重力波とEOS

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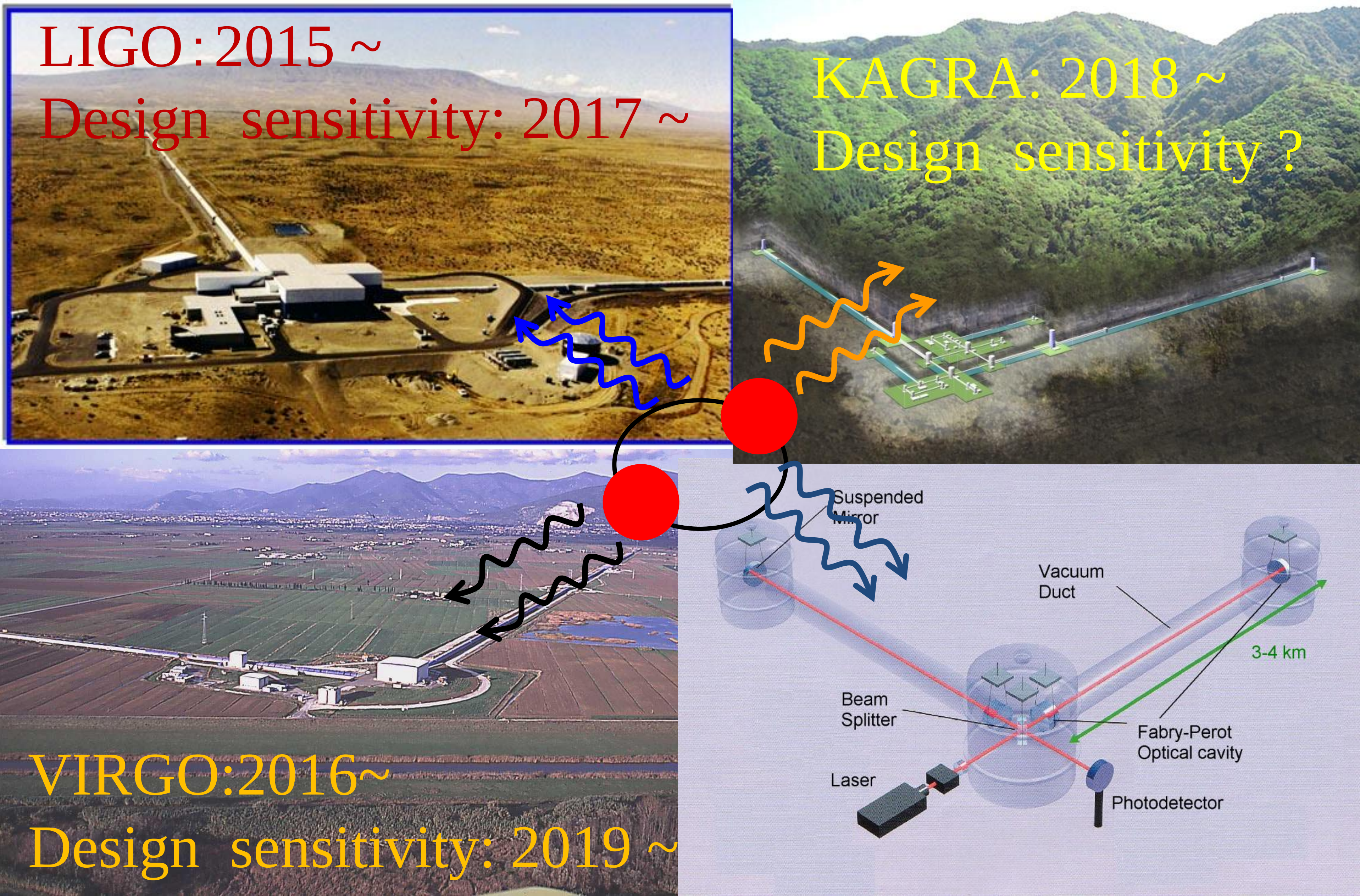
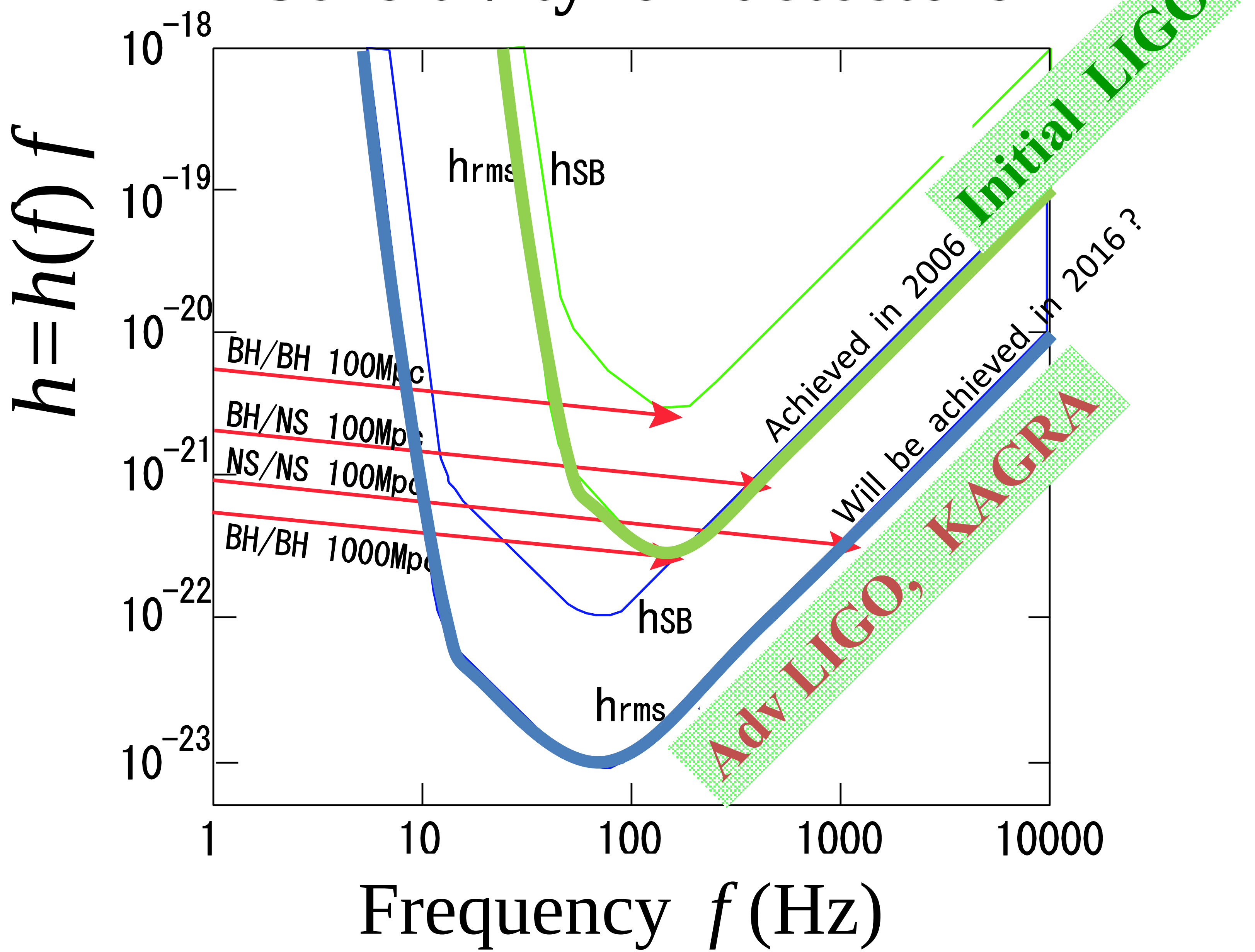
重力波検出器


LIGO：2015 ~
Design sensitivity: 2017 ~
KAGRA: 2018 ~
Design sensitivity ?
VIRGO:2016~
Design sensitivity: 2019 ~
Suspended Mirror
Vacuum Duct
3-4 km
Beam Splitter
Fabry-Perot Optical cavity
Laser
Photodetector

Sensitivity of detectors

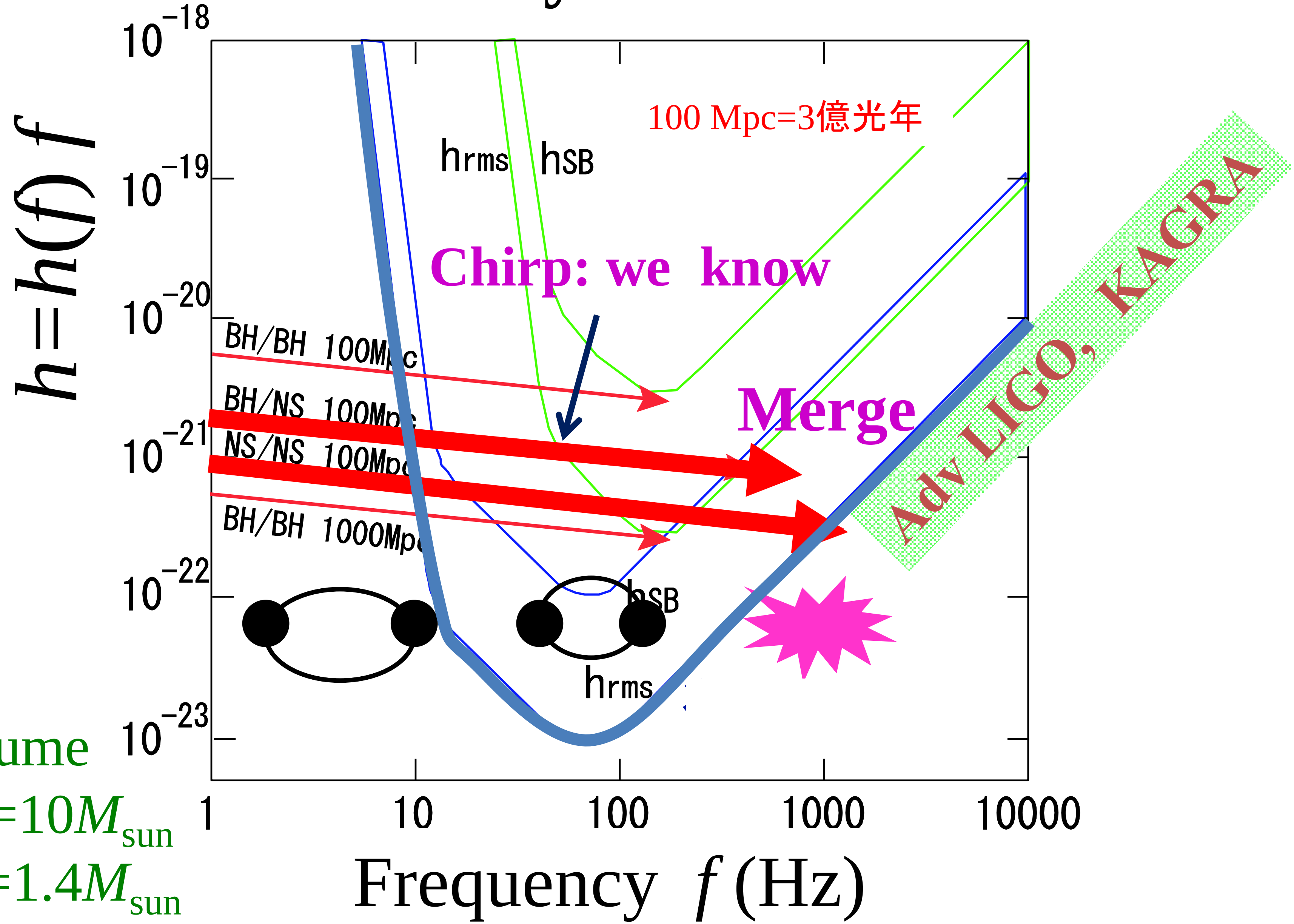


確実な重力波源＝中性子星または ブラックホールからなる連星の合体

1. Invaluable **laboratory for studying high-density nuclear matter**
2. Possible origins of **short-hard GRBs**
3. Sources of strong transient **EM emission (**predicted, but no observation)
4. Possible sources for r-process nuclei

以下では、NS-NS連星、BH-NS連星からの重力波を用いたEOSの制限可能性について述べる。

Sensitivity of detectors

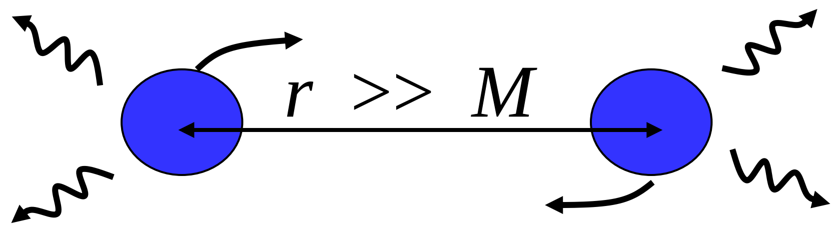


Assume
BH=10M_{sun}
NS=1.4M_{sun}

連星中性子星
NS-NS

Evolution of NS-NS $(1.35M_{\rm sun}\text{-}1.35M_{\rm sun})$

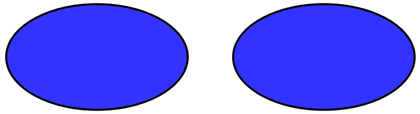
Evolve by GW emission



Adiabatic evolution

Point particlelike

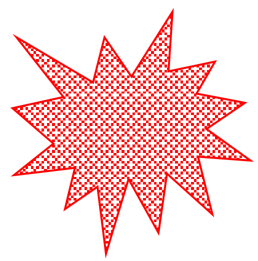
Tidal deformation at $r \sim$ 40-50 km



$t_{\rm GW} \sim t_{\rm orb}$

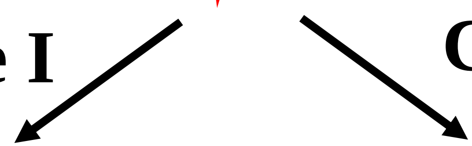
Dynamical evolution

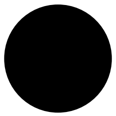
Merger sets in at $f_{\rm GW} \sim$ 1 kHz

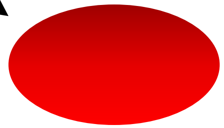


Case I

Case II







Soft EOS

Stiff EOS

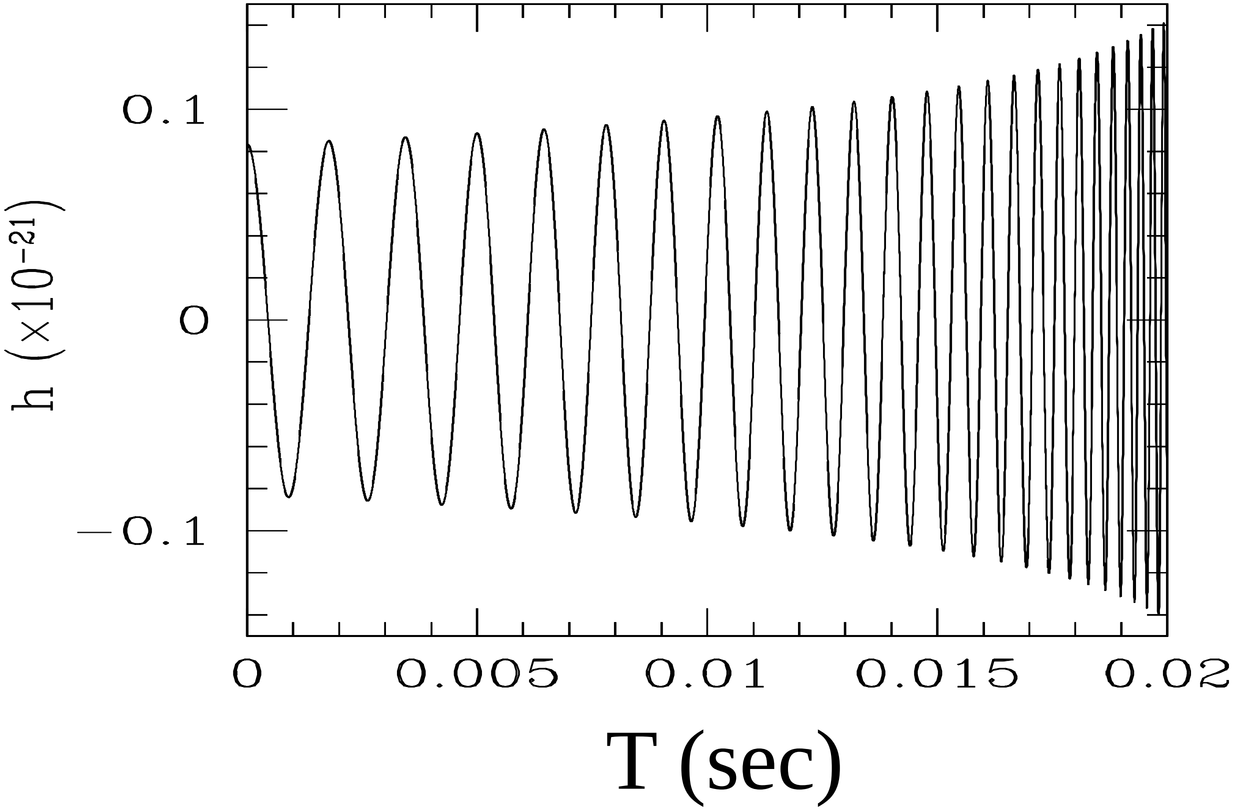
Black hole is formed

"Hypermassive NS"

Large EOS-dependence

Gravitational waveforms

Chirp signal



Post-Newtonian, point-particle
(L. Blanchet, Living Review)

GR gravity
Finite-size
Hydrodynamics
EOS

?

Numerical Relativity

Brief introduction of numerical relativity

$$G_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu}$$

- General relativistic gravity; including GW radiation reaction

$$\left\{ \begin{array}{l} \nabla_\mu T^\mu_\nu = 0 \\ \nabla_\mu \left(\rho u^\mu \right) = 0 \\ +\mathrm{EOS} \end{array} \right\}$$

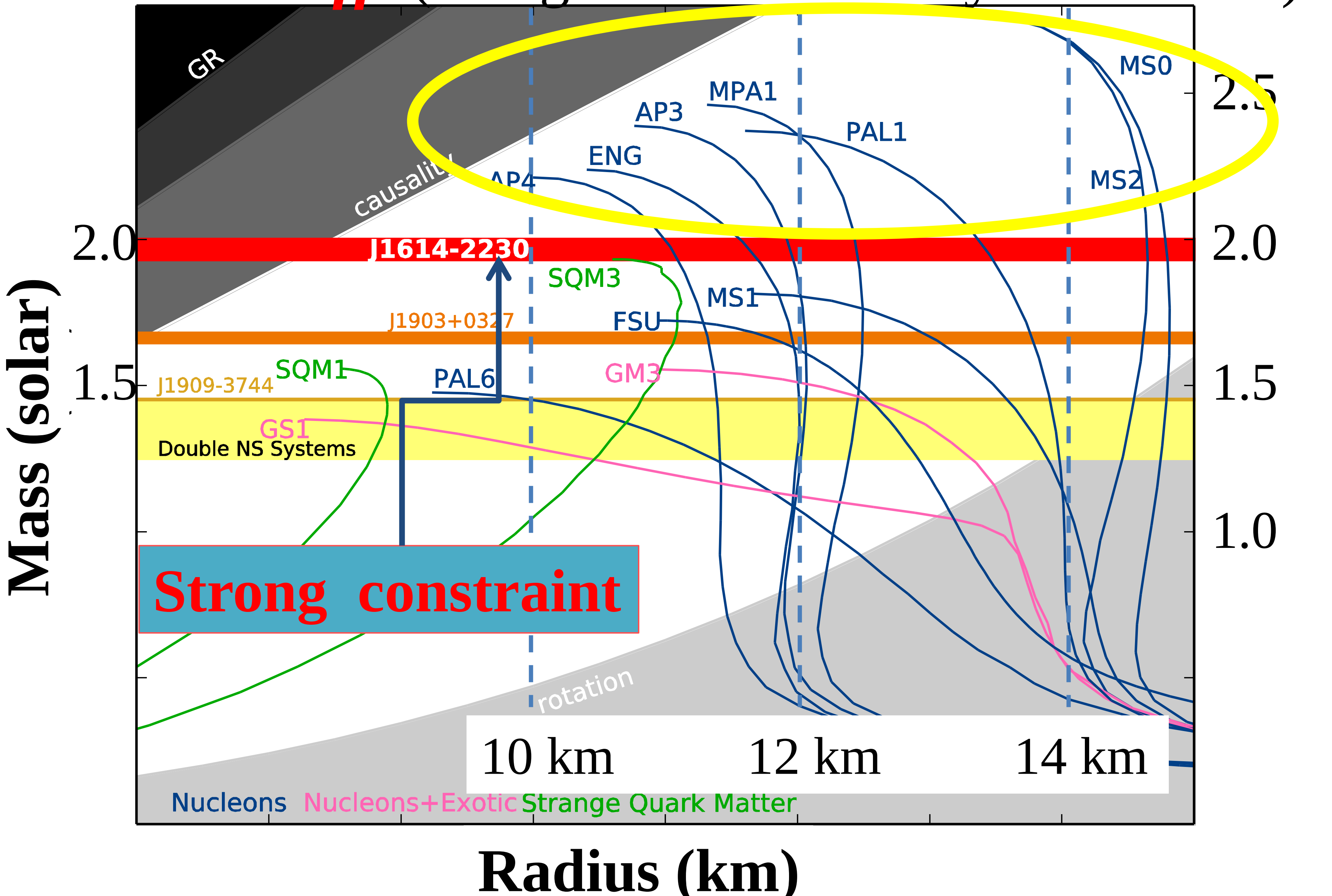
- Hydodynamics/MHD
- Equations of state for nuclear matter

$$\left(\begin{array}{l} \nabla_\mu F^{\mu\nu} = -4\pi j^\nu \\ \nabla_{[\mu} F_{\nu\lambda]} = 0 \\ \text{Radiation } ..... \end{array} \right)$$

- Magnetic fields
- Neutrino emission

現状は多様な第一原理的計算が可能である。

EOS is *stiff* (though still too many candidates)



NS-NS merger with finite-temperature EOS + neutrino leakage

<u>Example</u>:

- EOS = Shen's EOS

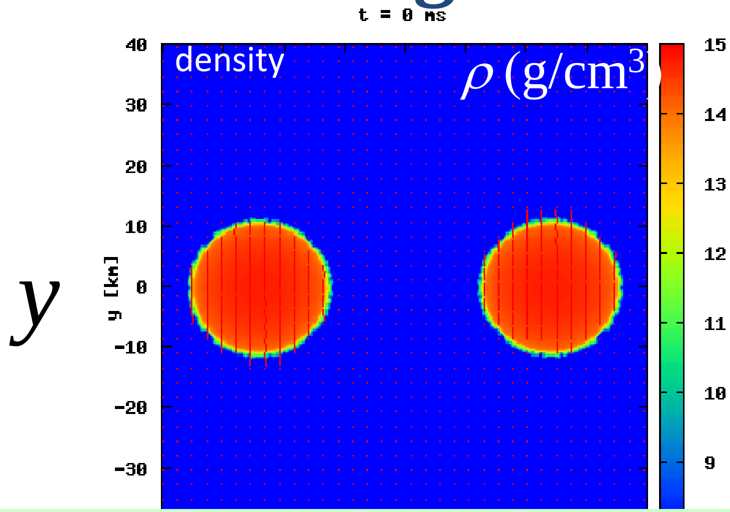
➢ Maximum mass of spherical star
$M_{\rm max}=2.2M_{\rm sun}$ (T=0: zero temperature)

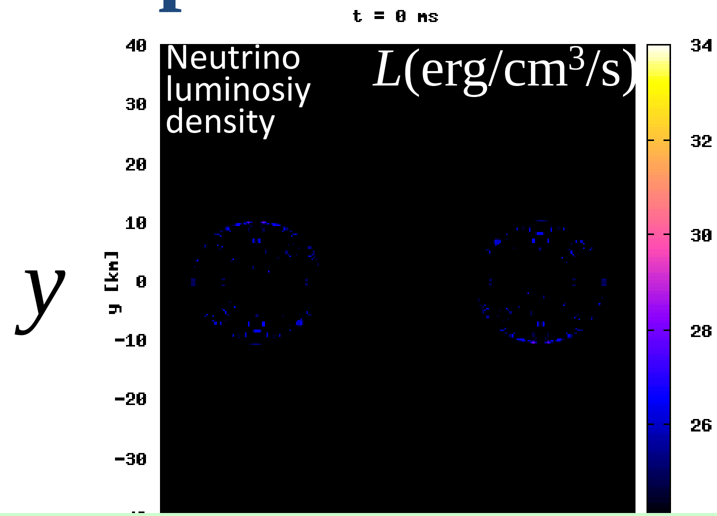
➢ R (1.4$M_{\rm sun}$) ~ 14.5km → Stiff

Mass of NS-NS for simulation

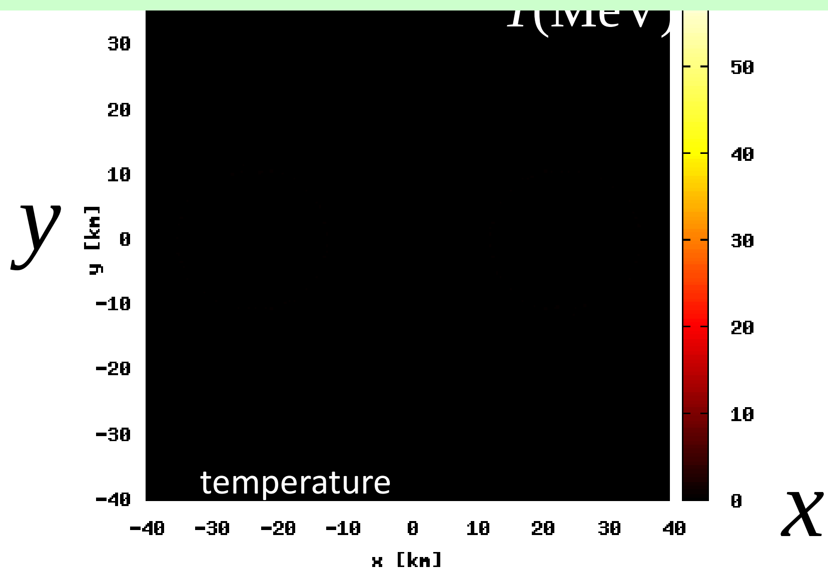
→ 1.5—1.5 $M_{\rm sun}$

NS-NS merger with finite-temp EOS + neutrino





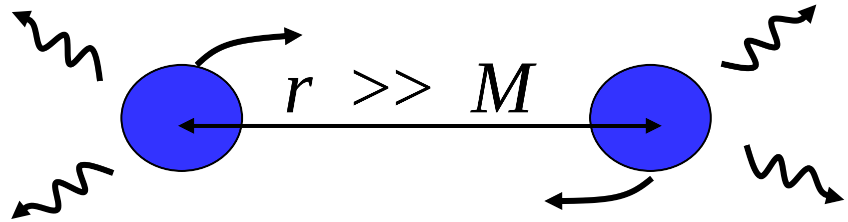
- **Long-lived hot HMNS is the outcome:**
  Supported by thermal pressure & centrifugal force



Sekiguchi, Kiuchi, Kyutoku, Shibata
PRL107, 2011

Evolution of NS-NS $(1.35M_{sun}\text{-}1.35M_{sun})$

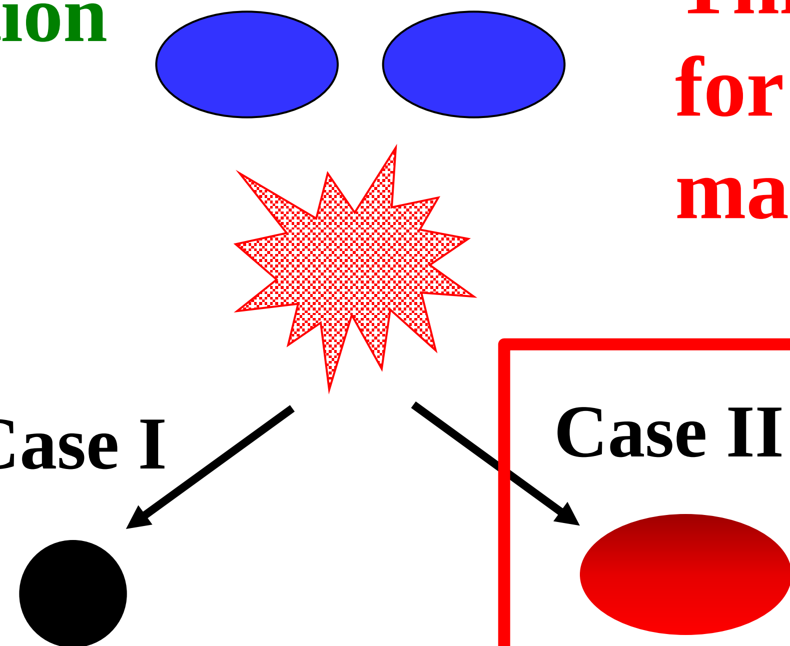
Evolve by
GW emission



Tidal deformation

This is likely for canonical mass case

Merger sets in
at $f_{GW} \sim 1$ kHz



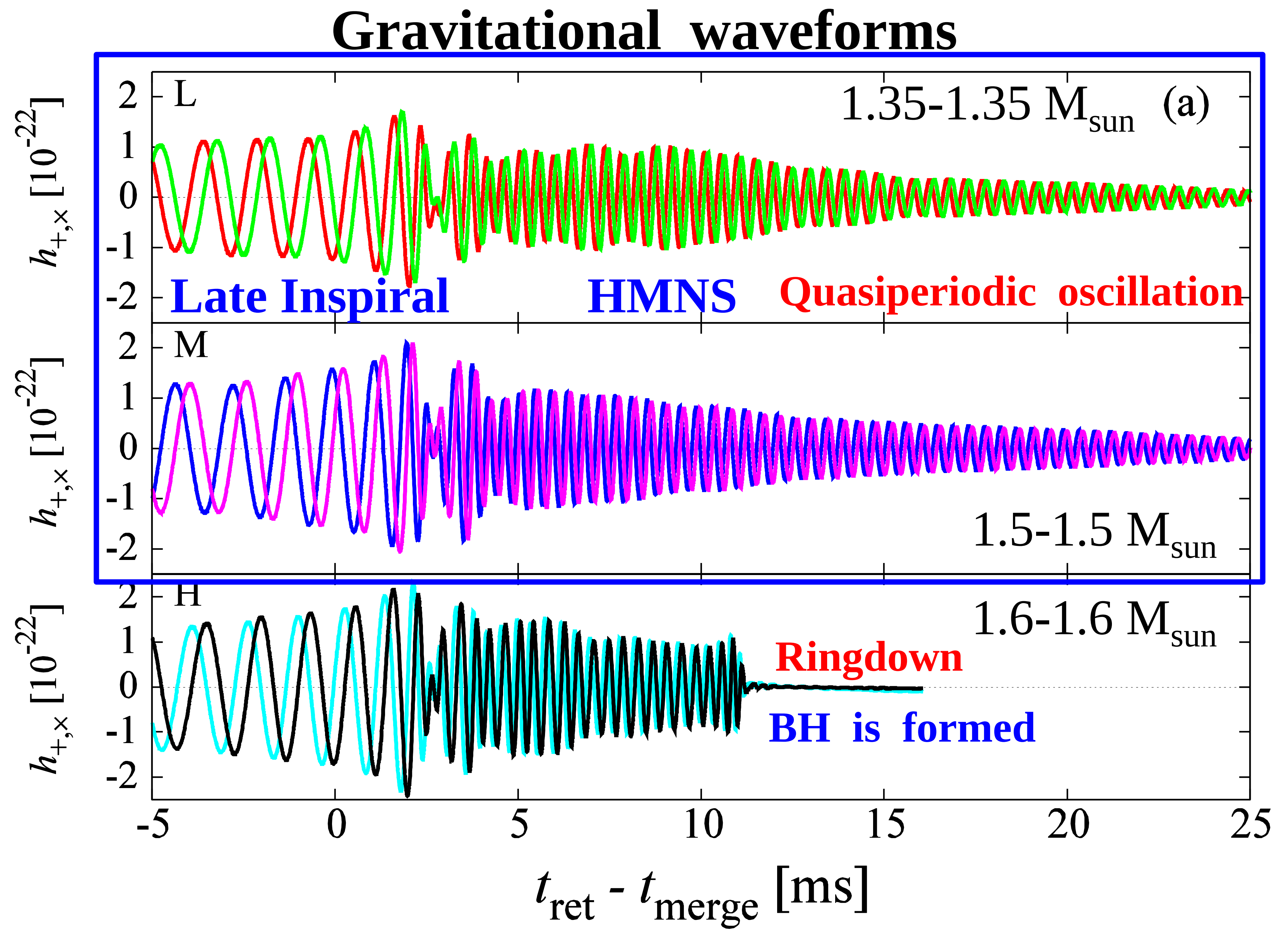
Soft EOS

Black hole is formed

Stiff EOS

"Hypermassive NS"

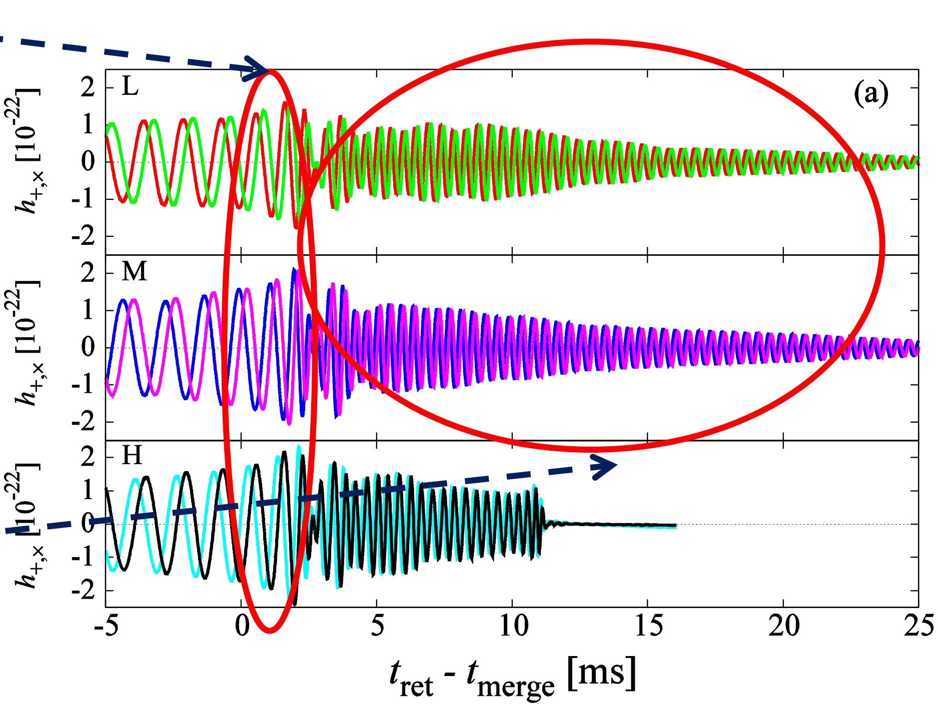
Large EOS-dependence


Gravitational waveforms
L
1.35-1.35 M_sun (a)
Late Inspiral
HMNS
Quasiperiodic oscillation
M
1.5-1.5 M_sun
H
1.6-1.6 M_sun
Ringdown
BH is formed
h_{+,×} [10^-22]
2
1
0
-1
-2
-5
0
5
10
15
20
25
t_ret - t_merge [ms]

Two interesting phases

1. ***Late Inspiral***
   (Damour+, Baiotti+, ….) **:**
   Effects of *tidal deformation*
   ***f* ~ 500 – 1kHz**

2. ***Merger → HMNS***
   (Janka+, Hotokezaka+)
   GW from *HMNS*
   ***f* ~ 2 – 4 kHz**

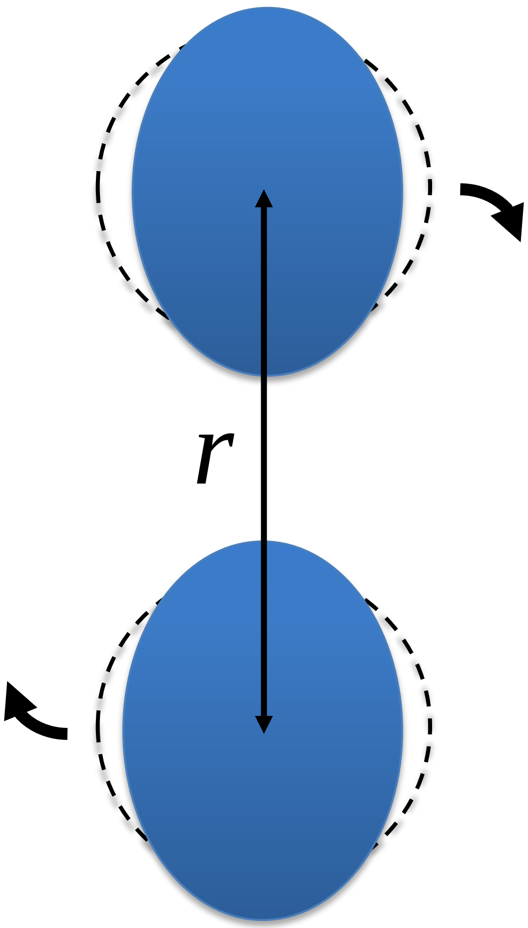


Both waveforms play an important role for constraining EOS of neutron stars

1 Gravitational waves from late inspiral (Hotokezaka +)

Tidal effects in a binary inspiral

(originally pointed out by Lai+ 1992)



Close Binary System

➡ Tidal deformation;
Quadrupole is induced

$$\phi \sim -\frac{GM}{r} - \frac{C}{r^6}$$

5PN correction:

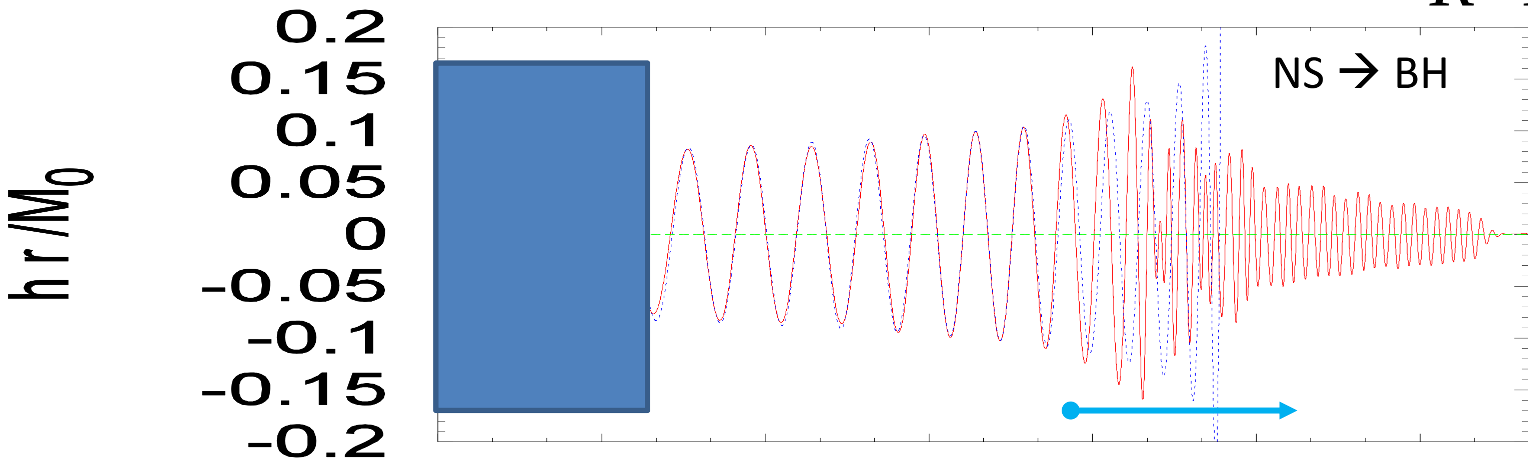
But $C \sim MR^5$, $R \sim 5$—$8\,M$

For $r \sim 2R$, it could play a role.

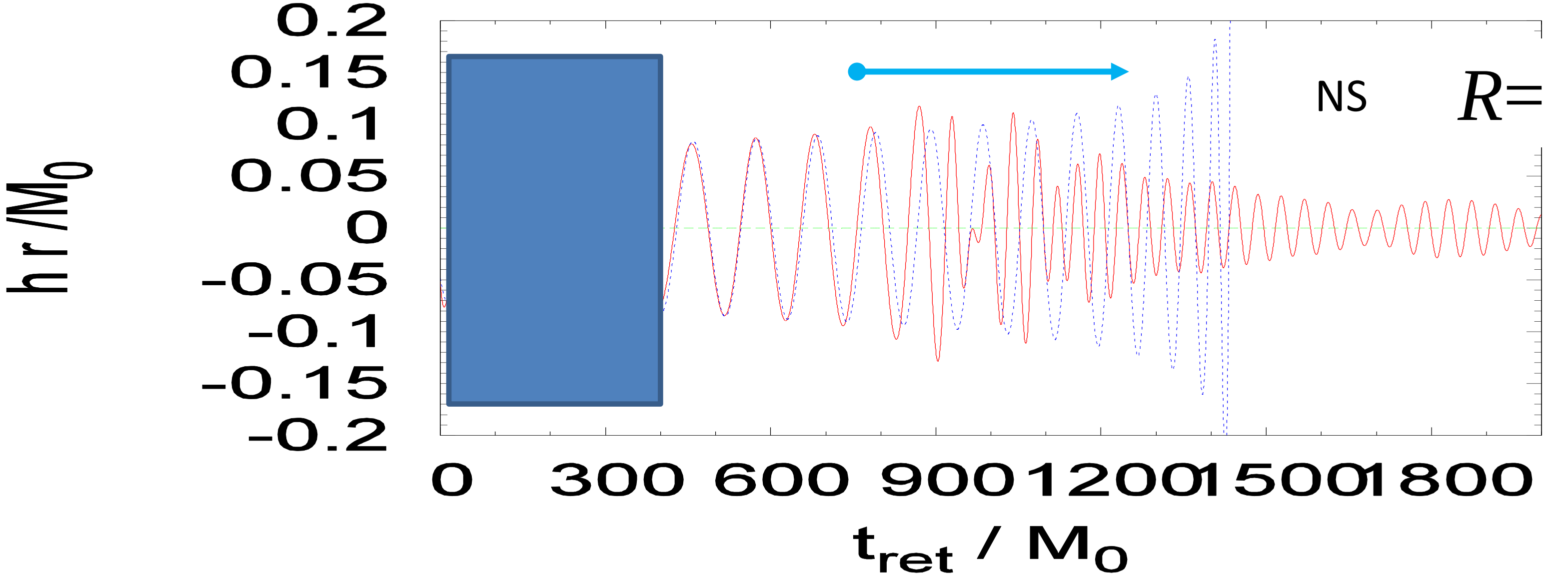
$$h = h(t, M_1, M_2, C_1, C_2)$$

For all, 1.35-1.35 M_{sun}

R=11.6 km

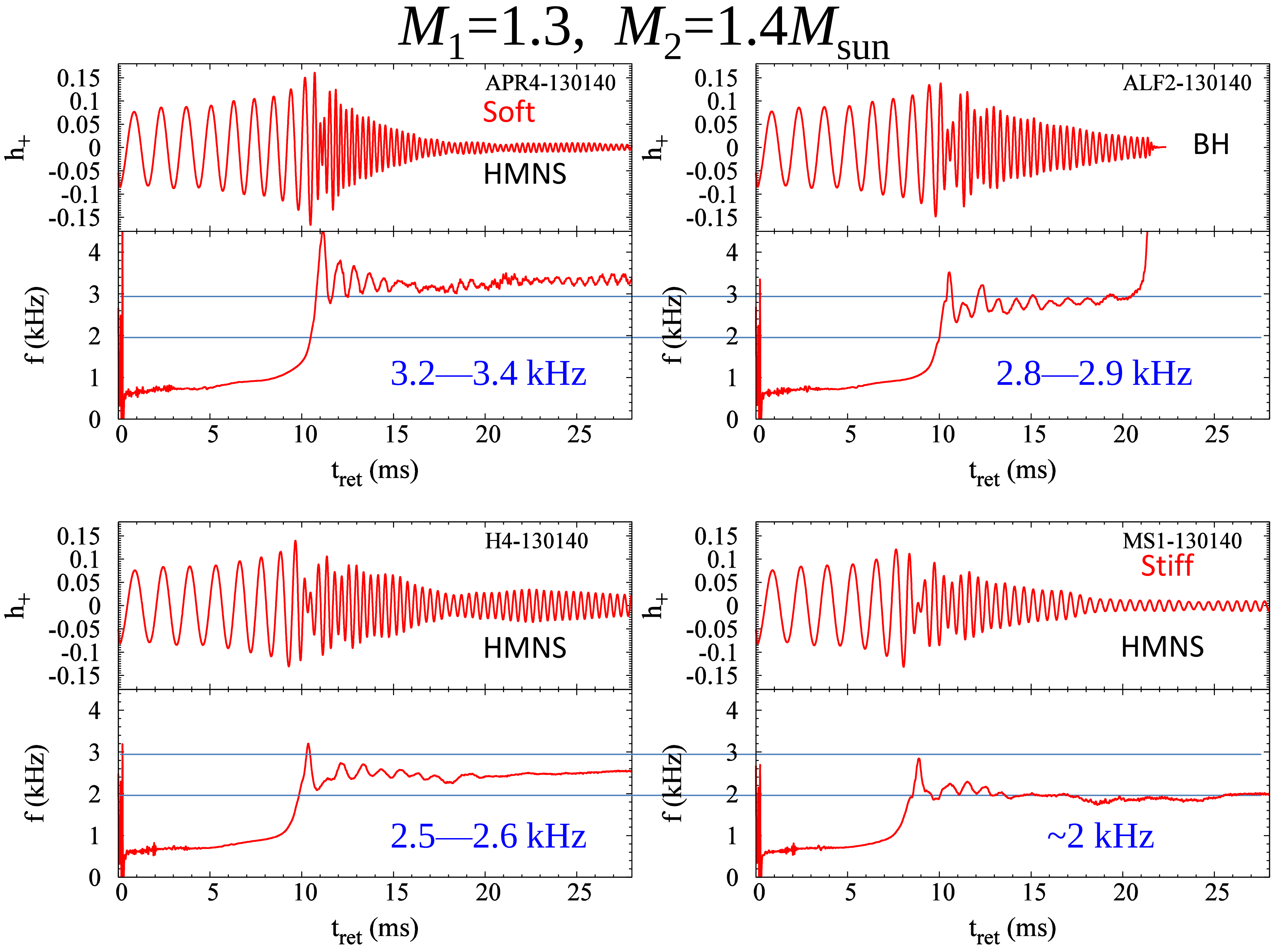


赤：数値相対論による計算結果
青：点粒子近似を用いた、計算



R=15.2 km

2 Gravitational waves from hypermassive NS

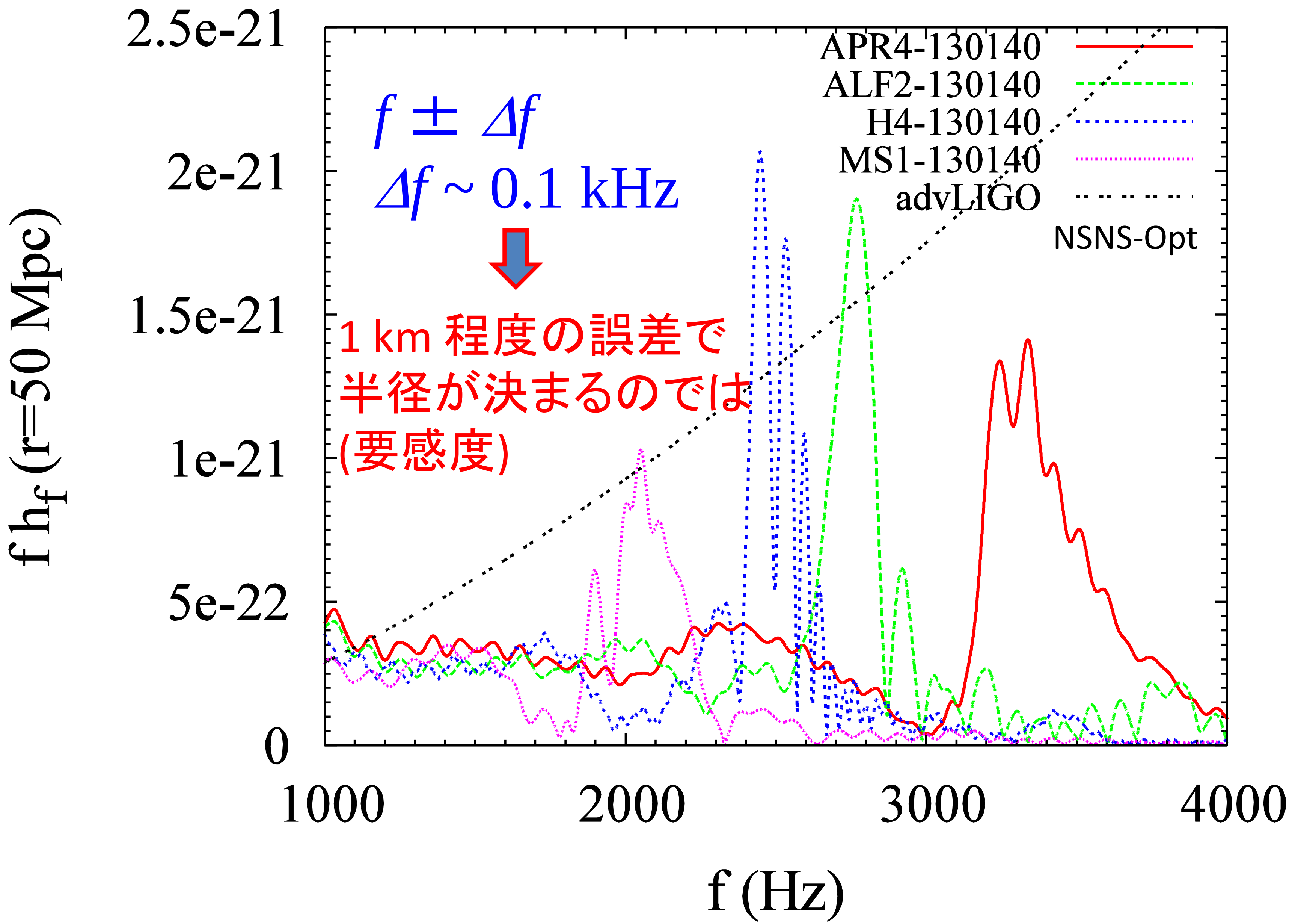


M1=1.3, M2=1.4Msun
APR4-130140
Soft
HMNS
3.2—3.4 kHz
ALF2-130140
BH
2.8—2.9 kHz
H4-130140
HMNS
2.5—2.6 kHz
MS1-130140
Stiff
HMNS
~2 kHz
h+
f (kHz)
tret (ms)

Properties of GW from HMNS

- **Gravitational-wave frequency from HMNS depends strongly on EOS**
- **The frequency has correlation with stiffness** (Janka+, 11)
- Gravitational-wave frequency appears to be approximately constant (but not exactly constant due to GW reaction)
  → Gravitational waves make a broad peak in the Fourier spectrum

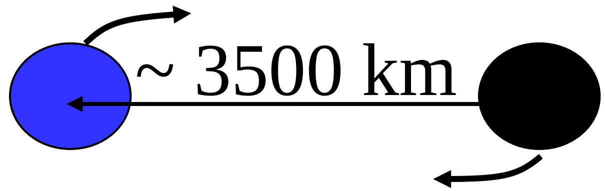
Fourier spectrum



ブラックホール・中性子星連星
BH-NS

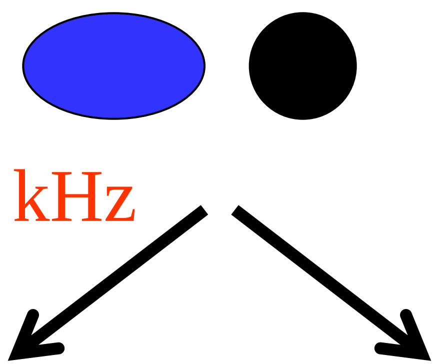
Evolution of BH-NS ($4.05M_{sun}$-$1.35M_{sun}$)

Evolve by
GW emission

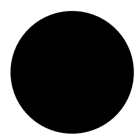


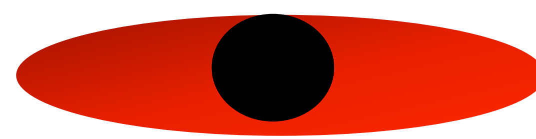
Last 1 hour ; $f_{GW} \sim 1$ Hz

Merger sets in
at $r \sim 40$ km; $f_{GW} \sim 1$ kHz



Case I





Case II

NS is swallowed by BH
for small R_{NS}* or *$M_{BH} >> M_{NS}$

NS is disrupted

Large EOS-dependence

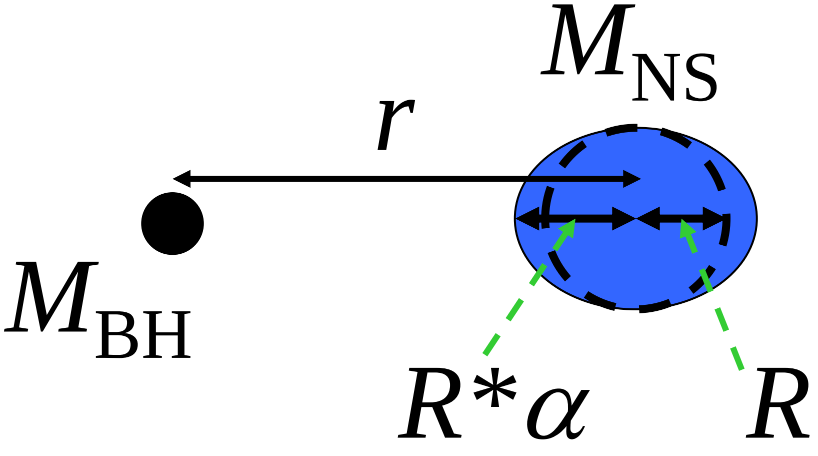
Condition for tidal disruption

- BH tidal force > NS self-gravity

$$\left(\frac{M_{\rm BH}}{M_{\rm NS}}\right) \le 2.0\zeta^{3/2}\left(\frac{\alpha}{1.5}\right)^{3/2}\left(\frac{c^2R}{6GM_{\rm NS}}\right)^{3/2}$$

$$\zeta = 1\text{–}6 \quad \text{for} \quad a/M_{\rm BH} = 0\text{–}1$$
$$c = G = 1$$

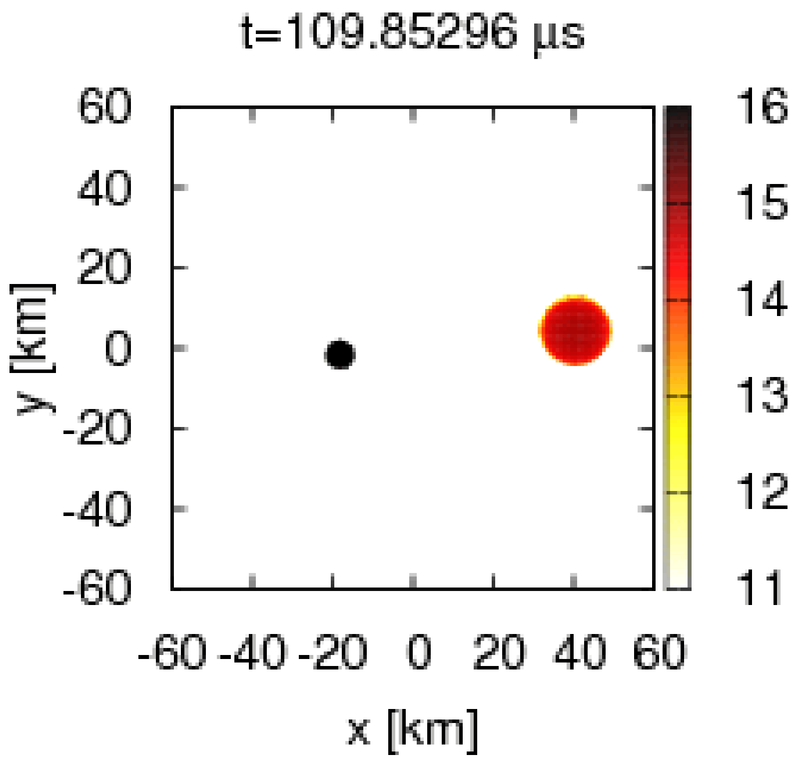
✓**Low-mass BH** or
✓**Large NS radius** or
✓**Large BH spin**
is necessary

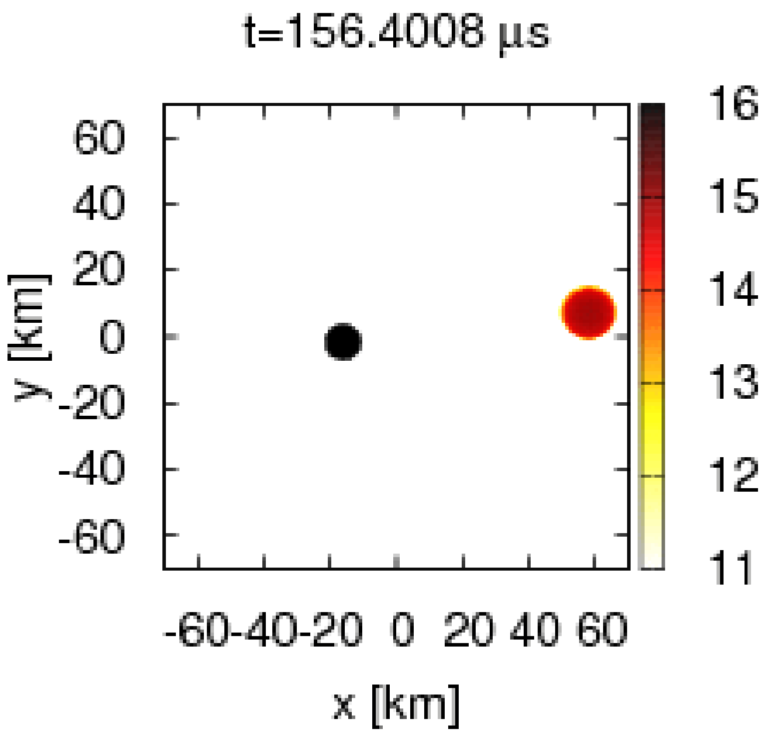


BH(a=0)-NS with piecewise polytrope

$M_{BH}=2.7M_{sun}$
$M_{NS}=1.35M_{sun}$
R=11.6 km, Q=2

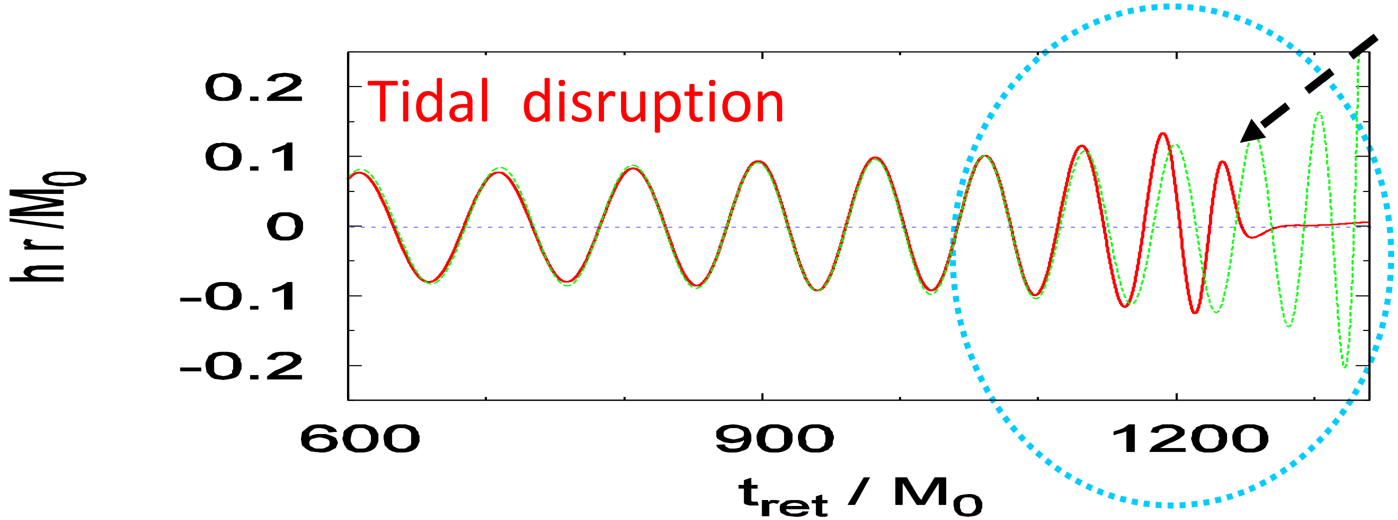
$M_{BH}=4.05M_{sun}$
$M_{NS}=1.35M_{sun}$
R=11.0 km, Q=3





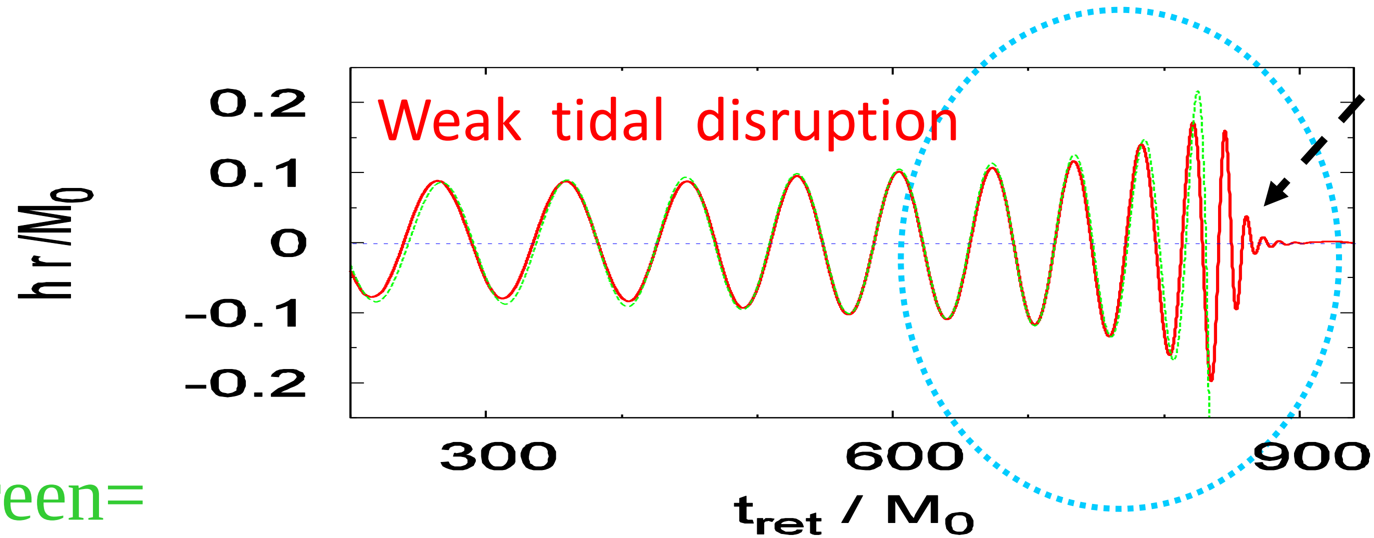
Kyutoku + PRD 2011

$M_{\rm BH}=2.7M_{\rm sun}$, $a=0$, $M_{\rm NS}=1.35M_{\rm sun}$



sudden shutdown

R=15.2 km



BH ringdown

R=11.6 km

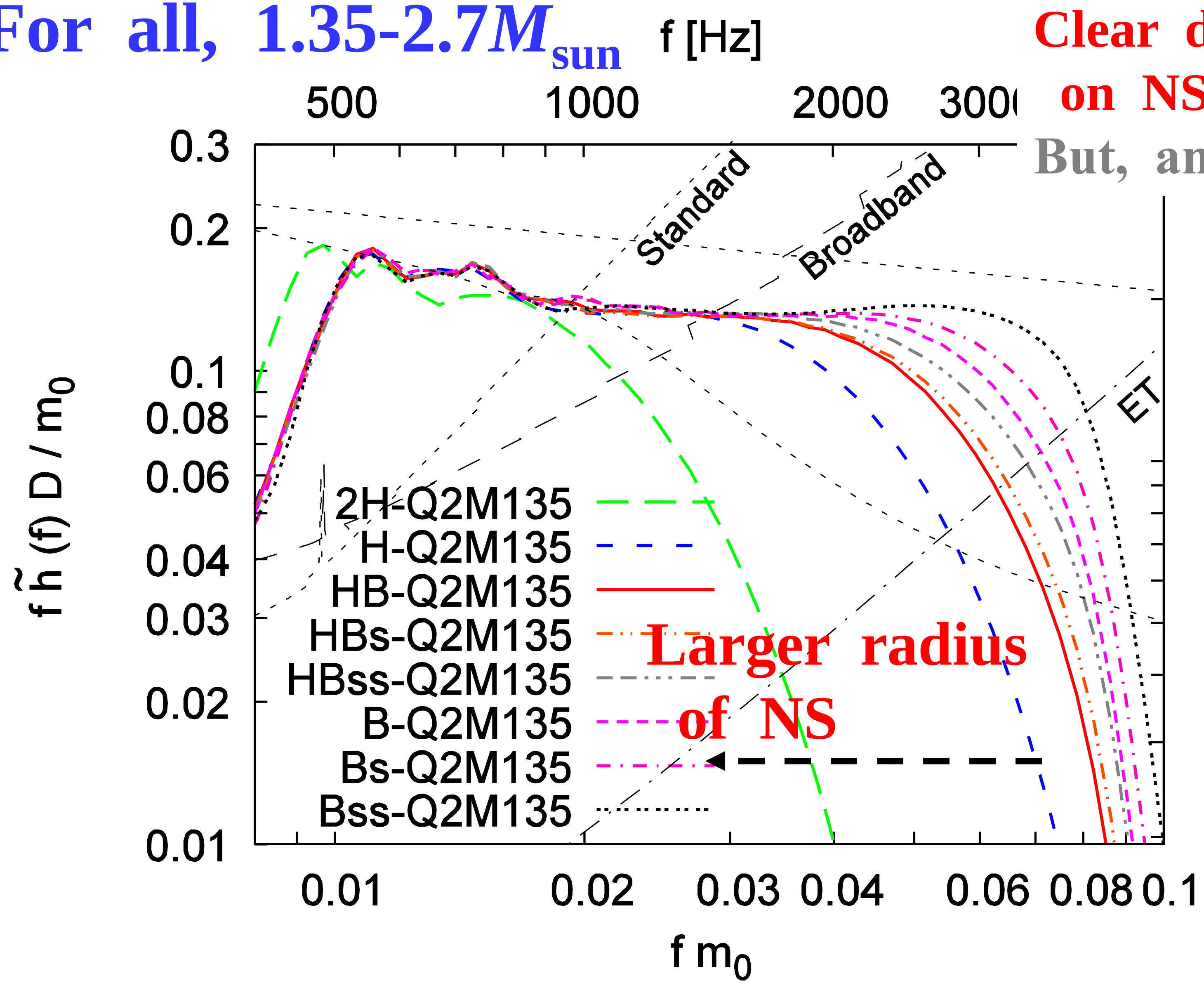
Green= Tayloy T4

BH-NS with piecewise polytrope (a=0)

For all, 1.35-2.7M_{sun}

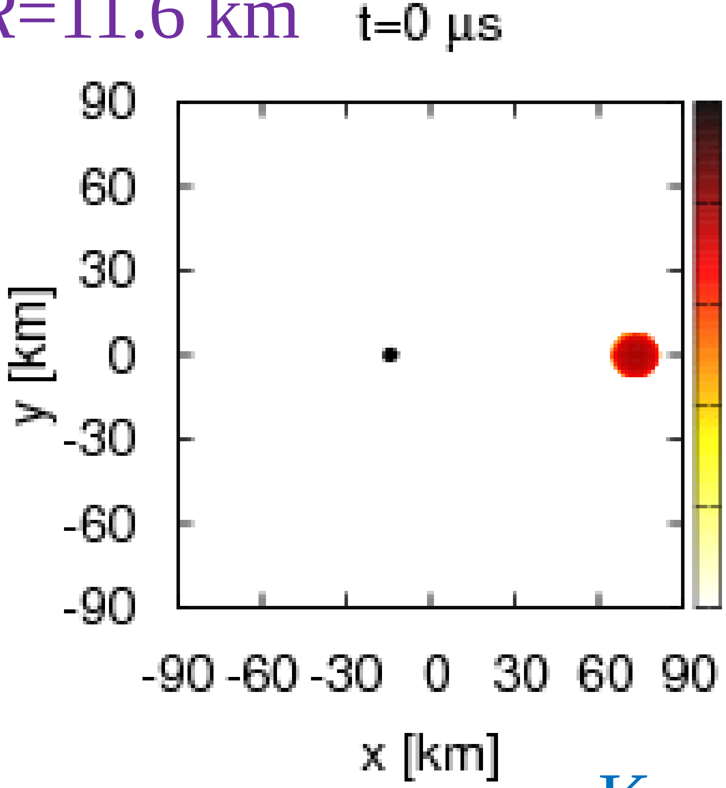
Clear dependence on NS radius

But, amp is low…

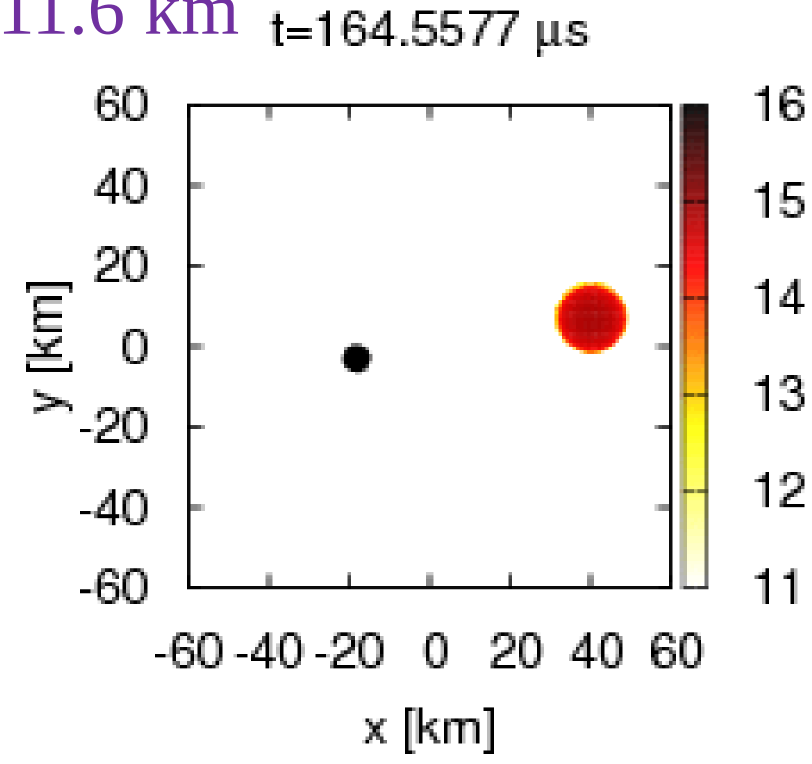


Spinning BH-NS; more promising

$M_{BH}=5.4M_{sun}$
$a=0.75, \ Q=4$
$M_{NS}=1.35M_{sun}$
$R=11.6$ km

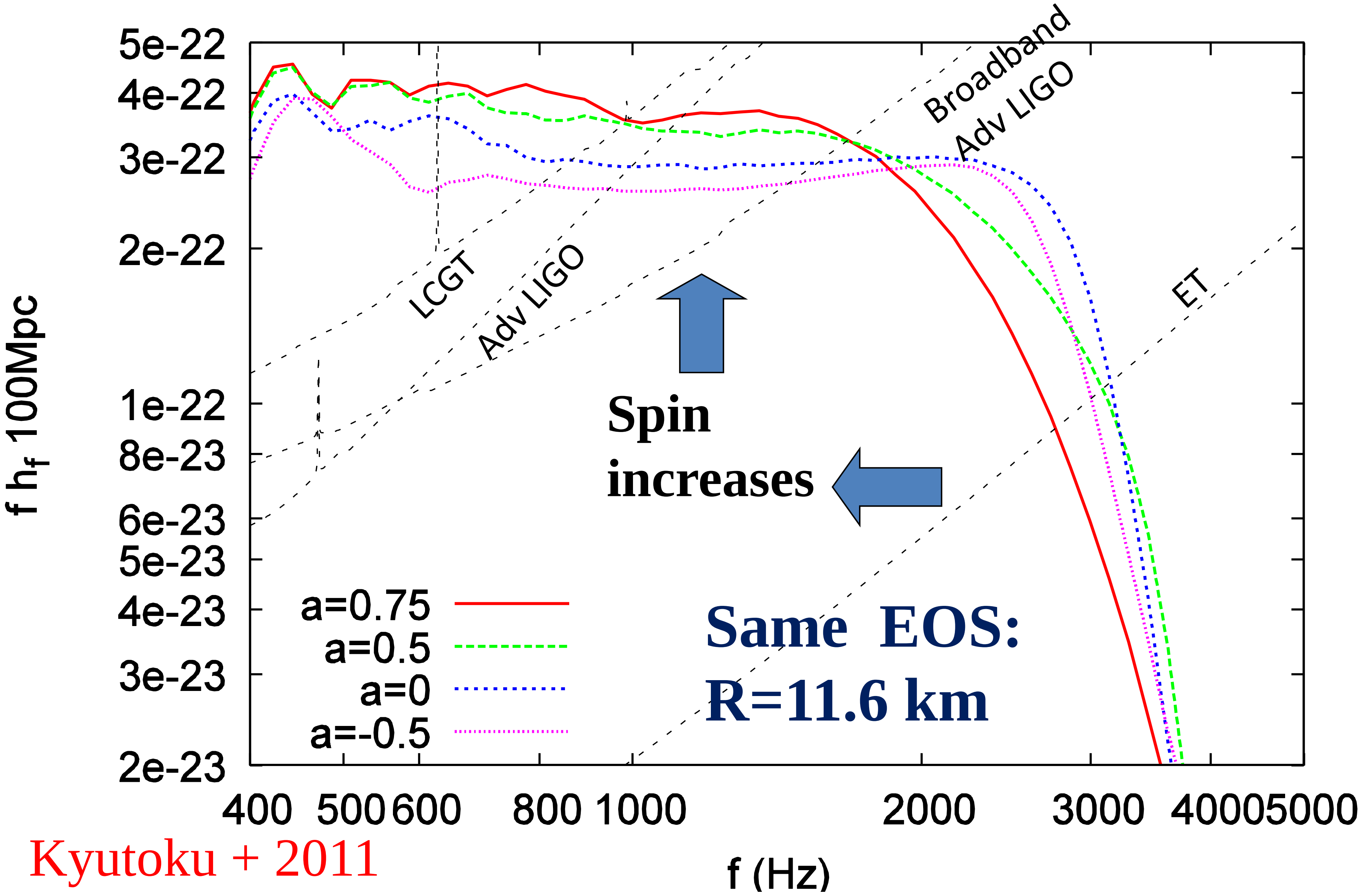


$M_{BH}=2.7M_{sun}$
$a=-0.5, \ Q=2$
$M_{NS}=1.35M_{sun}$
$R=11.6$ km



Kyutoku et al. 2011

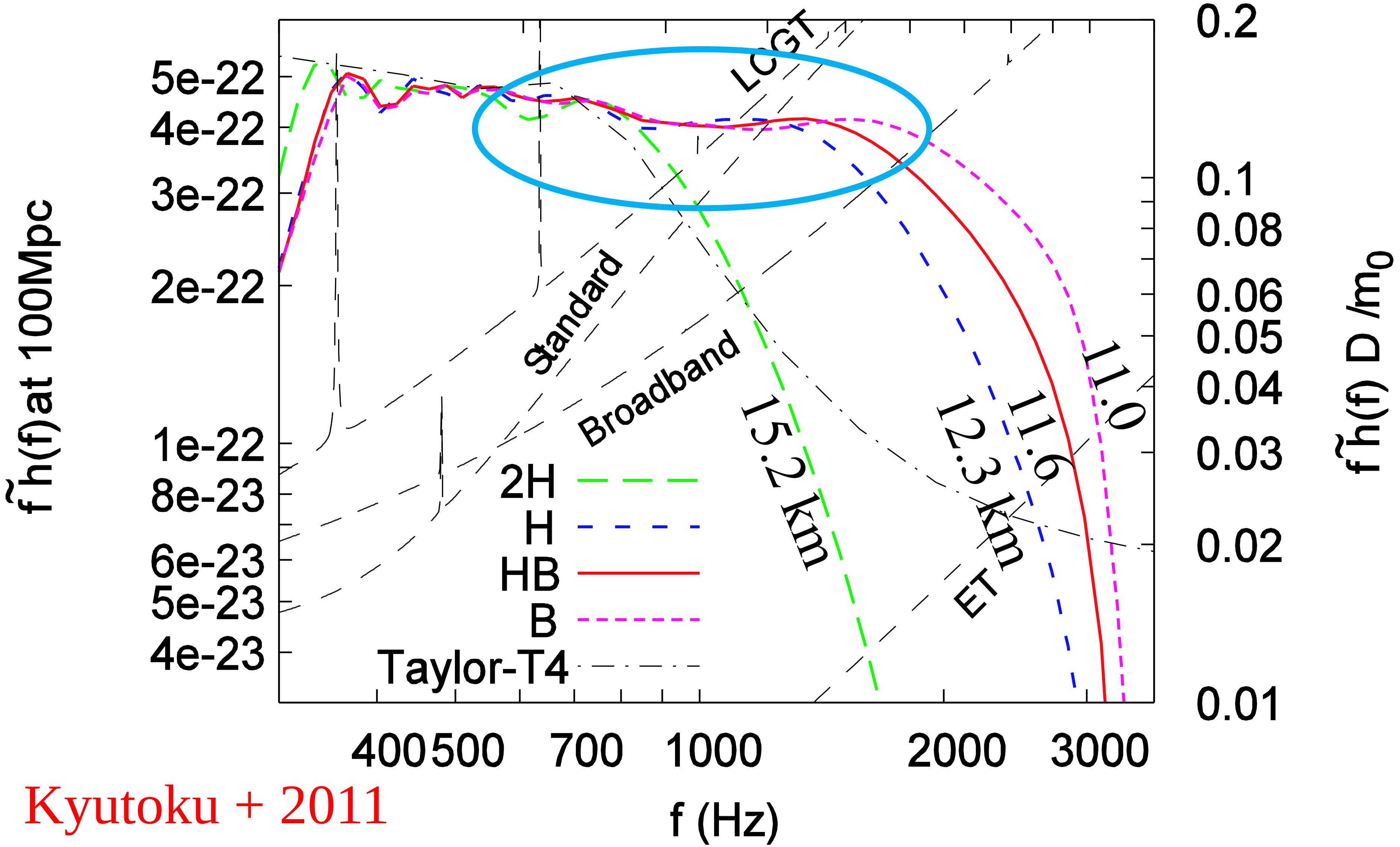
GW spectrum for Q=3, M_{NS}=1.35M_{sun}



Kyutoku + 2011

With BH spin & high-mass BH

For all, a=0.75 1.35-5.4M_{sun}



Kyutoku + 2011

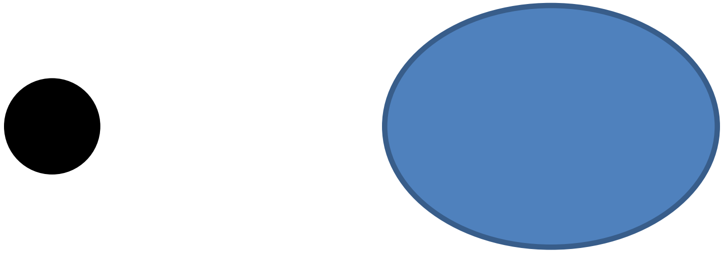
Summary

- **Late-inspiral waveforms of NSNS reflect NS EOS (although it is a small effect)**
- **GWs from HMNS reflect NS radius; Radius may be constrained with ~1 km error for small-distance events**
- **GWs at tidal disruption reflect NS radius; high-spin BH events could constrain EOS even by advLIGO/VIRGO/KAGRA**

Thanks

Imprint of EOS in tidal disruption

- Large NS Radius → tidal disruption at a distant orbit, *i.e.*, at a ***low frequency***



Assume the same mass

- Small NS Radius → tidal disruption at a ***high frequency***