Astrophysical constraints on the high-density equation of state

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Theoretical Physics Colloquium
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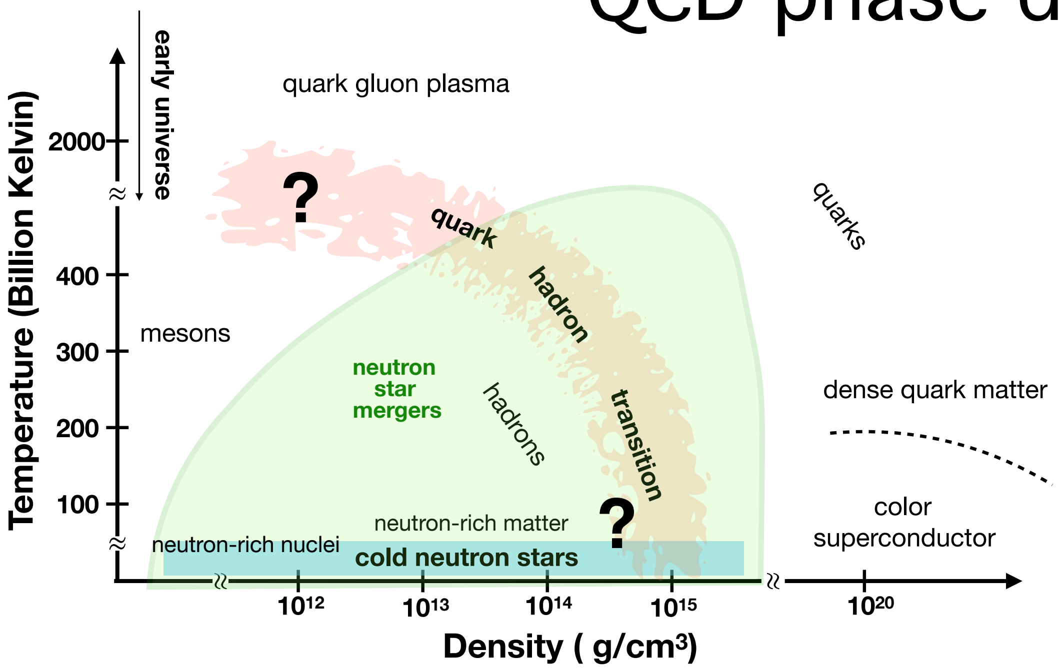
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

Outline

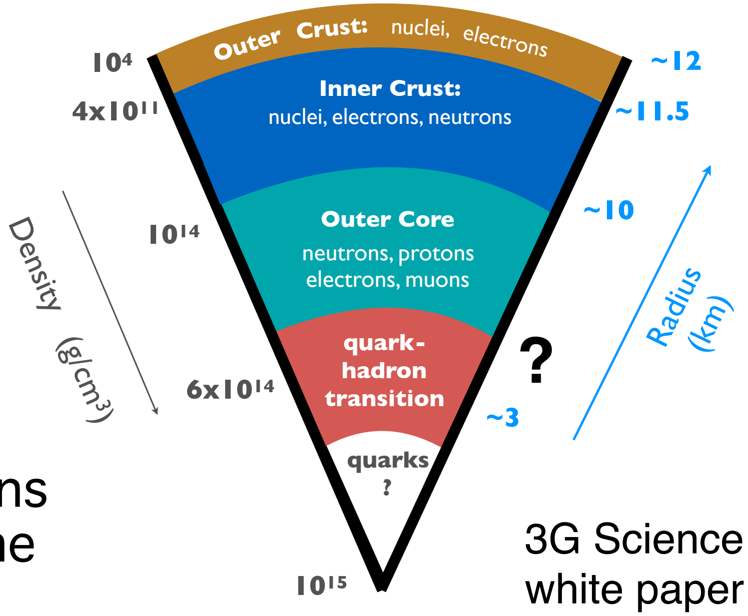
- **Introduction - dense matter and neutron stars**
- **Neutron star structure and the equation of state (EoS)**
- **Multi-messenger constraints on the EoS: what have we learned so far?**
- **Future directions**

QCD phase diagram



- lattice QCD gives good result at finite temperature, but is stymied currently at finite density
- perturbative QCD: only valid at asymptotically high densities
- can't calculate properties of cold dense matter, must **observe**!

- properties of ultra-dense matter in the inner cores of neutron stars (NSs)
- a challenging problem as no terrestrial experiments can probe such high densities
- also because reliable first-principle calculations break down at the strongly-interacting regime



3G Science white paper

credit: Dany Page

Dense matter in NSs

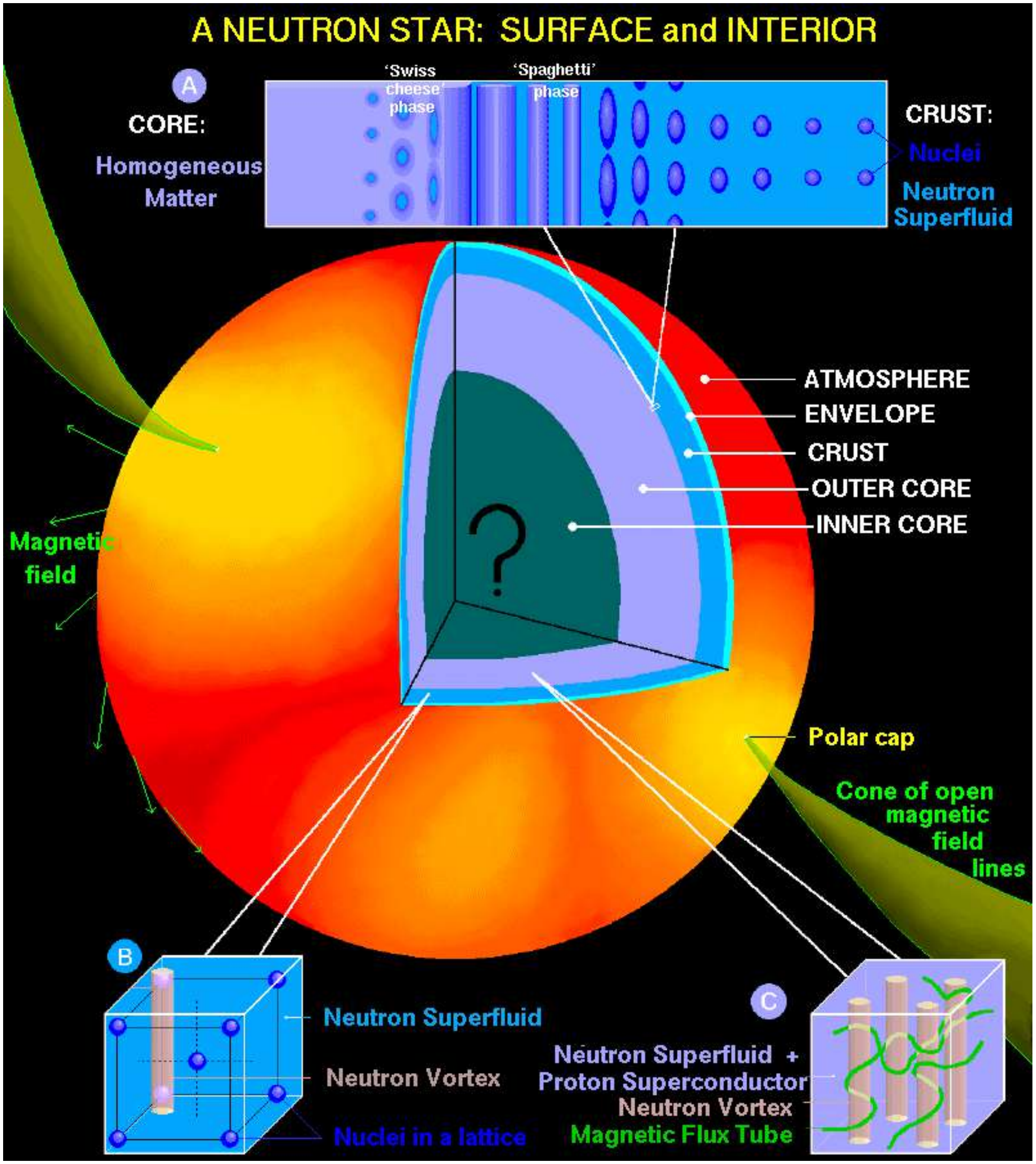
- stable nuclei
- neutron-rich nuclei
- neutron-rich nuclei with quasi-free neutrons

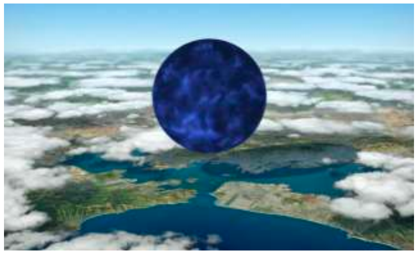
……

- homogeneous nucleonic matter (liquid)
- exotica

Fundamental questions

- what are the most relevant lower-energy degrees of freedom?
- how does deconfinement evolve as T->0 on the QCD phase diagram?





Nature's extreme labs

micro
theo.

$p(\varepsilon)$

GR

$M(R)$

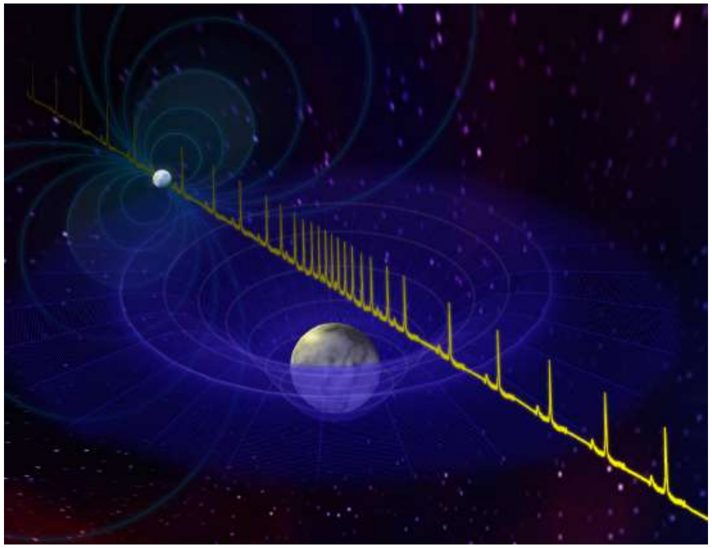
astro
obs.

- for the interior of a spherical, static, relativistic star

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

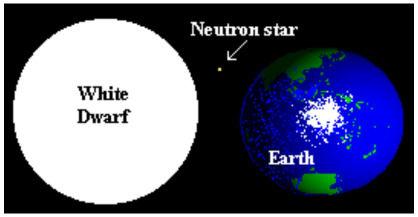
$$m(r) \equiv 4\pi\int_0^r \varepsilon(r)r^2dr$$

radio pulsar timing ©NRAO



massive neutron stars ~ $2\,M_\odot$ **do exist!**

Source	Mass ($M_\odot$)	References
PSR J1614-2230	1.97 ± 0.04	Demorest et al. (2010)
	1.928 ± 0.017	Fonseca et al. (2016)
	1.908 ± 0.016	Arzoumanian et al. (2018)
PSR J0438+0432	2.01 ± 0.04	Antoniadis et al. (2013)
PSR J0740+6620	$2.14^{+0.10}_{-0.09}$	Cromartie et al. (2019)
	2.08 ± 0.07	Fonseca et al. (2021)

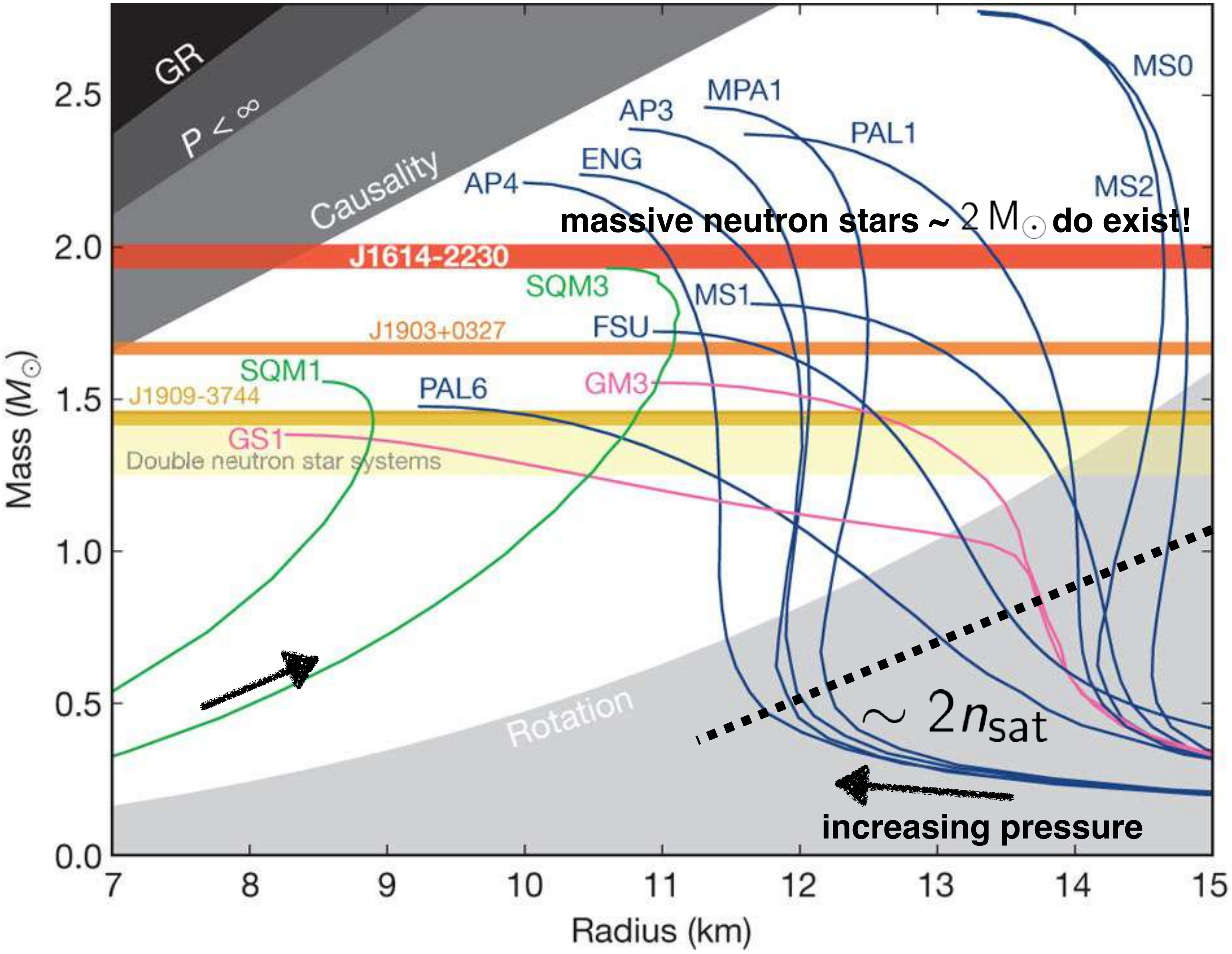


NS mass-radius diagram

micro
theo.
$p(\varepsilon)$

GR

$M(R)$
astro
obs.



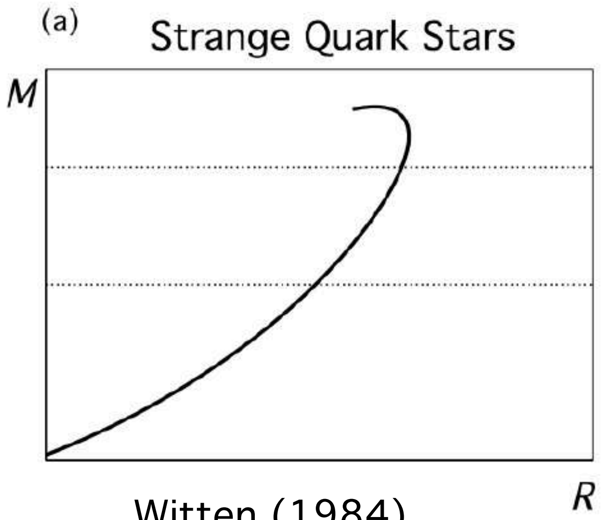
massive neutron stars ~ $2\,M_\odot$ **do exist!**

$\sim 2 n_{\mathrm{sat}}$

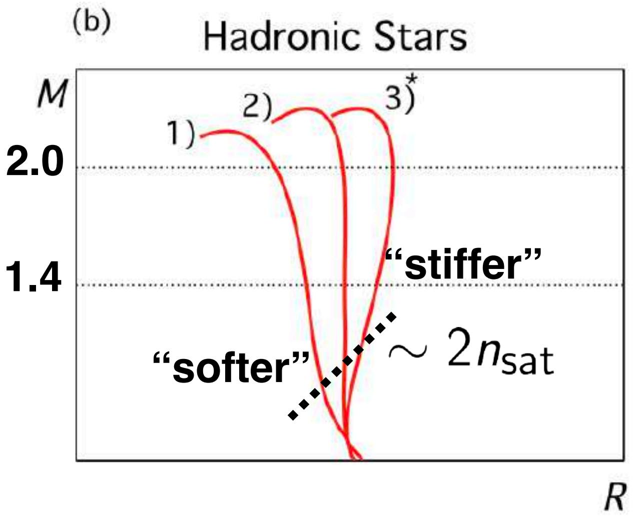
increasing pressure

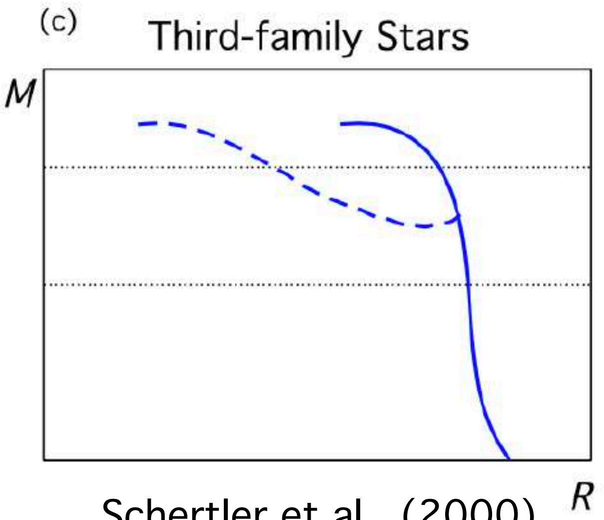
Categories of the M-R relation

SH & Prakash,
arXiv:2006.02207



Witten (1984)

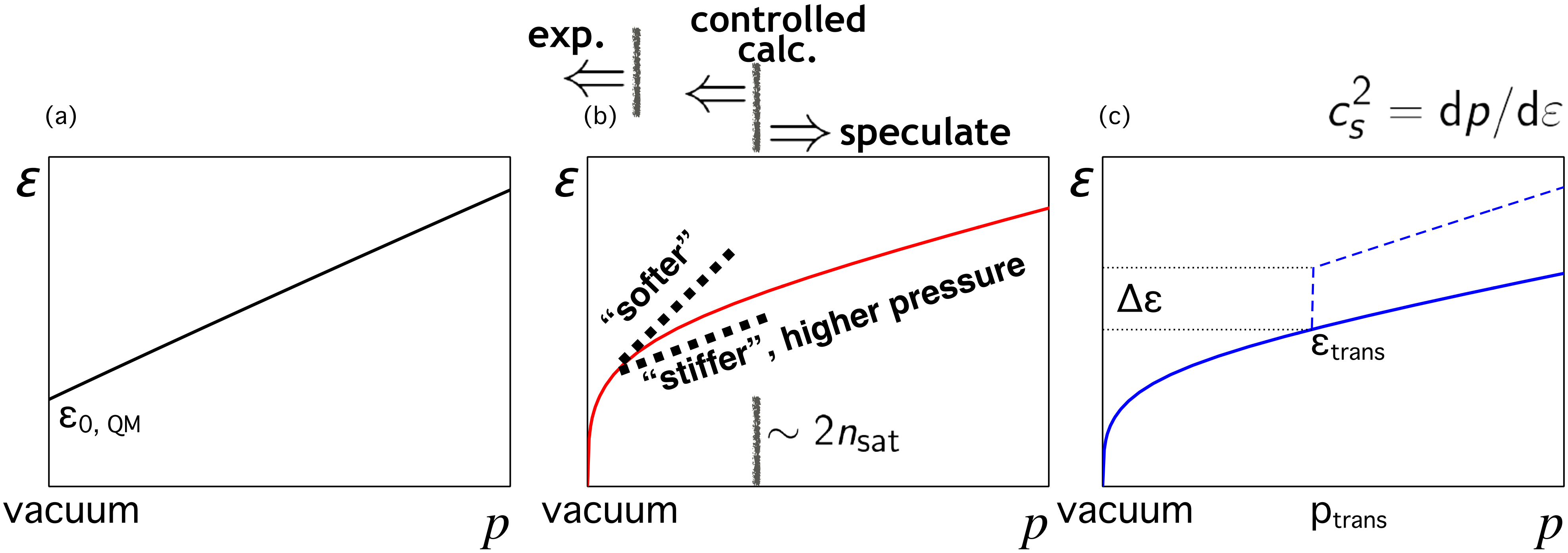




Schertler et al. (2000)

- self-bound 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

Schematic EoSs from theory



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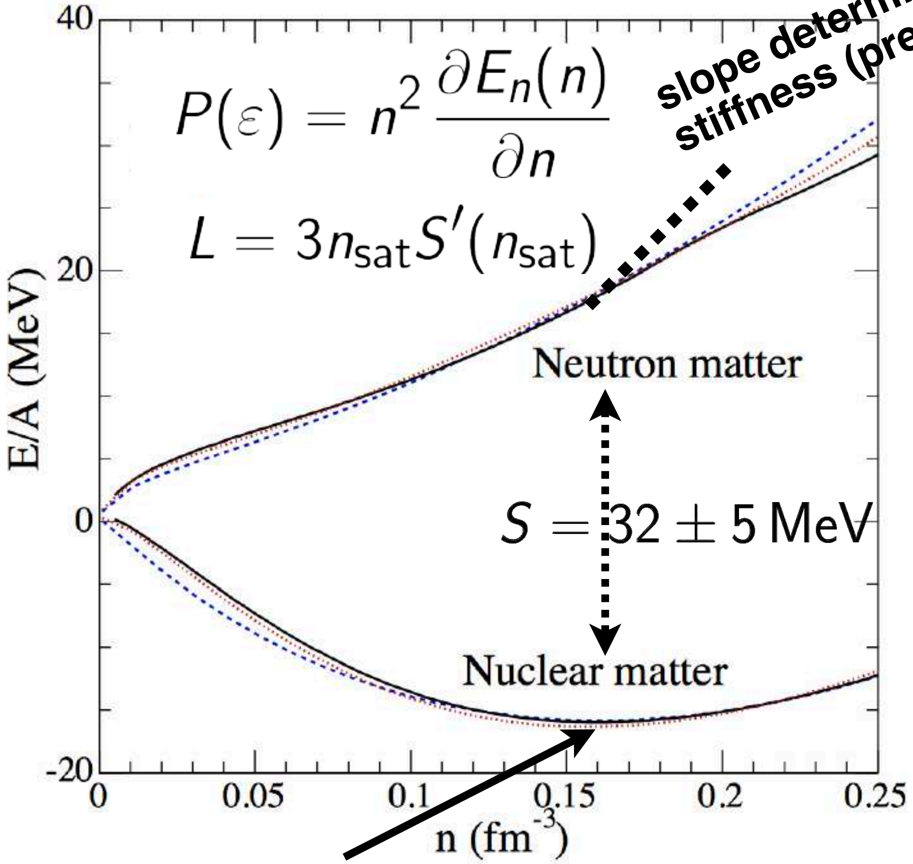
From nuclei to neutron stars

Steiner et al., Phys. Rept. 411 (2005) 325



$$P(\varepsilon) = n^2 \frac{\partial E_n(n)}{\partial n}$$

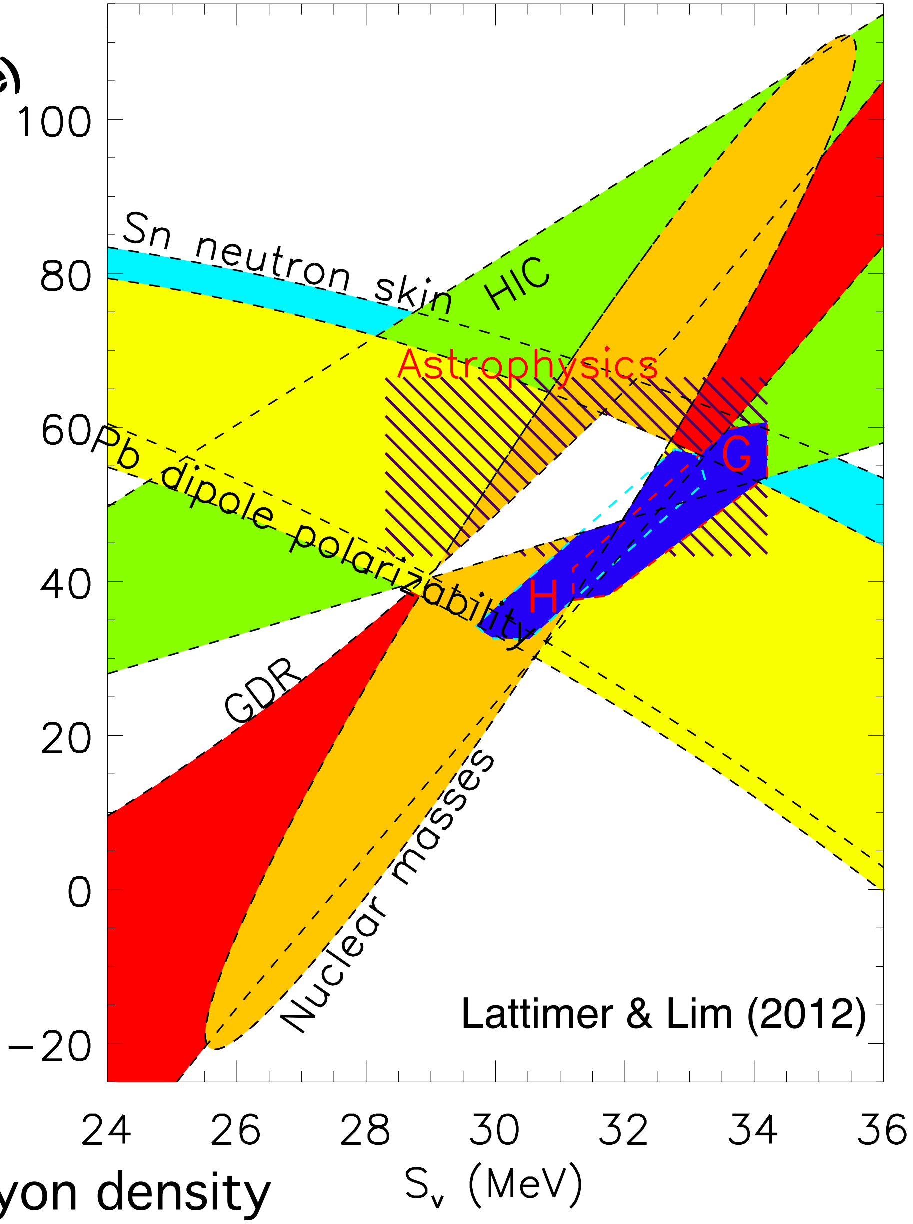
$$L = 3 n_{\mathrm{sat}} S'(n_{\mathrm{sat}})$$

$$S = 32 \pm 5\,\mathrm{MeV}$$

slope determines stiffness (pressure)

stable nuclei is here [self-bound system]

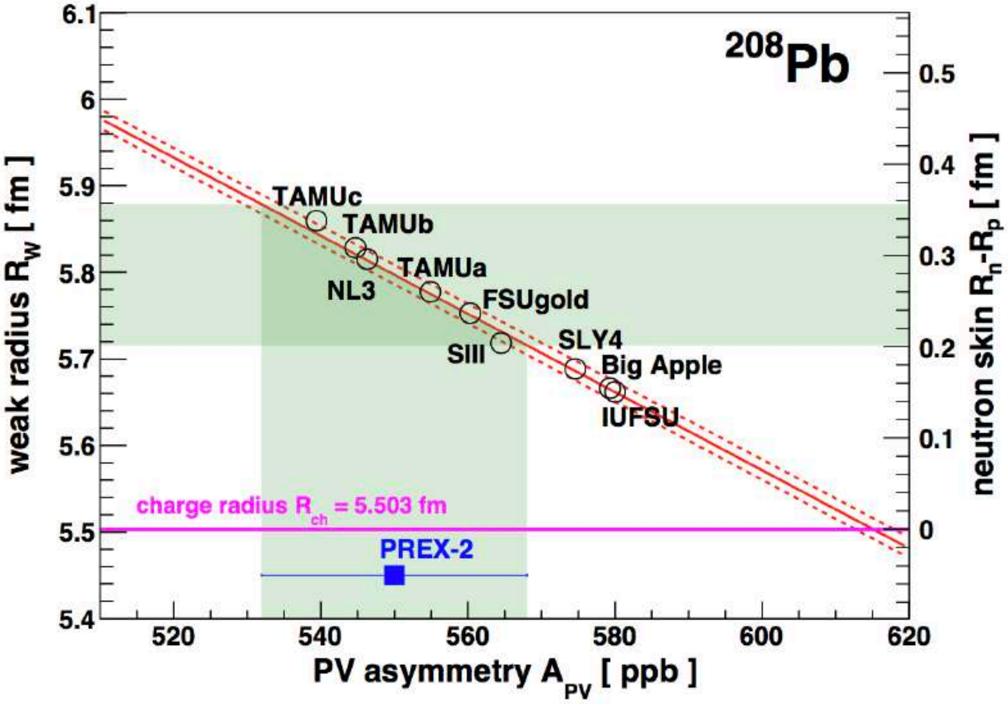
$n_{\mathrm{sat}} \simeq 0.16\,\mathrm{fm}^{-3}$



Lattimer & Lim (2012)

- nuclear experiments correlate S and L
- theory extrapolates in isospin and baryon density

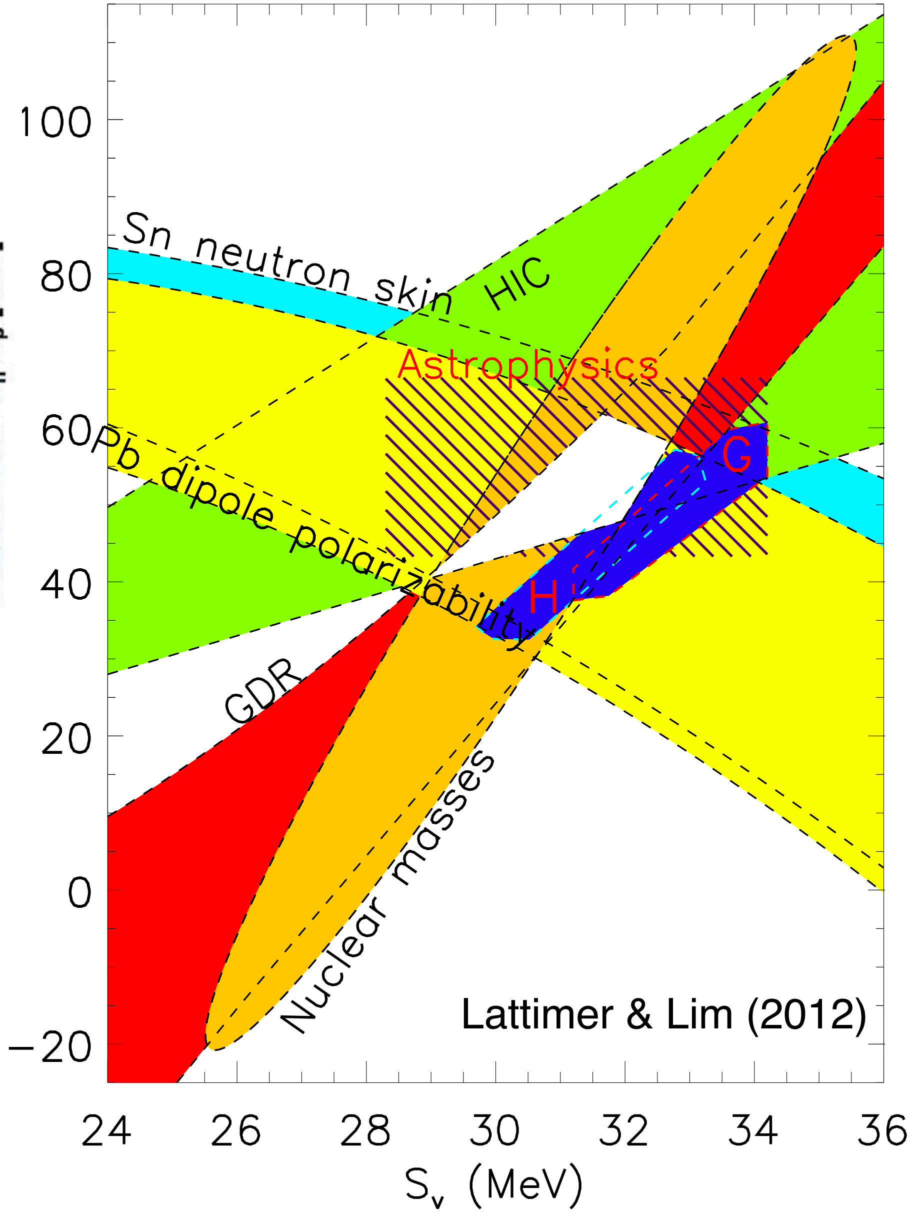
From nuclei to neutron stars



PREX Collaboration, arXiv: 2102.10767

new! neutron skin measurement @JLab

- under hot debate: pressures at sub-nuclear densities and the inferred value of L

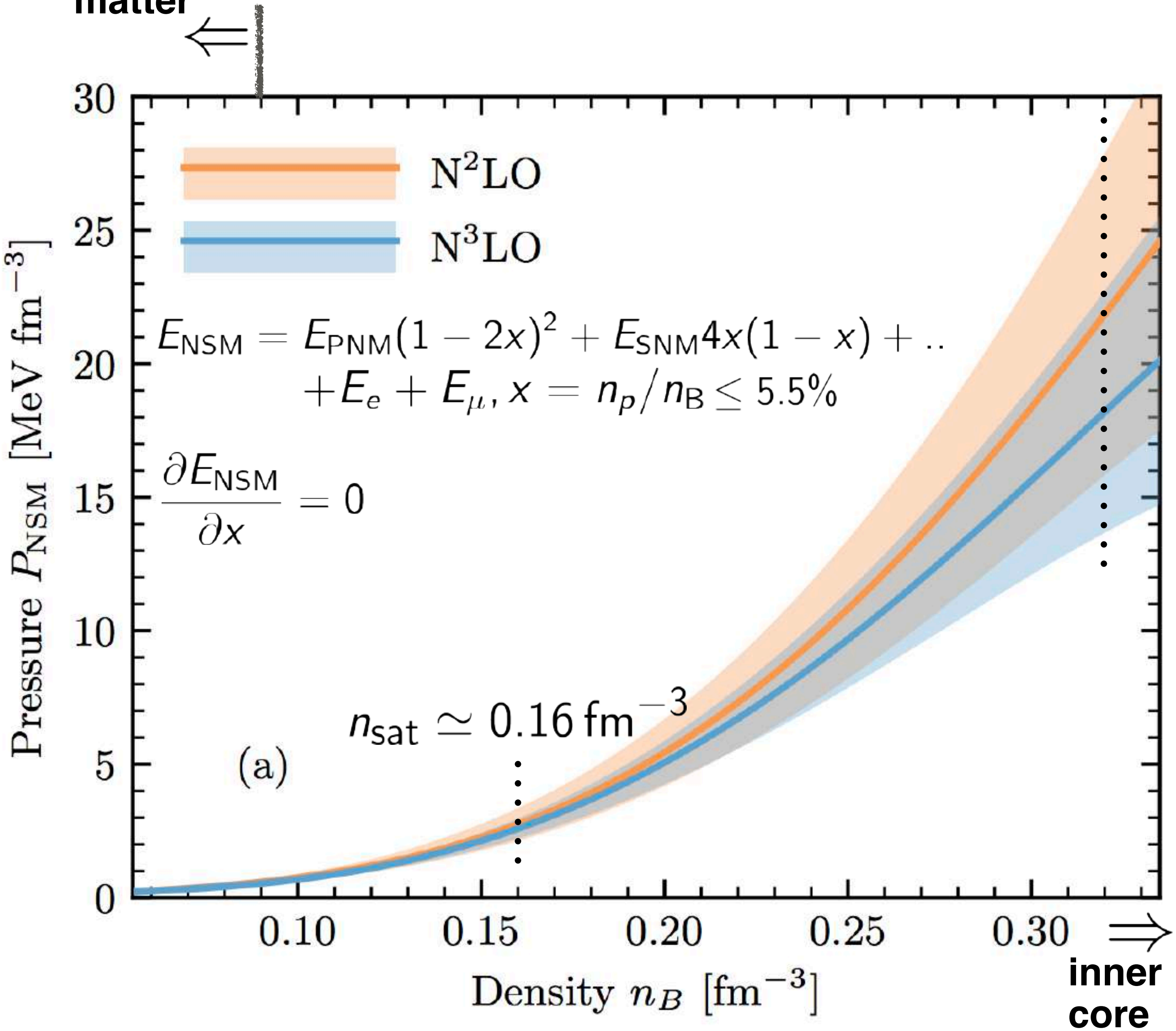


Lattimer & Lim (2012)

Nuclear physics input

Drischler, **SH**,
Lattimer, Prakash,
Reddy and Zhao,
arXiv:2009.06441

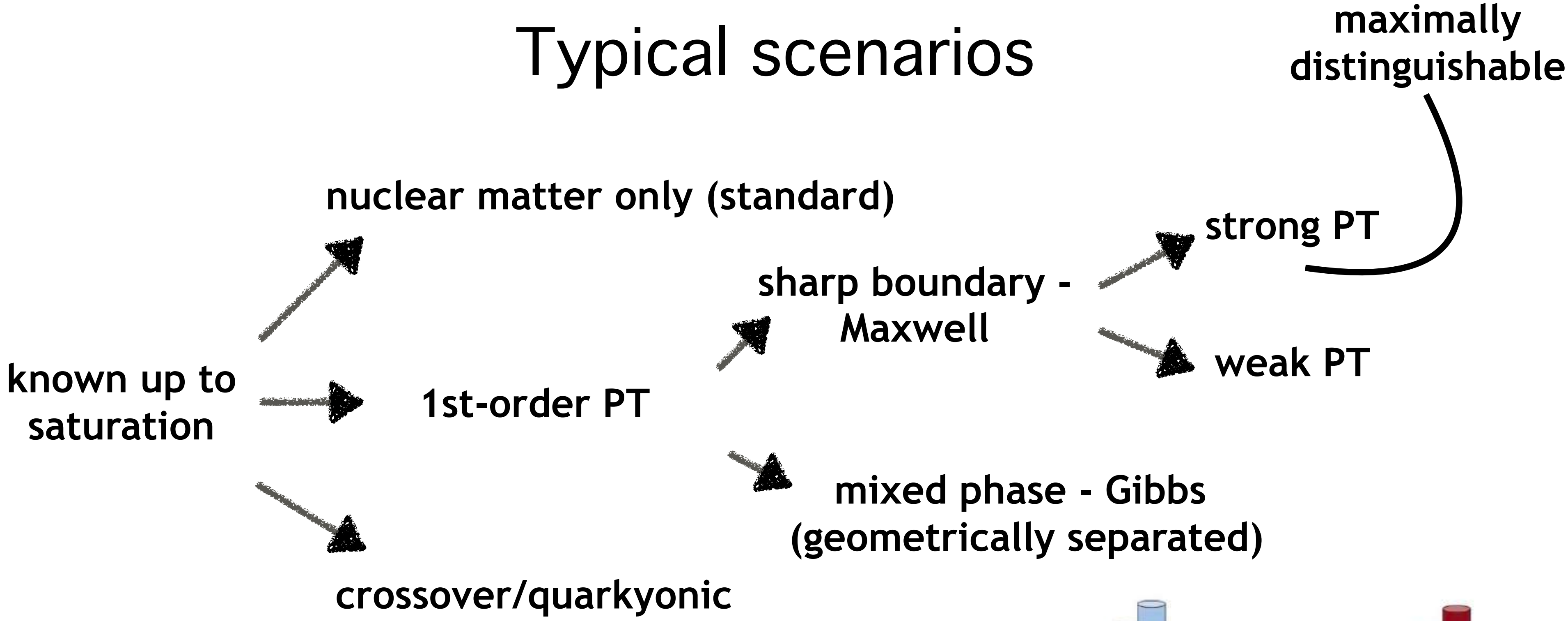
crustal matter ⇐



⇒ **inner core**

- 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

Typical scenarios



maximally distinguishable

nuclear matter only (standard)

strong PT

sharp boundary - Maxwell

weak PT

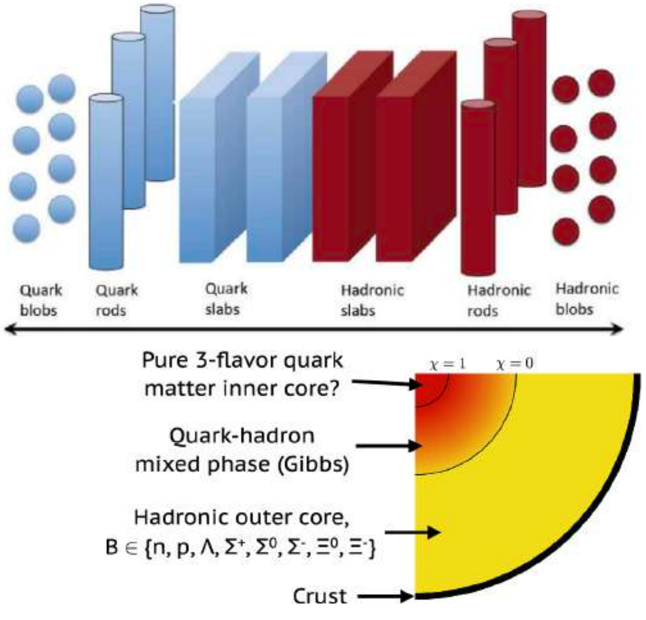
known up to saturation

1st-order PT

mixed phase - Gibbs (geometrically separated)

crossover/quarkyonic

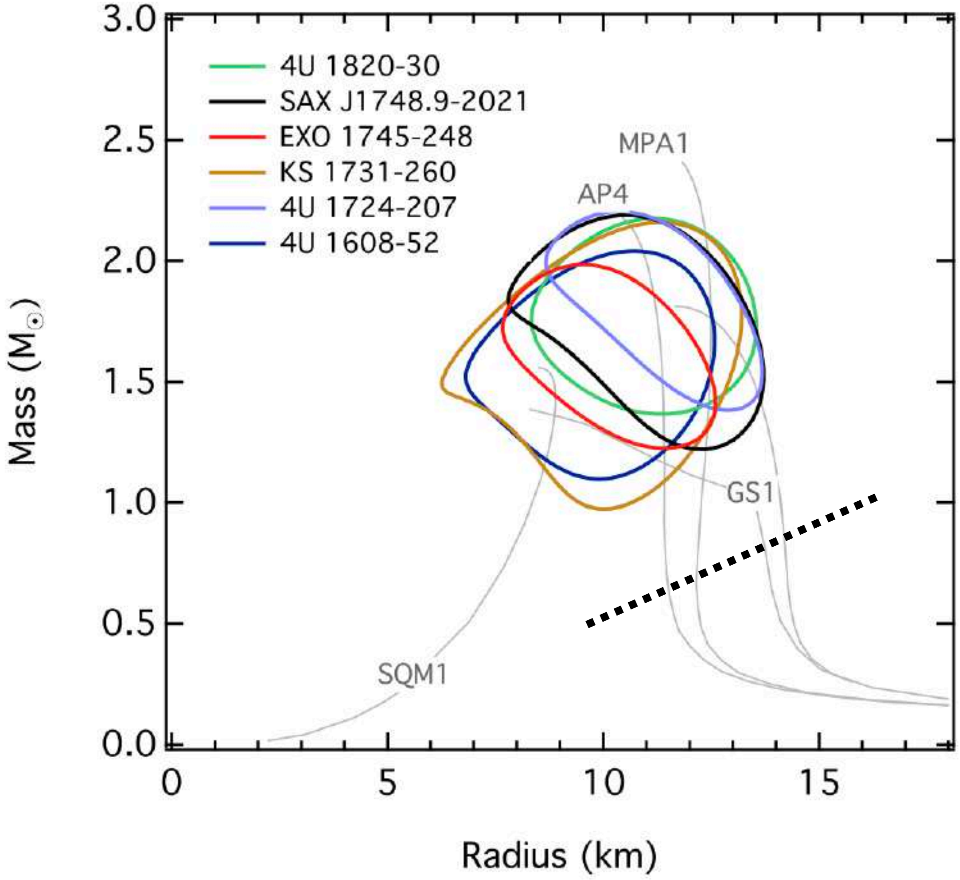
- masquerade problem: likely indistinguishable through observations that constrain M-R only
- smooth crossover: no more easily understood in terms of hadrons than in terms of quarks
- 1st-OPT: mixed phase (Gibbs) is favored if the hadron/quark surface tension is small



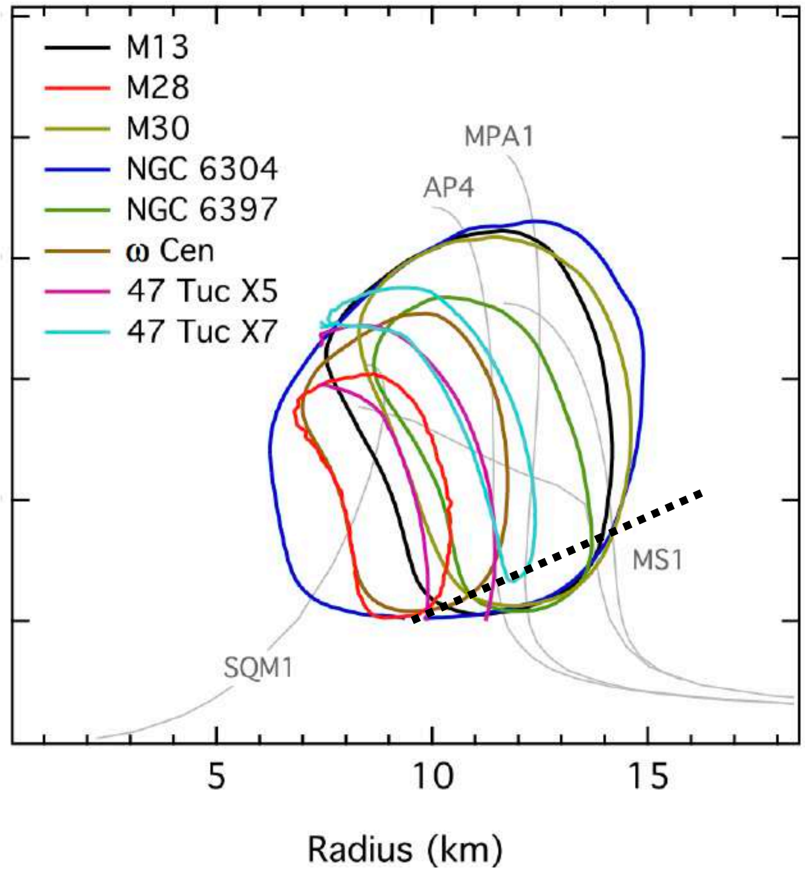
X-ray probes of NS radii

- conventional methods of radius estimates through surface photon emission detection suffer from large uncertainties

Ozel & Freire (2016);
Steiner et. al (2016)

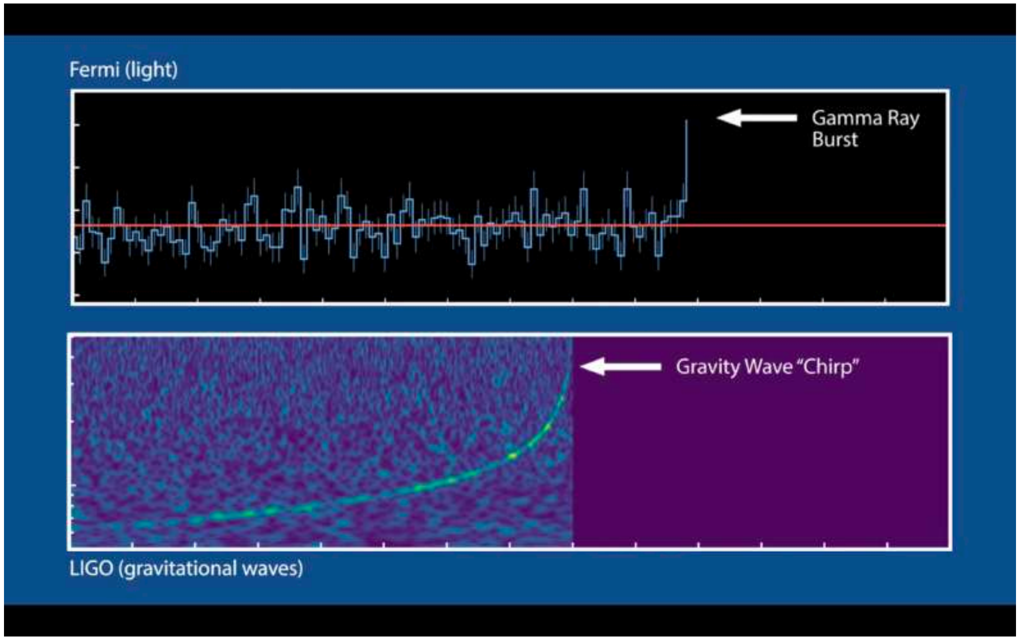


- photospheric radius expansions (PREs)



- quiescent low-mass x-ray binaries (QLMXBs)

First BNS merger detection



GW170817 that unveiled the multi-messenger era

- "hear" cosmic collisions between densest astronomical objects
- follow-up E&M signals; "see" e.g. evidence for nucleosynthesis

credit: Karan Jani/Georgia Tech

EoS affects GW emission during inspiral

$$Q_{ij} = -\lambda \varepsilon_{ij}$$

tidal effects

- tidal deformability

$$\Lambda \equiv \frac{\lambda}{M^5} \equiv \frac{2}{3} k_2 \left(\frac{Rc^2}{GM}\right)^5$$

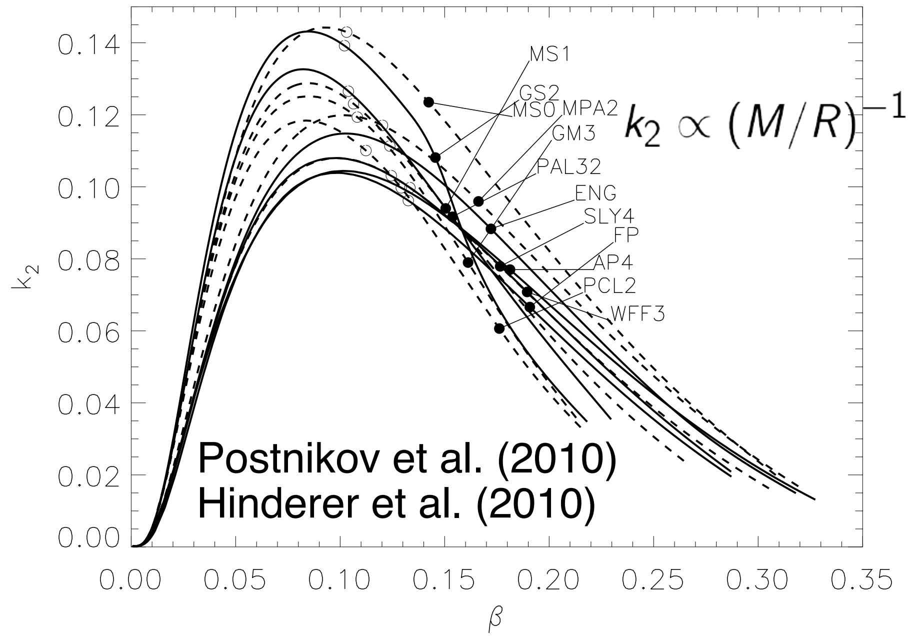
- compactness

$$k_2 \propto (M/R)^{-1}$$

$$\beta \equiv M/R$$

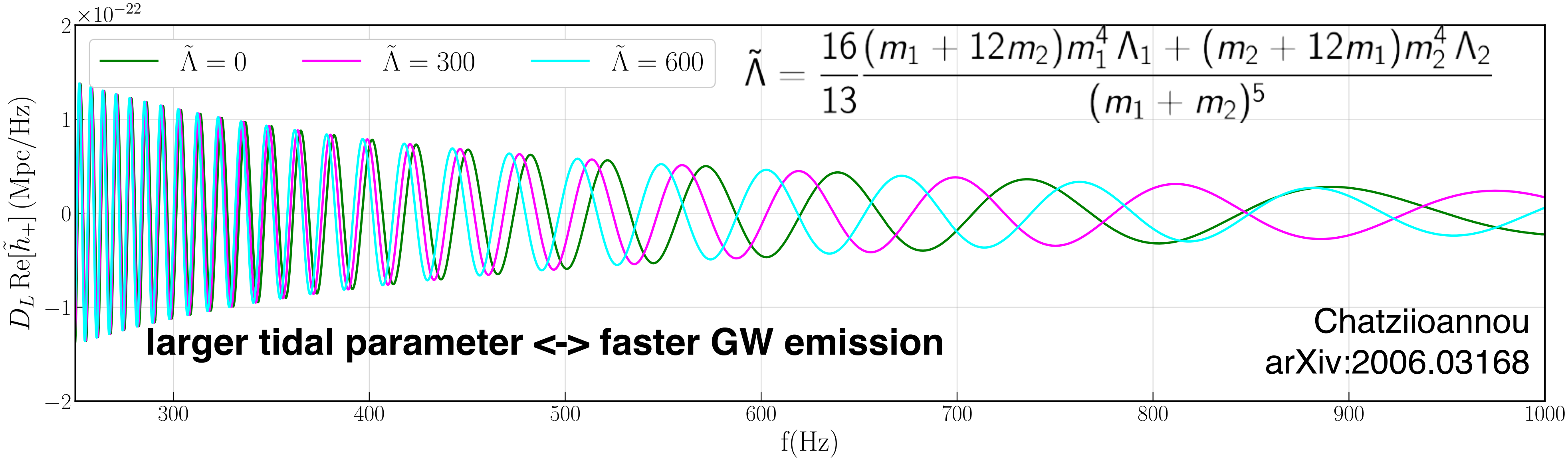
Impact on pre-merger GW signal

- tidal Love number depends on the EoS and the compactness M/R
- matter effects (NSs) leave imprints in the waveform - distinguish from point-particles (BHs)
- much cleaner systematics



$k_2 \propto (M/R)^{-1}$

Postnikov et al. (2010)
Hinderer et al. (2010)



$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12 m_2) m_1^4 \Lambda_1 + (m_2 + 12 m_1) m_2^4 \Lambda_2}{(m_1 + m_2)^5}$$

larger tidal parameter <-> faster GW emission

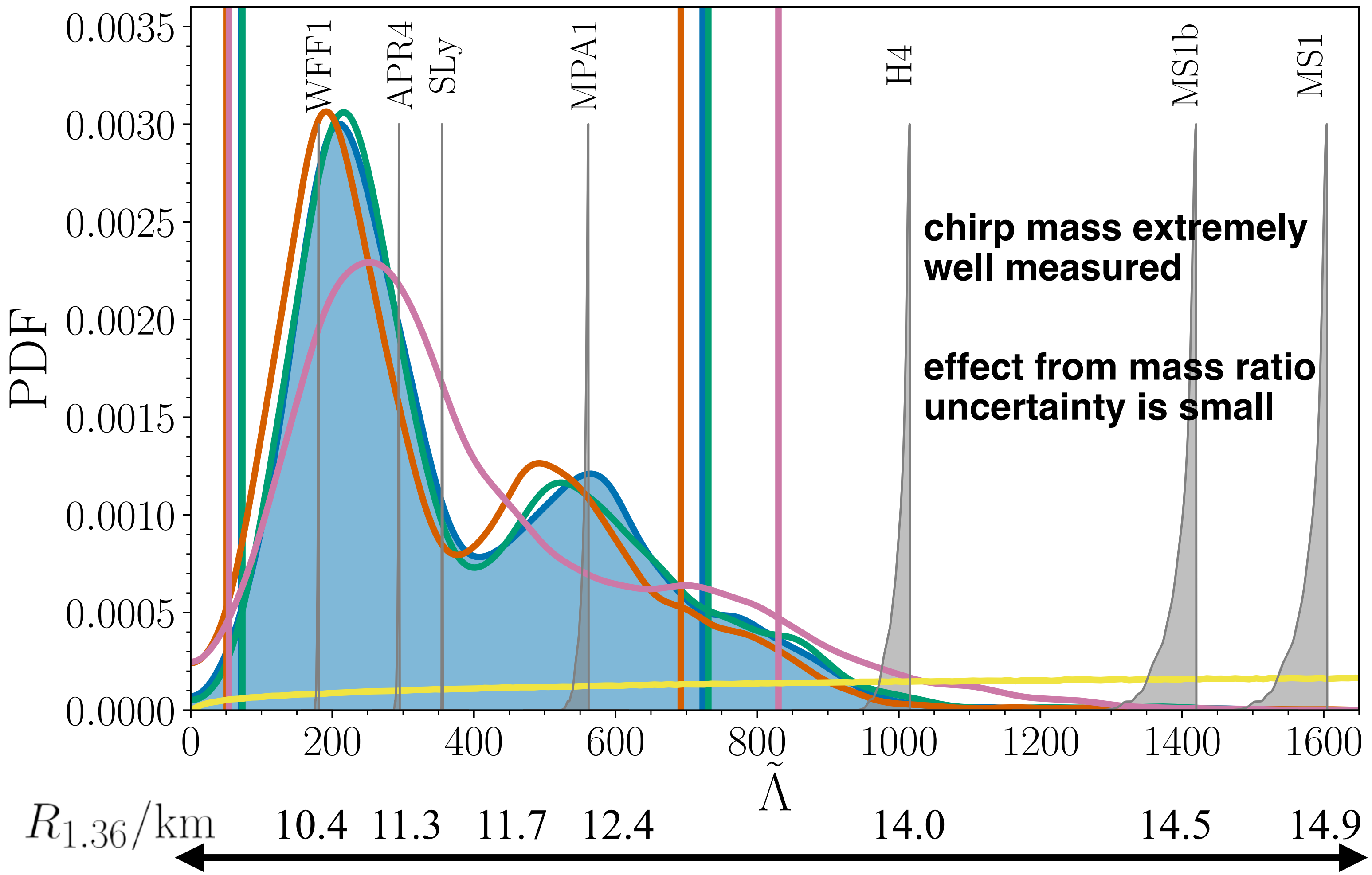
Chatziioannou
arXiv:2006.03168

Measuring NS radius with GWs

$$m_{\rm tot} = 2.73^{+0.04}_{-0.01} M_\odot$$

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

LVC collaboration, arXiv:1805.11579



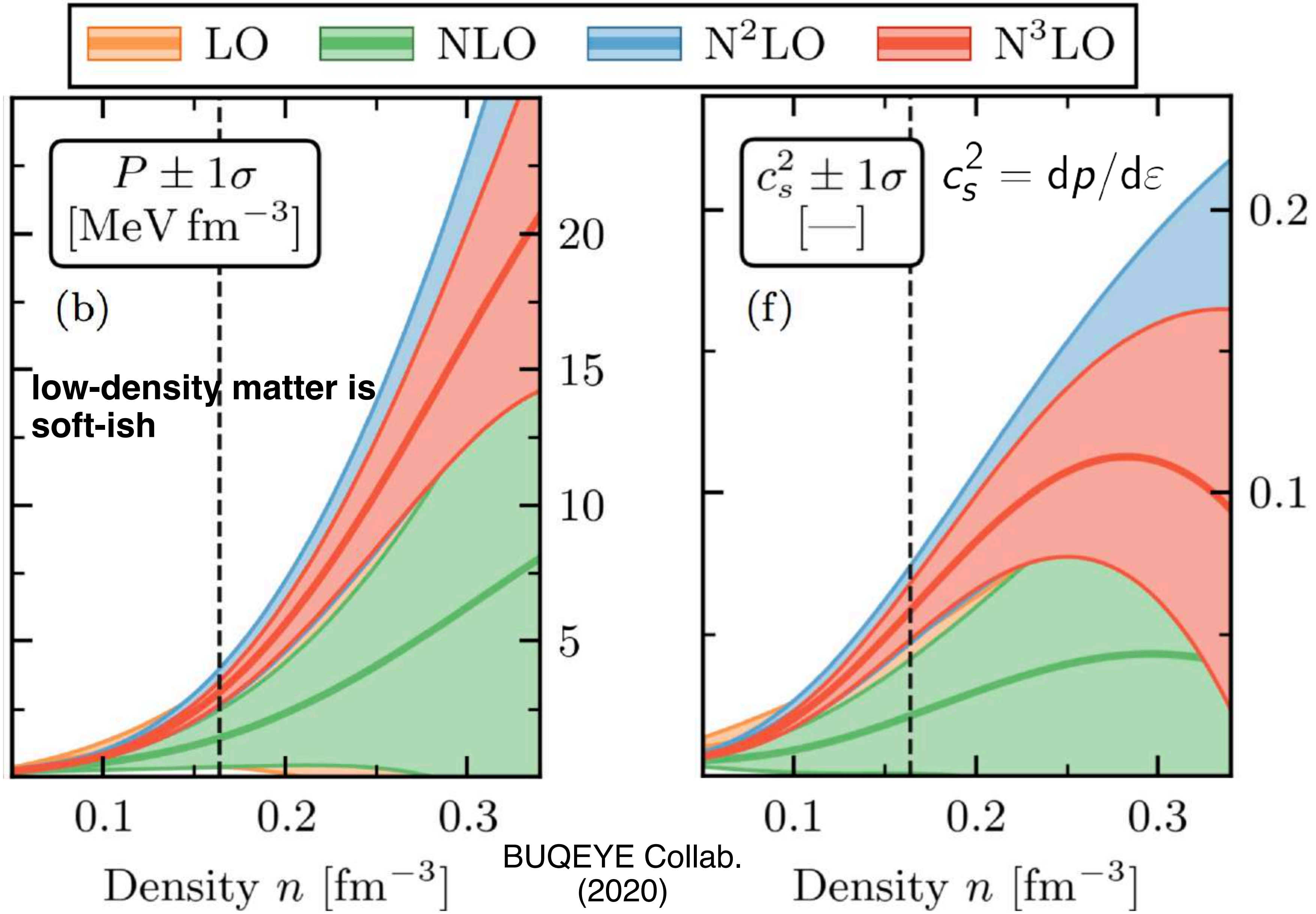
chirp mass extremely well measured

effect from mass ratio uncertainty is small

- **smaller R (favored) <13.6km**
- **larger R (disfavored)**

Pure neutron matter (PNM)

Drischler et al.
PRL 125, 202702
arXiv:2004.07232



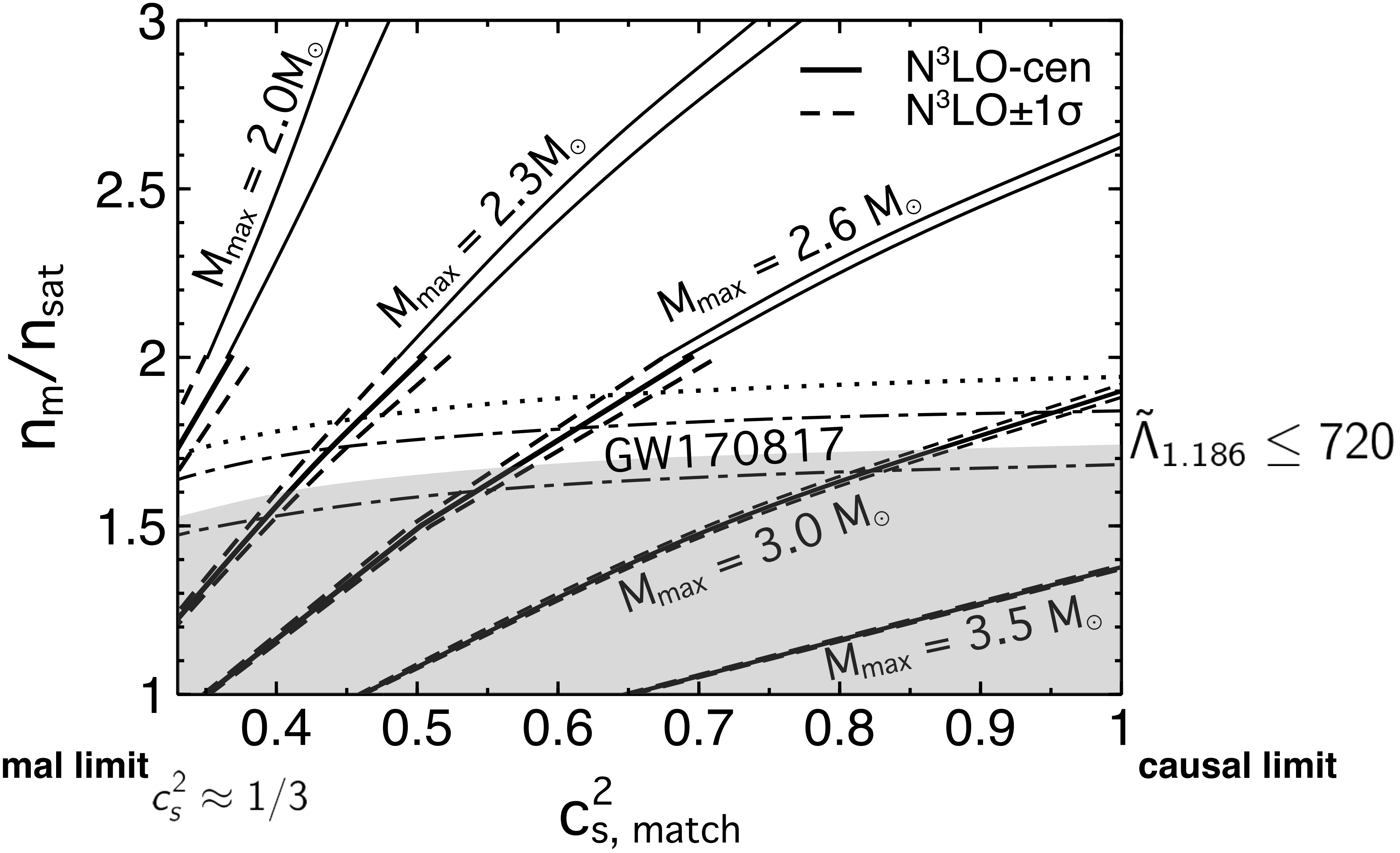
low-density matter is soft-ish

BUQEYE Collab.
(2020)

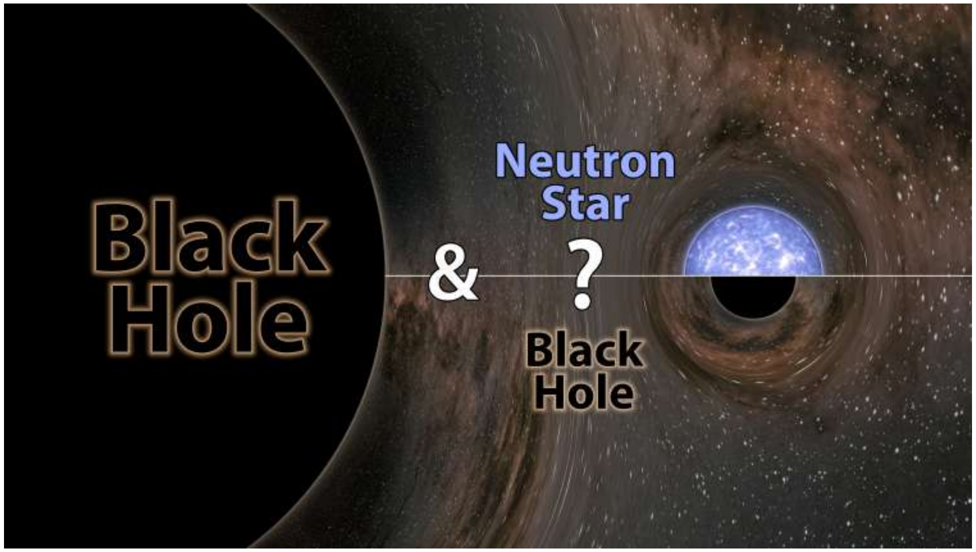
GW + heavy pulsars

Drischler, **SH**,
Lattimer, Prakash,
Reddy and Zhao,
arXiv:2009.06441

- sound speed in the **core** and **when** rapid stiffening in the EoS begins



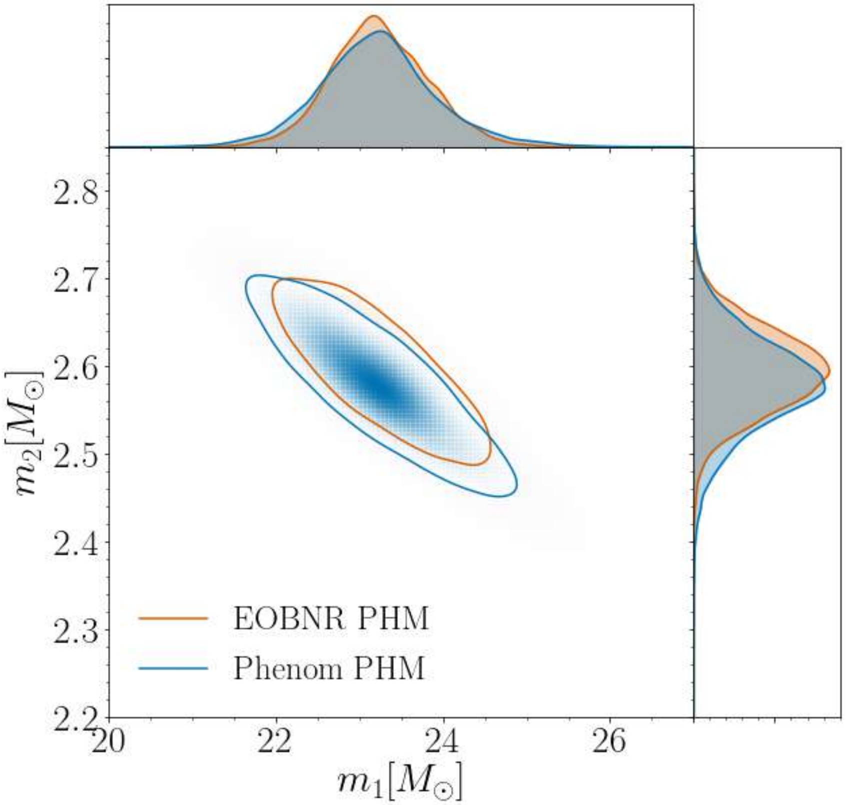
GW190814



- extremely loud event produced by the inspiral and merger of two compact objects -- one, a black hole, and the other of **undetermined** nature
- the mass measured for the lighter compact object makes it either the lightest black hole or the heaviest neutron star ever discovered

the most asymmetric system observed

$m_1 = 23.2^{+1.1}_{-1.0}\,\mathrm{M}_\odot \quad m_2 = 2.59^{+0.08}_{-0.09}\,\mathrm{M}_\odot$



LVC collaboration, arXiv:2006.12611

Sound speed in the core

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

how fast pressure rises with energy density

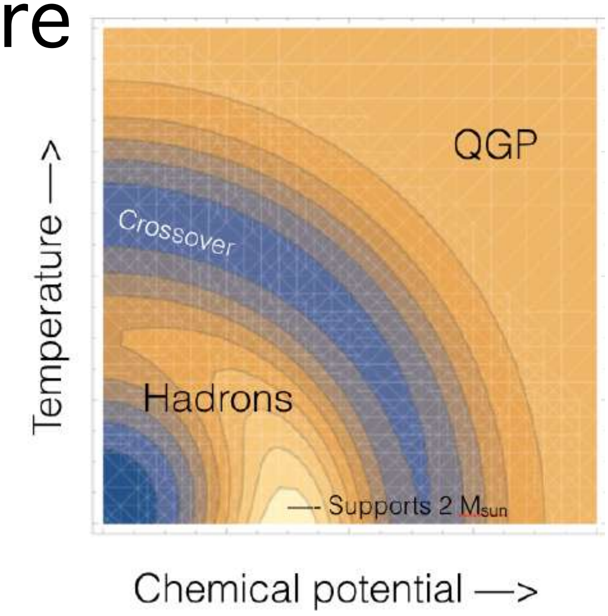
Possible behavior in neutron star interiors

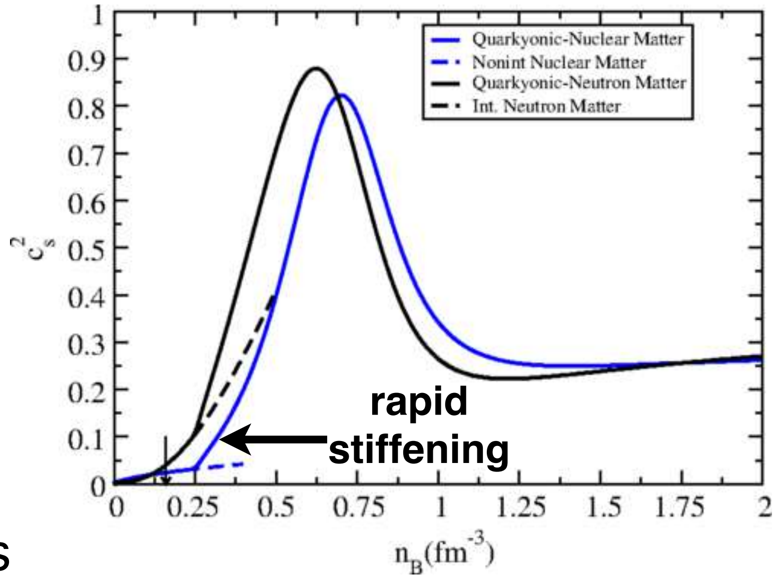
- minimal scenario of normal nuclear matter: (smoothly) continuous function of pressure
- first-order phase transition scenario: finite energy density discontinuity induces sudden softening near the phase boundary
- crossover scenario/quarkyonic matter

Limits

- 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)

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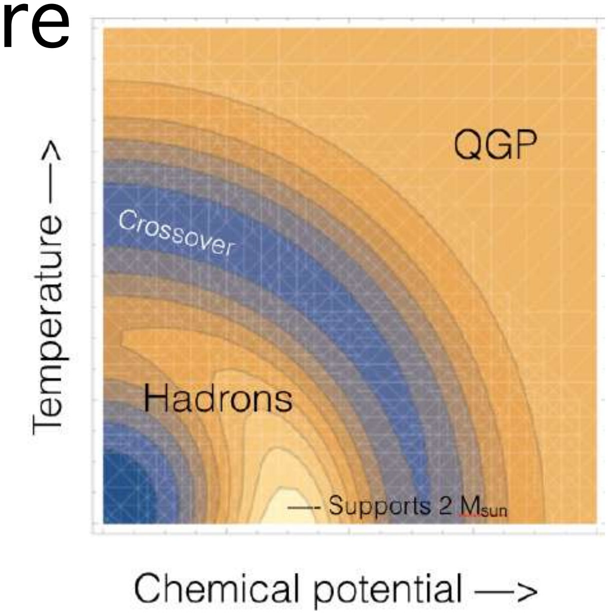
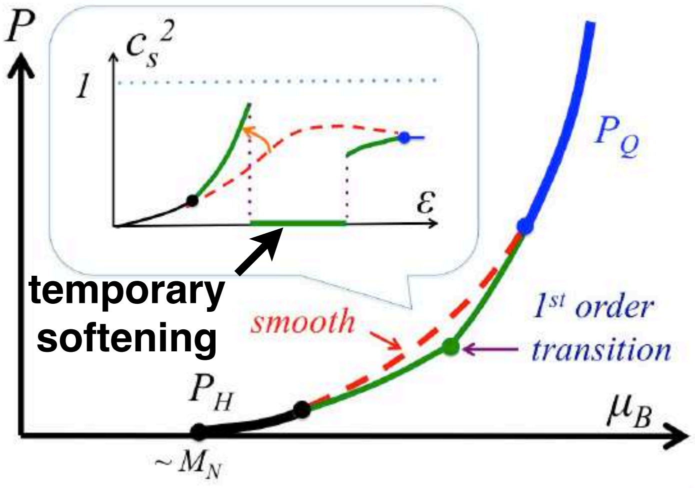


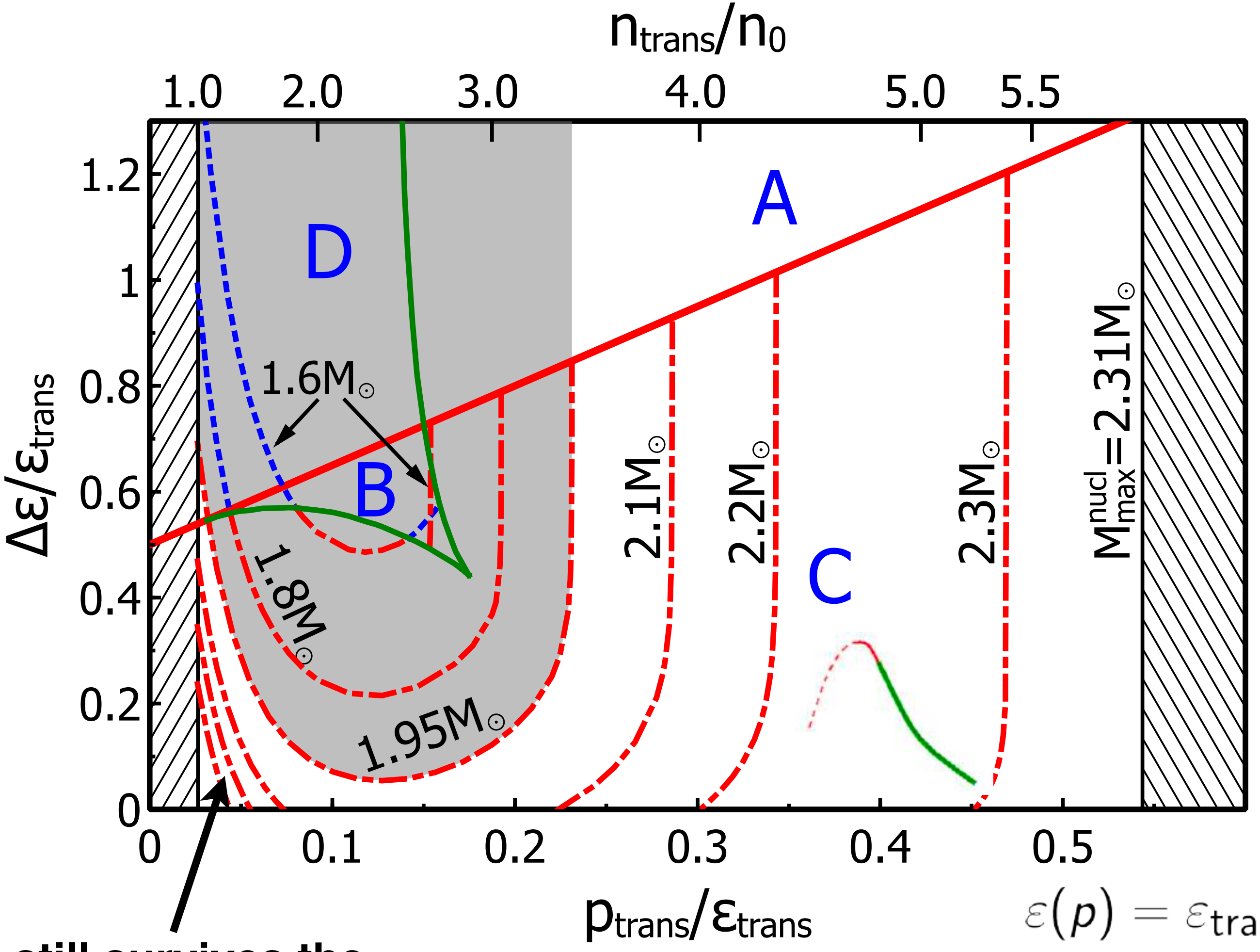


Baym et al. arXiv:1707.04966
Rept. Prog. Phys. 81, 056902

Alford & **SH**
arXiv:1508.01261

Constraints from max. mass

DBHF (stiff) NM, $c^2_{QM} = 1/3$



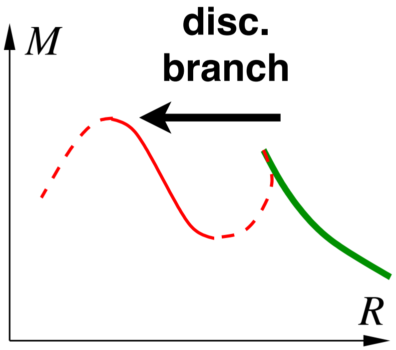
still survives the conformal limit

- with weakly interacting quarks, very limited to reach two solar masses
- high transition density scenario: resembles no PT; short extension
- low transition density scenario: no twin stars

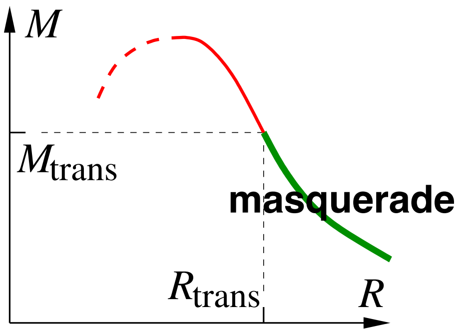
Generic ansartz

$$\varepsilon(p) = \varepsilon_{\rm trans} + \Delta\varepsilon + c_{\rm QM}^{-2}(p - p_{\rm trans})$$

e.g. a population of BNS events



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

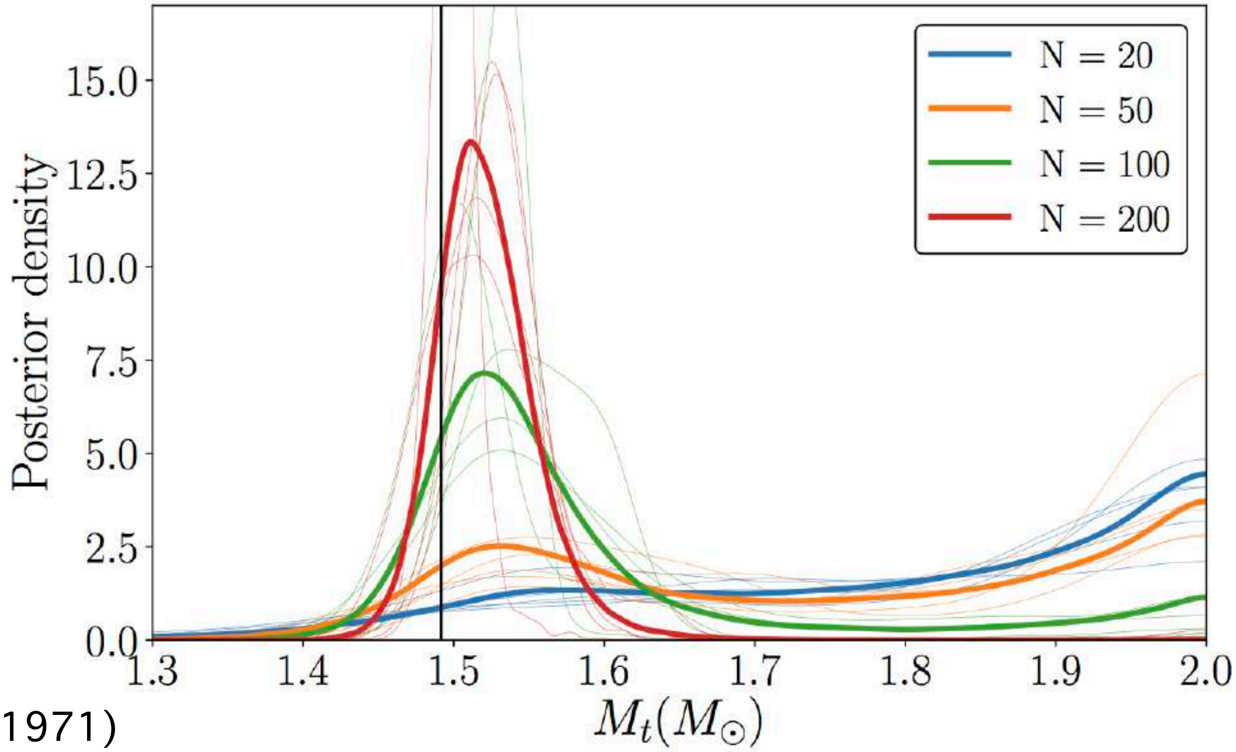


critical strength to trigger an instability

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

Seidov (1971)

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



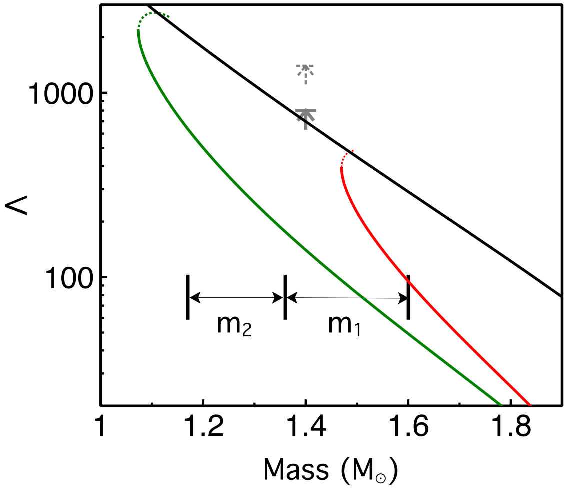
- might identify third-family stars [strong 1st-OPT] with **pre-merger** GWs
- requires multiple **(N~50-100)** future detections to separate different families: NS-NS, NS-HS, HS-HS mergers

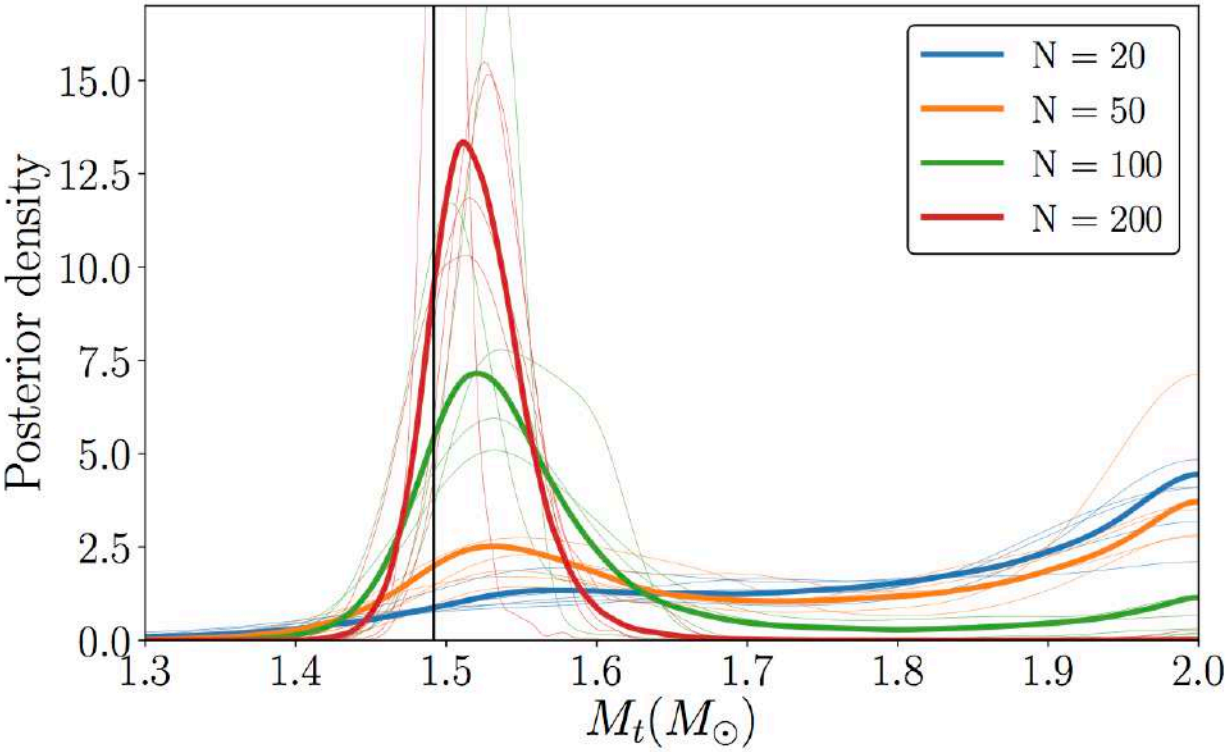
e.g. a population of BNS events

$$\Lambda \equiv \frac{\lambda}{M^5} \equiv \frac{2}{3}k_2\left(\frac{Rc^2}{GM}\right)^5$$

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

DBHF + CSS (c^2_{QM}=1)





most populated if the normal branch **> 13 km** and the high density matter is still **strongly interacting** $c_s^2 \gtrsim 0.4$

- might identify third-family stars [strong 1st-OPT] with **pre-merger** GWs
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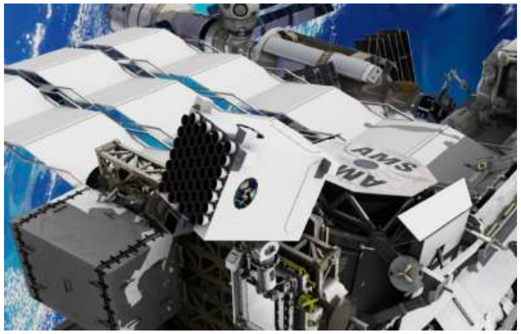
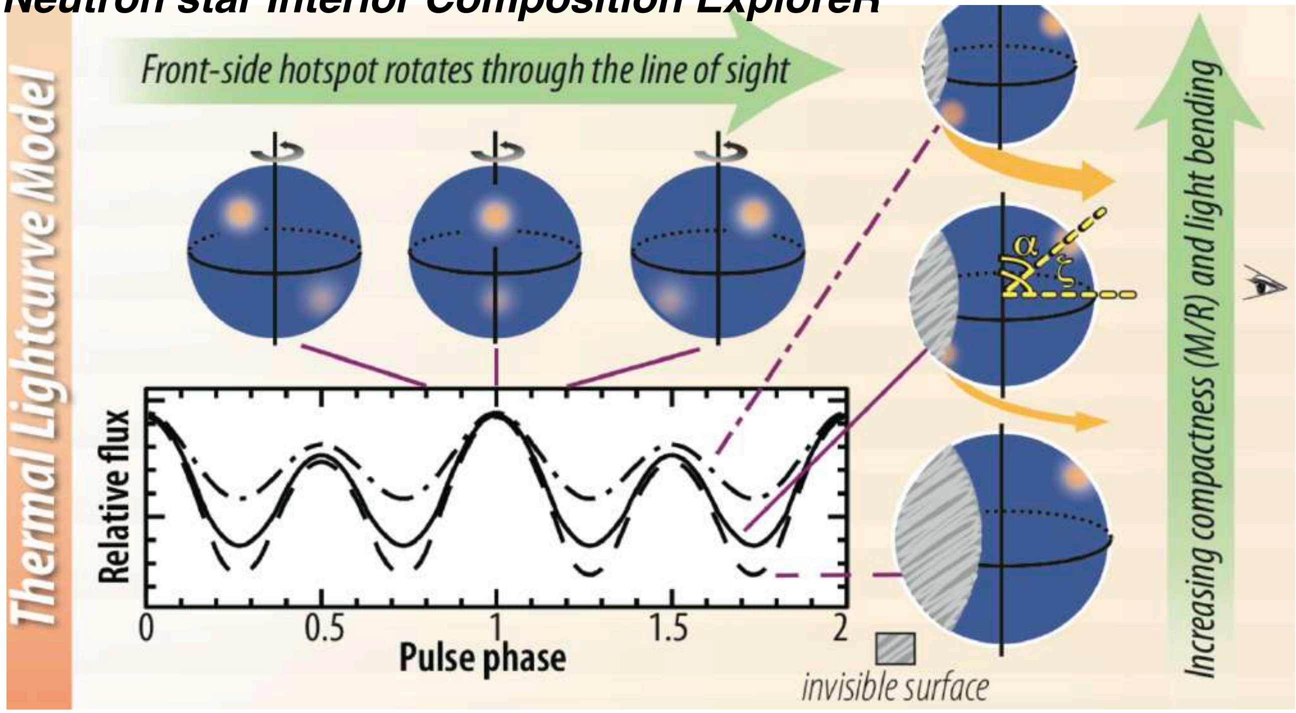
NS radii from hotspots

©NASA

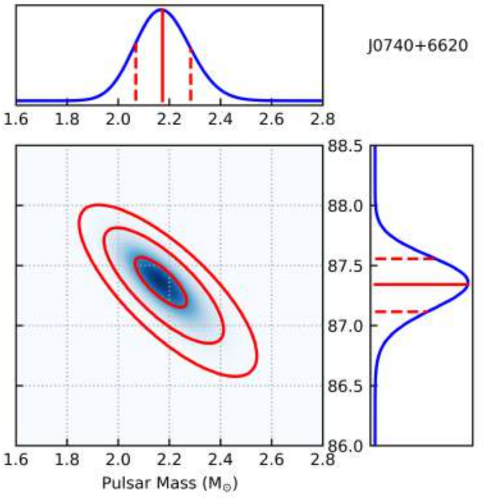


- light-curve modeling of x-ray pulse profiles that are sensitive to the stellar compactness M/R

Neutron star Interior Composition ExploreR



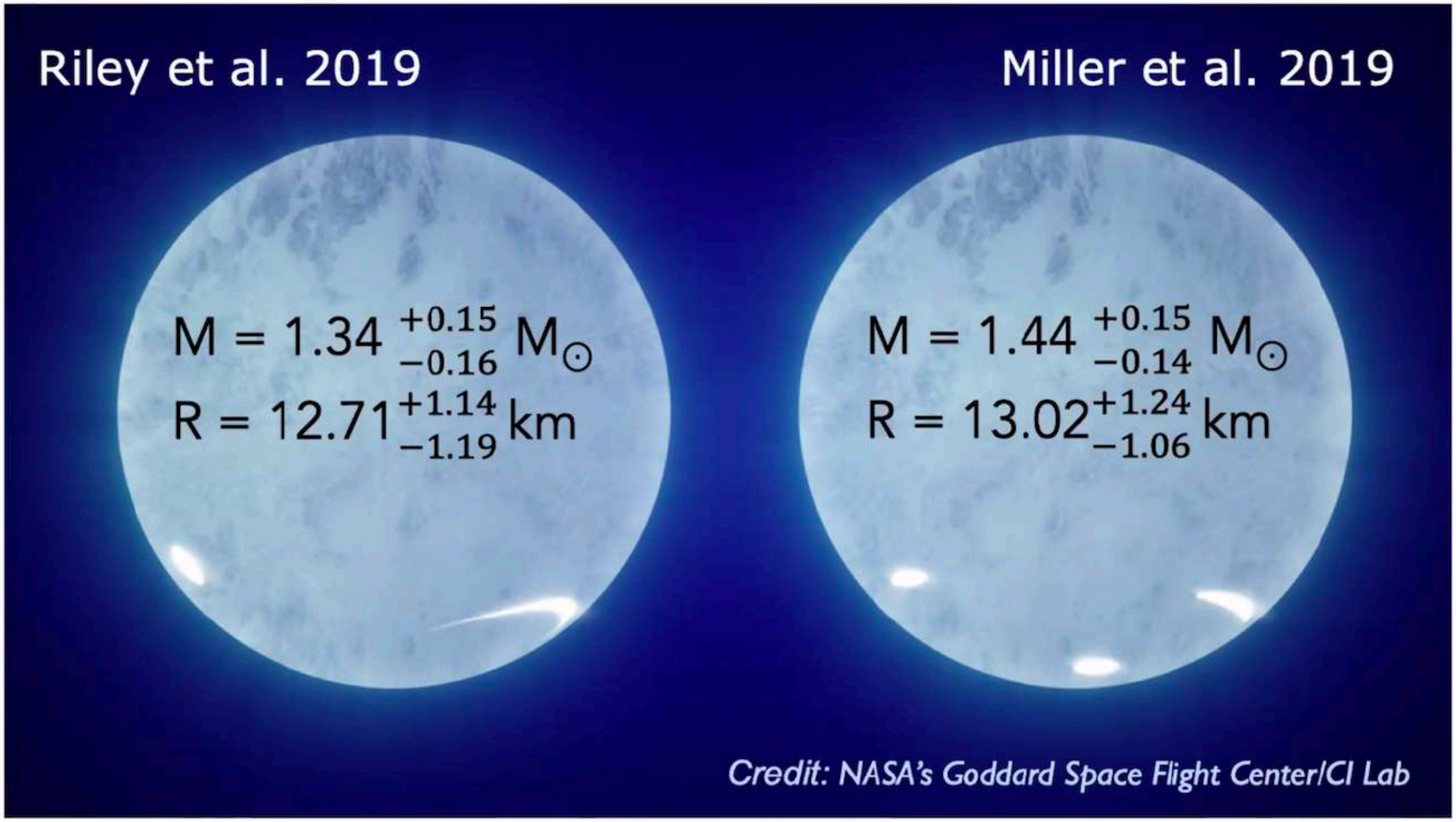
PSR J0740+6620



Cromartie et al.
Nature Astronomy (2019)

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

Independent NICER team analyses



Riley et al. 2019

$$M = 1.34^{+0.15}_{-0.16}\ M_\odot$$

$$R = 12.71^{+1.14}_{-1.19}\ \text{km}$$

Miller et al. 2019

$$M = 1.44^{+0.15}_{-0.14}\ M_\odot$$

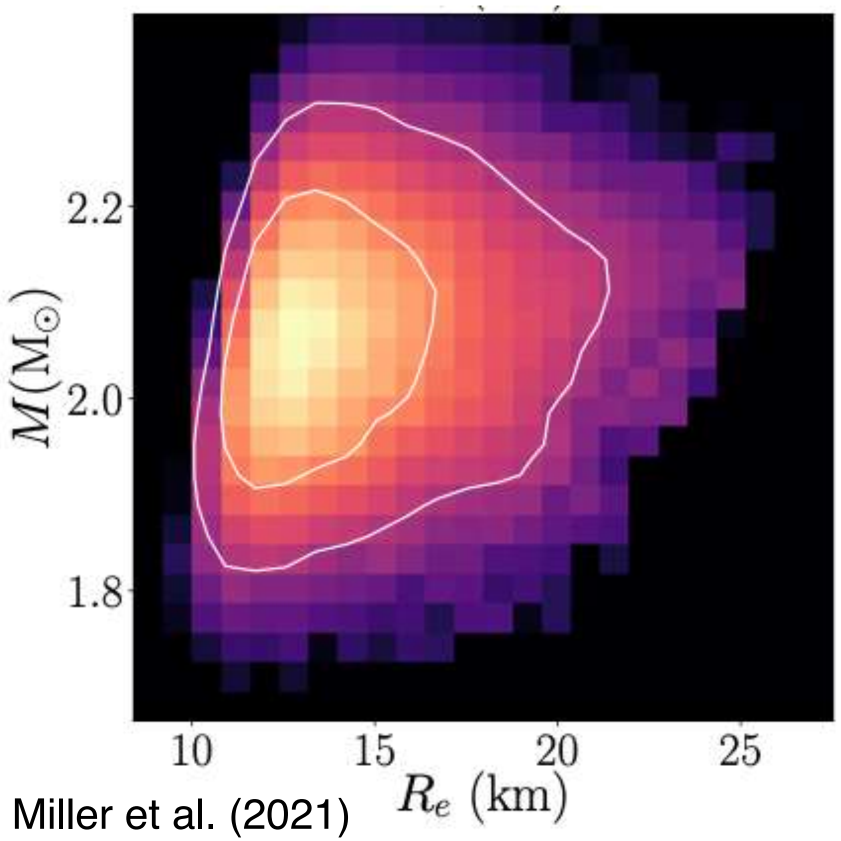
$$R = 13.02^{+1.24}_{-1.06}\ \text{km}$$

Credit: NASA's Goddard Space Flight Center/CI Lab

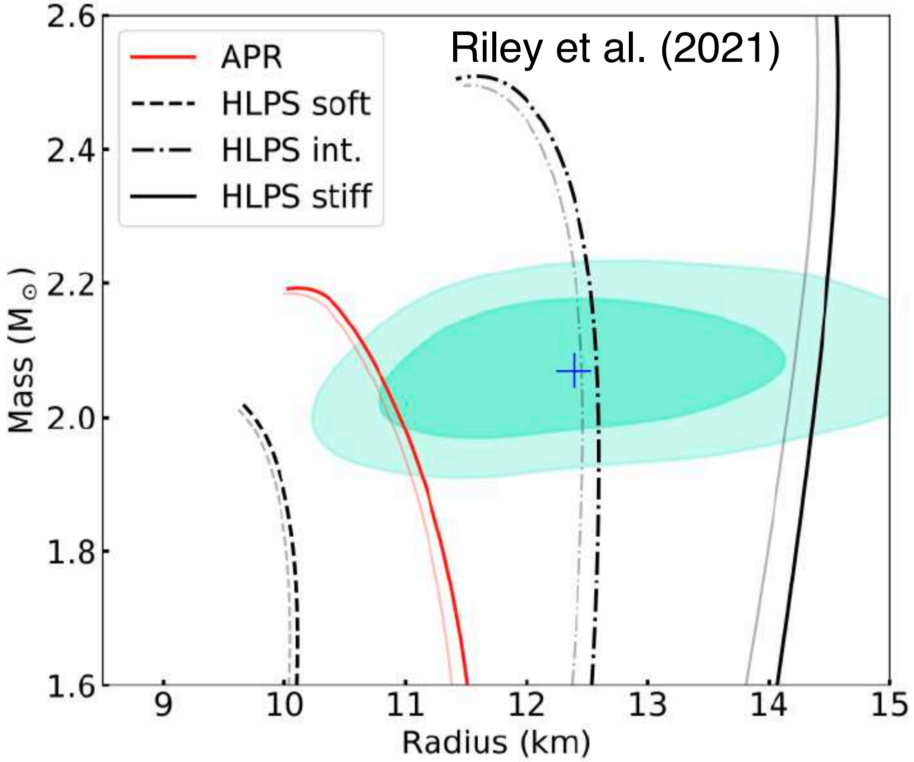
PSR J0030+0451

Results published together in an ApJ Letters Focus Issue in December 2019

NS radii from hotspots



Miller et al. (2021)



Riley et al. (2021)

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

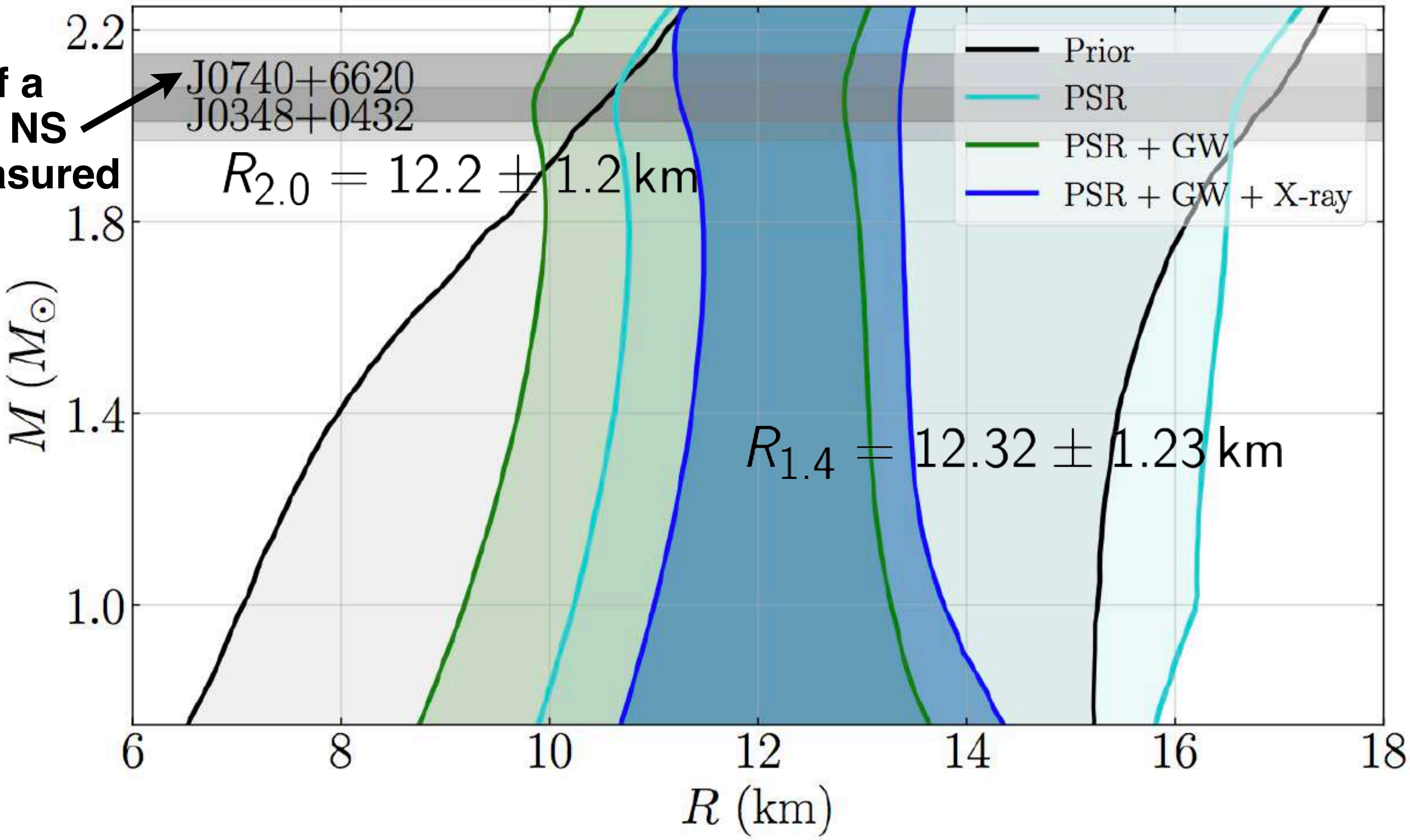
previously: PSR J0030+0451 $\sim 1.4\,\mathrm{M}_\odot$

- analyses of waveforms produced by hotspots of rotation-powered pulsars
- tend to favor relatively stiffer EoS at intermediate ($2 \sim 3 n_\mathrm{sat}$) densities

Multimessenger constraints

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

radius of a massive NS first measured

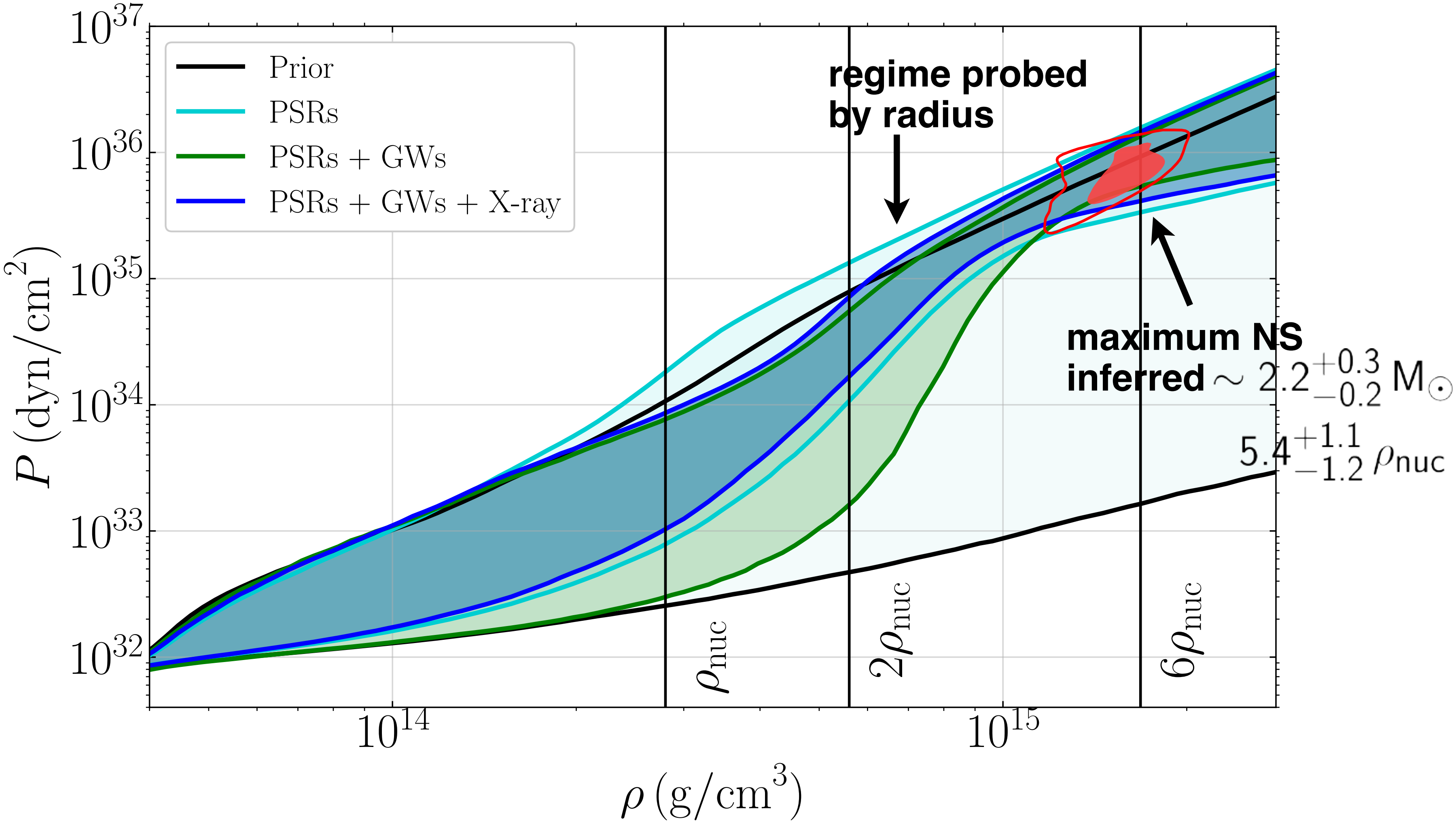


$R_{2.0} = 12.2 \pm 1.2\,\text{km}$

$R_{1.4} = 12.32 \pm 1.23\,\text{km}$

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

Pressure vs. density



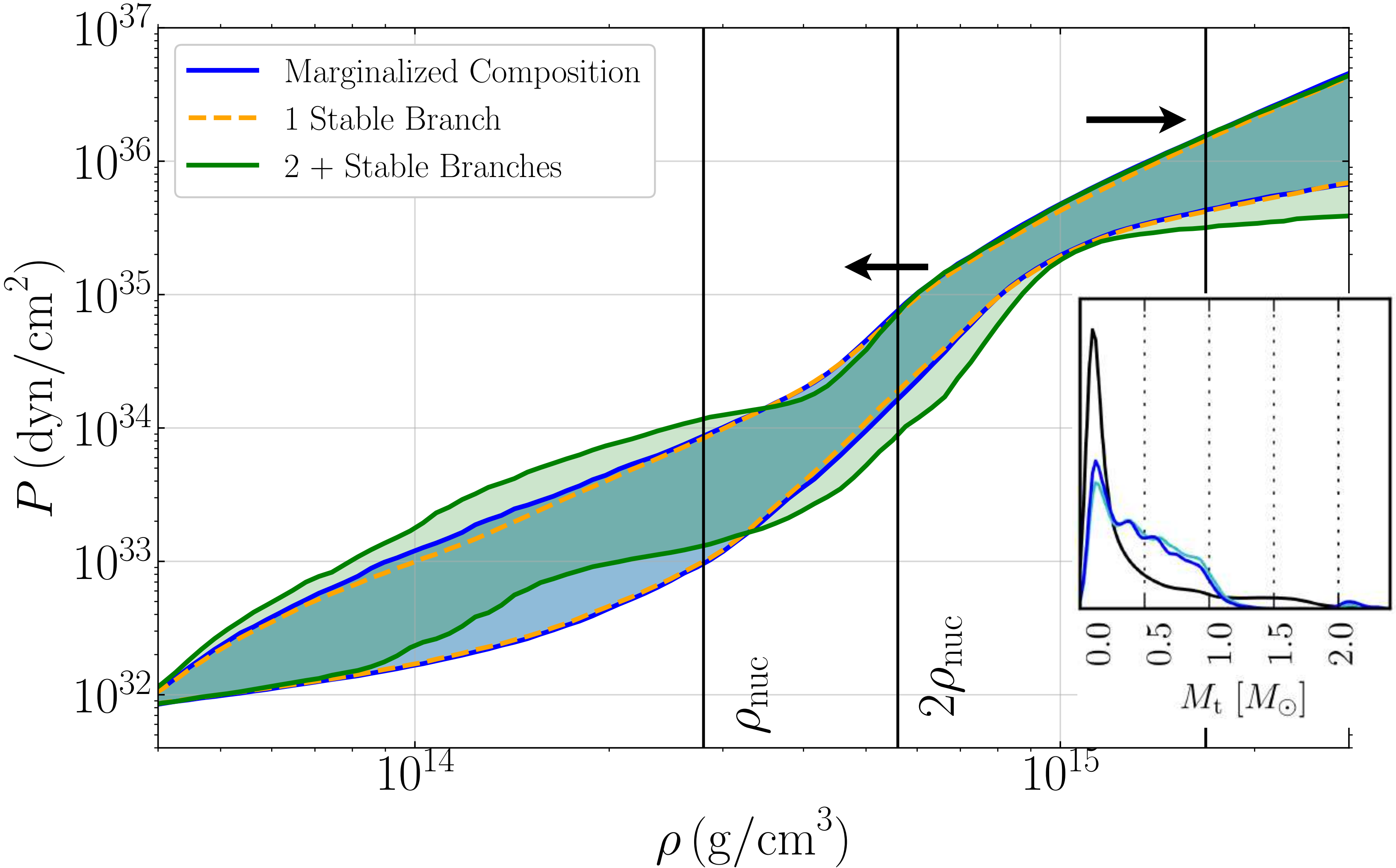
regime probed by radius

maximum NS inferred $\sim 2.2^{+0.3}_{-0.2}\,\mathrm{M}_\odot$

$5.4^{+1.1}_{-1.2}\,\rho_{\mathrm{nuc}}$

- tightening the pressure constraint at intermediate densities
- (90% symmetric credible intervals) best compatibility with data

Single branch vs. multiple branches



driven by radius

expected from max. mass

- full posterior is dominated by EoSs with a single stable branch
- onset for the unstable branch (extra softening) pushed to two ends

Summary

- **multimessenger constraints point to NS radii around 12.5 km \pm 1.5 km**
- **most extreme phase transitions that lead to drastic >2-3km reduction seem disfavored; onset restricted to either low or high densities**
- **milder PTs or smooth crossovers are fairly consistent with data; requires high sound speed in the inner core**
- **pressure or stiffness in nuclear EoS up to twice saturation density is crucial for interpretations of high-density behavior: the golden window**

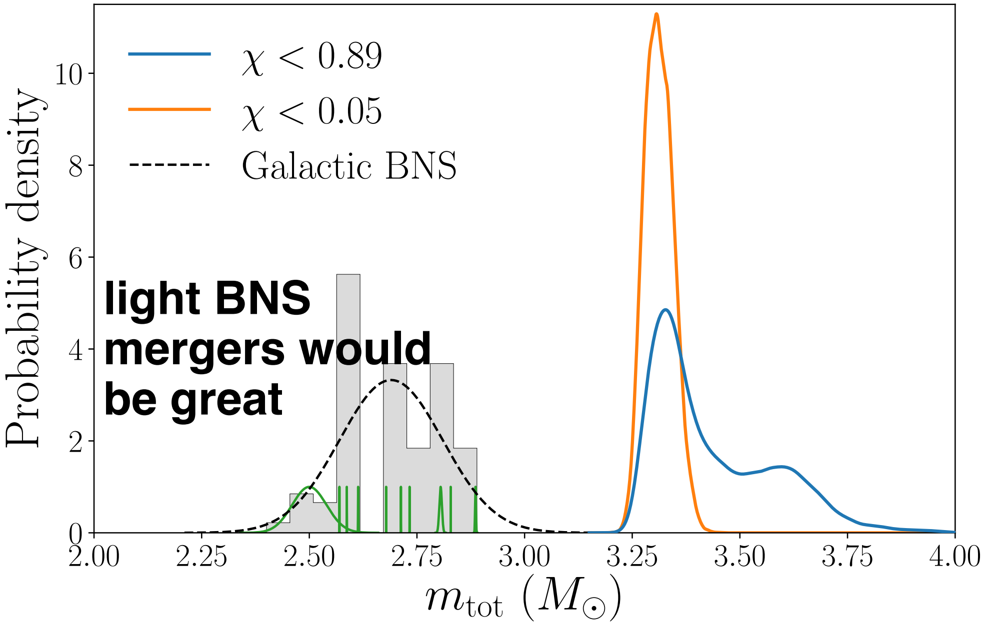
Looking forward

hunting for surprises..

GW190425

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

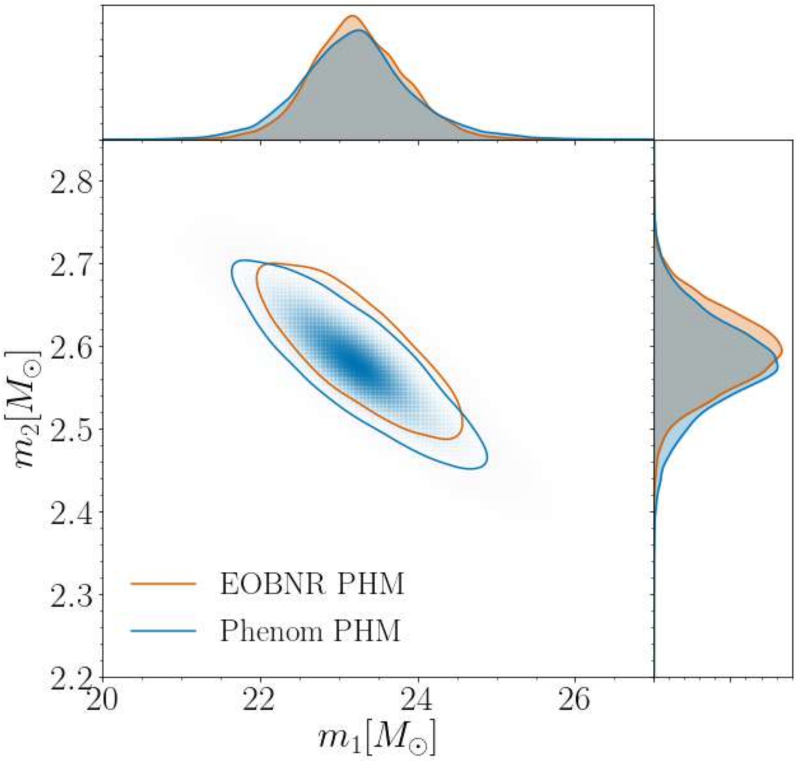
LVC collaboration
arXiv:2001.01761



light BNS mergers would be great

see events of GWTC-2: arXiv:2010.14527

LVC collaboration
arXiv:2006.12611

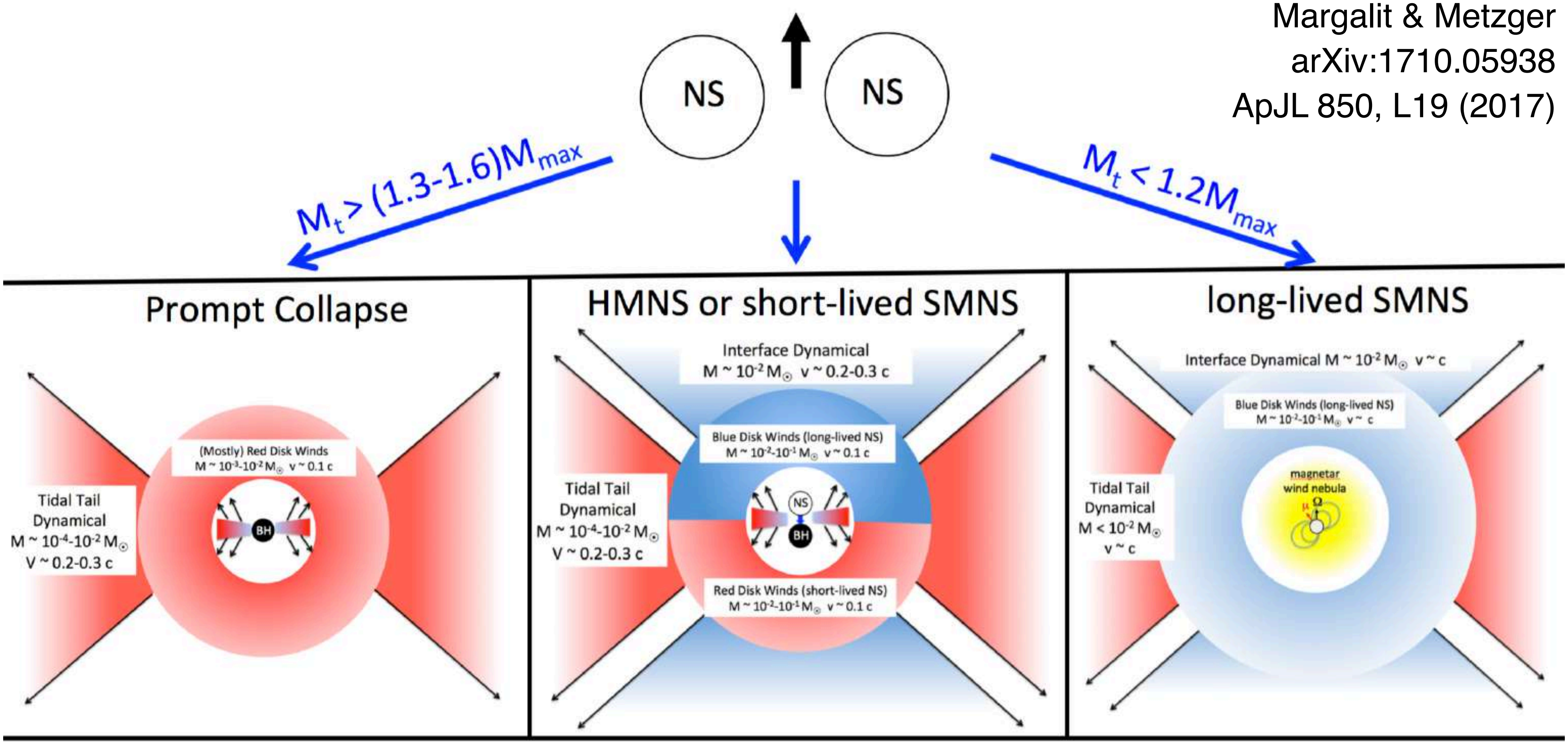


GW190814

more mass-gap objects?

- component of ambiguous nature
- most asymmetric system observed

Fate of merger remnant

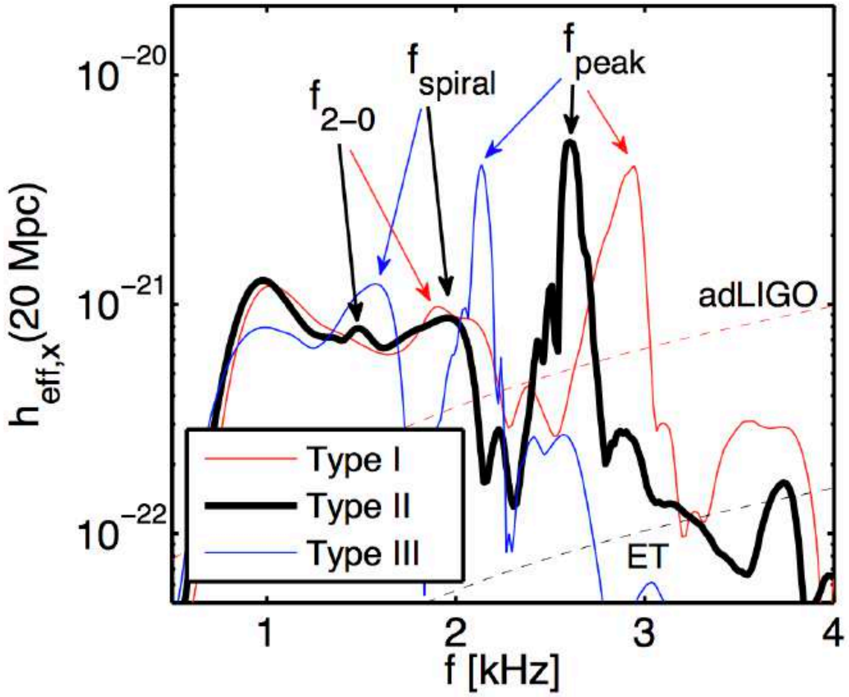


Margalit & Metzger
arXiv:1710.05938
ApJL 850, L19 (2017)

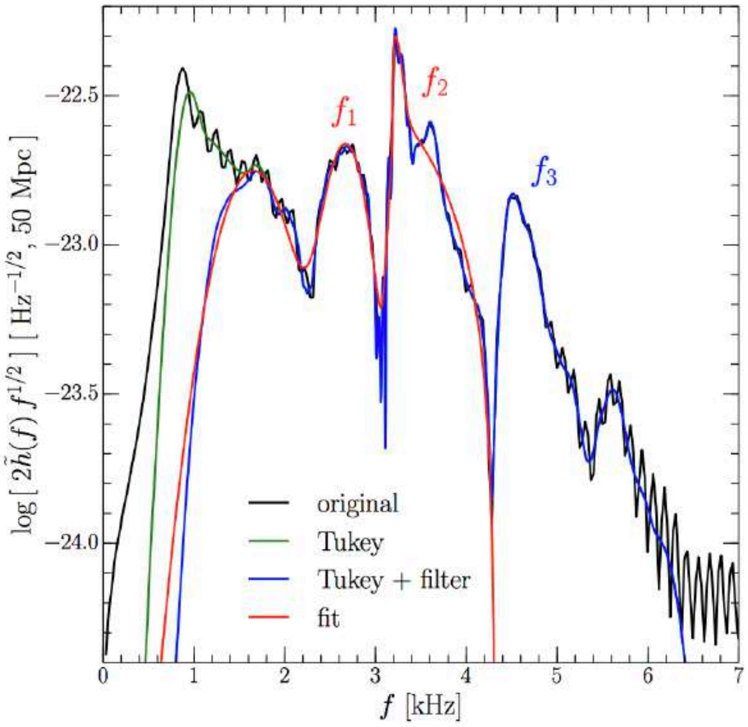
- GW + EM constraints from 170817 seem to favor Mmax<2.16~2.3 solar masses   Ruiz et al. (2018), Rezzolla et al. (2018), Shibata et al. (2019)
- radius >10.68 km to prevent prompt collapse   Bauswein et al. (2017)

Post-merger dynamics

Bauswein & Stergioulas, arXiv:1502.03176



Takami et al., arXiv:1412.3240

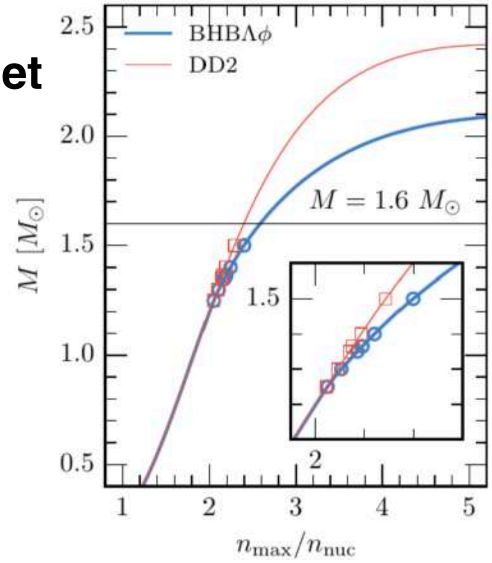


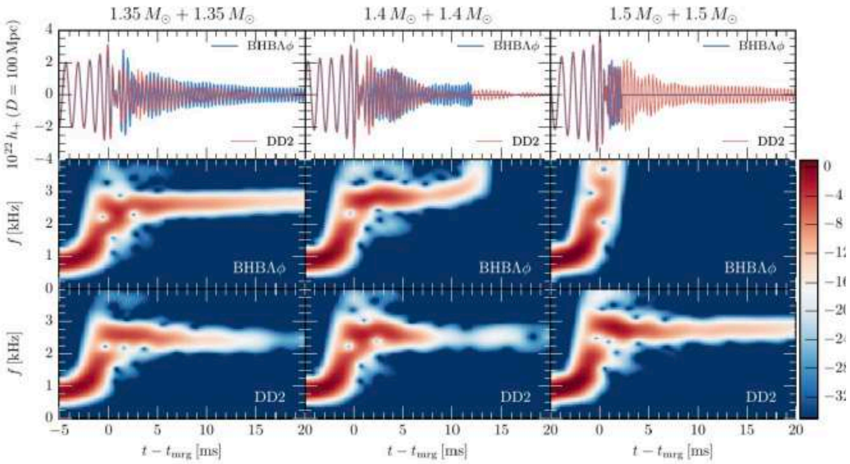
- complicated spectra of excited modes depend on the EoS
- location of the dominant peak strongly correlated with NS radii
- within reach of next generation GW detectors (~10 times more sensitive)

e.g. softening effects on post-merger GW

hyperon onset

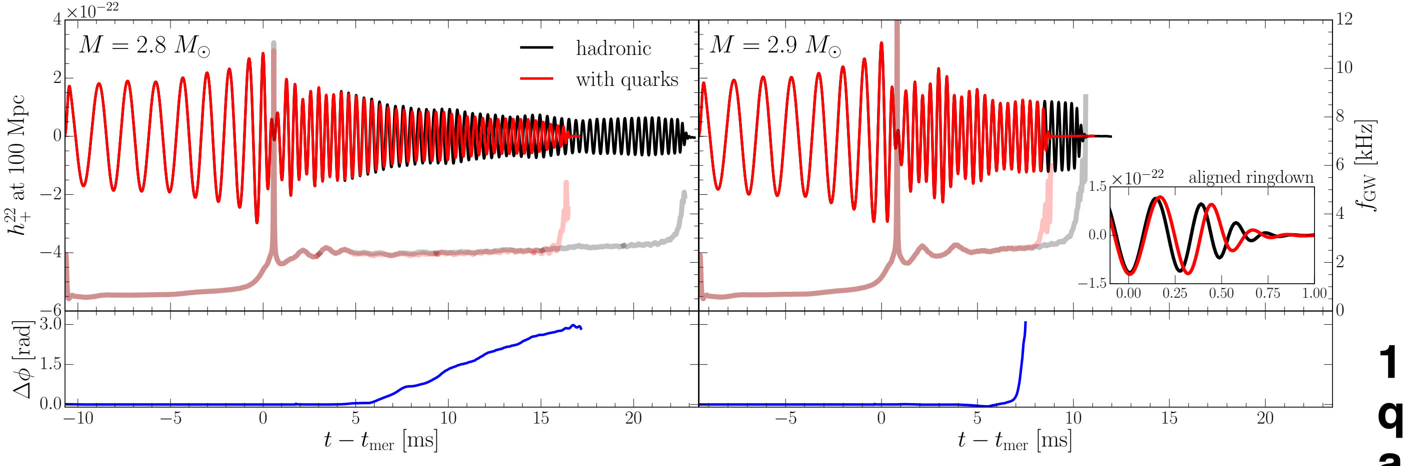
- more compact remnant (higher central density)
- earlier collapse; higher frequency





Most et al. arXiv:1807.03684
PRL 122, 061101 (2019)

Radice et al. arXiv:1612.06429
ApJL 842, L10 (2017)

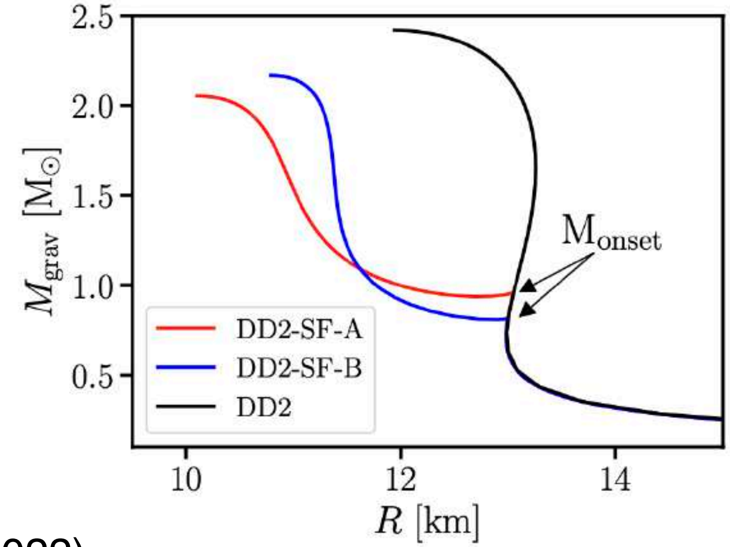


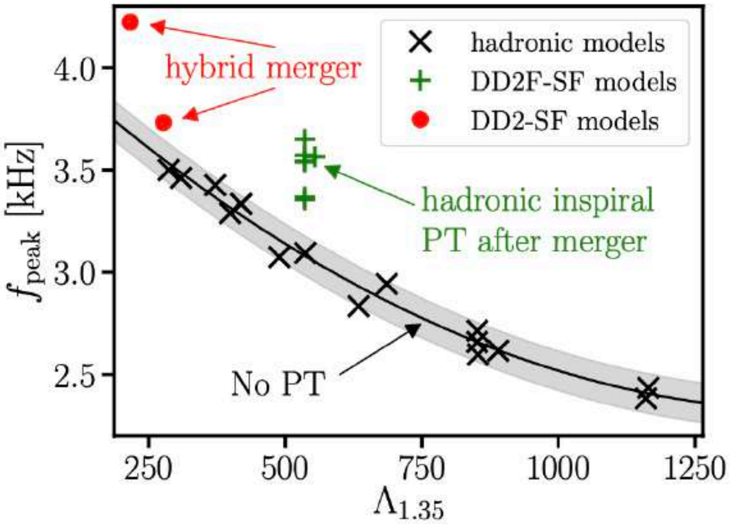
1st-OPT to soft quark matter after merger

e.g. softening effects on post-merger GW

third-family stars

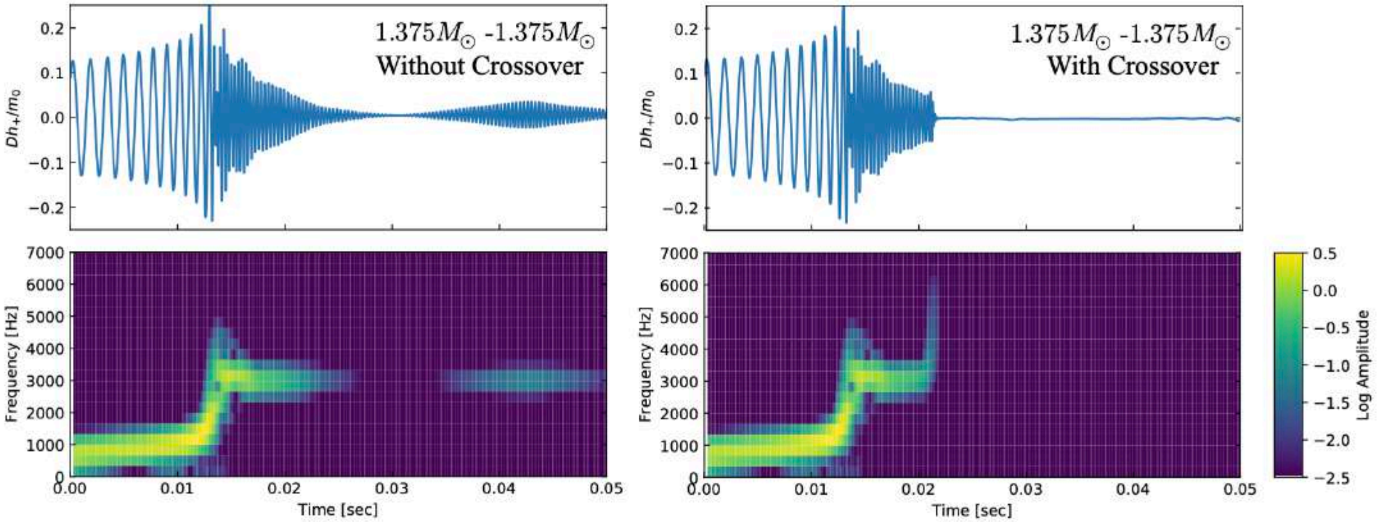
- stiff EoS at low density -DD2
- strong 1st-OPT to stiff quark matter





Bauswein & Blacker (2020)

Fujimoto et al. (2022)

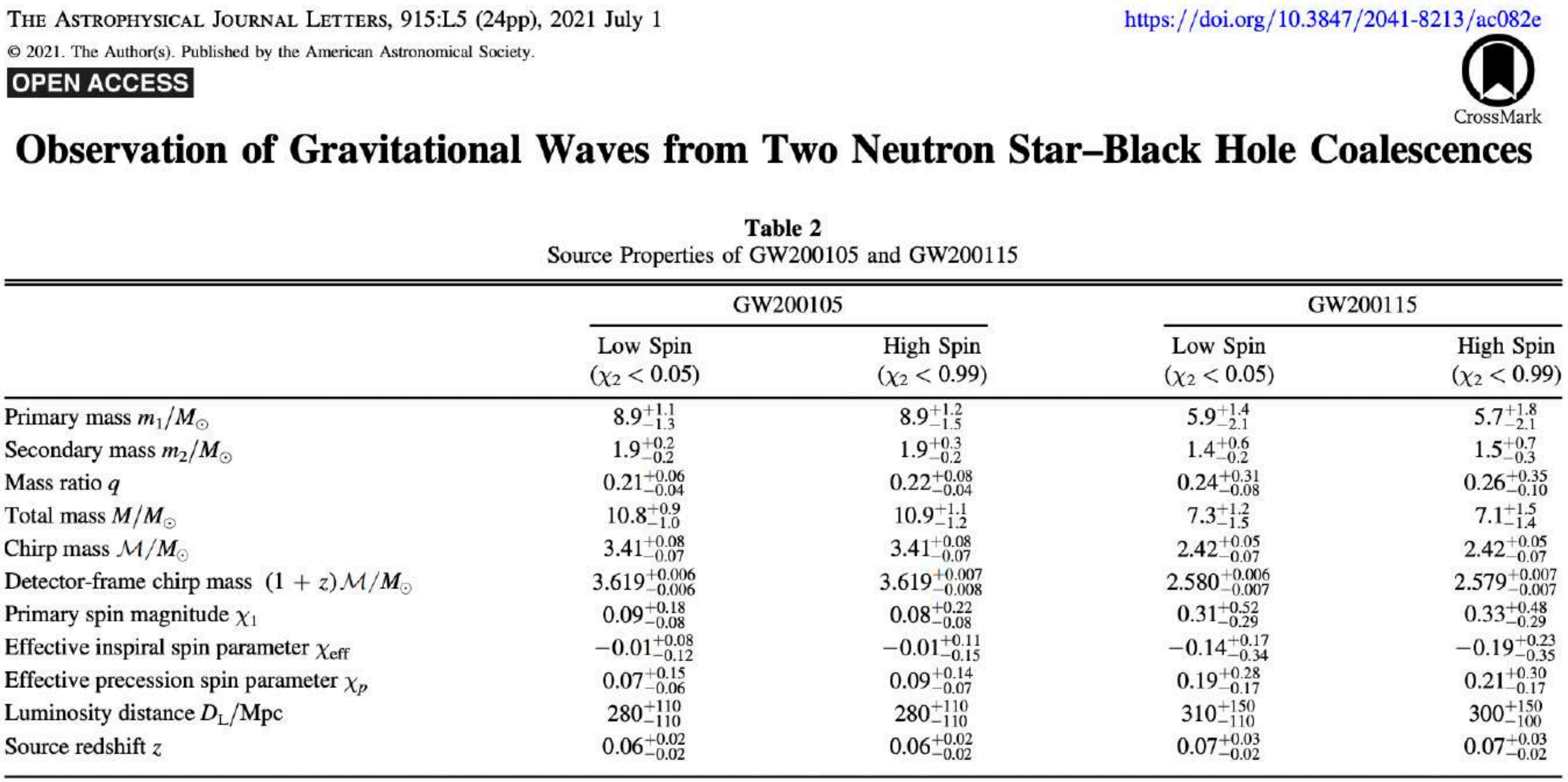


- soft EoS at low density ~N3LO chiEFT
- rapid stiffening in the crossover regime

crossover to soft quark matter after merger

NSBH mergers

LVK collaboration
arXiv:2106.15163



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

Table 2
Source Properties of GW200105 and GW200115

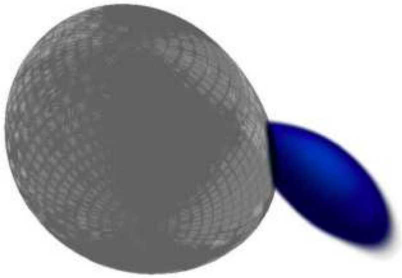
	GW200105		GW200115	
	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)
Primary mass $m_1/M_\odot$	$8.9^{+1.1}_{-1.3}$	$8.9^{+1.2}_{-1.5}$	$5.9^{+1.4}_{-2.1}$	$5.7^{+1.8}_{-2.1}$
Secondary mass $m_2/M_\odot$	$1.9^{+0.2}_{-0.2}$	$1.9^{+0.3}_{-0.2}$	$1.4^{+0.6}_{-0.2}$	$1.5^{+0.7}_{-0.3}$
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 χ_{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_{L}/Mpc	280^{+110}_{-110}	280^{+110}_{-110}	310^{+150}_{-110}	300^{+150}_{-100}
Source redshift z	$0.06^{+0.02}_{-0.02}$	$0.06^{+0.02}_{-0.02}$	$0.07^{+0.03}_{-0.02}$	$0.07^{+0.03}_{-0.02}$

no information on matter effects
no significant EM detections

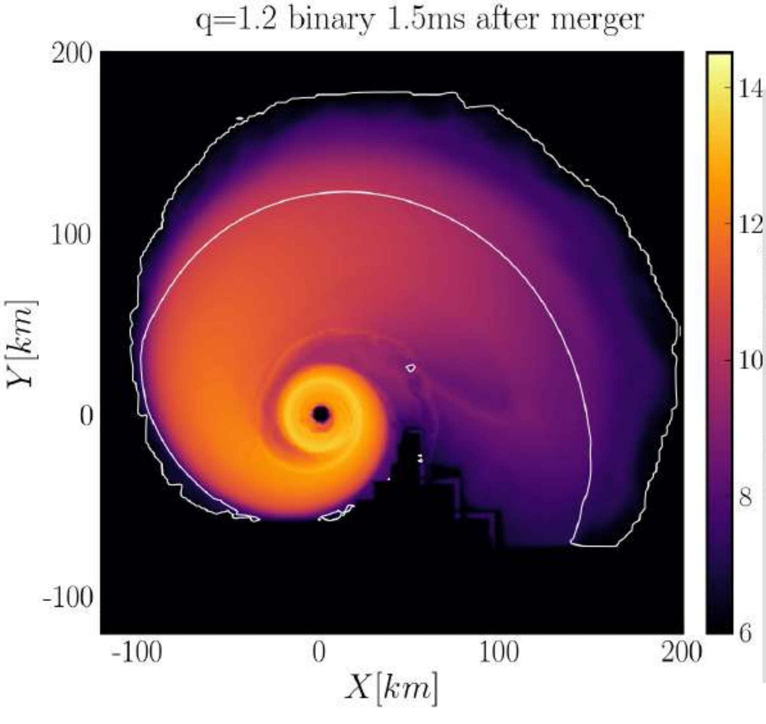
- GW200105: ~1.9 + ~9 solar masses
- GW200115: ~1.5 + ~6 solar masses

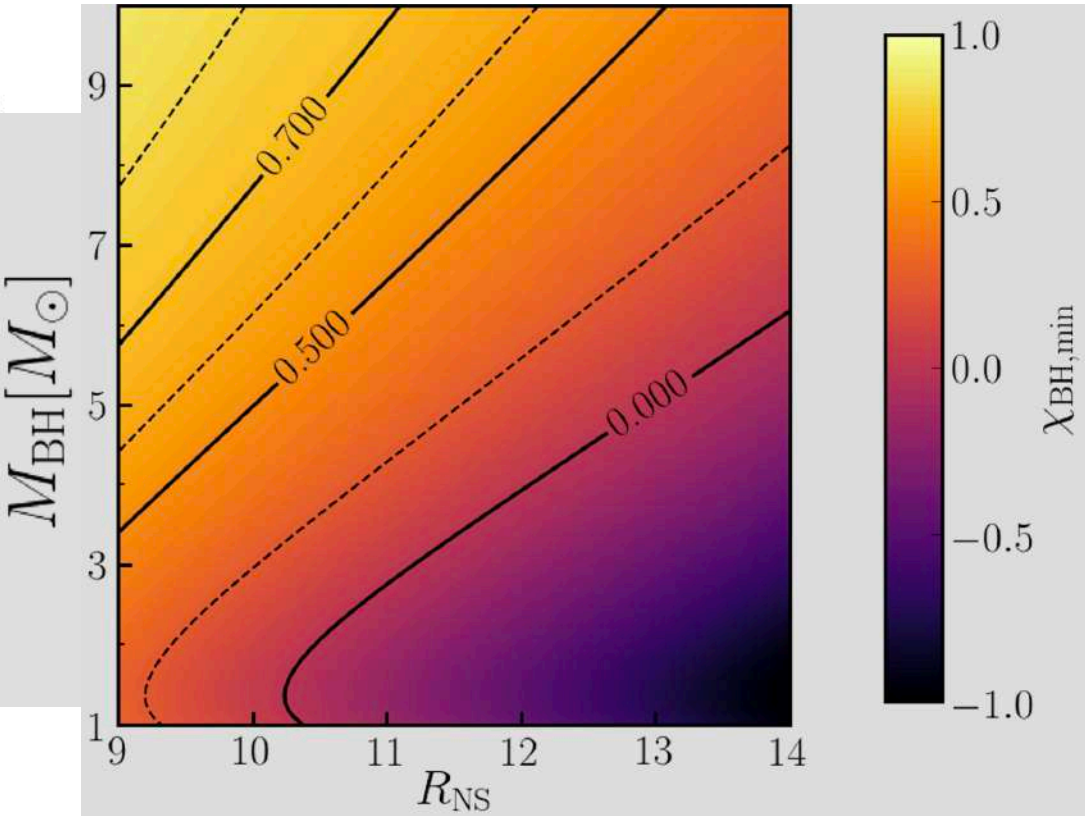
see events of GWTC-3: arXiv:2111.03606

Outcome of a NSBH merger



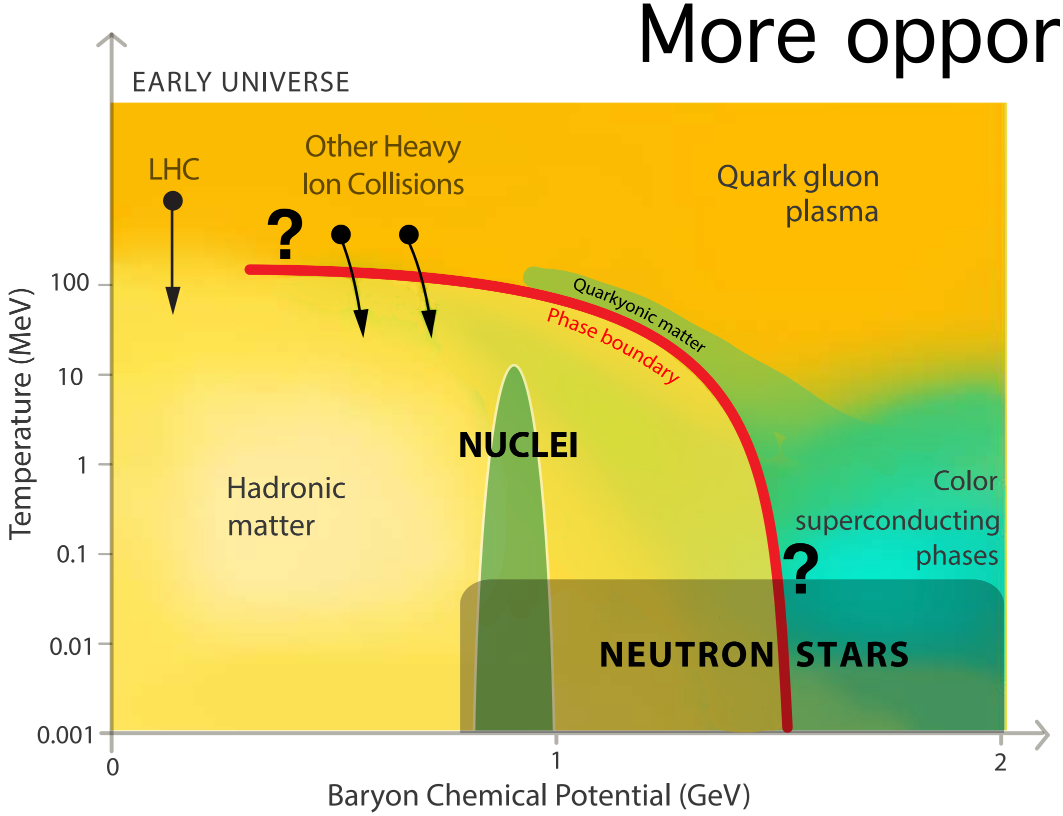
Foucart et al. (2018)

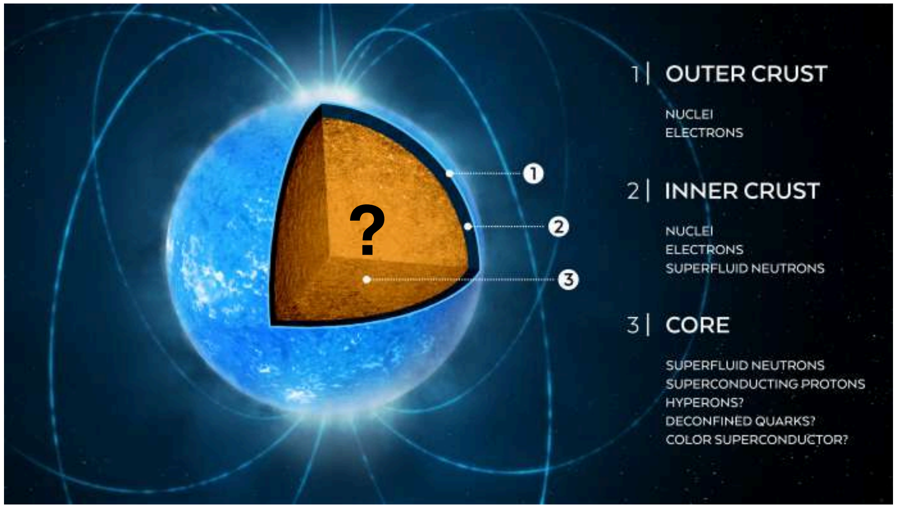




- NS is either tidally disrupted or plunges into the BH - mass ratio, spin, EoS
- radius determines if tides are **measurable** & if **EM** signals can be produced

More opportunities





probing dense matter in NSs

new!

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

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

THANK YOU!

Q & A