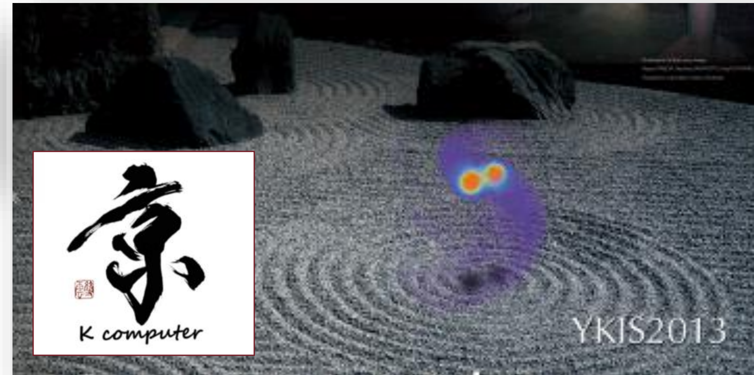


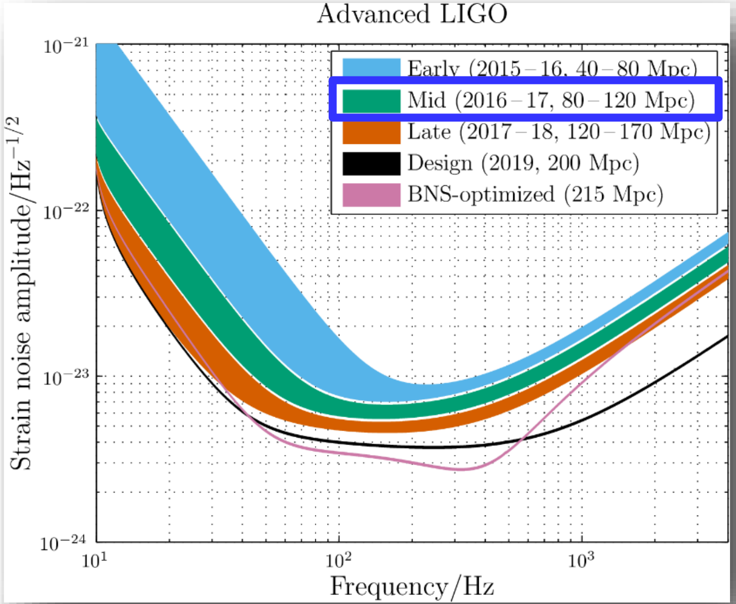
The 34th Reimei Workshop "Physics of Heavy-Ion Collisions at JPARC"

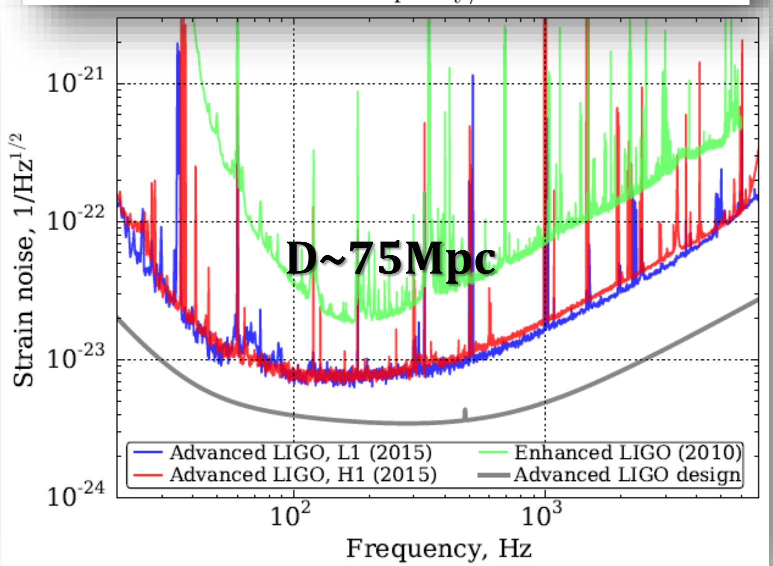
Exploring physics of NS matter by GW from NS-NS merger

Yuichiro Sekiguchi (Toho Univ.)

The First Word: GW astronomy era comes !

- **GW150914** : The first direct detection of GWs from **BH-BH**
  - Opened the era of GW astronomy
- **NS-NS** merger rate based on the observed galactic binary pulsars
  - $\mathbf{8^{+10}_{-5}\ yr^{-1}}$ @95% confidence for adv. LIGO
  - **D = 200 Mpc** (Kim et al. 2015)
- Current status: 75 Mpc (O1:finished)
  - Simple estimation ⇒ $0.3^{+0.5}_{-0.2}\ \mathrm{yr}^{-1}$?
- Planned O2 (2016~) : **80-120 Mpc**
  - $\mathbf{0.5^{+0.6}_{-0.3}\ yr^{-1} \sim 1.5^{+4}_{-1}\ yr^{-1}}$
- **We are at the edge of observing GWs from NS-NS !**





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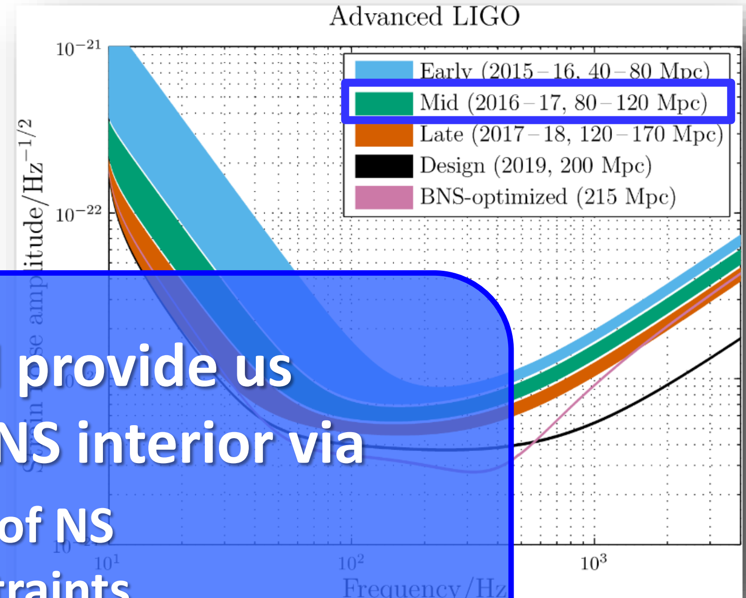
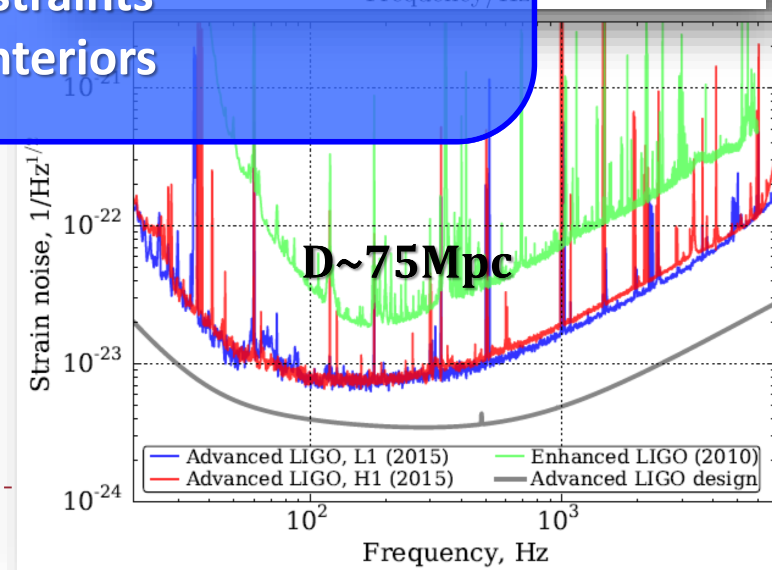
GWs from NS-NS will provide us unique information on NS interior via

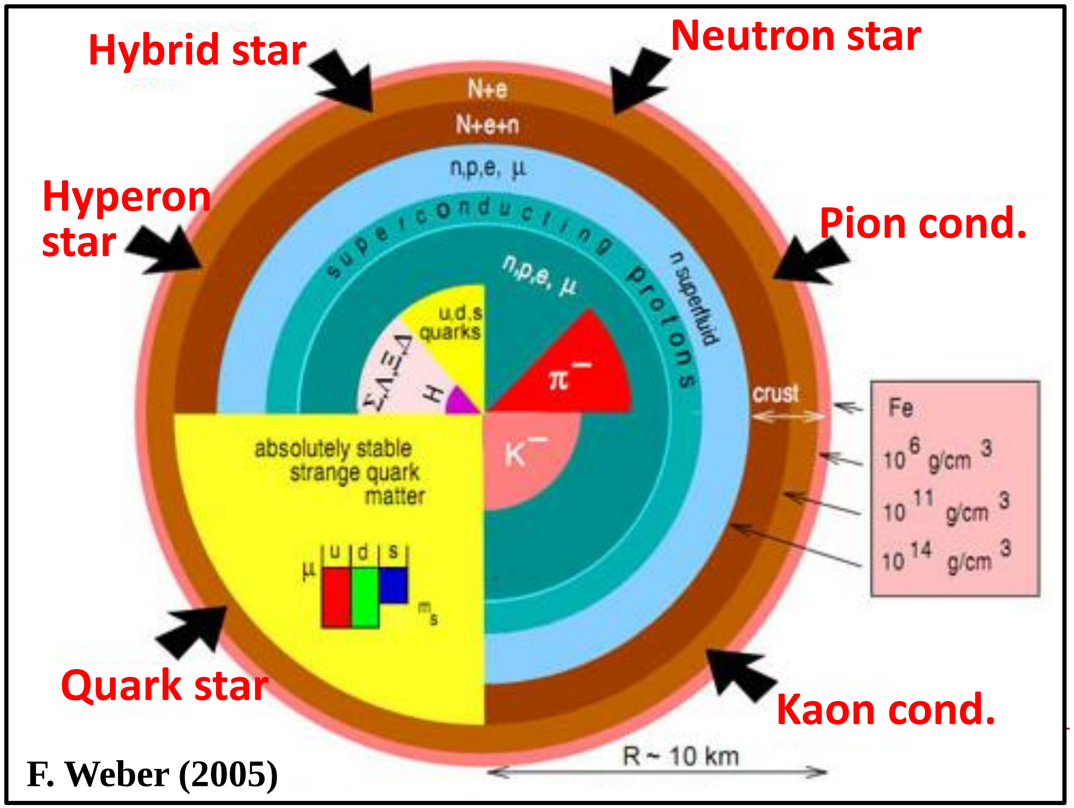
- M and R information of NS
- Maximum mass constraints
- Composition of NS interiors



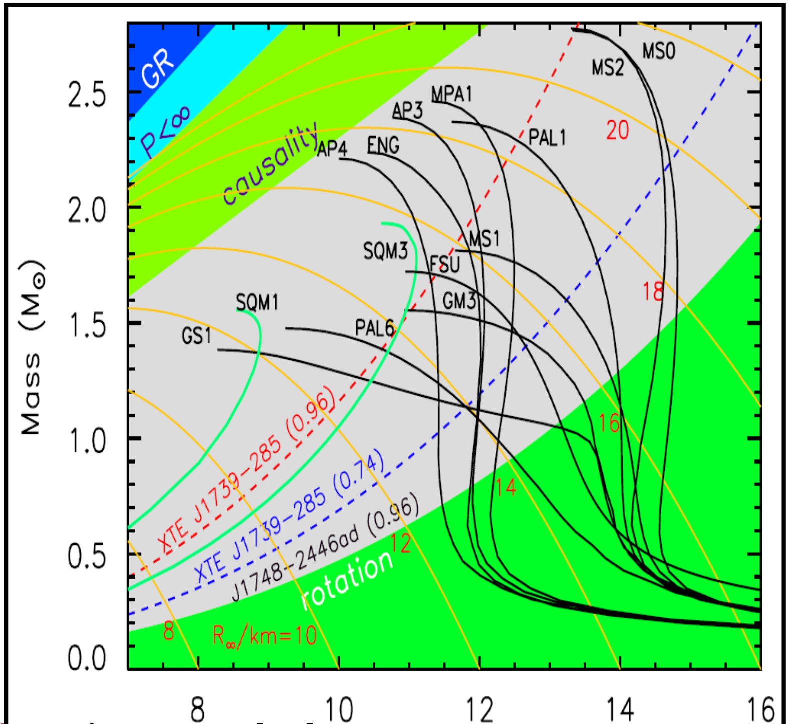


NS structure ⇔ Theoretical model

- Interiors of NS is not completely known : many theoretical models
  - Each model predicts its own equation of state (EOS) with which structure of NS is uniquely determined (model (EOS) ⇒ NS structure)
- Inverse problem : NS structure ⇒ constraining the models/EOS (Physics)
- Studying of NS interior ⇒ exploring a unique region in QCD phase diagram



F. Weber (2005)



Lattimer & Prakash (2007)

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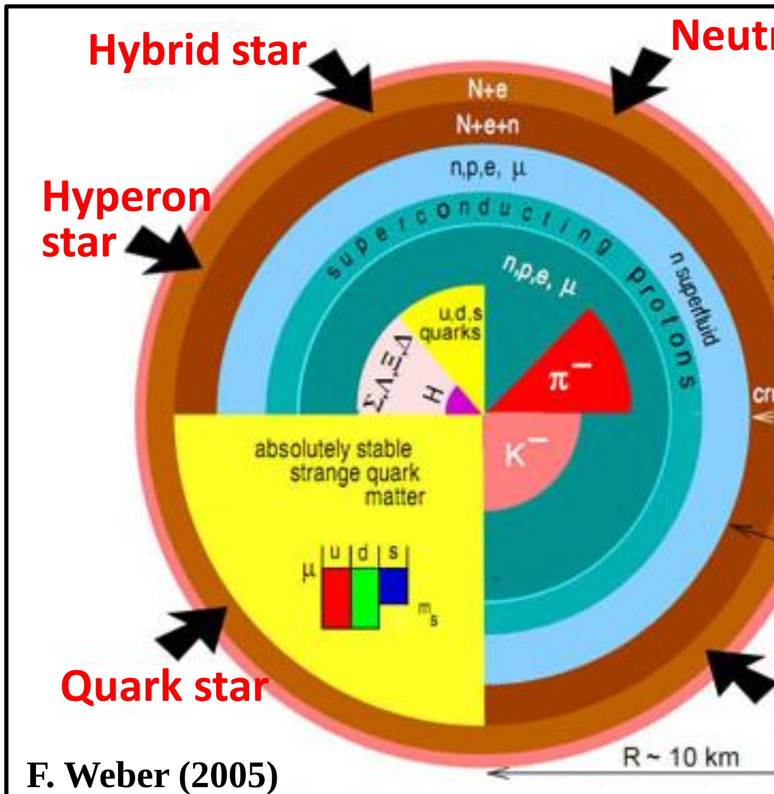
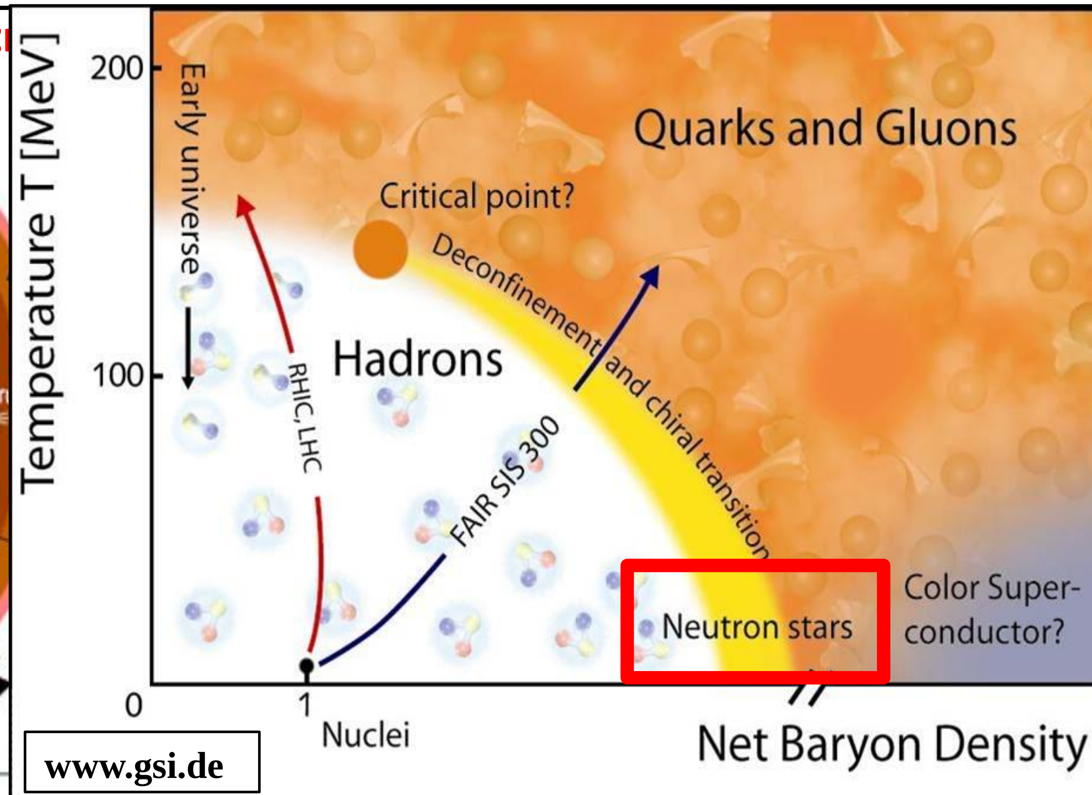




TOV equations : the theoretical basis

- put one-to-one correspondence between EOS ⇔ NS M-R relation
  - Lindblom (1992) ApJ 398 569
- **provide an EOS-characteristic relation between M and R**
  - Newtonian polytrope

$$P = K\rho^{1+1/n} = K\rho^{\Gamma}$$

$$R \propto M^{(1-n)/(3-n)} K^{n/(3-n)}$$

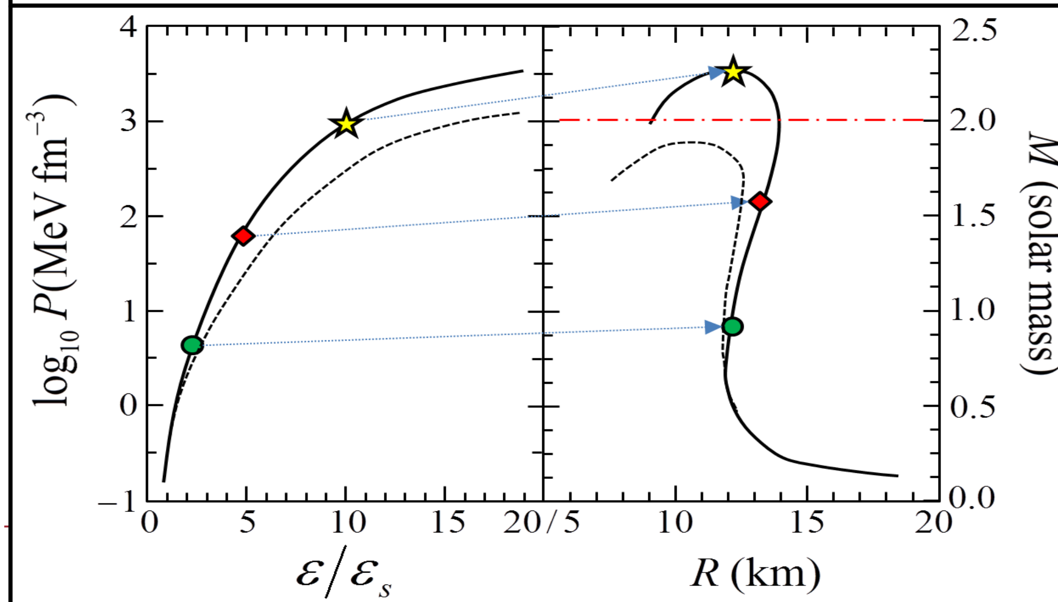
$$\Gamma > 2_{(n<1)} \Rightarrow dR/dM > 0$$

$$\Gamma > 4/3_{(n<3)} \Rightarrow dR/dK > 0$$

  - Softening of EOS (Γ < 2, K↓) ⇒ decrease of R
  - dM/dR determination provides EOS information

Tolman-Oppenheimer-Volkov equations

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



TOV equations : the theoretical basis

- put one-to-one correspondence between EOS ⇔ NS M-R relation
  - Lindblom (1992) ApJ 398 569
- set maximum mass $M_{EOS,max}$ of NS associated with EOS (model)
  - models with $M_{EOS,max}$ not compatible with $M_{obs,\,max}$ should be discarded
- **Impact of PSR J1614-2230 !**
  - M_{NS} = 1.97±0.04 Msun
    - Demorest et al. (2010)
  - M_{NS} is determined kinematically (reliable)
    - Edge on orbit ⇒ M_{tot}
    - Shapiro Time delay ⇒ M_{WD}

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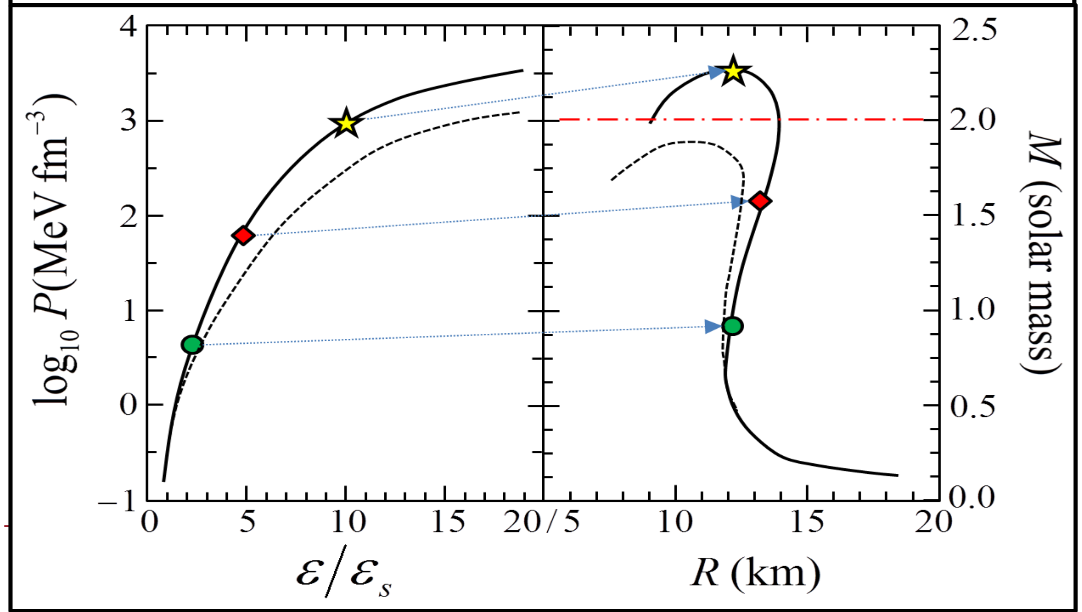

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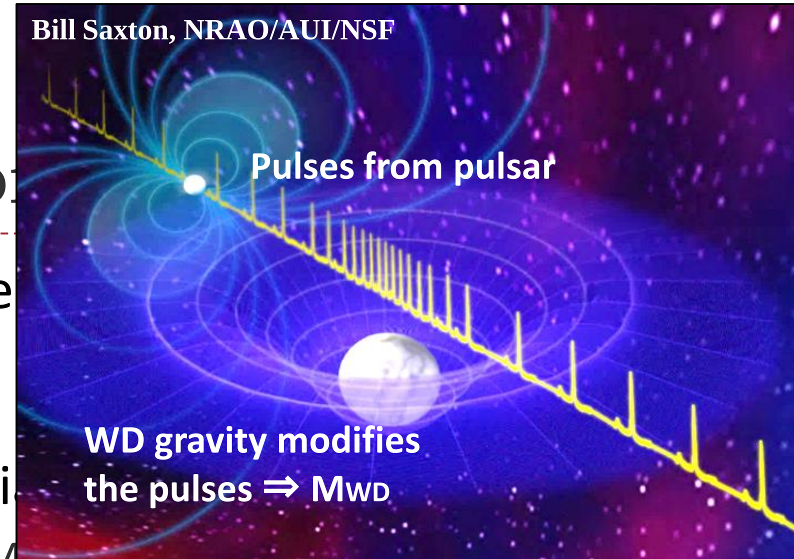
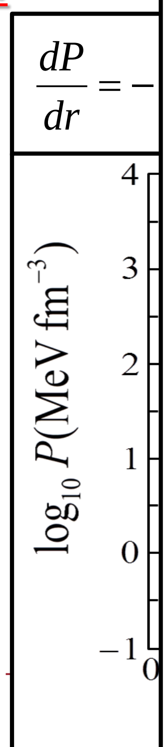
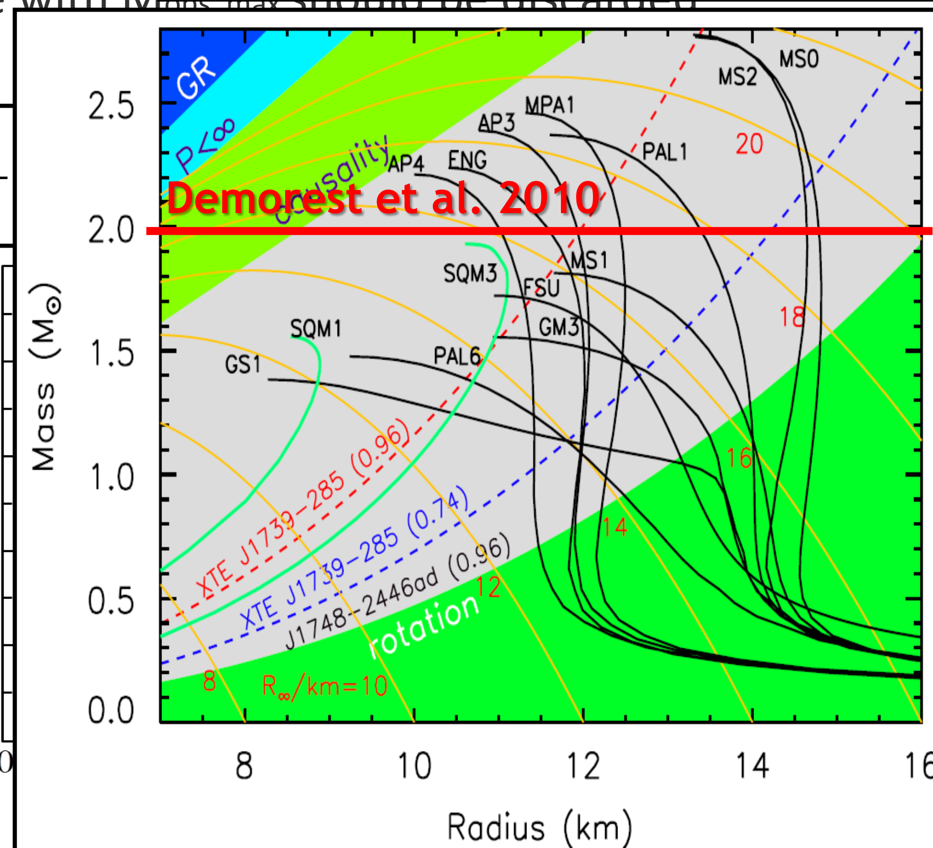
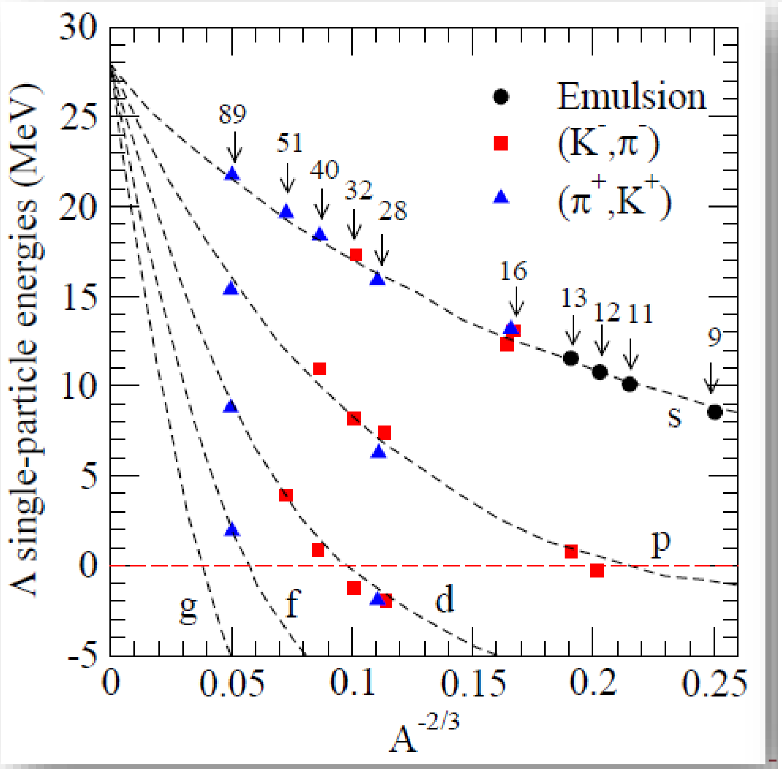




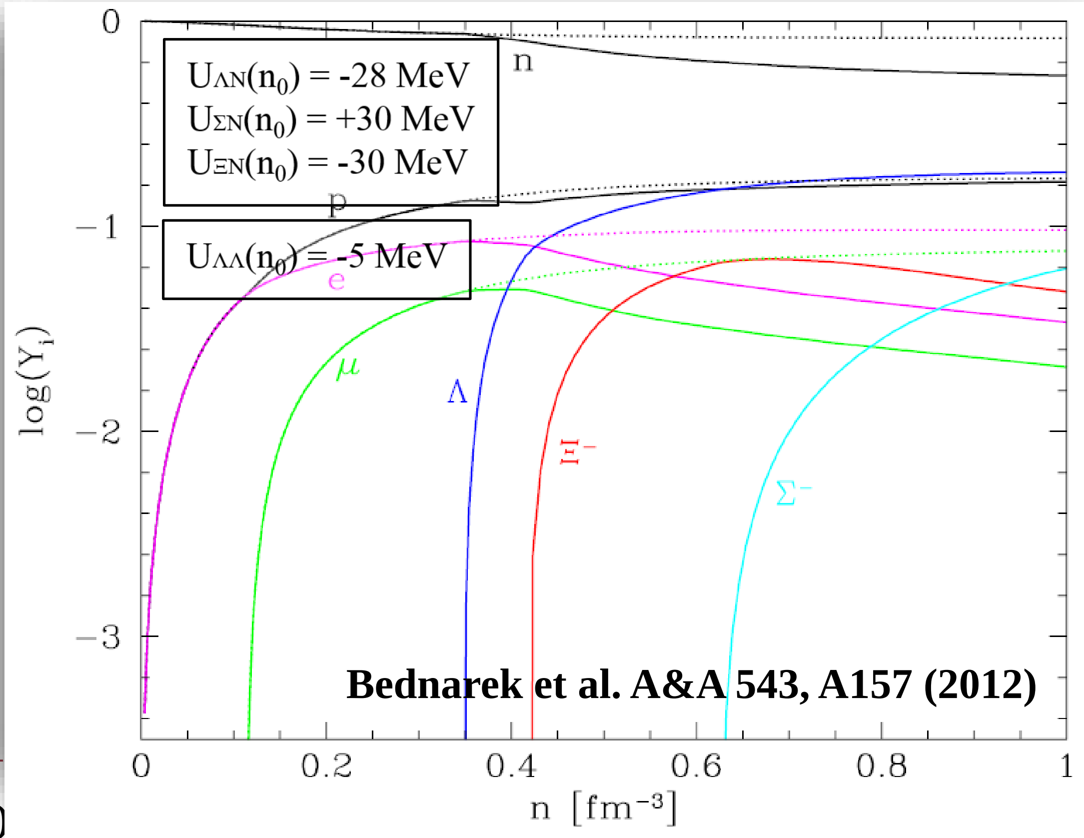


Hyperon/(quark) puzzle and NS radius

- $\mu_n > m^*_{\text{hyperon}}$ in dense nuclear matter inside NS ⇒ hyperons appear ⇒ Fermi energy is consumed by rest mass ⇒ EOS gets softer ⇒ difficult (impossible) to support 2Msun NS (**hyperon puzzle**)



Chatterjee & Vidana EPJA 52, 29 (2016)



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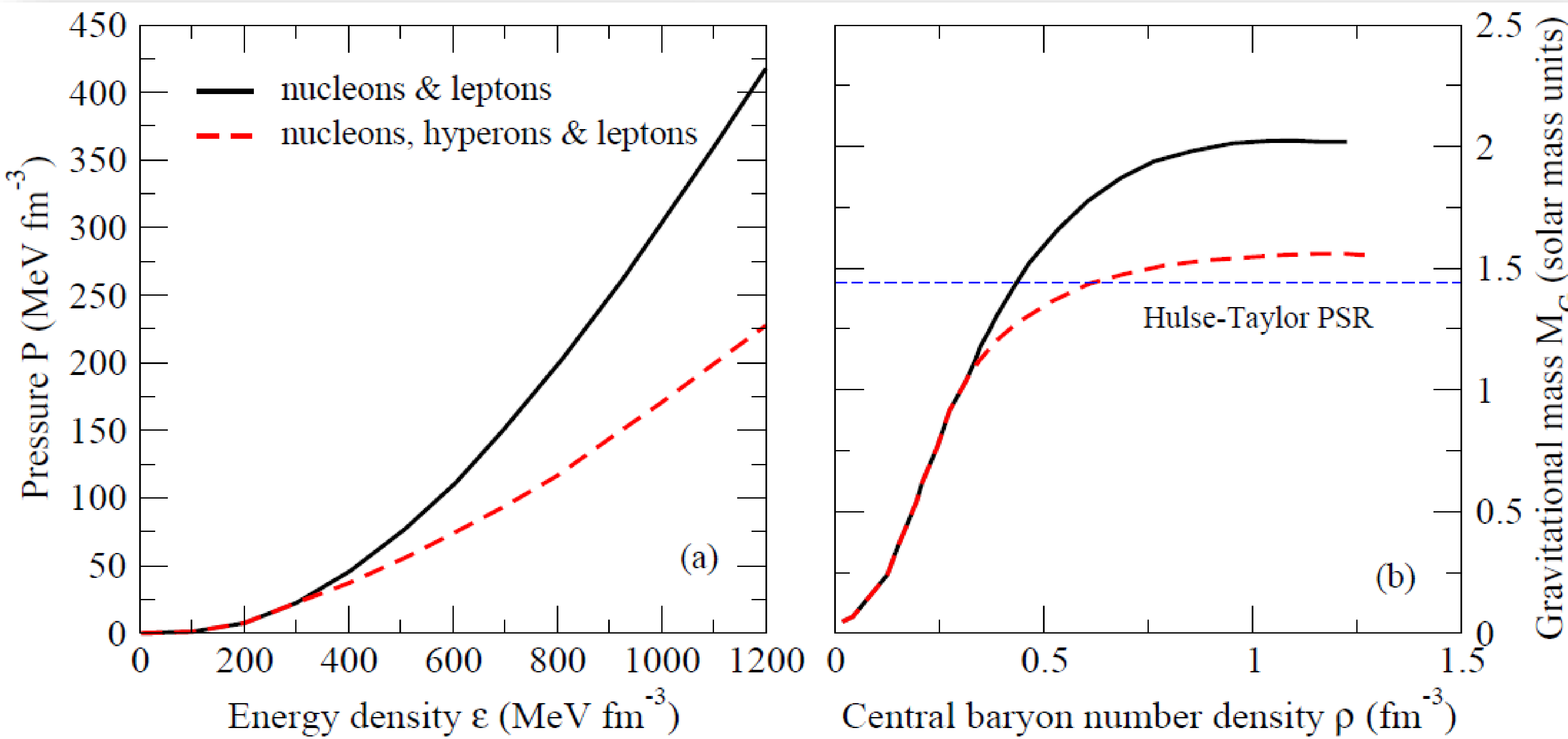
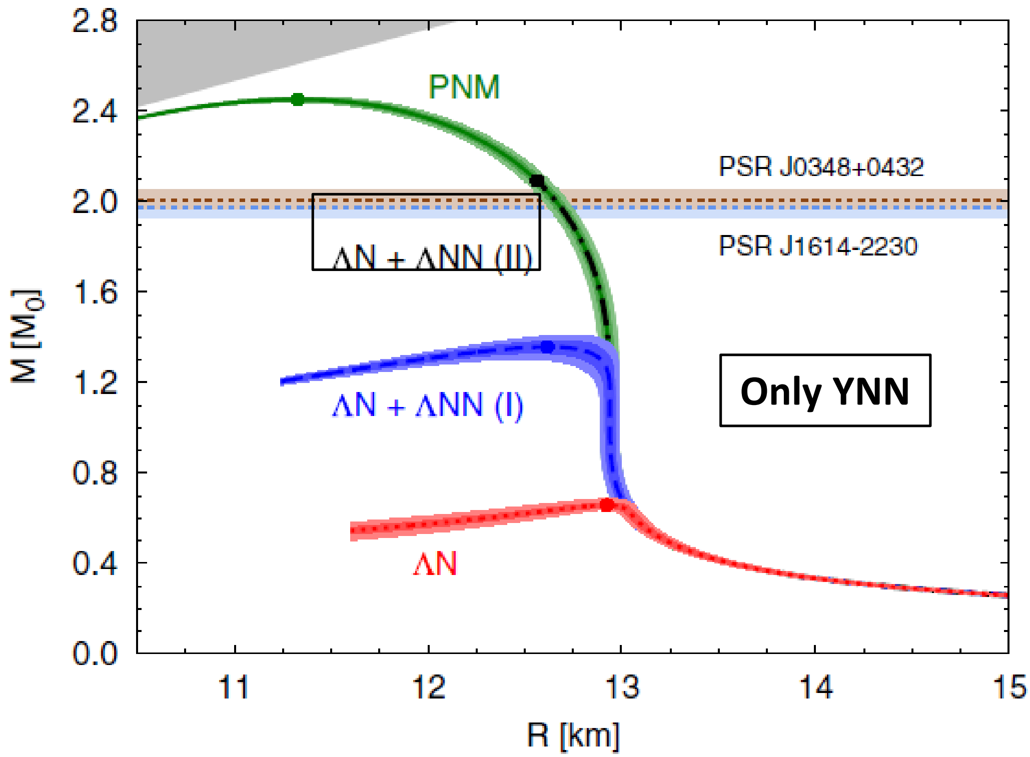


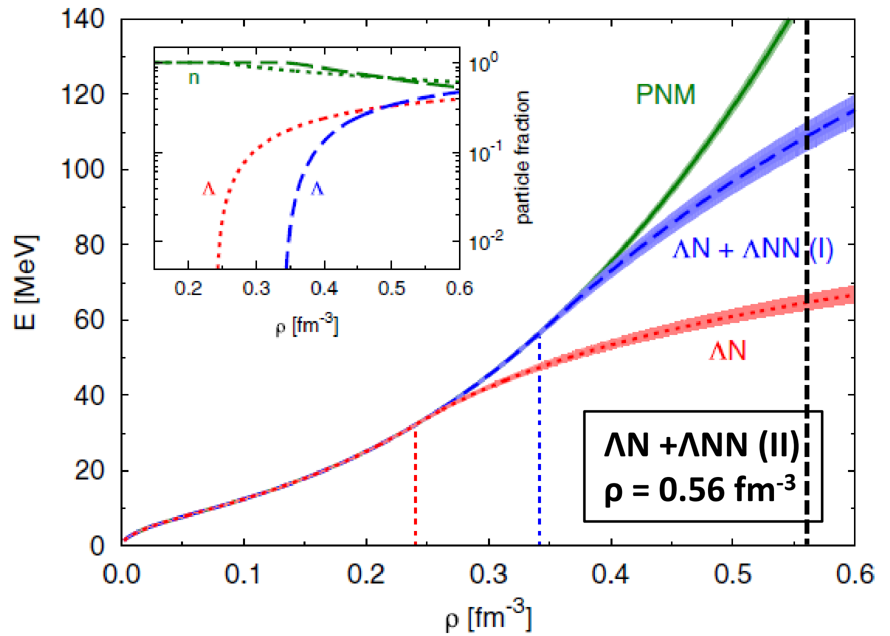
Hyperon puzzle (from a numerical relativist's viewpoint)

- Introduction of (unknown) repulsive interactions : YY, YNN, YYN, YYY
  - delayed appearance of hyperons / reduced pressure depletion
- Stiff nucleonic EOS seems to be necessary : **$R_{1.35}$ > 13 km (YN+YNN)**
  - Softer EOS ⇒ higher ρ for same M_{NS} ⇒ larger hyperon influence

Lonardoni et al. PRL 114, 092301 (2015)

$R_{1.35}$ ~ 13 km : successfully supports NS of $2M_{sun}$ with a hyperon TBF (YNN-II) but failed with YNN-I





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- Stiff nucleonic EOS seems to be
  - Softer EOS ⇒ higher ρ for same M

The authors of Ref. [49] reported a parametrization, hereafter referred to as parametrization (I), that simultaneously reproduces the hyperon separation energy of ${}^{5}_{\Lambda}$He and ${}^{17}_{\Lambda}$O obtained using variational Monte Carlo techniques. In Ref. [34], a diffusion Monte Carlo study of a wide range of Λ hypernuclei up to $A = 91$ has been performed. Within that framework, additional repulsion has been included in order to satisfactorily reproduce the experimental hyperon separation energies. We refer to this model of ΛNN interaction as parametrization (II).

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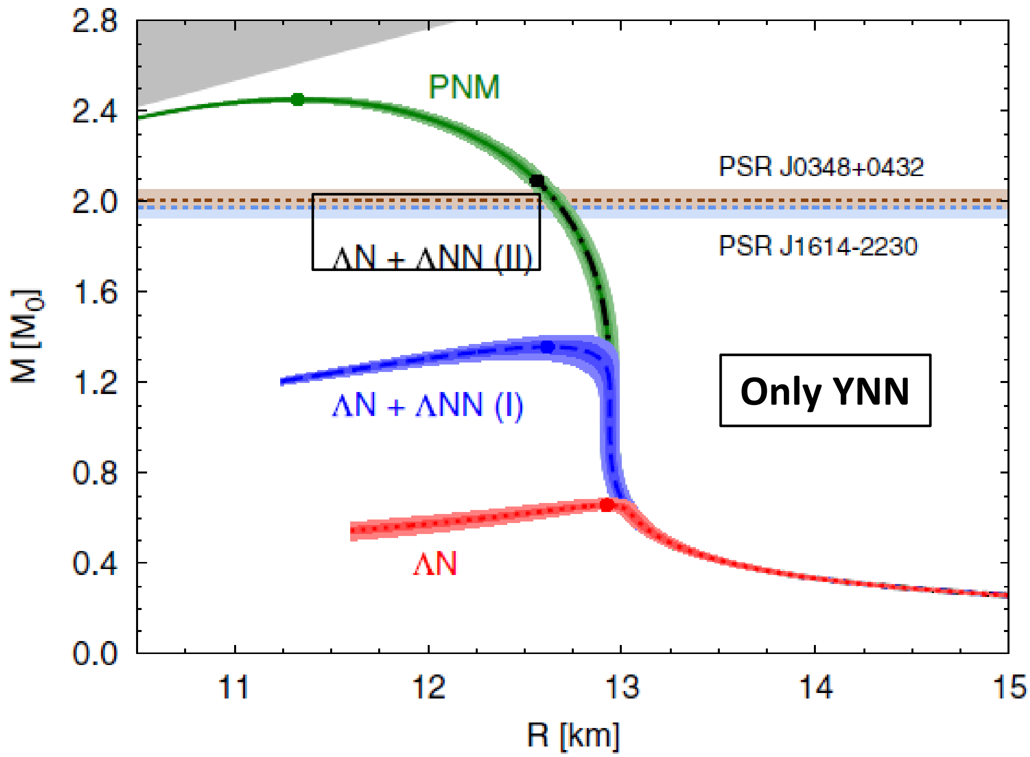

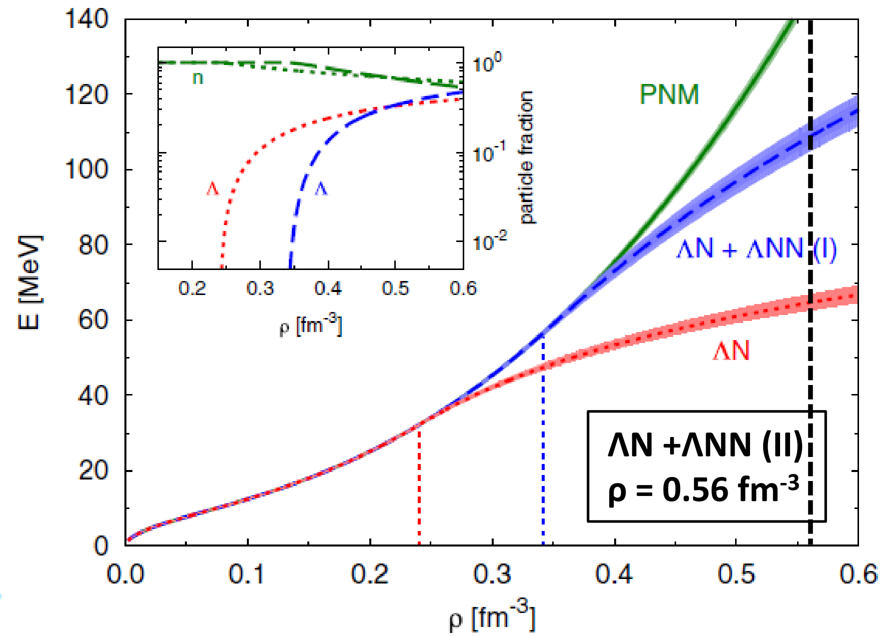

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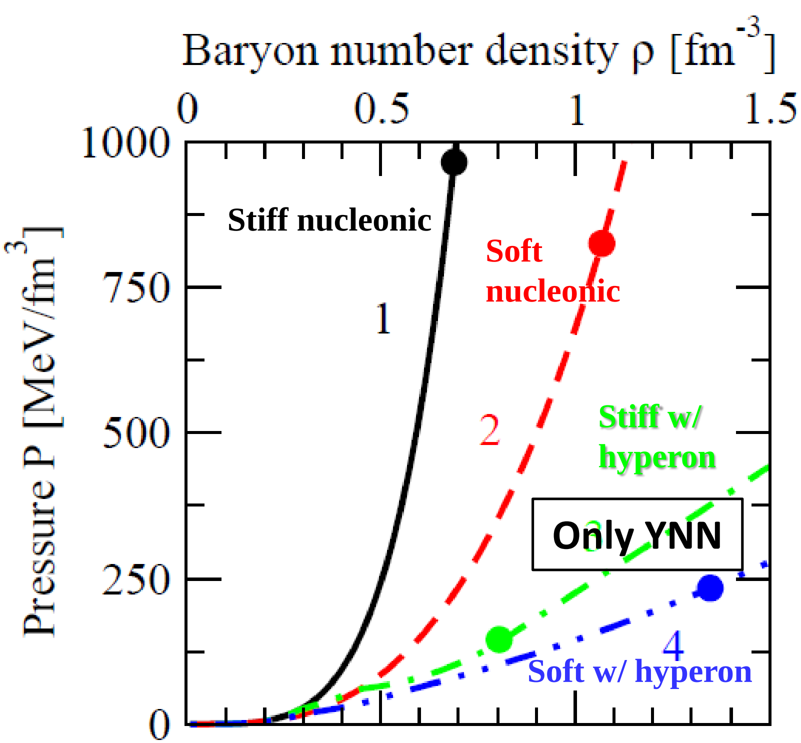
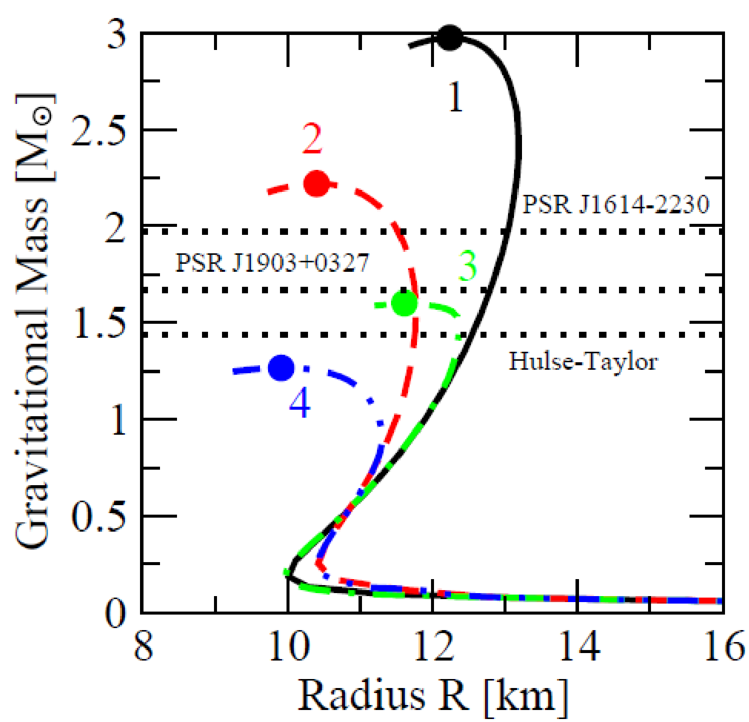
- For a soft nucleonic EOS ($R_{1.35}$ ~ 11.5-12 km), hyperon puzzle may not be resolved even with a very repulsive YNN interaction (Vidana et al. 2011)



Vidana et al. EPL 94, 11002 (2011)

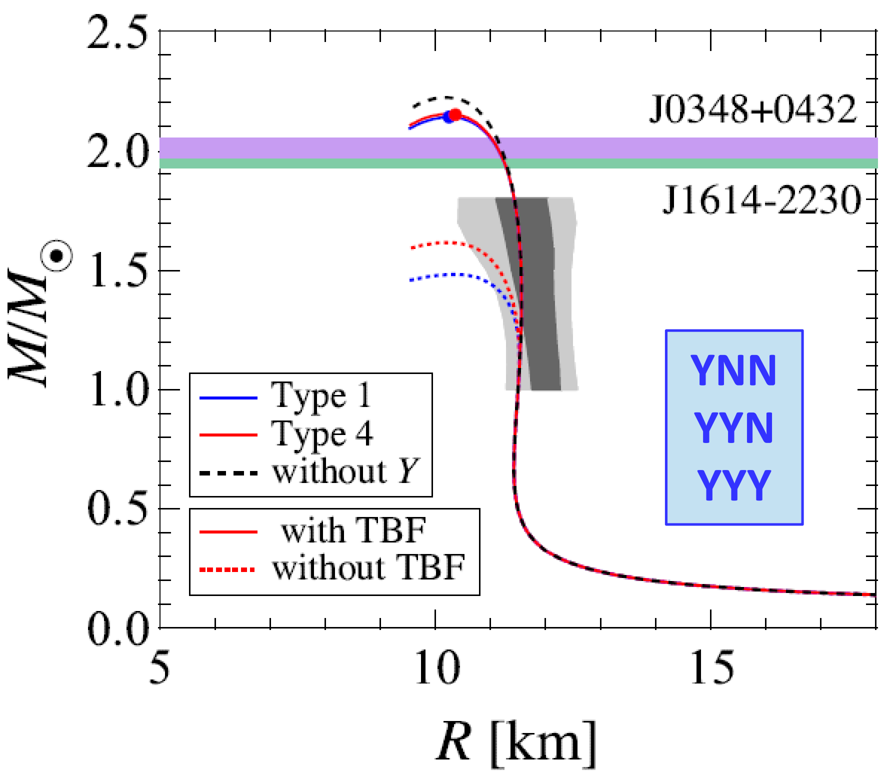
$R_{1.35}$ ~ 11-12 km : fail to support NS of $2M_{sun}$ even with a most repulsive YNN



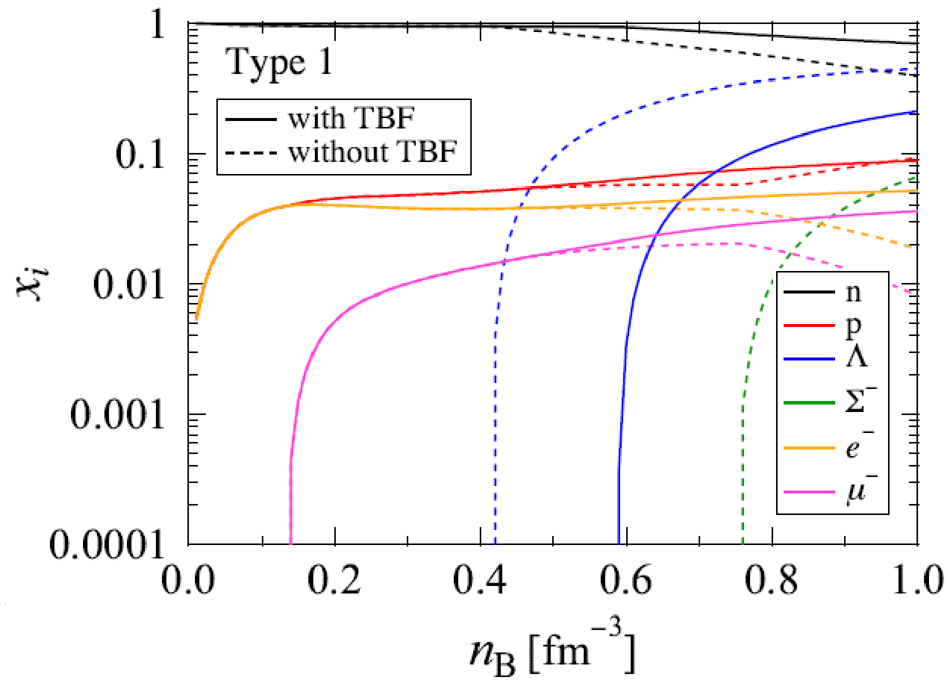
Hyperon puzzle (from a numerical relativist's viewpoint)

- Introduction of (unknown) repulsive interactions : YY, YNN, YYN, YYY
  - delayed appearance of hyperons / reduced pressure depletion
- With YNN, YYN, and YYY, a soft nucleonic EOS ($R_{1.35}$ ~ 11.5-12 km) may be compatible (Togashi et al. 2016)

Togashi et al. PRC 93, 035808 (2016)



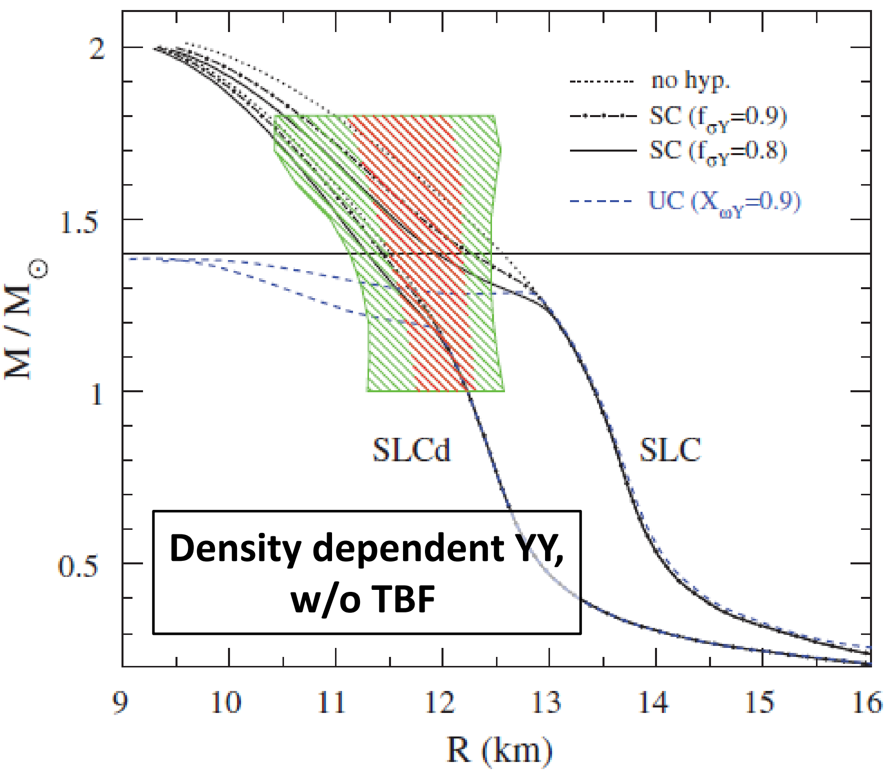
Supports 2Msun NS even in the case of $R_{1.35}$ ~ 11.5 km with YNN, YYN, and YYY
Q. How about $R_{1.35}$ < 11 km case ?



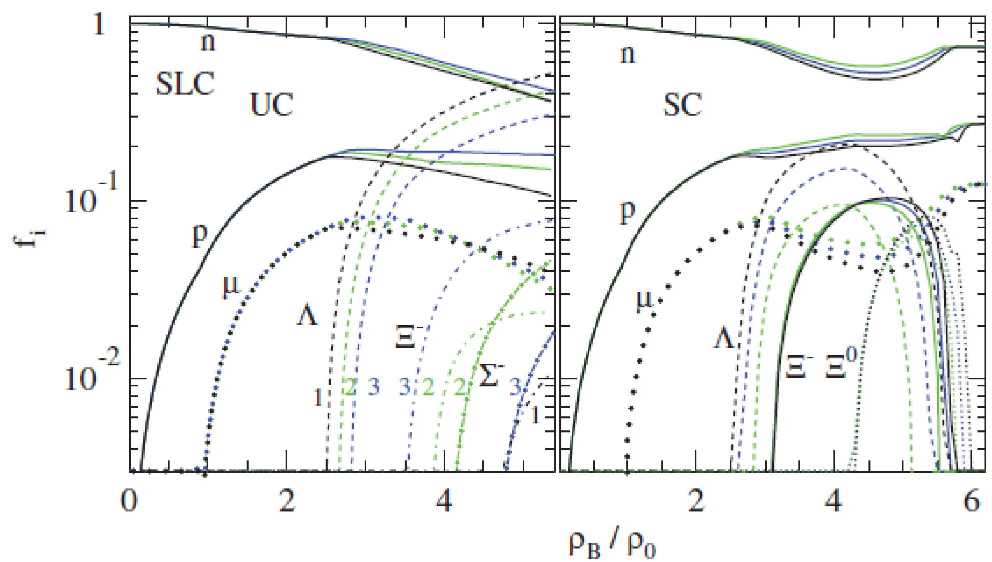
Hyperon puzzle (from a numerical relativist's viewpoint)

- Introduction of (unknown) repulsive interactions : YY, YNN, YYN, YYY
  - delayed appearance of hyperons / reduced pressure depletion
- A density-dependent YY model predicts dM/dR < 0 (Jiang et al 2012)

Jiang et al. ApJ 756, 56 (2012)



Can support 2Msun NS with a stiff nucleonic EOS. But to achieve $R_{1.35}$ ~ 12 km suggested by nuclear experiments & NS observations, need **dM/dR < 0**



Hyperon puzzle (fron

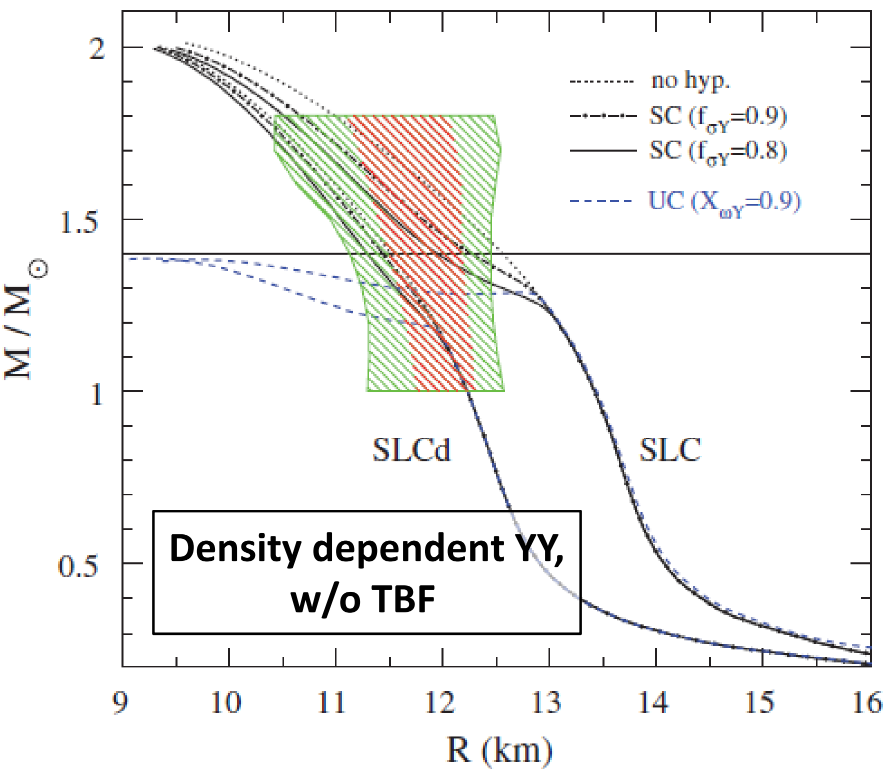
- Introduction of (unknown) re
  - delayed appearance of hyperor
- A density-dependent YY mode

1991; Avancini & Menezes 2006). Considering that the nucleonic sector of our models respects chiral limits at high densities, we assume two cases for hyperons: the usual case (UC) that the hyperons have a similar medium effect to nucleons, and the separable case (SC) that the meson–hyperon coupling constant is separated into density-dependent and density-independent parts regardless of the chiral limit constraint on the strange sector in hyperons. Nevertheless, the hyperon potentials (Millener et al. 1988; Hausmann & Weise 1989; Fukuda et al. 1998),

$$U_{\Lambda}^{(N)} = -30\ \mathrm{MeV} = -U_{\Sigma}^{(N)}, \qquad U_{\Xi}^{(N)} = -18\ \mathrm{MeV}, \qquad (4)$$

in nuclear matter at saturation density are used to preserve the relation between the vector and scalar meson coupling constants.

Jiang et al. ApJ 756, 56 (2012)



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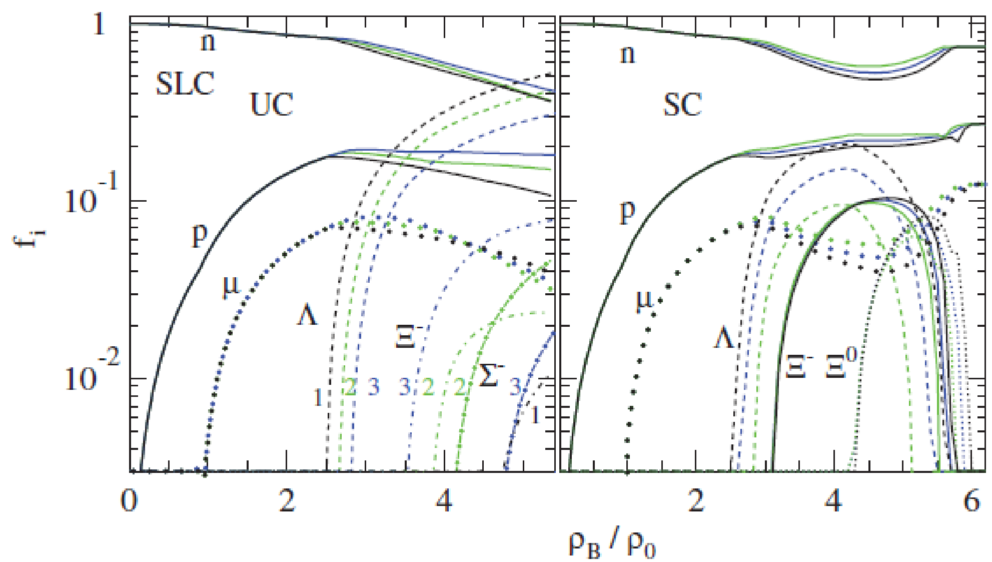
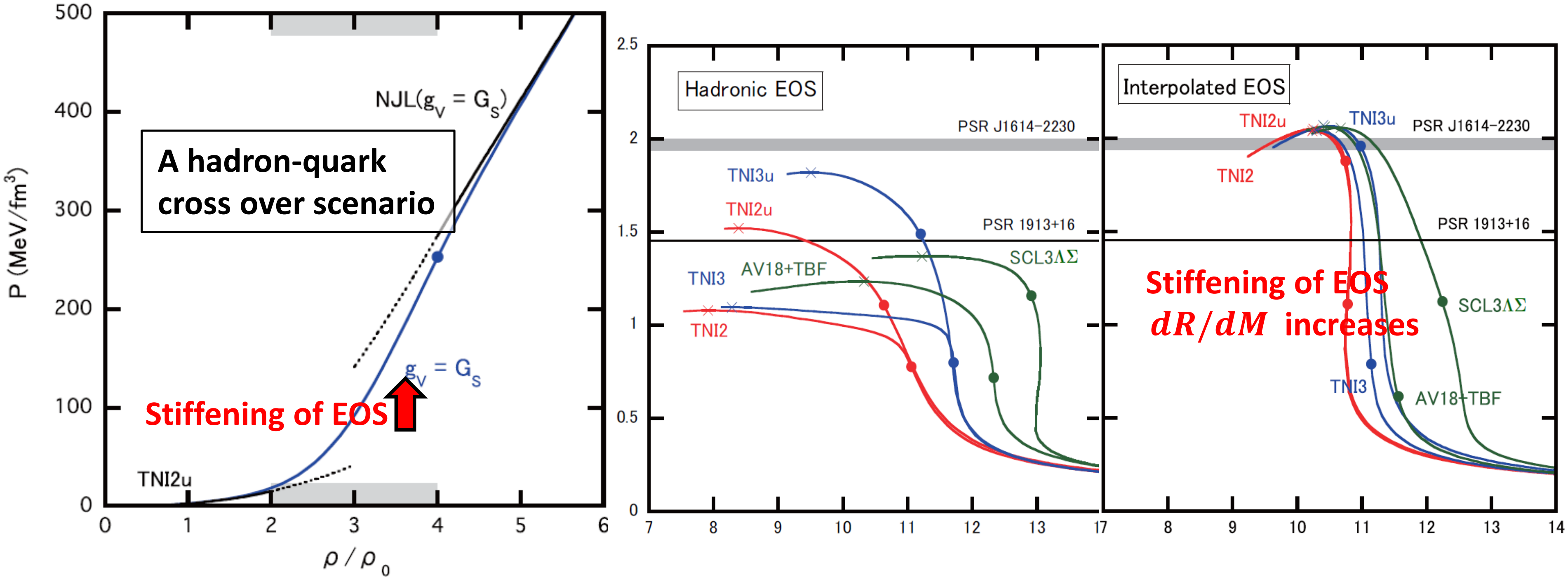


Quark puzzle (from a numerical relativist's viewpoint)

- For strong 1st order phase transition, a stiff nucleonic EOS (R~14 km) seems to be necessary (Blashke's talk)
- Hadron-quark cross over scenario: a soft EOS ($R_{1.35}$ ~ 11-12 km) may be possible; shows stiffening of EOS in intermediate density range
- For APR EOS, dM/dR > 0

Masuda et al. (2013); Kojo et al. (2015); Fukushima & Kojo ApJ 817, 180 (2016)



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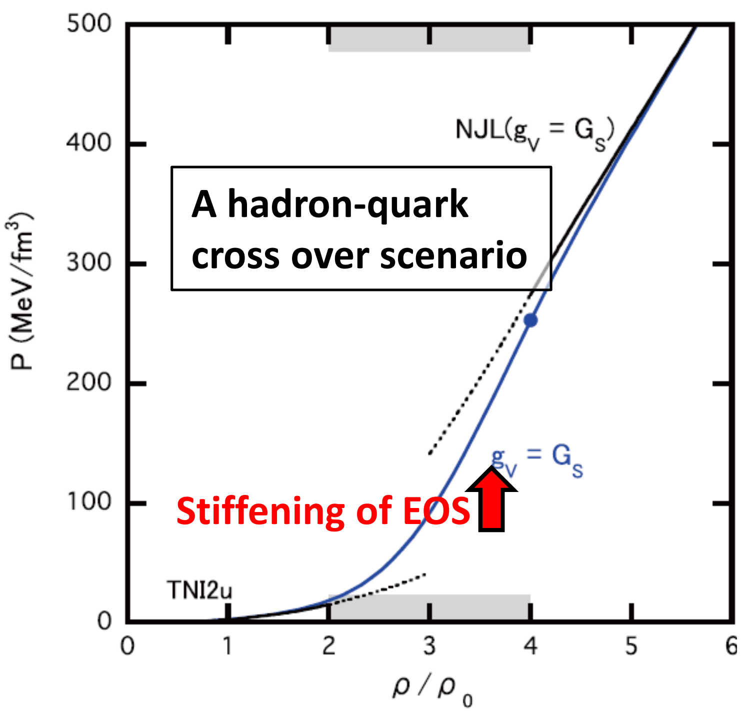
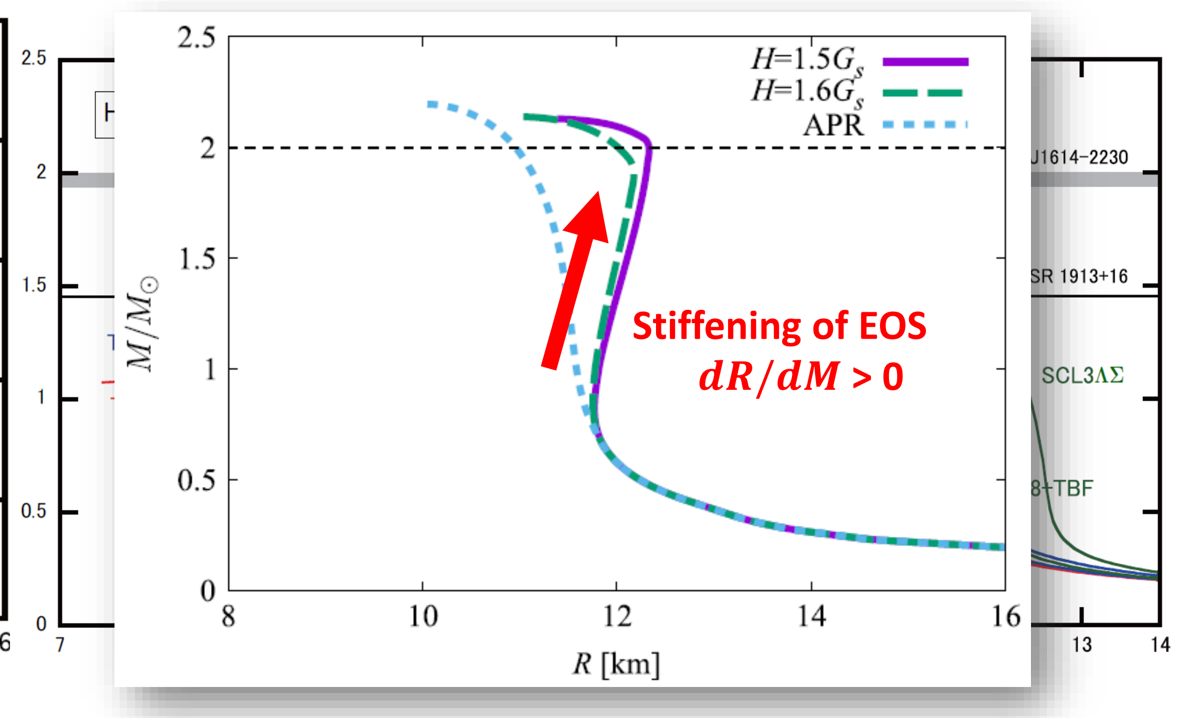




R_{NS} may provide a clue to solve Hyperon puzzle

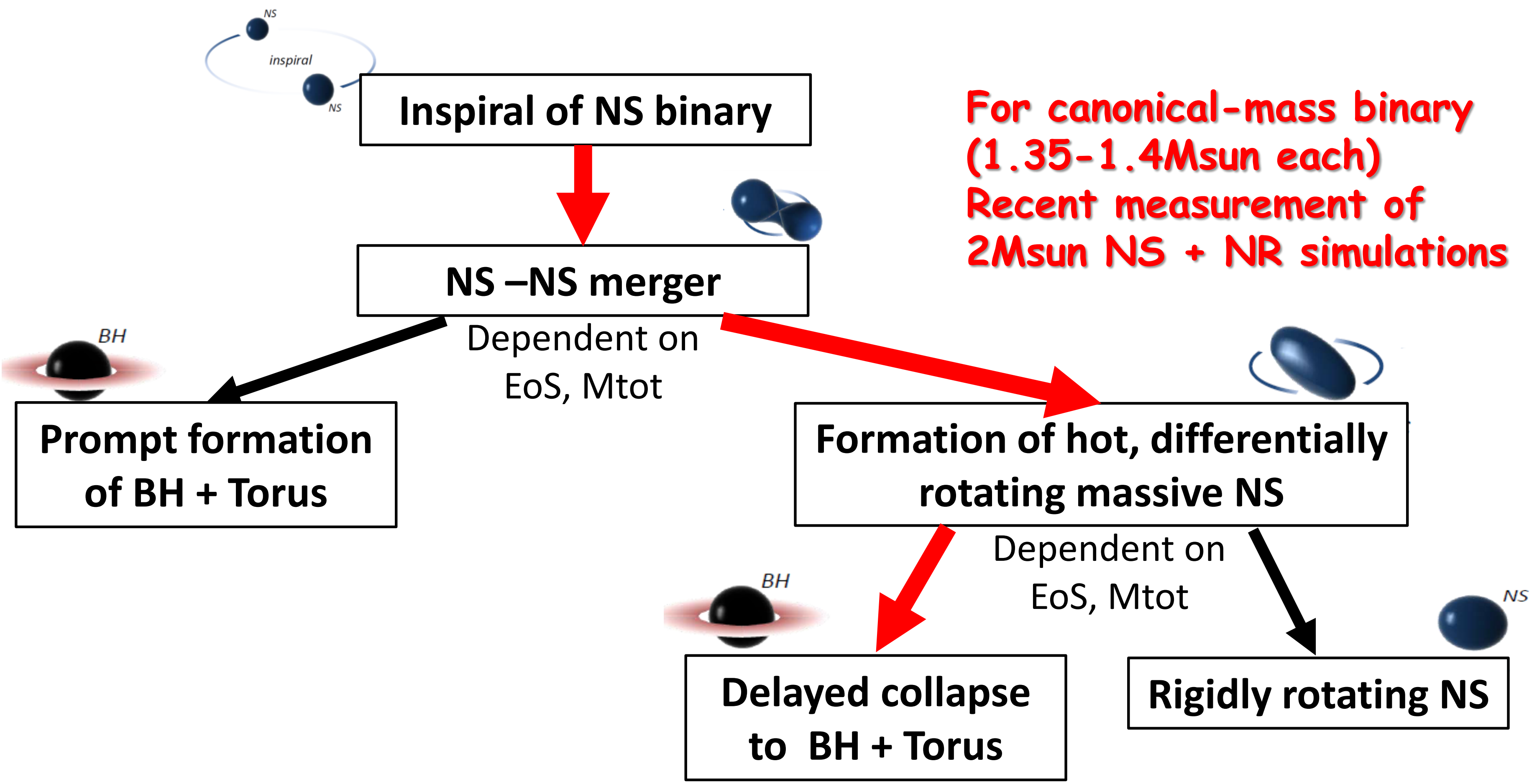
- Introduction of repulsive interactions or hadron-quark crossover
  - delayed appearance of hyperons / reduced pressure depletion
- Stiffer nucleonic EOS is preferable for the former ($R_{1.35,\,crit}$ > 11.5-12 km)
  - Softer EOS ⇒ higher ρ for same M_{NS} ⇒ larger hyperon influence
- $R_{1.35,\,crit}$ depends on details of hyperon TBF
  - Only YNN : $R_{1.35}$ = 12km model is not compatible with 2Msun (Vidana et al. 2011)
  - YNN+YYN+YYY : can pass $R_{1.35}$ = 12km constraints (Togashi et al. 2016)
- Information of hyperon TBF which will be provided by lattice QCD simulations and experiments at J-PARC is a key
  - weaker repulsion ⇒ $R_{1.35,crit}$ should be larger, say, > 13 km
  - If $R_{1.35,\,obs.}$ is much smaller, say, < 12 km ? ⇒ suggest hadron-quark scenario ?
- Determining R_{NS} with ΔR < 1km is necessary
  - dR/dM may provide a useful information (density-depend YN : dR/dM <0, crossover : dR/dM > 0 ?)

How small ΔR can be estimated by GWs from NS-NS ?

Extracting R_{NS} by GWs from NS-NS

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

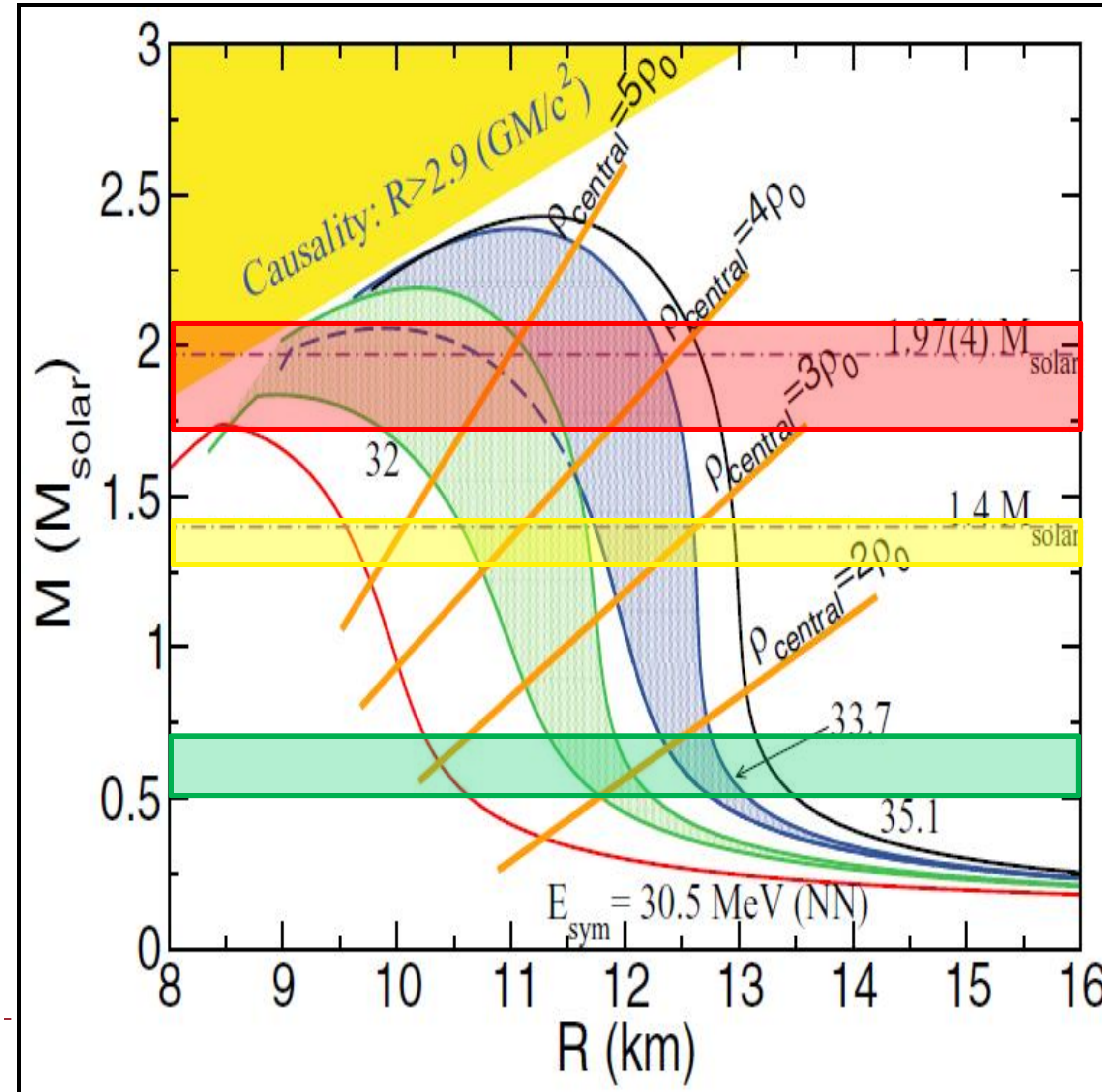
Evolution of NS-NS binary



Massive NS is important to explore high density region

- core bounce in supernovae
  - mass : 0.5~0.7Msun
  - ρ_c : a few ρ_s
- canonical neutron stars
  - mass : 1.35-1.4Msun
  - ρ_c : several ρ_s
- massive NS (> 1.6 Msun)
  - ρ_c : > 4ρ_s
- massive NSs are necessary to explore higher densities
  - Such a massive NS is very rare
  - NS-NS merger : NS with M > 2 Msun after the merger

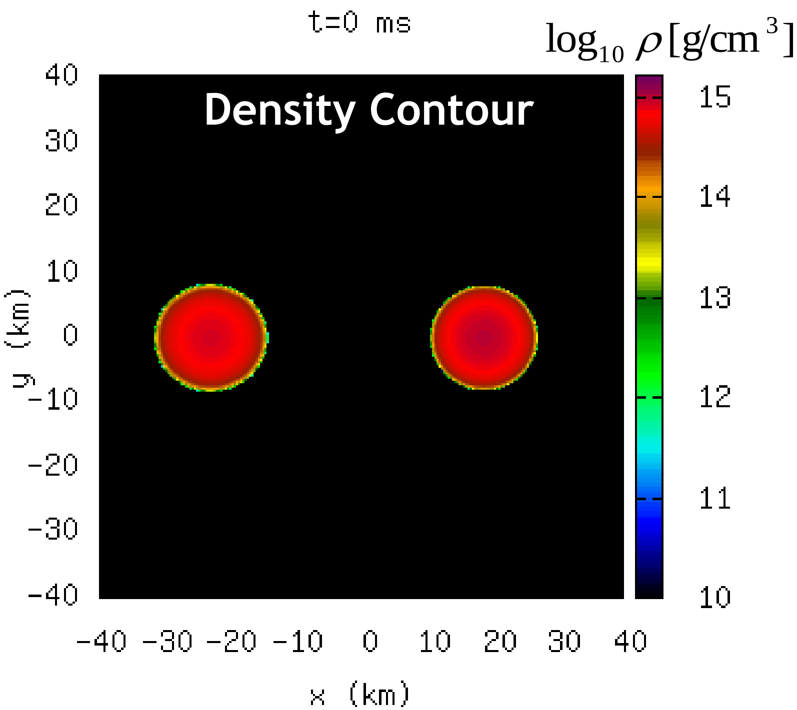
Gandolfi et al. (2012) PRC 85 032801(R)

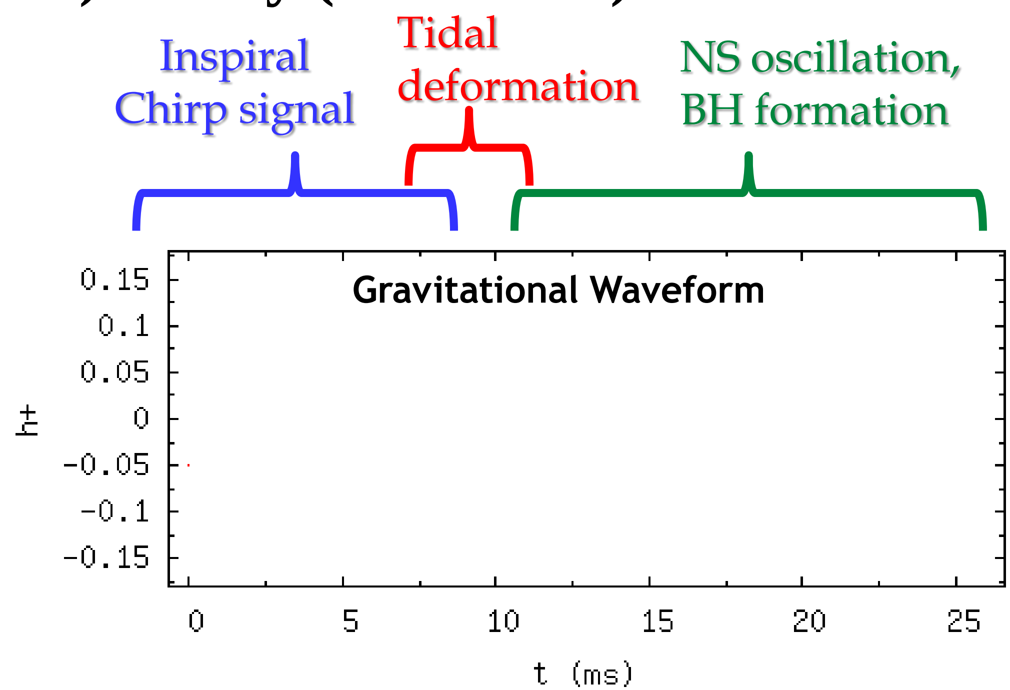


Sekiguchi et al, 2011; Hotokezaka et al. 2013

Gravitational Waves from NS-NS merger

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



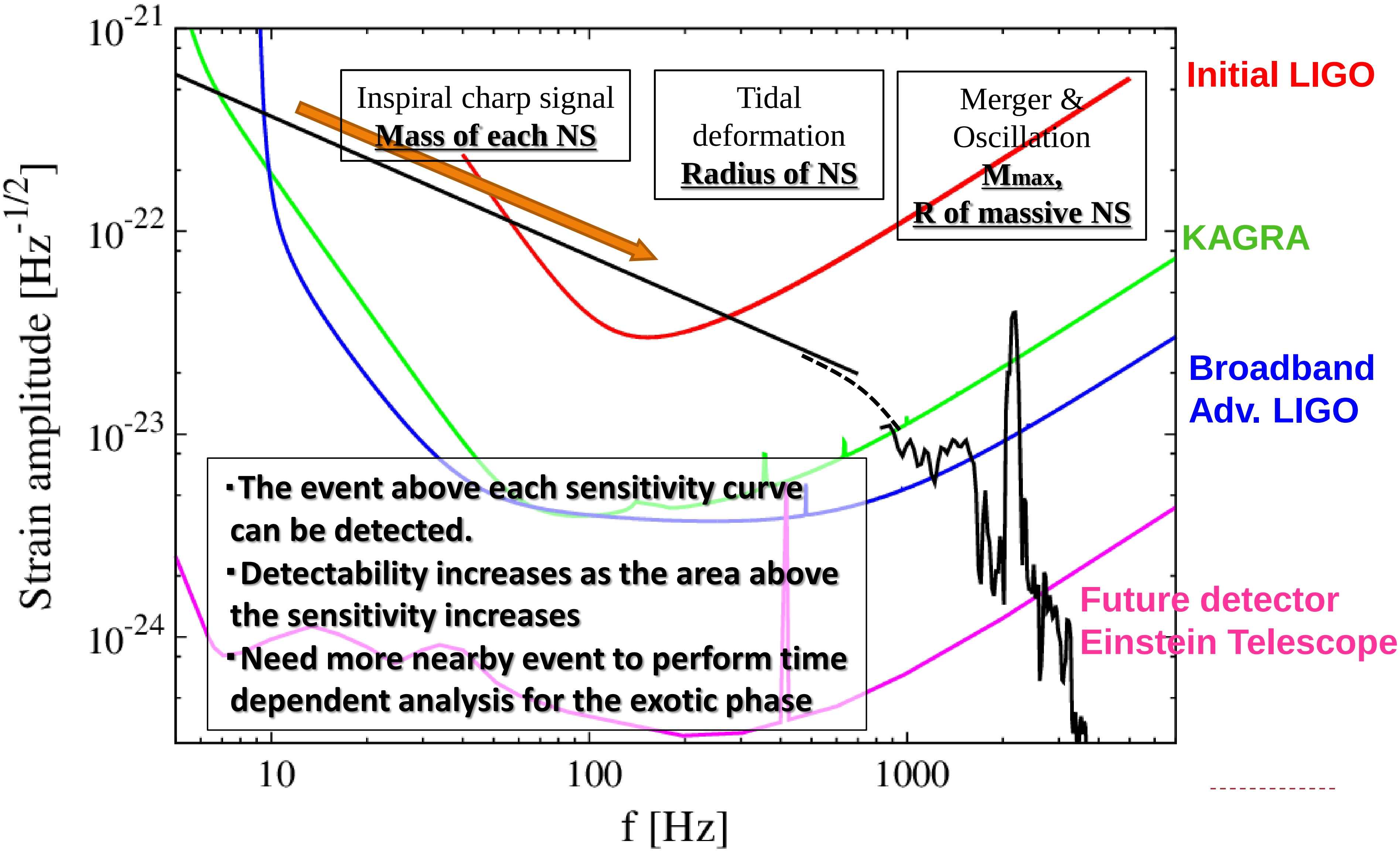


- Point particle approx.
- Information of orbits, **NS mass**, etc.

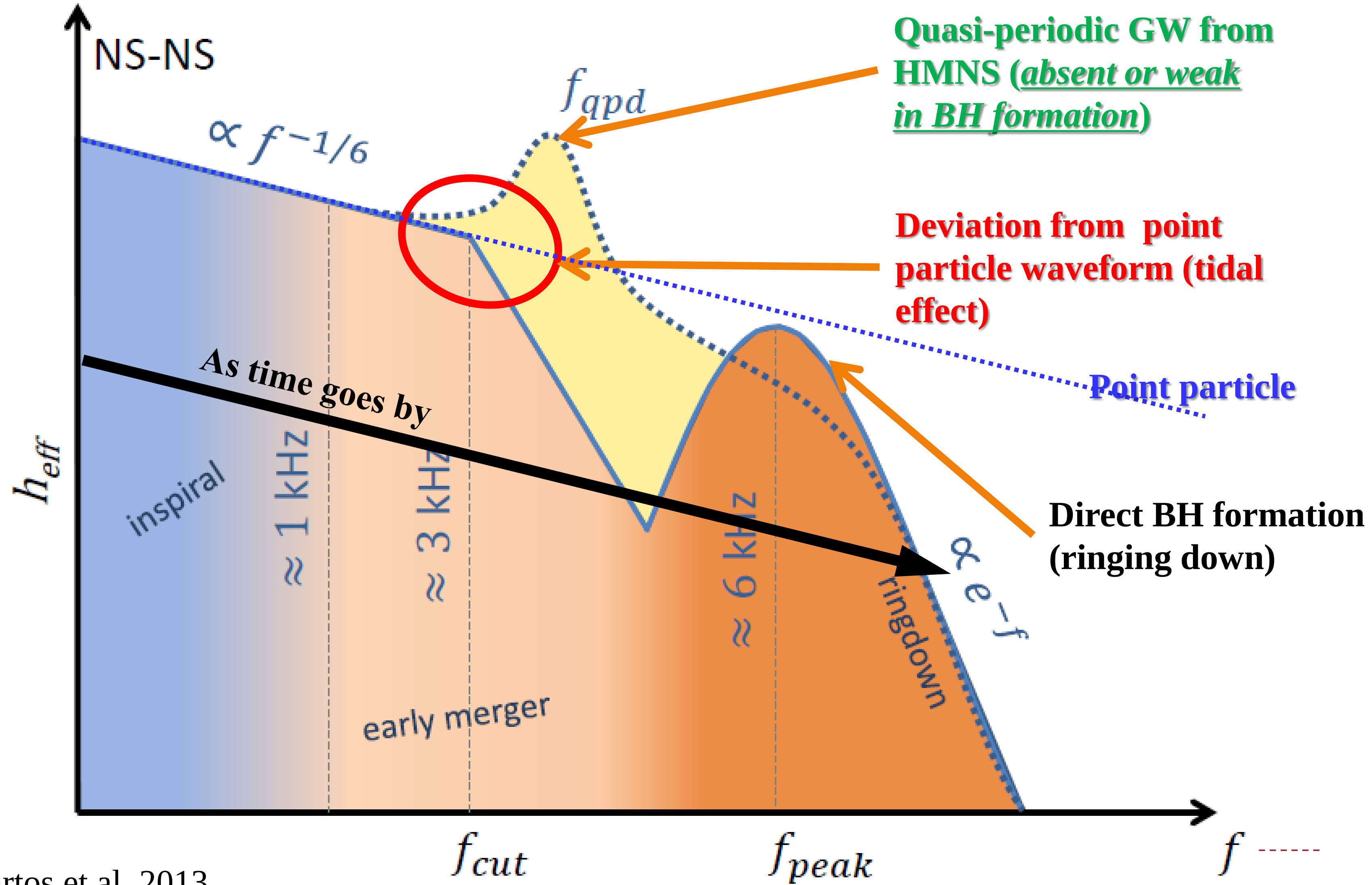
- Finite size effects appear
- **tidal deformability**
- **radius**

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

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



Schematic picture of GW spectra



Bartos et al. 2013

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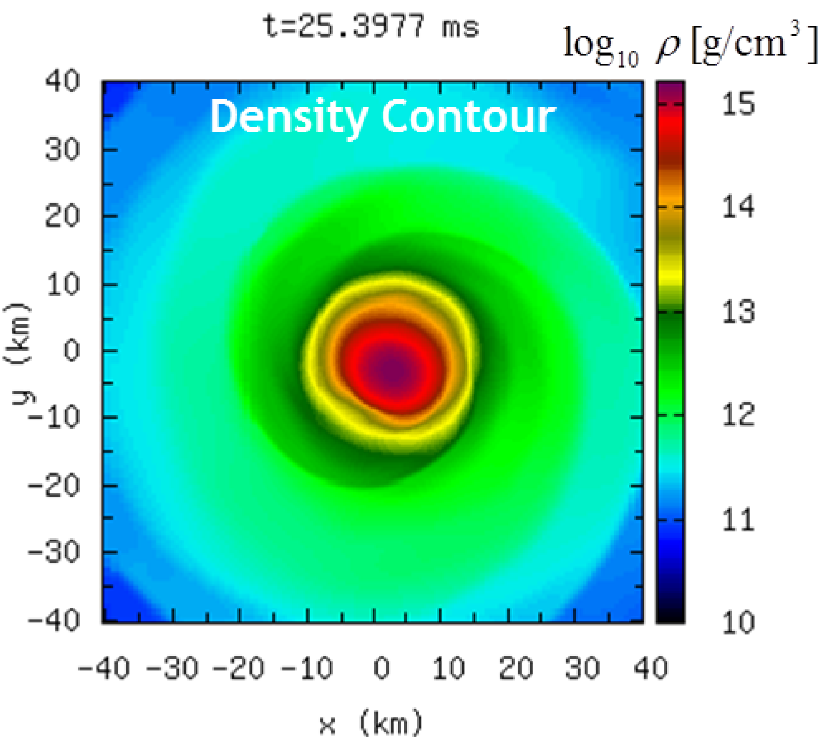

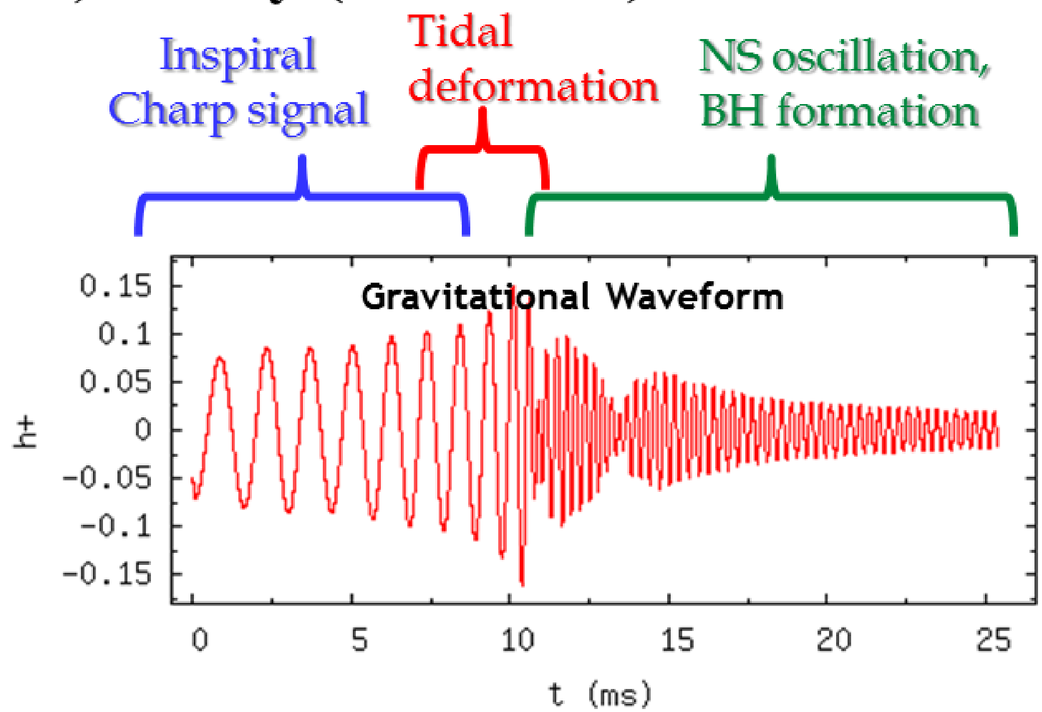

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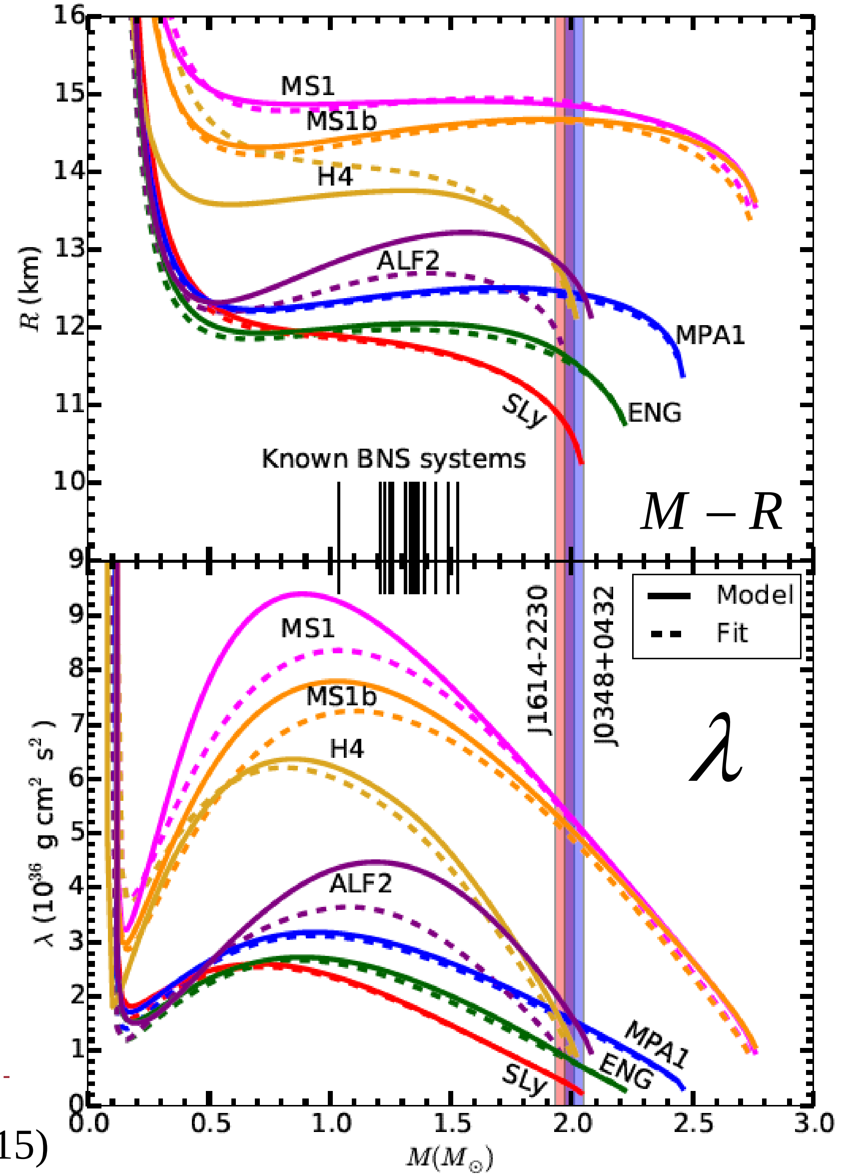
- GWs from massive NS ⇒ **NS radius of massive NS**

Effect of tidal deformation on GWs

- GW emission is described by the quadrupole formula (L.O.)
- The quadrupole moment changed by tidal field by the companion (finite size effect)
  - Orbit and GWs deviate from those in the point particle approximation.
    - L.O. effect appears in GW phase : faster evolution for larger deformation
- Tidal deformability : $\boldsymbol{\lambda}$
  - Response to tidal field (EOS dependent)
  - stiffer EOS ⇒ less compact NS ⇒ larger $\boldsymbol{\lambda}$

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



Lackey & Wade (2015)

Effect of tidal deformation on GWs

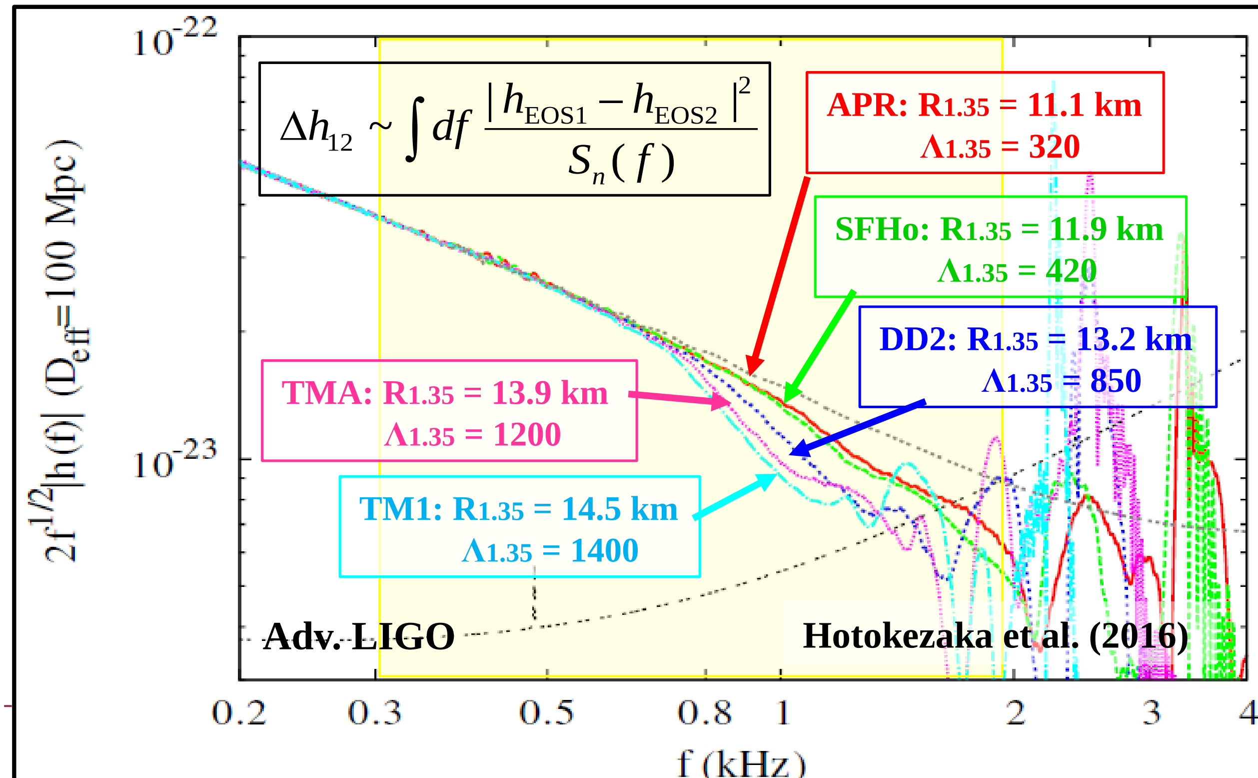
- The tidal effect is contained in GWs
- Define distinguishability Δh_{12}
  - $\Delta h_{12} = 1$: marginally distinguishable
  - E.g. APR and TM1 are distinguishable (~3-σ level) for Deff = 200 Mpc

$\Delta h_{12} @ D_{\rm eff} = 200{\rm Mpc}$ (upper right); ΔR (lower left)

	APR	SFHo	DD2	TMA	TM1
APR	—	0.7	2.3	3.0	3.5
SFHo	0.8 km	—	1.9	2.7	3.3
DD2	2.1 km	1.3 km	—	1.3	2.5
TMA	2.8 km	2.0 km	0.7 km	—	1.7
TM1	3.4 km	2.6 km	1.3 km	0.6 km	—

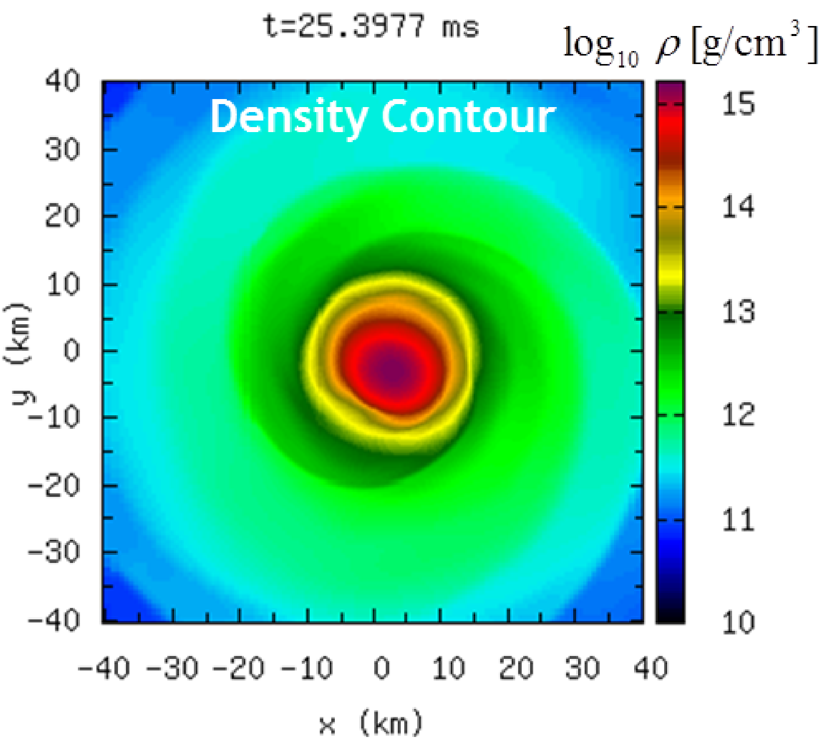
- **ΔR < 1 km @ 200Mpc**
  - **for $R_{1.35}$ > 14 km (2-σ)**
  - **~ 8 event / yr**
- **ΔR < 1 km @ 100Mpc**
  - **for $R_{1.35}$ > 12 km (2-σ)**
  - **~ 1 event / yr**
- **ΔR < 1 km @ 70Mpc**
  - **for $R_{1.35}$ > 11 km (2-σ)**
  - **~ 0.1 event / yr**

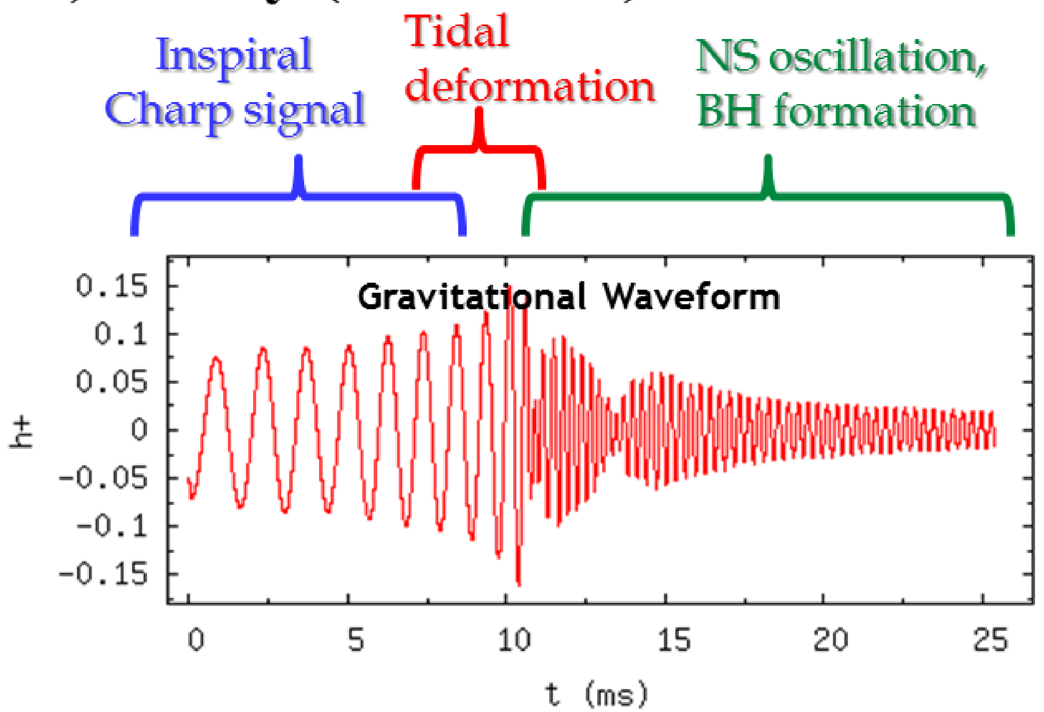
A very optimal estimate



Gravitational Waves from NS-NS binary

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





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

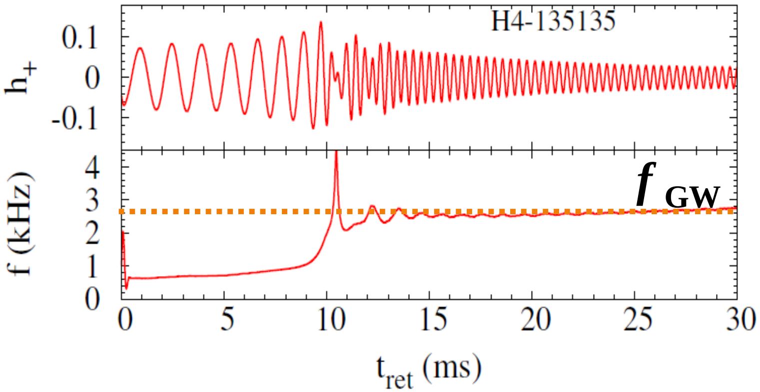
- Finite size effects appear
- **tidal deformability**
- **radius**

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

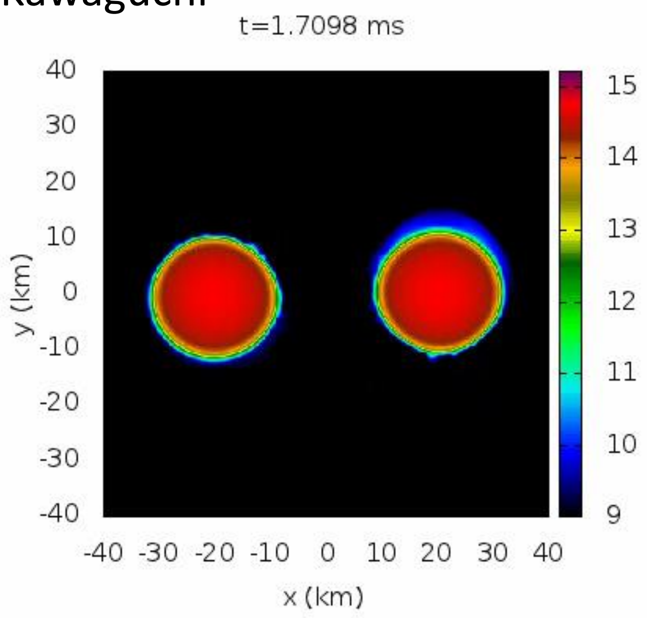
Hearing sounds of GWs from merger: characteristic modes

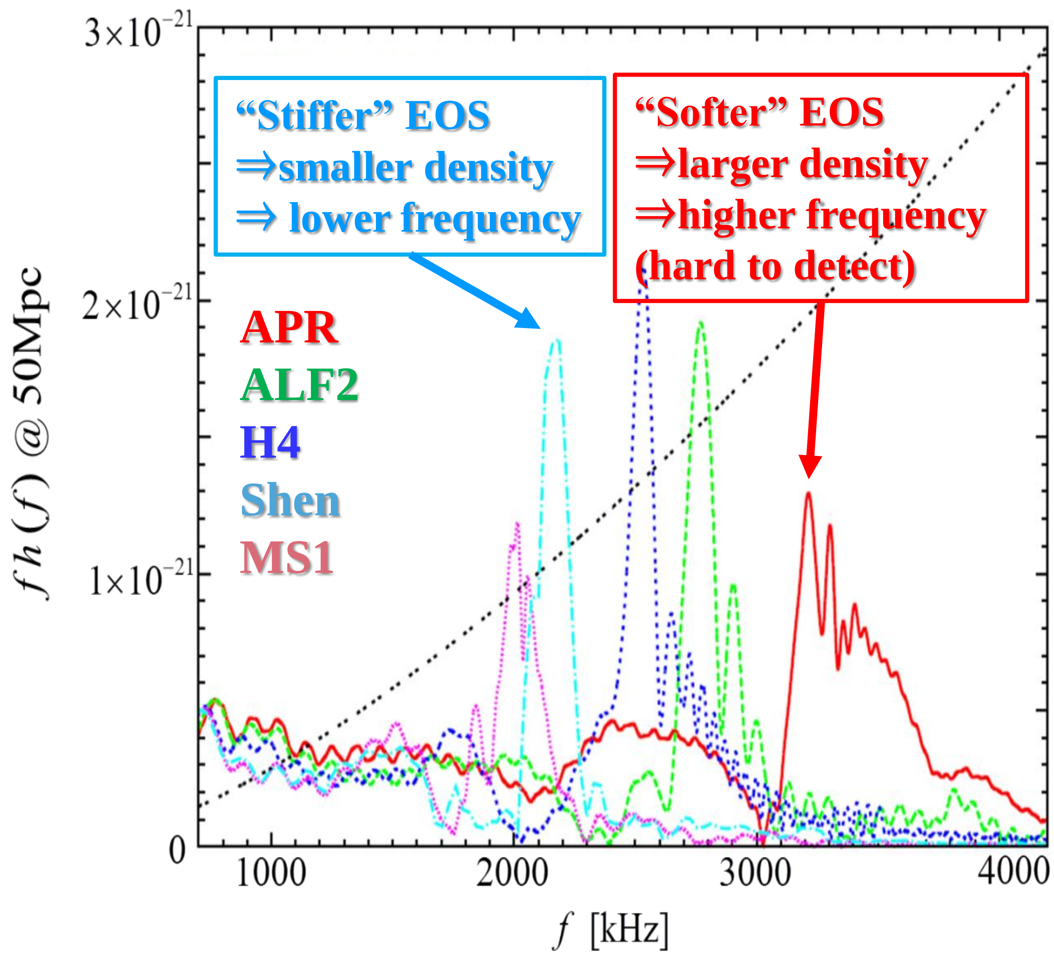
Sekiguchi et al. 2011; Hotokezaka et al. 2013; Bauswein et al. 2013

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



By Kawaguchi

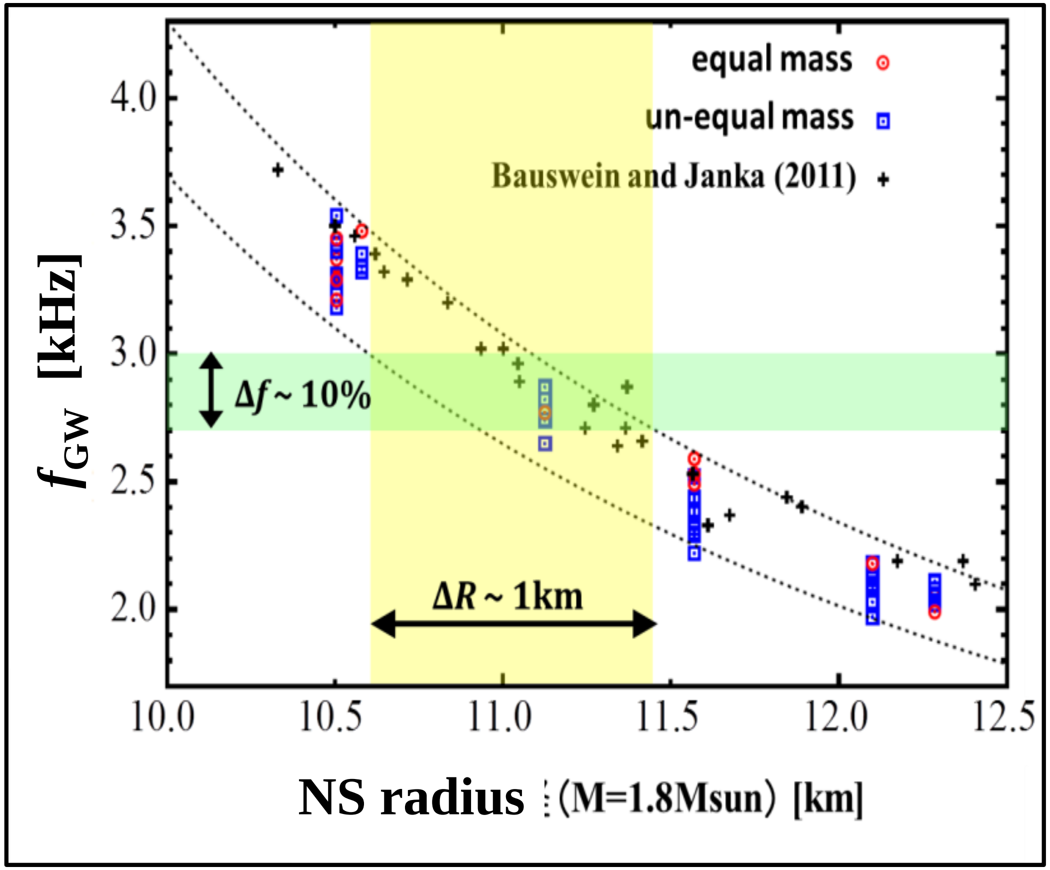




From f_{GW} to NS radius : correlation

- 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)
    - Approx. GR study
  - radius of 1.8Msolar NS
    - Hotokezaka et al. (2013)
    - Full GR study
- tight correlation : ΔR_{model} ~ 1 km
- Further developments
  - Takami et al. PRD 91 (2015)
  - Bauswein & Stergioulas PRD 91 (2015)

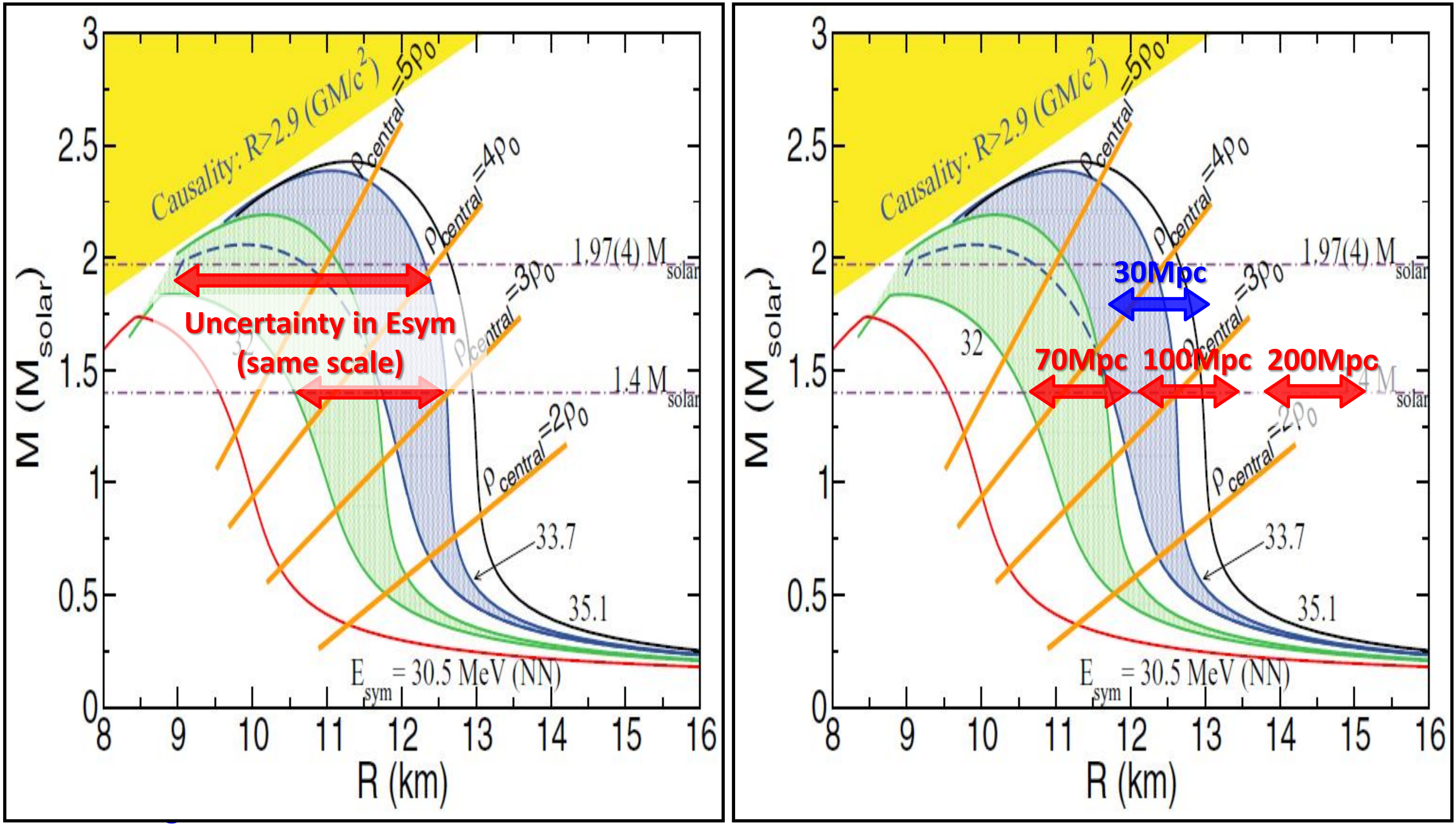


Clark et al. PRD 90, 062004 (2014); CQG 33, 085003 (2016)

From f_{GW} to NS radius : detectability

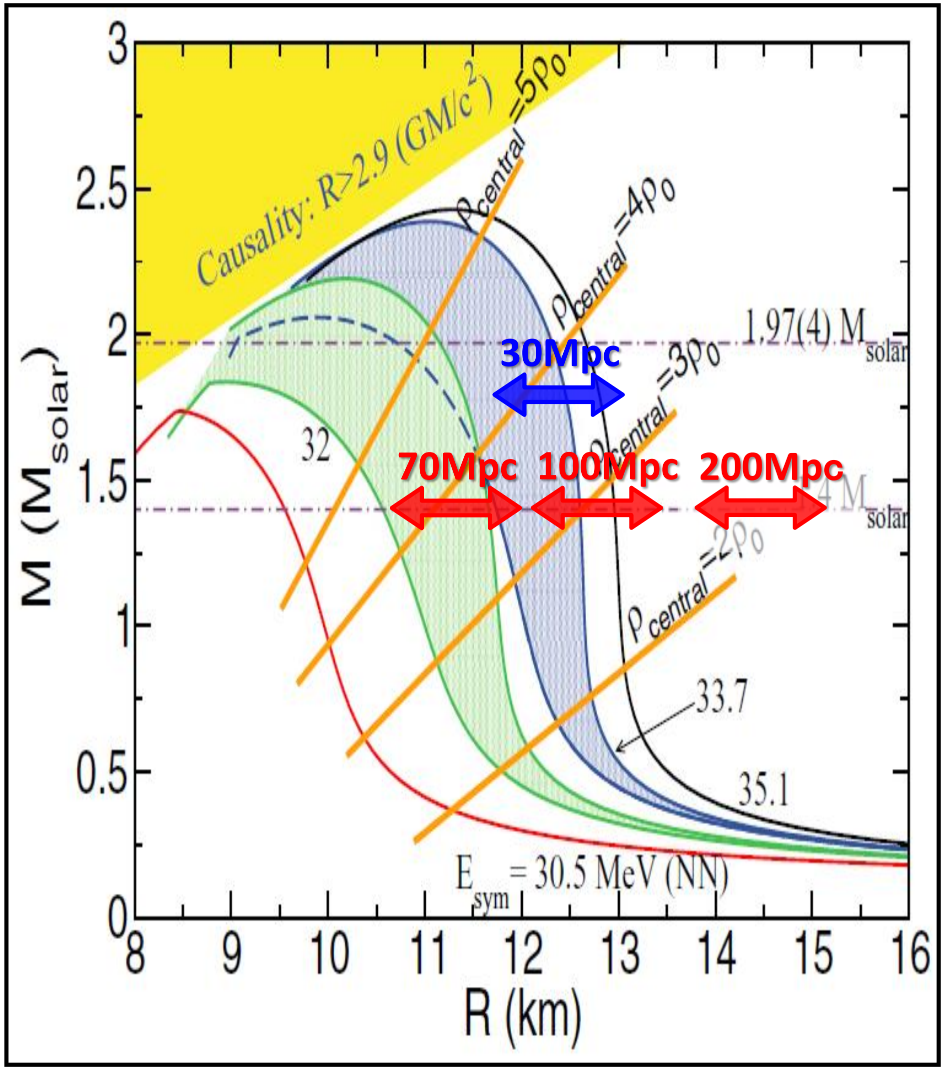
- D_{eff} for detection of f_{GW} is ~ 30 Mpc (Clark et al. 2016) with Δf ~ 140 Hz, for which ΔR due to uncertainty in determining f_{GW} is ΔR ~ 500 m
  - Deff depends on EOS
  - Uncertainty in R is dominated by modelling
- Expected rate : 0.01—0.05 / yr
  - Such golden events are rare but will provide valuable information otherwise never obtained

Measurement of R_{NS} by GWs : Summary



Measurement of R_{NS} by GWs : Summary

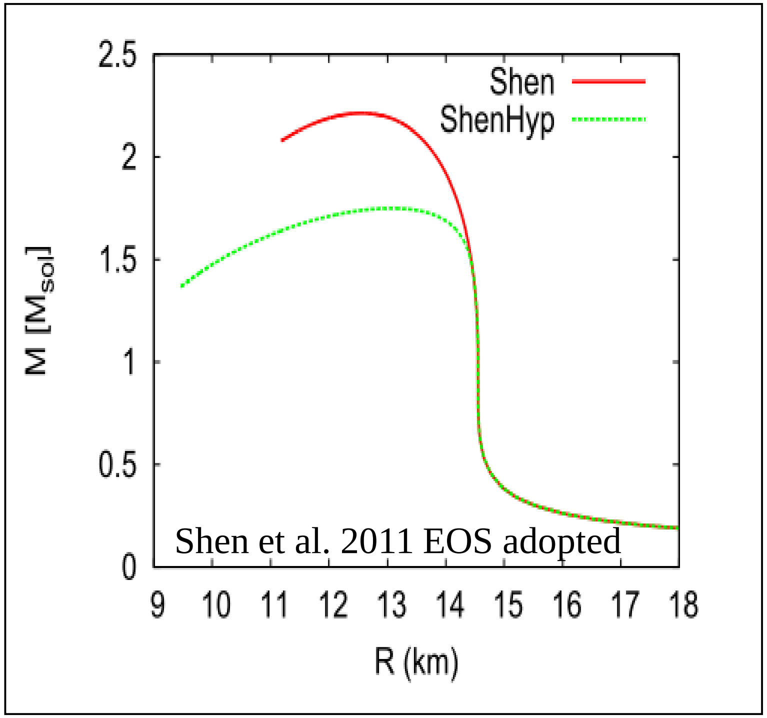
- **Tidal effect :** determination of R with $\Delta R_{1.35}$ < 1km may be possible for events at
  - 200 Mpc if $R_{1.35}$ > 14 km
  - 100 Mpc if $R_{1.35}$ > 12 km
  - 70 Mpc if $R_{1.35}$ > 11 km
- **Oscillation of MNS :** current systematic error is ΔR ~ 1km
  - f_{GW} may be determined for a nearby event within Deff ~ 30 Mpc with Δf ~ 140 Hz
    - Deff depends on EOS
    - Need more systematic study to reduce the systematics
  - $R_{1.8}$ may can be constrained with a golden event

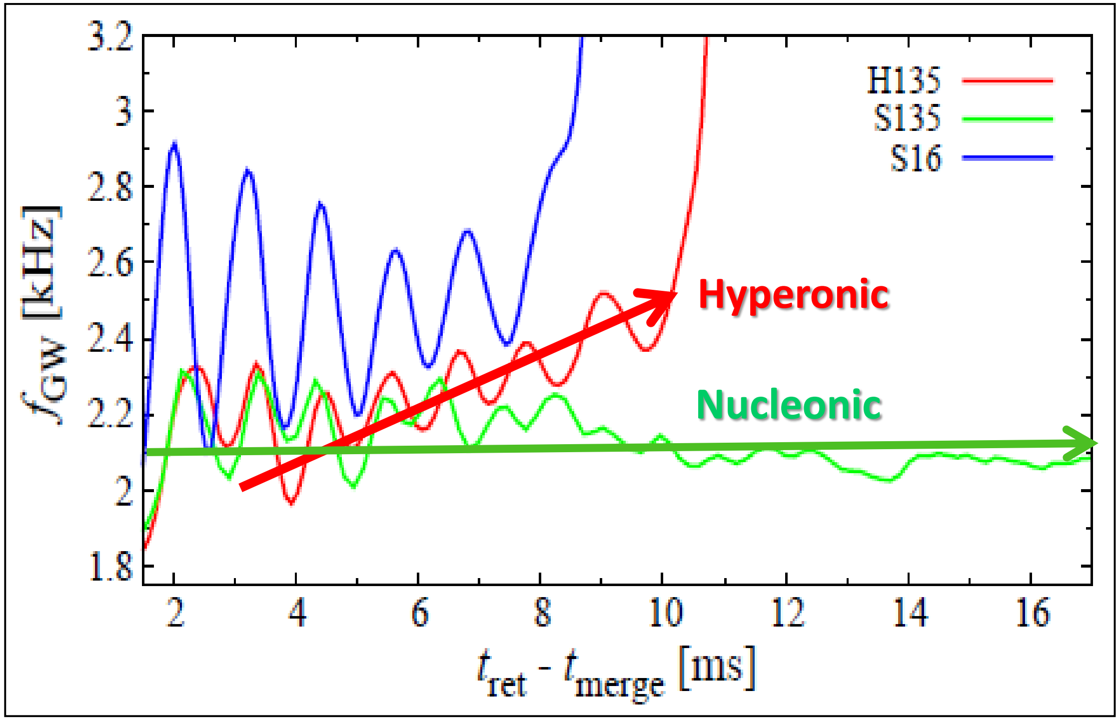


Sekiguchi et al. PRL (2011)

Proving emergence of '*exotic*' phases by GW

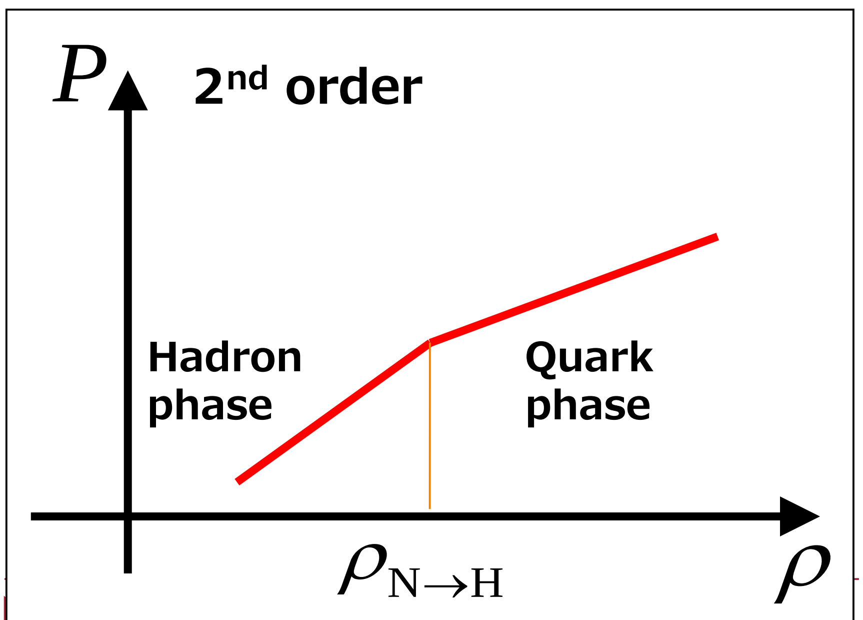
- **Nucleonic** : NS shrinks by angular momentum loss in a **long** GW timescale
- **Hyperonic** : GW emission ⇒ NS shrinks ⇒ More Hyperons appear ⇒
  EOS becomes softer ⇒ NS shrinks more ⇒ ….
- **⇒ the characteristic frequency of GW for hyperonic EOS increases with time**
  - ***Could*** provide potential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

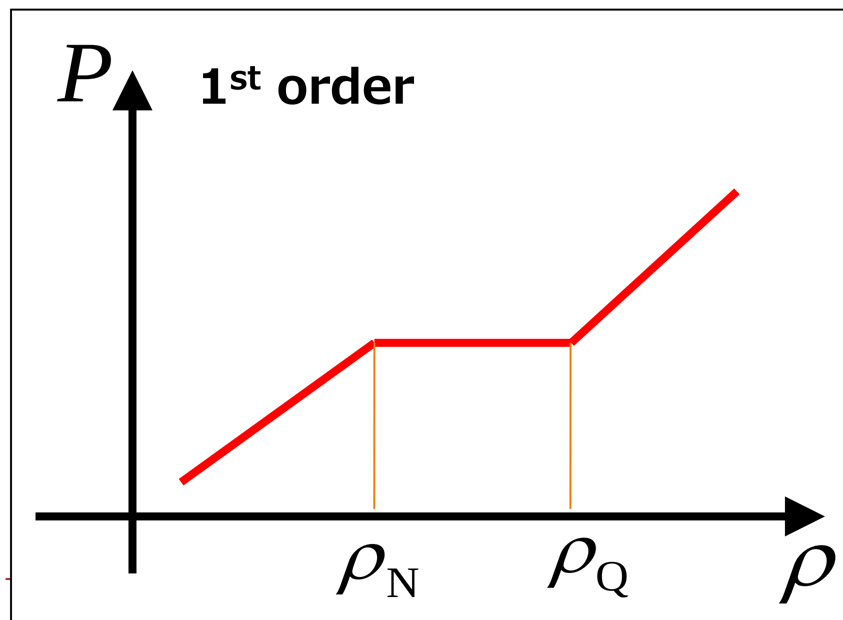




Further possibility ?

- 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 to explore it





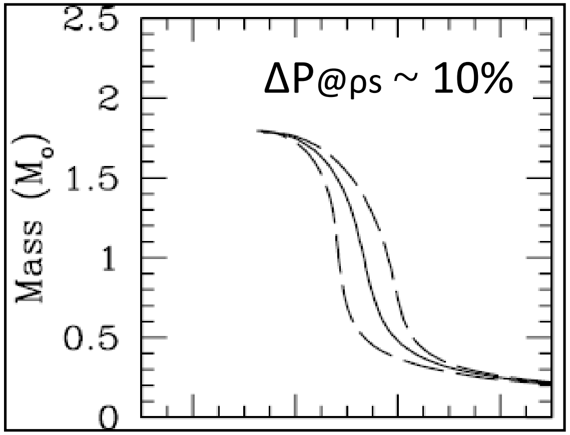
Summary

- GW150914: The first direct detection of GWs from BH-BH
  - It marks the dawn of GW astronomy era
  - NS-NS merger is a promising candidate of GWs
  - GWs will provide us unique information of the physics inside NSs
- 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 ?

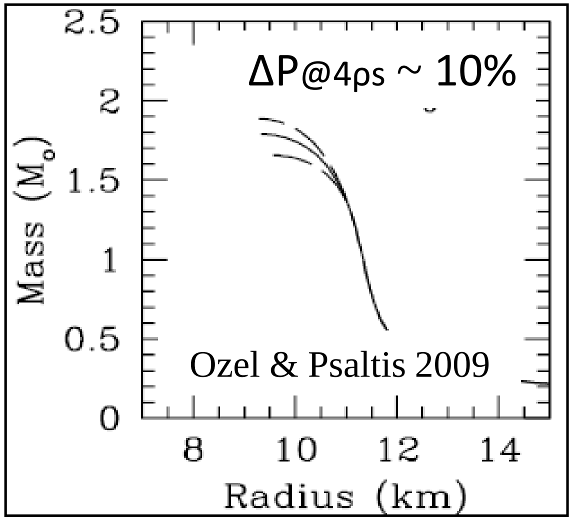
Appendix
On Rns determination by EM obs.

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 obs. rare)**
  - GW : quadrupole formula, no interaction with matter
    - EOS (what we want to know) is only uncertain (**provided GR is correct and GWs are detected**) ⇒could be smoking-gun
  - EM : a number of parameters, models
    - Atmosphere, distance, column density, B-field, fc, …
      (recent debate : Ozel et al., Steiner&Lattimer, Guillot et al.)



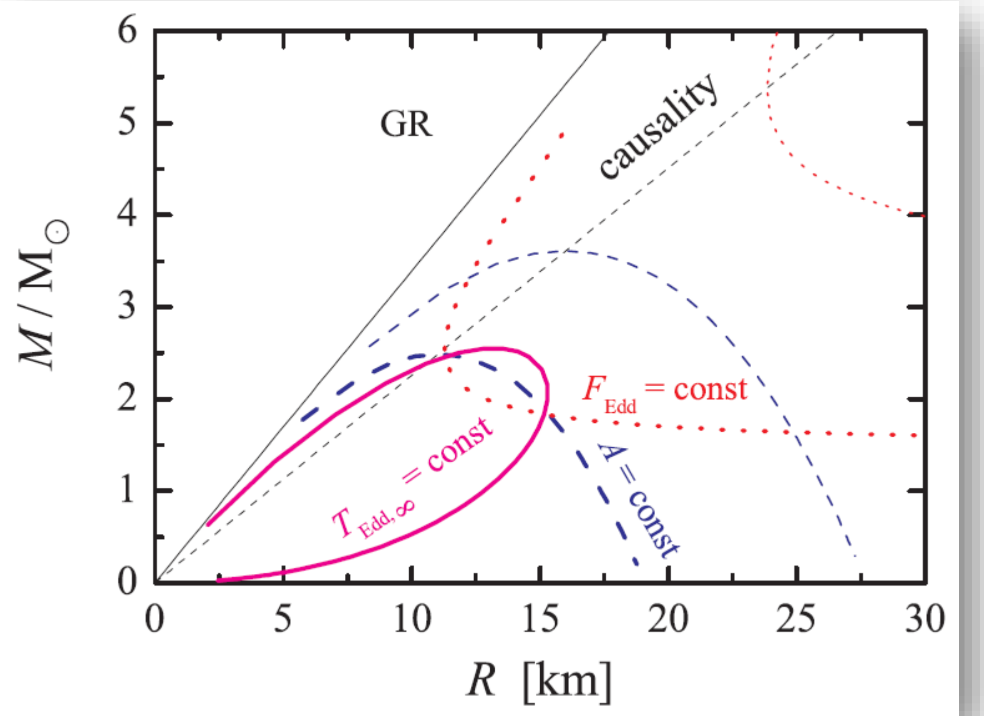
Radius is sensitive to relatively low density parts



Maximum mass depends on most dense parts

Comments on RNS determination by EM

- NS in X-ray binaries sometimes show burst activity
  - Three observables can be obtained in a model dependent manner : **A (apparent size)**, **F_{Edd}** and **T_{Edd}** (**Eddington flux** and **temperature**)
  - Each observables draw a curve in M-R plane
  - If the model is good, these three curves will intersect self-consistently
  - But often they do not
    - In some case, no intersection
  - **After statistical manipulation, intersection point emerges**
    - M and R depends on Authors
- Situation is similar for the other EM observation
  - Observation of quiescent low mass X-ray binaries (qLMXB)



Sulemimanov et al. (2011)

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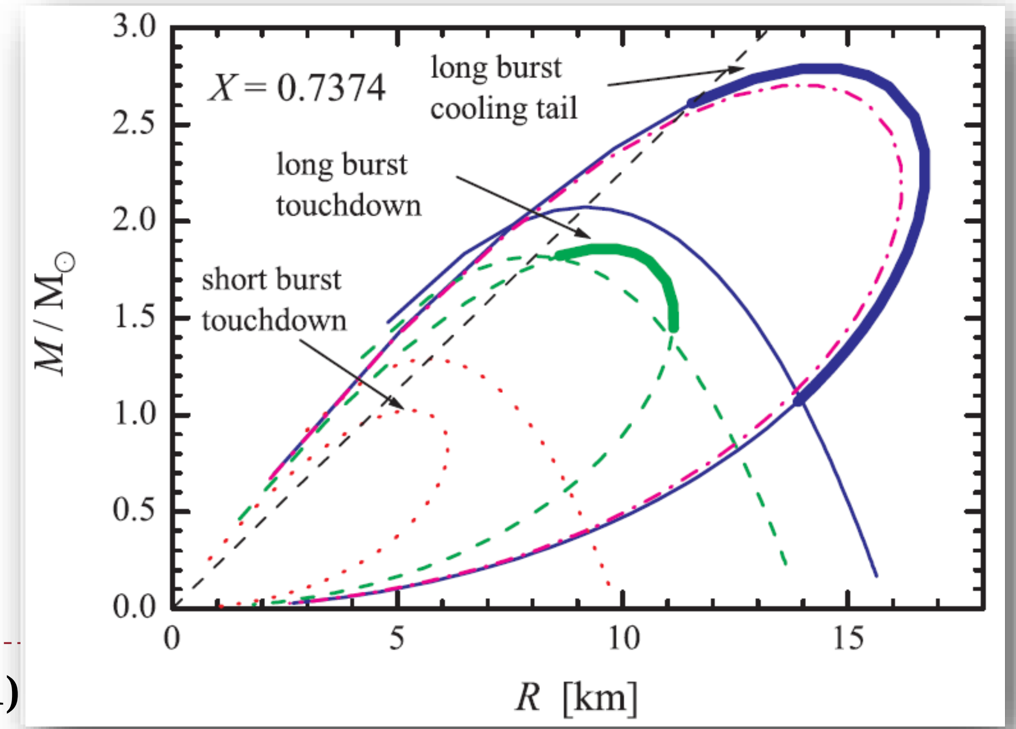

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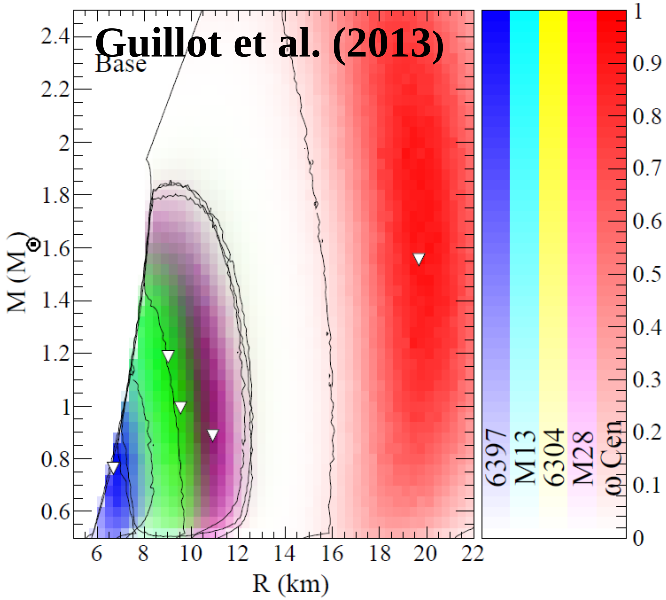

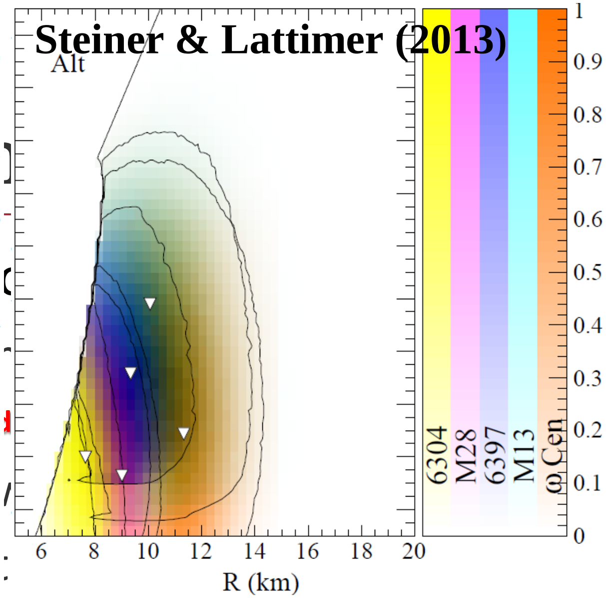

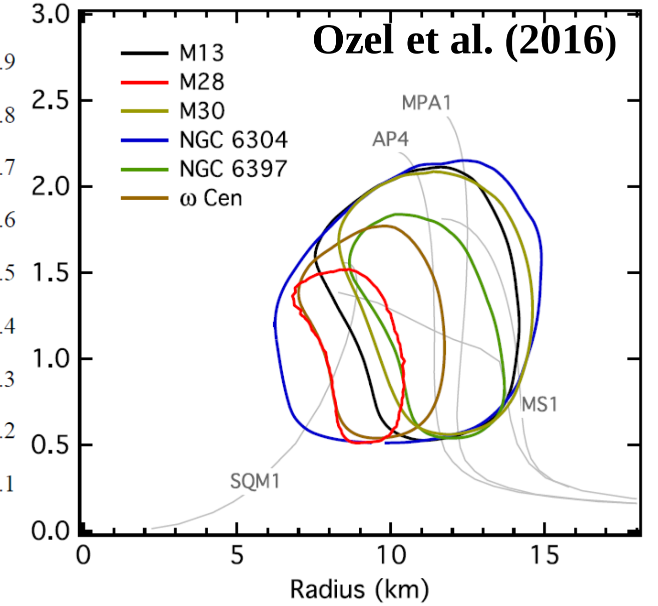

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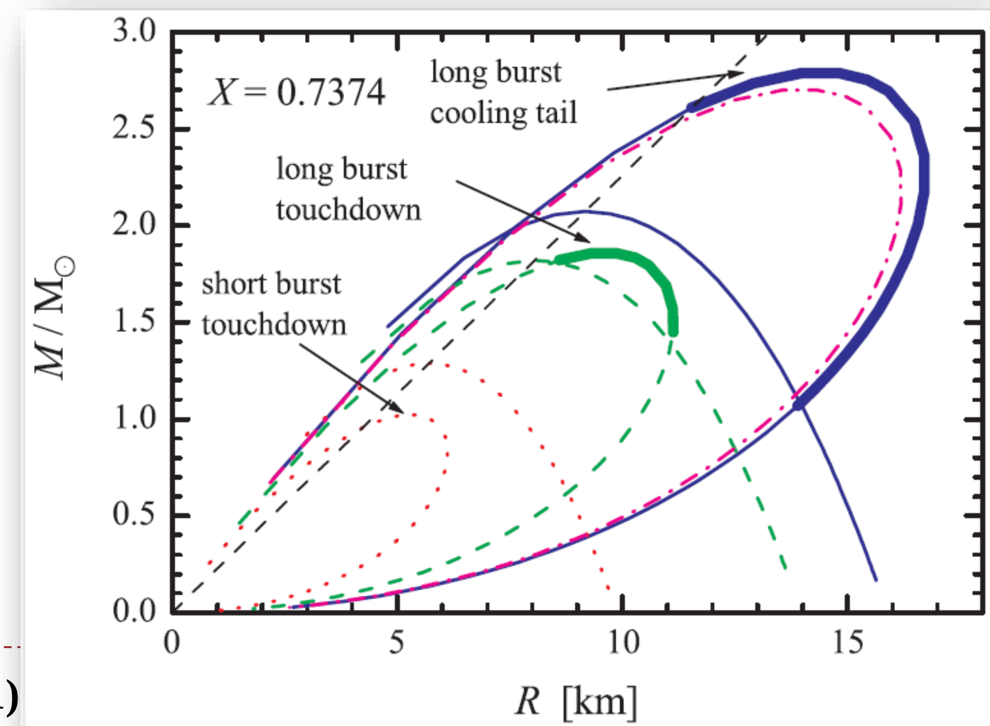
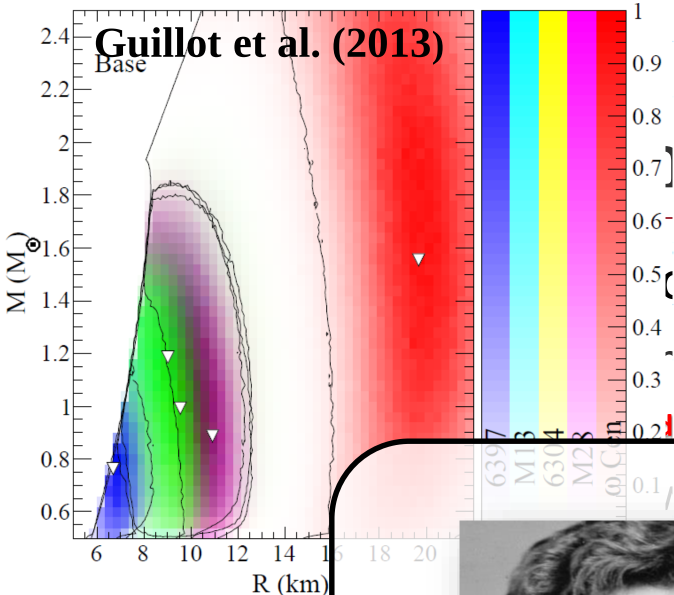
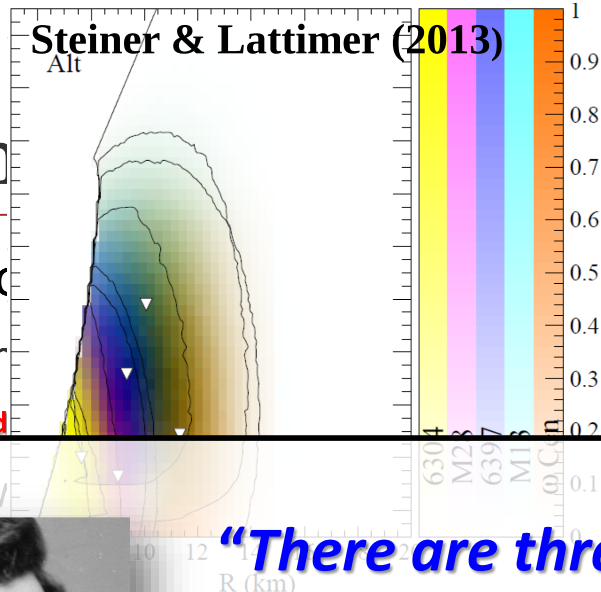
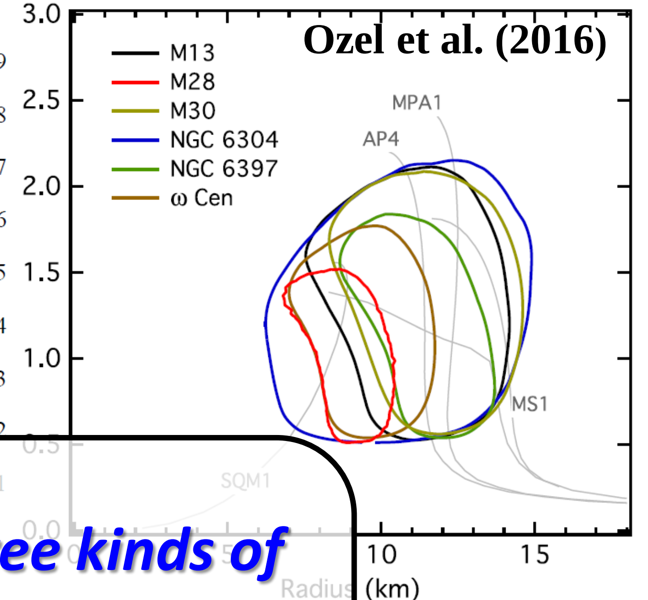
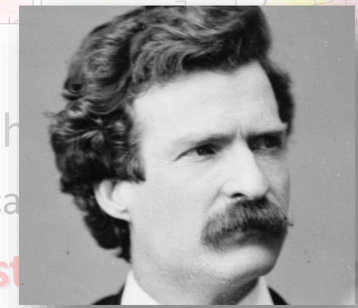


Sulemimanov et al. (2011)









> ***"There are three kinds of lies; lies, dammed lies, and statistics"***
>
> — Mark Twain

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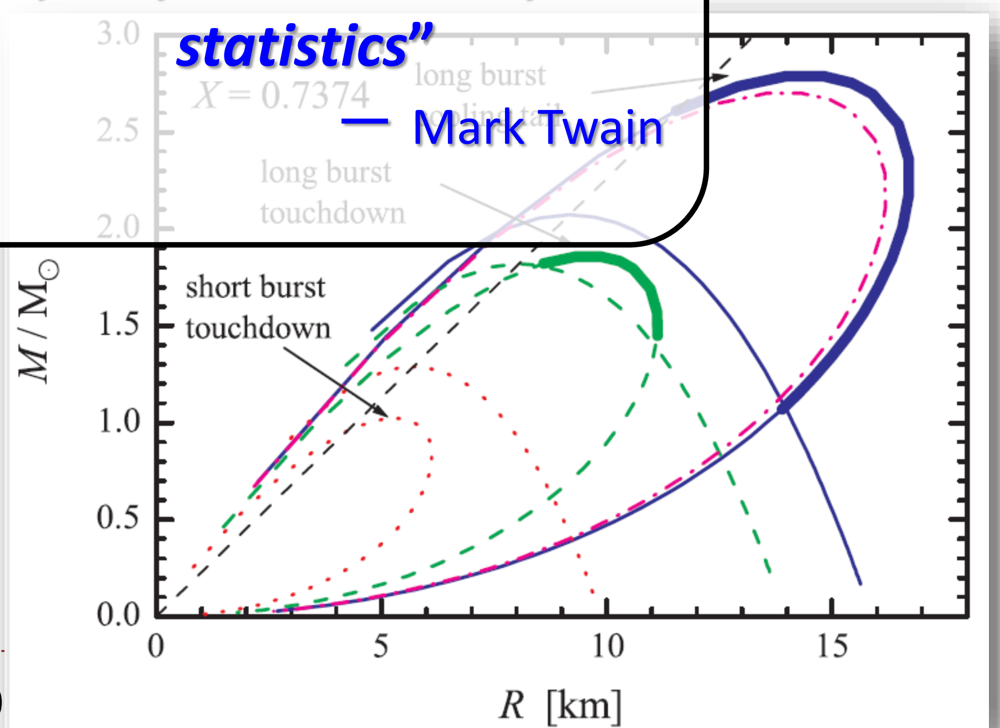
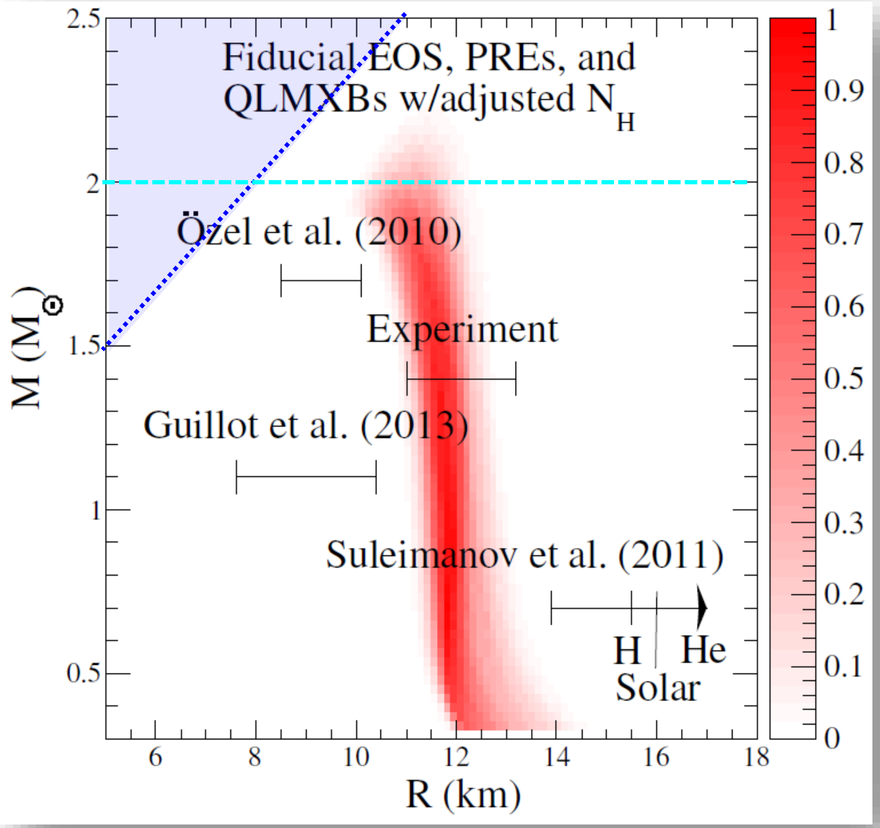


Sulemimanov et al. (2011)

NS mass/radius measurements by EM

- 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

Appendix
Nuclear symmetry energy and Rns

What basically determines radius ?

Symmetry energy and NS radius

- Nuclear matter parameters are defined via Taylor expansion of nuclear energy by density (n, n0 is nuclear matter density) and symmetry parameter

$$x = n_p/(n_n + n_p) = n_p/n$$

$$E(n,x) = E(n,1/2) + S(n)(1-2x)^2 + \ ...$$

$$E(n,1/2) = B + \frac{K}{18}(1 - n/n_0)^2 + ...$$

$$S(n) = S + \frac{L}{3}(n - n_0) + ...$$

$B = -16$ MeV

$K = 210 - 250$ MeV

- For pure neutron matter (x=0), pressure at nuclear matter density is given by

$$P(n_0) = n_0{}^2 \frac{\partial E(n_0, 0)}{\partial n} = \frac{L}{3} n_0$$

- Symmetry energy parameters are important for the neutron structure in particular for radius (Lattimer & Prakash 2001)
  - Empirical relation between R and $P(n \sim n_0)$: $R \propto P^{1/4}(n \sim n_0)$
  - $P(n \sim n_0)$ is sensitive to the symmetry energy parameters => relation between L and R
- low-M NS radius (astrophysics) ⇔ Symmetry energy (nuclear physics)

What basically determi

Symmetry energ

- Nuclear matter parameters a
  energy by density (n, n0 is nu

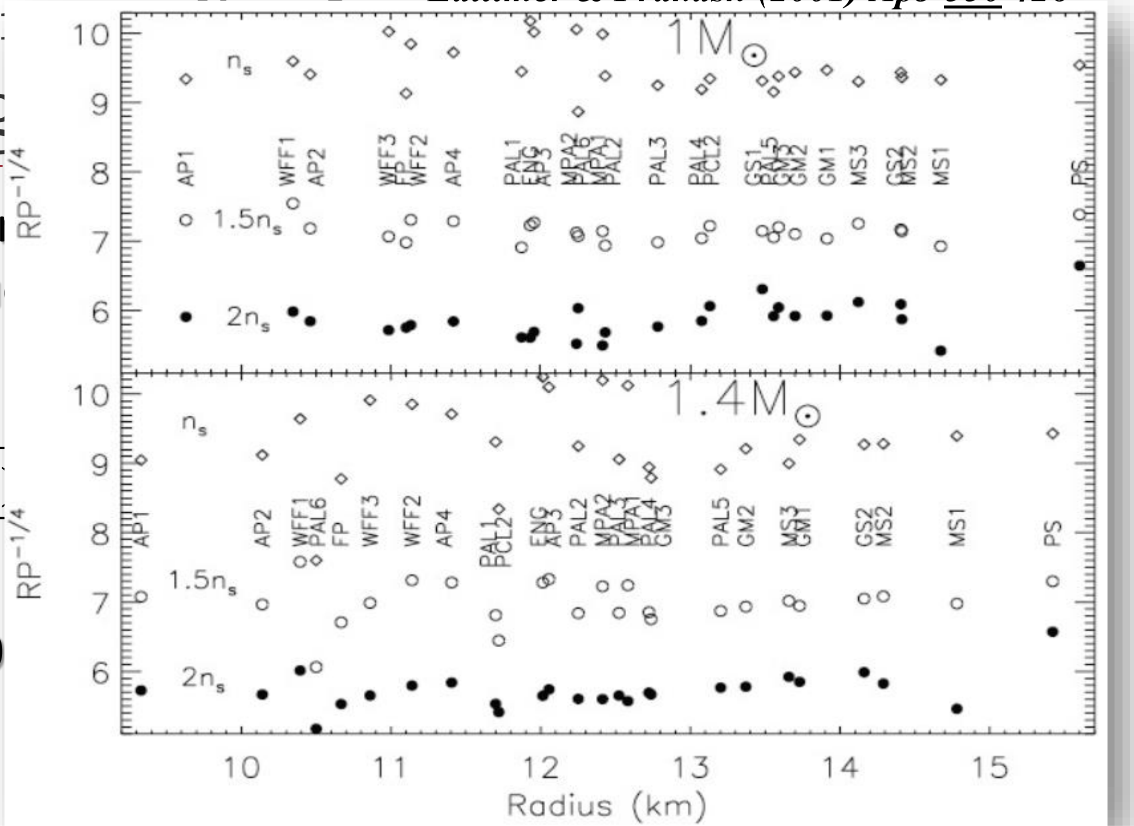
$$x = n_p/(n_n + n_p) = n_p/n$$

$$E(n,x) = E(n,1/2) + S(n)(1-2x$$

- For pure neutron matter (x=0

$$P(n_0) = n_0^2 \frac{\partial E(n_0,0)}{\partial n} = \frac{L}{3} n_0$$

Lattimer & Prakash (2001) ApJ 550 426



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  - Empirical relation between R and P(n~n0) : R ∝ $P^{1/4}$(n~n0)
  - P(n~n0) is sensitive to the symmetry energy parameters => relation between L and R
- **low-M NS radius (astrophysics) ⇔ Symmetry energy (nuclear physics)**

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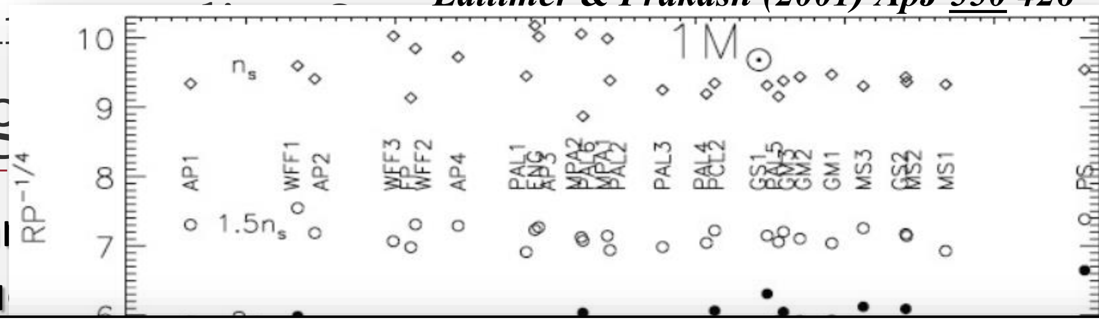

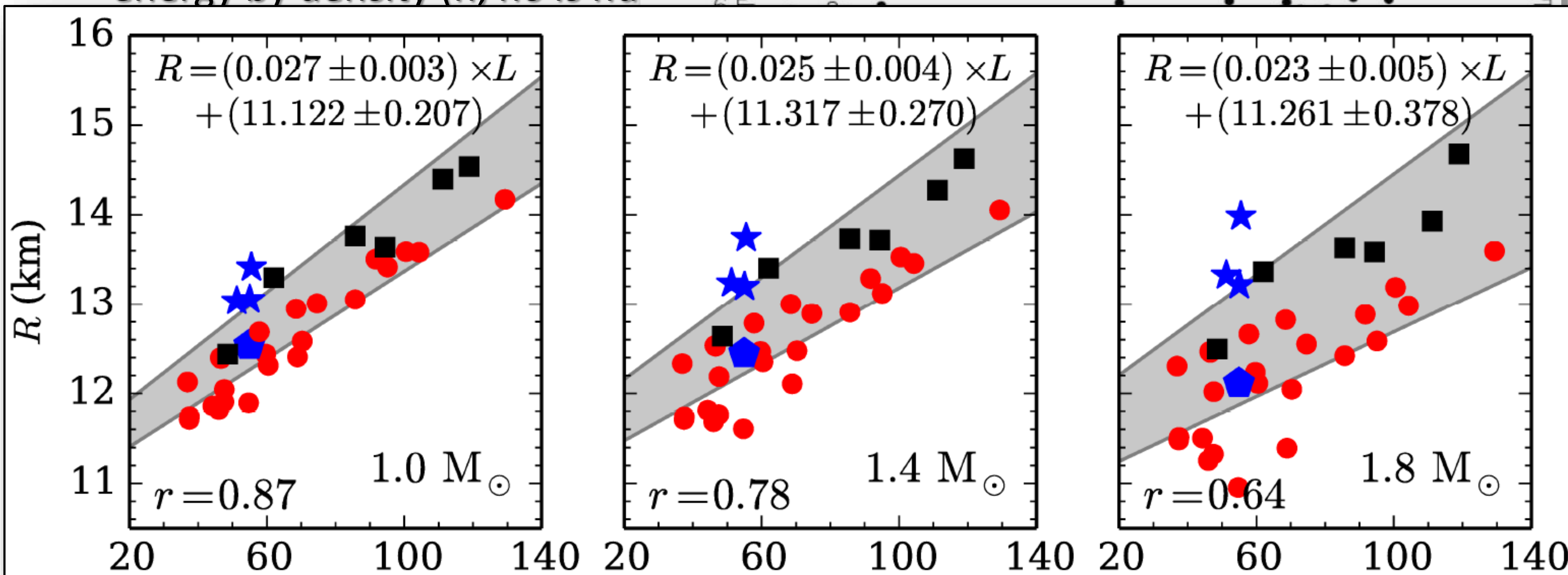

Fortin et al. arXiv 1604.01944

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- low-M NS radius (astrophysics) ⇔ Symmetry energy (nuclear physics)

Constraints on the symmetry energy

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t al. (2010) PRC 82 024313

nickness of Sn

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larizablility

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(2008) PRC 77 061304

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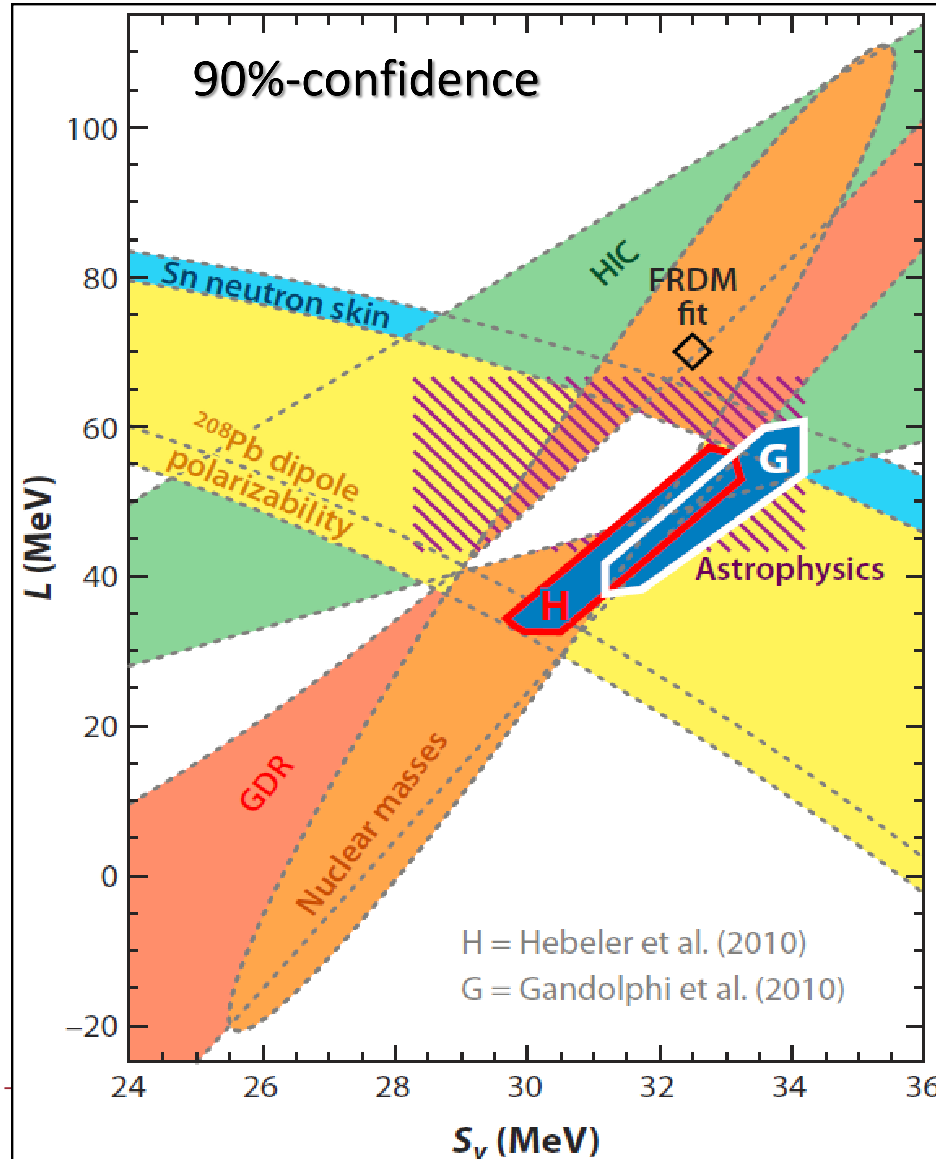

Lattimer (2012) Annu. Rev. Nucl. Part. Sci. 62 485

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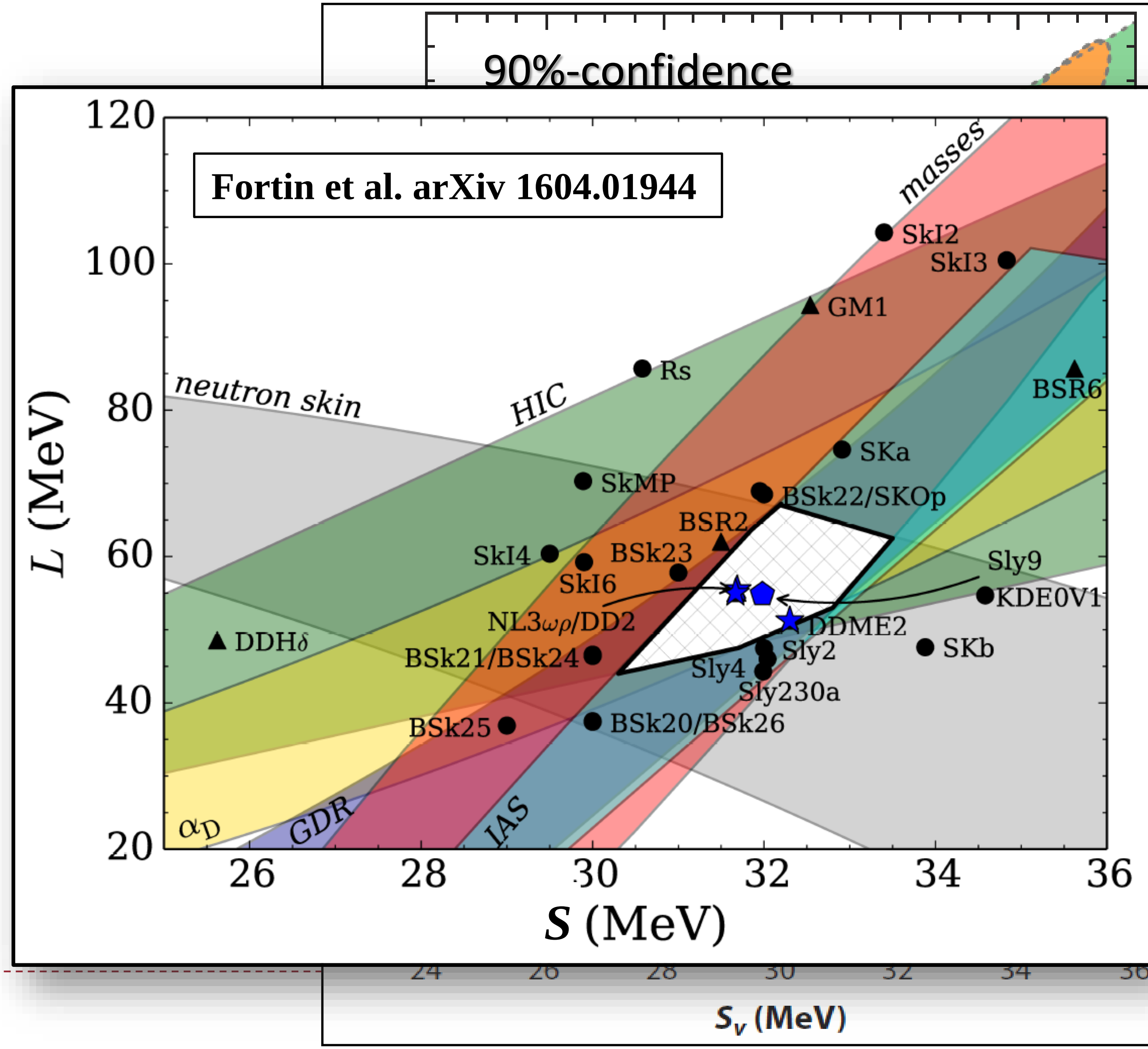
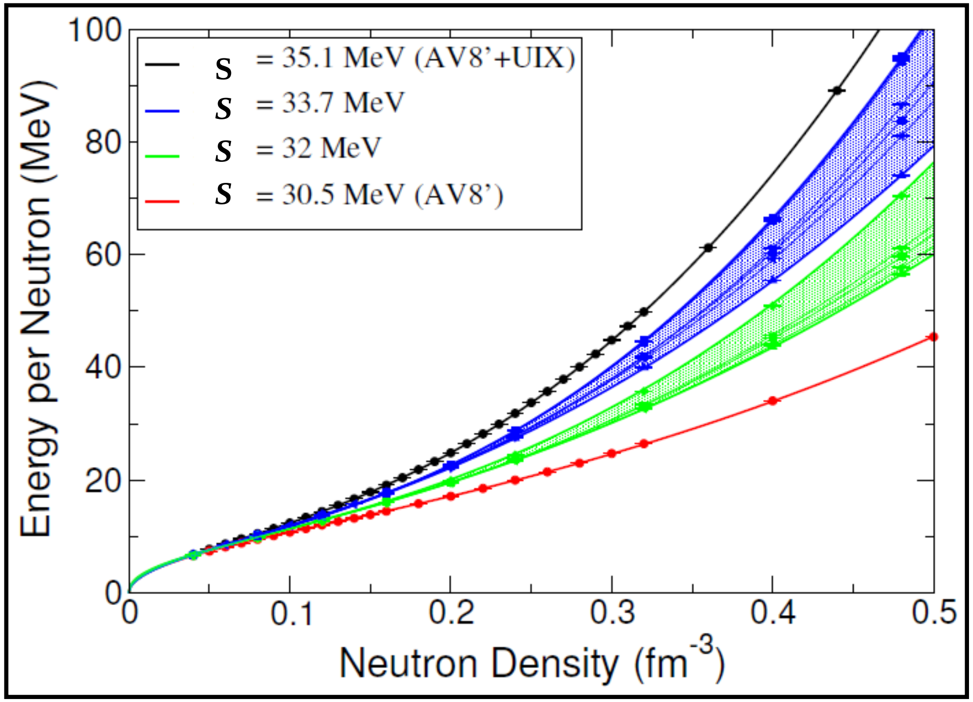
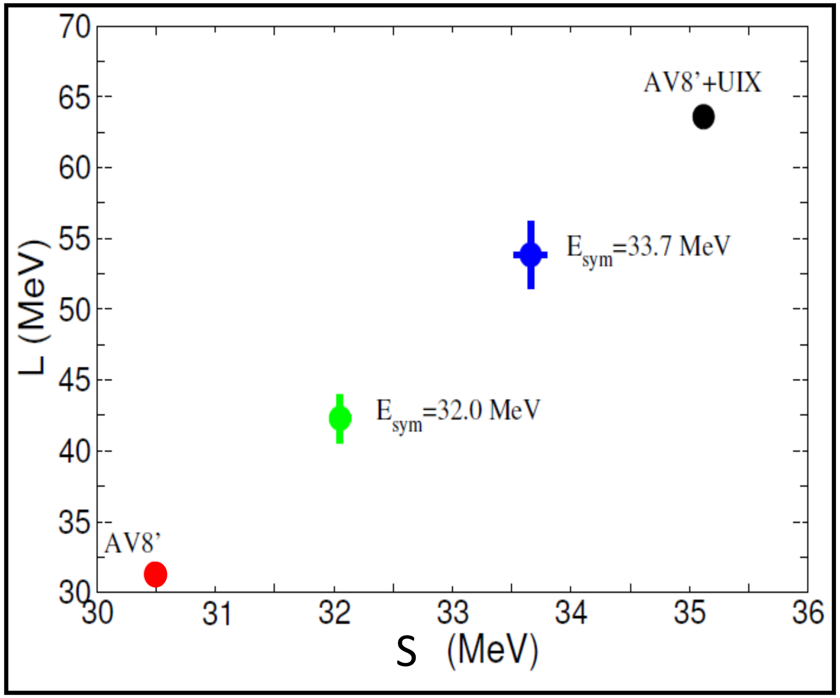


Gandolfi et al. (2012) PRC *85* *032801(R)*

Impact of symmetry energy on NS radius

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





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

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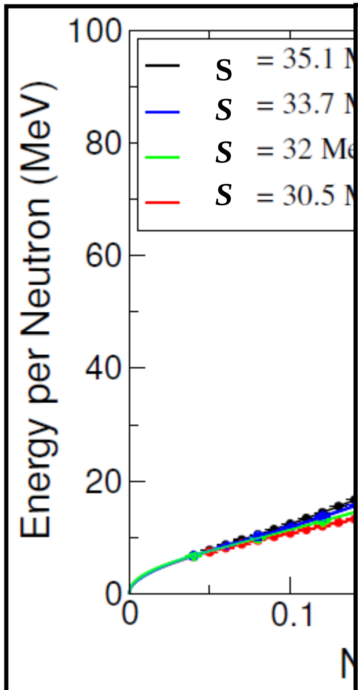

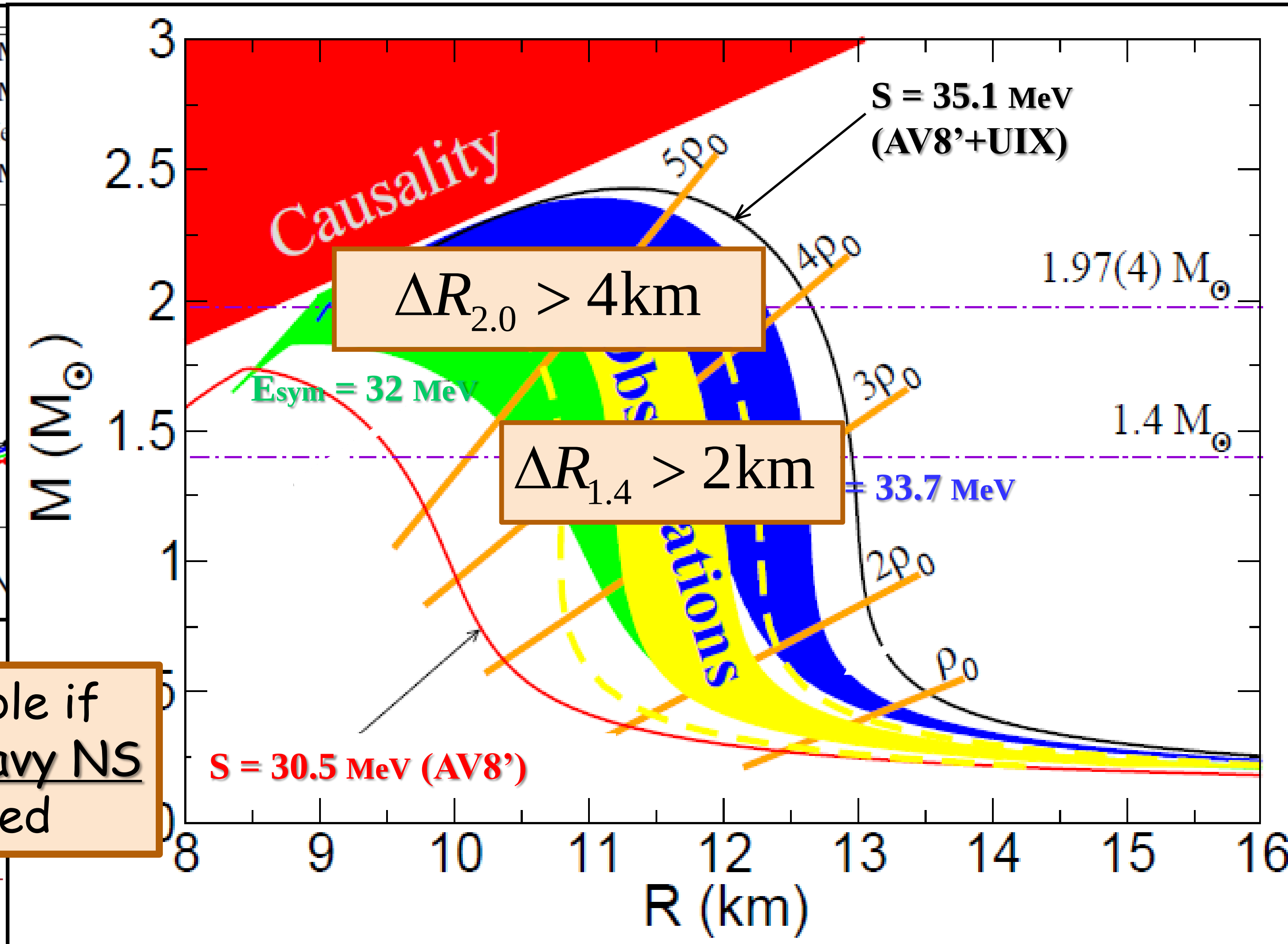

It is valuable if
radius of heavy NS
is obtained