Neutron-star mergers: Predictions by numerical relativity

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Many people are exploring NS binaries in numerical relativity

- Shibata & Uryu (1999), Taniguchi
- Sekiguchi, Kiuchi, Kyutoku, Hotokezaka, Kawaguchi
- Rezzolla, Baiotti, Giacomazzo, Kastaun, Alic, Ciolfi, ..
- Shapiro, Liu, Etienne, Pachalidis, ..
- Bernuzzi, Dietrich, Nagar, Bruegmann, Gold, ..
- Lehner, Palenzuele, Liebling, Nielsen, Anderson, ..
- Bauswein, Stergioulas, Janka, ..
- Foucart, Duez, O'Connor, Ott, Haas, Scheel, Kidder, Pfeiffer,..
- Loeffler and his colleagues & many others

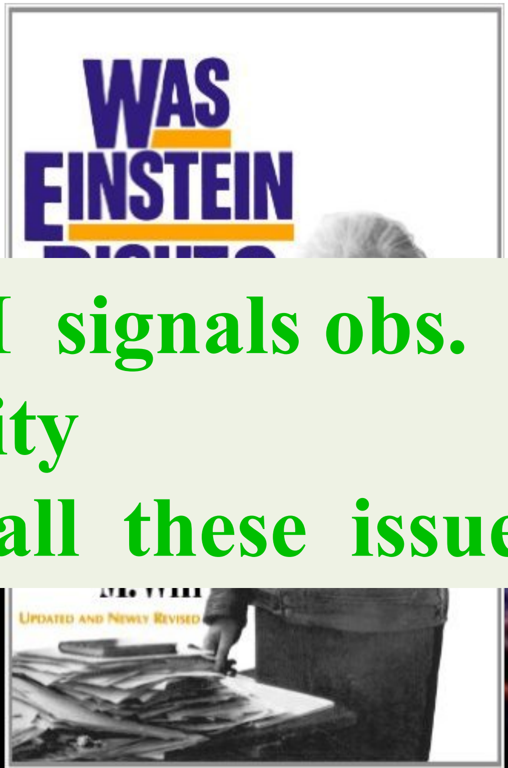
- **Solid progress on understanding NS-NS/ NS-BH binary by numerical relativity**

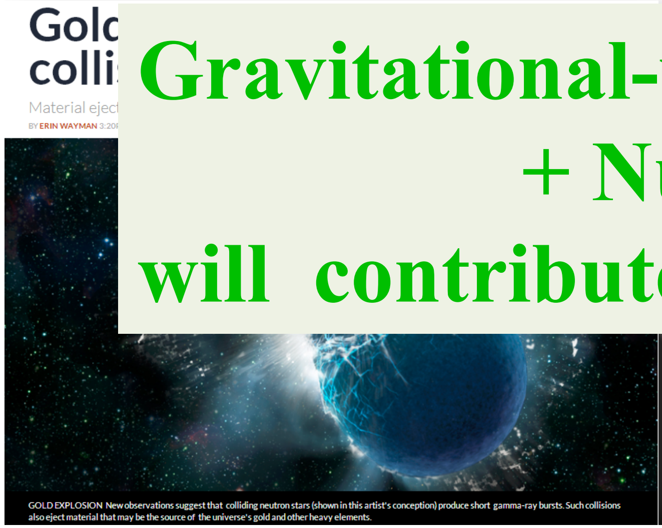
Outline

1. Brief introduction
2. Standard scenarios of NS-mergers
3. Gravitational waves and equations of state
4. Mass ejection
5. R-process nucleosynthesis
6. Summary

1 Many aspects of NS-NS/BH-NS

1. One of the most promising **sources of gravitational waves for LIGO/VIRGO/KAGRA**
2. Laboratory for **high-density nuclear matter**
3. Promising progenitors of **short-hard GRBs**
4. Possible site of **r-process nucleosynthesis**
5. Laboratory for **testing GR**




Gol
colli
Material eject
BY ERIN WAYMAN 3:20

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.

Gravitational-wave obs. + EM signals obs.
+ Numerical relativity
will contribute to exploring all these issues

2 Standard scenarios of NS-NS/BH-NS merger

2A Binary neutron stars

Boundary conditions from latest observations

✧ Binary pulsar observations suggest

- **Mass of NS in compact NS-NS** is likely to be in a narrow range, $m \approx 1.35 \pm 0.15\, M_{\rm sun}$
- **Spin of NS** is likely to be not very high, $P_{\rm rot} > \sim 10$ ms or $a < \sim 0.05$
- **NS radius (EOS)** is still uncertain, but **maximum mass of NS > 2 $M_{\rm sun}$**

  (Demorest 2010; Antoniadis 2013)

  → EOS of NS has to be stiff

Current understanding of NS-NS

Merger of 1.35-1.35$M_{\rm sun}$ NS with four EOSs

APR4: R=11.1km

ALF2: R=12.4km

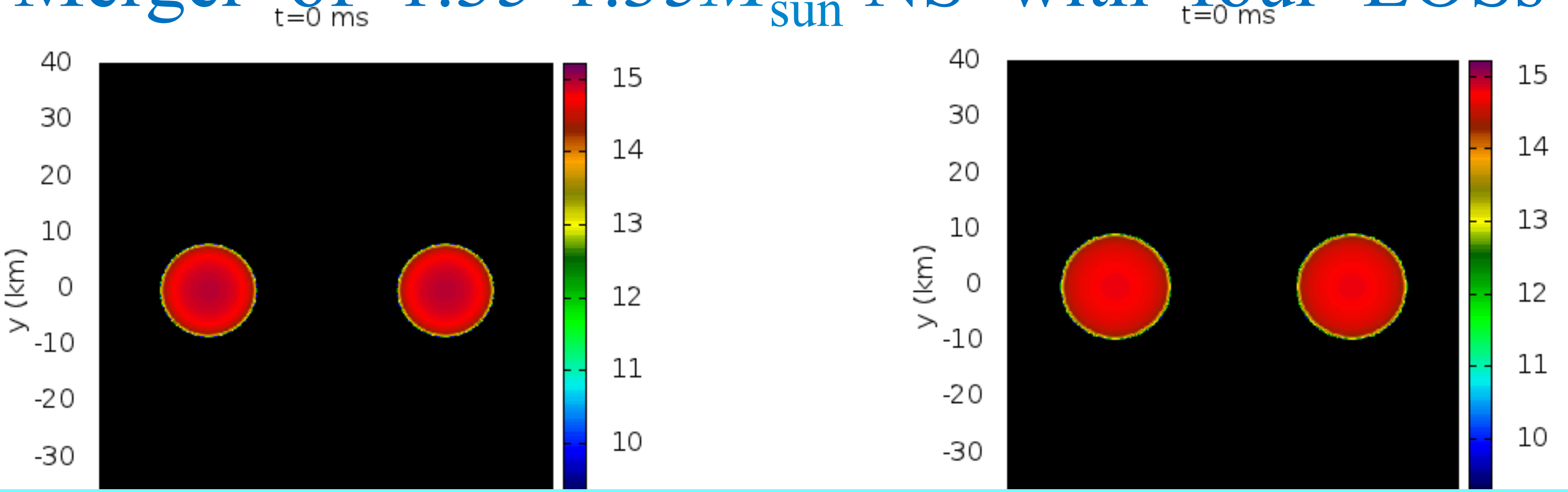
All EOSs satisfy $M_{\rm max} > 2M_{\rm sun}$

H4: R=13.6km

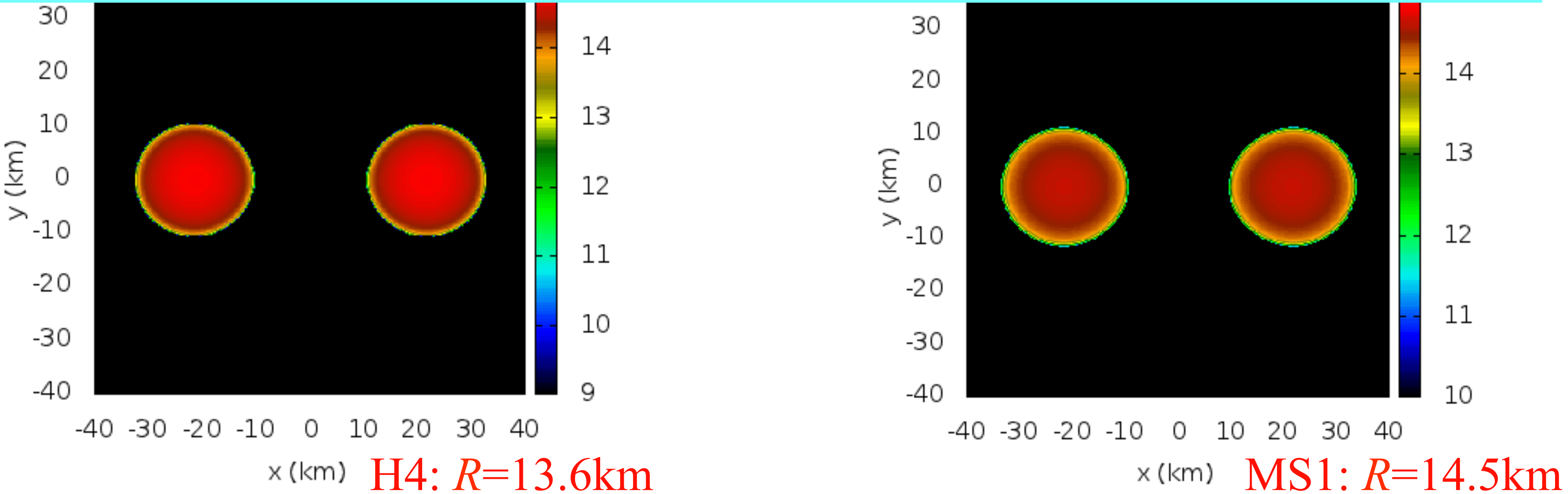
MS1: R=14.5km

Merger of 1.35-1.35M_{sun} NS with four EOSs

By hotokezaka + 2013



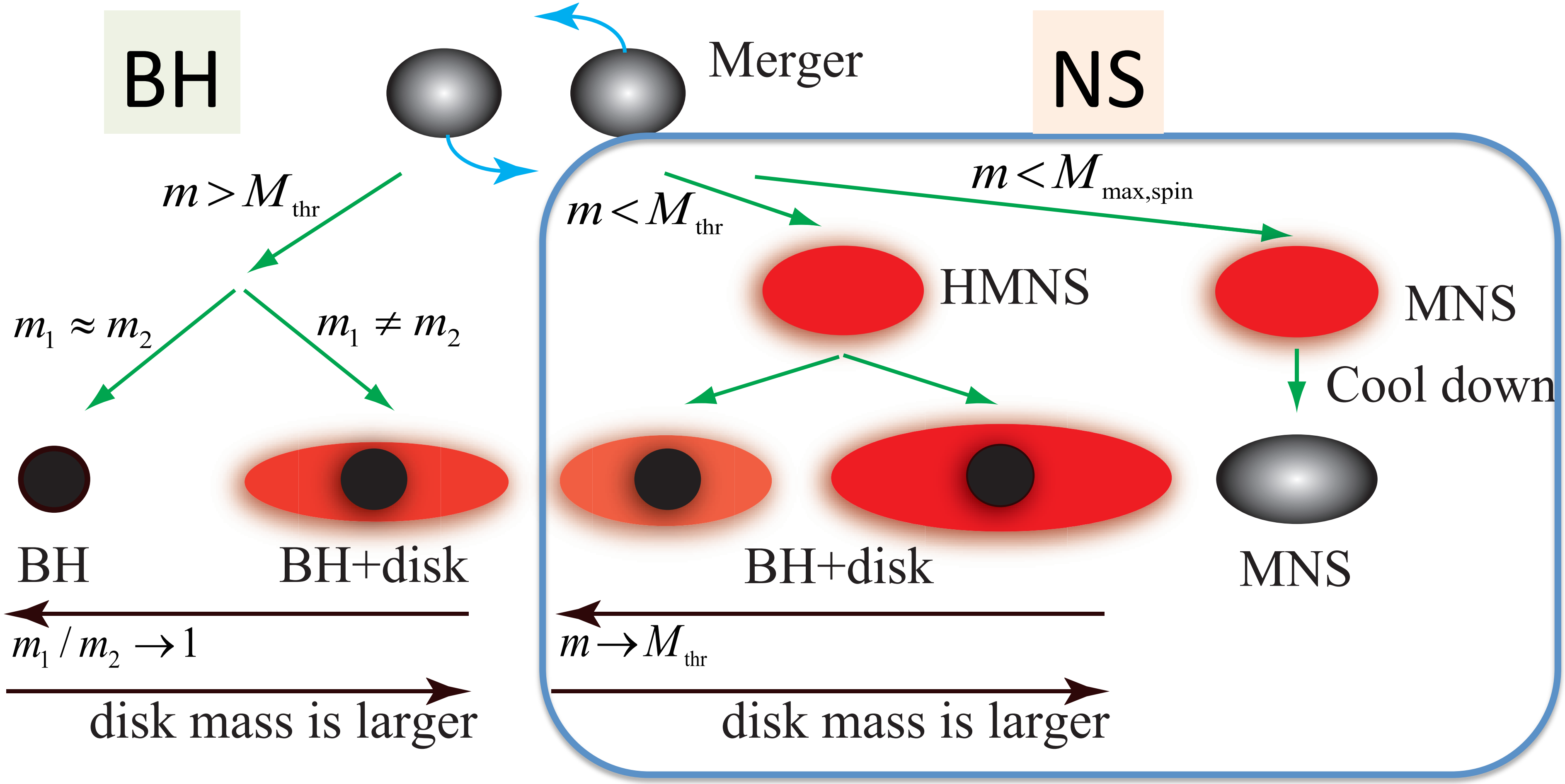
Massive neutron stars are remnants irrespective of EOS for canonical mass



H4: *R*=13.6km

MS1: *R*=14.5km

Possible outcomes of NS-NS mergers



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

Likely for $M < \sim 2.8 M_{\rm sun}$

I.e., irrespective of EOS, threshold mass >~$2.8\mathrm{M}_{\rm sun}$

2B Black hole-neutron star binaries

Two possibilities: Tidal disruption or not

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

$$\Downarrow$$

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

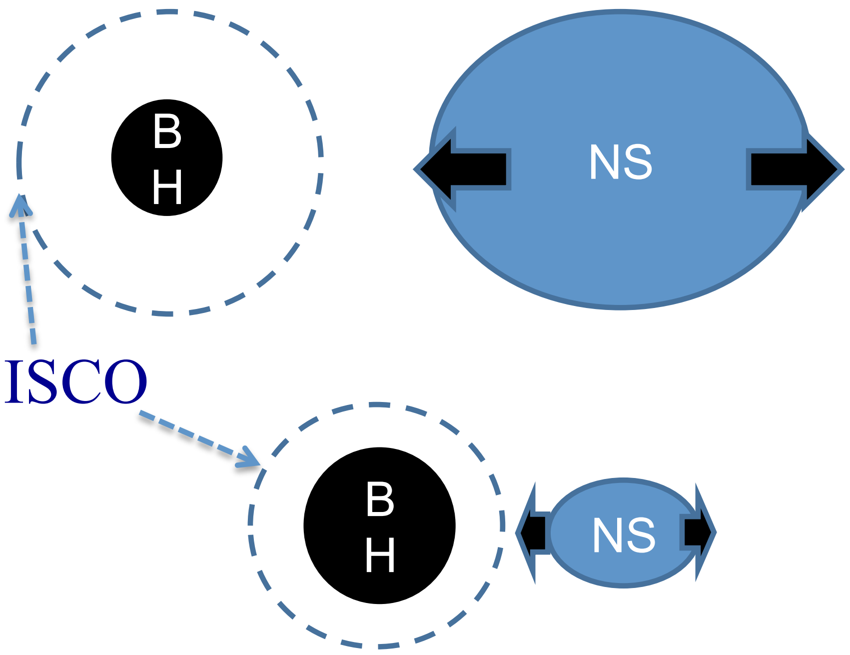
- **For tidal disruption**

❖ **Large NS Radius** **or**

❖ **Small BH mass** **or**

❖ **High corotation spin**

is necessary



BH-NS with aligned BH spin

$M_{\mathrm{BH}}=6.75M_{\mathrm{sun}}$
$a=0.75$
$M_{\mathrm{NS}}=1.35M_{\mathrm{sun}}$
$R=11.1$ km

$M_{\mathrm{BH}}=4.05M_{\mathrm{sun}}$
$a=0$
$M_{\mathrm{NS}}=1.35M_{\mathrm{sun}}$
$R=11.0$ km

BH-NS with aligned BH spin

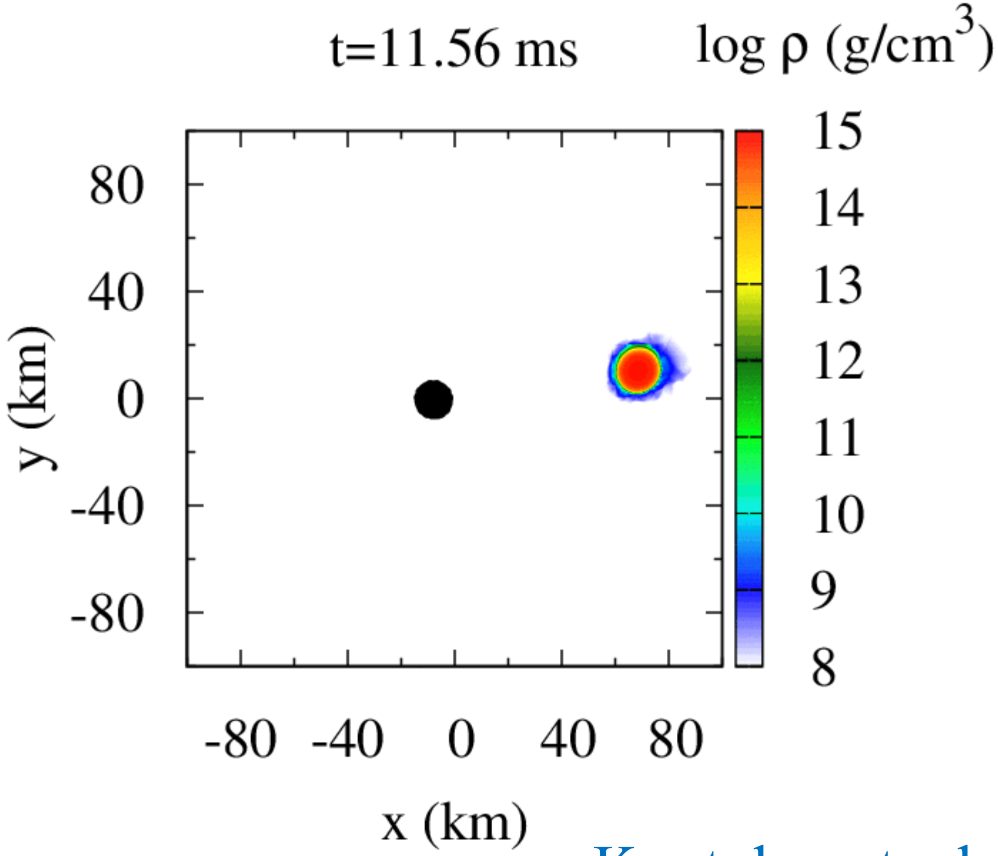
M_{BH}=6.75M_{sun}
a=0.75

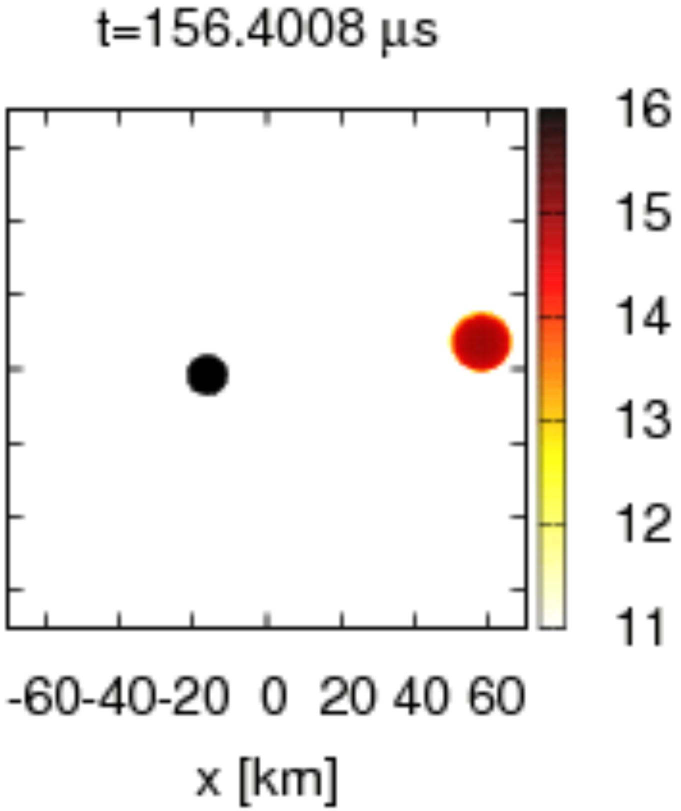
M_{NS}=1.35M_{sun}
R=11.1 km

↔

M_{BH}=4.05M_{sun}
a=0

M_{NS}=1.35M_{sun}
R=11.0 km





Kyutoku et al. 2011, 2015

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

⇓

High BH spin is necessary $> \sim 0.75$

Foucart et al. (2013, 2014); Kyutoku et al. (2015)

If high-mass BH, 20–30 solar mass, is standard,
tidal disruption is not very likely:
Only quite high−spin BH can tidally disrupt NS.

3 Gravitational waves
& equations of state

3A NS-NS case

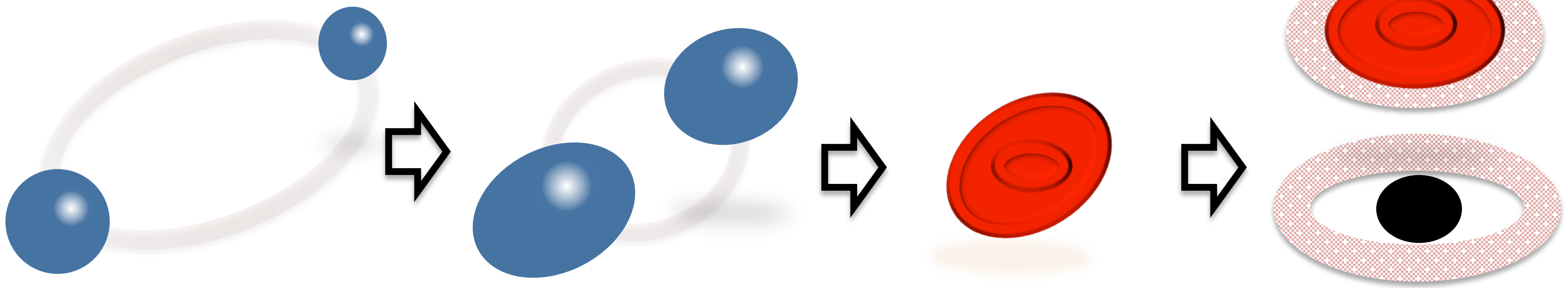
$M \sim 2.5 - 2.7 M_{\rm sun}$

Early Inspiral
($r_{\rm orb} >> R_{\rm NS}$)

Late inspiral
($r_{\rm orb} \leq 5 R_{\rm NS}$)

Merger =>
Massive NS

Black hole/MNS
+ torus → GRB?



Point mass +
adiabatic phase

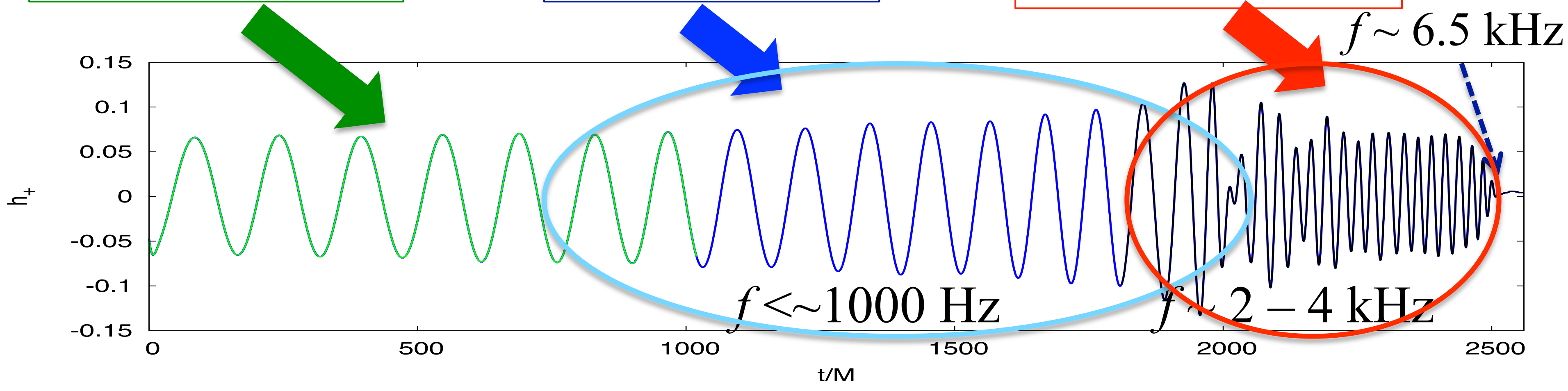
Tidally deformed phase

Dynamical & GR phase

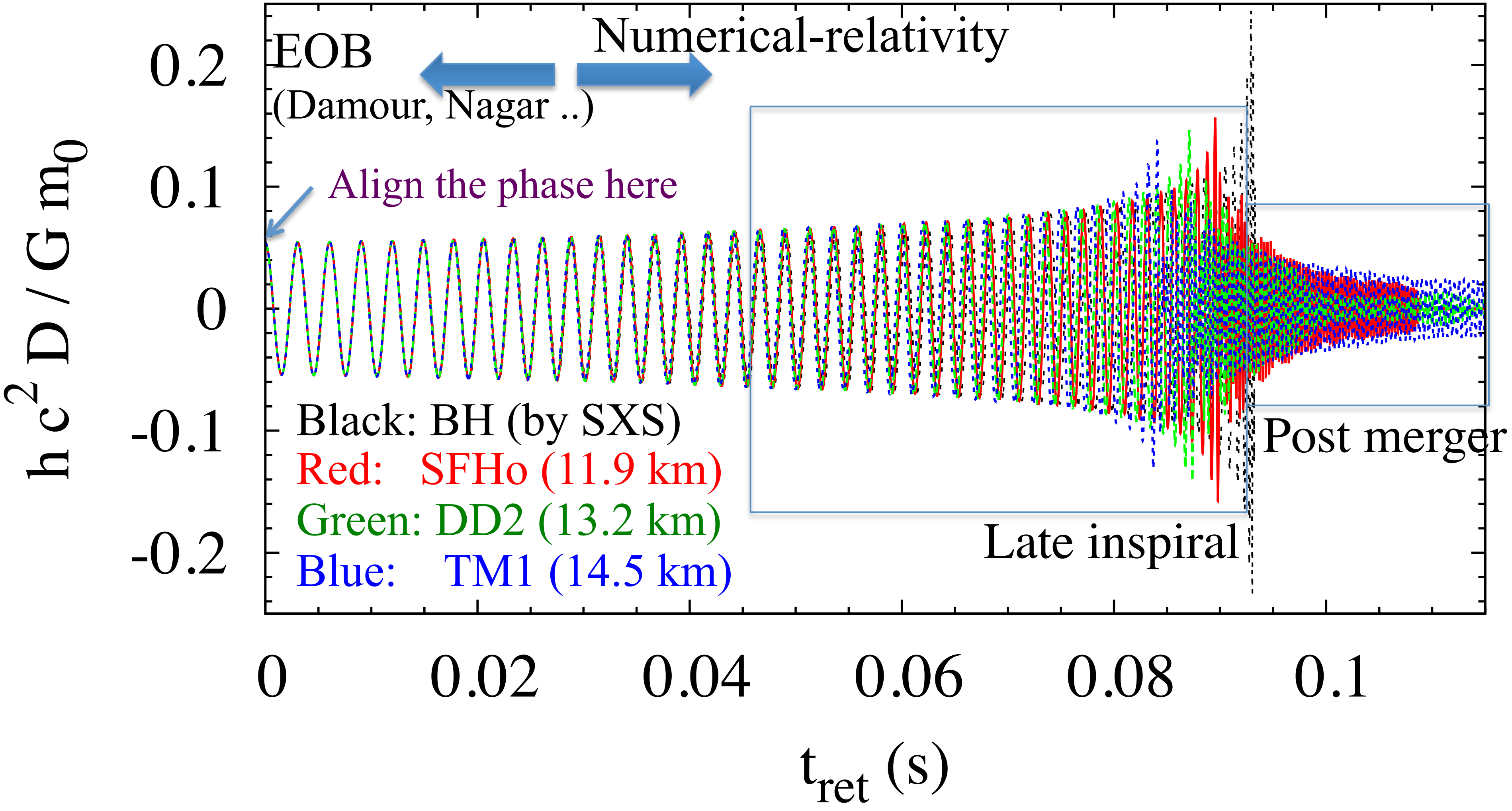
Post-Newtonian

Late inspiral

Post merger
Massive NS/BH

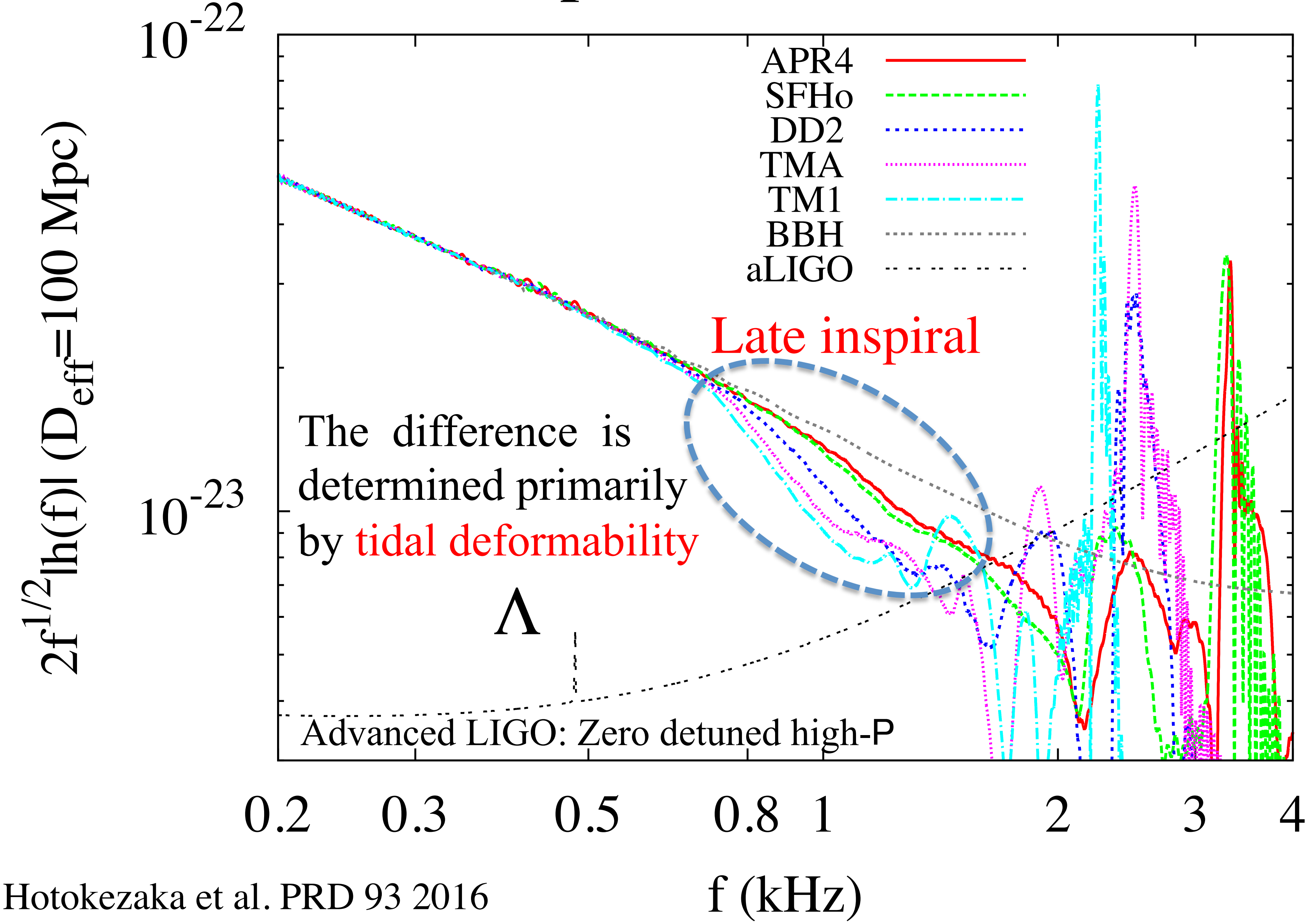


Gravitational waveform from NS-NS:
hybrid waveform (1.35-1.35 solar mass)



Hotokezaka et al. 2016 (see also efforts by Bernuzzi,…2011–)

Spectrum



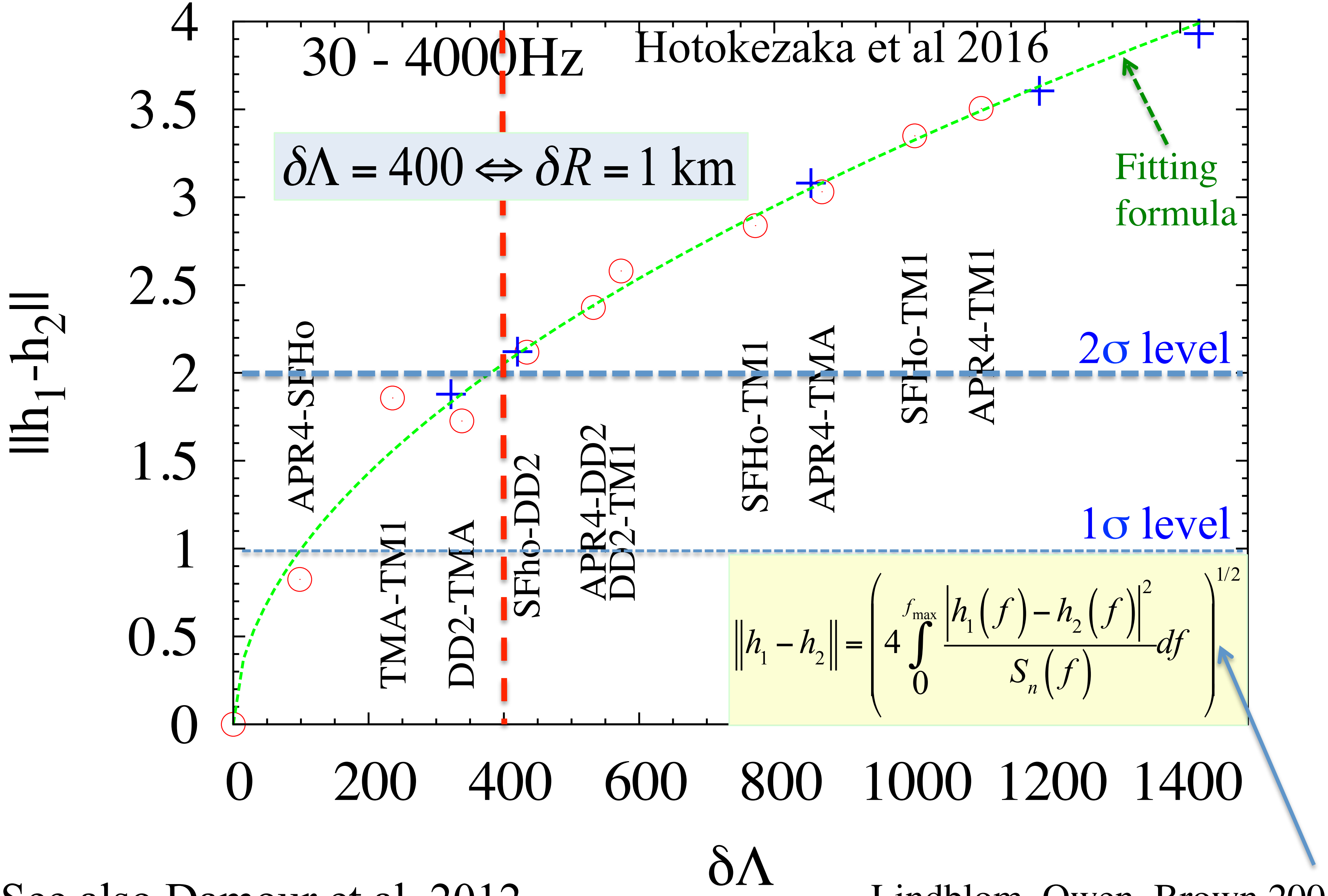
Late inspiral

The difference is determined primarily by tidal deformability

Λ

Hotokezaka et al. PRD 93 2016

Measurability @D_{eff}=200Mpc (SNR ~ 17)



30 - 4000Hz

Hotokezaka et al 2016

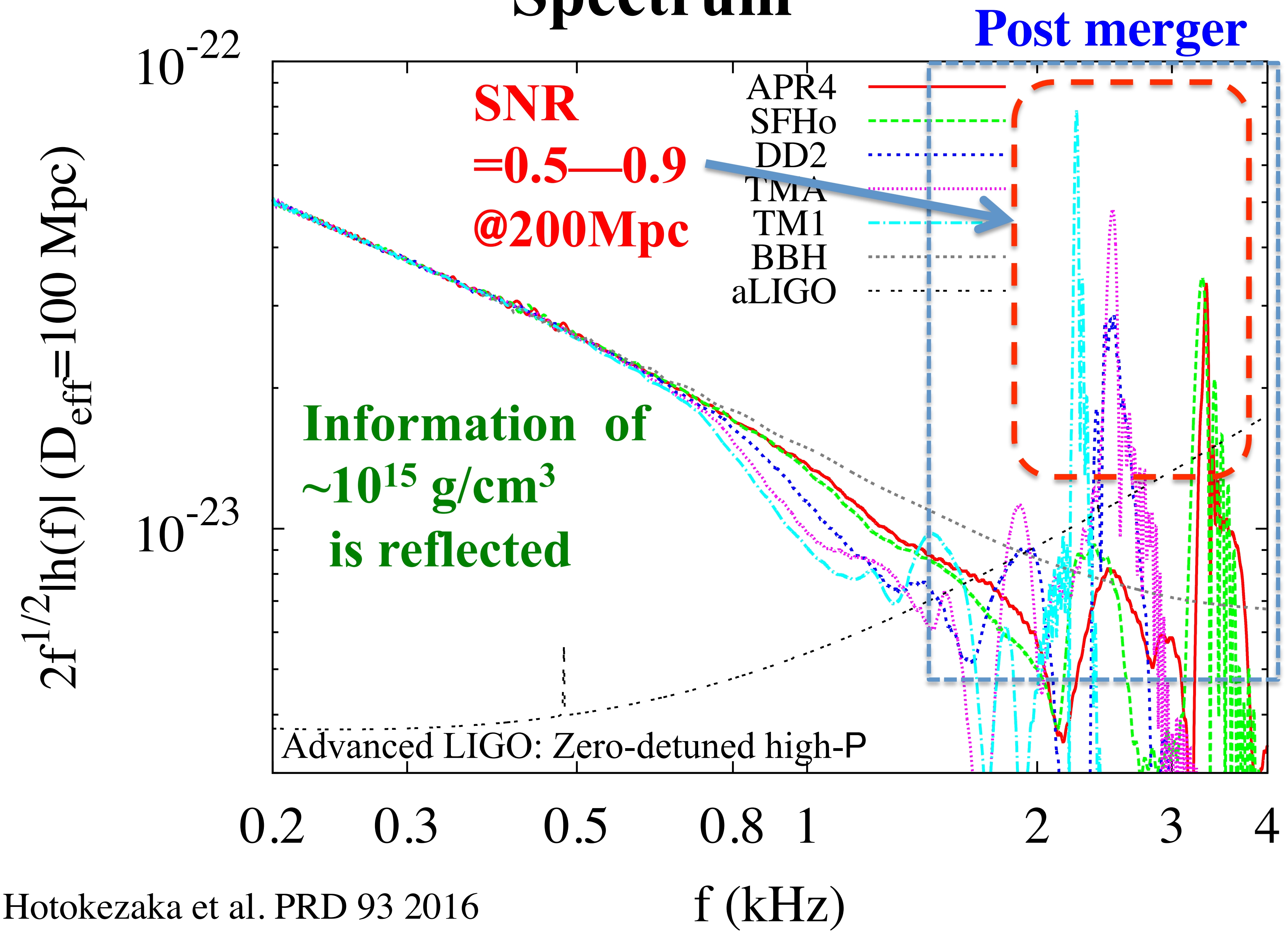
$\delta\Lambda = 400 \Leftrightarrow \delta R = 1$ km

$$\left\| h_1 - h_2 \right\| = \left(4 \int_0^{f_{\max}} \frac{\left| h_1(f) - h_2(f) \right|^2}{S_n(f)} df \right)^{1/2}$$

Lindblom, Owen, Brown 2008

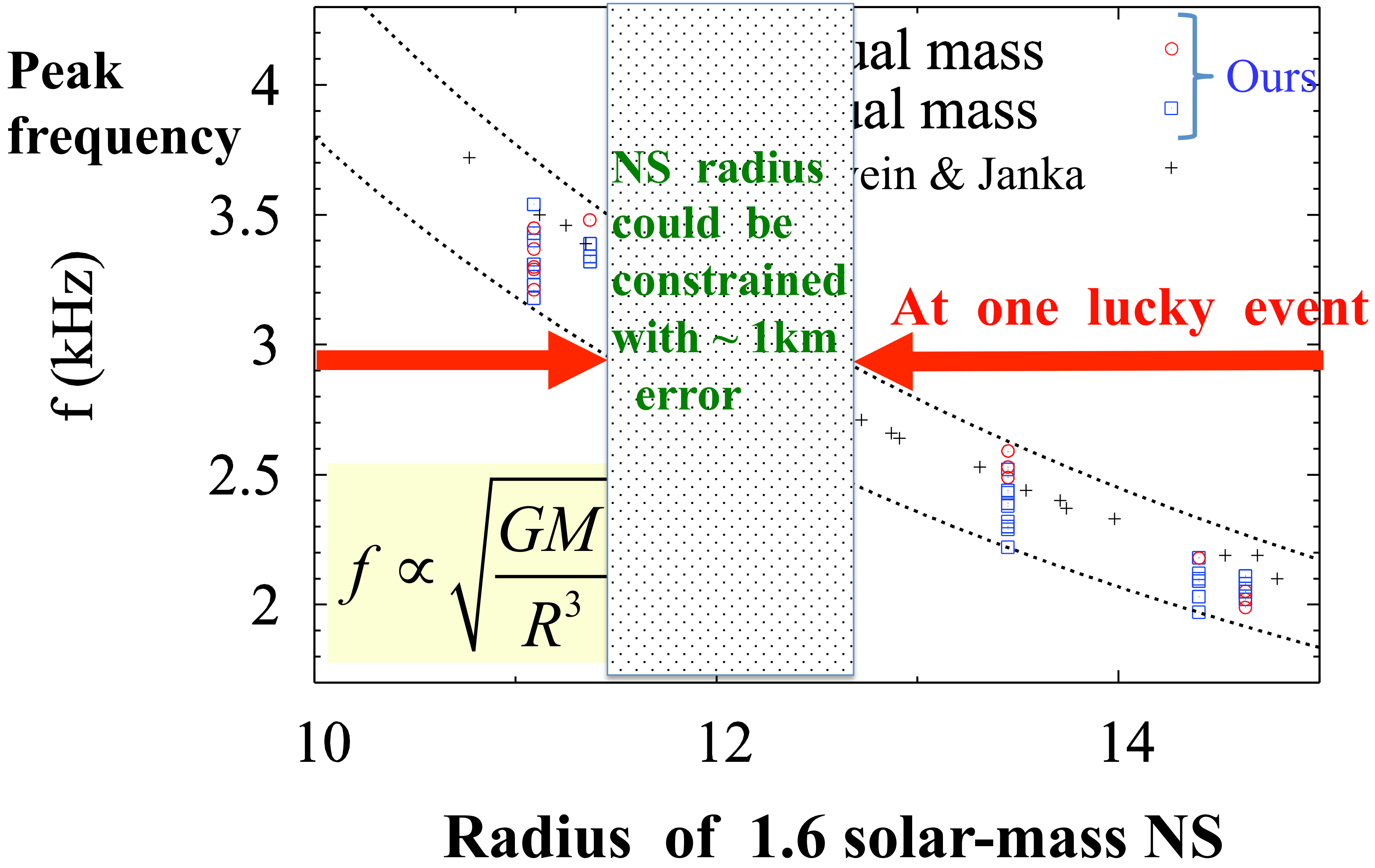
See also Damour et al. 2012

Spectrum



Hotokezaka et al. PRD 93 2016

Clear correlation between peak and radius



$$f \propto \sqrt{\frac{GM}{R^3}}$$

NS radius could be constrained with ~ 1km error

At one lucky event

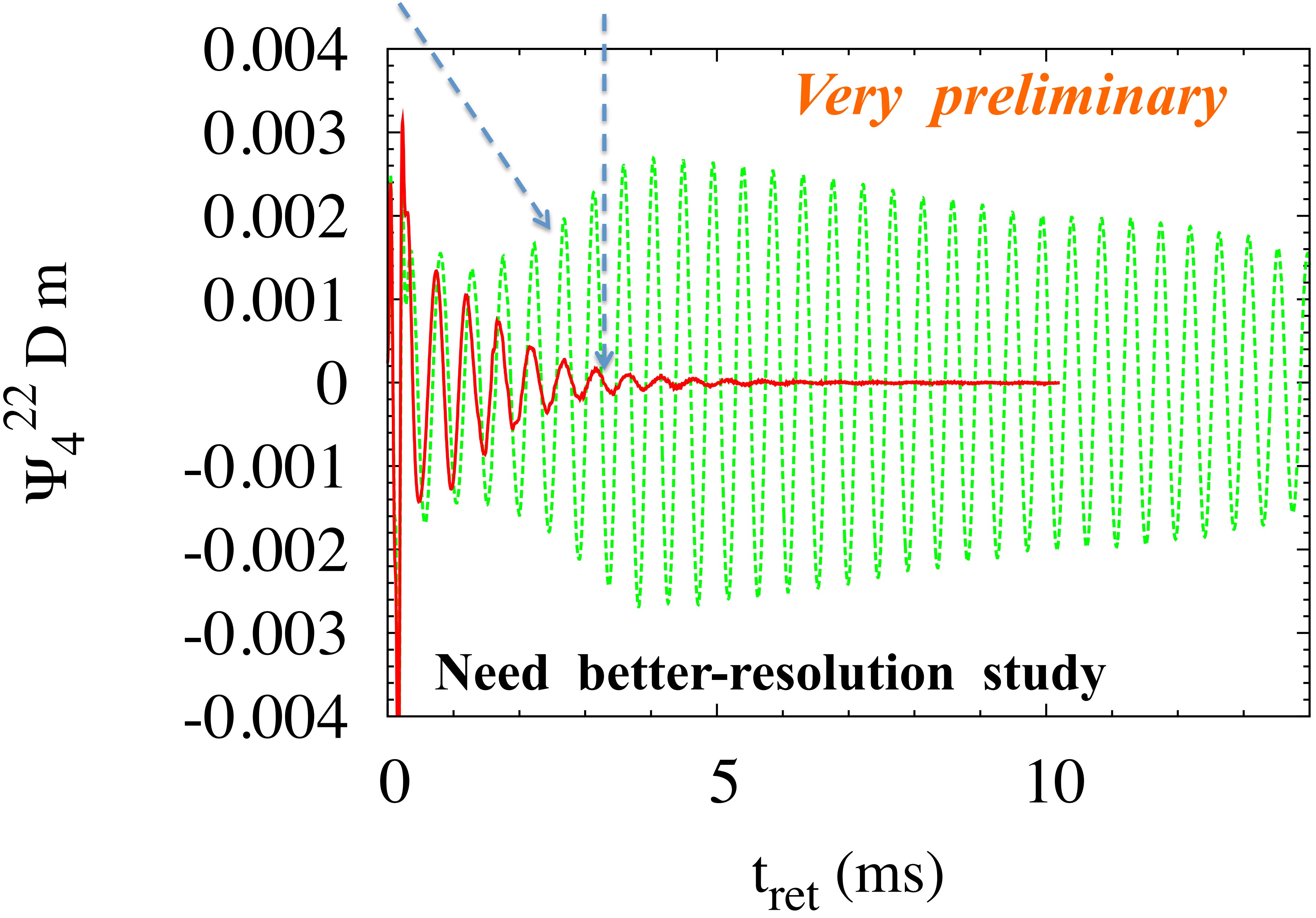
Caveat

- Merger waveforms have been computed in quite simple setting (essentially, pure hydro)
- **Post-merger phase would be in reality determined by complicated physics**
- **Turbulence** will be excited by MHD instability (e.g., **Kelivin-Helmholtz instability, MRI;** Kiuchi's talk)

→ Magnetic fields would be amplified to ~ 10^{16} G

→ Turbulent viscosity could change velocity profile, modifying waveform ?? (but no detailed simulation)

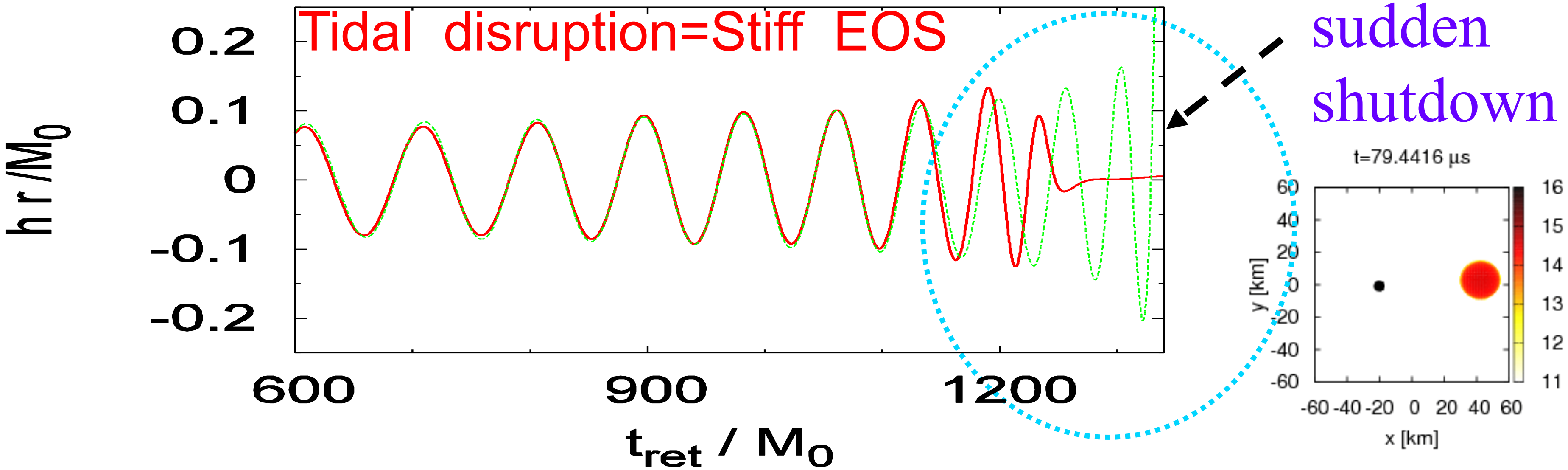
Pure hydro vs **viscous hydro (α_{vis}~0.02)**



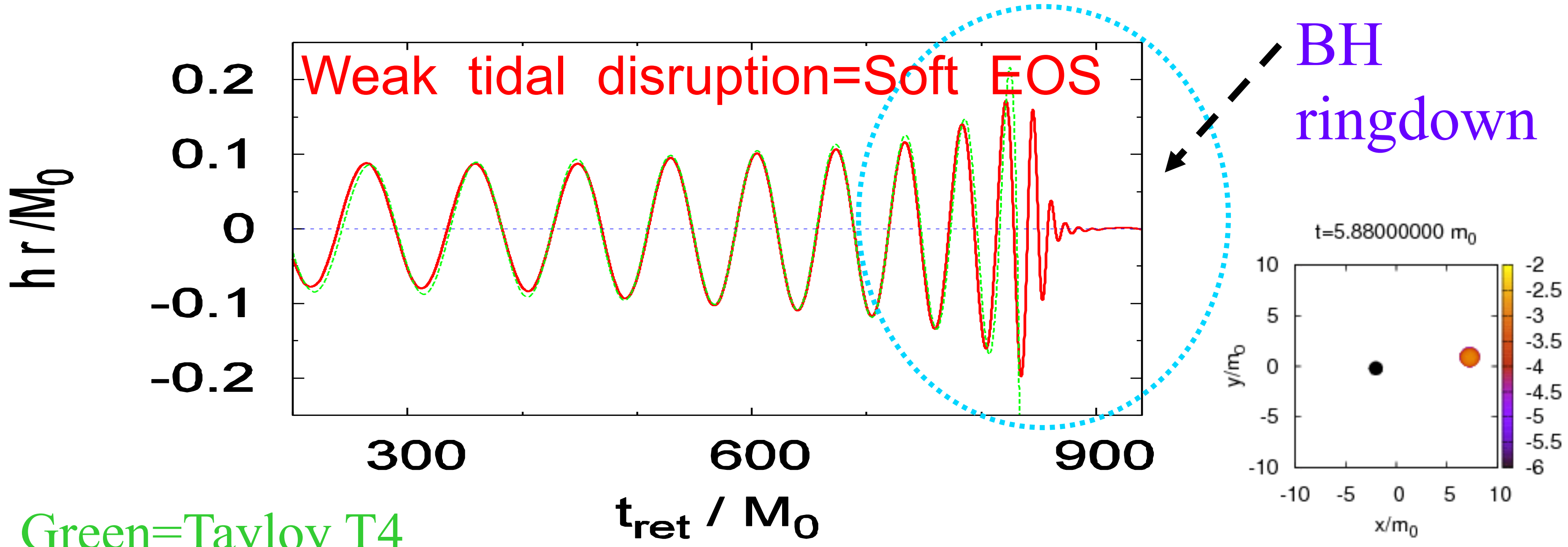
Very preliminary

Need better-resolution study

3B BH-NS: Signal of tidal disruption



sudden shutdown

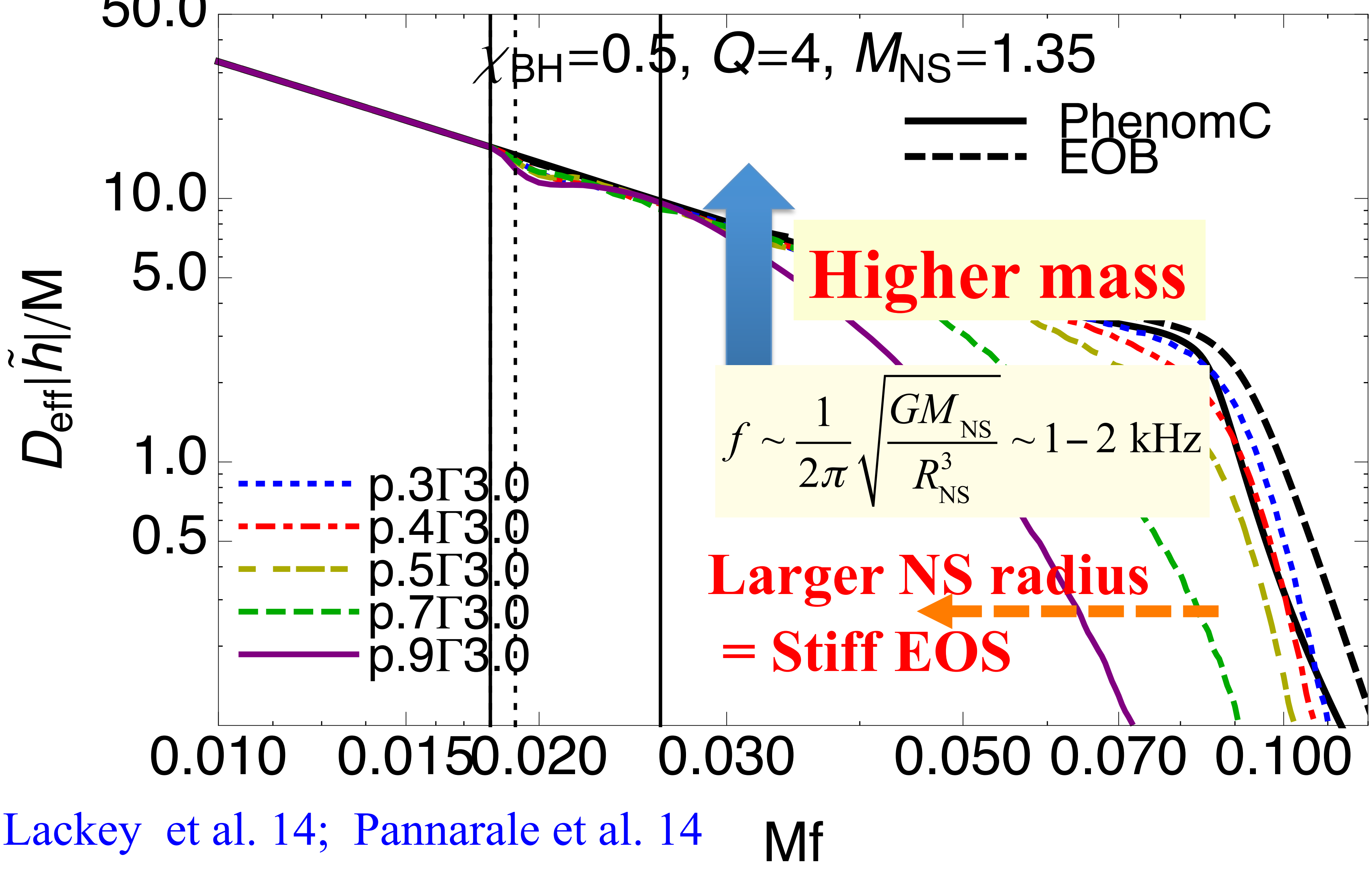


BH ringdown

Green=Tayloy T4

BH-NS Fourier spectrum

For all, a=0.5, 1.35-5.40$M_{\rm sun}$



Higher mass

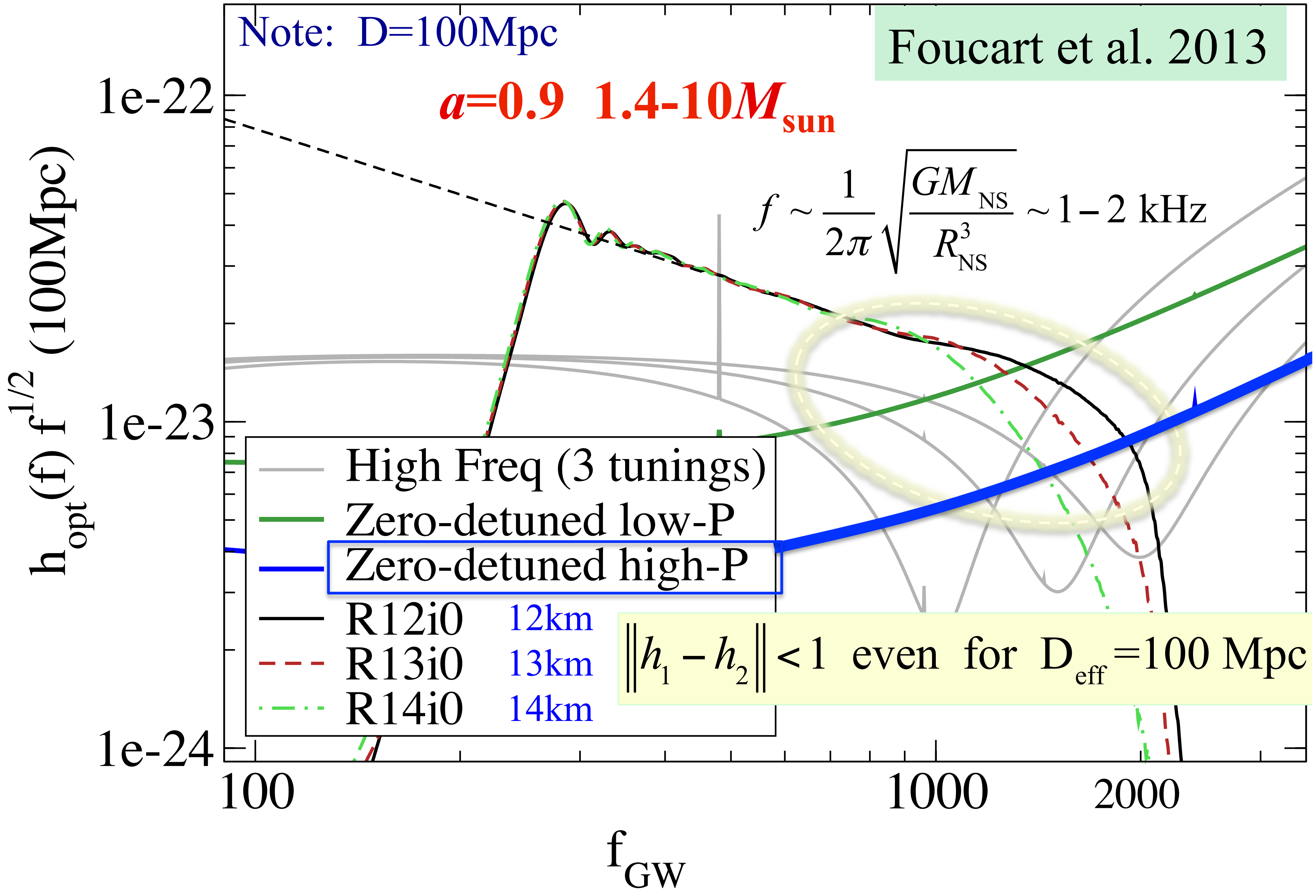
$$f \sim \frac{1}{2\pi}\sqrt{\frac{GM_{\rm NS}}{R_{\rm NS}^3}} \sim 1-2\ {\rm kHz}$$

Larger NS radius

= Stiff EOS

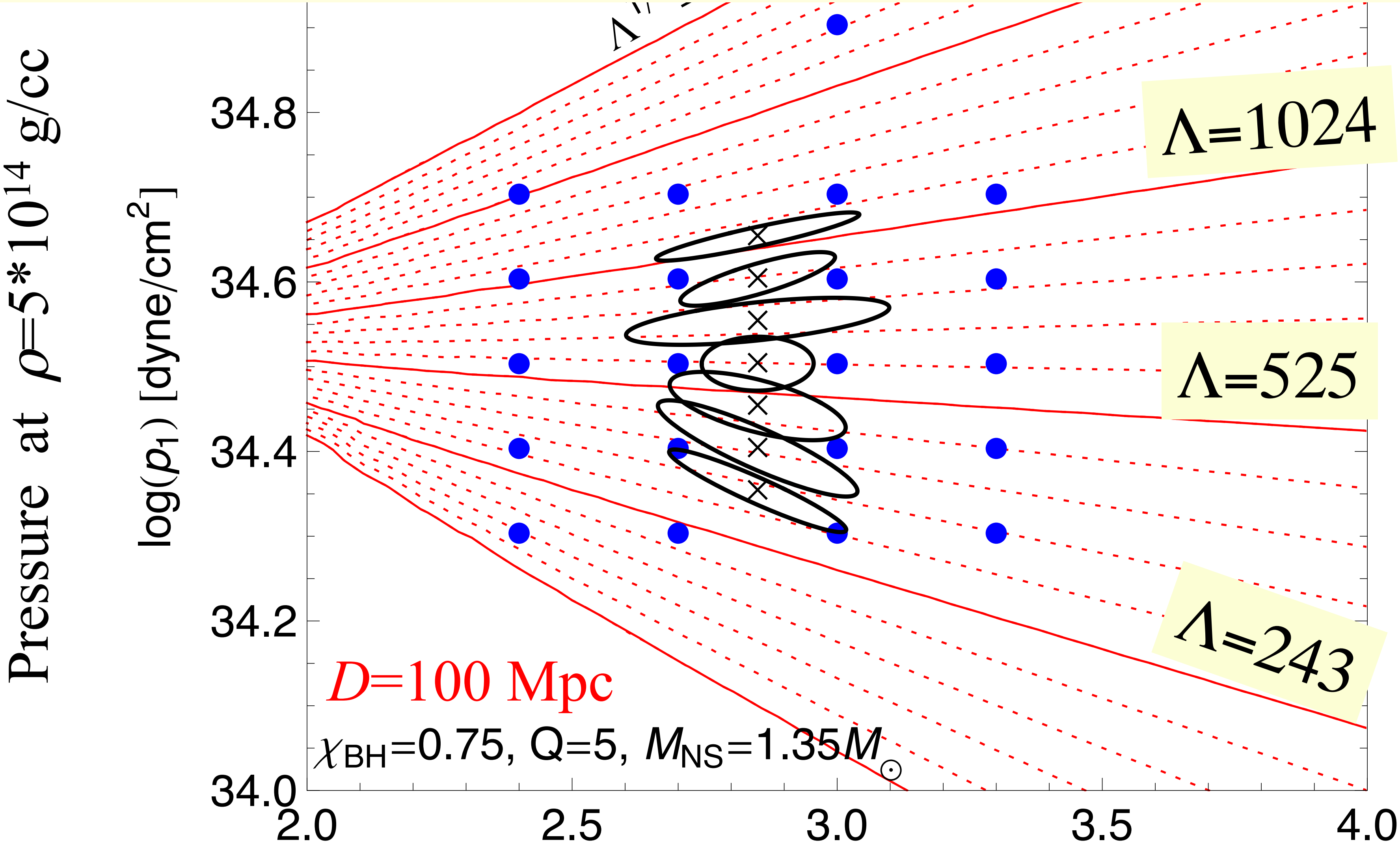
Lackey et al. 14; Pannarale et al. 14

Cutoff frequency is high, and SNR is small



$\|h_1 - h_2\| < 1$ even for D_{eff} =100 Mpc

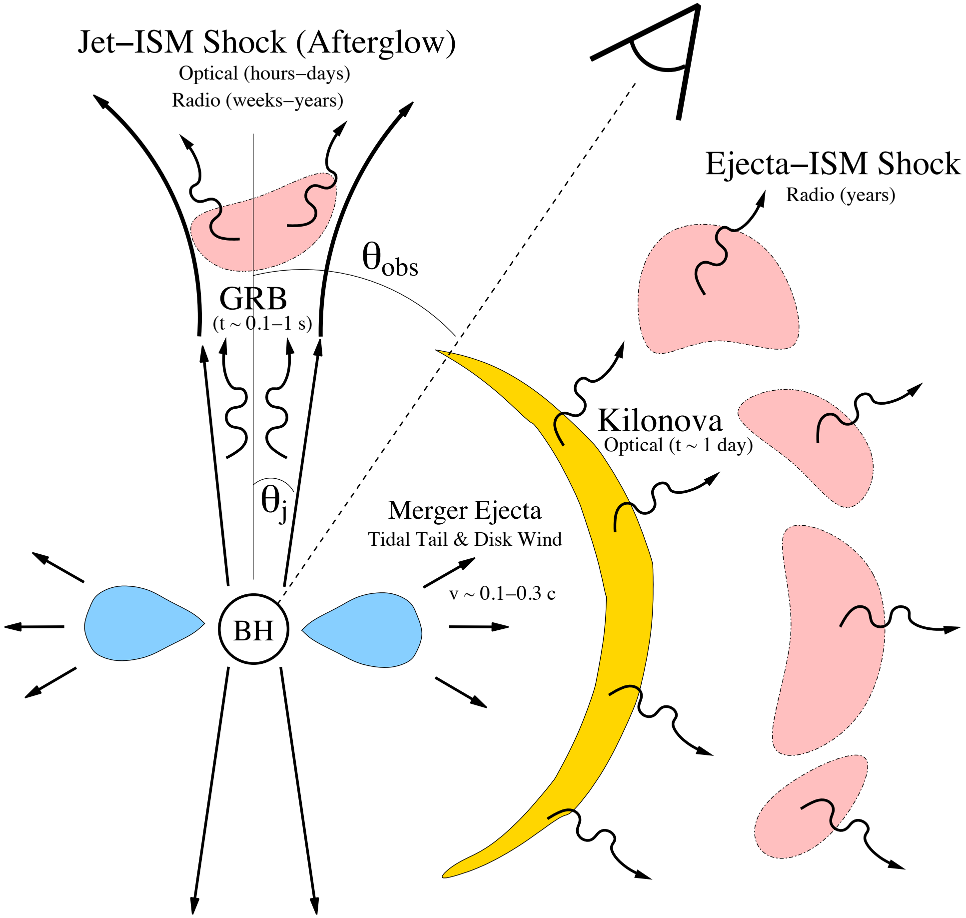
Data analysis using numerical-relativity data:
ET level (or nearby event) is necessary



Lackey et al. (2014)

4 Mass ejection

Metzger & Berger 2012



In binary merger, neutron-rich matter is ejected and it could shine (Piran's talk)

→ NR should clarify the ejecta properties

For radioactive (macronova) scenario

(Li-Paczynski ‘98)

$$L_{\max} \sim 4\times10^{41}\ \text{ergs/s}\left(\frac{\overset{\substack{\text{Ejecta mass}\\ \downarrow}}{M}}{0.01M_{\odot}}\right)^{1/2}\left(\frac{\overset{\substack{\text{Velocity}\\ \downarrow}}{v}}{0.2c}\right)^{1/2}\left(\frac{\overset{\substack{\text{Opacity(composition)}\\ \downarrow}}{\kappa}}{10\ \text{cm}^2/\text{g}}\right)^{-1/2}\left(\frac{f_{\text{r-proc}}}{3\times10^{-6}}\right)$$

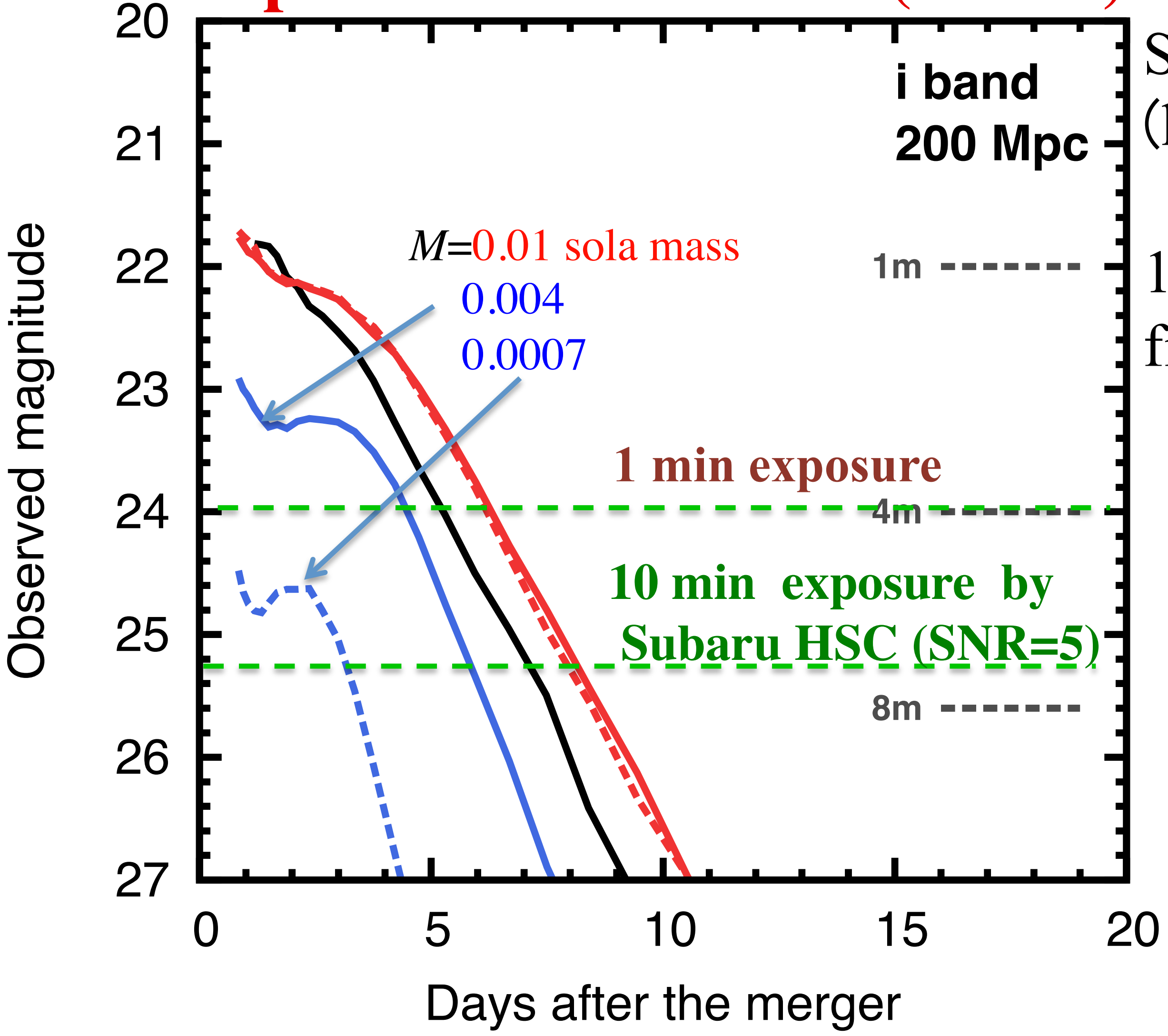
$$\text{at}\ \ t\sim5\ \text{days}\left(\frac{M}{0.01M_{\odot}}\right)^{1/2}\left(\frac{v}{0.2c}\right)^{-1/2}\left(\frac{\kappa}{10\ \text{cm}^2/\text{g}}\right)^{1/2}$$

$$3\times10^{41}\ \text{ergs/s} \Leftrightarrow \text{M}=-15.0\ \text{mag} \Rightarrow \text{m=21.5 mag}\ \ @\ 200\text{Mpc}$$

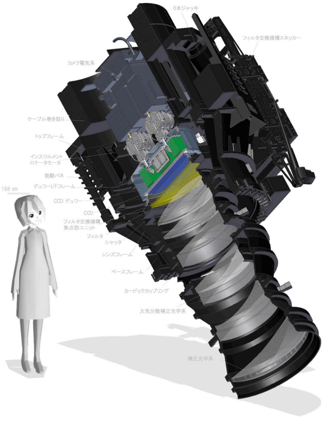
Bright in near−infrared for 1 week after the merger

Expected light curves @ 200Mpc

Optical/Near infrared (i band)



Subaru HSC
(hyper-supreme
-camera)
1.75 deg^2
field of view

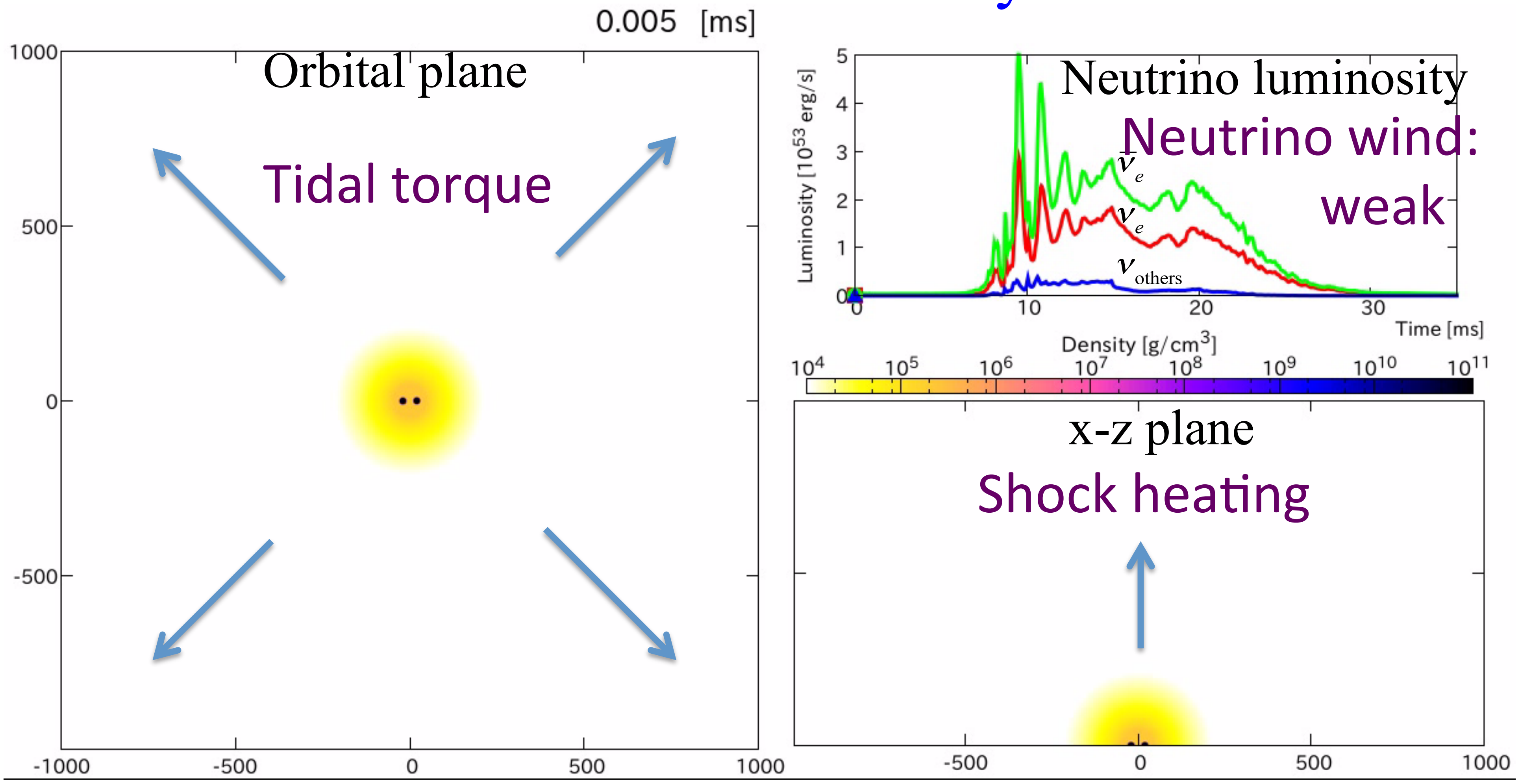


Tanaka & Hotoke 2013; see also Barnes & Kasen 2013, 2016

Neutrino-radiation hydrodynamics simulation

SFHo (R~11.9 km): 1.35-1.35 M_{sun}

Rest-mass density



Orbital plane

Tidal torque

Neutrino luminosity

Neutrino wind: weak

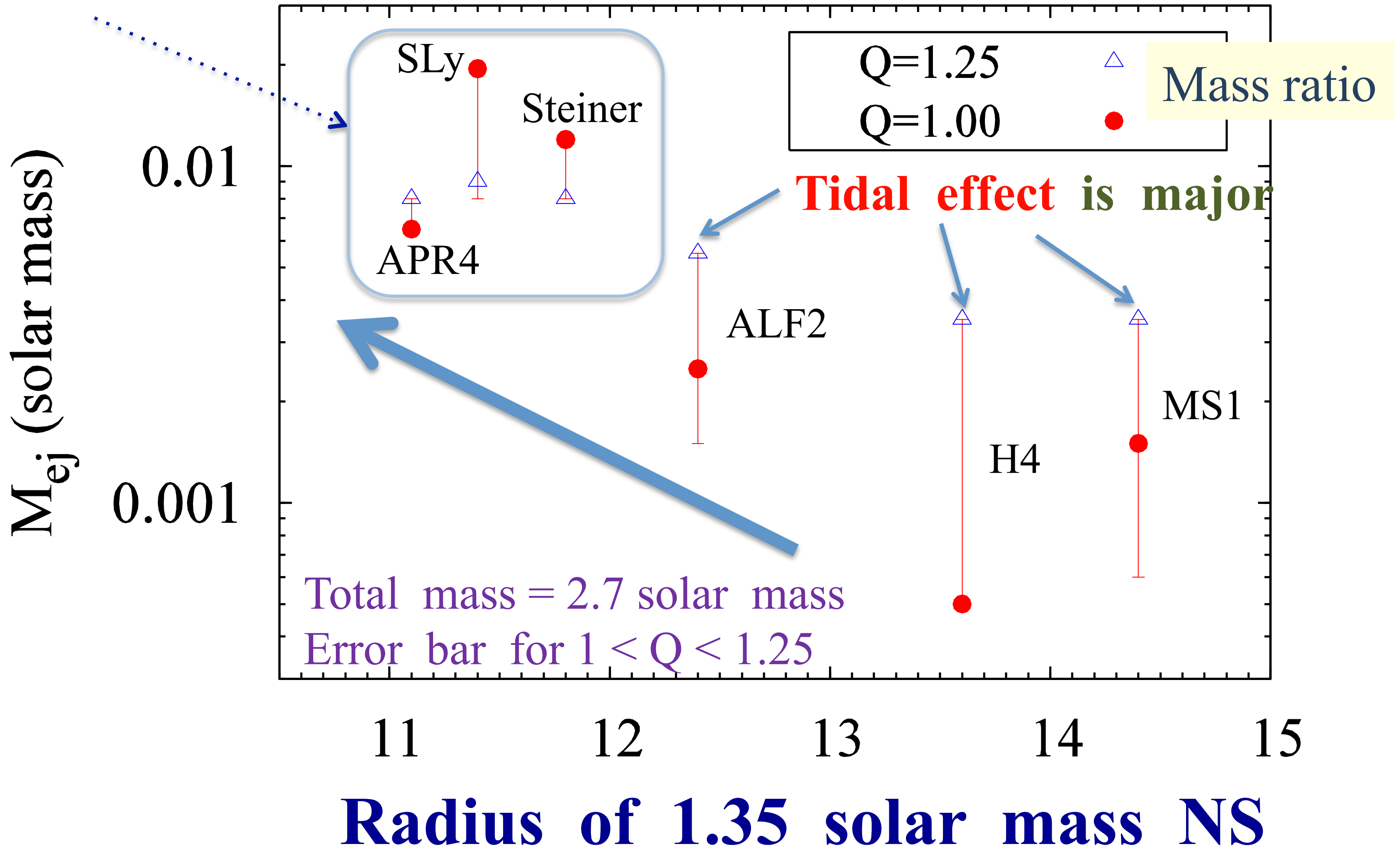
x-z plane

Shock heating

Sekiguchi et al. 2015

Ejecta mass depends on EOS : NS-NS case

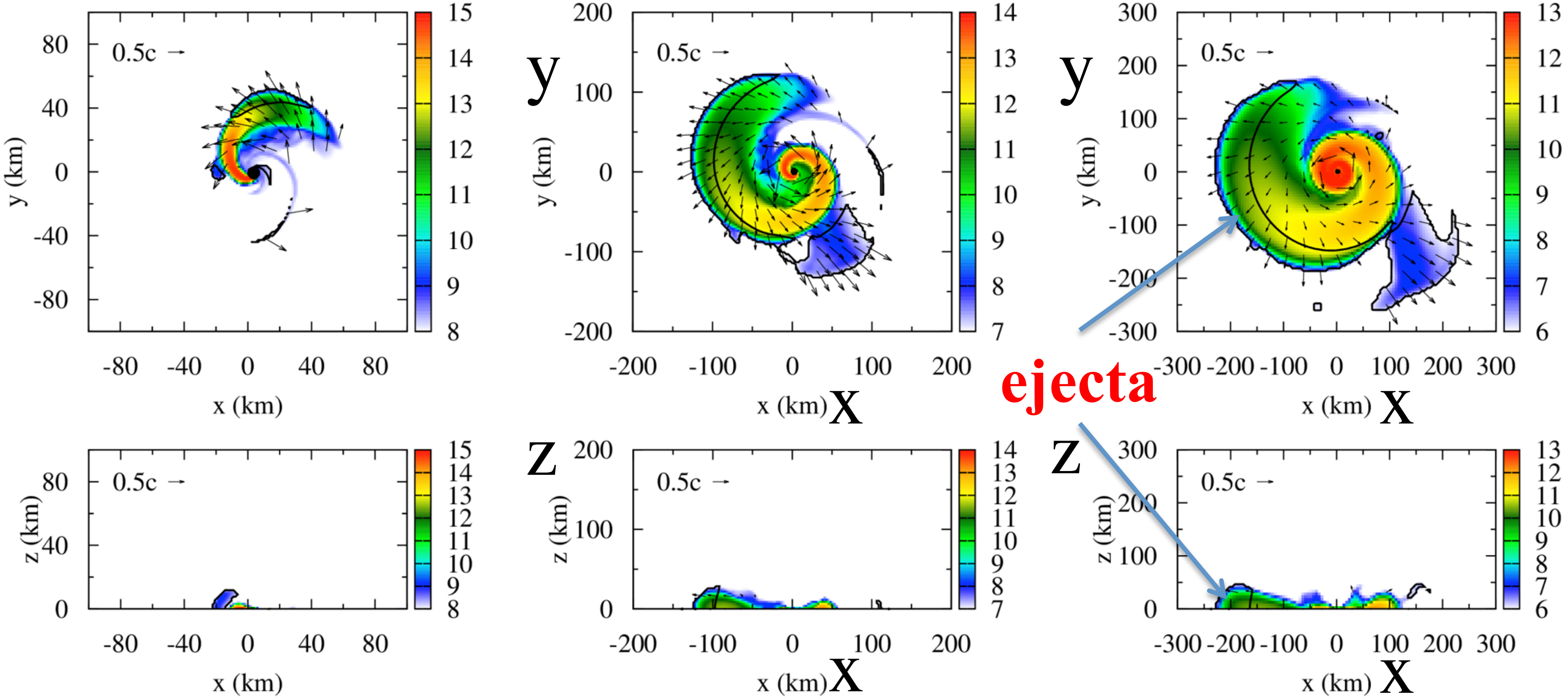
Soft EOS → strong gravity → SHOCK → high-mass ejection



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

BH-NS: disruption → ejection

Tidal torque by BH induces mass ejection



ejecta

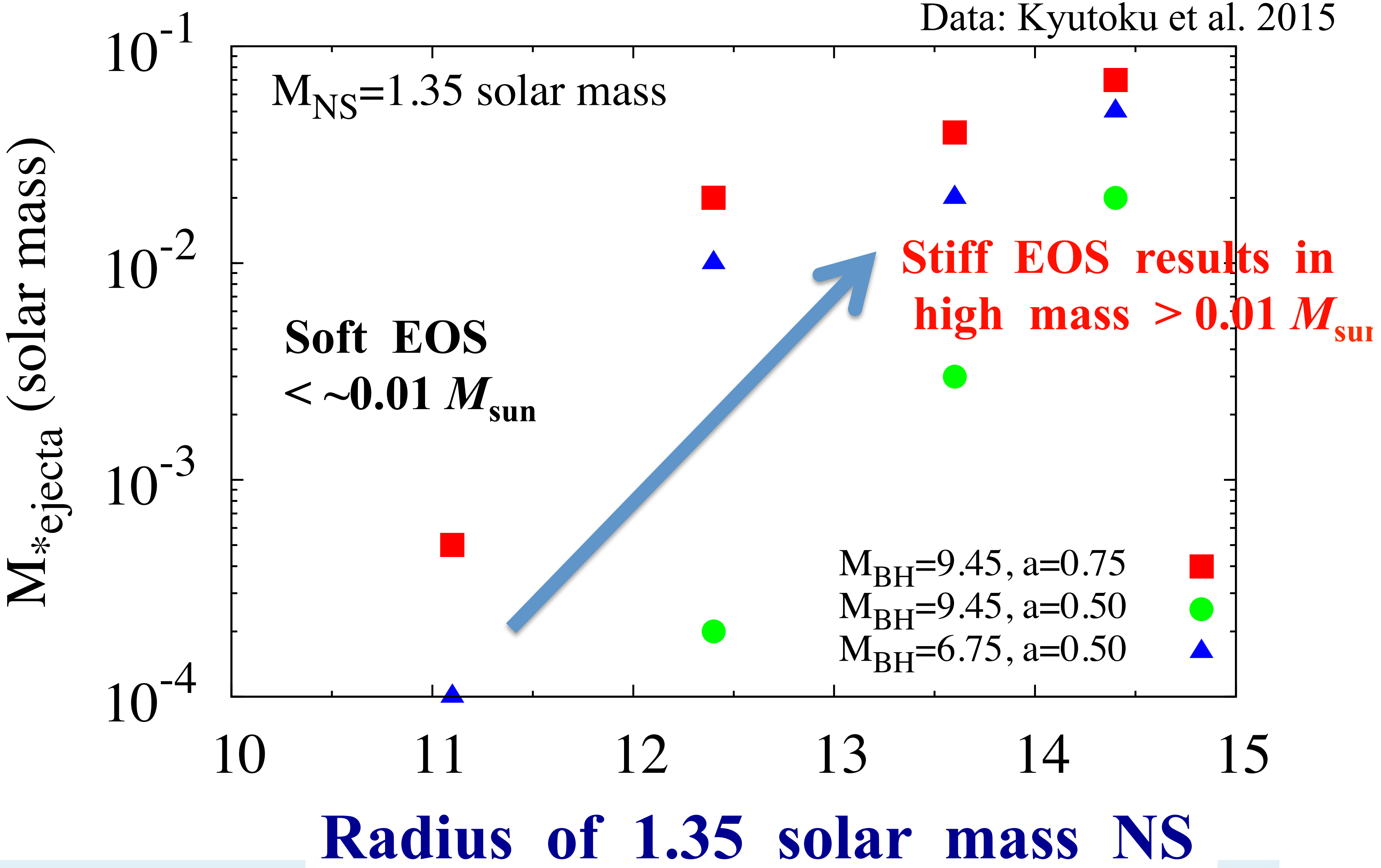
Anisotropic ejection along the orbital plane:

Note: Disk wind is not taken into account.

Kyutoku et al. 2015

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

Data: Kyutoku et al. 2015



Soft EOS
$< \sim 0.01\ M_{\mathrm{sun}}$

Stiff EOS results in high mass $> 0.01\ M_{\mathrm{su}}$

High BH spin is important for mass ejection

Dynamical ejecta properties in numerical relativity

- **Mass:**

➢ NS-NS: **~10^{-3}—0.02 $M_{\rm sun}$** depending on each mass & EOS: **Soft EOS is favorable**
(Hotoke+ 13, Sekiguchi+ 15,16, Radice+ 16, Lehner+ 15,16)

➢ BH-NS: **0—0.1 $M_{\rm sun}$** depending on each mass, BH spin, & EOS: **Stiff EOS is favorable; high BH spin is also the key** (Foucart+13,14, Kyutoku+15)

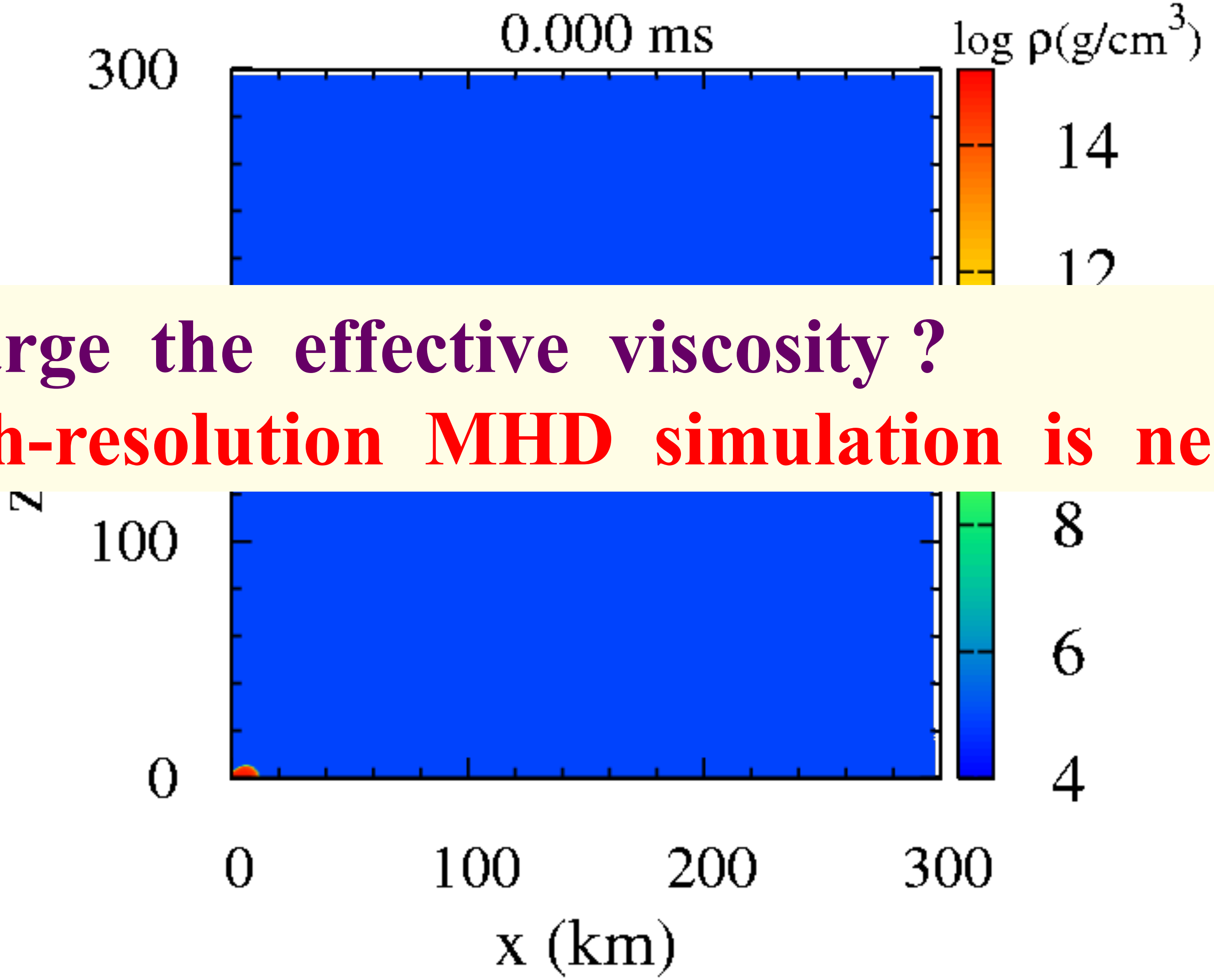
➢ **Typical velocity:** 0.15—0.25 c; max ~ 0.8 c

⬇

Detectable for macronova from NS-NS by 8-m class telescopes

Other effects ?

Viscous hydrodynamics (α_v=0.02): *preliminary*

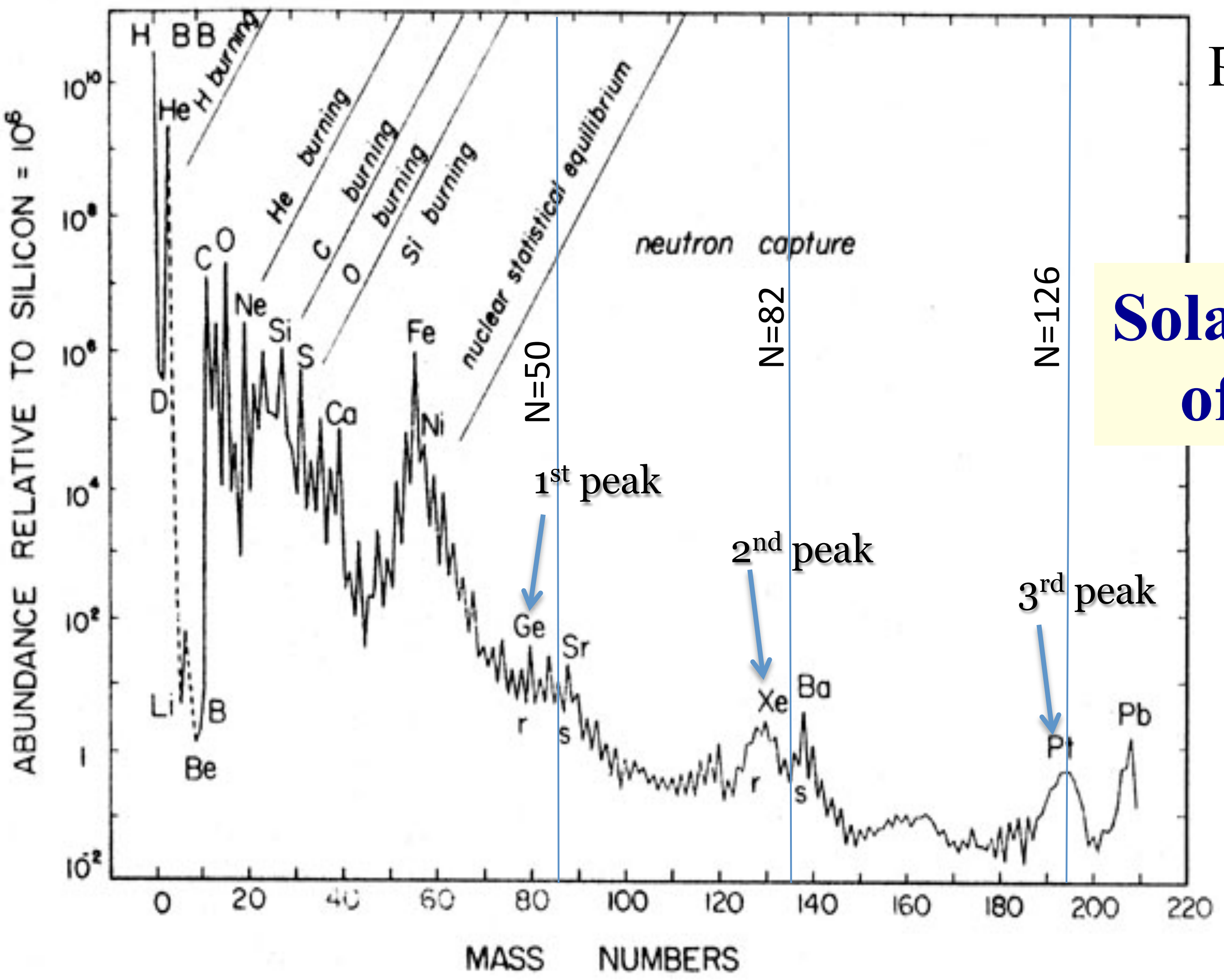


How large the effective viscosity ?

→ High-resolution MHD simulation is needed

See Fernandez & Metzger, Perego+, Just+ for related works

5 R-process nucleosynthesis



Pagel (1997)

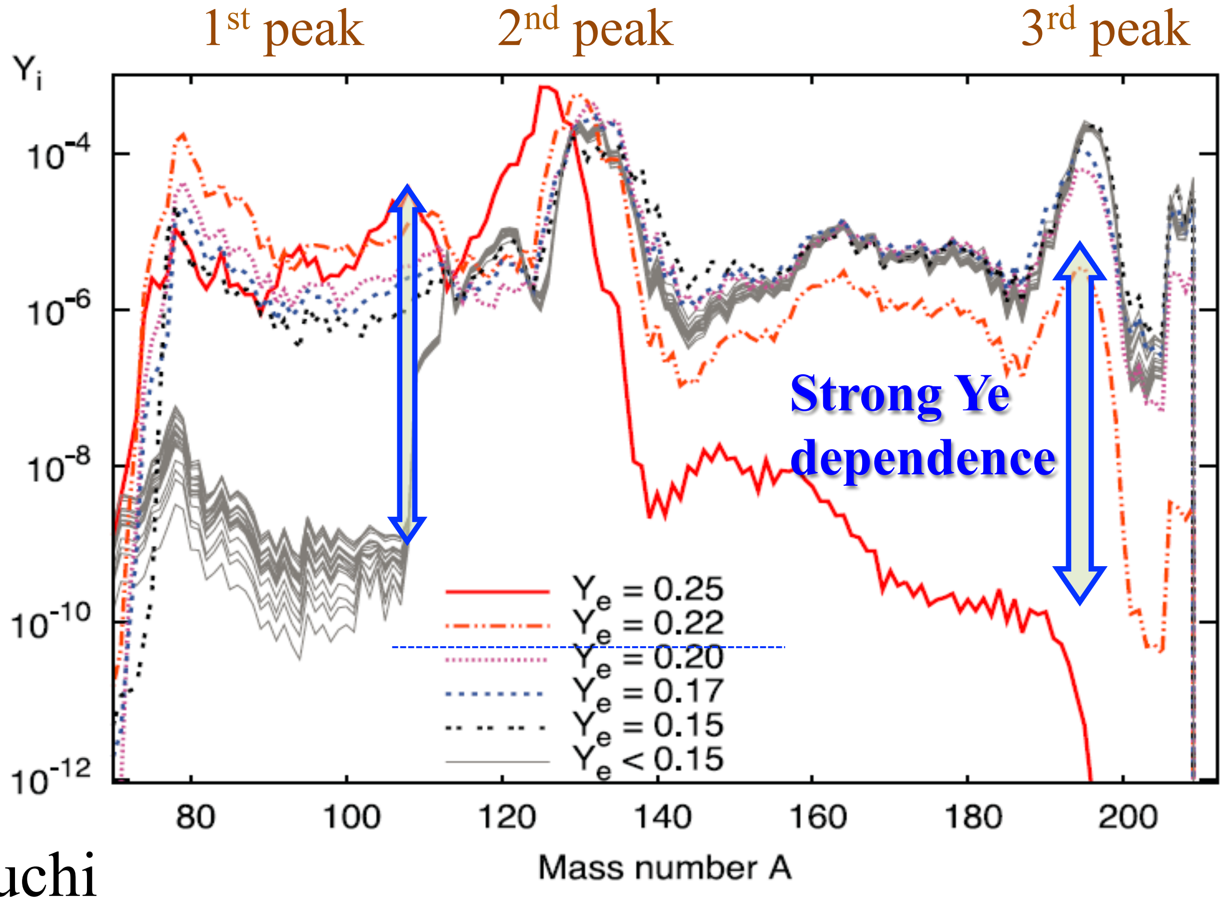
Solar abundance of elements

Key = electron fraction: $Y_e=[p]/([n]+[p])$

Courtesy Sekiguchi

Importance of Y_e=[p]/([p]+[n]) in r-process

- **$Y_e \sim$ 0.2-0.25 is critical threshold**
  - – $Y_e < 0.22$: strong r-process ⇒ nuclei with $A > 130$
  - – $Y_e > 0.22$: weak r-process ⇒ nuclei with $A < 130$



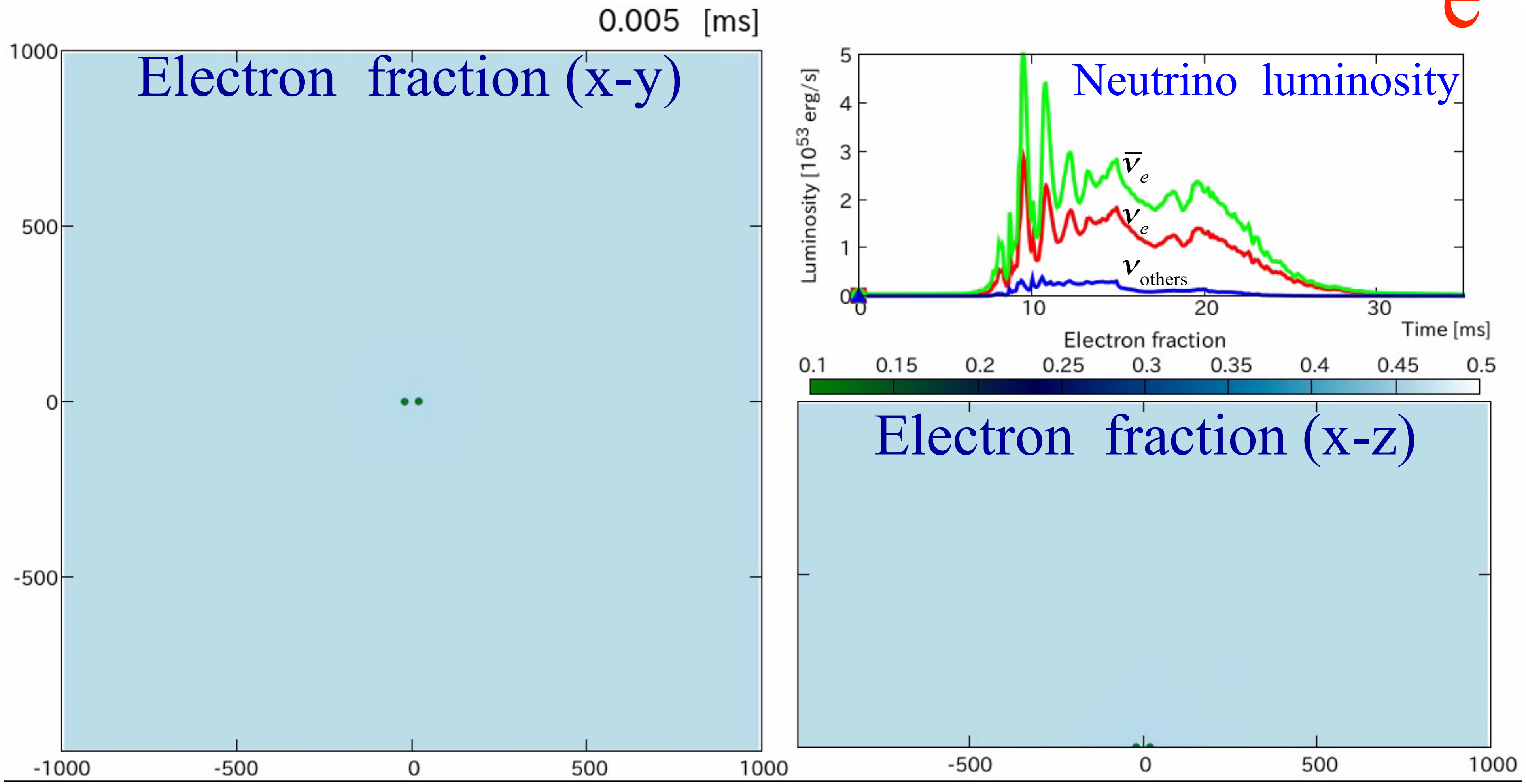
Korobkin et al. 2012

Courtesy Sekiguchi

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

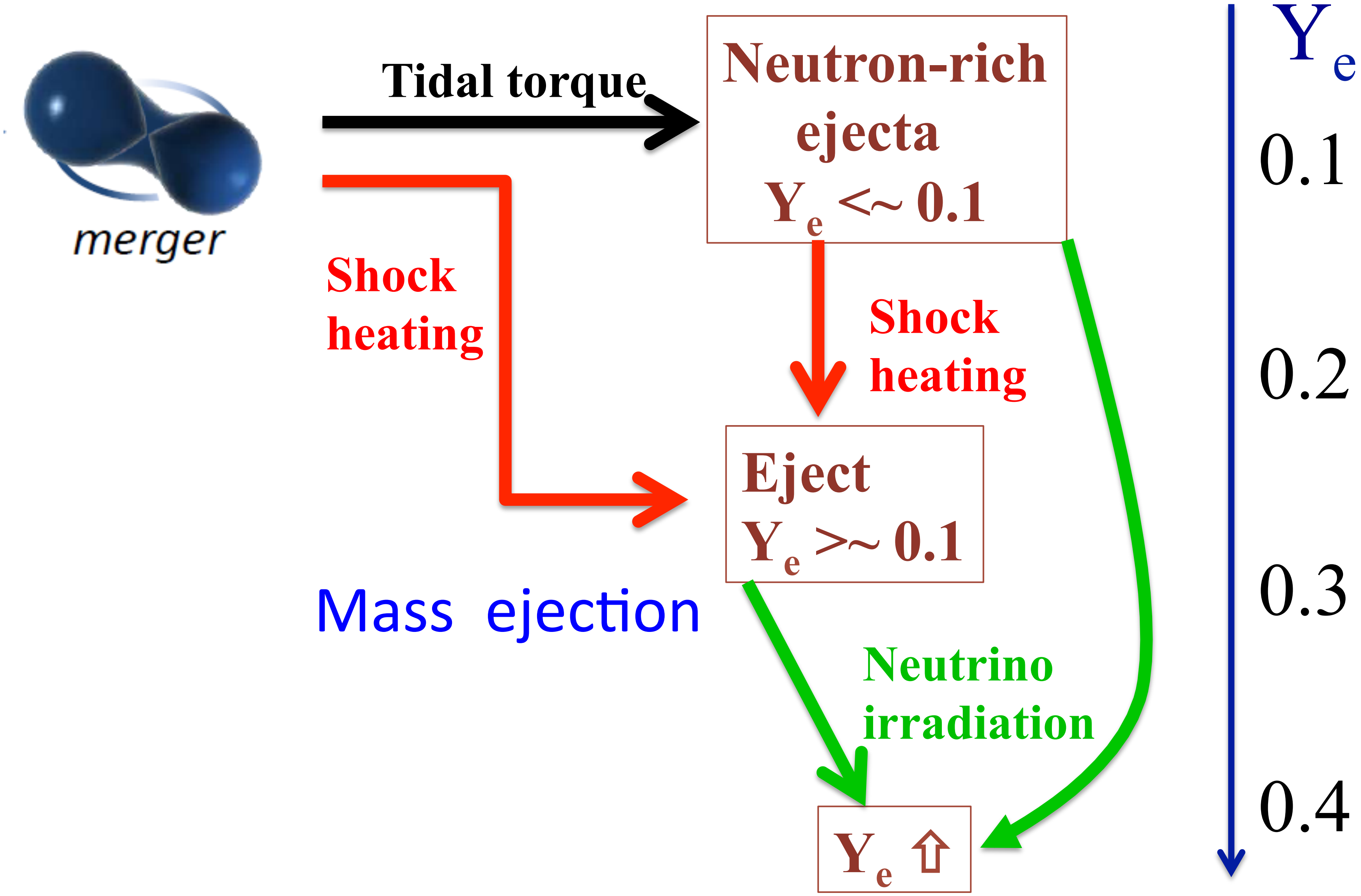
Neutrino irradiation ⇒ $n + \nu \rightarrow p + e^-$

Y_e



Sekiguchi et al. (2015)

Dynamical evolution of neutron richness



merger

Tidal torque

Neutron-rich ejecta
Y_e <~ 0.1

Shock heating

Shock heating

Eject
Y_e >~ 0.1

Mass ejection

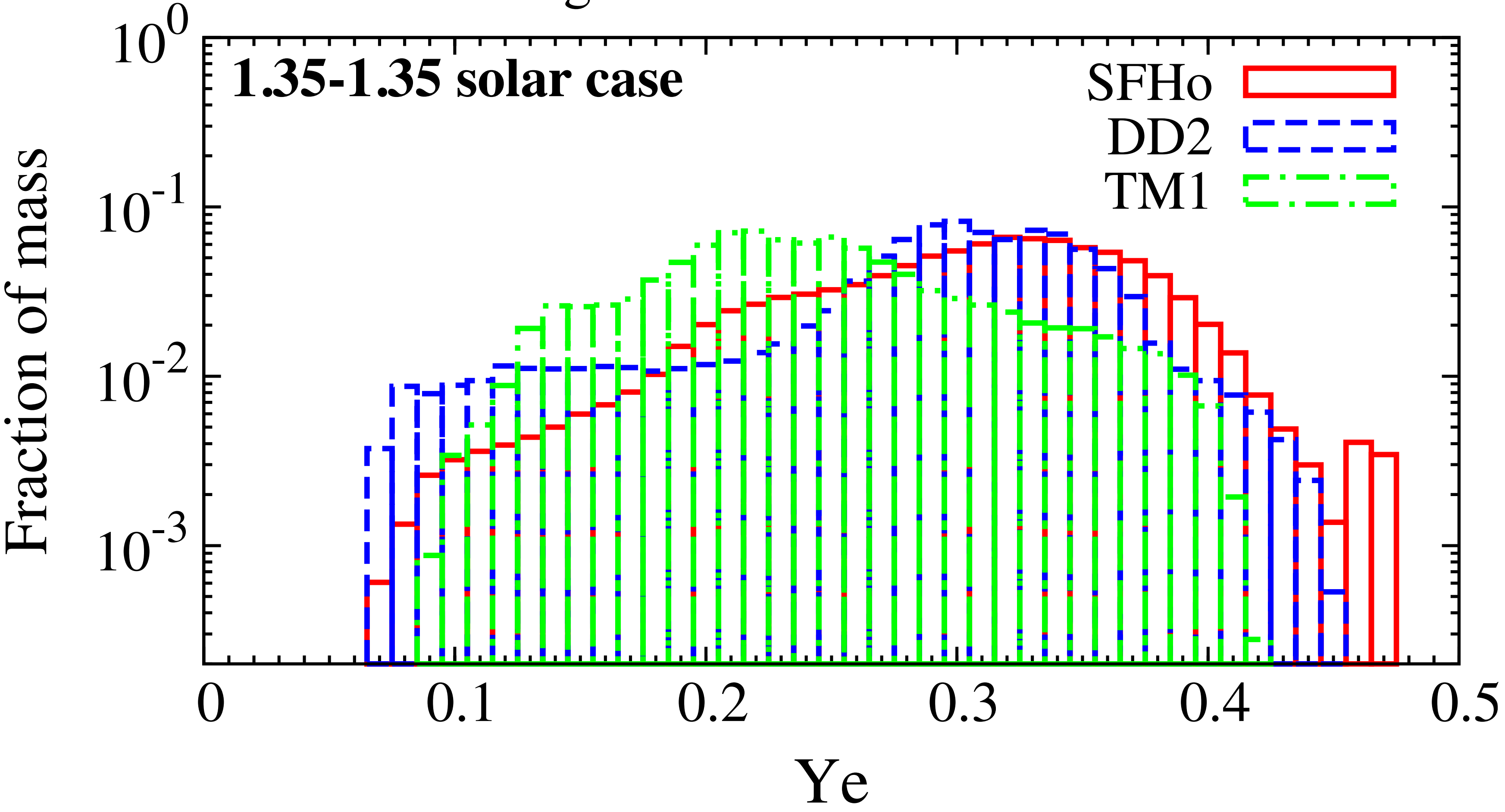
Neutrino irradiation

Y_e ⇧

Y_e
0.1
0.2
0.3
0.4

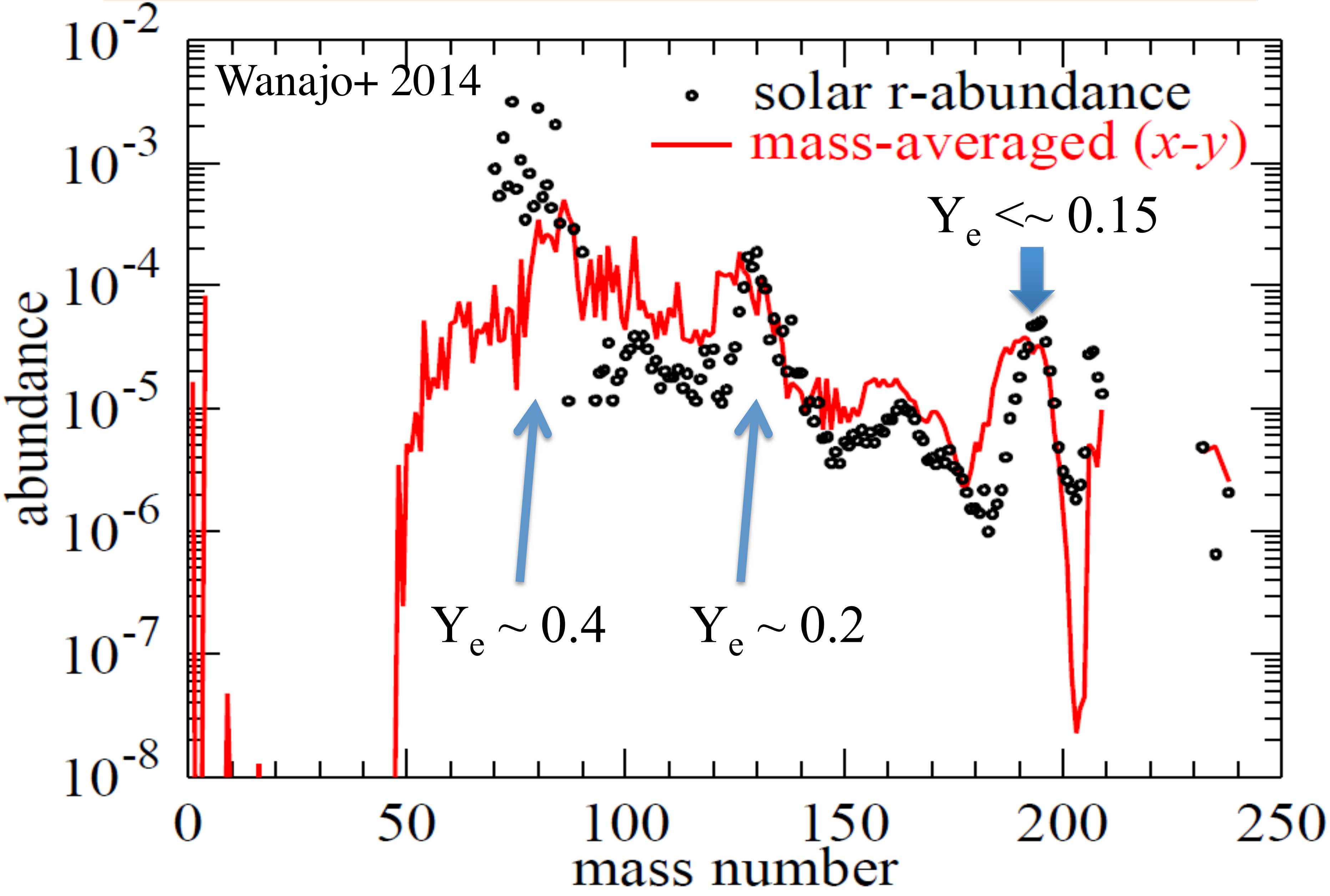
Electron fraction profile: Broad

Sekiguchi et al. 2015 PRD

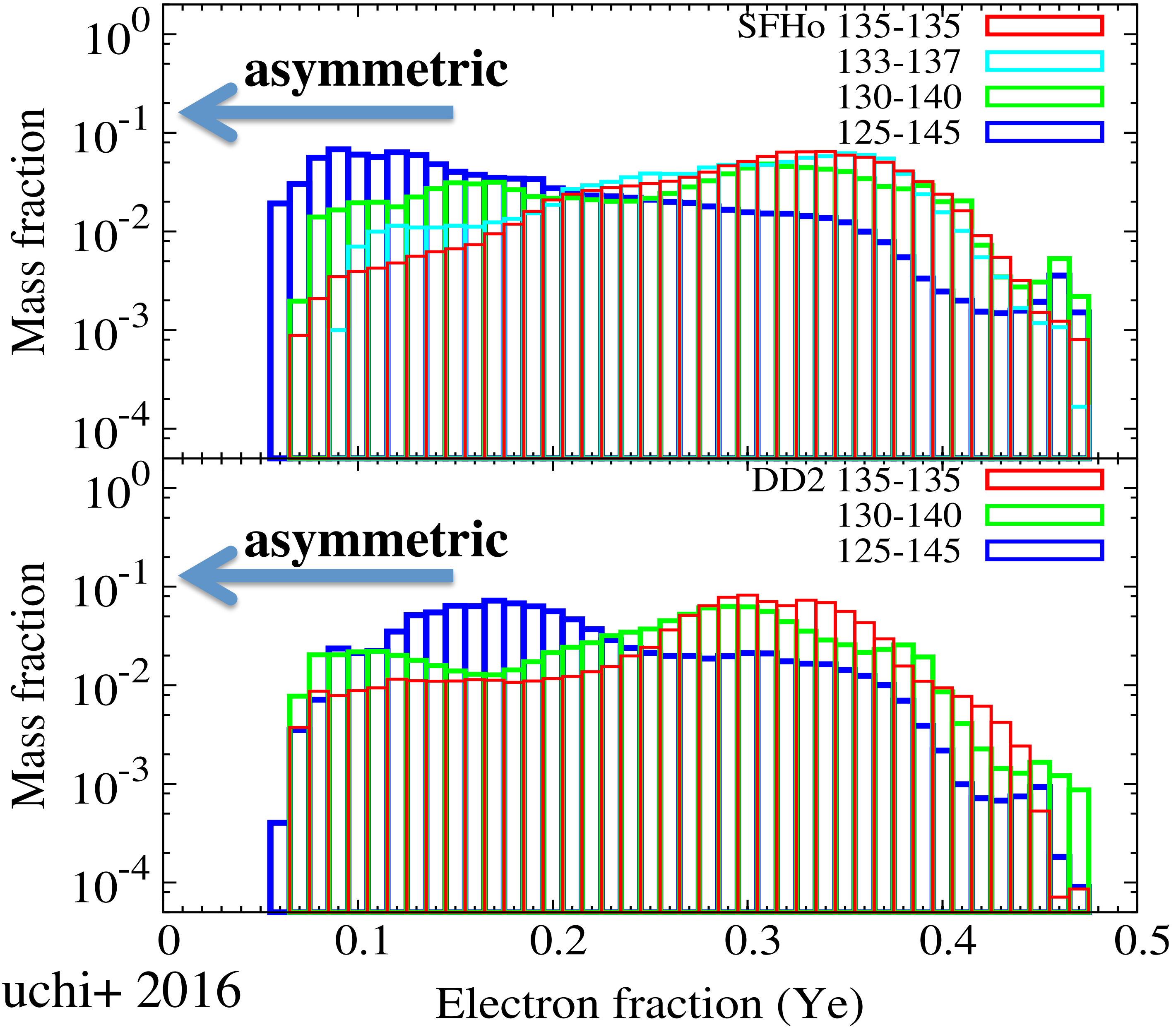


- Average depends on EOS but typically 0.2—0.3
- **Broad distribution** irrespective of EOS
- Similar results by Radice+16, Lehner+15,16

Consistent with solar abundance pattern



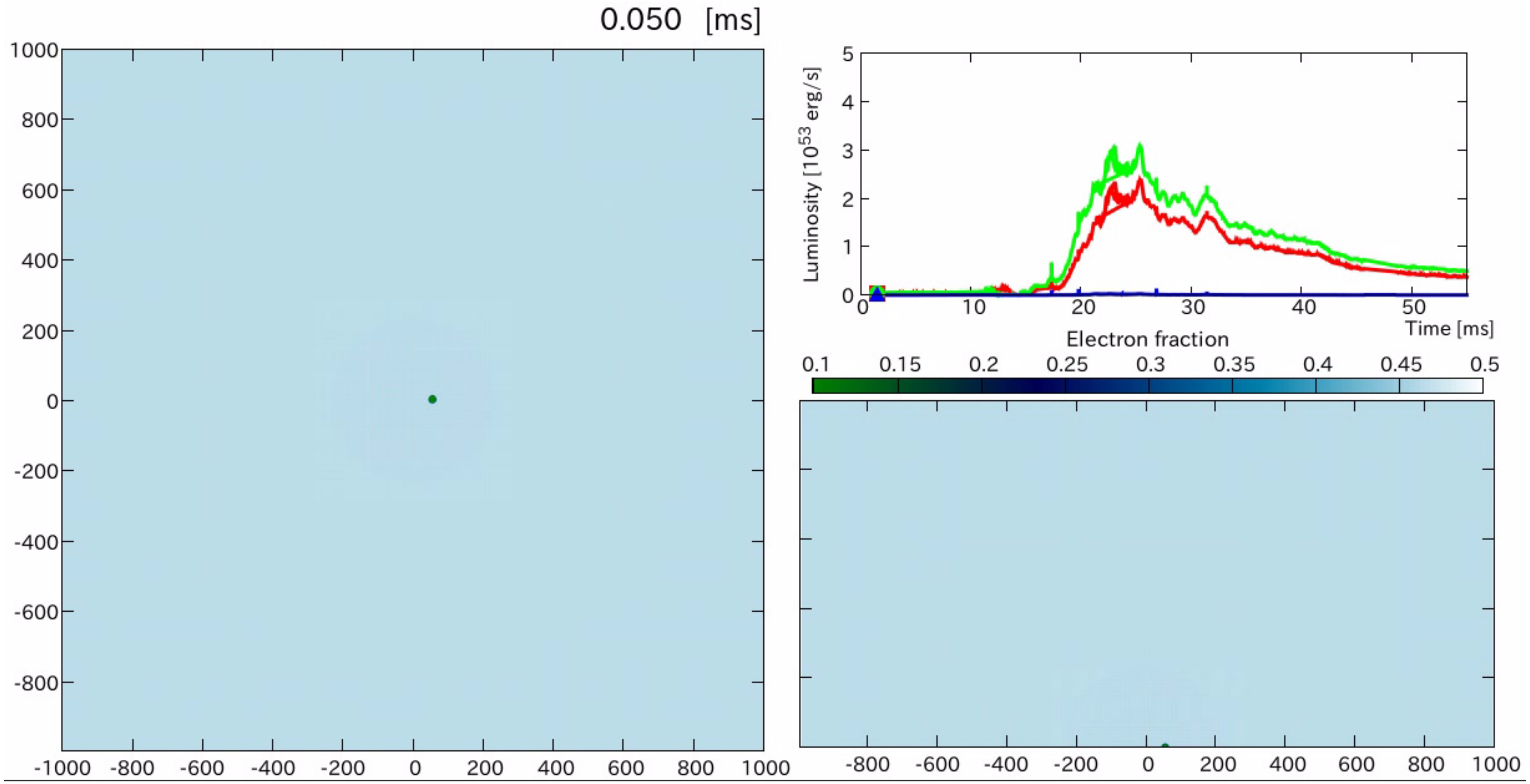
Results for a variety of mass ratios



Sekiguchi+ 2016

BH-NS merger (DD2 EOS: Y_e)

M_{BH}=5.5M$_{sun}$, M_{NS}=1.35M$_{sun}$, a_{BH}=0.75



Kyutoku, Sekiguchi + 2016

Still many issues remain

- MHD/Viscous wind from torus ?
- How large is the effective viscosity ?

→ **High-resolution & better physics is necessary**

↓

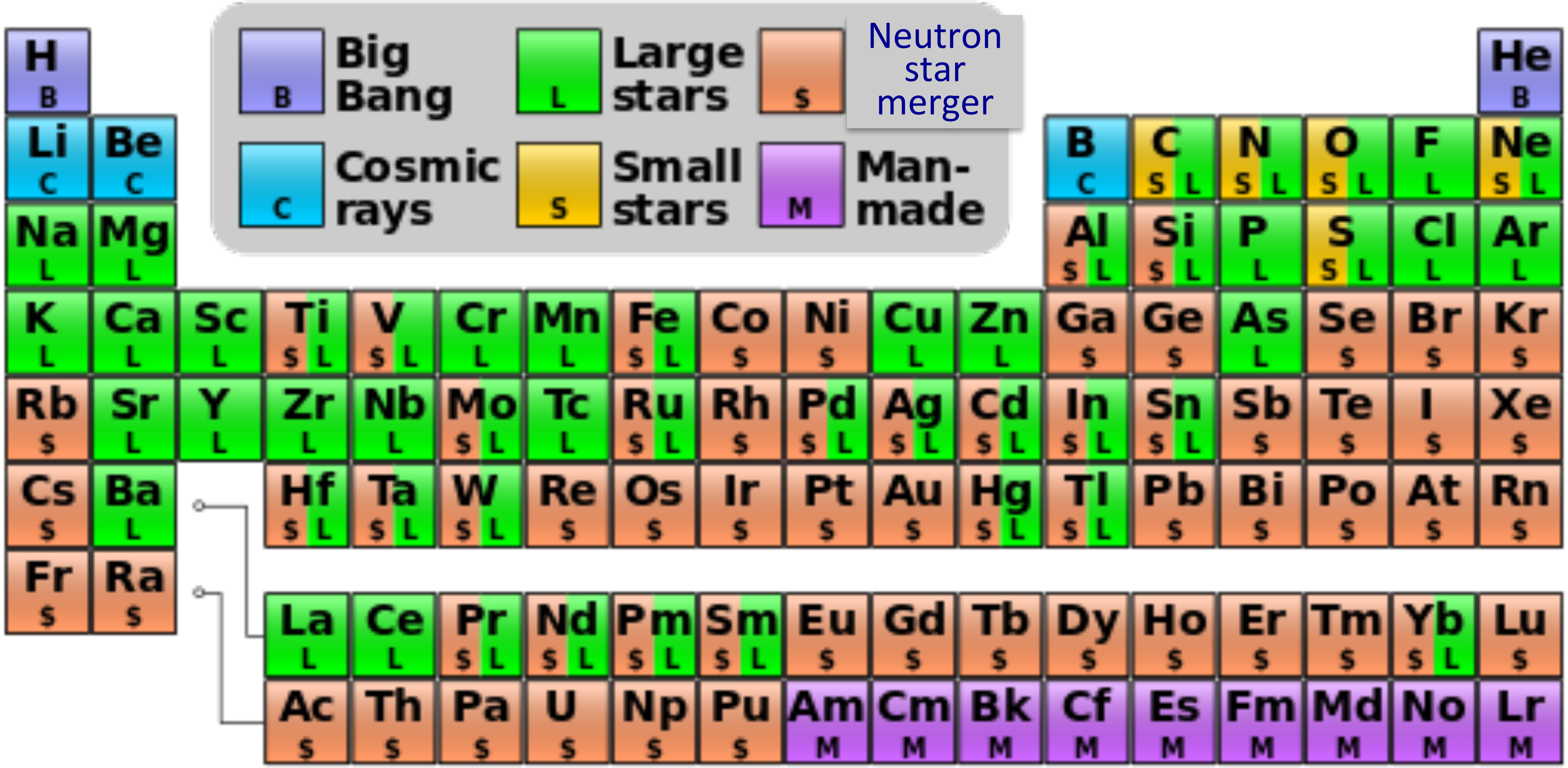
Issues in numerical relativity
in the next ~ a few years

- Neutrino wind alone is likely to be minor effect
  (Sekiguchi+ 2015)

5 Summary

- Many NR simulations are ongoing for NS-NS/BH → "Standard scenarios" have been established.
- Detecting **late-inspiral gravitational waves** from NS-NS will constrain EOS for $D_{\mathrm{eff}} <\sim 200\mathrm{Mpc}$.
- **Ejecta mass**: ~0.001–0.02 M_{sun} for NS-NS, and up to 0.1 M_{sun} for BH-NS: depends on NS- EOS: → $L \sim 10^{40—42}$ erg/s at 1—10 days for radioactive-power nova (for $\kappa \sim 10\ \mathrm{cm}^2/\mathrm{g}$) . → EM counterparts; luminosity depends on NS EOS & BH spin: Observation will reveal them.
- **NS-NS merger could be the site for r-process nucleosynthesis .**

Origin of elements



B Big Bang

L Large stars

S Neutron star merger

C Cosmic rays

S Small stars

M Man-made

H B																	He B
Li C	Be C											B C	C S L	N S L	O S L	F L	Ne S L
Na L	Mg L											Al S L	Si S L	P L	S S L	Cl L	Ar L
K L	Ca L	Sc L	Ti S L	V S L	Cr L	Mn L	Fe S L	Co S	Ni S	Cu L	Zn L	Ga S	Ge S	As L	Se S	Br S	Kr S
Rb S	Sr L	Y L	Zr L	Nb L	Mo S L	Tc L	Ru S L	Rh S	Pd S L	Ag S L	Cd S L	In S L	Sn S L	Sb S	Te S	I S	Xe S
Cs S	Ba L		Hf S L	Ta S L	W S L	Re S	Os S	Ir S	Pt S	Au S	Hg S L	Tl S L	Pb S	Bi S	Po S	At S	Rn S
Fr S	Ra S																
			La L	Ce L	Pr S L	Nd S L	Pm S L	Sm S L	Eu S	Gd S	Tb S	Dy S	Ho S	Er S	Tm S	Yb S L	Lu S
			Ac S	Th S	Pa S	U S	Np S	Pu S	Am M	Cm M	Bk M	Cf M	Es M	Fm M	Md M	No M	Lr M

Galactic *compact* NS-NS observed

E.g., http://stellarcollapse.org/nsmasses

	PSR	P(day)	e	$M(M_{\rm sun})$	M_1	M_2	$T_{\rm GW}$
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	2.57	1.29	1.32	3.1

$*10^8$ yrs

In globular cluster

Orbital period

Eccentricity

Mass

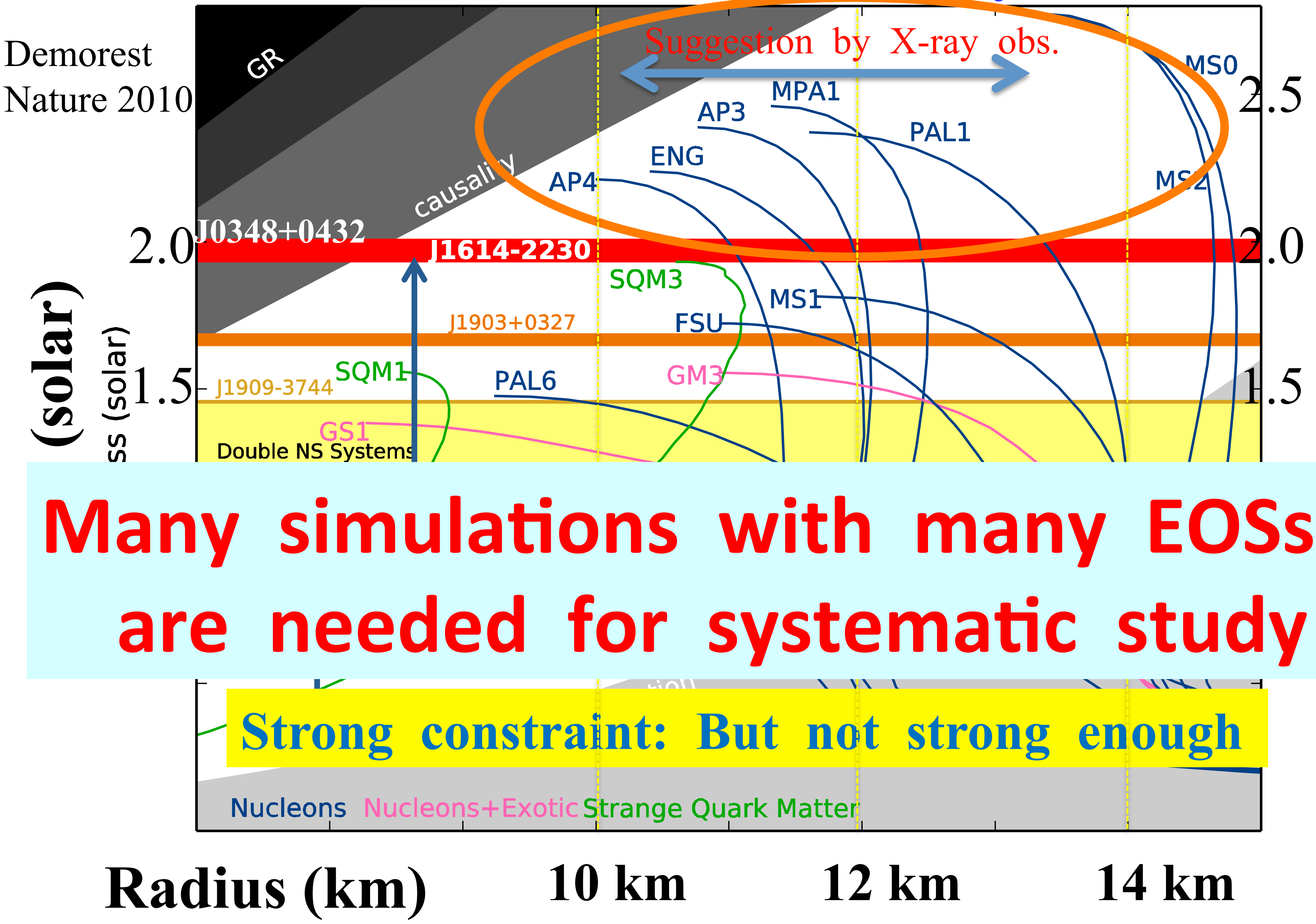
Merger time

→ Galactic merger rate ~1/$10^{5\pm1}$ yrs

(e.g. Kalogera et al., 2007, Abadie et al. 2010)

→ Merger rate ~1-100/yr/$(300\mathrm{Mpc})^3$

The most crucial uncertainty is EOS



Many simulations with many EOSs are needed for systematic study

Strong constraint: But not strong enough