Credit: Tohoku U.

Long-term evolution and mass ejection of binary neutron star mergers

Sho Fujibayashi (Tohoku U., Japan)

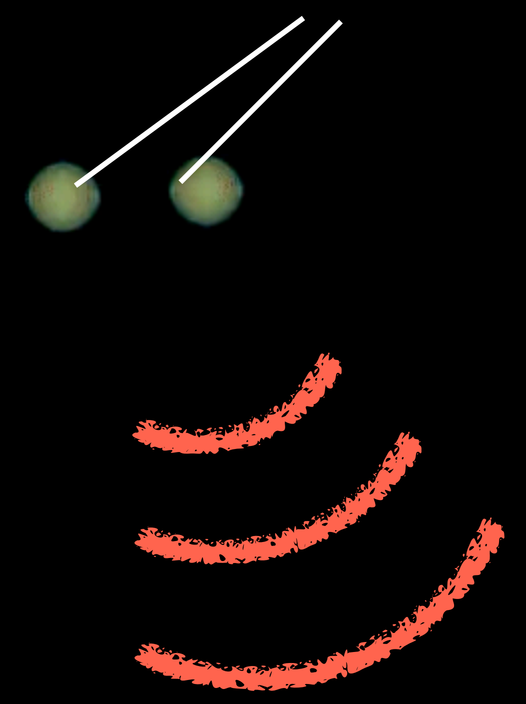
EANAM10, 2025/9/18, Jeju, South Korea

NS-mergers and nucleosynthesis

Introduction

t = -8.466 ms

Simulation by K. Kiuchi



Gravitational waves

Binary NS is …

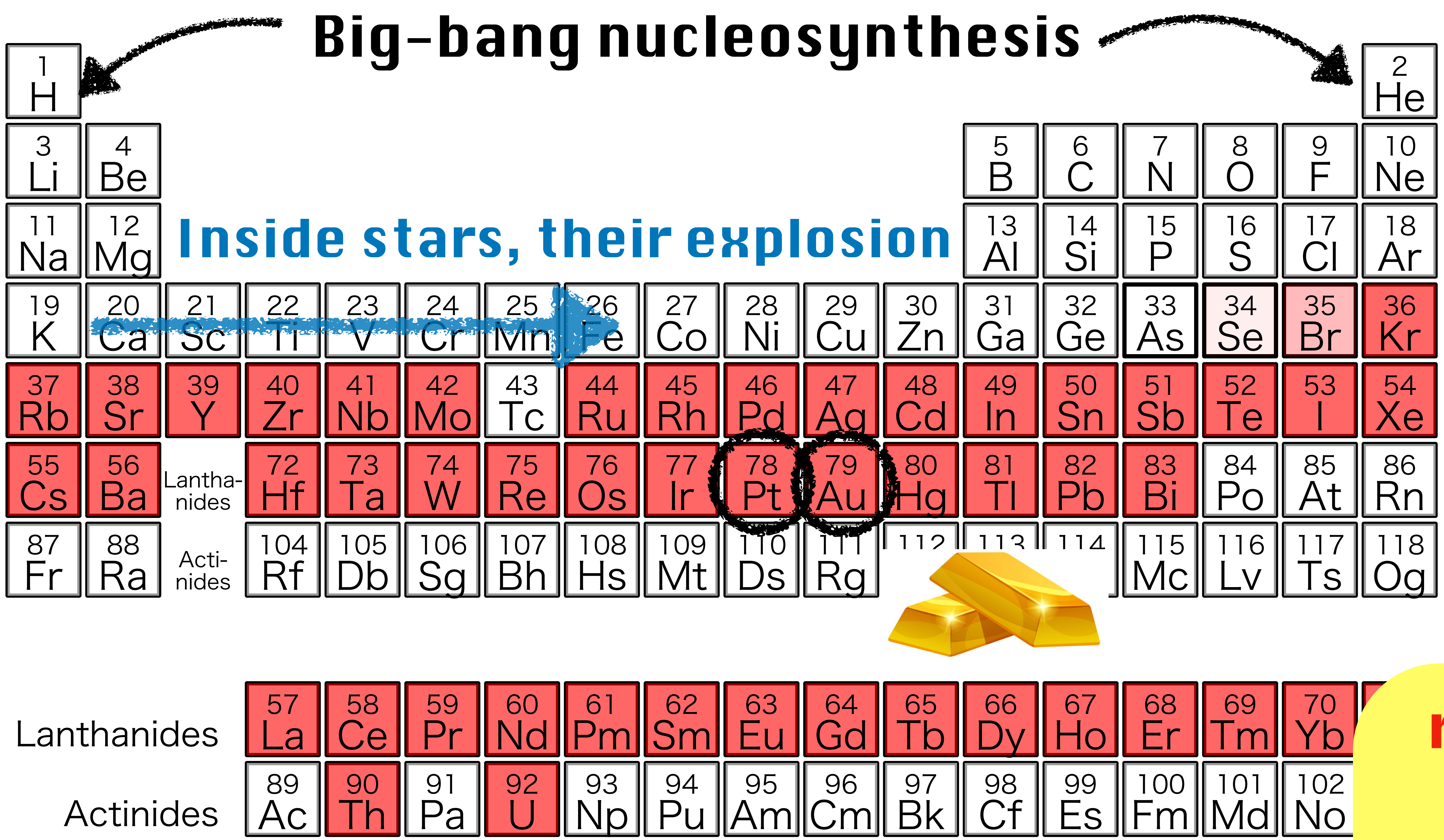
- One of the primary sources of GWs (targeted by ground-based detectors)
    - Constituent masses
    - Nuclear matter properties
- Promising site of heavy-element synthesis

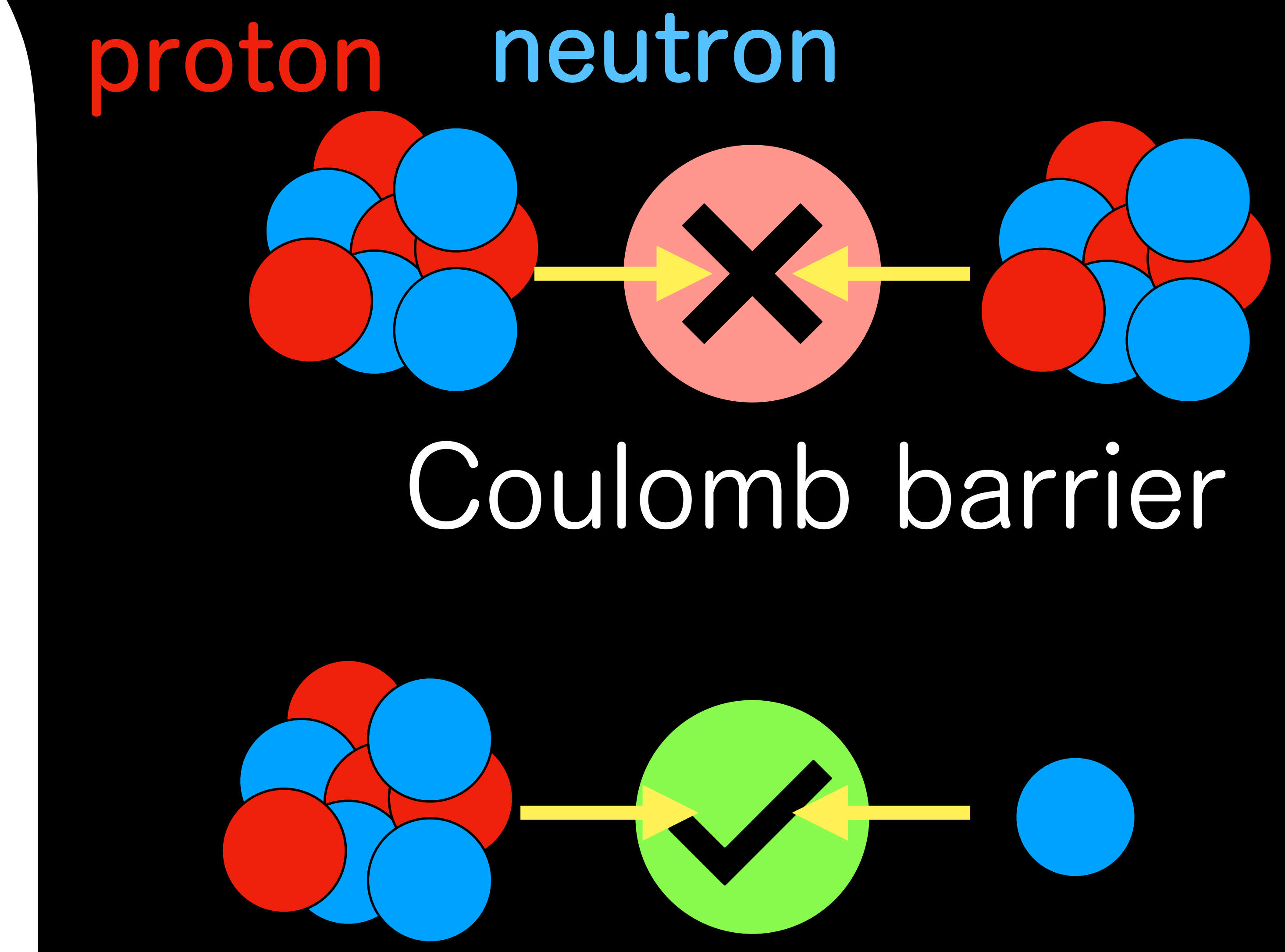
  Origin of elements

  Electromagnetic signal (kilonova)

    - Dynamics of the merger, post-merger activities

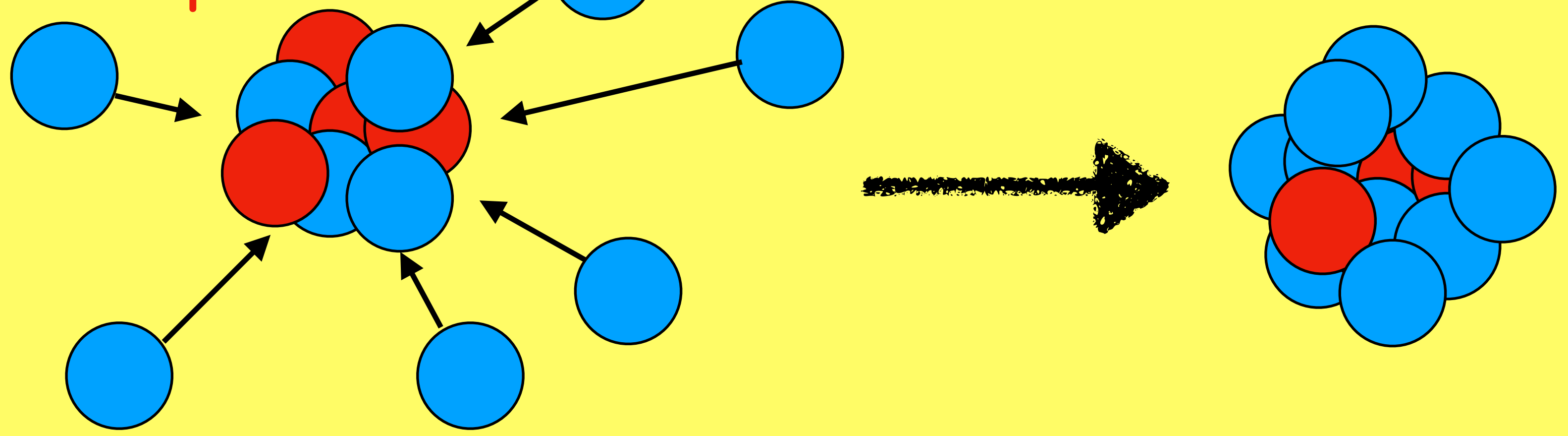
Origin of elements





Origin of (half of) elements heavier than iron is still unknown.

r(rapid)-process



High n-richness, $\tau(\text{n-capture}) \ll \tau(\text{beta-decay})$

r-process in NS-NS merger

Symbalisty & Schramm 82, Eichler+ 89, …

Simulation by K. Kiuchi

A fraction of matter becomes unbound.

Likely neutron-rich → r-process nucleosynthesis!

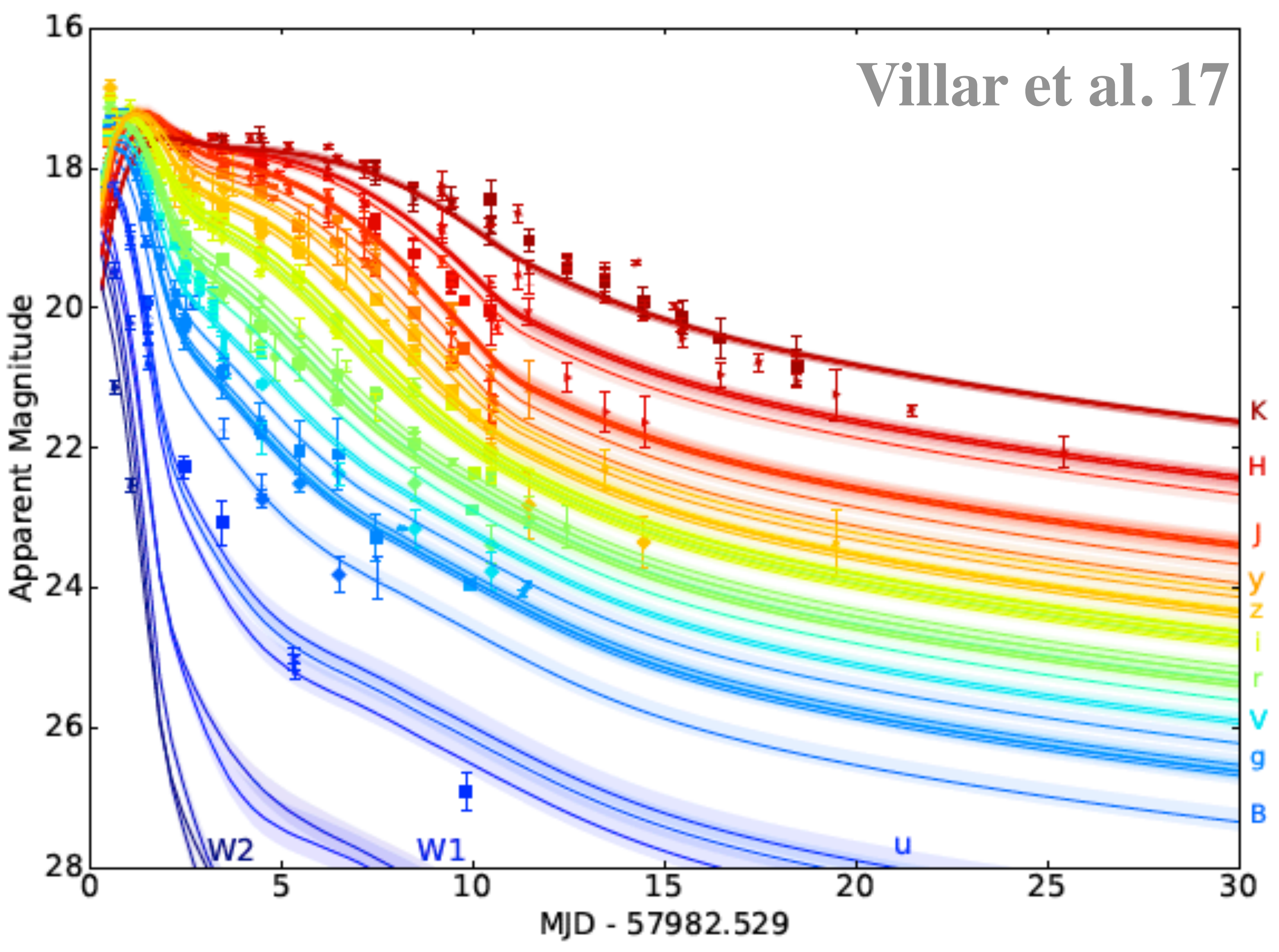
GW170817 and "Kilonova"

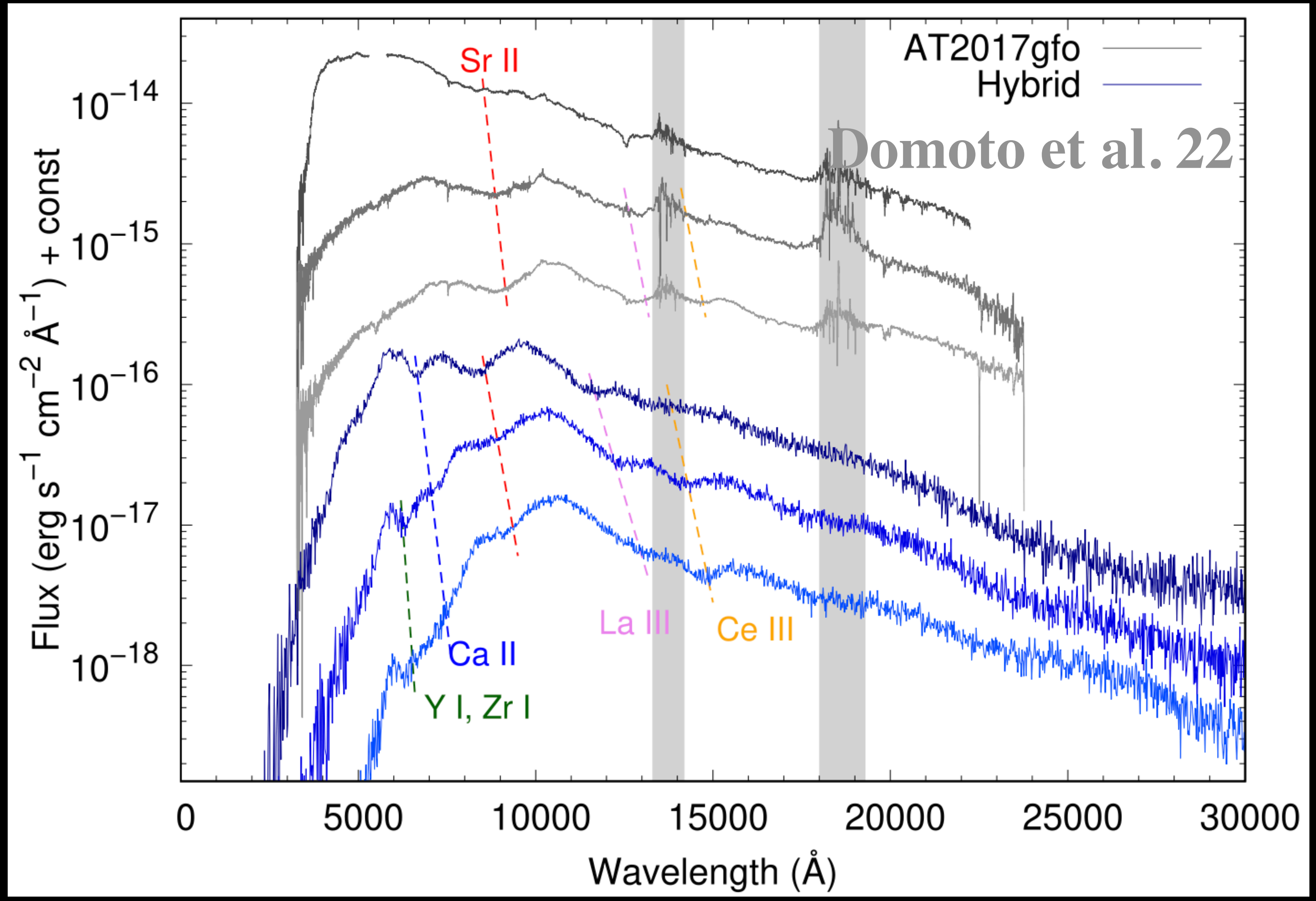
The first observation of GWs from NS-NS merger

Multi-wavelength follow-up campaign

Optical-NIR emission: consistent with "Kilonova"

Some elements identified [Sr, Ce, La, Te, ...]

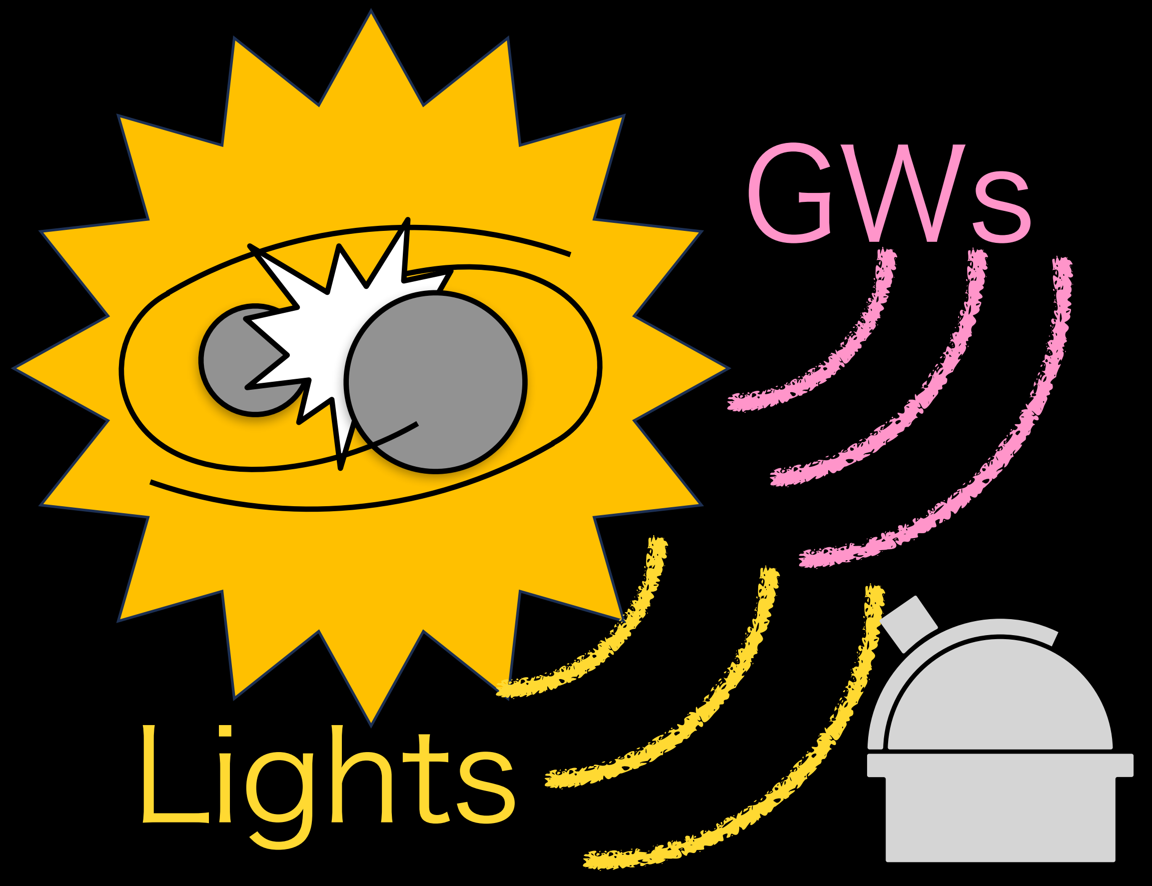


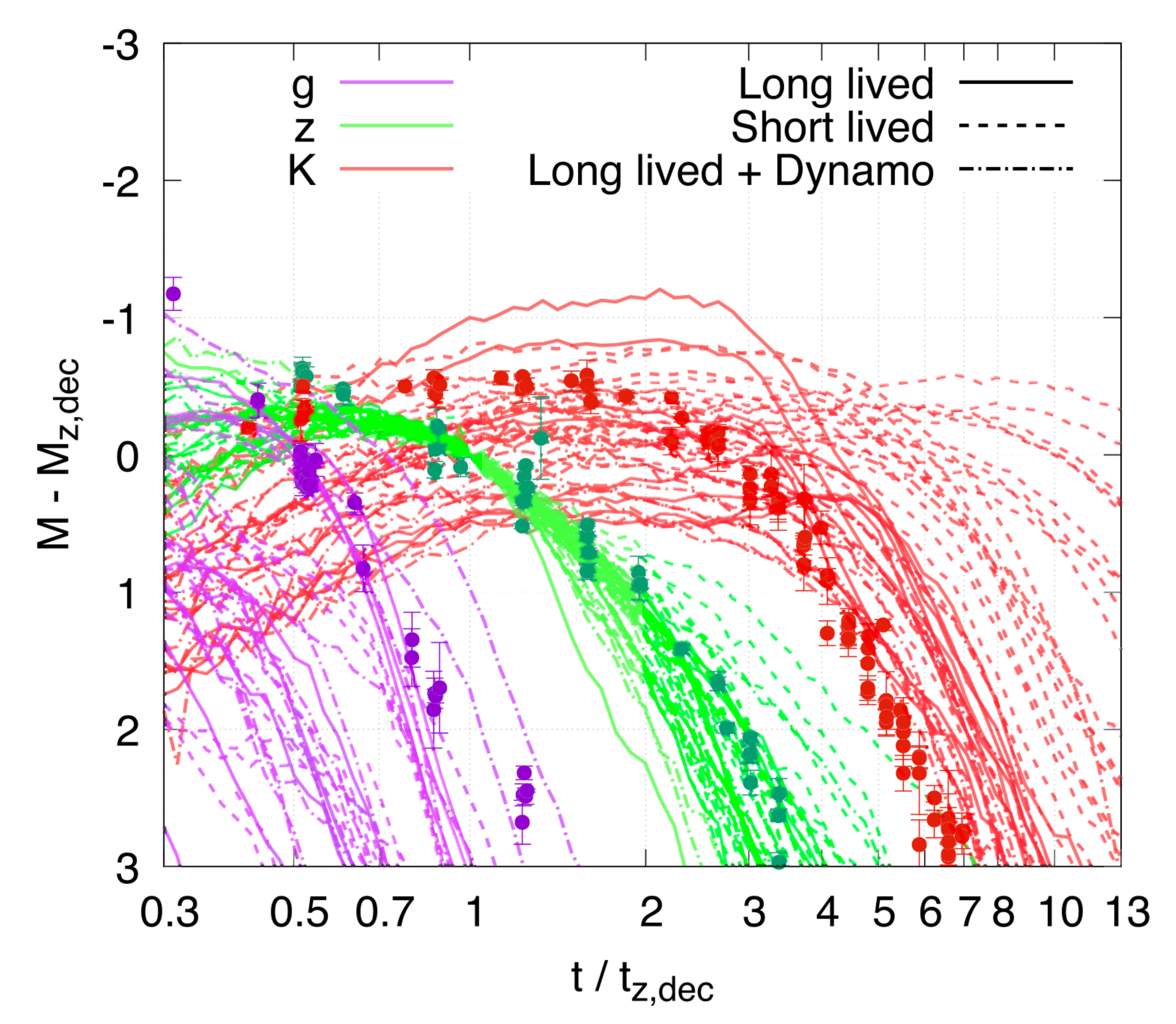


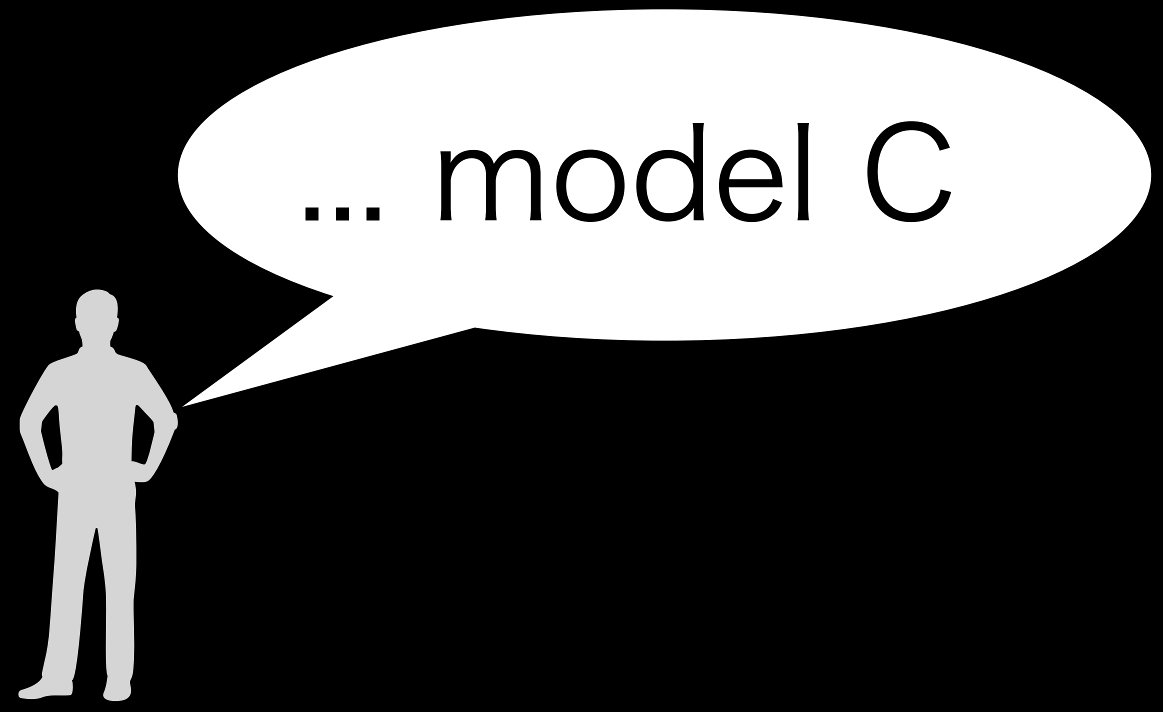
Andreoni et al. 2017; Chornock et al. 2017; Kasliwal et al. 2017; Pian et al. 2017; Smartt et al. 2017; Tanvir et al. 2017; Troja et al. 2017
Watson et al. 2019; Domoto et al. 2022; Gillanders et al. 2022; Perego et al. 2022; Tarumi et al. 2023; Hotokezaka et al. 2023

To understand what happens in NS merger…

Comparison of observation and theoretical models







Performing numerical simulations is essential

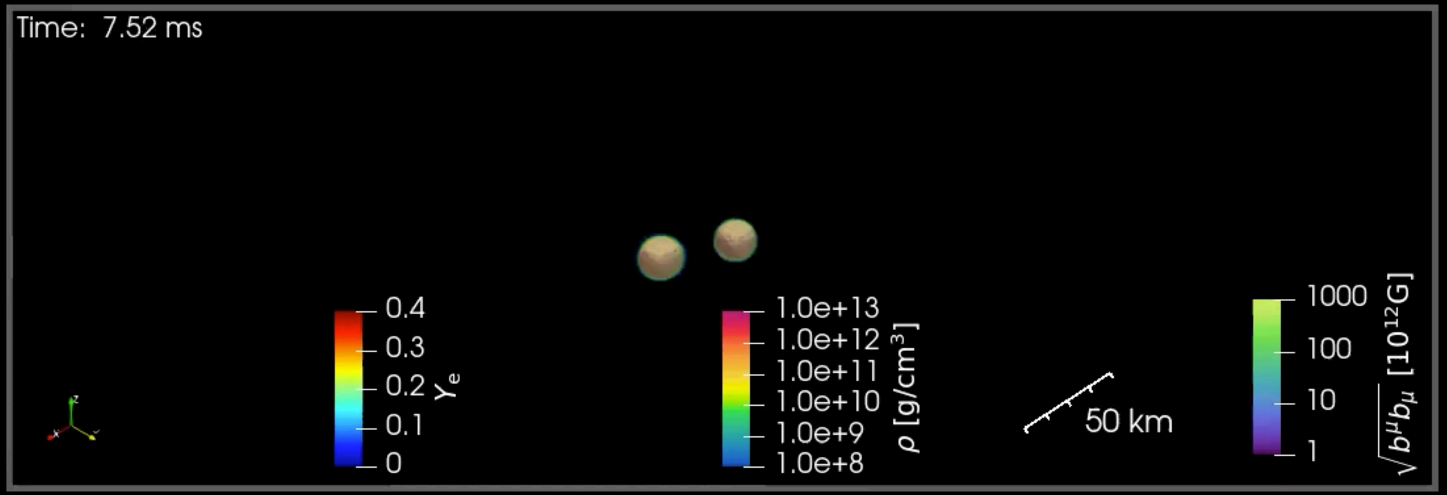
Highly non-linear system with

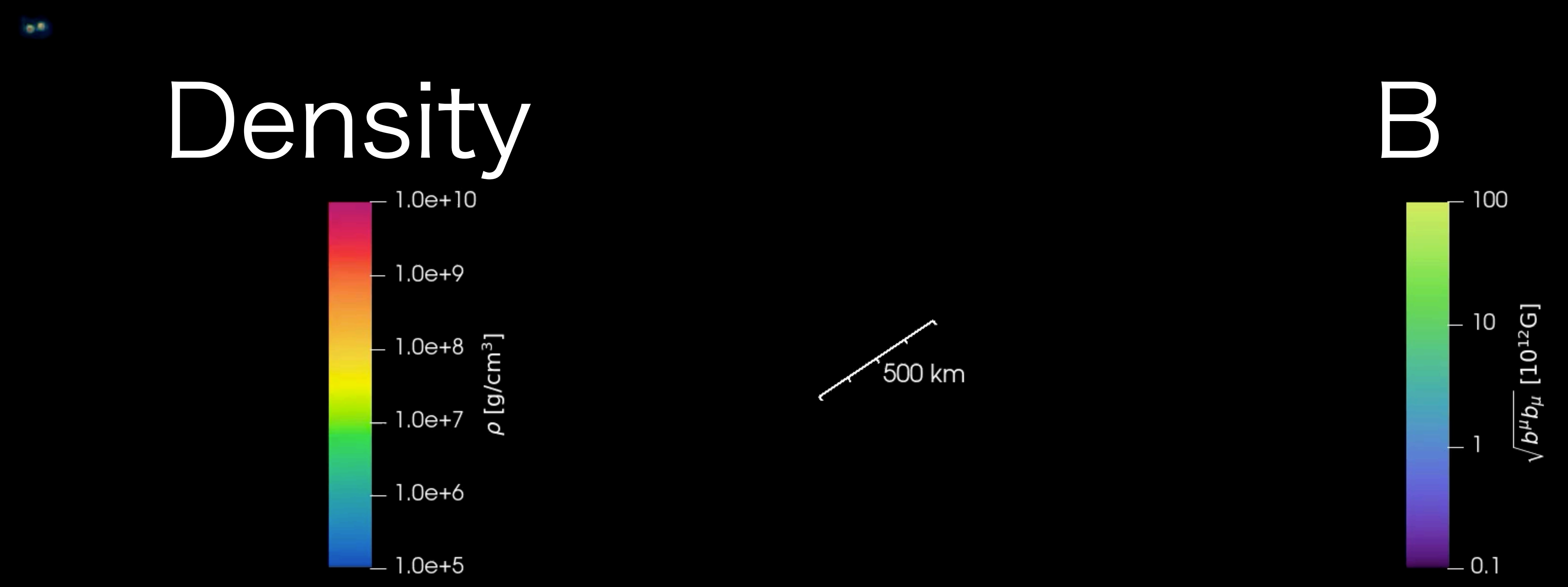
- Strong and dynamical gravity
- Neutrino radiation (highly coupled to nearly free-streaming)
- Possible MHD effects

Time evolution and mass ejection

Mass ejection activities of merger

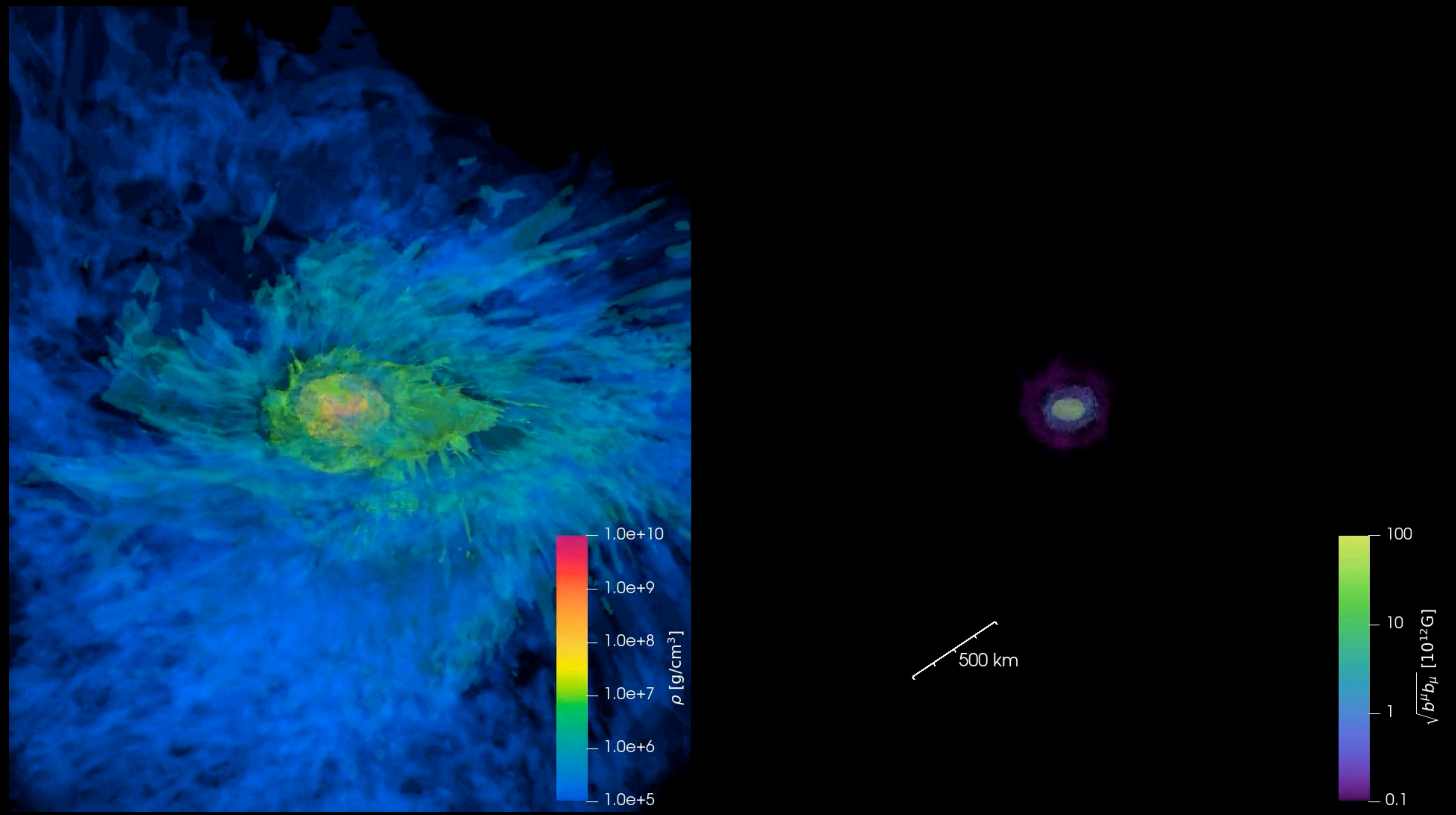
Kiuchi, SF+23 (visualized by K. Hayashi)





Dynamical mass ejection
(tidal force, shock heating) ~ 10 ms
→ Disk formation

Mass ejection activities of merger



- Magnetic field is amplified due to MHD processes.
- MRI in the disk → Viscosity (by turbulent motion) emergence
- Viscous angular momentum transport/heating → **mass ejection**

$t_{\rm vis} \sim 1\,{\rm s} \left(\frac{\alpha_{\rm vis}}{0.03}\right)^{-1} \left(\frac{R_{\rm disk}}{50\,{\rm km}}\right)^{3/2} \left(\frac{M_*}{3M_\odot}\right)^{1/2} \left(\frac{3H_{\rm scale}}{R_{\rm disk}}\right)^{-2}$ (assuming standard disk)

- High temperature → weak interaction plays an important role

$t_{\rm weak} \sim 1\,{\rm ms} \left(\frac{kT}{5\,{\rm MeV}}\right)^{-5} \lesssim$ timescale of the evolution

$e^- + p \rightleftarrows \nu_e + n$

$e^+ + n \rightleftarrows \bar{\nu}_e + p$

  - Neutrino emission cooling evolves the system
  - Determine the neutron-richness

Implications of numerical simulation: Dynamical Ejecta

Neutron-richness

Measures efficiency of r-process

"Electron fraction" $Y_e := \frac{n_e}{n_{\text{baryon}}} = 1 - \frac{n_n}{n_{\text{baryon}}}$ (= proton fraction)

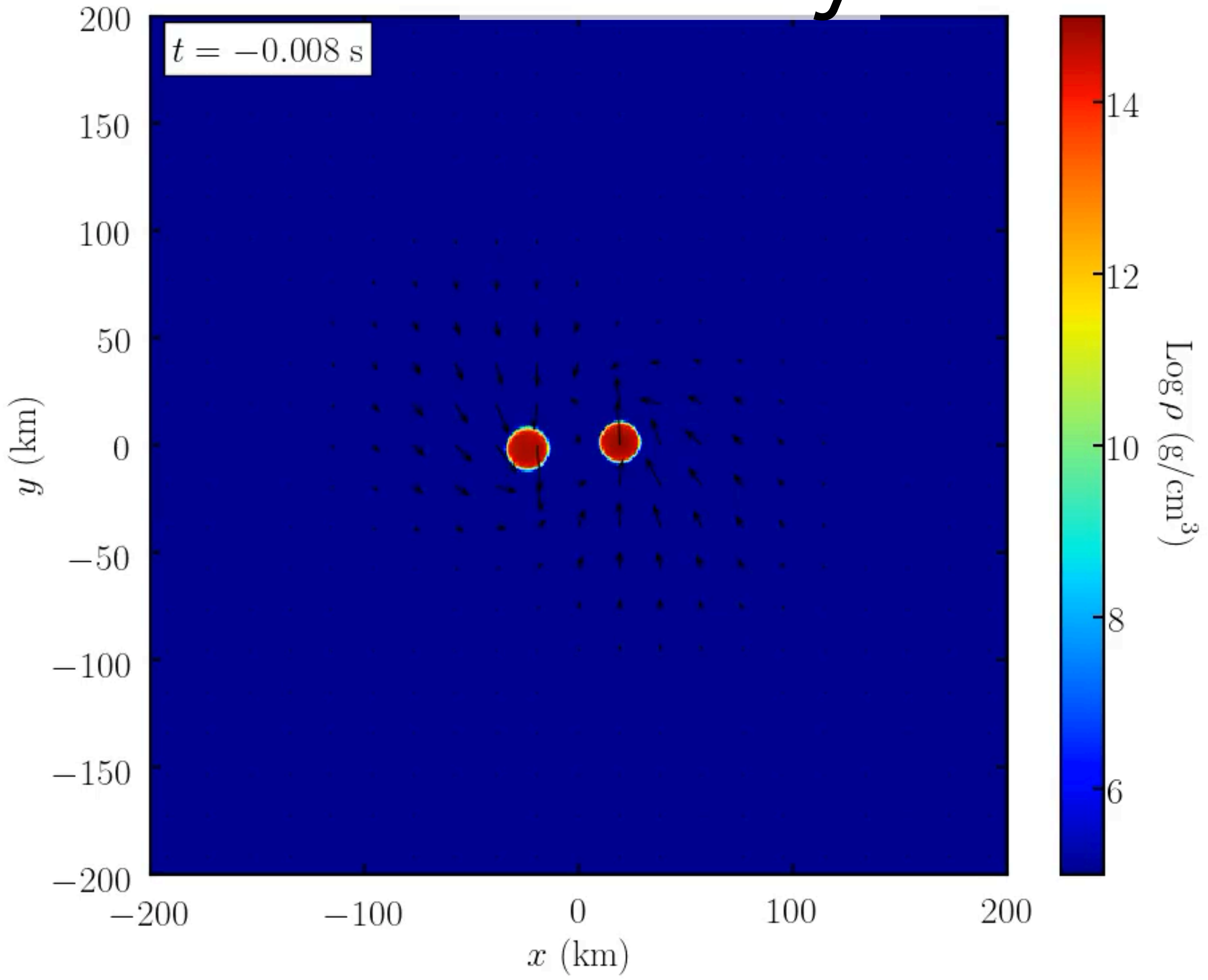
Lower-Y_e ↔ more neutron-rich

N-richness of Dynamical ejecta

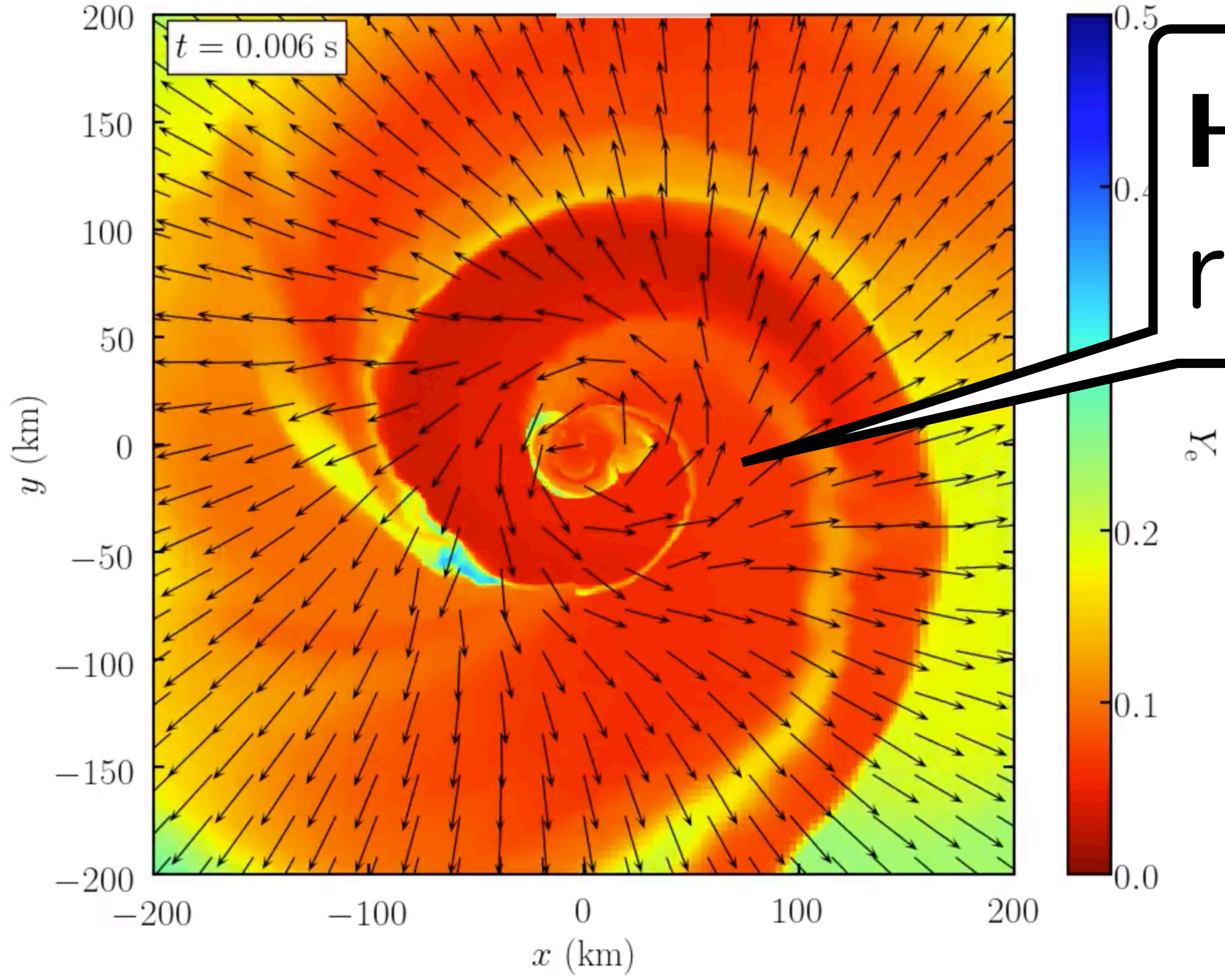
$m_1 \neq m_2$

$1.20 - 1.50 M_\odot$

Density

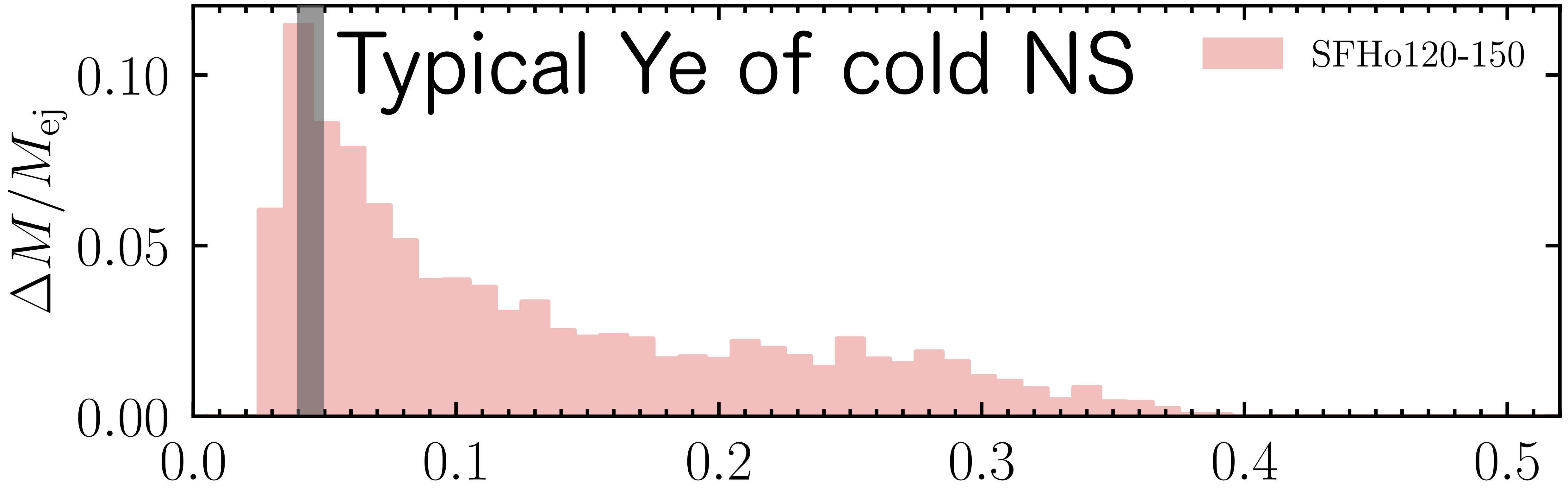


Ye



Highly degenerate
remains very n-rich

Unequal-mass (asymmetric) merger → more BH-NS-like.



(2.70 Msun in total, SFHo EOS is adopted.)

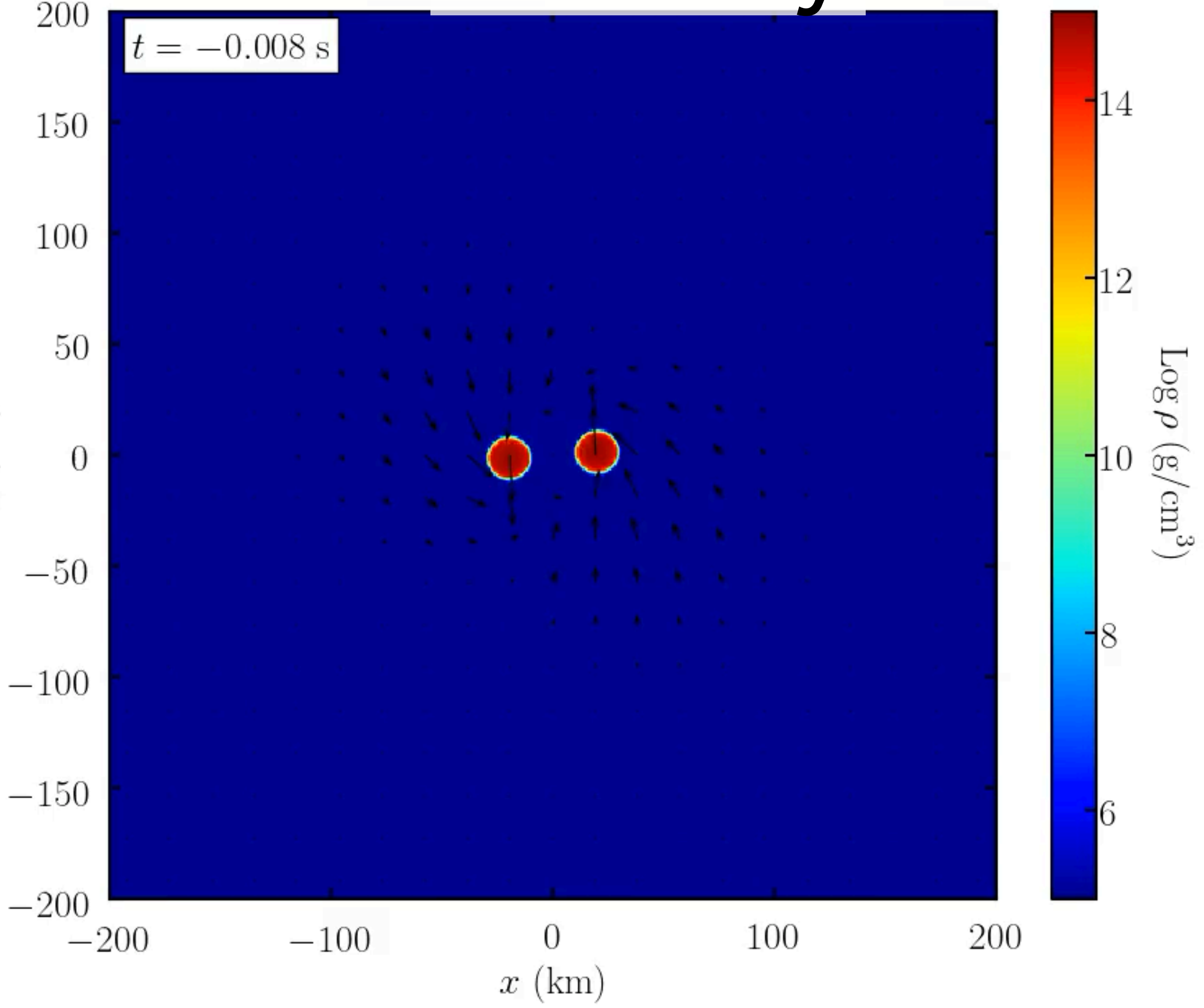
Electron fraction $Y_e := \frac{n_e}{n_{\rm baryon}} = 1 - \frac{n_n}{n_{\rm baryon}}$

N-richness of Dynamical ejecta

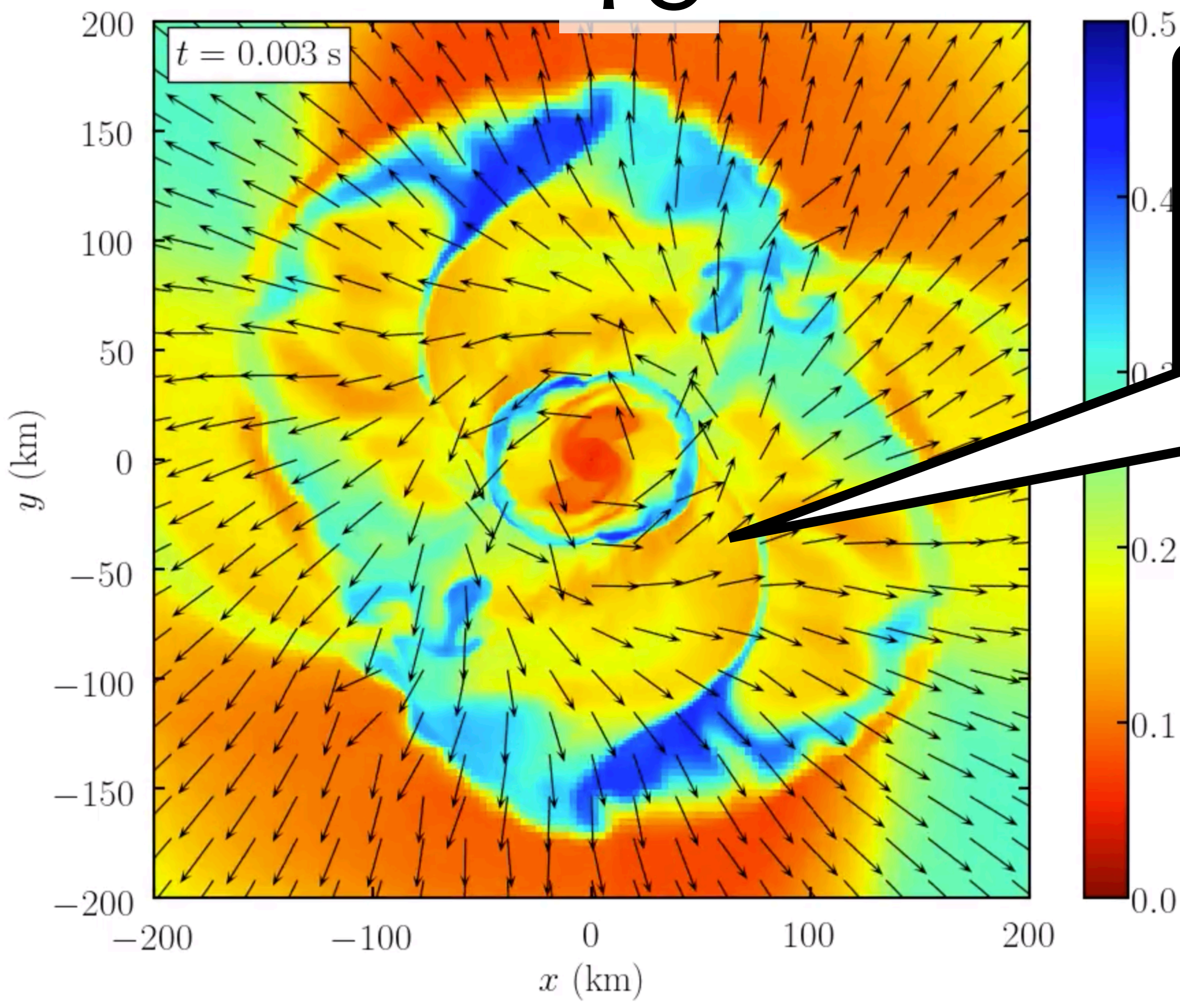
$m_1 = m_2$

$1.35 - 1.35 M_\odot$

Density



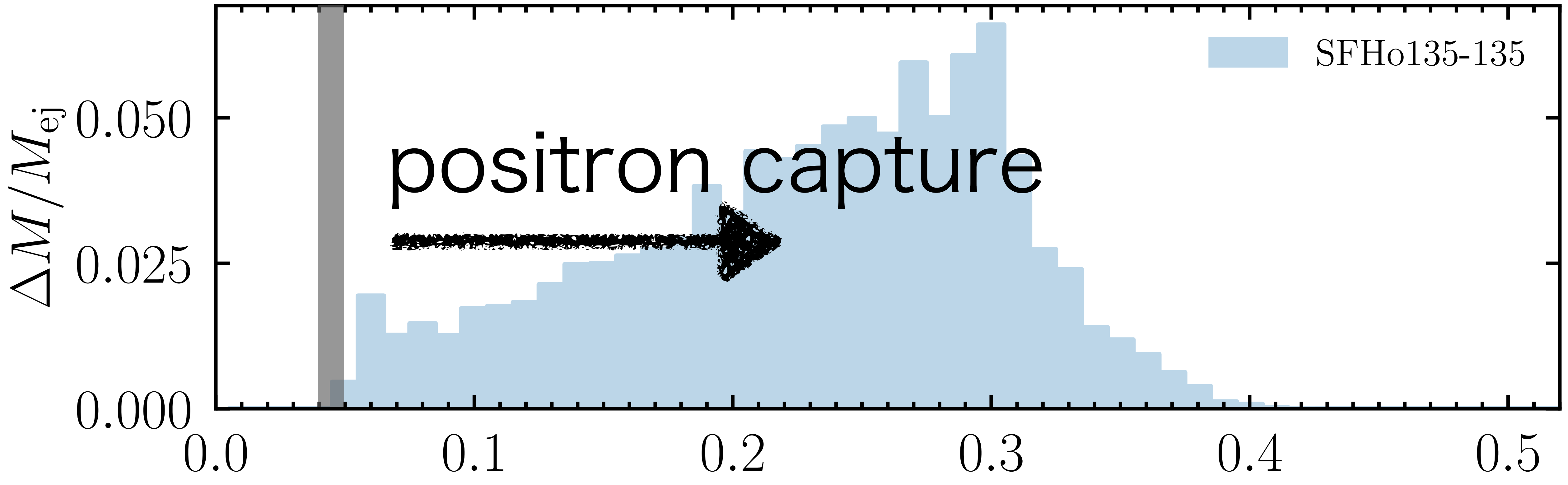
Ye



Weak interact.

$$e^+ + n \rightarrow \bar{\nu}_e + p$$

Equal-mass merger: matter reprocessed → higher Ye (lower n-richness)

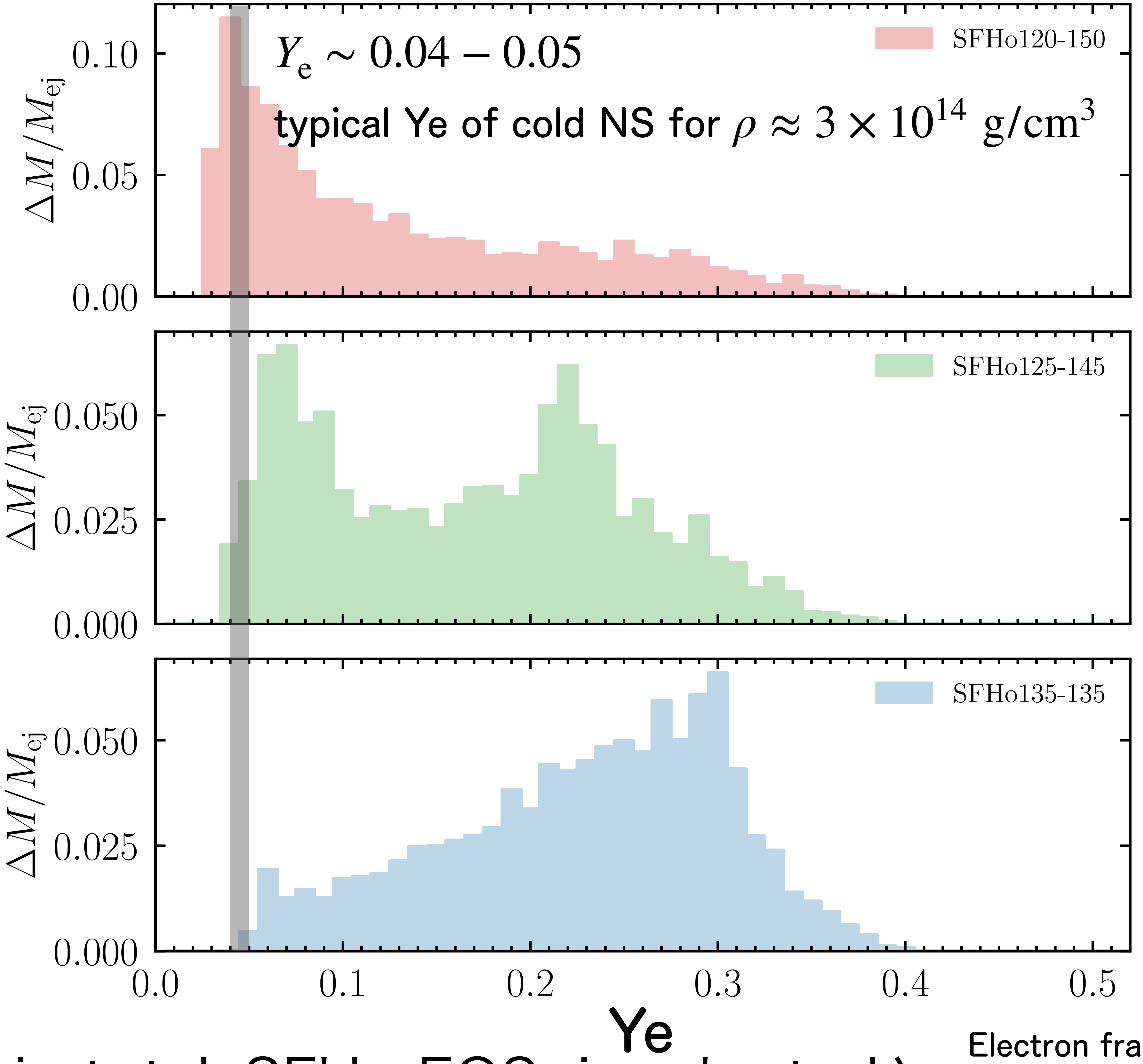


(2.70 Msun in total, SFHo EOS is adopted.)

Electron fraction $Y_e := \frac{n_e}{n_{\mathrm{baryon}}} = 1 - \frac{n_n}{n_{\mathrm{baryon}}}$

N-richness of dynamical ejecta

SF+23
also Radice+18, Just+23



(2.70 Msun in total, SFHo EOS is adopted.)

<u>Asymmetric merger</u>

- Mainly tidal effect
- ~Original Ye preserved

↓

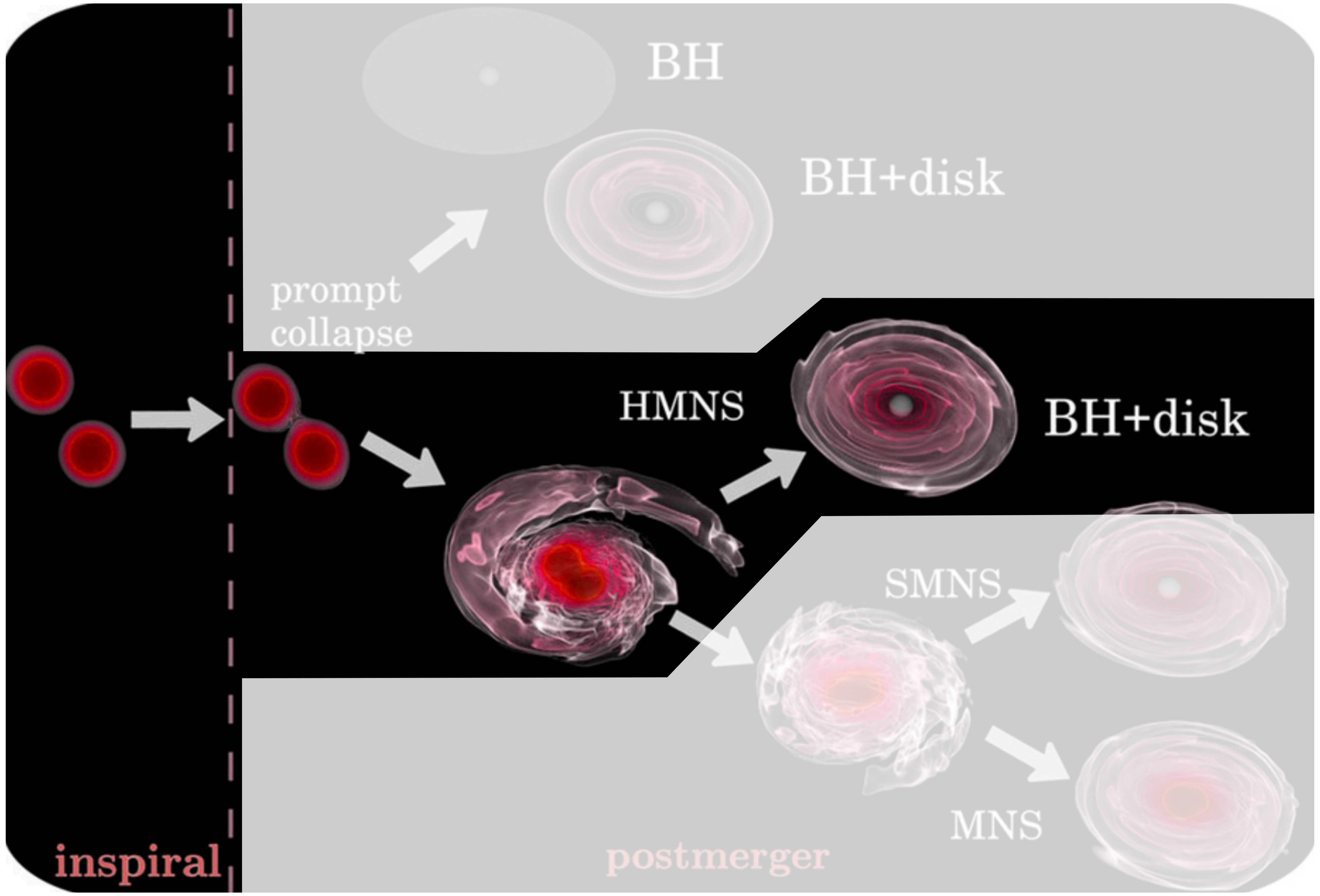
<u>Symmetric merger</u>

- Stronger shock effects
- higher Ye (less n-rich)

Electron fraction $Y_e := \frac{n_e}{n_{\text{baryon}}} = 1 - \frac{n_n}{n_{\text{baryon}}}$

Implications of numerical simulation: Post-merger Ejecta

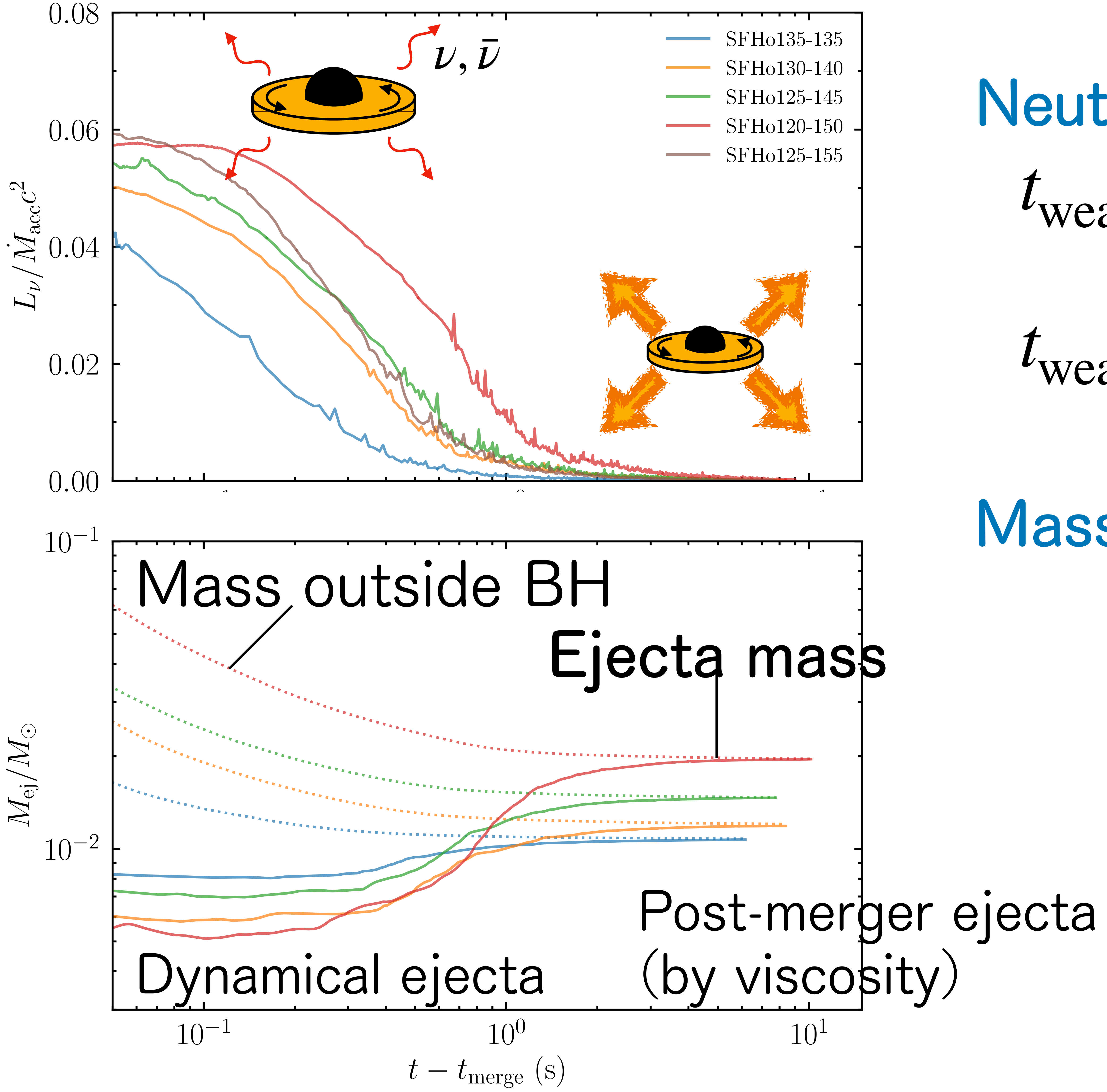
Short-lived massive NS



- Soft EOS and/or large total mass
- SFHo EOS (max. mass ~$2.0M_\odot$), total mass $2.7M_\odot$ with different mass ratios
- Collapse into a BH in 20 ms

Post-merger mass ejection

Cooling efficiency = Luminosity/Accretion rate



Neutrino cooling vs viscous heating

$t_{\rm weak} \lesssim t_{\rm vis}$ phase: weak/no outflow

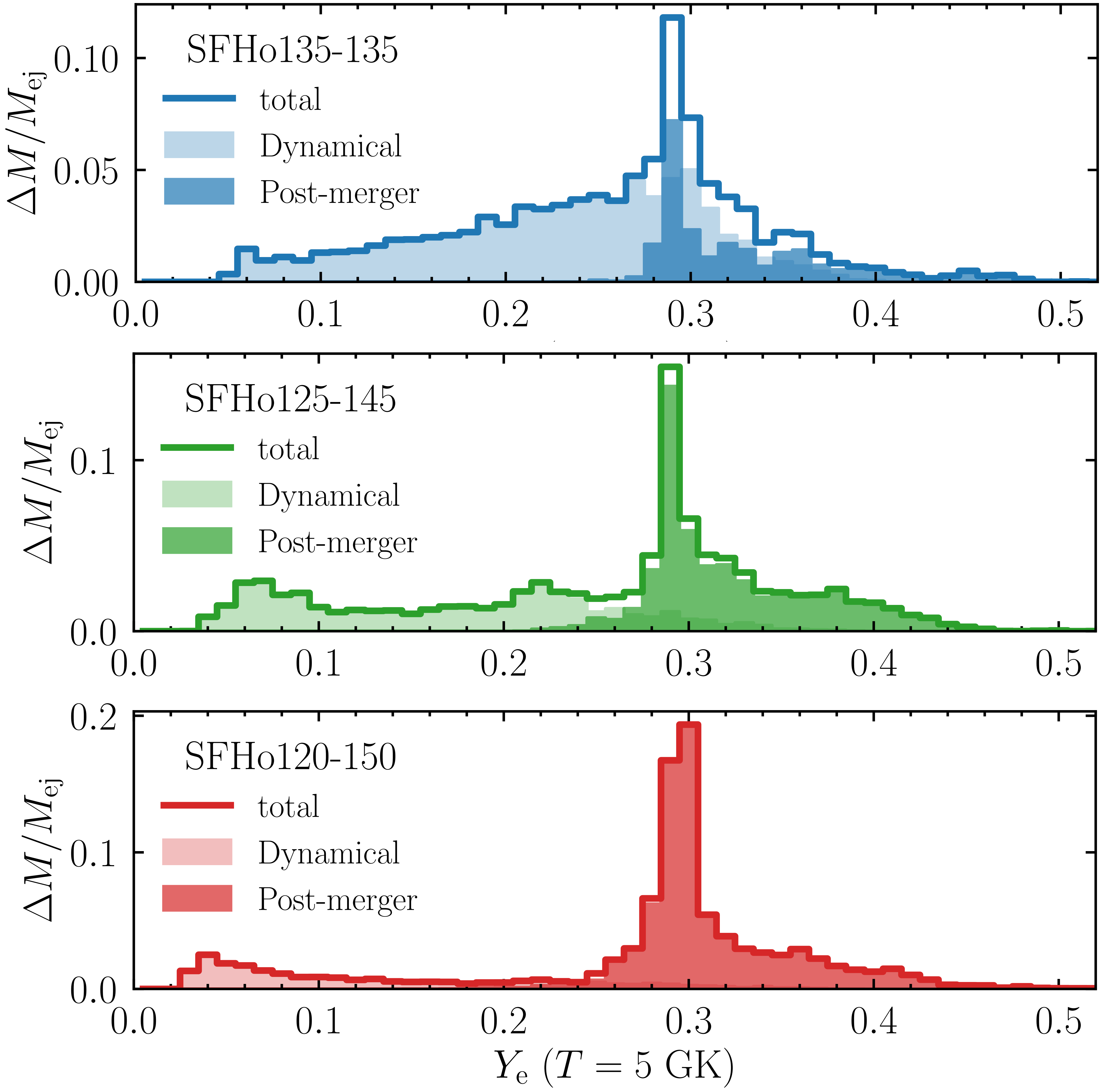
$t_{\rm weak} \gg t_{\rm vis}$ phase: viscosity can drive outflow

Mass-ejection mechanism

Disk temperature decreases
due to the drop of accretion rate

Cooling efficiency drops
→Mass ejection by viscous heating

Neutron-richness of the ejecta



- Larger post-merger contribution in more asymmetric case ← Larger disk mass.
- The peak at Ye ≈ 0.3 irrespective of mass ratio.

More asymmetric

Electron fraction $Y_e := \frac{n_e}{n_{\rm baryon}} = 1 - \frac{n_n}{n_{\rm baryon}}$

Neutron-richness of the ejecta

SF+20, 23
see also Just+22

At high temperature $T \gtrsim 1-2$ MeV,

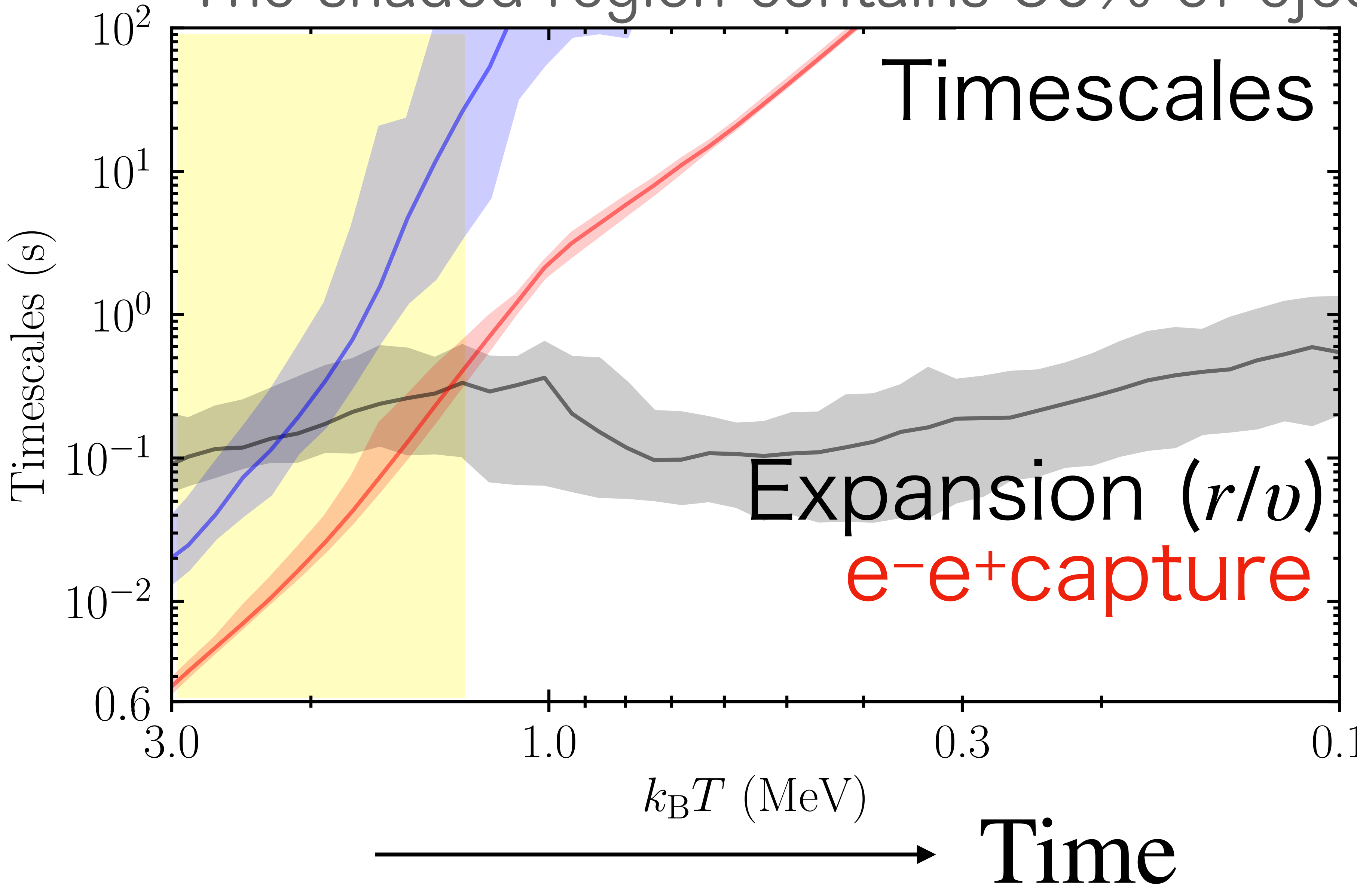
$$e^- + p \rightarrow \nu_e + n$$
$$e^+ + n \rightarrow \bar{\nu}_e + p$$

timescale is shorter than dynamical time.

Ye settles into a (dynamical) equilibrium of these reactions.

Post-merger ejecta of SFHo 1.2-1.5 case

The shaded region contains 80% of ejecta mass



Neutron-richness of the ejecta

SF+20, 23
see also Just+22

At high temperature $T \gtrsim 1-2$ MeV,

$$e^- + p \to \nu_e + n$$
$$e^+ + n \to \bar{\nu}_e + p$$

timescale is shorter than dynamical time.

Ye settles into a (dynamical) equilibrium of these reactions.

Ye freezes out when

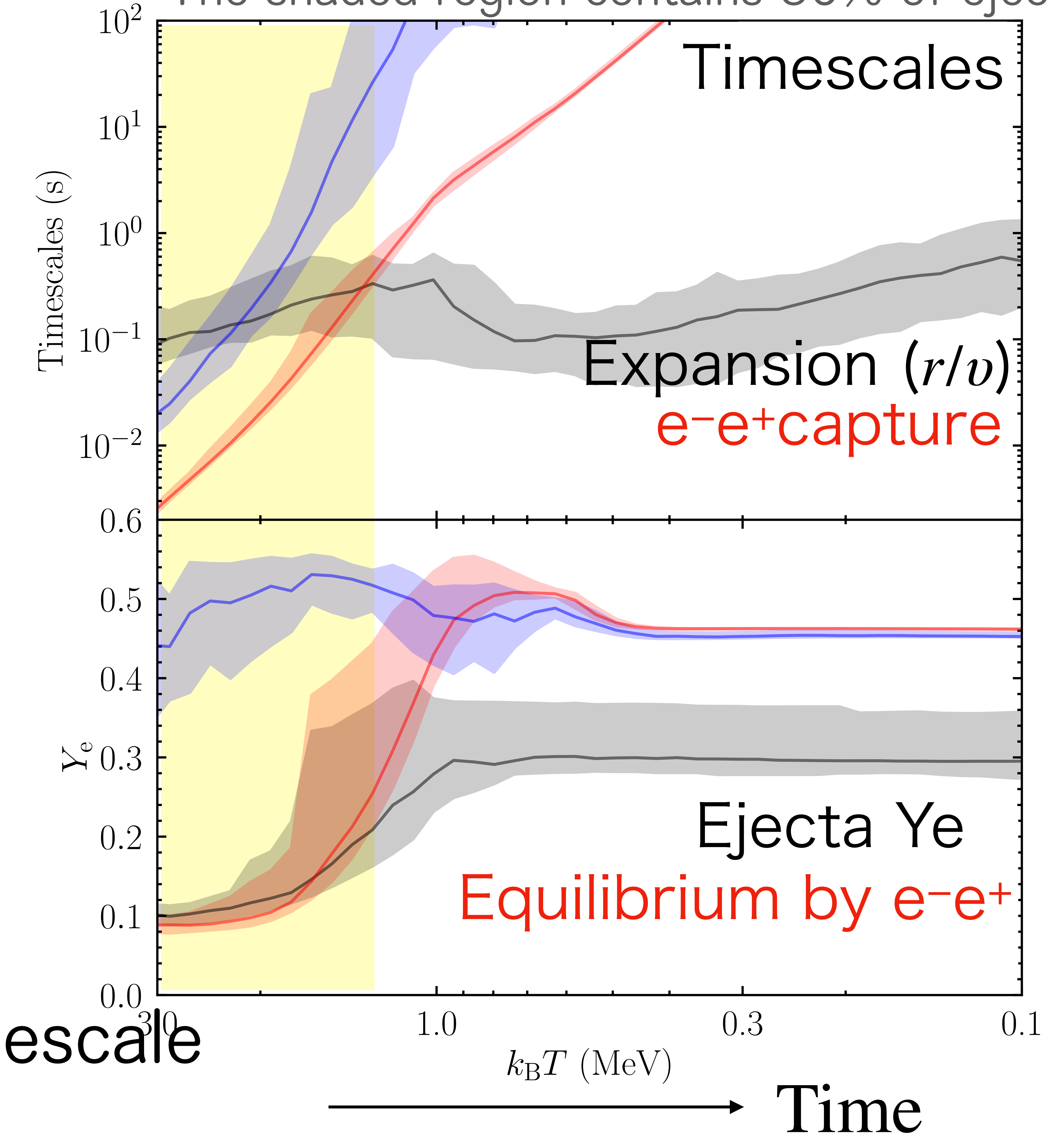
$$t_{\mathrm{expansion}} \sim t_{\mathrm{weak}} \quad (k_{\mathrm{B}}T \sim 1-2\,\mathrm{MeV})$$

- In this case, $Y_{\mathrm{e}} \approx 0.3$.

  Resulting Y_{e} depends on the expansion timescale (strength of the viscosity).

Post-merger ejecta of SFHo 1.2-1.5 case

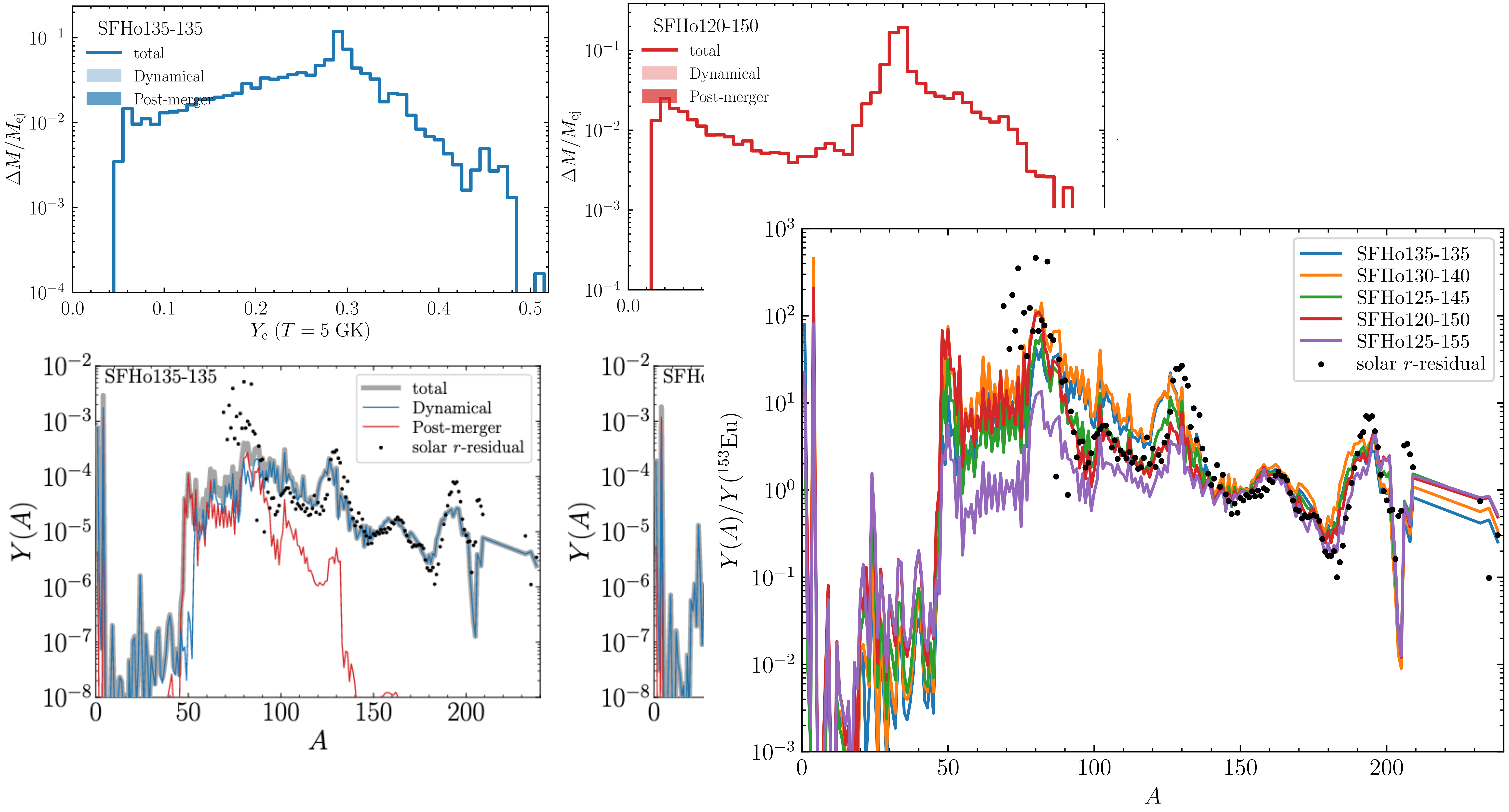
The shaded region contains 80% of ejecta mass



Composition of the ejecta

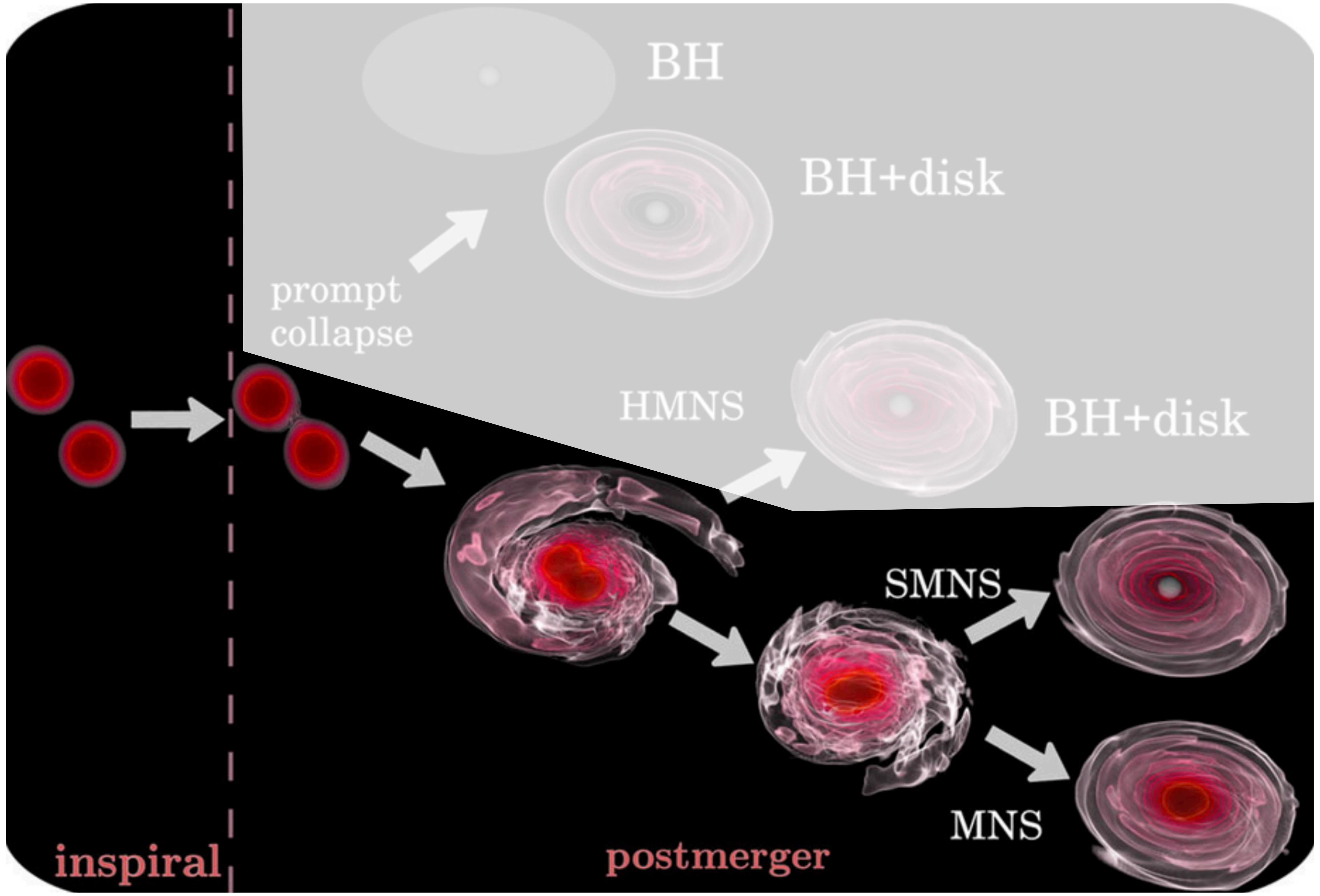
Short-lived massive NS

equal-mass（1.35-1.35）　asymmetric（1.20-1.50



Solar-like r-process pattern can be approximately reproduced irrespective of the binary mass ratio for short-lived NS cases.

Long-lived massive NS case



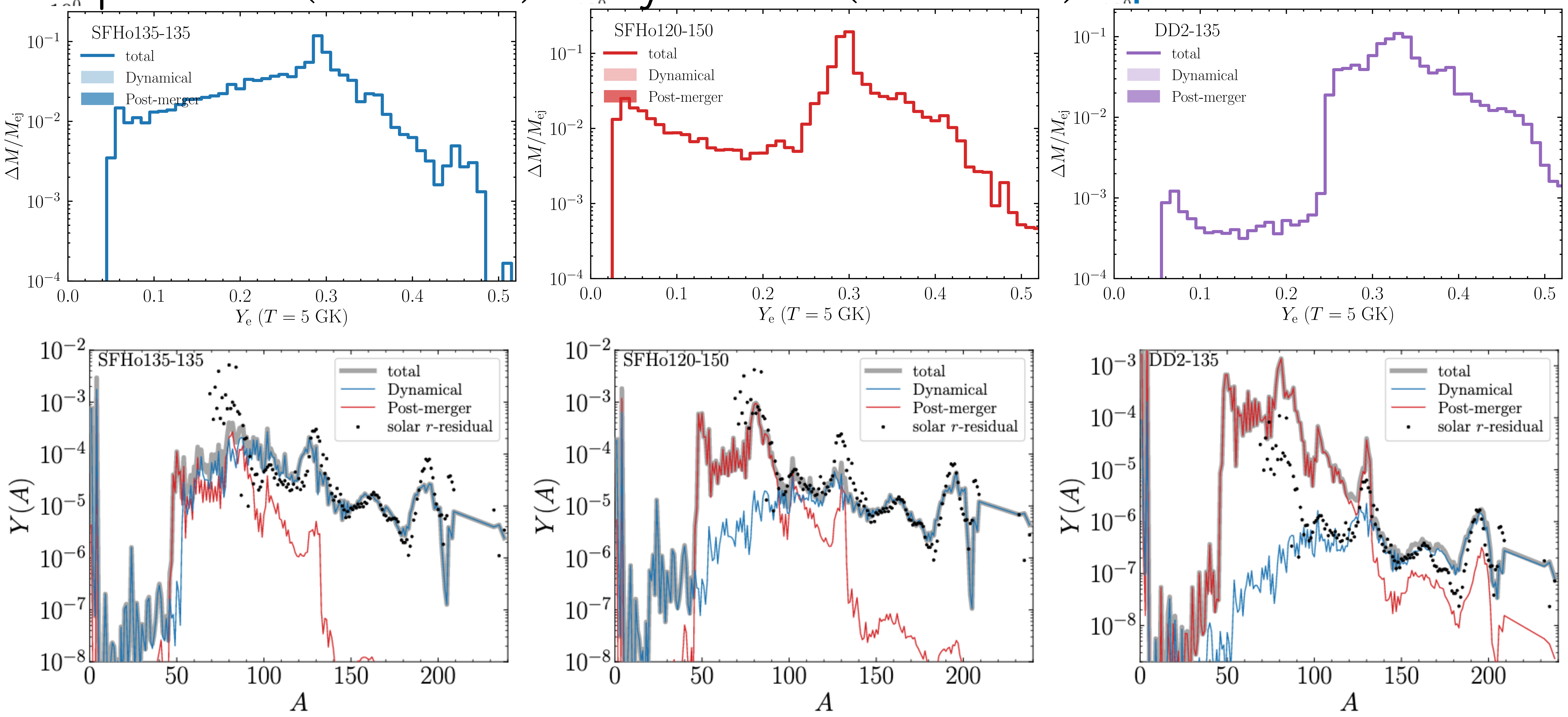
- Stiffer EOS and/or lighter total mass
- DD2 EOS (max. mass ~$2.4M_\odot$), $1.35-1.35M_\odot$
- NS lifetime $\gtrsim 10$ sec.

Long-lived massive NS case

Short-lived massive NS

equal-mass (1.35-1.35) asymmetric (1.20-1.50)

Long-lived massive NS
equal-mass (DD2 1.35-1.35)



Post-merger ejecta is too massive.
(If binary NS merger is the main r-process site)
Mergers leaving long-lived NSs should be minor.

Beyond viscous hydrodynamics model

- MHD: the most consistent way to model angular momentum transport.

    Disk dynamics: Viscous hydro is a good approximation

    e.g., Just+22, Fernandez+19,
    Hayashi+22, Kiuchi, SF+23
    Wanajo, SF+ in prep.

- MHD effect may be underestimated in the presence of a long-lived NS.
- Strongly magnetized massive neutron star may drive a strong wind.

    e.g., Ciolfi+17, Mösta+20, Shibata+21, Combi & Siegel 23, Most & Quataert 23, Kiuchi+24

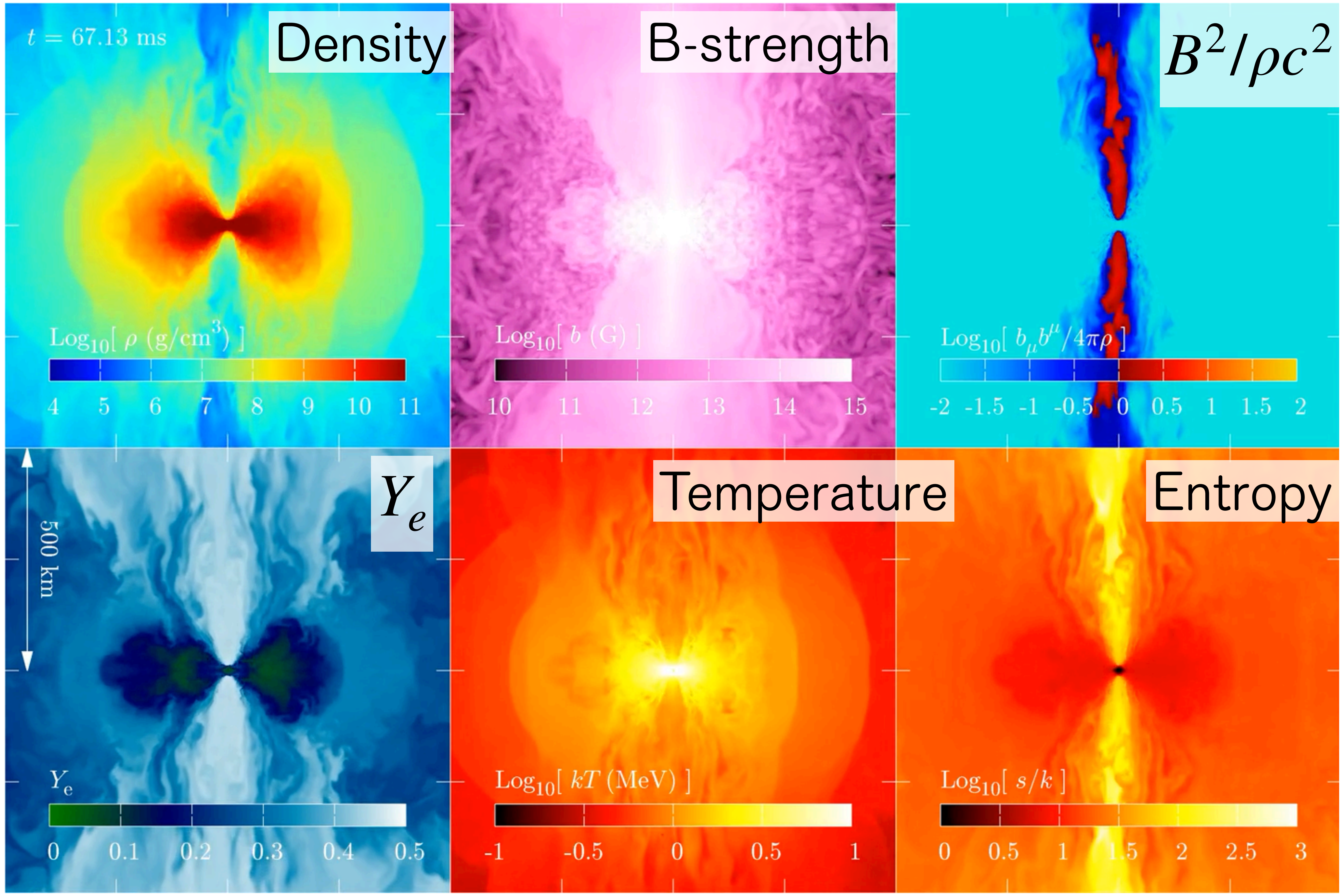
- The ejecta profile may be significantly modified Kawaguchi+22

    Effects on kilonova lightcurves

MHD effects for long-lived NS case

Strongly magnetized massive neutron star drives a strong wind.

Kiuchi+24 (Visualized by K. Hayashi)



→ Sekiguchi's talk in the next!

Summary

- Galactic BNS distribution $(M_{\rm tot} \lesssim 2.8 M_\odot)$ → Temporal formation of massive NS

  We can expect mass ejection!

Short-lived NS case:

Asymmetric → **Equal-mass**

- Dyn. ejecta has Ye closer to original NS (→ limit: BH-NS)
- More post-merger ejecta → solar r-process abundance

- Dyn. ejecta reprocessed
  → Higher Ye, broader distribution
  → solar abundance
- Post-merger ejecta sub-dominant

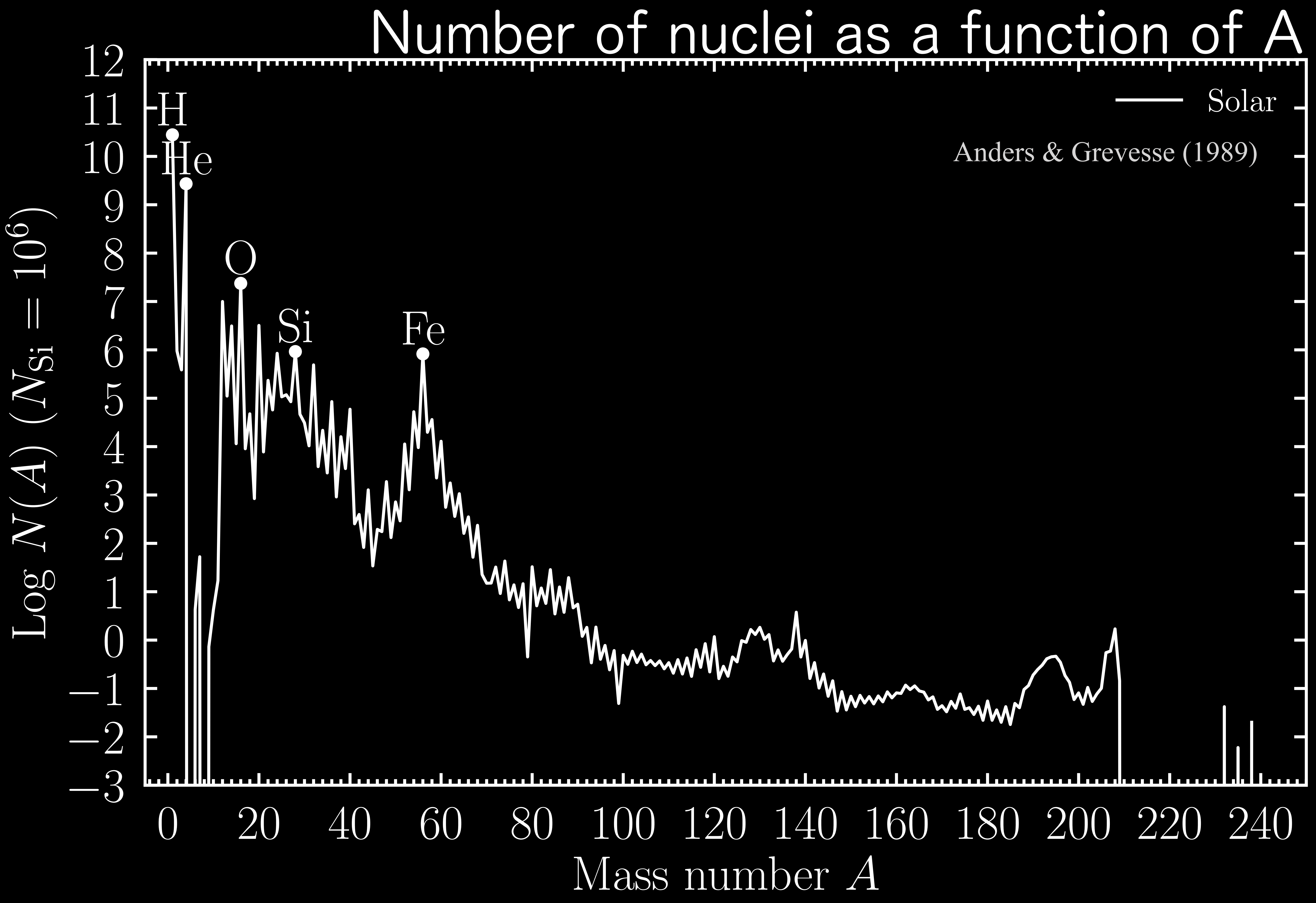
Long-lived NS case:

- Post-merger ejecta too massive.
- Fail to reproduce solar r-process abundance
- MHD may be more important for long-lived cases

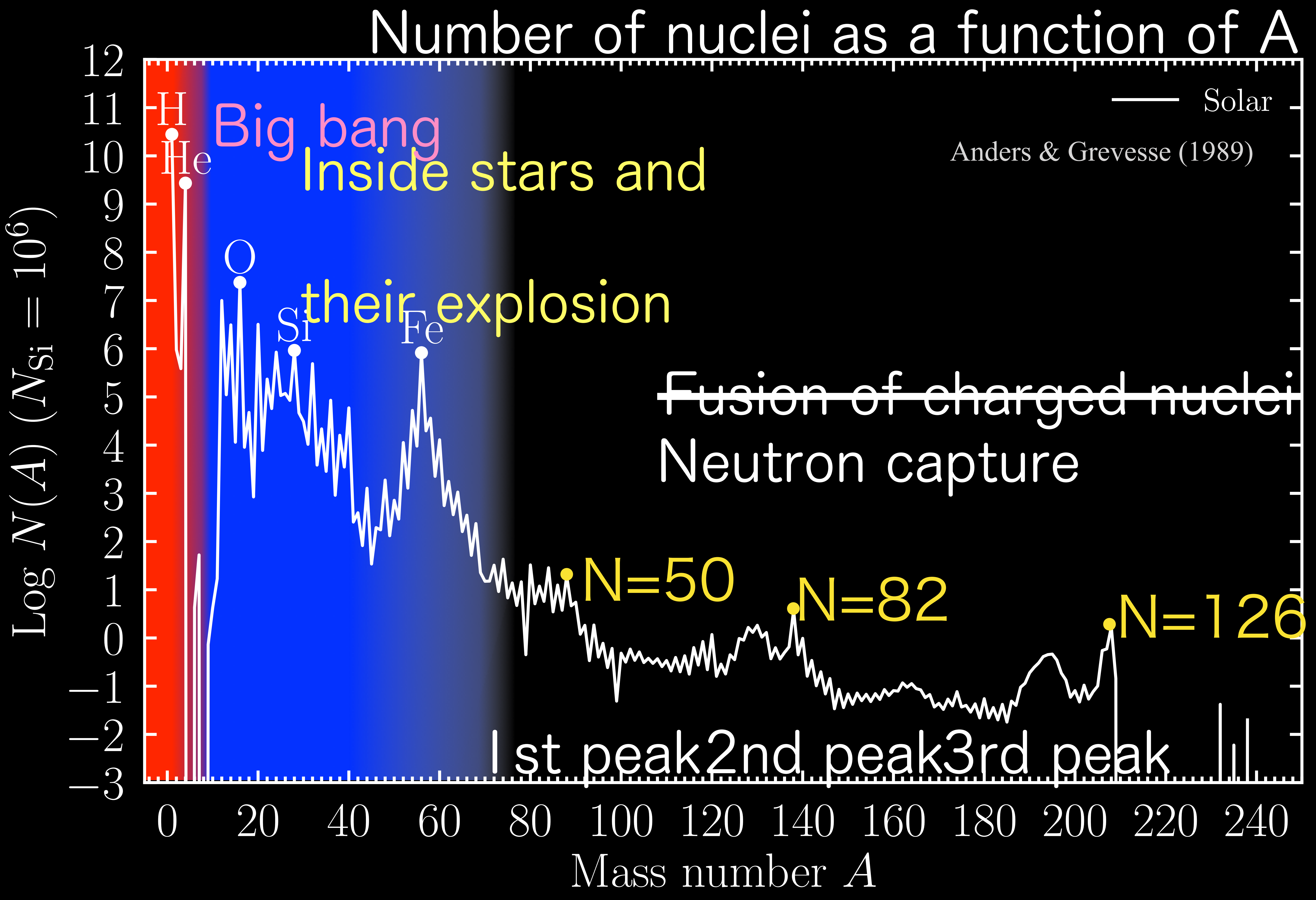
Thank you for your attention!

Back-up slides

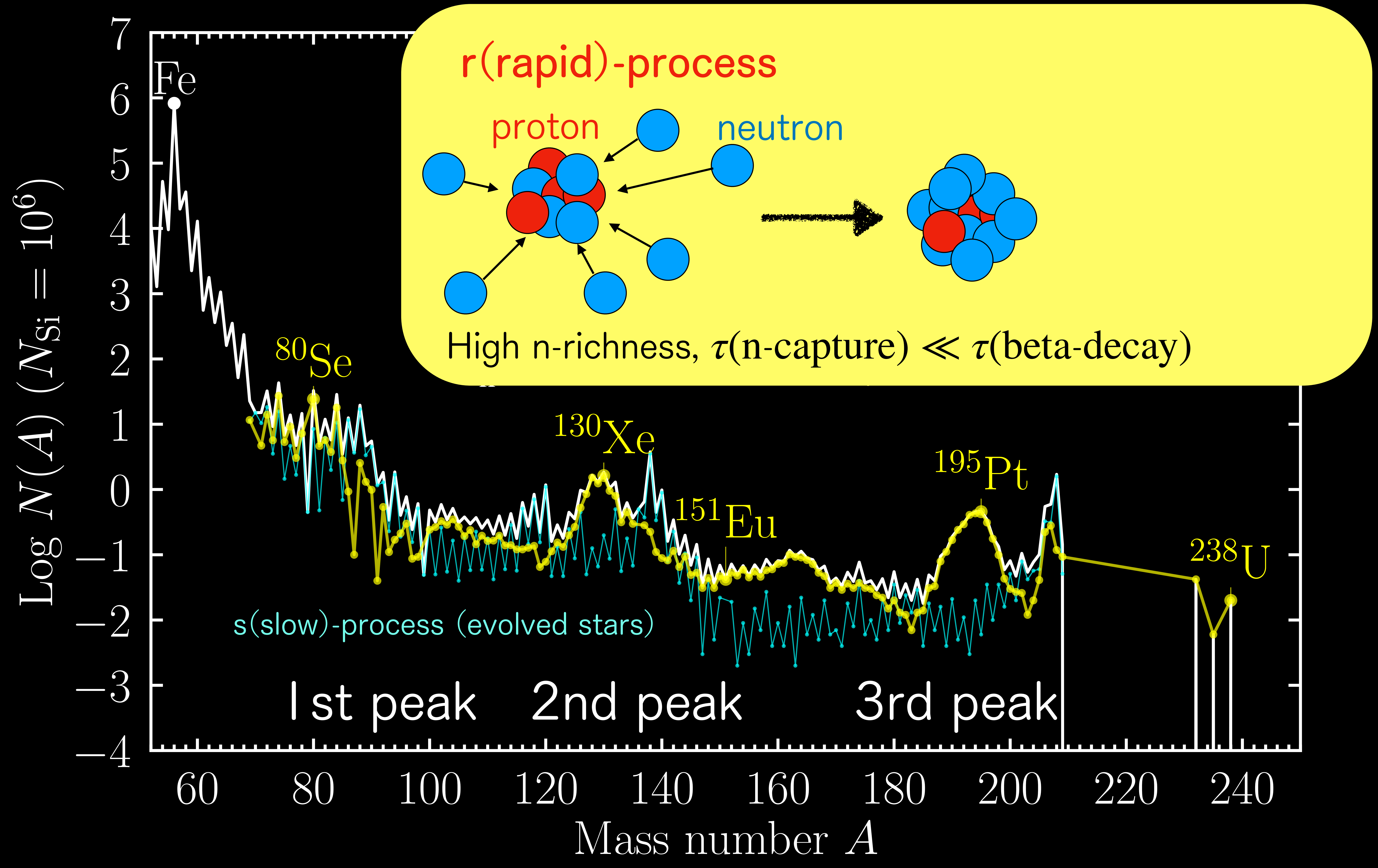
Solar nuclear pattern



Solar nuclear pattern



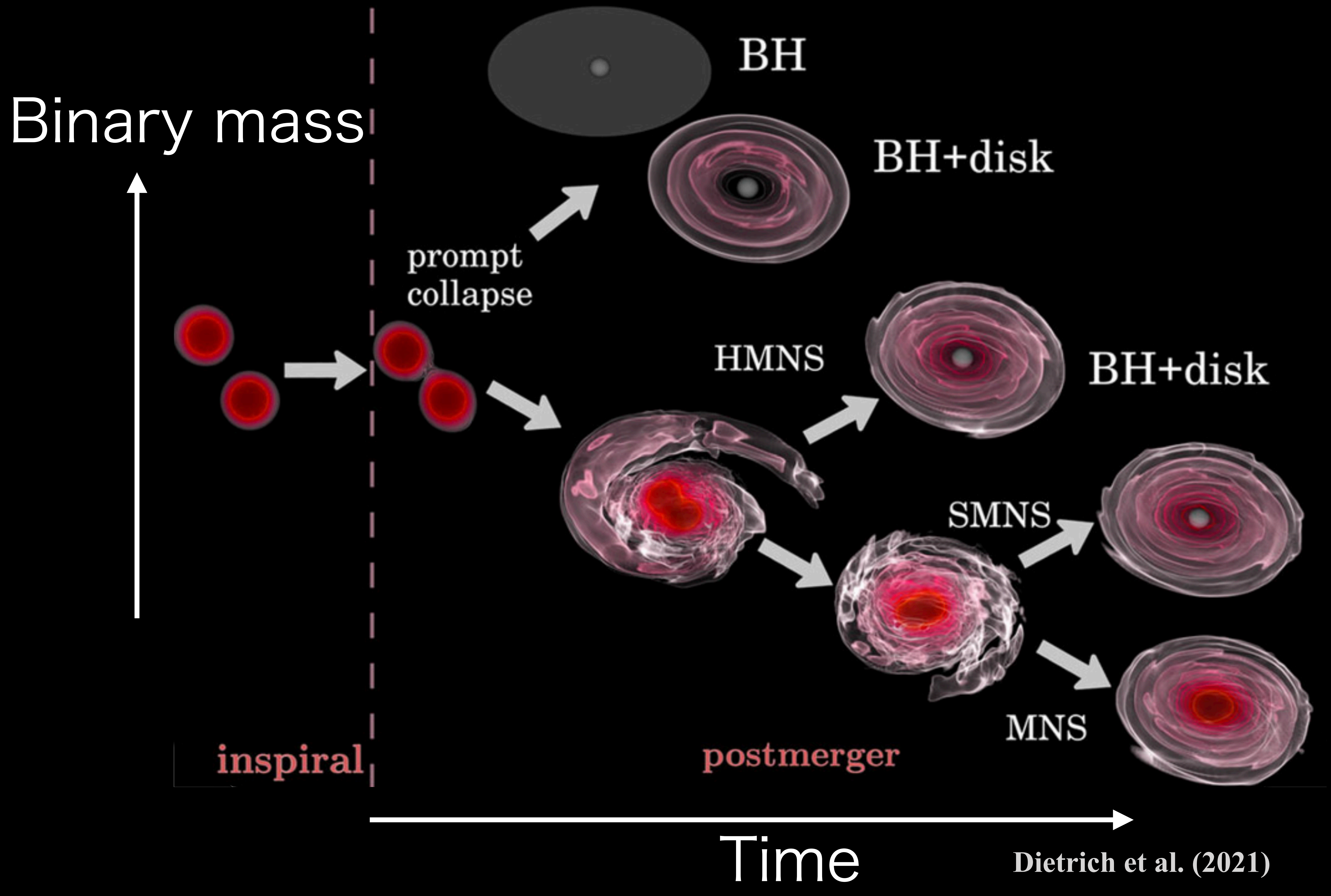
r-process



r(rapid)-process
proton
neutron
High n-richness, τ(n-capture) ≪ τ(beta-decay)
Fe
^{80}Se
^{130}Xe
^{151}Eu
^{195}Pt
^{238}U
s(slow)-process (evolved stars)
1st peak
2nd peak
3rd peak
Log $N(A)$ ($N_{\mathrm{Si}} = 10^6$)
7
6
5
4
3
2
1
0
−1
−2
−3
−4
60
80
100
120
140
160
180
200
220
240
Mass number A

Evolution path of mergers

Remnant evolution depends on the binary mass and unknown NS EOS.

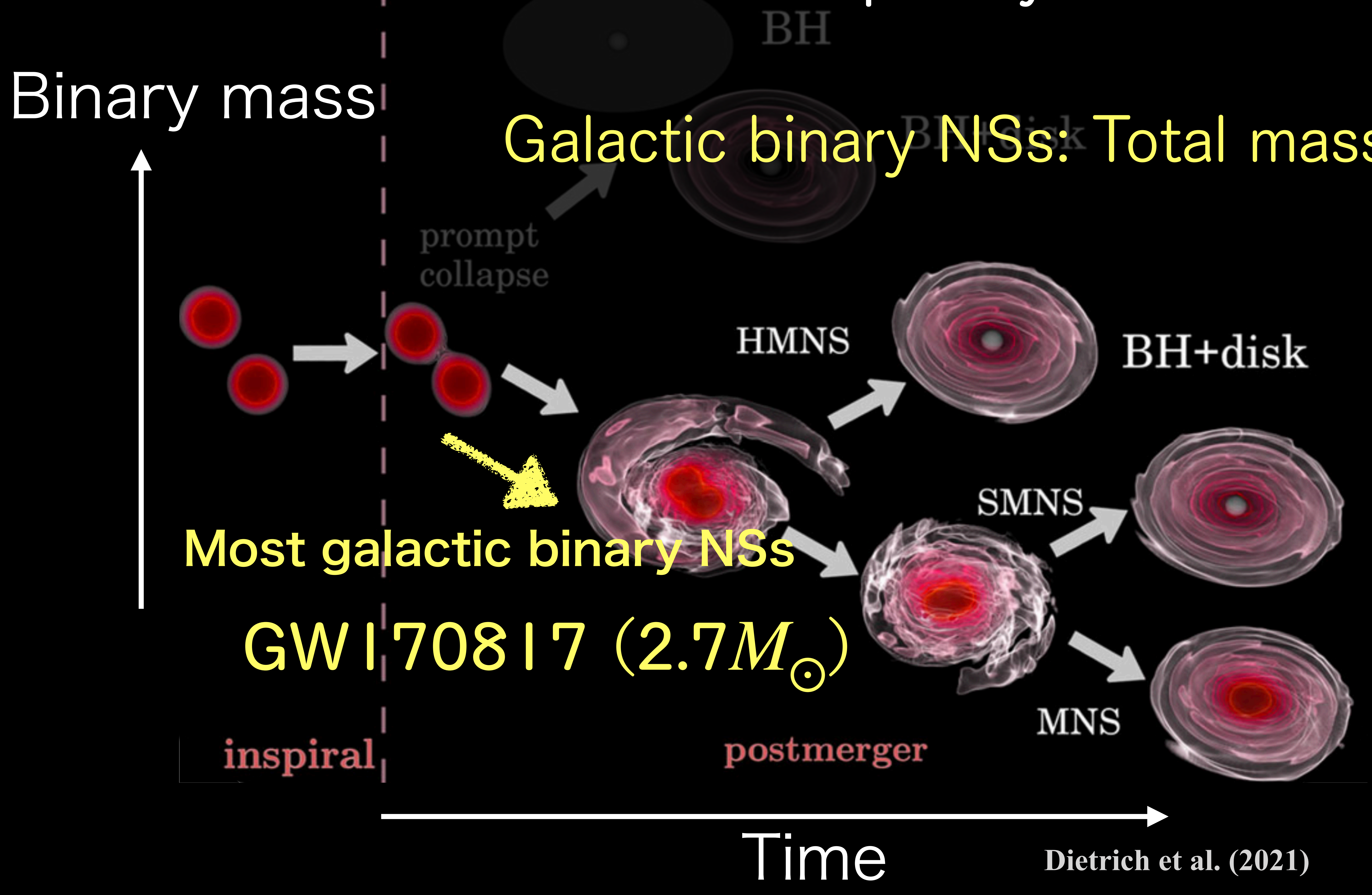


Dietrich et al. (2021)

Evolution path of mergers

EOS that can support $2M_\odot$ NS → $M_\mathrm{total} \lesssim 2.8M_\odot$ binary form a massive NS at least temporarily.

Hotokezaka+11
Dietrich+17



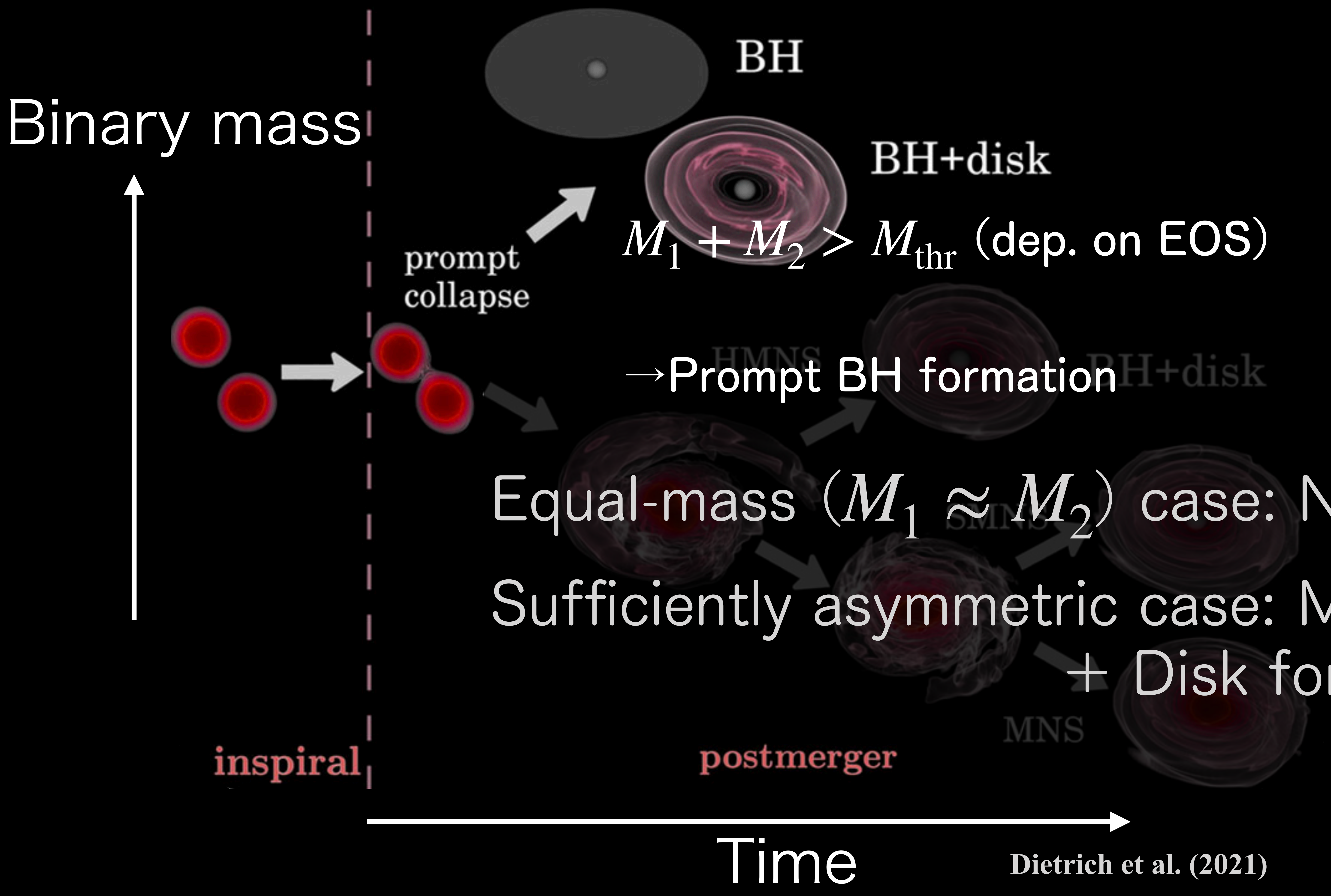
Galactic binary NSs: Total mass 2.5—$2.8M_\odot$

Most galactic binary NSs

GW170817 ($2.7M_\odot$)

Dietrich et al. (2021)

Evolution path of mergers



$M_1 + M_2 > M_{\rm thr}$ (dep. on EOS)

→Prompt BH formation

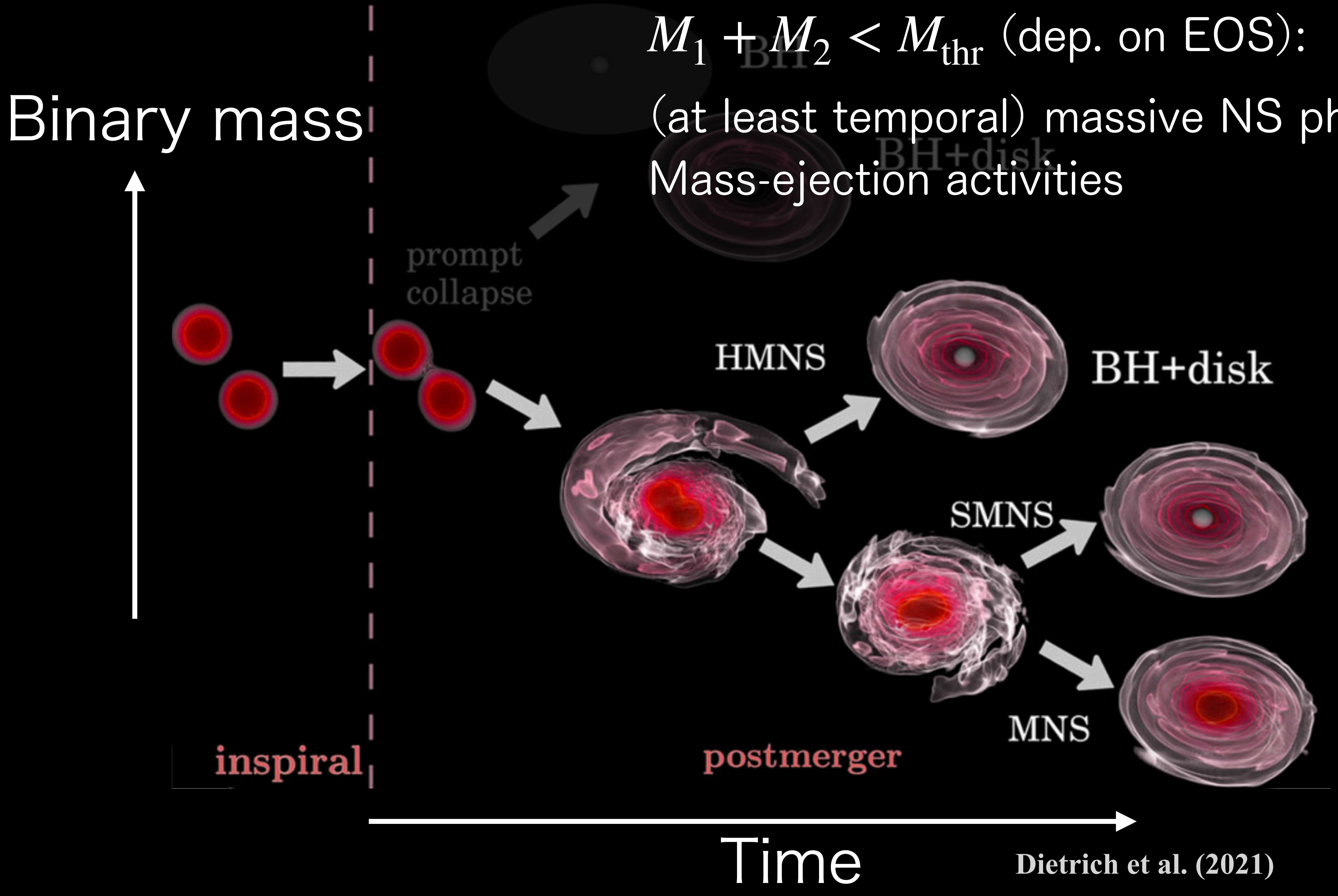
Equal-mass $(M_1 \approx M_2)$ case: Negligible mass ejection

Sufficiently asymmetric case: Mass ejection by tidal for

＋ Disk formation

Dietrich et al. (2021)

Evolution path of mergers



$M_1 + M_2 < M_{\mathrm{thr}}$ (dep. on EOS):

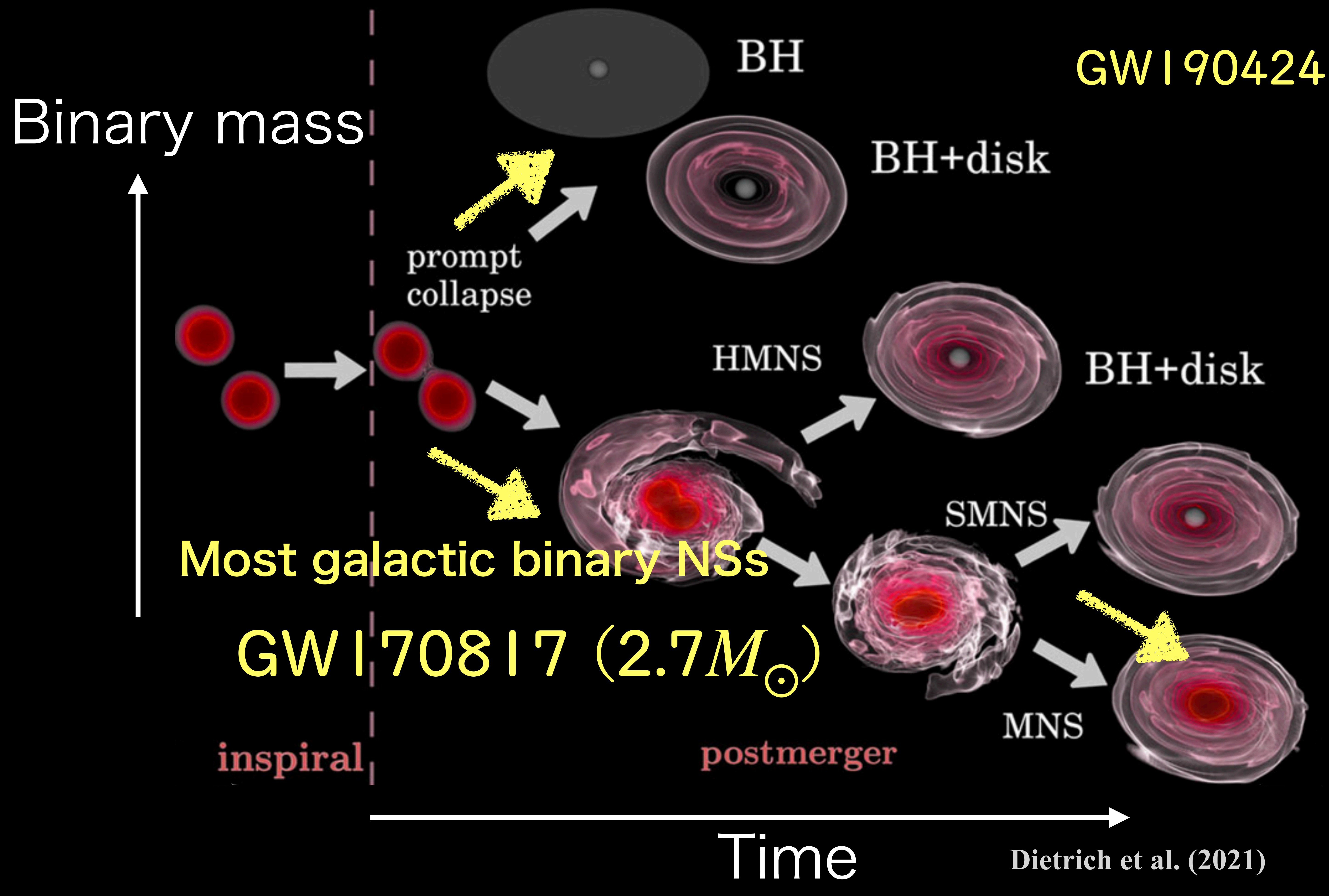
(at least temporal) massive NS phase

Mass-ejection activities

Dietrich et al. (2021)

Evolution path of mergers

EOS that can support $2M_\odot$ NS → $M_{\rm thr} \gtrsim 2.8M_\odot$



GW190424 $(3.4M_\odot)$

Most galactic binary NSs

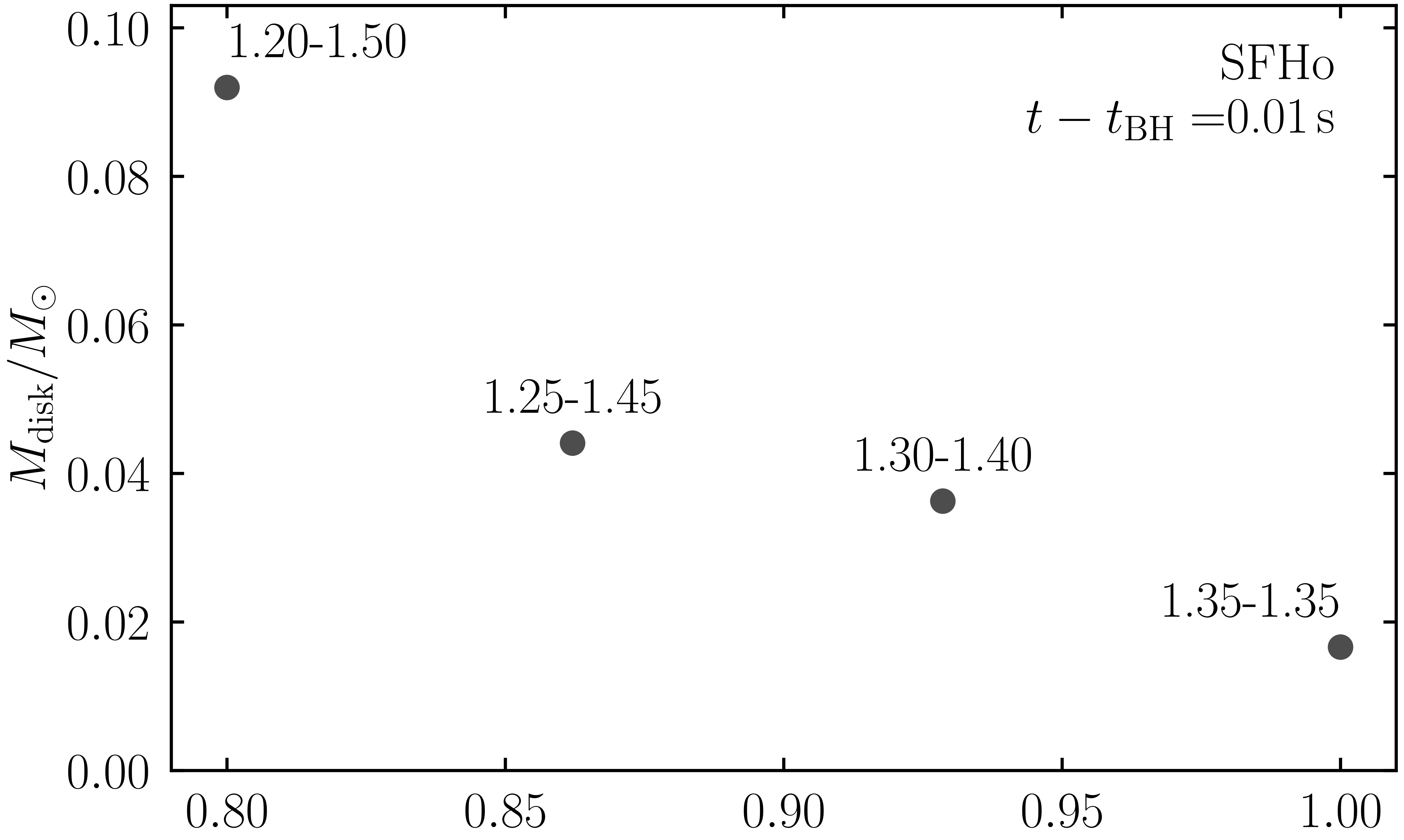
GW170817 $(2.7M_\odot)$

PSR J1946+2052 $(2.5M_\odot)$

Dietrich et al. (2021)

Mass-ratio dependence of disk mass

Disk mass after BH formation

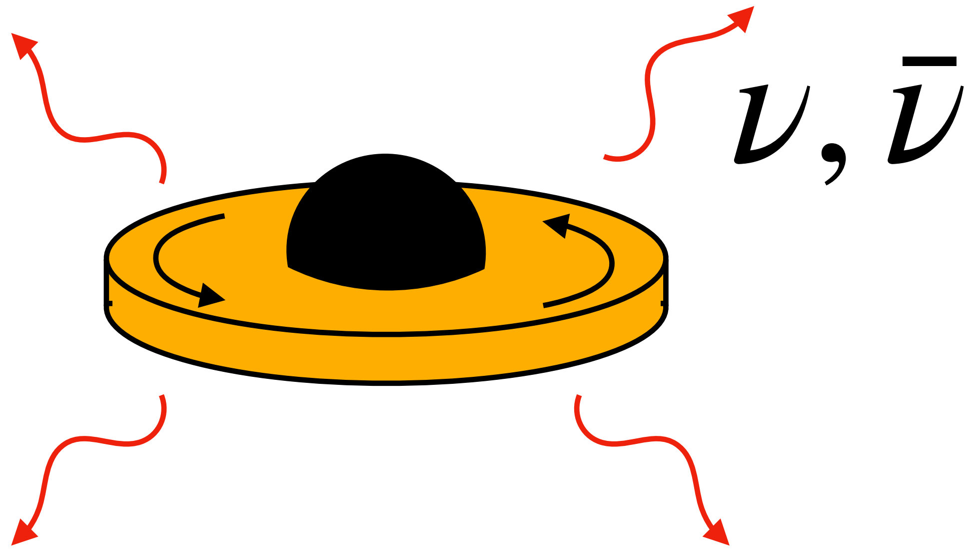


Asymmetric ↔ Equal-mass

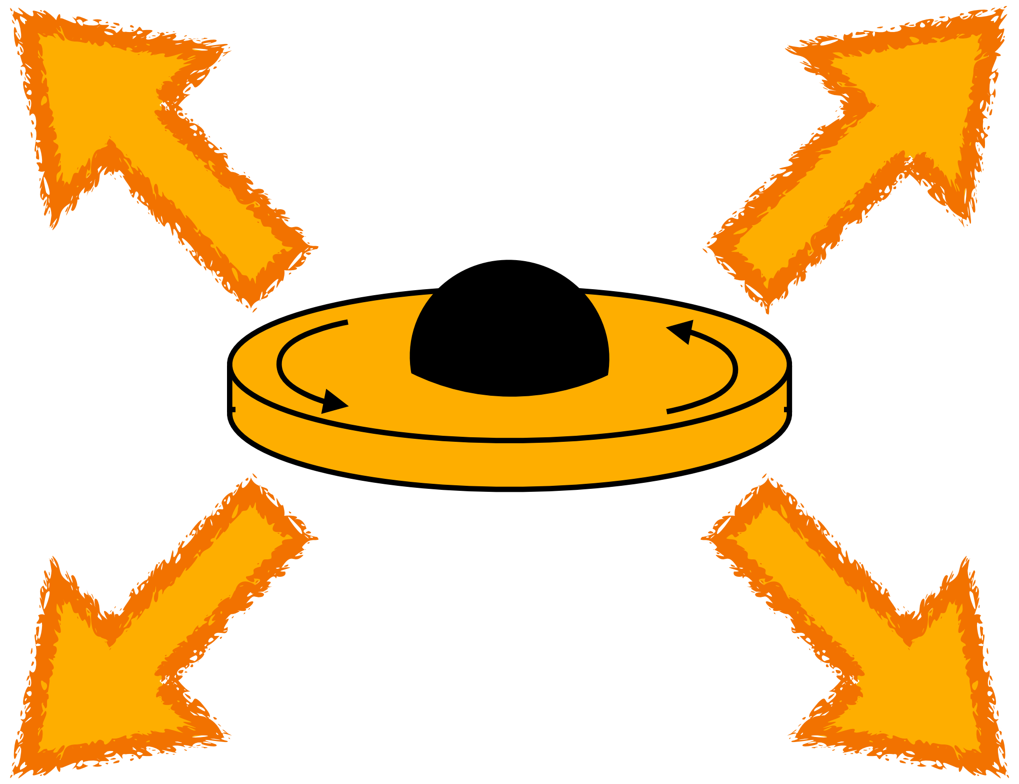
Disk mass（↔ Importance of post-merger ejecta）
is larger for the merger of more asymmetric binary（more tidal effect）

Neutrino cooling vs viscous heating

- Neutrino emission cooling
- MHD turbulence → Viscous angular momentum transport/heating

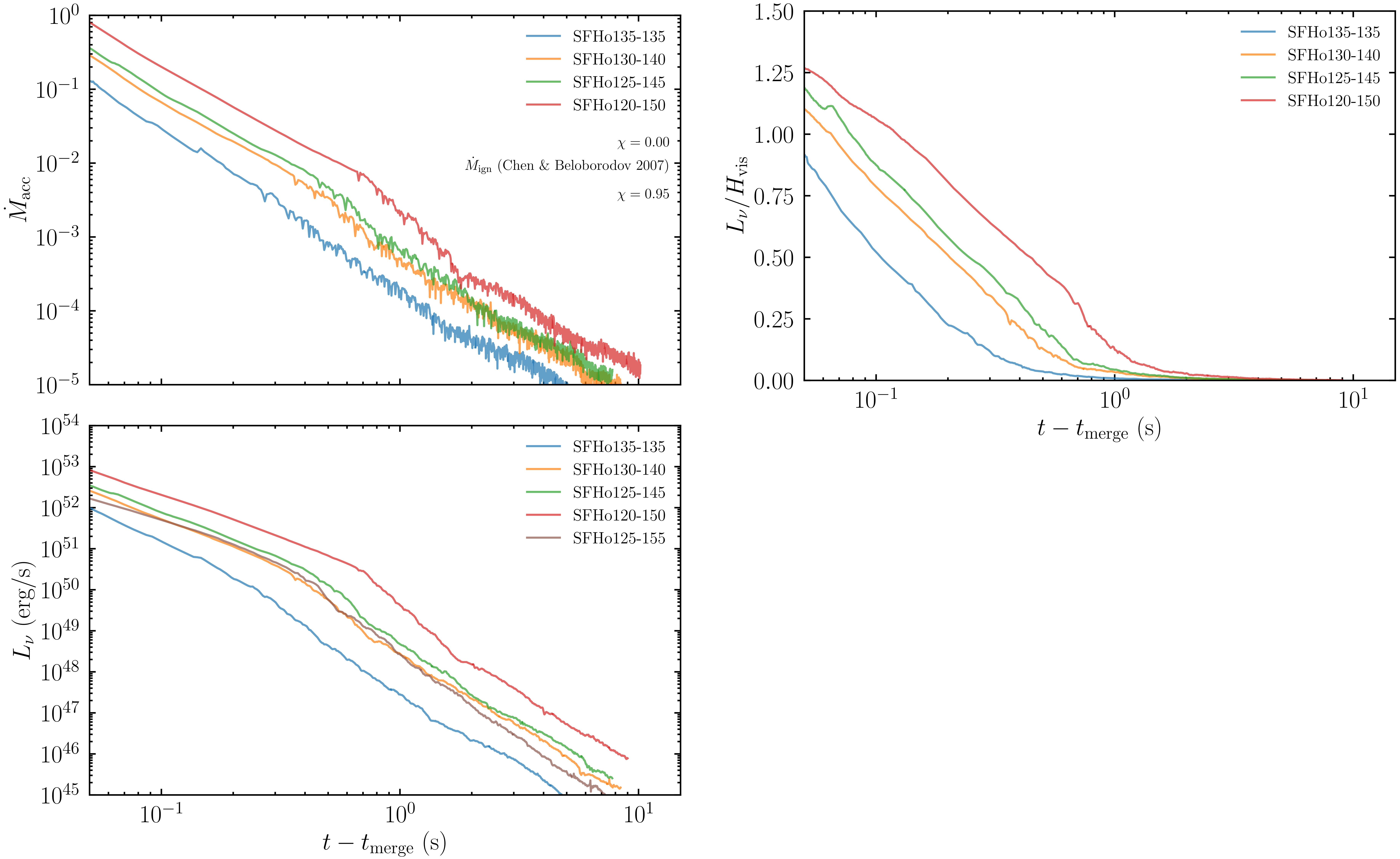


$t_{\mathrm{weak}} \lesssim t_{\mathrm{vis}}$ phase: weak/no outflow



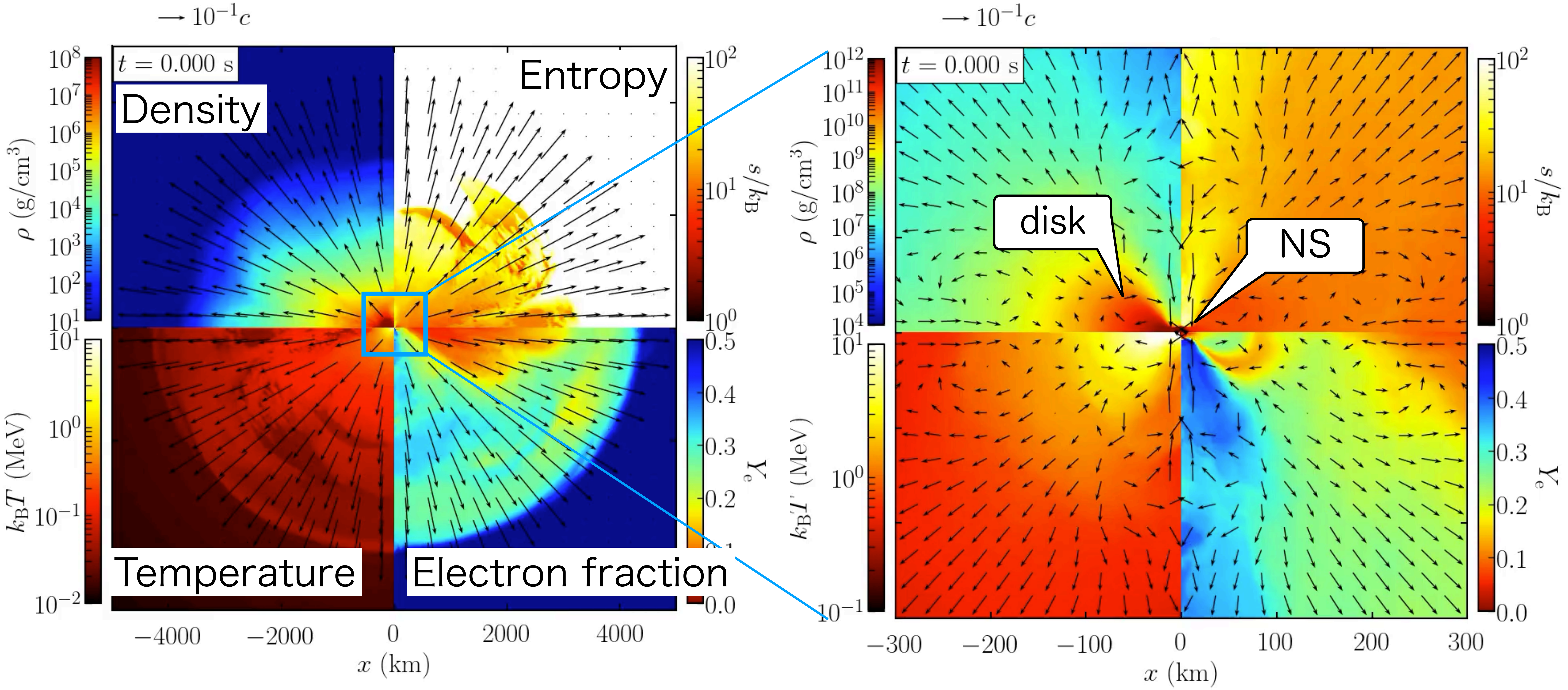
$t_{\mathrm{weak}} \gg t_{\mathrm{vis}}$ phase: viscosity can drive outflow

Other properties



Post-merger viscous evolution

Viscous hydro simulation of post-merger system SF+23

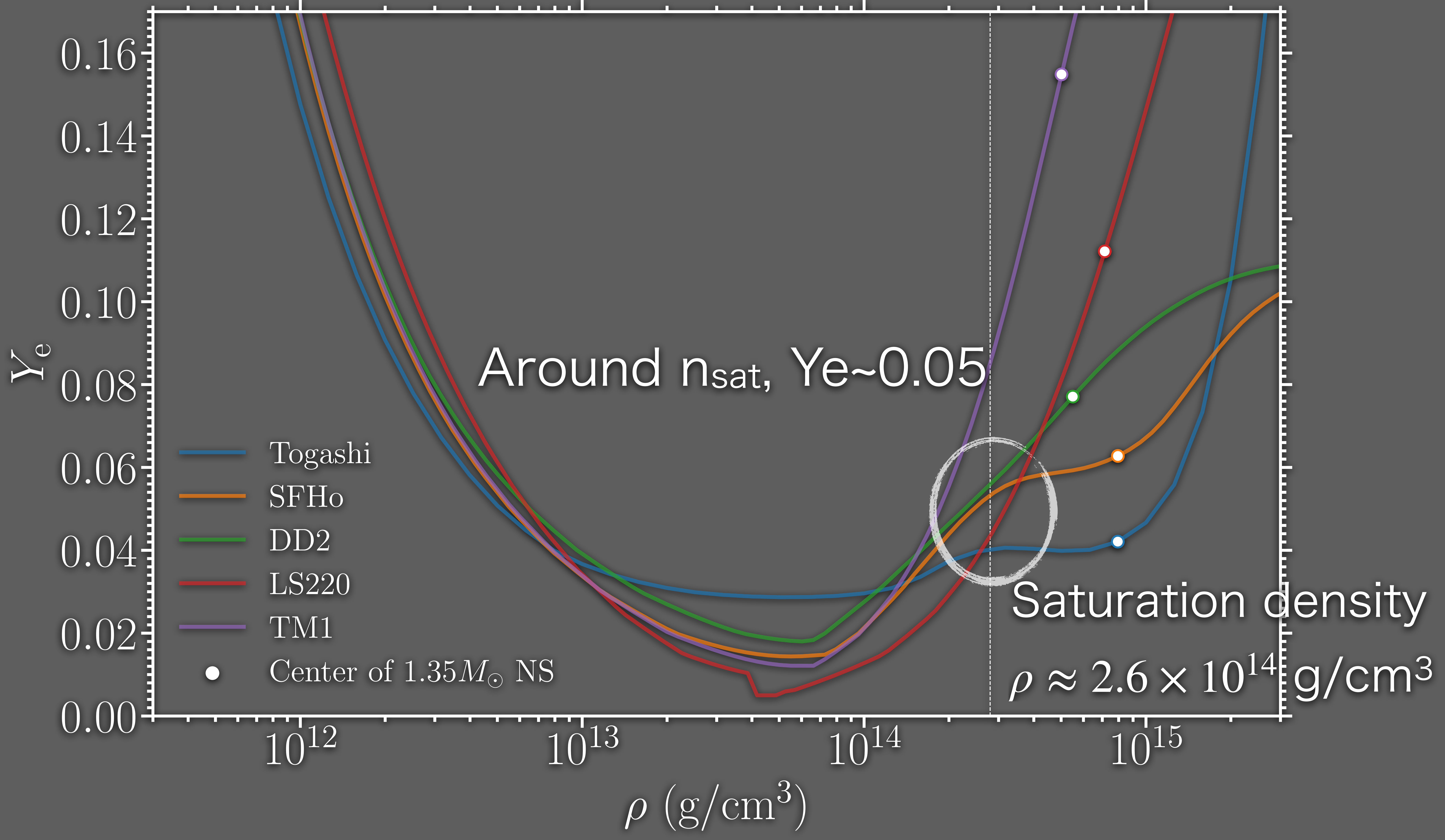


$1.20 - 1.50M_\odot$ case:

A formed massive NS collapses into a BH in ~20 ms.
Post-merger ejecta is developed after the cooling efficiency drops.

Neutron-richness

Ye of T=0 neutrino-less beta equilibrium $\mu_p + \mu_e = \mu_n$

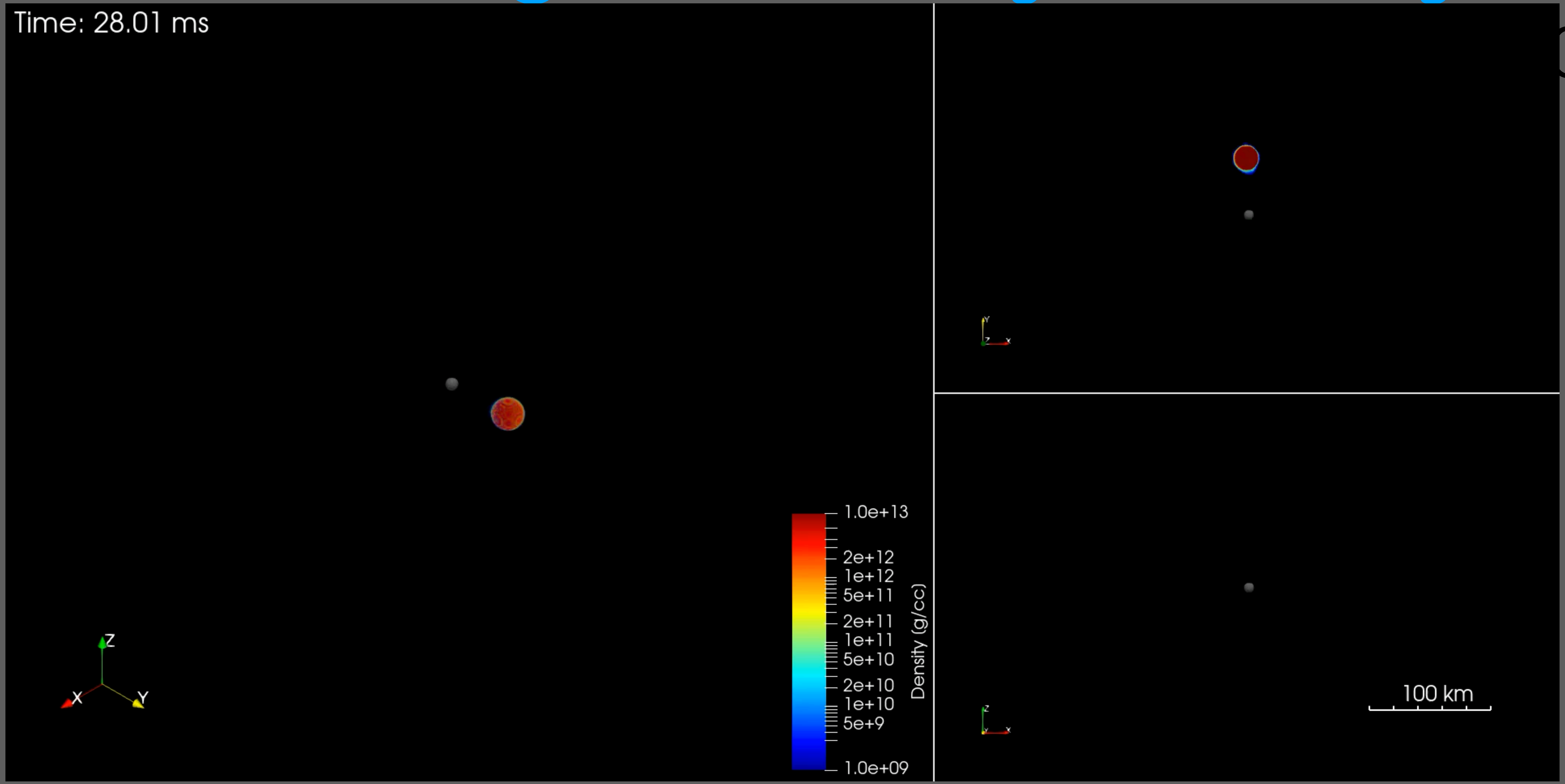


Around nsat, Ye~0.05

Saturation density

$\rho \approx 2.6 \times 10^{14}$ g/cm^3

BH-NS merger: Purely tidal ejecta



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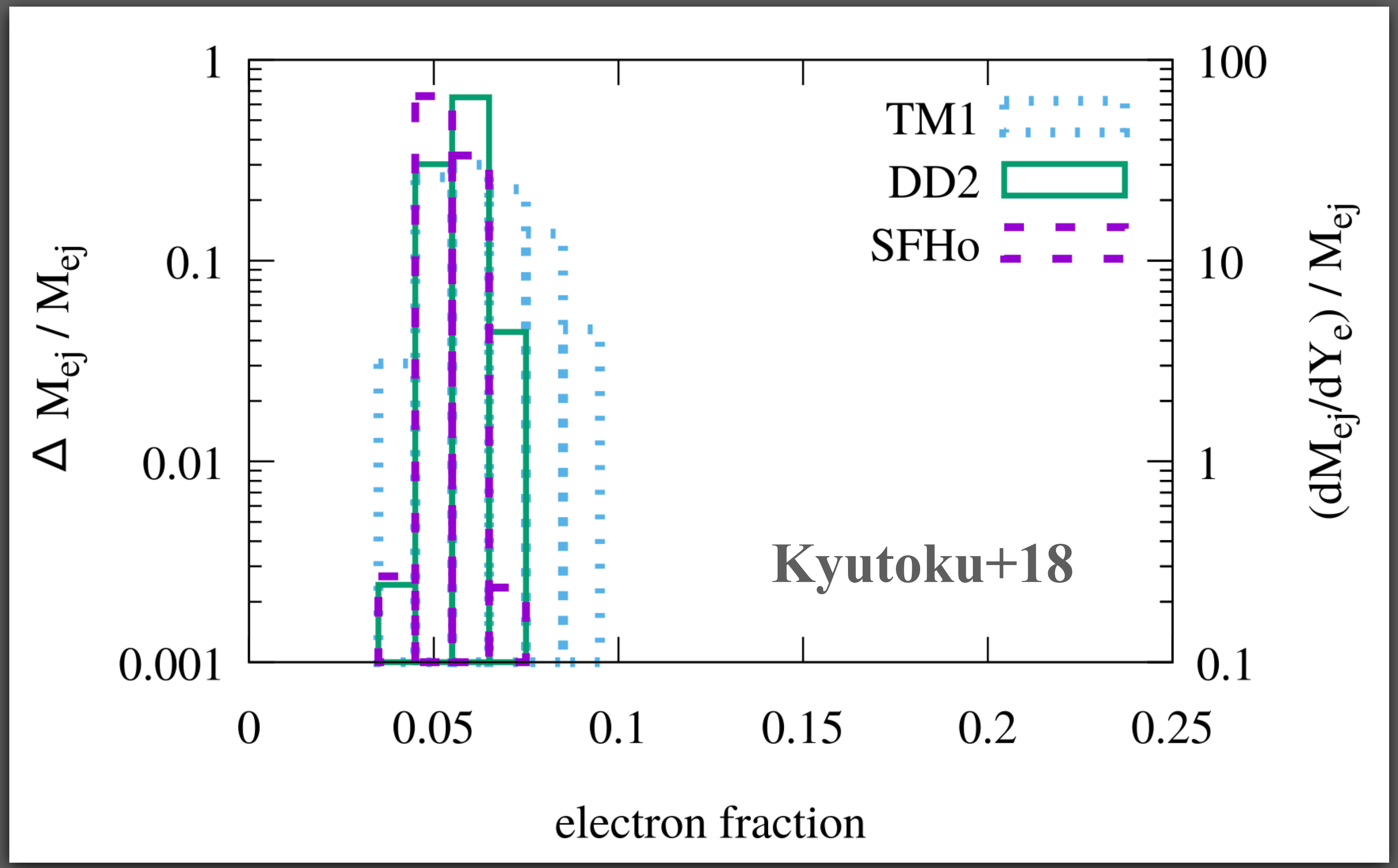
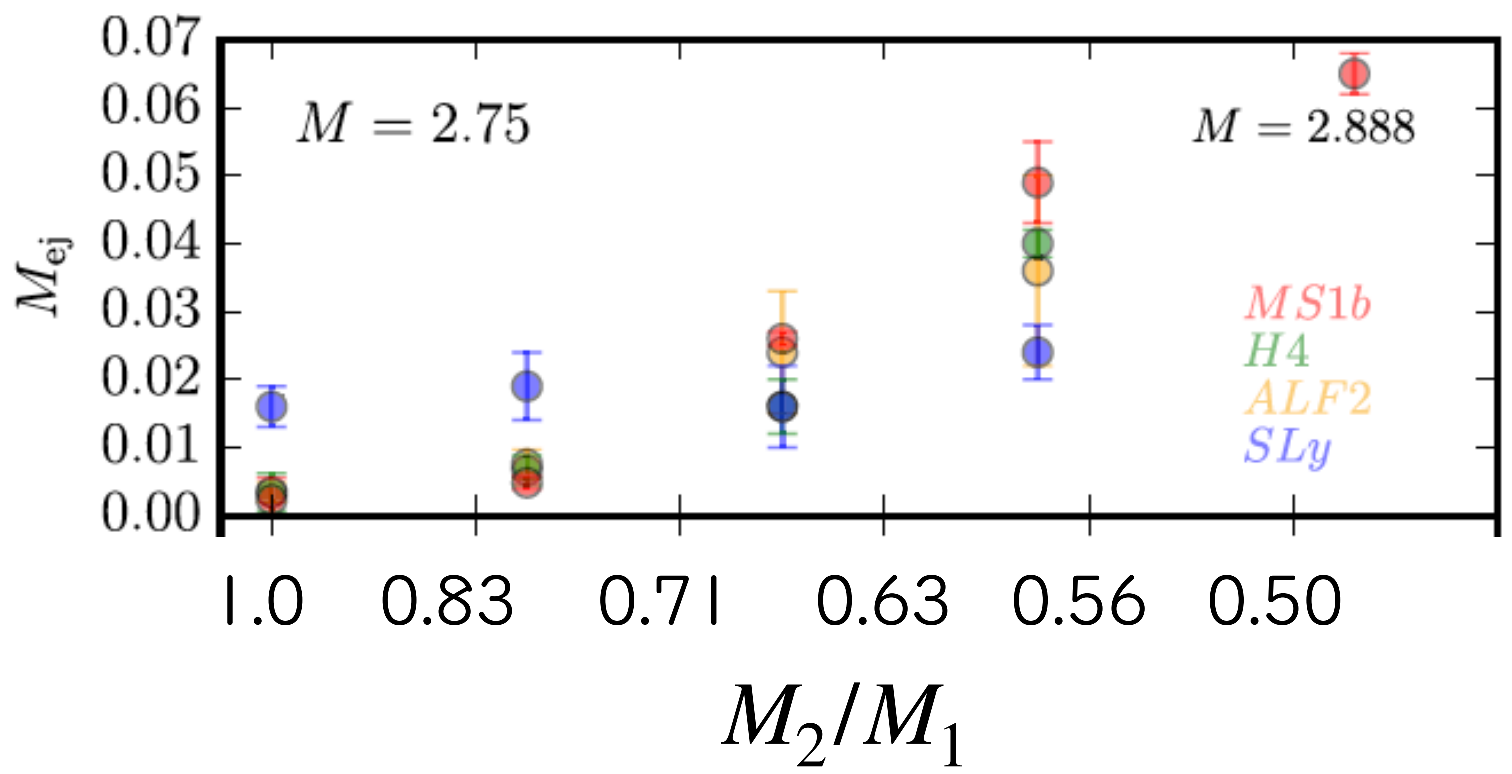


- Tidal effect only
- Original Ye preserved.

Dependence on EOS and binary parameter

Dietrich+17, modified



Equal-mass ↔ Asymmetric

MS1b
H4
ALF2
SLy

EOS	Shock heating efficiency	Tidal effect
Stiff	Low	Large
↕	↕	↕
Soft	High	Small

For equal-mass ($M_2/M_1 \approx 1$) binary, shock heating is the main mass ejection channel.

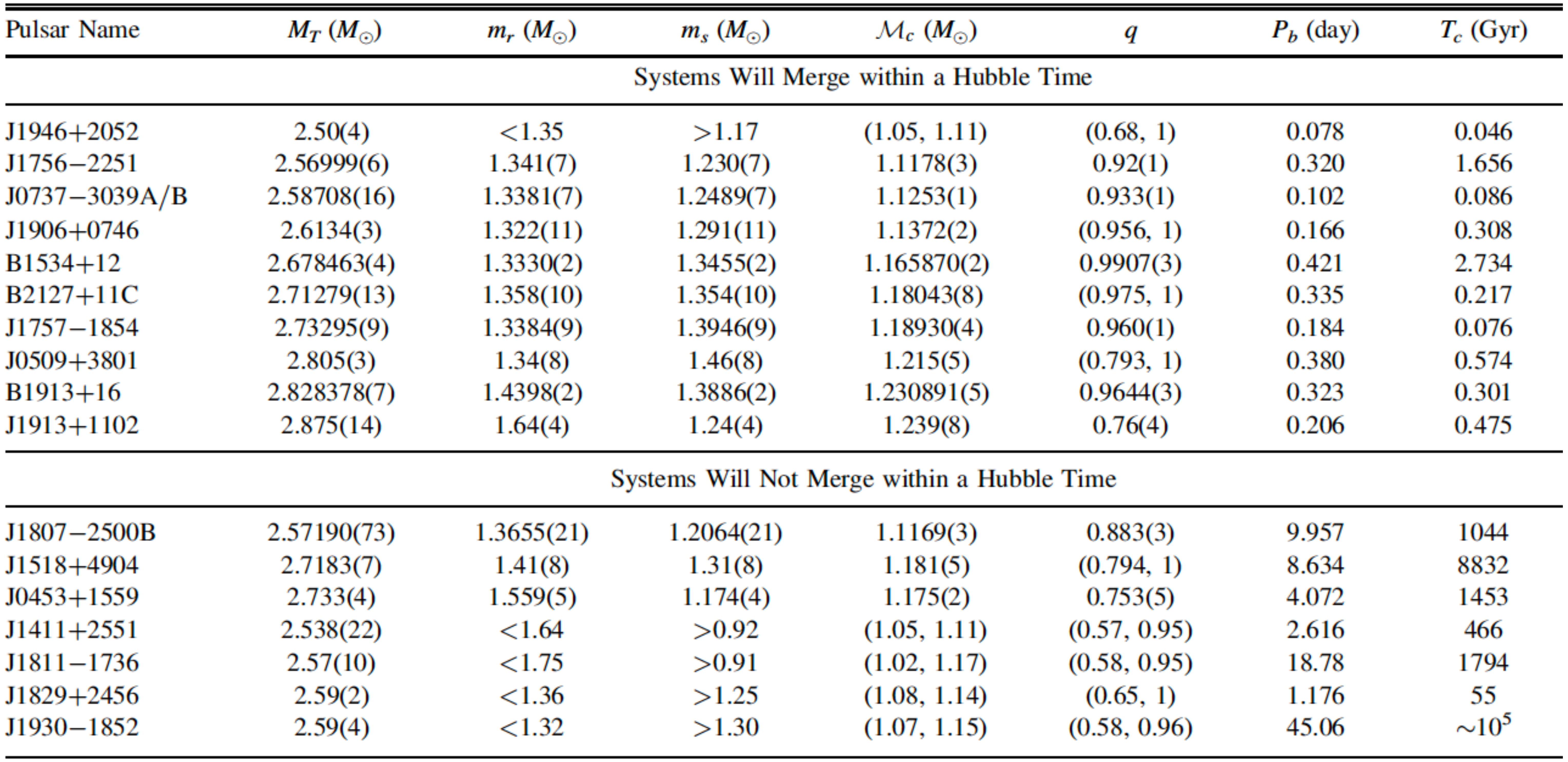
Softer (smaller radius) EOS: larger ejecta mass due to more efficient shock heating.

For asymmetric merger, tidal interaction is the main channel.

Stiffer (larger-radius) EOS: stronger mass-ratio dependence.

Hotokezaka+13, Bauswein+13, Dietrich+17

Farrows et al. (2019)

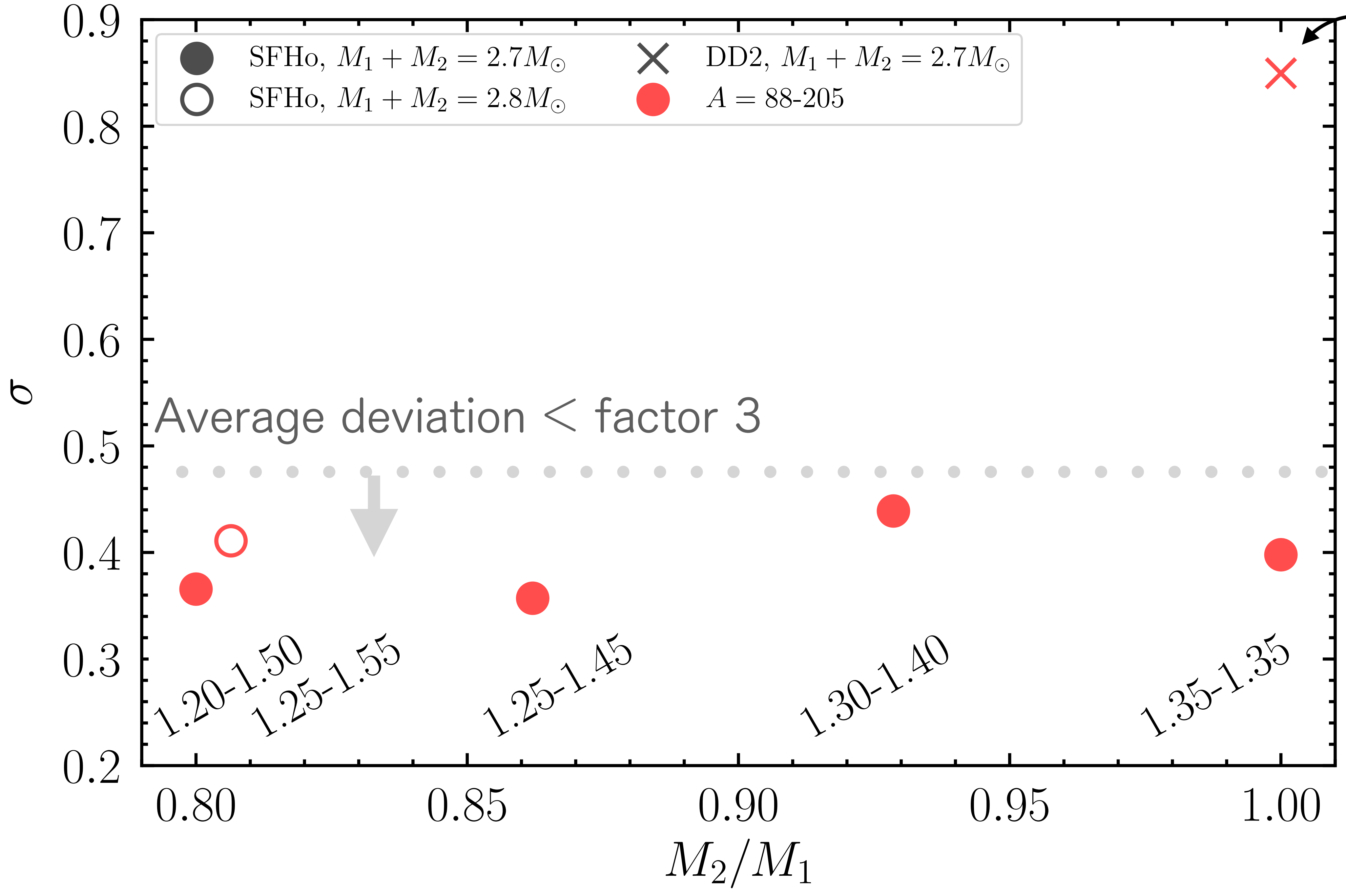


Pulsar Name	M_T ($M_\odot$)	m_r ($M_\odot$)	m_s ($M_\odot$)	$\mathcal{M}_c$ ($M_\odot$)	q	P_b (day)	T_c (Gyr)
Systems Will Merge within a Hubble Time							
J1946+2052	2.50(4)	$<$1.35	$>$1.17	(1.05, 1.11)	(0.68, 1)	0.078	0.046
J1756−2251	2.56999(6)	1.341(7)	1.230(7)	1.1178(3)	0.92(1)	0.320	1.656
J0737−3039A/B	2.58708(16)	1.3381(7)	1.2489(7)	1.1253(1)	0.933(1)	0.102	0.086
J1906+0746	2.6134(3)	1.322(11)	1.291(11)	1.1372(2)	(0.956, 1)	0.166	0.308
B1534+12	2.678463(4)	1.3330(2)	1.3455(2)	1.165870(2)	0.9907(3)	0.421	2.734
B2127+11C	2.71279(13)	1.358(10)	1.354(10)	1.18043(8)	(0.975, 1)	0.335	0.217
J1757−1854	2.73295(9)	1.3384(9)	1.3946(9)	1.18930(4)	0.960(1)	0.184	0.076
J0509+3801	2.805(3)	1.34(8)	1.46(8)	1.215(5)	(0.793, 1)	0.380	0.574
B1913+16	2.828378(7)	1.4398(2)	1.3886(2)	1.230891(5)	0.9644(3)	0.323	0.301
J1913+1102	2.875(14)	1.64(4)	1.24(4)	1.239(8)	0.76(4)	0.206	0.475
Systems Will Not Merge within a Hubble Time							
J1807−2500B	2.57190(73)	1.3655(21)	1.2064(21)	1.1169(3)	0.883(3)	9.957	1044
J1518+4904	2.7183(7)	1.41(8)	1.31(8)	1.181(5)	(0.794, 1)	8.634	8832
J0453+1559	2.733(4)	1.559(5)	1.174(4)	1.175(2)	0.753(5)	4.072	1453
J1411+2551	2.538(22)	$<$1.64	$>$0.92	(1.05, 1.11)	(0.57, 0.95)	2.616	466
J1811−1736	2.57(10)	$<$1.75	$>$0.91	(1.02, 1.17)	(0.58, 0.95)	18.78	1794
J1829+2456	2.59(2)	$<$1.36	$>$1.25	(1.08, 1.14)	(0.65, 1)	1.176	55
J1930−1852	2.59(4)	$<$1.32	$>$1.30	(1.07, 1.15)	(0.58, 0.96)	45.06	$\sim 10^5$

Some quantitative arguments

- Average logarithmic deviation

$$\sigma^2 = \frac{1}{n}\sum_A \left(\log_{10} N(A) - \log_{10} N_\odot(A)\right)^2$$

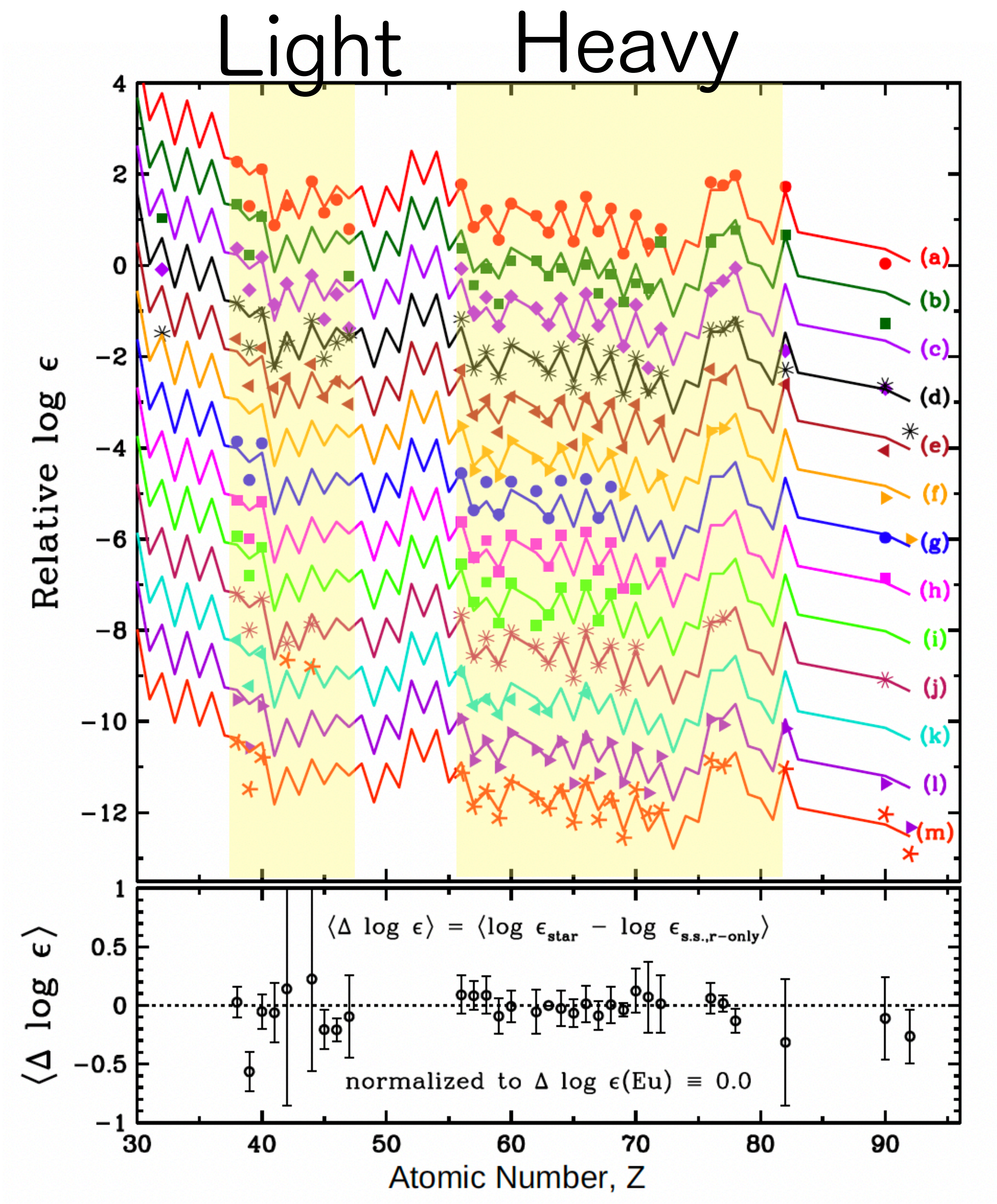


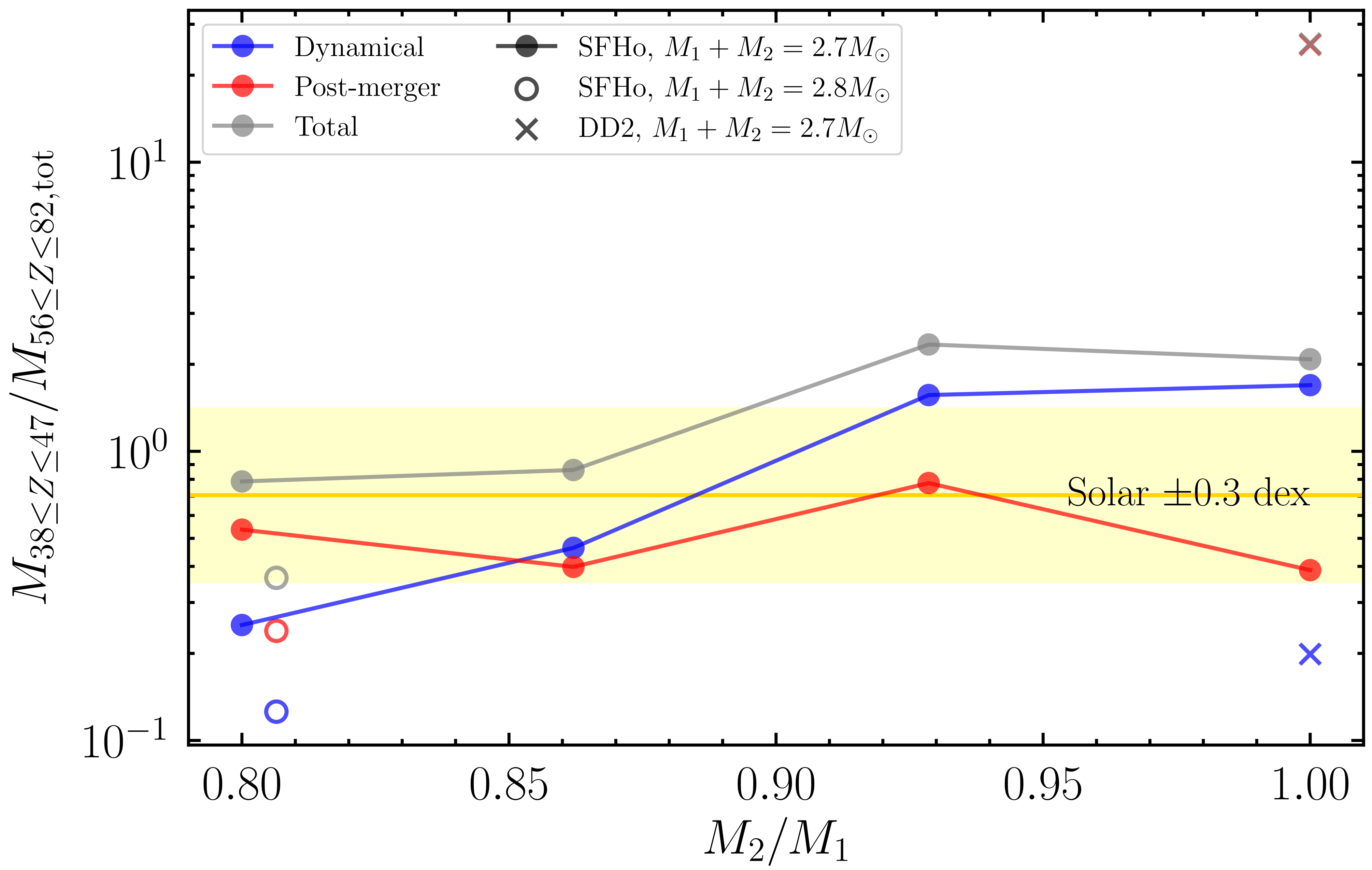
Long-lived NS case（DD2 EOS, equal mass）

Average deviation factor ~7.

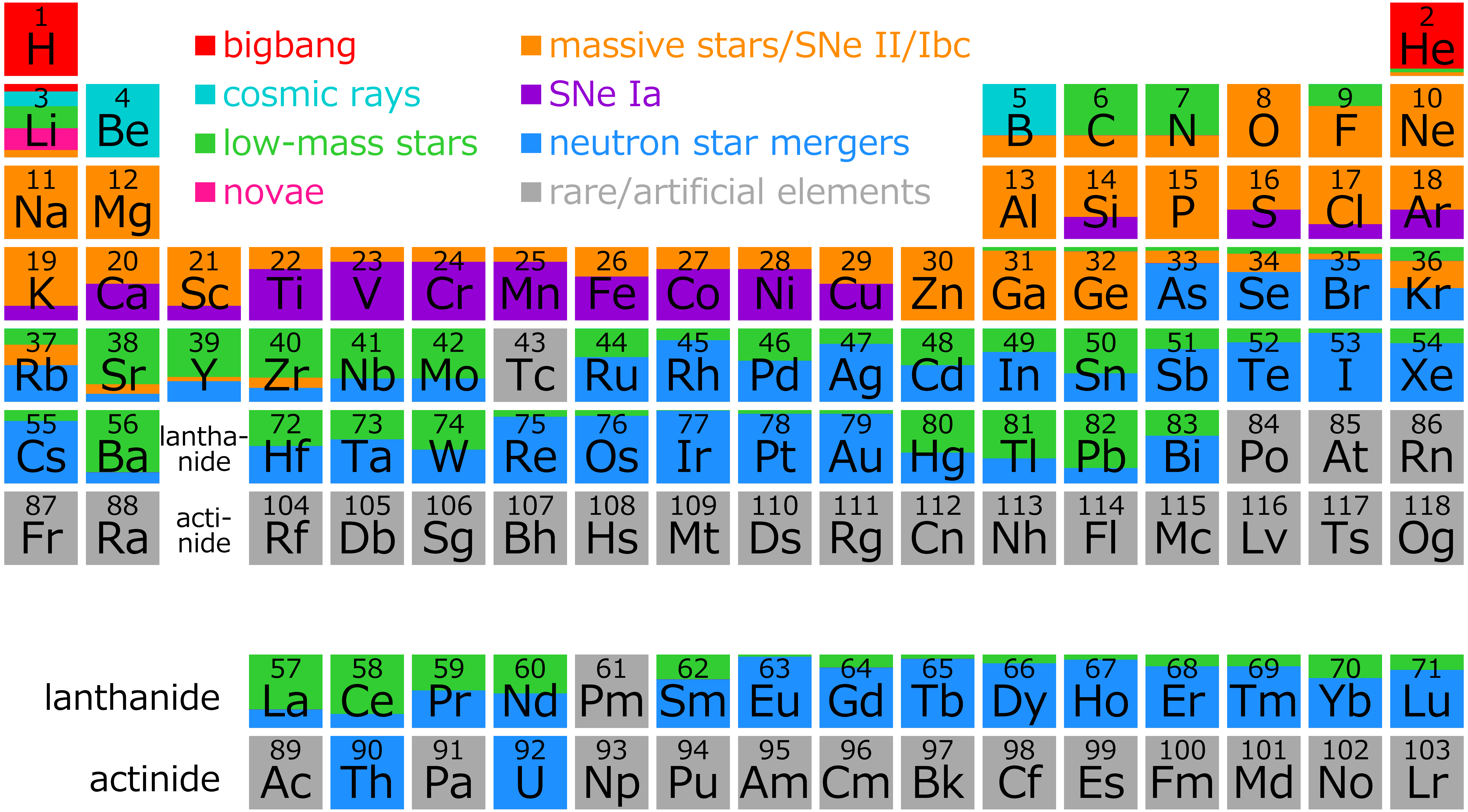
Some quantitative arguments

- Light-to-heavy ratio





Periodic table of elments

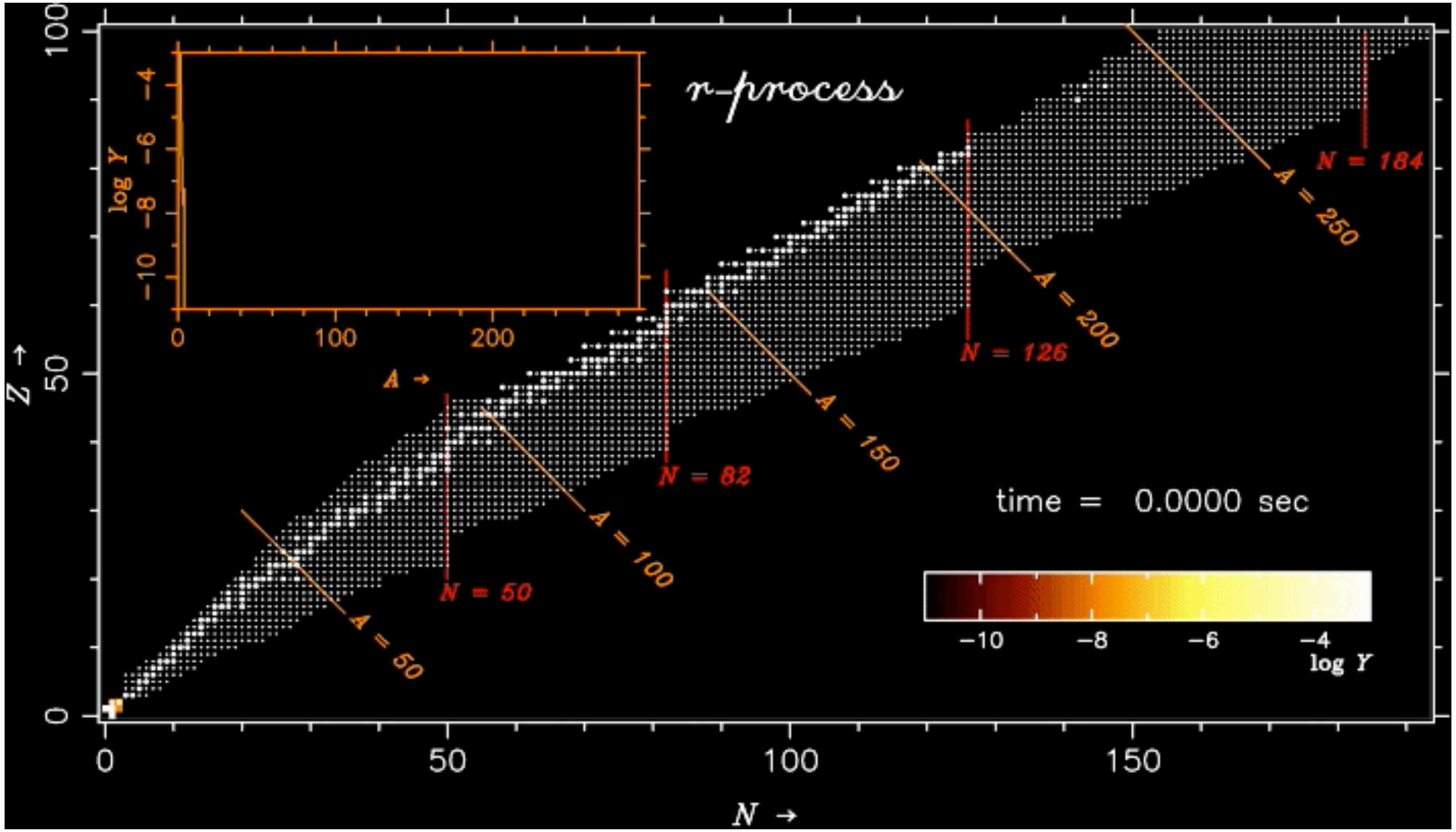


■ bigbang
■ cosmic rays
■ low-mass stars
■ novae
■ massive stars/SNe II/Ibc
■ SNe Ia
■ neutron star mergers
■ rare/artificial elements

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	lanthanide	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	actinide	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
lanthanide			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
actinide			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	103 Lr

By S. Wanajo

r-process

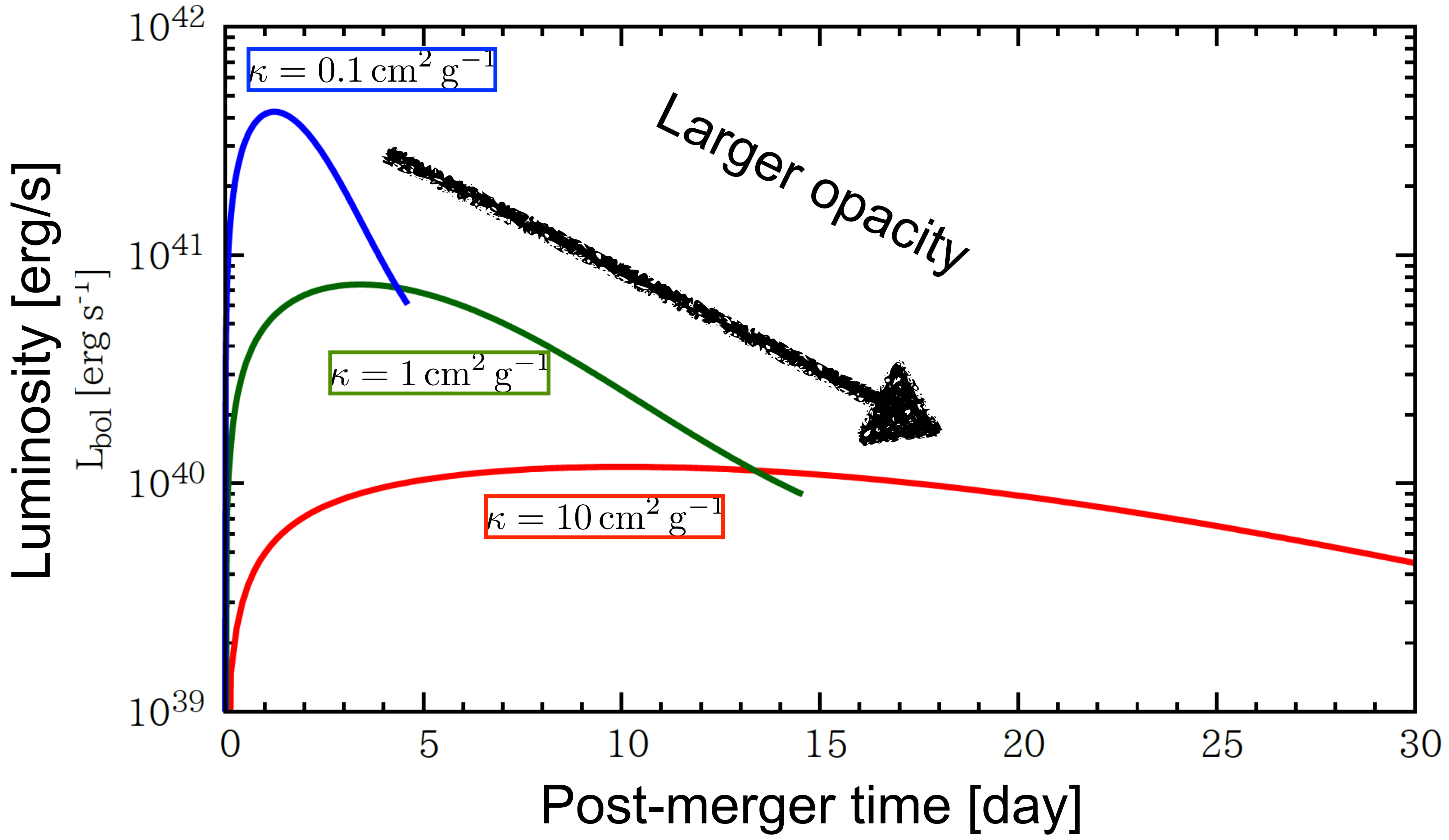


r-process
log Y
−4
−6
−8
−10
0
100
200
A →
Z →
100
50
0
N →
0
50
100
150
N = 50
N = 82
N = 126
N = 184
A = 50
A = 100
A = 150
A = 200
A = 250
time = 0.0000 sec
−10
−8
−6
−4
log Y

Effect of Lanthanides on Kilonova Emission

○ Lanthanides have significantly high opacity

$\kappa \sim 10\ \mathrm{cm^2/g}$; 10 - 100 times larger than Lanthanide-free material



one-zone, free-expansion (Li & Paczyński 98)
heating rate: Korobkin et al. 12, thermalization eff.: Barnes et al. 16

Opacity : Low ——— High

Luminosity : **High** ——— Low

Timescale : Short ——— Long

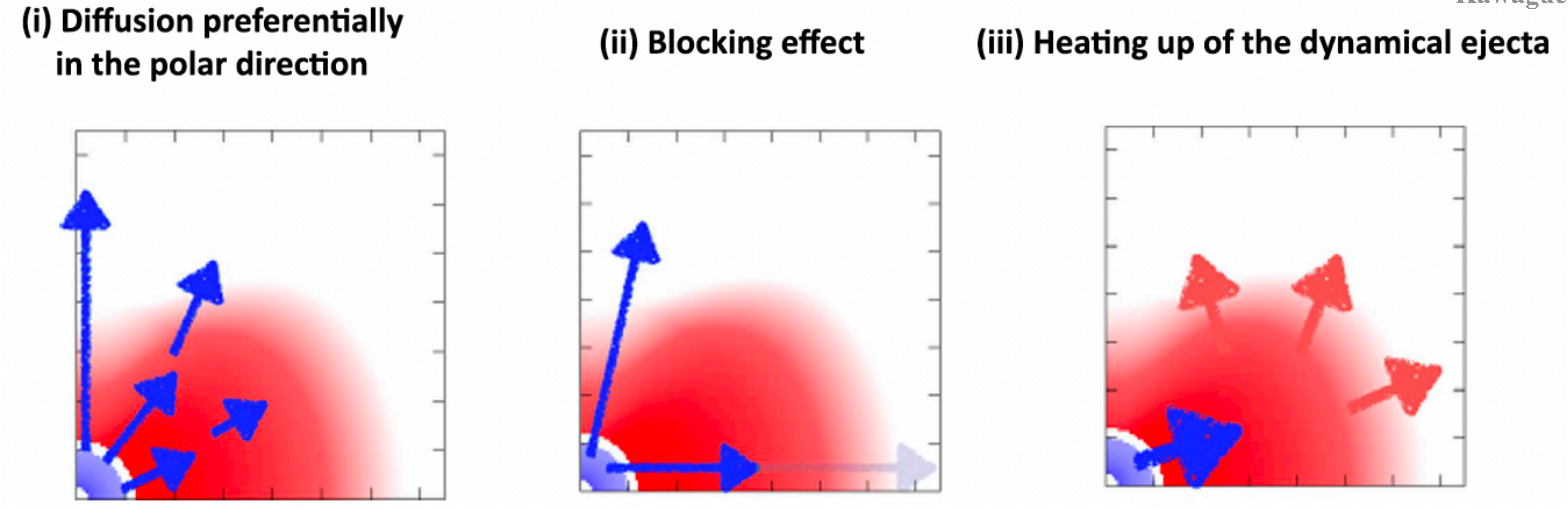
Color : **Blue** ——— **Red**

○ Weak interaction processes determines the production of Lanthanides

Electron fraction
$$Y_e = \frac{n_e}{n_B} = \frac{n_p}{n_n + n_p}$$

It is modified by
$$\bar{\nu}_e + p \rightleftarrows e^+ + n \text{'} \quad \nu_e + n \rightleftarrows e^- + p$$

Multi-component/dimensional effects



Kawaguchi+20

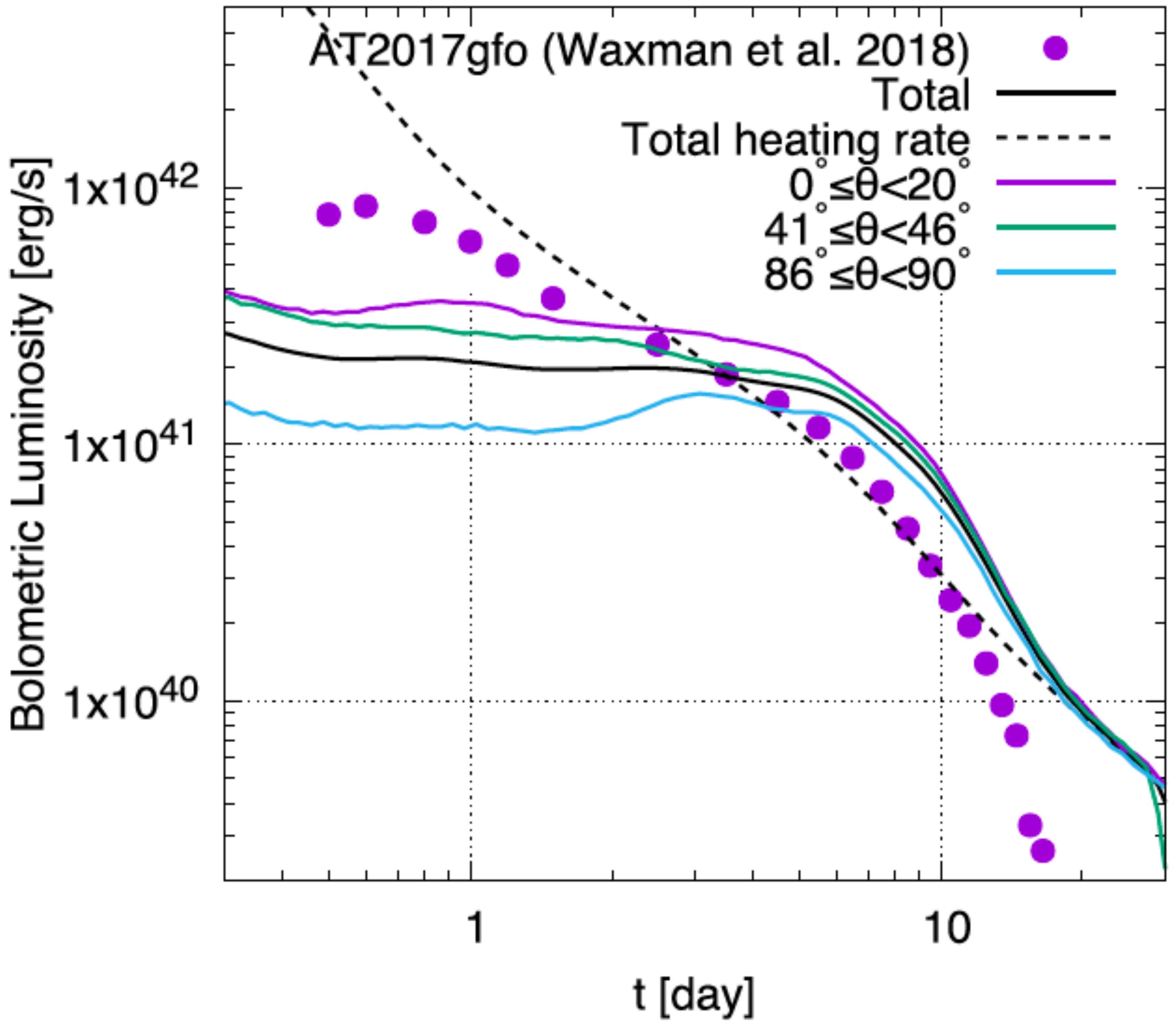
(i) Diffusion preferentially in the polar direction

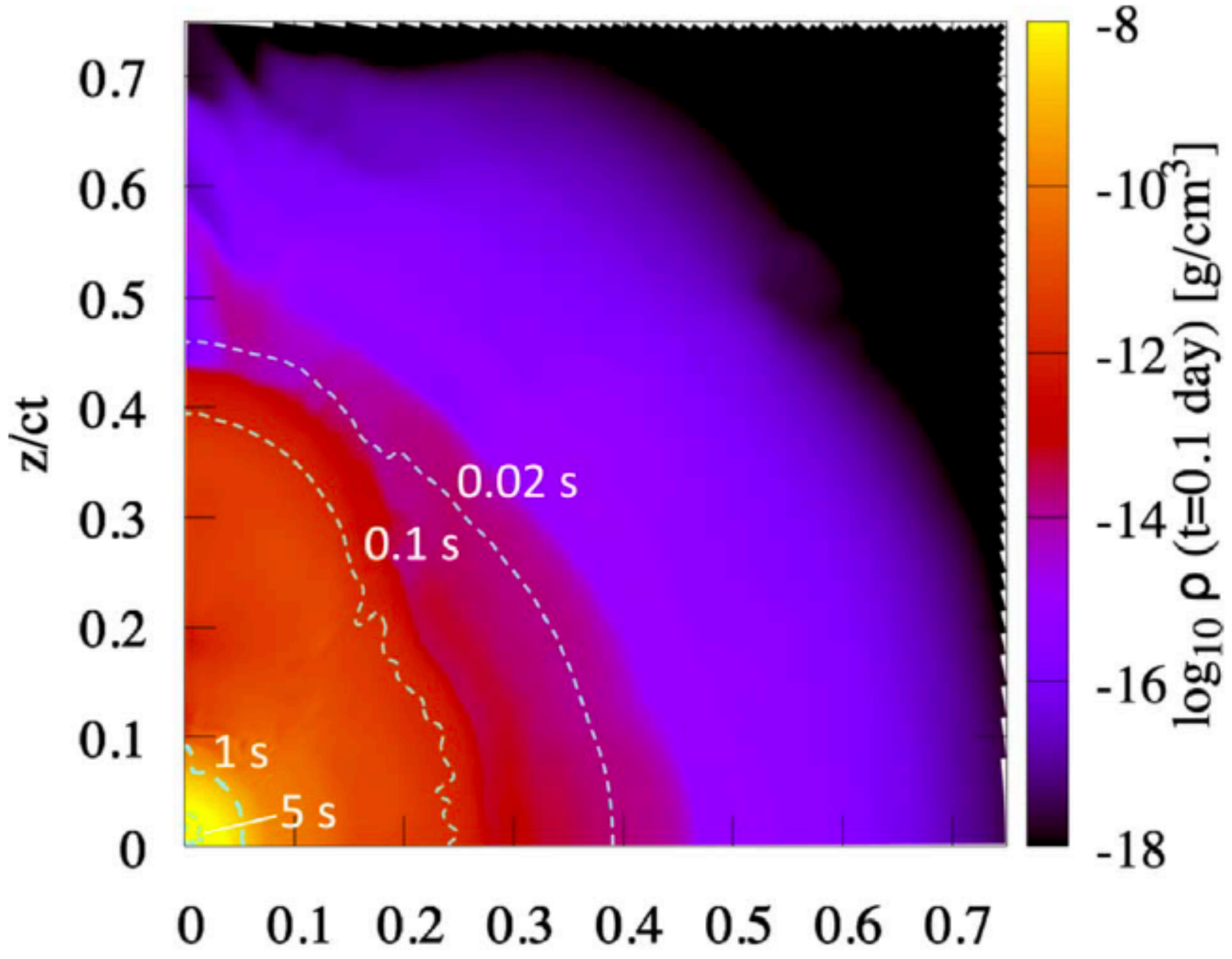
(ii) Blocking effect

(iii) Heating up of the dynamical ejecta

Kilonova based on numerical simulation

Kawaguchi+ 21



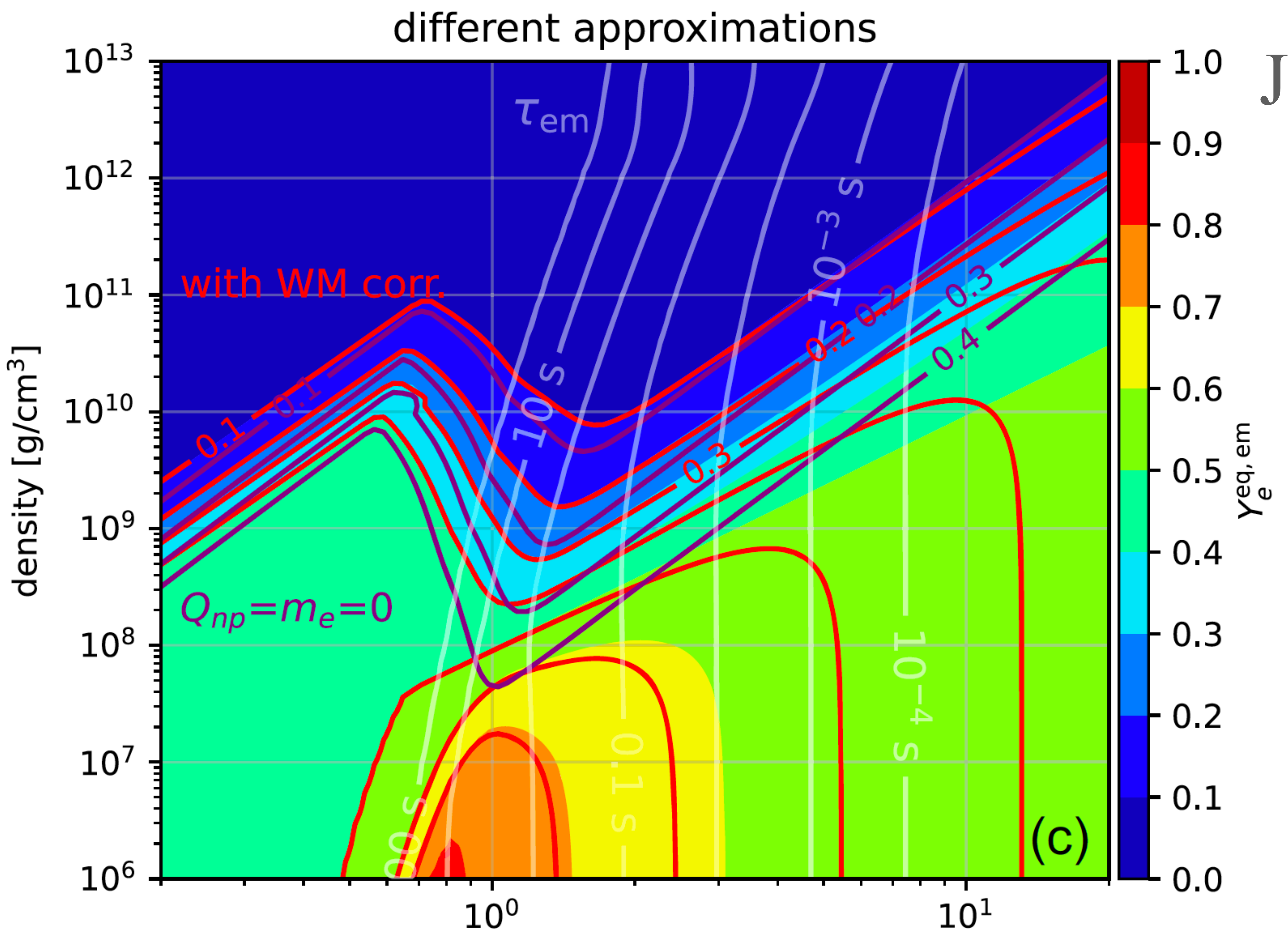


★ Long-lived NS cases

Monte-Carlo transfer by K. Kawaguchi based on our numerical data (DD2 1.25-1.25 case; $M_{\rm ej} \approx 0.11 M_\odot$)

Total heating rate seems compatible for KN for GW170817, but multi-D effect and some opacity source in polar direction suppresses luminosity.

Effect of different approx. on Ye



Just et al. 22

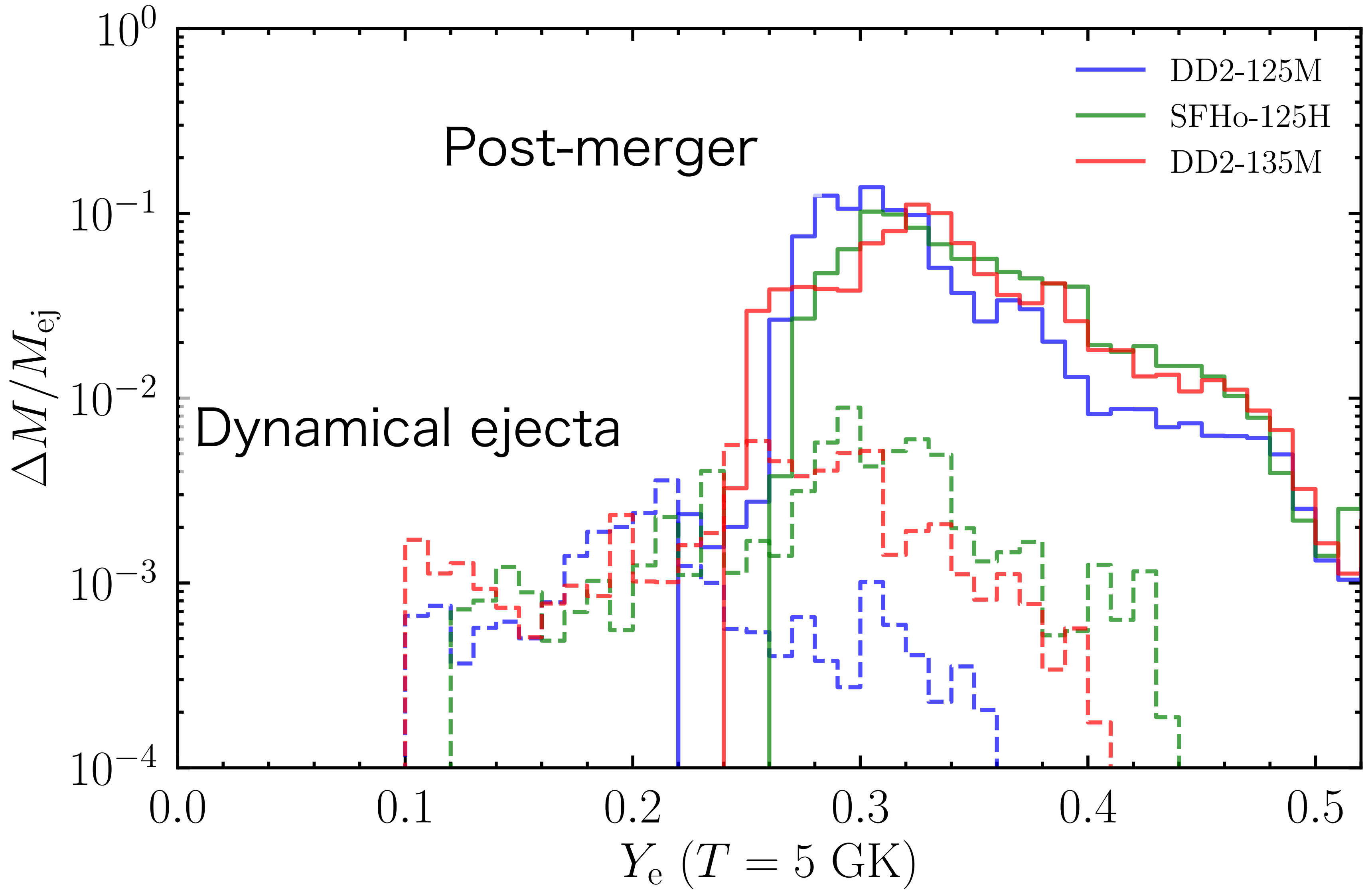
derives Ye at equilibrium of e$^-$/e$^+$ capture
as a function of ρ and T

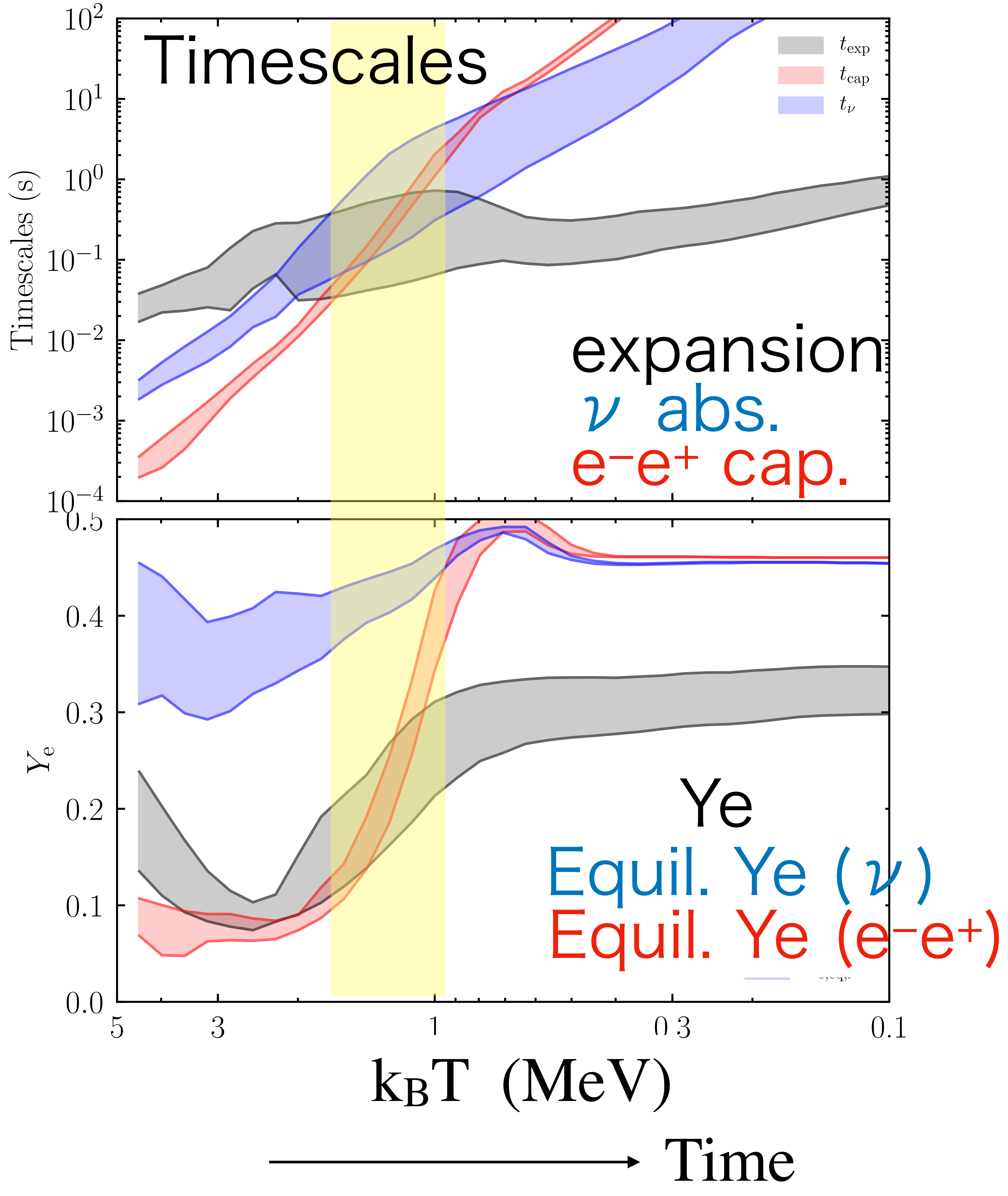
$$\lambda_{e^+} Y_n - \lambda_{e^-} Y_p \Big|_{\rho, T, Y_e^{eq,em}} = 0$$

- Approximation of $m_n - m_p = 0$ and $m_e = 0$ reduces equilibrium Ye by up to ~0.1.
- Including weak magnetism enhances the equilibrium for high-T region.

Composition of the ejecta (long-lived NS)

SF+20, also Just+21





Ye peaks at ~0.3

Ye follows an equil. value of

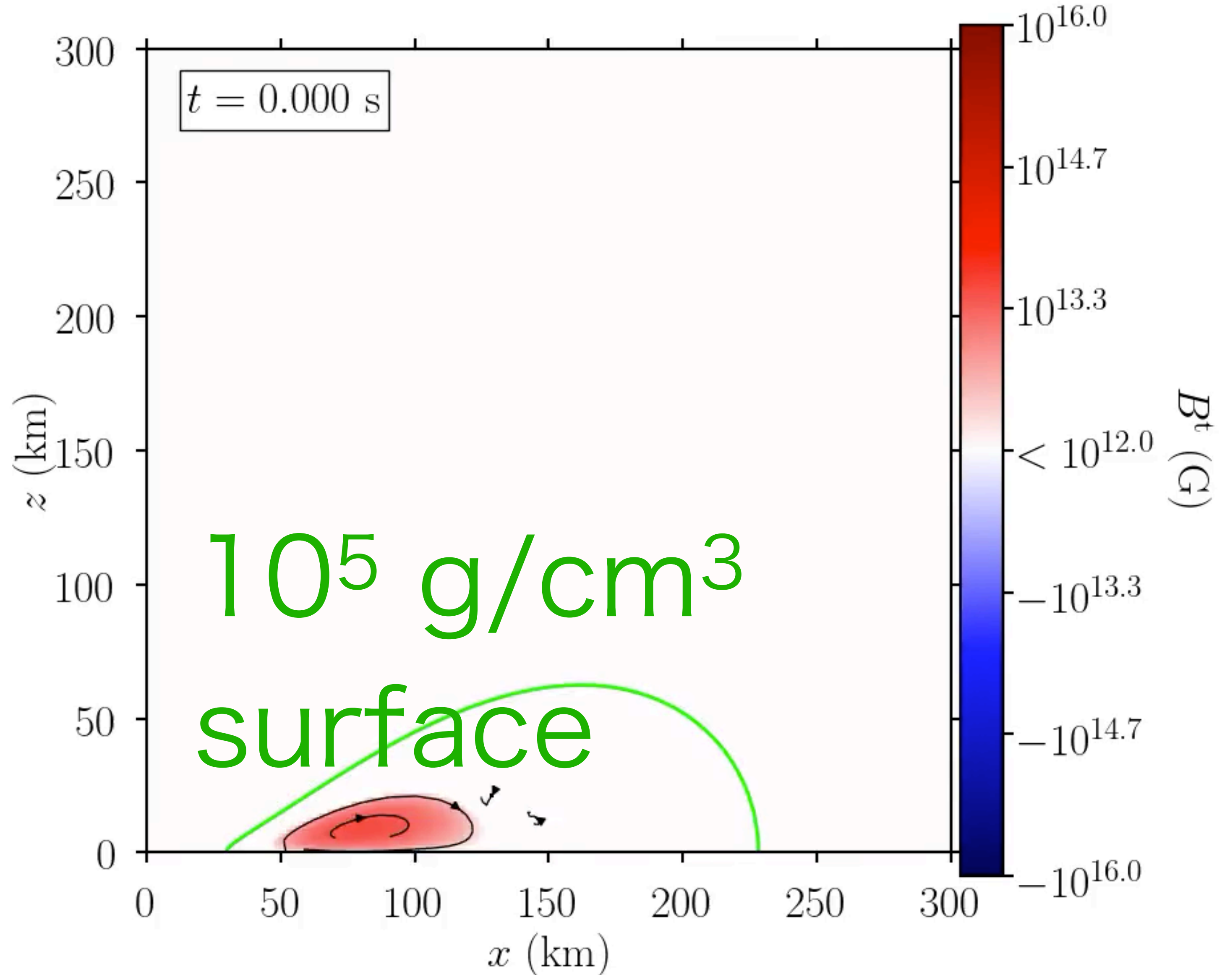
$$e^- + p \rightarrow \nu_e + n$$

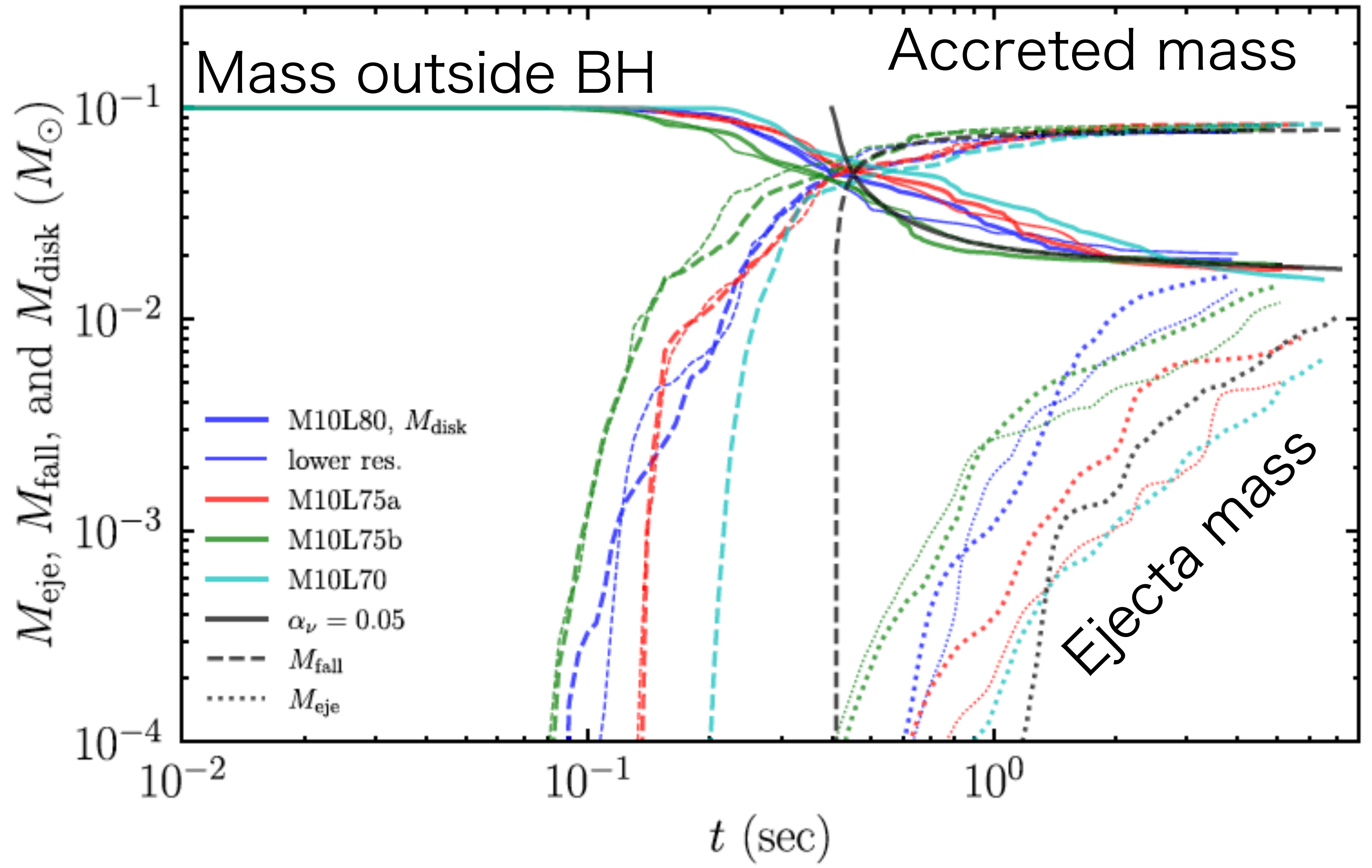
$$e^+ + n \rightarrow \bar{\nu}_e + p$$

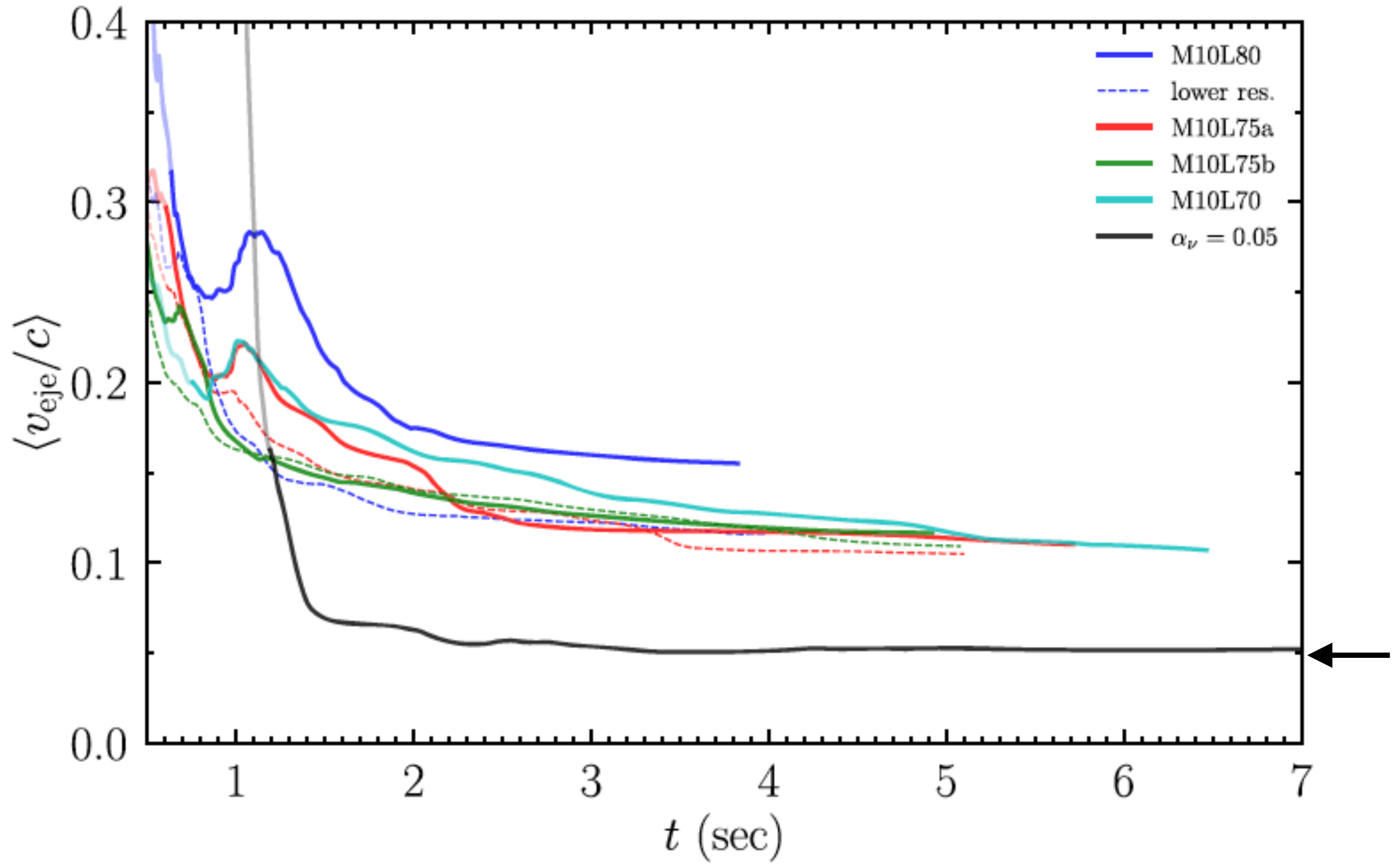
and freezes out when $t_{\rm weak} \sim t_{\rm expansion}$

RMHD simulation with effective dynamo term for BH-disk

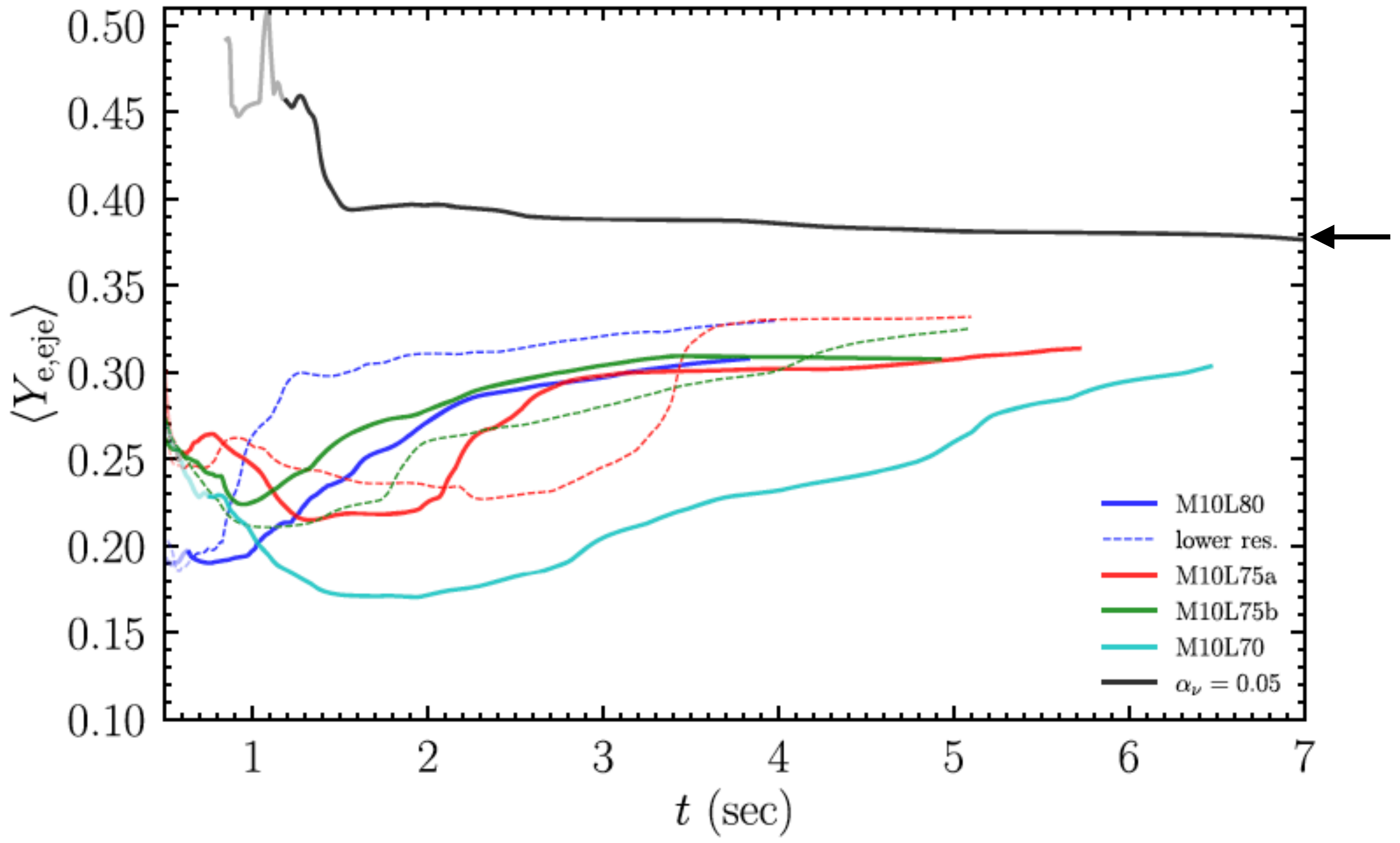
Shibata, SF, and Sekiguchi, accepted







viscous model



viscous model

(Roughly speaking) consistent with viscous hydrodynamics case.