Probing dense QCD matter with neutron stars

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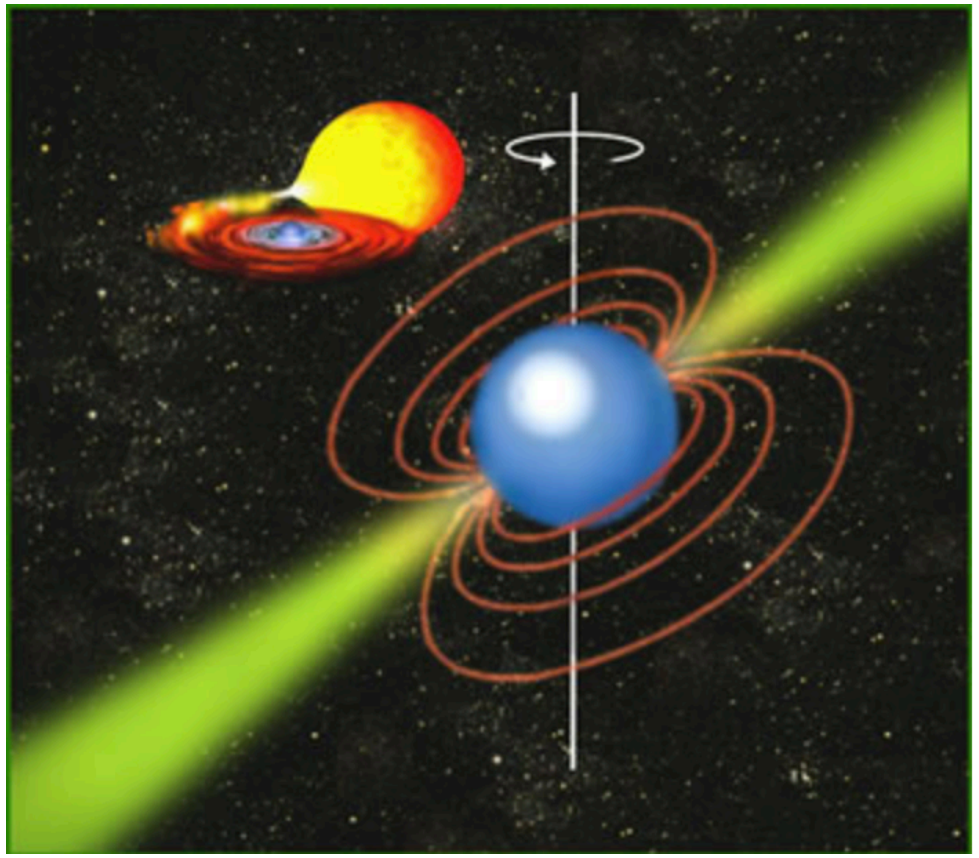
Motivation

the most compact objects
second only to black holes



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- still far from understanding NSs' composition over half a century since their discovery..
- NS mass-radius <-> pressure vs. energy density (***equation of state***): important, yet not enough

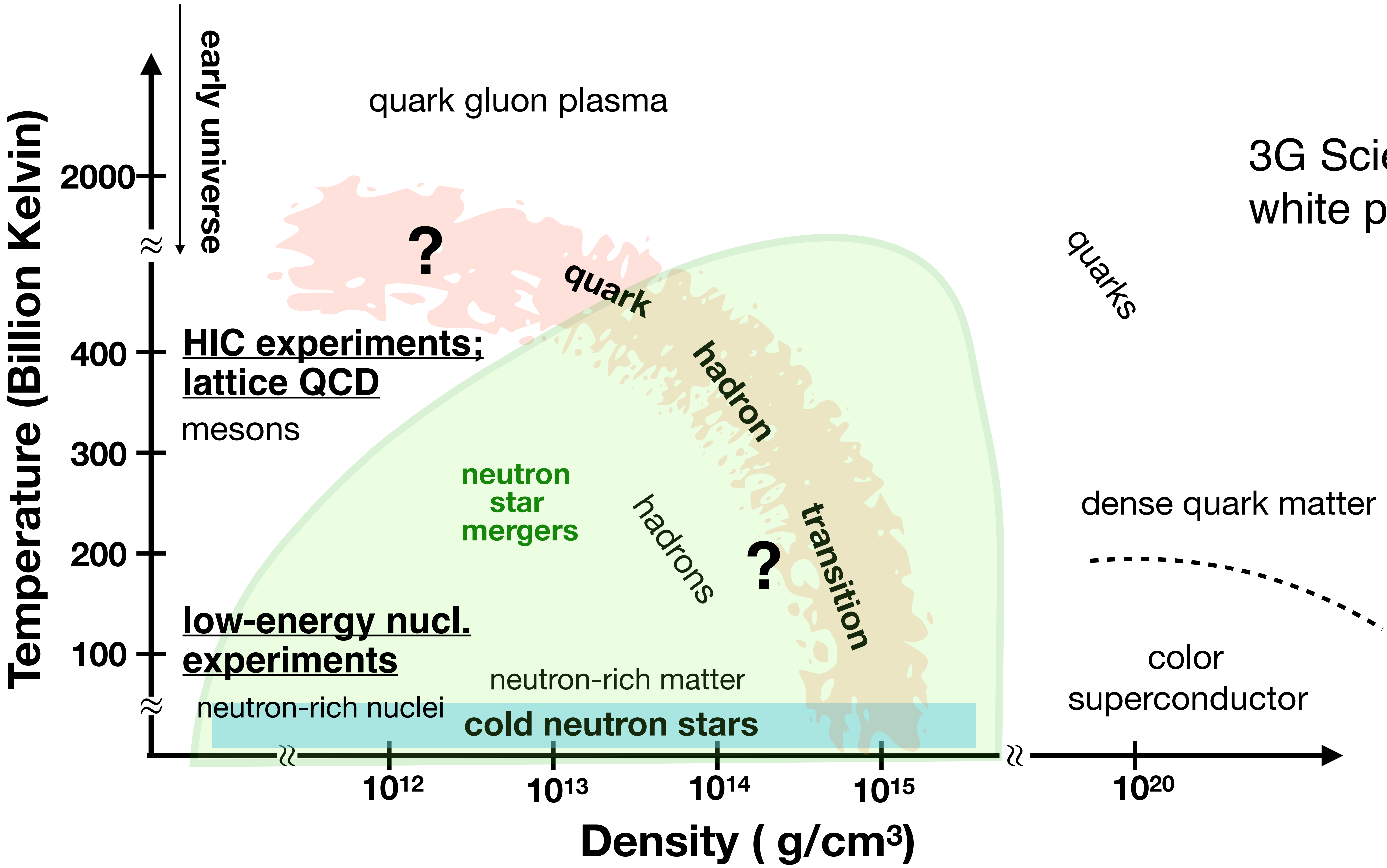
main sources for LIGO-Virgo-KAGRA:

- NS, BH binary mergers
- supernovae, NS/BH formation
- spinning NSs in x-ray binaries
- isolated NSs: instabilities, deformations

WDs: $M/R \sim 10^{-4}$
NSs: $M/R \sim 0.2$
BHs: $M/R = 0.5$

mass	radius	density	initial temp
$\sim 1.4 M_\odot$	$\mathcal{O}(10\,\mathrm{km})$	$\gtrsim \rho_{\rm nuclear}$	$\sim 30\,\mathrm{MeV}$

Laboratory for theoretical physics



- no terrestrial experiments can probe such high densities
- reliable first-principle calculations break down at the strongly-interacting regime

- can't calculate properties of cold dense matter; must **observe**!

What can we observe?

- orbital characteristics in binaries
- surface luminosity
- spin
- gravitational waves (NS merger)
- neutrinos (supernova)
- explosions and flares

What can we infer?

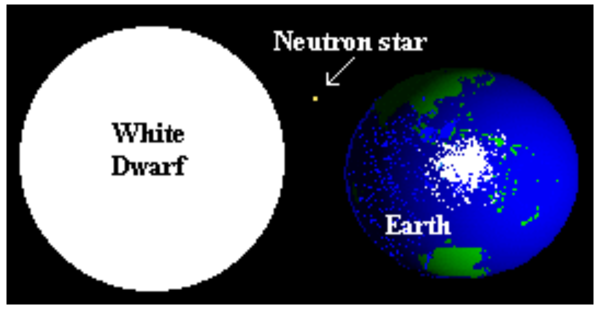
ground state EoS

- mass, radius, tidal deformability
- moment of inertia, crust thickness
- oscillation frequencies

lower energy excitations

- surface & internal temperatures
- neutrino cooling & scattering rates
- electrical & thermal conductivities
- damping rates

NS mass-radius diagram



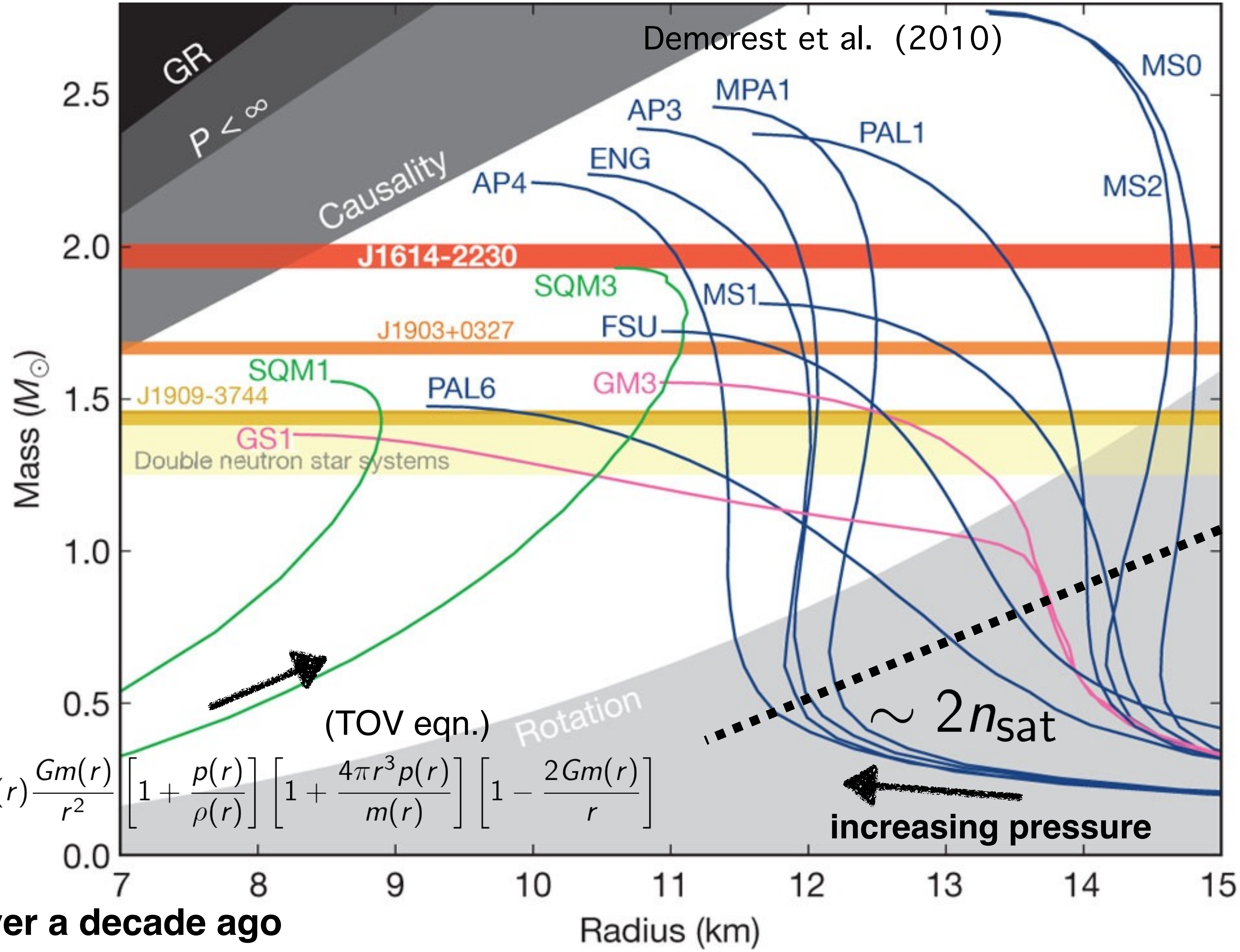
micro theo.

$p(\varepsilon)$

GR

$M(R)$

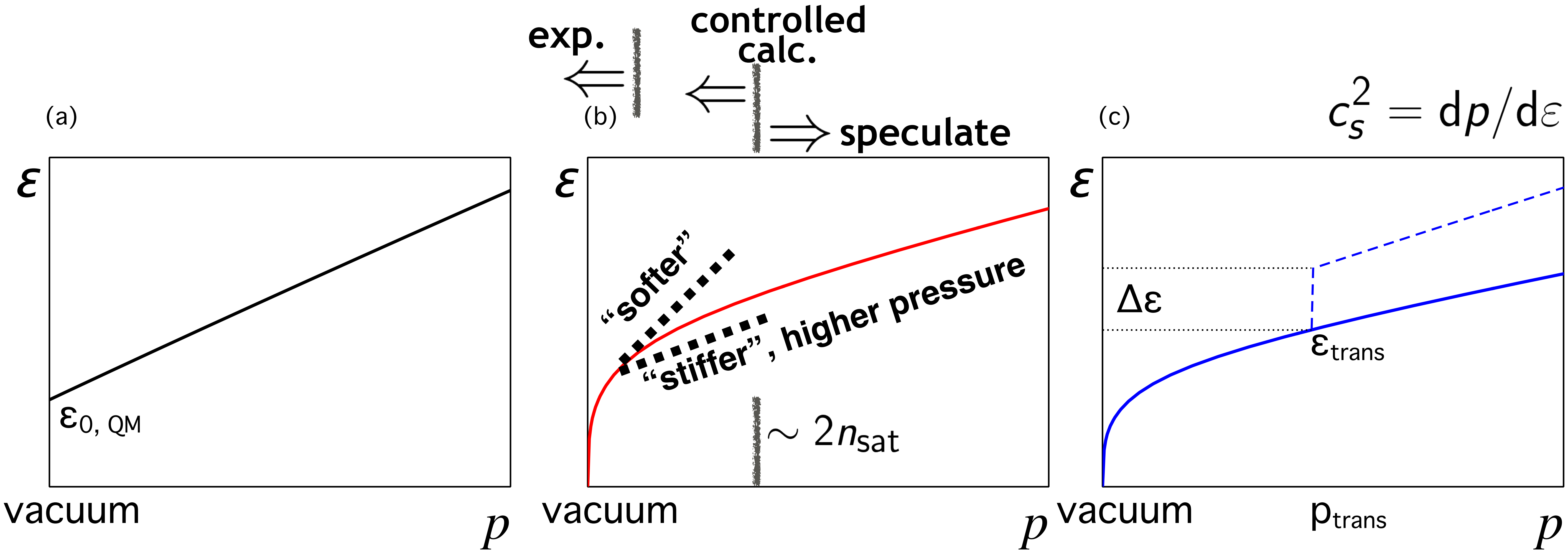
astro obs.



$$\frac{dp}{dr} = -\rho(r)\frac{Gm(r)}{r^2}\left[1+\frac{p(r)}{\rho(r)}\right]\left[1+\frac{4\pi r^3 p(r)}{m(r)}\right]\left[1-\frac{2Gm(r)}{r}\right]$$

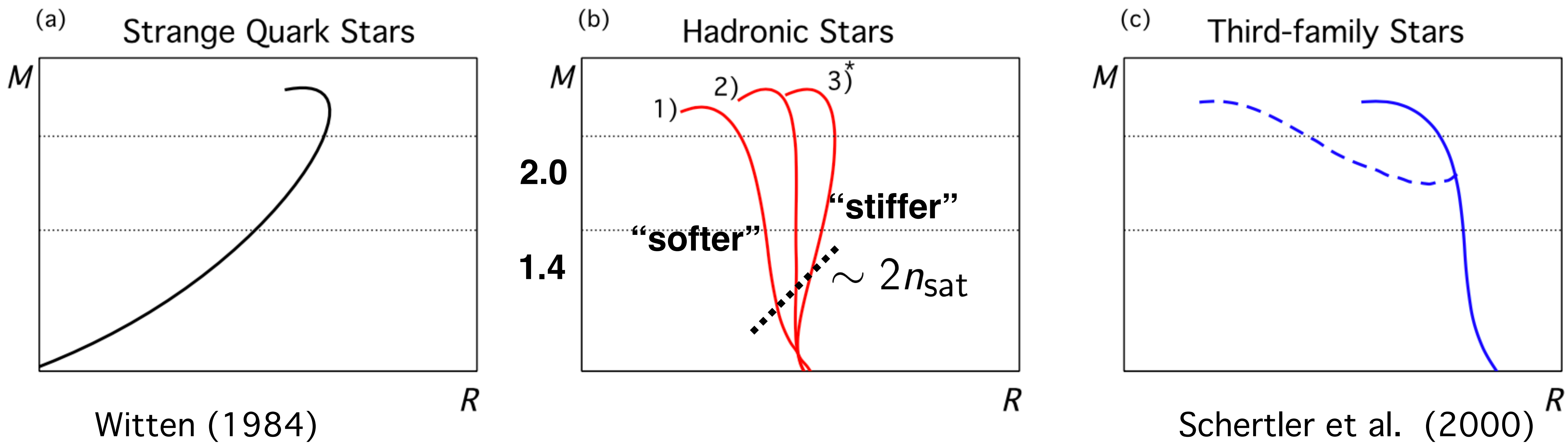
over a decade ago

Schematic EoSs from theory



- self-bound quark stars with a bare surface e.g. **strange matter hypothesis**
- continuous (and mostly smooth) profile for normal hadronic EoSs; *also possible with weak/mild phase transition or crossover
- substantial softening e.g. discontinuity in the energy density induced by a strong sharp phase transition; possibly lead to **"third-family stars"**

Categories of the *M*-*R* relation



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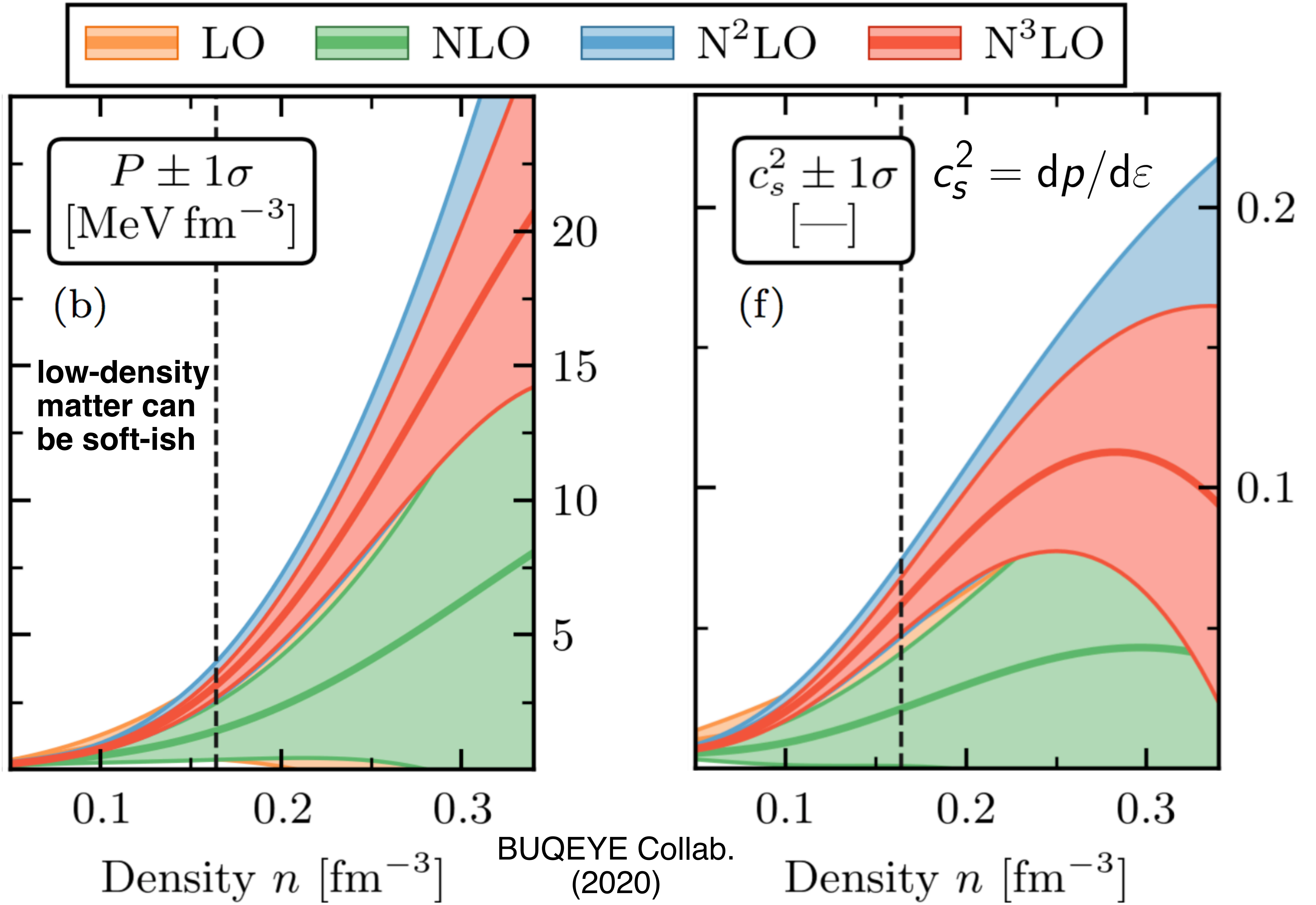
Pure neutron matter (PNM)

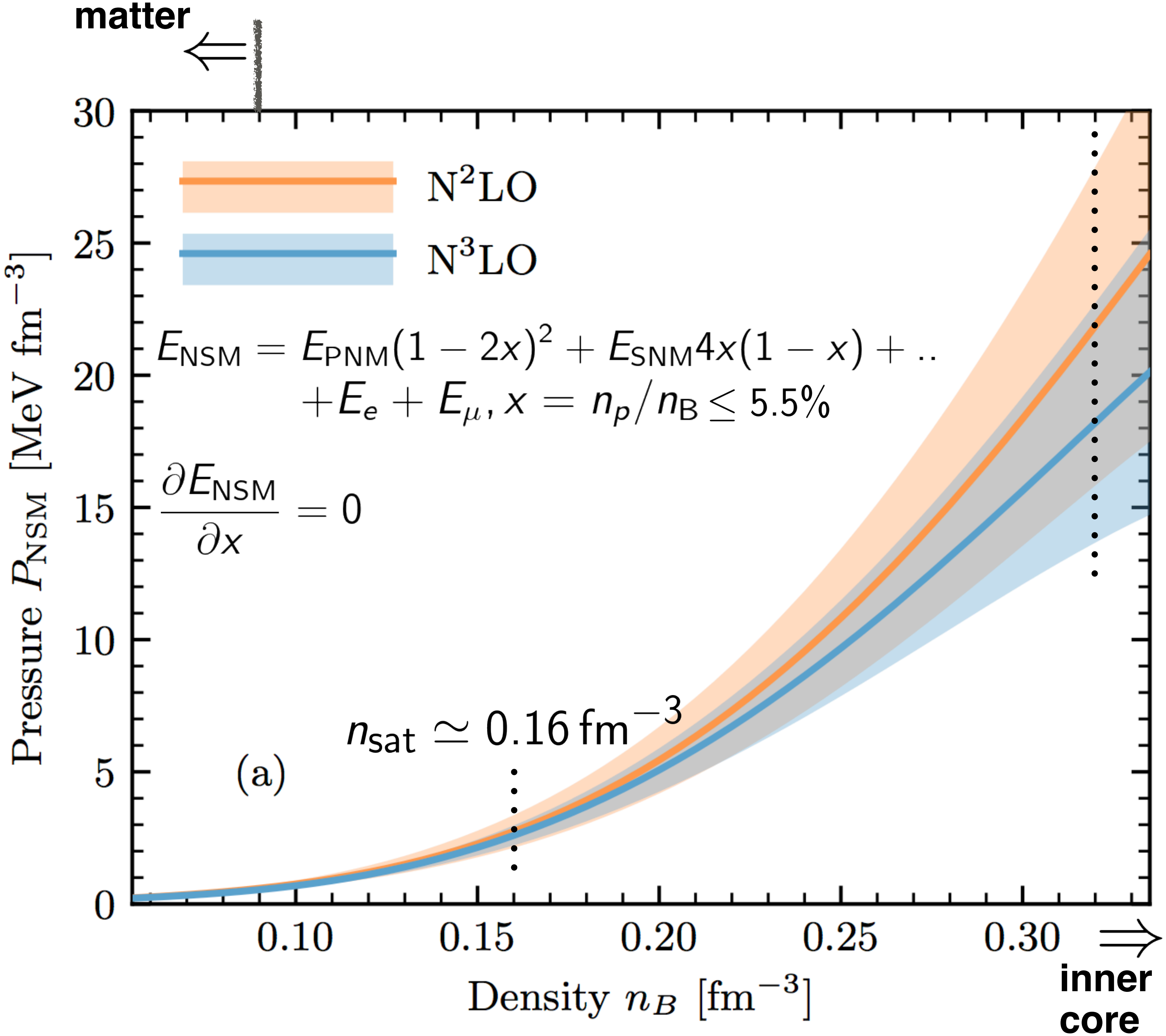
Drischler et al.
arXiv:2004.07232



BUQEYE Collab.
(2020)

Neutron-star matter (NSM)

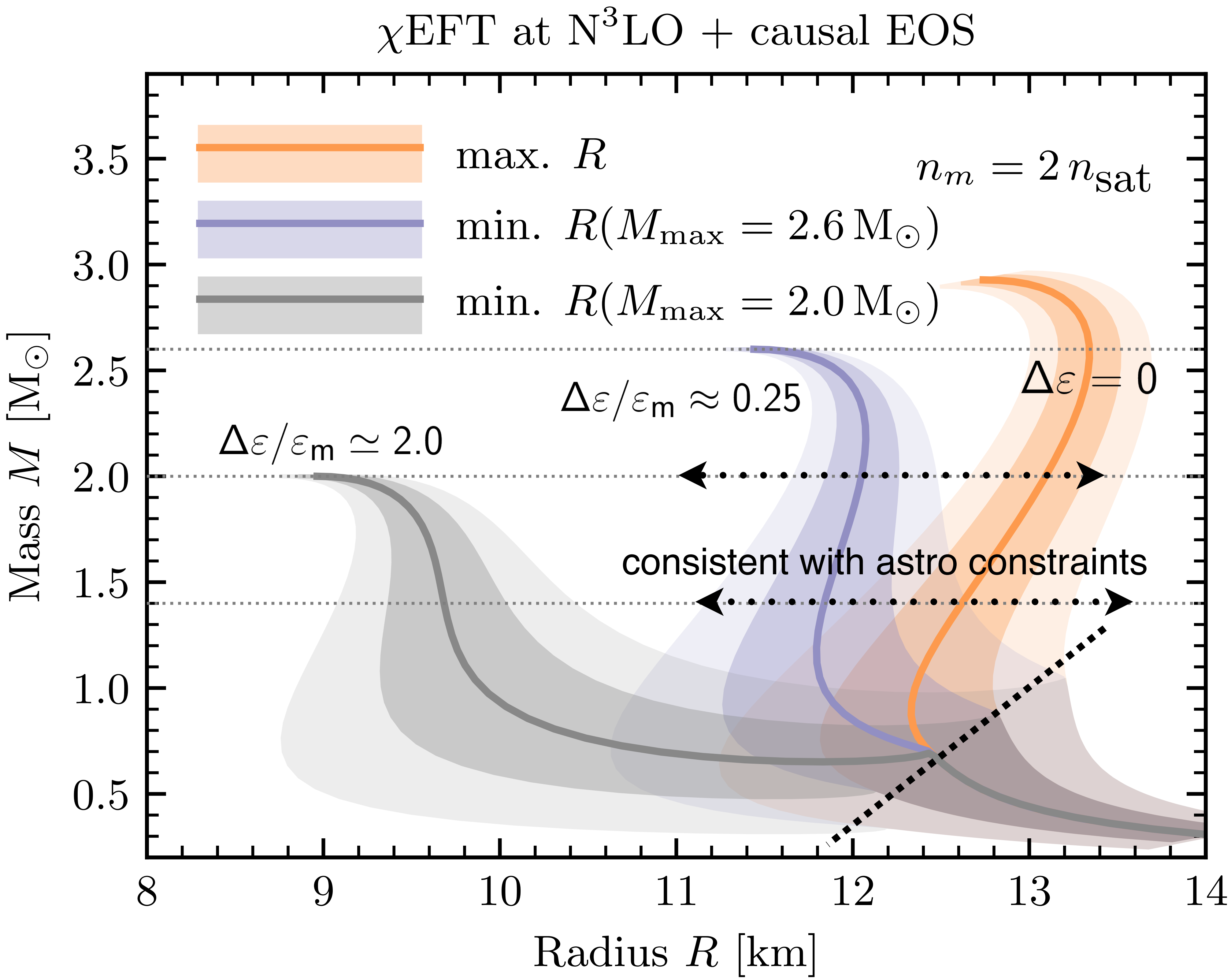
Drischler et al. (including **SH**), arXiv:2009.06441



- pressure at low densities **[outer core]** controls typical NS radii: stiff or soft?
- reliably **quantified** uncertainties from chiEFT for beta-equilibrated NSM
- less than **~5%** deviation from PNM pressures
- to **extrapolate** or match at higher densities in the inner core

Bounds from causality

Drischler et al.
(including **SH**),
arXiv:2009.06441



- pressure at low densities **[outer core]** controls typical NS radii: stiff or soft?
- reliably **quantified** uncertainties from chiEFT for beta-equilibrated NSM
- absolute **causal** limits imposed at high densities
- confronted with data: **interplay** between M_max and NS radii

Measuring NS masses and radii

pulsar timing (radio) can accurately measure masses

- most are between $1.2M_\odot$ and $1.5M_\odot$; lowest well-measured mass is $1.174 \pm 0.004M_\odot$, highest are $2.08 \pm 0.07M_\odot$ and $2.01 \pm 0.04M_\odot$

- higher masses are found for some sources (notably black widow pulsars) but these estimates have large uncertainties

x-ray observations yield radii, but uncertain to a few km:

- quiescent binary sources in globular clusters

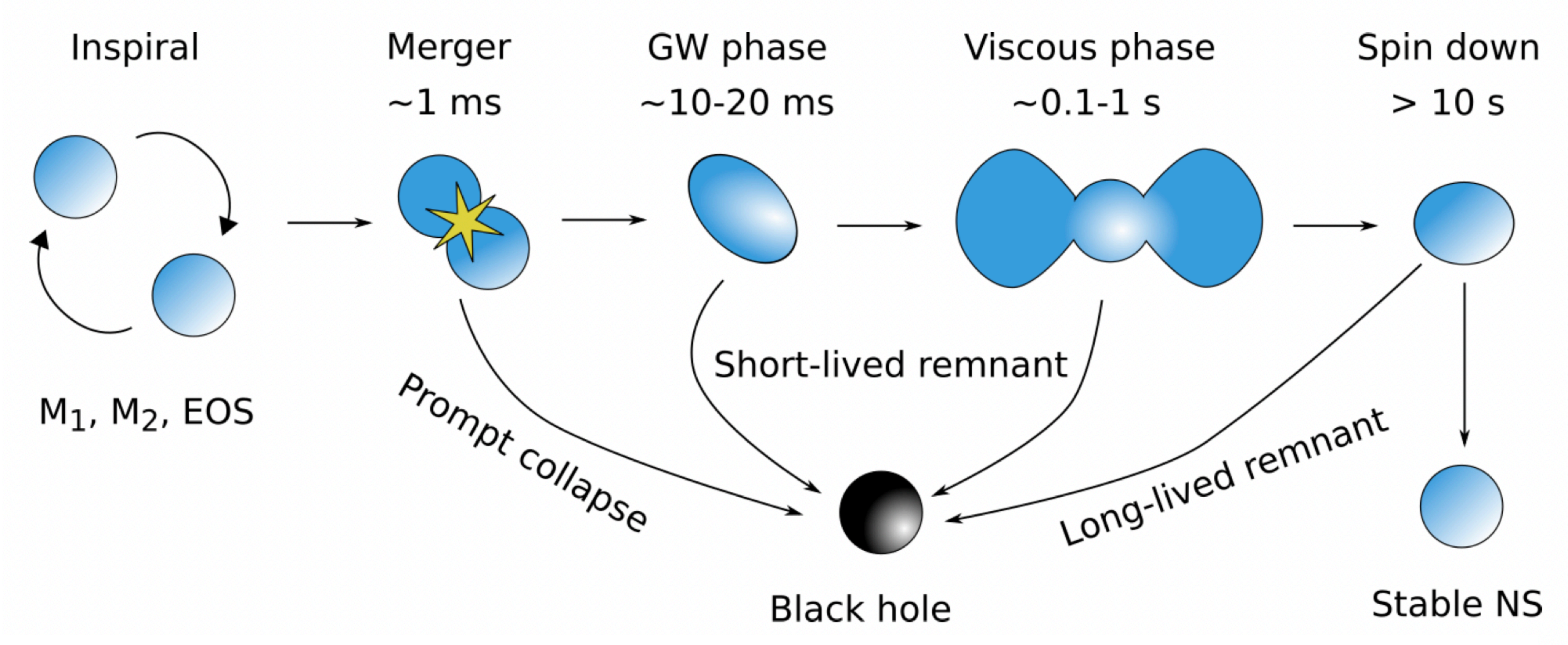
- thermonuclear explosions leading to photospheric radius expansion bursters on accreting neutron stars in binaries

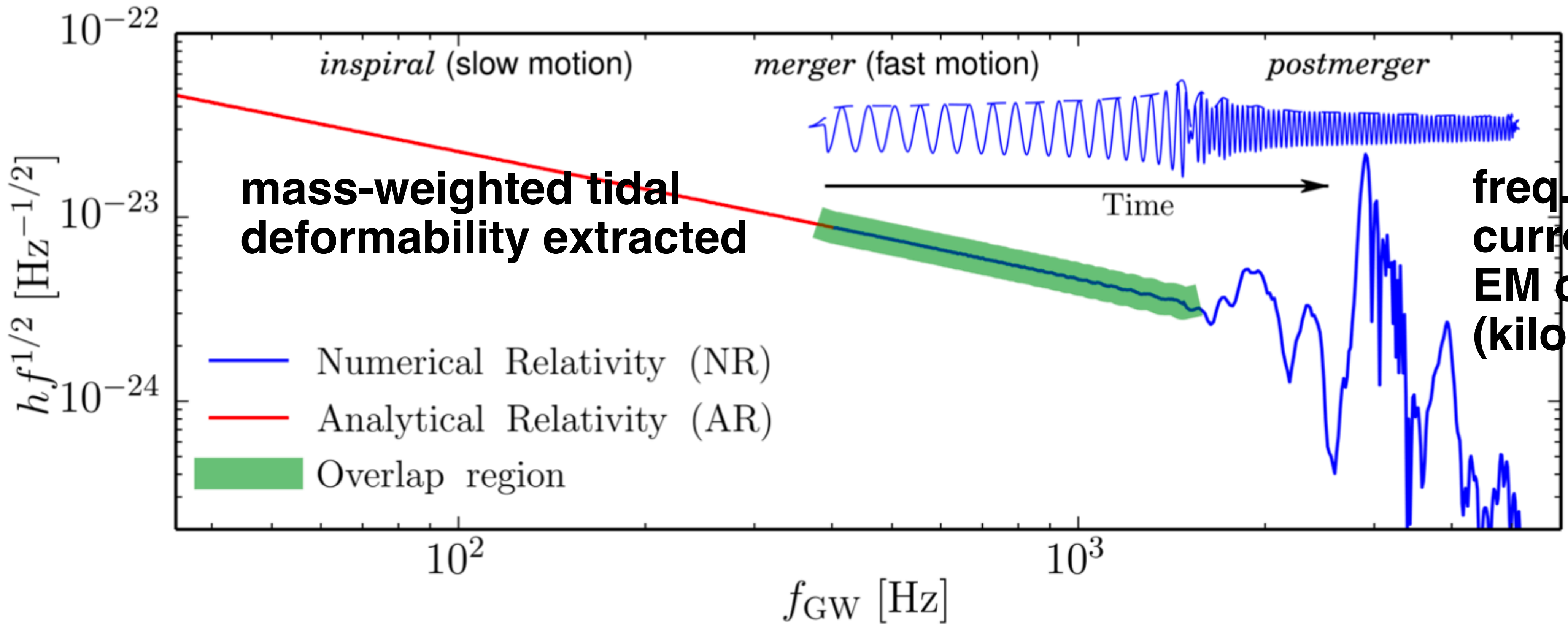
- pulse **profile modeling of hot spots** on rapidly rotating neutron stars, e.g., *Neutron Star Interior Composition ExploreR (NICER)* mission

gravitational waves from merging binary neutron stars (BNSs) measure masses and tidal deformabilities

Stages of evolution in BNS mergers

Radice et al. (2020)





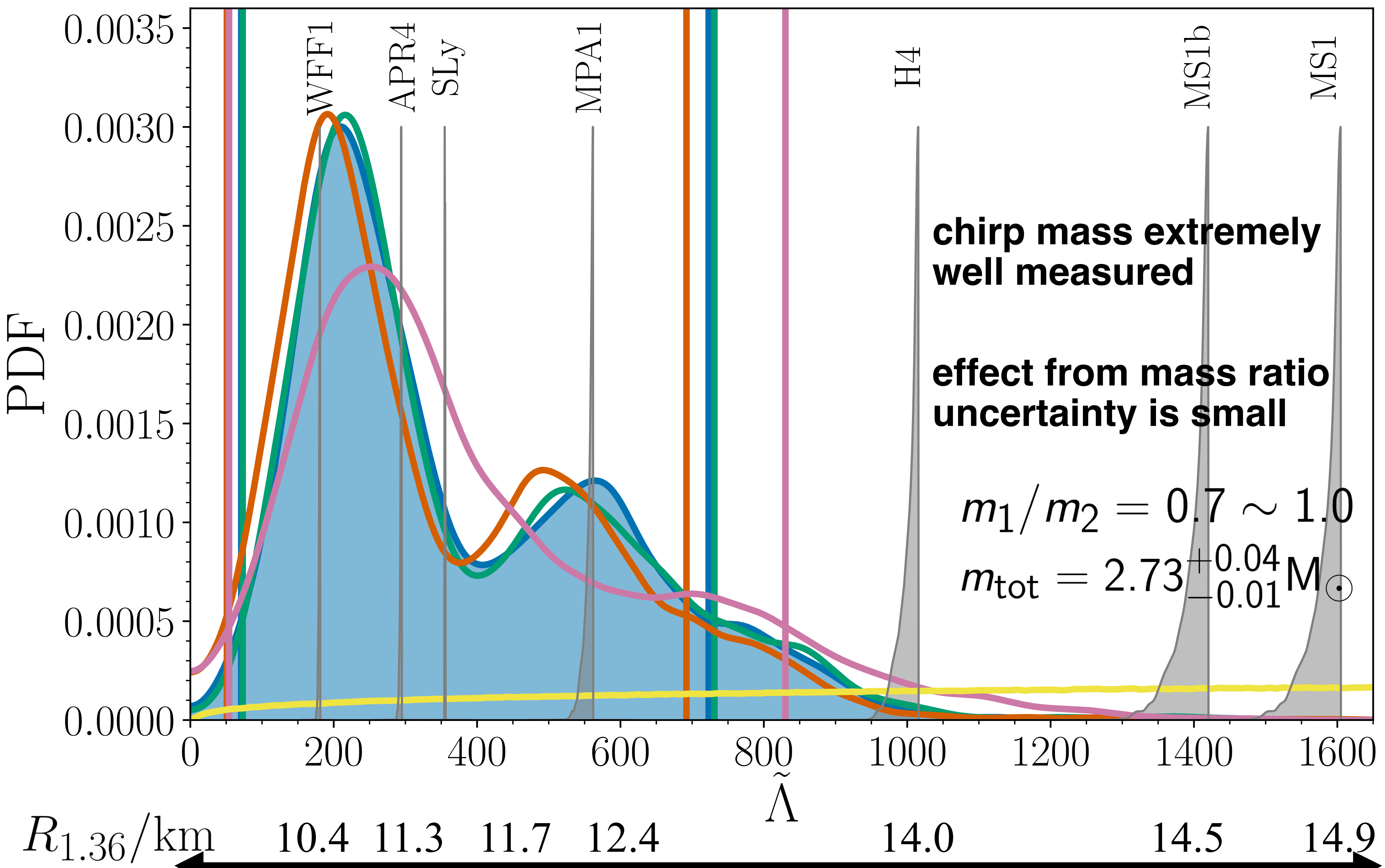
mass-weighted tidal deformability extracted

freq. too high wrt current sensitivity; EM counterparts (kilonovae) seen

Robust limit on NS radius from GW170817

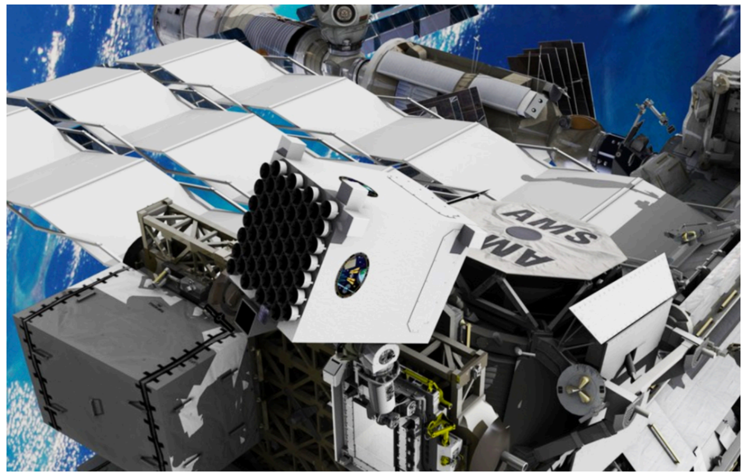
$$\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5} = 1.186^{+0.001}_{-0.001}\,\mathrm{M}_\odot$$

LVC collaboration, arXiv:1805.11579



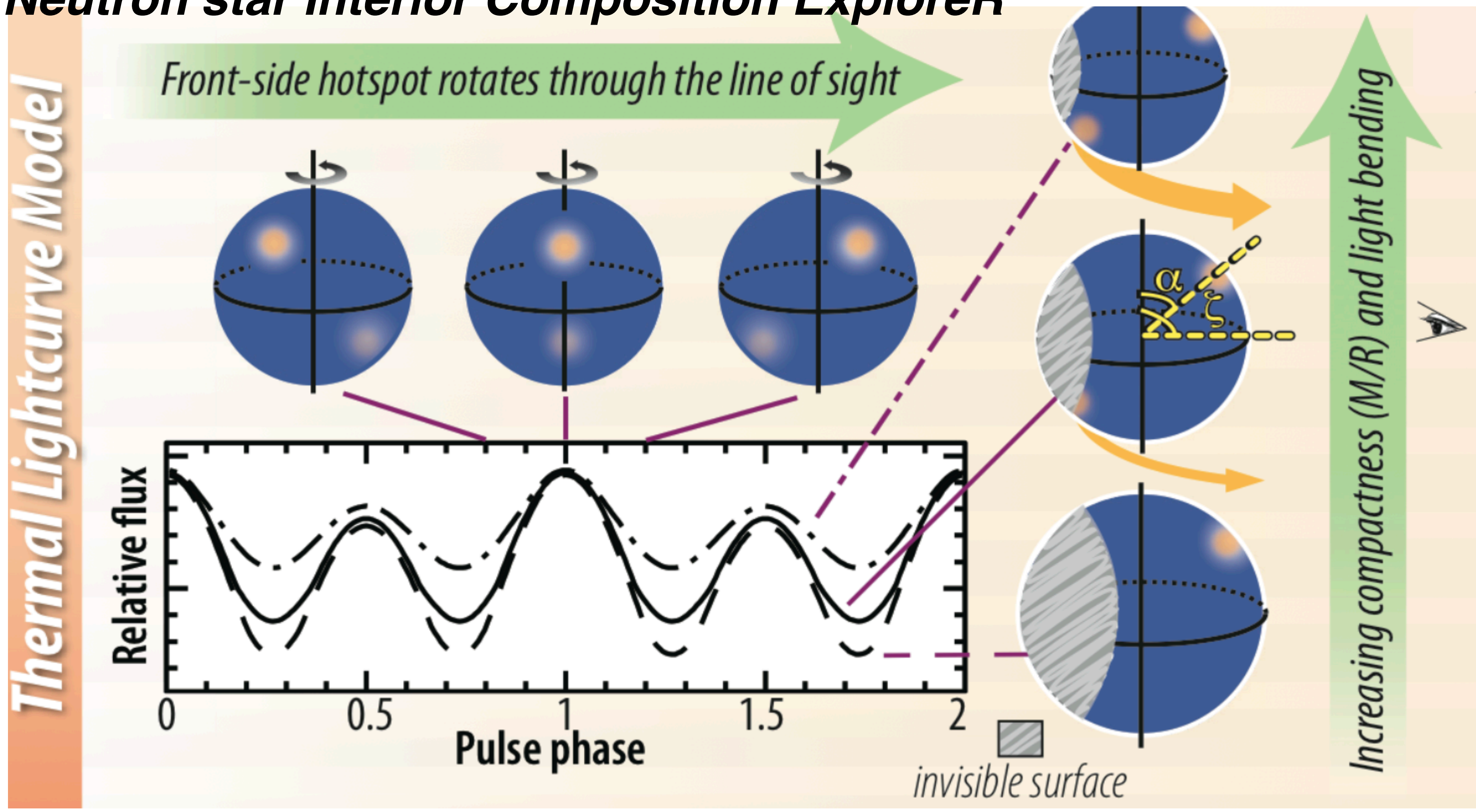
- **smaller, more compact NS [<u>≤13.5 km strongly favored</u>]**
- **larger, puffier NS [almost ruled out..]**

NS radii from hotspots

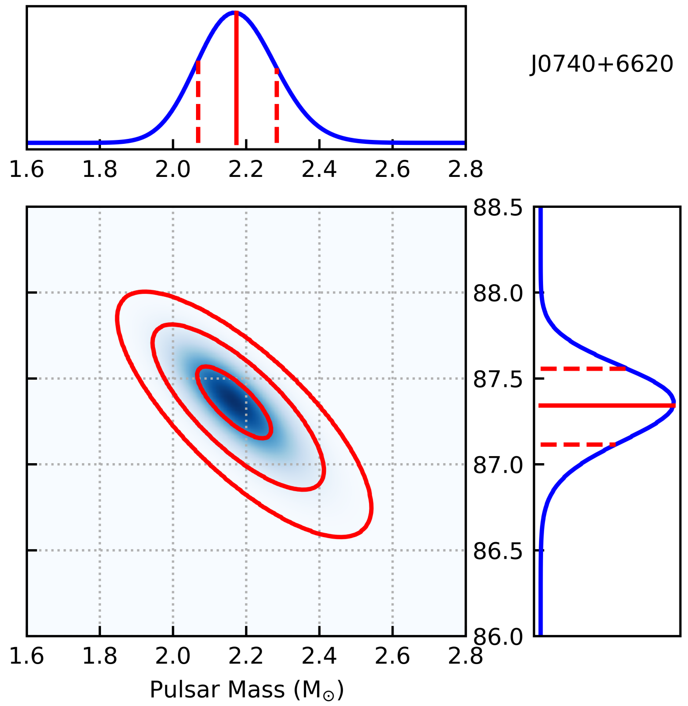


- light-curve modeling of **x-ray** pulse profiles that are sensitive to the **stellar compactness M/R**

Neutron star Interior Composition ExploreR



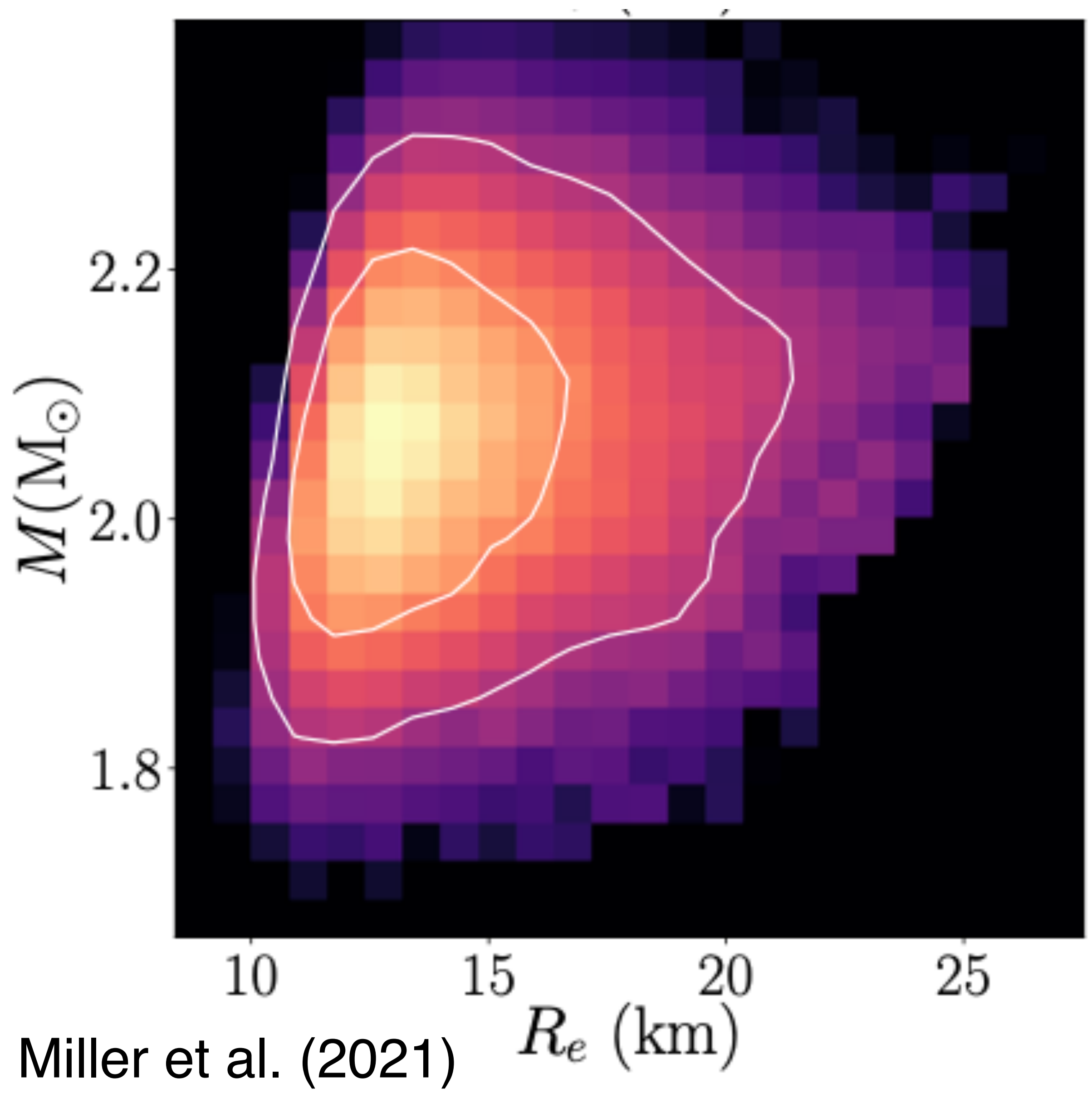
PSR J0740+6620



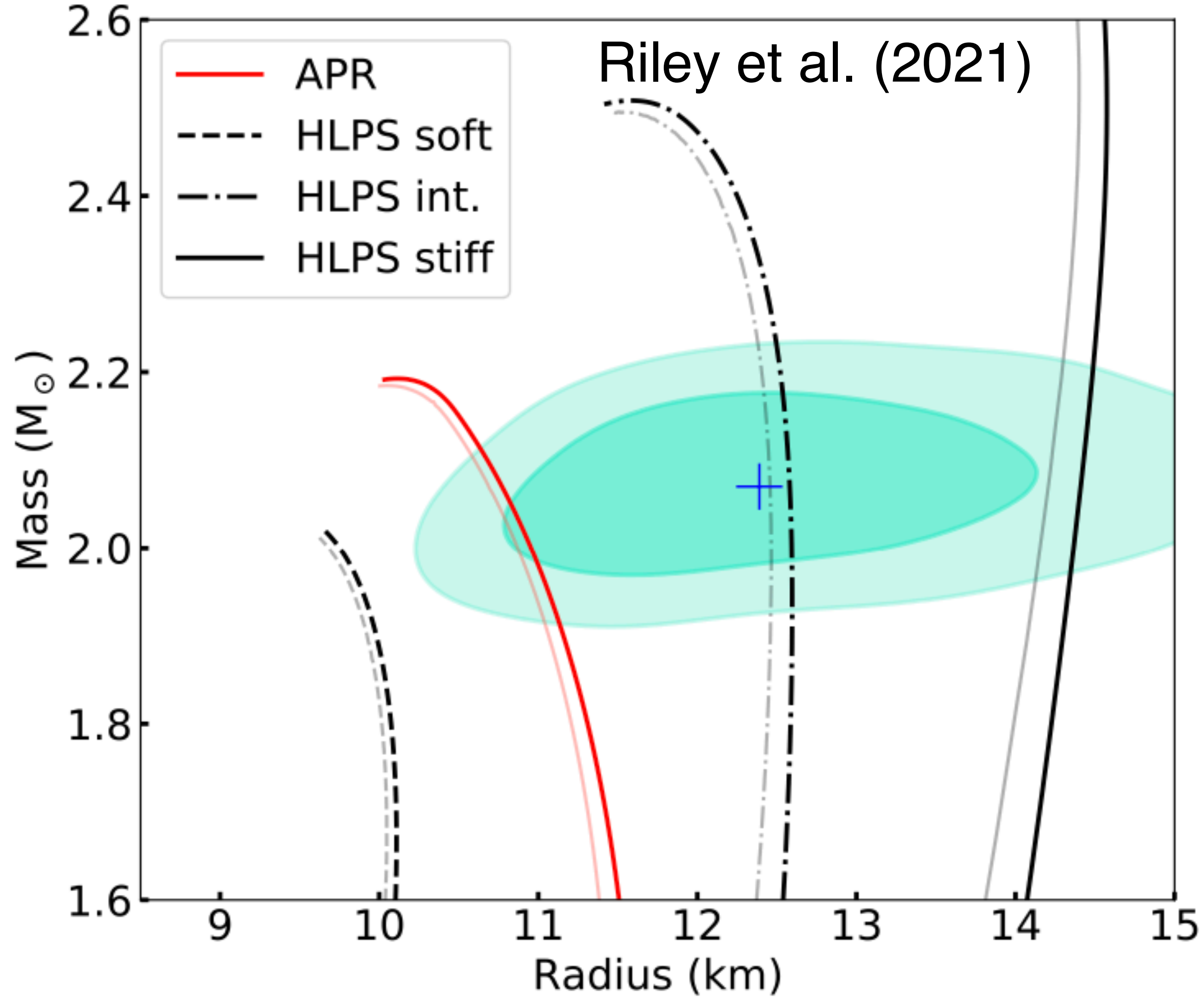
Cromartie et al.
Nature Astronomy (2019)

- recent data on the **heaviest NS known** so far: combined information with precise mass measurements through **Shapiro delay (radio)**

NS radii from hotspots



Miller et al. (2021)



(new!) radius of *massive* PSR J0740+6620 $\sim 2\,\mathrm{M}_\odot$ $13.7^{+2.6}_{-1.5}$ km vs. $12.4^{+1.3}_{-1.0}$ km

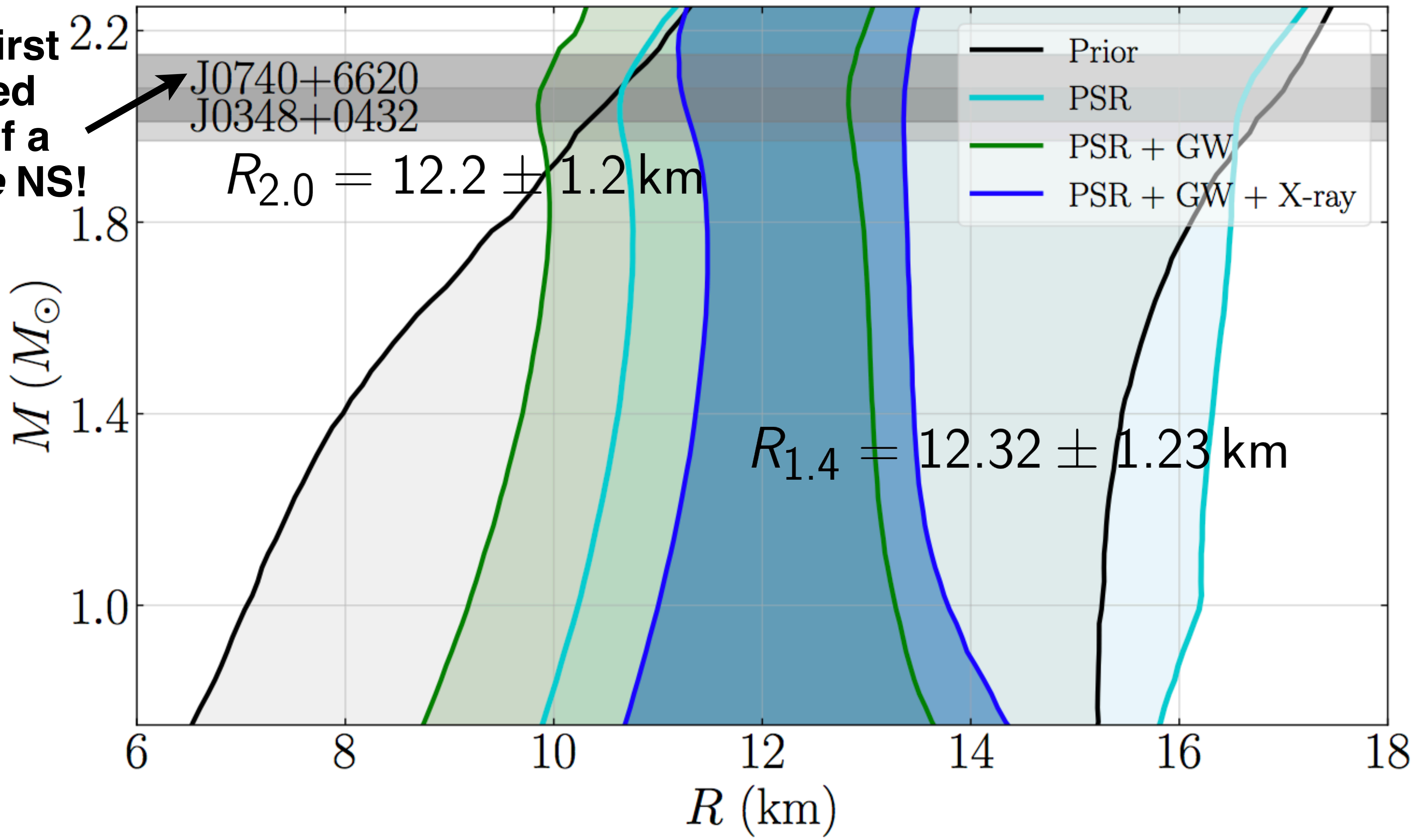
previously: *canonical-mass* PSR J0030+0451 $\sim 1.4\,\mathrm{M}_\odot$

- analyses of waveforms produced by hotspots of rotation-powered pulsars
- relatively stiffer EoS at intermediate ($2 \sim 3 n_{\mathrm{sat}}$) densities **<u>opposite</u> to GW constraints**

Multimessenger constraints

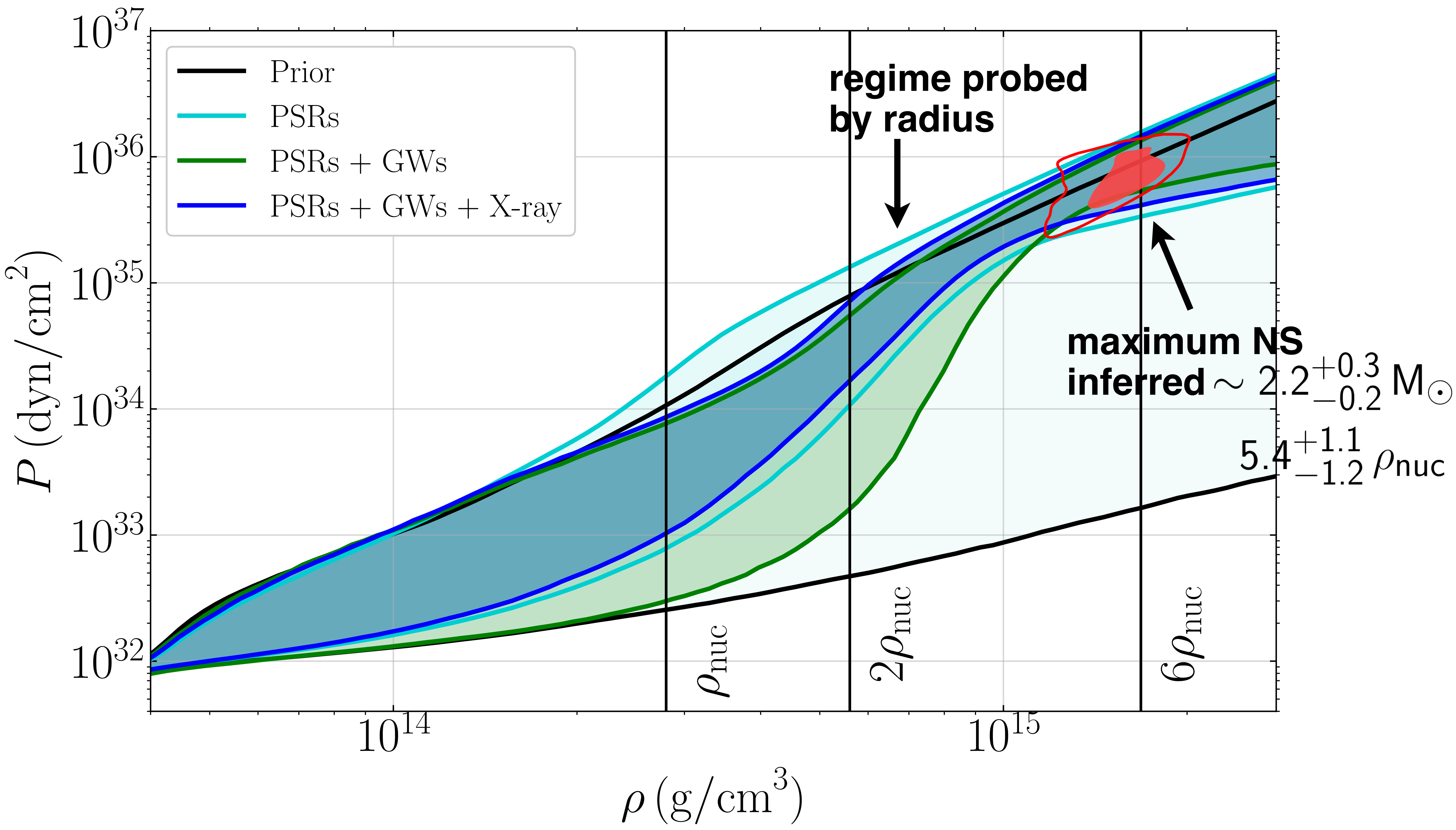
Legred et al. (including **SH**), arXiv:2106.05313

NICER first measured radius of a *massive* NS!



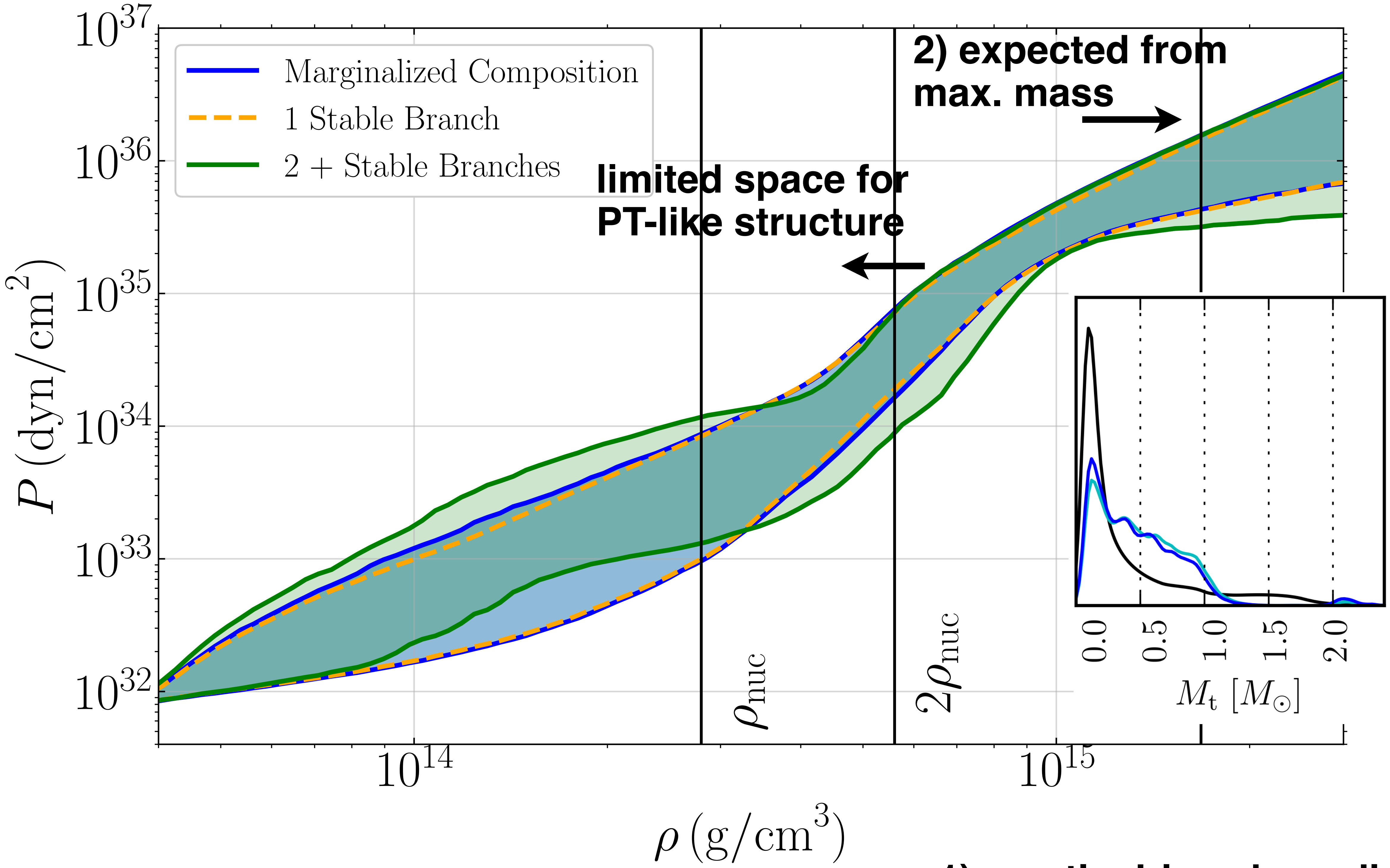
- nonparametric survey conditioned on ensembles of existing model EoSs
- GW170817+190425, NICER J0030 & J0740, and massive pulsars

Pressure vs. density



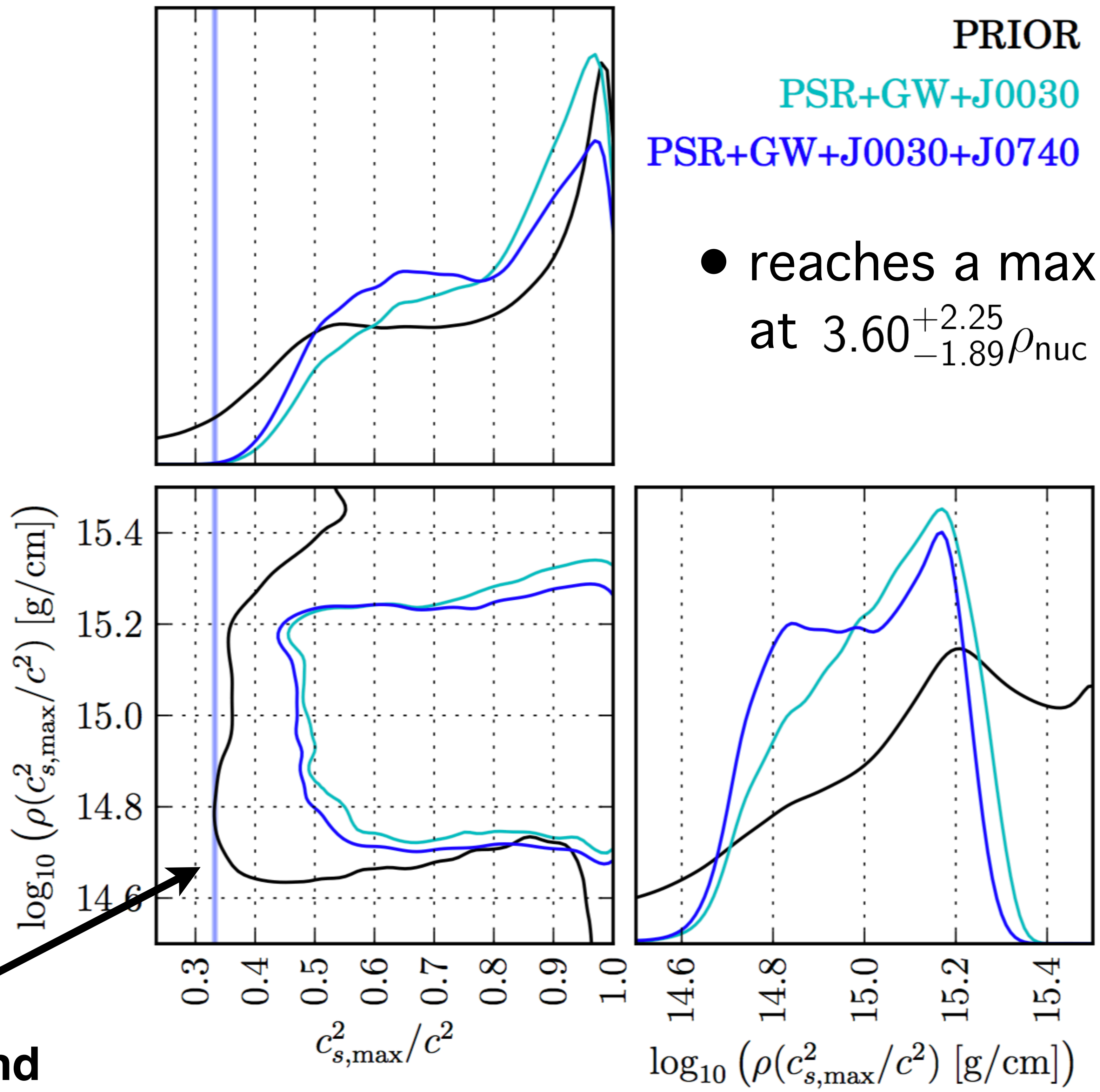
- towards a converging picture of the EoS at intermediate densities
- (90% symmetric credible intervals) best compatibility with data

Single branch (minimal) vs. multiple branches



- full posterior is dominated by EoSs with a single stable branch
- **onset** for the unstable branch **i.e. extra softening** pushed to two ends

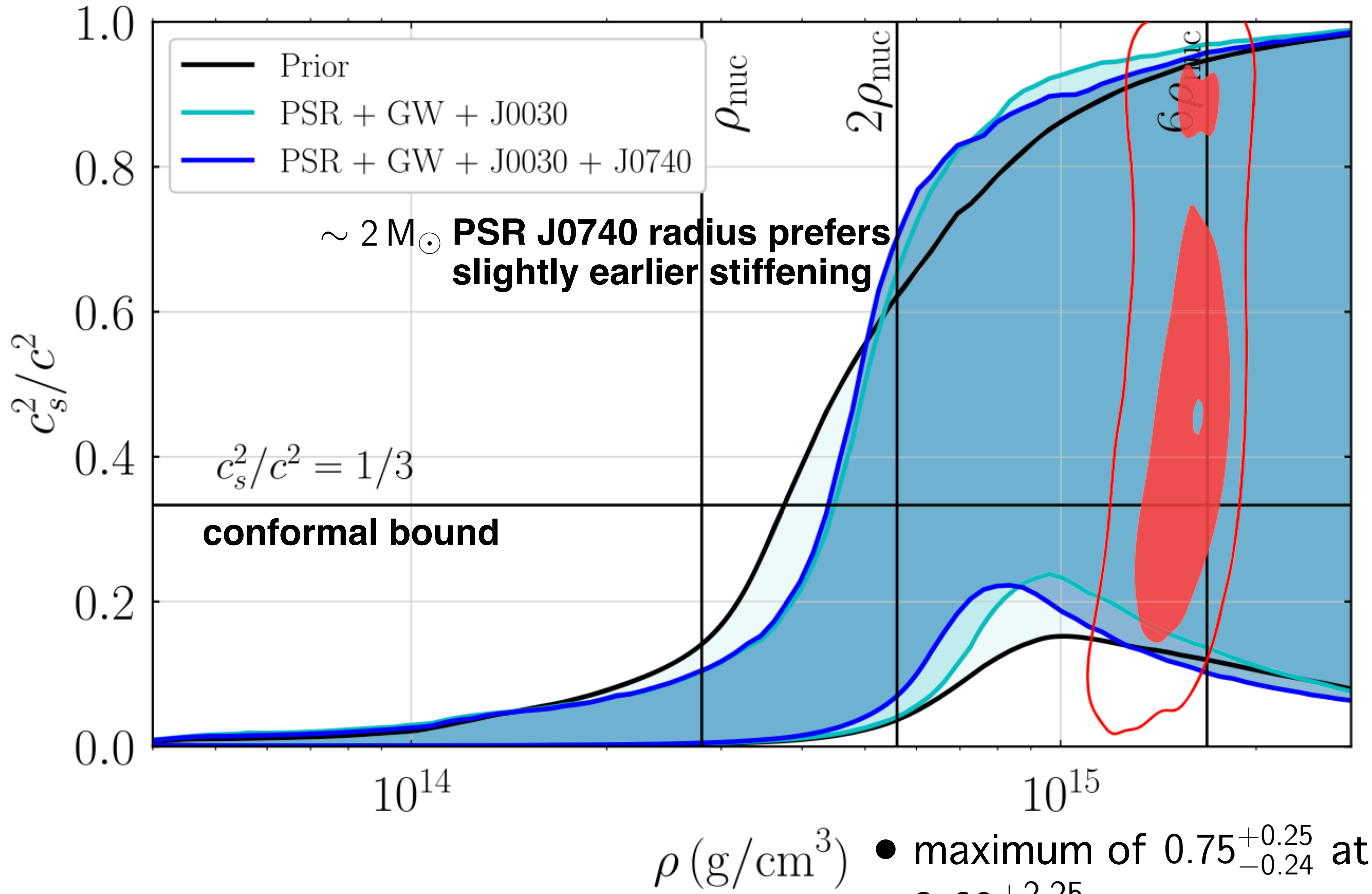
Inferring the peak sound velocity



conformal bound

- reaches a maximum of $0.75^{+0.25}_{-0.24}$ at $3.60^{+2.25}_{-1.89}\rho_{\rm nuc}$

Inferring the peak sound velocity



- maximum of $0.75^{+0.25}_{-0.24}$ at $3.60^{+2.25}_{-1.89}\rho_{\rm nuc}$

Sound speed in dense QCD

$$c_s^2(r) \equiv dp(r)/d\varepsilon(r)$$

how fast pressure rises with energy density

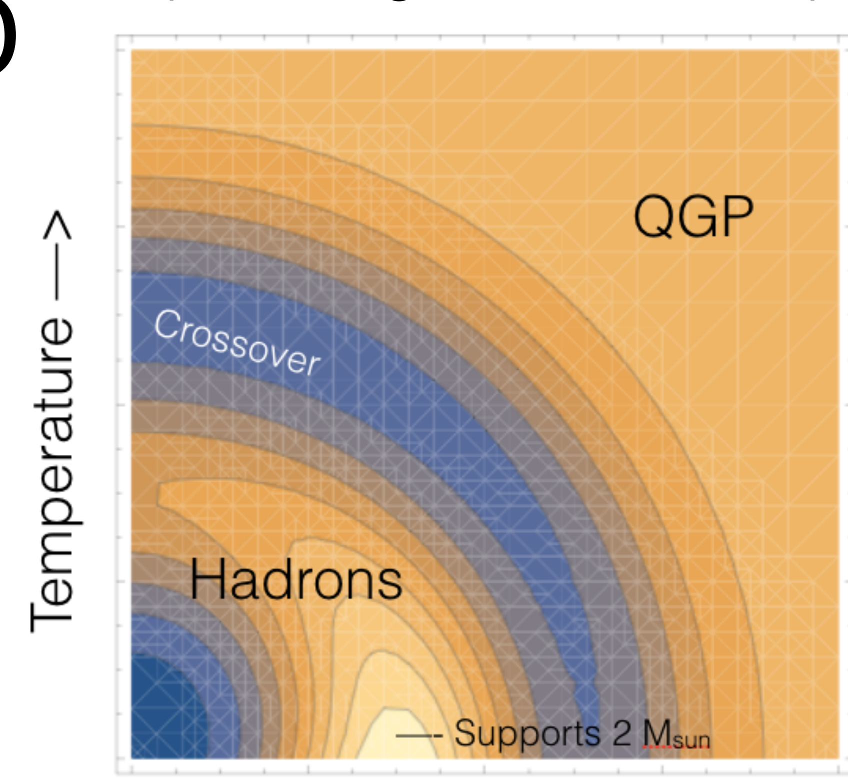
Possible behavior in neutron star interiors

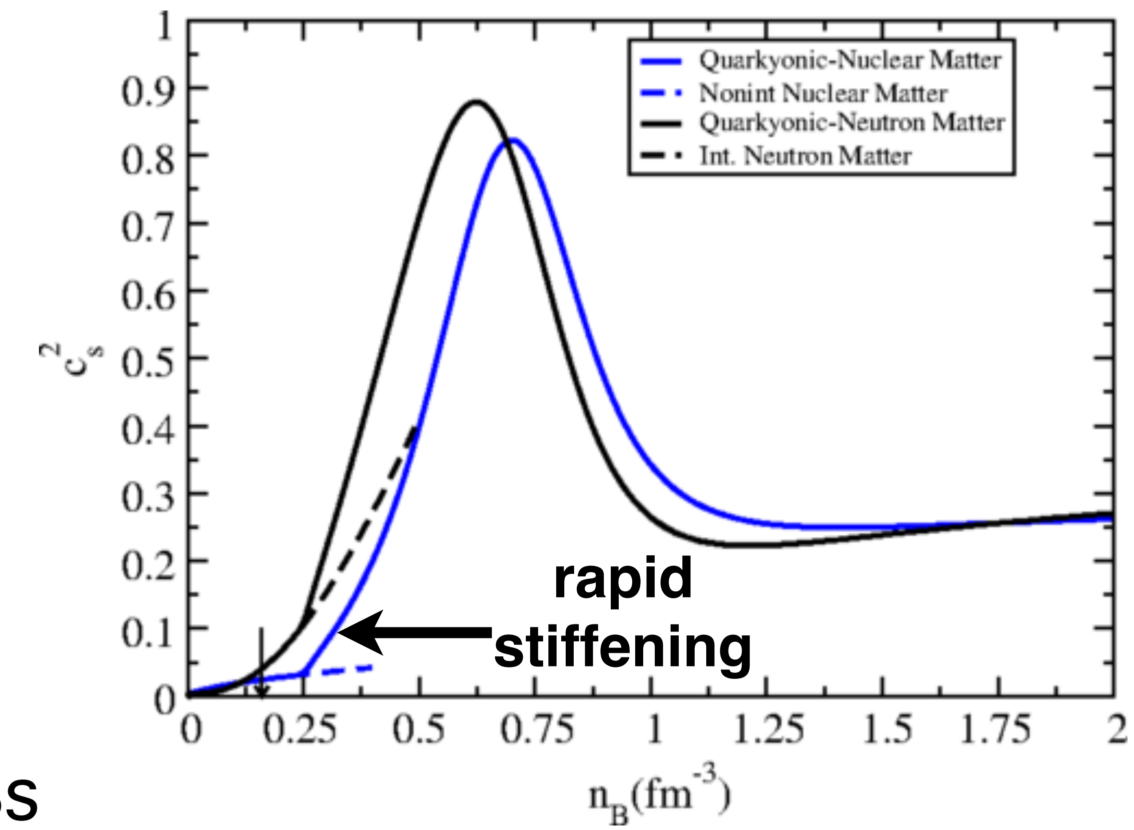
- minimal scenario of normal nuclear matter: smoothly increasing function of pressure
- first-order phase transition scenario: finite energy density **discontinuity** induces sudden **softening** near the phase boundary
- crossover scenario (quarkyonic matter)

Limits **see talks later this afternoon**

- asymptotically high density: ~1/3
- ~4-8 times saturation: supports massive NSs
- high-T: matches lattice calc./heavy-ion data

Phases of Dense Matter
(INT Program INT-16-2b)





McLerran & Reddy,
PRL 122, 122701 (2019)

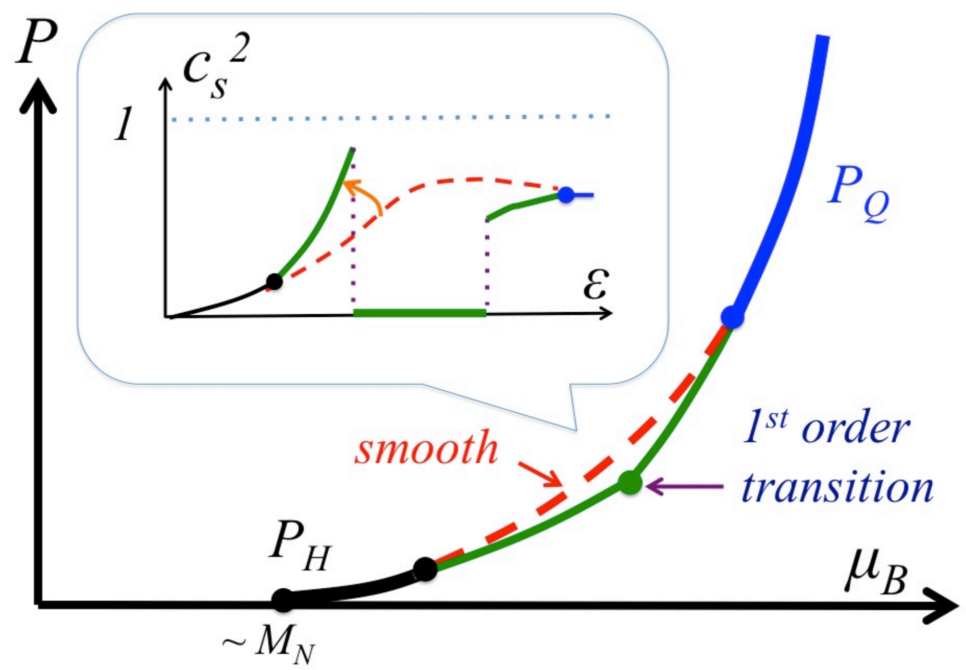
Paths towards high-density EoS

known up to saturation →

- purely hadronic/nucleonic matter (standard)
- 1st-order PT -> quarks?
  - sharp boundary - Maxwell
  - mixed phase - Gibbs (geometrically separated)
- smooth crossover (quarkyonic)?

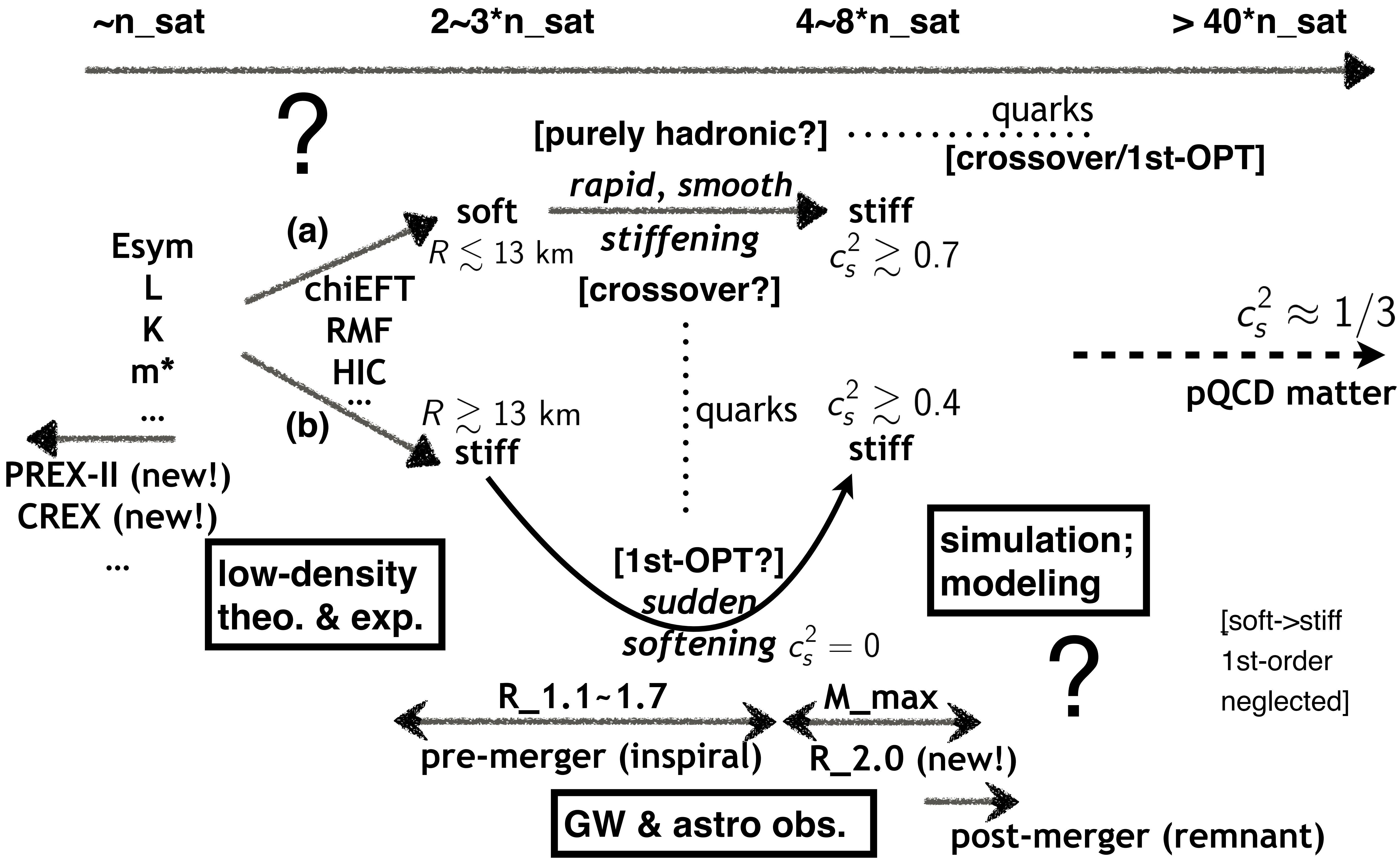
“golden window” in the vicinity of ~2*nsat; hints from exp.?

Baym et al. Rept. Prog. Phys. 81, 056902 (2018)



- **masquerade** problem: EoSs with or without PTs may hardly be distinguishable via observations that constrain *M-R* only
- crossover models motivated by e.g. lattice calc.
- 1st-OPT: mixed phase (Gibbs) favored if the hadron/quark surface tension is small

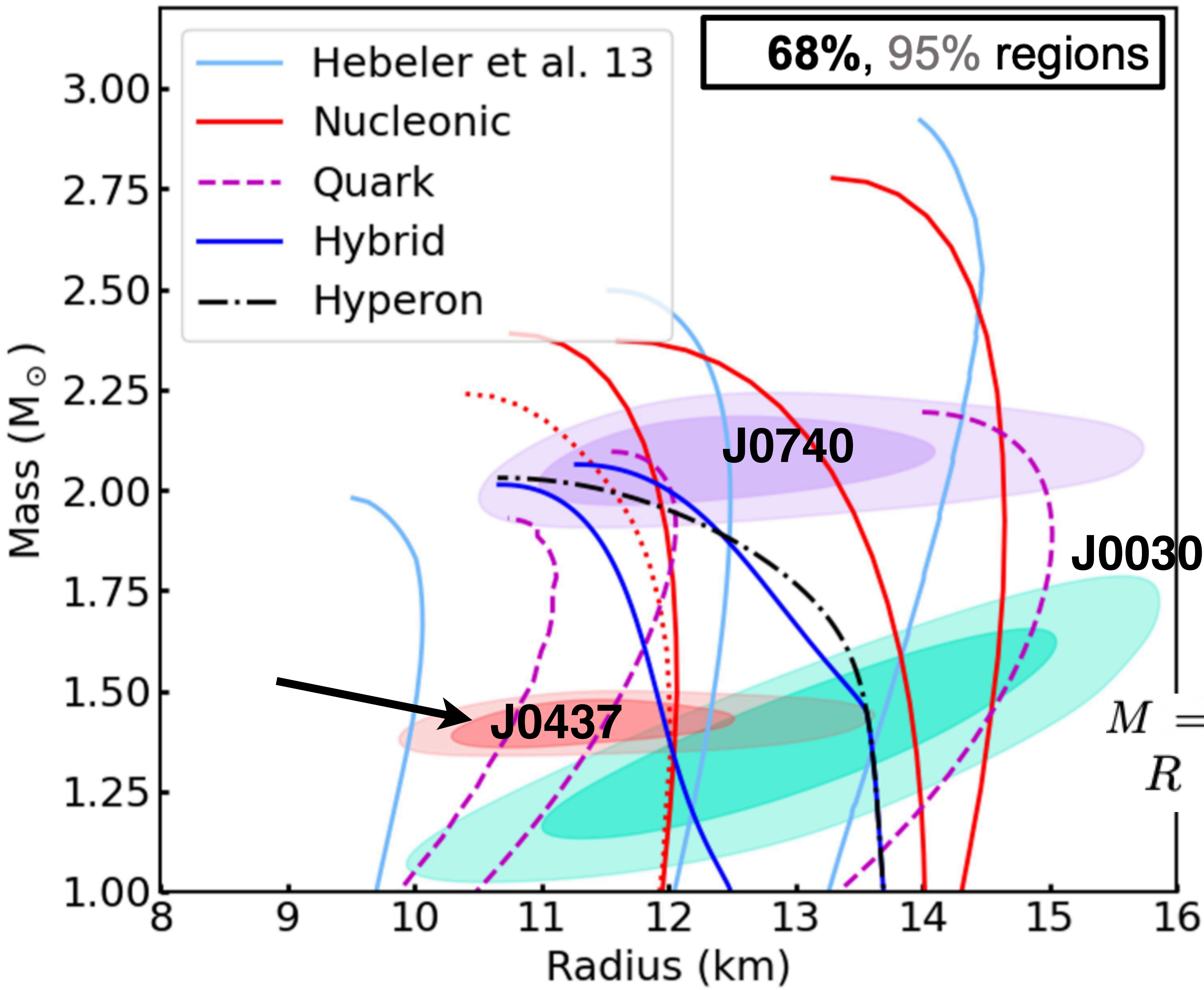
Summary: Crossroads



A NICER VIEW OF PSR J0437−4715 (new!)

arXiv:2407.06789
arXiv:2407.06790

nearest and brightest millisecond pulsar

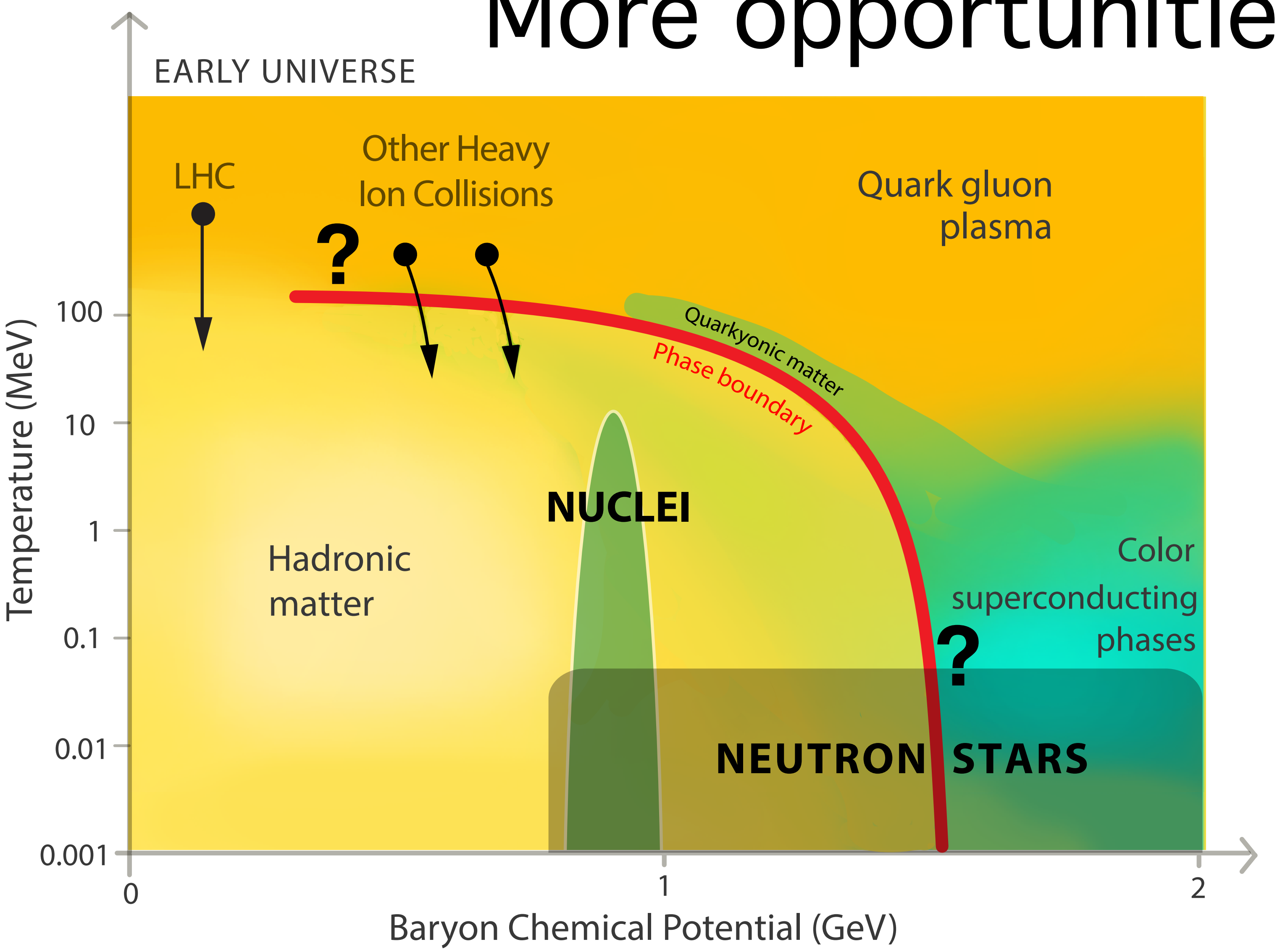


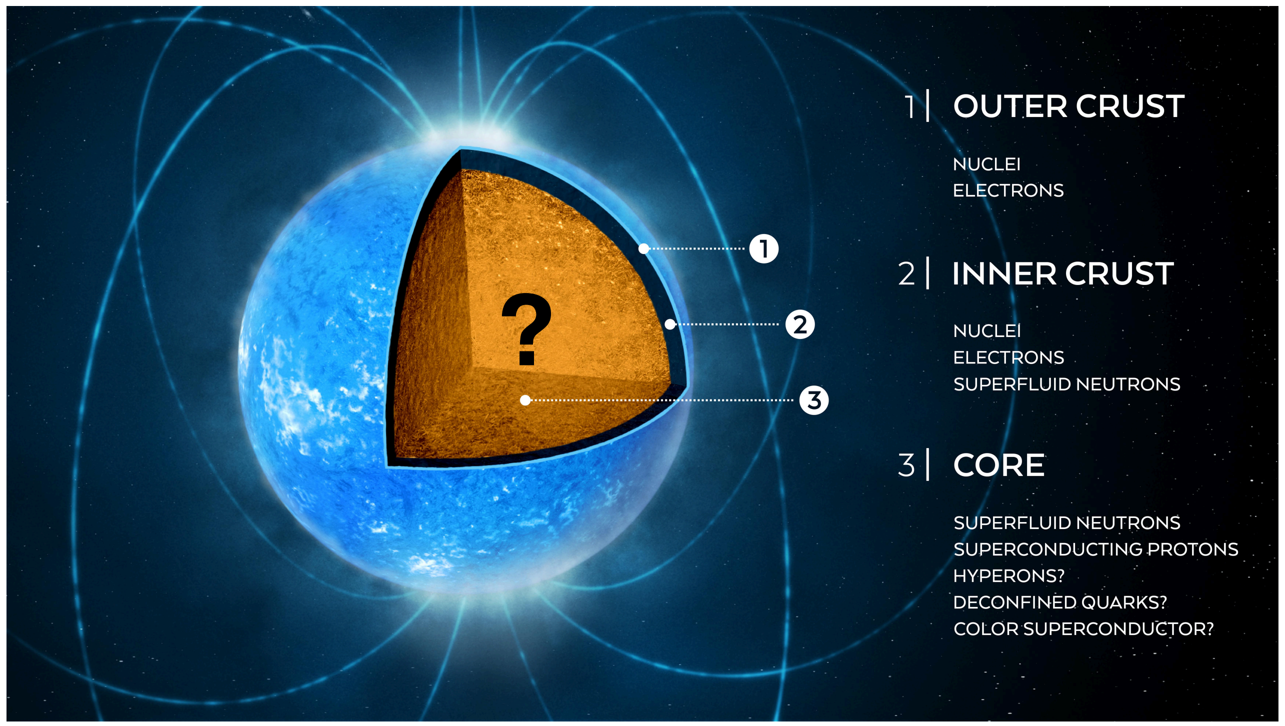
$$M = 1.418 \pm 0.037\ M_\odot$$
$$R = 11.36^{+0.95}_{-0.63}\ \mathrm{km}$$

mass, distance, inclination all well known from pulsar timing

Courtesy: Anna Watts

More opportunities beyond EoS





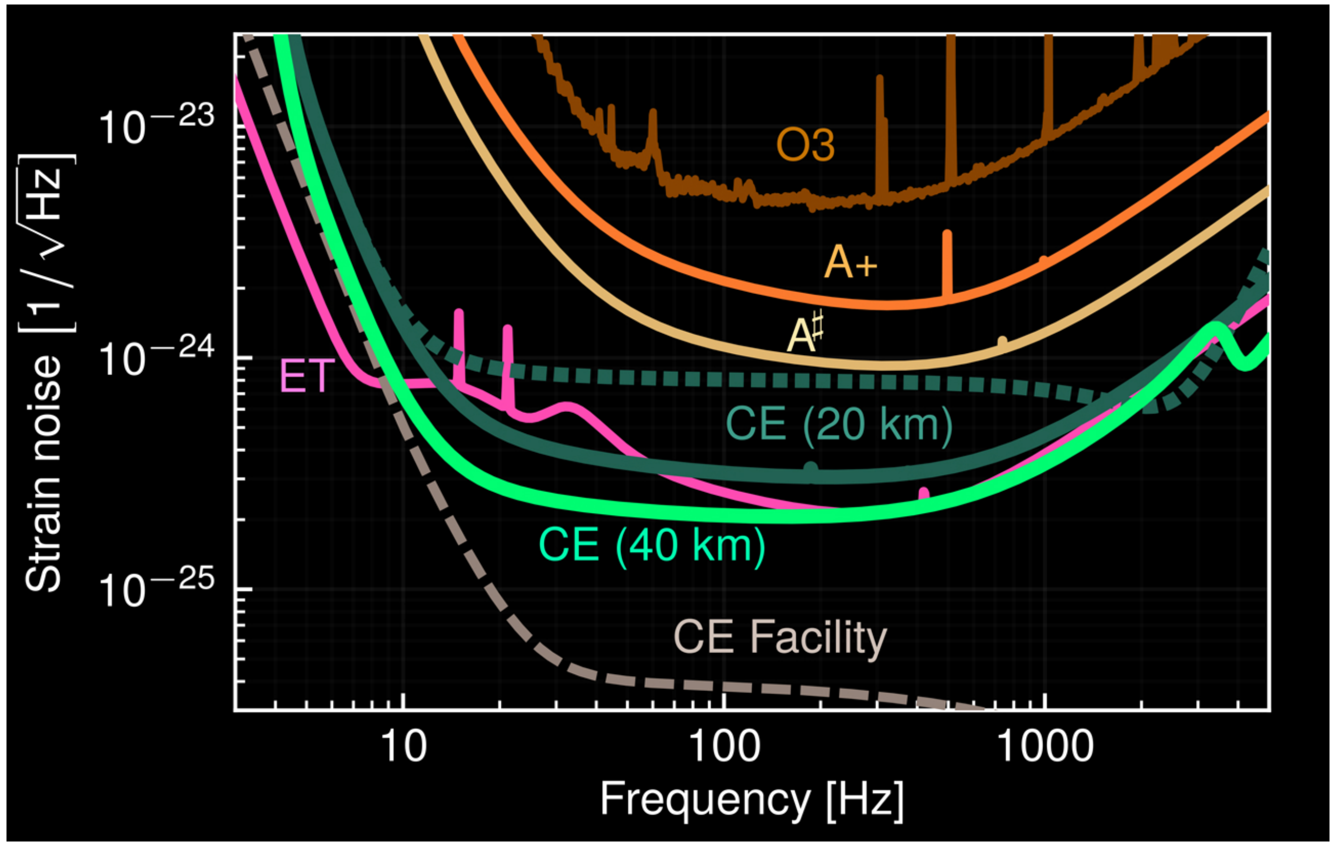
studying dense QCD with NSs

- cooling of NS 1987A? - neutrino emissivity, stellar superfluids **[nuclear theory, transport prop.]**
- merger evolution with astro/GW signals - out-of-equilibrium (visc.) physics; composition details **[simulations, nucleosynthesis]**
- next Galactic supernova? **[neutrino physics]**
- asteroseismology **[hydrodynamics, GR, nucl-th]**
- ...and more - add your own

Rev. Mod. Phys. 88, 021001 (2016)

e.g. stellar oscillations

©LIGO-Virgo-KAGRA



stable oscillation modes ("ringing") -> **continuous** GWs

- f-mode (fundamental mode) scales with average density
- p-mode (pressure mode) probes the sound speed
- ***g*-mode (gravity mode)** sensitive to **composition**/thermal gradients
- w-mode, s-mode, i-mode/r-mode..

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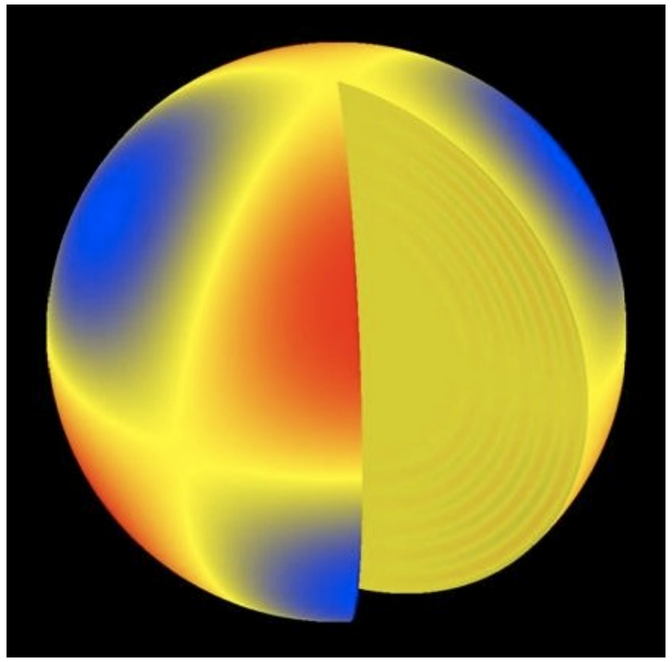
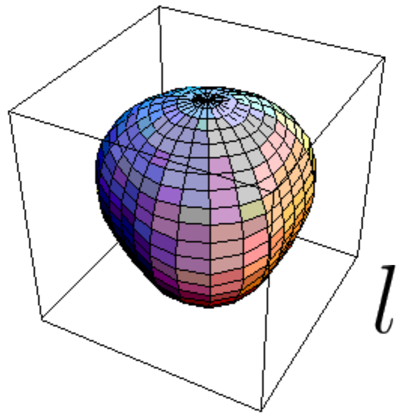




$l = 3,\ m = 3$

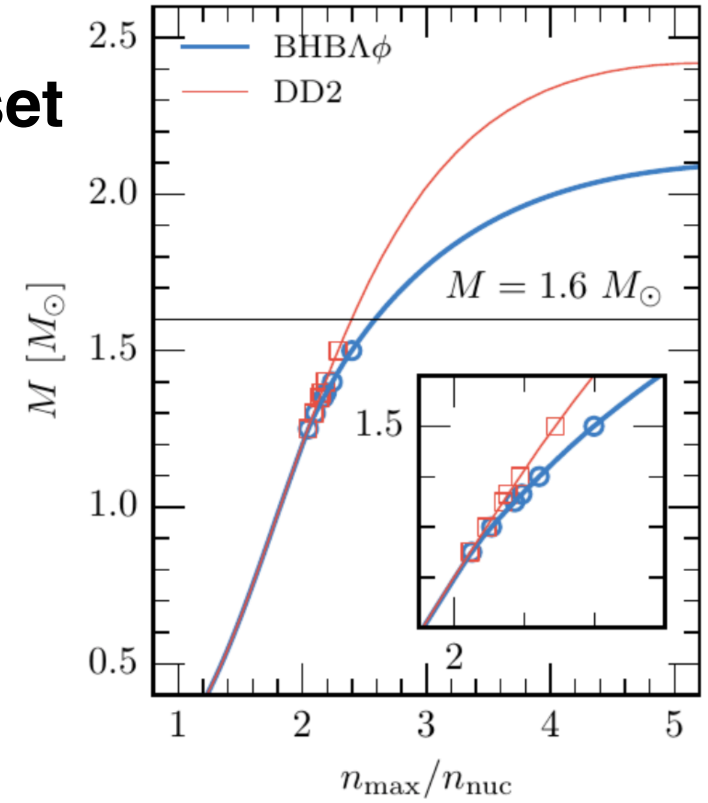
promising sources for XG detectors

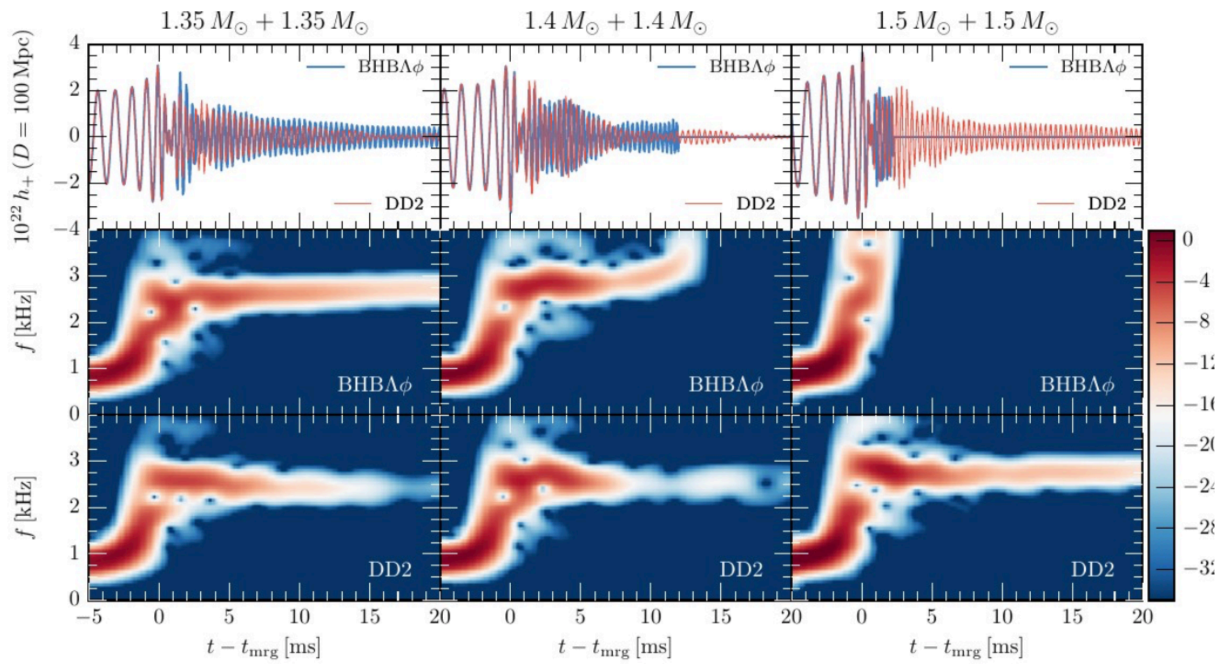
small amplitude oscillations -> weak (continuous) emission of GWs

e.g. softening effects on post-merger GWs

hyperon onset

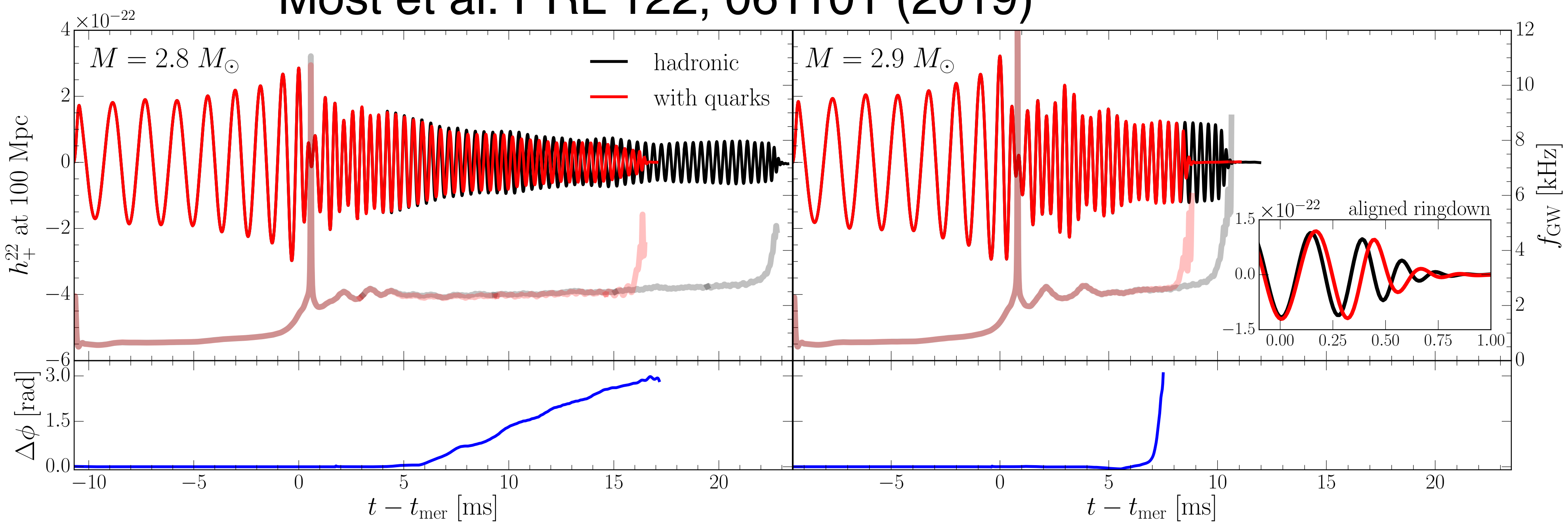
- more compact remnant (higher central density)
- earlier collapse; higher frequency





Radice et al. ApJL 842, L10 (2017)

Most et al. PRL 122, 061101 (2019)

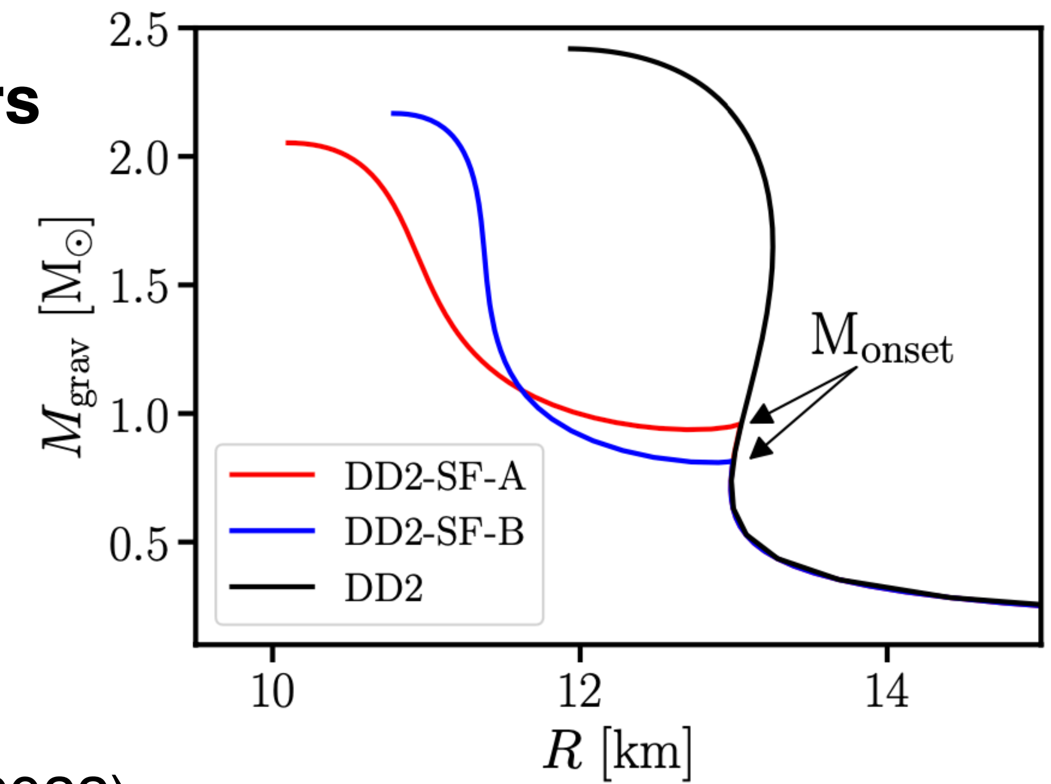


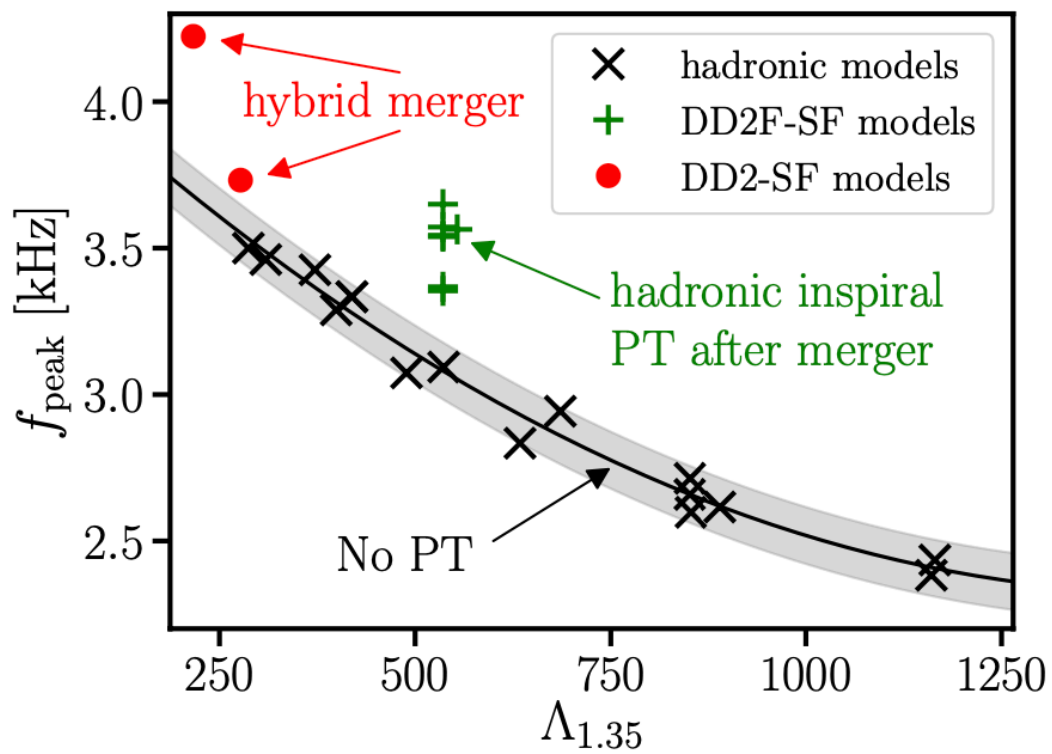
1st-OPT to soft quark matter after merger

e.g. softening effects on post-merger GWs

third-family stars

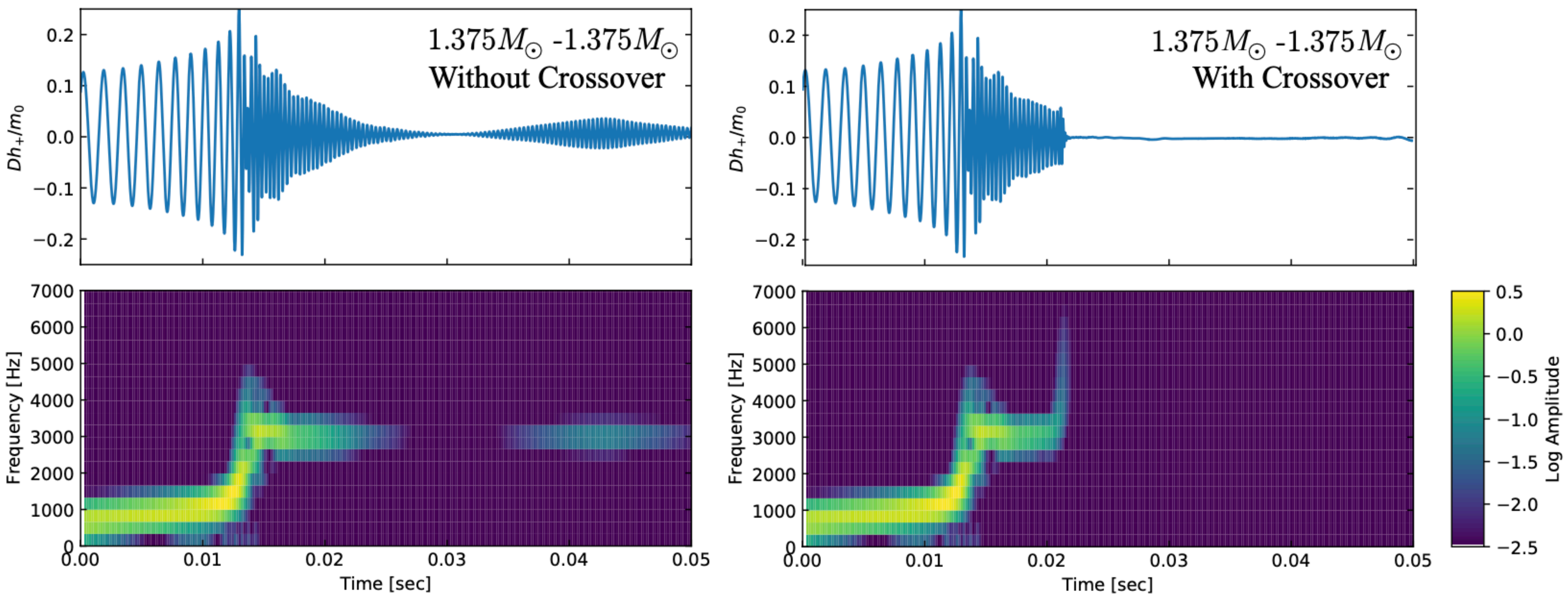
- ***stiff*** EoS at low density -DD2
- strong **1st-OPT** to ***stiff*** quark matter **before merger**





Bauswein & Blacker (2020)

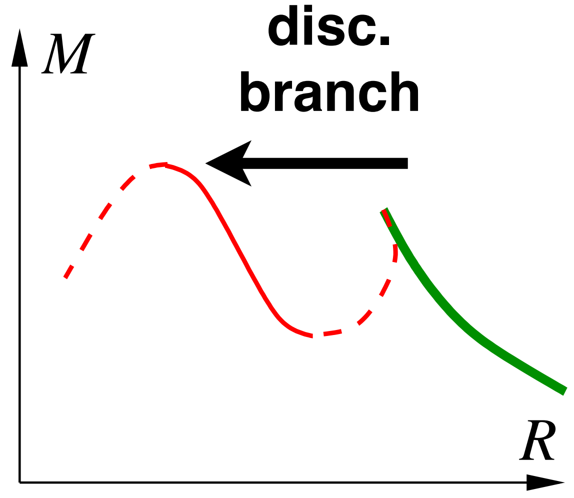
Fujimoto et al. (2022)



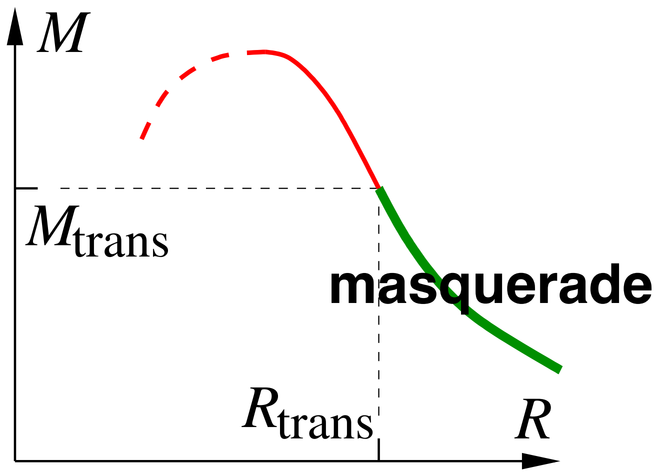
- ***soft*** EoS at low density ~N3LO chiEFT
- rapid ***stiffening*** within the crossover regime

crossover into *soft* quark matter after merger

e.g. a population of BNS events



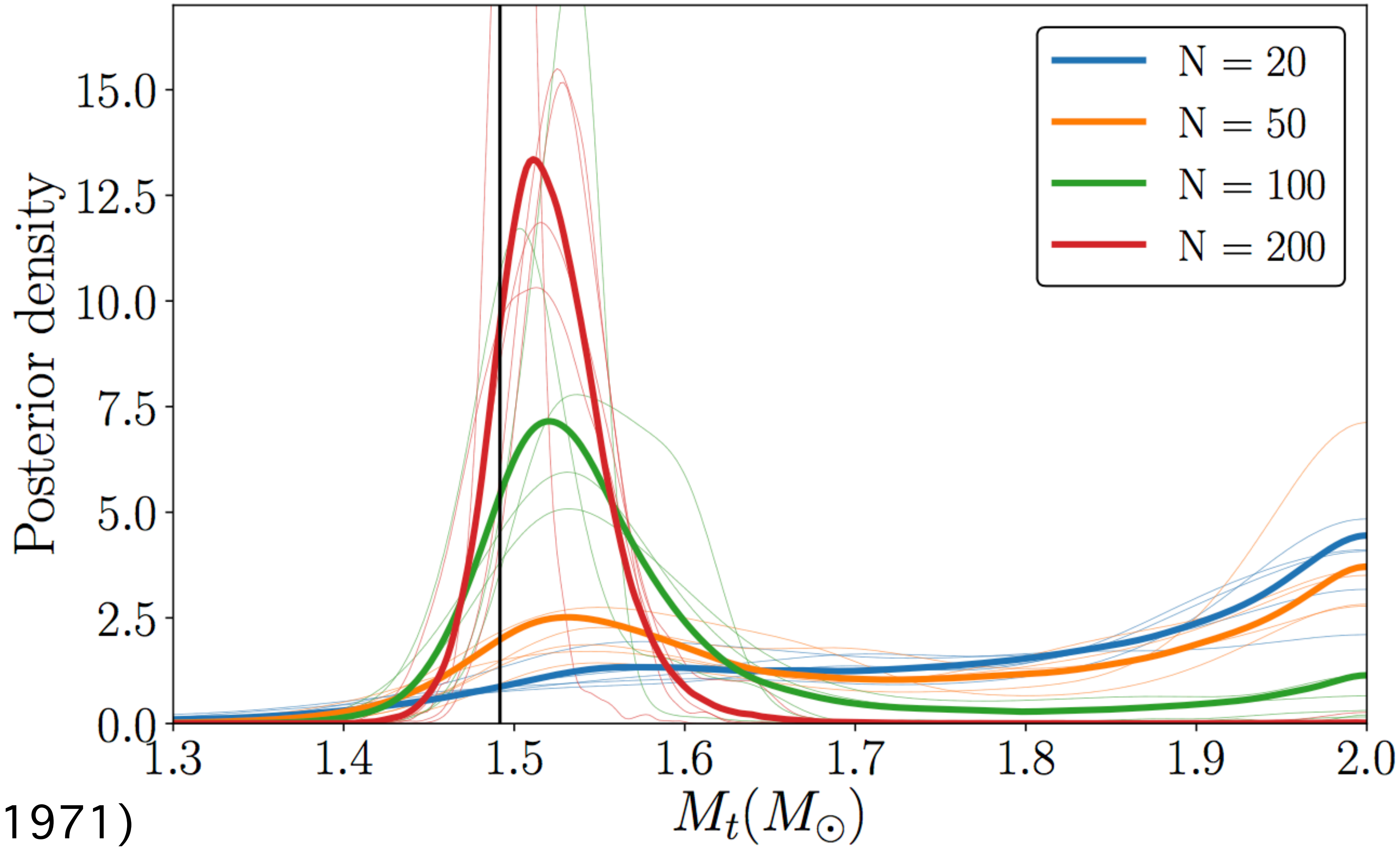
Alford, **SH** & Prakash
PRD 88, 083013 (2013)



critical strength to trigger an instability

$$\frac{\Delta\varepsilon_{\rm crit}}{\varepsilon_{\rm trans}} = \frac{1}{2} + \frac{3}{2}\frac{p_{\rm trans}}{\varepsilon_{\rm trans}}$$ Seidov (1971)

Chatziioannou & **SH**, arXiv:1911.07091
SH & Steiner, arXiv:1810.10967



- may help identify third-family stars [strong 1st-OPT] with **inspiral** GWs
- requires multiple **(N~50-100)** future detections to separate different families: NS-NS, NS-HS, HS-HS mergers

Looking forward

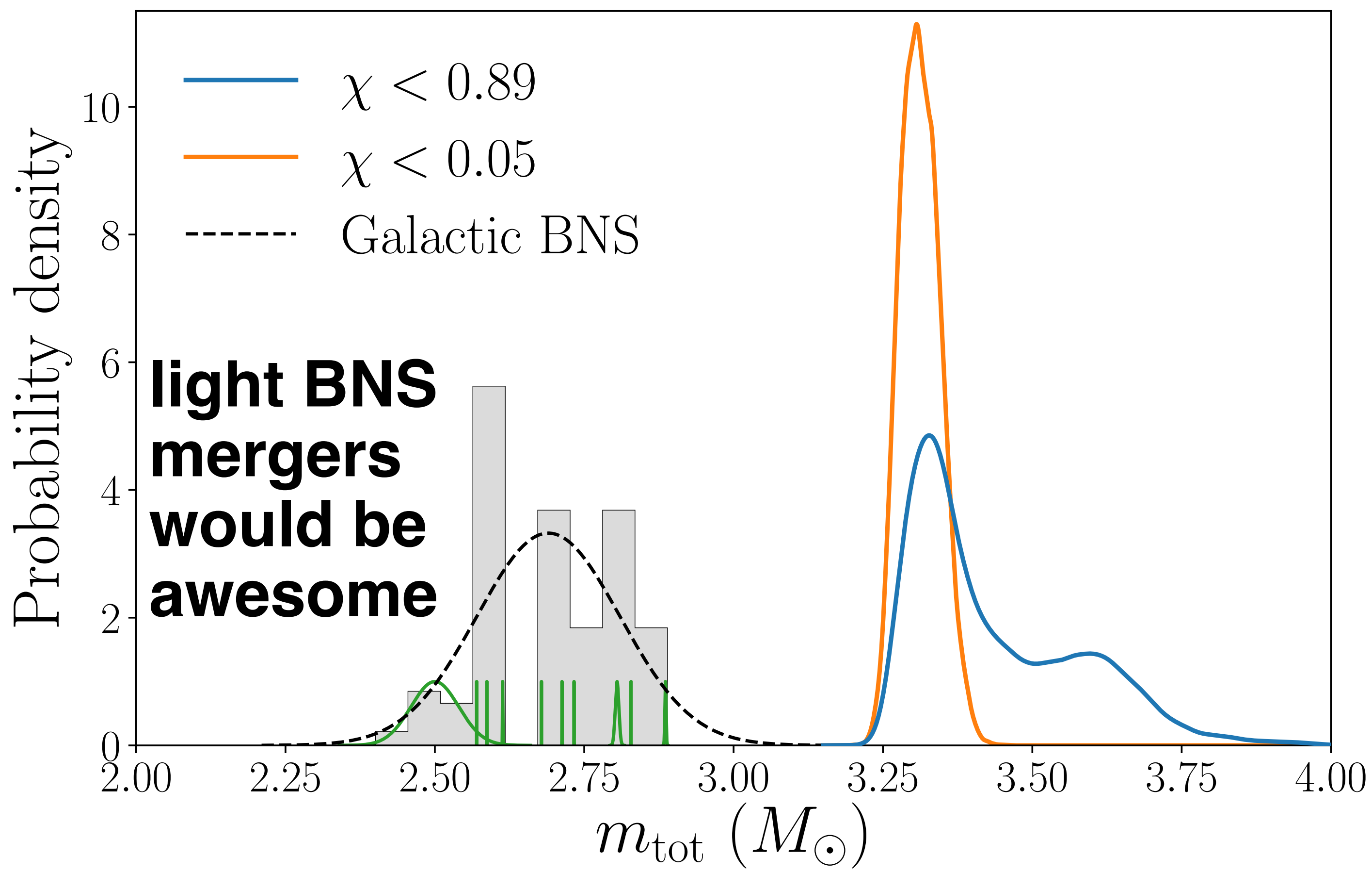
GW190425

hunting for surprises..

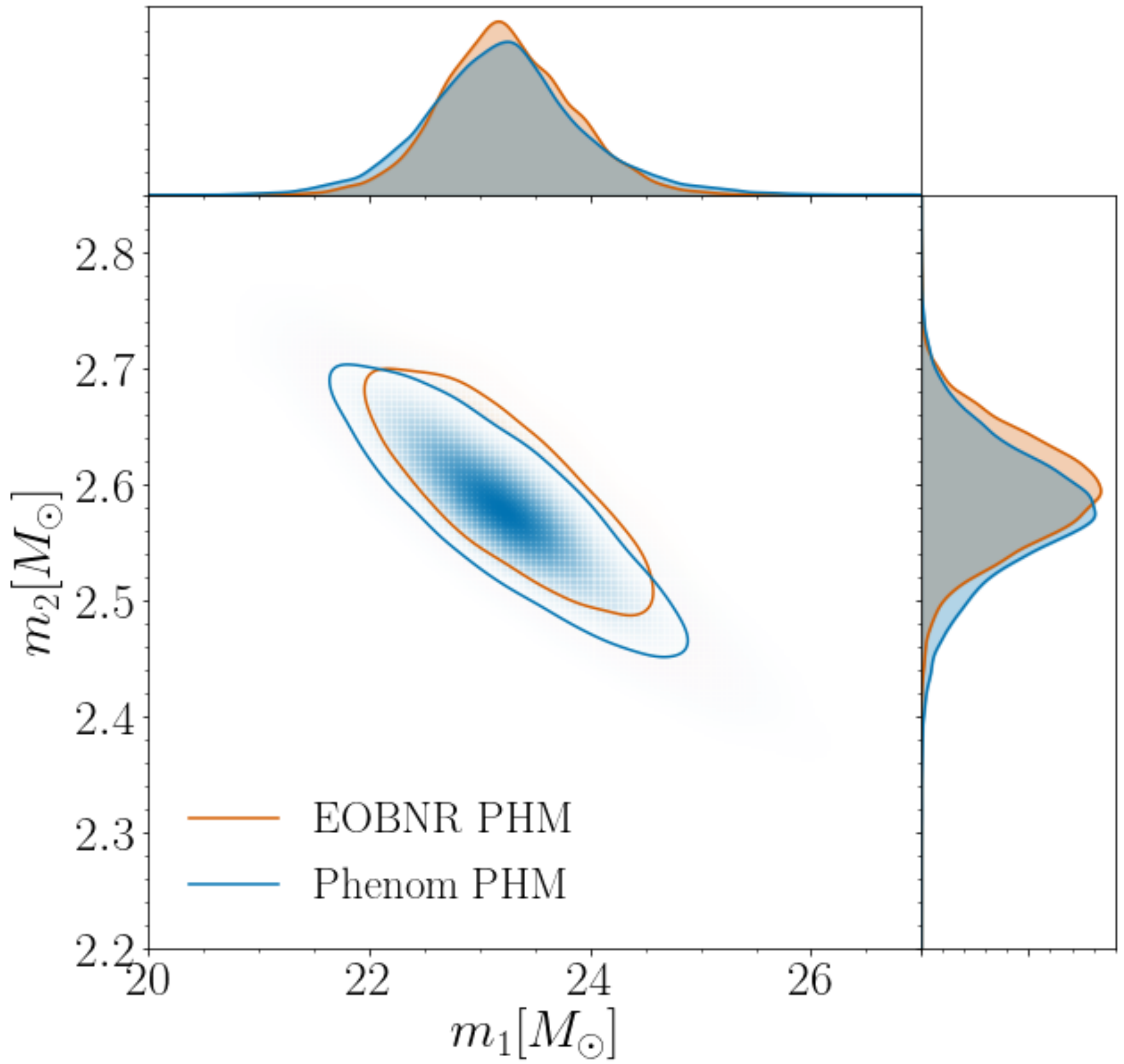
LVC collaboration
arXiv:2006.12611

- total mass ~3.4 solar masses
- signal too weak to provide further EoS constraints R<16 km

LVC collaboration
arXiv:2001.01761



see events of GWTC-2: arXiv:2010.14527



GW190814

more mass-gap objects?

- component of ambiguous nature
- most **asymmetric** system observed

NSBH mergers

LVK collaboration
arXiv:2106.15163

The Astrophysical Journal Letters, 915:L5 (24pp), 2021 July 1 https://doi.org/10.3847/2041-8213/ac082e

Observation of Gravitational Waves from Two Neutron Star–Black Hole Coalescences

Table 2
Source Properties of GW200105 and GW200115

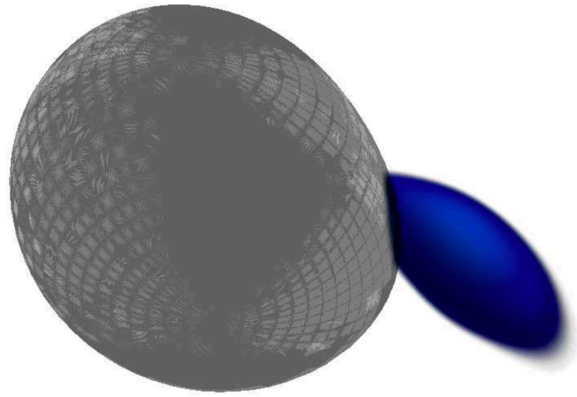
	GW200105		GW200115	
	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)
Primary mass $m_1/M_\odot$	$8.9^{+1.1}_{-1.3}$	$8.9^{+1.2}_{-1.5}$	$5.9^{+1.4}_{-2.1}$	$5.7^{+1.8}_{-2.1}$
Secondary mass $m_2/M_\odot$	$1.9^{+0.2}_{-0.2}$	$1.9^{+0.3}_{-0.2}$	$1.4^{+0.6}_{-0.2}$	$1.5^{+0.7}_{-0.3}$
Mass ratio q	$0.21^{+0.06}_{-0.04}$	$0.22^{+0.08}_{-0.04}$	$0.24^{+0.31}_{-0.08}$	$0.26^{+0.35}_{-0.10}$
Total mass $M/M_\odot$	$10.8^{+0.9}_{-1.0}$	$10.9^{+1.1}_{-1.2}$	$7.3^{+1.2}_{-1.5}$	$7.1^{+1.5}_{-1.4}$
Chirp mass $\mathcal{M}/M_\odot$	$3.41^{+0.08}_{-0.07}$	$3.41^{+0.08}_{-0.07}$	$2.42^{+0.05}_{-0.07}$	$2.42^{+0.05}_{-0.07}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$3.619^{+0.006}_{-0.006}$	$3.619^{+0.007}_{-0.008}$	$2.580^{+0.006}_{-0.007}$	$2.579^{+0.007}_{-0.007}$
Primary spin magnitude χ_1	$0.09^{+0.18}_{-0.08}$	$0.08^{+0.22}_{-0.08}$	$0.31^{+0.52}_{-0.29}$	$0.33^{+0.48}_{-0.29}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.01^{+0.08}_{-0.12}$	$-0.01^{+0.11}_{-0.15}$	$-0.14^{+0.17}_{-0.34}$	$-0.19^{+0.23}_{-0.35}$
Effective precession spin parameter χ_p	$0.07^{+0.15}_{-0.06}$	$0.09^{+0.14}_{-0.07}$	$0.19^{+0.28}_{-0.17}$	$0.21^{+0.30}_{-0.17}$
Luminosity distance $D_{\rm L}$/Mpc	280^{+110}_{-110}	280^{+110}_{-110}	310^{+150}_{-110}	300^{+150}_{-100}
Source redshift z	$0.06^{+0.02}_{-0.02}$	$0.06^{+0.02}_{-0.02}$	$0.07^{+0.03}_{-0.02}$	$0.07^{+0.03}_{-0.02}$

- GW200105: ~1.9 + ~9 solar masses
- GW200115: ~1.5 + ~6 solar masses

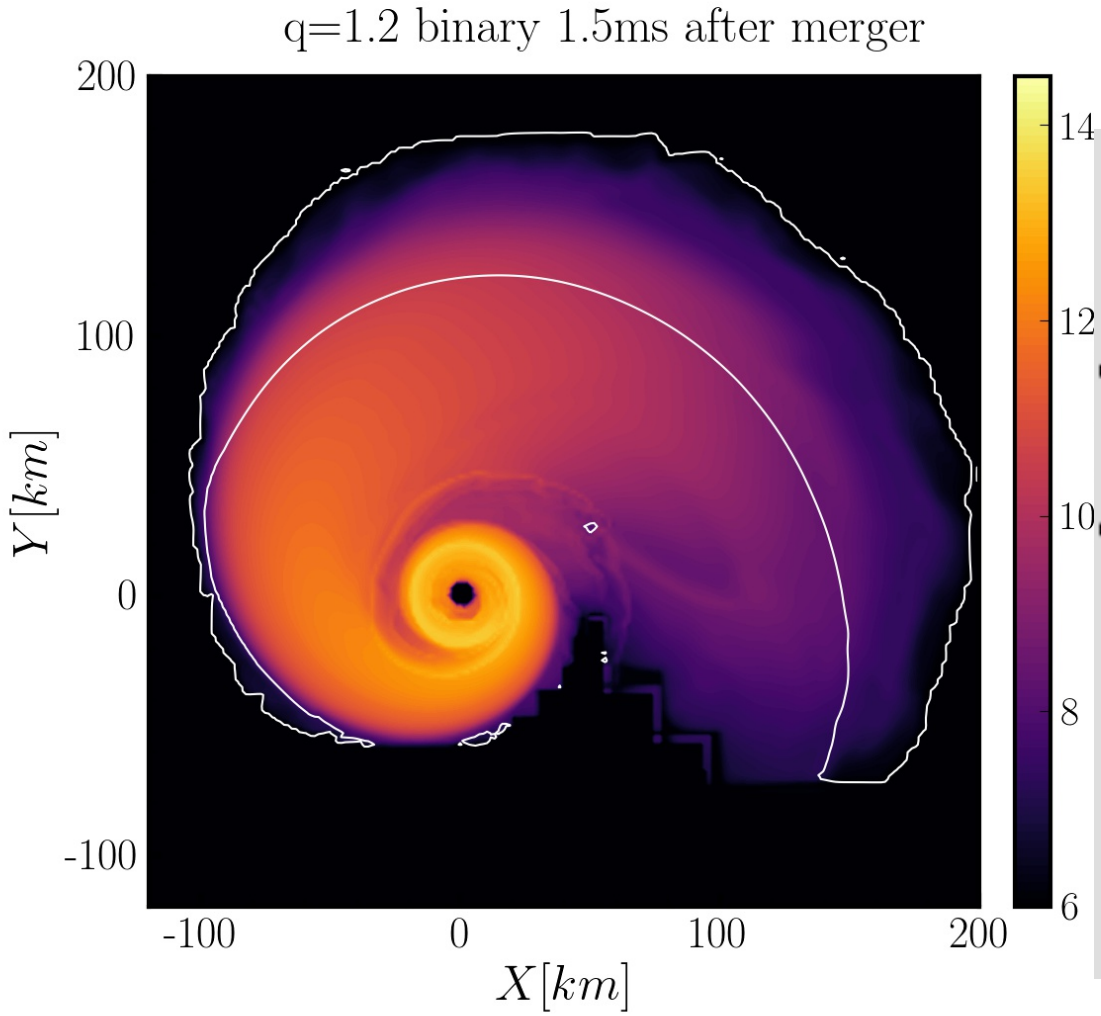
no information on matter effects
no significant EM detections

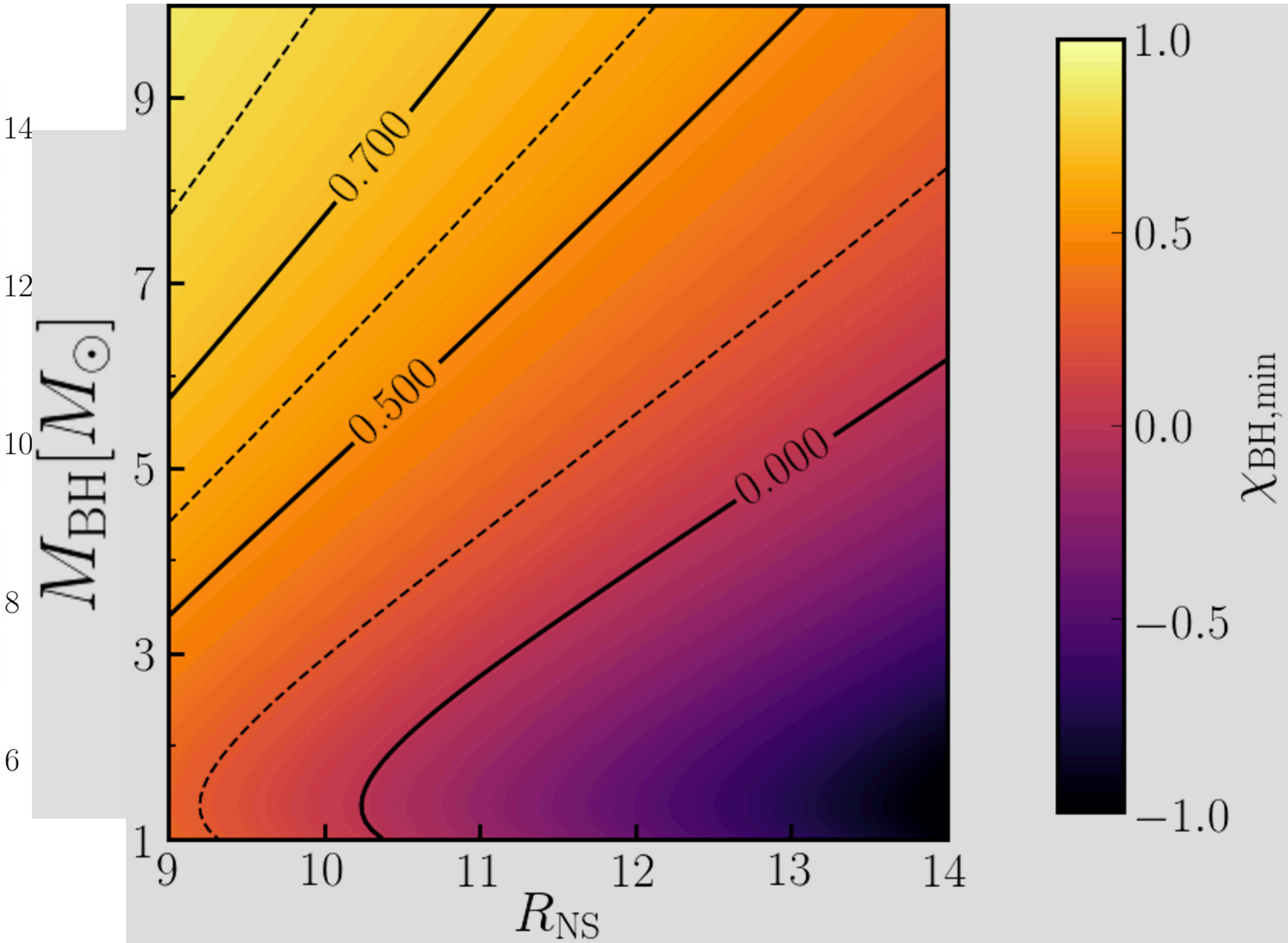
see events of GWTC-3: arXiv:2111.03606

Outcome of a NSBH merger



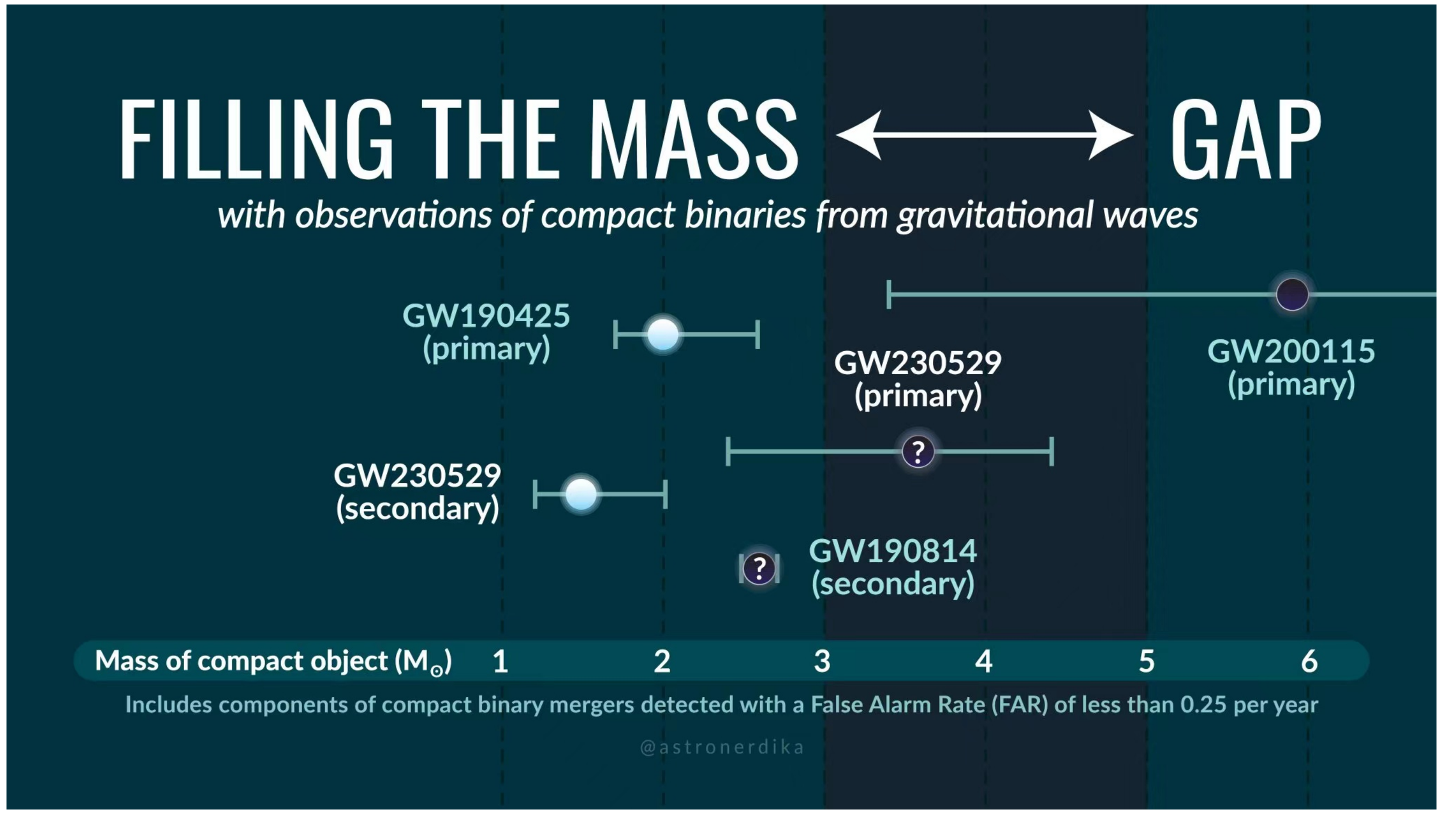
Foucart et al. (2018)



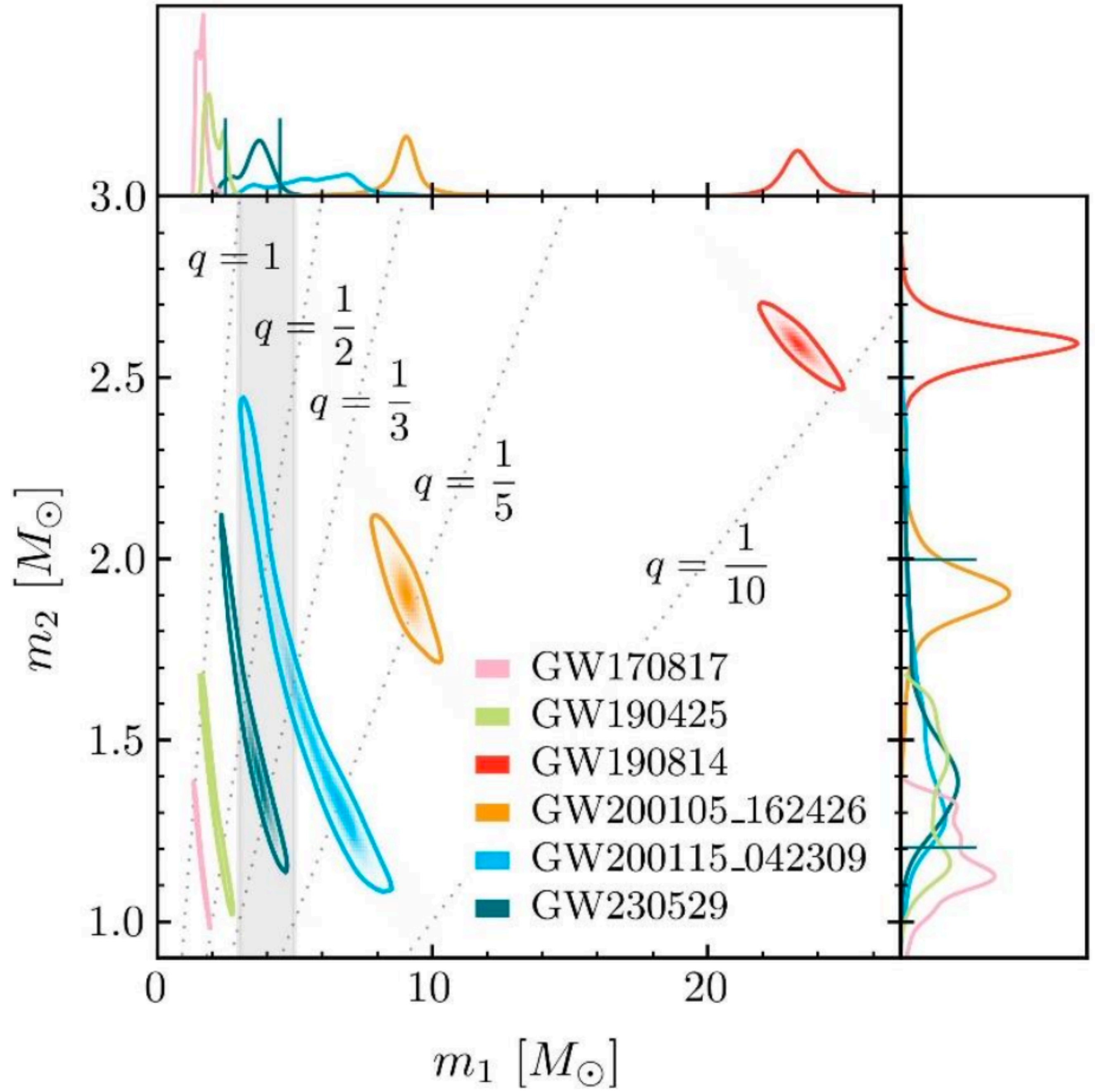


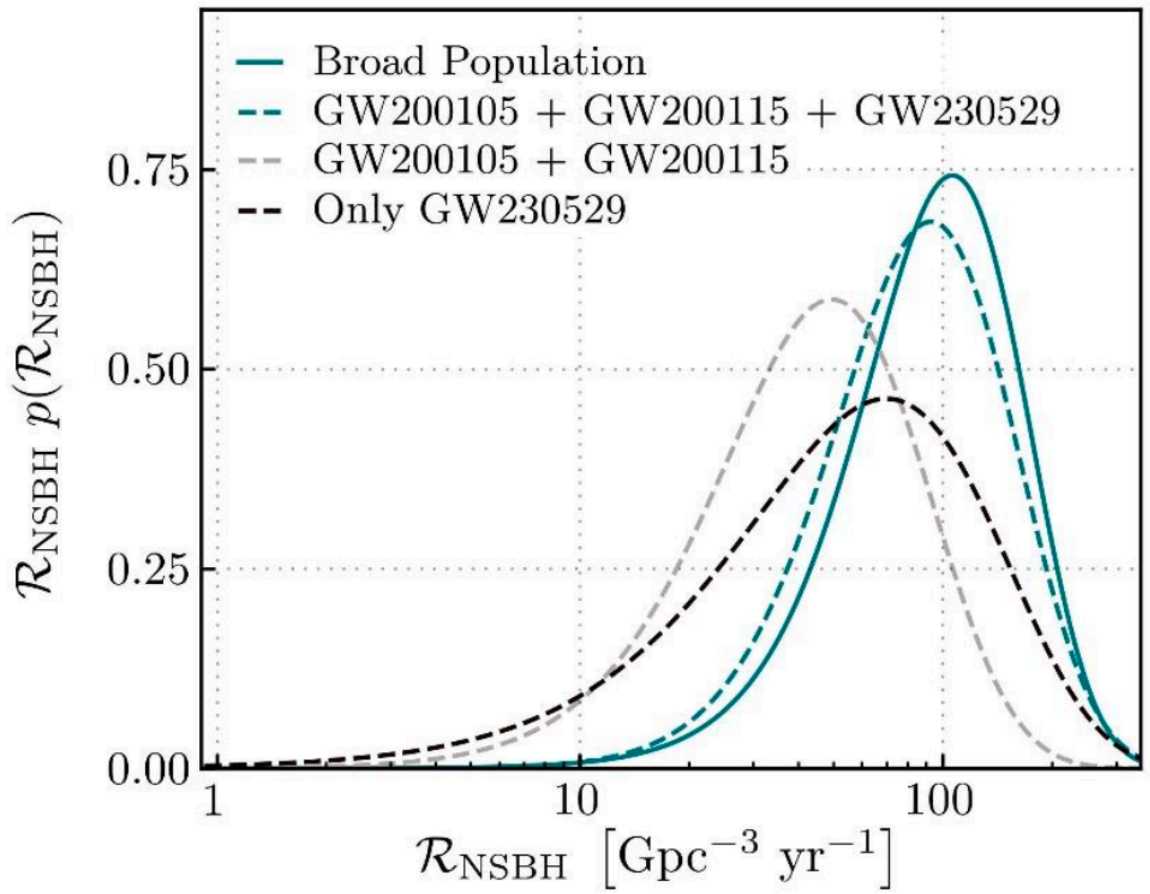
- NS is either tidally disrupted or plunges into the BH - mass ratio, spin, EoS
- radius determines if tides are **measurable** & if **EM** signals can be produced

GW230529 (new!)



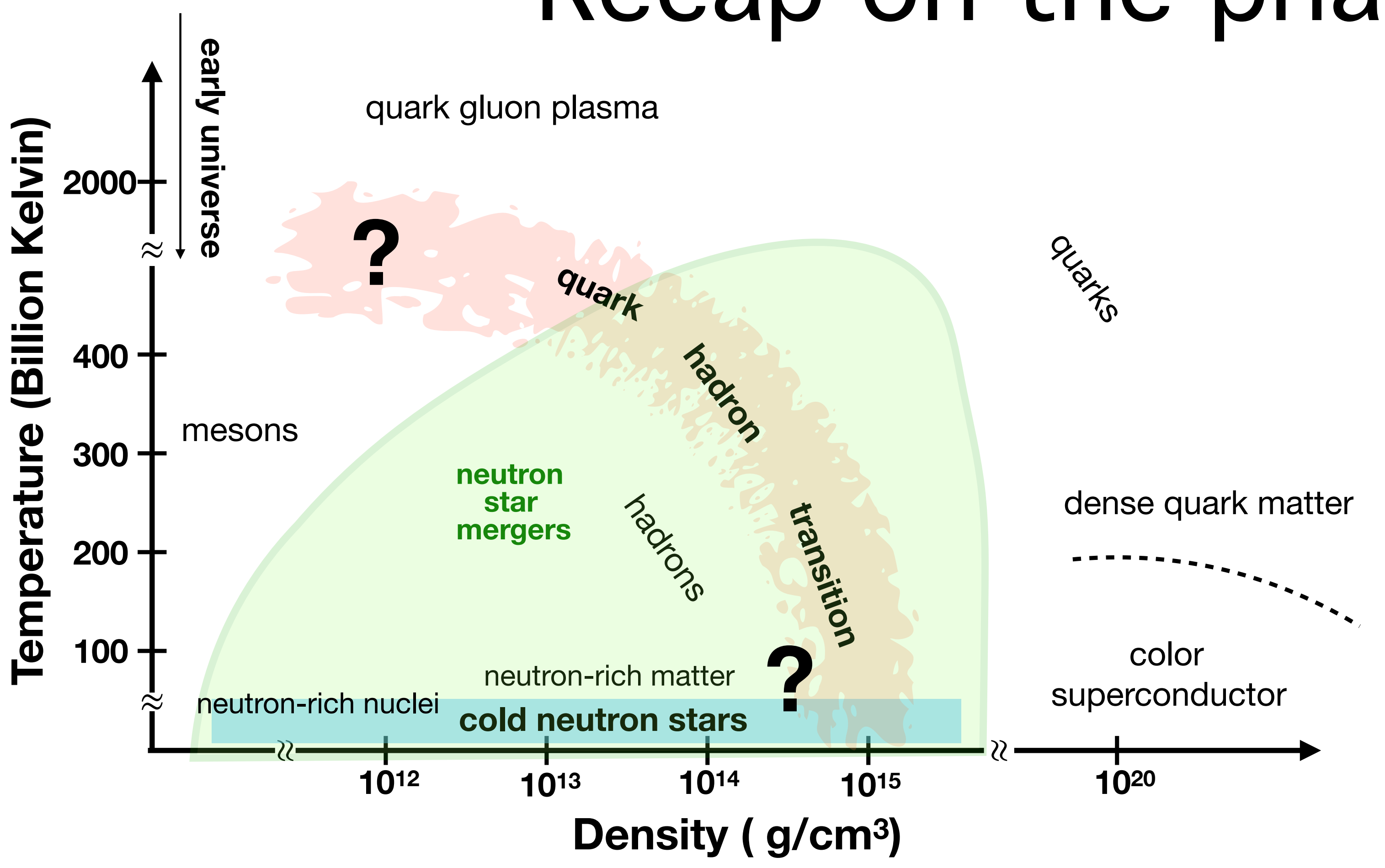
LVK collaboration
arXiv:2404.04248

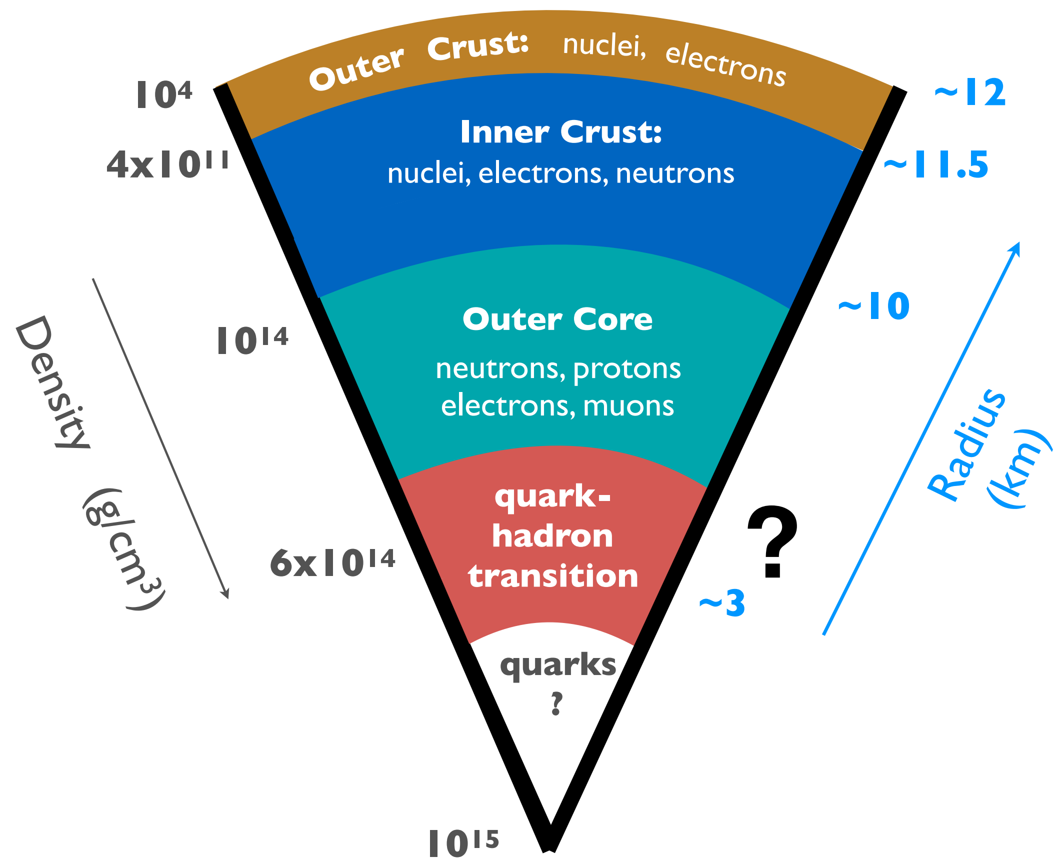




- ~1.4 (NS) + ~3.6 (BH) solar masses
- most **symmetric** NSBH event so far

Recap on the phase diagram





3G Science white paper

puzzle of QM in NSs

- has a phase transition already taken place in canonical-mass (cold) NSs before they merge in the binary system?
- are quarks only able to appear temporarily in the (warm) massive, transient remnant of mergers or supernovae?
- when and how do they emerge - **the onset density, temperature, nature** of PT?
- imprints in observations? possible links to e.g. HICs?

THANK YOU!

Q & A

BACKUP

SLIDES

Impact of J0740 radius constraint

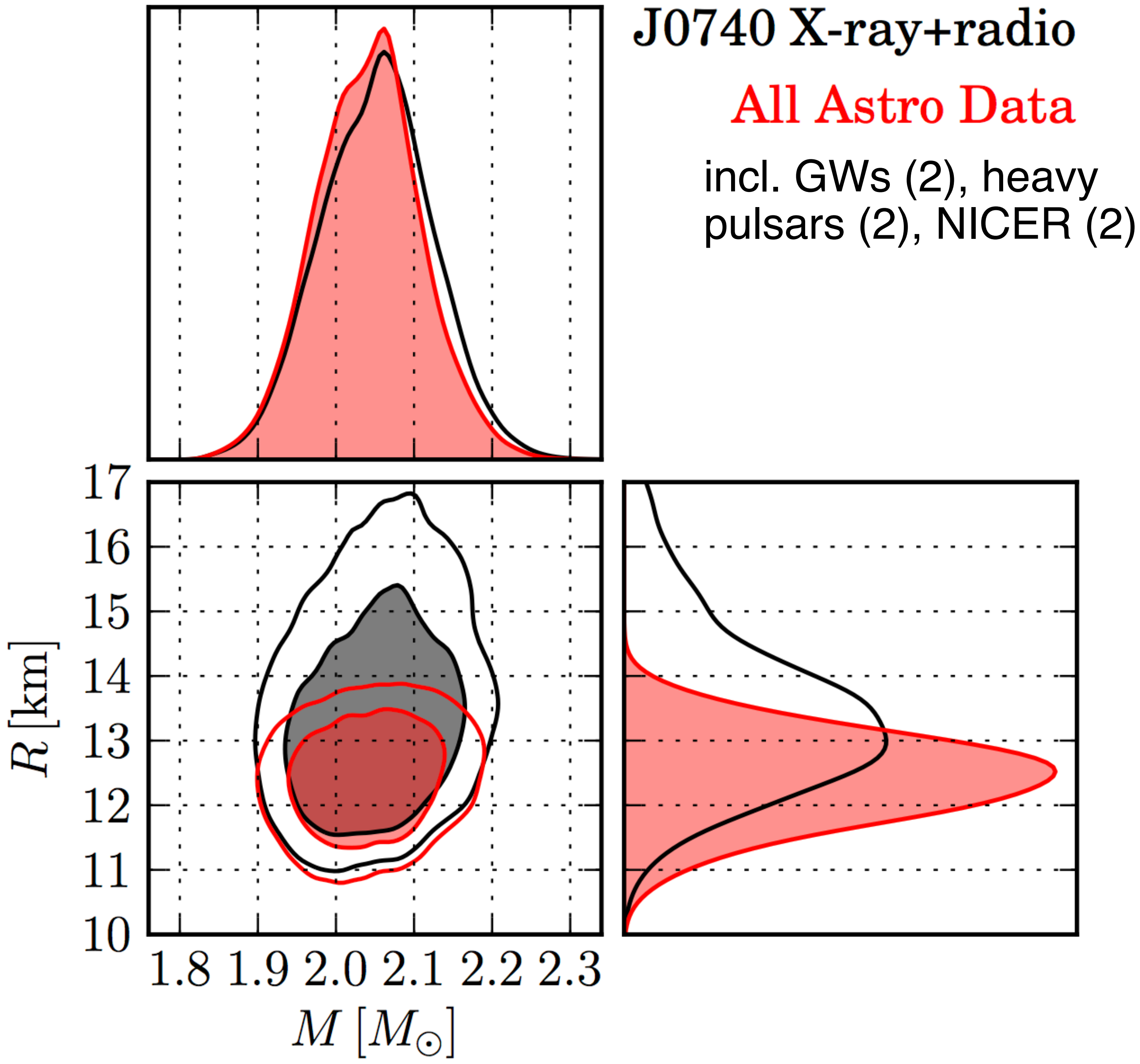
Bayesian analyses

- hierarchical inference scheme and the **nonparametric** priors (not assuming a specific functional form but correlations within a function - GP processes)

  Landry et al., arXiv:2003.04880

- ***NICER*** data + XMM-Newton: Riley+Watts (Amsterdam) and Miller+ (Maryland/Illinois),
- $12.4^{+1.3}_{-1.0}$ km vs. $13.7^{+2.6}_{-1.5}$ km

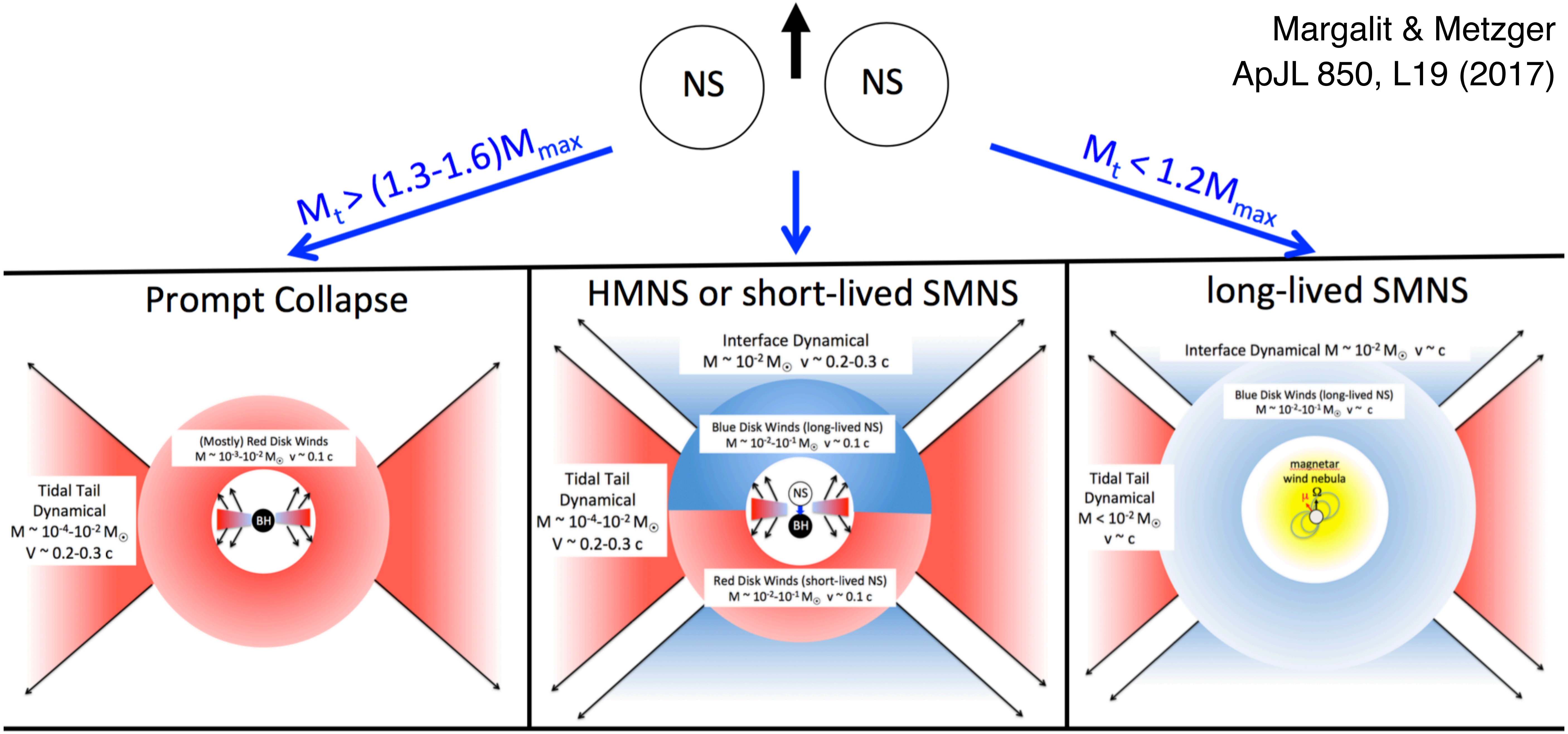
- **other** astrophysical observations overall reduce the inferred radius of J0740+6620 from ~13.34 km to ~12.47 km at 90% credibility



inferred central density ~ $3.0^{+1.6}_{-1.6}\,\rho_{\rm nuc}$

Remnant dynamics

Margalit & Metzger
ApJL 850, L19 (2017)



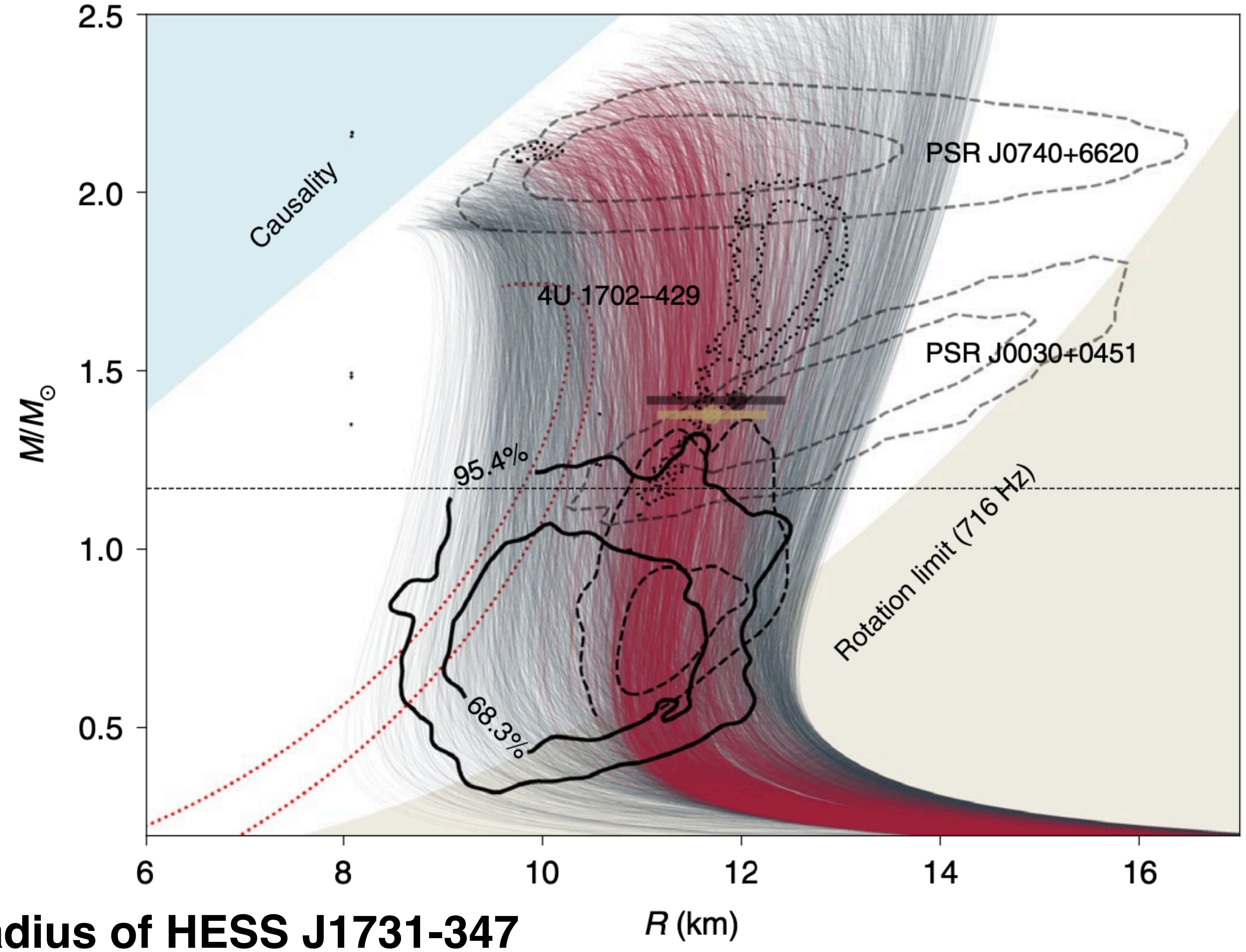
- **GW + EM** constraints from 170817 seem to favor Mmax<2.16~2.3 solar masses   Ruiz et al. (2018), Rezzolla et al. (2018), Shibata et al. (2019)
- **NS radius >10.68 km** to prevent prompt collapse   Bauswein et al. (2017)

other x-ray probes of NS radii

Article

potential outlier candidate?

Doroshenko et al. Nature Astronomy 6, 1444 (2022)



new! mass & radius of HESS J1731-347

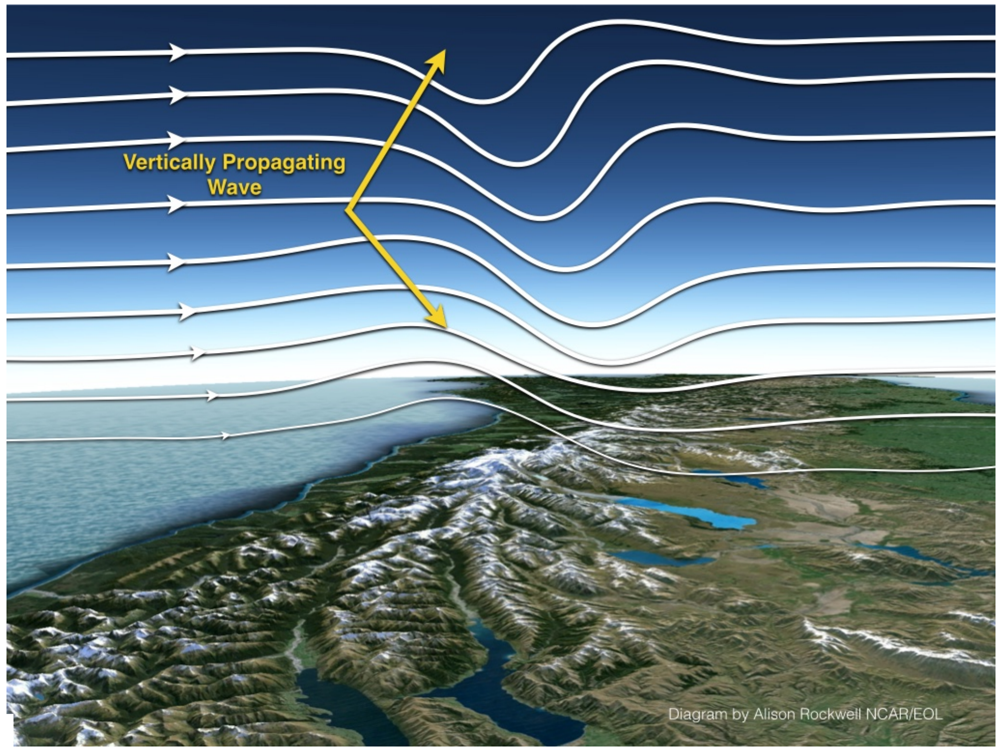
- “A strangely light neutron star within a supernova remnant”

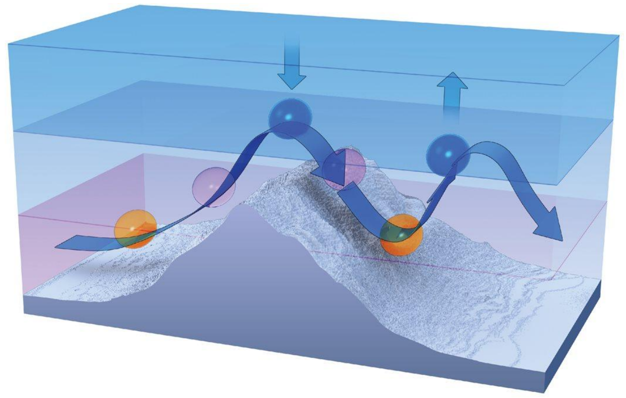
- relies on specific assumptions about EoS prior, atm-models, temp. distribution etc.

g-modes (gravity modes)

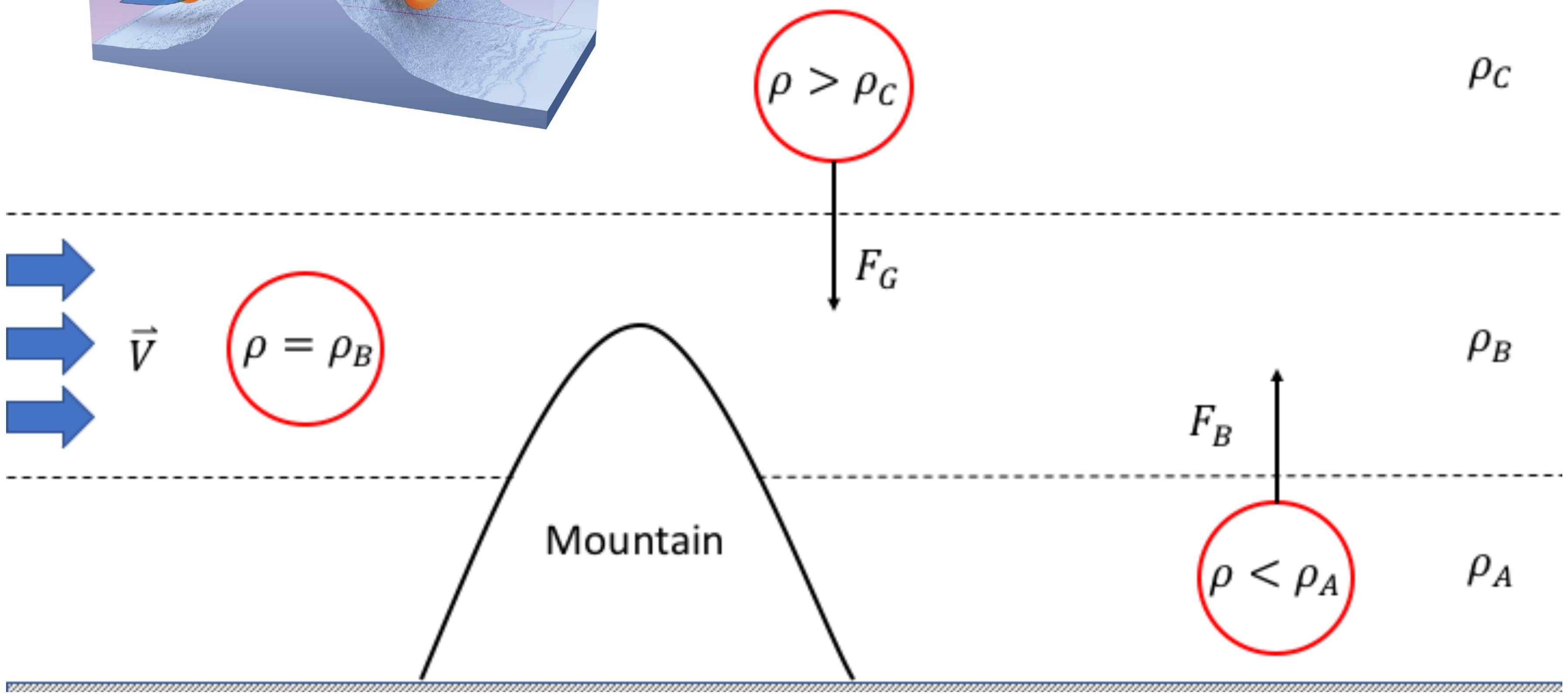
restoring forces from buoyancy/gravity

- e.g. atmospheric or ocean waves
- hydrostatic equilibrium: gravitational force balanced by pressure gradient force
- perturbed from equilibrium -> gravity or buoyancy pulls/pushes it back -> oscillation





AUSTRALIAN ANTARCTIC PROGRAM



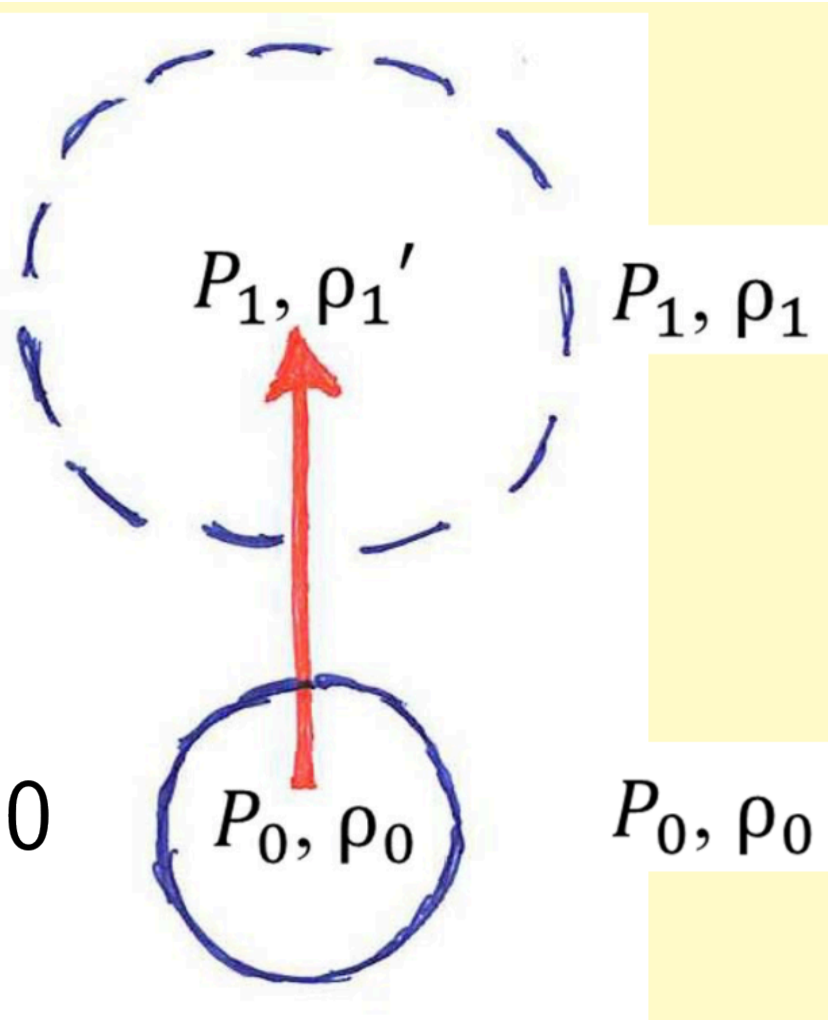
Local (buoyancy) frequency

- pressure instantaneously equilibrated, but not for composition and density
- continuity equation & the equation of motion
- "**adiabatic**" (composition frozen) sound speed vs. "**equilibrium**" sound speed

$$\Delta\rho = -\rho \frac{\partial^2 \xi}{\partial t^2}$$

$\downarrow \vec{g}$

$$\frac{\partial^2 \xi}{\partial t^2} + N^2 \xi = 0$$



credit: Andreas Reisenegger

$$dp/dr = -\rho g$$

[hydrostatic equilibrium]

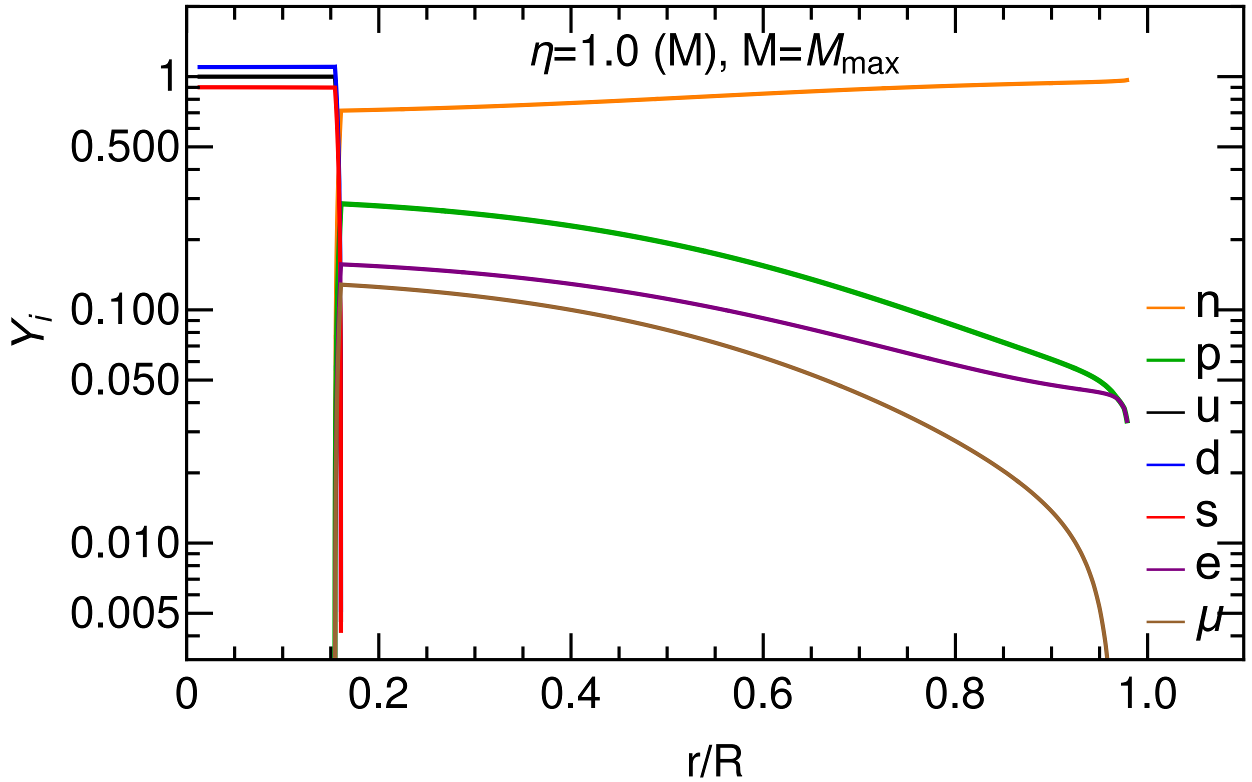
$$N^2 \equiv g^2 \left(\frac{1}{c_{eq}^2} - \frac{1}{c_{ad}^2} \right) e^{\nu - \lambda}$$

← [local metric coefficients]

$$c_{eq}^2 = \left(\frac{dp/dr}{d\varepsilon/dr} \right) \qquad c_{ad}^2 = \left(\frac{\partial p}{\partial \varepsilon} \right)_{y_i}$$

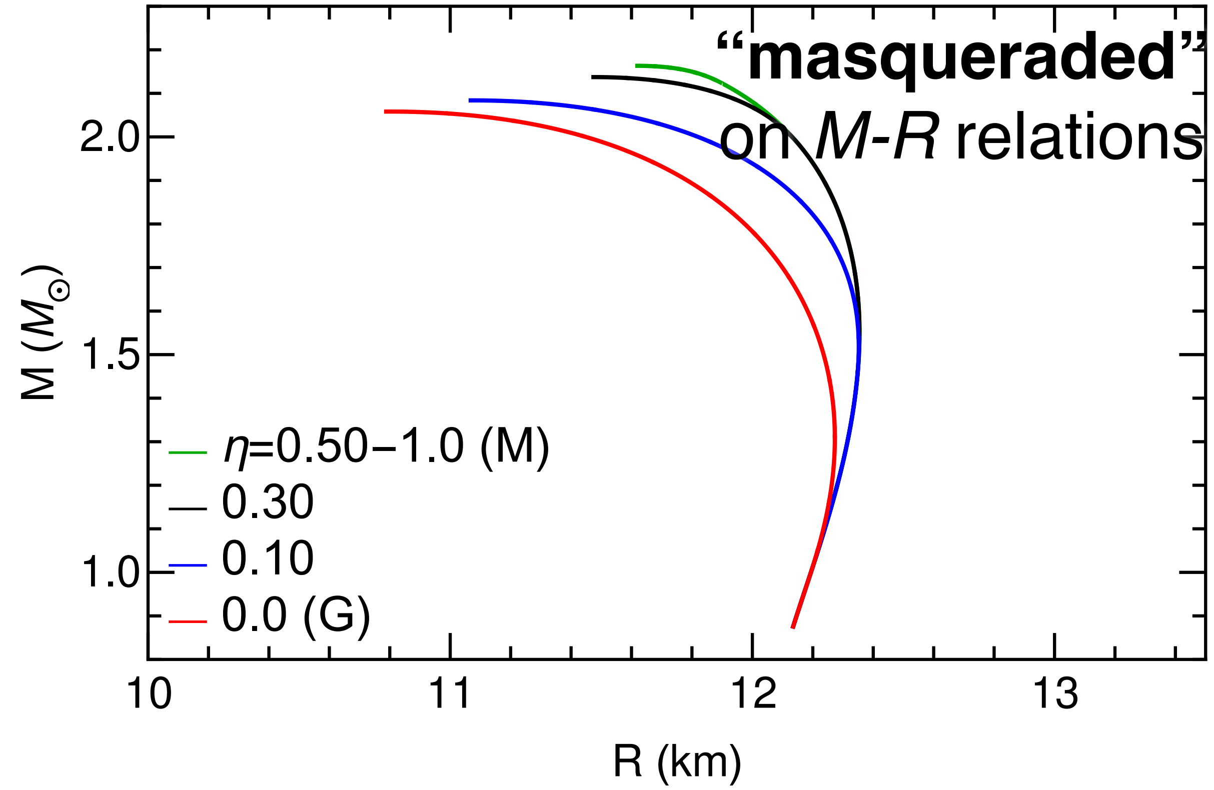
Global g-mode frequency with PTs

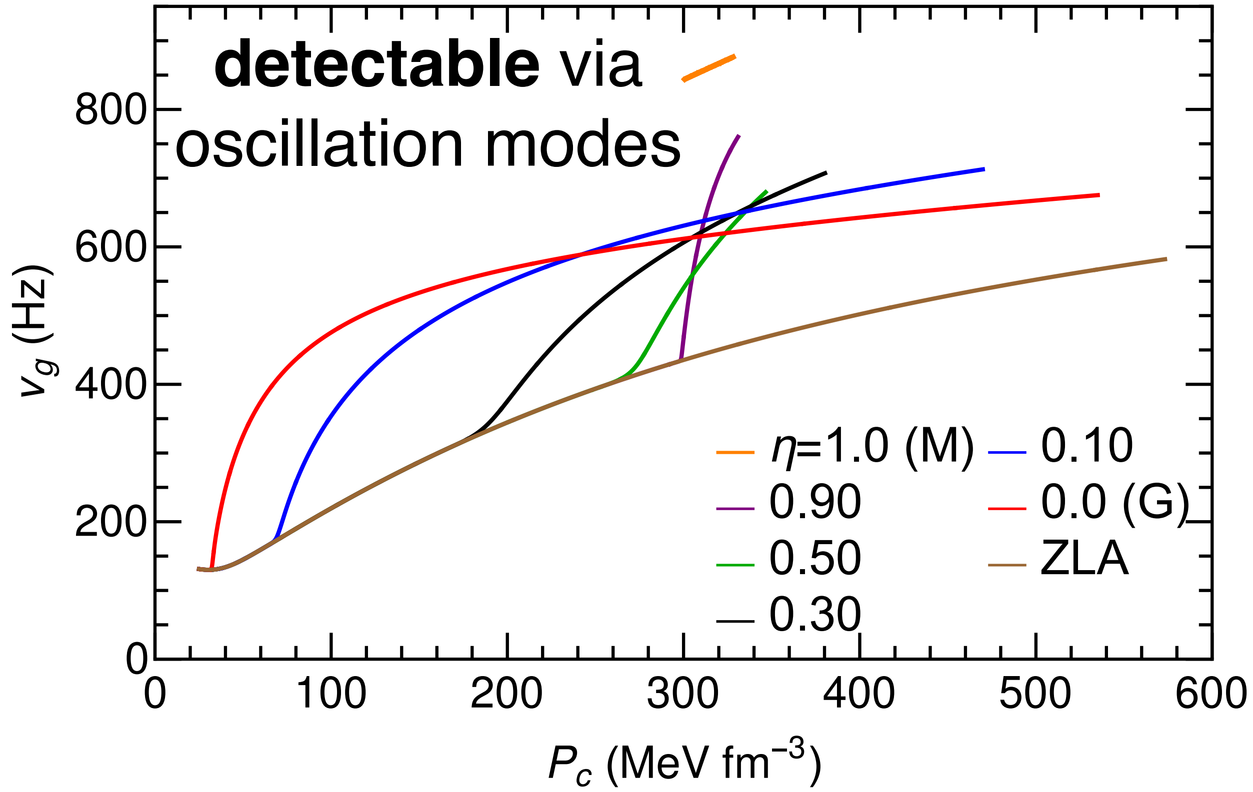
- hybrid system under local vs. global charge neutrality in Maxwell (M) vs. Gibbs (G) construction for a 1st-OPT



- "discontinuity" g-mode observed when there exists a sharp boundary

- **<u>distinct signature of exotic phases</u>:** higher frequency indicates larger fraction of quark matter





Constantinou et al. (including **SH**), arXiv:2302.04289