中性子星合体におけるR過程元素合成

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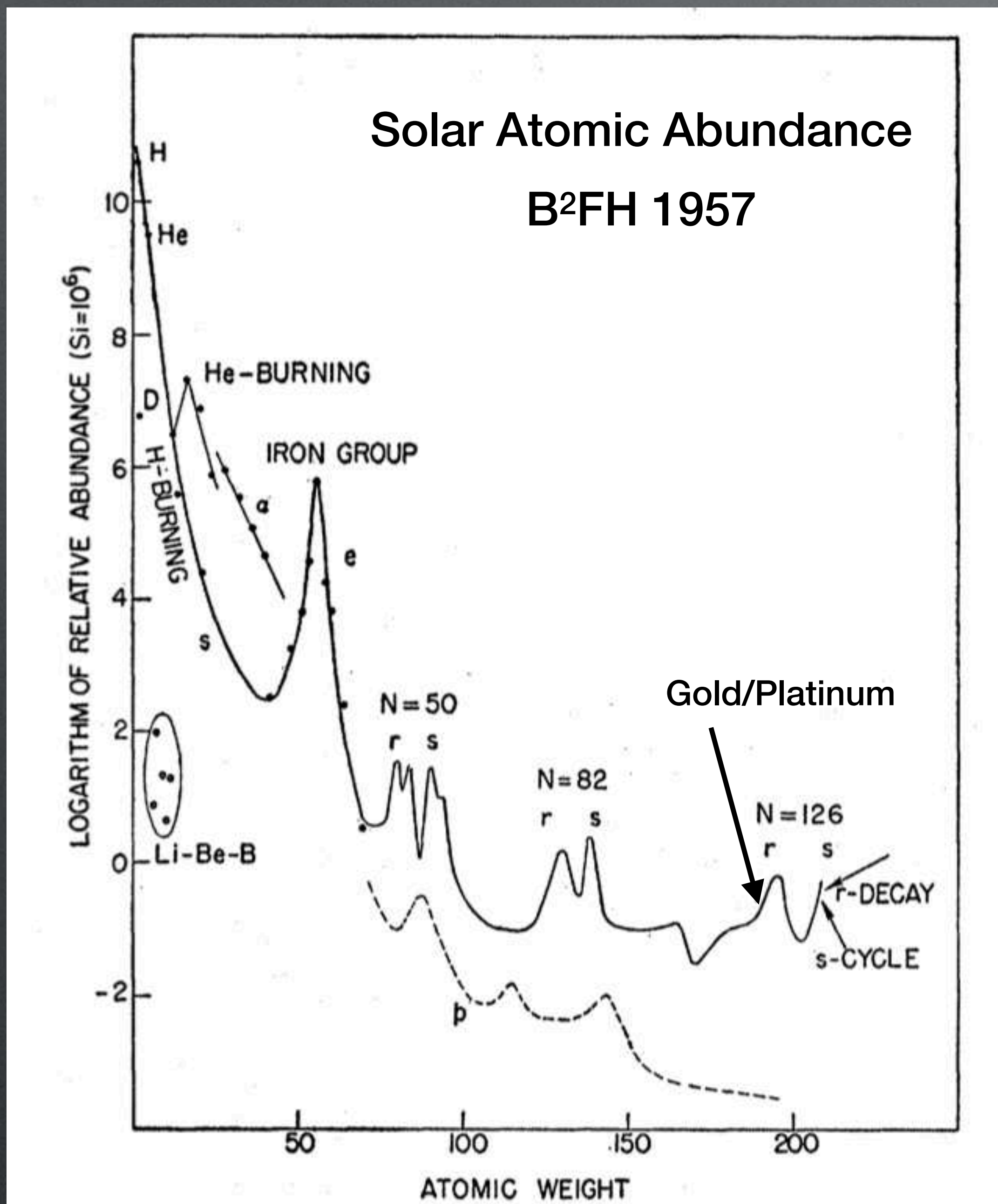
Neutron Star Merger: heavy element factory

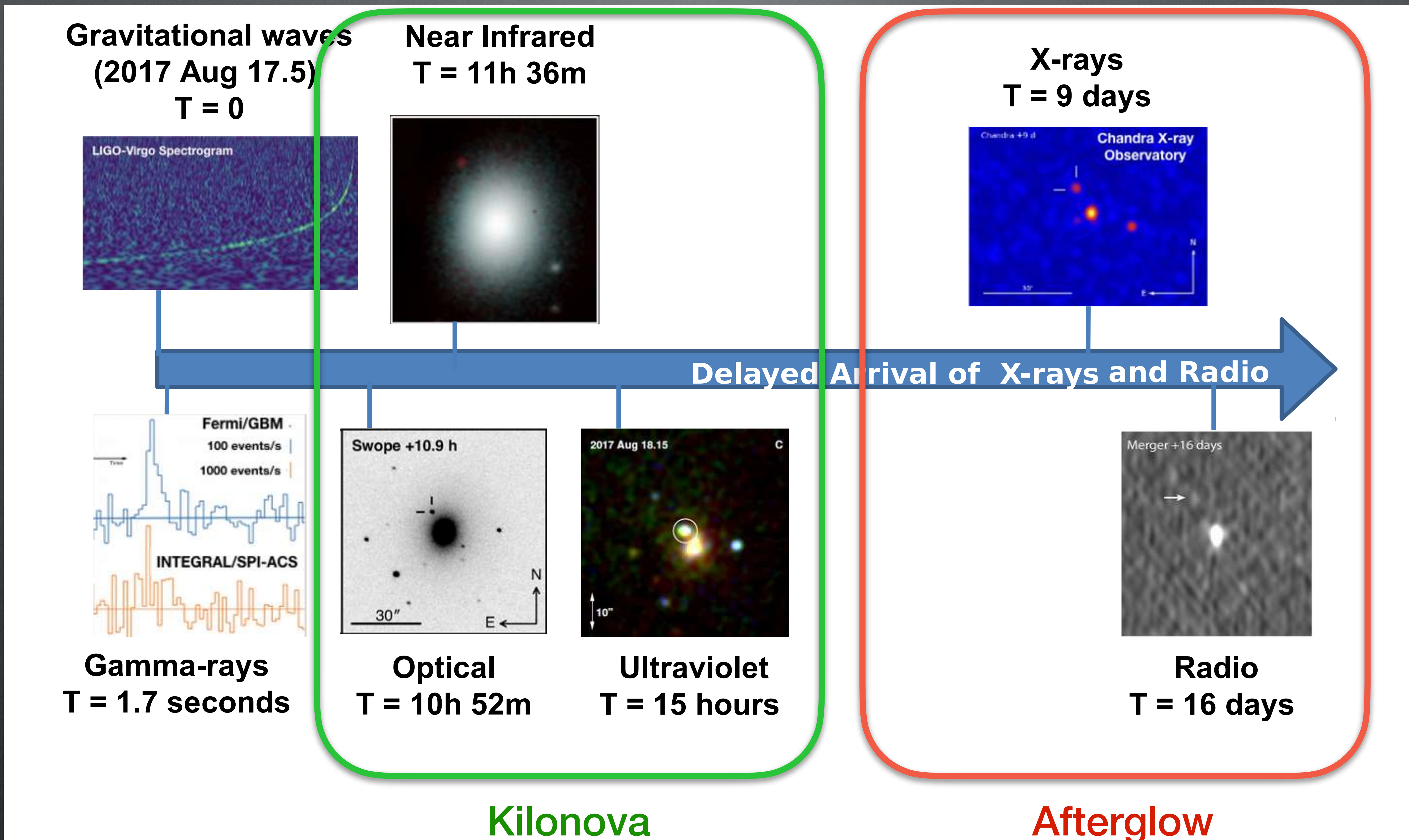


- Heavy elements (>the iron peak) are produced via neutron capture processes, (r)apid or (s)low process (B2FH 57, Cameron 57).
- The origin of r-process elements is still a mystery in astrophysics.
- The leading scenarios are core-collapse supernovae and neutron star mergers (Lattimer & Schramm 74).
- Metal poor stars & dwarf galaxies suggest that the r-process events must be rare (e.g. Ji et al 2015): r-process rate << supernova rate.

（この後、垂水さん）

- A kilonova in GW170817 reveals that mergers produce some r-process elements.

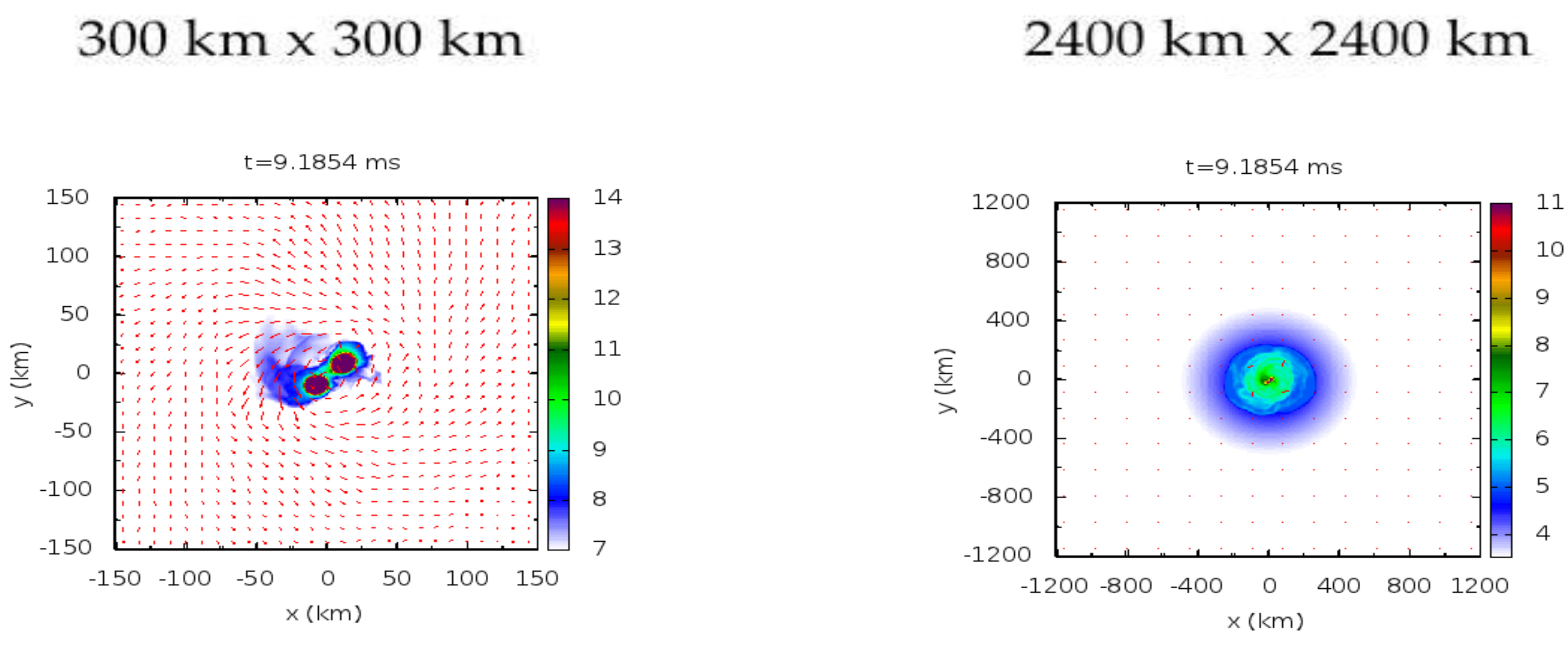
The first neutron merger in 2017 and its Electromagnetic (EM) counterparts



Abbott et al., ApJL. 848, L12 (2017)

Dynamical Ejecta in Merger

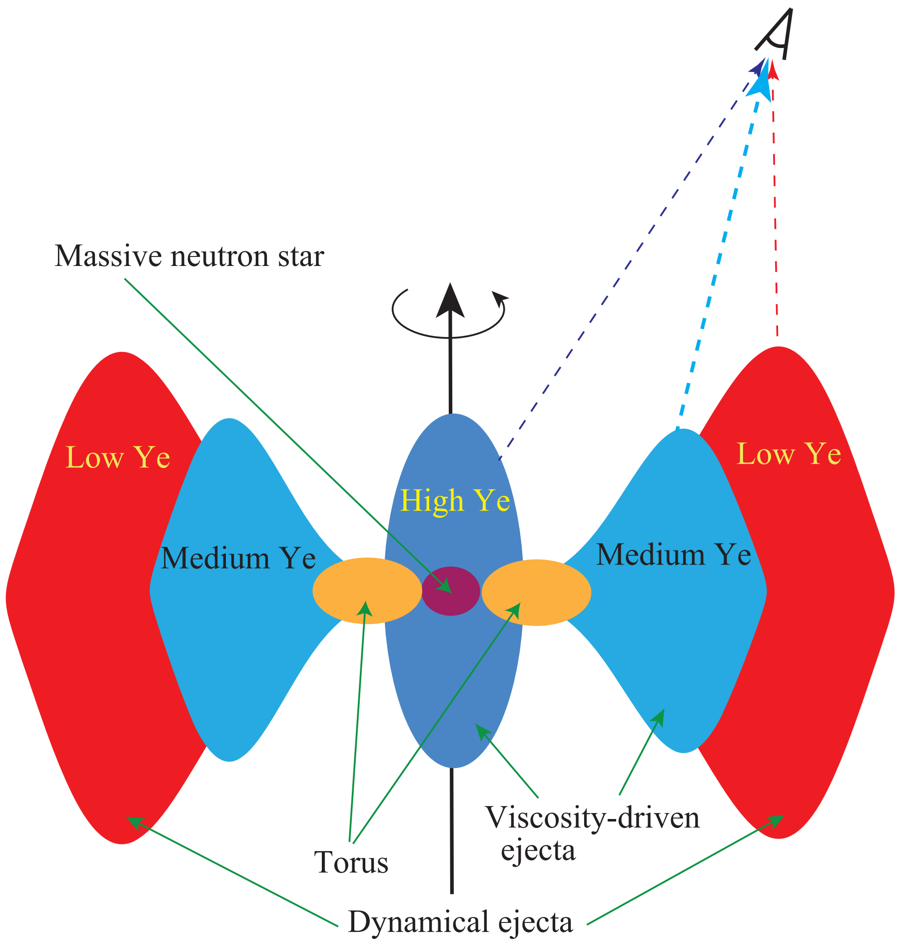
KH + 13



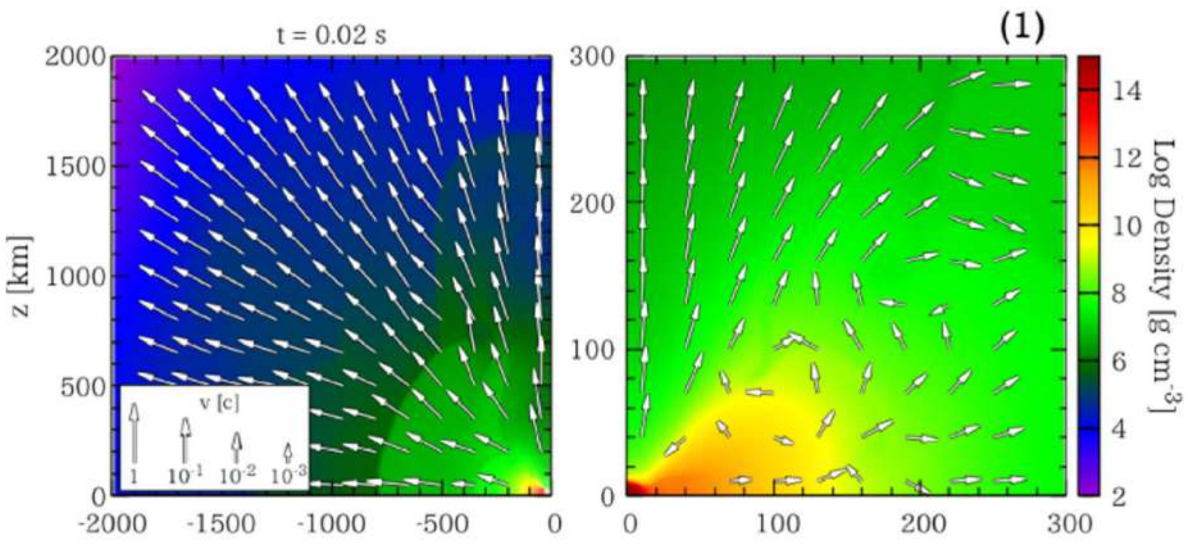
- Dynamical ejecta mass ~ $0.01M_{sun}$, v~0.2-0.8c driven by tidal force and shock heating.
- E~10^{51} erg, resulting in EM emission.

also Baustein + 13, Piran + 13, Rosswog 2013, Kyutoku+15, Sekiguchi + 15, 16, Radice+16

Disk Outflow from the remnant



Shibata+17, Fujibayashi+18

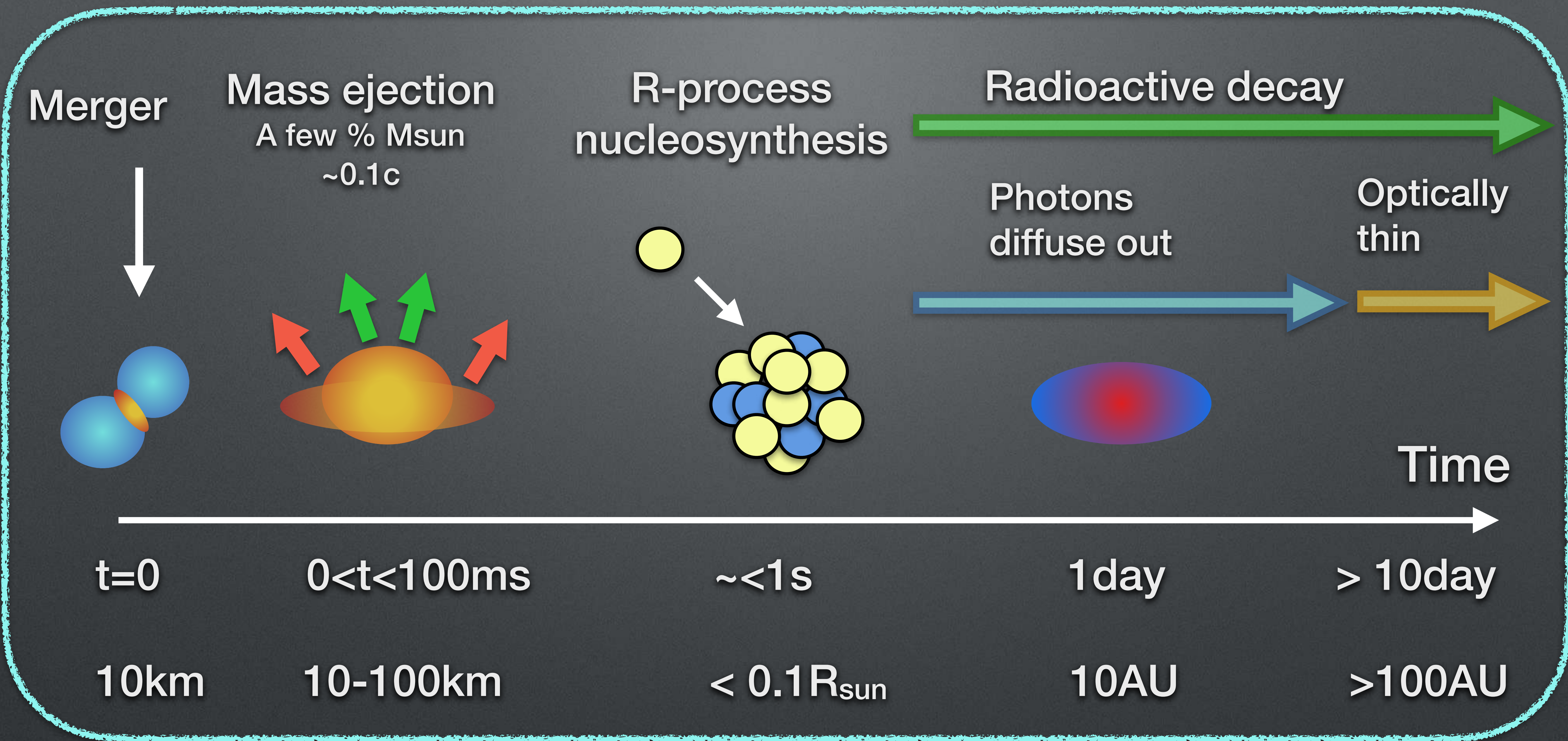


also Baustein + 13, Piran + 13, Rosswog 2013, Kyutoku+15, Sekiguchi + 15, 16, Radice+16

- Disk ejecta mass can be ~ $0.05M_{sun}$, but slower v~0.1c.
- In total, a few % Msun and E~10^{51} erg, resulting in EM emission.

Kilonova

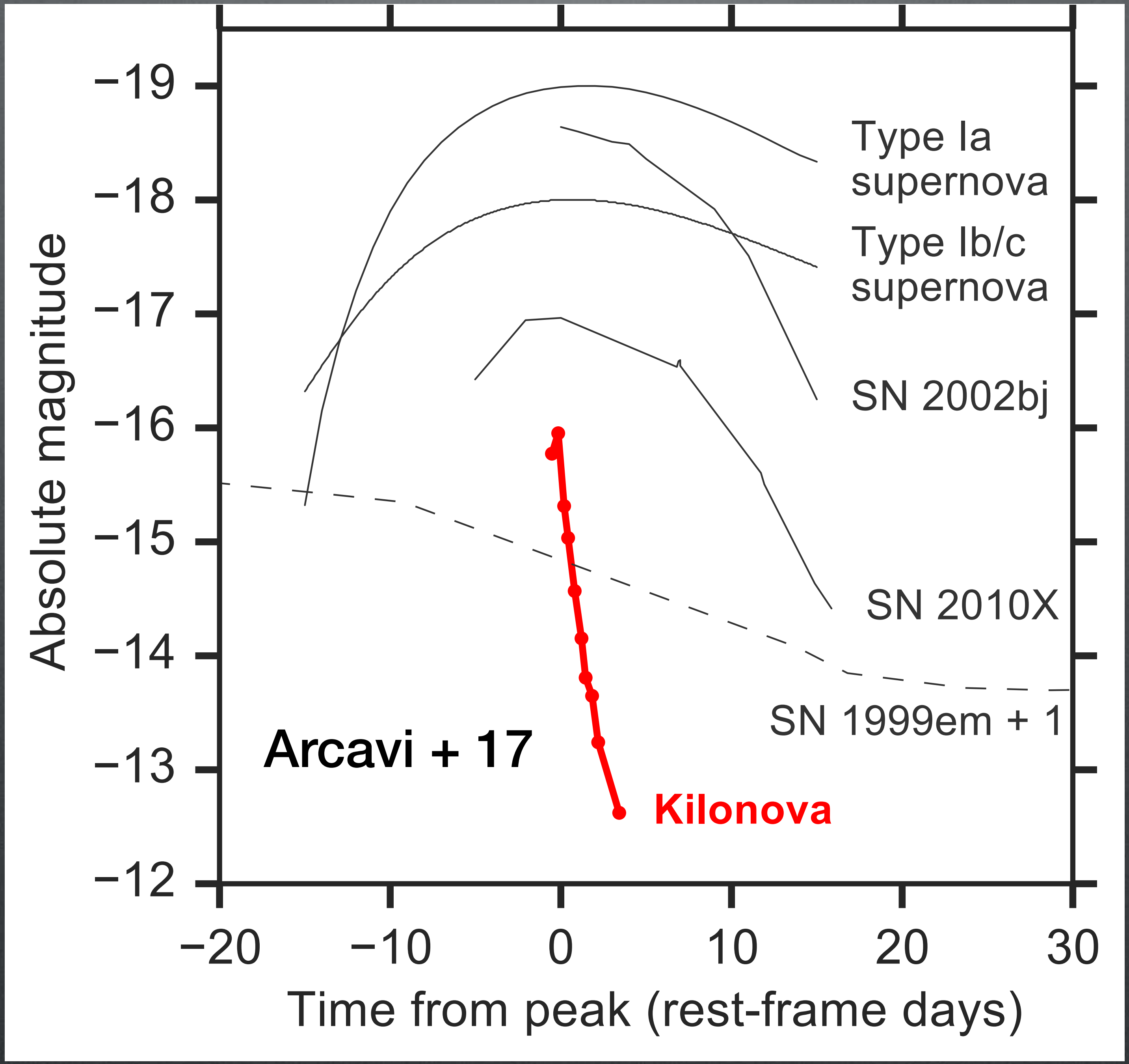
Li & Paczynski 98, Kulkarni 05, Metzger + 10, Barnes & Kasen 13, Tanaka & KH 13



- 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).

A Kilonova in GW170817

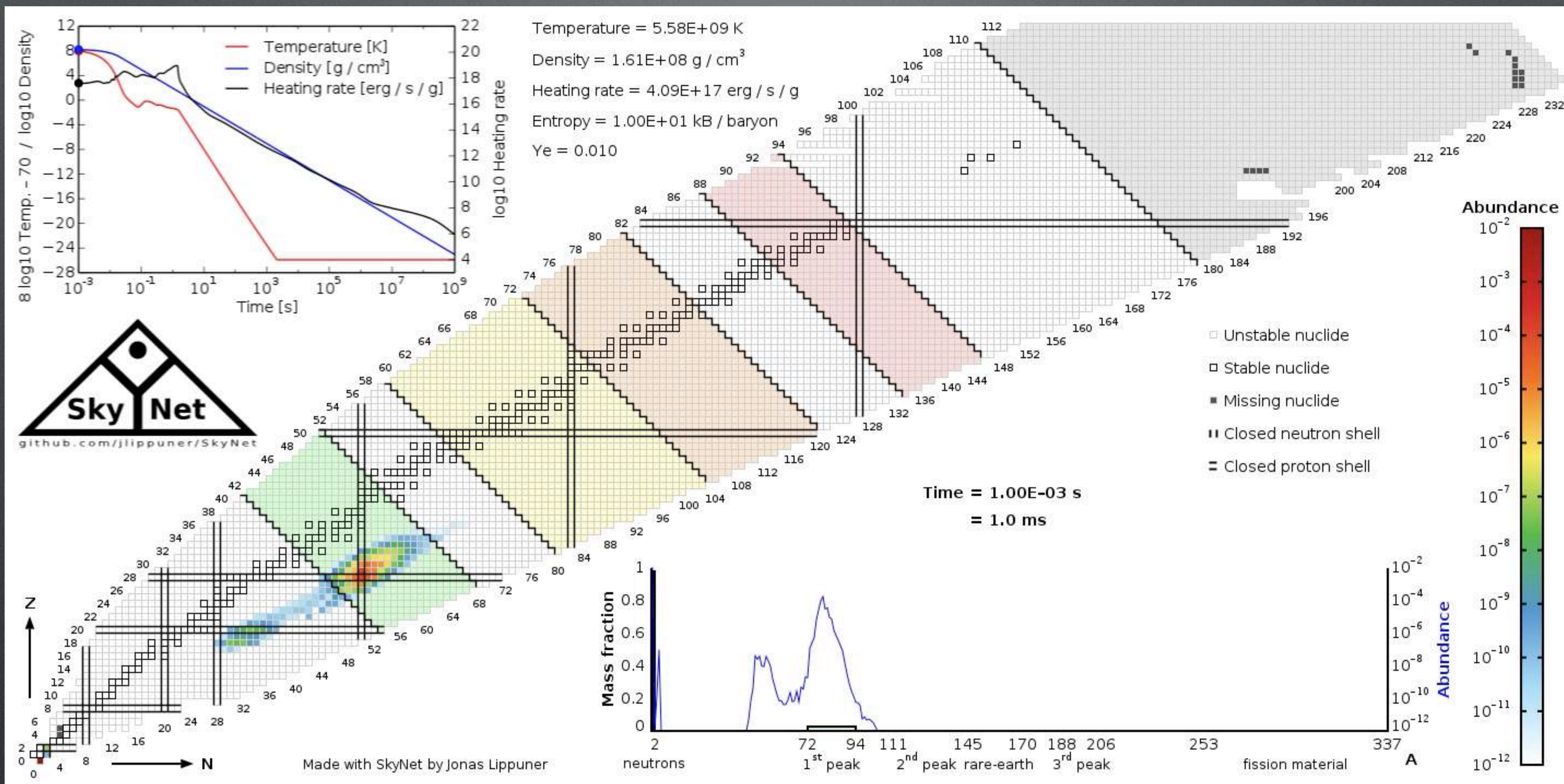
Arcavi+17, Coulter+17, Lipunov+17, Soares-Santos+17, Tanvir+17, Valenti+17, Kasliwal+17,Drout+17, Evans+17, Utsumi+17



The kilonova is much fainter and faster than supernovae.

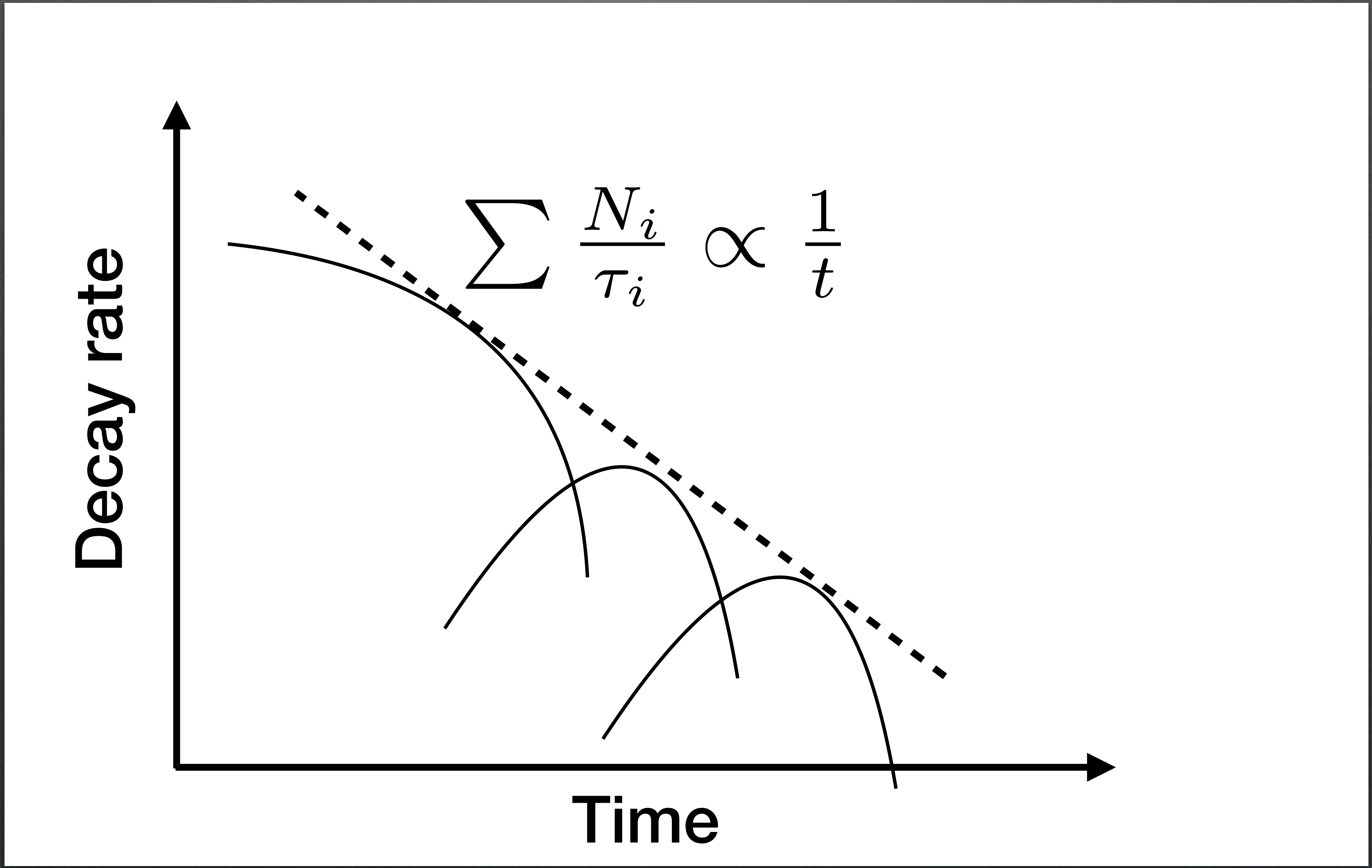
Knowing the merger times and locations from GW greatly helps to find kilonovae.

R-process Nucleosynthesis in merger ejecta



R-process heating

(Metzger et al 10, Goriely et al 11, Roberts et al 11, Korobkin et al 12, Wanajo et al 2014, Lippuner and Roberts 2015, KH, Sari, Piran 2017)



Simple estimate of heating

KH,Sari,Piran 17

- Many radioactive decay chains:

$$\frac{dN}{dt} \propto \frac{1}{t} \quad \longrightarrow \quad \dot{Q}(t) \propto \frac{E(t)}{t}$$

- A relation between the lifetime and decay energy:

$$\tau \propto E^{-5} \quad \longrightarrow \quad \dot{Q}(t) \propto t^{-1.2}$$

- Physical constants in beta decay:

Energy: $m_e c^2$

Time: $t_F \equiv \frac{2\pi^3}{G_F^2}\frac{\hbar^7}{m_e^5 c^4} \approx 9000 \text{ s}$

Heating rate per unit mass:

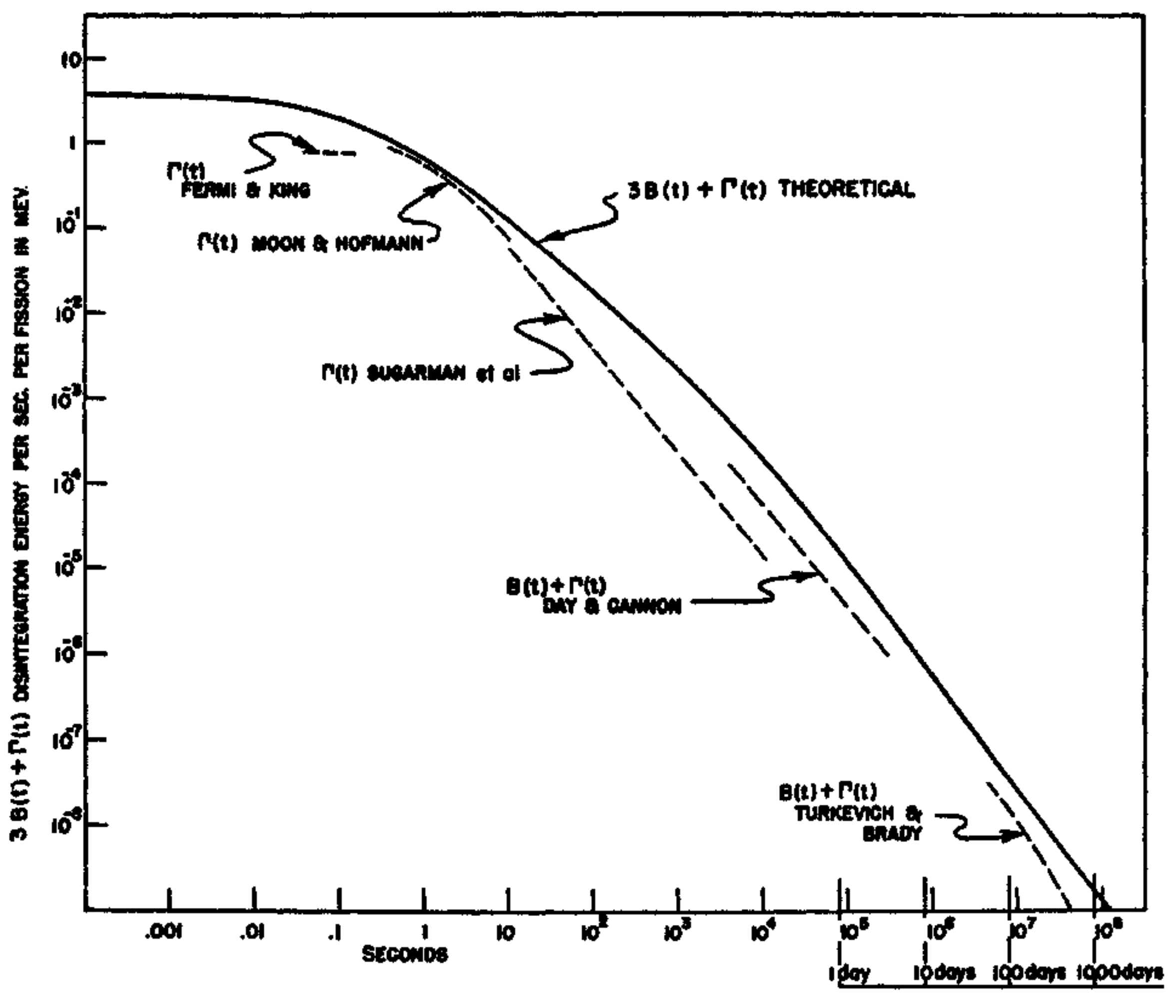
$$\longrightarrow \quad \dot{Q}(t) \sim \frac{1}{\langle M \rangle}\frac{m_e c^2}{t_F}\left(\frac{t}{t_F}\right)^{-1.2} \sim 10^{10} t_{\rm day}^{-1.2}\,{\rm erg/s/g}$$

Very similar to the nuclear network results.

Energy source: radioactive decay of many species

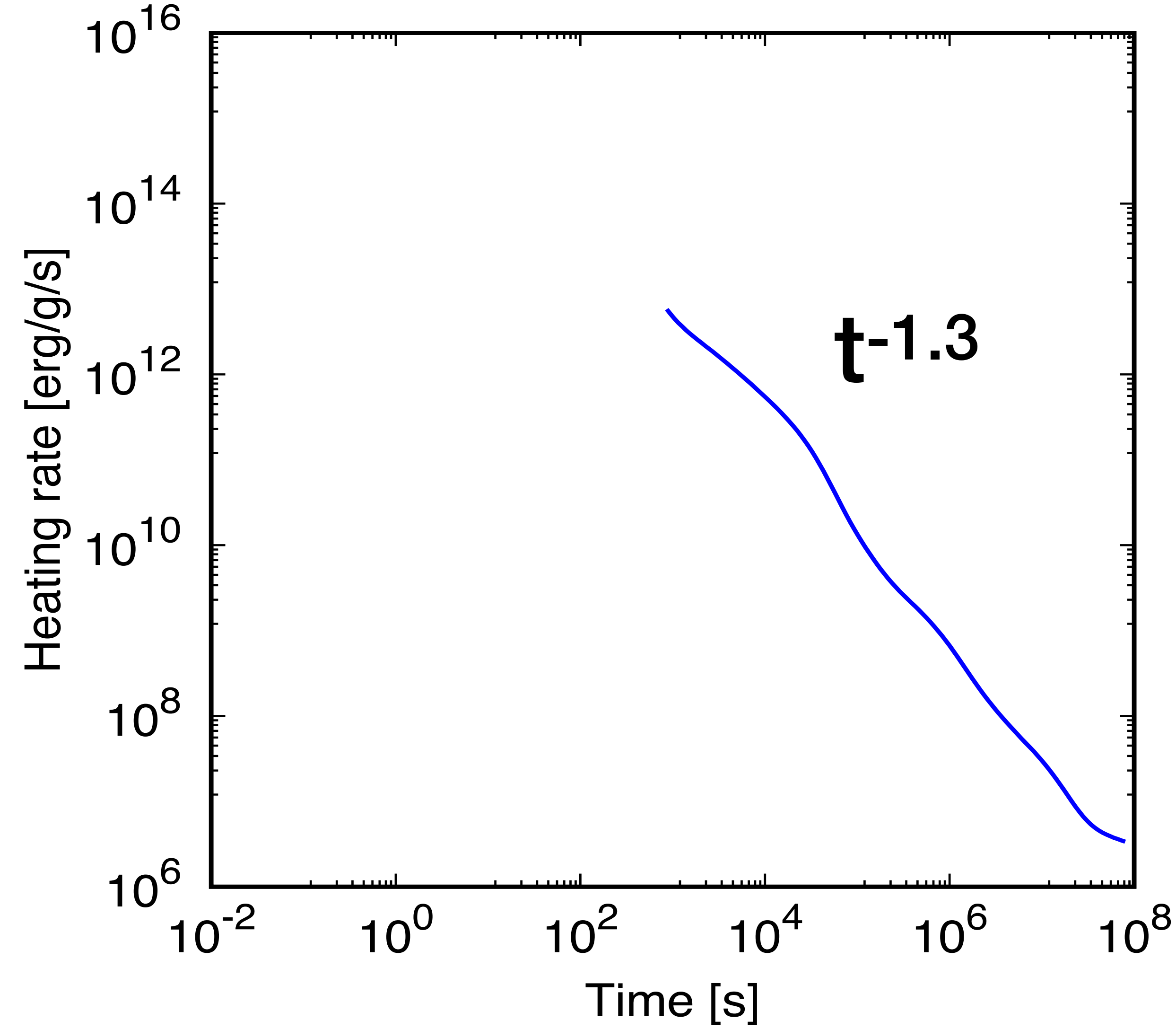
Way & Wigner 1948

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



(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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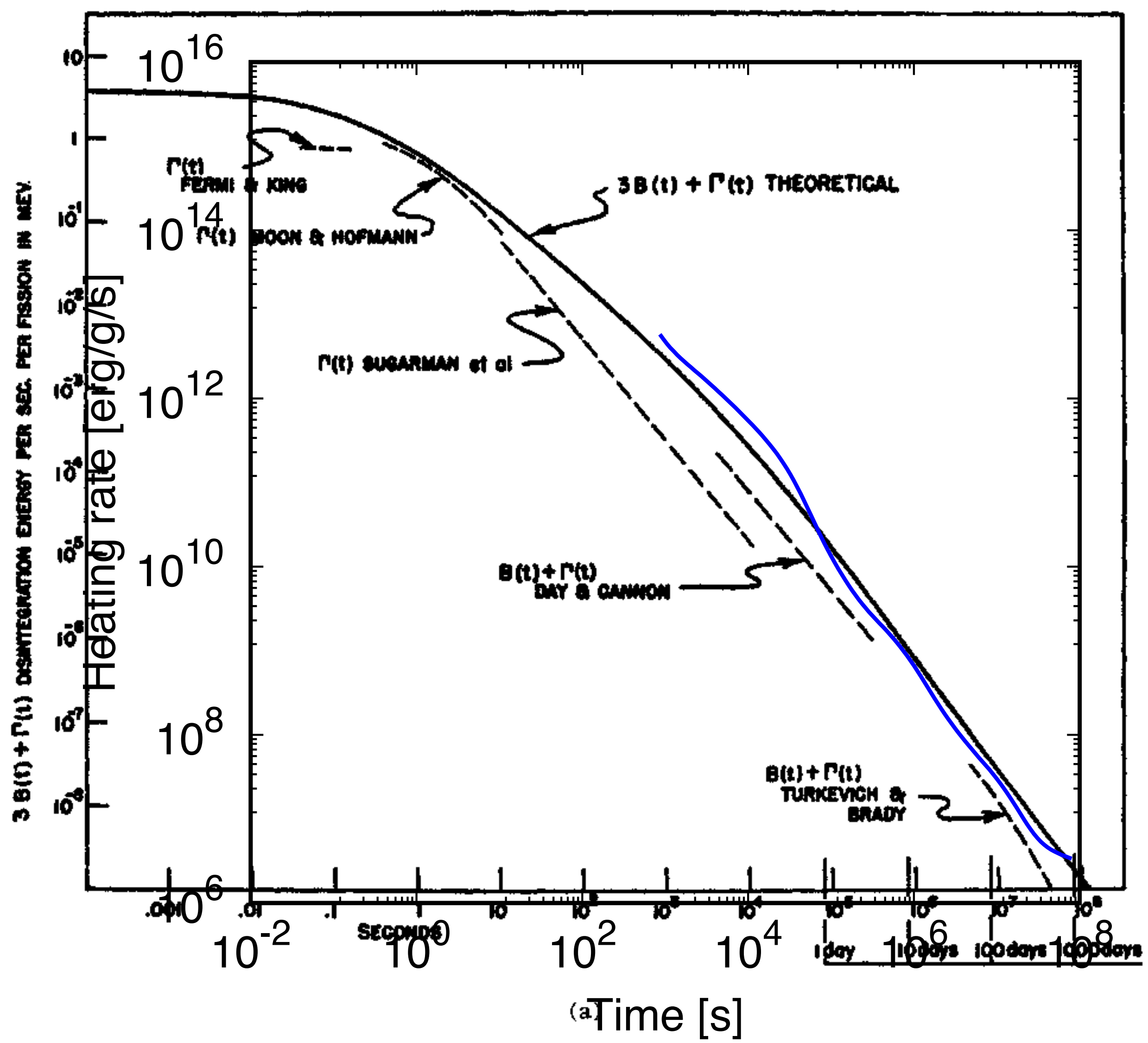
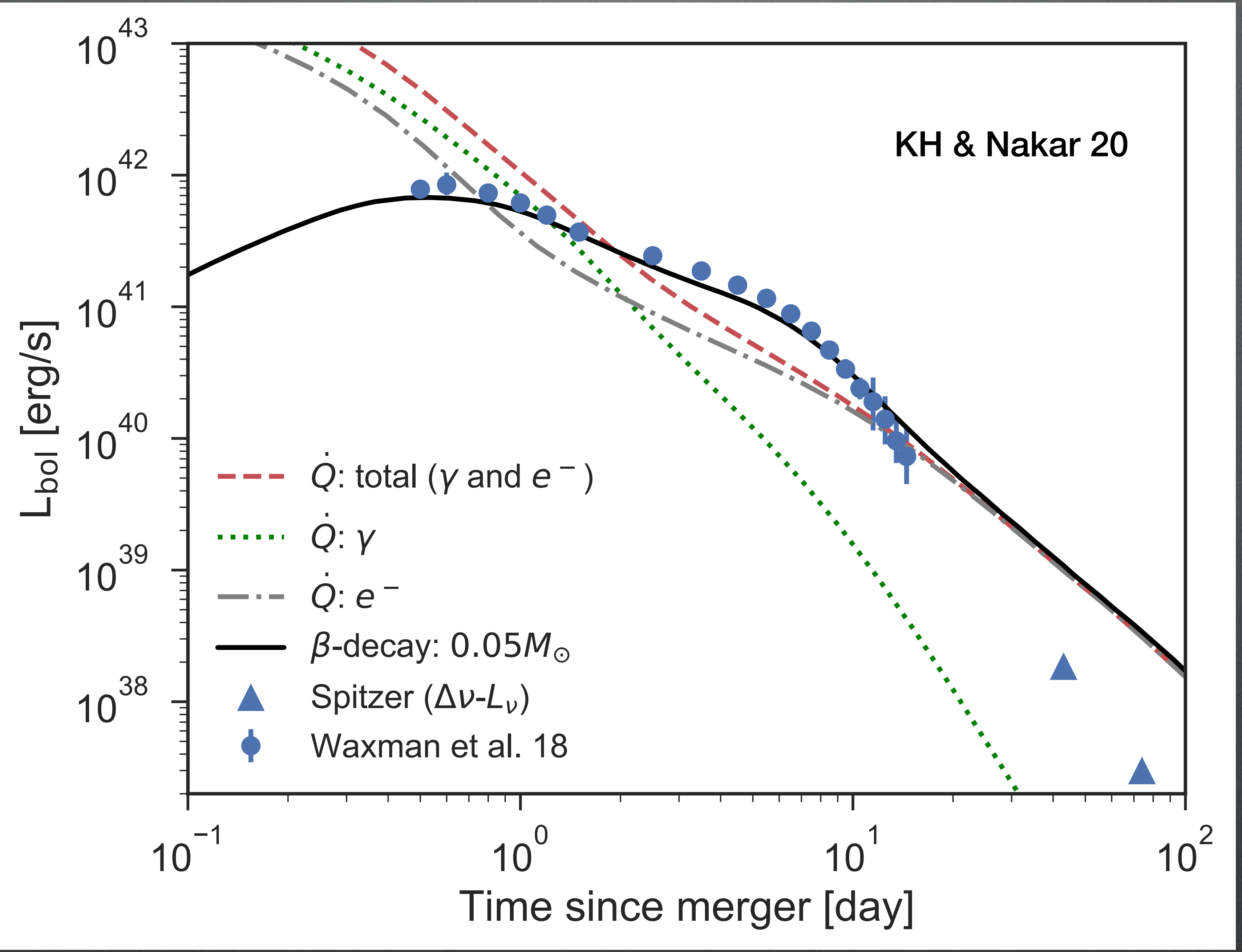


Heating rate of nuclear waste

Heating rate after r-process

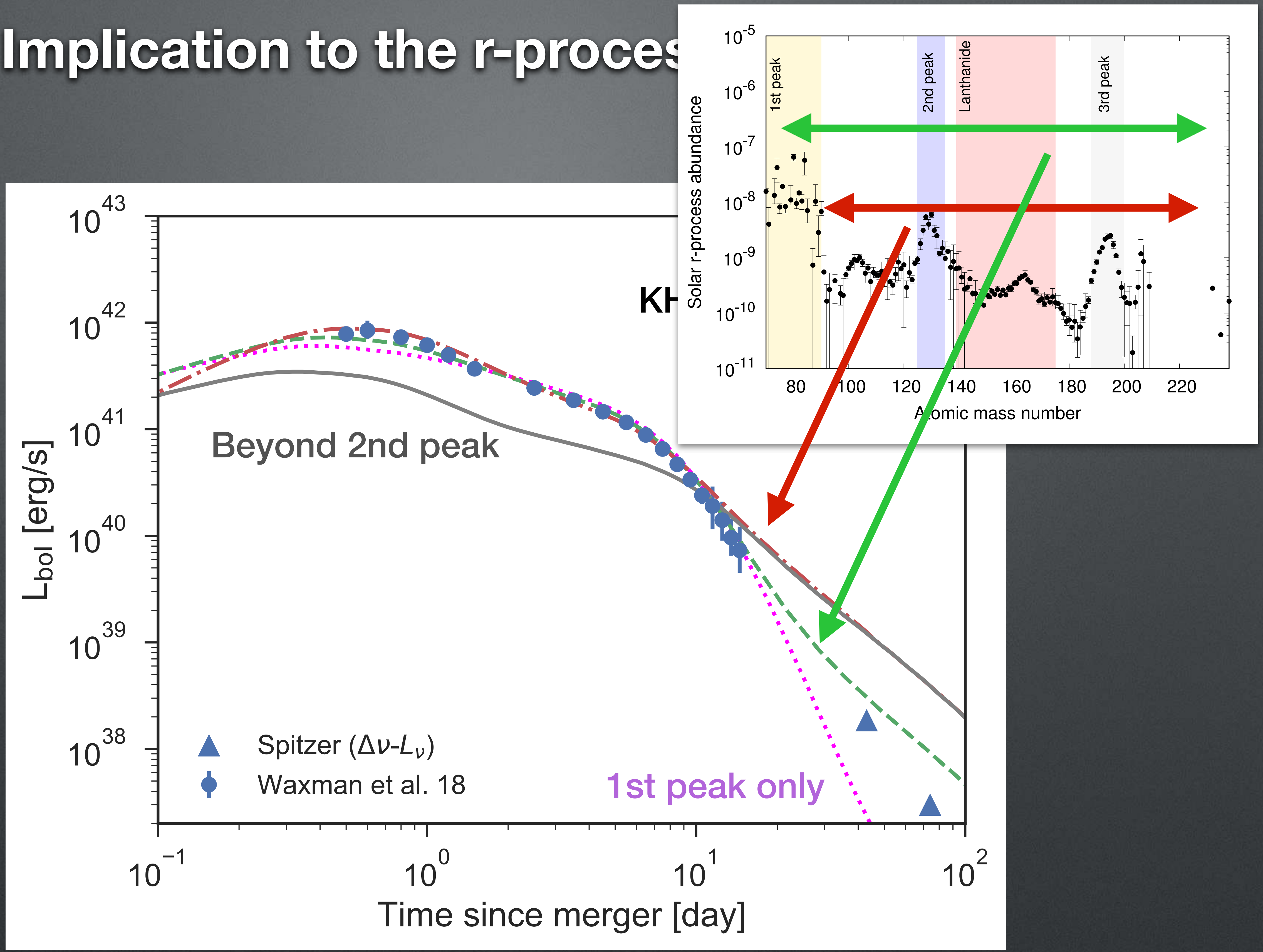
This is a unique properties of the heating rates of many beta-decay chains.

The energy budget of the Kilonova in GW170817



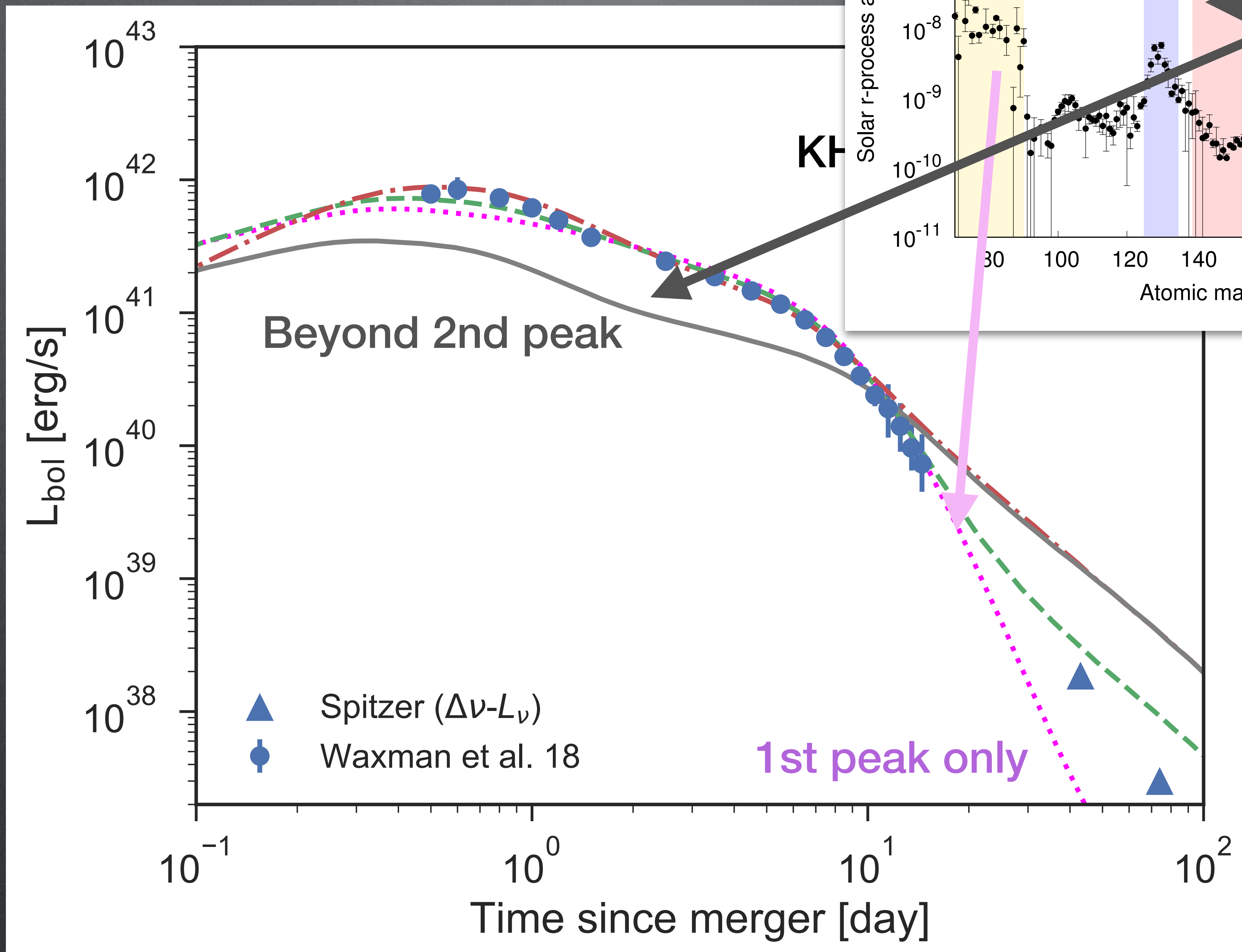
- The light curve follows the β-decay heating rate.
- Ejecta mass is~ 0.05Msun.
- The photospheric velocity ~0.1-0.3c.
- The photospheric temperature evolves T=5000K -> 2000K.

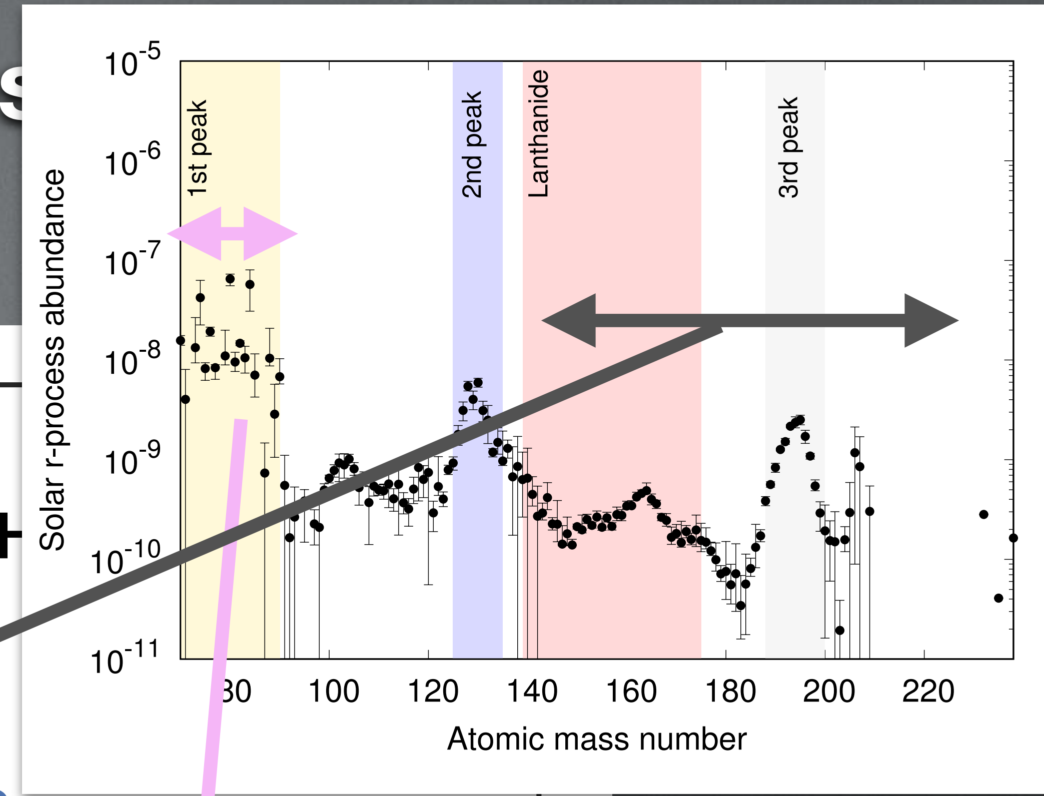
Implication to the r-process



As long as, the 2nd and 3rd elements are abundant, radioactivity can explain the energy budget.

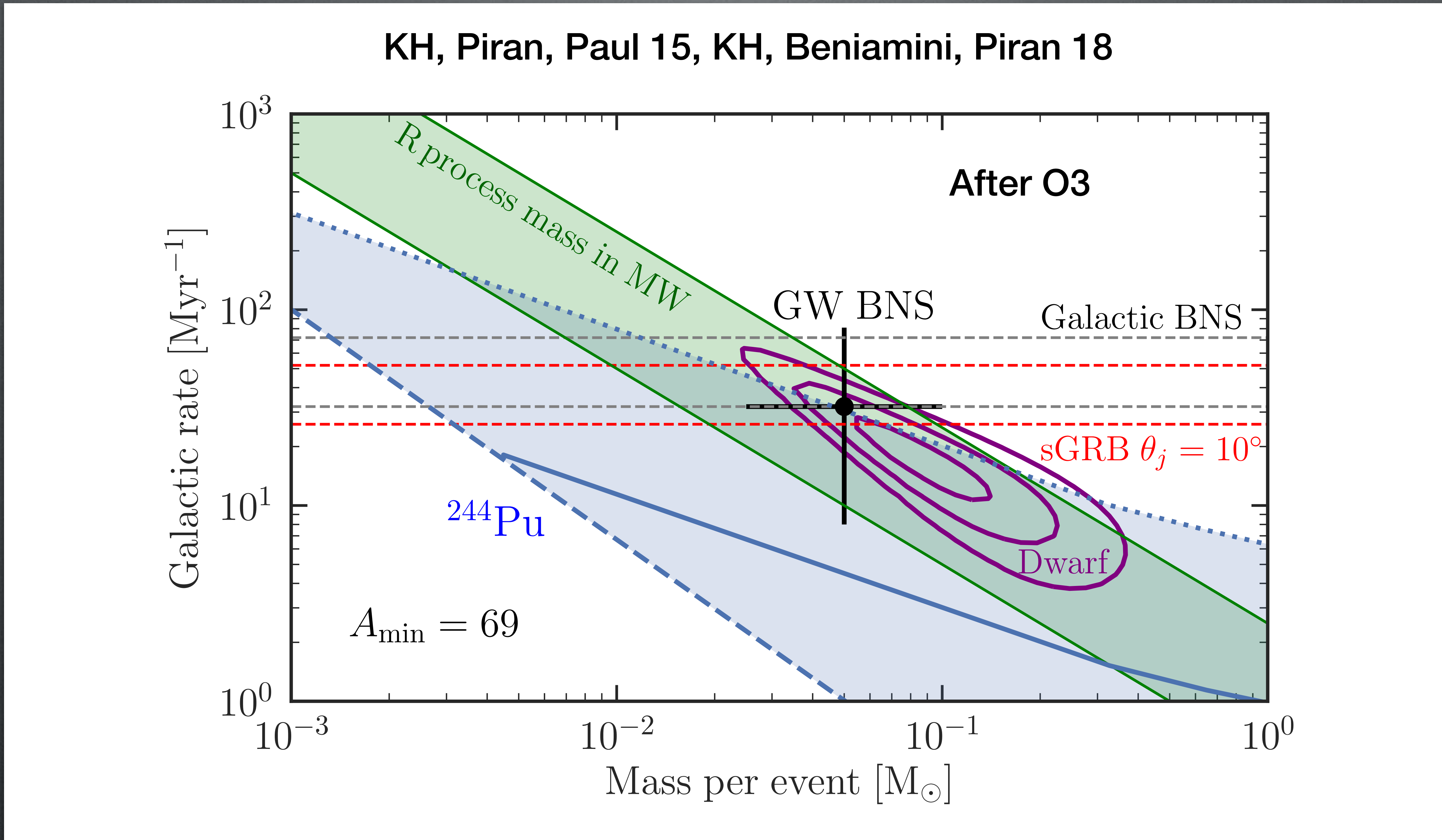
Implication to the r-proces





(i) the 1st peak only cannot explain the observation.
(ii) Beyond 2nd peak only also cannot.

R-process mass budget from GWTC-2

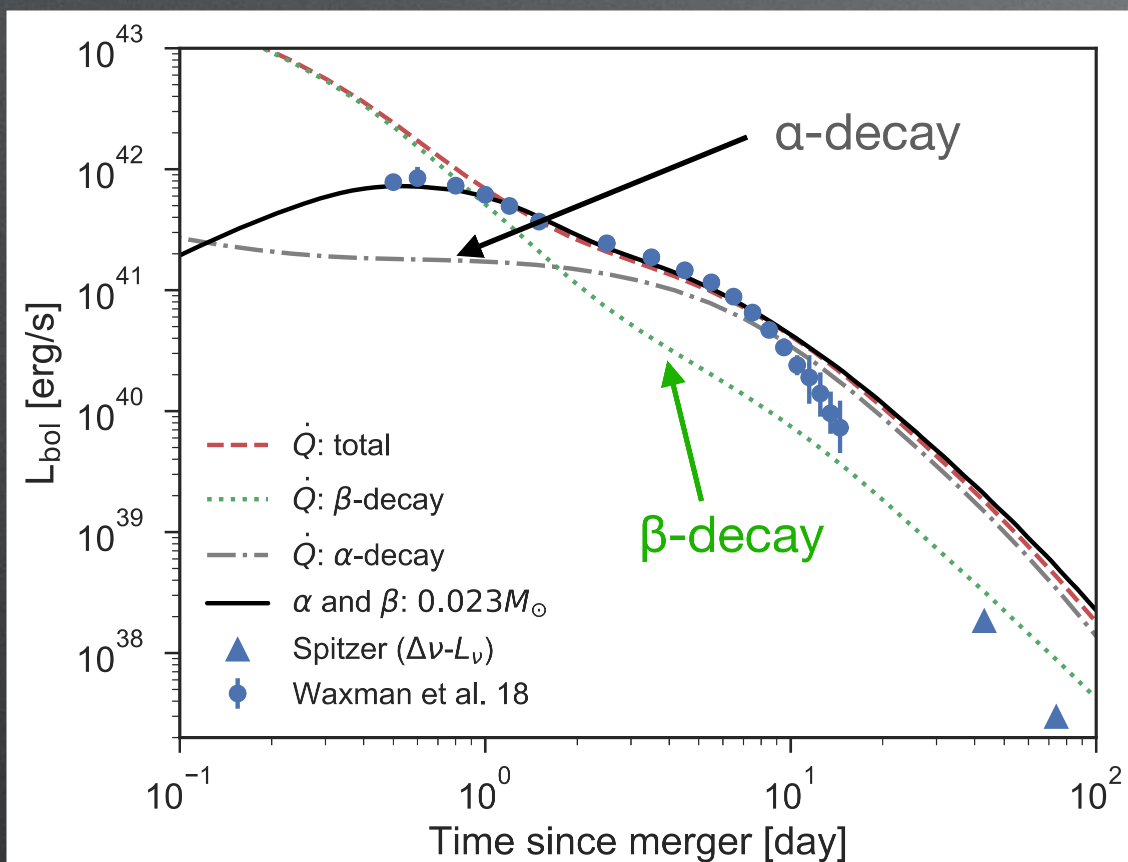


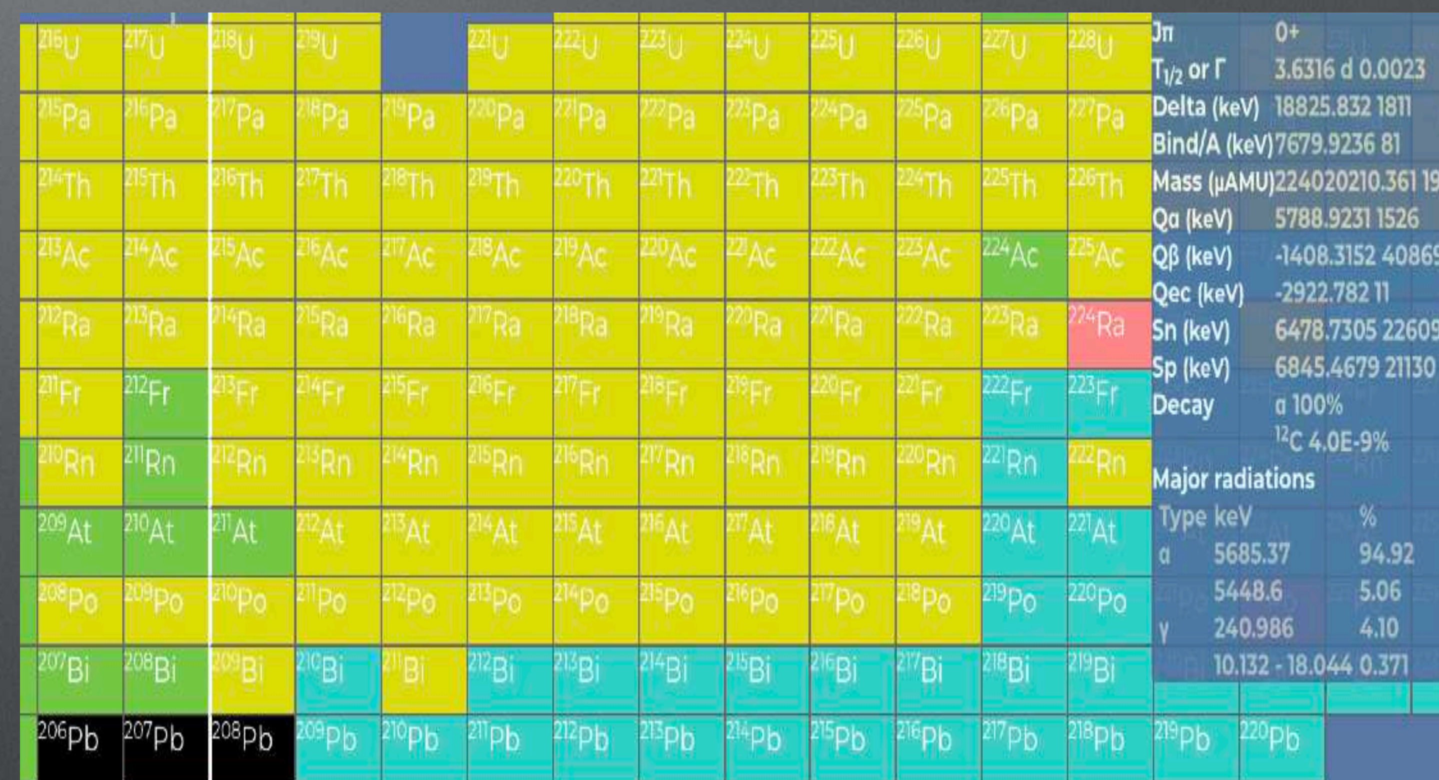
Ref: Goriely 1999, Lodders et al 2009, Wanderman & Piran 2015, Fong+2015, KH, Piran, Paul 2015, Beniamini, KH, Piran 2016, Pol, McLaughlin, Lorimer 2019, KH & Nakar 2020, LVC 2020

α-decay and fission as the energy source?

KH & Nakar 20, see also, Wanajo+14, KH+16, Barnes+16, Zhu+18, Wu+19

α-decay





- α-decay can dominate the energy source (^{222}Rn, ^{223}Ra, ^{224}Ra, ^{225}Ra). But the relative importance to β-decay is very uncertain.
- Spontaneous fission can also be important at late times > 10 day. But it is also highly uncertain.

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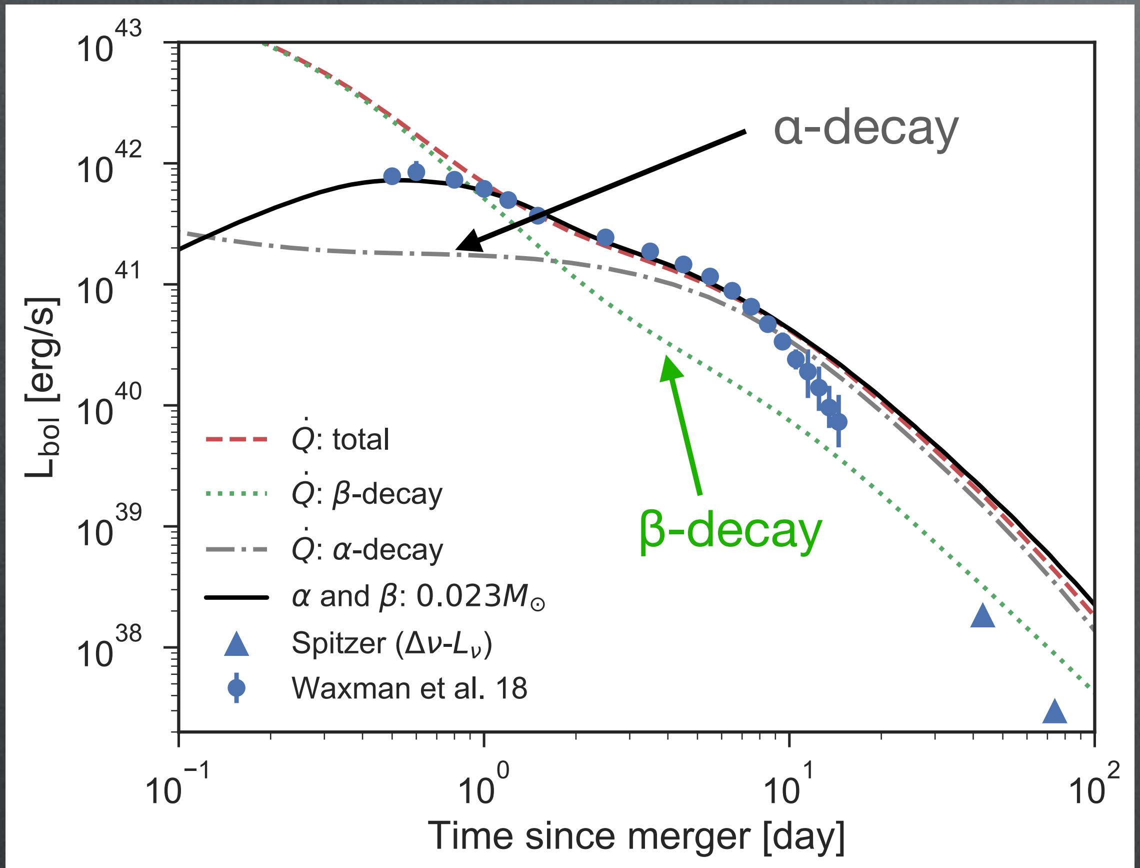
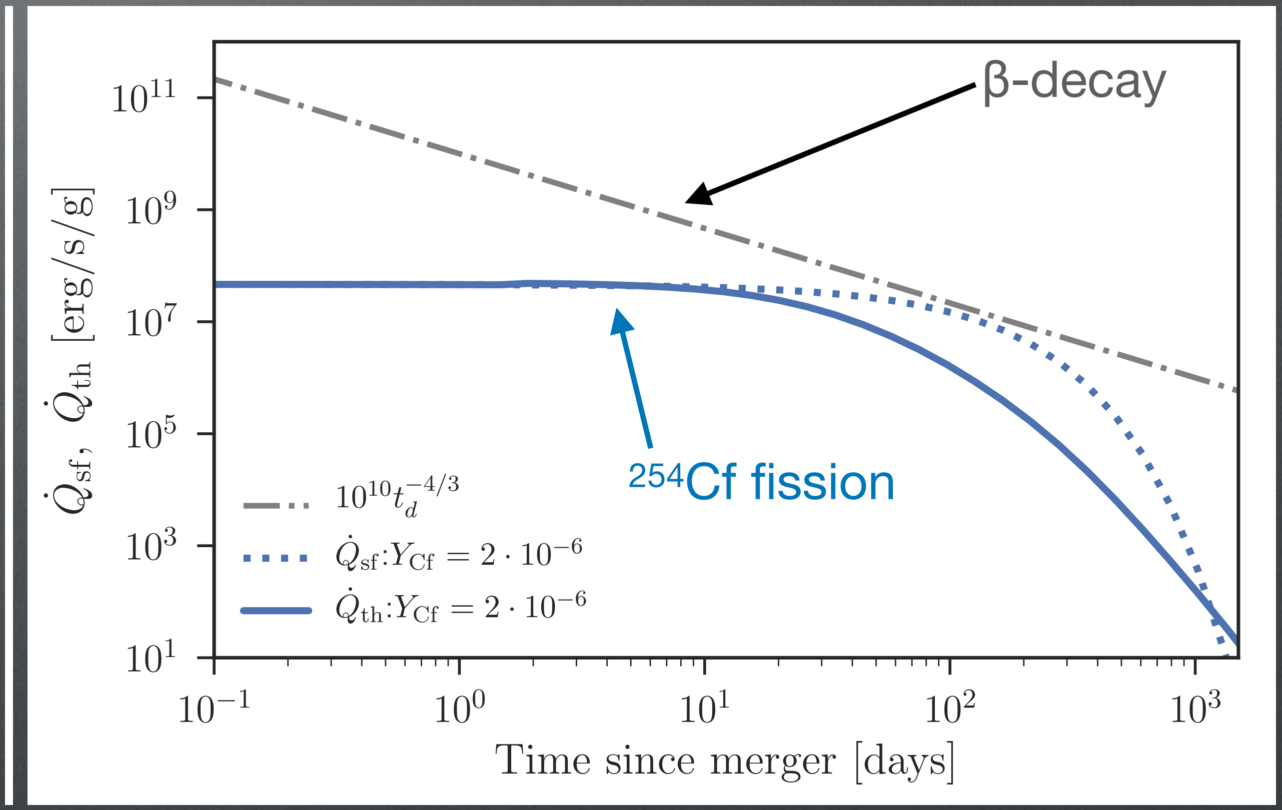
α-decay



Spontaneous fission



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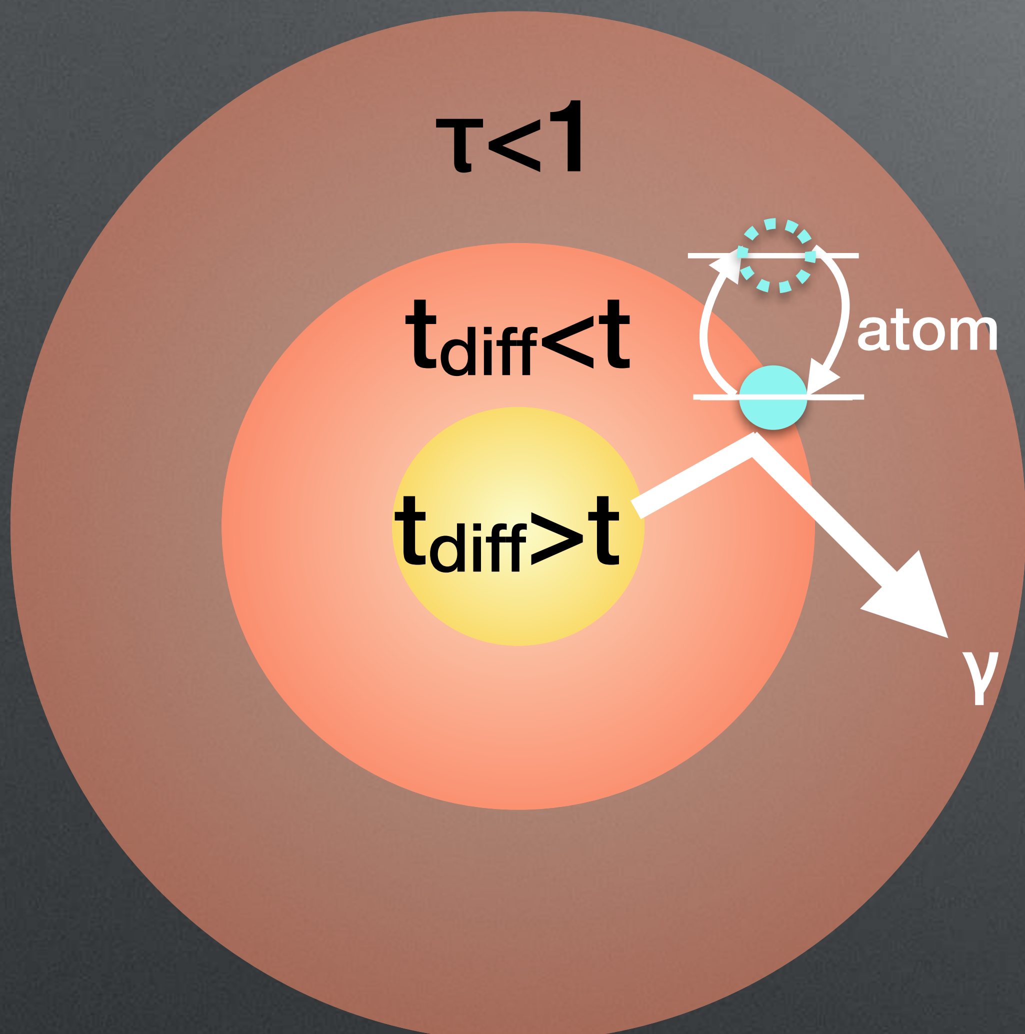
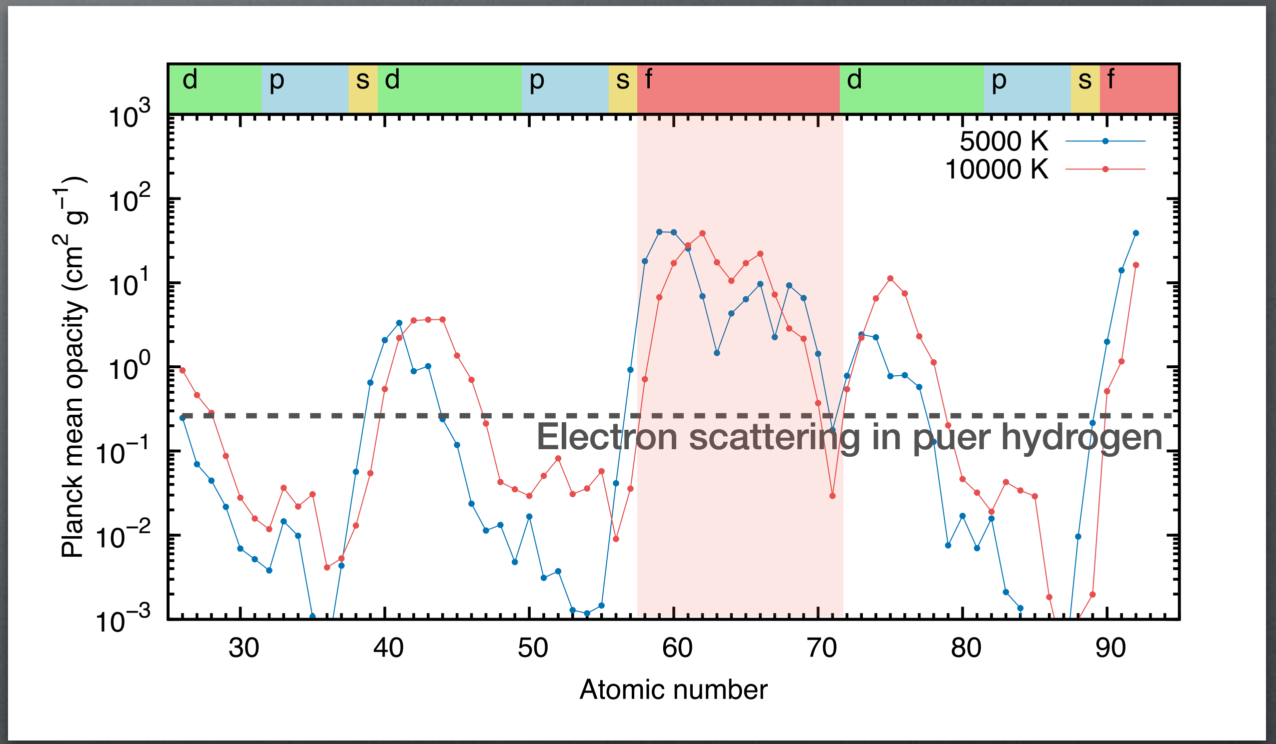
Kilonova Radiation Transfer

Photospheric phase (t<10 day)



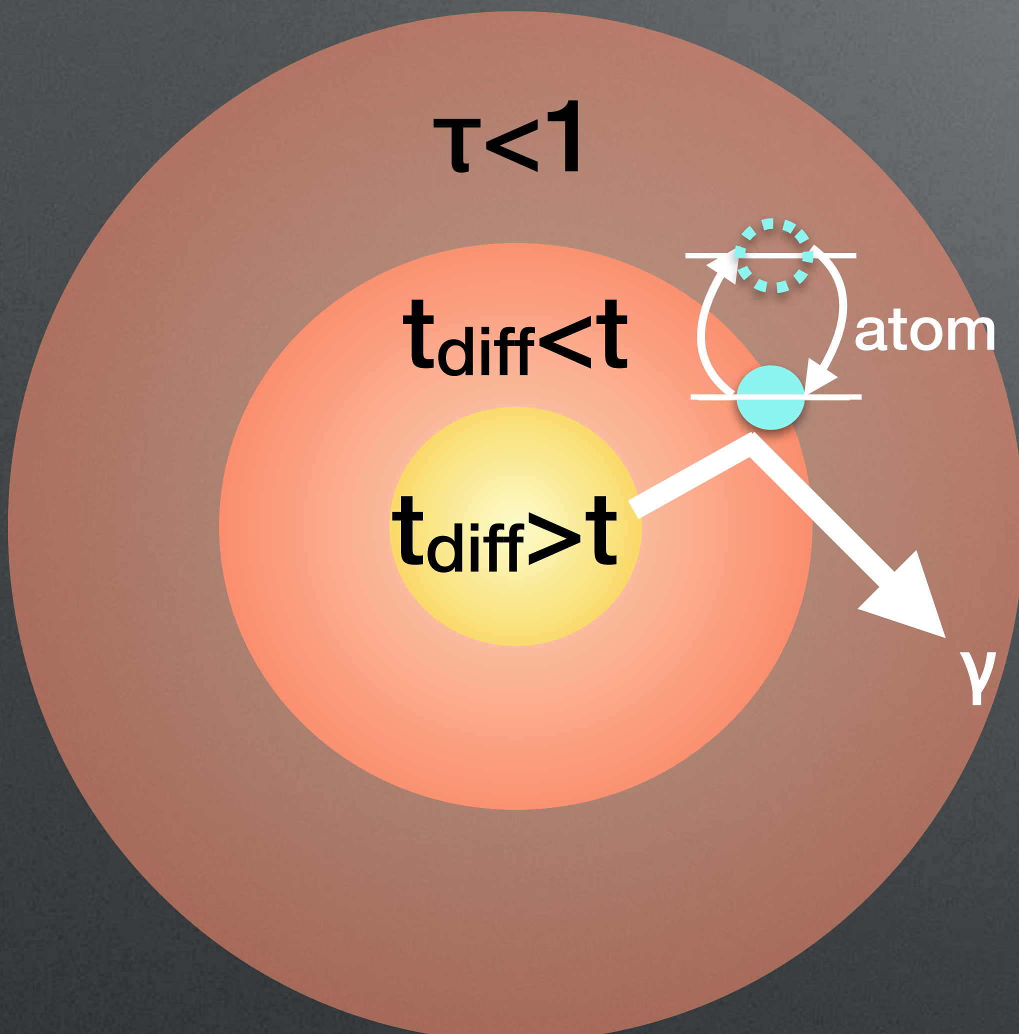
Tanaka+2020



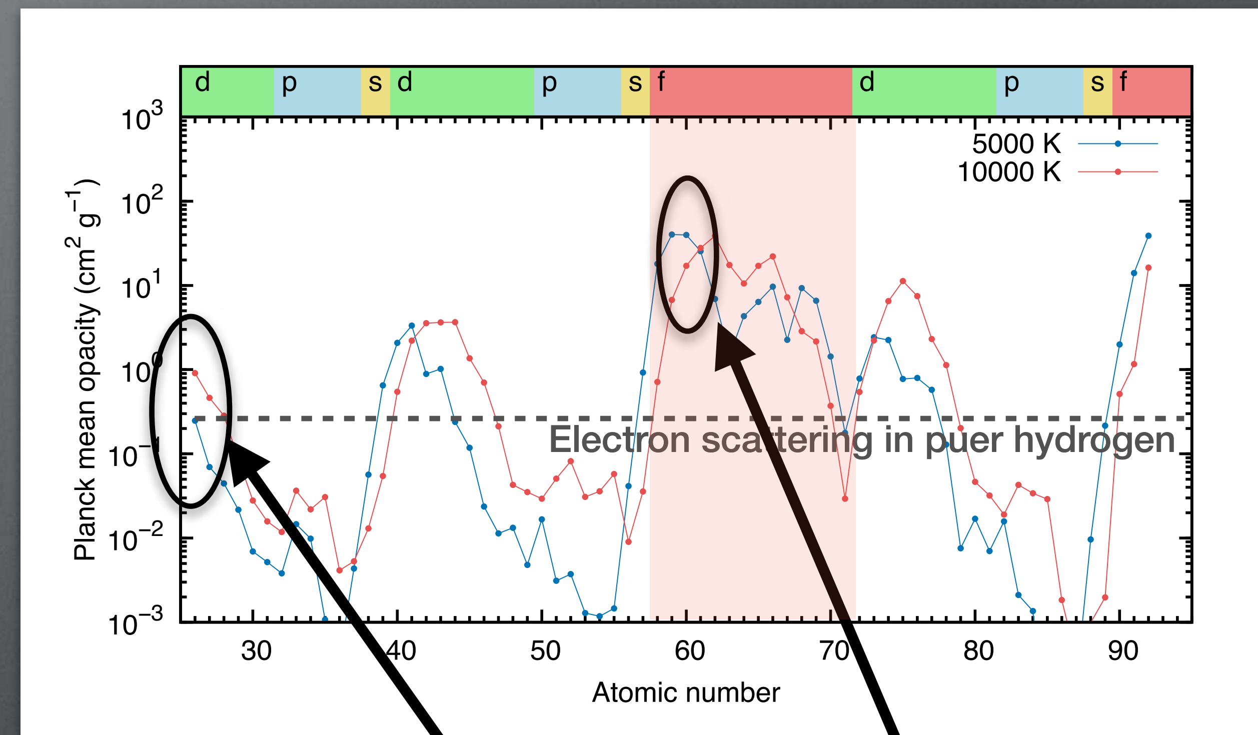
- The photosphere is in the middle (v~0.1-0.2c).
- The photospheric temperature is $T=O(10^3 K)$.
- The spectrum peaks at optical-nIR. Rich observation data exist for GW170817.

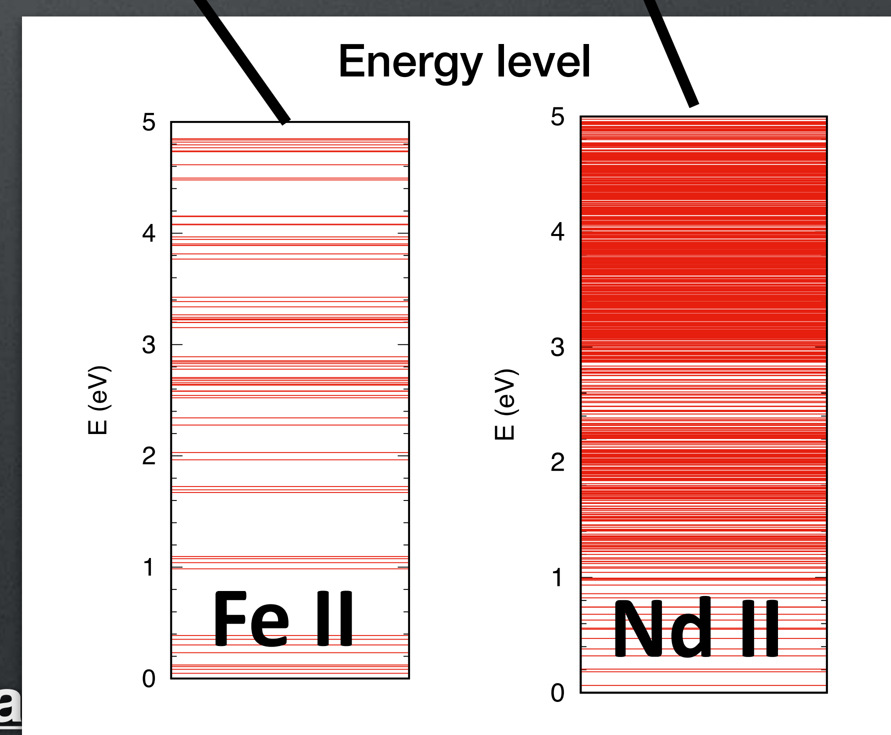
Kilonova Radiation Transfer

Photospheric phase (t<10 day)



Tanaka+2020





- The photosphere is in the middle (v~0.1-0.2c).
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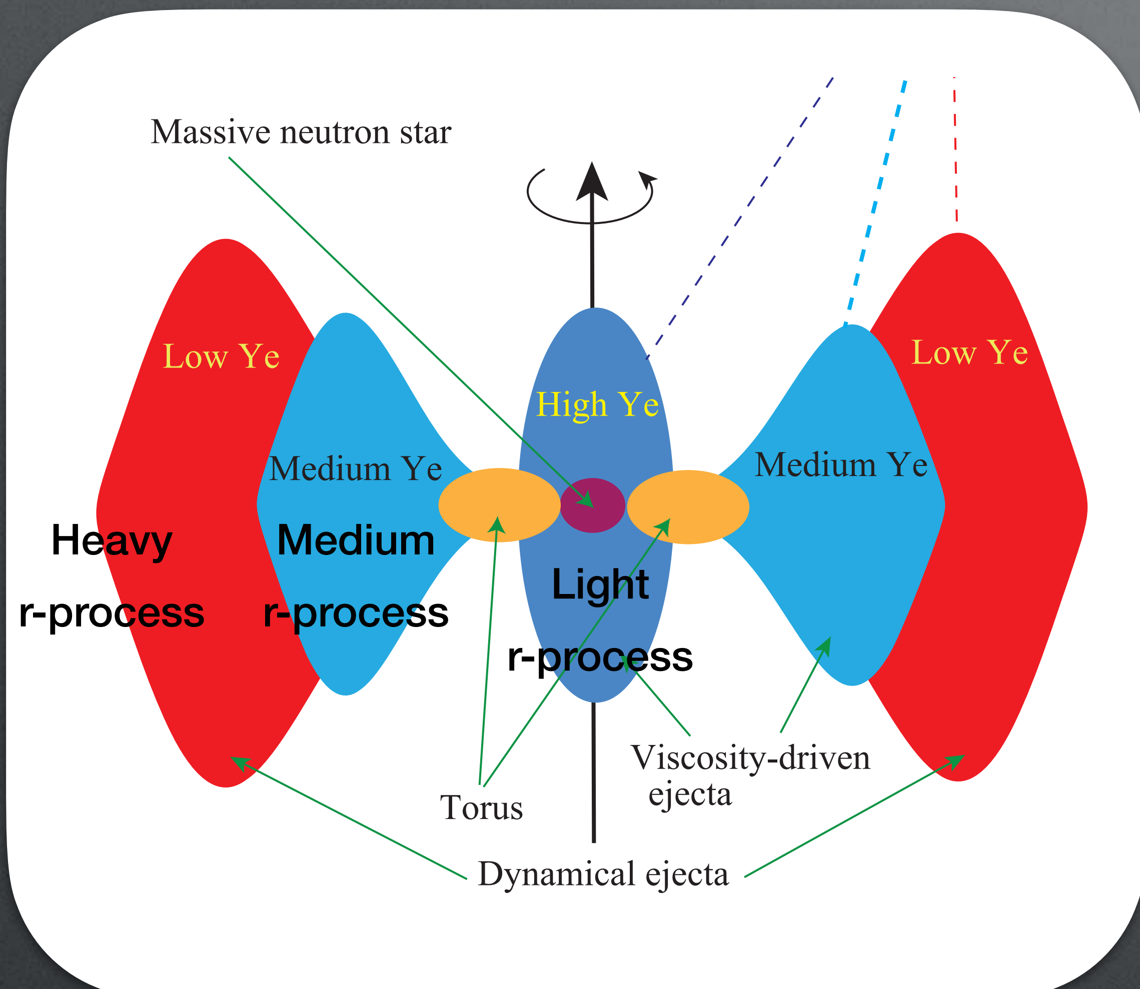
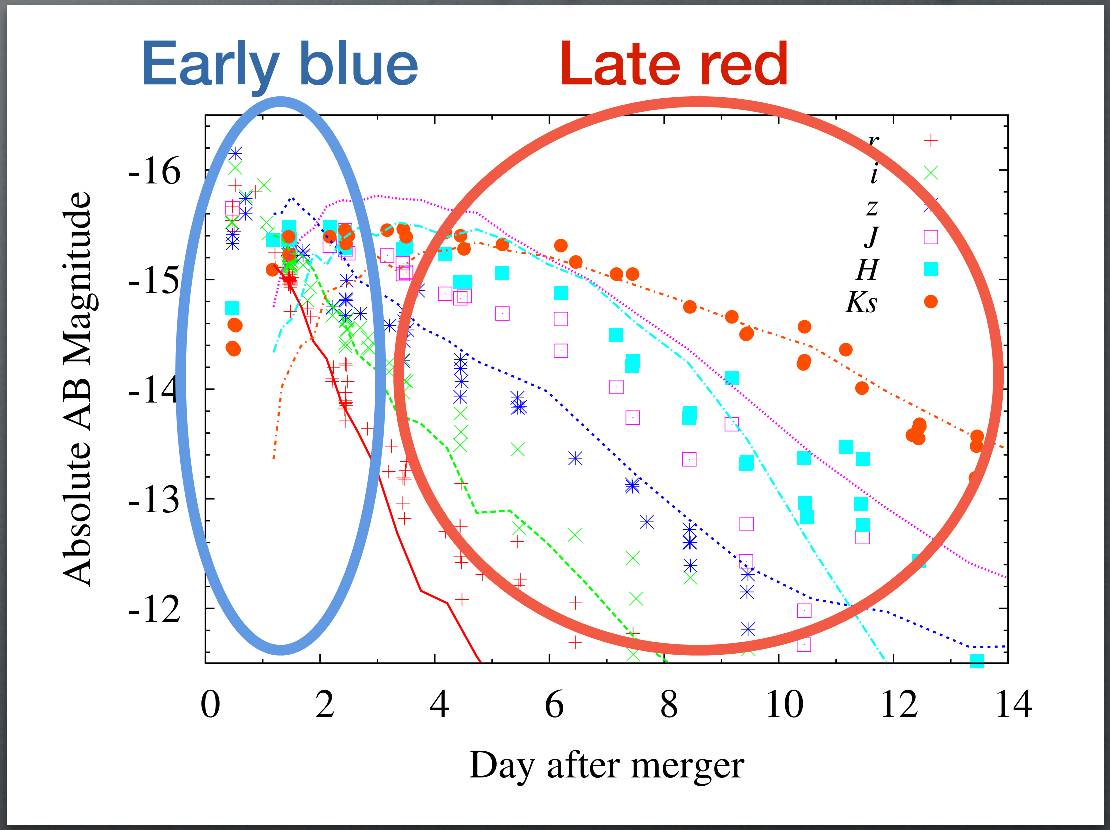
Kilonova Radiation Transfer Result

Shibata, Fujibayashi, KH+17, Kawaguchi+19

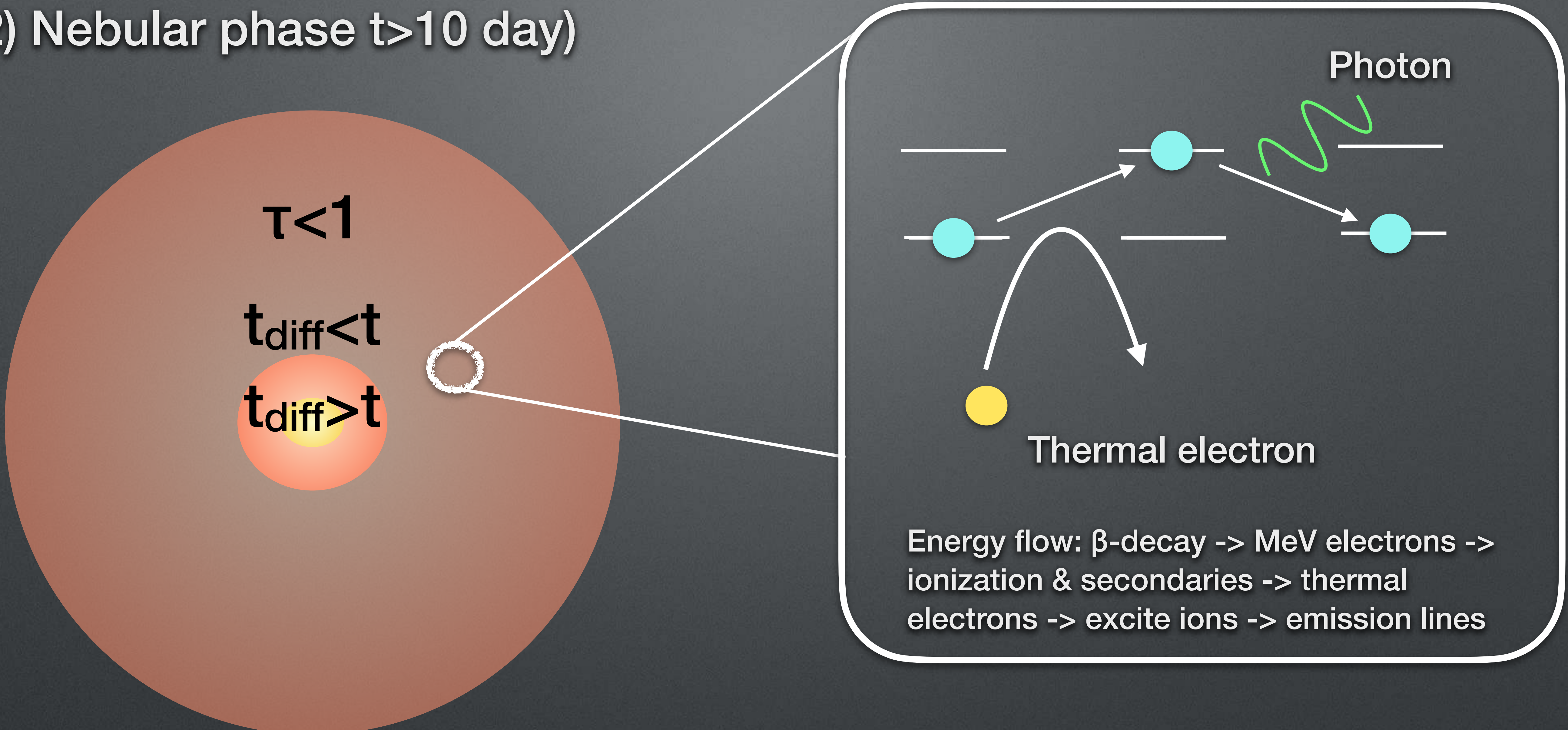




- From the observed data, the opacity must increase with time.
- The early blue emission (~ 1 day) => low opacity, e.g., lanthanide-free light r-process.
- The late red emission (~5 days) => high opacity, e.g., lanthanide-rich heavy r-process.
- However, the models are generally too red. We probably miss something.
- We'll hear more about the kilonova spectrum from Domoto-san.

Kilonova Nebular Phase

2) Nebular phase t>10 day)



- Photons escape from the almost entire ejecta without absorption, i.e., tau<1.
- Kilonova radiation is dominated by emission lines, which are narrower.
- Although it is fainter, we may have good chance to identify more elements.

Kilonova Nebular Phase

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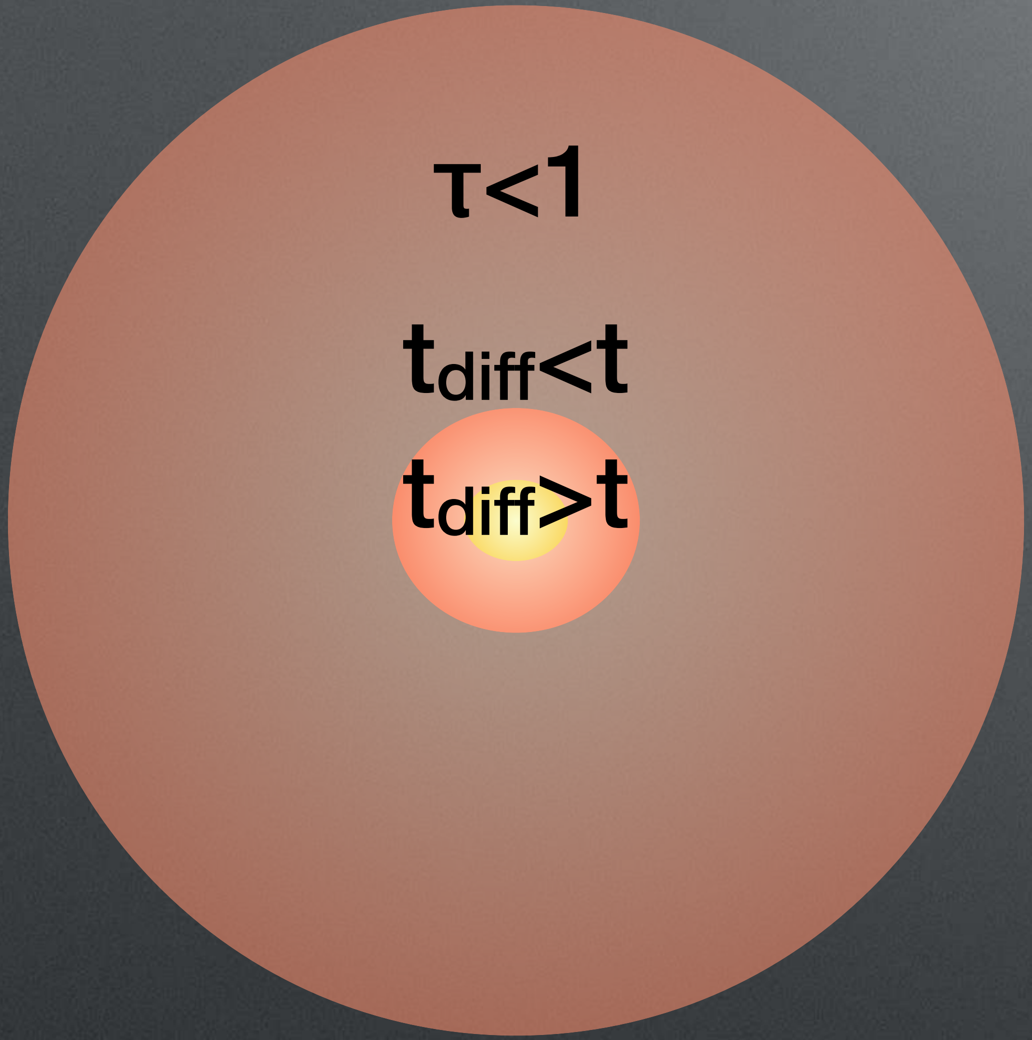
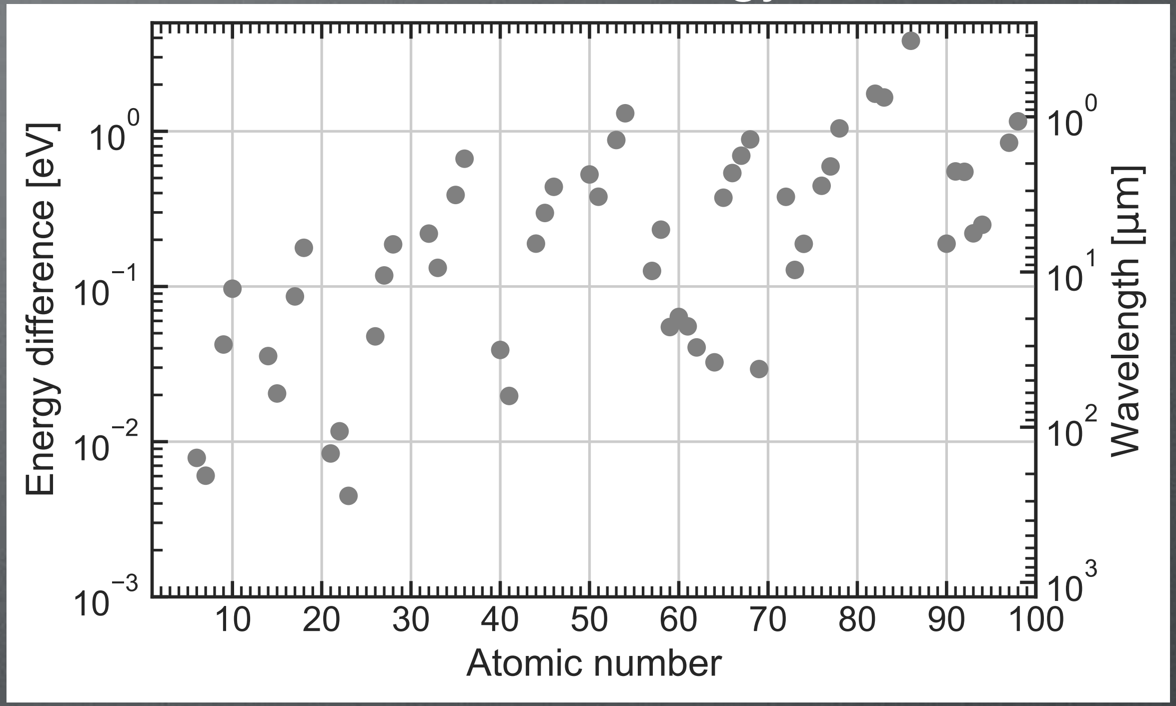
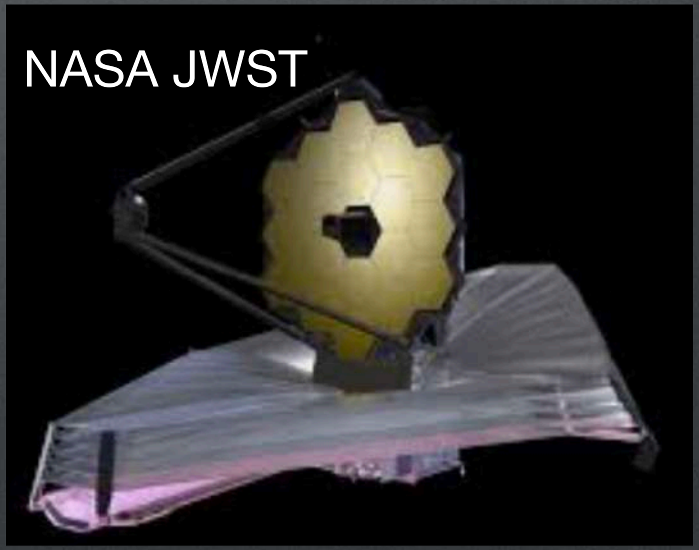


Fine Structure Energy Scale





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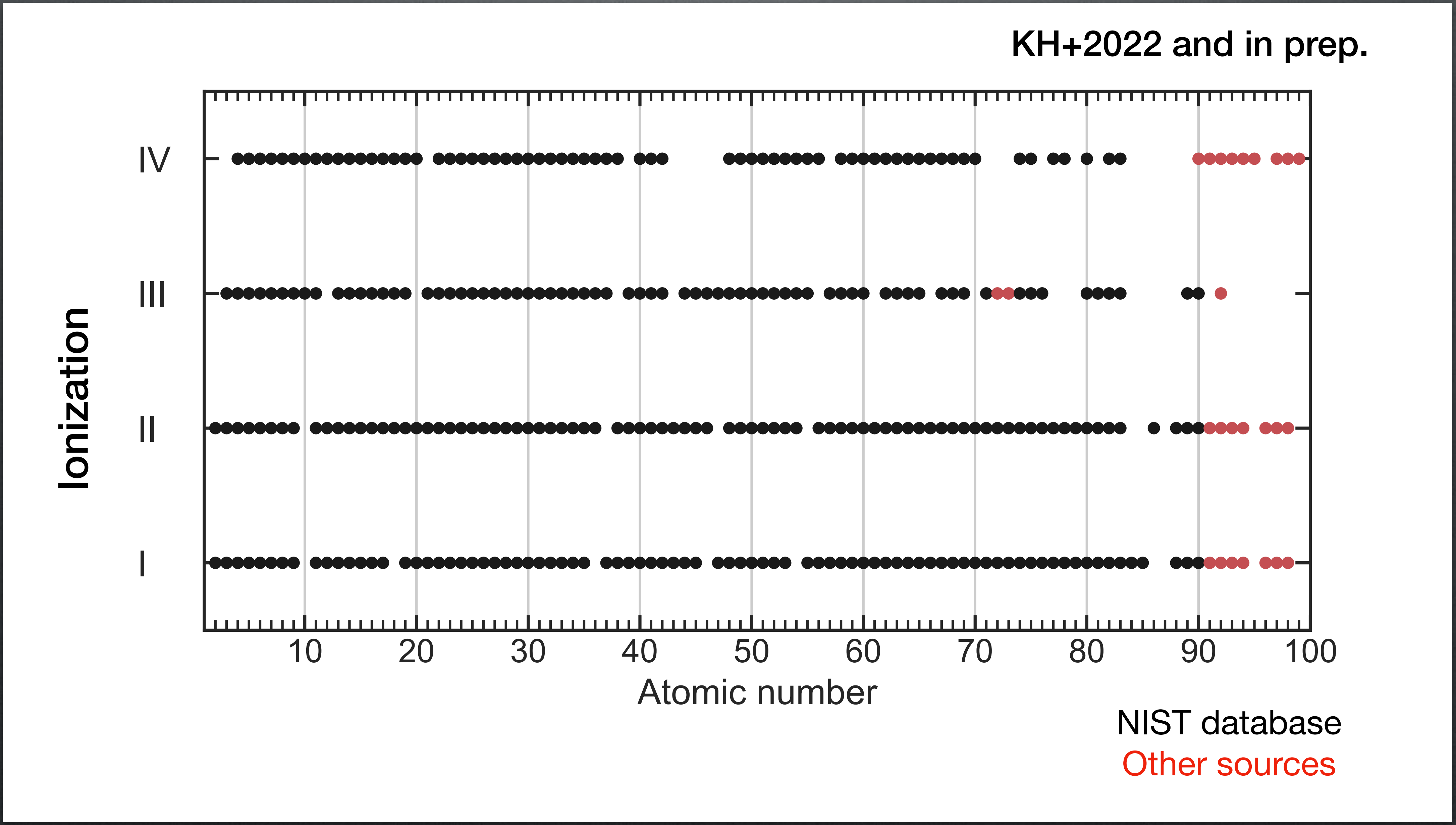
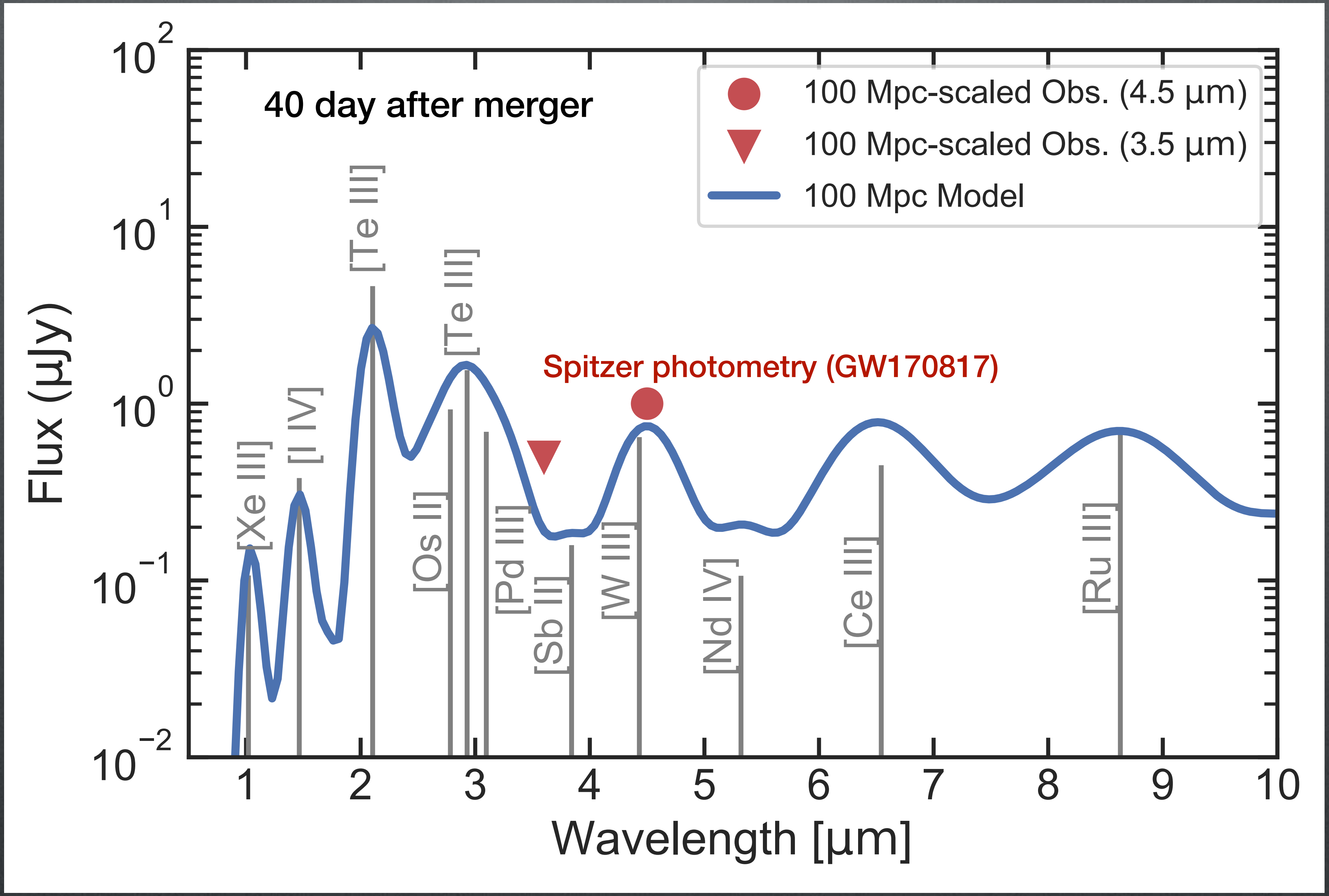
Line list for kilonova nebula

- We constructed a forbidden (M1) line list up to Eeinsteinium (Z=99).
- The experimentally calibrated levels and the LS selection rules are used.
- *A* values are assigned with an analytic formula (Pasternack 40, Shortley 40, Bahcall & Wolf 68)
- Some ions are missing because the energy levels are unknown.



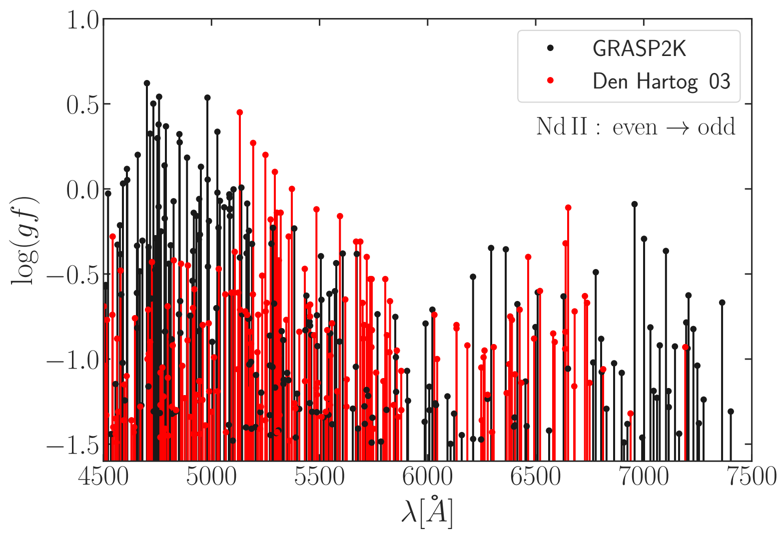
Kilonova nebular spectrum: 40 days



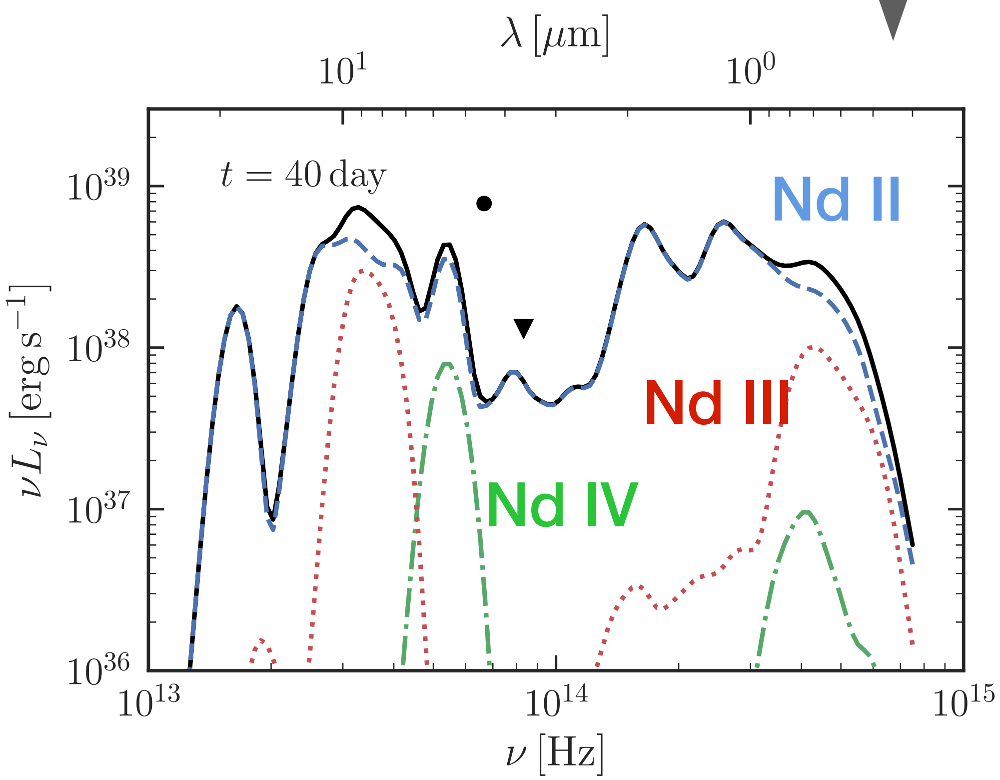
- We can now generate synthetic nebular spectra with the accurate line location.
- JWST can resolve the emission lines for kilonovae at ~100Mpc.
- With this model and data, the amounts of ions can be estimated.

Forward & Reverse modelings

Forward model

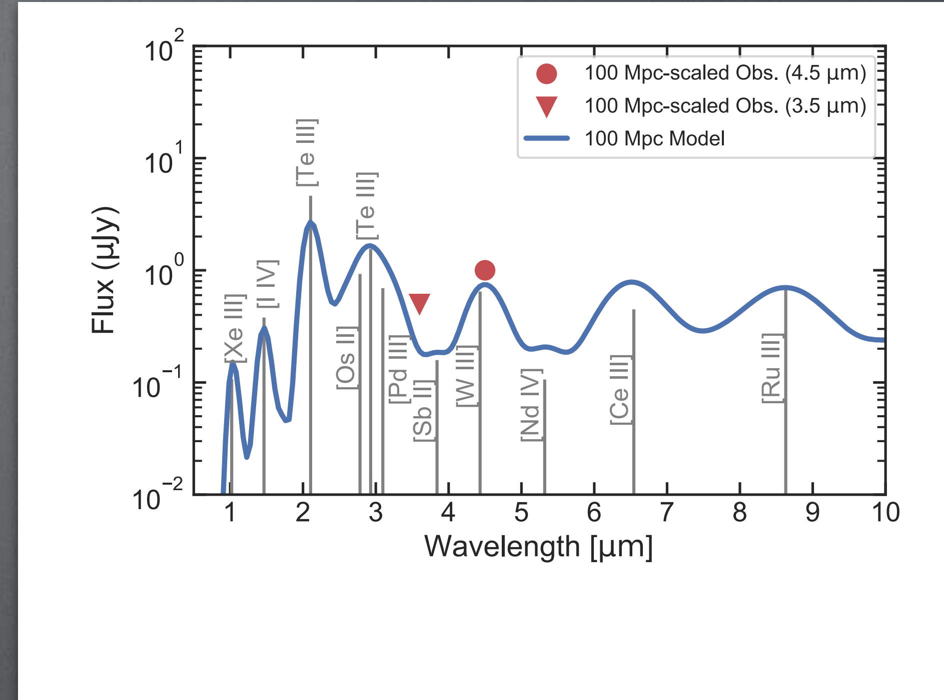


Starting from atomic data



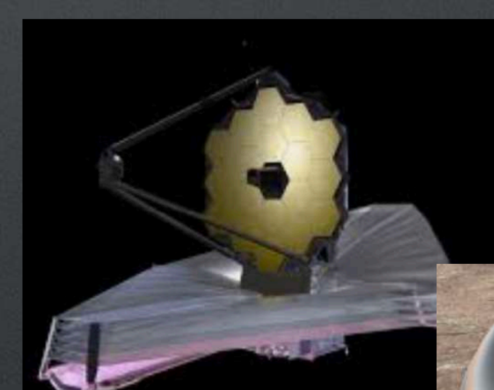
Forward modeling (KH+21)

Currently, the model is limited to a few elements.



Synthetic model

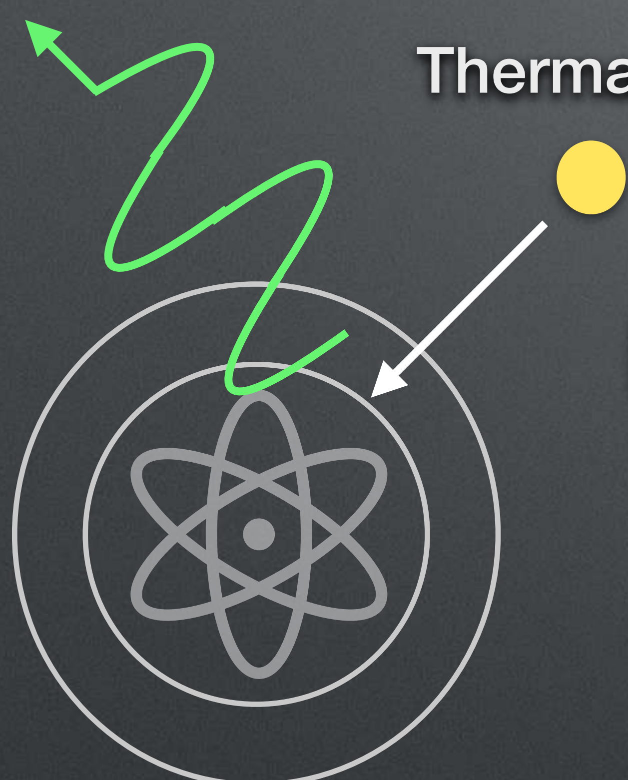
Observation



再結合係数の問題

1, 放射再結合

Thermal electron: Ee

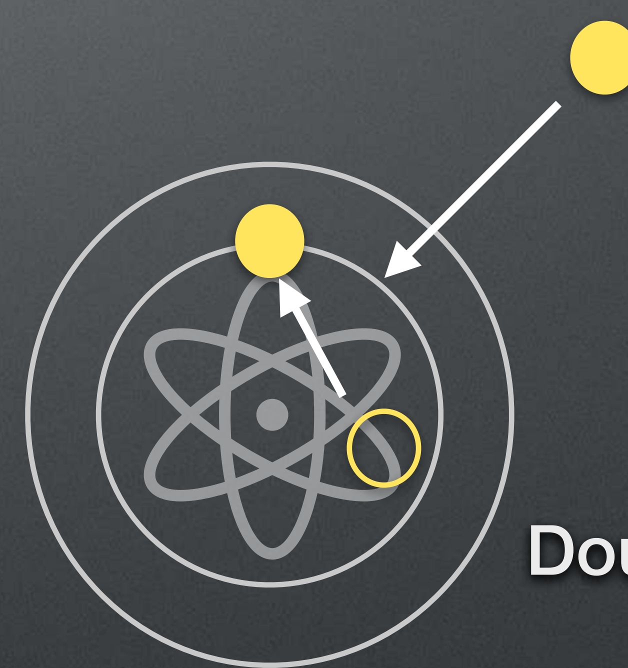


$$E_\gamma=E_e+E_b$$

2, 二重電子再結合

(resonant process)

Thermal electron

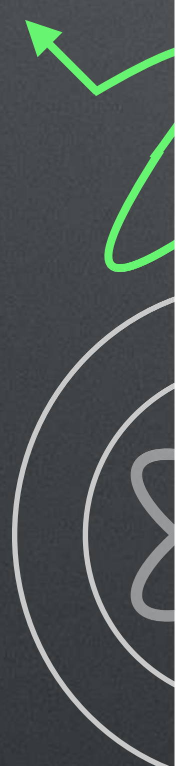


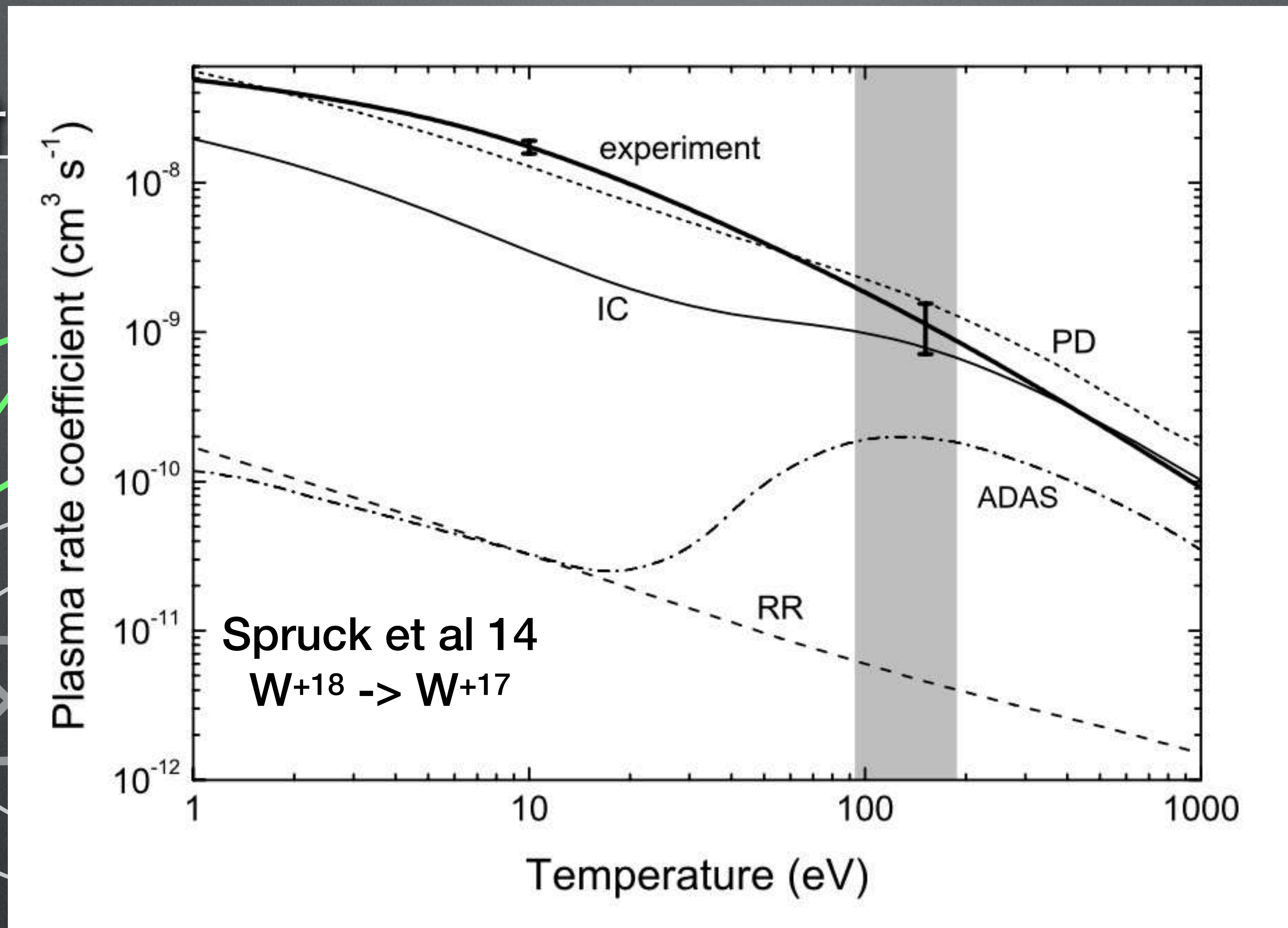
$$E(X^{**}) = E_e$$

Doubly excited state

再結合係数の問題

1, 放射





再結合

ocess)

rmal electron

$E(X^{**}) = E_e$

bly excited state

- 重元素はしばしば二重電子過程が放射過程よりも圧倒的に大きい。
- 原子コードで計算可能だが、キロノバの温度(<1eV)では信頼性が低い。

Summary

- Mass ejection of O(0.01Msun) is expected from numerical relativity.
- A kilonova is powered by radioactivity of neutron-rich nuclei.
- The observed kilonova light curve points to many radioactive species of 0.05Msun.
- The late-time Spitzer observation is indicative of the existence of W.
- JWST will cover a good range of the kilonova nebular spectrum.