# Mass ejection from neutron-star mergers in numerical relativity

**Masaru Shibata**

[1] Center for Gravitational Physics, Yukawa Institute for Theoretical Physics, Kyoto U.

[2] Max Planck Institute for Gravitational Physics at Potsdam

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

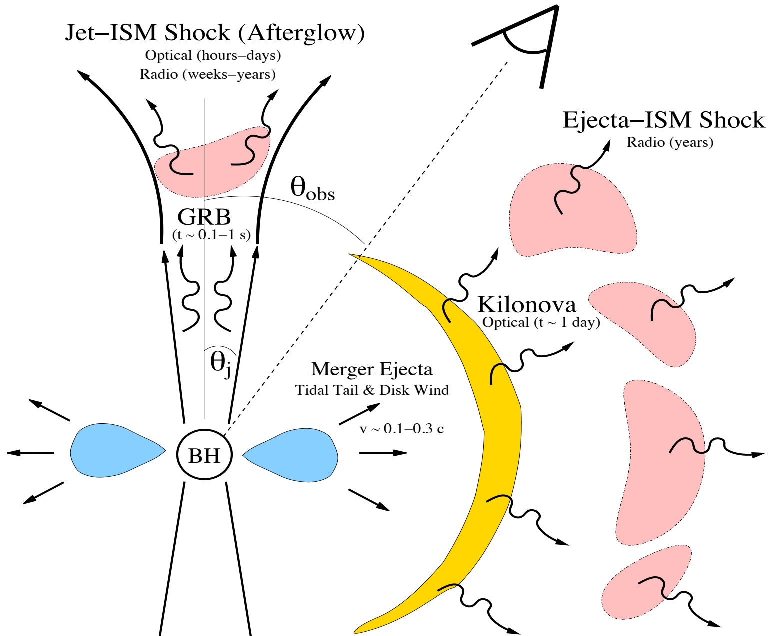
CGP
Center for Gravitational Physics
Yukawa Institute

# Outline

I. Brief introduction
II. Scenarios for NS mergers (NS-NS & BH-NS)
III. Dynamical mass ejection
IV. MHD/viscous ejection from merger remnants
V. Summary

# I Introduction: Why mass ejection from NS binaries is important ?

1. Electromagnetic counterparts of NS merger:
   **Key for confirming gravitational-wave detection**
   (talks by Tanaka, Metzger, and others this week)
2. Possible site of **r-process nucleosynthesis**
   (talk by Lattimer)

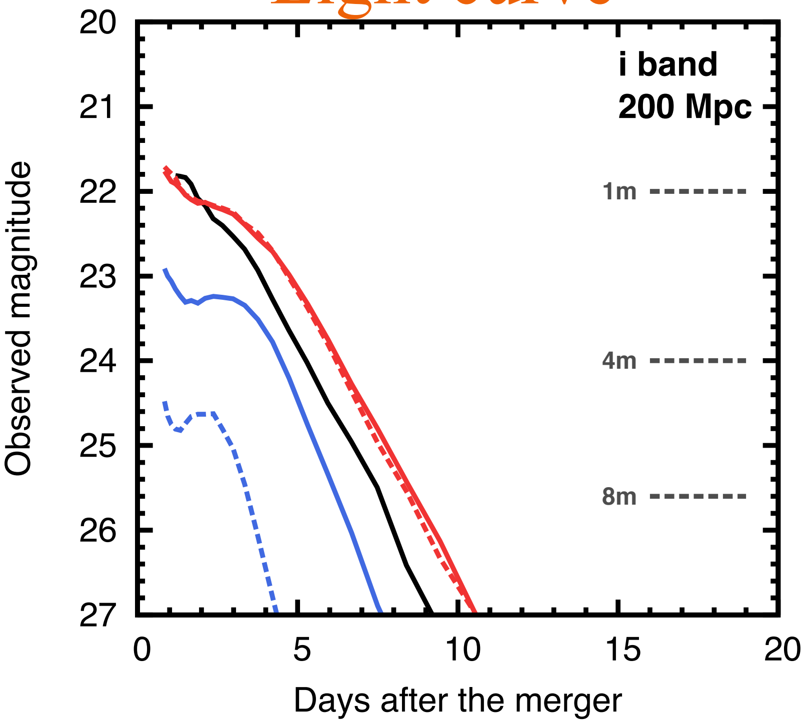



Metzger & Berger 2012

# In this talk, I focus on

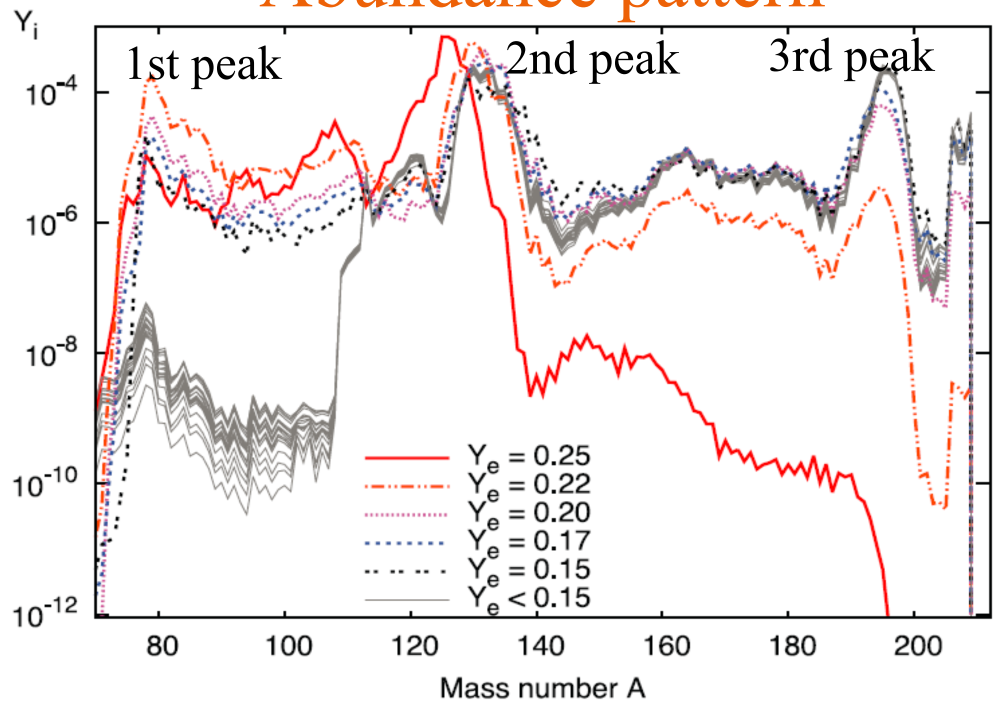
- **Ejecta mass $M_{eject}$**
- **Electron fraction $Y_e$ (=[p]/[nucleon])**

Light curve




Tanaka & Hotokezaka 2013

Abundance pattern




Korobkin et al. 2012

# II A Typical scenarios for NS-NS merger

- **Constraints from radio-telescope observations**:

1. Approximately 2-solar-mass NSs exist
   (Demorest ea 2010, Antoniadis ea 2013)
   → Constraint to equation of state (EOS) for NS
2. Typical total mass of compact binary neutron stars
   → ~ 2.73±0.15 solar mass (by Pulsar timing obs.)

# Compact NS-NS system in our galaxy

| | PSR | Orbital period $P$(day) | Eccentricity $e$ | $M(M_{sun})$ | Each mass $M_1$ | $M_2$ | lifetime $T_{GW}$ |
|---|---|---|---|---|---|---|---|
| 1. | B1913+16 | 0.323 | 0.617 | 2.828 | 1.441 | 1.387 | 3.0 |
| 2. | B1534+12 | 0.421 | 0.274 | 2.678 | 1.333 | 1.345 | 27 |
| 3. | B2127+11C | 0.335 | 0.681 | 2.71 | 1.35 | 1.36 | 2.2 |
| 4. | J0737-3039 | 0.102 | 0.088 | 2.58 | 1.34 | 1.25 | 0.86 |
| 5. | J1756-2251 | 0.32 | 0.18 | 2.57 | 1.34 | 1.23 | 17 |
| 6. | J1906+746 | 0.166 | 0.085 | 2.61 | 1.29 | 1.32 | 3.1 |
| 7. | J1913+1102 | 0.206 | 0.090 | 2.875 | 1.65 | 1.24 | ~5 |
| 8. | J1757-1854 | 0.184 | 0.606 | 2.74 | 1.35 | 1.39 | ~0.75 |

$\times 10^8$ yrs

➢ **Total Mass of NS in compact NS-NS** is likely to be in a narrow range, $m \approx 2.73 \pm 0.15\, M_{sun}$

# II A Typical scenarios for NS-NS merger

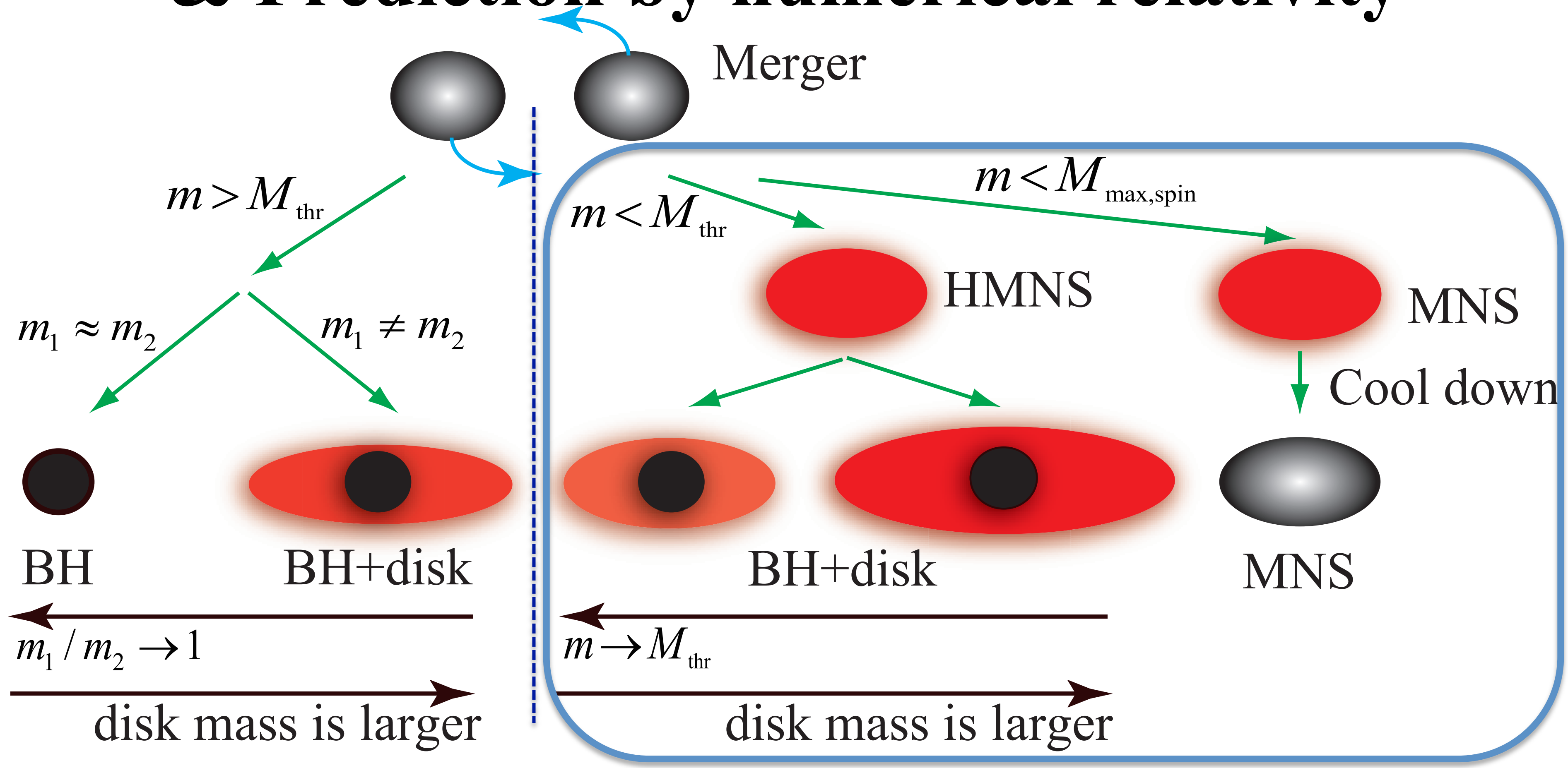
- **Constraints from radio-telescope observations**:

1. Approximately 2-solar-mass NSs exist
   (Demorest ea 2010, Antoniadis ea 2013)
   → equation of state (EOS) for NS has to be **stiff**
2. Typical total mass of compact binary neutron stars
   → ~ 2.73±0.15 solar mass (by Pulsar timing obs.)

⇩

- **Numerical relativity simulations have shown that** merger results typically in **high-mass neutron stars** (not BH) (Shibata et al. 2005, 2006.. recently many works….)

# Possible outcomes of NS-NS mergers & Prediction by numerical relativity

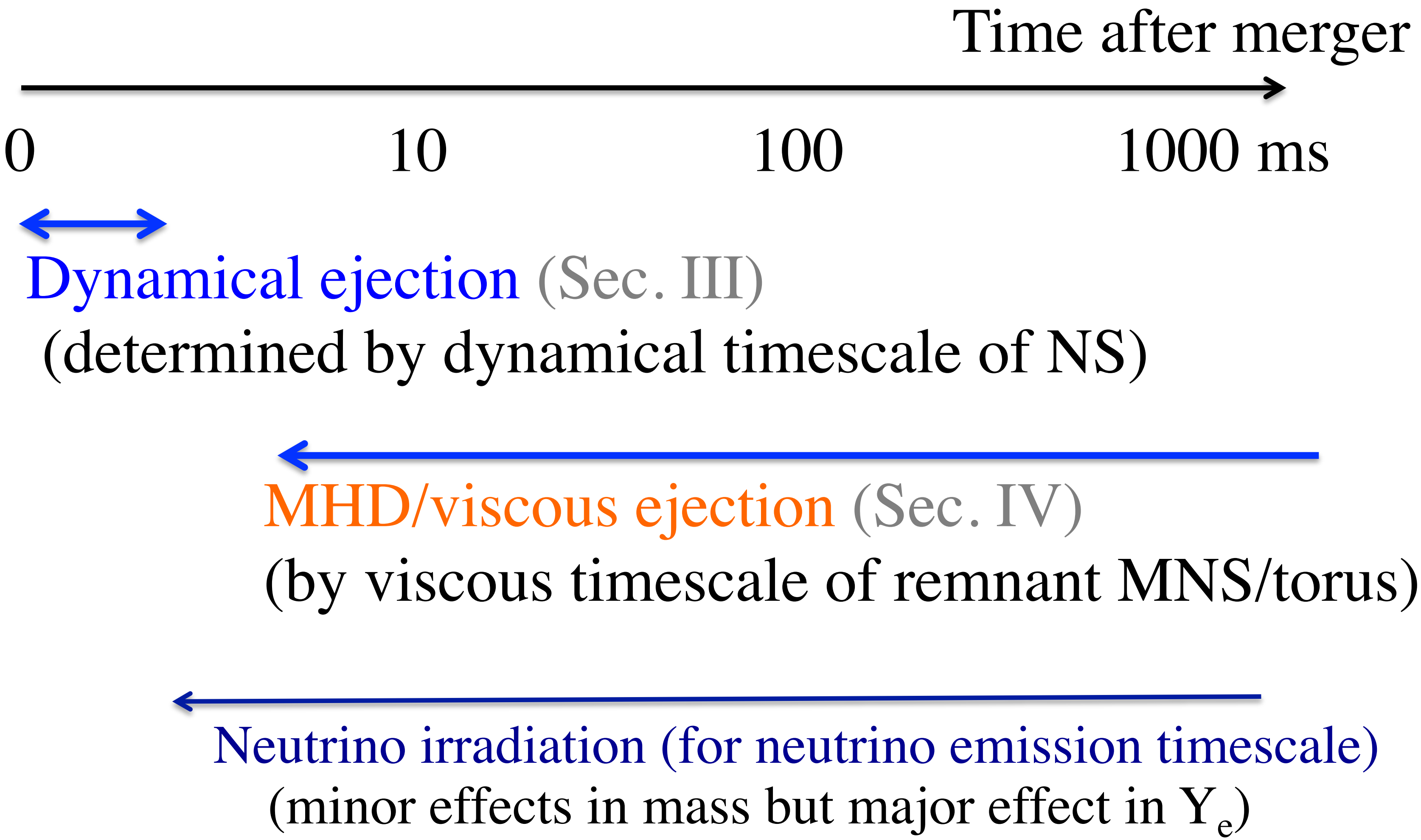



$M_{thr} > \sim 2.8 M_{sun}$

Depends on EOS

**Likely typical cases for $M_{tot} = 2.6$—$2.8 M_{sun}$**

# Mass ejection history for MNS formation



# II B Scenarios for BH-NS merger

- Almost no observational constraints
  → Wide parameter space has to be explored
- Fate = two possibilities:

1. Tidal disruption of NS
2. Simple plunge of NS into BH (no disruption)

# Condition for tidal disruption

For tidal disruption, $(\text{Self gravity of NS}) < (\text{BH tidal force})$

$$\Downarrow$$

$$\frac{M_{\rm NS}}{(\alpha R_{\rm NS})^2} < \frac{M_{\rm BH}(\alpha R_{\rm NS})}{r^3} \quad (\alpha > 1) \Rightarrow 1 \le \left(\frac{M_{\rm BH}}{r_{\rm ISCO}}\right)^3 \left(\frac{M_{\rm NS}}{M_{\rm BH}}\right)^2 \left(\frac{\alpha R_{\rm NS}}{M_{\rm NS}}\right)^3$$

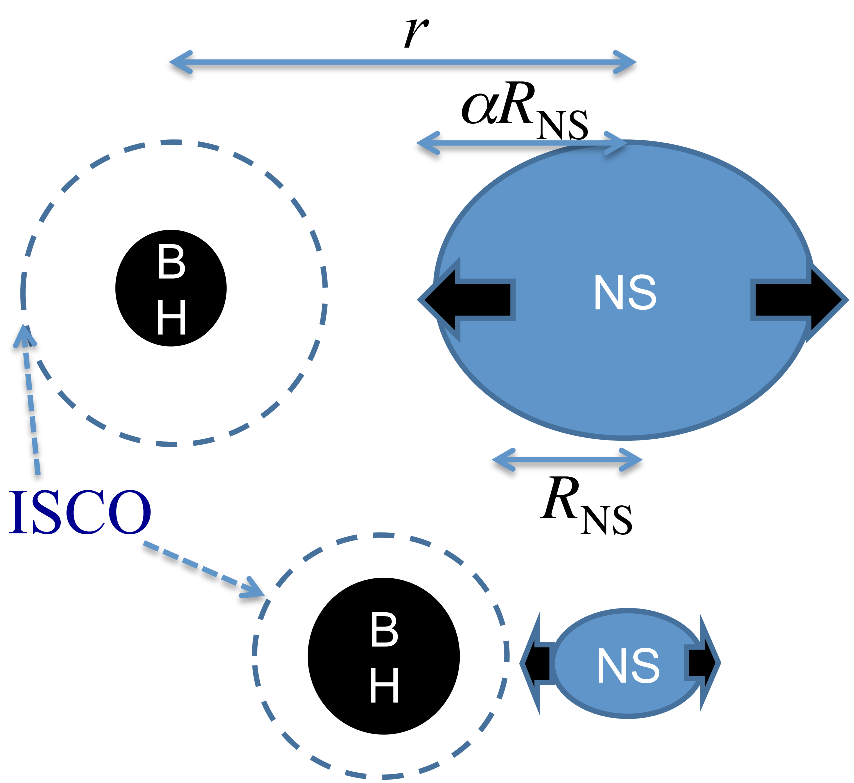
- For tidal disruption

❖ **Large NS Radius** or

❖ **Small BH mass** or

❖ **High corotation spin**

is necessary



## For tidal disruption of plausible BH-NS with $M_{NS}$=1.35$M_{sun}$, $R_{NS}$ ~ 12 km, & $M_{BH}$ > 5 $M_{sun}$

**High BH spin is necessary > ~ 0.5**

Foucart et al. ('13,14,…); Kyutoku et al. ('15)

$$1 \leq 0.1 \left( \frac{6M_{BH}}{r_{ISCO}} \right)^3 \left( \frac{7M_{NS}}{M_{BH}} \right)^2 \left( \frac{R_{NS}}{6M_{NS}} \right)^3 \left( \frac{\alpha}{1.7} \right)^3$$

$$(M_{BH} \leq r_{ISCO} \leq 9M_{BH})$$

# Mass ejection history for BH-NS

(in the case of tidal disruption of NS)

& NS-NS → prompt collapse to BH

Time after merger

0 10 100 1000 ms

Dynamical ejection (Sec. III)

(determined by dynamical timescale of system)

Long-term MHD/viscous ejection (Sec. IV)

(by viscous timescale of disk/torus)

(Fernandez-Metzger '13, '14, Just+ '15…)

Neutrino irradiation

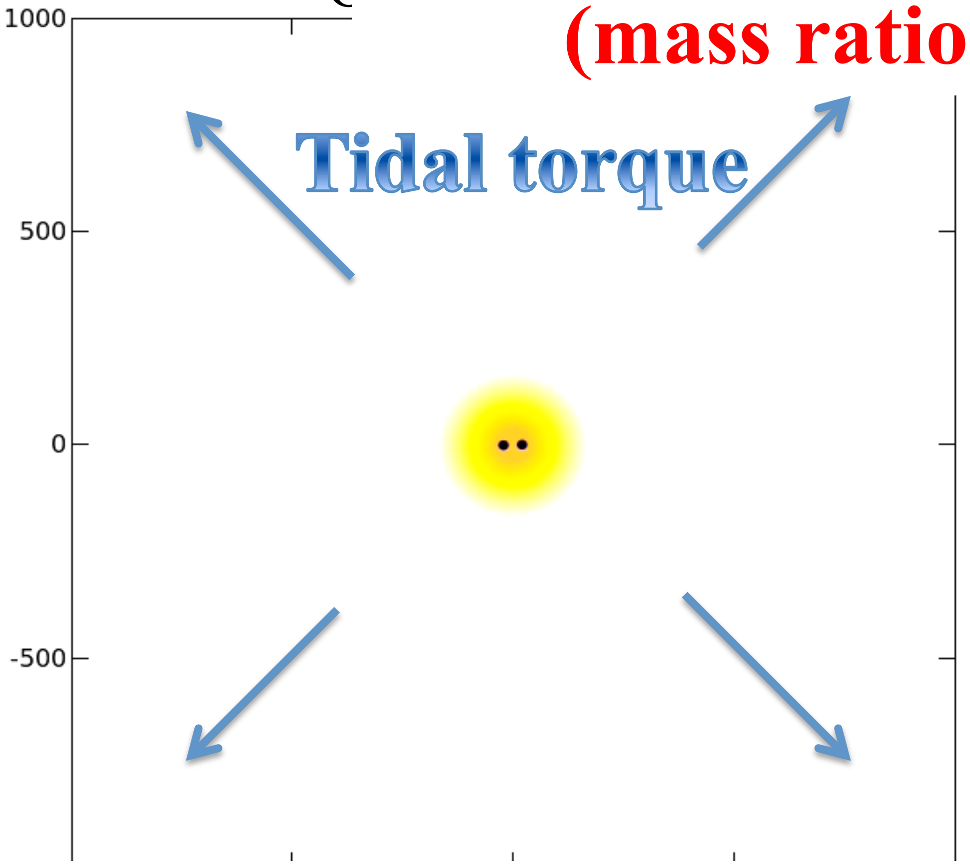
(would be minor)

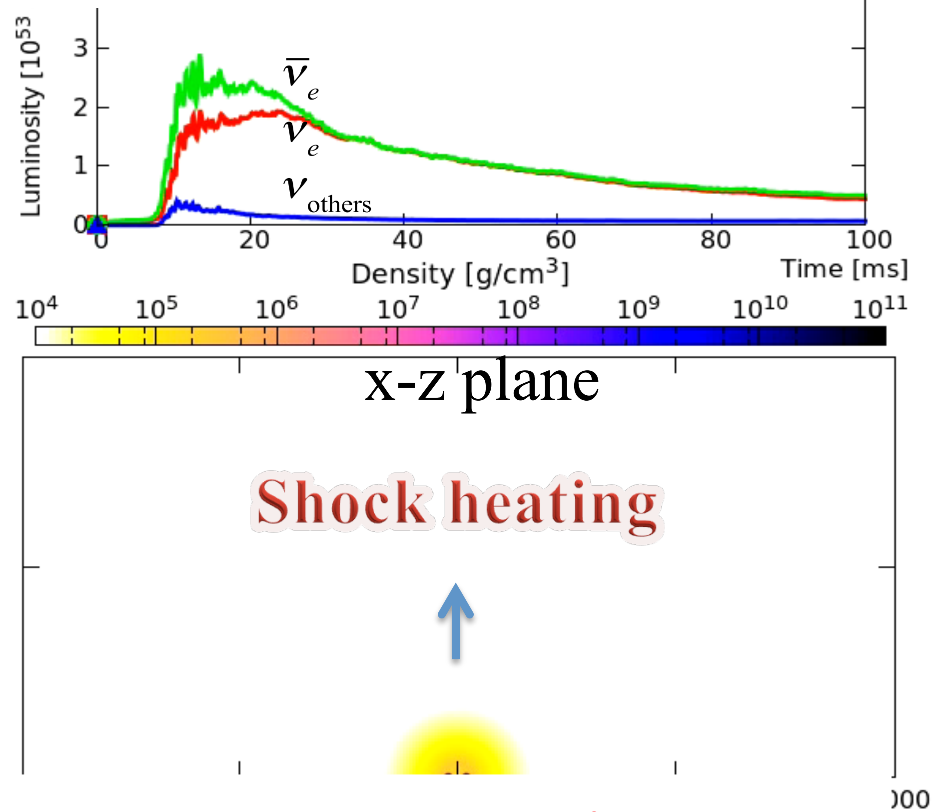
# III Dynamical mass ejection

- First, for NS-NS
- Then, for BH-NS

# Neutrino-radiation hydro for dynamical ejecta

**Total mass ~ 0.001—0.01 $M_{sun}$**
**depending on EOS & each mass**
**(mass ratio 0.8—1.0)**




**Ejection occurs primarily toward equatorial plan**

Sekiguchi et al. 2016

# Summary for dynamical ejecta mass in NR

**Ejecta mass depends significantly on NS EOS & mass**

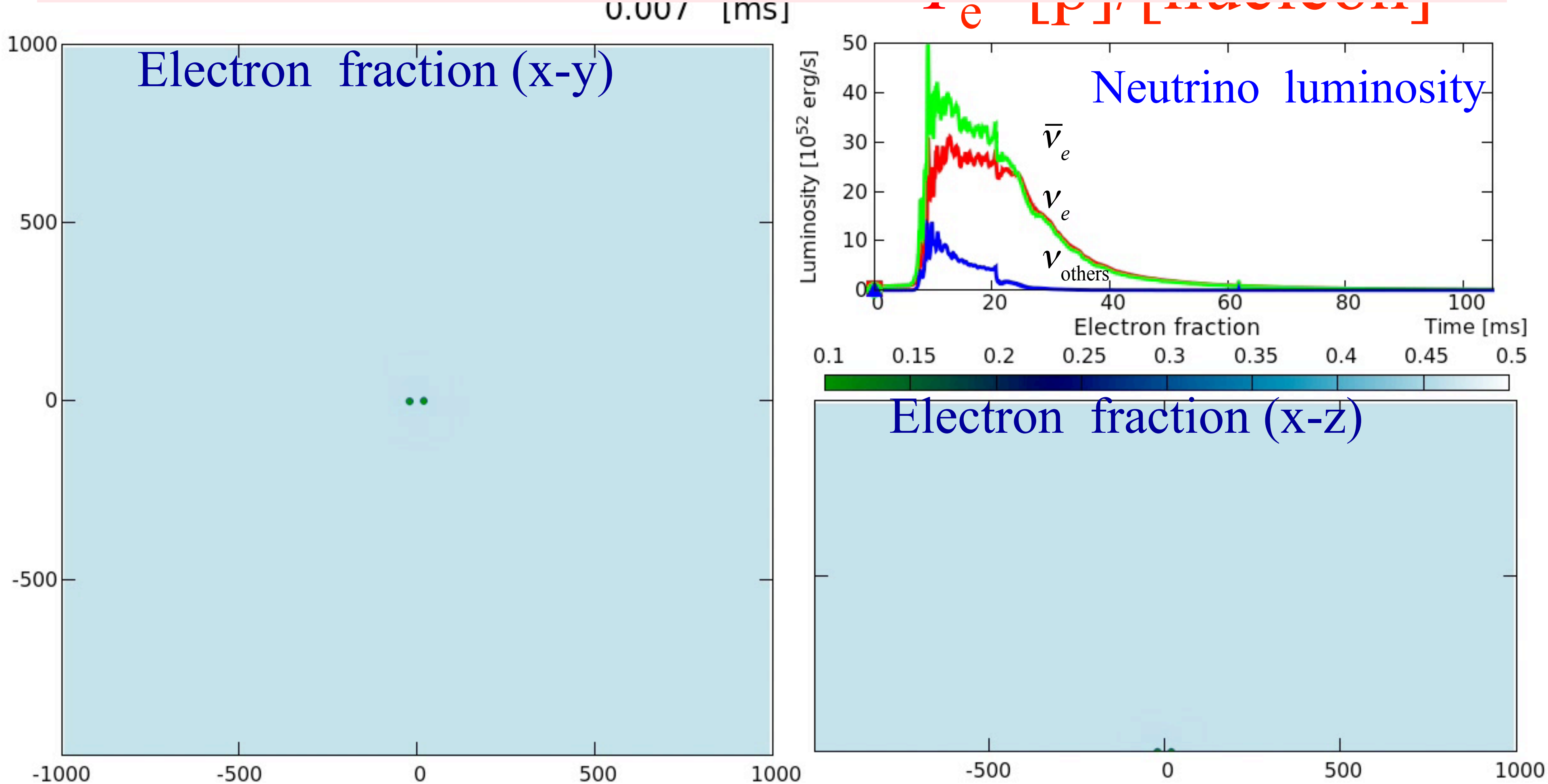
| | **Nearly equal mass ($M_{tot} \sim 2.7 M_{sun}$)** | **Unequal mass: $m_1/m_2 < 0.9$ ($M_{tot} \sim 2.7 M_{sun}$)** | **Small total mass system ($< 2.6 M_{sun}$)** |
|---|---|---|---|
| Soft EOS ($R$=11-12 km) | HMNS → BH $M_{eje} \sim 10^{-2}\ M_{sun}$ | HMNS → BH $M_{eje} \sim 10^{-2}\ M_{sun}$ | MNS (long lived) $M_{eje} \sim 10^{-3}\ M_{sun}$ |
| Stiff EOS ($R$=13-15km) | MNS (long lived) $M_{eje} \sim 10^{-3}\ M_{sun}$ | MNS (long lived) $M_{eje} \sim 10^{-2.5}\ M_{sun}$ | MNS (long lived) $M_{eje} \sim 10^{-3}\ M_{sun}$ ↑ e.g. Foucart et al. '16 |

➢ Typical average velocity: 0.15—0.25 c

See also the talk slide by Bauswein on June 5th

High temperature $\Rightarrow \gamma\gamma \to e^- + e^+, \quad n + e^+ \to p + \bar{\nu}_e$

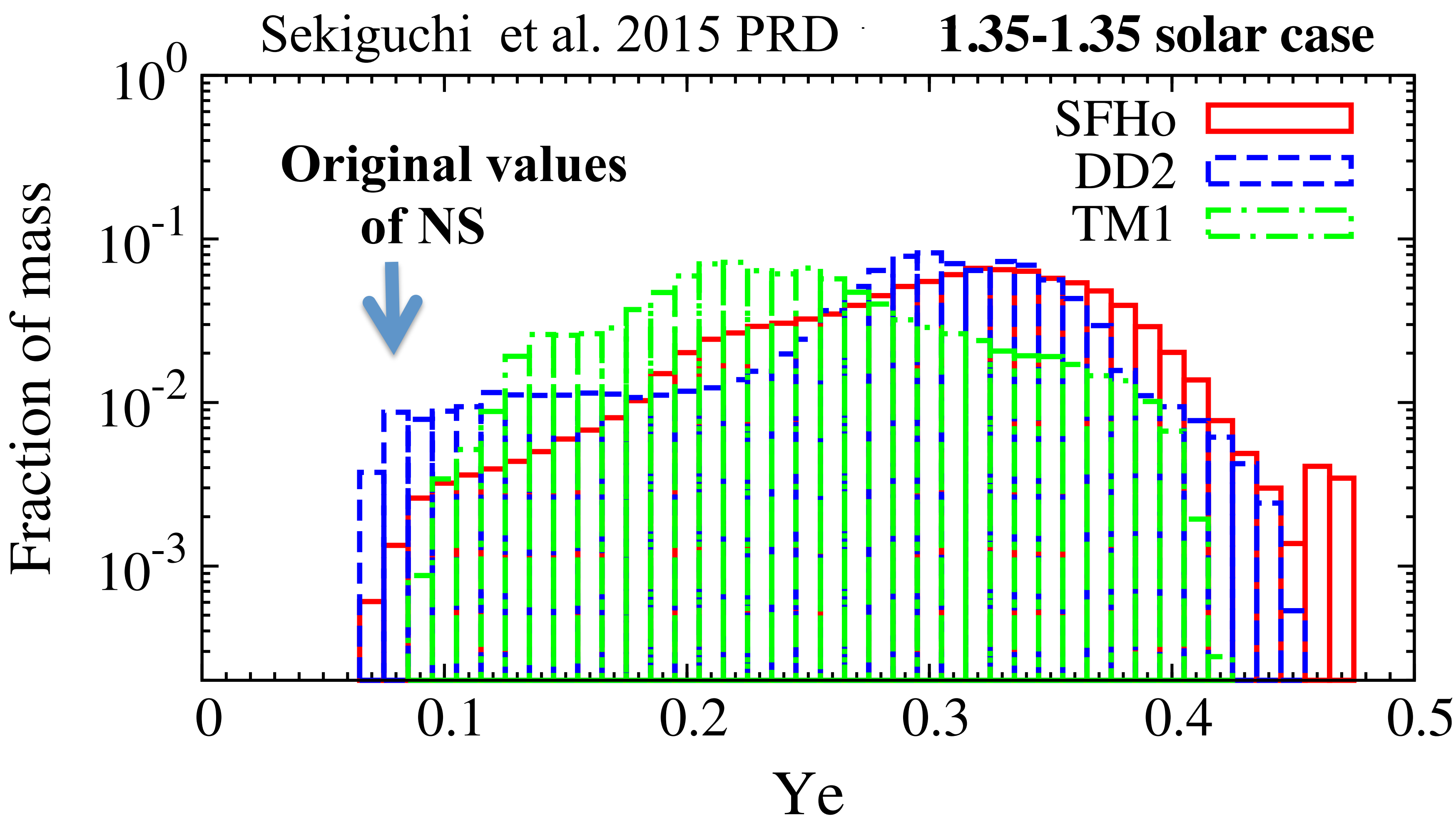
Neutrino irradiation $\Rightarrow n + \nu \to p + e^-$




**Green = neutron rich**

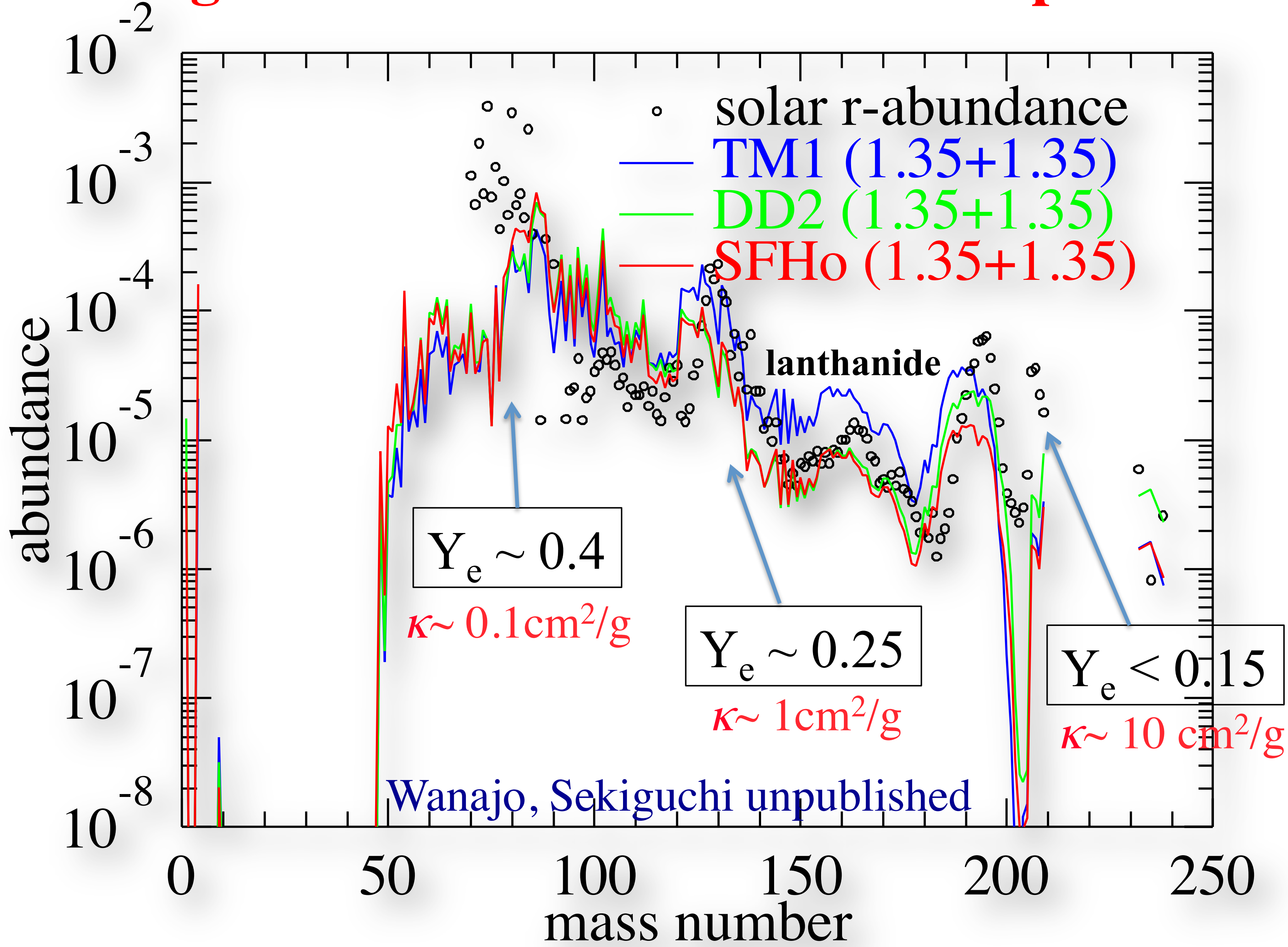
Sekiguchi et al. (2016)

# Electron fraction profile: Broad




- Average depends on EOS but typically peak at 0.2—0.3
- **Broad distribution** irrespective of EOS
- Similar results by Radice+16, Lehner+15,16 ……..

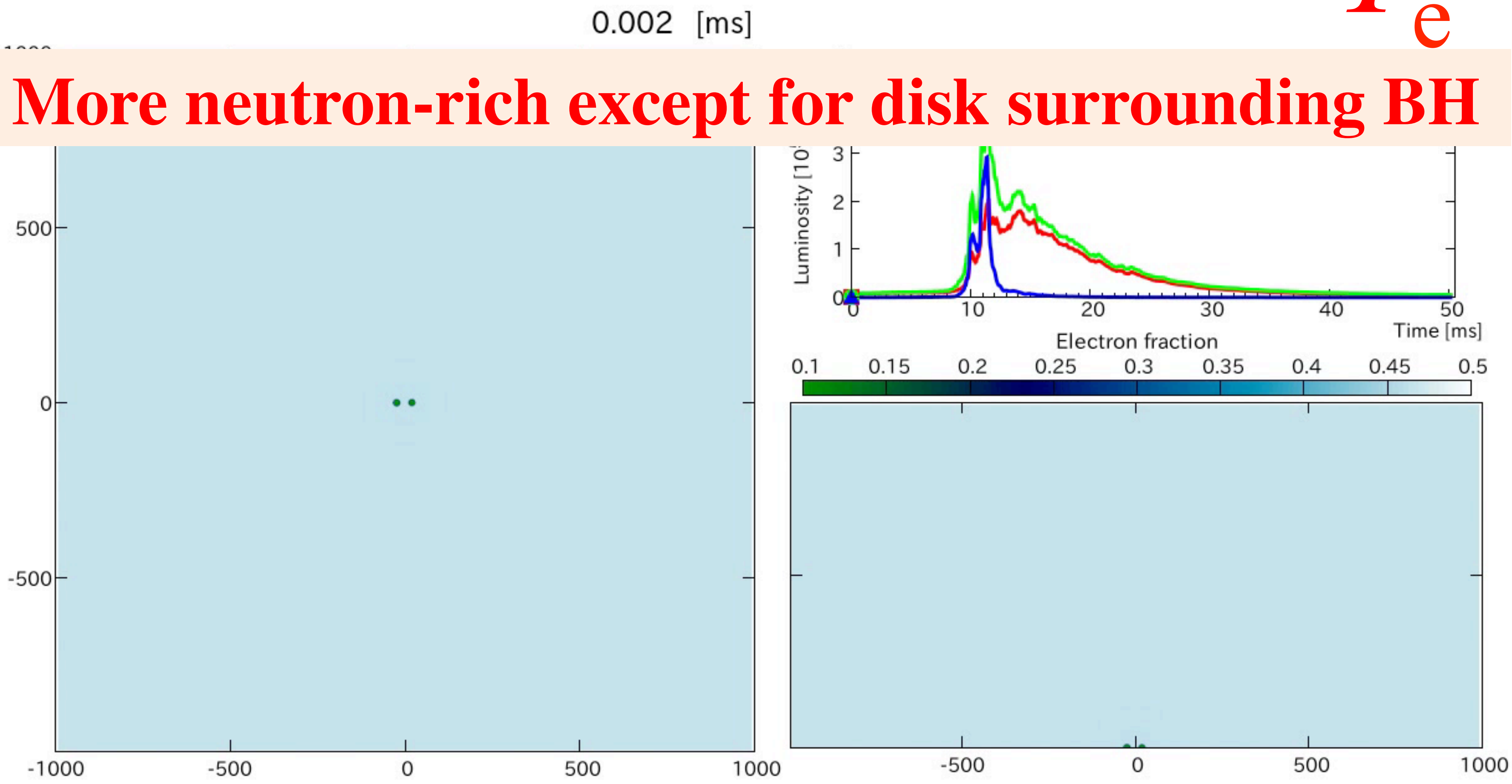
# Good agreement with solar abundance pattern



# Neutrino-radiation hydrodynamics simulation

SFHo ($R$~11.9 km): 1.25-1.55 $M_{sun}$

$Y_e$




**More neutron-rich except for disk surrounding BH**

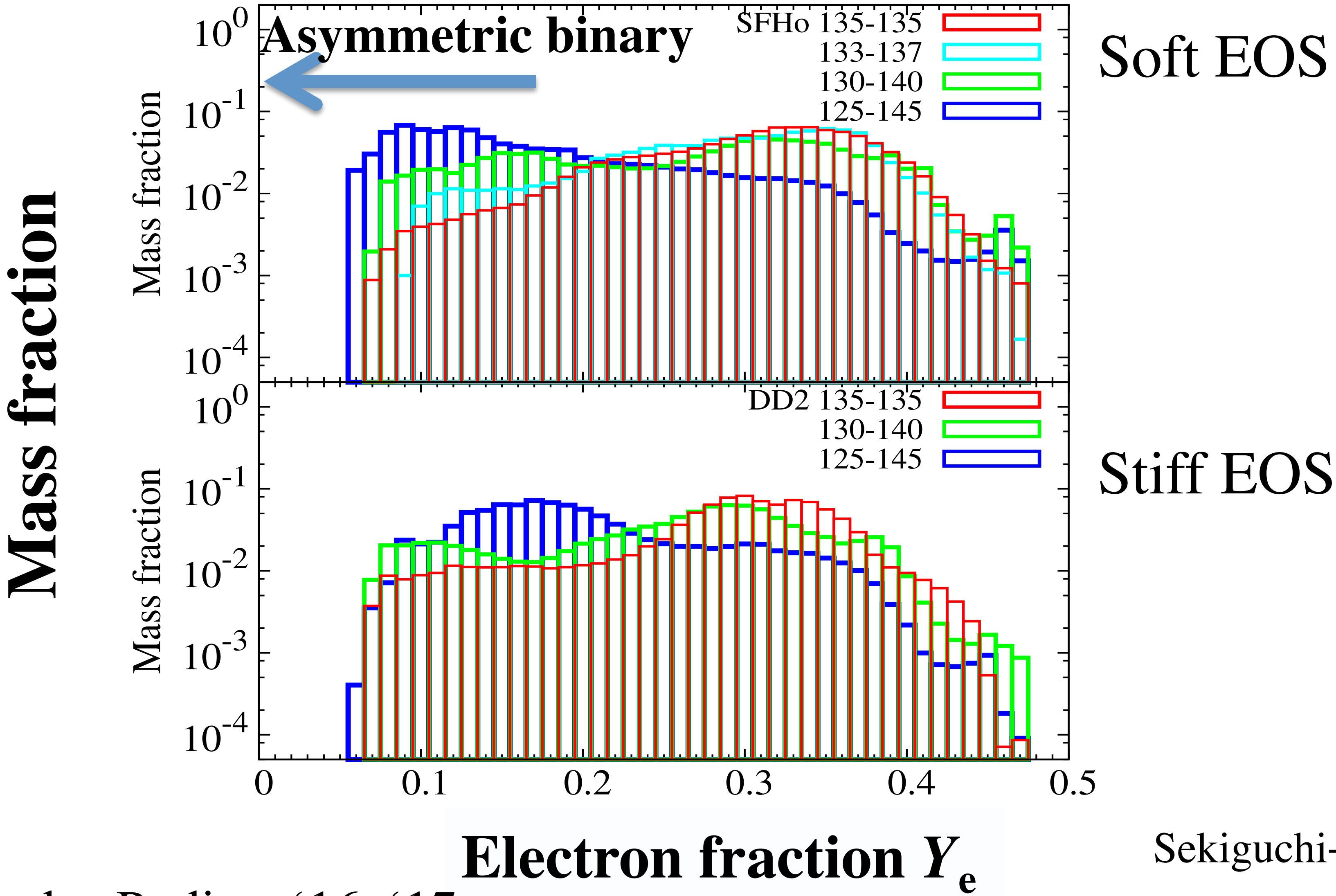
**Green = neutron rich**

Shibata et al. (2017)

# Electron fraction distribution:

**Broad irrespective of EOS and mass**

**→ Good for producing a variety of r-elements**

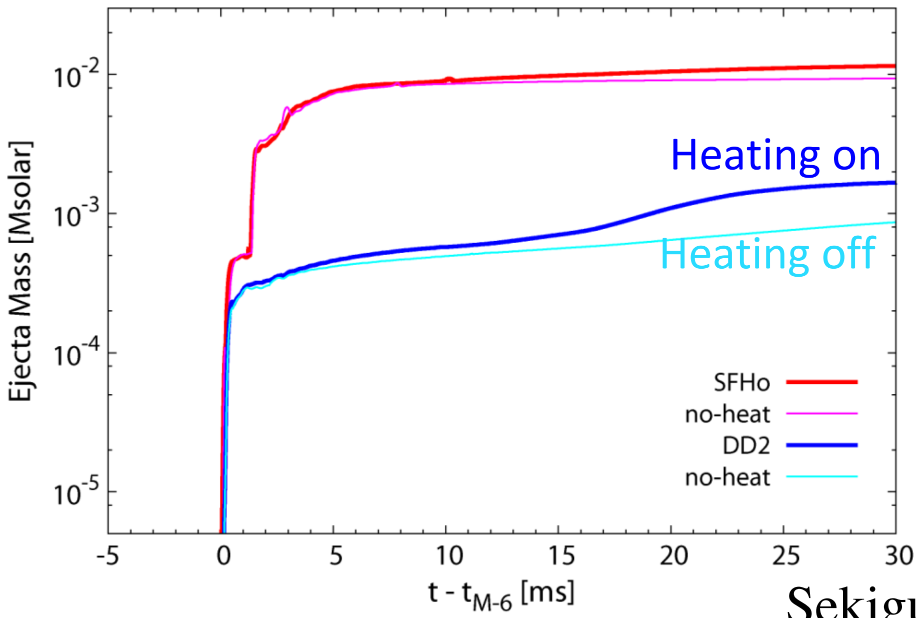



Sekiguchi+ '16

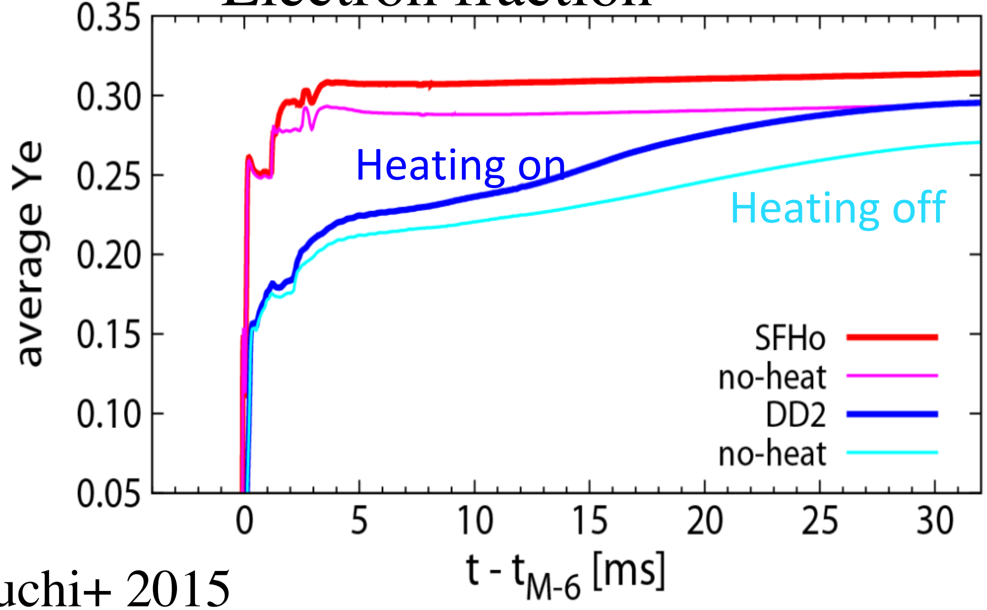
See also Radice '16, '17

# Neutrino irradiation: subdominant effect for mass ejection but important for $Y_e$

Ejecta mass




Electron fraction




Sekiguchi+ 2015

Neutrino irradiation from MNS increases

- **the ejecta mass increases by ~ 0.001 solar mass**
- **Average value of $Y_e$ increases by ~ 0.03 in 30 ms**

See also, Perego et al. 2014; Goriely et al. 2015; Martin et al. 2015; Foucart et al. 2016

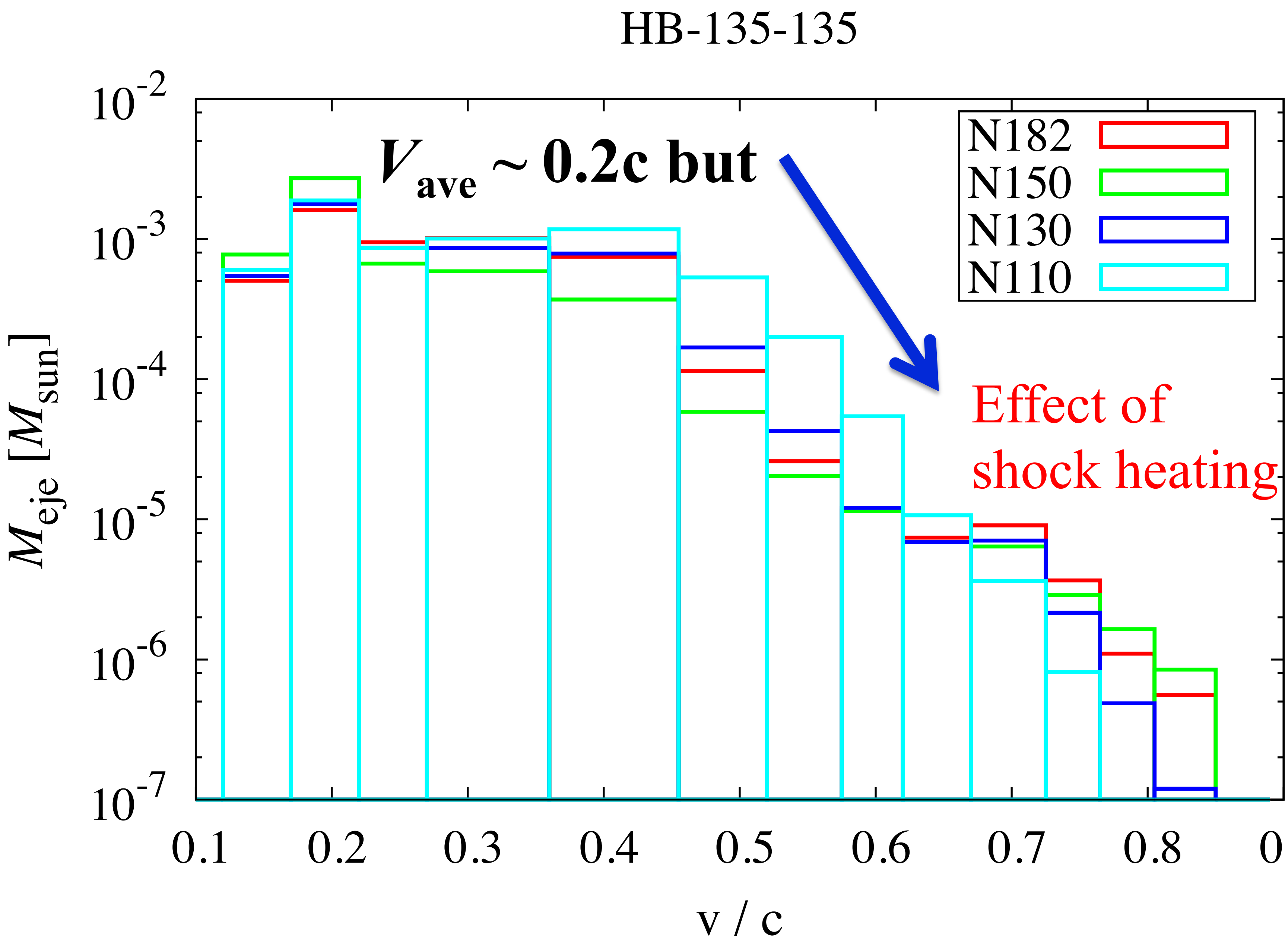
# Note on massive NS-NS merger → Direct BH formation

May be the fate for PSR J1913+1102 of total mass 2.875 $M_{sun}$

- For this case, **mass ejection is possible only at a merger phase of short timescale**
- **Nearly equal-mass**: negligible mass ejection < 0.001 solar mass (e.g., Shibata + '06, Hotokezaka et al '13)
- **Asymmetric case**: Mass increases with the degree of asymmetry; could be ~ 0.01 solar mass for $q$ ~0.75
- $Y_e$ would be always low (almost no heating & no neutrino irradiation)

See also talk slide by Bauswein on June 5th

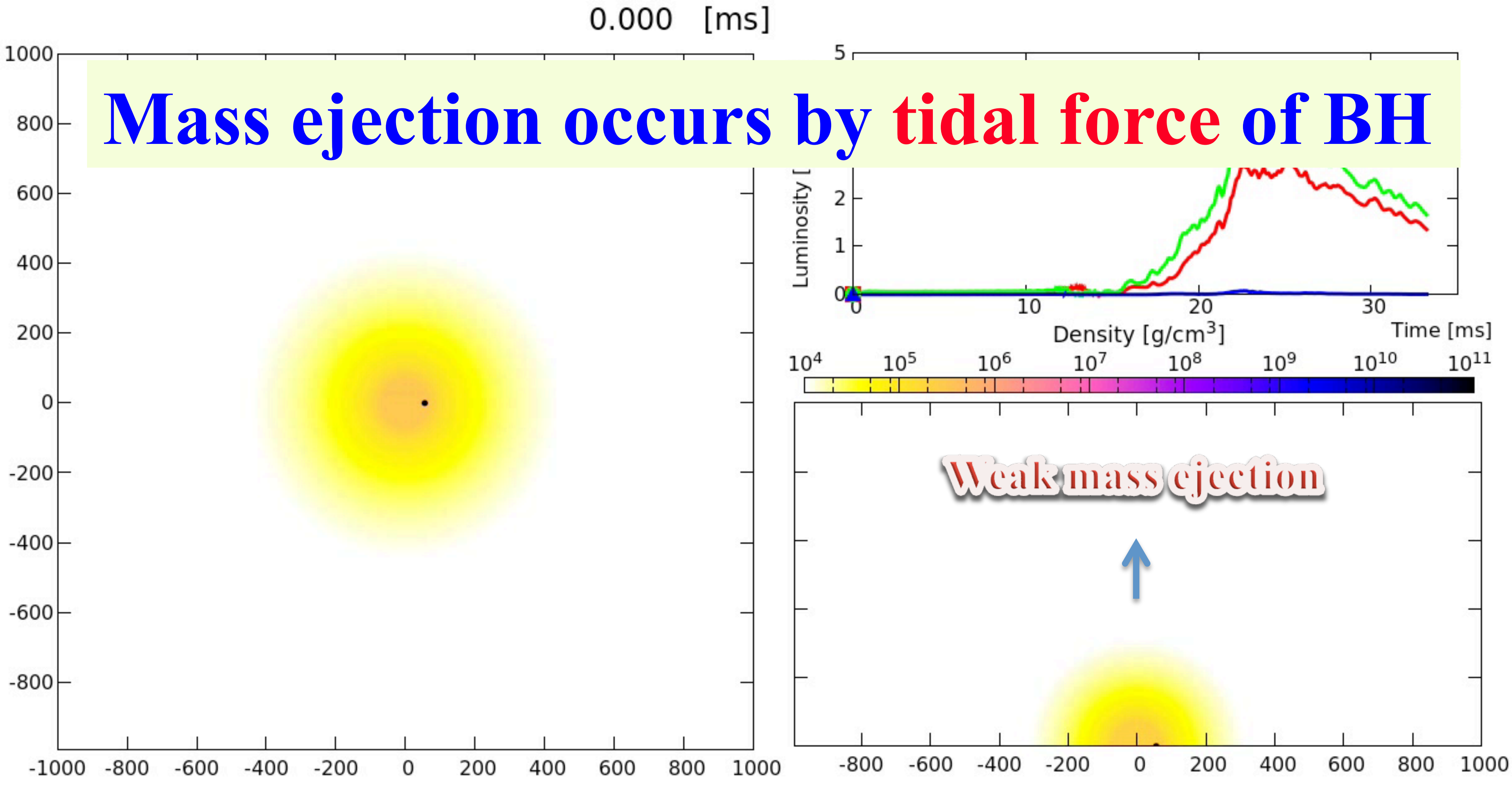
# Note on ejecta velocity: presence of high *v*



# **BH-NS merger** (SFHo EOS: density)

$M_{BH}$=5.4$M_{sun}$, $M_{NS}$=1.35$M_{sun}$, $a_{BH}$=0.75

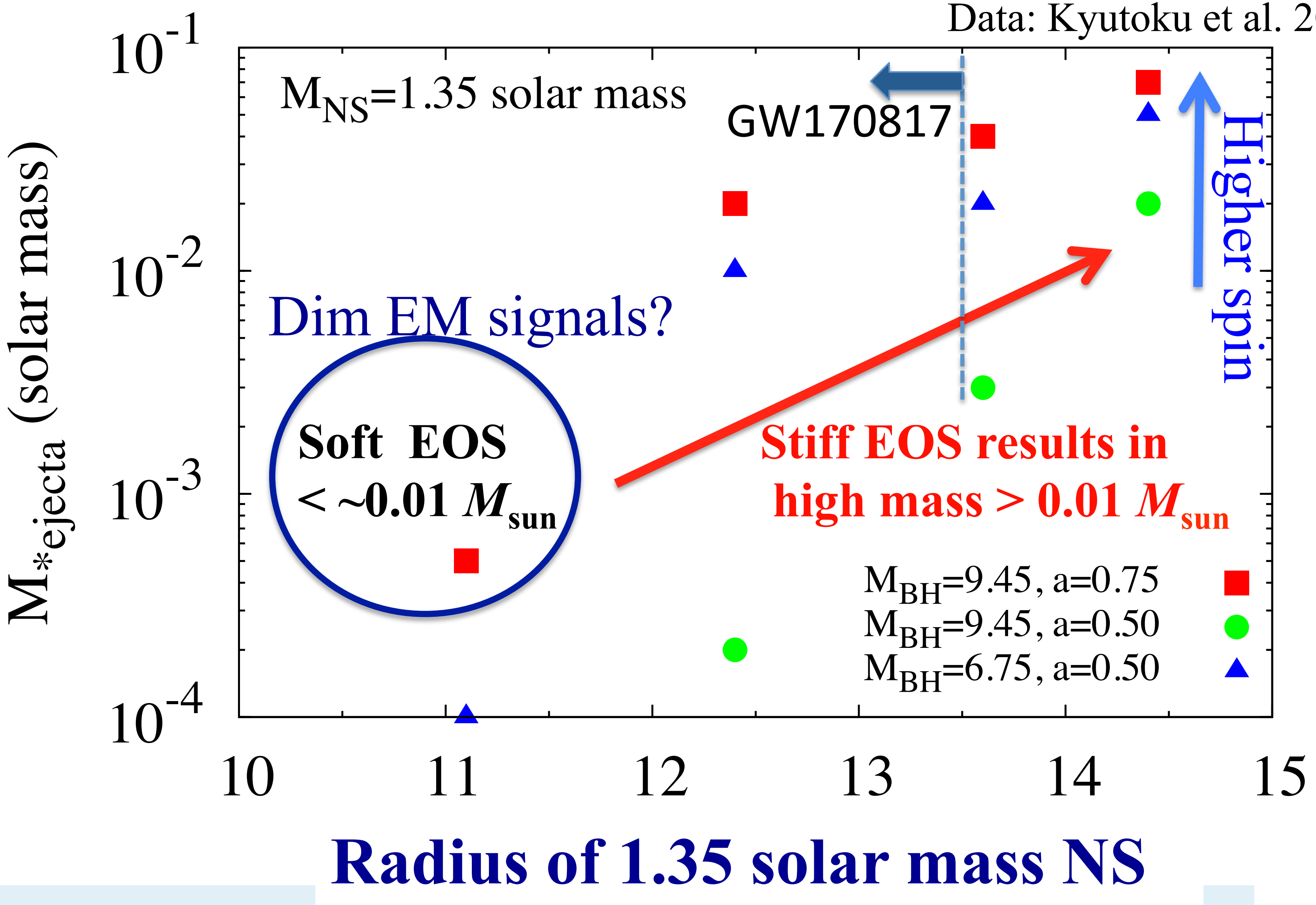
## Mass ejection occurs by tidal force of BH




Kyutoku et al. 2018; Also many pioneer works by F. Foucart et al.

# BH-NS with NS mass 1.35$M_{sun}$ (Q=5 & 7)

Data: Kyutoku et al. 2015



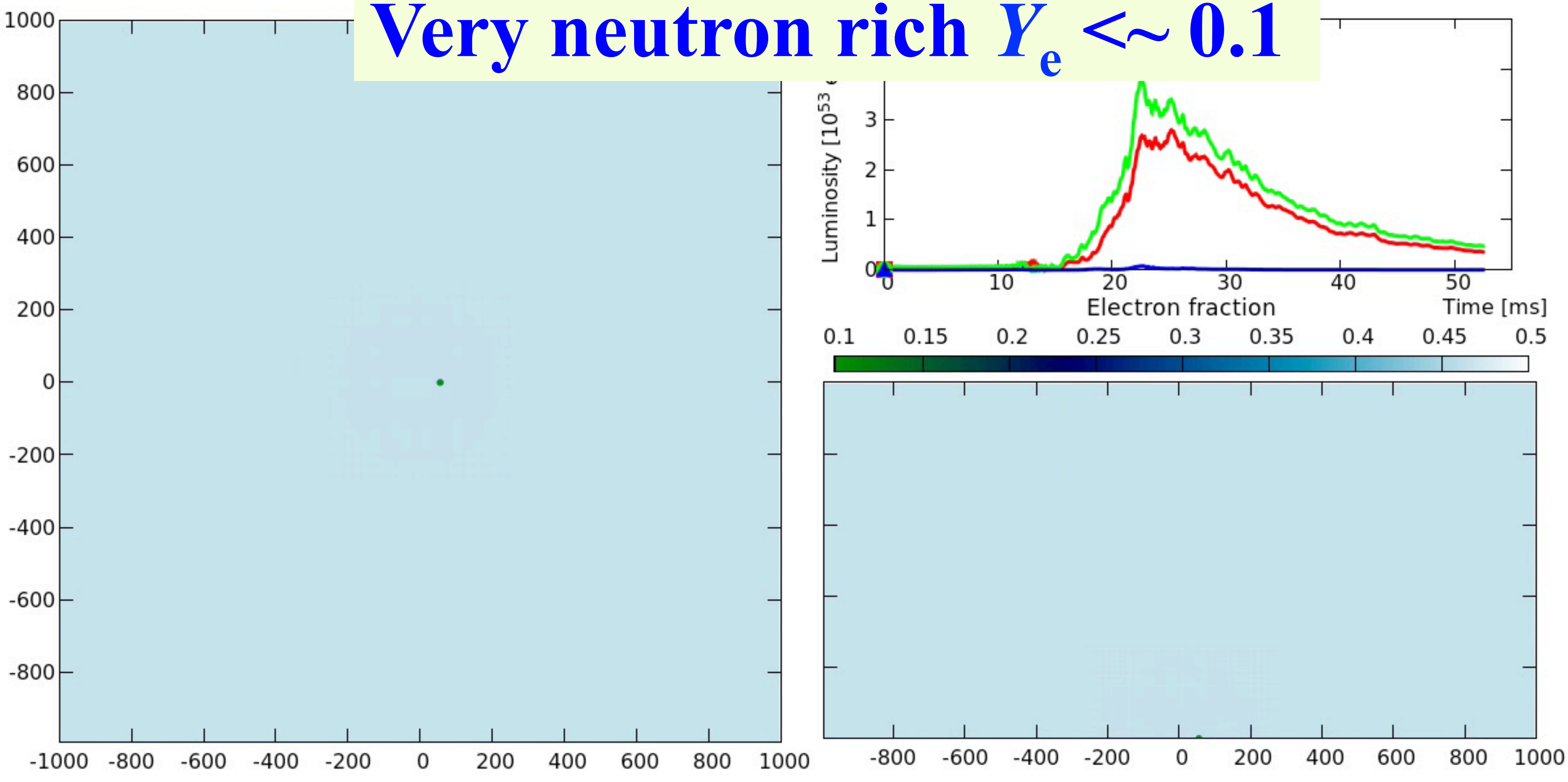

**High BH spin is important for mass ejection**

**BH-NS merger** (SFHo EOS: electron frac)

$M_{BH}$=5.4$M_{sun}$, $M_{NS}$=1.35$M_{sun}$, $a_{BH}$=0.75

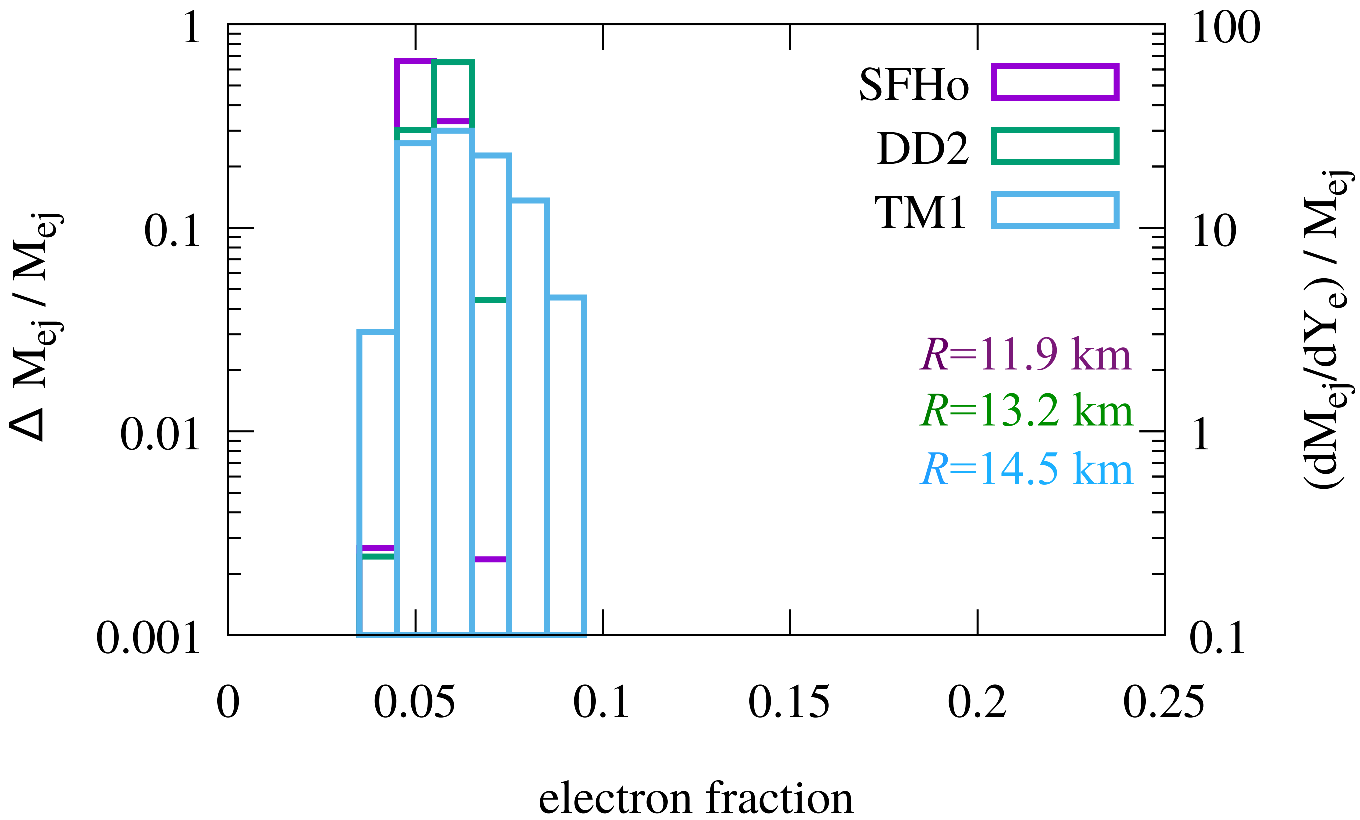
$Y_e$

**Very neutron rich $Y_e$ <~ 0.1**




Kyutoku et al. 2018; Also many works by F. Foucart et al.

# Electron fraction of ejecta




- **Quite low electron fraction** irrespective of EOS (Foucart, Duez et al., '13— '18, Kyutoku '18)
- **Tiny neutrino irradiation, weak shock heating**
- Likely to primarily synthesize **heavy r-elements**

# Dynamical ejecta properties in NR

◆**Mass**:

- NS-NS: **~$10^{-3}$—$10^{-2}$ $M_{sun}$** depending on total mass, mass ratio & EOS (Hotoke+ 13, Bauswein+ 13, Sekiguchi+ 15,16, Radice+ 16, Lehner+ 15,16…….many others)
- BH-NS: **0—0.1 $M_{sun}$: High BH spin & EOS are the key** (Foucart+ '13-15, Kyutoku+15): $M_{eject} \sim 0.2\, M_{disk}$

◆ **Electron fraction**

- NS-NS: Broad distribution of $Y_e$ with average $\langle Y_e \rangle \sim$ 0.2—0.3: For asymmetric case, $\langle Y_e \rangle$ could be $< 0.2$; for prompt BH formation case, $Y_e$ would be $< \sim 0.1$
- BH-NS: Peak at $Y_e < 0.1$ (Foucart+ '13-18, Kyutoku+ '18)

◆**Typical velocity**: 0.15—0.25 c; max could be ~ 0.8 c

# IV Viscous/MHD ejecta for post merger

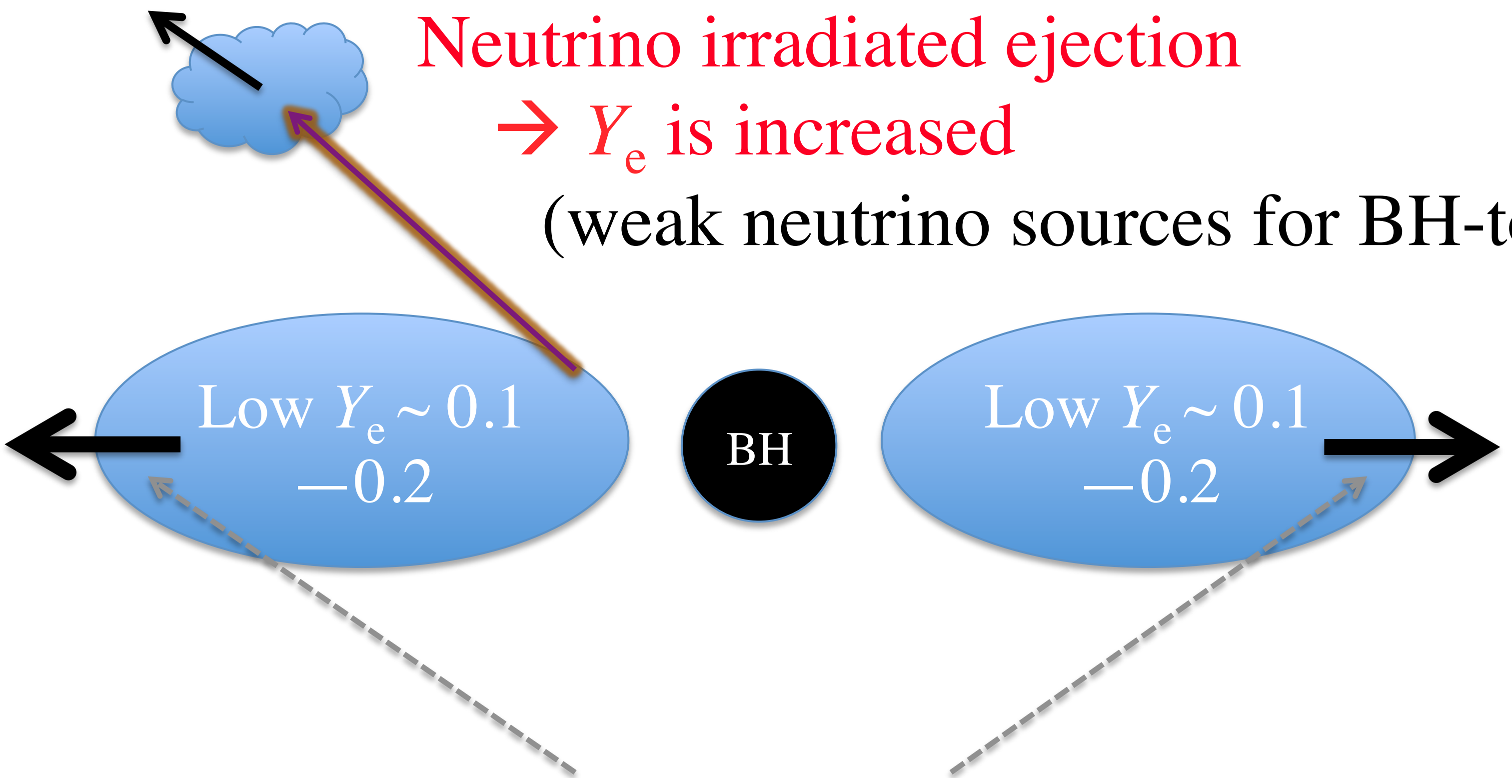
- MHD/viscous effects are likely to play a major role for post merger ejecta, i.e., **central remnant + disk**
  (Fernandez & Metzger+ '13-'15, Just et al. '15, Siegel-Metzger '17)

➢ Many Studies have been done for **BH-disk** systems
(Fernandez & Metzger+, '13-15, Just+ '15, Siegel-Metzger '17;
Natural model for BH-NS or high-mass asymmetric NS-NS)

- 10—30% of mass of disk surrounding a spinning BH is likely to be ejected by **viscous ejection → dynamical ejecta mass and viscous ejecta mass are comparable**
- Due to the absence of strong neutrino sources, **low $Y_e$ matter** would be ejected for BH + disk

# Basic Picture for BH-disk system

(Fernandez-Metzger '13, Metzger-Fernandez '14, Just ea '15, ……)




Neutrino irradiated ejection

→ $Y_e$ is increased

(weak neutrino sources for BH-torus)

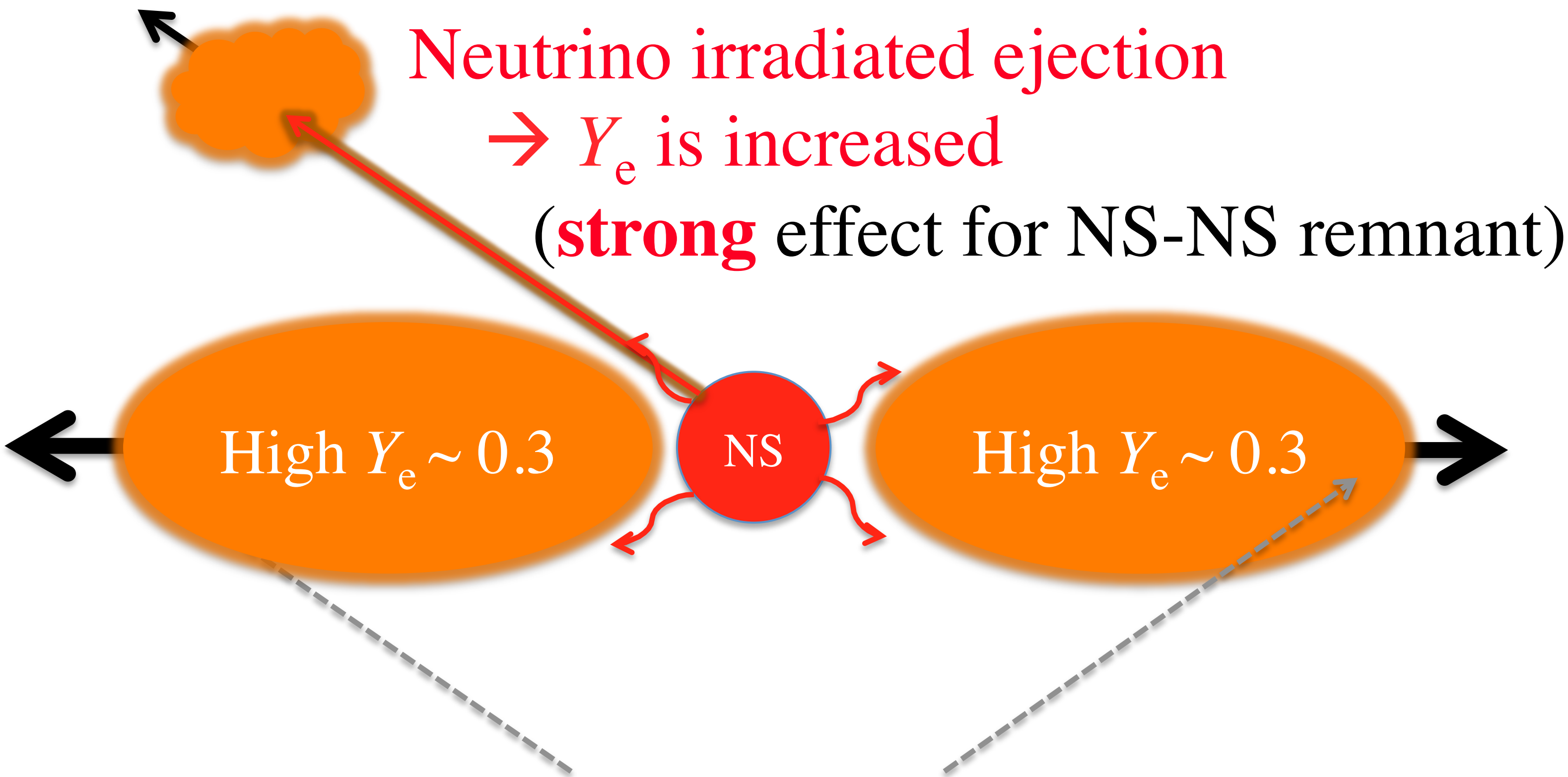
As the temperature decreases, $\tau_{vis} < \tau_{cool,\nu}$

→ $Y_e$ freeze out → Low $Y_e$ is preserved →Viscous expansion

→ Viscous ejection of mass 10—30% of torus mass

# Significant difference for NS-NS remnant

(Metzger-Fernandez ’14, Fujibayashi et al. ’18)




Viscous ejection of mass ~50% or more of torus mass

$Y_e$ is enhanced by neutrino irradiation from MNS

→ high $Y_e$ (weak r-process)

# Viscous neutrino-radiation hydrodynamics for post-merger remnant: MNS + torus

(S. Fujibayashi et al., ApJ. 2018)

- Employ **covariant & causal GR viscous hydrodynamics** (following Israel & Steward '79)
- Initial condition: Remnant of NS-NS merger simulation with mass 1.35-1.35$M_{\rm sun}$
- EOS: DD2 ($R_{\rm NS}$ = 13.2 km) → long-lived MNS is formed
- Axial symmetry is assumed (to evolve for > seconds)
- Alpha viscosity: $\nu = \alpha_\nu c_s H$ with $\alpha_\nu$= O(0.01) and $H$=10 km

$$\text{Viscous timescale of MNS } \sim 10\left(\frac{\alpha_\nu}{0.02}\right)^{-1} \text{ ms}$$

$$\text{Viscous timescale of disk } \sim 300\left(\frac{\alpha_\nu}{0.02}\right)^{-1} \text{ ms}$$

# **Viscous-rad hydrodynamics in GR for post-merger MNS** (S. Fujibayashi et al. ApJ 2018)

Rest-mass density $\alpha_v$=0.04

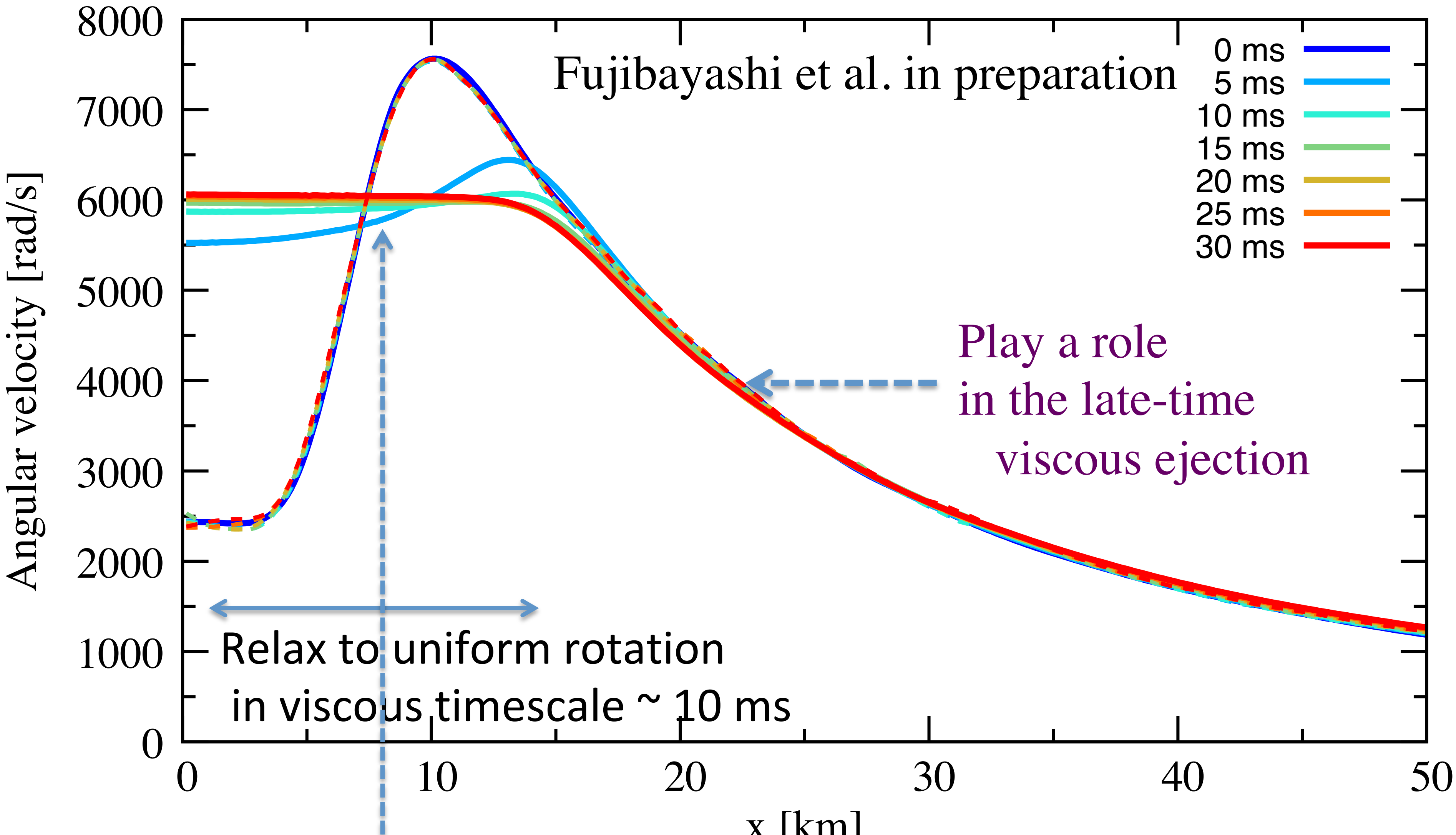
$M \sim$ 0.05 solar mass, $v \sim$ 0.05 $c$

Wide 4500×4500 km

300×300 km

**FOCUS ON THIS**

# Evolution of angular velocity




**Kinetic energy of ~$10^{52}$ erg is released**

**→ early viscous ejection**

# Viscous-rad hydrodynamics for post-merger MNS

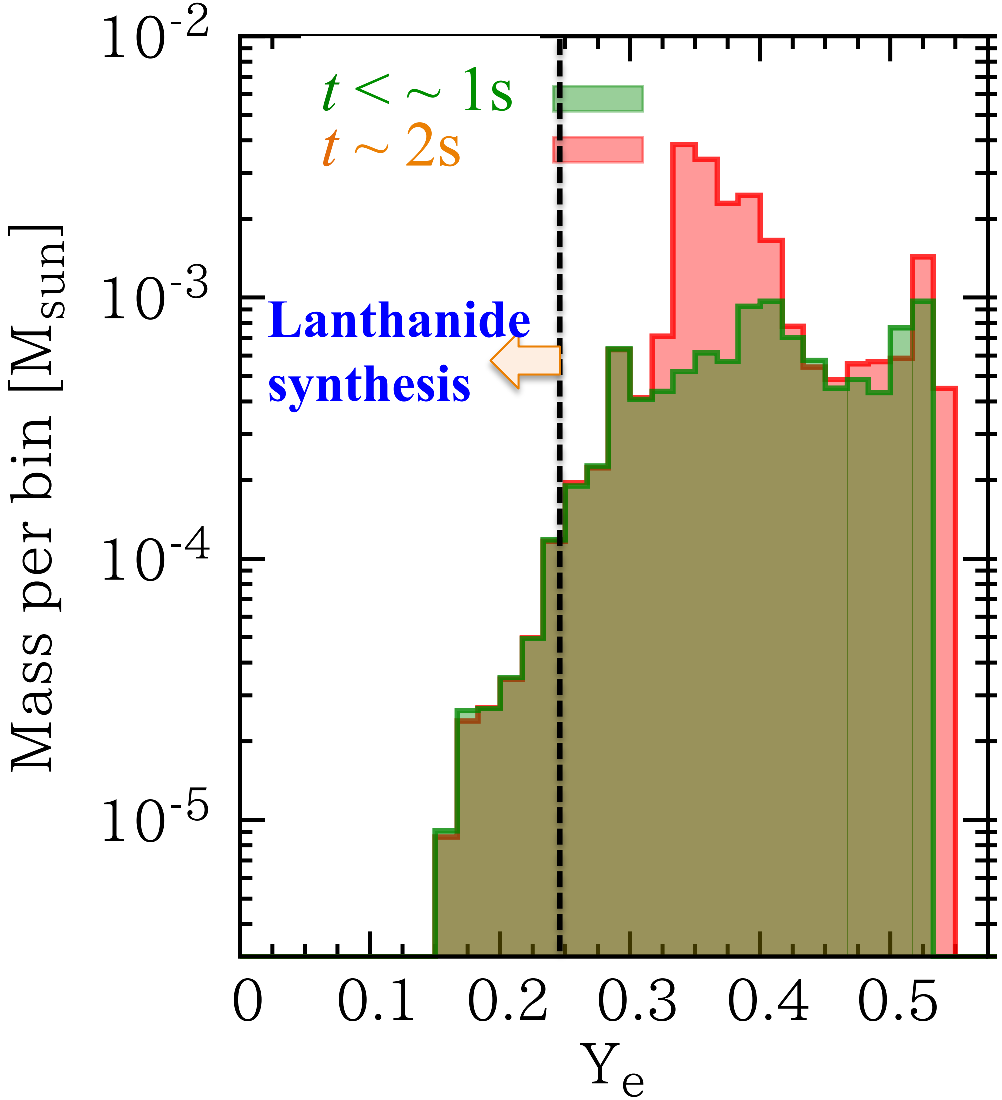
(S. Fujibayashi et al., ApJ 2018)

Electron fraction: $Y_e$, $\alpha_\nu$=0.04

$M \sim$ 0.05 solar mass, $v \sim$ 0.05 $c$, $Y_e \sim$ 0.3—0.4,
predominantly toward equatorial plane

Wide 4500×4500 km 300×300 km

# Electron fraction distribution for viscous ejecta




Neutrino irradiation from MNS

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

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

$$\Downarrow$$

Longterm irradiation

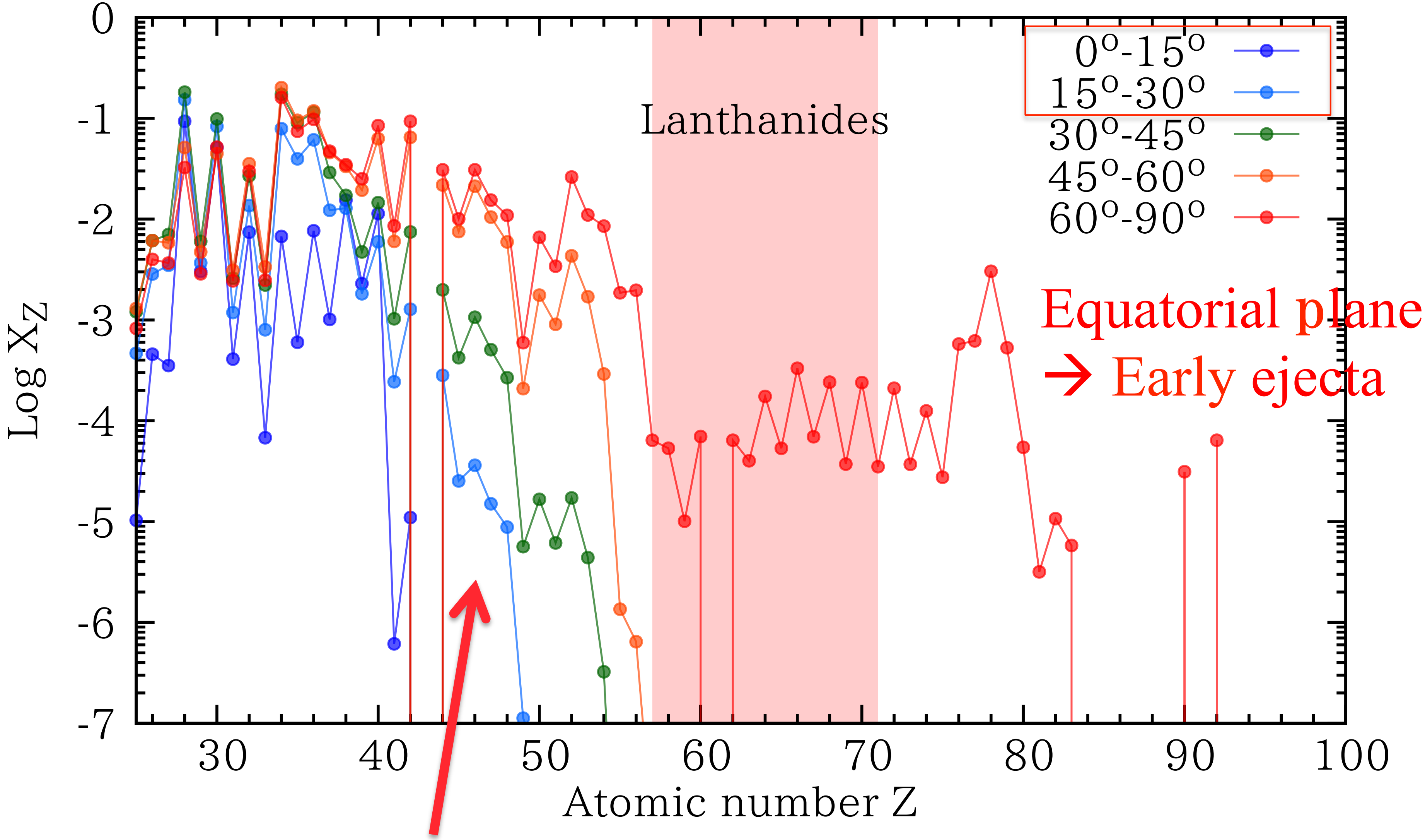
$$\Downarrow$$

$$Y_{e,equil} \sim \left[ 1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\langle E_{\bar{\nu}_e} \rangle - 2(m_n - m_p)}{\langle E_{\nu_e} \rangle + 2(m_n - m_p)} \right]$$

(Qian & Woosley, 1996)

Only ***small lanthanide synthesis*** due to **strong neutrino irradiation from remnant NS**

# No lanthanide along the line of sight from merger remnant ejecta




**Neutrino irradiation from remnant neutron star**

# IV Summary

| | Dynamical ejection | Post-merger ejection |
|---|---|---|
| 1. Low-mass NS-NS | $M \sim 10^{-3}\ M_{sun}$<br>$Y_e \sim 0.05$—$0.5$ | $M \sim 10^{-2} - 10^{-1} M_{sun}$<br>$Y_e \sim 0.3$—$0.5$ |
| 2. NS-NS→HMNS (e.g., GW170817) | $M \sim 10^{-3} - 10^{-2}\ M_{sun}$<br>$Y_e \sim 0.05$—$0.5$ | $M >\sim 10^{-2}\ M_{sun}$<br>$Y_e \sim 0.2?$—$0.5$ |
| 3. NS-NS → BH (assume not very asymmetric) | $M < \sim 10^{-3}\ M_{sun}$<br>$Y_e <\sim 0.1$ | $M < 10^{-3}\ M_{sun}$<br>$Y_e <\sim 0.1$ |
| 4. BH-NS with tidal disruption and/or asymmetric NS-NS | $M \sim 10^{-2} - 10^{-1}\ M_{sun}$<br>$Y_e <\sim 0.1$ | $M \sim 10^{-2}\ M_{sun}$<br>$Y_e \sim 0.1$—$0.25$ |

# IV Summary

| | Dynamical ejection | Post-merger ejection |
|---|---|---|
| 1. Low-mass NS-NS | $M \sim 10^{-3}\ M_{sun}$<br>$Y_e \sim 0.05$—$0.5$<br>Faint Red | $M \sim 10^{-2} – 10^{-1} M_{sun}$<br>$Y_e \sim 0.3$—$0.5$<br>Blue, **very luminous** |
| 2. NS-NS→HMNS (e.g., GW170817) | $M \sim 10^{-3} – 10^{-2}\ M_{sun}$<br>$Y_e \sim 0.05$—$0.5$ | $M >\sim 10^{-2}\ M_{sun}$<br>$Y_e \sim 0.2$?—$0.5$ |
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# IV Summary

| | Dynamical ejection | Post-merger ejection |
|---|---|---|
| 1. Low-mass NS-NS | $M \sim 10^{-3} M_{sun}$<br>$Y_e \sim 0.05$—$0.5$<br>Faint Red | $M \sim 10^{-2} - 10^{-1} M_{sun}$<br>$Y_e \sim 0.3$—$0.5$<br>Blue, **very luminous** |
| 2. NS-NS→HMNS (e.g., GW170817) | $M \sim 10^{-3} - 10^{-2} M_{sun}$<br>$Y_e \sim 0.05$—$0.5$<br>Late Red, **luminous** | $M >\sim 10^{-2} M_{sun}$<br>$Y_e \sim 0.2?$—$0.5$<br>Early Blue, **luminous** |
| 3. NS-NS → BH (assume not very asymmetric) | $M < \sim 10^{-3} M_{sun}$<br>$Y_e <\sim 0.1$ | $M < 10^{-3} M_{sun}$<br>$Y_e <\sim 0.1$ |
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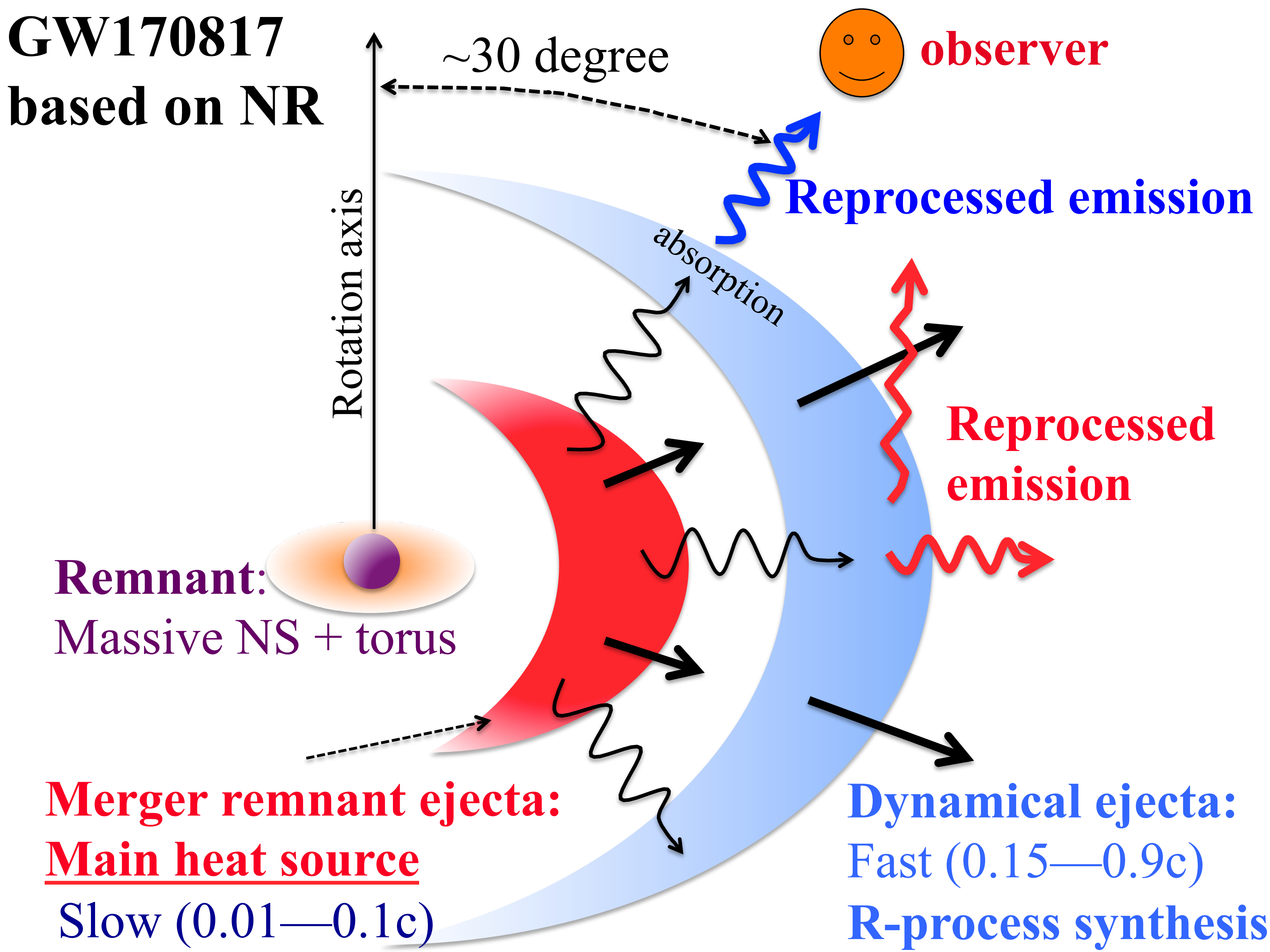
# IV Summary

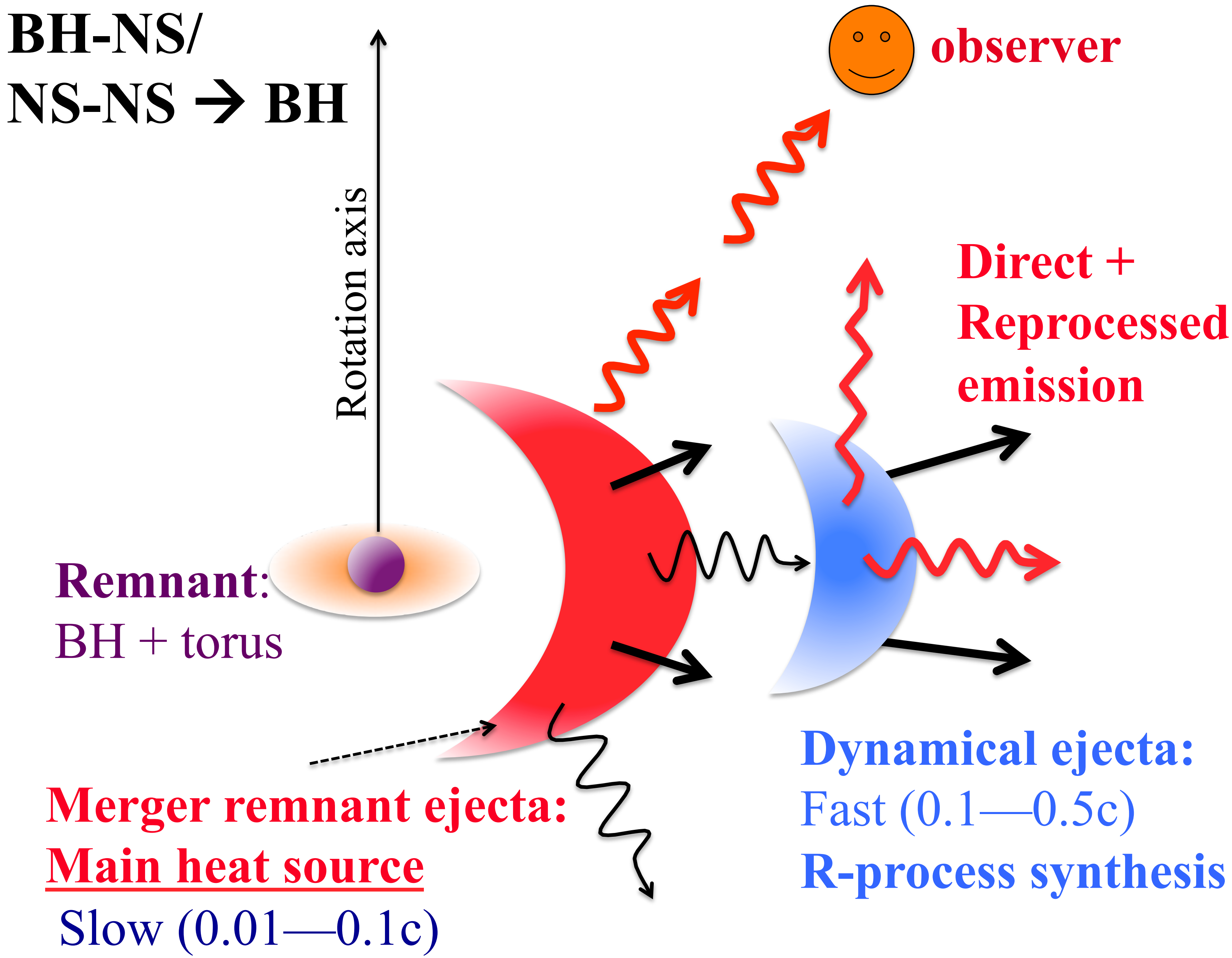
| | Dynamical ejection | Post-merger ejection |
|---|---|---|
| 1. Low-mass NS-NS | $M \sim 10^{-3}\ M_{sun}$<br>$Y_e \sim 0.05$—$0.5$<br>Faint Red | $M \sim 10^{-2} - 10^{-1} M_{sun}$<br>$Y_e \sim 0.3$—$0.5$<br>Blue, **very luminous** |
| 2. NS-NS→HMNS (e.g., GW170817) | $M \sim 10^{-3} - 10^{-2}\ M_{sun}$<br>$Y_e \sim 0.05$—$0.5$<br>Late Red, **luminous** | $M >\sim 10^{-2}\ M_{sun}$<br>$Y_e \sim 0.2?$—$0.5$<br>Early Blue, **luminous** |
| 3. NS-NS → BH (assume not very asymmetric) | $M < \sim 10^{-3}\ M_{sun}$<br>$Y_e <\sim 0.1$<br>Faint Red | $M < 10^{-3}\ M_{sun}$<br>$Y_e <\sim 0.1$<br>Faint Red |
| 4. BH-NS with tidal disruption and/or asymmetric NS-NS | $M \sim 10^{-2} - 10^{-1}\ M_{sun}$<br>$Y_e <\sim 0.1$ | $M \sim 10^{-2}\ M_{sun}$<br>$Y_e \sim 0.1$—$0.25$ |

# IV Summary

| | Dynamical ejection | Post-merger ejection |
|---|---|---|
| 1. Low-mass NS-NS | $M \sim 10^{-3} M_{sun}$<br>$Y_e \sim 0.05$—$0.5$<br>Faint Red | $M \sim 10^{-2} - 10^{-1} M_{sun}$<br>$Y_e \sim 0.3$—$0.5$<br>Blue, **very luminous** |
| 2. NS-NS→HMNS (e.g., GW170817) | $M \sim 10^{-3} - 10^{-2} M_{sun}$<br>$Y_e \sim 0.05$—$0.5$<br>Late Red, **luminous** | $M >\sim 10^{-2} M_{sun}$<br>$Y_e \sim 0.2?$—$0.5$<br>Early Blue, **luminous** |
| 3. NS-NS → BH (assume not very asymmetric) | $M < \sim 10^{-3} M_{sun}$<br>$Y_e <\sim 0.1$<br>Faint Red | $M < 10^{-3} M_{sun}$<br>$Y_e <\sim 0.1$<br>Faint Red |
| 4. BH-NS with tidal disruption and/or asymmetric NS-NS | $M \sim 10^{-2} - 10^{-1} M_{sun}$<br>$Y_e <\sim 0.1$<br>Late Red, dim/ luminous ? | $M \sim 10^{-2} M_{sun}$<br>$Y_e \sim 0.1$—$0.25$<br>Late Red |



GW170817
based on NR
~30 degree
observer
Rotation axis
Reprocessed emission
absorption
Reprocessed
emission
Remnant:
Massive NS + torus
Merger remnant ejecta:
Main heat source
Slow (0.01—0.1c)
Dynamical ejecta:
Fast (0.15—0.9c)
R-process synthesis


BH-NS/
NS-NS → BH
Rotation axis
observer
Direct +
Reprocessed
emission
Remnant:
BH + torus
Merger remnant ejecta:
Main heat source
Slow (0.01—0.1c)
Dynamical ejecta:
Fast (0.1—0.5c)
R-process synthesis

# Mass-radius relation for various EOS