Mass ejection from neutron–star mergers in numerical relativity

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Outline

I. Brief introduction

II. Typical scenarios for NS mergers
(both for NS-NS and BH-NS)

III. Dynamical mass ejection

IV. Early MHD/viscous ejection from NS-NS

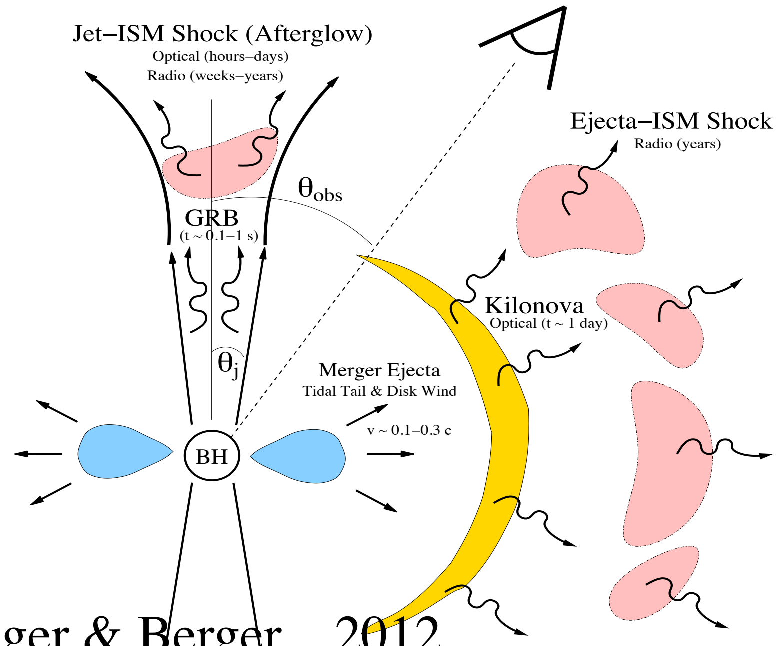
V. Viscous (+neutrino-assisted) disk wind

VI. Summary

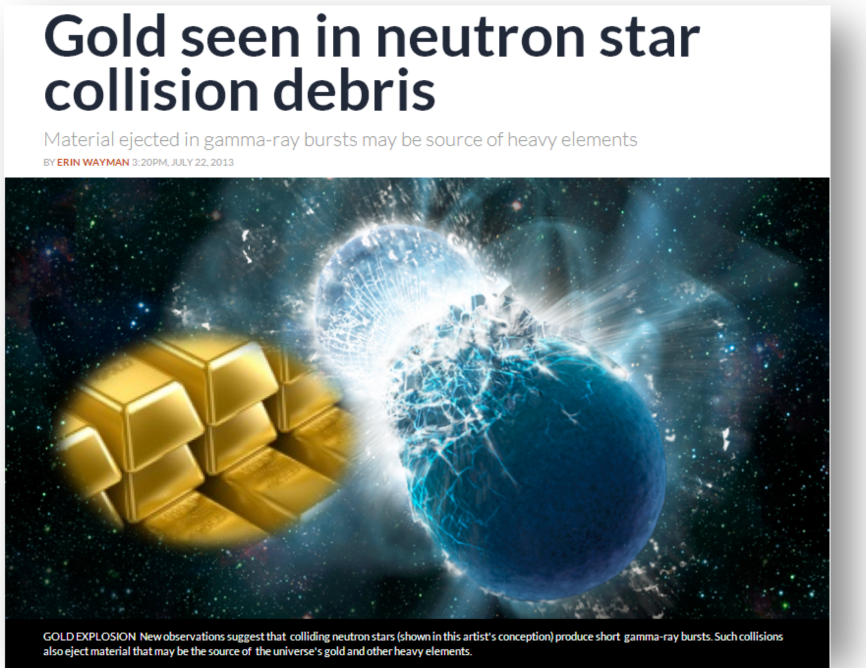
I Introduction (not necessary ?)

Why mass ejection from NS binaries is important ?

1. Electromagnetic counterparts of NS merger:
   Key for confirming gravitational-wave detection
   (talks by Tanaka & Cowperthwaite)
2. Possible site of **r-process nucleosynthesis**
   (talks by Foucart & Hotoke)



Metzger & Berger 2012



Gold seen in neutron star collision debris

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

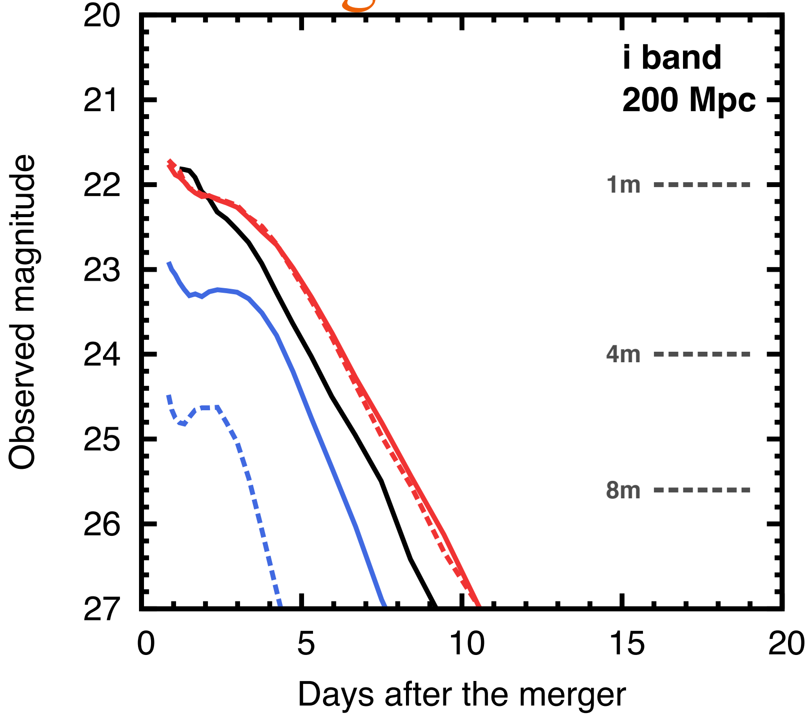
BY ERIN WAYMAN 3:20PM, JULY 22, 2013

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 on

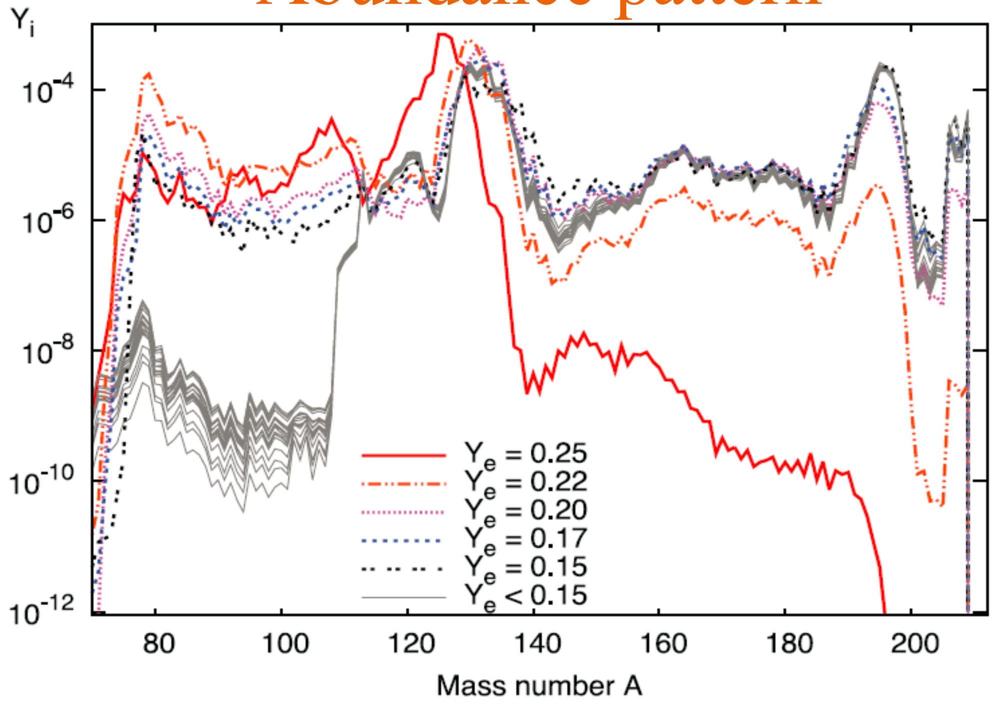
- **Ejecta mass M_{eject}**
- **Electron fraction Y_e**

Light curve



Tanaka & Hotoke 2013

Abundance pattern



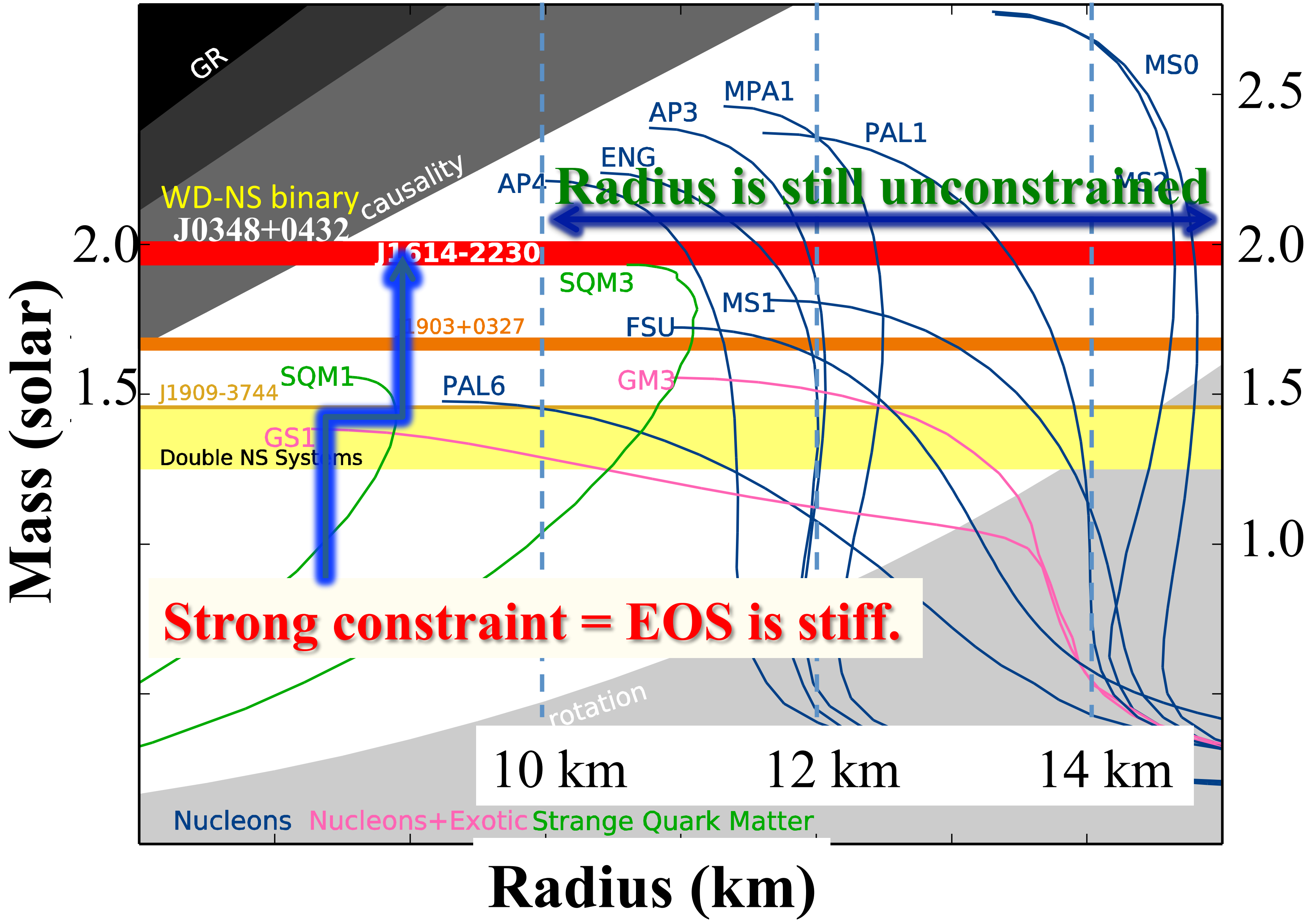
Korobkin et al. 2012

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)
   → 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.)

Mass-radius relation for various EOS



Radius is still unconstrained

Strong constraint = EOS is stiff.

Compact NS-NS system in our galaxy

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

		Orbital period	Eccentricity		Each mass		lifetime
	PSR	P(day)	e	$M(M_{sun})$	M_1	M_2	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.	A24	0.184	0.606	2.74	1.35	1.39	~0.75

$\times 10^8$ yrs

II A Typical scenarios for NS-NS merger

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

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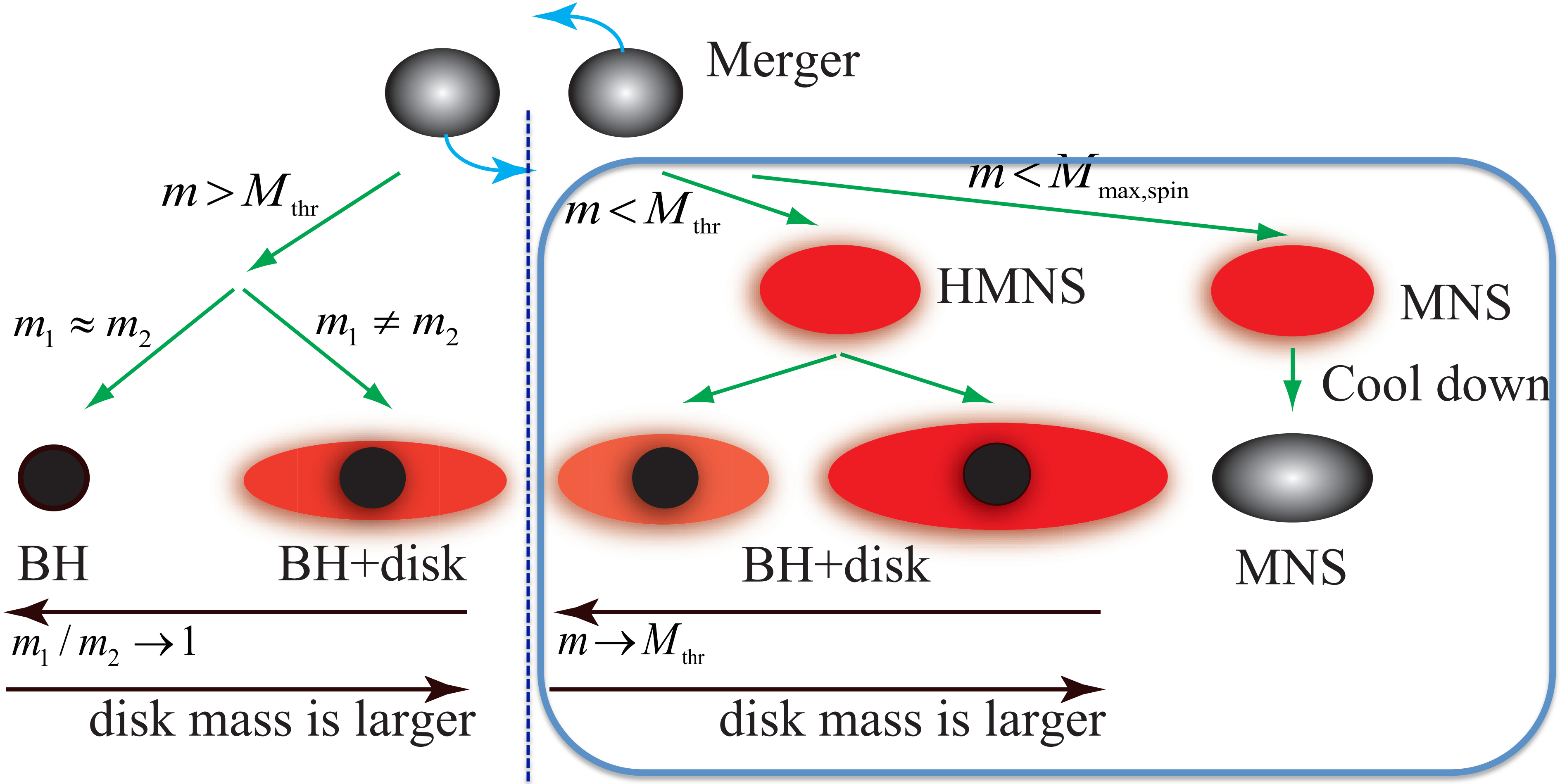
⇩

- **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



Merger

$m > M_{\rm thr}$

$m_1 \approx m_2$

$m_1 \neq m_2$

BH

BH+disk

$m_1 / m_2 \to 1$

disk mass is larger

$m < M_{\rm thr}$

$m < M_{\rm max,spin}$

HMNS

MNS

Cool down

BH+disk

MNS

$m \to M_{\rm thr}$

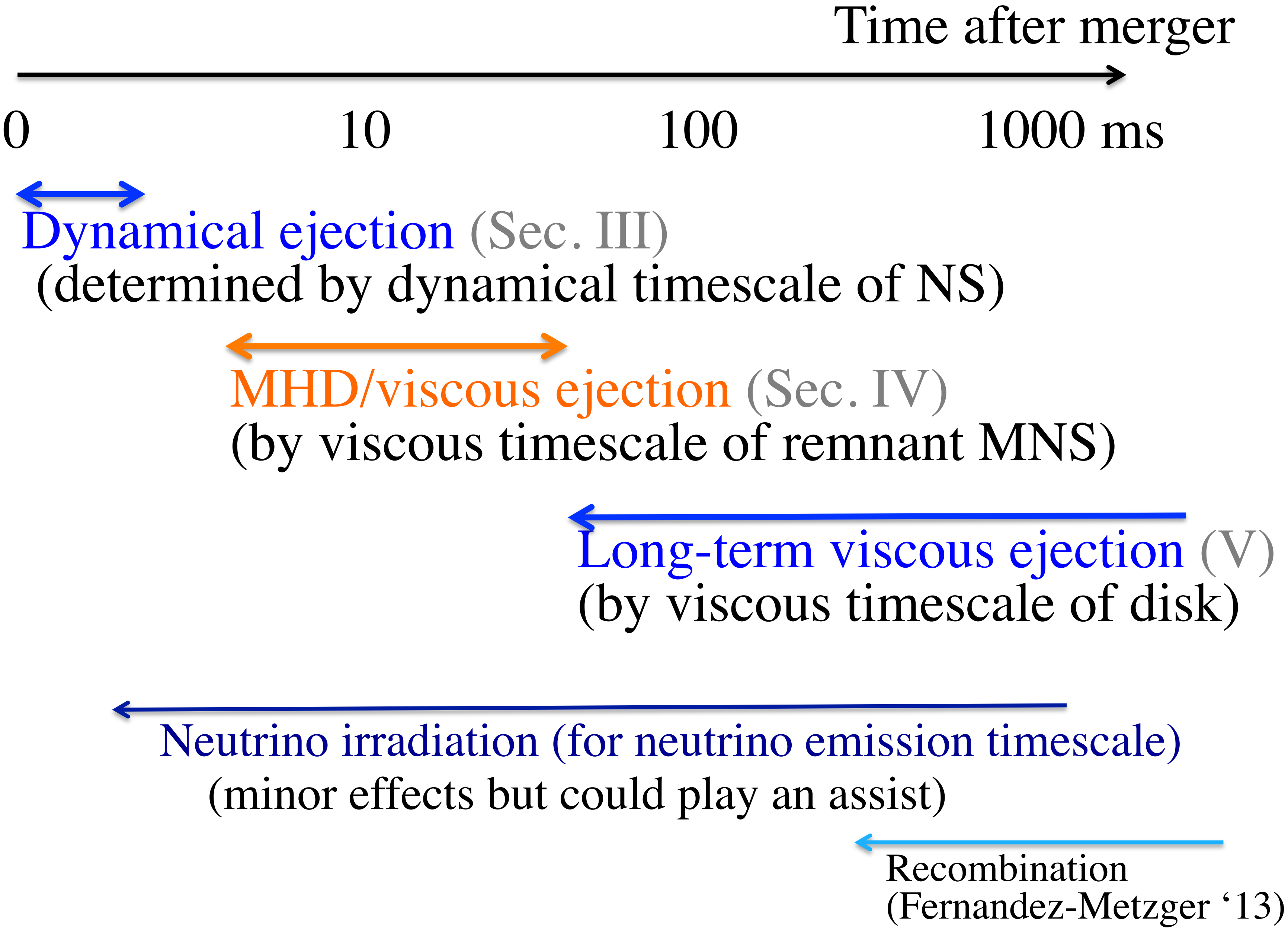
disk mass is larger

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

Depends strongly on EOS

Likely typical cases for $M = 2.6$—$2.8 M_{\rm sun}$

Mass ejection history for MNS formation



Time after merger

0 10 100 1000 ms

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

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

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

Neutrino irradiation (for neutrino emission timescale)
(minor effects but could play an assist)

Recombination
(Fernandez-Metzger ‘13)

II B Scenarios for BH-NS merger

- **Almost no observational constraints but for black hole mass likely >~5M_{sun}**
  → Wide parameter space has to be explored
- **Fate = two possibilities:**

1. **Tidal disruption of NS**
2. **Simple plunge of NS into BH**

Condition for tidal disruption

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

$$\Downarrow$$

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

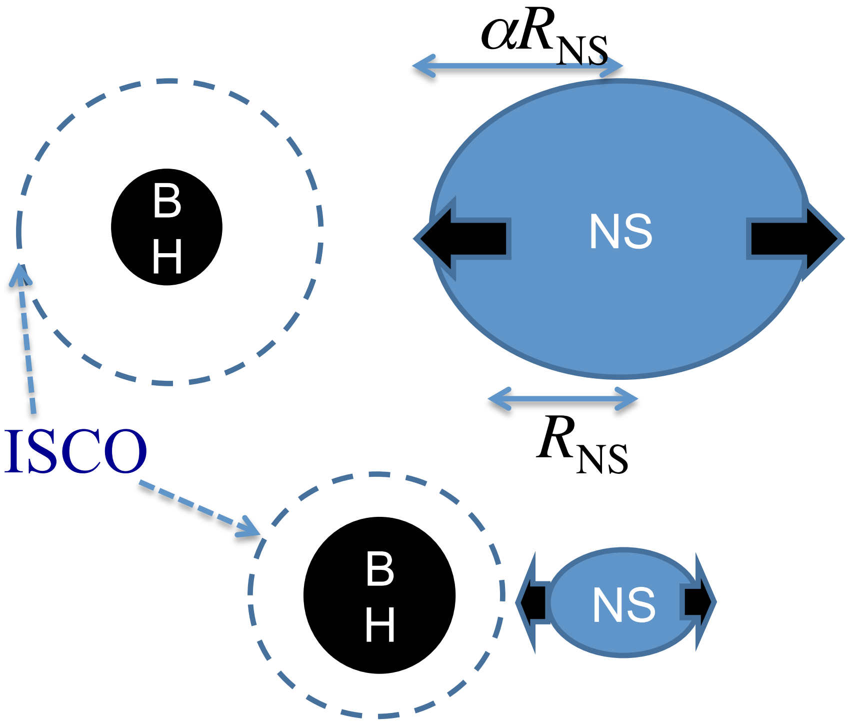
- For tidal disruption

❖ **Large NS Radius** or

❖ **Small BH mass** or

❖ **High corotation spin**

is necessary



For tidal disruption of plausible BH-NS with $M_{\rm NS}=1.35M_{\rm sun}$, $R_{\rm NS}\sim 12$ km, & $M_{\rm BH}>6\,M_{\rm sun}$

High BH spin is necessary $>\sim 0.5$

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

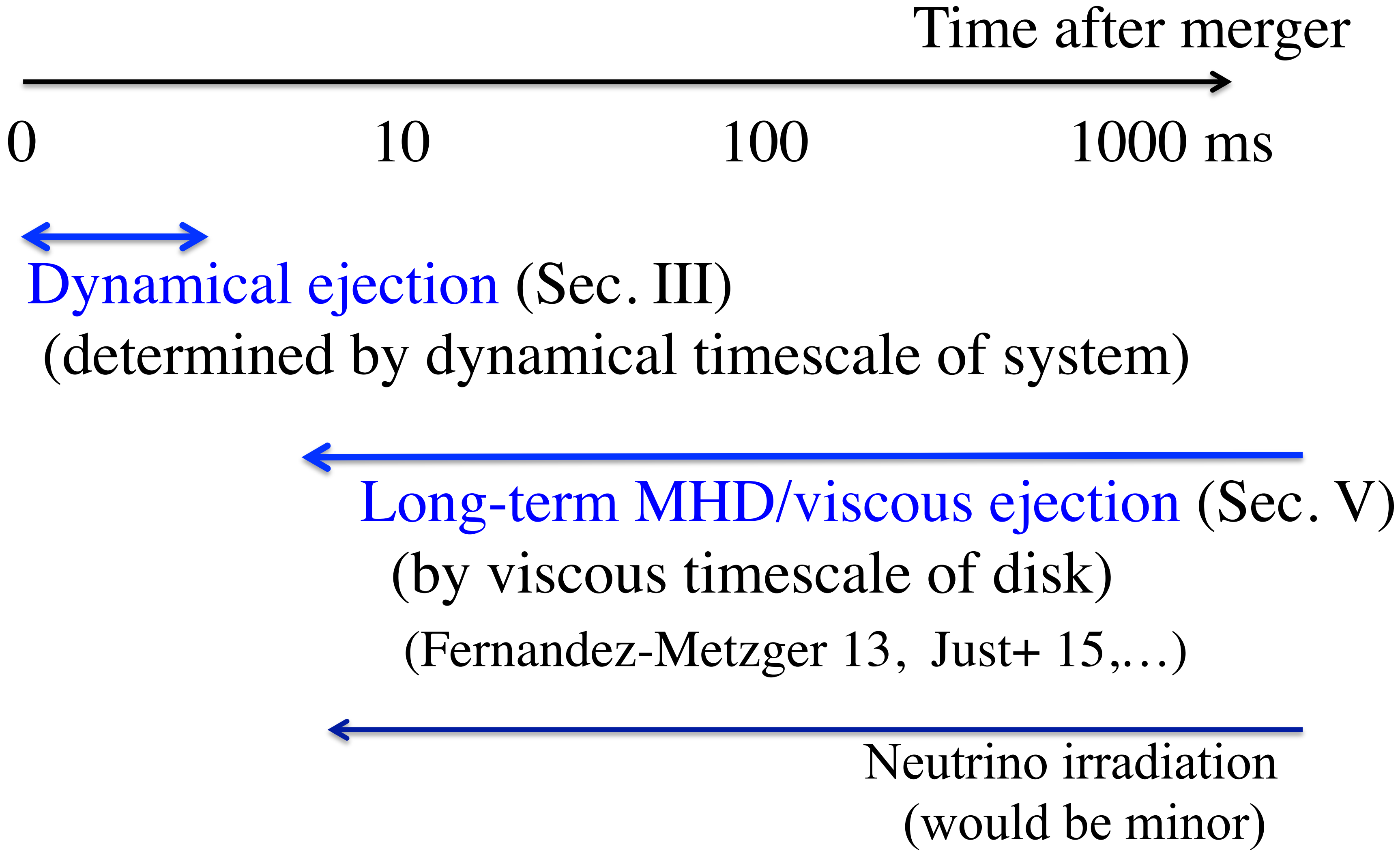
$$1 \le 0.1\left(\frac{6M_{\rm BH}}{r_{\rm ISCO}}\right)^3\left(\frac{7M_{\rm NS}}{M_{\rm BH}}\right)^2\left(\frac{R_{\rm NS}}{6M_{\rm NS}}\right)^3\left(\frac{\alpha}{1.7}\right)^3$$

$$(M_{\rm BH}\le r_{\rm ISCO}\le 9M_{\rm BH})$$

- Natural conclusion: BH-disk systems formed as a remnant should have a high BH spin

Mass ejection history for BH-NS

(in the presence of tidal disruption of NS)



Time after merger

0 10 100 1000 ms

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

Long-term MHD/viscous ejection (Sec. V)
(by viscous timescale of disk)
(Fernandez-Metzger 13, Just+ 15,…)

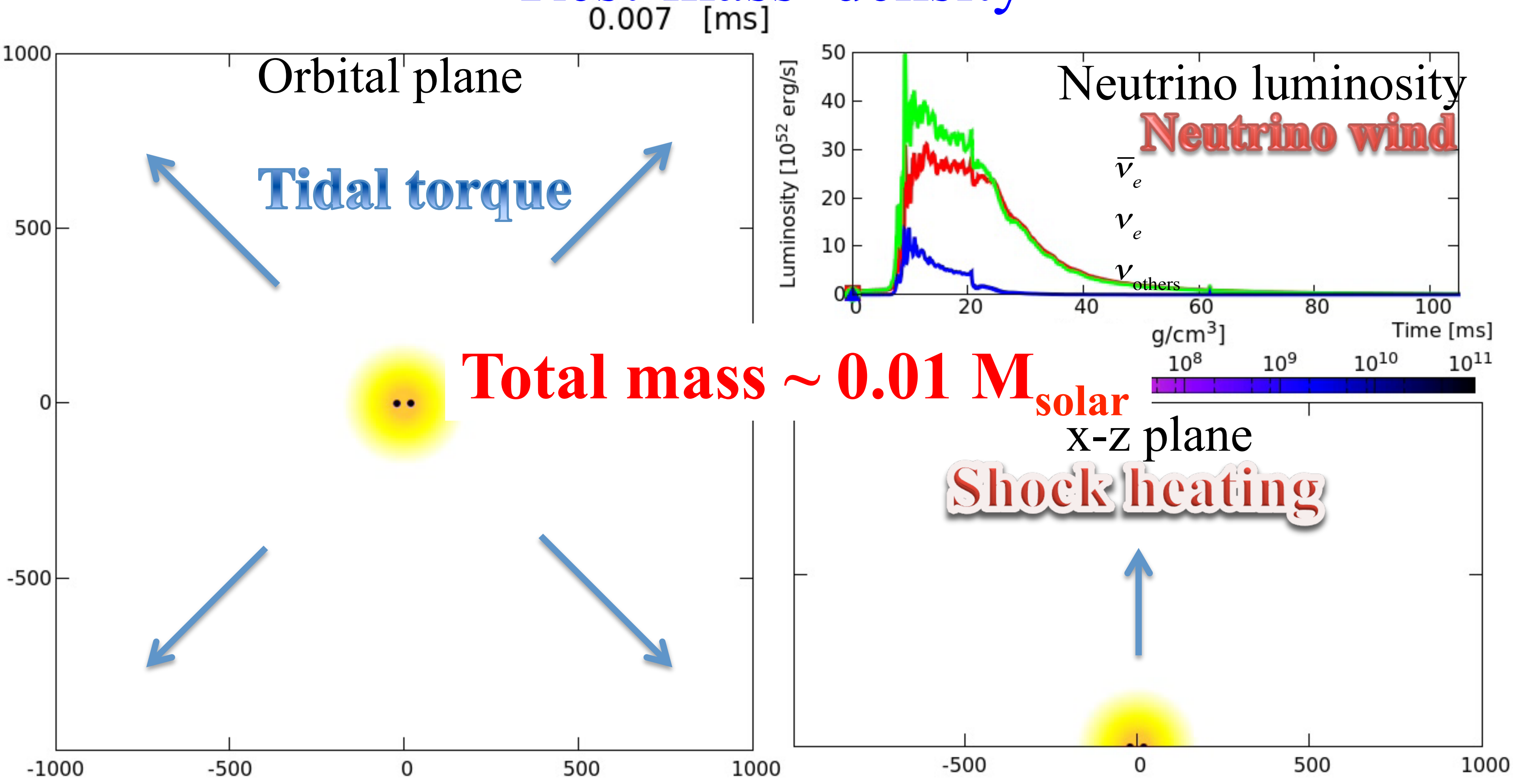
Neutrino irradiation
(would be minor)

III Dynamical mass ejection

NS-NS: Neutrino-radiation hydro simulation

Soft EOS (SFHo, R~11.9 km): 1.30-1.40 M_{sun}

Rest-mass density



Tidal torque

Neutrino wind

Total mass ~ 0.01 M_{solar}

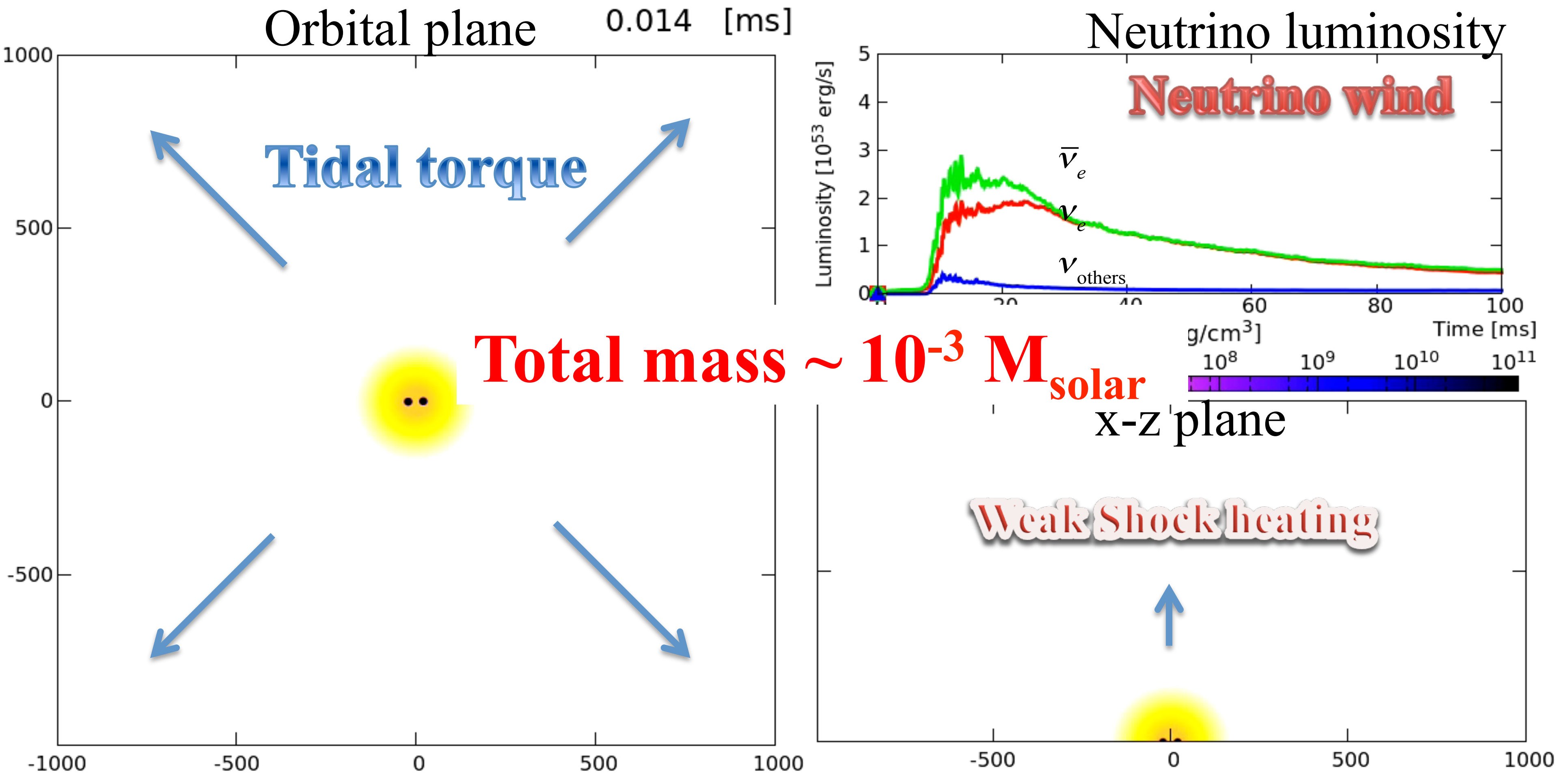
Shock heating

Sekiguchi et al. 2016

NS-NS: Neutrino-radiation hydro simulation

Stiff EOS (DD2, *R*~13.2 km): 1.30-1.40 M_{sun}

Rest-mass density



Tidal torque

Neutrino wind

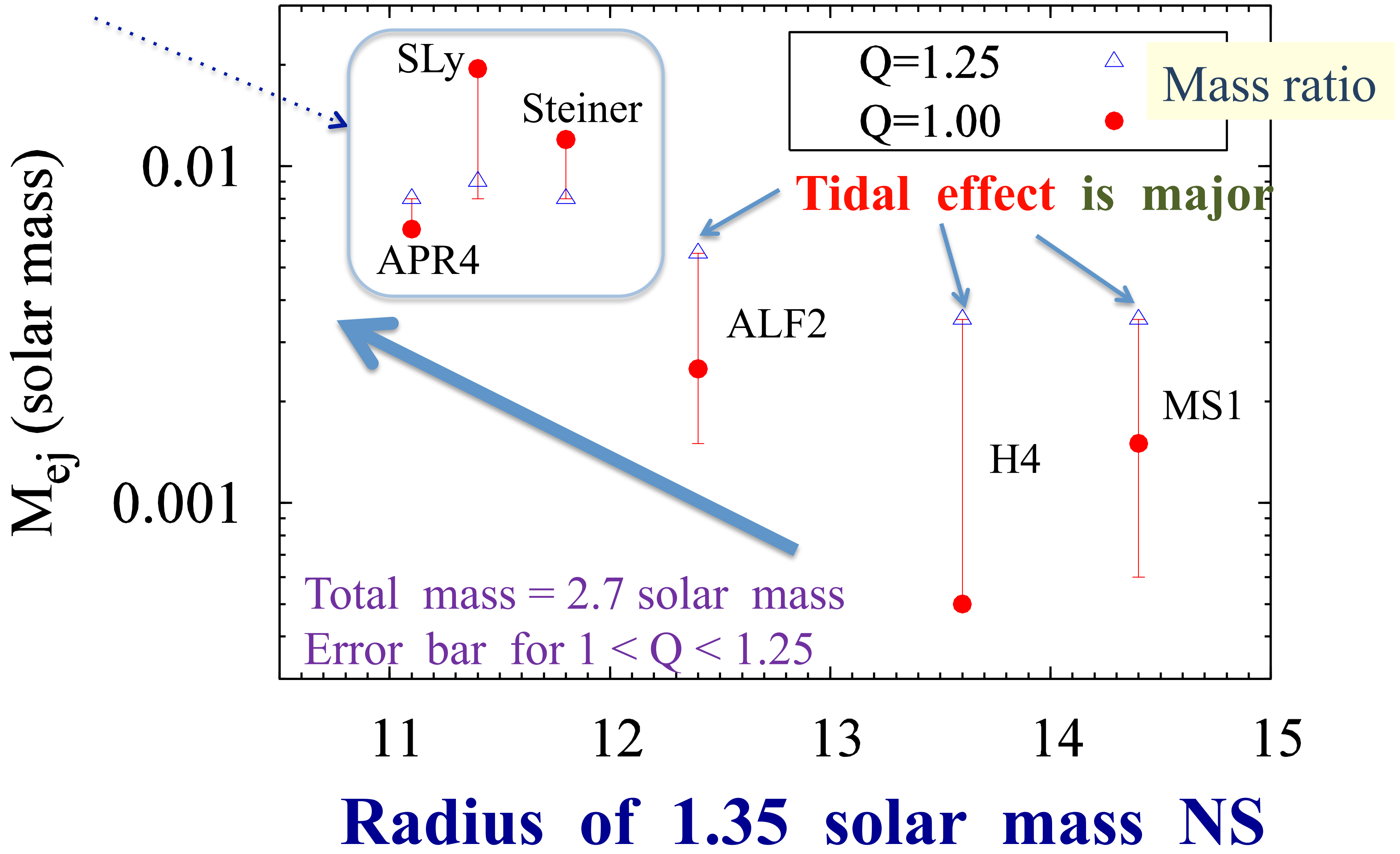
Total mass ~ 10^{-3} M_{solar}

Weak Shock heating

Sekiguchi et al. 2016

Ejecta mass depends on EOS : NS-NS case

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



Mass ratio

Tidal effect is major

Total mass = 2.7 solar mass

Error bar for 1 < Q < 1.25

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

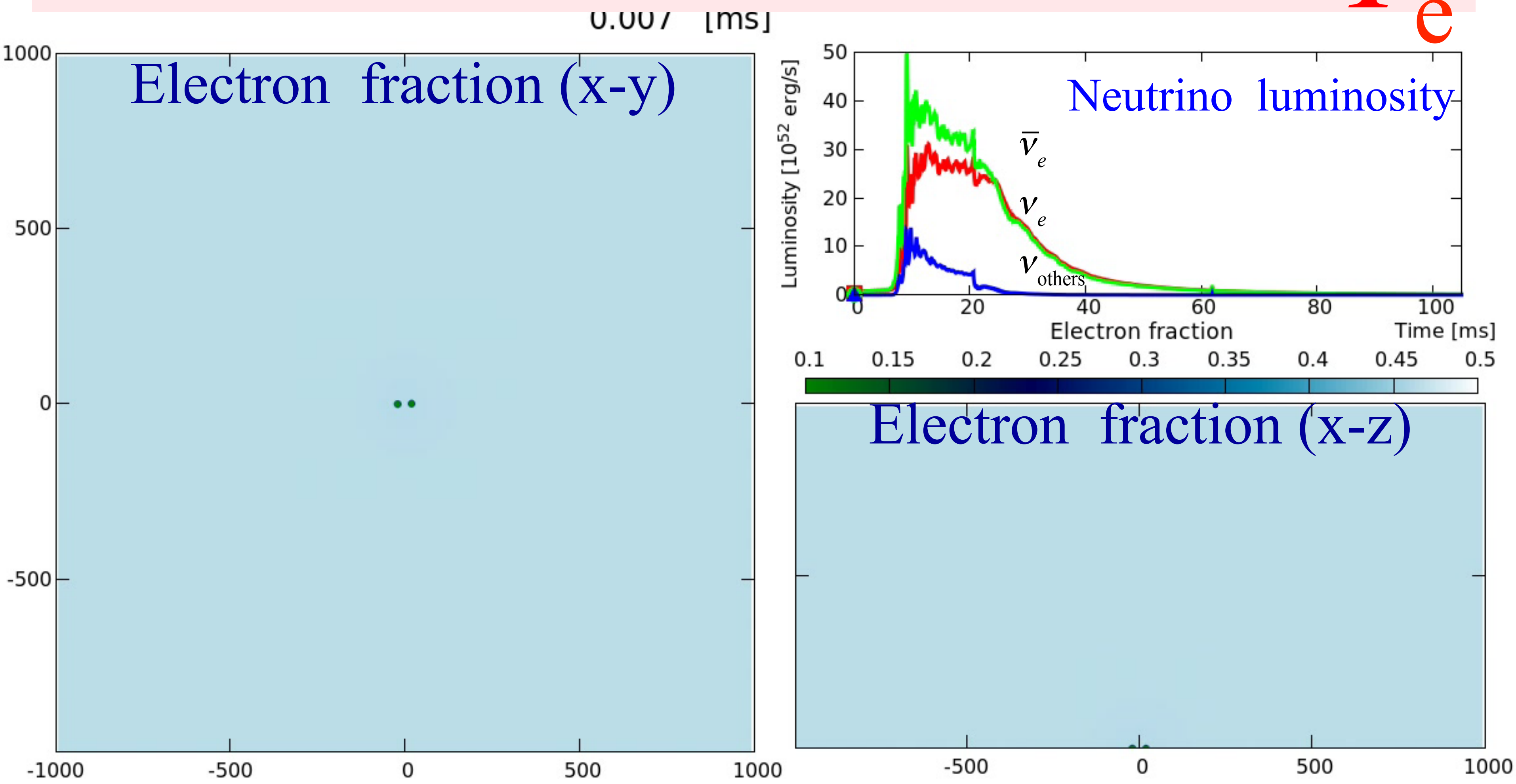
↑
Foucart et al ’16
Shibata unpublished
Sekighichi+ ‘17

- Typical velocity: 0.15—0.25 c

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

Neutrino irradiation ⇒ $n + \nu \rightarrow p + e^-$

Y_e

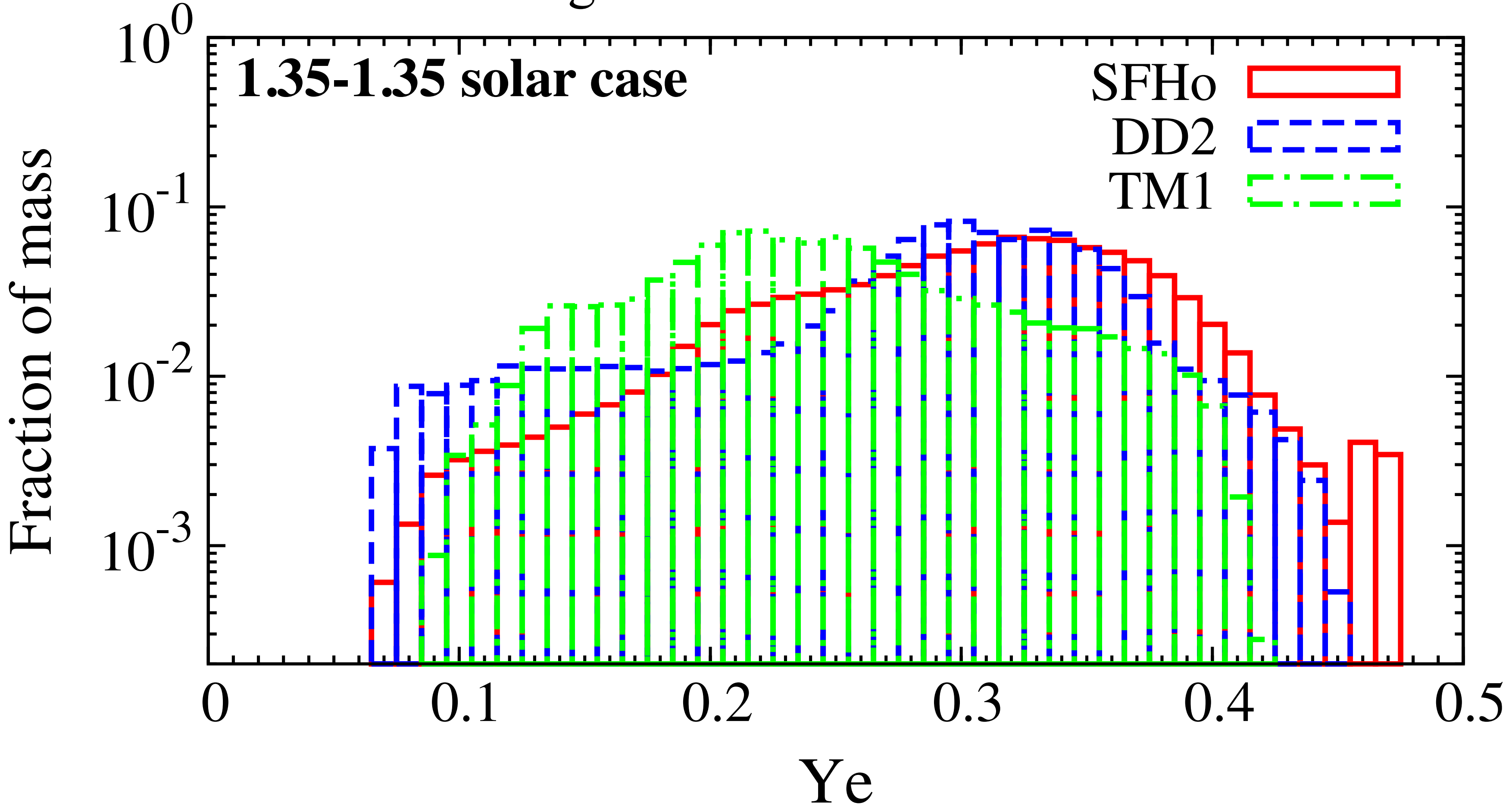


Green = neutron rich

Sekiguchi et al. (2016)

Electron fraction profile: Broad

Sekiguchi et al. 2015 PRD



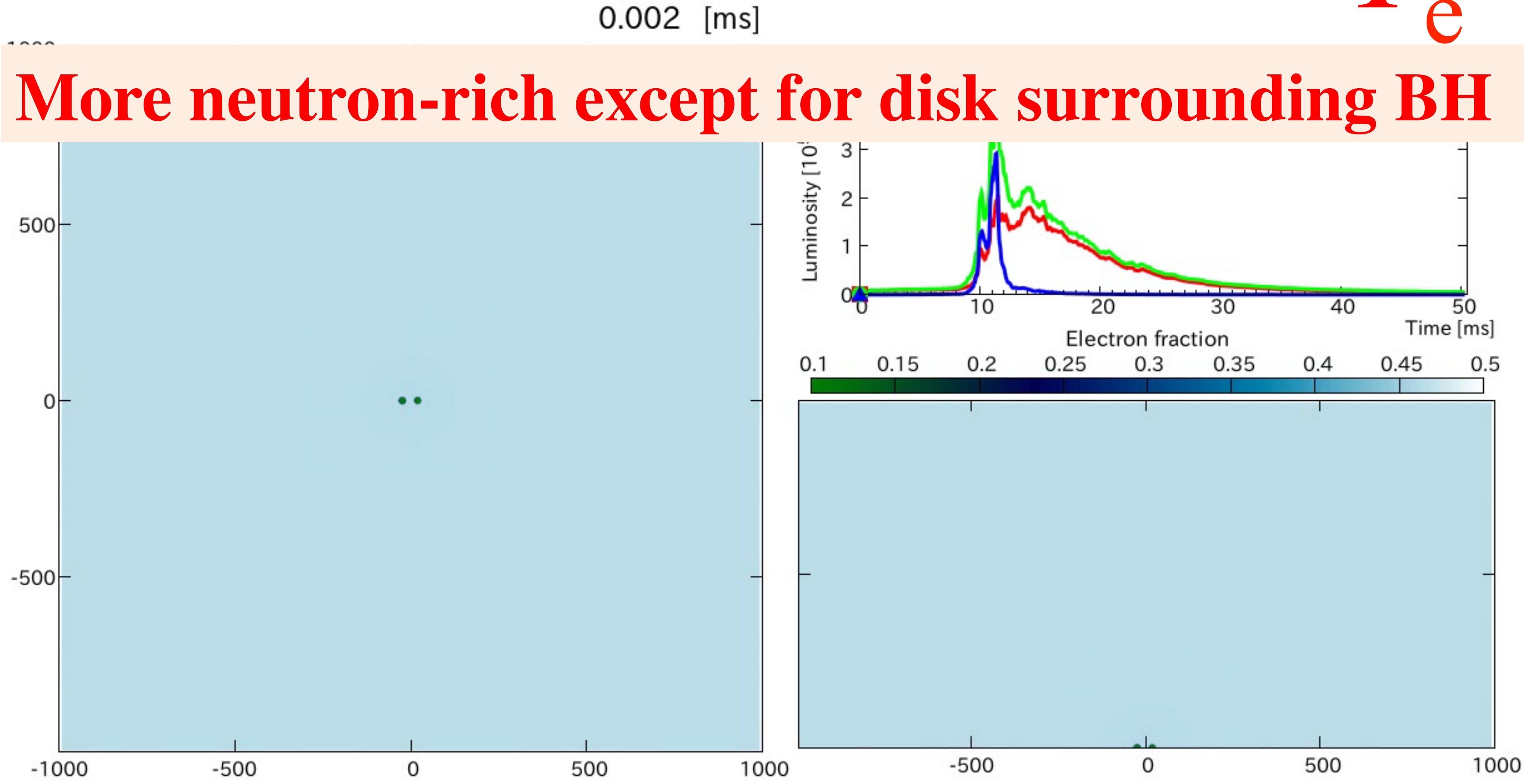
- Average depends on EOS but typically peak at 0.2—0.3
- **Broad distribution** irrespective of EOS
- Similar results by Radice+16, Lehner+15,16

Neutrino-radiation hydrodynamics simulation

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

Y_e

More neutron-rich except for disk surrounding BH



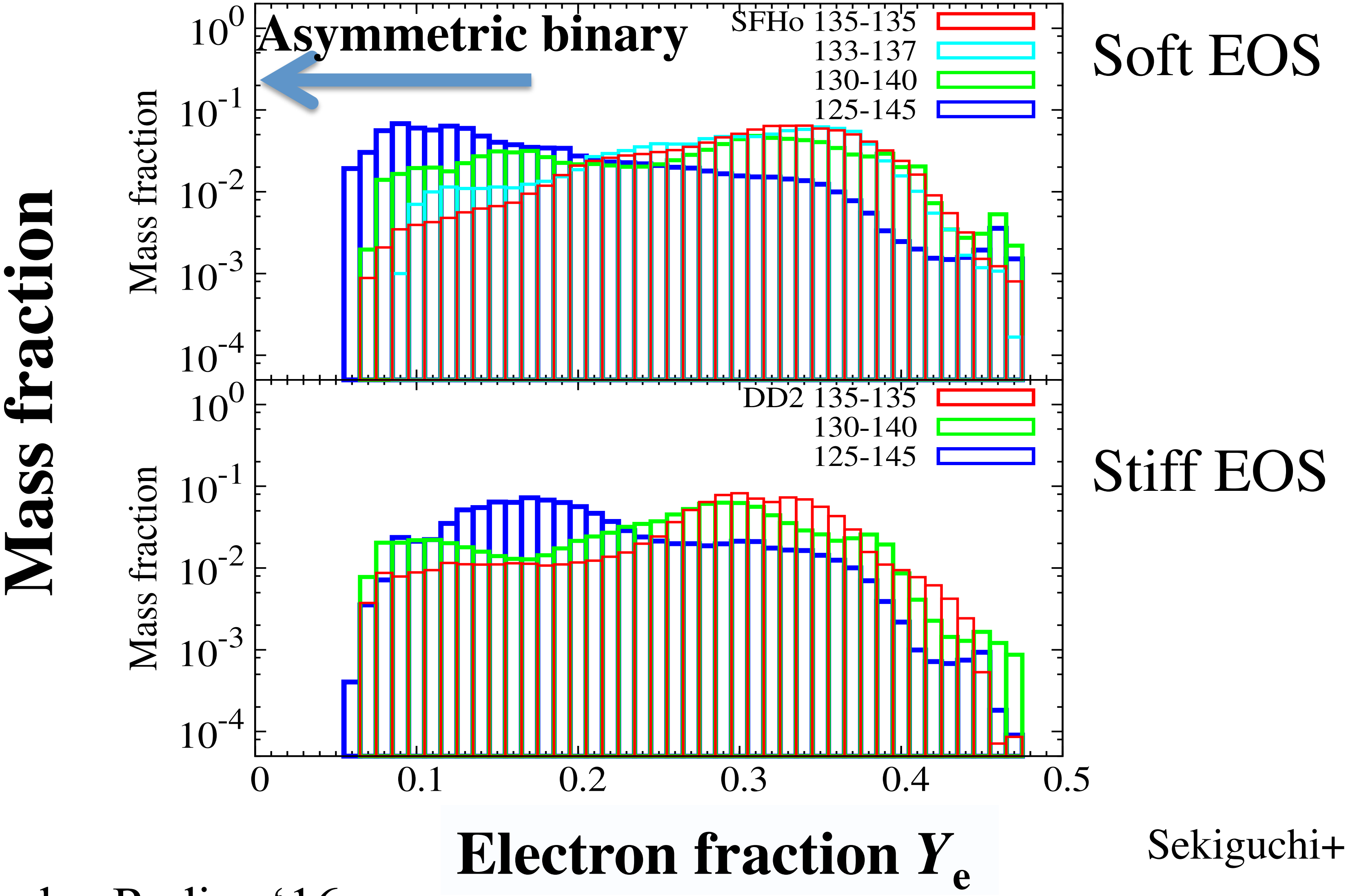
Green = neutron rich

Sekiguchi et al. (2017 hopefully)

Electron fraction distribution:

Broad irrespective of EOS and mass

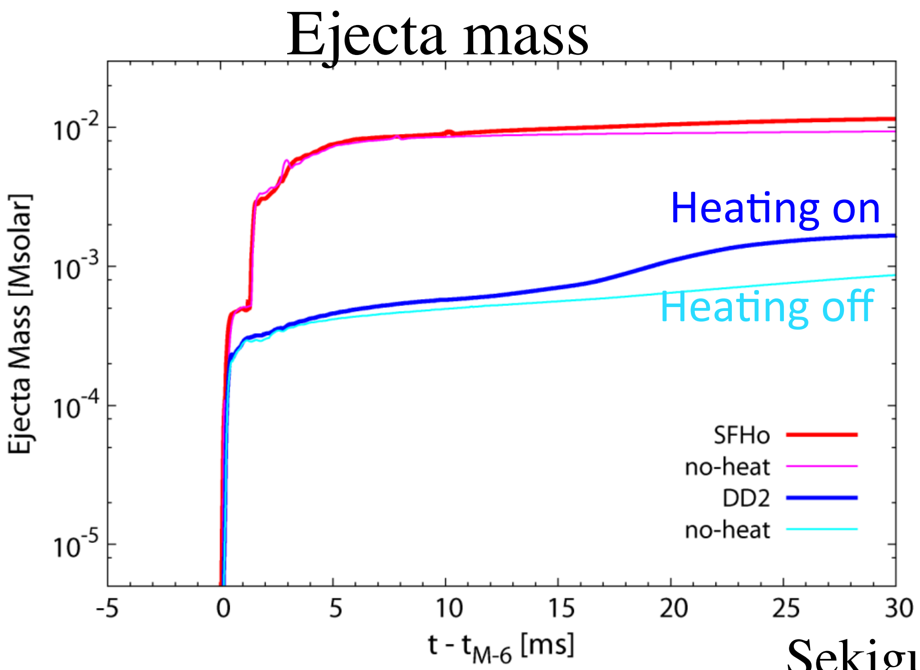
→ Good for producing a variety of r-elements

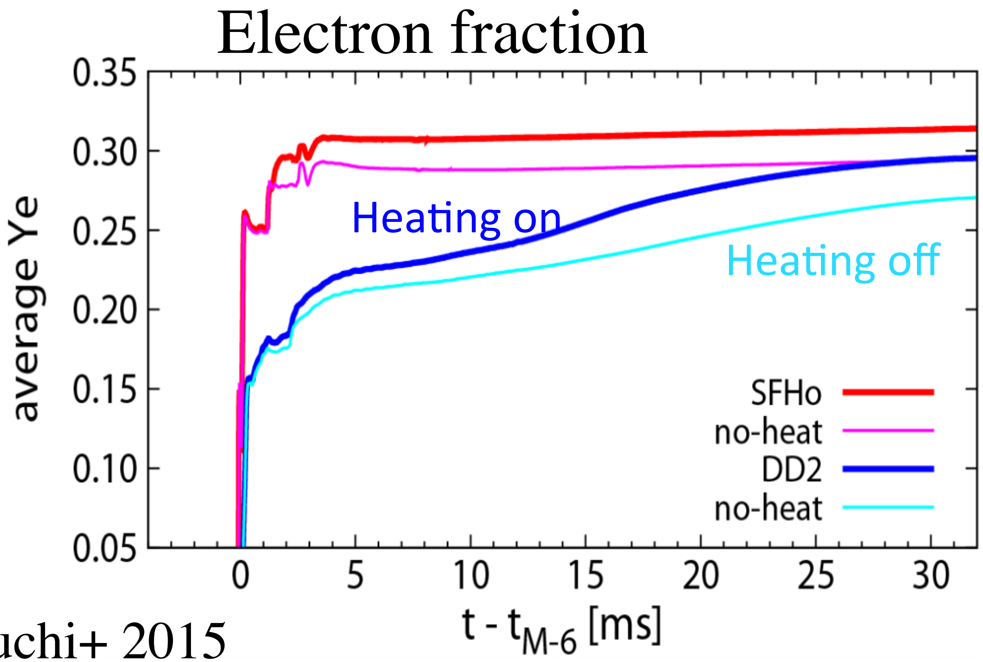


Sekiguchi+ '16

See also Radice '16

Neutrino irradiation: subdominant effect


Ejecta mass


Electron fraction

Sekiguchi+ 2015

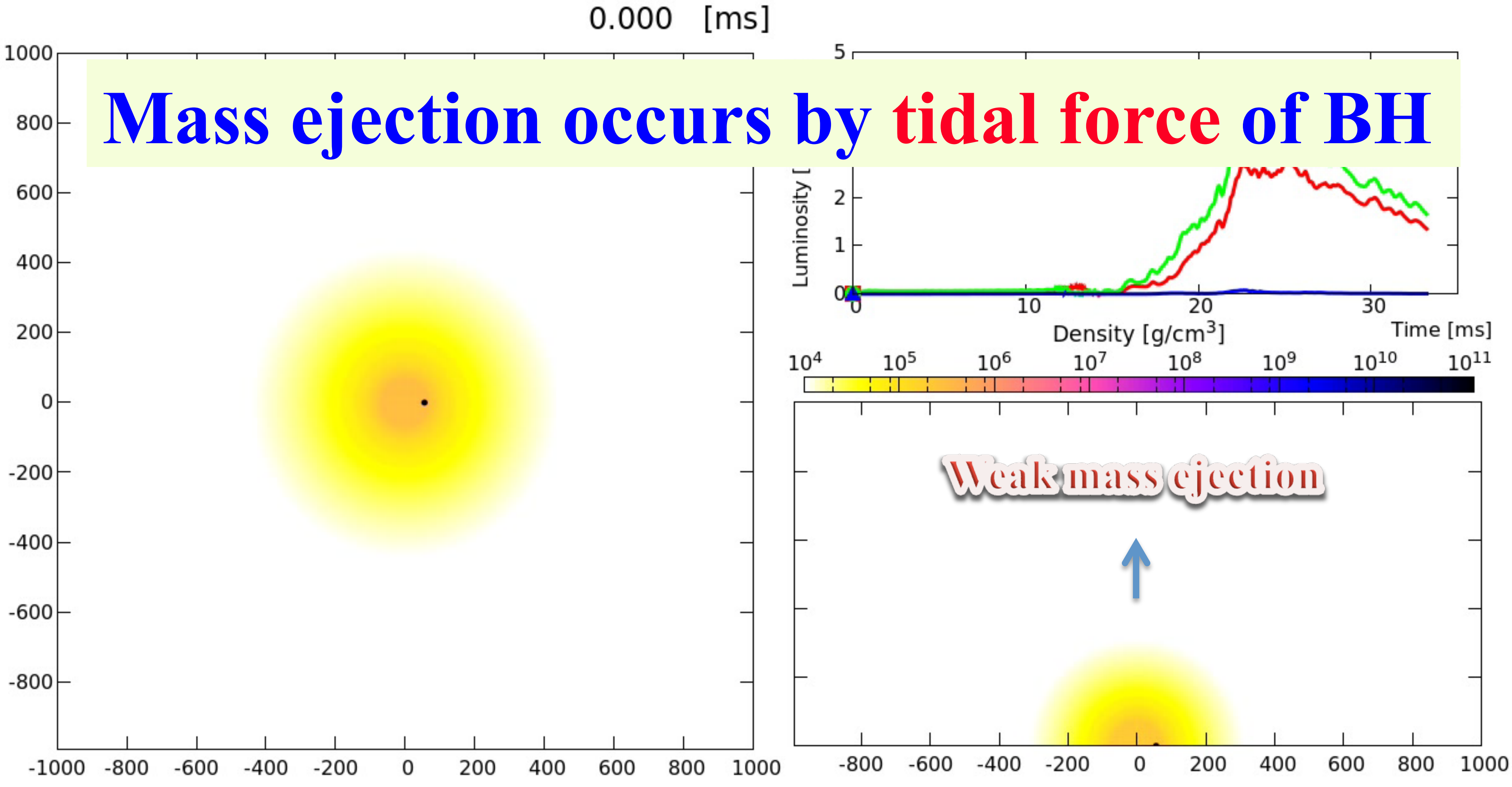
Neutrino irradiation from MNS increases

- ➢ **the ejecta mass by ~ 0.001 solar mass**
- ➢ **Average value of Y_e by ~ 0.03**
- ✓ **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

BH-NS merger (SFHo EOS: density)

$M_{\mathrm{BH}}=5.4\mathrm{M}_{\mathrm{sun}}$, $M_{\mathrm{NS}}=1.35\mathrm{M}_{\mathrm{sun}}$, $a_{\mathrm{BH}}=0.75$



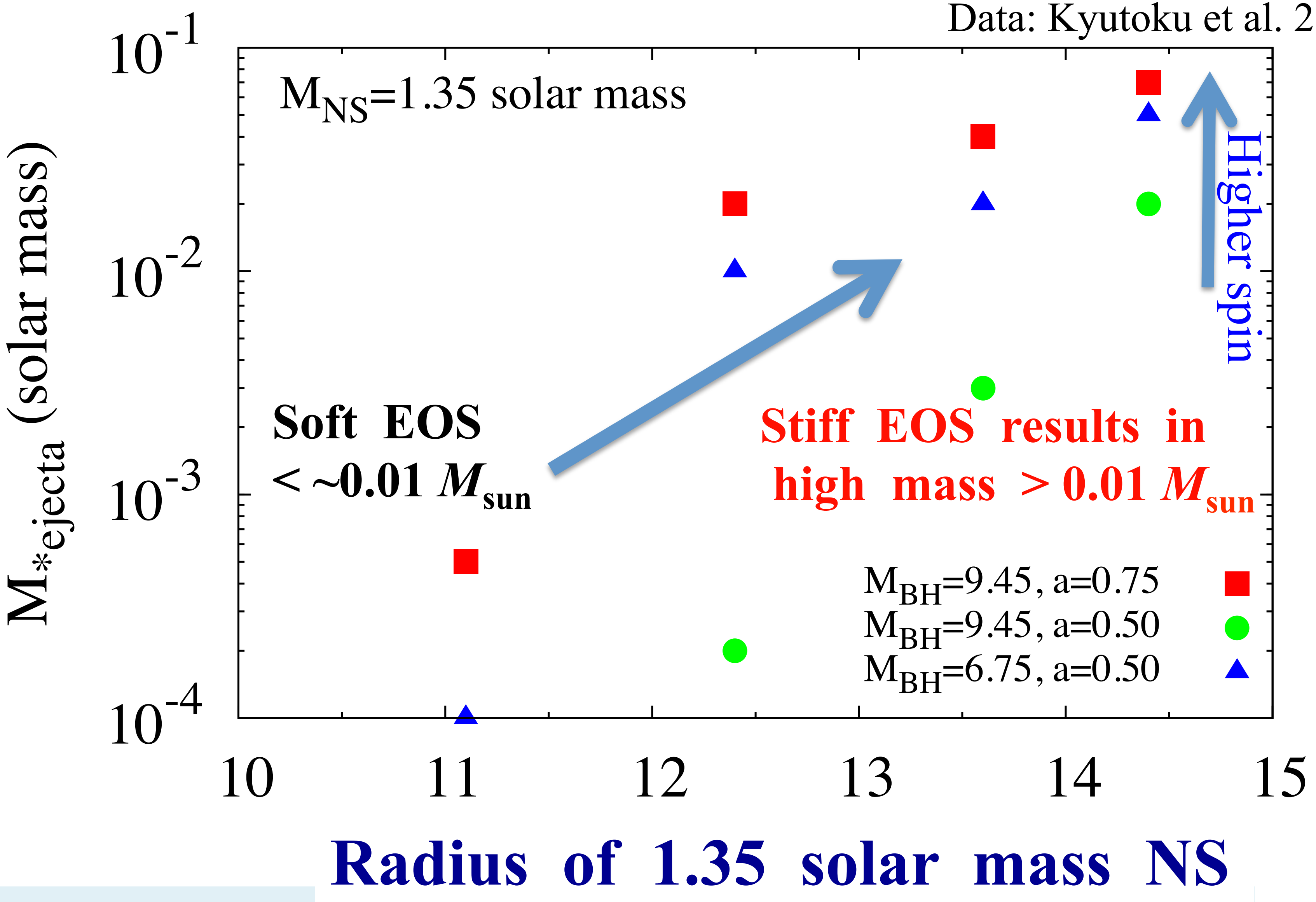
Mass ejection occurs by tidal force of BH

Weak mass ejection

Kyutoku et al. hopefully 2017

BH-NS with NS mass $1.35M_{sun}$

Data: Kyutoku et al. 2015



Soft EOS
< ~0.01 M_{sun}

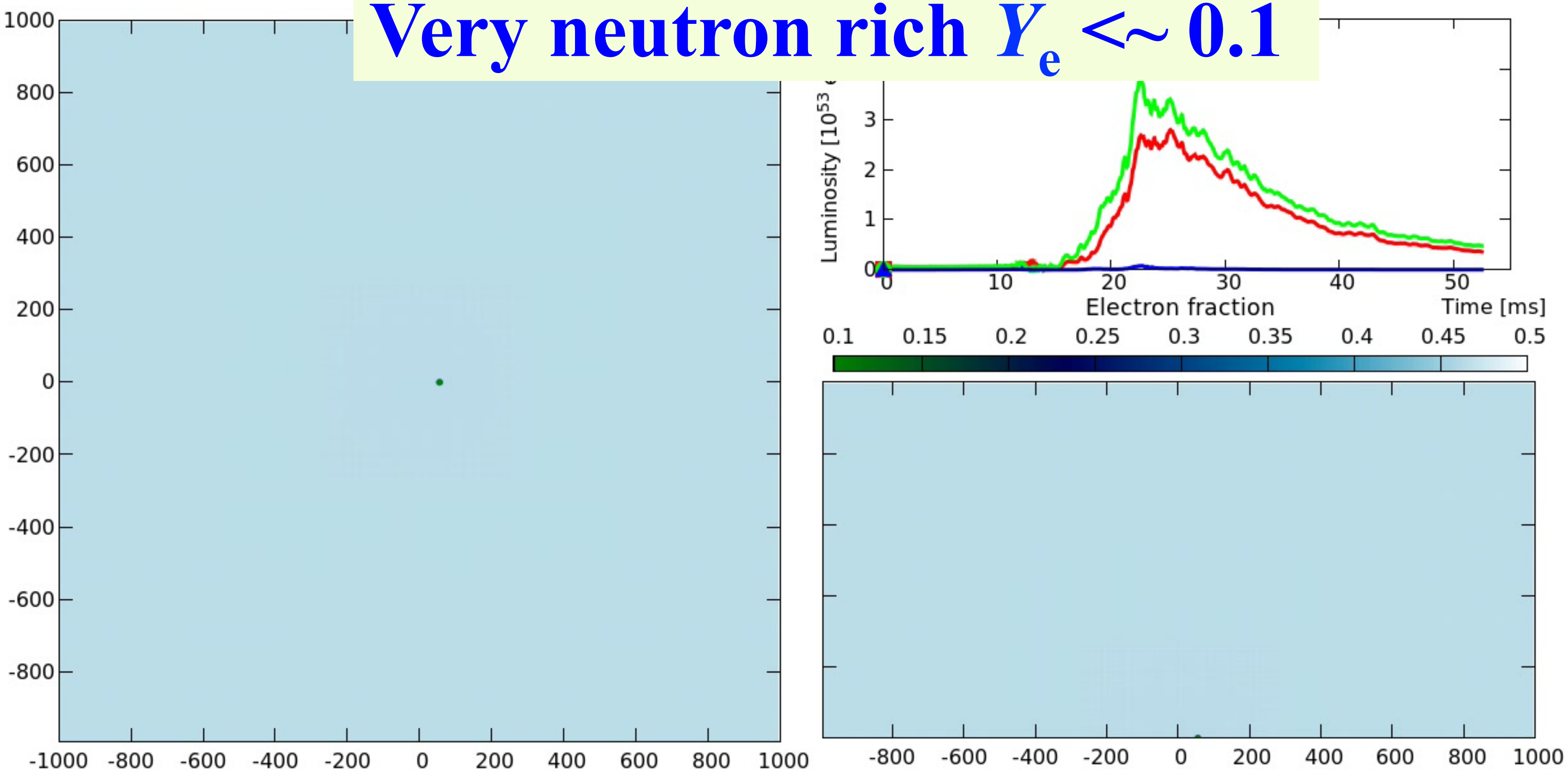
Stiff EOS results in
high mass > 0.01 M_{sun}

Radius of 1.35 solar mass NS

High BH spin is important for mass ejection

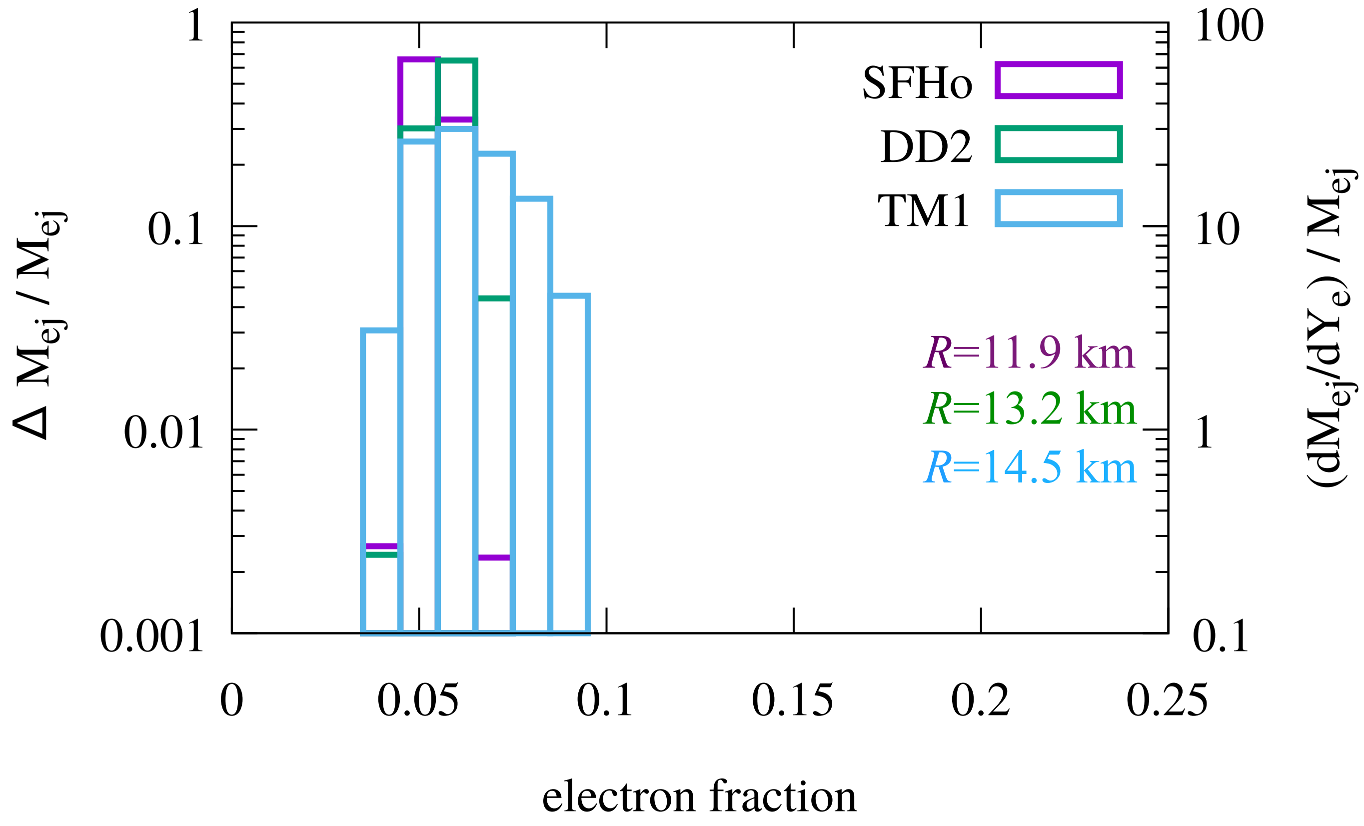
BH-NS merger (SFHo EOS: electron frac)
$M_{\rm BH}$=5.4M$_{\rm sun}$, $M_{\rm NS}$=1.35M$_{\rm sun}$, $a_{\rm BH}$=0.75

Very neutron rich $Y_{\rm e}$ <~ 0.1



Kyutoku et al. hopefully 2017

Electron fraction of ejecta



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

Dynamical ejecta properties in NR

◆**Mass:**

- NS-NS: **$\sim 10^{-3}$—0.02 $M_{\rm sun}$** depending on each mass & EOS: **Soft EOS & ~2.7 $M_{\rm sun}$ is favorable** (Hotoke+ 13, Sekiguchi+ 15,16, Radice+ 16, Lehner+ 15,16)
- BH-NS: **0—0.1 $M_{\rm sun}$: Stiff EOS is favorable; high BH spin is also the key** (Foucart+ '13-15, Kyutoku+15): -- $M_{\rm eject} \sim 0.2$—$0.5\ M_{\rm disk}$

◆ **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
- BH-NS: Peak at $Y_e < 0.1$ (Foucart+ '13-15, Kyutoku+ '17)

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

IV Early Viscous/MHD ejecta for NS-NS

- MHD/viscous effects are likely to play a role (Fernandez-Metzger+ ‘13—15, Just et al. ‘15 ….)
- But, previous simulations are studied only for **torus surrounding BH** (or very artificial NS)
- Realistic remnants = MNS + torus, for which no well-resolved MHD or viscous simulations
- **MNS of *differential rotation* has potential for mass ejection**

Physical state for the merger remnants

- Remnant MNS are ***magnetized & differentially rotating***

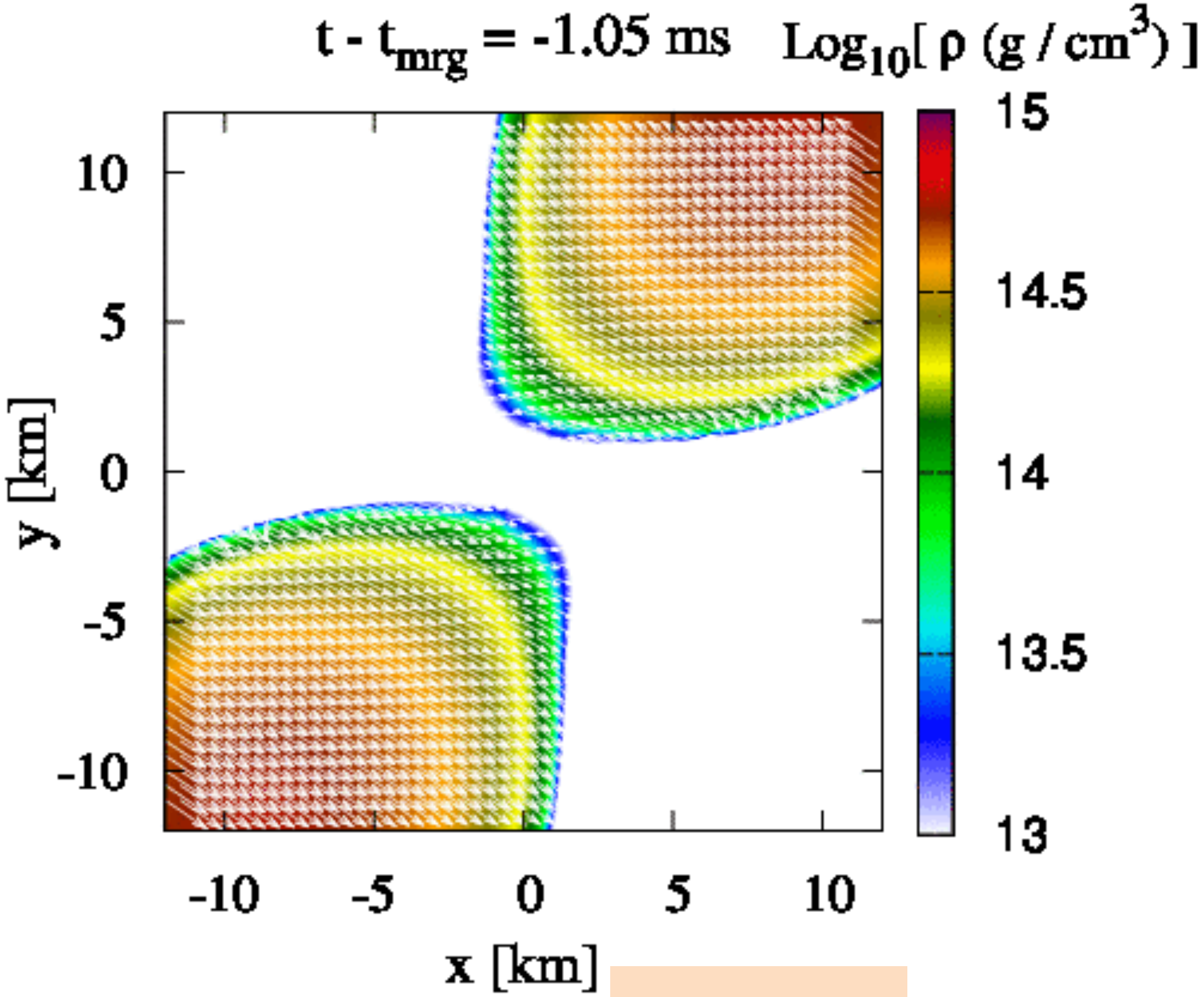
  → **subject to MHD instabilities**
- MHD simulations (e.g., Price & Rosswog, '07, Kiuchi et al. '14, '15) suggest that magnetic fields would be significantly amplified by Kelvin-Helmholtz instability

  → **turbulence may be induced**

High-resolution GRMHD for NS-NS

Kiuchi et al. 2015

Δx=17.5m



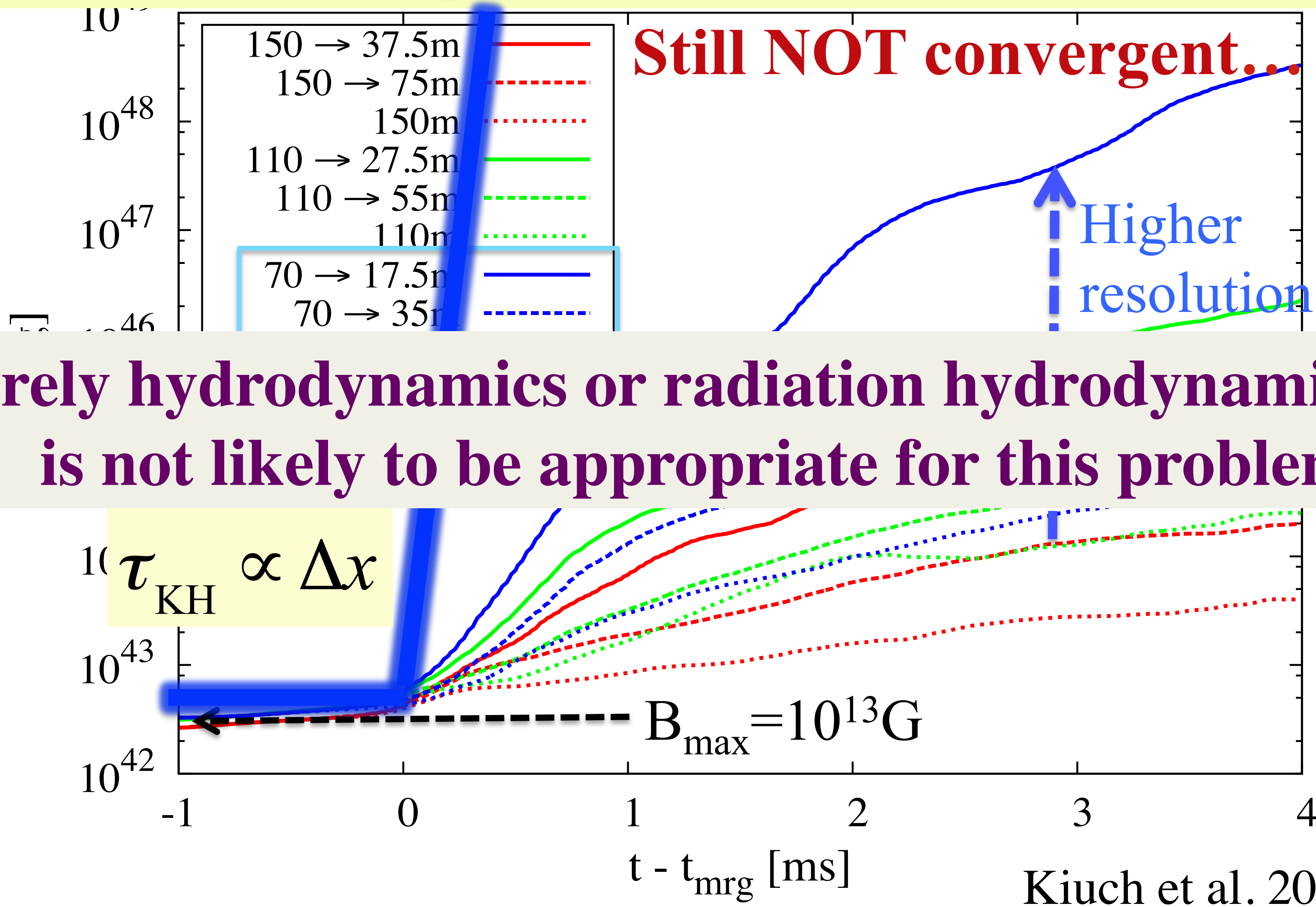
Kelvin-Helmholtz instability: $\tau_{\rm KH} \propto \Delta x$

→ **Magnetic field should be 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 ?



Still NOT convergent…

Higher resolution

$\tau_{KH} \propto \Delta x$

Purely hydrodynamics or radiation hydrodynamics is not likely to be appropriate for this problem

Kiuch et al. 2015

Shear motion at the merger

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

→ further shear motion → **turbulence**

→ **turbulent (effectively global) viscosity**

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 viscous hydrodynamics can precisely describe turbulence fluid

Vis s for

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

Employ covariant & causal GR viscous hydro (Israel & Steward)

Initial condition: Merger remnant of 1.35-1.35M_{sun} NS-NS

Alpha viscosity; $\nu = \alpha_\nu c_s^2 \Omega^{-1}$ with $\alpha_\nu = 0.01$

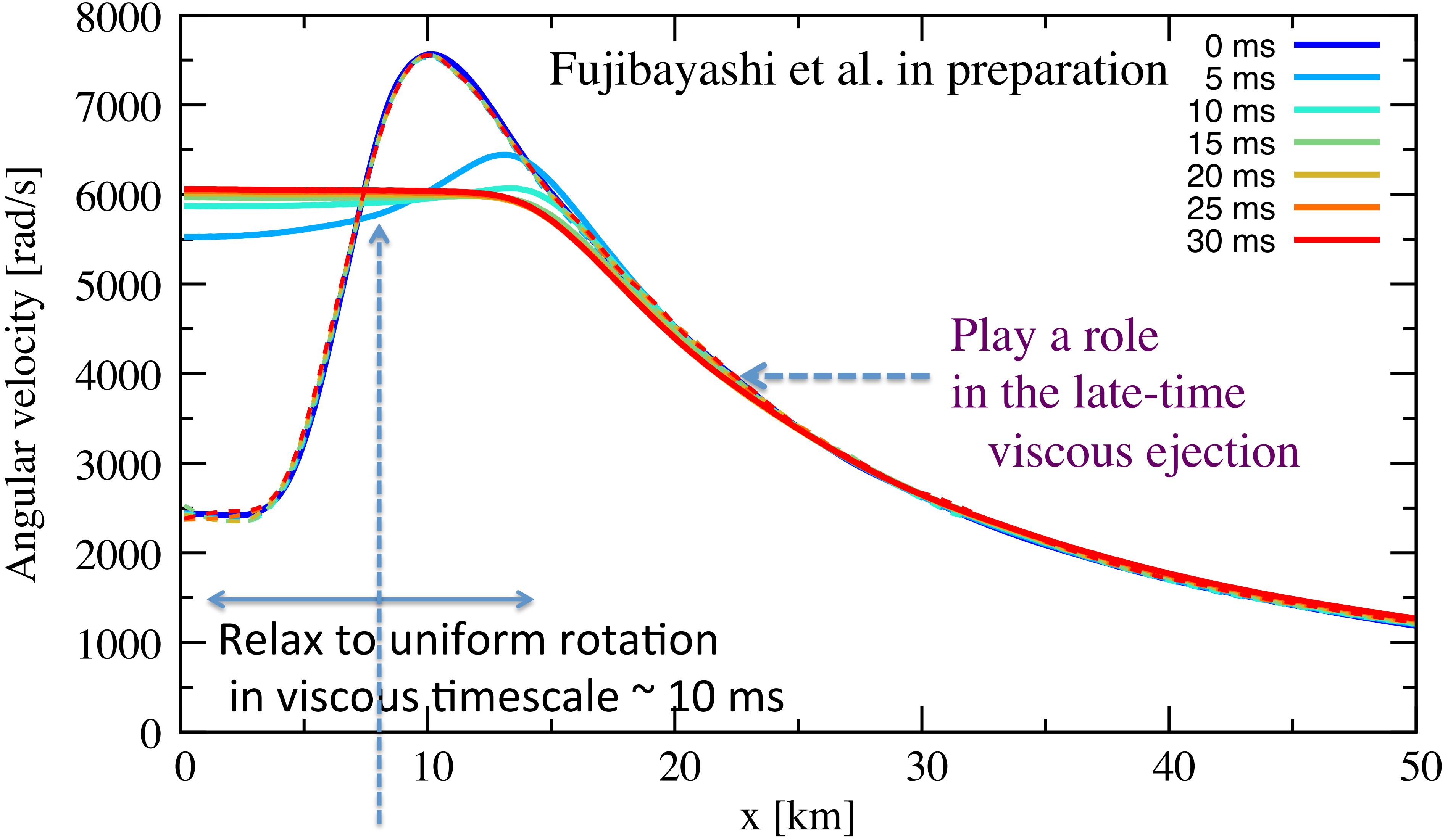
EOS: DD2 (R_{NS} = 13.2 km)

→ Dynamical ejecta mass ~ 0.001 M_{sun}

Wide 1500×1500 km 300×300 km

Density in *x*-*z* plane

Evolution of angular velocity



Fujibayashi et al. in preparation

Play a role
in the late-time
viscous ejection

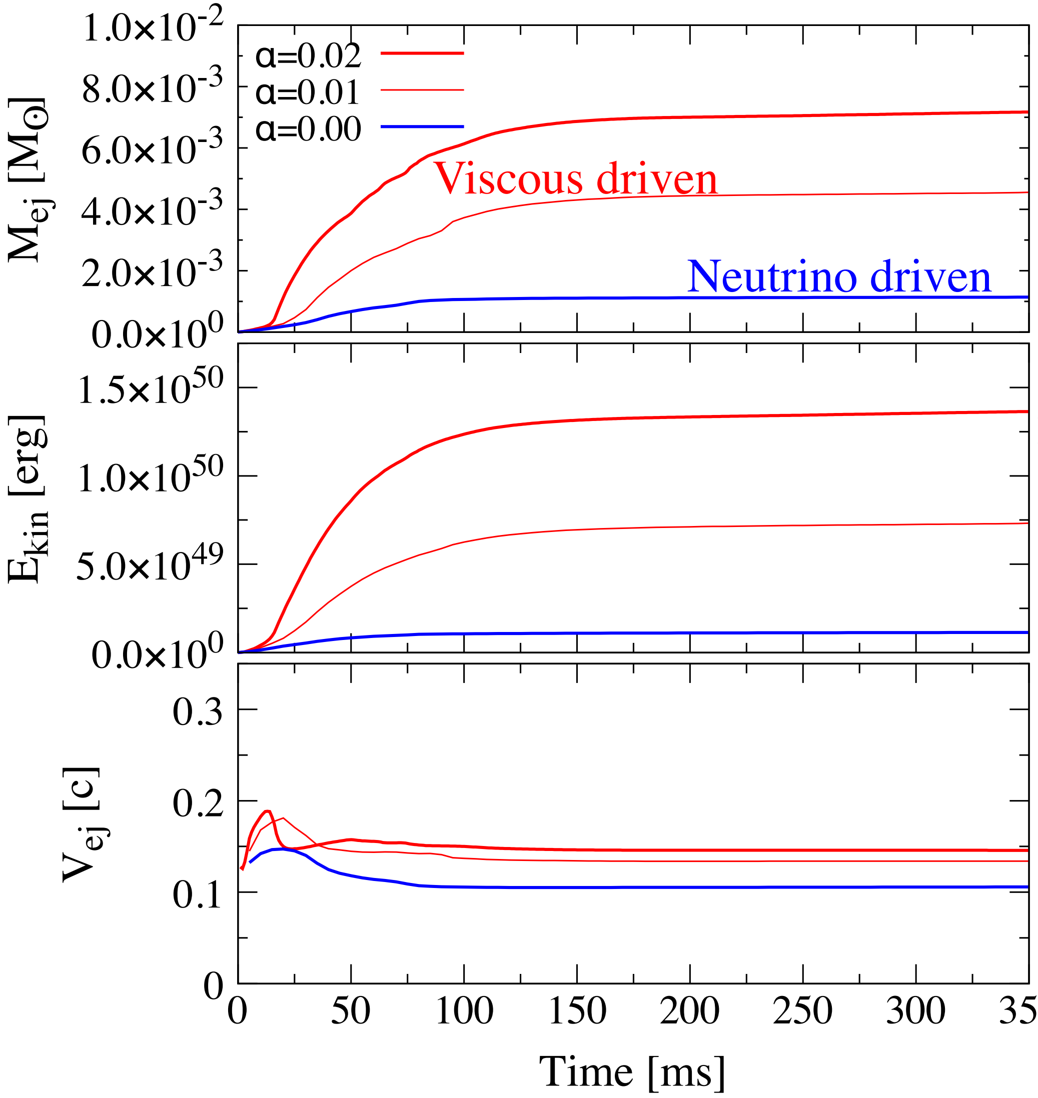
Relax to uniform rotation
in viscous timescale ~ 10 ms

Kinetic energy of ~10^{52} erg is released
→ early viscous ejection

Ejecta mass and Y_e distribution

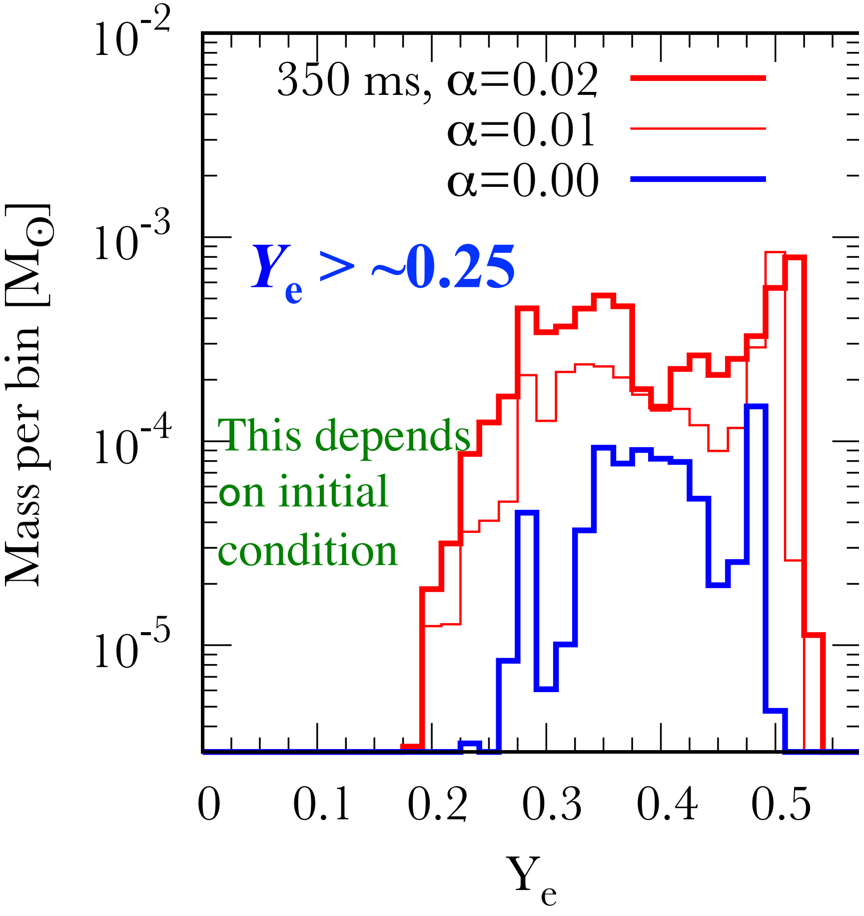
t < 10—20 ms: Differential rotation of MNS → rigid rotation

→ viscous heating → ejecta of mass > $10^{-2.5}$ M_{sun}



Viscous driven

Neutrino driven



$Y_e > \sim 0.25$

This depends on initial condition

Fujibayashi et al. in prep.

Viscous hydrodynamics for post-merger MNS

(S. Fujibayashi et al. in preparation)

Electron fraction

Wide 1500×1500 km

300×300 km

Dynamical + MHD/viscous ejecta in NR

Total ejecta mass could be ~0.01 M_{sun} or more

	Nearly equal mass ($M_{\mathrm{tot}} \sim 2.7 M_{\mathrm{sun}}$)	**Unequal mass: $m_1/m_2 < 0.9$ ($M_{\mathrm{tot}} \sim 2.7 M_{\mathrm{sun}}$)**	**Small total mass system ($< 2.6 M_{\mathrm{sun}}$)**
Soft EOS (R=11-12 km)	MNS → BH $M_{\mathrm{eje}} \sim 10^{-2}\ M_{\mathrm{sun}}$	MNS → BH $M_{\mathrm{eje}} \sim 10^{-2}\ M_{\mathrm{sun}}$	MNS (long lived) $M_{\mathrm{eje}} \sim$??
Stiff EOS (R=13-15km)	MNS (long lived) $M_{\mathrm{eje}} \sim 10^{-2}\ M_{\mathrm{sun}}$	MNS (long lived) $M_{\mathrm{eje}} \sim 10^{-2}\ M_{\mathrm{sun}}$	MNS (long lived) $M_{\mathrm{eje}} \sim$??

To be studied

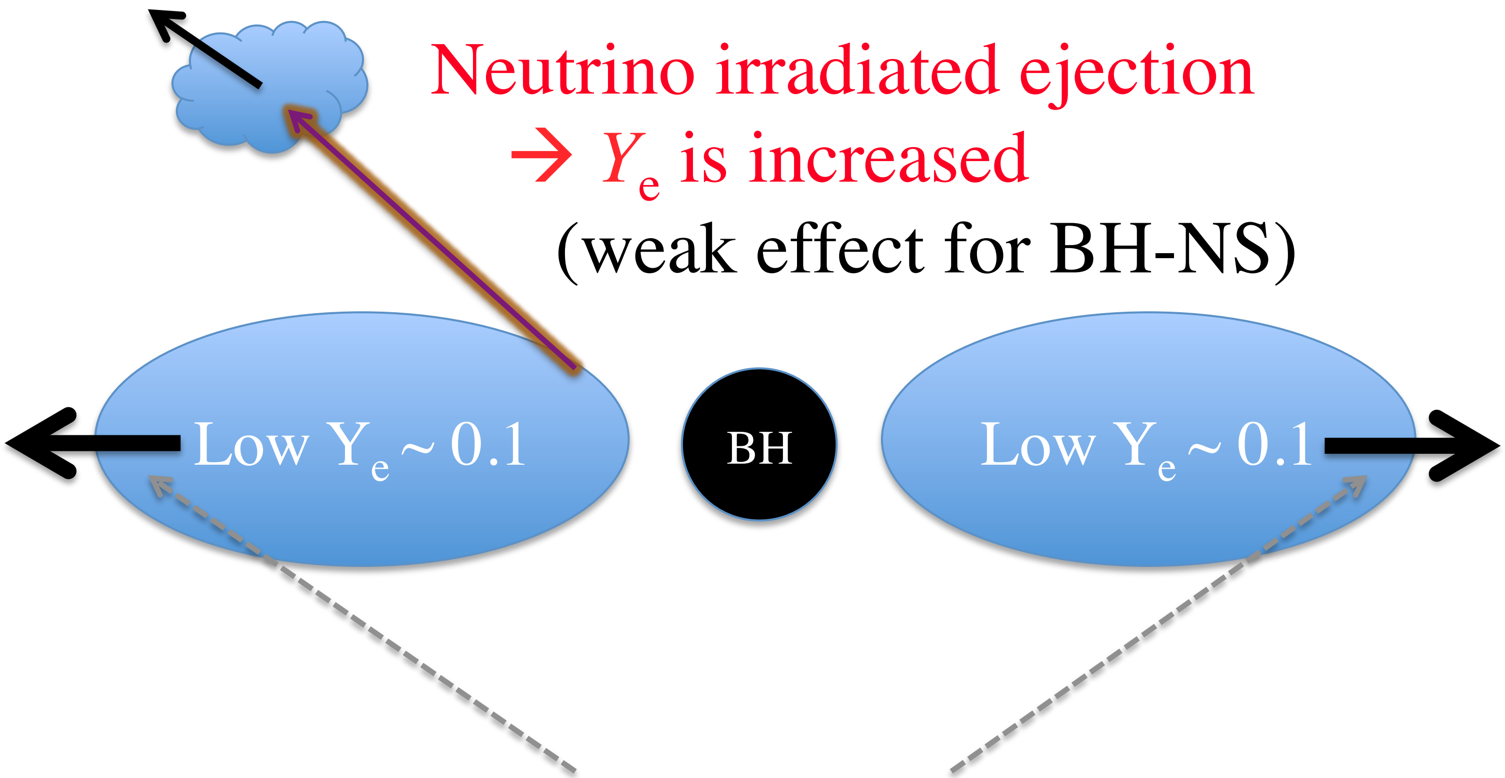
- $\langle Y_e \rangle \sim 0.2$—$0.3$ (likely)
- **Y_e has a wide distribution** → Good for nucleo-synthesis

V Long-term viscous disk wind

- ➢ Studies have been done mostly for **BH-disk** systems (Fernandez-Metzger, '13-15, Just+ '15, Siegel-Metzger '17; Natural model for BH-NS merger)
- 10—20% of mass of disk surrounding a spinning BH is likely to be ejected by **viscous ejection**
- Due to Y_e **freeze-out** in the absence of strong neutrino sources, low Y_e matter could be ejected

Basic Picture

(Fernandez-Metzger ’13,14, Just ’15, ……)



Neutrino irradiated ejection
→ Y_e is increased
(weak effect for BH-NS)

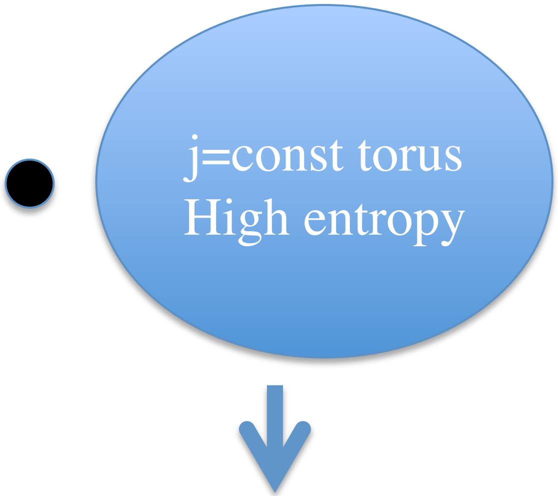
Viscous ejection of mass 10—20% of torus mass

Y_e freeze out → Low Y_e is preserved (good r-process)

Concern

✓ Initial disk model is rather artificial, in particular,

- j=const angular momentum distribution is often used, but it's unphysical, and in this case, torus becomes geometrically thick leading to easy ejection:



Overestimated mass ejection ?
Overestimated neutrino heating ?

More realistic

Throughout mass ejection of BH-NS merger

- For tidal disruption of NS, high BH spin is necessary
  → **remnant should be high-spin BH + disk**

➢ Dynamical ejecta: $M_{\mathrm{eject}} \sim 0.2\text{–}0.5 M_{\mathrm{disk}}$ (e.g., Kyutoku+ '15)

➢ Viscous ejecta from disk could be ~ 0.1–0.2 M_{disk}
→ Comparable to dynamical ejecta

✧ Dynamical ejecta has small $Y_e < 0.1$ (e.g., Forcart+, '14)

✧ Viscous ejecta is also likely to give $Y_e \sim 0.1-0.2$
because of the absence of strong neutrino sources and resulting freeze-out effect
(Fernandez-Metzger '13, 14, Just + '15, Siegel-Metzger '17)

→ Likely to be a strong site for the r-process nucleosyn.

Conclusion seems to be robust

Long-term viscous disk wind: NS-NS case

➢ Remnant MNS-disk systems have been studied only with artificial treatments of MNS

- The presence of a strong neutrino emitter like MNS would change Y_e significantly
  (Metzger-Fernanndez ‘13, Perego+ ’14, Fujibayashi+ ‘17)

✓ Caution:

- Luminosity of MNS decreases with time
- Low-Y_e disk initial condition may not be realistic for MNS-disk system
- Need more realistic studies from NR merger simulation

IV Summary

◆ NS-NS:

- Dynamical + subsequent short-term MHD/viscous ejection are likely to provide ejecta mass of > 0.01 M_{sun} *irrespective of EOS and each mass of binary*
- Y_e is mildly low & broadly distributed: good
- Long-term evolution of post-merger MNS-torus: **???**

◆ BH-NS: likely robust conclusion

- Dynamical ejection could provide 0.01–0.1 M_{sun}, in the case of TD and resulting Y_e is low < 0.1
- Post-merger BH-torus could also eject mass 20—50% of disk mass by viscous effect → M_{eje} >~0.01 M_{sun}: Y_e could also be mildly low ~ 0.1—0.2