Quark and Compact Stars (QCS2014), KIAA, Peking Univ. Oct. 20-22, 2014

Exploring physics of dense matter using GWs from BNS merger

Yuichiro Sekiguchi

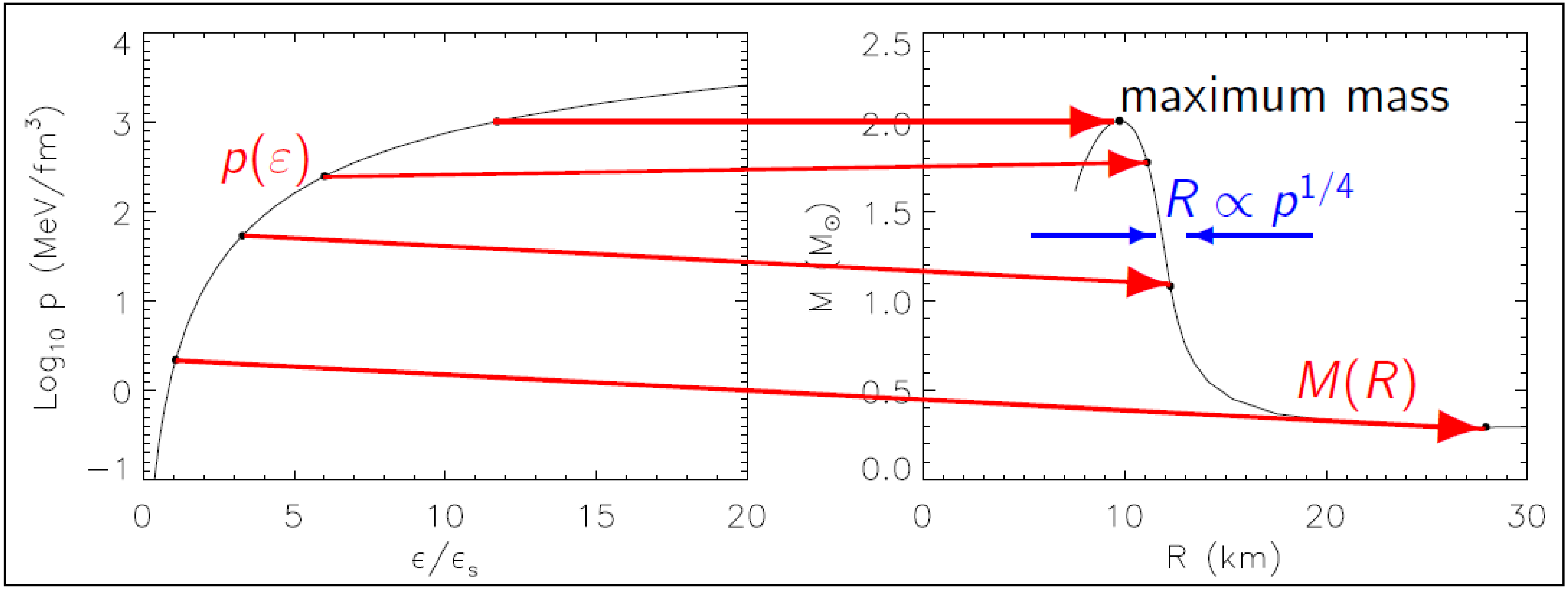
(Yukawa Institute for Theoretical Physics, Kyoto University)

Constraining EOS by NS observations

- One-to-one correspondence between Equation of state (EOS) ⇔ neutron star (NS) mass-radius relation
  - *Lindblom (1992) ApJ 398 569*
- Heaviest NS mass (~2Msolar: ***Demorest et al. (2010) Nature 467 1081***)

Tolman-Oppenheimer-Volkov equations

$$\frac{dP}{dr} = -\frac{G}{c^4}\frac{(mc^2 + 4\pi pr^3)(\varepsilon + P)}{r^2}\left(1 - \frac{2GM}{c^2 r}\right)^{-1}, \qquad \frac{dm}{dr} = 4\pi\frac{\varepsilon}{c^2}r^2$$

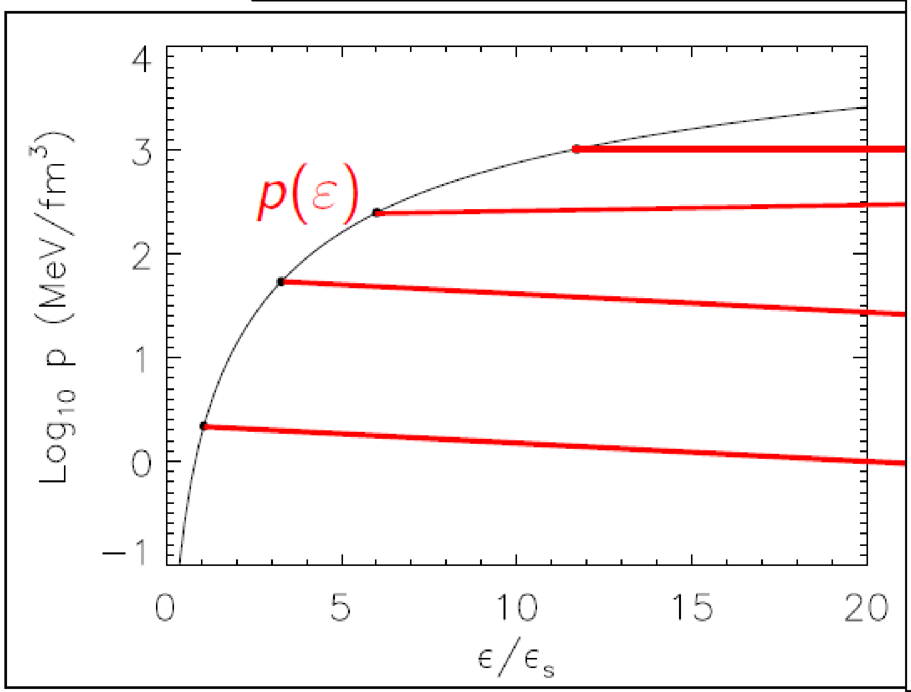


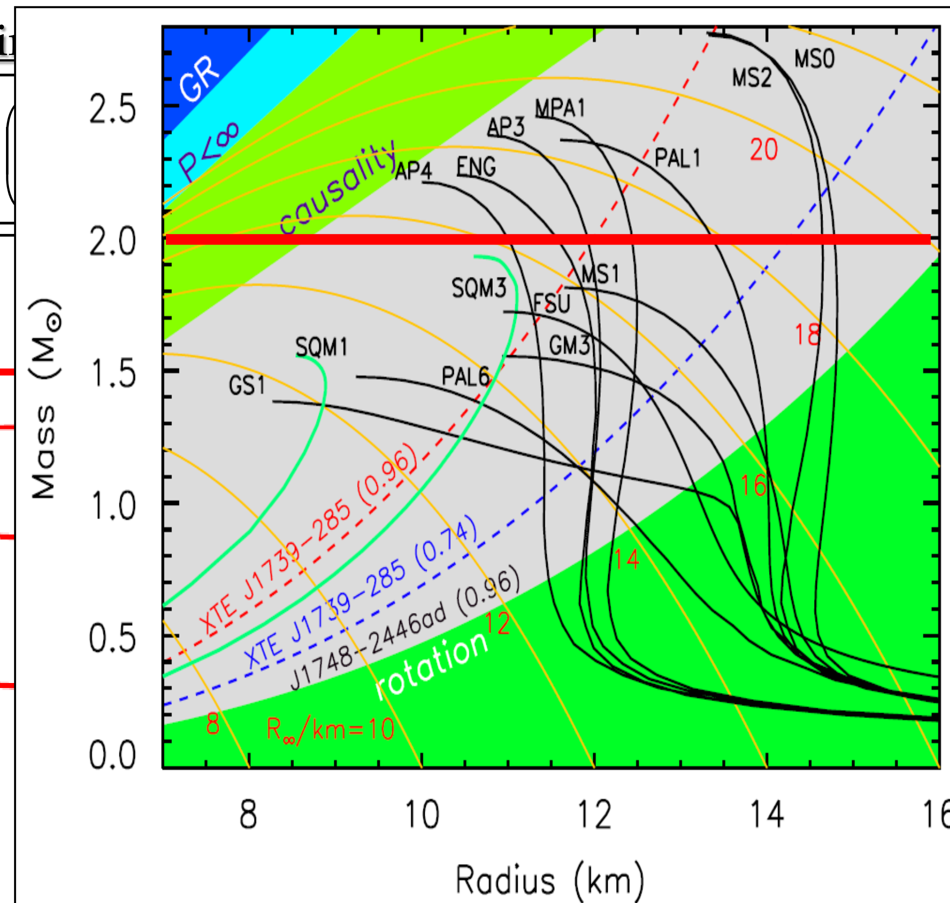
Constraining EOS by NS observations

- One-to-one correspondence between
  Equation of state (EOS) ⇔ neutron star (NS) mass-radius relation
  - *Lindblom (1992) ApJ <u>398</u> 569*
- Heaviest NS mass (~2Msolar: ***Demorest et al. (2010) Nature <u>467</u> 1081***)

<u>Tolman-Oppenhei</u>

$$\frac{dP}{dr} = -\frac{G}{c^4}\frac{(mc^2 + 4\pi pr^3)(\varepsilon + P)}{r^2}$$





Symmetry energy and NS radius

- **NS radius is sensitive to symmetry energy (@ρs)**
  - empirical correlation for radius and pressure near the saturation density

$$R_{NS}(n_S, M_{NS}) \approx C(n_S, M_{NS}) \left(\frac{P(n_S)}{\text{MeV fm}^{-3}} \right)^{1/4}$$

  - For pure neutron matter, P @ saturation depends on symmetry energy

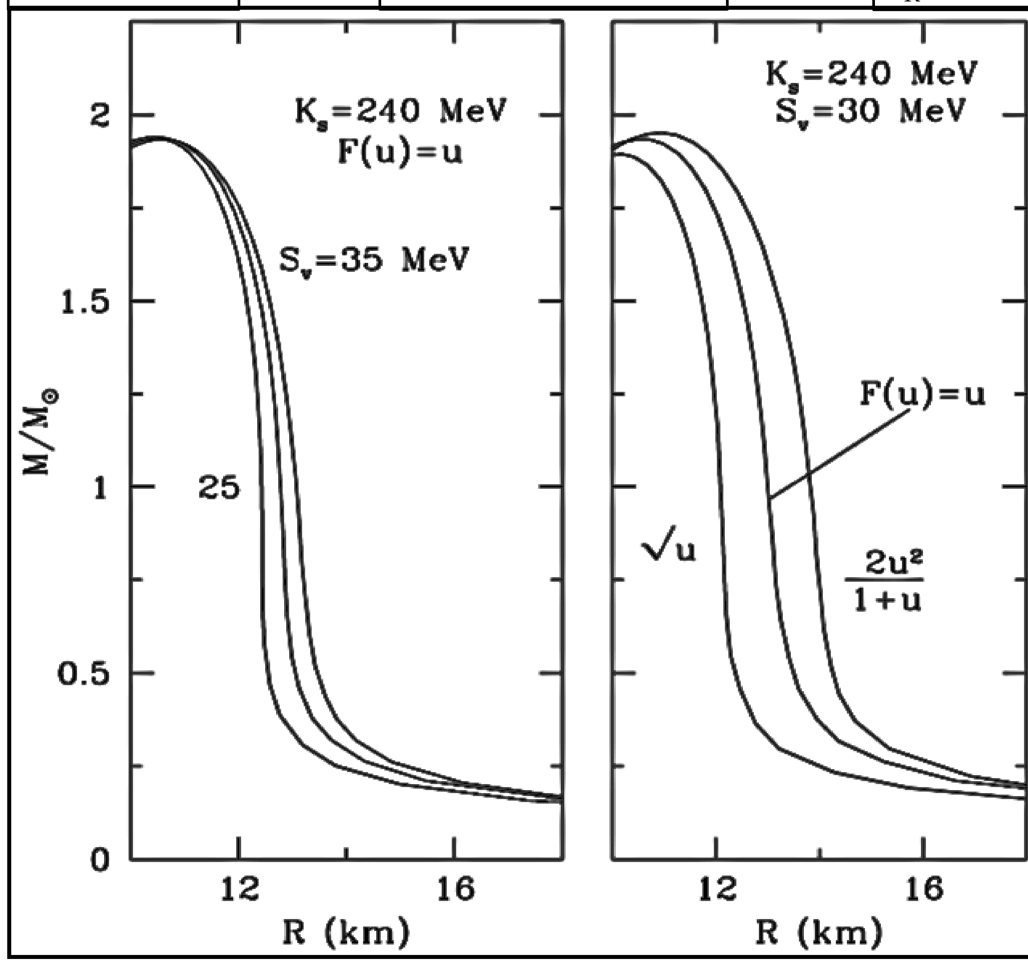
$$P(n_S, x=0) \propto L \approx S_V n_S$$

- NS radius (astrophysics) ⇒ Symmetry energy (nuclear physics)

$S_{\text{potential}}$: fixed

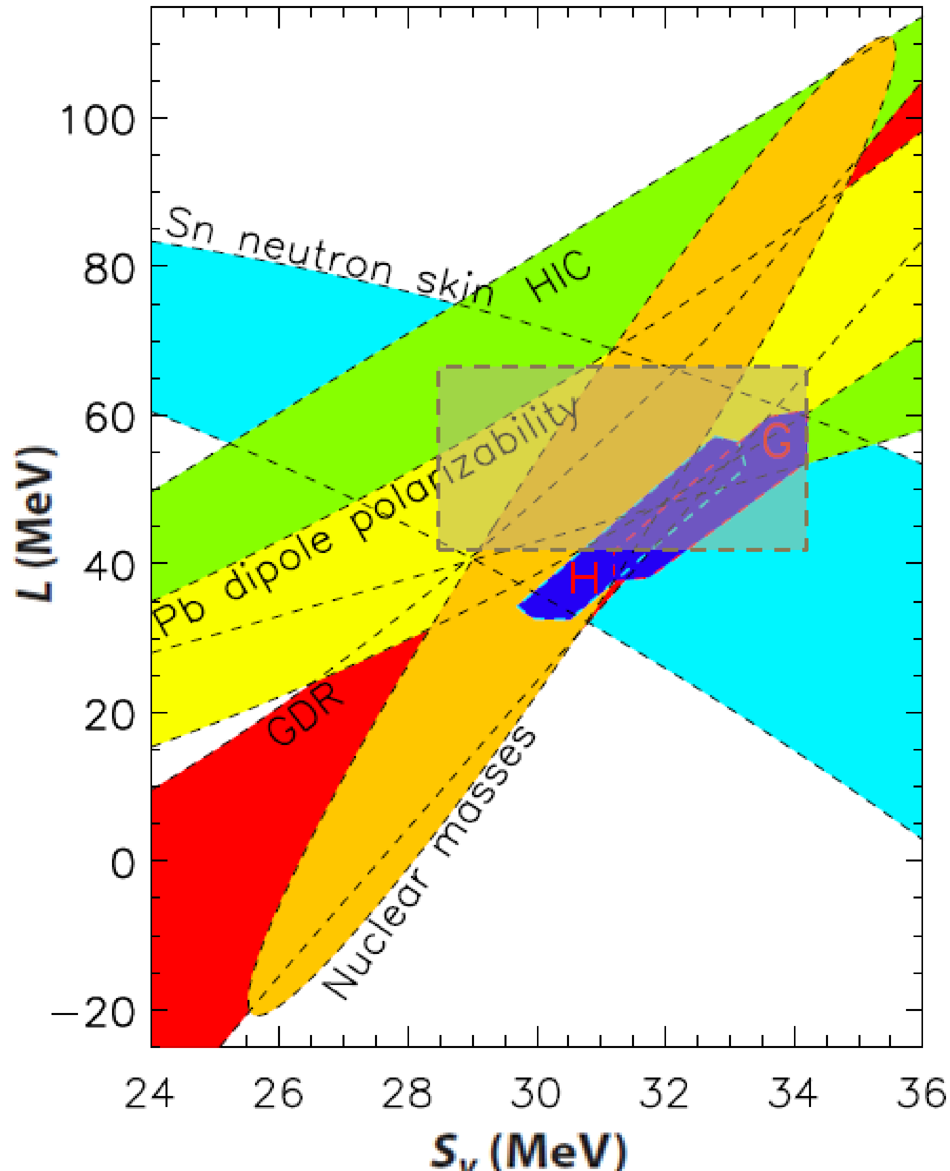
$S_V = S_K + S_{\text{potential}}$

S_K : fixed



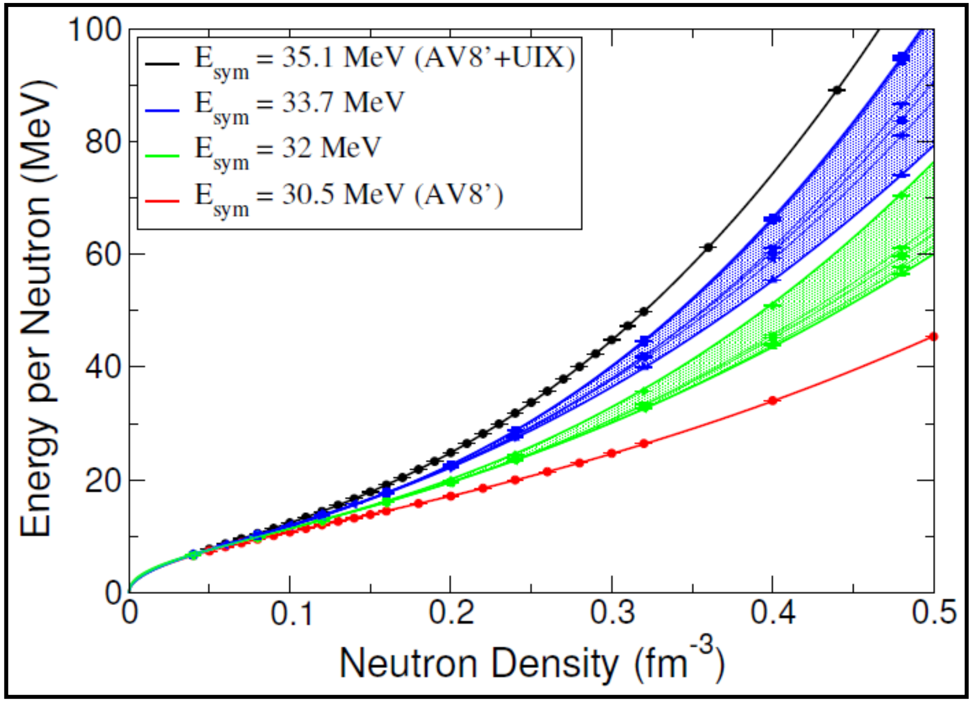
Recent constraints on the symmetry energy

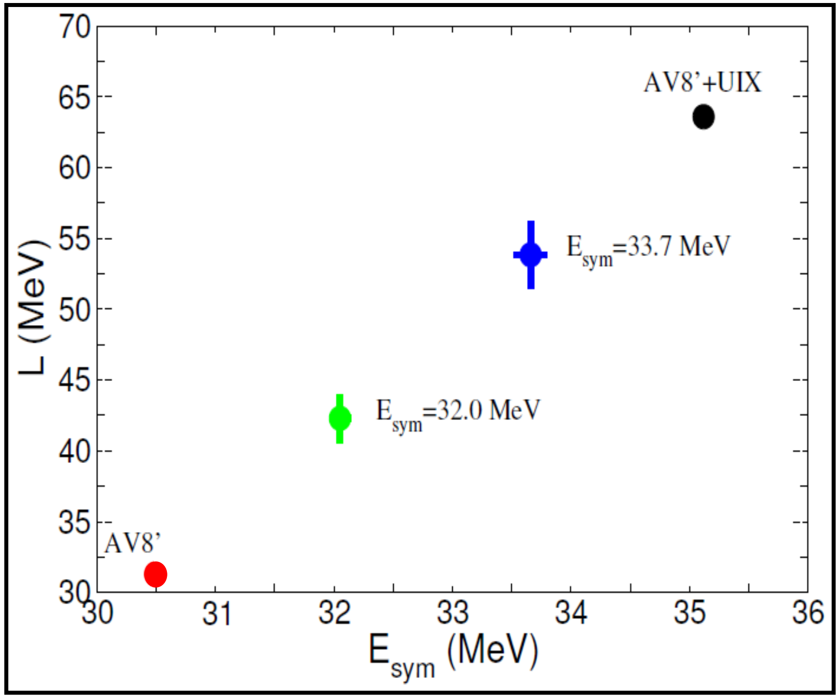
- nuclear mass fitting
  - *Kortelainen et al. (2010) PRC 82 024313*
- neutron skin thickness of Sn
  - *Chen et al. (2010) PRC 82 024321*
- heavy ion collision
  - *Tsang et al. (2009) PRL 102 122701*
- giant dipole resonances
  - *Trippa et al. (2008) PRC 77 061304*
- ^{208}Pb dipole polarizablility
  - *Piekarewicz et al. (2012) PRC 85 041302*
- Theoretical calculation
  - Chiral effective field theory
    - *Hebeler et al. (2010) PRL 105 161102*
  - Quantum Monte Carlo
    - *Gandolfi et al. (2012) PRC 85 032801*
- neutron star M-R observations
  - *Steiner et al. (2010) ApJ 722 33*



Uncertainty of symmetry energy and NS radius

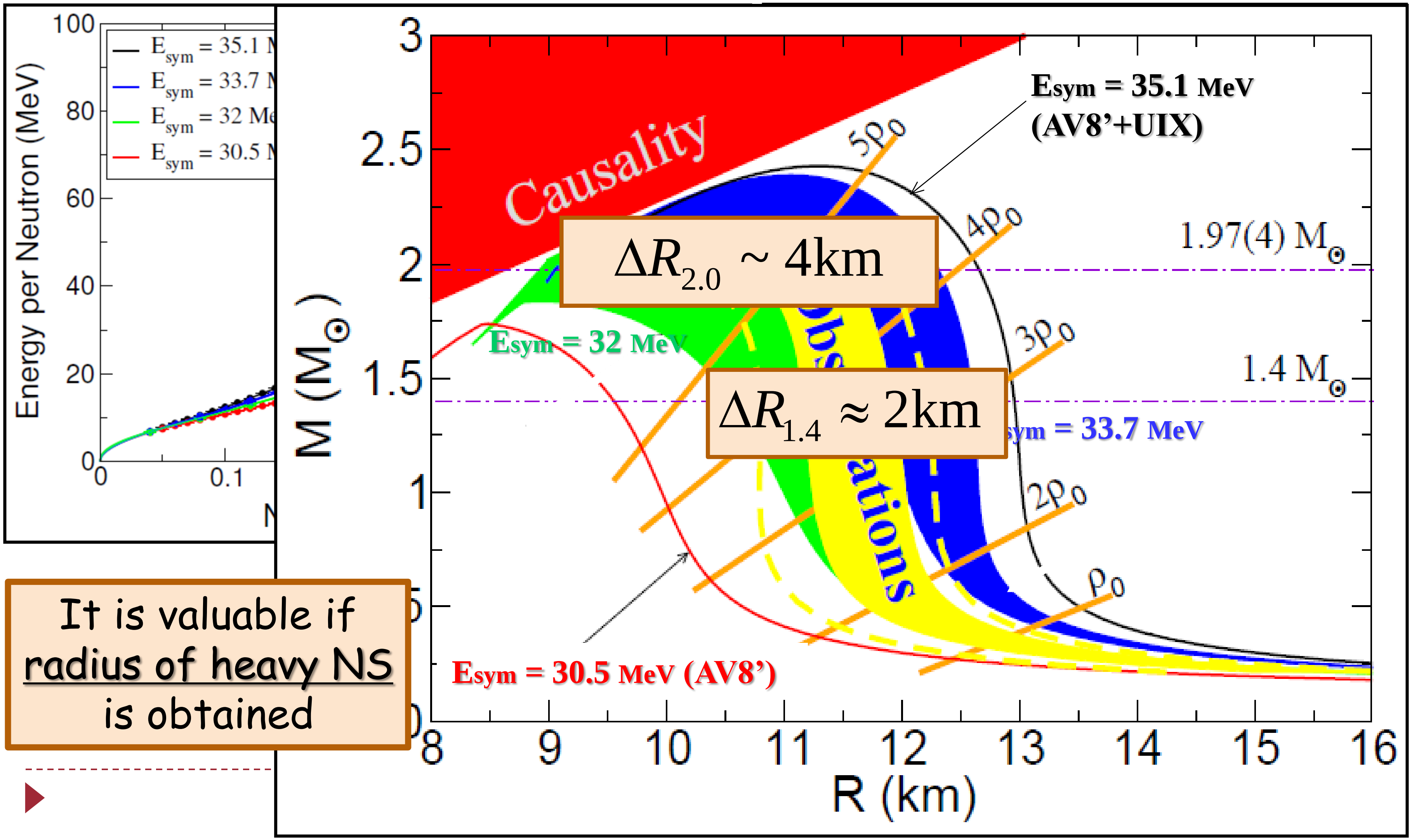
- **Phenomenological potential + quantum Monte Carlo :**





Uncertainty of symmetry energy and NS radius

- **Phenomenological potential + quantum Monte Carlo :**

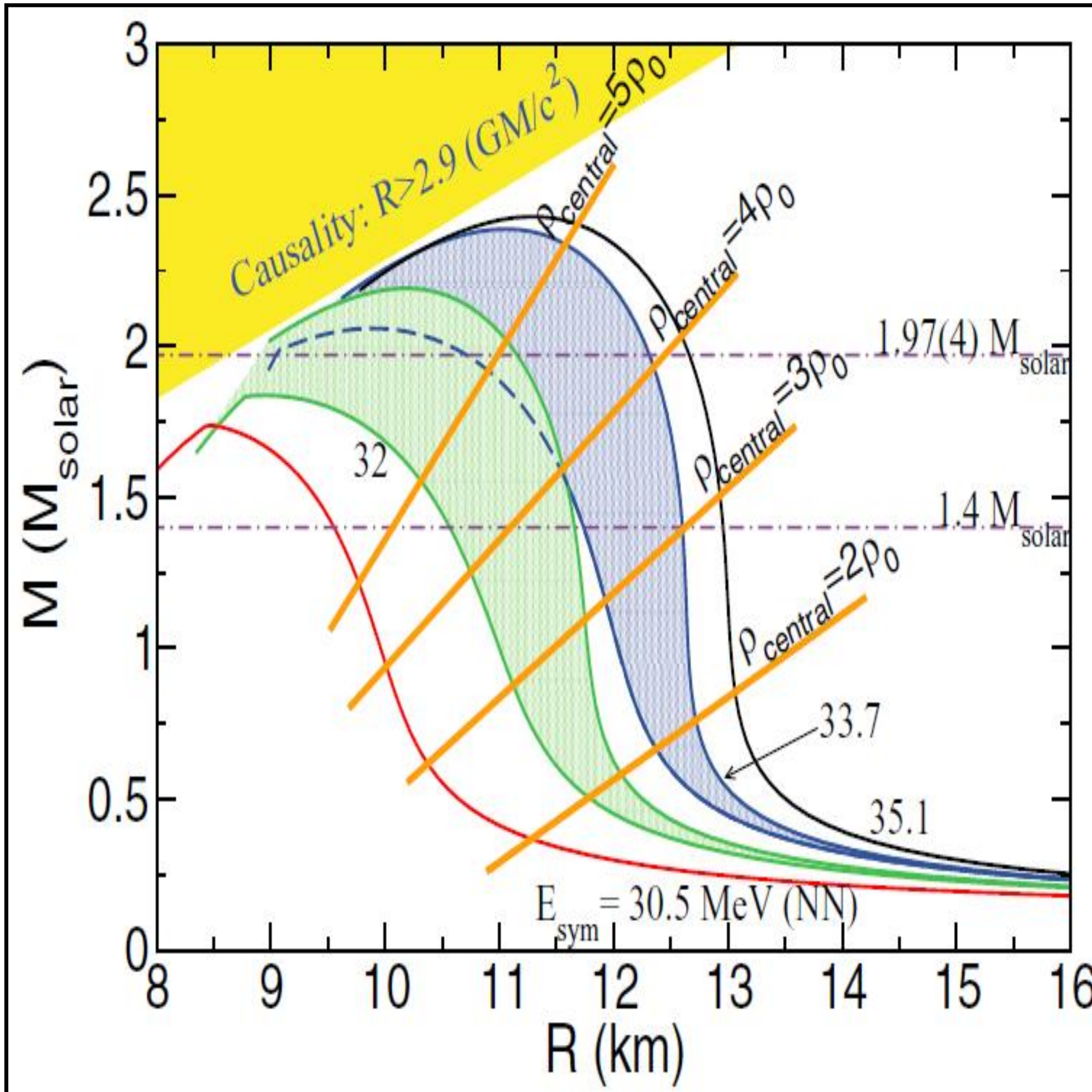


It is valuable if radius of heavy NS is obtained

Massive NS formed after the merger is important to explore high density region

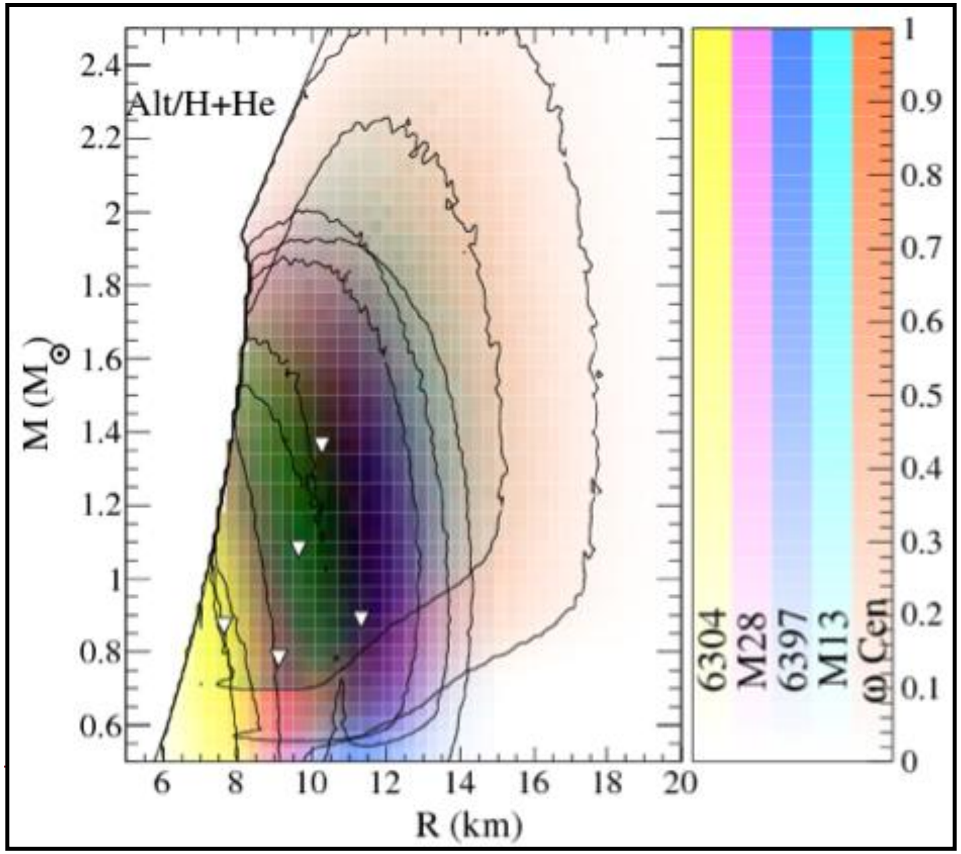
- **core bounce in supernovae**
  - mass : 0.5~0.7Msolar
  - **ρc : 1-a few ρs**
- **canonical neutron stars**
  - mass : 1.35-1.4Msolar
  - **ρc : several ρs**
- **massive NS (~ 2Msolar)**
  - **ρc : > 4ρs**
- massive NSs are necessary to explore higher densities
  - Such a massive ***isolated*** NS is very rare
  - Binary NS merger : M>2Msolar
  - BH formation

Gandolfi et al. (2012) PRC 85 032801(R)



NS mass/radius measurements

- The measurement of flux and temperature yields an apparent angular size (pseudo-BB) $\frac{R_\infty}{D} = \frac{R}{D}\frac{1}{\sqrt{1-GM/Rc^2}}$ $F \propto T_{\rm eff}^4 \frac{R_\infty^2}{D^2}$
  - Many uncertainties : **redshift**, distance, interstellar absorption, atmospheric composition
- Good Targets:
  - Quiescent X-ray binaries in globular clusters
  - Bursting sources with peak flux close to Eddington limit
- Imply rather small radius
  - **If true, maximum mass may not be much greater than 2Msun**



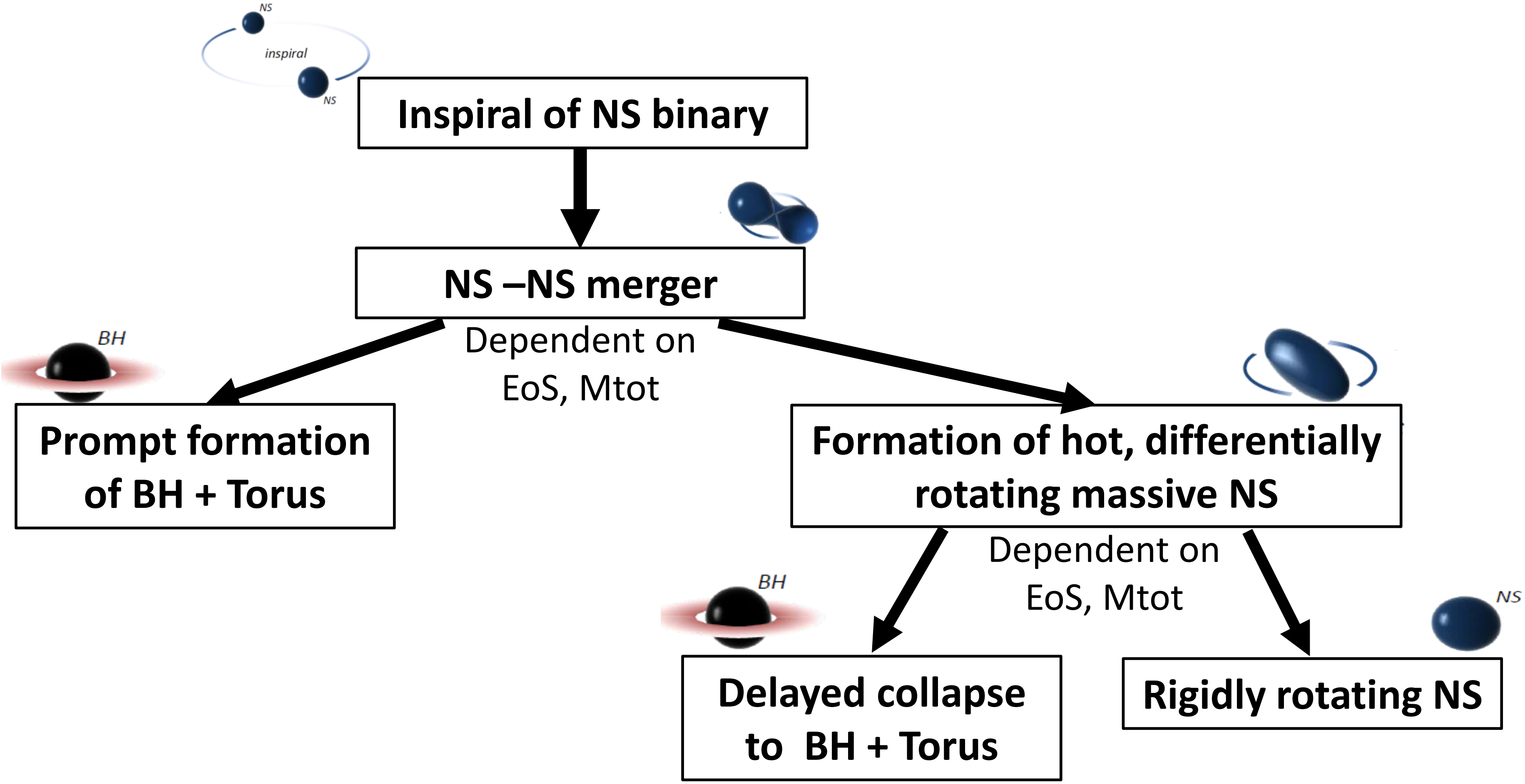
- Lattimer & Steiner 2014 for quiescent LMXBs

Short summary : a numerical relativist's thinking

- One-to-one correspondence between EOS and NS mass-radius
  - In principle, we can reconstruct EOS from mass-radius information
- Stronger constraint on EOS if more massive NSs are discovered
  - Current status : 2Msolar Future : maximum mass by GW observations
- NS radius is sensitive to the symmetry energy
  - Current uncertainty of symmetry energy corresponds to
    - $\Delta R \sim 3\mathbf{km}$ for 1.4Msolar NS
    - $\Delta R > 4\mathbf{km}$ for 2.0Msolar NS
  - **Can NS observations give more tight constraints on NS radius ?**
- To explore higher density regions, we need heavier NS
  - Highest density achieved in (proto-) NS
    - Supernova core : $\rho_c \sim$ 1-2 ρ_s
    - Canonical-mass NS : $\rho_c \sim$ several ρ_s
    - Maximally compact NS : $\rho_c \sim 9\ \rho_s$
  - **Importance of NS-NS merger and BH formation to explore higher ρ**

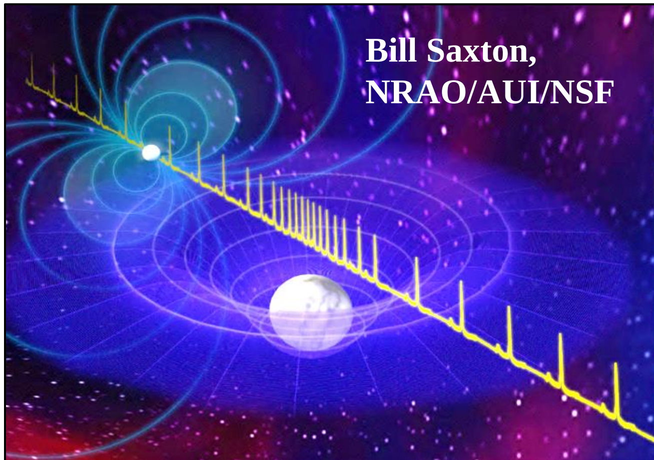
Shibata et al. 2005,2006
Sekiguchi et al, 2011
Hotokezaka et al. 2013

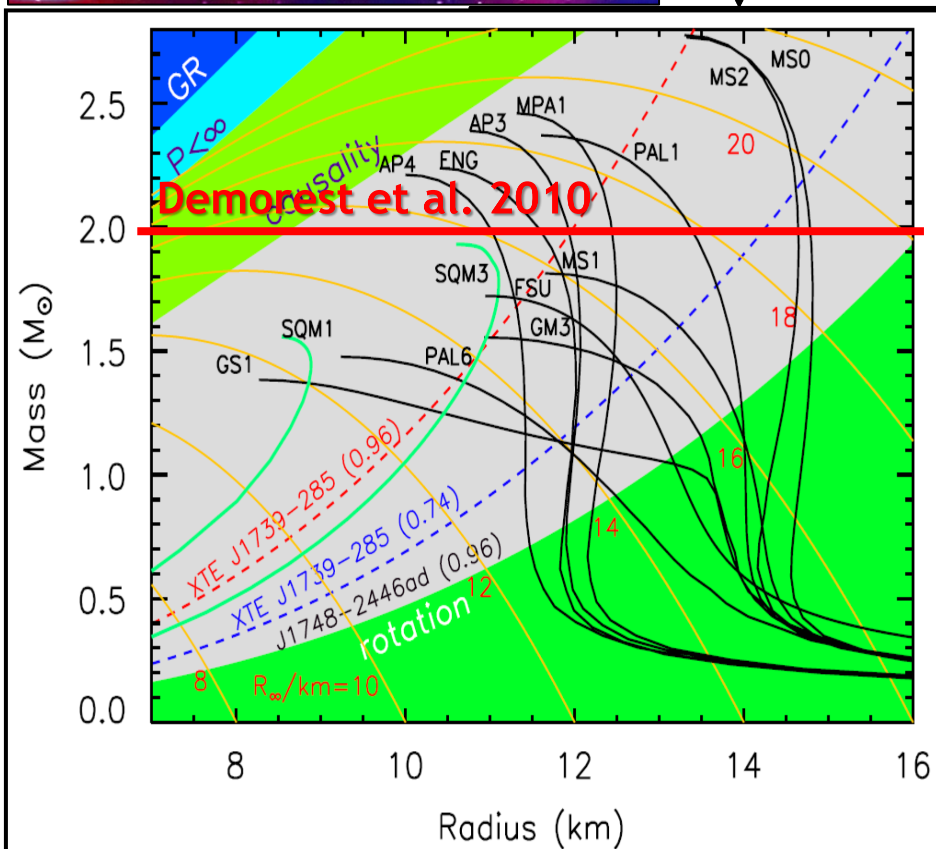
Evolution of NS-NS mergers

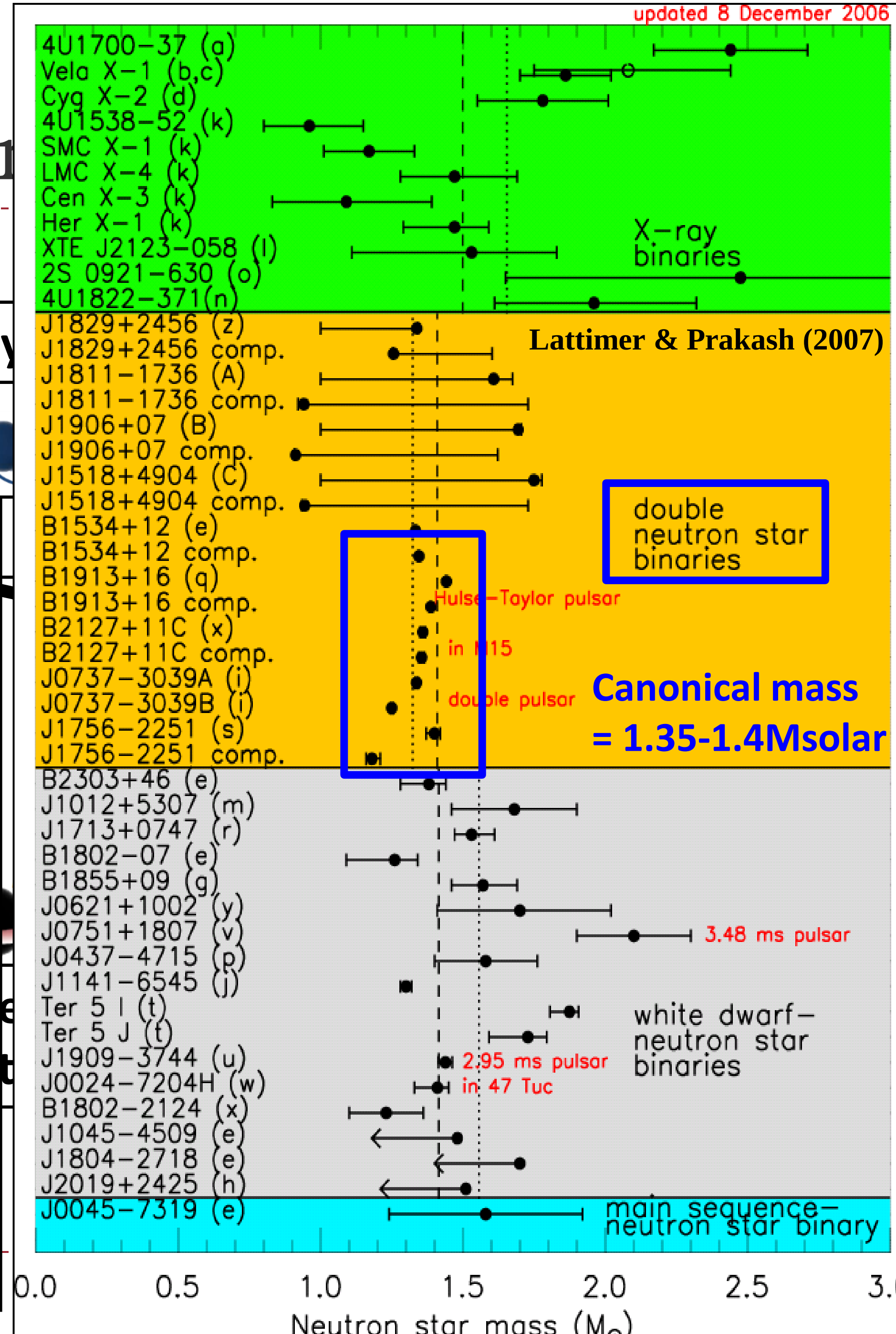


NS-NS r

al of NS binary

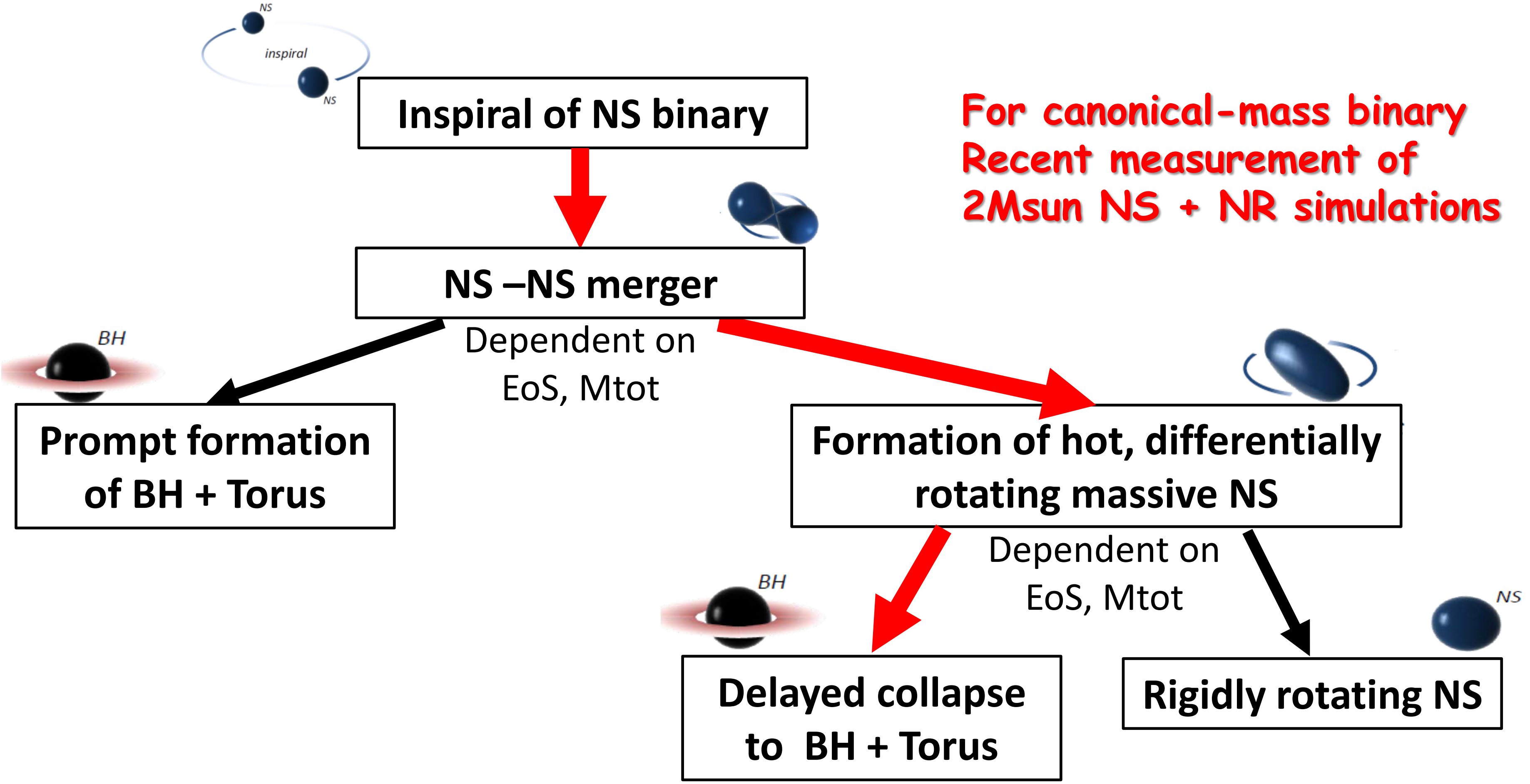






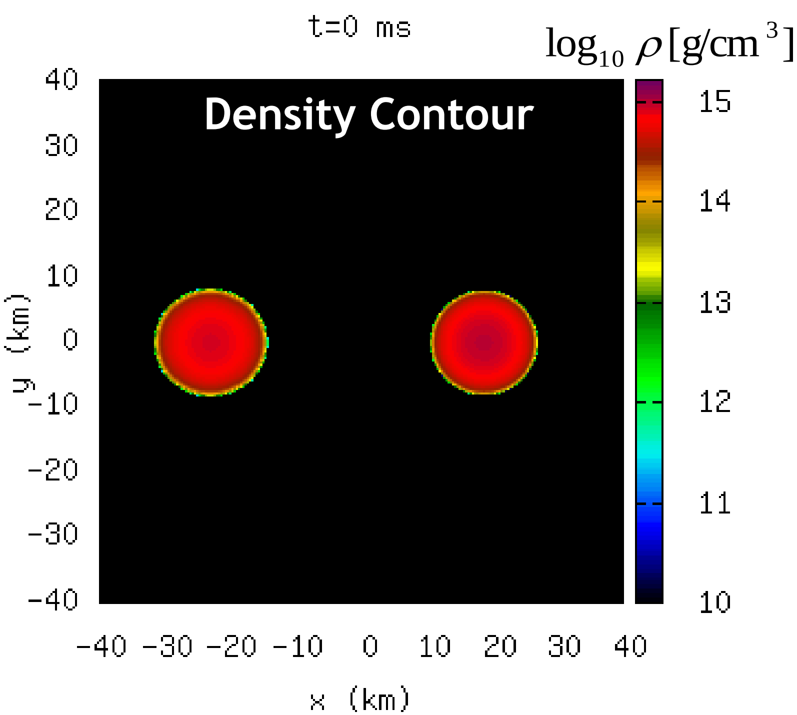
Shibata et al. 2005,2006
Sekiguchi et al, 2011
Hotokezaka et al. 2013

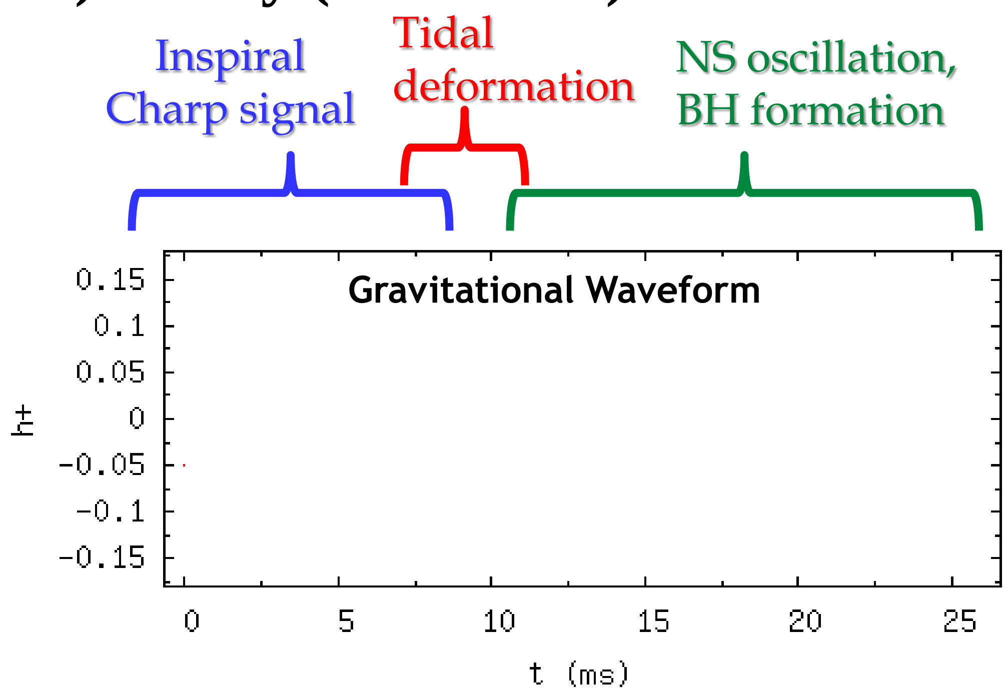
Evolution of NS-NS mergers



Gravitational Waves from NS-NS binary

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



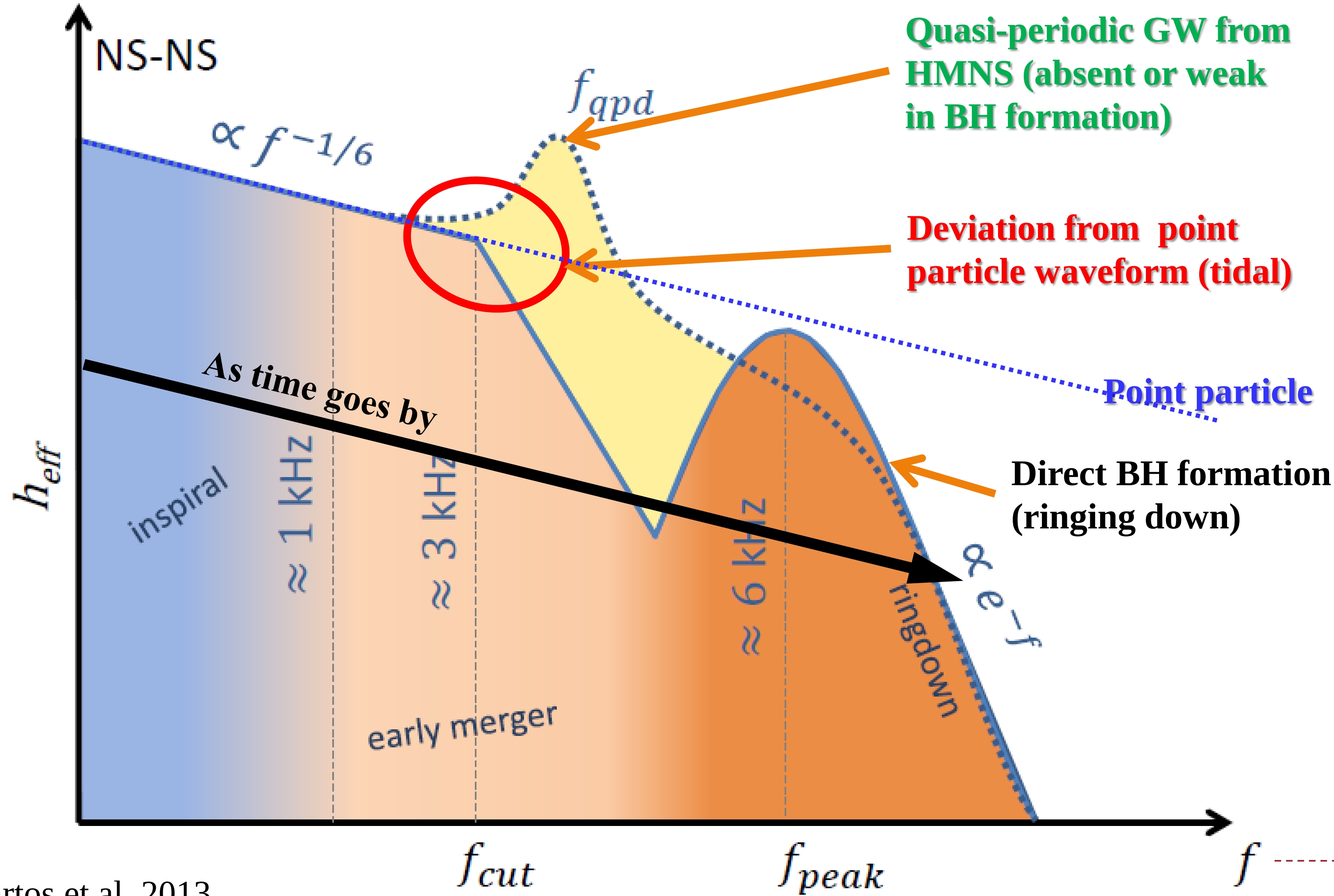


- Point particle approx.
- Information of orbits, **NS mass**, etc.

- Finite size effects appear
- **tidal deformability**
- **radius**

- BH or NS ⇒ **maximum mass**
- GWs from massive NS
  ⇒ **NS radius of massive NS**

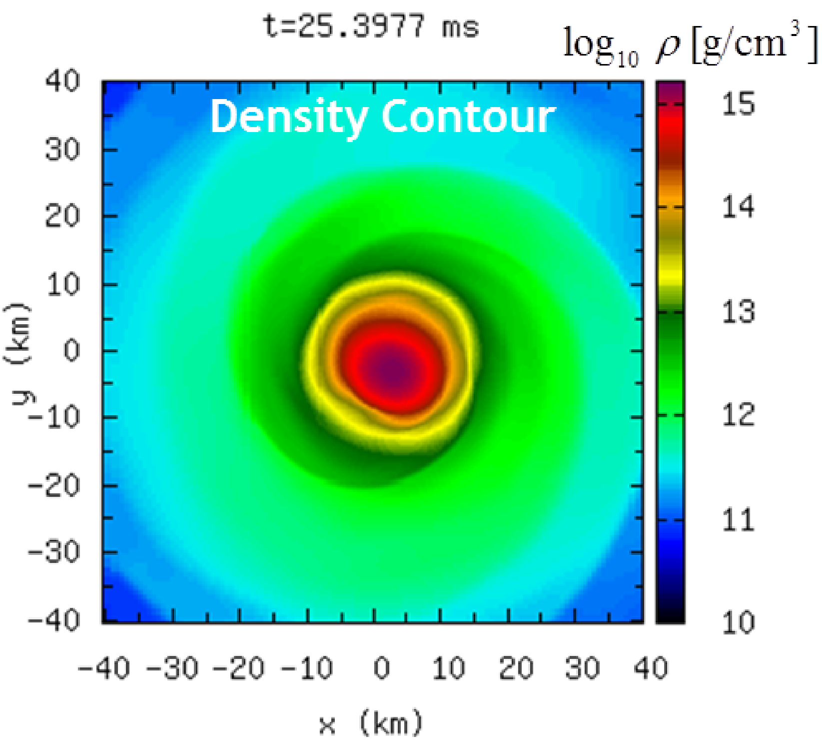
Schematic picture of GW spectra

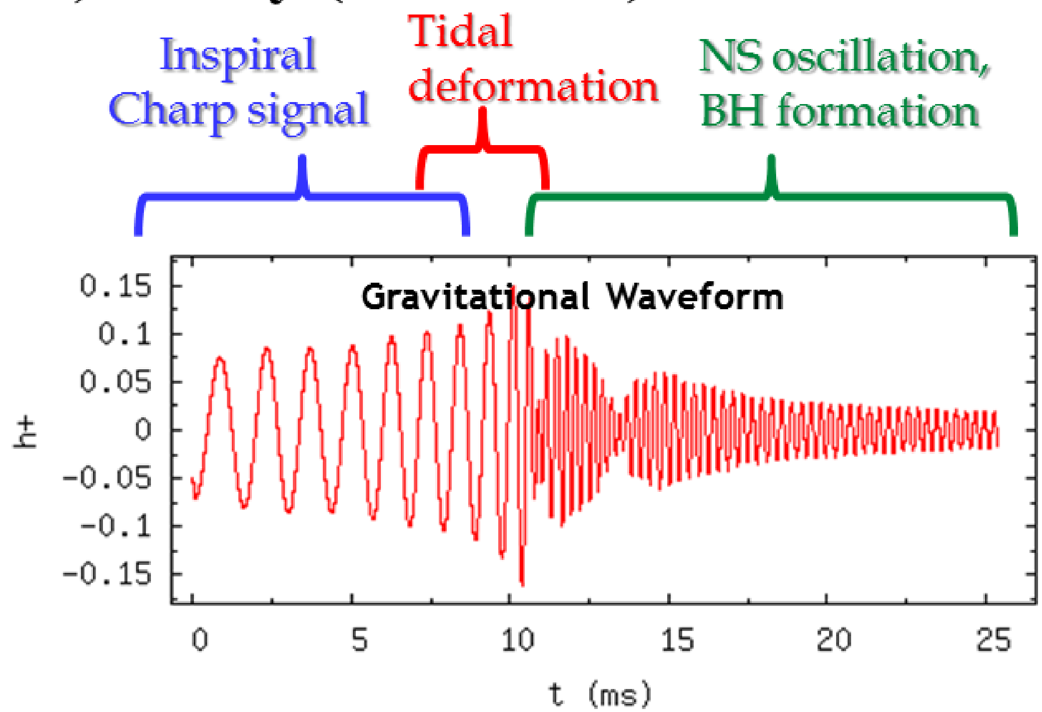


- Bartos et al. 2013

Gravitational Waves from NS-NS binary

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





- Point particle approx.
- Information of orbits, **NS mass**, etc.

- Finite size effects appear
- **tidal deformability**
- **radius**

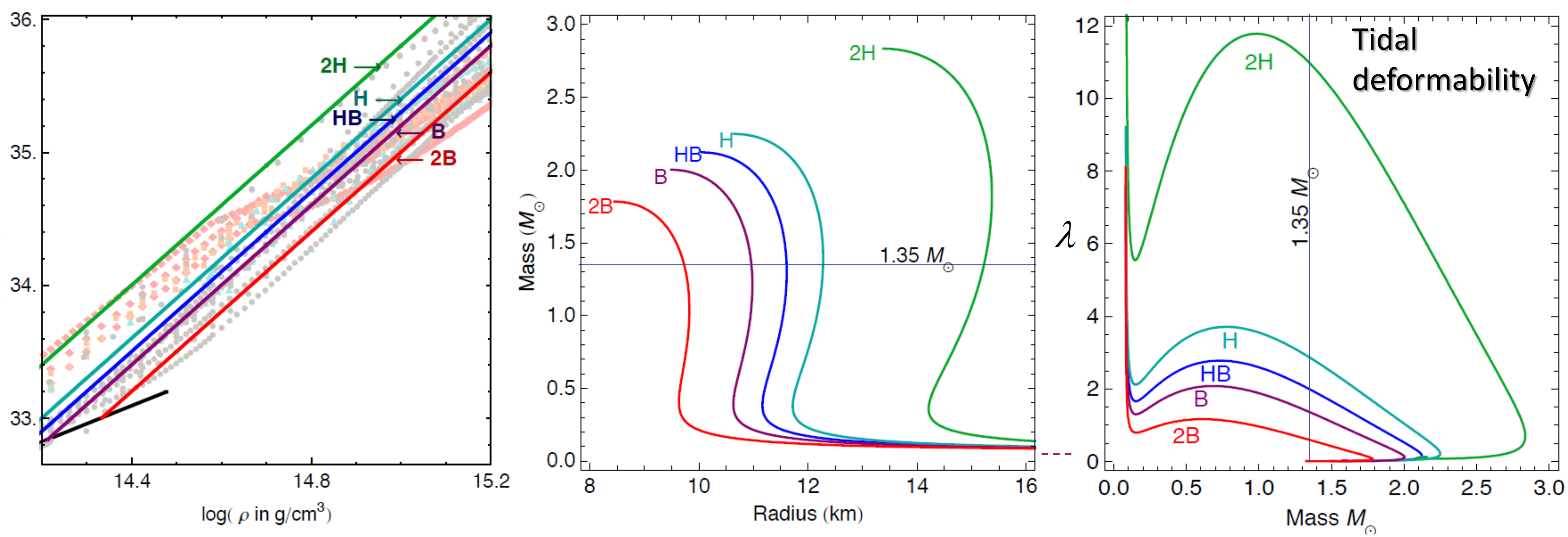
- BH or NS ⇒ **maximum mass**
- GWs from massive NS ⇒ **NS radius of massive NS**

Read et al. (2013) PRD 88 044042 (c.f. Hotakezaka et al. (2013) PRD 87 044001)

Effect of tidal deformation on GWs

- GW emission is described by quadrupole formula (L.O.)
- The quadrupole moment changed by tidal field by companion (finite size effect)
  - Finite-size effect : evaluated by comparison with point particle approx.
  - L.O. effect appears in GW phase : faster evolution for larger deformation
- **Tidal deformability : $\boldsymbol{\lambda}$**
  - Response to tidal field (EOS dependent)
  - stiffer EOS ⇒ larger radii ⇒ larger $\boldsymbol{\lambda}$

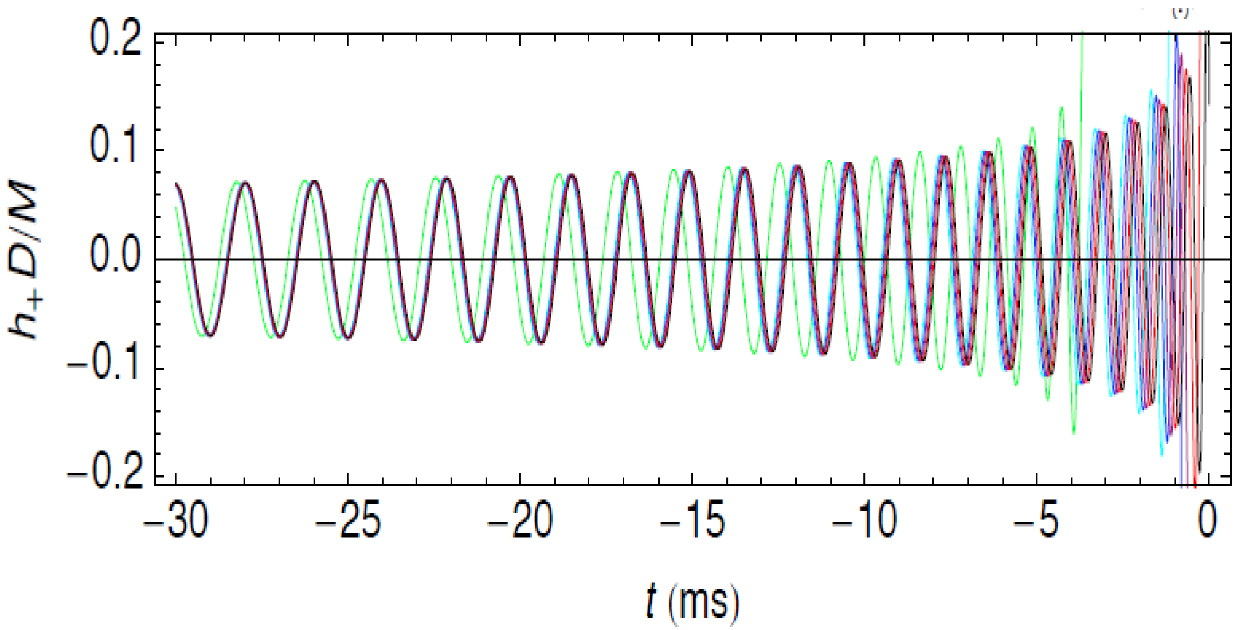
$$\lambda = \frac{\text{degree of quadrupole deformation}}{\text{strength of external tidal field}}$$

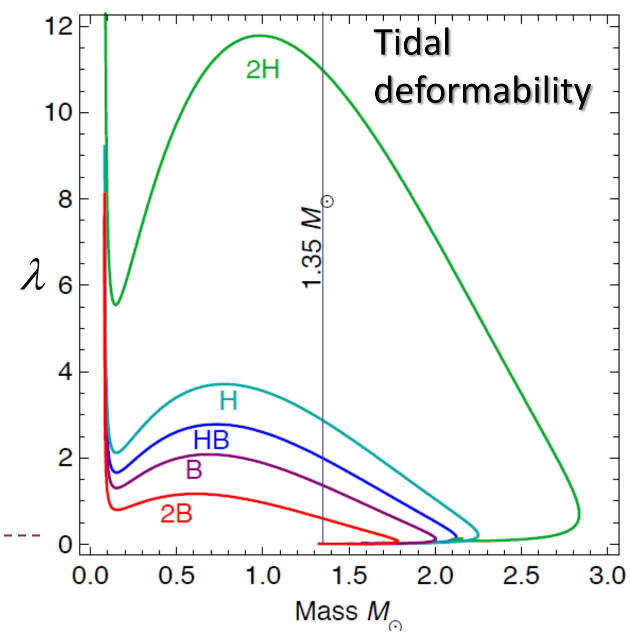


Effect of tidal deformation on GWs

- GW emission is described by quadrupole formula (L.O.)
- The quadrupole moment changed by tidal field by companion (finite size effect)
  - Finite-size effect : evaluated by comparison with point particle approx.
  - L.O. effect appears in GW phase : faster evolution for larger deformation
- **Tidal deformability : λ**
  - Response to tidal field (EOS dependent)
  - stiffer EOS ⇒ larger radii ⇒ larger λ

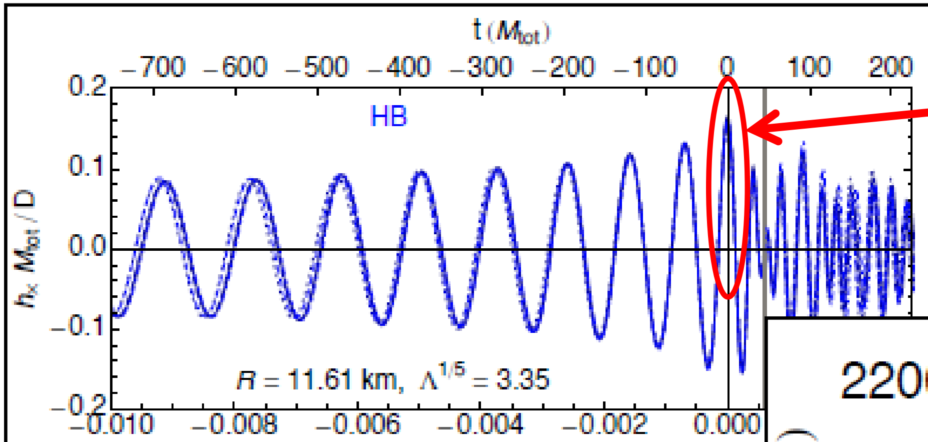
$$\lambda = \frac{\text{degree of quadrupole deformation}}{\text{strength of external tidal field}}$$





Read et al. (2013) PRD 88 044042

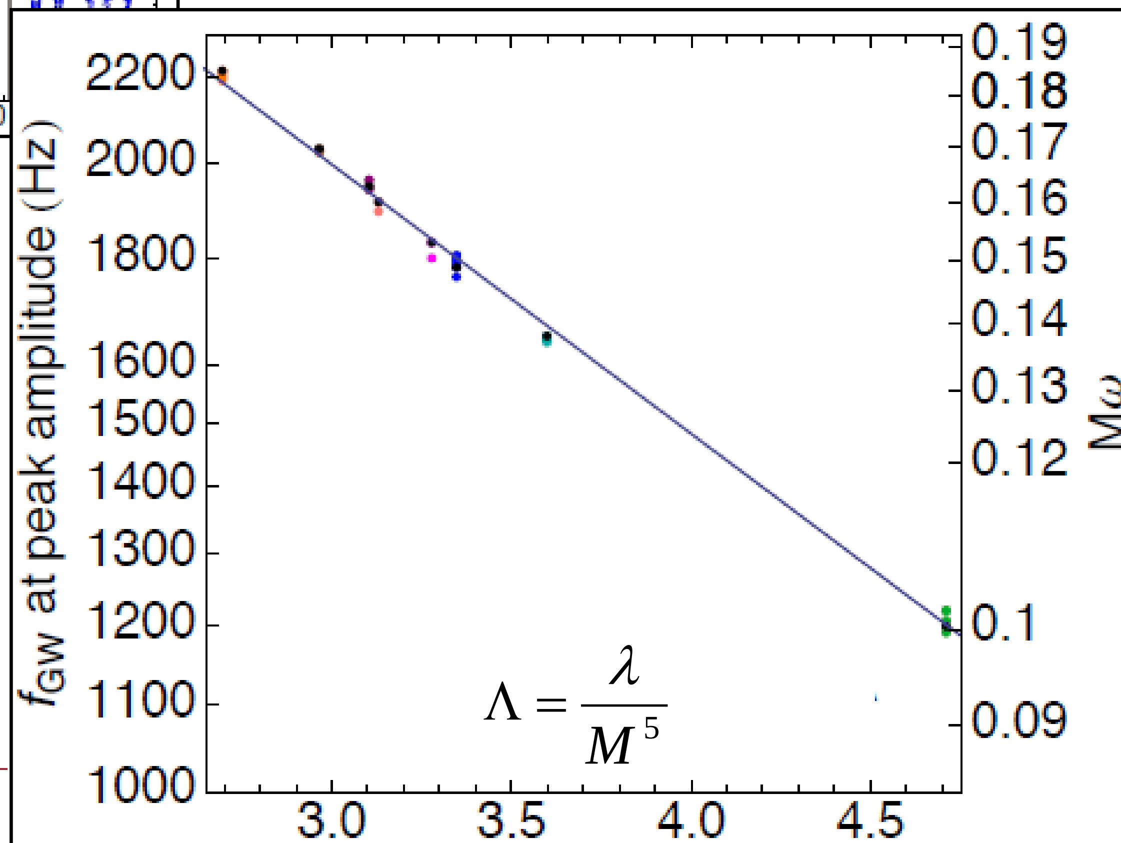
Extract information of tidal deformability from GWs



Extract the frequency at peak amplitude for many EOS

And plot them as a function of Λ

Tight correlation ↓

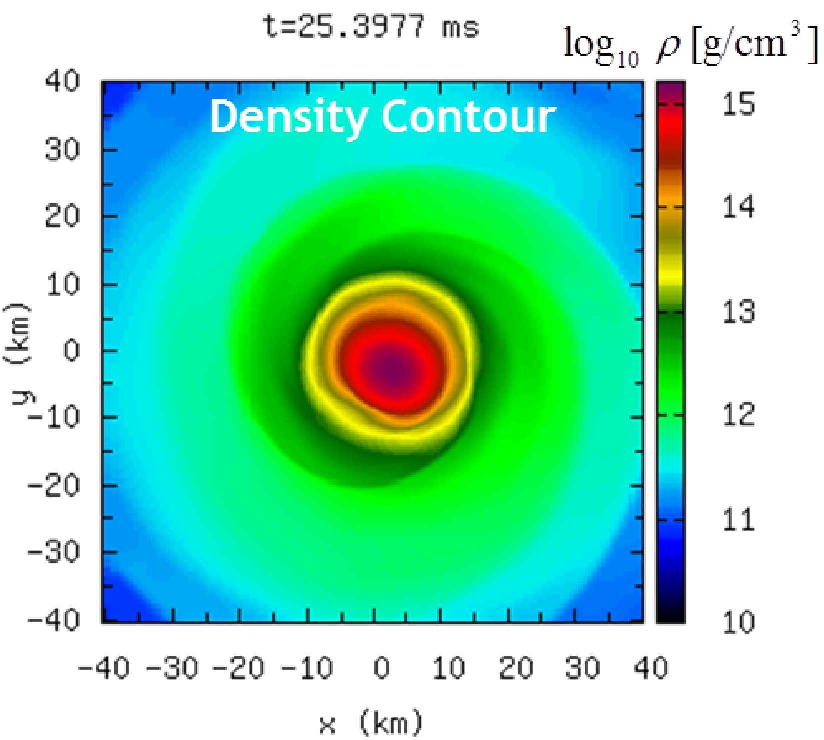


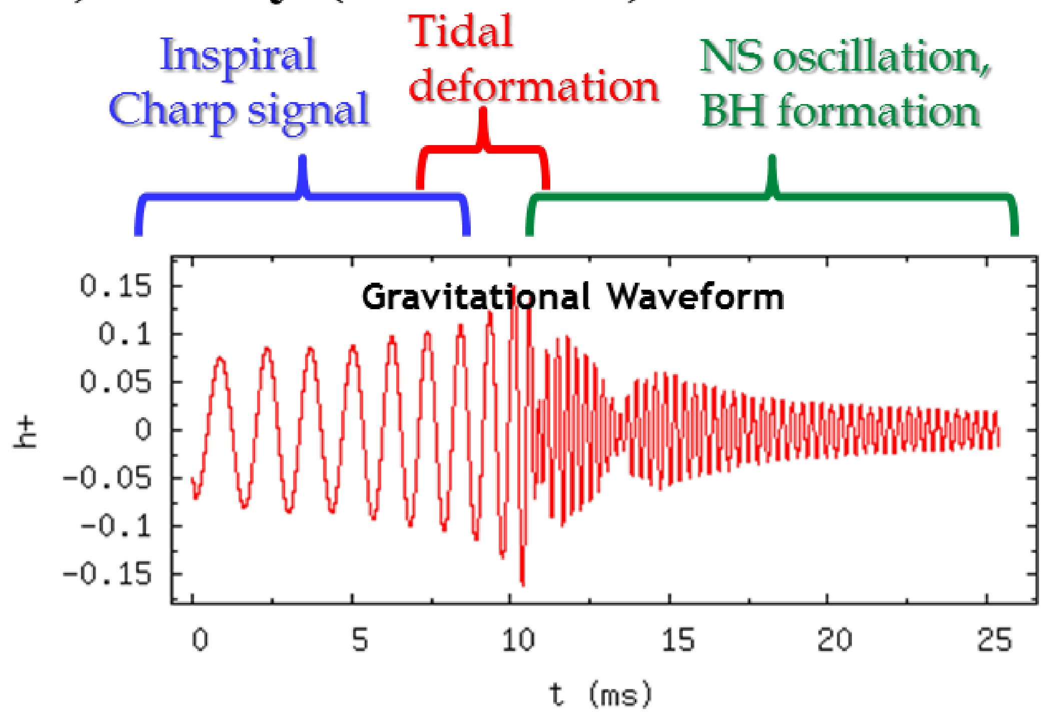
Empirical dependence of the peak frequency on the tidal deformability

This type of study (deriving empirical relation from systematic simulation) was first applied in Kiuchi, YS, et al. (2010) and now become popular

Gravitational Waves from NS-NS binary

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





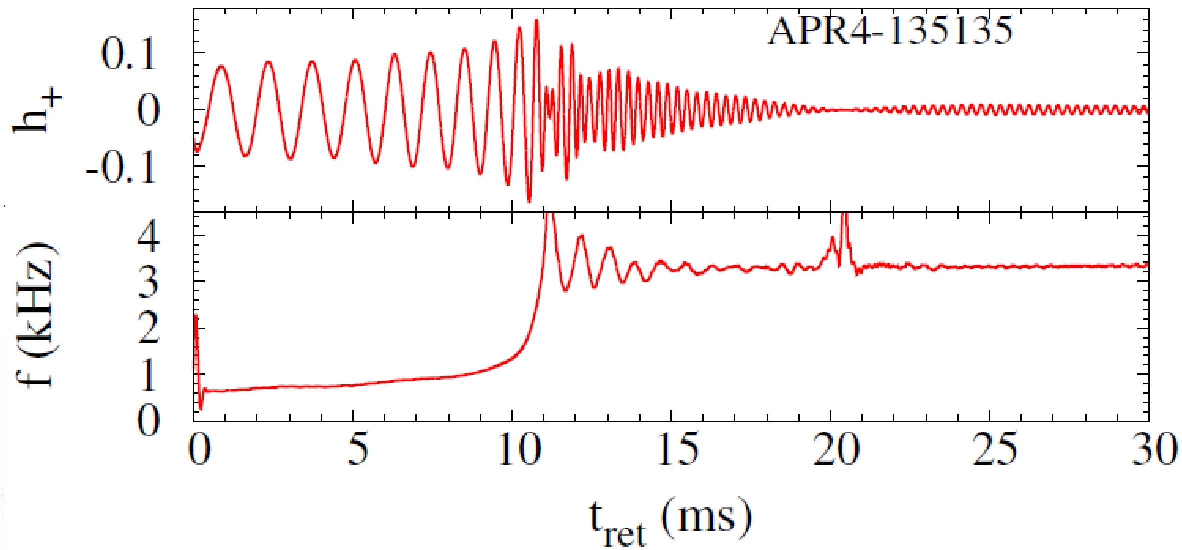
- Point particle approx.
- Information of orbits, **NS mass**, etc.

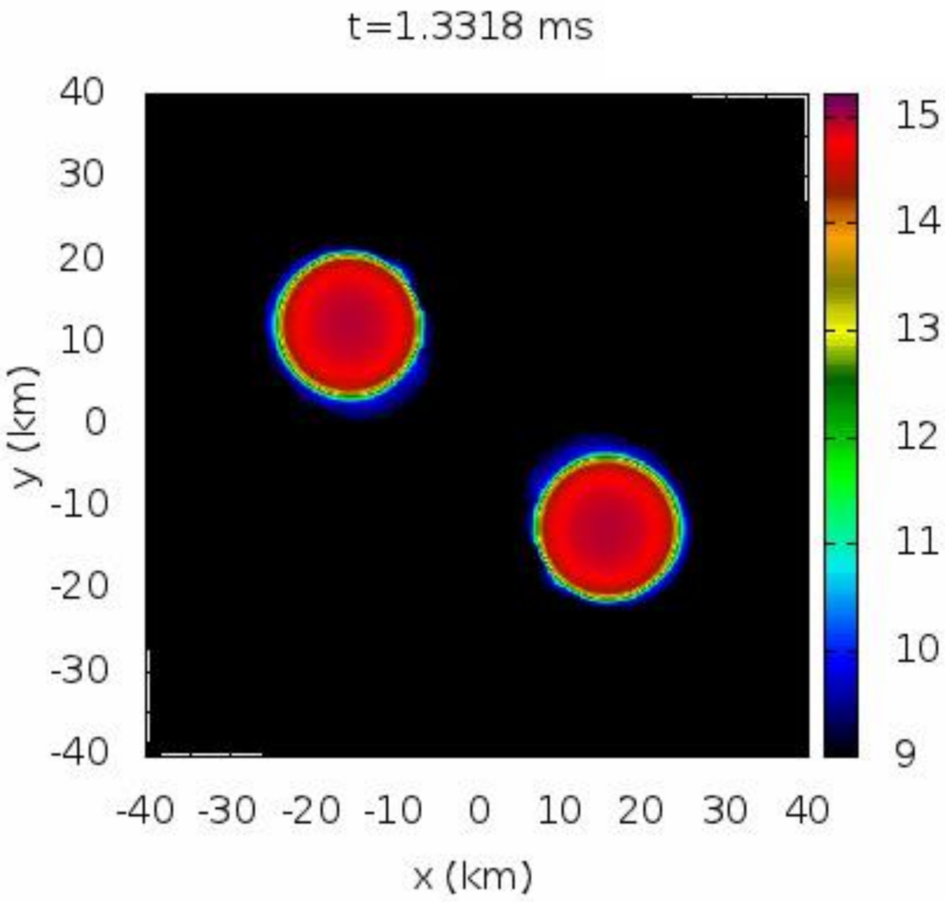
- Finite size effects appear
- **tidal deformability**
- **radius**

- BH or NS ⇒ **maximum mass**
- GWs from massive NS
  ⇒ **NS radius of massive NS**

Hearing 'sounds' of GW

By Kawaguchi





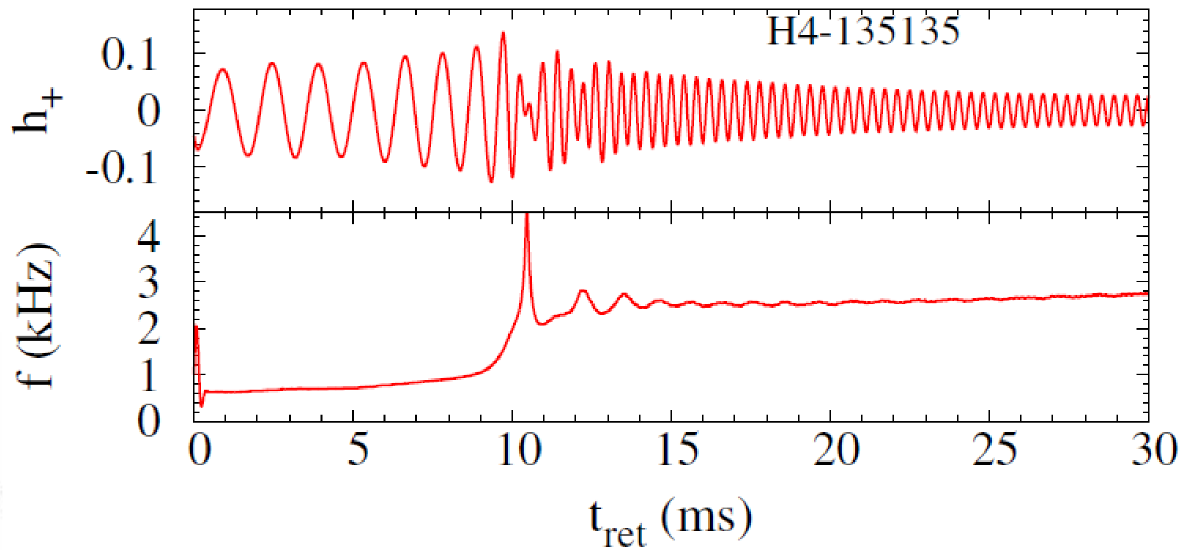
APR EOS: softer

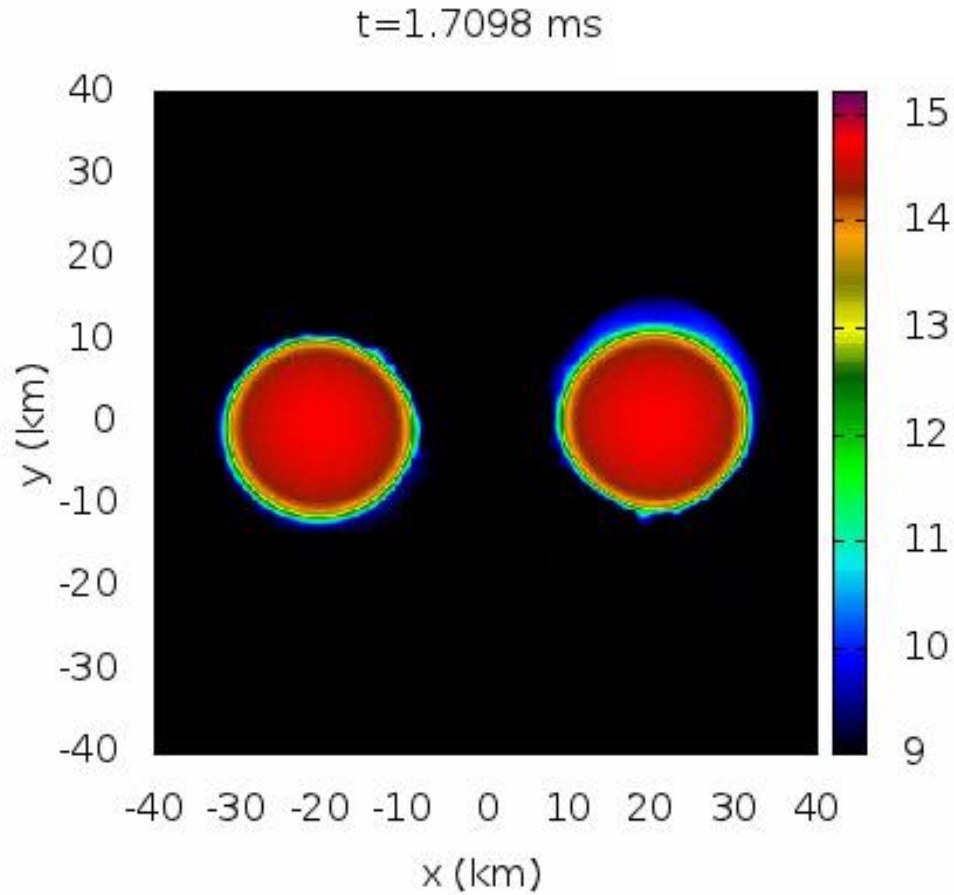
More compact NS after merger

Higher frequency
f_{GW} ~ **3.2kHz**

Hearing ‘sounds’ of GW

By Kawaguchi





H4 EOS: stiffer

less compact NS after merger

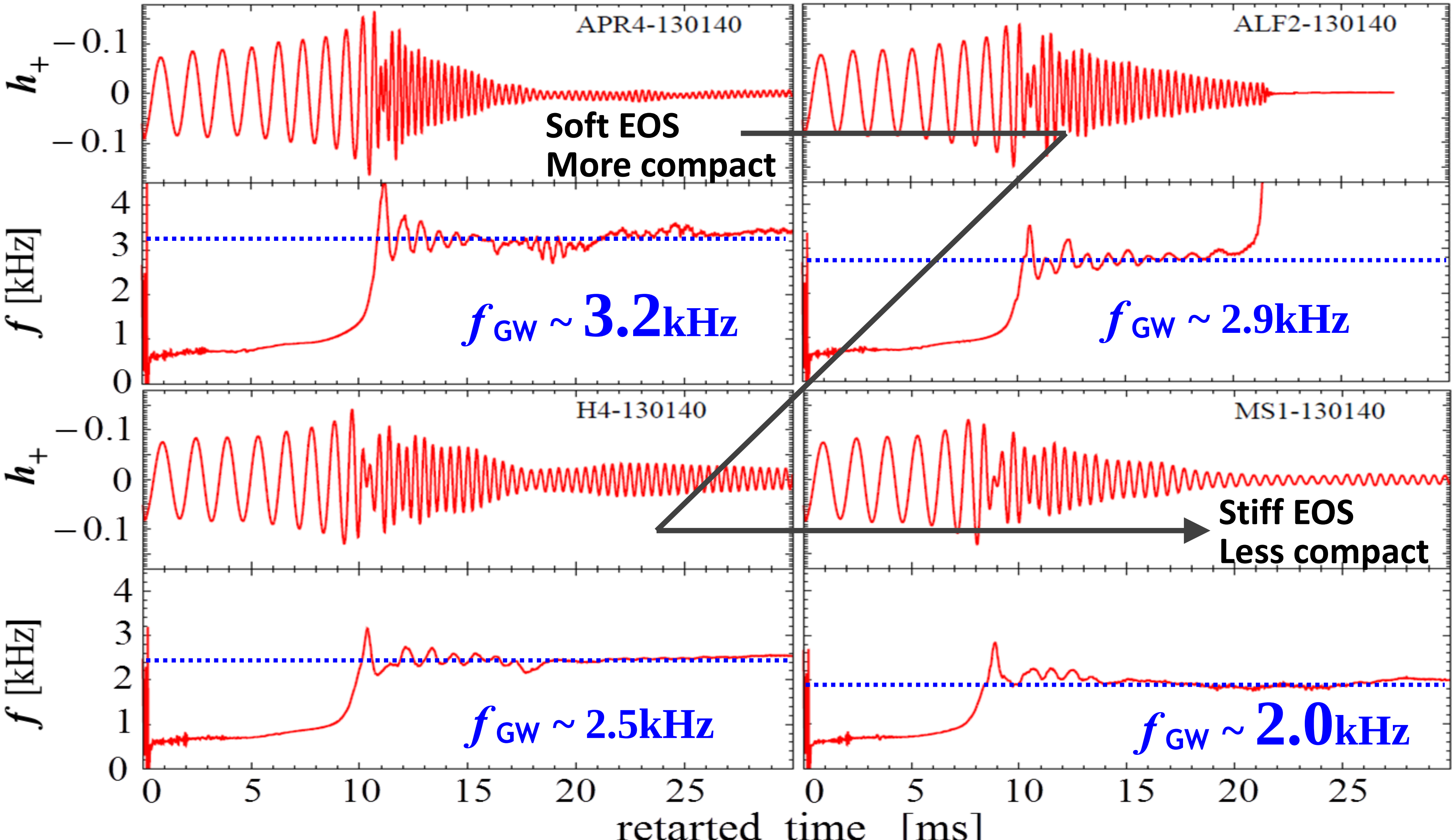
lower frequency

f_{GW} ~ **2.5kHz**

Hotokezaka et al. (2013)

GWs from merger NS : characteristic modes

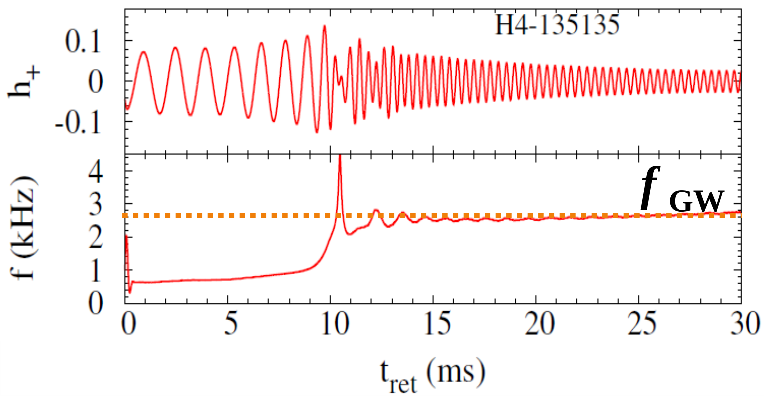
- GWs have characteristic frequency depending on EOS : f_{GW}



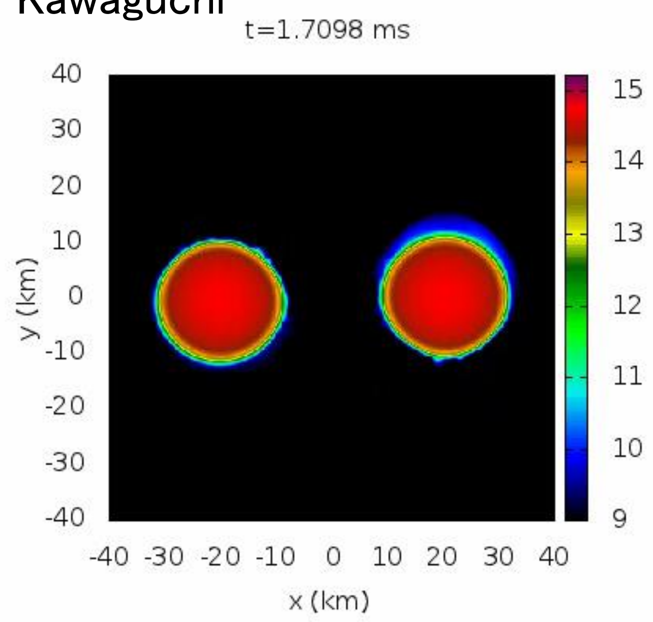
Hearing sounds of GWs from merger: characteristic modes

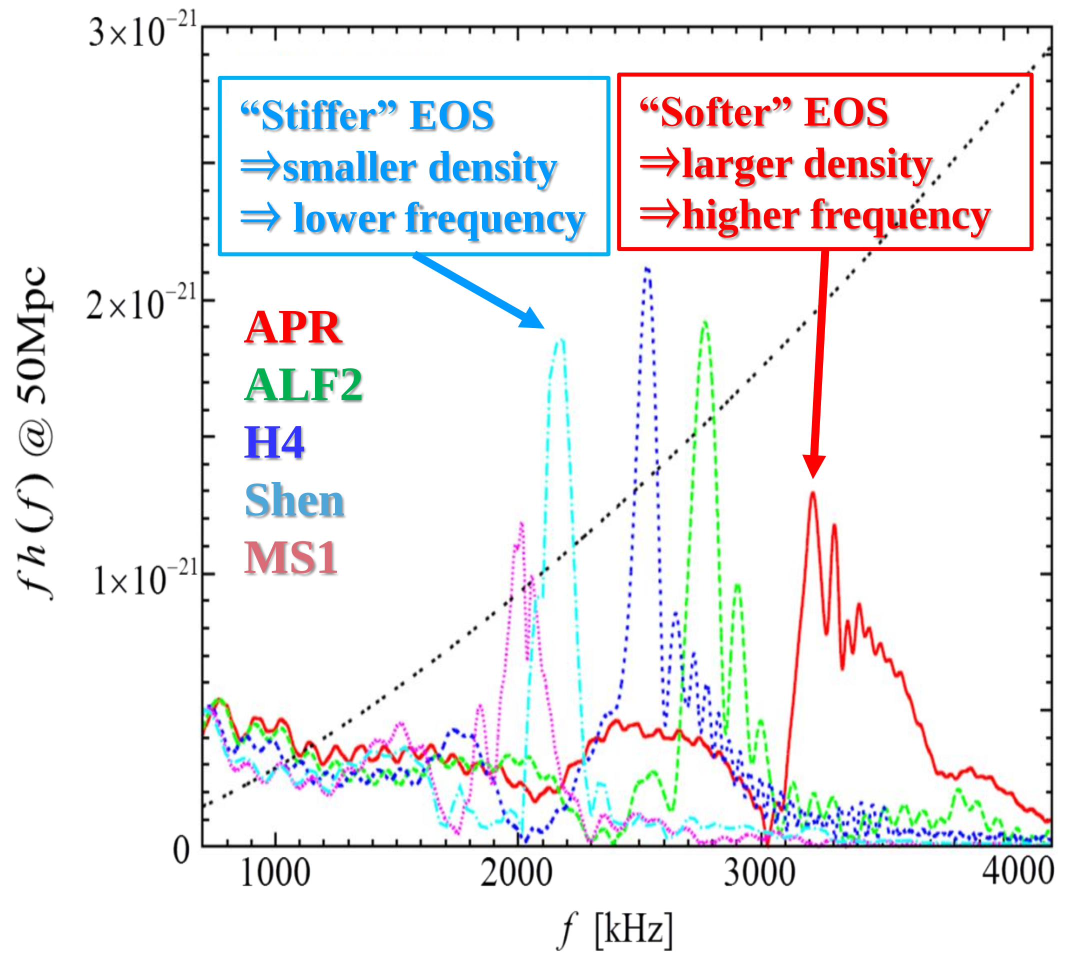
Sekiguchi et al. 2011; Hotokezaka et al. 2013; Bauswein et al. 2013

- <u>GWs have characteristic frequency ('line') depending on EOS</u> : f_{GW}



By Kawaguchi

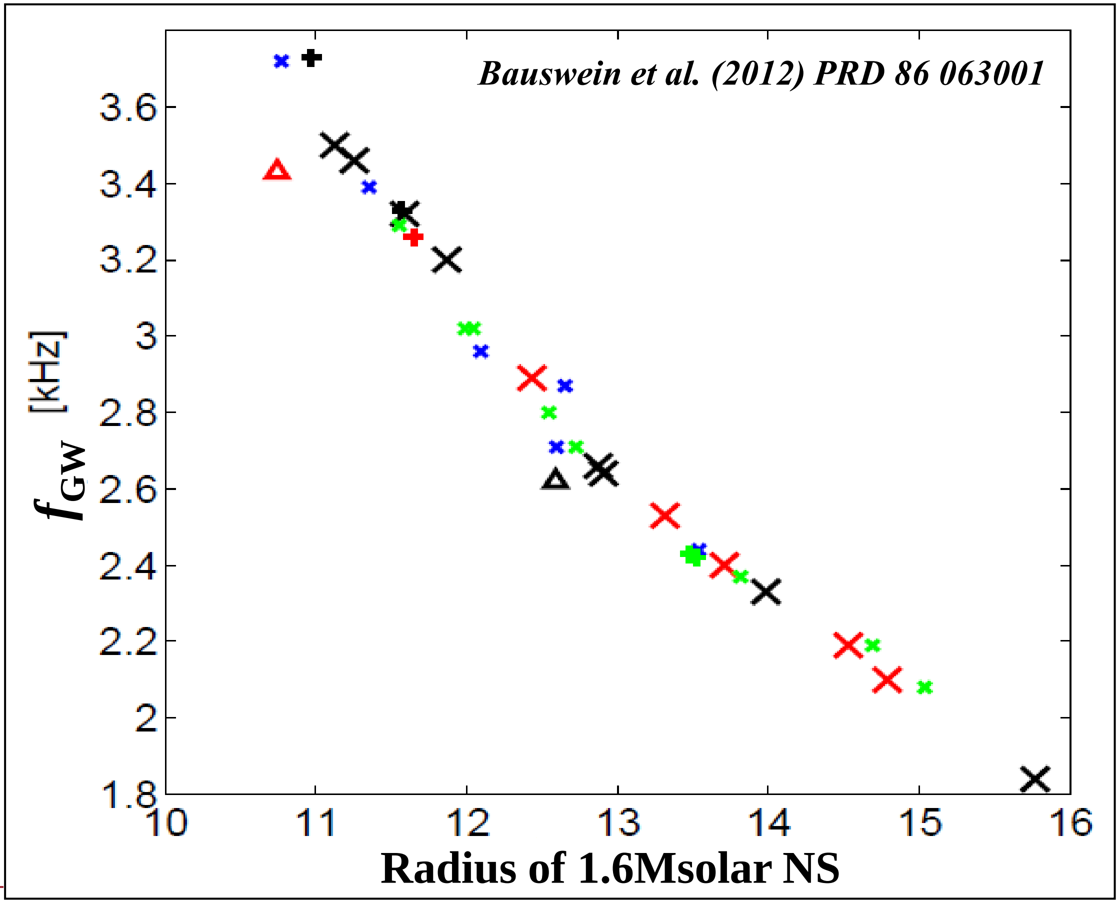




From f_{GW} to NS radius

- stiff EOS ⇒ larger NS radii, smaller mean density ⇒ low f_{GW}
- soft EOS ⇒ smaller NS radii, larger mean density ⇒ high f_{GW}

- **Empirical relation for f_{GW}**
  - Good correlation with
  - radius of 1.6Msolar NS
    - ***Bauswein et al. (2012) PRD 86 063001***
  - radius of 1.8Msolar NS
    - ***Hotokezaka et al. (2013) PRD 88 044026***

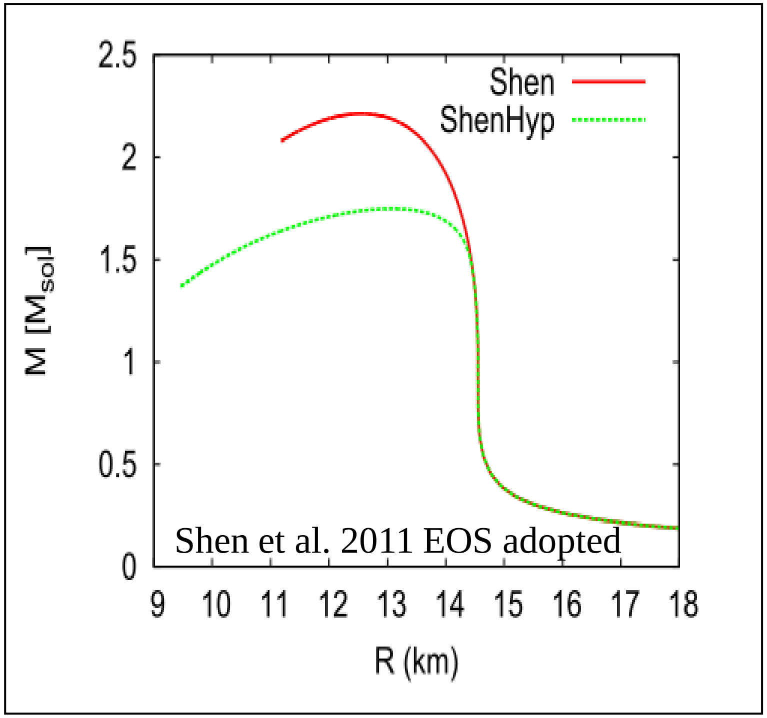


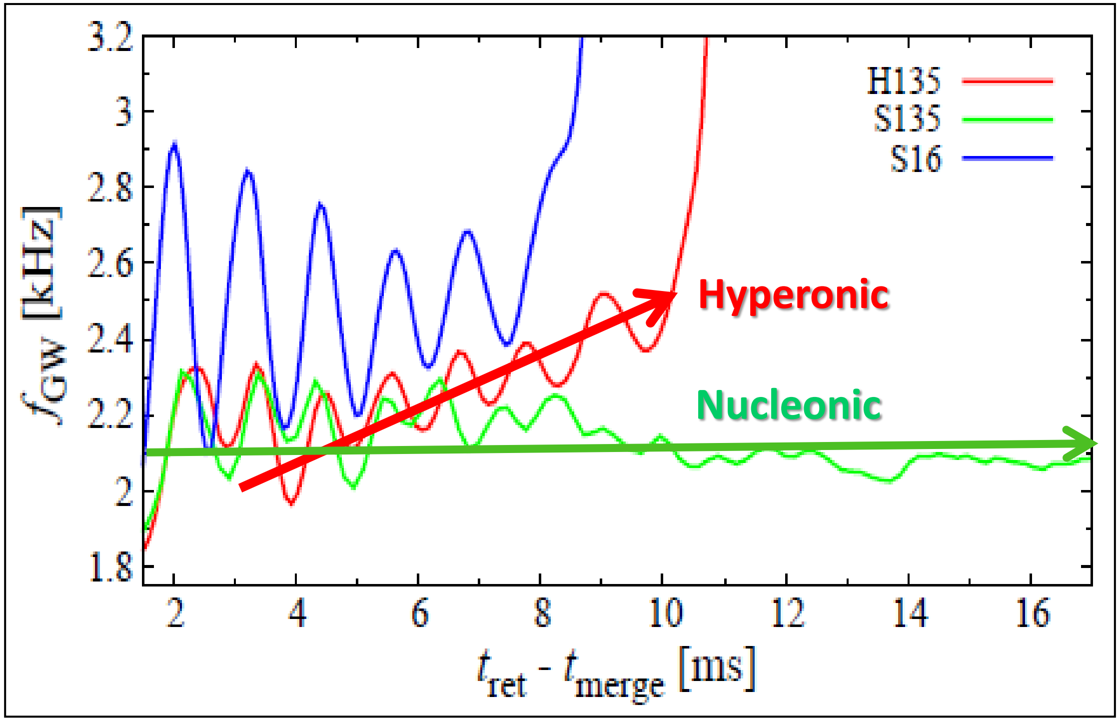
- tight correlation
  - ΔR ~ 1-2km

Sekiguchi et al. (2011)

Emergence of exotic phases imprinted in GW ?

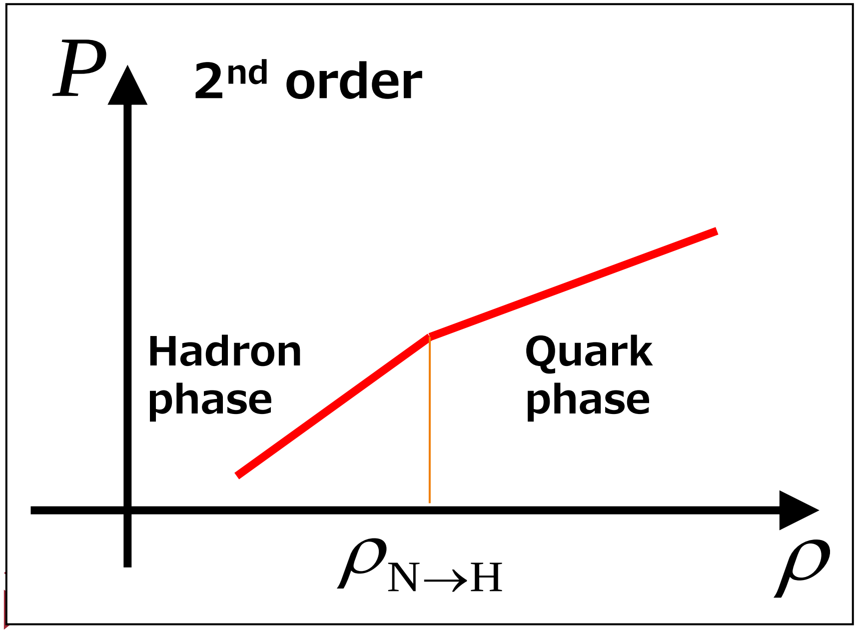
- **Nucleonic** : NS shrinks by angular momentum loss in a **long** GW timescale
- **Hyperonic** : GW emission ⇒ NS shrinks ⇒ More Hyperons appear ⇒ EOS becomes softer ⇒ NS shrinks more ⇒ ....
- **⇒ the characteristic frequency of GW for hyperonic EOS increases with time**
  - ***Could*** provide potential way to tell existence of hyperons (exotic particles)

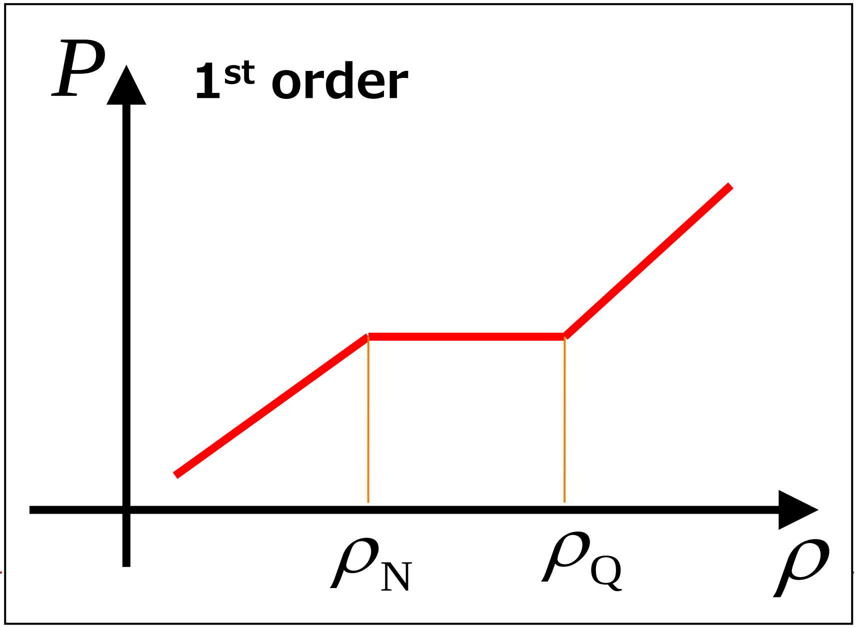




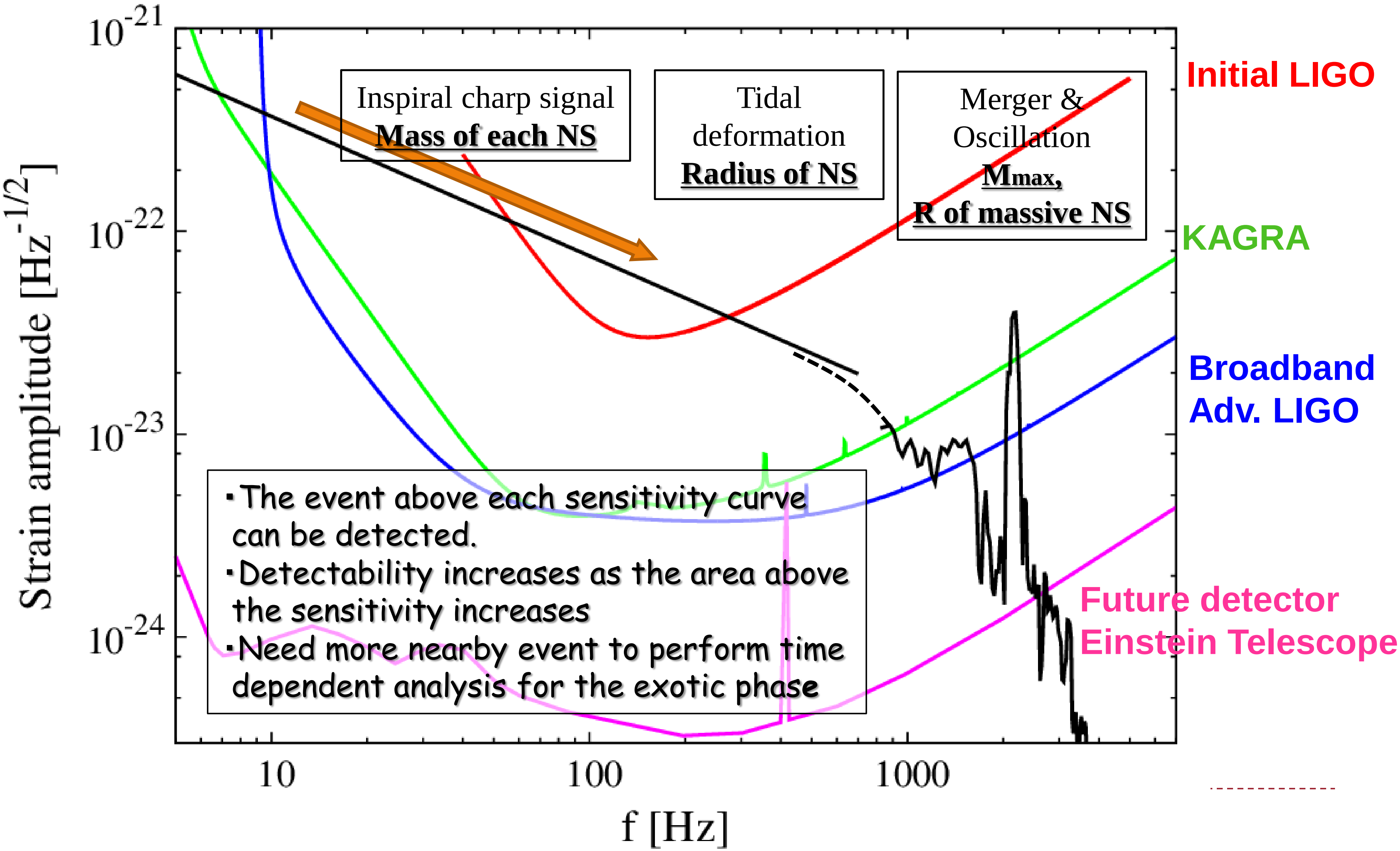
Further possibility ?

- Exploring quark-hadron phase transition by GWs
  - 2^{nd} order (like hyperons) $\Rightarrow$ frequency shift in time
  - 1^{st} order $\Rightarrow$ frequency may jump **NS** to **quark star**
    $\Rightarrow$ **double peak in GW spectra ?**
- We need a good quark-hadron EOS: Could you provide it ?



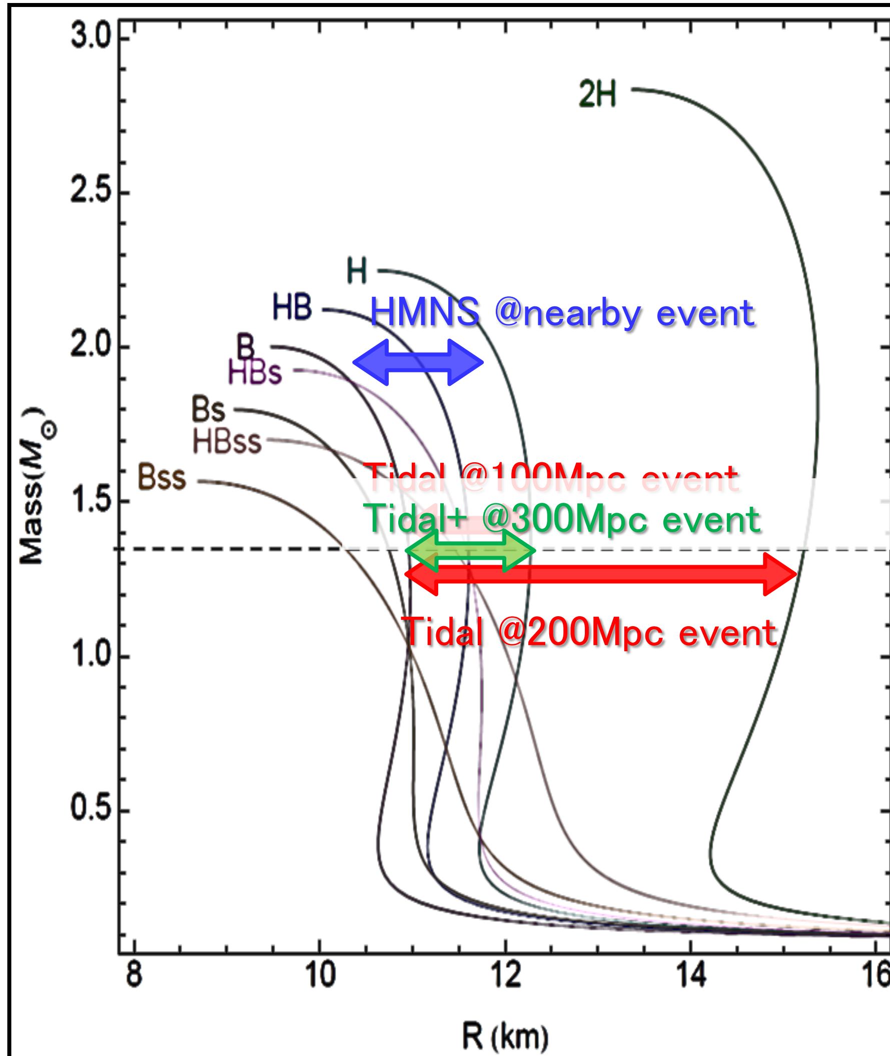


An example of expected GW spectrum：
BNS 1.35-1.35Msolar optimal @ 100Mpc



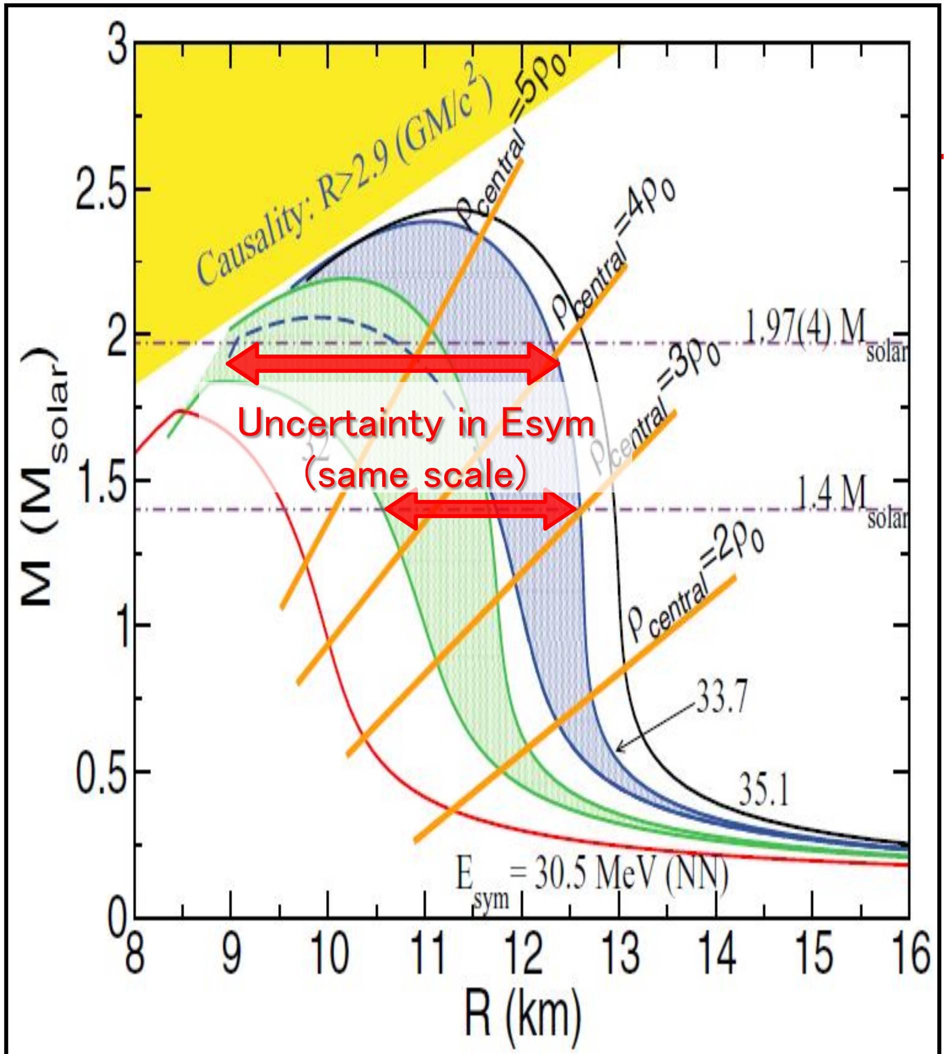
Constraints on NS radius by GW using next generation detectors (adv. LIGO, adv. VIRGO, KAGRA)

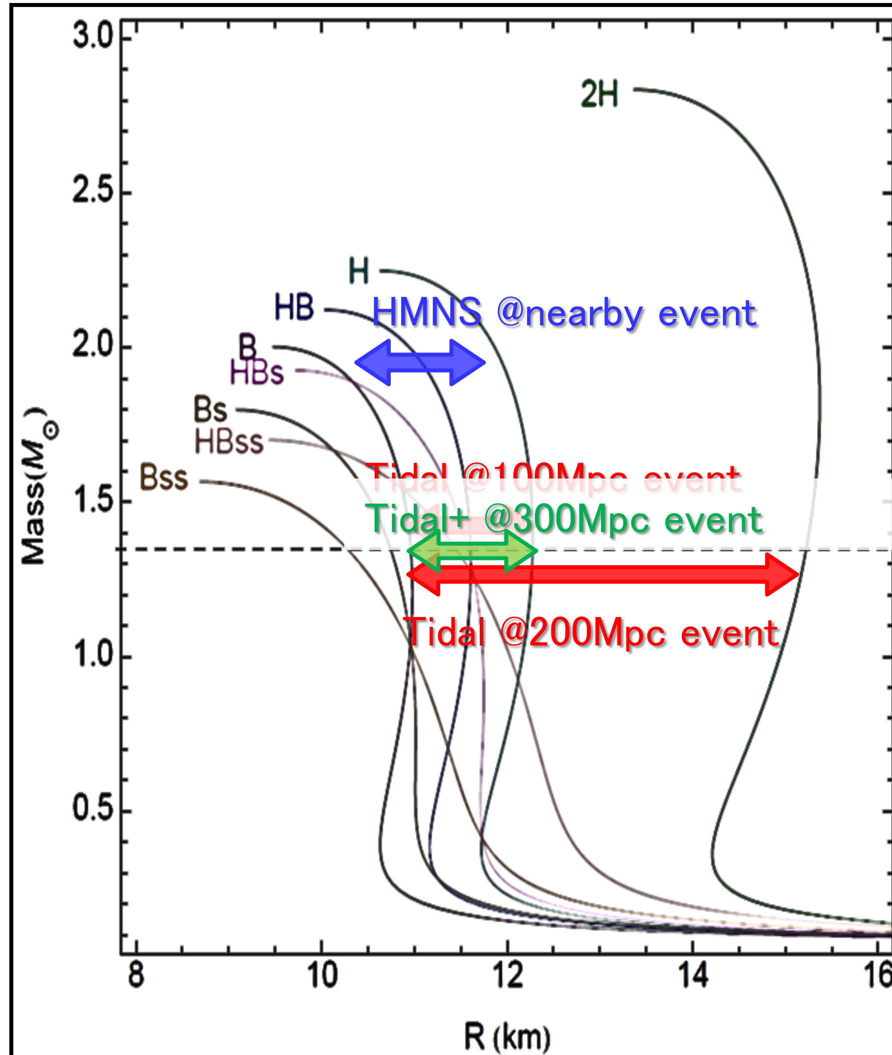
- Tidal effect *(Read et al. (2013) PRD 88 044042)*
  - **ΔR ~ 1km for canonical NS (1.35Msolar) @ 300 M light yr event**
  - **ΔR ~ 4km for canonical NS @ 600 M light yr event**
- Oscillation of MNS *(Bauswein et al. (2013); Hotokezaka et al. (2013)*
  - **ΔR ~ 1km for massive NS (>2.6Msolar) @ < 100 M light yr**
  - *a very simple estimate*



- Numerical + Analytic GW
  - Tidal effect *(Read et al. (2013) PRD 88 044042)*
    - **ΔR ~ 1km for canonical NS (1.35Msolar)@ 1 G light yr event**
- **event rate: 1—100 events/yr for 1 G light yr ⇒ GW astronomy !**

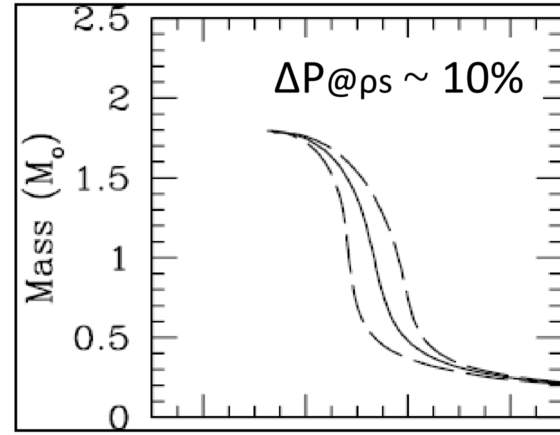
Constraints on NS radius by GW using next generation detectors (adv. LIGO, adv. VIRGO, KAGRA)



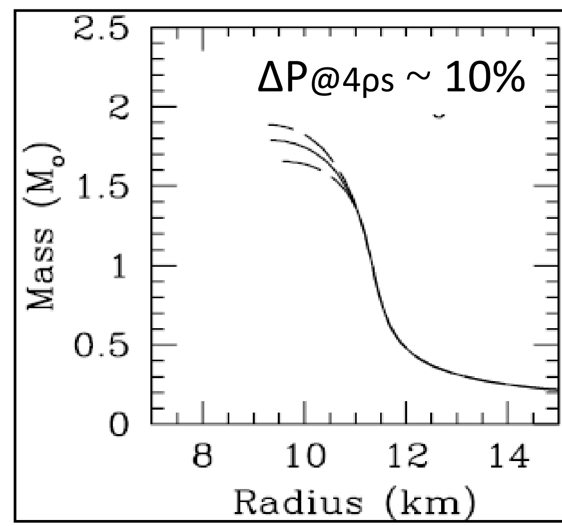


NS mass/radius measurement: GW vs. EM

- **GW : Simultaneous mass and radius measurement**
  - **Inspiral waveform naturally provides the mass** of each NS
  - Degeneracy of M and R in EM observations : additional information (assumption) required
- **GW : contains multiple information**
  - Tidal deformation (radius) : lower (~ρs) density
  - Oscillation of NS after the merger : higher density
  - Maximum mass : highest density
- **Simple in a complementary sense**
  - GW : quadrupole formula, no interaction with matter
    - EOS (what we want to know) is only uncertain (**provided GR is correct and GWs are detected**)
  - EM : a number of parameters, models
    - Atmosphere, distance, column density, B-field, fc, … (recent debate : Ozel et al., Steiner&Lattimer, Guillot et al.)



Radius is sensitive to relatively low density parts

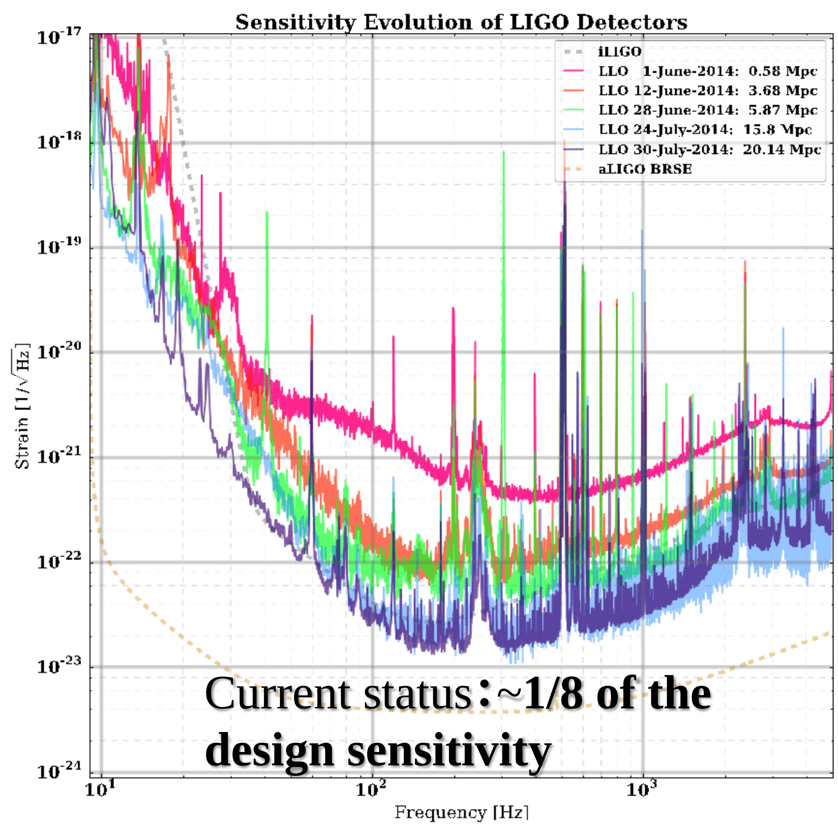


Maximum mass depends on most dense parts

Ozel & Psaltis 2009

When will GWs be detected ?

- Event rate expected next generation detectors (events/yr)
  LIGO-Virgo Scientific Collaboration 2010 (NS: Neutron Star, BH: Black Hole)
  - **NS-NS : 0.4 ~ 40** **BH-NS : 0.2 ~ 10** **BH-BH : 0.1 ~ 20**
- Expected schedule when the designed sensitivity is achieved
  - Adv. LIGO : **2016~2017**
  - Adv. Virgo : 2017~2018
  - KAGRA : 2017 ~ ?
- Sensitivity improved continuously
  - Twice the sensitivity (distance), event rate (volume) becomes 8 times
  - NOW：0.0008 ~ 0.08 (events/yr)
  - It is not surprising even if GWs are detected in the next year !



Current status：~1/8 of the design sensitivity

GWs may be detected in next 1-2 years if we are lucky

Summary

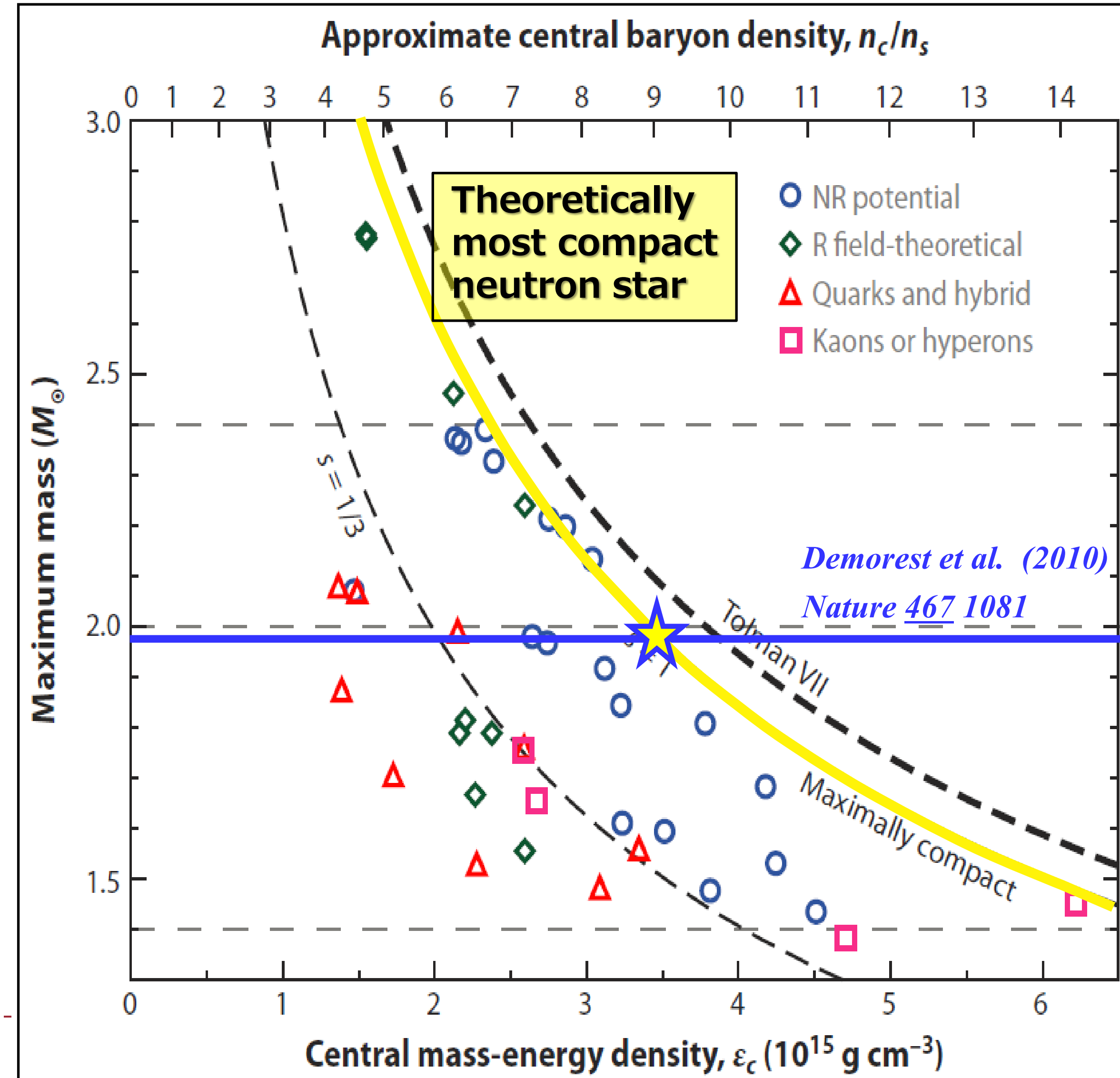
- Neutron star (NS) structure and EOS
  - One-to-one correspondence between M-R and EOS
  - NS radius is sensitive to the symmetry energy

- GWs from binary NS mergers and EOS
  - Tidal deformation : information of EOS @ ρs, tight constraint
  - Oscillation of NS : information of EOS @ higher densities
  - Maximum mass : information of EOS @ highest part
  - Time dependent analysis : constraint on exotic phase ?

Appendix

To which density can we explore by (stable) NS ?

- Theoretically most compact NS structure
  - achieves highest density
- Heaviest NS so far ~2Msolar
- ⇒ up to n~9ns
  - Further regimes could be studied by BH formation, NS-NS collision
  - EOS based on relativistic mean field are stiff and maximum density achieved tends to be low
  - EOS which can support 2Msolar NS is close to maximally compact



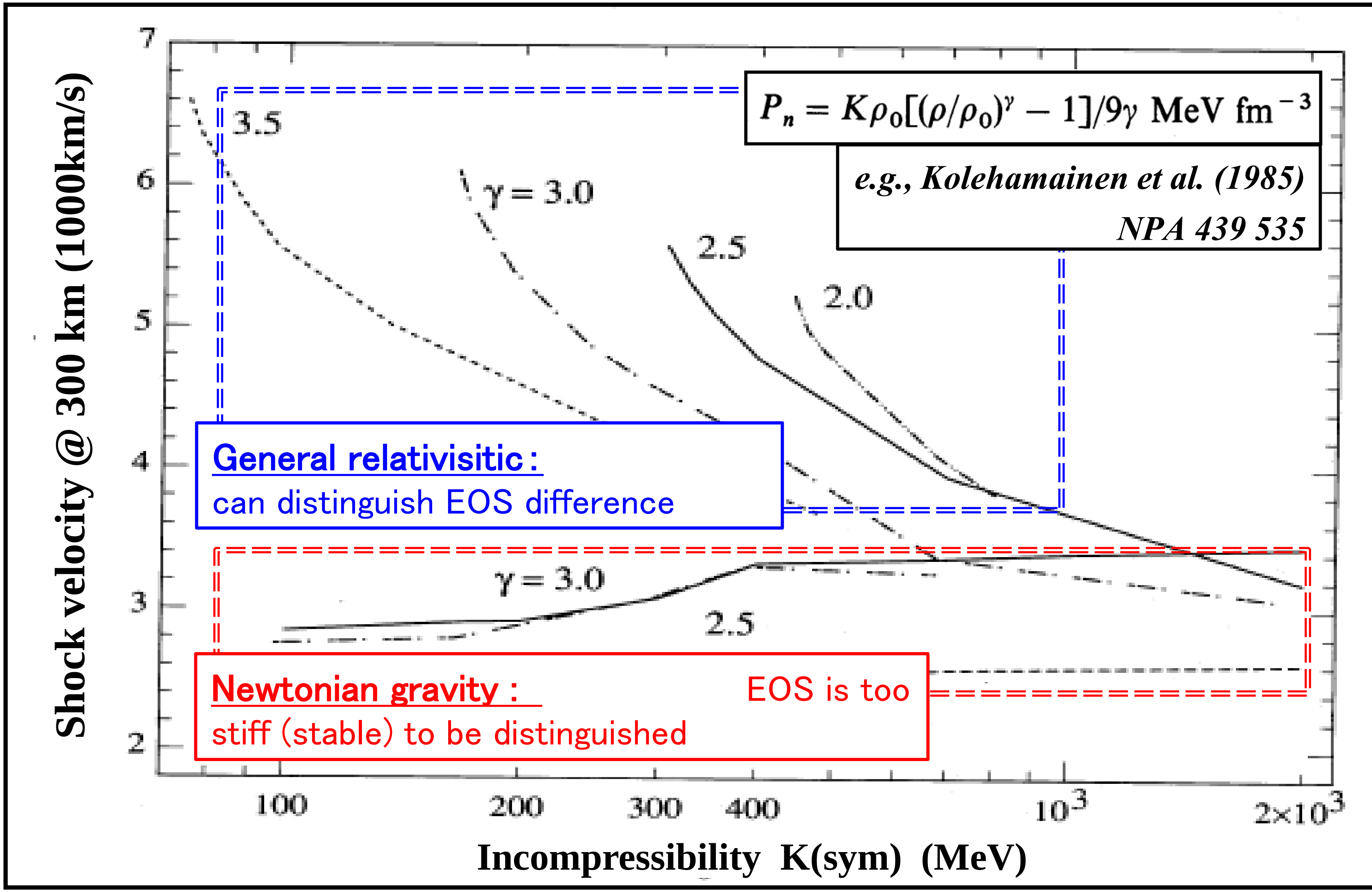
Shibata et al. 2006; Sekiguchi et al, 2011; Hotokezaka et al. 2013; Kepran et al 2014

Maximum mass of HMNS

- $$M_{\rm crit} \approx M_{\rm max,sph.cold.NS} + \Delta M_{\rm rot}^{\rm rigid} + \Delta M_{\rm rot}^{\rm diff} + \Delta M_{\rm thermal}$$
  - $M_{\rm max,sph.cold.NS}$: maximum mass of spherical NS at $T = 0$, depends on EOS
    - Most massive NS accurately observed : 1.97 Msolar (Demorest et al. 2010)
  - $\Delta M_{\rm rot}^{\rm rigid}$: effects of rigid rotation $\sim O(10\%)$
  - $\Delta M_{\rm rot}^{\rm diff}$: effects of differential rotation typically $\sim O(10\%)$
  - $\Delta M_{\rm thermal}$: effects of finite temperature $\sim O(10\%)$
    - HMNS formed after the merger is very hot as $T \sim O(10\,\mathrm{MeV})$
- The enhancement parameter : k $$M_{\rm crit} \approx k\, M_{\rm max,sph.cold.NS}$$
  - 1.4 < k < 1.7 (depend strongly on EOS and weakly on mass ratio)

Importance of GR

van Riper (1988) ApJ 326 235



Importance of *T* and microphysics

- High density (>10^{12} g/cc) and T (> 1-10 MeV) regions
  - $\lambda_\nu >> \lambda_\gamma, \lambda_e \Rightarrow$ neutrinos drive the thermal / chemical evolution
    - 99% of energy released *in ste*
    - **Neutrino : Weak interactio**
    - Strong dependences of weak
- NS-NS, BH-NS mergers (*T*
  - Inspiral : NS is cold ($k_B T/ E_F$
  - Meger : Compression, shock
  - **Prompt BH formation ⇒ h**
    - **Effects of finite temperature**
  - **HMNS, late time BH, and n**
    - **Shock heating, neutrino cooli**