Lecture at Hongo in May

- Jim Fuller (Caltech): Stellar evolution & Seismology

  - 5/20, 21, 23

- Dan Kasen (Berkeley): Transient phenomena, Radiation transfer

  - 5/27, 28, 29

Let me know if you are interesting in attending the lectures.

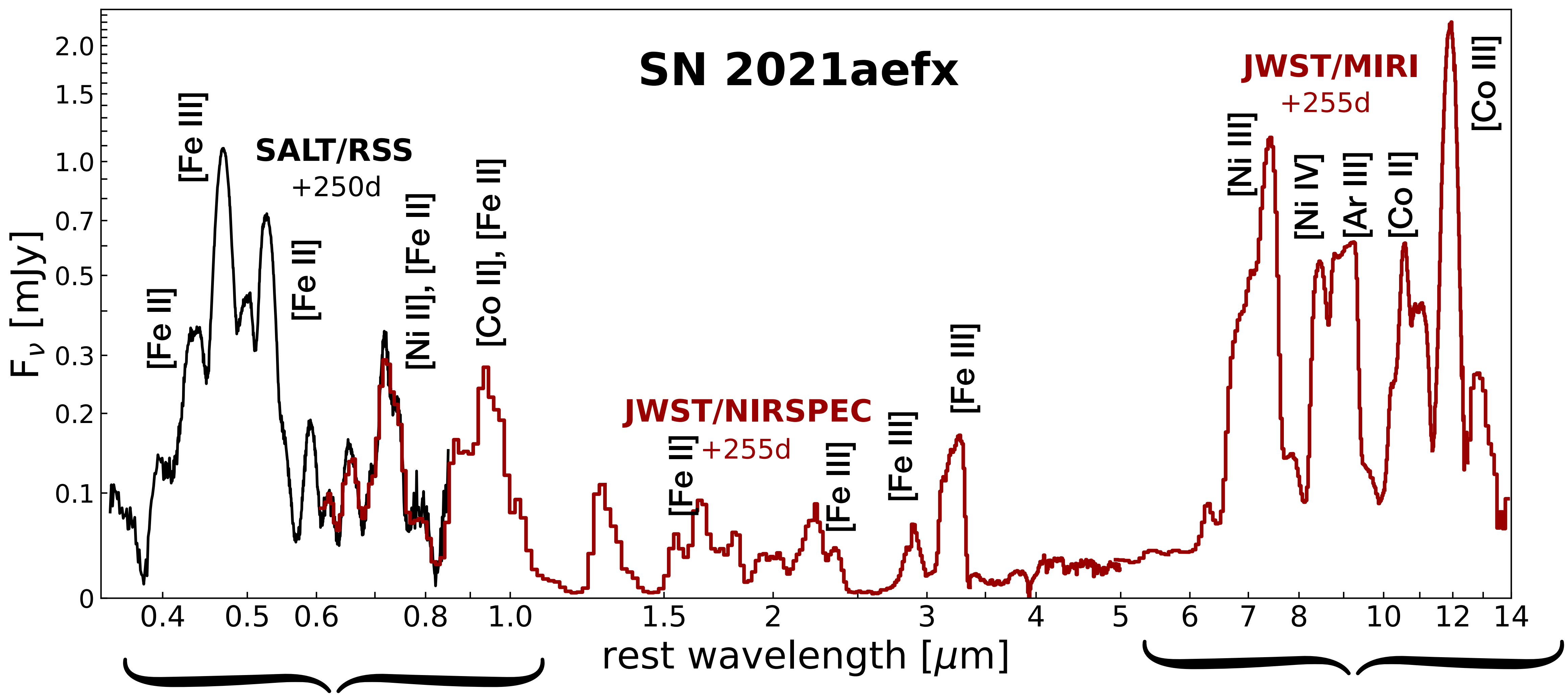
Nebular emission of r-process elements

Kenta Hotokezaka
(University of Tokyo)

Collaboration with M. Tanaka (Tohoku), D. Kato (NIFS),
G. Gaigalas (Vilnius), G. Ricigliano, A. Arcones (TU Darmstadt)

Nebular Emission of SN Ia at 250 day

SN 2021aefx (Kwok+23, see also DerKacy+23)



Optical Iron Forest

(Electric quadrupole: E2 & M1)

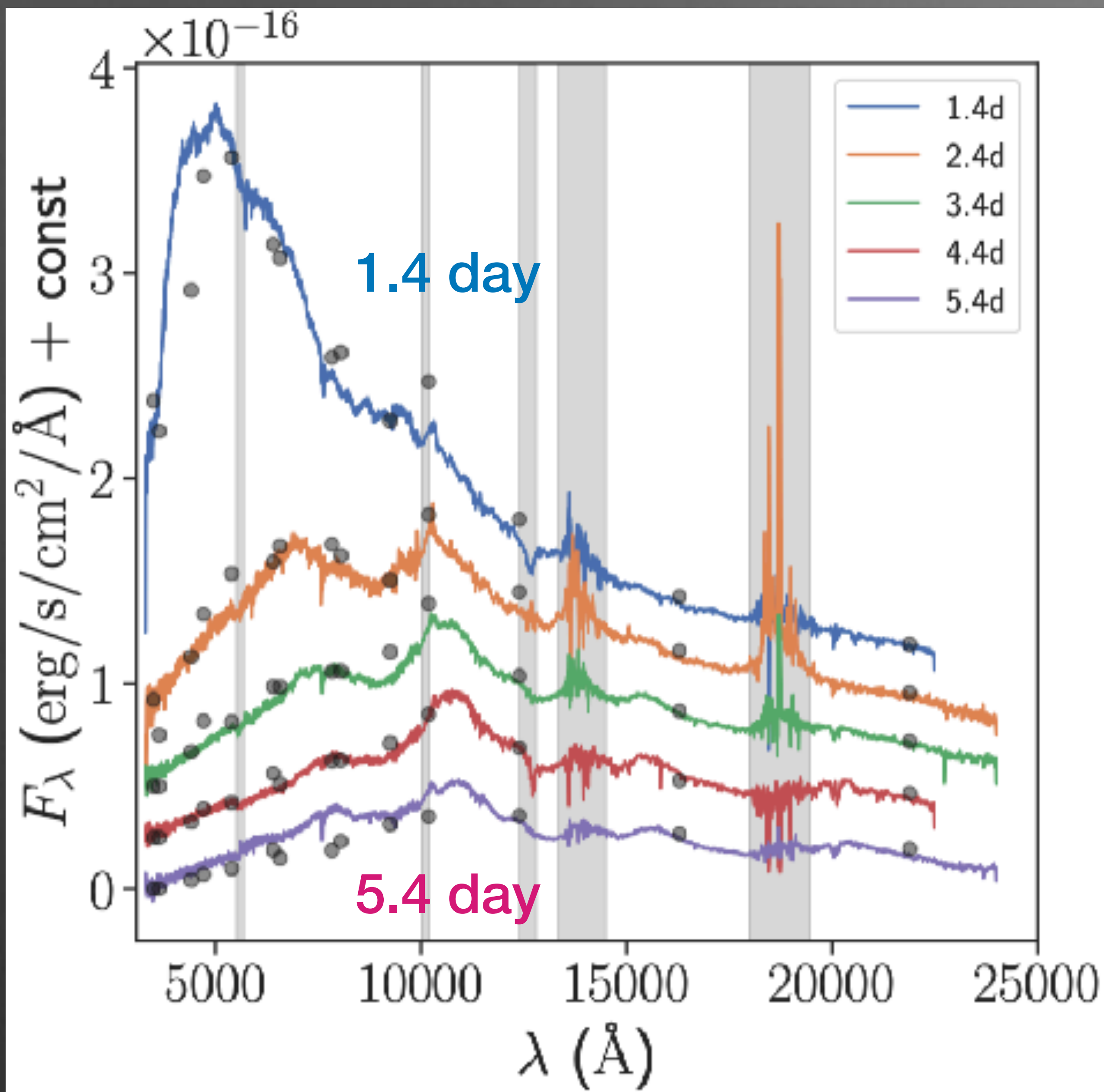
Iron Fine Structure

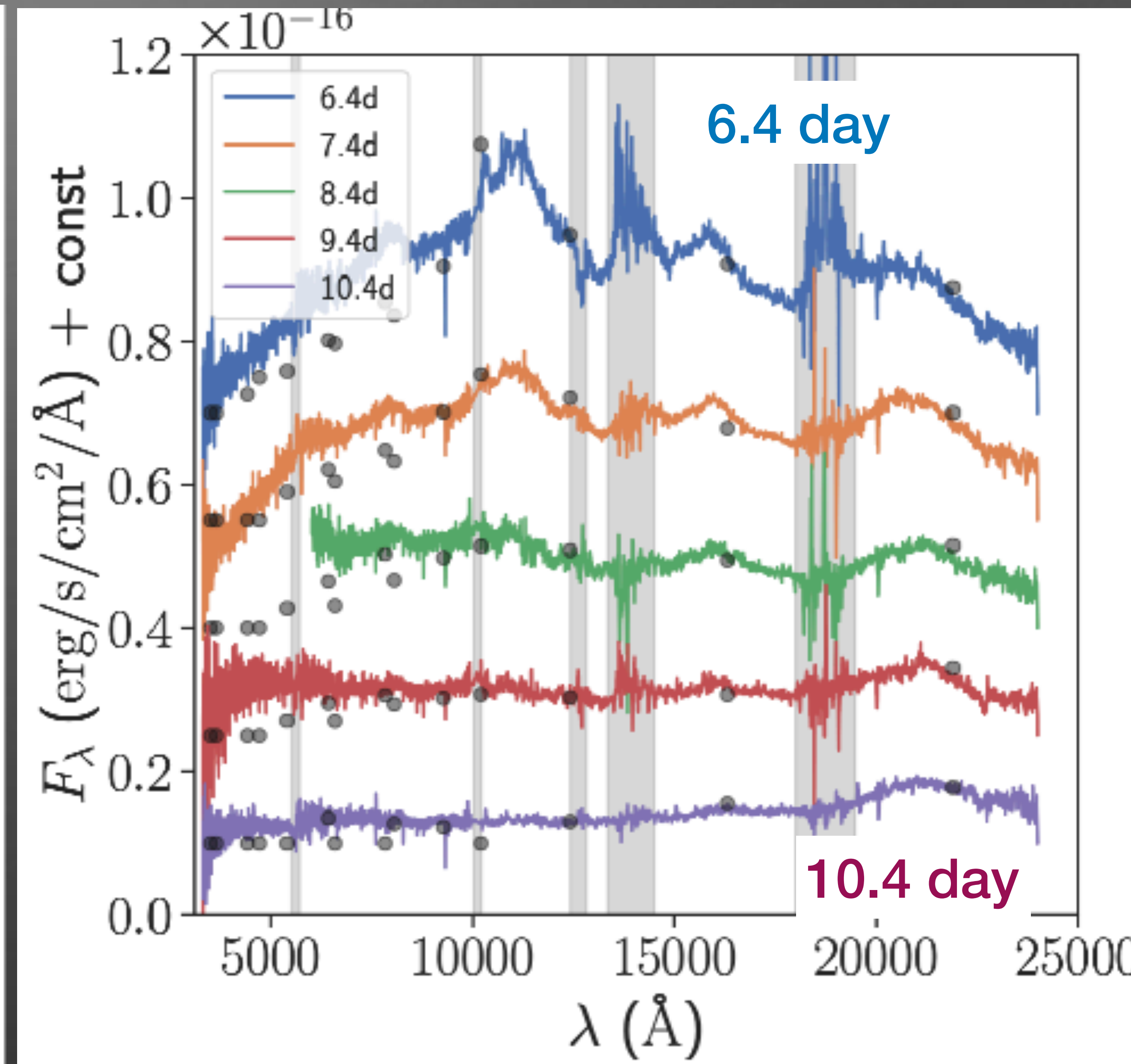
(Magnetic dipole: M1)

- Apparently an iron explosion!

Kilonova in GW170817

VLT X-Shooter (Pian+ 2017, see also, Watson+19,Gillanders+22,24,Sneppen+24)



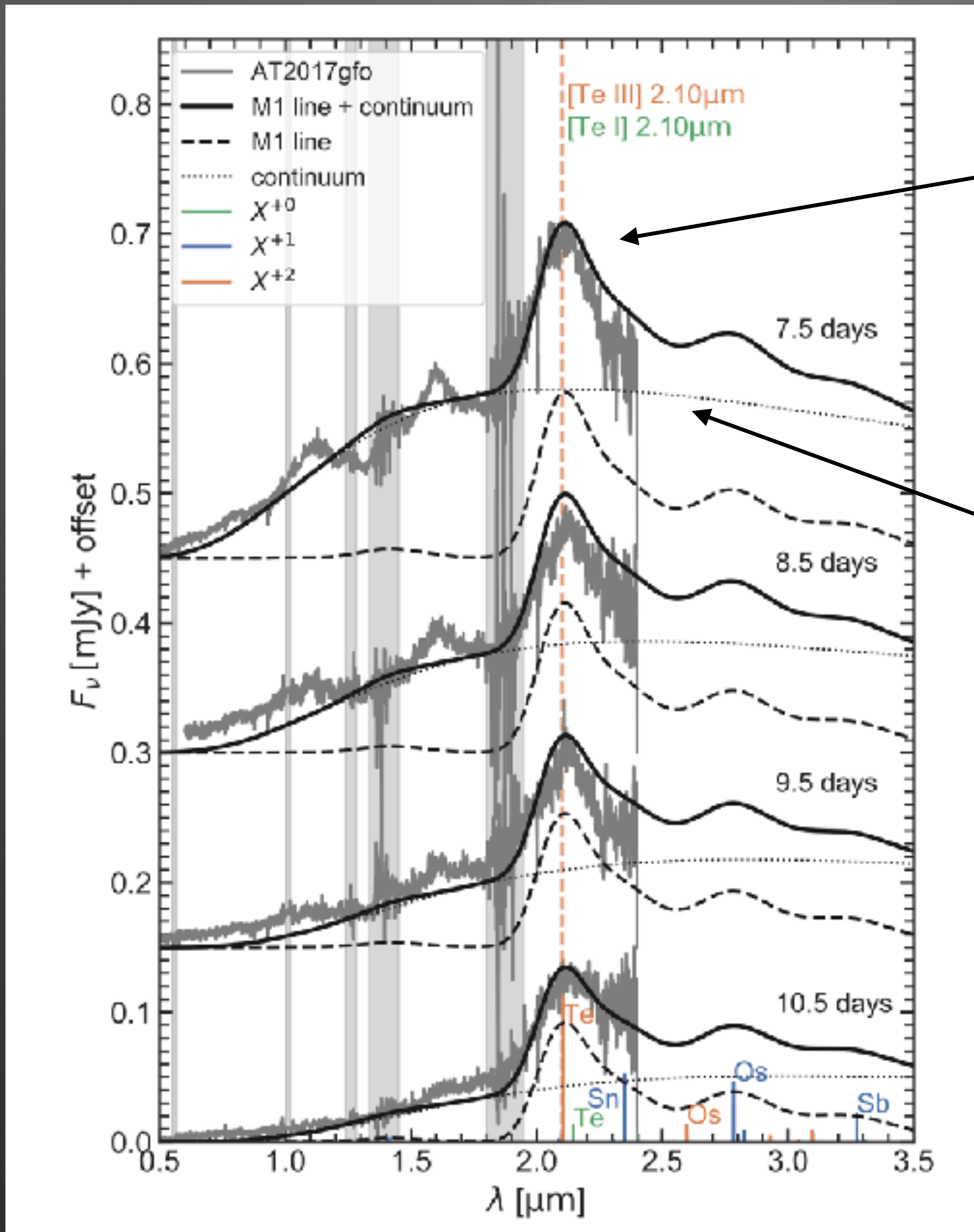


Absorption lines at early times (Nanae Domoto, Albert Sneppen, Salma Rahmouni here)

Emission lines gradually appear at late times.

Kilonova Nebular Emission

Hotokezaka+23



- Emission line v_{exp} ~ 0.1c, probably Te III
- Blackbody like continuum (<2000K)

Some remarks

- R-process elements have fine-structure transitions (M1) among the levels of J splits of ground levels at 1 - 100 μm, c.f, light & Fe-group elements > 10 μm

- The number of relevant M1 lines is much less than E1 lines that contribute to the opacity in the photospheric phase.

- The number of M1 lines is large enough to cool the ejecta down to the fine-structure energy scale < 2000 K.

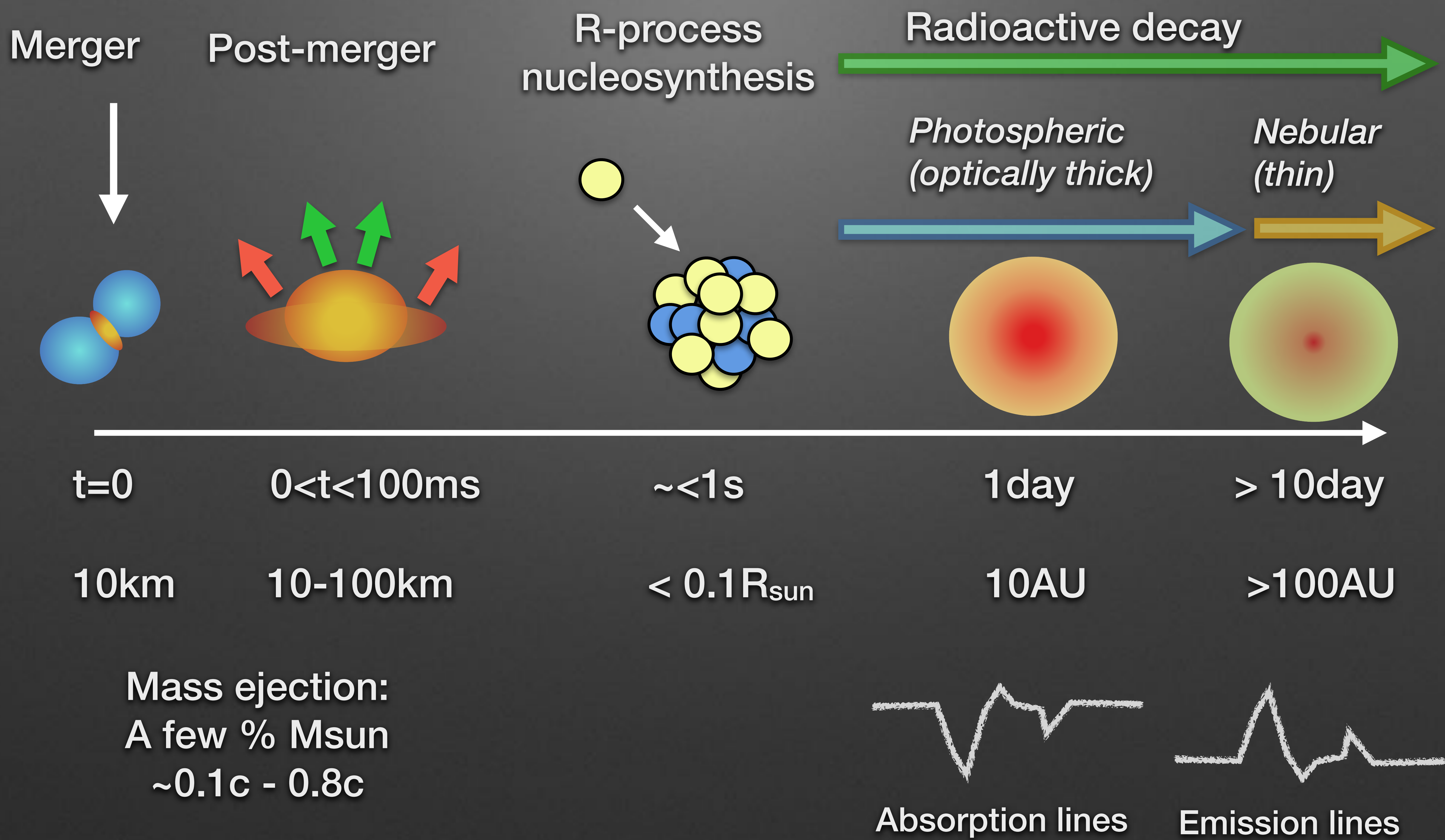
- R-process nebular emission radiates most energy in the IR wavelengths. Each wavelength is experimentally known.

Out line

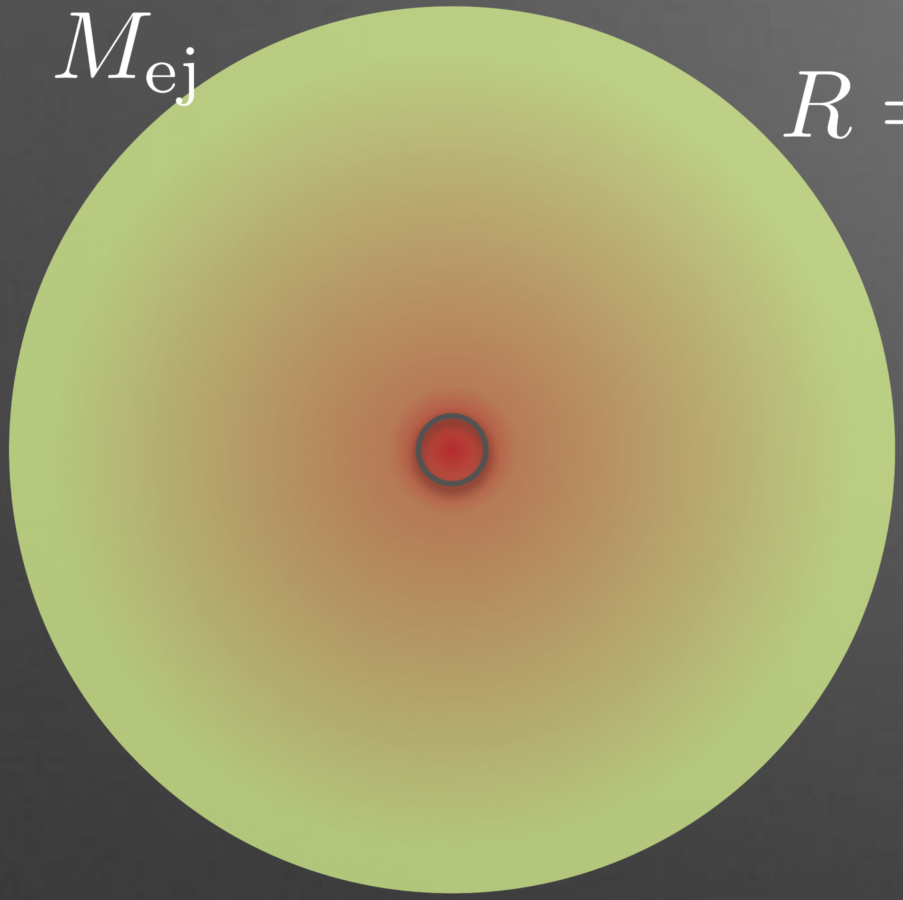
- Kilonova Nebular Emission
- Kilonova nebular emission lines in GW170817
- Kilonova nebular emission in GRB 230307A
- R-process emission from supernovae
- Summary

Neutron Star Merger & Kilonova

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



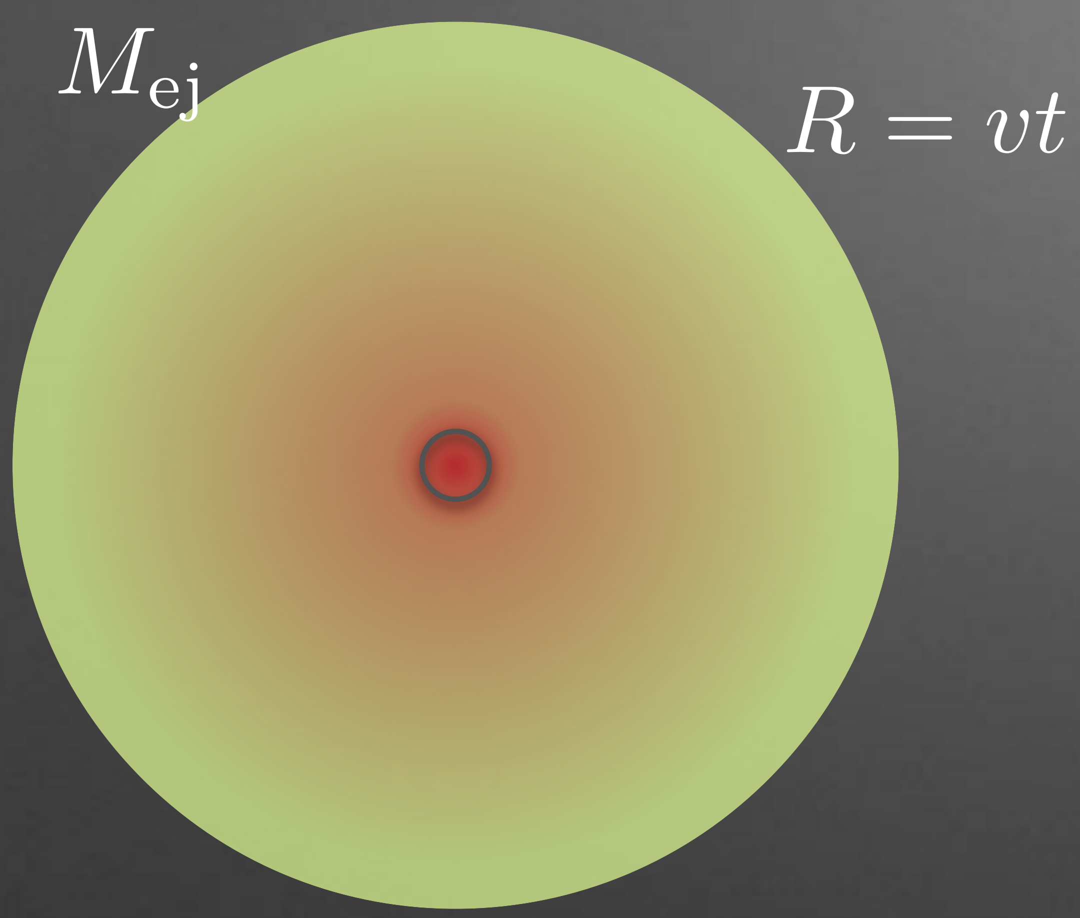
Nebular phase



- Ejecta optical depth

$$\tau \sim \frac{\kappa M_{\rm ej}}{4\pi R^2}$$

Nebular phase



- Ejecta optical depth

$$\tau \sim \frac{\kappa M_{\rm ej}}{4\pi R^2}$$

- Nebular phase begins when

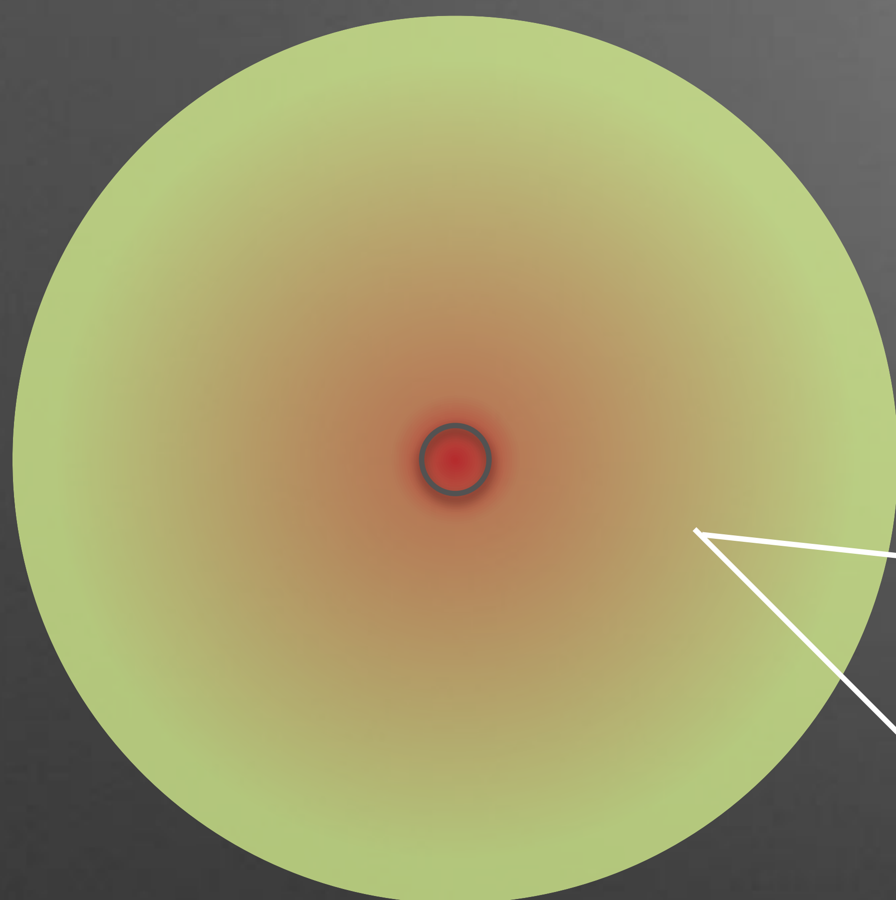
$$\tau \sim 1$$

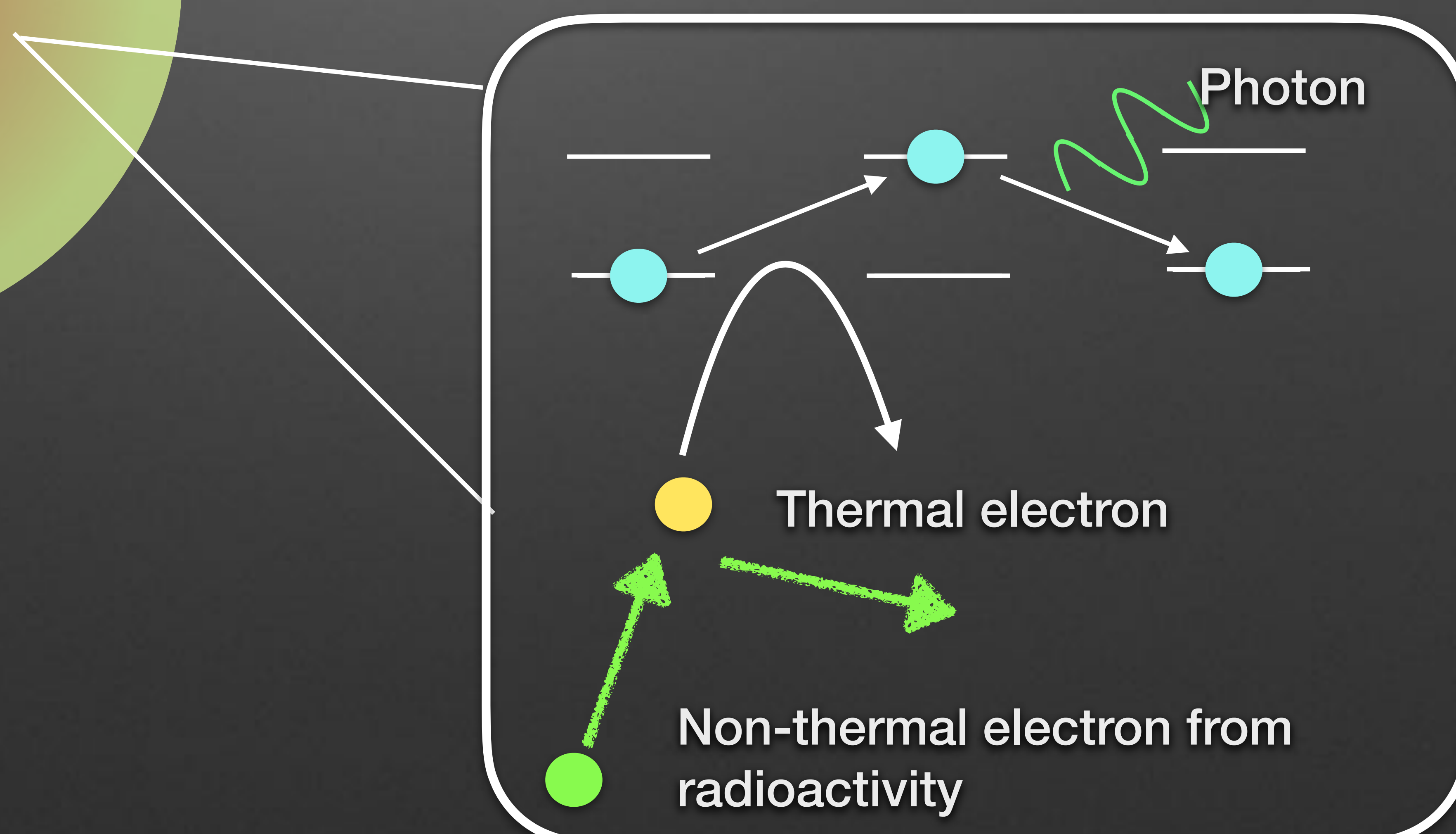
$$t \sim \sqrt{\frac{\kappa M_{\rm ej}}{4\pi v^2}}$$

$$t \sim 10\,{\rm day}\left(\frac{\kappa}{1\,{\rm cm^2/g}}\right)^{1/2}\left(\frac{M_{\rm ej}}{0.05 M_\odot}\right)^{1/2}\left(\frac{v}{0.1c}\right)^{-1}$$

Nebular phase

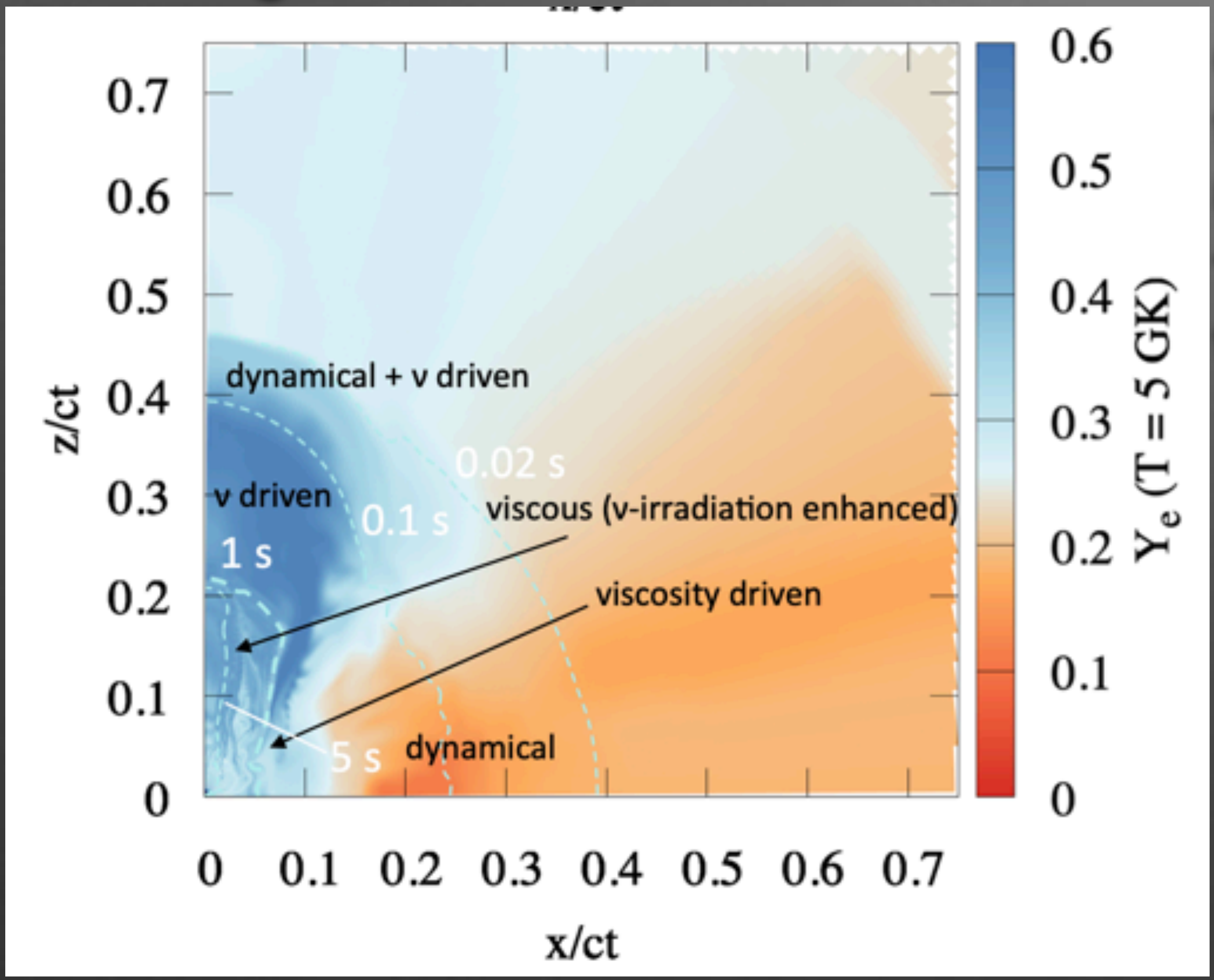
- Collisionally excited lines induced by free electron impacts
- Collision strengths for allowed and forbidden transitions are not very different (both can be important)
- Temperature is set by balance between the heating and line cooling.





Nebular phase

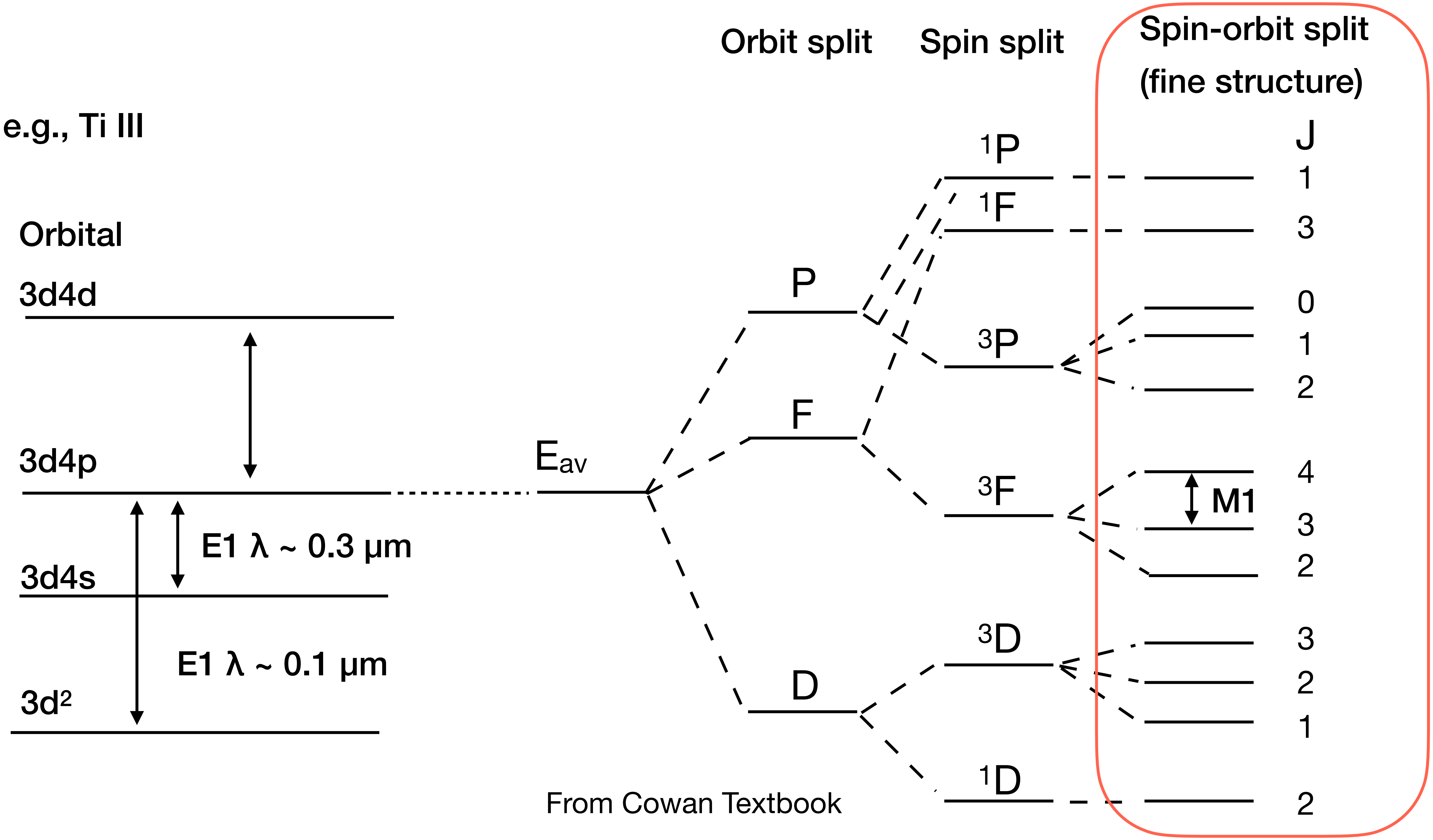
Kawaguchi+2021



- Collisionally excited lines induced by free electron impacts
- Collision strengths for allowed and forbidden transitions are not very different (both can be important)
- Temperature is set by balance between the heating and line cooling.

- Most abundant elements are usually important
- Mass in emitting ions can be measured
- Most density (lower velocities < 0.1c)
- Making M1 line list is relatively easy

Atomic structure



From Cowan Textbook

Allowed transitions => absorptions

Forbidden transitions

(Pasternack 40, Shortley 40)

M1 transition rate

Bahcall & Wolf 1968

where λ is the wavelength of the transition, S_z is the z-component of the total electron spin operator, and $\bar{n}_\lambda$ is the average number of photons present per available photon state in a small interval near λ. The relevant values of λ^{-1} are given in the fourth column of Table 1. If LS coupling is valid and $J_{\text{initial}} = (J_{\text{final}} + 1)$, then (Pasternack 1940; Shortley 1940)

$$\left|\frac{\langle m|S_z|n\rangle}{\hbar}\right|^2 = \frac{\{[J^2 - (L - S)^2][(L + S + 1)^2 - J^2]\}}{12J(2J + 1)} . \tag{10a}$$

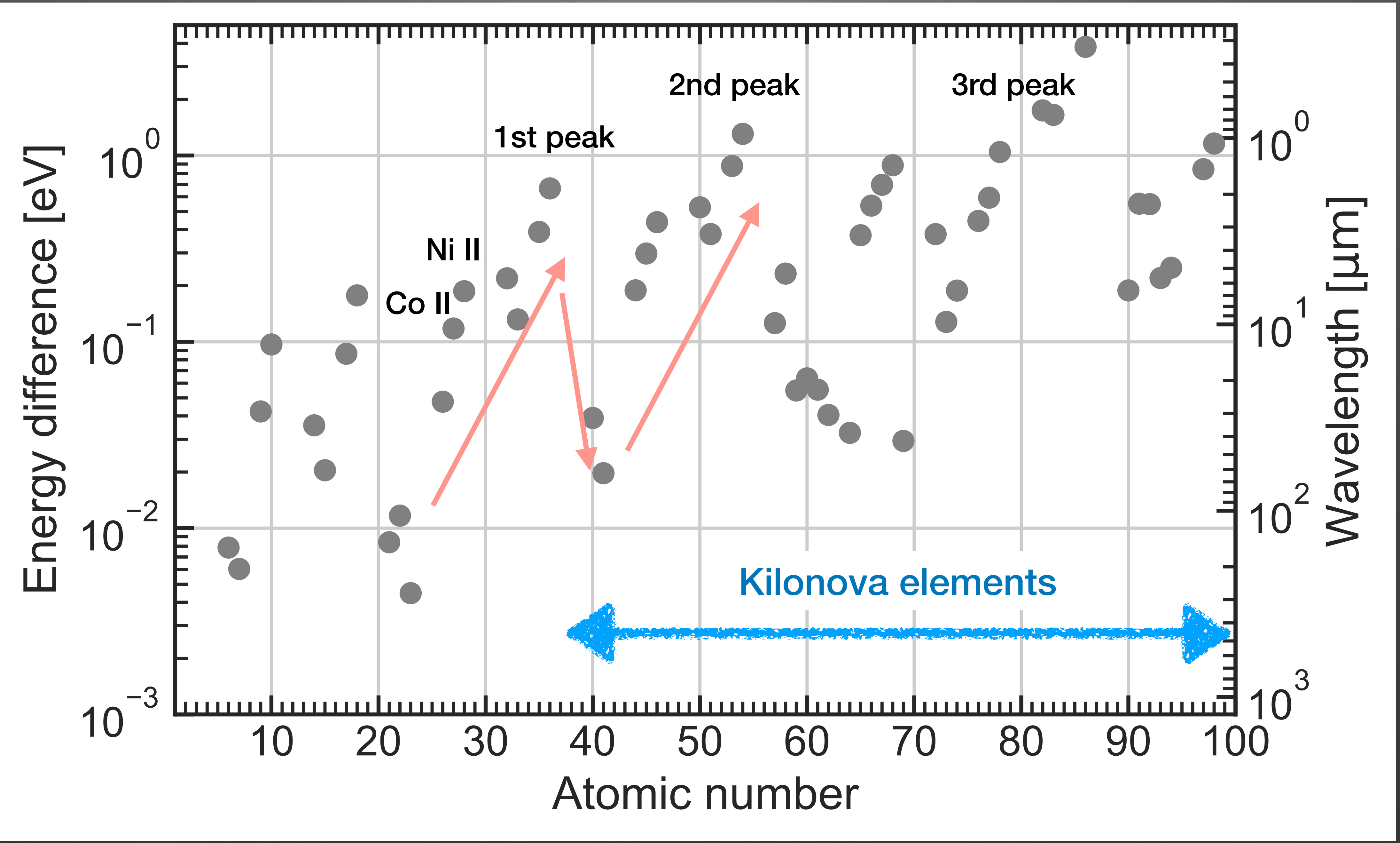
If $J_{\text{initial}} = (J_{\text{final}} - 1)$, then

$$\left|\frac{\langle m|S_z|n\rangle}{\hbar}\right|^2 = \frac{[(L + S + 1)^2 - (J + 1)^2][(J + 1)^2 - (L - S)^2]}{12(J + 1)(2J + 1)} . \tag{10b}$$

This formula gives reasonably accurate values.

Fine-structure lines of heavy elements

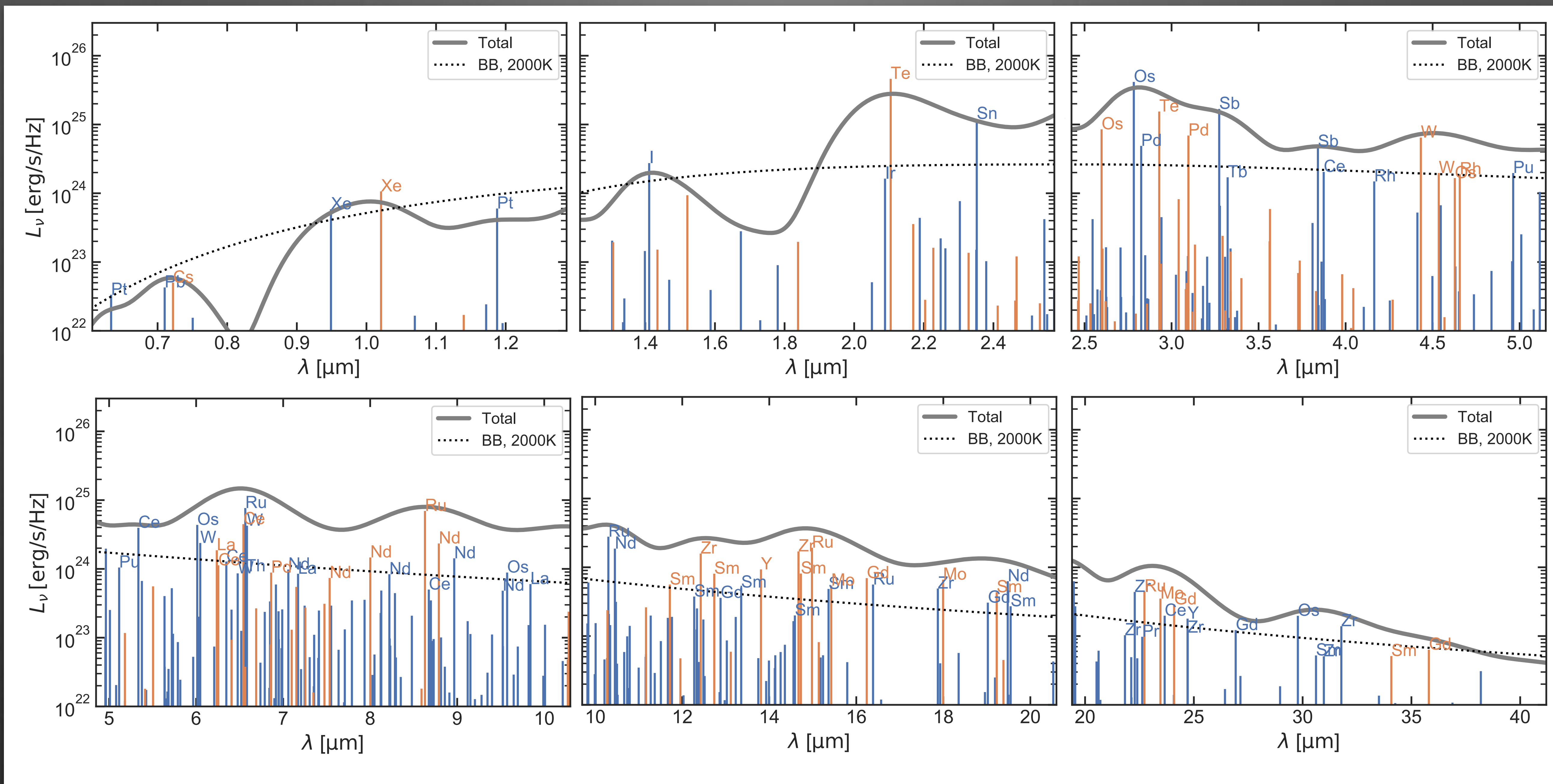
Singly ionized, the first fine structure level



- Heavy elements have fine-structure lines at ~ 1 - 30 μm.
- The energy scale of 1st, 2nd, and 3rd peak elements ~ 1 μm.
- The fine structure lines can dominate the kilonova cooling.

Kilonova Nebular Spectrum (only M1 lines included

KH+ in prep, collision strengths are computed with HULLAC.

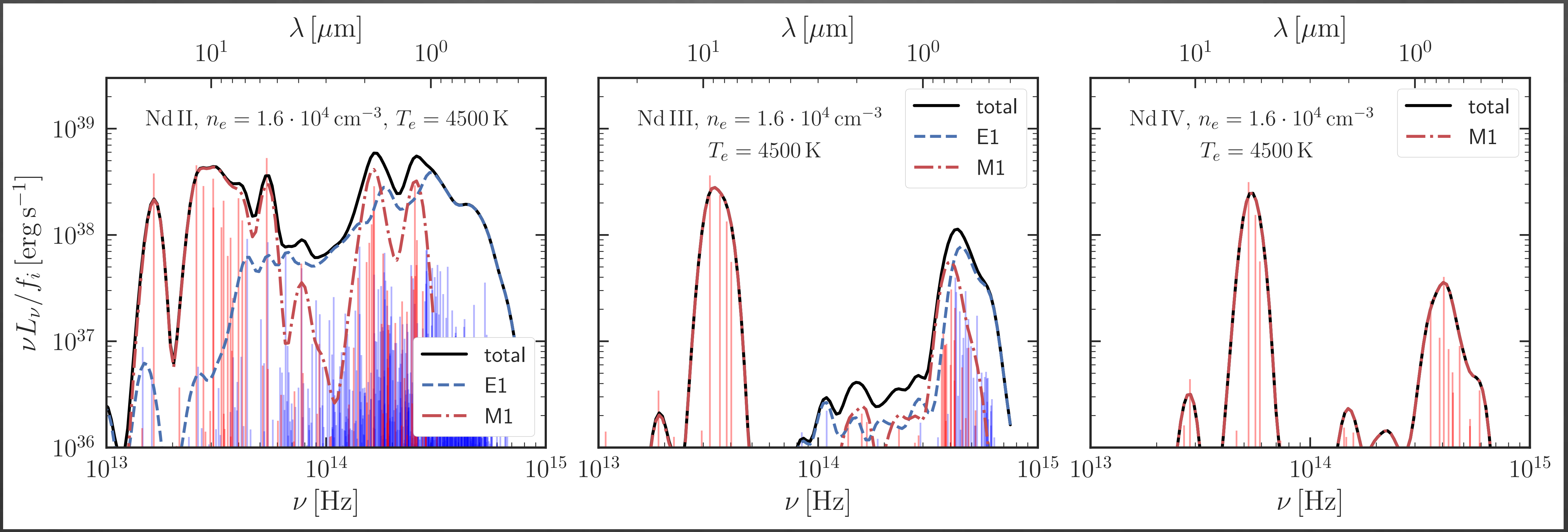


- The solar abundance (2nd - 3rd r-process peaks) is assumed. $X^{+1} = X^{+2} = 0.5$
- [Te III] 2.1μm is among the strongest M1 line.

Caveats

- We have included only M1 lines but E1 lines of lanthanides may also contribute.

KH+2021



Out line

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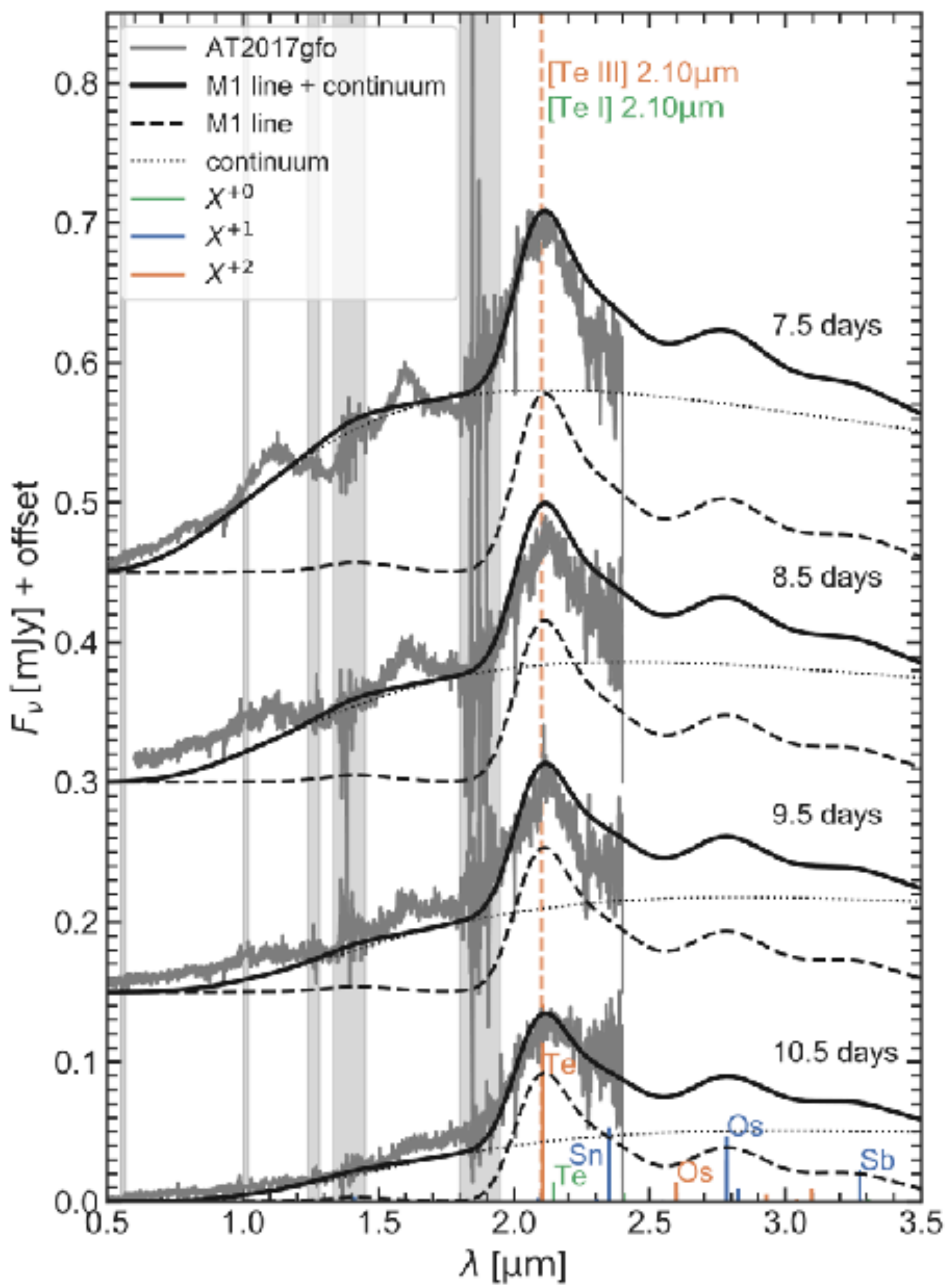
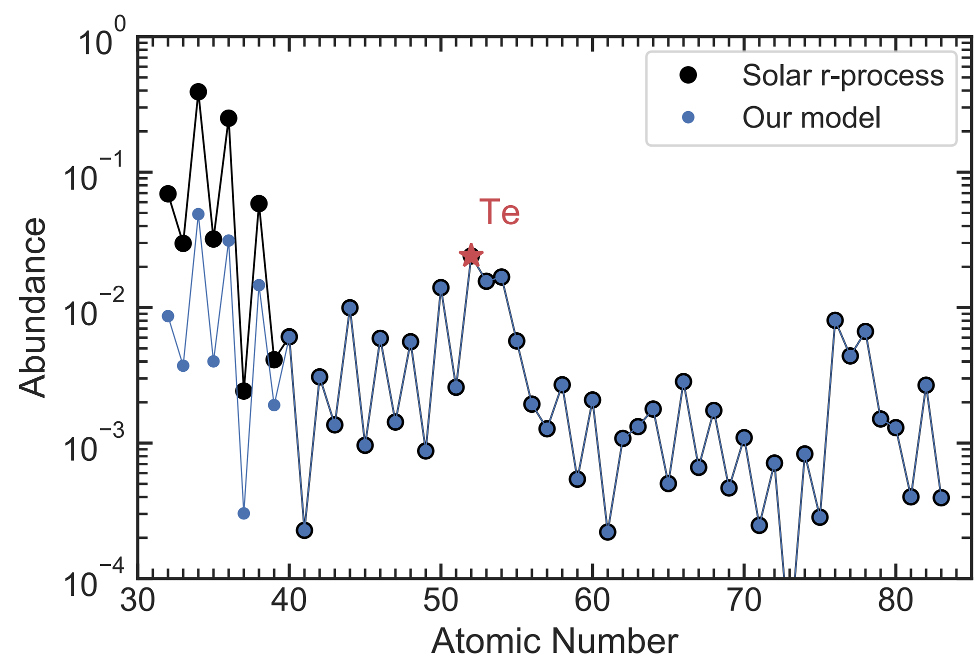
2.1μm line in kilonova spectra and modeling

AT 2017gfo (KH+23, data from Pian+17)

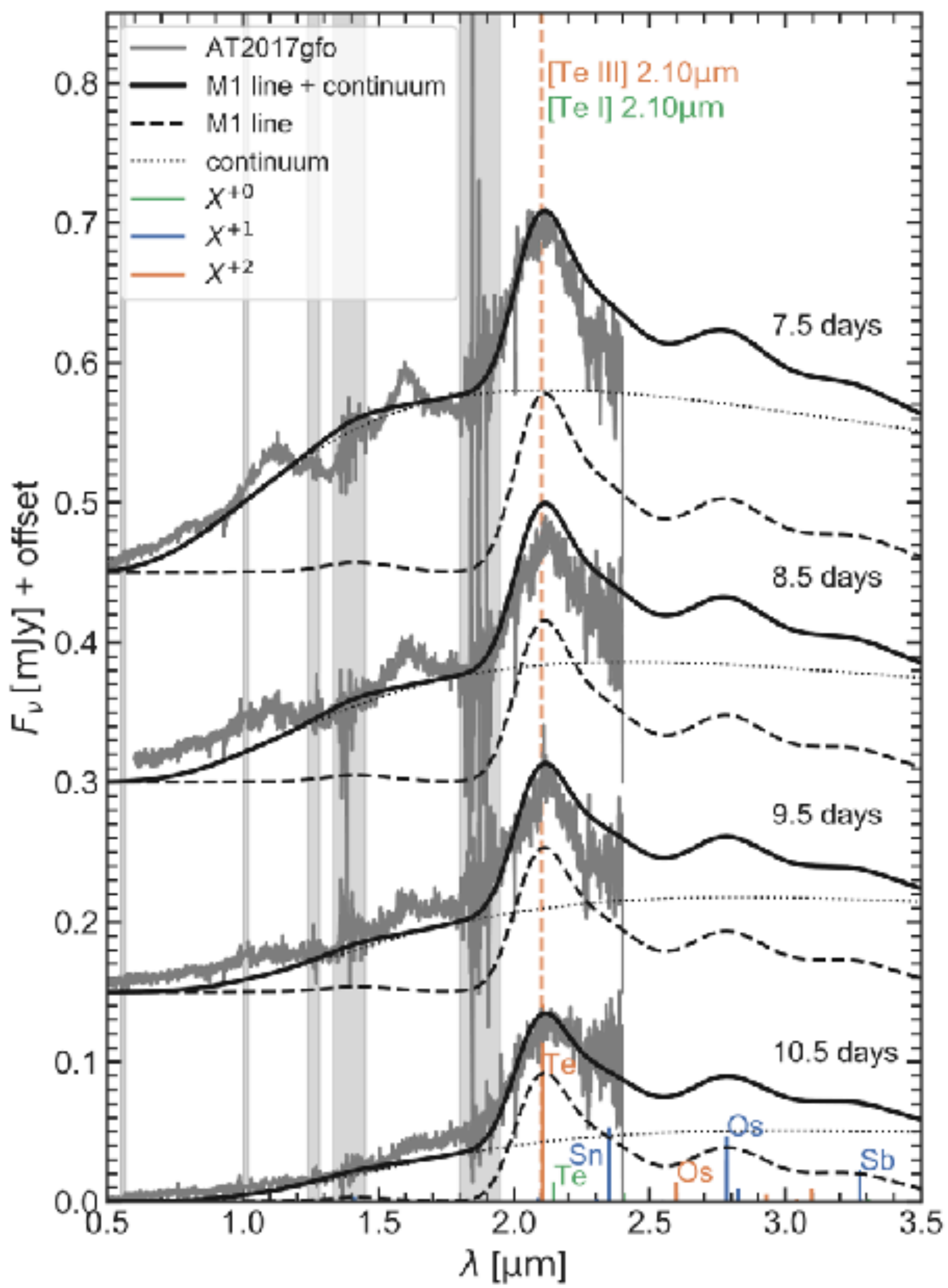


- Blackbody + M1 line analysis
- T_{BB} ~ 2000K
- M_{ej}=0.05M_{sun}, v_{ej} =0.07c, the solar pattern A>88
- A strong line at 2.1μm can be [Te III]

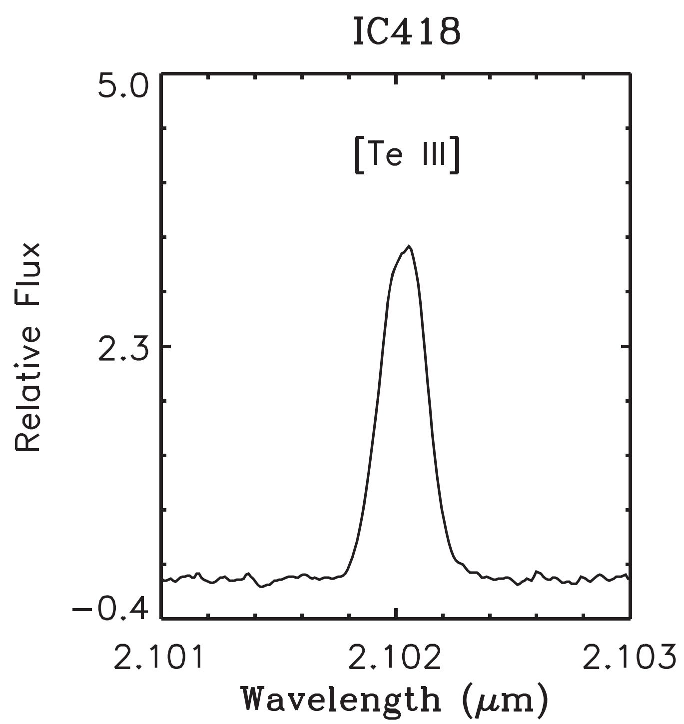


2.1μm line in kilonova spectra: GW170817

AT2017gfo (KH+23, data from Pian+17)



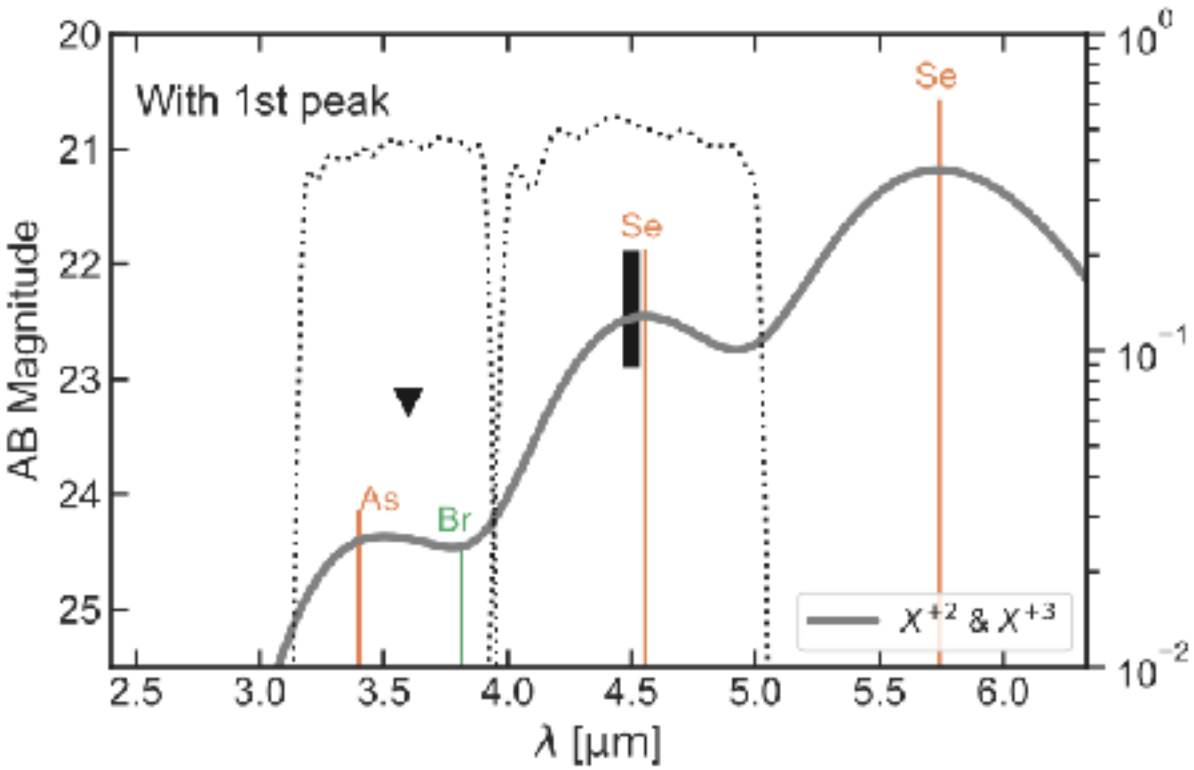
- Blackbody + M1 line analysis
- T_{BB} ~ 2000K
- M_{ej}=0.05M_{sun}, v_{ej} =0.07c, the solar pattern A>88
- A strong line at 2.1μm can be [Te III]
- [Te III] 2.1μm is seen in planetary nebulae (Madonna+18)



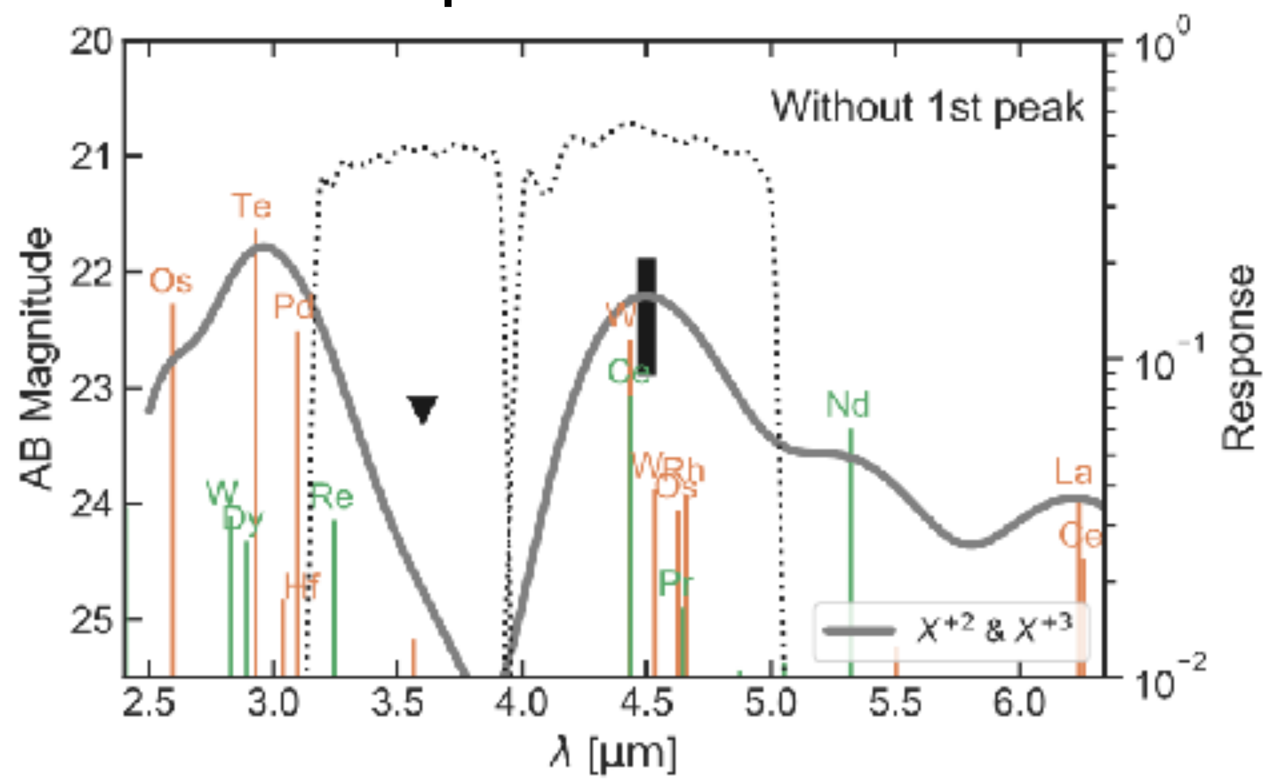
Spitzer view of GW170817, very red at late times

Spitzer limit (3.6μm) and detection (4.5μm) (KH+22 see also McCann+24, data from Kasliwal+22 and Viller+18)

The 1st peak is abundant



The 1st peak is less abundant



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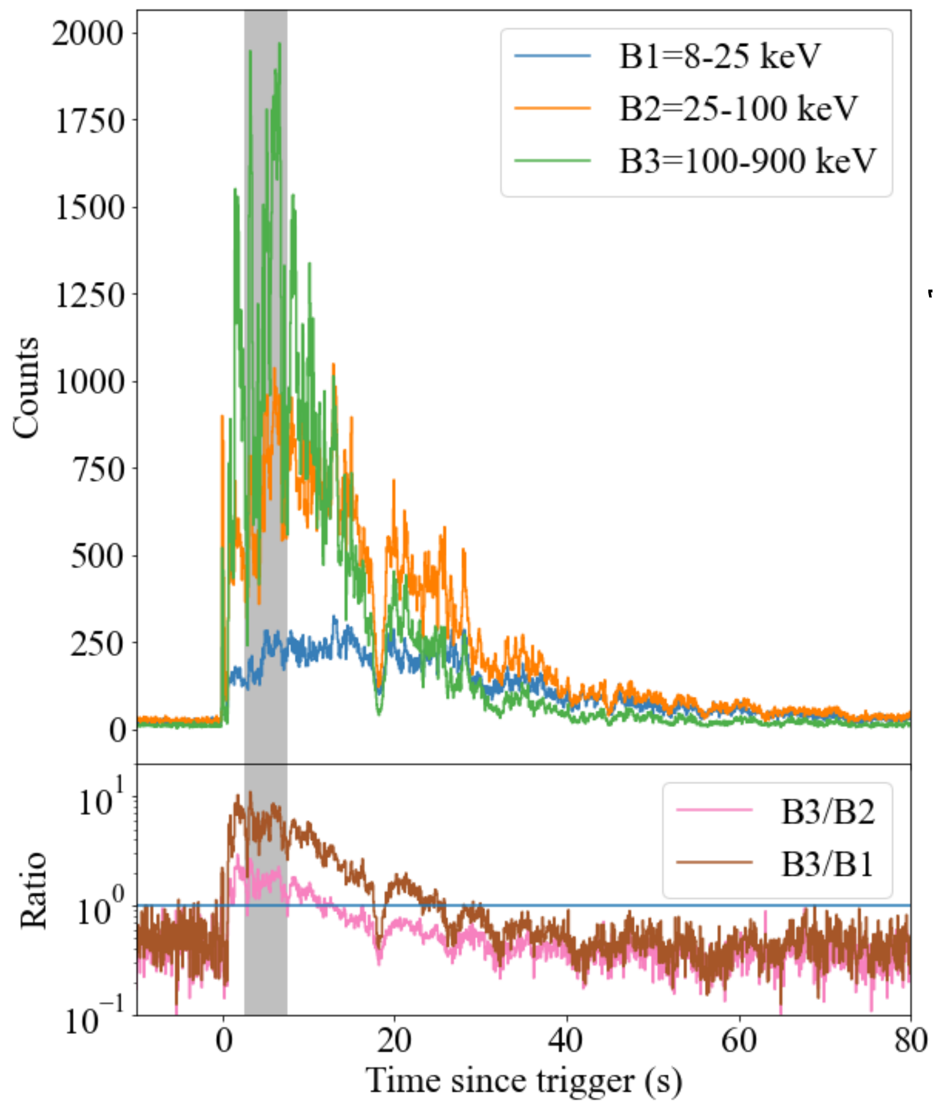
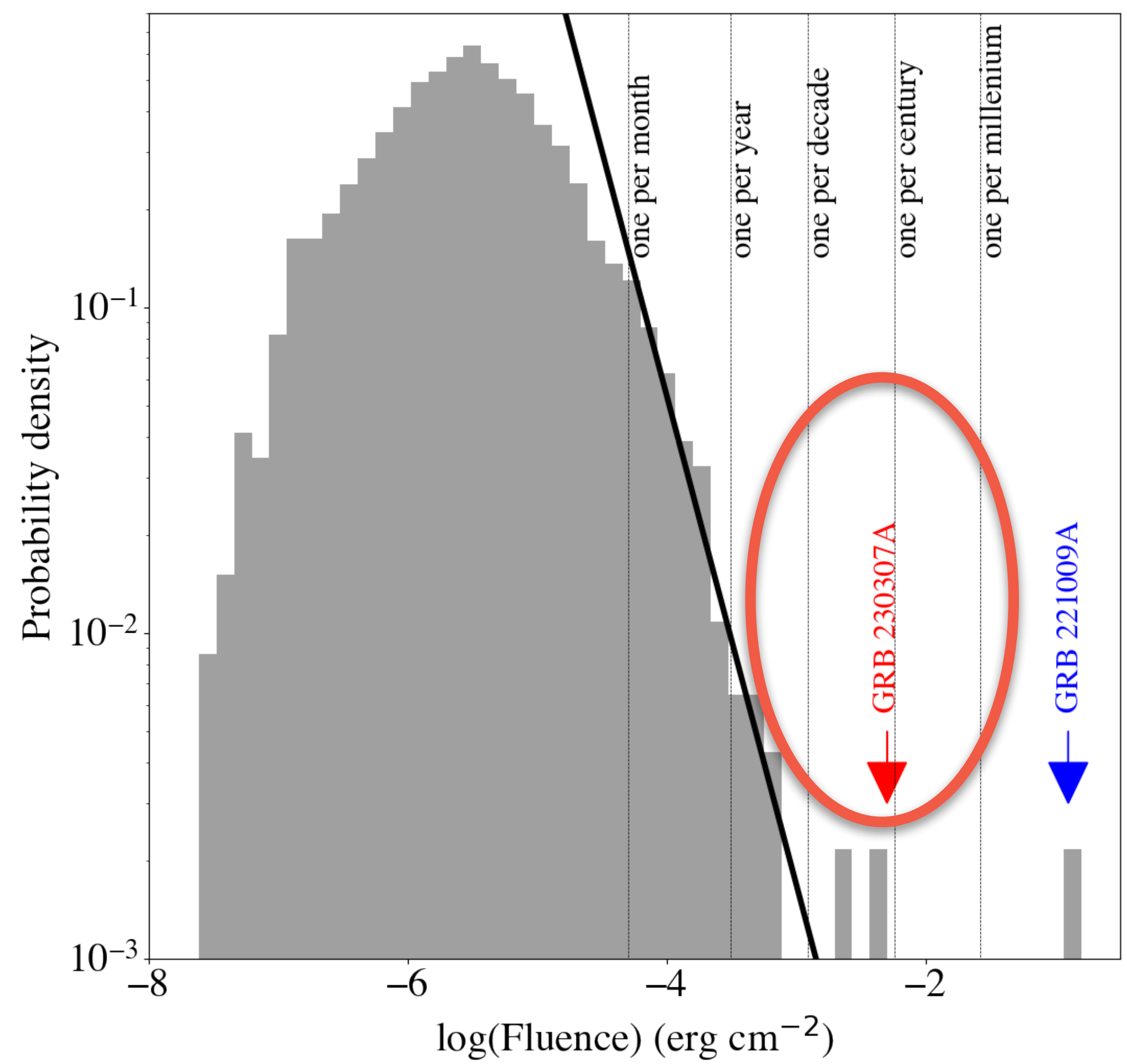
An extremely bright GRB 230307A

GRB 230307A



Levan,..,KH+23

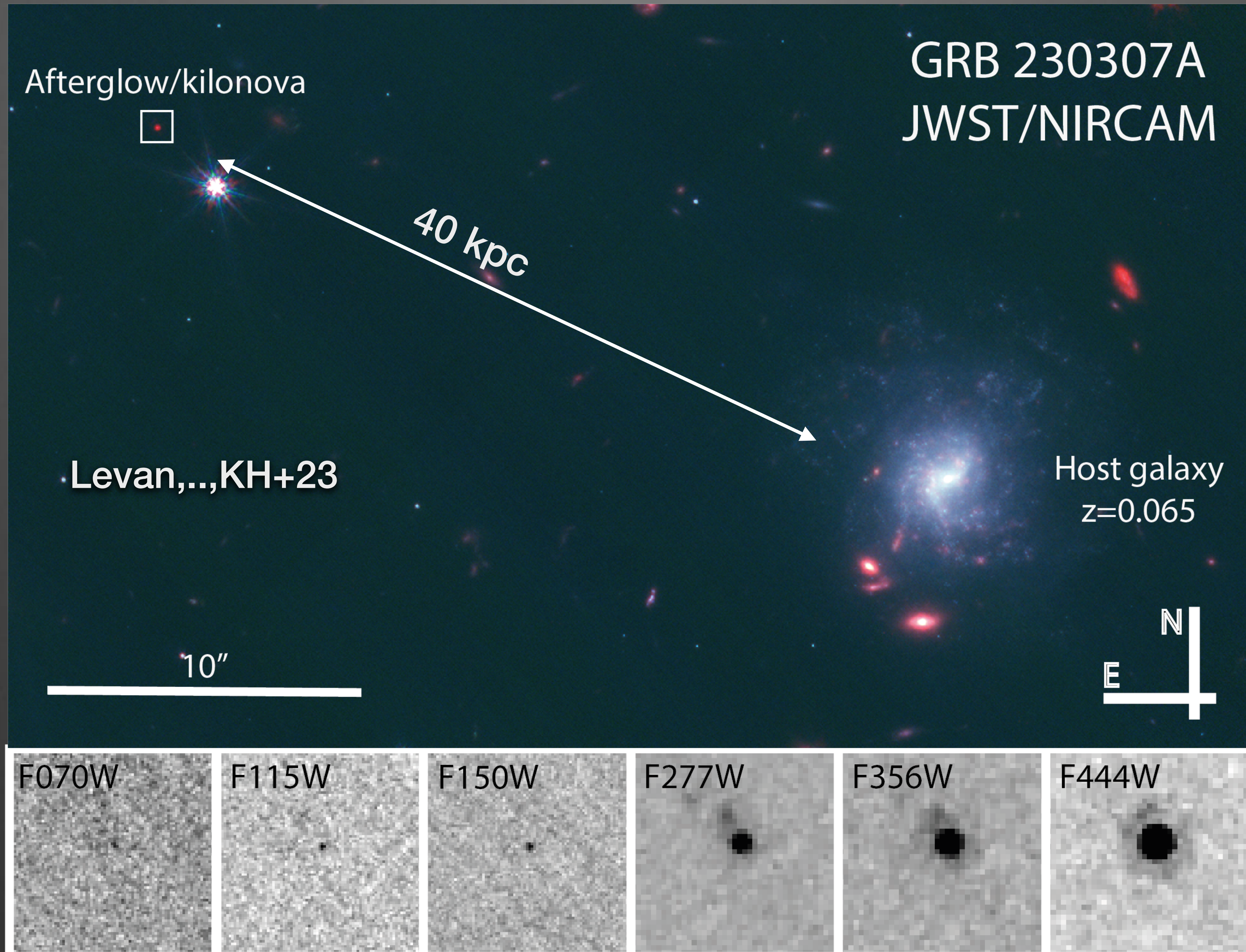


- T_{90} ~ 35 s : Typical long GRB.
- The 2nd brightest GRB.
- LIGO/Virgo/KAGRA were not in operation.

Remarks on GRB 230307A

- The 1st JWST observation for a kilonova candidate.
- One of the nearest GRBs.
- The 2nd long GRB associated with a kilonova candidate.

GRB 230307A: JWST NIRCam Image

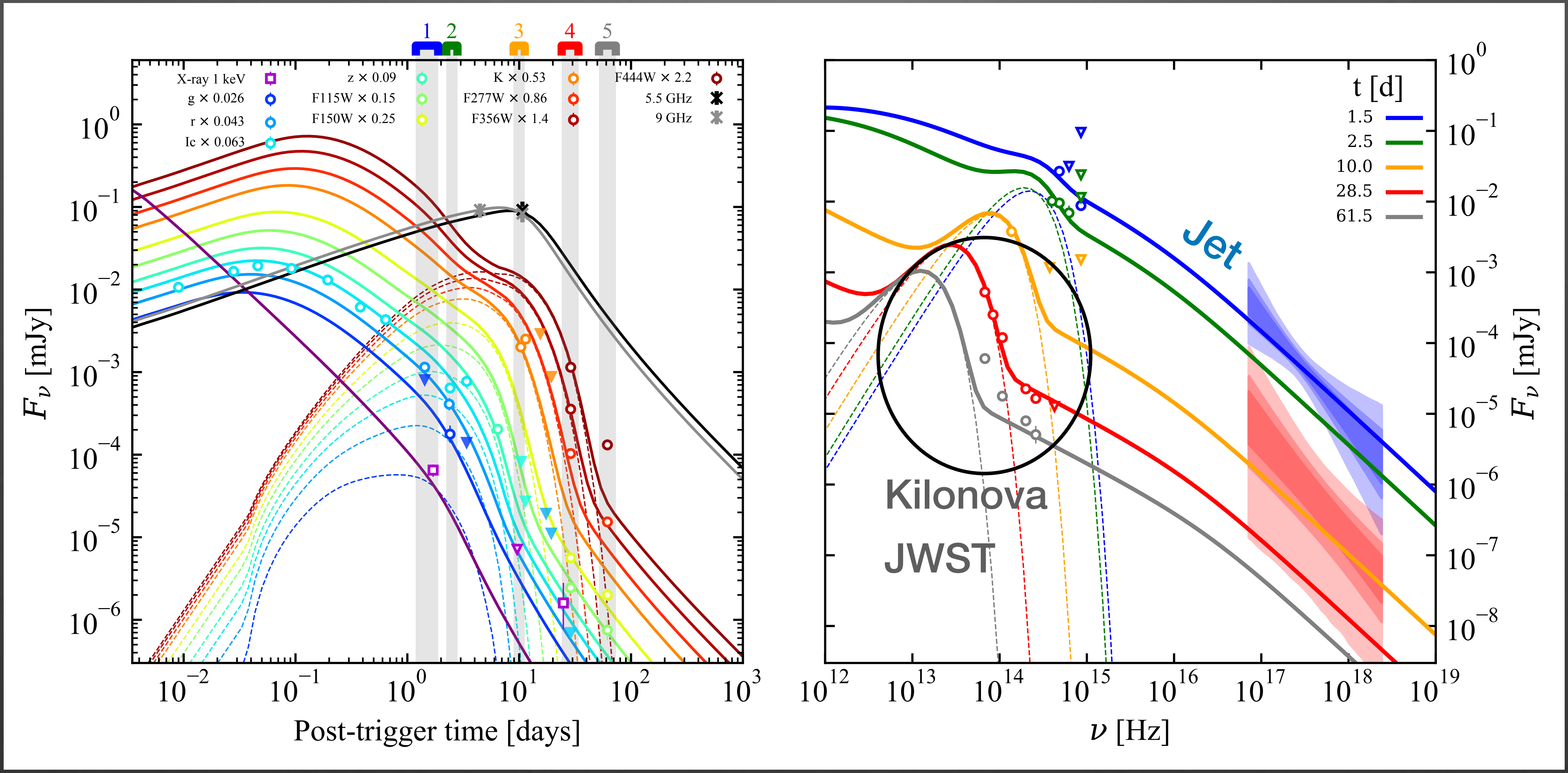


- The most probable host ~ 300Mpc, large off-set ~ 40 kpc
- The large off-set rules out the collapsar scenario.

GRB 230307A and JWST photometry

Levan,..KH+23

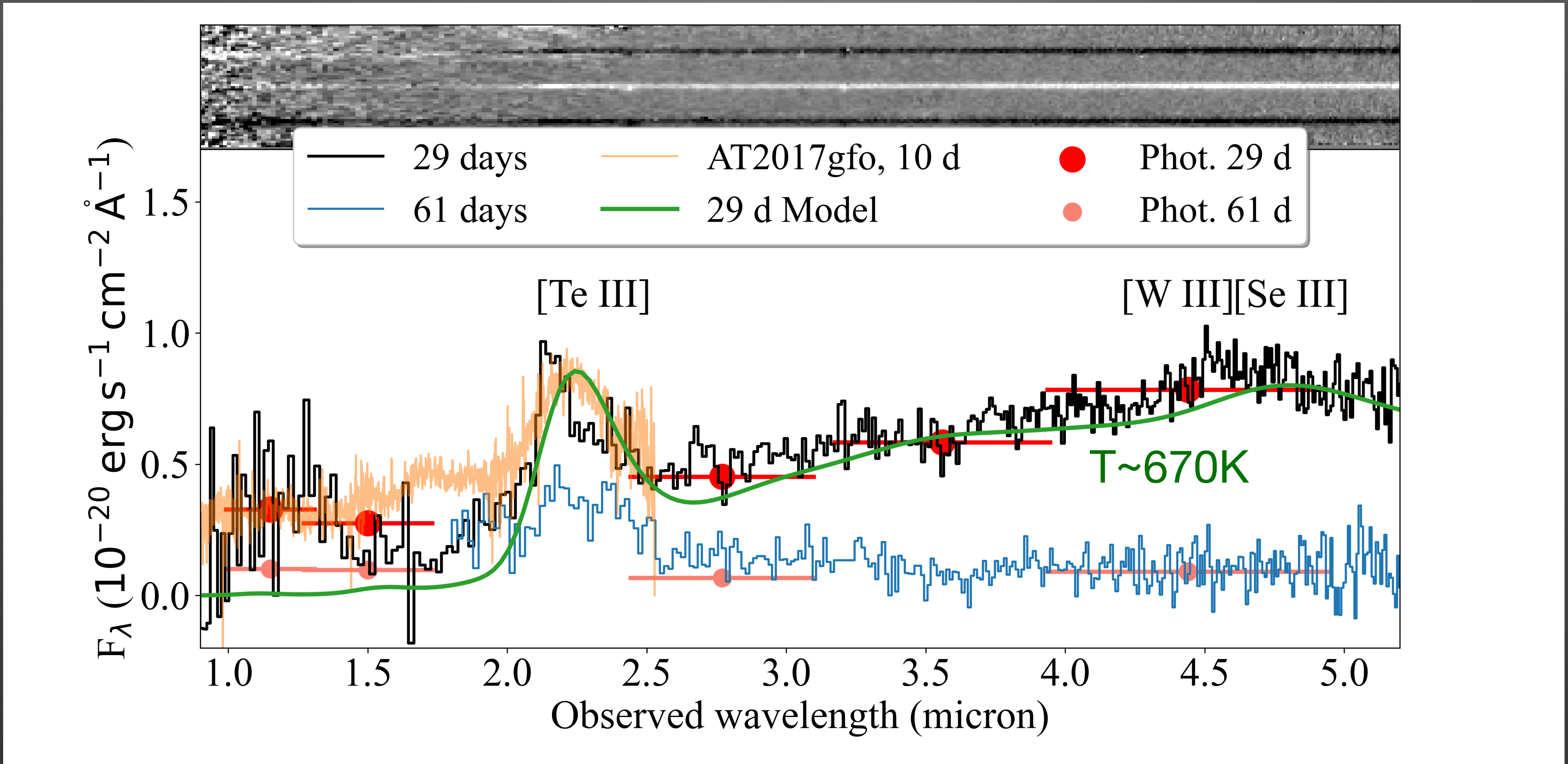
Afterglow+Kilonova light curve | Afterglow+Kilonova SED



- The light curve is somewhat similar to AT2017gfo (GW170817).
- Extremely red, see JWST data at 30 & 60 days.

JWST Spectrum of the KN candidate 230307A

Levan,..,KH+23, see also Gillanders+23



- A line feature at 2.1μm is similar to that seen in GW170817.
- M(Te III)=$10^{-3}M_{sun}$ in the line forming region, v_{ej} =0.08c.
- The total mass ~ $0.05M_{sun}$ if the solar r-process abundance.
- Most energy is radiated at > 5 μm !!?

What the IR bump means?

- GRB 230307A is not a neutron star merger.
  Consider other progenitors

What the IR bump means?

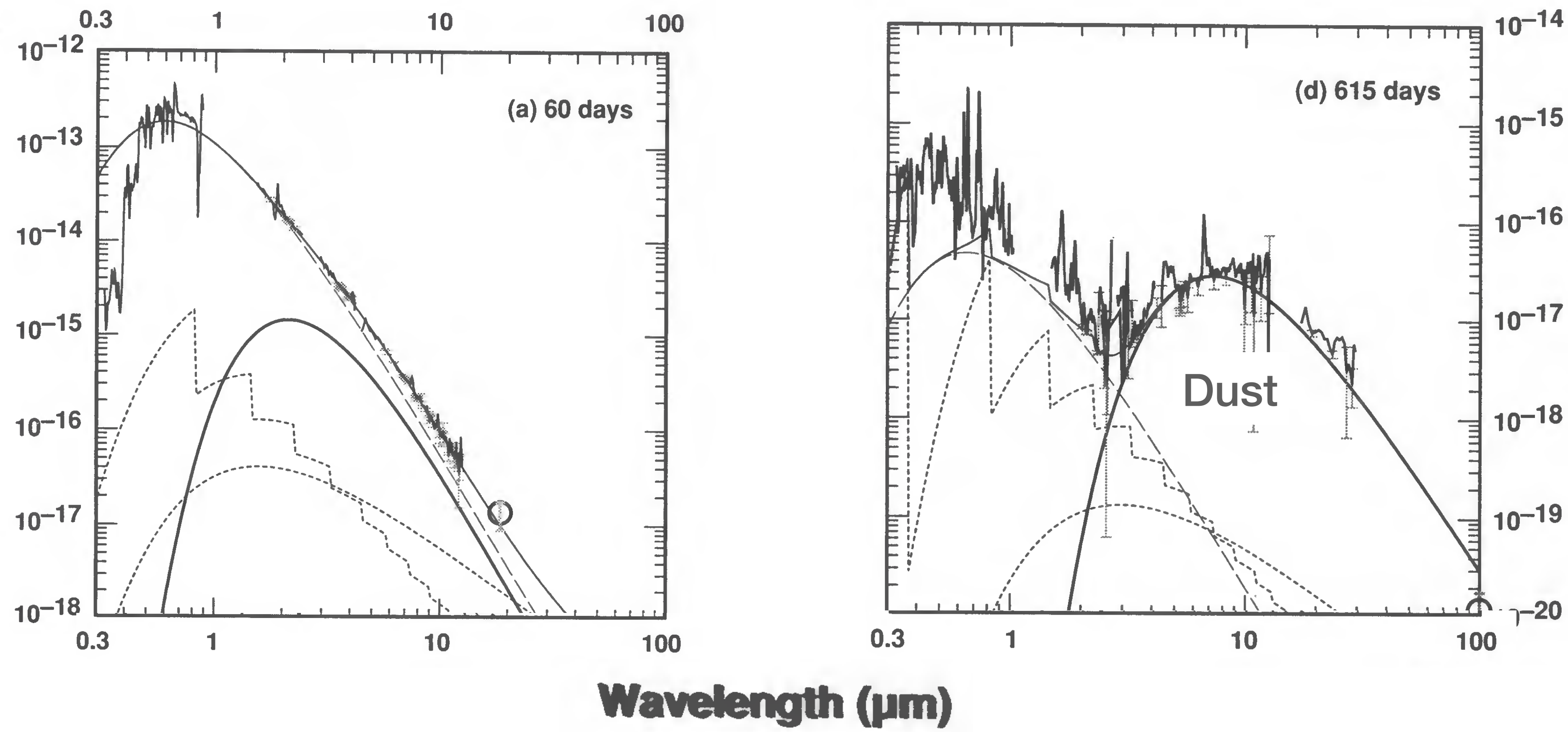
- GRB 230307A is not a neutron star merger. Consider other progenitors
- If it is a neutron star merger
    - Actinide optical property, which we haven’t understood?

SN 1987A (Wooden+1993)

What the IR bump means?

- GRB 230307A is not a neutron star merger. Consider other progenitors
- If it is a neutron star merger
    - Actinide optical property, which we haven't understood?
    - Dust?

SN 1987A (Wooden+1993)



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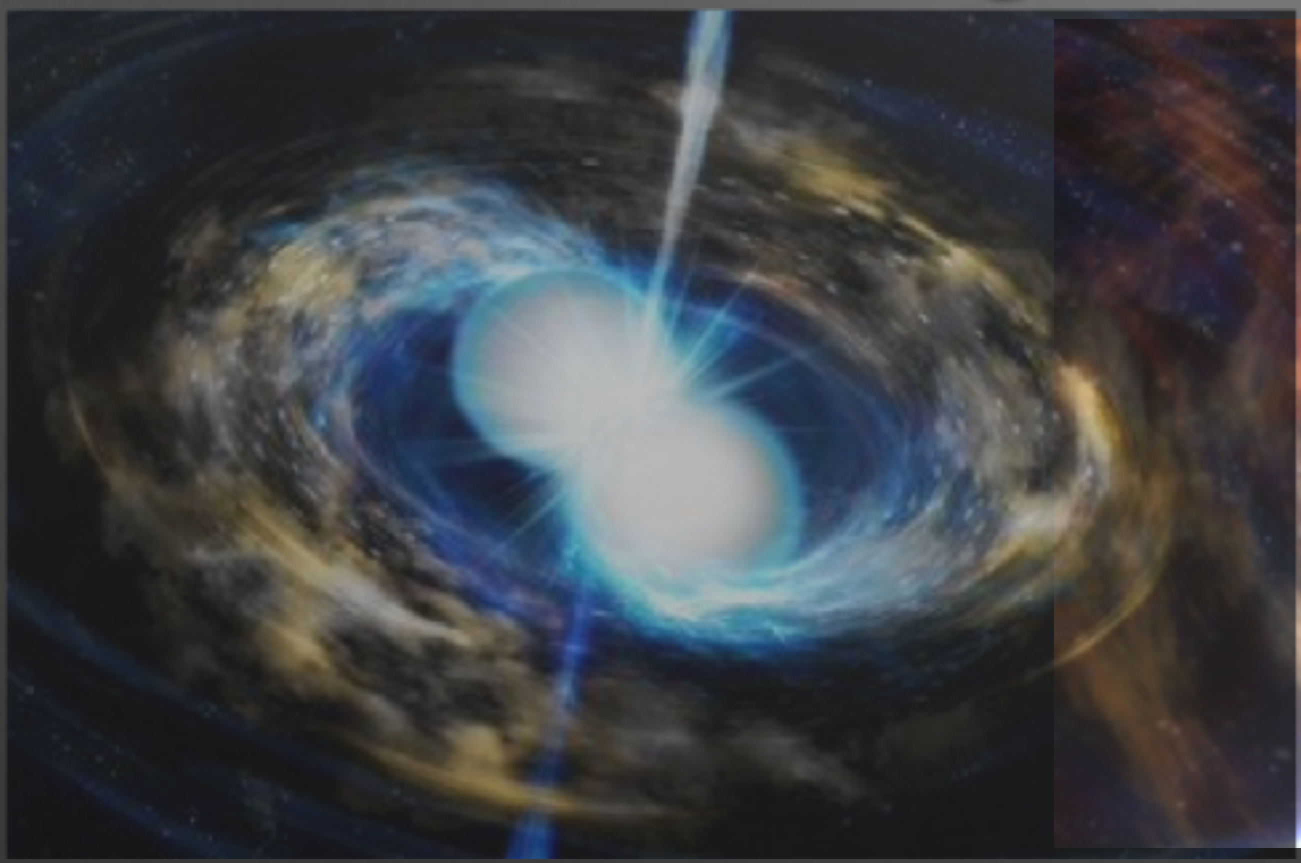
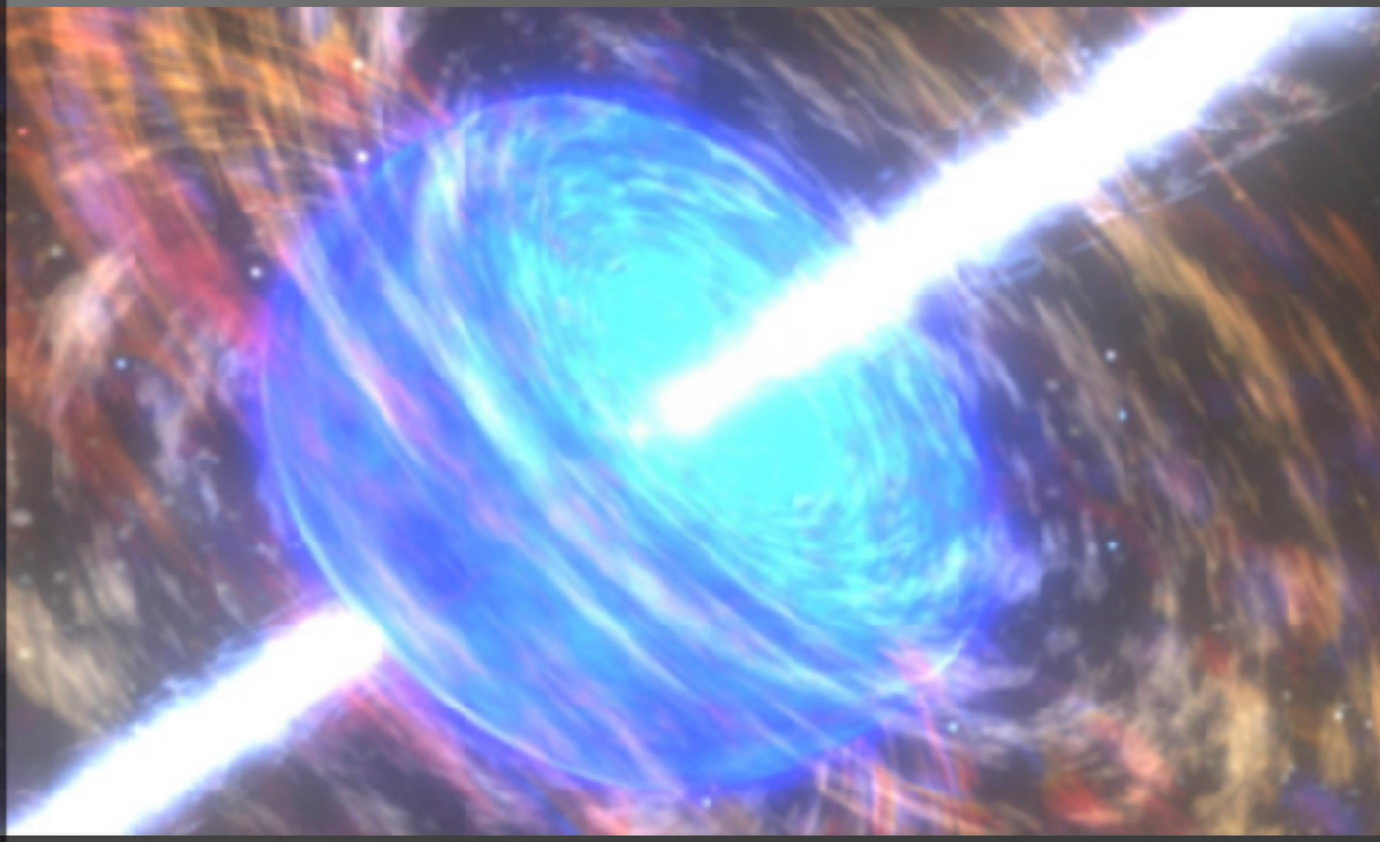
The r-process origin

Neutron star merger?



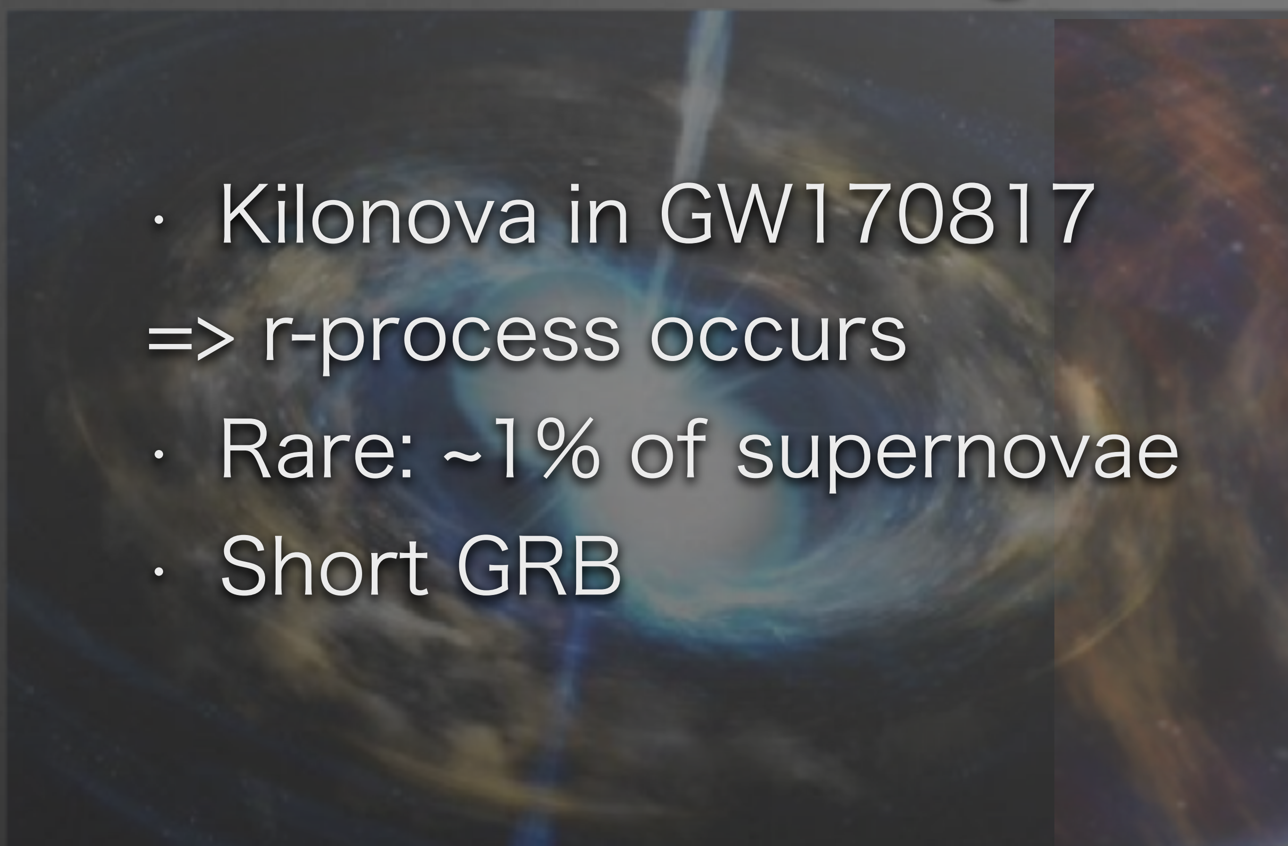
Collapsar?



Something else?

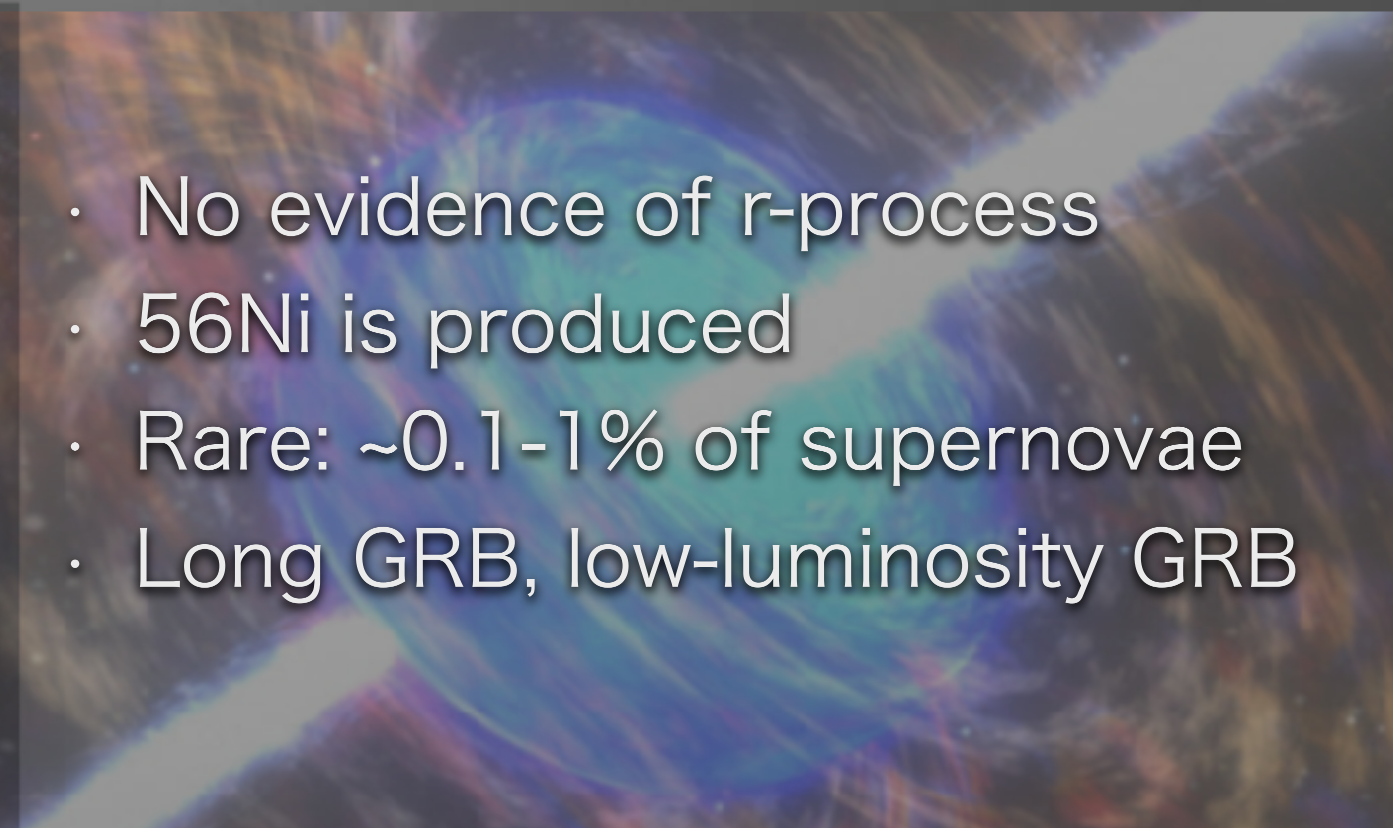
The r-process origin

Neutron star merger?



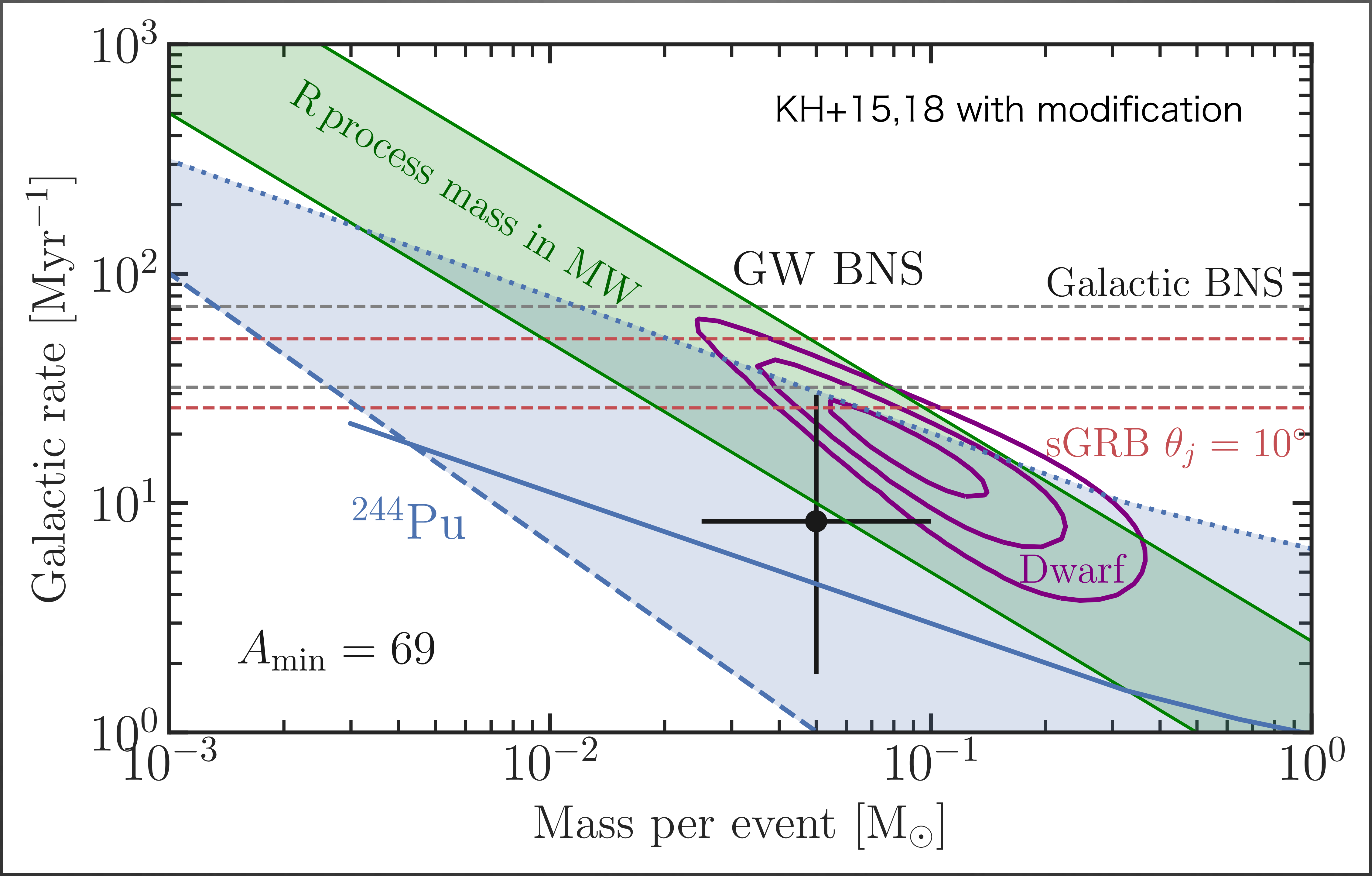
- Kilonova in GW170817
=> r-process occurs
- Rare: ~1% of supernovae
- Short GRB

Collapsar?



- No evidence of r-process
- 56Ni is produced
- Rare: ~0.1-1% of supernovae
- Long GRB, low-luminosity GRB

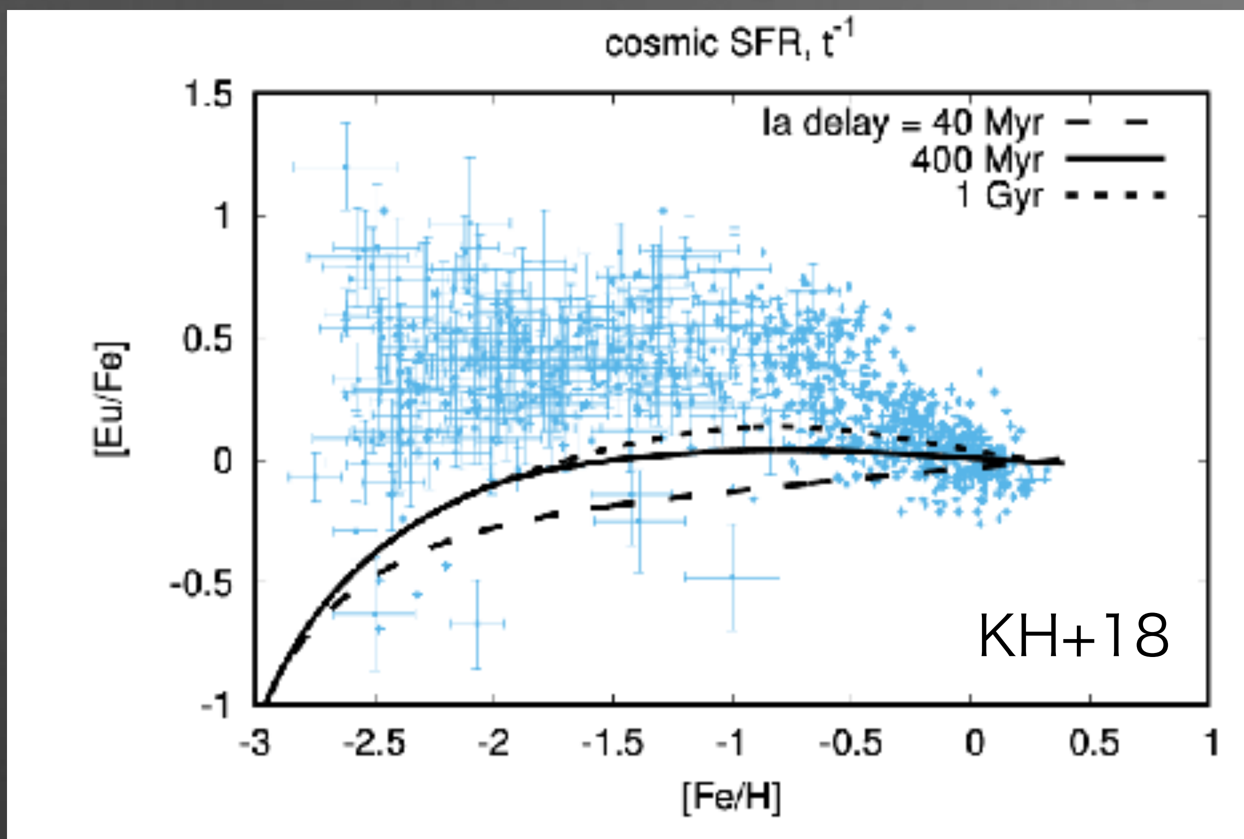
R-process: Rate and Mass



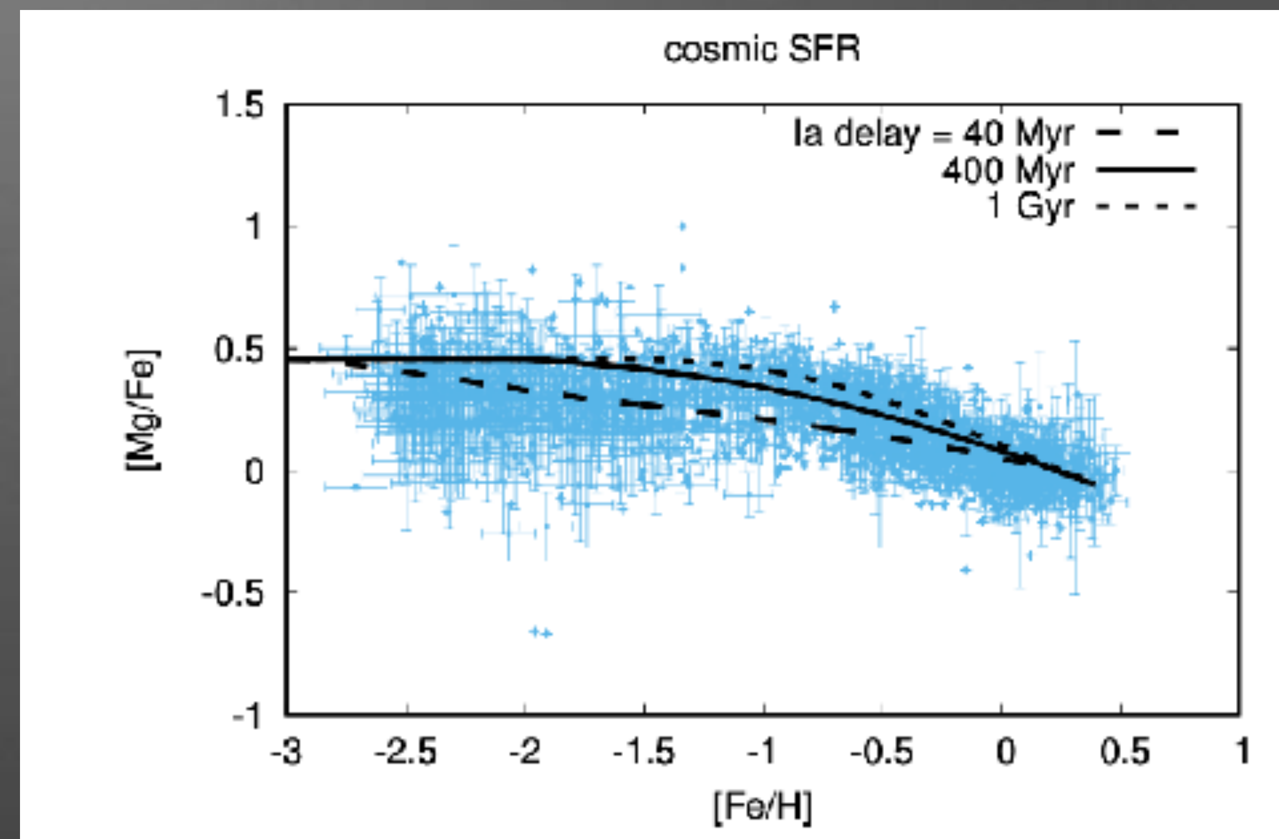
In principle, neutron star mergers can provide all the r-process elements.

Delay problem of NS mergers

Neutron star mergers (delay)

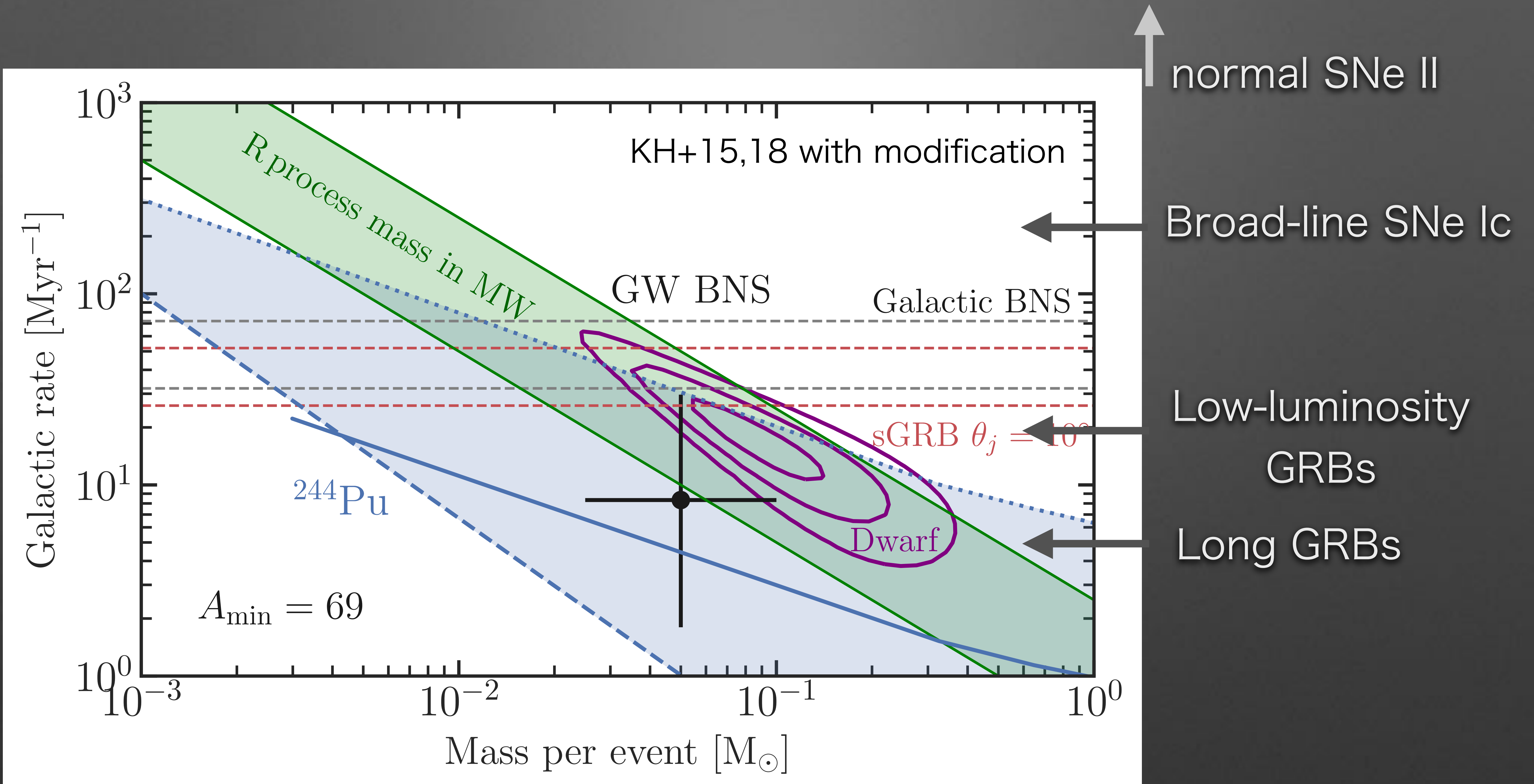


Core collapse (no delay)



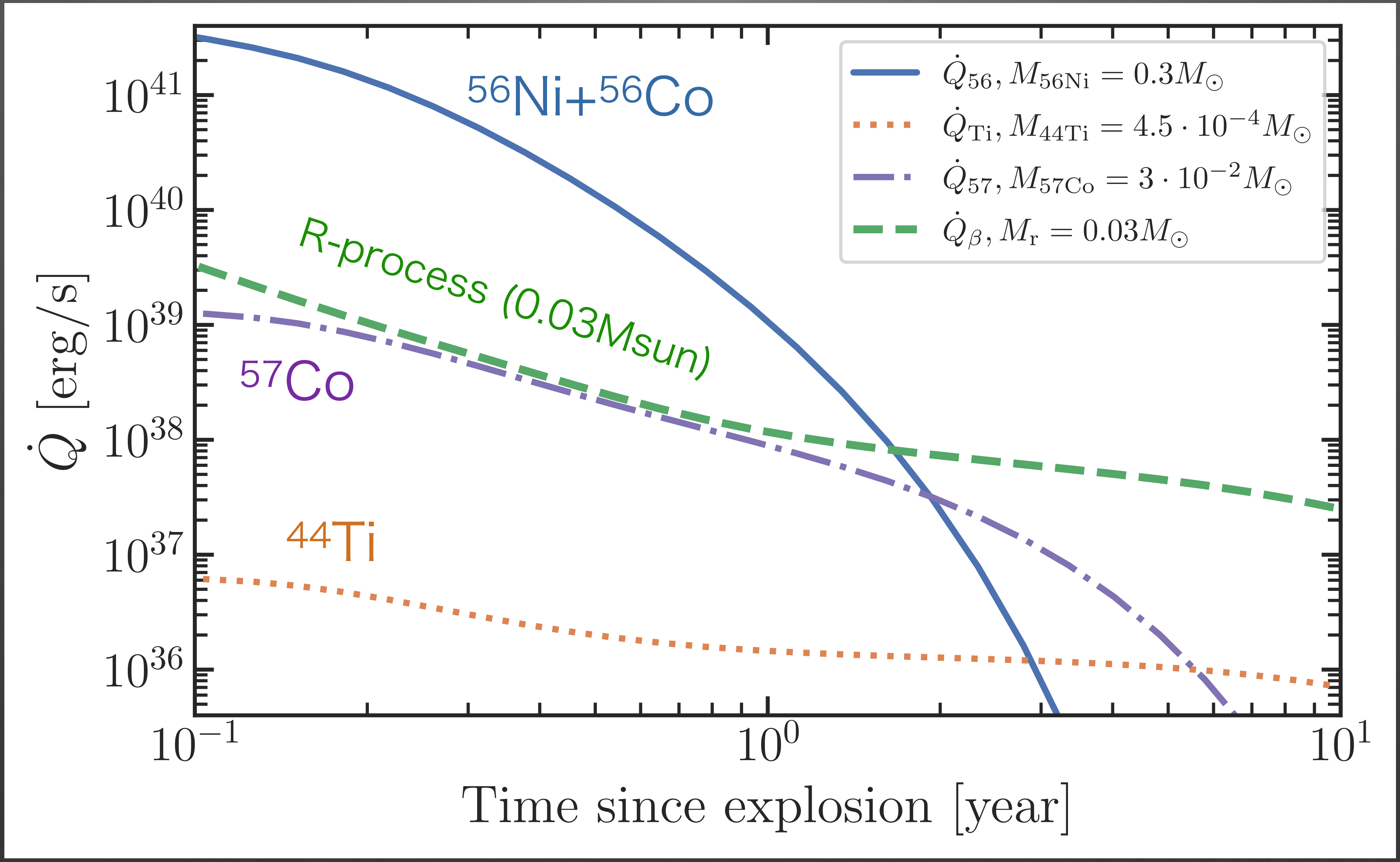
- **R-process production** rate follows the star formation **without delay** at least in our Galaxy.
- This fact challenges neutron star mergers as the dominant production site, c.f., 1-10 Gyr delay for GW170817.

R-process: Rate and Mass



The rates of mergers, llGRBs, long GRBs correspond to **0.01 - 0.1Msun**.
We'd like to test whether these events produce r-process elements or not.

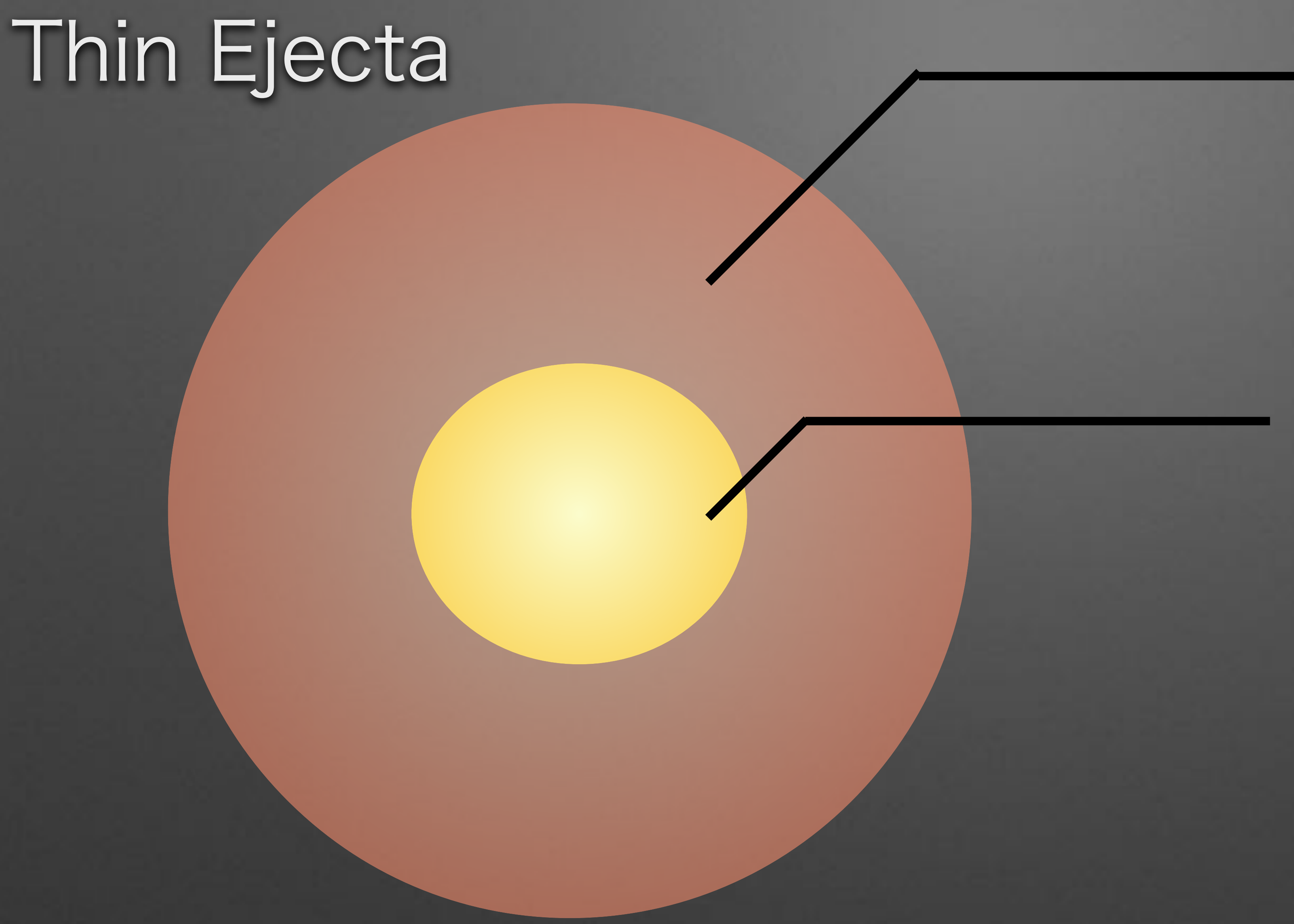
Energy budget in broad-lined SN Ic including GRB/SNe



R-process of 0.03Msun can dominate the heating t>2yr.

However, it is likely difficult to distinguish from overproduction of ^{44}Ti.

Set up



Envelope

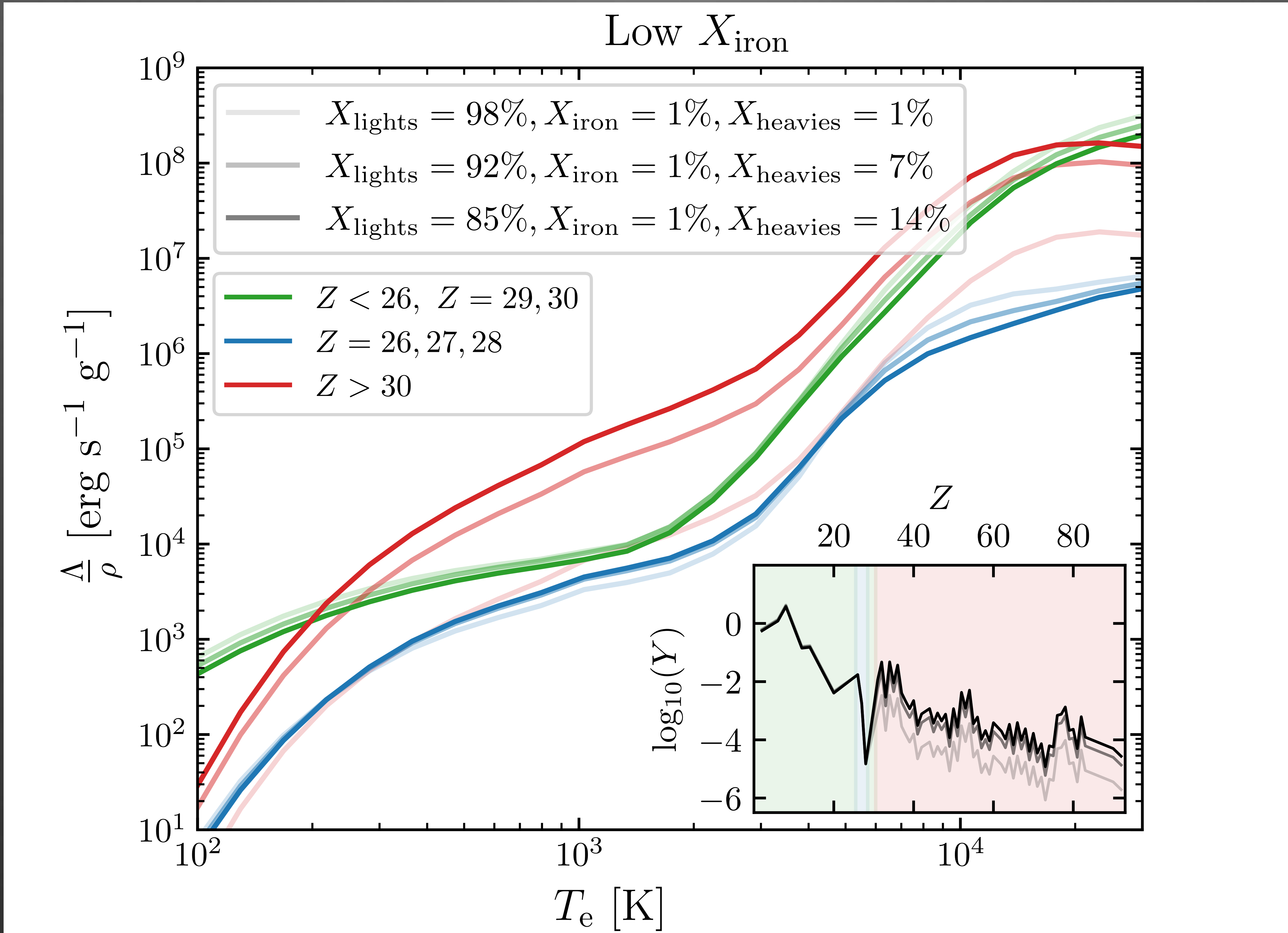
- α-elements
- no radioactivity
- no emission

Radioactive Core

- α-elements (~3Msun)
- Iron group (0.3Msun)
- R-process (0.1Msun)
- v_{exp} ~ 5000km/s
- Solar r-process abundance
- No molecules

- Collision excitation/deexcitation, radiative decay, escape probability are included. For r-process, only M1 lines are included.
- Temperature is set such that the optical spectrum agrees with SN 1998bw (Dessart+17, see also, Patat+01, Mazzalli + 01, Maeda+06).

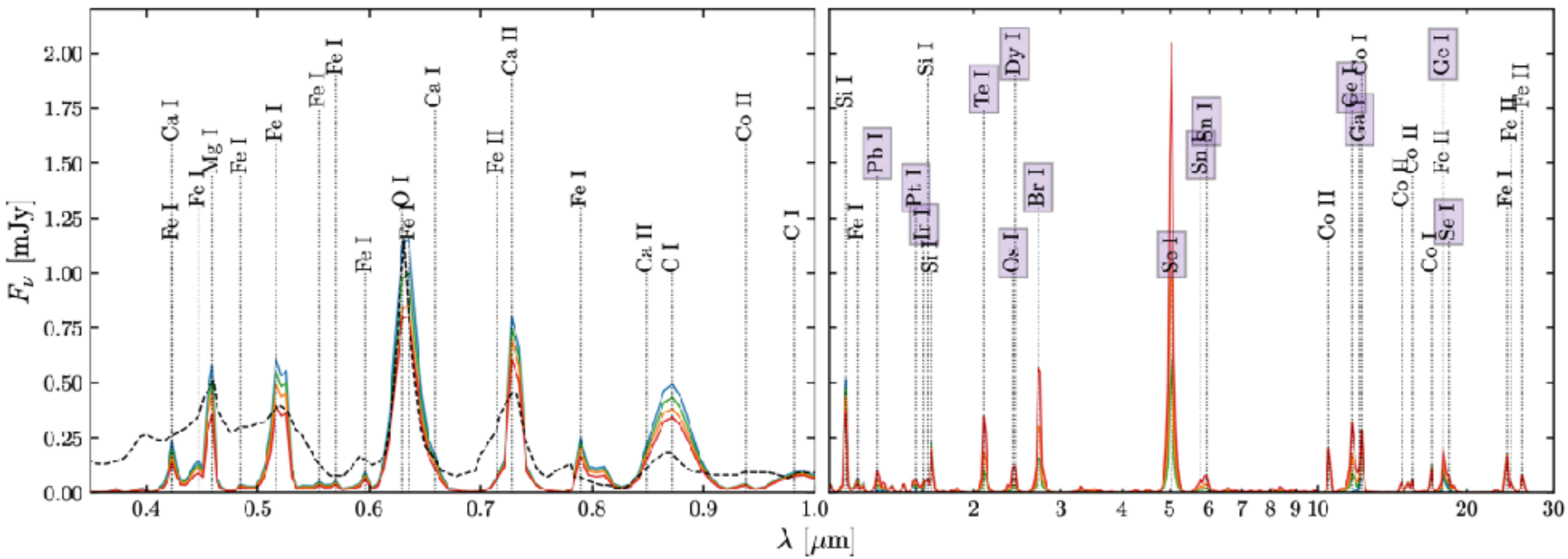
Abundance & Cooling function



Ricigliano, KH, Arcones in prep

SN Ic Nebular Emission with r-process

Ricigliano, KH, Arcones in prep



- Optical region is dominated by light and Fe-group elements.
- Optical E1 & E2 lines of r-process elements may be missing.
- R-process elements appear in 1 - 10 μm.
- O(10^{-3}) M_{sun} of r-process elements can produce observable features.

Summary & Discussion

- Forbidden (Fine structure, M1) lines appear in the kilonova nebular phase. It is relatively easy to construct an M1 line list. But, other atomic data are needed.

- 2.1μm line seen in GW170817 and GRB 230307A can be [Te III] line.

- The Spitzer detection (4.5μm, GW170817) can be explained by W III or Se III.

- The IR bump (peaking at 5μm, GRB 230307A) is unexplained. If GRB 230307A is a merger, unknown property of atoms or dust?

- R-process production in SNe Ic with a mass of > 10^{-3} M_{sun} can be detectable through nebular spectra.