Equation of state of dense matter from multi-messenger observations of neutron stars

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Contents

- Introduction on dense matter;
- Symmetry energy, maximum mass, typical radius, strange phase transistion;
- Take-home message

Neutron stars as dense matter probes

- QCD: The theory which describes the interaction of nucleons and quarks;
- Heavy-ion collisions (HICs) and lattice QCD (LQCD) sensitive primarily to high T, low μ regions;
- Electronmagetic (EM) and gravitational wave (GW) observations of neutron stars are ideal probe of cold, dense QCD.

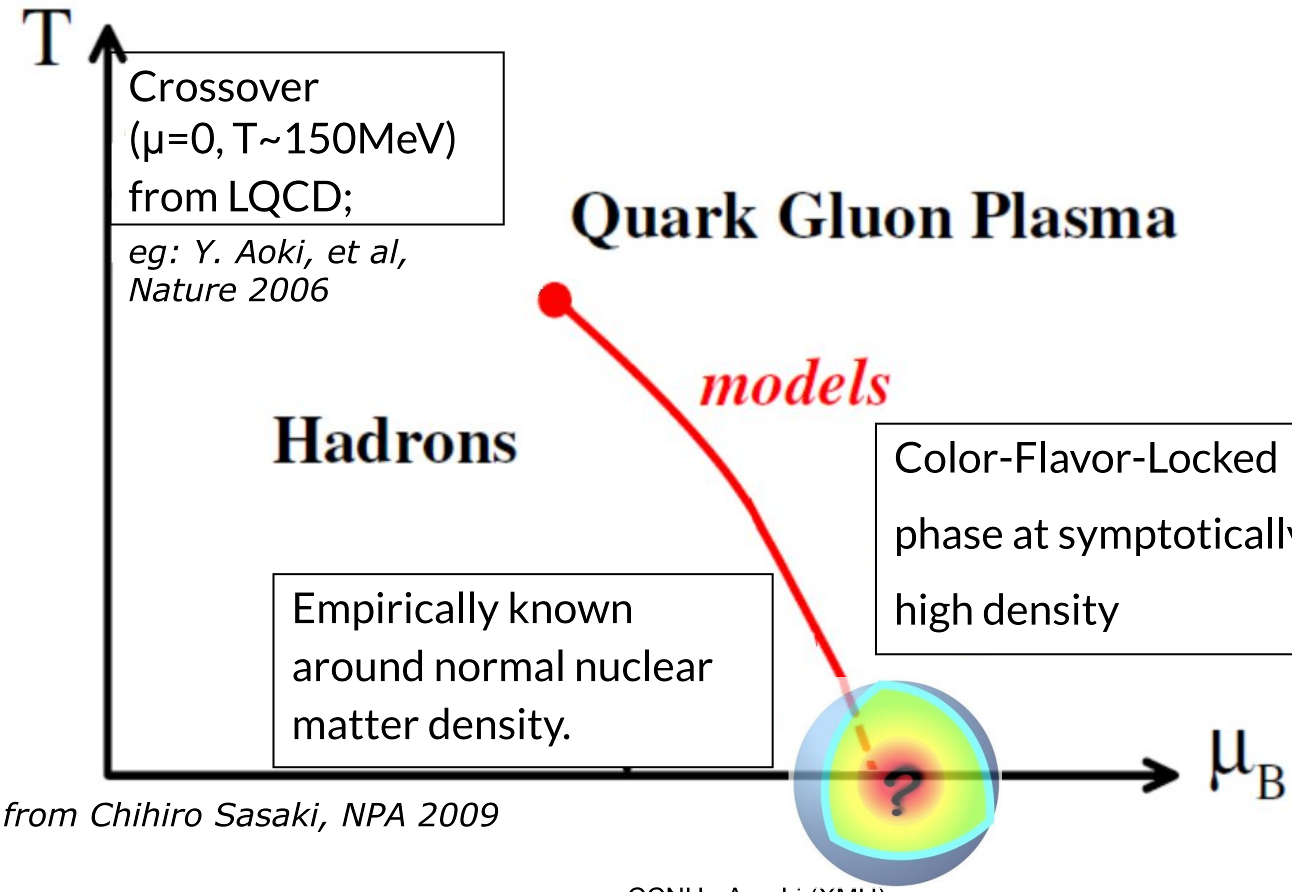
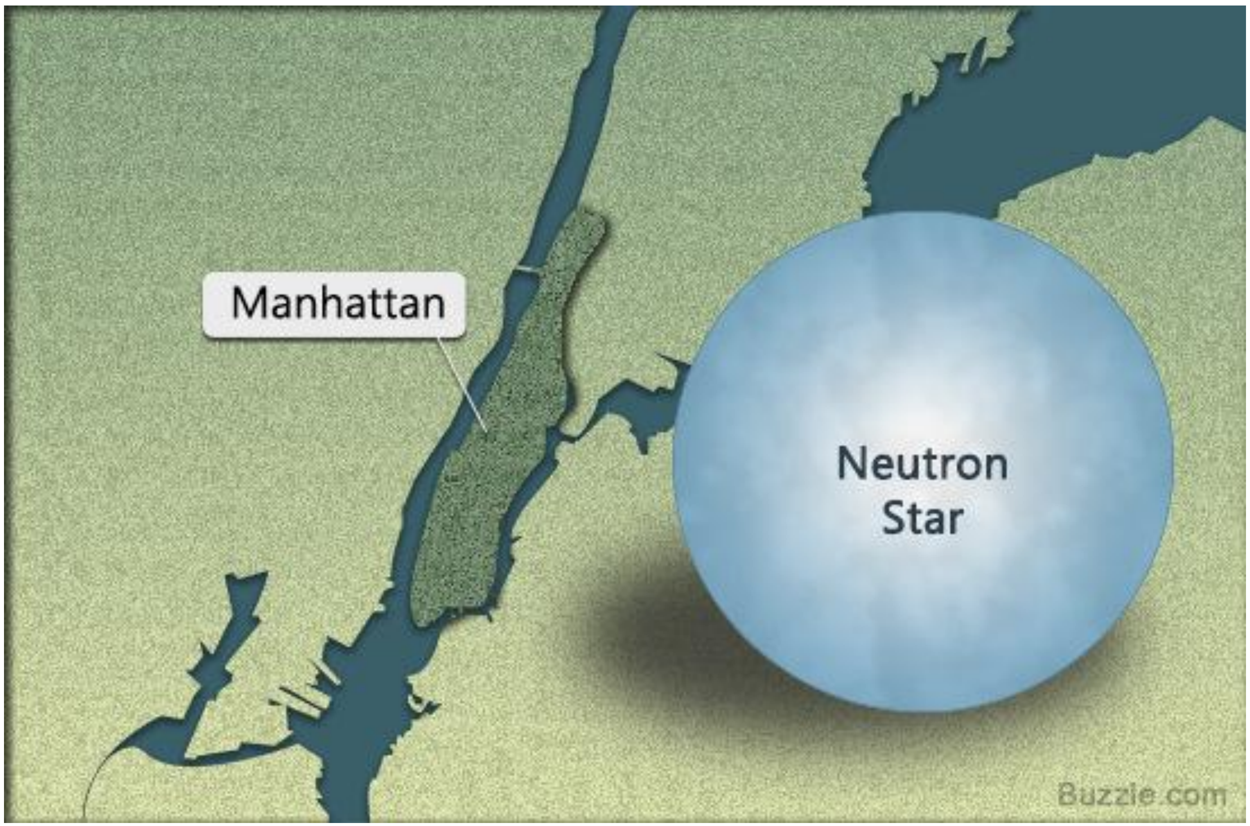


Fig. from Chihiro Sasaki, NPA 2009

Neutron star structure and size

- Radius: R ~ 10 - 13.6 km; Mass M ~ 1.2 - 3 $M_{\odot}$;
- For R = 10 km, M = 1.4 $M_{\odot}$, average number density ~ 0.4 fm^{-3} ; average (energy) density: ~ 6.9 $\times 10^{14}$ g/cm^3 ~ (2-3)ϱ_0 ;
- Spin frenquency ~ 714 Hz (fastest known); Magnetic fields: ~10^8 - 10^{14} G.



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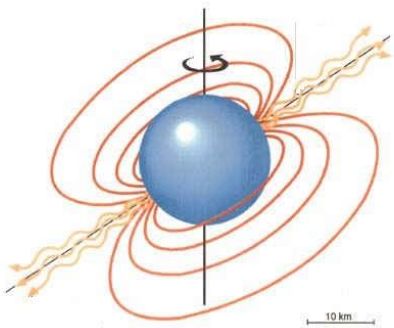
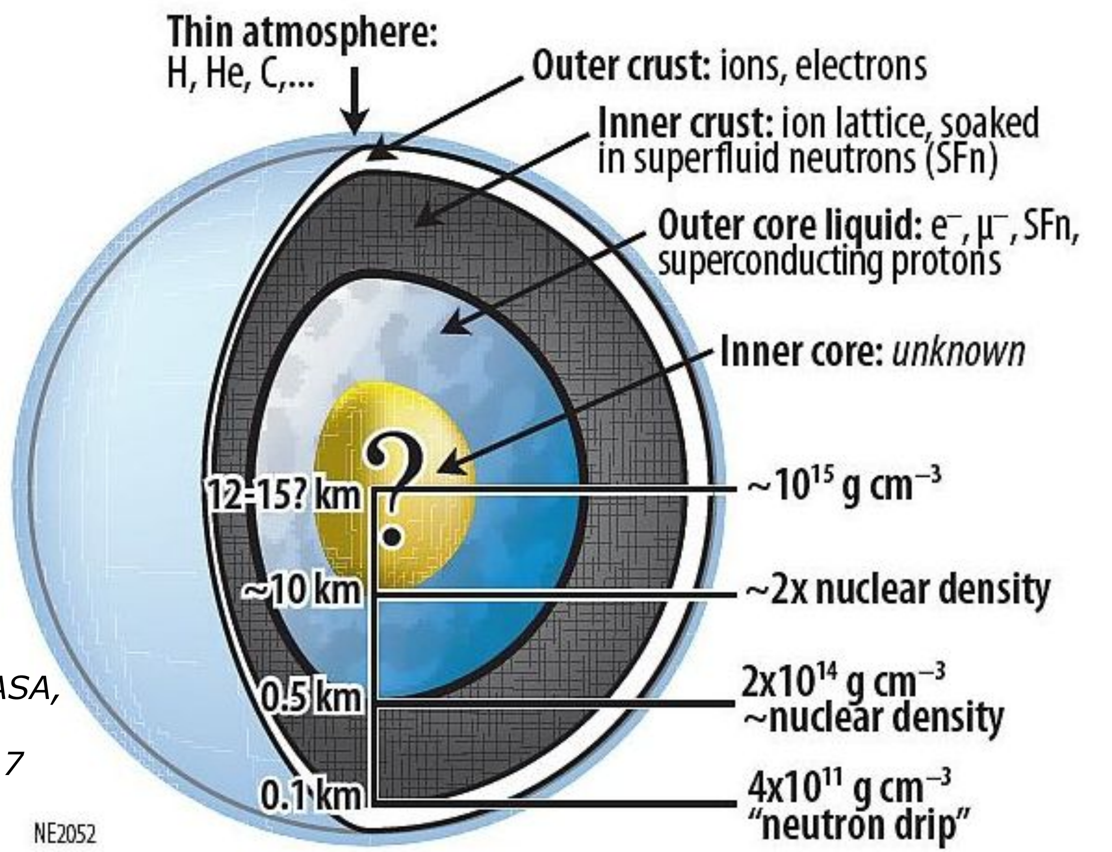
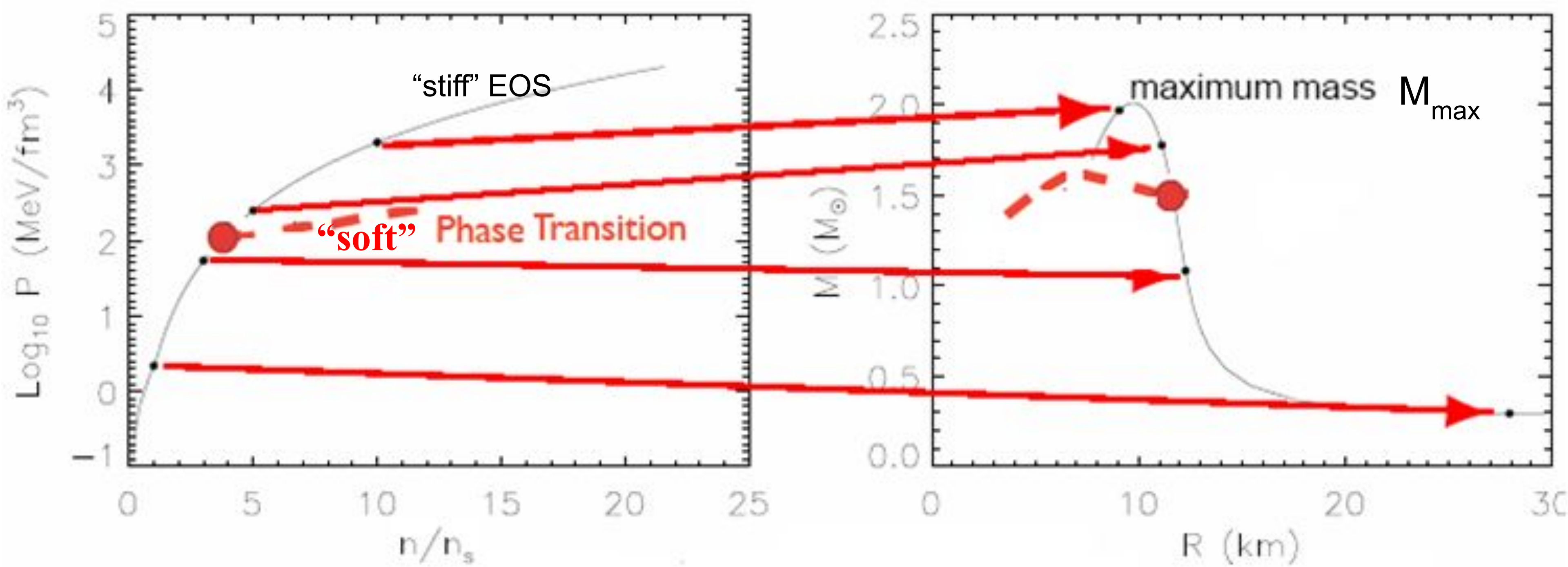




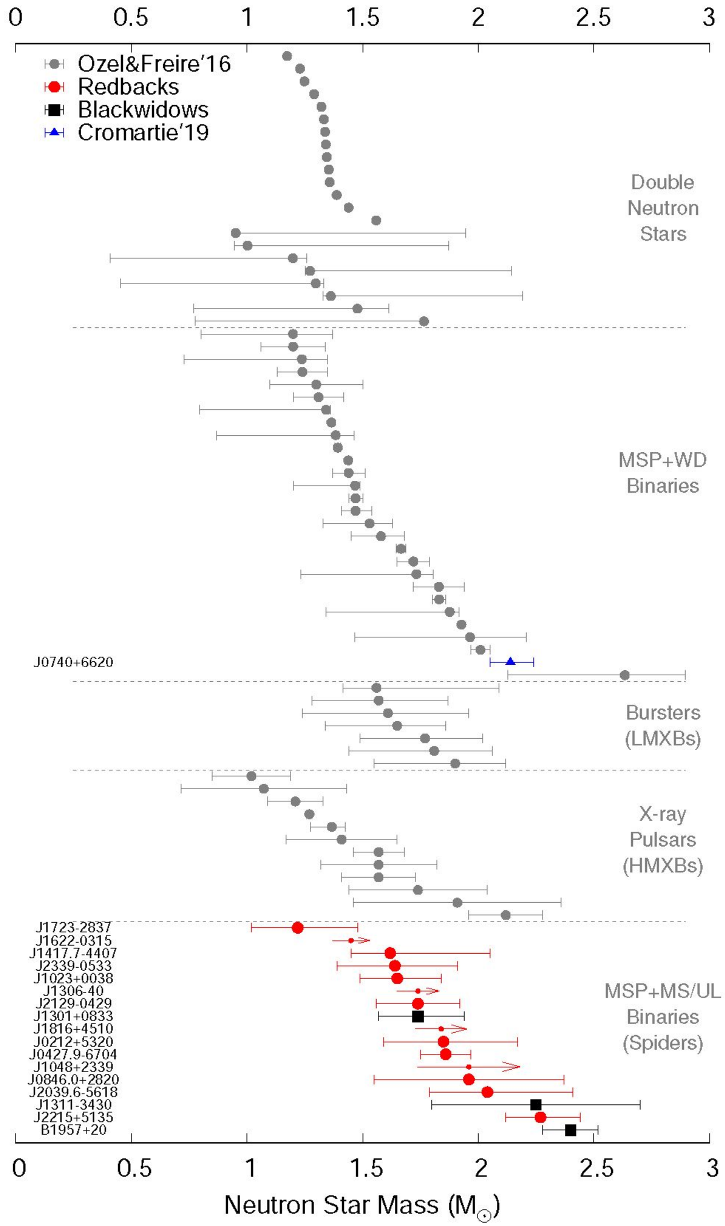
(image credit: NASA, NICER Team)
Launch: Feb. 2017

Neutron star M-R relation and the equation of state

- M-R relation is unique to the underlying equation of state (EOS):
- M_{max} (EOS) ≥ all measured neutron star masses;
- $M_{max} \geq 2.14^{+0.20}_{-0.18}$ $M_{\odot}$ **: Very stringent constraint on the EOS!**



Neutron star maximum mass: Observational



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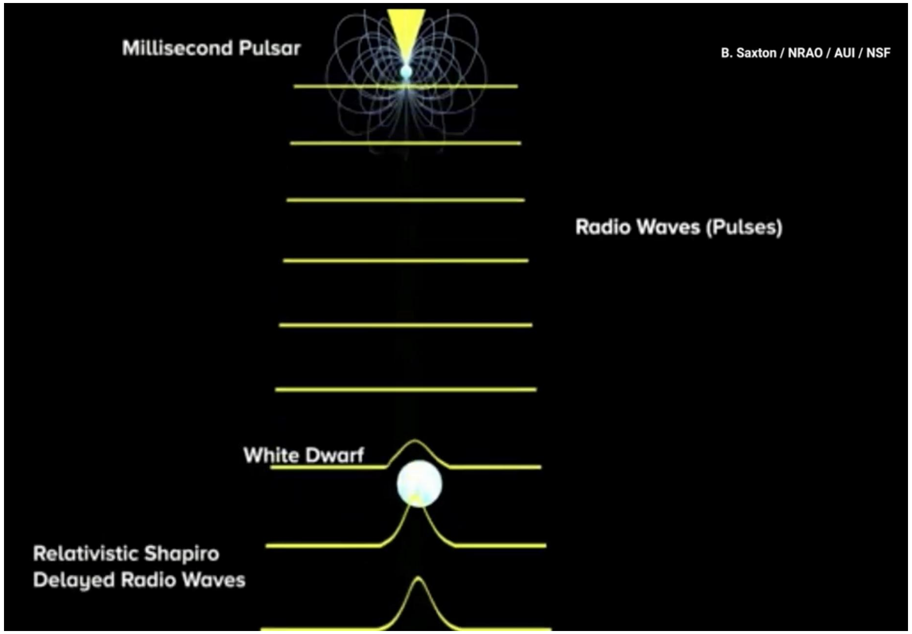

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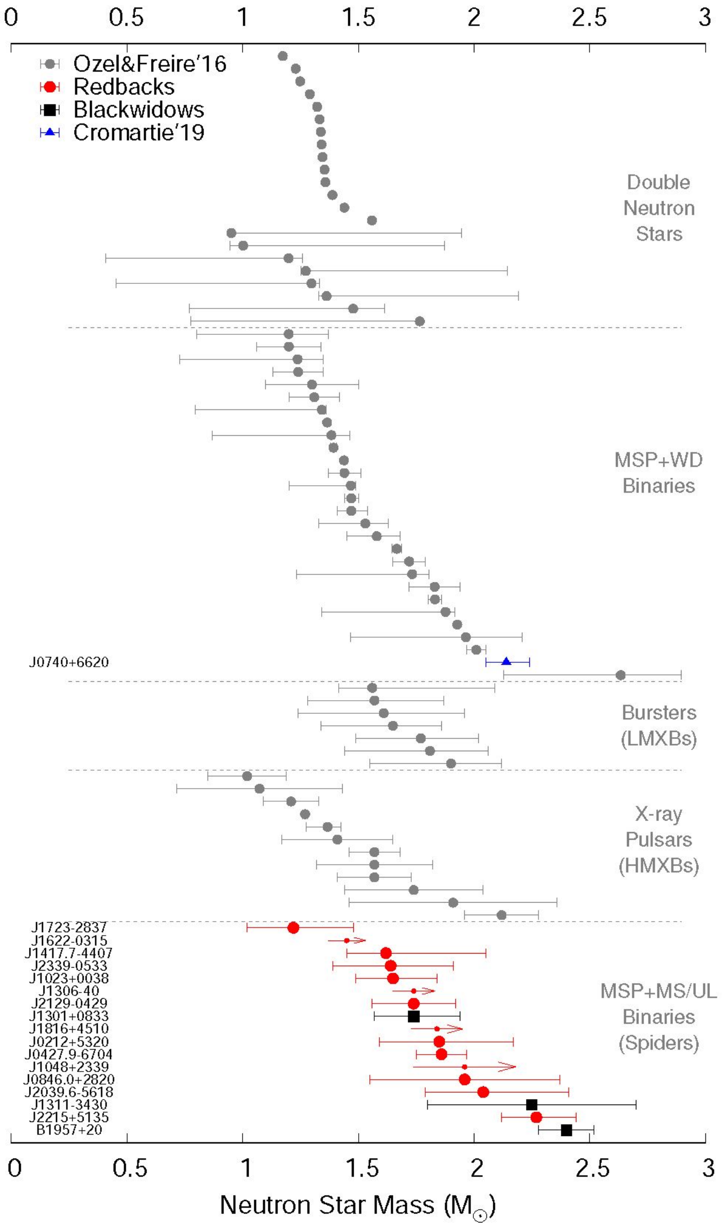

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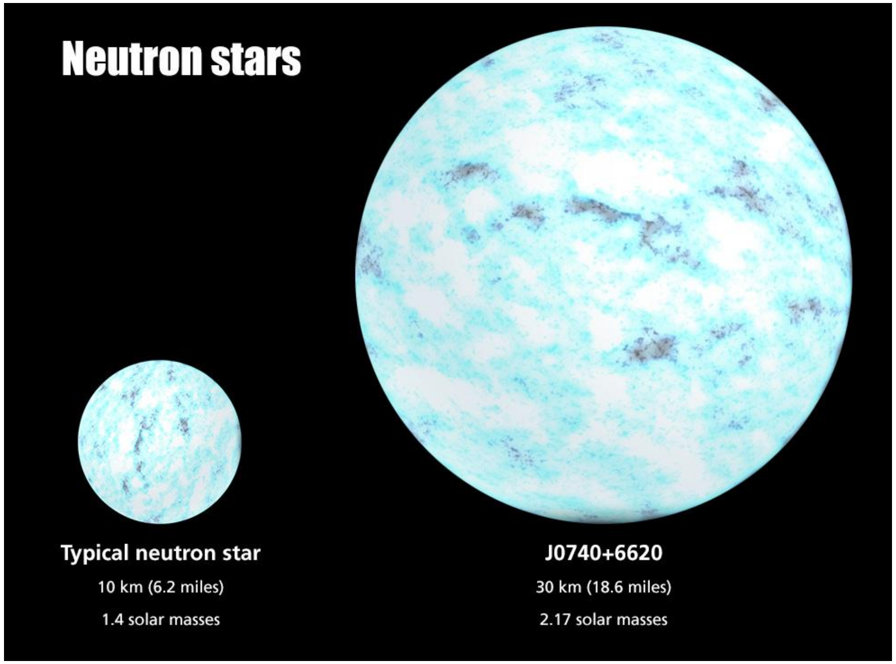
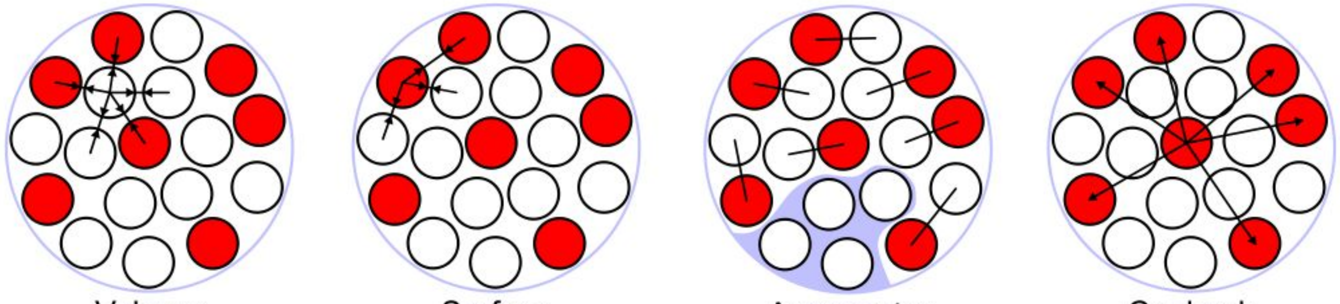


Basic things about EOS

Nuclear binding



$$B(A,Z) = a_V A + a_S A^{\frac{2}{3}} + S_N \frac{(N-Z)^2}{A} + a_C \frac{Z^2}{A^{\frac{1}{3}}}$$

$$4\pi R^2$$

$$R = R_0 A^{1/3}$$

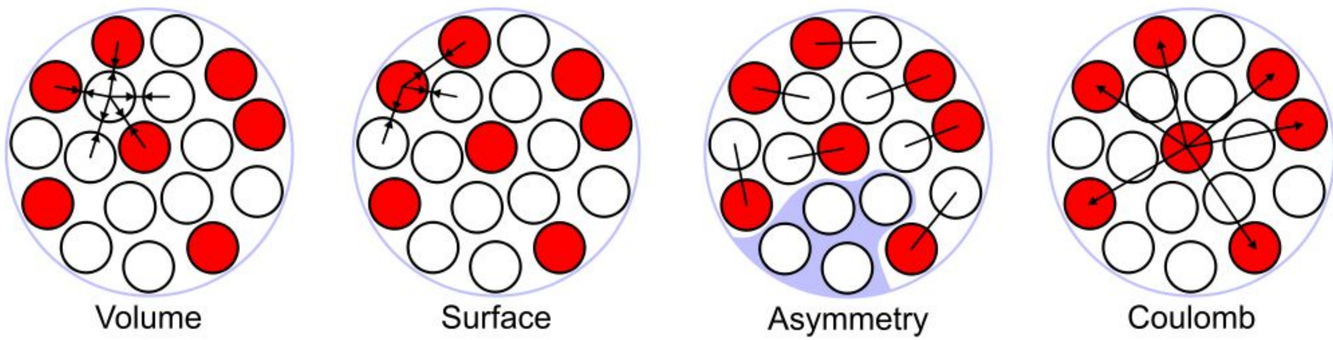
$$R^2 \propto A^{2/3}$$

$$\frac{Q_1 Q_2}{4\pi\varepsilon_0 R}$$

$$\propto \frac{1}{R}$$

$$\propto \frac{1}{A^{1/3}}$$

Nuclear matter = infinite uniform system of nucleons interacting through the strong interaction



V -> ∞
A -> ∞
Z -> ∞
A/V = ρ ≠ ∞

$$B(A,Z) = a_V A + \cancel{a_S A^{\frac{2}{3}}} + S_N \frac{(N-Z)^2}{A} + \cancel{a_C \frac{Z^2}{A^{\frac{1}{3}}}}$$

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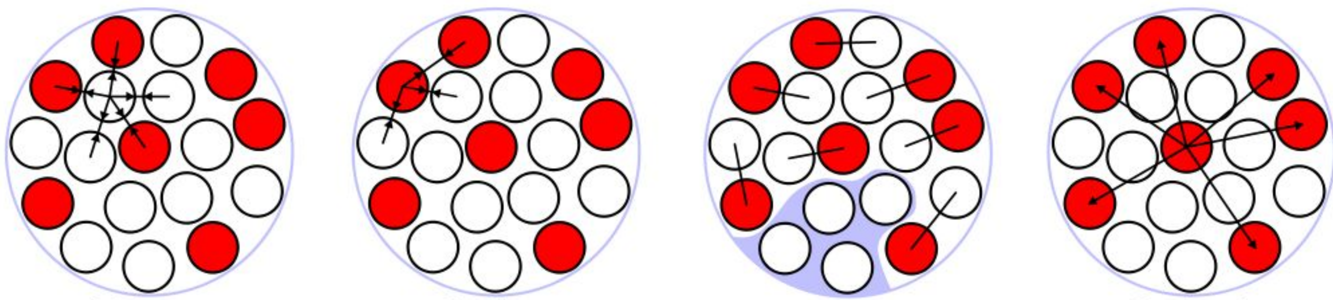
Nuclear matter equation of state, mainly P(ρ)



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$$E(\rho,\delta) \approx E_0(\rho) + E_{\rm sym}(\rho)\delta^2$$

$$P(\rho) = \rho^2 (\partial^2 E/\partial^2 \rho)$$

symmetry energy

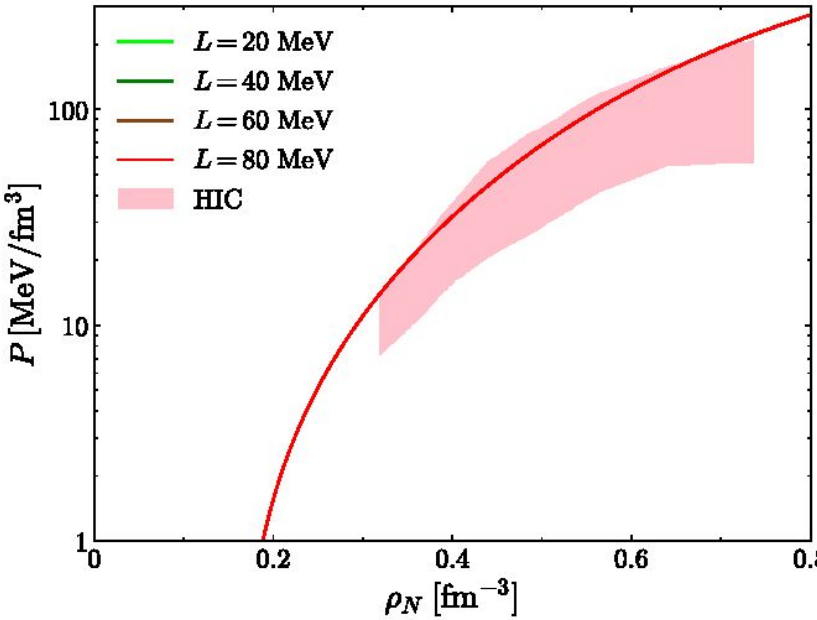
(N-Z)/A ->

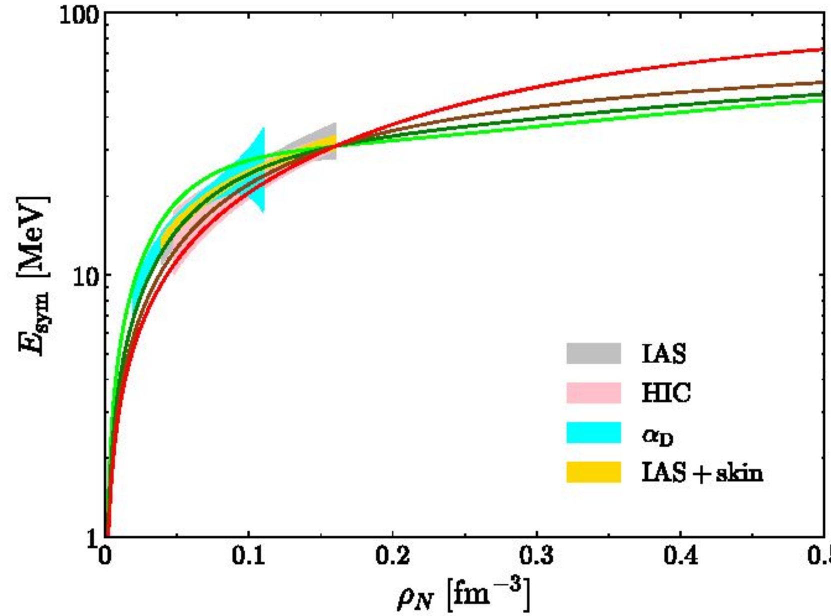
$\boldsymbol{\delta}$ = $(\rho_n - \rho_p)/\rho$

$$\boxed{L(\rho) = dE_{\rm sym}(\rho)/d\rho}$$

Nuclear matter equation of state, mainly P(ρ)

- L~30-60 MeV, if following ab-initio calculations and other constraints.





$$E(\rho,\delta) \approx E_0(\rho) + E_{\rm sym}(\rho)\delta^2$$

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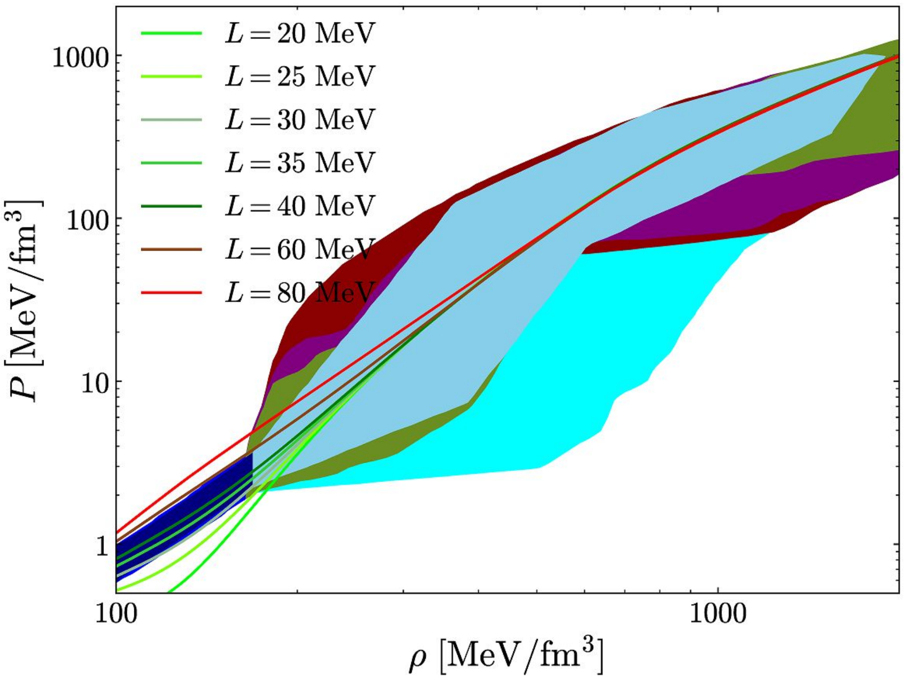
symmetry energy

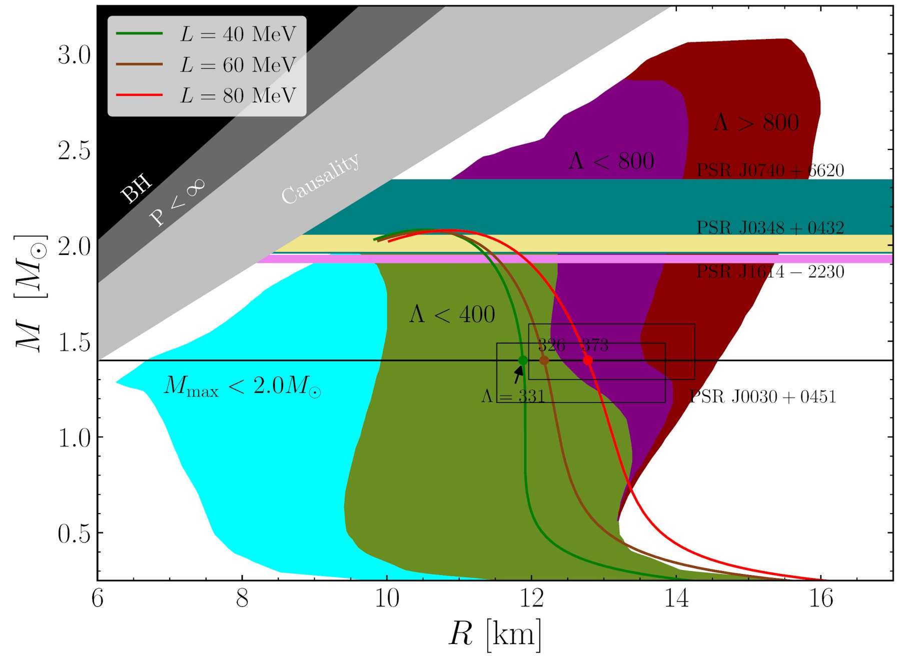
*Zhu, Zhou & **AL****, *1802.05510, ApJ*

$$\boxed{L(\rho) = dE_{\rm sym}(\rho)/d\rho}$$

Neutron star M-R relation and the equation of state

- EOS confronting with multi-messenger neutron star observations on M_{Max}, $R_{1.4}$, Λ.





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symmetry energy

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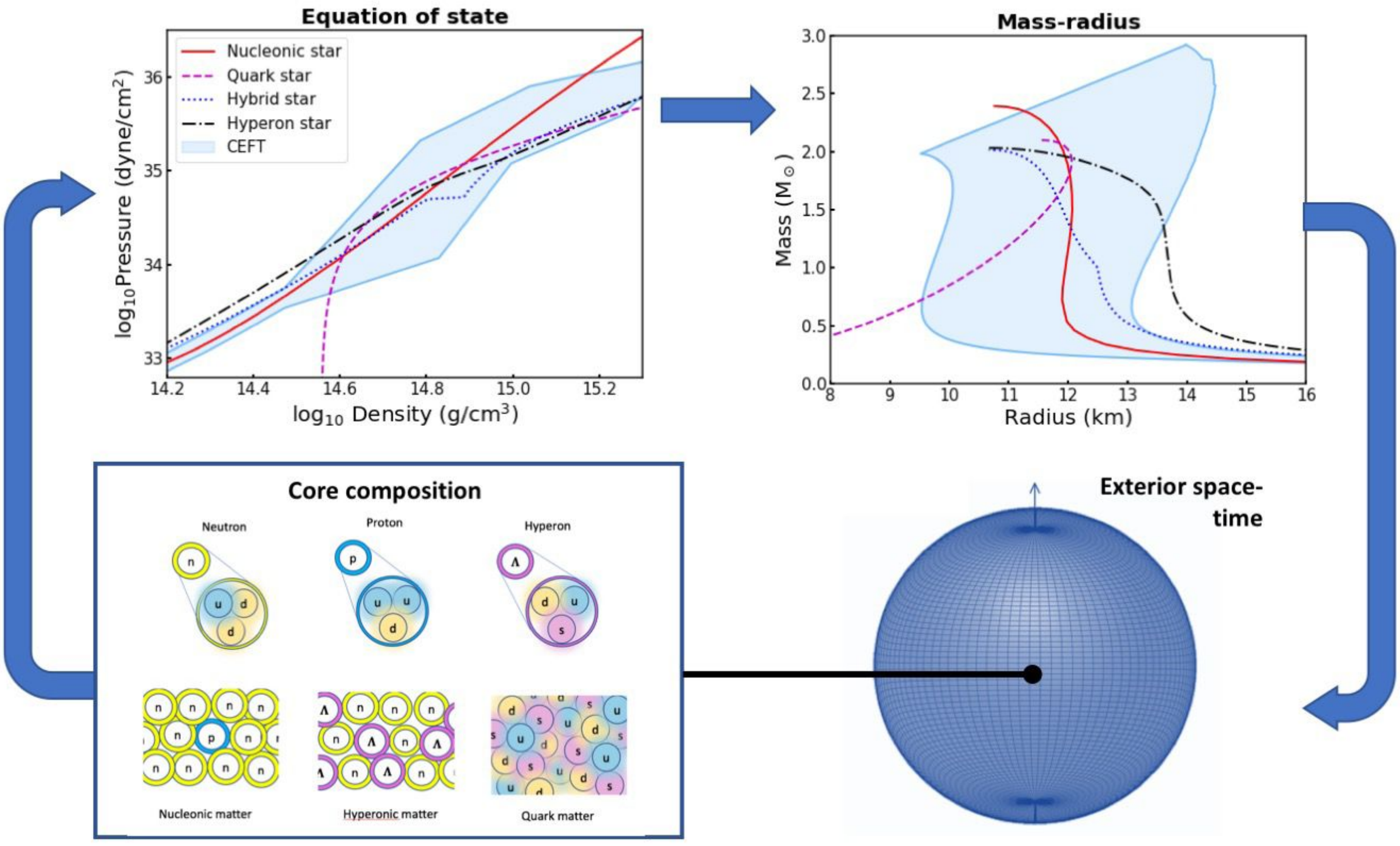
Radius measurements

X-ray observations of the neutron star surface permit radius measurements

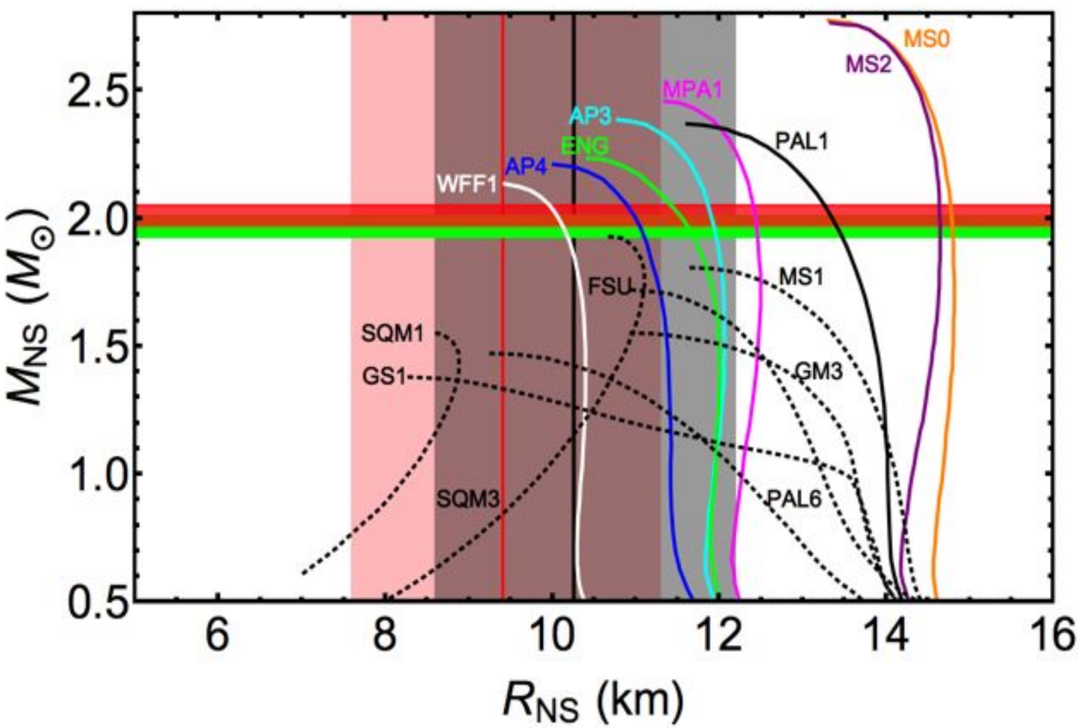


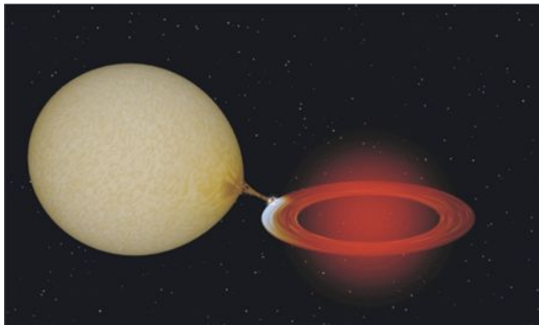
STROBE-X White paper

X-ray observations of the neutron star surface permit radius measurements 1/3

- Quiescent low-mass X-ray binaries;
- Many analysis assumptions on e.g., atmosphere, negligible surface magnetic field, isotropic emission, slowly rotating;
- Routinely used but only place weak constraints on EOS;

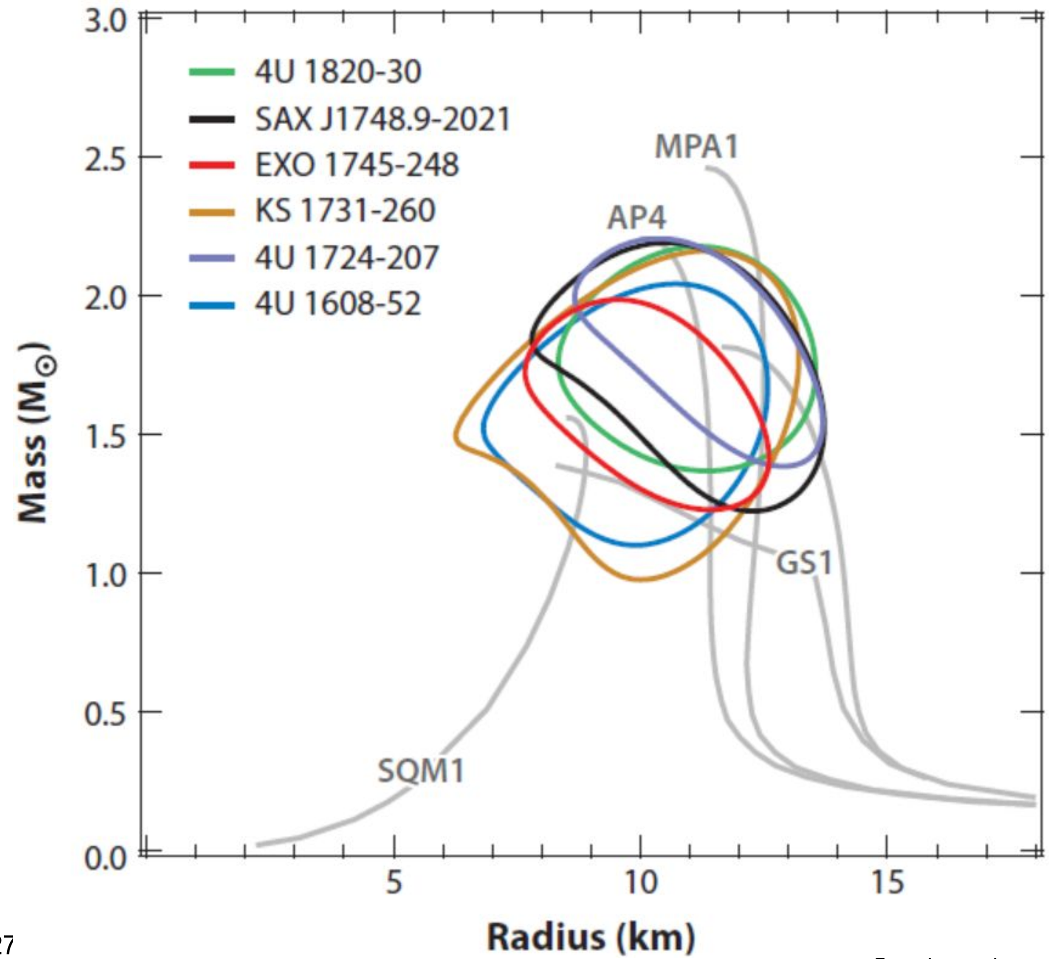
10.3+1.9-1.7 km

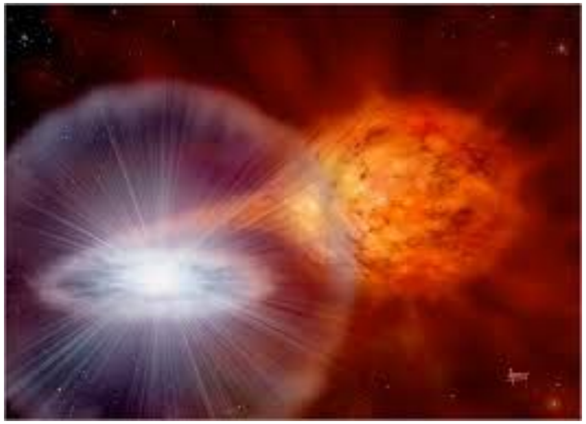




X-ray observations of the neutron star surface permit radius measurements 2/3

- Type I X-ray bursts;
- Many difficulities (e.g., burst selecing; distance; atmosphere).

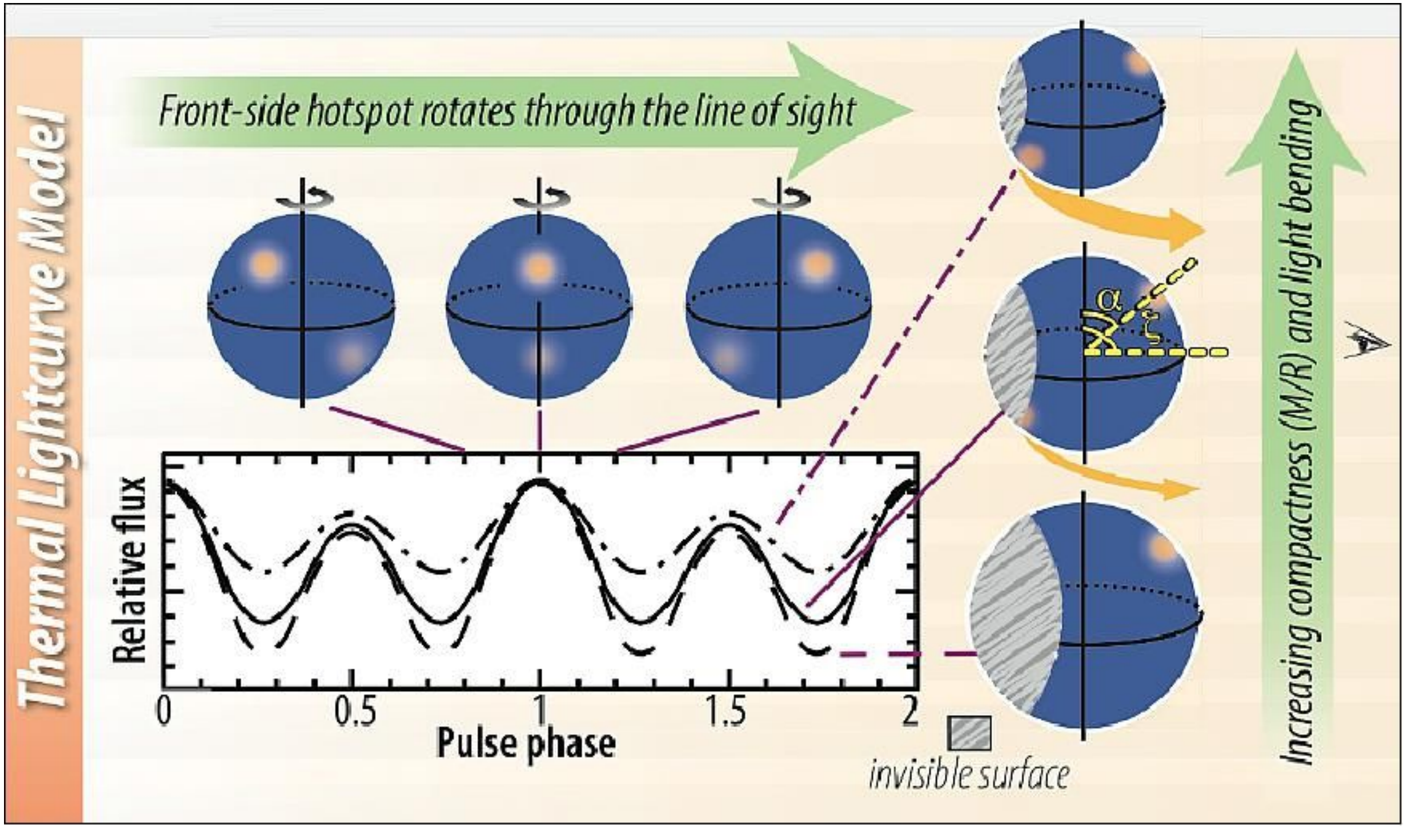




Özel & Freire 2016

X-ray observations of the neutron star surface permit radius measurements 3/3

- Pulsed emission caused by hot spots on a rotating neutron star can help measure the compactness M/R;
- NICER, eXTP(~2025), ATHENA(~2030), STROBE-X(~2030);

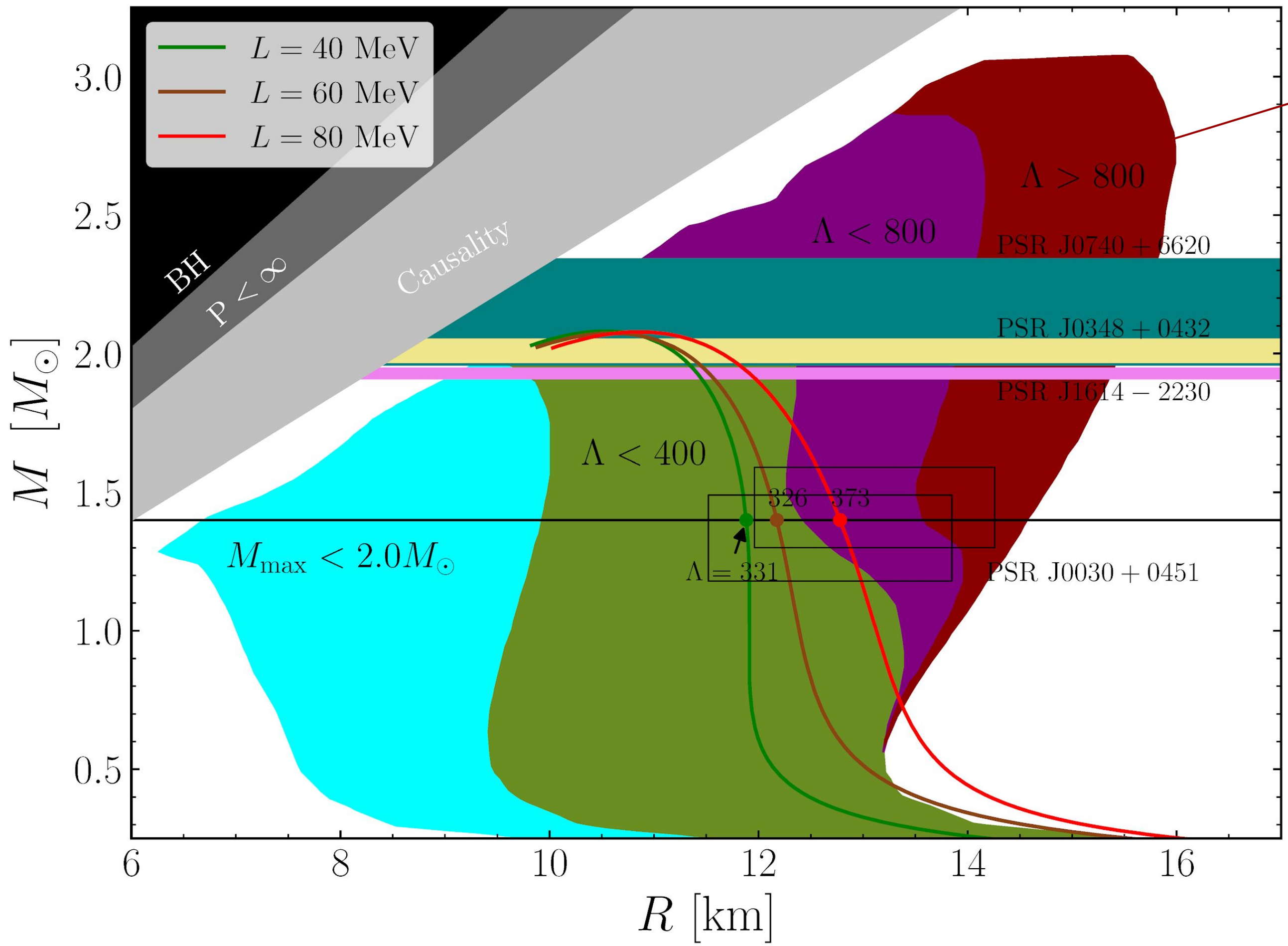


Joint estimation of the mass and radius of neutron stars by NICER

- For PSR J0030+0451: (68% CFL)

$$M = 1.44^{+0.15}_{-0.14} M_\odot,\ R = 13.02^{+1.24}_{-1.06}\ \text{km (Miller et al. 2019)}$$

$$M = 1.34^{+0.15}_{-0.16} M_\odot,\ R = 12.71^{+1.14}_{-1.19}\ \text{km (Riley et al. 2019)}$$



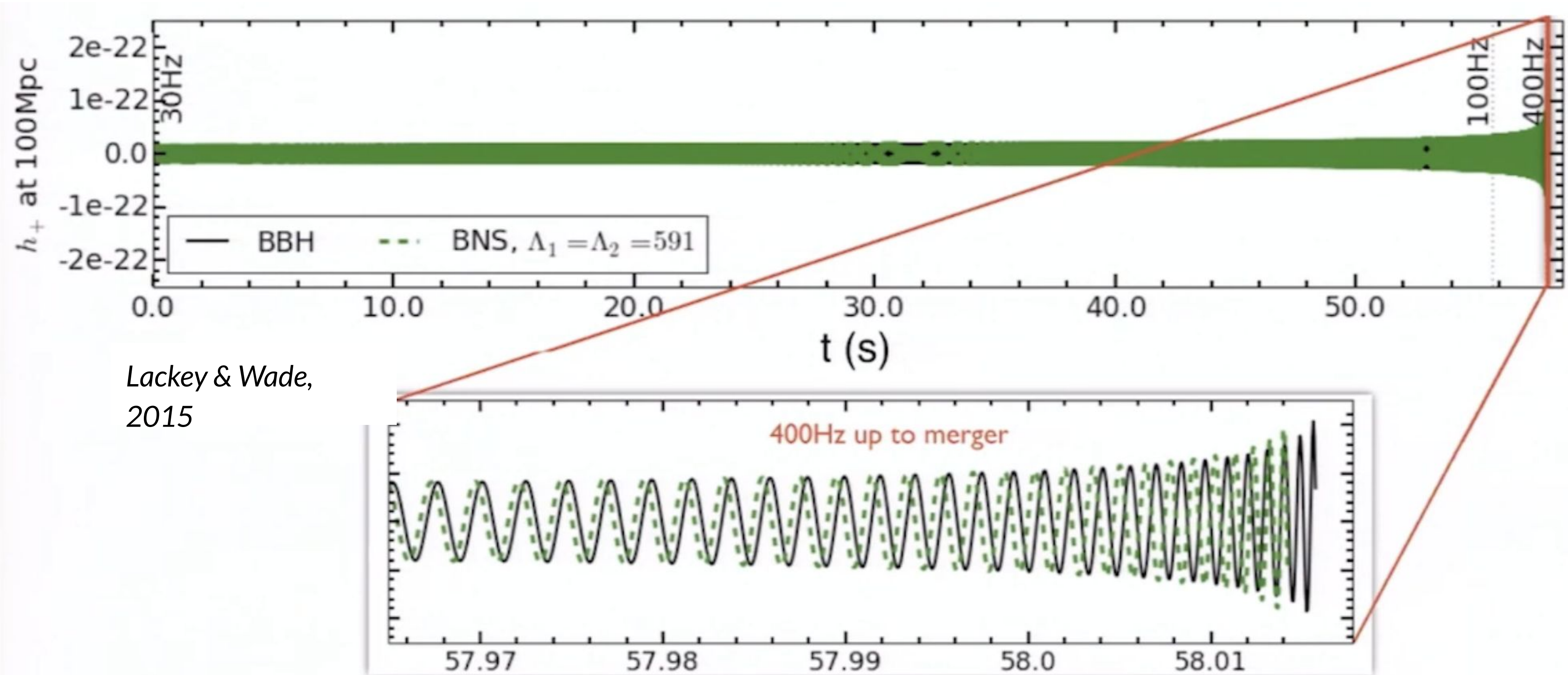
excluded by $\Lambda(1.4) \lesssim 800$ of GW170817

$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$$

Neutron stars (especially the radii) strongly constrain L.

Tidal deformability from binary neutron star mergers

- Finite size effects of the merging star will alter the late inspiral GW signal
- Dimensionless tidal deformability of each star: $\Lambda = \frac{2}{3}k_2(\frac{R}{M})^5$



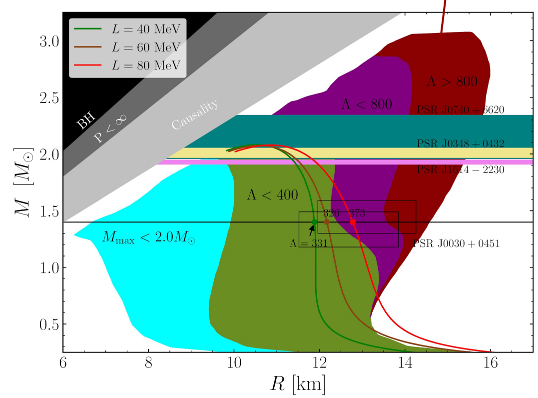
Lackey & Wade, 2015

Tidal deformability from GW170817

- Λ_1, Λ_2 depends on M/R and the EOS: $\Lambda = \frac{2}{3}k_2(\frac{R}{M})^5$
- Assume that GW170817 is a bianry neutron star;
- Both neutron stars obey the same EOS;

	Low-spin priors ($\vert\chi\vert \leq 0.05$)
Primary mass m_1	1.36–$1.60\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$
Using NGC 4993 location	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800
Dimensionless tidal deformability $\Lambda(1.4M_\odot)$	≤ 800

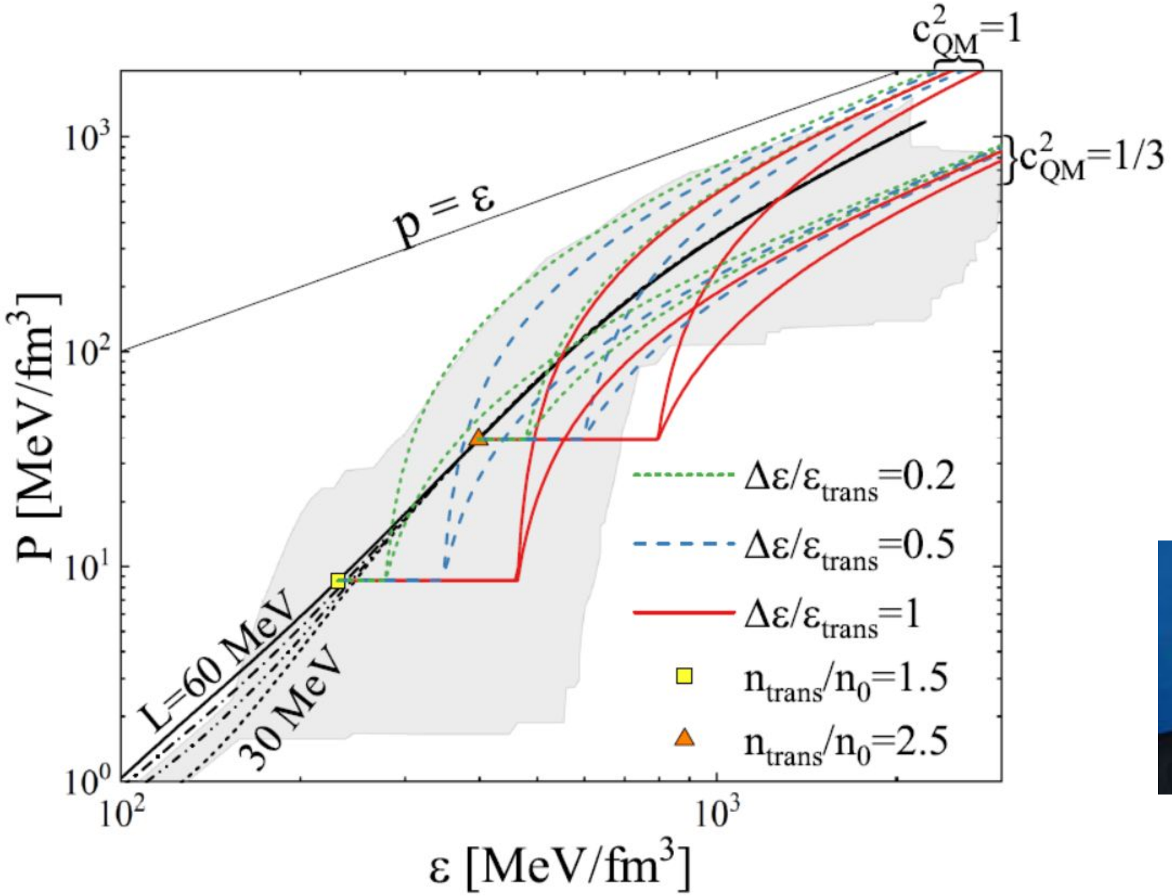
excluded by $\Lambda(1.4) \lesssim$ 800 of GW170817



More physics necessary at the EOS modelling stage:
With prior considering phase transition!

Including strangeness phase transition

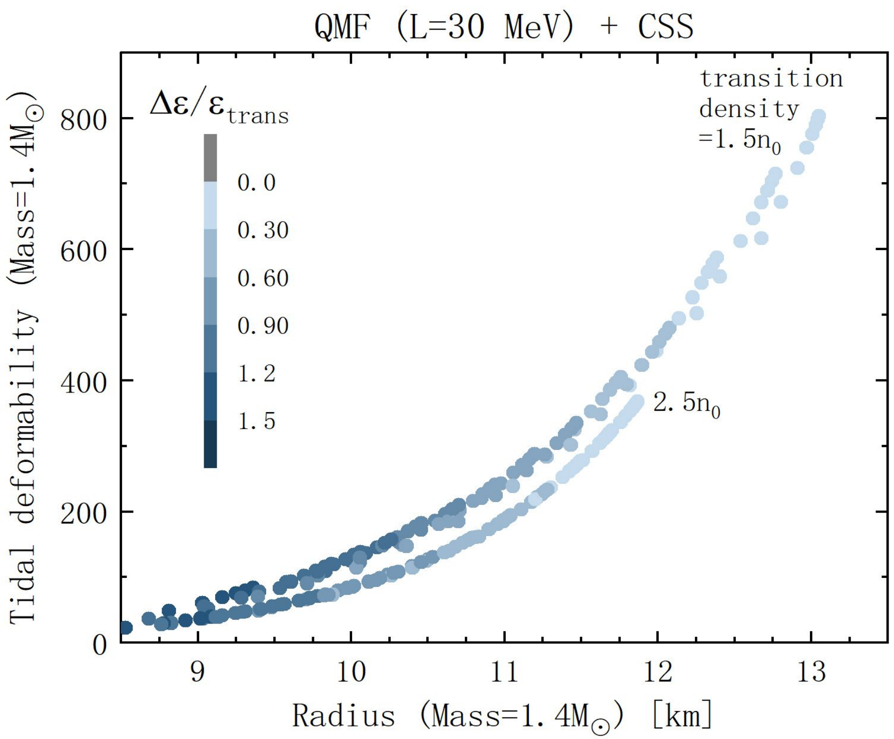
- QMF (quark mean-field) nuclear matter EOS + constant-speed-of-sound (CSS) parametrization for high-density (quark matter) EOS;
- Assuming strong first-order phase transition, most promising scenario to be tested or distinguished from pure hadronic matter by future observations.

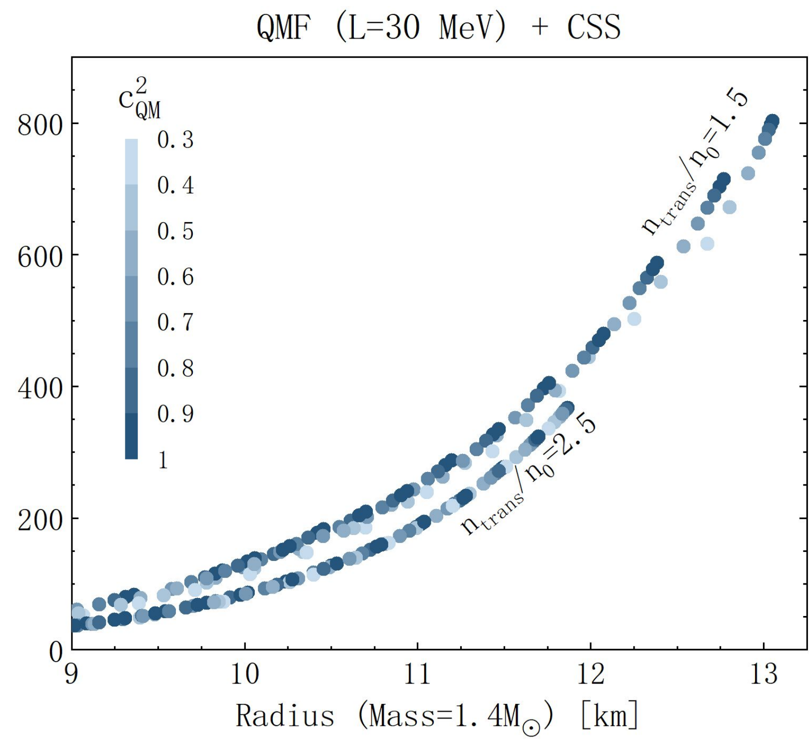


Miao et al. (2020)
to be submitted

Tidal deformability of hybrid stars

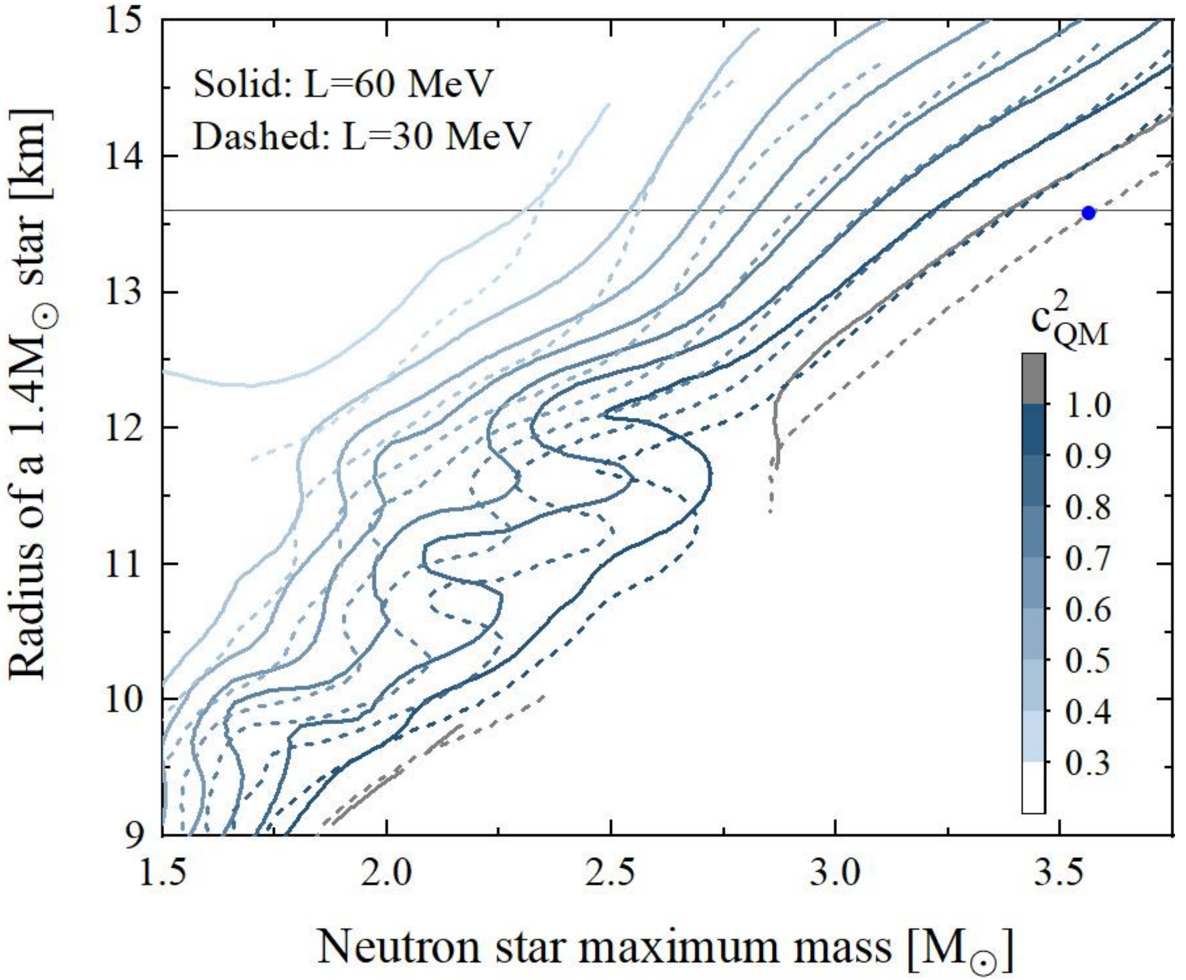
- Unknown threshold density has a non-trivial effect on empirical Λ-R relations for a given nuclear matter model.



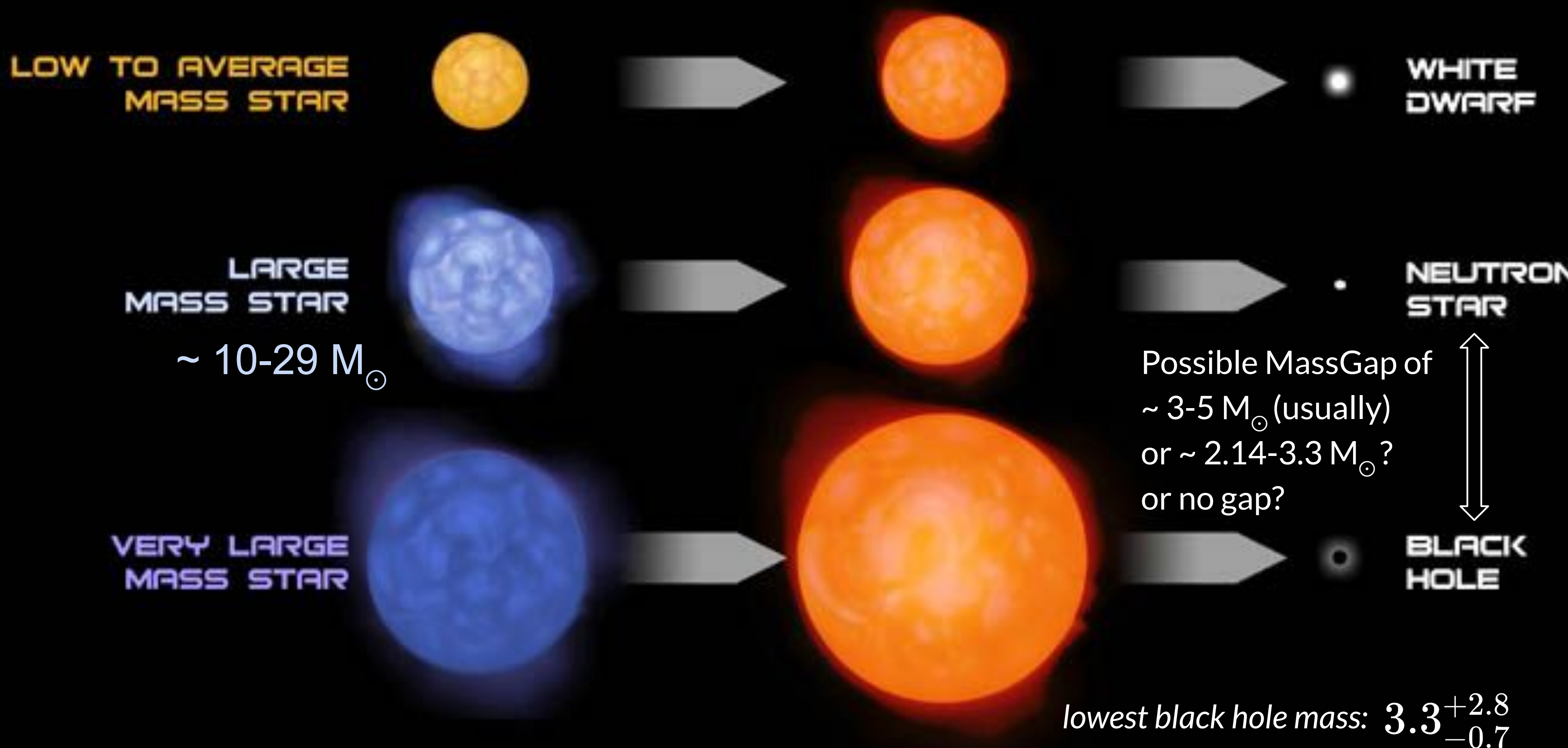


Neutron star maximum mass: Theoretical

- Robust upper limit on the maximum mass ~3.6 $M_\odot$ based on the casulity condition.



Neutron star maximum mass



~ 10-29 $M_\odot$

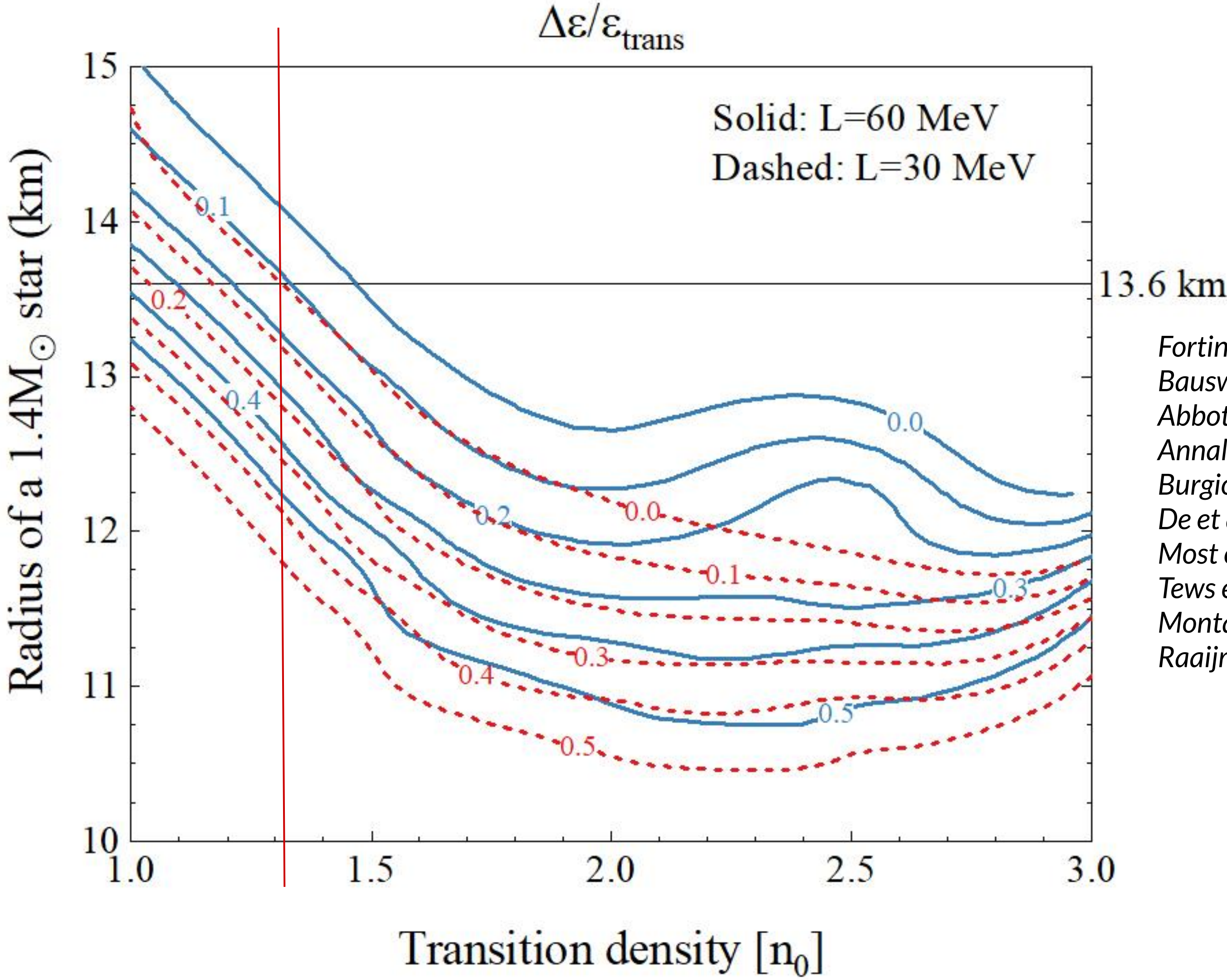
Possible MassGap of ~ 3-5 $M_\odot$ (usually) or ~ 2.14-3.3 $M_\odot$? or no gap?

lowest black hole mass: $3.3^{+2.8}_{-0.7}$

(Thompson, et a. 2019 Science 2019)

New limits on phase transition onset density

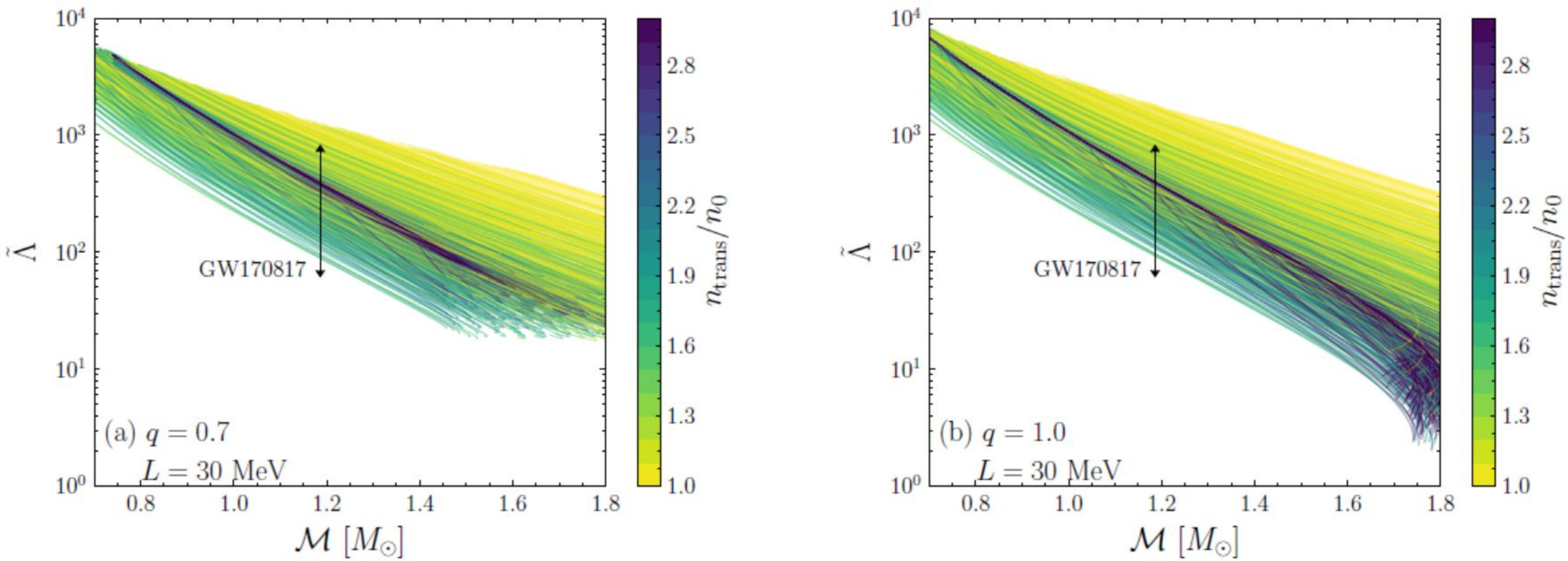
- Onset density >~1.3n_0 from a conservative radius limit $R_{1.4}$<13.6 km.



Fortin et al. 2016;
Bauswein et al. 2017;
Abbott et al. 2018;
Annala et al. 2018;
Burgio et al. 2018;
De et al. 2018;
Most et al. 2018;
Tews et al. 2018;
Monta~na et al. 2019;
Raaijmakers et al. 2020

Current Λ uncertainties for hybrid stars within QMF+CSS

- Very low onset density <~1.3n_0 also strongly disfavored by GW170817;
- More neutron star mergers with different chirp masses and mass ratios measured hold promise of reducing the uncertainties significantly.

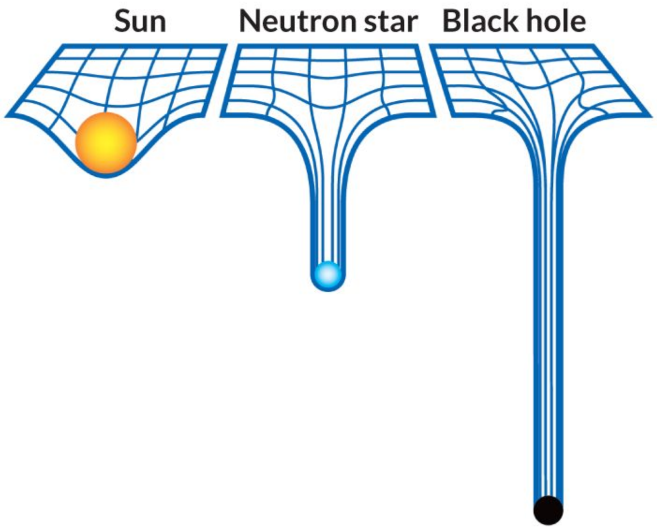


$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4}{(m_1+m_2)^5}\Lambda_1 + (1 \leftrightarrow 2)$$

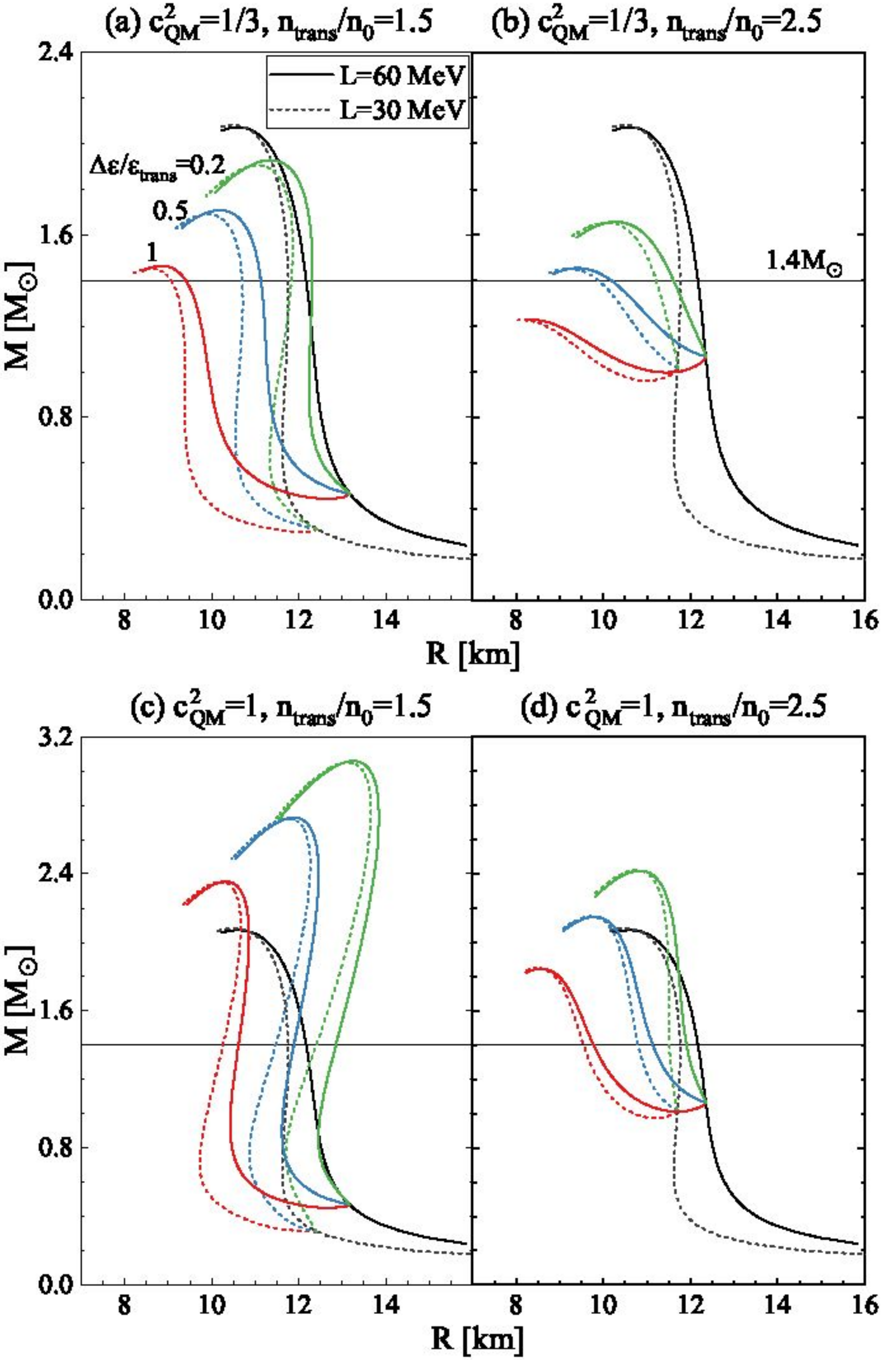
Take-home message

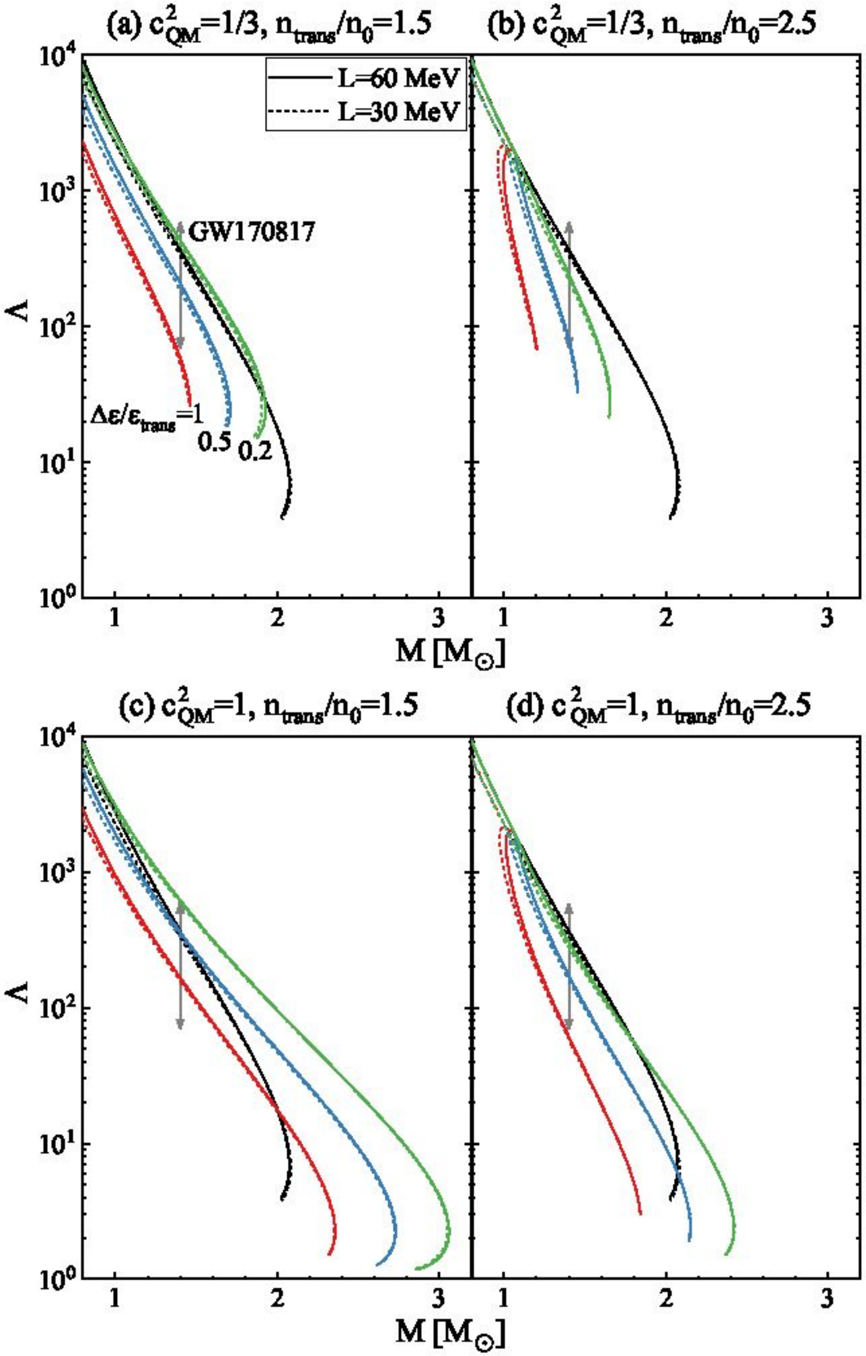
- The "golden" event of GW170817 brings the best time of multi-messenger era;
- The golden age of neutron-star physics has arrived! (*Nature*|*doi:10.1038/d41586-020-00590-8*)
- Limits on symmetry energy: L~30-60 MeV;
- New limits on maxmimum mass: ~2.3-3.3(observational) ~2.4-3.6(theoretical);
- New limits on radii: ~10-13.6 km;
- EOS: Not too stiff/soft; stiff-low soft-high?
- The composition: Strangeness present

  lower than ~1.3 times nuclear density.



Backup slides


(a) c^2_{QM}=1/3, n_{trans}/n_0=1.5
(b) c^2_{QM}=1/3, n_{trans}/n_0=2.5
(c) c^2_{QM}=1, n_{trans}/n_0=1.5
(d) c^2_{QM}=1, n_{trans}/n_0=2.5
L=60 MeV
L=30 MeV
$\Delta\varepsilon/\varepsilon_{trans}$=0.2
0.5
1
$1.4M_\odot$
M [$M_\odot$]
R [km]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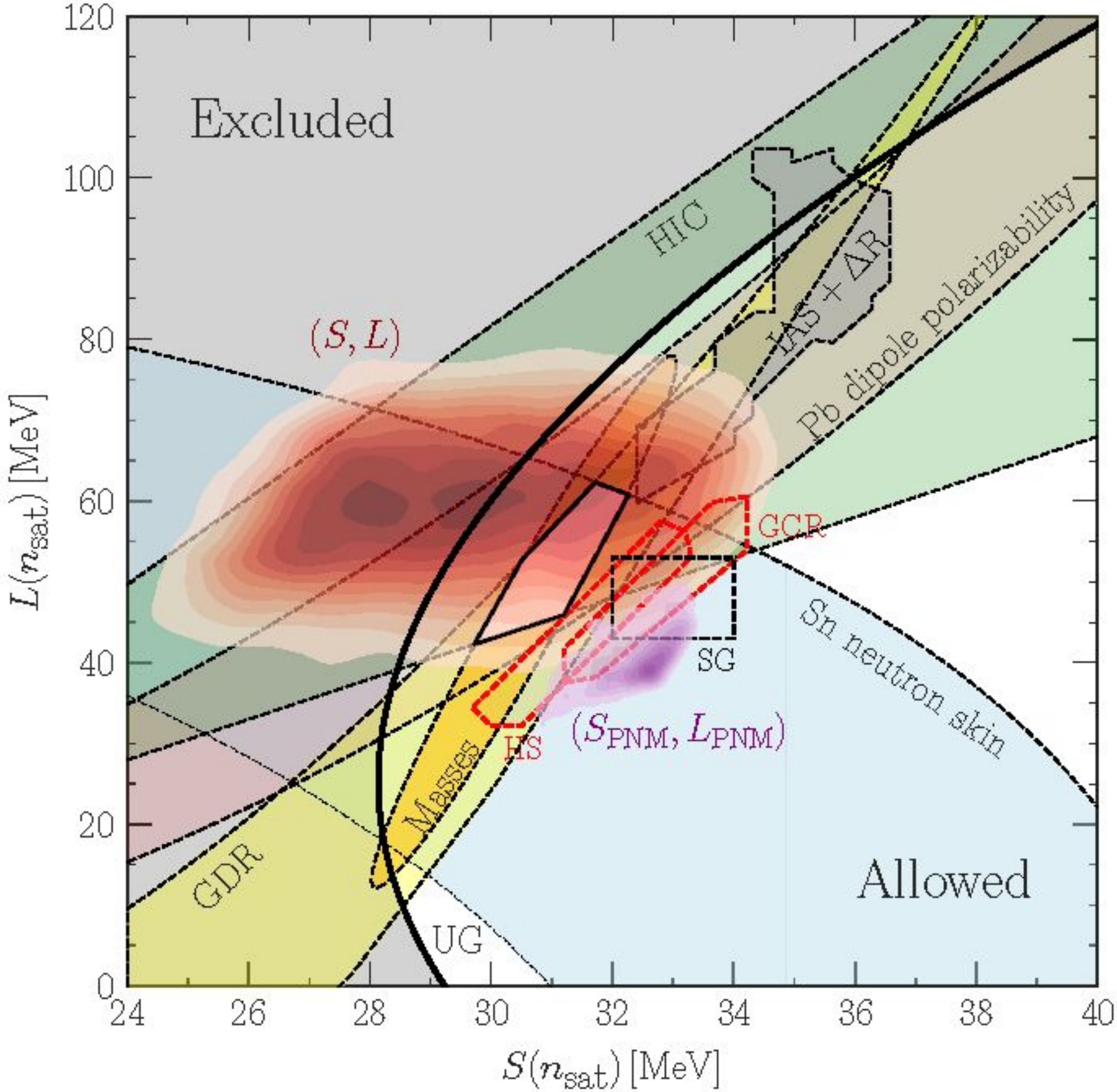
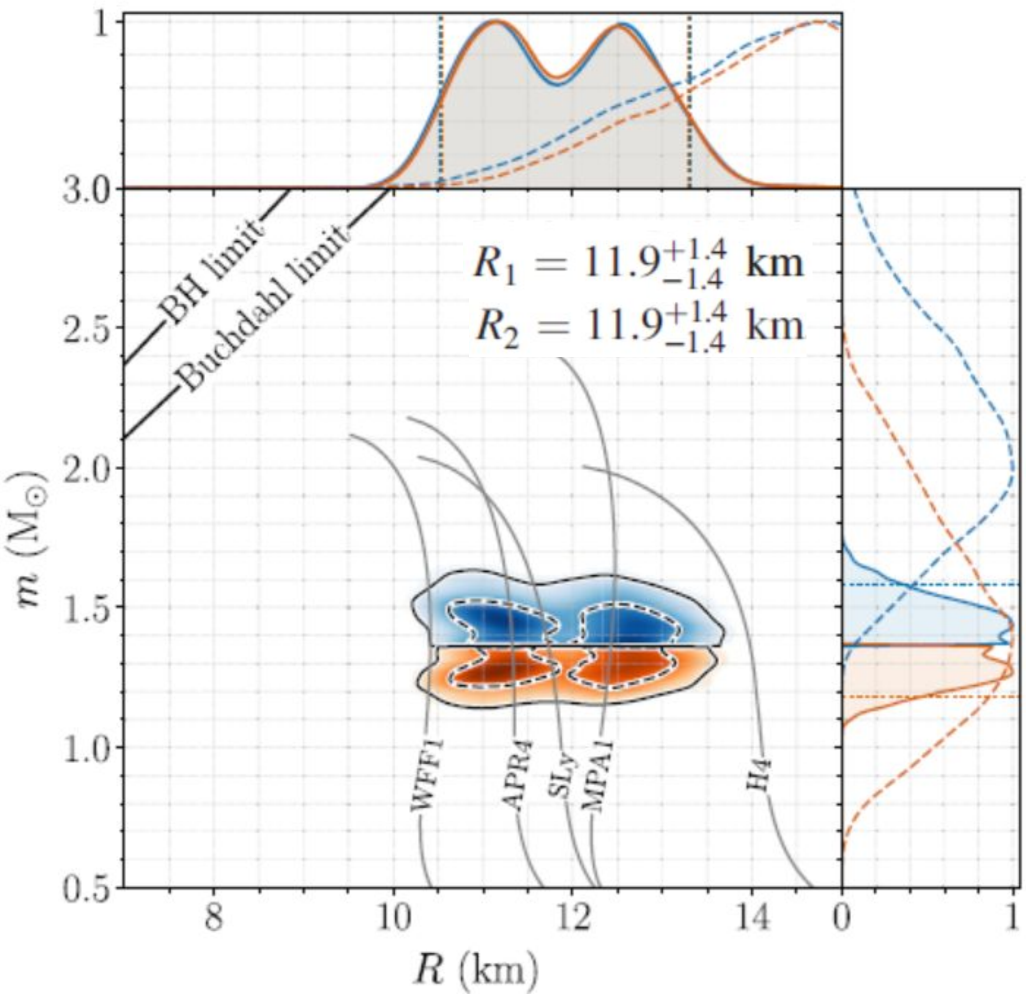
L=60 MeV
L=30 MeV
GW170817
$\Delta\varepsilon/\varepsilon_{trans}$=1
0.5
0.2
Λ
M [$M_\odot$]



Lonardoni et al. 2020

GW 170817: GW signal

$$\Gamma = (\rho + P)(dP/d\rho)/P$$

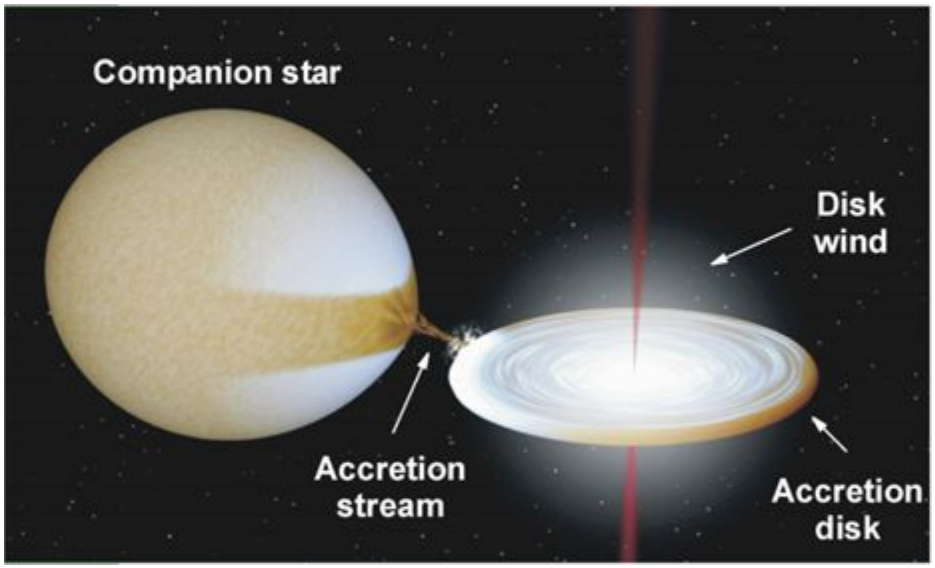


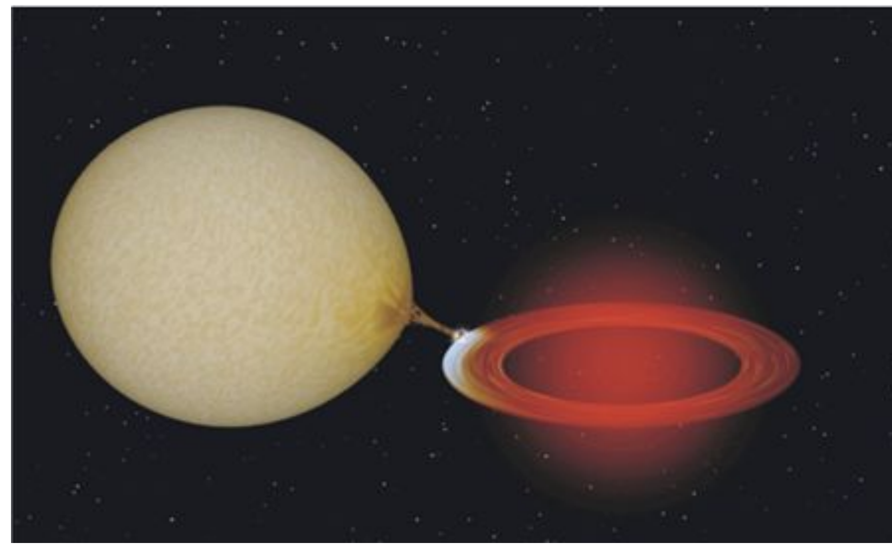
LVC group, 2018 PRL

- Piecewise polytrope EOS: Logarithm of the adiabatic index (Γ) of the EOSs are treated as polynomial: **Little to no microphysics**;
- More physics necessary at the EOS modelling stage: With prior considering phase transition, **results less constrained**;
- Tidal deformbality with strangeness phase transitions (*Zhu, Zhou & **AL****, *1802.05510, ApJ*)

X-ray observations of the neutron star surface permit radius measurements

- Quiescent low-mass X-ray binaries;
- Also many analysis assumptions on e.g., atmosphere, negligible surface magnetic field, isotropic emission, slowly rotating;
- Routinely used but only place weak constraints on EOS;

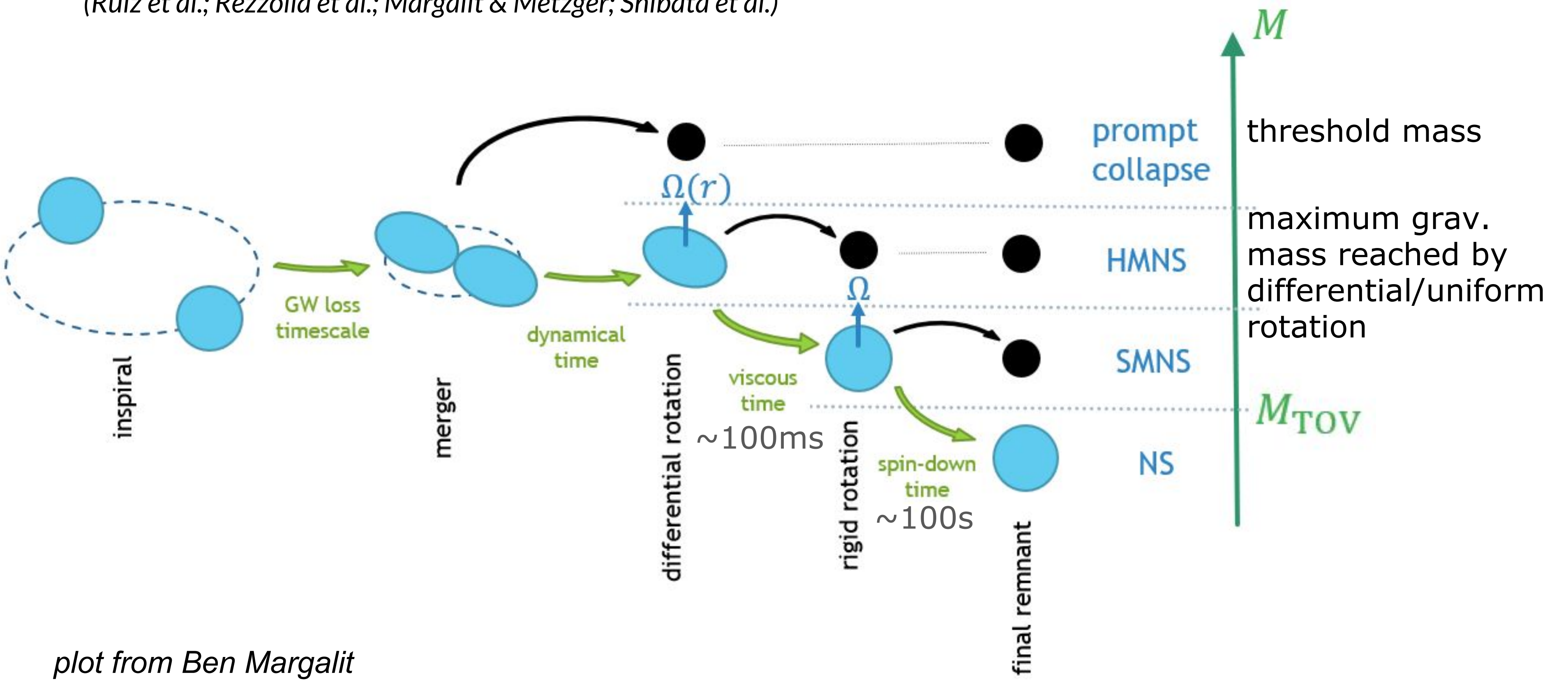




Merger remnants from binary neutron star mergers

- GW & SGRB & kilonova: EOS sensitive: Confronting with numerical simulations;
- A neutron star maximum mass <~2.3$M_\odot$ may be indicated from EM observations.

(Ruiz et al.; Rezzolla et al.; Margalit & Metzger; Shibata et al.)



plot from Ben Margalit

Merger remnants from binary neutron star mergers

- Sensitive to the maximum mass (Li et al. 2017);
- Further information coming from kilonava events.