kHz gravitational waves from numerical relativity

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Outline

0. Introduction

1. Binary neutron star merger

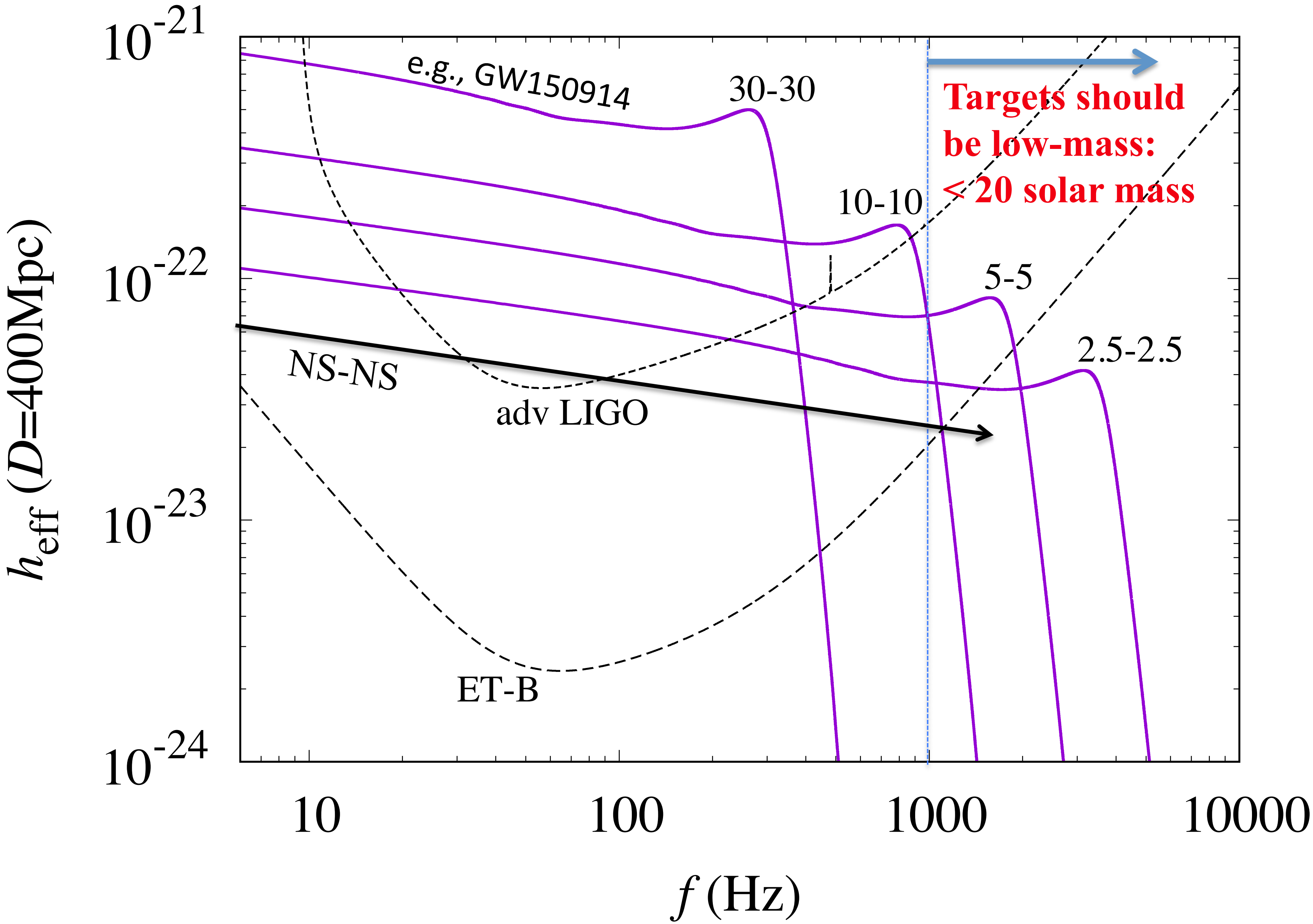
2. Black hole-neutron star tidal disruption

3. Stellar core collapse of massive stars

I will not talk

- Low-mass BH+BH merger
- Higher QNM modes (l >= 3) for BH-BH
- Collapse of exotic objects to BH (e.g., cosmic string loop, axion stars) & merger of exotics

Introduction: What are high-freq sources ?



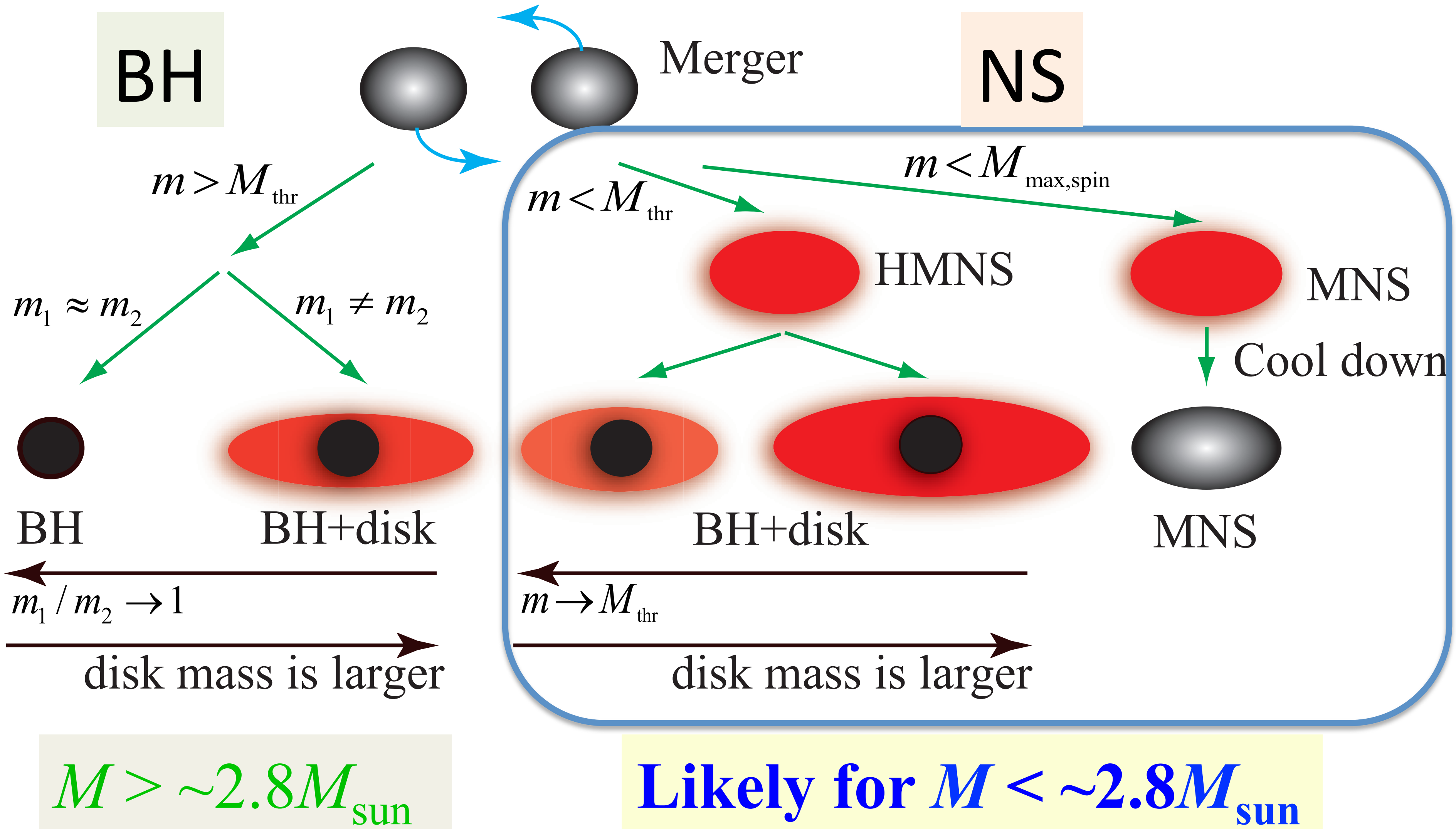
Orbital & oscillation timescale of stars

- $f_{\mathrm{orb}} \approx \dfrac{1}{\pi}\sqrt{\dfrac{GM}{r^3}} = 1.16\ \mathrm{kHz}\left(\dfrac{r}{30\ \mathrm{km}}\right)^{-3/2}\left(\dfrac{M}{2.7M_{\mathrm{sun}}}\right)^{1/2}$
- $\tau_{\mathrm{osc}} \approx \dfrac{1}{\sqrt{G\rho}} = 0.387\ \mathrm{ms}\left(\dfrac{\rho}{10^{14}\,\mathrm{g/cm^3}}\right)^{-1/2}$

$$\Rightarrow f_{\mathrm{osc}} \approx \sqrt{G\rho} = 2.58\ \mathrm{kHz}\left(\dfrac{\rho}{10^{14}\,\mathrm{g/cm^3}}\right)^{1/2}$$

- **Neutron stars** are only (non-exotic) matter sources of kHz-gravitational waves: other (normal) stars are not

1 Binary neutron stars: Their fates



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

Compact NS-NS system in our galaxy

	PSR	Orbital period P(day)	Eccentricity e	$m(M_{sun})$	Each mass M_1	M_2	$\times 10^8$ yrs 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	0.181	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	5.0
8.	J1757-1854	0.184	0.606	2.74	1.35	1.39	0.77
9.	J1946+2052	0.078	0.064	~2.50	~1.2	~1.3	0.46

➤ **Total Mass of NS in compact NS-NS** is in a narrow range, $m \approx 2.7 \pm 0.2\ M_{sun}$ and for many, $m < 2.8\ M_{sun}$

NS-NS typical case

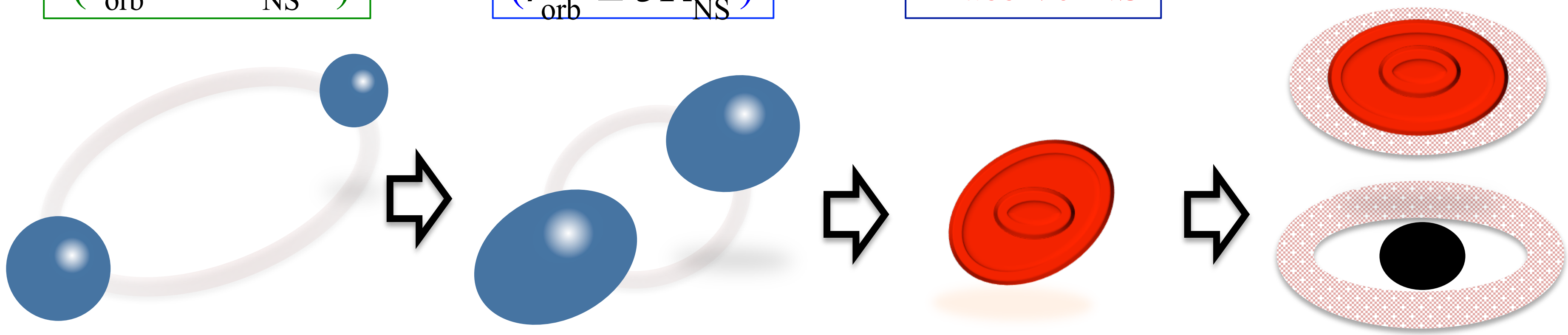
$M \sim 2.5 - 2.8 M_{\rm sun}$

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

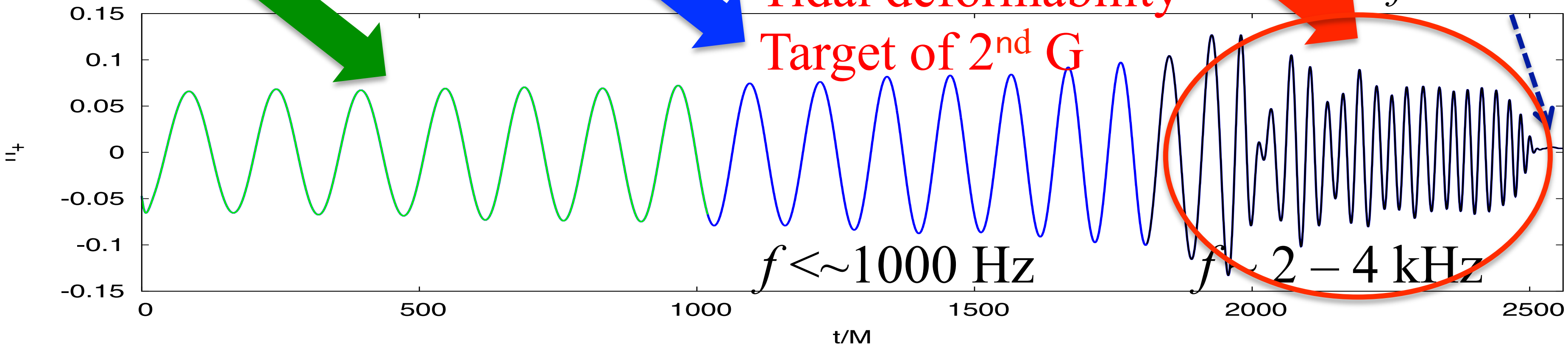
Post-Newtonian

Late inspiral

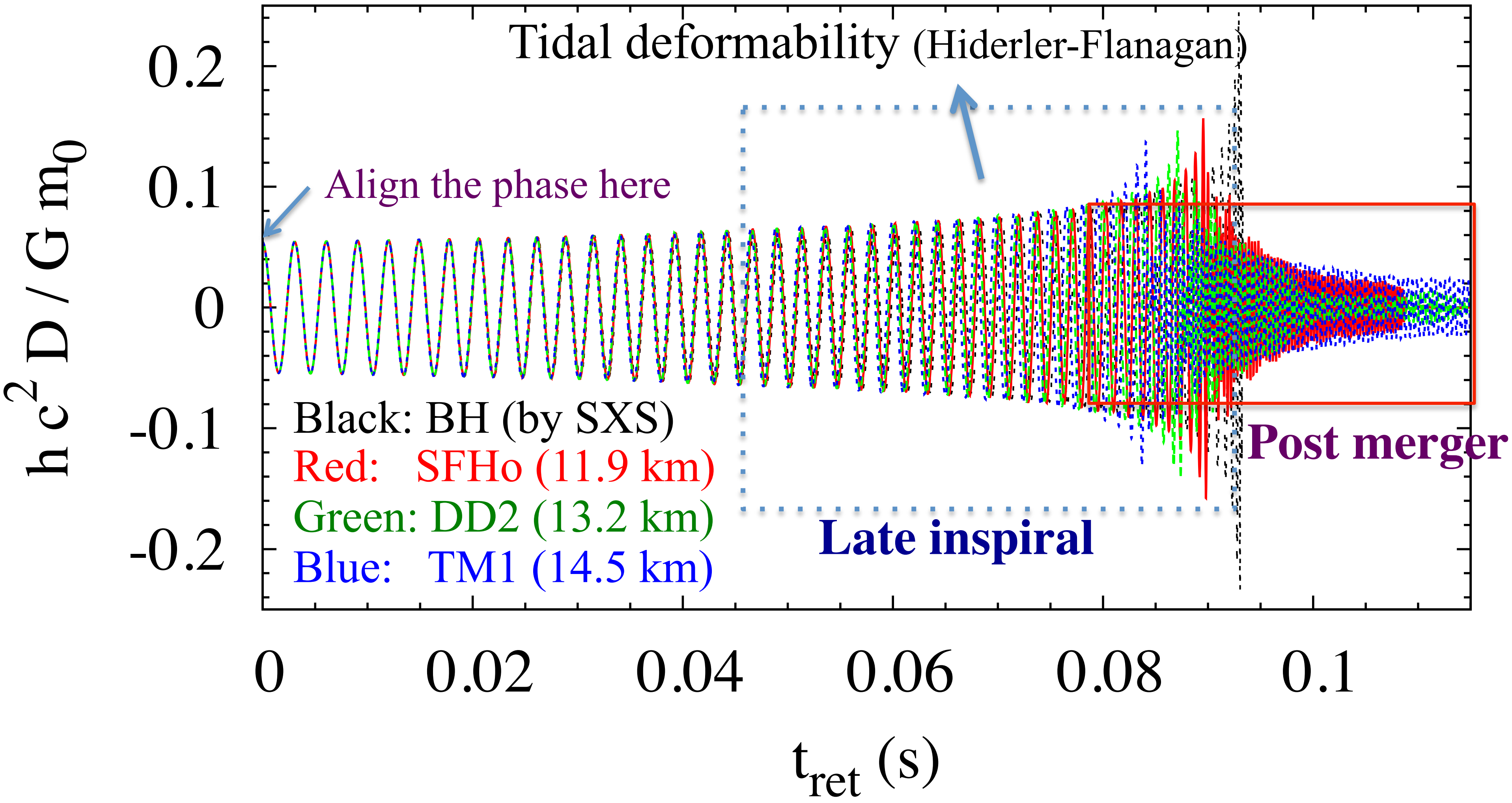
Post merger
Massive NS / BH

Tidal deformability
Target of 2nd G

$f \sim 6.5$ kHz

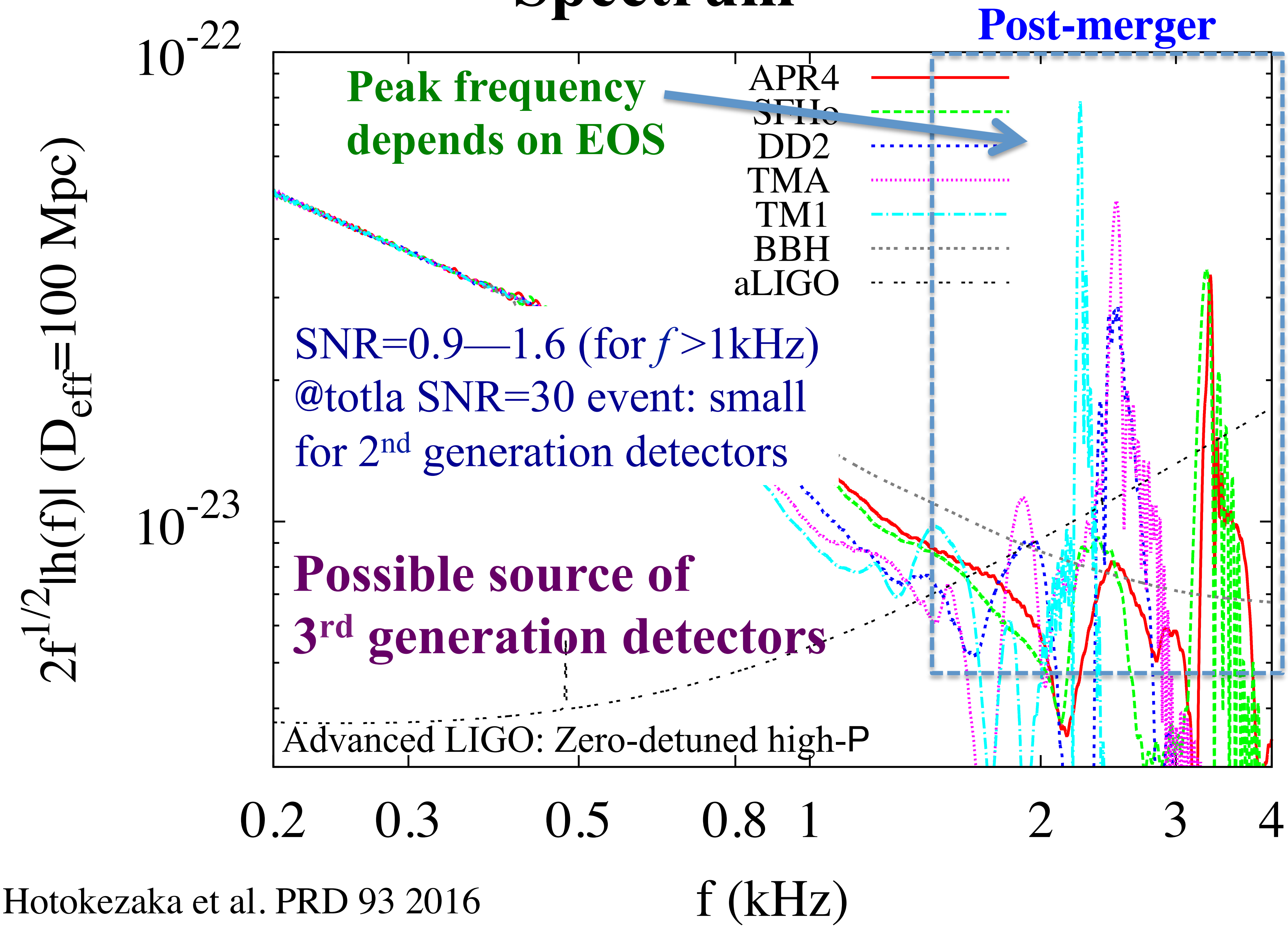


Gravitational waveform from NS-NS
(1.35-1.35 solar mass)



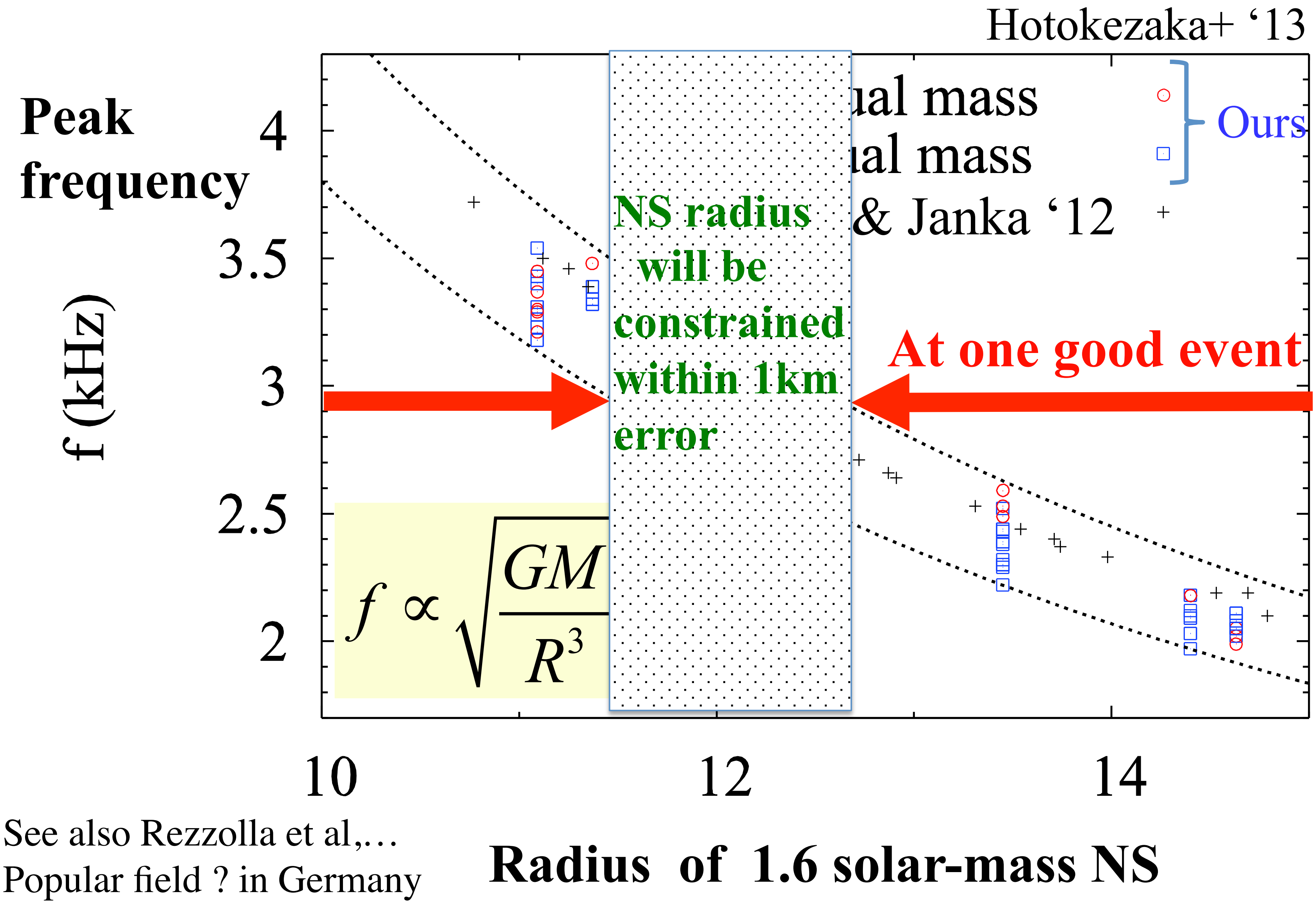
Hotokezaka et al. 2016 (Many efforts by Bernuzzi, Dietrich, etc)

Spectrum



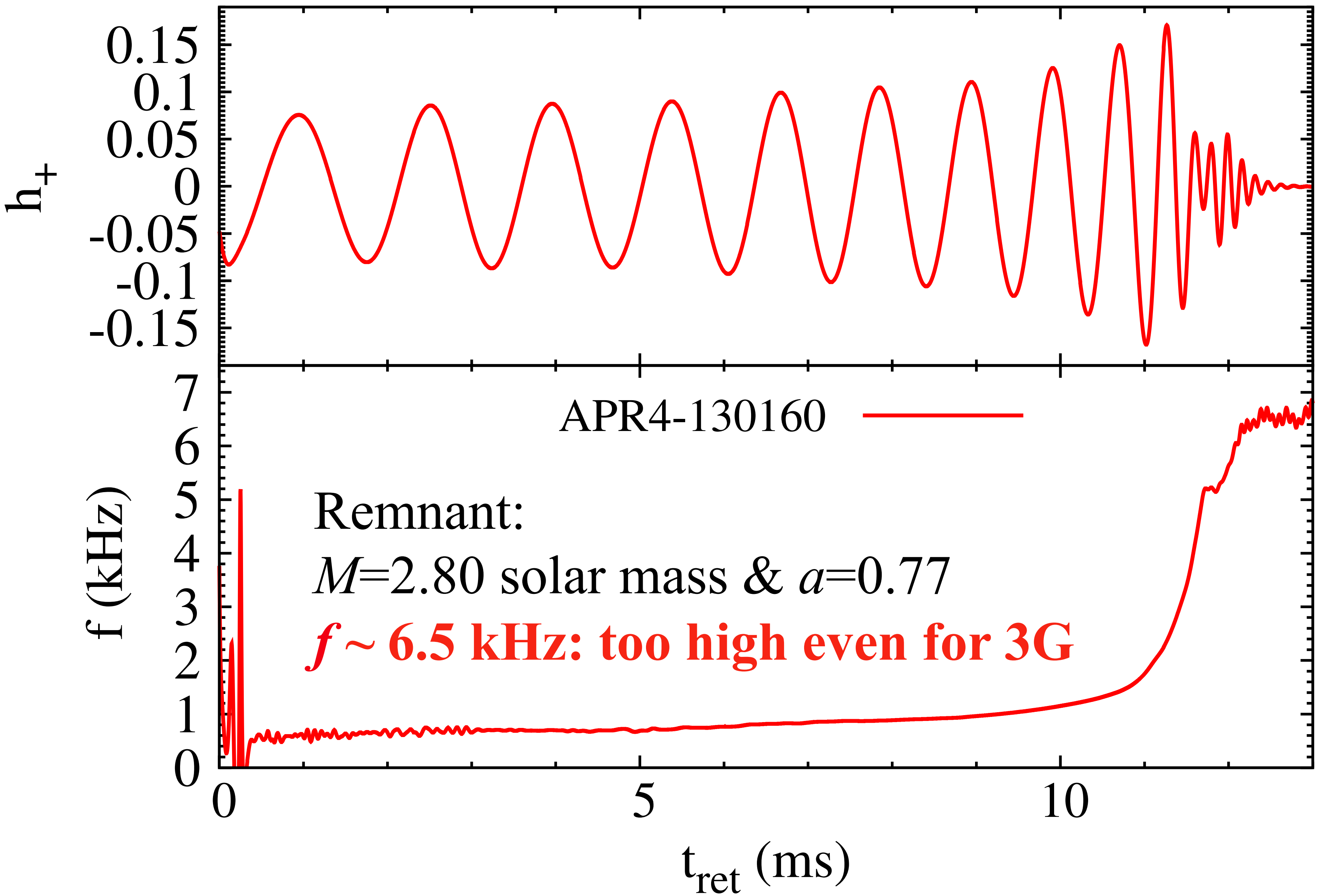
Hotokezaka et al. PRD 93 2016

Clear correlation between peak and radius



See also Rezzolla et al,…
Popular field ? in Germany

Black hole formation case



Caution:
Physical state of remnant NS is very uncertain,
similar to supernova case

✧ **Magnetic fields are surely amplified**
(Price-Rosswog 2006, Kiuchi et al. 2014, 15, 18)

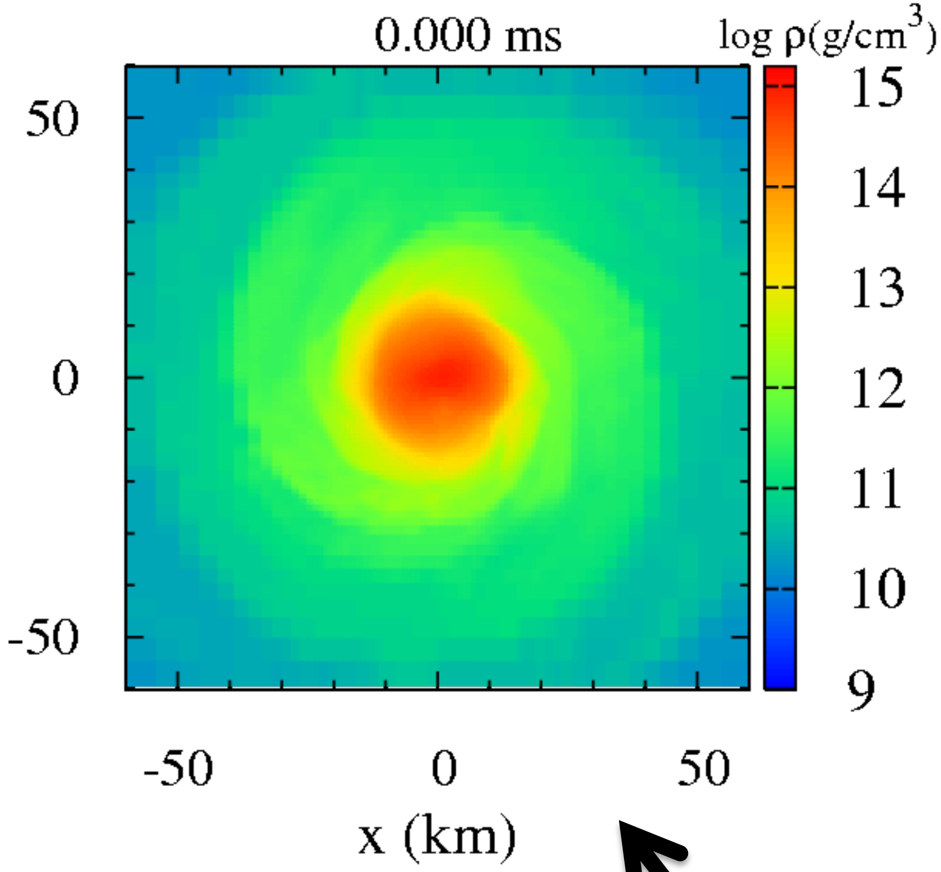
→ It is natural to consider that **turbulence** will be excited
(cf. the first talk in the today's morning on Tokamac)

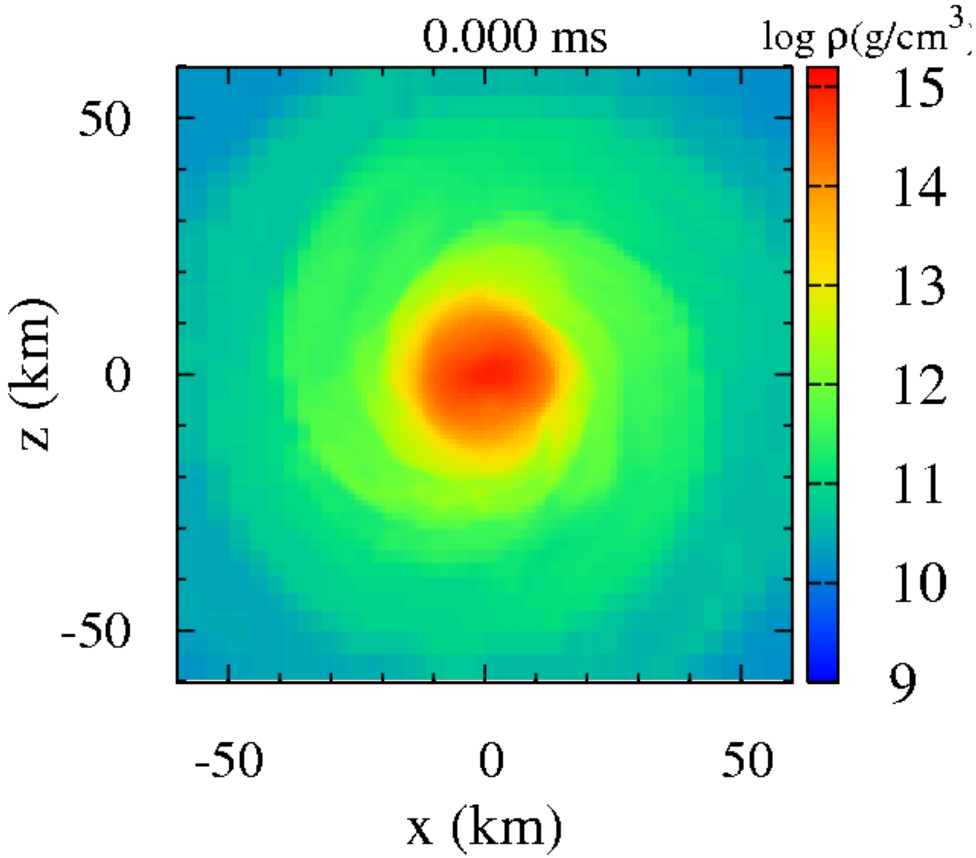
→ **Turbulence viscosity** is likely to be excited

→ Typically $\nu = \alpha_\nu\, c_s\, H$ with $\alpha_\nu = 0.01$: **but uncertain**
(c_s: sound velocity, H: scale height)

α_v=0.01: With viscosity

α_v=0: No iscosity

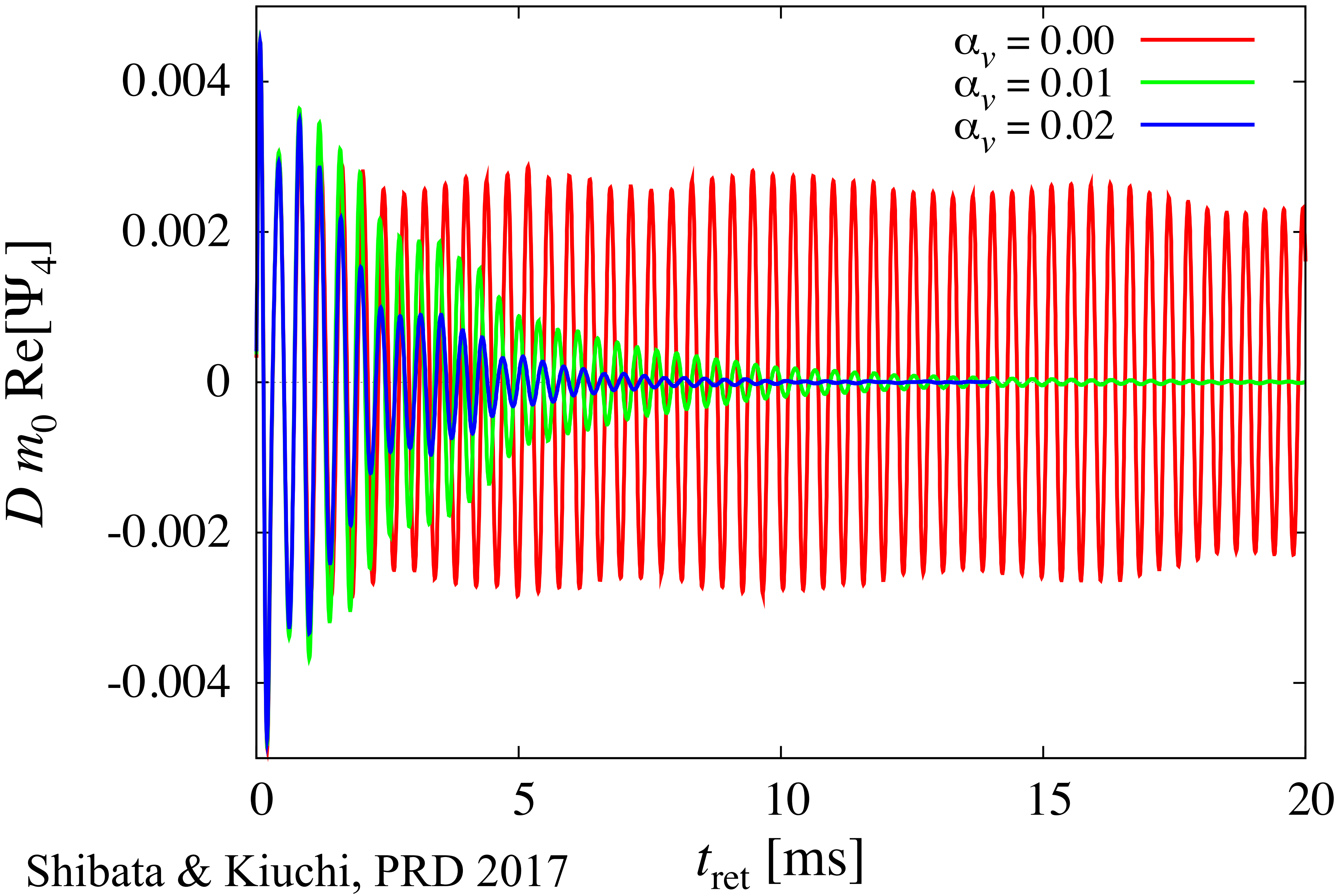




Non-axisymmetry disappears in short timescale

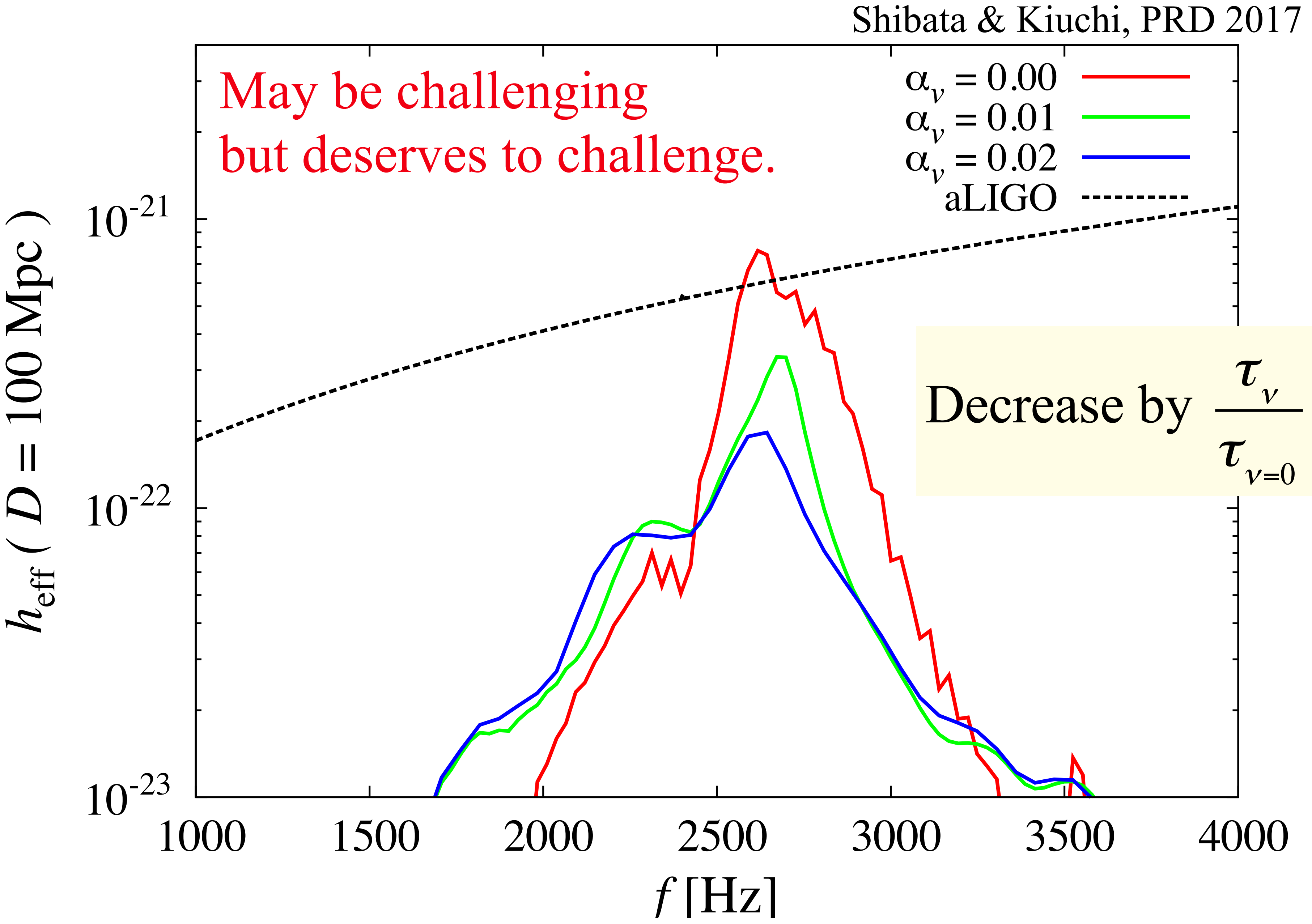
Shibata & Kiuchi, PRD 2017

Gravitational waveforms in viscous hydro



Shibata & Kiuchi, PRD 2017

Spectrum



Shibata & Kiuchi, PRD 2017
May be challenging
but deserves to challenge.
$\alpha_\nu = 0.00$
$\alpha_\nu = 0.01$
$\alpha_\nu = 0.02$
aLIGO
Decrease by $\frac{\tau_\nu}{\tau_{\nu=0}}$
10^{-21}
10^{-22}
10^{-23}
$h_{\rm eff}$ (D = 100 Mpc)
1000
1500
2000
2500
3000
3500
4000
f [Hz]

2 BH-NS: Tidal disruption or not

For tidal disruption, (Self gravity of NS) < (BH tidal force)

before ISCO $\Downarrow$

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

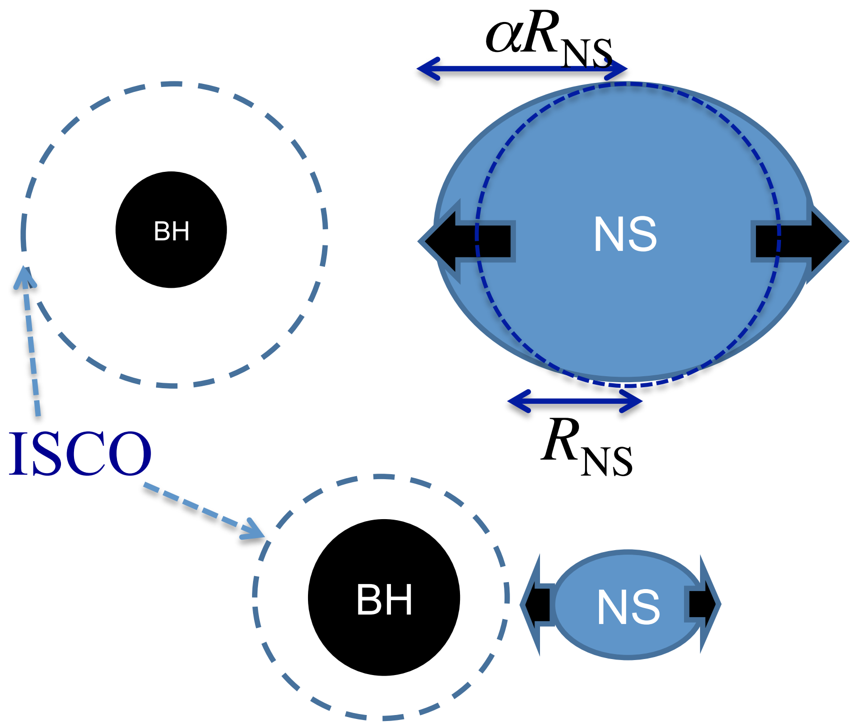
- **For tidal disruption**

❖ **<u>Large NS Radius</u>** **or**

❖ **<u>Small BH mass</u>** **or**

❖ **<u>High corotation spin</u>**

is necessary



BH-NS with aligned BH spin

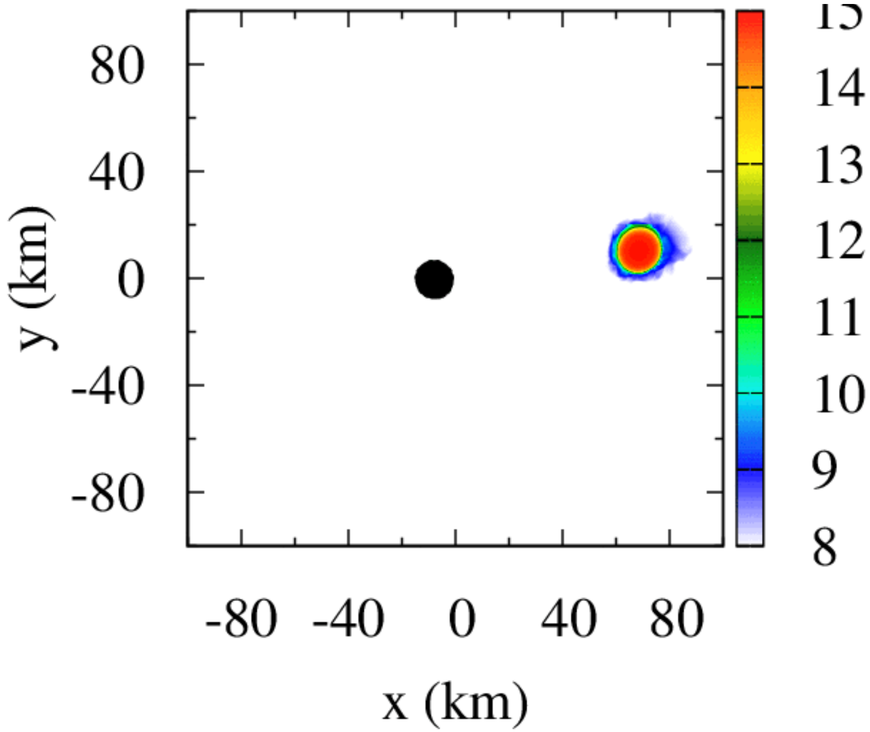
$M_{BH}=6.75M_{sun}$ $\boldsymbol{a=0.75}$ $M_{NS}=1.35M_{sun}$ $R=11.1$ km	⟷	$M_{BH}=4.05M_{sun}$ $\boldsymbol{a=0}$ $M_{NS}=1.35M_{sun}$ $R=11.0$ km

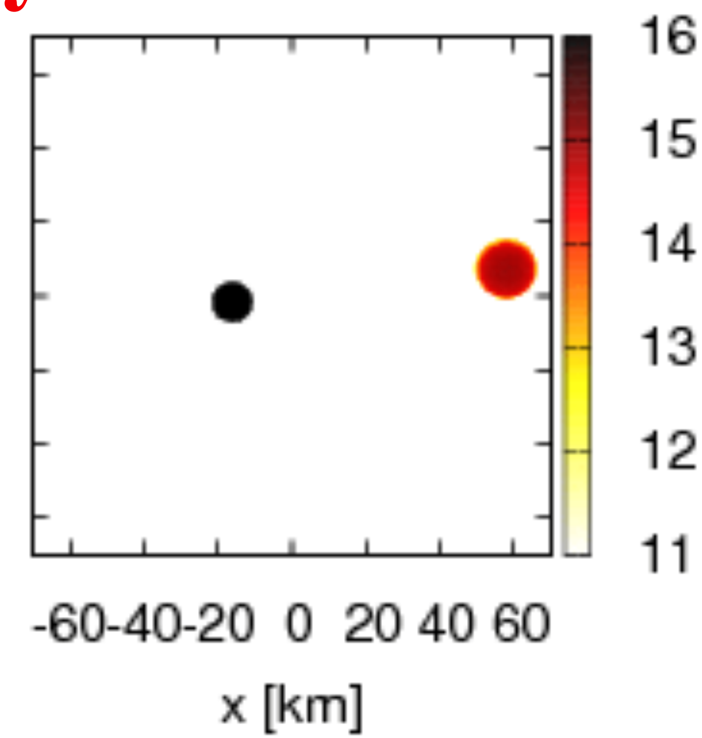
BH-NS with aligned BH spin

$M_{BH}=6.75M_{sun}$
***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

High BH spin is key for TD





Kyutoku et al. 2011, 2015; See also great effort by Foucart+

GW frequency at tidal force

$$\Omega = \sqrt{\frac{GM}{r_{\mathrm{TD}}^3}} = \sqrt{\frac{GM_{\mathrm{NS}}(1+Q)}{r_{\mathrm{TD}}^3}} = \sqrt{\frac{GM_{\mathrm{NS}}(1+Q)}{(\alpha R_{\mathrm{NS}})^3 Q}} = \sqrt{G\rho}\sqrt{\frac{4\pi(1+Q)}{3\alpha^3 Q}}$$

Mass ratio $Q = M_{\mathrm{BH}} / M_{\mathrm{NS}}$

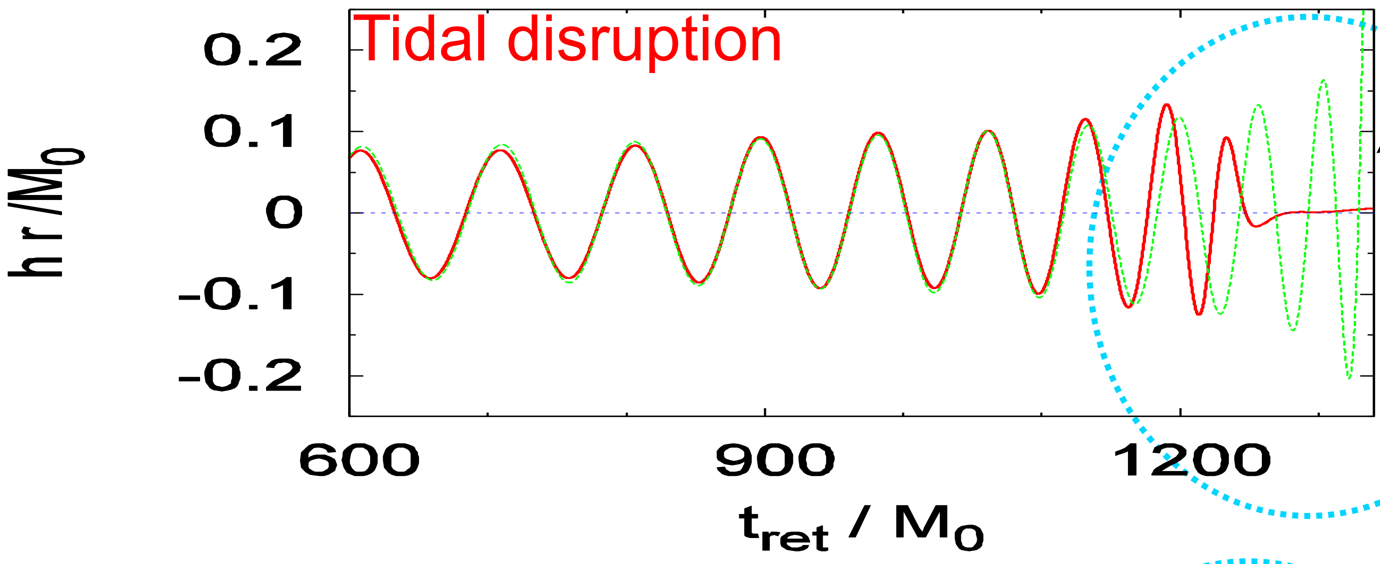
At the onset of tidal disruption, $r_{\mathrm{TD}} = \alpha R_{\mathrm{NS}} Q^{1/3}$

Here, $\dfrac{4\pi}{3\alpha^3} = 1.02\left(\dfrac{\alpha}{1.6}\right)^3$ & $\dfrac{1+Q}{Q} = 1.05 \sim 1.2$ for $Q = 5-20$

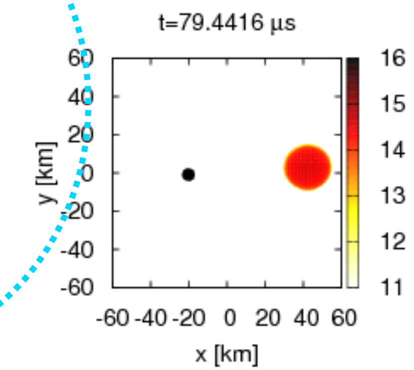
$$\rightarrow \; f = \frac{\Omega}{\pi} \propto \sqrt{G\rho}$$

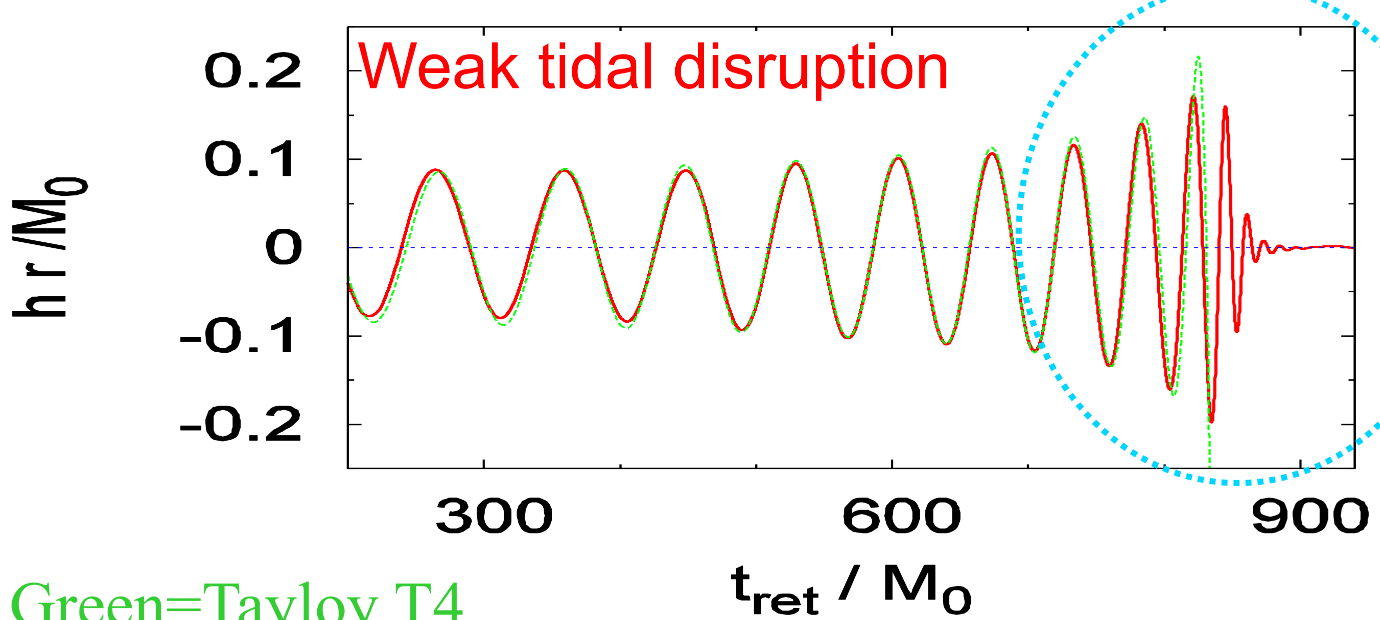
This frequency reflects neutron-star average density !

BH-NS: Signal of tidal disruption

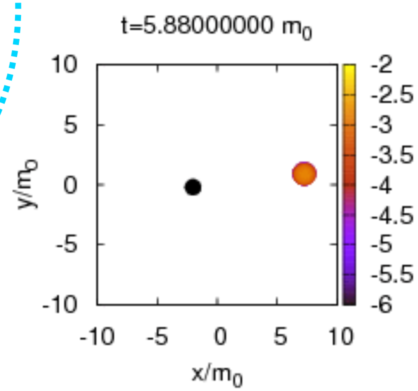


sudden
shutdown





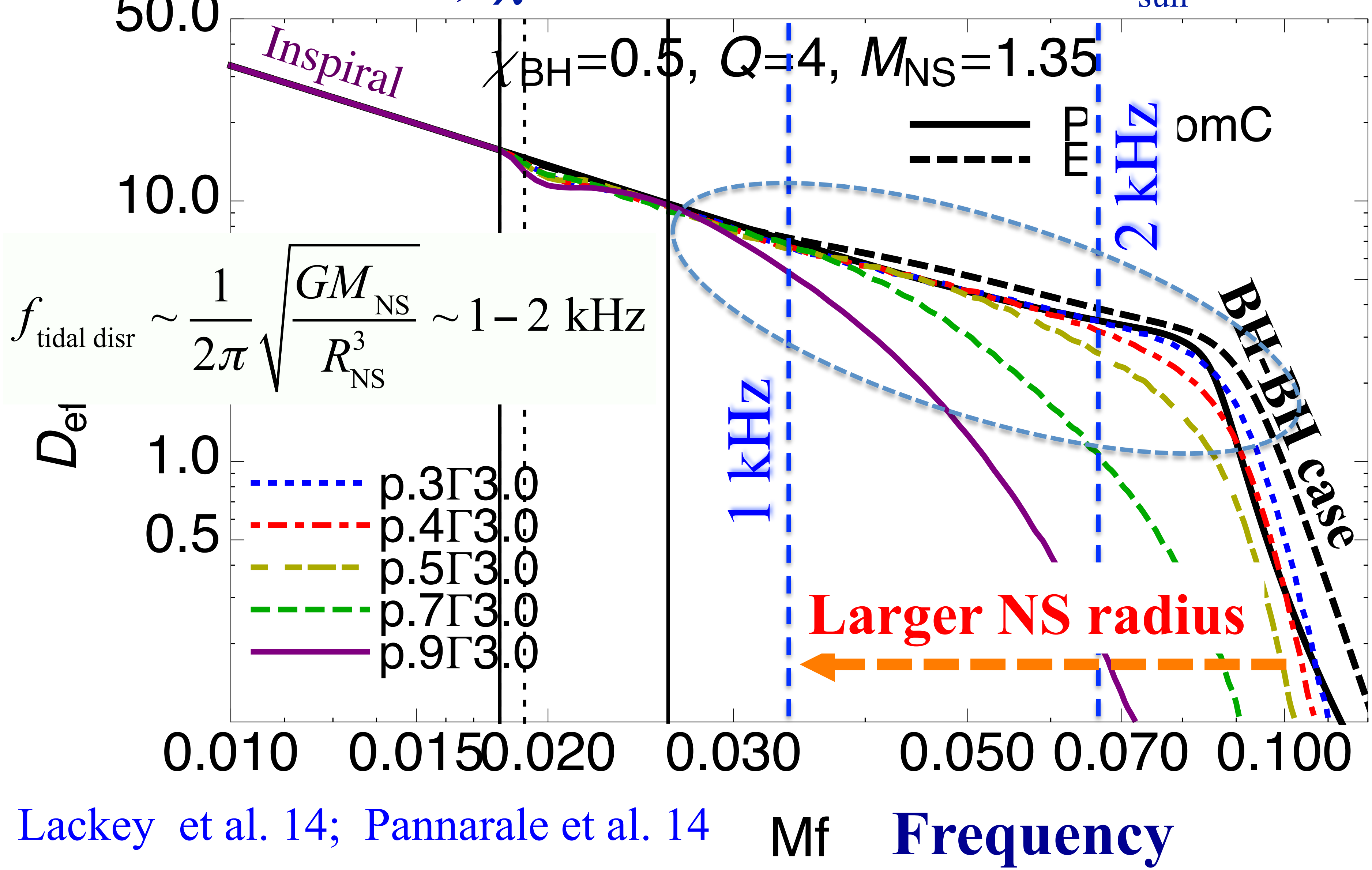
BH
ringdown



Green=Tayloy T4

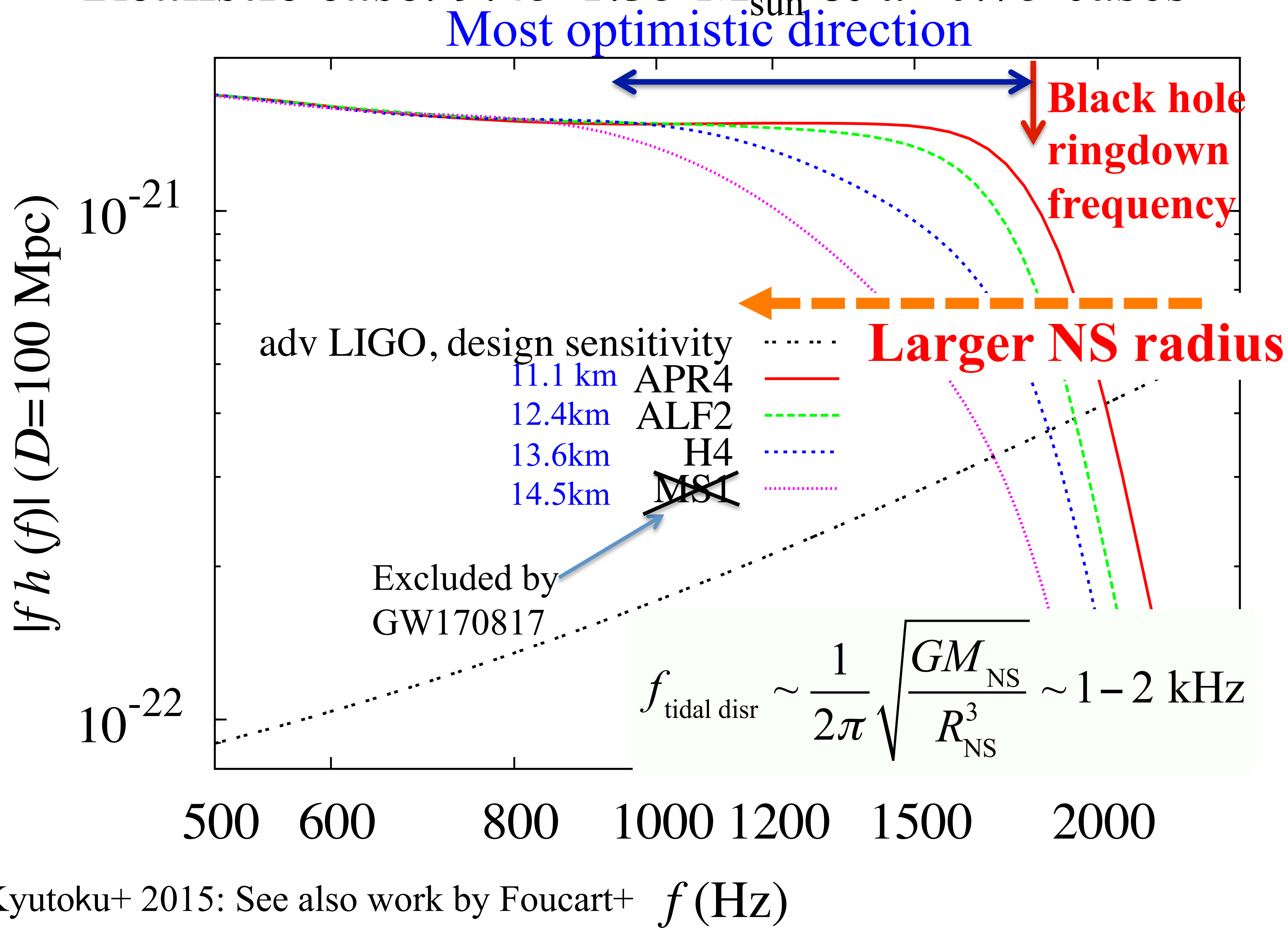
BH-NS Fourier spectrum

For all, χ=0.5 & NS:BH=1.35:5.40$M_{\rm sun}$



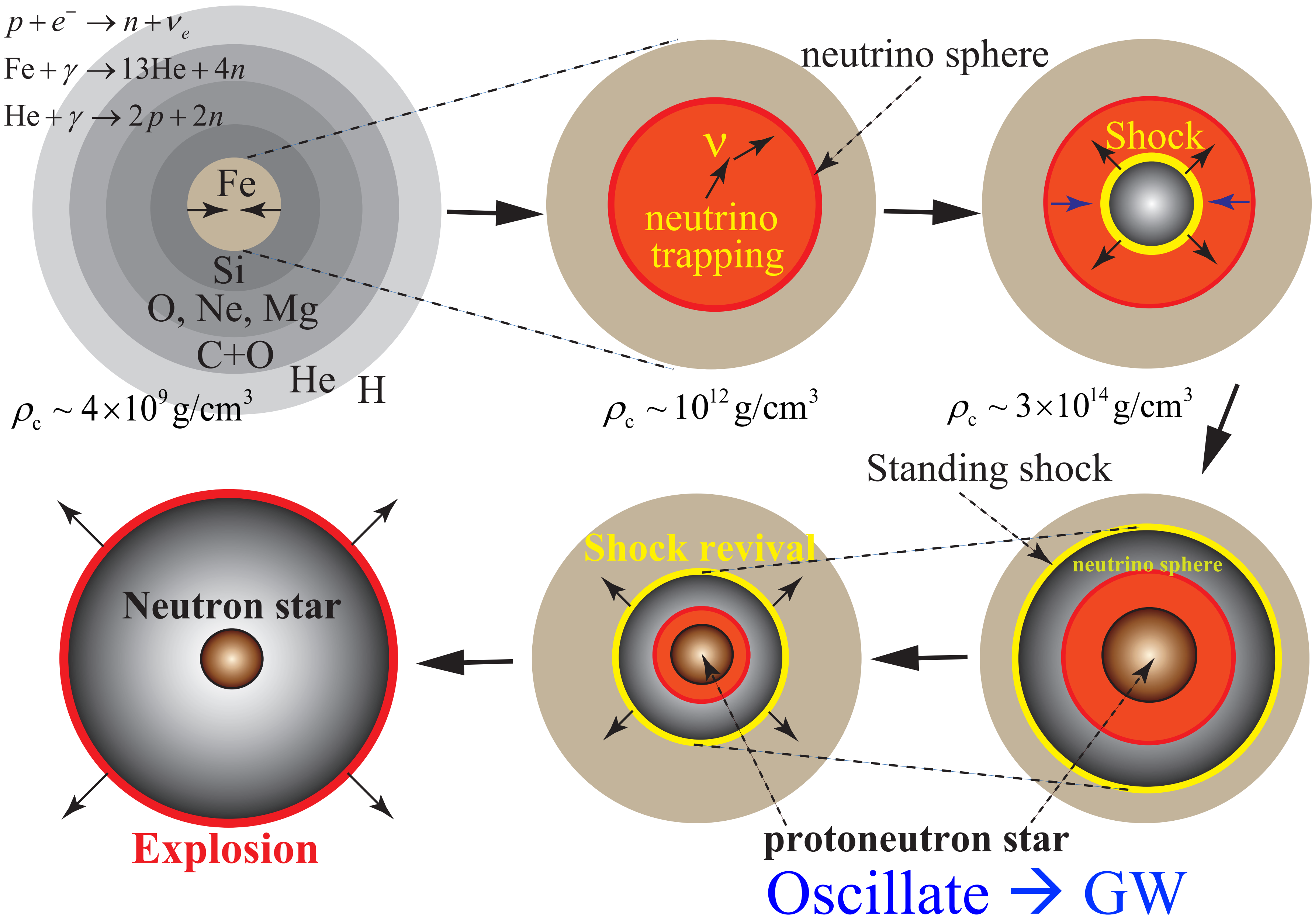
Lackey et al. 14; Pannarale et al. 14

Realistic case: 9.45-1.35 M_{sun} & a=0.75 cases

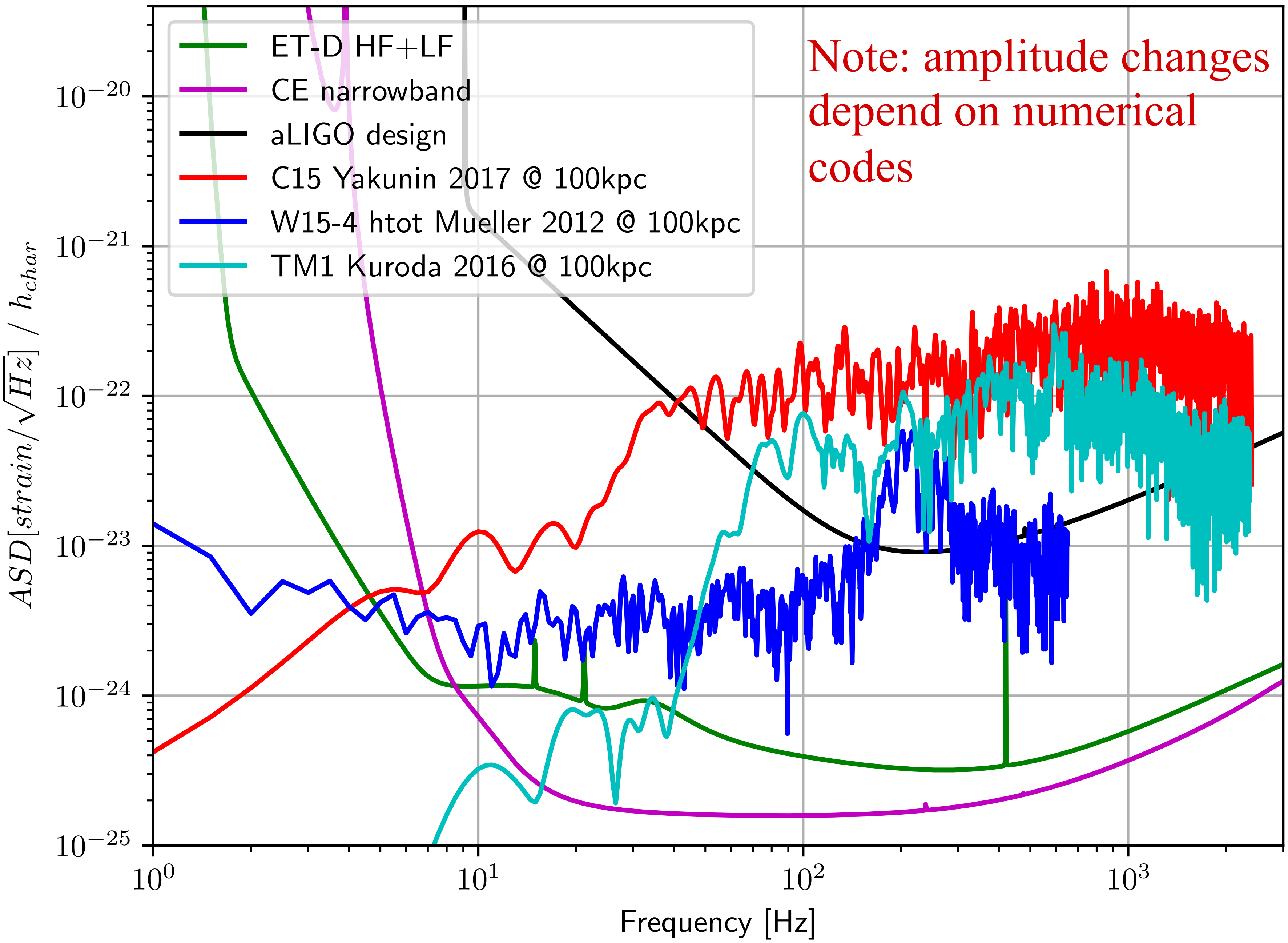


Kyutoku+ 2015: See also work by Foucart+

3 supernovae

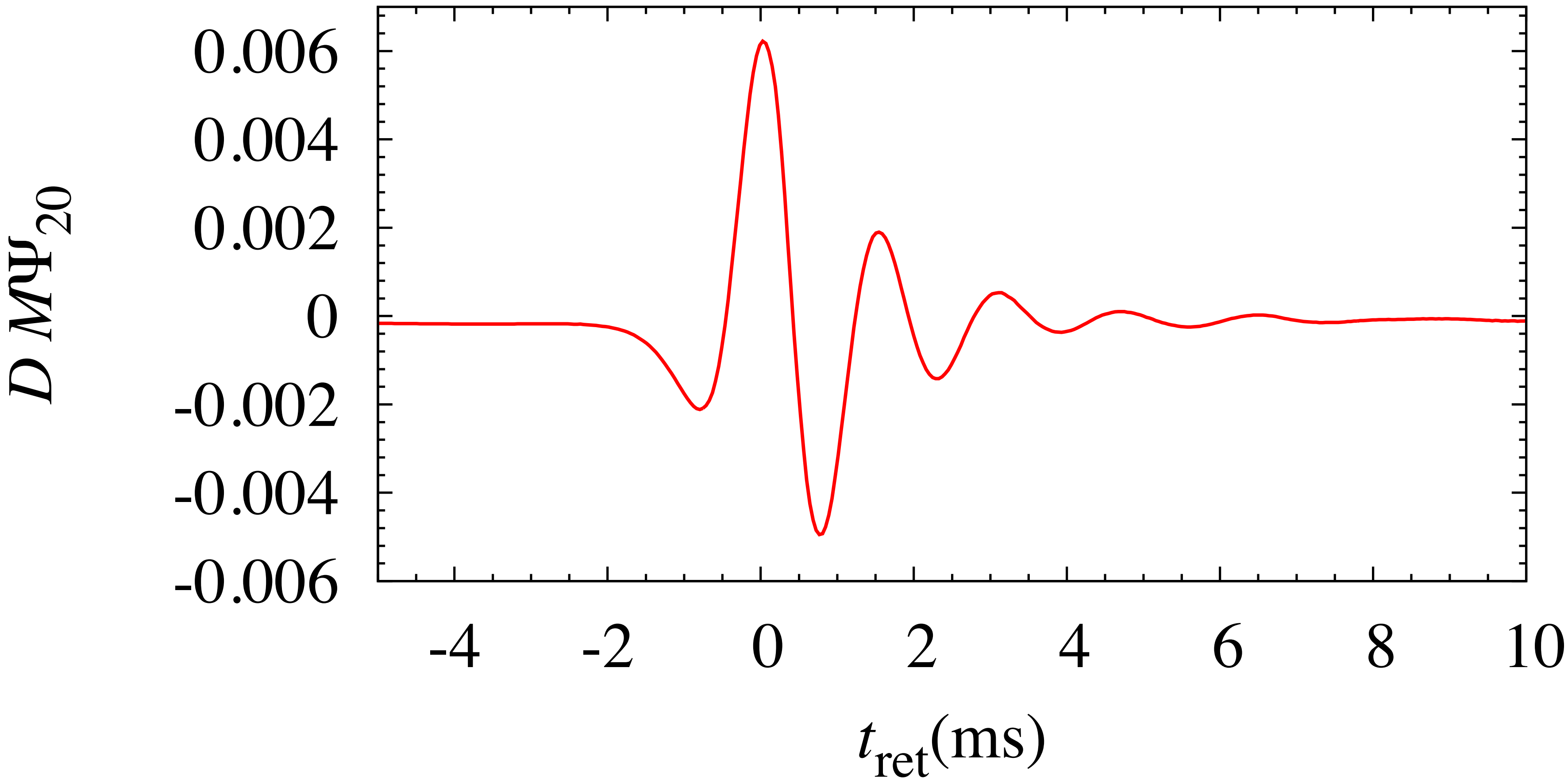


Spectrum (arXiv: 1903.09224)



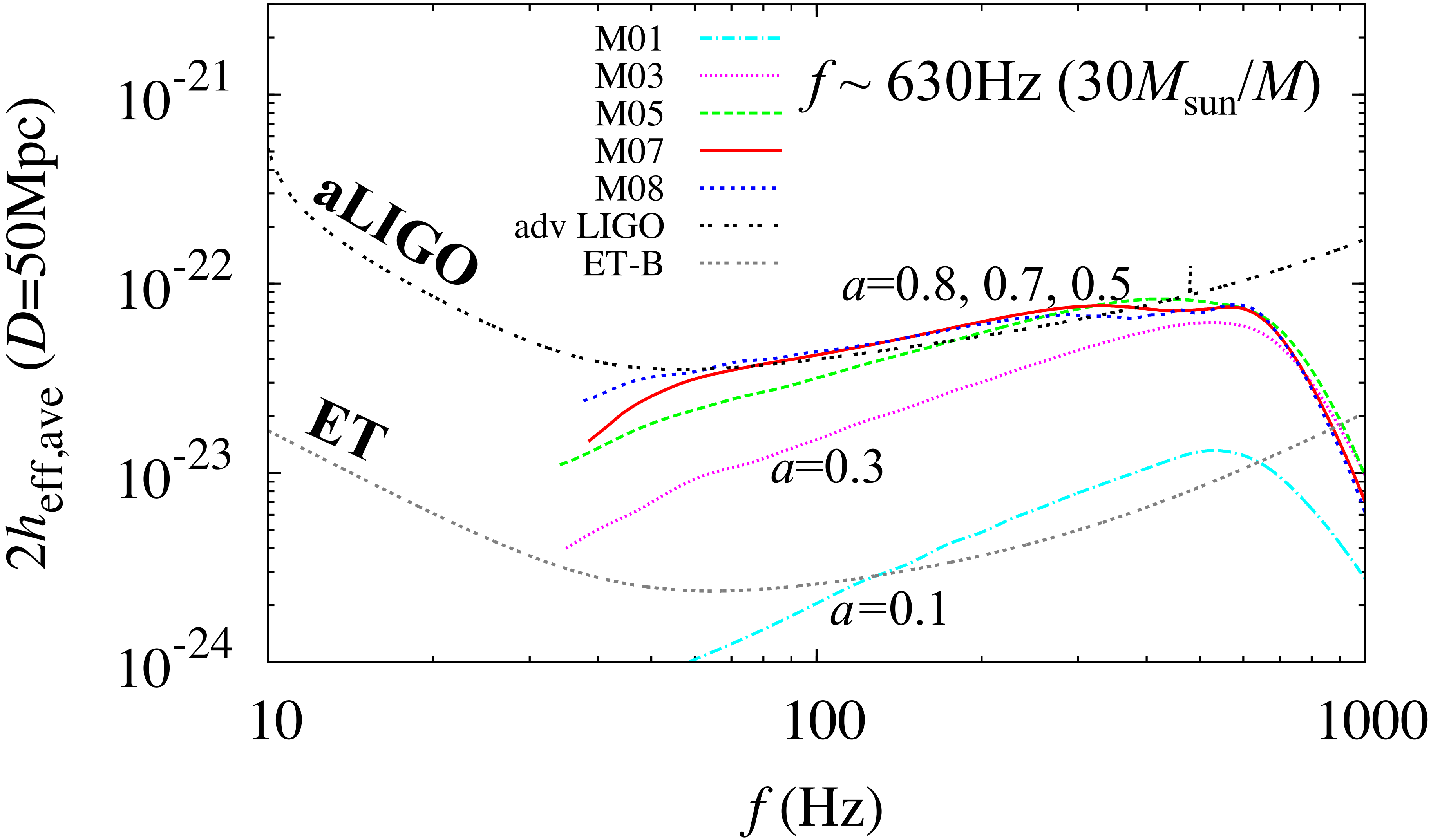
Black hole formation from direct collapse of very massive star

Black hole mass at formation ~ 20 solar mass
dimensionless spin ~0.8



Uchida et al., PRD **99**, 041402, 2019

Spectrum: spin > ~0.5 is promising



Uchida et al., PRD **99**, 041402, 2019

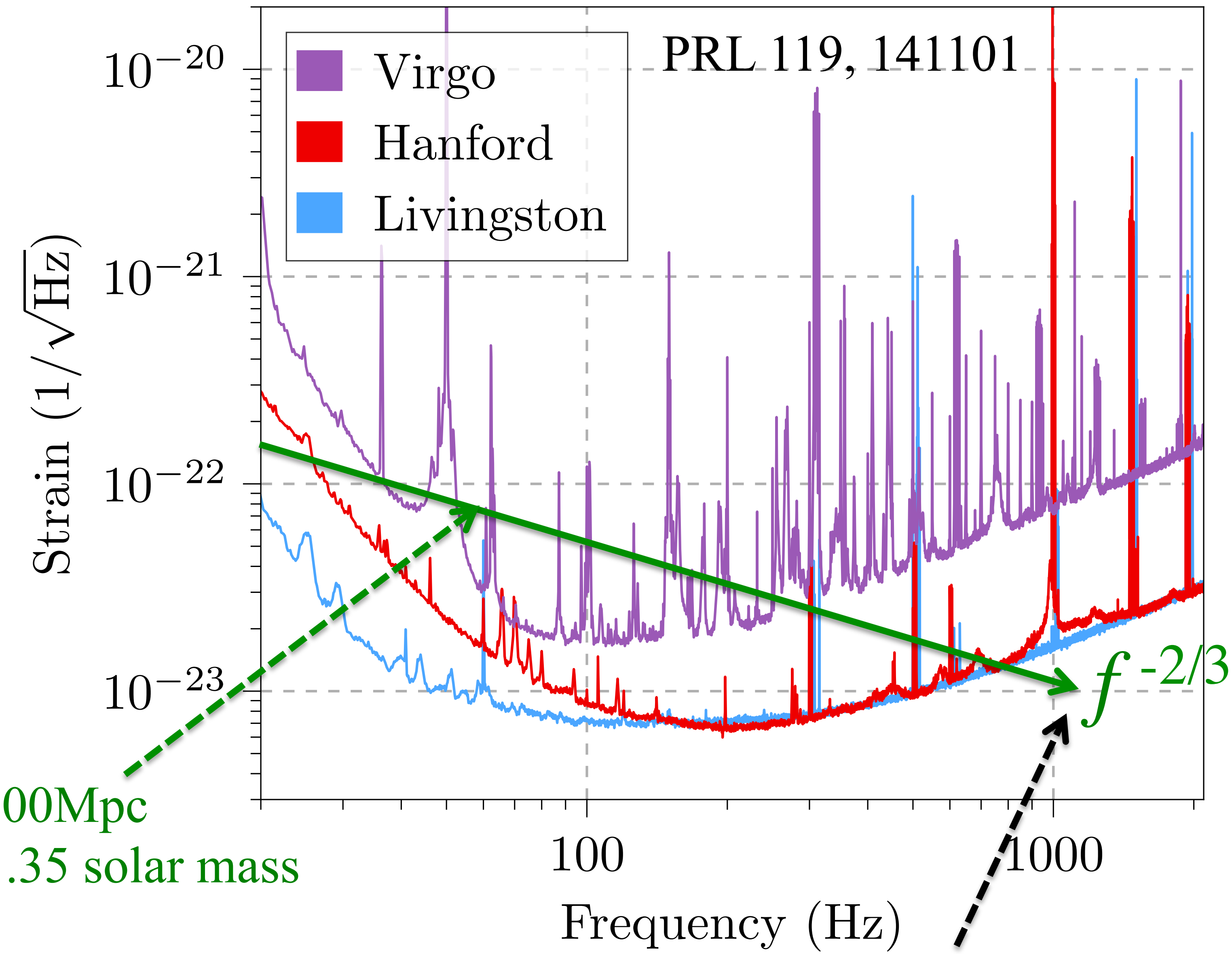
Summary

- **Promising high-freq sources for 3G detectors**

1. Merger remnant of NS-NS → NS radius
2. Tidal disruption of BH-NS → NS average density
3. Supernovae, protoNS → Mechanism of SN
4. Supernovae, BH formation → Finding BH formation from collapse for the first time

- BH-BH → ringdown (relatively low mass)
- Other exotic possibilities: Axion star collapse, cosmic string collapse, primordial BH-BH mergers, axion stars merger ……

Sensitivity of LIGO & VIRGO O2

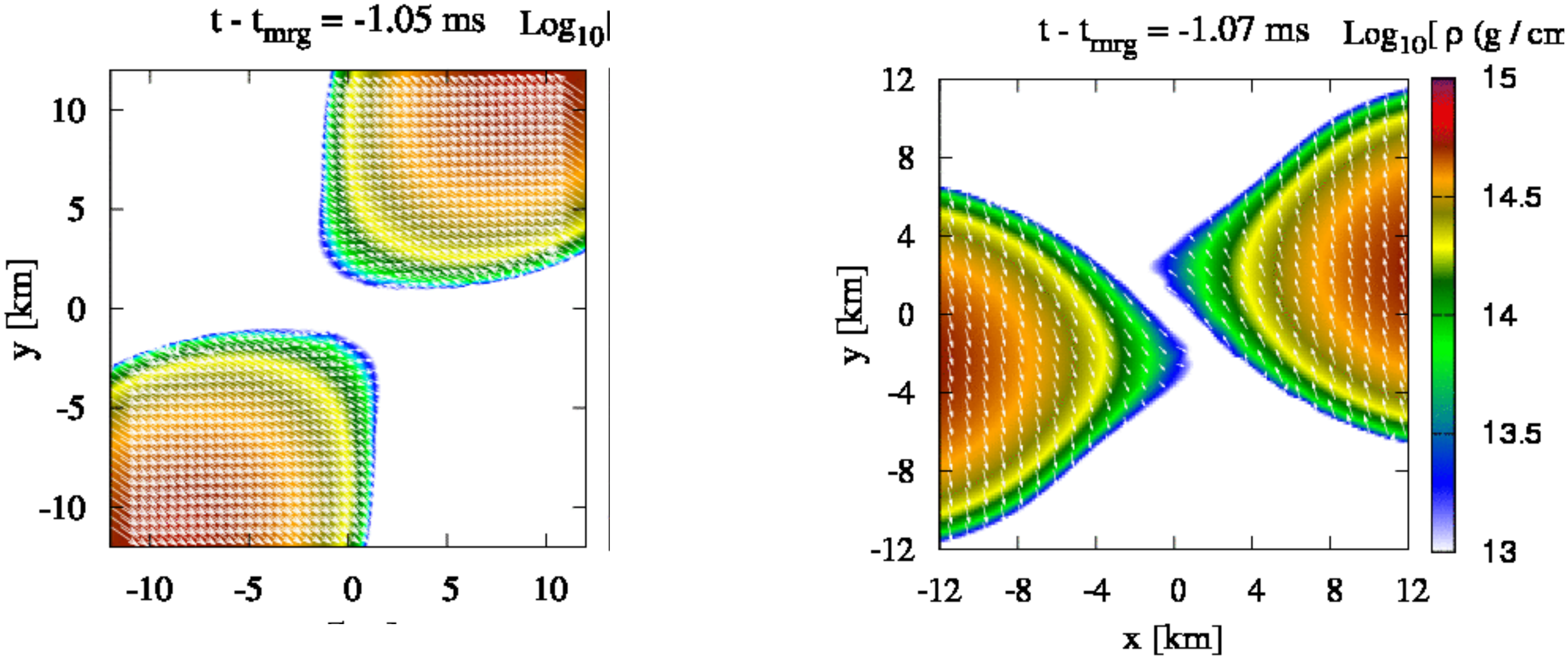


D_{eff}=100Mpc
1.35-1.35 solar mass

***f* > 1kHz is not reachable now**

High-resolution GRMHD for NS-NS

Kiuchi et al. 2015



Δx=17.5m Δx=70m

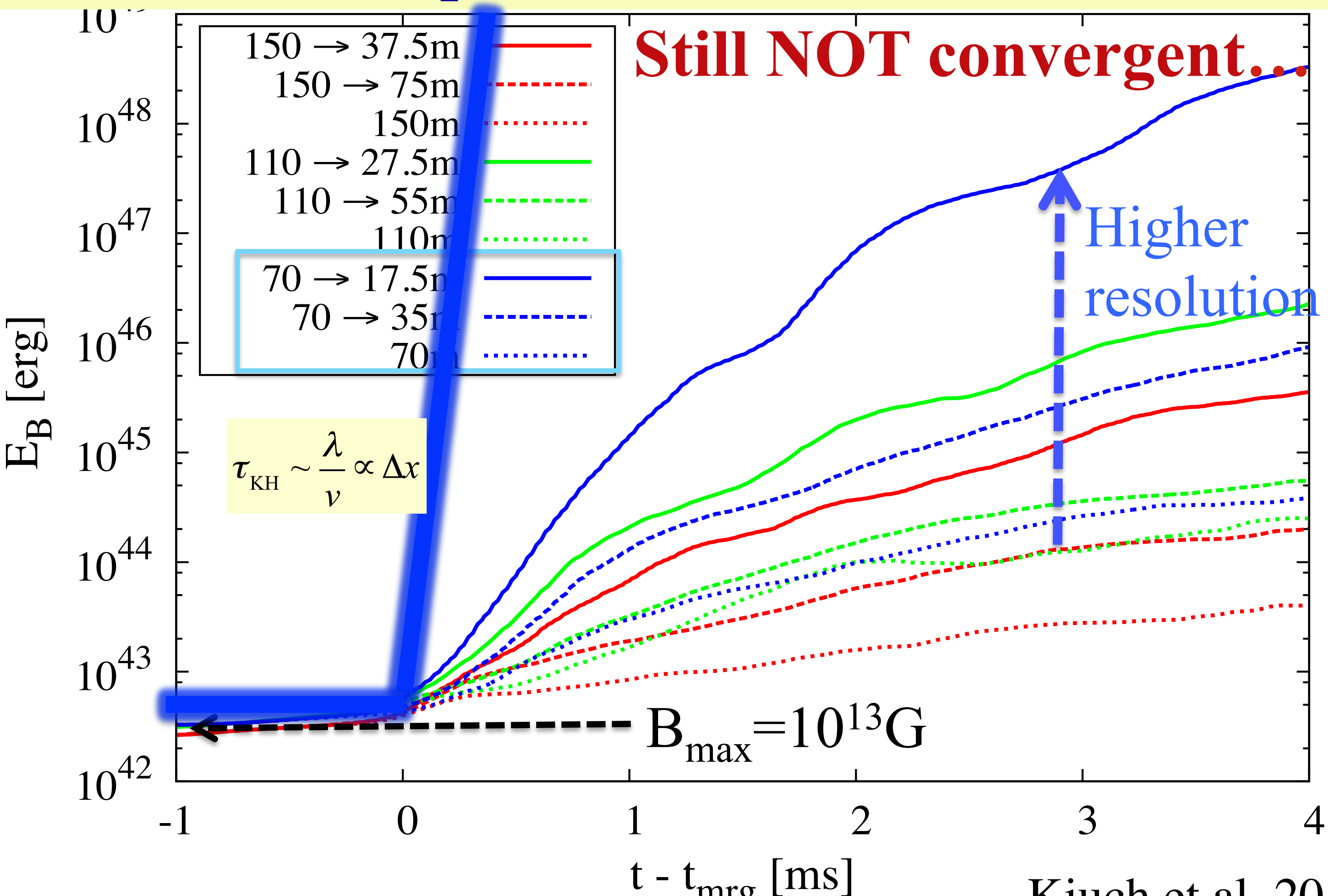
Kelvin-Helmholtz instability:

→ Magnetic field should be amplified by winding

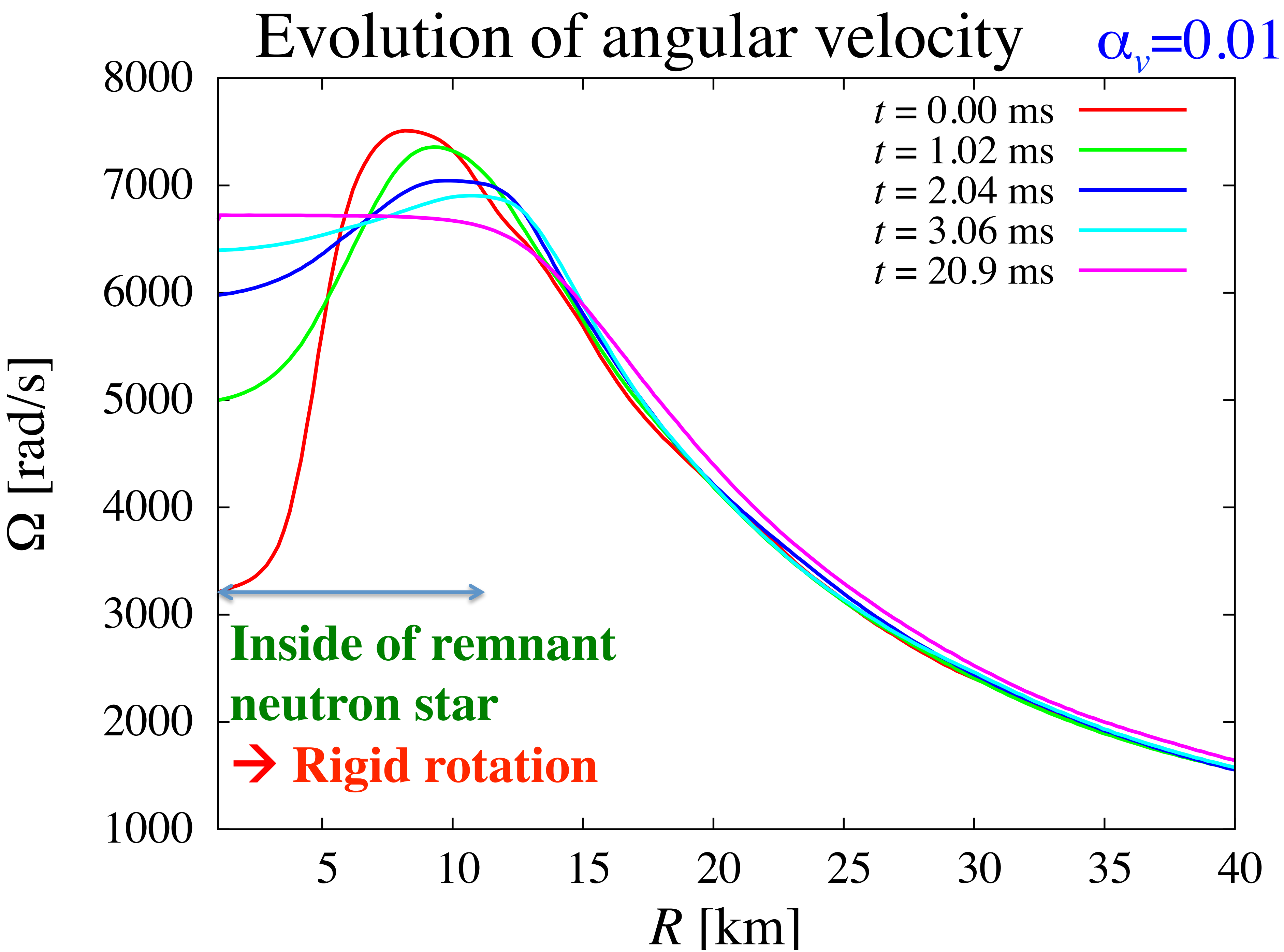
→ Quick angular momentum transport ? (not yet seen)

Magnetic energy: Resolution dependence

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



Kiuch et al. 2015


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

Frequency evolution