Kilonova Nebula and r-process origin

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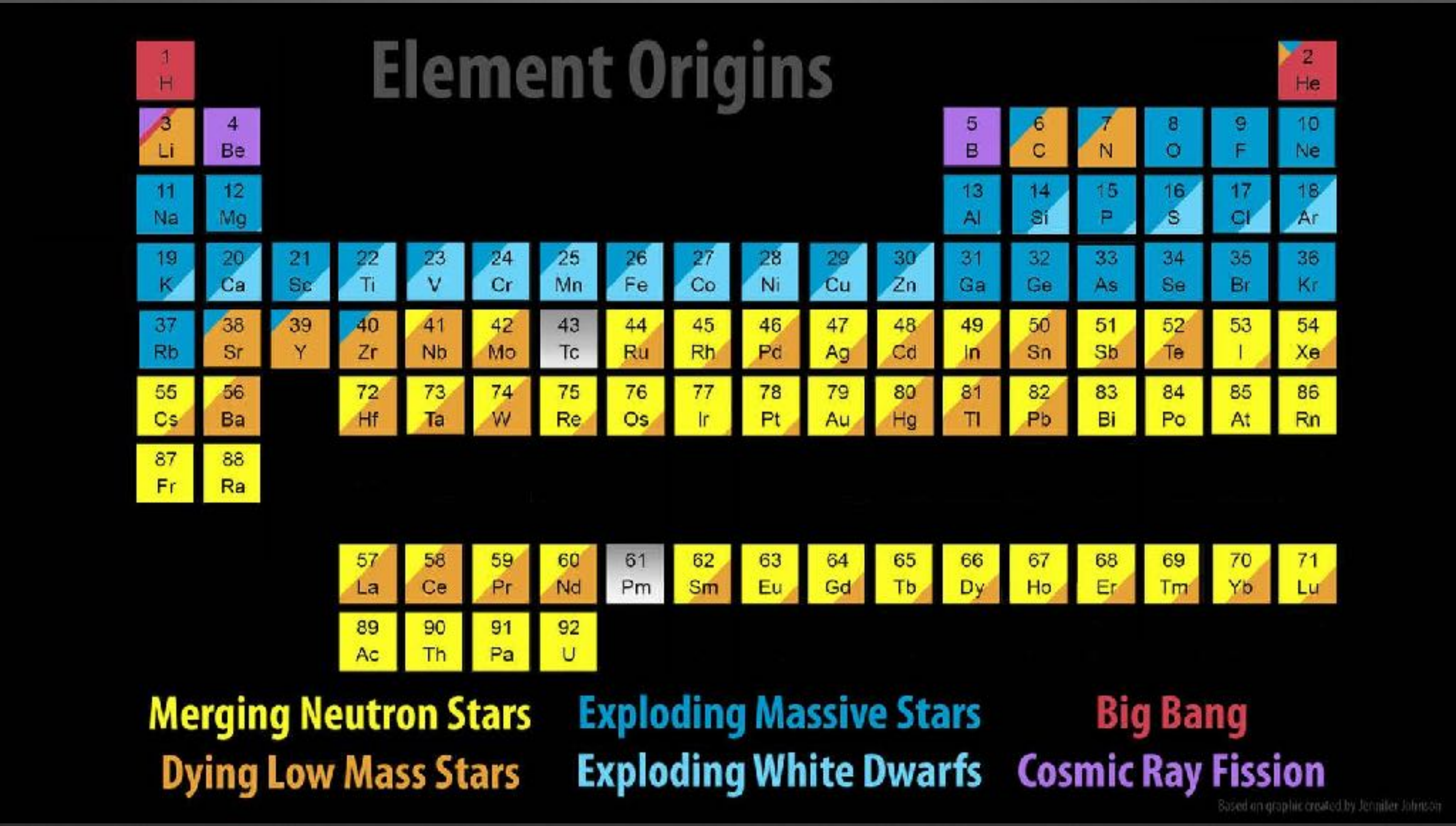
Outline

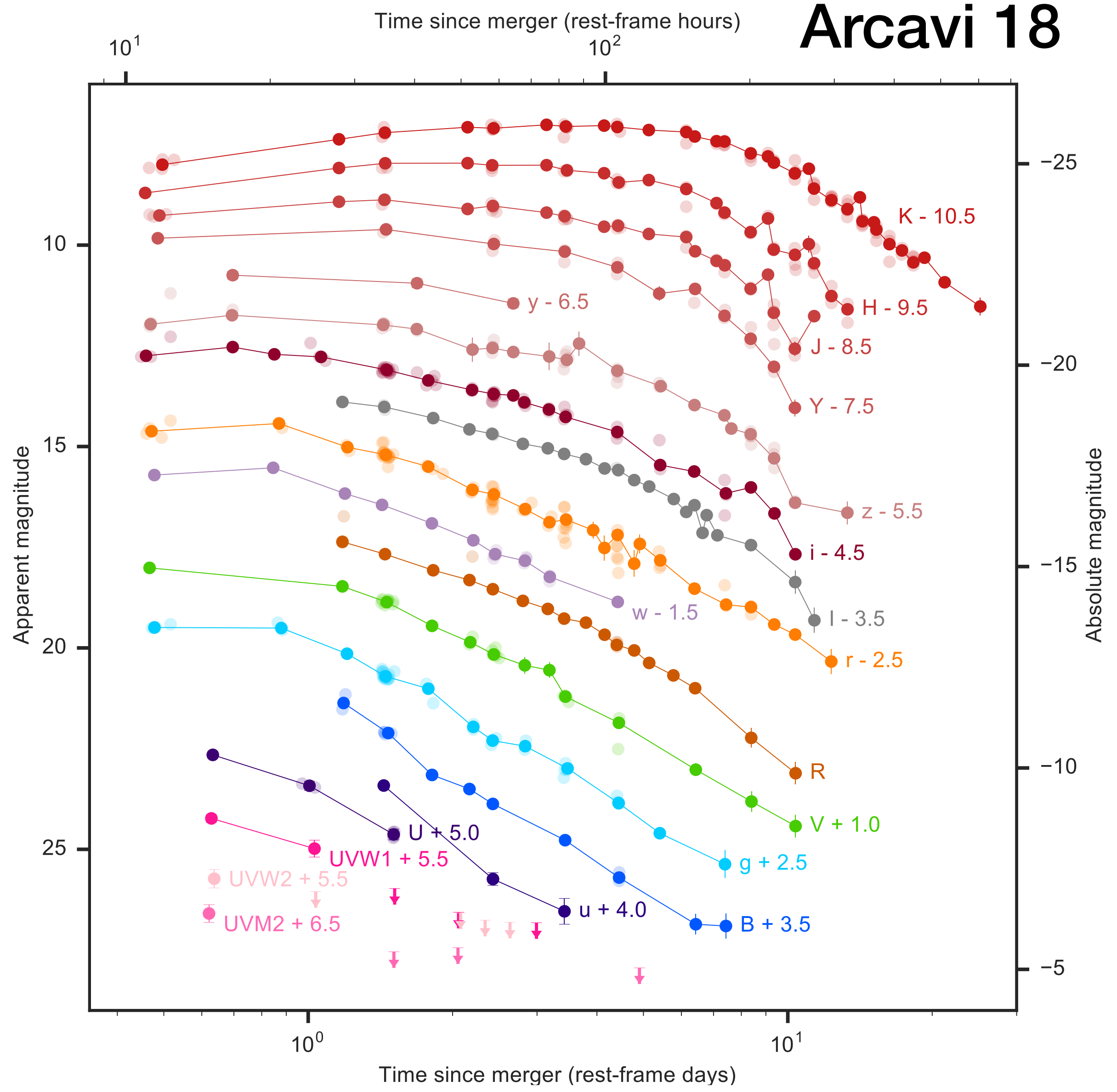
- Introduction
- Radioactivity
- Thermal History of merger ejecta and Nebular emission
- Milky-way r-process puzzle

The origin of elements

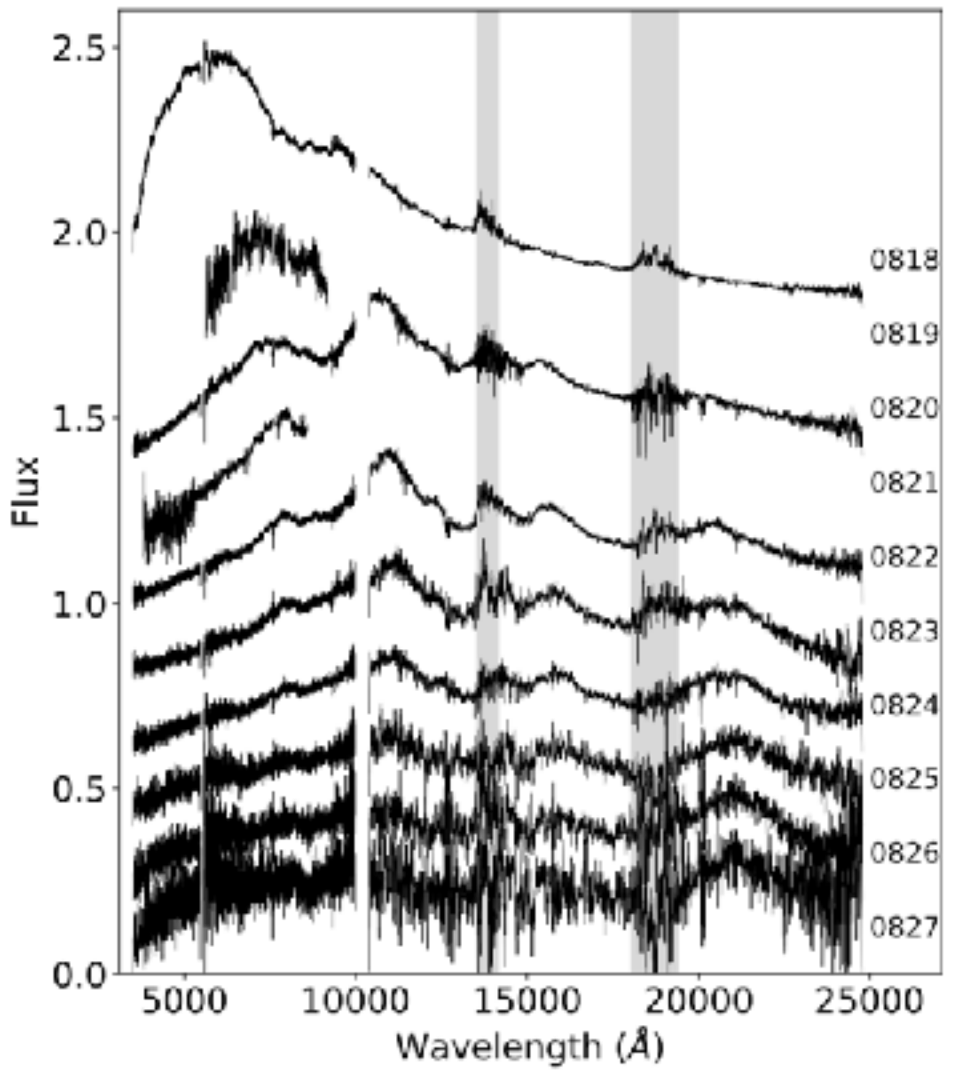


Kilonova GW170817

Arcavi 18



Pian+ 17

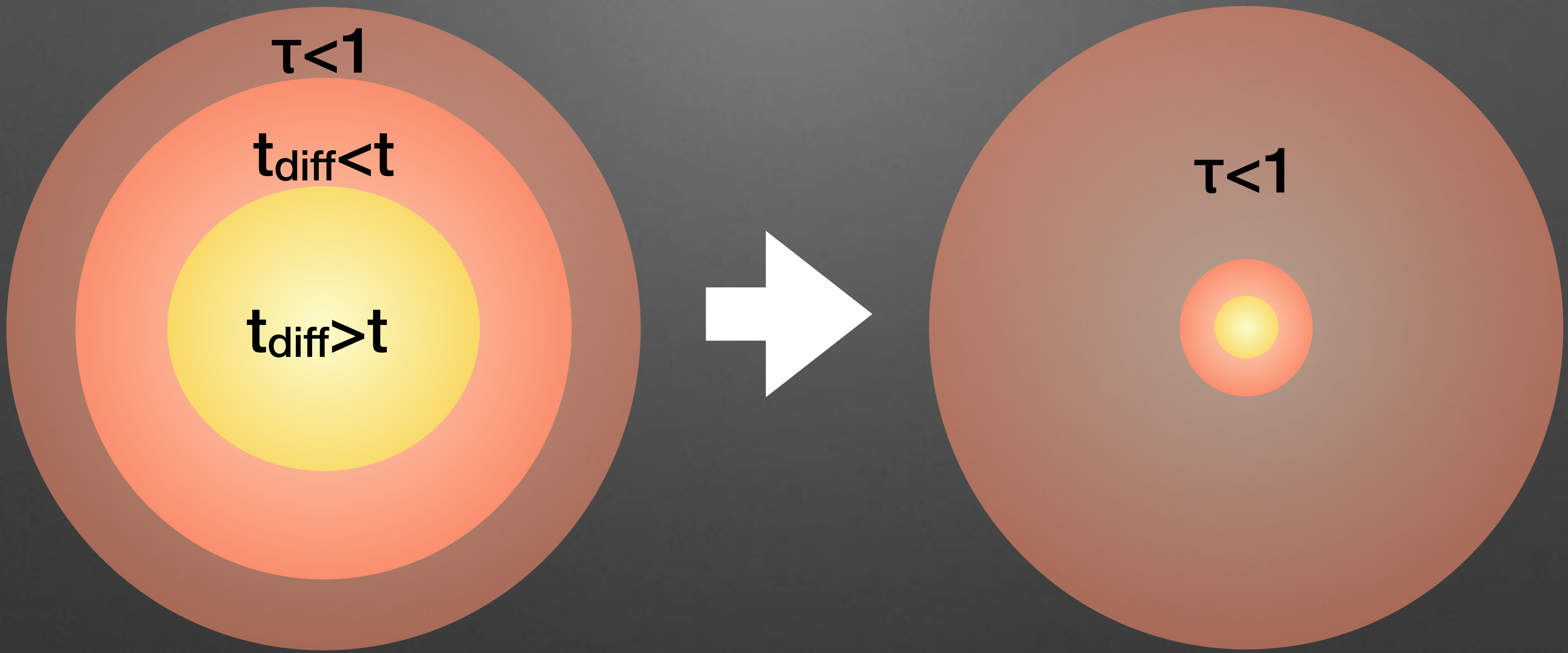


Photometric light curve and Spectrum:

- Consistent with r-process heating
- Mass ~ 0.05Msun
- v ~ 0.1-0.3 (photospheric)
- Some evidence for heavy elements (lanthanide)

Kilonova Nebula

Early times | Late times (nebula)

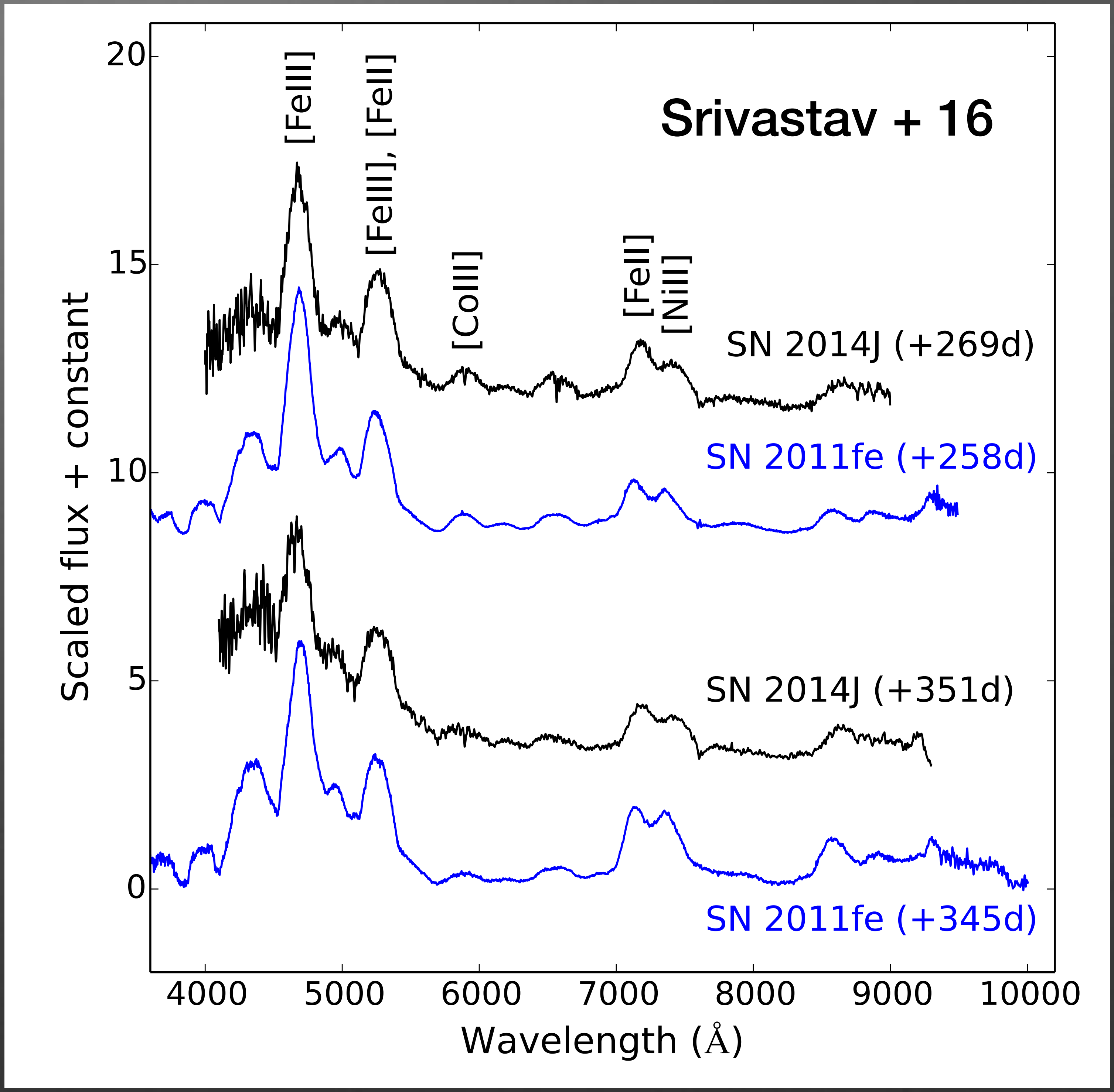


Nebular phase:

- Most of the ejecta can be seen.
- Inner parts are slower => Lines are narrower.
- Photon luminosity ~ heating rate (imprints of α, β, fission).

Nebular emission of type Ia SNe

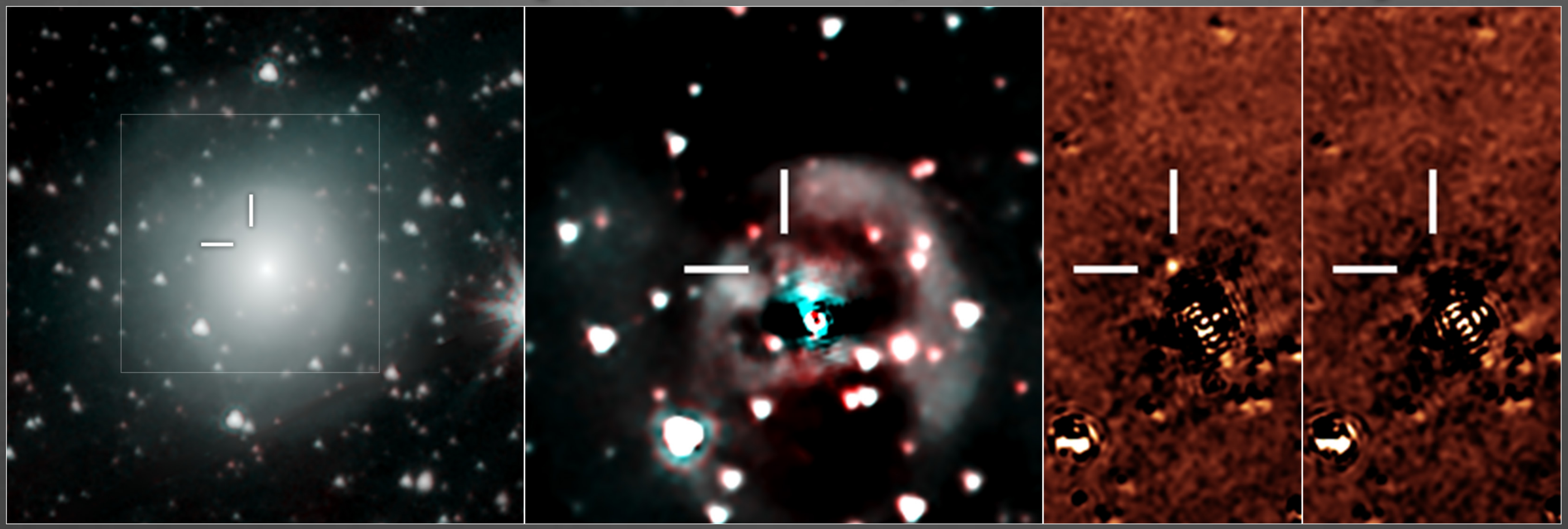
- Clear emission lines
- Time evolution of the amount of ^{56}Co and ^{56}Fe has been measured.



Question:
How kilonova nebulae look like?

GW170817: Hint for Nebular phase

Spitzer observation (Villar+18, Kaliwal+19)



UTC (Phase)	Instrument	Filter	Reference	Mag (Vega)	Mag (AB)
2017-09-29 (+43 d)	*Spitzer*/IRAC	4.5μm	2018-05-08	18.62	21.88 $\pm$ 0.04 ($\pm$ 0.05)
2017-10-30 (+74 d)	*Spitzer*/IRAC	4.5μm	2018-05-08	20.60	23.86 $\pm$ 0.22 ($\pm$ 0.05)
2017-09-29 (+43 d)	*Spitzer*/IRAC	3.6μm	2018-05-08	>20.42 (3σ)	>23.21 (3σ)
2017-10-30 (+74 d)	*Spitzer*/IRAC	3.6μm	2018-05-08	>20.26 (3σ)	>23.05 (3σ)

The Spitzer detections and upper limits point to the nebular spectrum has a structure.

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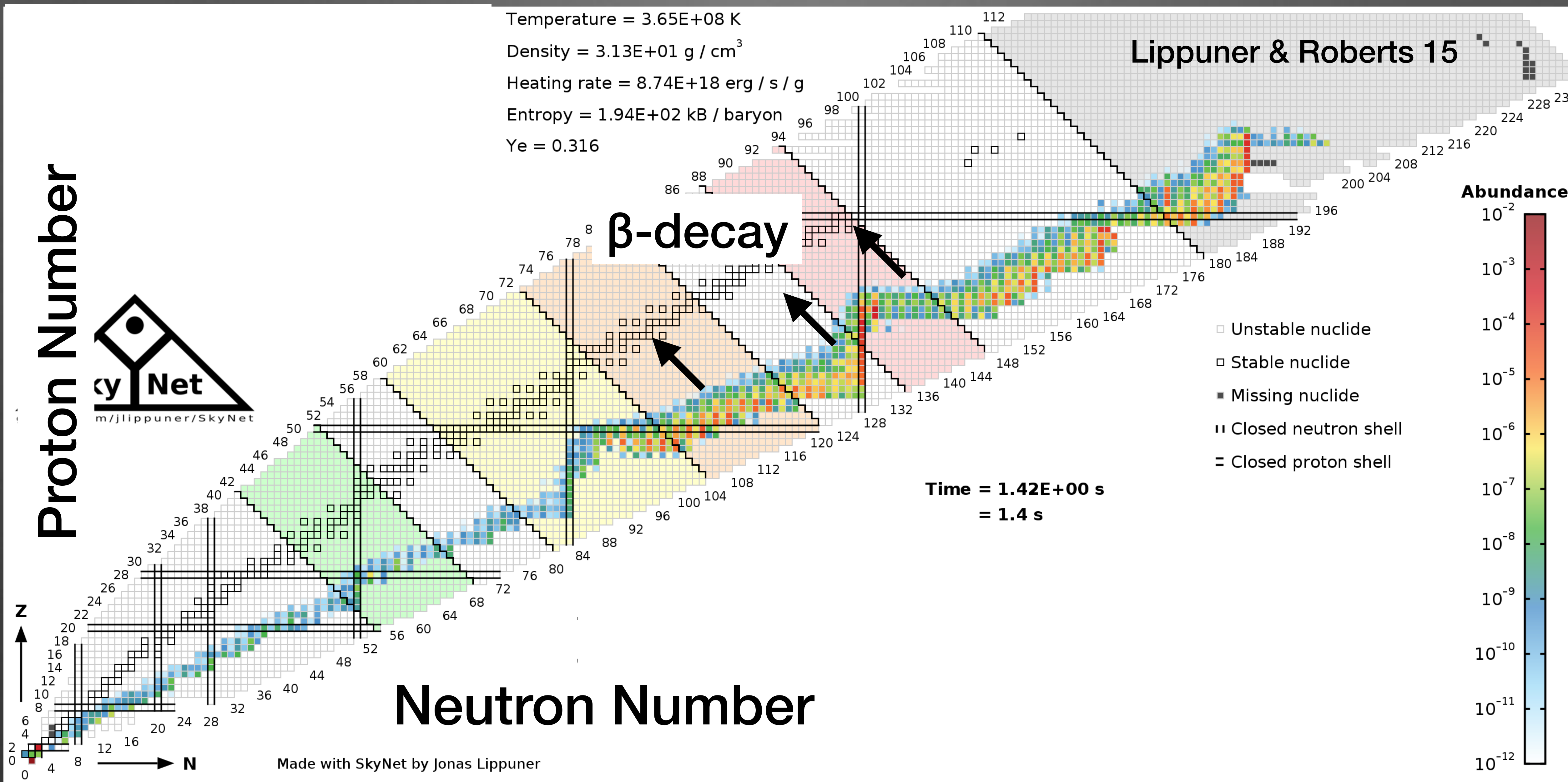
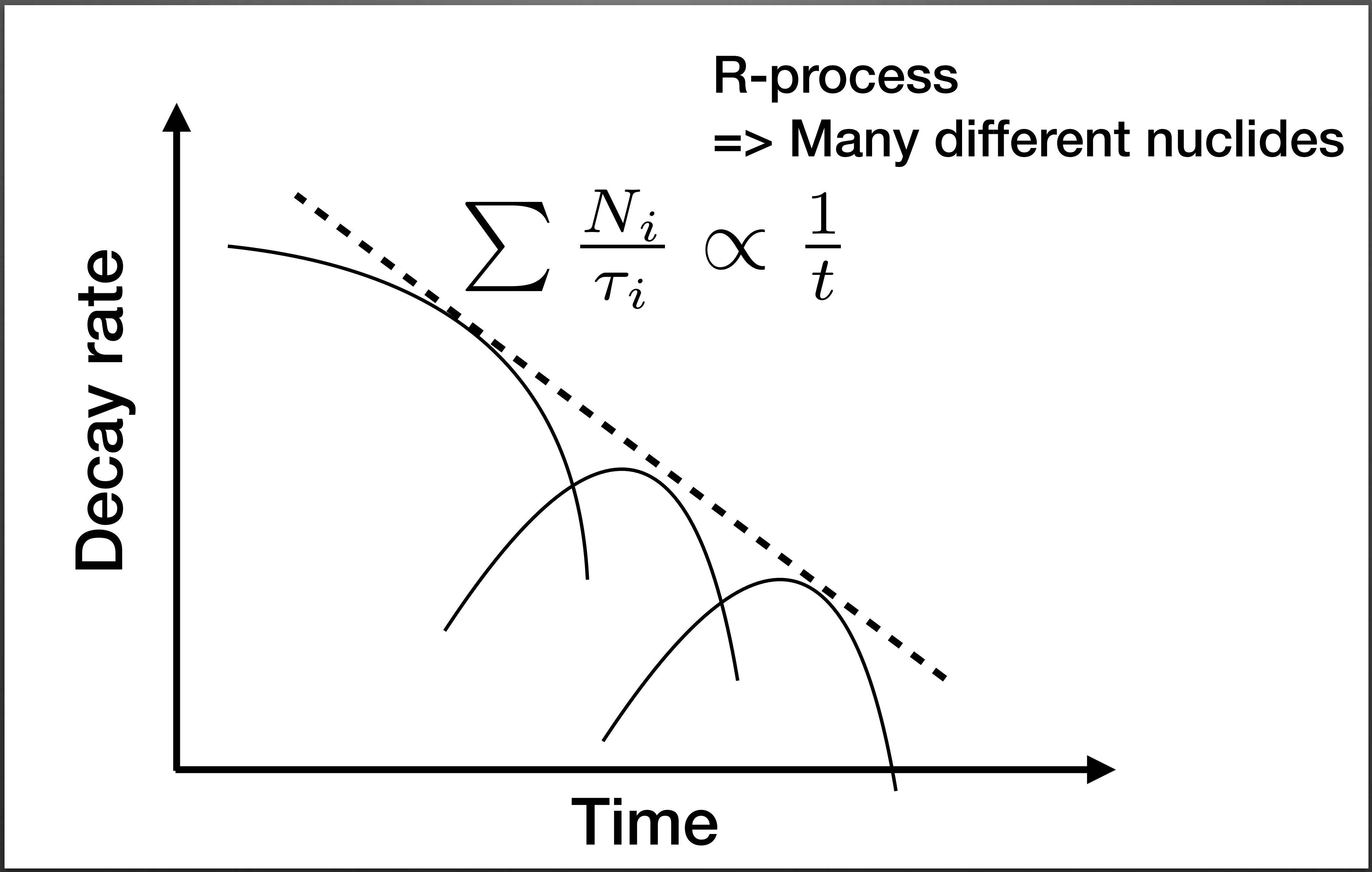
R-process nuclei in mergers



- Almost all the mass is composed of radioactive r-process elements.
- There are many beta-decay chains.

R-process heating

(Metzger et al 10, Goriely et al 11, Roberts et al 11, Korobkin et al 12, Wanajo et al 14, Lippuner & Roberts 2015, KH et al 16, 18)



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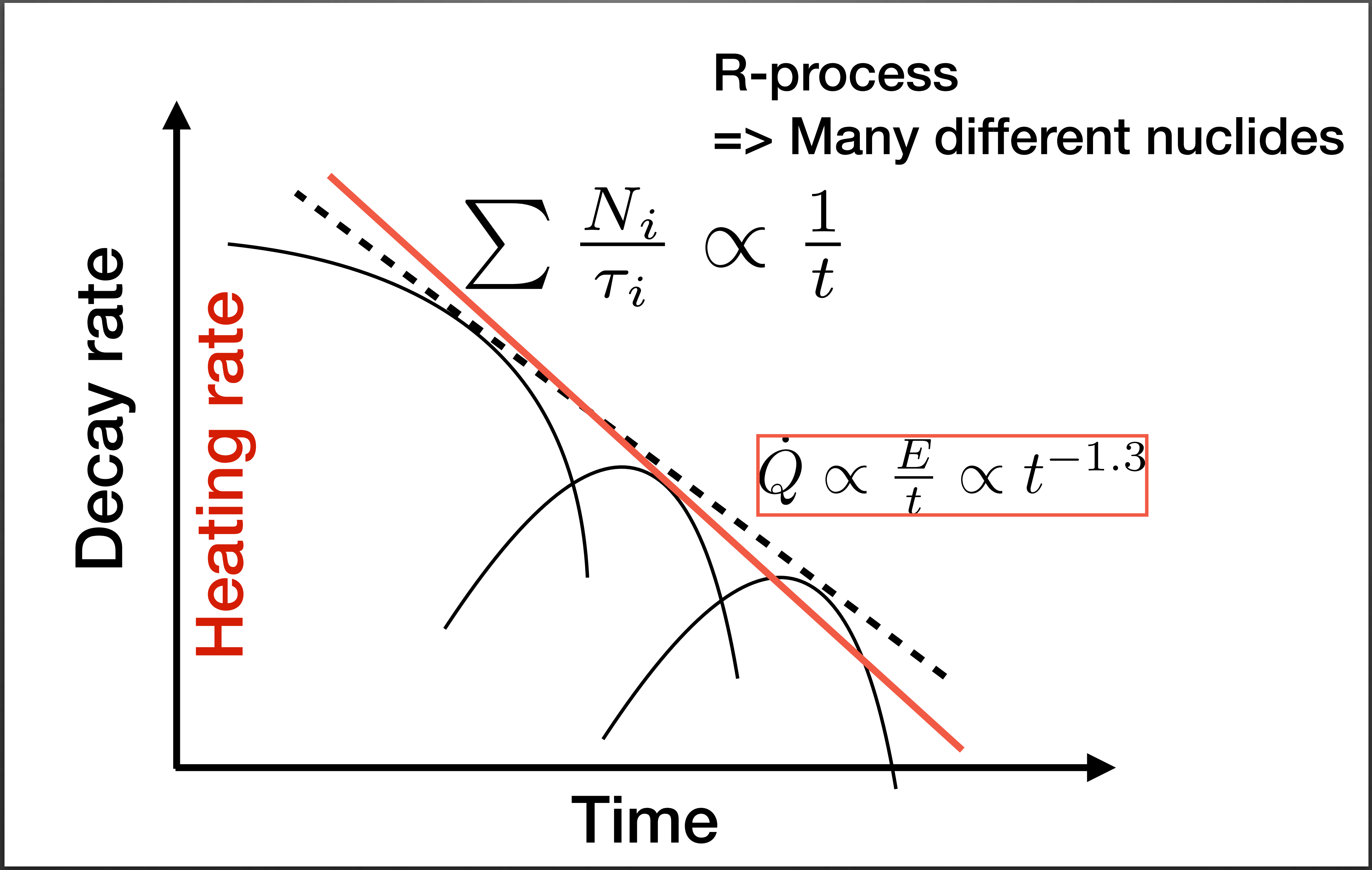
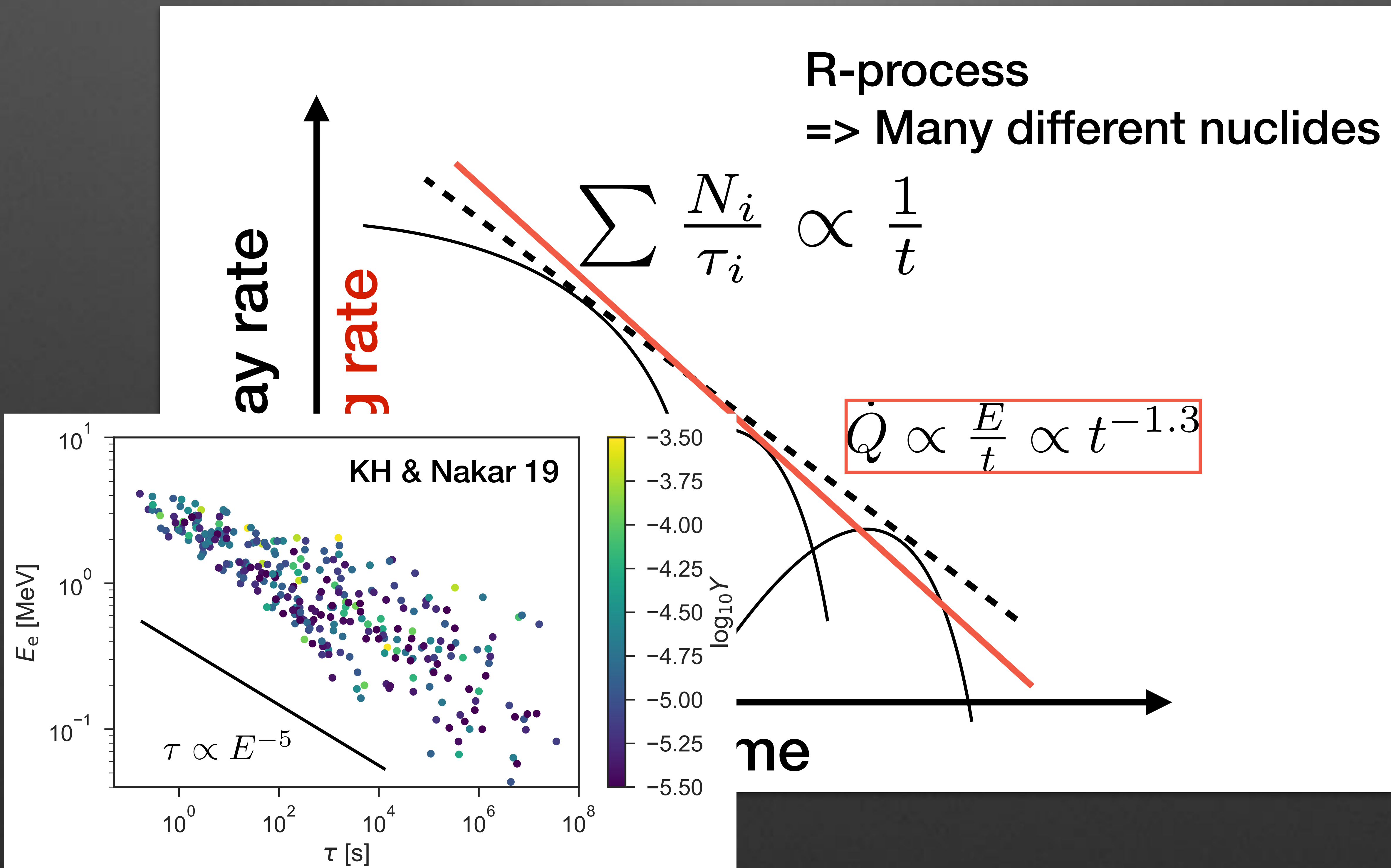
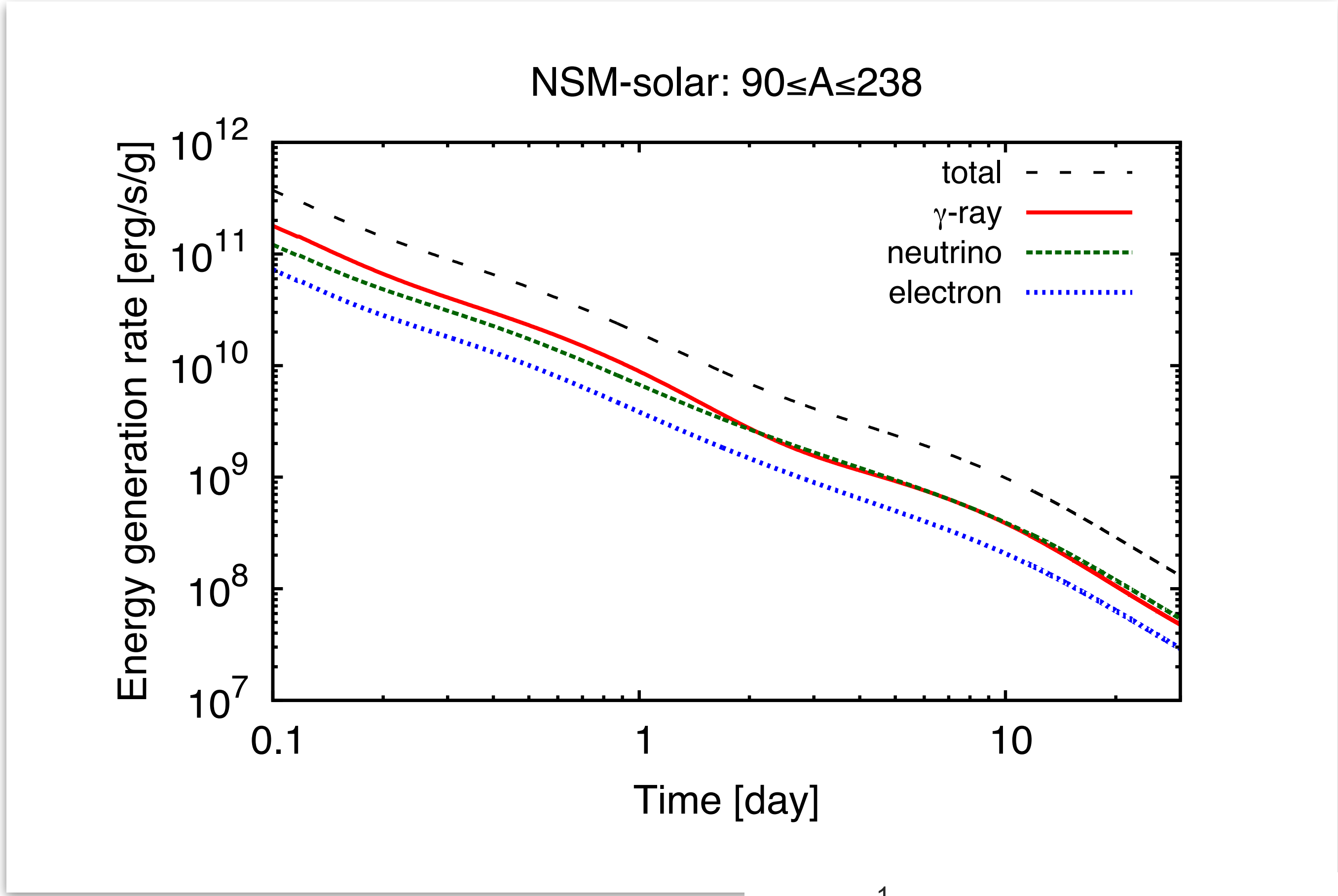


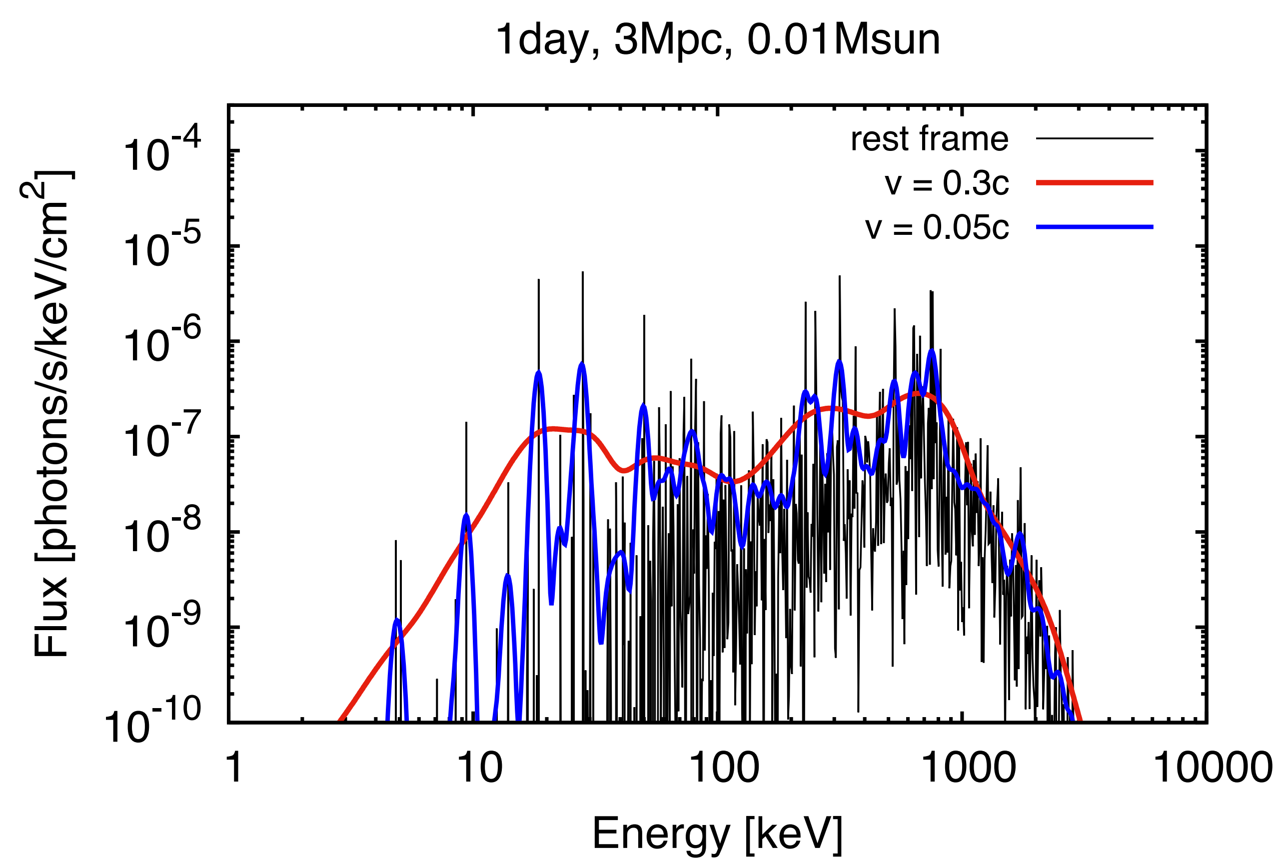
R-process heating

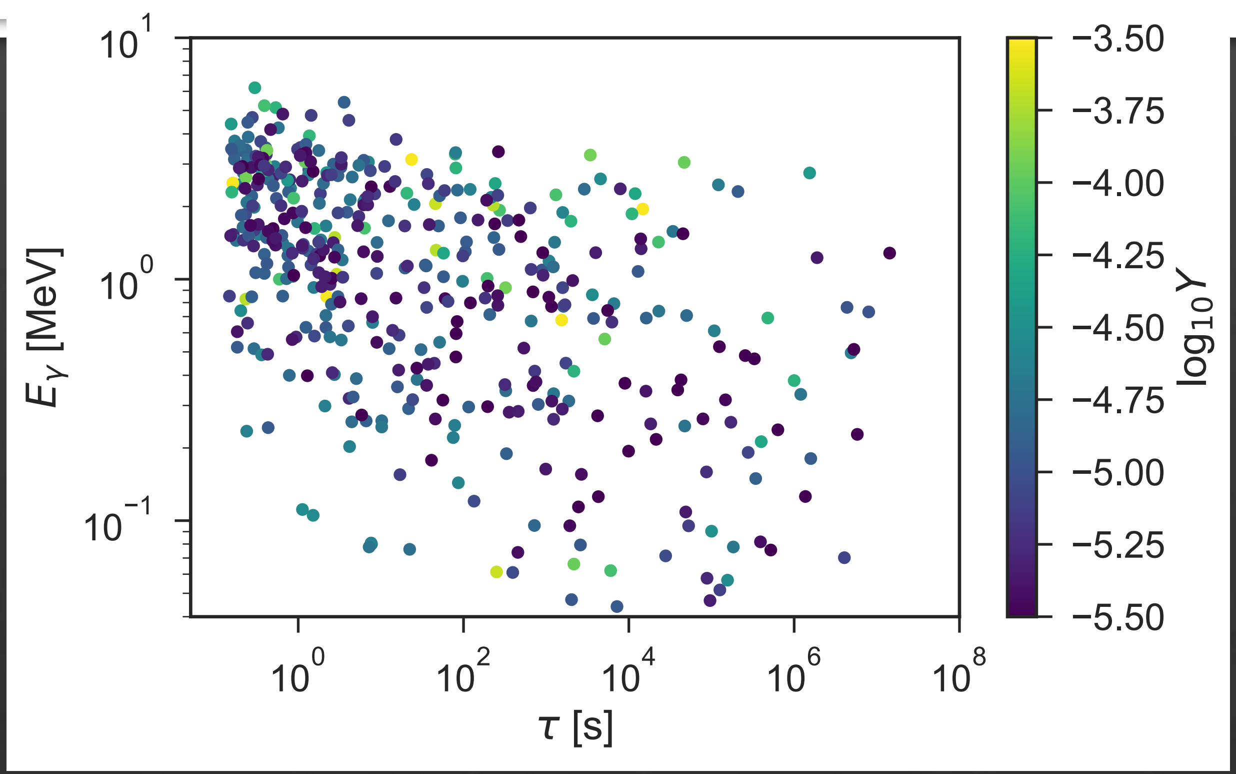
Li & Paczynski 98, Metzger et al 10, Goriely et al 11, Roberts et al 11, Korobkin et al 12, Wanajo et al 14, Lippuner & Roberts 2015, KH et al 16, 18



Gamma-rays from β-decay

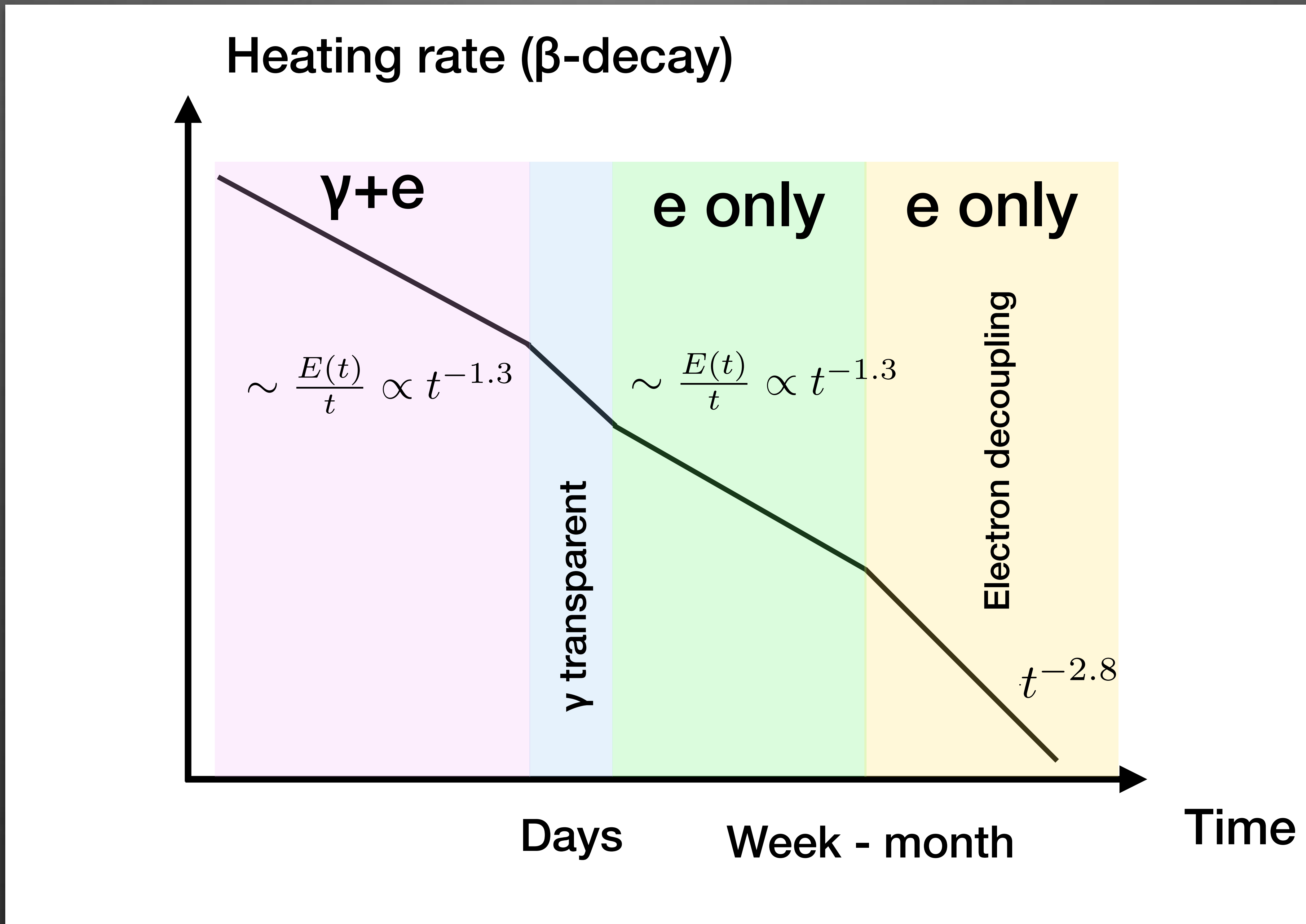






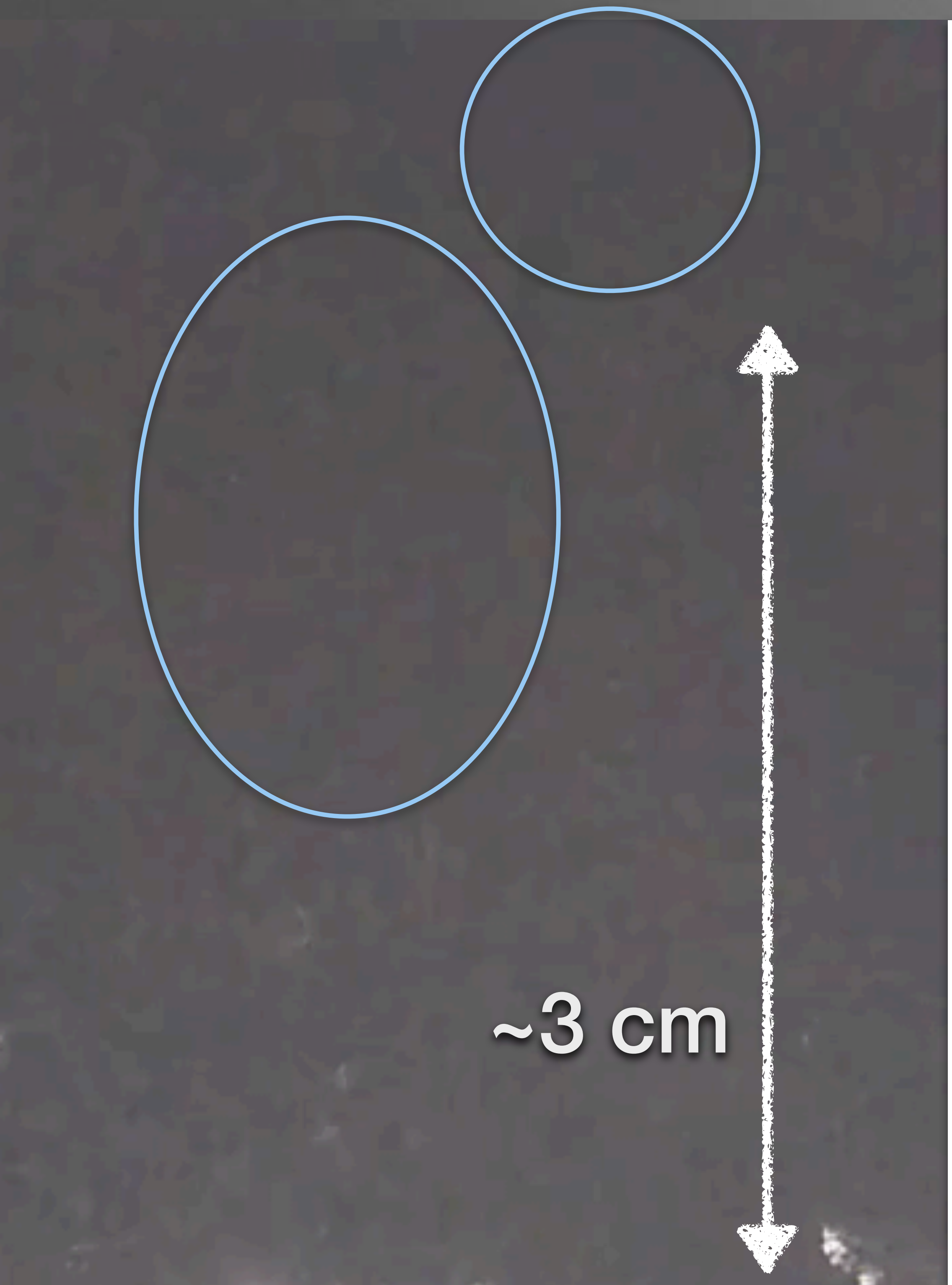
R-process heating rate with thermalization

Barnes+16, KH+16, Kasen & Barnes 19, Wu+18, Waxman+19, KH & Nakar 19



Energy deposition of charged particles

Barnes+16, KH+16, Kasen & Barnes 19, Wu+18, Waxman+19, KH & Nakar 19



The energy evolution of β-electrons:

collision

$$\frac{dE}{dt} = -K_{\rm st}\rho_m v_c$$

Energy deposition of charged particles

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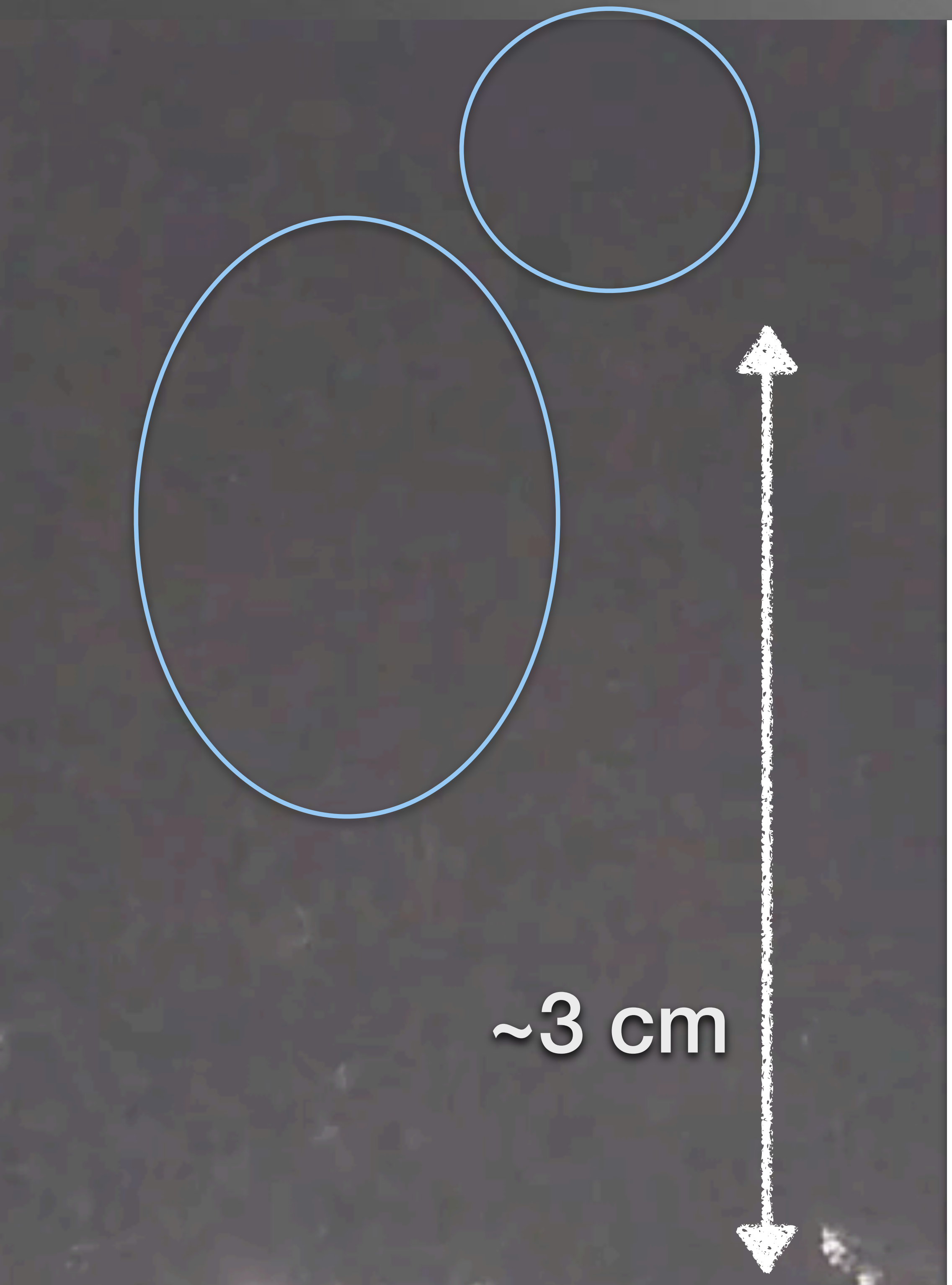

For mergers, the stopping medium expands.

The energy evolution of β-electrons:

collision adiabatic loss

$$\frac{dE}{dt} = -K_{\rm st}\rho_m v_c - 3(\gamma_{\rm ad} - 1)\frac{E}{t},$$

Ejecta density ~ t^{-3}

Energy deposition of charged particles

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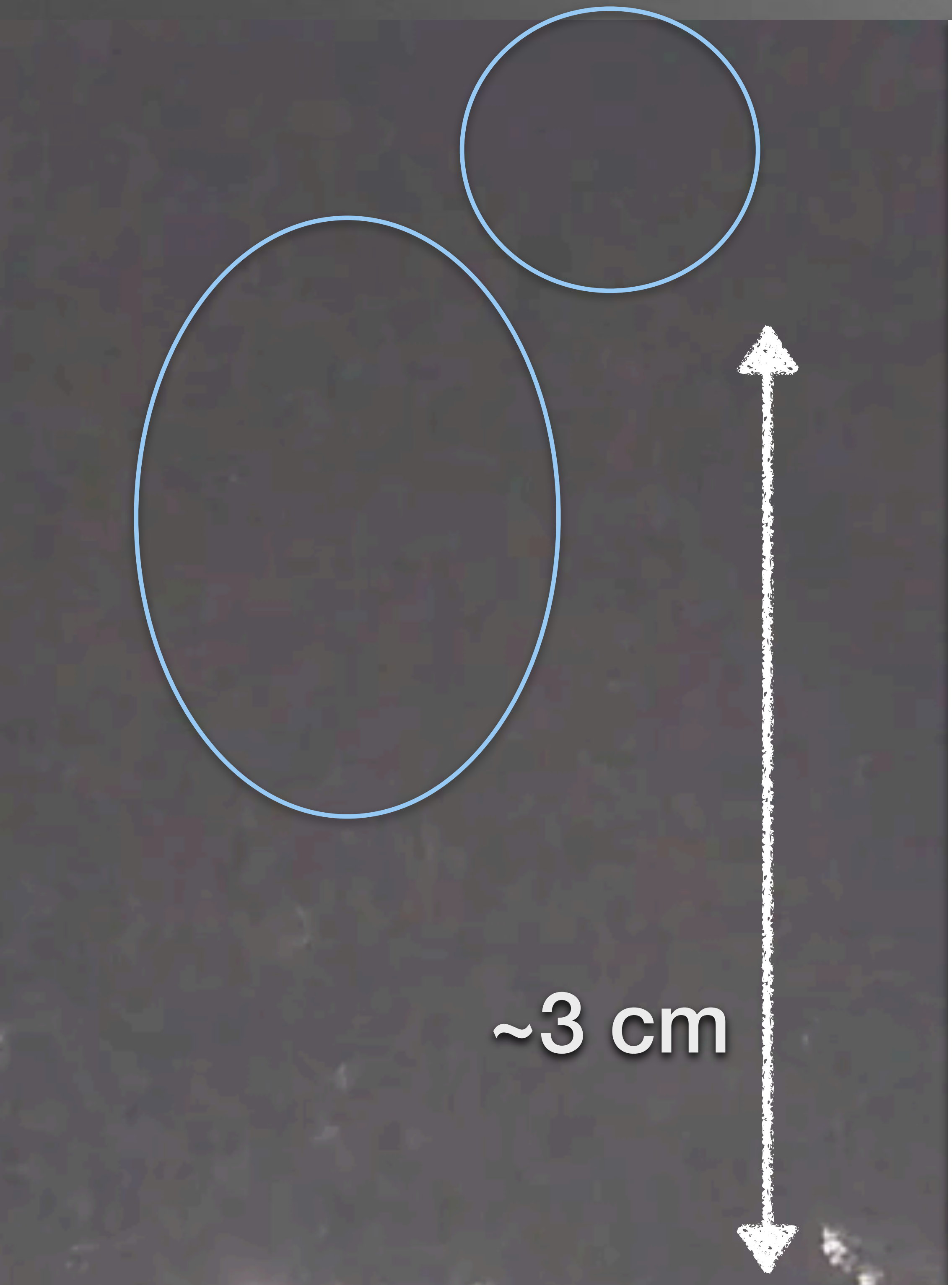

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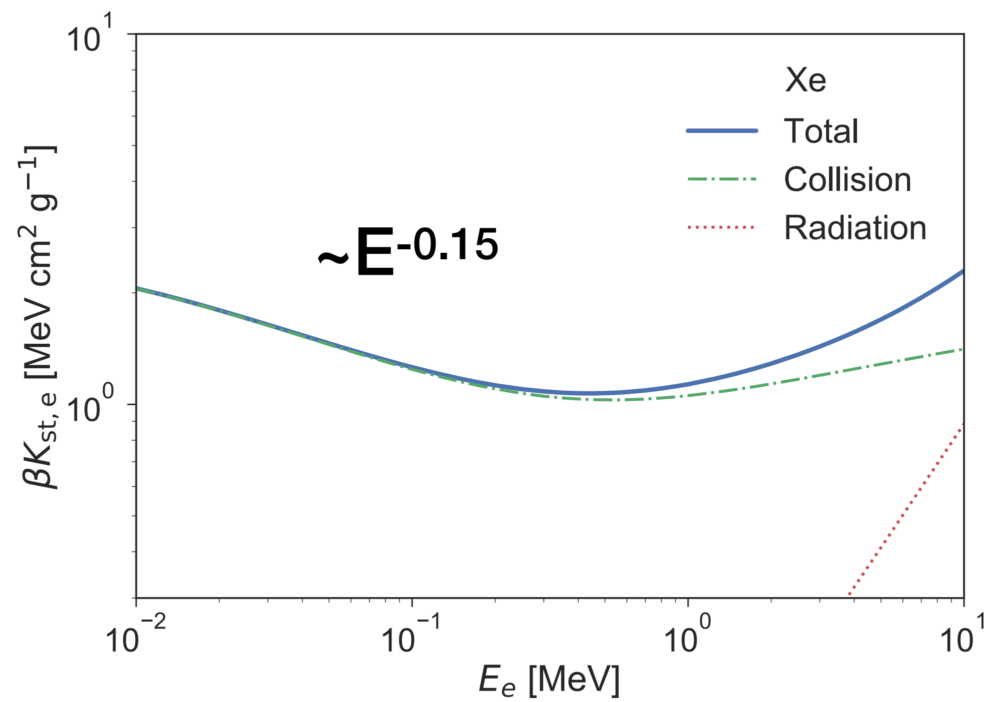

Energy deposition of charged particles

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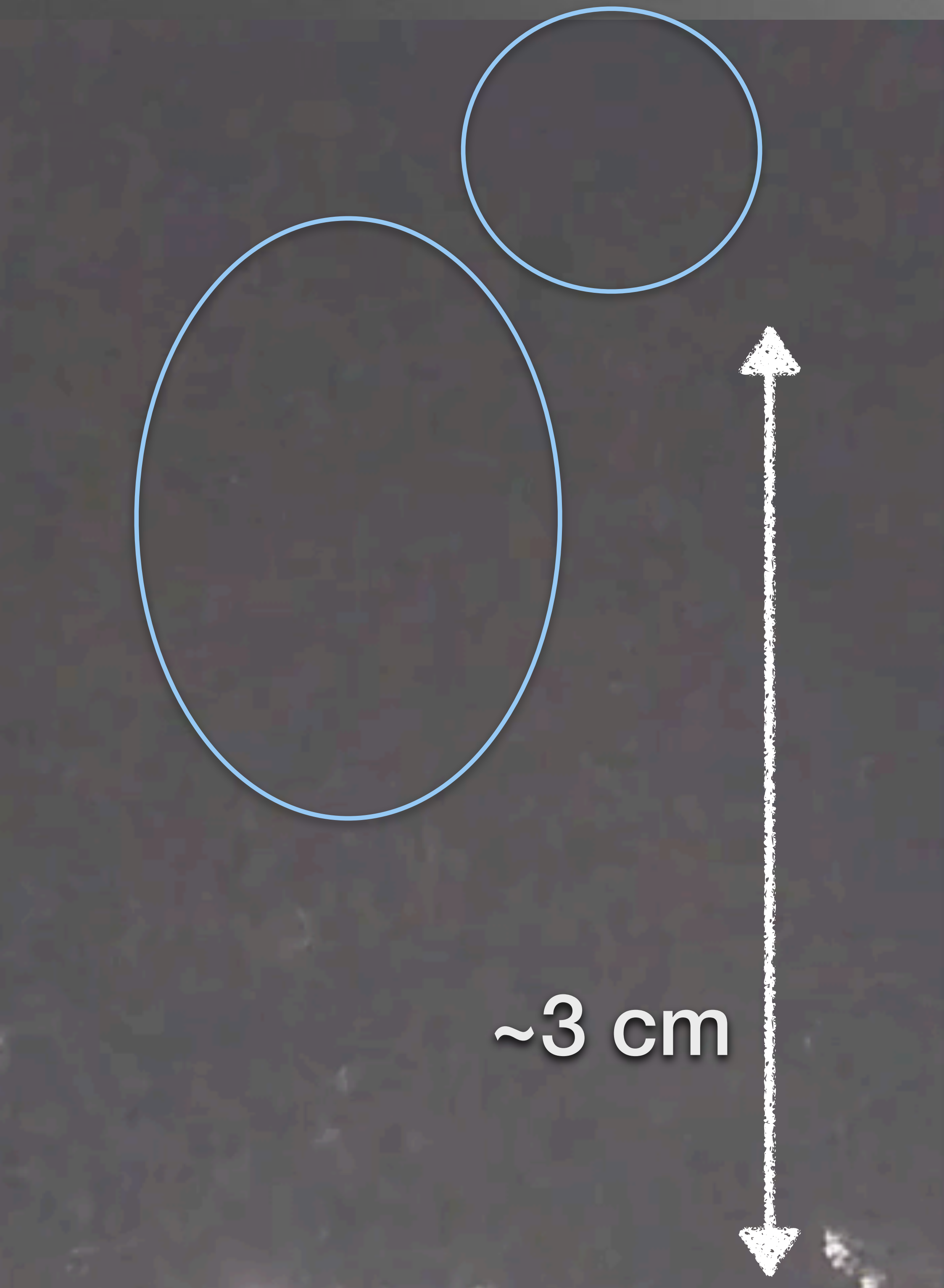

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Ejecta density ~ t^{-3}

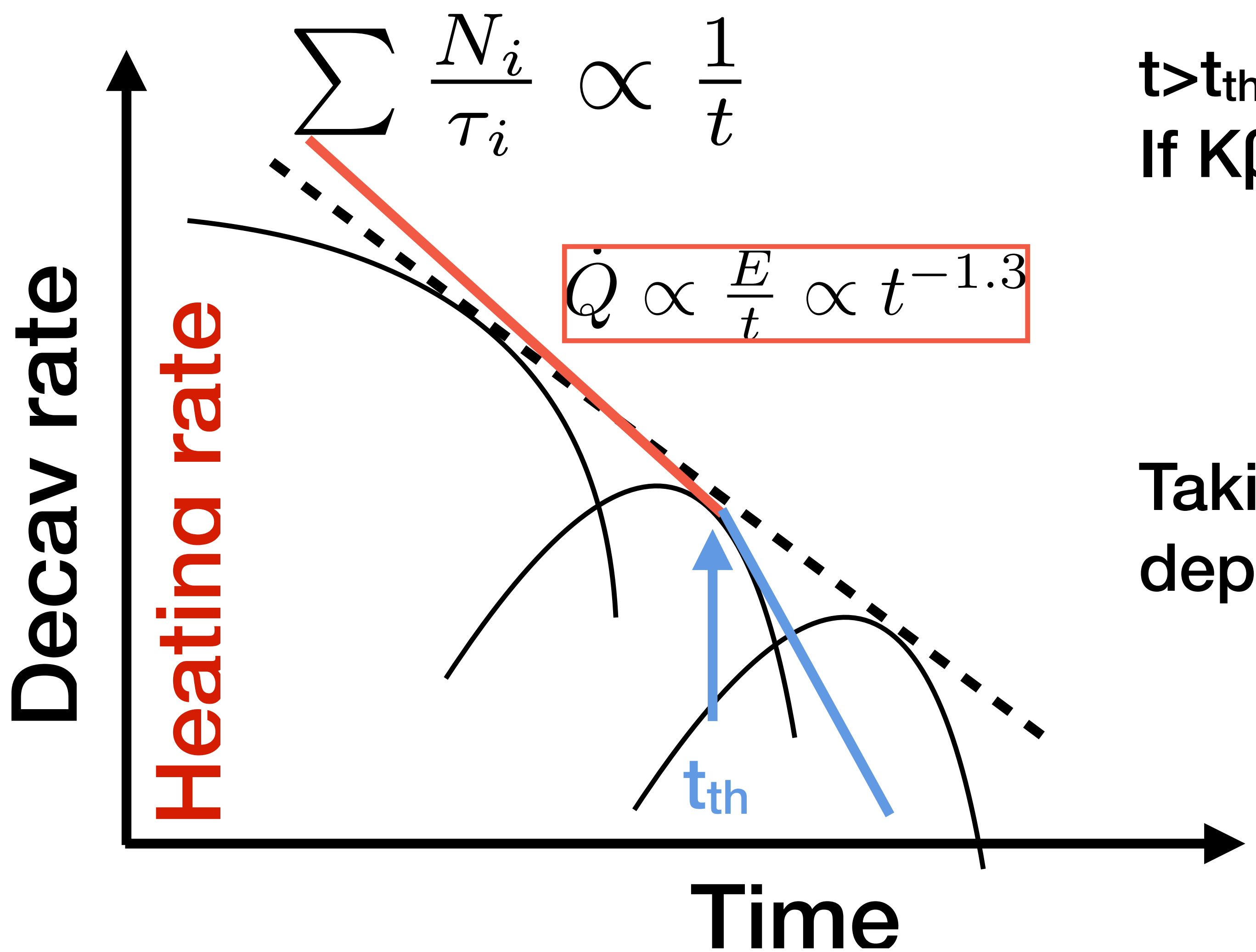
Thermalization time:

$$t_{\mathrm{th},\beta} \approx 55\,\mathrm{day}\left(\frac{C_\rho}{0.05}\right)^{1/2}\left(\frac{M_{\rm ej}}{0.05M_\odot}\right)^{1/2}\left(\frac{\kappa_{\beta,\rm eff}}{4.5\,\mathrm{cm}^2/\mathrm{g}}\right)^{1/2}\left(\frac{v_0}{0.1c}\right)^{-3/2}$$

After t_{th}, fast electrons decouple with matter, i.e., the collisional energy loss takes longer than one dynamical time.

Late time heating rate

Kasen & Barnes 19, Waxman+19, KH & Nakar 19



$t>t_{th}$, fast particles accumulate.
If Kβ is constant, the heating rate is

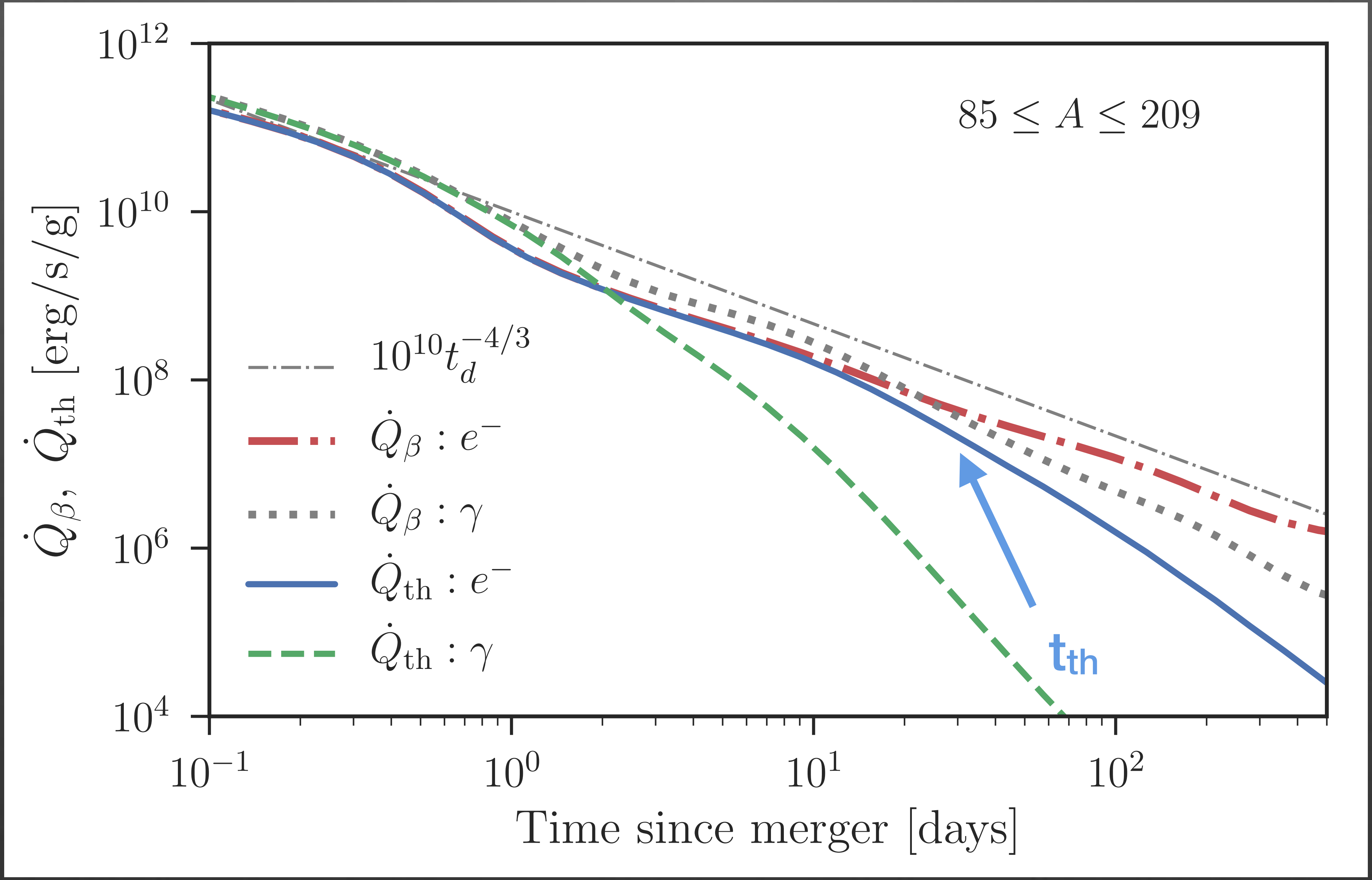
$$\dot{Q}_{\rm th}(t) \propto \rho(t) \propto t^{-3}$$

Taking into account for the energy dependence of Kβ:

$$\dot{Q}_{\rm th}(t) \lesssim t^{-2.8}$$

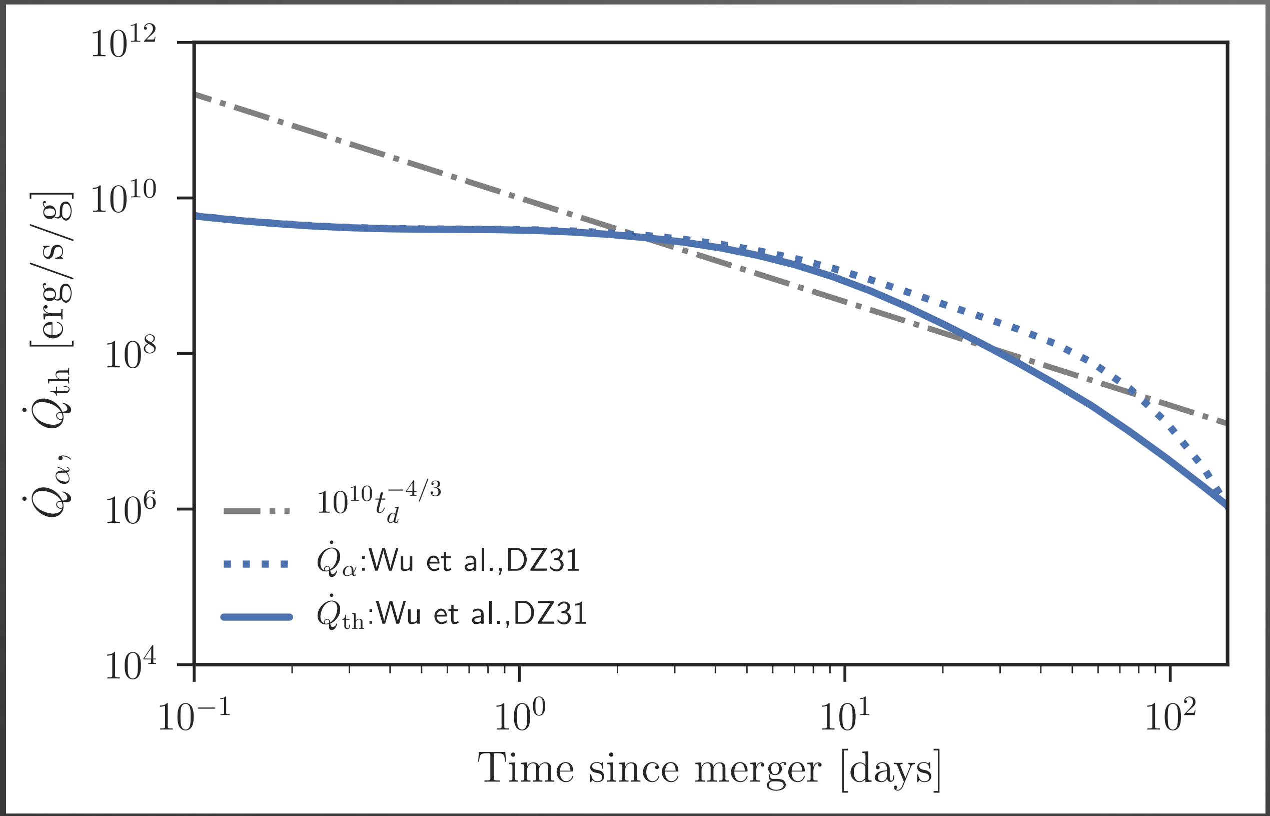
β-decay Heating rate

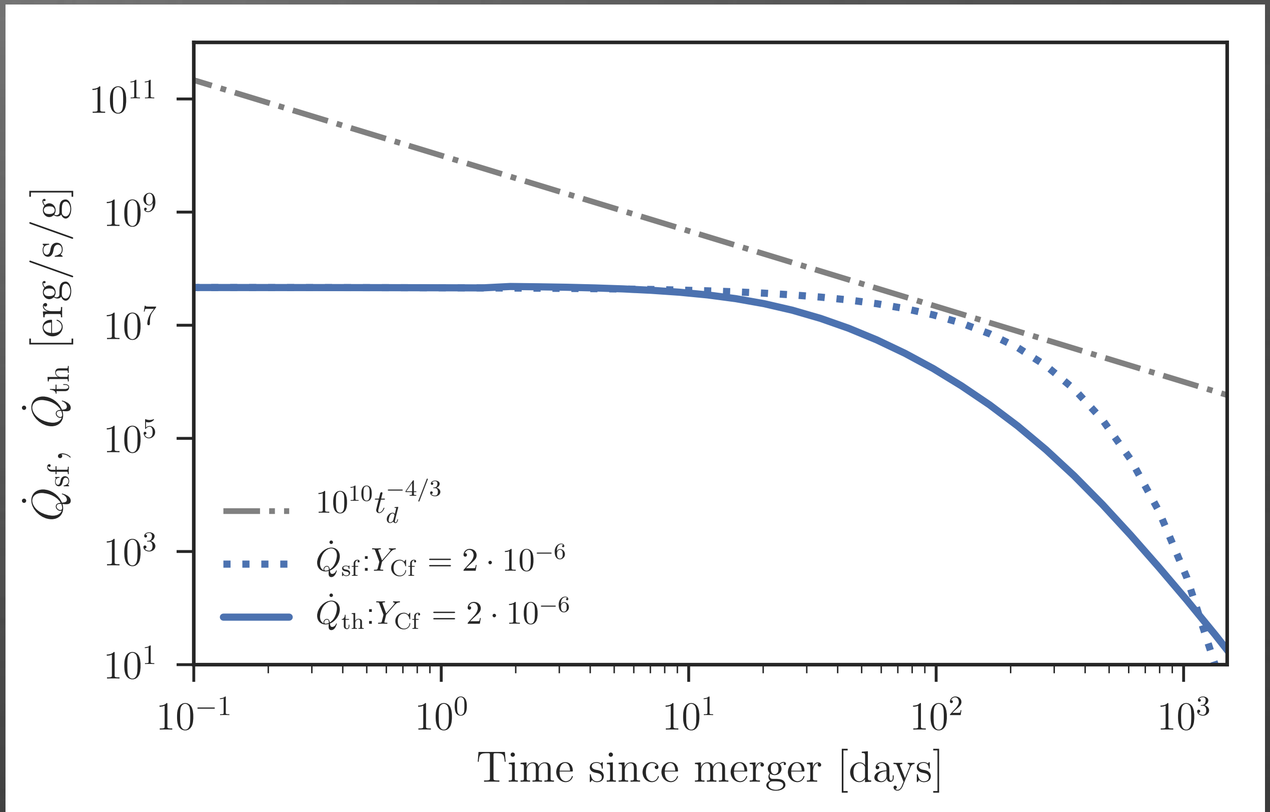
KH & Nakar 19, https://github.com/hotokezaka/HeatingRate



Thermalization of alpha and fission

KH & Nakar 19, https://github.com/hotokezaka/HeatingRate





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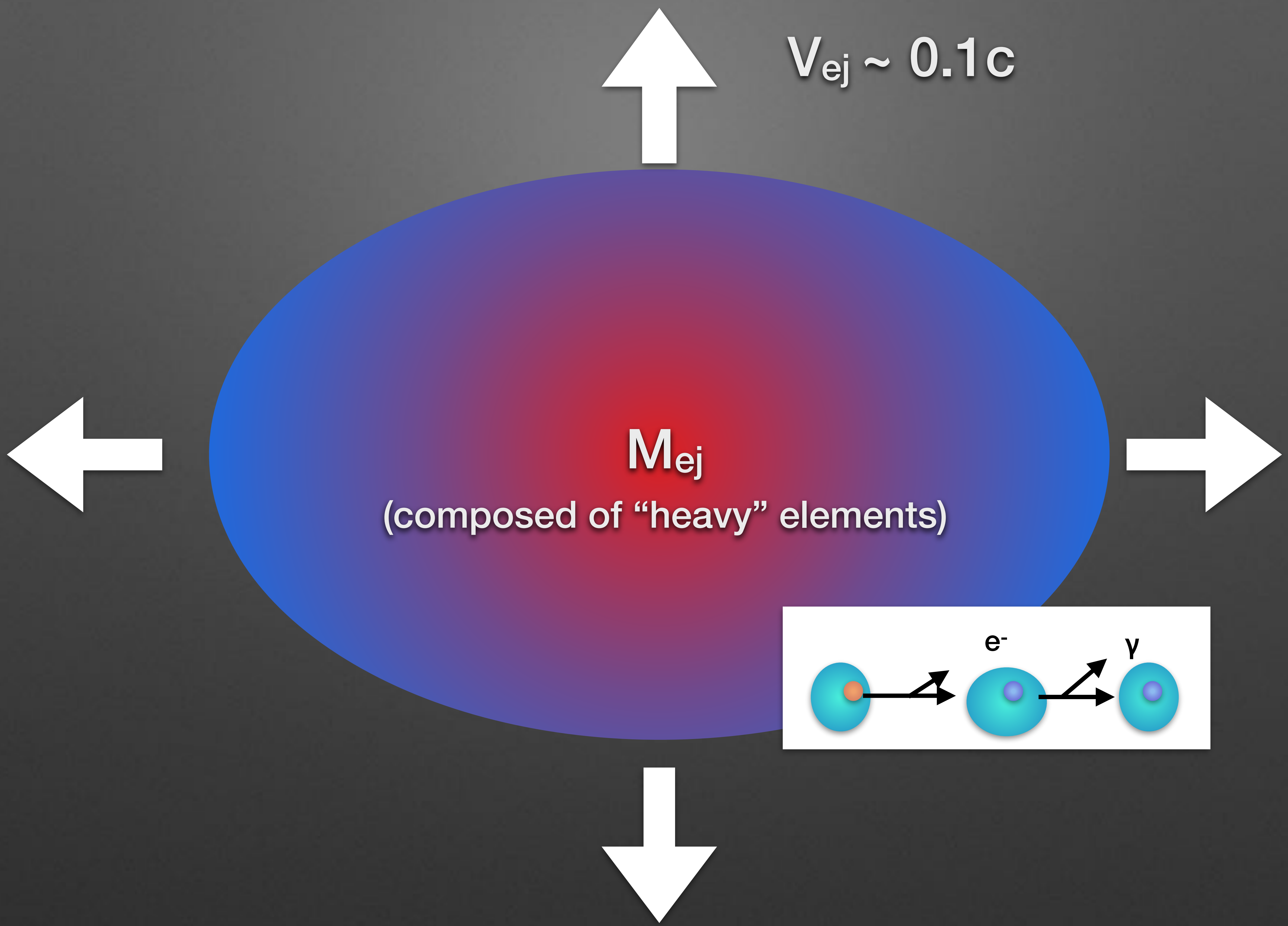


$V_{ej} \sim 0.1c$
M_{ej}
(composed of “heavy” elements)
e^-
γ

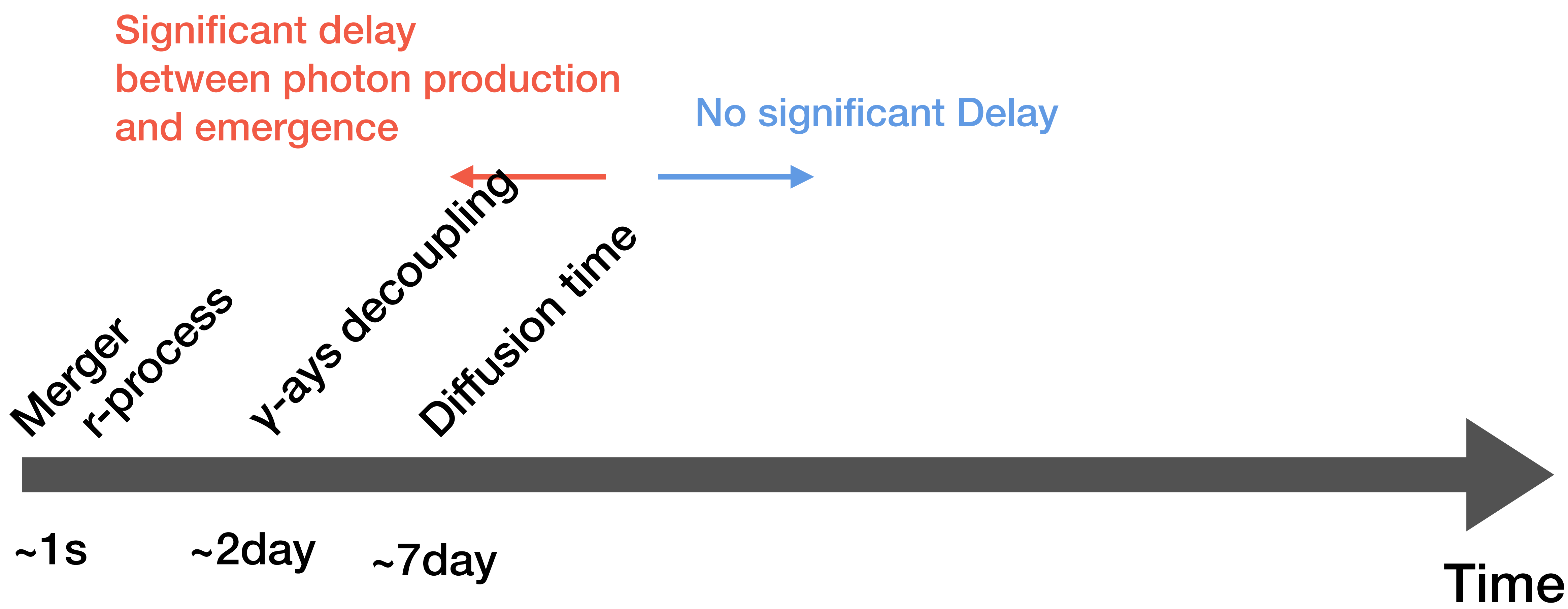
Relevant Particles

- Fast electrons from β decay (heat source)
- γ-rays from decay (heat source)
- Thermal free electrons
- Heavy elements
- Low energy photons

There are also

- Fast α-particles from α-decay
- Fast heavy particles from fission

Thermal History of Merger Ejecta



Example: Mej ~ 0.05Msun, v ~ 0.1c, n ~ t^{-3}

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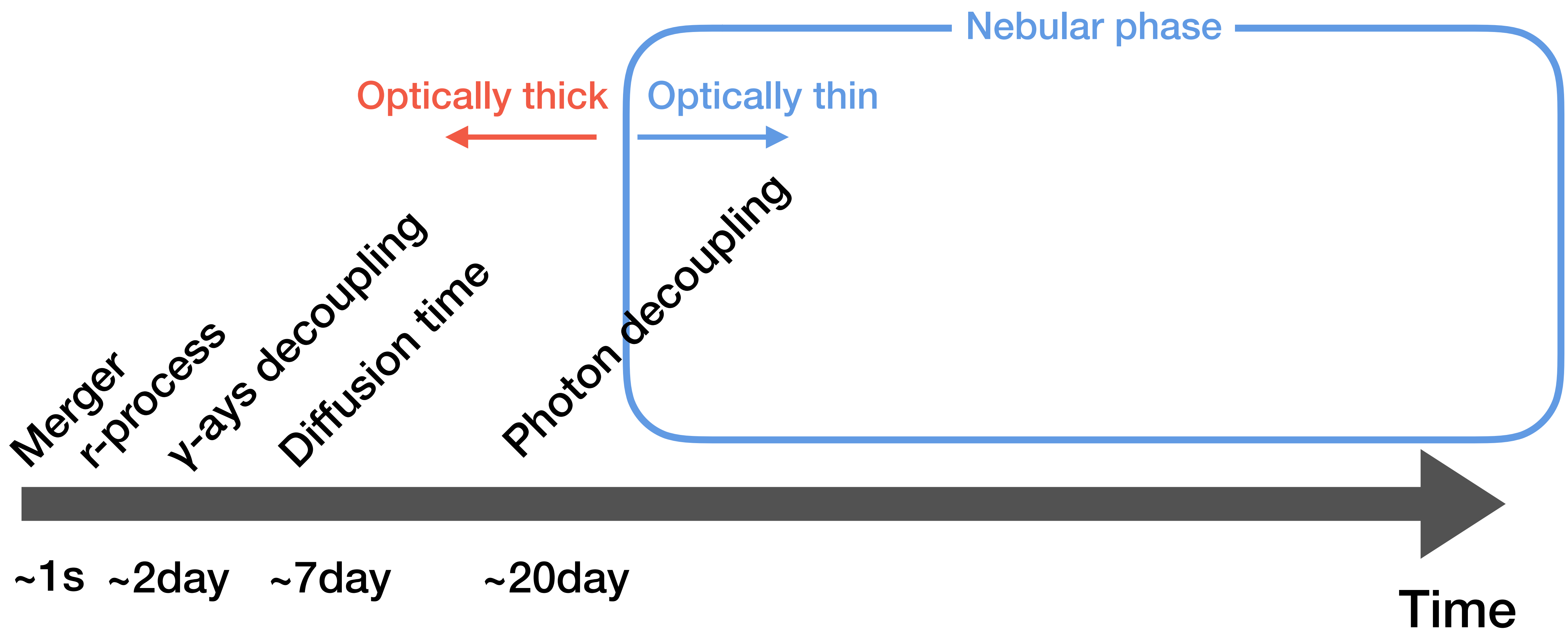

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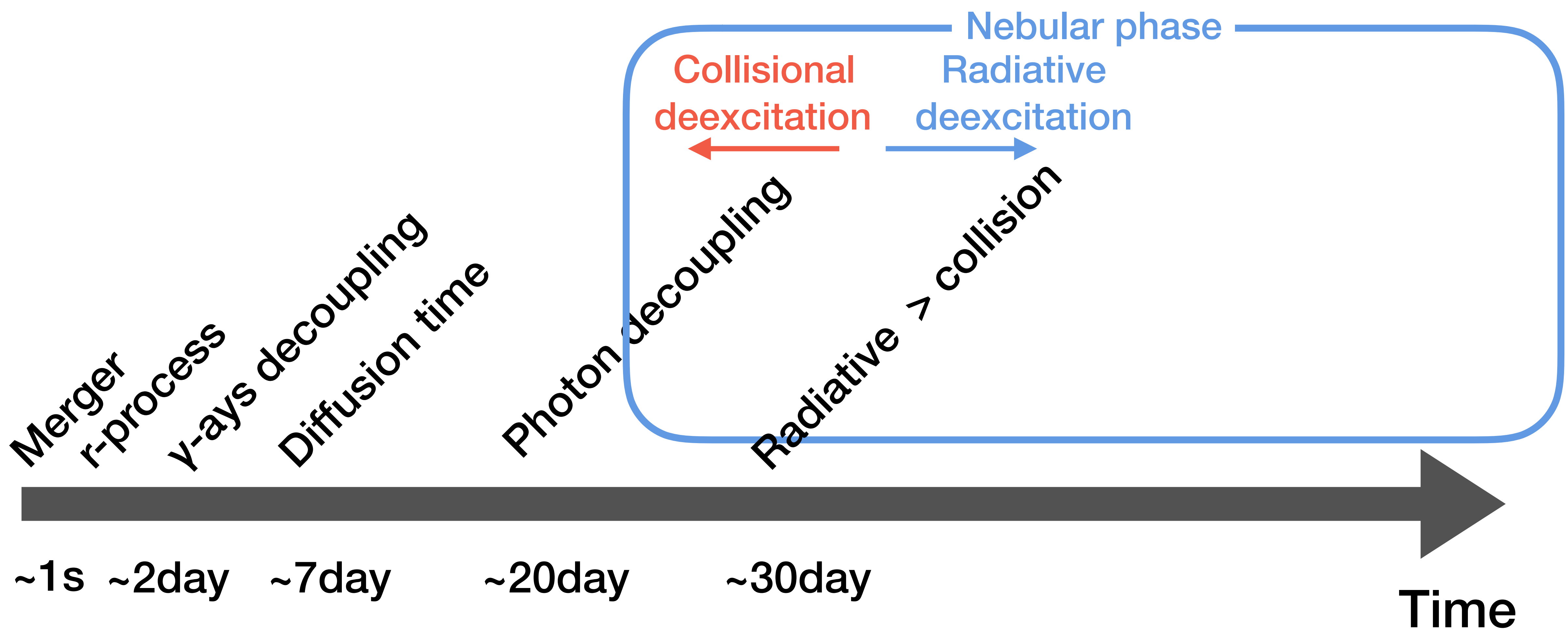

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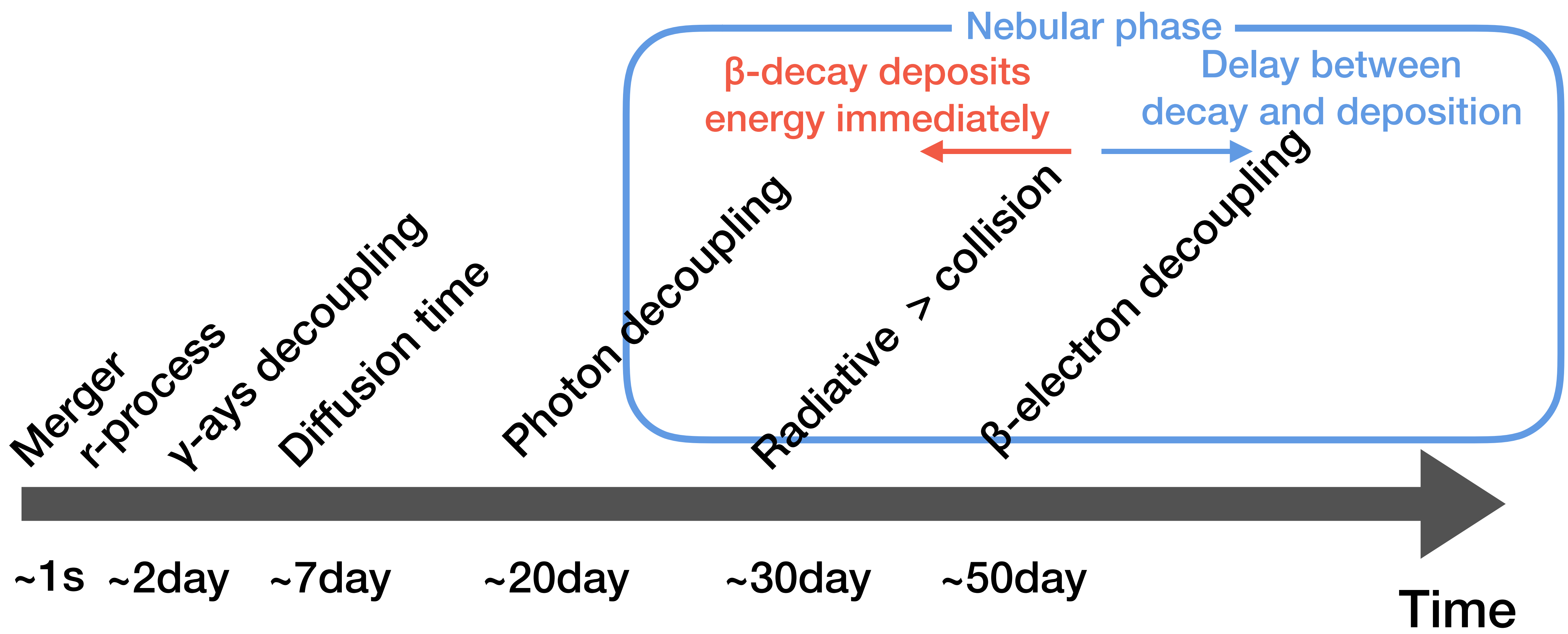

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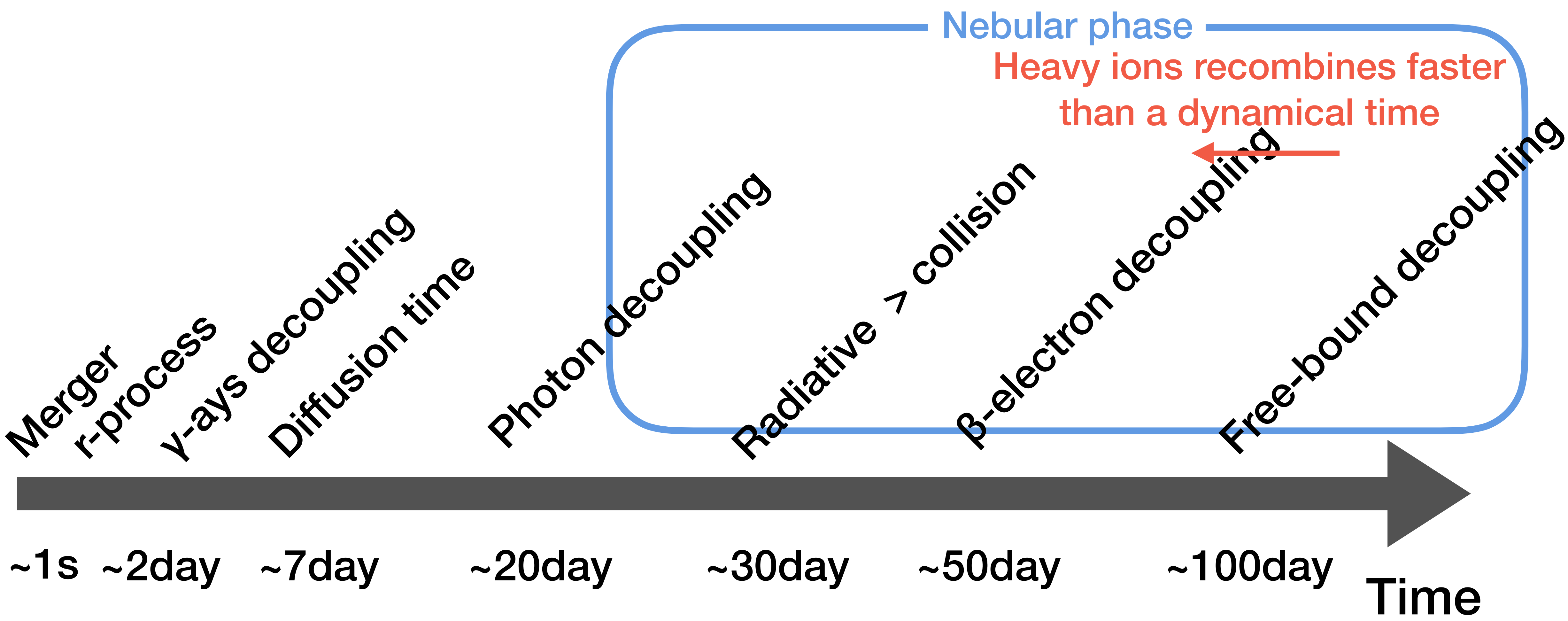

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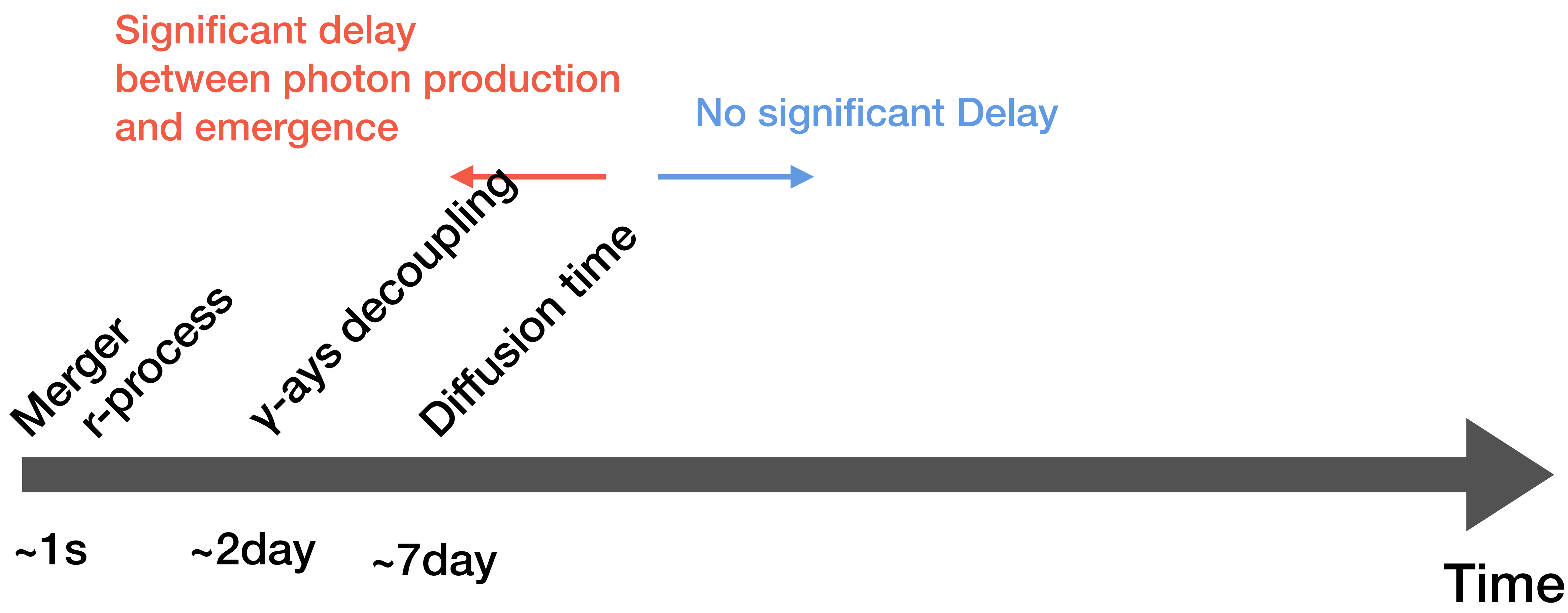

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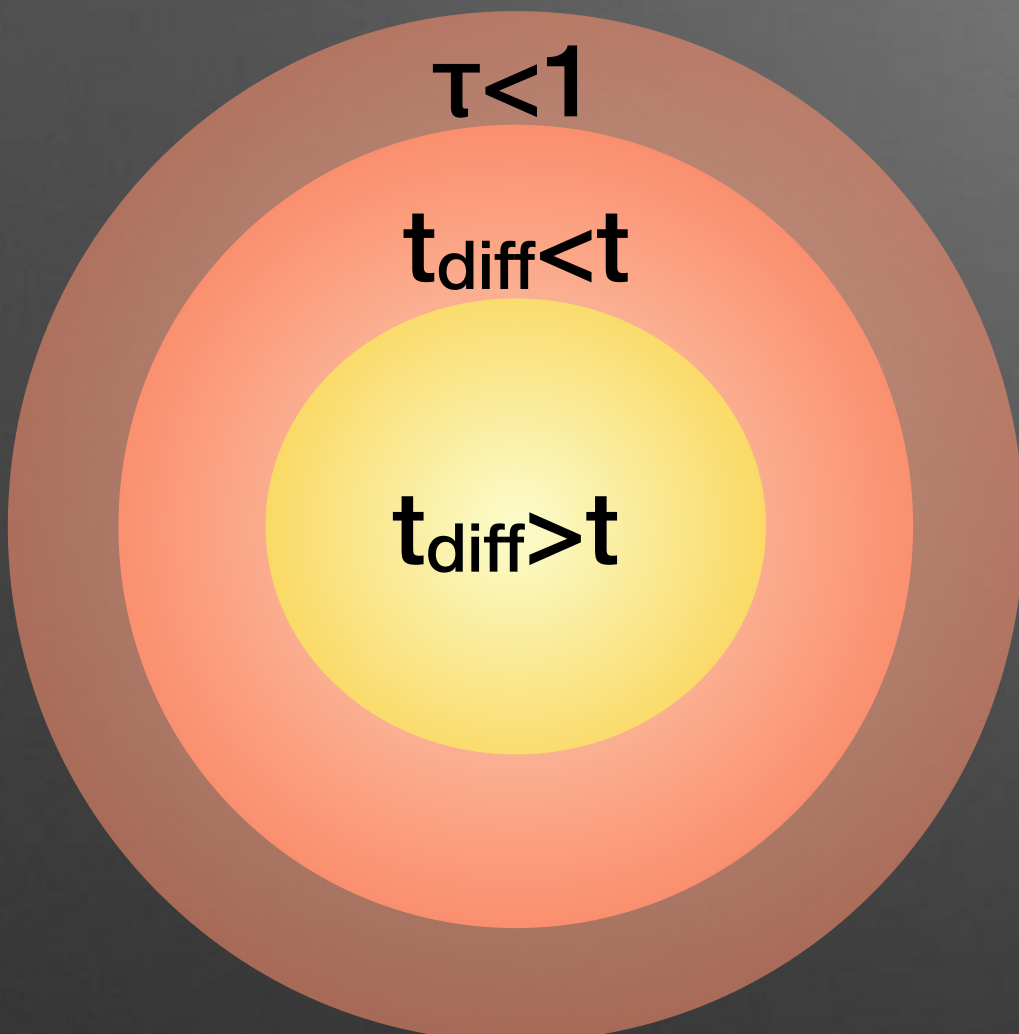
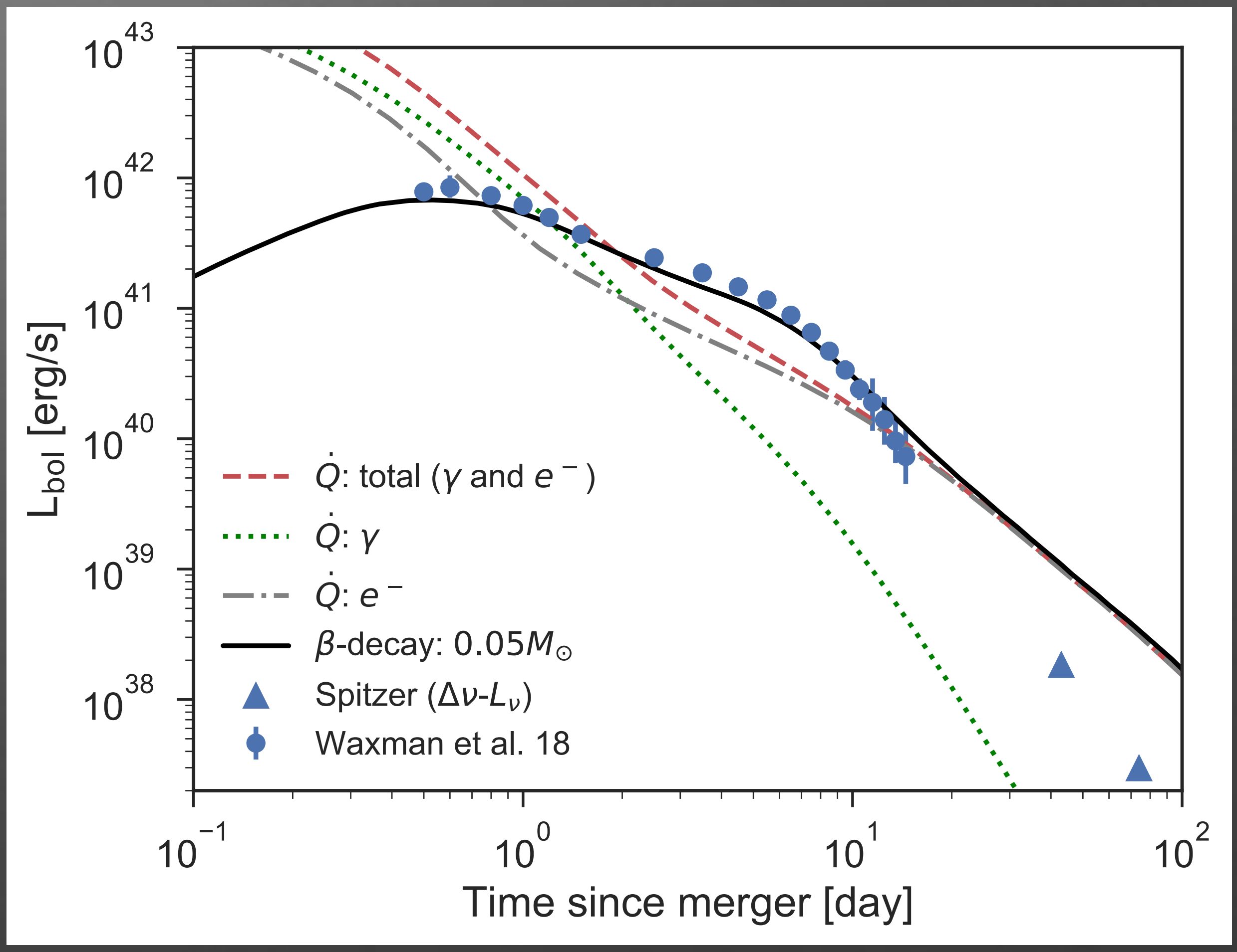
Pre-Nebular Phase: Kilonova

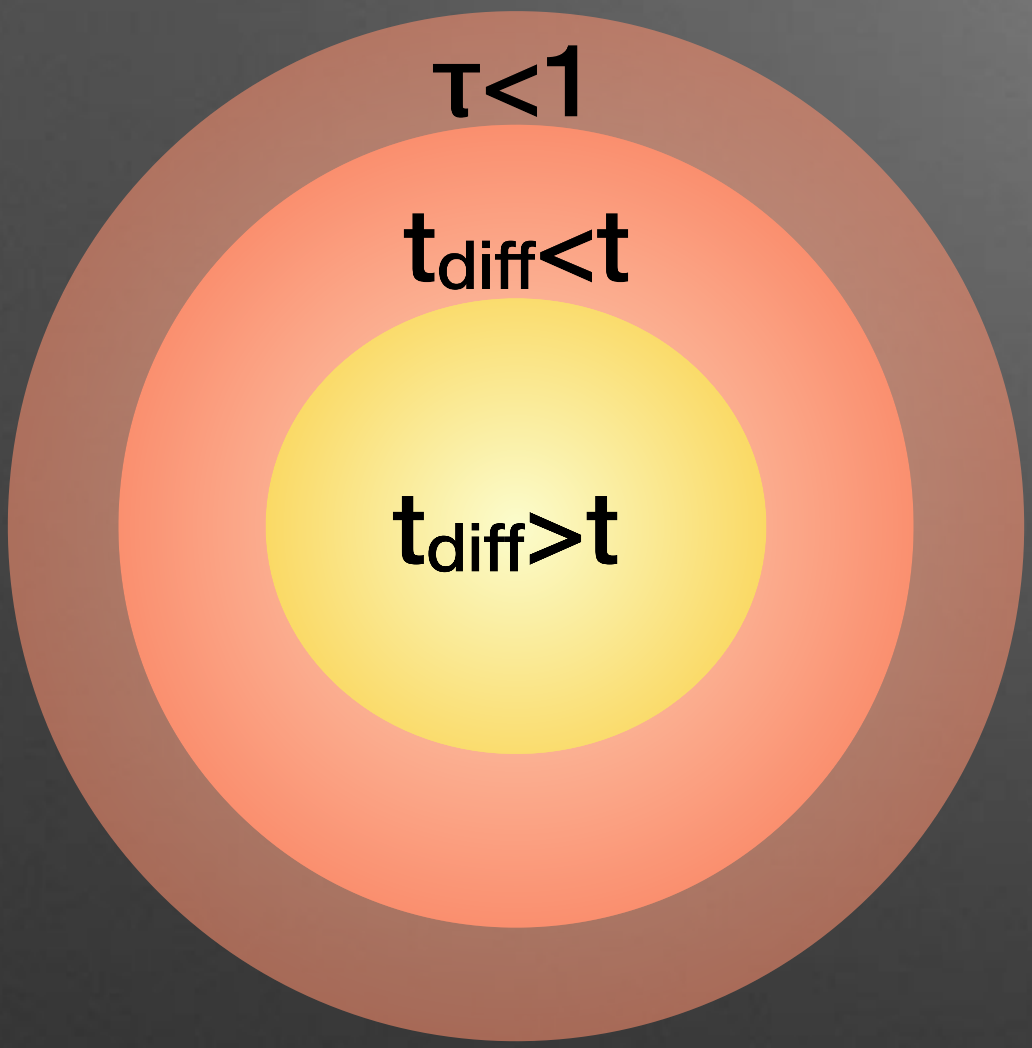


KH & Nakar 19, https://github.com/hotokezaka/HeatingRate



- Bolometric light curve follows the r-process heating rate.
- The steep decline around a week can be interpreted as the diffusion wave crossing the entire ejecta.

Pre-Nebular Phase: Kilonova



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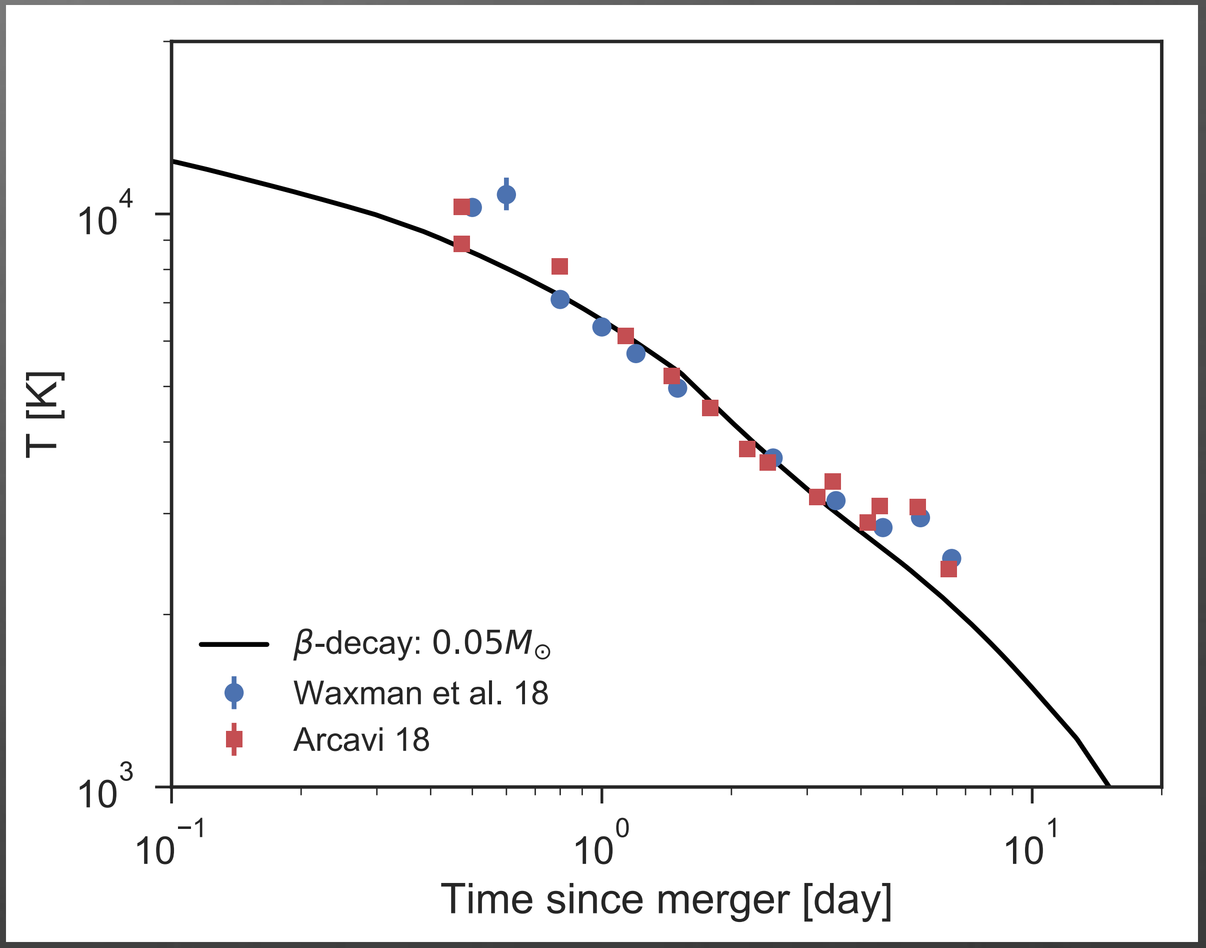
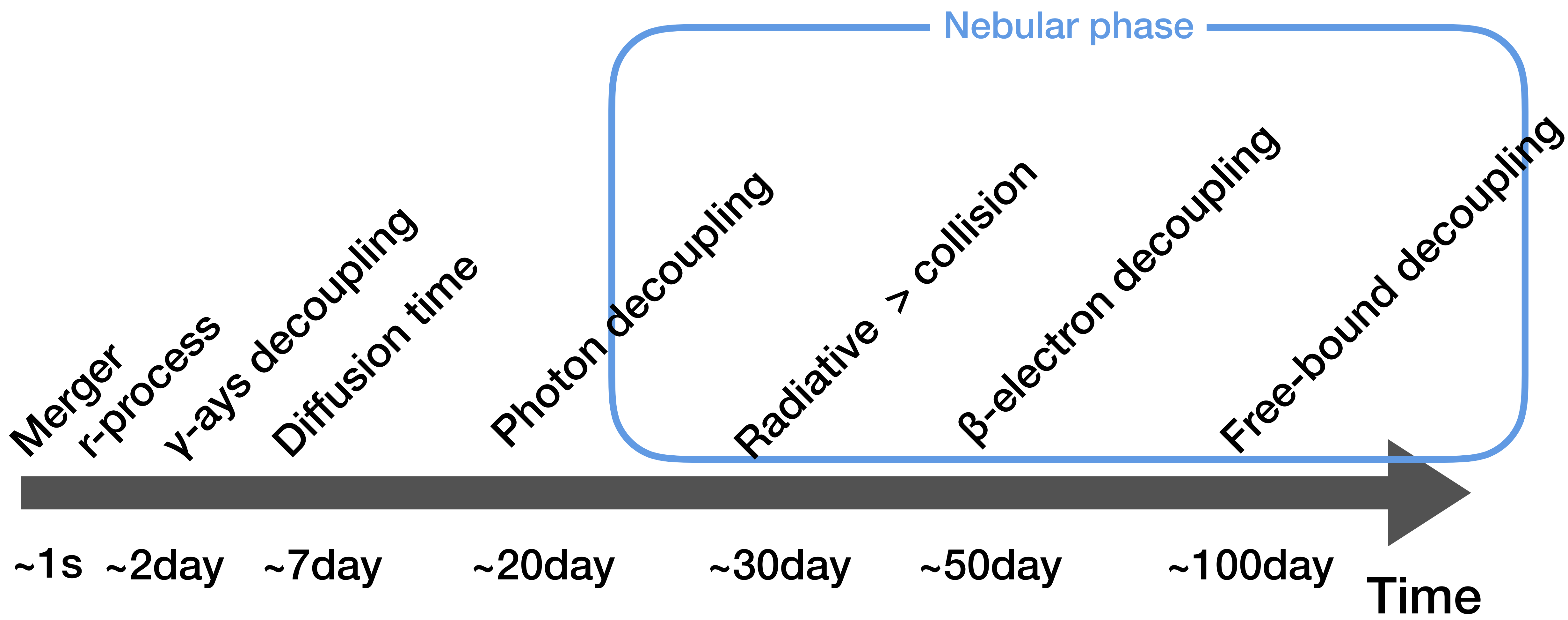


- The temperature decreases in this phase.

Thermal History of Merger Ejecta

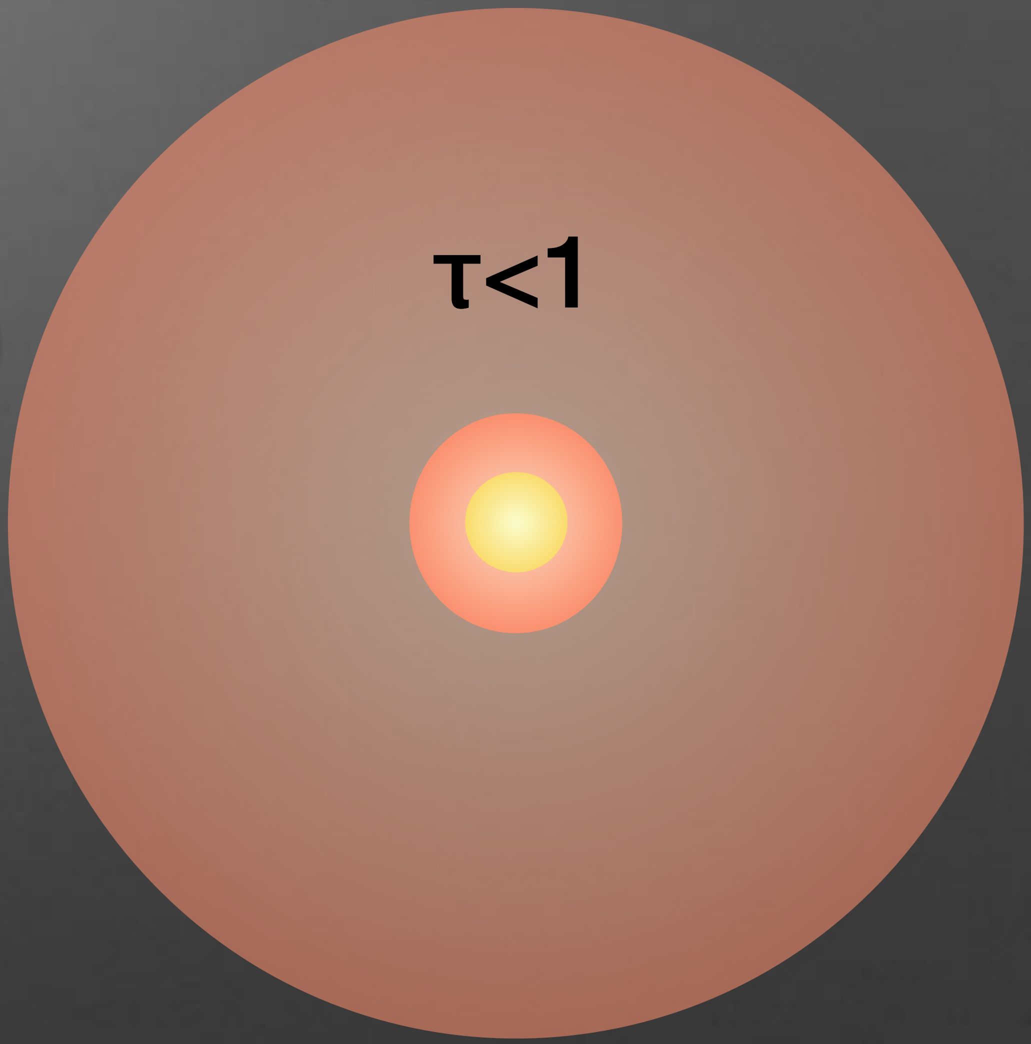


Example: Mej ~ 0.05Msun, v ~ 0.1c, n ~ t^{-3}

Calculation of Nebular Spectrum

Local thermodynamic equilibrium is no longer valid.

One must solve consistently
1. Ionization balance
2. Thermal balance (cooling = heating)
3. Level population => Emission



Solving Nebular State

Heating Rate $\dot{Q}(t)$
Baryon density $n(t)$

→ Guess T_e

↓

Solve ionization states
$n(X^{+i})$, n_e

↓

Solve atomic level population
$n(X^{+i})_j$

↓

Get cooling function (erg/s/cm^3)
$\Lambda(T_e)$

↓

Get new T_e
from $\Lambda = \Gamma$, where $\Gamma = Q/n^2$

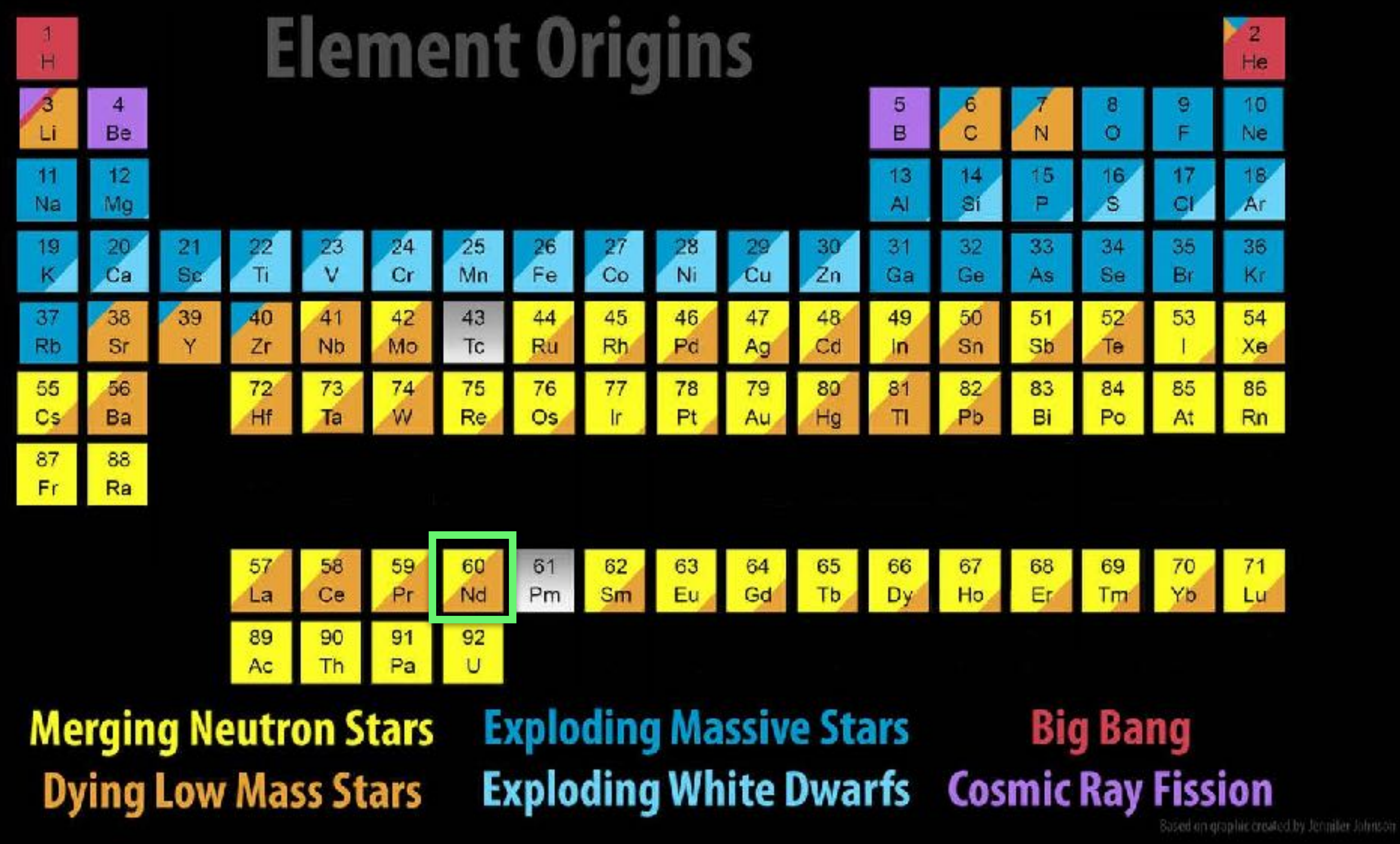
Atomic quantities

- Work per unit ion pair: $w(X^{+i})$
- Recombination rate coefficient: $\alpha(X^{+i})$
- Energy levels: E_i
- Radiative transition rate: A_{ij}
- Collision strength: Ω_{ij}

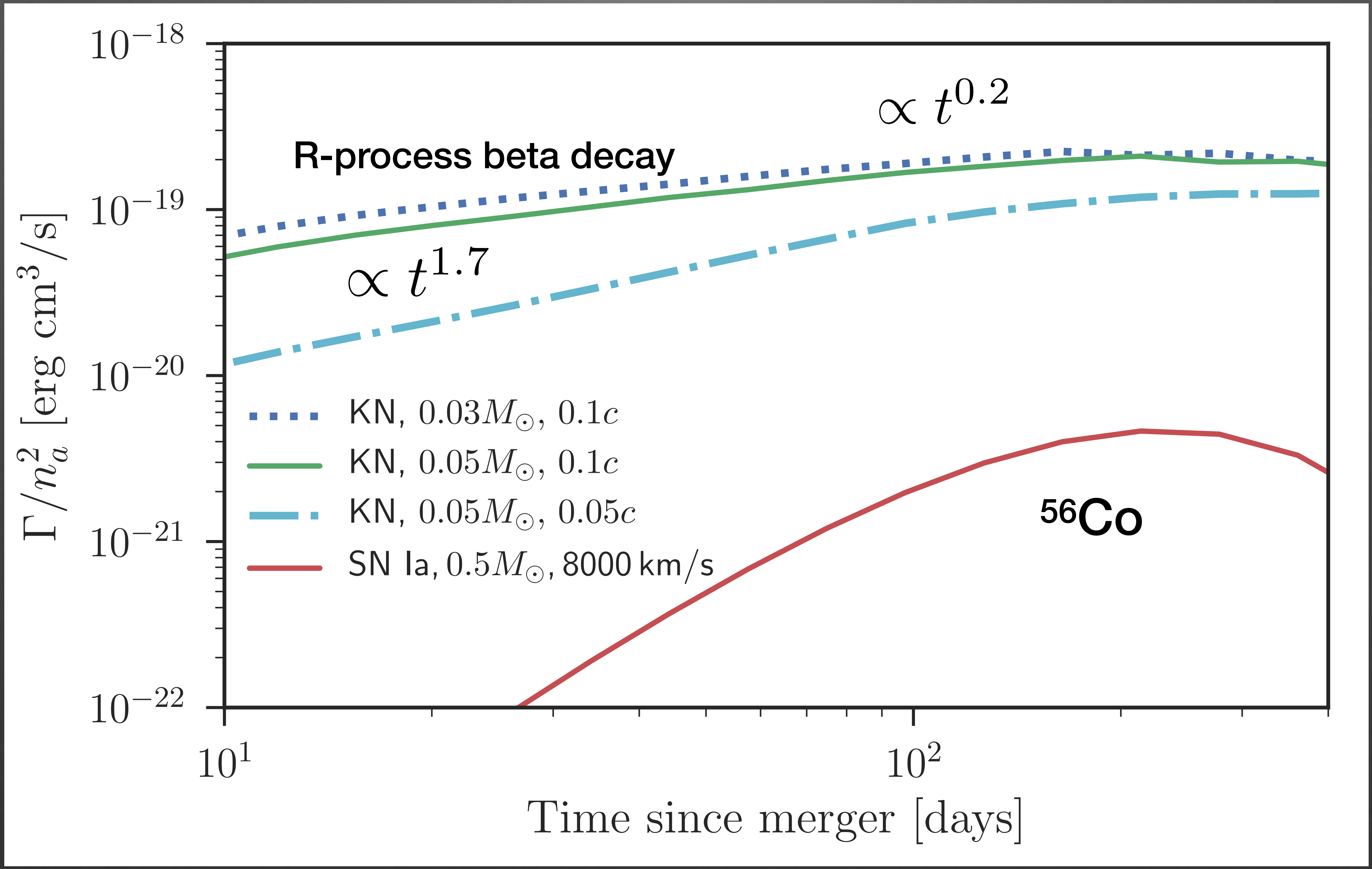
Unfortunately, most of them are not experimentally know.

We use Hebrew University Lawrence Livermore Atomic code (HULLAC) and General-purpose Relativistic Atomic Package (GRASP).

Focusing on Nd

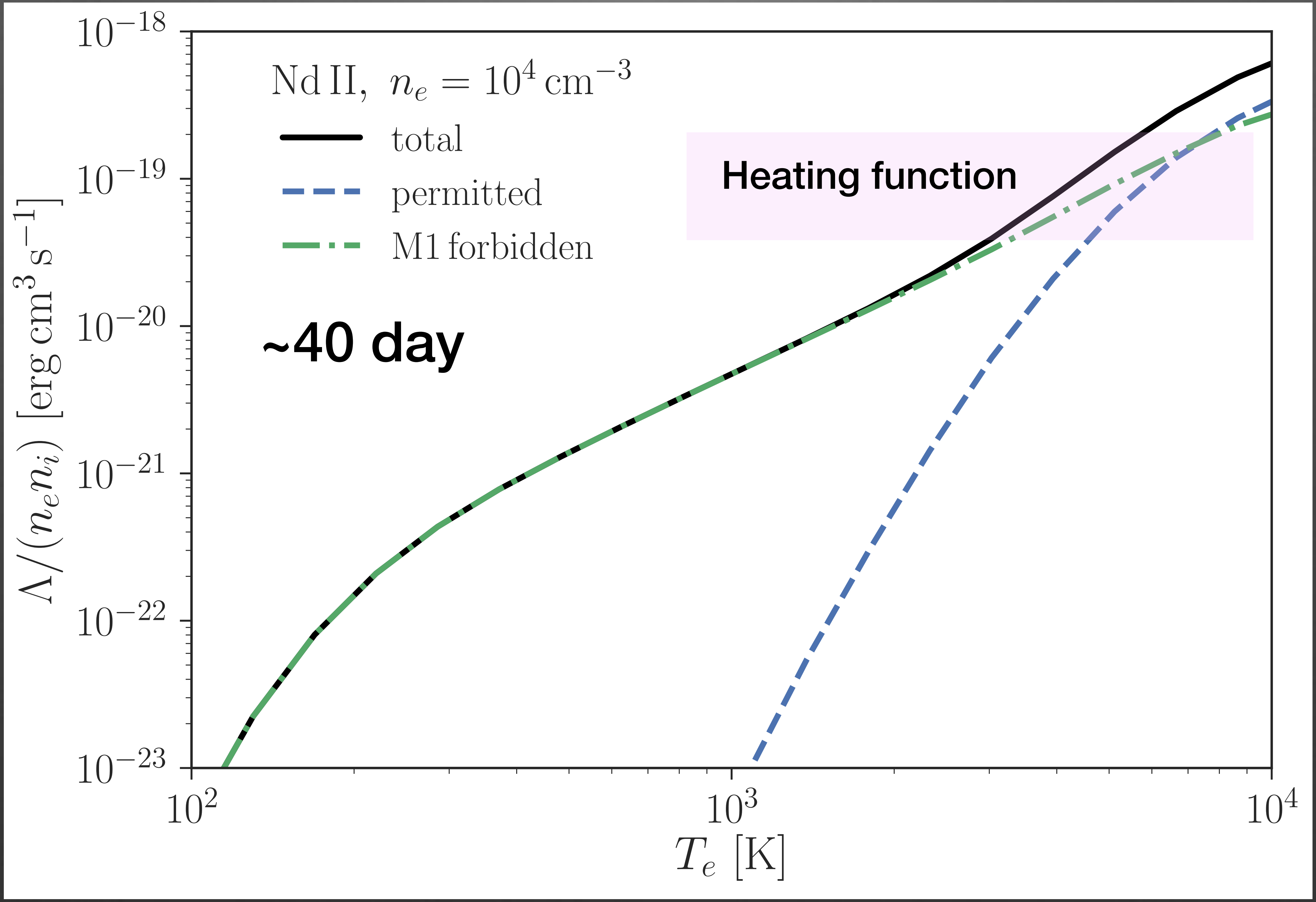


Heating (ionization) function



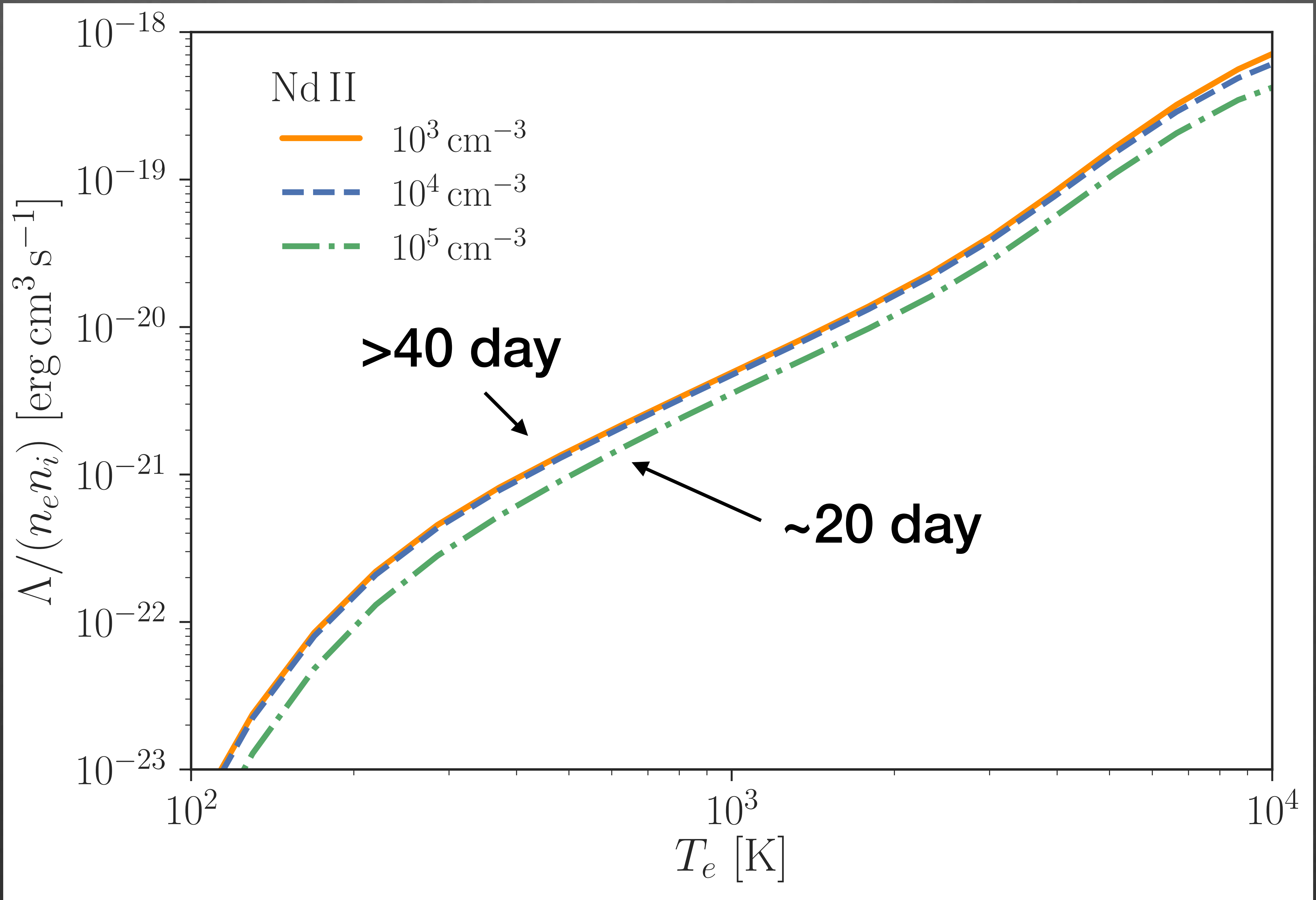
- Temperature is frozen after the electron decoupling time.
- The ionization degree behaves similarly.

Cooling functions



Both permitted and forbidden lines are important.

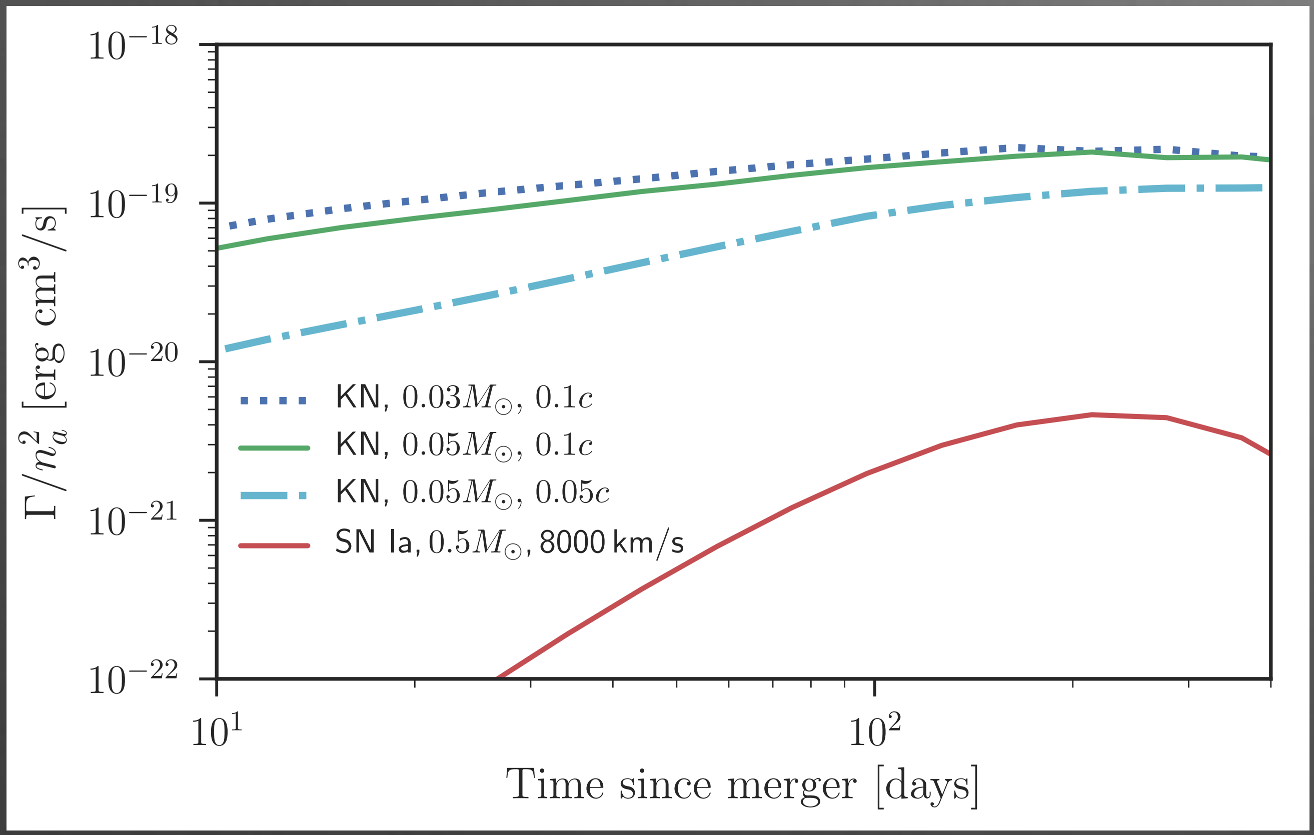
Cooling functions



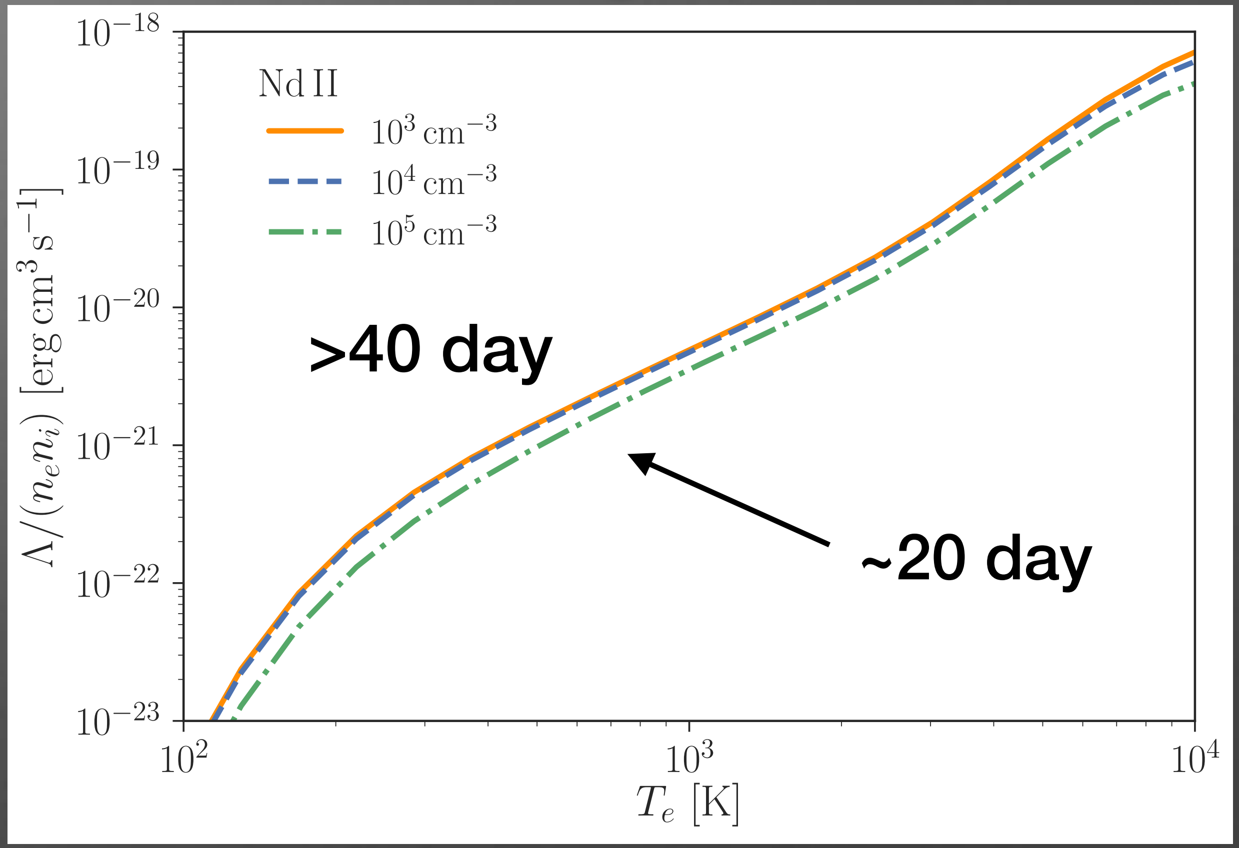
At later times (lower density), Λ/n^2 is independent of time.

Slowly evolving T_e

Heating function



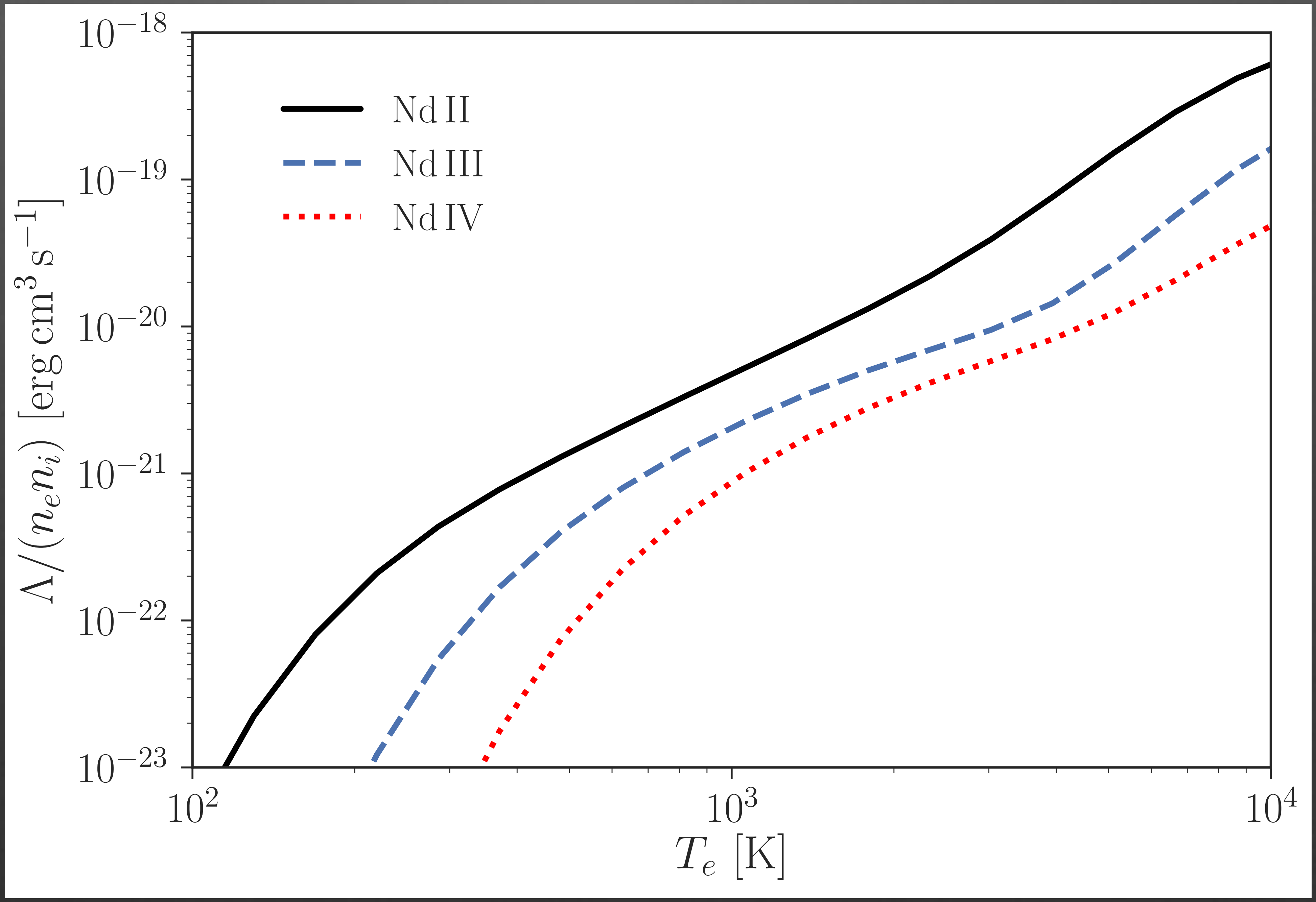
Cooling function



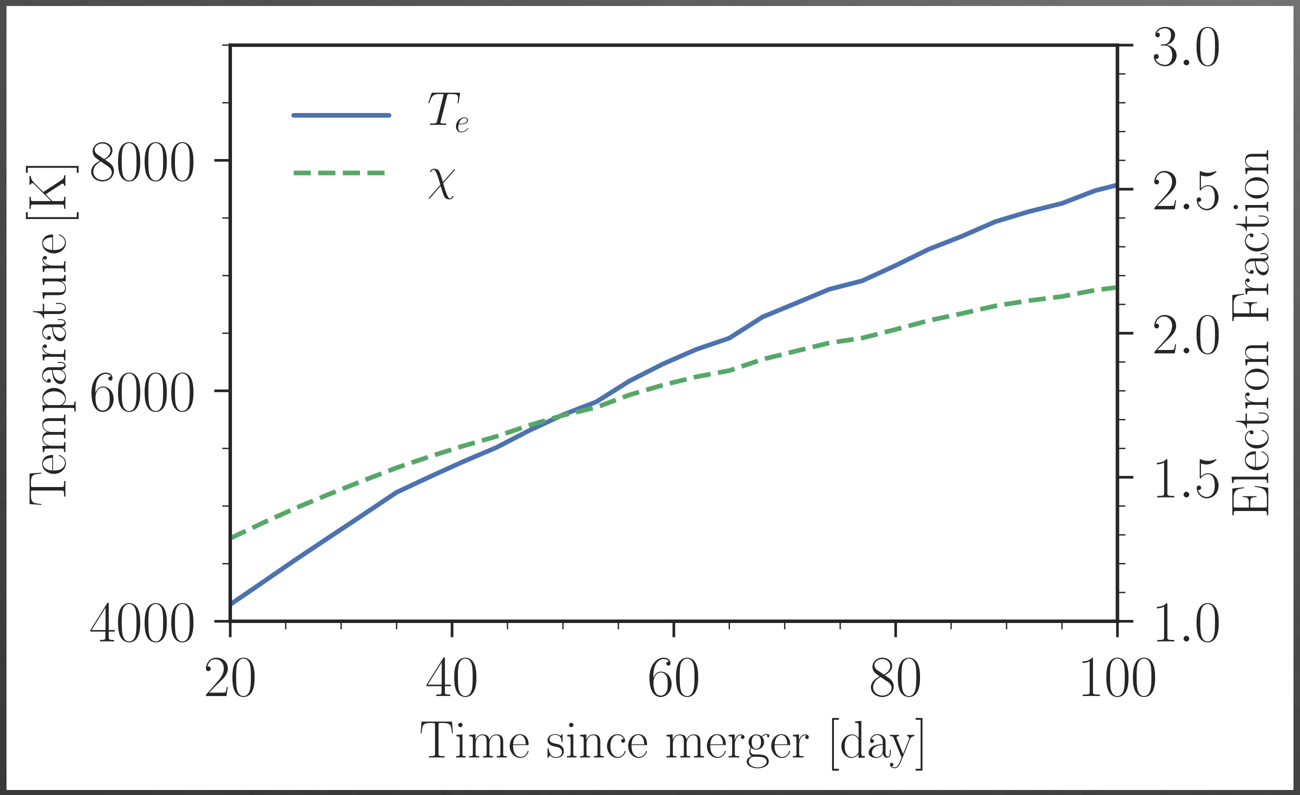
Thermal balance: $\Gamma/n^2 \sim \Lambda/n^2$

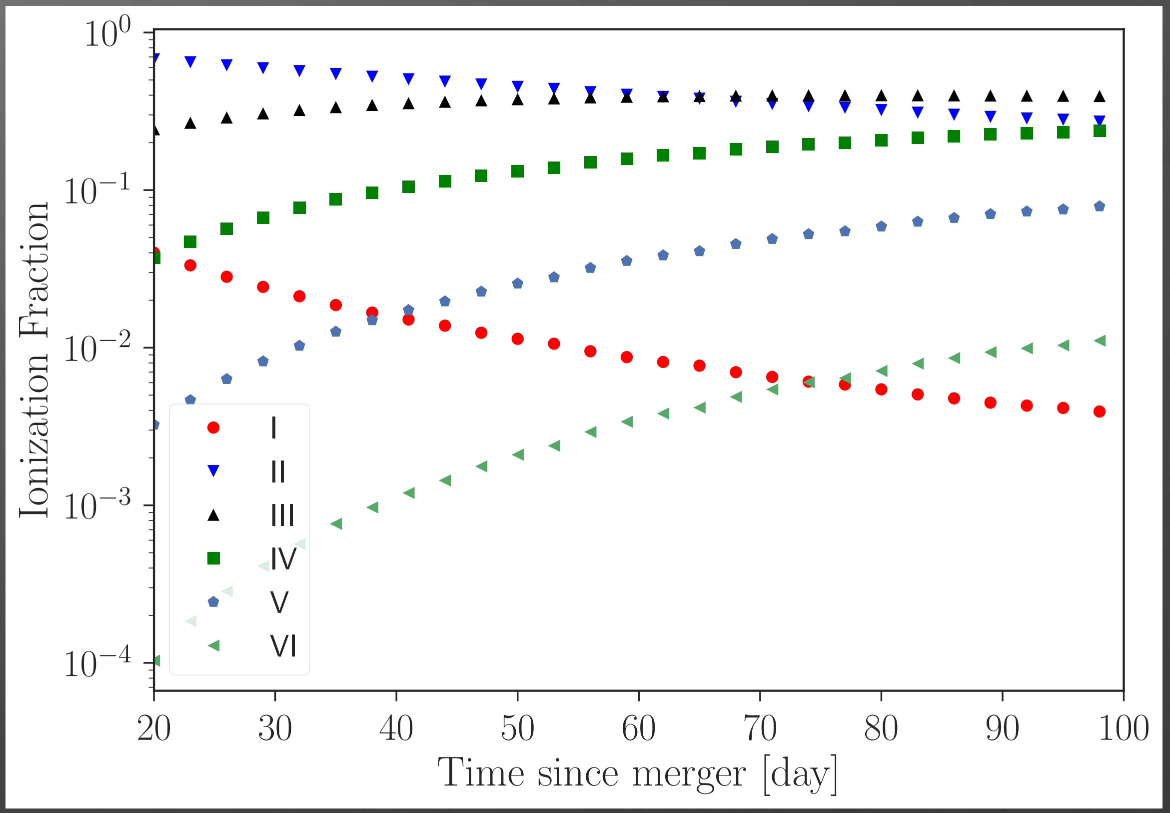
Both sides are constant with time after t_{th} ~50 day.
Temperature and ionization are approximately frozen.
=> The spectral shape is also expected to be frozen.
This is not due to the properties but due to the r-process heating rate.

Cooling functions: different Ionization

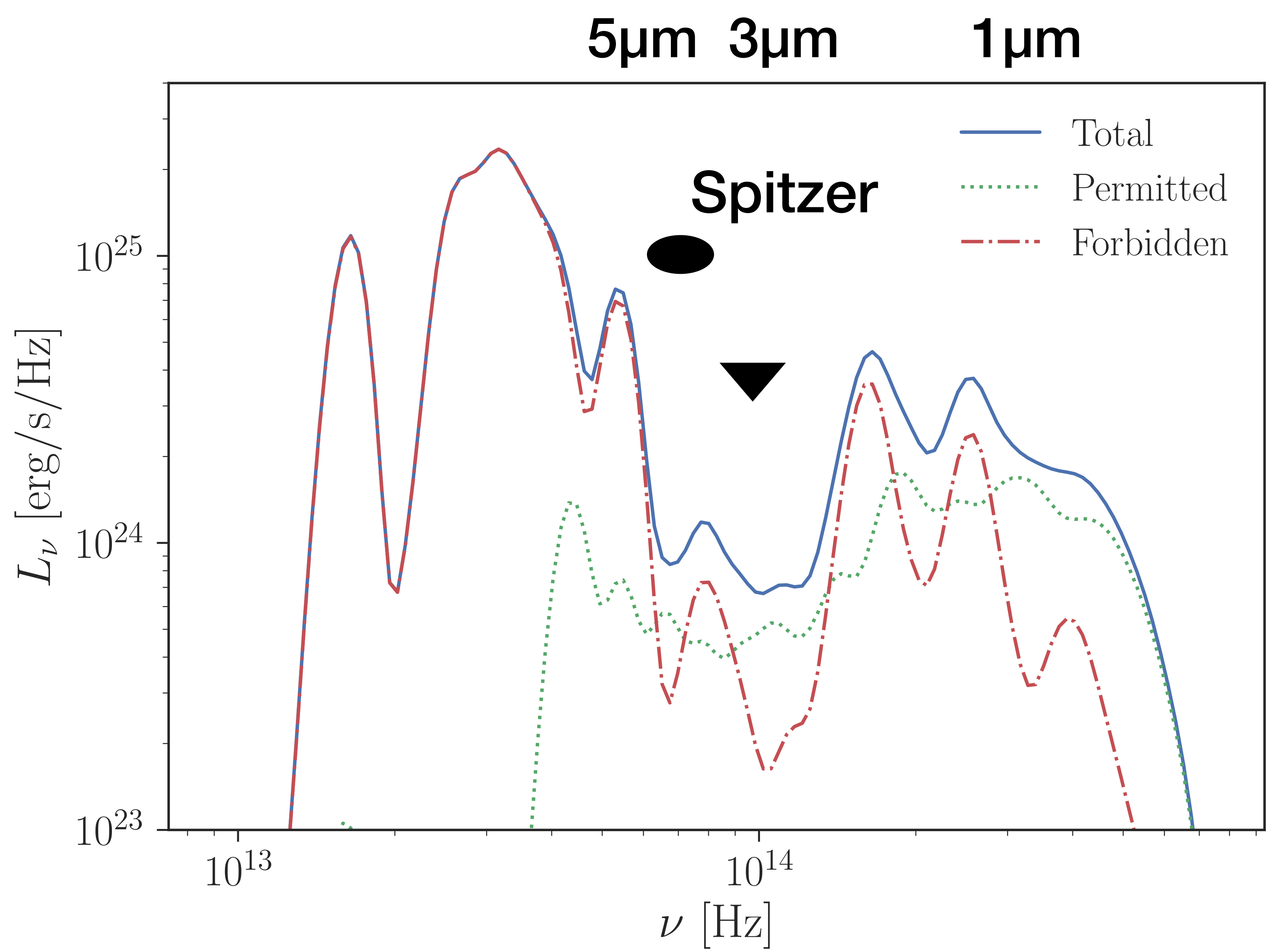


Temperature & Ionization of Nd Nebula





Kilonova Nebular Spectrum at 40 day (Pure Nd)



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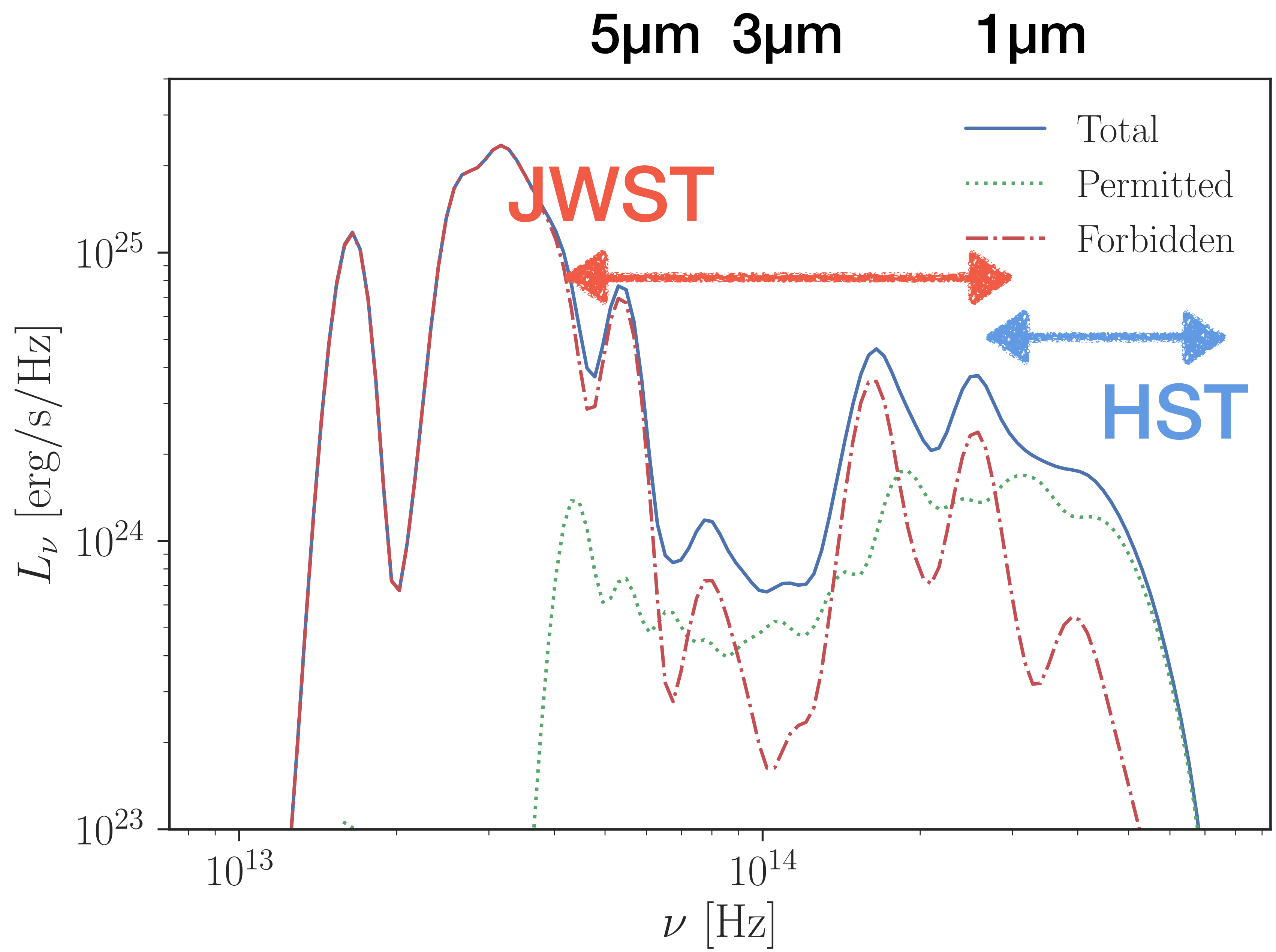
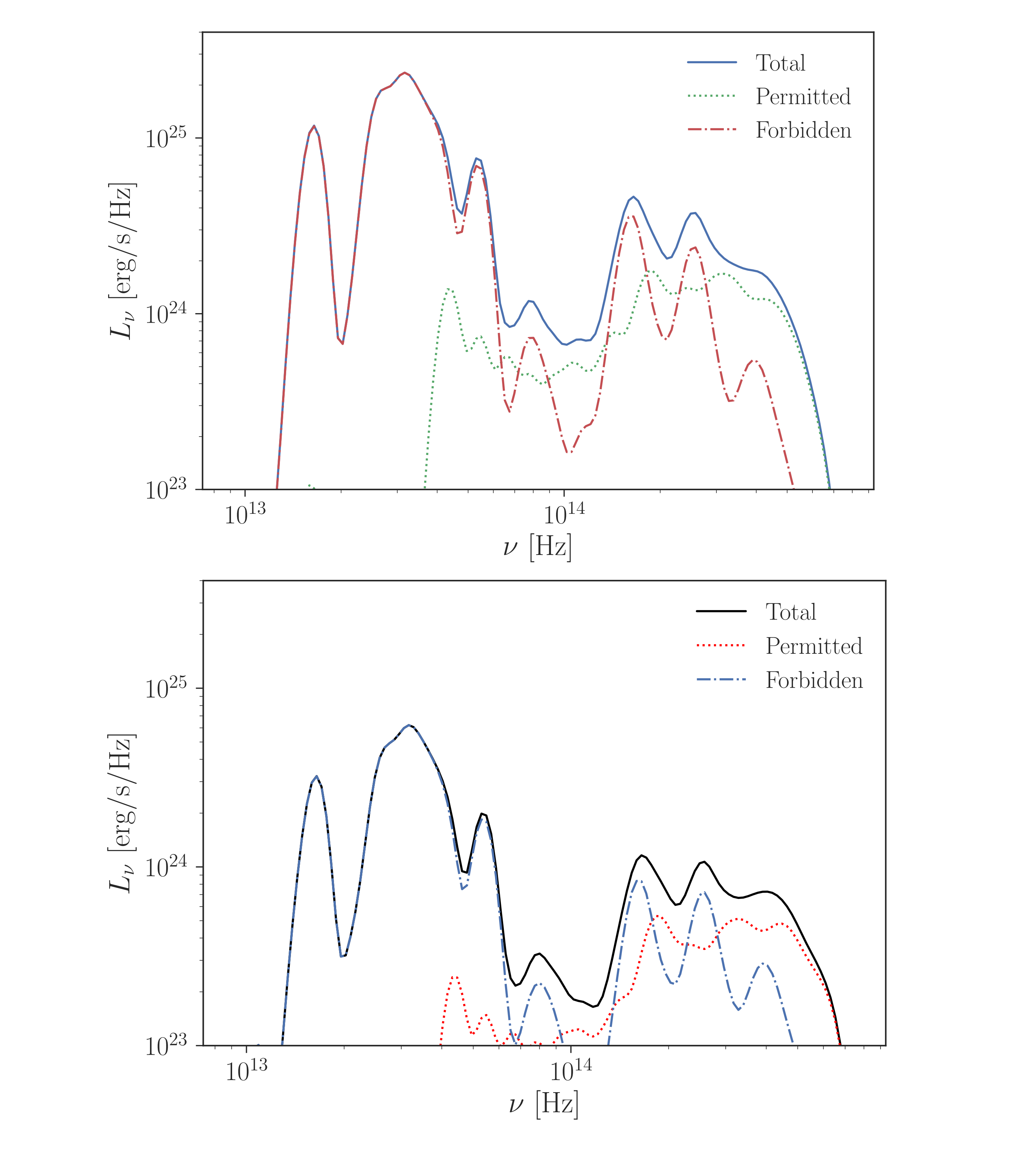
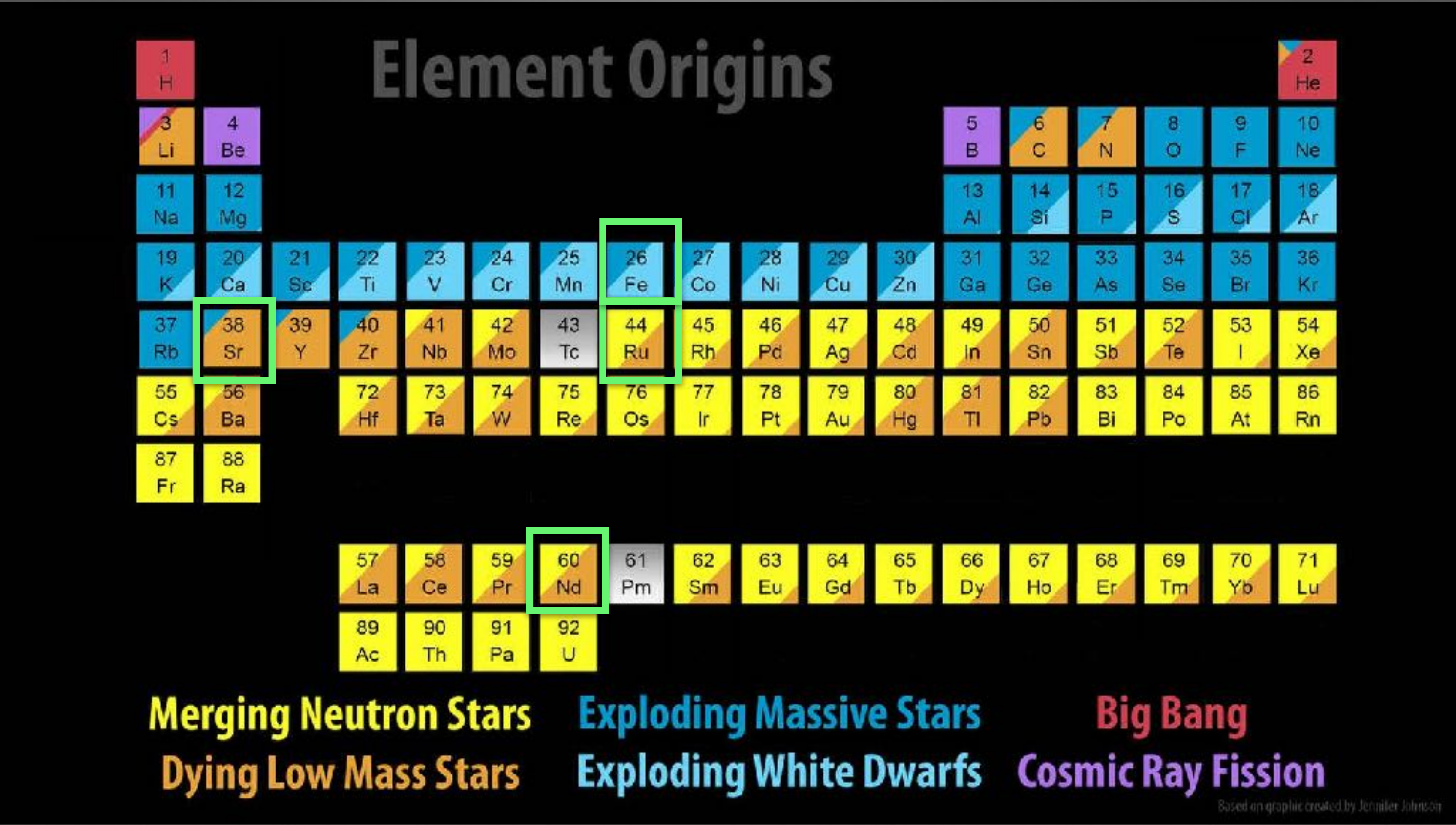


JWST can easily resolve the nebular spectrum at 200Mpc.

Spectrum at 40 and 70 day



Comparison with other elements



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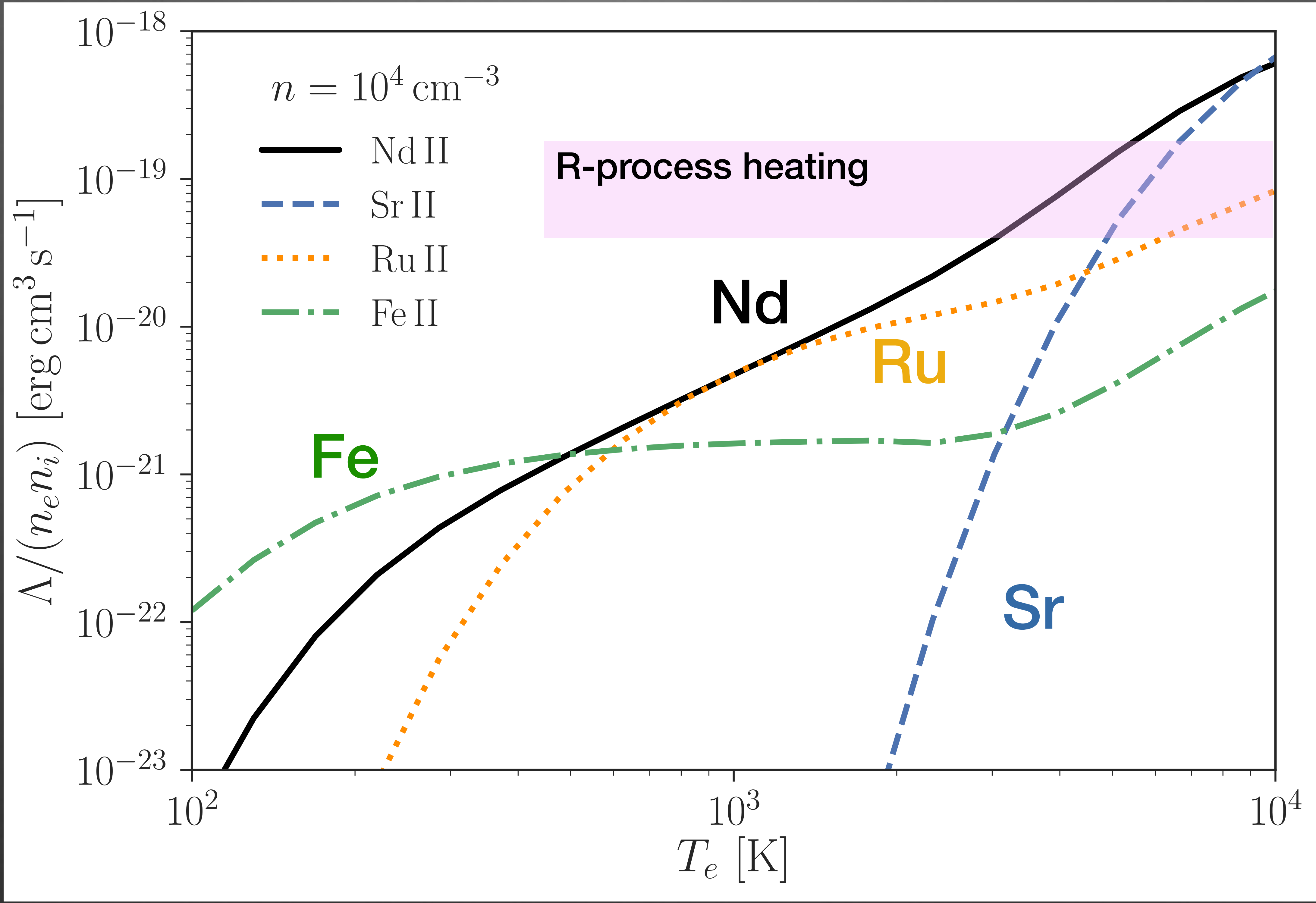
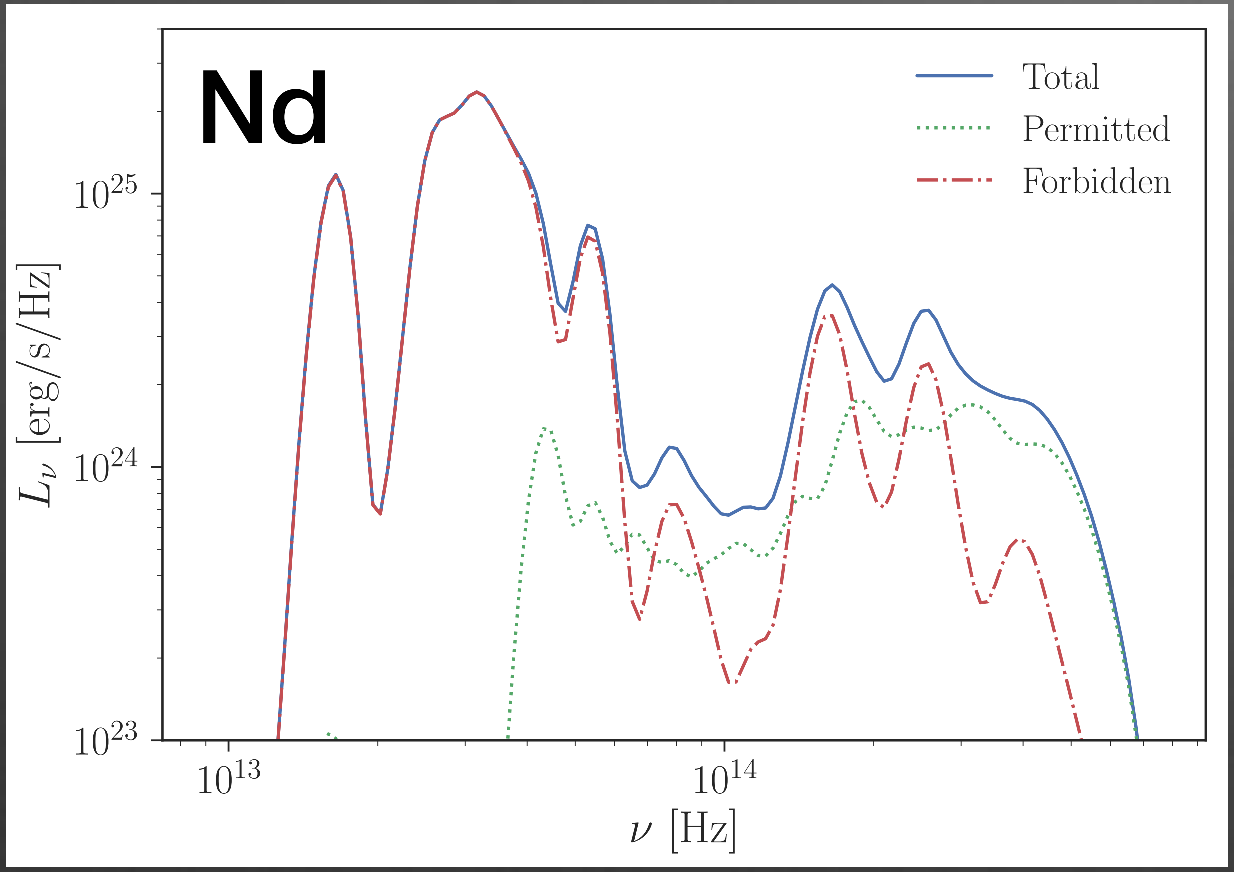
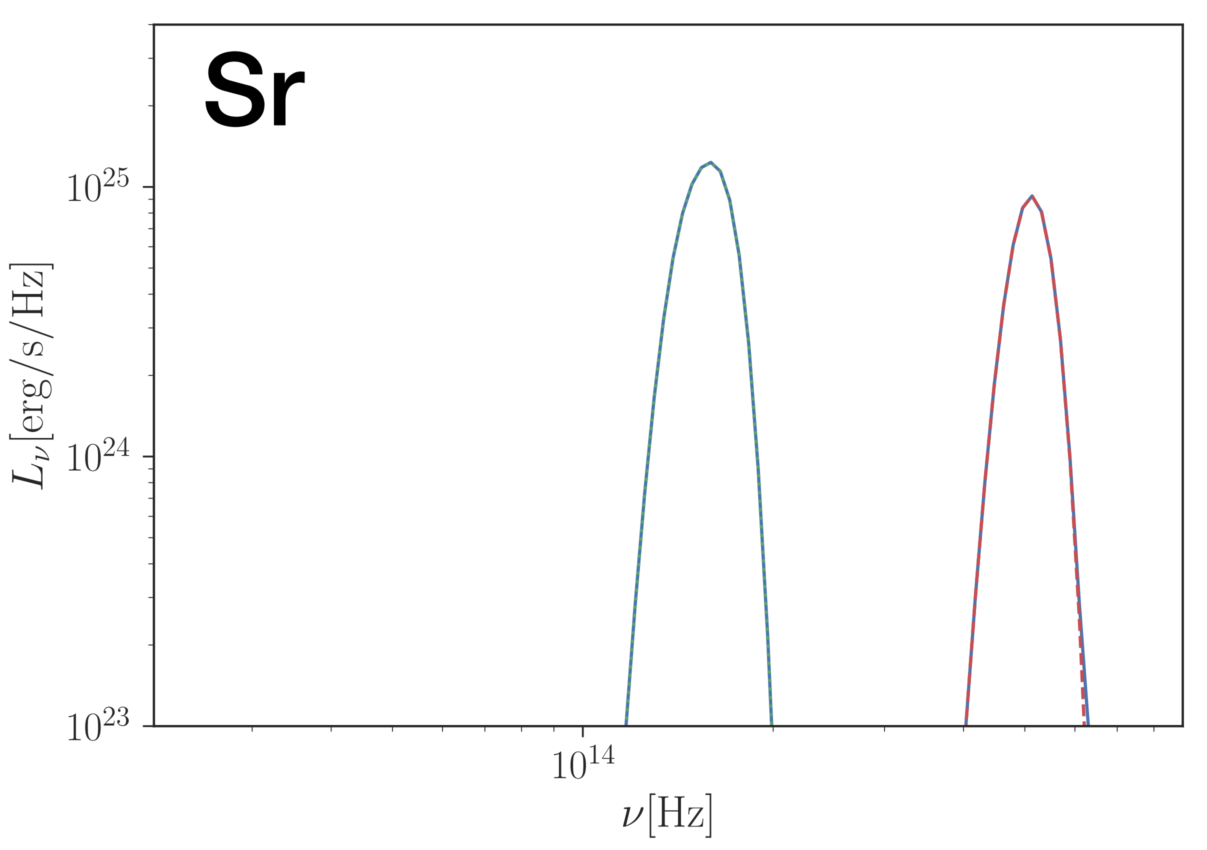


- Lanthanides (Nd) have a stronger cooling function.
- It is not trivial if they are more important as their abundance is low.

Comparing with other elements





Outline

- Introduction
- Radioactivity
- Thermal History of merger ejecta and Nebular emission
- Milky-way r-process puzzle

R-process mass budget

1, Total mass of r-process elements in the Galaxy.

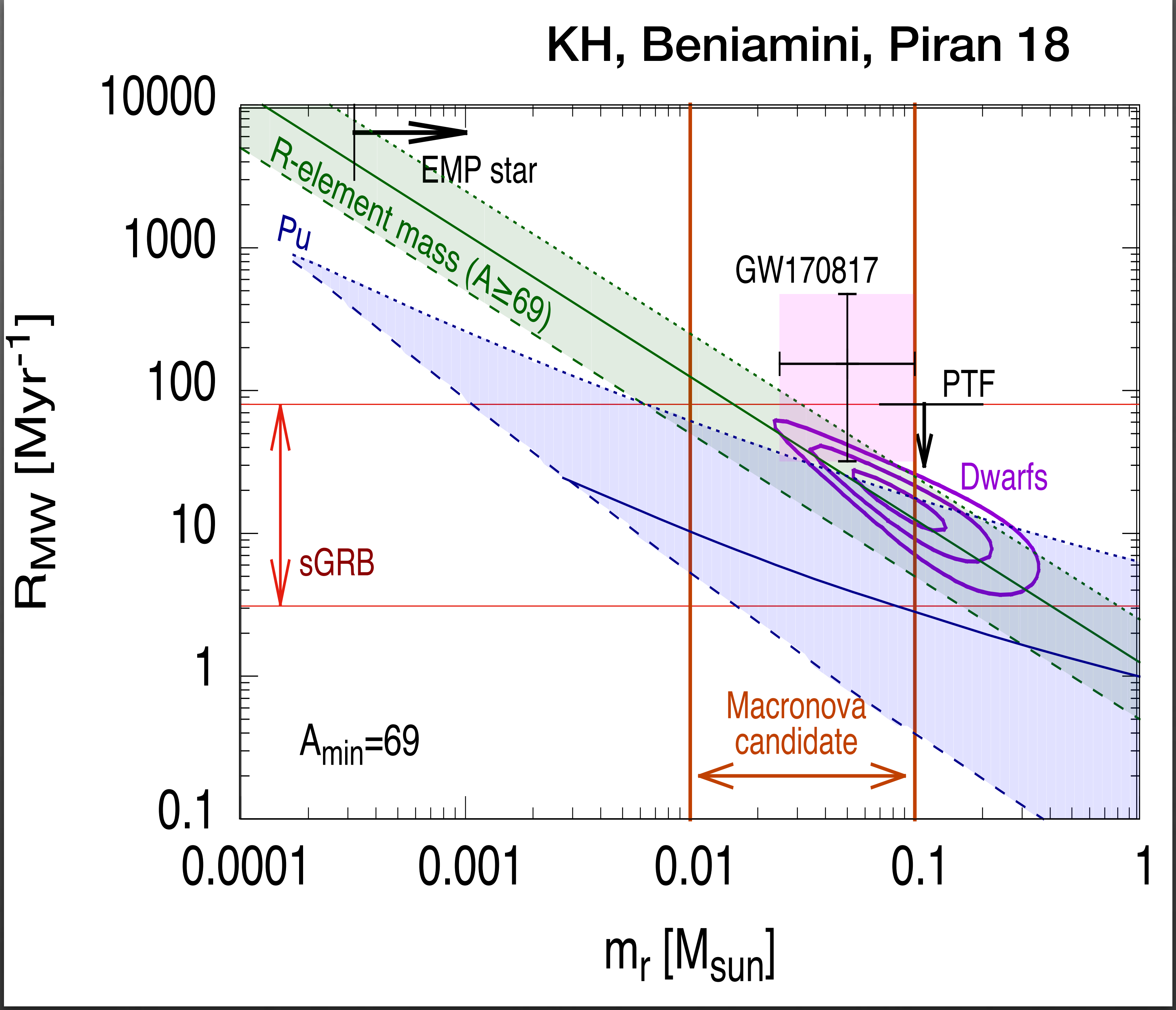
$\sim 10^4 M_{sun}$

2, Live ^{244}Pu ($t_{1/2}$=81Myr) accumulates on the deep sea floor from the ISM.

(Waller+15, KH, Piran, Paul 15)

3, A few ultra-faint dwarf galaxies contain r-enriched stars.

(Ji+16, Roederer +16, Beniamini+16)



Neutron star mergers produce r-process elements sufficient to provide all of them in the Galaxy.

GW170817 and r-process

GW:

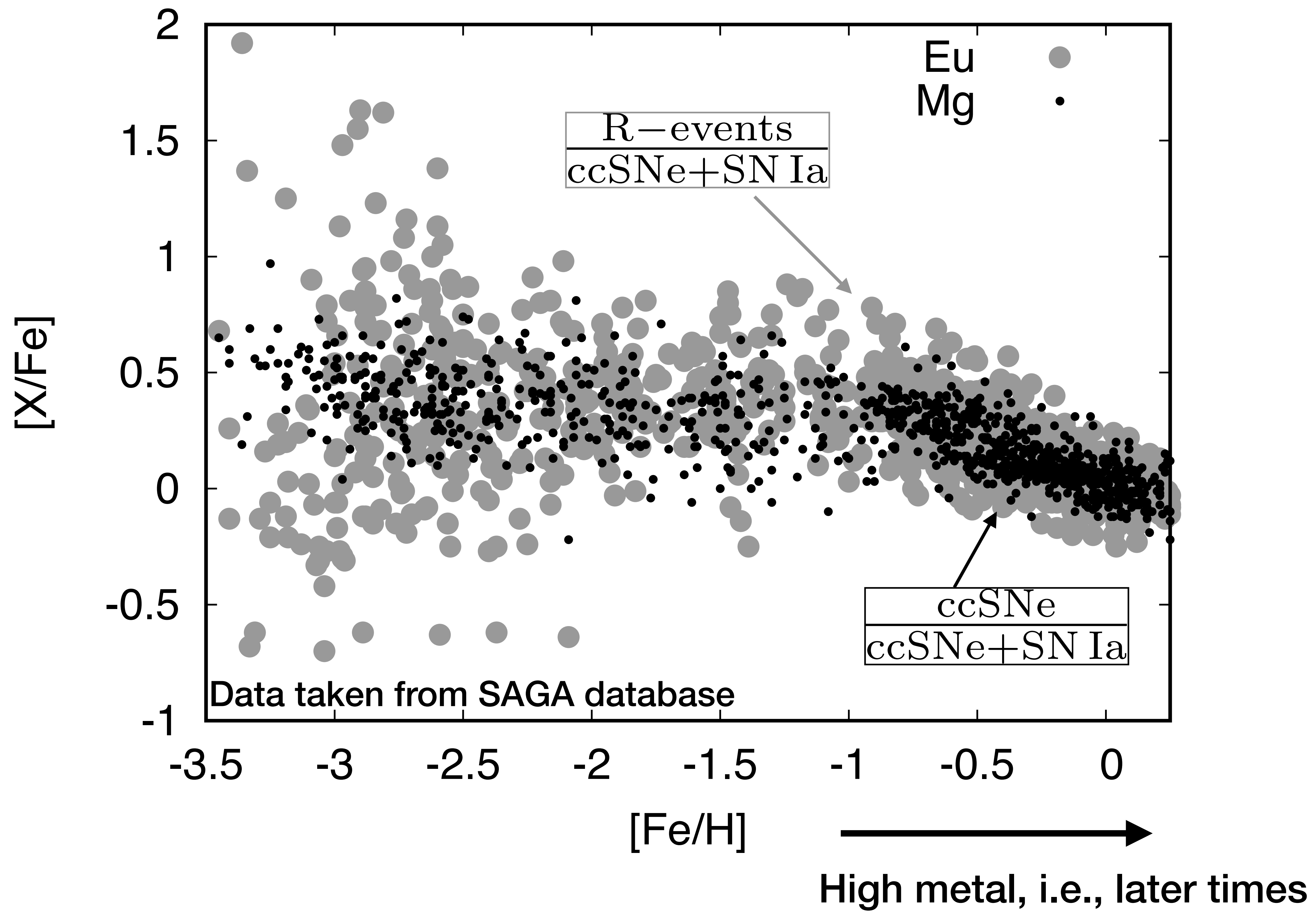
- GW170817 host galaxy suggests a significant delay between the formation and merger. (1-10Gyr)

Astrophysics:

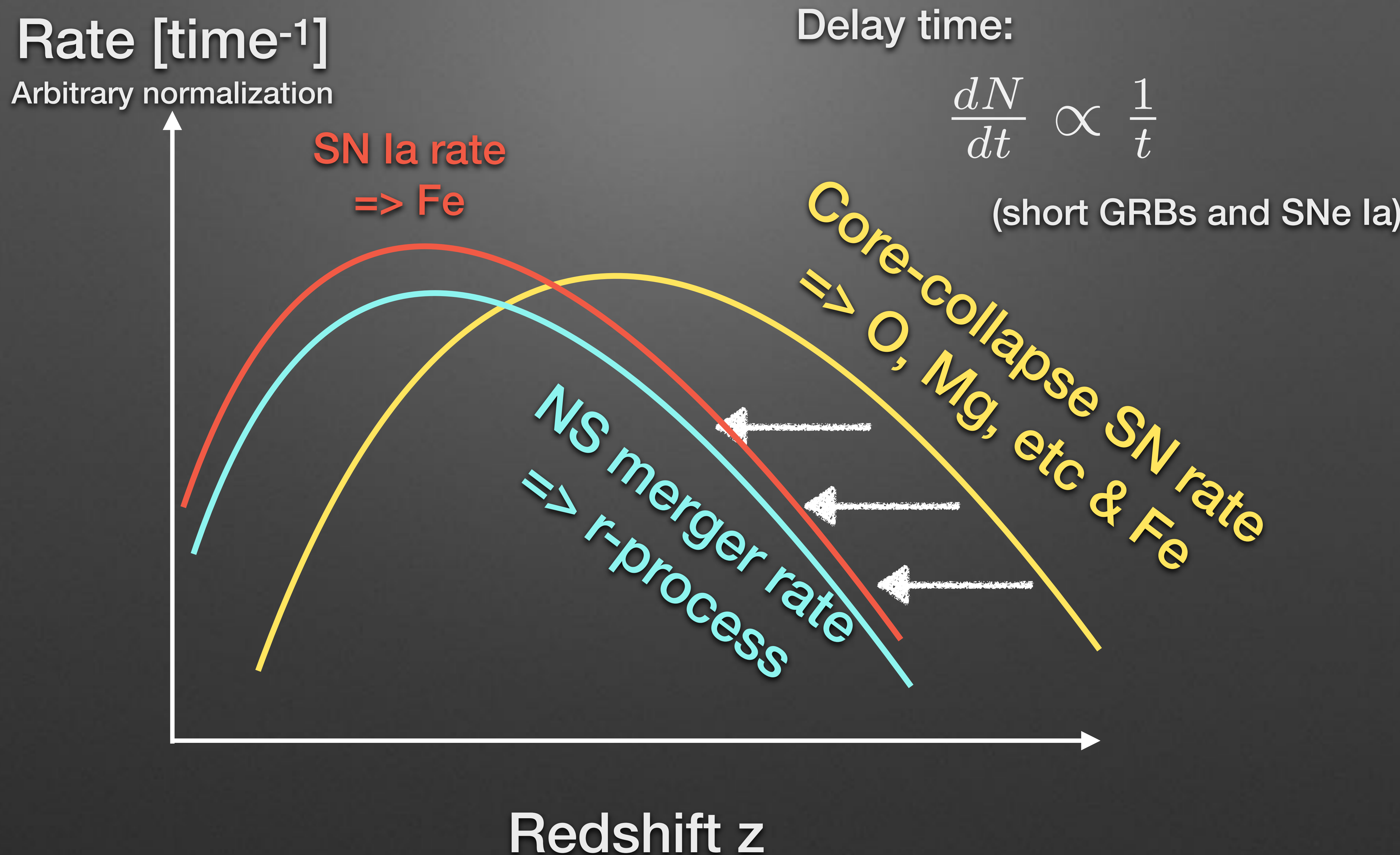
- There is no strong evidence supporting any time delay between star formation and r-process production.

- Chemical abundance of stars is even against the delay.

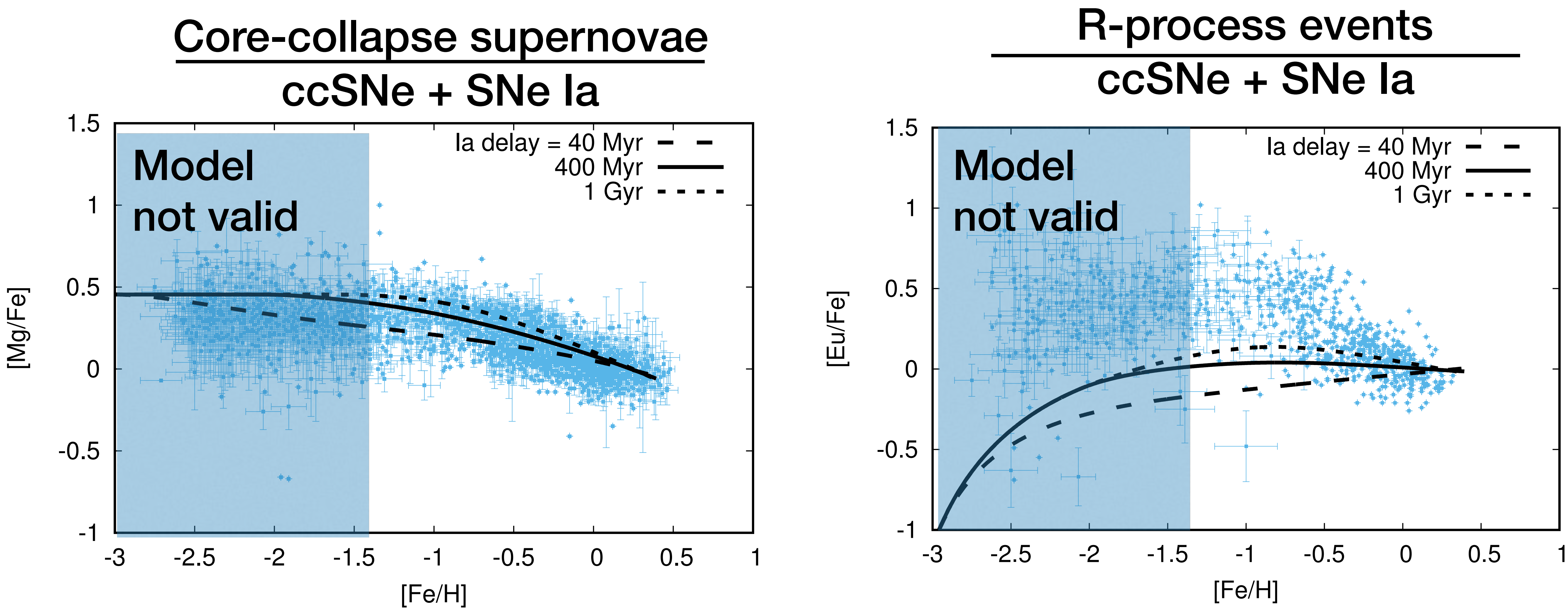
Puzzle: why r-elements trace α-elements?



Galactic Chemical Evolution



A chemical evolution problem



KH, Beniamini, Piran 2018, the data from the SAGA database

The production history of r-process elements is similar to that of α-elements.
=> R-process production seems to follow star formation (no delay?).

- How the steep decline occurs if mergers?
- Not merger, but, e.g., long GRBs produce r-process elects?

Summary

- Late-time kilonova nebular spectrum contains atomic information.
- After the thermalization time, heating, ionization, recombination, cooling rate per ion are roughly proportional to the density -> T and spectrum shape are roughly independent of the density and thus frozen.
- We need more atomic data and calibrate with experiments.
- Spitzer observations of GW170817 at 40 and 70 days are roughly consistent with this picture.
- JWST will do a fantastic job.
- Galactic Eu abundance traces Mg abundance (core-collapse), which is not expected for the neutron star merger scenario.