Predicting neutron-star mergers by numerical relativity

Masaru Shibata

Center for Gravitational Physics,

Yukawa Institute for Theoretical Physics,

Kyoto University

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

CGP
Center for Gravitational Physics
Yukawa Institute

Outline of this talk

1. Introduction
2. The standard scenario of NS mergers:
   - Gravitational waves
   - Mass ejection and EM counterparts
3. More details are required

I Introduction:
Why NS merger is important ?

Galactic *compact* binary neutron stars observed

	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	2.57	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

Galactic merger rate ~ $1/10^{4\text{-}5}$ yrs

(e.g. Kalogera et al. 2007, Kim et al. 2015)

→ Merger rate ~ 0.4−4/yr/$(100\text{Mpc})^3$

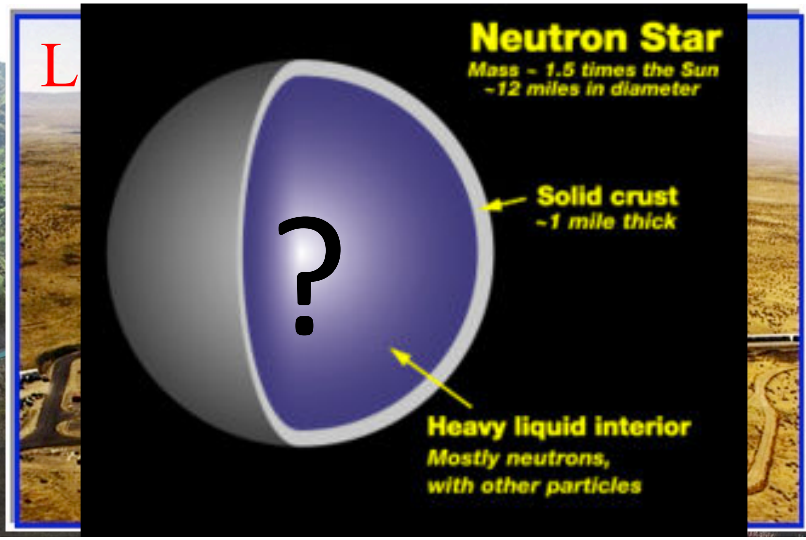
Why NS merger is important ?

A. **Most promising sources of gravitational waves for advanced LIGO/VIRGO/KAGRA**

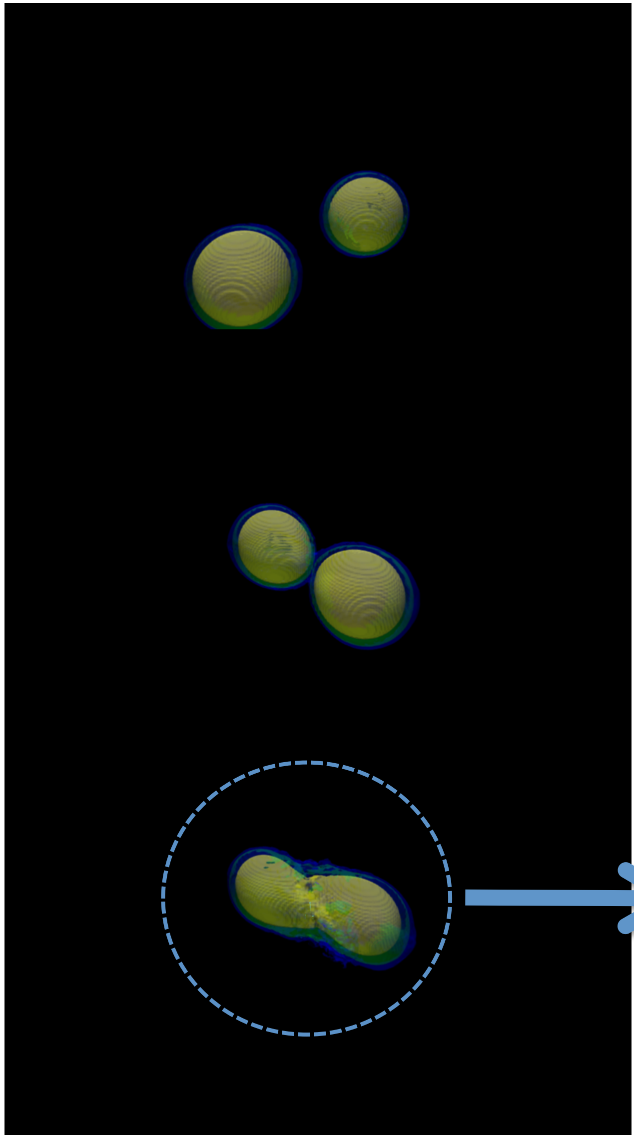
Why NS merger is important ?

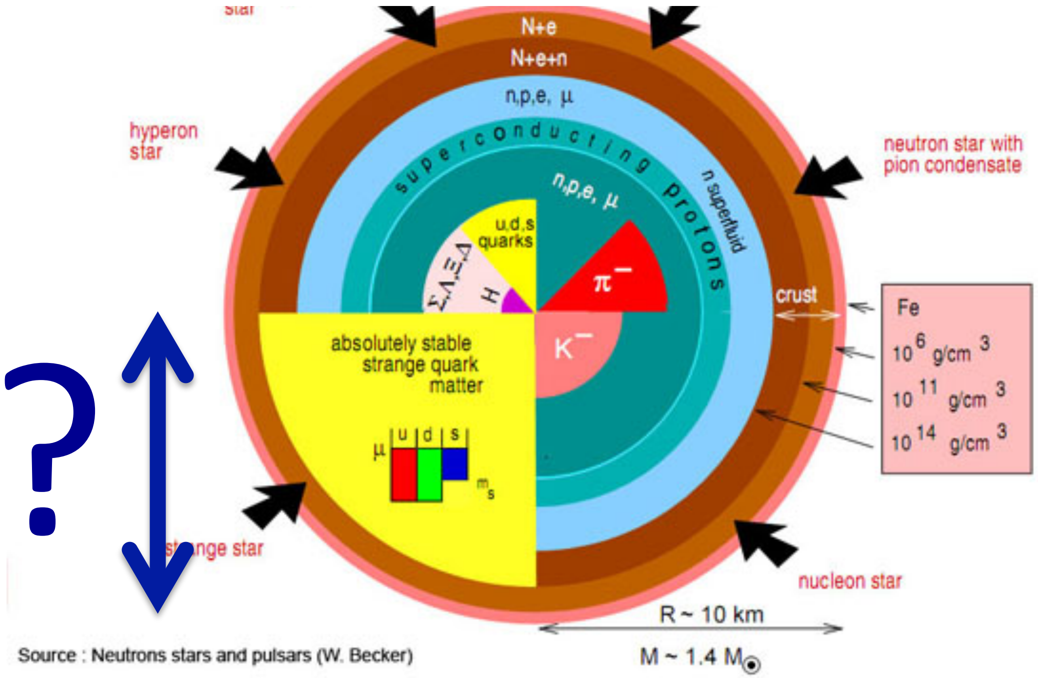
A. **Most promising sources of gravitational waves for advanced LIGO/VIRGO/KAGRA**

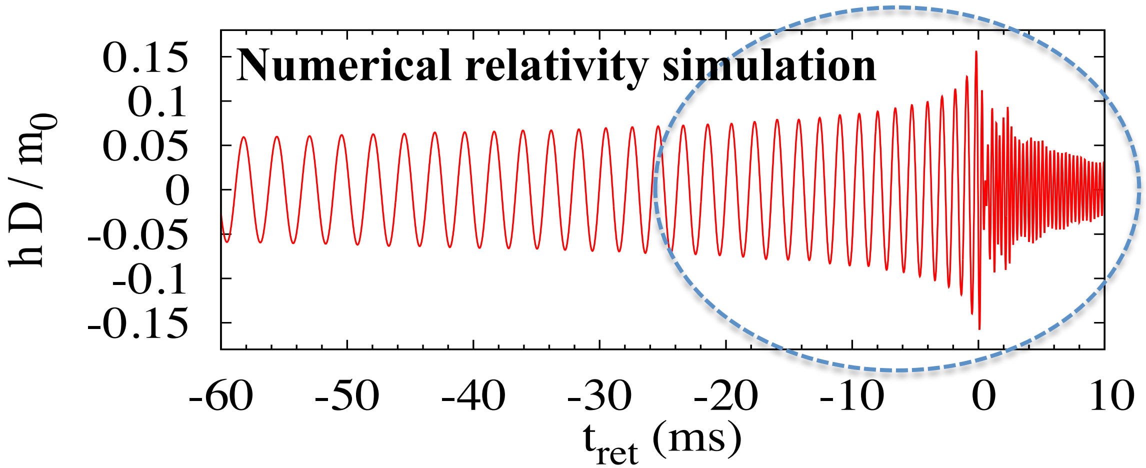
B. **Laboratory for high-density nuclear matter**



Gravitational waves from NS mergers are likely to tell us how large NS is .

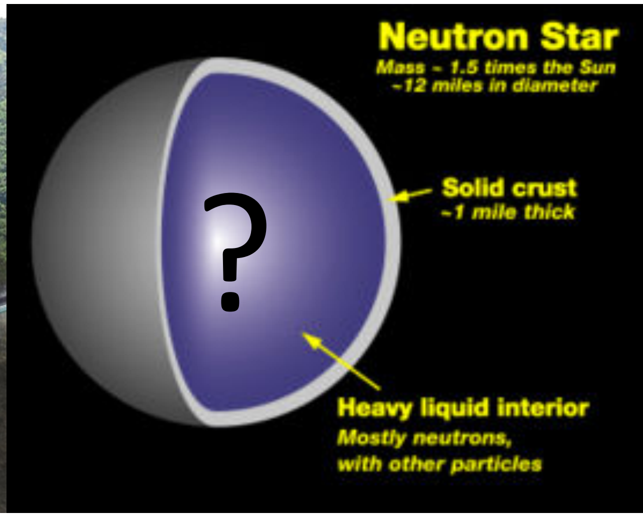


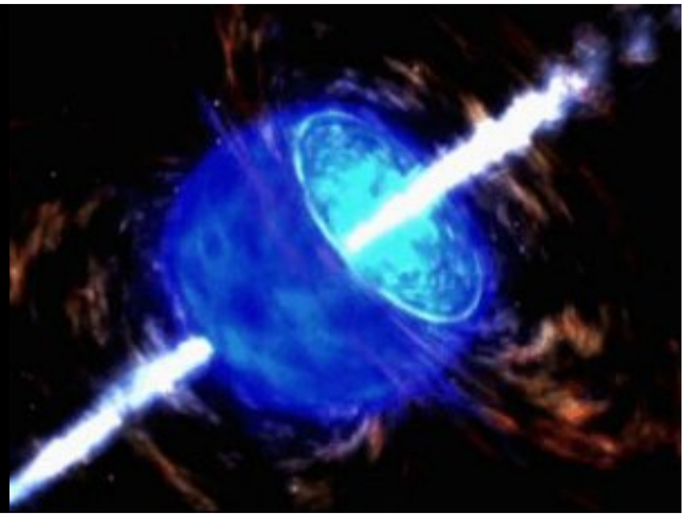




Why NS merger is important ?

A. Most promising sources of gravitational waves for advanced LIGO/VIRGO/KAGRA
B. Laboratory for high-density nuclear matter
C. Promising origins of short-hard GRBs





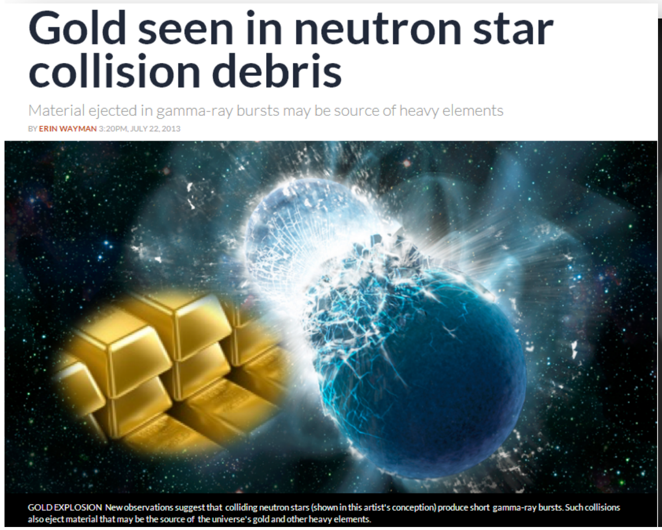
Why NS merger is important ?

A. Most promising sources of gravitational waves for advanced LIGO/VIRGO/KAGRA

B. Laboratory for high-density nuclear matter

C. Promising origins of short-hard GRBs

D. Possible site for heavy elements produced by rapid neutron-capture process (r-process)

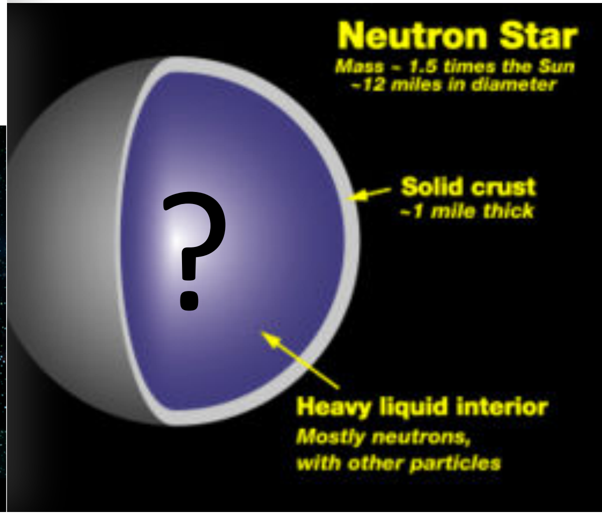


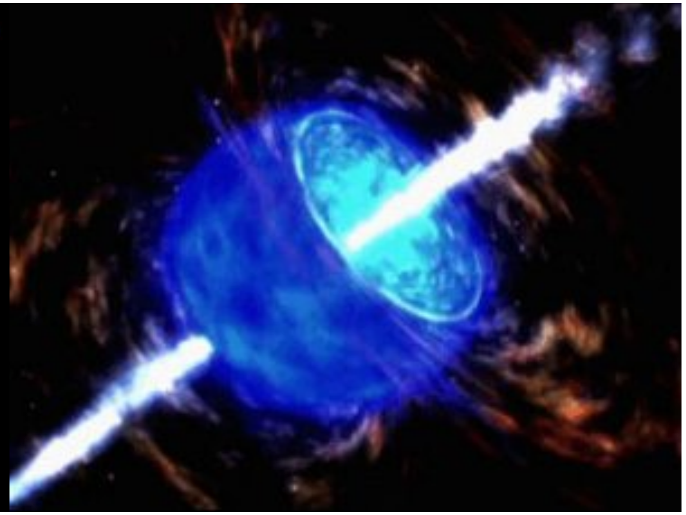
Gold seen in neutron star collision debris

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

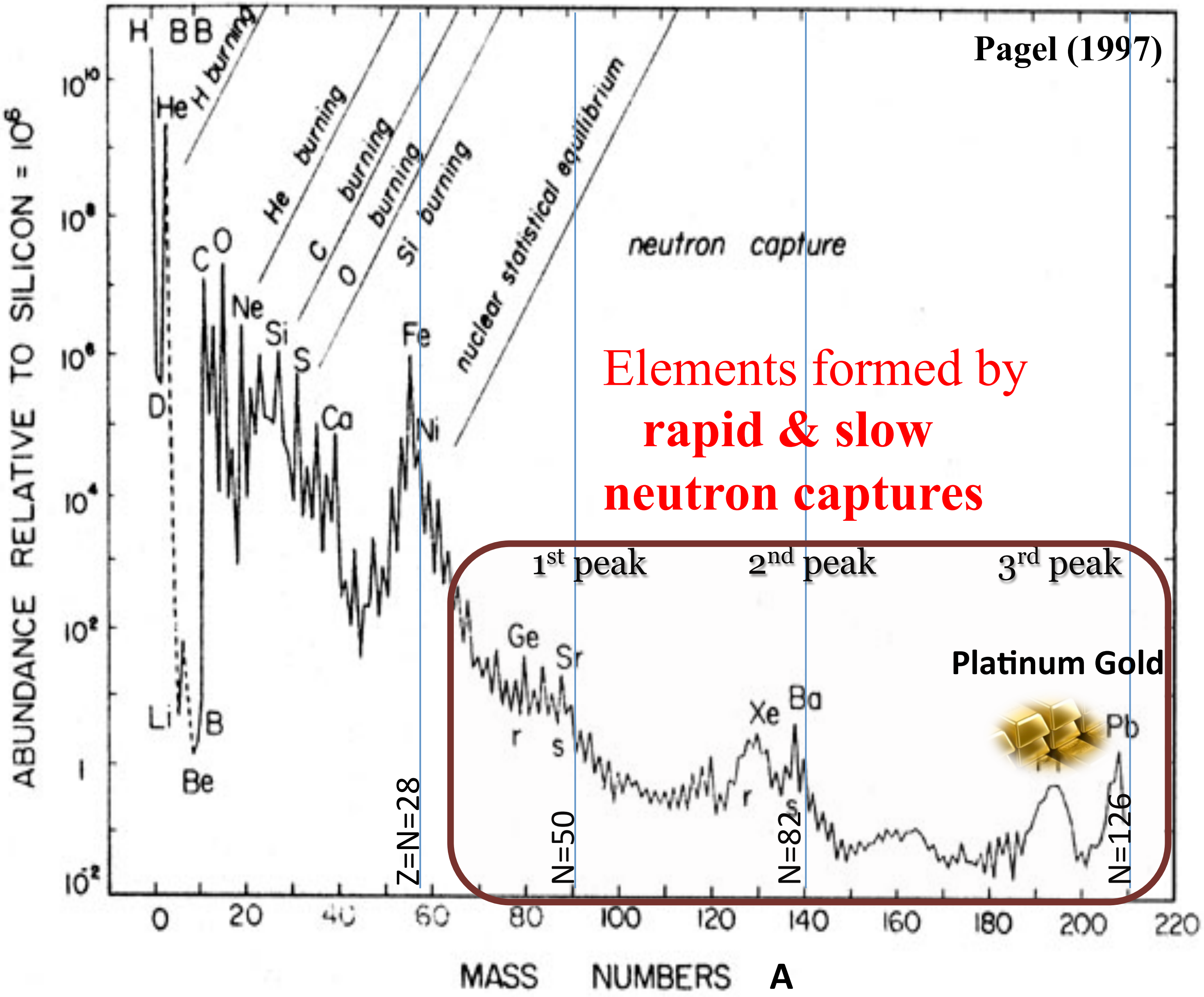
BY ERIN WAYMAN 3:20PM, JULY 22, 2013

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.



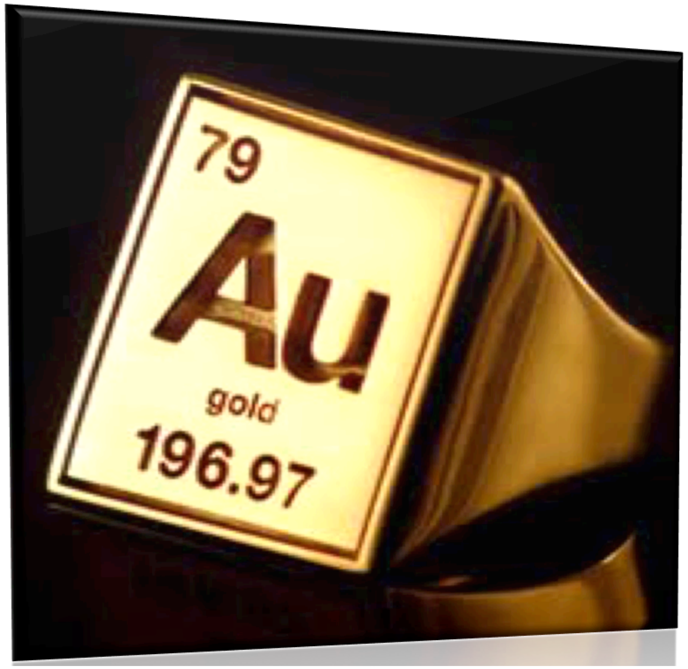


Origin of heavy elements?



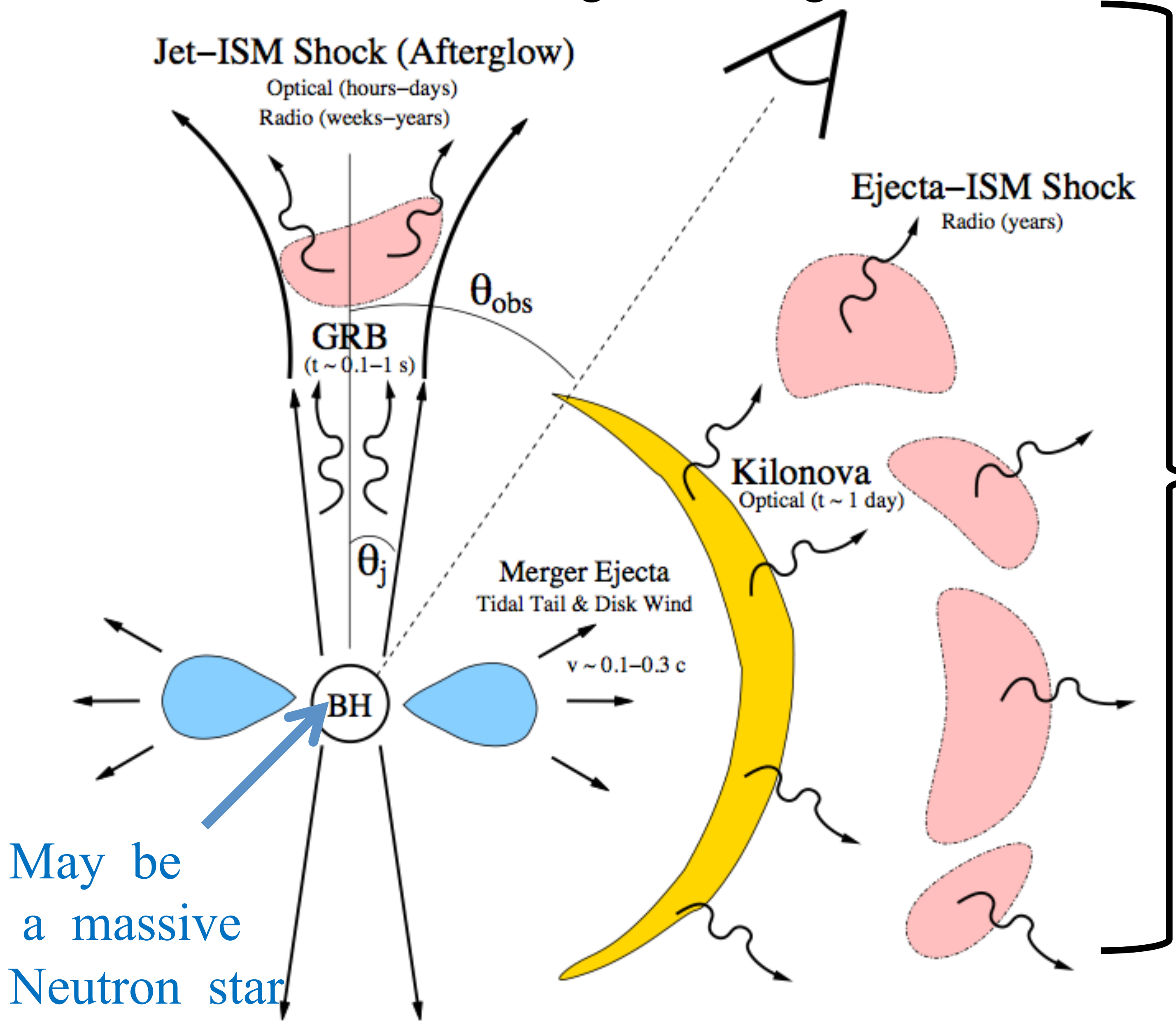
Origin of r-process elements
(gold, silver, platinum) ?

- Until quite recently, people believed that core-collapse supernovae (CCS) would be the production site for the r-process elements (textbooks say usually so)
- Latest CCS simulations indicate ***negative answer***
- **NS merger is another potential candidate**
(Lattimer & Schramm 74)



Schematic picture of NS mergers

Metzger & Berger, 2012



Mass ejection

↓

r-process, β-decay

↓

Shine !

↓

possibility for detection

For radioactive (macronova) scenario

(Li-Paczynski '98)

Ejecta mass   Velocity   Opacity(composition)

$$L_{\rm max} \sim 4\times 10^{41}\ \text{ergs/s}\left(\frac{M}{0.01M_{\odot}}\right)^{1/2}\left(\frac{v}{0.2c}\right)^{1/2}\left(\frac{\kappa}{10\ \text{cm}^2/\text{g}}\right)^{-1/2}\left(\frac{f_{\text{r-proc}}}{3\times 10^{-6}}\right)$$

$$\text{at}\ \ t \sim 5\ \text{days}\left(\frac{M}{0.01M_{\odot}}\right)^{1/2}\left(\frac{v}{0.2c}\right)^{-1/2}\left(\frac{\kappa}{10\ \text{cm}^2/\text{g}}\right)^{1/2}$$

$$3\times 10^{41}\ \text{ergs/s} \Leftrightarrow \text{M} = -15.0\ \text{mag} \Rightarrow \text{m}{=}21.5\ \text{mag}\ \ @\ 200\text{Mpc}$$

Bright in near−infrared for 1 week after the merger

Many unsolved issues could be solved by observing gravitational waves & electromagnetic signals from neutron star mergers

(statement on 18th Nov. 2016 @AEI)

Many unsolved issues are being solved by observing gravitational waves & electromagnetic signals from neutron star mergers

2 Standard scenario for NS-NS merger

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

1. Approximately 2 solar-mass neutron stars exist
   → equation of state (EOS) for NS has to be stiff
2. Typical total mass of binary neutron stars
   → ~ 2.6—2.8 solar mass (exception is found)

➢ Merger results in high-mass neutron stars (not BH)
(Shibata et al. 2005, 2006, Hotokezaka et al. 2011, 2013…)

➢ Difference in EOS is reflected in gravitational waves emitted from the late inspiral to merger phases
(Shibata et al. 2005, Hotokezaka et al. 2011, 2013…)

➢ During the merger, neutron-rich matter is ejected with mass of 0.001—0.02 solar mass
(Hotokezaka et al. 2013, Sekiguchi et al. 2015…)

Current understanding of NS-NS

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

APR4: R=11.1km

ALF2: R=12.4km

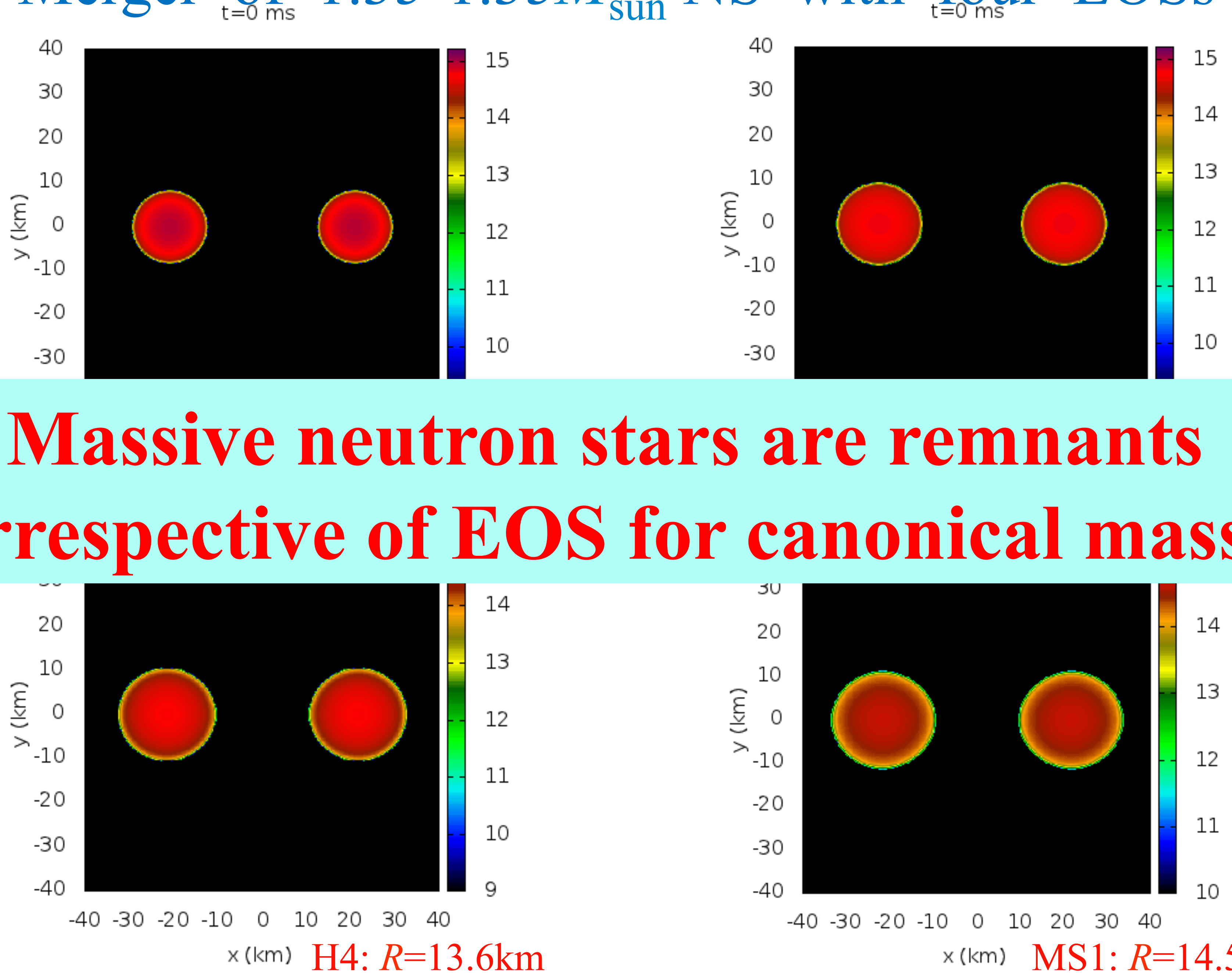
All EOSs satisfy $M_{max} > 2M_{sun}$

H4: R=13.6km

MS1: R=14.5km

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

By Hotokezaka



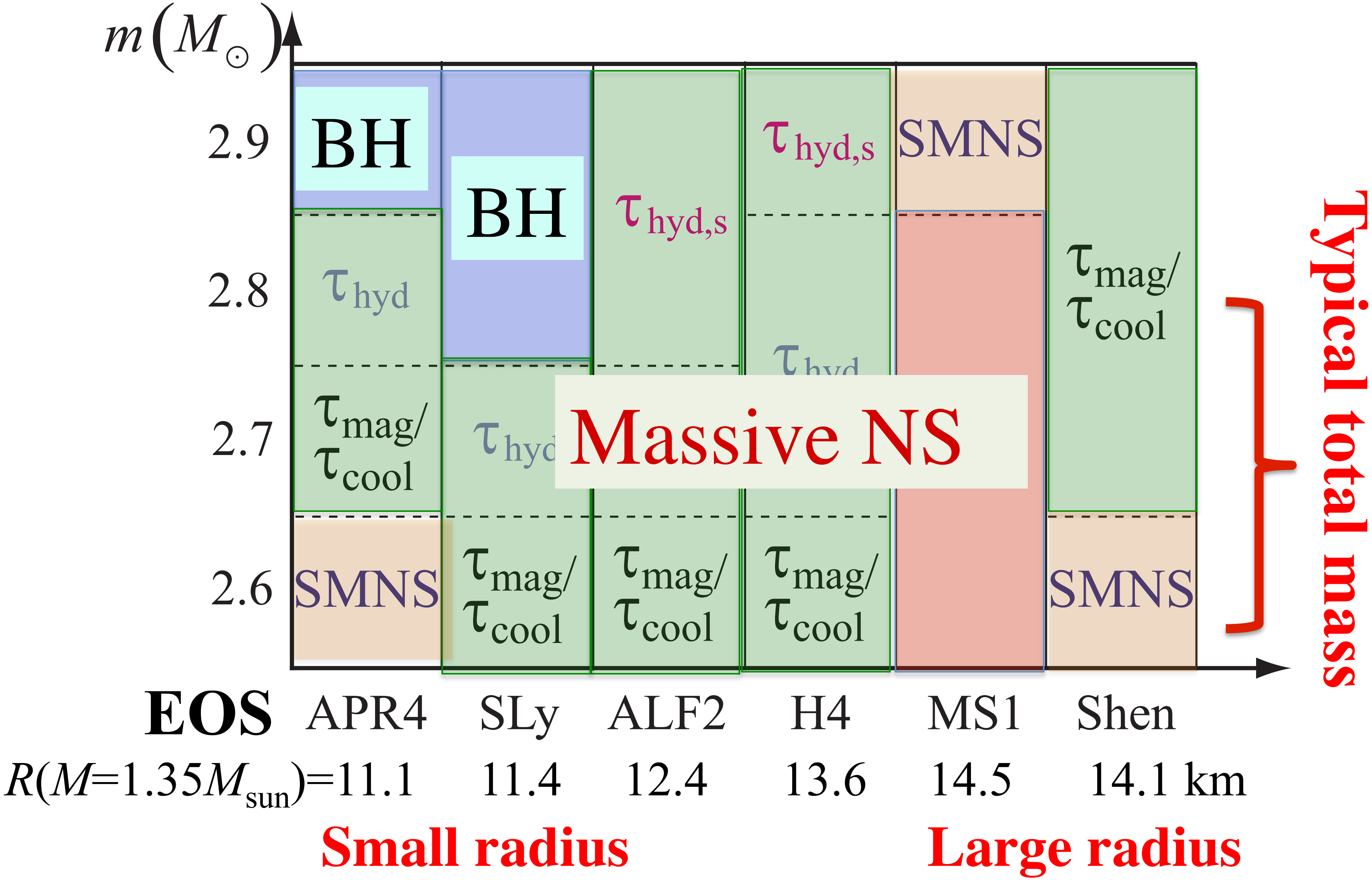
Massive neutron stars are remnants Irrespective of EOS for canonical mass

H4: R=13.6km

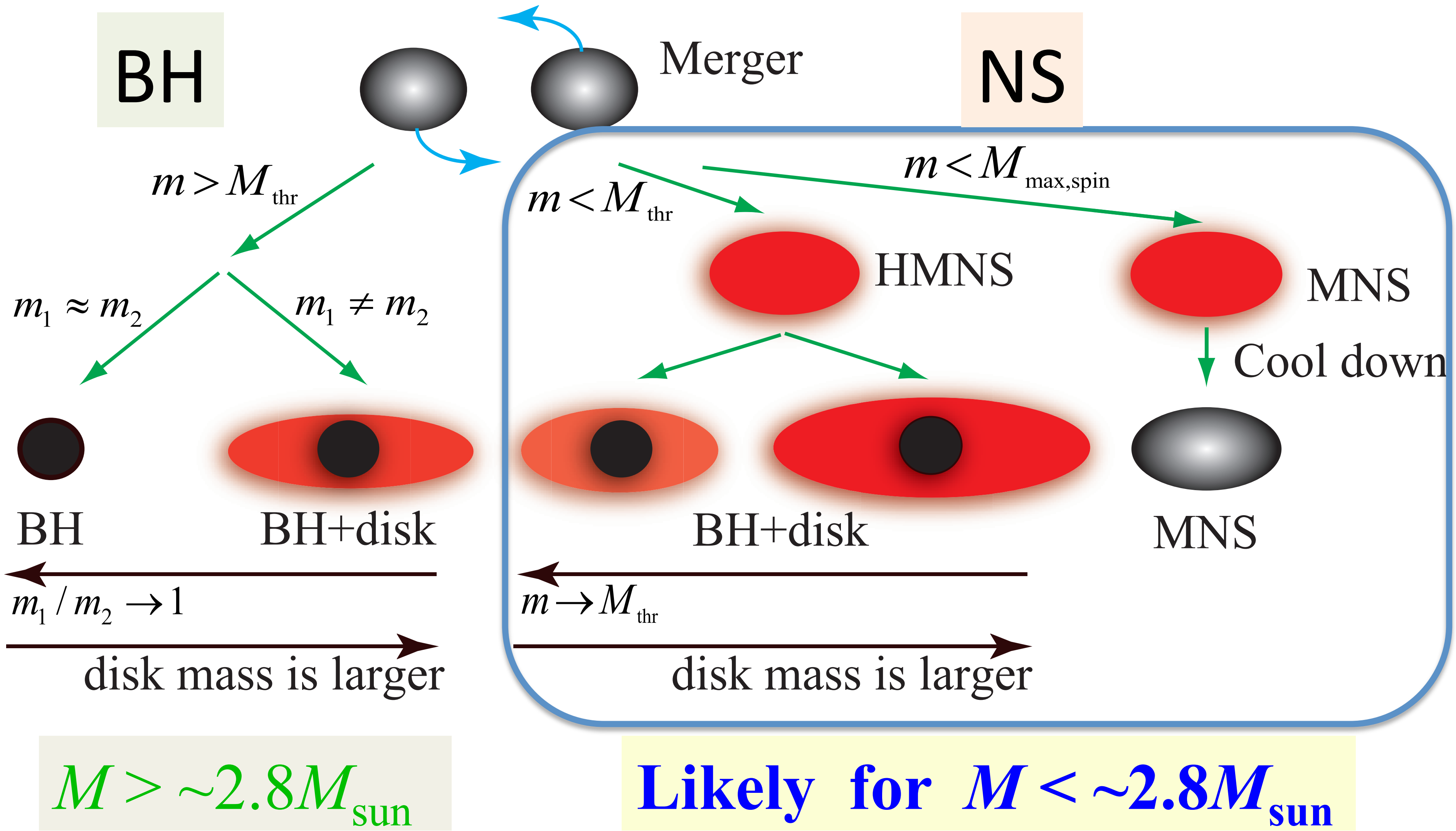
MS1: R=14.5km

Dependence on EOS and total mass

Hotokezaka et al. 2011, 2013

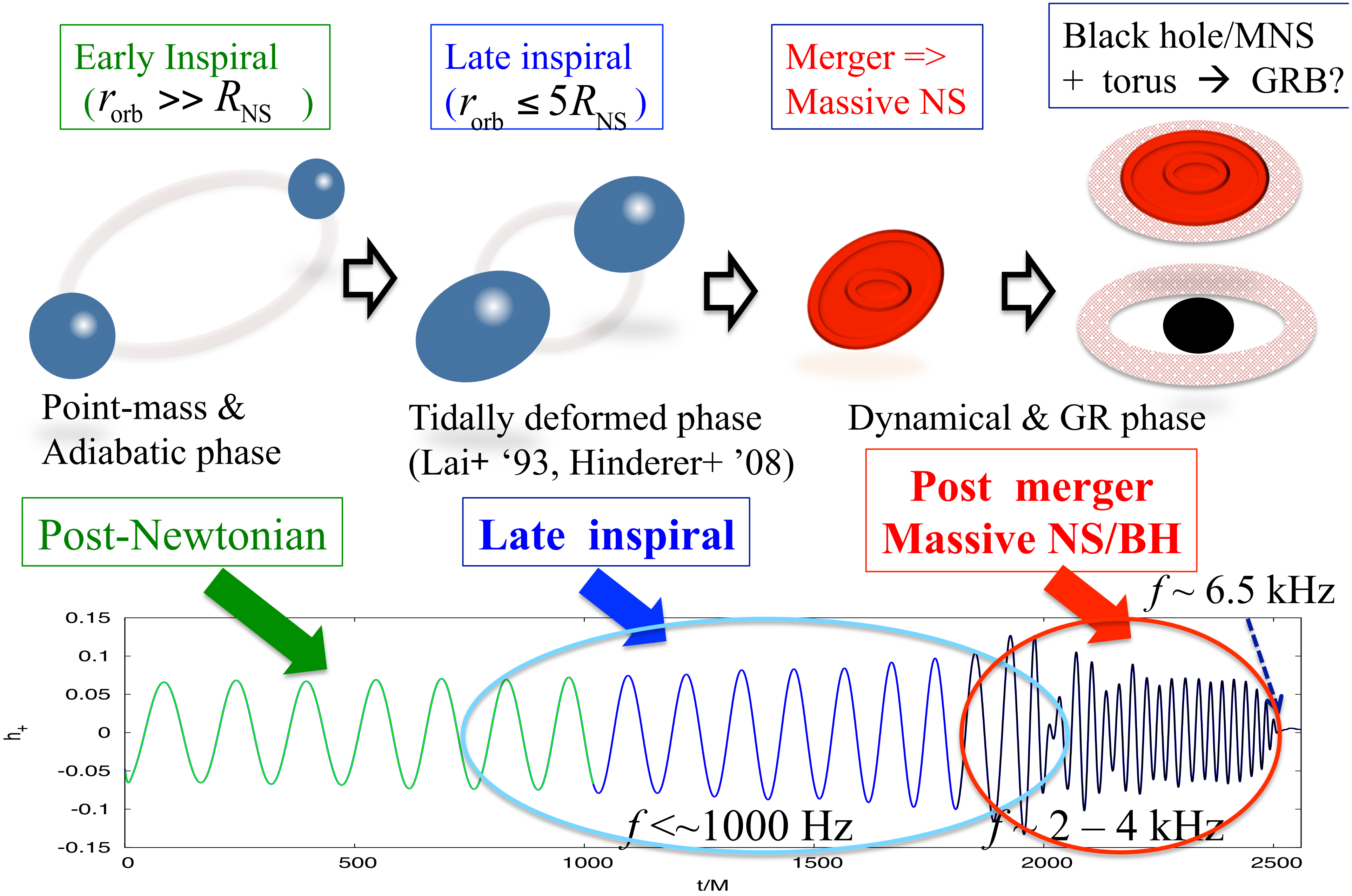


Possible fates of NS-NS mergers

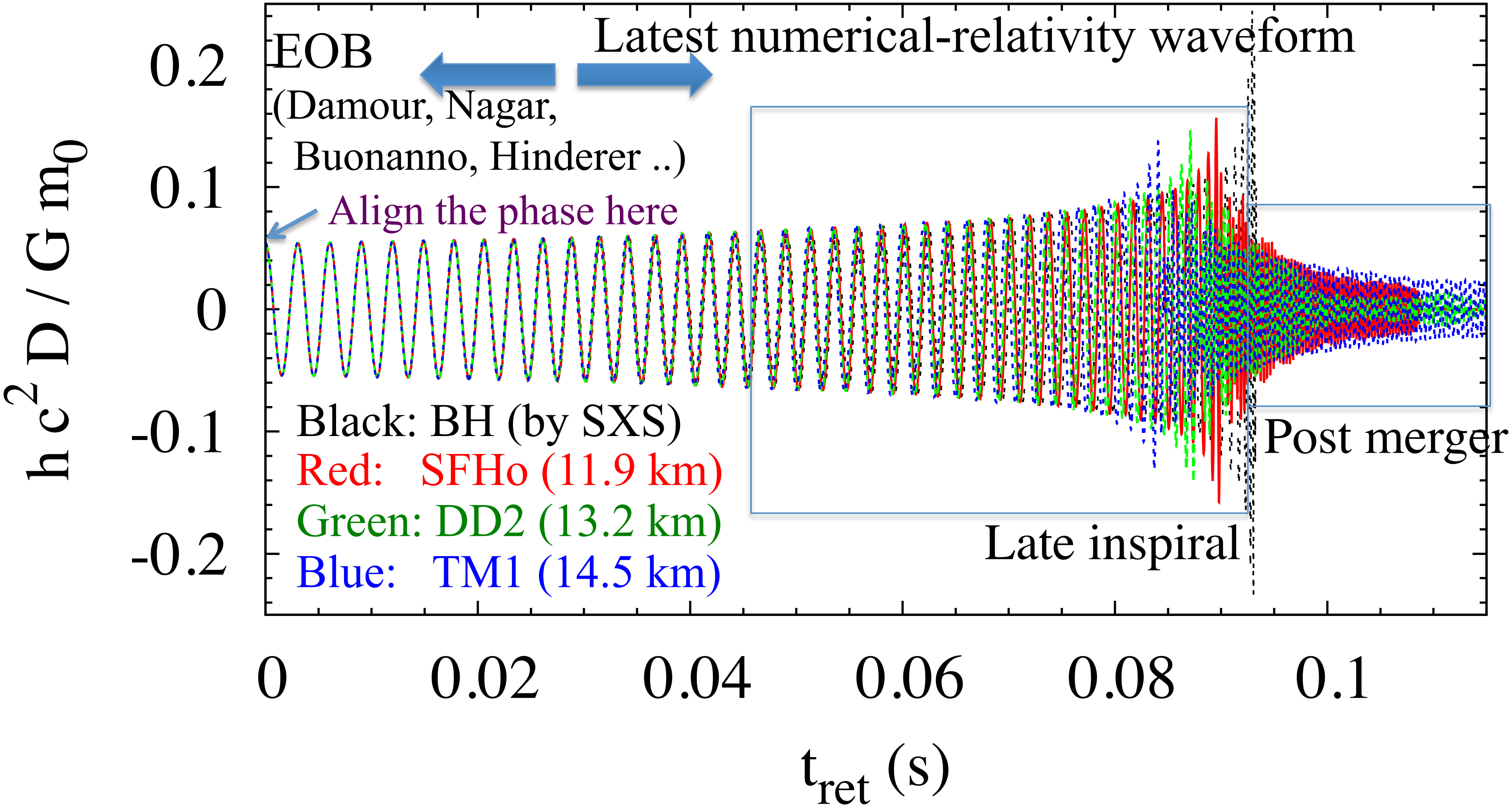


I.e., irrespective of EOS, threshold mass $>\sim 2.8 M_{\rm sun}$

Gravitational waves from binary NS-NS

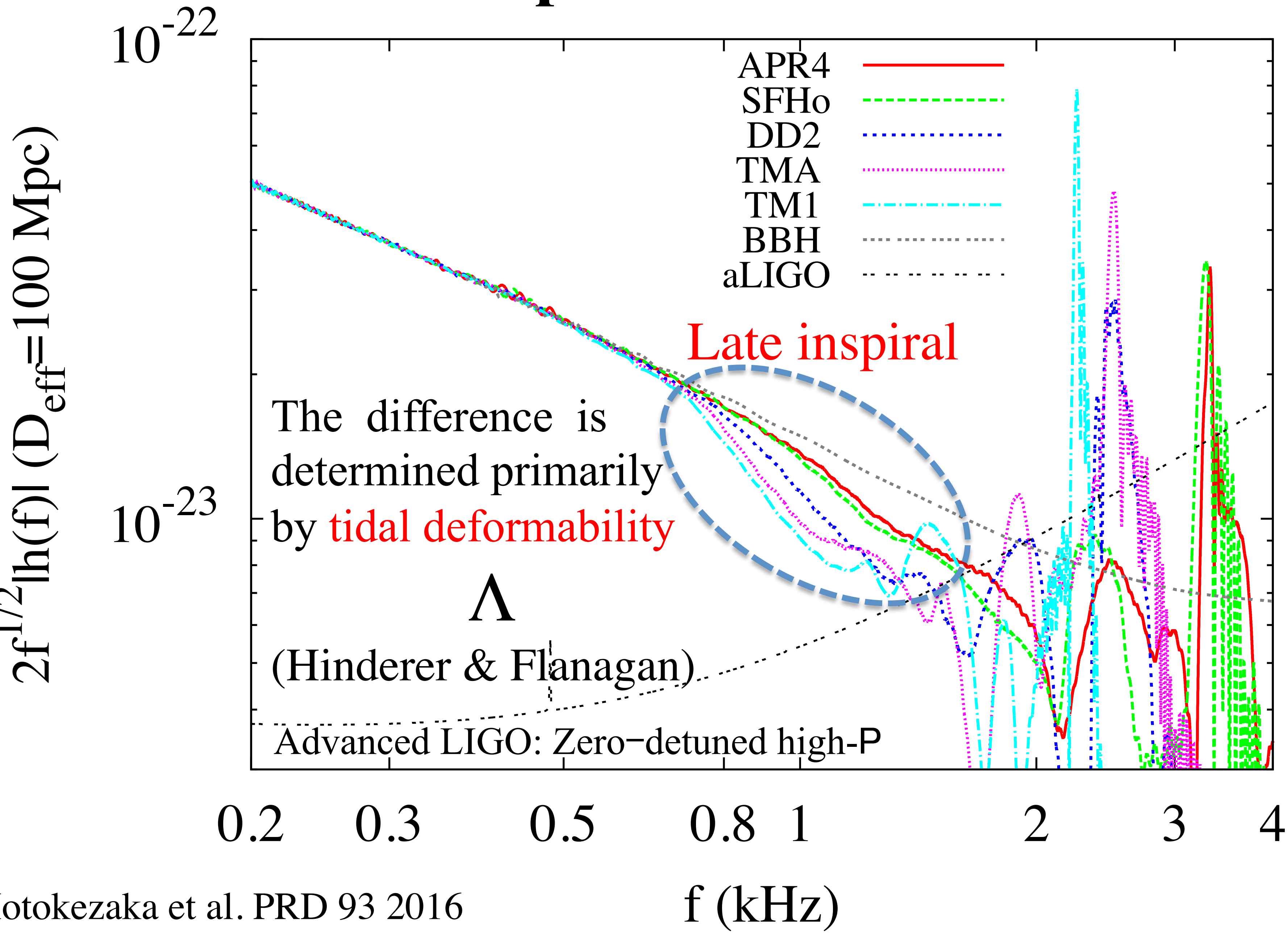


Gravitational waveform from NS-NS:
hybrid waveform (1.35-1.35 solar mass)



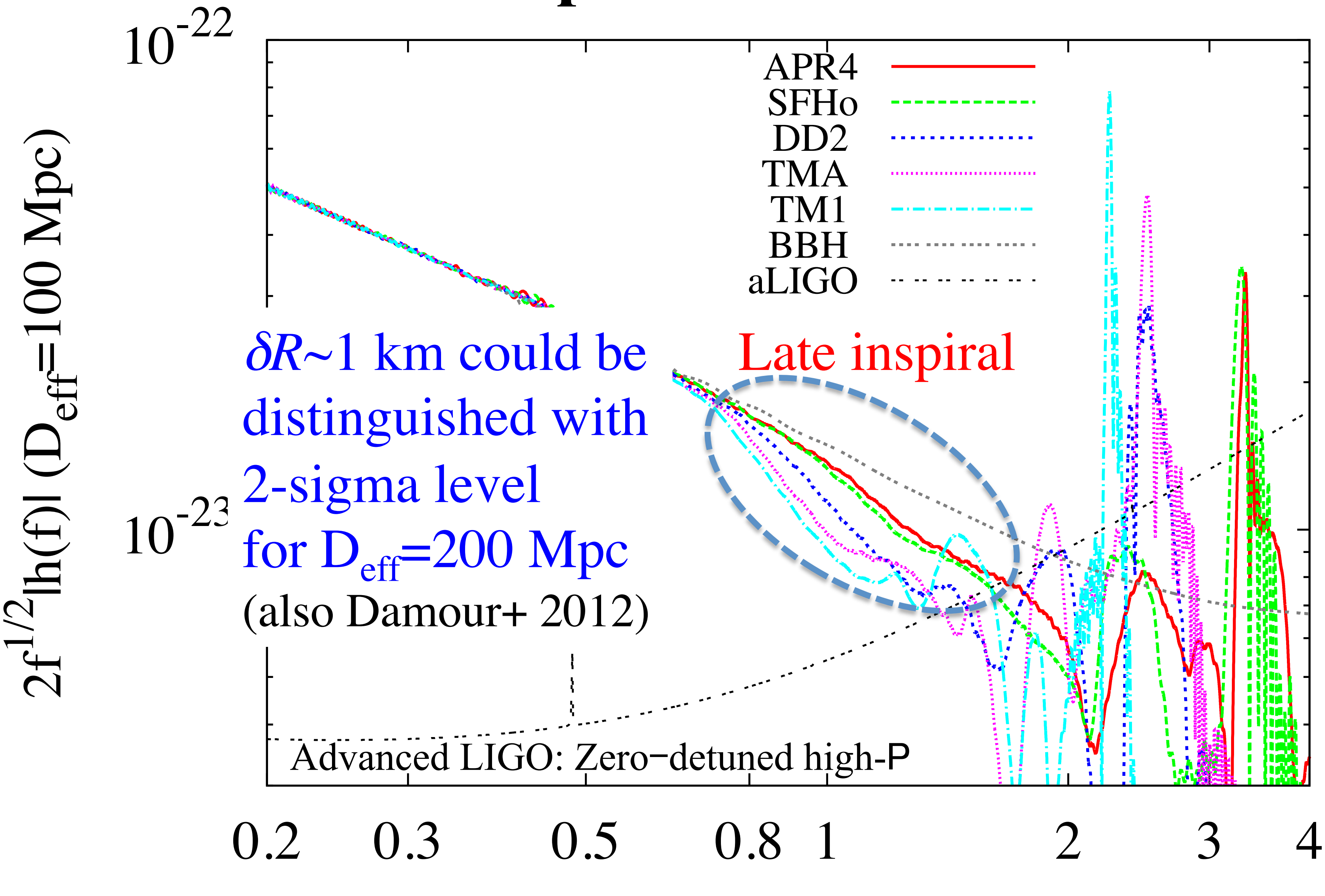
Hotokezaka et al. 2016 (see also efforts by Bernuzzi,…2011–)

Spectrum



Hotokezaka et al. PRD 93 2016

Spectrum

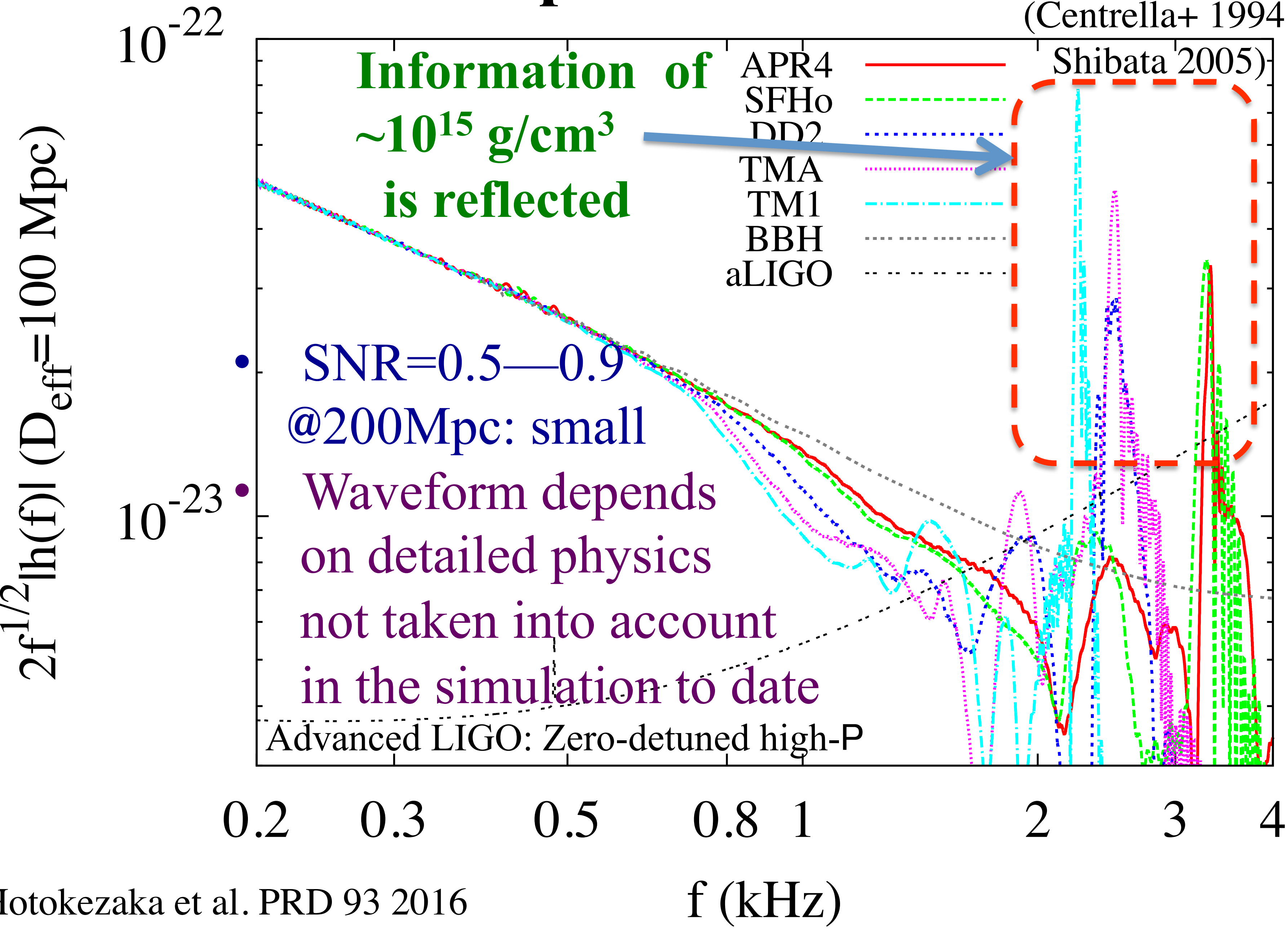


Hotokezaka et al. PRD 93 2016

Spectrum

Post merger

(Centrella+ 1994, Shibata 2005)



Hotokezaka et al. PRD 93 2016

Mass ejection, nucleosynthesis, and shine
(kilonova/macronova scenario)

- **Merger**

→ **Neutron-rich, high-entropy, dense ejecta**

$$\boxed{\tau_{n-\mathrm{capture}} < \tau_{\beta-\mathrm{decay}}}$$

→ **r-process nucleosynthesis**
(Lattimer-Schramm '74, Symbalisty-Schramm '82)

→ **Production of unstable heavy nuclei**

→ β-decay (fission)

→ Heating ejected material

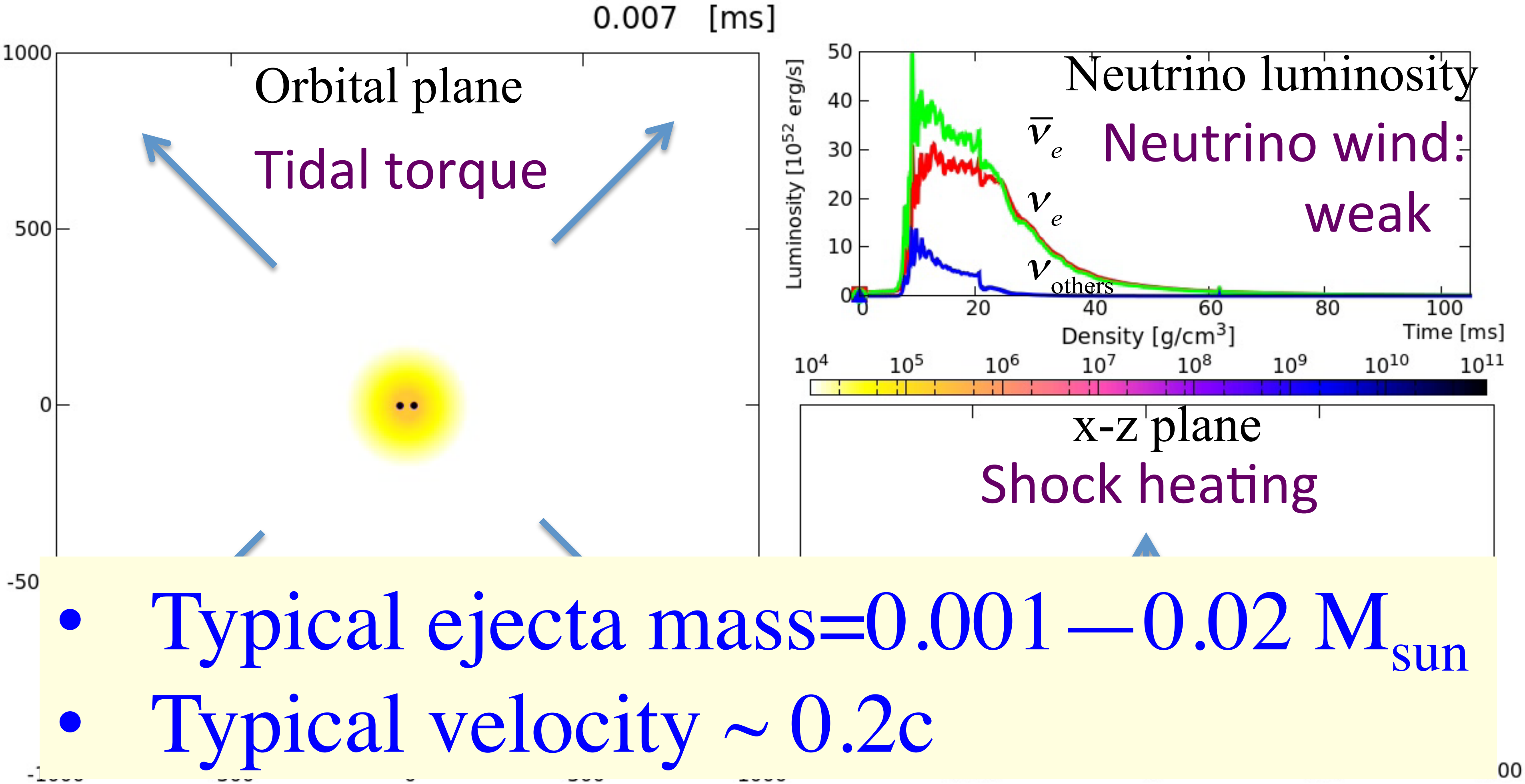
→ UV ~ IR emission (Li-Paczynski '98)

How much mass ? How high neutron-richness ?

Neutrino-radiation hydrodynamics simulation

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

Rest-mass density



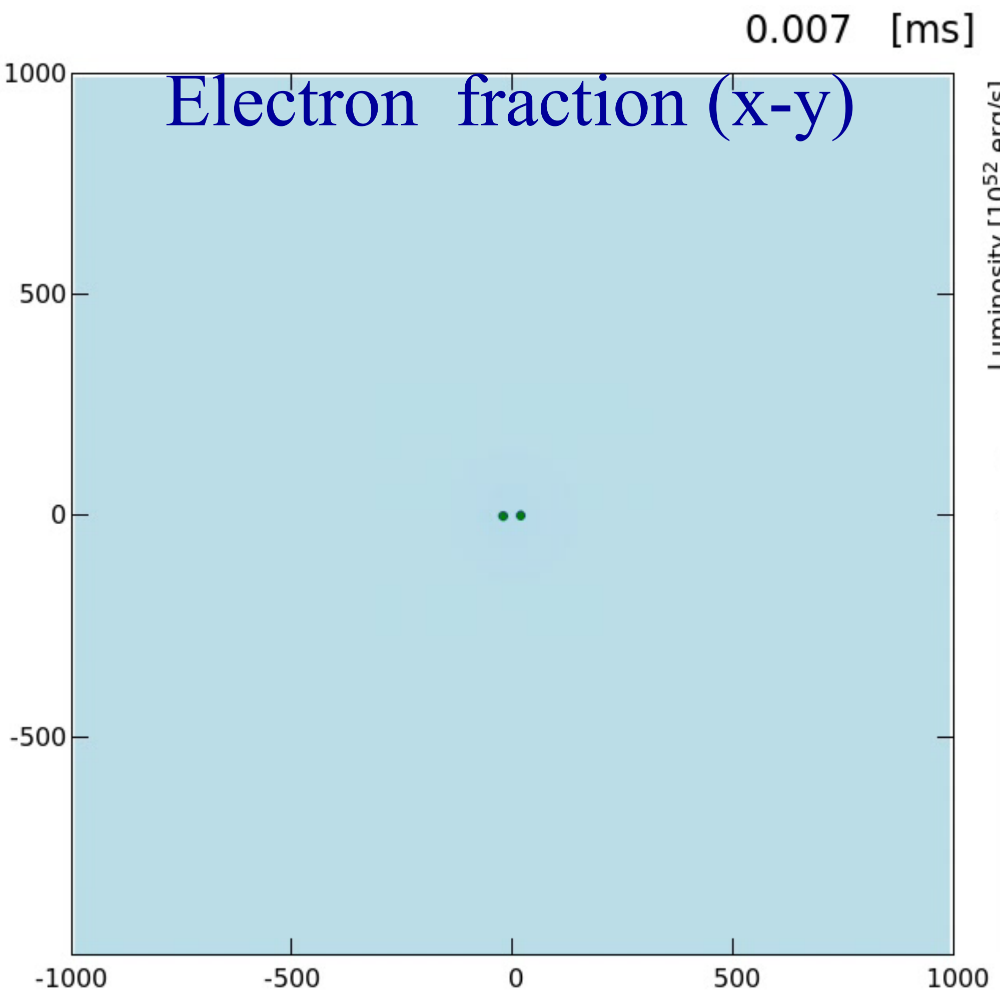
- Typical ejecta mass=0.001—0.02 M_{sun}
- Typical velocity ~ 0.2c

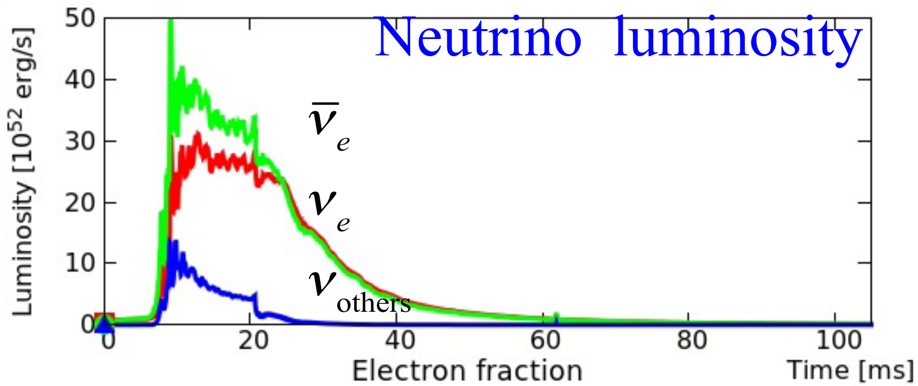
Sekiguchi et al. 2016

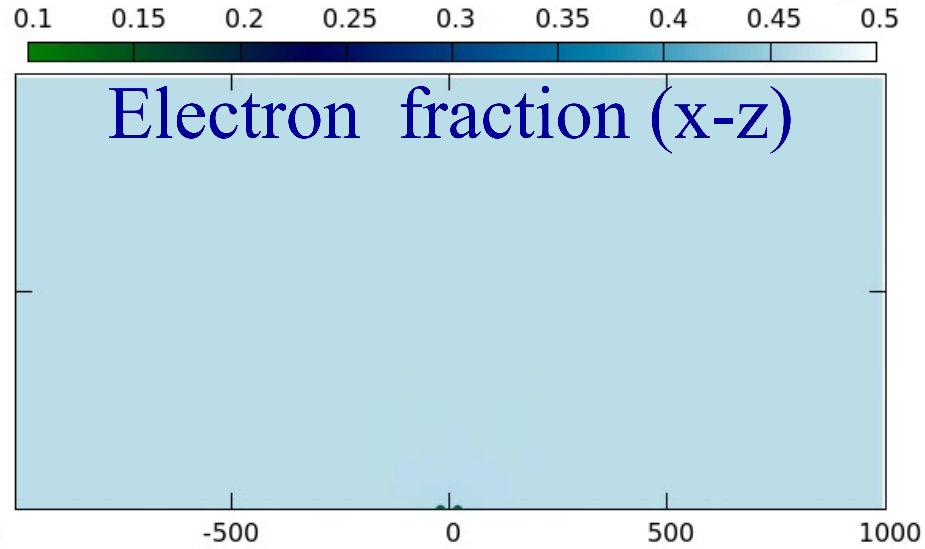
High temperature $\Rightarrow \gamma\gamma \rightarrow e^- + e^+, \quad n + e^+ \rightarrow p + \bar{\nu}_e$

Neutrino irradiation $\Rightarrow n + \nu_e \rightarrow p + e^-$

$Y_e = [p]/([n]+[p])$

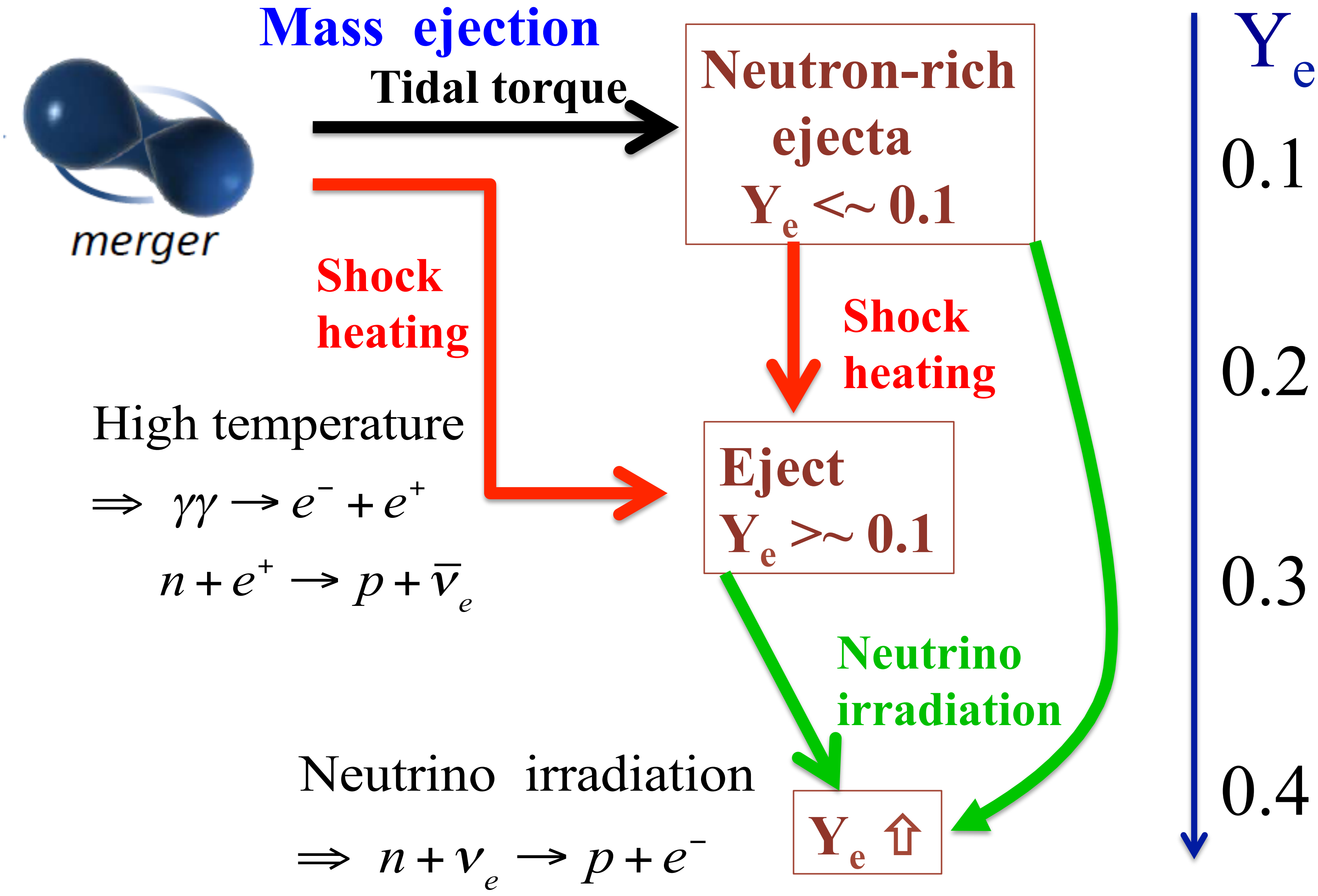






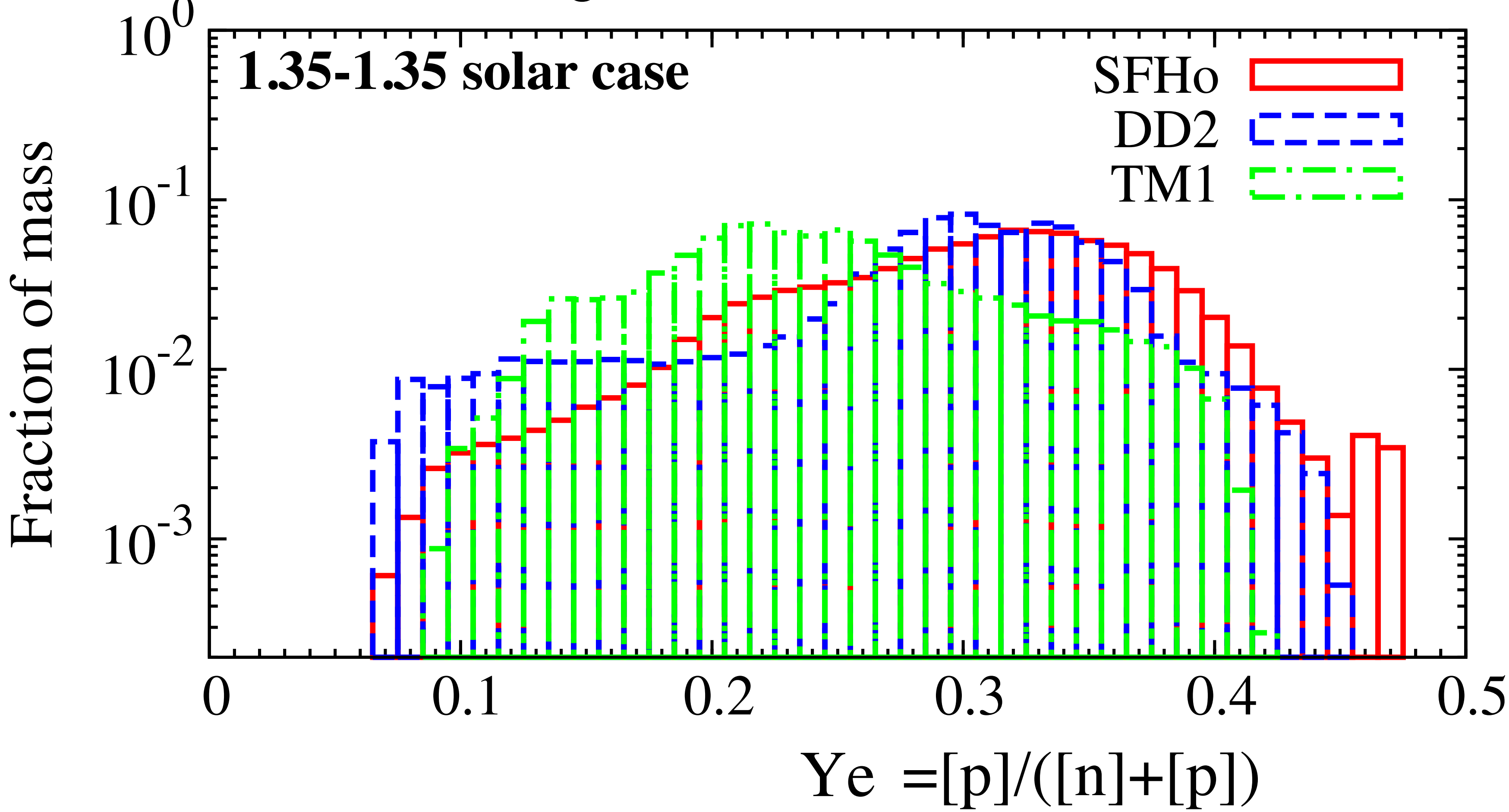
Sekiguchi et al. (2016)

Dynamical evolution of neutron richness



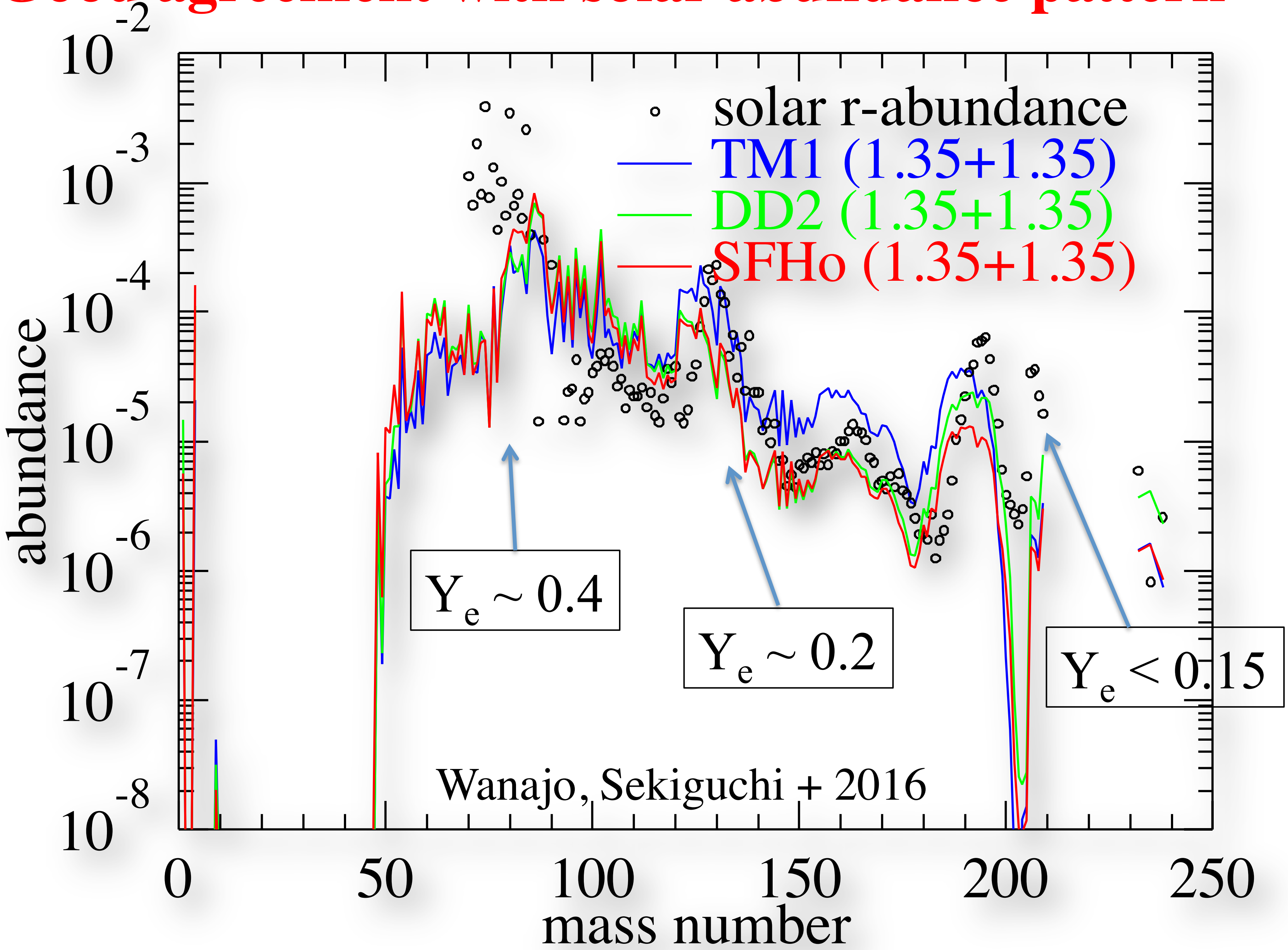
Electron fraction profile: Broad

Sekiguchi et al. 2015 PRD

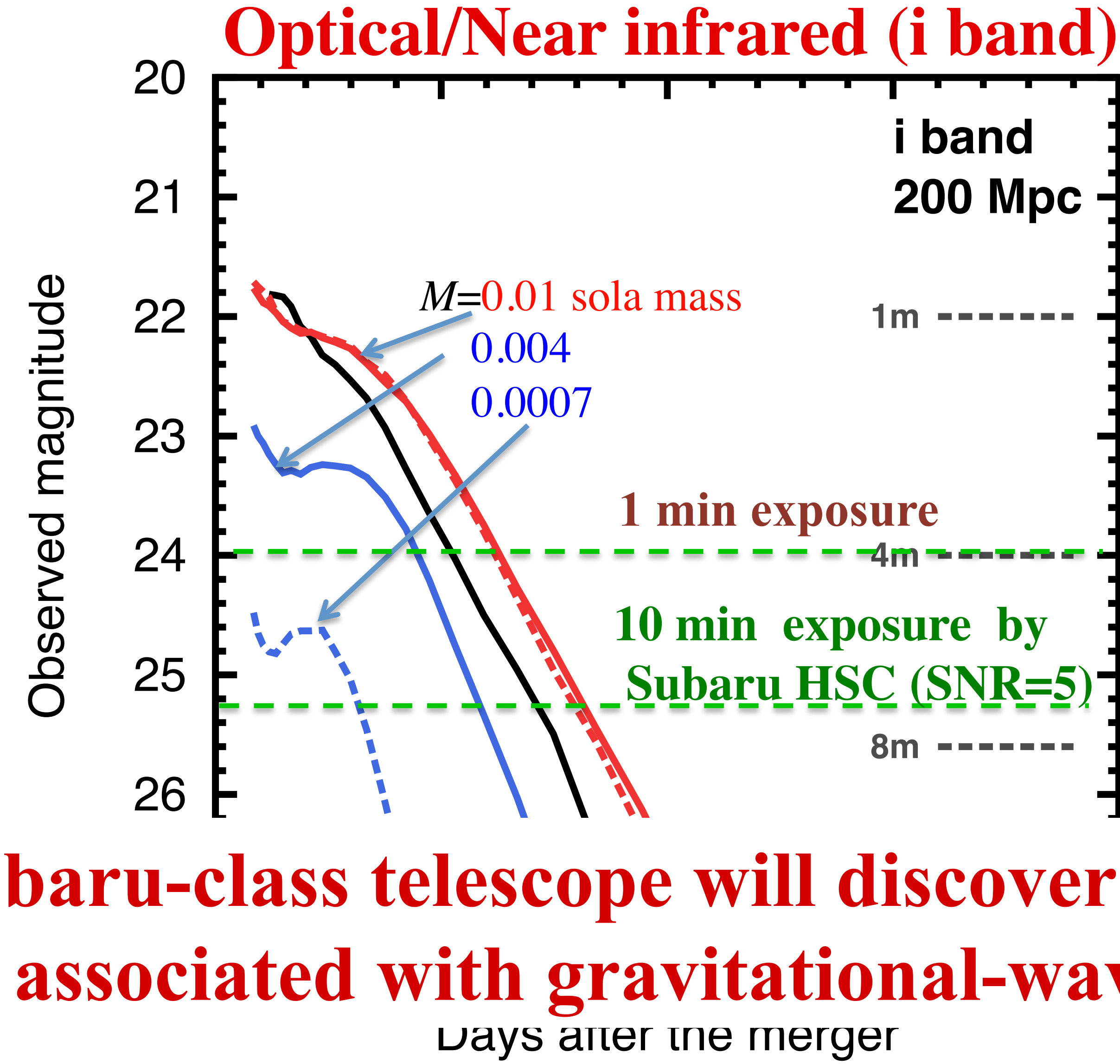


- **Broad distribution of Y_e** irrespective of EOS

Good agreement with solar abundance pattern



Expected light curves @ 200Mpc



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

Subaru-class telescope will discover macronova associated with gravitational-wave events

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

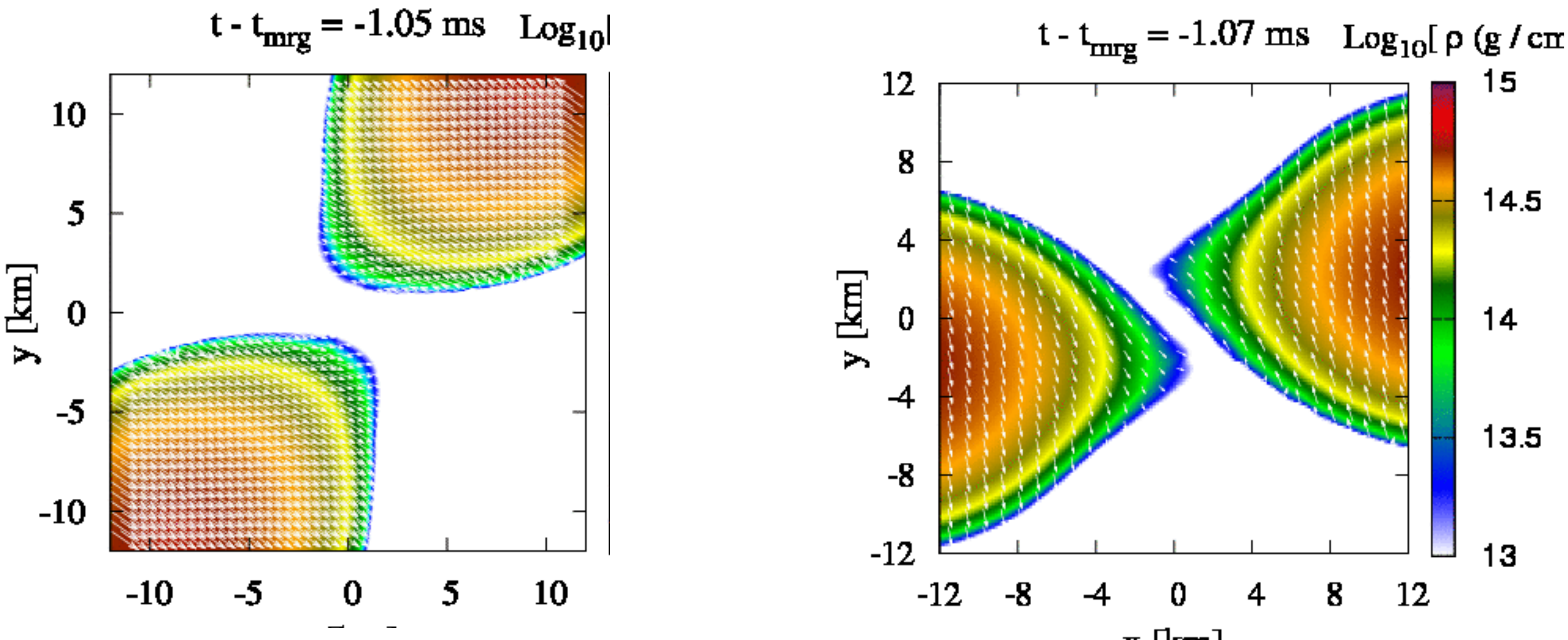
3 More details are required

- Post merger process would be determined primarily by **magneto-hydrodynamcis** (MHD)
- MHD instabilities, Kelvin-Helmholtz and magneto rotational instabilities, are keys → By them, turbulence will be developed and determine the transport an dissipation processes
- To date, no simulations in realistic setting have fully resolved them
  → **They are NOT MHD simulations in reality**
  → We have to pursue this

□ Viscous hydrodynamics could be approximate alternative effective treatment

High-resolution GRMHD for NS-NS

Kiuchi et al. 2015



Δx=17.5m Δx=70m

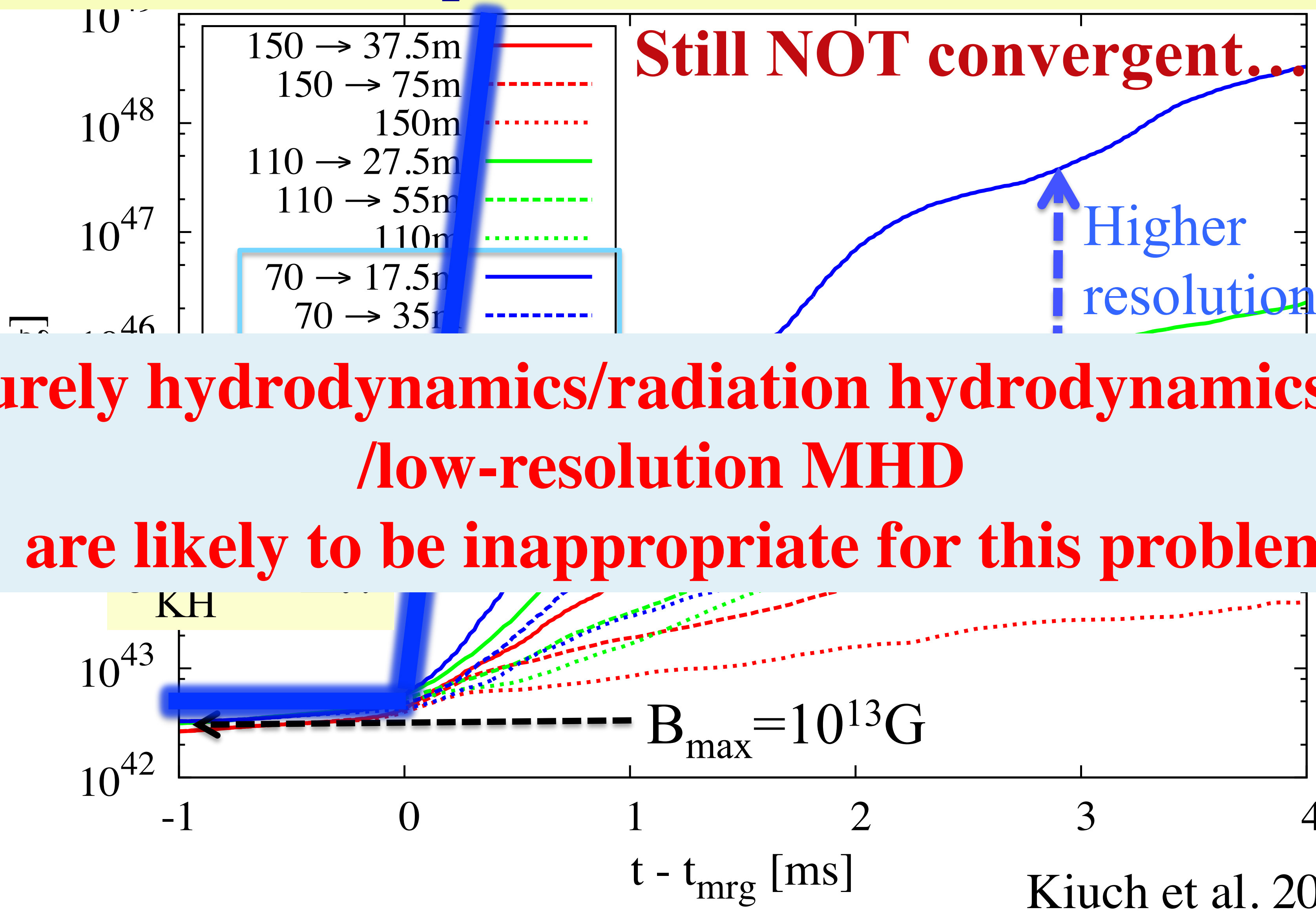
Kelvin-Helmholtz instability

→ Magnetic fields are amplified by winding

→ Turbulence ? Quick angular momentum transport ?

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)
  "Current GRMHD simulations for NS mergers are not GRMHD simulations"
- **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

Visc … **s for**

(S. … onth)

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

Employ covariant & causal GR viscous hydrodynamics

(Israel & Steward, ’79, Shibata+ ‘17)

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

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

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

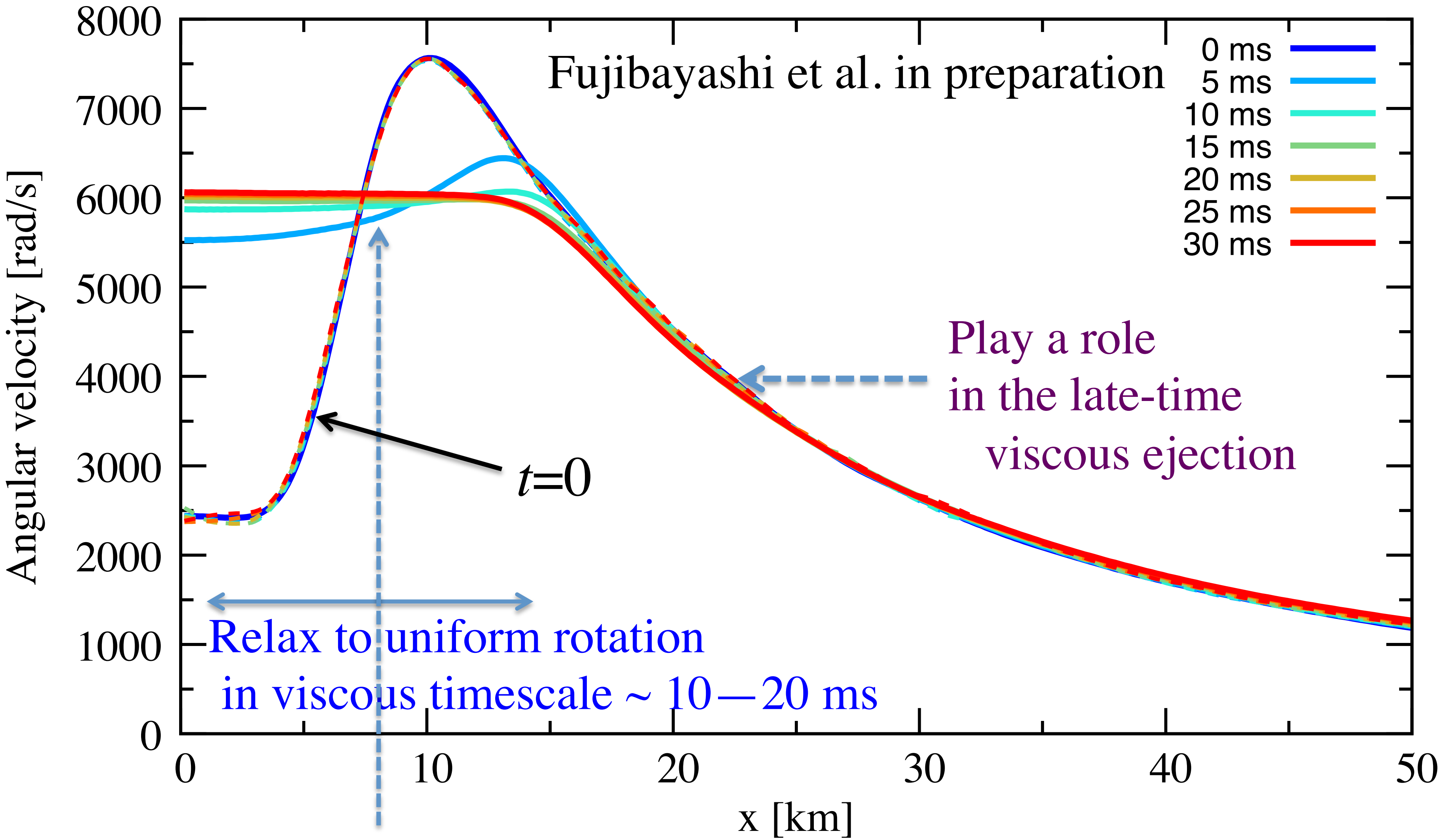
→ Dynamical ejecta mass ~ 0.001 $M_\odot$

Axis symmetric simulation

Wide 1500×1500 km 300×300 km

Density in *x*-*z* plane

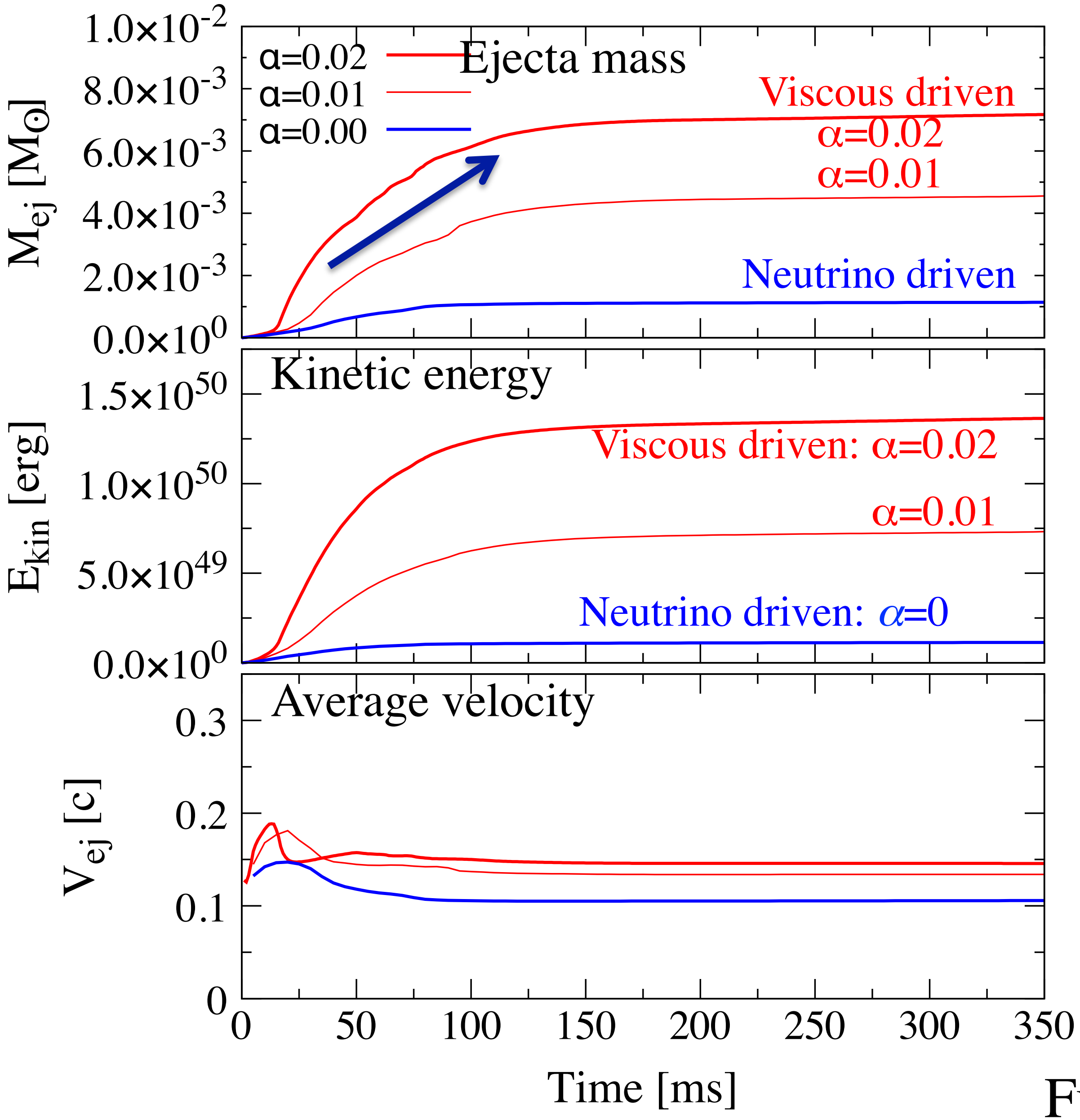
Evolution of angular velocity



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 $\sim 10^{-2}\,(\alpha/0.03)M_{\odot}$

Fujibayashi et al. in prep.

3D viscous hydrodynamics simulation for remnant of binary neutron star merger

(Shibata & Kiuchi PRD June 2017)

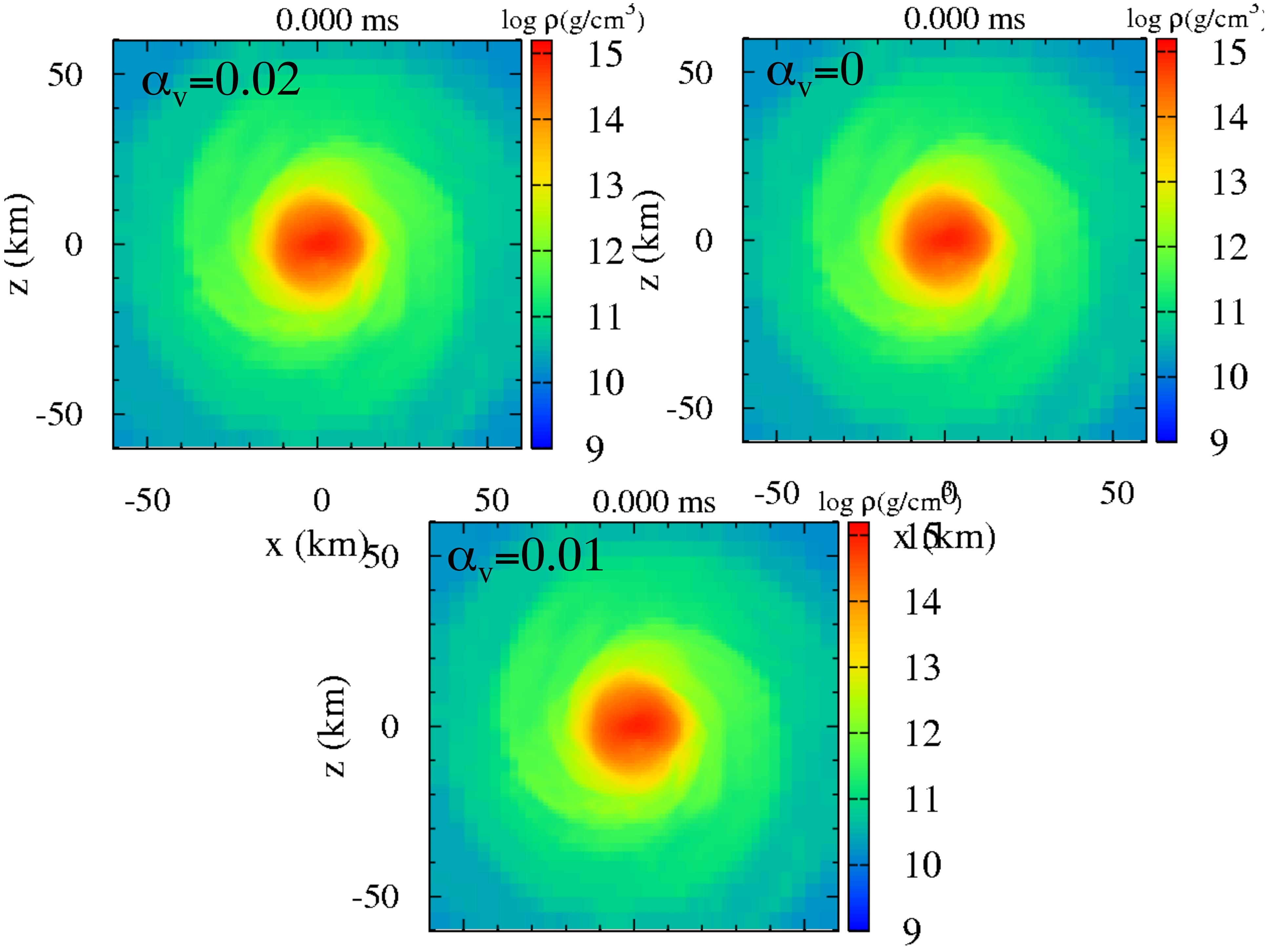
- Merger remnant is used as initial condition

✓ H4 EOS (stiff EOS)

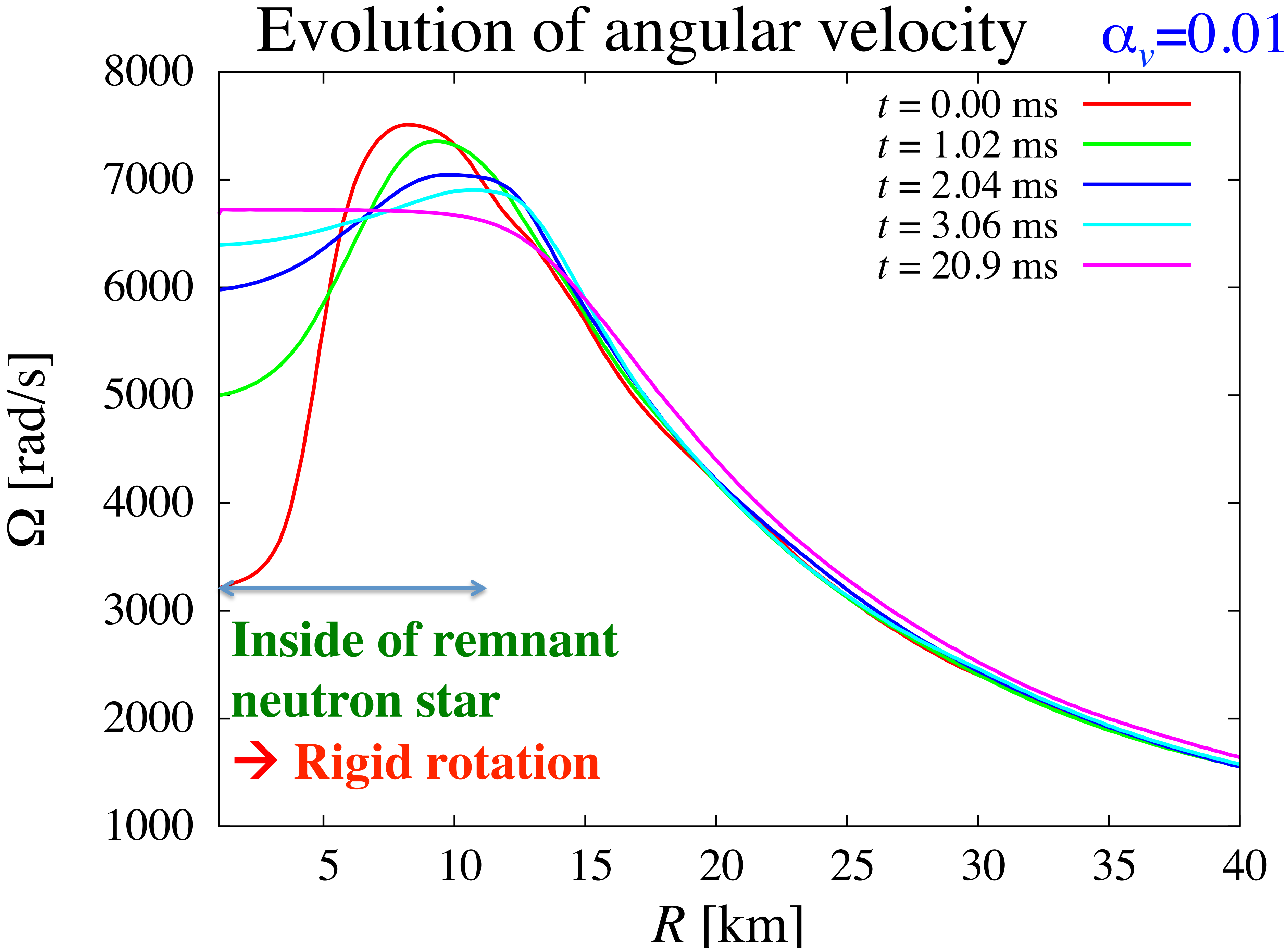
✓ Mass = 1.35-1.35 solar mass

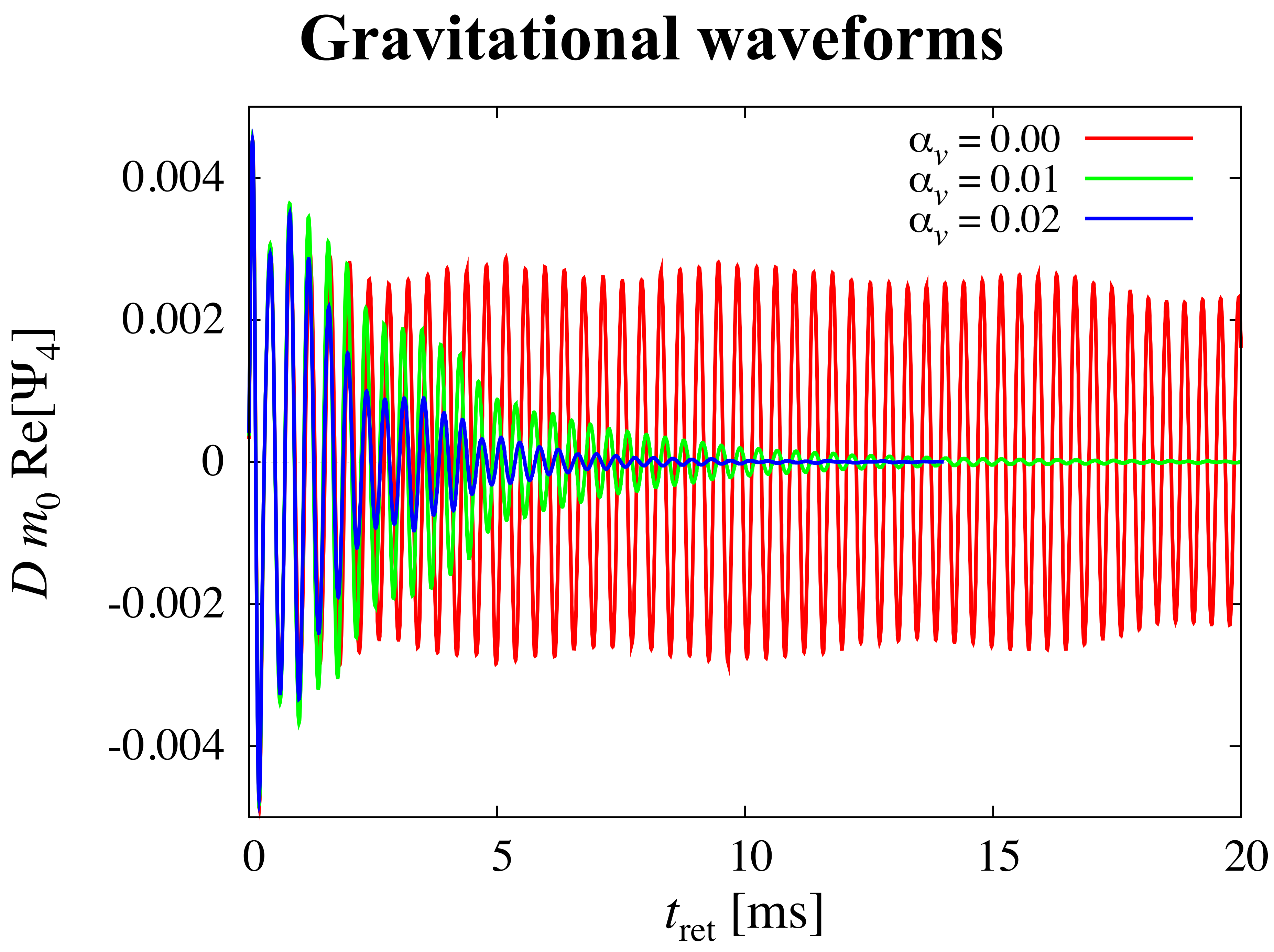
- Simulation is started at ~ 5ms after the onset of merger
- ν is set to be $\alpha_\nu\, c_s^{\,2}\, \Omega^{-1} \sim \alpha_\nu\, c_s X$ ($X \sim 10$ km): α model
- α parameter = 0.01—0.02 taking into account the latest MHD simulation results for accretion disks (such as Jim Stone and his colleagues have been doing)

See also recent work by Radice (2017)

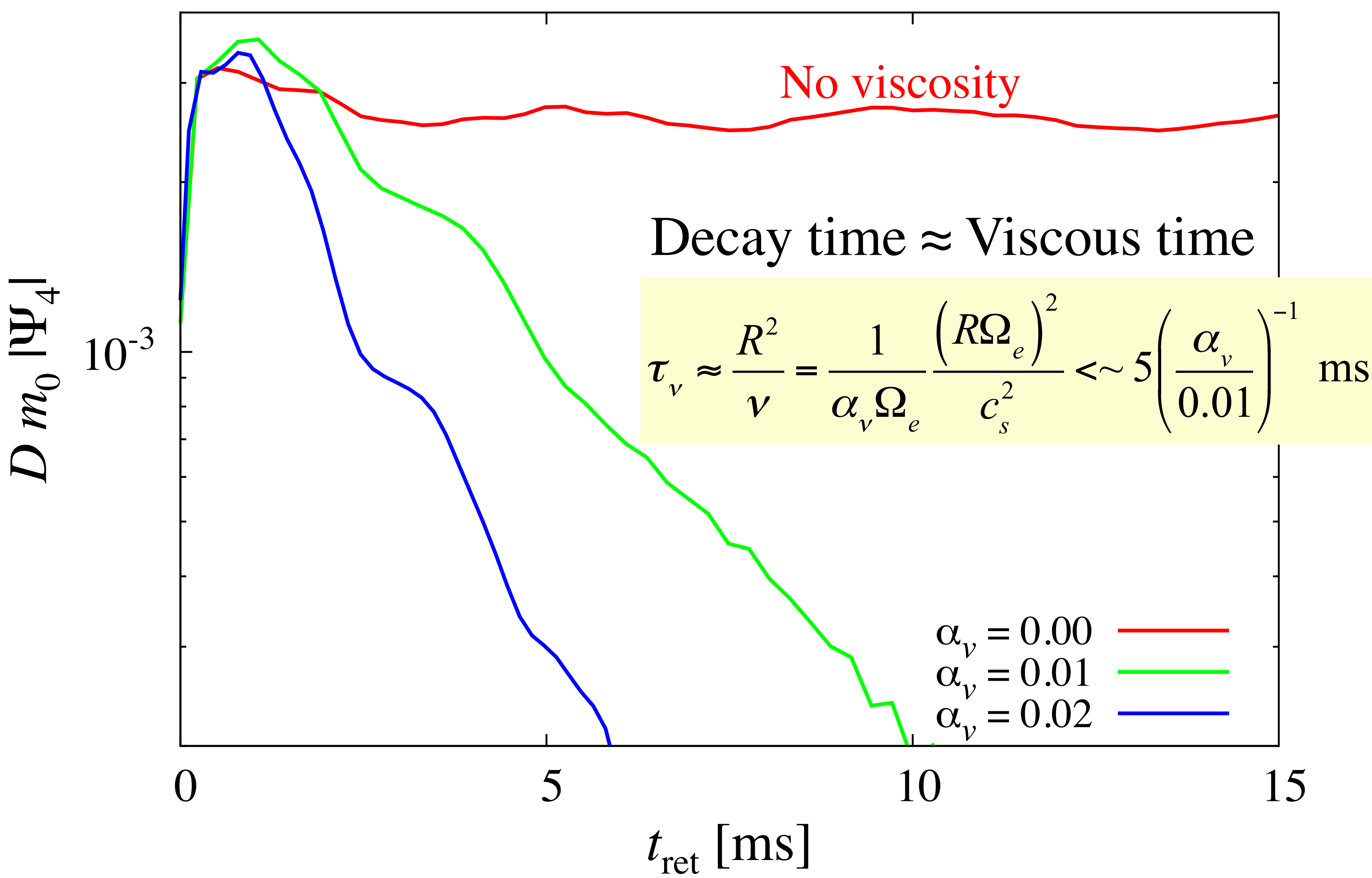


0.000 ms
log ρ(g/cm³)
α_v=0.02
z (km)
x (km)
0.000 ms
log ρ(g/cm³)
α_v=0
z (km)
x (km)
0.000 ms
log ρ(g/cm³)
α_v=0.01
z (km)

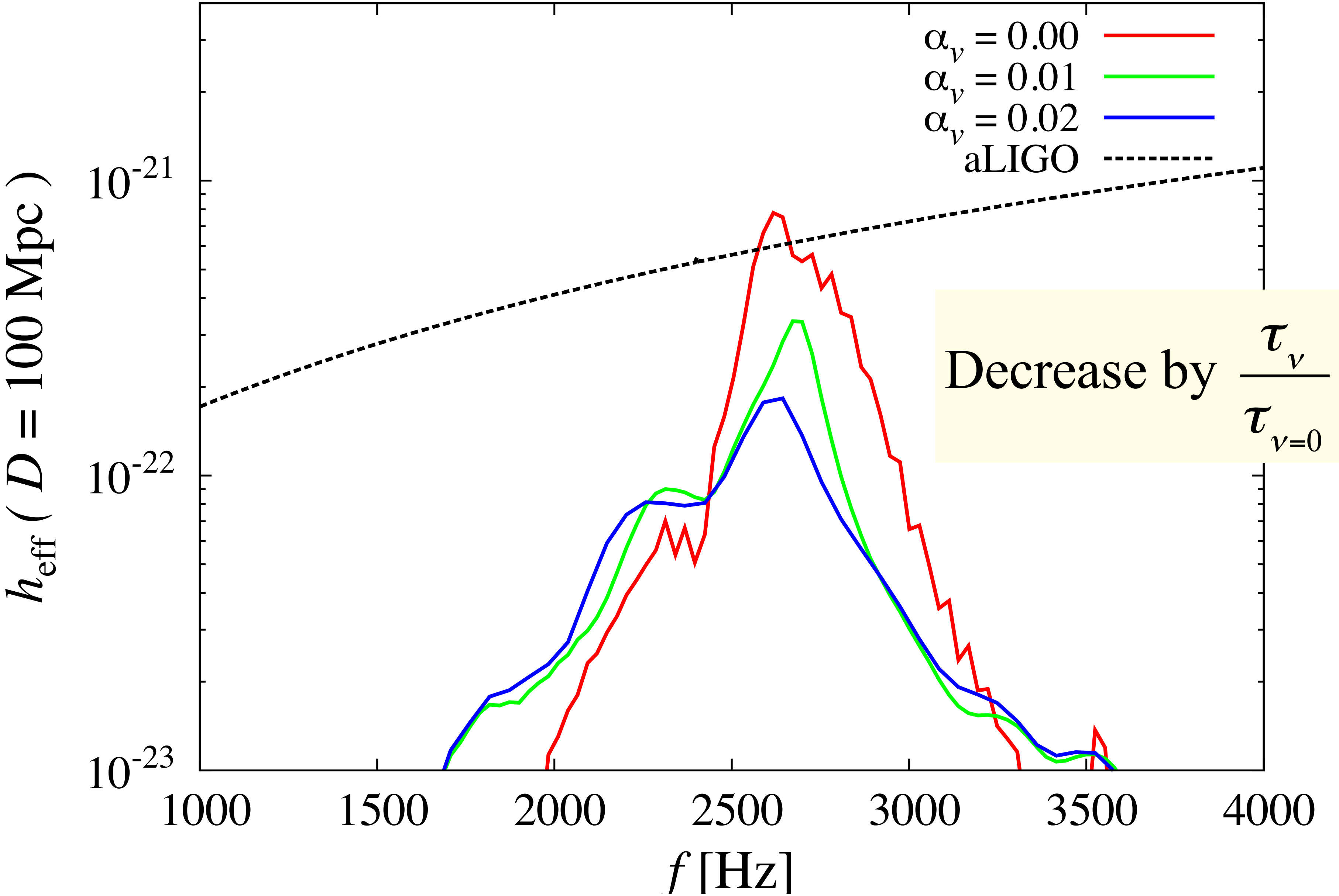

Evolution of angular velocity
α_ν=0.01
8000
7000
6000
5000
4000
3000
2000
1000
5
10
15
20
25
30
35
40
Ω [rad/s]
R [km]
t = 0.00 ms
t = 1.02 ms
t = 2.04 ms
t = 3.06 ms
t = 20.9 ms
Inside of remnant
neutron star
→ Rigid rotation


Gravitational waveforms
$\alpha_v = 0.00$
$\alpha_v = 0.01$
$\alpha_v = 0.02$
0.004
0.002
0
-0.002
-0.004
$D\, m_0\, \mathrm{Re}[\Psi_4]$
0
5
10
15
20
t_{ret} [ms]

Amplitude of gravitational waves



Spectrum



$\alpha_\nu = 0.00$
$\alpha_\nu = 0.01$
$\alpha_\nu = 0.02$
aLIGO
Decrease by $\frac{\tau_\nu}{\tau_{\nu=0}}$
10^{-21}
10^{-22}
10^{-23}
1000
1500
2000
2500
3000
3500
4000
f [Hz]
h_{eff} (D = 100 Mpc)

Summary

❖ Typical scenarios for NS-NS merger: NS-NS → HMNS or MNS → Long-term evolution by viscous process

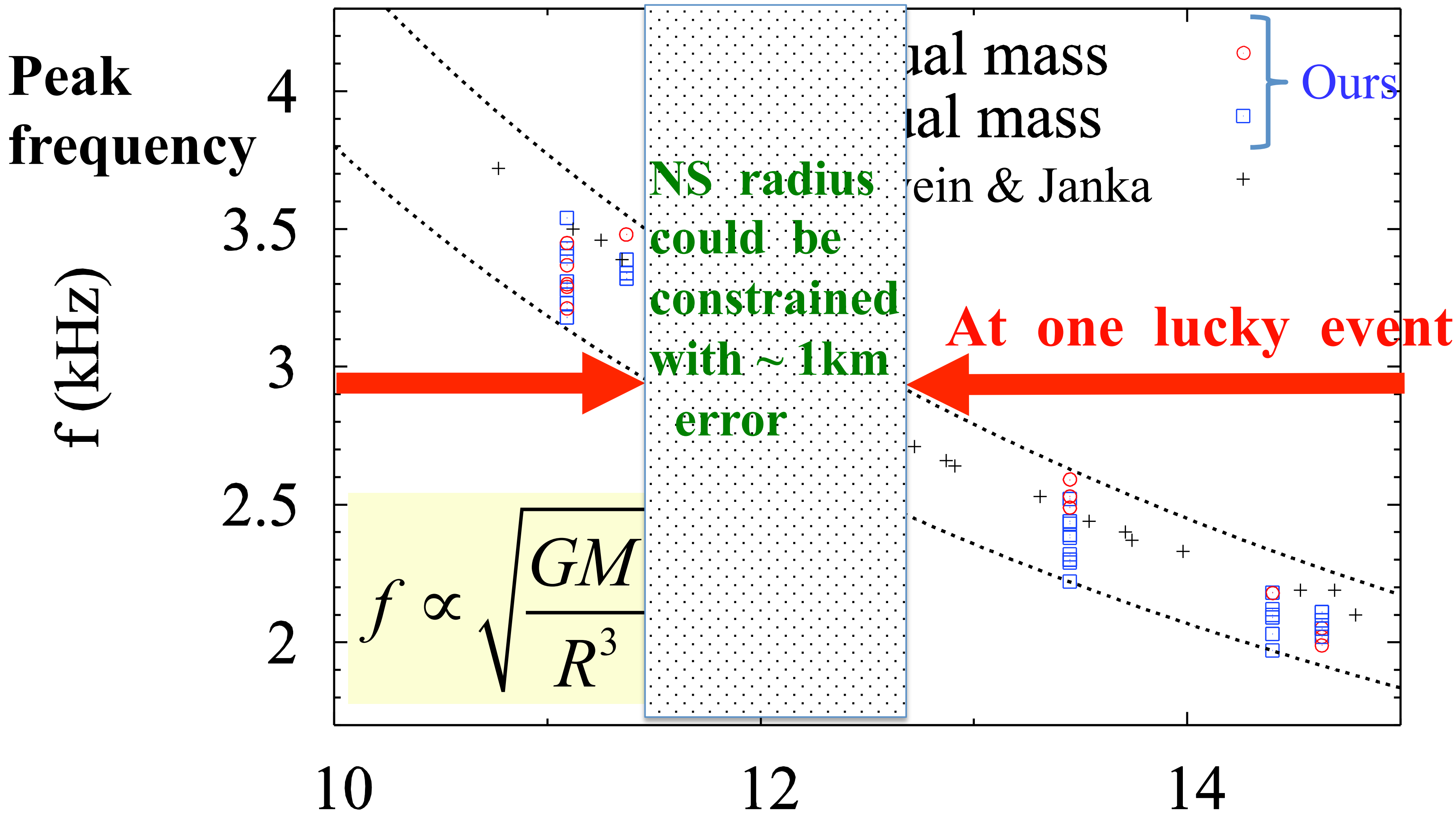
❖ Gravitational waves from late inspiral phase is the primary target for constraining the NS EOS

❖ There are likely to be a few mass ejection processes:

1. For the presence of a long-lived MNS: dynamical mass ejection (Y_e=0.05—0.5) + early viscous ejection (Y_e >~ 0.2) + disk wind (Y_e > ~0.3)
2. For the BH formation: dynamical mass ejection (Y_e=0.05—0.5) + disk wind (Y_e=0.1—0.5)

❖ For both, ejecta mass ~ 0.01 solar mass or more

Clear correlation between peak and radius



Radius of 1.6 solar-mass NS