Kilonovae

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Ehud Nakar,
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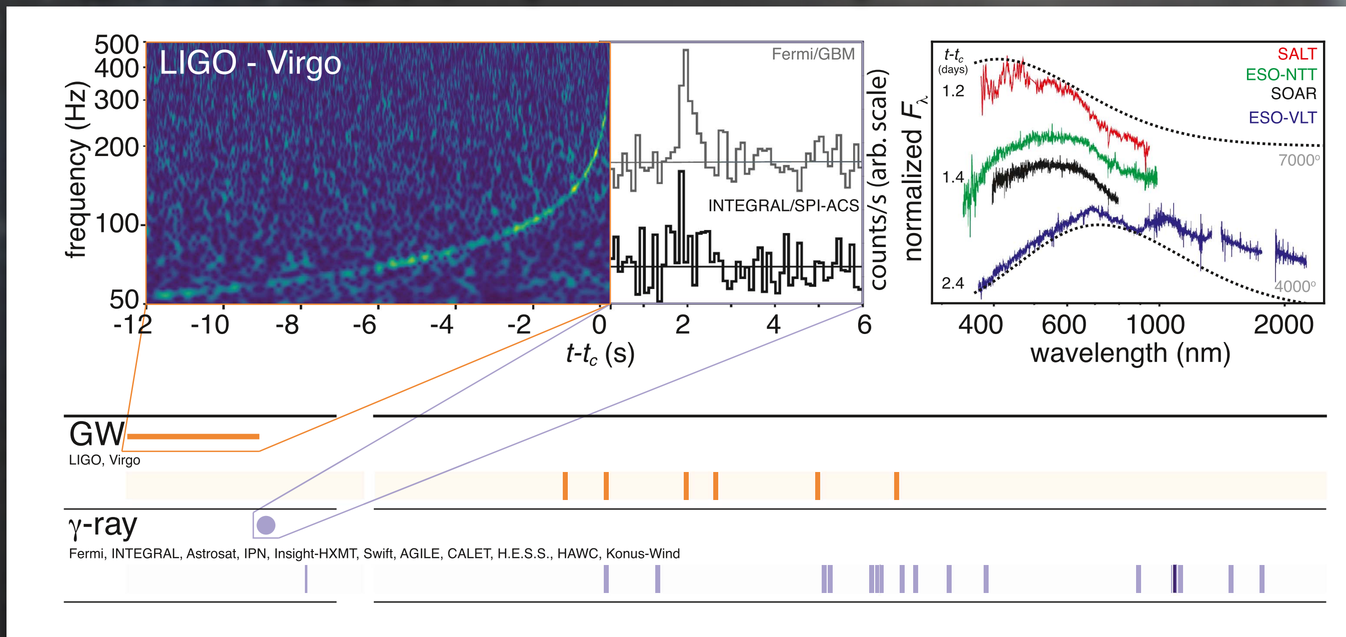
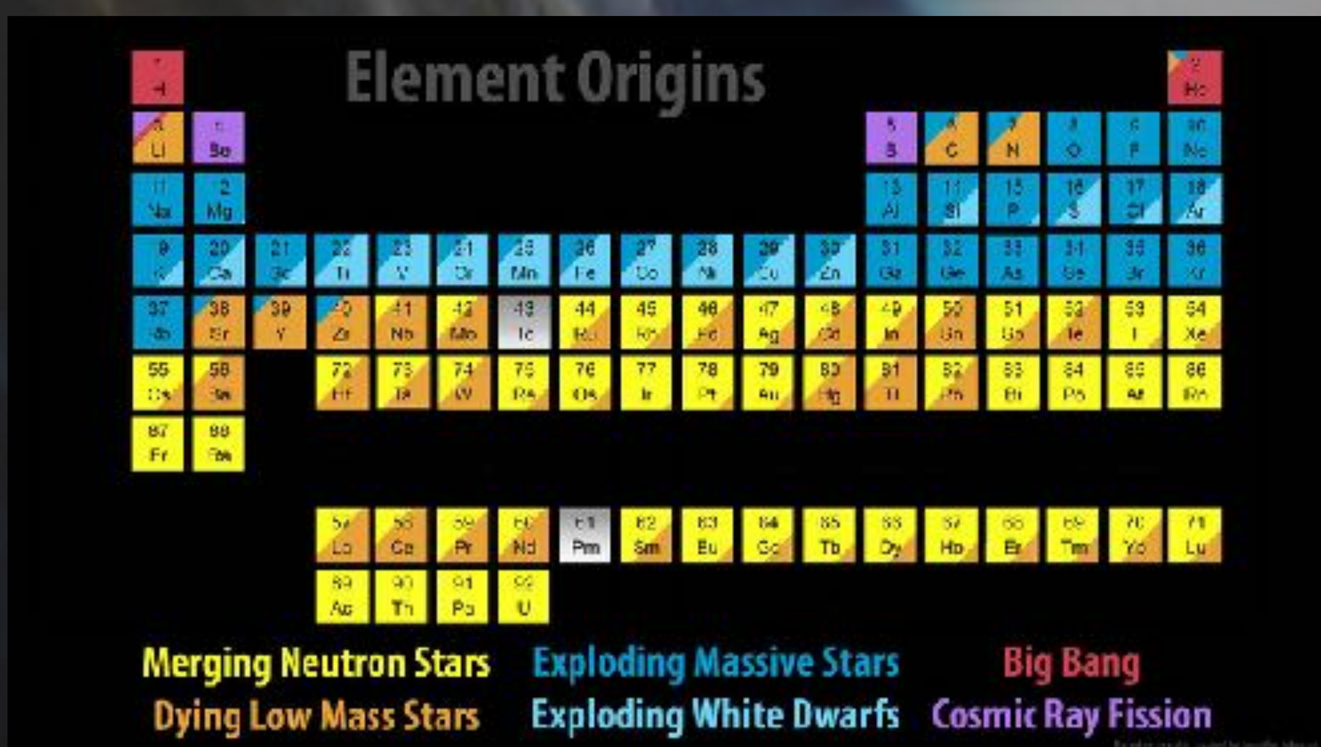
Multi-Messenger Astronomy of Neutron Star Merger

GW170817 (Abbott+17)



Aug. 17th 2017

- 1st GW-EM merger
- 1st direct observation of r-process nucleosynthesis (Kilonova AT2017gfo)
- Relativistic jet emerges
- Only GW-EM merger as of Feb 2026

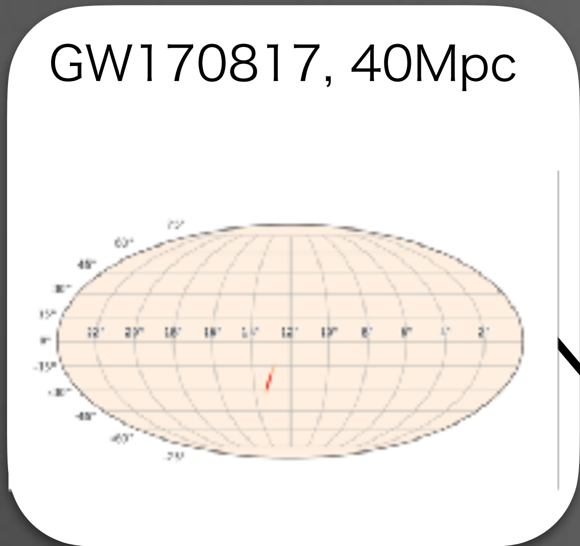


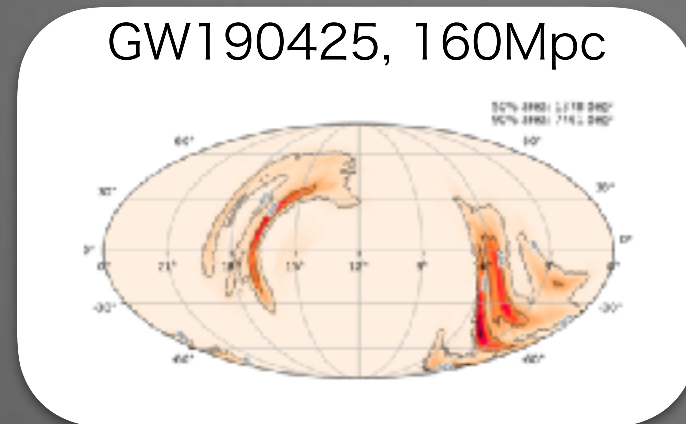
Questions

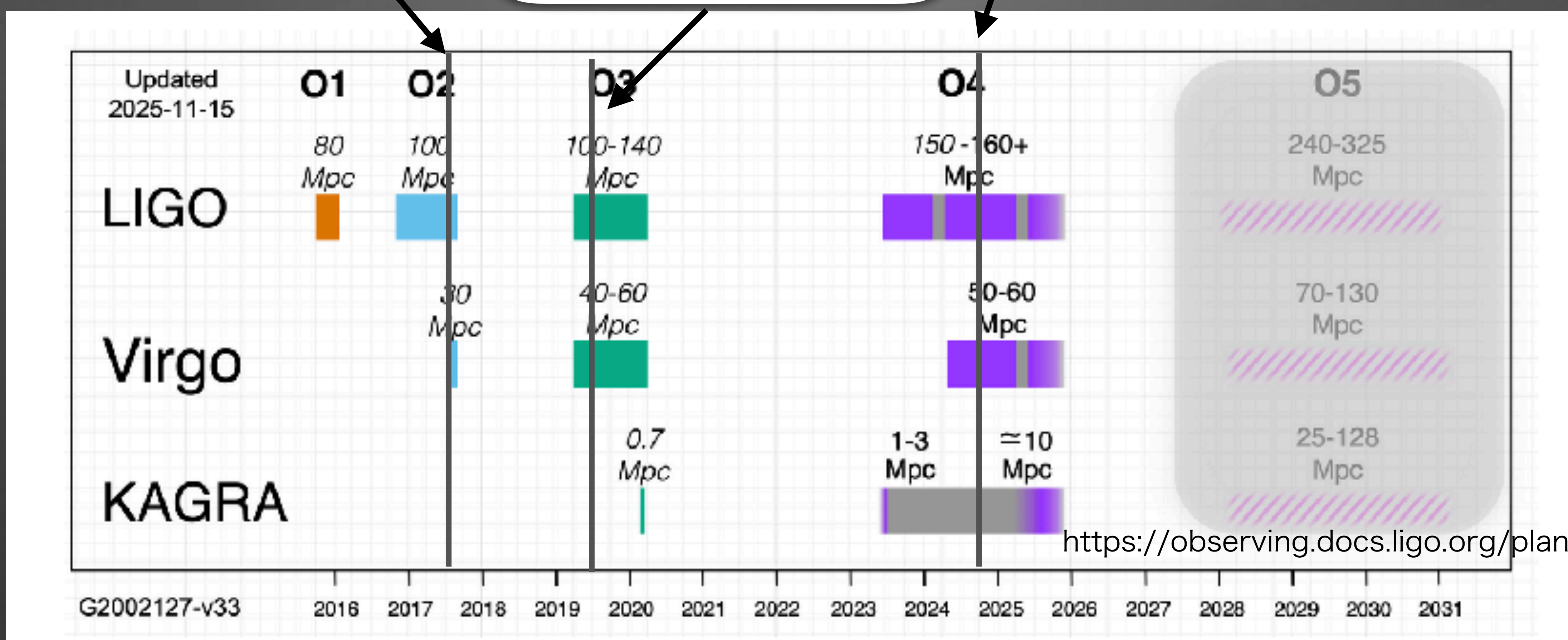
- Which elements are produced?
- How much?
- What is the merger remnant? Black hole or hypermassive neutron star?
- When and how the jets were launched?

…

Events since GW170817

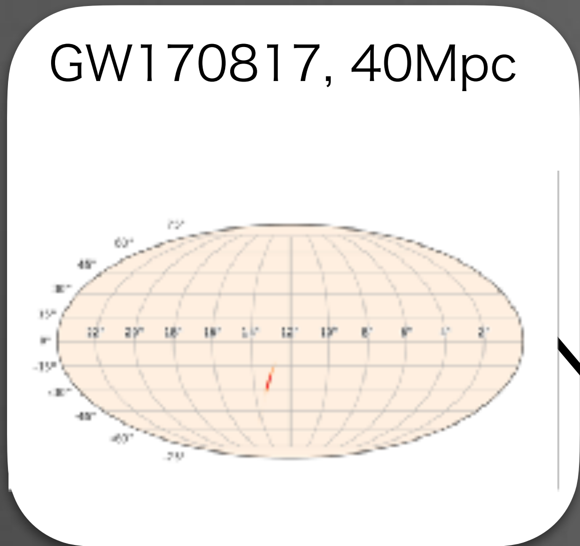


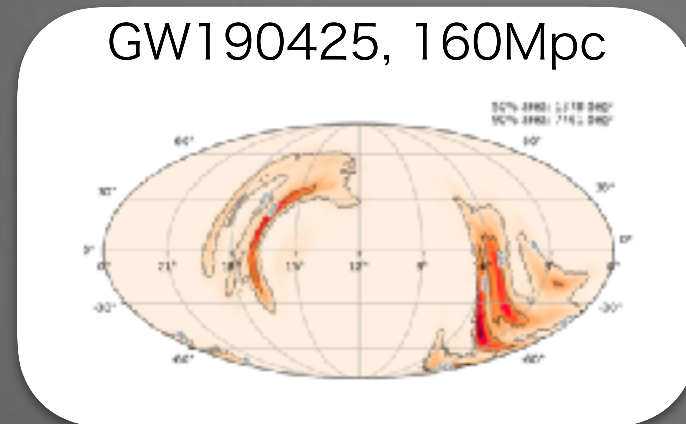




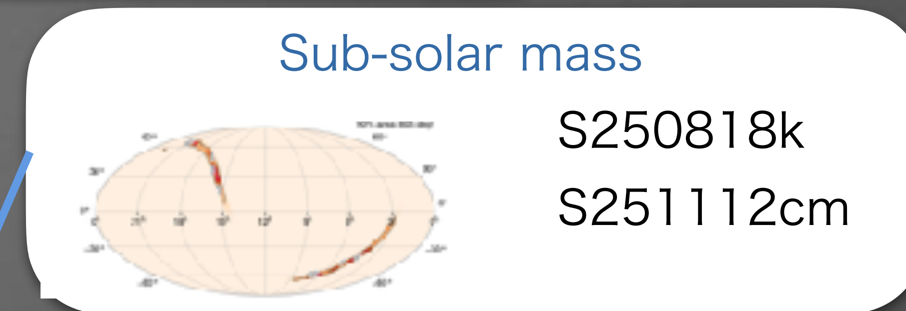
- In addition, black hole neutron star mergers (e.g. GW200105, GW200115) were detected.
- However, they are likely EM dark according to the mass and spin.

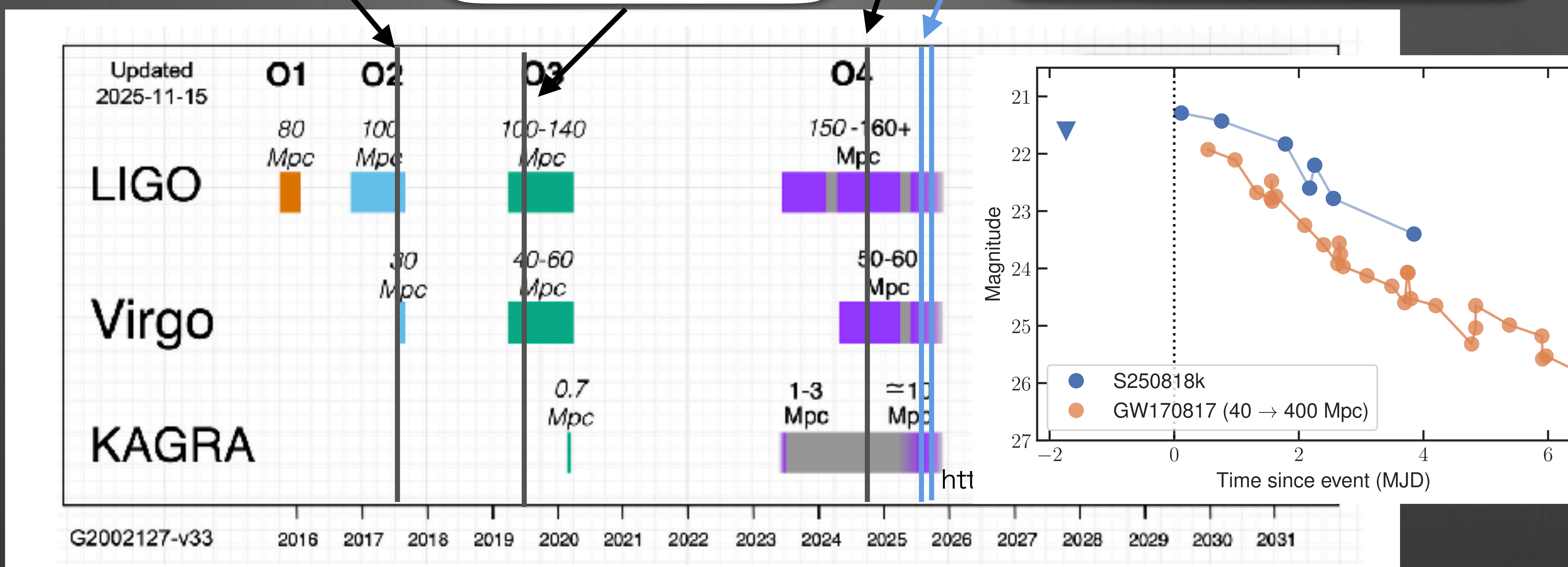
Events since GW170817





Sub-threshold S231109ci

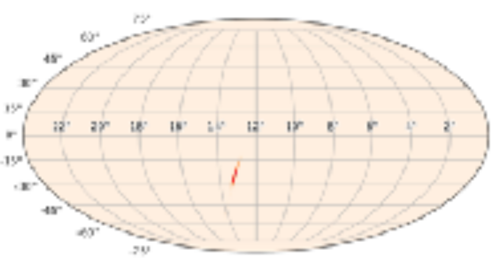




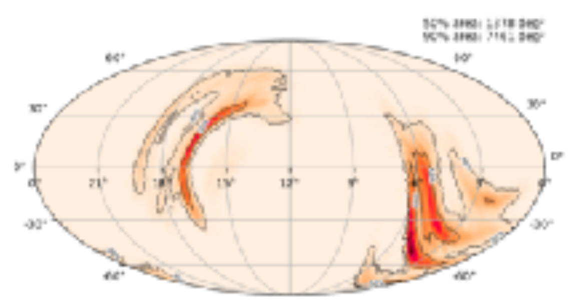
- ZTF identified one kilonova candidate, AT2025ulz, for a sub-solar mass event S250818k within 3 hr (Kasliwal+25).

Events since GW170817

GW170817, 40Mpc



GW190425, 160Mpc

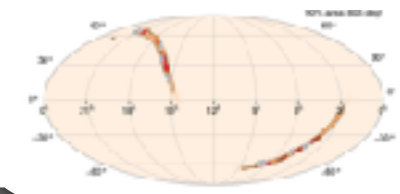


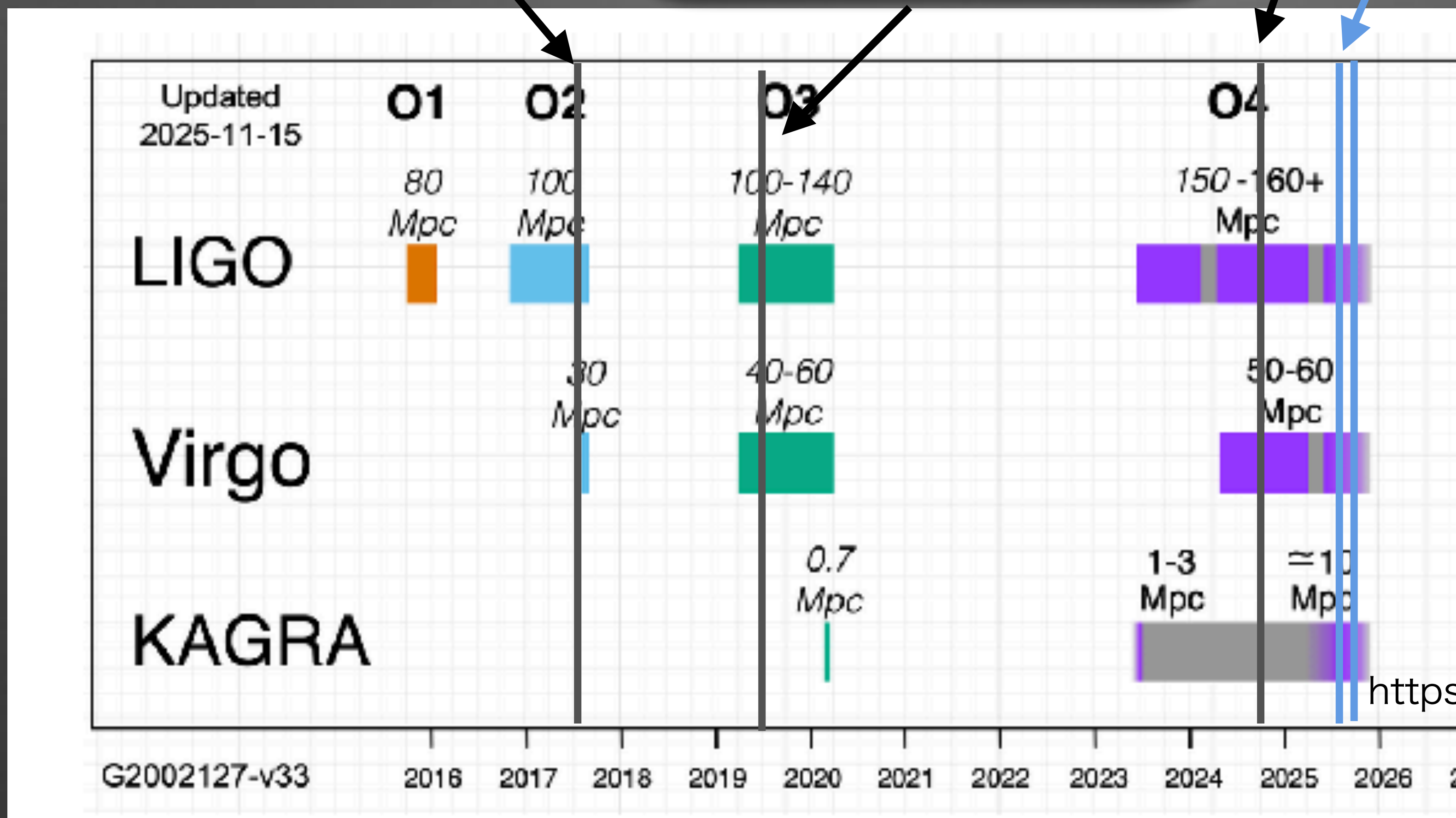
Sub-threshold S231109ci

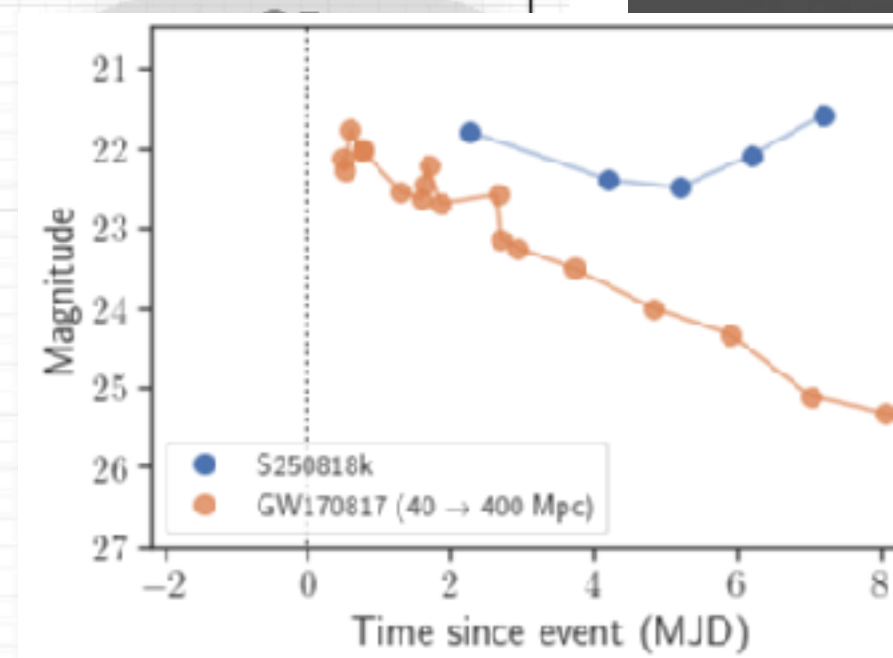
Sub-solar mass

S250818k

S251112cm







- ZTF identified one kilonova candidate, AT2025ulz, for a sub-solar mass event S250818k within 3 hr (Kasliwal+25).
- It turned out to be a supernova (Hall+25, Franz+25, Gillanders+25, Yang+26).

Events since GW170817

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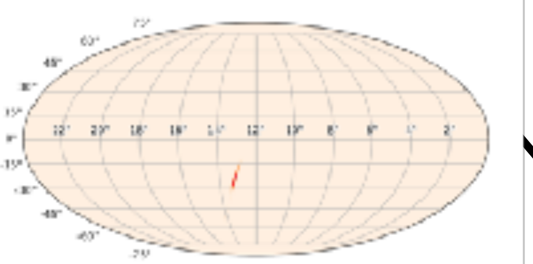

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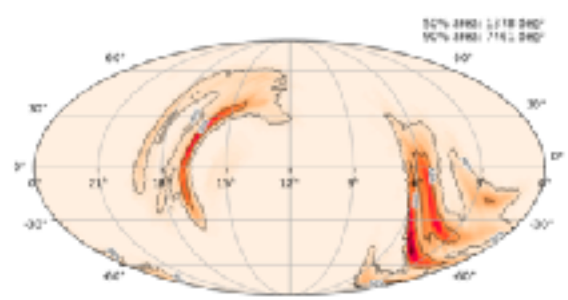

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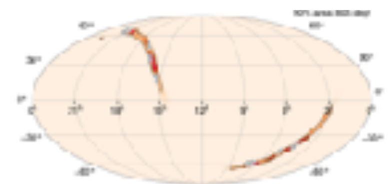
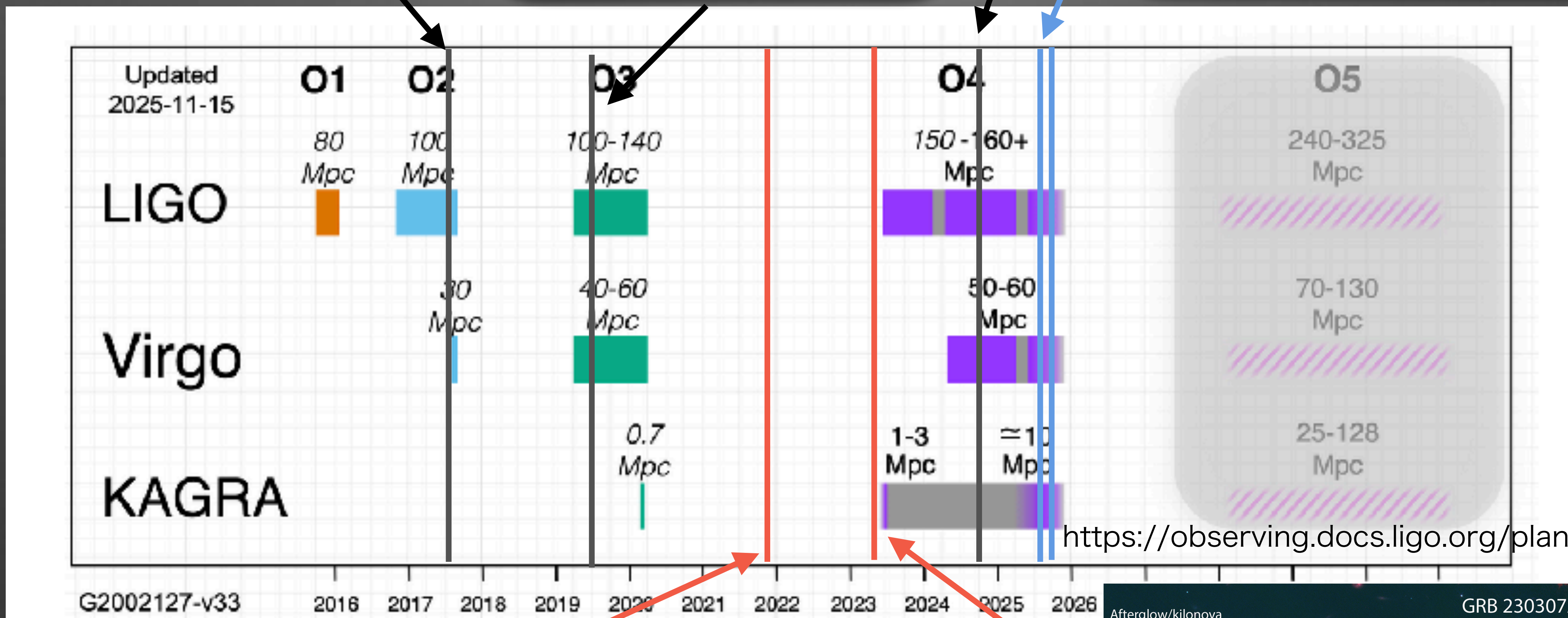
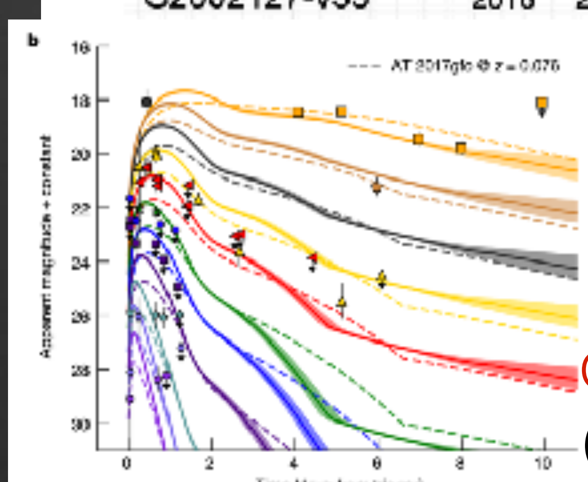
Sub-solar mass



S250818k
S251112cm



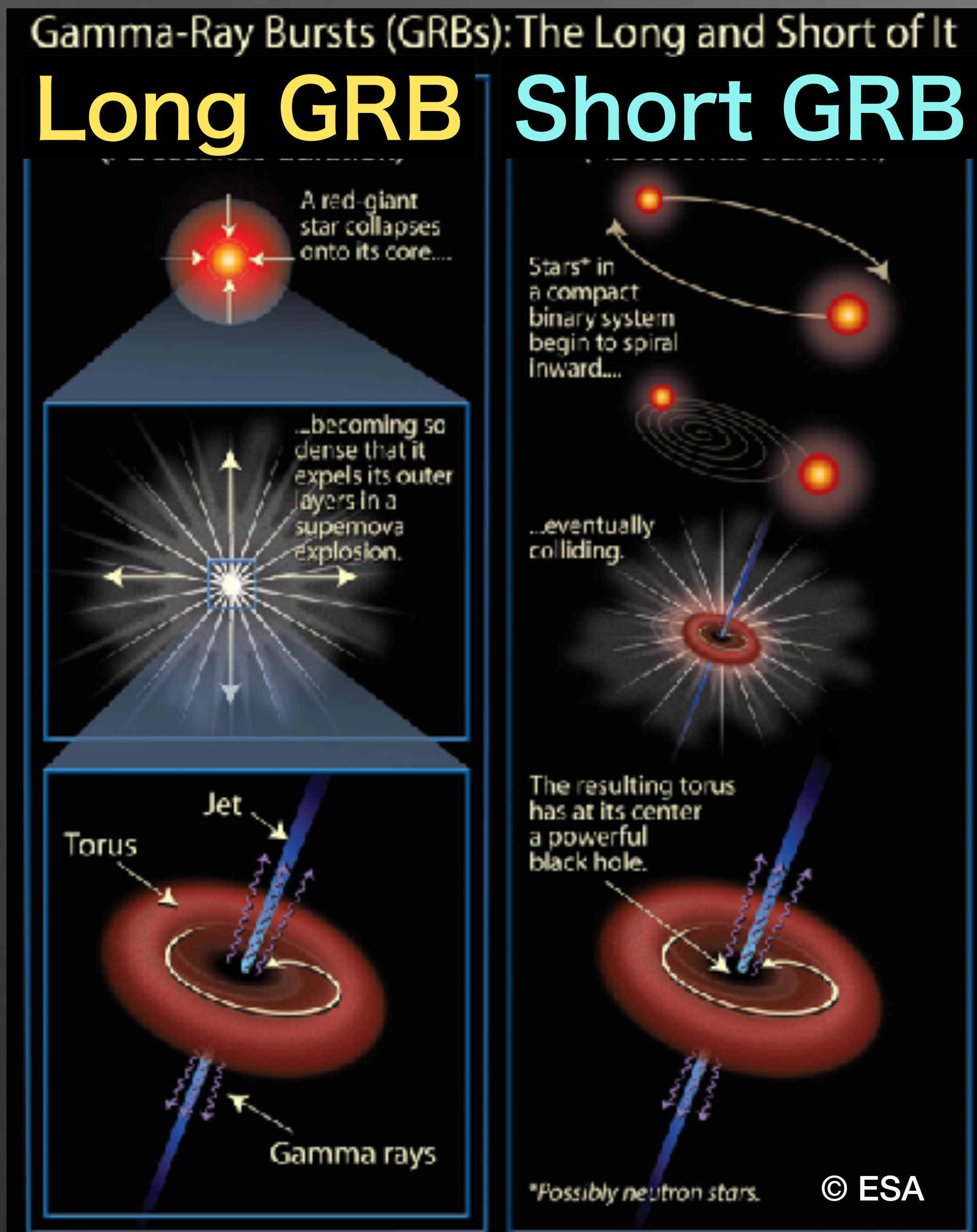
https://observing.docs.ligo.org/plan/



GRB 211211A with a kilonova (Rastinejad+,Troja+22), 350Mpc

GRB 230307A with a kilonova (Levan+24, Yang+24), 300Mpc

Connection between mergers and γ-ray bursts?



Kouveliotou+93, Nakar 07, Bromberg+12

The classical picture:

Merger => Short GRB => Kilonova

Collapsar => Long GRB => Supernova

- Kilonovae in ***short*** GRBs:

e.g., GRB 050709, 060505, 060614, 080905A, 130603B, 150101B, 160821B, 200522A

- ‘Short GRB’ in GW170817

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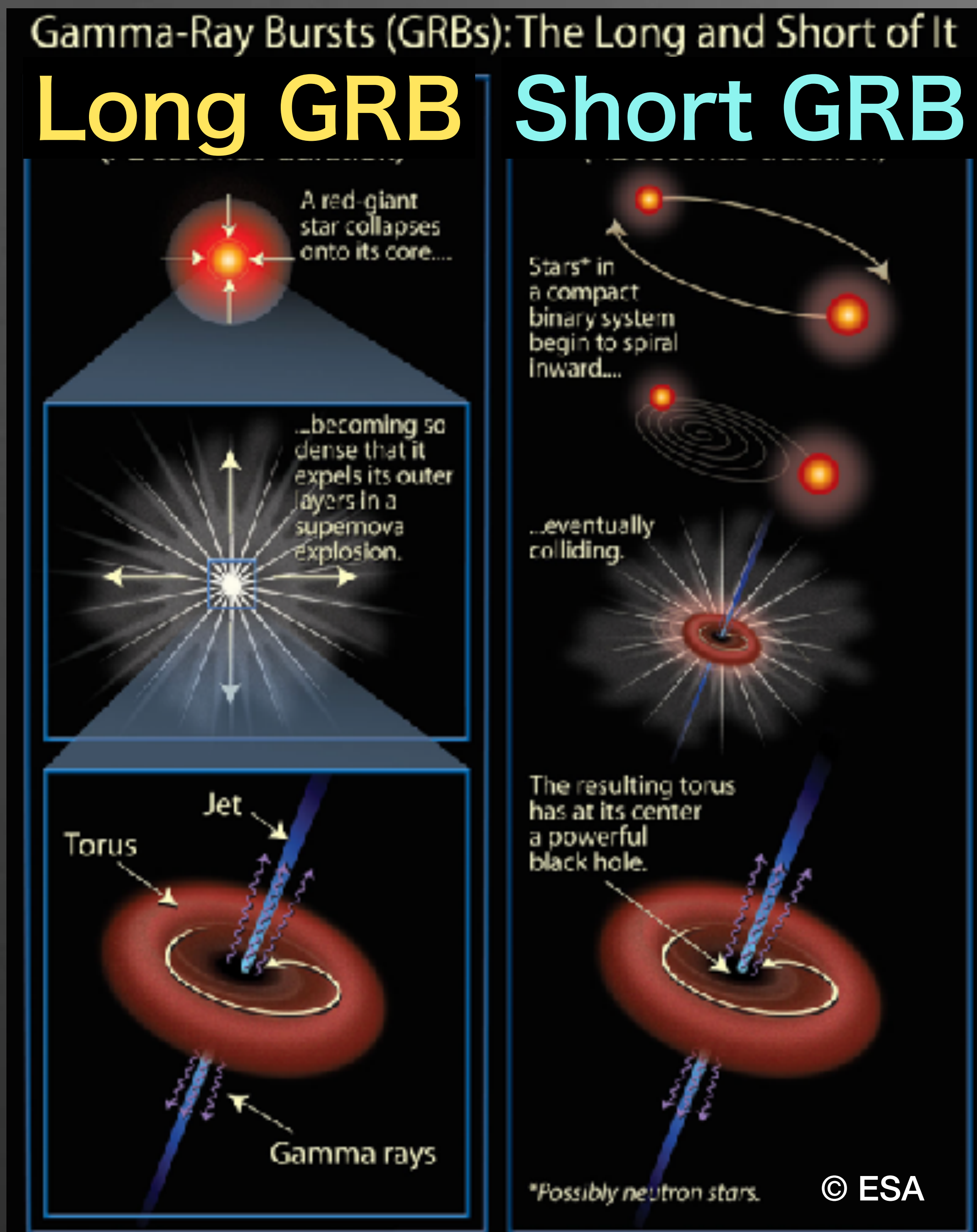

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- Kilonovae in *long* GRBs:

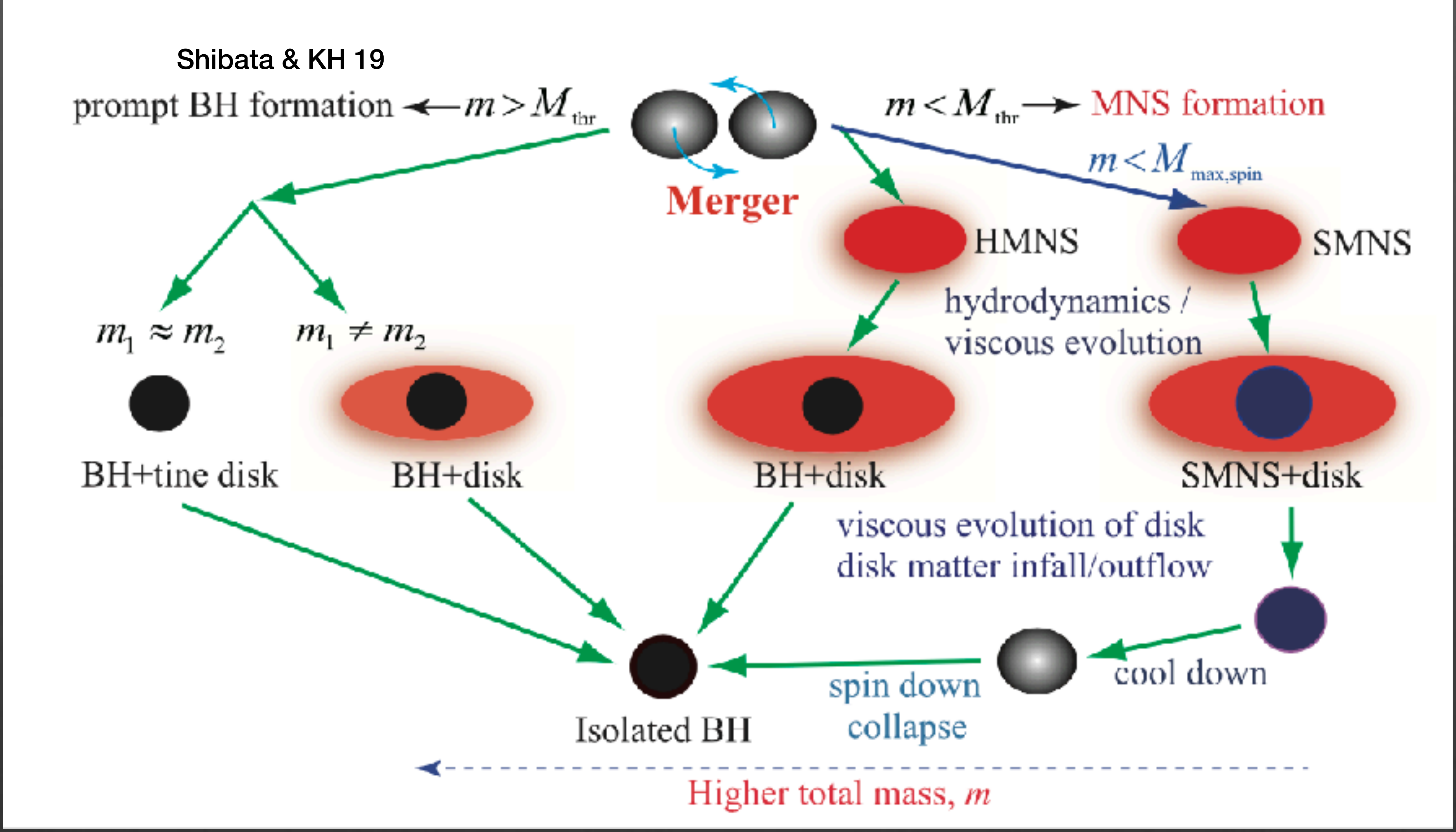
GRB 190109A, 211211A, 230307A

What determines short or long?

Do collapsars produce r-process?

(Surman+06, Siegel+19, Miller+20, Just+22, Fujibayashi+23, Shibata+25)

Variety of neutron star mergers?



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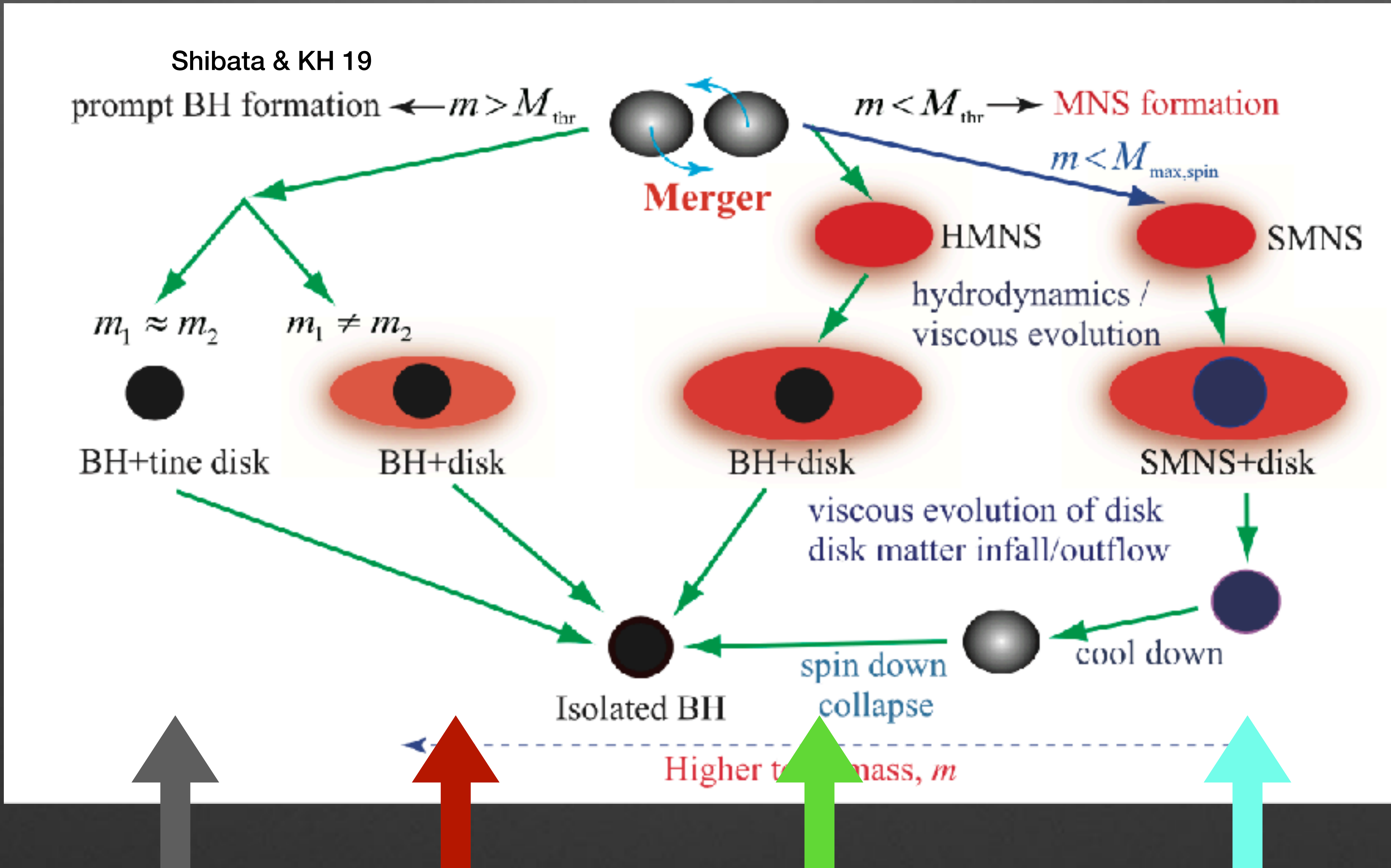


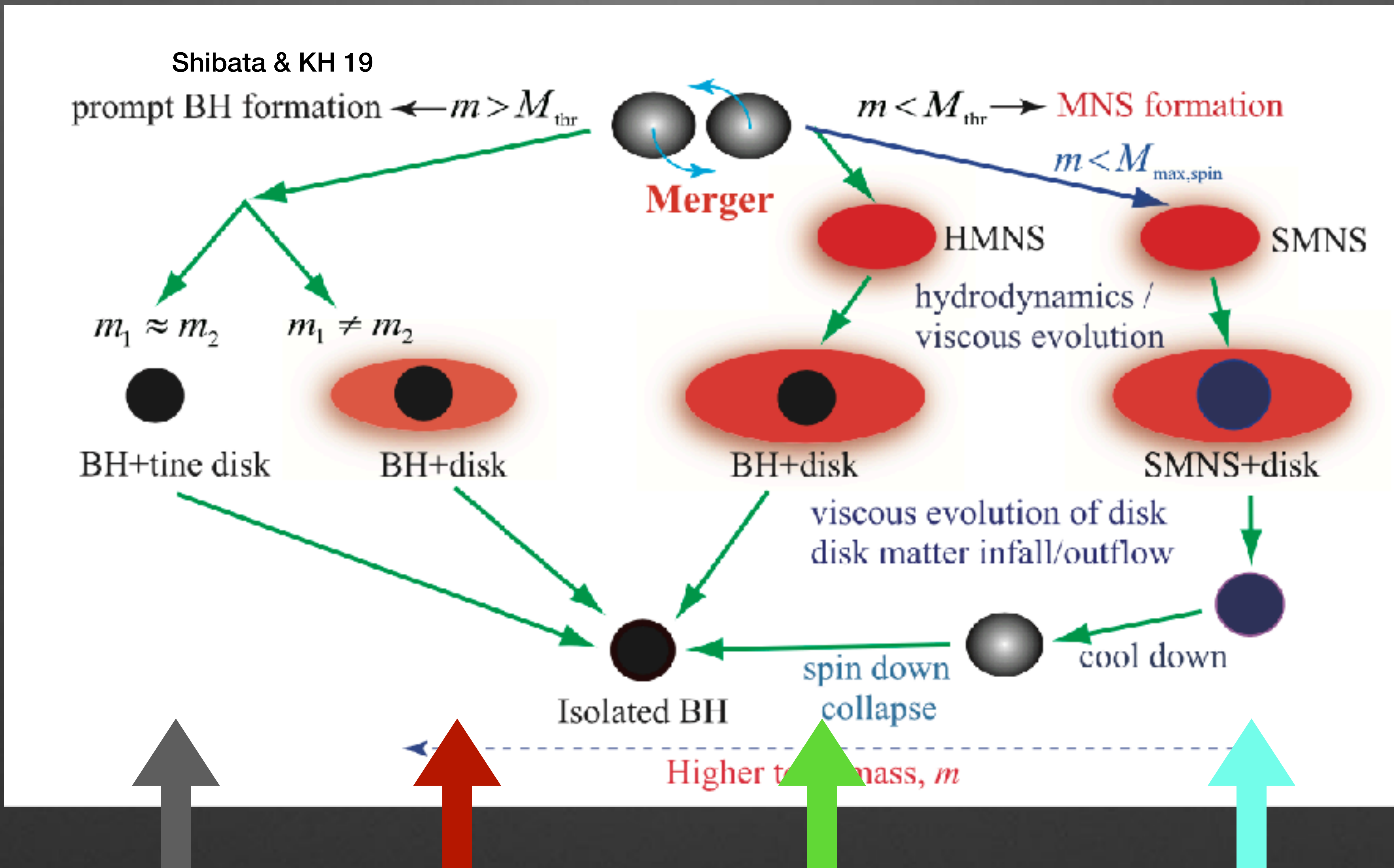
No jet?

Jet?

Jet?

No jet?

Variety of neutron star mergers?



Dark Kilonova

Dim Kilonova

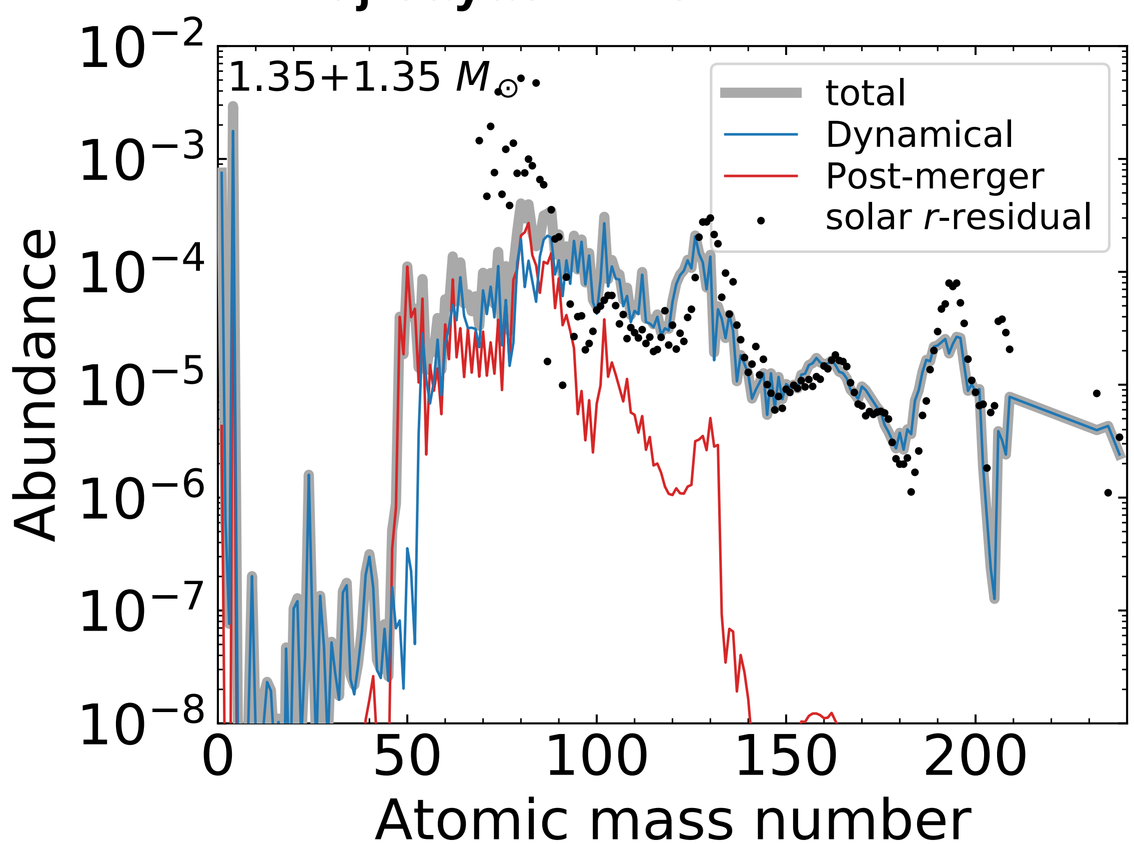
Bright Kilonova

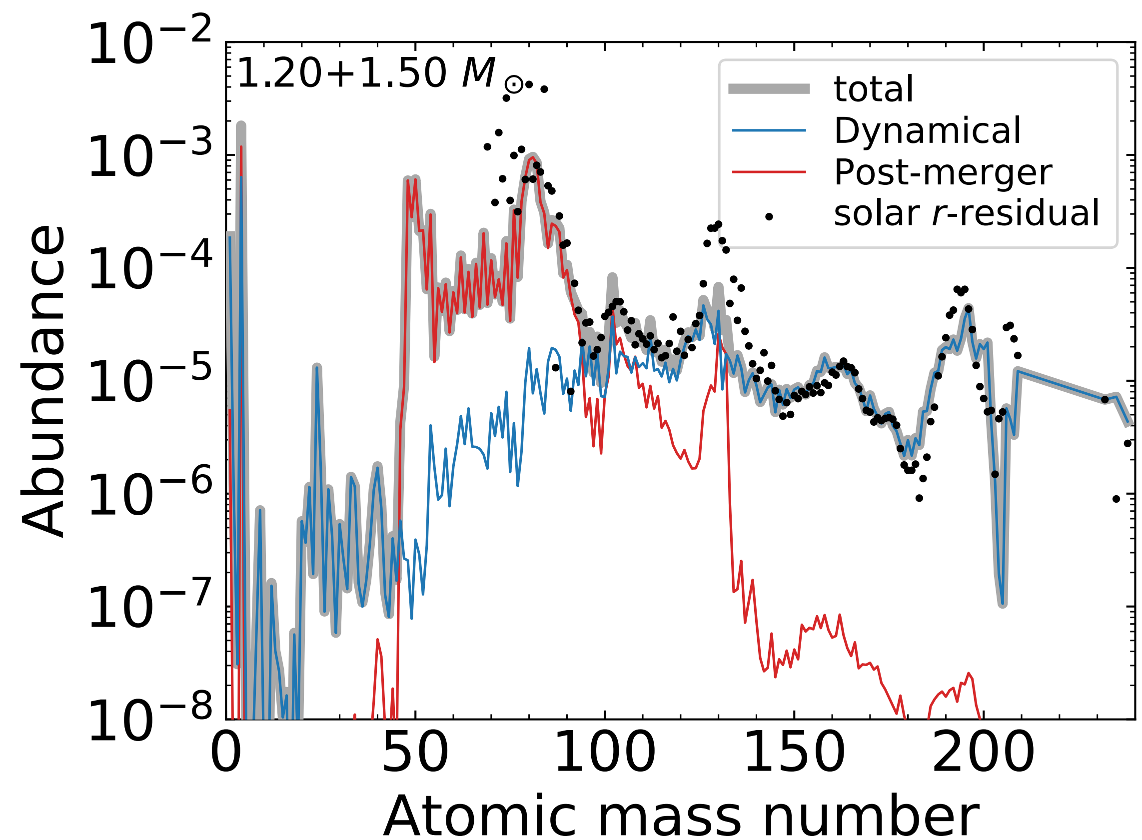
Super-kilonova

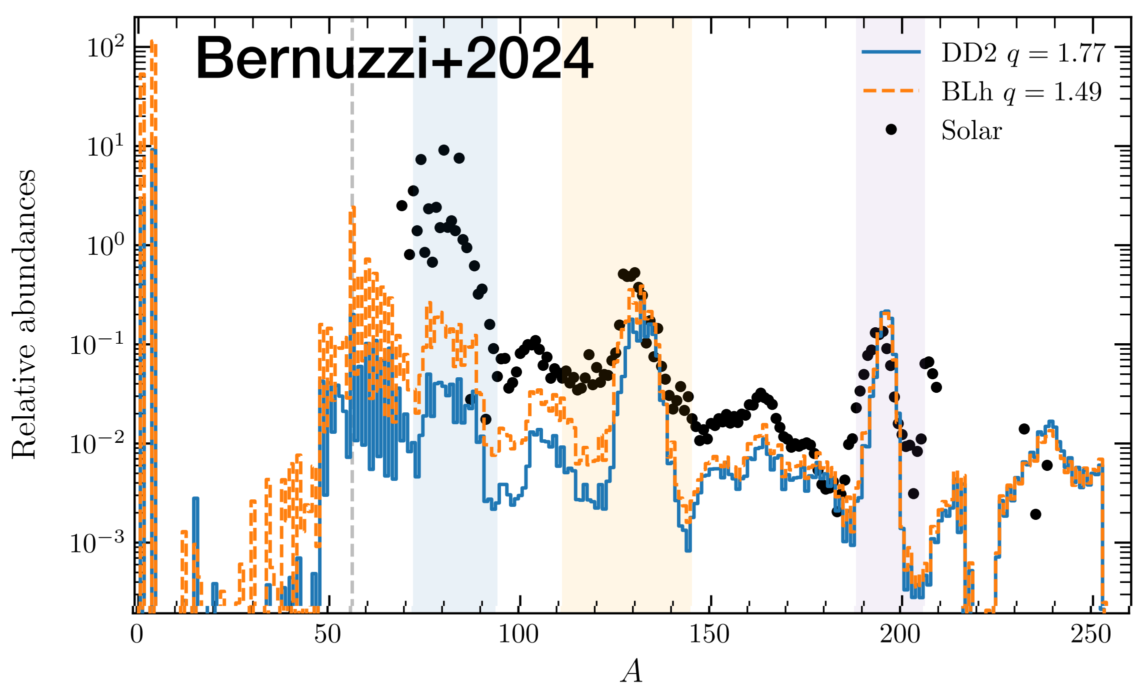
Superluminous Super-kilonova …

Variation in Abundance pattern

Fujibayashi+23







- **The abundance pattern of outflows is sensitive to the remnant neutron star's lifetime.**

Perego+14, Wanajo+14, Sekiguchi+15, Shibata+17, Radice+18, Miller+19, Combi & Siegel 23, Fahlman & Fernandez 22, Haddai+23,Just+23, Fujibayashi+23, Bernuzzi+24. Kiuchi+24, Schianchi+24, Rosswog+25,Jacobi+24 and more

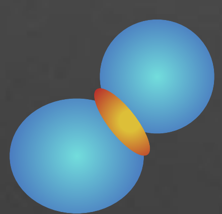
Outline

- Introduction to Kilonova
- Non-LTE Kilonova
- Elemental identification in GW170817
- Kilonova observed by JWST after a long GRB
- Where are heavy elements? W, Pt, Os
- Conclusion

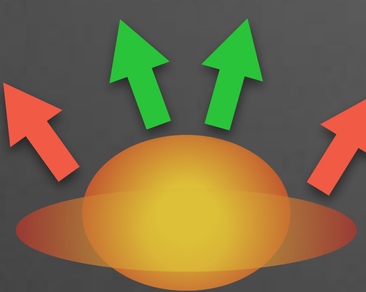
Neutron Star Merger & Kilonova

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

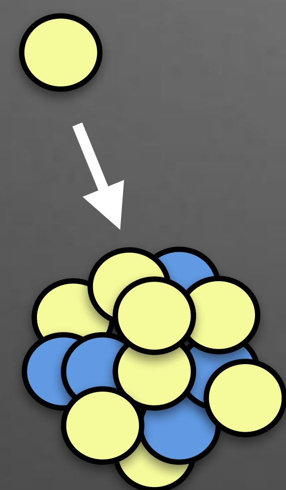
Merger



Post-merger



R-process nucleosynthesis



$t=0$ | $0<t<1$s | $\sim<1$s

MeV | 0.1MeV

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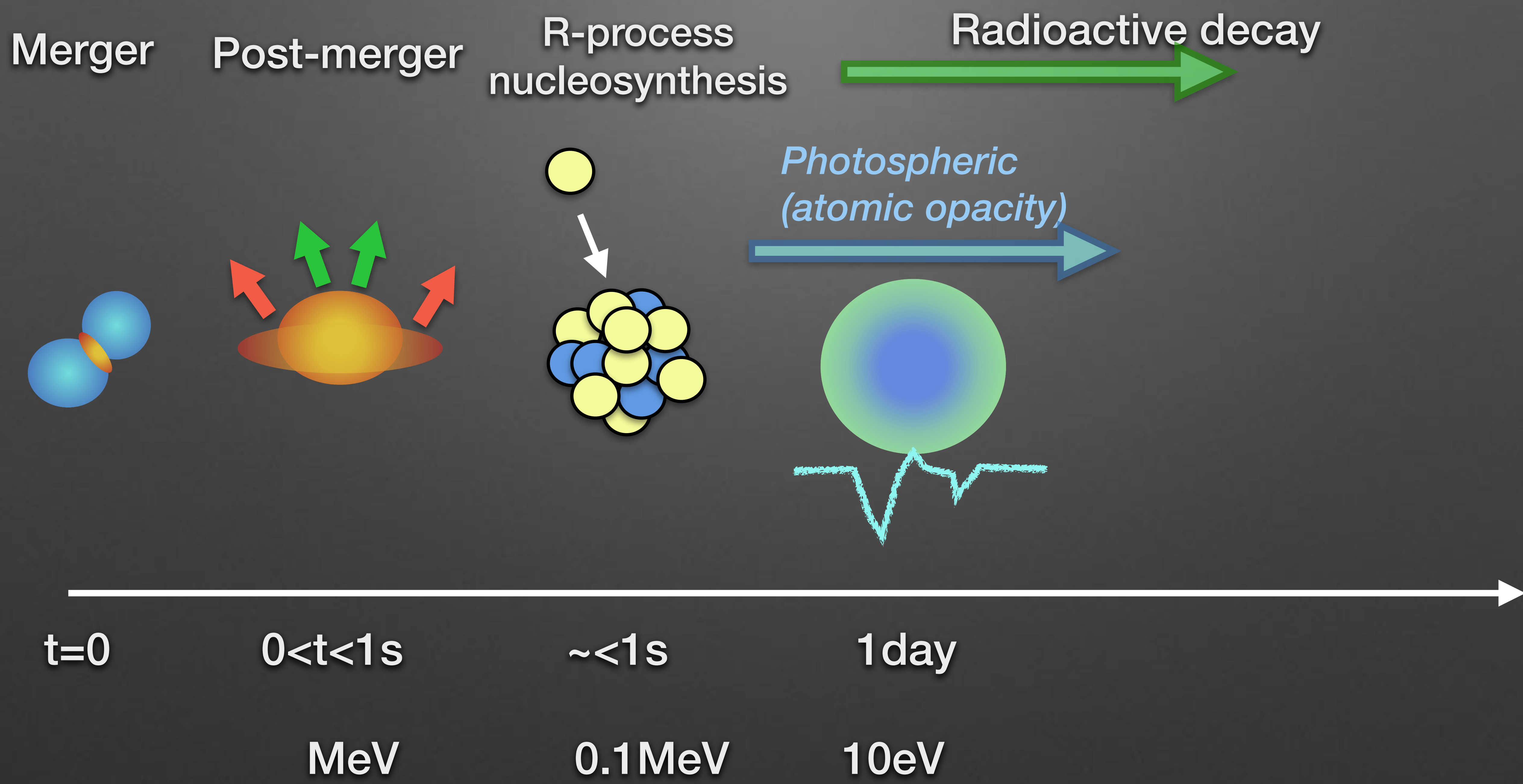

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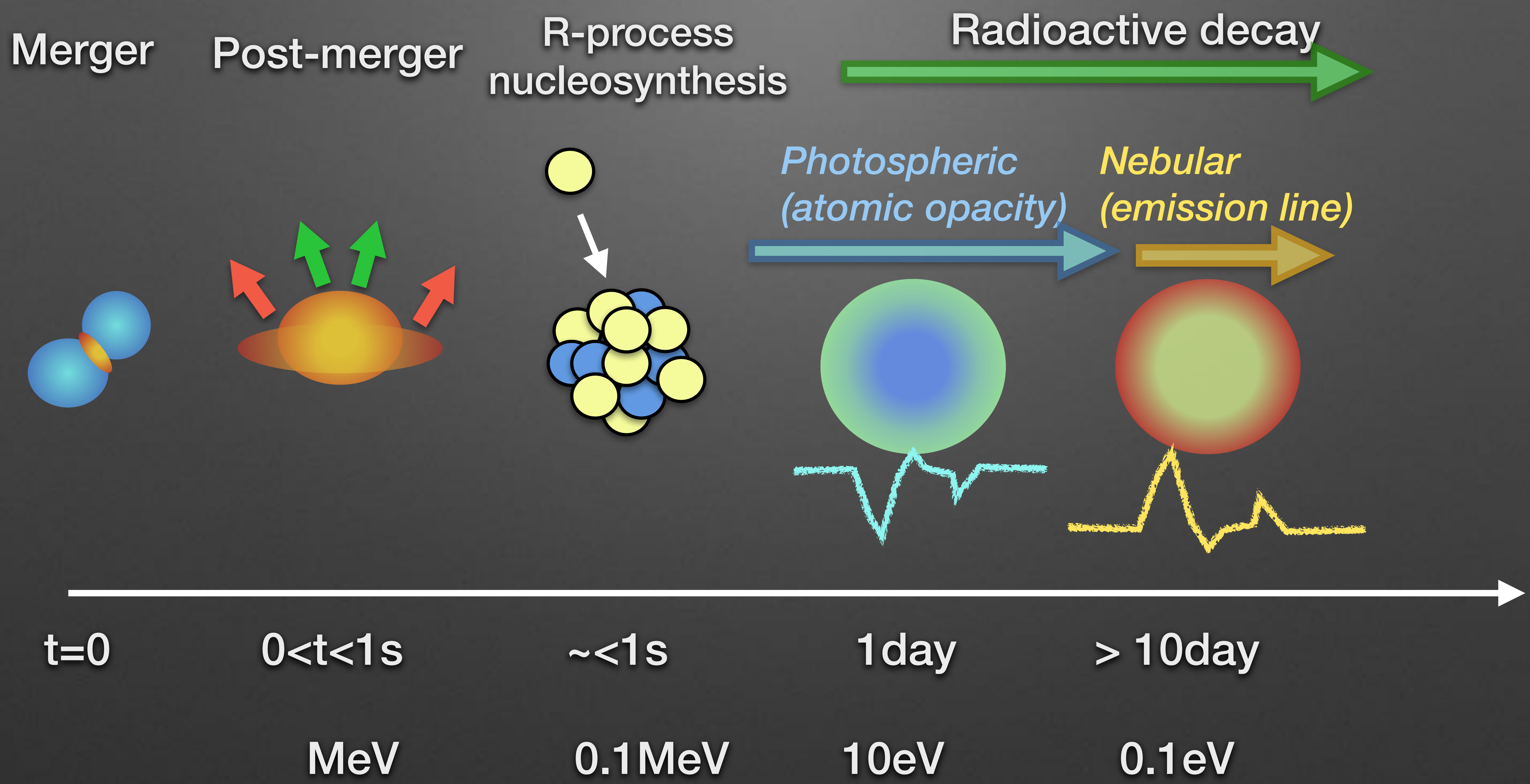

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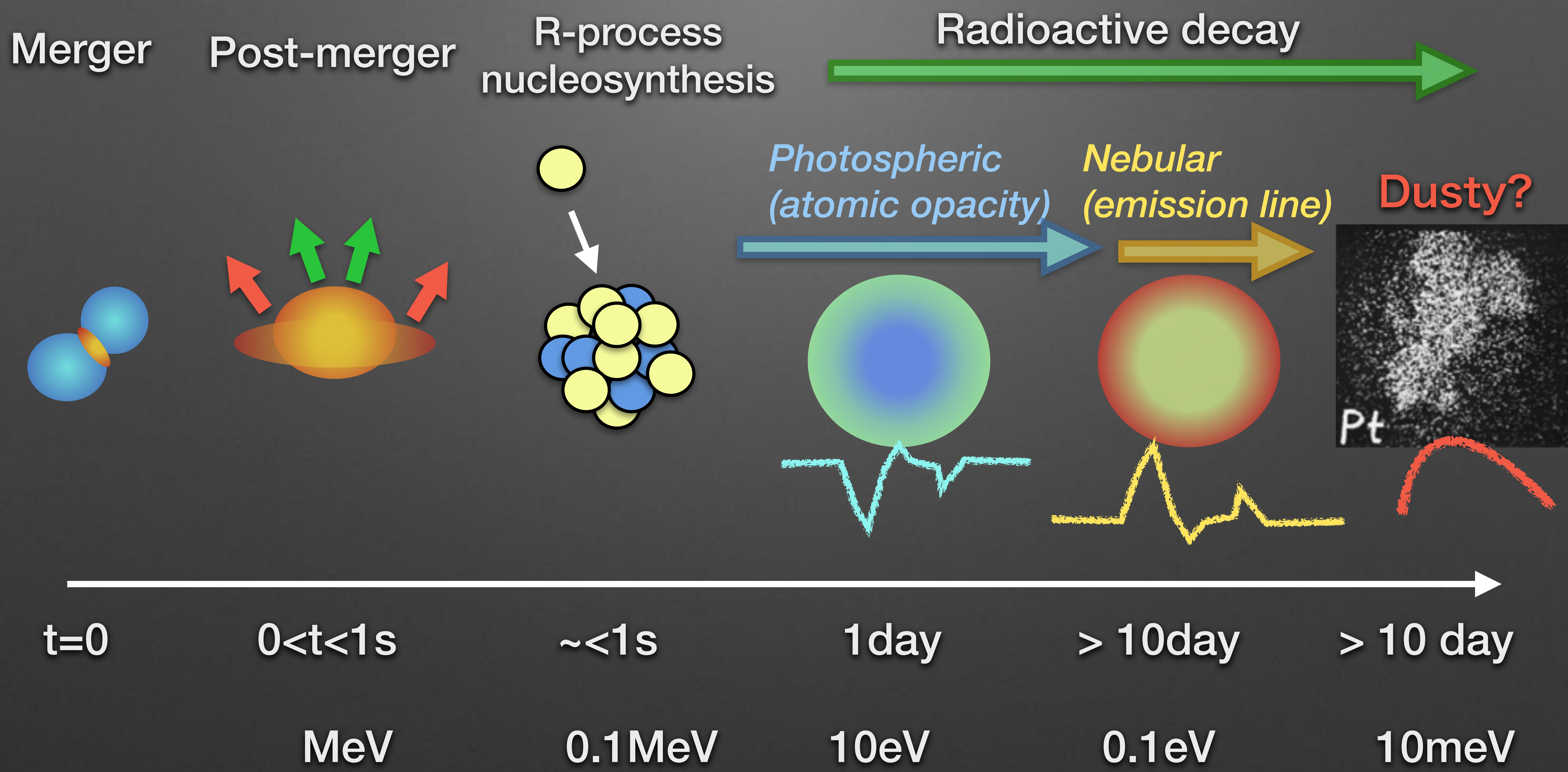
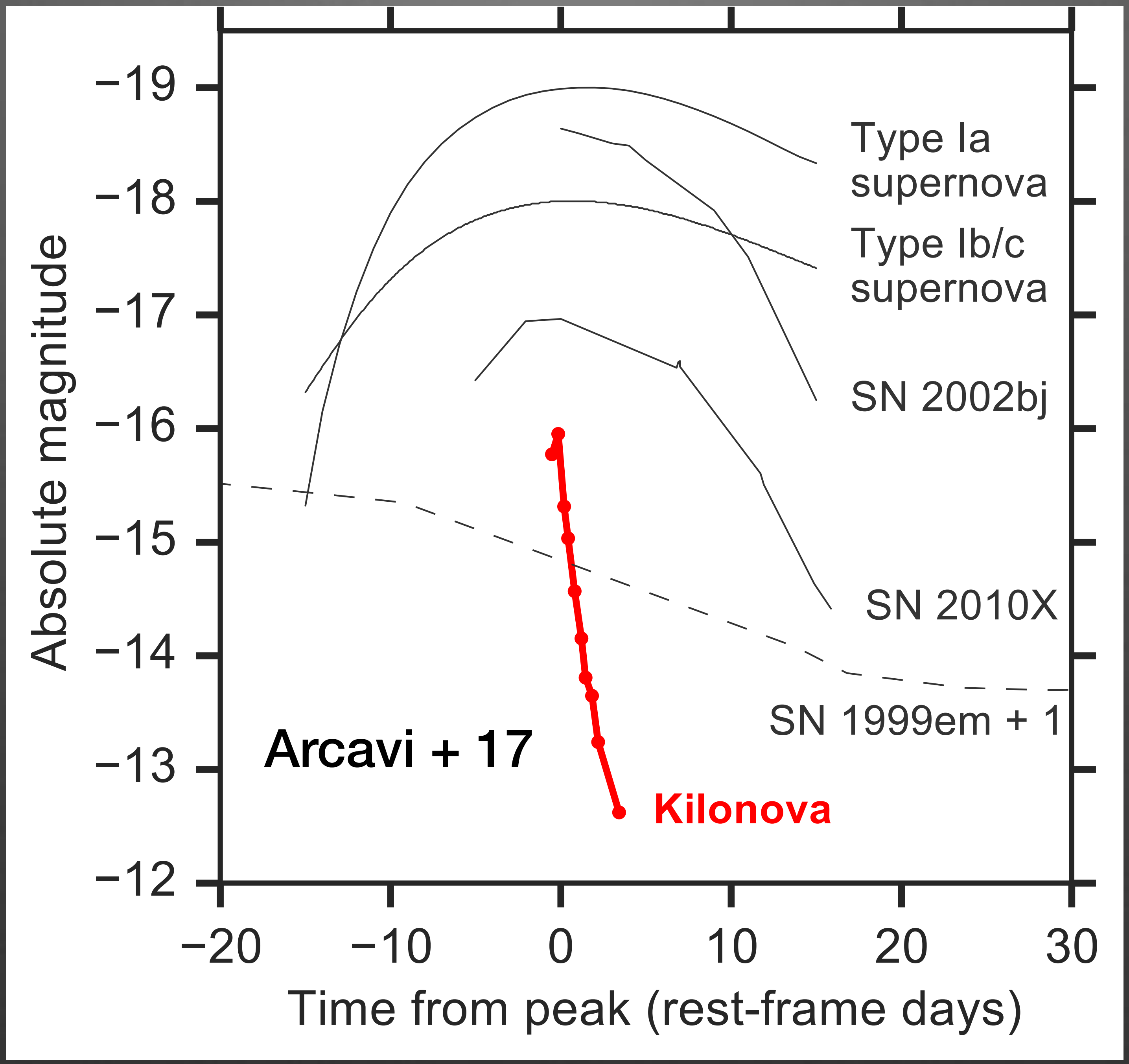


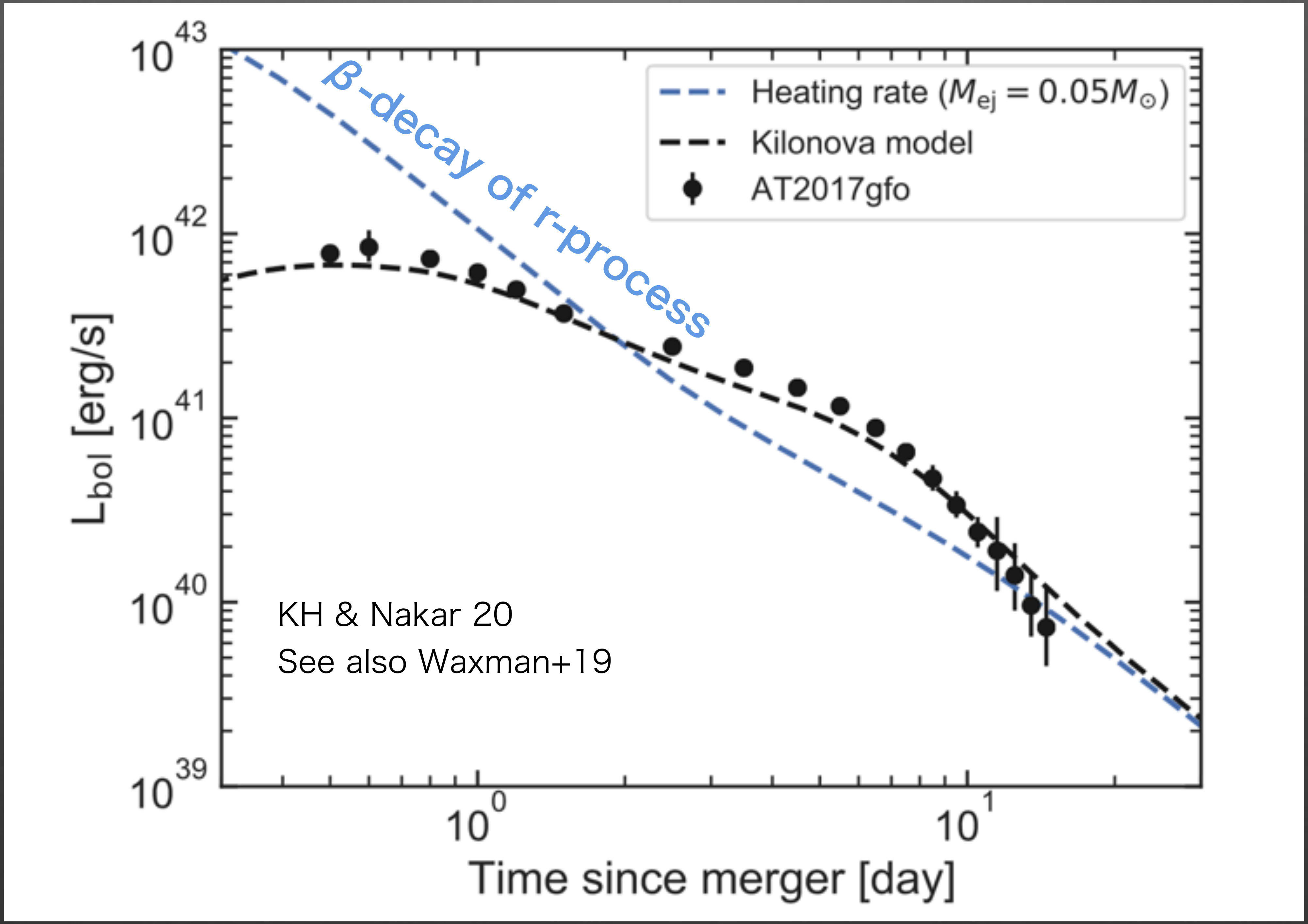
Kilonova AT2017gfo in GW170817

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



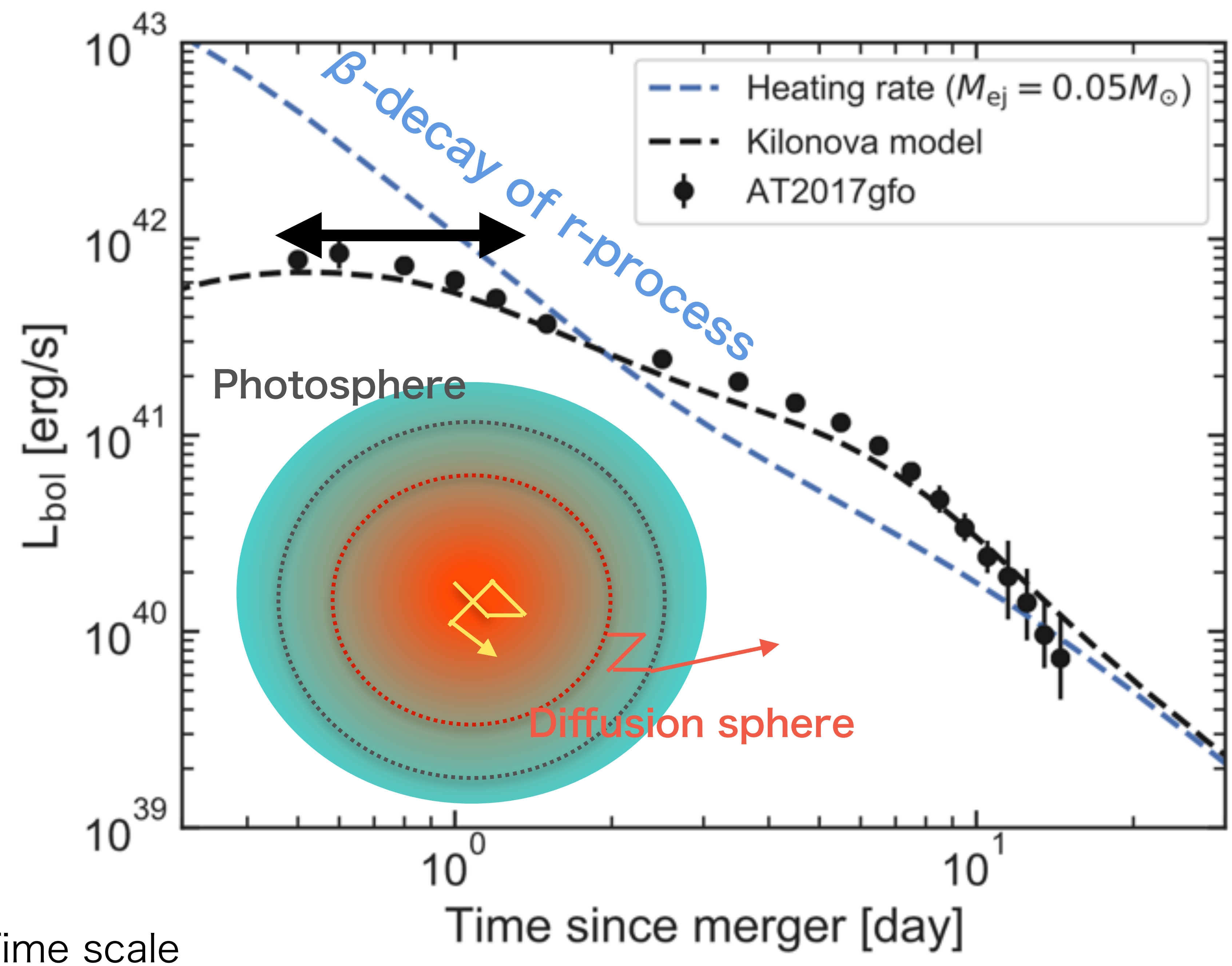
- Kilonova is much fainter and evolve much faster than supernovae.
- GW observations greatly help to find kilonovae.

Observed Light curve & β-decay



- The light curve follows the radioactive heating of r-process nuclei.
- 0.05Msun of r-process is needed to explain the kilonova AT2017gfo.

Peak of Kilonova Light Curve



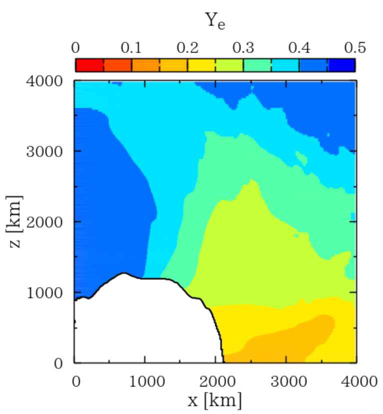
Time scale

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

The peak time of ~< 1day suggests κ ~< 1 $\mathrm{cm^2/g}$

Efforts on Kilonova Study

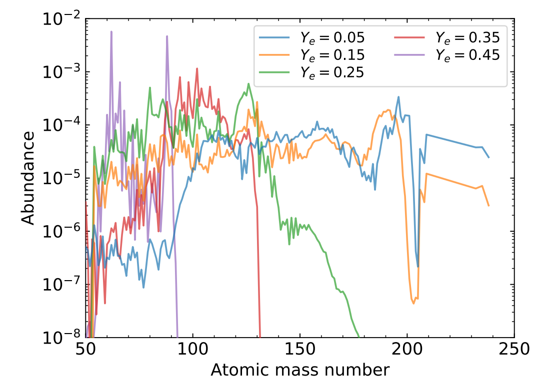
GRRMHD simulations



Perego+14, Sekiguchi+15, Shibata+17, Radice+18, Miller+19, Combi & Siegel 23, Fahlman & Fernandez 22, Haddai+23,Just+23, Fujibayashi+23, Bernuzzi+24. Kiuchi+24, Schianchi+24, Rosswog+25,Jacobi+24

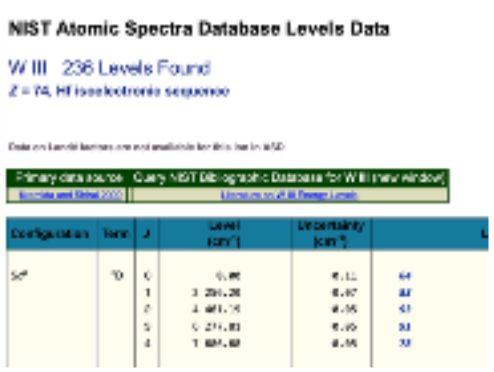
Kenta Kiuchi talk

Nucleosynthesis



Freiburghasu+99, Metzger+10, Goriely+11, Korobkin+12, Surman+13, Wanajo+14, Eichler+15, Lippuner& Roberts 15, Zhu+18,21, Wu+16, 19, Barnes+21, Bulla 23, Ricigliano+24

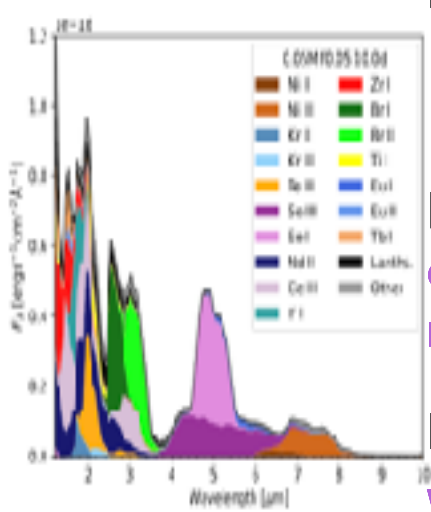
Atomic data



Kasen+13, Tanaka+20, Gaigalas+19, Banerjee+2024, Fontes+20, Da Silva+22, Domoto+23,25, Mulholland+24, Flors+25, McCann+25, Rahmouni+25

Radiation Transfer/Plasma modeling

Barnes & Kasen 13, Tanaka & KH 13, Wollaeger+18.21



Multi-D

Bulla+19,21, Korobkin+21 ,Collins+23,24, Shrestha+23, Shingles+

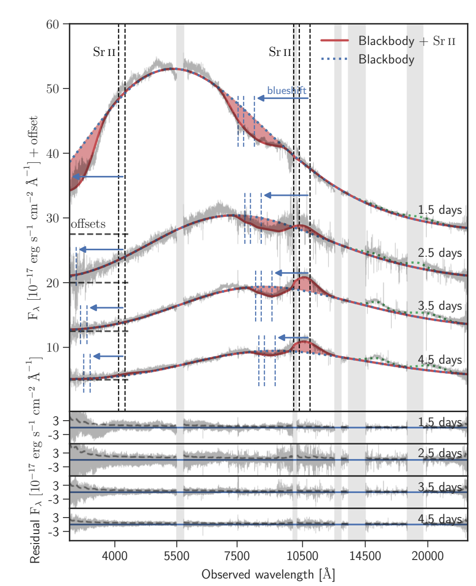
Element ID

Gillanders+22,24,25, Sneppen+, Domoto+23, Tarumi+23, KH+23,24

NLTE/Non-thermal

Waxman+19, KH & Nakar 20, KH+21, Pognan+22, 23, 25, Jerkstrand+25

Observation

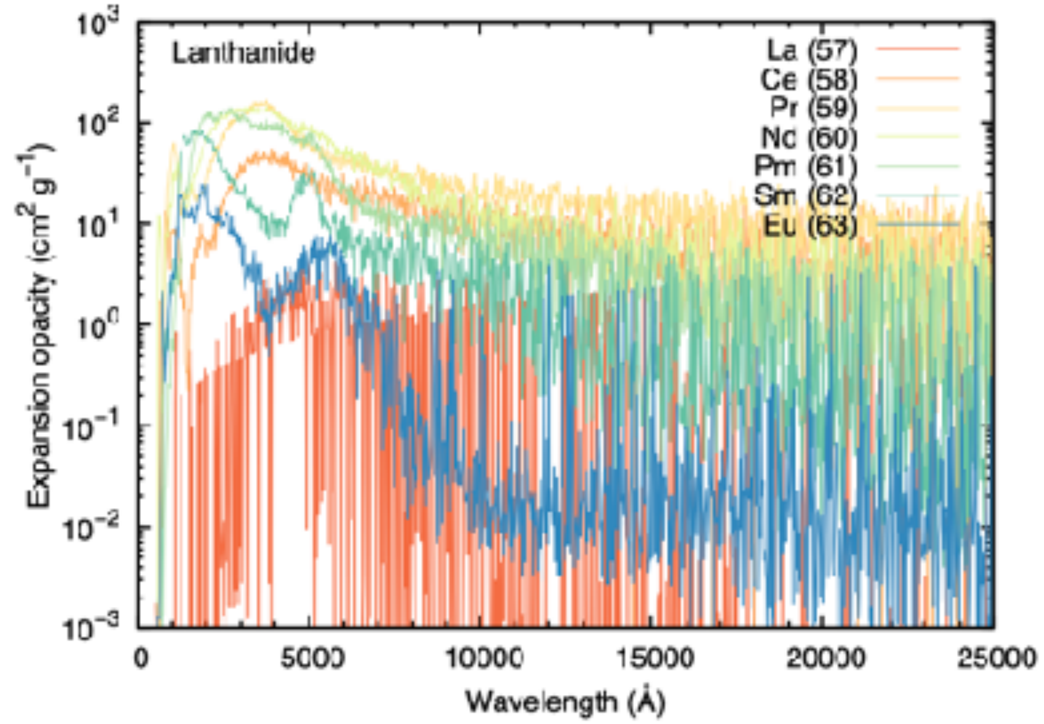


e.g. Pian+17, Troja+17, Watson+19, Levan+24, Gillanders & Smart 25

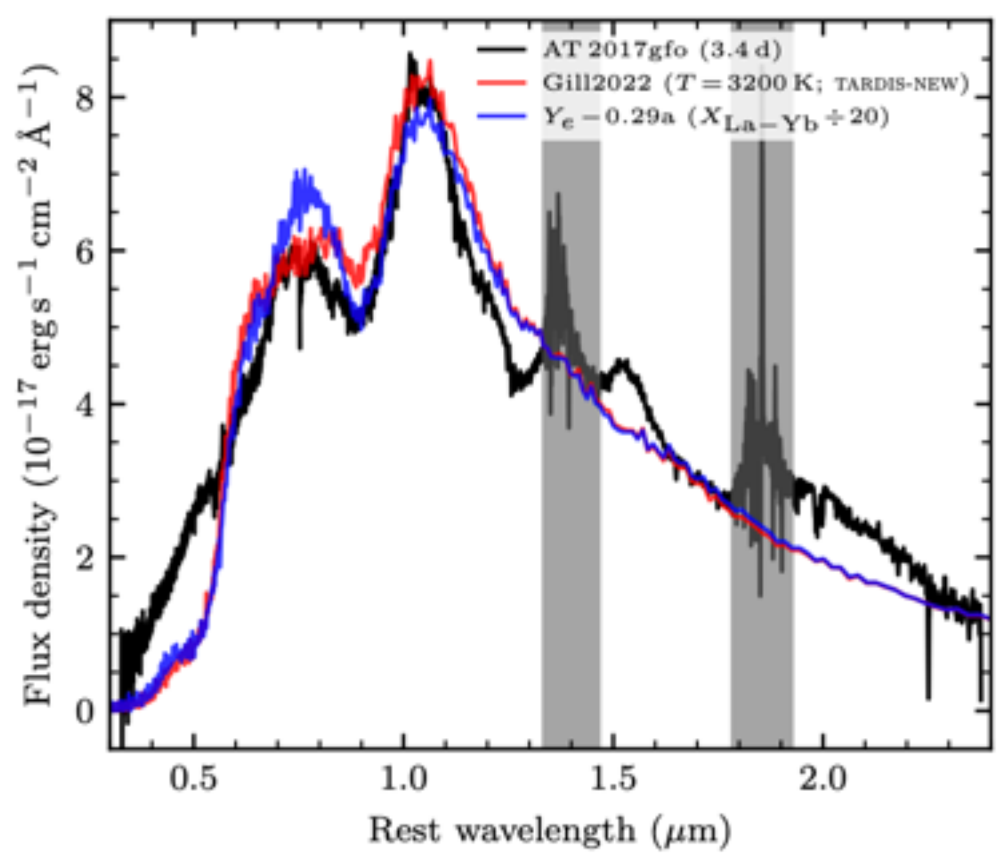
Efforts on Opacity data

- IR lines of heavy elements were largely missing before 2017.
- Completeness matters for opacity, which is solved with atomic codes:
  - Autostructure (e.g. Kasen+17)
  - Hullac (e.g. Tanaka+20)
  - GRASP2K (e.g. Gaigalas+19)
  - ATOMIC (e.g. Fontes+20)
  - FAC (Flors+25)
  - HFR (e.g. Deprince+25)
- Atomic codes must be tuned with experimental data for high accuracy (Domoto+23,25, Rahmouni+25,Flors+25).
- KN data => X_{lan} is ~0.1 x solar r-process

Tanaka+20



Gillanders+25



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What does non-LTE mean?

Non-LTE:
Any situation different from local thermodynamic equilibrium (LTE).

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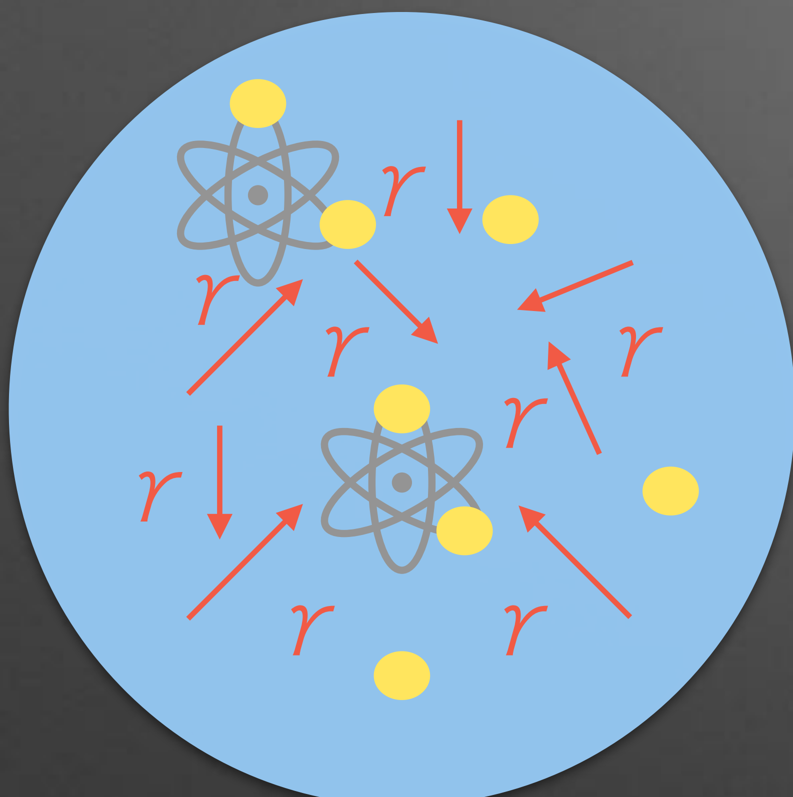
LTE:
Local thermodynamic equilibrium
Matter at a given location is characterized by a single local temperature T.

LTE

LTE = Local Thermodynamics Equilibrium



For example, if many ‘thermal’ photons exist and density is high enough

$$X^{+i} + \gamma \longleftrightarrow X^{+i+1} + e^{-}$$

(ionization) (recombination)

$$X^{+i}(E_l) + \gamma \longleftrightarrow X^{+i}(E_u)$$

(excitation) (de-excitation)

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LTE

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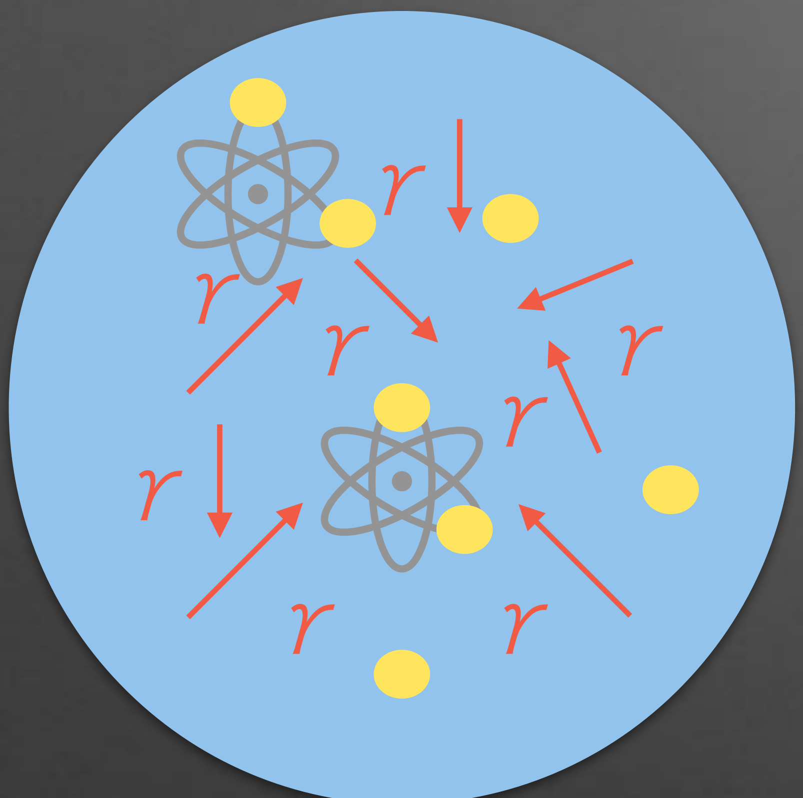

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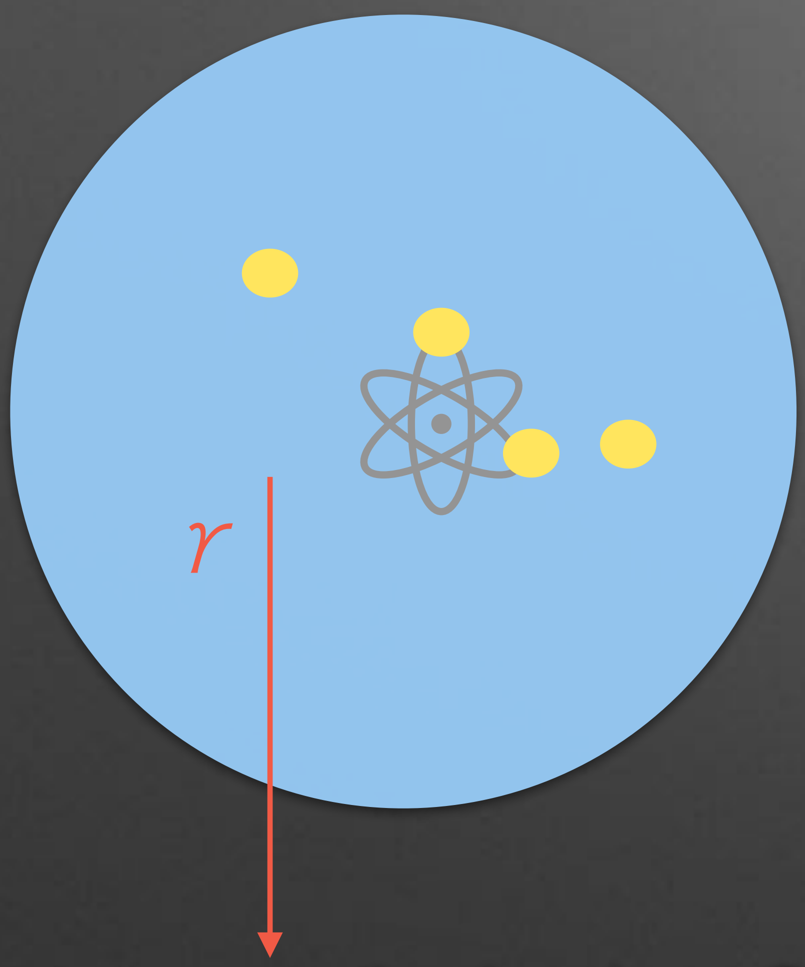
Ionization: Saha equilibrium (T)

Level: Boltzmann distribution (T)

Particle motion: Maxwell-Boltzmann distribution (T)

Non-LTE: examples



For example, if photon and gas densities are low

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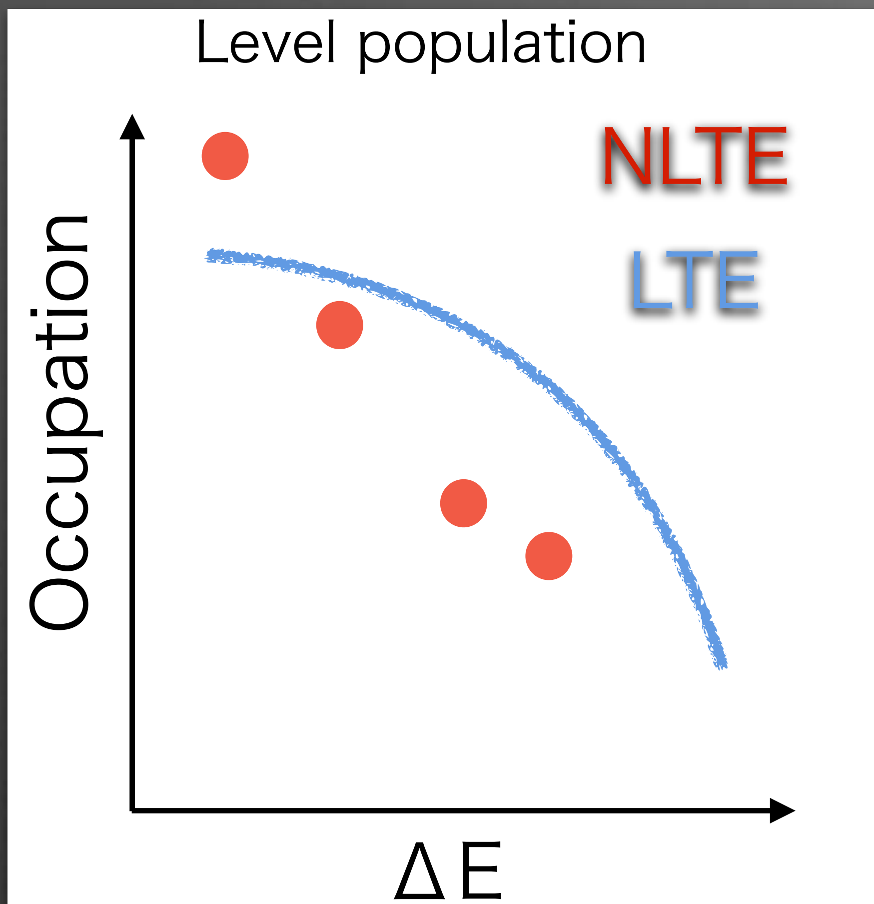

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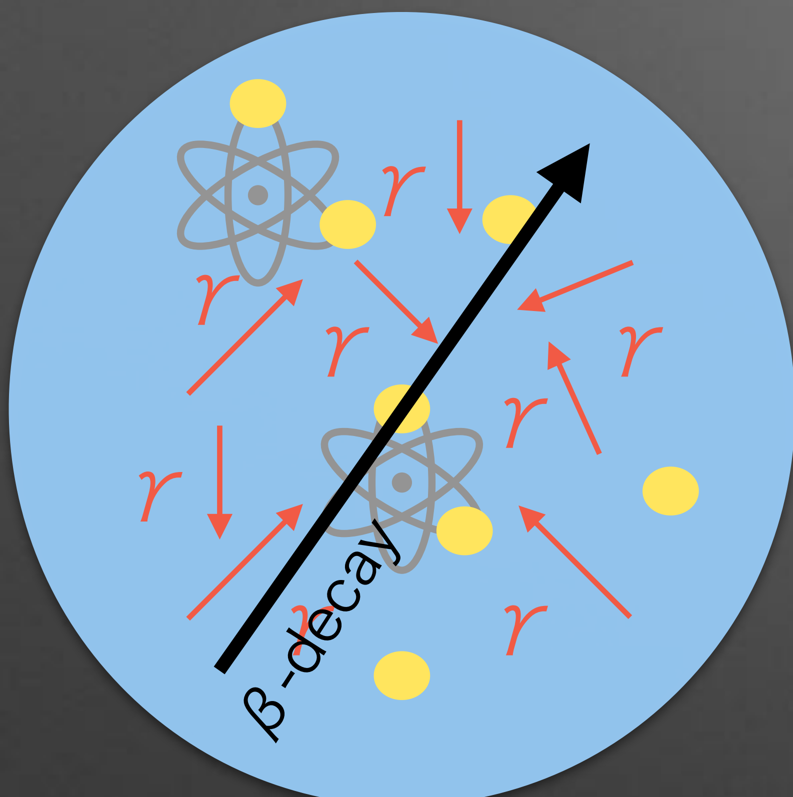
Level: ~~Boltzmann distribution (T)~~ each line T_{lu}.

Particle motion: Maxwell-Boltzmann distribution (T)

Non-LTE: examples



For example, radioactive (KN, SN)

$$X^{+i} + e^- \longrightarrow X^{+i+1} + 2e^-$$

$$X^{+i} + \gamma \rightleftharpoons X^{+i+1} + e^-$$

(ionization) (recombination)

$$X^{+i}(E_l) + \gamma \rightleftharpoons X^{+i}(E_u)$$

(excitation) (de-excitation)

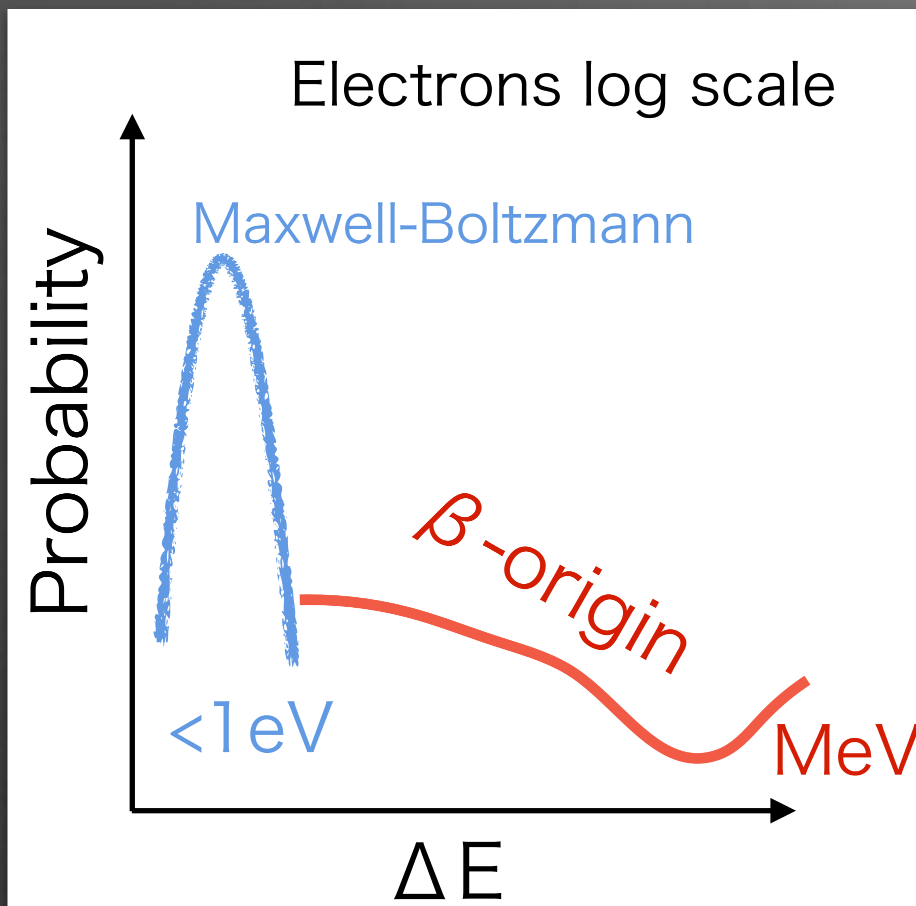
$$X^{+i}(E_l) + e^- \rightleftharpoons X^{+i}(E_u) + e^-$$

Ionization: ~~Saha equilibrium (T)~~

Level: ~~Boltzmann distribution (T)~~

Particle motion: ~~Maxwell-Boltzmann distribution (T)~~

Non-LTE: examples



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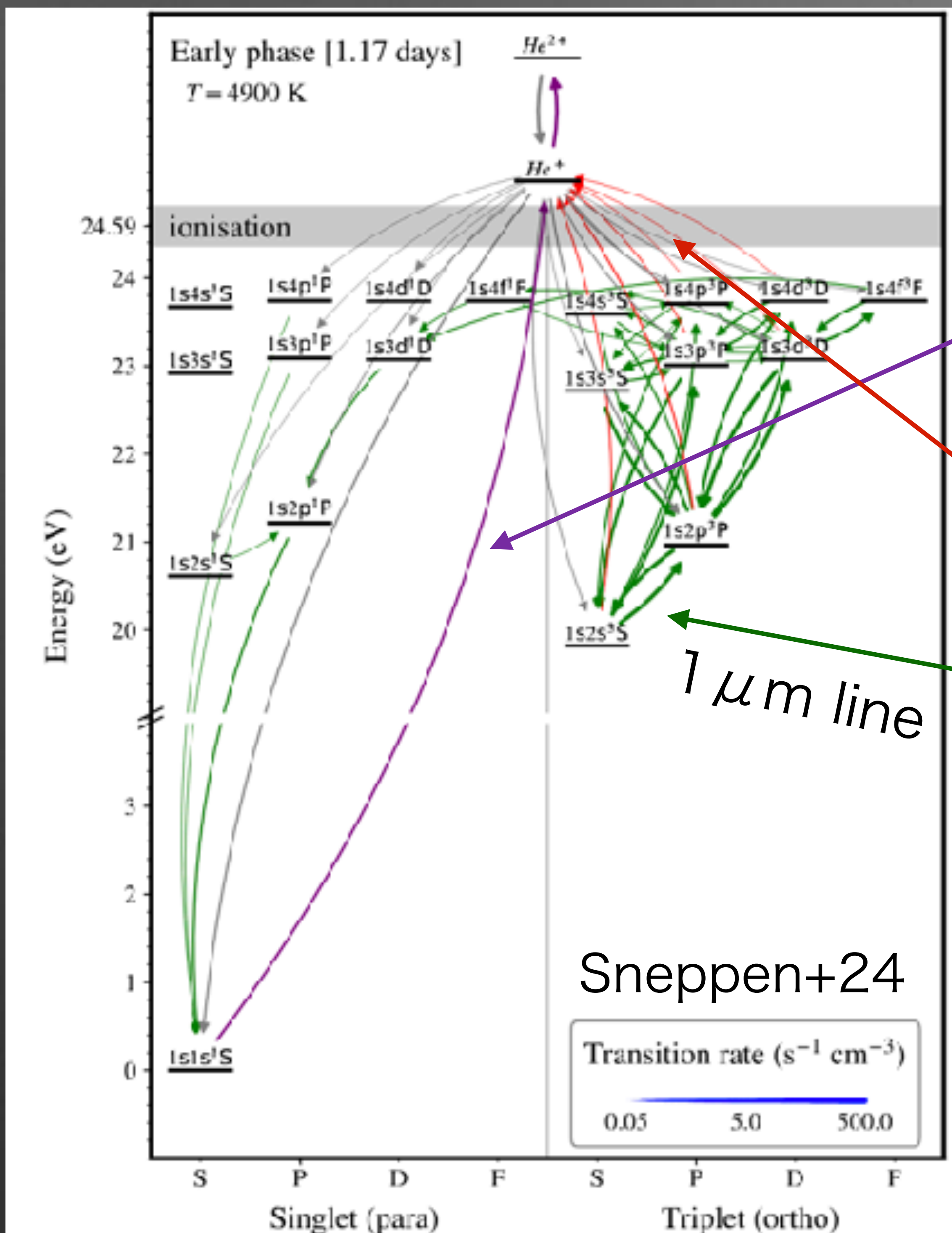
Non-LTE: examples



Kilonova Helium problem (Tarumi,KH+23, Sneppen+24, Chiba's poster)

$He^{+0}+e^- \longrightarrow He^{+}+2e^-$

$He^{+0}+\gamma \rightleftarrows He^{+}+e^-$

(ionization) (recombination)

$He^{+0}(2^3S)+\gamma \rightleftarrows He^{+0}(2^3P)$

(excitation) (de-excitation)

$He^{+0}(1^1S)+e^-$

$\longleftarrow He^{+0}(2^3S)+e^-$

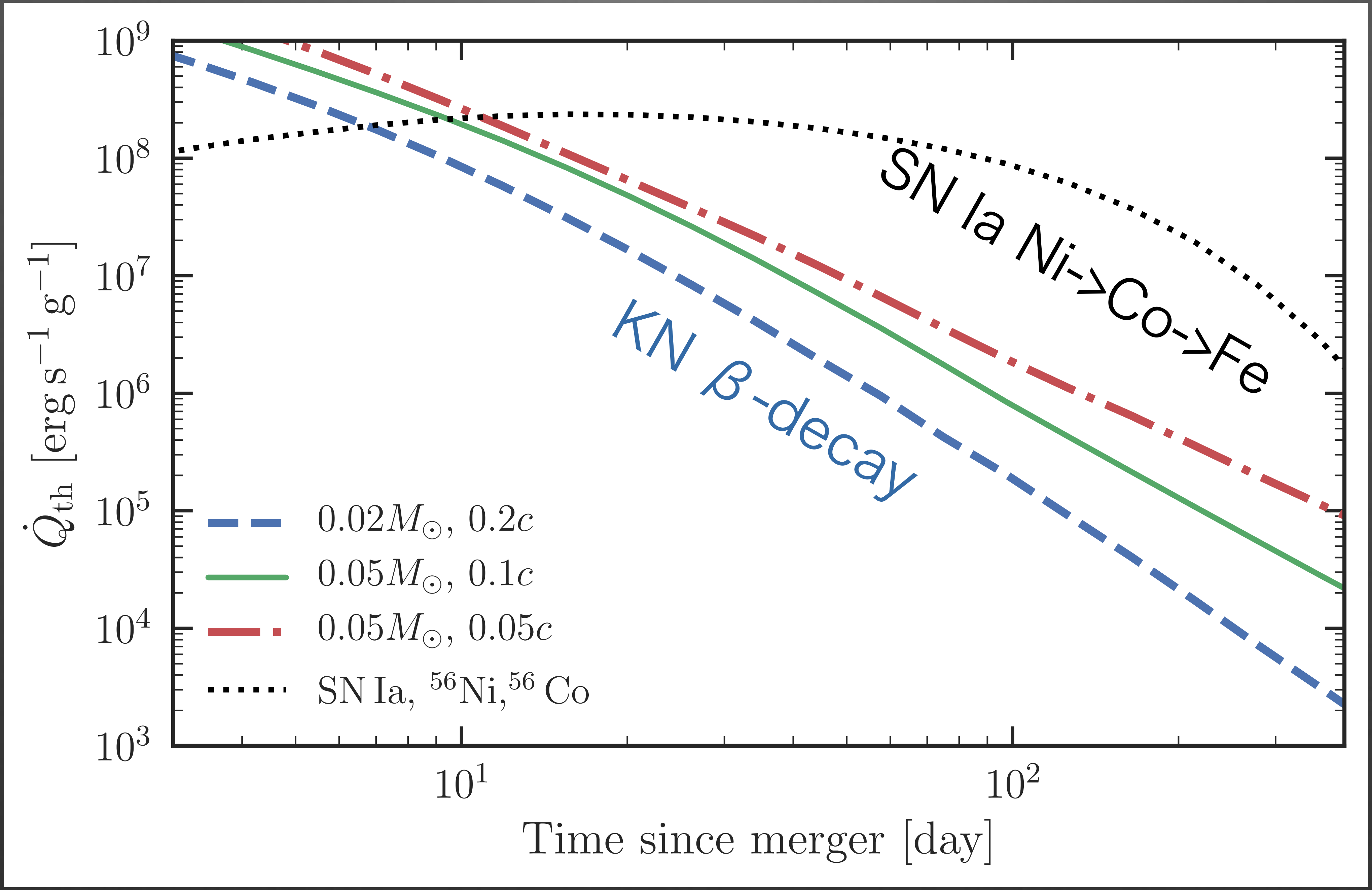
~~uilibrium (T)~~

~~istribution (T)~~

Particle motion: ~~Maxwell Boltzmann distribution (T)~~

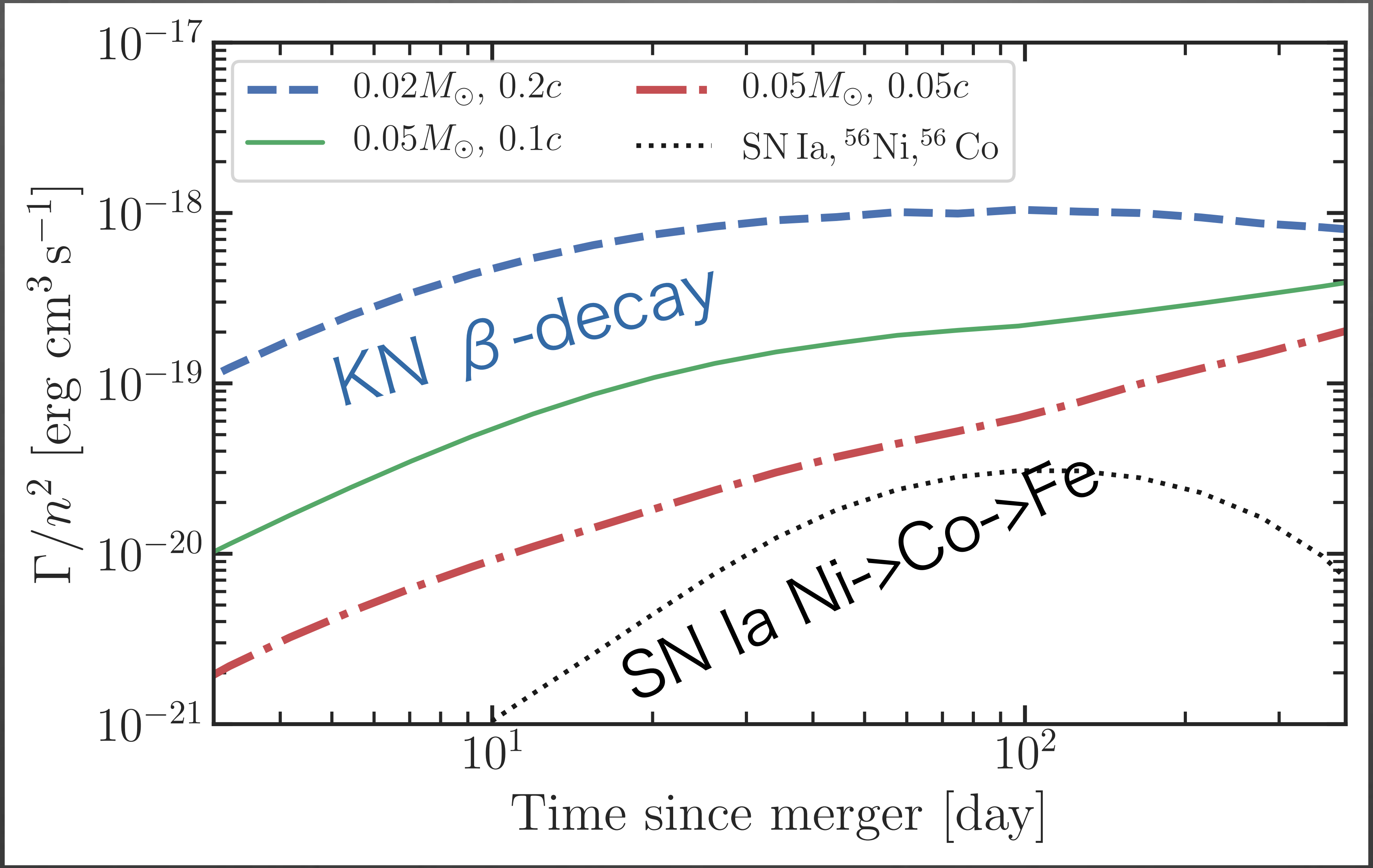
Radioactive heating and thermalization

Metzger+10, Goriely+11, Korobkin+12, Barnes+16, Waxman+19, KH & Nakar 19, KH+20, Kasen & Barnes 19



Radioactive heating and thermalization

KH + 20, Pognan+22



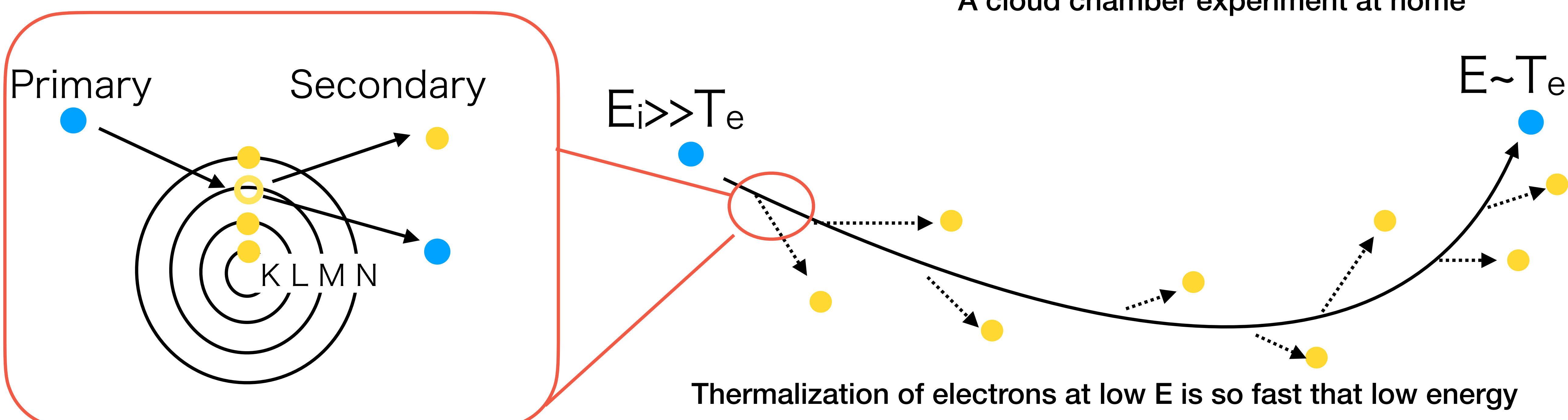
This should be compared with rate coefficients: recombination $\alpha(T_e)$ ($cm^3\ s^{-1}$), excitation $<\sigma_{ex}v>$ (T_e) ($cm^3\ s^{-1}$)

=> Ionization and heating 'efficiency' increase with time

KN density is much lower than SN Ia => The efficiency higher for KNe

Ionization Energy loss of charged particles

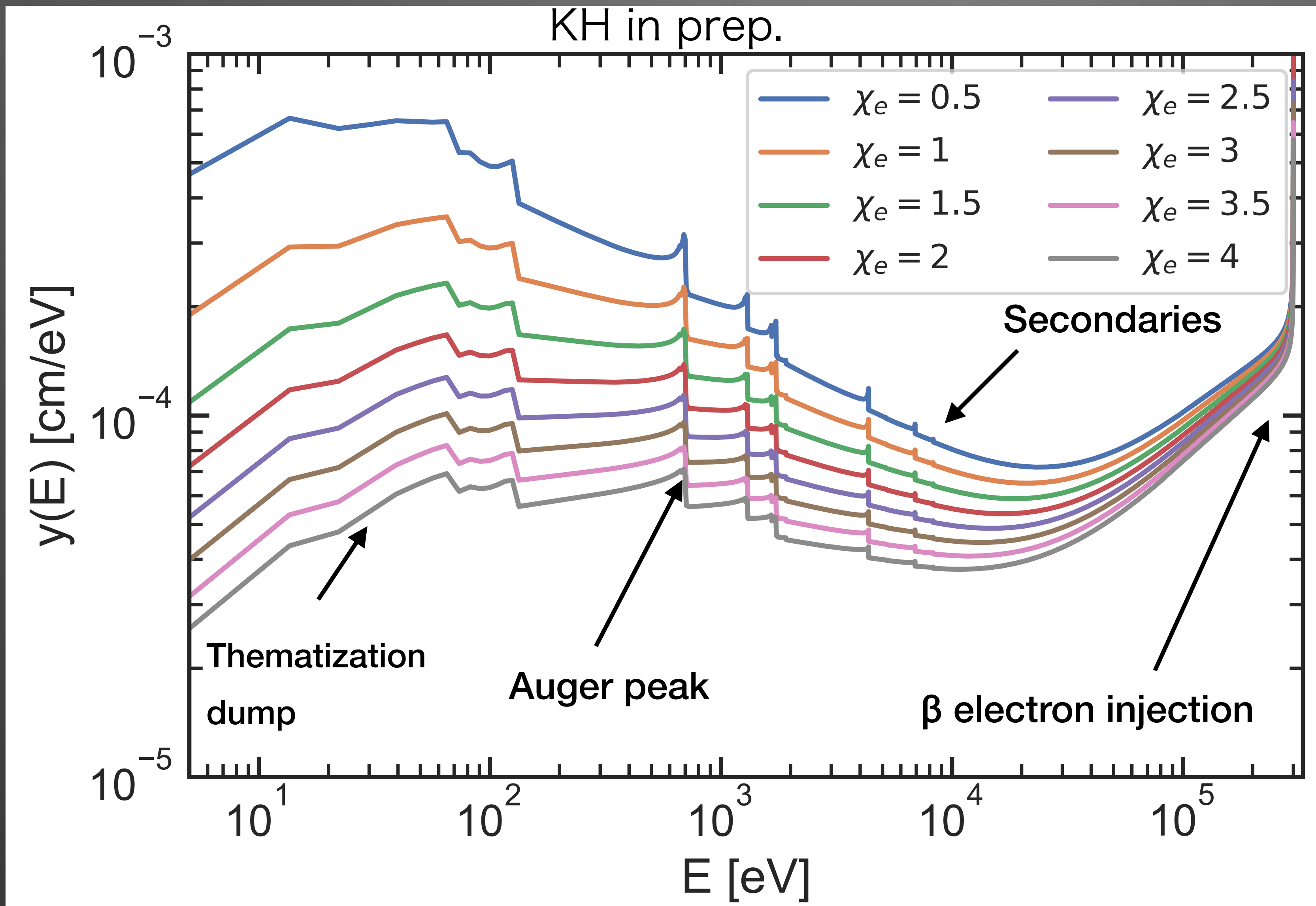
A cloud chamber experiment at home



Thermalization of electrons at low E is so fast that low energy electrons follow the Maxwell-Boltzmann

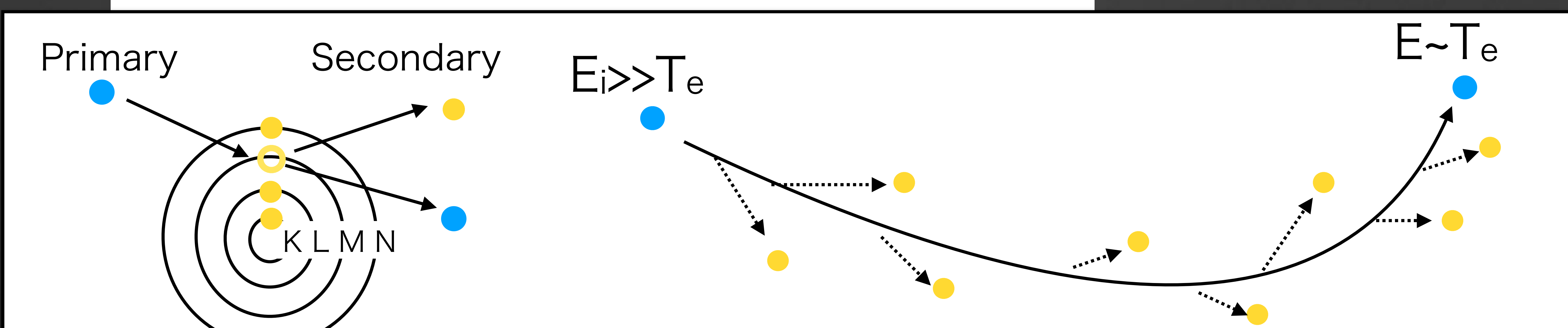
Non-thermal electron spectrum

Degradation spectrum (electron flux)



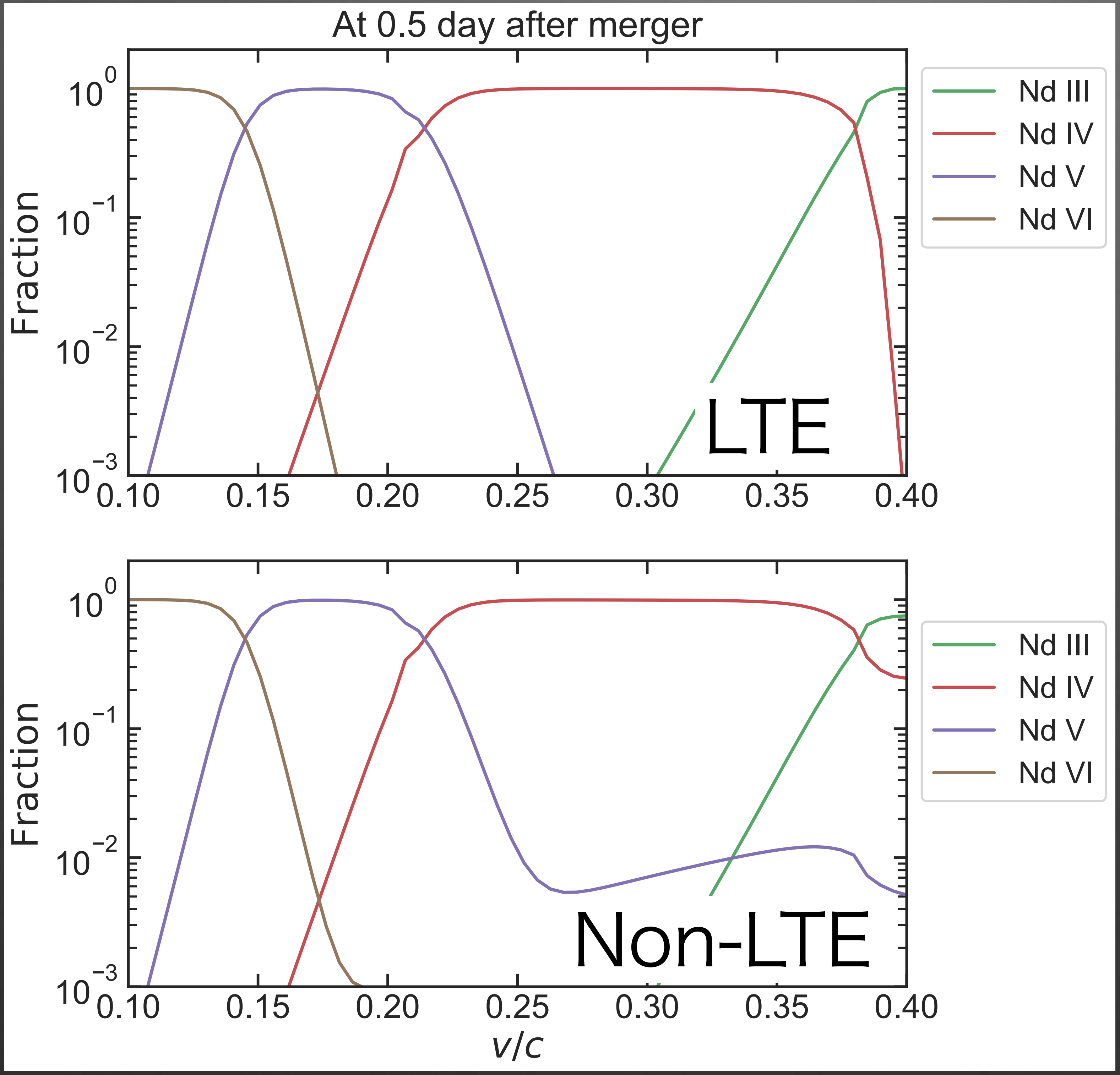
Spencer & Fano 54, Kozma & Franson 92, KH+19, Shingles+21, Wollaeger+24

This spectrum determines non-thermal ionization and excitation.



Impact of β-radiation at 0.5d

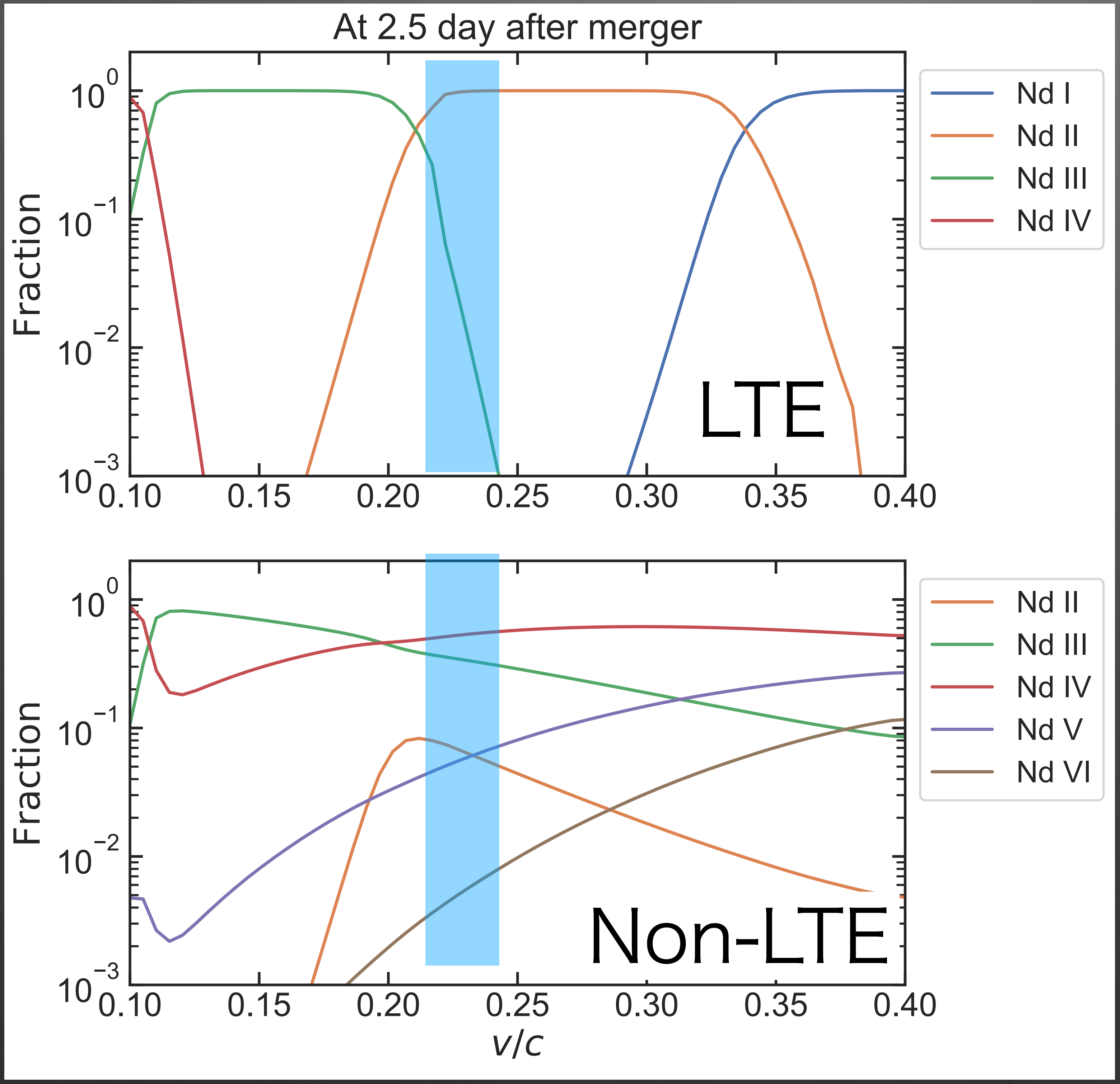
We compute atomic data by Hebrew University Lawrence Livermore Atomic Code (HULLAC).



- At 0.5 day, *T* is so high that the thermal ionization dominates over the radioactive.
- LTE should be good approximation.

Impact of β-radiation at 2.5d

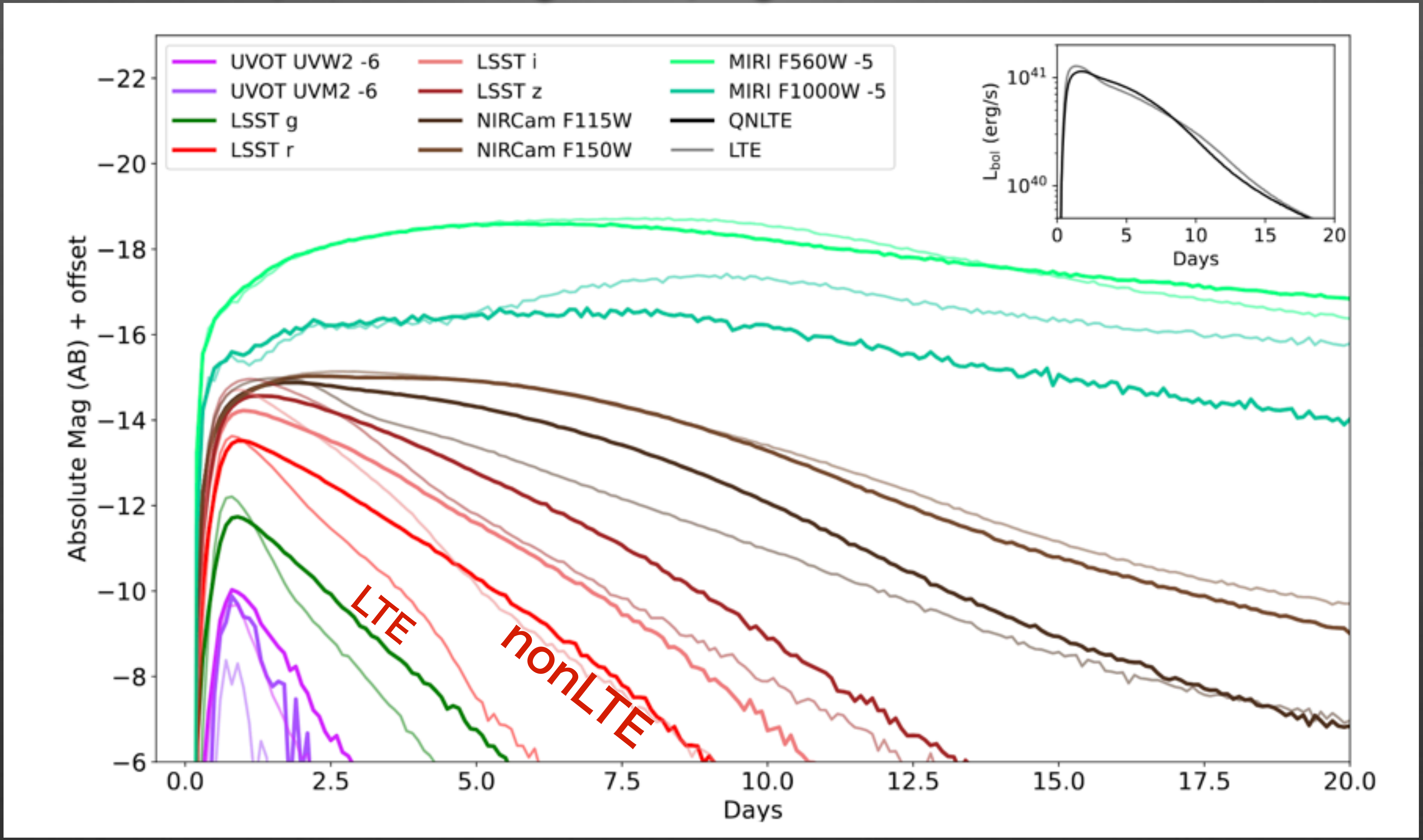
We compute atomic data by Hebrew University Lawrence Livermore Atomic Code (HULLAC).



- At 2.5 day, *radioactive ionization can be important*.
- The deviation from LTE is significant.

Impact of non-thermal ionization on Color

Brethauer+26, see also Kawaguchi+22, Pognan+23



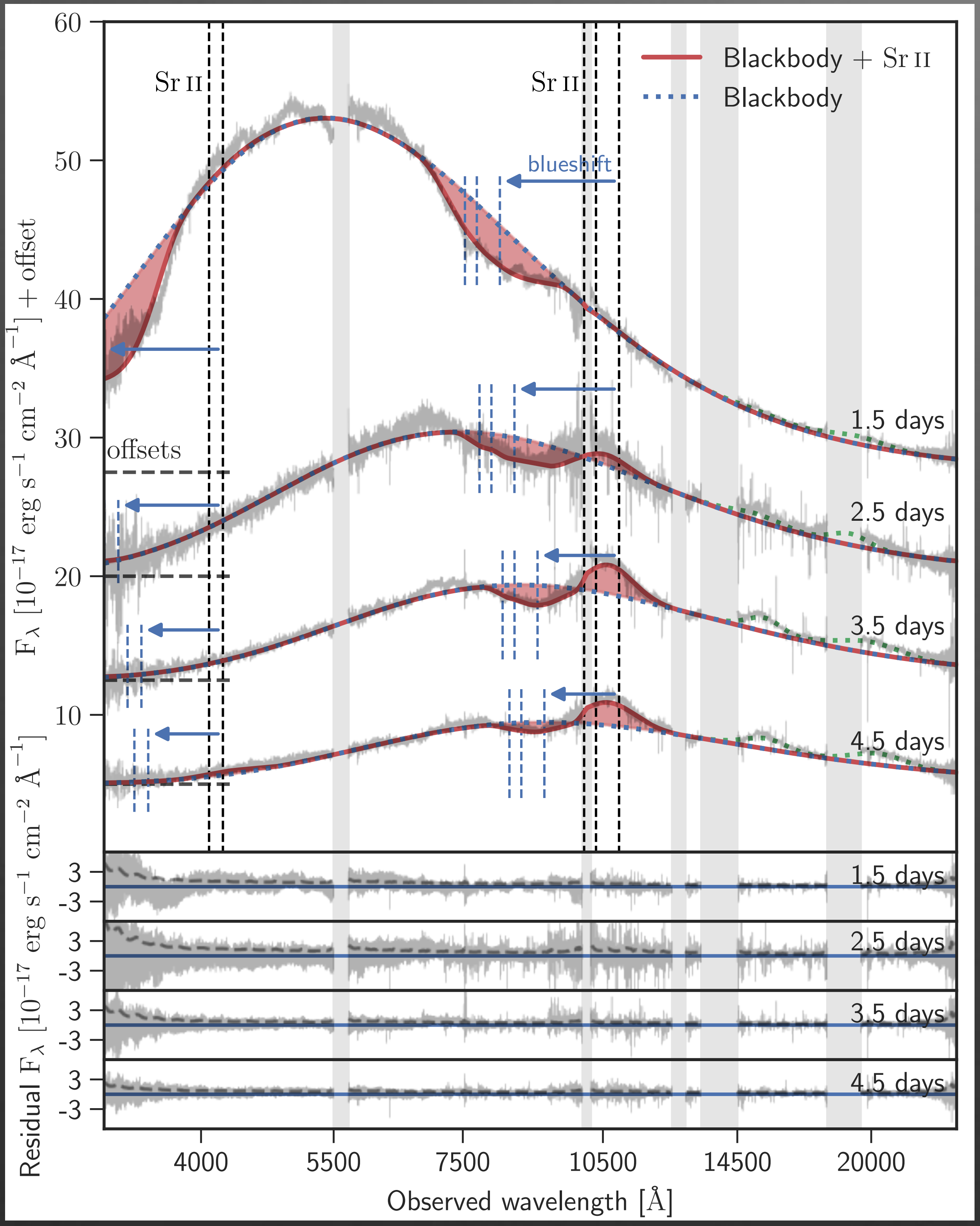
Radioactive ionization is very important for optical light curves after ~ 2 days.

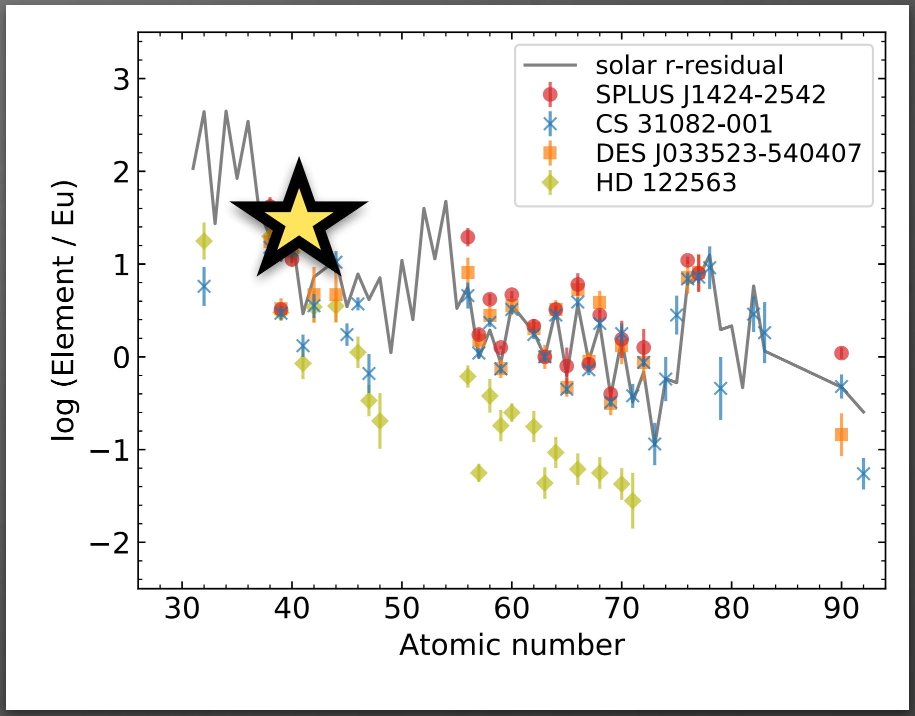
Outline

- Introduction to Kilonova
- Non-LTE Kilonova
- Elemental identification in GW170817
- Kilonova observed by JWST after a long GRB
- Where are heavy ones? W, Pt, Os
- Conclusion

Sr II identification

Watson+2019



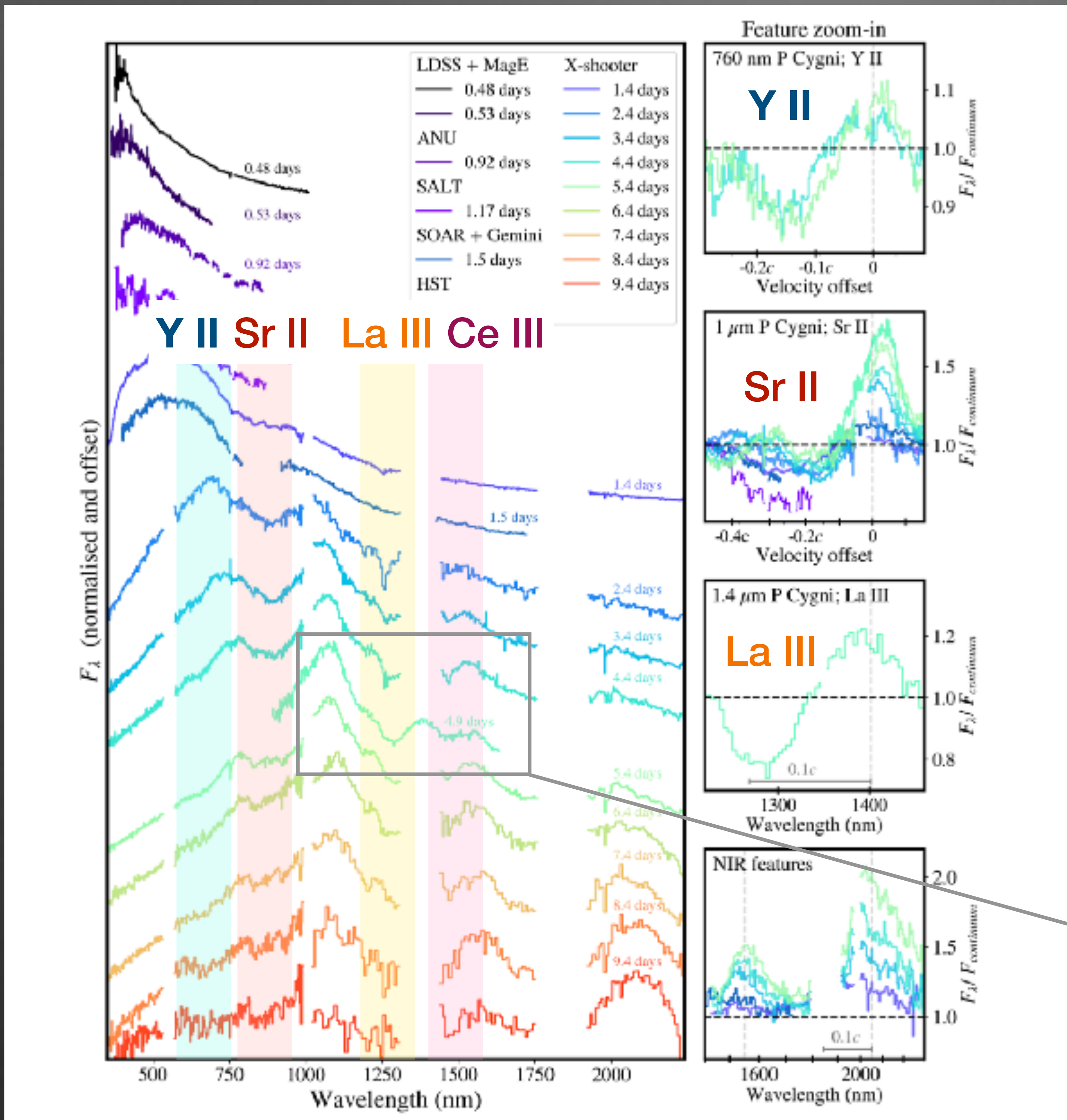


Points:

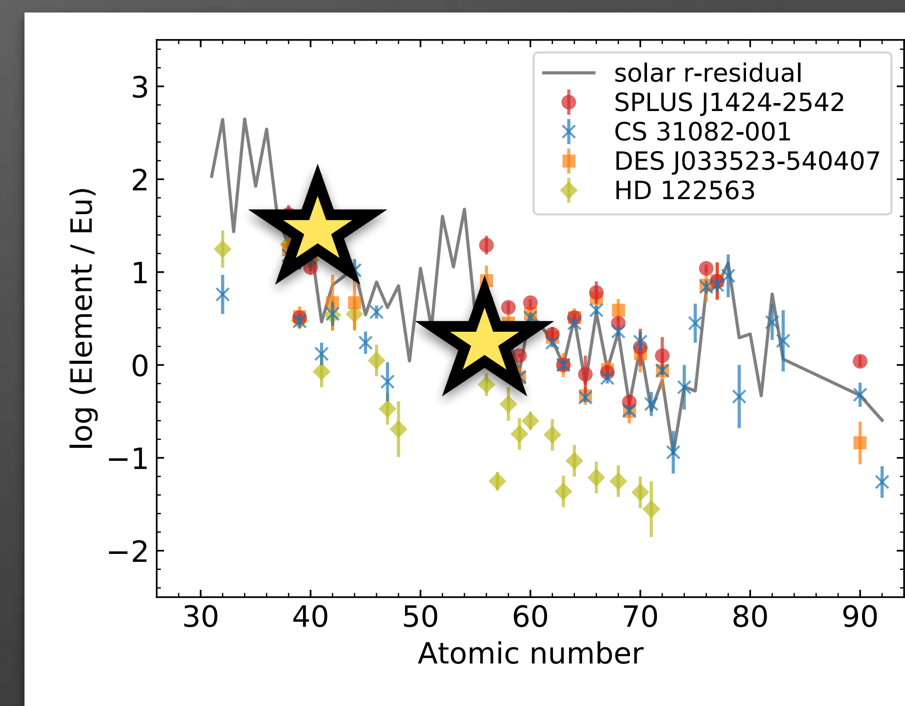
- The first convincing identification
- Sr II triplet at ~ 10^4A is one of the most well-known lines of heavy elements in stars.

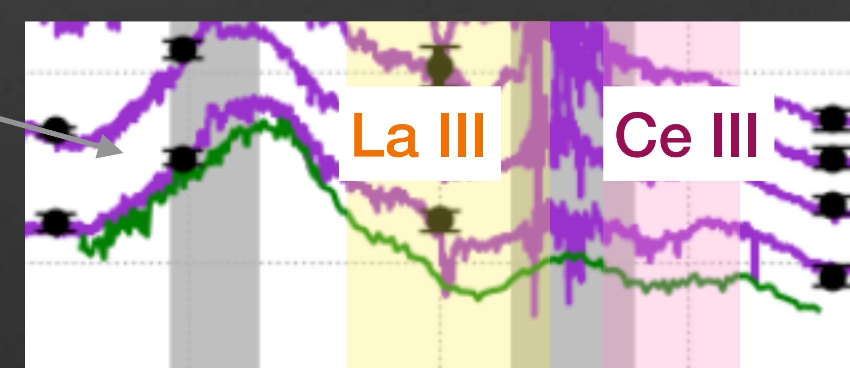
P-Cygni line candidates in AT2017gfo

Sneppen + 24, see also, Watson+19, Pian +17, Gillanders+22,24



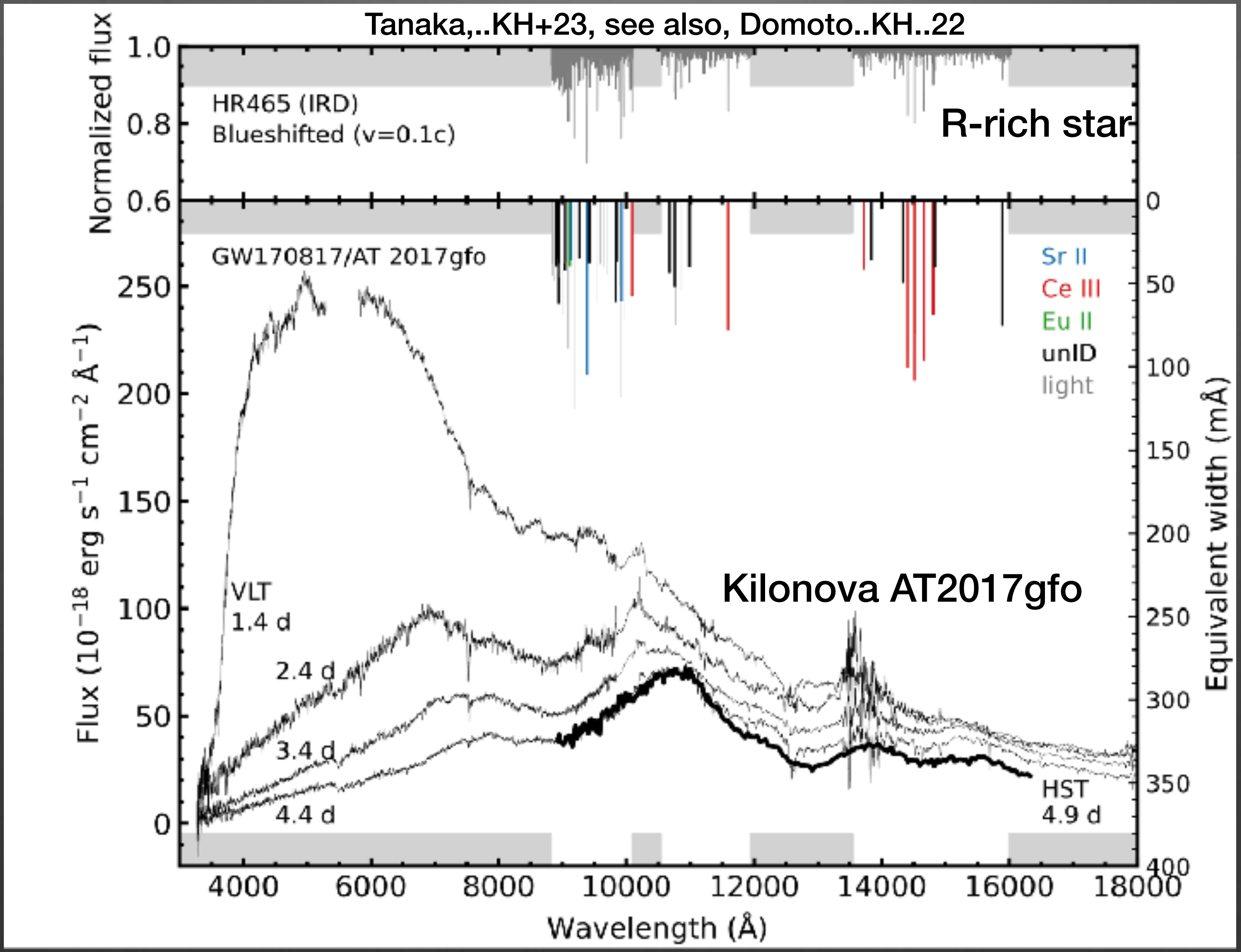
- Y II: Sneppen & Watson 23
- La III: 1.3μm feature (Domoto…KH, 22)
- Ce III: 1.6μm feature (Domoto…KH, 22, 23, Tanaka…KH, 23)





Hubble Space Telescope

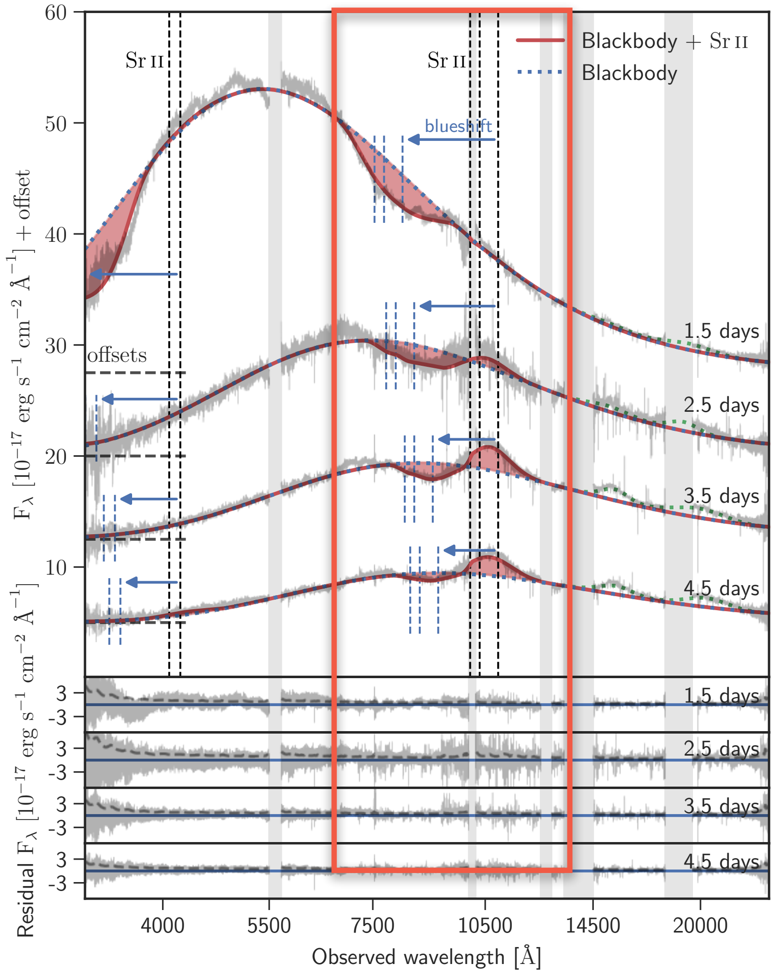
Kilonova vs R-rich star



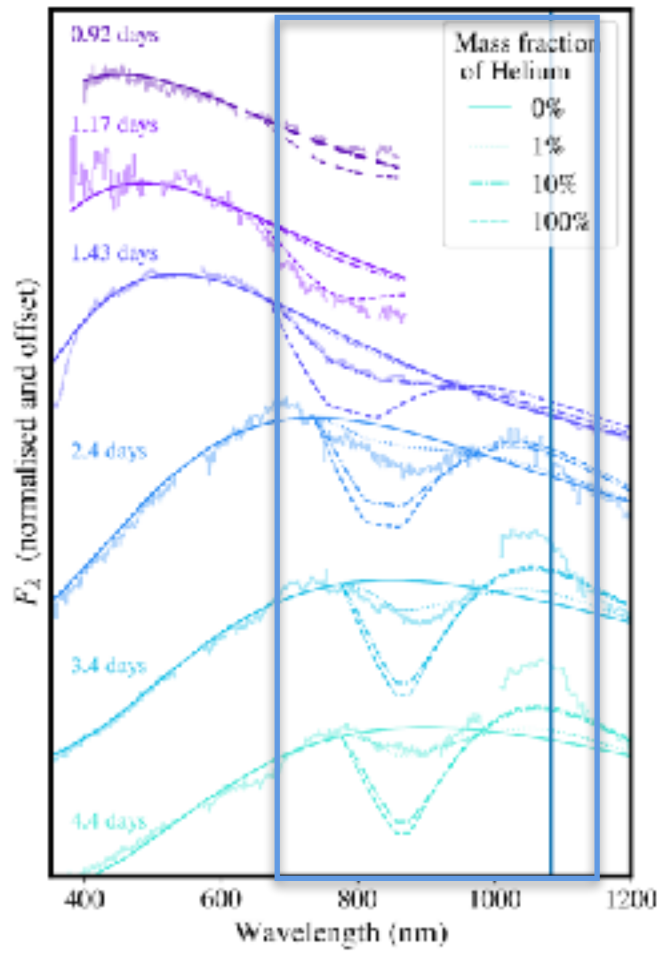
IR spectra of r-rich stars are useful to get atomic data relevant for kilonovae.

KN 1μm conspiracy

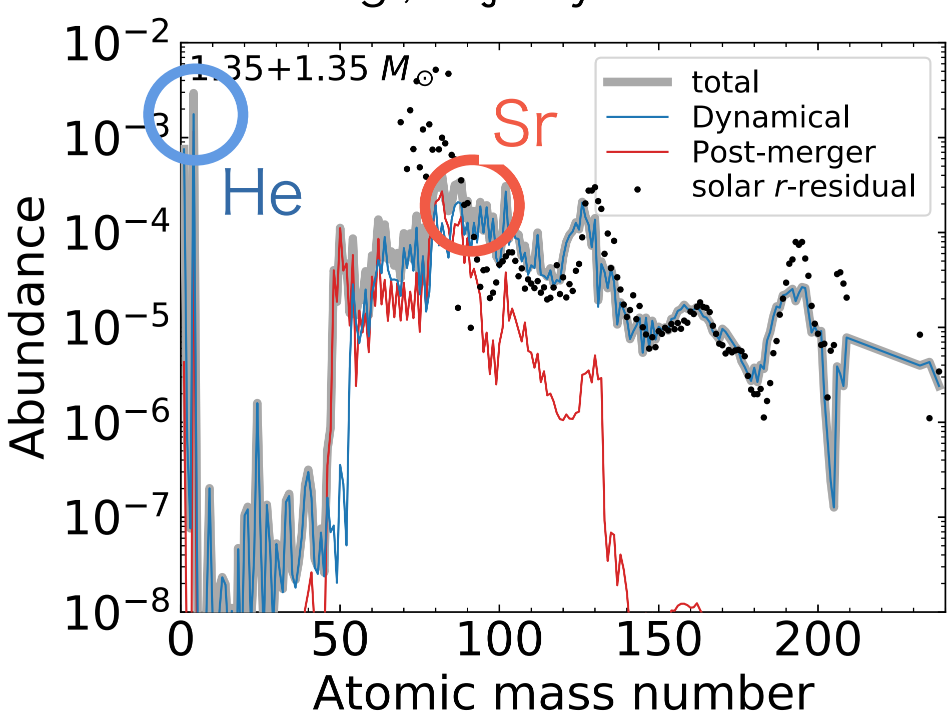
Sr II triplet (Watson+19, Gillanders+22, Sneppen+24)



He I 1.083 μm(Sneppen+24, Perego+22, Tarumi, KH+23)



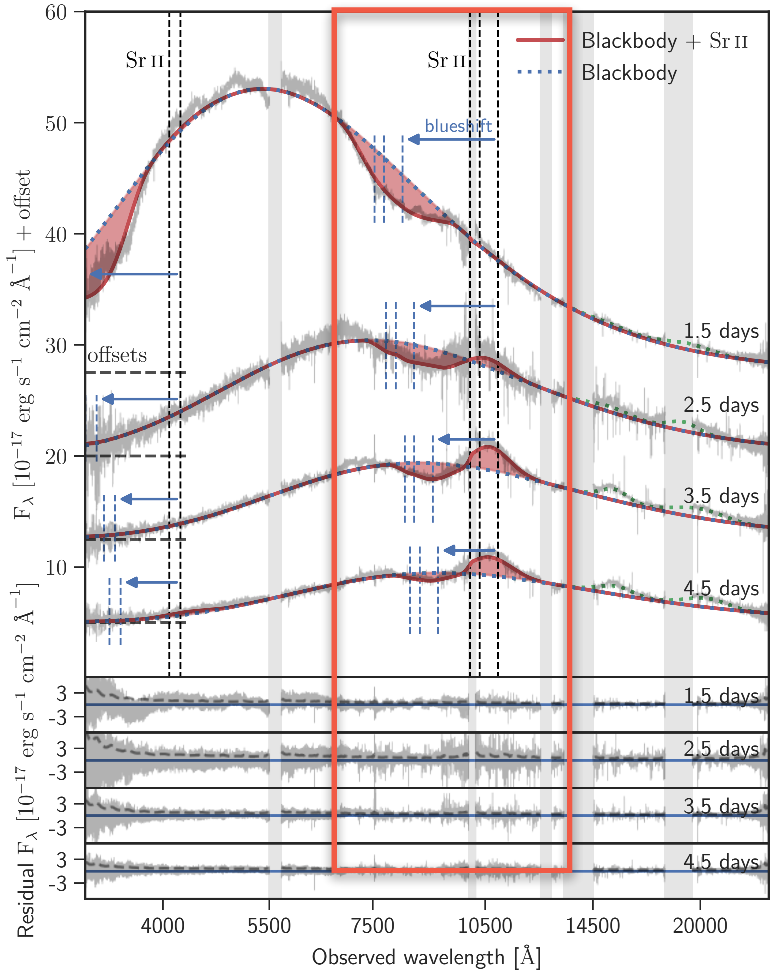
e.g., Fujibayashi+23



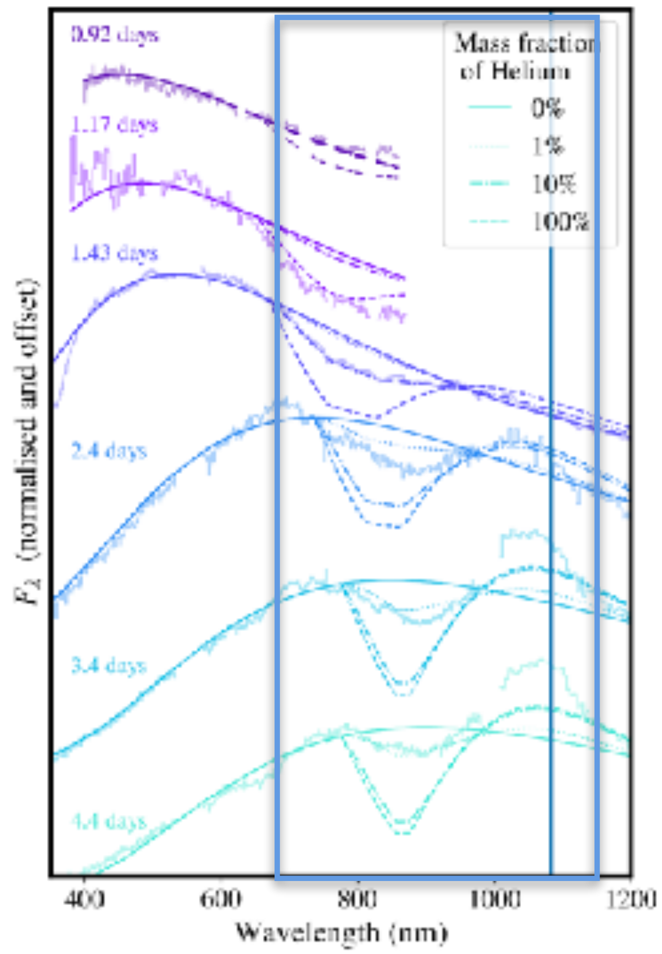
- He I line from a metastable level in NLTE.
- He can be most abundant atom in merger ejecta.
- Sneppen+24 show 1 μm line at early times should be Sr II (see also Arya poster, Sneppen & Chiba talks next week).

KN 1μm conspiracy

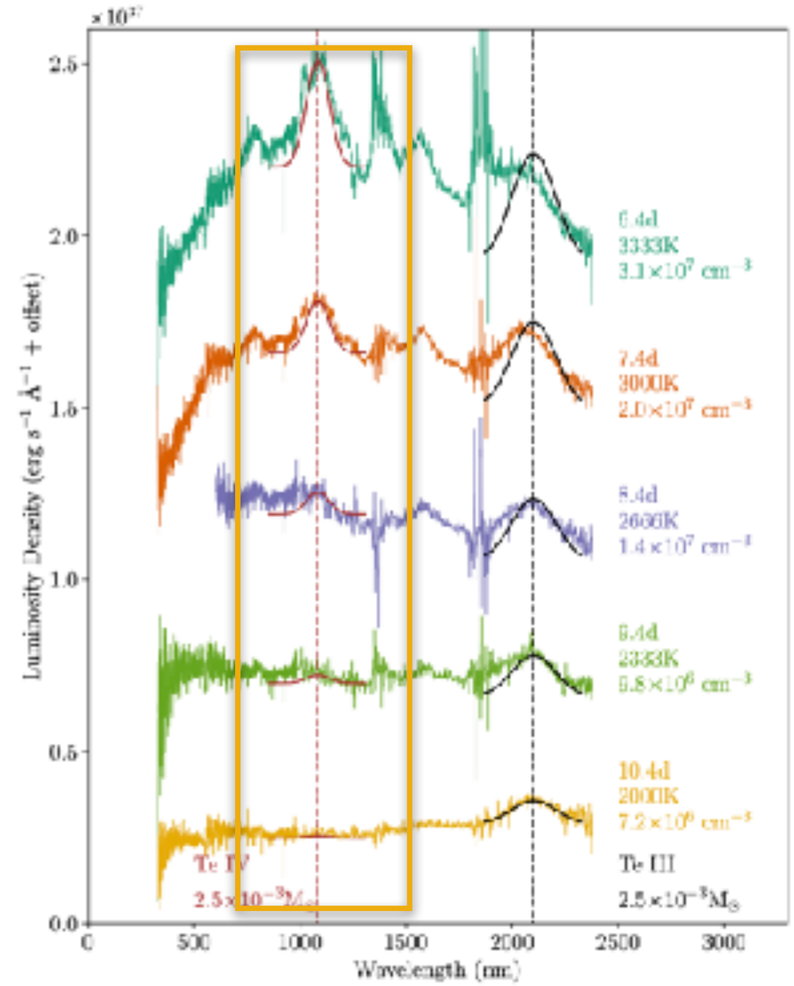
Sr II triplet (Watson+19, Gillanders+22, Sneppen+24)



He I 1.083 μm (Sneppen+24, Perego+22, Tarumi, KH+23)



[Te IV]1.08 μm (Mulholland+25)



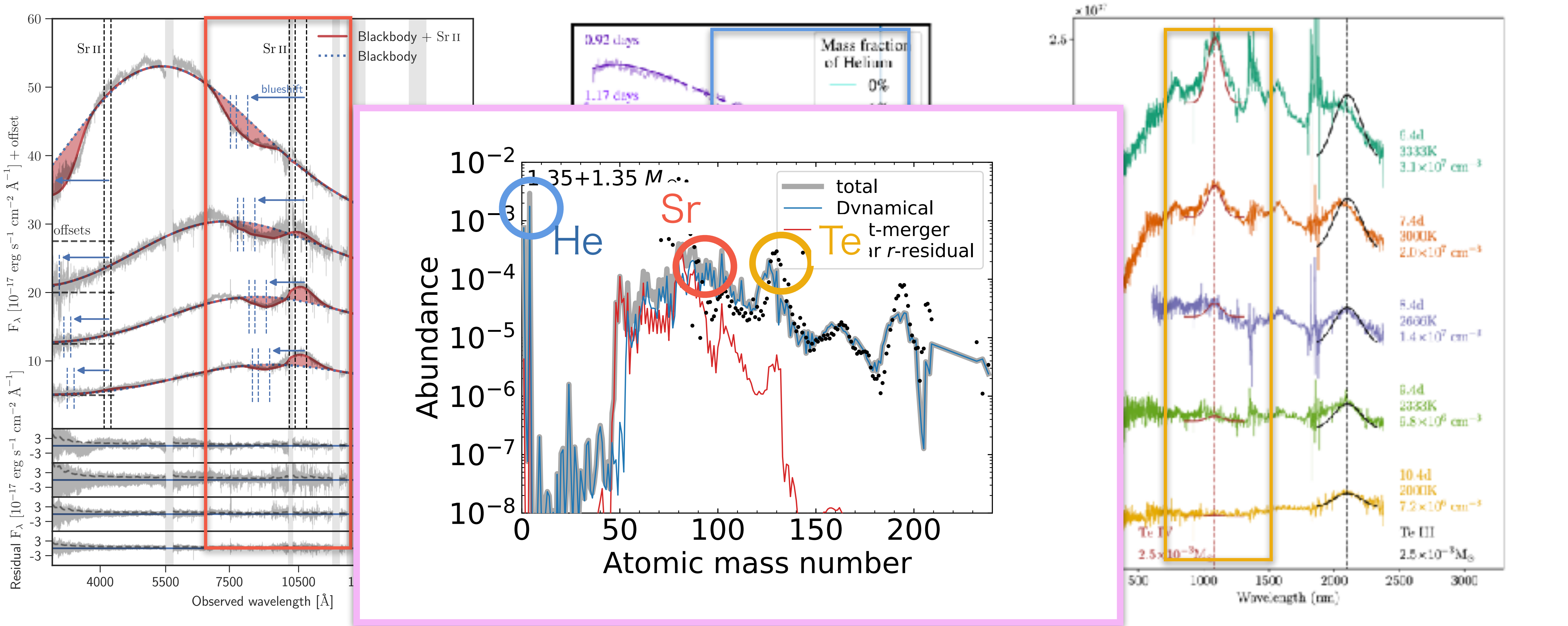
- A forbidden line [Te IV] 1.08 μm was recently suggested as the third option.
- It can appear at later times t > 5 days if Te is highly ionized.

KN 1μm conspiracy

Sr II triplet (Watson+19, Gillanders+22, Sneppen+24)

He I 1.083 μm(Sneppen+24, Perego+22, Tarumi, KH+23)

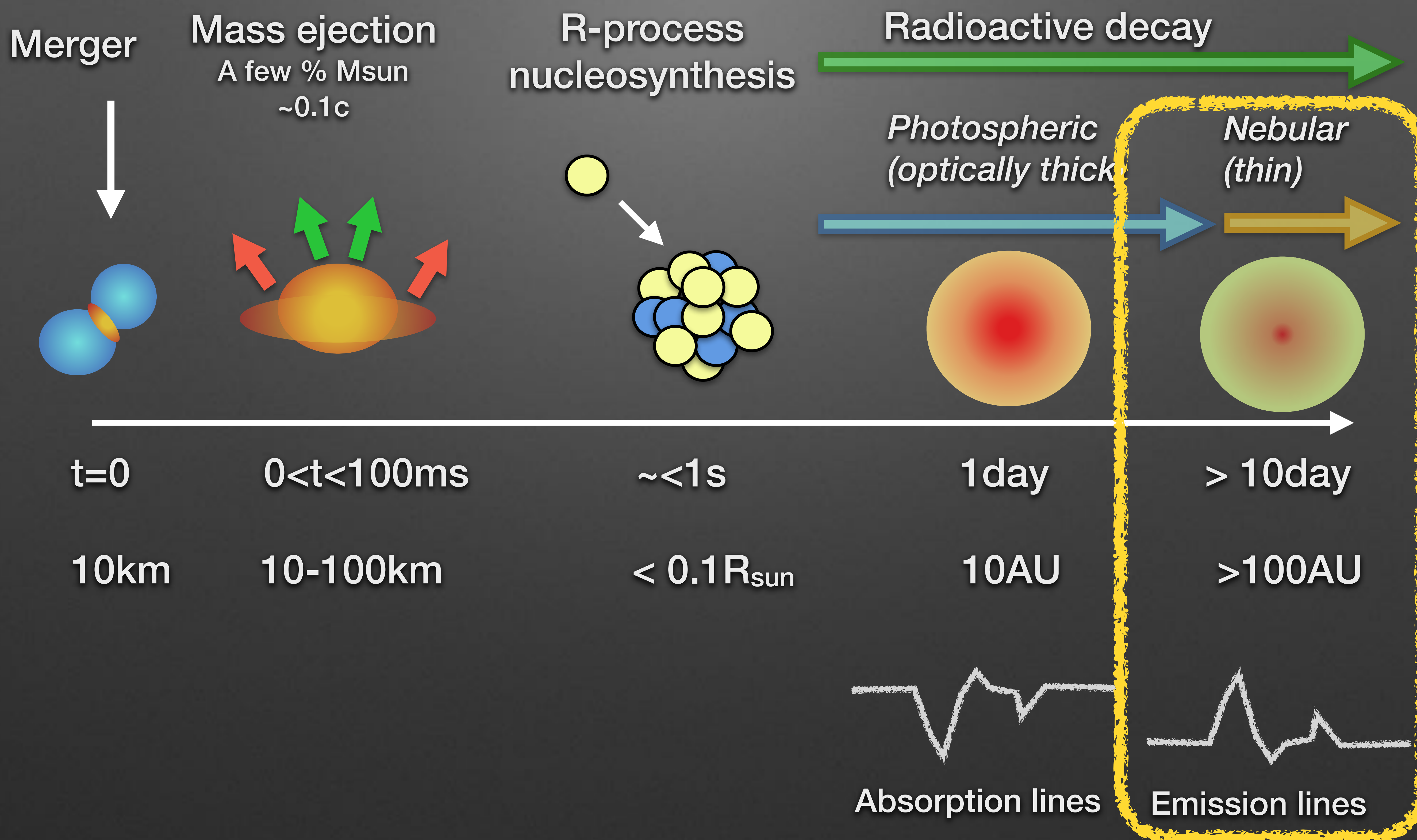
[Te IV]1.08 μm (Mulholland+25)



- A forbidden line [Te IV] 1.08μm was recently suggested as the third option.
- It can appear at later times t > 5 days if Te is highly ionized.
- All three are expected to be abundant.

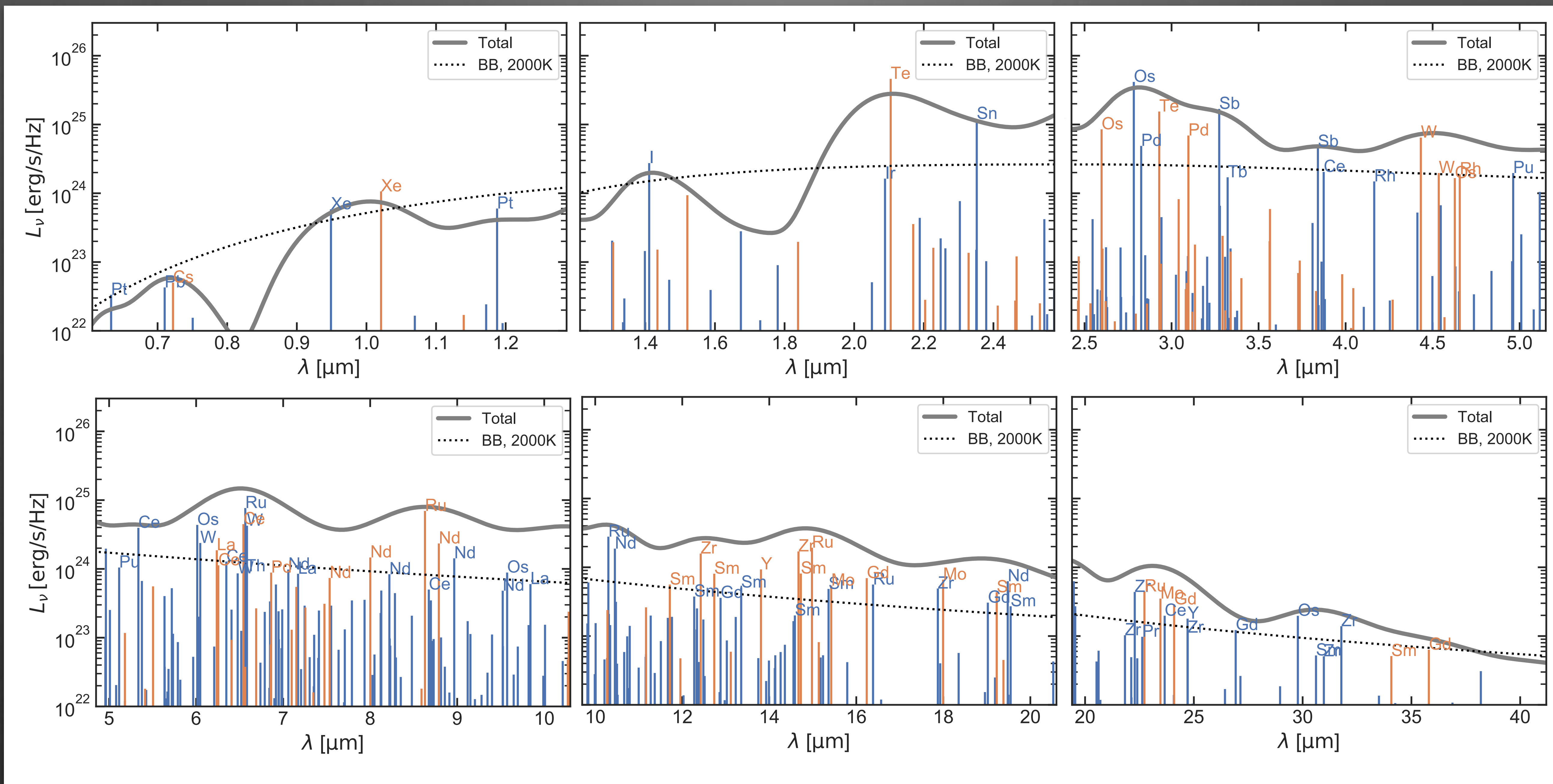
Neutron Star Merger & Kilonova

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



Kilonova Nebular Spectrum (~10 days post merger)

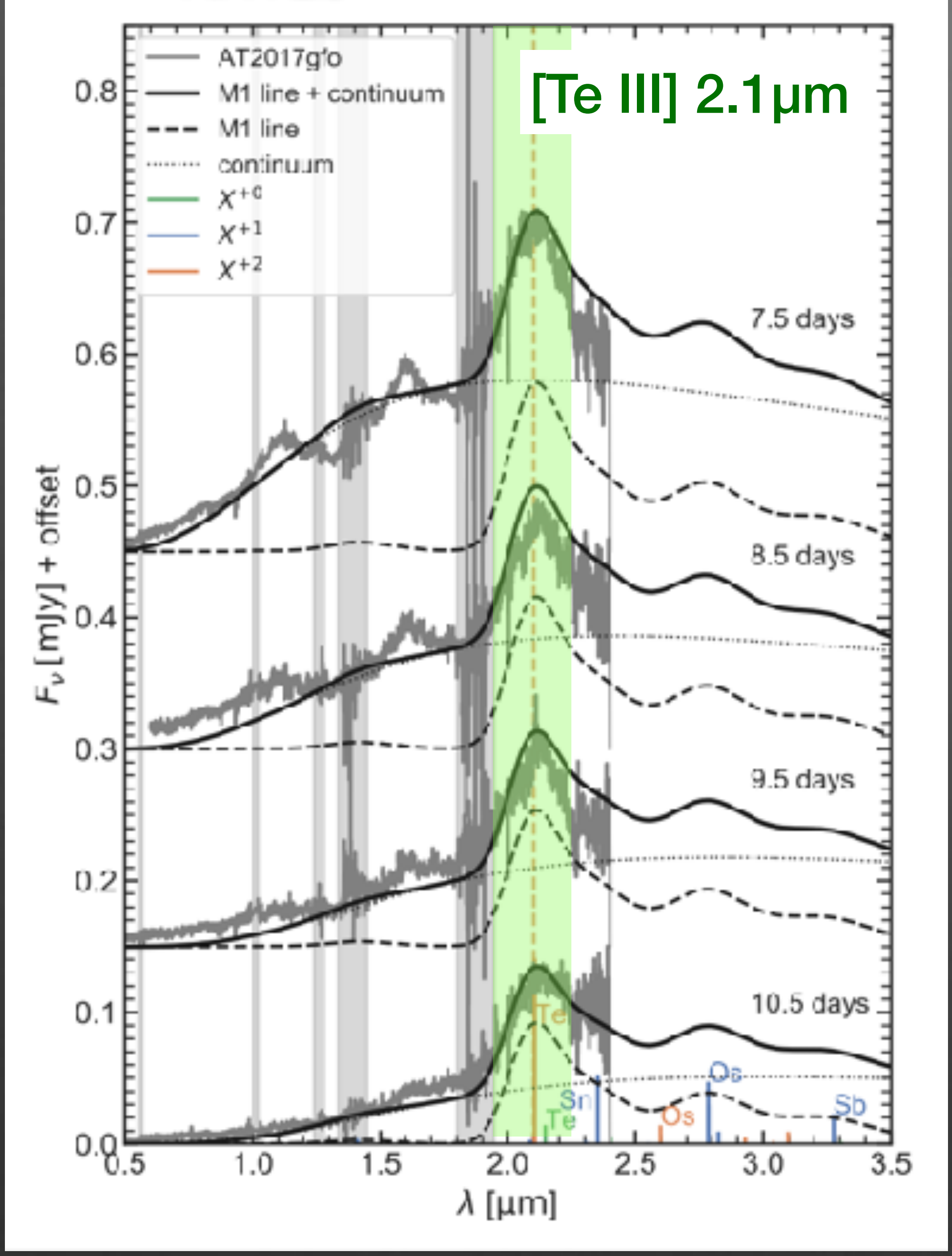
KH + 23, where the ejecta is assumed to be optically thin at ~10 days.

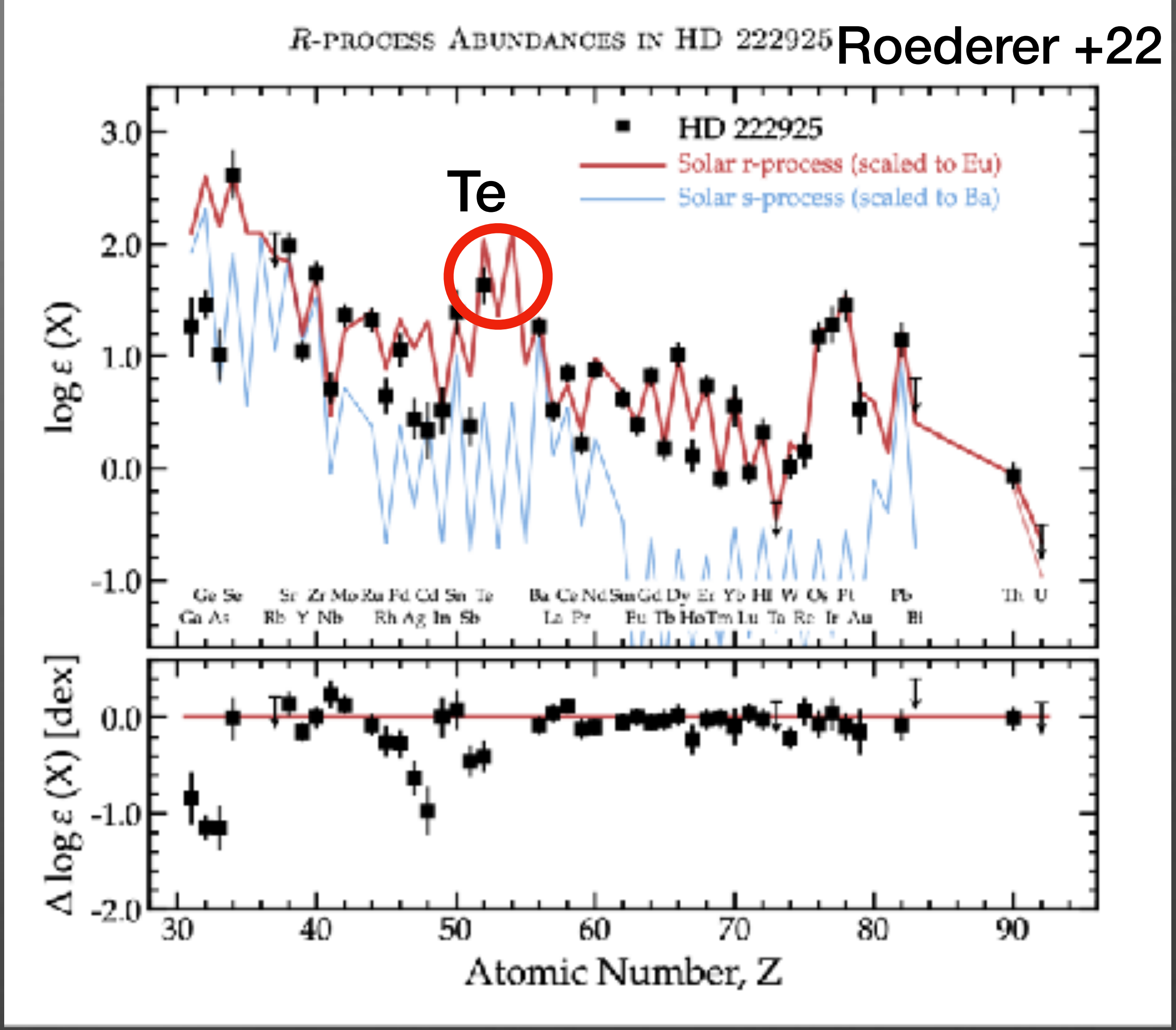


- The solar abundance (2nd - 3rd r-process peaks) is assumed. $X^{+1} = X^{+2} = 0.5$
- [Te III] 2.1μm is the strongest M1 line.
- See also Rahmouni's talk next week

[Te III]2.1μm line in the kilonova AT2017gfo

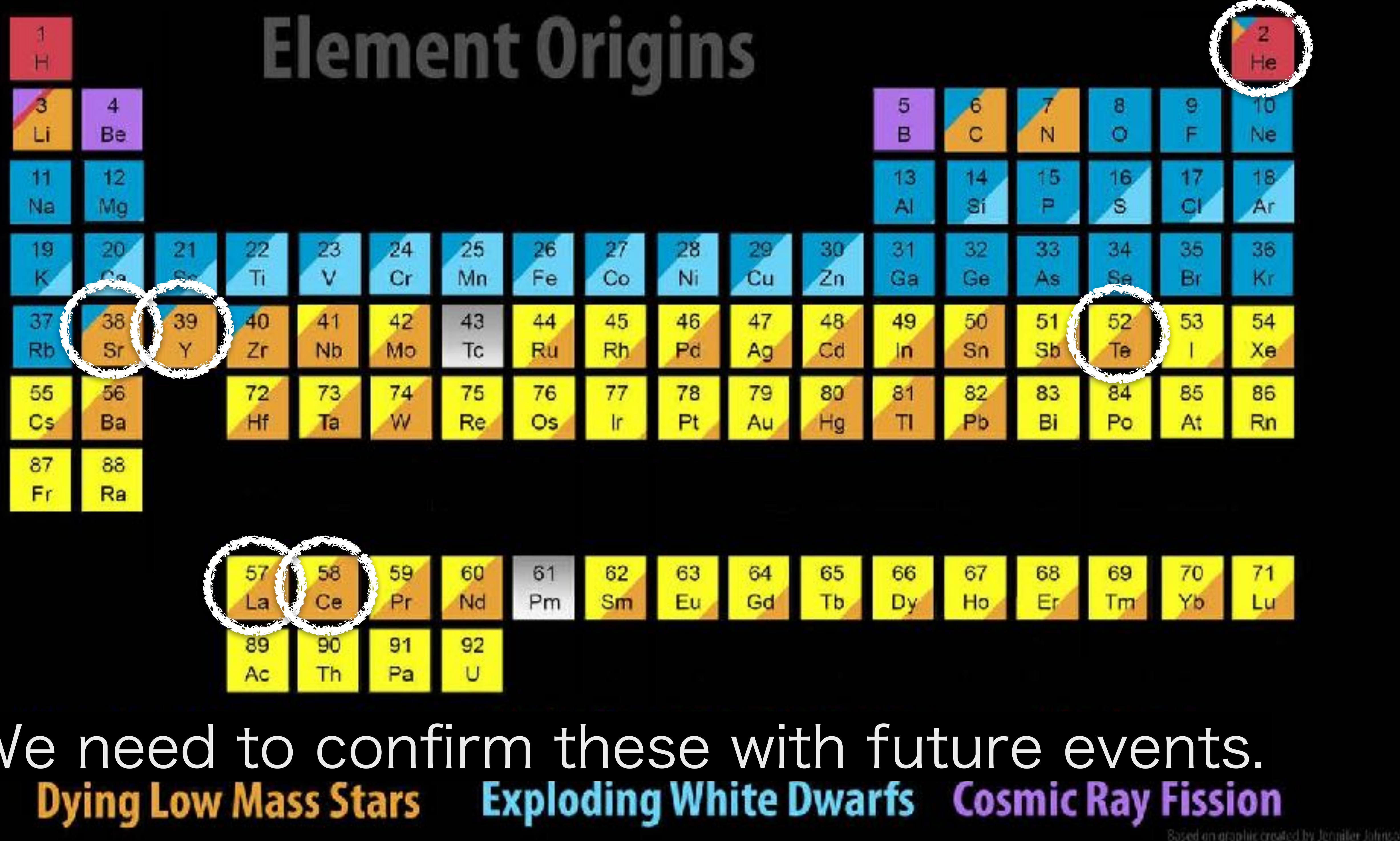
KH+23





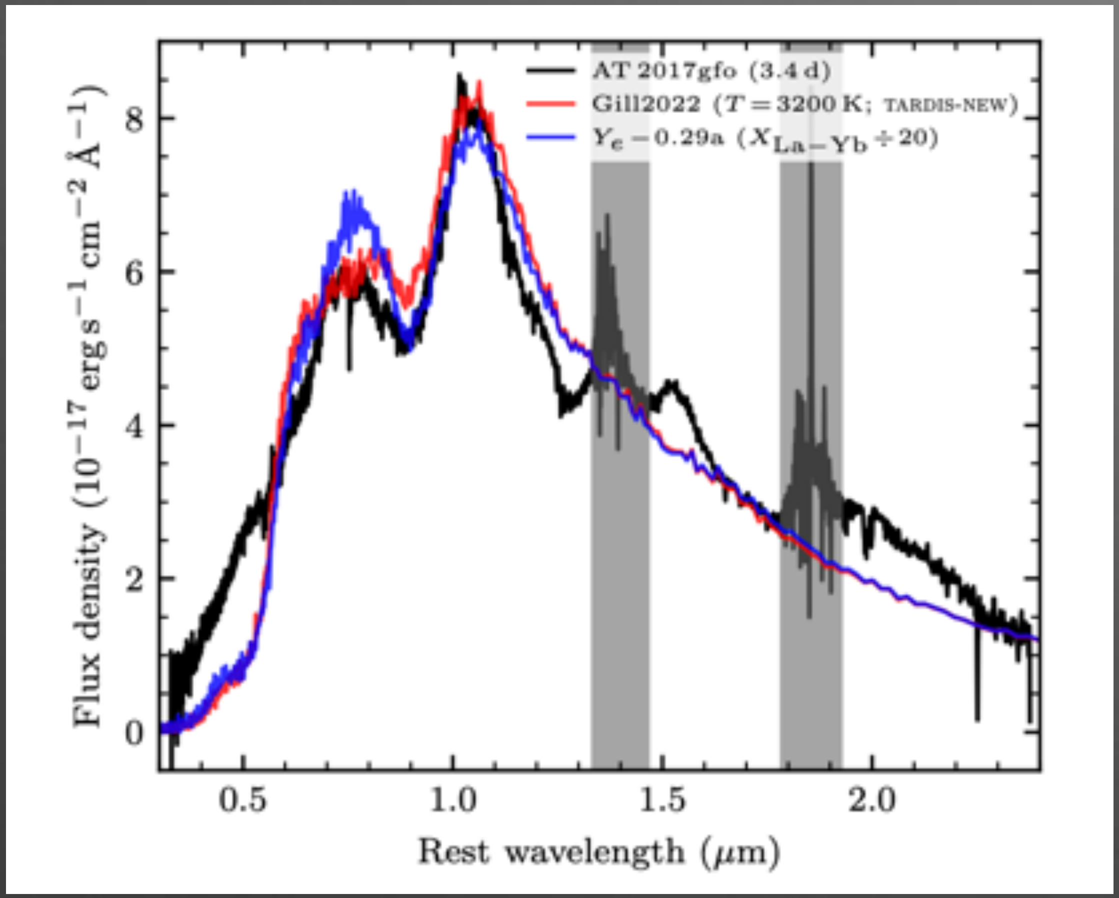
- The Te III line is expected to be the strongest M1 line because it is a second r-process peak element.

Summary of Elemental Identification in GW170817 with spectroscopy



We need to confirm these with future events.

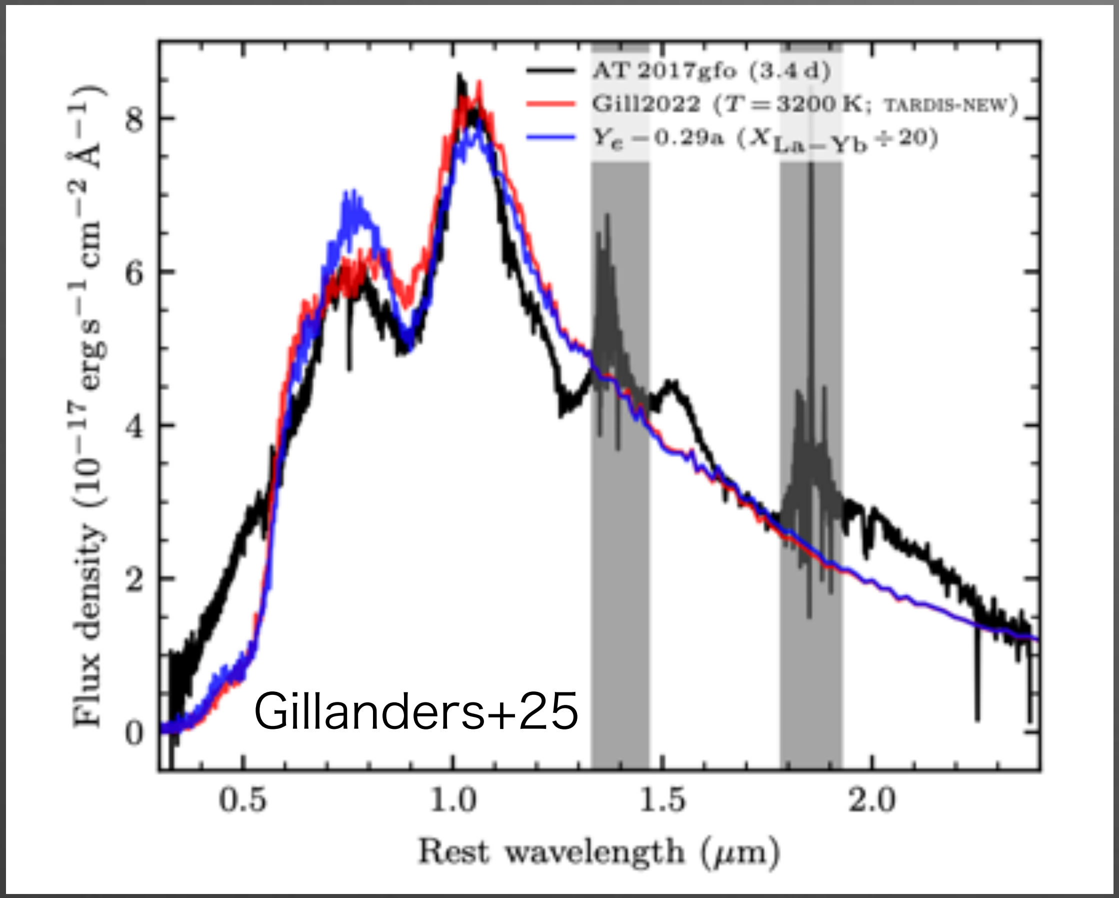
Early vs Late-abundance of KN

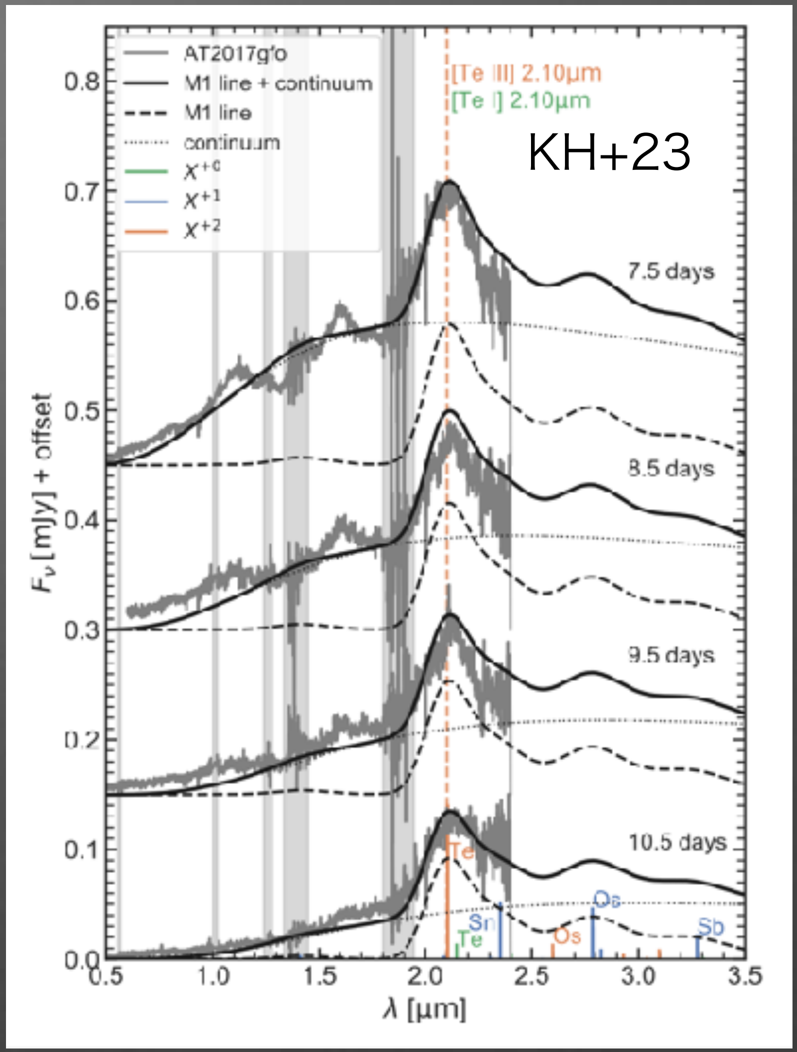


- Early photospheric emission Tanaka+17, Kasen+17, Gillaners+22,25, Domoto+23

=> Low lanthanide fraction ~< 10% of the Solar

Early vs Late-abundance of KN





- Early photospheric emission Tanaka+17, Kasen+17, Gillaners+22,25, Domoto+23

=> Low lanthanide fraction ~< 10% of the Solar

- Late-Nebular emission

=> Te emission & Ce, La emission (Salma Rehmouni's talk)

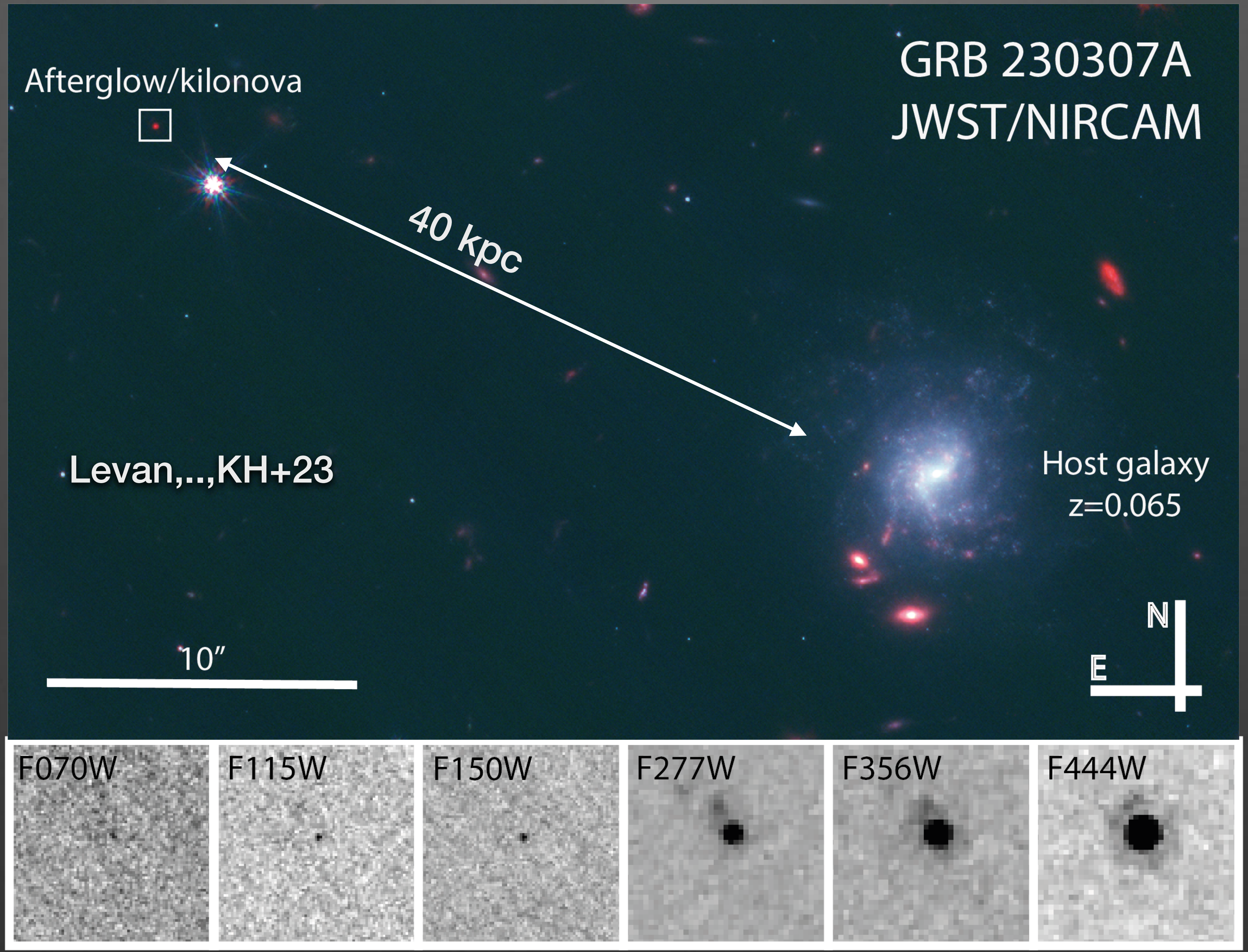
=> High lanthanide fraction ~ the Solar

=> No Kr emission => Light r-process must be suppressed (KH+23, Jerkstrand+25).

Outline

- Introduction of Kilonova
- Elemental identification in GW170817
- A Long GRB and kilonova seen by JWST
- Where are heavy elements? W, Pt, Os
- R-process in collapsars
- Conclusion

GRB 230307A: JWST NIRCam Image



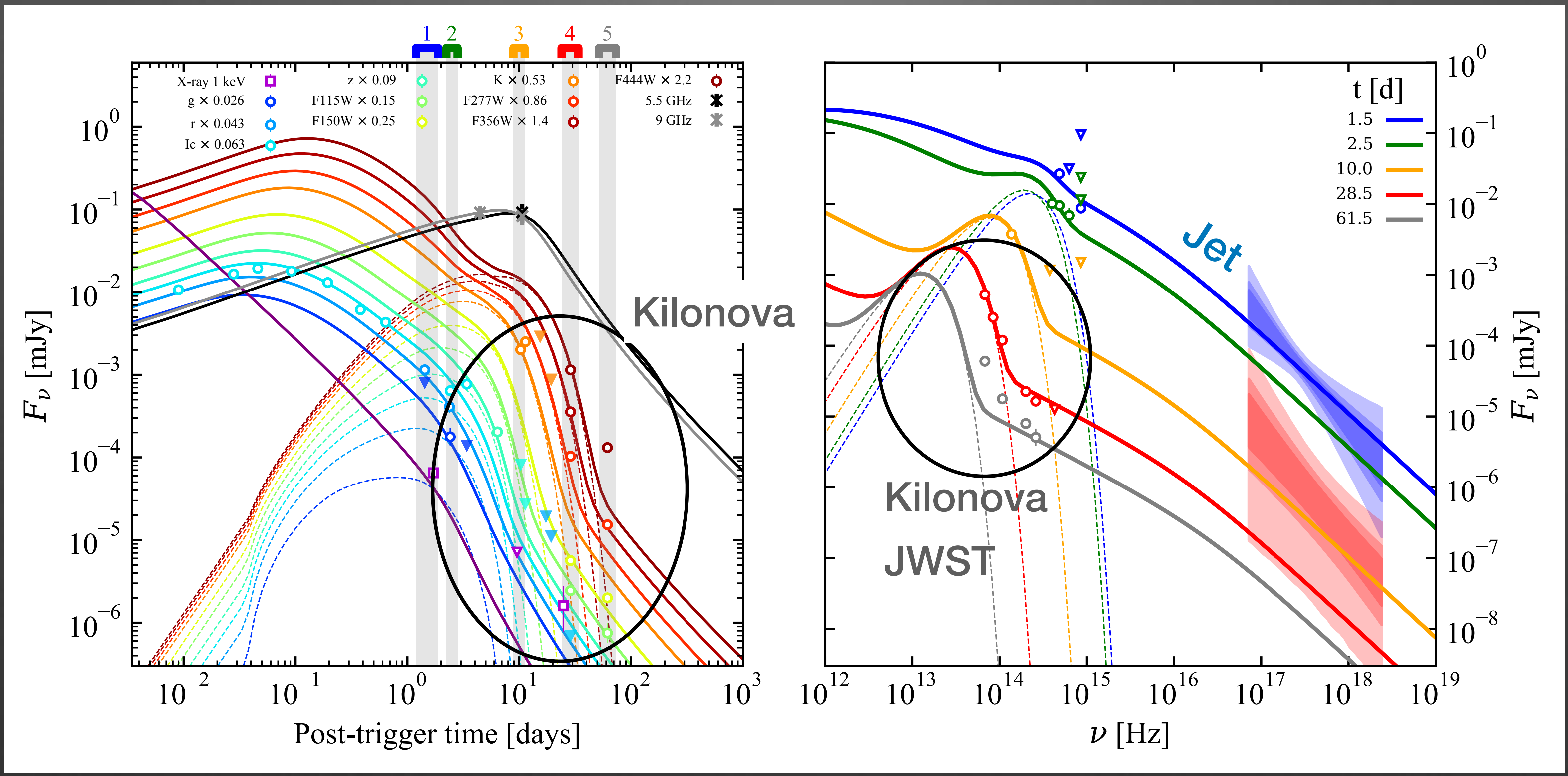
- The most probable host ~ 300Mpc, large off-set ~ 40 kpc
- The large off-set rules out the collapsar scenario.

GRB 230307A and JWST photometry

Levan,..KH+23

Afterglow+Kilonova light curve

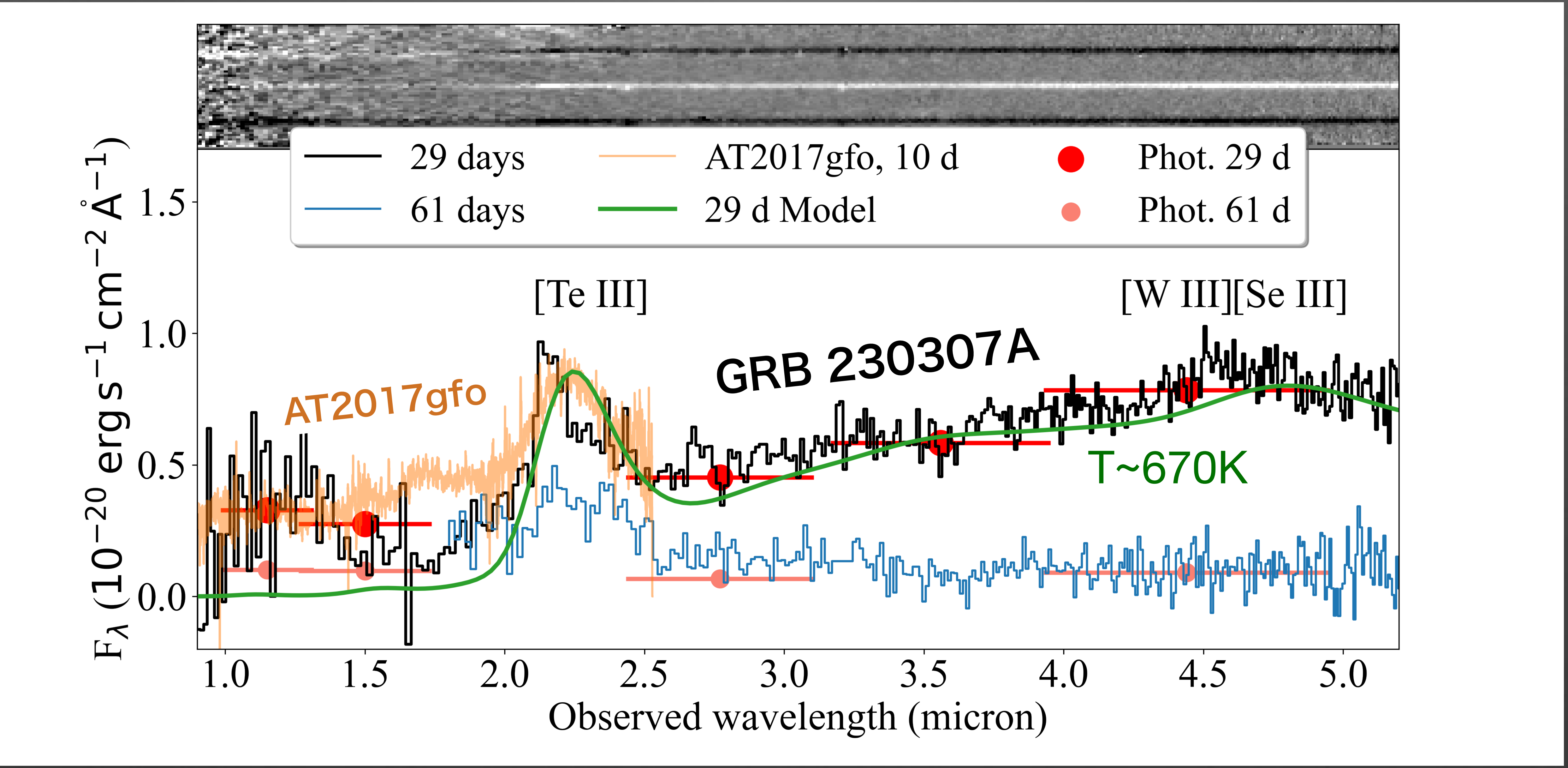
Afterglow+Kilonova SED



- The light curve is very similar to AT2017gfo (GW170817).
- This supports a neutron star merger scenario.

JWST Spectrum of the KN 230307A

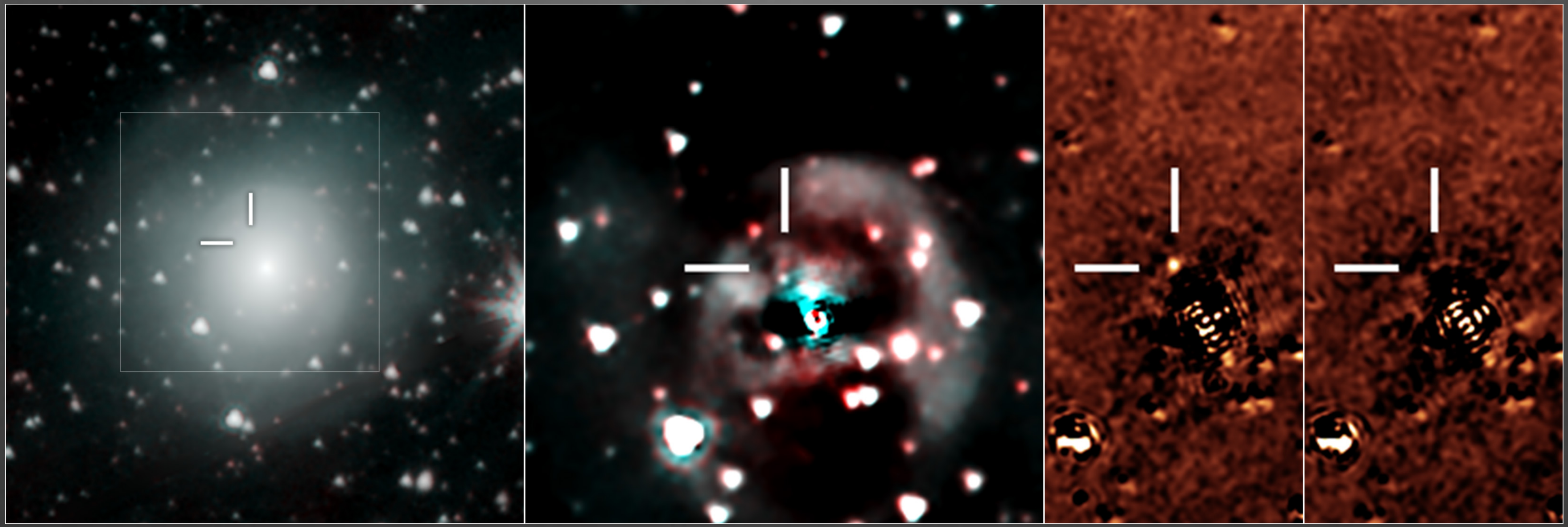
Levan,..,KH+23, see also Gillanders+23



- An emission line feature around 2.1 μm is consistent with [Te III] 2.1μm.
- The total r-process mass ~ $0.05M_{sun}$. (~ GW170817)
- Evidence that mergers produce long GRBs
- What is the red bump T ~ 670K? Dust?

IR emission in AT2017gfo

Spitzer Observation (Kasliwal+22, Villar+18)



4.5 μm

- Spitzer detected an emission at 4.5 μm at 45 day but no detection at 3.5 μm.
- A very cold emission or non-trivial lines (e.g., KH+22)
- Dust?

Pt-rich nuggets in meteorite

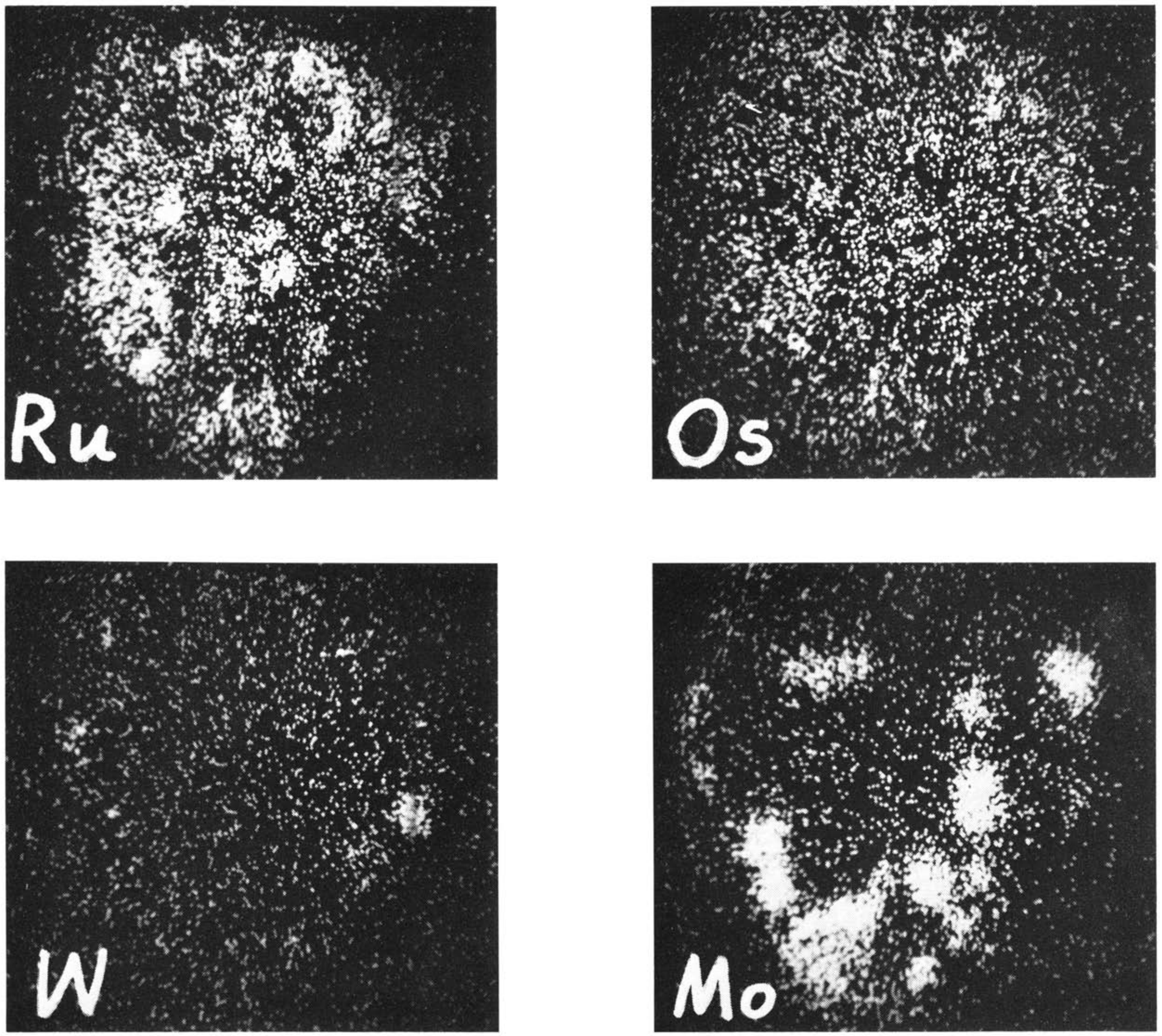


Fig. 3. X-ray scanning pictures of particle shown in Fig. 1.

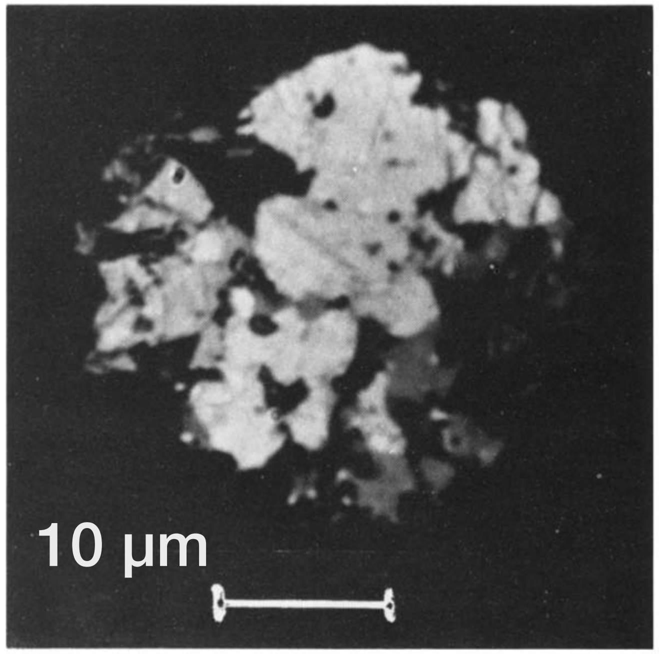
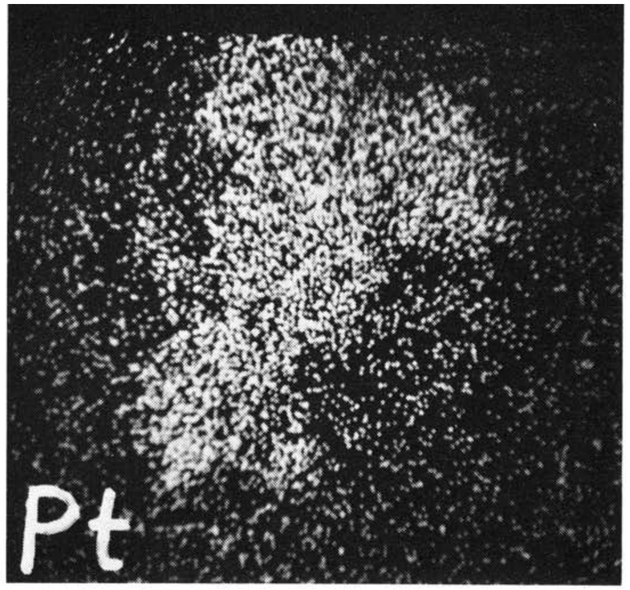


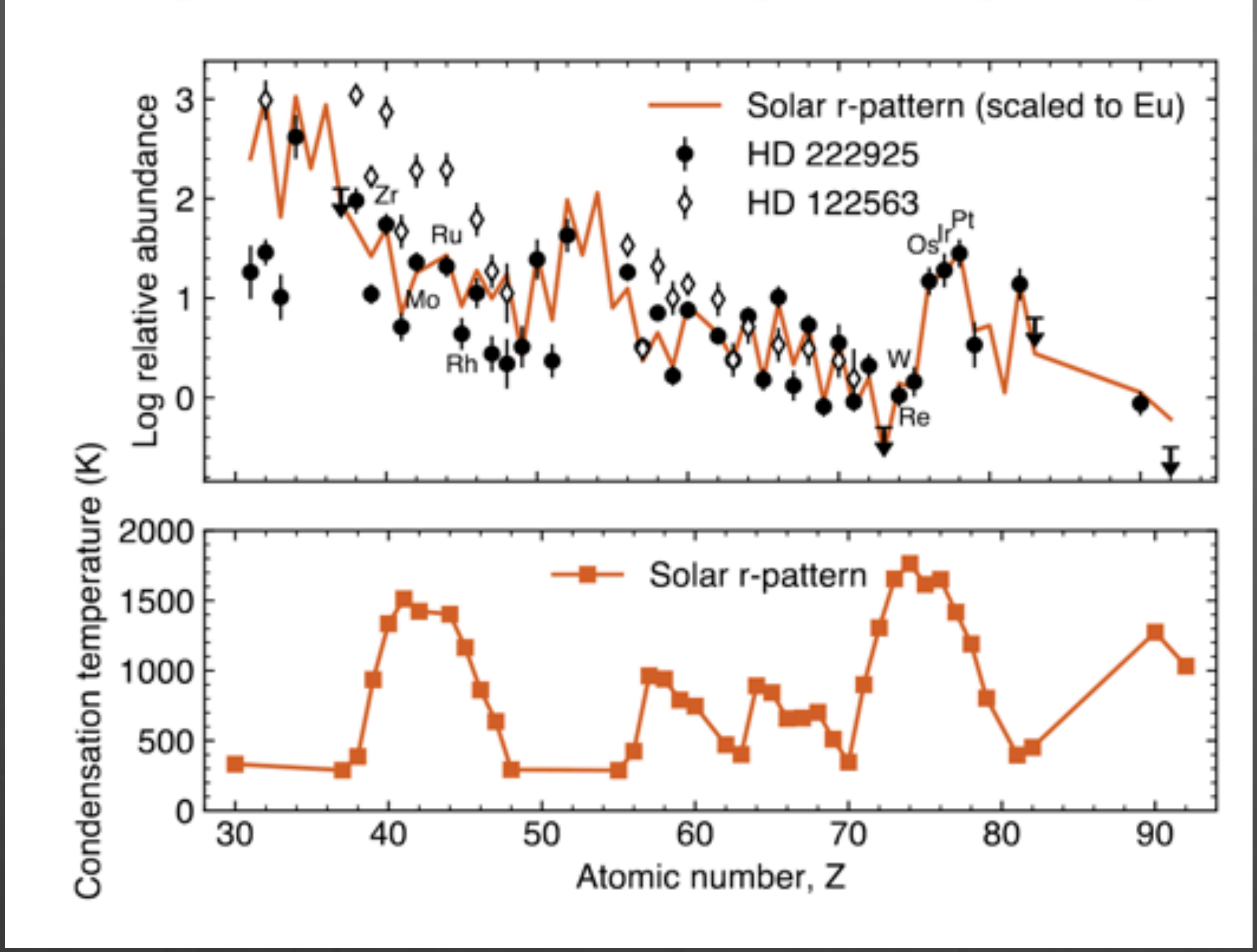
Fig. 1. Polished section of metal particle, reflected light. Light grey areas in center are metal, darker grey sulfide. Scale bar 10 μm.



Palme & Wlotzka 1976

Condensation of W-Os… in proto-solar system

- R-process condensation (Domoto poster)



Condensation of W-Os… in proto-solar system

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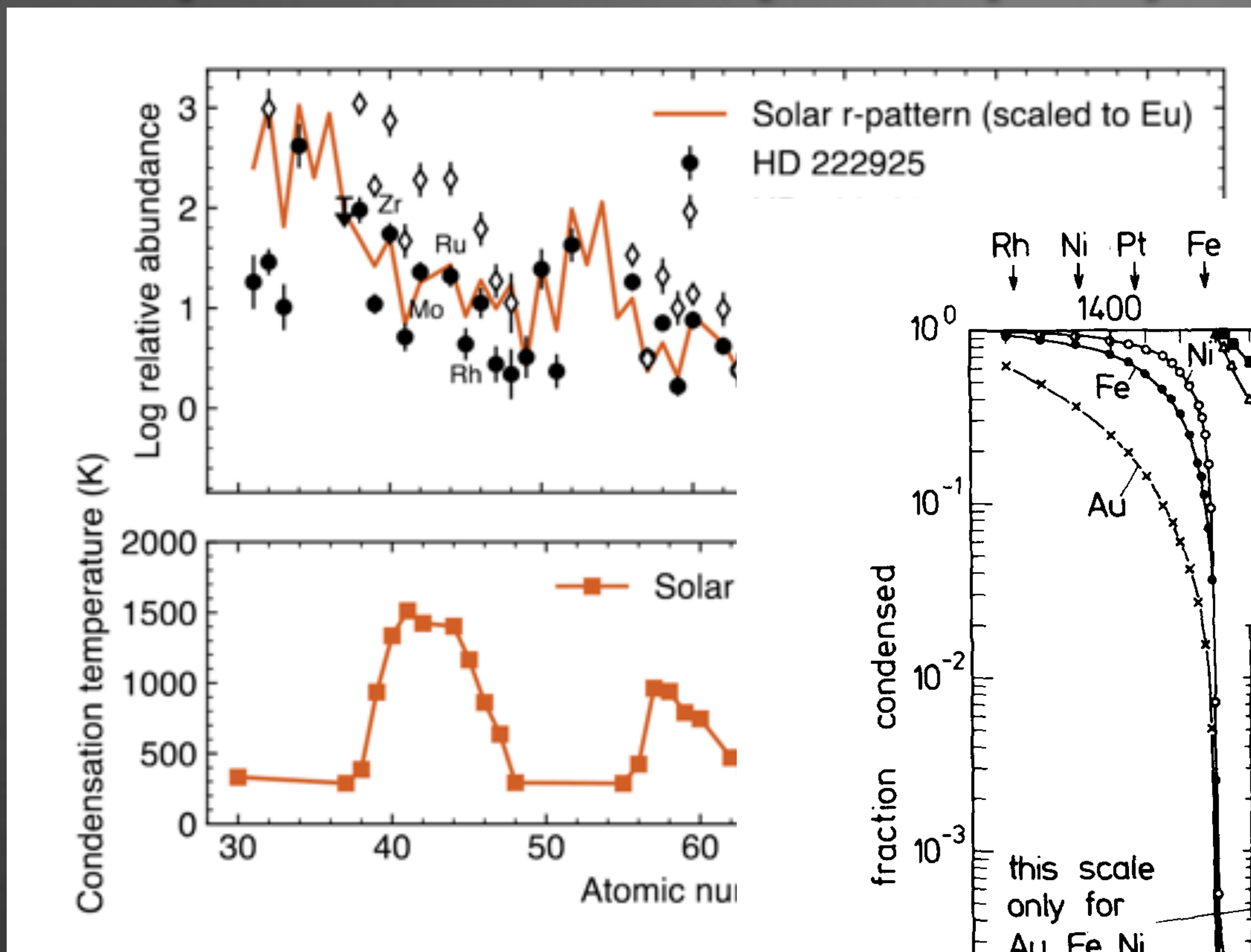


- Proto-Solar System (Palme & Wlotzka 1976)

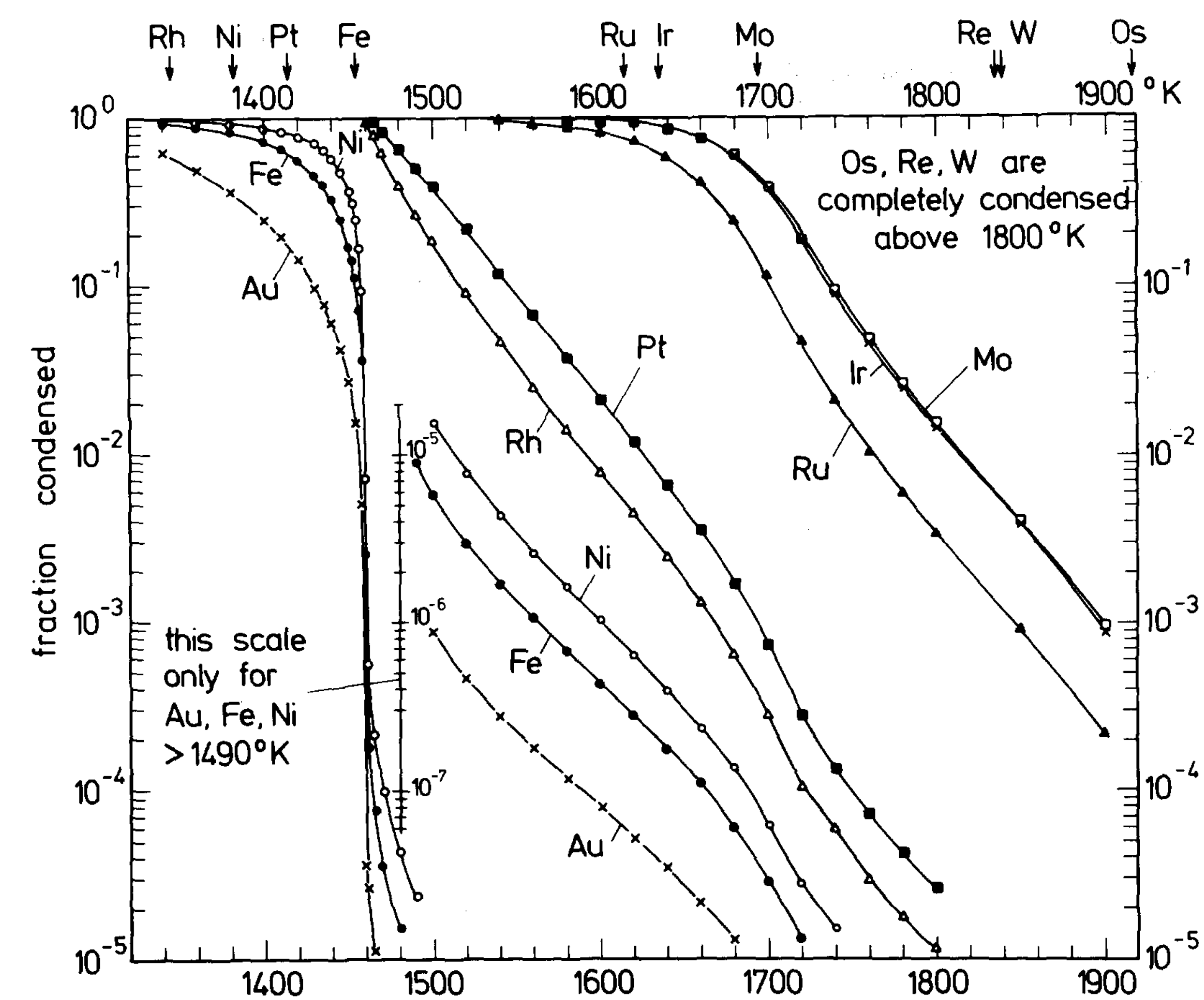
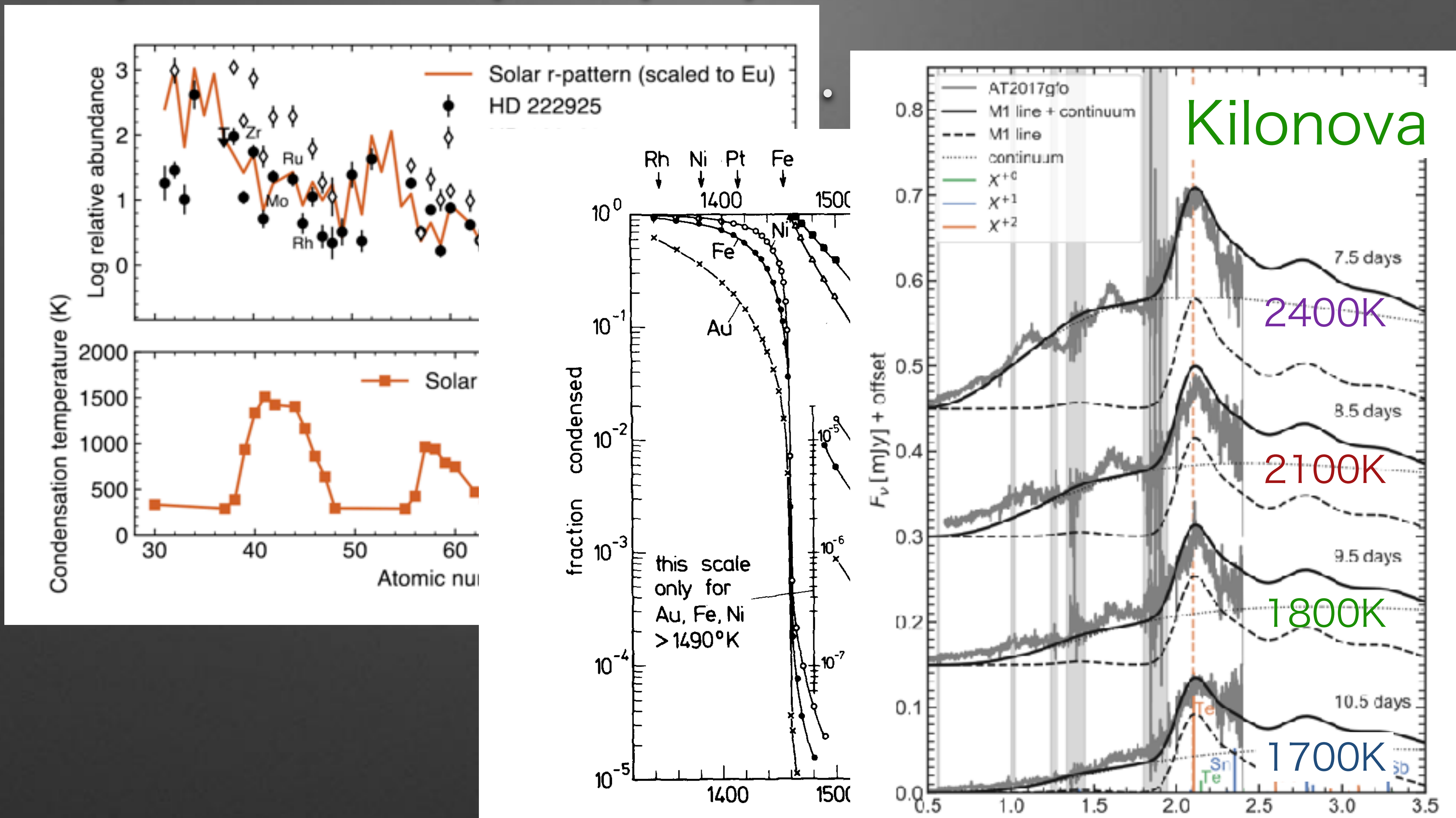


Fig. 4. Condensation curves for Mo, Ir, Ru, Rh, Pt, Ni, Fe and Au condensing in an alloy of 13 metals (Os, Re, W, Mo, Ir, Ru, Rh, Pt, Ni, Fe, Co, Pd and Au). The condensed fraction of each element is plotted as a function of temperature. The condensation temperatures of pure metals are indicated by arrows. The assumed pressure is 10^{-3} atm. Ideal solid solution was assumed for all metals.

Condensation of W-Os… in proto-solar system

- R-process condensation (Domoto poster)



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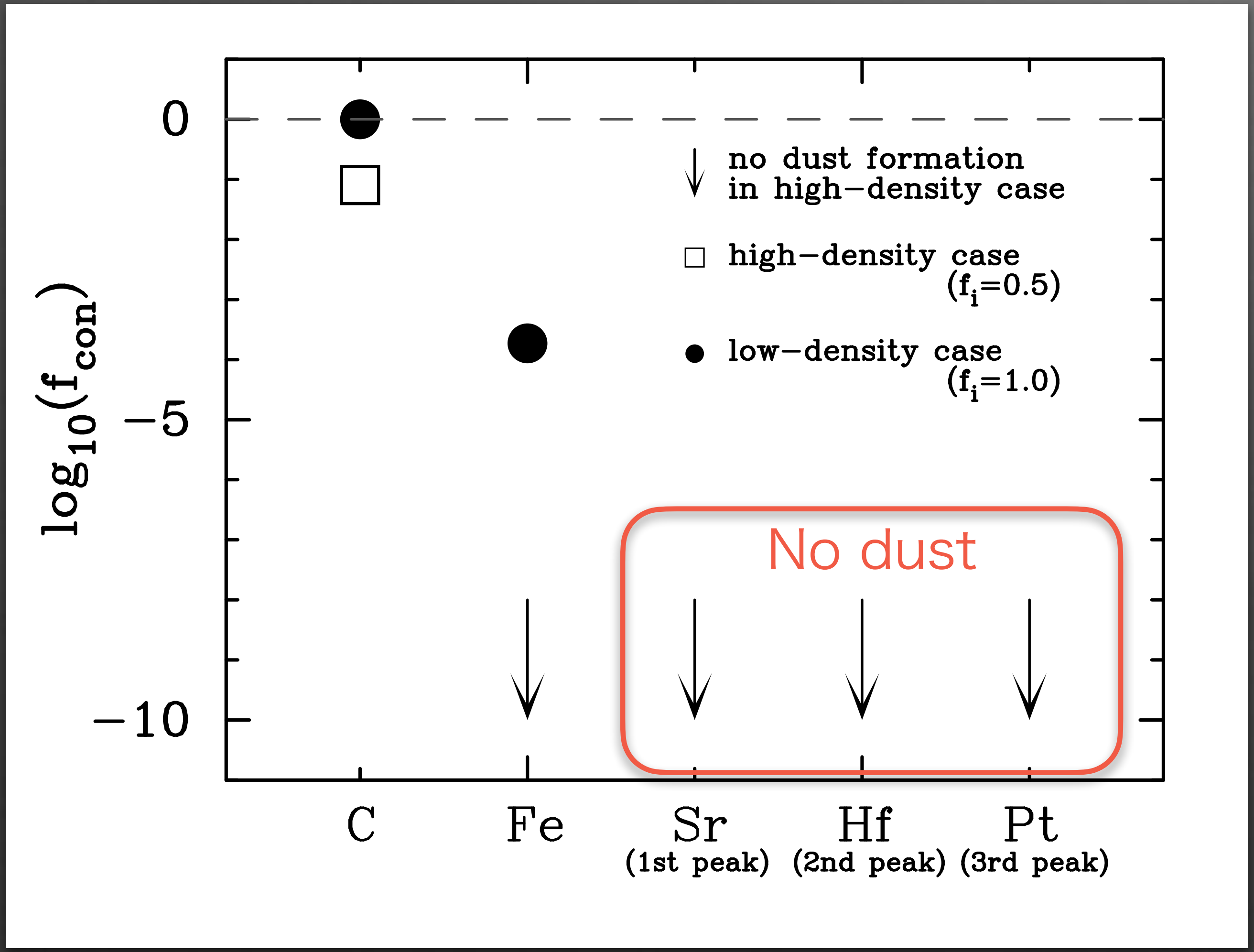
Previous study of grain formation in KNe

- Takami, Nozawa, Ioka14 -

Condensation fraction

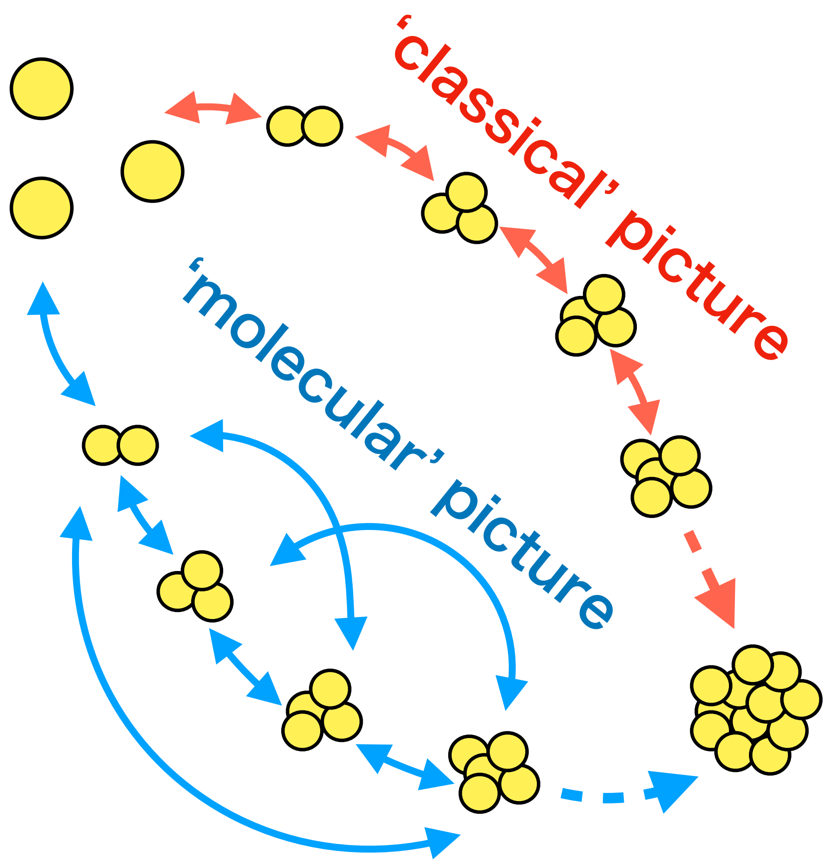


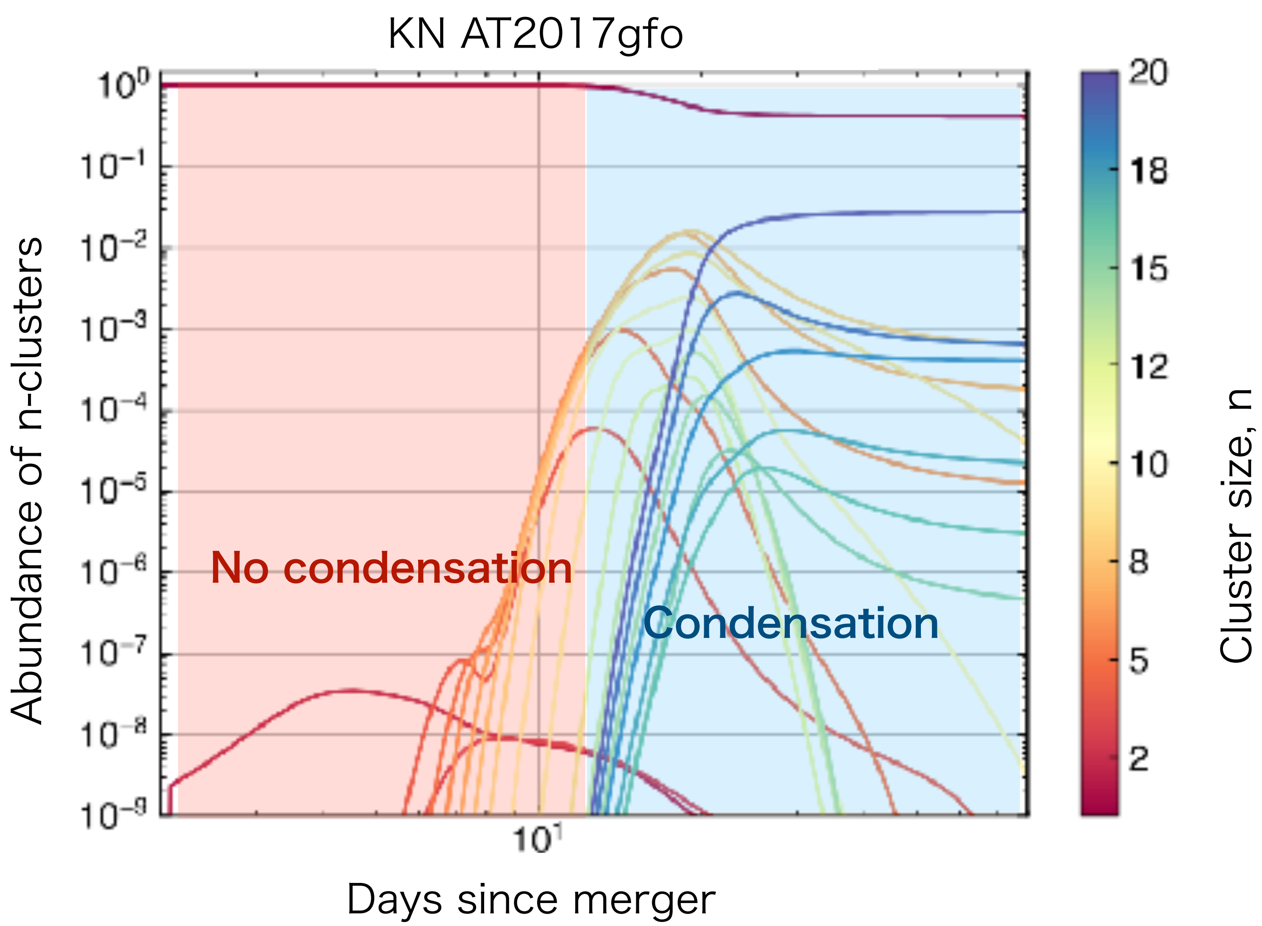
The issues:

1. Takami+14 considered only **low density ejecta**. So, atom-atom collision rarely occurs.
2. They use **the nucleation theory**, which is not reliable for small cluster formation (e.g. Draine 1979).
3. They consider **only Hf** but refractory elements condense together and form alloy.

R-process grain growth in merger ejecta

We solve the kinetic rate equation (Domoto, KH, Kasen in prep.)

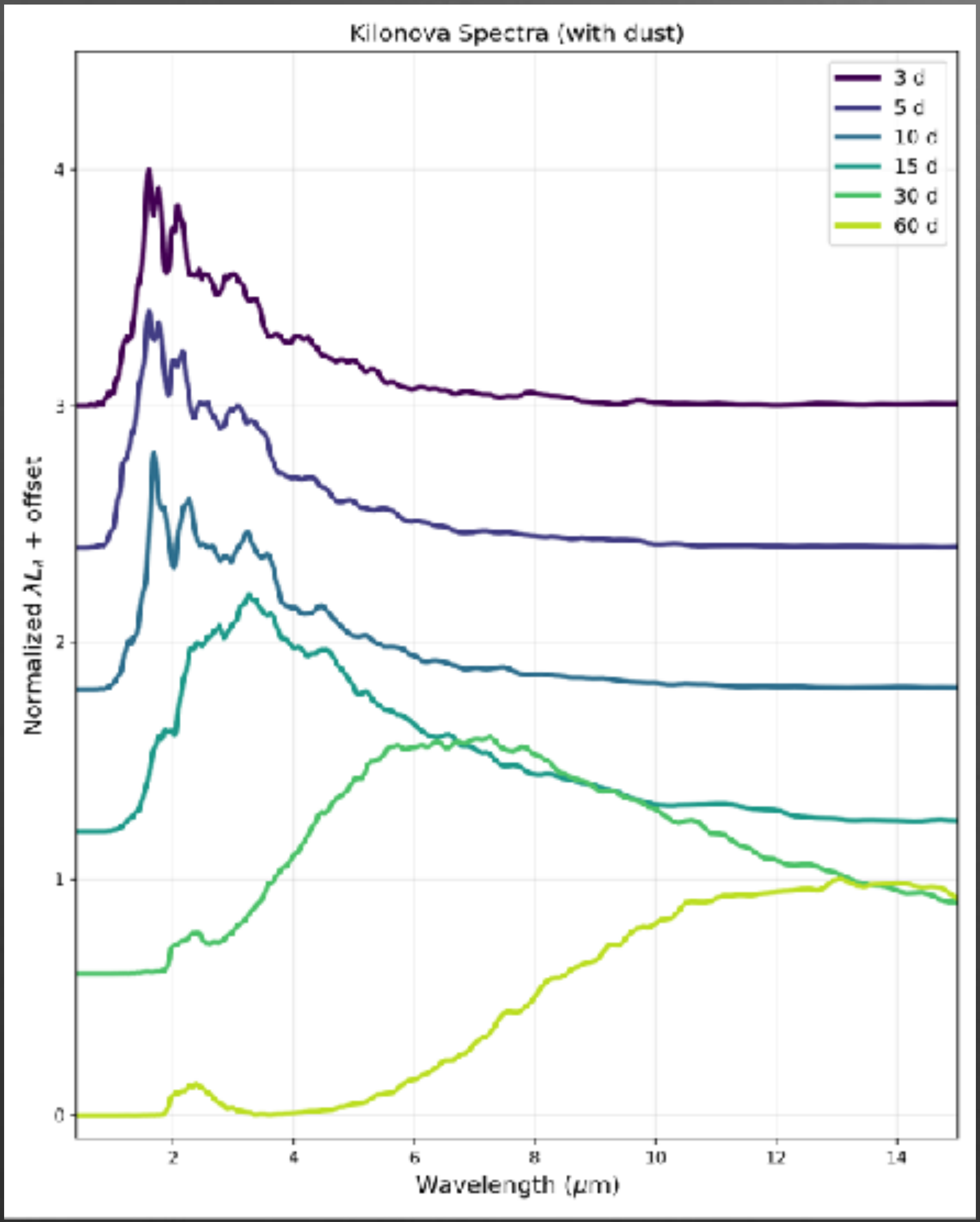


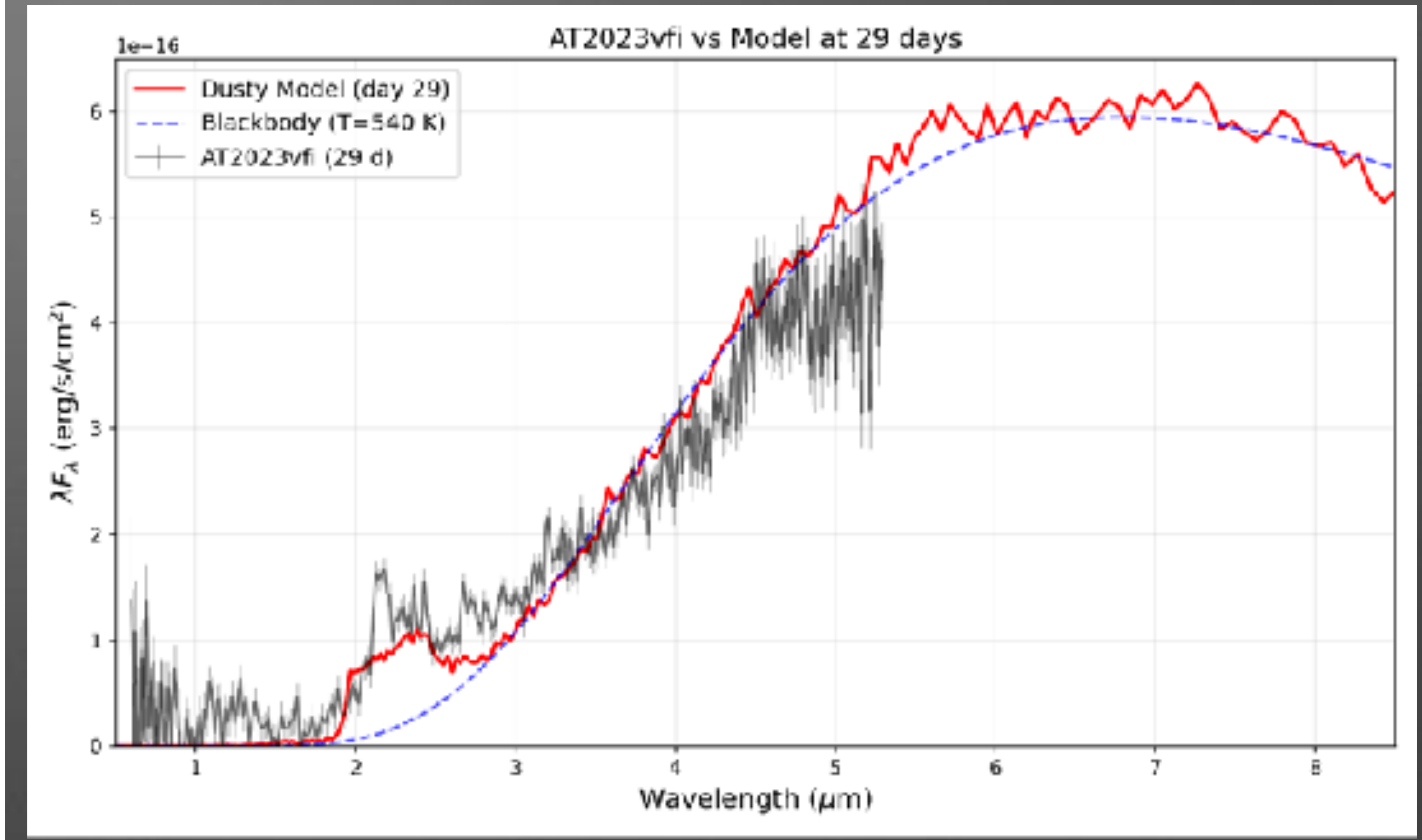


- Early cluster formation is suppressed by low molecular formation rate.
- Fragmentation accelerates cluster formation via creating seed.
- 0.05Msun, v ~< 0.1c are good for dust formation.

Kilonova with Dust

Expected spectral evolution





Very preliminary

Summary

- Opacity Tables for KNe have been constructed by multiple groups. Atomic data for non-LTE KNe are in progress.

- Photospheric emission and nebular emission seem to require different r-process abundances. (Photospheric-> Light, Nebular -> Heavy).

- Late-KN emission may be dominated by r-process dust.

- Refractory elements may condense together around 10 day. More studies are necessary.