Identifications of Heavy Element in Kilonova Infrared Spectra

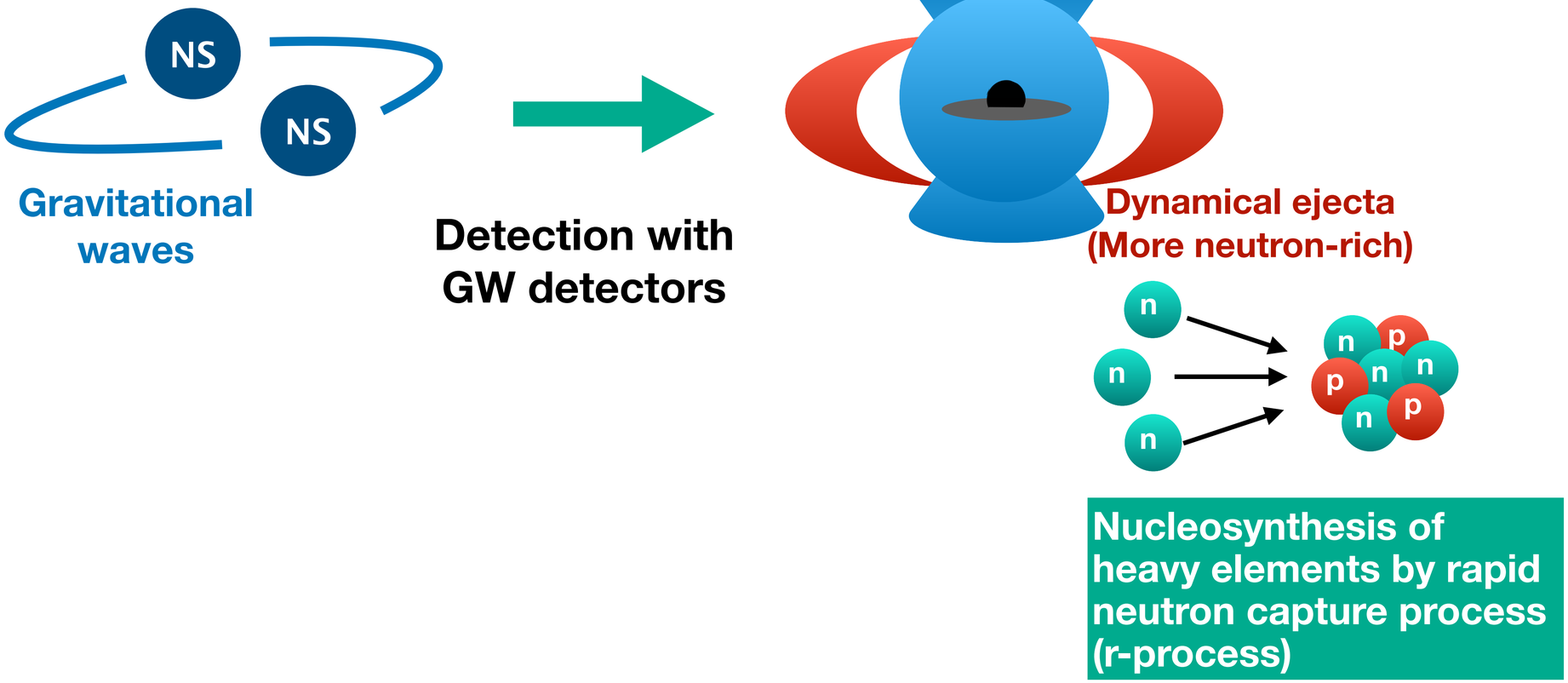
Implications for GW170817

Salma Rahmouni, Masaomi Tanaka (Tohoku University)

11th East Asian Meeting on Astronomy @Niigata

Introduction

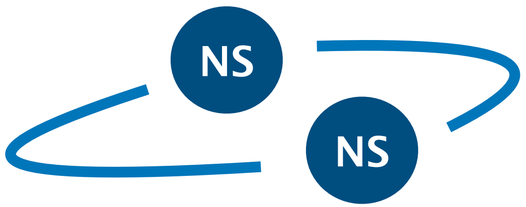
Neutron star mergers



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

Introduction

Neutron star mergers

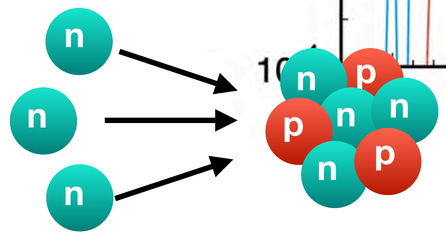


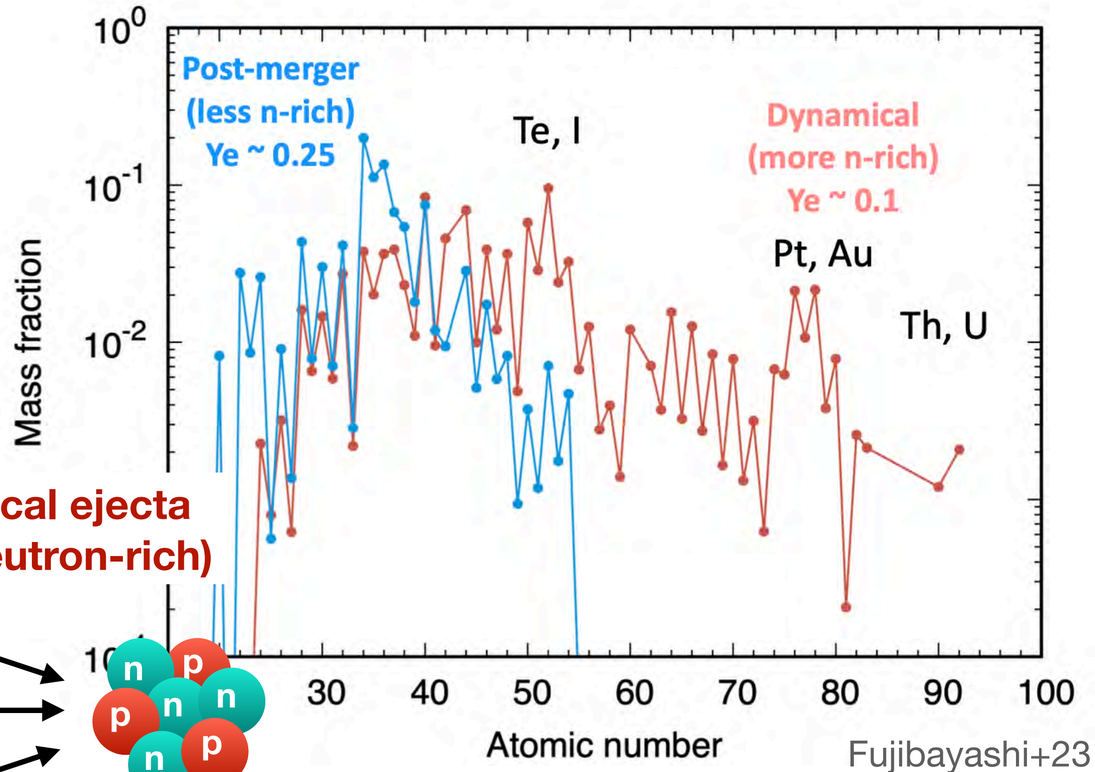
Gravitational waves

Detection with GW detectors

Post-merger ejecta (Less neutron-rich)

Dynamical ejecta (More neutron-rich)

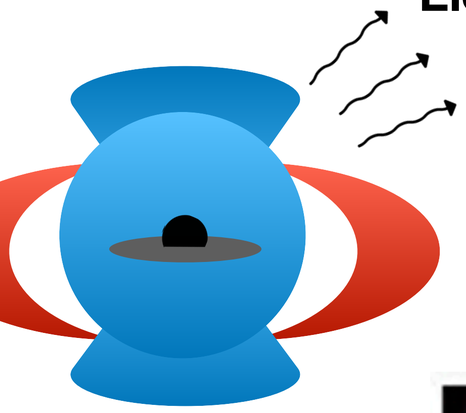




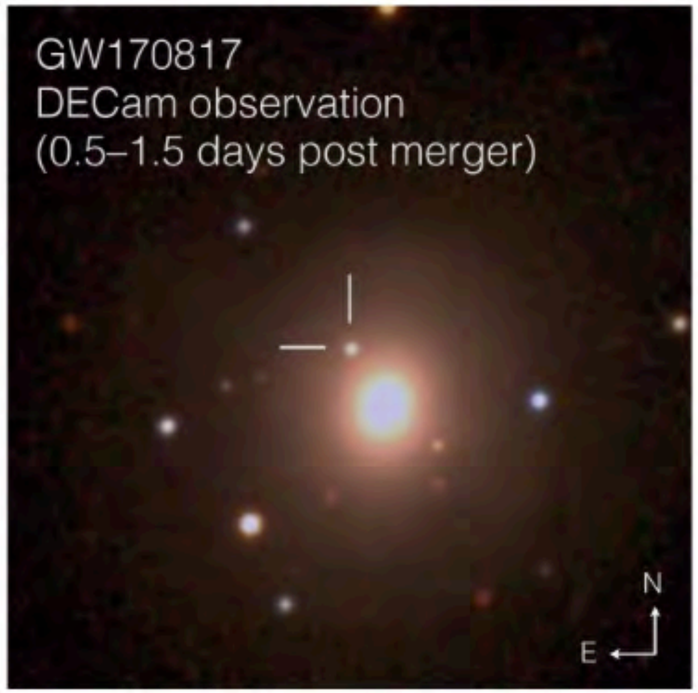
Nucleosynthesis of heavy elements by rapid neutron capture process (r-process)

Introduction

Electromagnetic emission
“Kilonova”

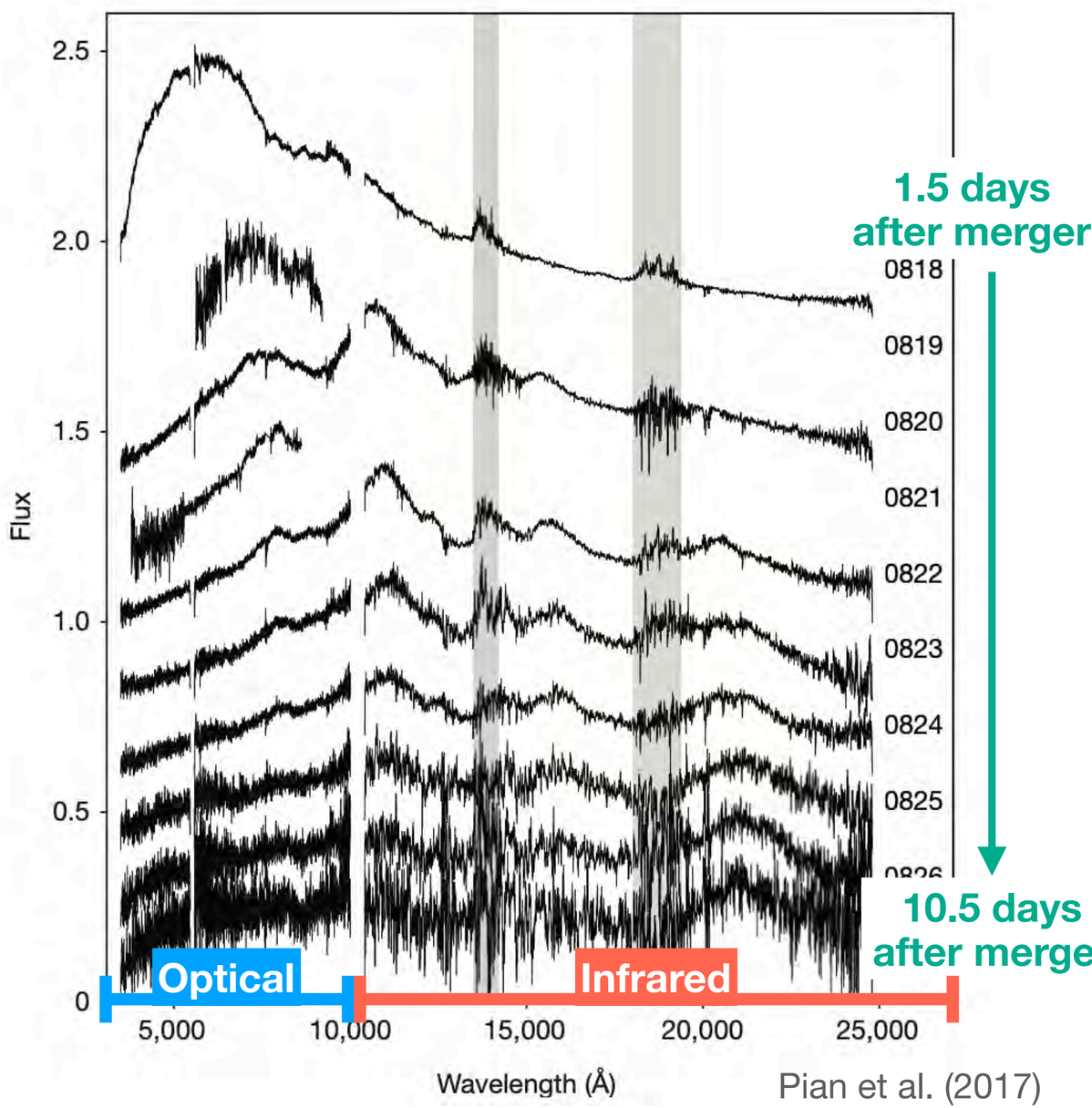


Kilonova of GW170817



Soares-Santos et al. (2017)

GW170817 spectrum

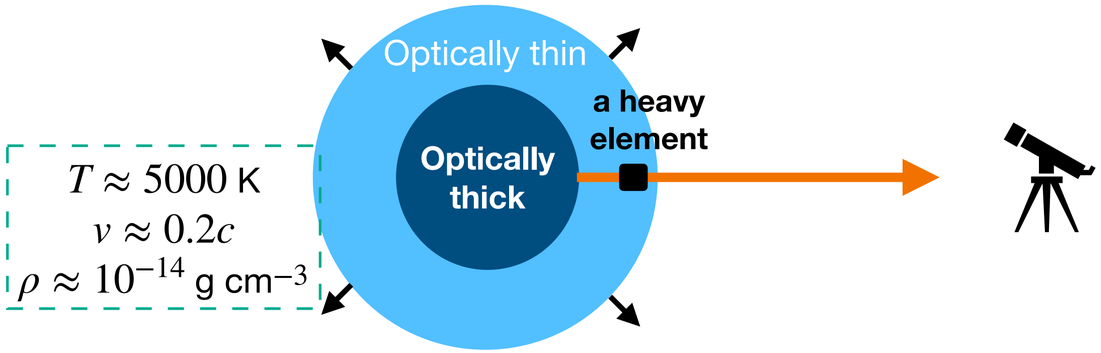


Pian et al. (2017)

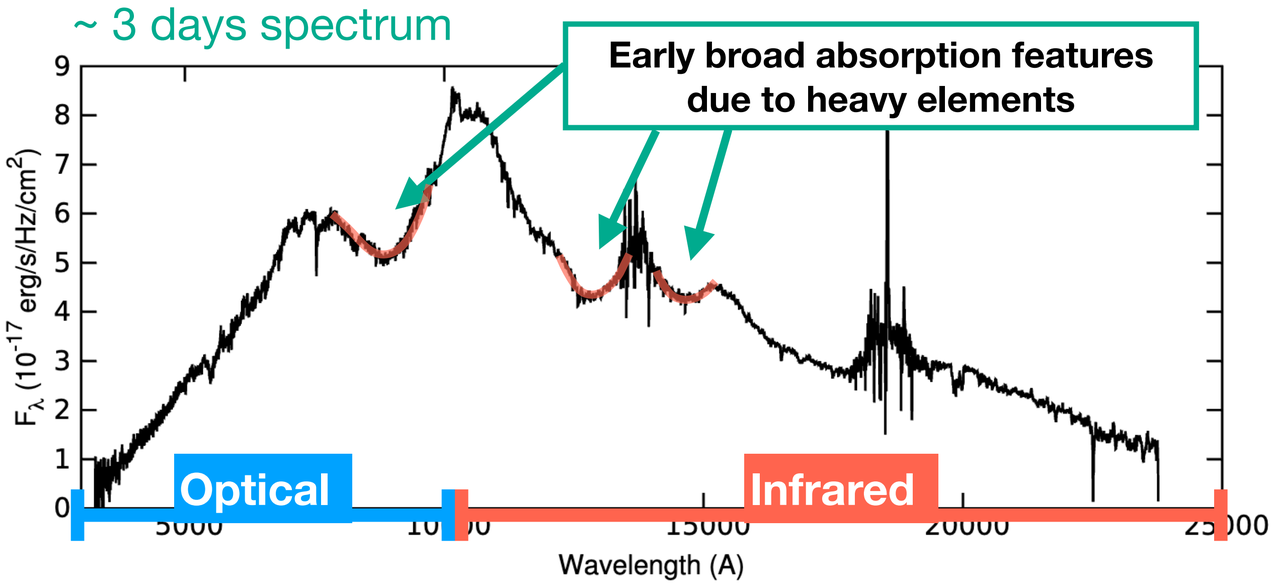
Introduction

(Very) simplified picture of NSM ejecta

Early-phase



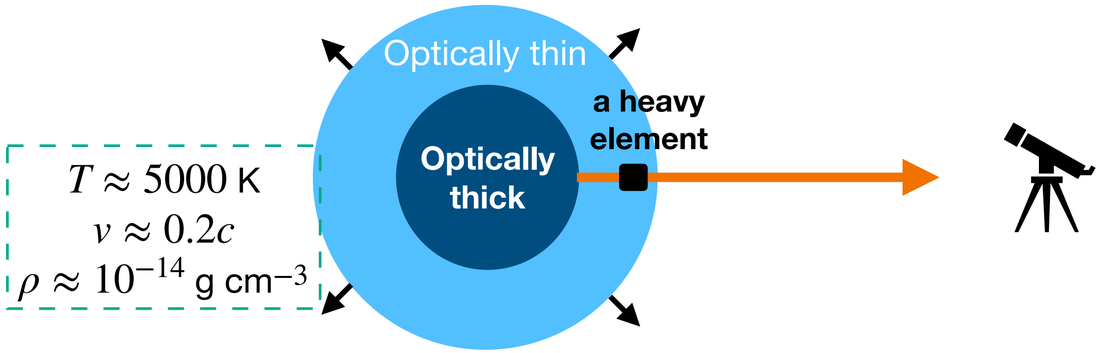
Spectrum of GW170817



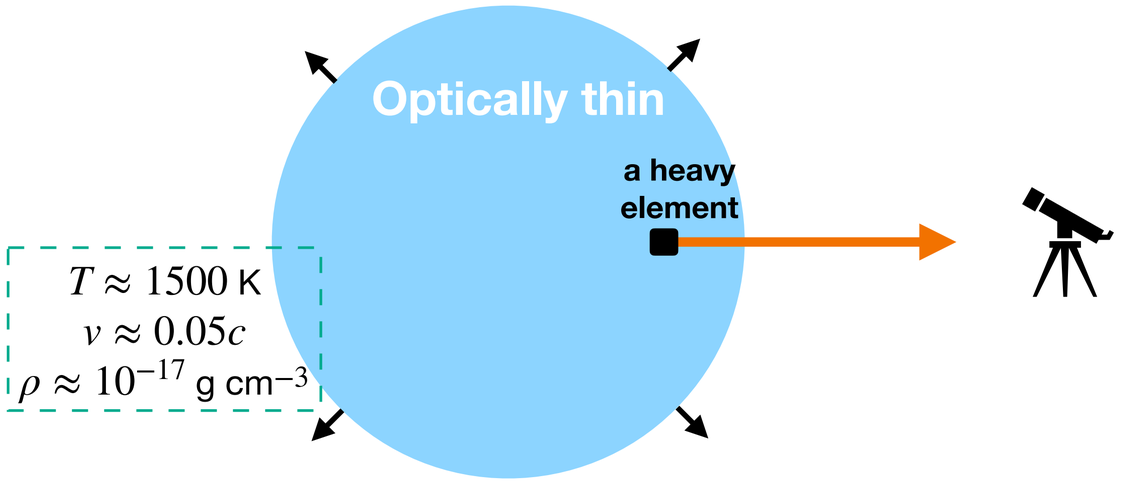
Introduction

(Very) simplified picture of NSM ejecta

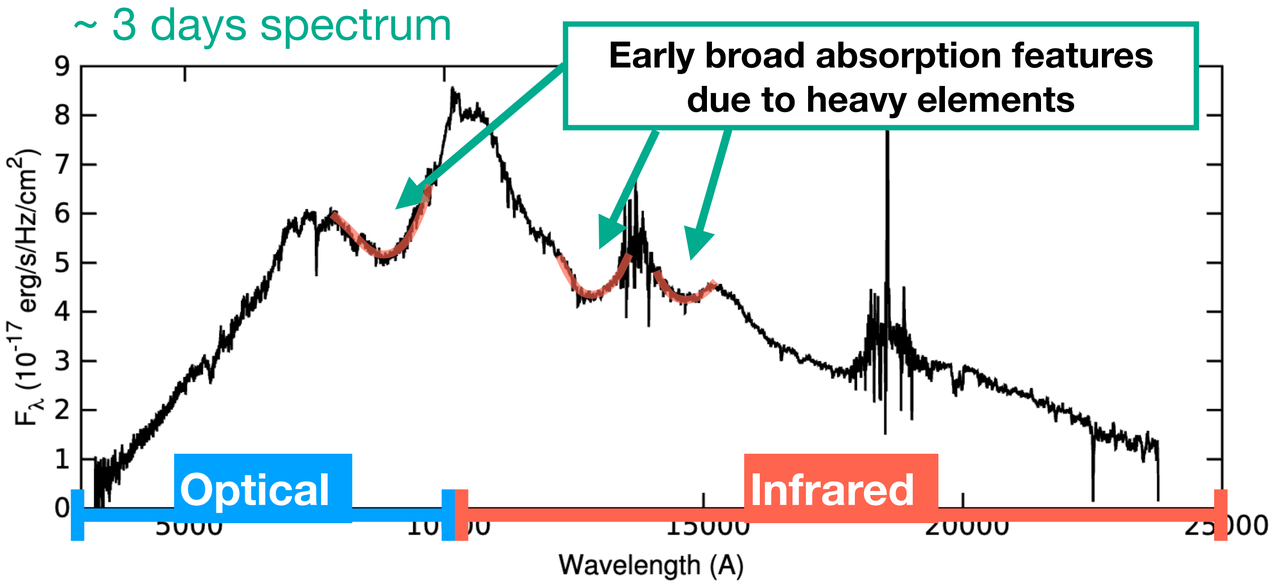
Early-phase

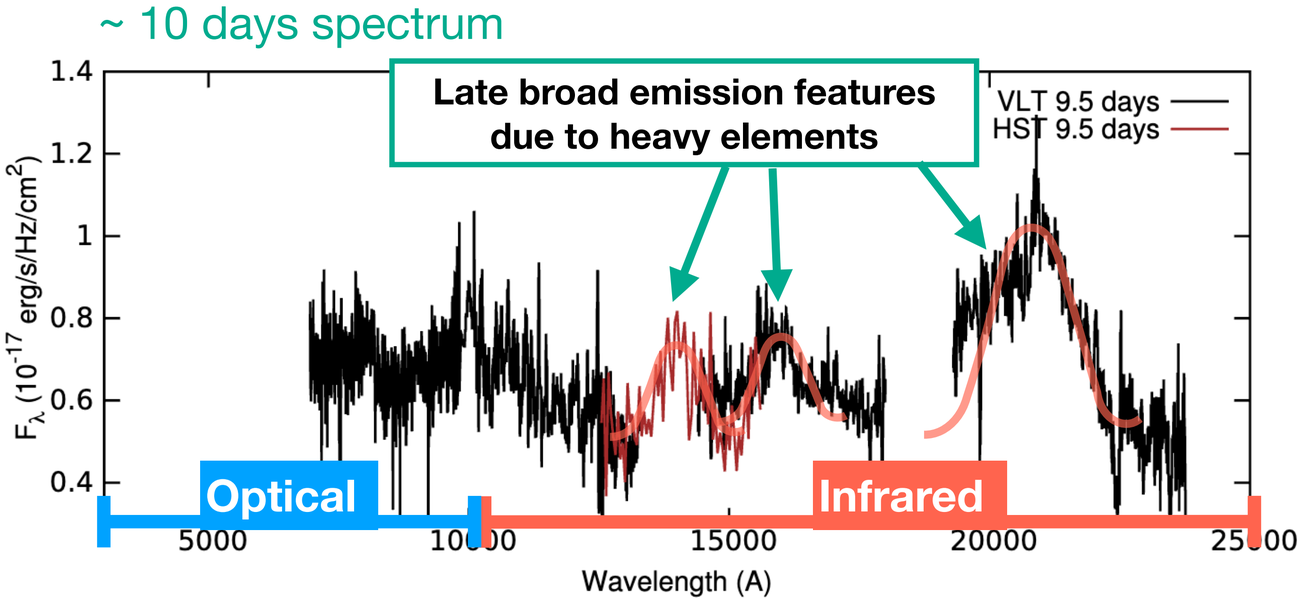


Late-phase



Spectrum of GW170817





Introduction

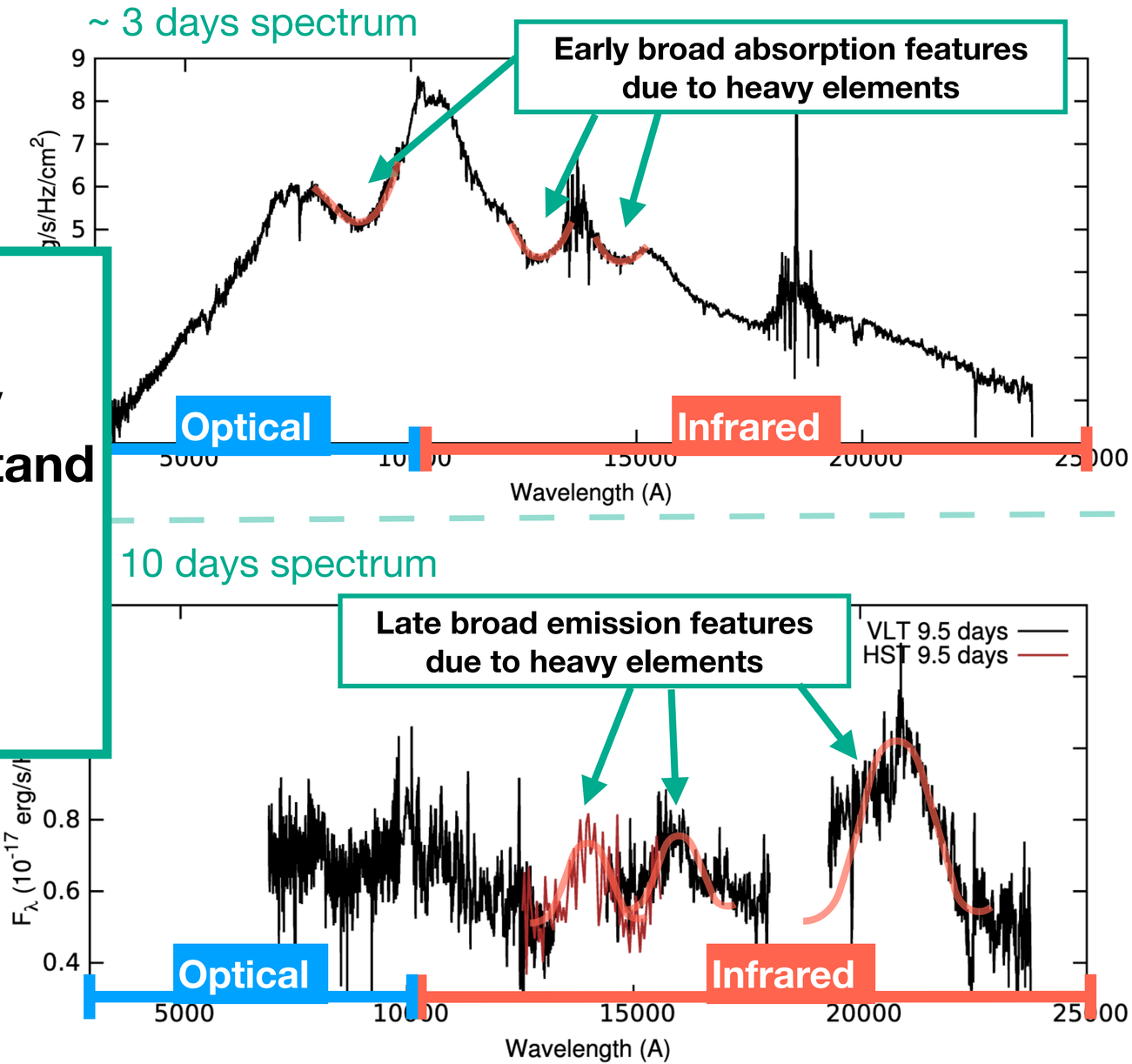
(Very) simplified picture of NSM ejecta

Goal

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

First step: Spectral Investigation

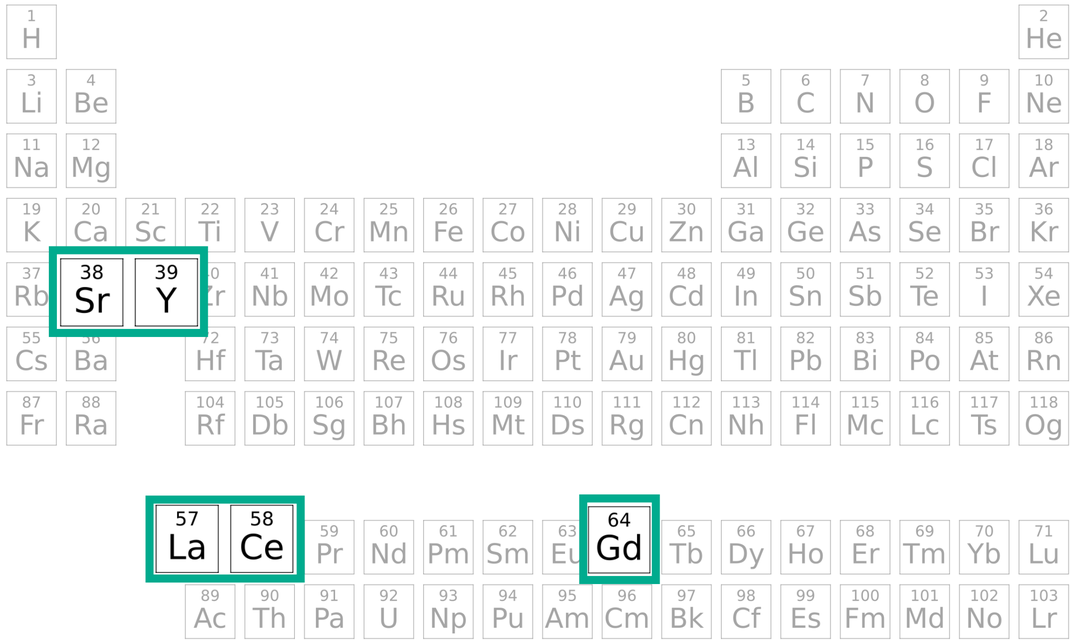
Spectrum of GW170817



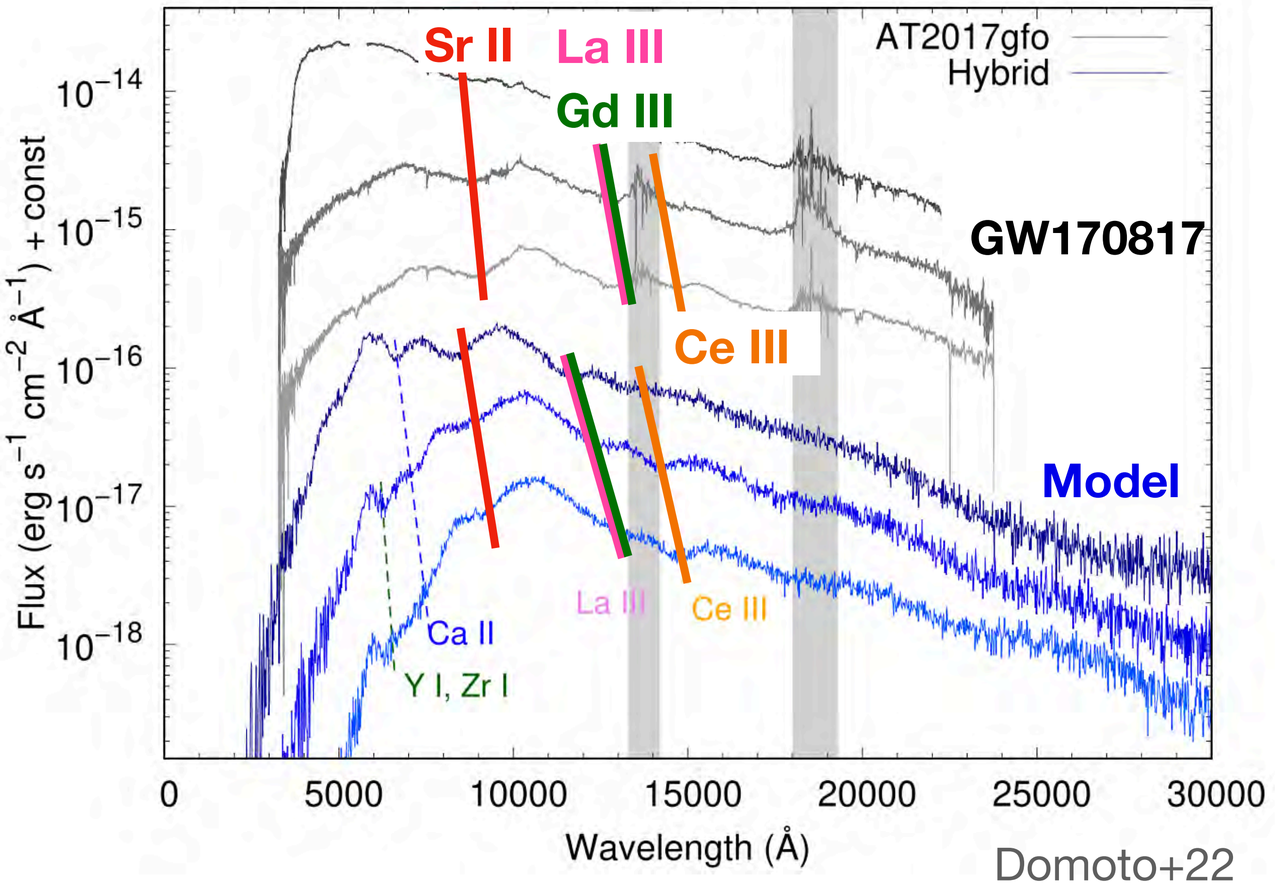
Early-Phase Spectral Investigation

Identification of Most Features

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



Early GW170817 spectra + theoretical model



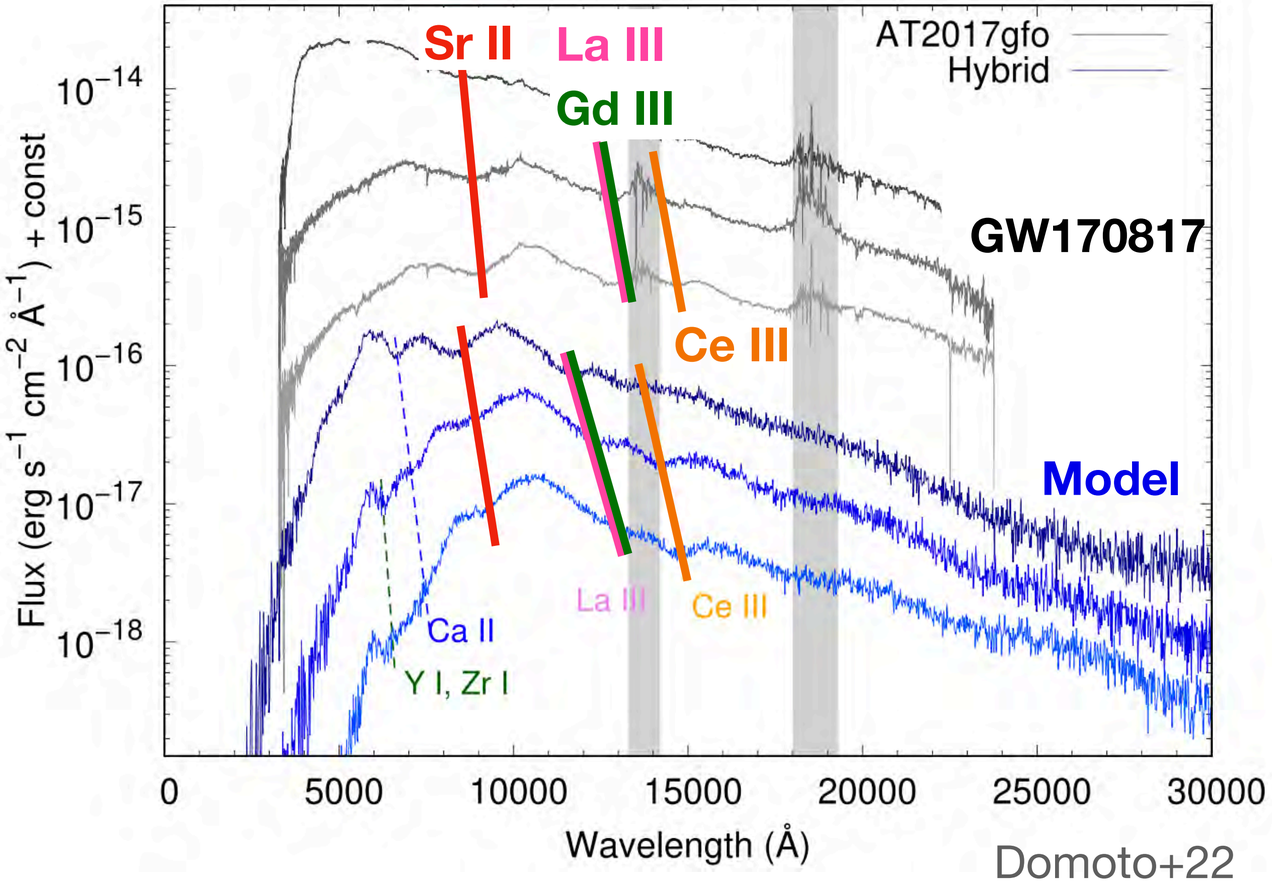
Domoto+22

Early-Phase Spectral Investigation

Identification of Most Features

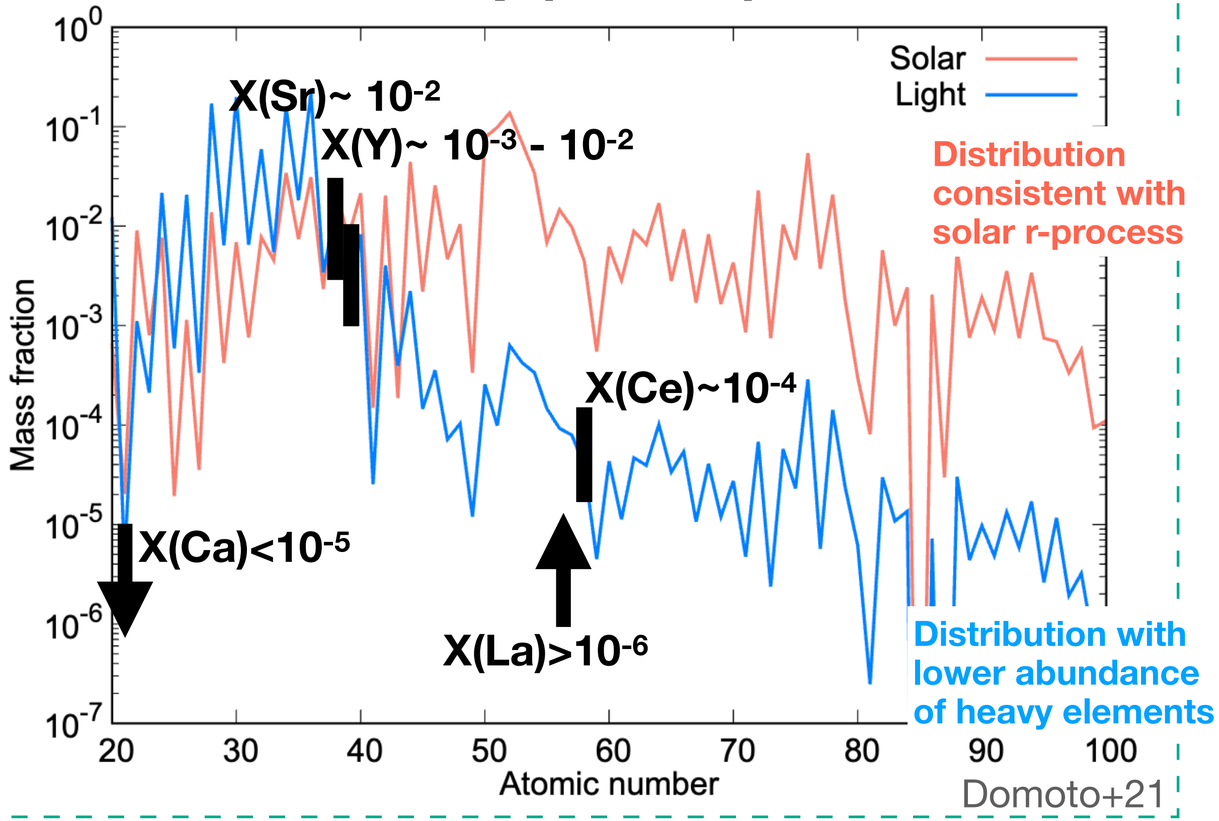
(Watson+19, Domoto+22, Sneppen+23, Rahmouni+25)

Early GW170817 spectra + theoretical model



Domoto+22

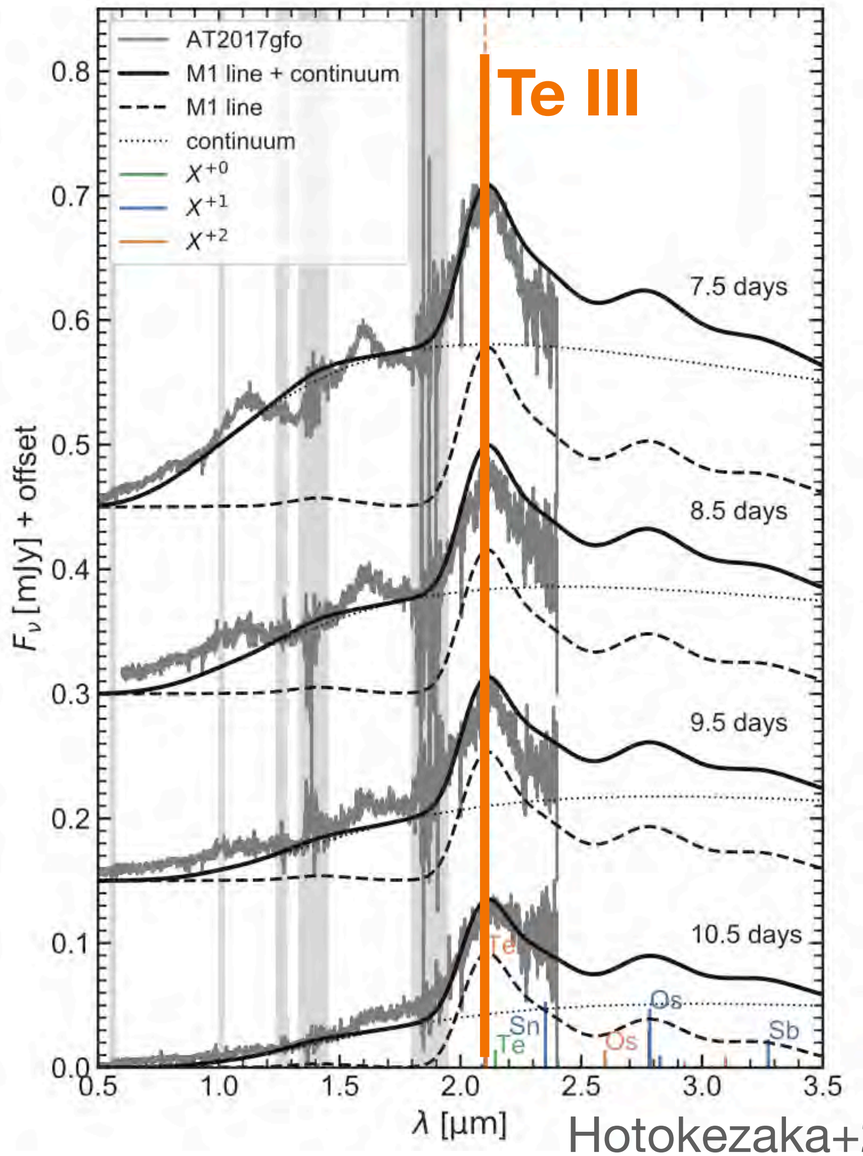
Constraints on Nucleosynthesis from early-phase spectra



Domoto+21

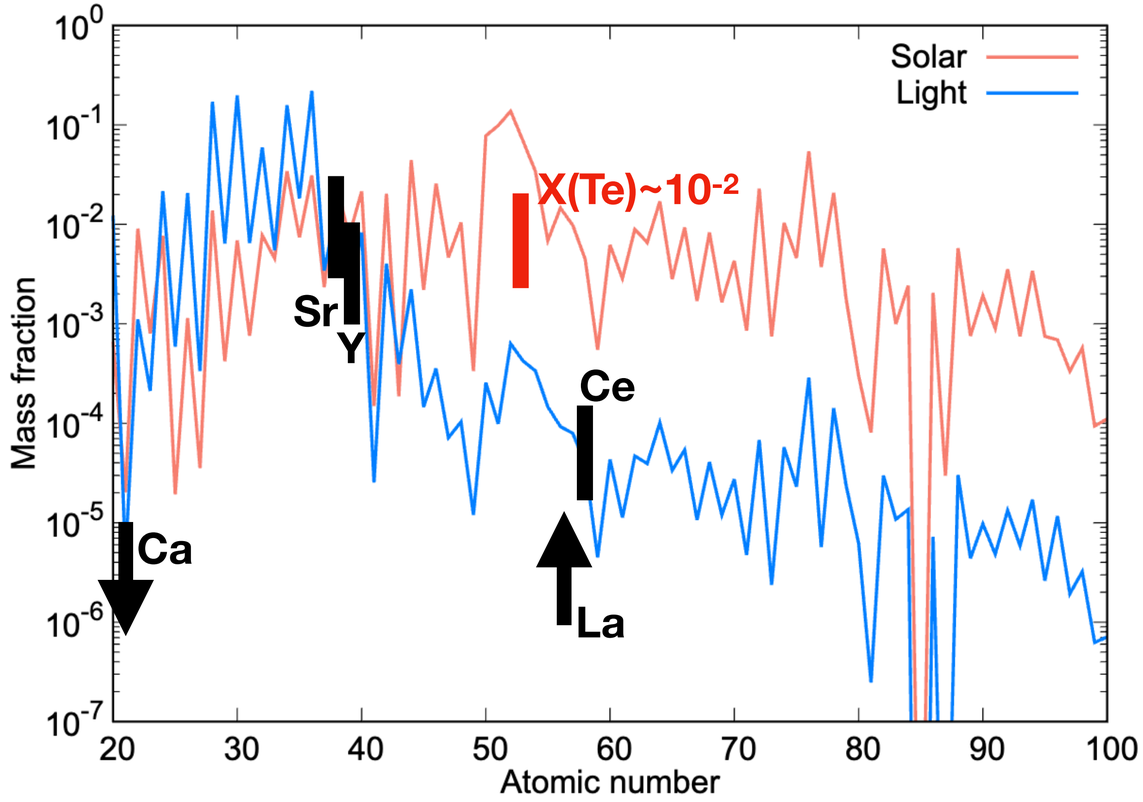
Late Phase Spectral Investigation

Identification of a single feature



Hotokezaka+23

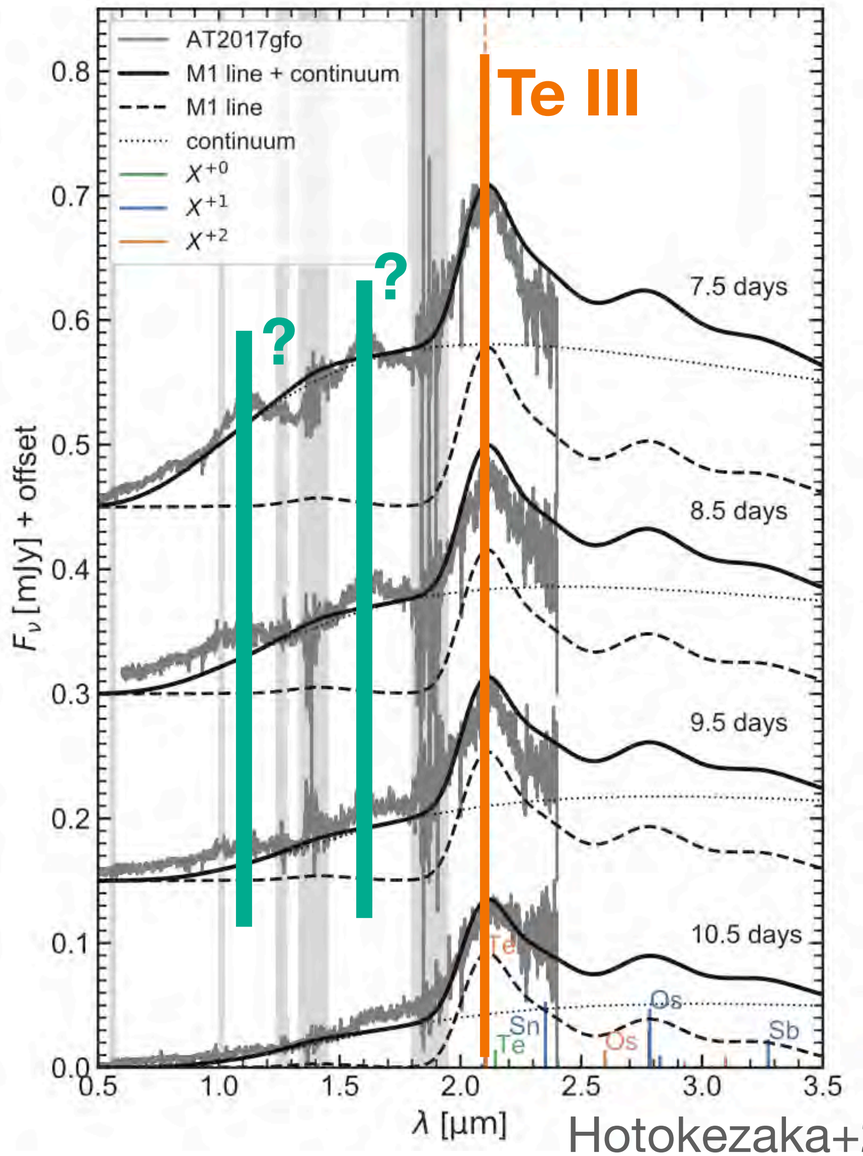
Constraints on Nucleosynthesis



Inconsistency?

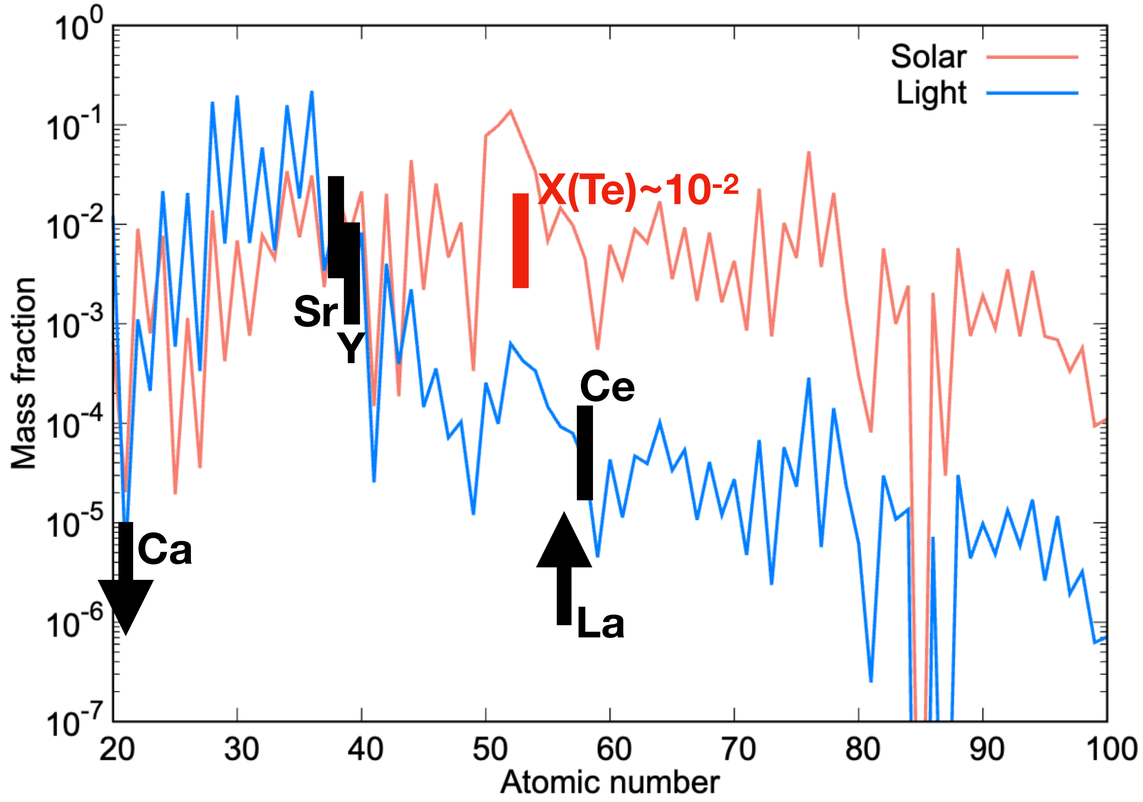
Late Phase Spectral Investigation

Identification of a single feature



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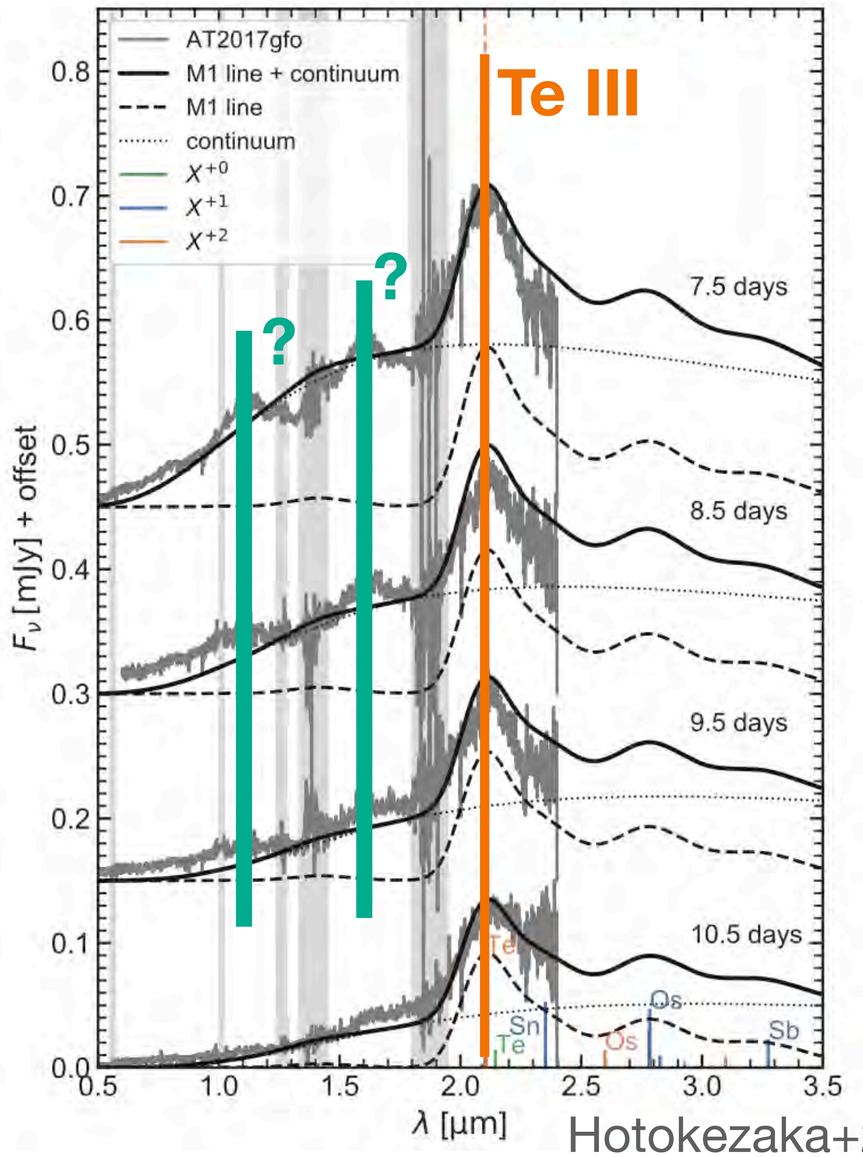
Constraints on Nucleosynthesis



Inconsistency?

Late Phase Spectral Investigation

Identification of a single feature



Hotokezaka+23

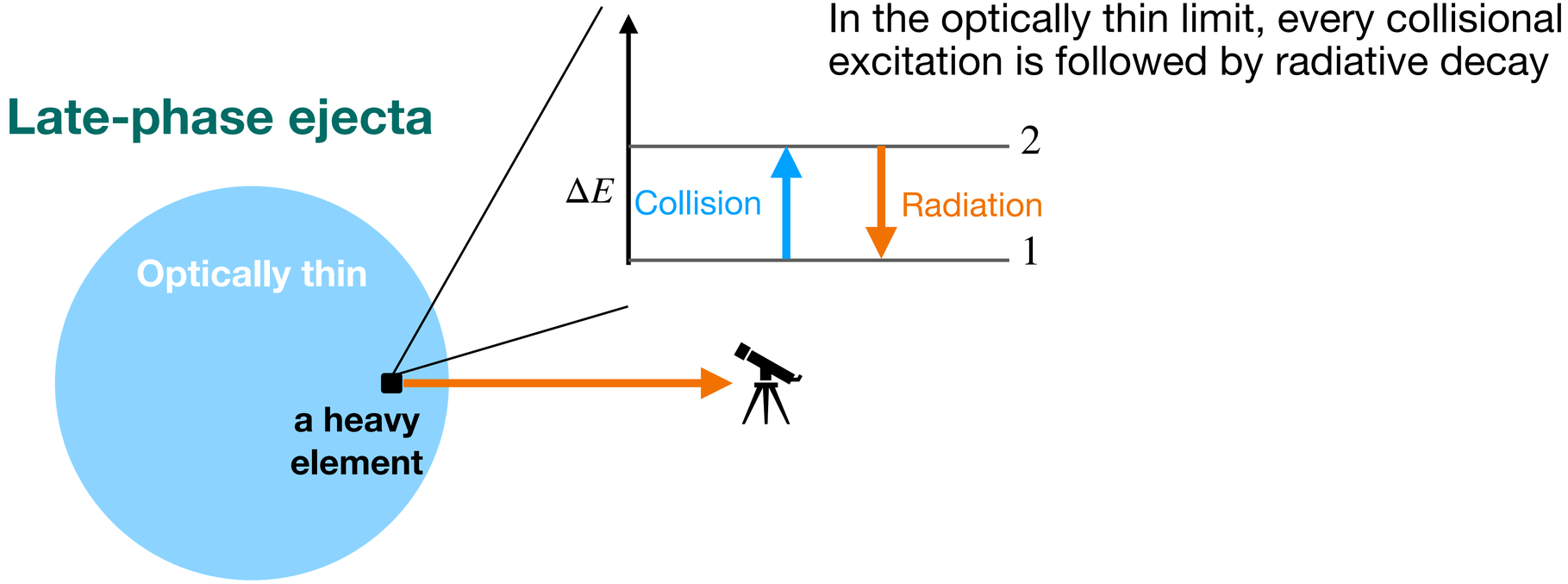
This work

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

→ **Provide further constraints on nucleosynthesis**

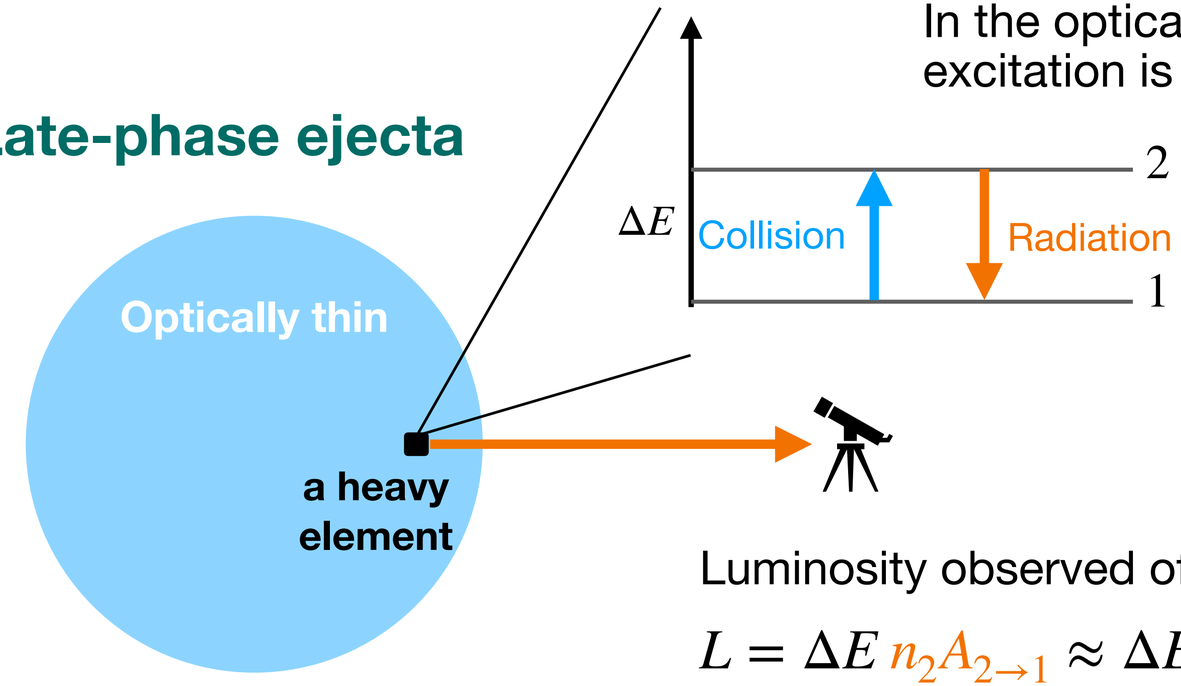
Spectral Model

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



Spectral Model

Late-phase ejecta



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

Luminosity observed of one transition is therefore:

$$L = \Delta E\, n_2 A_{2\to1} \approx \Delta E\, n_e n_1 q_{1\to2}$$

Radiative decay rate

Collisional excitation rate

Rate coefficient:

$$q_{1\to2} = \frac{8.629\times10^{-6}}{T^{1/2}} \frac{\Upsilon_{1\to2}}{g_1} \exp(-\Delta E/kT)$$

Atomic property

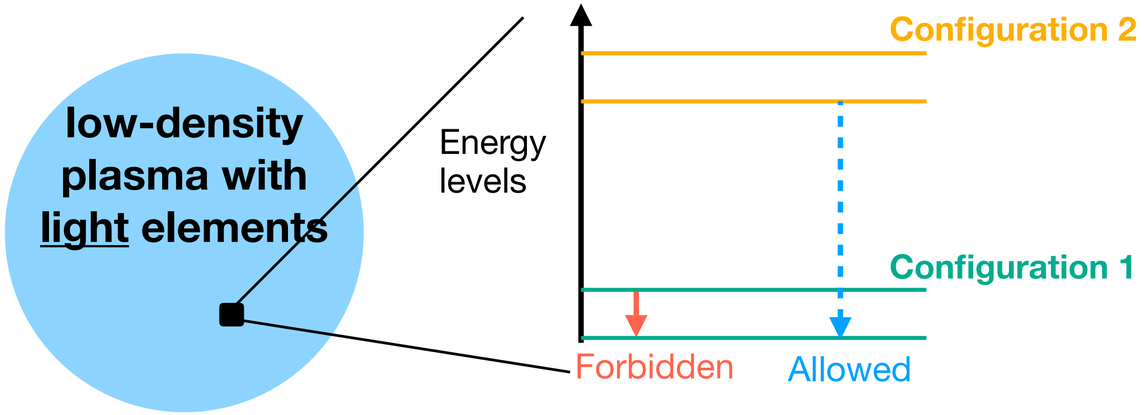
We calculate expected luminosity of <u>all transitions</u> of <u>all elements</u> to find candidates likely to exhibit strong emission features at late time

Spectral Model

Transitions Included

Light Elements

No mixing of energy levels



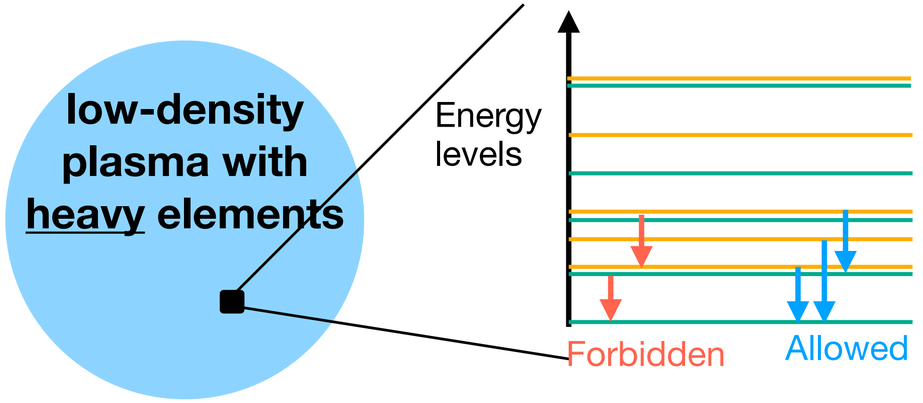
e.g. H II regions, SN late-phase ejecta

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

Allowed radiative decays suppressed due to low collisional excitation rate

Heavy Elements

large mixing of energy levels due to complex structure



Kilonova ejecta

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

Allowed and Forbidden decays are comparably strong

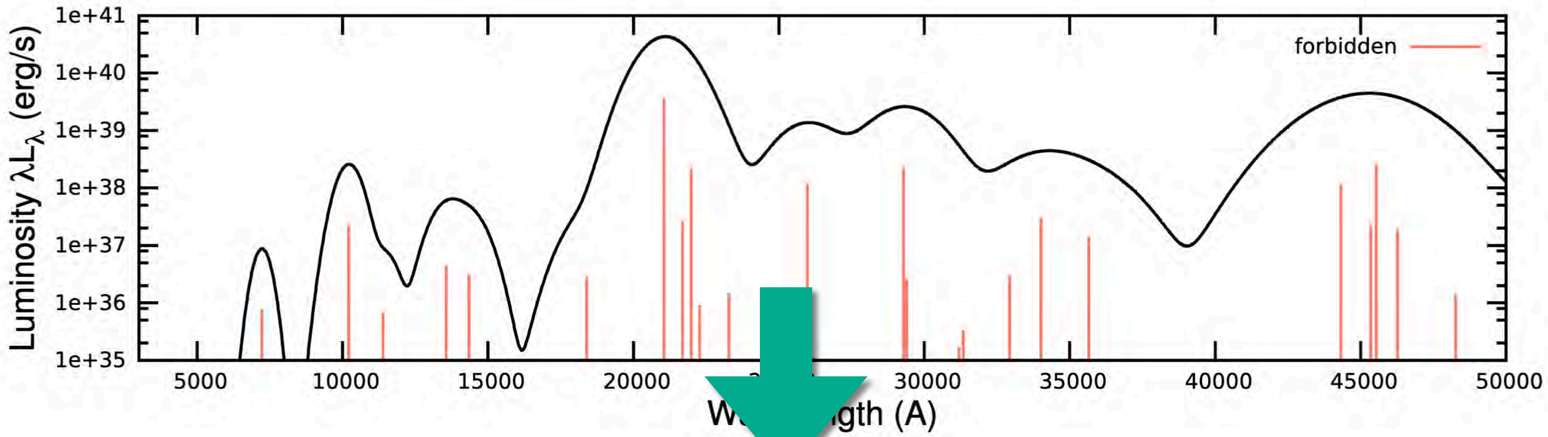
Both **allowed** and **forbidden** transitions should be included in late-phase spectral models of kilonovae

Spectral Model

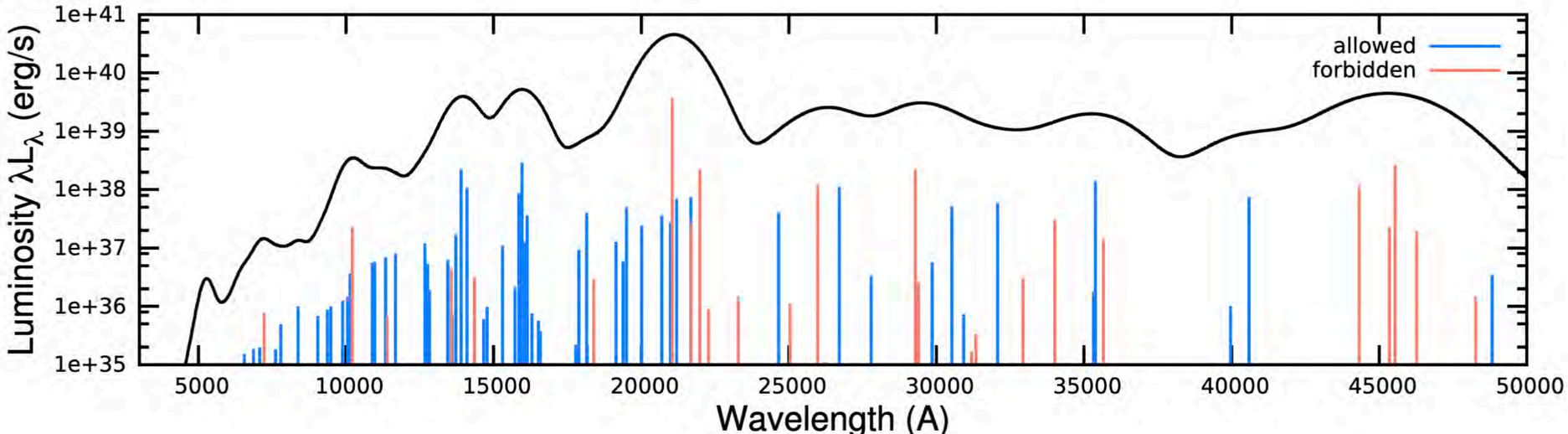
Resulting Spectrum

- Example of doubly ionized state with solar abundance
- Doppler broadening of $0.07c$

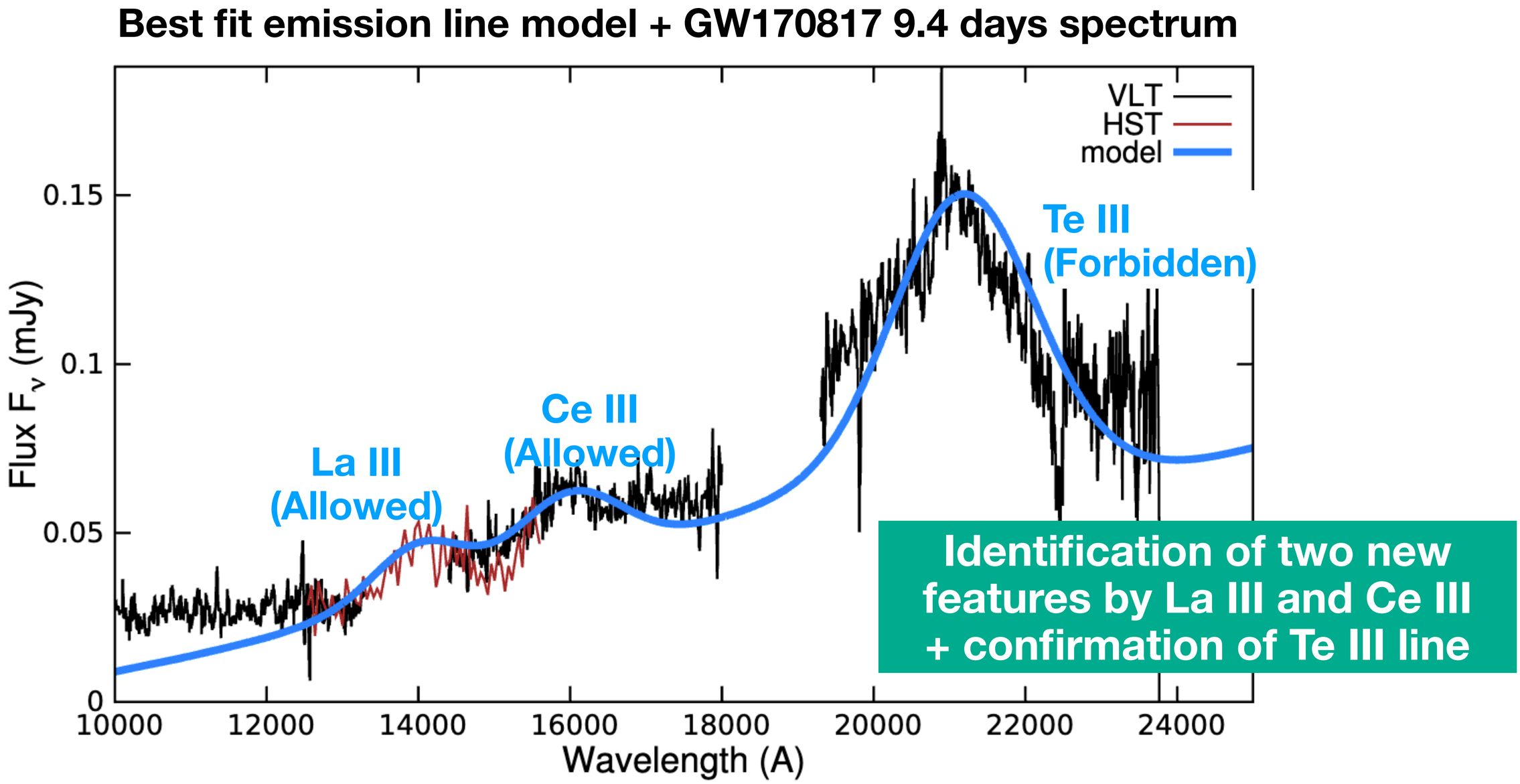
Forbidden transitions only (previous works)



Forbidden + Allowed transitions (this work)

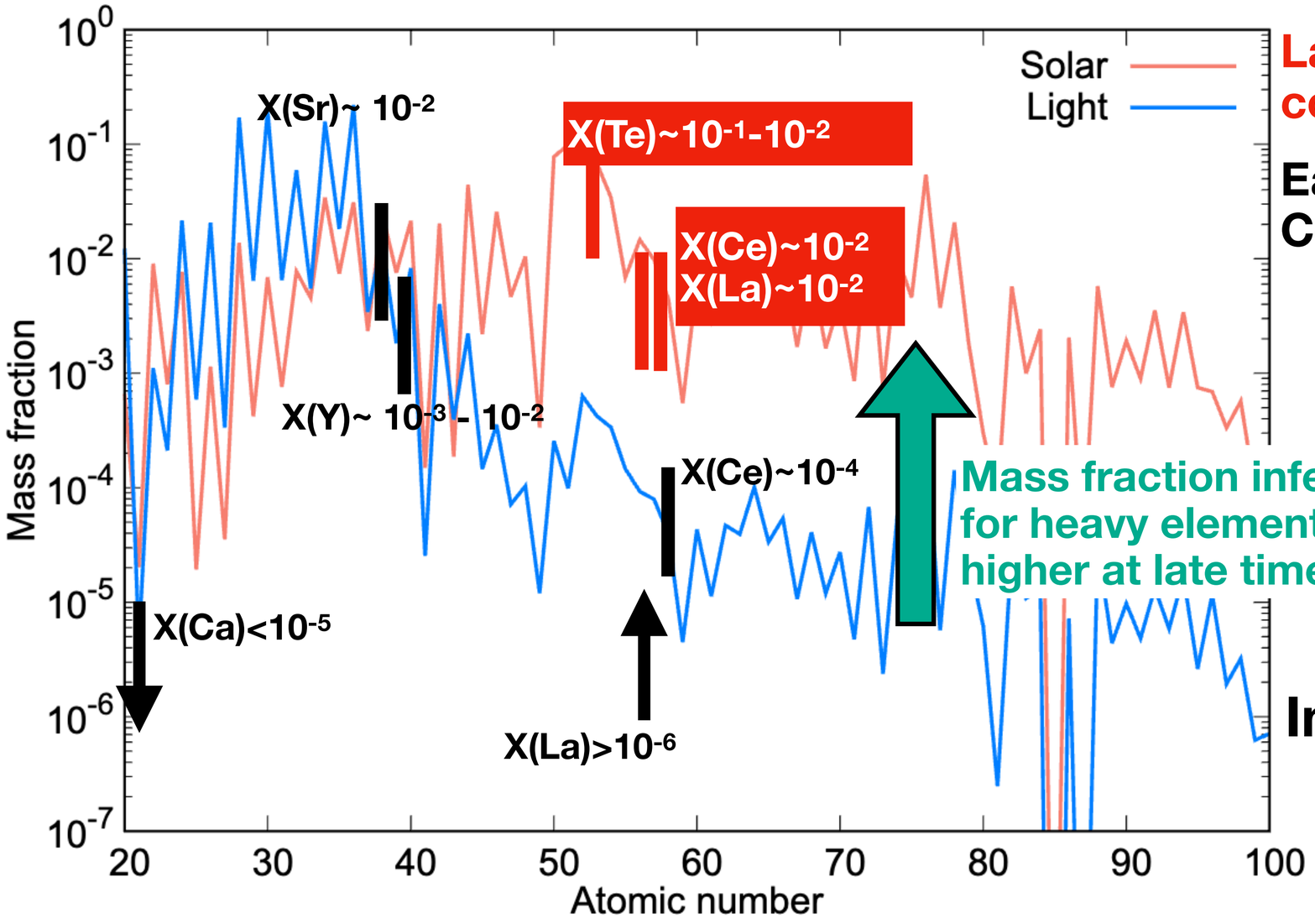


Comparison with GW170817



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

Nucleosynthesis constraints



Late-phase constraints

Early-phase Constraints

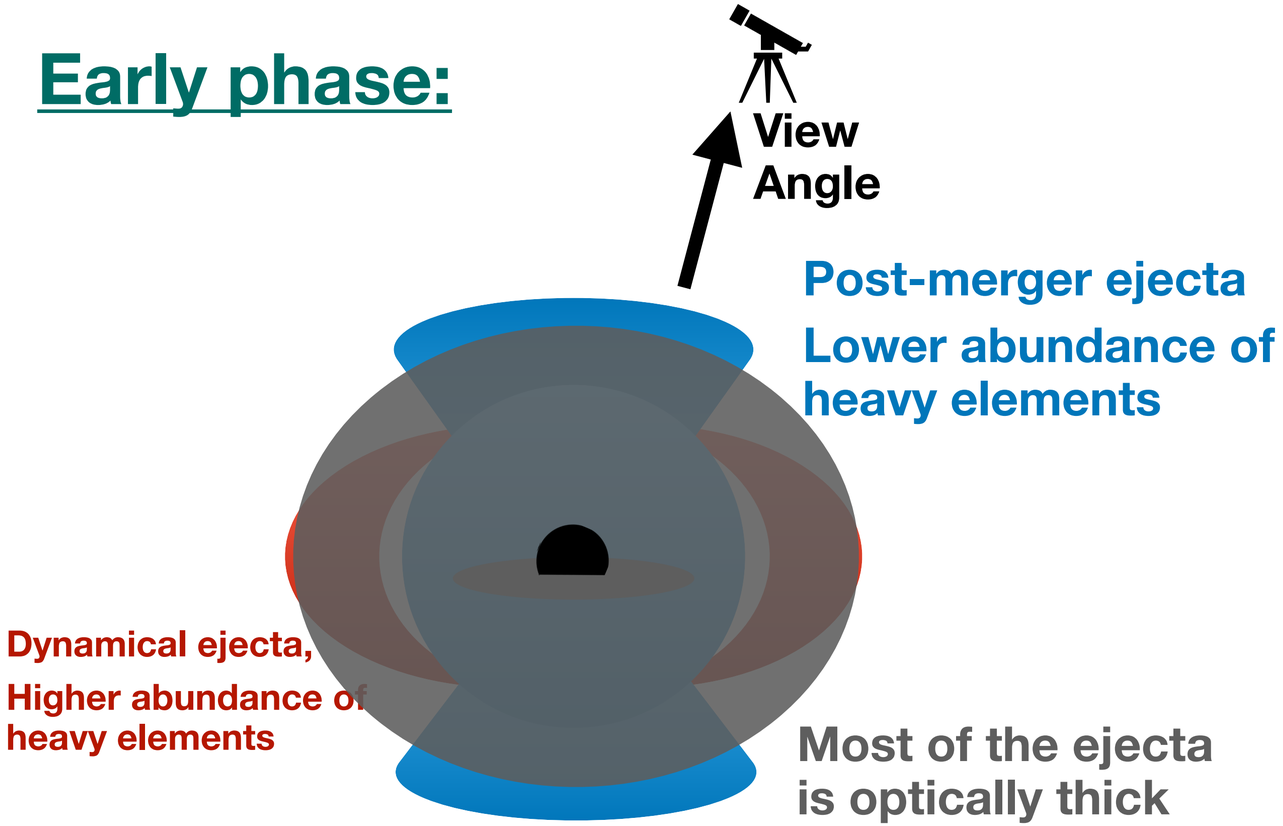
Mass fraction inferred for heavy elements is higher at late time

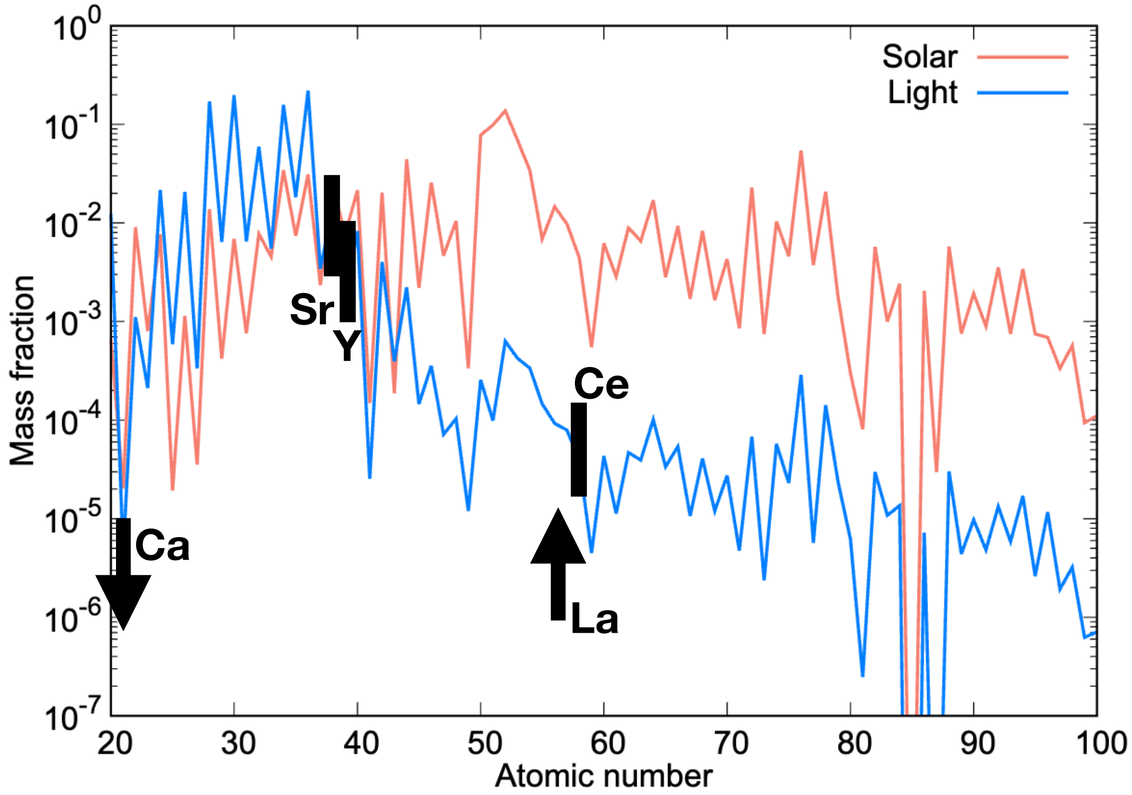
Inconsistency remains?

Discussion

Why different abundance distributions are needed to explain different epochs?

Early phase:





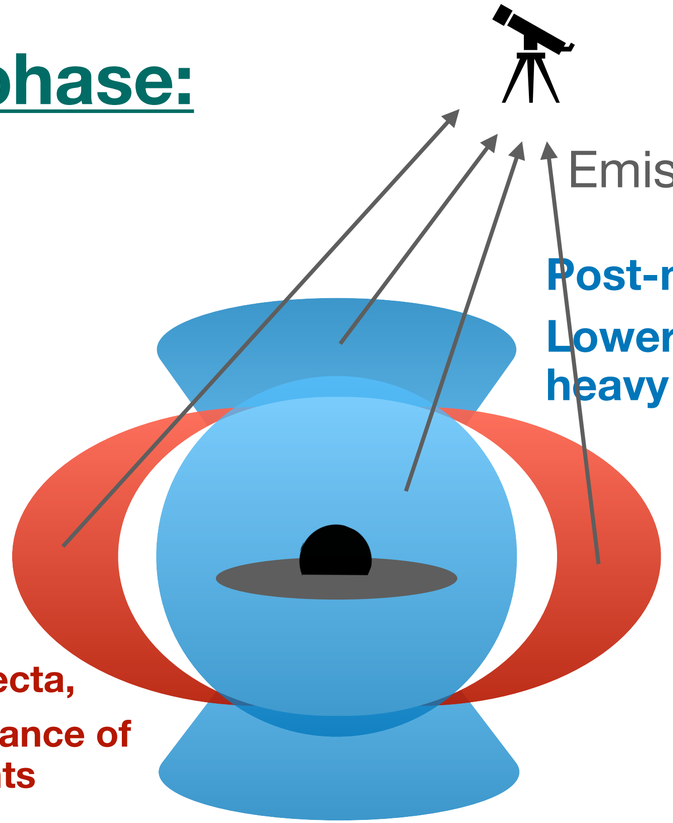
Absorption features appear due to elements in the polar post-merger ejecta

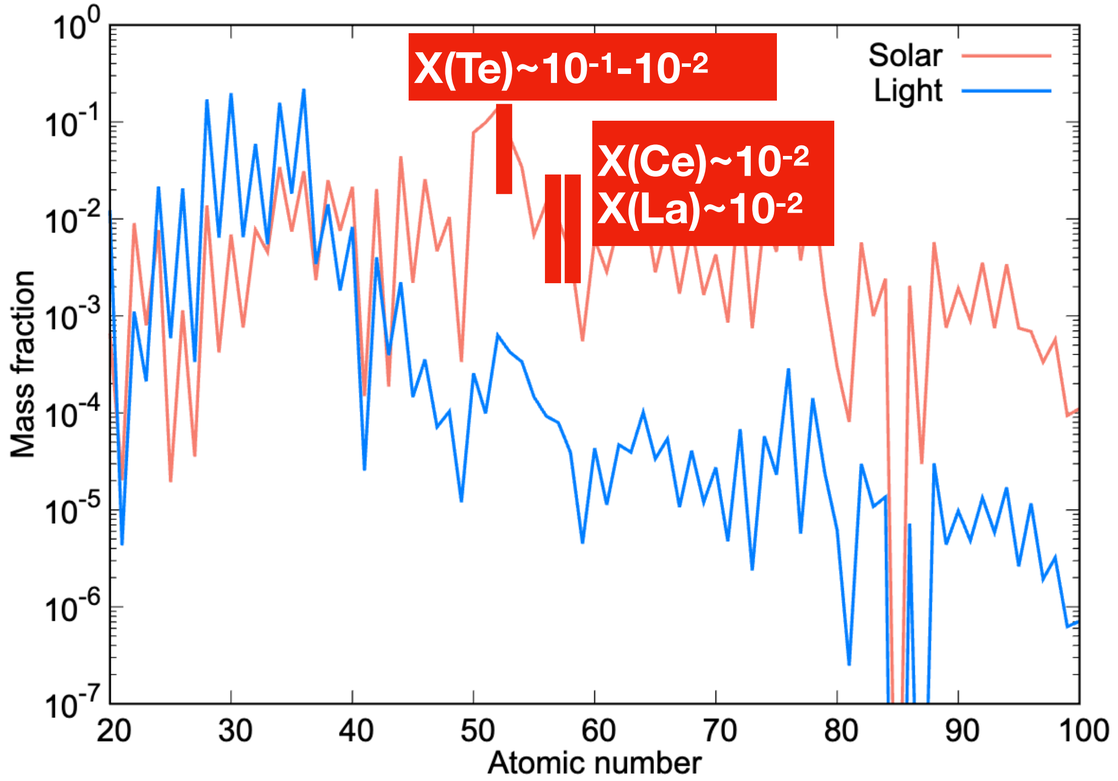
→ **Lower inferred mass fraction**

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**