Neutron Stars and the Hidden Lives of Quarks

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Based on work with Susan Gardner — arXiv:2104.xxxxx?

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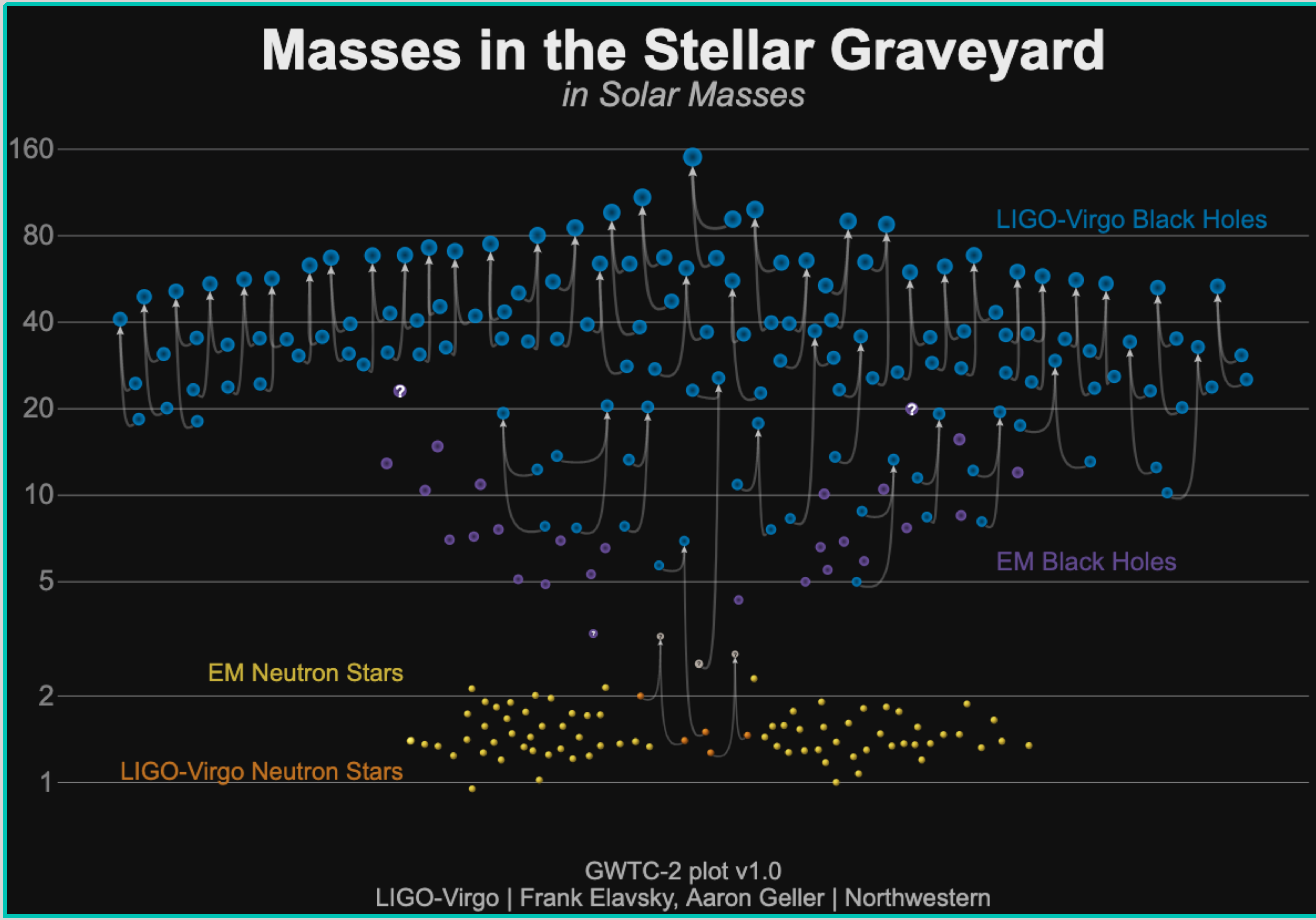
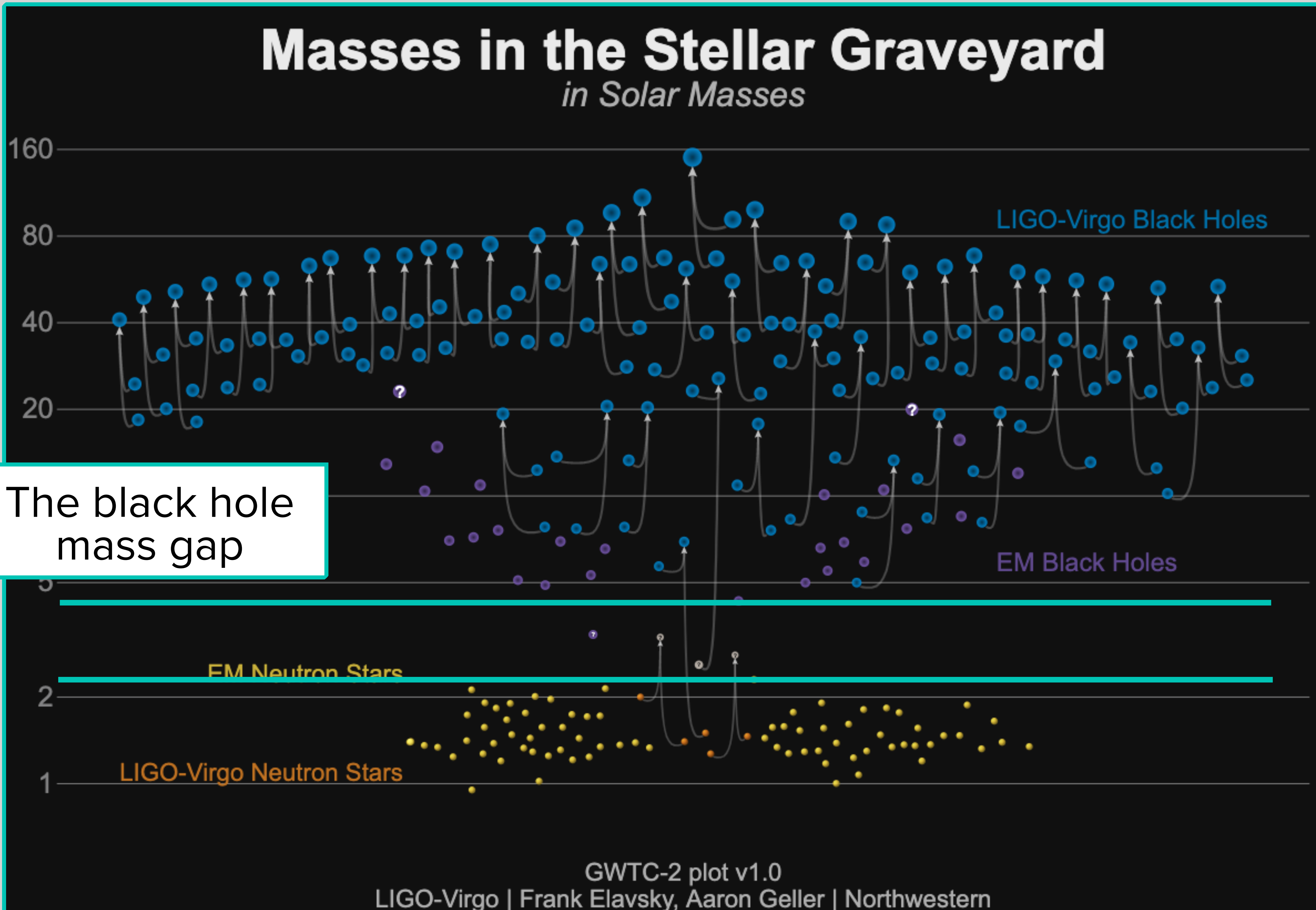
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF



C. L. Fryer & V. Kalogera, ApJ 554 (2001) 548; F. Özel, et al., ApJ, 725 (2010) 1918
https://ligo.northwestern.edu/media/mass-plot/index.html



The black hole mass gap

C. L. Fryer & V. Kalogera, ApJ 554 (2001) 548; F. Özel, et al., ApJ, 725 (2010) 1918

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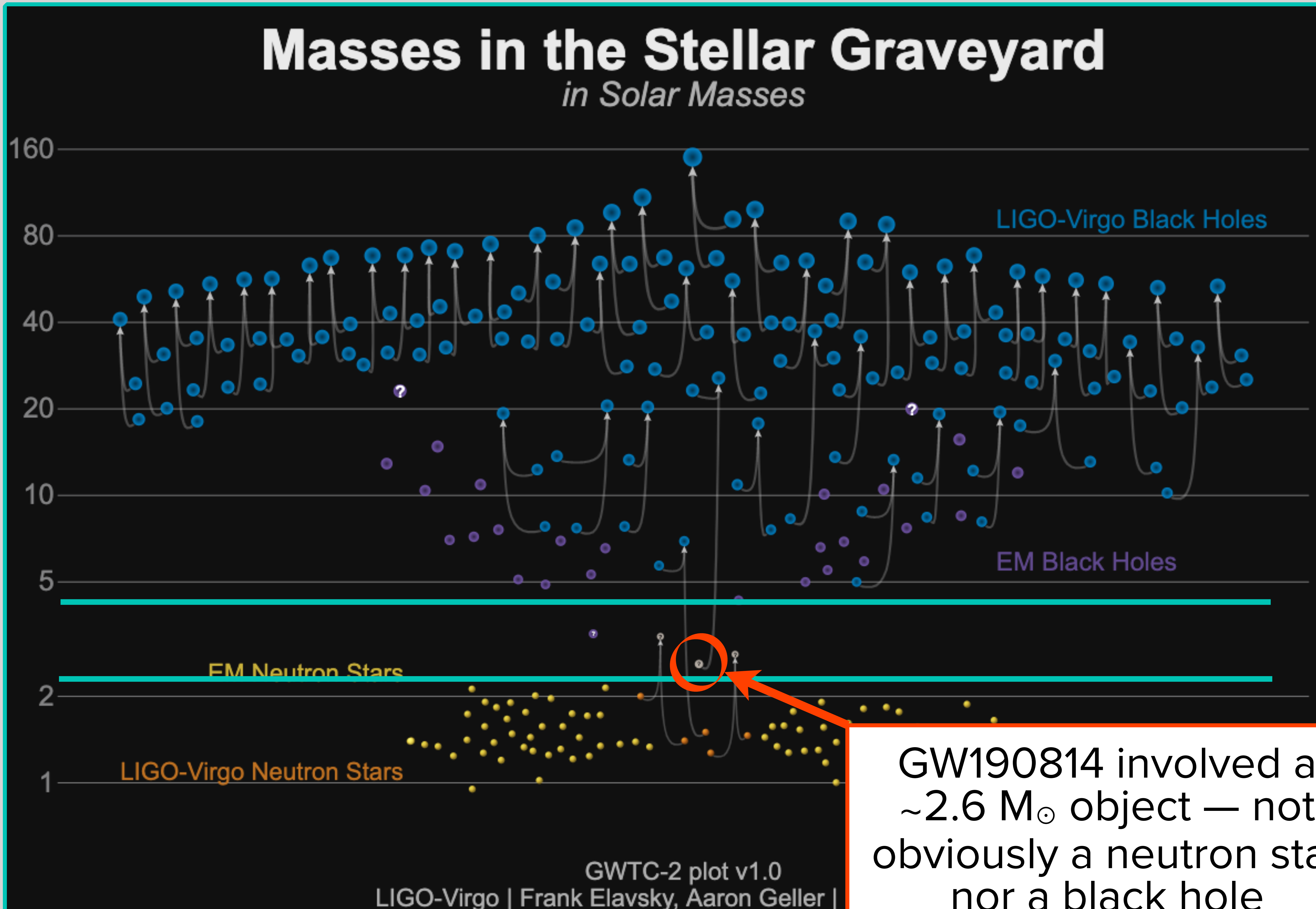

GW190814 involved a ~2.6 $M_\odot$ object — not obviously a neutron star nor a black hole

C. L. Fryer & V. Kalogera, ApJ 554 (2001) 548; F. Özel, et al., ApJ, 725 (2010) 1918

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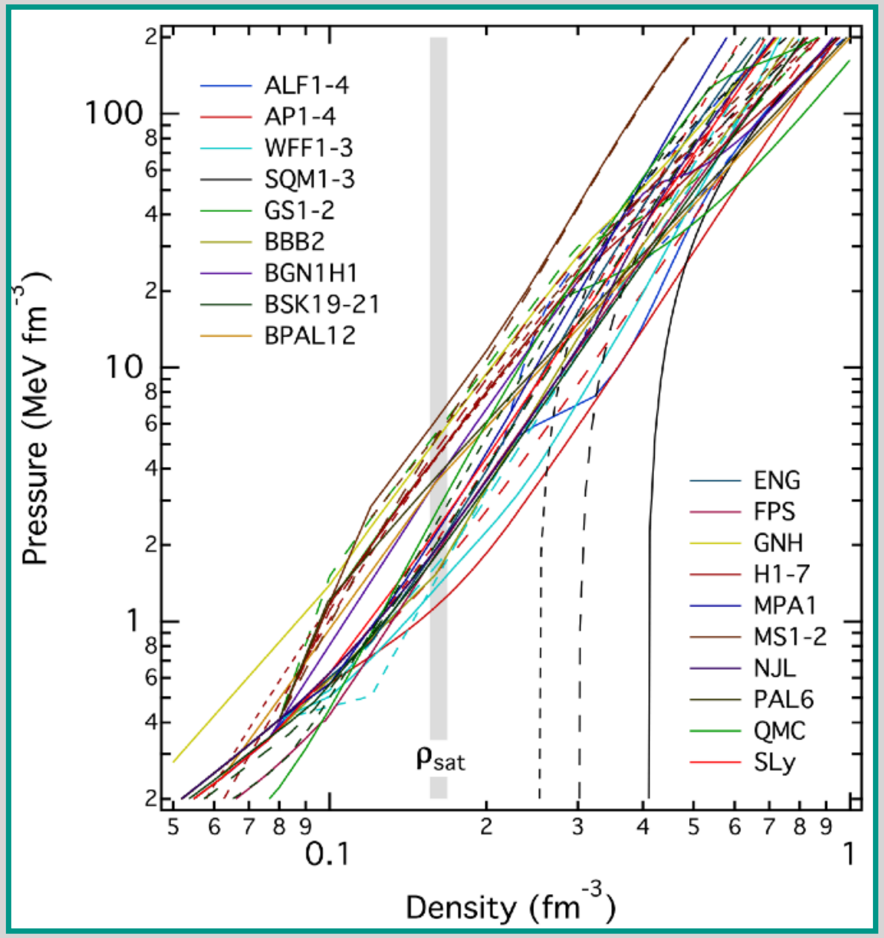
GW190814 — A Neutron Star or Not?

Why does this *matter*?

- GW events can tell us about the *equation of state* (EoS) of nuclear matter
- Most candidate EoS cannot *easily* accommodate a NS this heavy — such an object would have to be rather *special*



In all likelihood, we'll never *know* what this object was – but we're very likely to find more objects in this mass range with GWs!

If the black hole mass gap is populated with heavy NSs, then there's likely something *new* happening in nuclear matter

F. Özel & P. Freire, Ann. Rev. Astron. Astrophys. 54 (2016) 401 *; C. Breu & L. Rezzolla, MNRAS 459 (2016) 1, 646;*
R. Essick & P. Landry, ApJ 904 (2020) 1, 80

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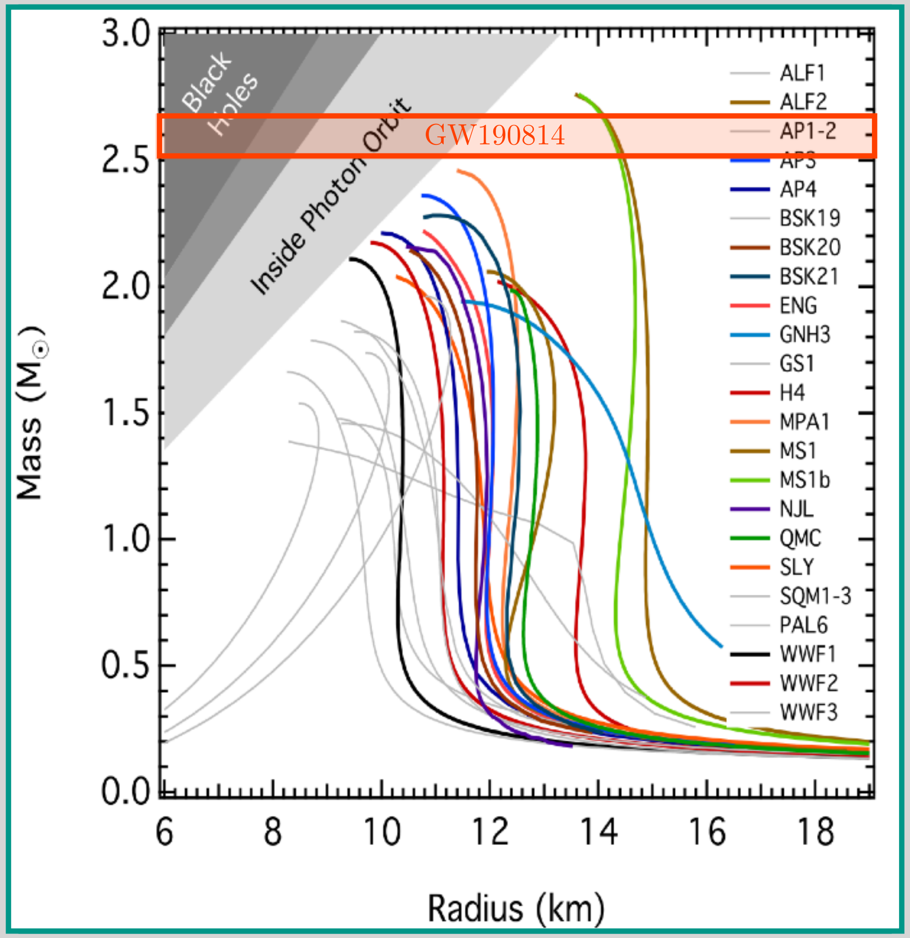

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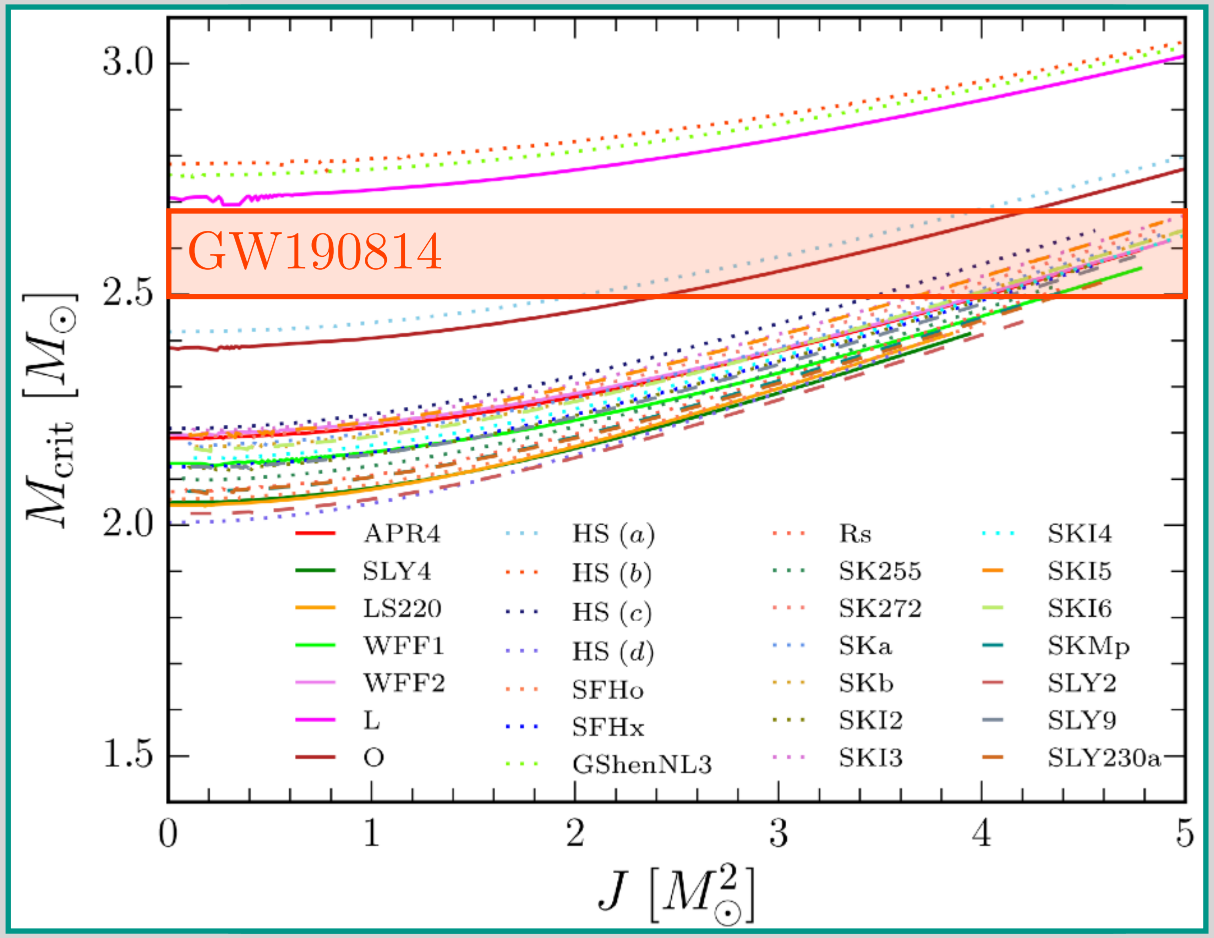

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New Physics in Neutron Stars

The big question: *To what extent can new baryon-coupled physics modify the properties of neutron stars?*

- If the new interaction is a *vector* interaction, then it is necessarily *repulsive* between neutrons – this makes the EoS *stiffer*, which allows for heavier stars

$$V_{\mathrm{NP}} = \frac{\alpha_{nn}}{r} e^{-M_X r}$$

- This heavy boson is associated with some *spontaneously broken gauge symmetry*; symmetry-breaking effects may be observable elsewhere
- If the new boson is heavier than the pion, then its effects in nuclei can be obscured — but it may have observable effects at supranuclear densities
- There are opportunities to probe the existence of a new boson in this mass range in η and η' decays

Calculation Details — An Overview

There are two main pieces to the calculation:

1. Evaluate the EoS using *Brueckner-Hartree-Fock* (BHF) theory:

$$G(\omega) = V + V\frac{Q}{\omega - h_0}G(\omega);\; V = V_{\mathrm{AV18}} + V_{\mathrm{NP}}$$

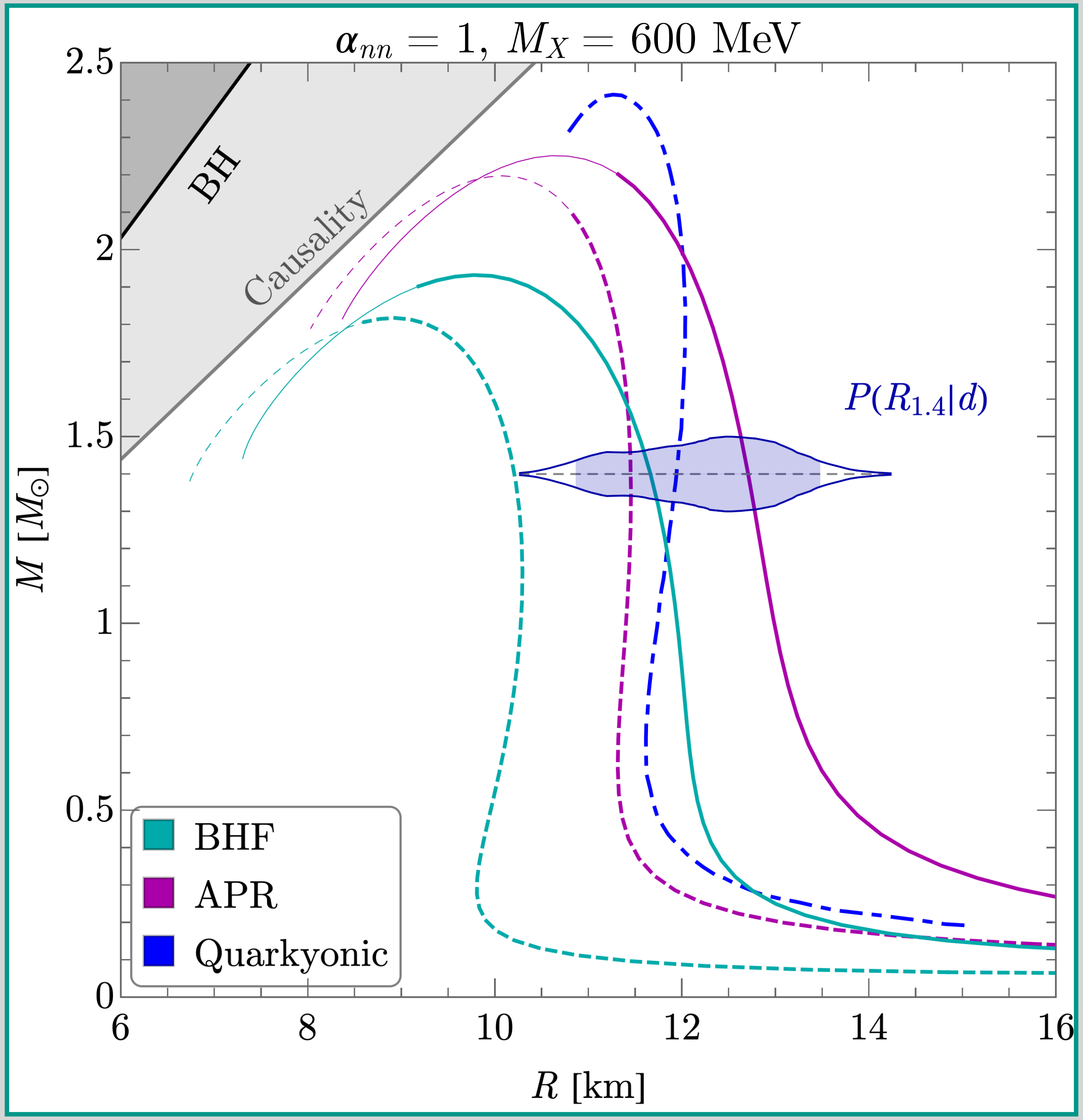
$$U(k_m) = \int_{k_n \leq k_F} d^3\vec{k}_n\, G(\omega = E(k_m) + E(k_n))$$
$$E = \int_{k_m \leq k_F} d^3\vec{k}_m \left(T(k_m) + \tfrac{1}{2}U(k_m)\right)$$

2. Numerically integrate *Tolman-Oppenheimer-Volkov* (TOV) equations:

$$\frac{dp}{dr} = \frac{[p(r) + \varepsilon(r)]\,[m(r) + 4\pi r^3 p(r)]}{r\,[r - 2m(r)]} \qquad \frac{dm}{dr} = 4\pi r^2 \varepsilon(r)$$

R. B. Wiringa, et al., PRC 51 (1995) 38; M. Piarulli, et al., PRC 101 (2020) 4, 045801

Masses and Radii



We consider two baseline EoS for *pure neutron matter*:

1. Our nominal BHF treatment
2. Splice with APR EoS

The inclusion of our new interaction allows for *heavier stars* — but they're also *puffier!*

For comparison, we show candidate EoS with transition to *quarkyonic matter*

We require $\mathcal{O}(1)$ couplings — *large*, but sma*ller than in SM!*

J. Lattimer, Ann. Rev. Nucl. Part. Sci. 62 (2012) 485; A. Akmal, PRC 58 (1998) 1804
P. Landry, et al., PRD 101 (2020) 12, 123007; L. McLerran & S. Reddy, PRL 122 (2019) 12, 122701

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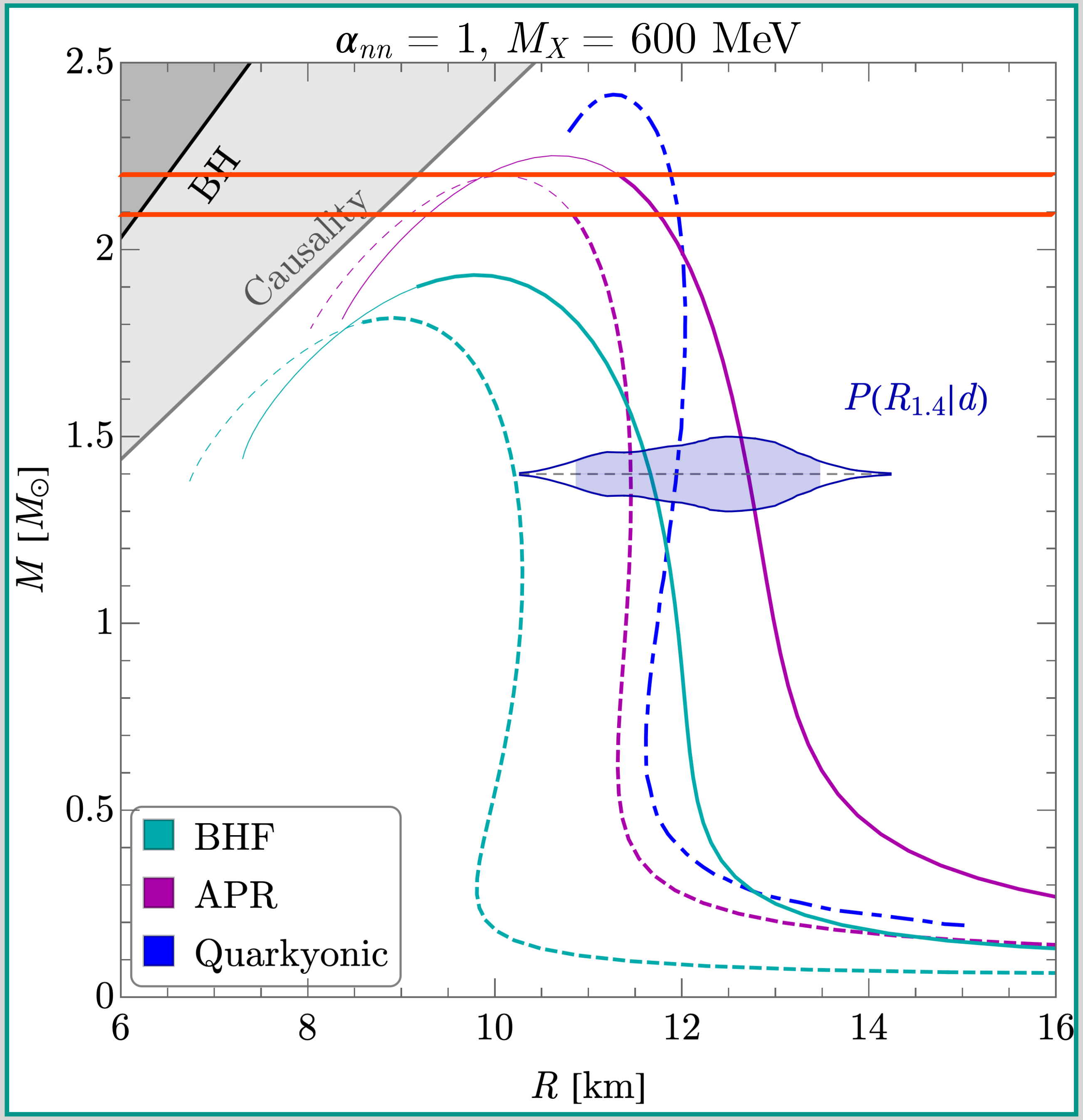

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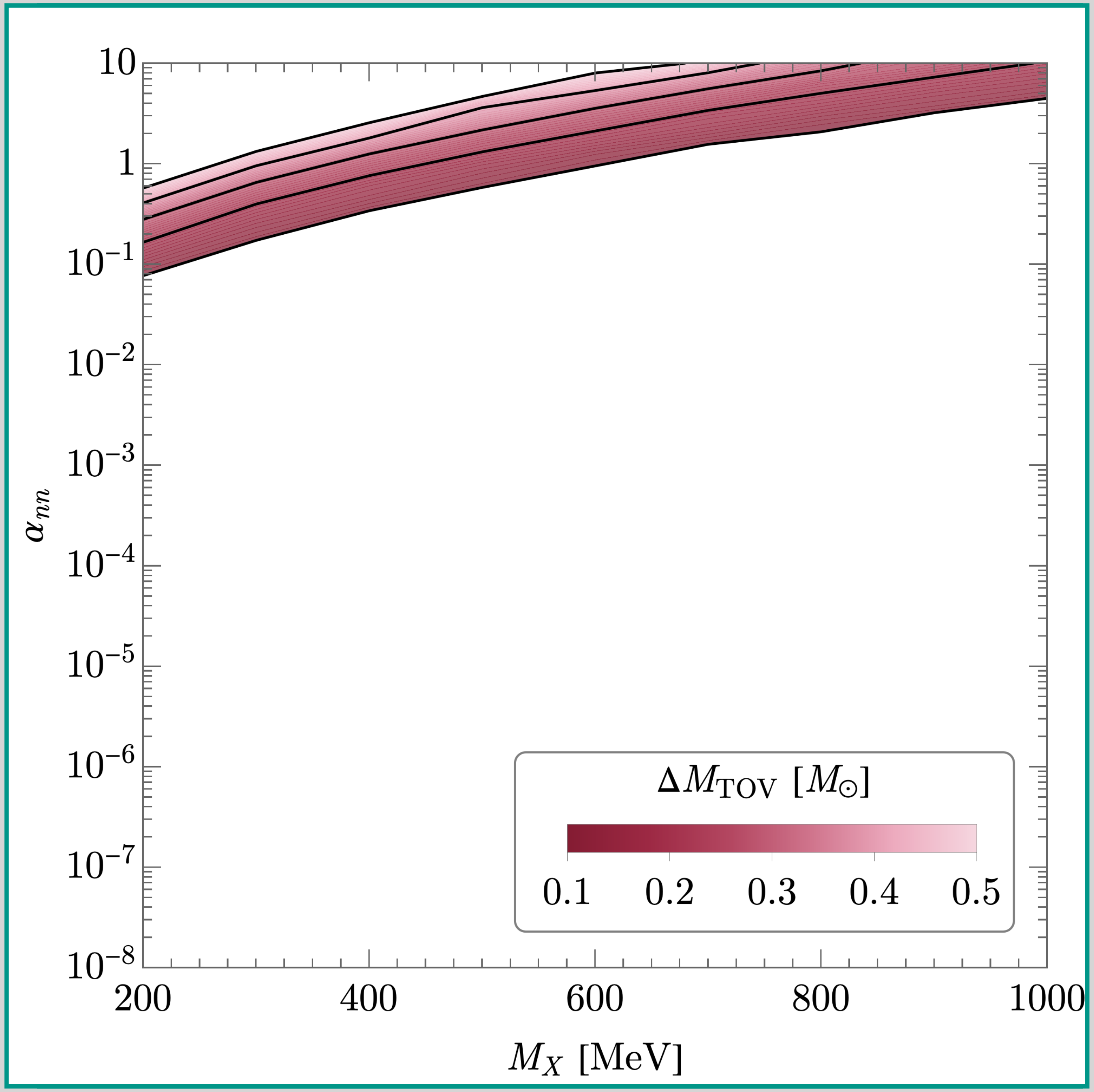

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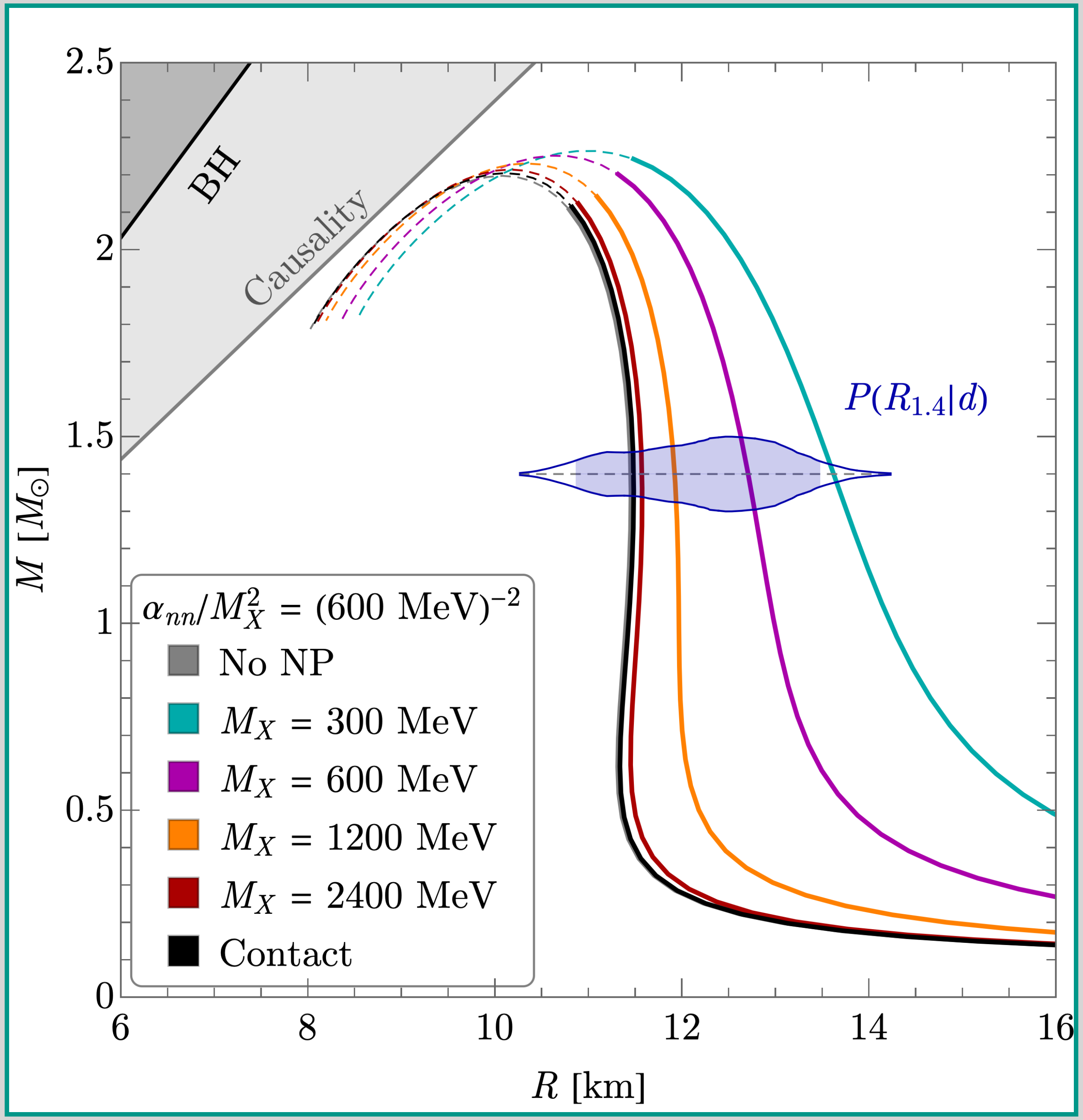
Peeking Inside Contact Interactions



In-medium effects change the dependency on α_{nn} & M_X relative to naive expectation

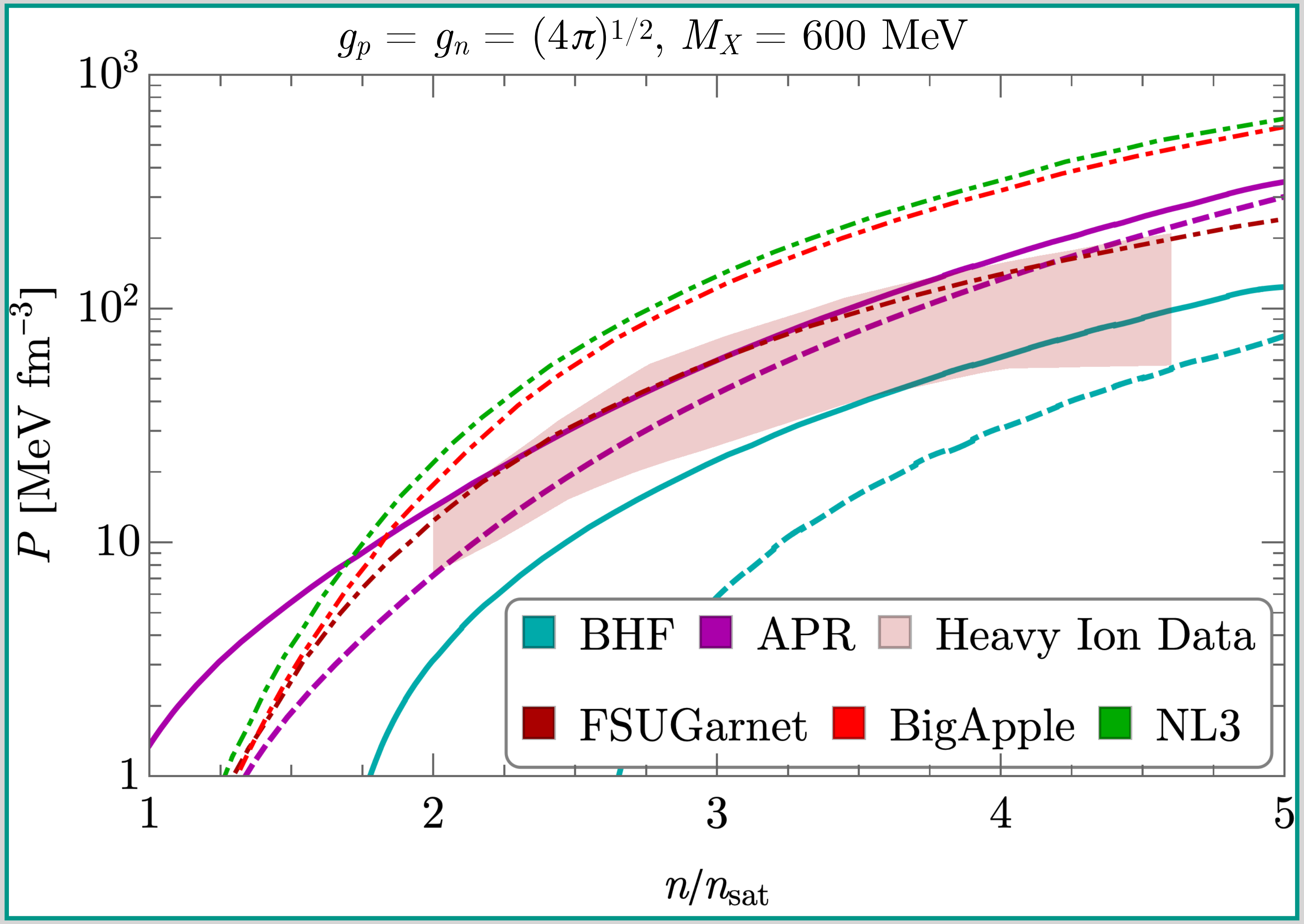
These are sensitive to all energy scales; this induces a difference between a *contact* interaction with this strength and a specific *completion* thereof!

Going beyond contact limit also introduces *higher partial waves*

(Note the *small* difference between no NP and contact interaction)

J. Lattimer, Ann. Rev. Nucl. Part. Sci. 62 (2012) 485; A. Akmal, PRC 58 (1998) 1804
P. Landry, et al., PRD 101 (2020) 12, 123007

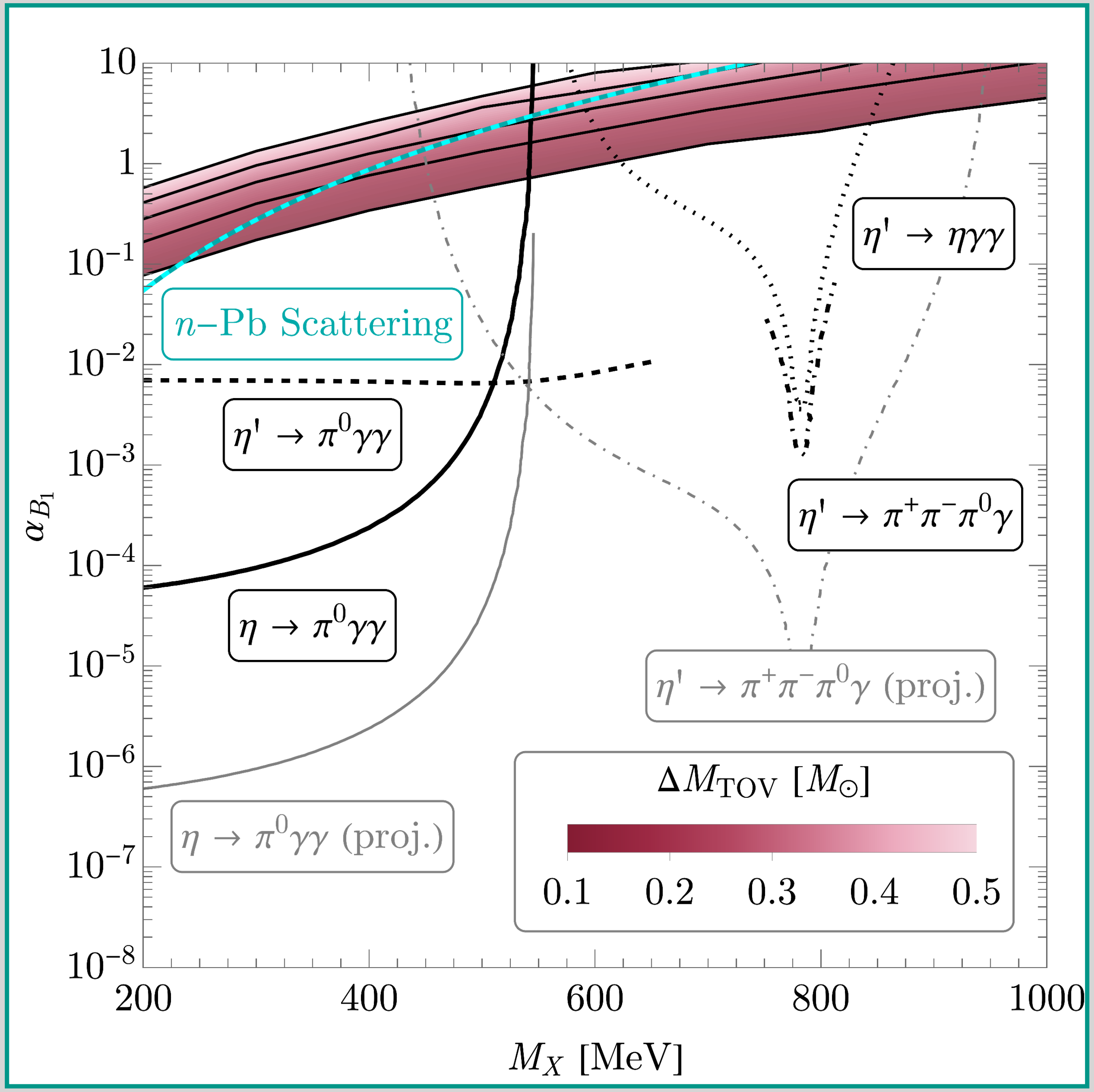
Comparison with Heavy-Ion Data



Our candidate EoS are reasonably consistent with heavy-ion collision (HIC) data; our approach has an advantage over mean-field models in this regard

P. Danielewicz, et al., Science 298 (2002) 1592; F. J. Fattoyev, et al., PRC 102 (2020) 6, 065805

Constraints and Sensitivities?



Constraints/sensitivities on a representative model, $U(1)_{B_1}$

- Couple to first generation to avoid J/ψ, Υ constraints
- Assuming negligible *kinetic mixing*
- *NN* scattering does not provide a robust constraint
- Pb-n scattering evaluated at *Born level*; requires dedicated reanalysis
- η/η' decay constraints *could be* quite restrictive, but demand further investigation

R. Barbieri & T. E. O. Ericson, PLB 57 (1975) 270; H. Leeb & J. Schmiedmayer, PRL 68 (1992) 1472; S. Tulin, PRD 89 (2014) 11, 114008; R. Escribano, et al., PRD 102 (2020) 3, 034026; L. Gan, et al., arXiv:2007.00664 & References Therein

Conclusions and Other Thoughts

In principle, introducing a new *repulsive* interaction between neutrons can stiffen the EoS such that NSs can be *demonstrably* and *naturally* heavier

This does not *replace* critical QCD phenomena as a possibility, but can give an *added* boost that is *testable* at existing facilities!

- Resolution to *hyperon puzzle?*
- Possible connections to *dark matter?*

Recall the orientation of this talk:

- As second- and third-generation GW observatories start up, we will be able to probe objects in the black hole mass gap
- If some of these can be demonstrated to be NSs, then this may be the result of new physics in the *strong* sector — and it may even be testable!

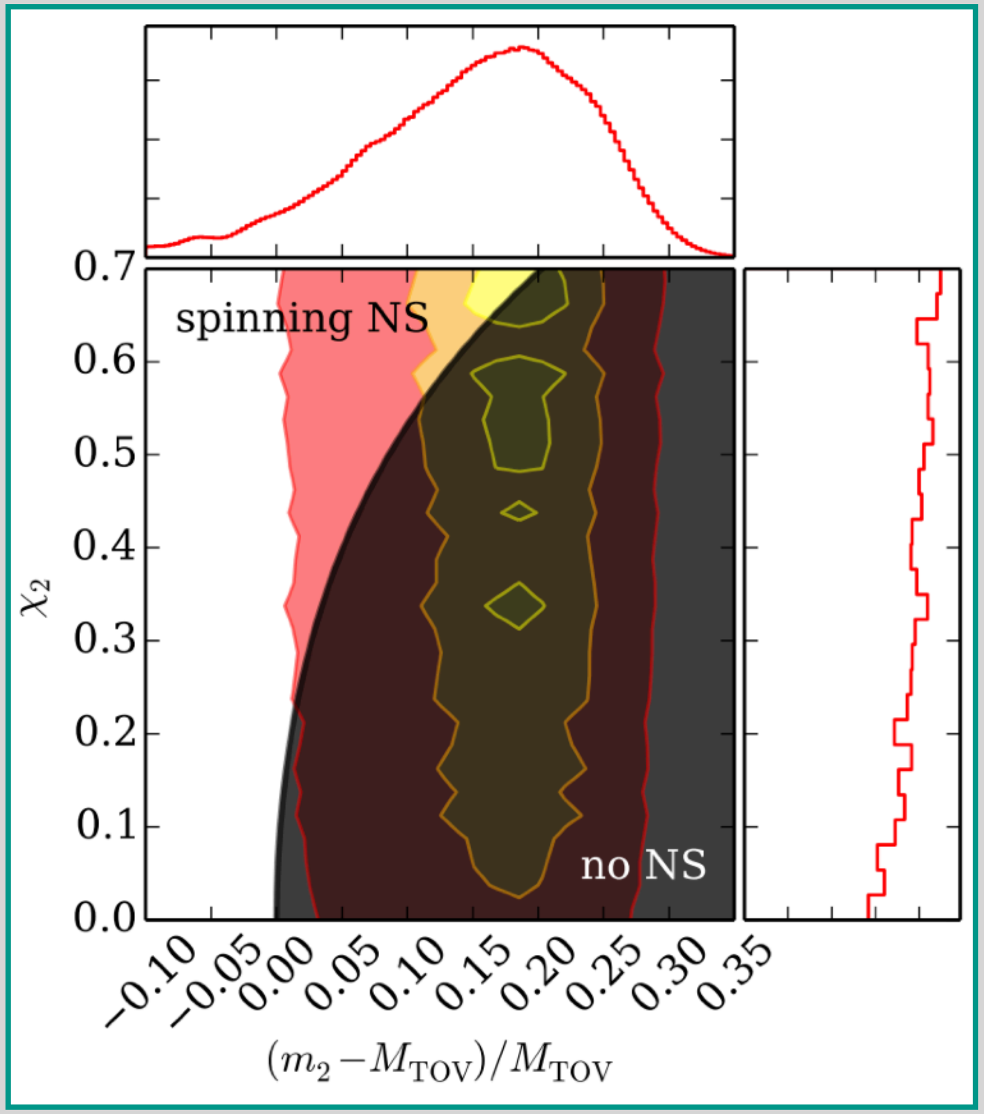
D. Lonardoni, PRL 114 (2015) 9, 092301; A. Del Popolo, et al., Phys. Dark Univ. 30 (2020) 100622

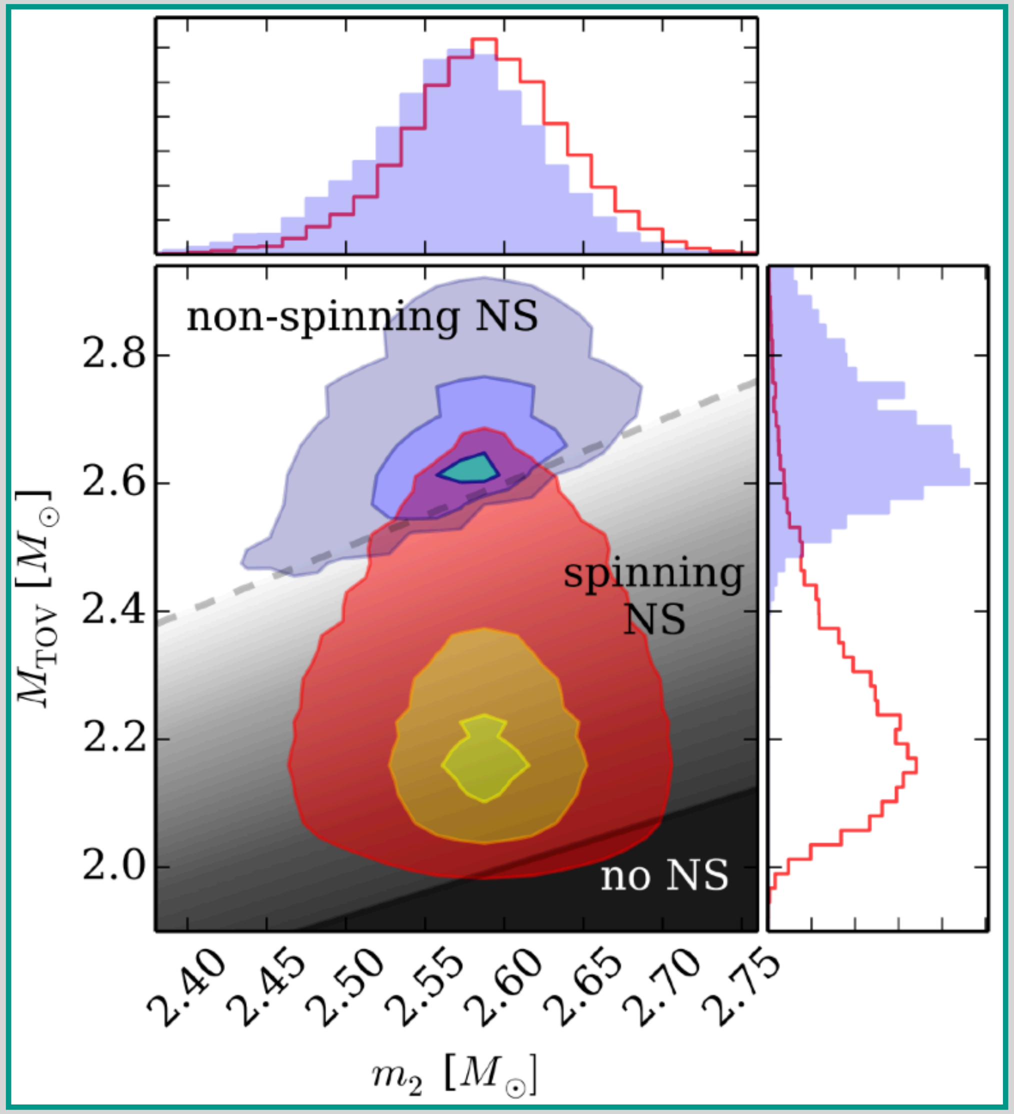
Back-Up Slides

Neutron Star Spin and GW190814

How compelling an explanation is spinning up the low-mass component of GW190814?

- As with most things, it depends on your prior!





R. Essick & P. Landry, ApJ 904 (2020) 1, 80

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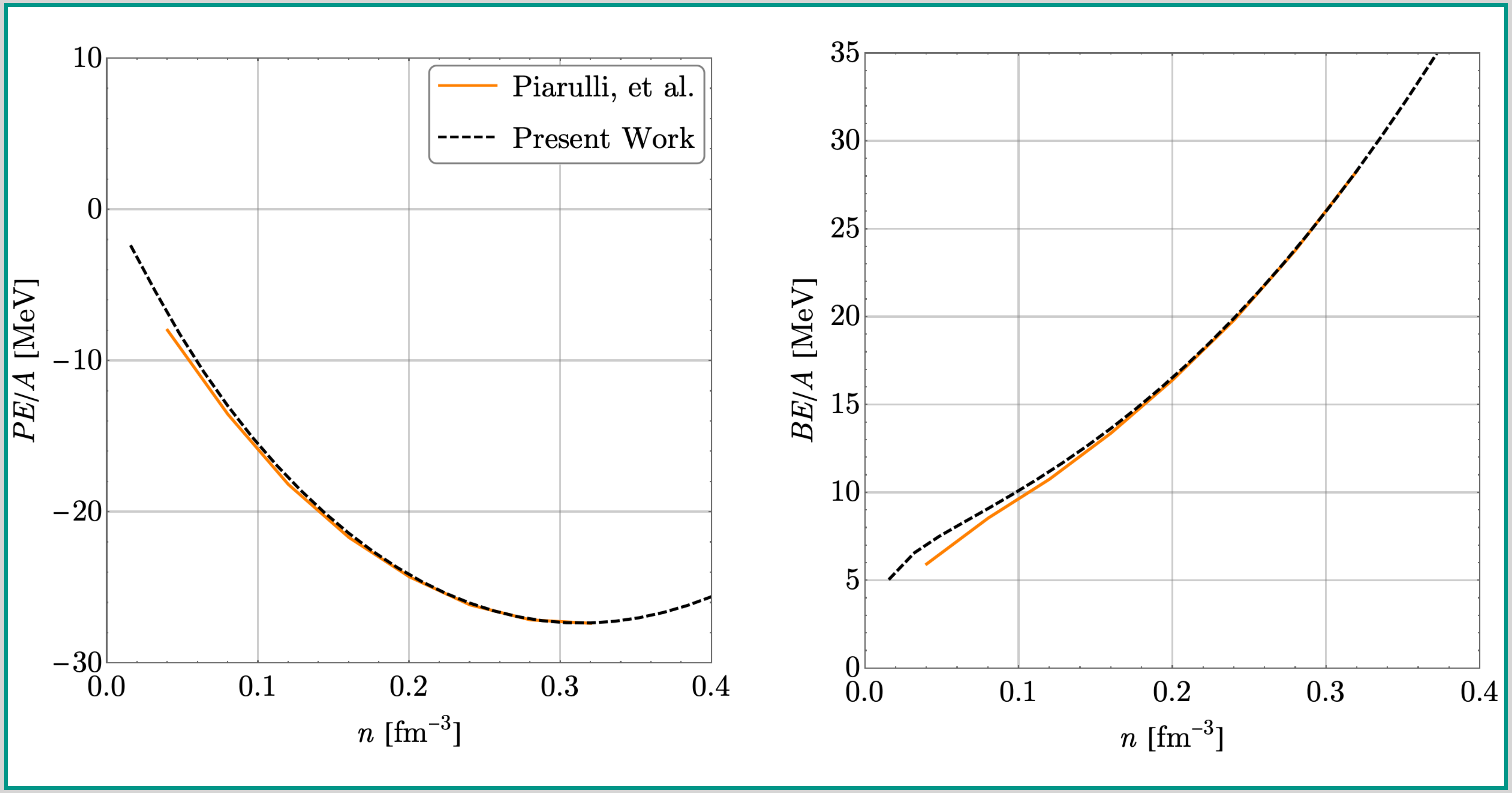
	$M_{\max}$	population prior $p(m_1, m_2)$				
		$p_0(m_1)p_0(m_2)$	$p_{\mathrm{PL}}(m_1)p_0(m_2)$	$p_{\mathrm{PL}}(m_1)p_{\mathrm{PL}}(m_2)q^4$	$p_{\mathrm{BRK}}(m_1)p_0(m_2)$	$p_{\mathrm{BRK}}(m_1)p_{\mathrm{BRK}}(m_2)q^4$
LEC	$M_{\mathrm{TOV}} \leq 2.3\,M_\odot$	$\leq 0.1\%$	$\leq 0.1\%$	$\leq 0.1\%$	$\leq 0.1\%$	$\leq 0.1\%$
LEC	M_{TOV}	$5.63 \pm 0.15\%$	$5.55 \pm 0.15\%$	$5.25 \pm 0.15\%$	$5.55 \pm 0.15\%$	$5.25 \pm 0.15\%$
LVC	M_{TOV}	$3.47 \pm 0.32\%$	$3.41 \pm 0.32\%$	$3.18 \pm 0.31\%$	$3.41 \pm 0.32\%$	$3.18 \pm 0.31\%$
FC	$M_{\max}$	$29.12 \pm 0.82\%$	$29.02 \pm 0.82\%$	$28.58 \pm 0.82\%$	$29.02 \pm 0.82\%$	$28.58 \pm 0.82\%$
LEC	$1.3M_{\mathrm{TOV}} \leq 2.7\,M_\odot$	$86.9 \pm 1.3\%$	$86.4 \pm 1.3\%$	$83.6 \pm 1.3\%$	$86.4 \pm 1.3\%$	$83.6 \pm 1.3\%$

R. Essick & P. Landry, ApJ 904 (2020) 1, 80

Comparing BHF Calculations



The punchline is that our results compare *favorably* to Piarulli, et al. ($J_{\mathrm{max}} = 11$); note these authors consider several many-body methods

M. Piarulli, et al., PRC 101 (2020) 4, 045801