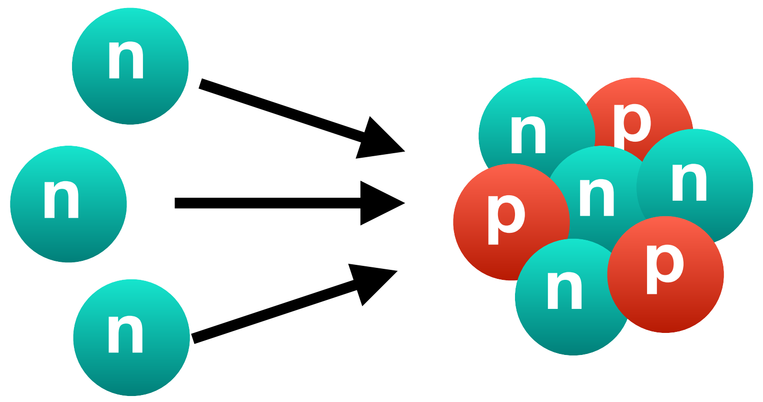
Our common goal

Understanding the origin of elements

s-process

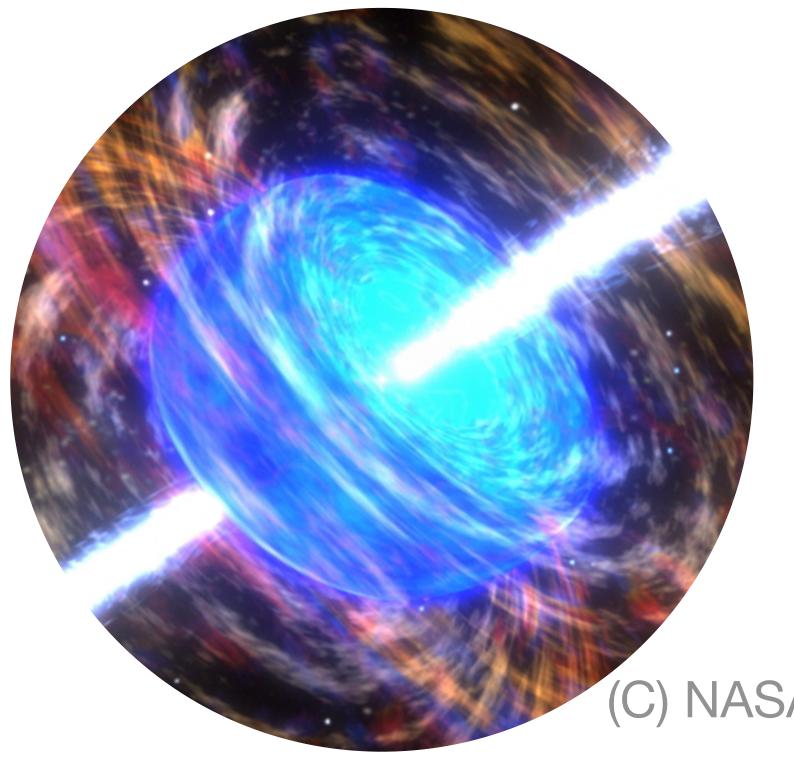
i-process

r-process

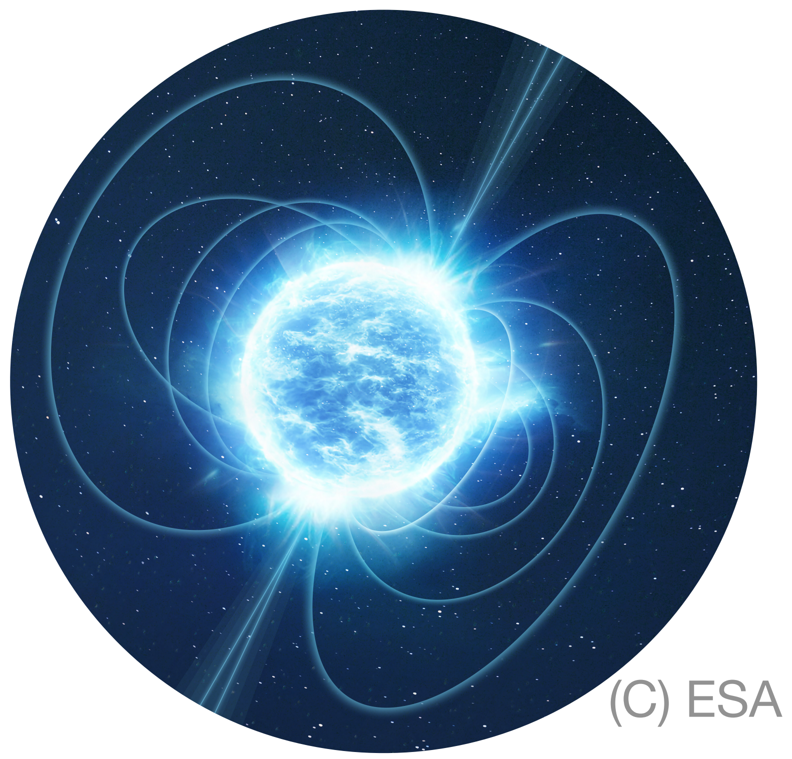


Process by which the heaviest elements are made

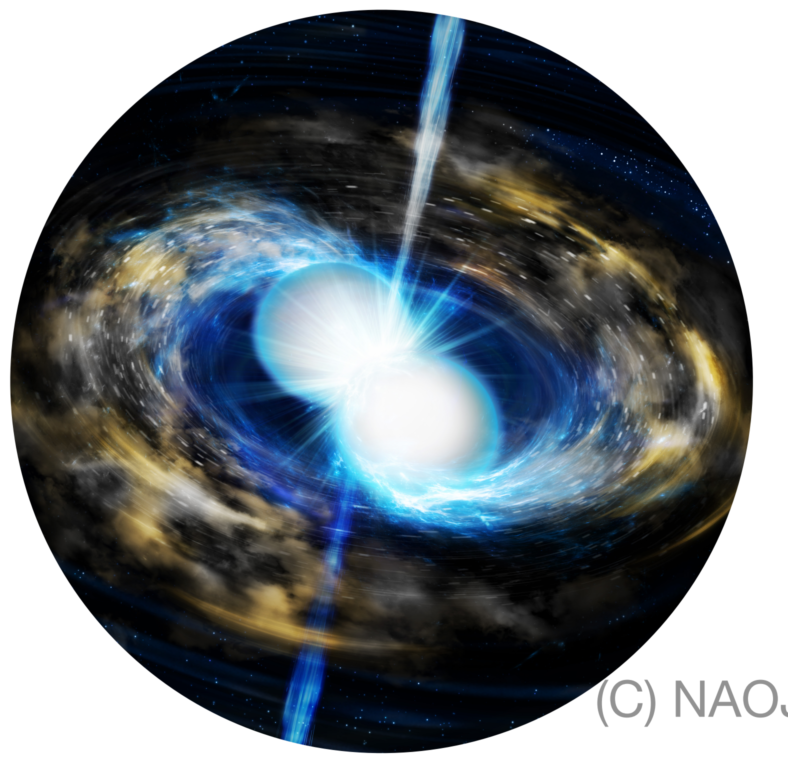
r-process sites


(C) NASA

Core-collapse SNe


(C) ESA

Magnetar Flares

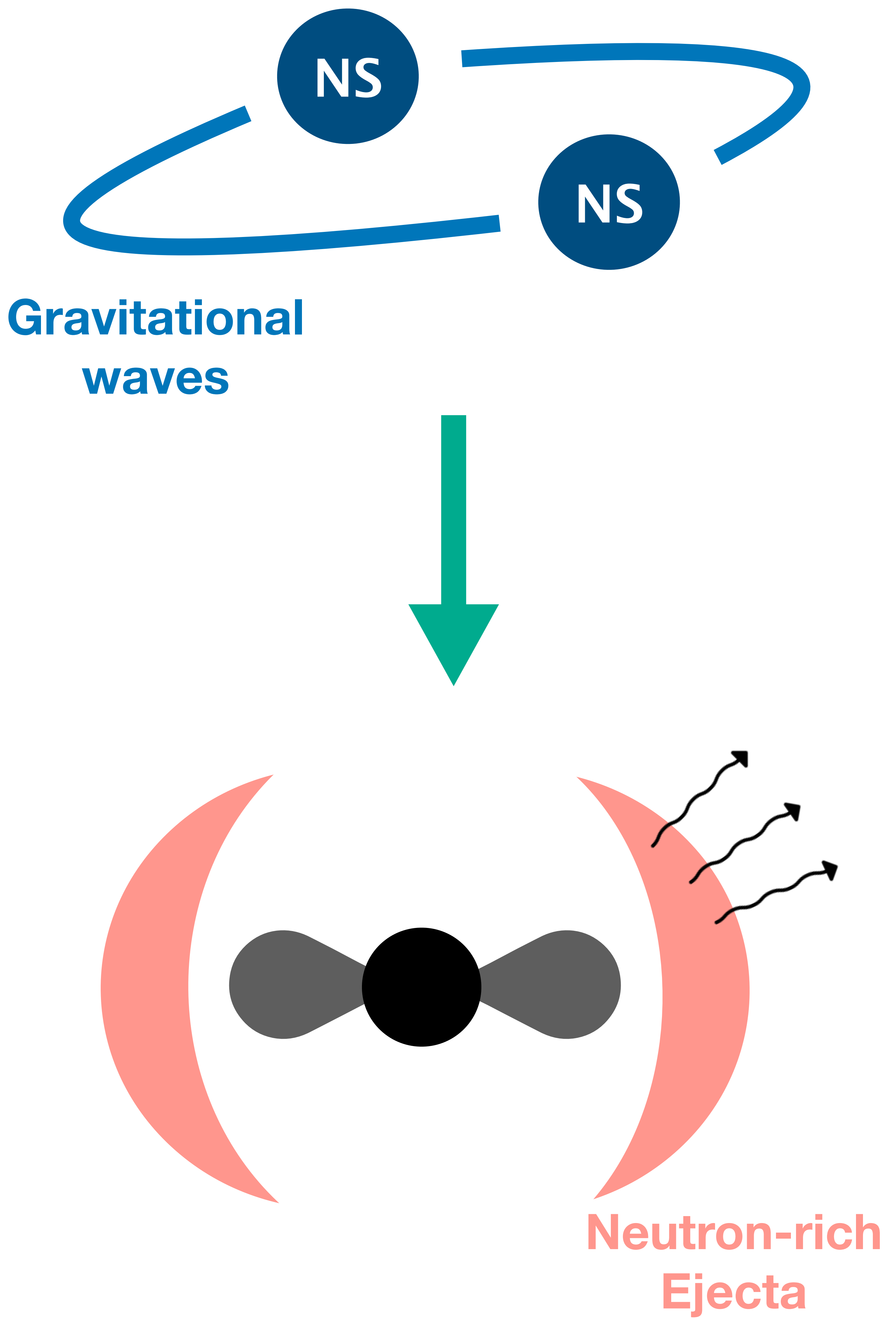

(C) NAOJ

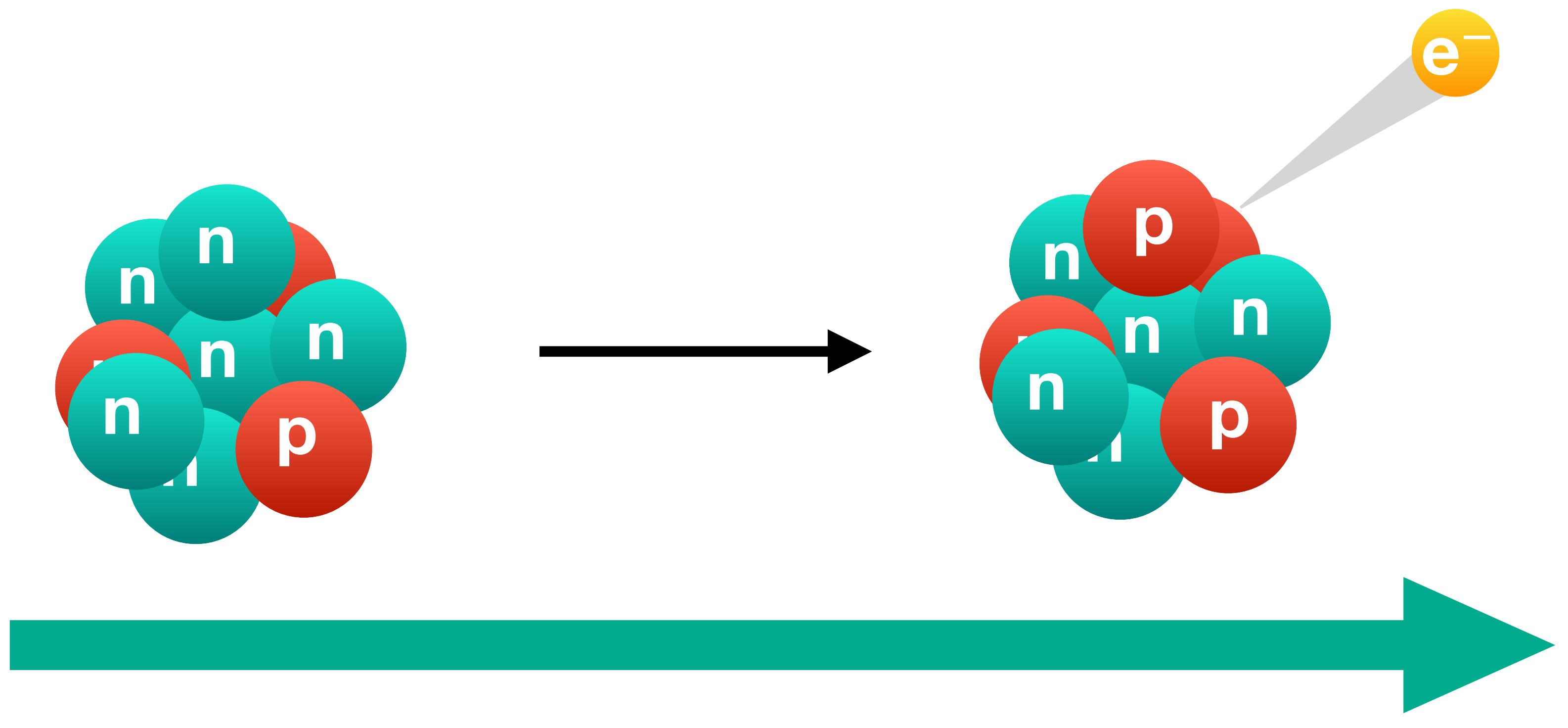
Neutron Star Mergers

Other…?

Introduction

Neutron star merger

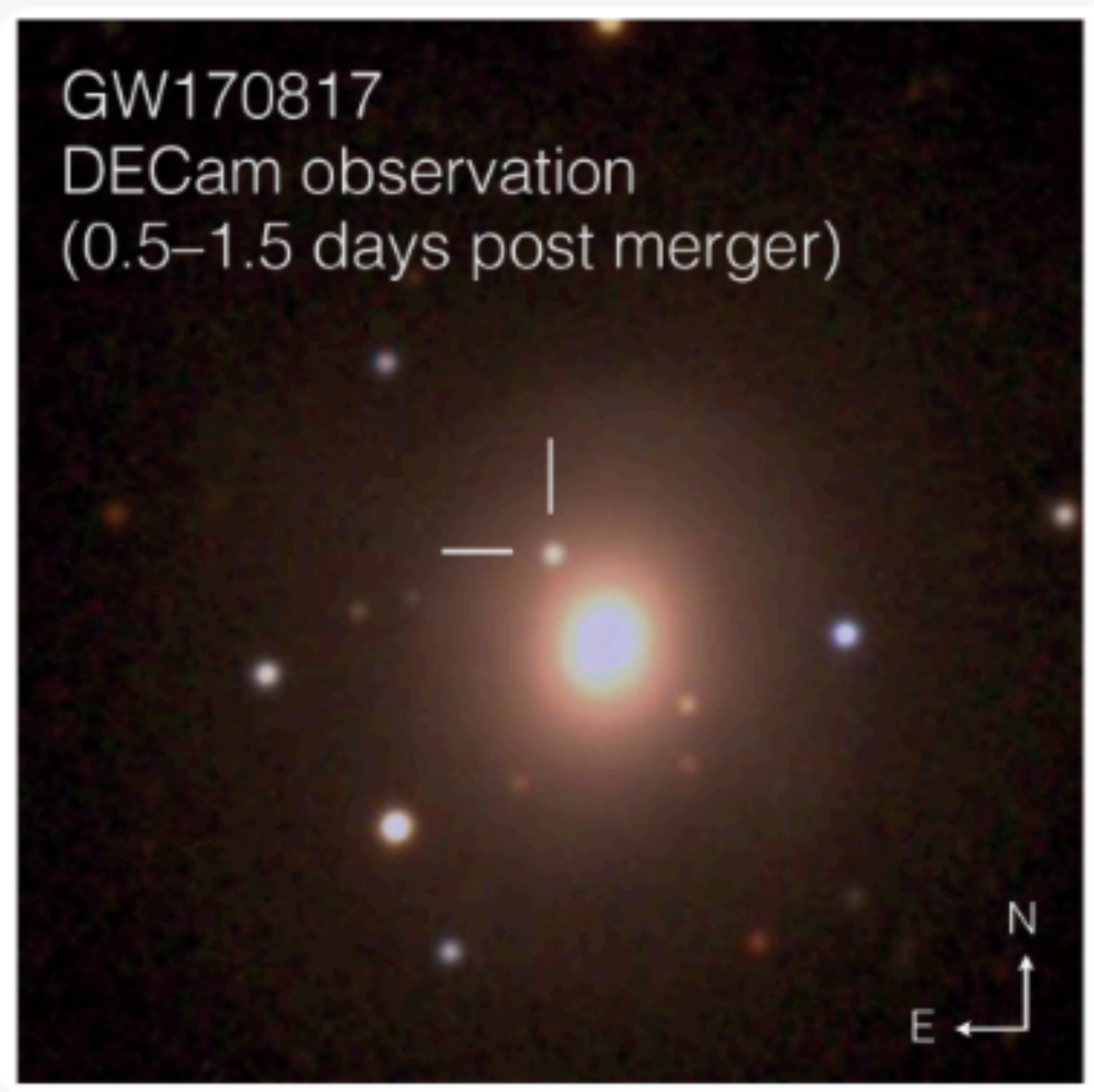




Decay of new heavy elements powers an electromagnetic emission

“Kilonova”

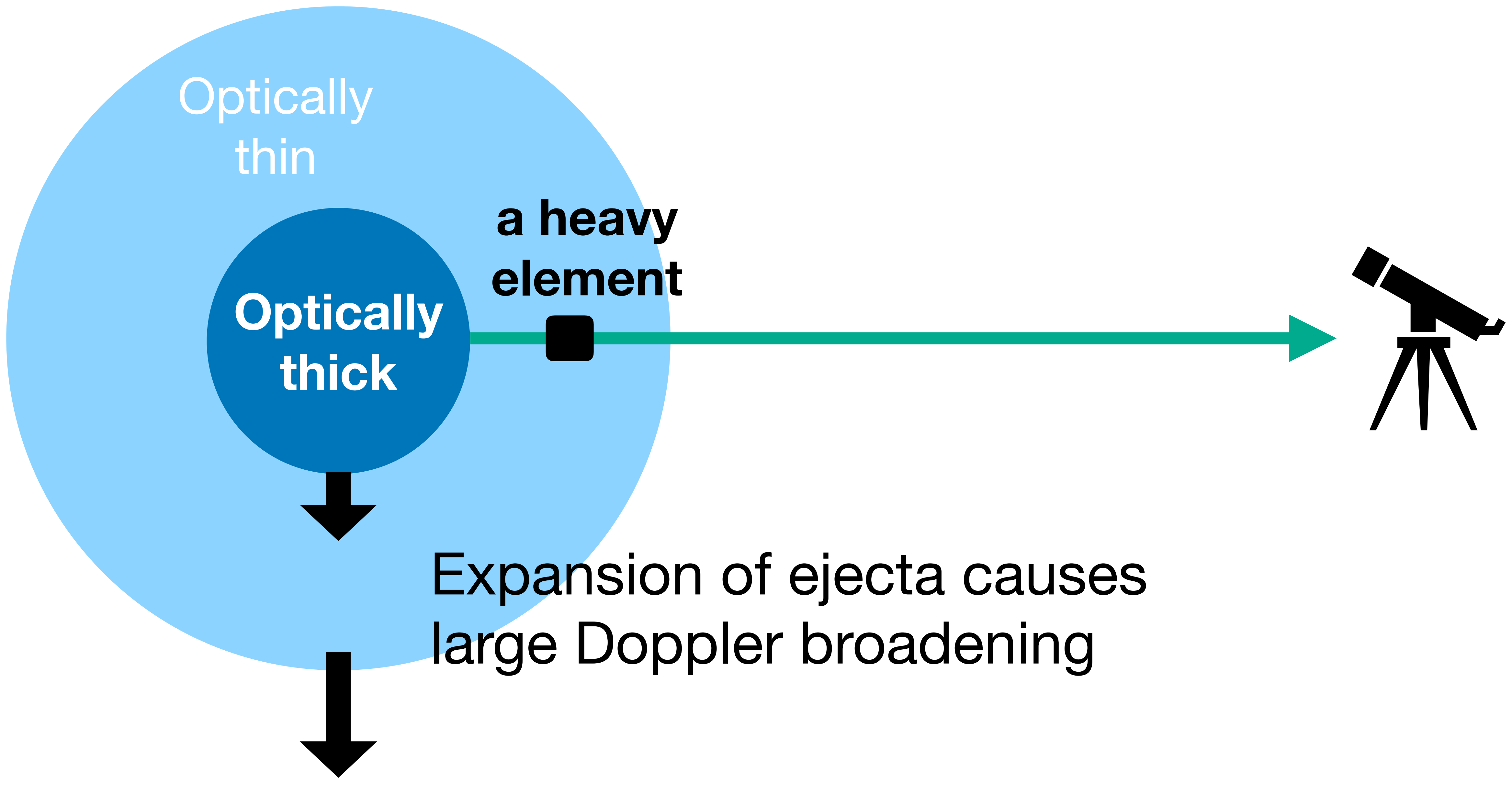
Kilonova of GW170817 observed in 2017



Soares-Santos et al. (2017)

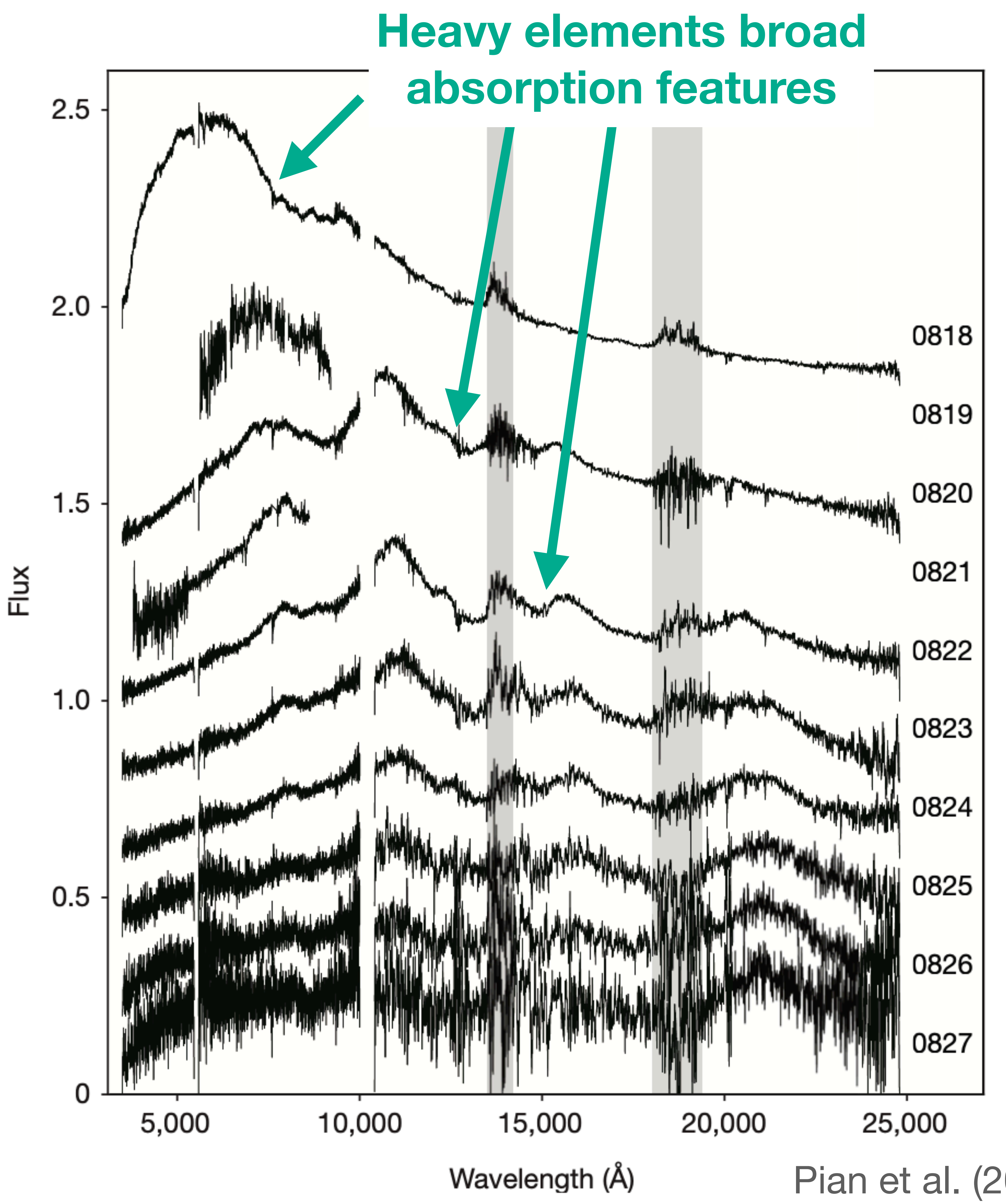
Introduction

Simplified picture of NSM ejecta



Expansion of ejecta causes large Doppler broadening

GW170817 spectrum



Pian et al. (2017)

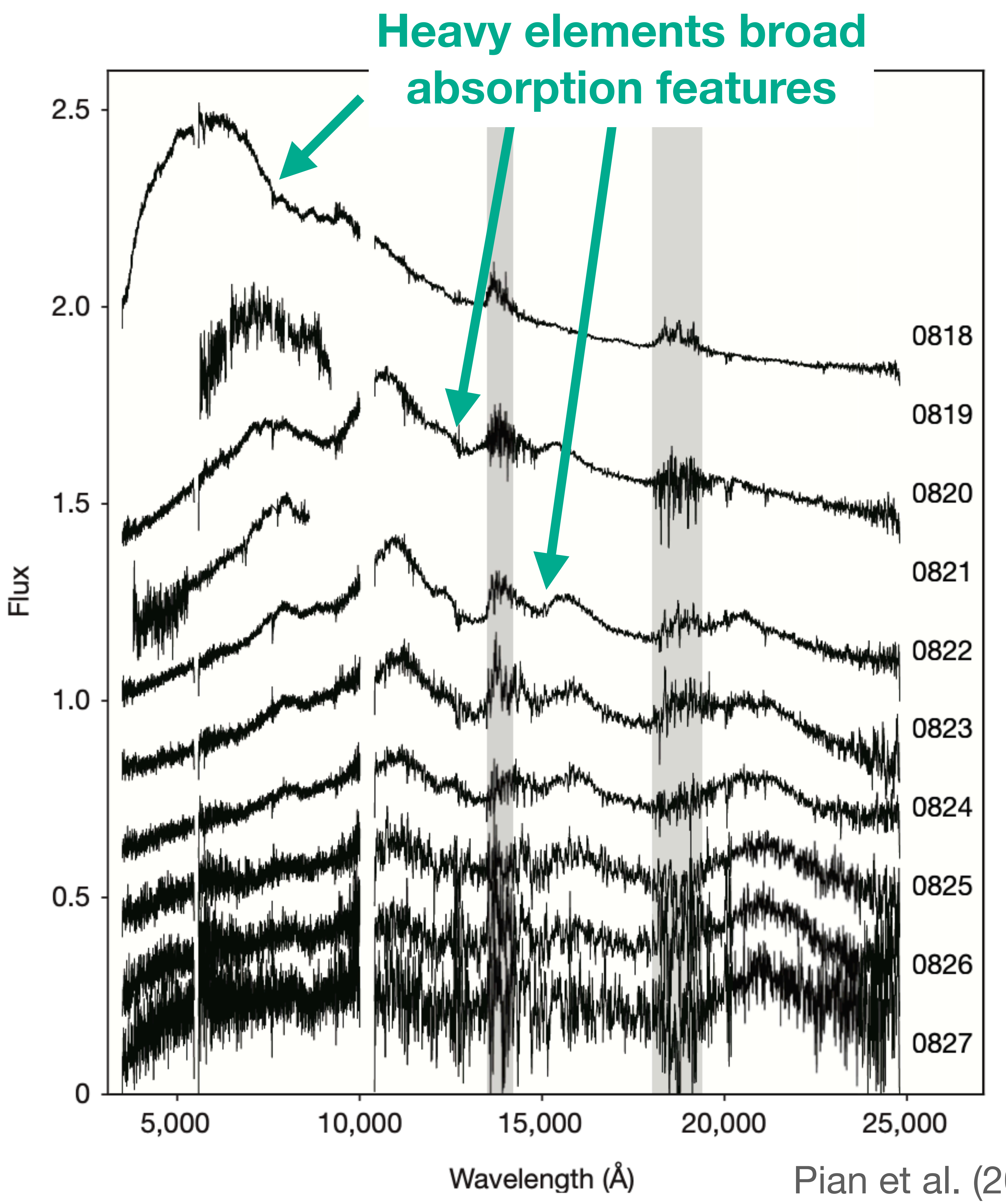
Introduction

Goal

Quantify the mass ejected of elements in NSMs to ultimately understand r-process nucleosynthesis

First step: Spectral Investigation

GW170817 spectrum

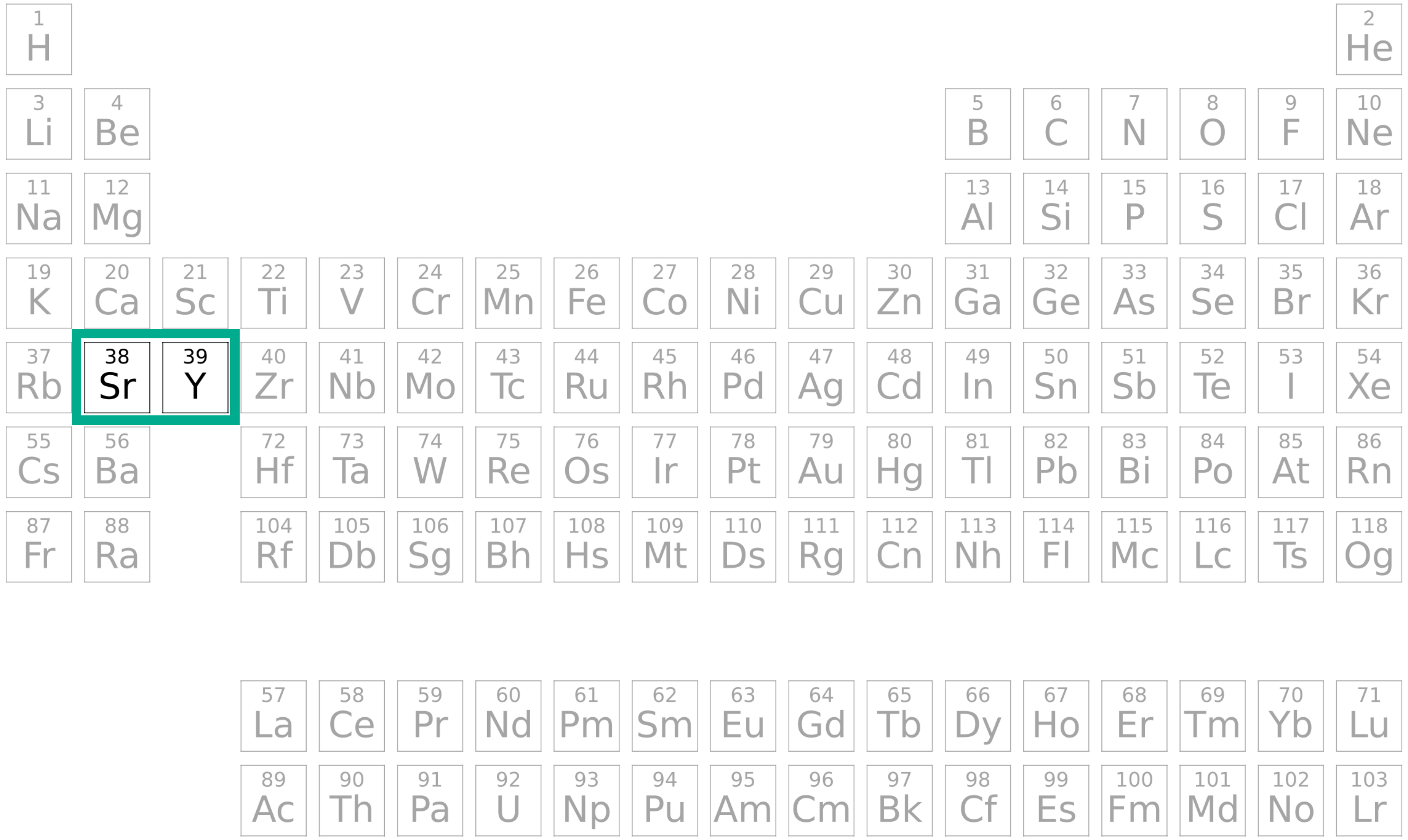


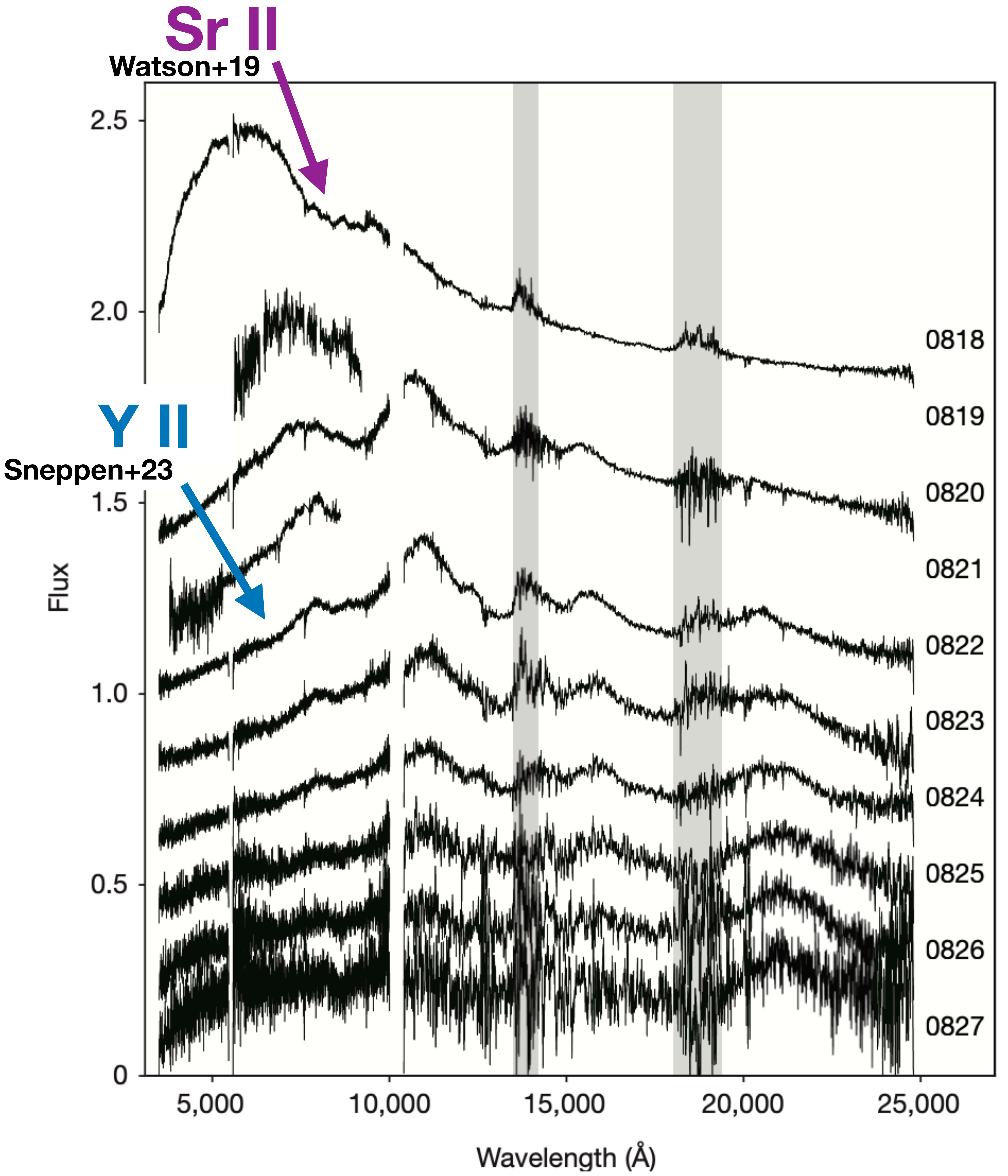
Pian et al. (2017)

Previous Work

Spectral Investigation of GW170817

Experimental Atomic transitions → Spectral feature identification in optical



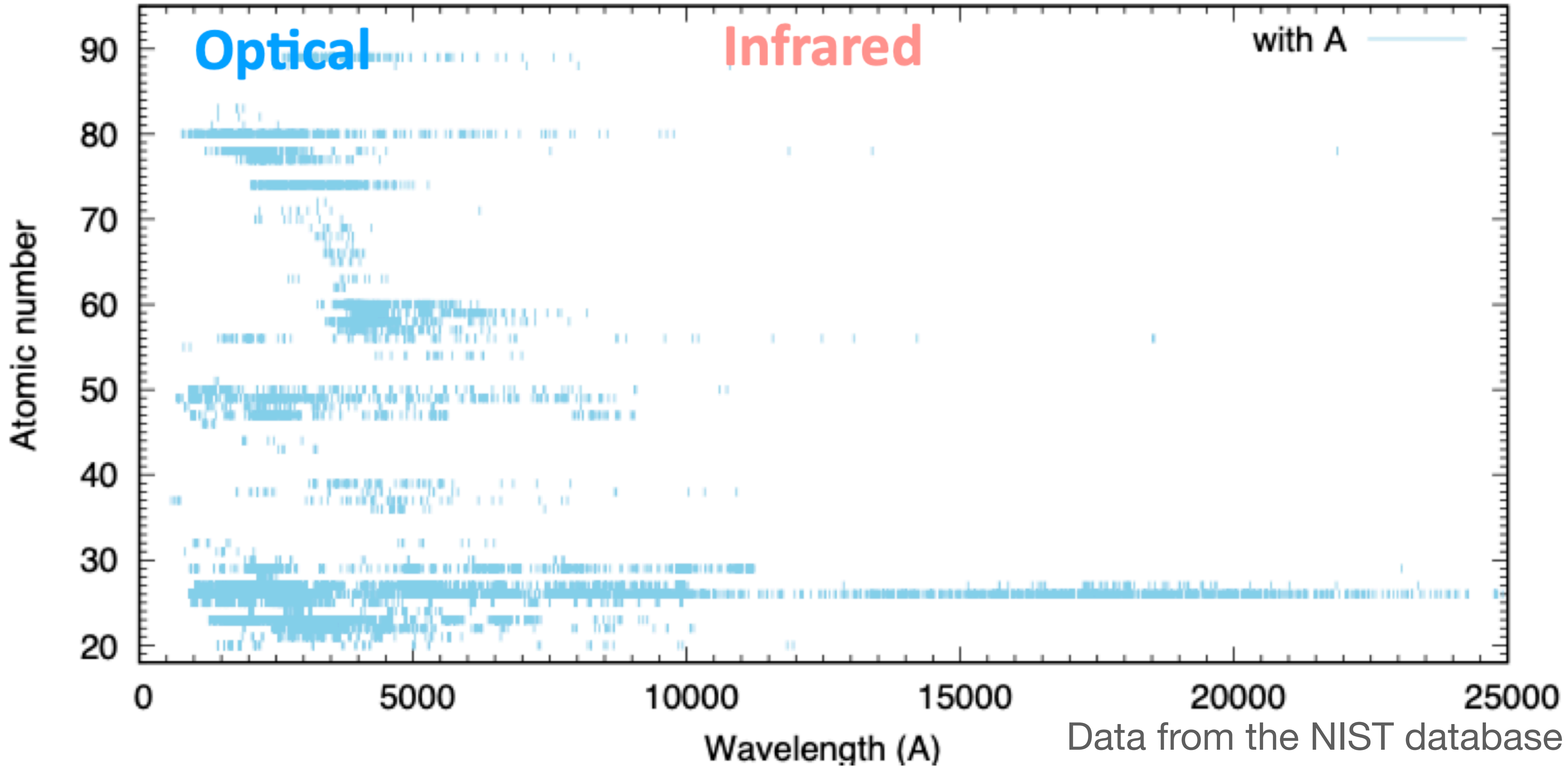


Pian et al. (2017)

Previous Work

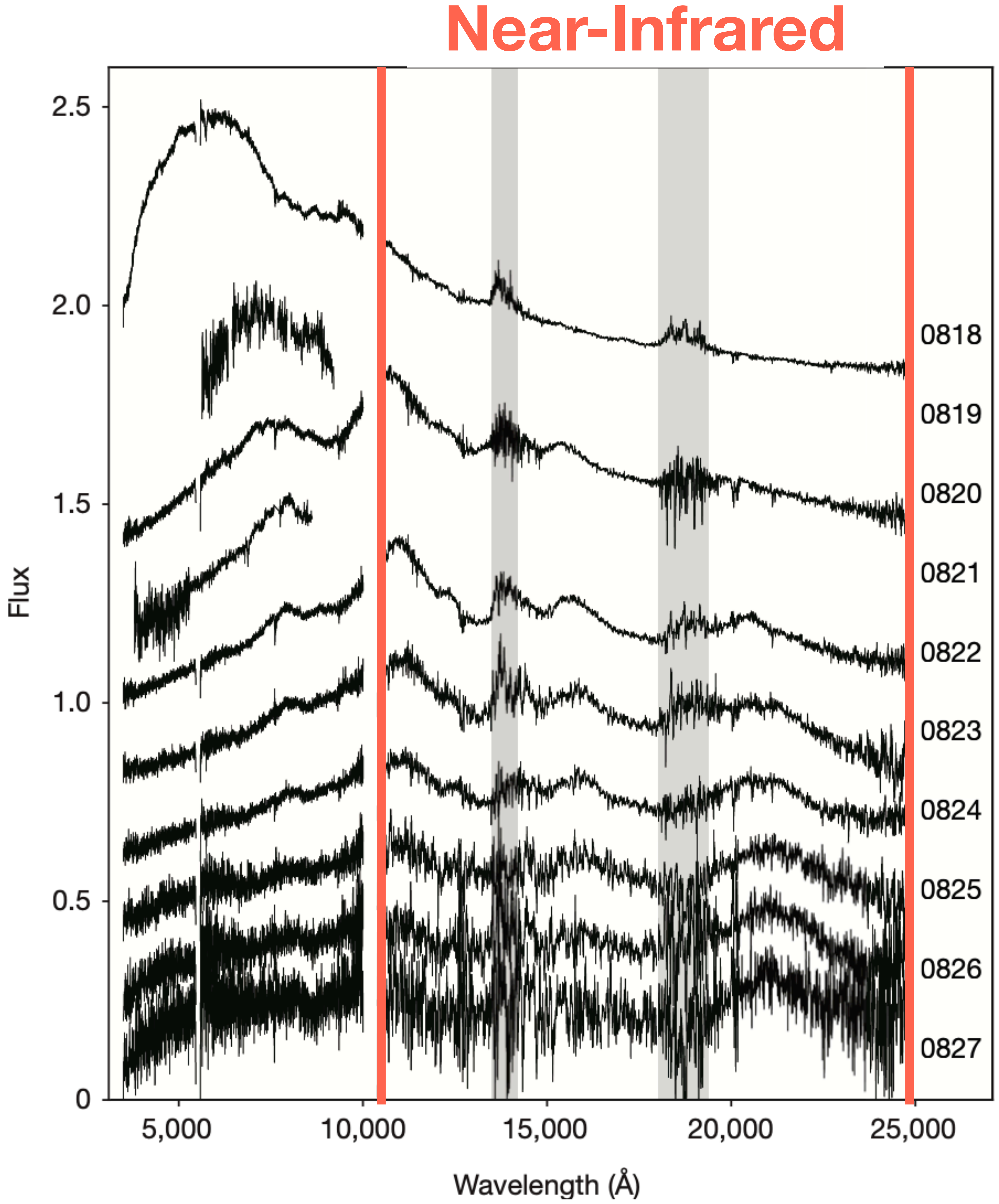
Spectral Investigation of GW170817

Lack of experimental atomic data for heavy elements in Infrared



Data from the NIST database

Other methods are needed to investigate near-infrared features, and search for features from the heaviest elements

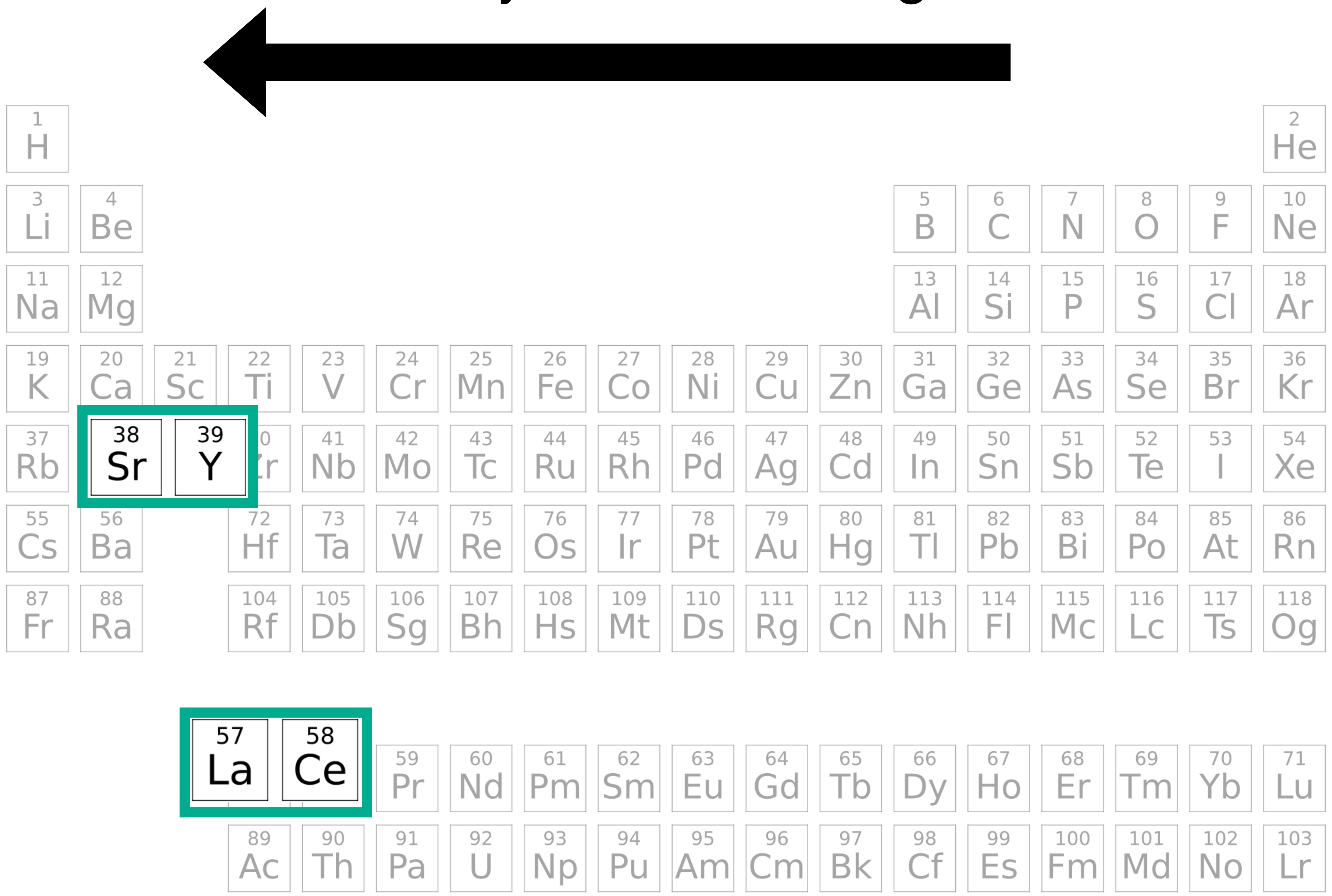


Pian et al. (2017)

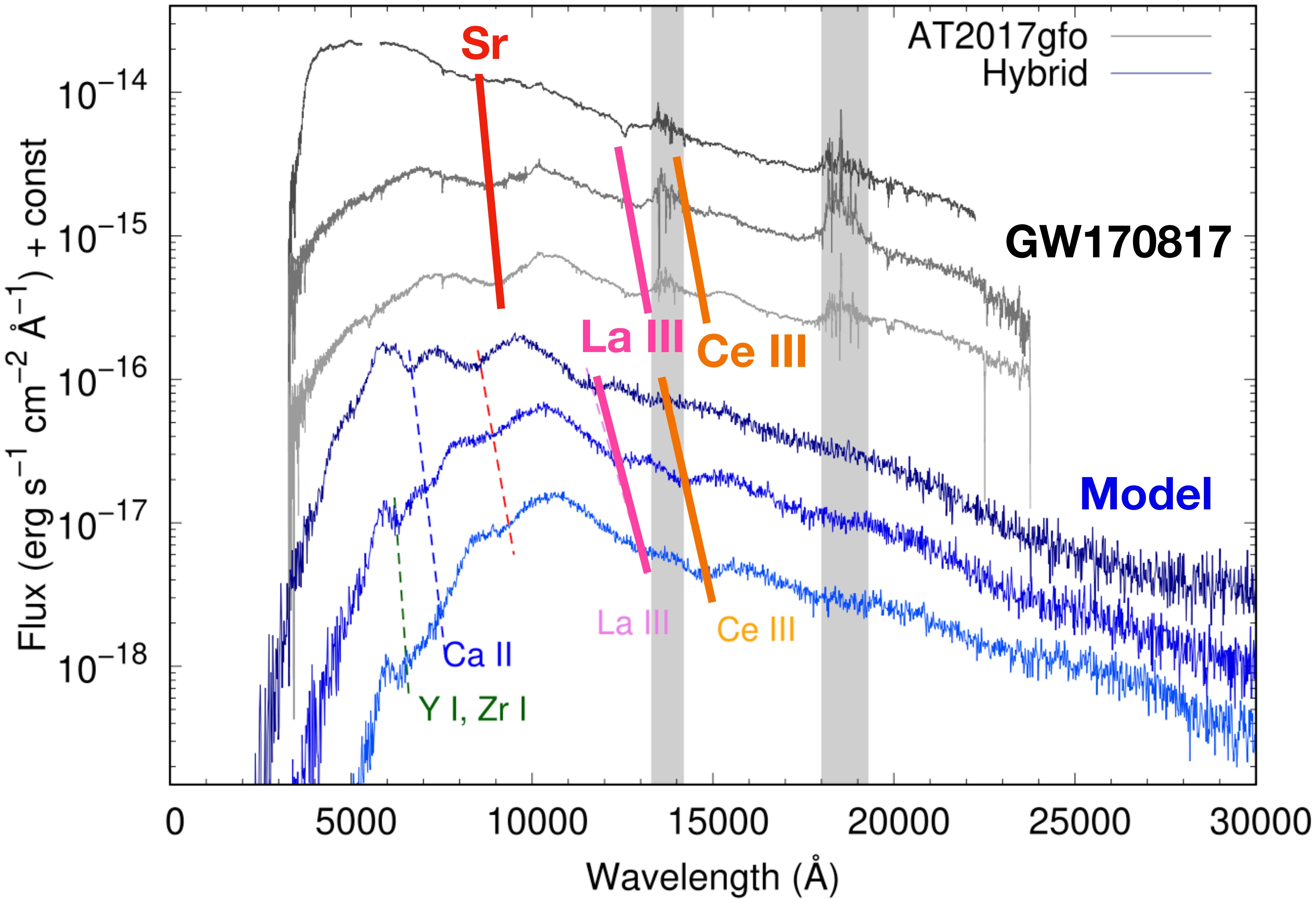
Identification of La and Ce (Domoto et al. 2022)

Method: Complete theoretical transition data calibrated for important elements

Elements on the left side of the periodic table
are most likely to show strong features



Confirmation of lanthanides production!



Identification of La and Ce **(Domoto et al. 2022)**

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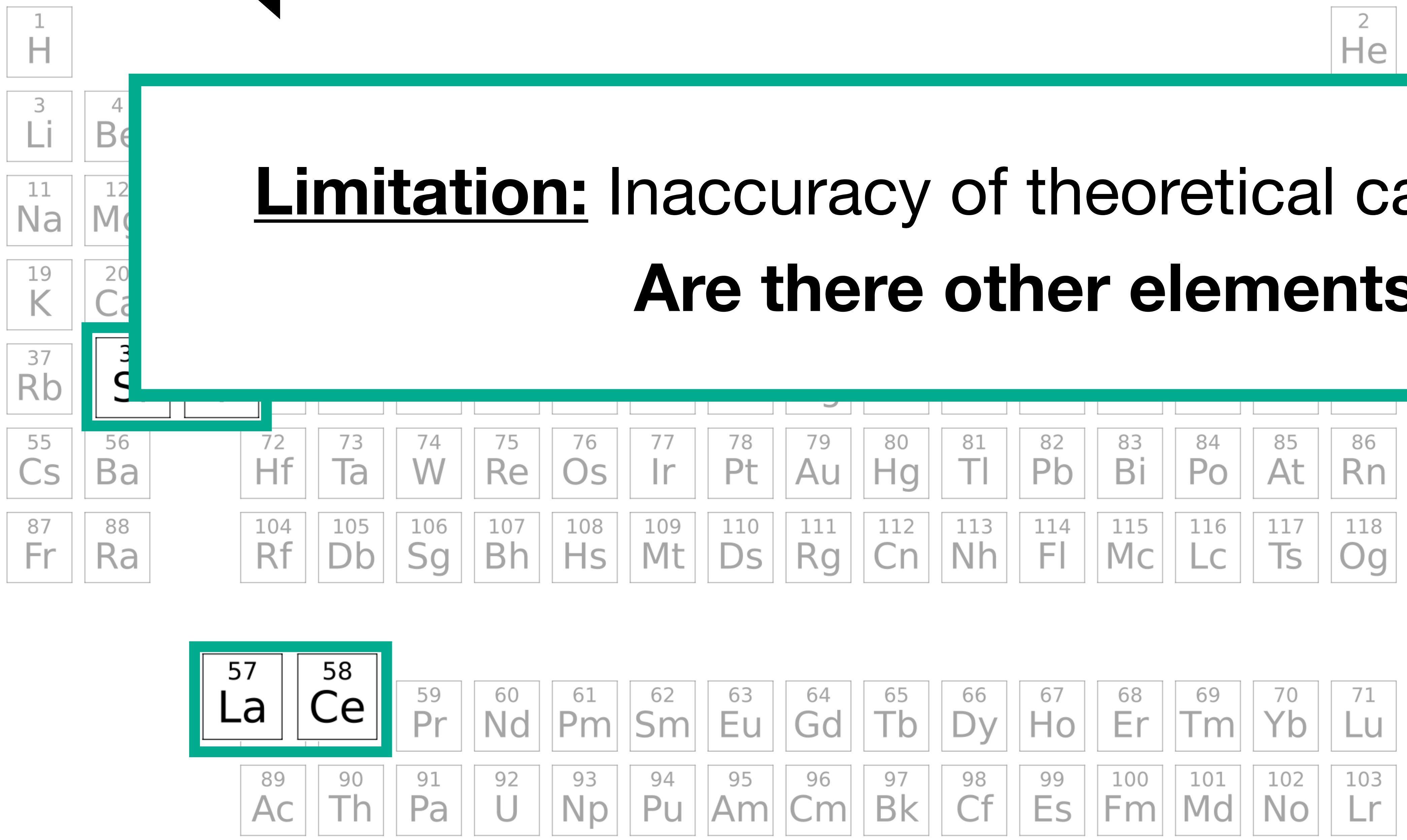

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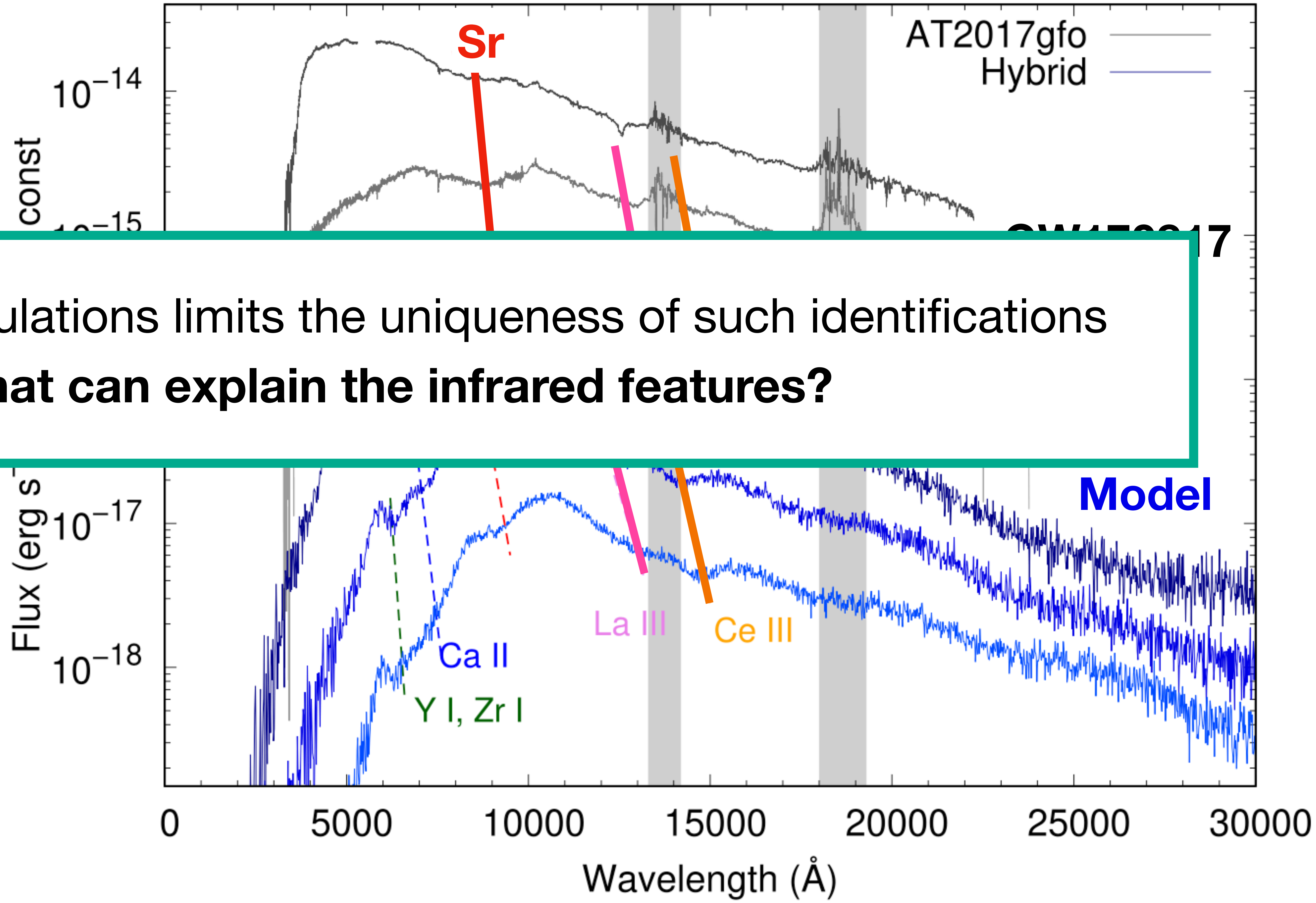
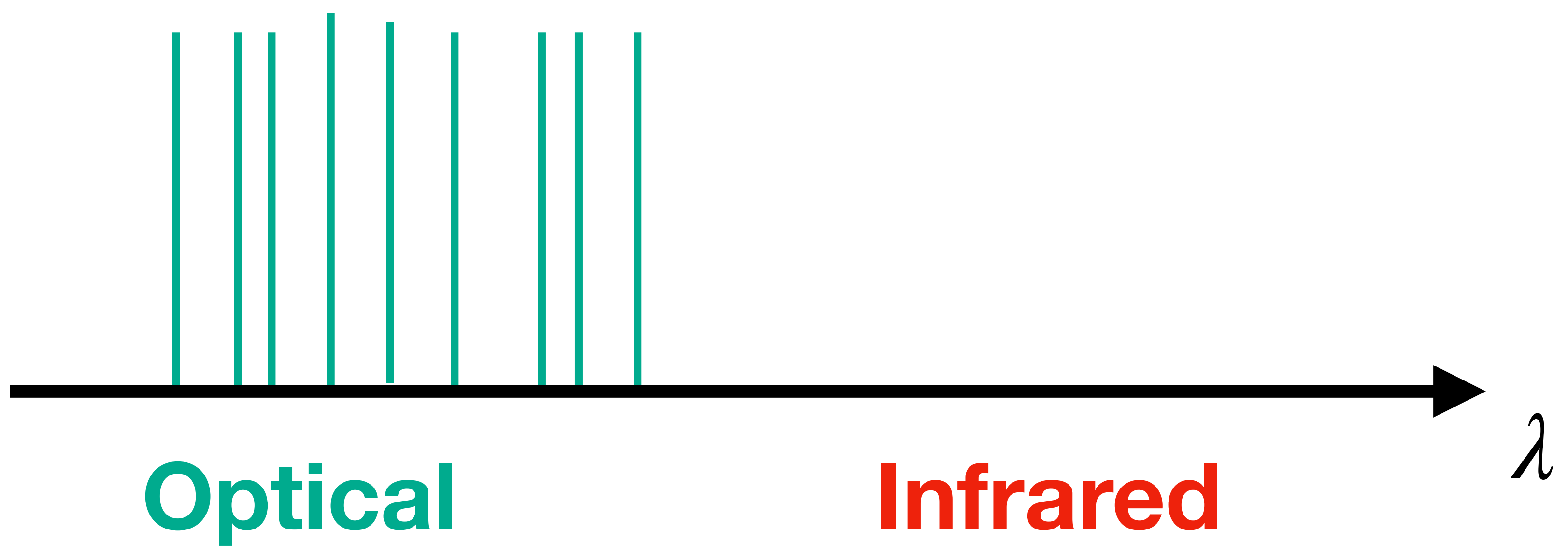


<u>Limitation:</u> Inaccuracy of theoretical calculations limits the uniqueness of such identifications

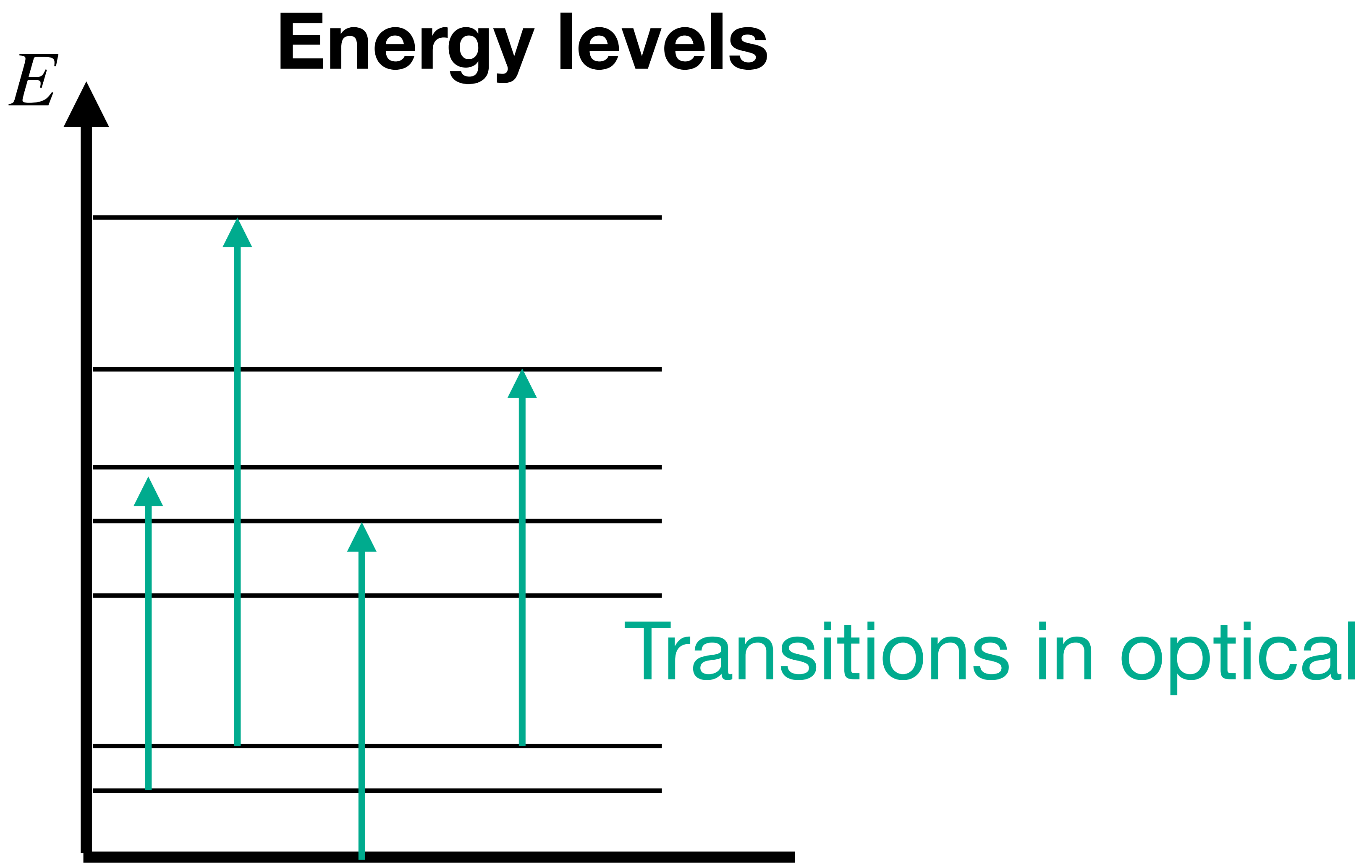
Are there other elements that can explain the infrared features?

New Method

Transition experiments done
in optical wavelength

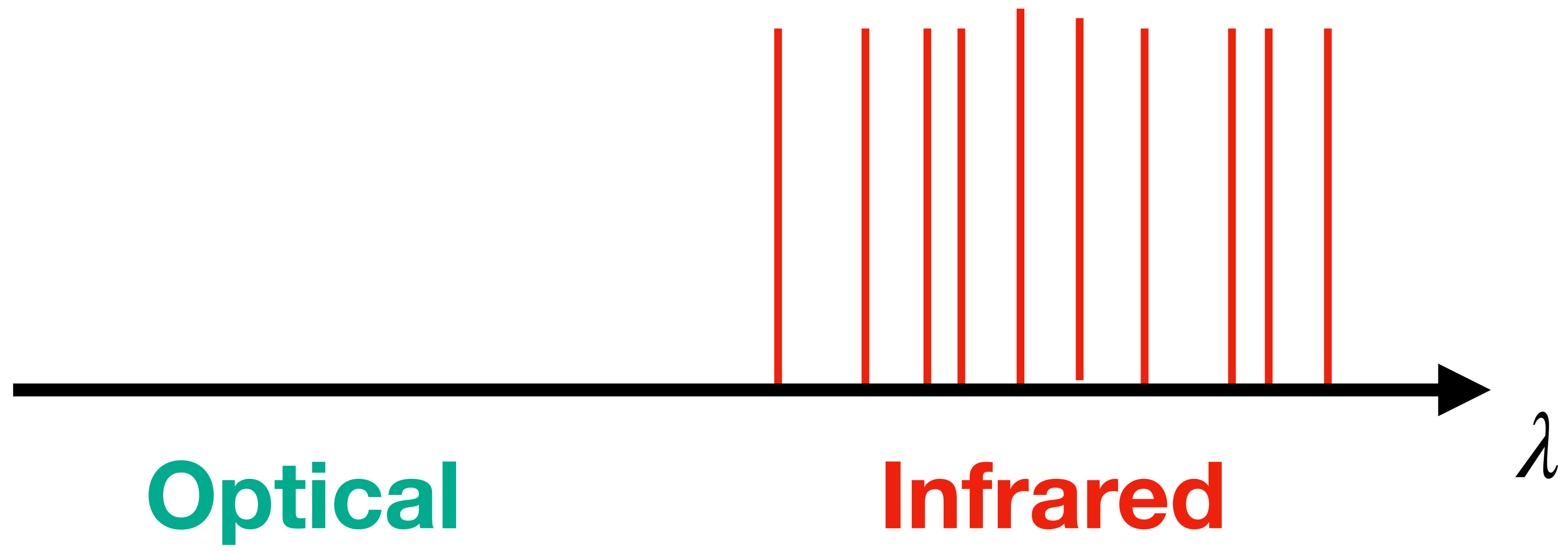


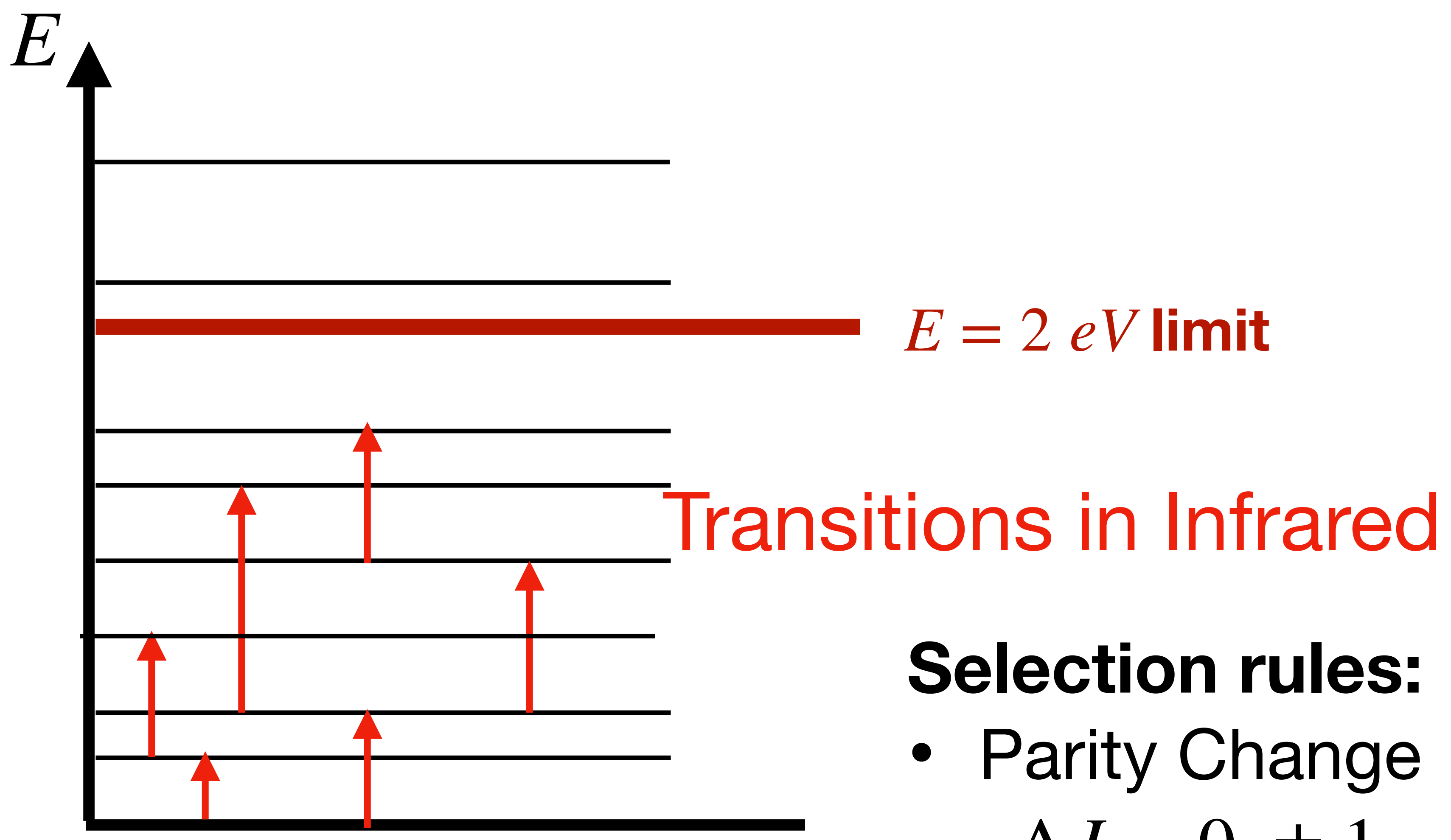
NIST database
Kramida+ 20



Our method

List of infrared transitions of singly
and doubly ionized elements

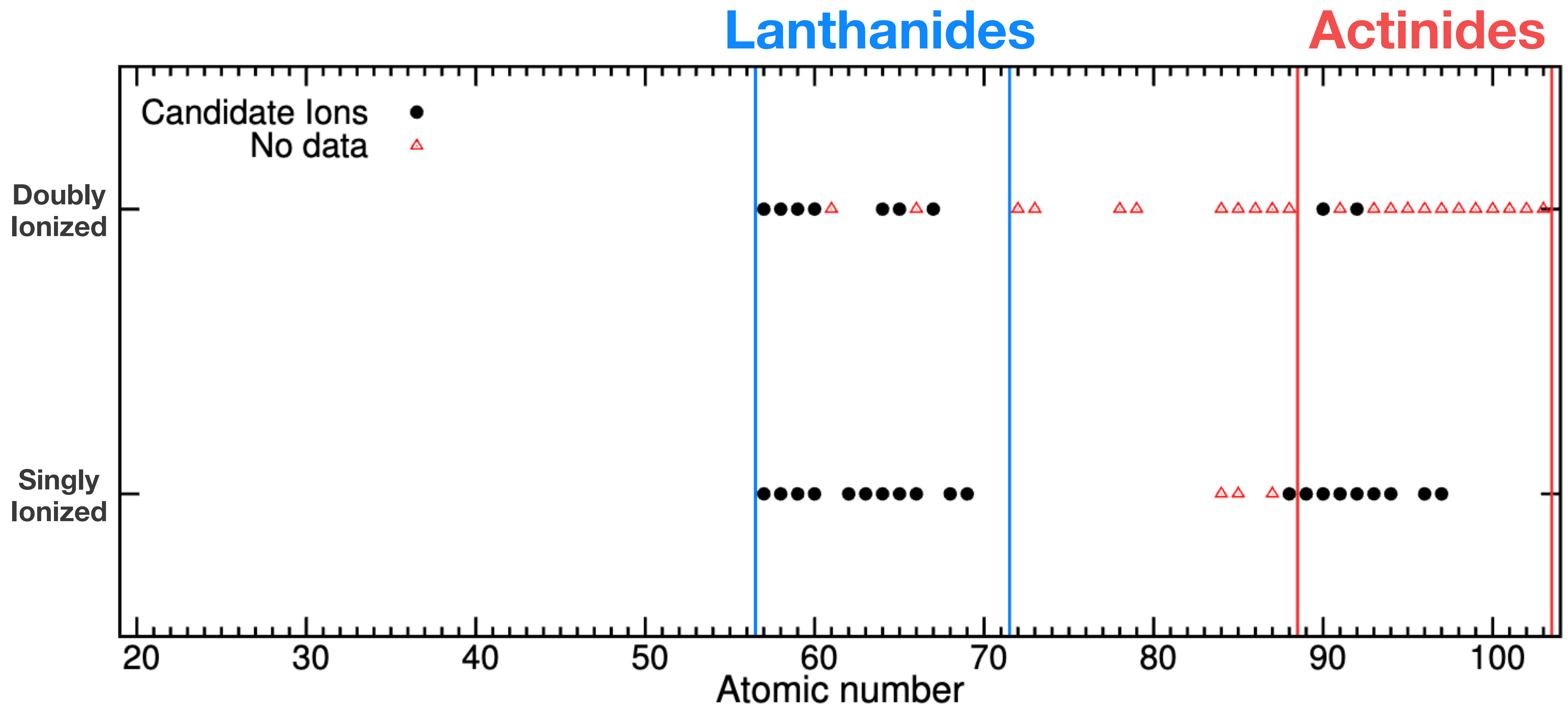


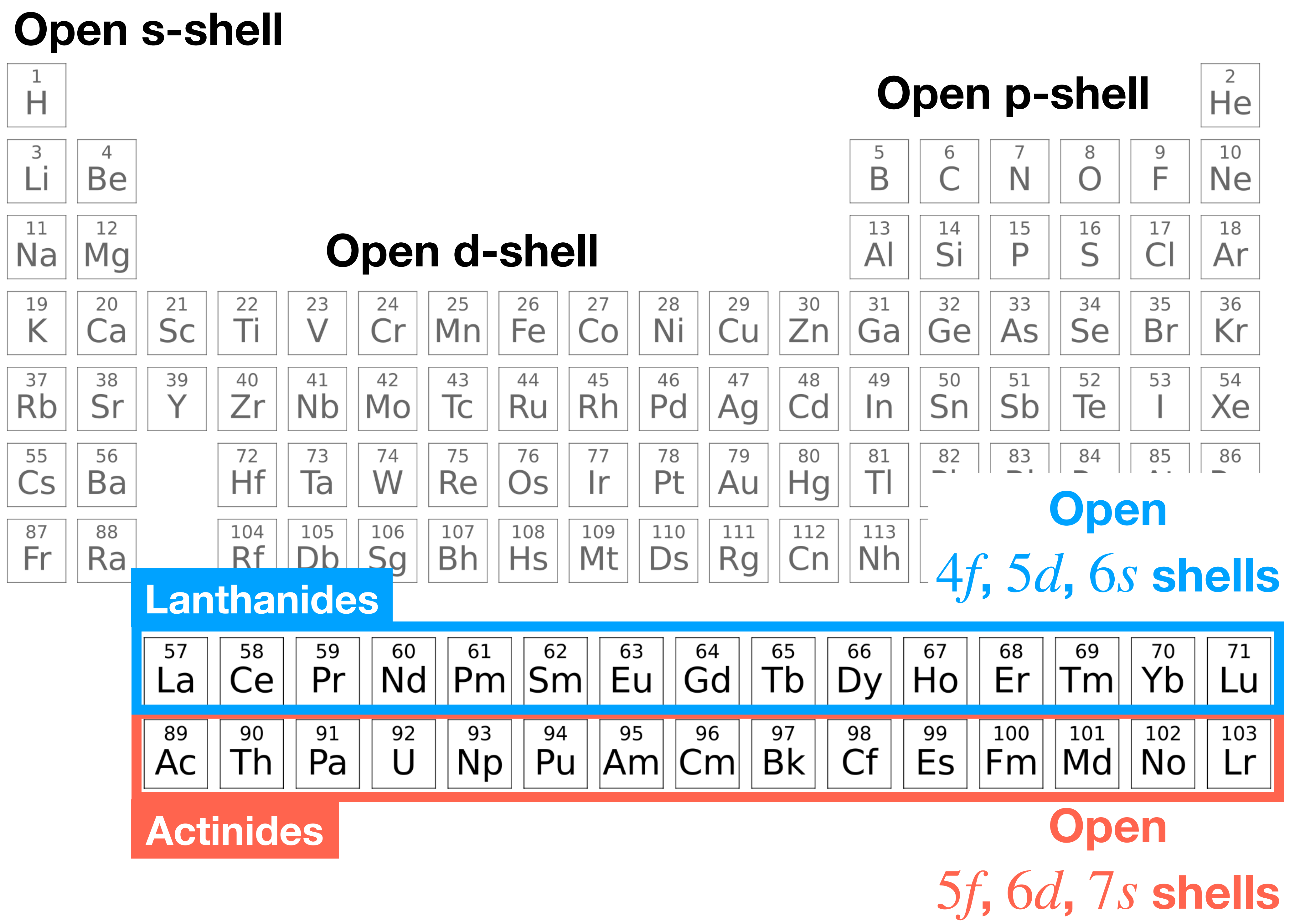


Selection rules:
- Parity Change
- $\Delta J = 0, \pm 1$
  (Except $0 \leftrightarrow 0$)

Results

Candidate elements with strong transitions in Infrared



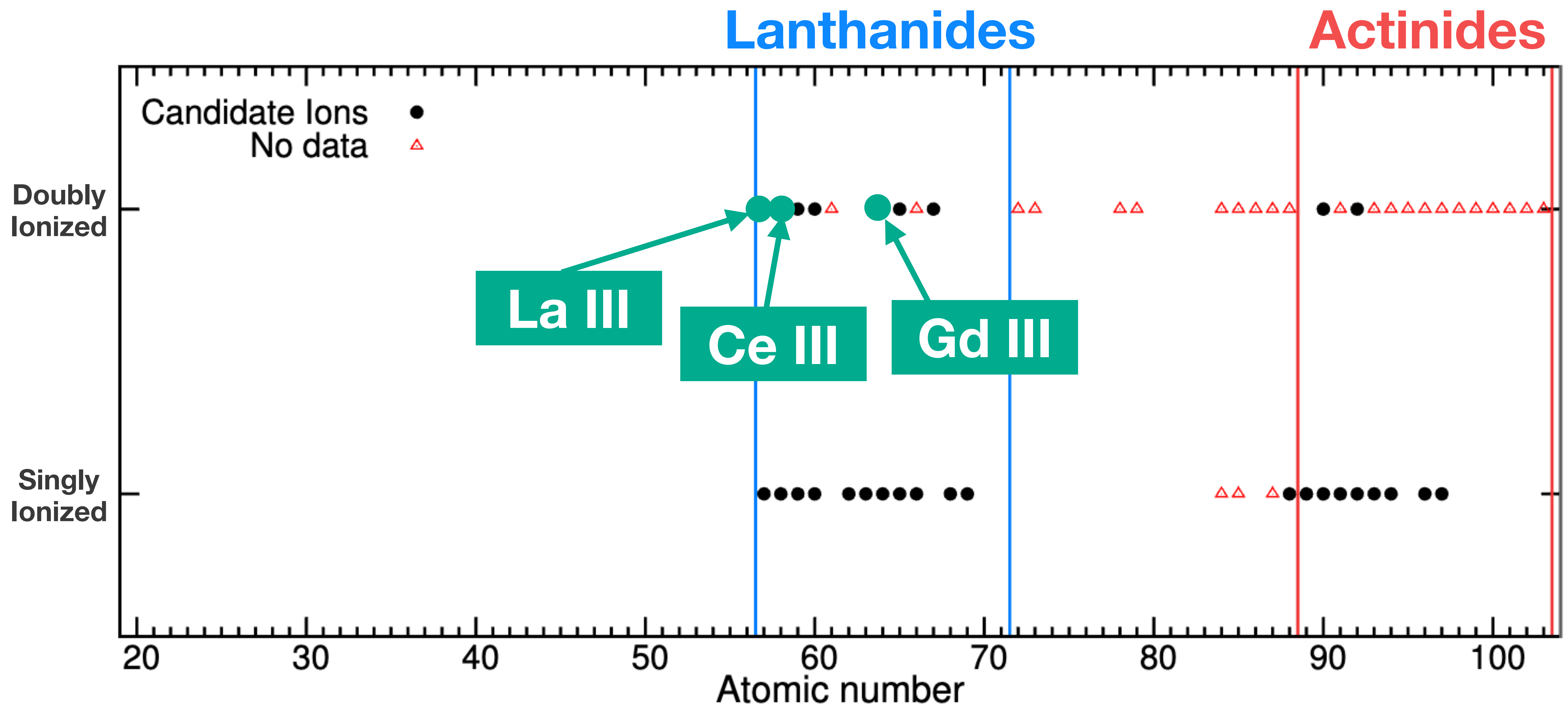


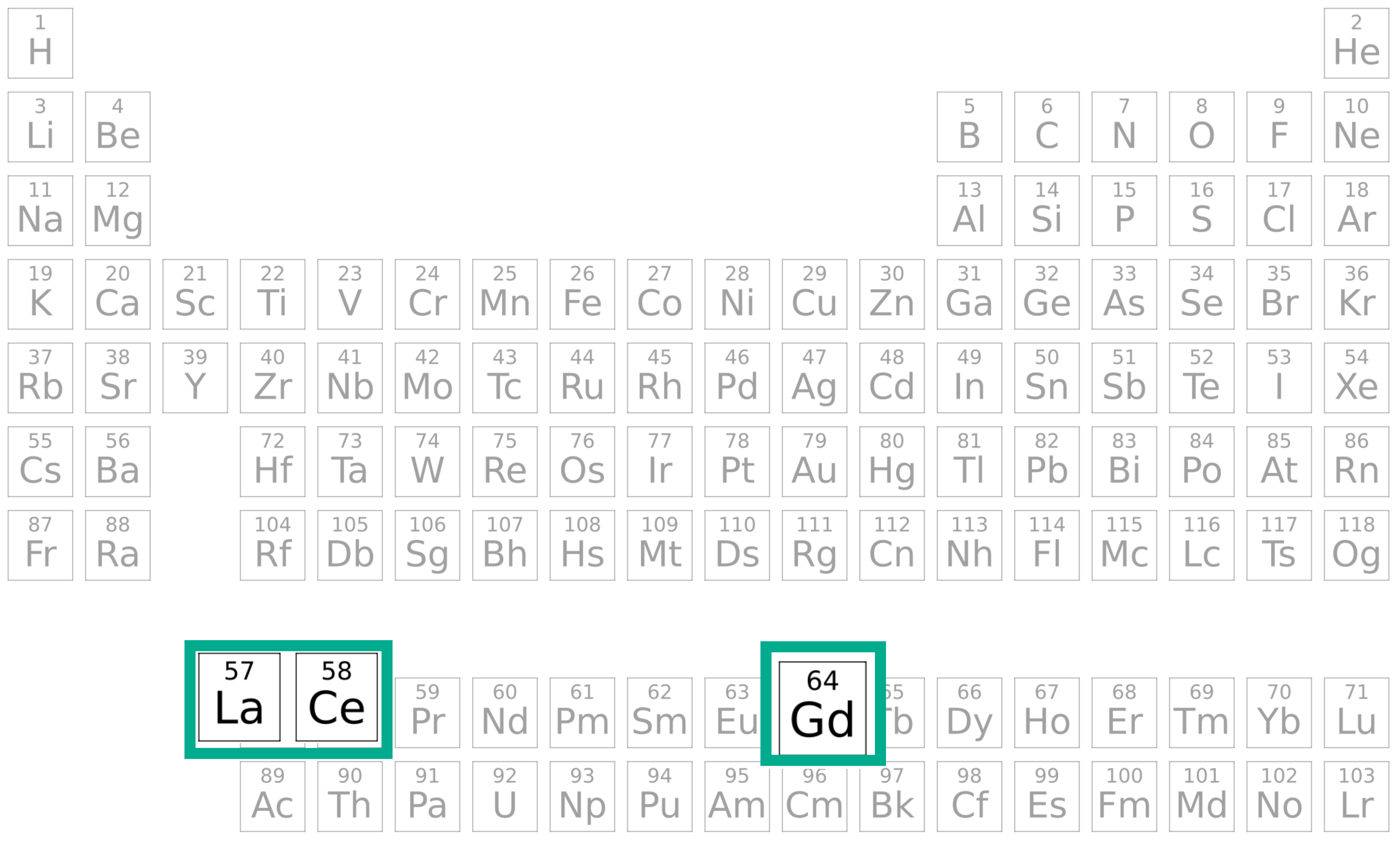
Lanthanide and actinide structure involving several open shells leads to many low-lying energy levels and many transitions in infrared

→ **Lanthanides and actinides are important for spectral investigations**

Results

Candidate elements with strong transitions in Infrared



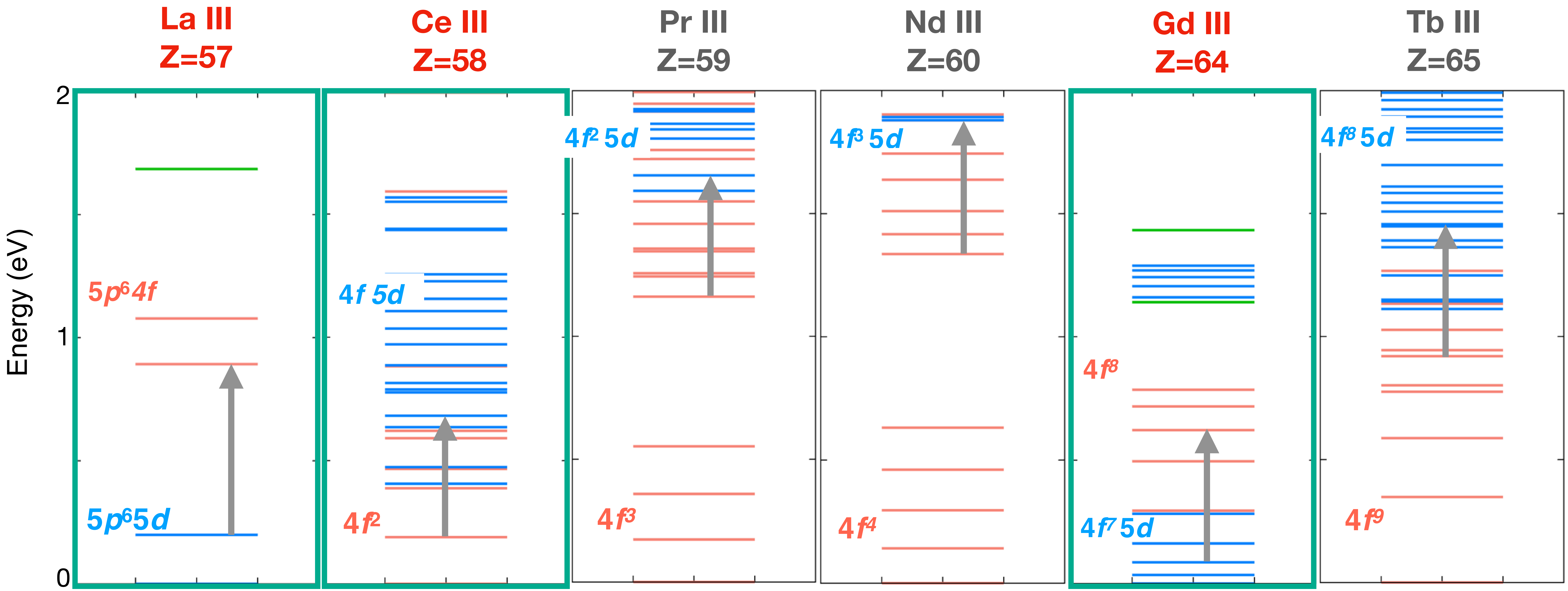


Similar to La and Ce, Gd has many interesting properties making it worth investigating

Perhaps an exception to the “left-side of periodic table” rule?

Common properties of La, Ce, and Gd

1- Atomic structure



Low number of valence electrons
→ **low-lying energy levels**

Half-filled $4f$ shell, the extra electron acts as a valence electron
→ **low-lying energy levels**

Common properties of La, Ce, and Gd

2- Strength of lines

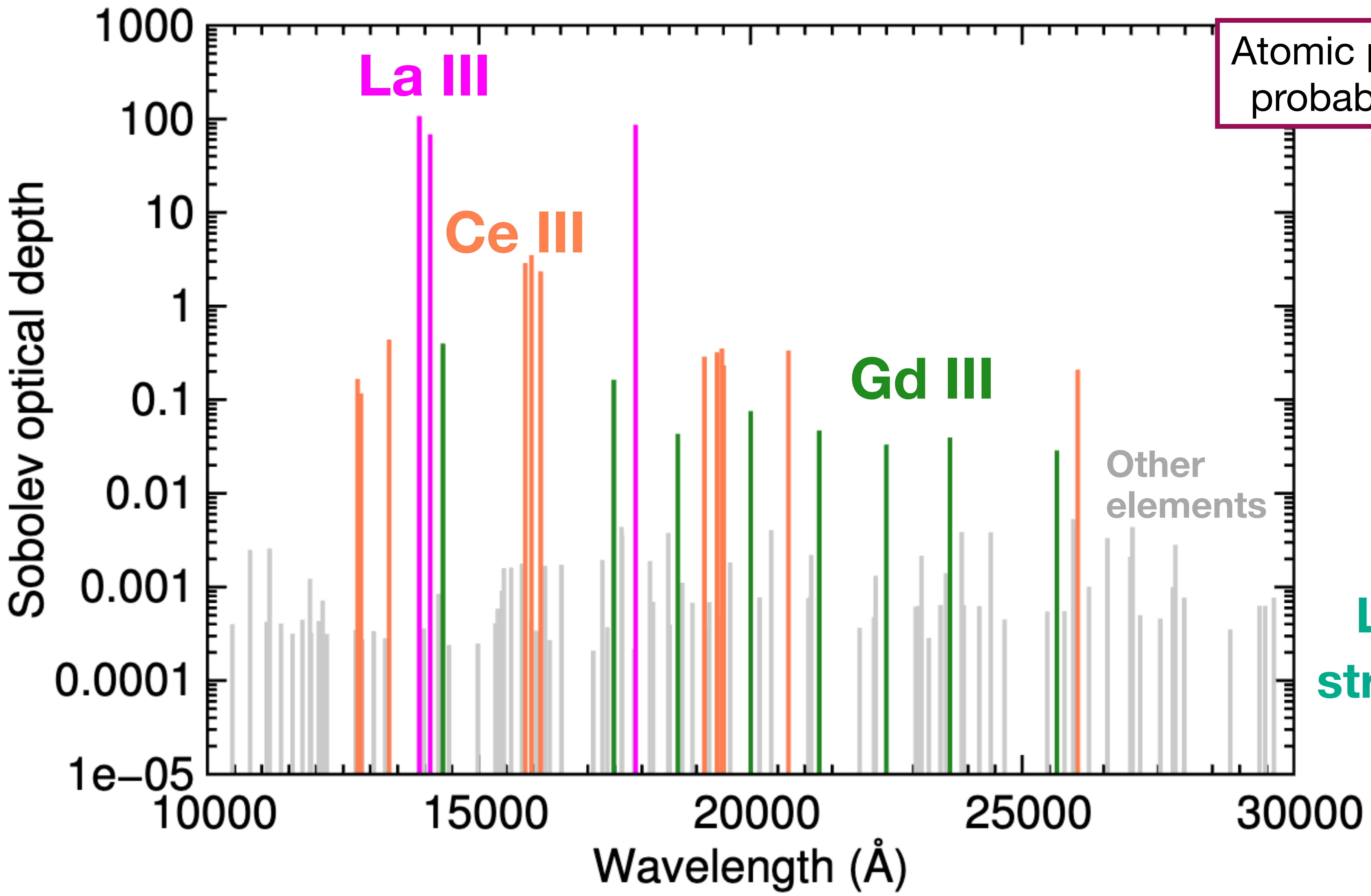
Sobolev optical depth

Strength of bound-bound transitions in an expanding ejecta

$$\tau = \frac{\pi e^2}{m_e c} n_{i,j}\, t\, \lambda \boxed{gf} \frac{1}{\Sigma} \boxed{e^{-\frac{E_l}{kT}}}$$

Atomic property showing probability of transition

Boltzmann distribution of lines
Lower-lying energy levels → stronger lines



La III have exceptionally strong transitions, followed by Ce III and Gd III

Common properties of La, Ce, and Gd

3- Emergence in Chemically Peculiar Stars

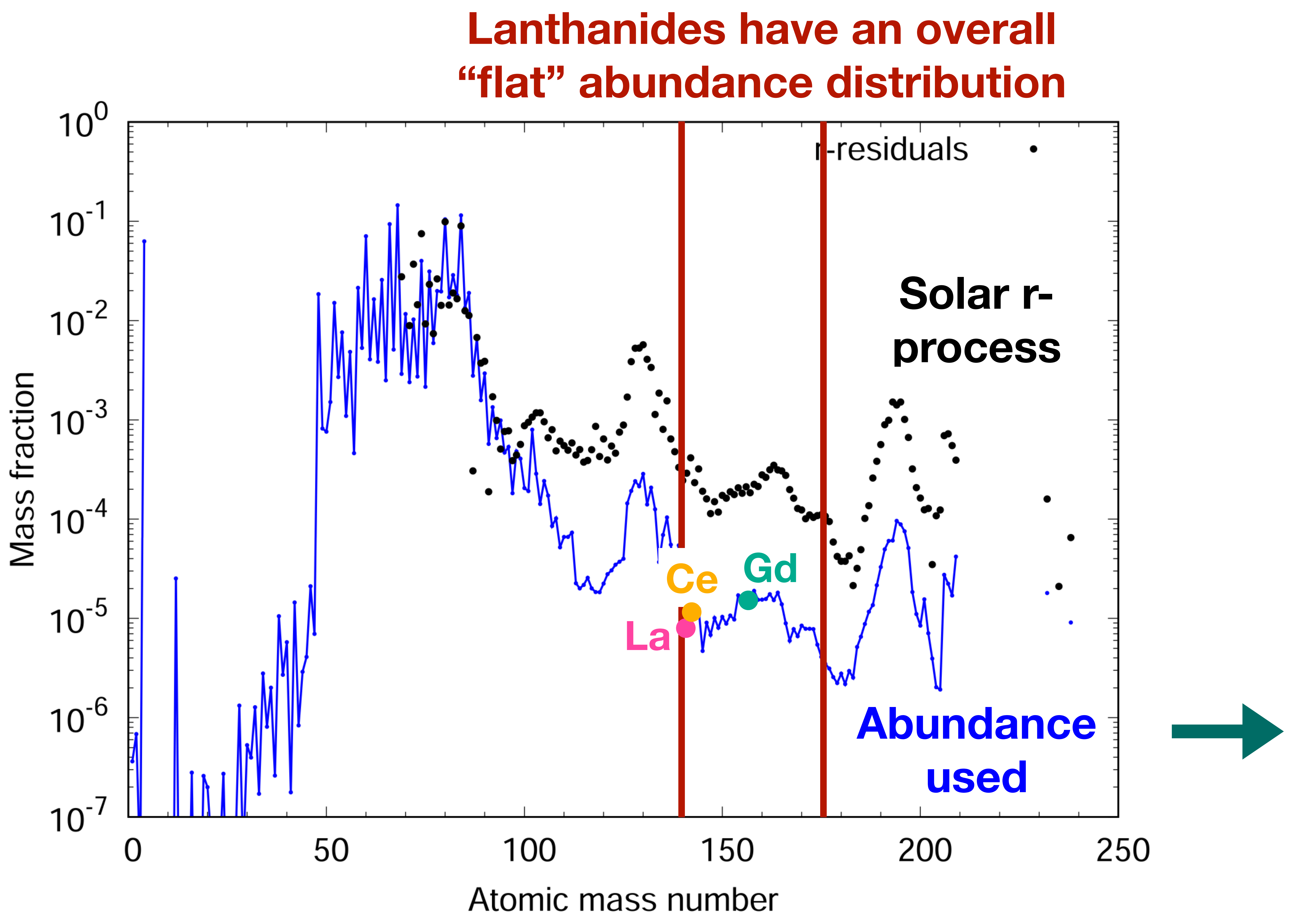
Chemically Peculiar Stars = Astrophysical laboratory for Kilonova spectra

(Tanaka+ 23)

→ **Such lines may appear in the kilonova spectra as well**

Radiative Transfer Simulations

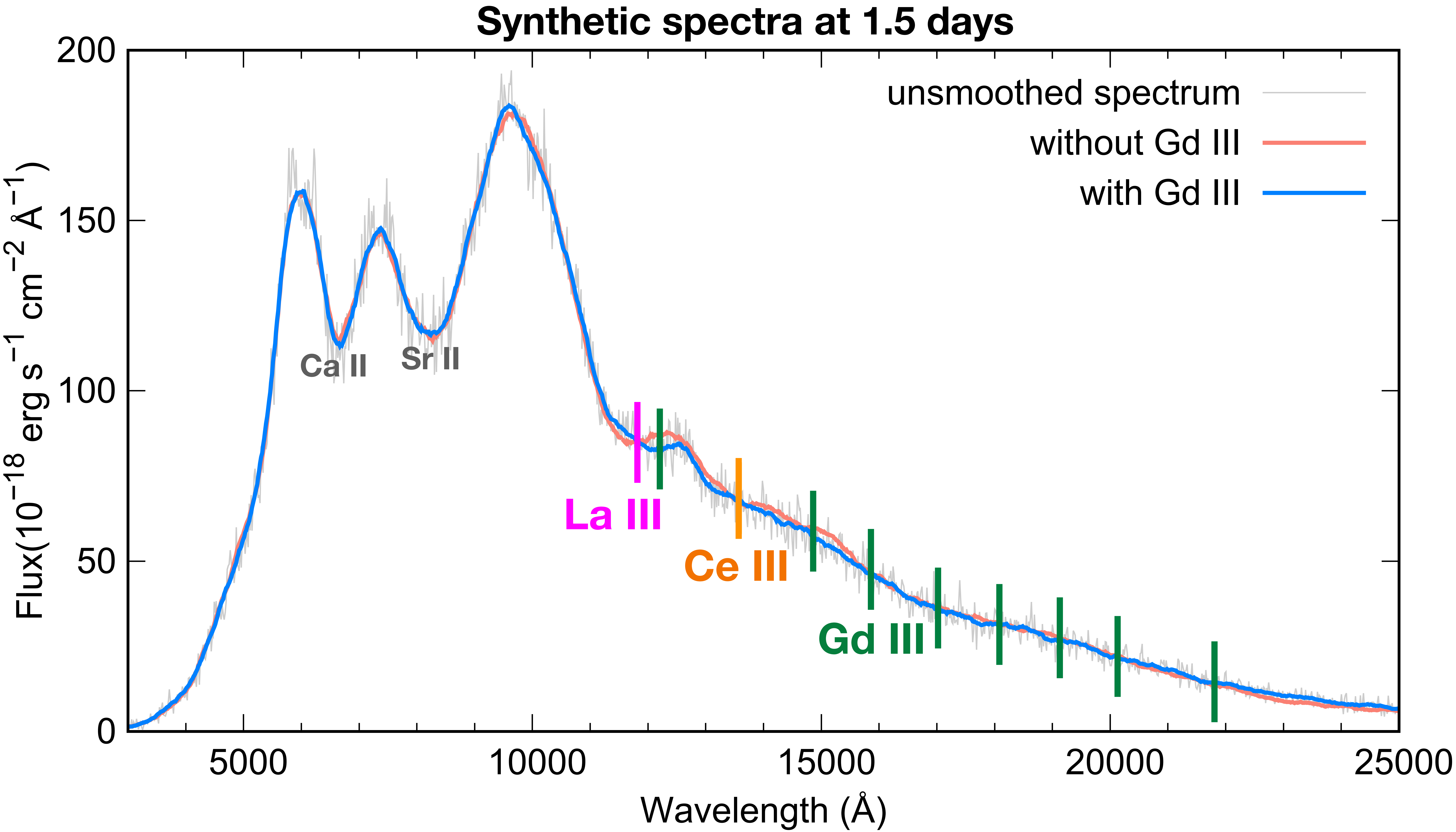
- Use wavelength-dependent radiative transfer code (Tanaka+13)
- Assume a similar abundance among lanthanides
- Investigate the effect Gd III has on the near-infrared spectrum besides La III and Ce III.



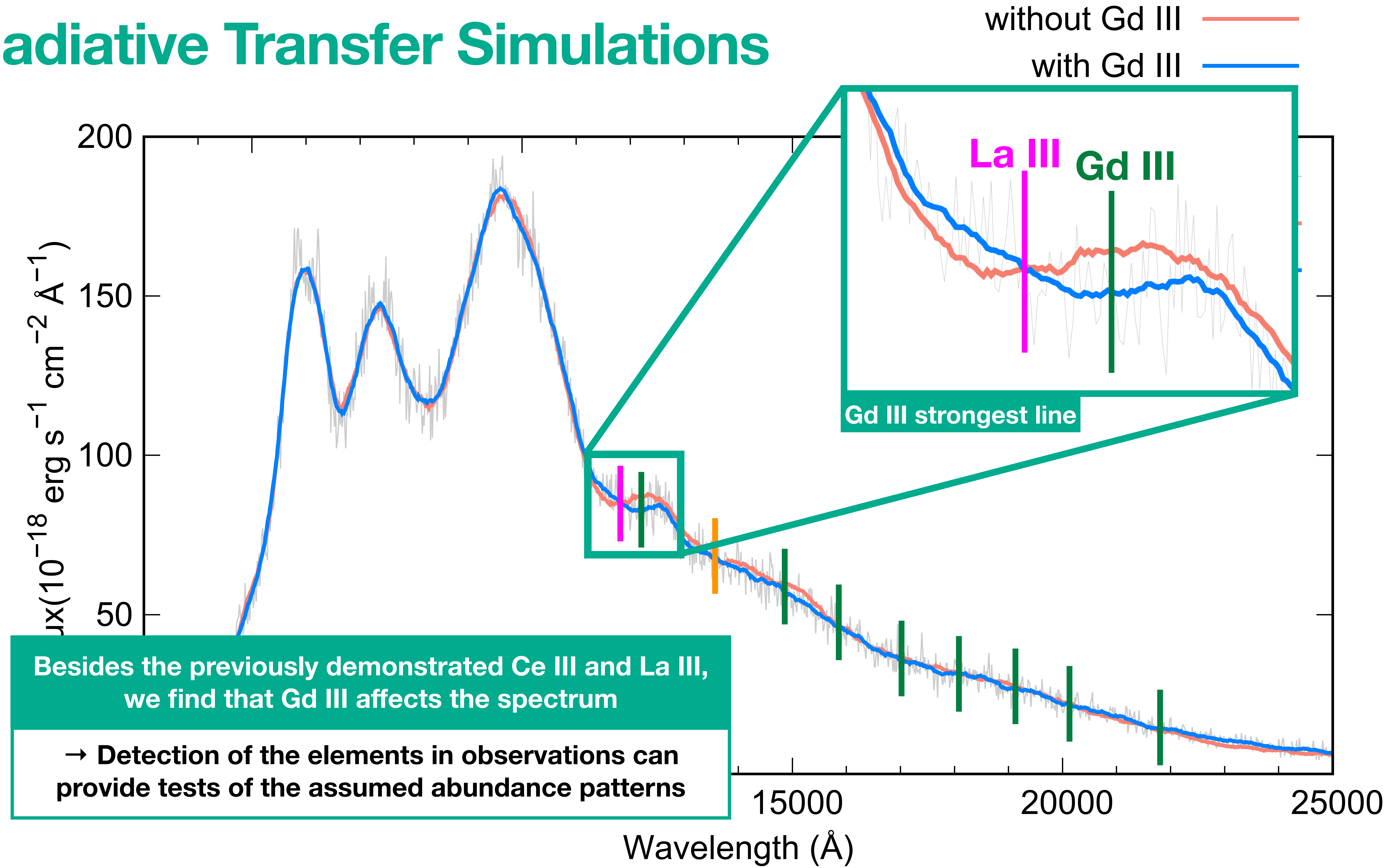
Gives best fit to GW170817

Domoto+22

Radiative Transfer Simulations



Radiative Transfer Simulations

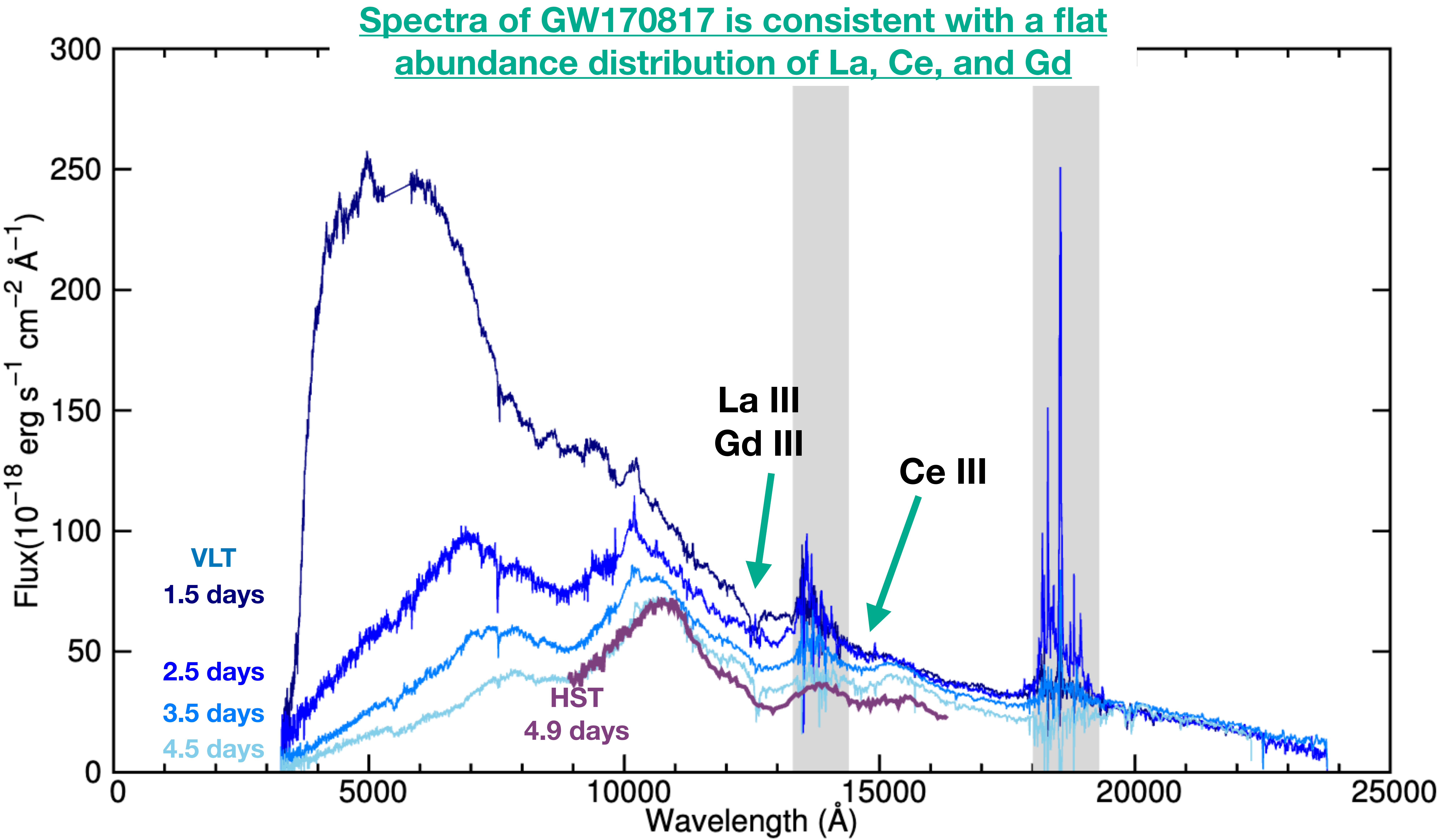


Besides the previously demonstrated Ce III and La III, we find that Gd III affects the spectrum

→ Detection of the elements in observations can provide tests of the assumed abundance patterns

Comparison with GW170817

Several spectral identifications in the near-infrared!



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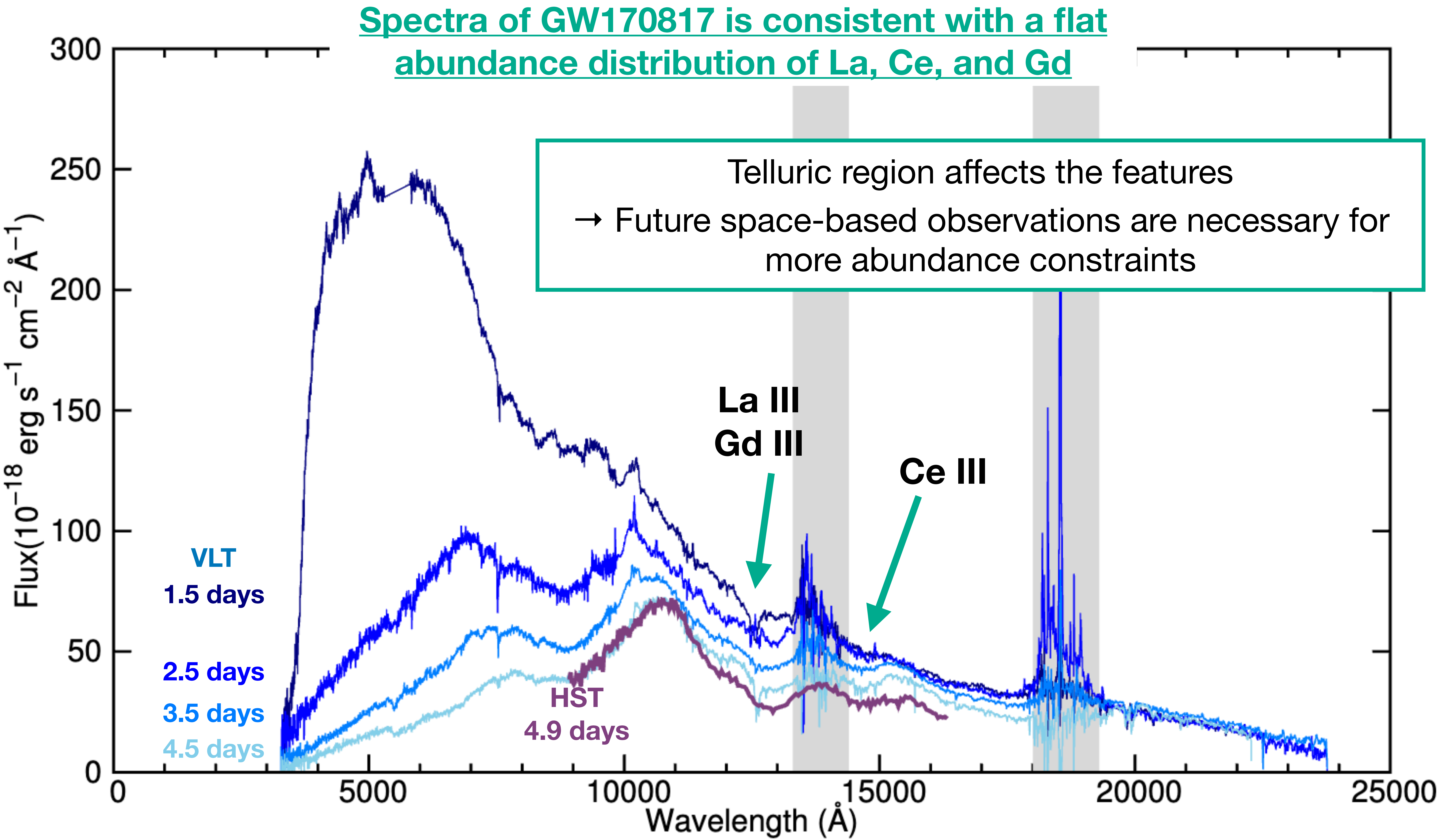


Summary:

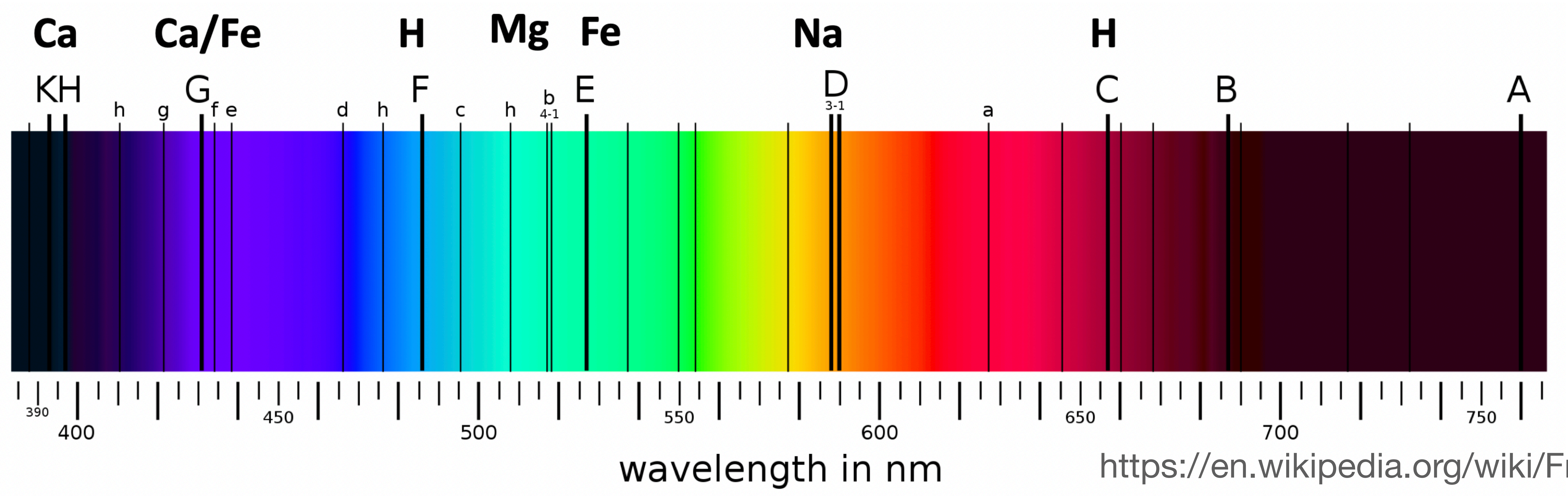
- **We were able to identify several r-process elements in kilonova infrared spectra: La III, Ce III and Gd III**
- **The detection of such elements in GW170817 is consistent with a constant abundance distribution among lanthanides**

    → Further observations are still necessary for better abundance constraints

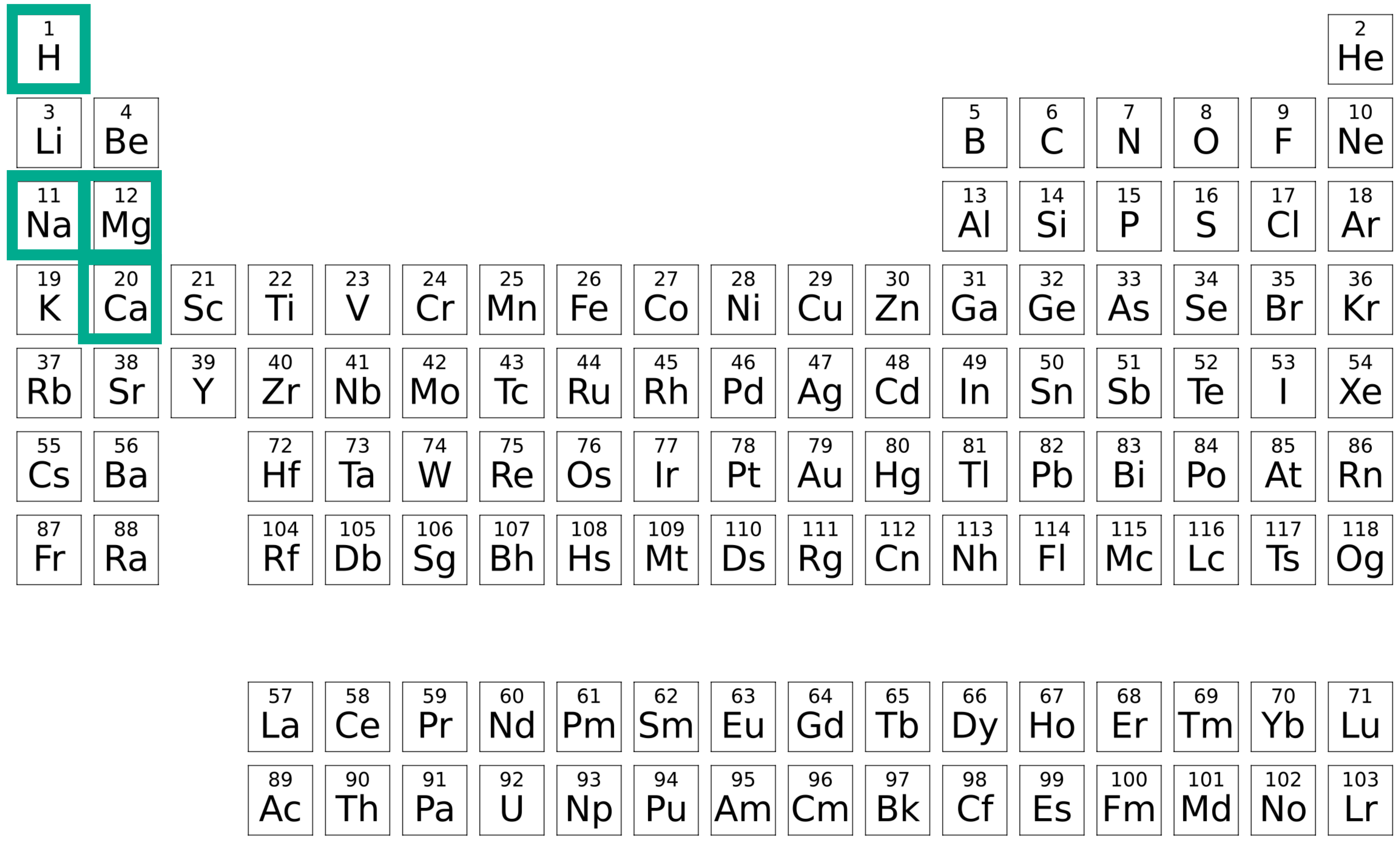
Further details on:
Rahmouni et al. (2025)
ApJ 980,43

Appendix

Sun spectra



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



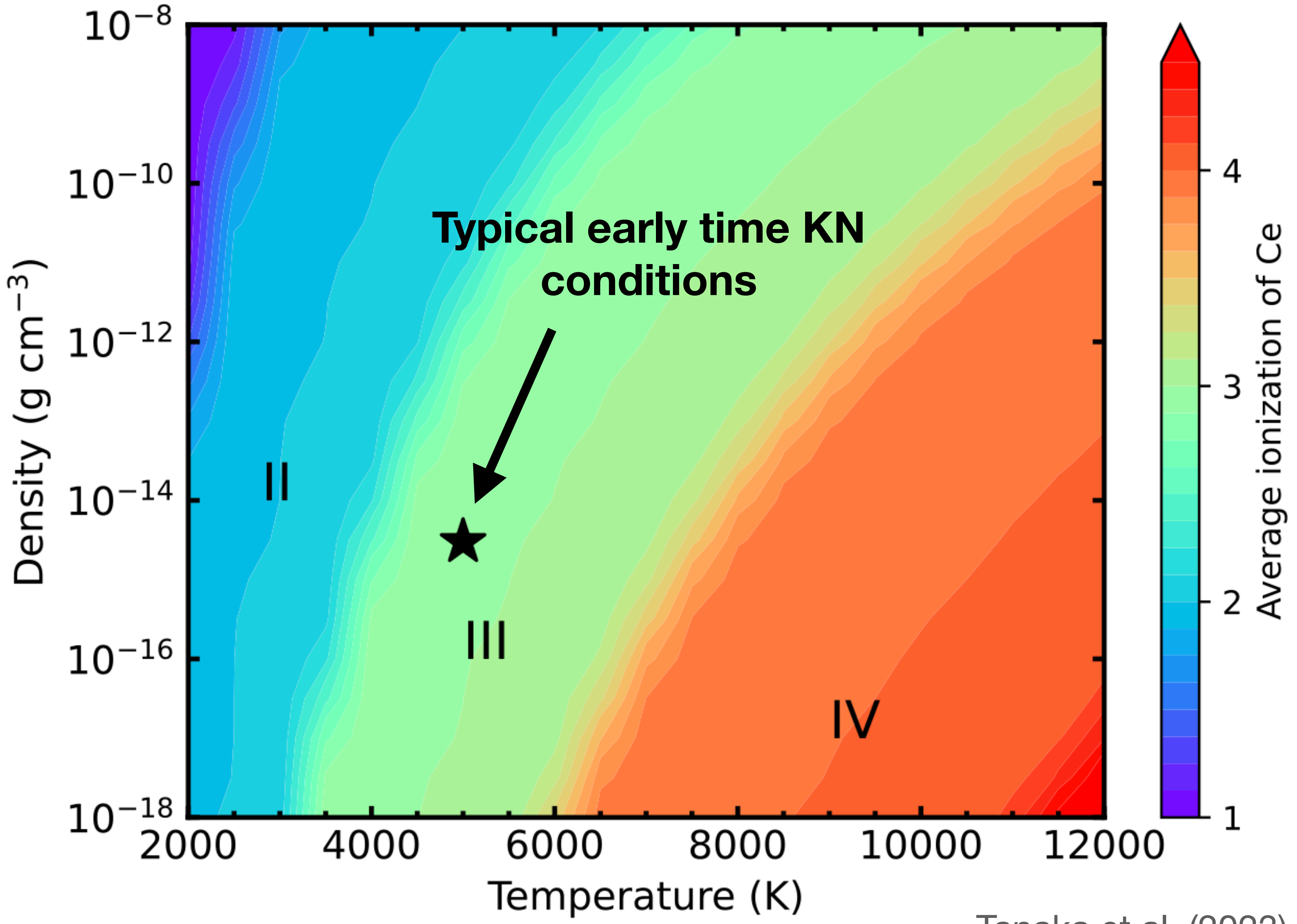
Elements with

(1) low-lying energy levels = higher population

(2) relatively simple structure = small number of transitions = high transition probability

Ionization

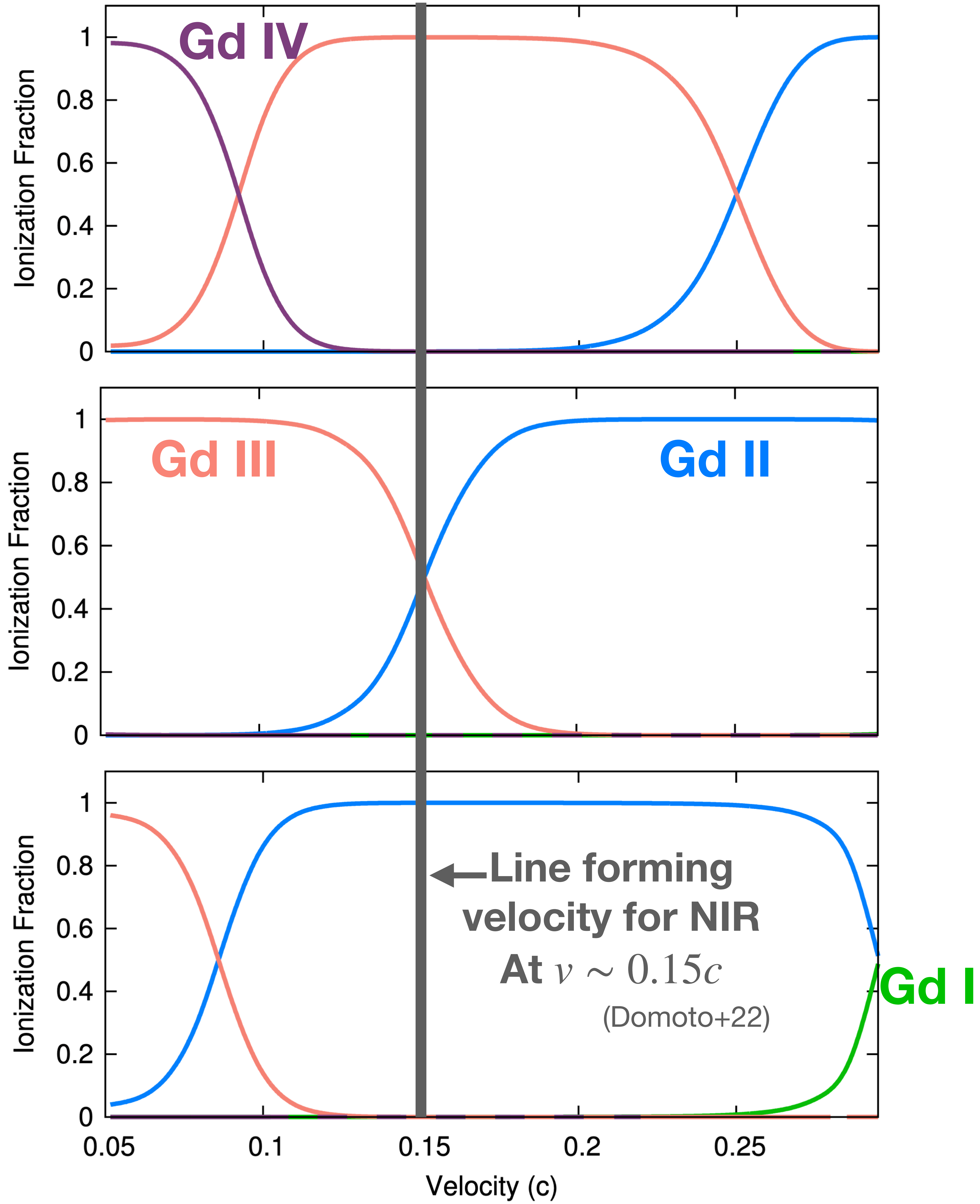
Average ionization of Ce in KNe conditions



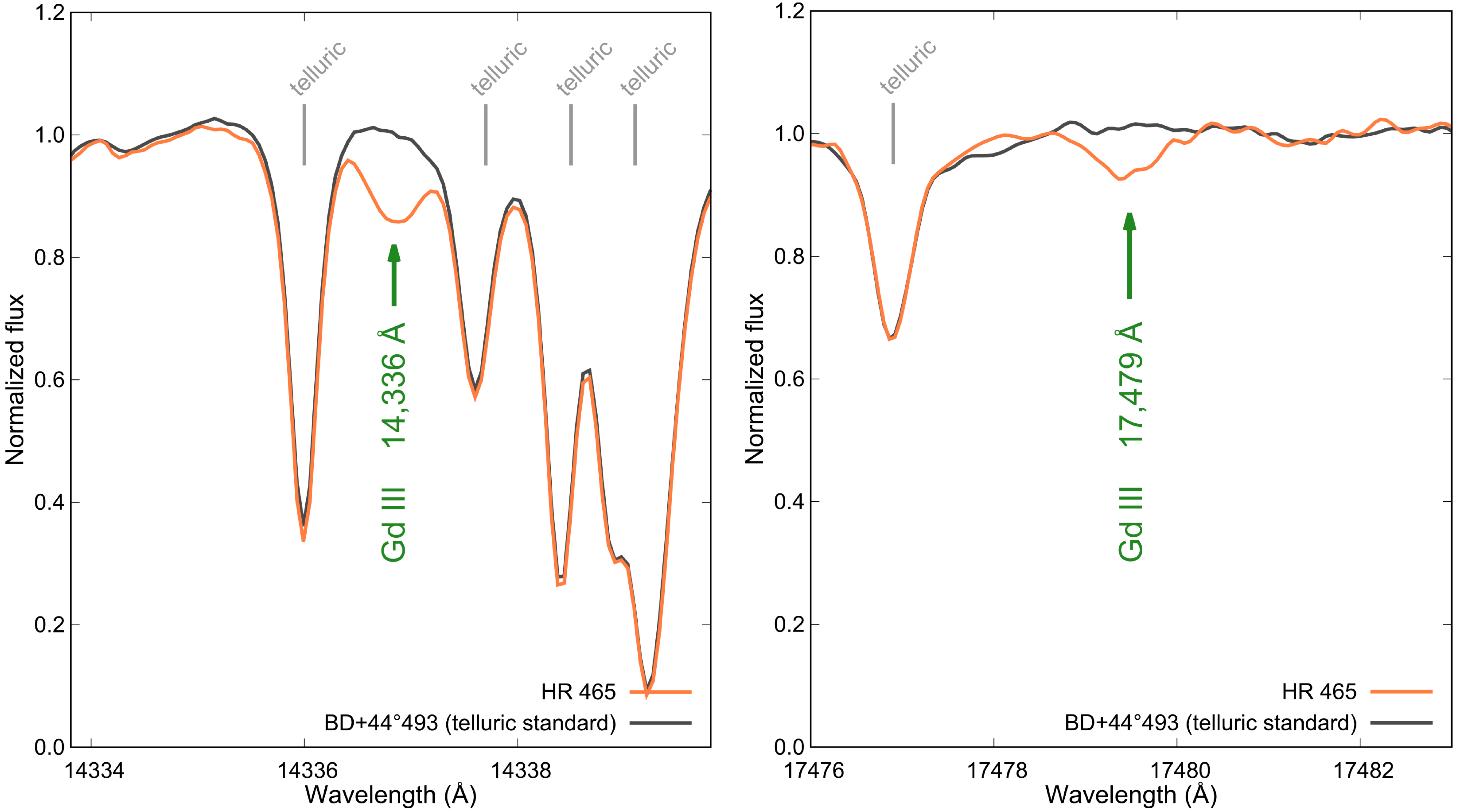
Tanaka et al. (2023)

Cerium is typically secondly ionized in early-time Kilonovae spectrum.
→ we expect other lanthanides to show similar ionization

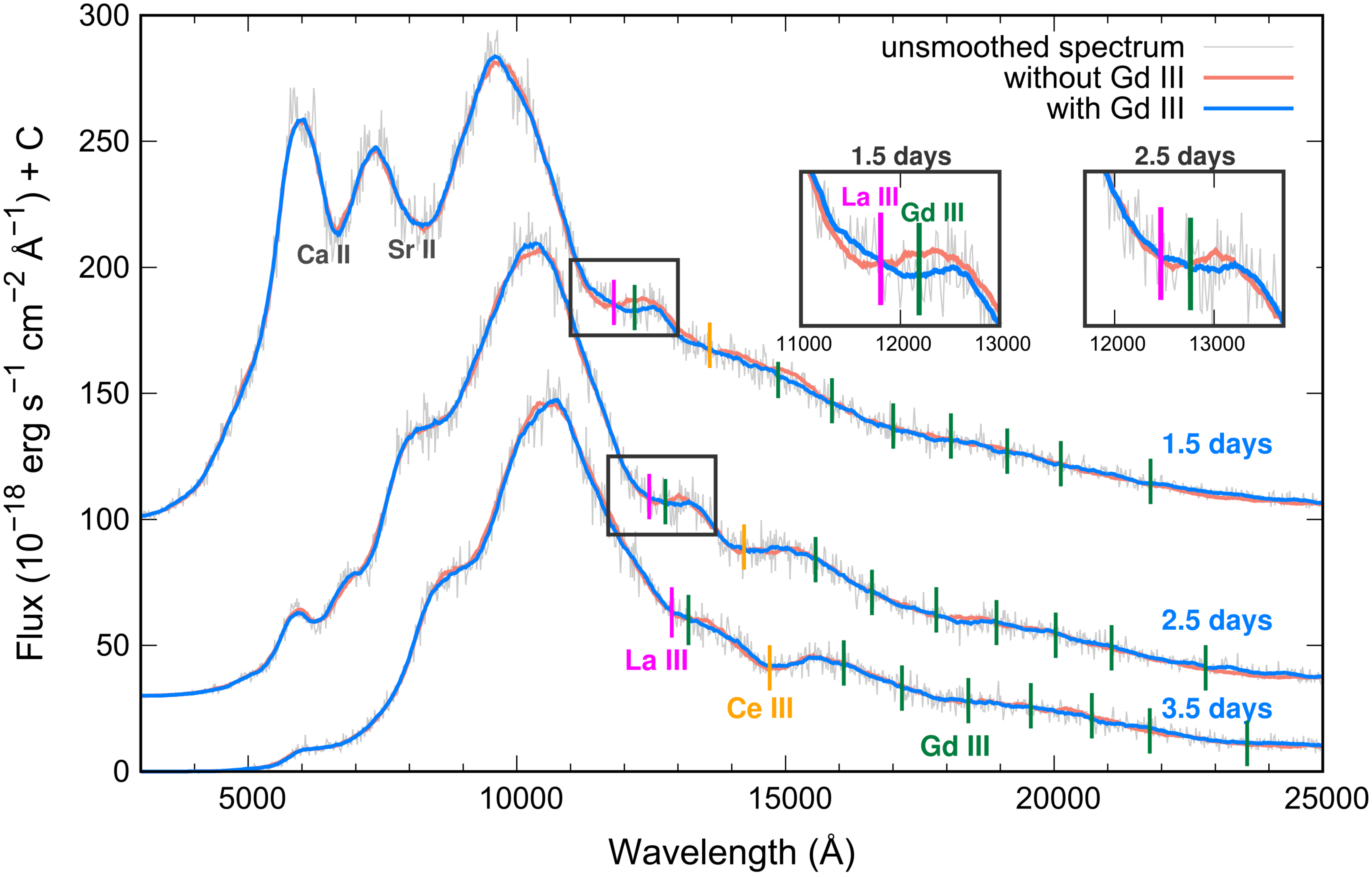
Ionization fraction of Gd at 1.5, 2.5 and 3,5 days



Gd III lines in HR 465



Time Evolution of Spectra



Gd III effect disappears before that of La III due to the higher ionization potential of Gd II compared to La II