Gravitational waves from neutron-star binaries

- Constraining Neutron Star EOS -

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Outline

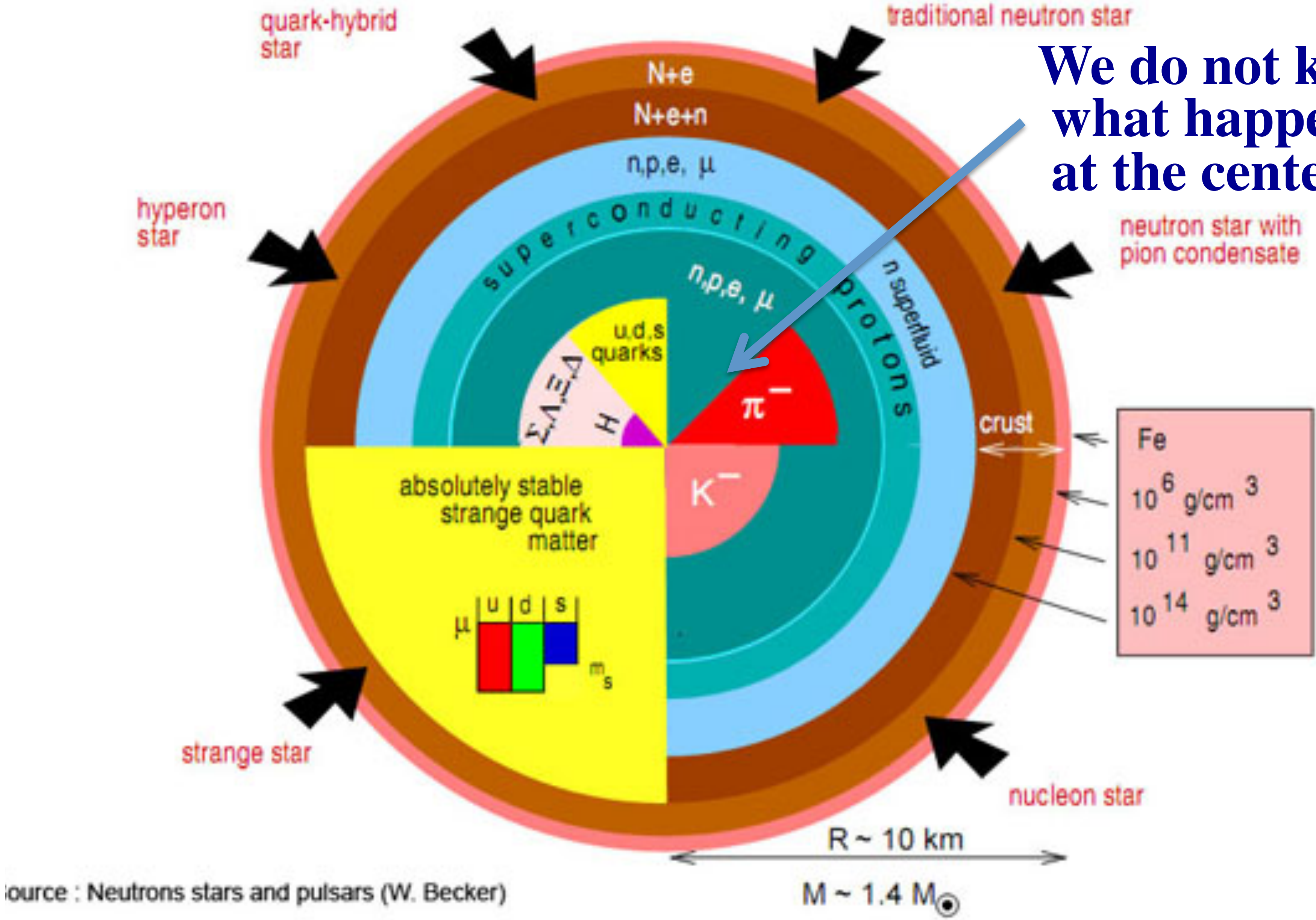
0. Brief introduction
1. Typical scenarios of NS-mergers
2. Gravitational waves & equations of state
3. Viscous hydrodynamics for post-merger of NS-NS
4. High-accuracy simulations for NS-NS inspiral
5. Summary

Many (young) people are exploring NS binaries in numerical relativity

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

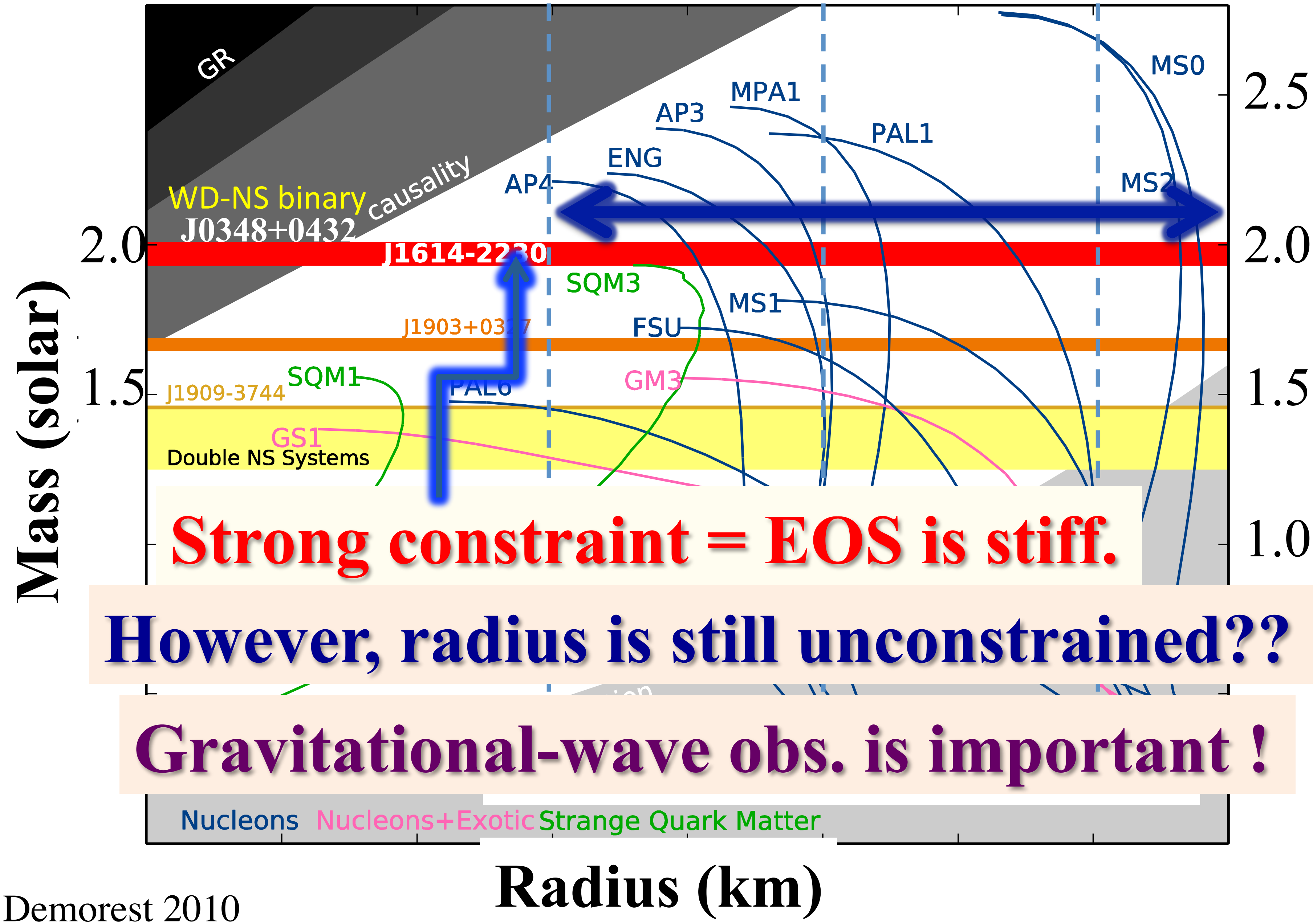
- **Solid progress on understanding NS-NS/NS-BH binary by numerical relativity**

Introduction: Neutron structure is still unsolved



We do not know what happens at the center

Mass-radius relation for various EOS



Strong constraint = EOS is stiff.

However, radius is still unconstrained??

Gravitational-wave obs. is important !

Demorest 2010

1 Typical scenarios of NS-NS/BH-NS merger

1-A Binary neutron stars

Boundary conditions from radio pulsar observation

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

	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.	A24	0.184	0.606	2.74	1.35	1.39	~0.75

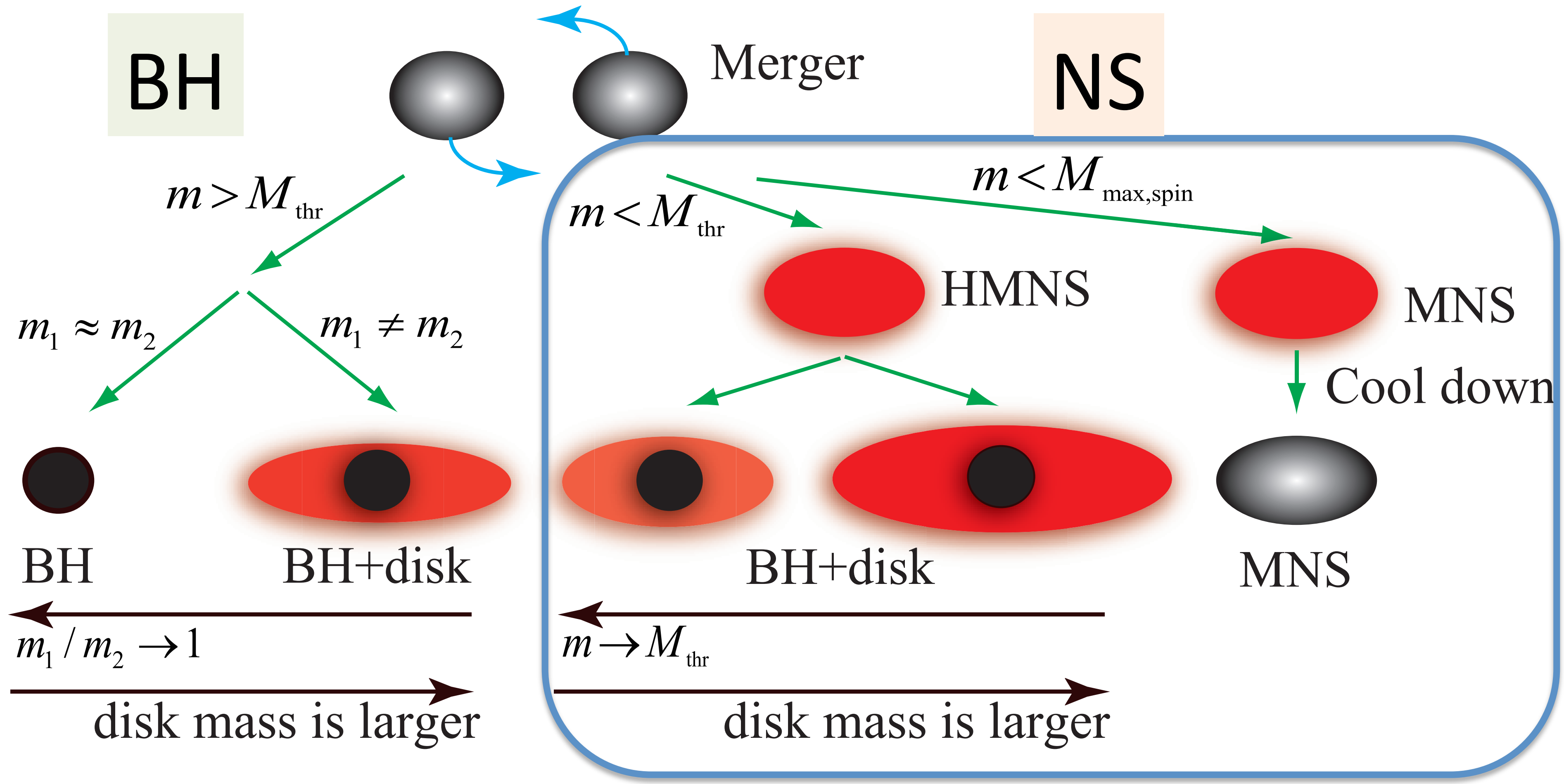
$\times 10^8$ yrs

Boundary conditions from radio pulsar observation

- **Total Mass of NS in compact NS-NS** is likely to be in a narrow range, $m \approx 2.73 \pm 0.15\ M_{sun}$
- **Spin of NS** is likely to be not very high, $P_{rot} > \sim 10$ ms or $\chi < \sim 0.04$ (1st NS=weakly recycled)
- **NS radius (EOS)** is still uncertain, but **maximum mass of NS would be ≥ 2 M_{sun}**
  (Demorest 2010; Antoniadis 2013)
  → **EOS of NS has to be sufficiently stiff**

- **Numerical relativity simulations have shown that massive neutron stars are formed after the merger**

Possible outcomes of NS-NS mergers



Likely for $M_{tot} < \sim 2.8 M_{sun}$

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

1-B Black hole-neutron star binaries

Two possibilities: Tidal disruption or not

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

$$\Downarrow$$

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

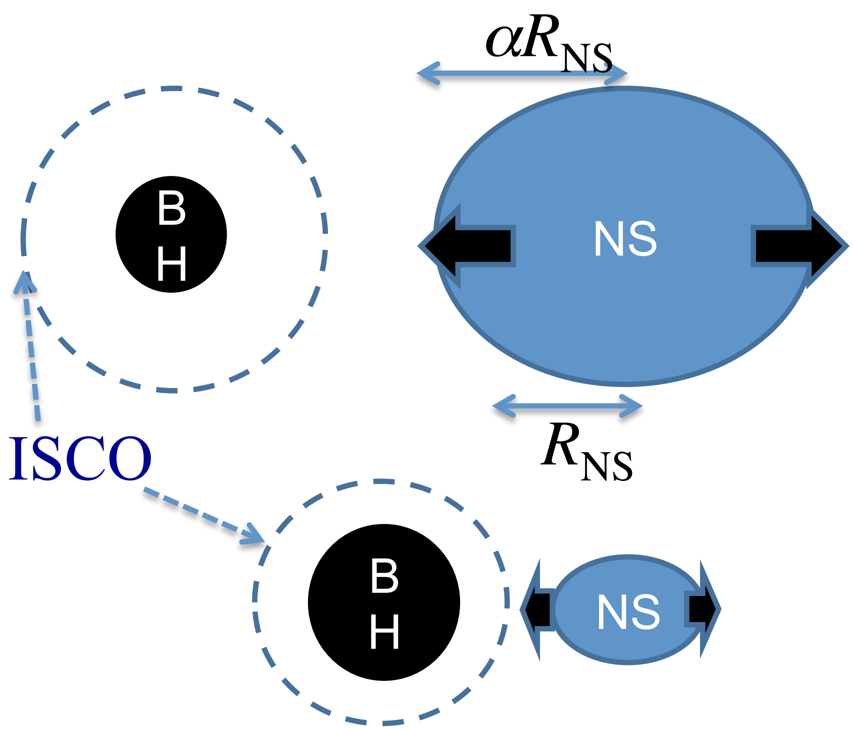
- **For tidal disruption**

❖ **Large NS Radius** **or**

❖ **Small BH mass** **or**

❖ **High corotation spin**

is necessary



BH-NS with aligned BH spin

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

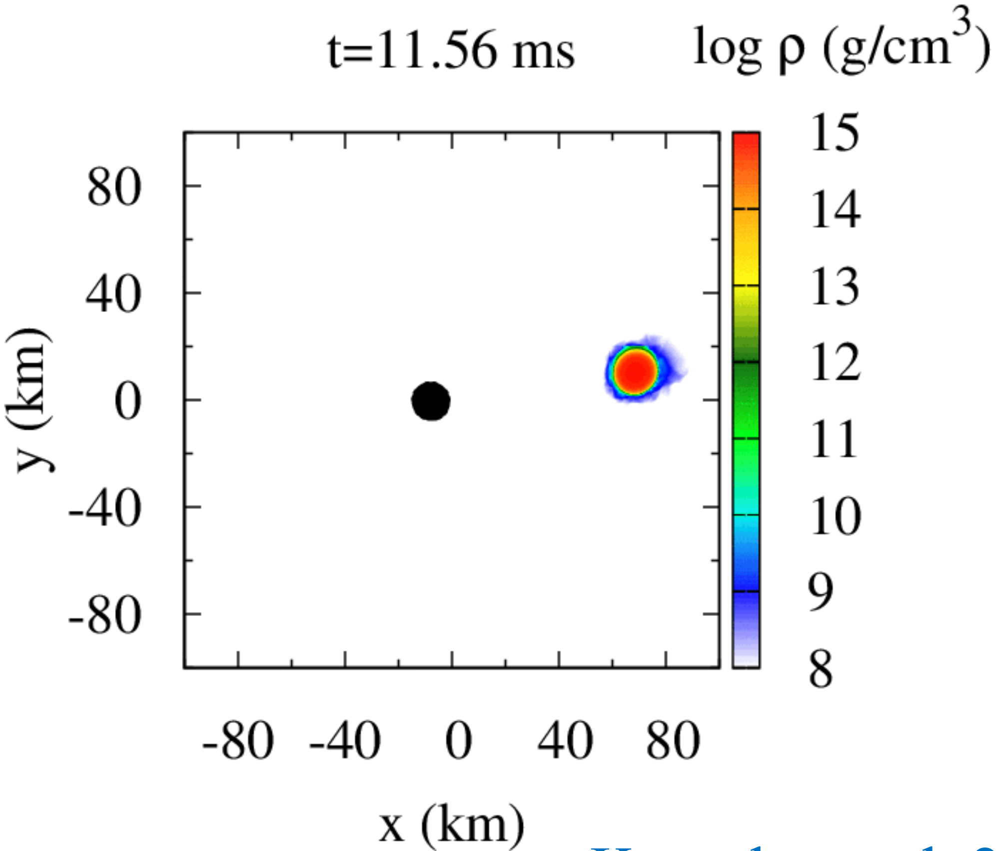
↔

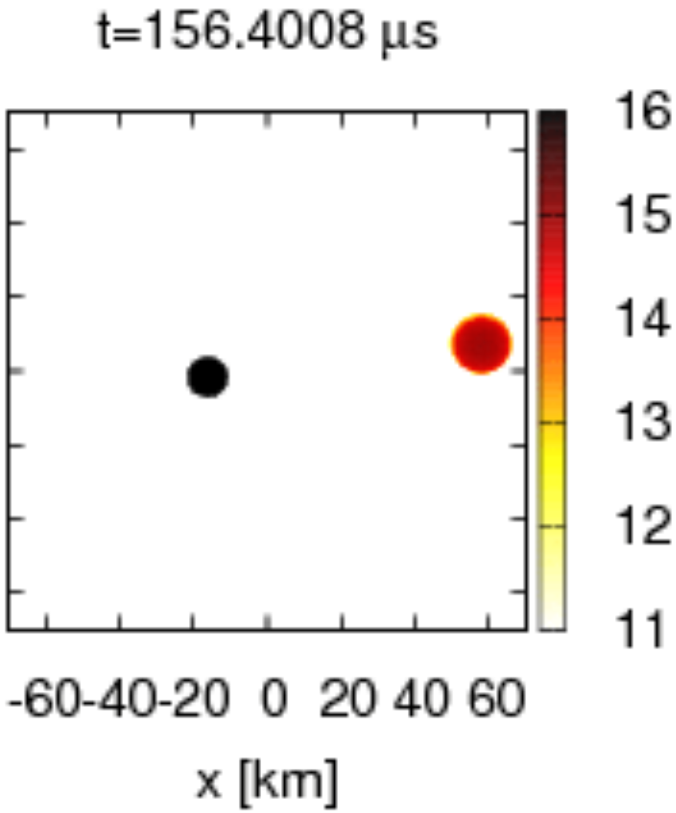
$M_{\rm BH}$=4.05$M_{\rm sun}$
a=0
$M_{\rm NS}$=1.35$M_{\rm sun}$
R=11.0 km

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_{NS} ~ 12 km, & M_{BH} > 6 M_{sun}

High BH spin is necessary > ~ 0.75

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

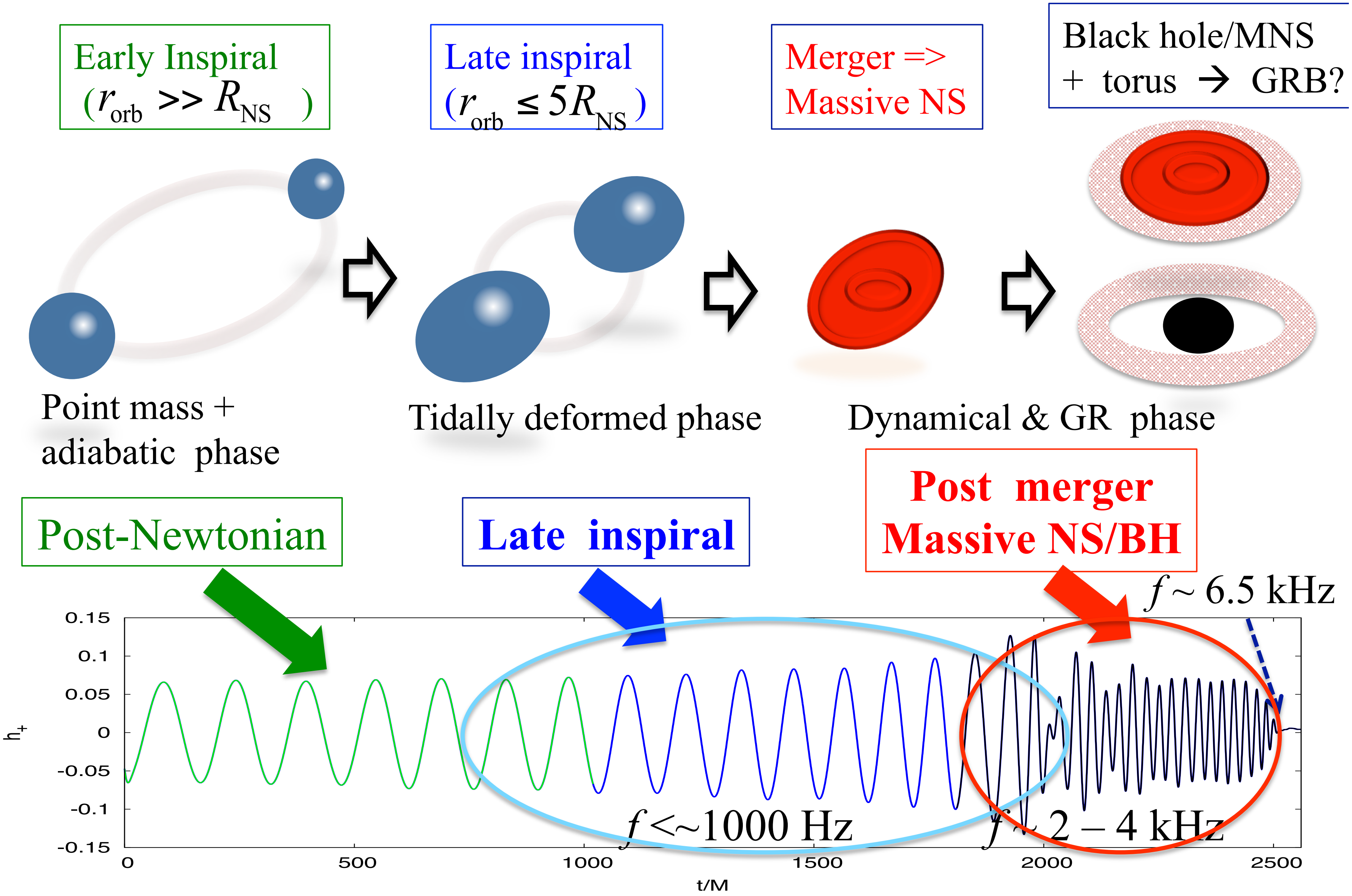
$$1 \leq \left(\frac{M_{BH}}{r_{ISCO}}\right)^3 \left(\frac{M_{NS}}{M_{BH}}\right)^2 \left(\frac{\alpha R_{NS}}{M_{NS}}\right)^3$$

- Note 1: BH mass should be smaller than ~20 solar mass for BH spin < ~0.9
- Note 2 : If high-mass BH, ~30 solar mass, is standard, ***ultra high spin*** is needed for tidal disruption

2 Gravitational waves & Equations of state

2-A NS-NS case

$M \sim 2.5 - 2.8 M_{sun}$

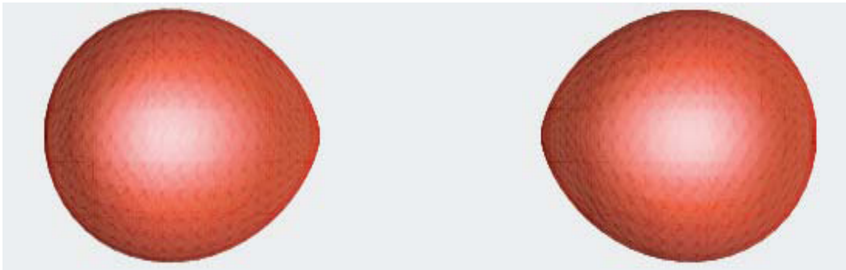


Imprint of EOS on late inspiral waveform

In a binary system, the tides raised on each NS depend on the **deformability** of that NS:

Stiff EOS = lager radius = large deformability

Soft EOS = small radius = small deformability

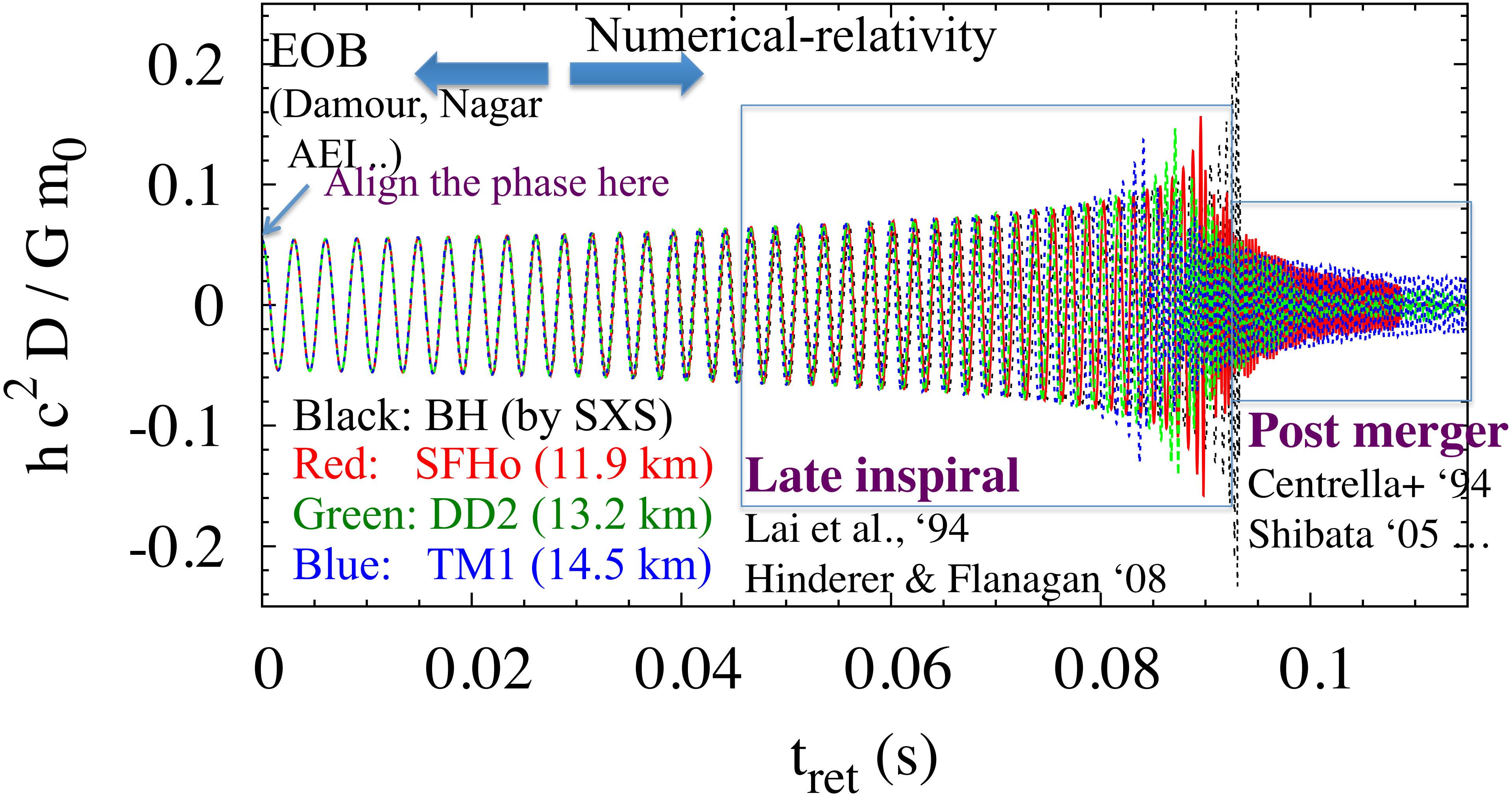


Courtesy J. Friedman

$$\phi \sim -\frac{GM}{r} - \frac{3 I_{ij}^{TF} n^i n^j}{2r^3} : I_{ij}^{TF} = O\left(r^{-3}\right)$$

Lai et al. (1994)

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



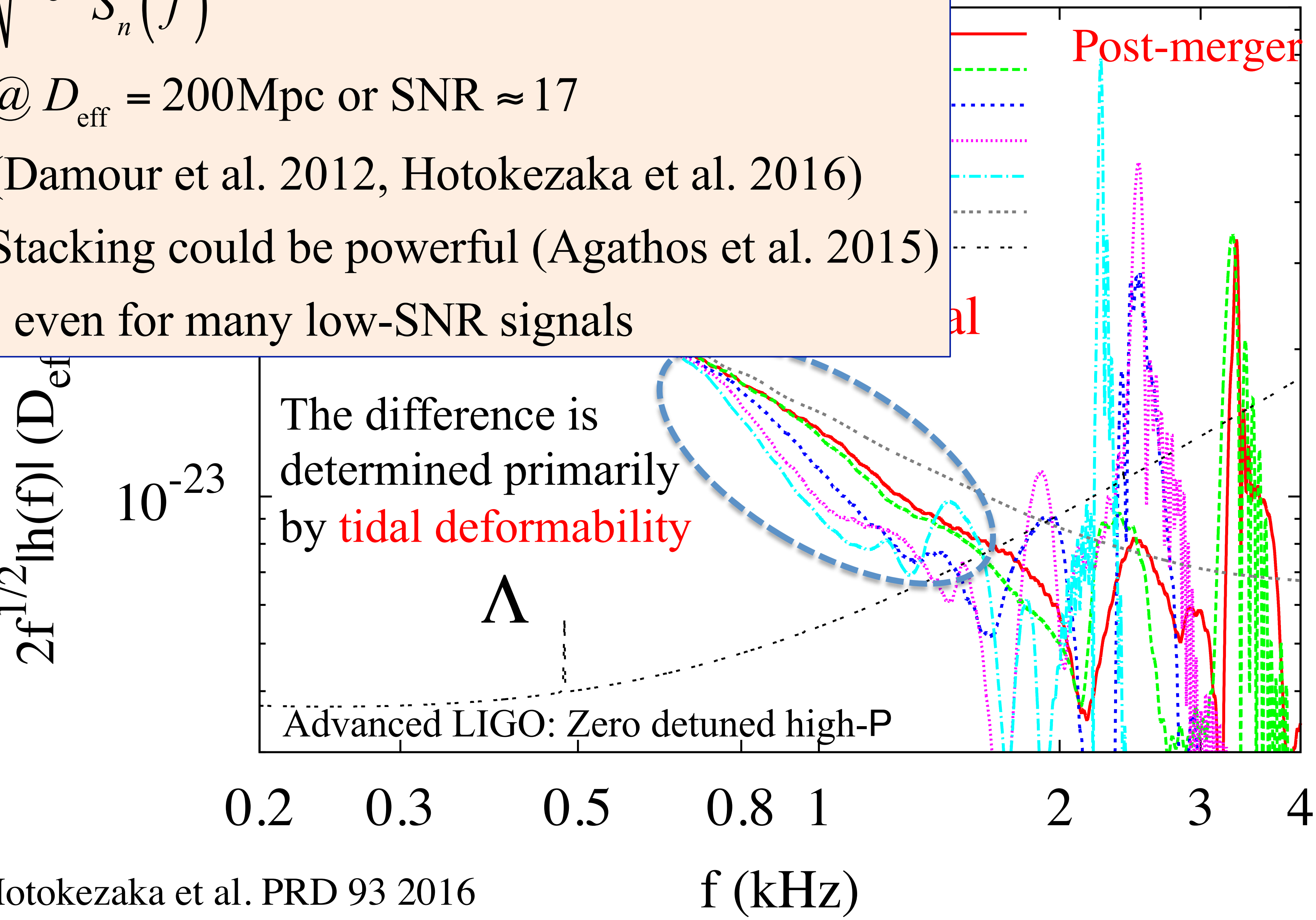
Hotokezaka et al. 2016 (see also efforts by Bernuzzi,…2011–)

$$\sqrt{4\int \frac{\delta h^2}{S_n(f)}df} \approx 2 \text{ for } \delta\Lambda{=}400 \;\Rightarrow\; \delta R \approx 1 \text{ km}$$

@ $D_{\rm eff} = 200$Mpc or SNR ≈ 17

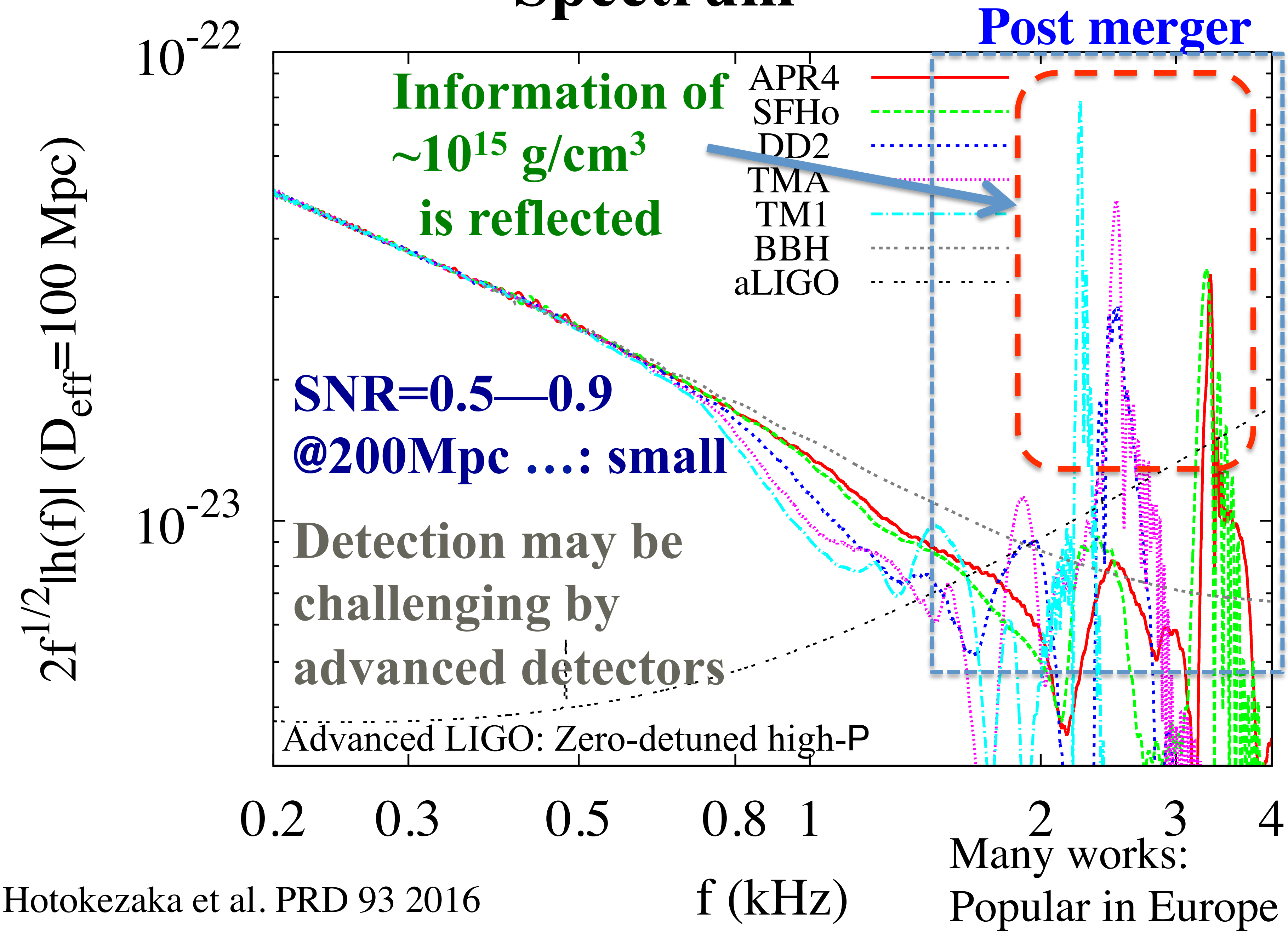
(Damour et al. 2012, Hotokezaka et al. 2016)

Stacking could be powerful (Agathos et al. 2015)
even for many low-SNR signals



Hotokezaka et al. PRD 93 2016

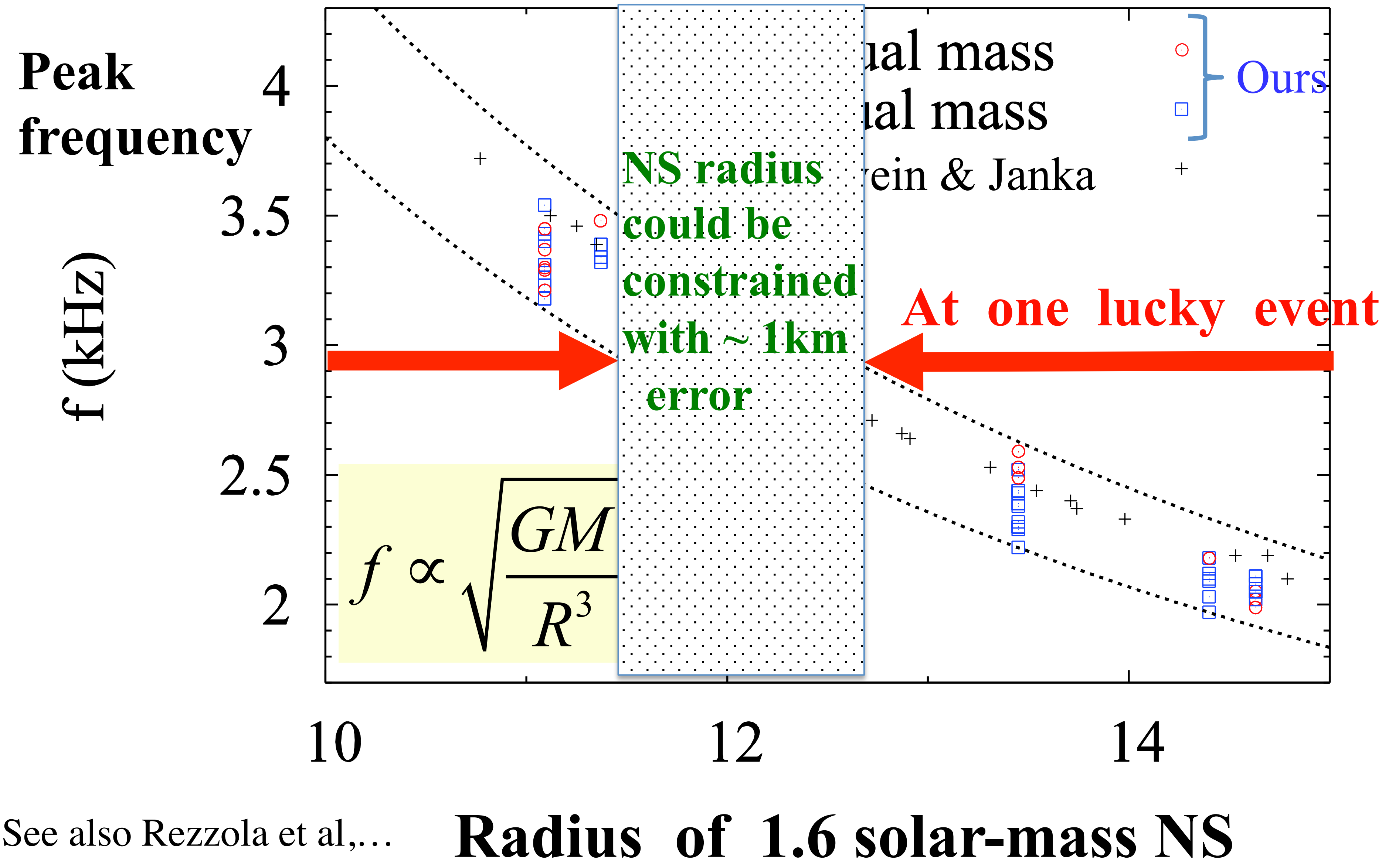
Spectrum



Hotokezaka et al. PRD 93 2016

Many works:
Popular in Europe

Clear correlation between peak and radius



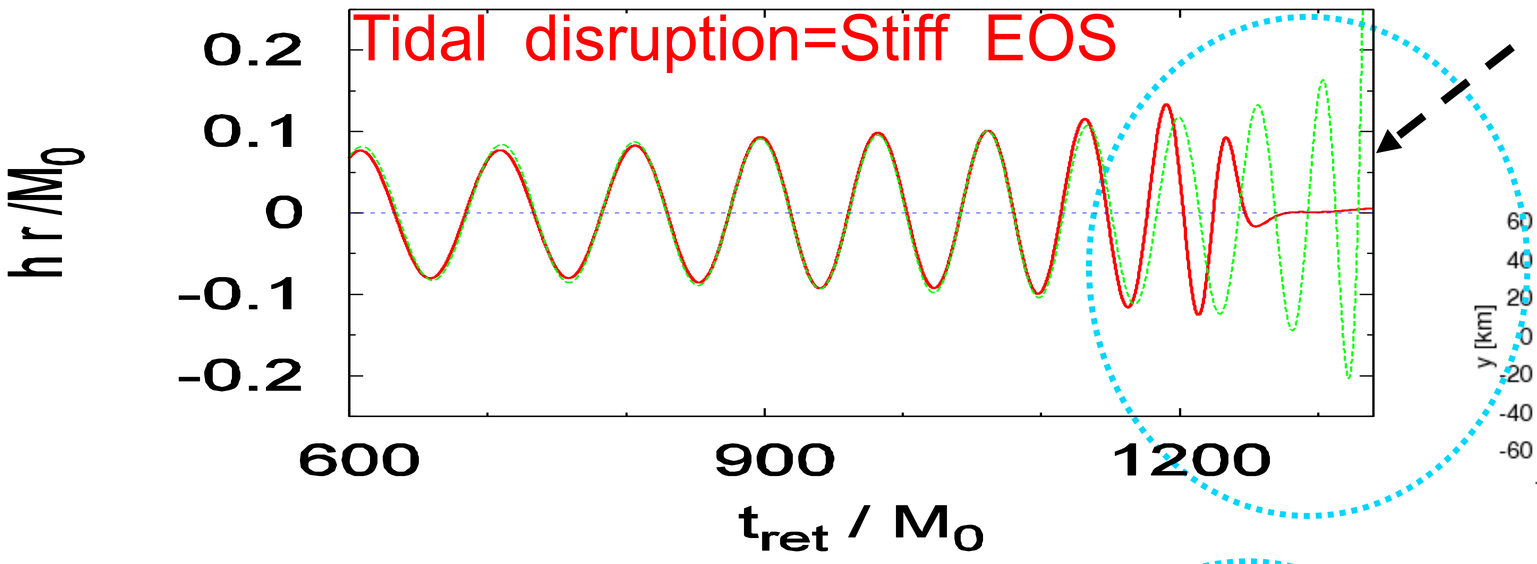
See also Rezzola et al,…

Current issues for NS-NS

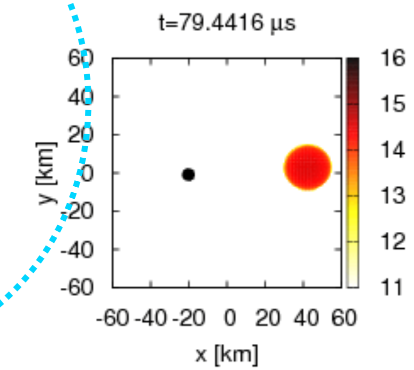
- For late inspiral (*clean system*):
  Need to construct accurate measurement templates
  → **high-resolution** numerical relativity simulations
  + sophisticated **modeling** (e.g., TEOB) are necessary
  (section 4 for our latest efforts)

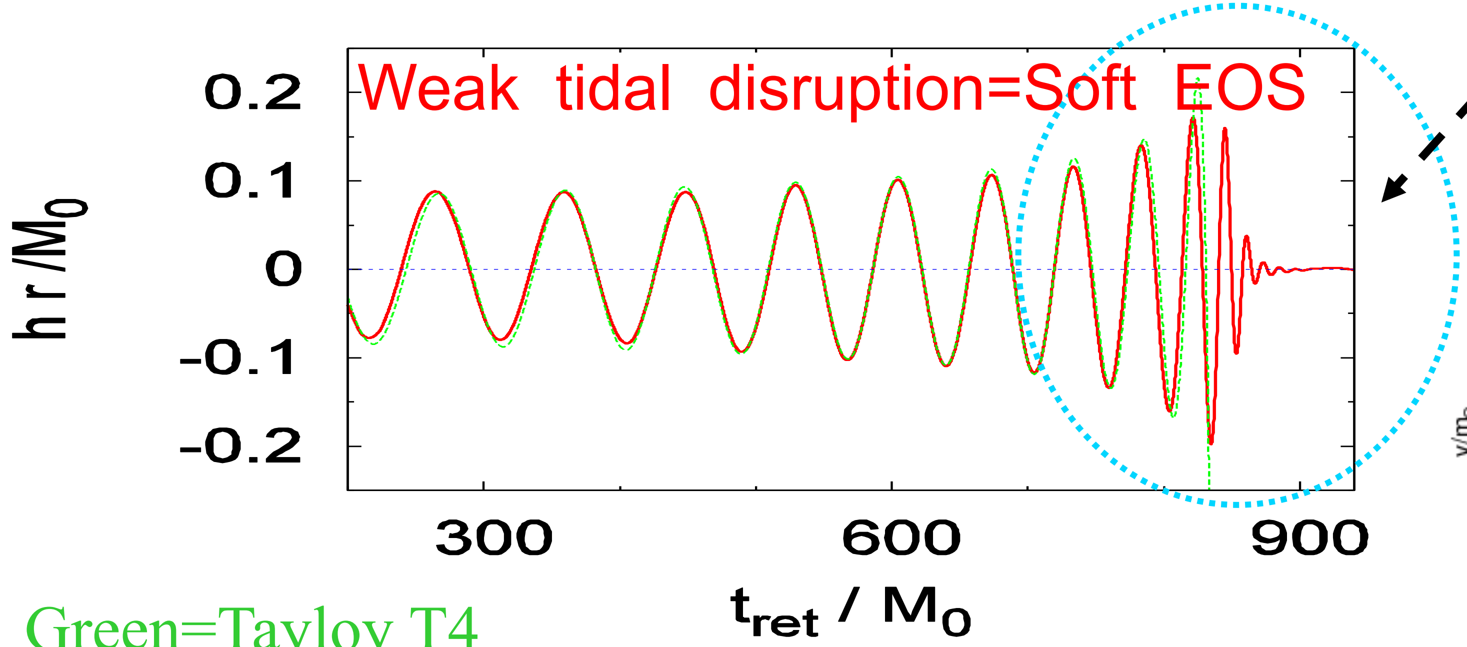
- For post-merger phase (*many physics play roles*):
  Careful physical modeling is necessary:
  Most of previous studies have neglected **systematics**
  (section 3)

2-B BH-NS: Signal of tidal disruption

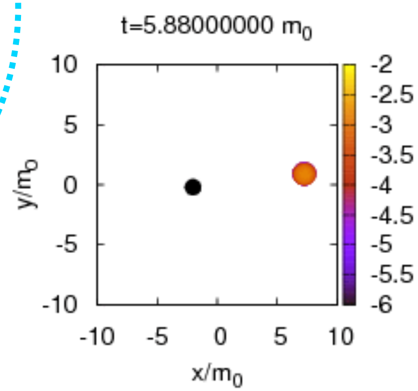


sudden shutdown



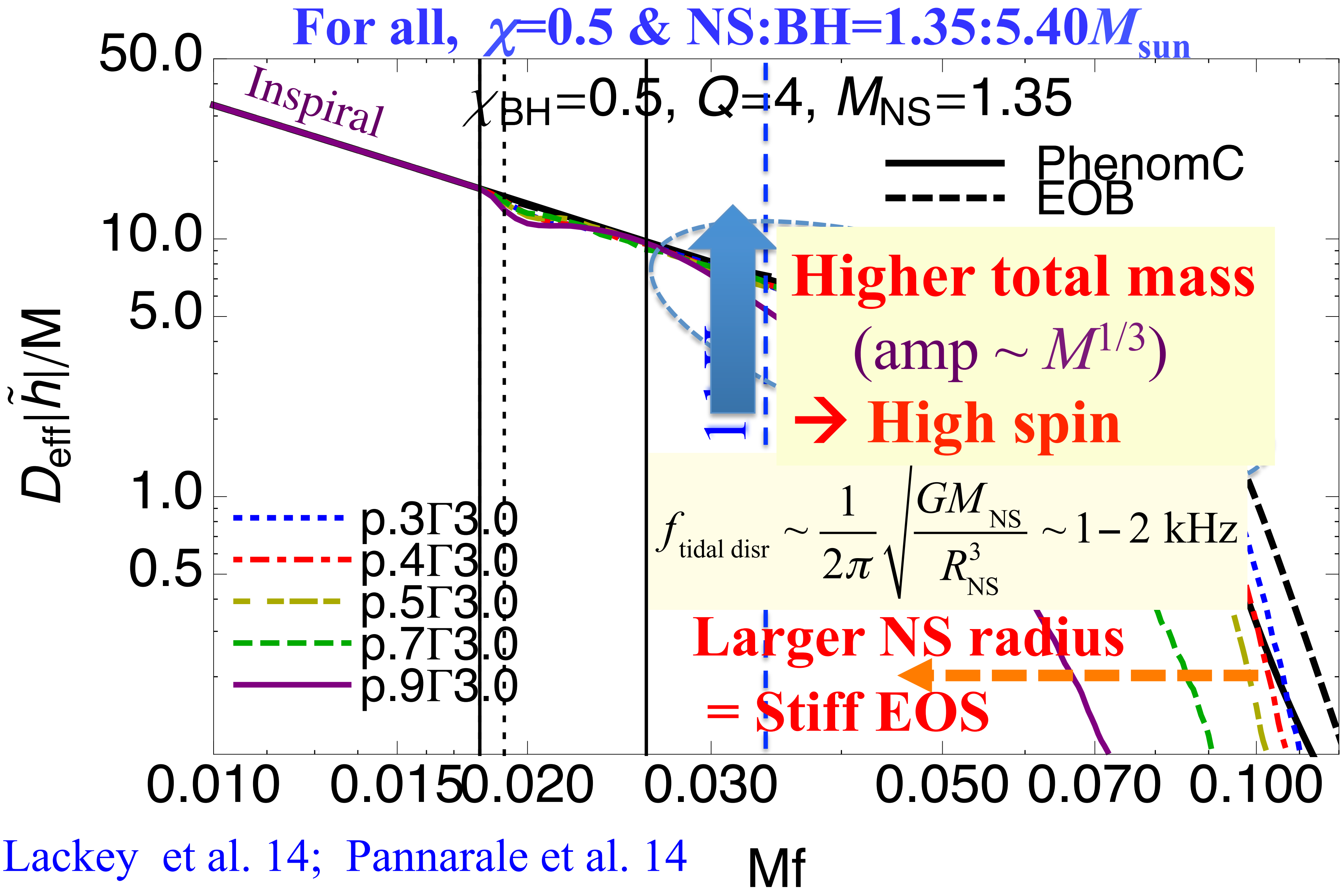


BH ringdown



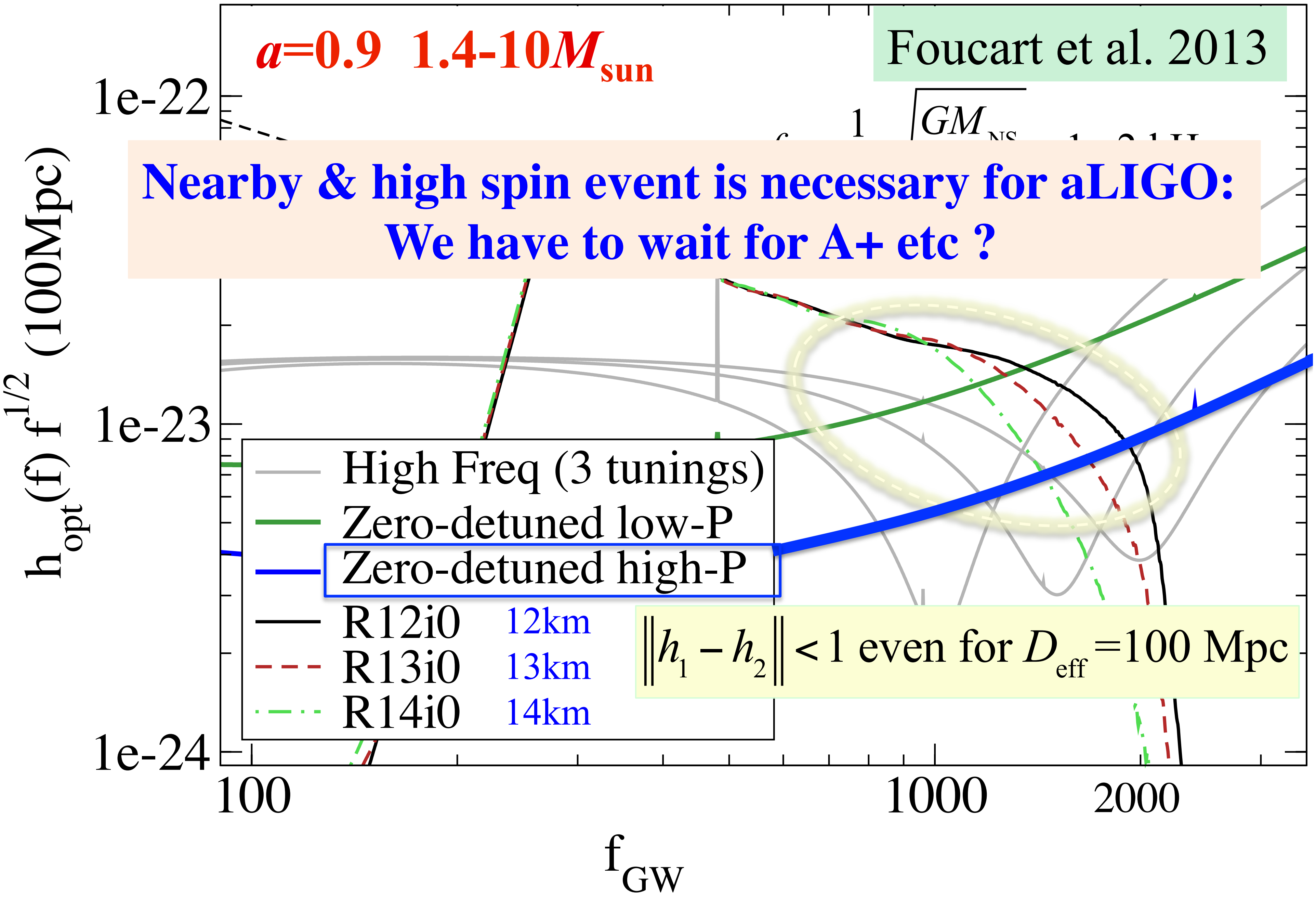
Green=Tayloy T4

BH-NS Fourier spectrum



Lackey et al. 14; Pannarale et al. 14

Cutoff frequency is high, & SNR is still small



3 Viscous hydrodynamics of post-merger of NS-NS

❖ Physical state for the merger remnants

- Massive neutron stars (MNS) are typical remnants
- MNS are ***magnetized*** & ***differentially rotating***

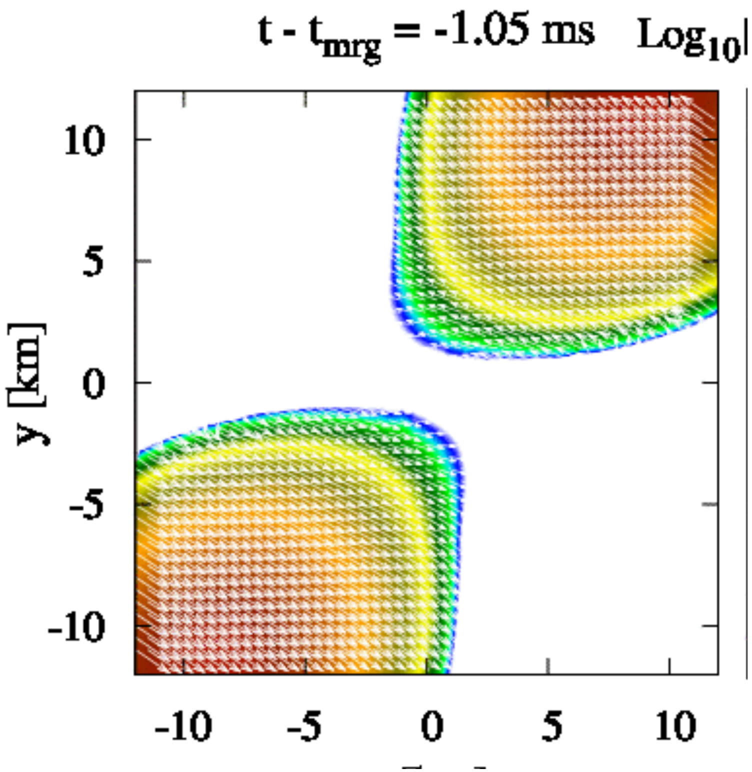
→ **subject to MHD instabilities**

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

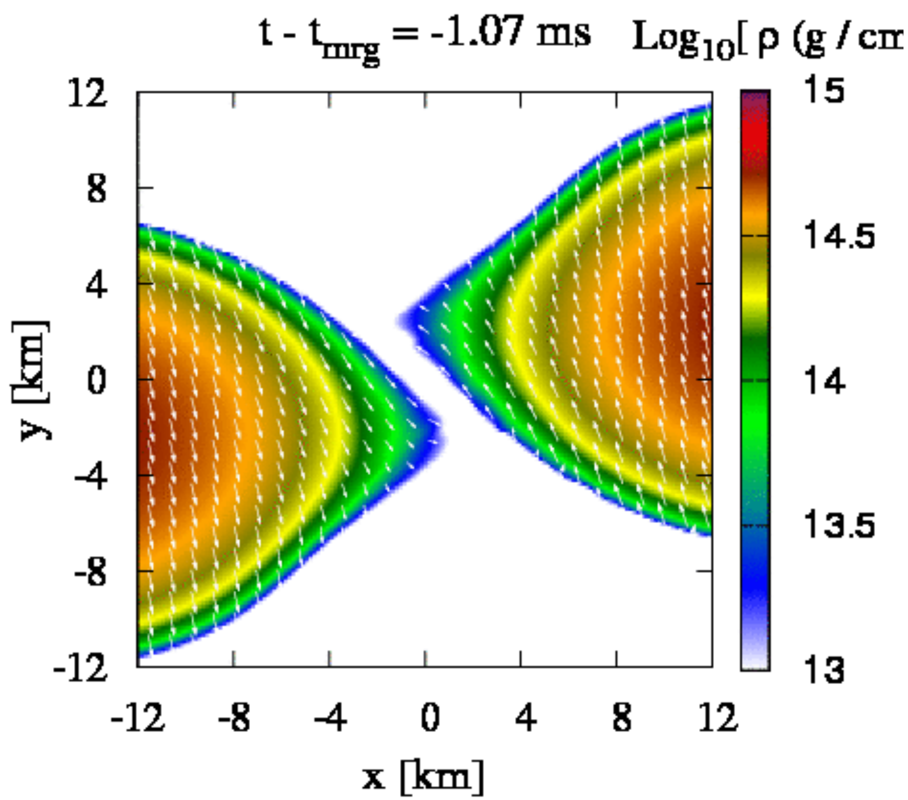
→ **turbulence could be induced**

High-resolution GRMHD for NS-NS

Kiuchi et al. 2015



Δx=17.5m



Δx=70m

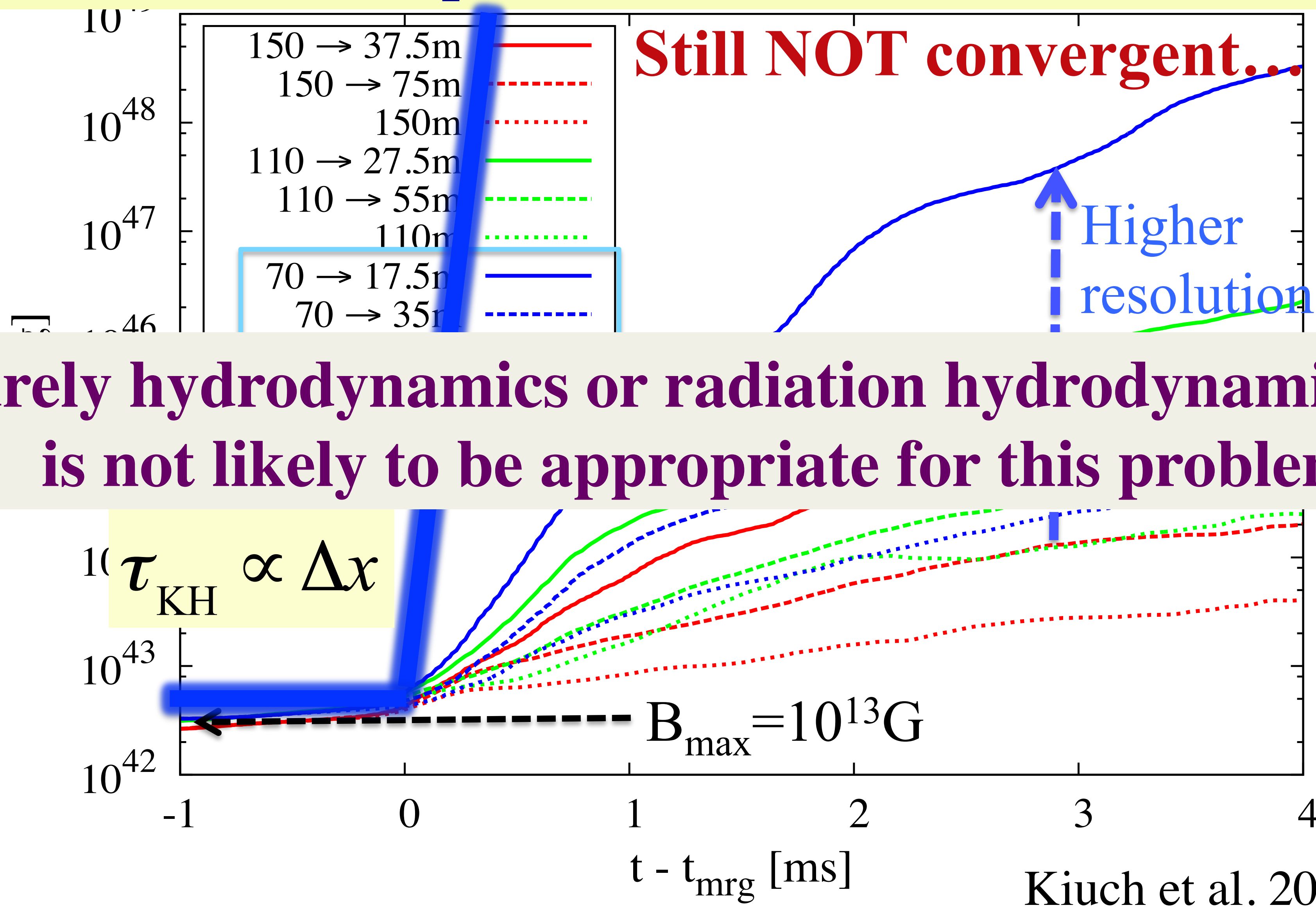
Kelvin-Helmholtz instability:

→ 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 ?



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

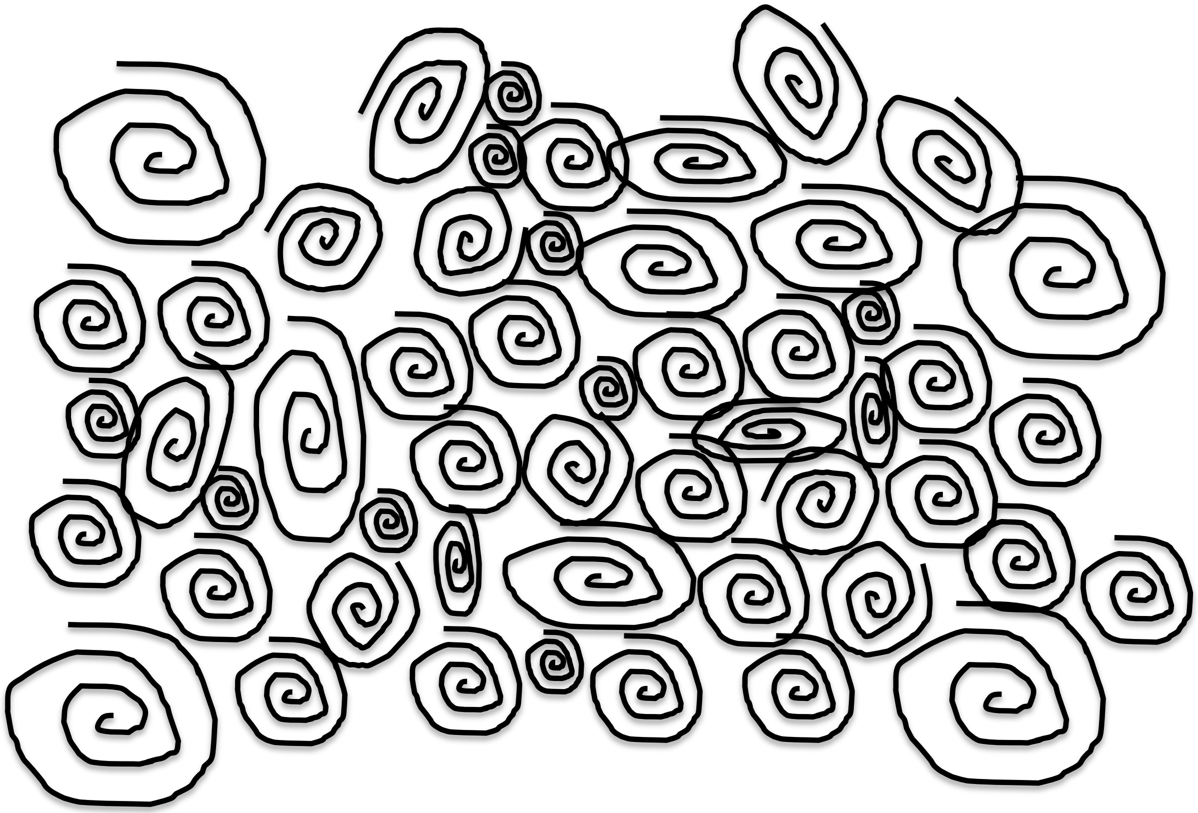
Kiuch et al. 2015

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



Current status in this issue

- High-resolution MHD simulation indicates that **obviously more resolved 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 appropriately describe the state resulting from turbulence fluid: But, viscous hydro would be able to explore one possible limiting case.

A GR viscous hydrodynamics

Well-known viscous hydrodynamics formulation
(e.g., “Classical theory of fields” by Landau-Lifshitz)

$$\nabla_b T^b{}_a = 0 : \quad T_{ab} = \rho h u_a u_b + P g_{ab} - \underline{\rho \nu \sigma_{ab}}$$

where $\sigma_{ab} := h^c{}_a h^d{}_b \left(\nabla_c u_d + \nabla_d u_c - \frac{2}{3} g_{cd} \nabla_e u^e \right)$

and $h_{ab} := g_{ab} + u_a u_b$. ν: viscous coefficient

- In this case, **parabolic equations** are derived

→ causality is violated and hence not physical

Israel-Stewart formalism

To guarantee causality, Israel and Stewart (1979) set

$$\nabla_b T^b{}_a = 0 : \ T_{ab} = \rho h u_a u_b + P g_{ab} - \rho \nu \sigma_{ab}$$

$$\mathcal{L}_u \sigma_{ab} = -\xi \left[\sigma_{ab} - h^c{}_a h^d{}_b \left(\nabla_c u_d + \nabla_d u_c - \frac{2}{3} g_{cd} \nabla_e u^e \right) \right]$$

ξ : $[\mathrm{Time}]^{-1}$ const parameter, short timescale

Lie derivative

- **Telegraph-type equation** is derived: causality preserving
- If we neglect the last term, the equations are simplified

→ Pay attention to shear viscous hydrodynamics

(Shibata et al. '2017)

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

(Shibata & Kiuchi PRD June 2017)

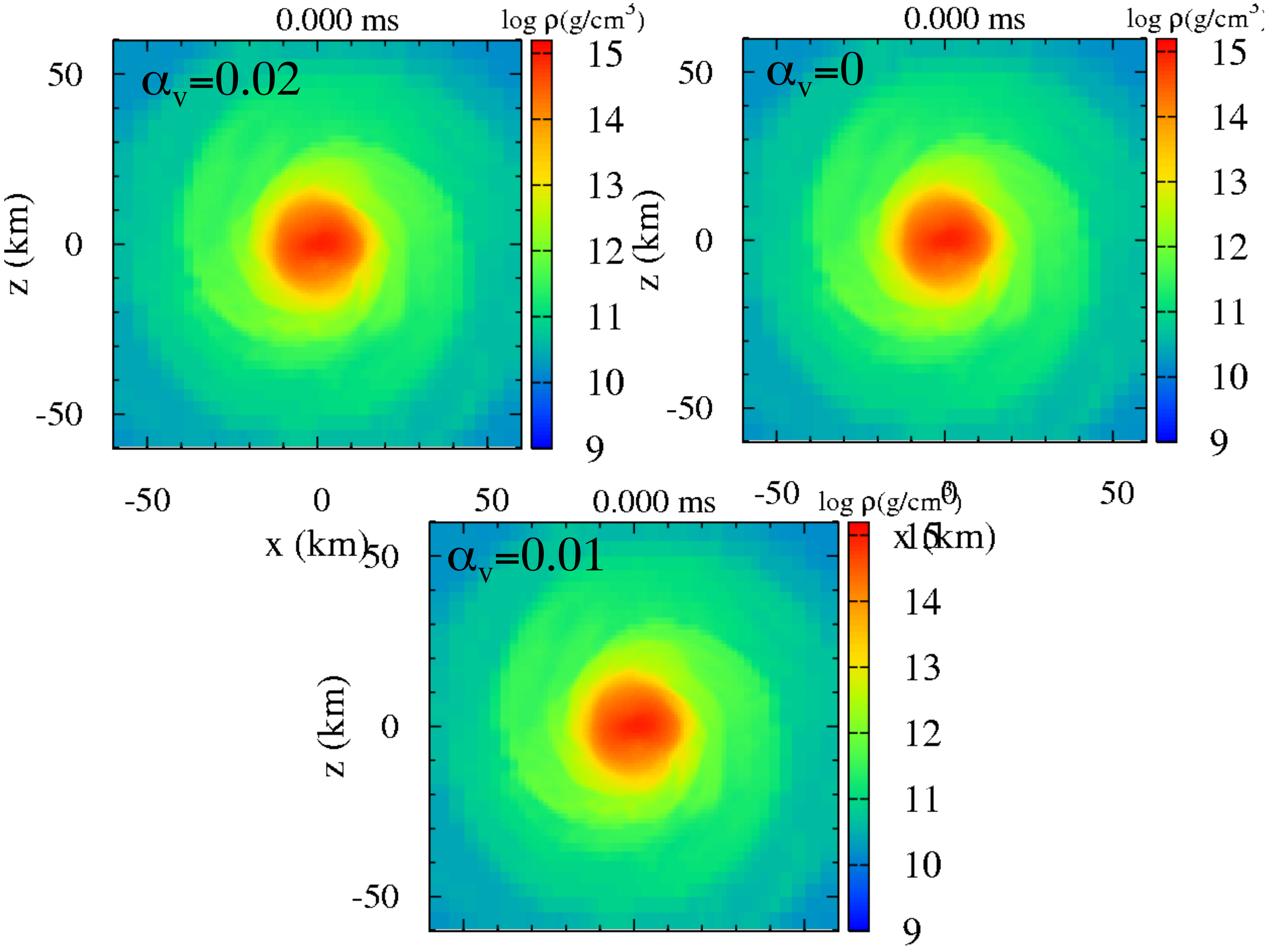
- Merger remnant is used as initial condition

✓ H4 EOS (stiff EOS)

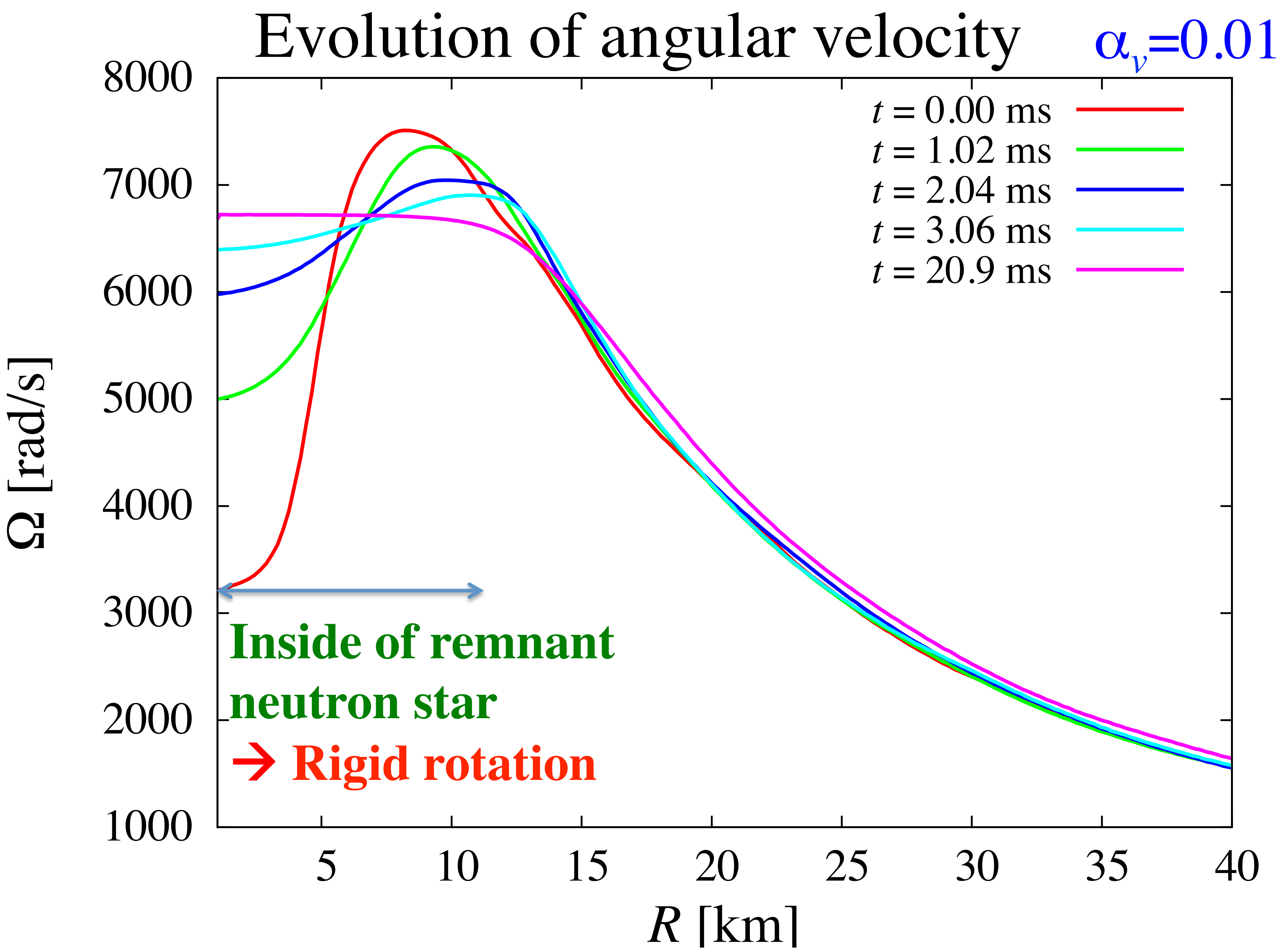
✓ Mass = 1.35-1.35 solar mass

- 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)

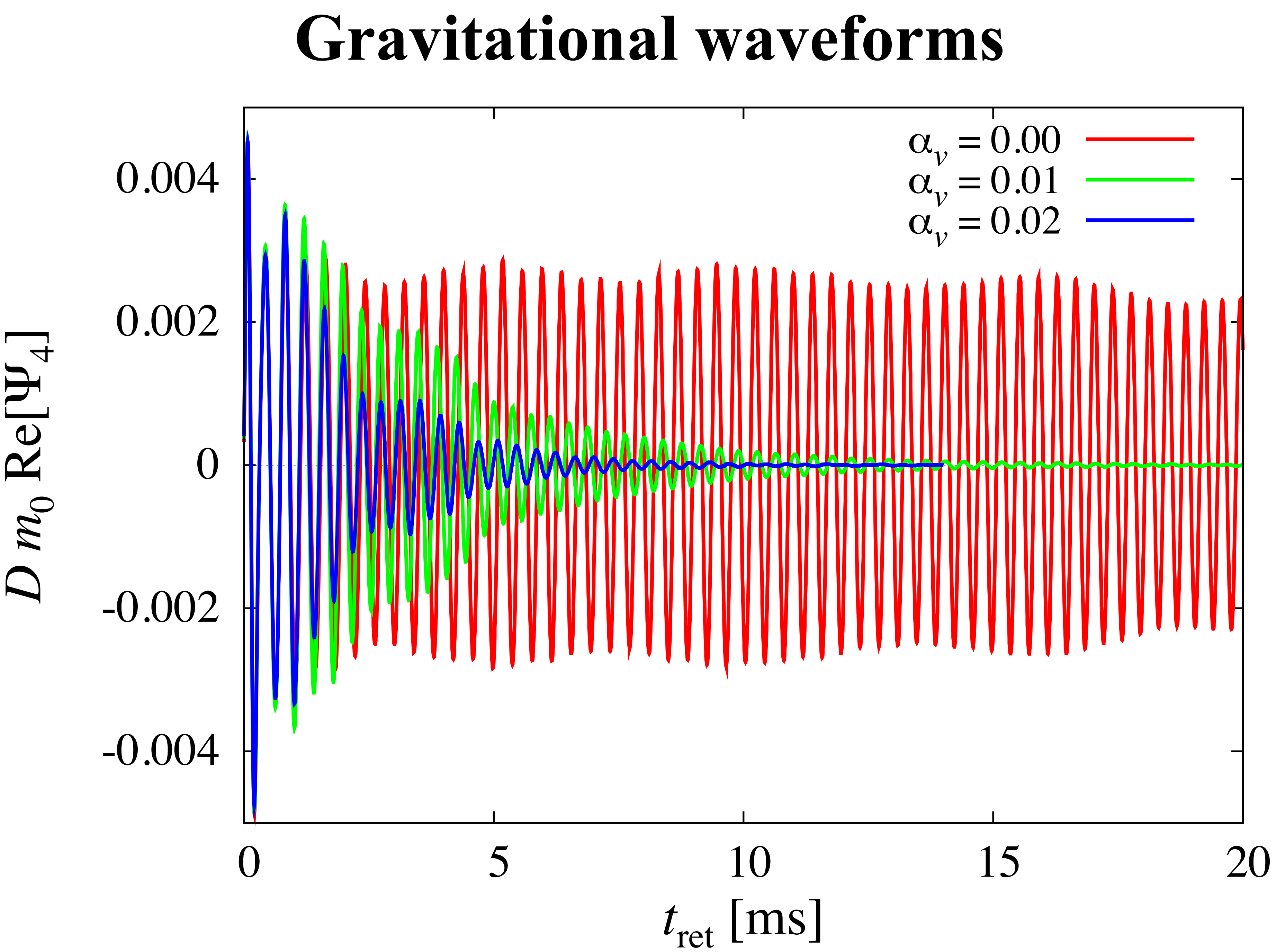
See also recent work by Radice (2017)



0.000 ms
log ρ(g/cm³)
α_v=0.02
50
0
-50
z (km)
x (km)
15
14
13
12
11
10
9
0.000 ms
log ρ(g/cm³)
α_v=0
0.000 ms
log ρ(g/cm³)
α_v=0.01

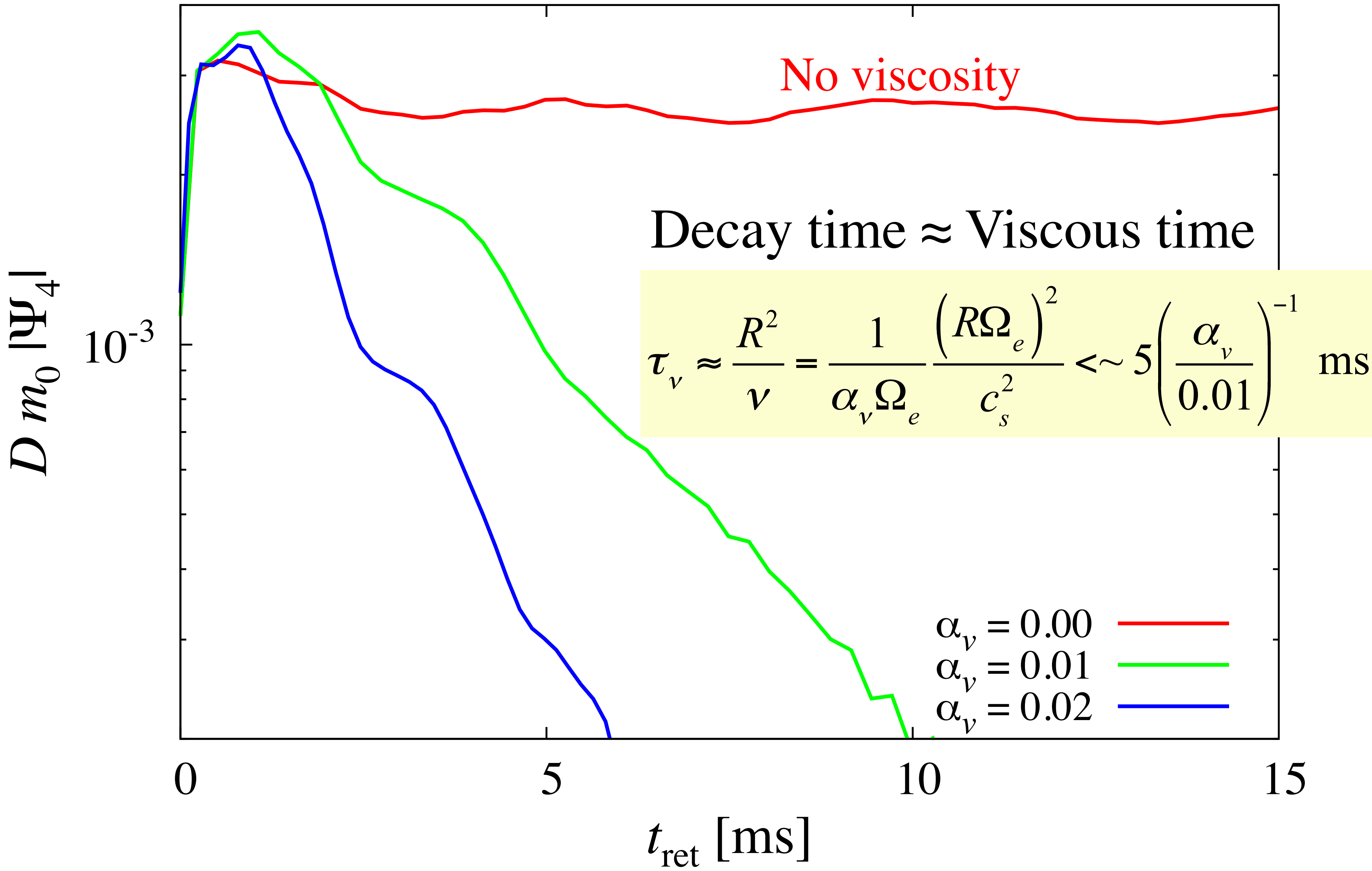


Evolution of angular velocity
αν=0.01
8000
7000
6000
5000
4000
3000
2000
1000
Ω [rad/s]
5
10
15
20
25
30
35
40
R [km]
t = 0.00 ms
t = 1.02 ms
t = 2.04 ms
t = 3.06 ms
t = 20.9 ms
Inside of remnant
neutron star
→ Rigid rotation



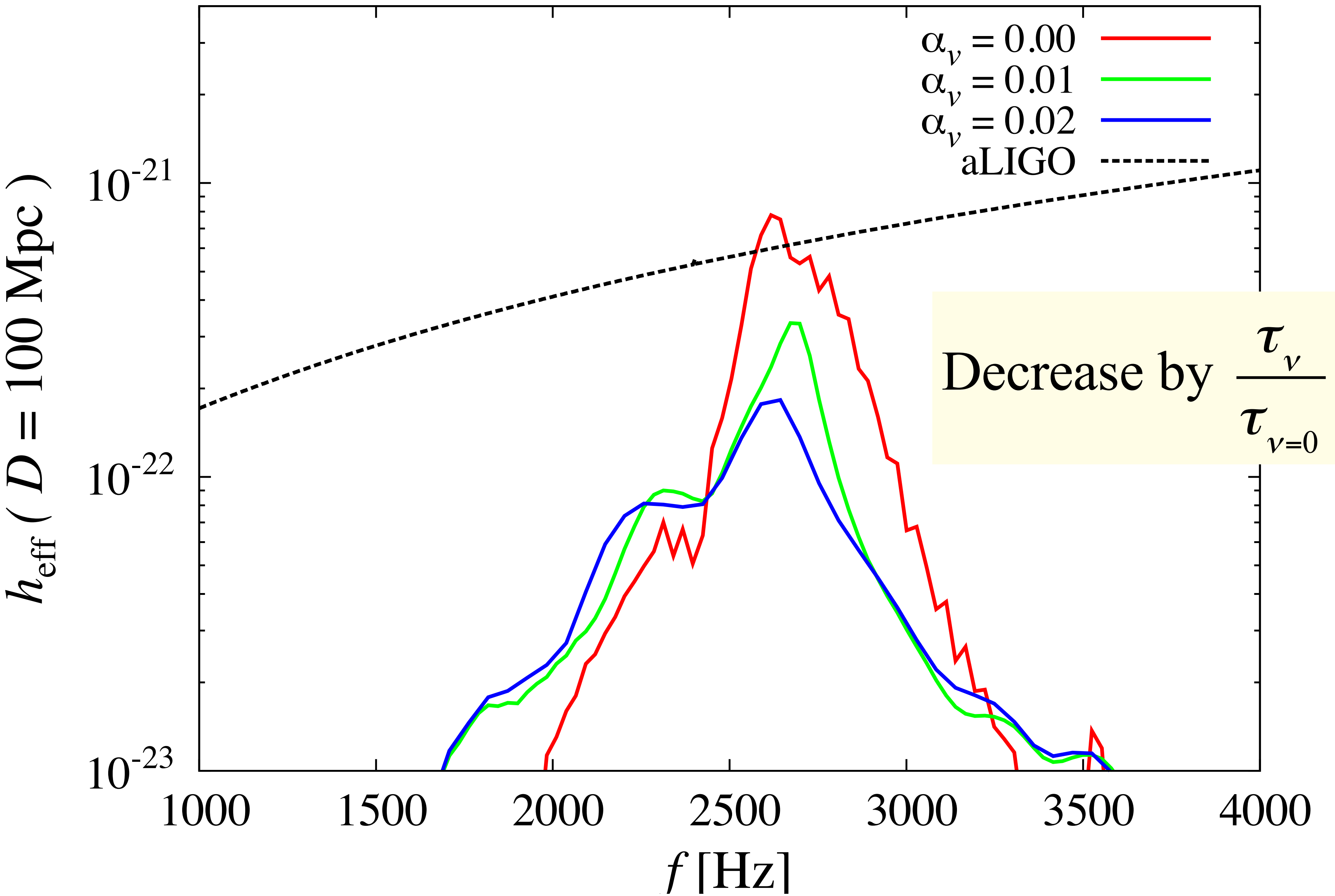
Gravitational waveforms
$\alpha_v = 0.00$
$\alpha_v = 0.01$
$\alpha_v = 0.02$
0.004
0.002
0
-0.002
-0.004
$D\, m_0\, \mathrm{Re}[\Psi_4]$
0
5
10
15
20
t_{ret} [ms]

Amplitude of gravitational waves



$$\tau_\nu \approx \frac{R^2}{\nu} = \frac{1}{\alpha_\nu \Omega_e}\frac{\left(R\Omega_e\right)^2}{c_s^2} <\sim 5\left(\frac{\alpha_\nu}{0.01}\right)^{-1} \text{ ms}$$

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
$h_{\rm eff}$ (D = 100 Mpc)
f [Hz]

Short summary

- If MHD turbulence ≈ viscous hydrodynamics with $\alpha_\nu \geq 0.01$, evolution of merger remnant of NS-NS would be **highly different from that by ideal fluid dynamics**
- Viscous hydrodynamics suggests that **post-merger gravitational waves could be quite weak**
- Caution is needed to GW community
  → No detection of post-merger gravitational waves does not always imply BH formation (MNS may exist)
- How large is α_ν ?
  → **High-resolution MHD is necessary in the future**

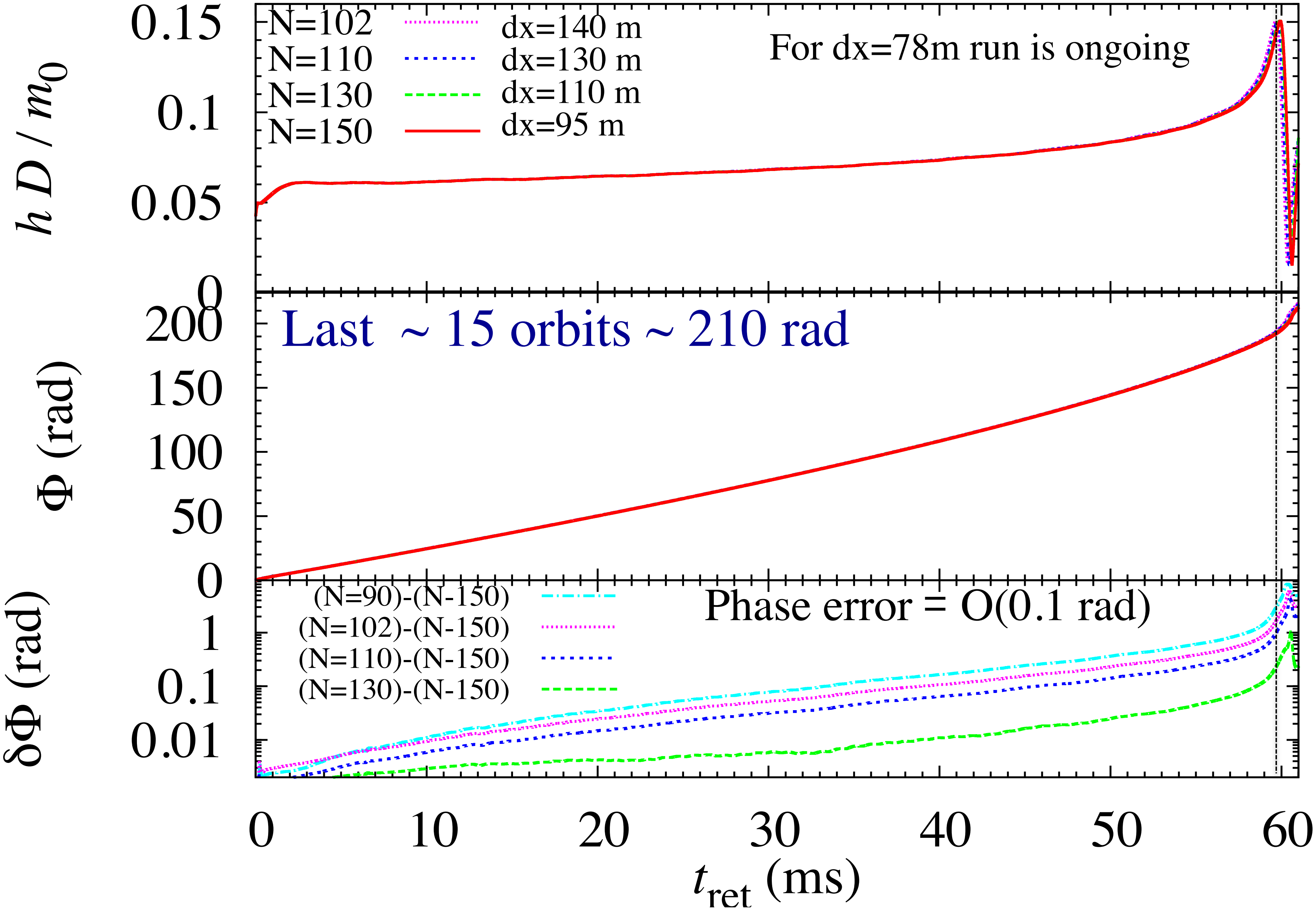
4 High-resolution simulation of inspiraling NS-NS

K. Kiuchi, K. Kawaguchi, K. Kyutoku, Y. Sekiguchi, M. Shibata

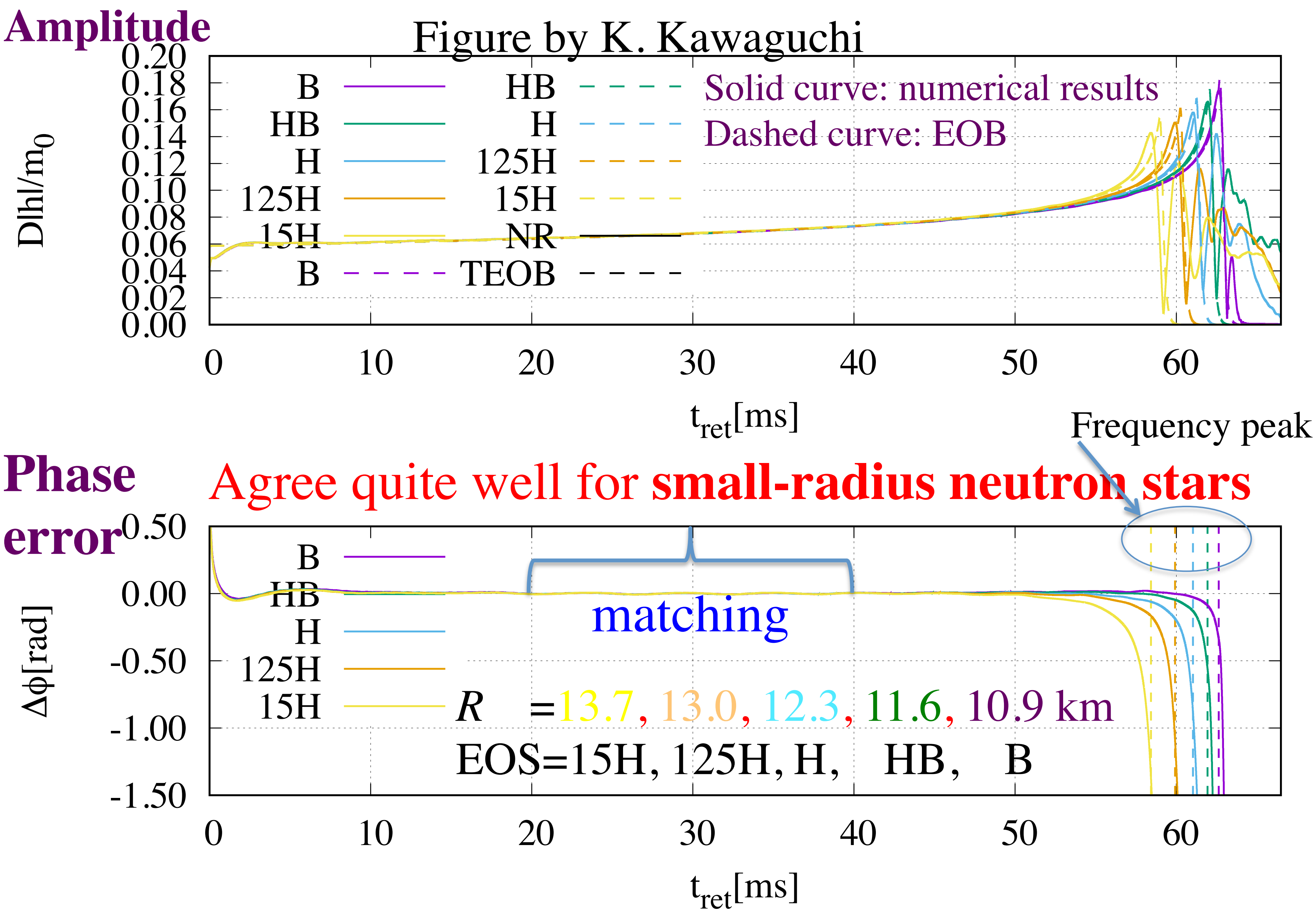
- For this issue, high-resolution run is needed anyhow
- Our previous simulation for this project : dx ~150 m
- Thorough resolution study is ongoing with dx up to 63—86 m (for EOS of radius 10.9—13.7 km)
- Piecewise polytropic EOS is employed:
  # only tidal deformability is important in this problem
- Initial eccentricity ~ 0.001: low eccentricity is the key for carefully comparing numerical data with EOB data

See also the efforts by Dietrich, Bernuzzi et al

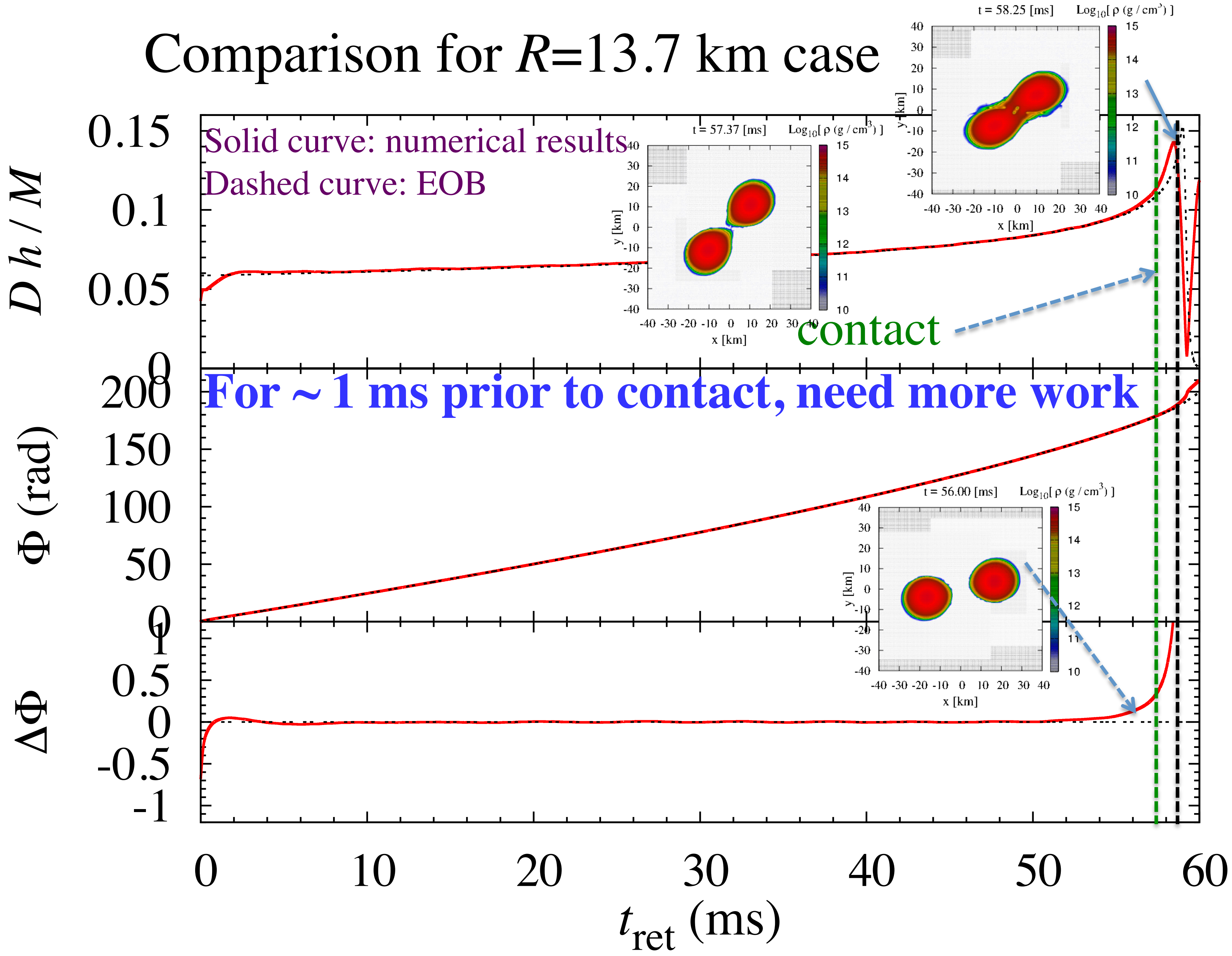
For EOS with 1.35-1.35M_{sun} & R=13.0 km



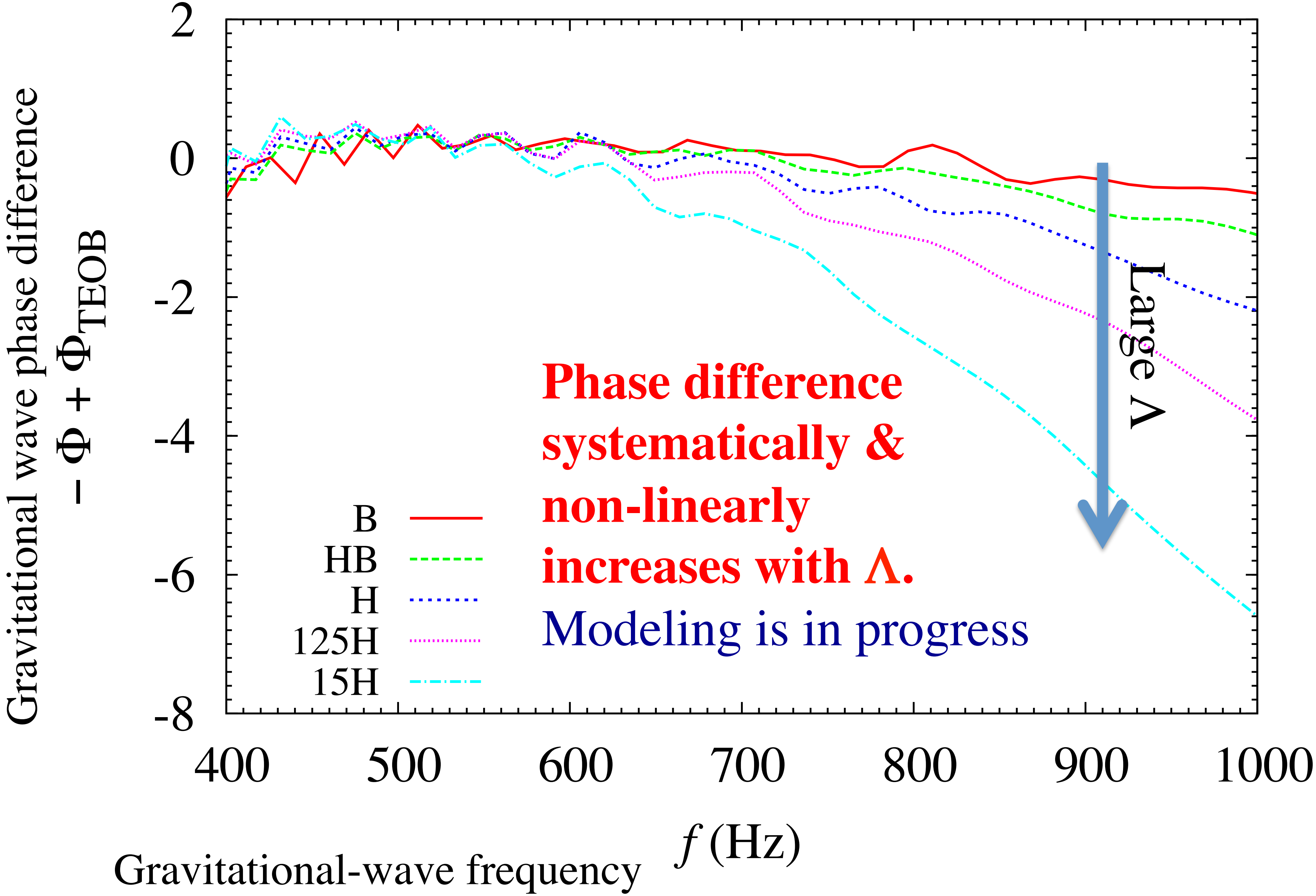
Comparison with a TEOB (Hinderer et al. 2016)



Comparison for R=13.7 km case



Phase difference between NR and TEOB



EOB is promising but need improvement

- ➢ For soft EOS, it works well up to amplitude peak
- ➢ For stiff EOS, it works well approximately up to ~ 1m prior to contact of two NSs
- After the contact, inspiral-like waveform continues for a few ms, in particular for stiff EOS (large-radius NSs)
- ✓ Modeling for such final phase would be the final piece

✧ Note: In the final phase, the dependence on the tidal deformability becomes most remarkable.

5 Summary

- Detecting **late-inspiral gravitational waves** from NS-NS will constrain EOS for $D_{\rm eff}$ <~ 200Mpc or by stacking: The GW frequency is ~ a few 100—1 kHz.
- **Post-Merger waveforms** for NS-NS may reflect the EOS of NS: **But** SNR would be too low for advanced detectors.

✧ **Physical consideration suggests that post-merger GWs could be even weaker**: **We should consider systematics**

- Gravitational waves at **tidal disruption of NS** in BH-NS will reflect the EOS of NS: f ~ 1—2 kHz: Rapidly spinning BH will be needed for the detection
- **Further high-resolution run is the key** for getting reliable prediction of late inspiraling gravitational waves