On the Minimum Radius of Very Massive Neutron Stars

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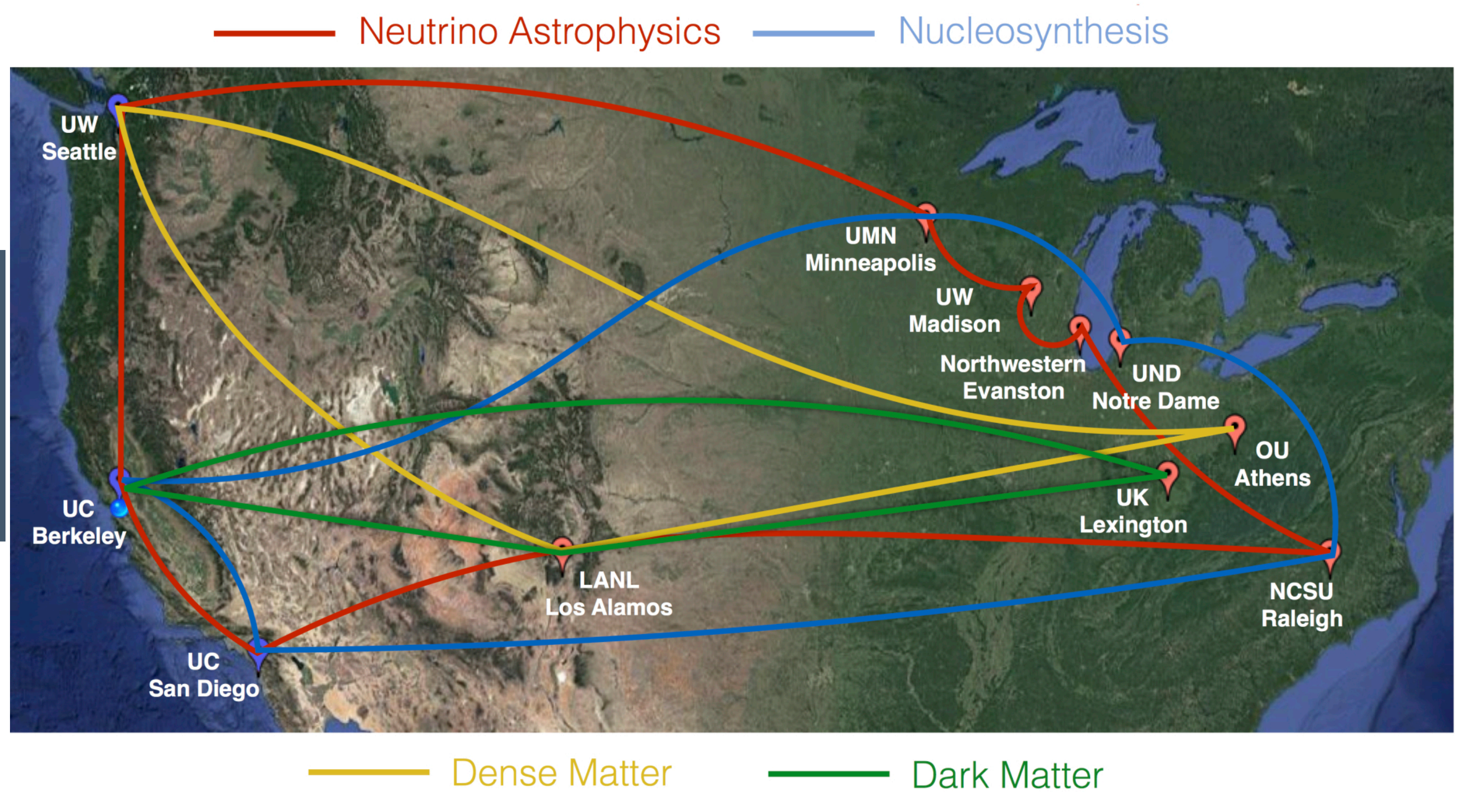
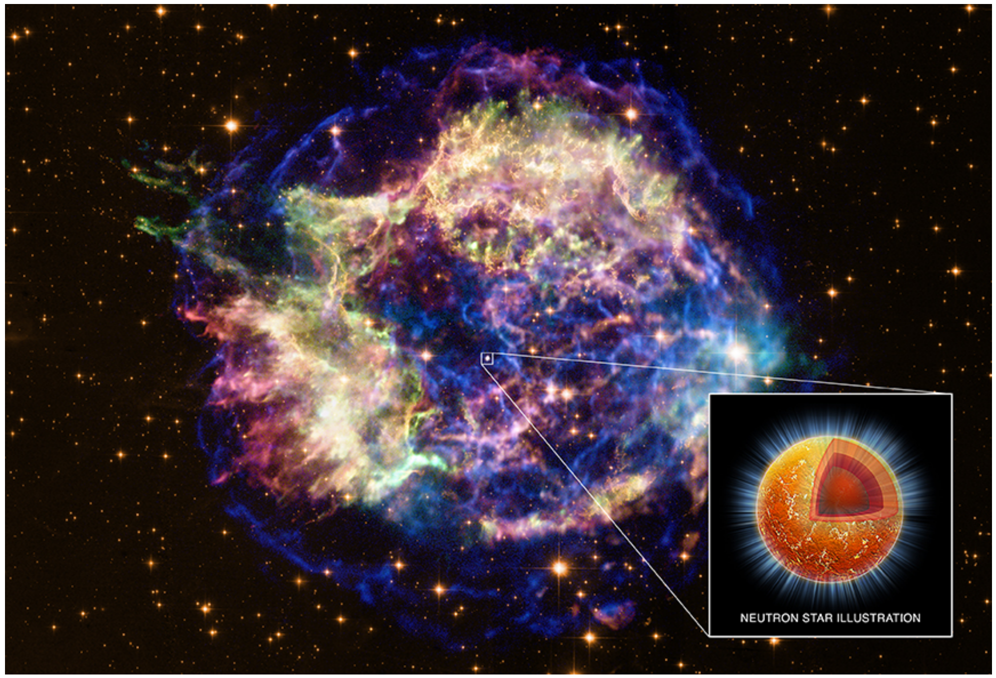
arXiv:2006.02207



N3AS online seminar
June 23, 2020

Compact Stars

A star of mass $M \gtrsim 10 M_\odot$ burns hydrogen by fusion, ending up with an iron core. Core grows to Chandrasekhar mass, collapses $\Longrightarrow$ supernova.



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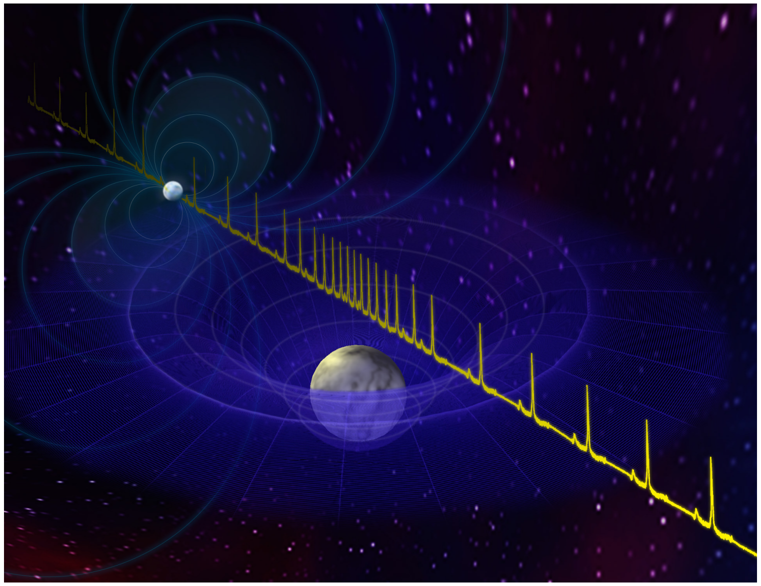
- remnant is a compact star

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

- the star cools by neutrino emission for the first million years

Global Structure

©NRAO



Microphysics input

- equations of state (EoS): pressure vs. energy density

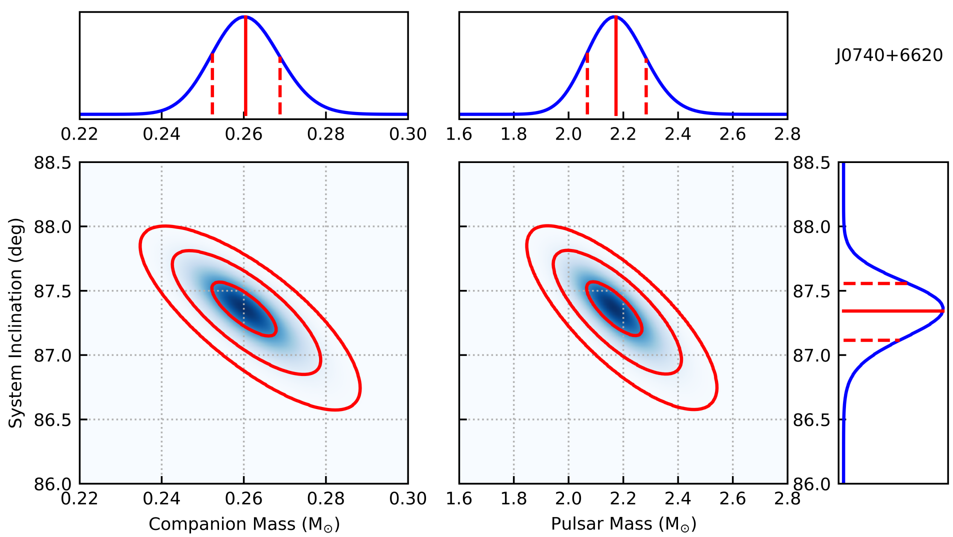
Context

- cold, beta-equilibrated neutron stars
- hydrostatic equilibrium in GR

Output

- masses and radii; compactness M/R
- binding energy
- tidal Love number & tidal deformability
- moment of inertia

new! PSR J0740+6620 with $2.14^{+0.20}_{-0.18} M_\odot$



Cromartie et al.
Nature Astronomy (2019)

new! GW190425

High-mass BNS merger

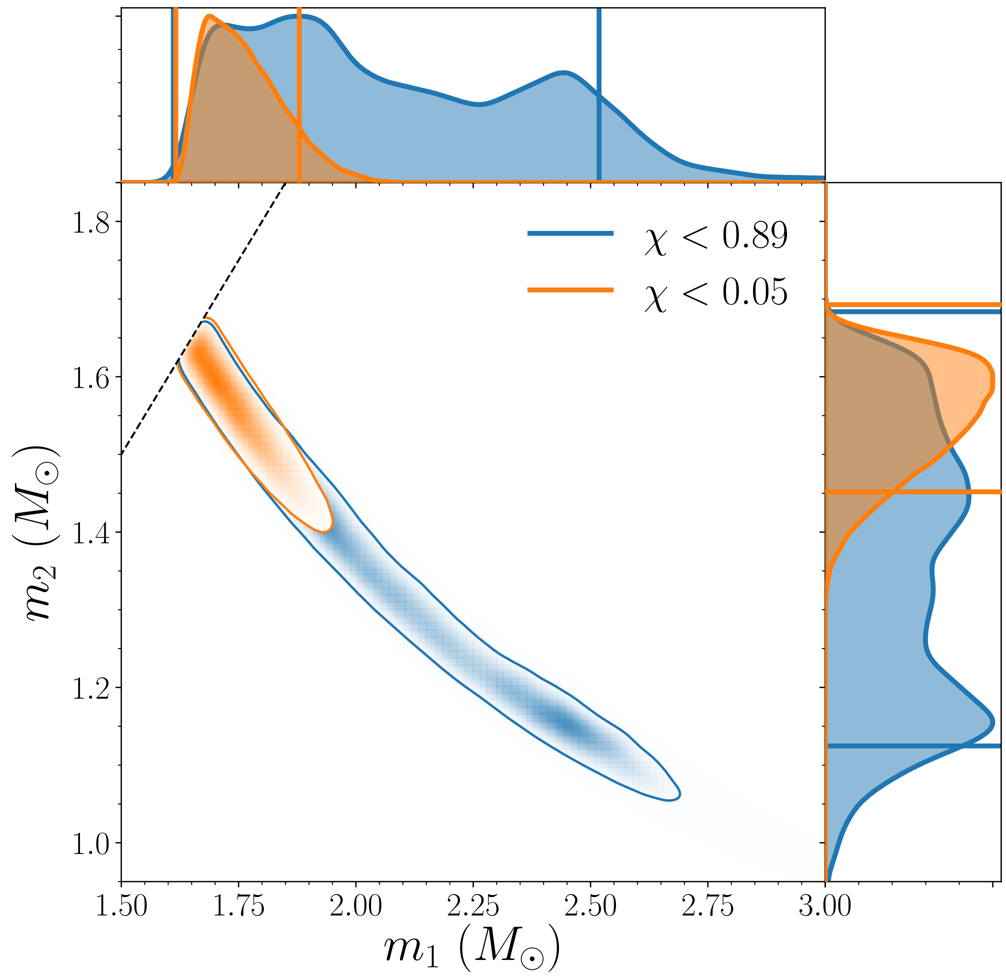
- total mass ~3.4 solar masses
- m2/m1: 0.8-1.0
- binary tidal deformability: <600
- direct collapse: missing EM signals
- seemingly different formation channels from known Galactic BNSs

Inferred radius

- assuming no exotic phases
- R<14.6 km
- signal too weak to provide further EoS constraints

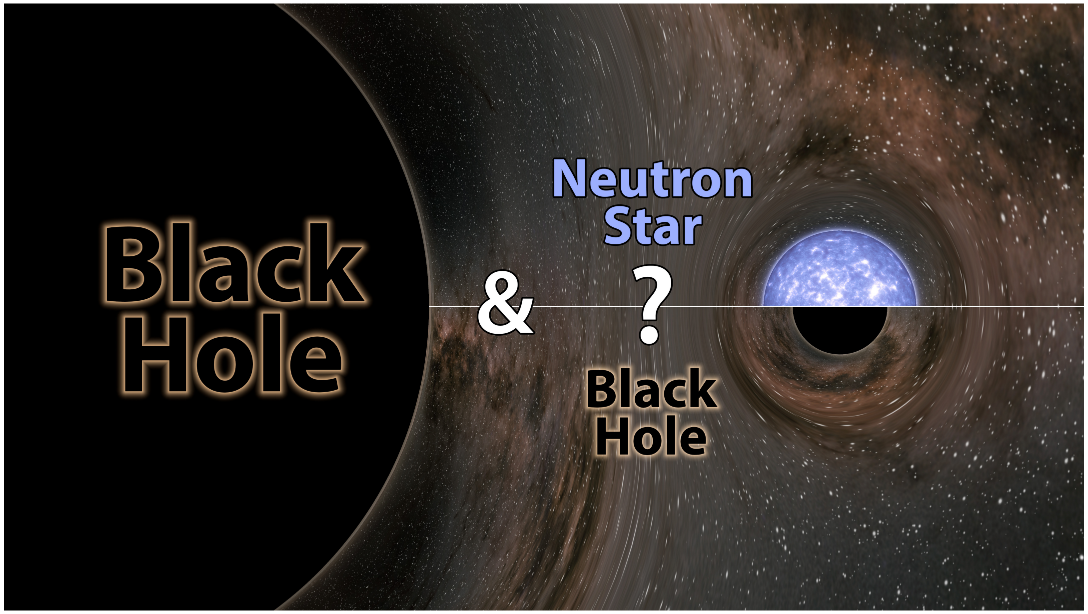
chirp mass

$\mathcal{M} = 1.44 \pm 0.02 M_\odot$

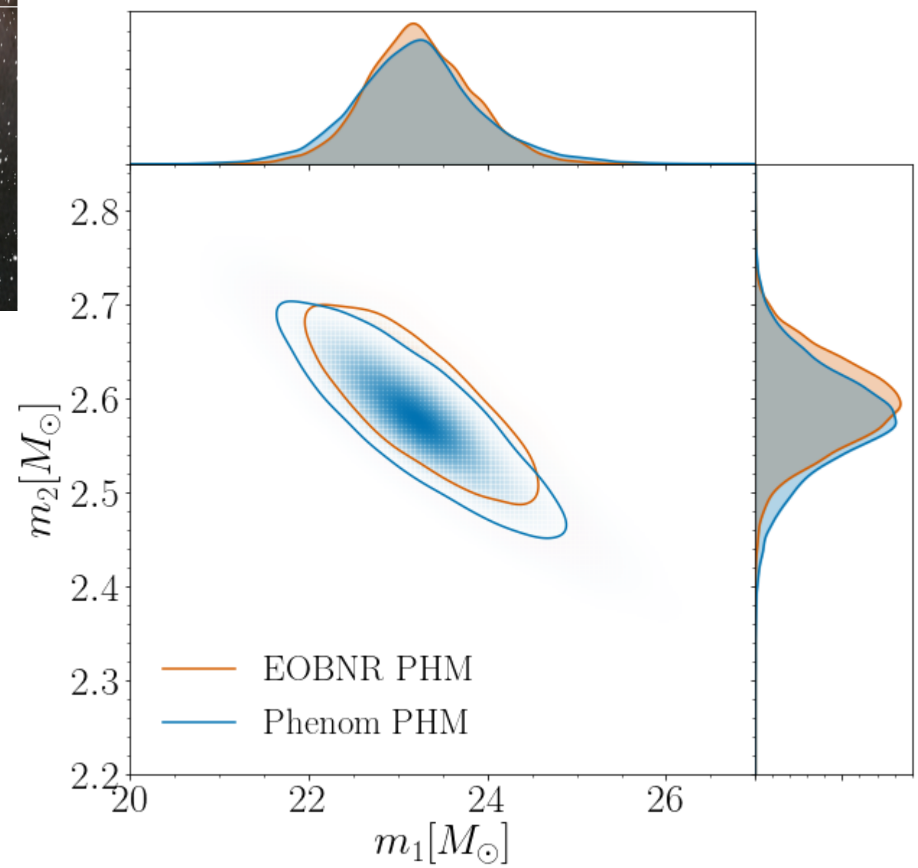


LVC collaboration, arXiv:2001.01761

new! GW190814



the most asymmetric system observed

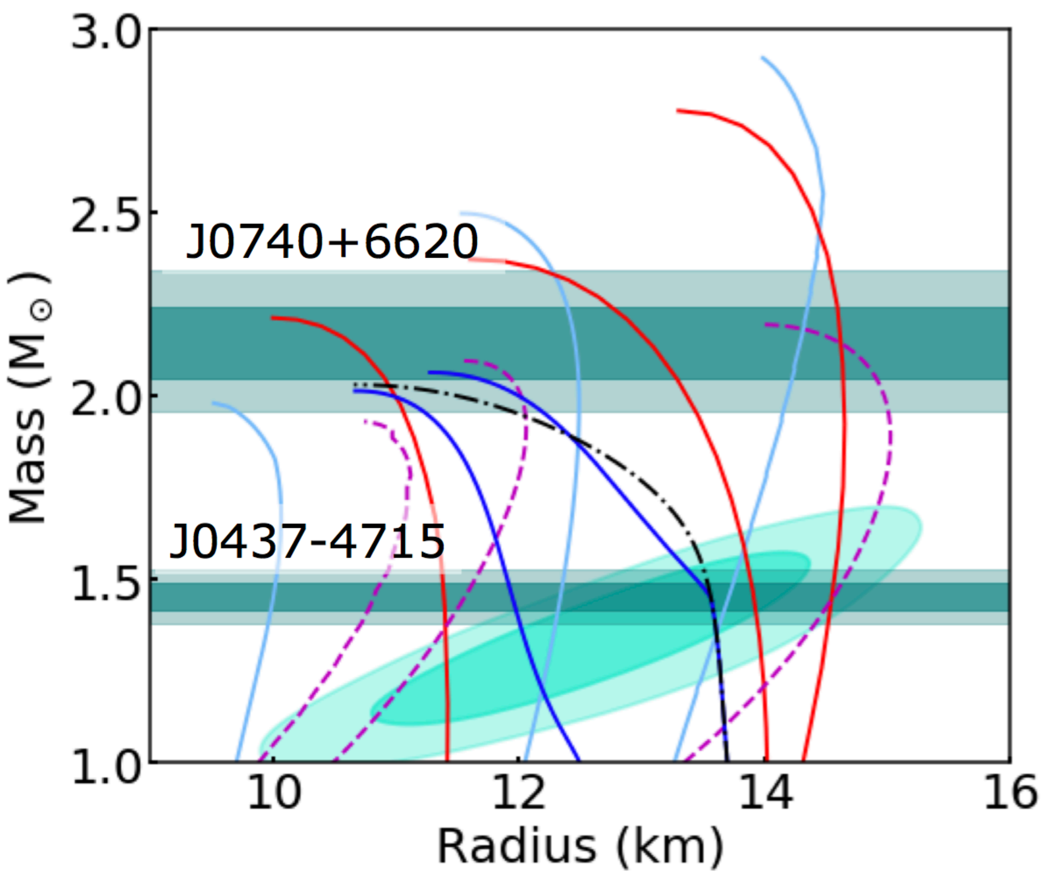


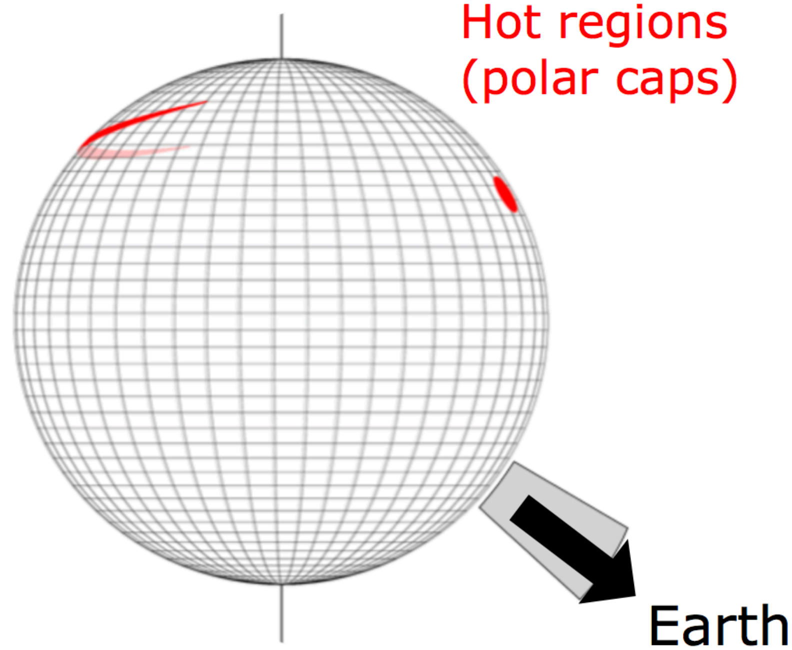
- extremely loud event produced by the inspiral and merger of two compact objects -- one, a black hole, and the other of undetermined nature
- the mass measured for the lighter compact object makes it either the lightest black hole or the heaviest neutron star ever discovered

https://www.ligo.org/detections/GW190814.php

NEXT STEPS FOR NICER

NICER extended to end 2022.
4 new sources in pipeline.
Many open questions!



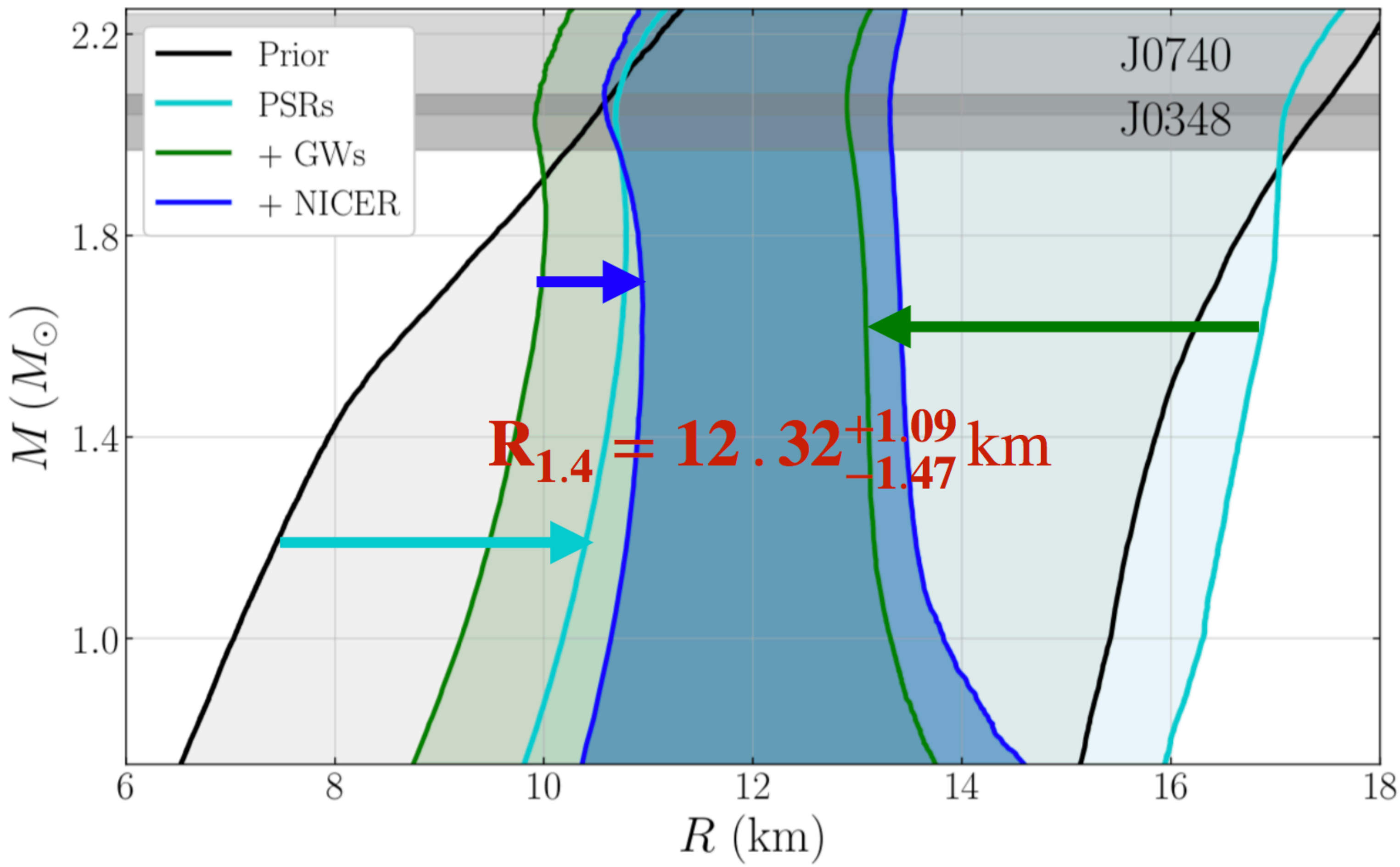


Surface map requires multipolar magnetic field: broader implications for neutron star evolution.

credit: Anna Watts

Constraining $R_{1.4}$

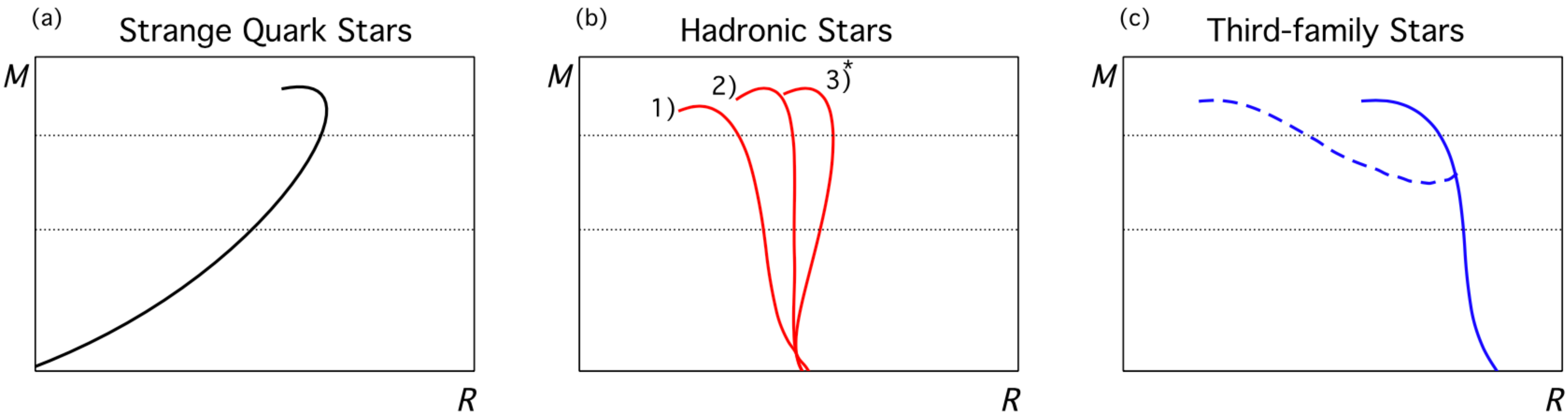
Landry, Essick & Chatziioannou,
arXiv:2003.04880



- e.g. nonparametric survey based on existing nuclear EoSs
- overlapped region reflects best compatibility with data

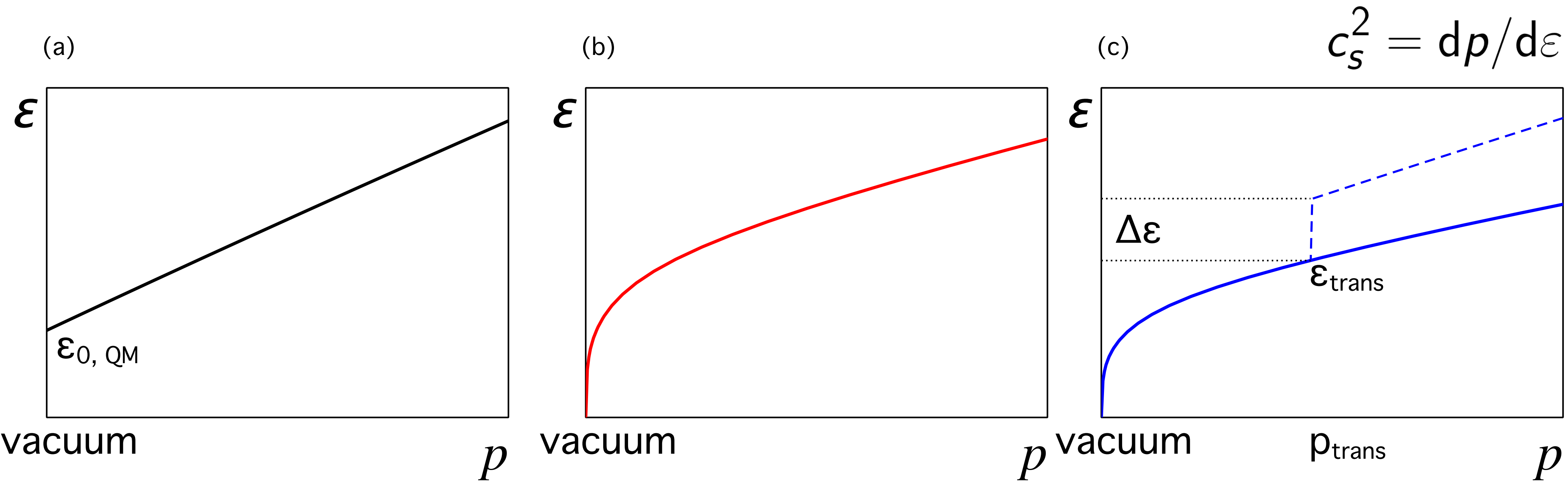
Relating $R_{1.4}$ and $R_{2.0}$

SH & Prakash,
arXiv:2003.04880



- strange matter hypothesis; self-bound strange stars
- continuous (and smooth) profile of normal hadronic EoS
- disconnected hybrid branch with a sharp phase transition

Relating $R_{1.4}$ and $R_{2.0}$



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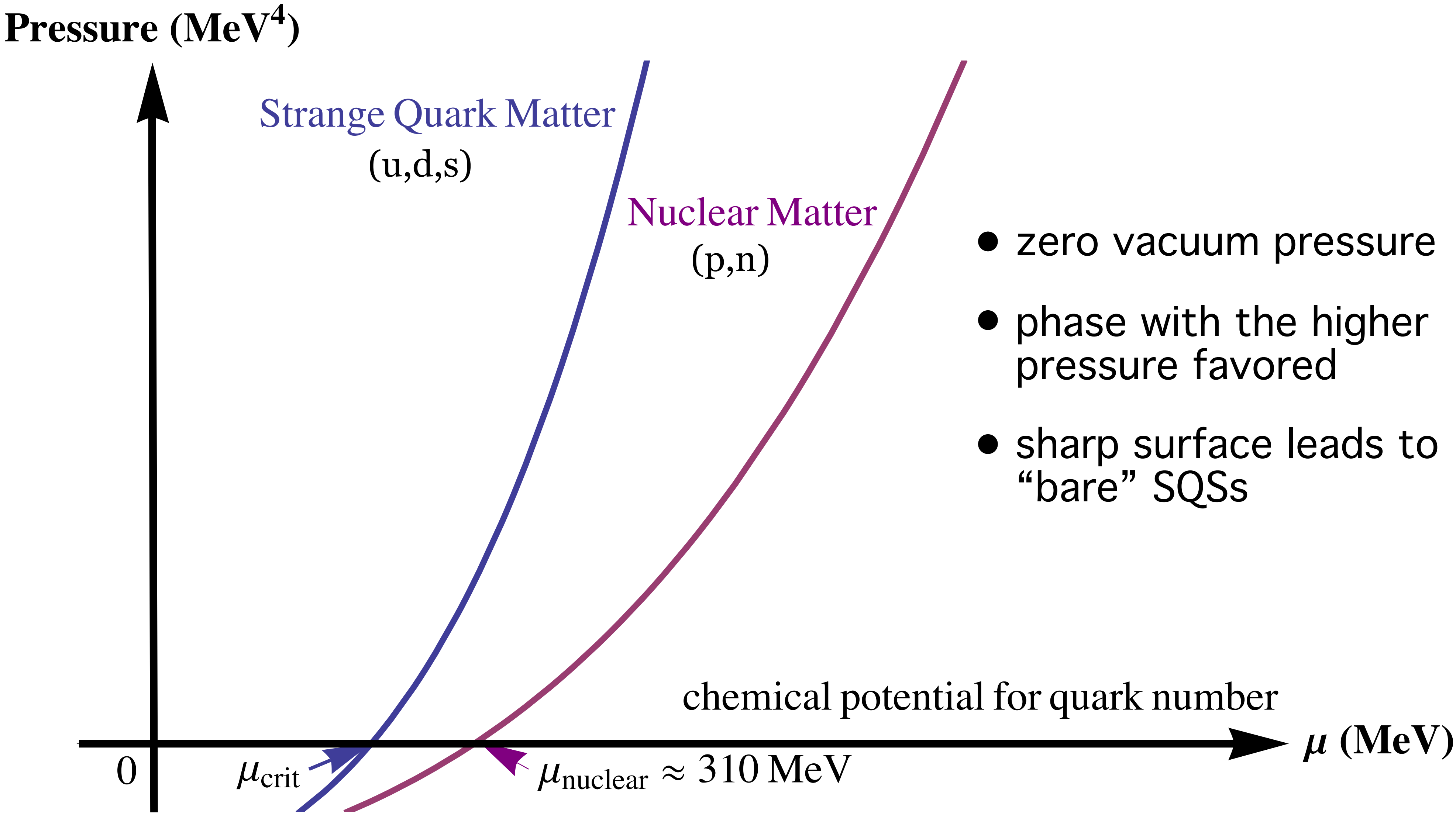
Strange matter hypothesis



- zero vacuum pressure
- phase with the higher pressure favored
- sharp surface leads to "bare" SQSs

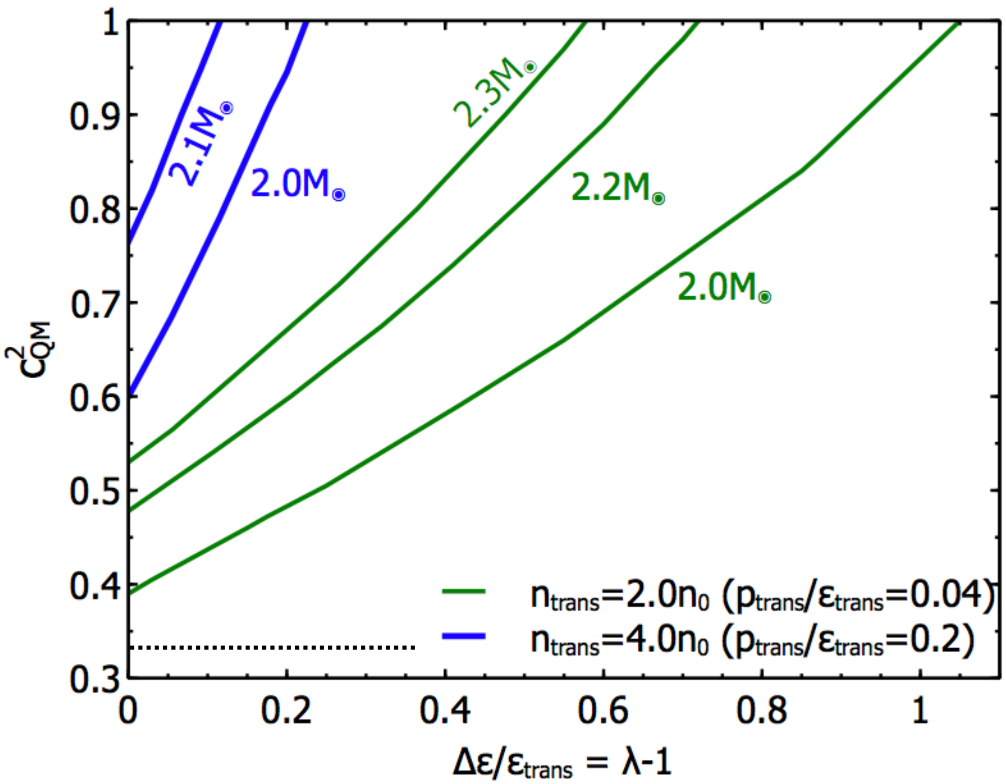
Bodmer, PRD 4 1601 (1971); Witten, PRD 30 272 (1984); Farhi, Jaffe, PRD 30 2379 (1984)

Constraints on the quark matter EoS

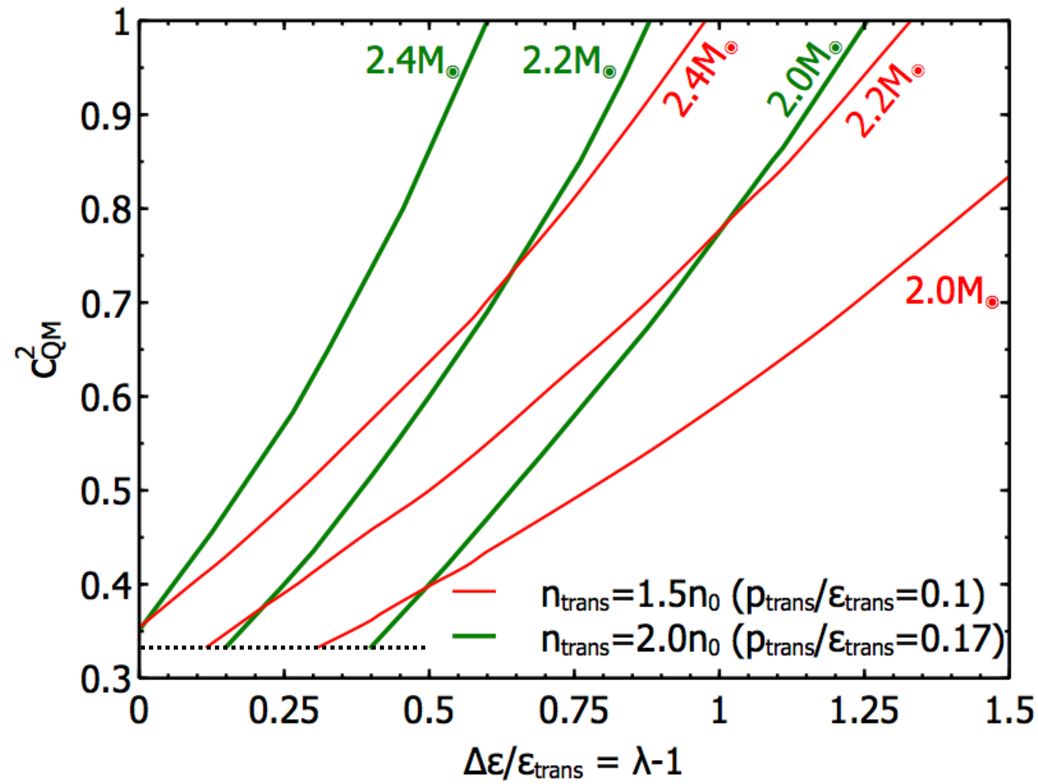
Generic ansartz $\varepsilon(p) = \varepsilon_{\mathrm{trans}} + \Delta\varepsilon + c_{\mathrm{QM}}^{-2}(p - p_{\mathrm{trans}})$

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

QM + Soft Nuclear Matter



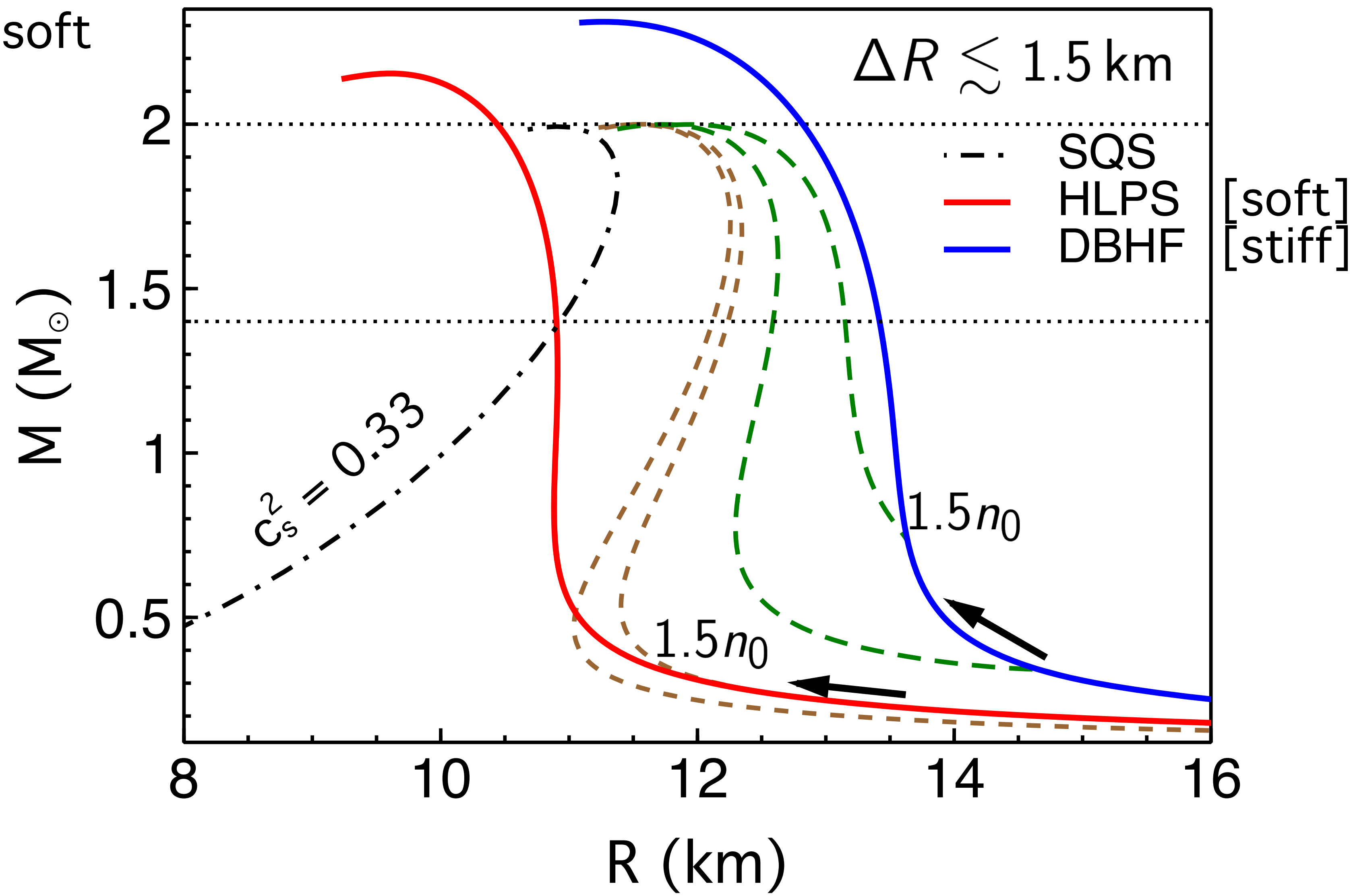
QM + Hard Nuclear Matter



- Mmax can constrain QM EoS but not rule out QM in general
- constraints depend on NM EoS up to saturation density

Stiffness vs. compactness

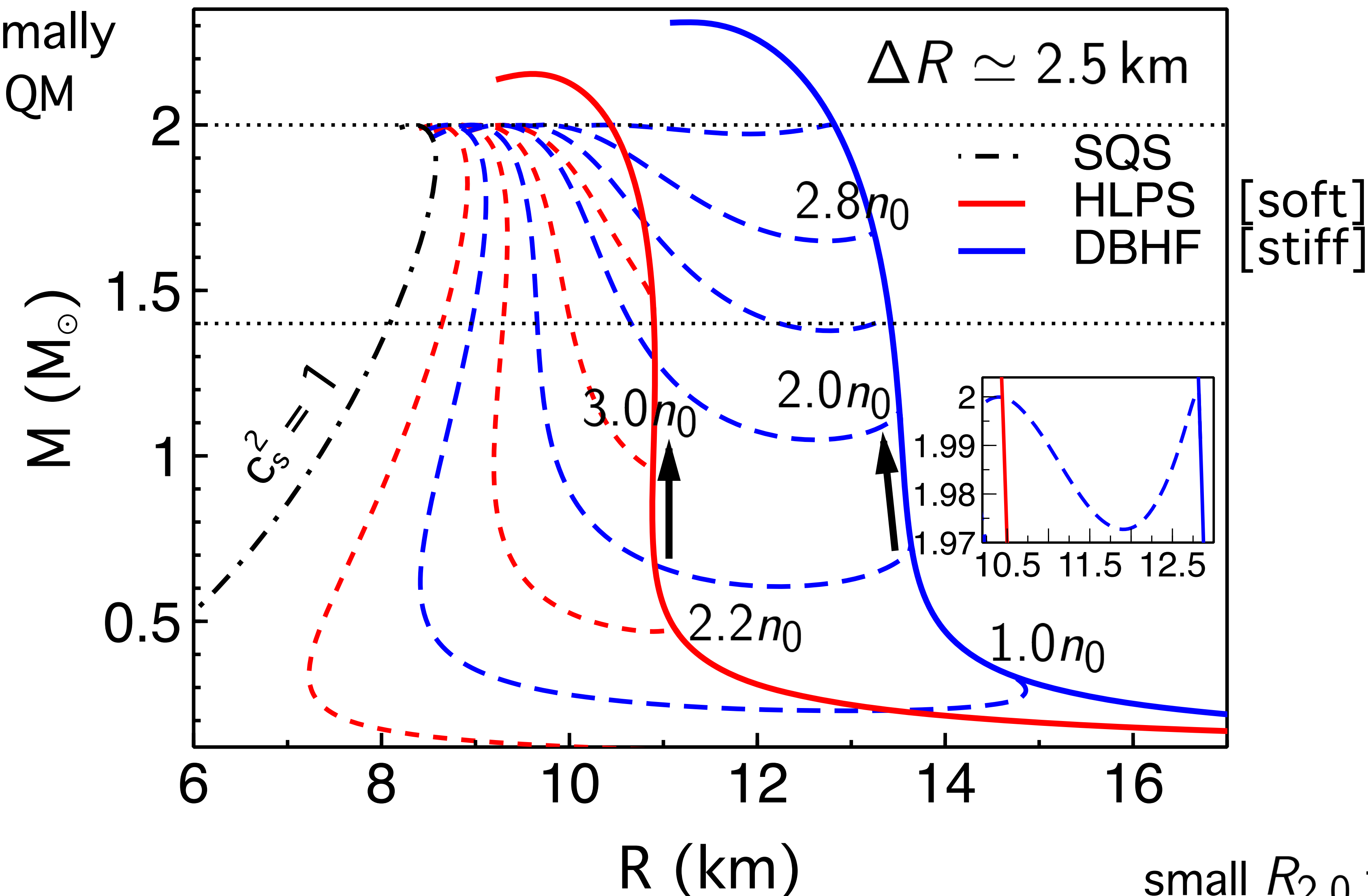
very soft QM



- low ntrans: $\lesssim 1.6 n_0$ for soft NM; $\lesssim 2.4 n_0$ for stiff NM; limited by **Mmax**
- **possibility** of obeying the conformal limit; in pert QCD $c_{\mathrm{QM}}^2 = 1/3 - \mathcal{O}(\alpha_s)$

Stiffness vs. compactness

maximally
stiff QM

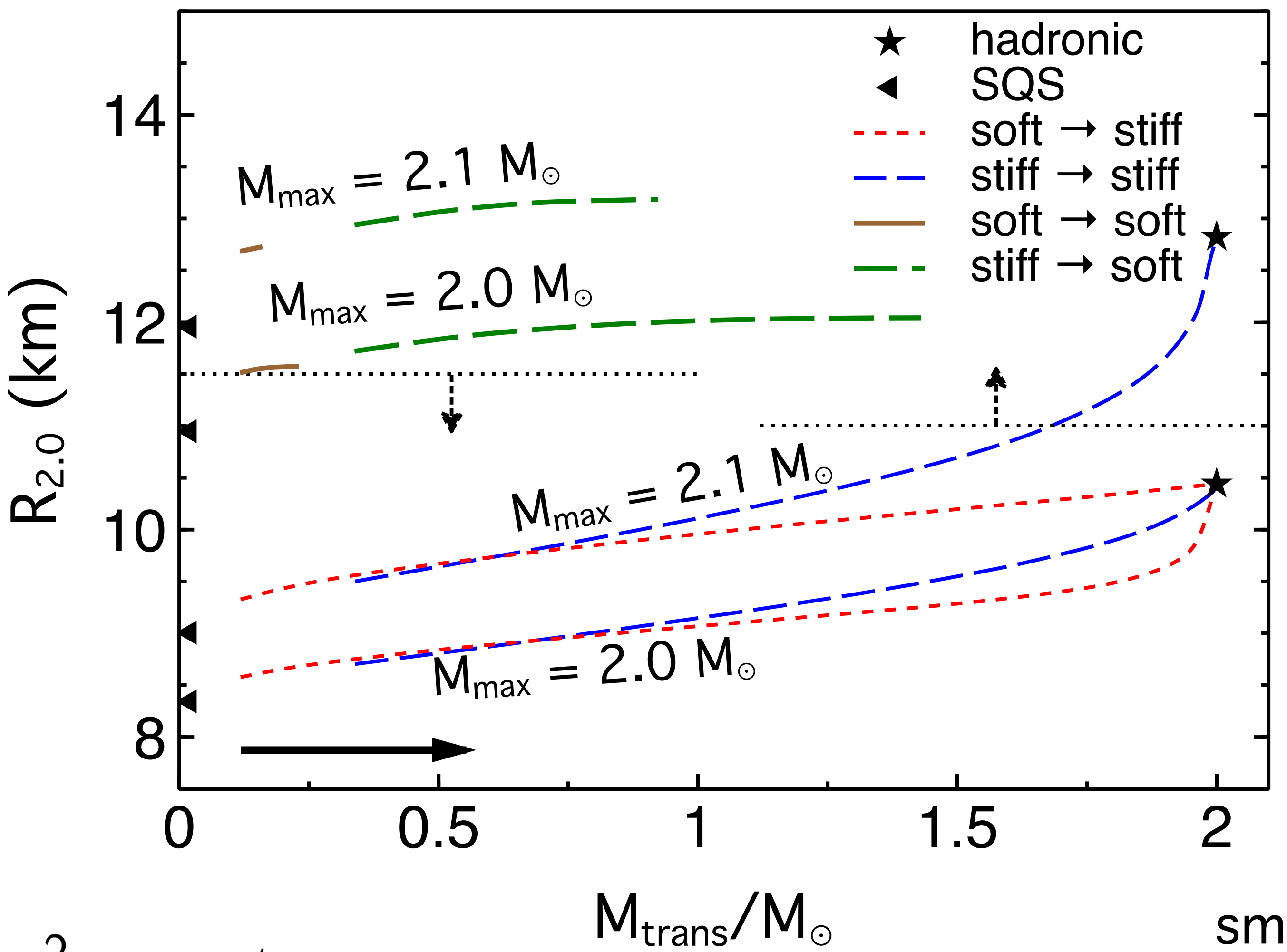


small $R_{2.0}$ favors
stiff QM

- the **smallest** possible radii
- R20 increases with Mmax and ntrans

inverse (!) trend

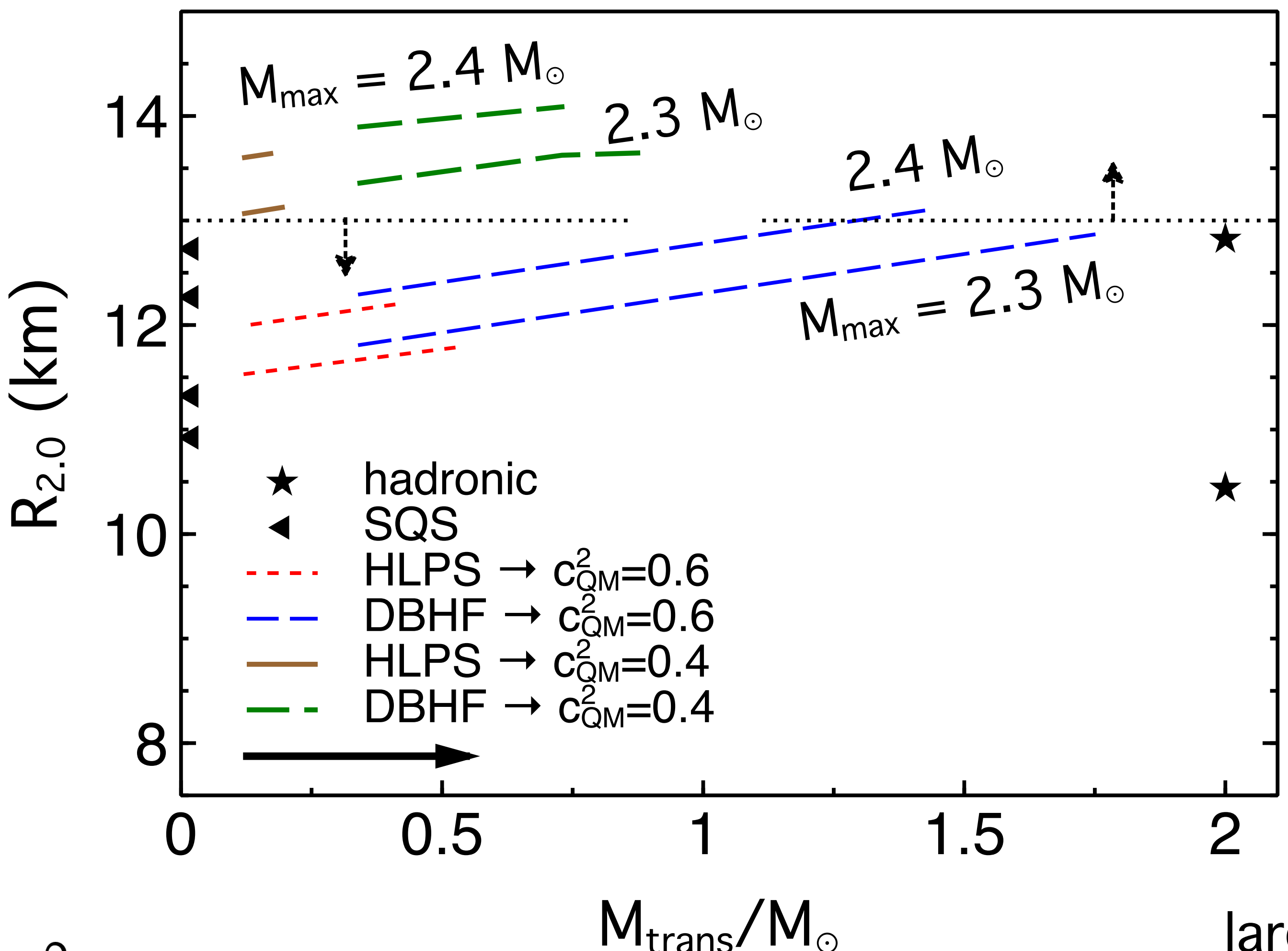
Combined constraints



small $R_{2.0}$ favors stiff QM

- testing $c^2_{\text{QM}} = 1/3, 1$
- $R_{2.0}$ increases with Mmax and ntrans $\Longrightarrow$
- **minimum** radius occurs at low-density **"soft to stiff"** transition

Combined constraints

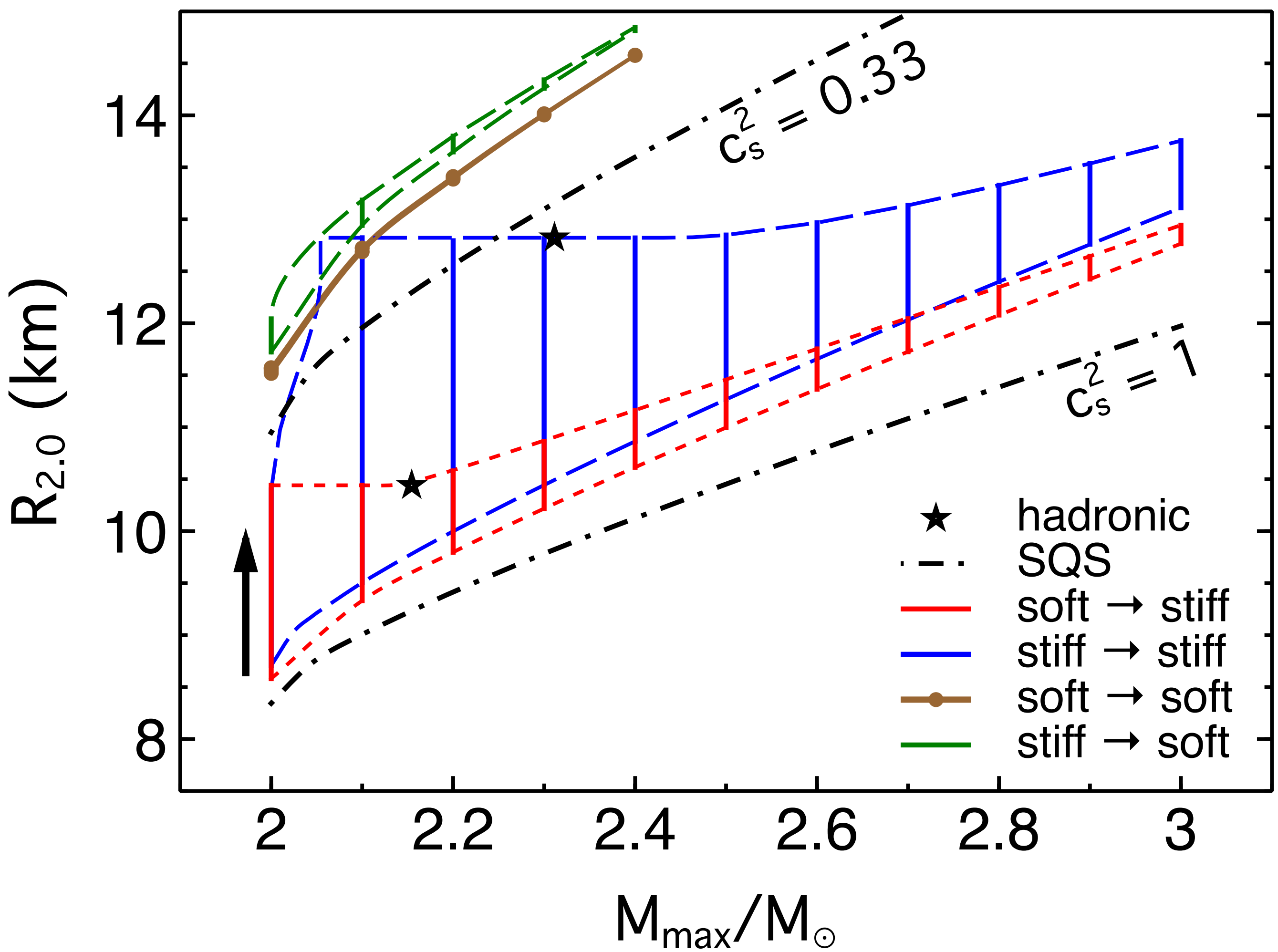


- testing $c^2_{QM} = 0.4, 0.6$
- hypothetical bounds on $R_{2.0}$ and Mmax
- sensitivity to the hadronic baseline assumed

large $R_{2.0}$ favors soft QM

inverse trend

Even higher masses (?)

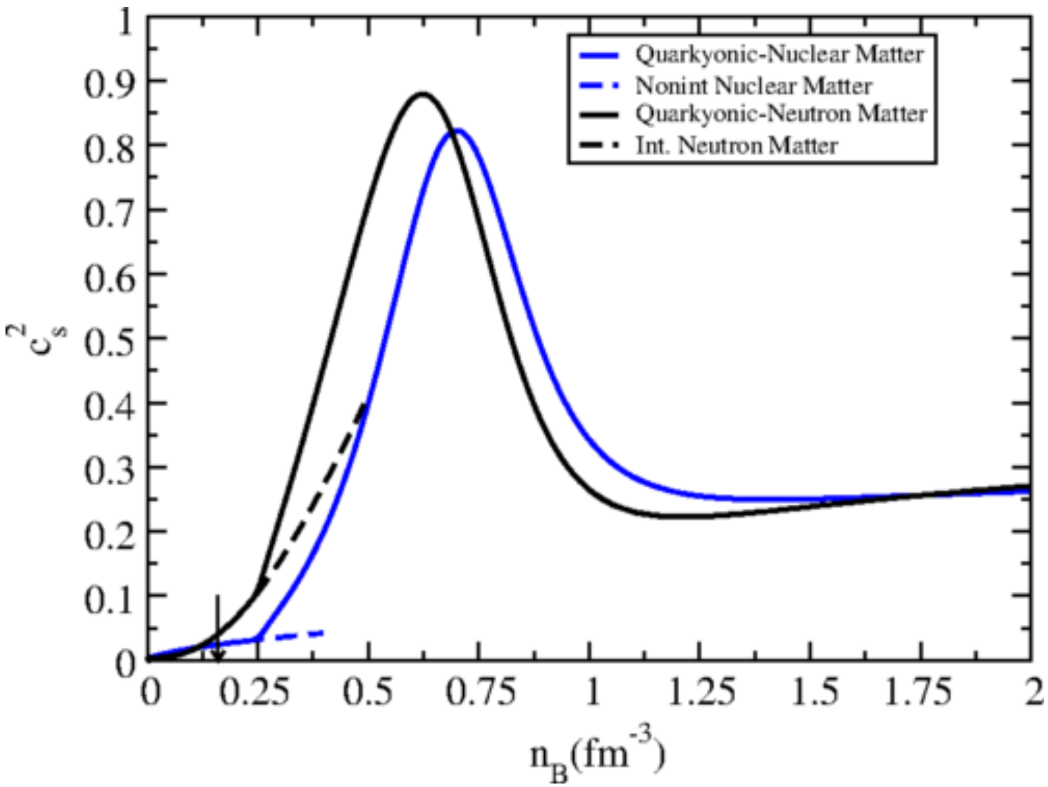


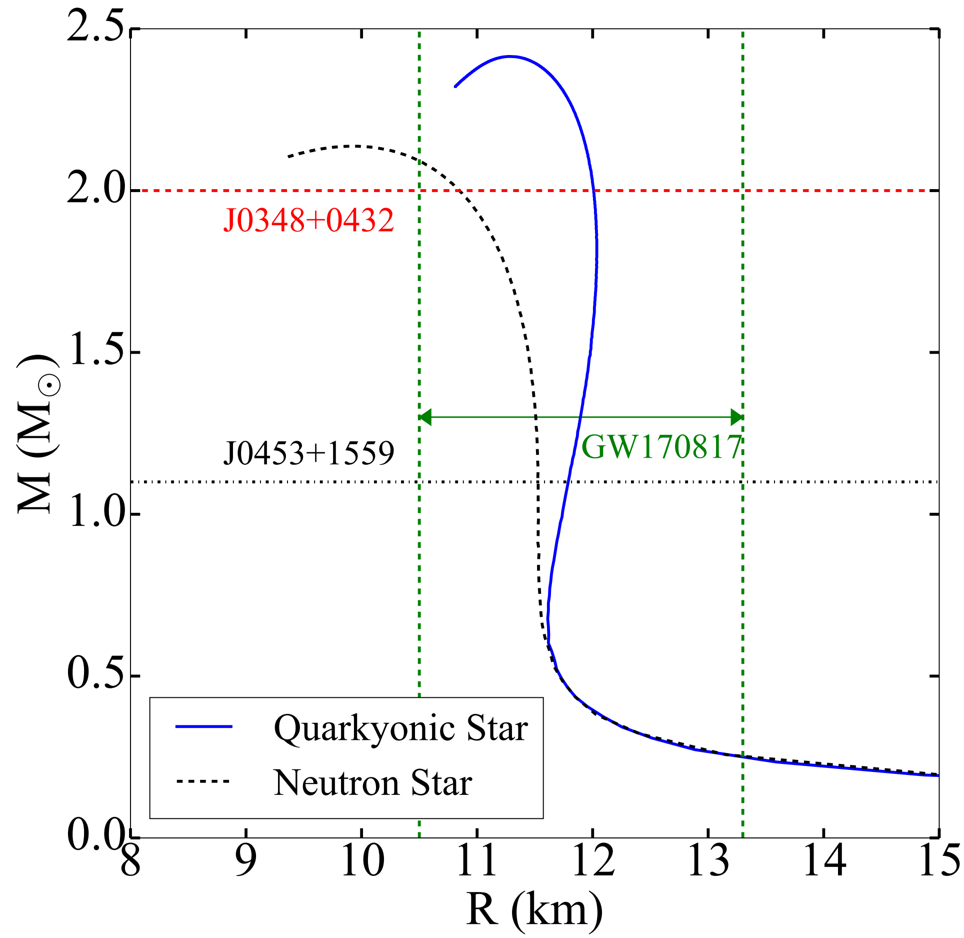
- hypothetical bounds on $R_{2.0}$ and Mmax
- ntrans is severely limited for soft nuclear matter

Quarkyonic Stars

McLerran & Reddy, PRL 122, 122701 (2019)

not identifiable through mass-radius relations

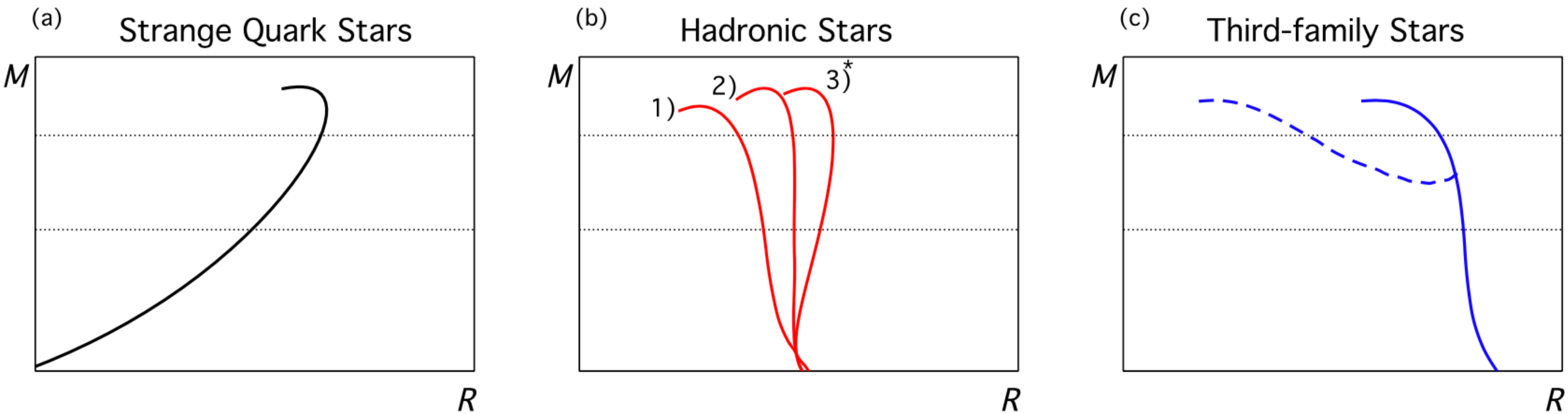




- there need be **no** 1st-order transition between the low and high density phases; smooth **crossover**: "quark-hadron continuity"
- **larger** radii; require nuclear matter **soft** enough to satisfy GW170817
- caution: not to violate causality

Relating $R_{1.4}$ and $R_{2.0}$

SH & Prakash,
arXiv:2003.04880



- strange matter hypothesis; self-bound strange stars
- continuous (and smooth) profile of normal hadronic EoS
- disconnected hybrid branch with a sharp phase transition

Source	Radius (km)	Mass ($M_\odot$)	References
X-ray Observations	$9 - 14$	~ 1.4	Lattimer (2012); Özel & Freire (2016)
	$10 - 14$	~ 1.4	Steiner et al. (2016, 2018)
GW170817	$8.9 - 13.2$	$1.36\,(1.17) - 1.60\,(1.36)$	De et al. (2018)
	11 ± 1	$1.36\,(1.17) - 1.60\,(1.36)$	Capano et al. (2020)
NICER	$13.02^{+1.24}_{-1.19}$	$1.44^{+0.15}_{-0.14}$	Miller et al. (2019)
(PSR J0030+0451)	$12.71^{+1.14}_{-1.19}$	$1.34^{+0.15}_{-0.16}$	Riley et al. (2019)

Table 1. Estimates of radii and masses of neutron stars.

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 J0348+0432	2.01 ± 0.04	Antoniadis et al. (2013)
PSR J0740+6620	$2.14^{+0.10}_{-0.09}$	Cromartie et al. (2019)
PSR 2215-5135	$2.27^{+0.17}_{-0.15}$	Linares et al. (2018)

Table 2. Largest measured masses of neutron stars.

THANK YOU!

Q & A

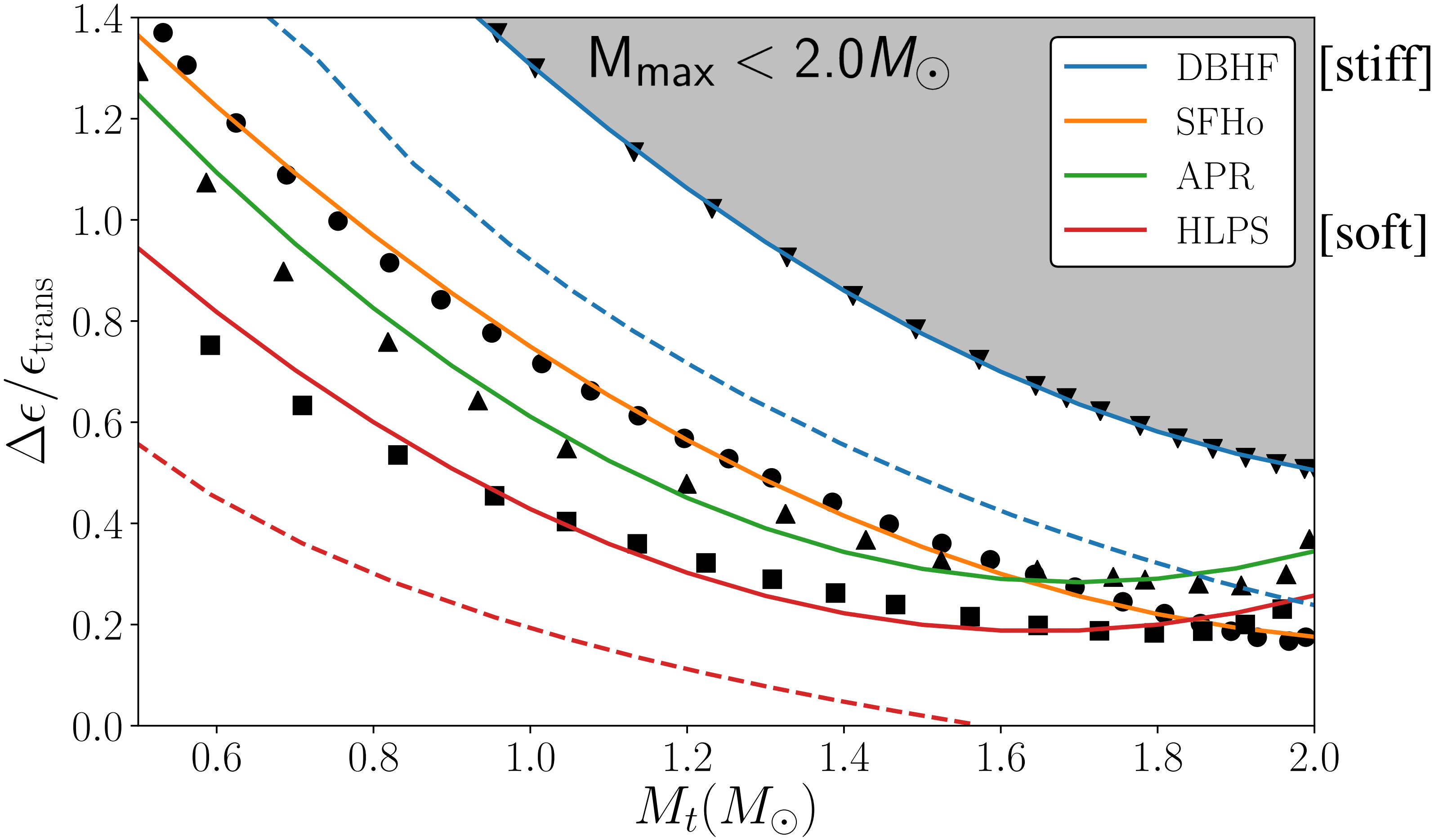
BACKUP

SLIDES

Tracking Mmax contours

$c_{\rm QM}^2 = 1$

Chatziioannou & **SH**,
arXiv: 1911.07091

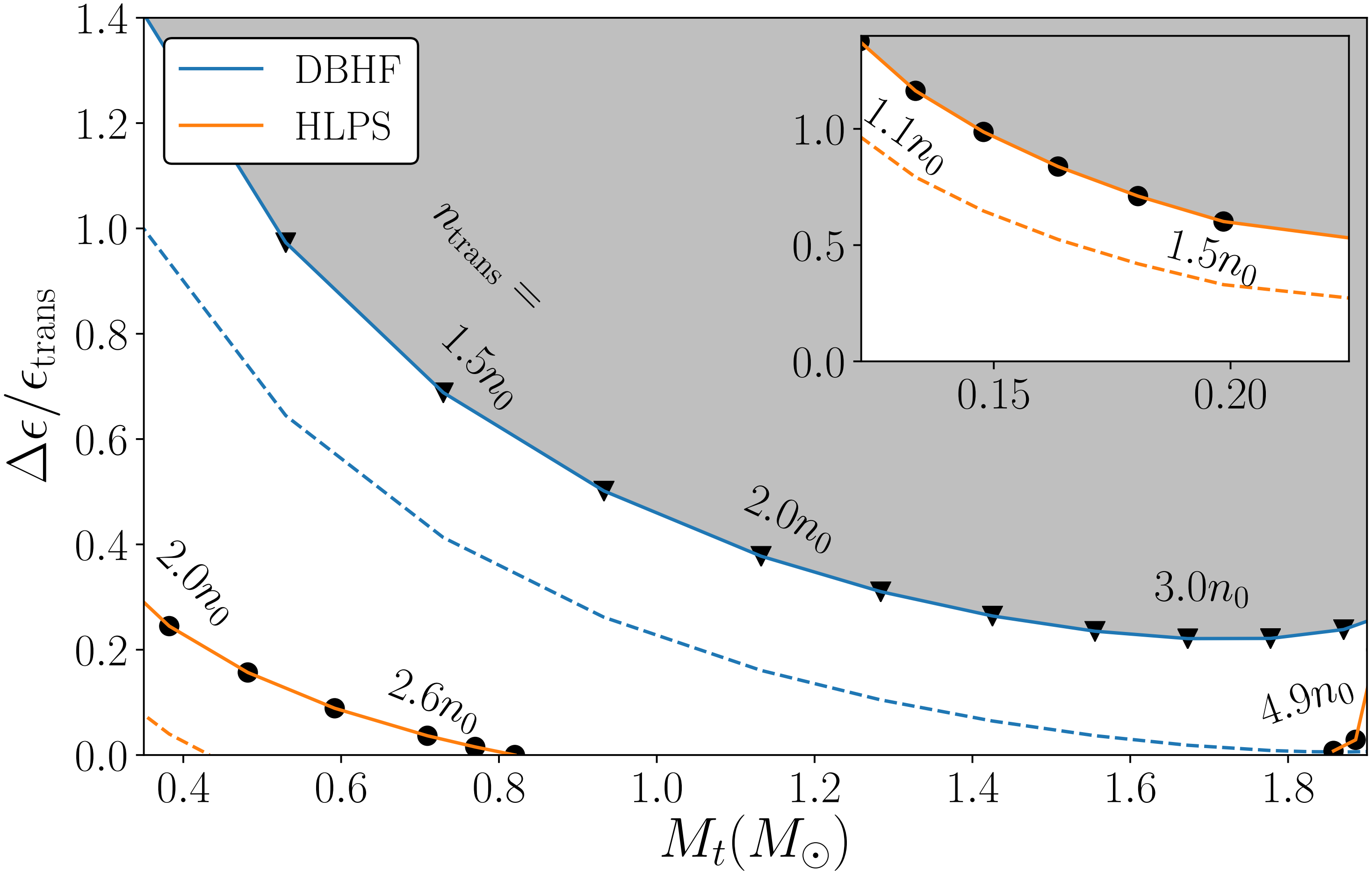


- allowed region is smaller for soft nuclear matter
- increasing Mmax to e.g. $2.2 M_\odot$ leads to more stringent constraint

Tracking Mmax contours

$c^2_{\mathrm{QM}} = 0.5$

Chatziioannou & **SH**,
arXiv: 1911.07091

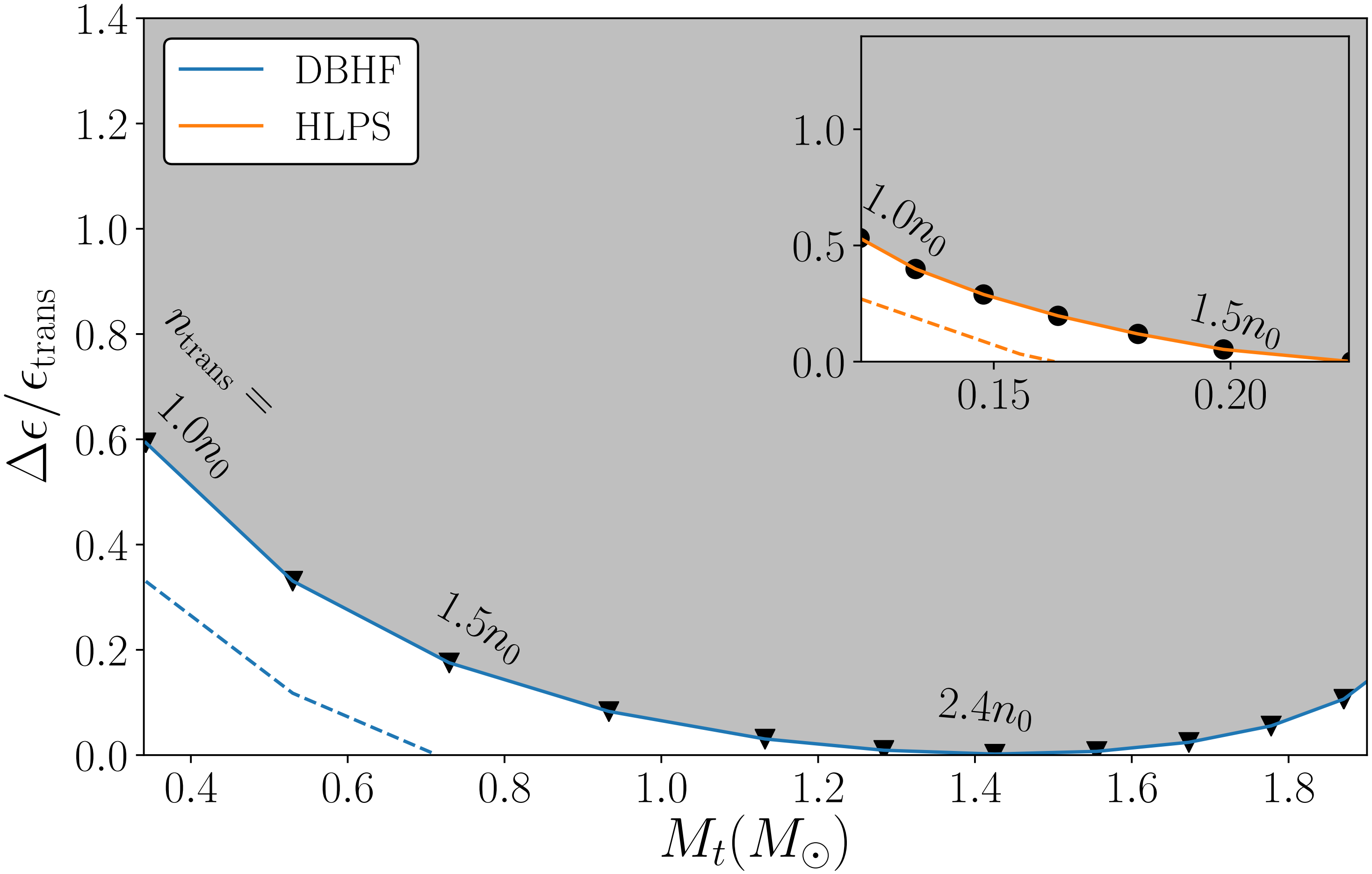


- with softer QM at high densities, again more space is ruled out
- ntrans is severely limited for soft nuclear matter

Tracking Mmax contours

$c^2_{\mathrm{QM}} = 0.33$

Chatziioannou & **SH**,
arXiv: 1911.07091



- low ntrans: approaching nuclear regime
- what about $R_{2.0}$?
- high ntrans: short hybrid branch; similar to hadronic stars