Kilonova Modeling

Kenta Hotokezaka
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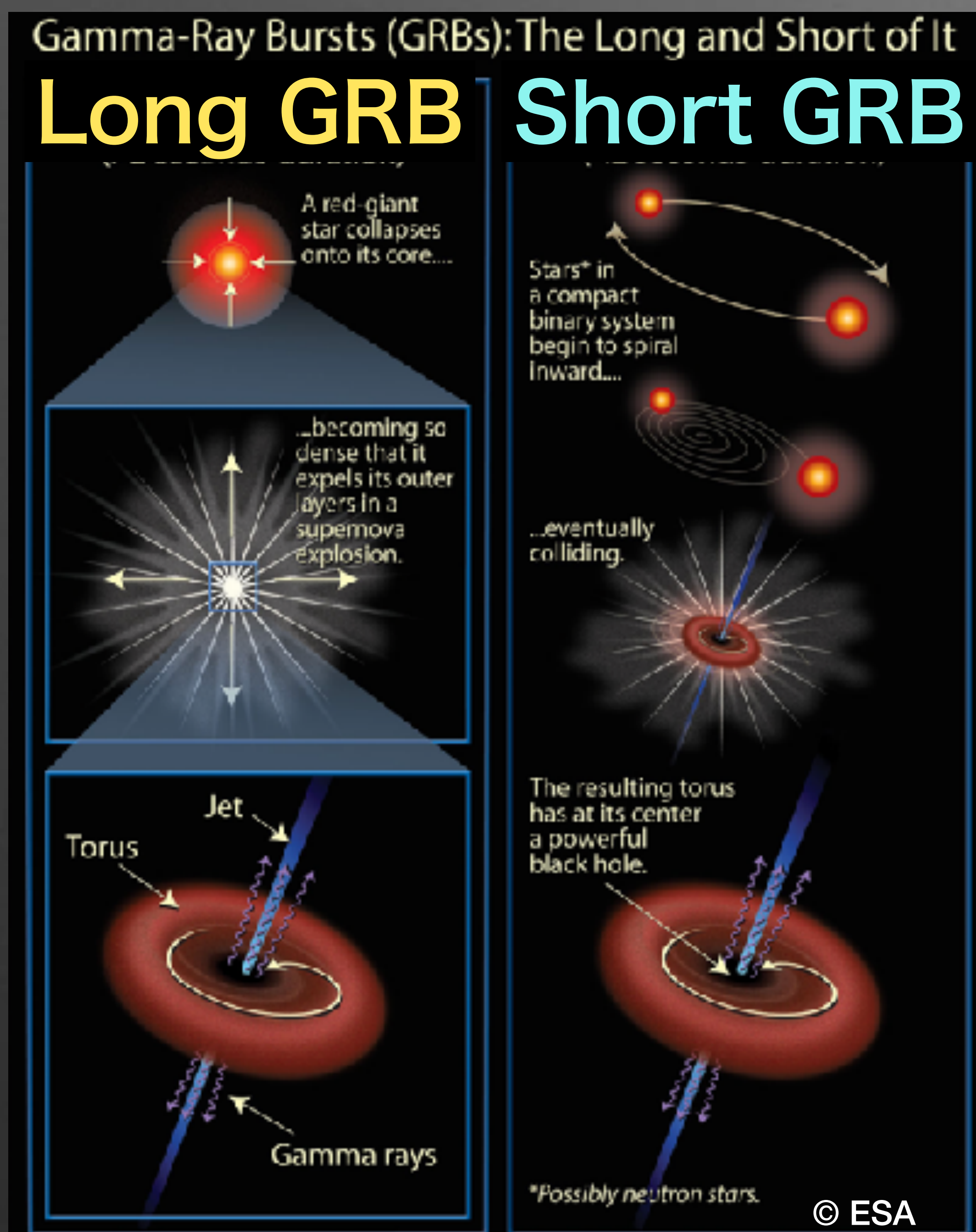
Key question: what is the connection between mergers and GRBs?

The classical hypothesis:



Kilonova candidates in GRBs

(No spectroscopic confirmation except one)

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

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

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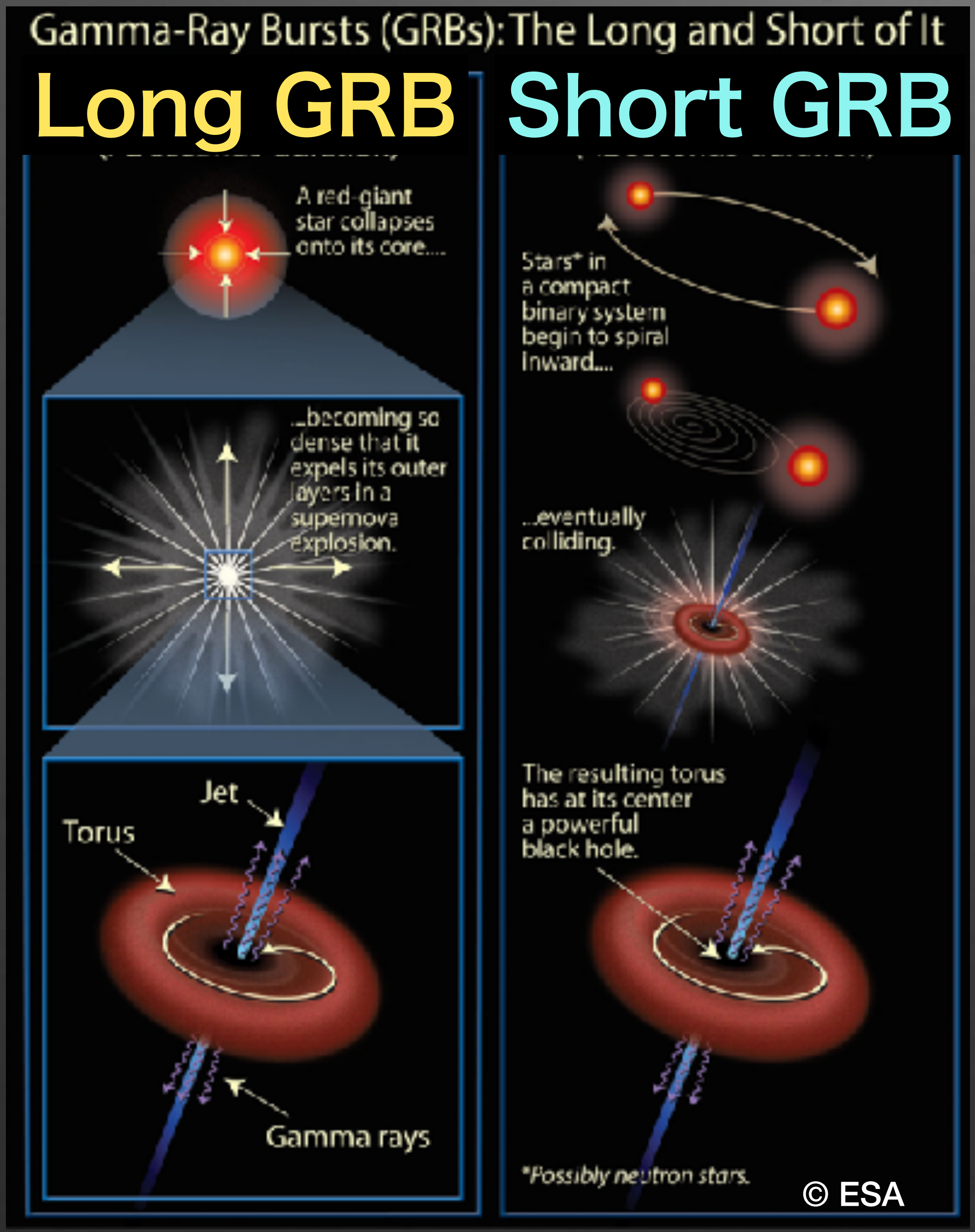


Kilonova candidates in GRBs

(No spectroscopic confirmation except one)

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

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

- Possible Kilonovae in ***long*** GRBs:

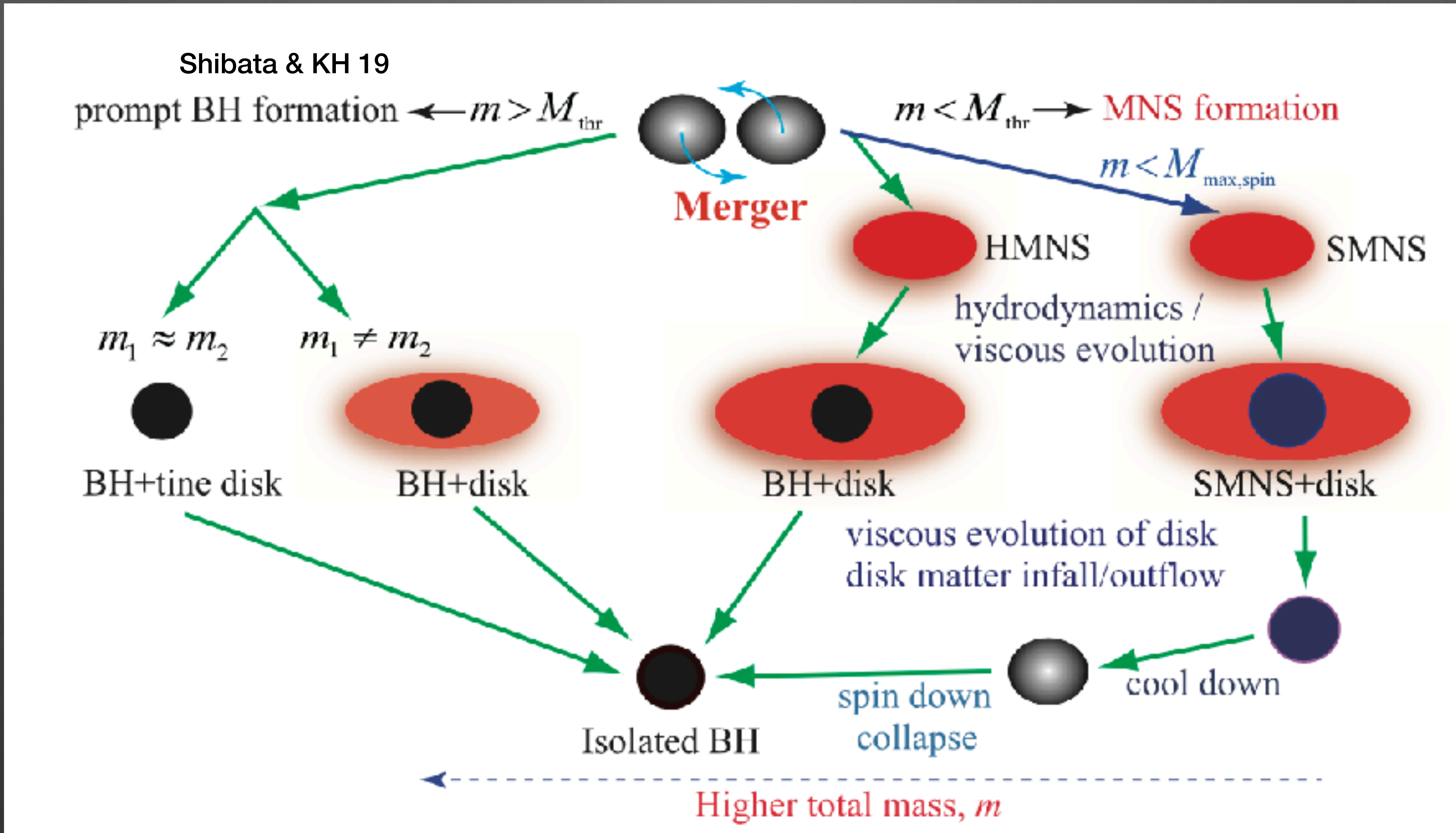
  e.g., GRB 190109A, 211211A, 230307A

- Possible **Supernovae** in ***short*** GRBs:

  e.g., GRB 040924, 200826A

The short-long classification seems controversial.

Key question: what are the details and diversity of neutron star mergers?



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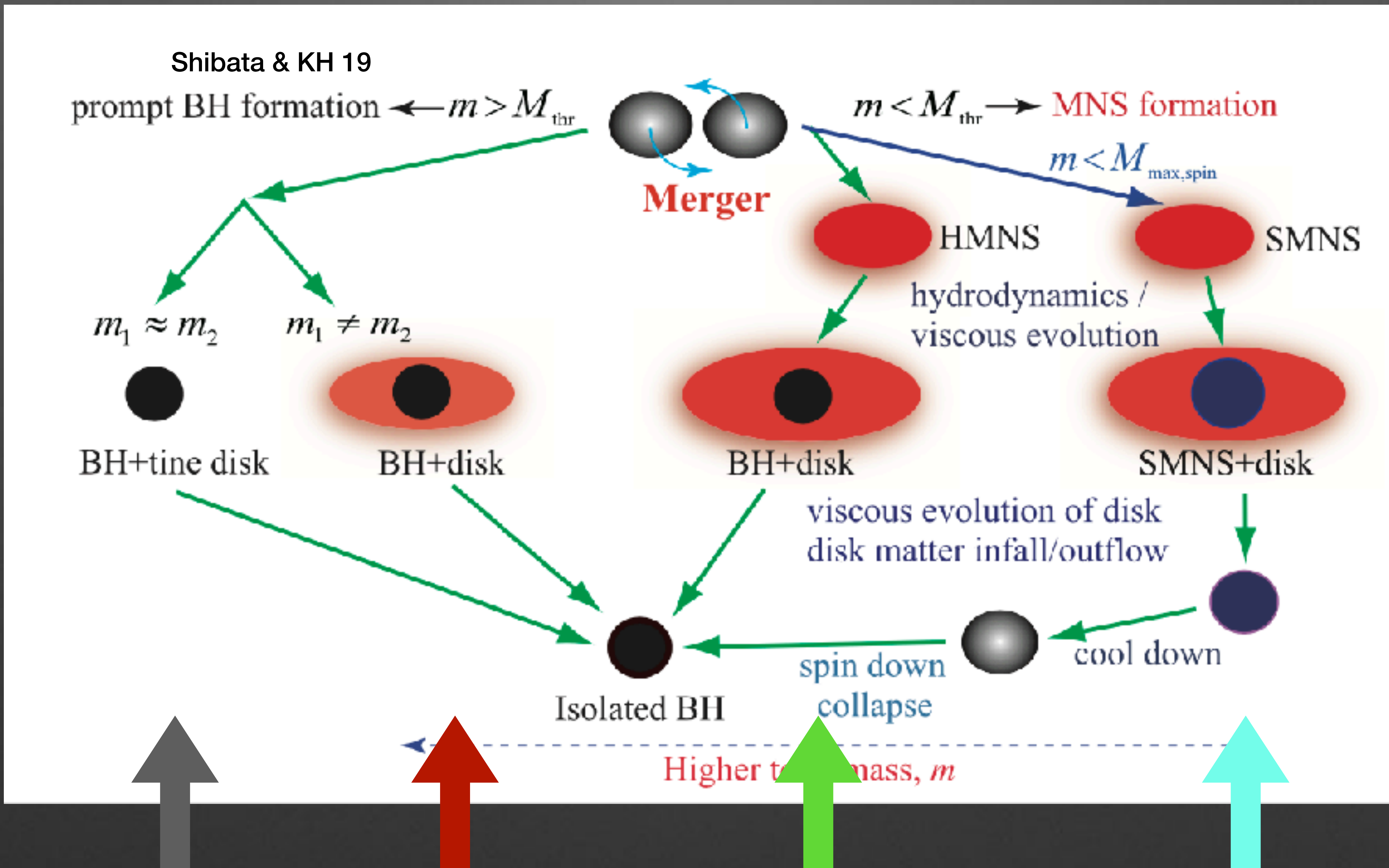
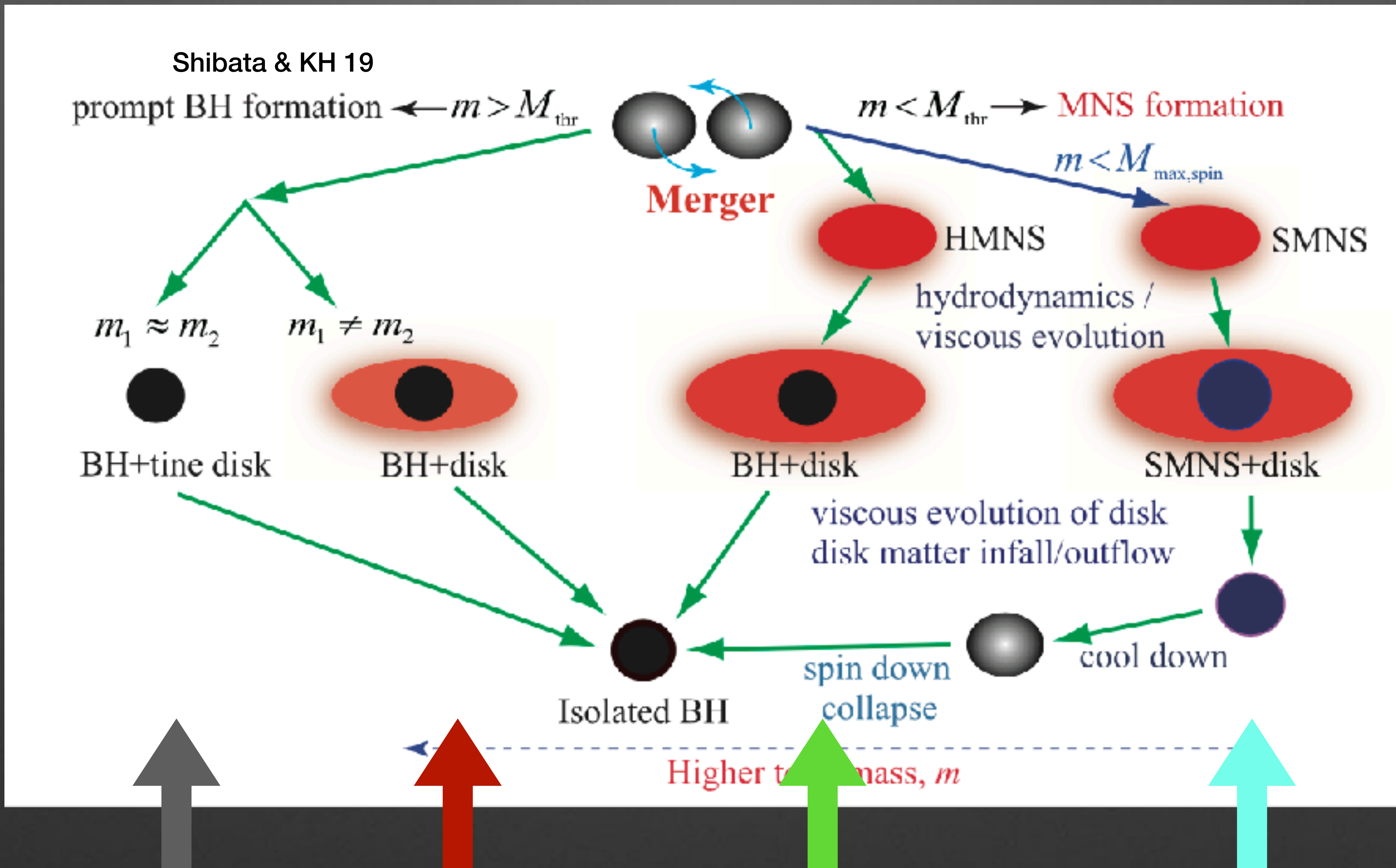


No jet? Jet? Jet? No jet?

Key question: what are the details and diversity of neutron star mergers?



Dark Kilonova

Dim Kilonova

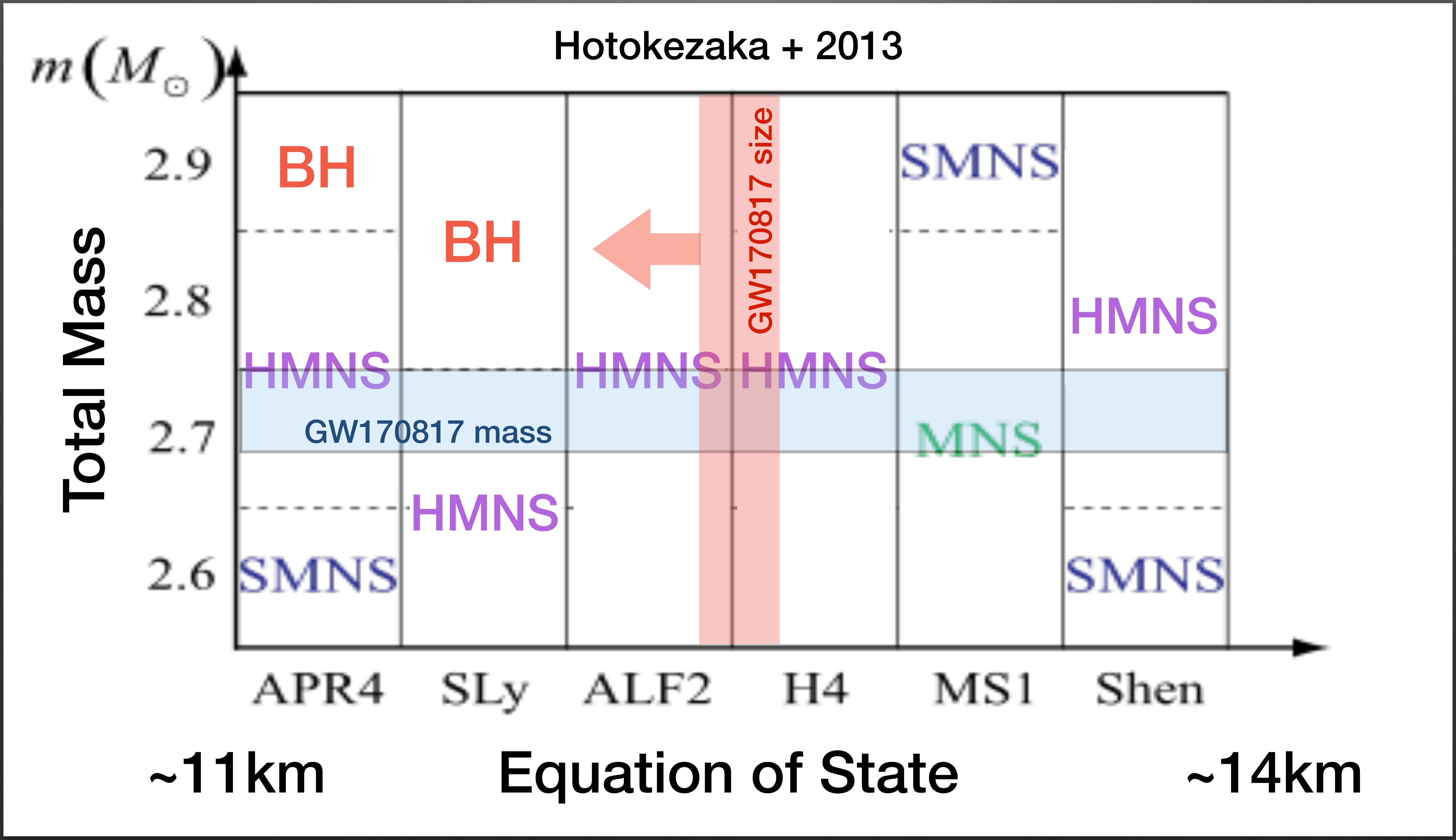
Bright Kilonova

Super-Kilonova

Superluminous Super-kilonova …

Remnants & Neutron Star Equation of State

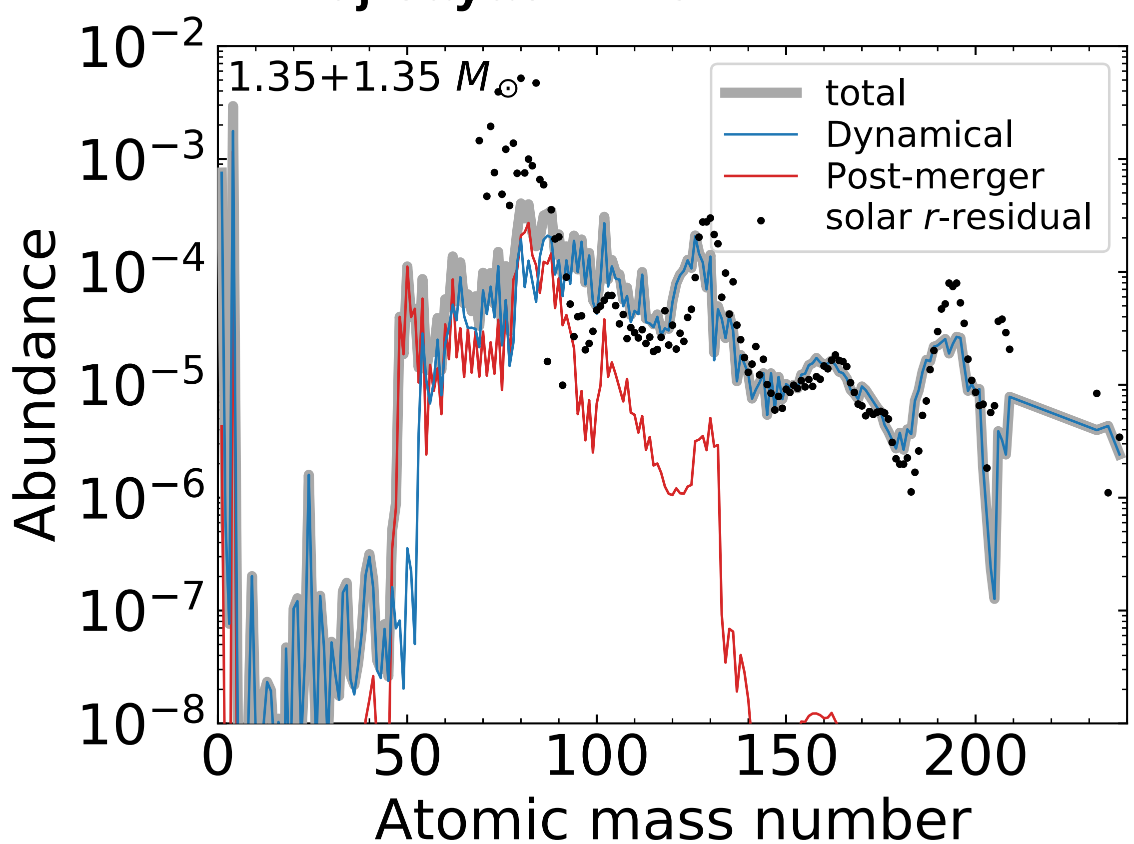
We selected EOSs satisfying $M_{\rm max} \gtrsim 2M_\odot$ (Demorest+2010, Antoniadis+2013)

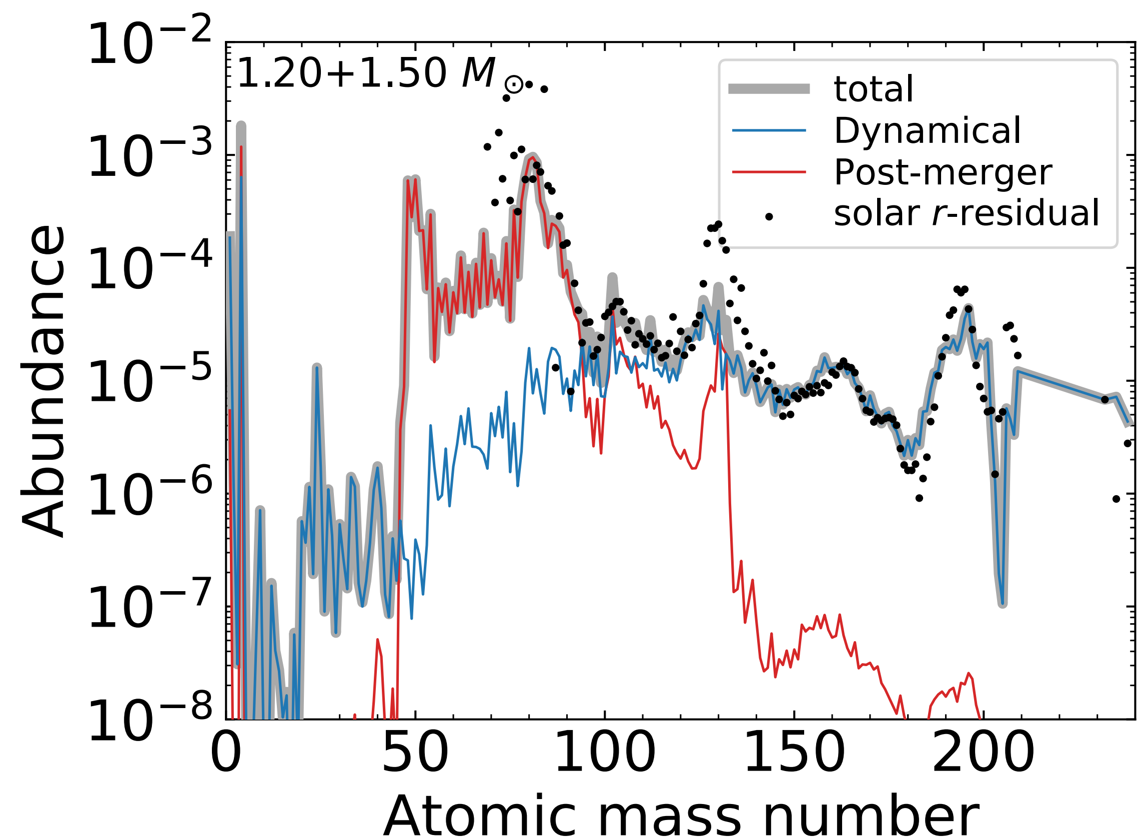


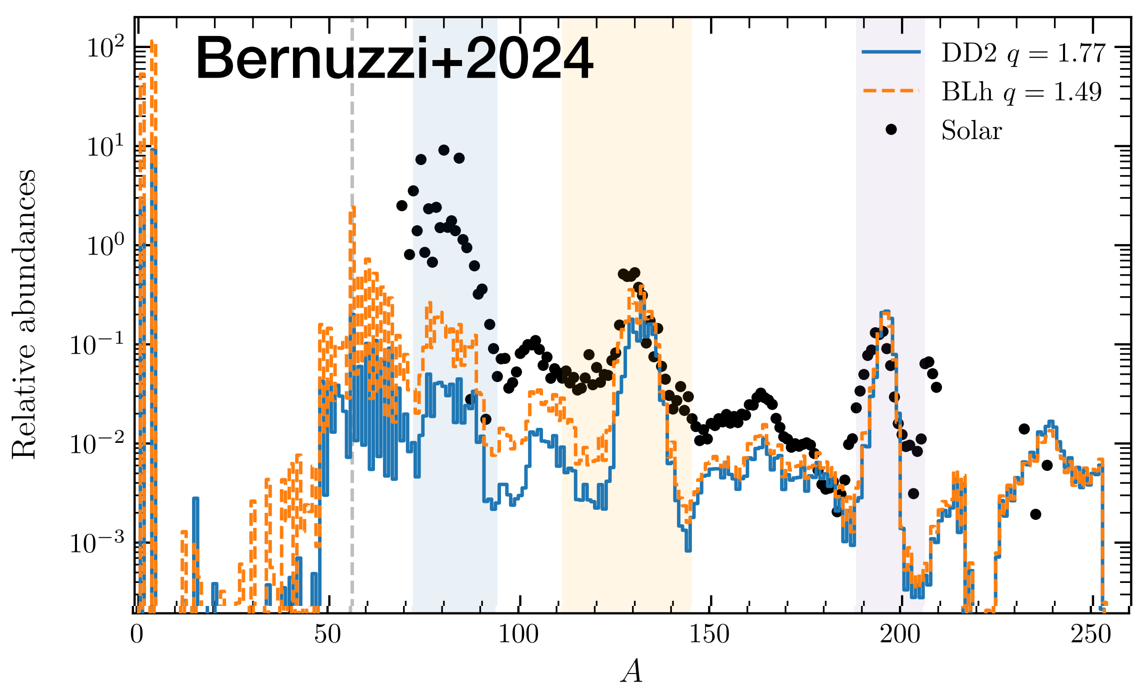
See also, Baumgarte, Shapiro, Shibata 00, Margalit & Metzger 17, Ruiz, Shapiro, Tsokaros 18, Beniamini & Lu 2021

Variation in Abundance pattern

Fujibayashi+23







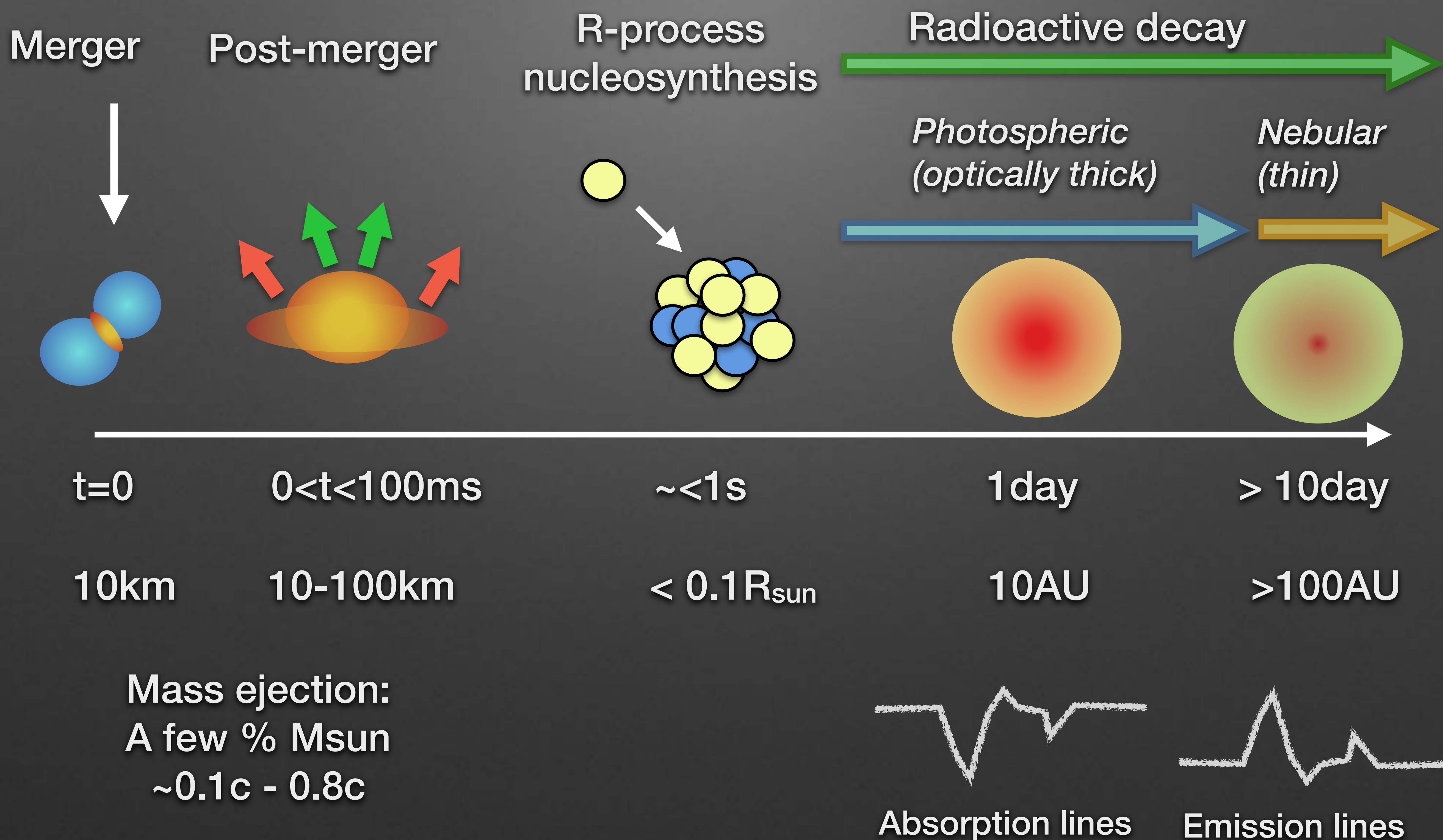
- The abundance pattern of post-merger outflow is sensitive to the remnant neutron star's lifetime.
- ^{4}He is often most abundant.

Outline

- Kilonova modeling and AT2017gfo in GW170817
- JWST observation of a kilonova after GRB 230307A
- Conclusion

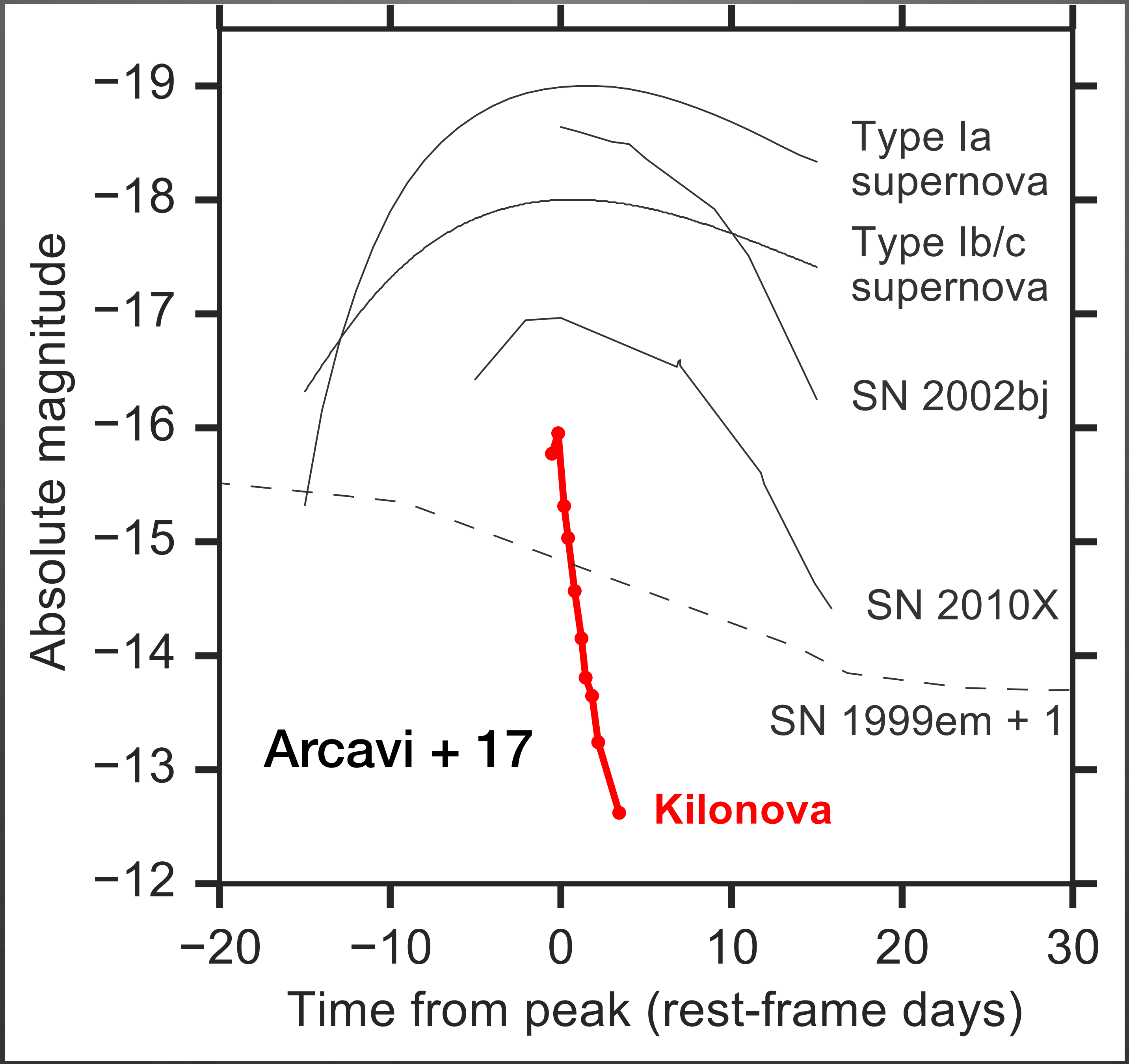
Neutron Star Merger & Kilonova

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



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

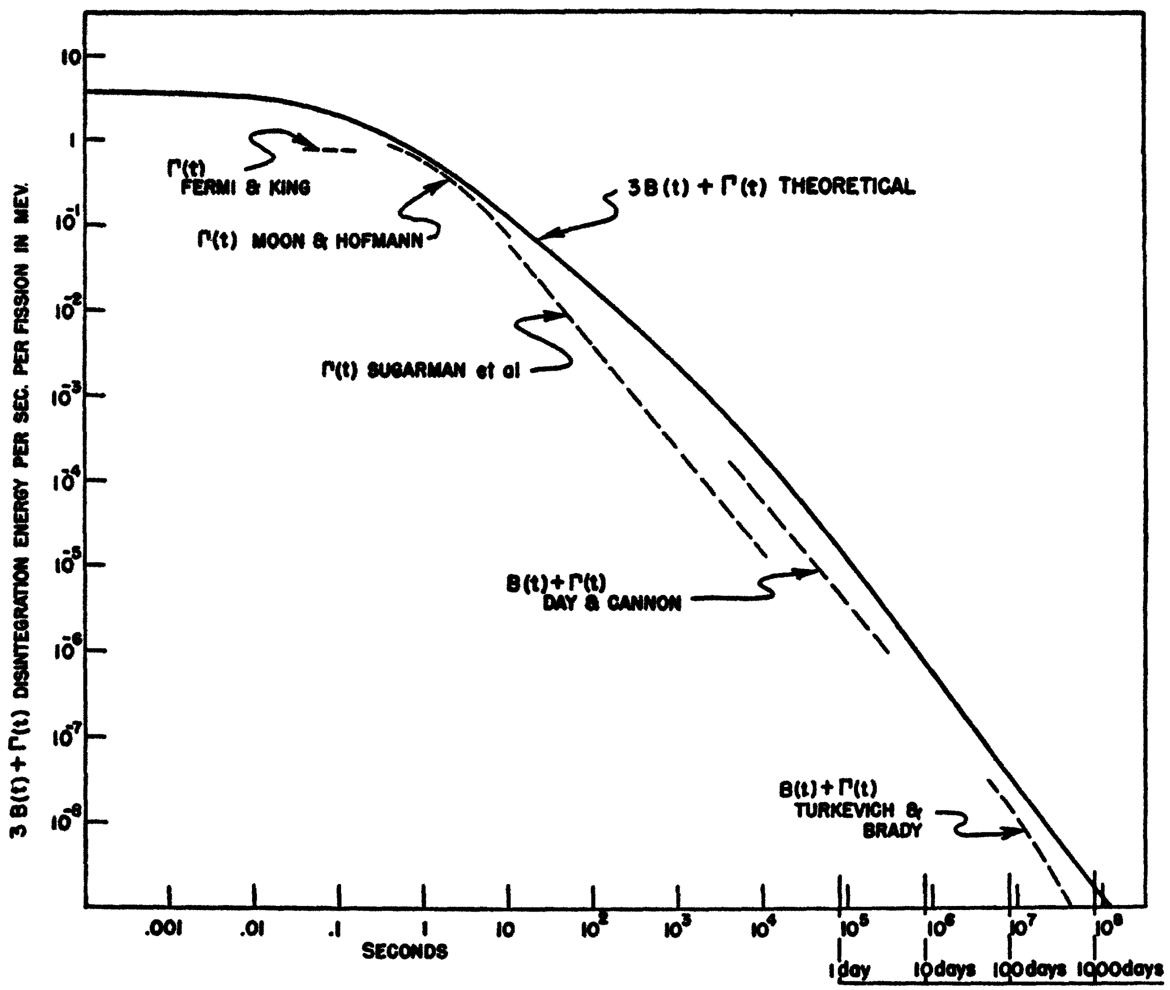


- Kilonova are much fainter and evolve much faster than supernovae.
- GW observations greatly help to find kilonovae.

Energy source: radioactive decay of many species

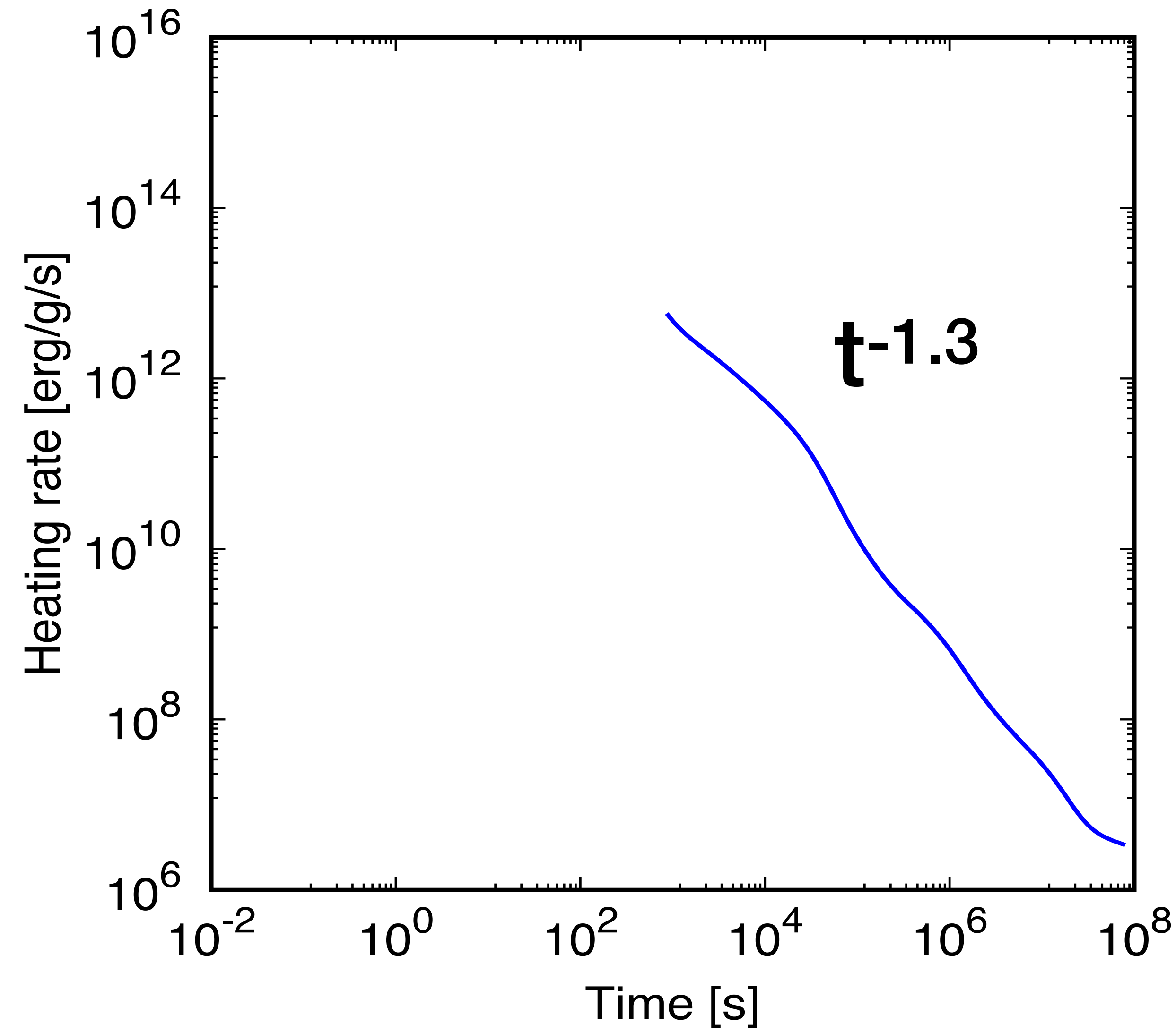
Way & Wigner 1948

KH, Sari, Piran 2017 also Metzger + 10, Korobkin+11, Goriely+11, Roberts+11, Wanajo+14,18, Lippuner & Roberts 14, more



(a)

Heating rate of nuclear waste



Heating rate of r-process

Energy source: radioactive decay of many species

Way & Wigner 1948

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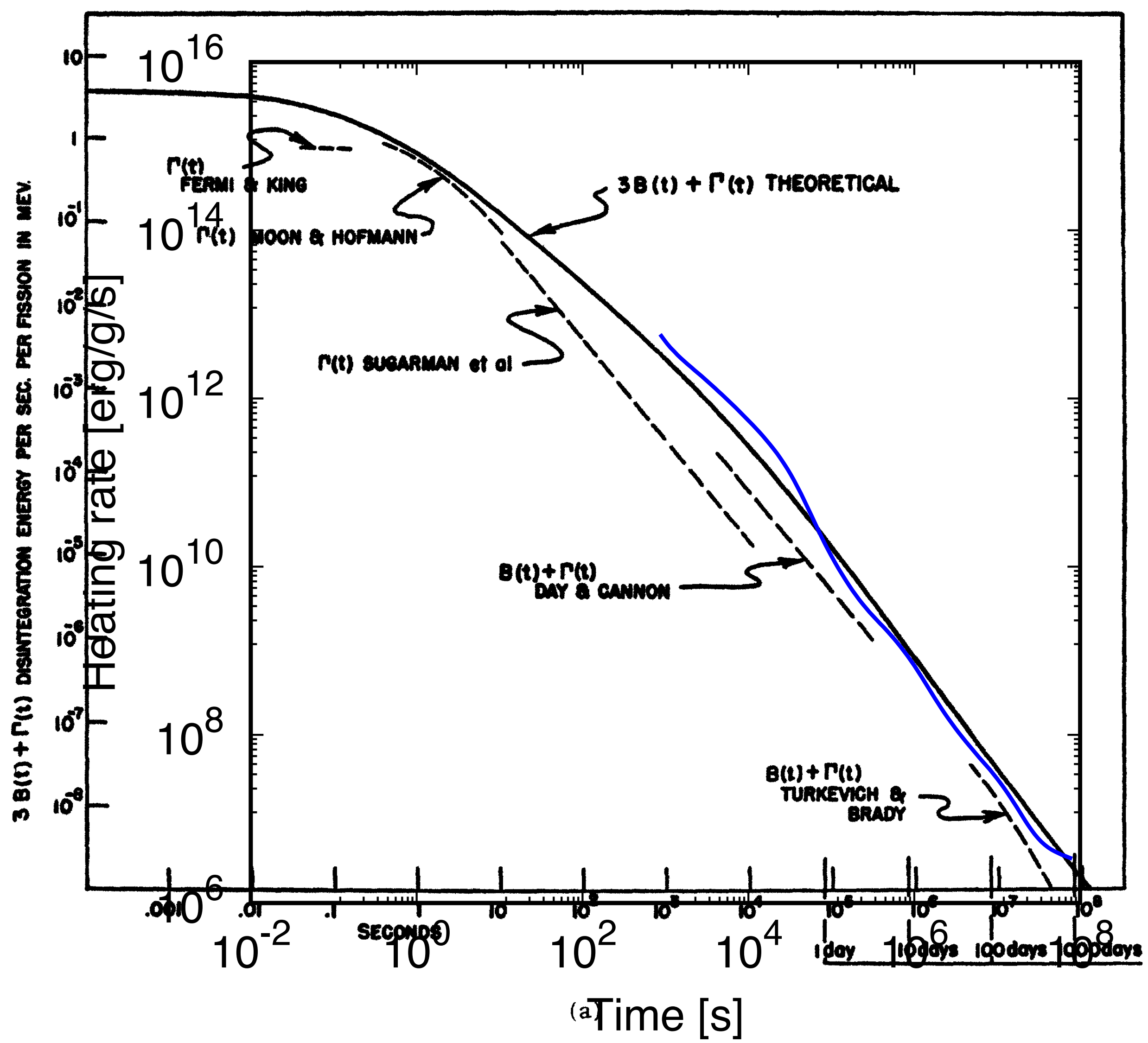
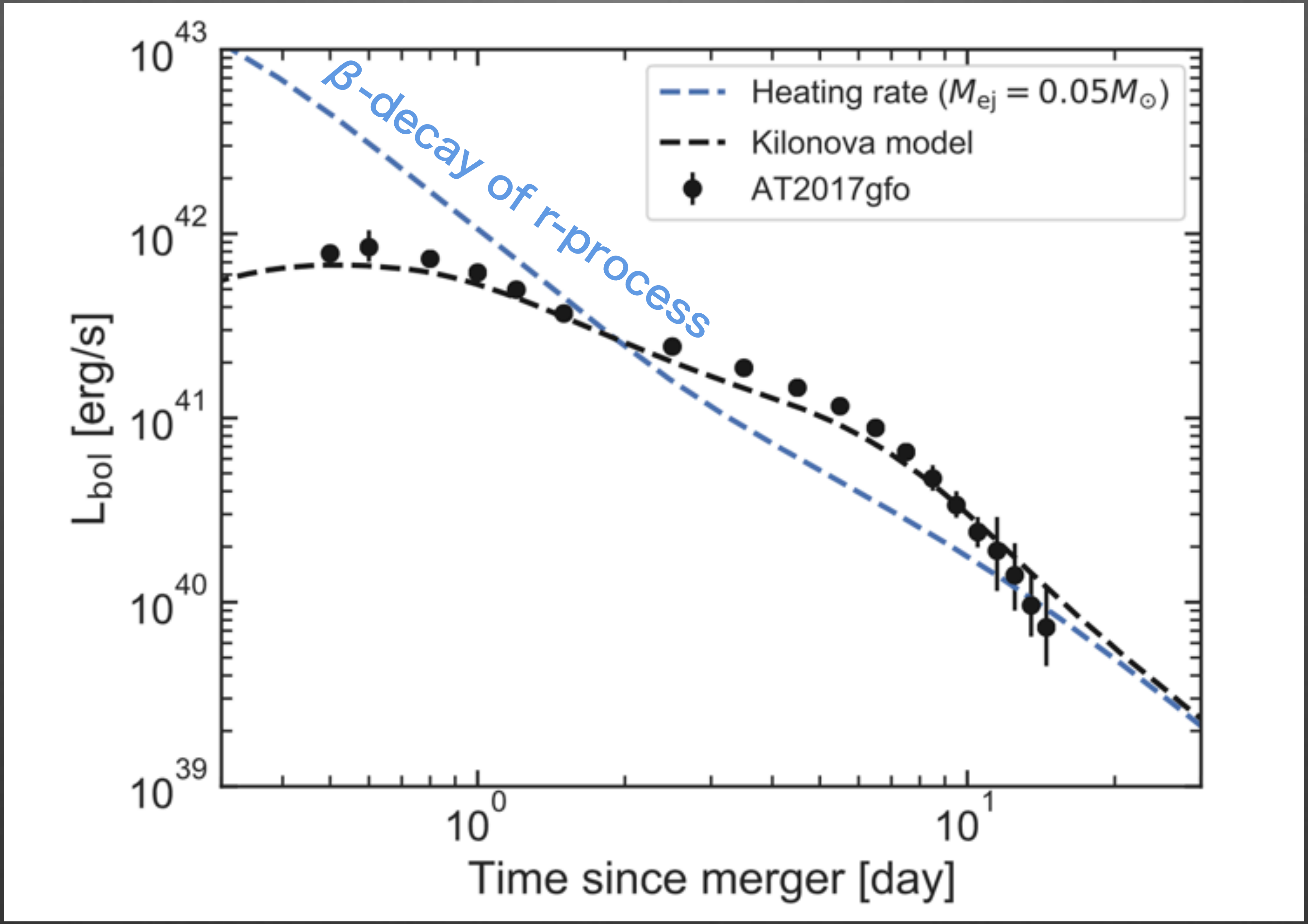


Heating rate of nuclear waste

Heating rate after r-process

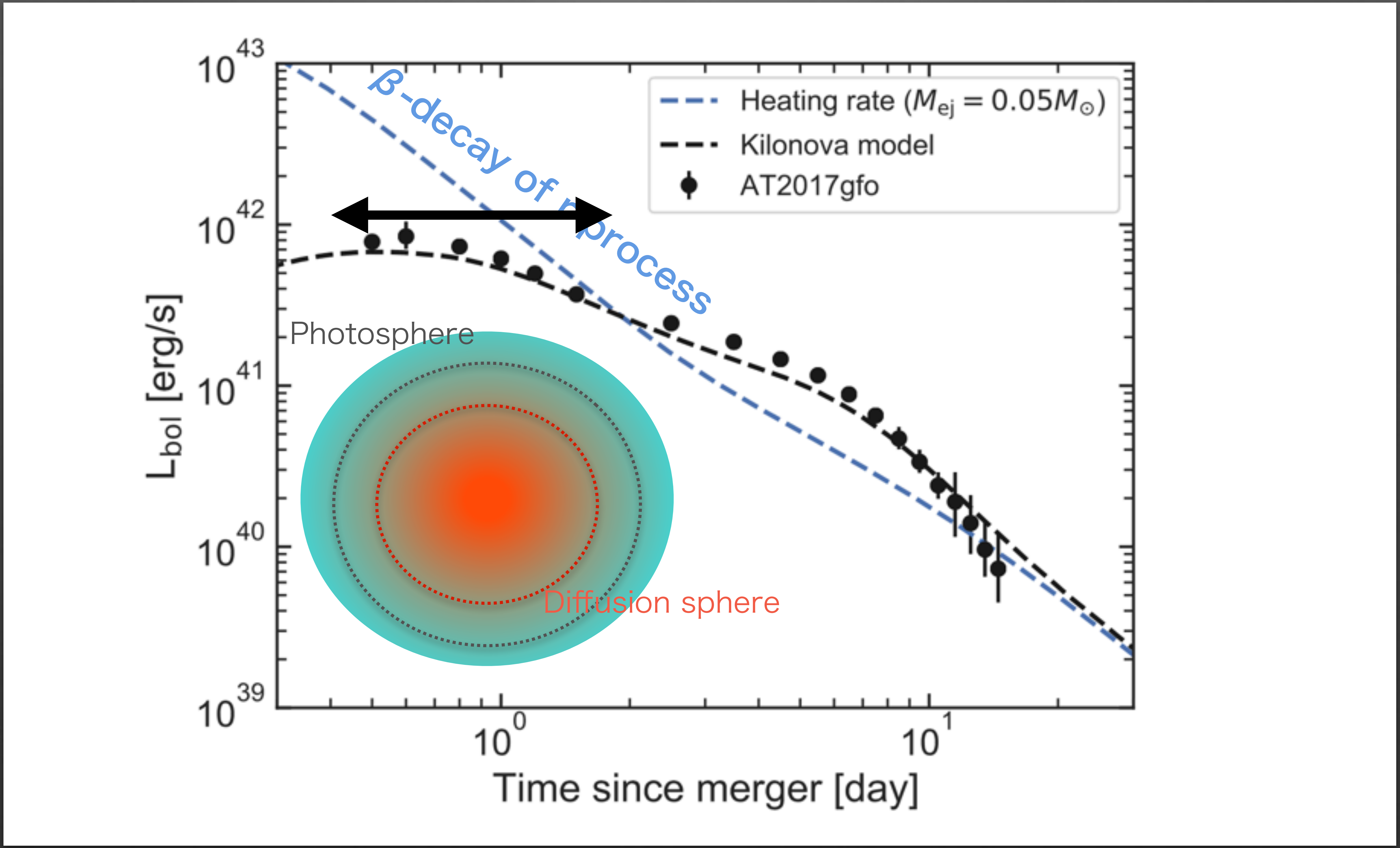
This is a unique properties of the heating rates of many beta-decay chains.

Observed Light curve & β-decay



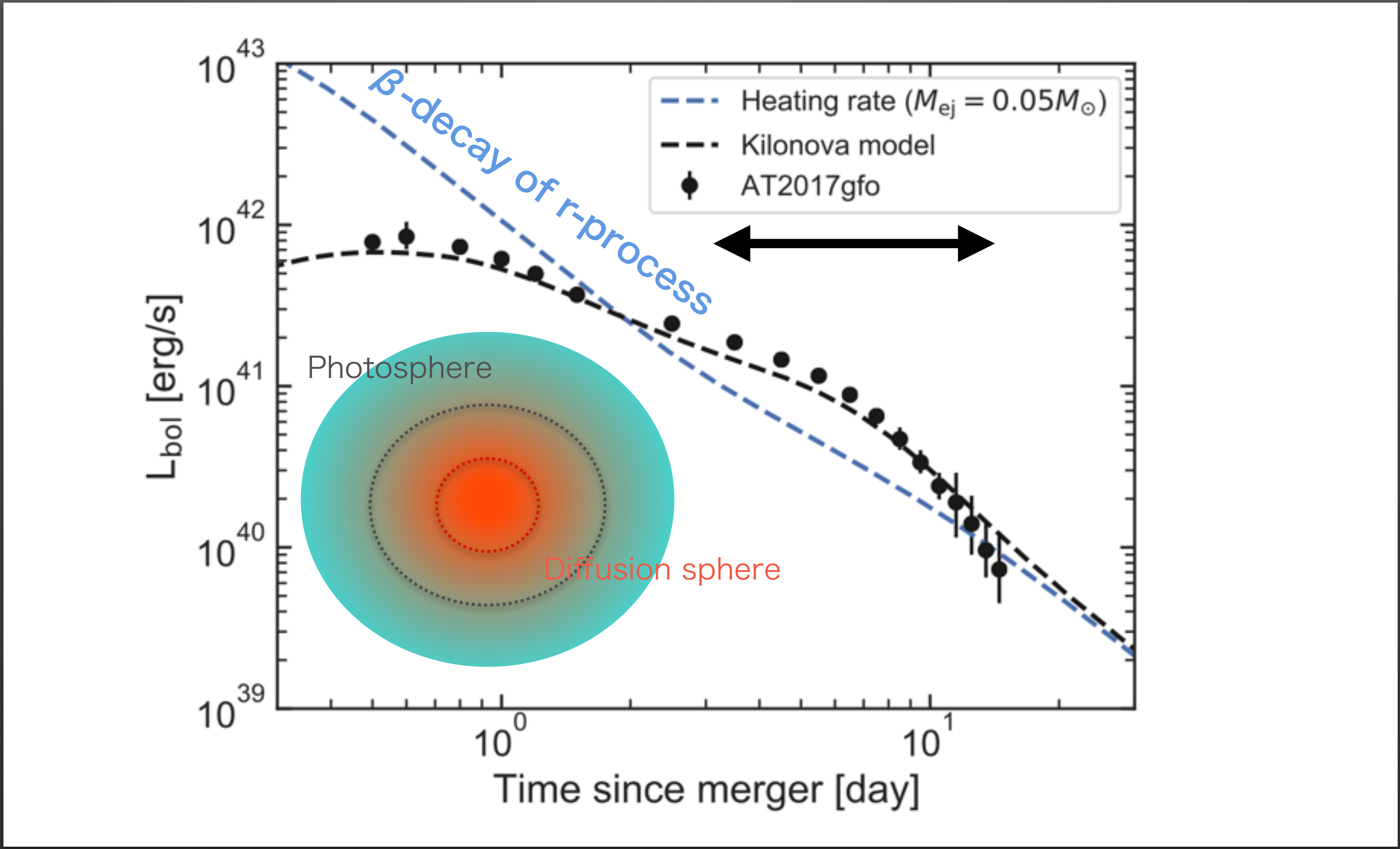
- The light curve follows the radioactive heating of r-process nuclei.
- 0.05Msun of r-process is needed to explain the kilonova AT2017gfo.

Early photospheric phase



- The peak time is <1 day, suggesting a low opacity < 1 cm^2/g

Late photospheric phase



- The peak time is <1 day, suggesting a low opacity < 1 cm^2/g
- The diffusion phase lasts for ~ 10 days, a high opacity ~ 10 cm^2/g

Efforts on kilonova modeling

GR(RM)HD inputs

Ejecta properties

Shibata+17, Radice+18, Miller+19, Combi & Siegel 23, Fahlman & Fernandez 22, Haddai+23,Just+23, Fujibayashi+23, Kiuchi+24, Schianchi+24, Rosswog+25

Albino, Eleonora's talks

Nuclear inputs

Abundances

Heating rates

Zhu+18,21, Wu+19, Barnes+21, Bulla 23, Jabobi+24, Ricigliano+24

Rebecca,Sebastein, Jan's talks

Atomic inputs

Energy levels, gf-values

Collision cross sections

Kasen+13,17,Barnes & Kasen 13,Tanaka & KH 13, Tanaka+18,20, Gaigalas+19, Banerjee+20,22, Fontes+20, Gillaners+22, Da Silva+22, Mulholland+24, McCann+25,

Ricardo Matteo's talks, Jorge's poster

Kilonova radiation

- Multi-D
- Elements ID
- LTE, non-LTE

Tanaka, KH+14, Perego+17, Wollaeger+18,21, Bulla+19,21, Breschi+21, Korobkin+21, Darbha+21, Collins+23,24, Shrestha+23, Sneppen+23, Shingles+24

Watson+19, Gillaners+21,24, ,Domoto+21,22,24, Sneppen+23, Rahmouni+25, Pognan+25, **Salma's talk**

KH+21, 22, Pognan+22, Ricigliano+25, **Blanka' talk**

Kilonova observations

Photomertic & Spectroscopic

Stellar observations

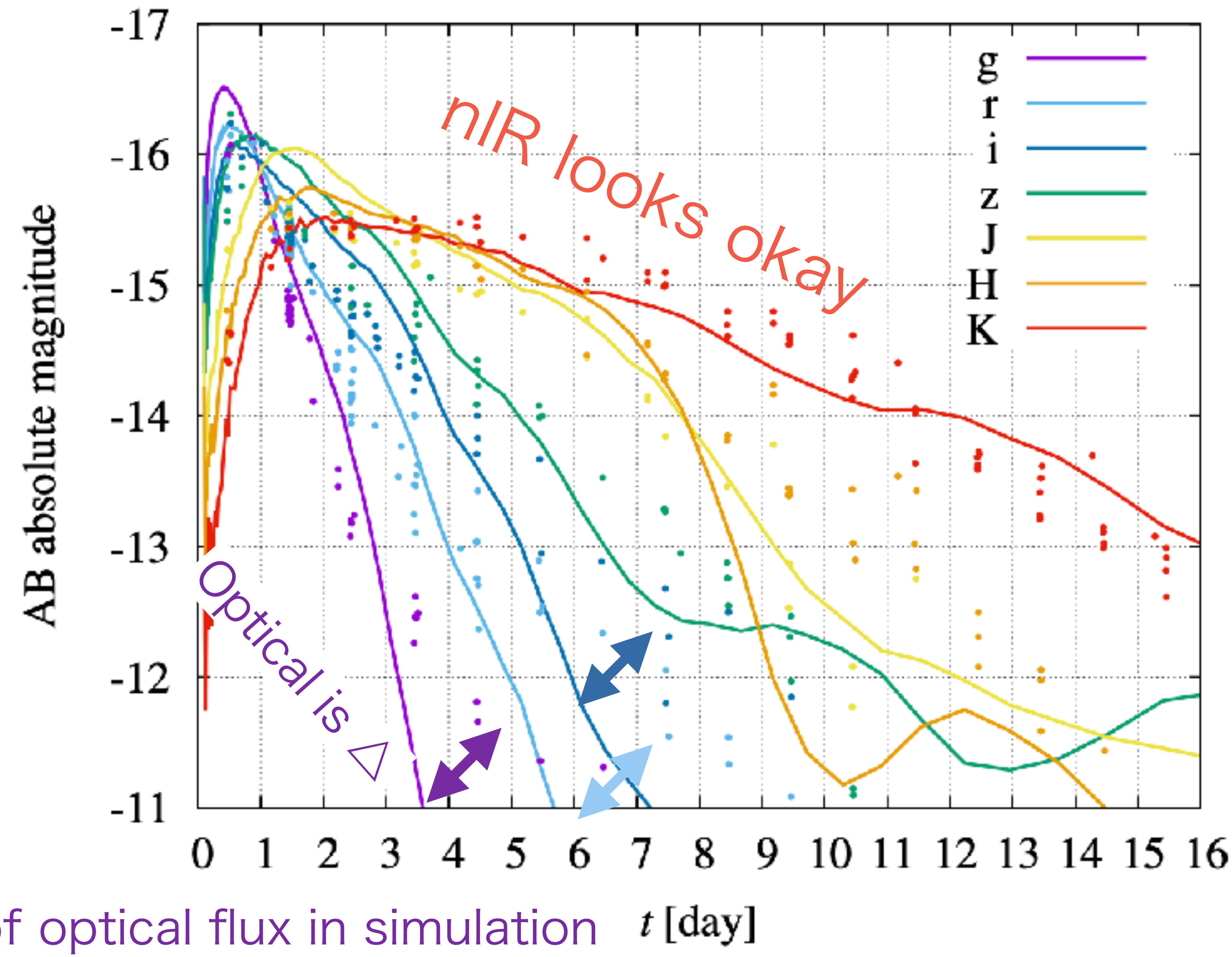
R-process abundances

nIR absorption lines

Beyond LTE: Color

Kawaguchi+22

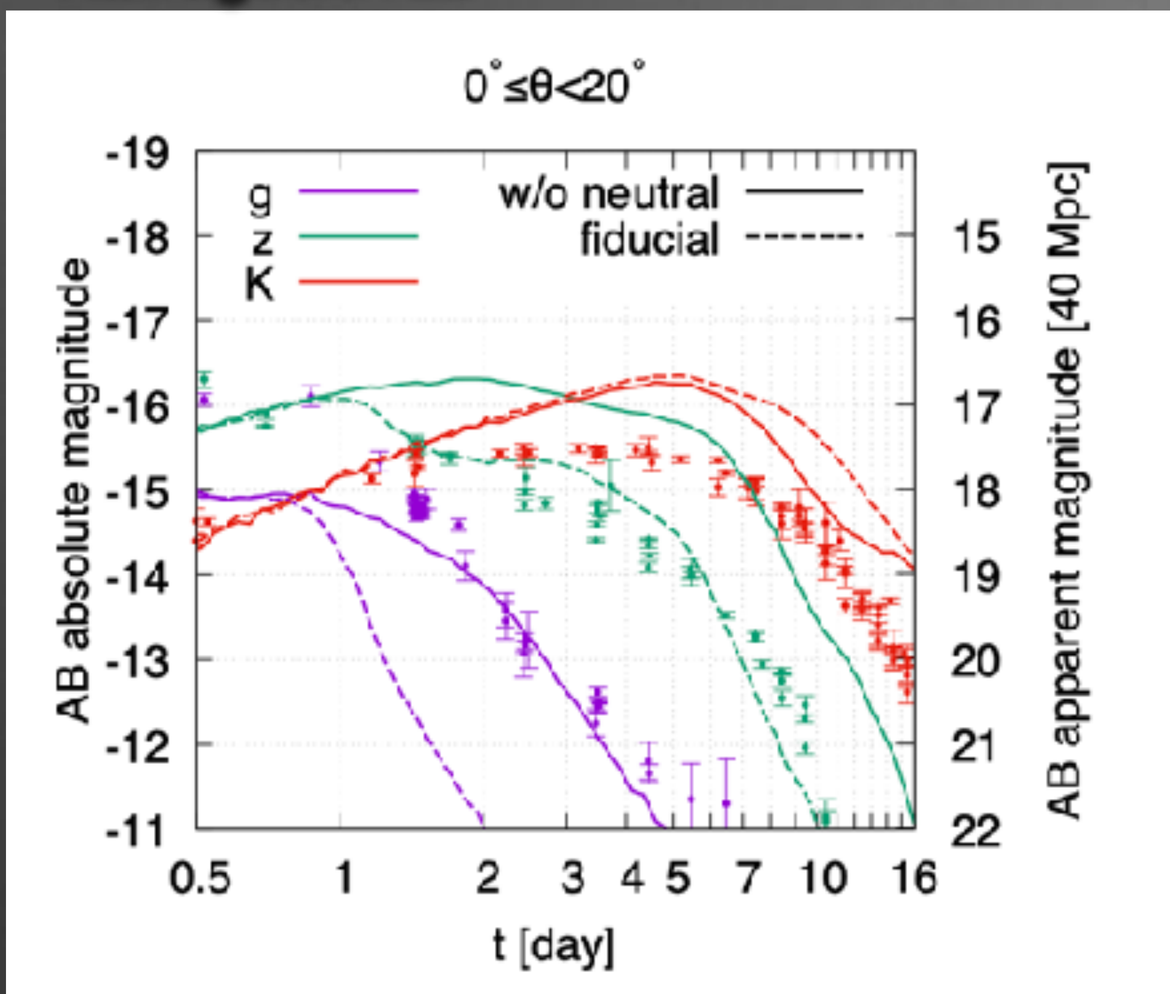
Lines: simulation, points: observation



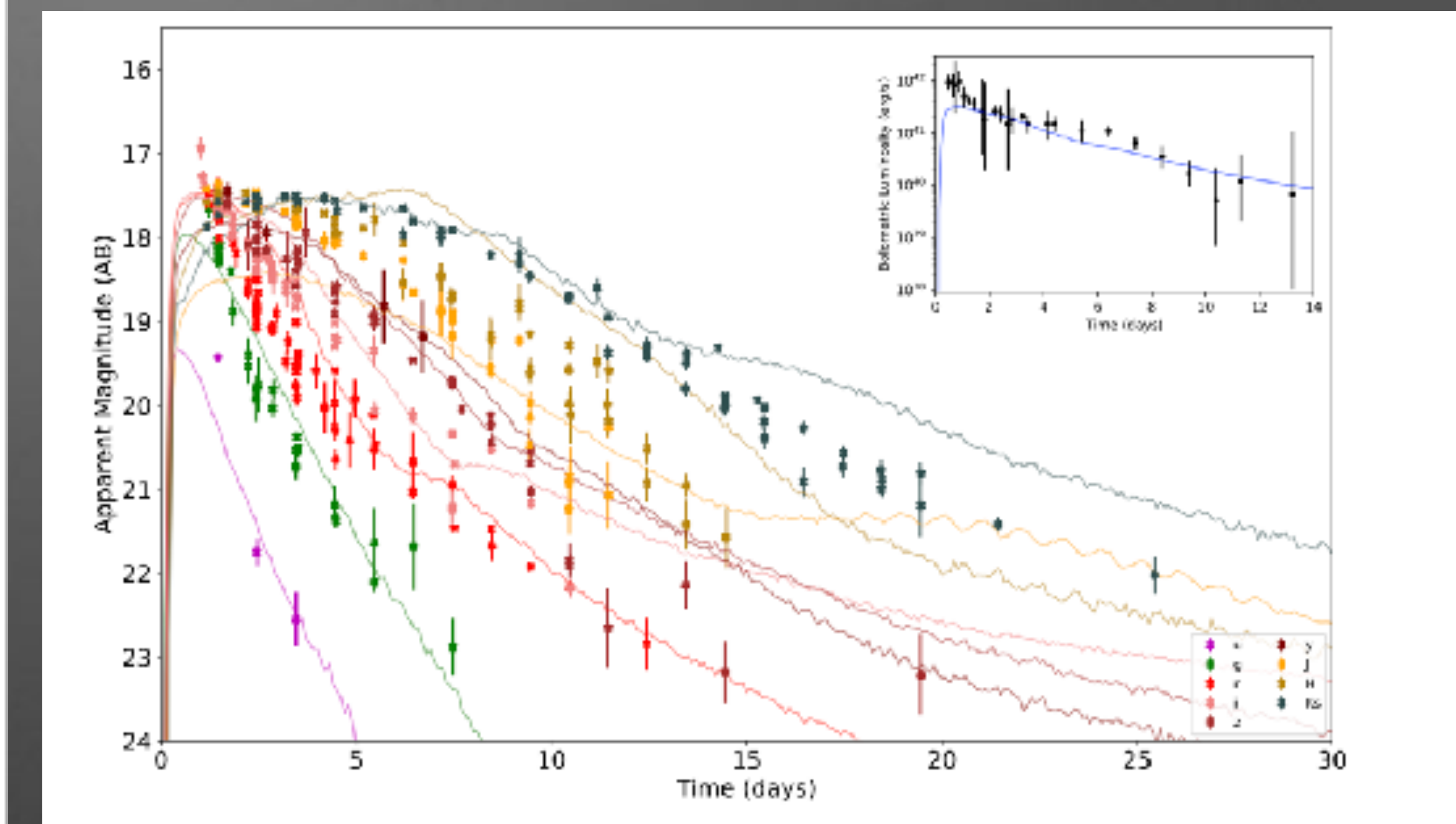
Lack of optical flux in simulation

Beyond LTE: Color

Kawaguchi+22



Brethauer+24



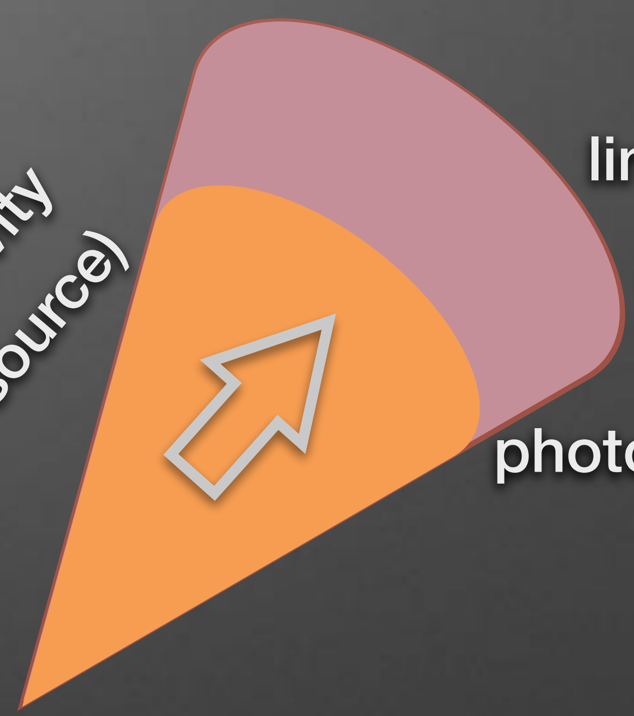
LTE simulations but neutral ions are artificially removed.

The color evolution can match the observed data.

Radioactivity everywhere in Kilonova

Stellar atmosphere

Kilonova

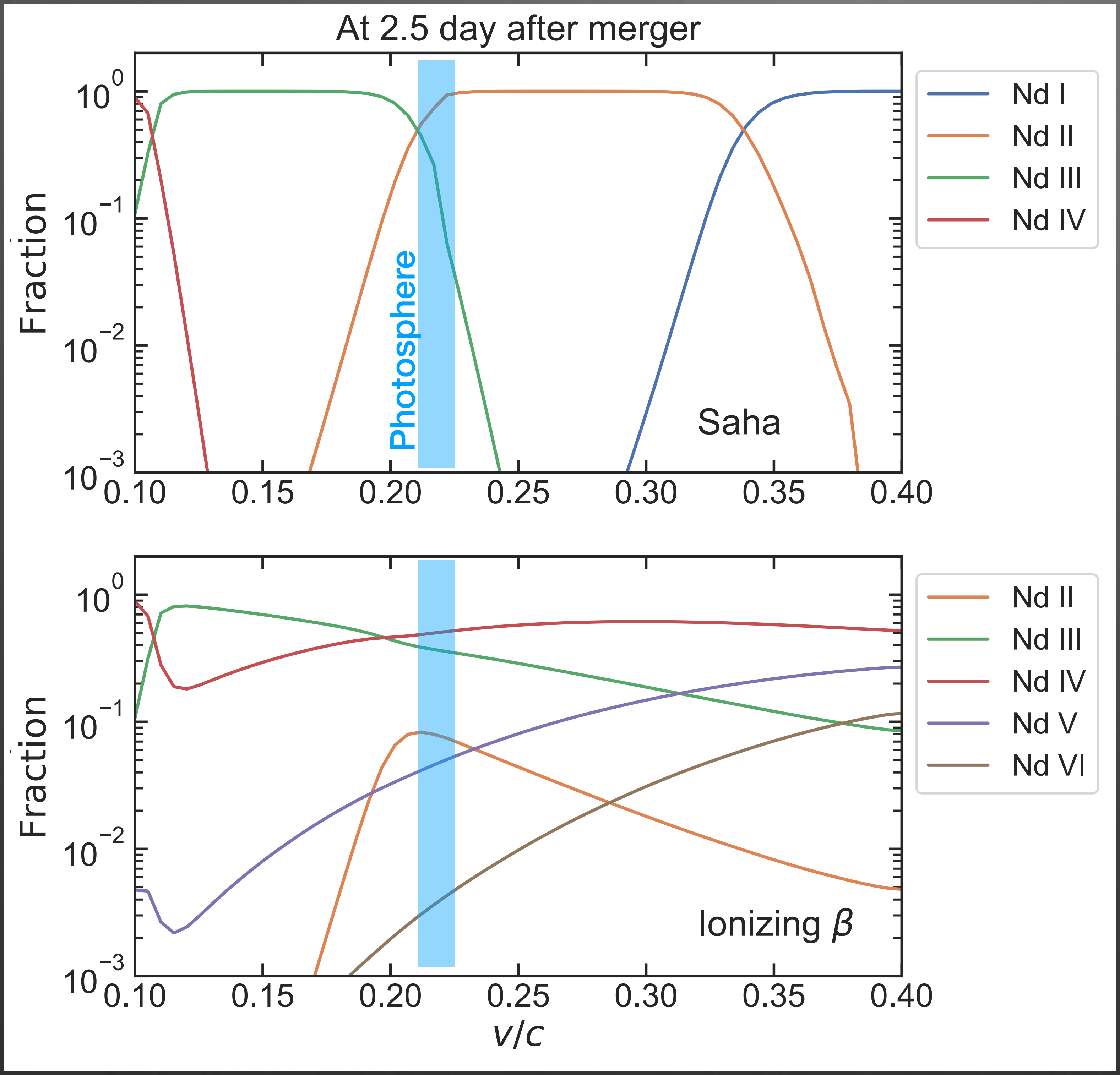


LTE (Saha equilibrium) is usually valid.

LTE (Saha equilibrium) may be strongly violated.

The material even in the line forming region is radioactive.
So you cannot put quiet atmosphere on top of the photosphere.

Impact of radioactive ionization



Very preliminary

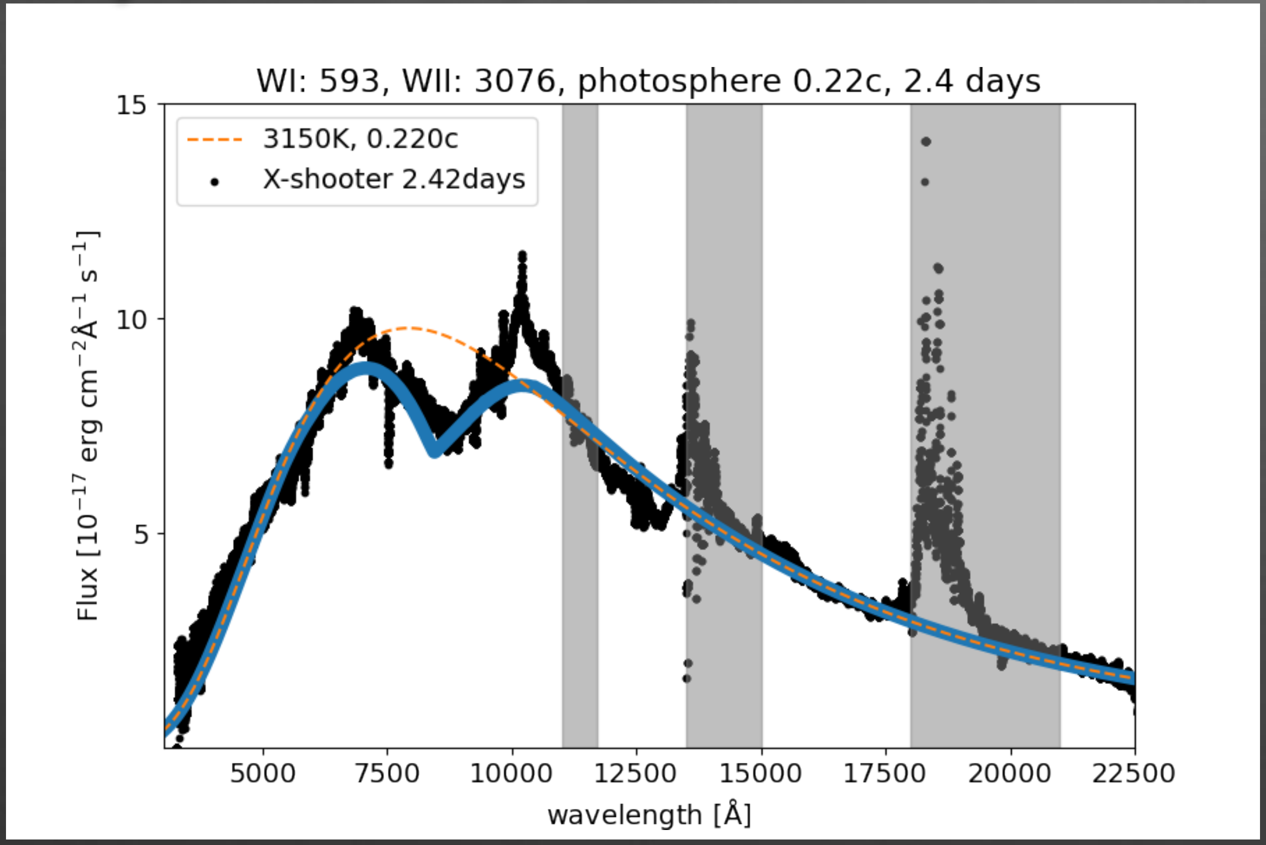
- Overioniation: The non-LTE abundances deviate from the LTE ones particularly for $v>0.2c$.
- Radiation transfer simulation is still on-going but this may significantly change the kilonova color and spectrum.
- I will come back to the hardest part in the calculation at the end of the talk.

The 0.8 μm feature: He I and Sr II lines

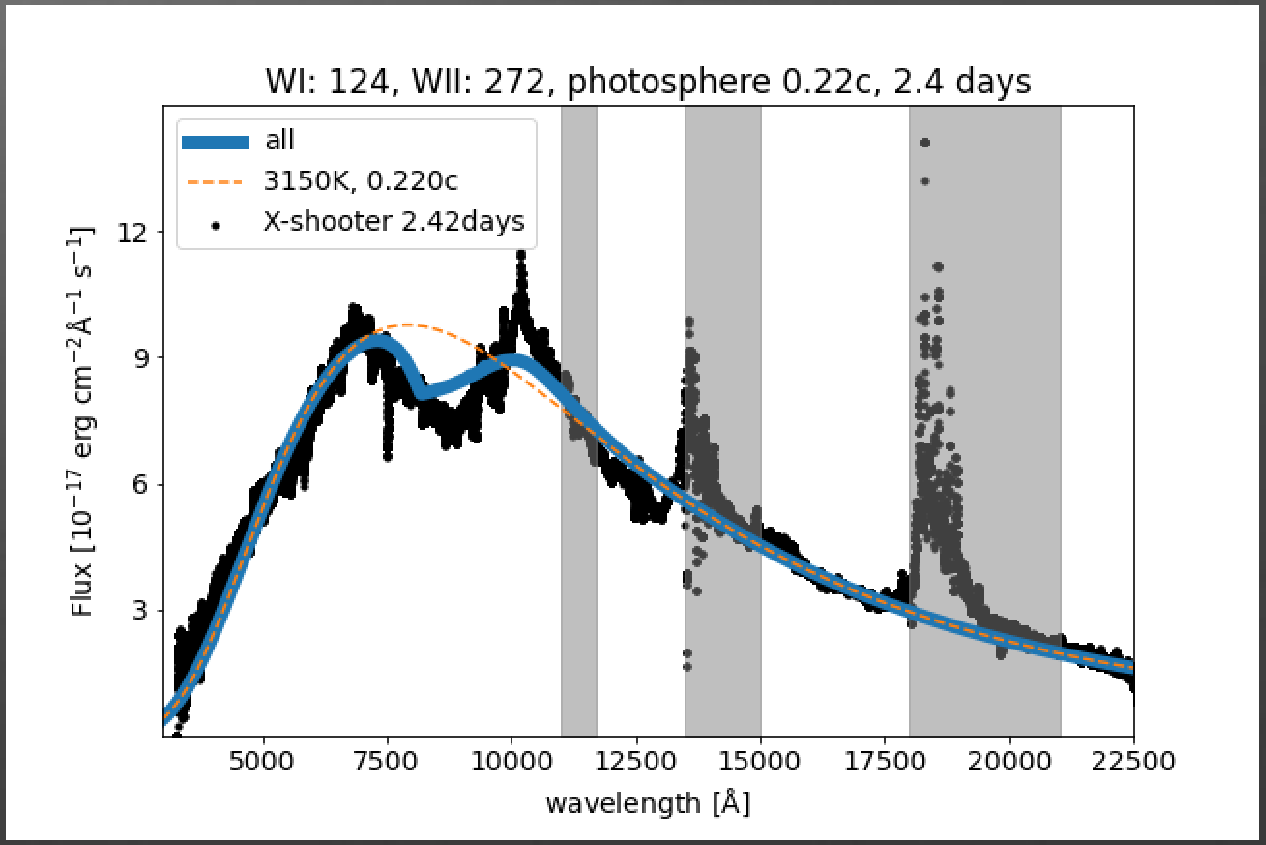
The 0.8μm feature is interpreted as Sr II by Watson+19.

However, He I can produce a similar feature (Pergo+22, Tarumi, KH+23).

Tarumi, KH+23 He I case



Sr II case



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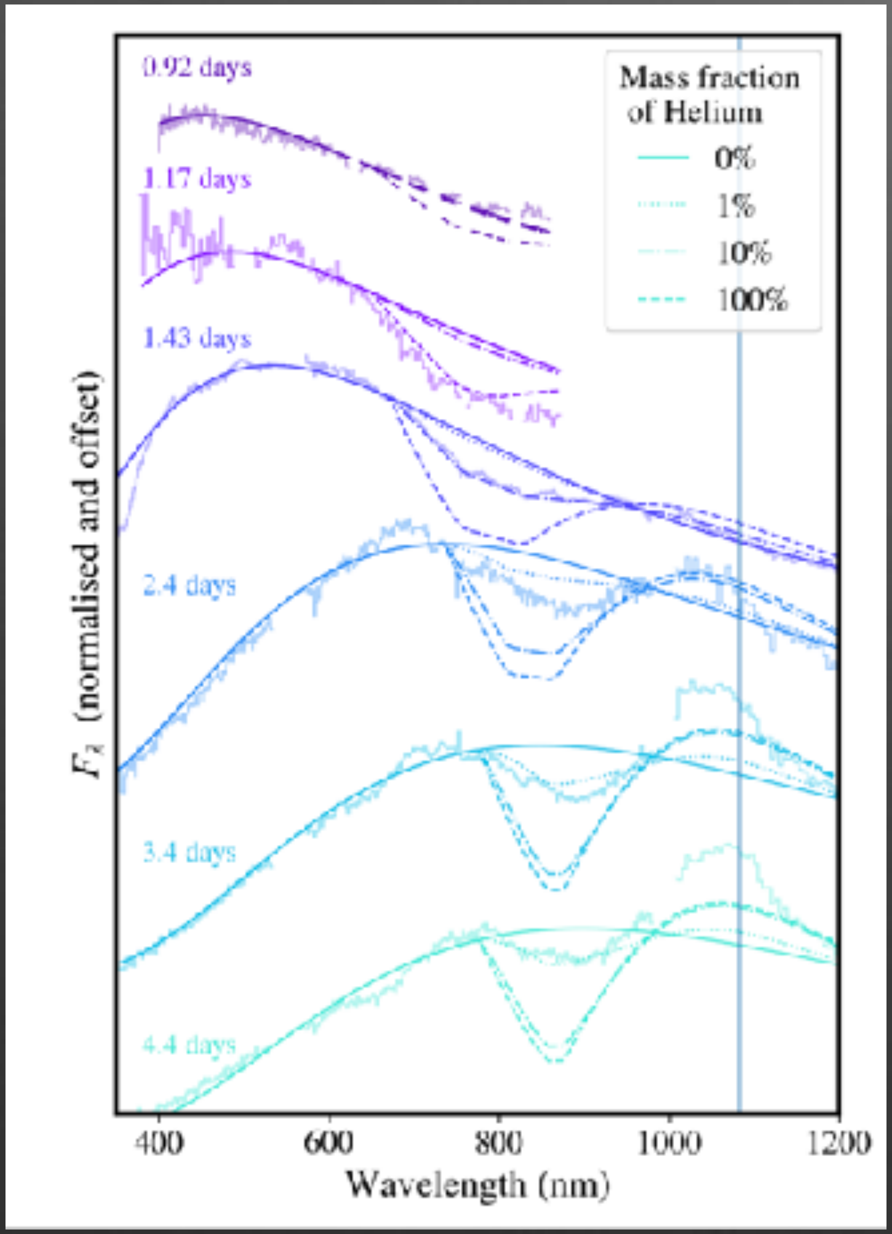
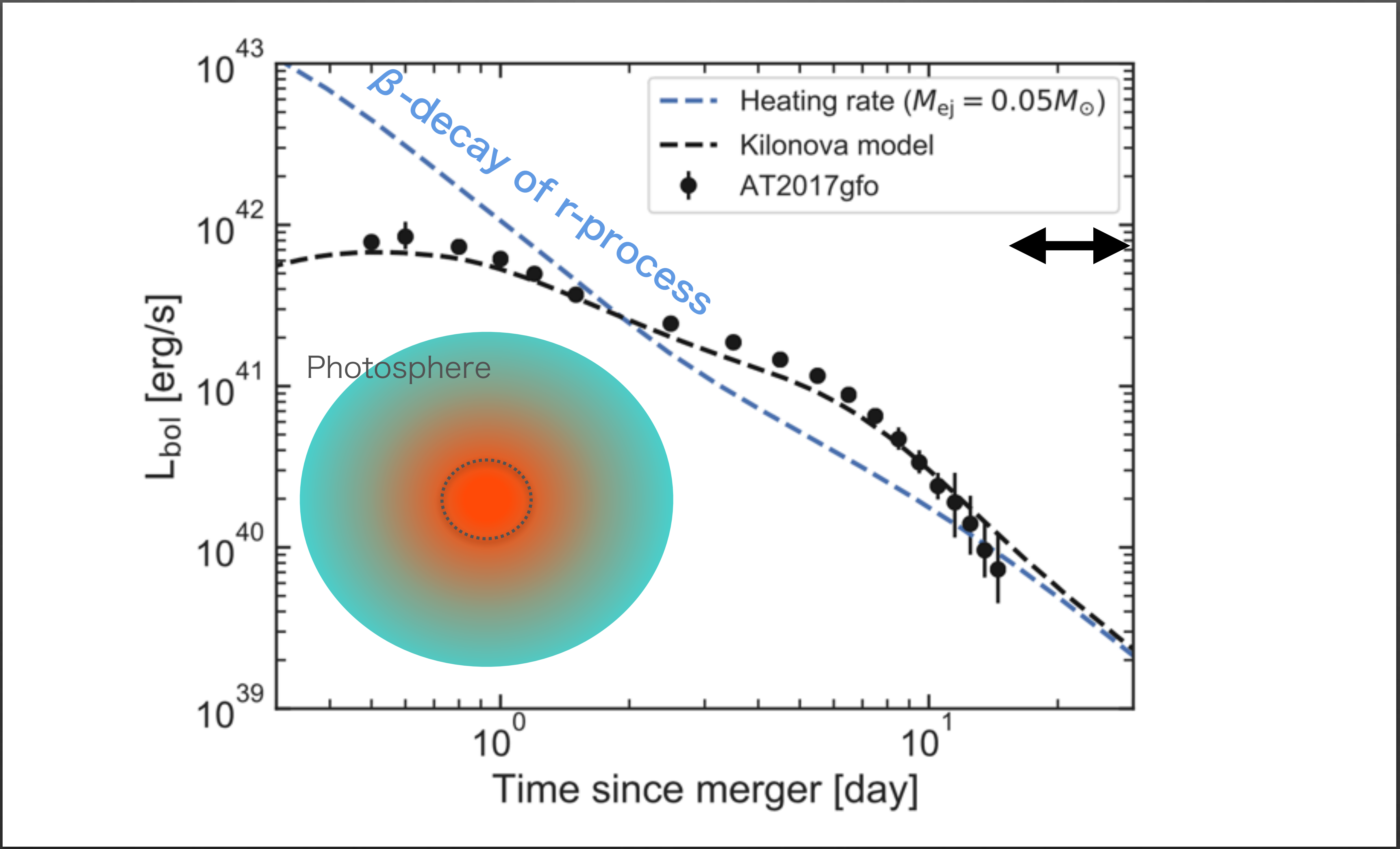


Sneppen+24 show that the He line gets too strong with time.

- Sr II is likely to dominate at early times (<2.4 days)
- He I significantly contributes at later (>2.4 days), even a mass fraction of 1%

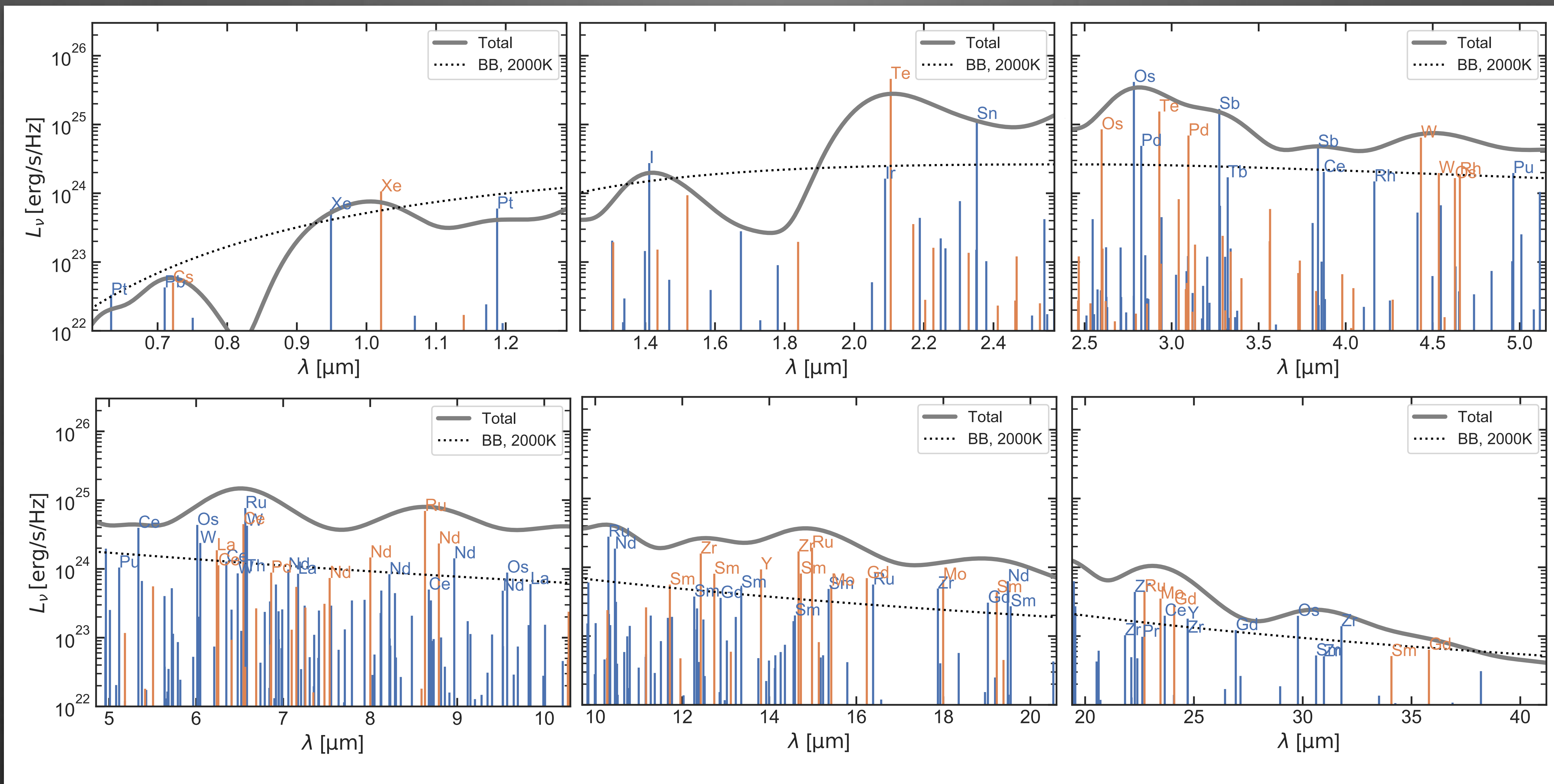
Nebular phase



- Most photons created by atoms emerge without being absorbed.
- But, fainter than the photospheric phase.

Kilonova Nebular Spectrum (~10 days post merger)

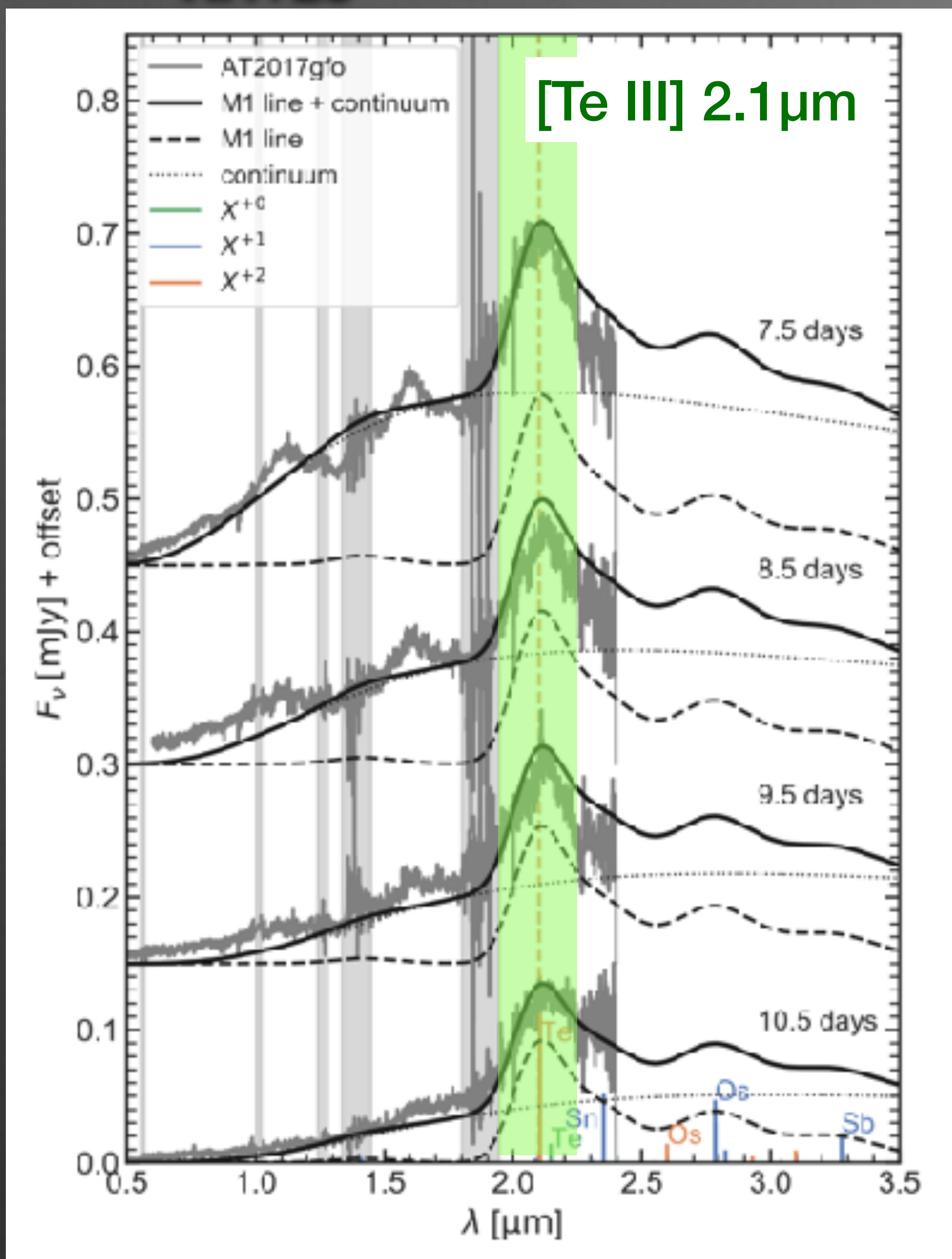
KH + 23, where the ejecta is assumed to be optically thin at ~10 days.

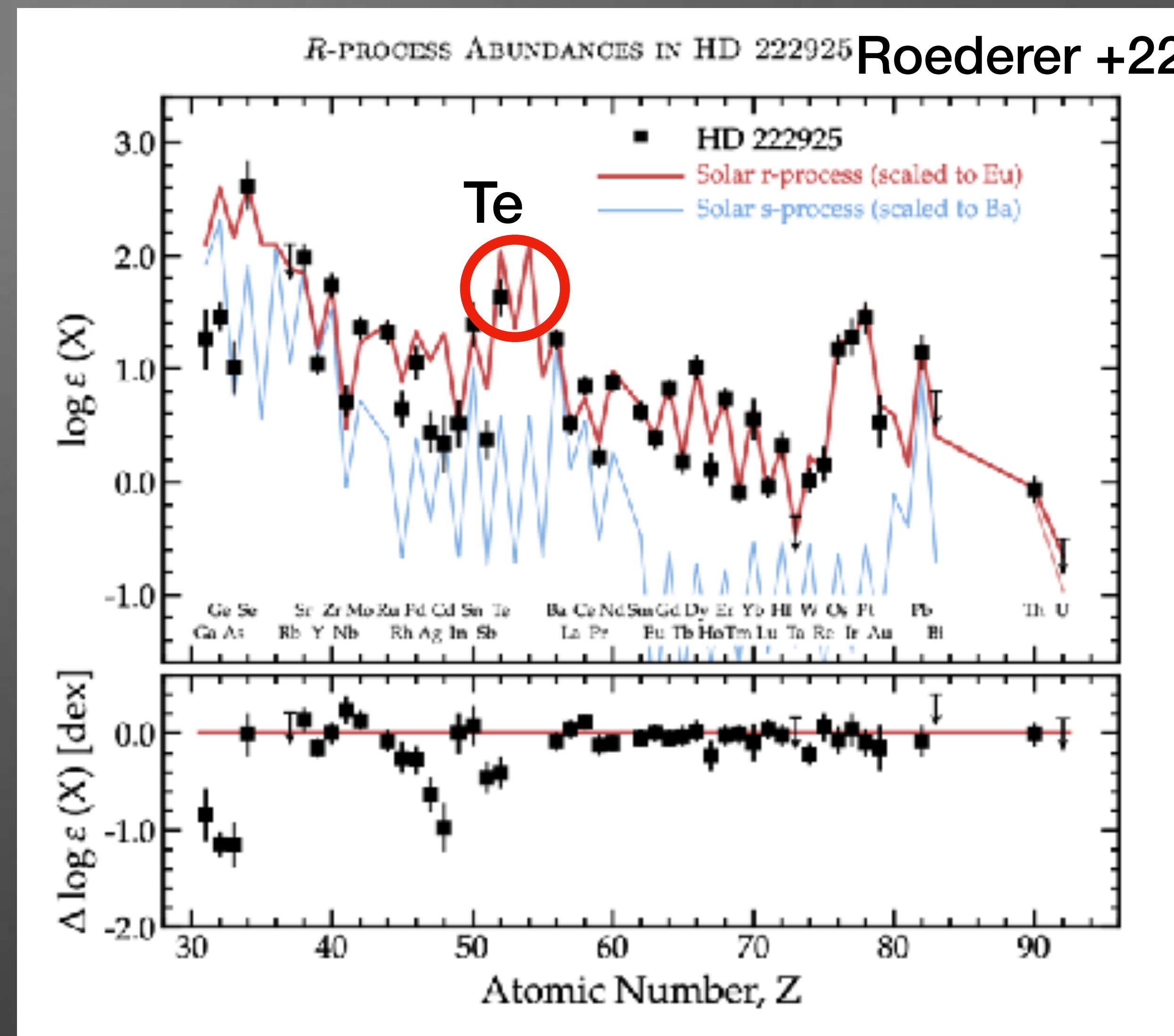


- The solar abundance (2nd - 3rd r-process peaks) is assumed. $X^{+1} = X^{+2} = 0.5$
- [Te III] 2.1μm is the strongest M1 line.

[Te III]2.1μm line in the kilonova AT2017gfo

KH+23





Terese's talk

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

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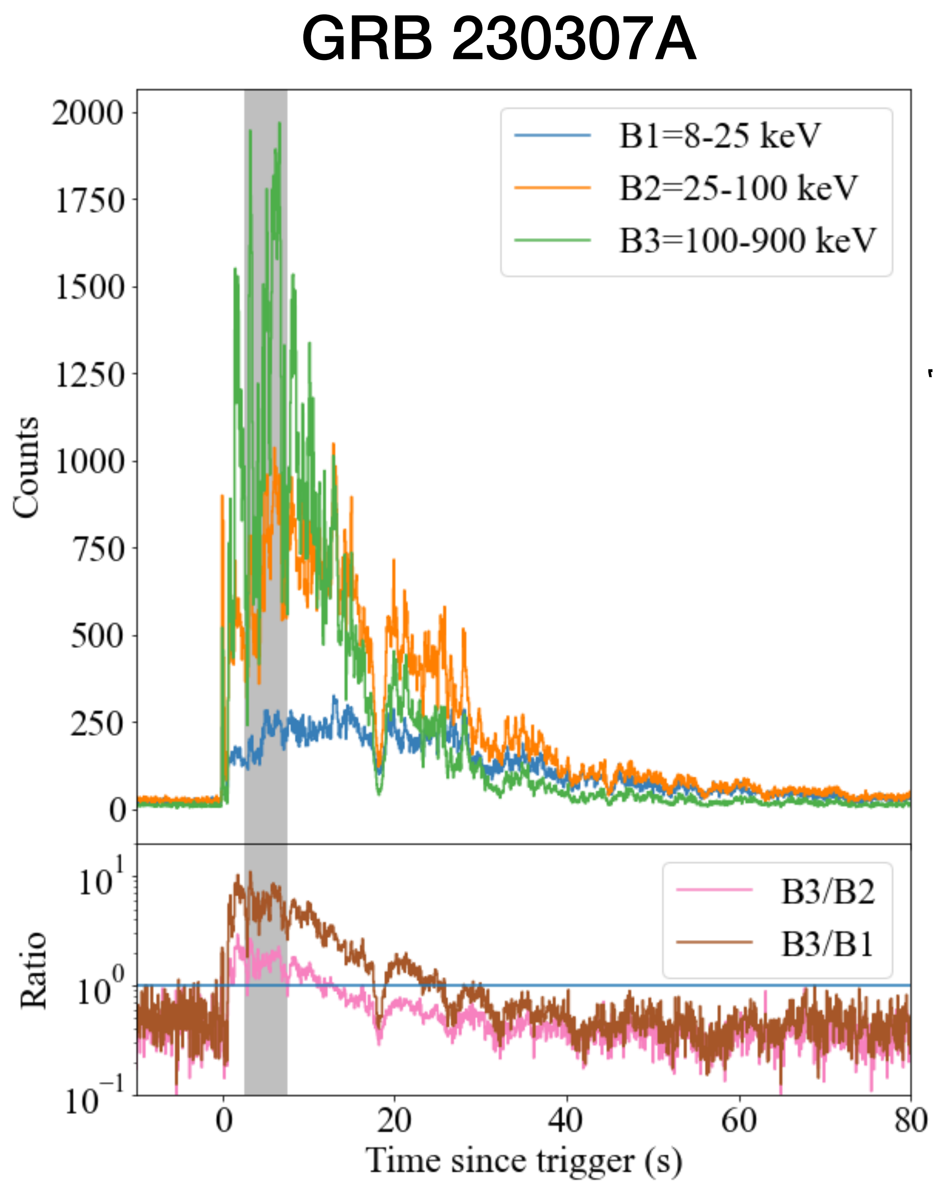
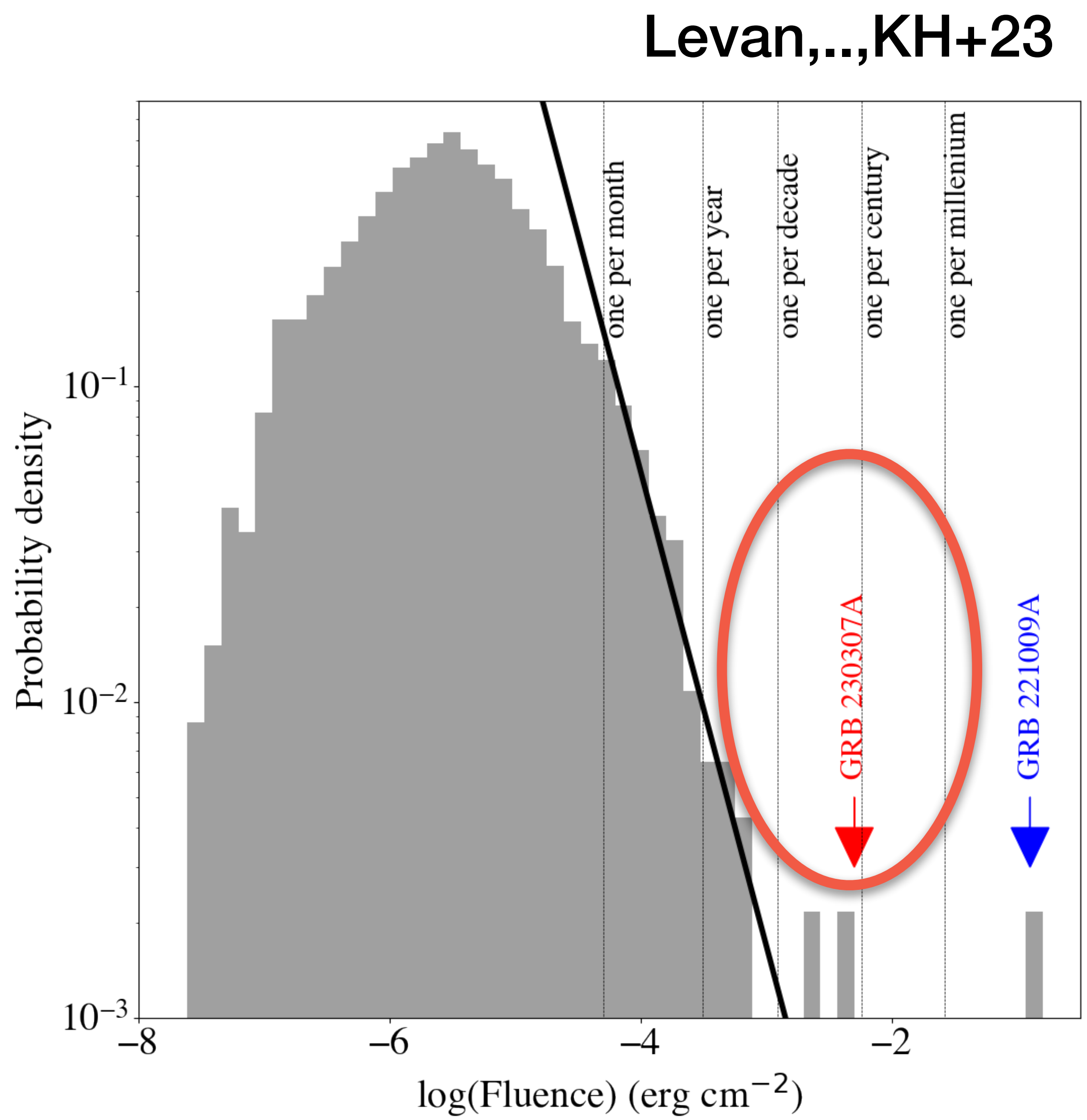
An extremely bright GRB 230307A



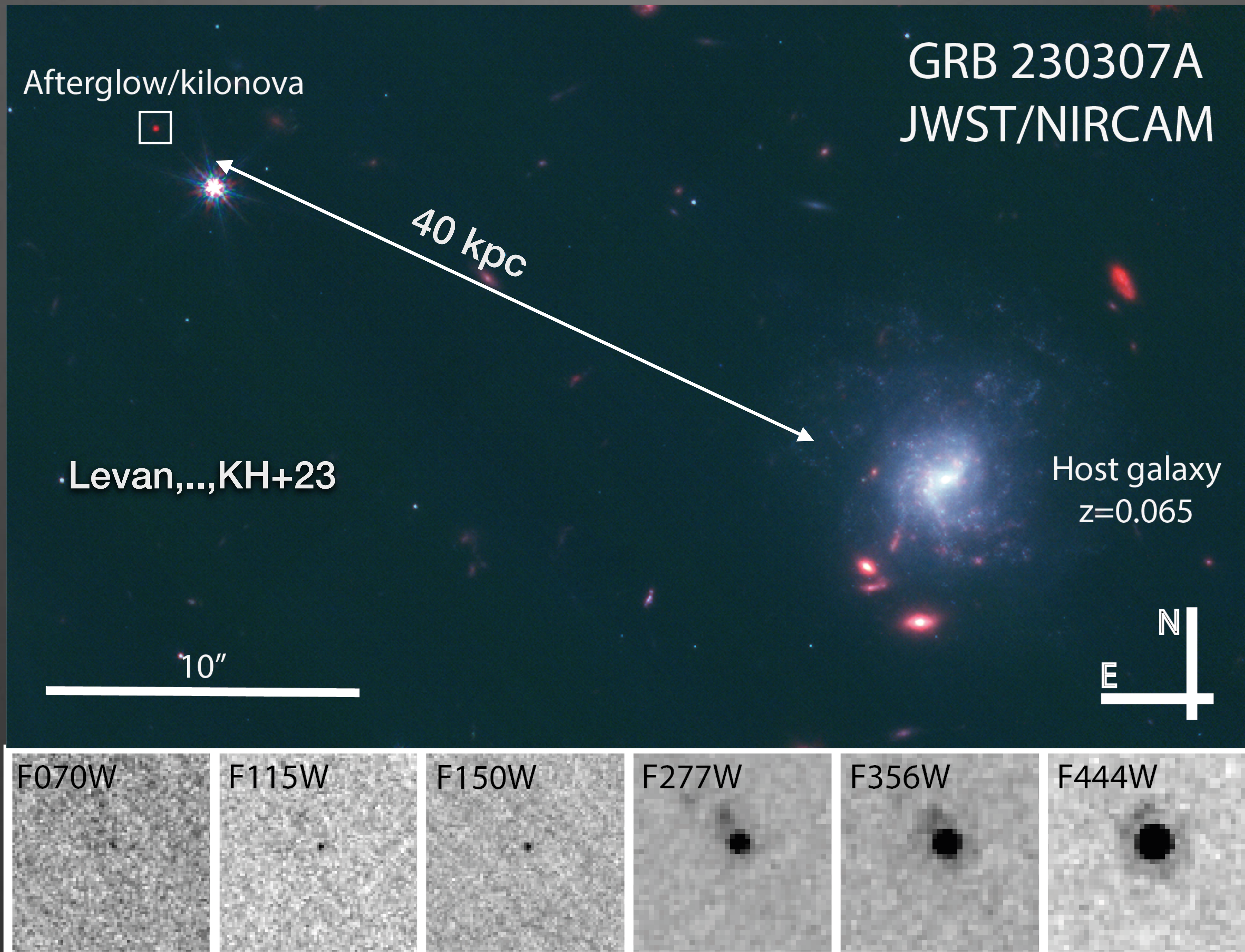


- T_{90} ~ 35 s : Typical long GRB.
- The 2nd brightest GRB.
- LIGO/Virgo/KAGRA were not in operation.

Remarks on GRB 230307A

- The 1st JWST observation of a kilonova candidate.
- One of the nearest GRBs but the afterglow was very faint.
- A long GRB associated with a kilonova candidate.

GRB 230307A: JWST NIRCam Image



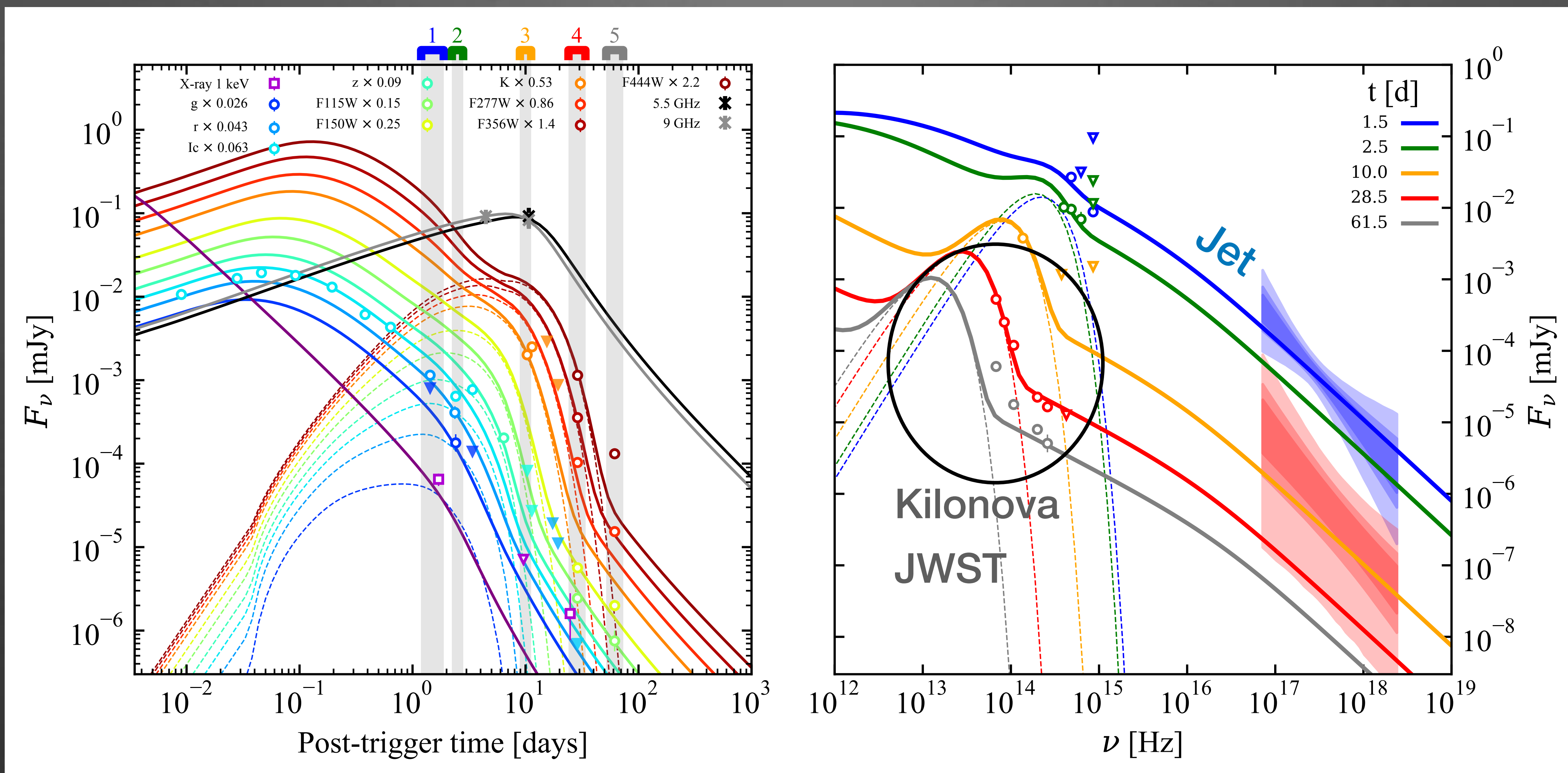
- The most probable host ~ 300Mpc, large off-set ~ 40 kpc
- The large off-set rules out the collapsar scenario.

GRB 230307A and JWST photometry

Levan,..KH+23

Afterglow+Kilonova light curve

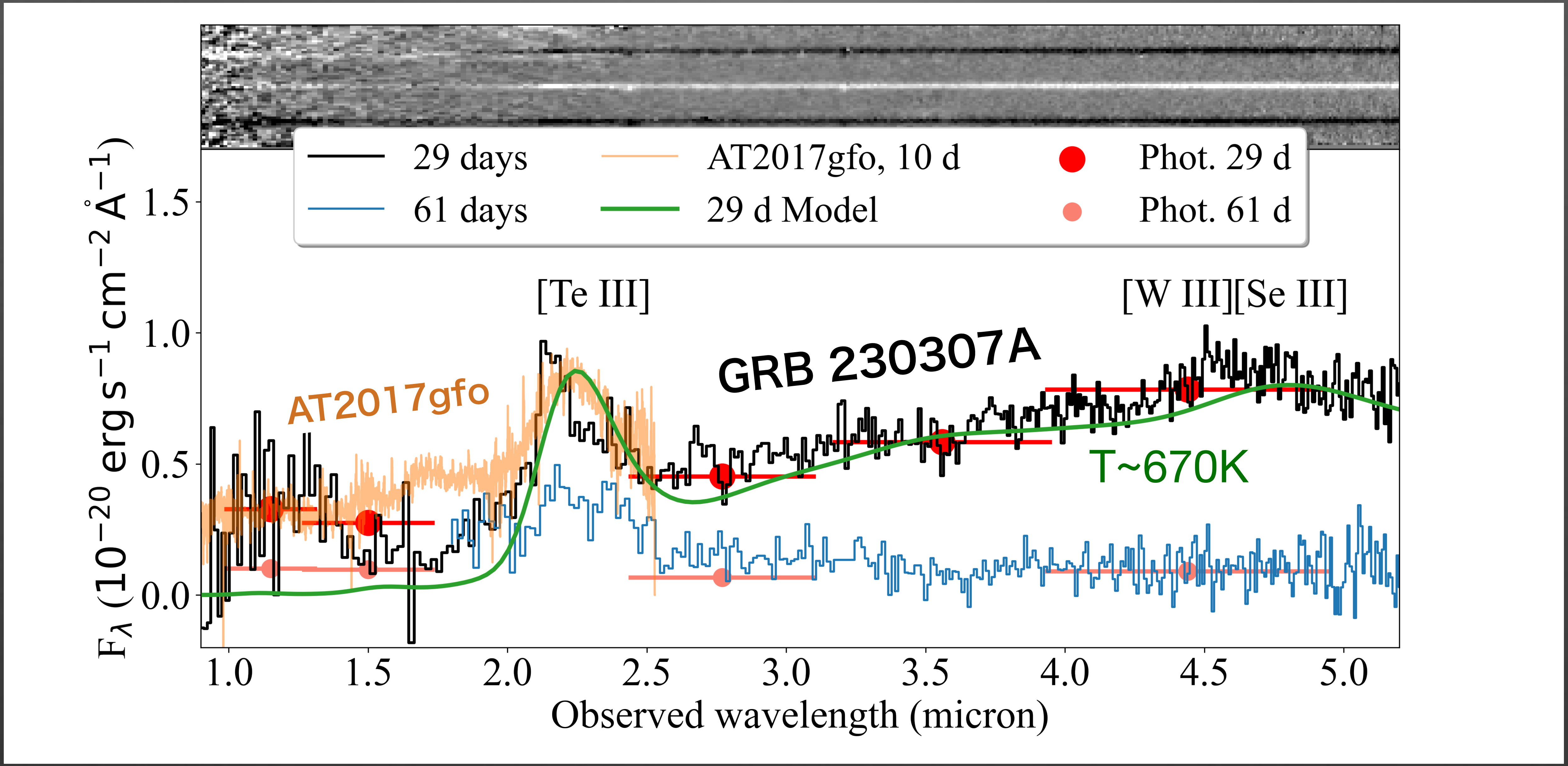
Afterglow+Kilonova SED



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

JWST Spectrum of the KN candidate 230307A

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



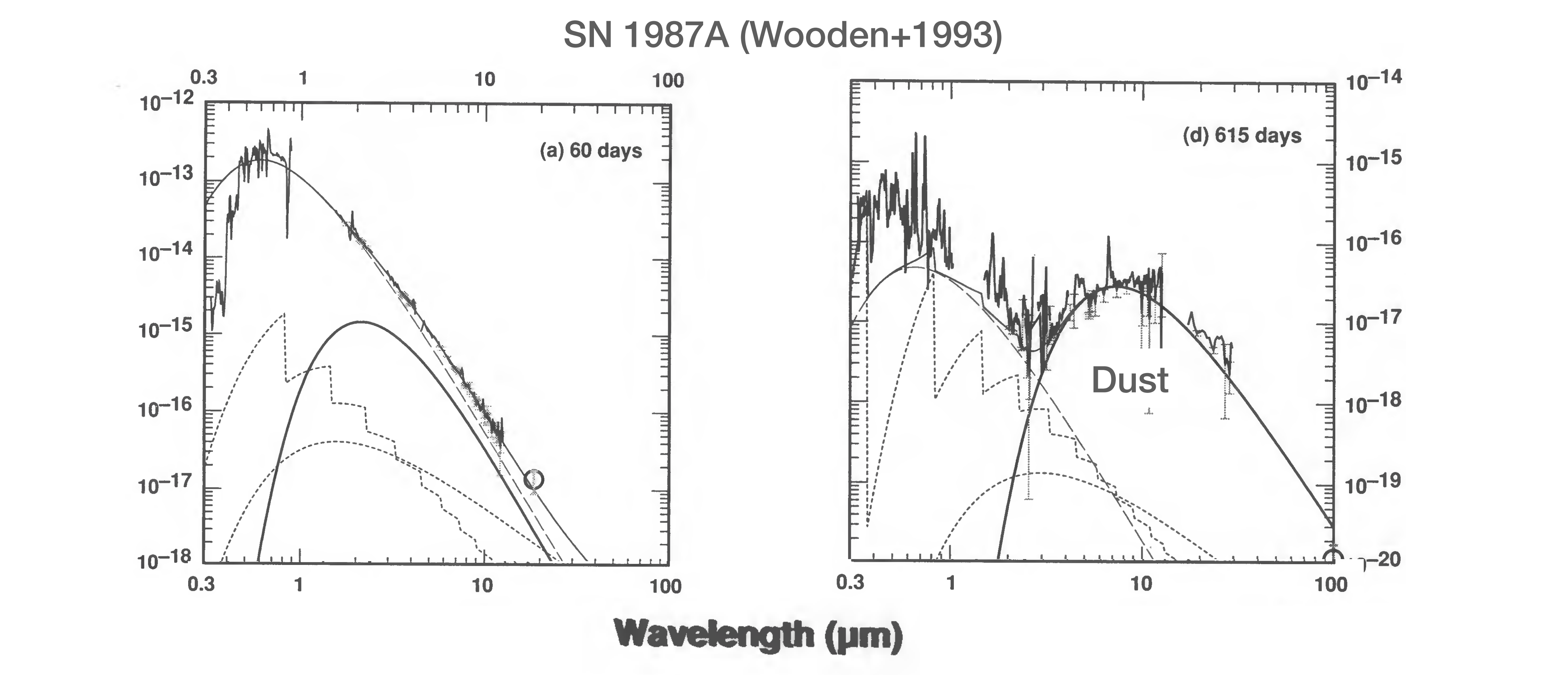
- An emission line feature around 2.1 μm is consistent with [Te III] 2.1μm.
- If correct, M(Te III)=$10^{-3}M_{sun}$ and v_{exp} =0.08c.
- The total r-process mass ~ $0.05M_{sun}$. (~ GW170817)

A mysterious IR bump (5μm)

- The IR bump (5μm) and 2.1 um emission require two temperatures, electrons: ~2000K and IR photons: ~700K.
- Curiously, a similar IR bump was detected by Spitzer at 45 days in GW170817.

A mysterious IR bump (5μm)

- The IR bump (5μm) and 2.1 um emission require two temperatures, electrons: ~2000K and IR photons: ~700K.
- Curiously, a similar IR bump was detected by Spitzer at 45 days in GW170817.
    - Actinide optical property, which we haven't understood?
    - R-process dust?



Conclusion

- The P-Cygni line features in AT2017gfo are attributed to Sr II or He I. He I may contribute significantly at later times.
- An emission line feature at 2.1μm is consistent with [Te III] 2.1μm. Te is a second r-process peak element.
- The optical-IR emission of the long GRB 230307A (1-30 days) is strikingly similar to the kilonova AT2017gfo.
- An emission line in the JWST spectrum around 2.1μm may be [Te III].
- A mysterious IR bump peaking at 5μm suggests a missing IR opacity, which may be actinides or r-process dust.

Expected rate within 100 Mpc

see, Mandel & Broekgaarden 22 for a review.

GWTC3: 0.05 - 8 yr^{-1} (90% level)
(Abbott et al., 2021)

The merger hypothesis of r-process: 0.7 yr^{-1}
(e.g., KH et al., 18)

Galactic binary pulsars: 2^{+1}_{-1} yr^{-1}
(e.g., Kim et al., 15, Pol et al 19)

Short GRBs (θ_{jet}~10^{o}): $0.5^{+0.5}_{-0.3}$ yr^{-1}
(e.g., Wanderman & Piran 14, see also Ghirlanda et al., 16)