# Mass ejection from binary neutron star mergers in numerical relativity

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# Outline

I. Brief introduction

II. Typical scenario for NS-NS mergers

III. Dynamical mass ejection

IV. MHD/viscous ejection

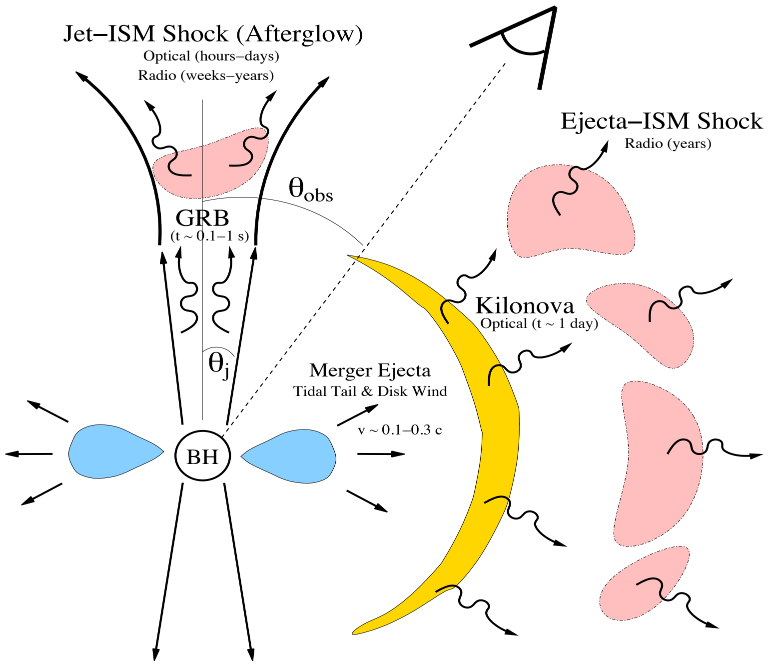
V. Summary

# I Introduction

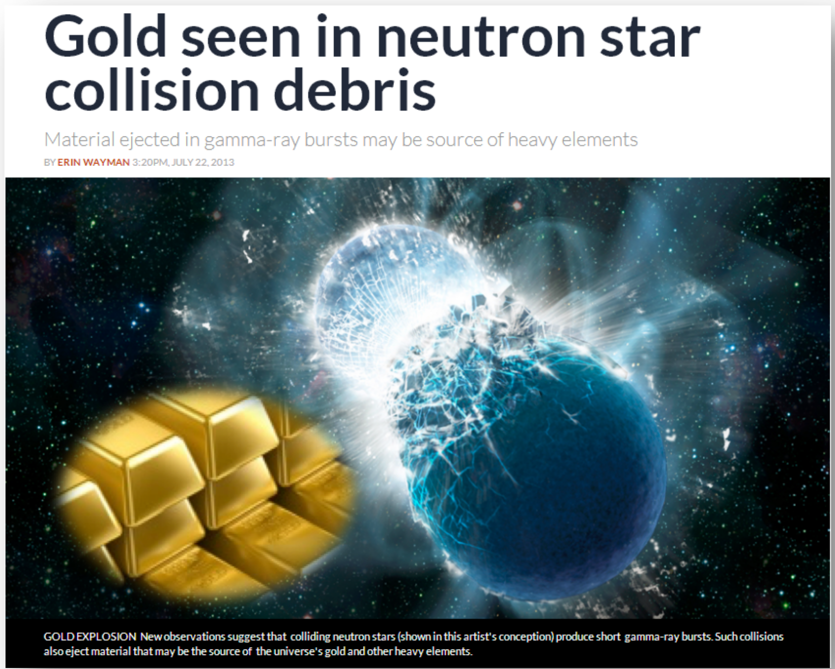
## Why mass ejection from NS binaries is important ?

1. Electromagnetic counterparts of NS merger:
   **Key for confirming gravitational-wave detection**
   (talks by Korobkin……)

2. Ejecta could produce **r-process heavy elements**
   (talks by Foucart……..)




Metzger & Berger 2012



Gold seen in neutron star collision debris

Material ejected in gamma-ray bursts may be source of heavy elements

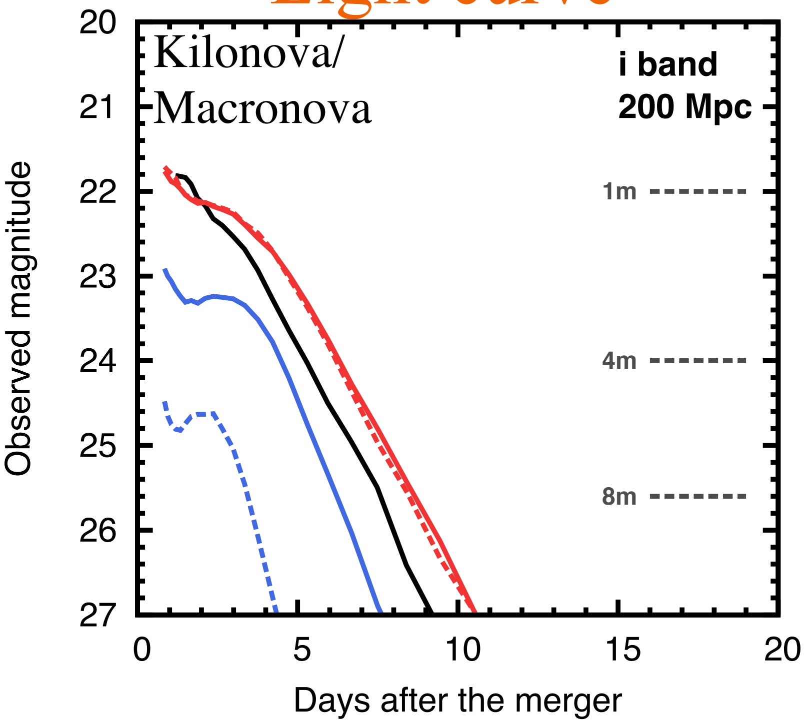
BY ERIN WAYMAN 3:20PM, JULY 22, 2013

GOLD EXPLOSION New observations suggest that colliding neutron stars (shown in this artist's conception) produce short gamma-ray bursts. Such collisions also eject material that may be the source of the universe's gold and other heavy elements.

# In the following, I focus in particular on

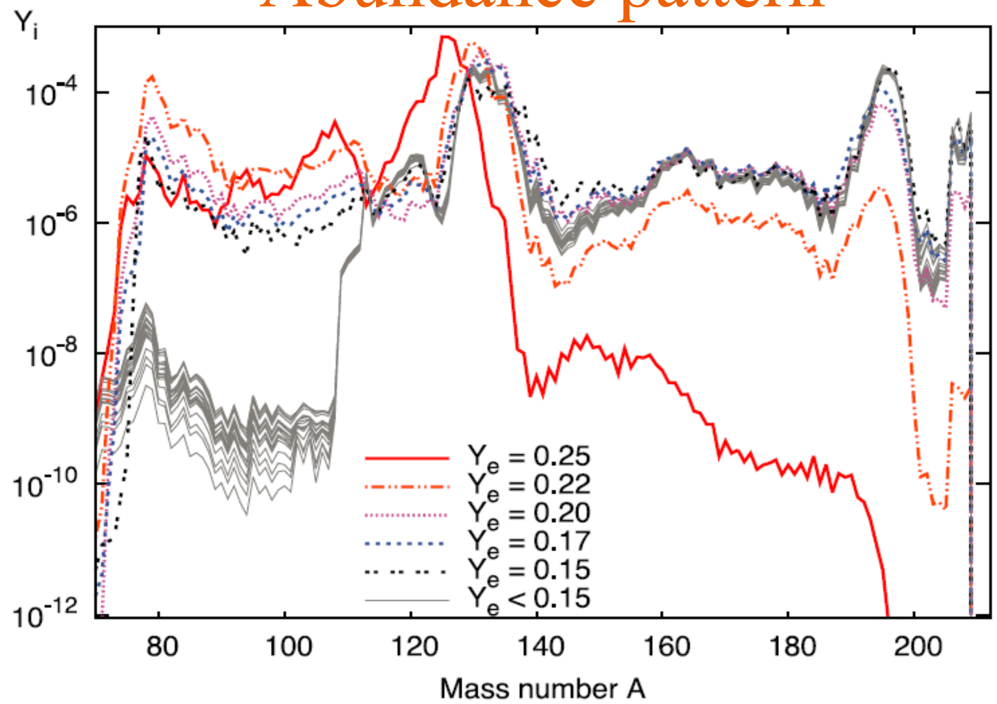
- **Ejecta mass $M_{eject}$**
- **Electron fraction $Y_e$ for ejecta**

Light curve




Tanaka & Hotoke 2013

Abundance pattern




Korobkin et al. 2012

# II Typical scenario for NS-NS merger

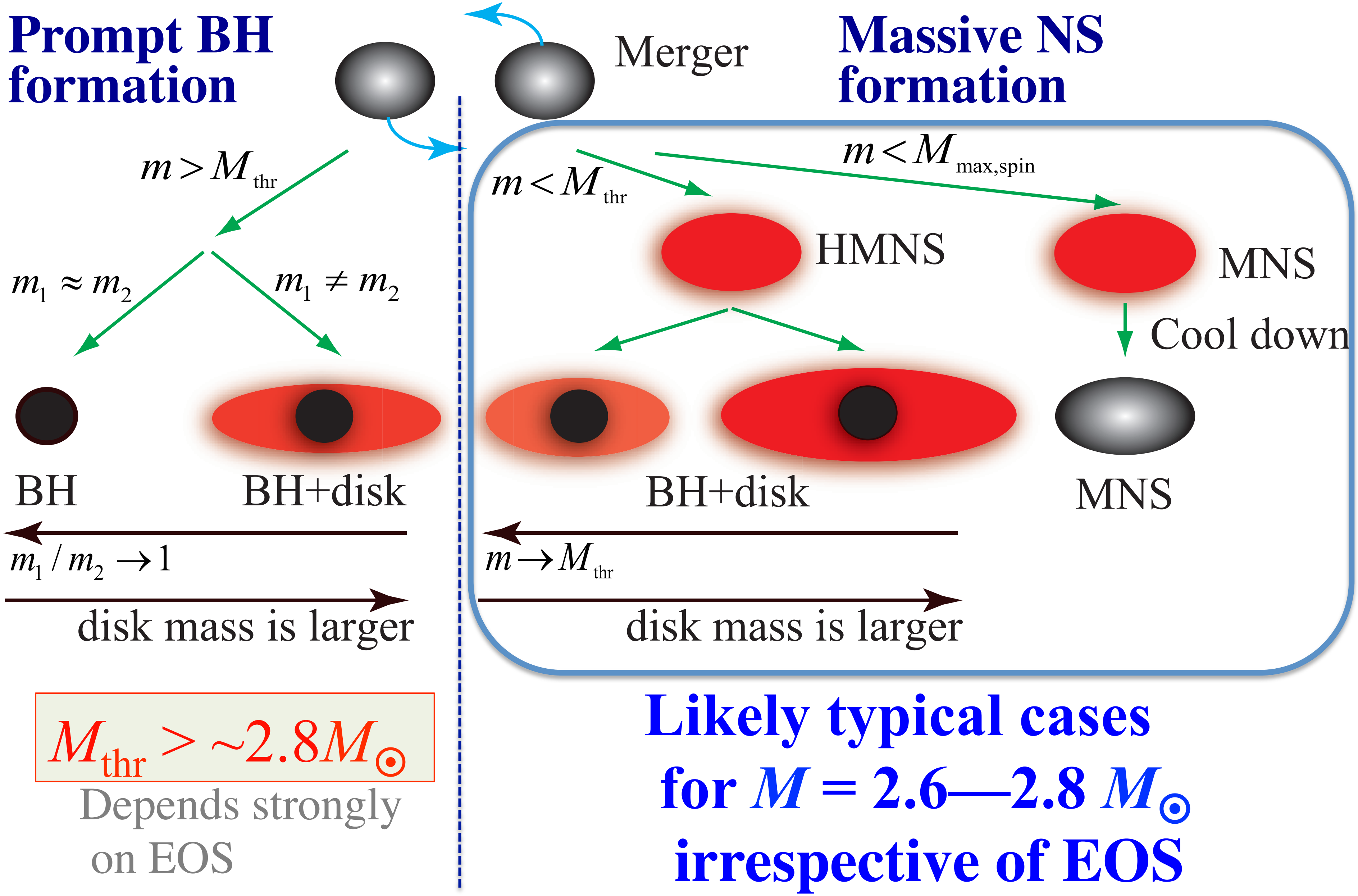
- **Radio-telescope observation shows**:

1. Approximately 2-$M_{\odot}$ 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 $M_{\odot}$ (by Pulsar timing obs. for 8 NS-NS)

- **Numerical relativity simulations have shown that**

➢ Merger results typically in **high-mass neutron stars** (not BH) (Shibata et al. 2005, 2006.. recently many works….)

# List of possible outcomes of NS-NS mergers




$M_{\rm thr} > \sim 2.8 M_\odot$

Depends strongly on EOS

**Likely typical cases for $M$ = 2.6—2.8 $M_\odot$ irrespective of EOS**

# Mass ejection history for MNS formation

Time after merger

0 10 100 1000 ms

Dynamical ejection (Sec. III)
(determined by dynamical timescale of NS)

early MHD/viscous ejection (Sec. IV)
(by viscous timescale of remnant MNS)

Long-term viscous ejection (IV)
(by viscous timescale of disk)

Neutrino irradiation (for neutrino emission timescale)
(minor effects but could play a role)

He Recombination
(Fernandez-Metzger '13)

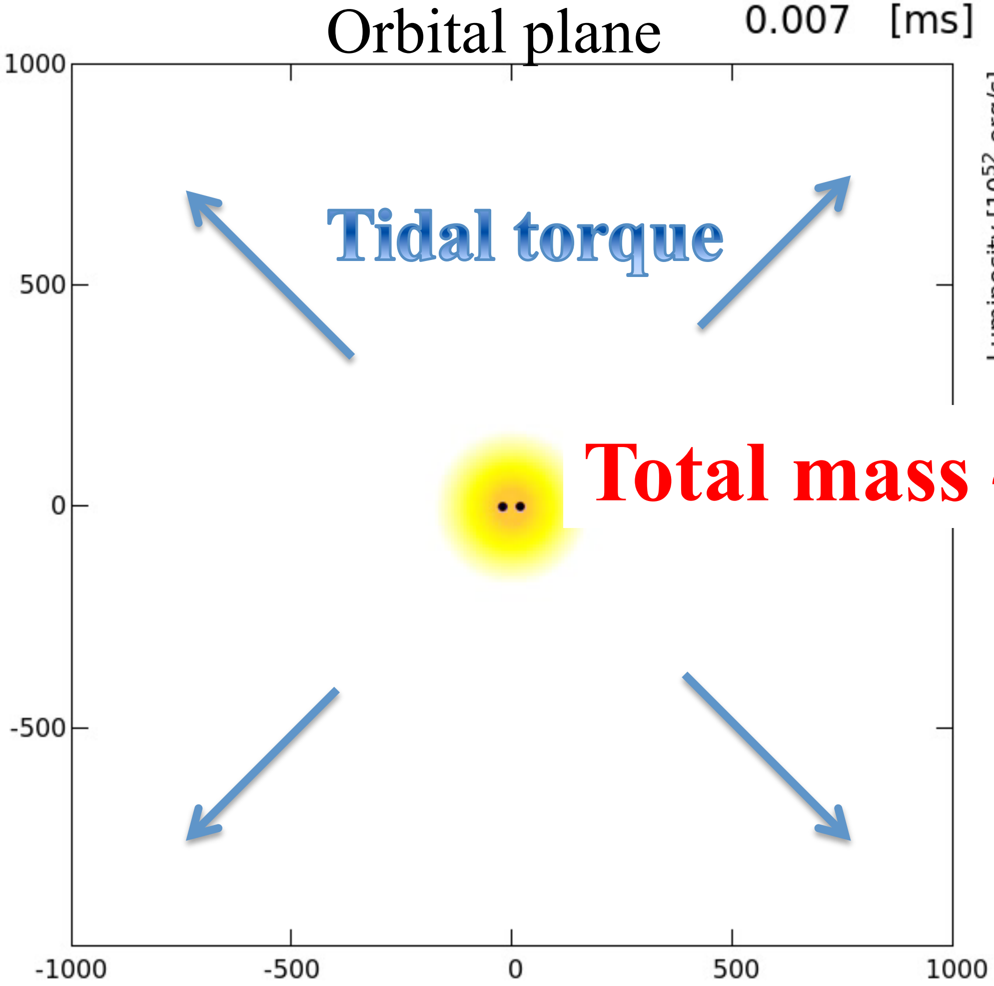
# III Dynamical mass ejection

- Mass ejection during the merger
- Ejecta mass depends on binary parameters & equations of state for NS
  (Hotokezaka et al. '13, ….)

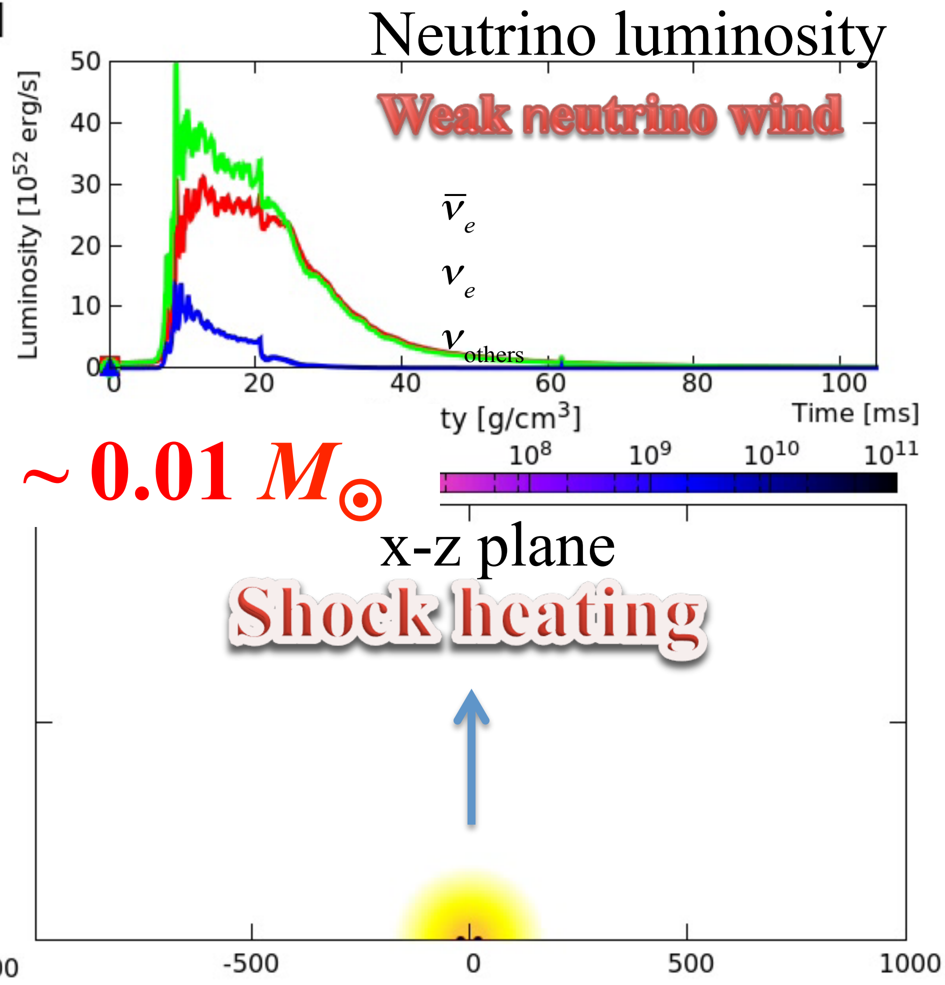
# NS-NS: Neutrino-radiation hydro simulation

**Soft EOS** (SFHo, ***R*~11.9 km**): 1.30-1.40 $M_{\odot}$

Rest-mass density




**Total mass ~ 0.01 $M_{\odot}$**

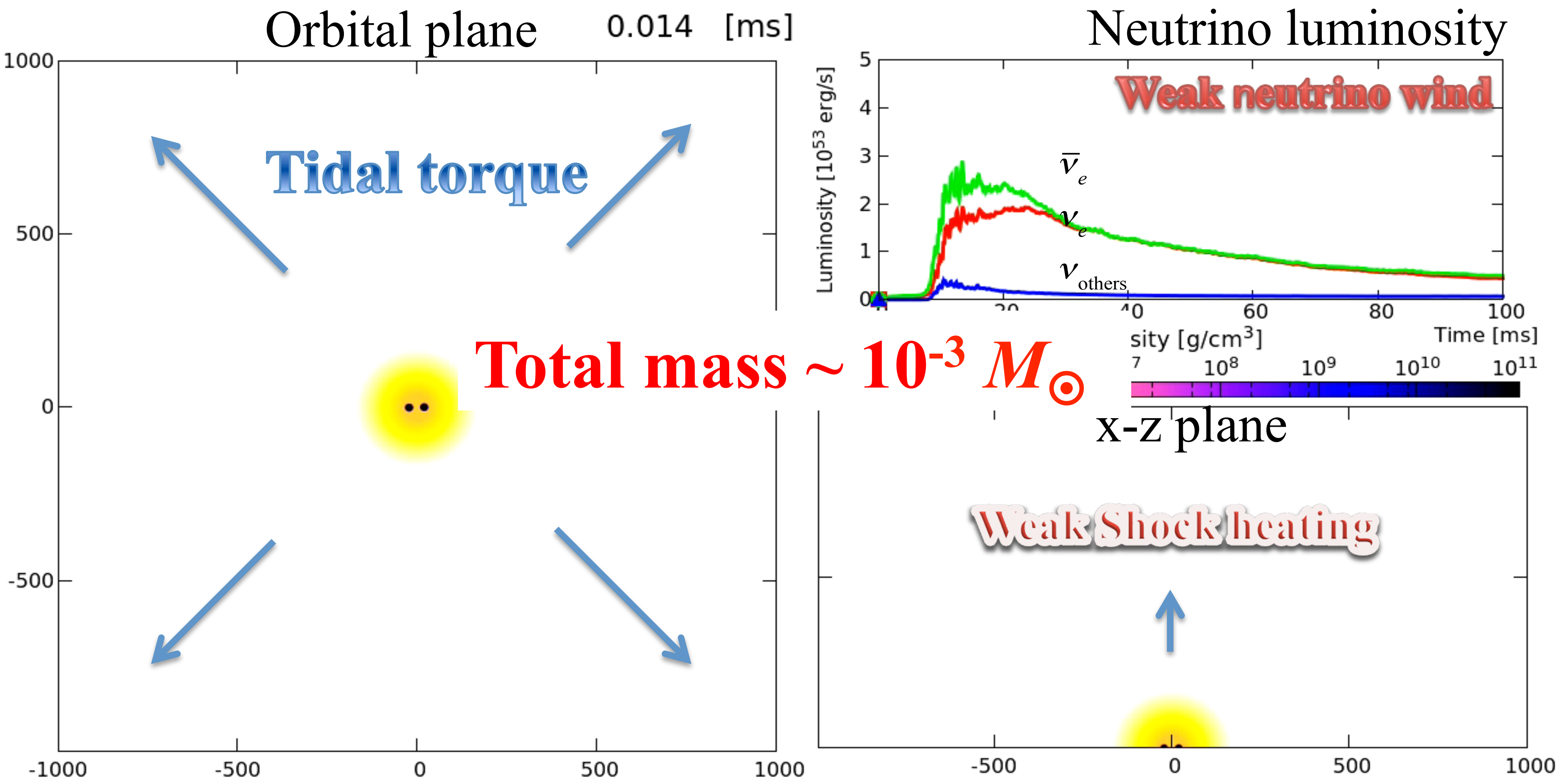



Sekiguchi et al. 2016

# NS-NS: Neutrino-radiation hydro simulation

**Stiff EOS** (DD2, ***R*~13.2 km**): 1.30-1.40 $M_\odot$

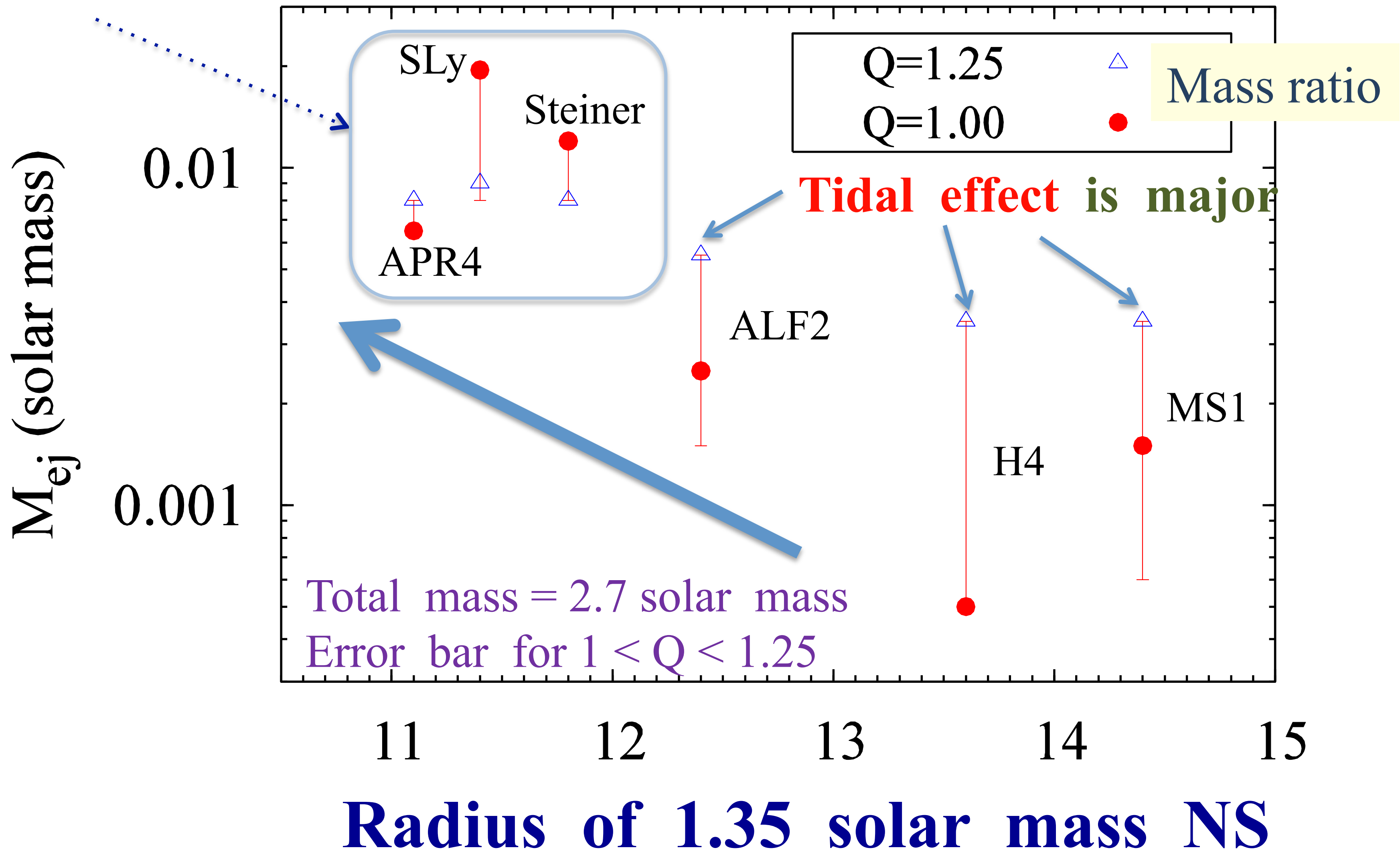
Rest-mass density




Sekiguchi et al. 2016

# Ejecta mass depends on EOS : NS-NS case

**Soft EOS → strong gravity → SHOCK → high-mass ejection**




Hotokezaka+ PRD '13 (See also Bauswein+ '13; Bernuzzi + '15)

# Summary for dynamical ejecta in NR

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

| | Nearly equal mass ($M_{tot} \sim 2.7\,M_\odot$) | Unequal mass: $m_1/m_2 < 0.9$ ($M_{tot} \sim 2.7\,M_\odot$) | Small total mass system ($< 2.6\,M_\odot$) |
|---|---|---|---|
| Soft EOS ($R$=11-12 km) | HMNS → BH<br>$M_{eje} \sim 10^{-2}\,M_\odot$ | HMNS → BH<br>$M_{eje} \sim 10^{-2}\,M_\odot$ | MNS (long lived)<br>$M_{eje} \sim 10^{-3}\,M_\odot$ |
| Stiff EOS ($R$=13-15km) | MNS (long lived)<br>$M_{eje} \sim 10^{-3}\,M_\odot$ | MNS (long lived)<br>$M_{eje} \sim 10^{-2.5}\,M_\odot$ | MNS (long lived)<br>$M_{eje} \sim 10^{-3}\,M_\odot$ |

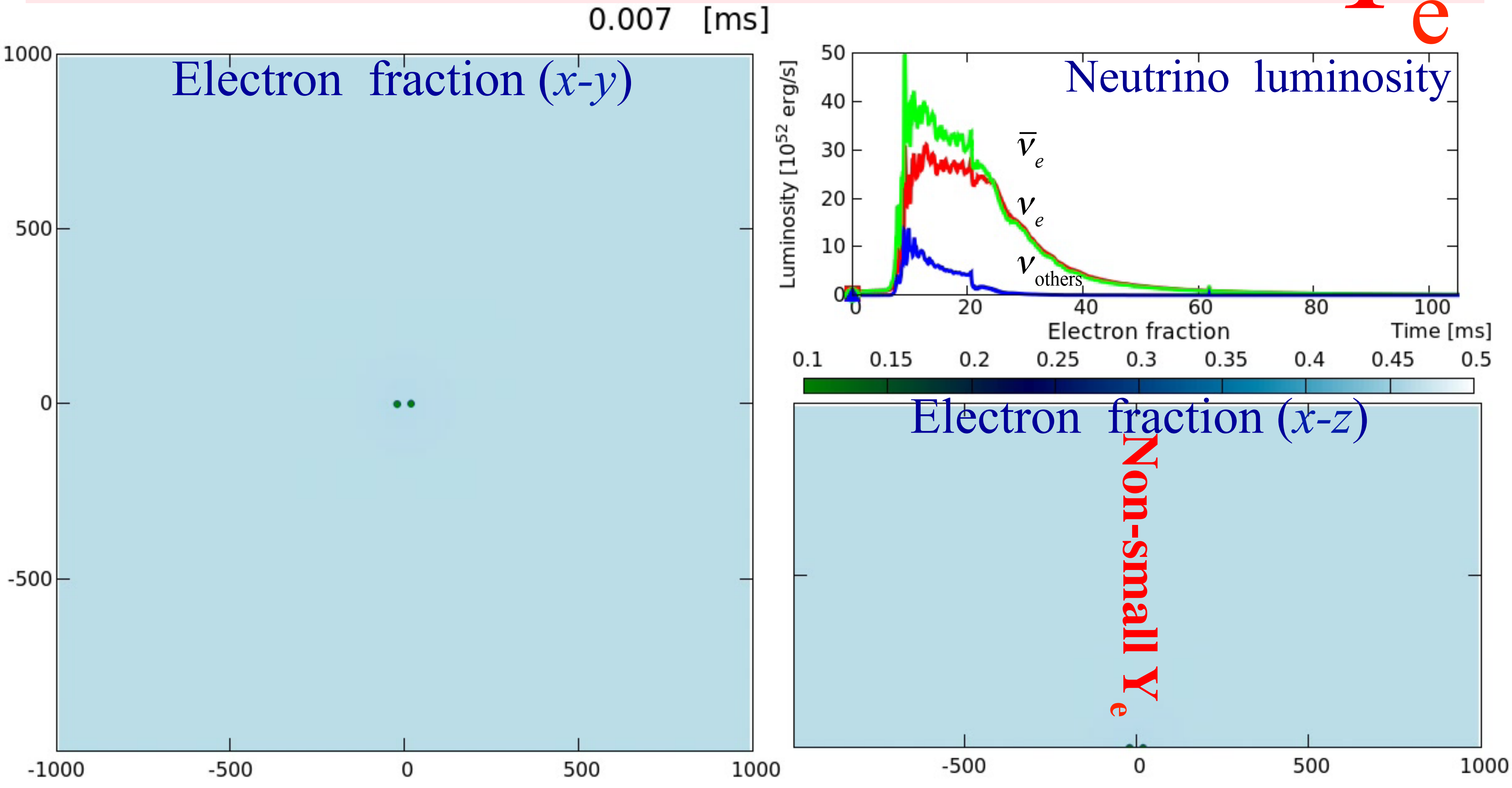
↑ Foucart et al '16
Shibata unpublished

- Typical velocity: 0.15—0.25 c irrespective of models

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

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

$Y_e$

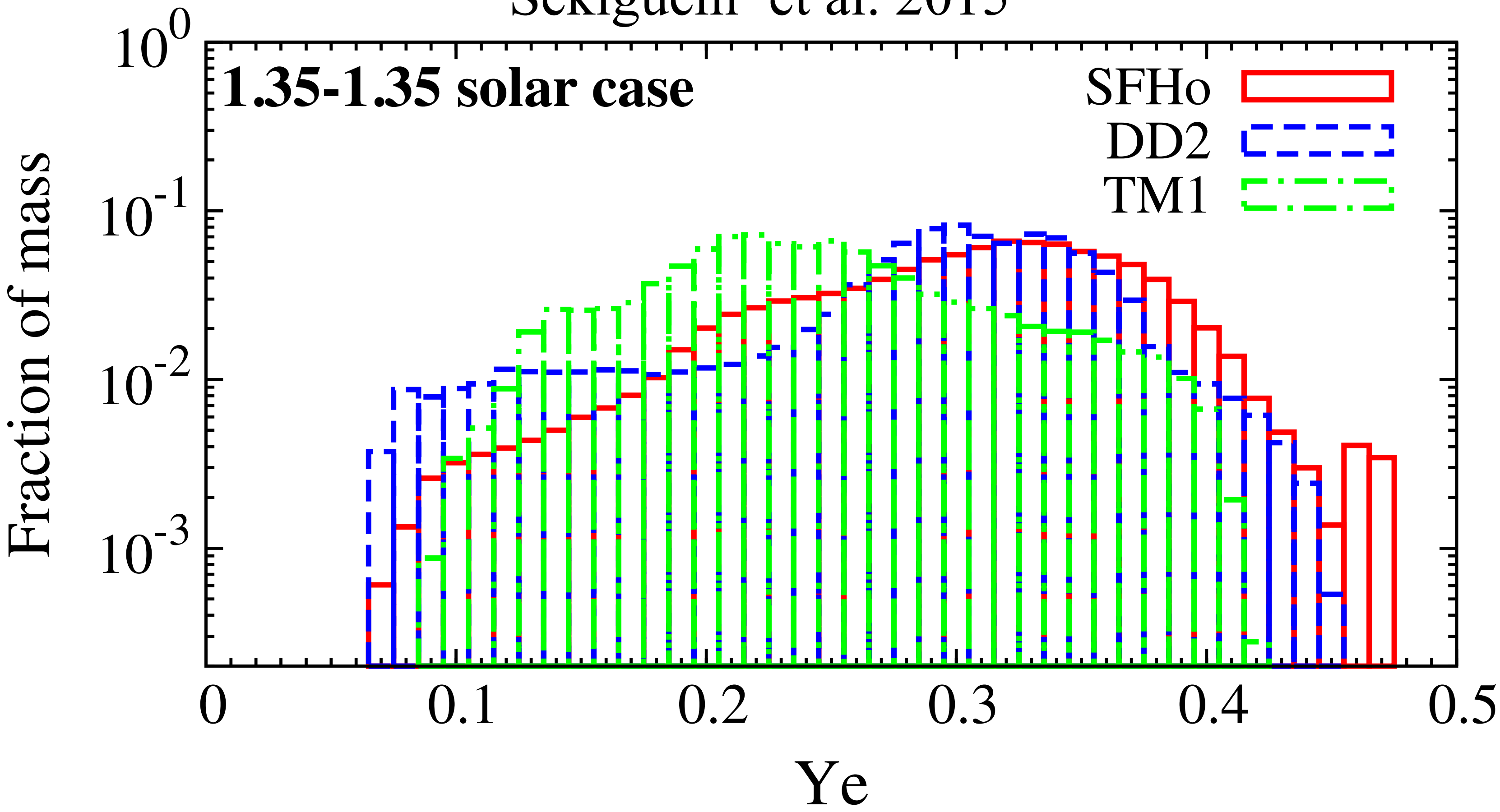



**Green = neutron rich**

Sekiguchi et al. (2016)

# Electron fraction profile: Broad

Sekiguchi et al. 2015

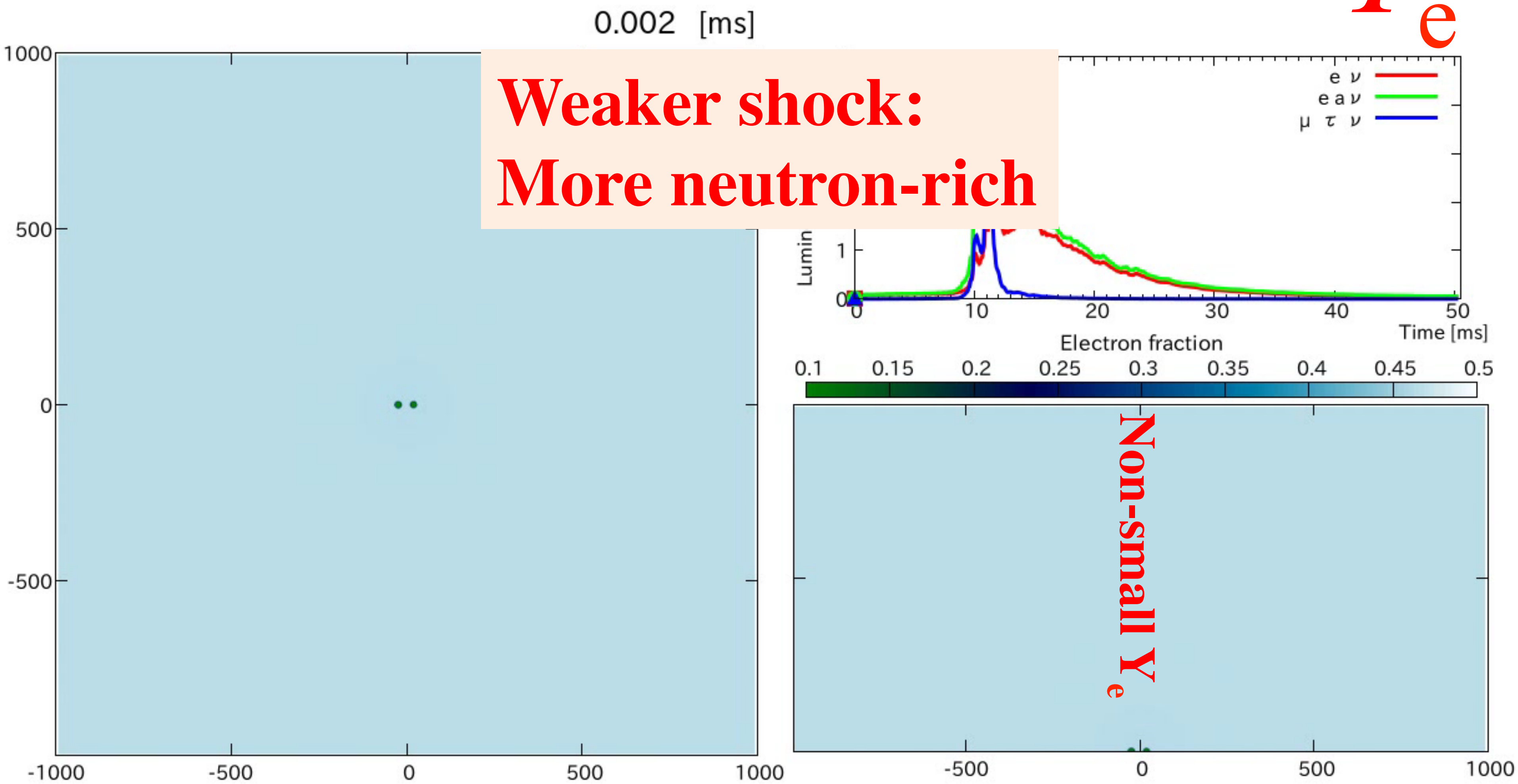



- **Broad distribution irrespective of EOS**
- Average depends on EOS but typically peak at 0.2—0.3
- Similar results by Radice+16, Lehner+15,16

# Neutrino-radiation hydrodynamics simulation

SFHo ($R$~11.9 km): **1.25-1.55 $M_\odot$**

$Y_e$



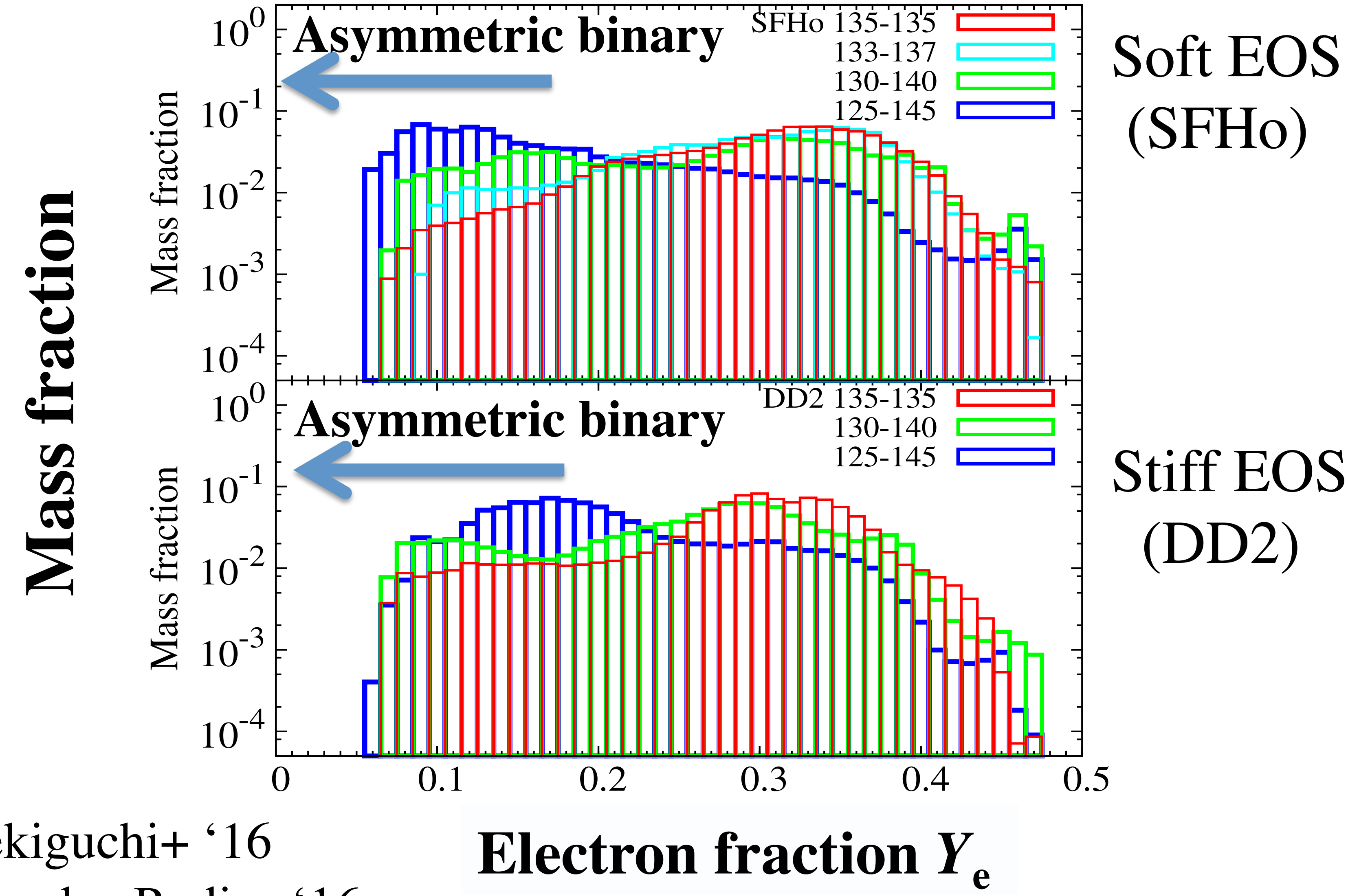

**Green = neutron rich**

Sekiguchi et al. (2017 hopefully)

# Electron fraction distribution:

**Broad irrespective of EOS and mass**

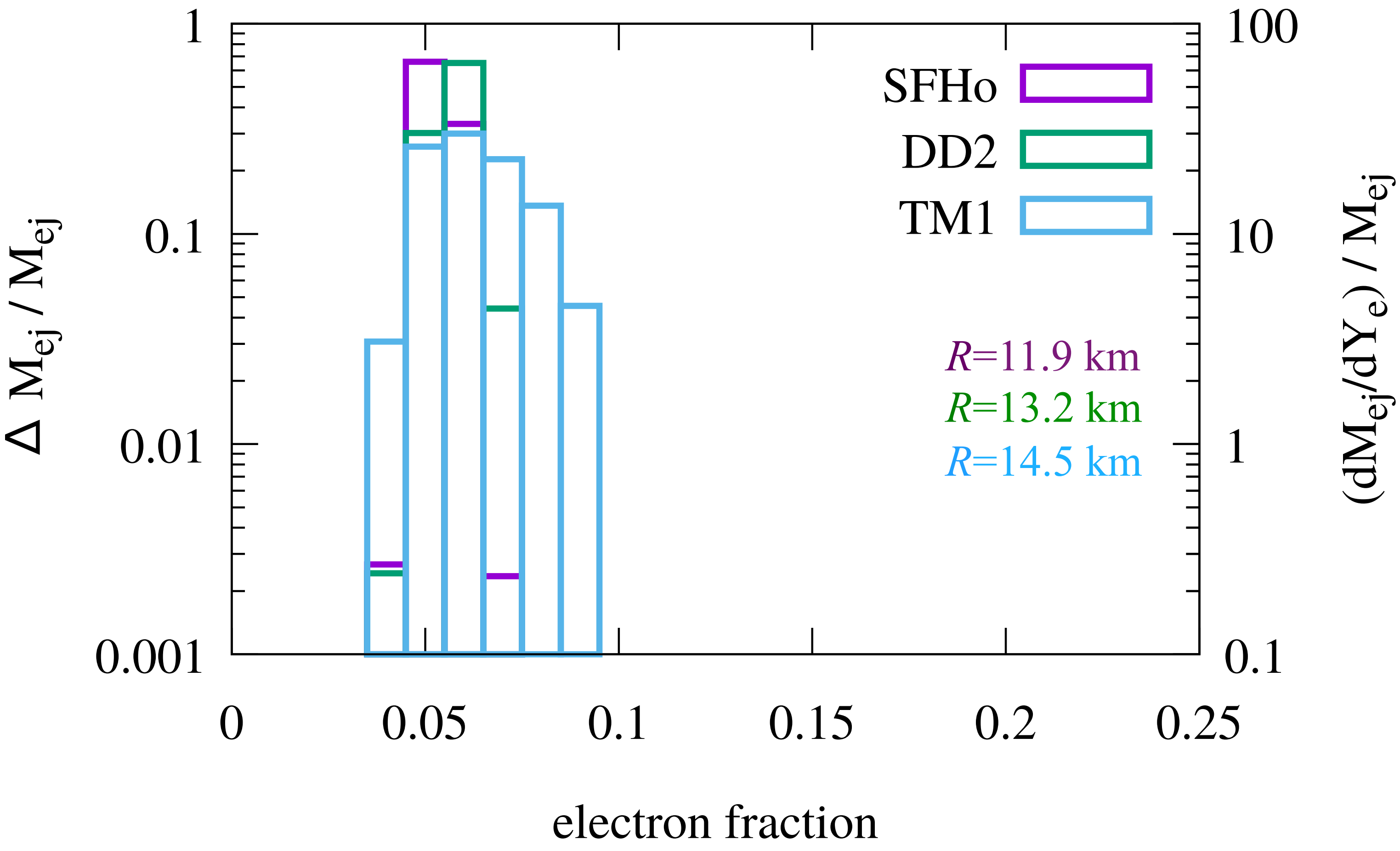
**→ Good for producing a variety of r-elements**




Sekiguchi+ '16

See also Radice '16

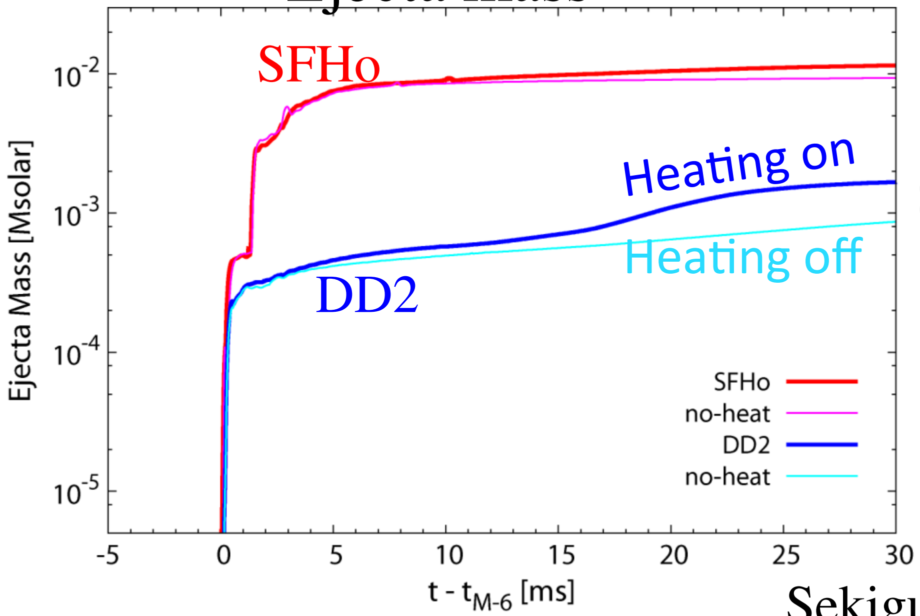
# Electron fraction of ejecta for BH-NS



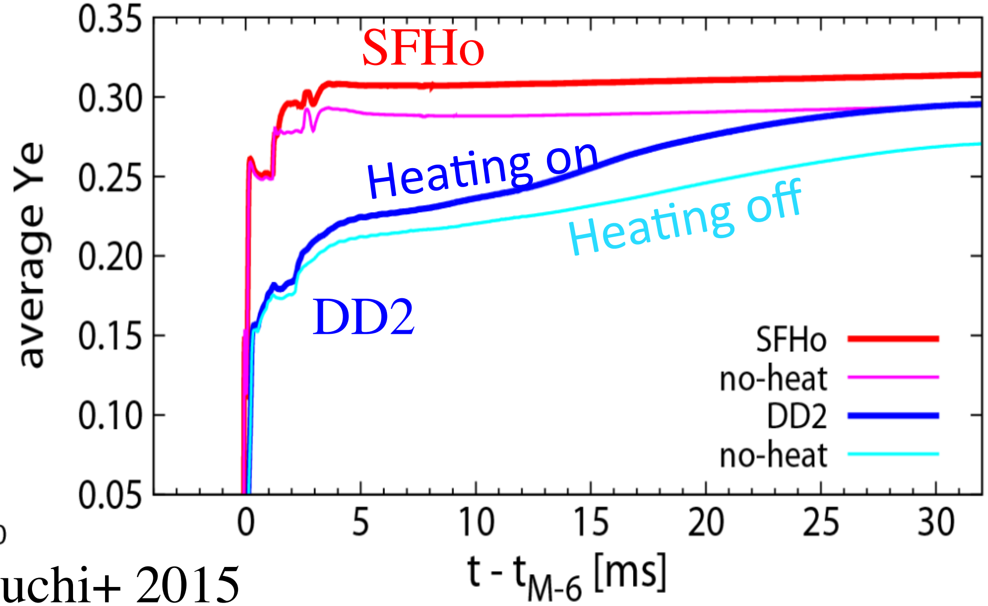

- **Quite low electron fraction irrespective of EOS**
  (Foucart et al., '13, 14, 15…, Kyutoku+ hopefully '17)
- Likely to primarily produce heavy r-elements

# Neutrino irradiation: subdominant effect

Ejecta mass




Electron fraction




Sekiguchi+ 2015

Neutrino irradiation from MNS increases

- **the ejecta mass by ~ 0.001 $M_\odot$**
- **Average value of $Y_e$ by ~ 0.03 or more (for longer term)**
- ✓ **Note that neutrino luminosity decreases in ~100 ms**

See also Perego et al. 2014; Goriely et al. 2015; Martin et al. 2015; Foucart et al. 2016 & talks by Foucart and Perego

# Dynamical ejecta properties in NR

◆**Mass**:

- **~0.001—0.02 $M_\odot$** depending on each mass & EOS:
  **Soft EOS & ~2.7 $M_\odot$ is favorable for large ejecta**
  (Hotoke+ 13, Sekiguchi+ 15,16, Radice+ 16, Lehner+ 15,16)

◆**Electron fraction**

- 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 $< 0.2$

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

# IV Early Viscous/MHD ejecta

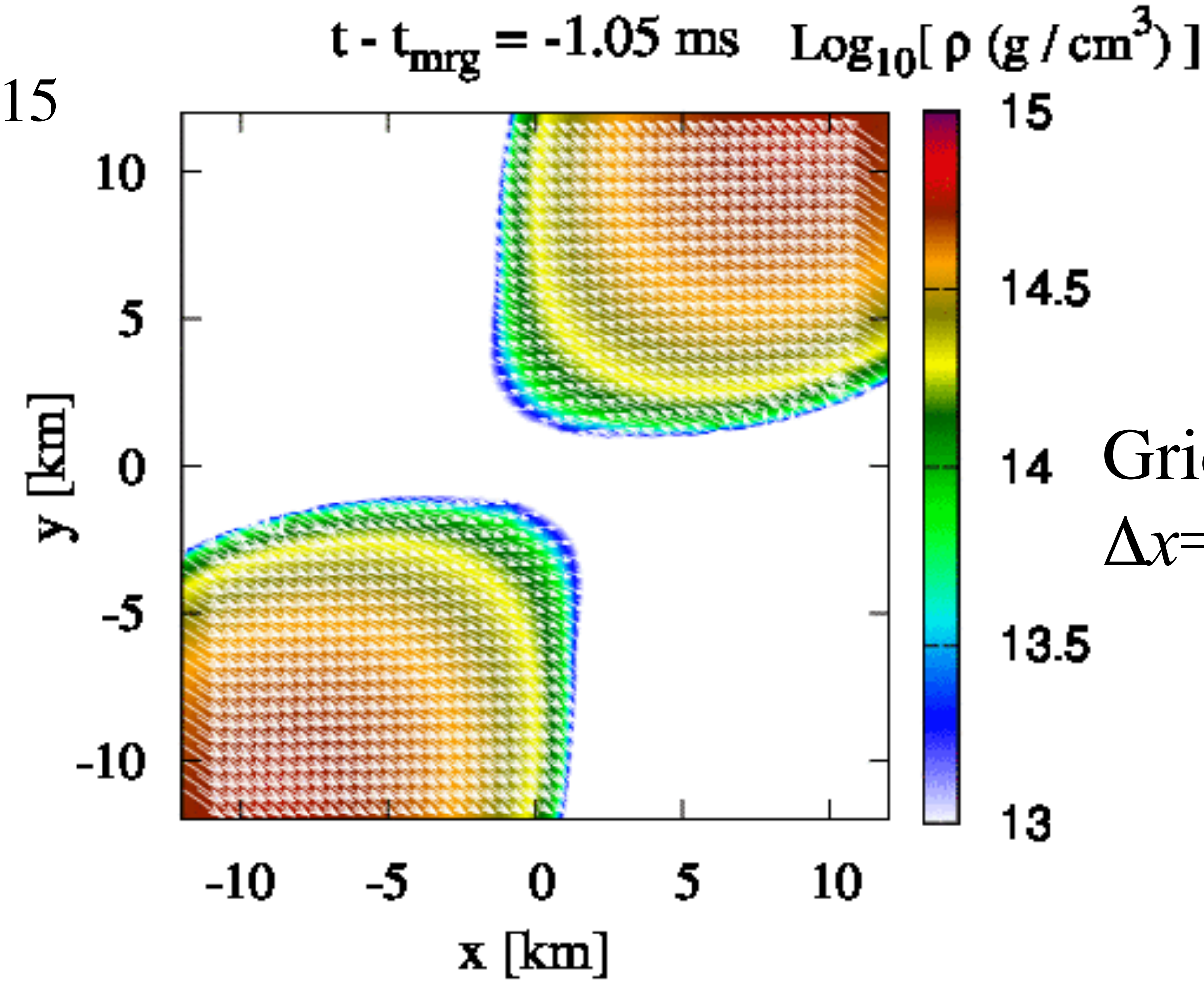
- MHD/viscous effects are likely to play a key role (Fernandez-Metzger+ ‘13—15, Just et al. ‘15 ….)
- However, previous simulations studied only for ***torus* surrounding BH** (or artificial NS)
- Realistic remnants = MNS + torus: for **MNS** no well-resolved MHD or viscous simulations were done

❖ MNS of ***differential rotation*** has potential for significant mass ejection induced by **MHD instability**

- MHD simulations (e.g., Price & Rosswog ‘07, Kiuchi+ ‘15) suggest that magnetic fields would be significantly amplified by Kelvin-Helmholtz instability
  → **turbulence may be induced**

# High-resolution GRMHD for NS-NS

Kiuchi et al. '15




Grid spacing
$\Delta x$=17.5m

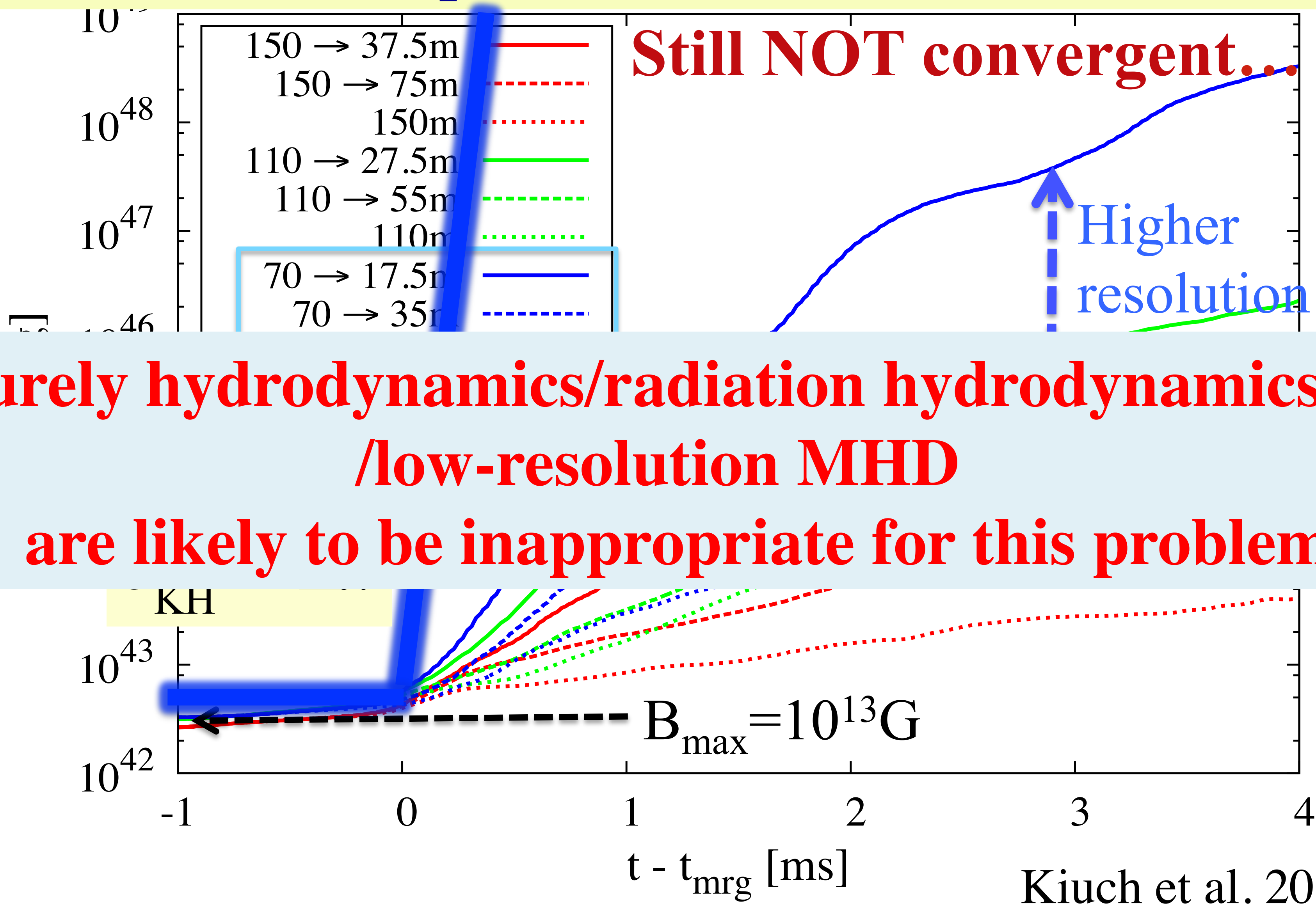
**Kelvin-Helmholtz instability in the shear layer**

**→ Vortexes → Magnetic fields are amplified by winding**

**→ Quick angular momentum transport ? (not yet seen)**

# Magnetic energy: Resolution dependence

**B field would be amplified in $\Delta t \ll 1$ ms → turbulence ?**




**Purely hydrodynamics/radiation hydrodynamics /low-resolution MHD are likely to be inappropriate for this problem**

Kiuch et al. 2015

Shear motion at the merger

→ **huge number of vortexes are formed** and **magnetic field is quickly amplified**

→ **Turbulence → Turbulent viscosity**

→ **Effectively viscous fluid (likely)**

# For post-merger dynamics,

- Obviously **more resolved MHD simulation** is needed
  → But it is not feasible due to the restriction of the computational resources (in future we have to do)
- **One alternative for exploring the possibilities is viscous hydrodynamics** (Radice '17, Shibata et al. '17)

✓ Note that we do not know whether our viscous hydrodynamics can precisely describe turbulence fluid

# Vis … s for

$$\tau_\nu \approx \frac{R^2}{\nu} = \frac{1}{\alpha_\nu \Omega_e} \frac{(R\Omega_e)^2}{c_s^2} \sim 10 \left( \frac{\alpha_\nu}{0.01} \right)^{-1} \text{ ms}$$

<u>Employ covariant & causal GR viscous hydrodynamics</u>

(Israel & Steward, '79, Shibata+ '17)

<u>Initial condition</u>: Merger remnant of 1.35-1.35$M_\odot$ NS-NS **at 50 ms** after the merger

<u>Alpha viscosity</u>: $\nu = \alpha_\nu c_s^2 \Omega^{-1}$ with $\alpha_\nu = 0.01$

<u>Equation of state</u>: DD2 ($R_{\rm NS}$ = 13.2 km, stiff)

→ Dynamical ejecta mass ~ 0.001 $M_\odot$

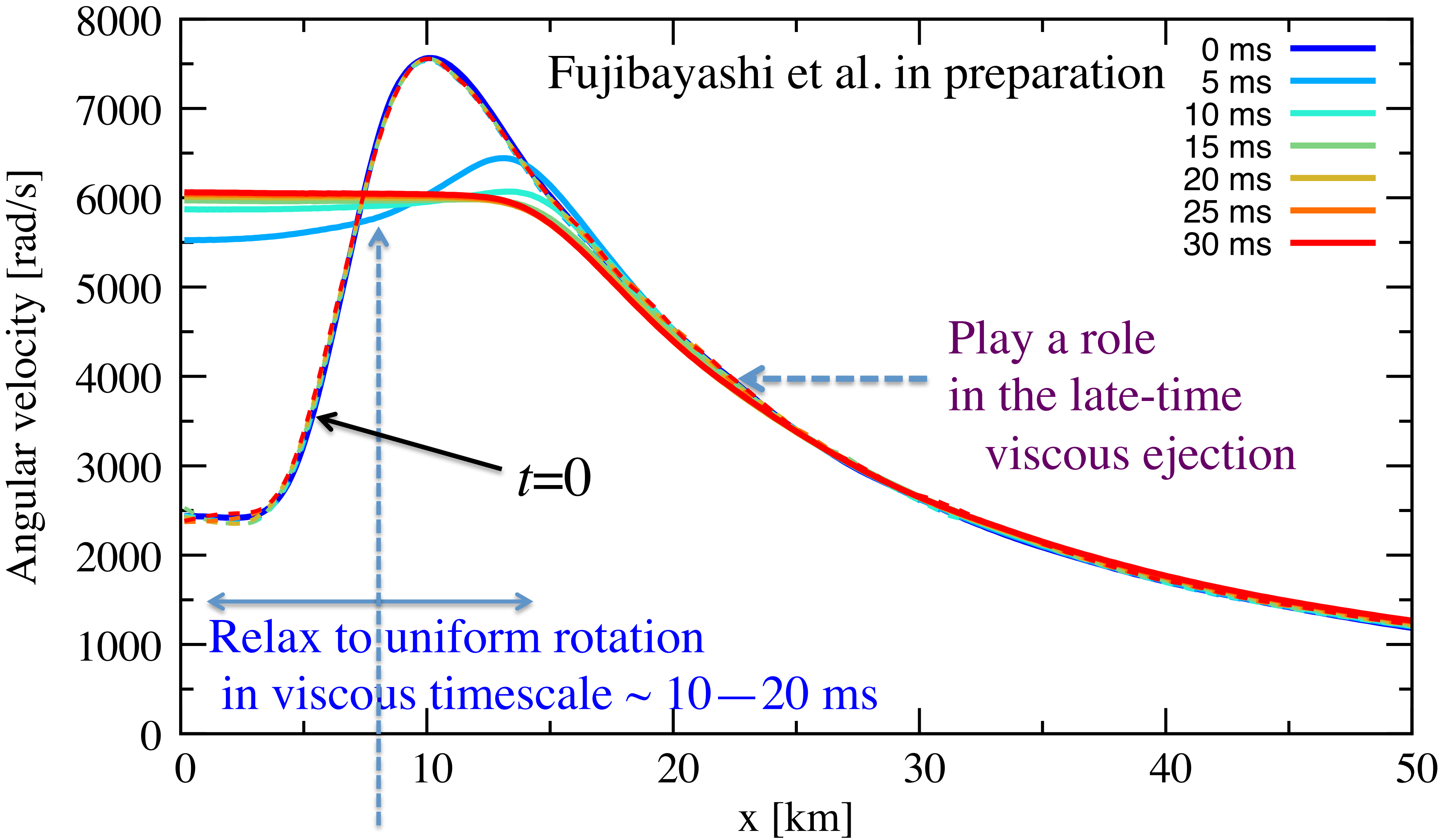
<u>Axis symmetric simulation</u>

Wide 1500×1500 km

300×300 km

Density in $x$-$z$ plane

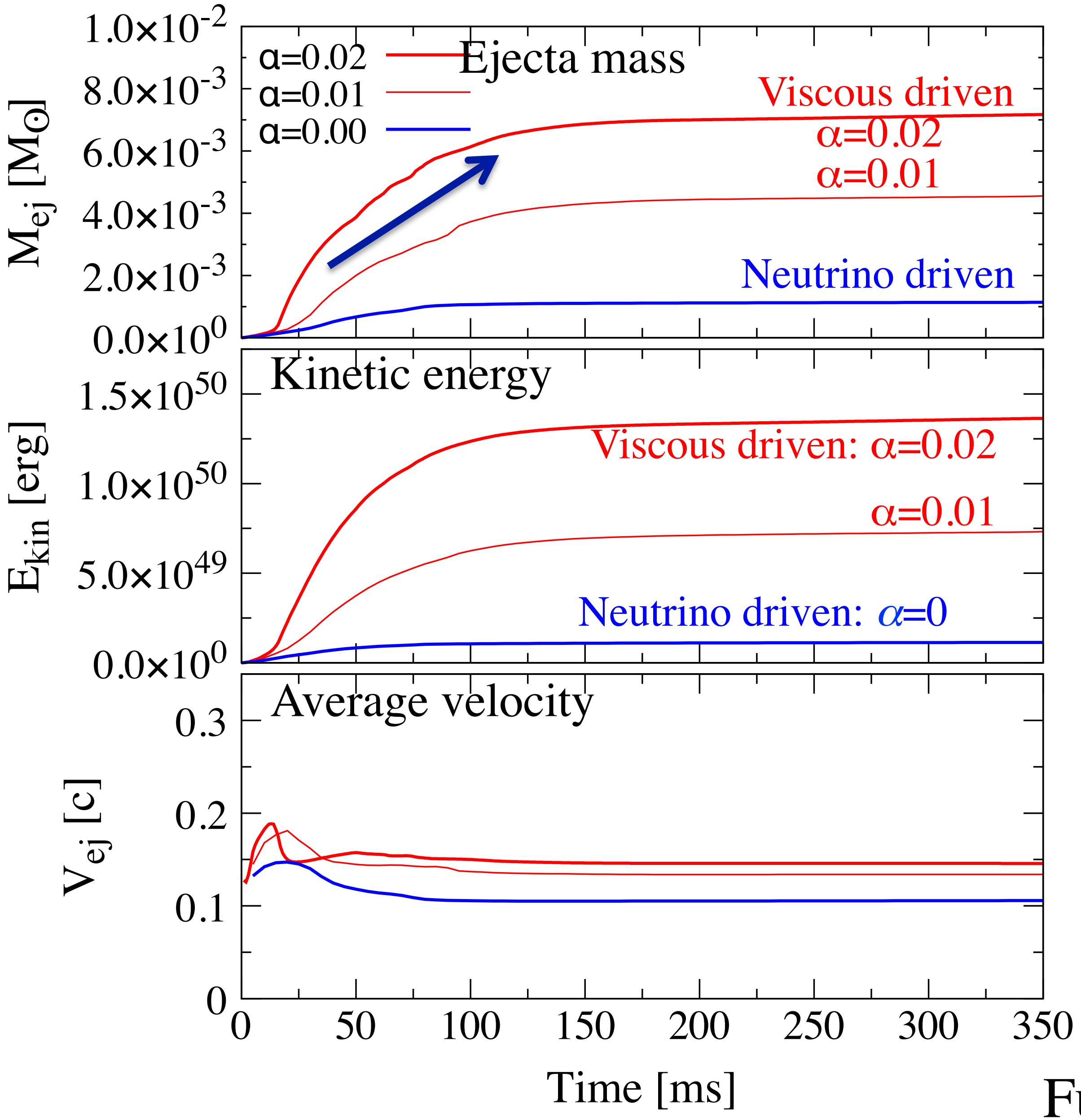
# Evolution of angular velocity




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

**→ early viscous ejection**

# Early viscous ejecta




For $t$ < 10—20 ms:

Differential rotation of remnant NS

→ Rigid rotation

→ Viscous heating

→ Outward motion

→ Ejecta from disk of mass ~ $10^{-2.5}\,M_\odot$

Fujibayashi et al. in prep.

# Only dynamical ejecta

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

| | **Nearly equal mass ($M_{tot} \sim 2.7\, M_\odot$)** | **Unequal mass: $m_1/m_2 < 0.9$ ($M_{tot} \sim 2.7\, M_\odot$)** | **Small total mass system ($< 2.6\, M_\odot$)** |
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Foucart et al ’16
Shibata unpublished

- Typical velocity: 0.15—0.25 c irrespective of models

# Dynamical + MHD/viscous ejecta in NR

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**To be studied**

**Total ejecta mass could be ~0.01 $M_\odot$ or more**

# Viscous hydrodynamics for post-merger MNS

(S. Fujibayashi et al. in preparation)

Electron fraction

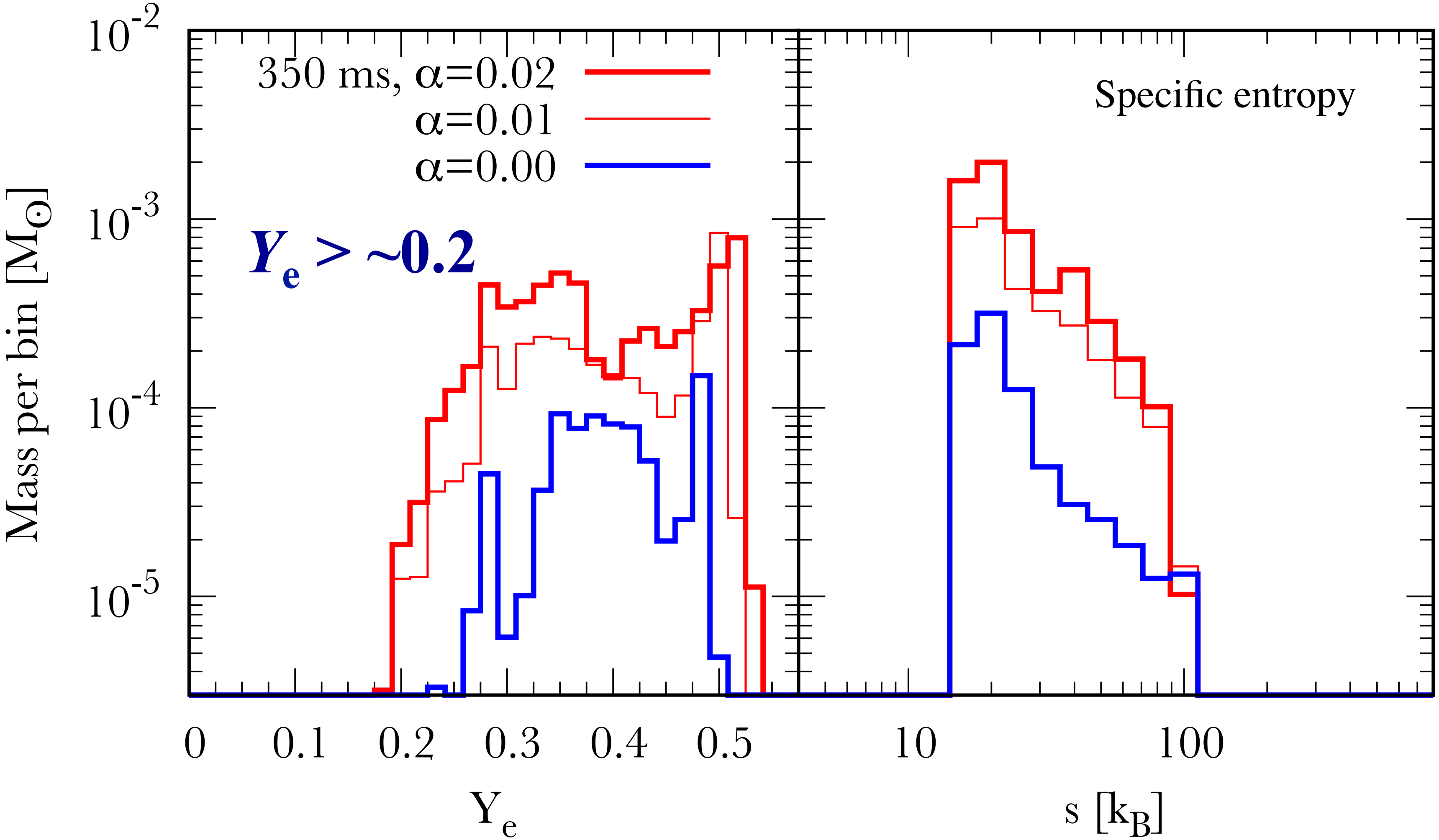
$Y_e$

Wide 1500×1500 km

300×300 km

# $Y_e$ distribution & entropy

- Outer layer of torus/disk is ejected with $Y_e$ preserved
  → $Y_e$ distribution depends on initial condition




Fujibayashi et al. in prep.

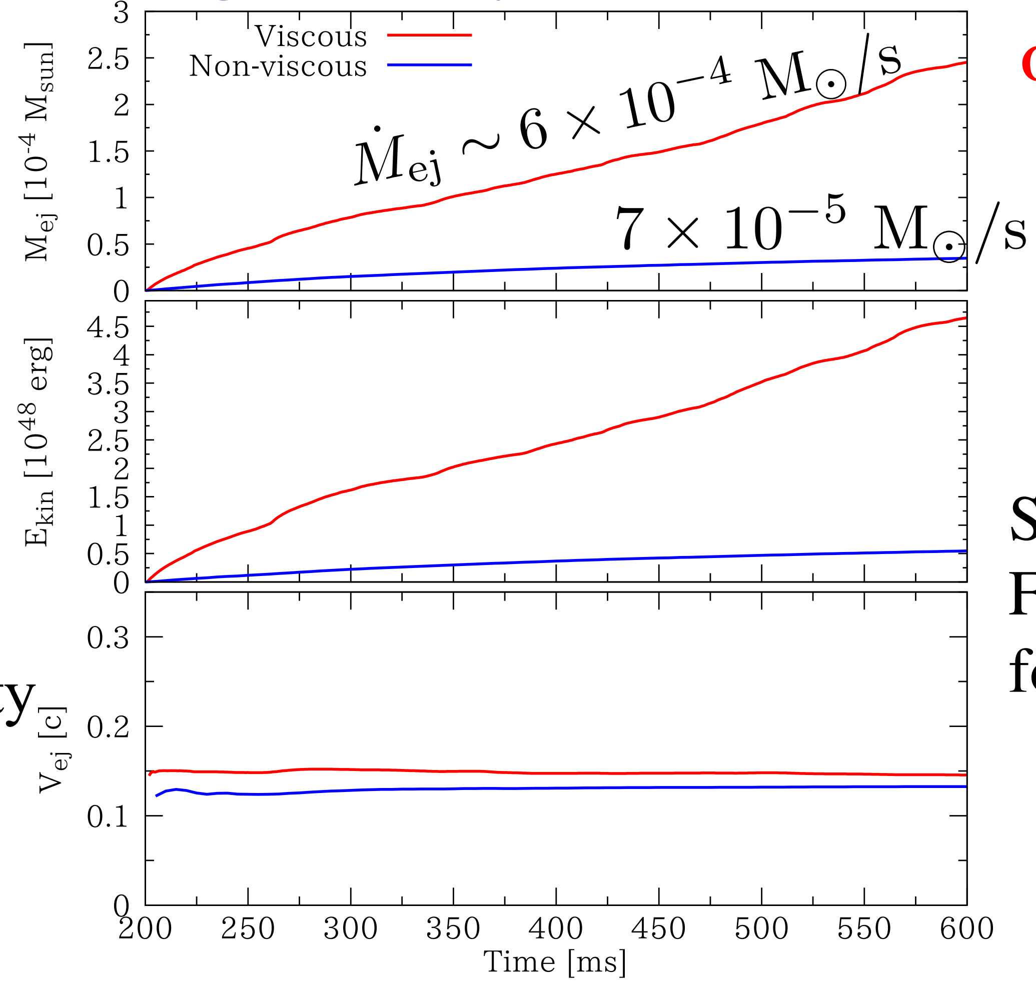
# Long-term mass ejection from merger remnant

## Integrate only for t > 200ms

Ejecta Mass

Kinetic Energy

Average Velocity




α=0.01

α=0

See also talks by Foucart & Perego for neutrinos

Viscosity-driven ejecta could be $M_{ej}$ >~ $10^{-3}$ $M_\odot$ if the ejection is sustained for ~ a few seconds.

# V Summary

## Mass ejection history for MNS formation

Time after merger

0 | 10 | 100 | 1000 ms

**Dynamical ejection**

$M_{ej} \sim 10^{-3}$—$10^{-2}$ $M_{\odot}$, $Y_e$=Broad distr. with $\langle Y_e \rangle \sim 0.2$—$0.3$

**MHD/viscous ejection from remnant NS**

$M_{ej} \sim 10^{-2.5}$ $M_{\odot}$ , $Y_e \sim 0.2$—$0.5$

**MHD/Viscous ejection from disk**

$M_{ej} >\sim 10^{-3}$ $M_{\odot}$ , $Y_e \sim 0.3$—$0.5$