Heavy Elements in Late-Time Kilonova Spectra

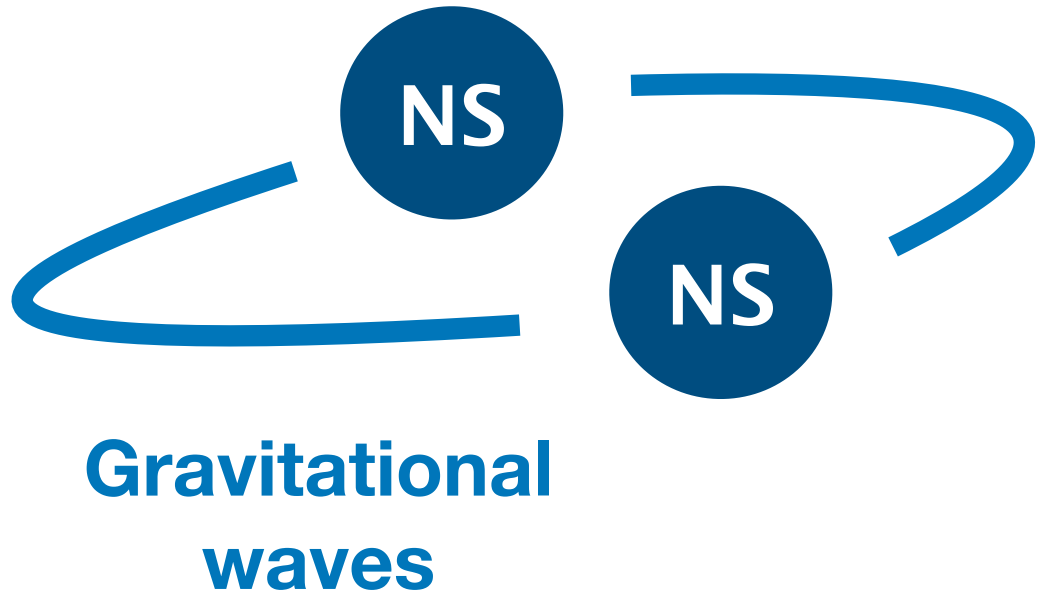
Abundance Constraints from GW170817

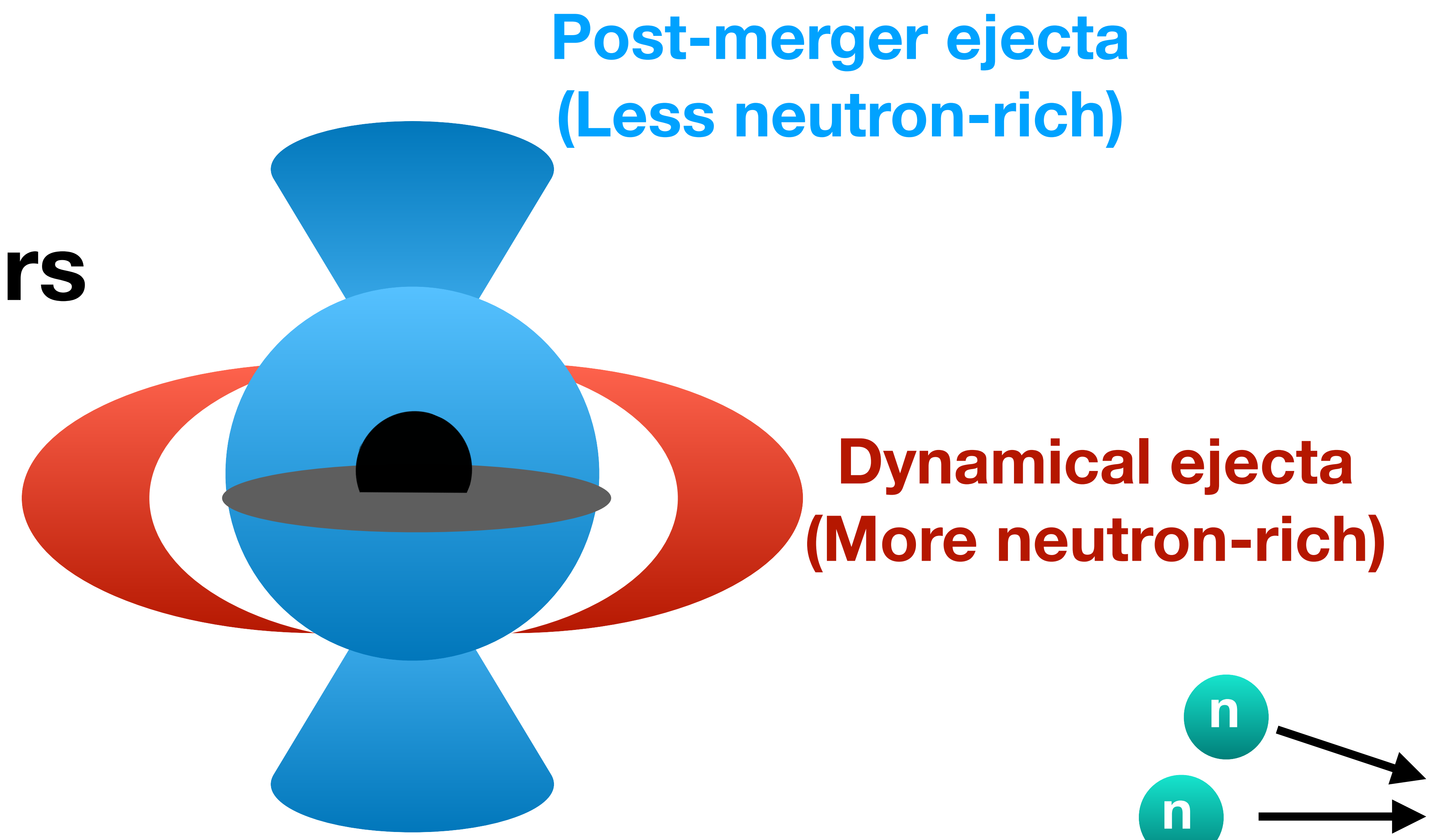
Salma Rahmouni, Masaomi Tanaka (Tohoku University)

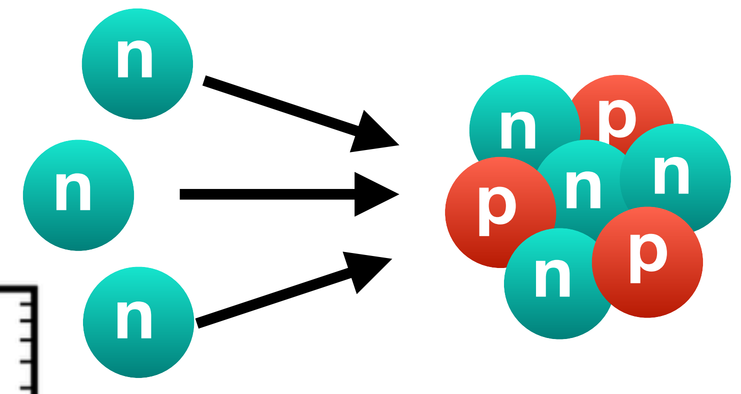
Multi-messenger Annual Conference (2025) @Naruko

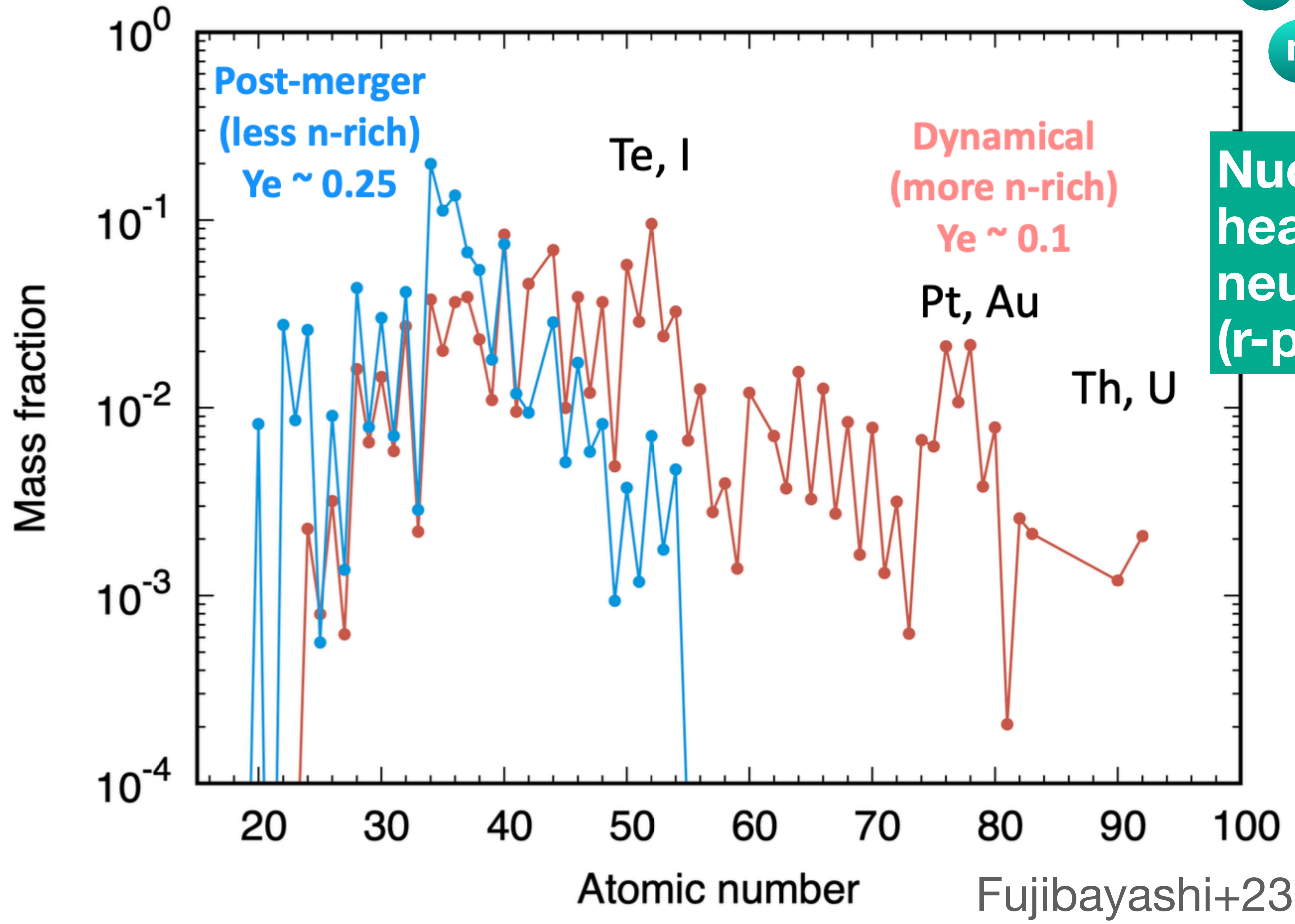
Introduction

Neutron star mergers





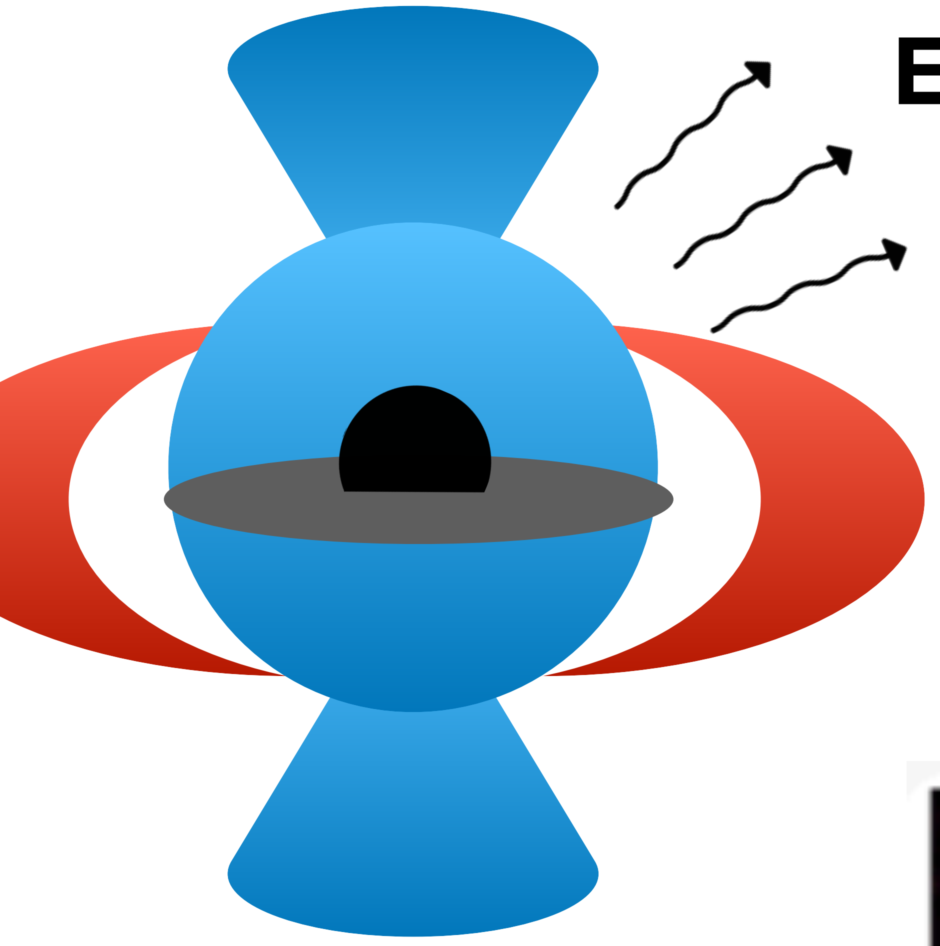




Fujibayashi+23

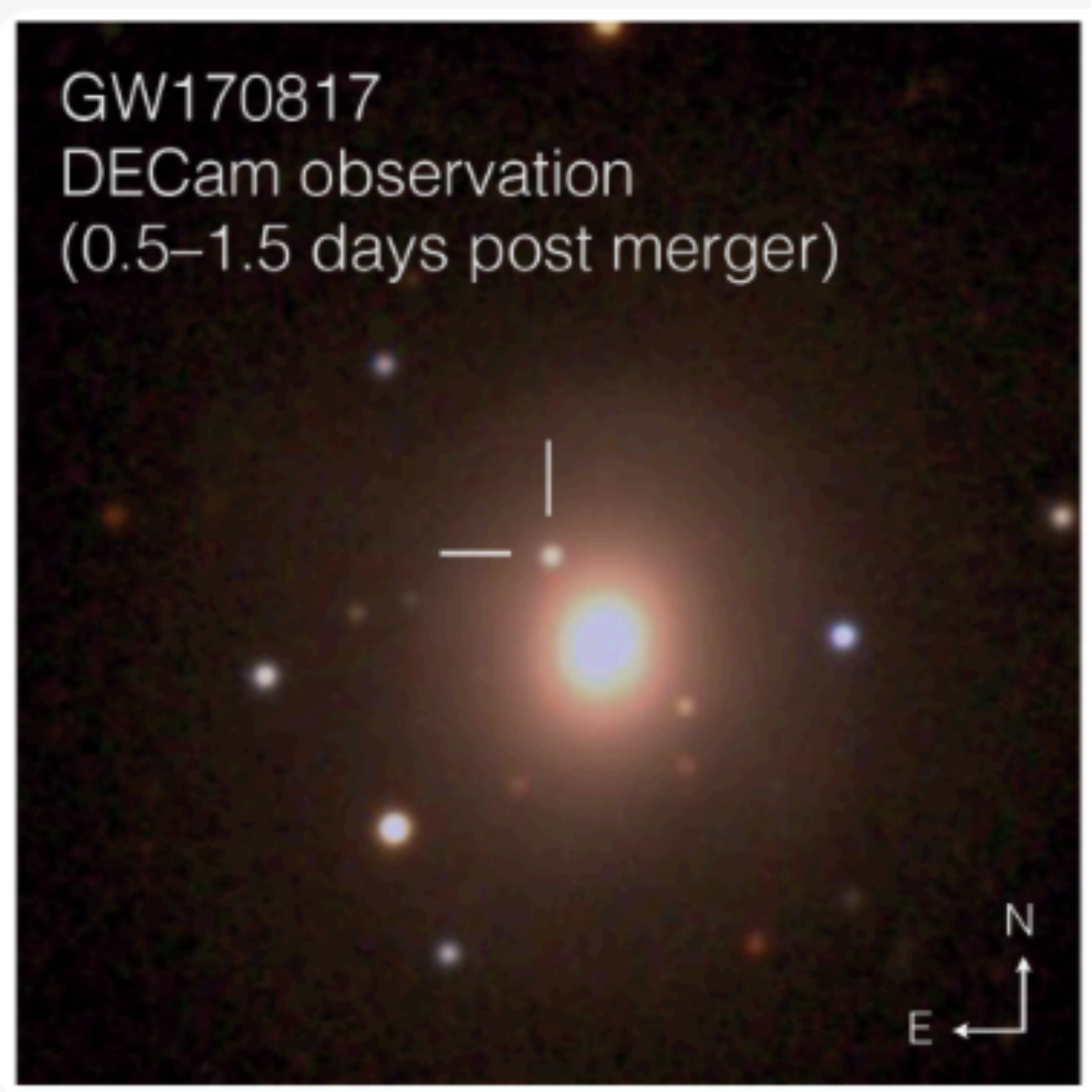
Nucleosynthesis of heavy elements by rapid neutron capture process (r-process)

Introduction



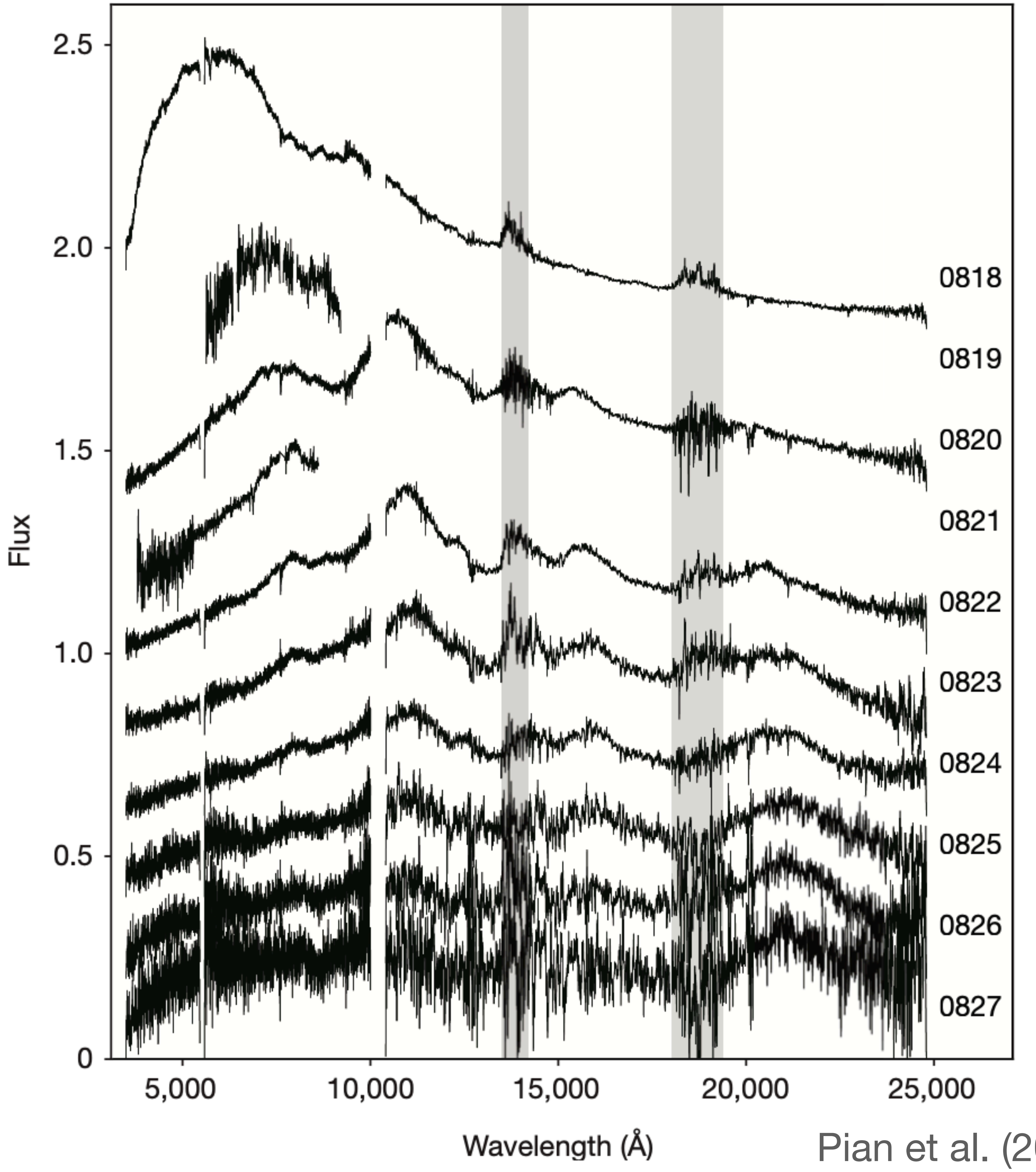
Electromagnetic emission
“Kilonova”

Kilonova of GW170817



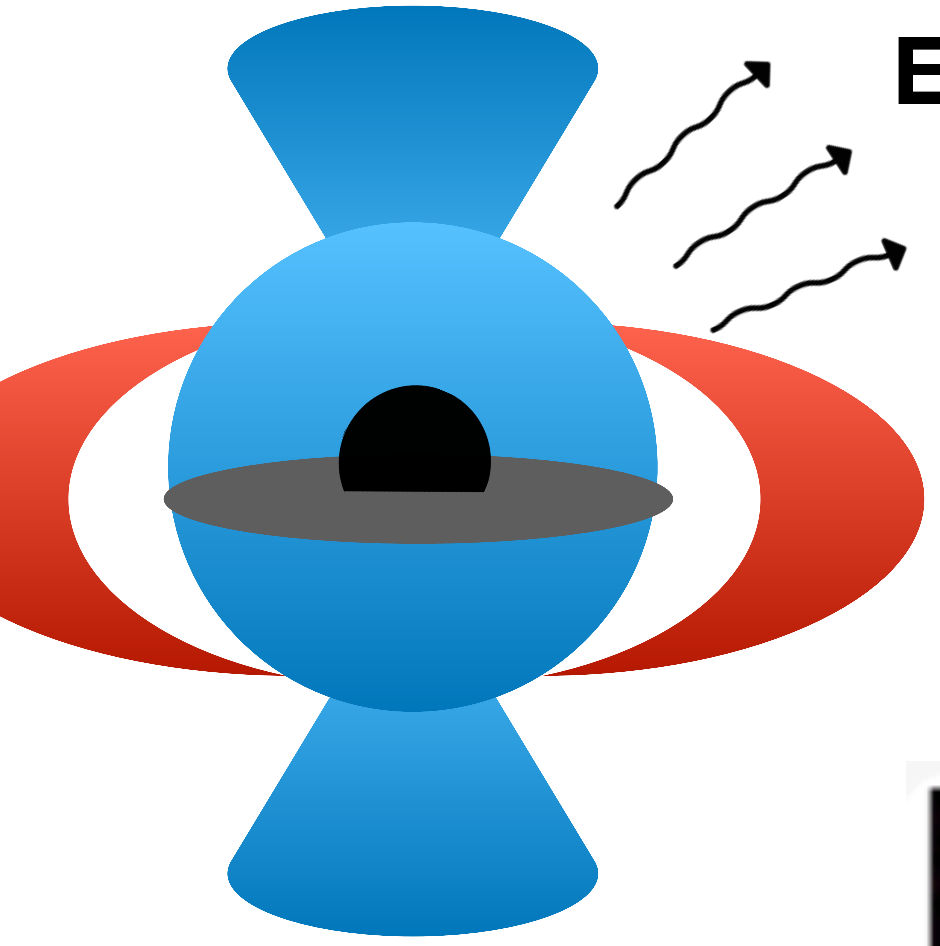
Soares-Santos et al. (2017)

GW170817 spectrum



Pian et al. (2017)

Introduction



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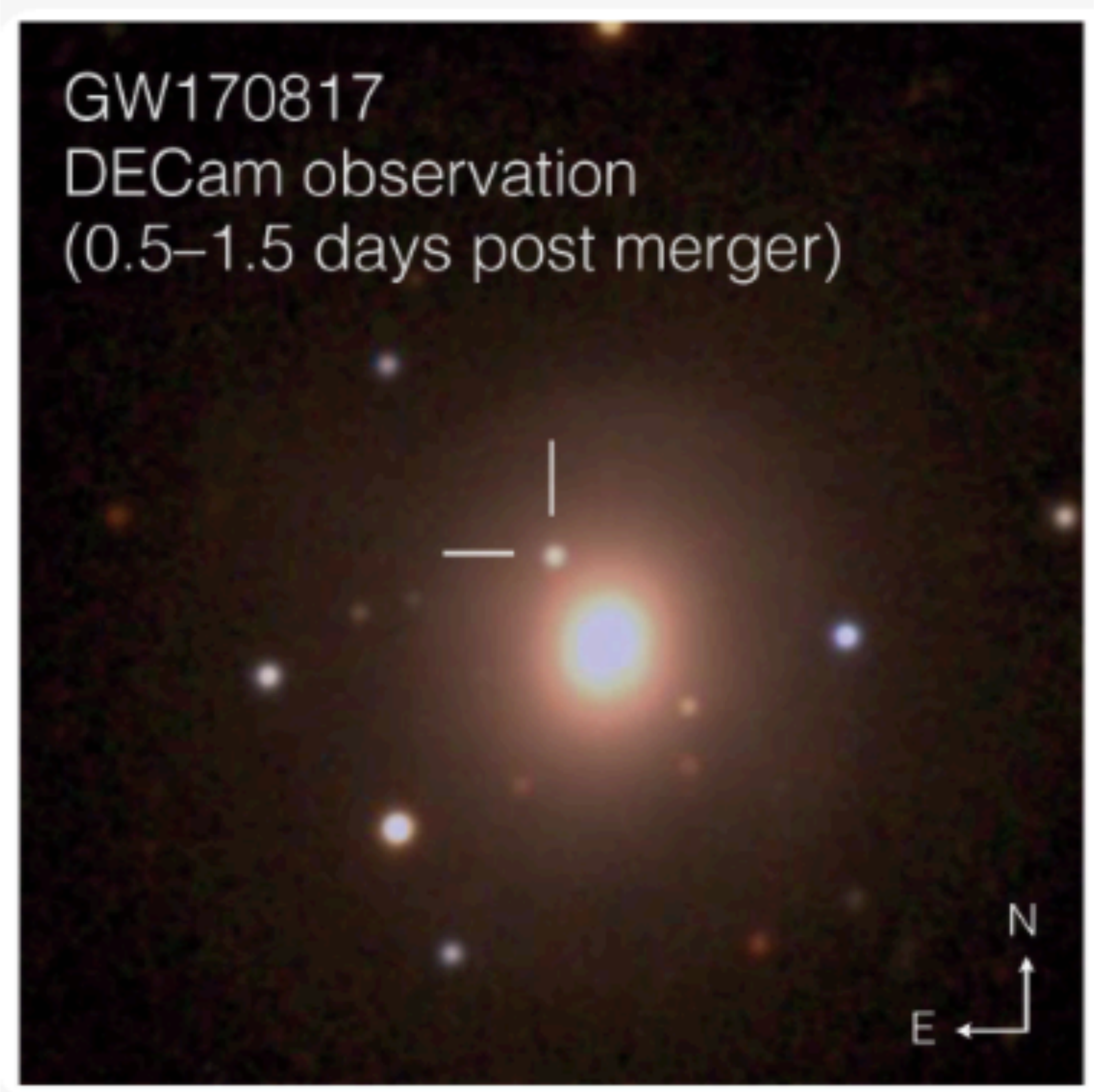
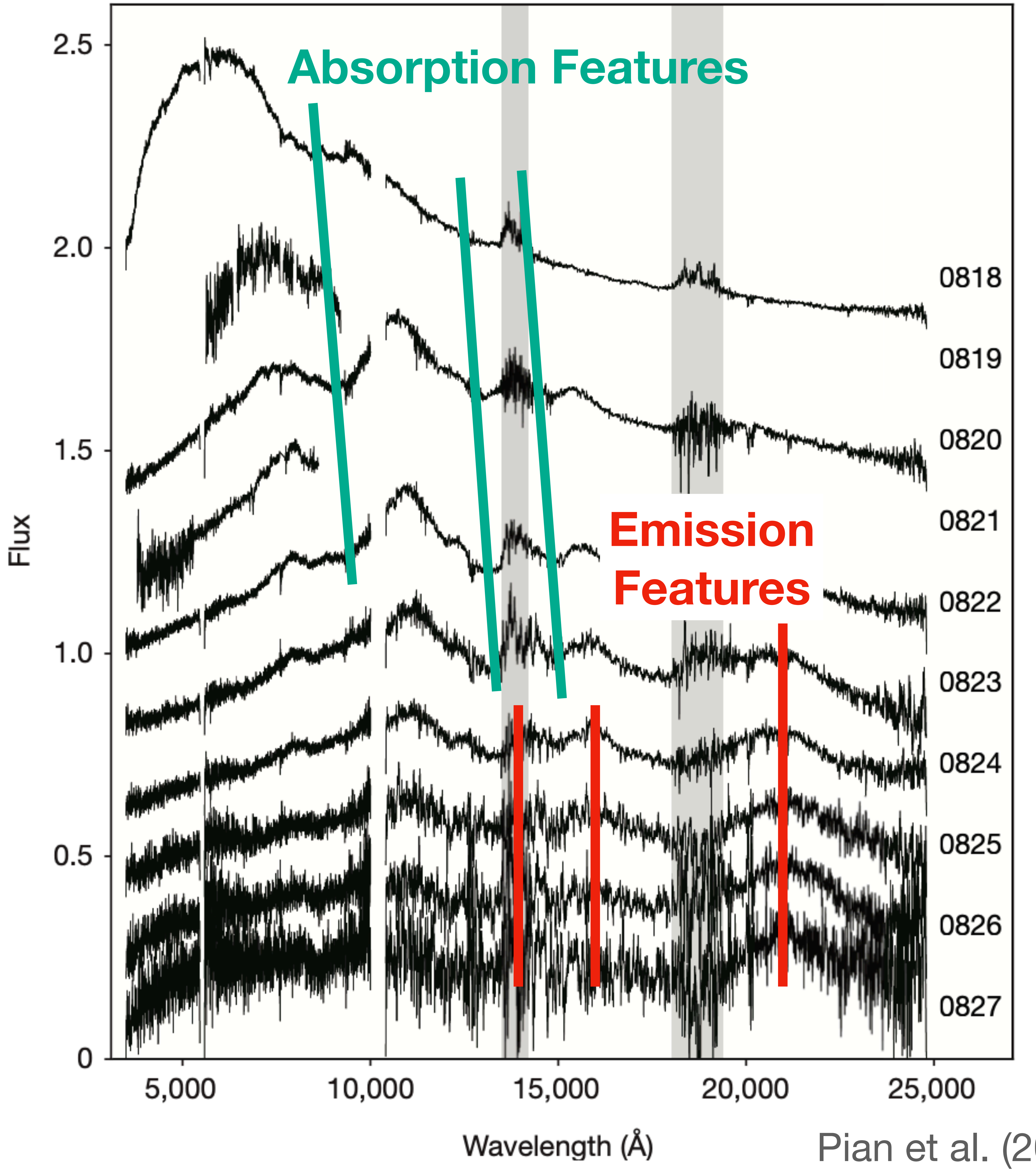


Soares-Santos et al. (2017)

GW170817 spectrum



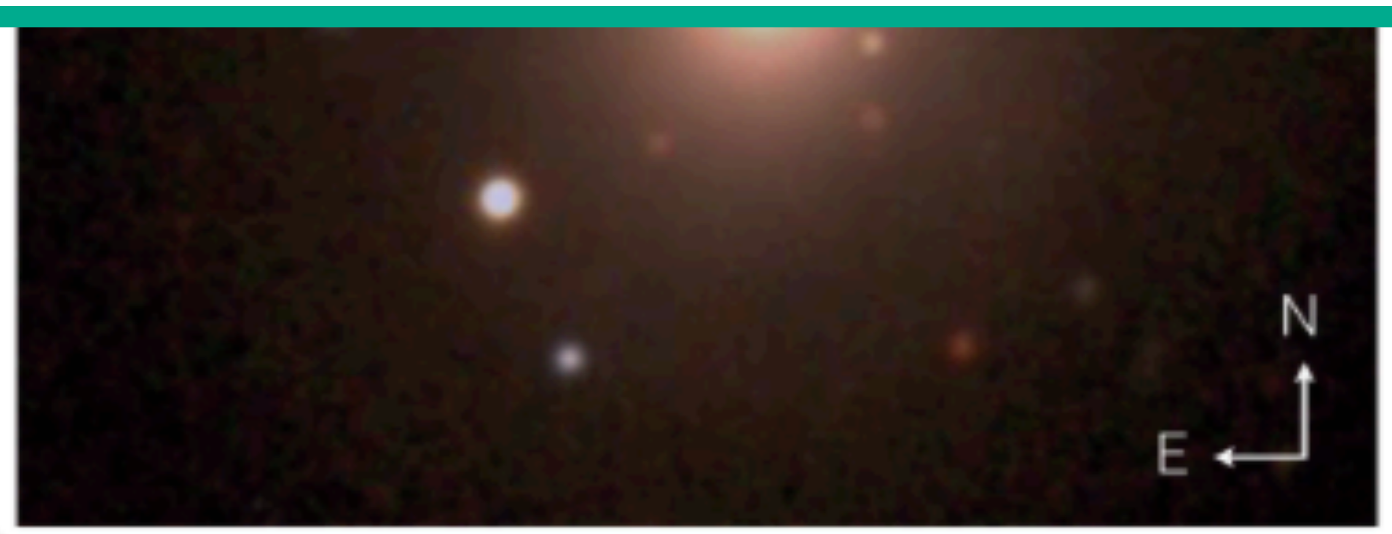
Pian et al. (2017)

Introduction

Goal

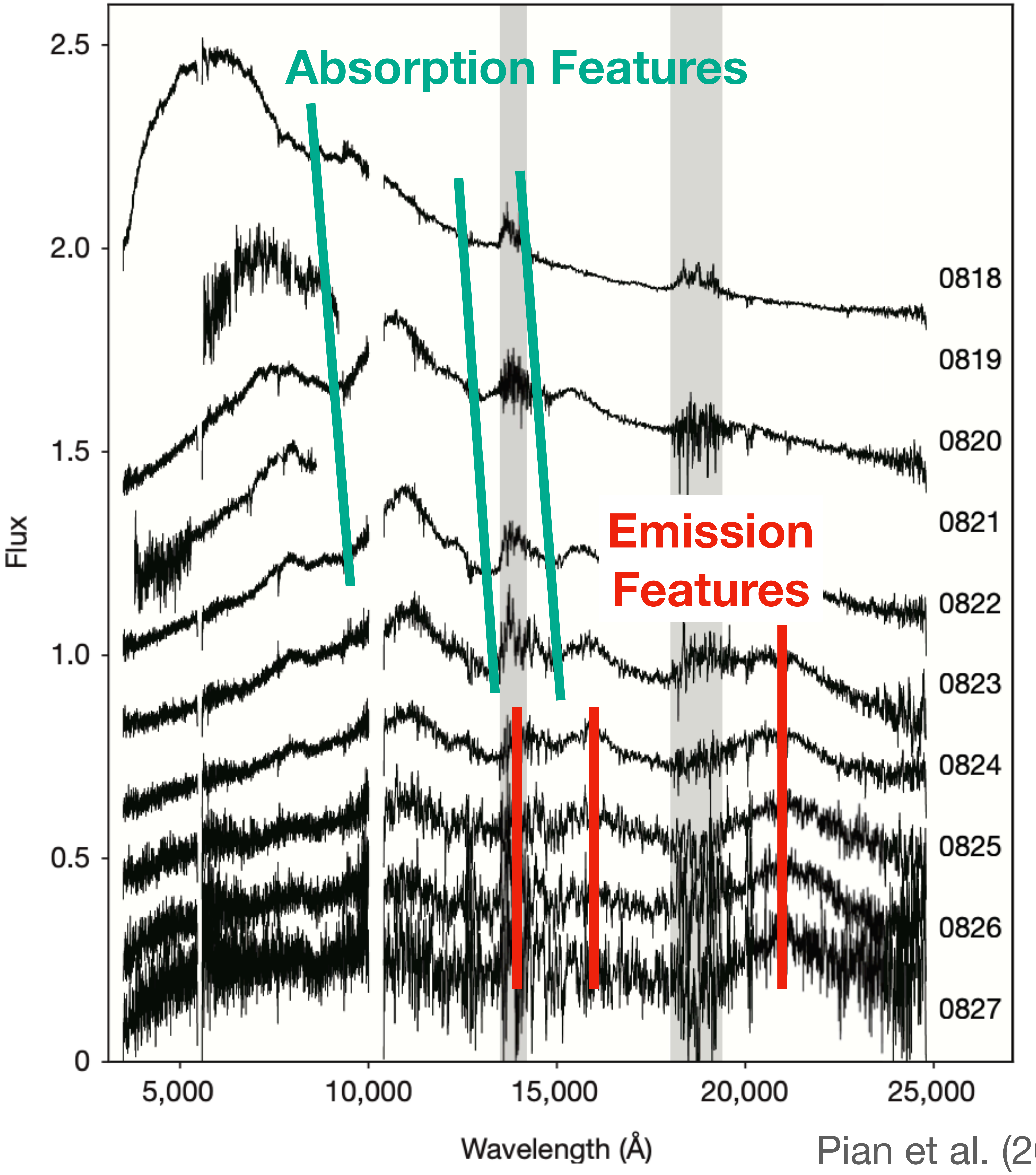
Quantify the mass fraction of heavy elements in NSMs to ultimately understand r-process nucleosynthesis

First step: Spectral Investigation



Soares-Santos et al. (2017)

GW170817 spectrum

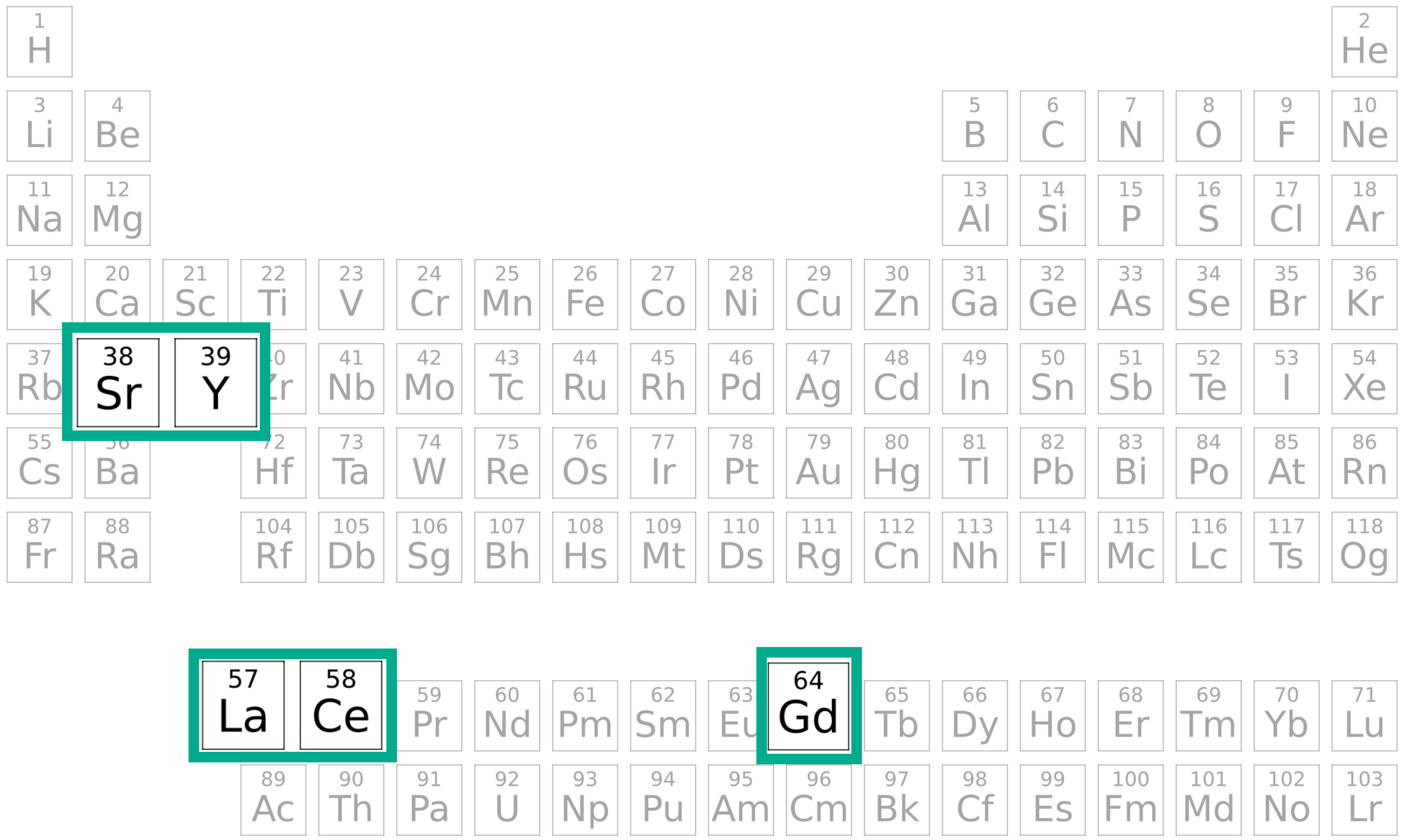


Pian et al. (2017)

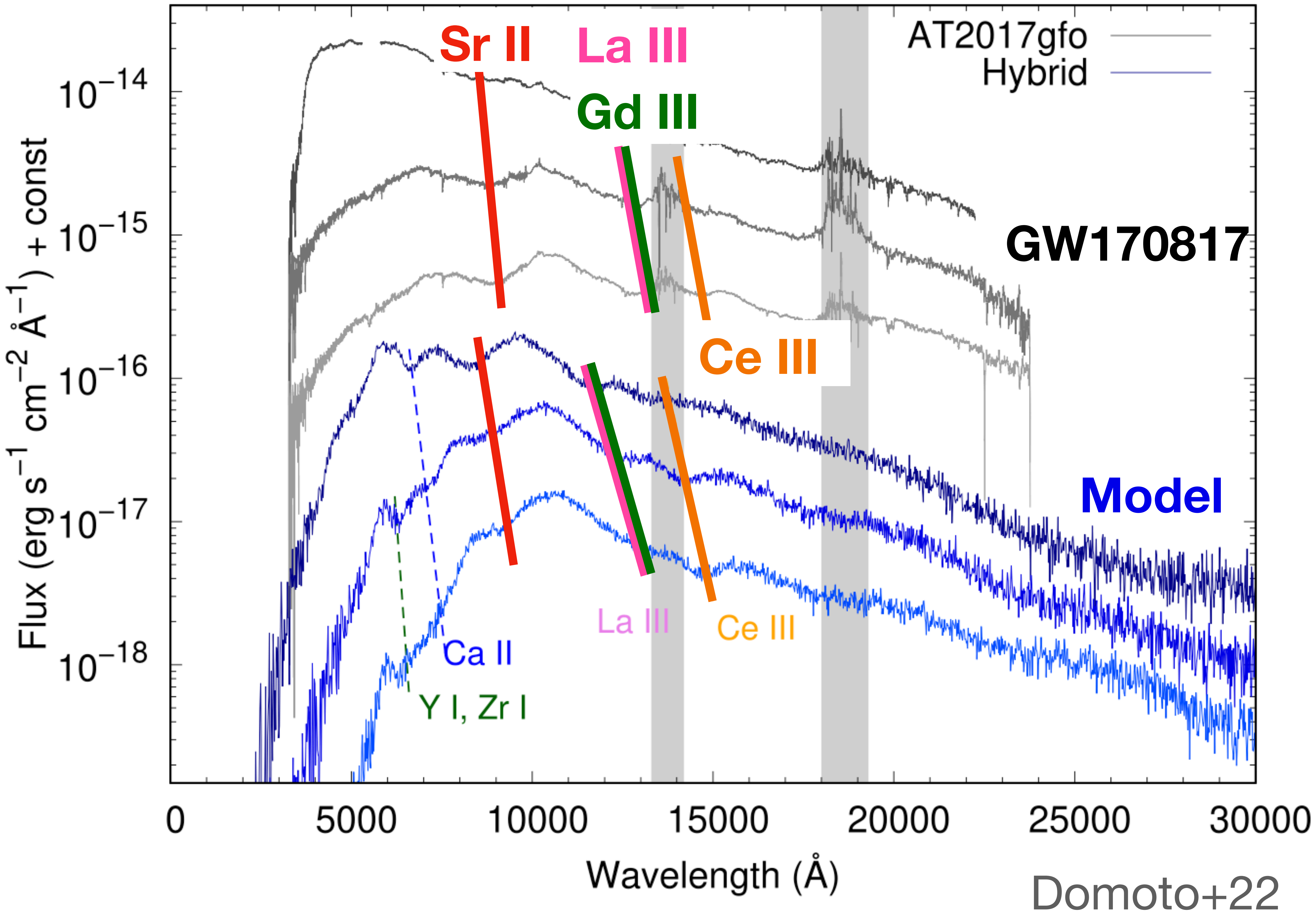
Early-Phase Spectral Investigation

Identification of Most Features

(Watson+19, Domoto+22, Sneppen+23, Rahmouni+25)



Early GW170817 spectra + theoretical model



Domoto+22

Early-Phase Spectral Investigation

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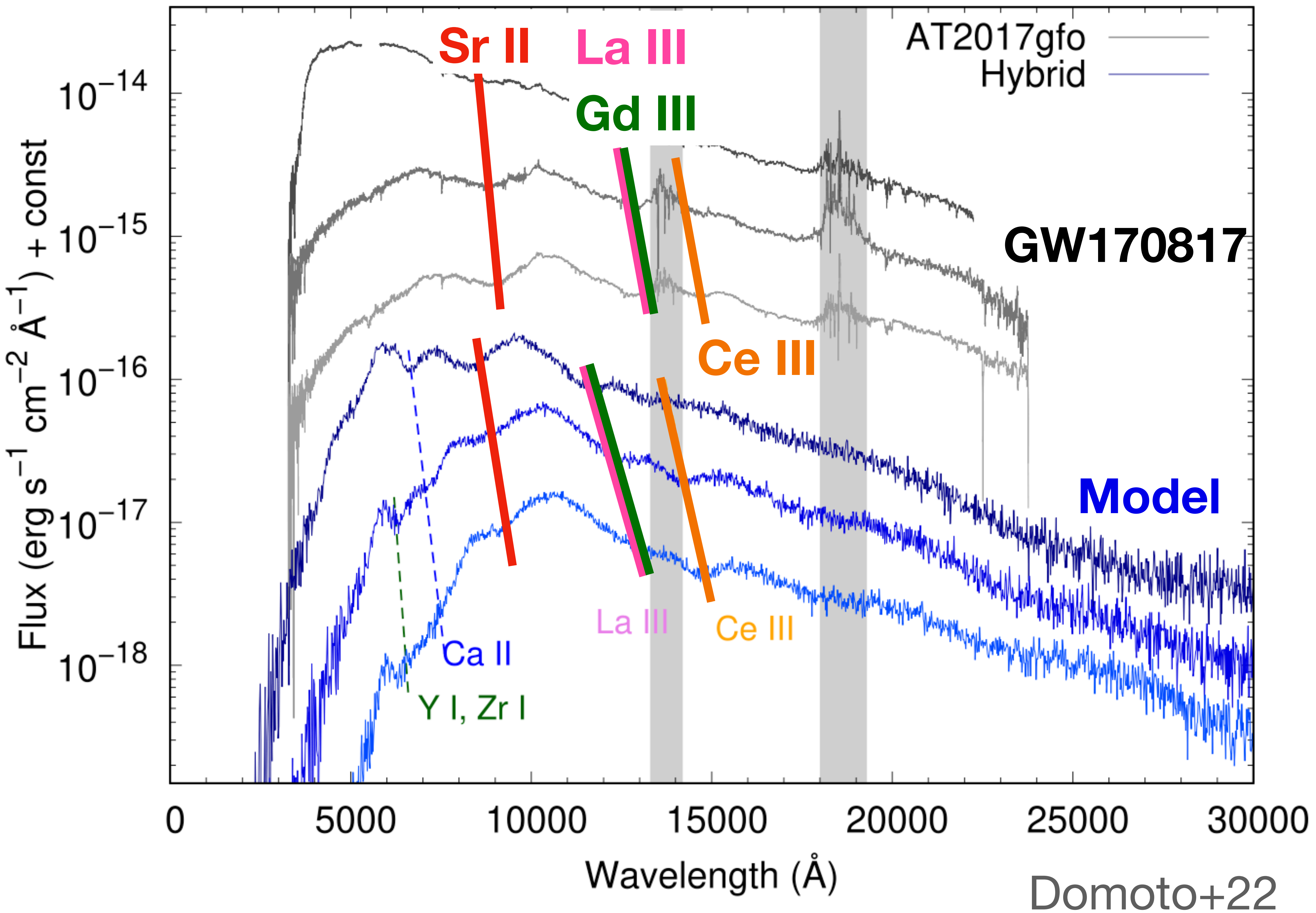
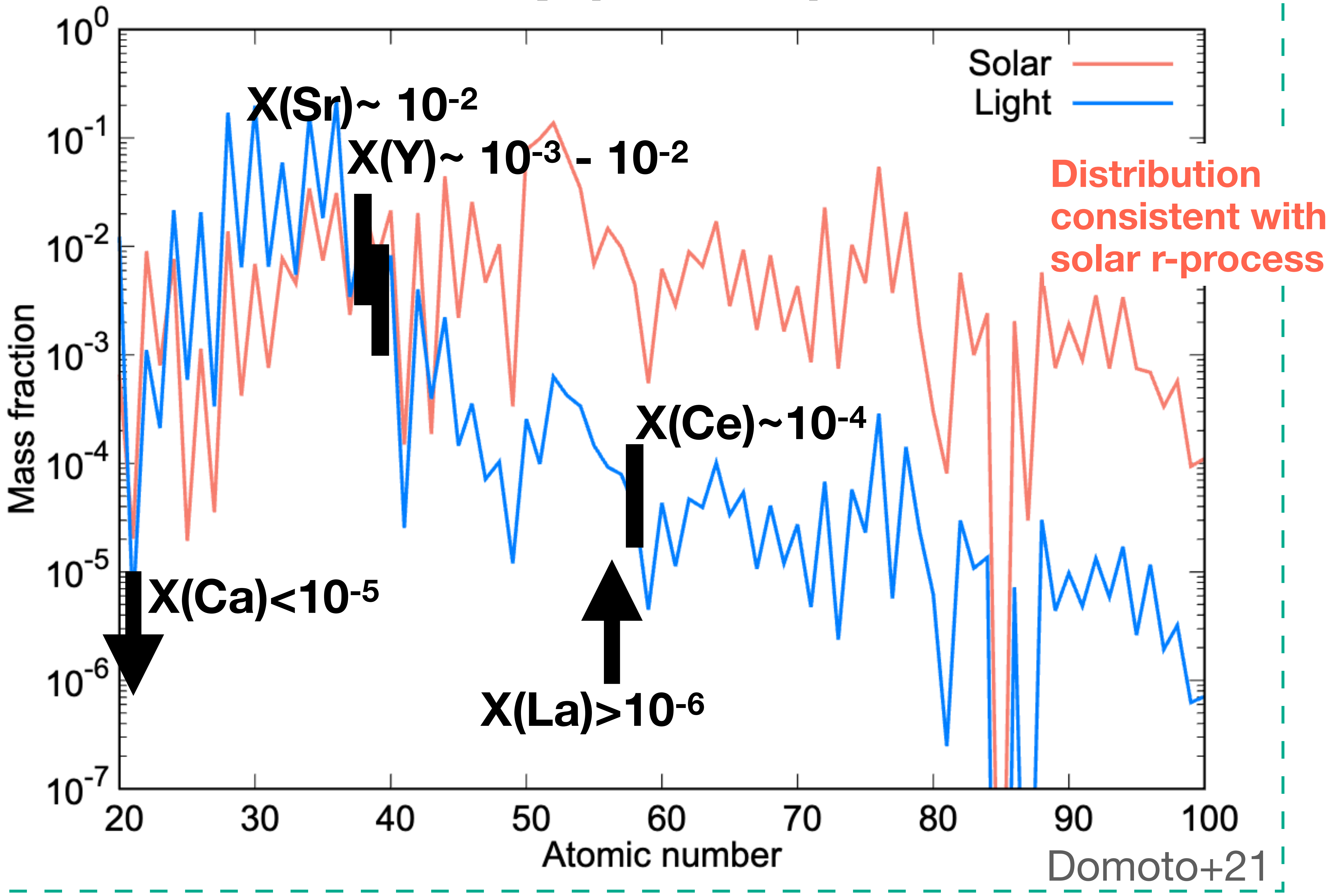


Domoto+22

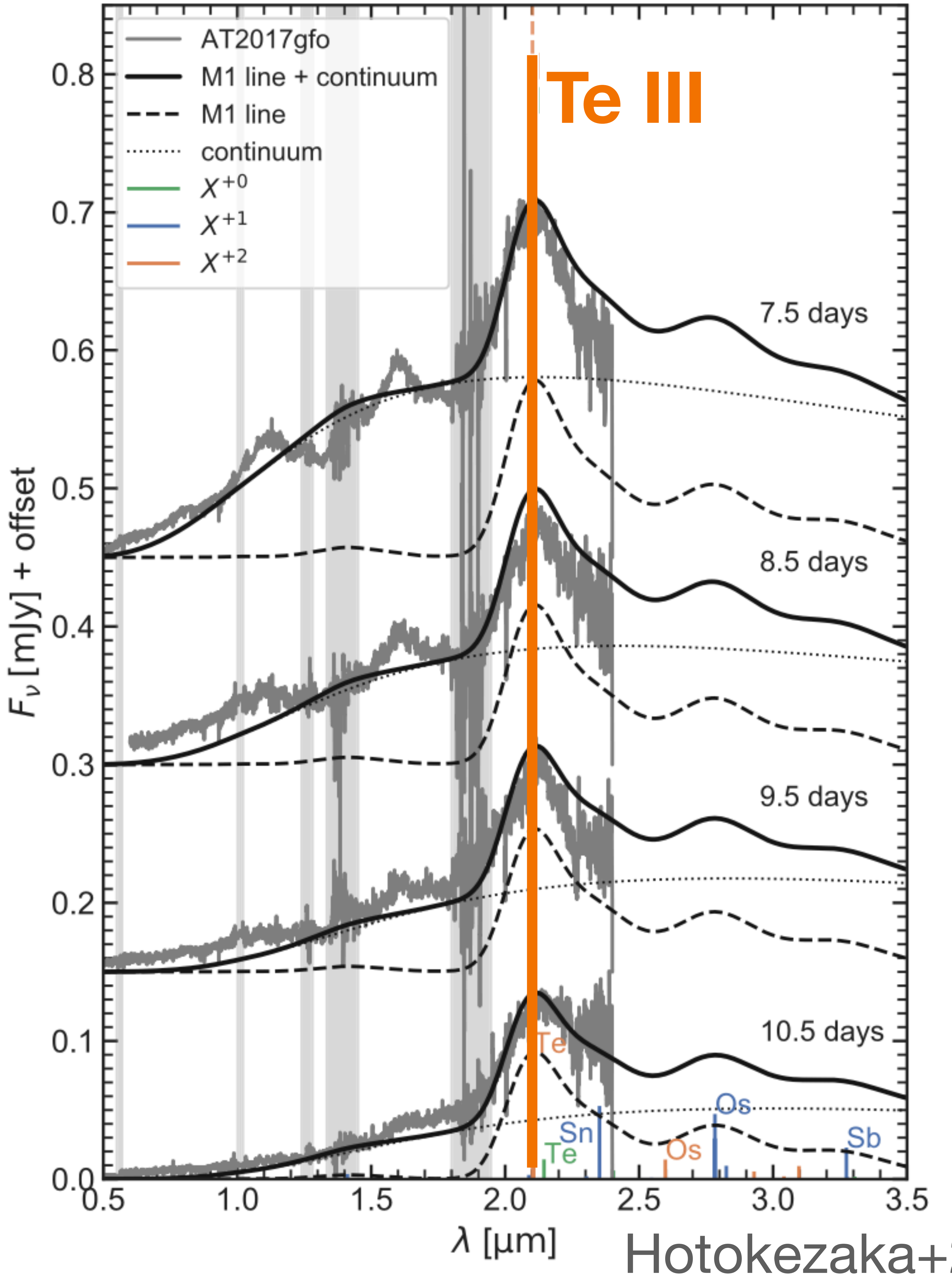
Constraints on Nucleosynthesis from early-phase spectra



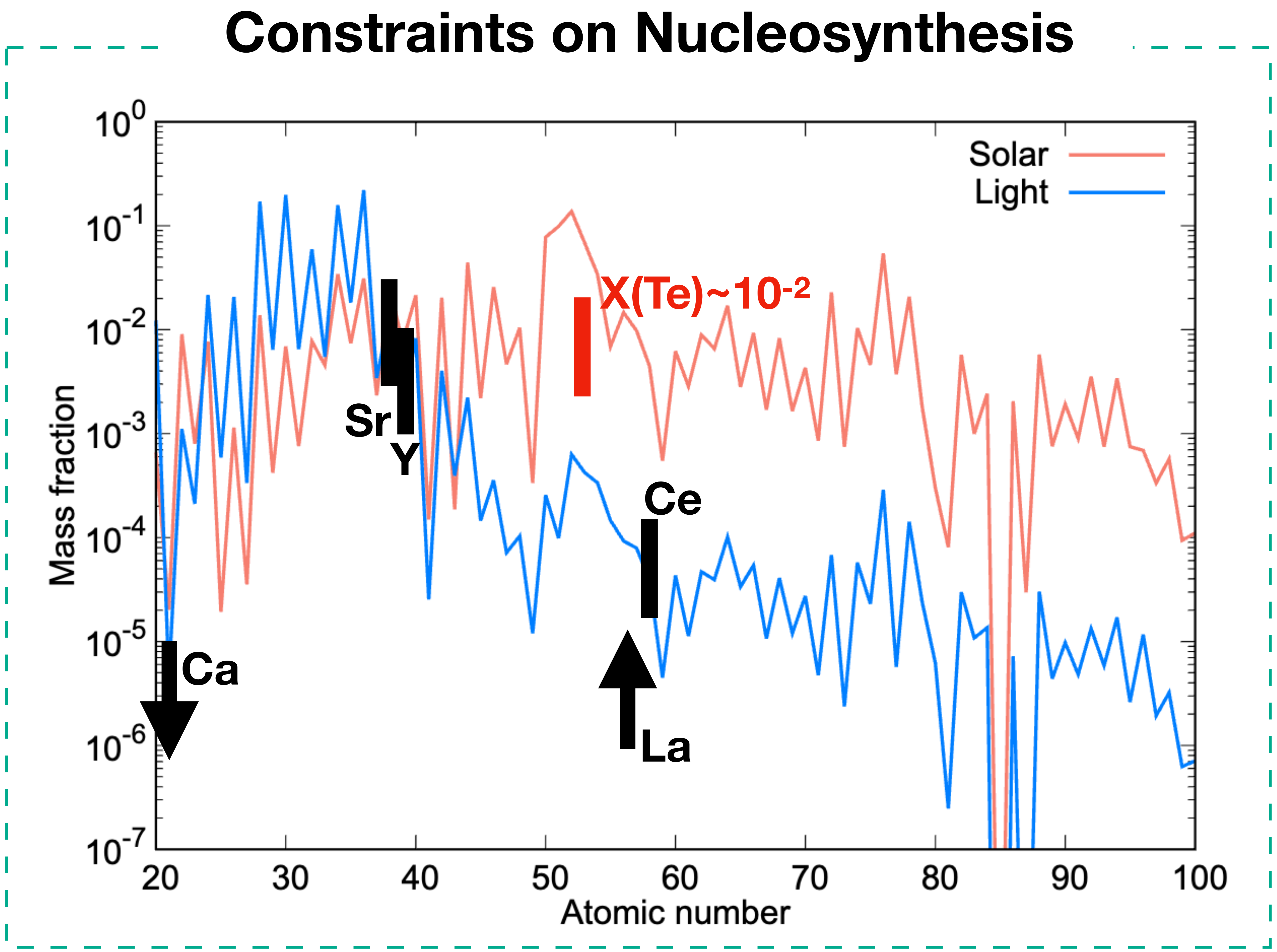
See also **Y. Matsubayashi**'s poster for abundance constraints from the absorption features

Late Phase Spectral Investigation

Identification of a single feature



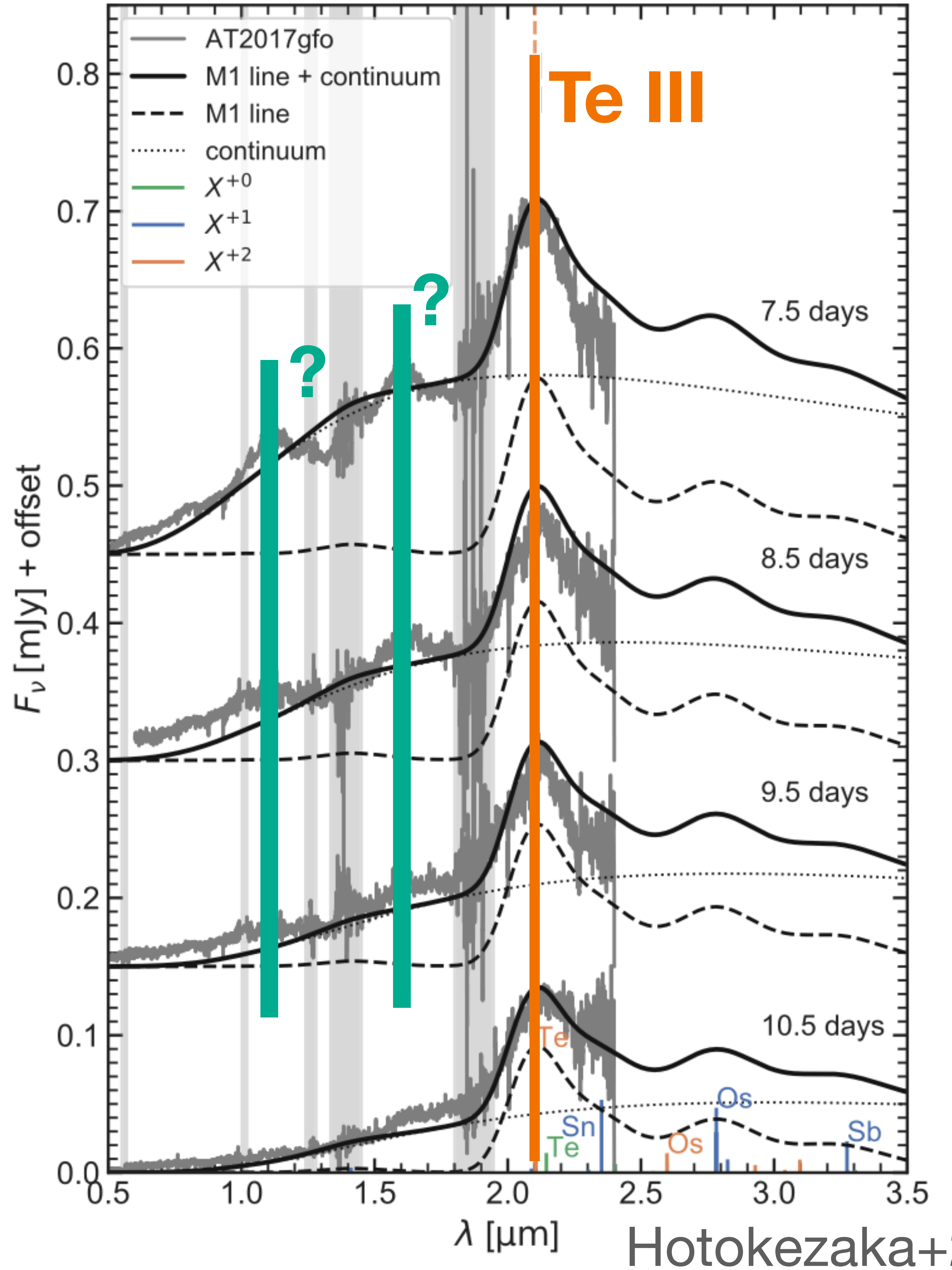
Hotokezaka+23



Inconsistency?

Late Phase Spectral Investigation

Identification of a single feature



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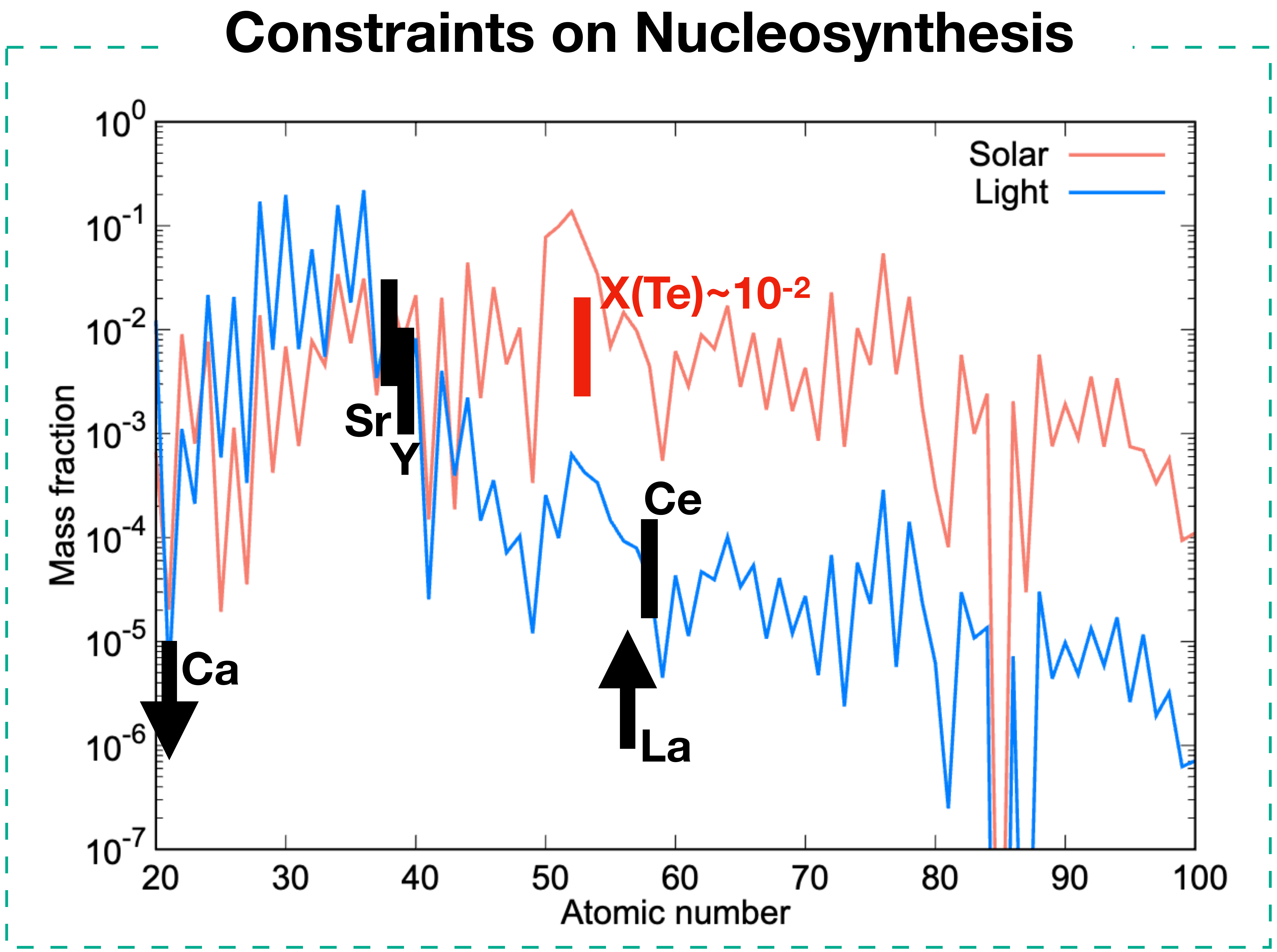
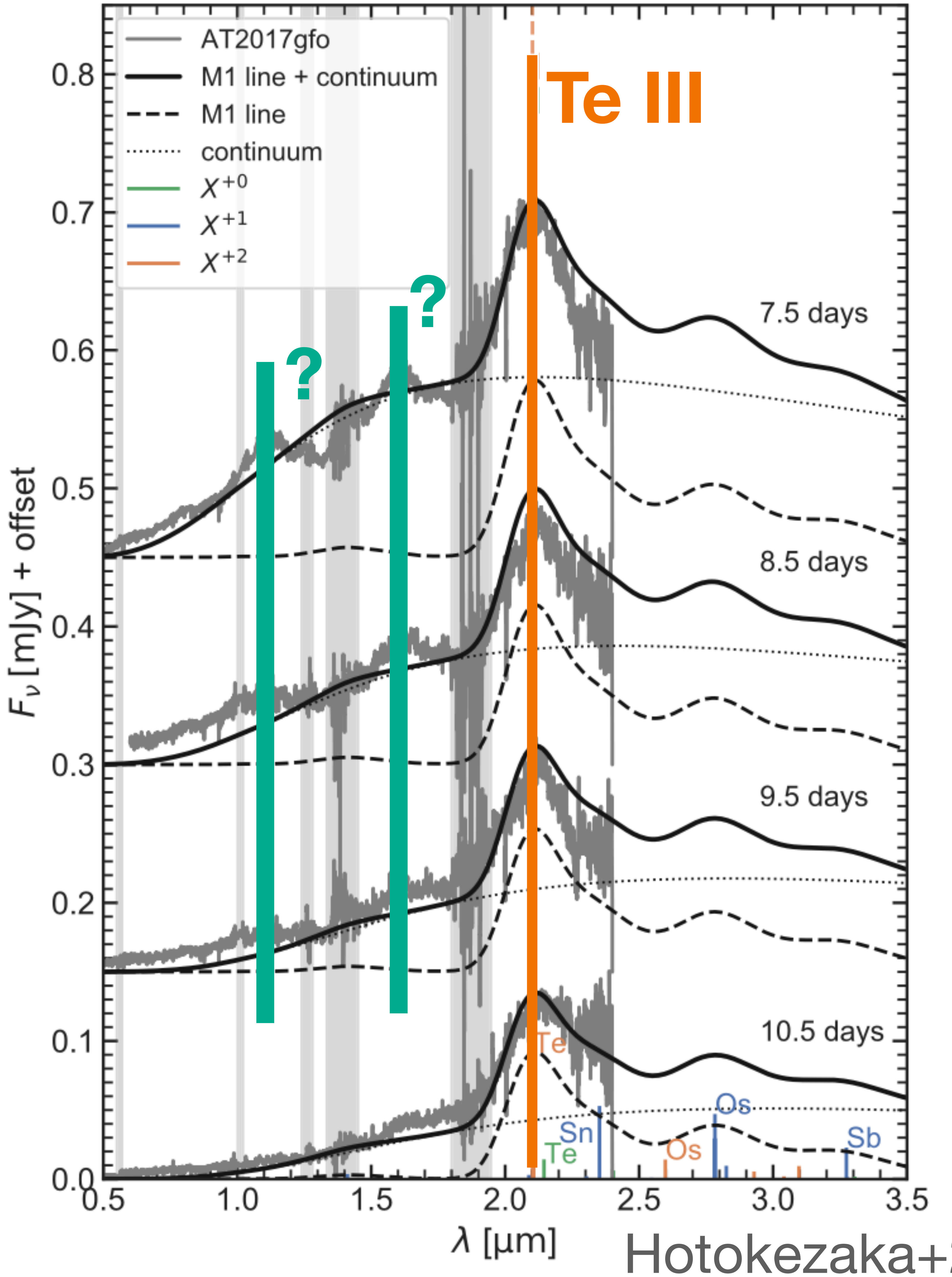


Inconsistency?

Late Phase

Identification of a single feature



Hotokezaka+23

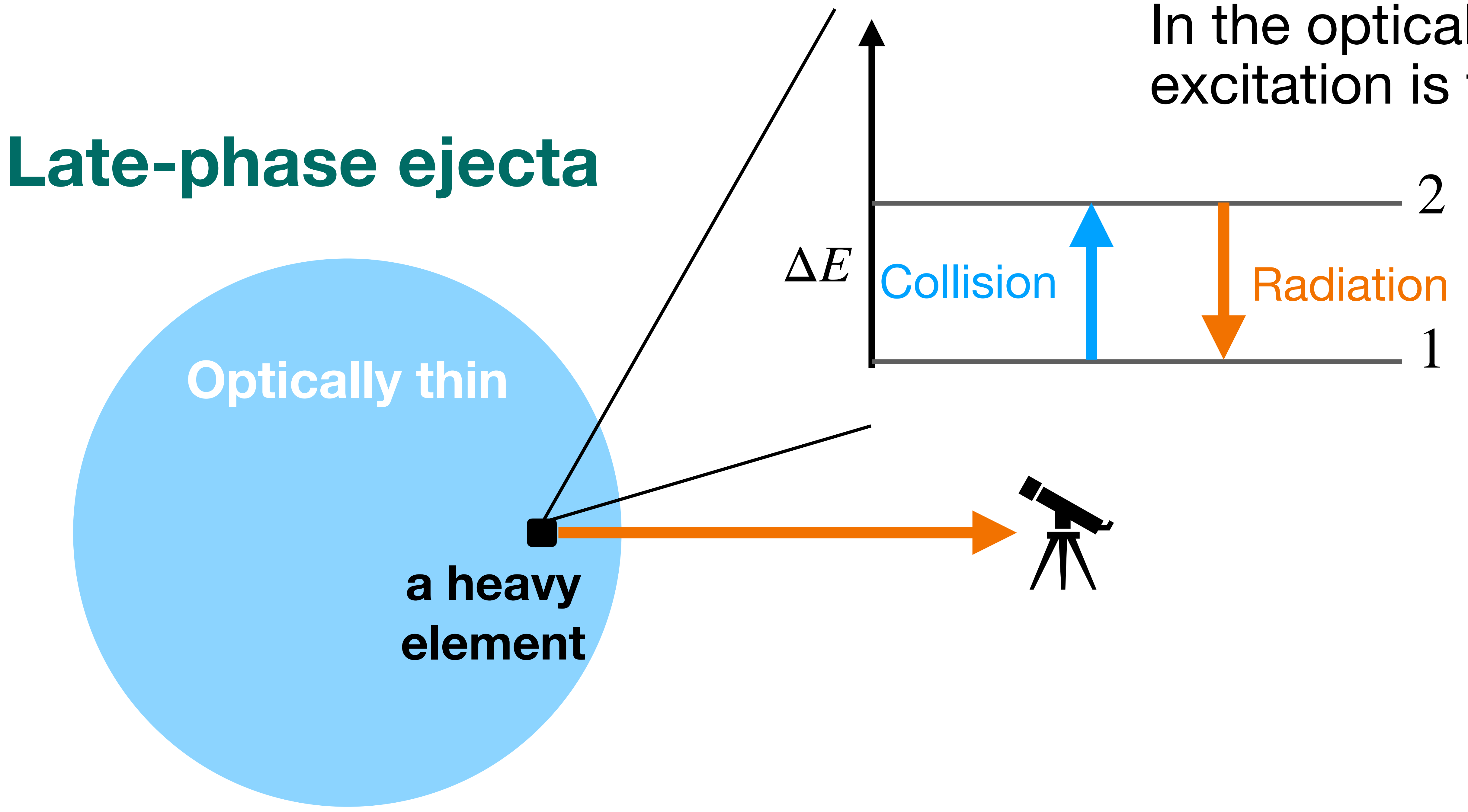
This work

Construct a spectral model to explain late-time emission features of GW170817

→ **Provide further constraints on nucleosynthesis**

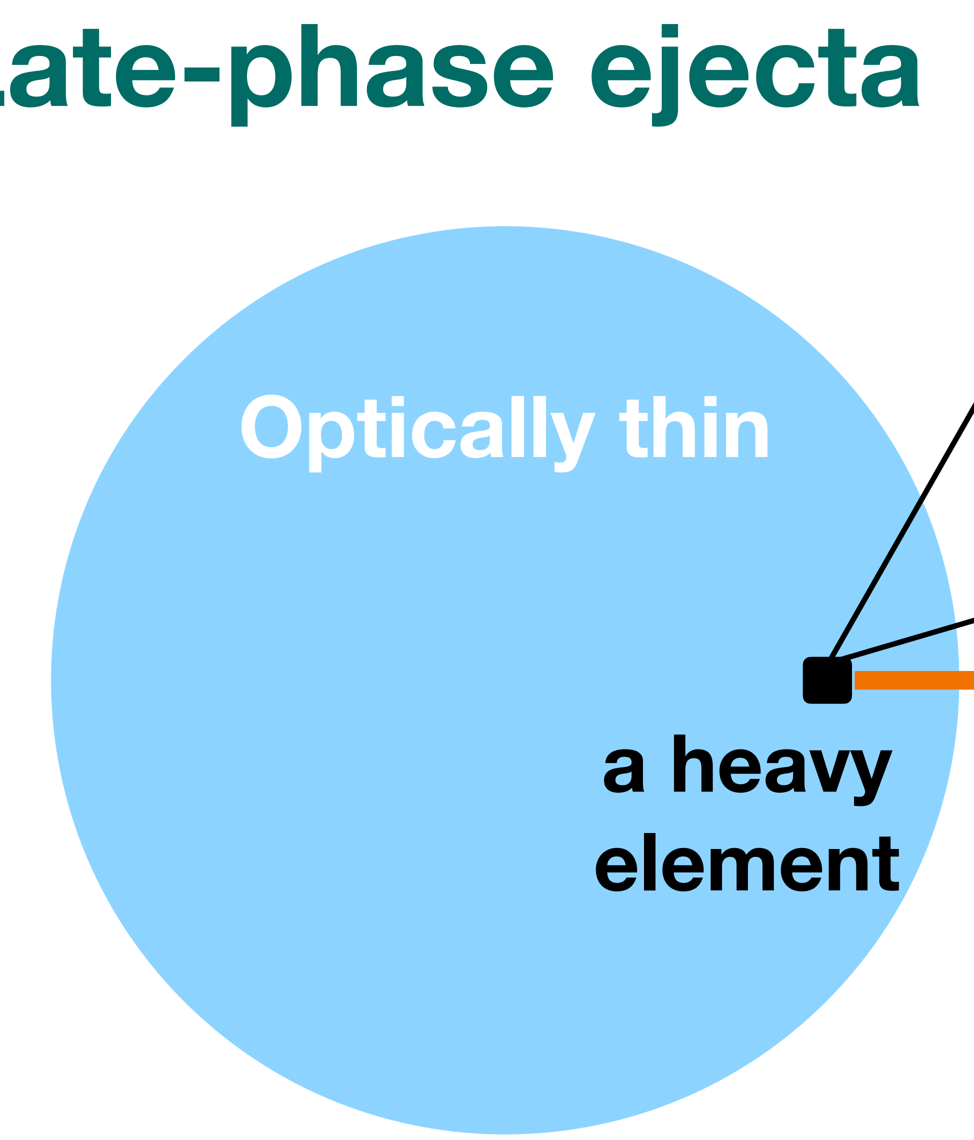
Spectral Model

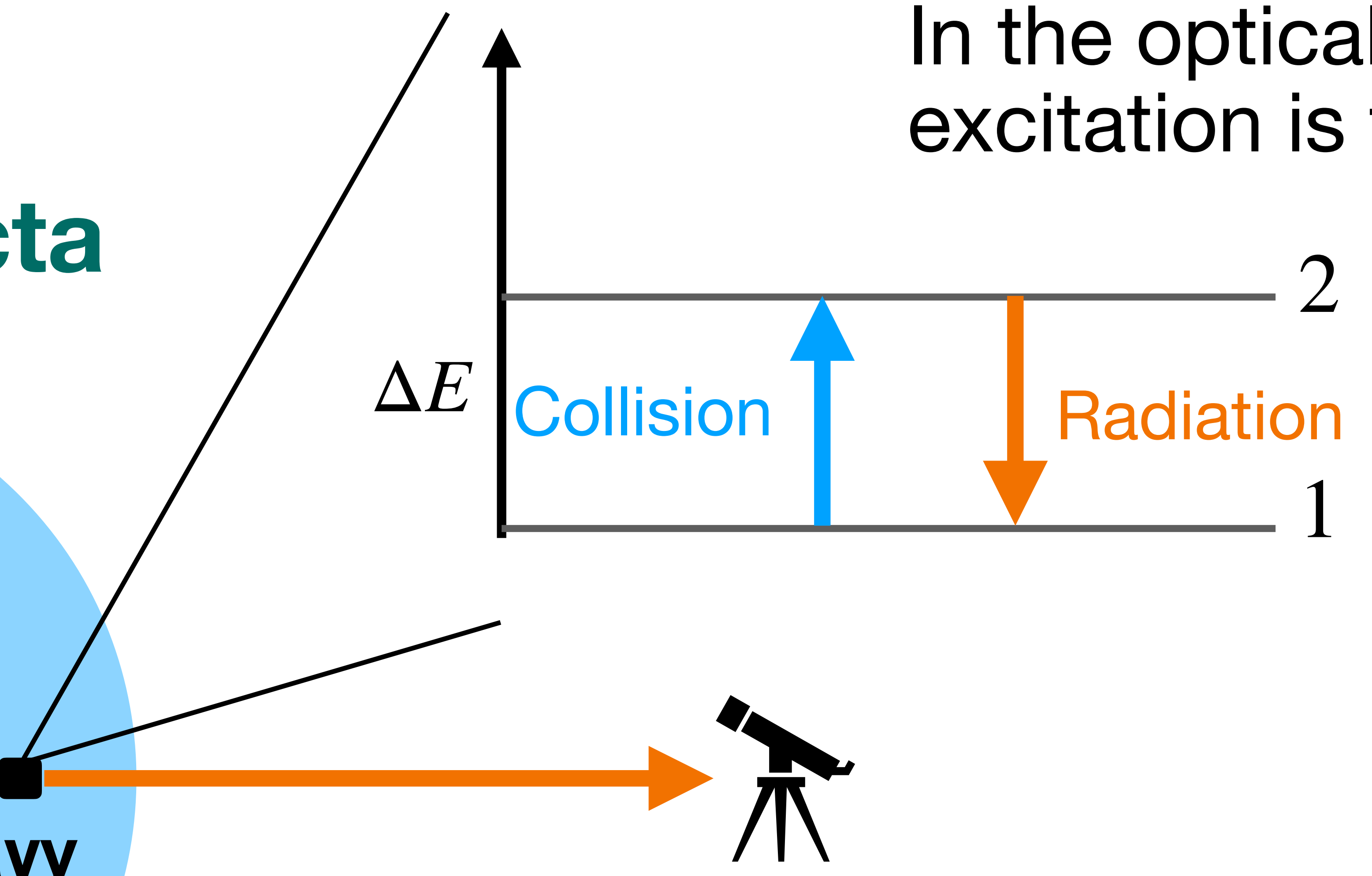
In the optically thin limit, every collisional excitation is followed by radiative decay



Spectral Model

In the optically thin limit, every collisional excitation is followed by radiative decay





Luminosity observed of one transition is therefore:

$$L = \Delta E \, n_2 A_{2\rightarrow 1} \approx \Delta E \, n_e n_1 q_{1\rightarrow 2}$$

Radiative decay rate ($n_2 A_{2\rightarrow 1}$)

Collisional excitation rate ($n_e n_1 q_{1\rightarrow 2}$)

Rate coefficient:

Atomic property ($\Upsilon_{1\rightarrow 2}$)

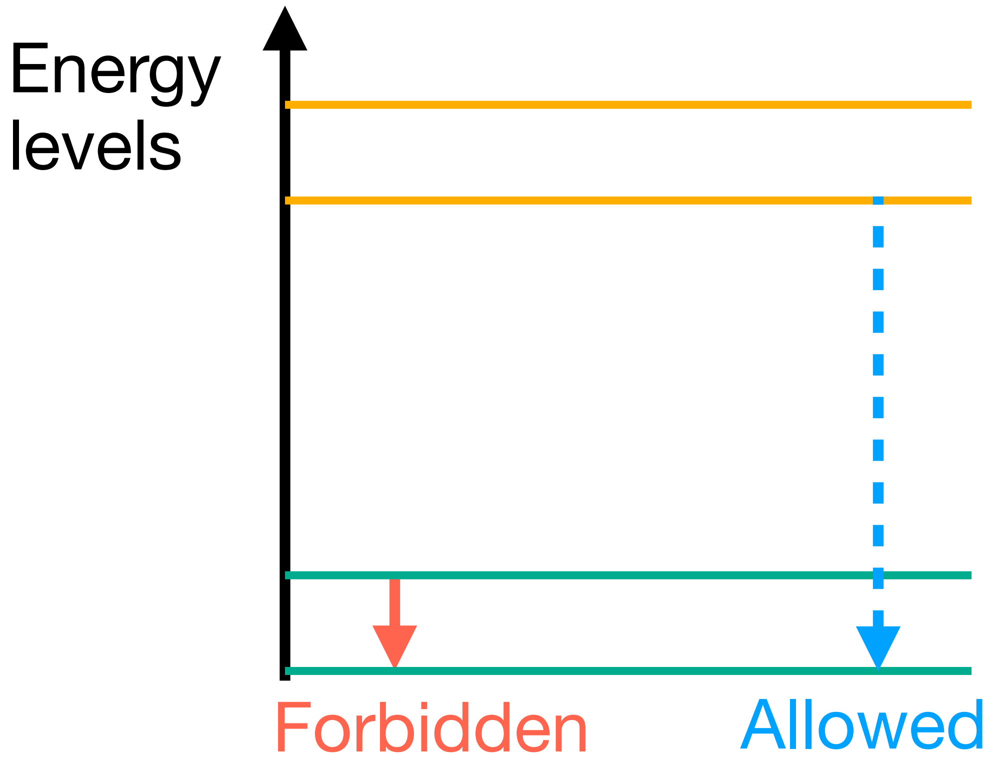
$$q_{1\rightarrow 2} = \frac{8.629 \times 10^{-6}}{T^{1/2}} \frac{\Upsilon_{1\rightarrow 2}}{g_1} \exp(-\Delta E/kT)$$

We calculate expected luminosity of <u>all transitions</u> of <u>all elements</u> to find candidates likely to exhibit strong emission features at late time

Spectral Model

Light Elements

No mixing of energy levels

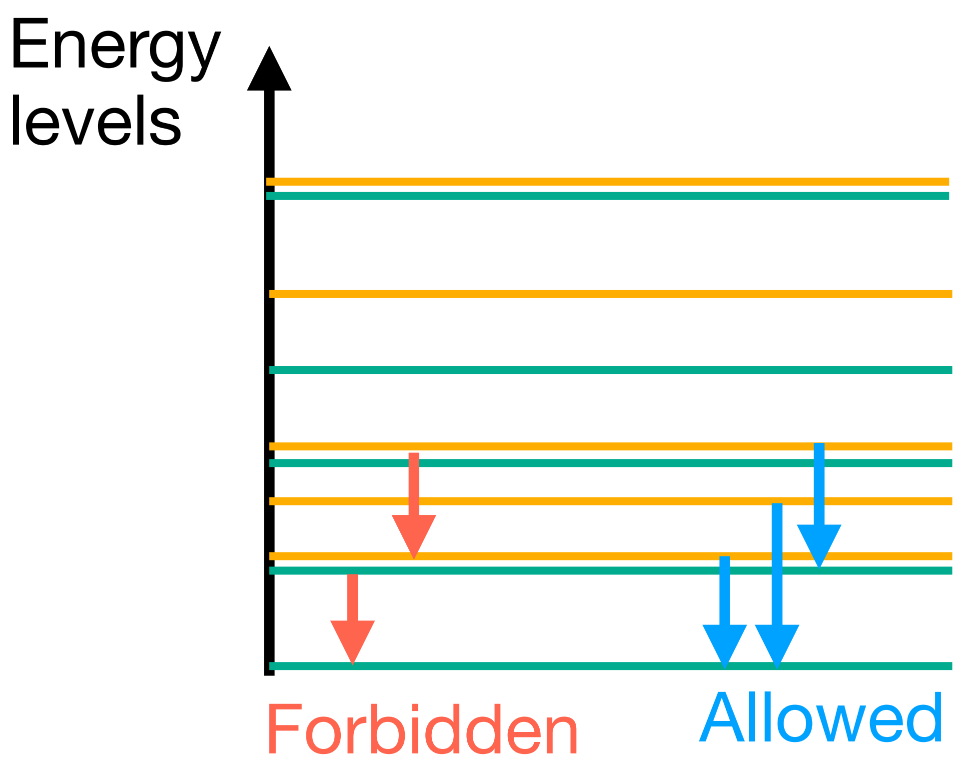


$$\Delta E_{allowed} >> \Delta E_{forbidden}$$

Allowed radiative decays suppressed due to low collisional excitation rate

Heavy Elements

large mixing of energy levels due to complex structure



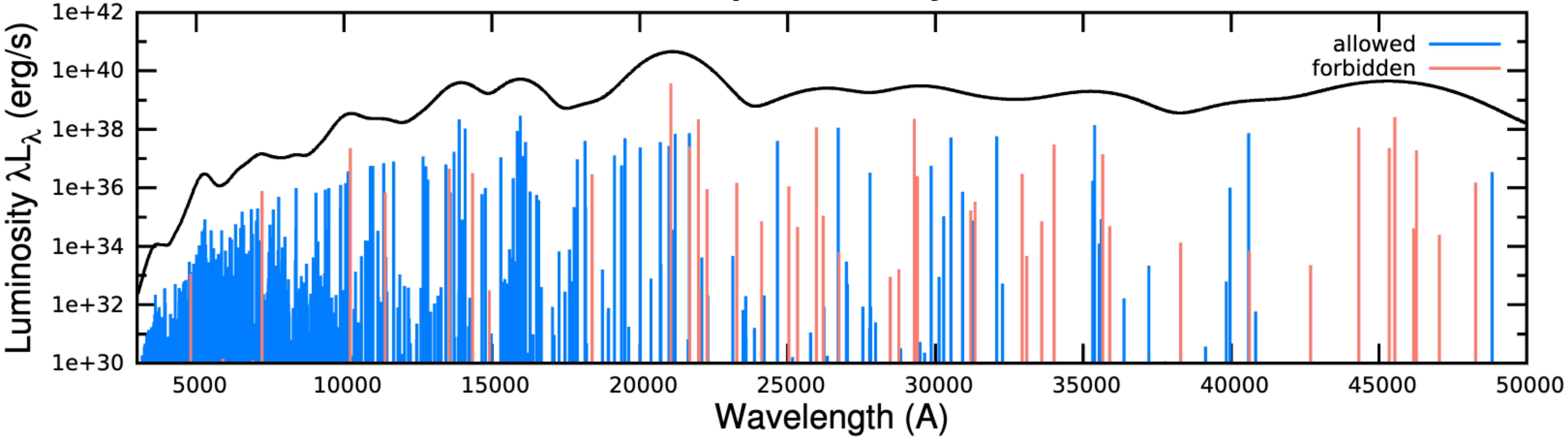
$$\Delta E_{allowed} \sim \Delta E_{forbidden}$$

Allowed and Forbidden decays are comparably strong

→ Resulting Spectrum:

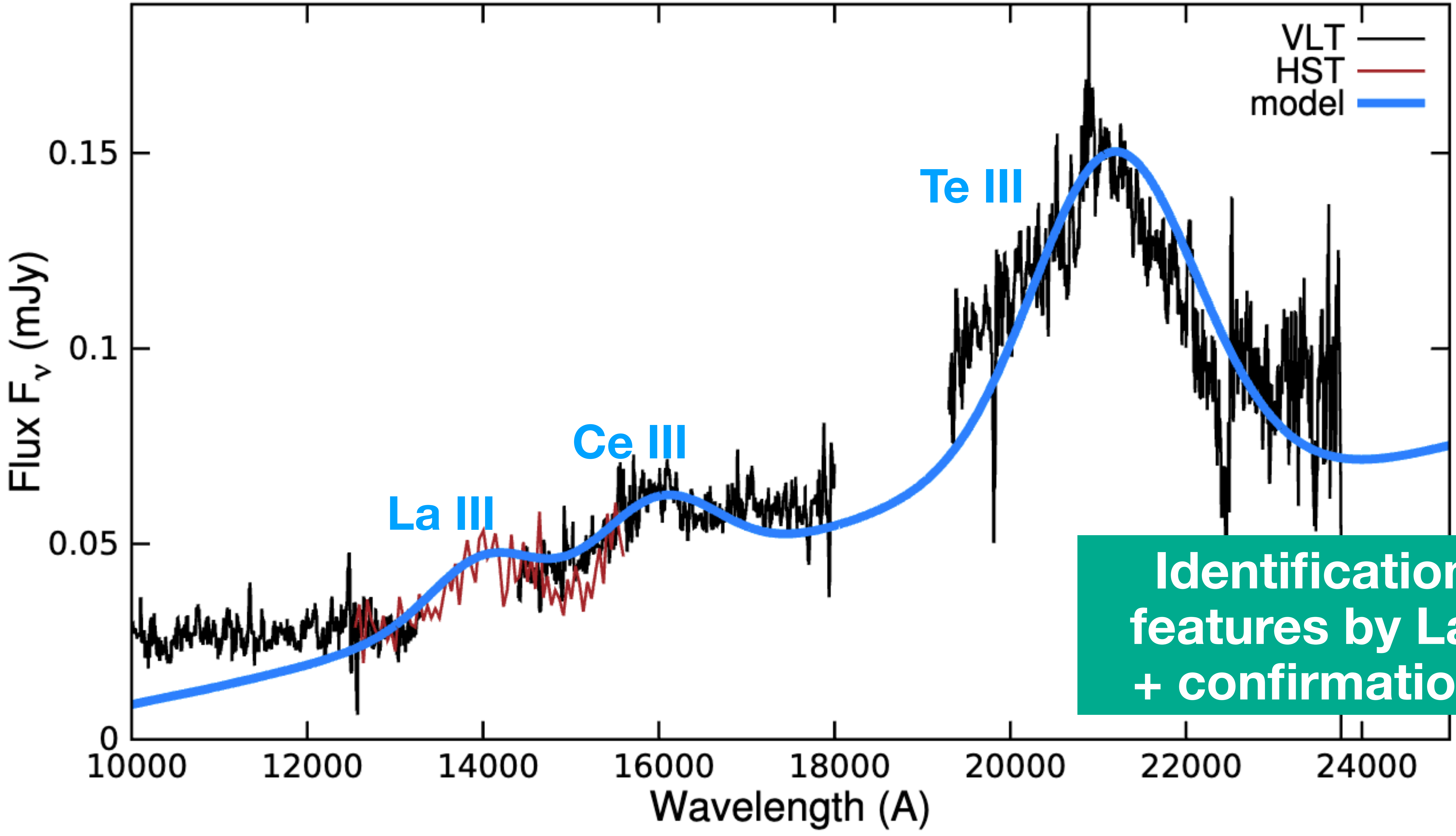
- Selection of forbidden and allowed transitions of all elements
- Doppler broadening of $0.07c$

Example of doubly ionized state with solar abundance



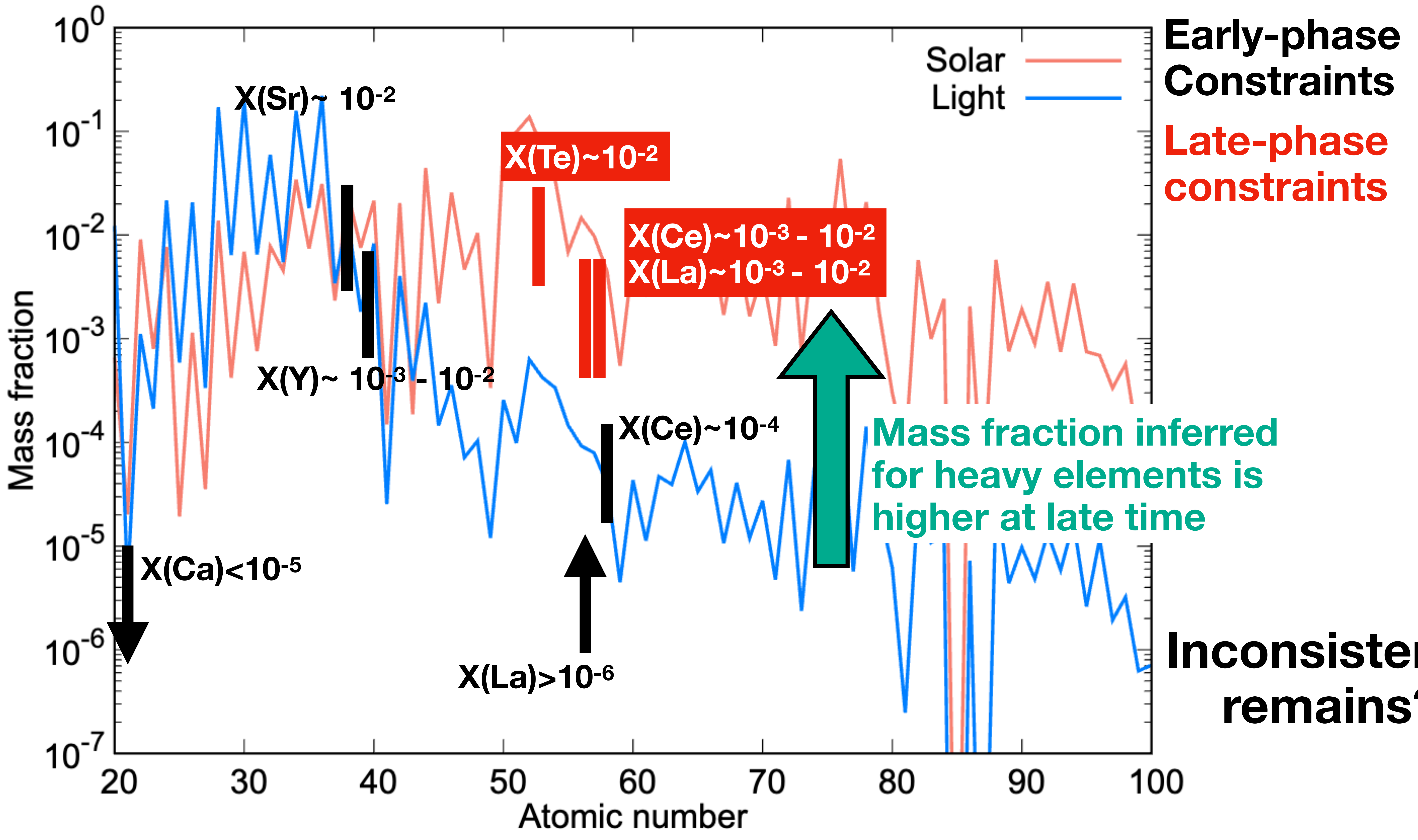
Comparison with GW170817

Best fit emission line model + GW170817 9.4 days spectrum



Identification of two new features by La III and Ce III + confirmation of Te III line

Nucleosynthesis constraints

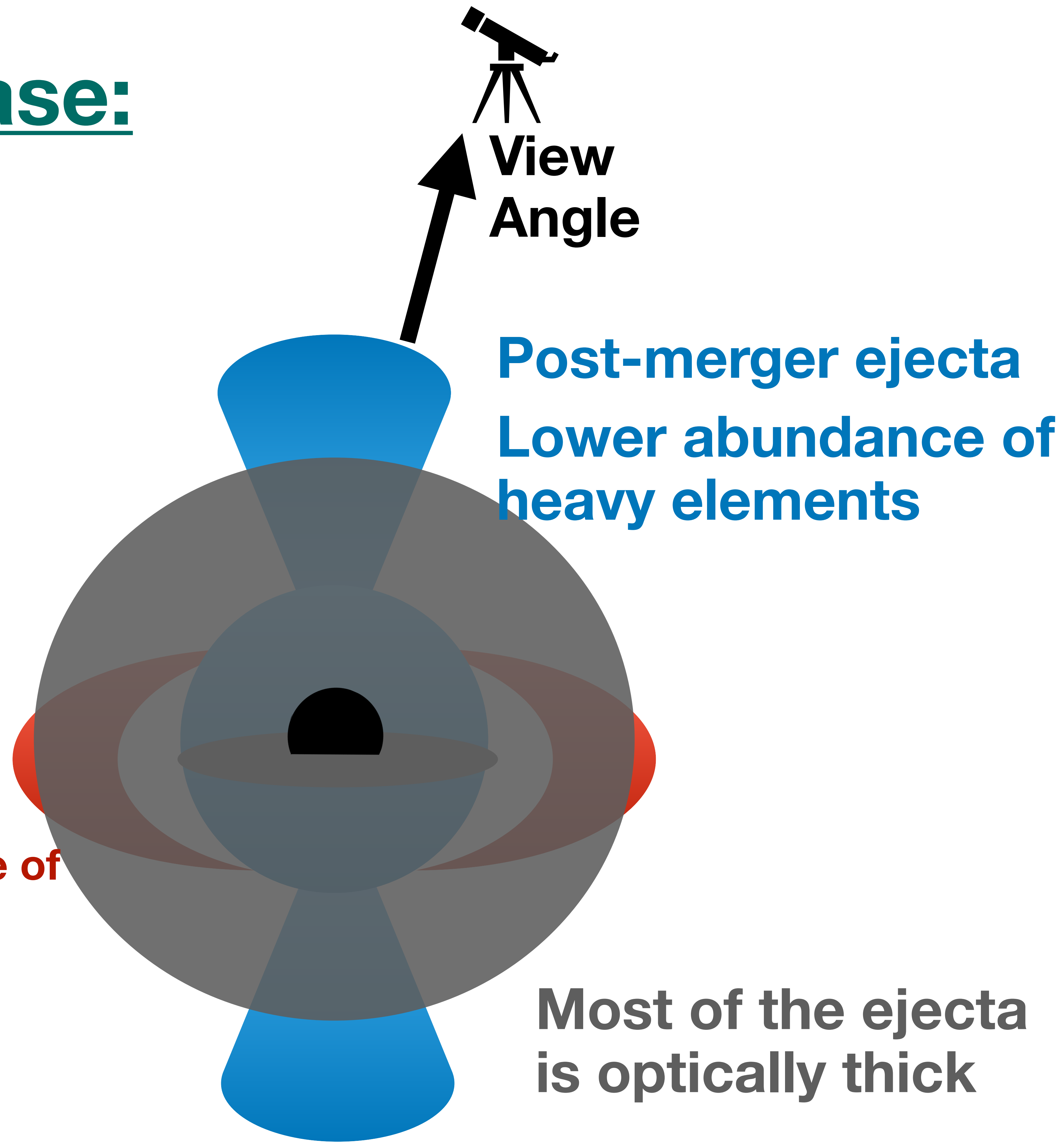


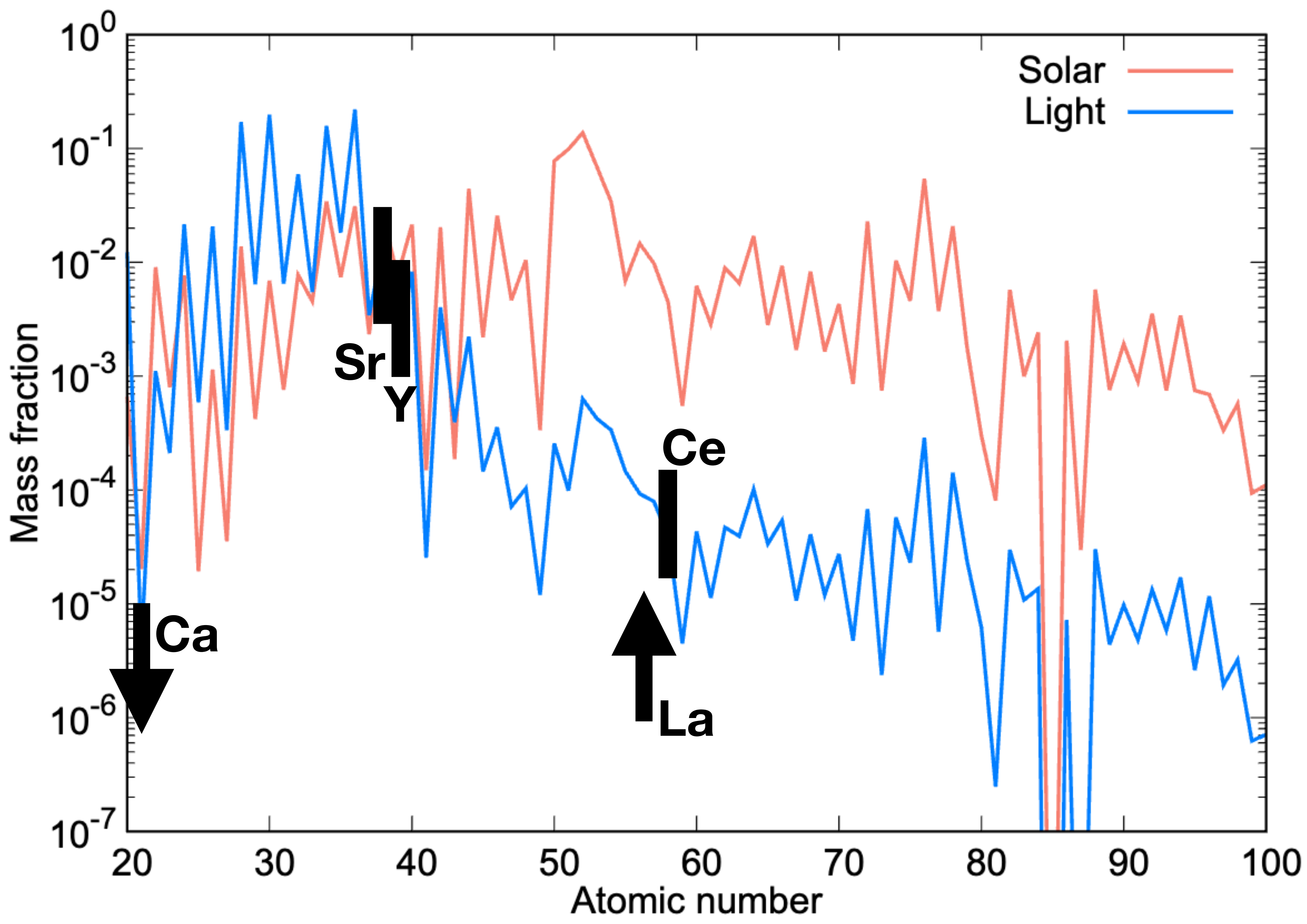
Inconsistency remains?

Discussion

Why different abundance distributions are needed to explain different epochs?

Early phase:





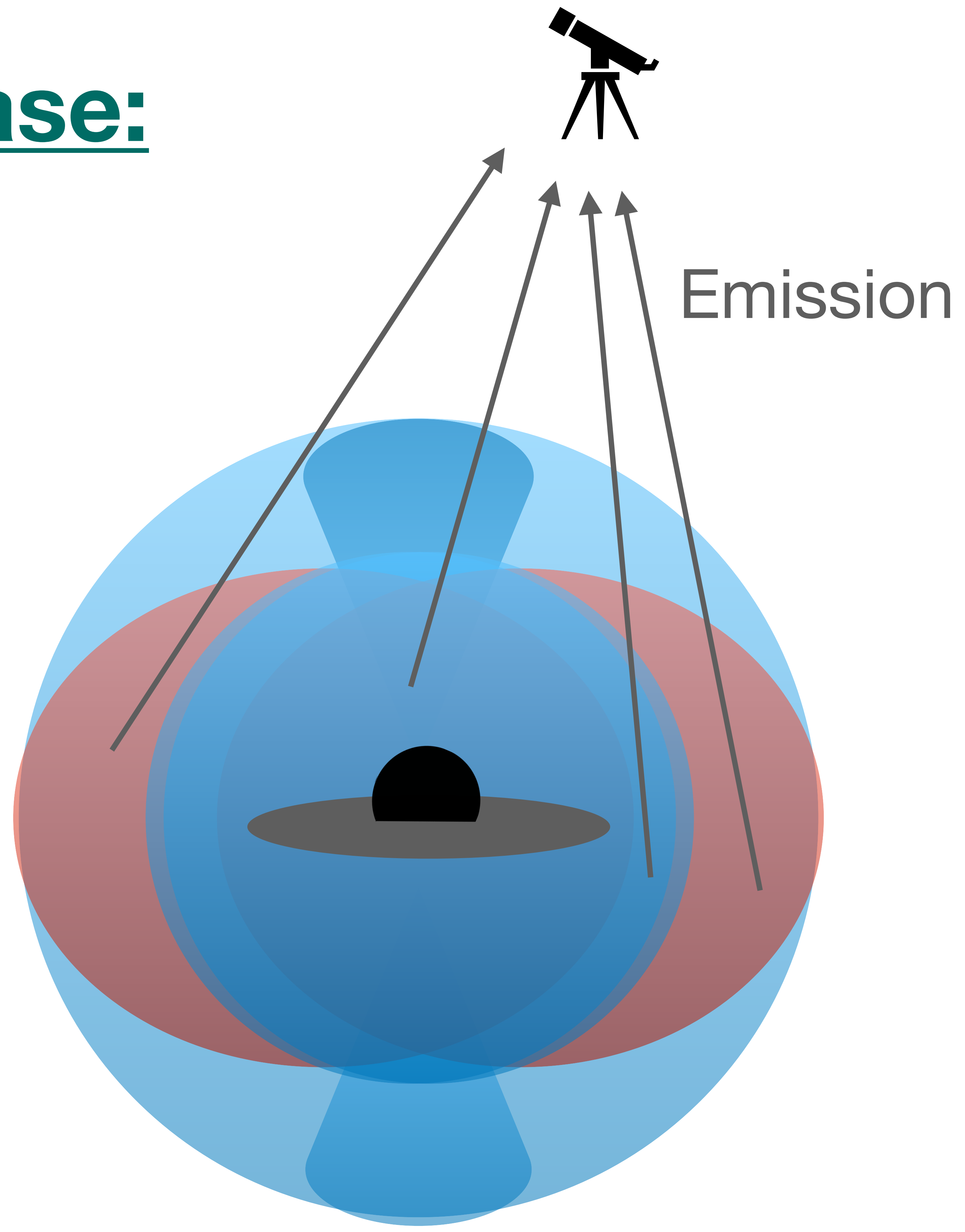
Absorption features appear due to elements in the polar post-merger ejecta

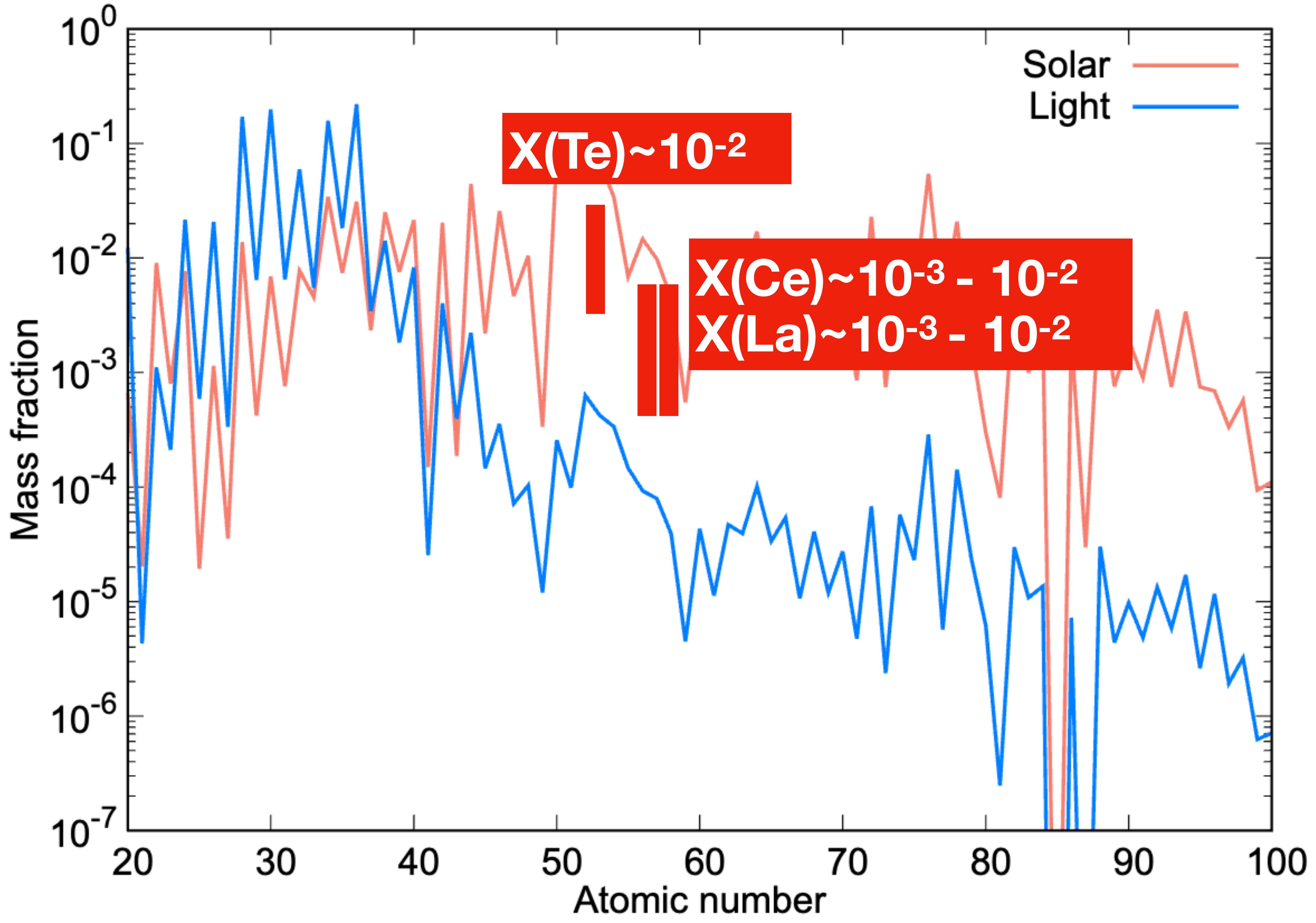
→ **Lower inferred mass fraction**

Discussion

Why different abundance distributions are needed to explain different epochs?

Late phase:





Most of the ejecta is optically thin and emission from different parts is observed

Mass fraction inferred reflects the overall synthesized matter in the merger

Summary

- Identification of three emission features at late phase: La III, Ce III, and Te III
- Late phase estimates provide better constraints to the overall synthesized matter in the ejecta
- Nucleosynthesis of heavy elements in GW170817 is consistent with solar r-process abundance

Appendix

Luminosity Calculation

When $n_{cr} > n_e$:

$$L_{3\to1} = \Delta E_{13} n_u A_{3\to1} = \Delta E_{13} n_e n_l q_{1\to3}$$

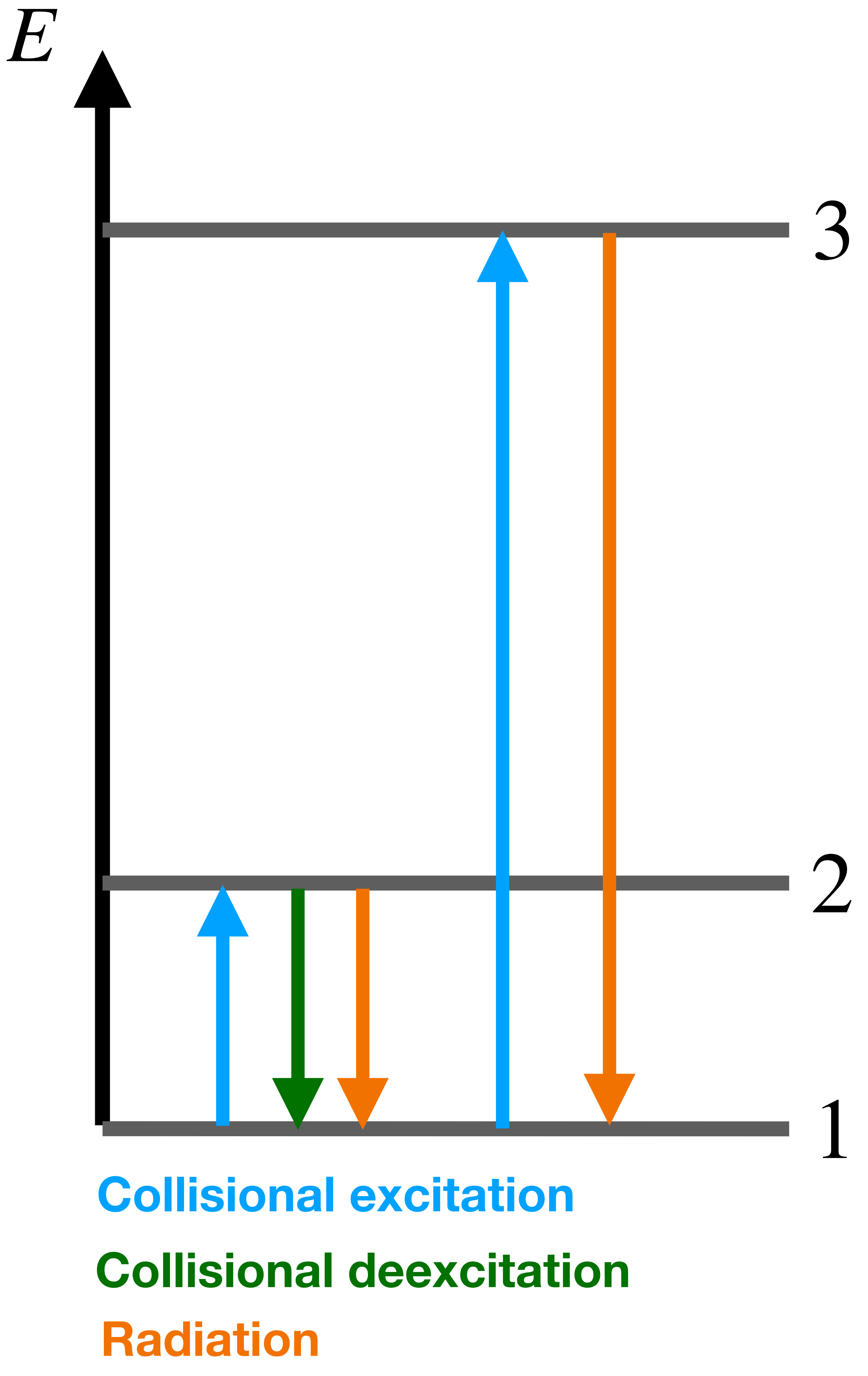
$$= \Delta E_{13} n_e \frac{n_X e^{-E_l/kT}}{\Sigma} \frac{8.629 \times 10^{-6}}{T^{1/2}} \frac{\Upsilon_{1\to3}}{g_1} e^{-\Delta E/kT}$$

When $n_{cr} < n_e$:

$$L_{2\to1} = \Delta E_{12} n_u A_{2\to1}$$

$$= \Delta E_{12} \frac{n_X e^{-E_u/kT}}{\Sigma} A_{2\to1}$$

$$n_{cr} = \frac{A_{2\to1}}{q_{2\to1}}$$



$n_{cr} > n_e$

Happens mainly when the radiative decay is allowed

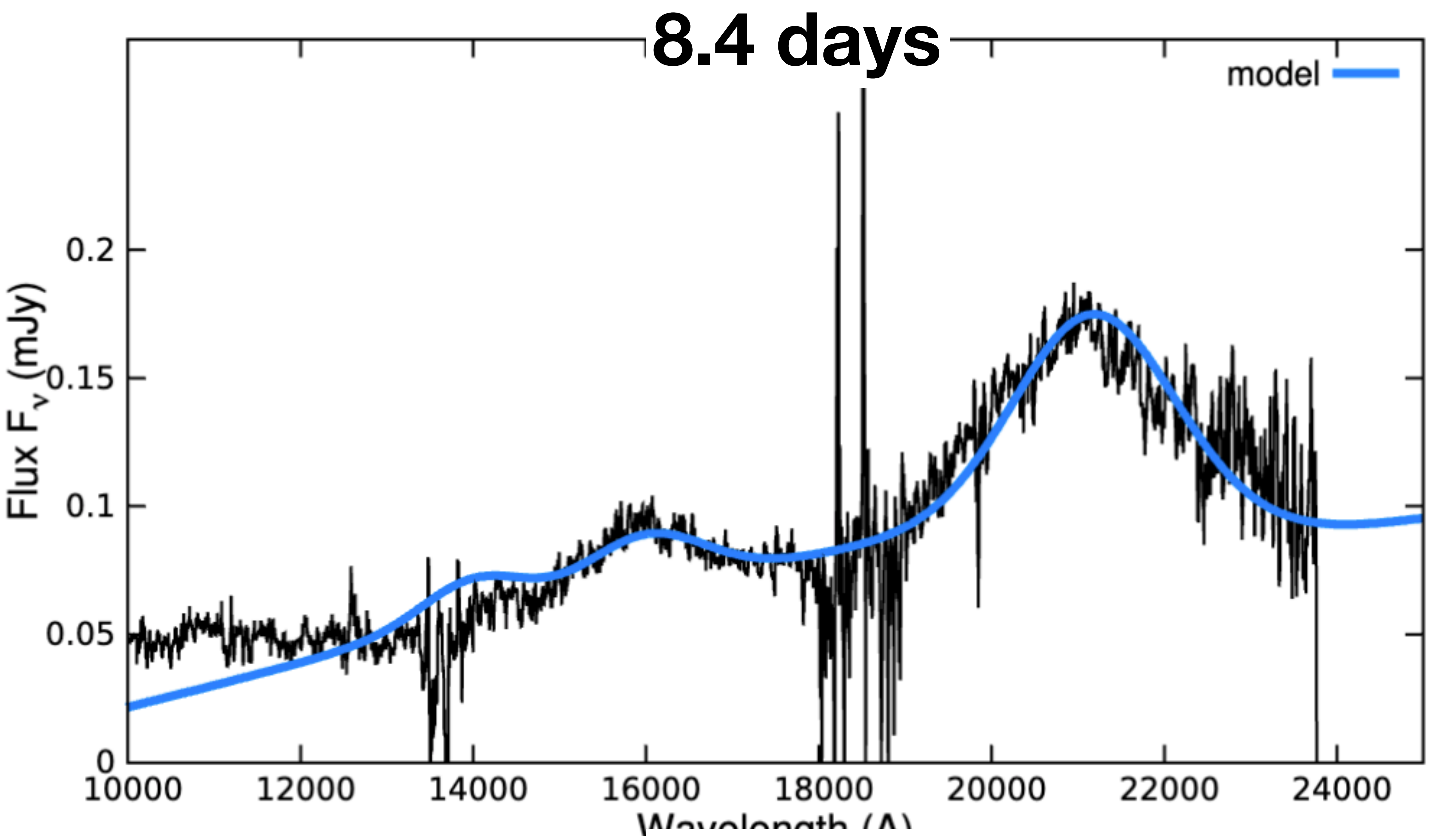
→ Collisional deexcitation is ignored, abundance of such levels is low

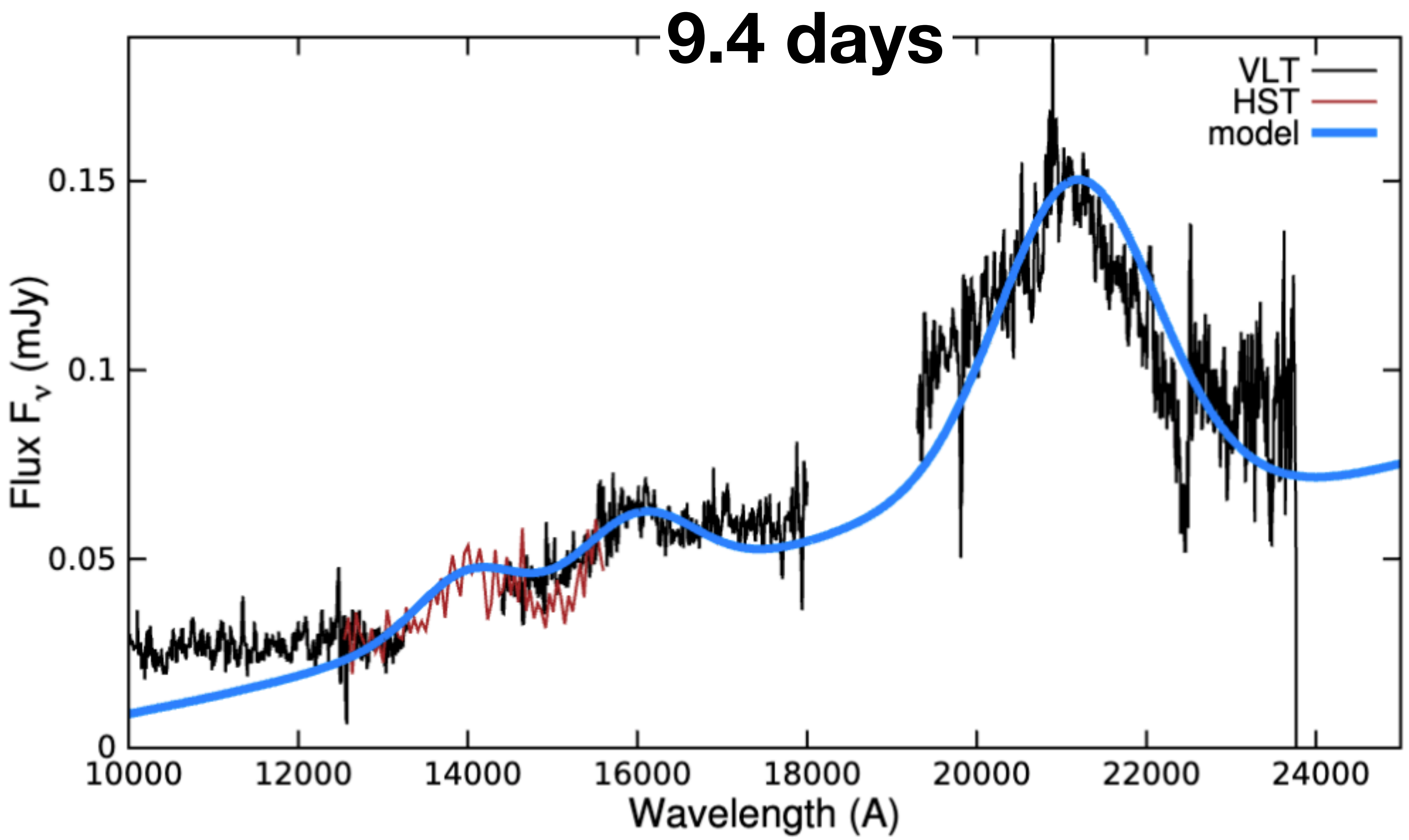
$n_{cr} < n_e$

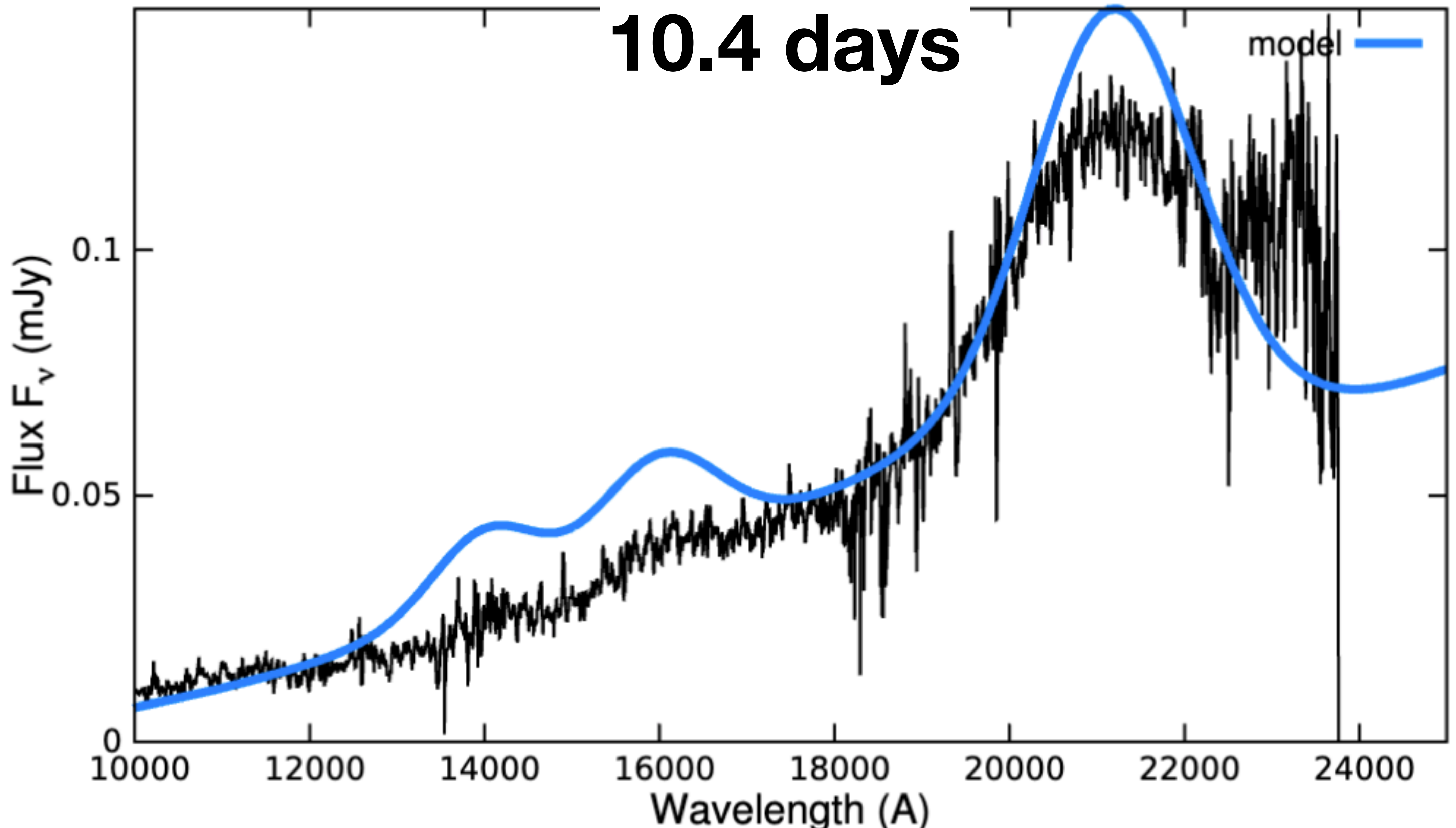
Happens when the radiative decay is forbidden

→ Collisional deexcitation is important and distribution can be Boltzmann

Comparison of best-fit spectrum with spectrum at different epochs

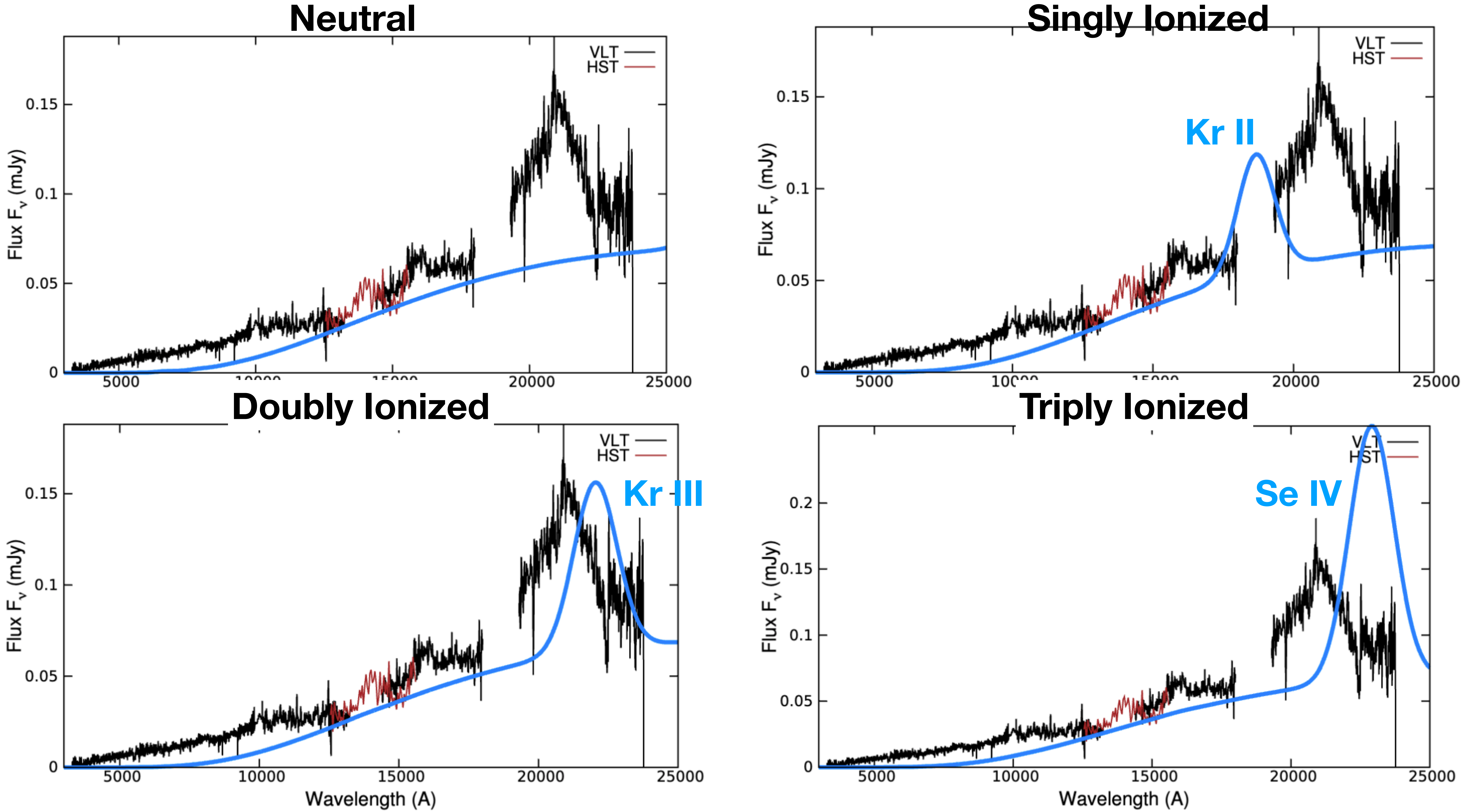






Emission becomes lower at later time most likely due to temperature decreasing

Models and Spectrum Comparison: light abundance



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