Kilonova Theory

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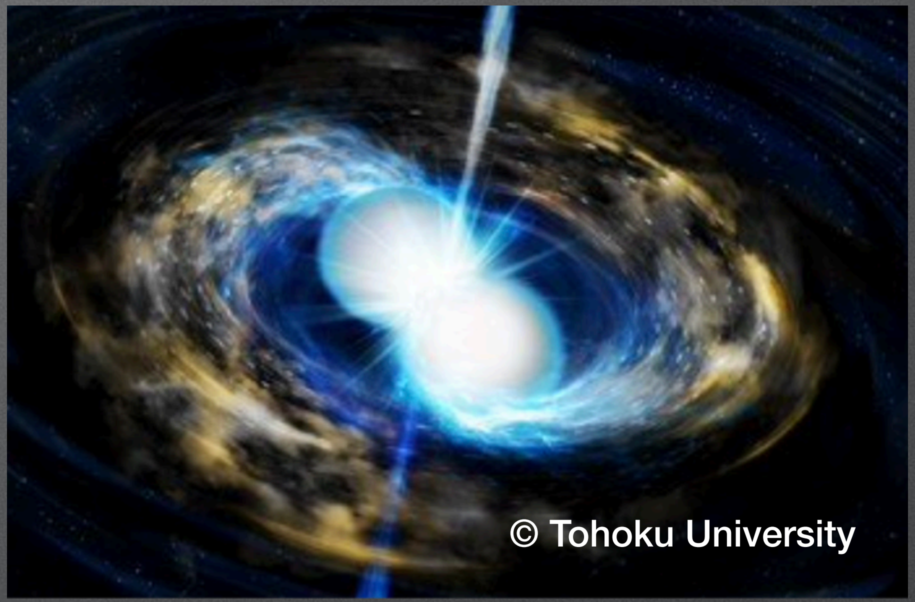
Outline

- Introduction
- Rapid neutron capture & Kilonova power
- Early Kilonova & absorption lines
- Kilonova Nebular Phase & James Webb Space Telescope (JWST)

Introduction: Kilonova

Concept:

- "*Kilonova*" is an electromagnetic counterpart of ***neutron star mergers (Li & Paczynski 98)***.
- ***Radioactivity*** in the neutron-rich ejecta powers kilonvoae. (e.g. Metzger+10).
- ***Lanthanides*** have many permitted lines in the optical - IR, which makes kilonvoae extremely ***red***. (e.g., Kasen+13, Tanaka & KH 13)



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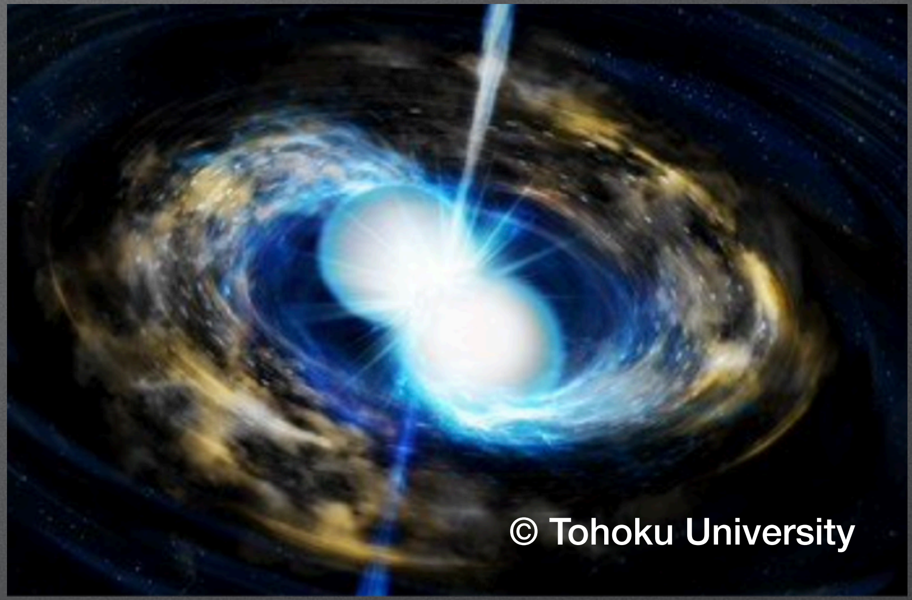


Observation history:

- The first kilonova candidate in 2013, followed a ***gamma-ray burst*** 130603B.

(Tanvir et al 2013)

- One kilonova after the 1st ***gravitational-wave merger*** GW170817.

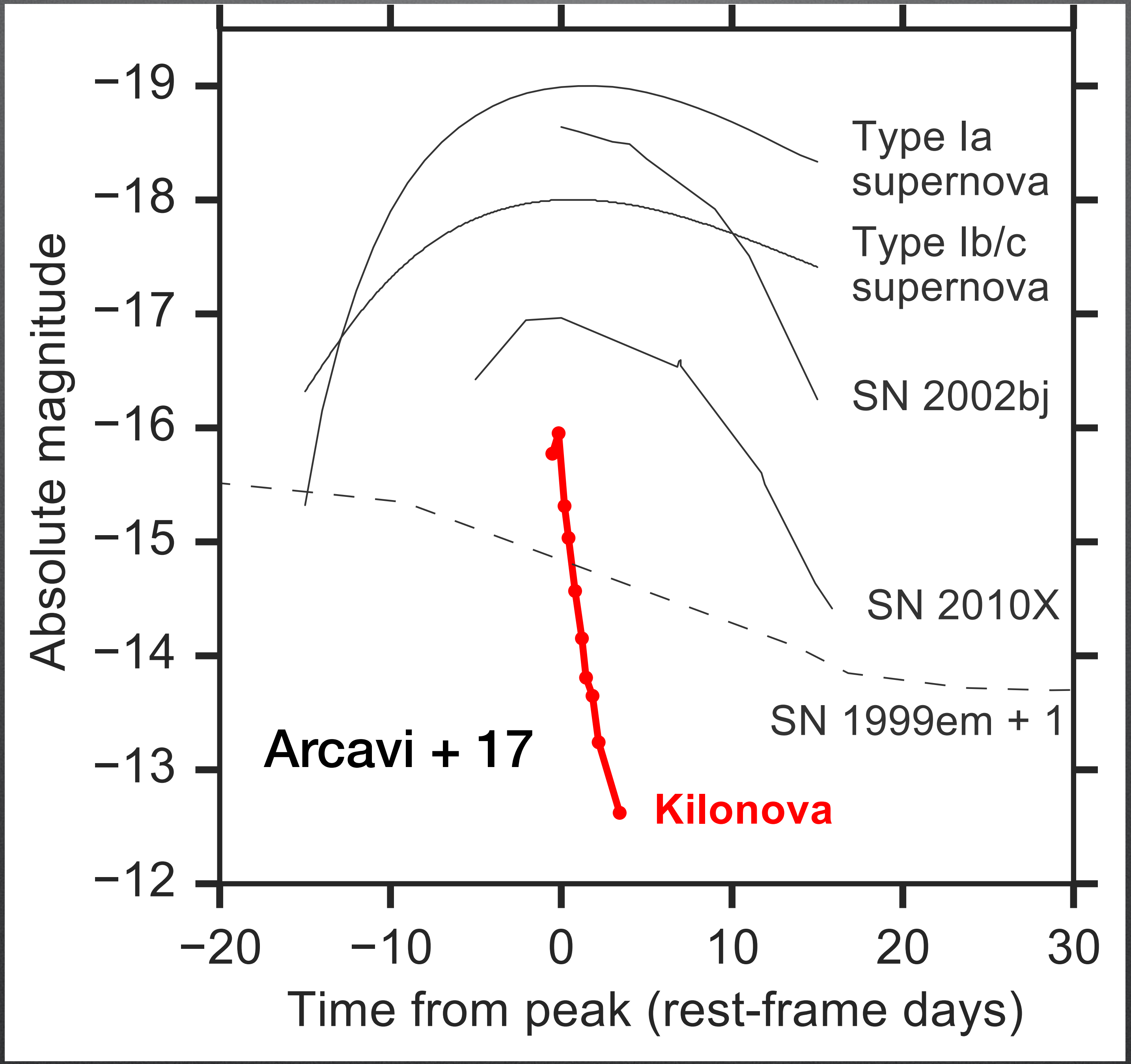
(Metzger 17, Margutti & Chornock 21, Nakar 20 for reviews)

- As of 2023, ~ 10 possible kilonovae after gamma-ray bursts.

(Troja 23 for a review)

A Kilonova in GW170817

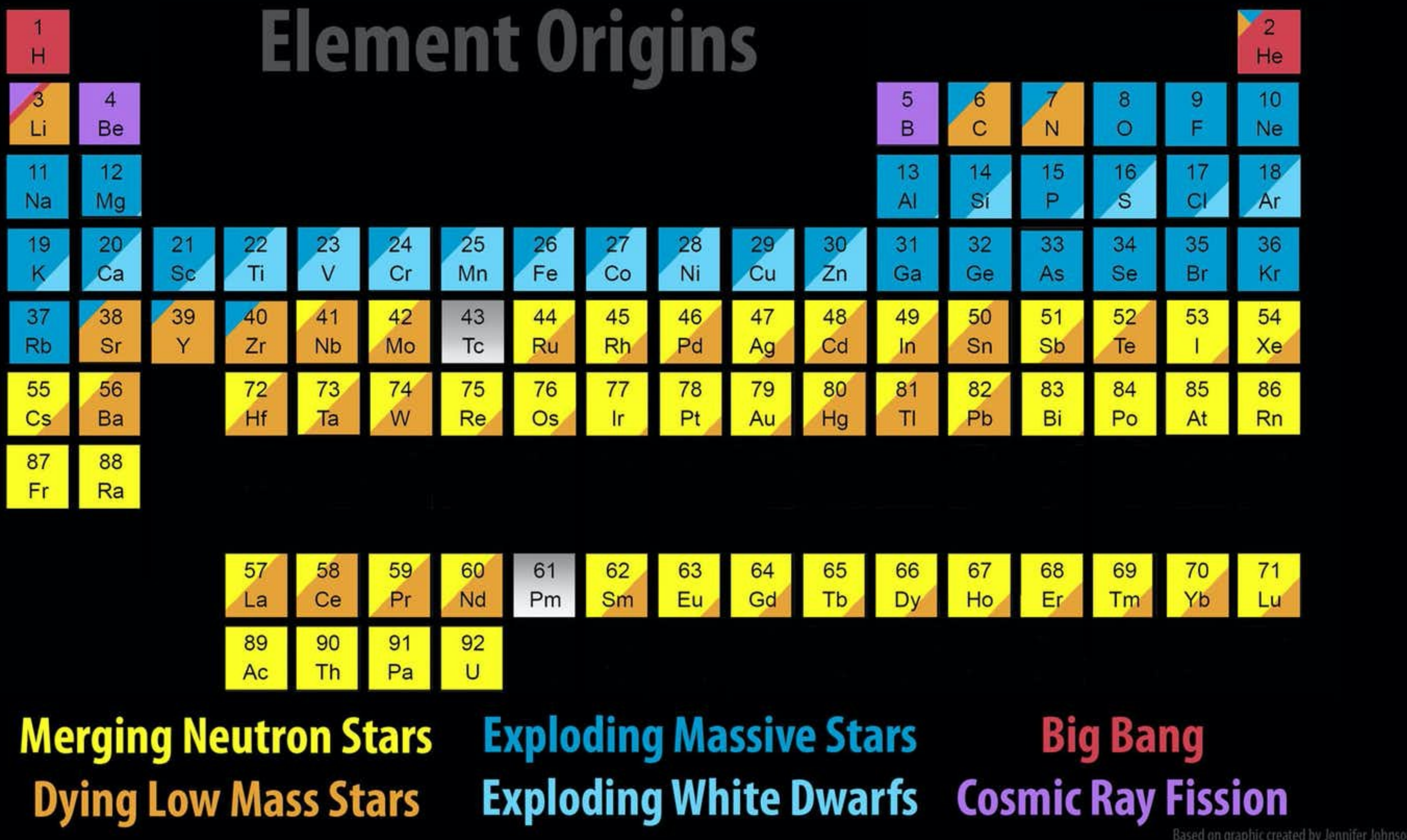
Arcavi+17, Coulter+17, Lipunov+17, Soares-Santos+17, Tanvir+17, Valenti+17, Kasliwal+17,Drout+17, Evans+17, Utsumi+17



The kilonova is much fainter and faster than supernovae.

Knowing the merger times and locations from GW greatly helps to find kilonovae.

A Goal of kilonova science: where elements come from?



In the next decade, we try to answer “which ones are produced in mergers and how much?”

We need more atomic data

- Kilonovae are explosion of heavy elements.
- They are bright in the infrared.
- We don't really know strong lines of heavy elements in the infrared.
- We also need recombination & collision strengths of heavy elements.

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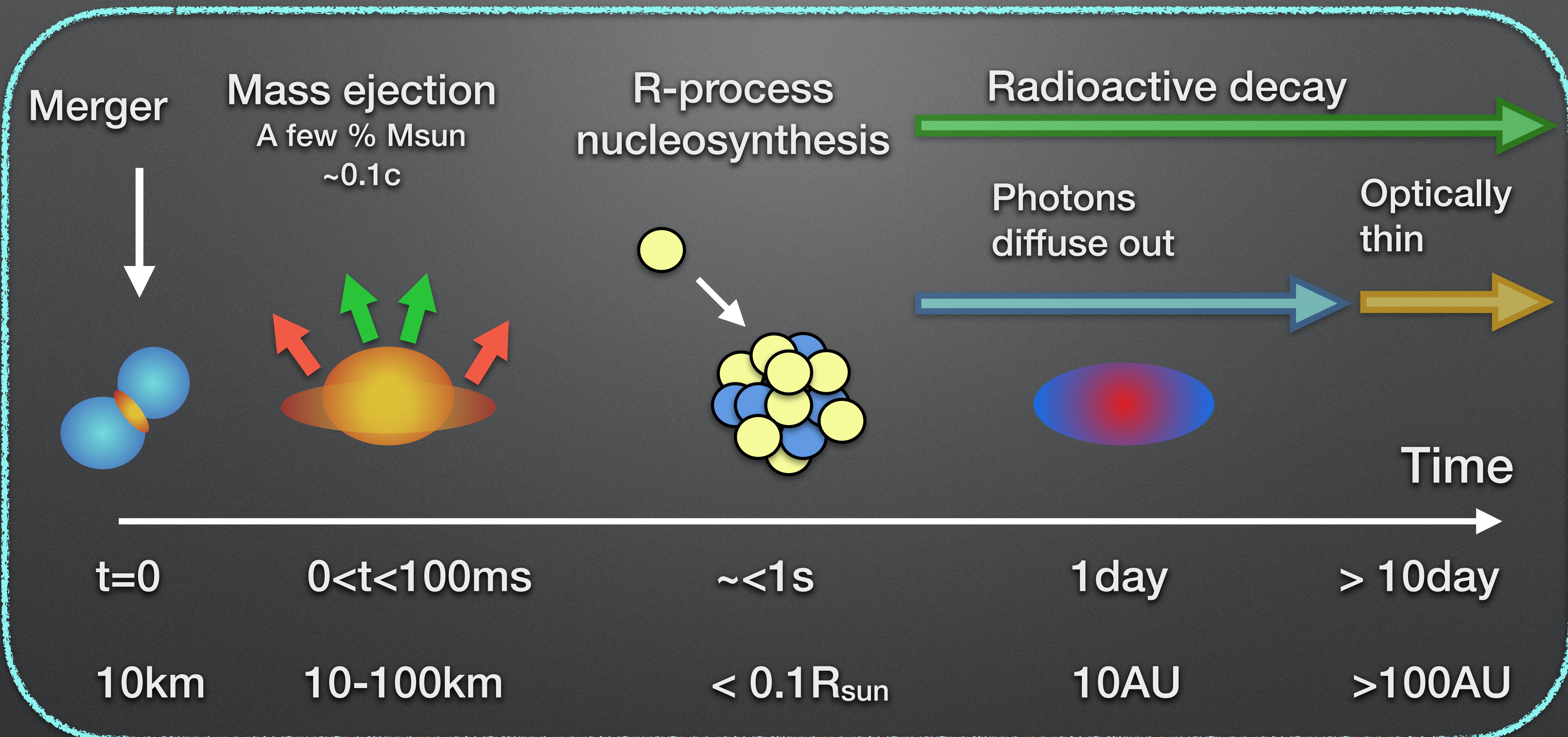
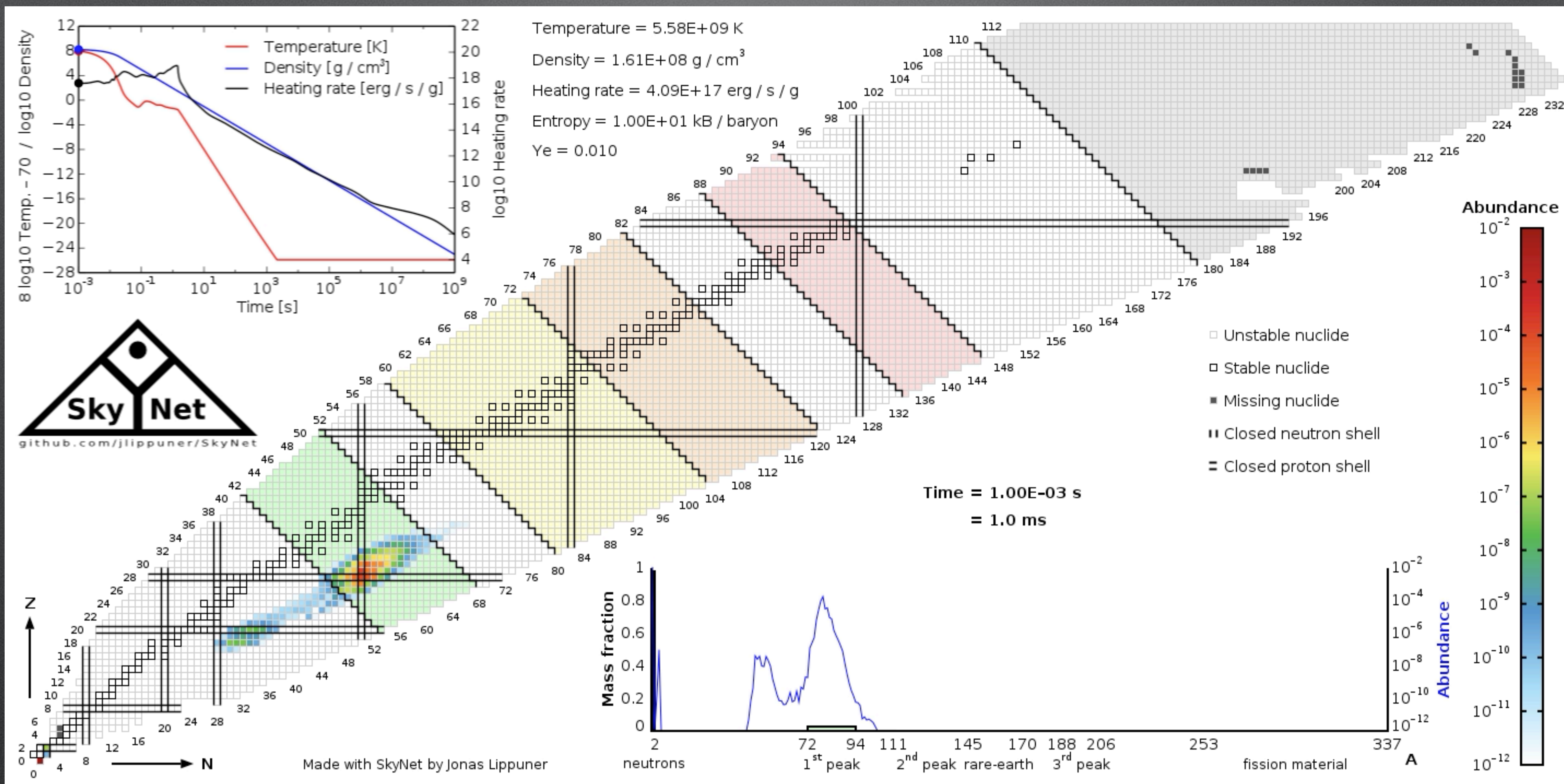
Kilonova

Li & Paczynski 98, Kulkarni 05, Metzger + 10, Barnes & Kasen 13, Tanaka & KH 13

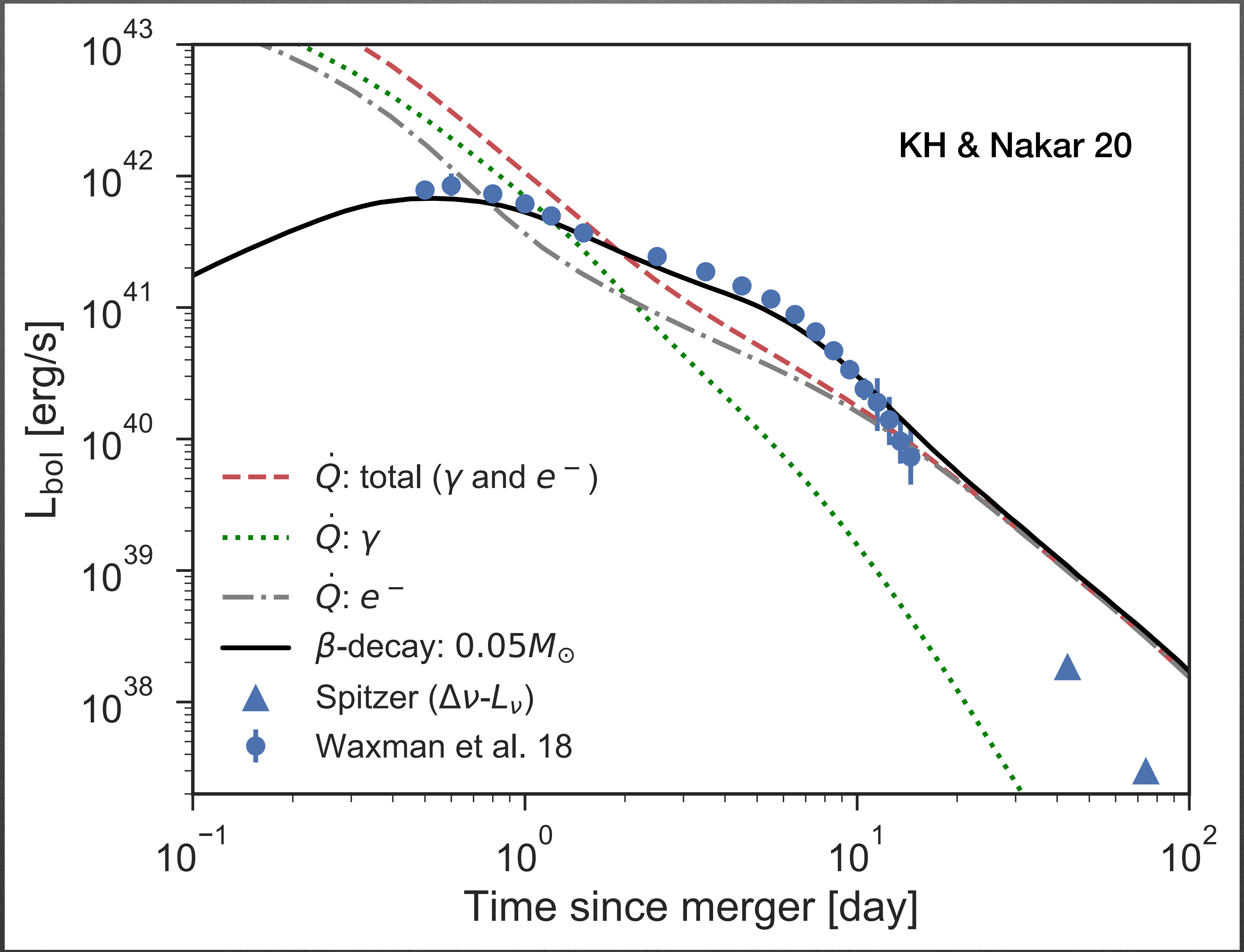


- Powered by radioactivity of r-process nuclei.
- The peak luminosity ~ 10^3-10^4 x nova.
- Spectrum ~ quasi-thermal.
- Atomic lines dominate the opacity (photon absorption).

Rapid neutron capture (R-) process in merger ejecta



The energy budget of the Kilonova in GW170817



- The light curve ~ the β-decay heating rate.
- Ejecta mass: ~ 0.05Msun.
- The photospheric velocity: ~0.1-0.3c.
- The photospheric temperature: T=5000K -> 2000K.

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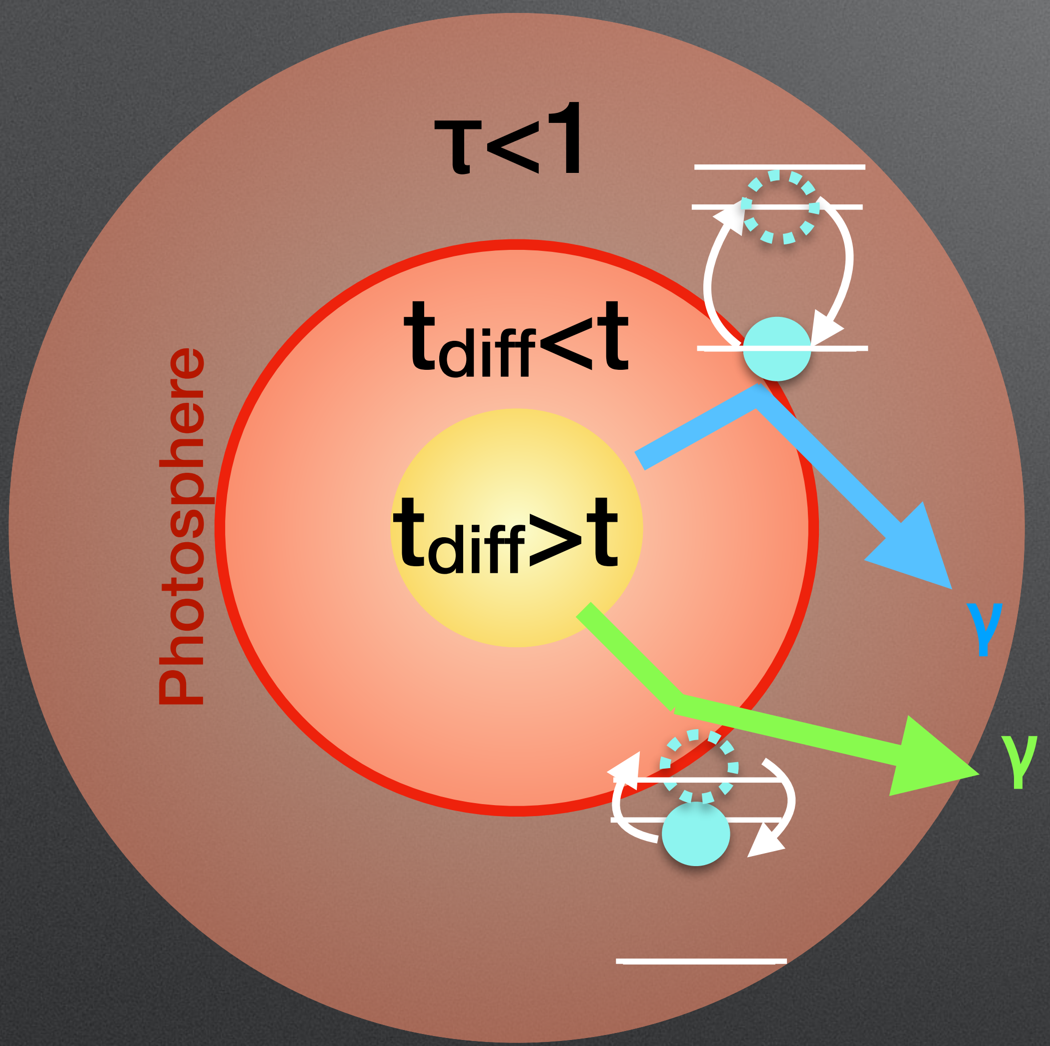
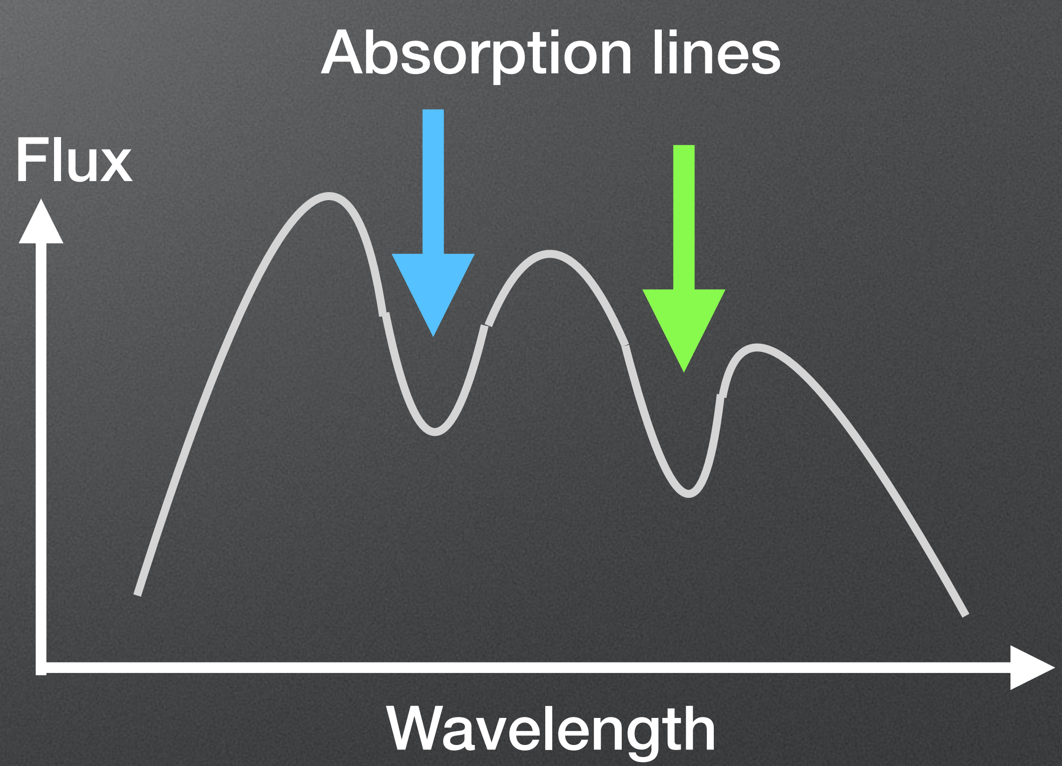
Early Phase of kilonvoa

- Photospheric phase

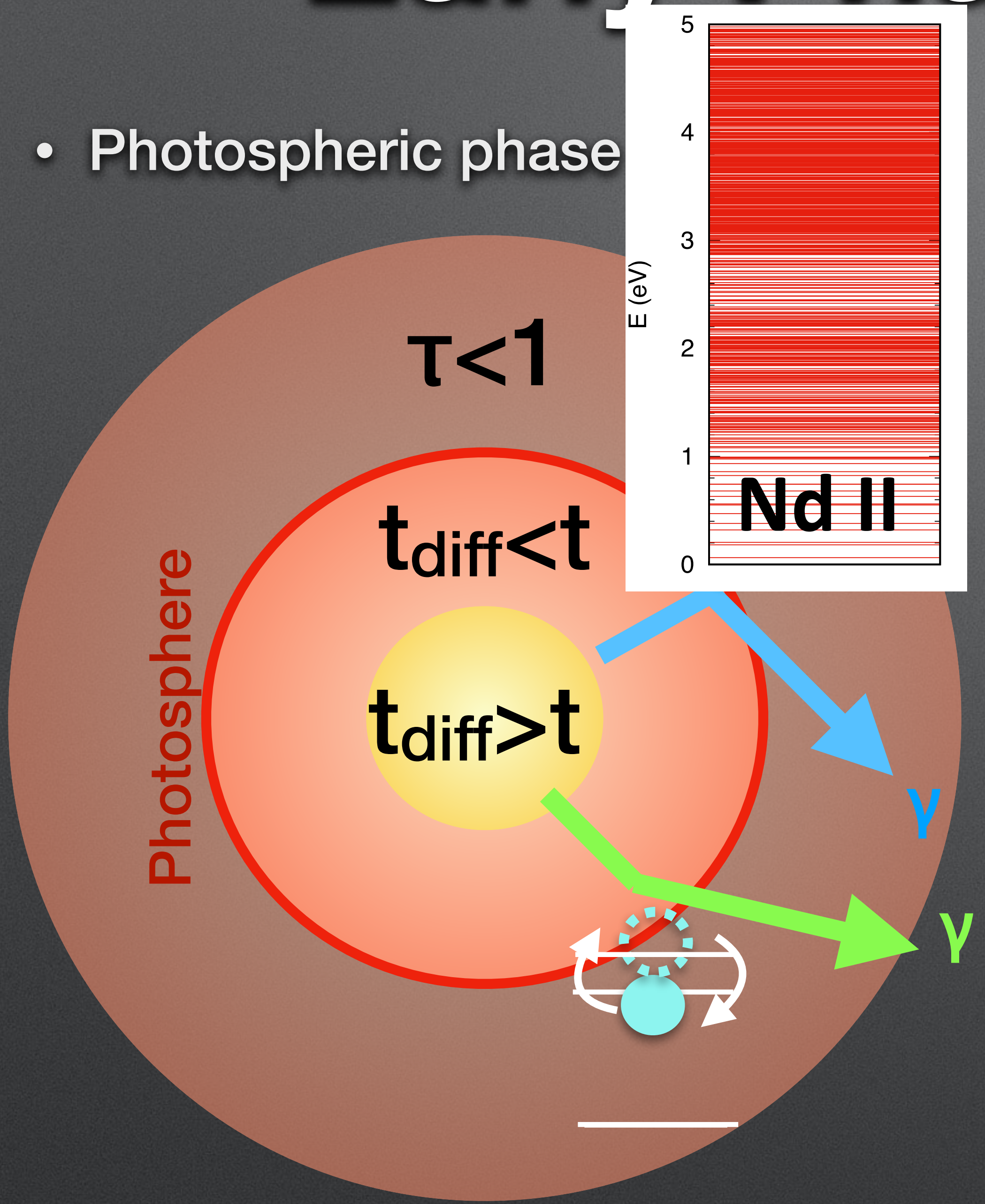


Kilonova ejecta



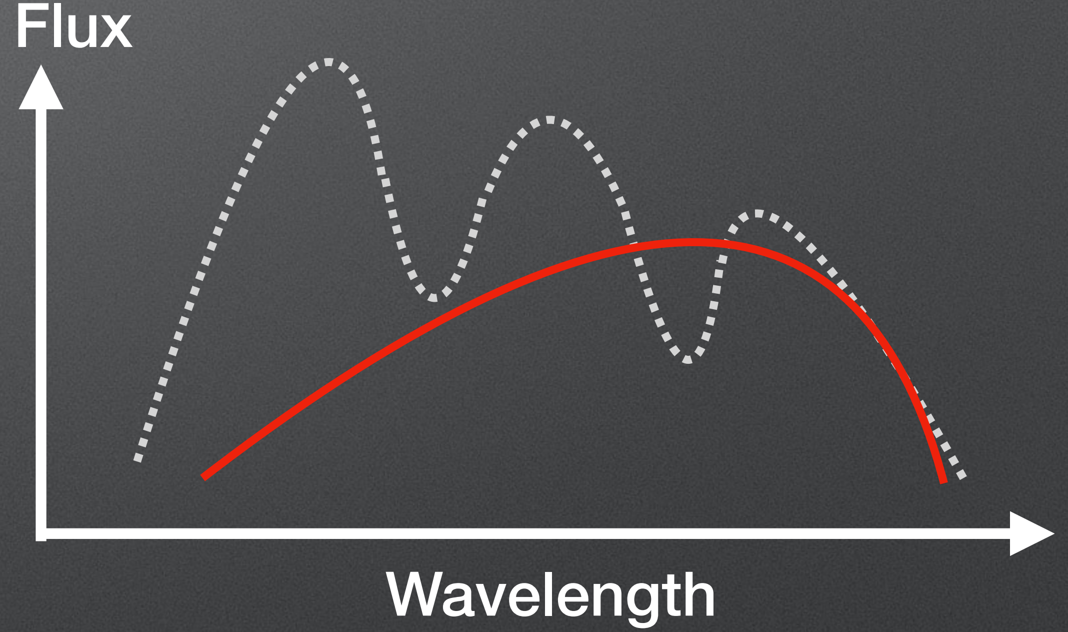
Early Phase of kilonvoa

- Photospheric phase



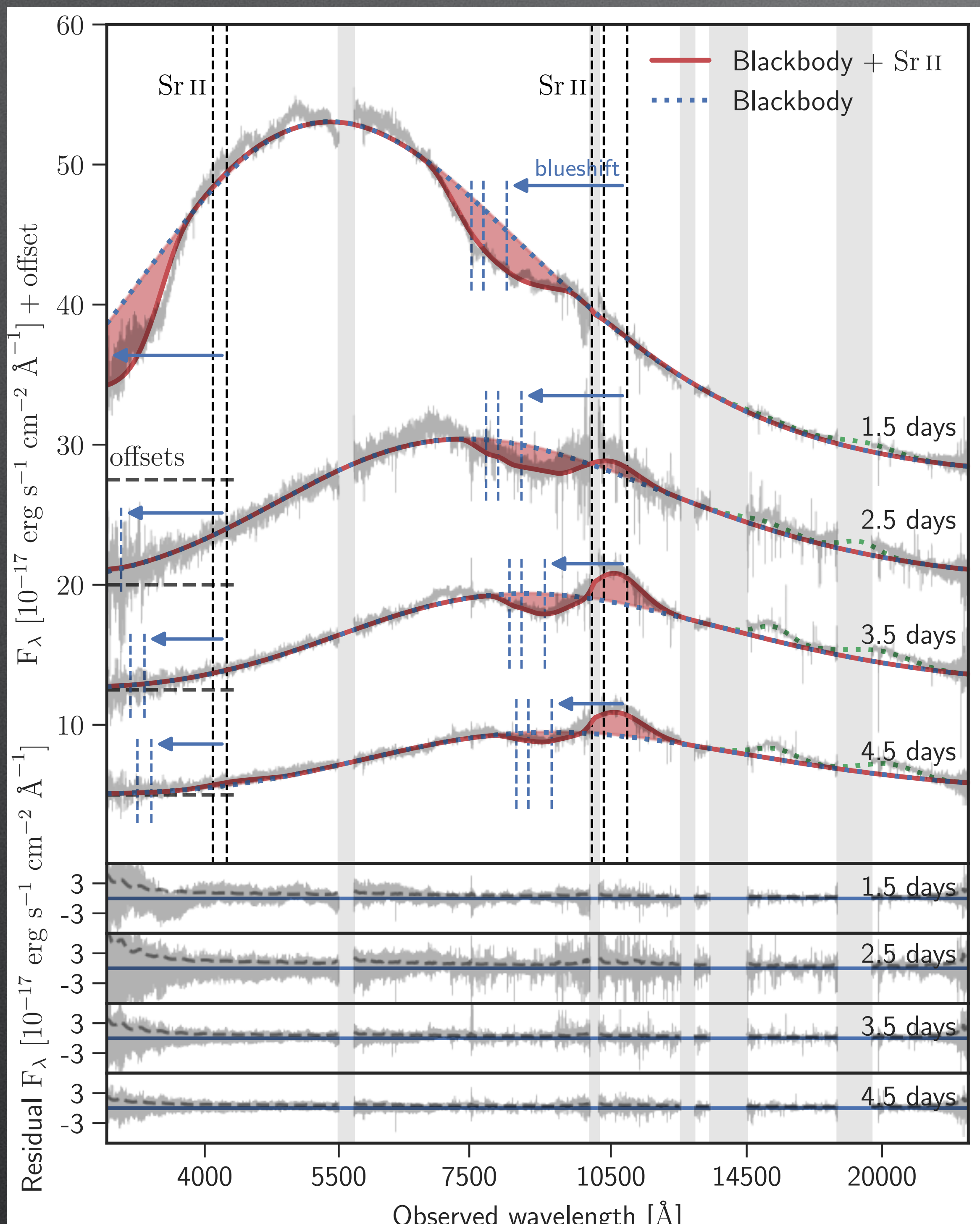
Kilonova ejecta

Lanthanides convert optical photons to IR photons.



- Lanthanides significantly enhance the opacity in the optical-IR (e.g., Kasen+13, Tanaka & KH 13)

Spectrum of the kilonova GW170817



Watson+19, see also Pian +17

Optical

near-IR

Observational facts

- The early emission (< 3 days) is characterized well by a **blackbody** with an absorption line at 8000Å.
- The late emission (>3 days) peaks around near IR.

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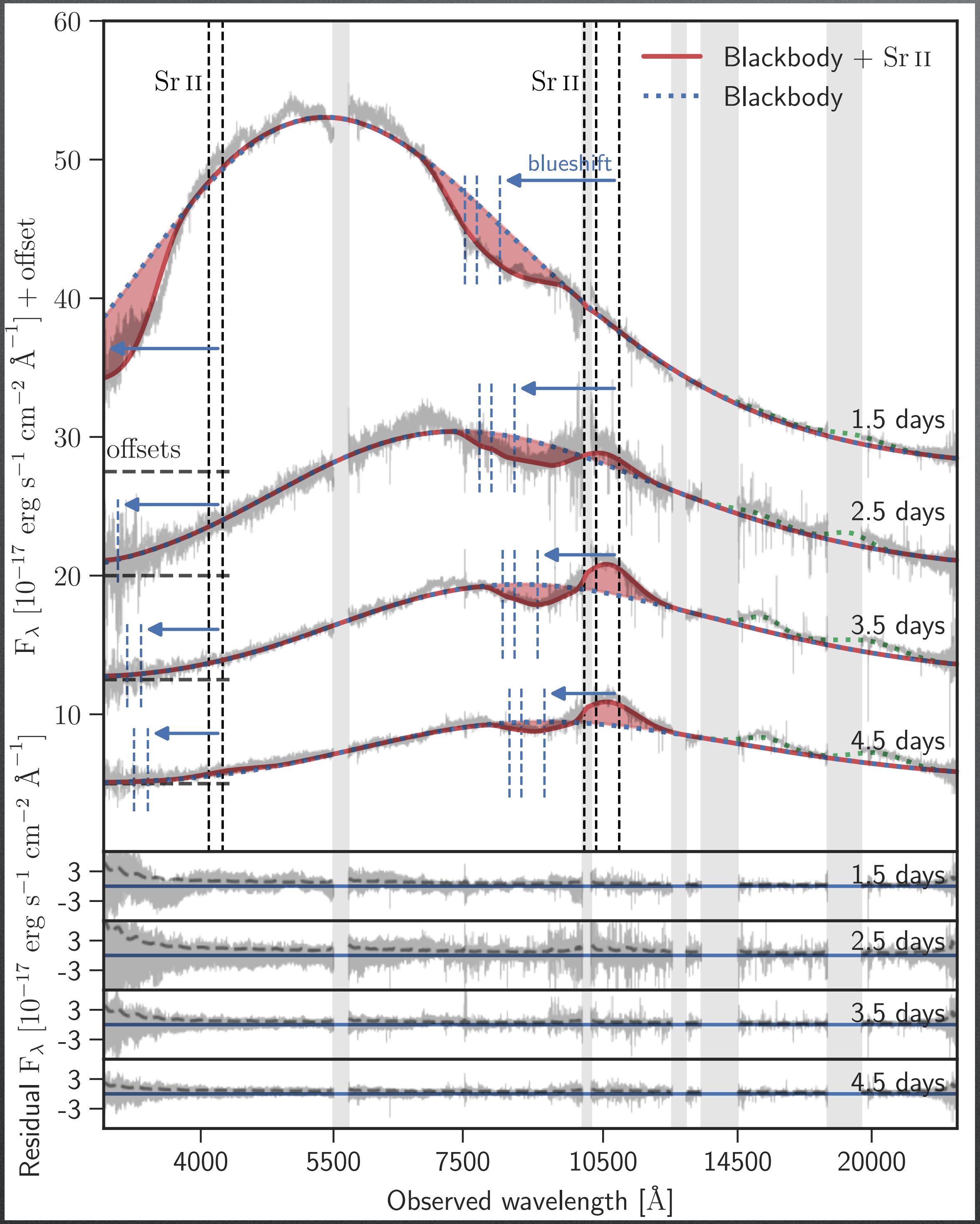
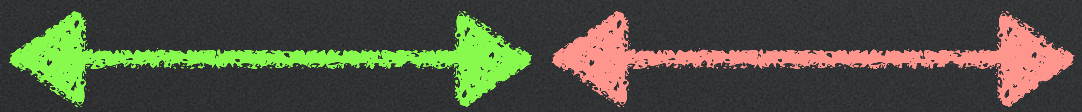
Watson+19, see also Pian +17





Optical

near-IR

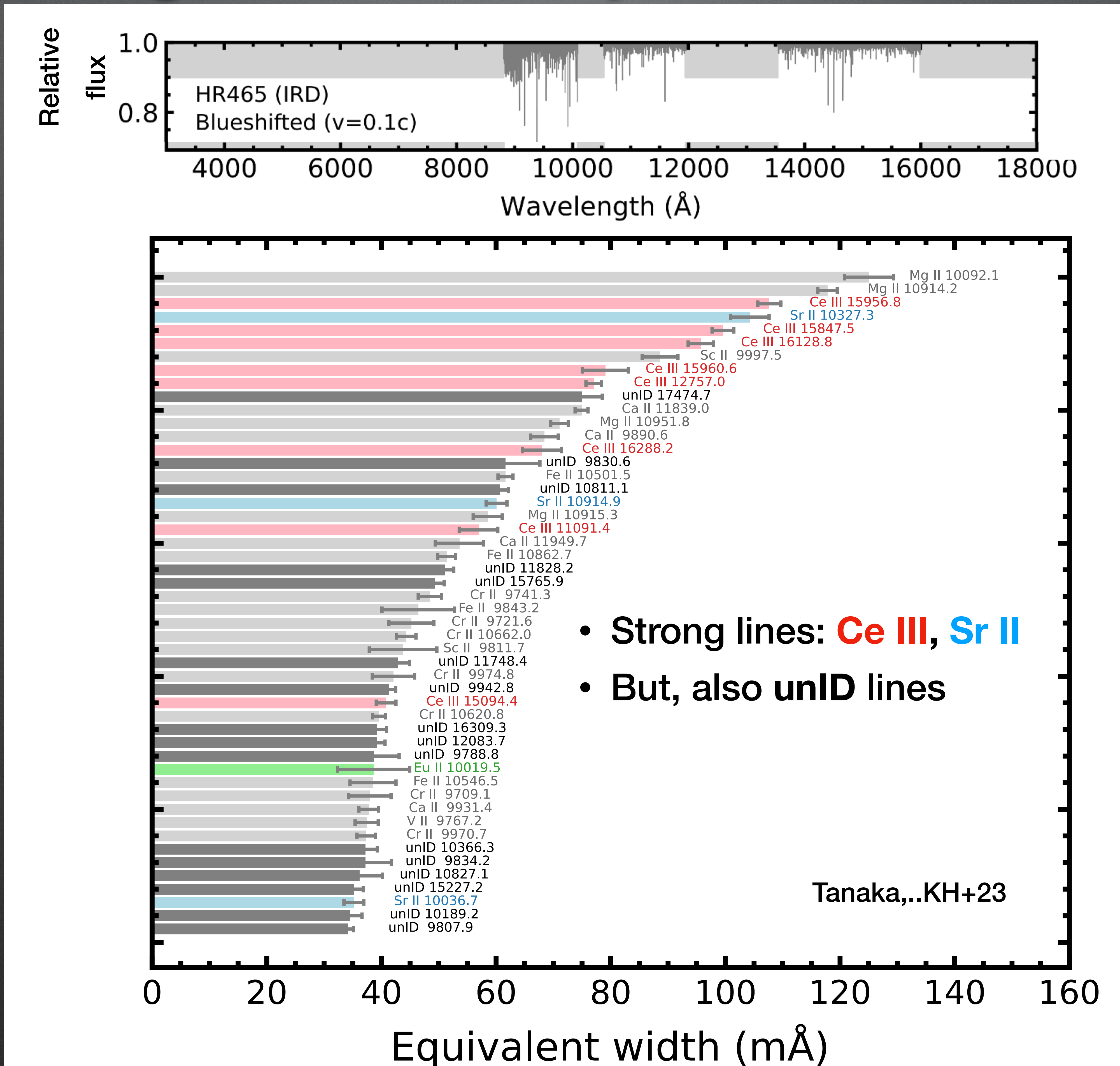
Observational facts

- The early emission (< 3 days) is characterized well by a **blackbody** with an absorption line at 8000Å.
- The late emission (>3 days) peaks around near IR.

Unsolved questions

- How is the blue blackbody emission produced? Do we need lanthanide free ejecta?
- Does the near IR emission > 3 days require lanthanide-rich ejecta?
- Is the line feature at 8000Å Sr II or He I? (e.g. Watson+19, Tarumi, KH et al 23)
- How about the other line feature?

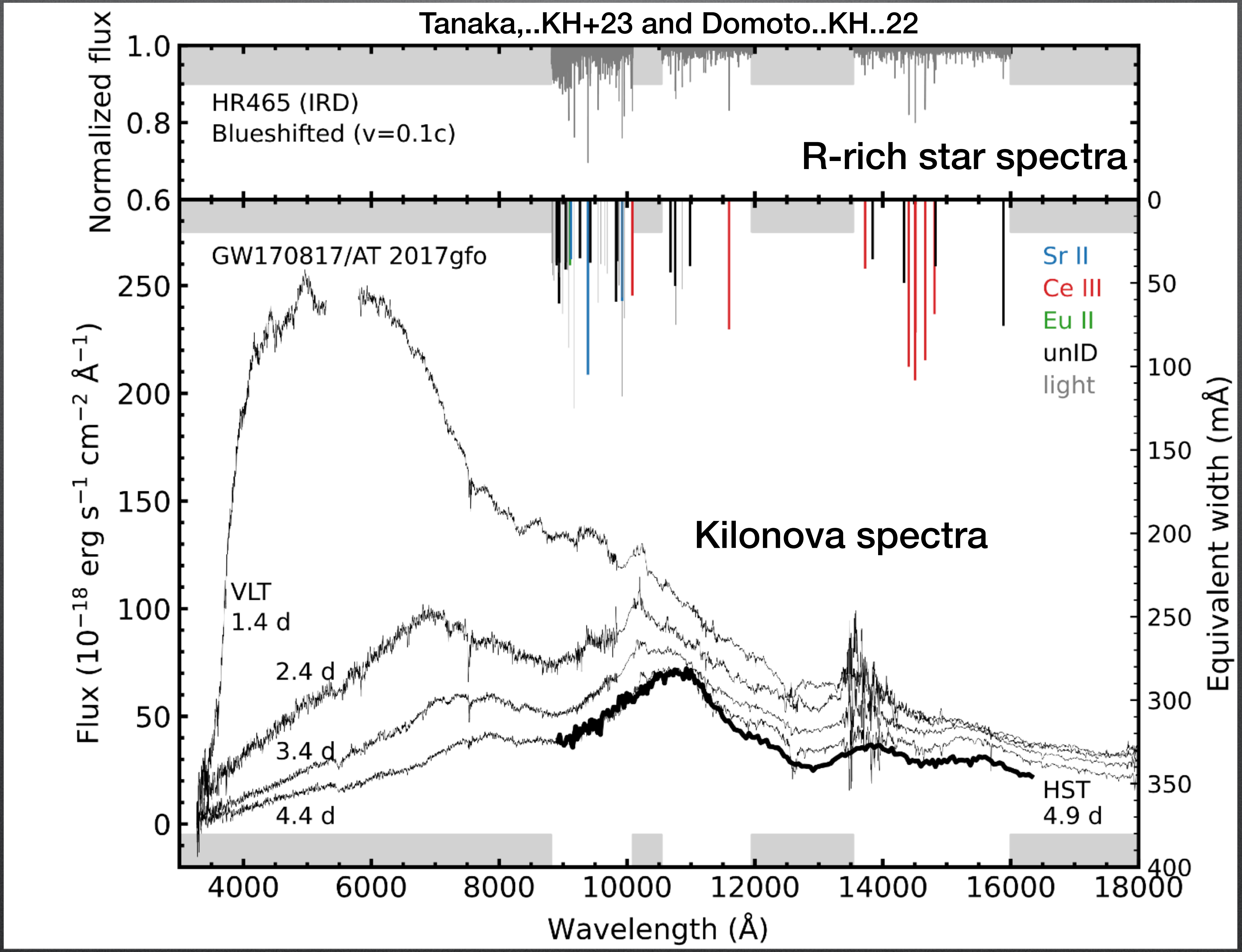
Strong IR lines in r-process rich star



- Strong lines: Ce III, Sr II
- But, also unID lines

Tanaka,..KH+23

Kilonova vs R-rich star



- The structure around 1.5 μm is likely due to Ce III.

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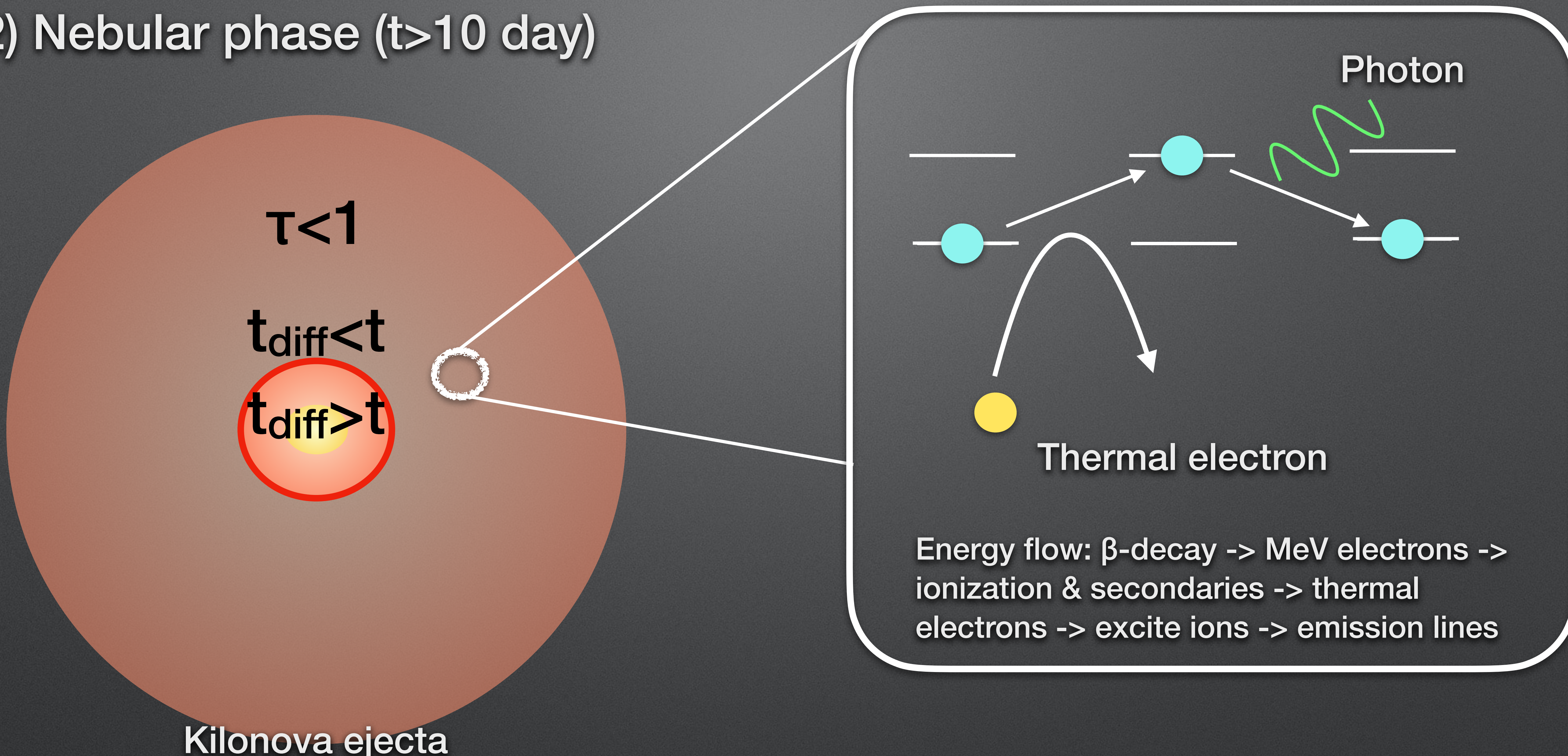
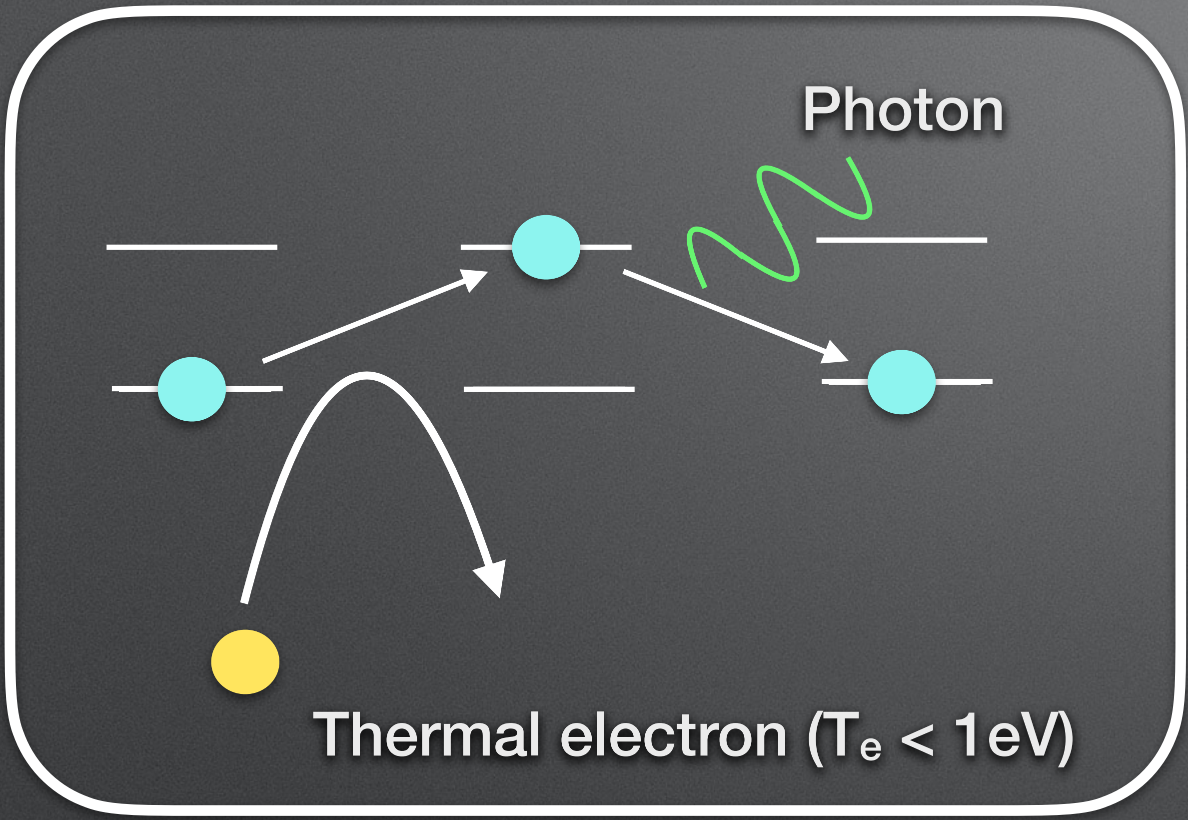
Kilonova Nebular Phase

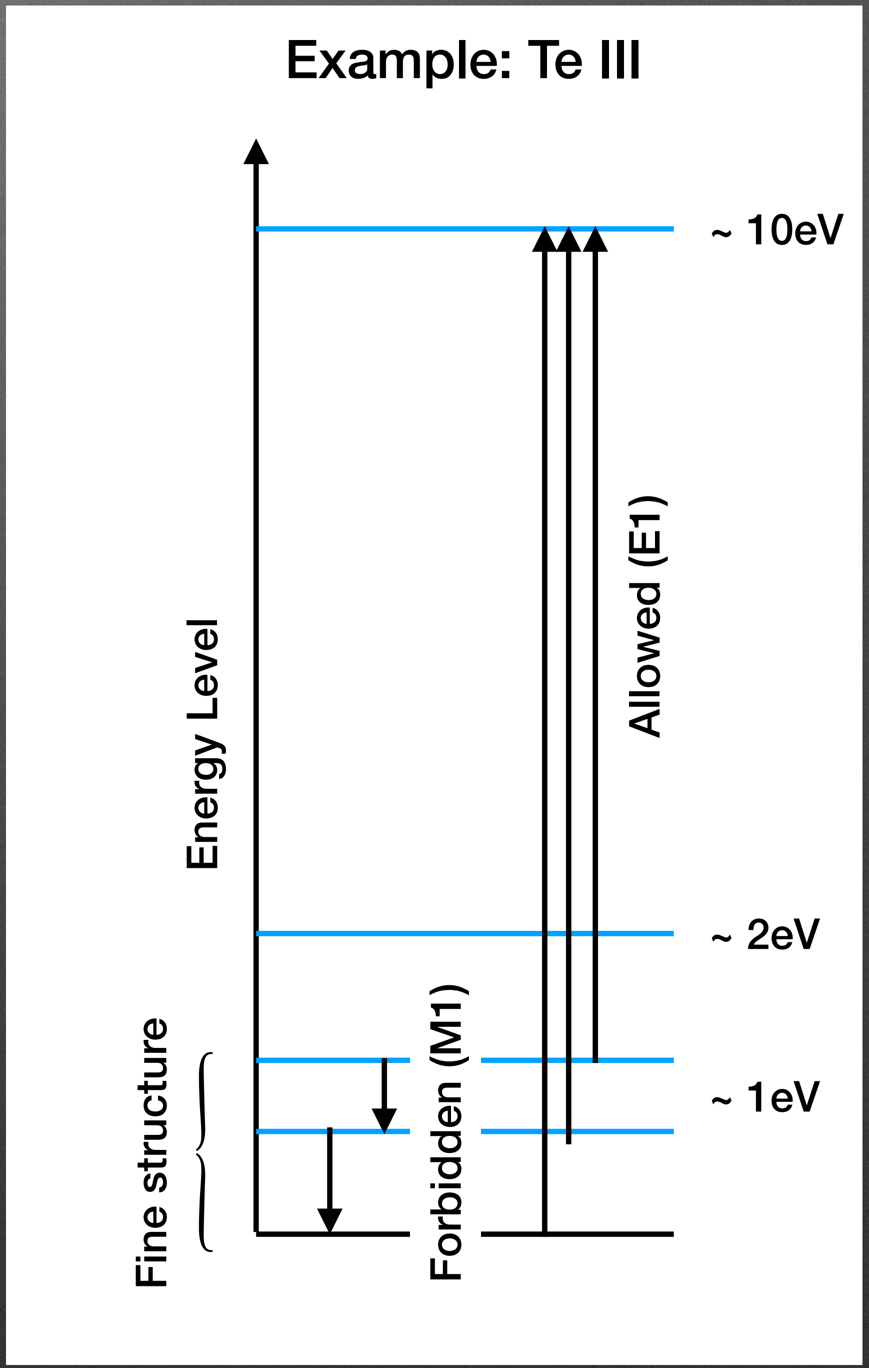
2) Nebular phase (t>10 day)



- Photons escape without absorption, i.e., tau<1.
- Kilonova radiation may be dominated by emission lines.
- Although it is fainter, good chance to identify more elements.

Importance of Fine-structure lines in kilonova nebula

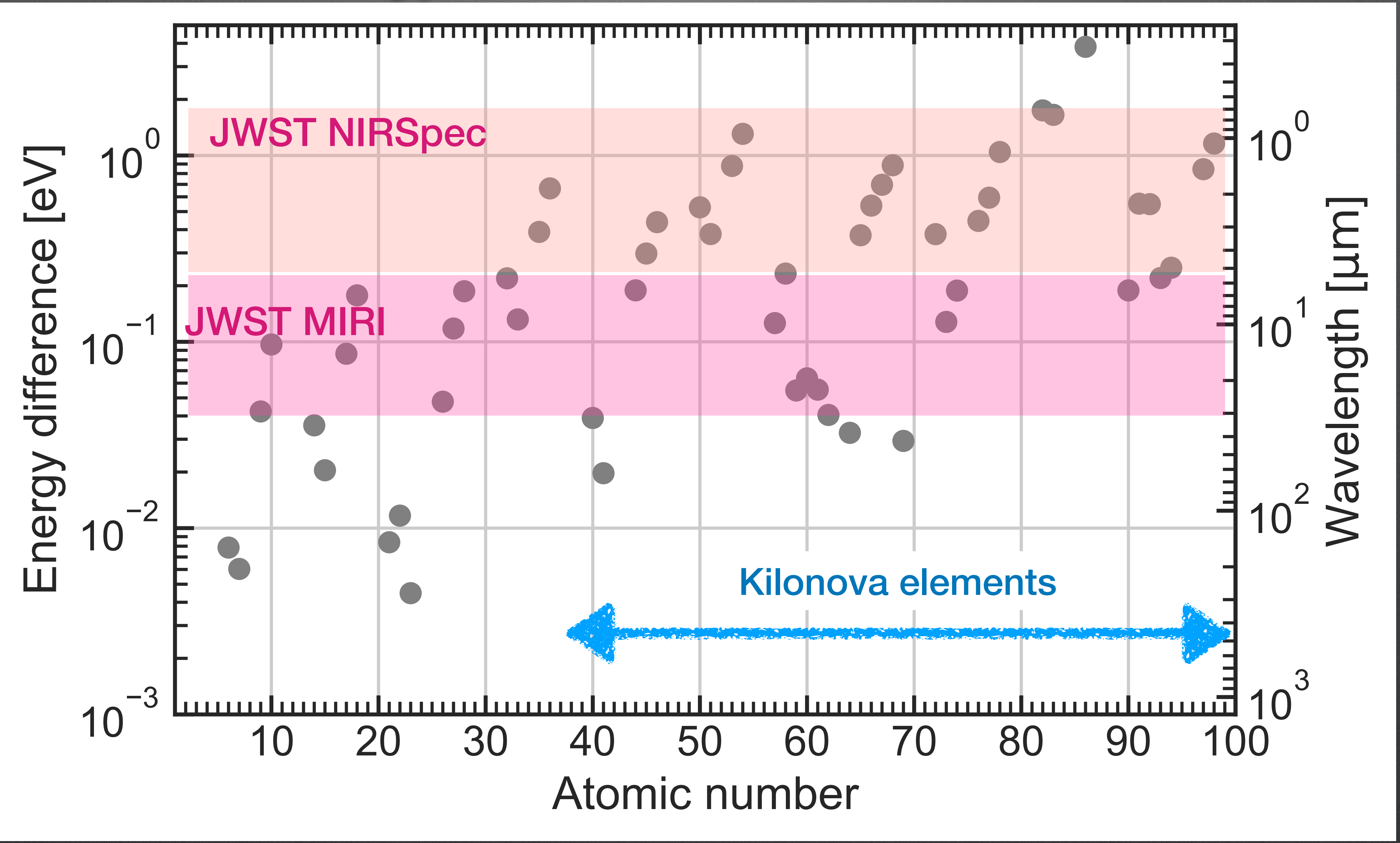




- Fine structure levels are predominantly excited.
- Lower-lying fine structure levels decay through forbidden lines (M1 lines).
- These lines are in the JWST band.

Fine-structure lines in kilonova nebula

Singly ionized, the first fine structure level

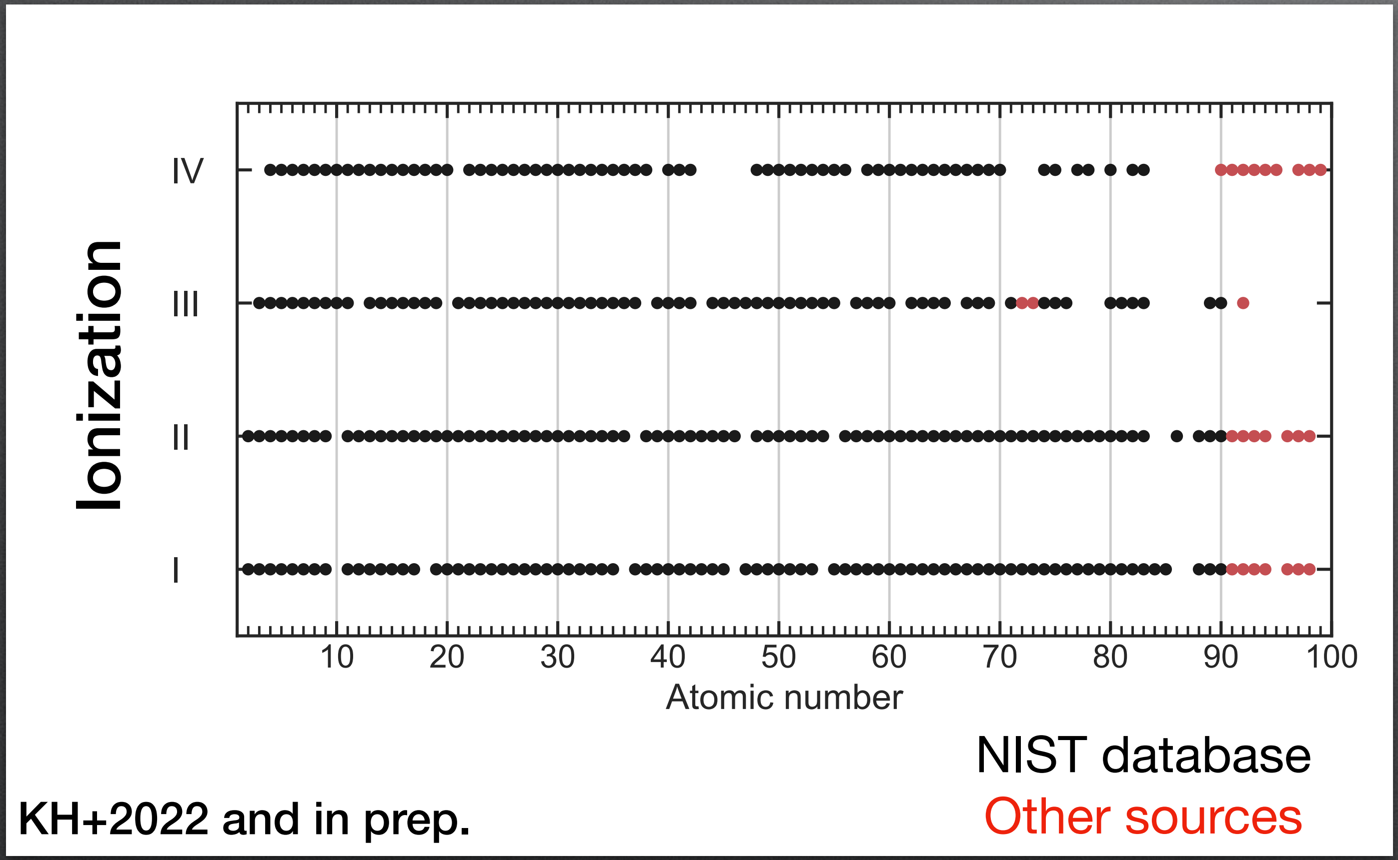


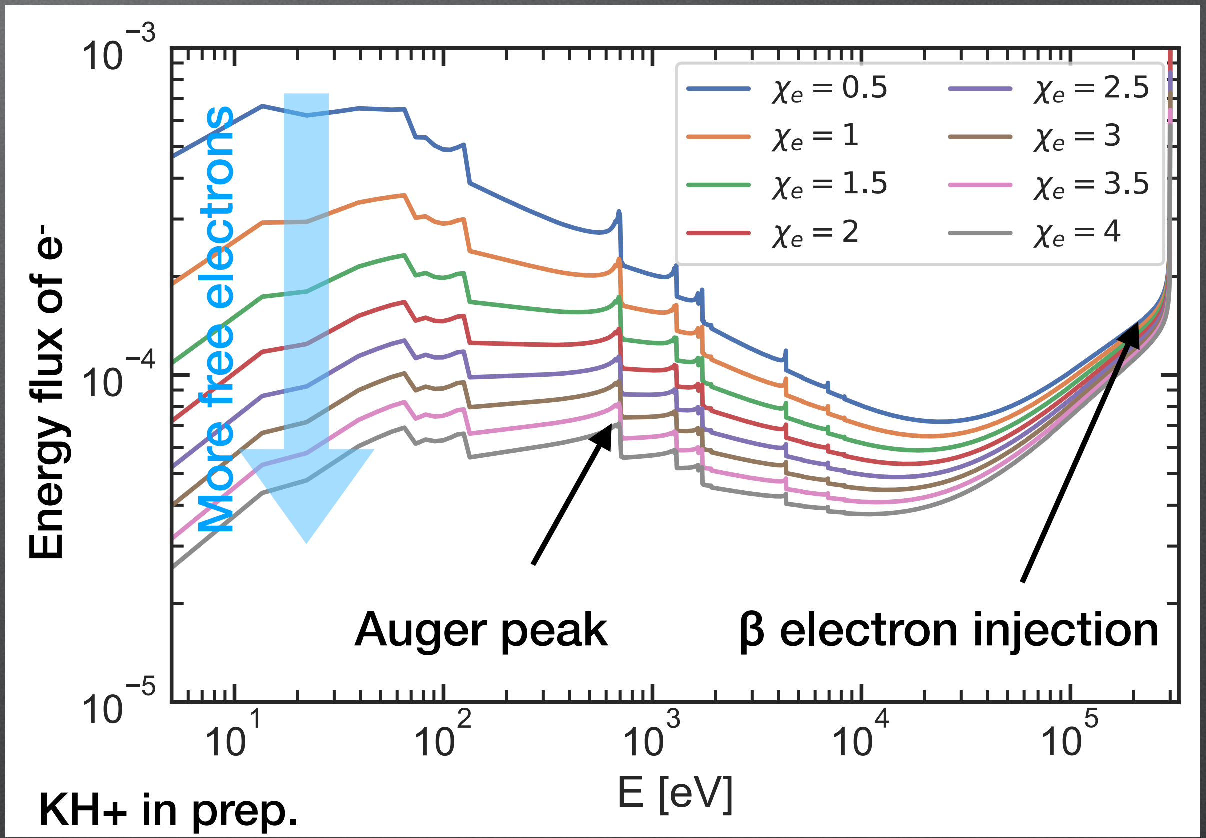
- Heavy elements have fine-structure lines at ~ 1 - 30 μm (JWST band).
- M1 lines can carry away a significant fraction of radioactive heat.

Kilonova nebula modeling

- M1 line list
  - Energy levels from NIST and Blaise & Wyart 1992 for actinides.
  - LS coupling with the single configuration approximation.

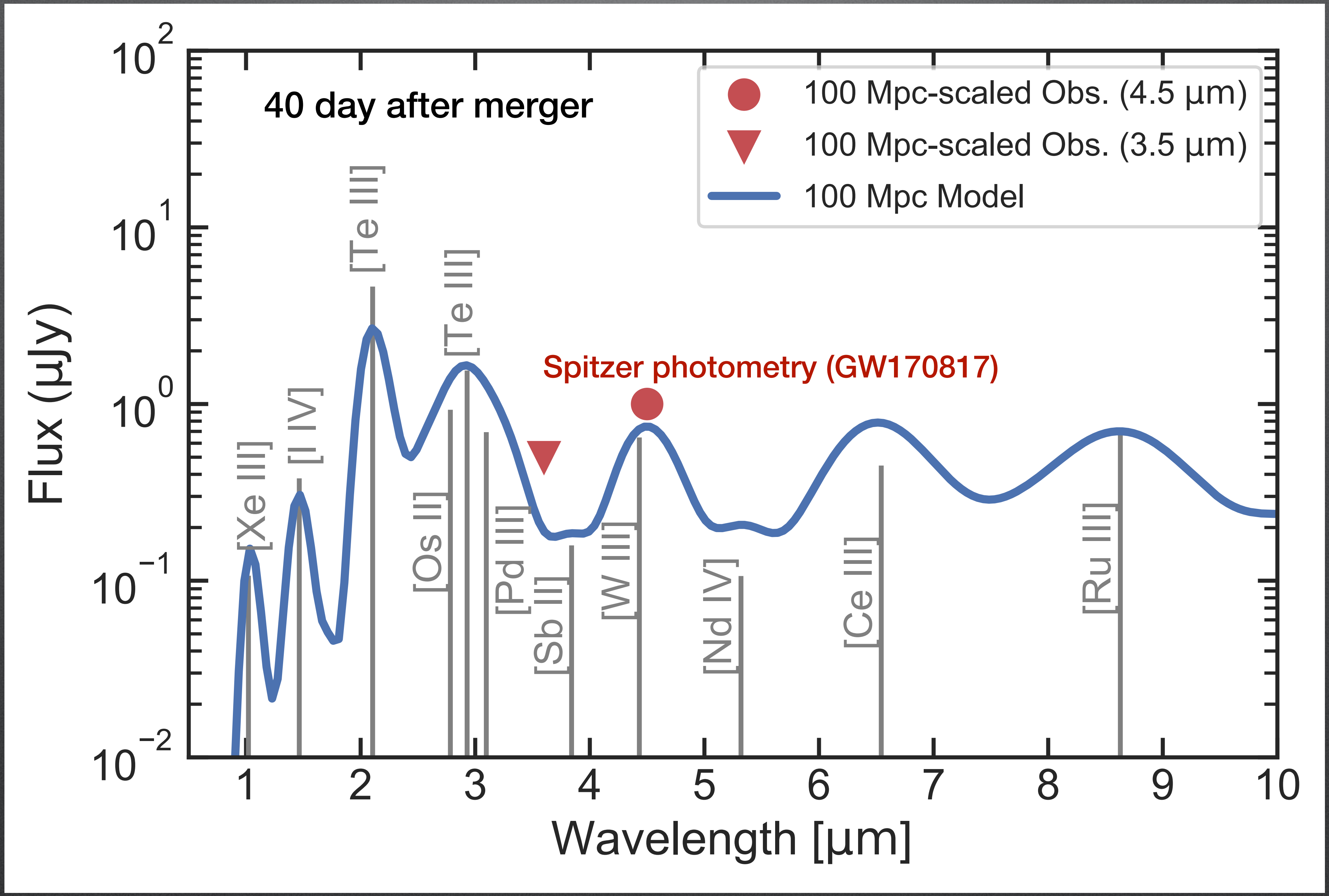
- Non-thermal electron and ionization solver





- We are developing line lists for heavy elements and ionization solver.

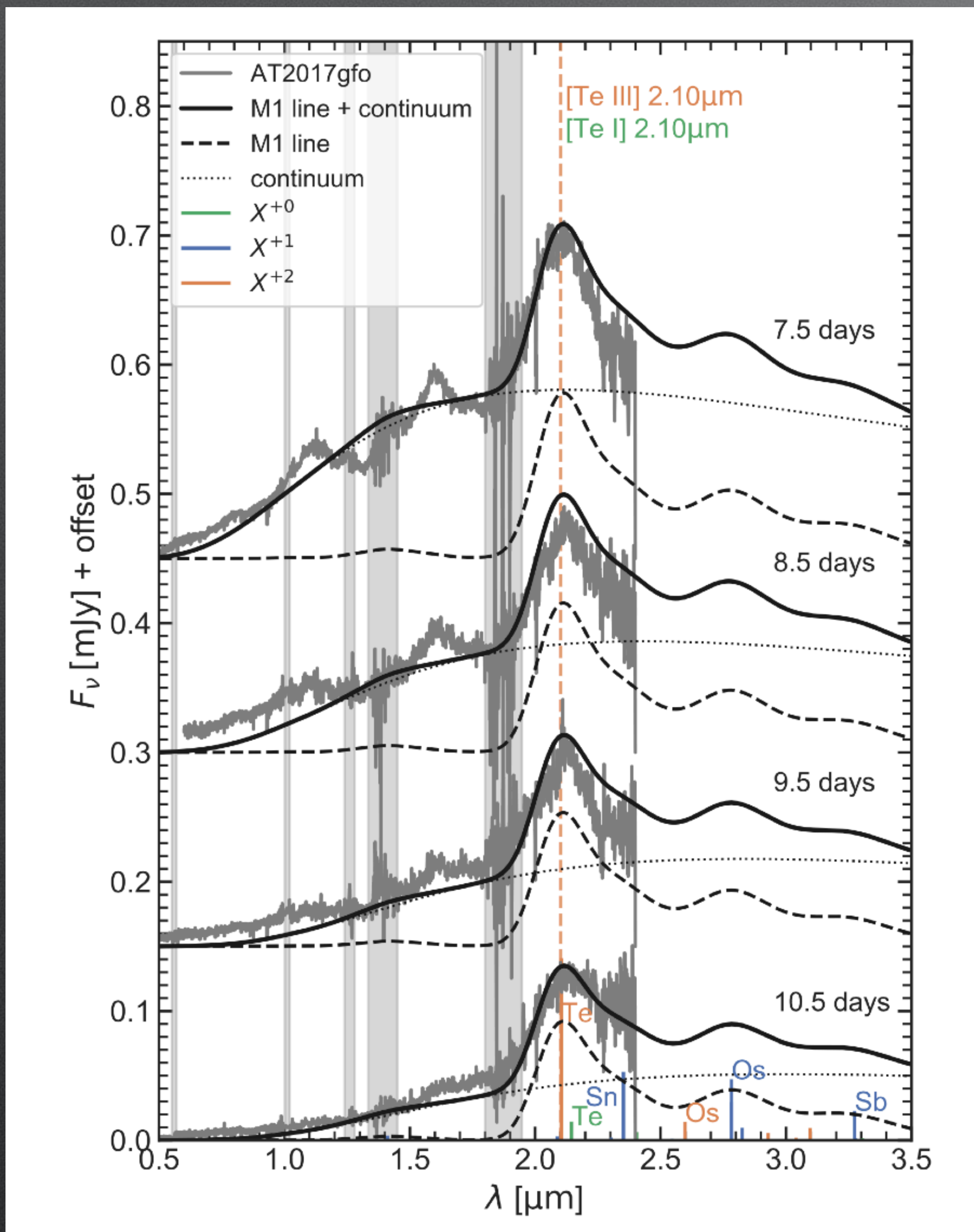
Kilonova M1 line spectrum: 40 days



- Synthetic nebular M1 spectra with the accurate line location.
- JWST may be able to resolve the emission lines for kilonovae.

Kilonova late spectrum: 10 days

Kilonova in GW170817 (KH+23)



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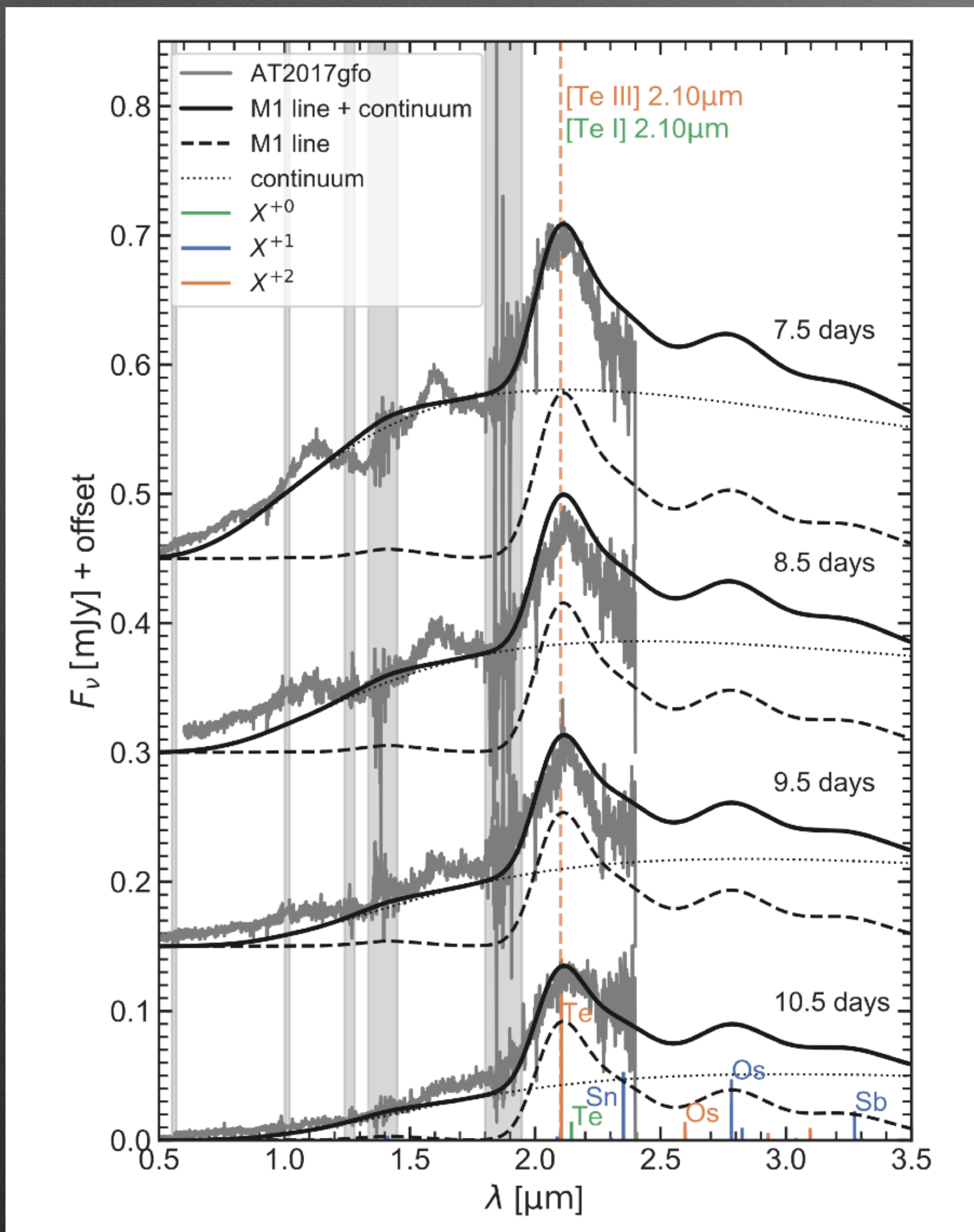
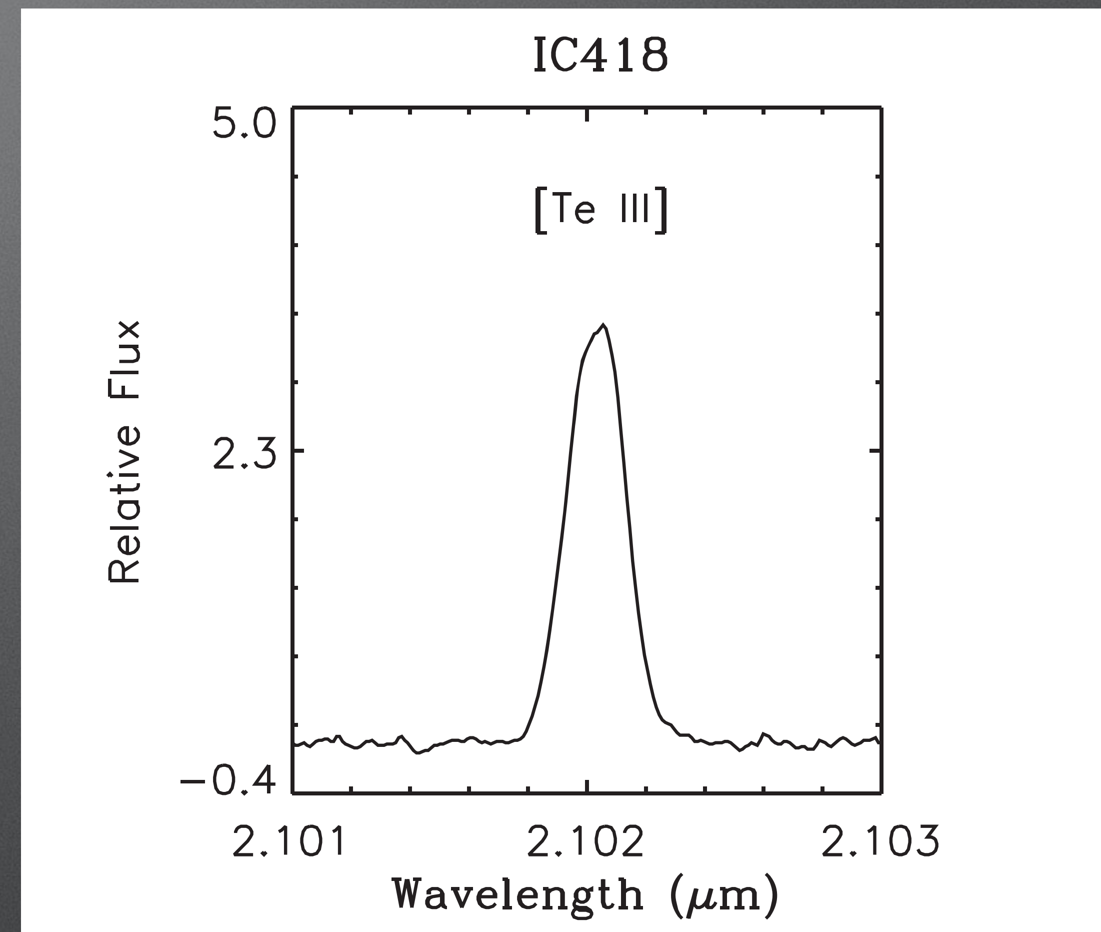


Planetary Nebula (s-process, Madonna+18)



- The peak at 2.1µm may be Te III.
- It has been detected in planetary nebulae (Madonna+18).

Kilonova late spectrum: 10 days

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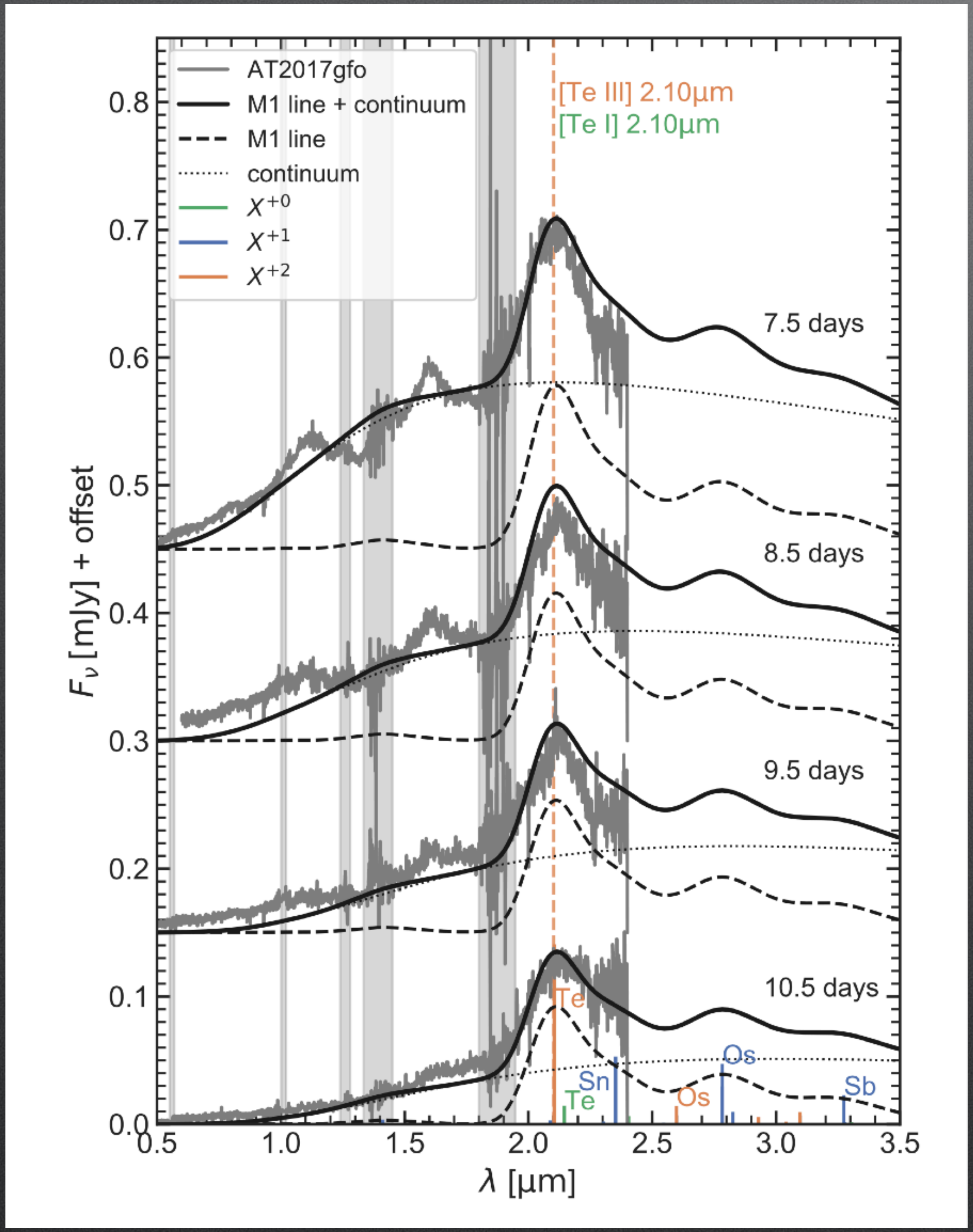
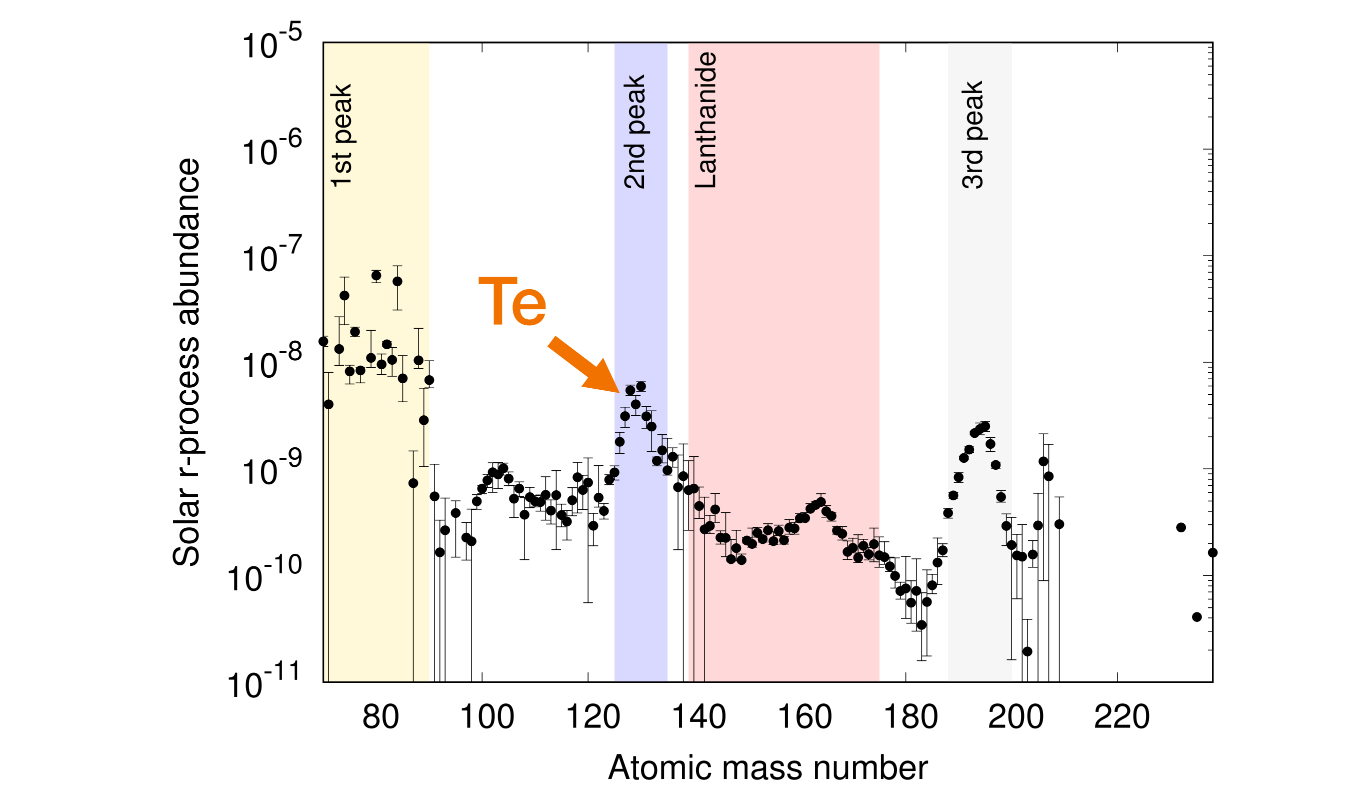
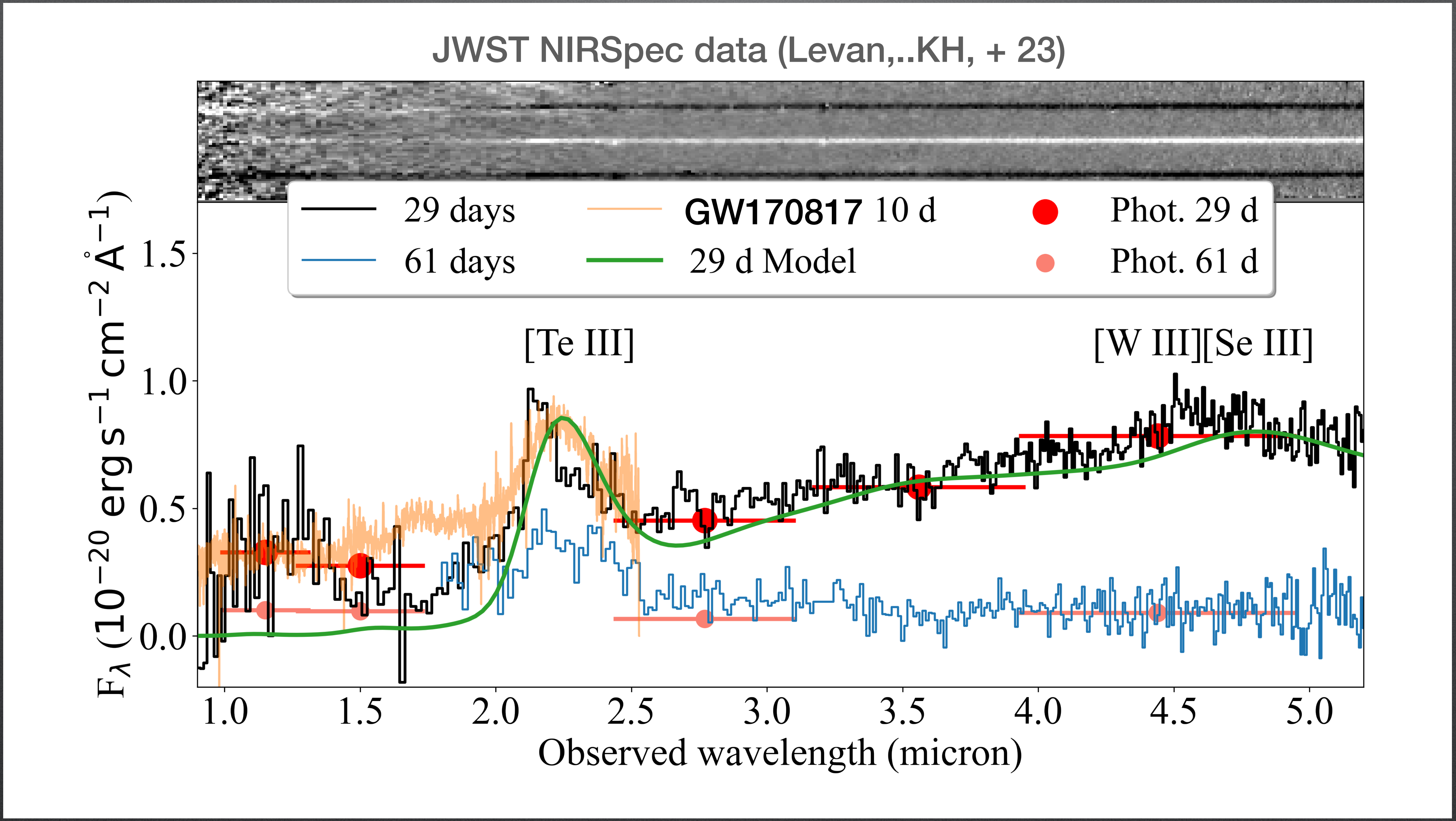


Solar r-process abundance (KH+18)



- The peak at 2.1μm may be Te III.
- It has been detected in planetary nebulae (Madonna+18).
- Te is among the most abundant r-process elements.

Preliminary News: A 'kilonova' in long GRB 230307A



- The light curve and spectrum resemble the kilonova GW170817.
- An emission line at 2.1 μm -> [Te III]?
- An extremely red continuum -> lanthanides?

We need more atomic data

- Astrophysicists will do:
  - Try to find kilonovae (1 yr^{-1}?) and obtain more data.
    - not easy because they are faint, rapidly fade, and infrared.
  - Try to interpret the spectral structure by improving the models.
    - also not easy because lines are broaden, lack of atomic data, and incompleteness of the models.

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        - also not easy because lines are broaden, lack of atomic data, and incompleteness of the models.
- What astrophysicists need from atomic physicists:
    - Oscillator strengths of heavy elements in the infrared.
        - Ce III and La III lines are most prominent in kilonovae.
    - Atomic data for plasma modelings.
        - recombination and collision rates (Te, W, Se seem important).

Summary

- Kilonova is an electromagnetic counterpart of neutron star mergers.
- The kilonova in GW170817 evolves quickly from 5000K to 2000K.
- Line id is challenging because of large Doppler broadening and blending.
- The strongest absorption is around 0.8μm (Sr II or He I). A weaker feature around 1.5μm (Ce III).
- A strong emission line at 2.1μm in late times (>10 day), likely [Te III] 2.1μm.
- A kilonova seems to follow a long GRB 230307A. James Webb observation points to a strong emission at 2.1μm, [Te III] 2.1μm?
- We need oscillator strengths, collision strengths, recombination rate for better modelings.