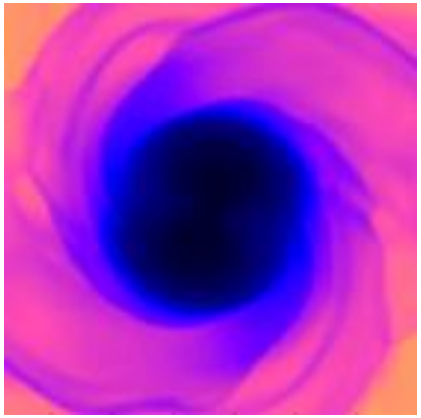
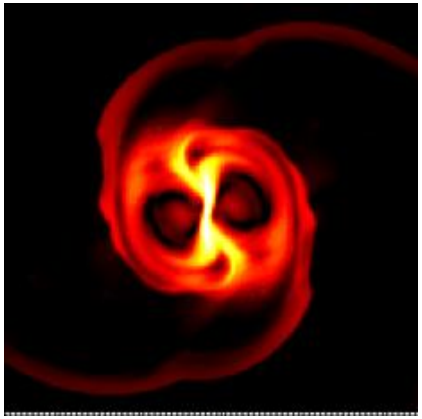




Merger of Binary Neutron Stars

Yuichiro Sekiguchi (YITP)

K. Kuchi, K. Kyutoku, M. Shibata, K. Hotokezaka

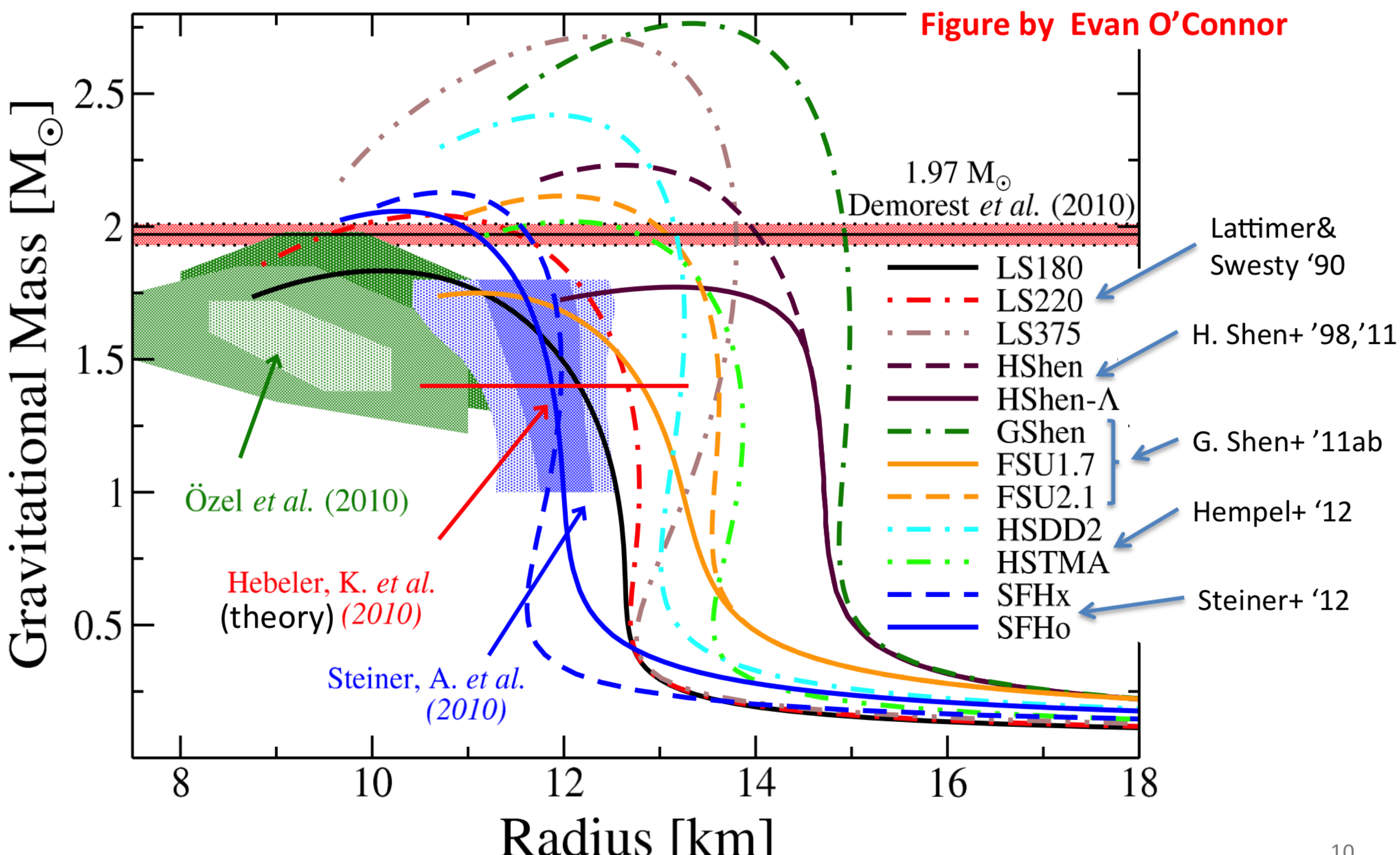
Introduction

- Merger of binary neutron star (BNS, NS-NS)
  - Theoretical candidate of Short GRBs
  - **Promising source of gravitational waves (GWs)**
  - **Laboratory for dense nuclear matter physics**
    - **Equation of state (EOS) ($P=P(\rho,Ye,T)$) of NS matter ($\rho \sim 10^{15}$ g/cm^3) could be constrained from GW observation**

EOS and NS structure (M-R relation)

Constraints on the Nuclear EOS (4)

- Application to available microphysical finite-temperature EOS:

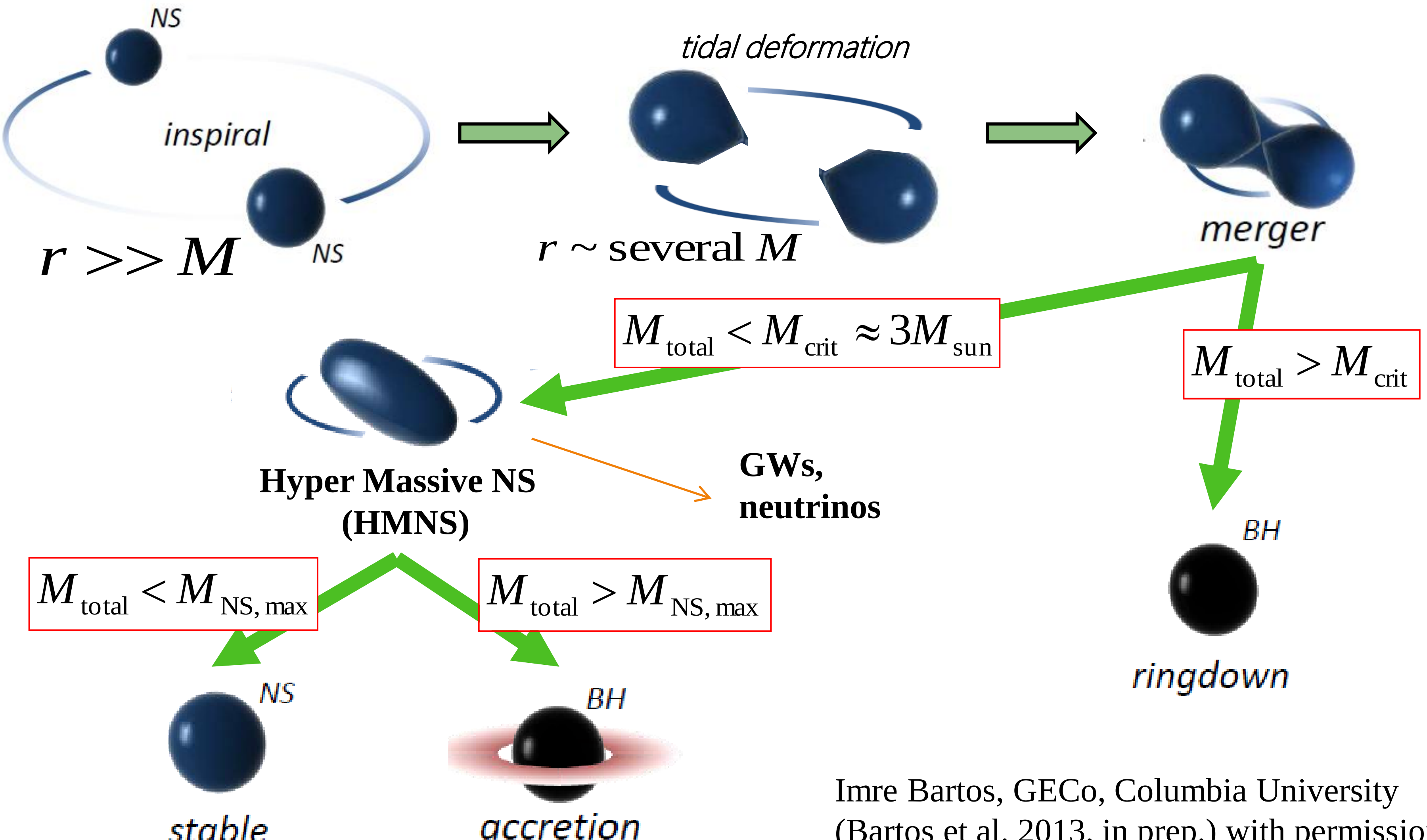


Gravitational waves

- Distortion of spacetime which propagates at the speed of light
- Generated by acceleration motion of mass (energy)
  - Cf. EM waves : generated by acceleration of charge
- **Binary of compact stars (NS-NS in this talk) is one of the most promising sources of GWs**
- Very little interaction with matters
  - Hard to detect/observe
  - GWs can carry information which is qualitatively different from those provided by EM signals
    - e.g. we can ‘see’ dense matter regions
  - ***Gravitational wave astronomy***

Evolution of NS-NS Binary

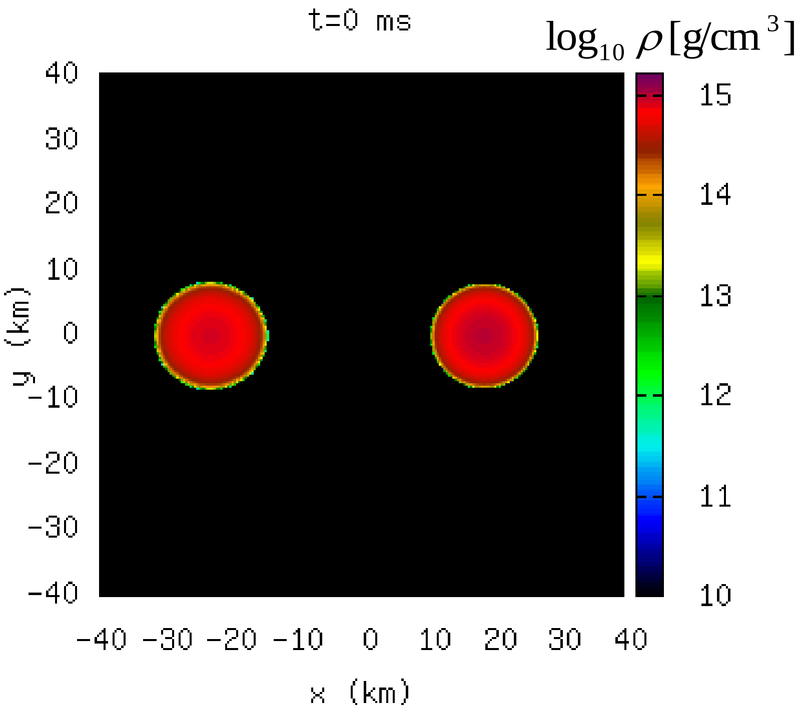
Shibata et al. 2005,2006

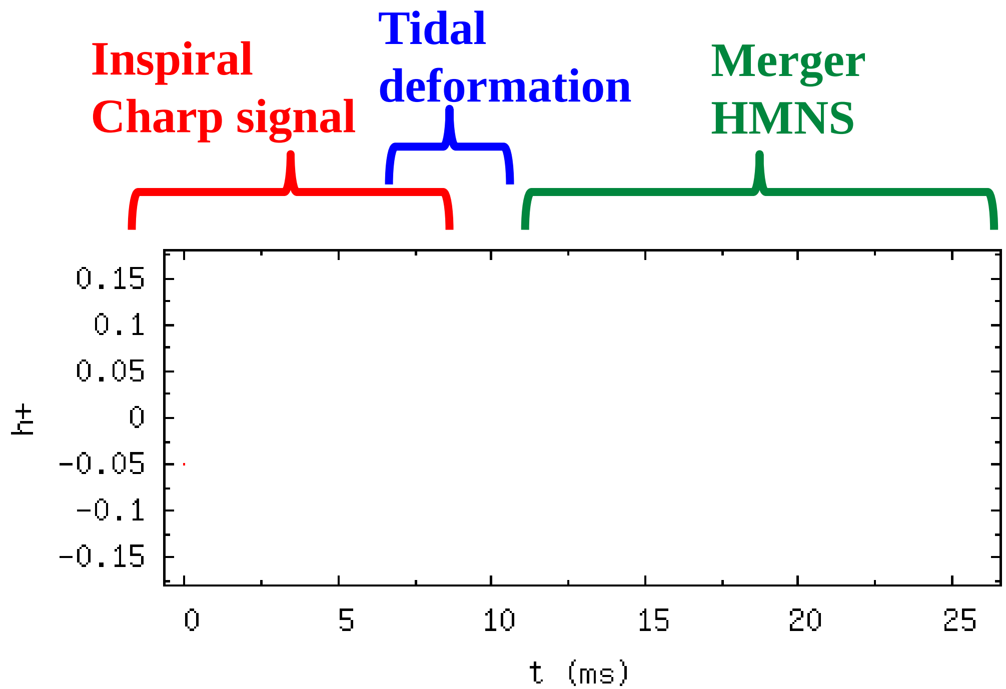


Imre Bartos, GECo, Columbia University
(Bartos et al. 2013, in prep.) with permission

GW from NS-NS (long lived HMNS)

NS(1.2Msolar)-NS(1.5Msolar) binary (APR EOS)

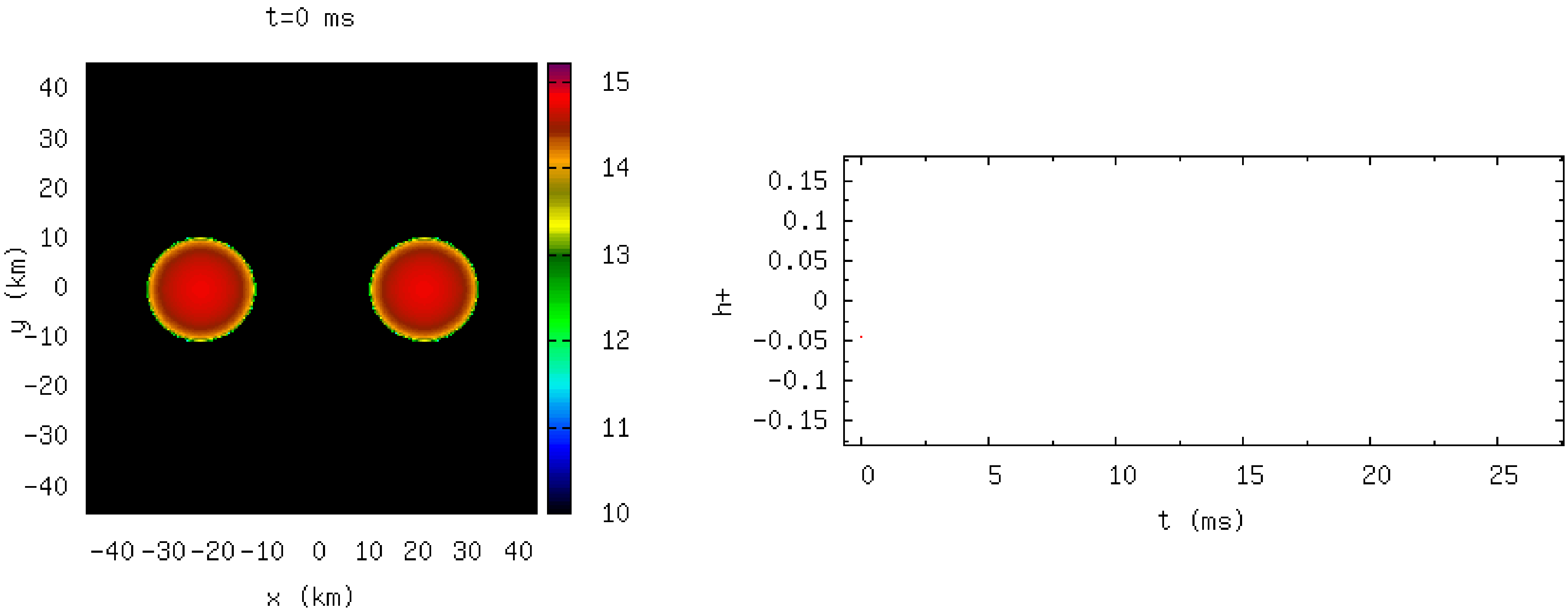




Animation by Hotokezaka

GW from NS-NS (HMNS ⇒ BH)

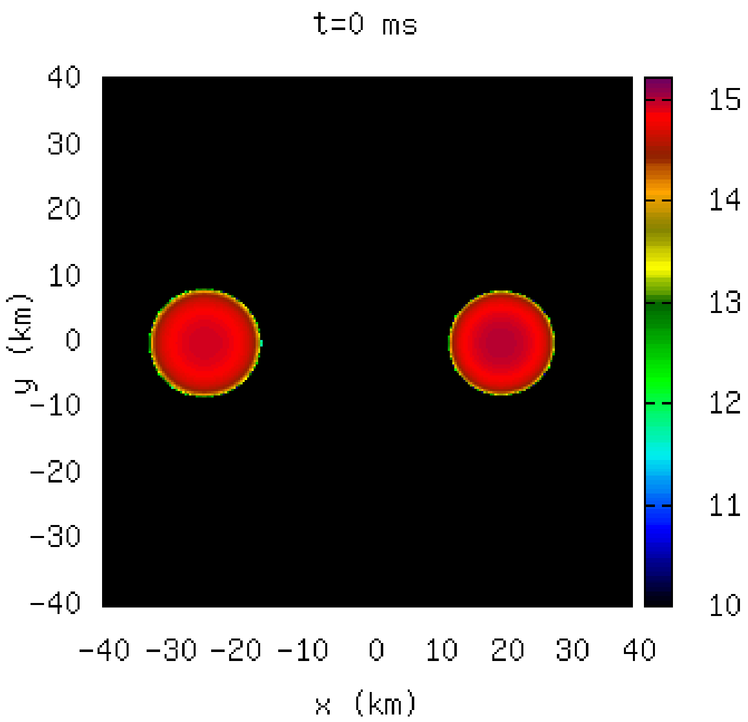
NS(1.4Msolar)-NS(1.4Msolar) binary (H4 EOS)

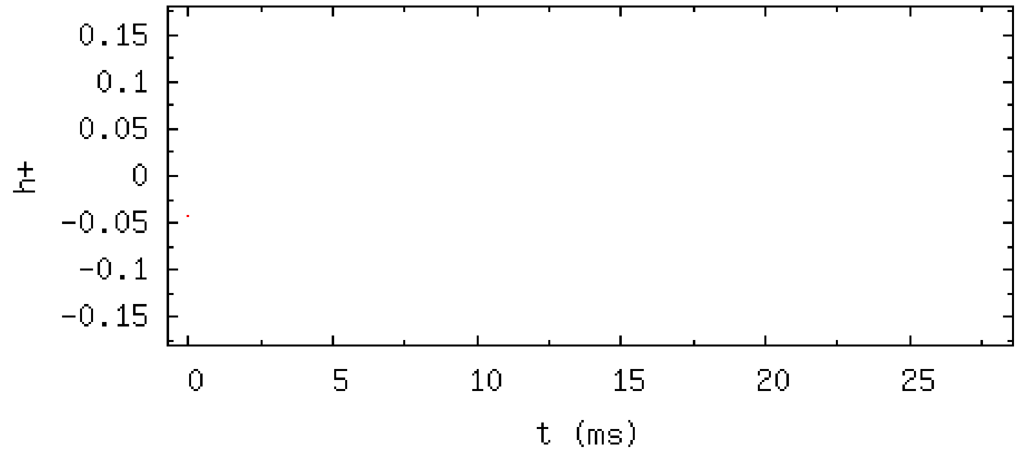


Animation by Hotokezaka

GW from NS-NS (Direct BH formation)

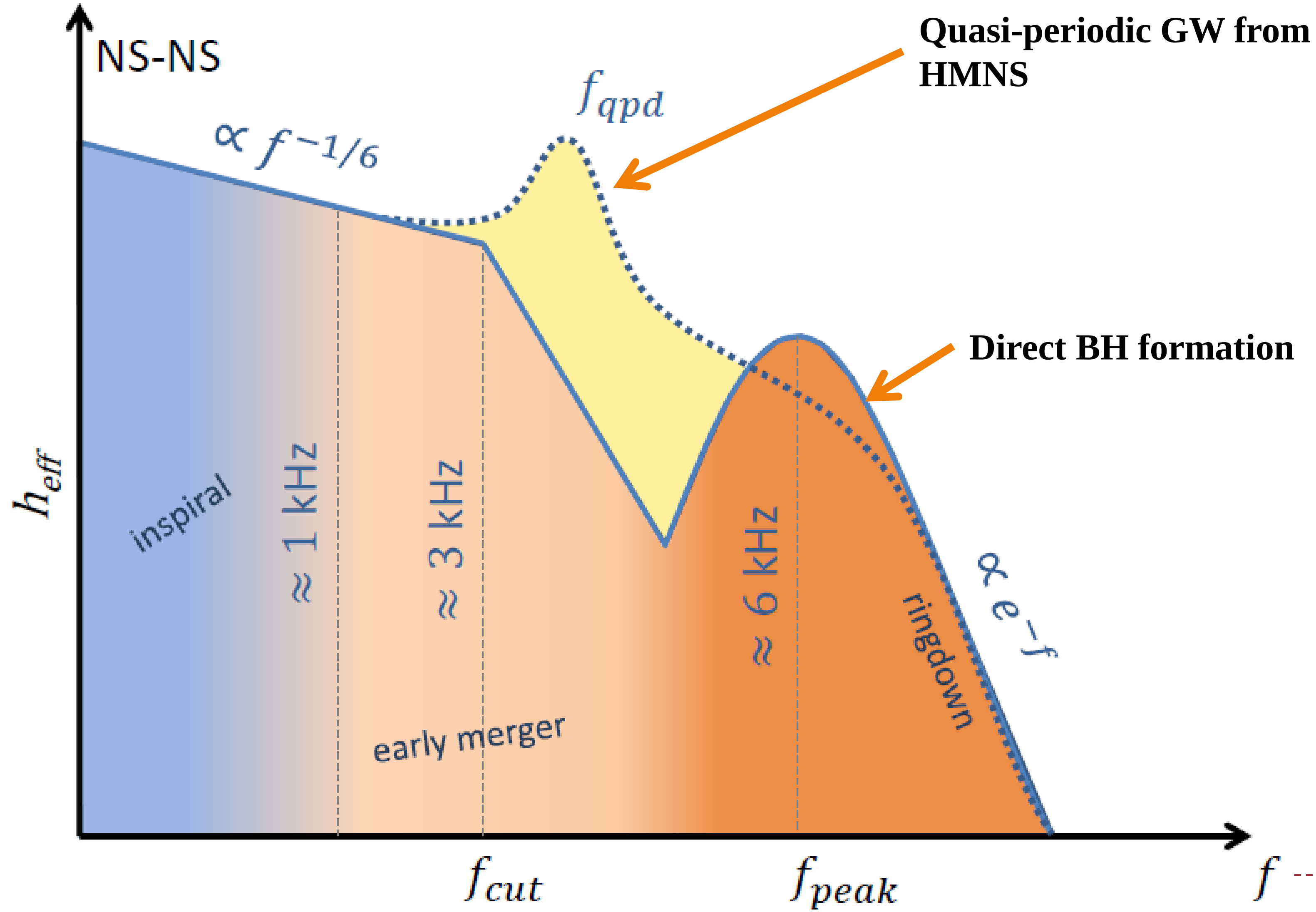
NS(1.3Msolar)-NS(1.6Msolar) binary (APR EOS)





Animation by Hotokezaka

Schematic picture of GW spectra



Exploring Dense matter physics by GW

Inspiral phase

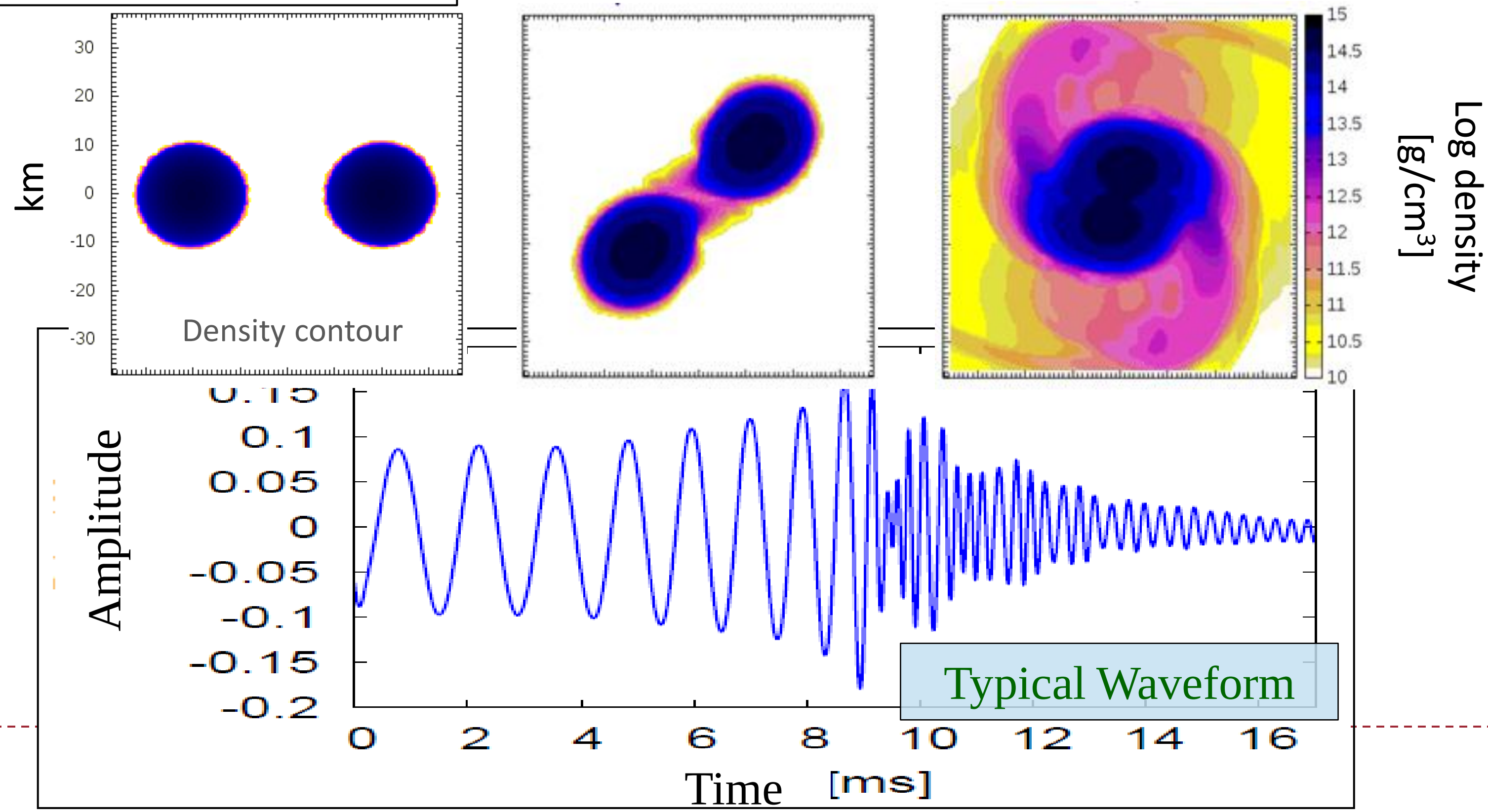
- Point particle approximation
- Information of orbits, neutron star mass etc.

Tidal deformation

- Finite size effect
- Information of NS radius (and EOS)

Merger and oscillation of HMNS

- Maximum mass, oscillation
- Information of NS radius and EOS



Exploring Dense matter physics by GW

Inspiral phase

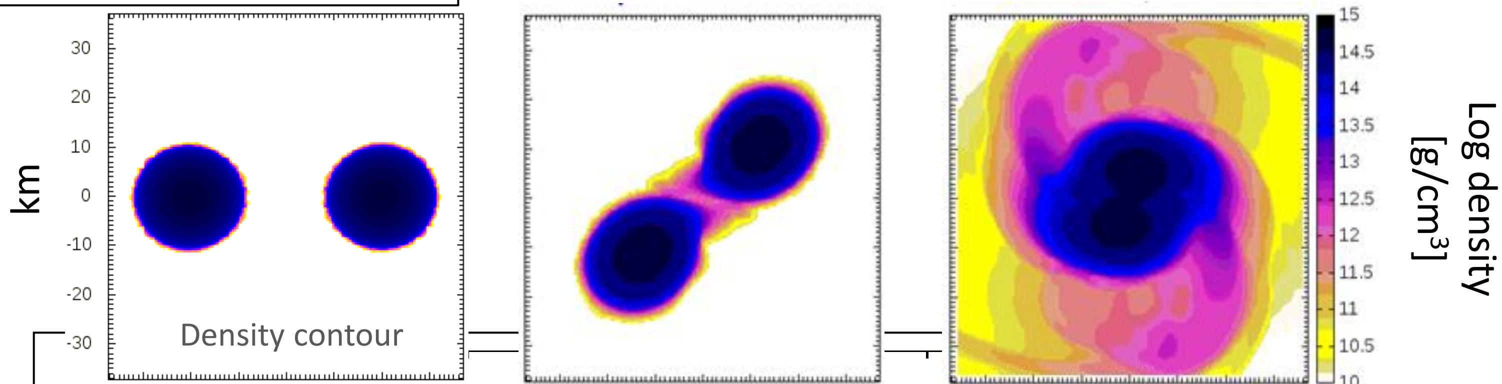
- Point particle approximation
- Information of orbits, neutron star mass etc.

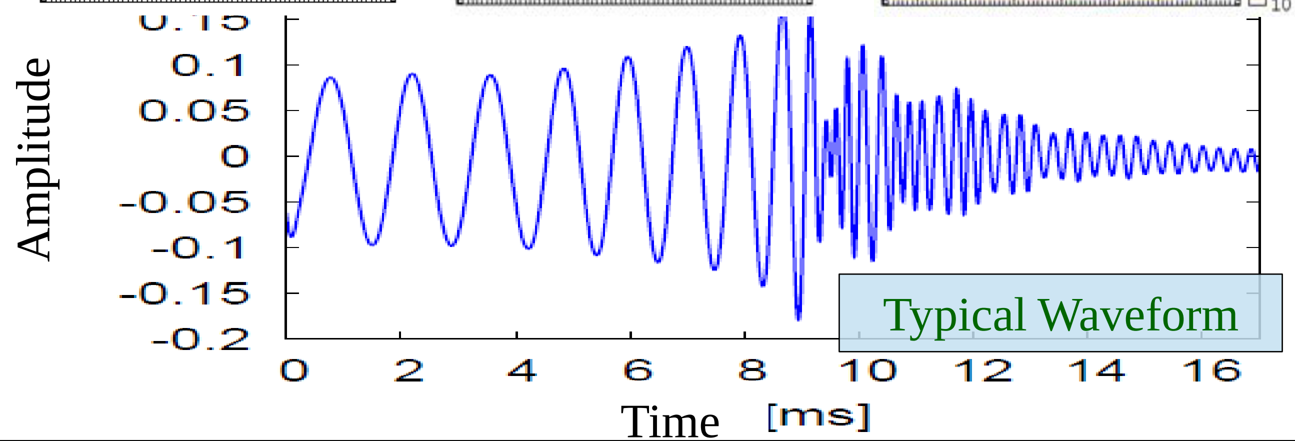
Tidal deformation

- **Finite size effect**
- **Information of equation of state**

Merger and oscillation

- Maximum mass, oscillation
- Information of equation of state

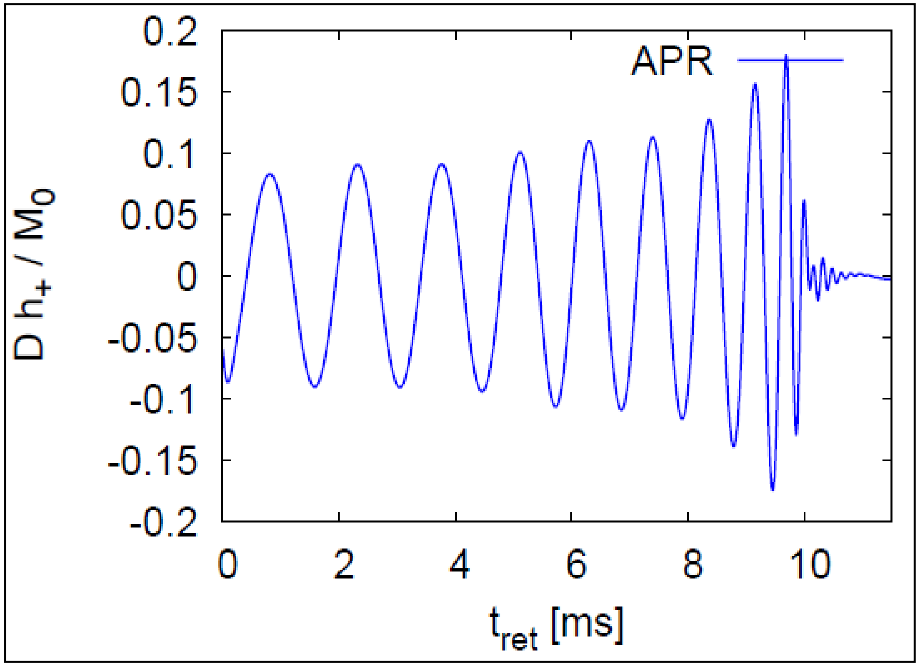


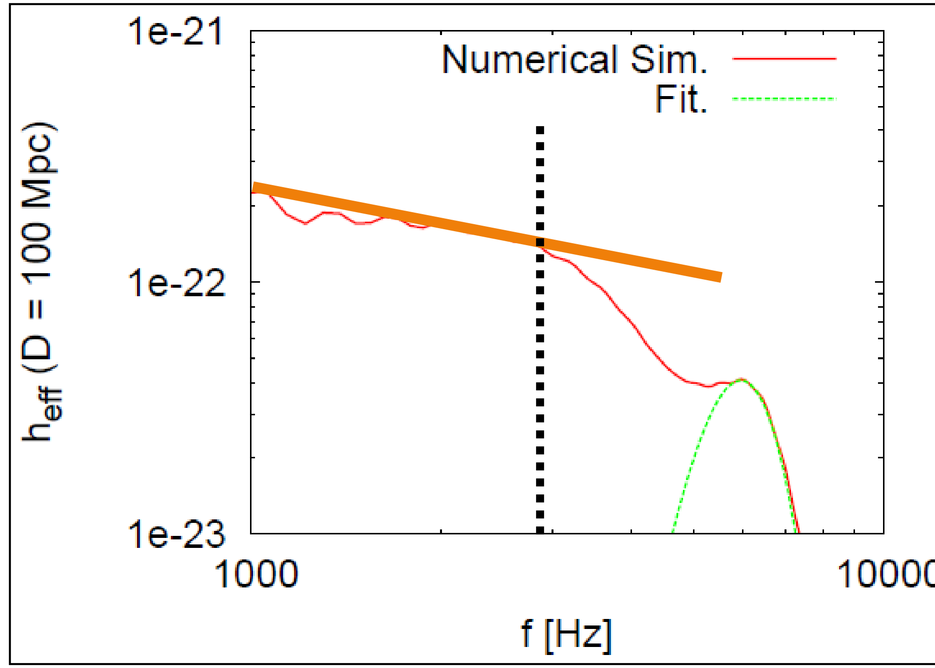


Exploring EOS by GW from tidal deformation

Kiuchi, YS et al. (2010) PRL 104 141101

- GWs in prompt BH formation





- No peak in spectra : we can distinguish from HMNS formation
  - Constraints on Maximum NS mass
- *At ～3kHz GWs show steep decline*

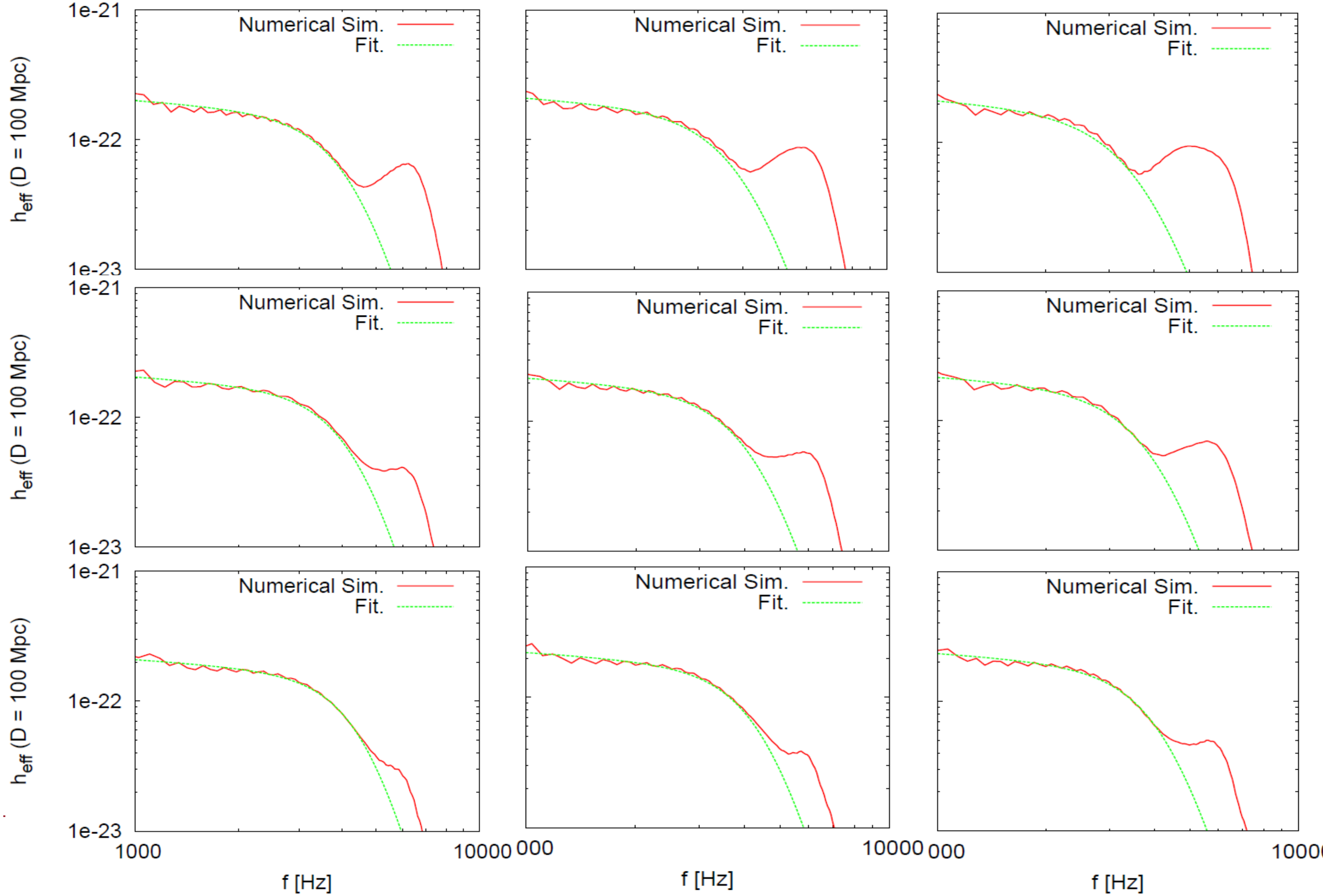
Gravitational Wave Spactra (APR)

$\eta = 1$ $\eta = 0.9$ $\eta = 0.8$

$2.9 M_{\text{solar}}$

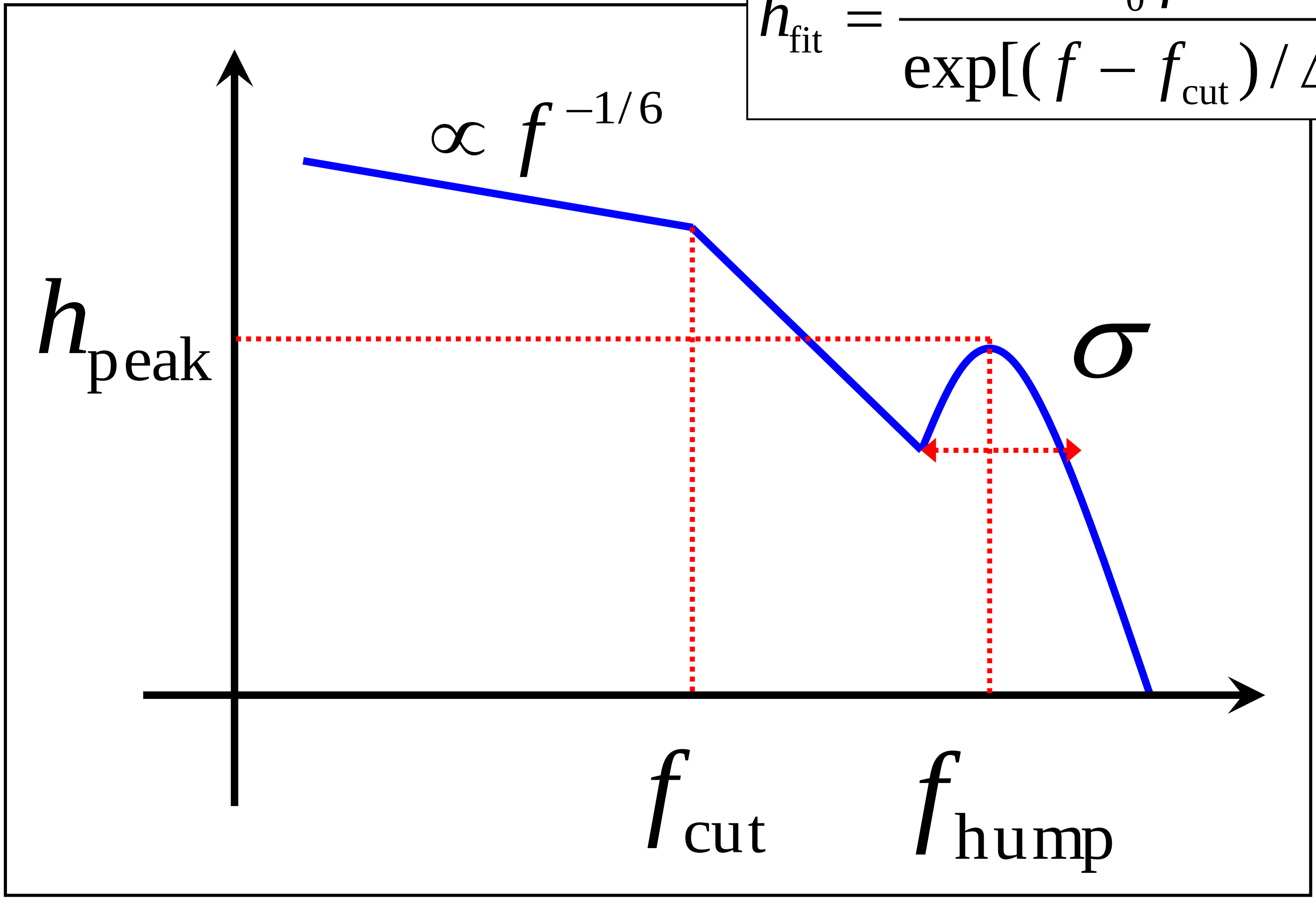
$3.0 M_{\text{solar}}$

$3.1 M_{\text{solar}}$



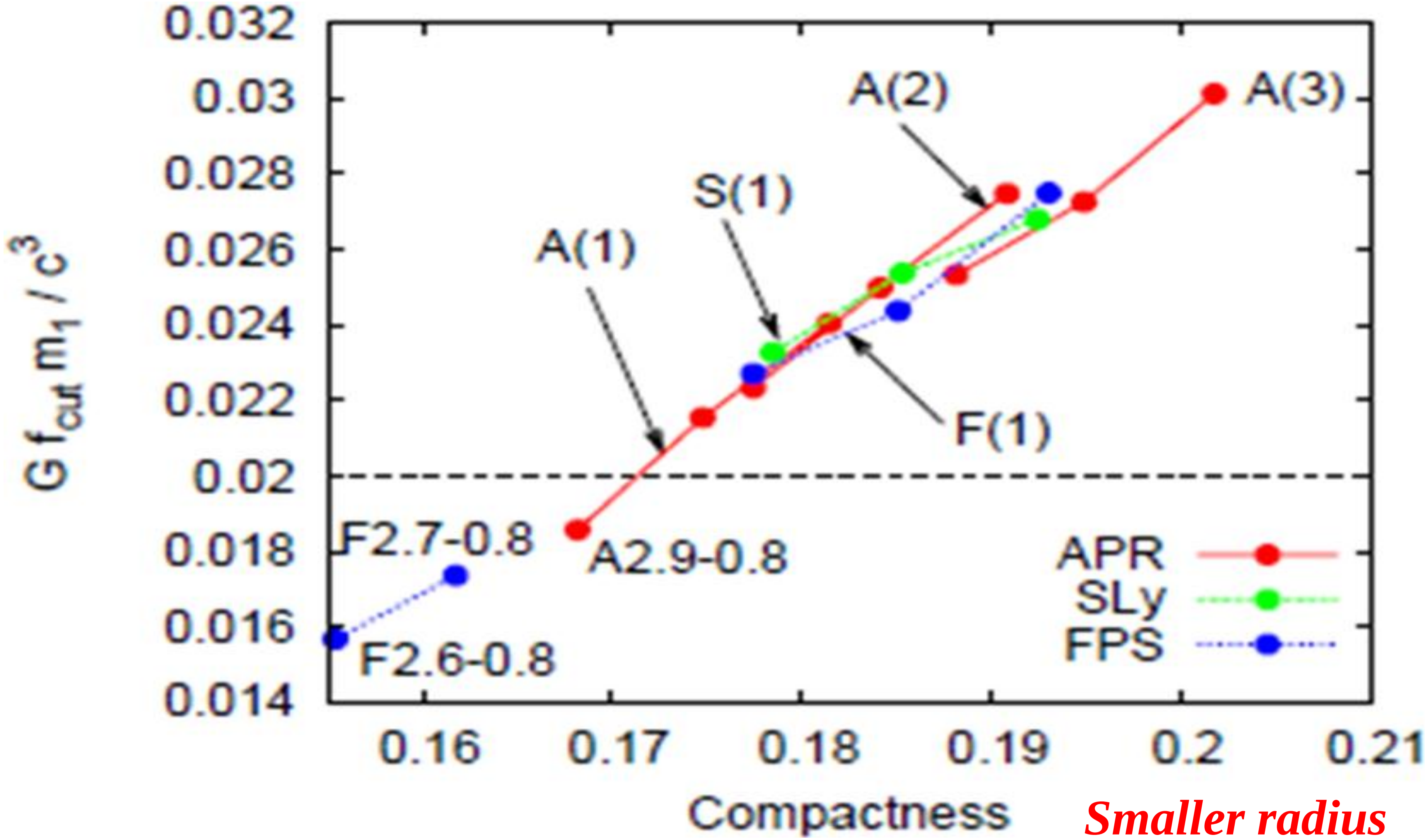
Modeling the spectra

$$h_{\mathrm{fit}} = \frac{h_0 f^{-1/6}}{\exp[(f - f_{\mathrm{cut}})/\Delta f]+1}$$



- We evaluate f_{cut} by performing simulations

Compactness (GM/Rc^2) – fcut relation

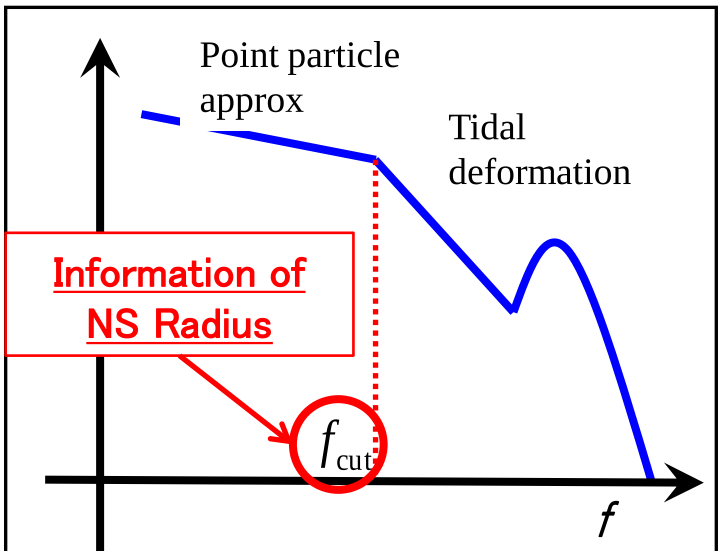


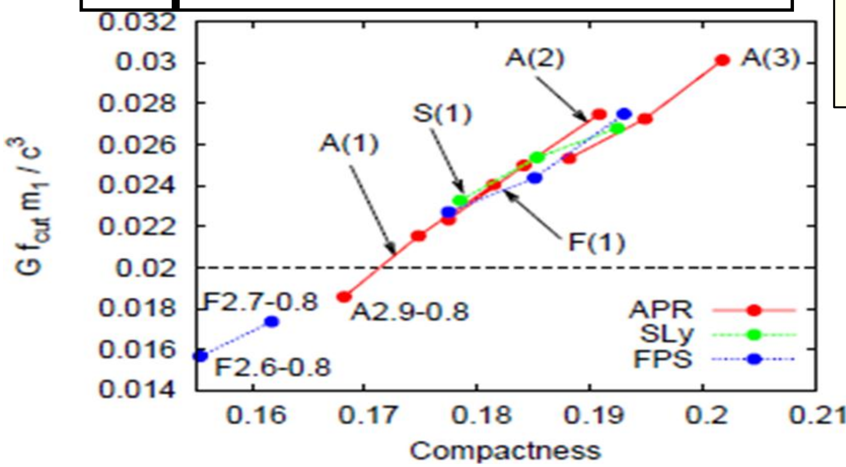
Smaller radius

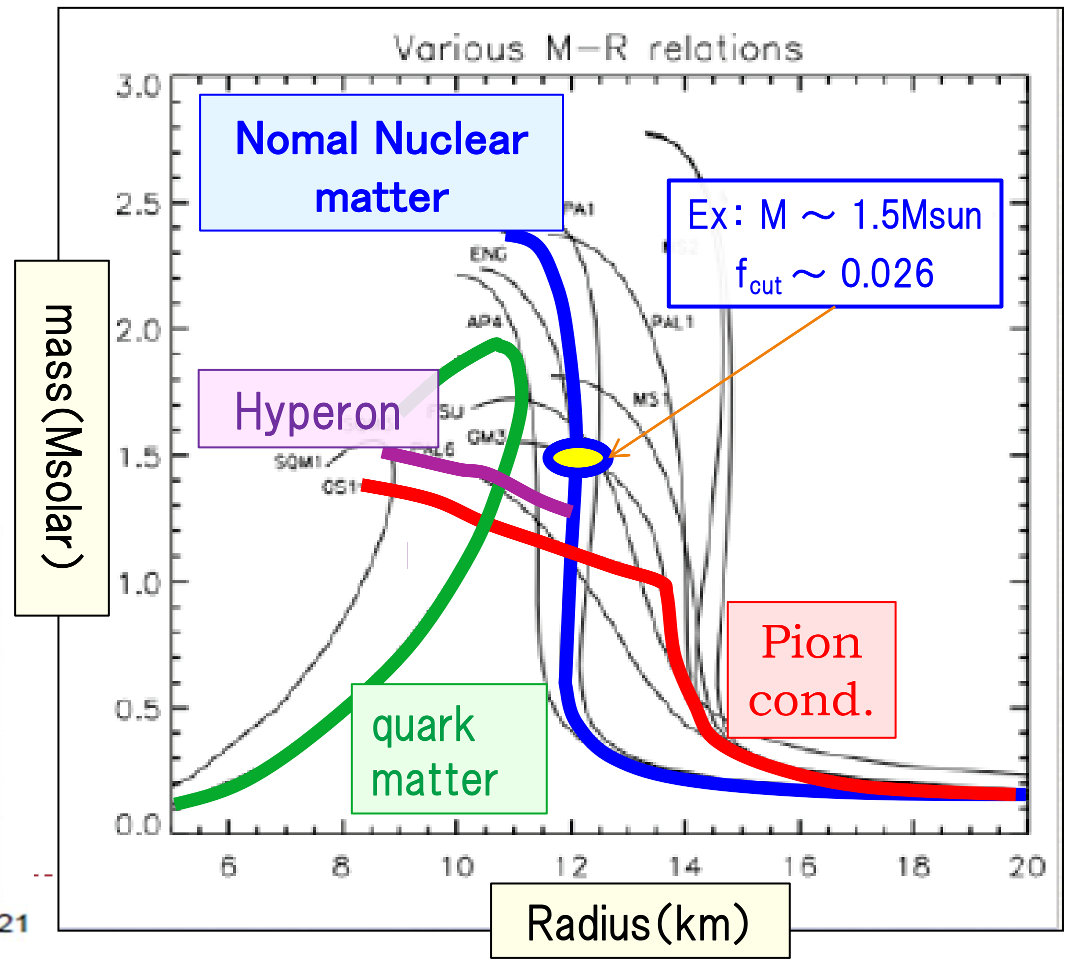
Exploring EOS by GW from tidal deformation

Kiuchi, YS et al. (2009, 2010)

- Mass: determined by analysis of inspiral GWs
- Radius: evaluated by tidal deformation (compactness = GM/Rc^2)







Exploring Dense matter physics by GW

Inspiral phase

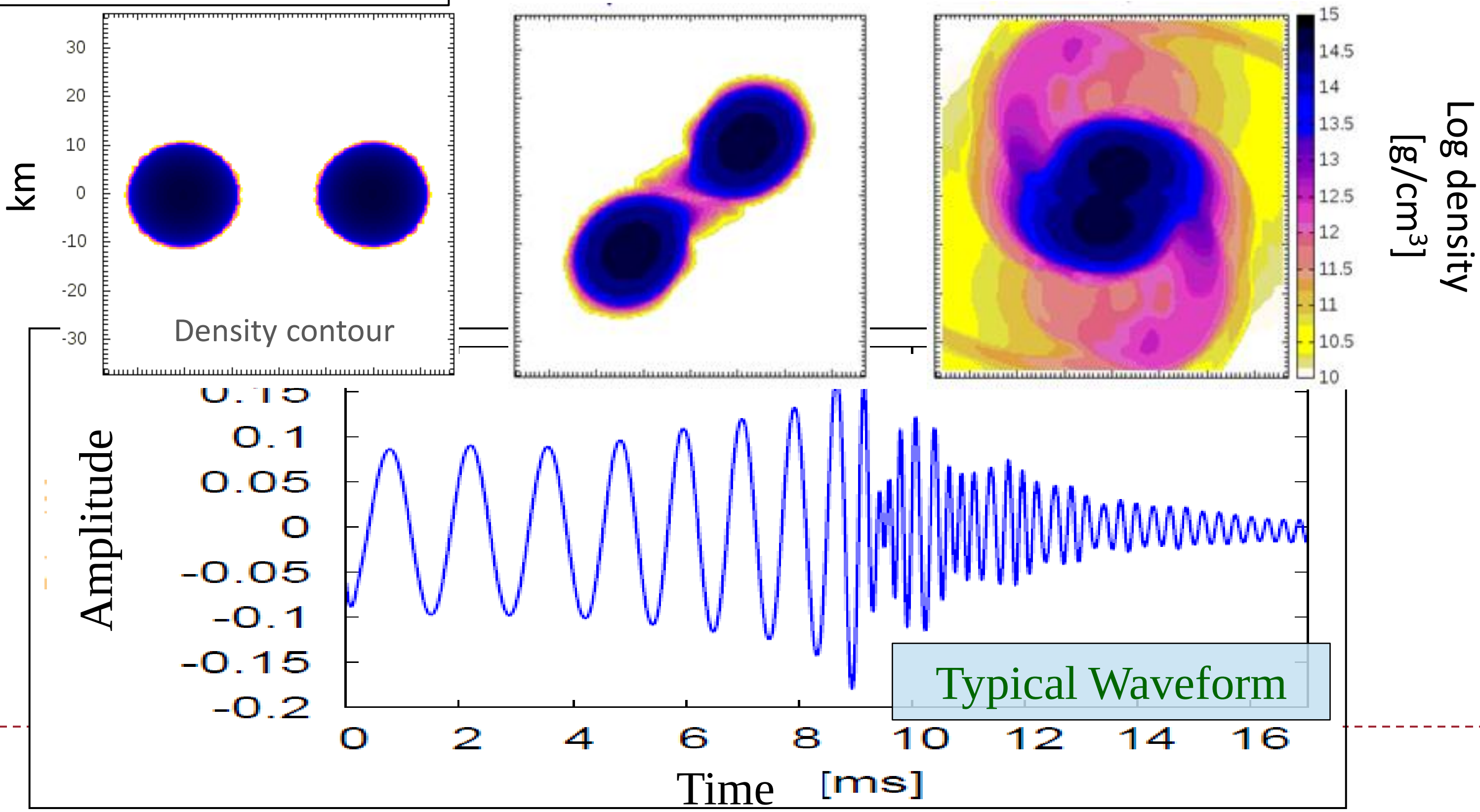
- Point particle approximation
- Information of orbits, neutron star mass etc.

Tidal deformation

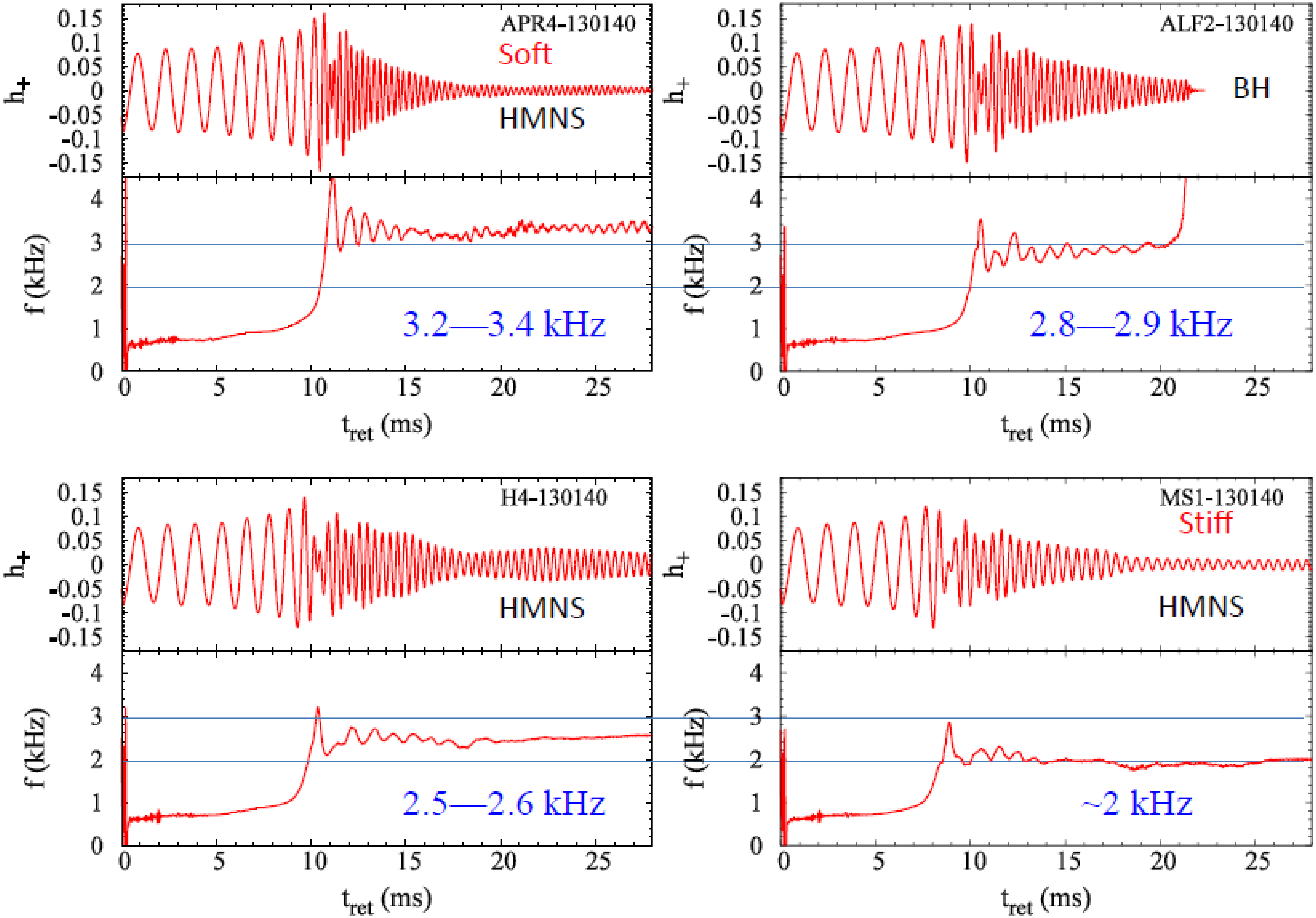
- Finite size effect
- Information of equation of state

Merger and oscillation of HMNS

- **Maximum mass, oscillation**
- **Information of equation of state**

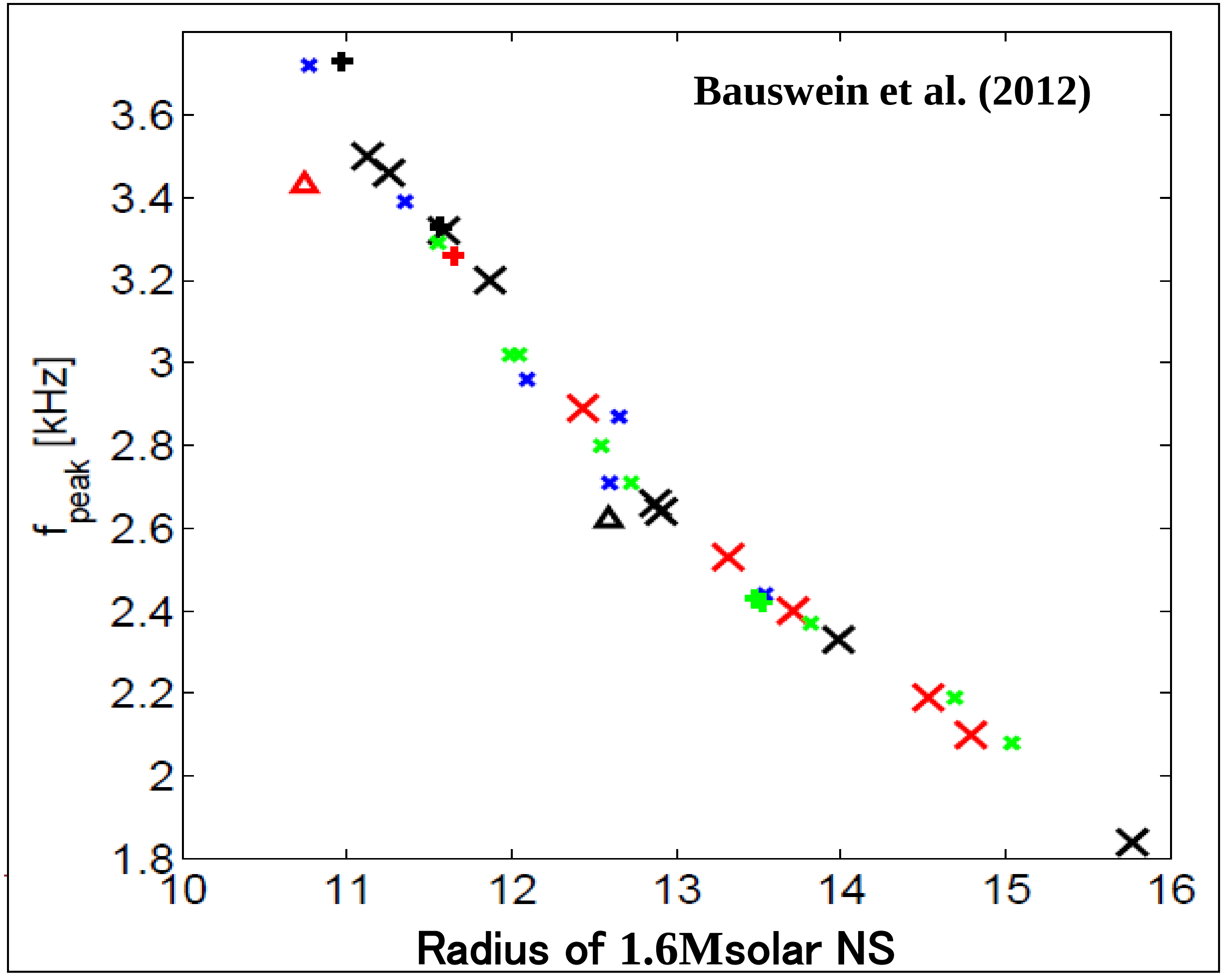


M_1=1.3, M_2=1.4M_{sun}



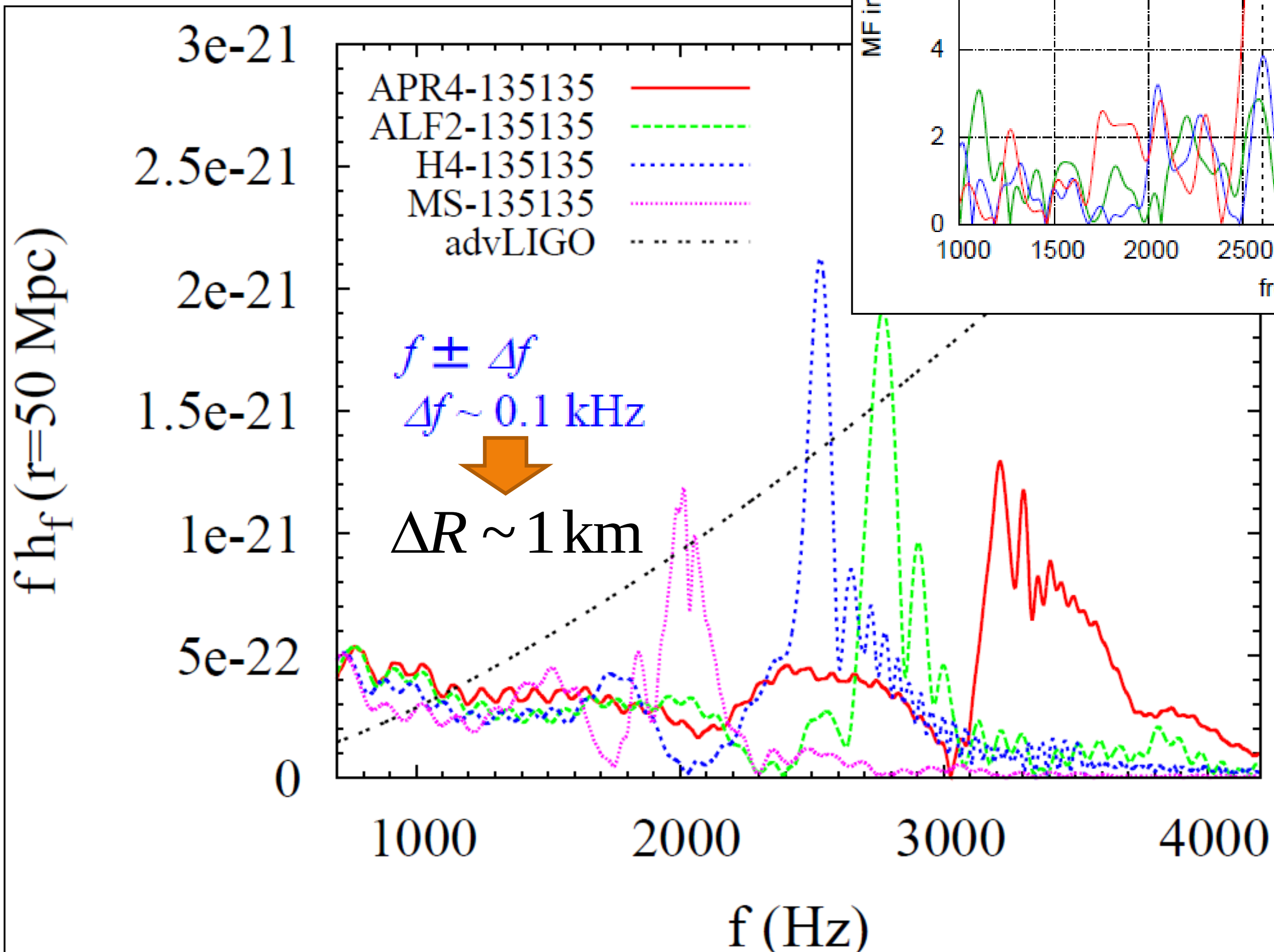
Properties of GWs from HMNS

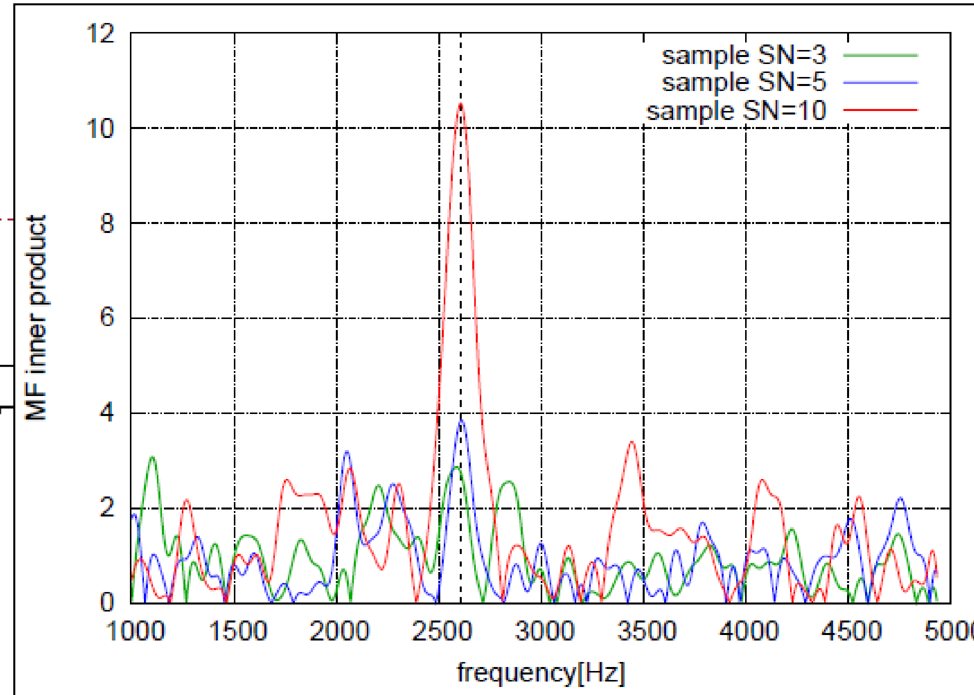
- GW frequency depends strongly on EOS
- The frequency has correlation with NS radius and stiffness of EOS
  - Bauswein et al. 2012
  - Hotokezaka et al. 2012



GW spectra

Events within 20Mpc can be detected

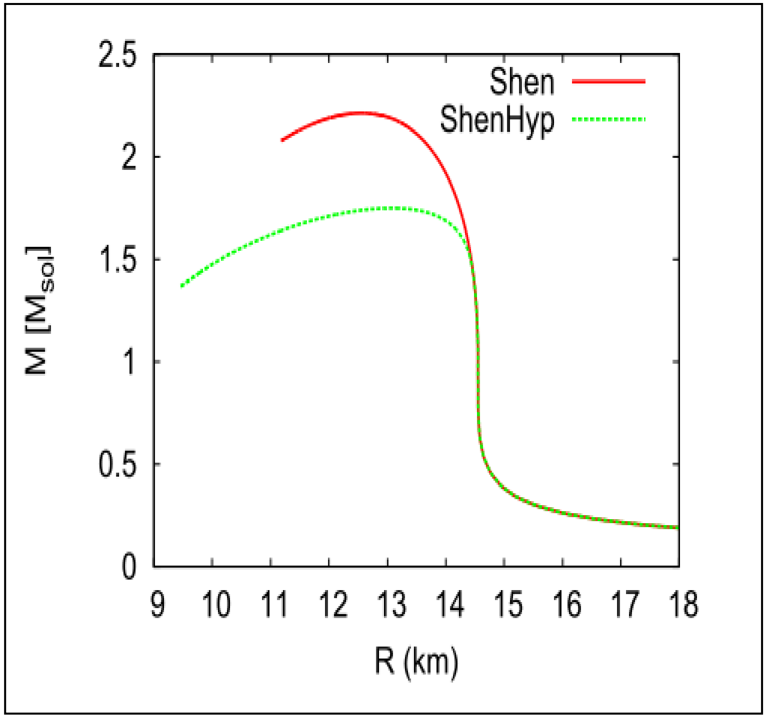


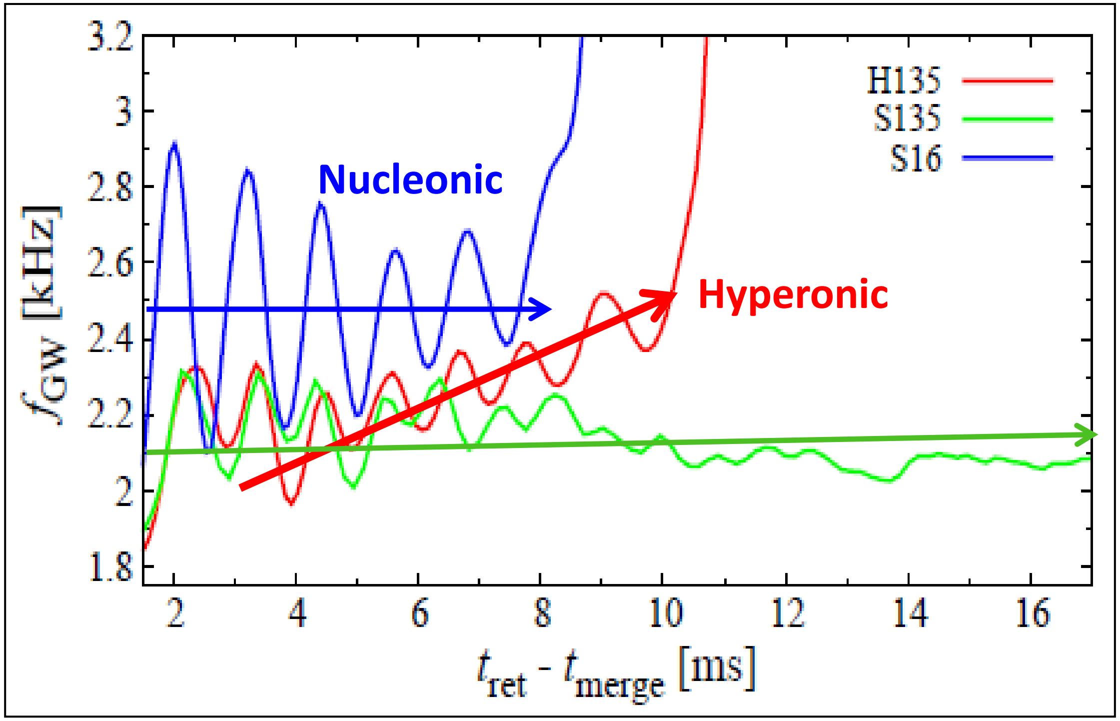


Peak frequency could be reproduced for events within a few Mpc

Frequency Shift due to Hyperon

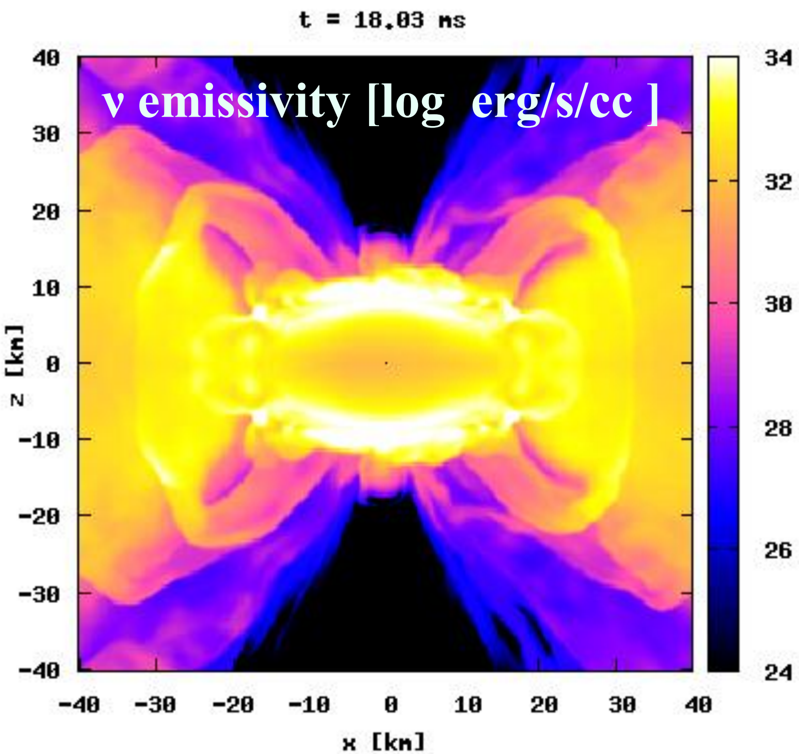
- Dynamics of HMNS formed after the merger
  - **Nucleonic** : HMNS shrinks by angular momentum loss in a long GW timescale
  - **Hyperonic** : GW emission ⇒ HMNS shrinks ⇒ More Hyperons appear ⇒ EOS becomes softer ⇒ HMNS shrinks more ⇒ ....
  - **As a result, the characteristic frequency of GW increases with time**
    - Providing potential way to tell existence of hyperons (exotic particles)

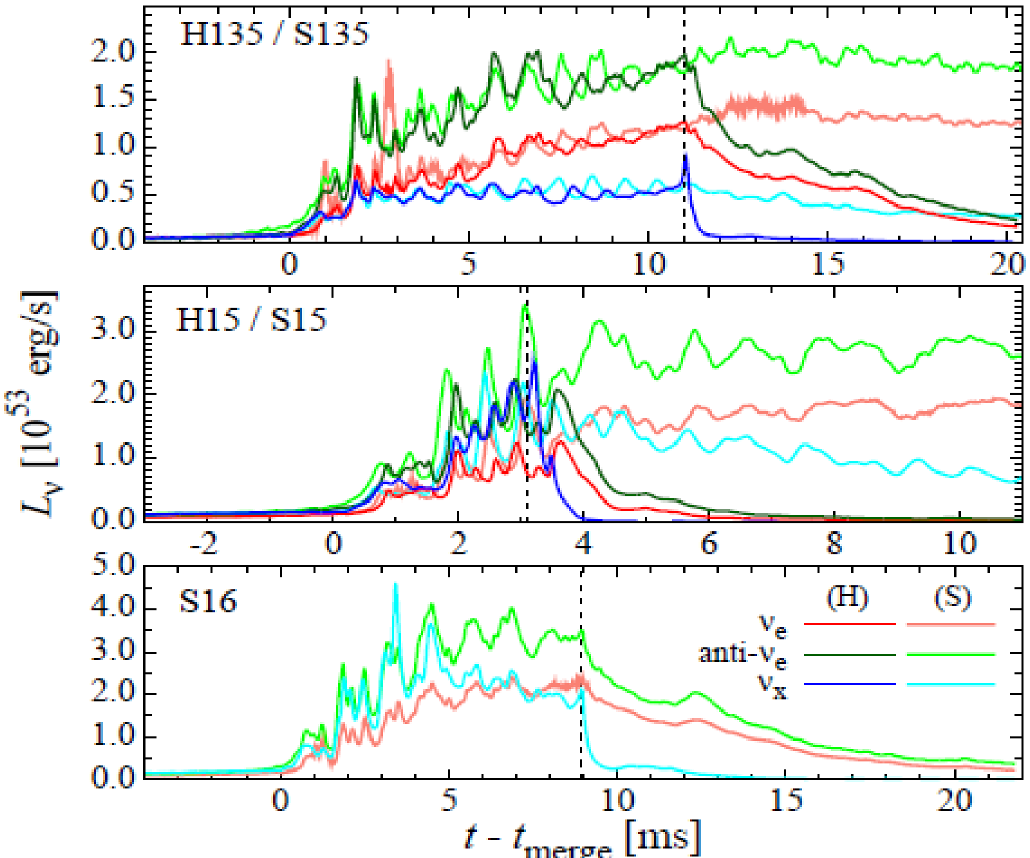




Neutrino signal

- There is no difference except for the duration until the BH formation
  - **Effects of hyperons are significant in the central region where neutrino diffusion time is very long, and swallowed into BH**
- **Difficult to tell the existence of hyperons using the neutrino signals alone**





Summary

- Late-inspiral gravitational waveform of NS-NS reflect EOS of NS matter through tidal effects
- GWs from HMNS show characteristic frequency which reflect the radius of NS: NS radius may be constrained with ~ 1km error for nearby events
- Existence of hyperons are imprinted in GWs
  - The characteristic GW frequency increases in time
  - Providing potential way to tell existence of hyperons by GW obs.

Current status of Numerical relativity simulation in Kyoto

- Einstein's equations: Shibata-Nakamura (BSSN) formalism
  - 4^{th} order finite difference in space, 4^{th} order Runge-Kutta time evolution
  - Gauge conditions : 1+log slicing, dynamical shift
- GR Hydrodynamics with ***GR Leakage Scheme*** (Sekiguchi 2010)
  - EOM of Neutrinos
  - Lepton Conservations
  - Weak Interactions
    - $e^{\pm}$ captures, pair annihilation, plasmon decay, Bremsstrahlung
  - A detailed neutrino opacities
  - BH excision technique
  - High-resolution-shock-capturing scheme
  - (Fixed) Mesh refinement technique

$$\boxed{\nabla_a T_b^a = -Q_b^{(\text{leak})}, \quad \nabla_a T_b^{a\ (\nu,\text{stream})} = Q_b^{(\text{leak})}}$$

$$\frac{d\,Ye}{dt} = -\gamma_{\text{e}-\text{cap}} + \gamma_{\text{e}+\text{cap}}$$

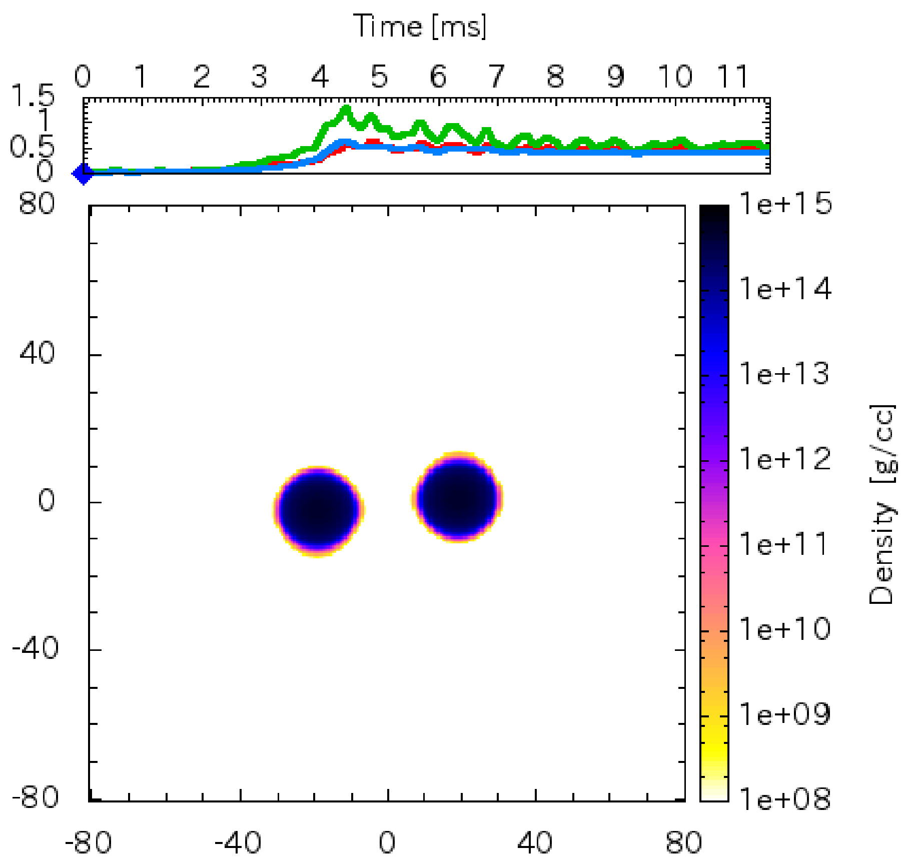
$$\frac{d\,Y\nu_{\text{e}}}{dt} = \gamma_{\text{e}-\text{cap}} + \gamma_{\text{pair}} + \gamma_{\text{plasmon}} + \gamma_{\text{Brems}} - \gamma_{\nu_{\text{e}}\text{leak}}$$

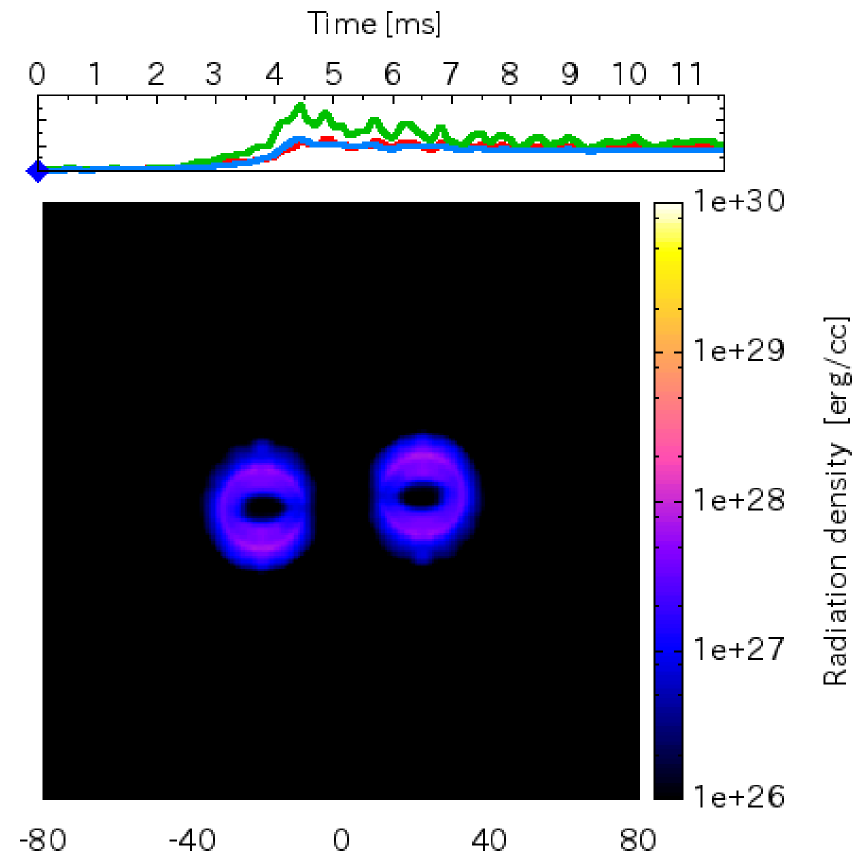
$$\frac{d\,Y\bar{\nu}_{\text{e}}}{dt} = \gamma_{\text{e}+\text{cap}} + \gamma_{\text{pair}} + \gamma_{\text{plasmon}} + \gamma_{\text{Brems}} - \gamma_{\bar{\nu}_{\text{e}}\text{leak}}$$

$$\frac{d\,Y\nu_{\text{x}}}{dt} = \gamma_{\text{pair}} + \gamma_{\text{plasmon}} + \gamma_{\text{Brems}} - \gamma_{\nu_{\text{x}}\text{leak}}$$

Recent update

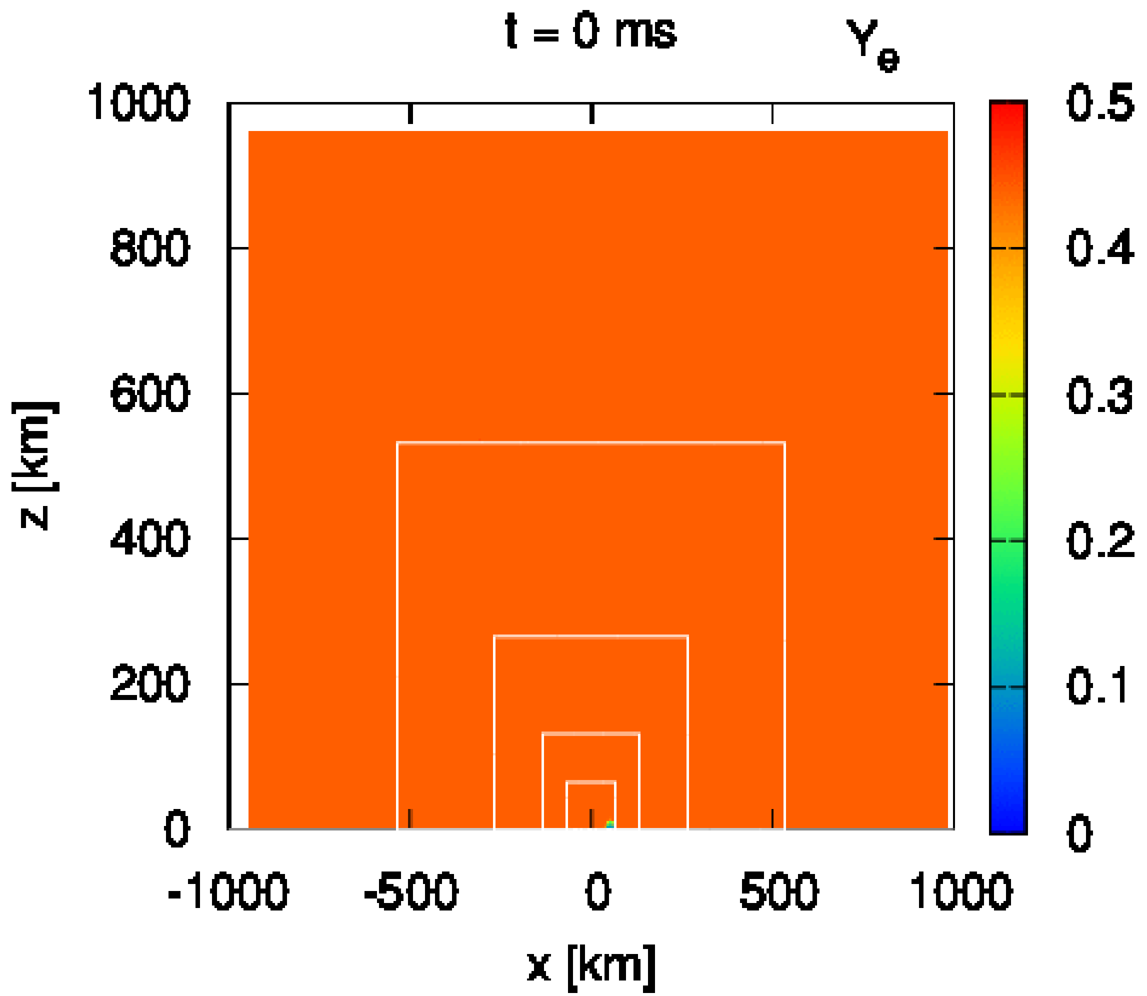
- Solving neutrino transfer equation by Moment scheme (Shibata et al. 2011) with a closure relation
  - Neutrino heating effect can be treated
  - ⇒ Short GRB





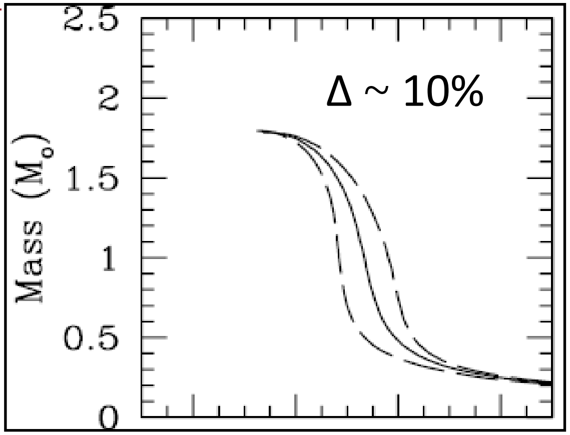
Future study: r-process in the ejecta

- Neutron rich materials are ejected in the compact binary merger: such materials are potential site of r–process element generation

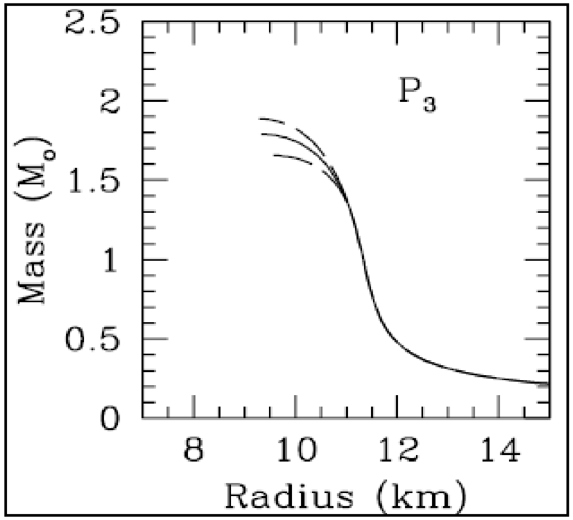


Why GWs from NS-NS are interesting ?

- **One of most promising source of GWs**
  - Next generation interferometer can see ~ 350Mpc
  - Expected event rate : more than 10/yr
- **Unique window to 'see' inside dense matters**
  - Very small cross section with matter
- **Dynamical response of dense matter**
  - By contrast with static, isolated neutron star
- **Multiple information of equation of state**
  - **Tidal deformation (radius) : relatively low density**
  - Maximum mass : most high density
  - Oscillation :
- **Less uncertain parameters**
  - Inspiral waveform provides information of mass
  - Mass should be determined in isolated neutron star
- **Simple in a complementary sense**
  - Essentially quadrupole formula
  - By contrast with optical observation



- Radius is sensitive to relatively low density parts



- Maximum mass depends on most dense parts