Kilonova and r-process in neutron star mergers

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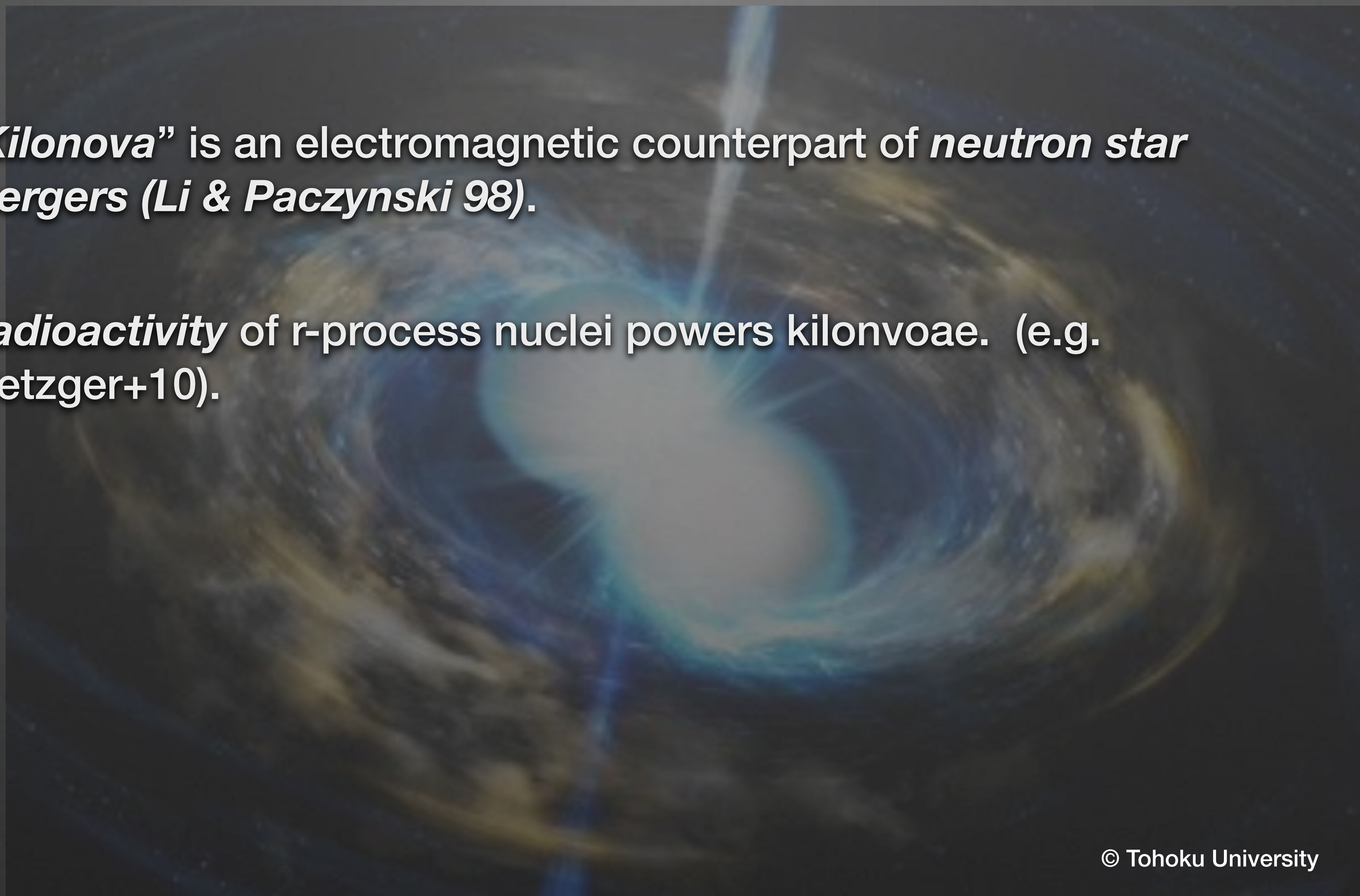
Collaboration with M. Tanaka, D. Kato, G. Gaigalas, Y. Tarumi, N. Domoto, E. Nakar

Introduction: Kilonova

- “*Kilonova*” is an electromagnetic counterpart of ***neutron star mergers (Li & Paczynski 98)***.
- ***Radioactivity*** of r-process nuclei powers kilonvoae. (e.g. Metzger+10).



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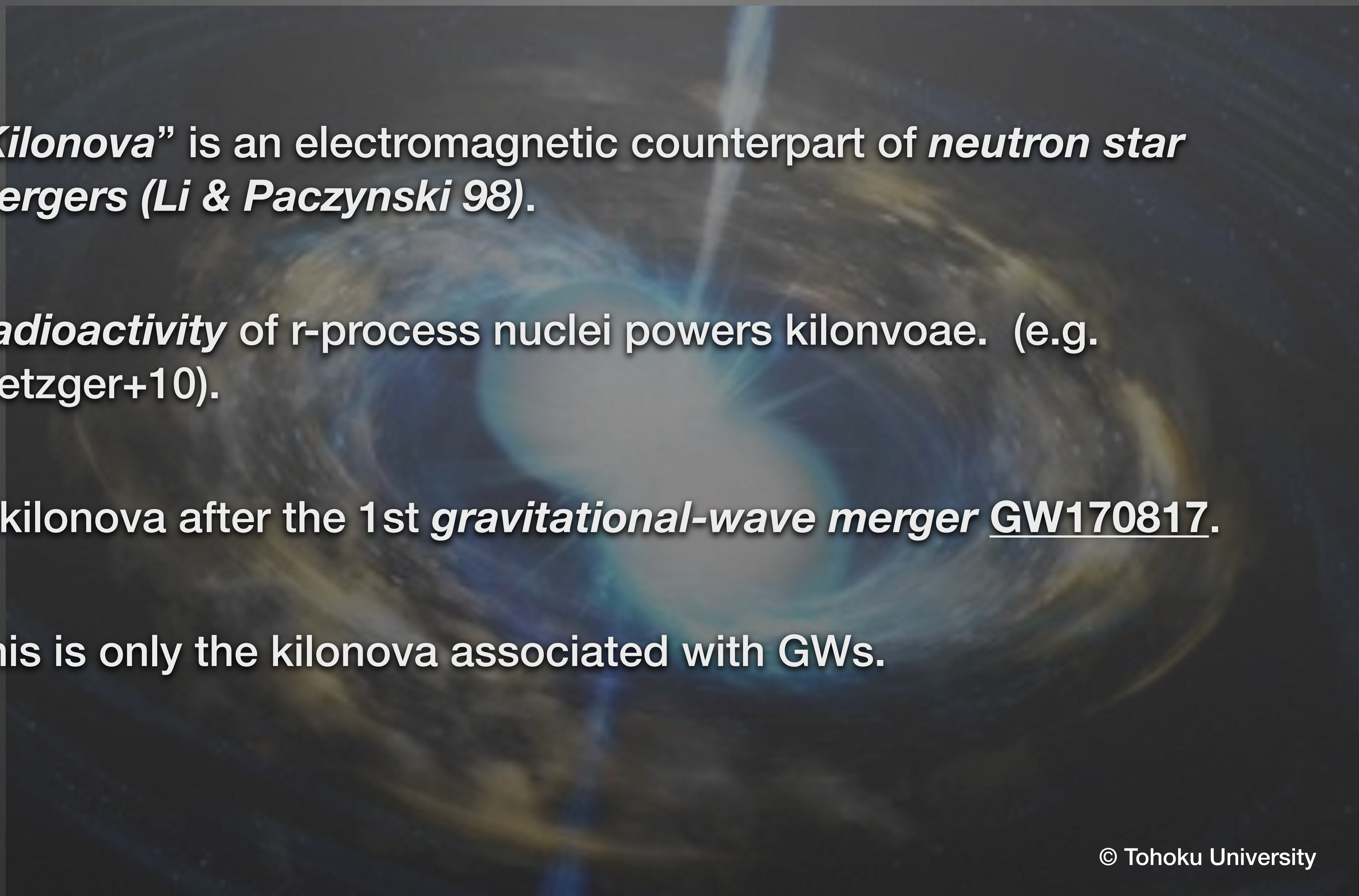

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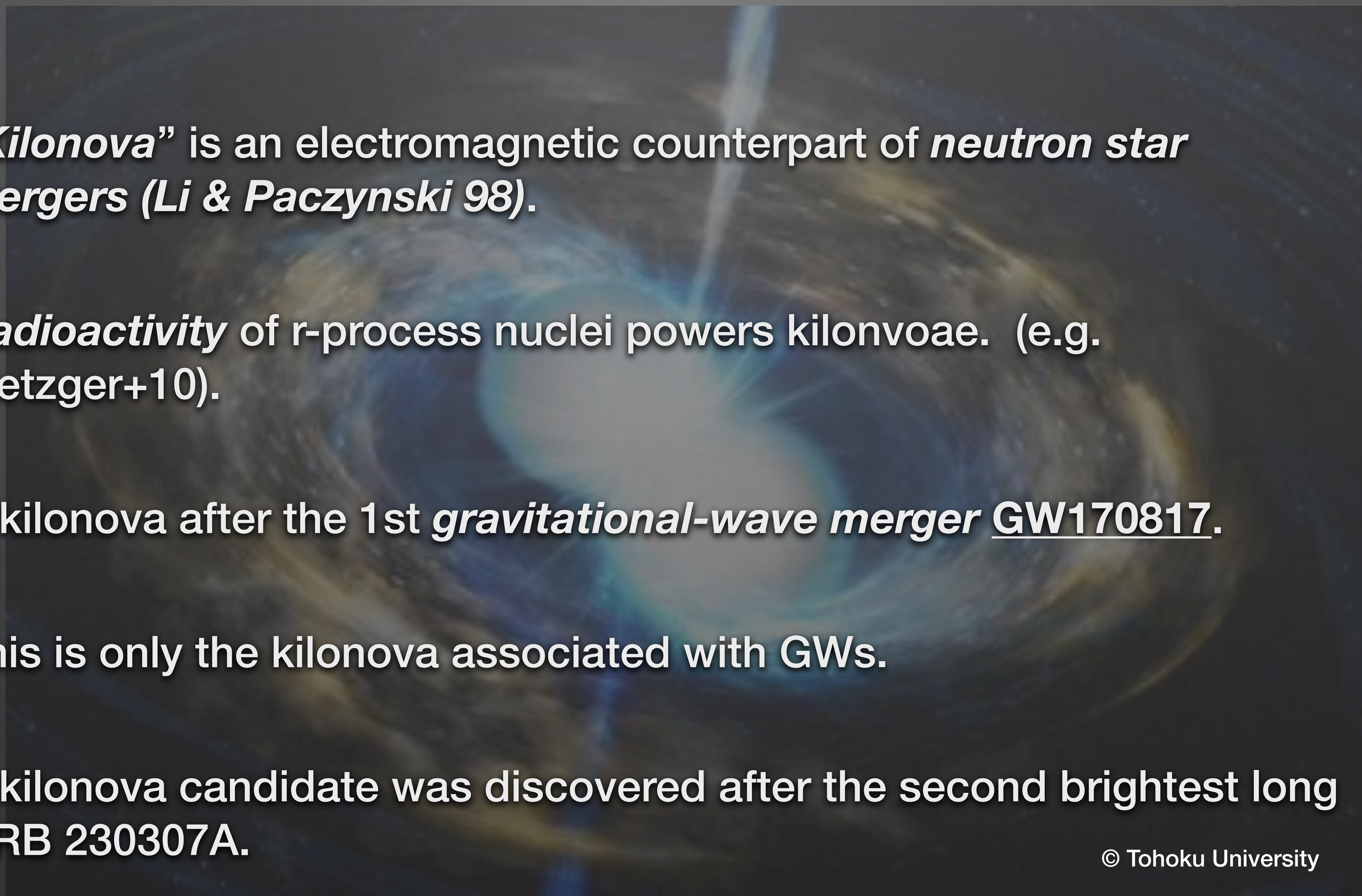
- A kilonova after the 1st ***gravitational-wave merger*** GW170817.
- This is only the kilonova associated with GWs.

Introduction: Kilonova



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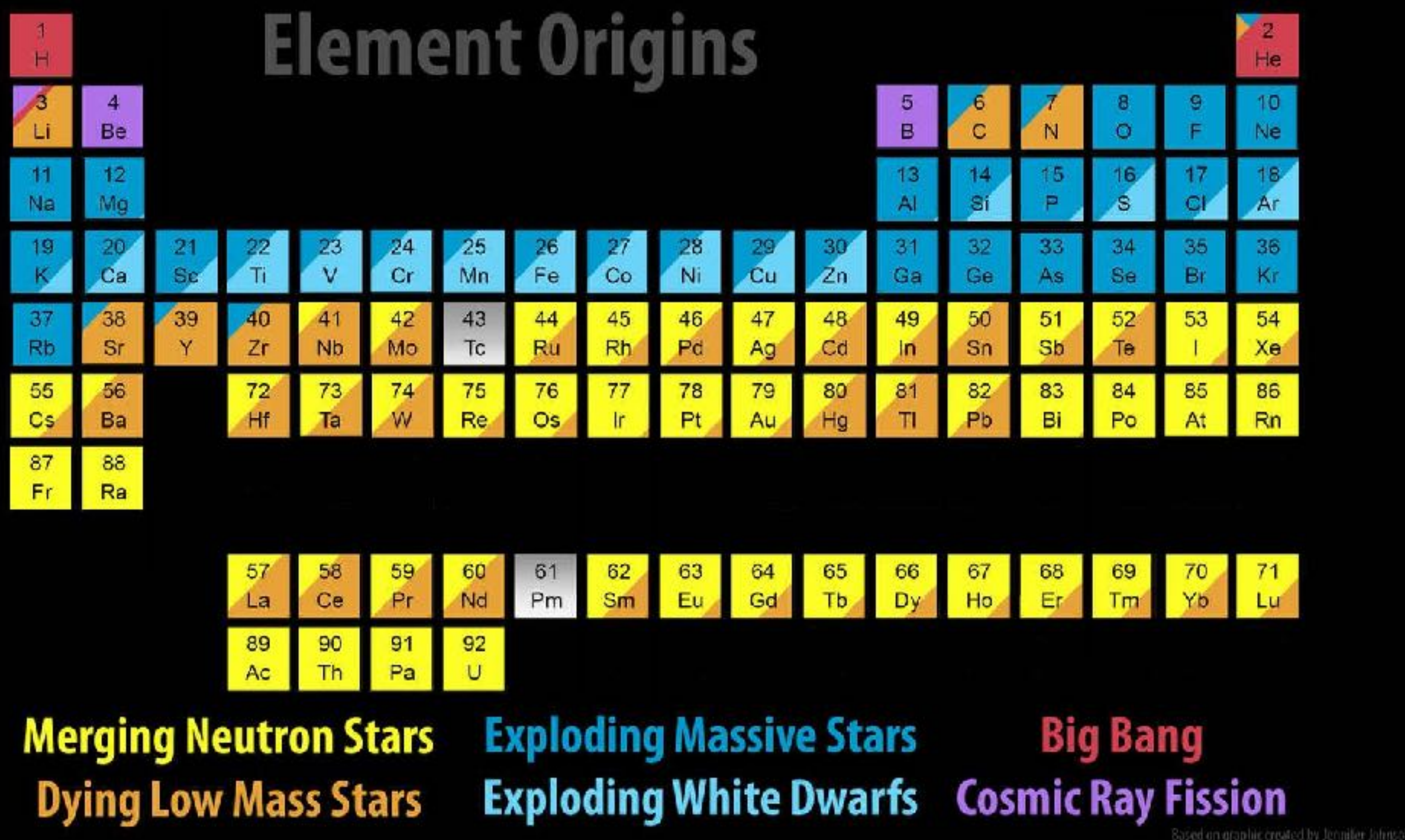
- This is only the kilonova associated with GWs.
- A kilonova candidate was discovered after the second brightest long GRB 230307A.

- JWST took the spectra of this event.

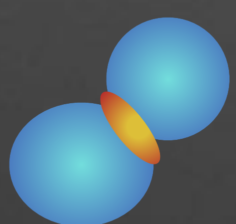
We wish to learn the elements' origin from kilonova observations



Neutron Star Merger & Kilonova

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

Merger



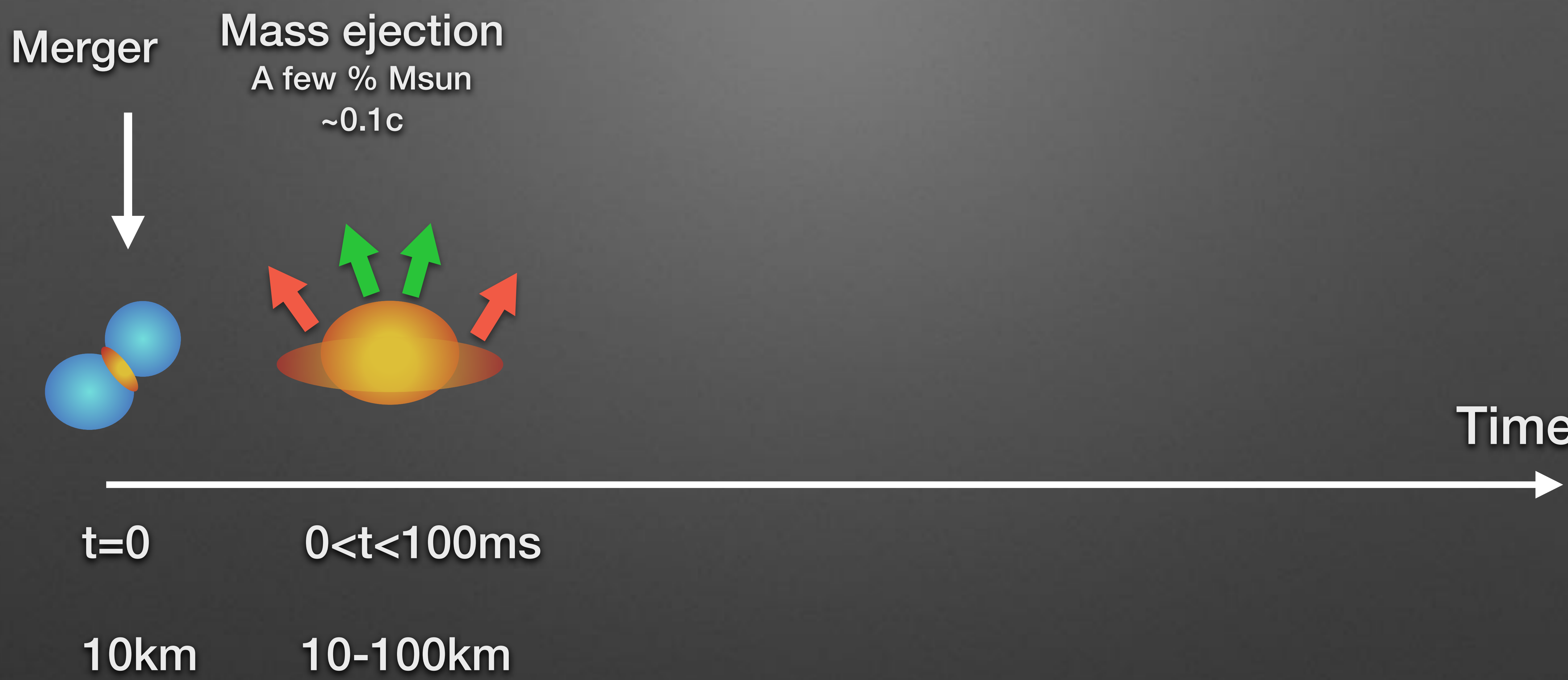
Time

t=0

10km

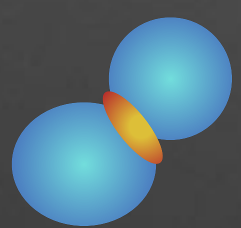
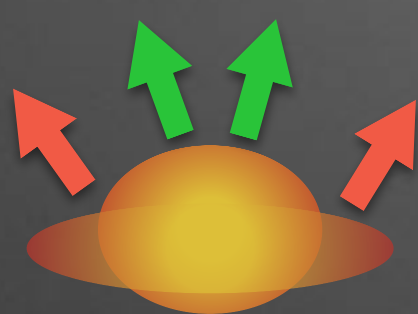
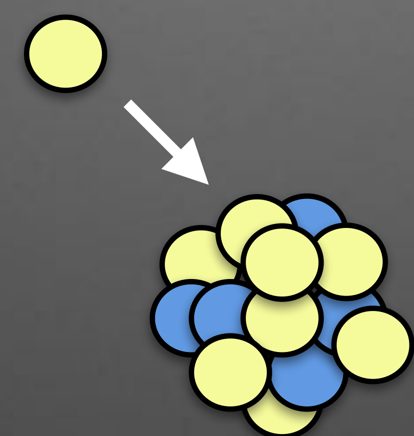
Neutron Star Merger & Kilonova

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



Neutron Star Merger & Kilonova

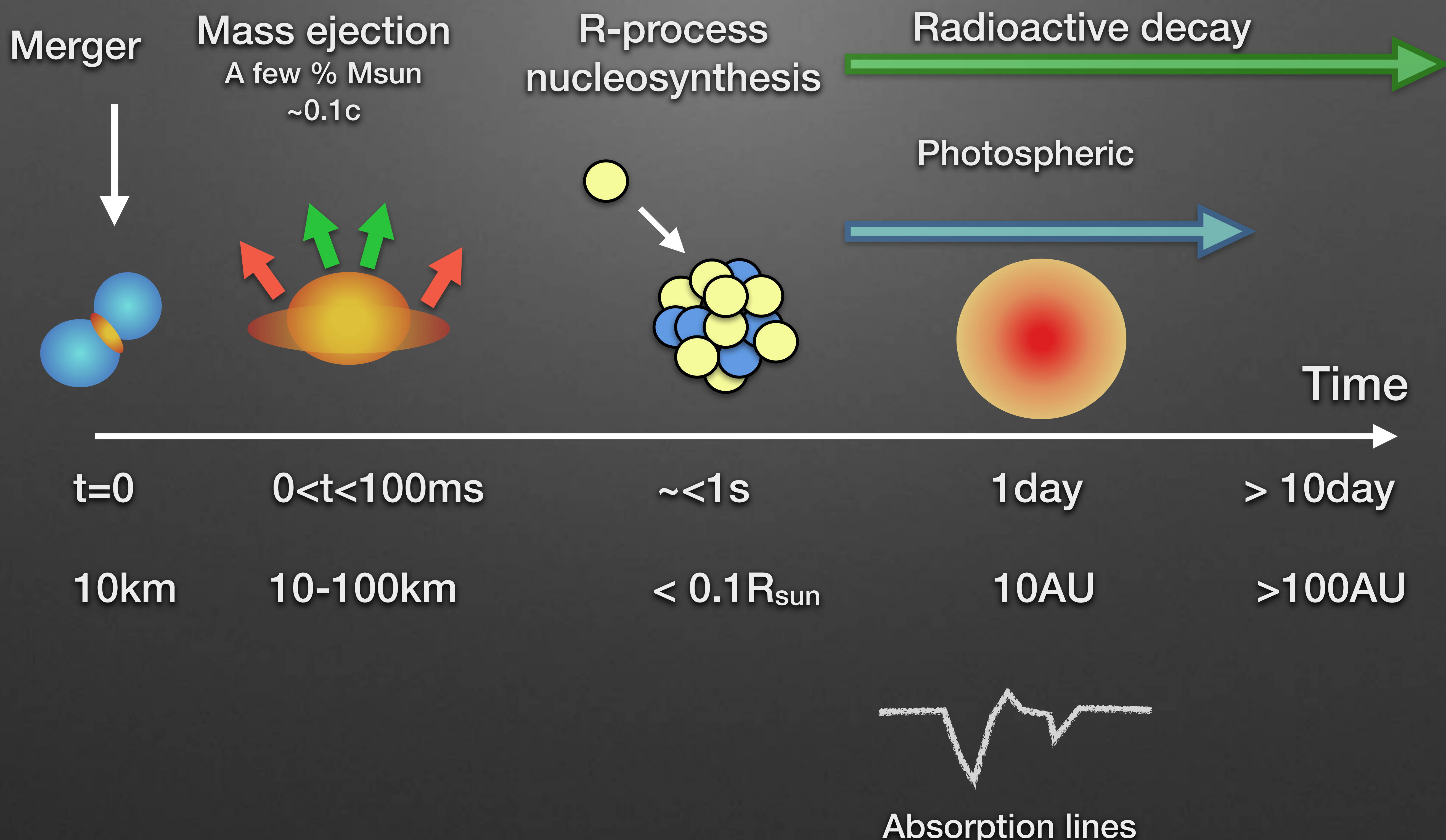
Li & Paczynski 98, Kulkarni 05, Metzger + 10, Barnes & Kasen 13, Tanaka & KH 13

Merger	Mass ejection A few % Msun ~0.1c	R-process nucleosynthesis
		
t=0	0<t<100ms	~<1s
10km	10-100km	$< 0.1 R_{sun}$

Time

Neutron Star Merger & Kilonova

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



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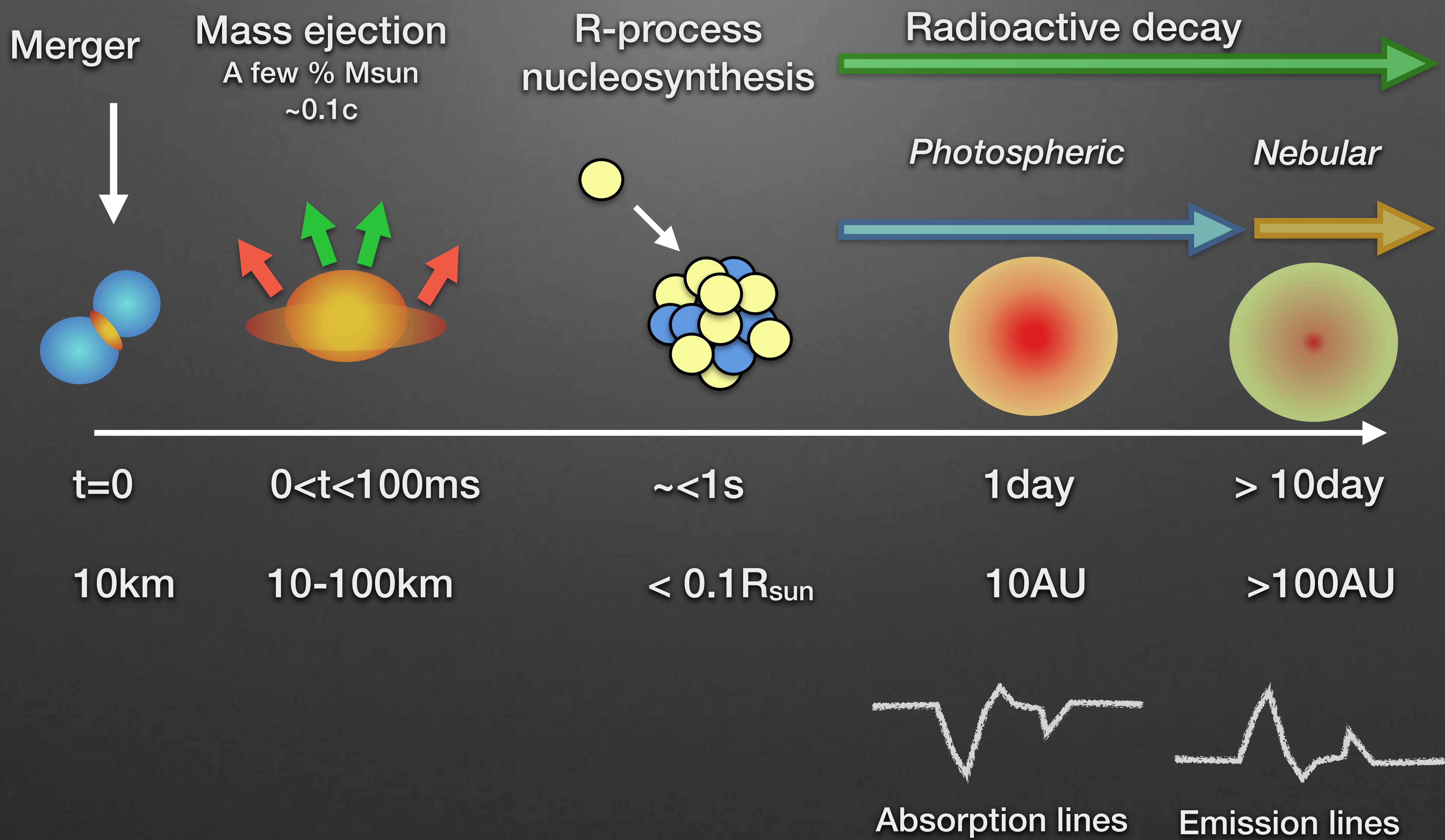
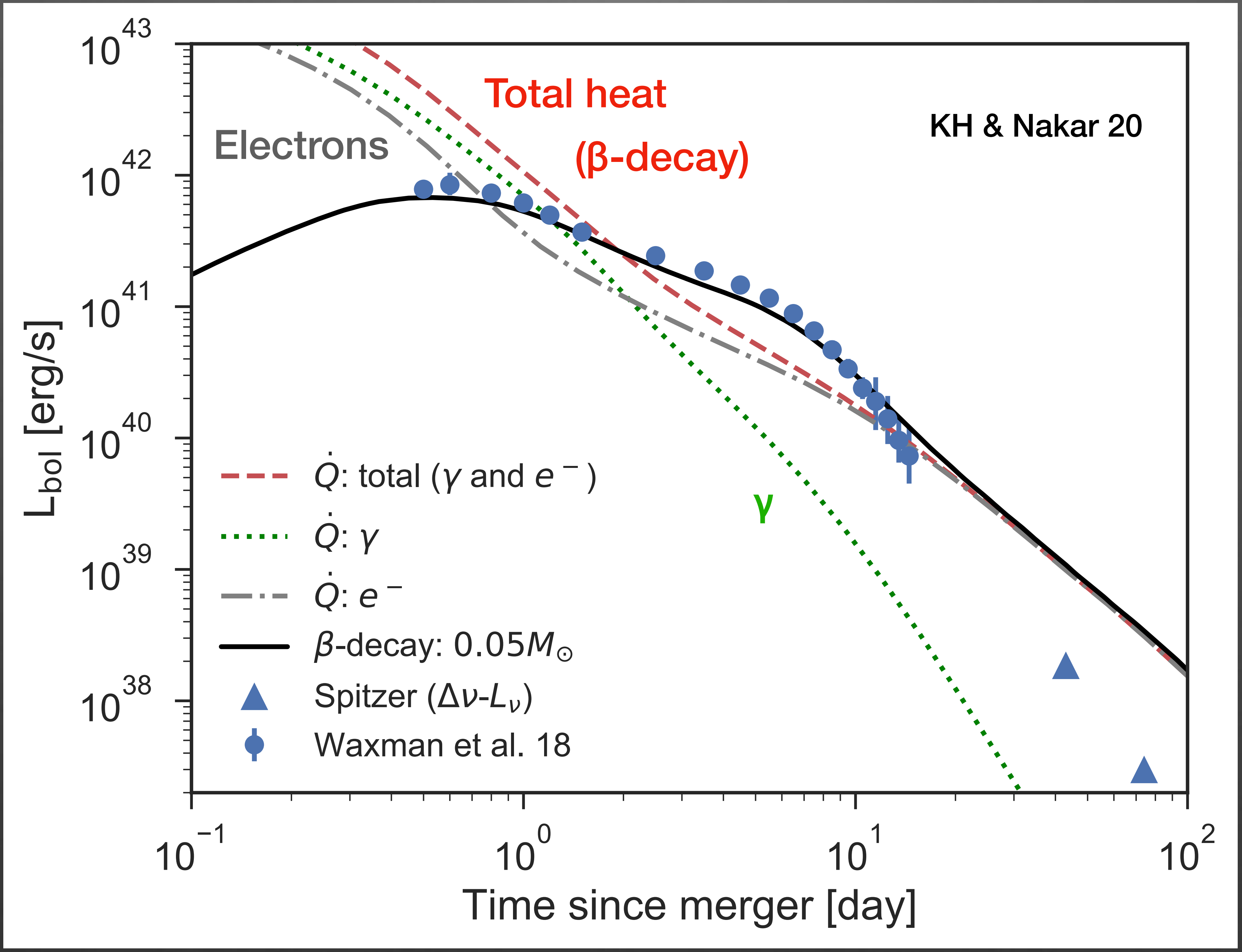


The energy budget of the Kilonova in GW170817



Kilonova: Mass, Velocity, Opacity, Radioactivity

Peak time:

$$t_{\rm p} \approx \sqrt{\frac{\xi\kappa M_{\rm ej}}{4\pi c v_{\rm ej}}} \approx 5\,{\rm days}\,\xi^{1/2}\left(\frac{\kappa}{10\,{\rm cm}^2/{\rm g}}\right)^{1/2}\left(\frac{M_{\rm ej}}{0.01M_\odot}\right)^{1/2}\left(\frac{v_{\rm ej}}{0.1c}\right)^{-1/2},$$

Peak Luminosity:

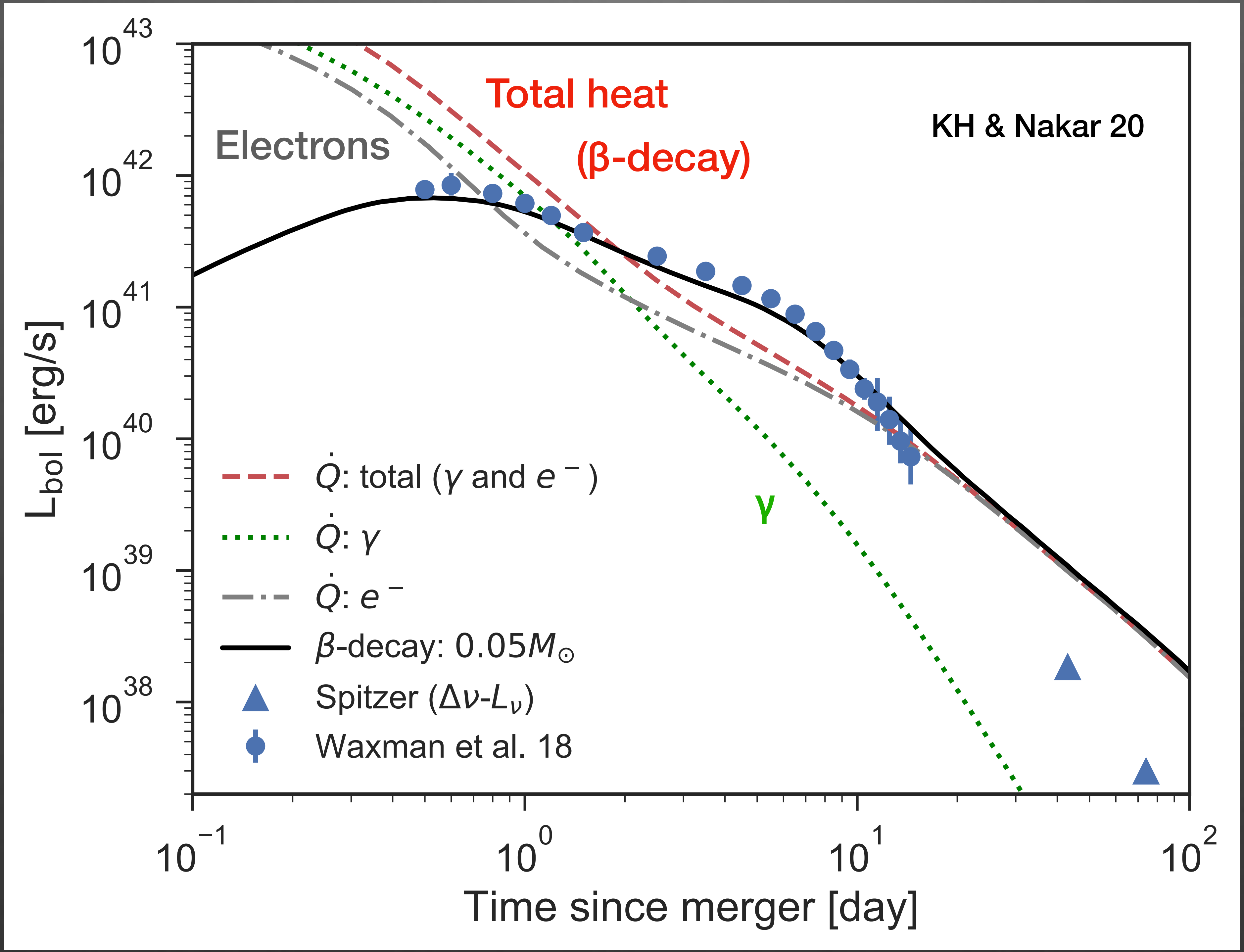
Radioactivity

$$L_{\rm bol}(t > t_{\rm p}) \approx M_{\rm ej}\cdot\dot{Q}(t) \approx 2.5\cdot 10^{40}\,{\rm erg/s}\left(\frac{t_p}{5\,{\rm day}}\right)^{-1.3}\left(\frac{M_{\rm ej}}{0.01M_\odot}\right),$$

Temperature:

$$T_{\rm eff}(t_{\rm p}) \approx \left(\frac{L_{\rm bol}(t_{\rm p})}{4\pi\sigma v_{\rm ej}^2 t_{\rm p}^2}\right)^{1/4} \approx 2200\,{\rm K}\left(\frac{L_{\rm bol,p}}{2.5\cdot 10^{40}\,{\rm erg/s}}\right)^{1/4}\left(\frac{v_{\rm ej}}{0.1c}\right)^{-1/2}\left(\frac{t_{\rm p}}{5\,{\rm day}}\right)^{-1/2} \quad (5)$$

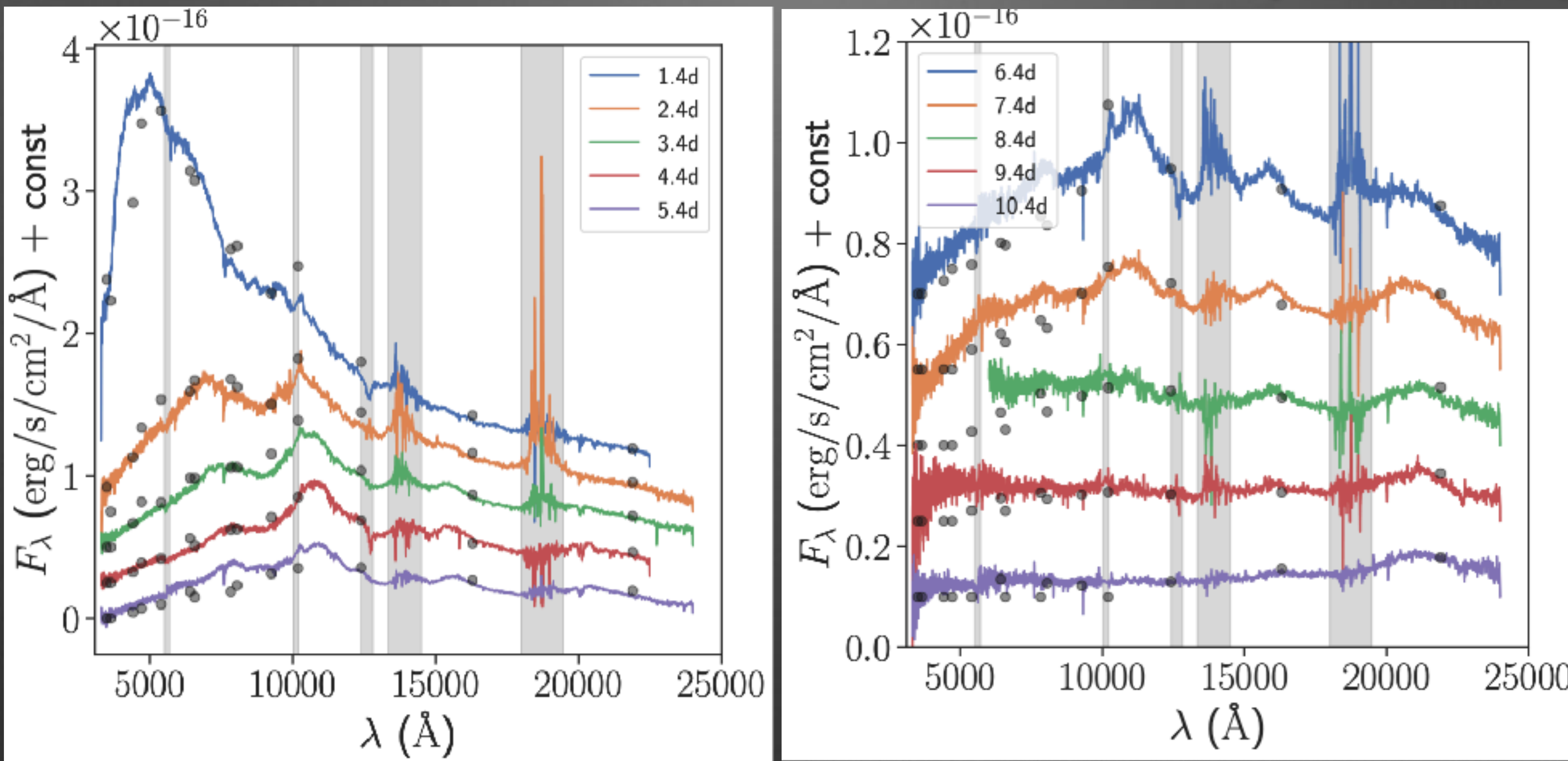
The energy budget of the Kilonova in GW170817



- Ejecta mass is~ 0.05Msun.
- The photospheric velocity ~0.1-0.3c.

Observed Spectrum of kilonova GW170817

VLT X-Shooter (Pian et al. 2017)



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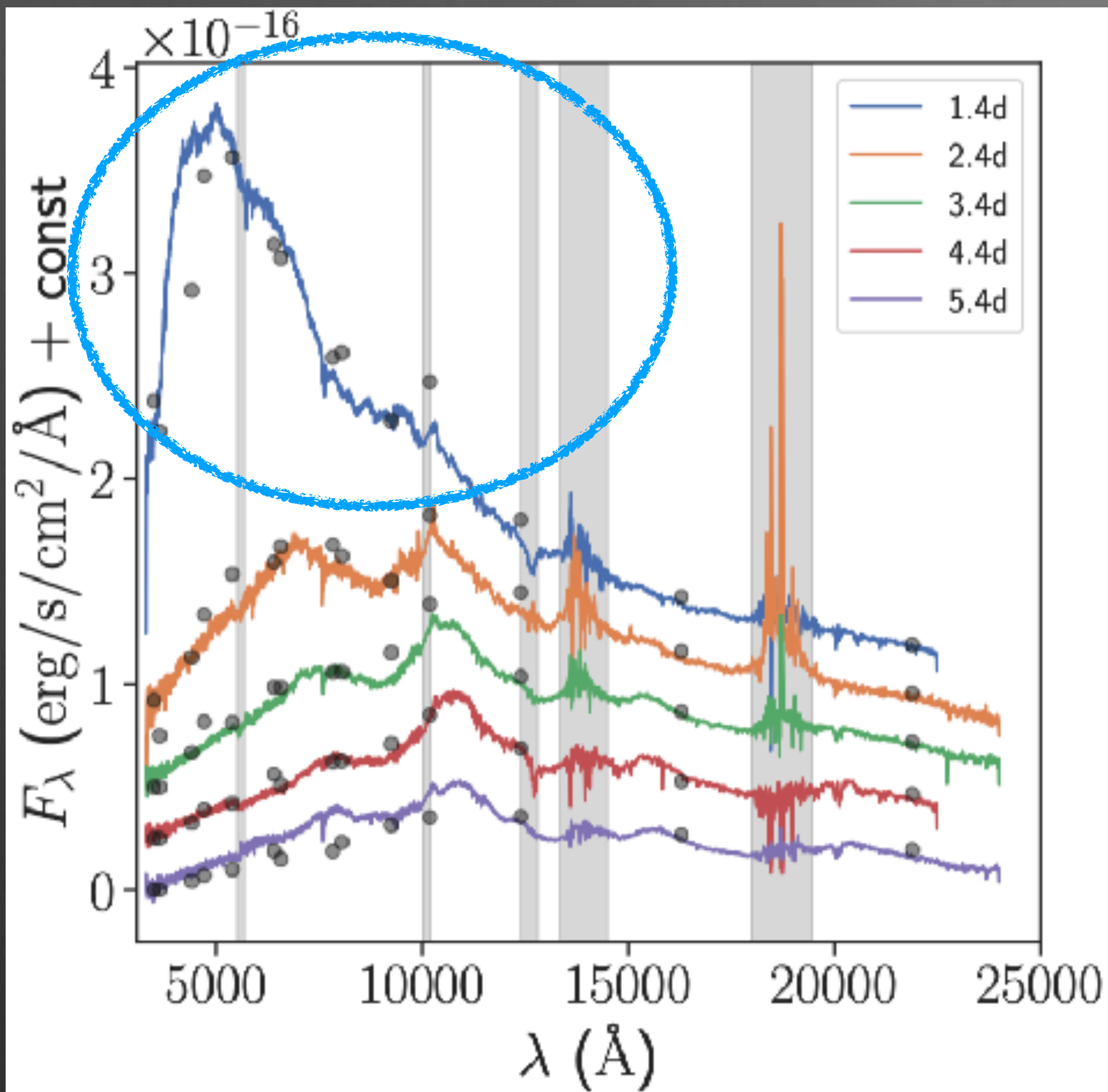

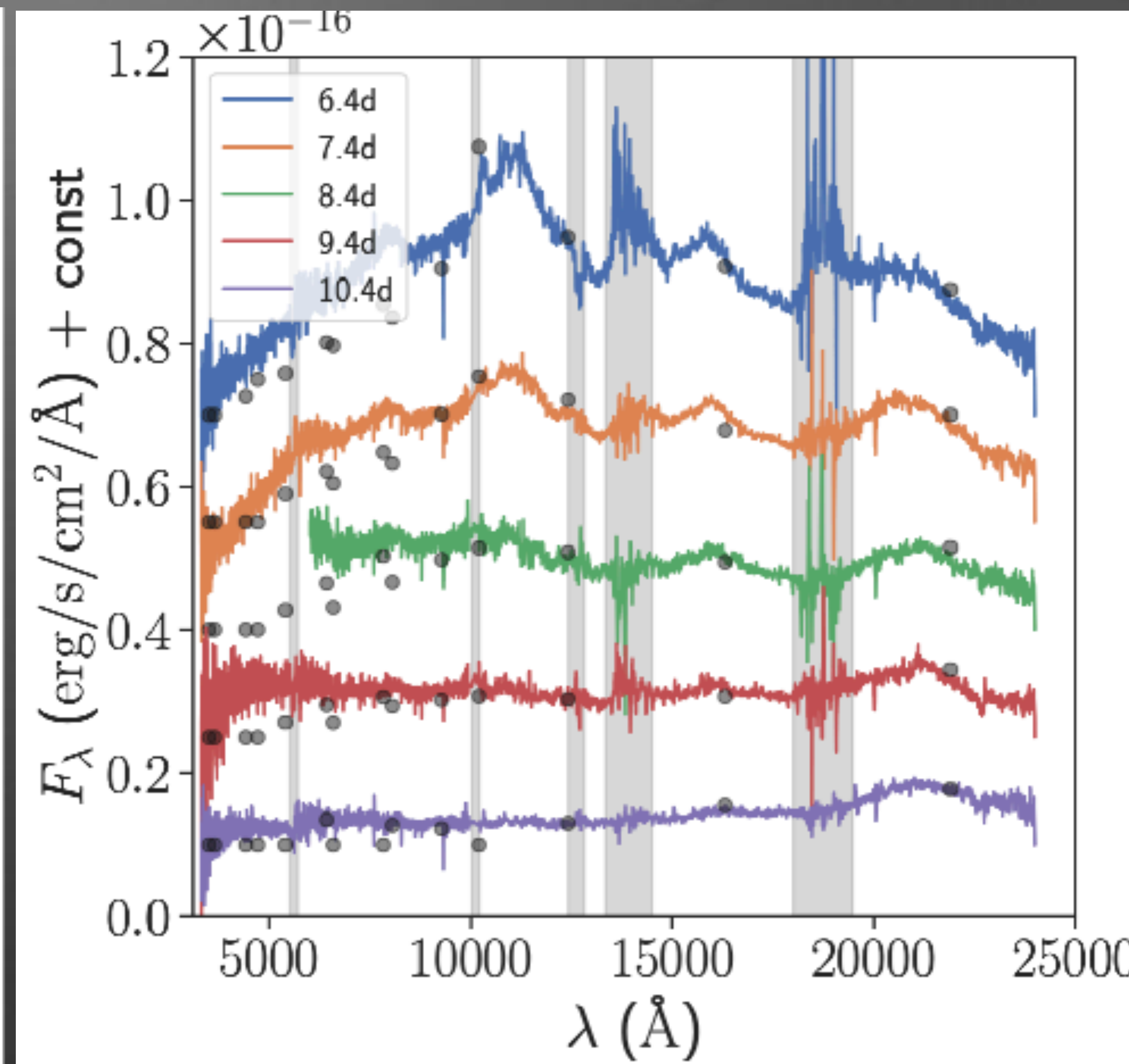

The temperature is low ~ 5000 K even at 1.5 day.

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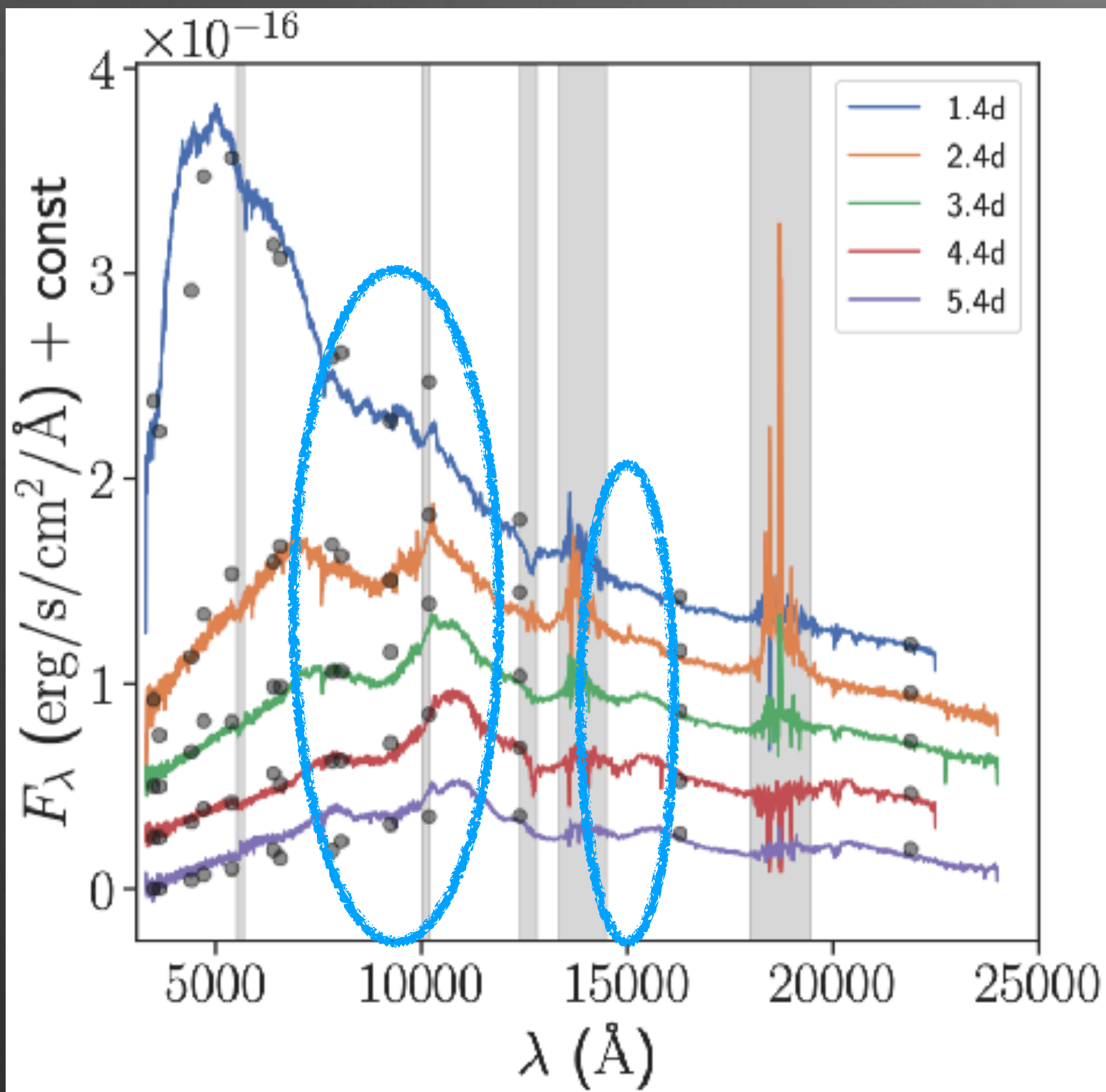

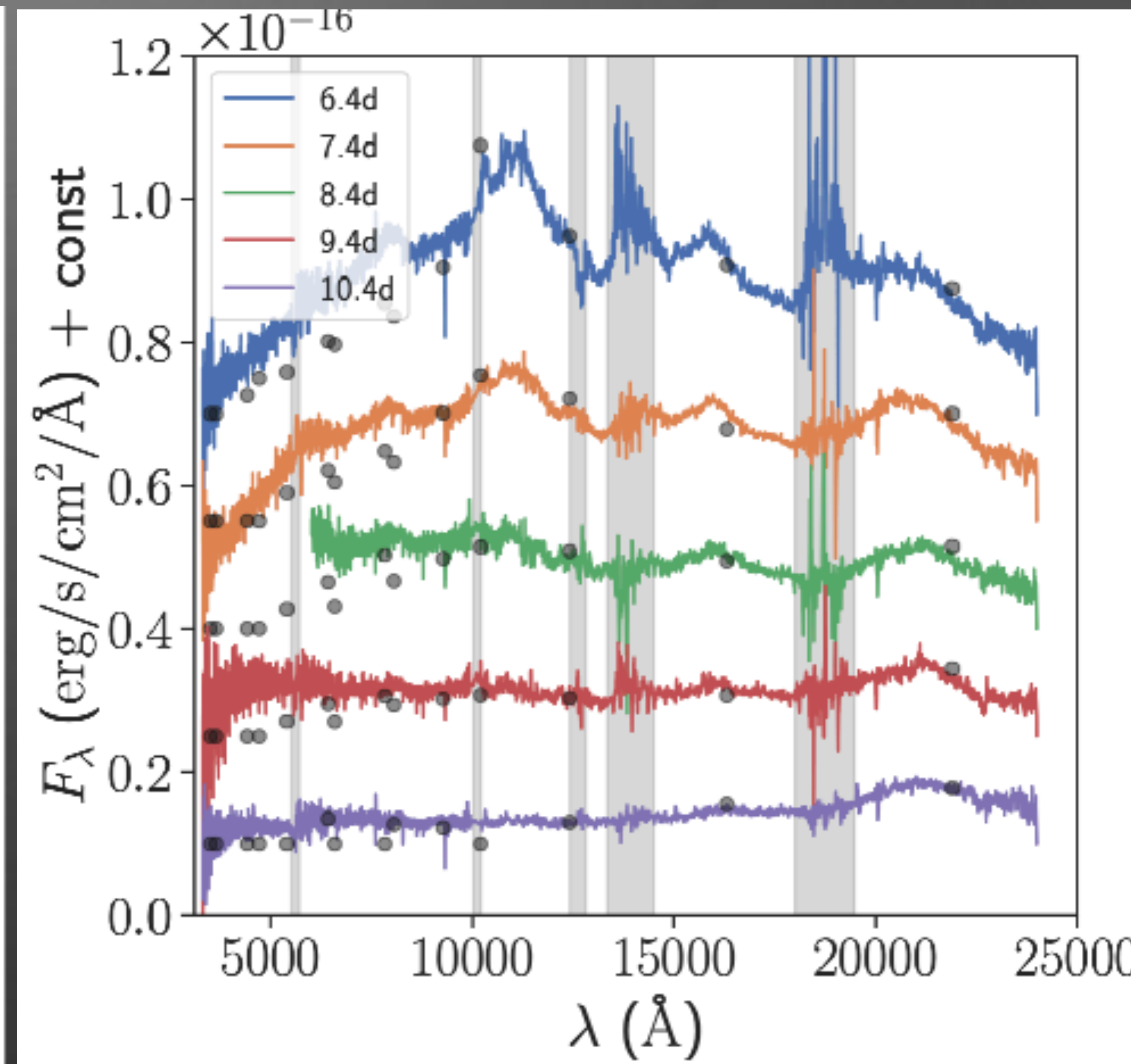

Two clear absorption line features at 8000A & 15000A.

Observed Spectrum of a kilonova GW170817

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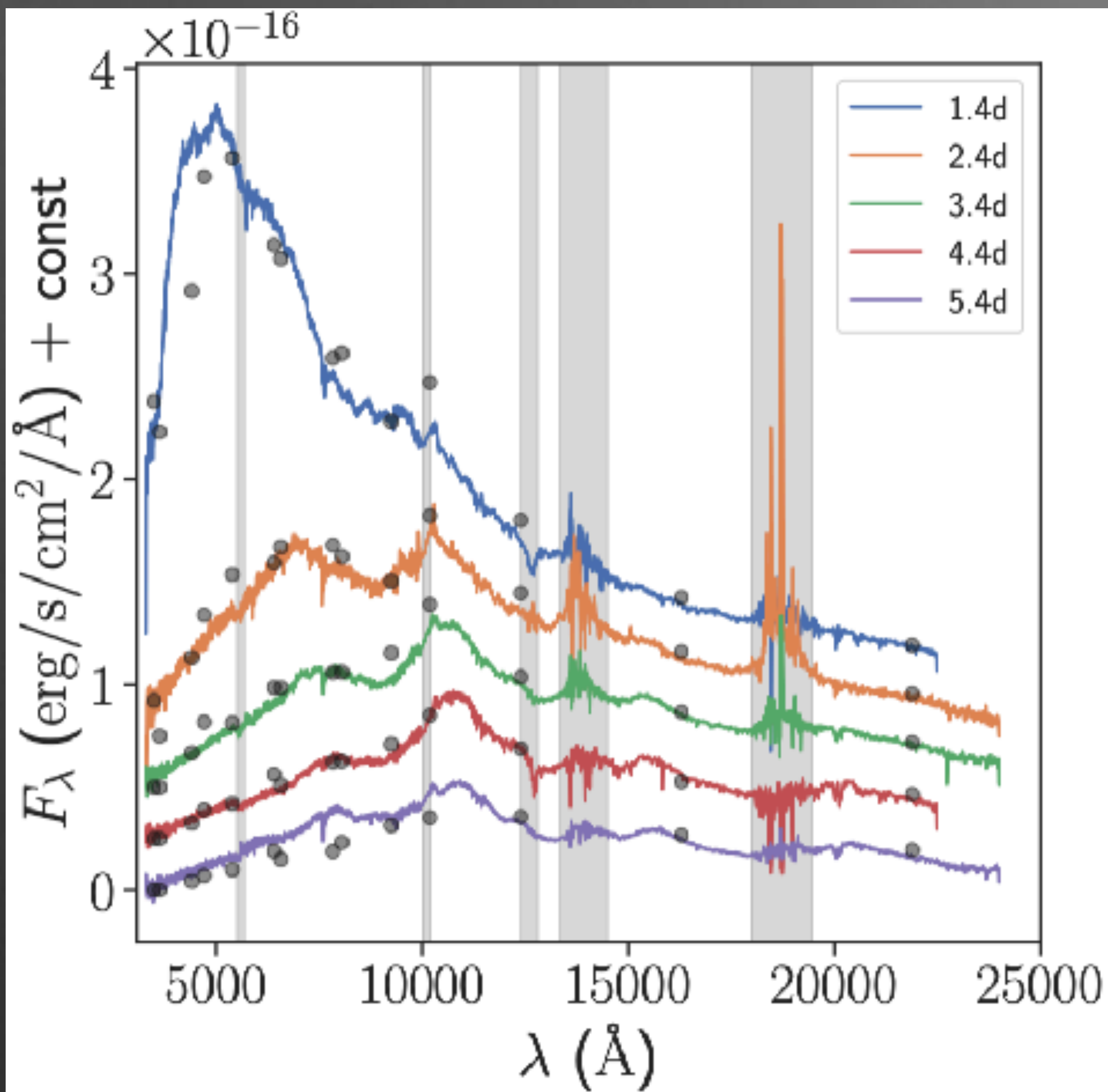
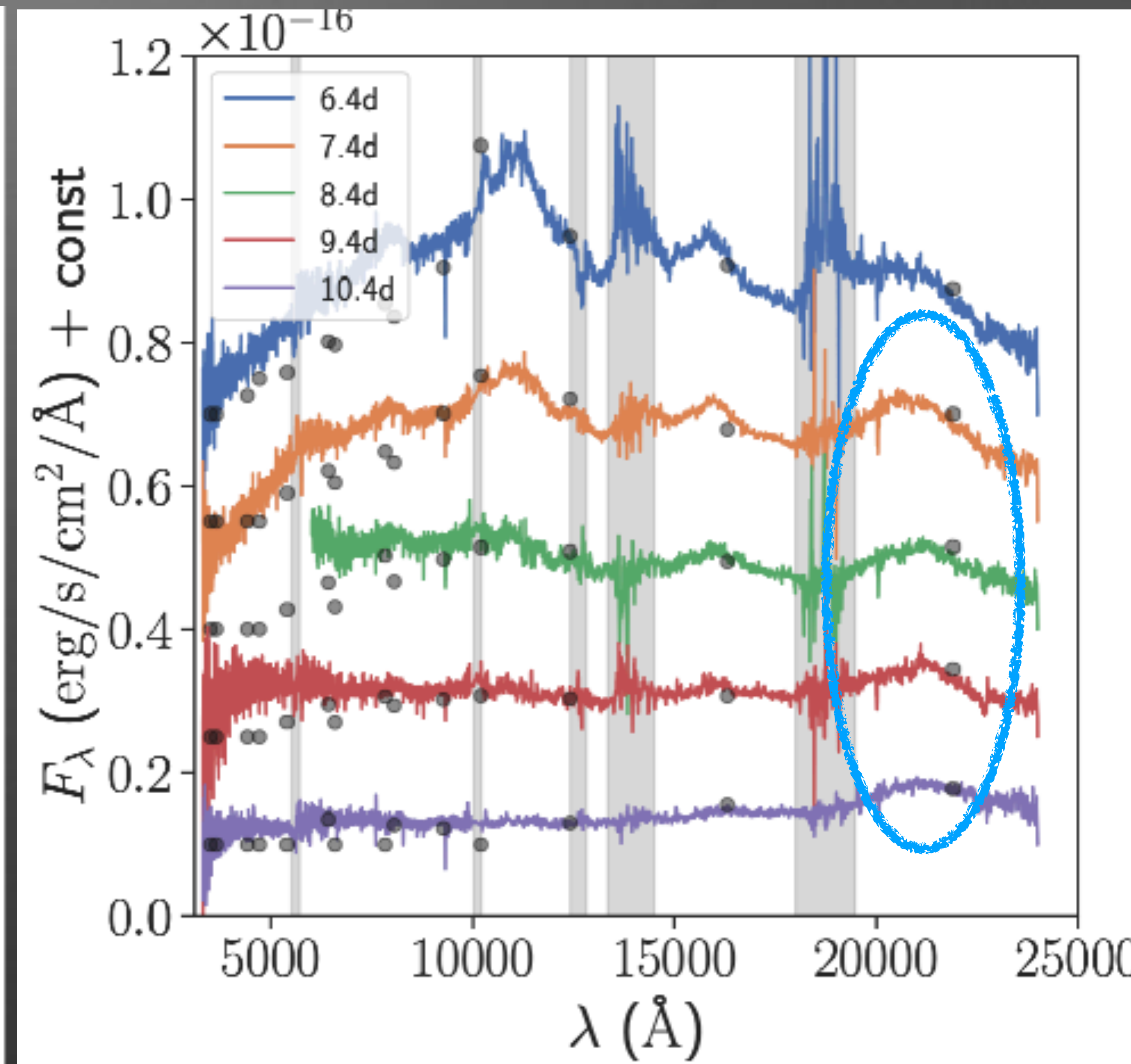
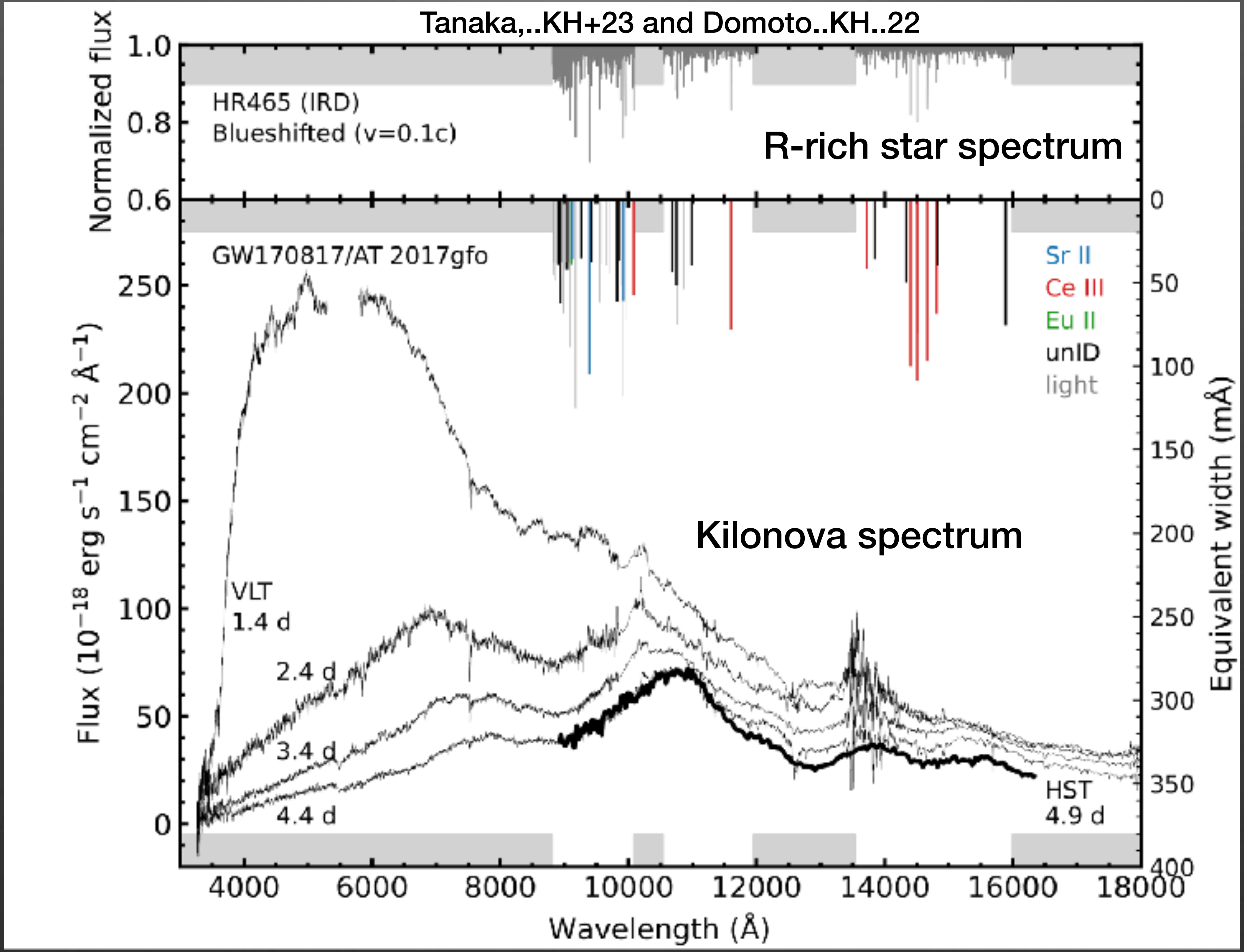




Later, >7.5d , an emission line feature appears at 2.1μm.

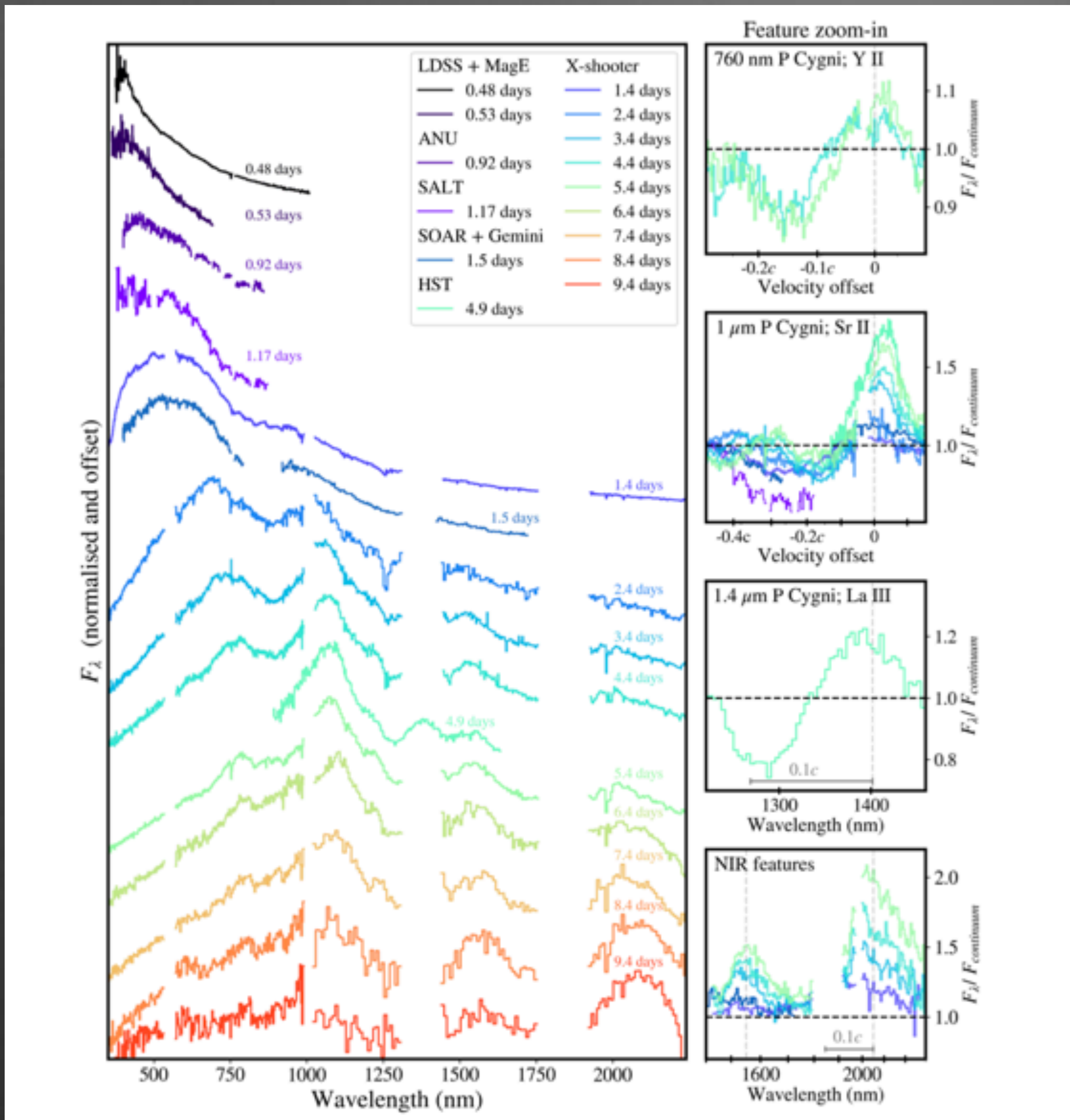
Kilonova vs R-rich star

Strong absorption lines in kilonova should exist in r-rich stars' spectra.



Absorption line identification in GW70817

Sneppen + 24, see also, Watson+19, Pian +17



P-Cygni lines (absorption-emission line)

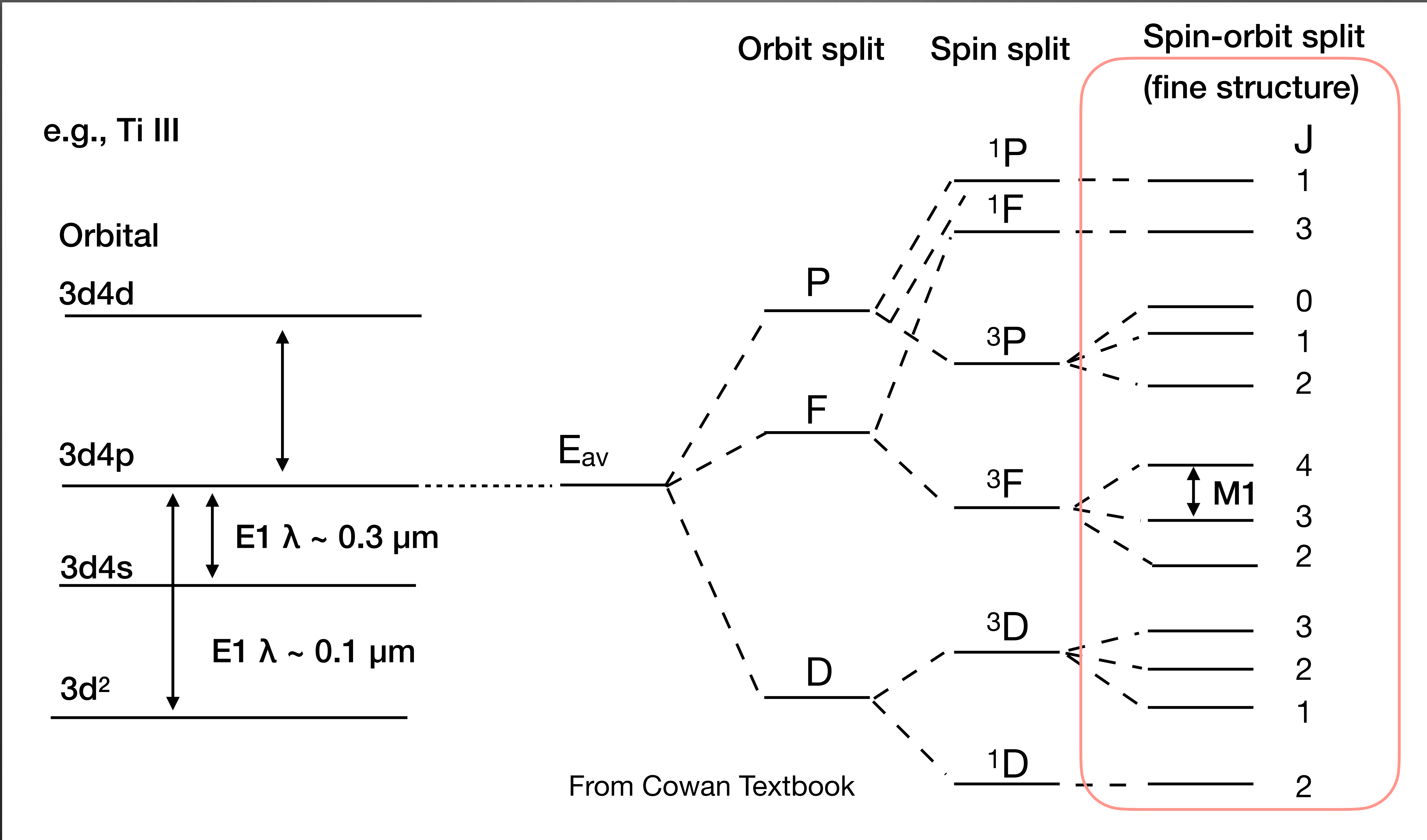
- Sr II: 0.8μm feature (Watson+19, Gillanders+21, but see Tarumi, KH, + 23 for He I)
- Y II: Sneppen & Watson 23
- La III: 1.3μm feature (Domoto…KH, 22)
- Ce III: 1.6μm feature (Domoto…KH, 22, Tanaka…KH, 23)

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	Ln	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	An															
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	102 Lr

Effective Z ↑, energy level split ↑

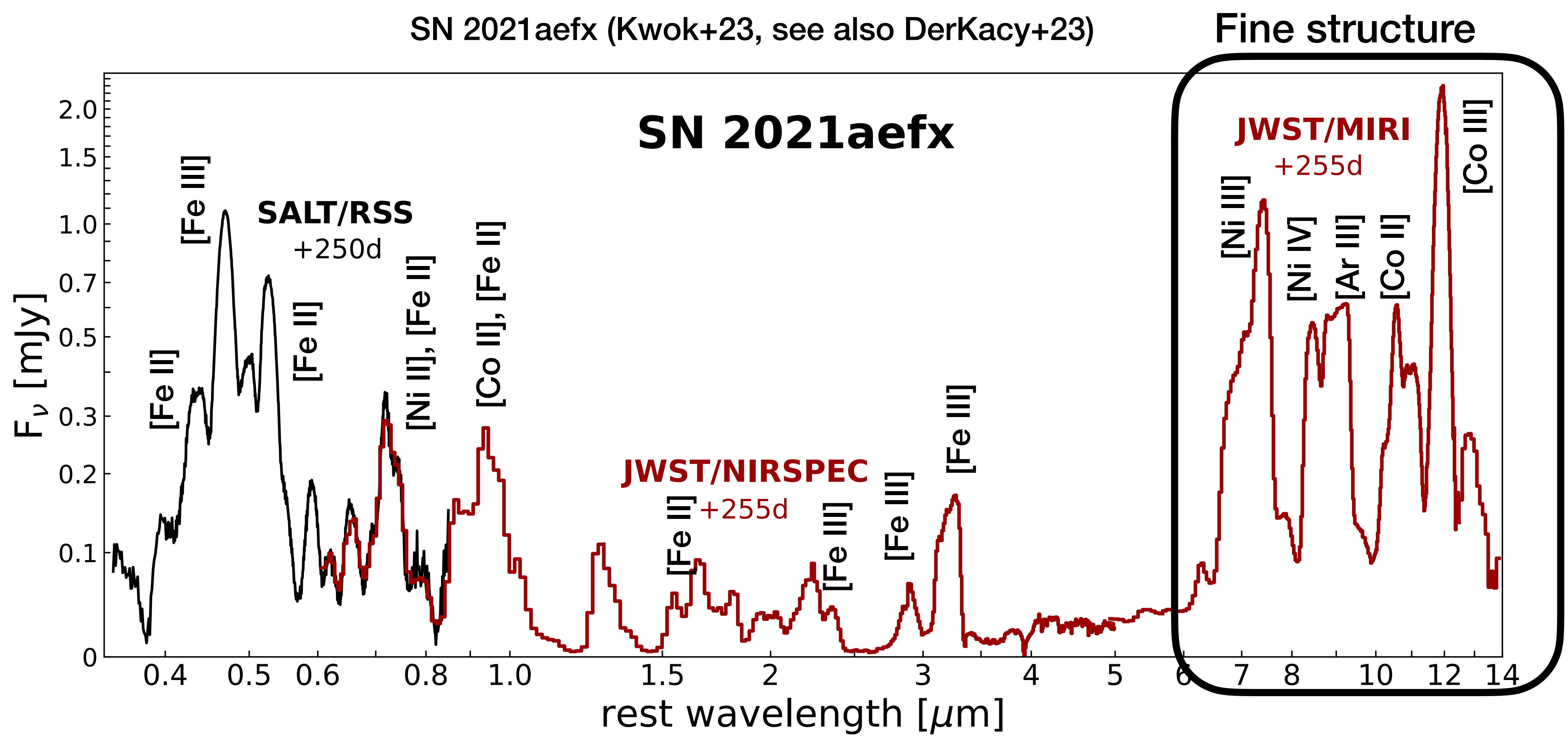
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	Ln	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	An															
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	102 Lr

Fine structure lines



- For example, [O III] 51.81 μm, 88.36 μm in the ISM, [Co III] 11.89 μm in SNe Ia.

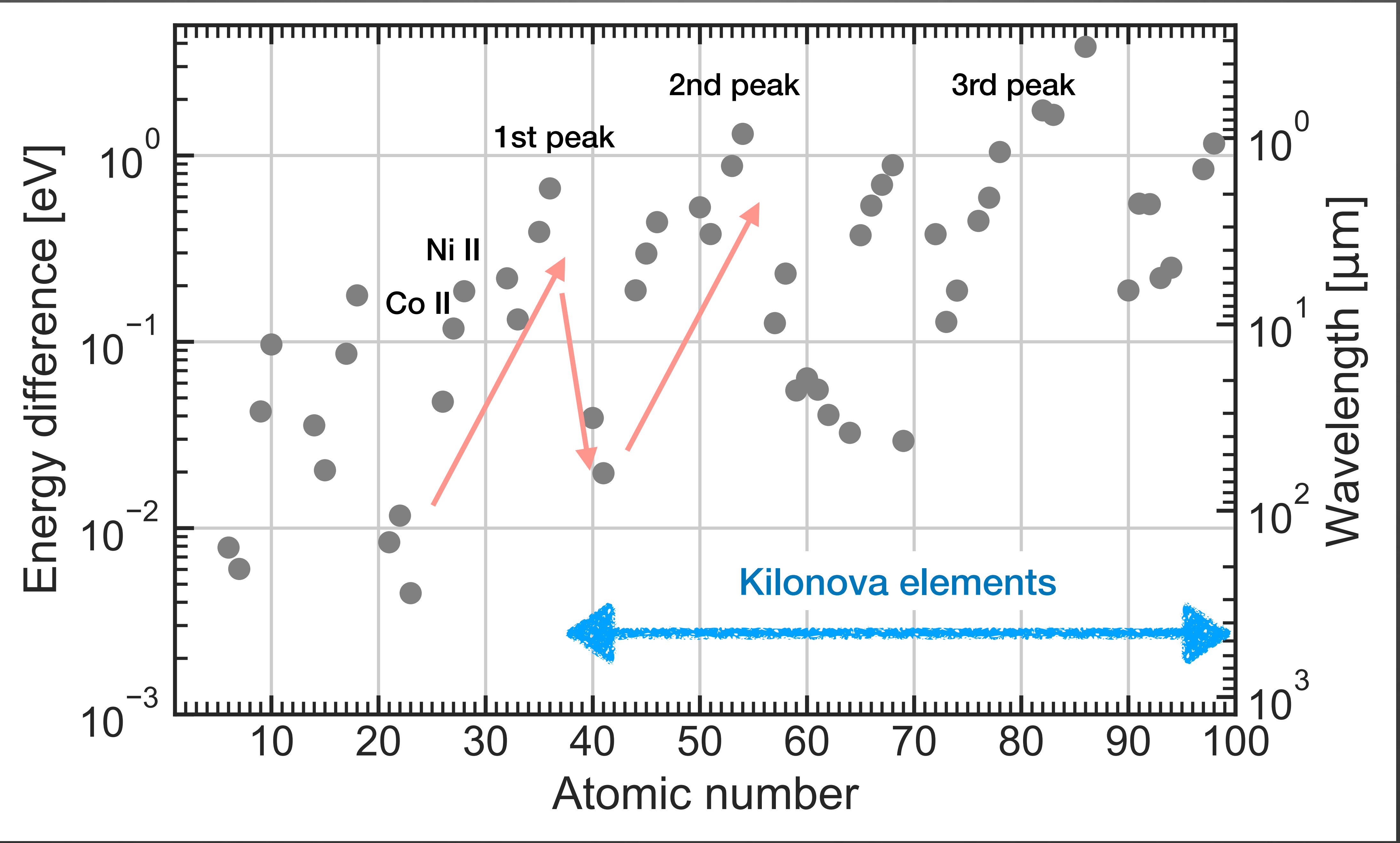
Example: Supernova Ia Nebula



- SN Ia is clearly an iron explosion
- Fine structure lines are seen.

Emission line list: Fine-structure of heavy elements

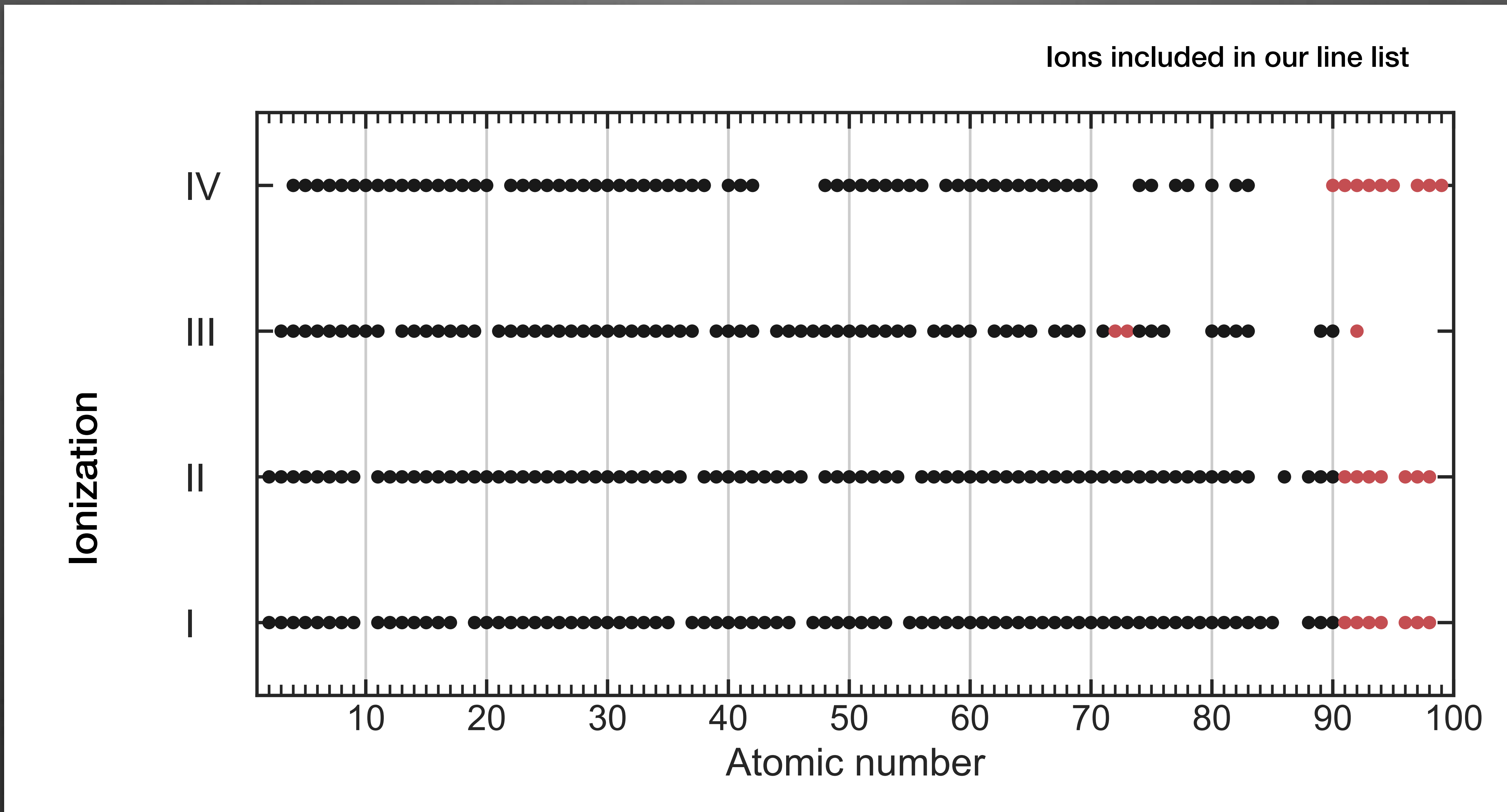
Singly ionized, the first fine structure level



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

A list up to Z=99 (Einsteinium)

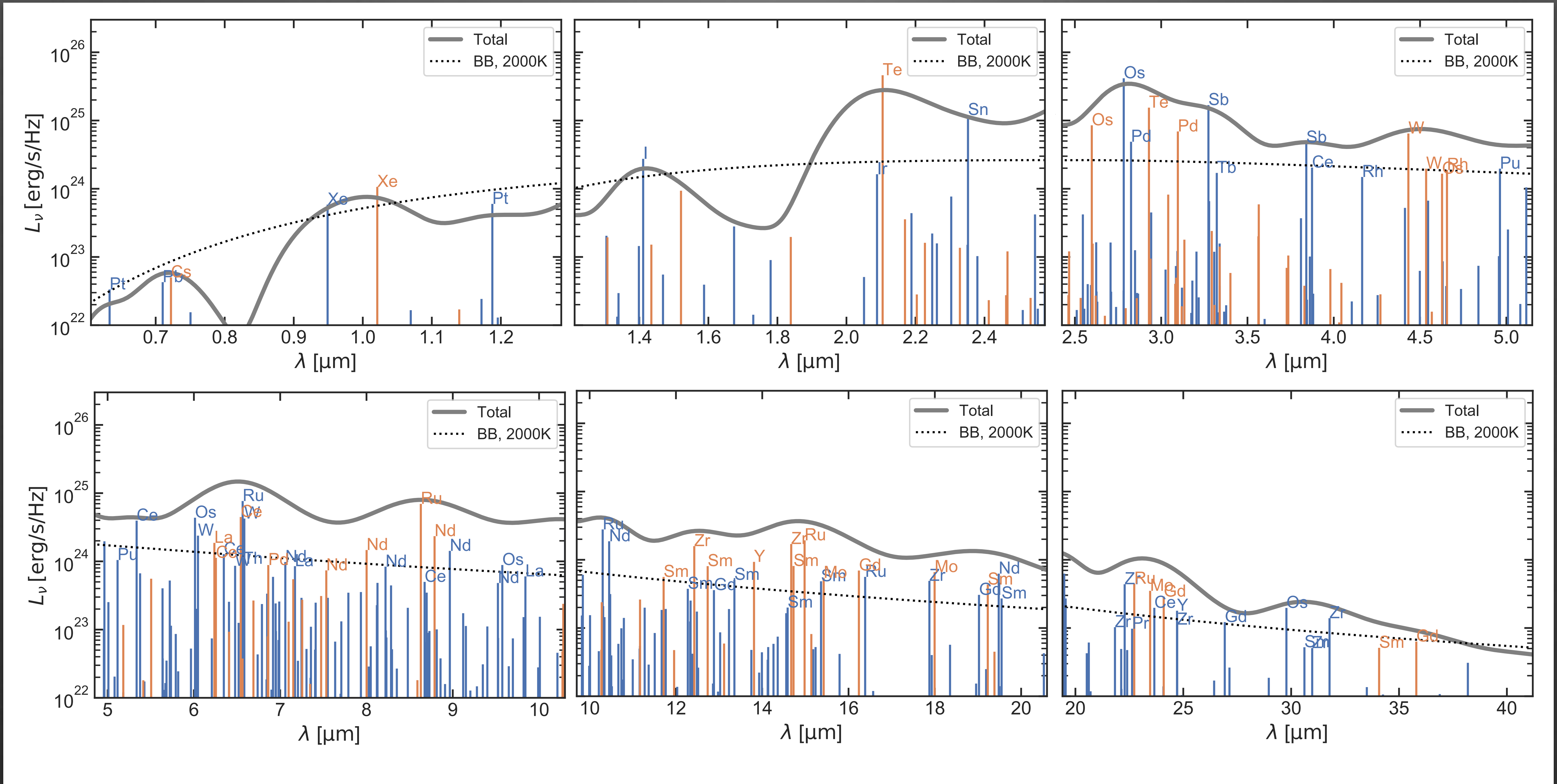
KH+in prep.



- 10^5 lines are included.
- Wavelengths and transition rates are reasonably accurate (<1%)

Kilonova Nebular Spectrum

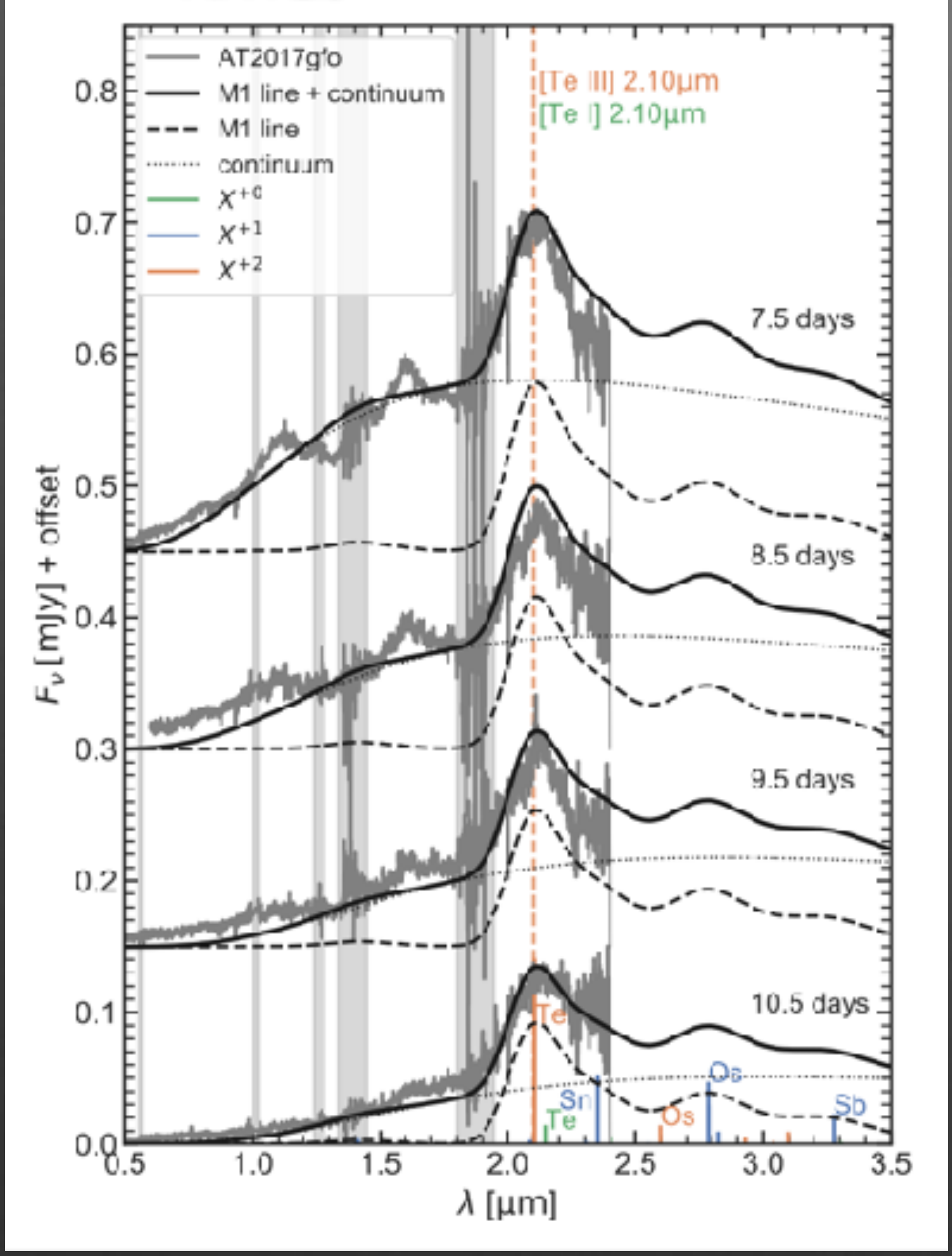
Preliminary result (KH+ in prep), collision strengths are computed with HULLAC.

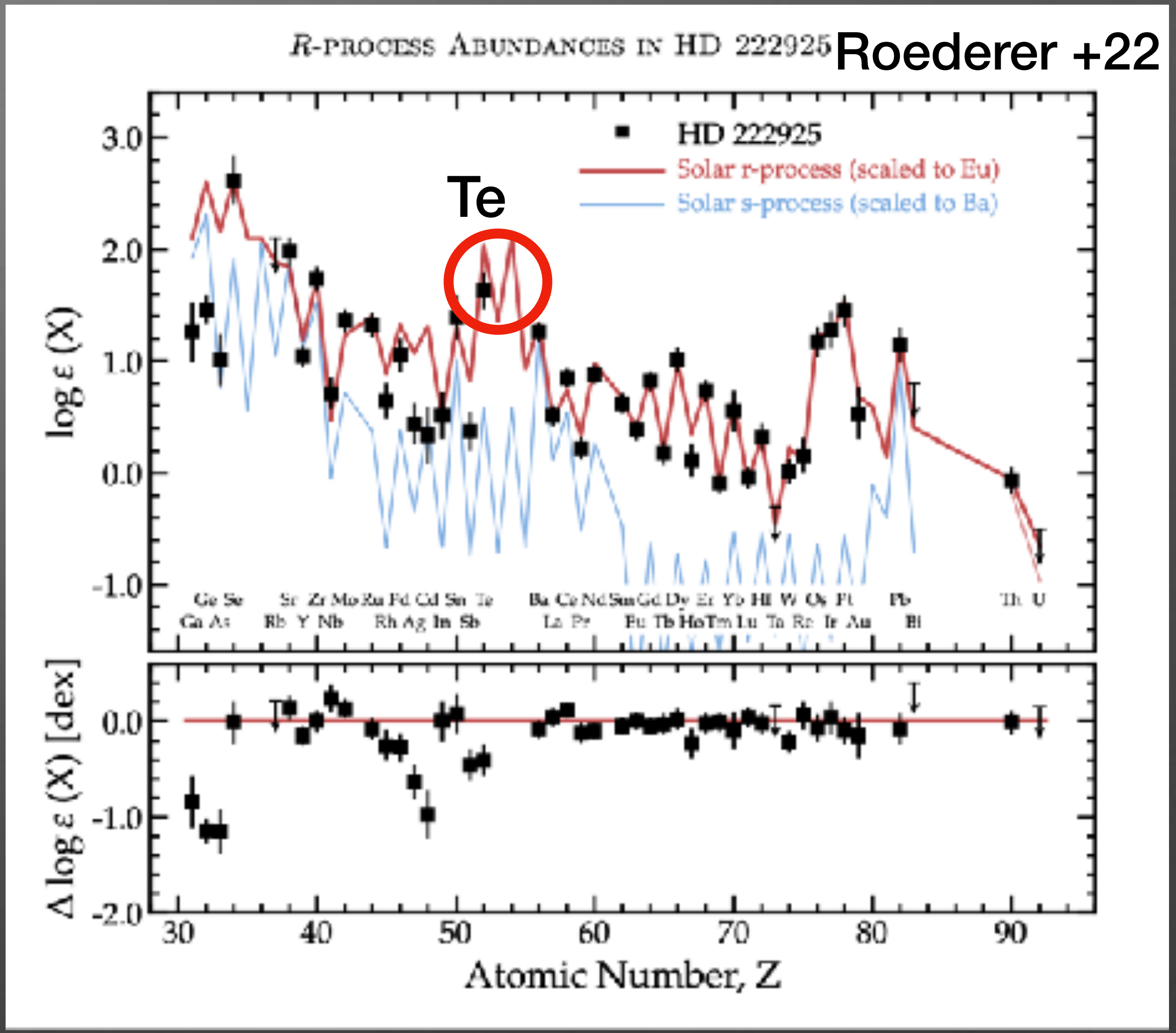


- The solar abundance (2nd - 3rd r-process peaks) is assumed. $X^{+1} = X^{+2} = 0.5$
- [Te III] 2.1μm is the strongest M1 line.

Te III line in the kilonova GW170817

KH+23

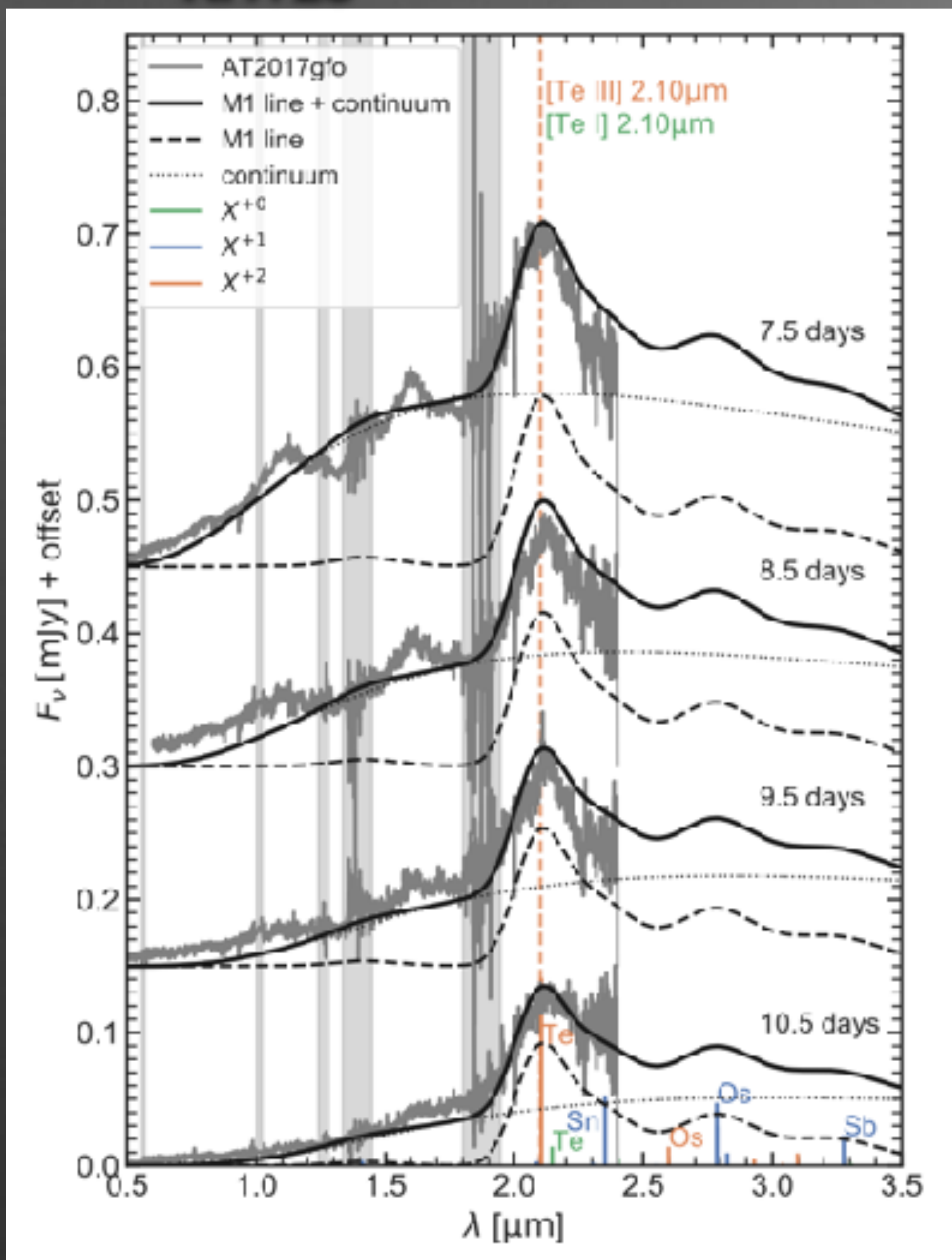




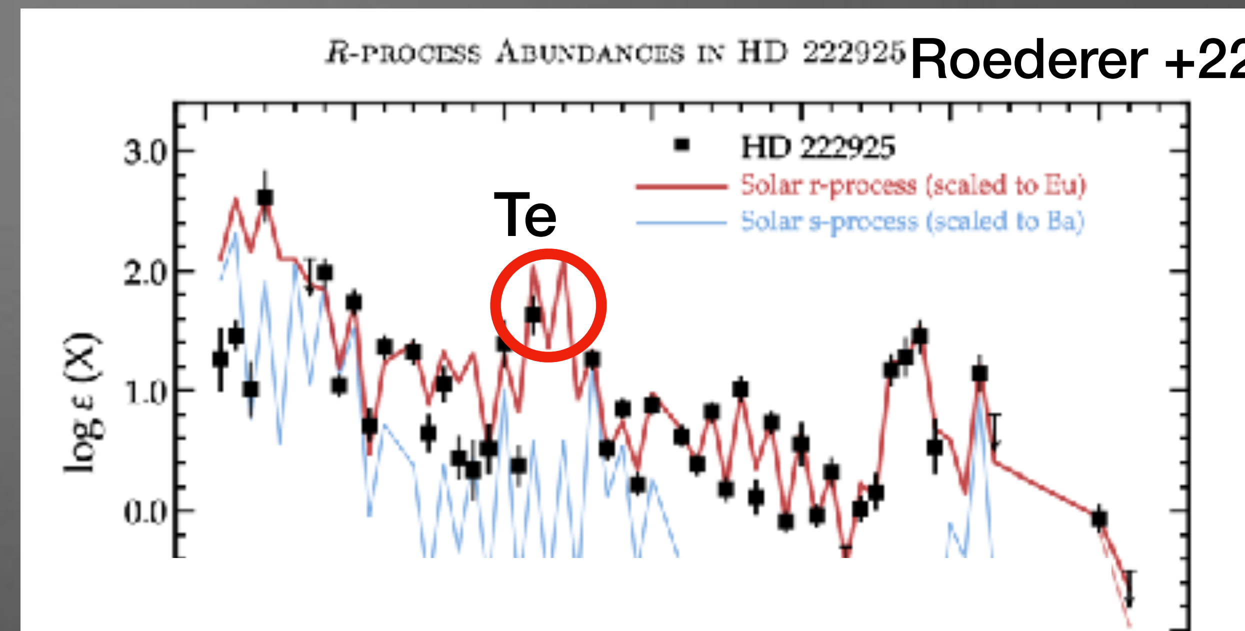
- The Te III line is expected to be the strongest M1 line because it is a second r-process peak element.

Te III line in the kilonova GW170817

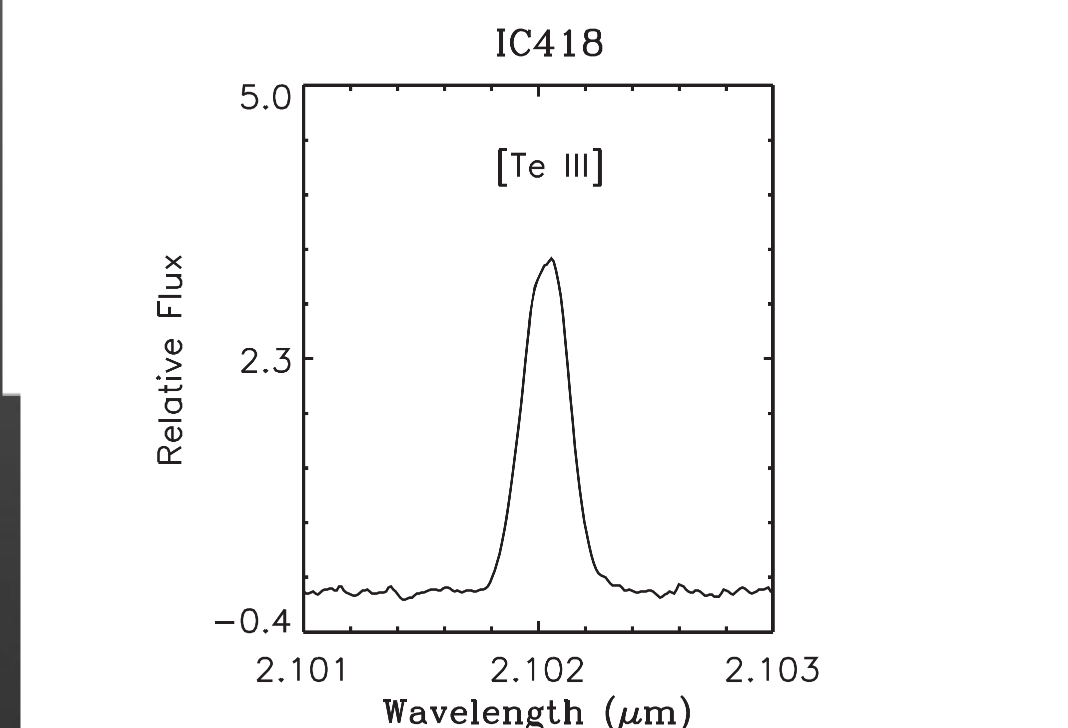
KH+23



Roederer +22



Planetary nebula (Madonna+18)



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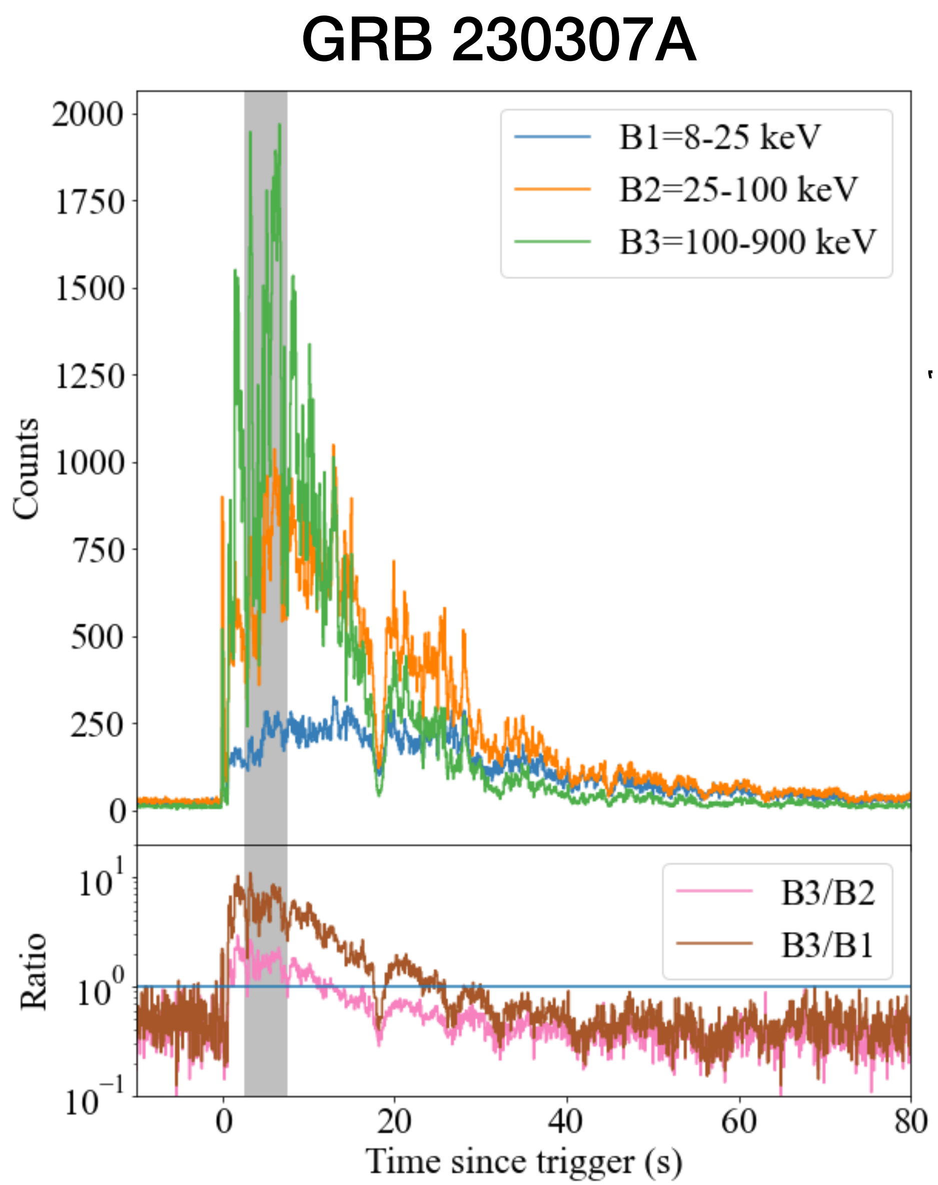
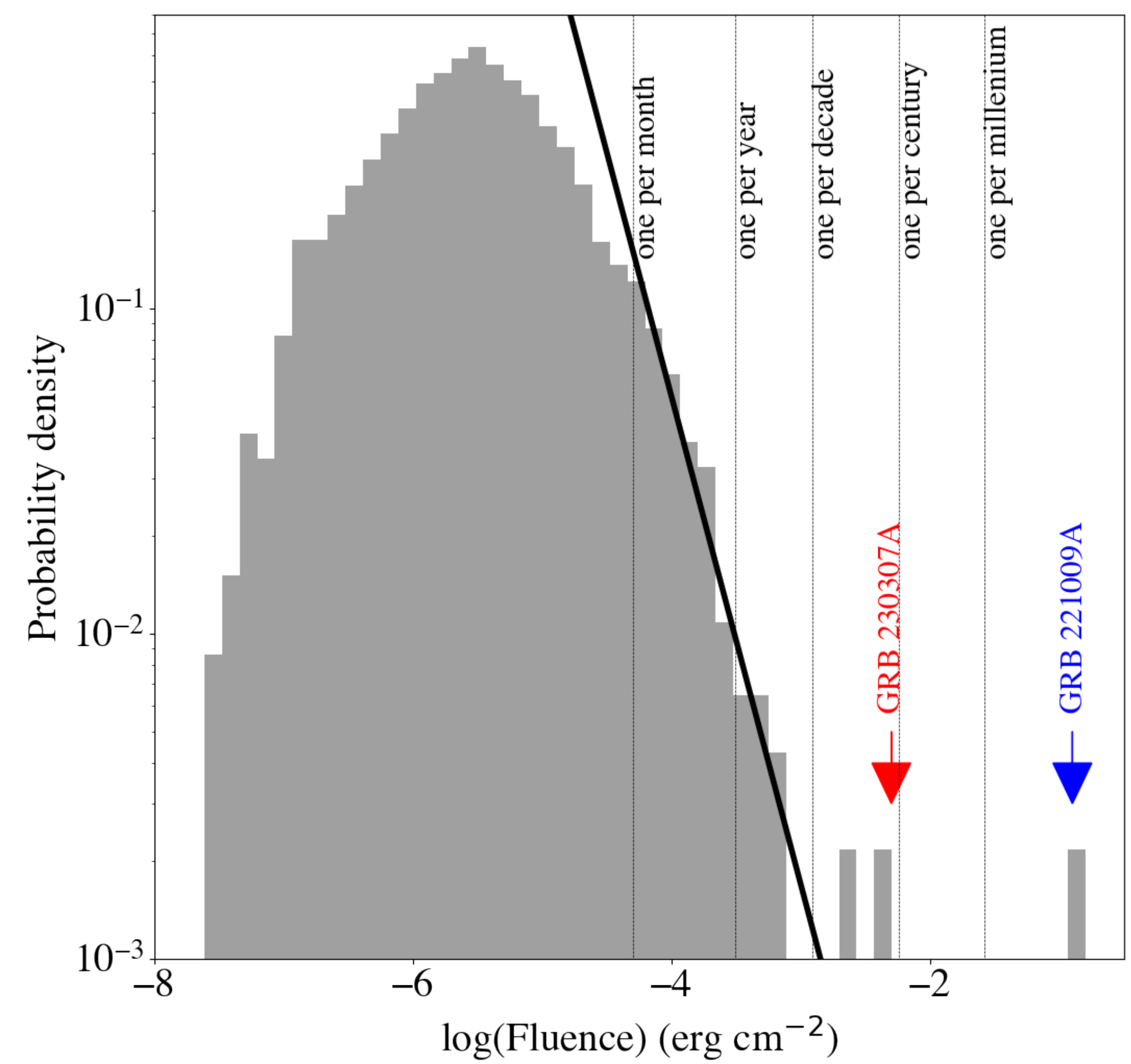
Out line

- Introduction Kilonova and nebular emission
- Kilonova in a long GRB 230307A
- Discussion

Extremely bright GRB 230307A

Levan,..,KH+23

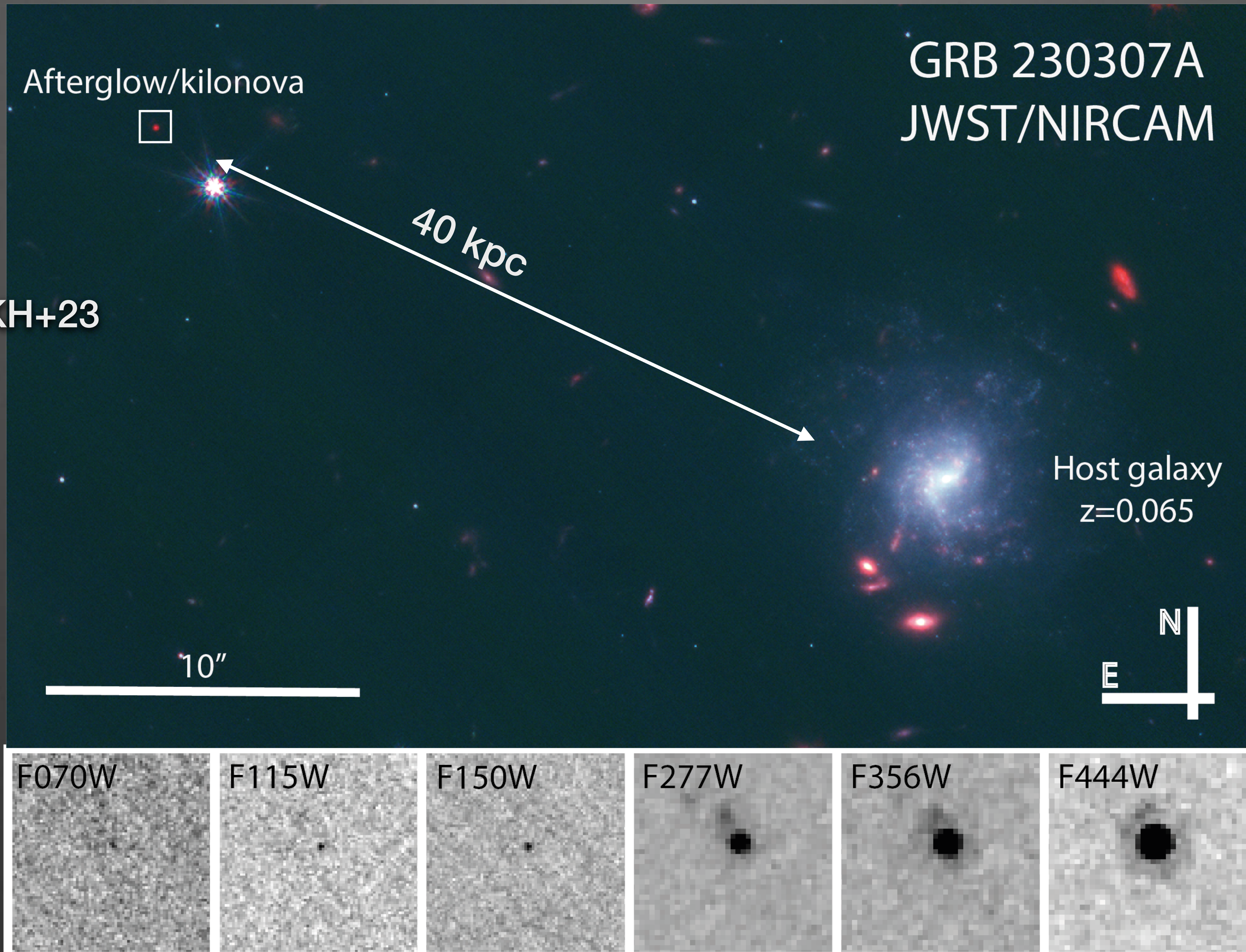




- T_{90} ~ 35 s : Typical long GRB.
- The 2nd brightest GRB.

GRB 230307A: JWST NIRCam Image

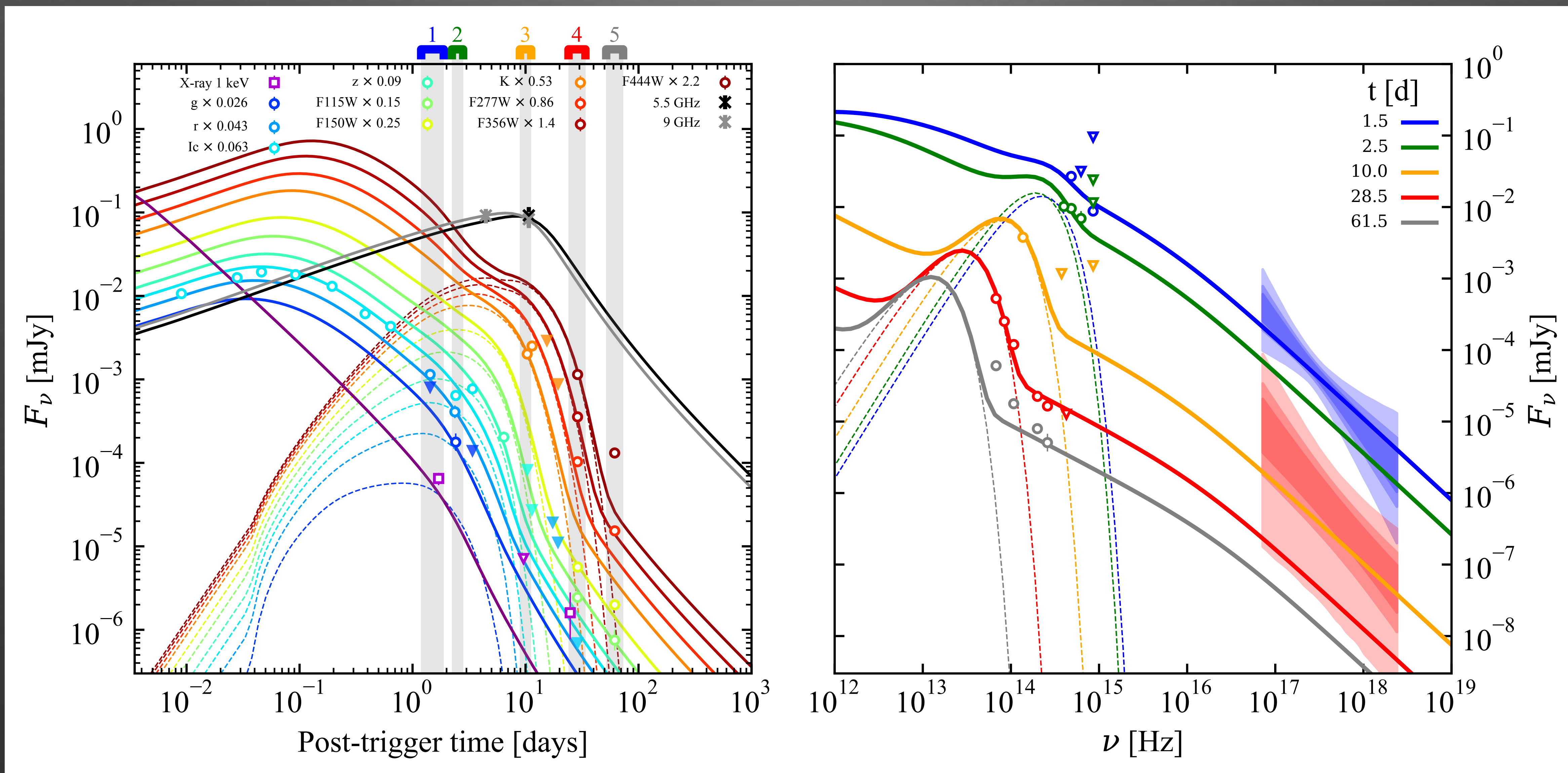
Levan,..,KH+23



- 30 days post burst
- Large off-set ~ 40kpc, extremely red.

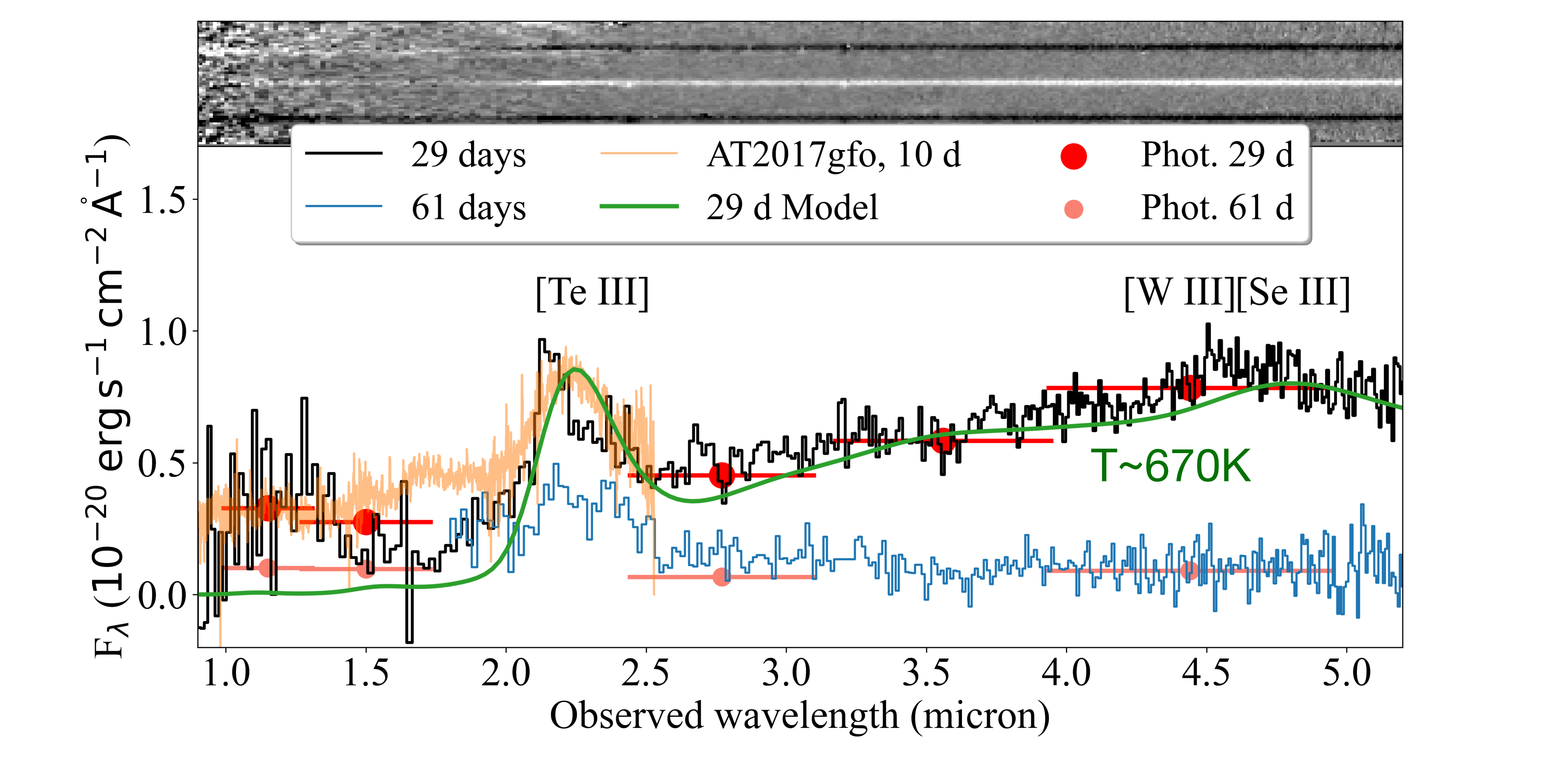
GRB 230307A light curve and JWST photometry

Levan,..KH+23



JWST Spectrum

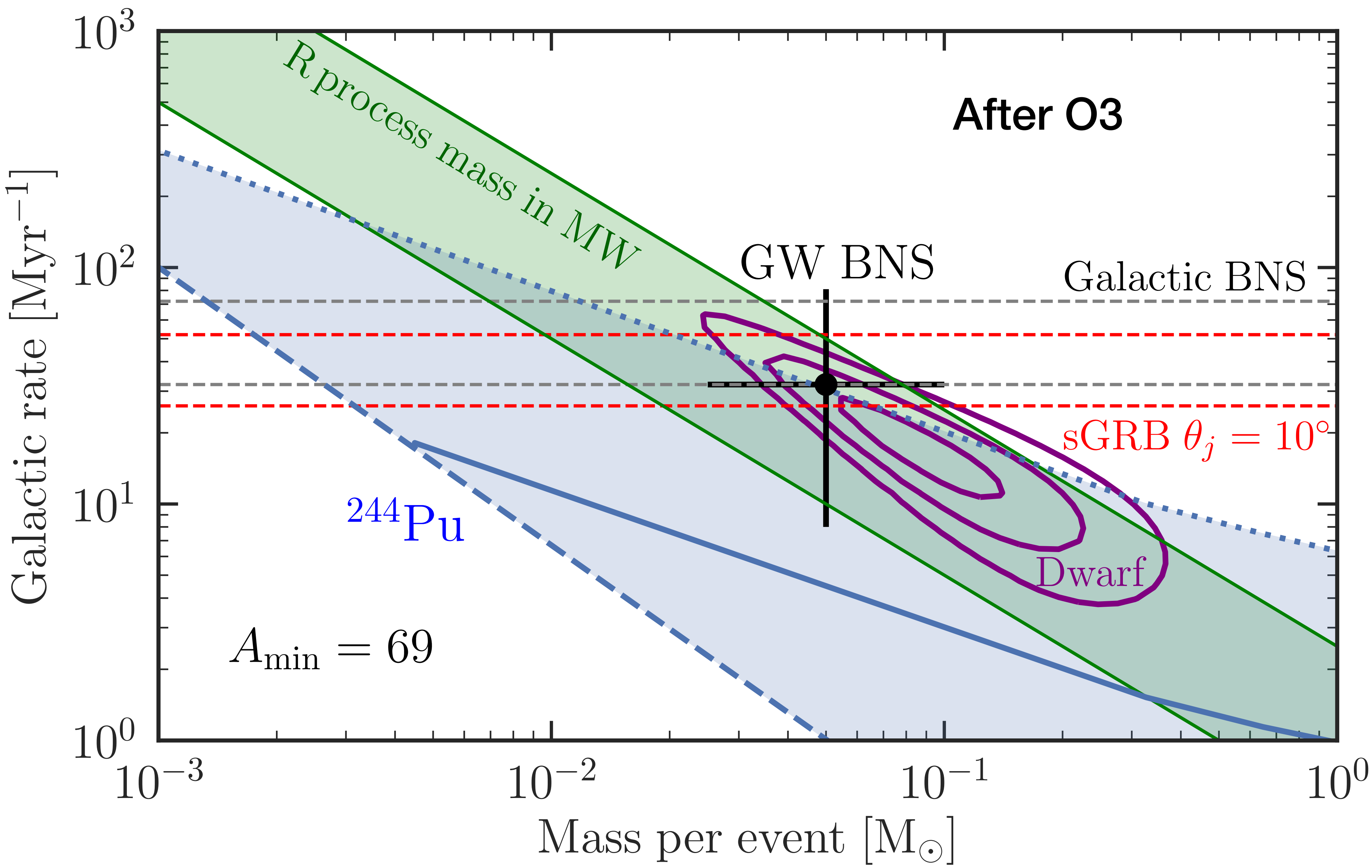
Levan,..,KH+23



- A line feature at 2.1μm exists in both 30 & 60 days after the burst.
- 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.

R-process mass budget from GWTC-2

KH, Piran, Paul 15, KH, Beniamini, Piran 18



Ref: Goriely 1999, Lodders et al 2009, Wanderman & Piran 2015, Fong+2015, KH, Piran, Paul 2015, Beniamini, KH, Piran 2016, Pol, McLaughlin, Lorimer 2019, KH & Nakar 2020, LVC 2020

Summary

- Sr, Y, Ce, La, He may be identified as absorption lines in the kilonova in GW70817.
- Te emission line 2.1μm seems to produce the late time spectral peak.
- GRB 230307A was associated with a kilonova-like counterpart.
- 2.1μm line exists in the JWST spectrum, which may be Te.
- We will test the line identifications with future kilonovae.