Gravitational Laboratories for Nuclear Physics

Prospects for Binary Neutron Star Observations
and their Impact on the Equation of State

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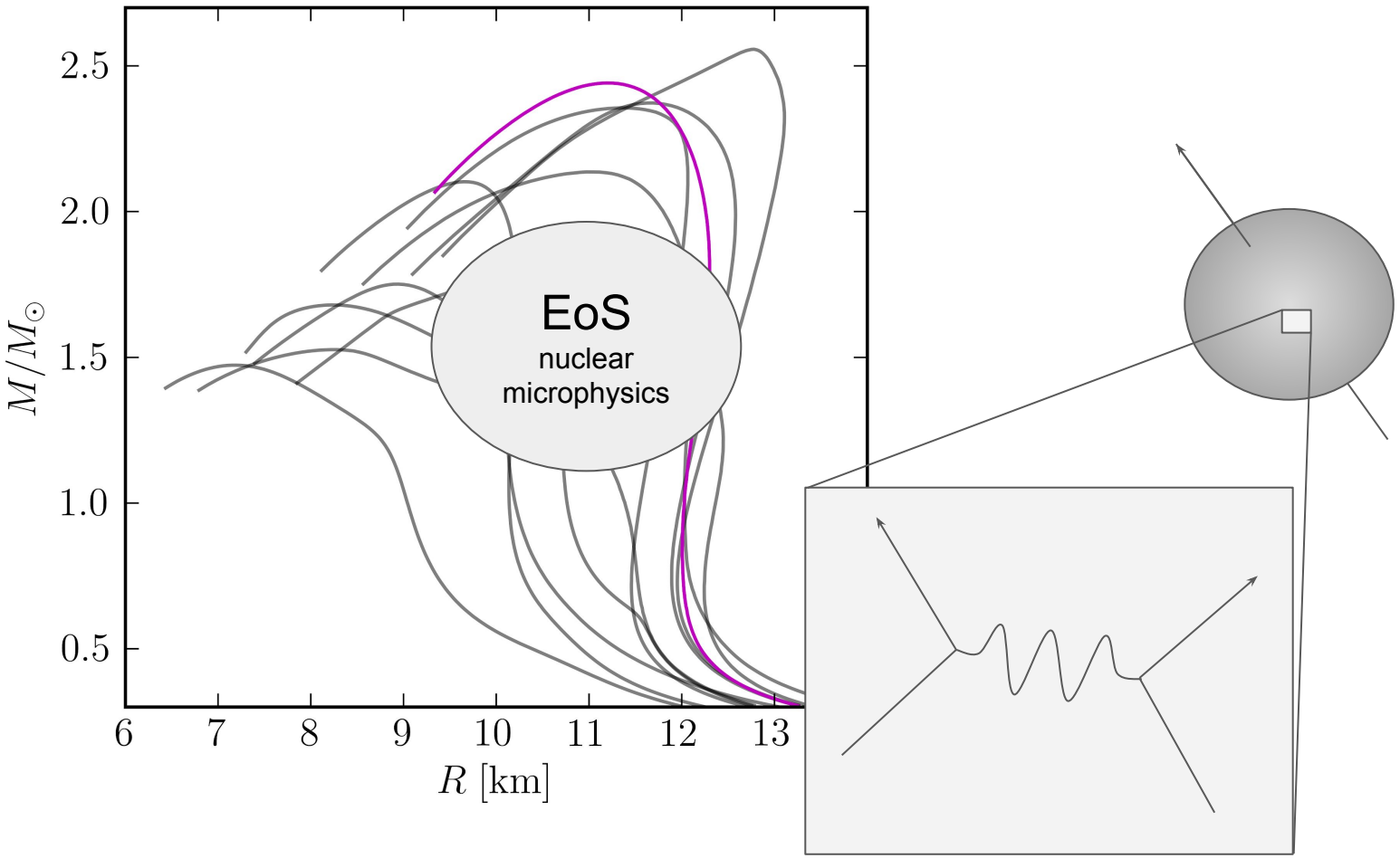
Perimeter Institute for Theoretical Physics

What Do We Observe?

What do we observe?



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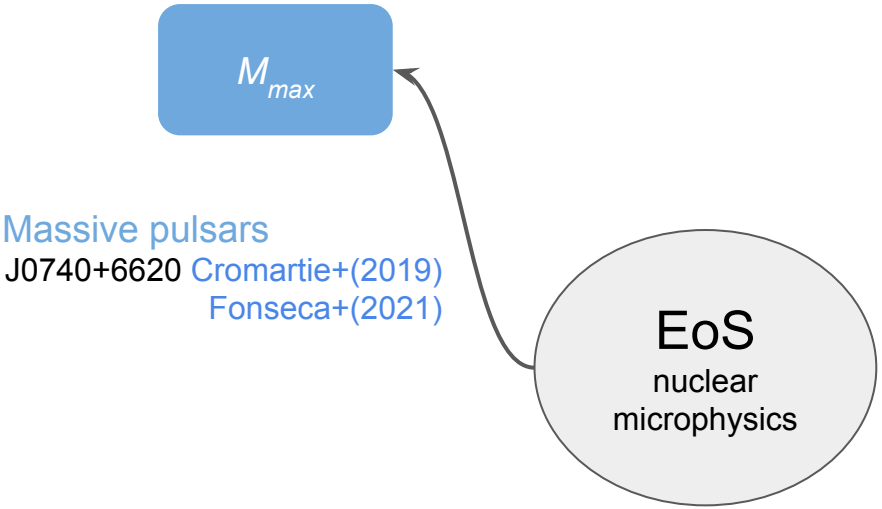
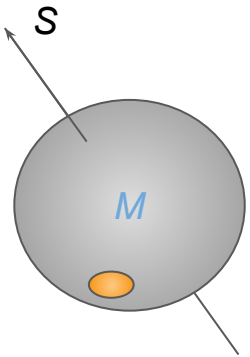
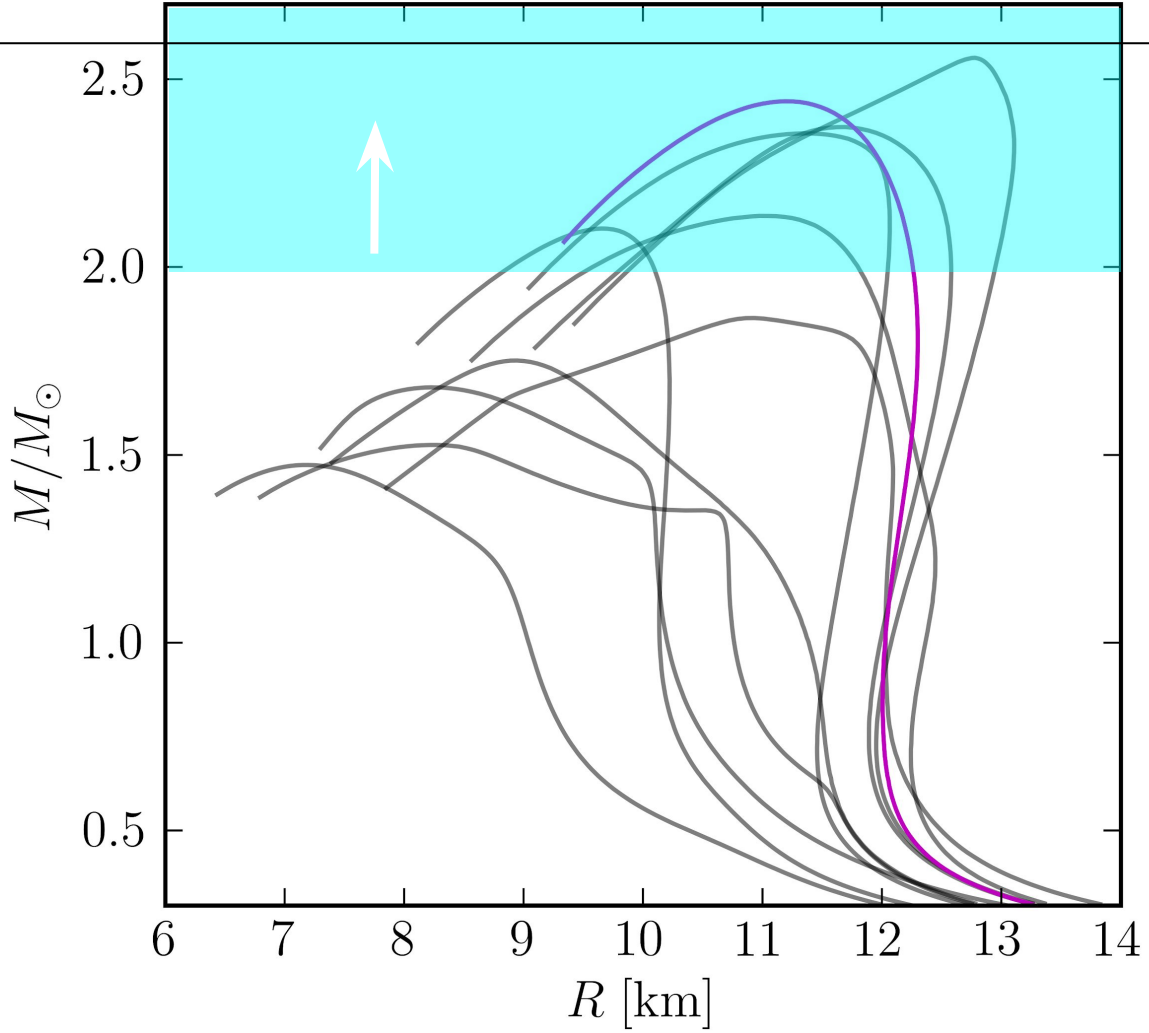




pulsar observations
radial velocity
Shapiro delay

What do we observe?



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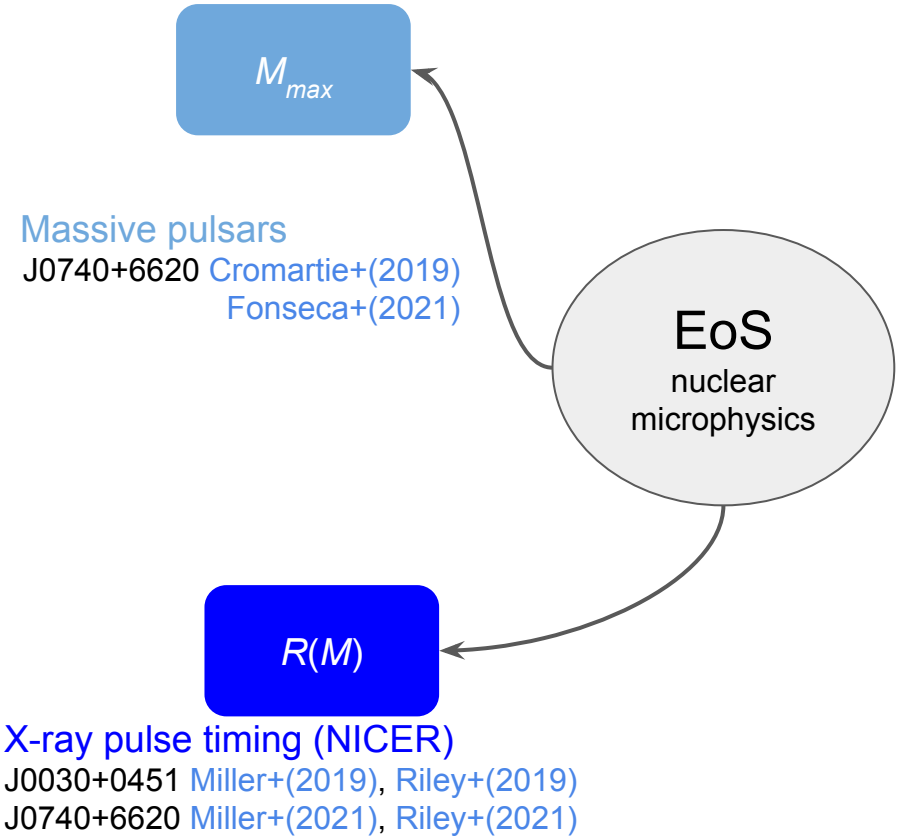

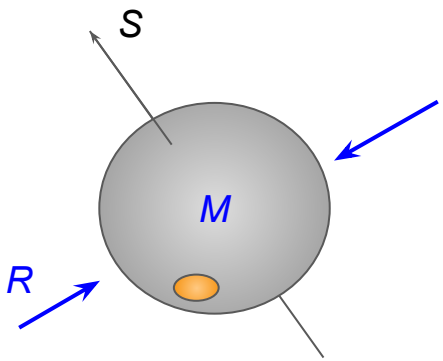

X-ray timing
Pulse profile modeling

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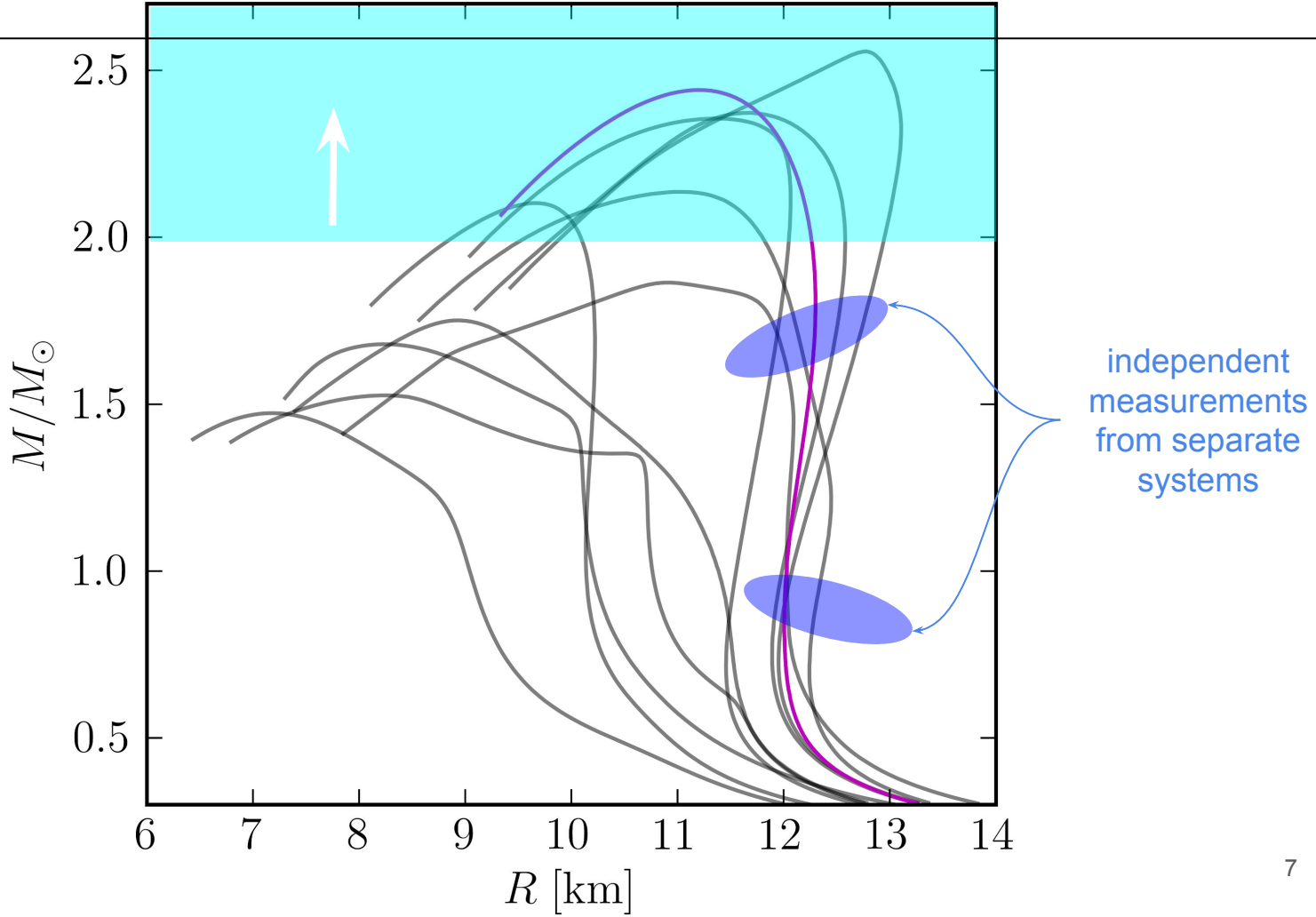

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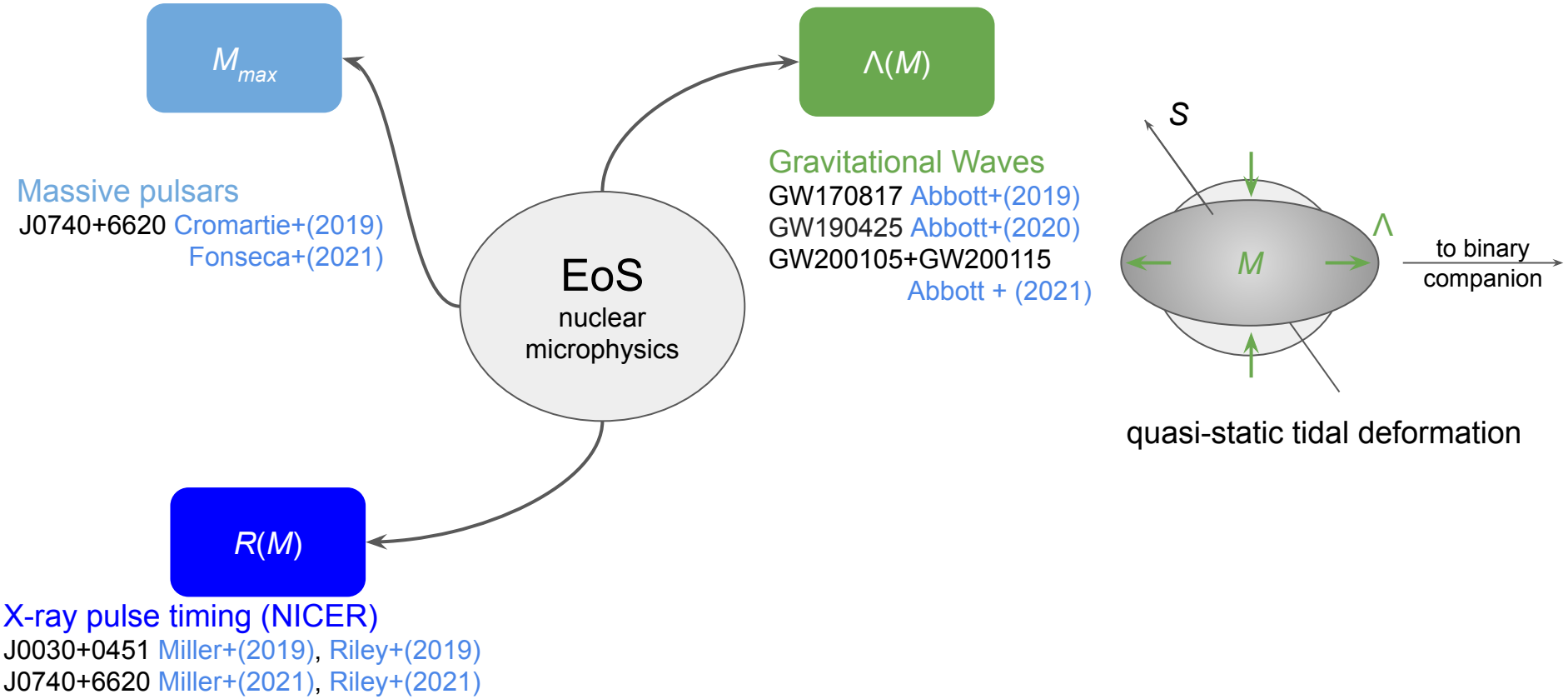

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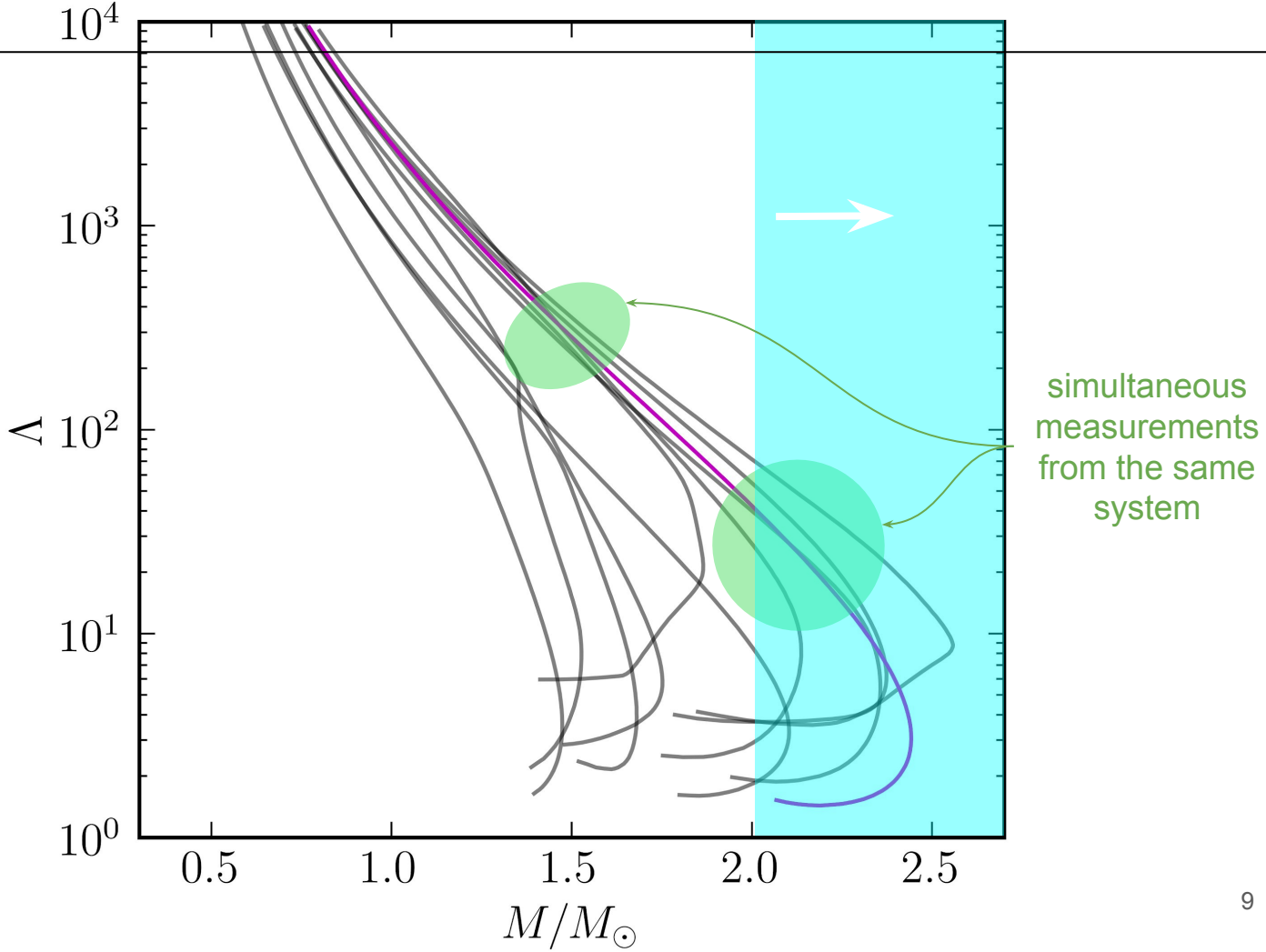

Current Astrophysical Constraints on the High-Density, Cold Equation of State

P. Landry and R. Essick, *Nonparametric Inference of the Neutron Star Equation of State from gravitational Wave Observations*, PRD 99, 084049 (2019)

R. Essick, P. Landry, and D. E. Holz, *Nonparametric Inference of Neutron Star Composition, Equation of State, and Maximum Mass with GW170817*, PRD 101, 063007 (2020)

P. Landry, R. Essick, and K. Chatziioannou, *Nonparametric Constraints on Neutron Star Matter with Existing and Upcoming Gravitational Wave and Pulsar Observations*, PRD 101, 123007 (2020)

I. Legred, K. Chatziioannou, R. Essick, S. Han, and P. Landry, *Impact of the PSR J0740+6620 Radius Constraint on the Properties of High-Density Matter*, PRD 104, 063003 (2021)

I. Legred, K. Chatziioannou, R. Essick, and P. Landry, *Implicit correlations within phenomenological parametric models of the neutron star equation of state*, PRD 105, 043016 (2022)

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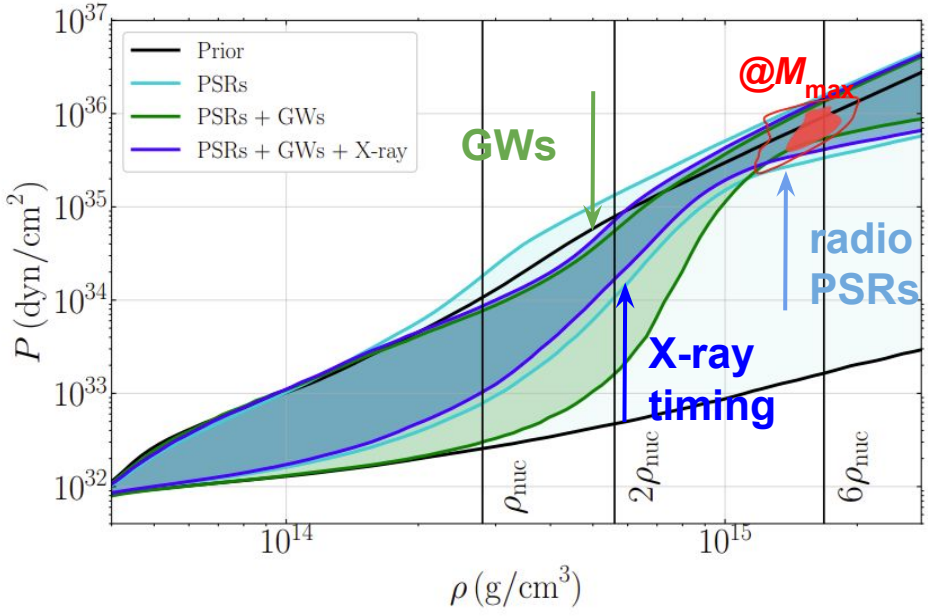

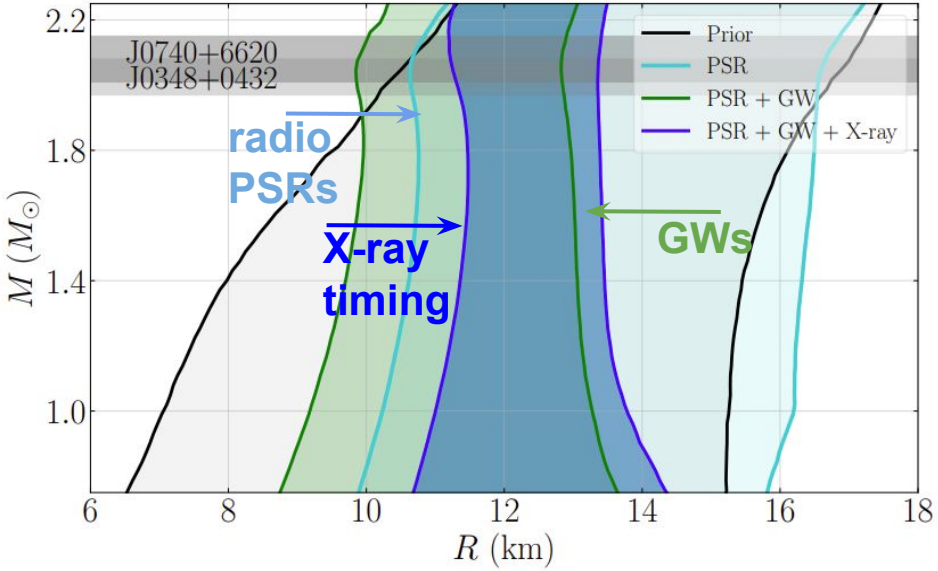

Legred+ (2021)

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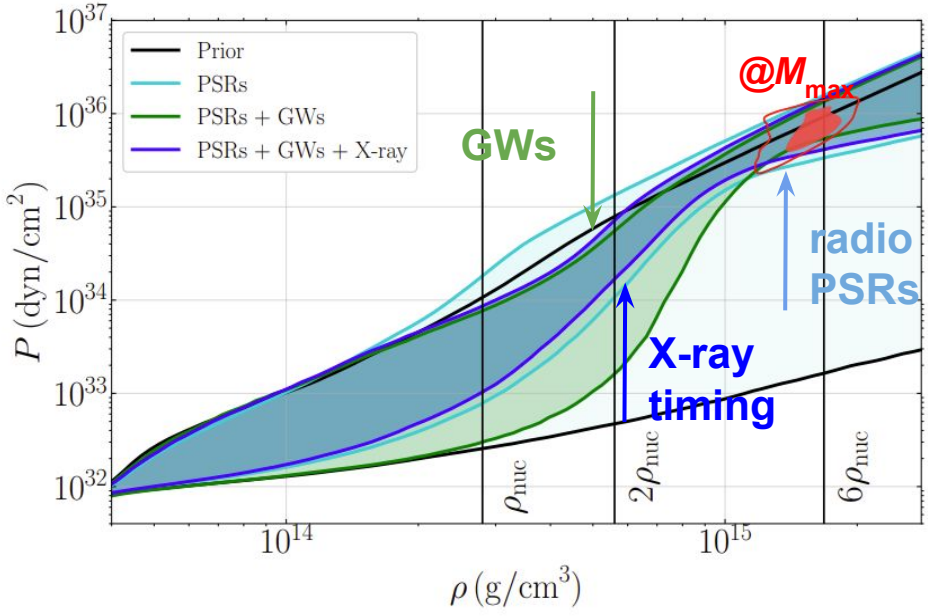
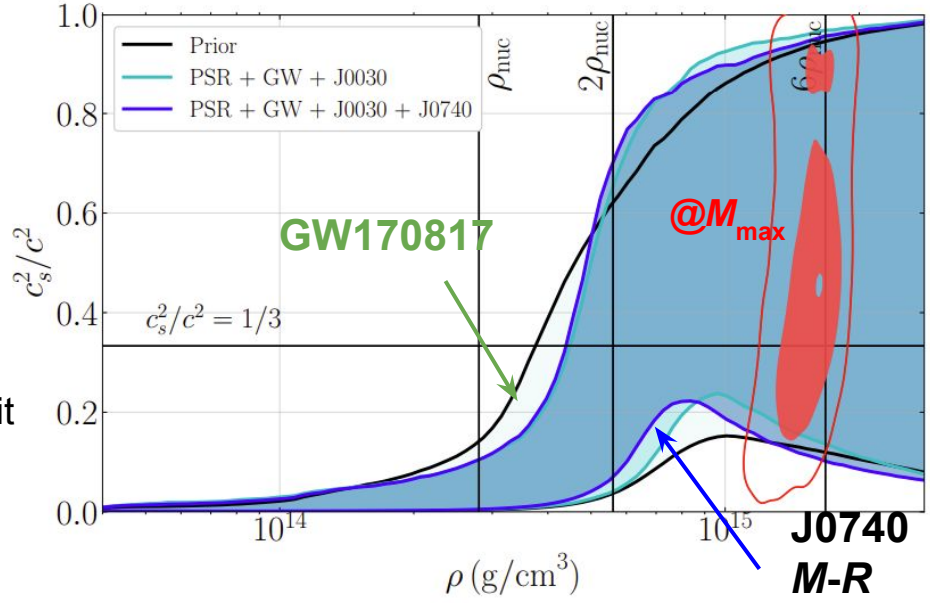


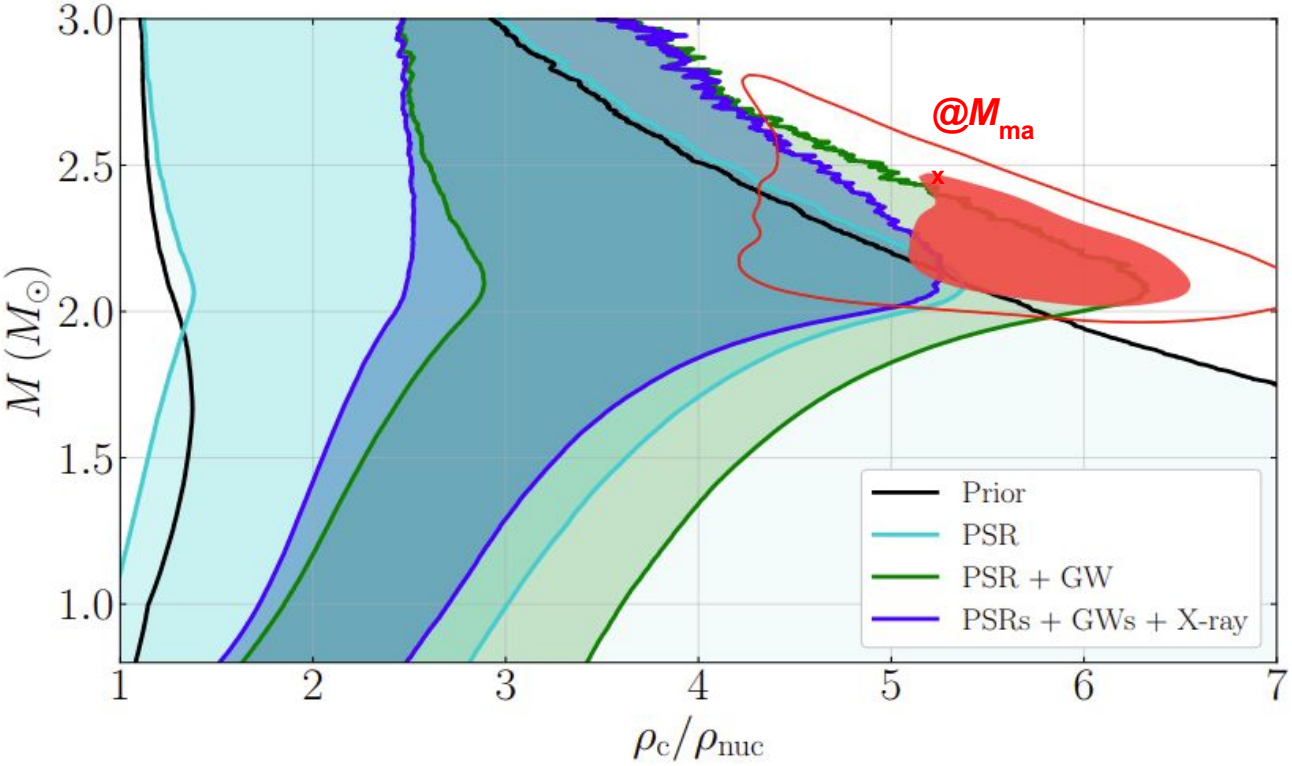


sound speed almost certainly exceeds the conformal limit
(suggests strongly-coupled interactions)

Legred+ (2021)

Current Astrophysical Constraints on the High-Density, Cold Equation of State

There is a limit to the densities we can probe within NSs



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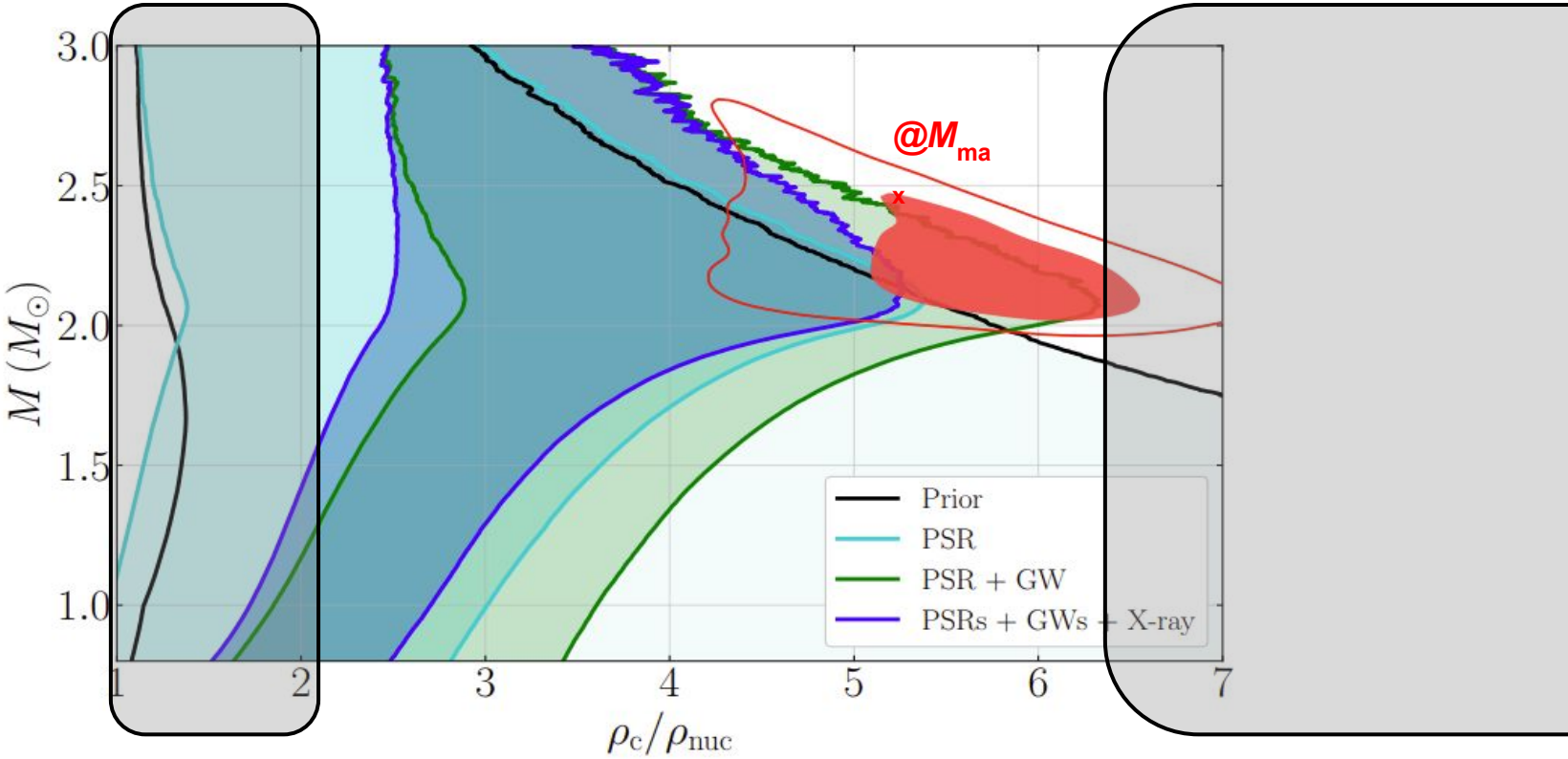

χEFT

Lynn+ (2016)
Drischler+ (2020), Drischler+ (2020)

pQCD

Komoltsev+Kurkela (2022)
Gorda+ (2022)

Legred+ (2021)

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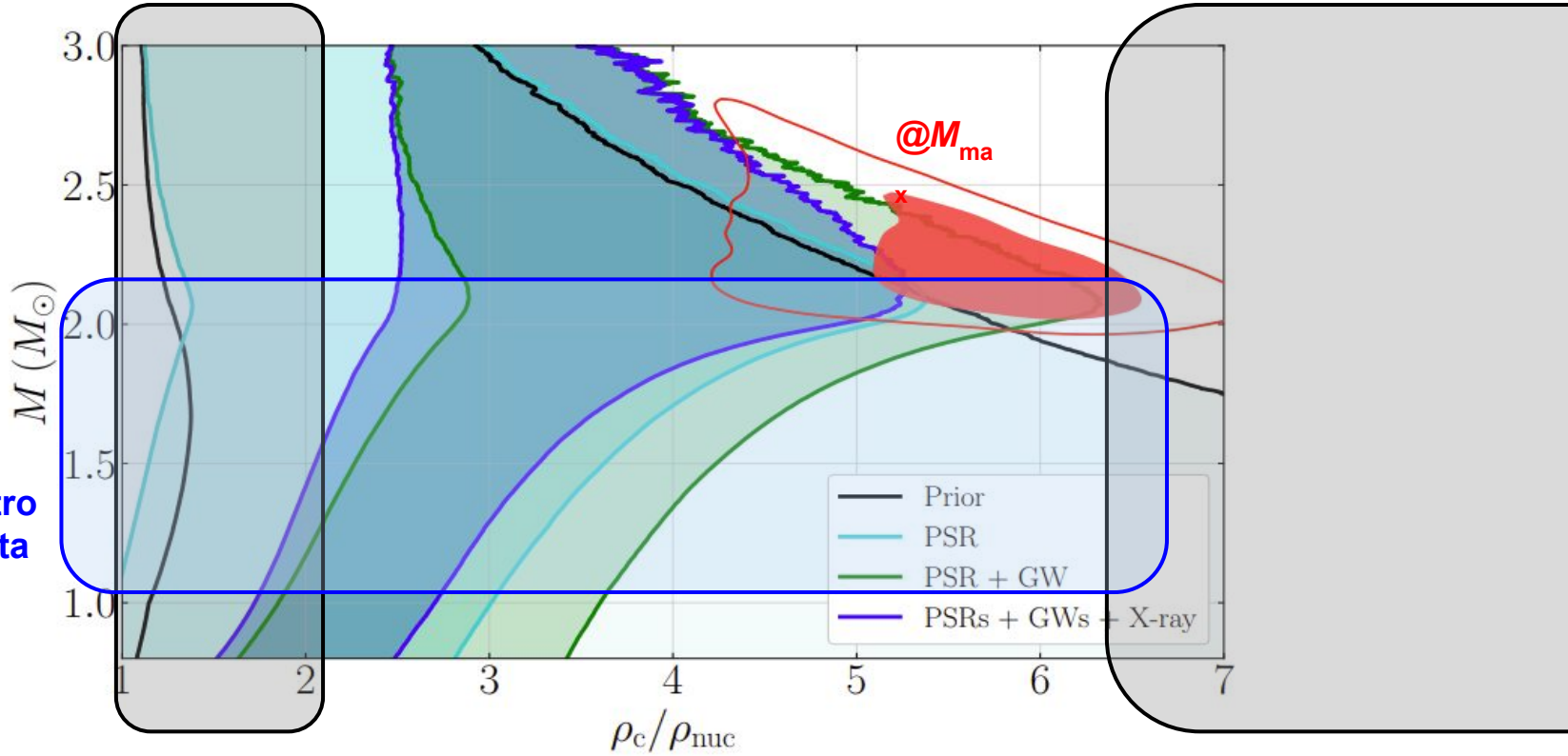

Astro Data

Abbott+ (2021)
Farah+ (2022)
Landry+Read (2021)

χEFT

Lynn+ (2016)
Drischler+ (2020), Drischler+ (2020)

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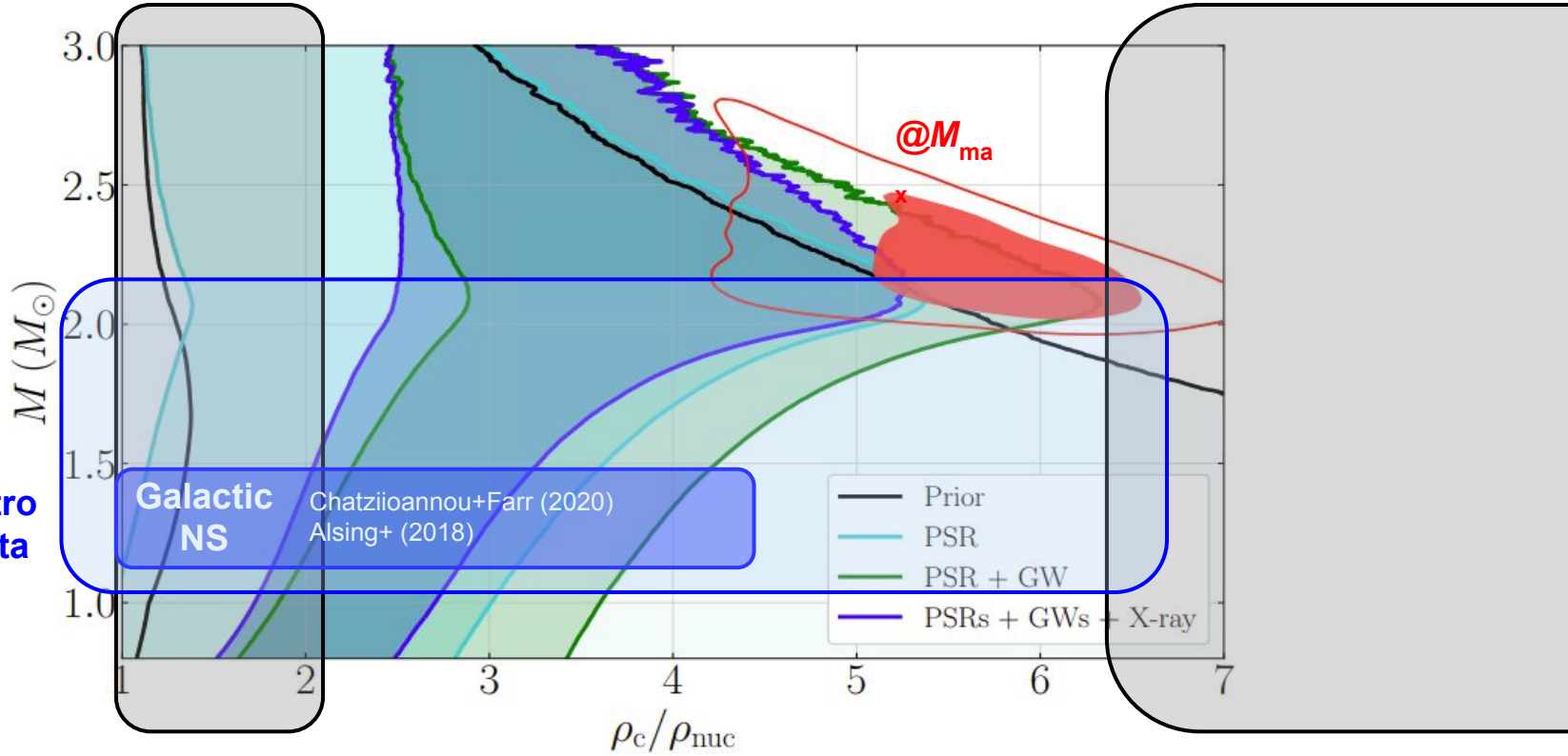

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Legred+ (2021)

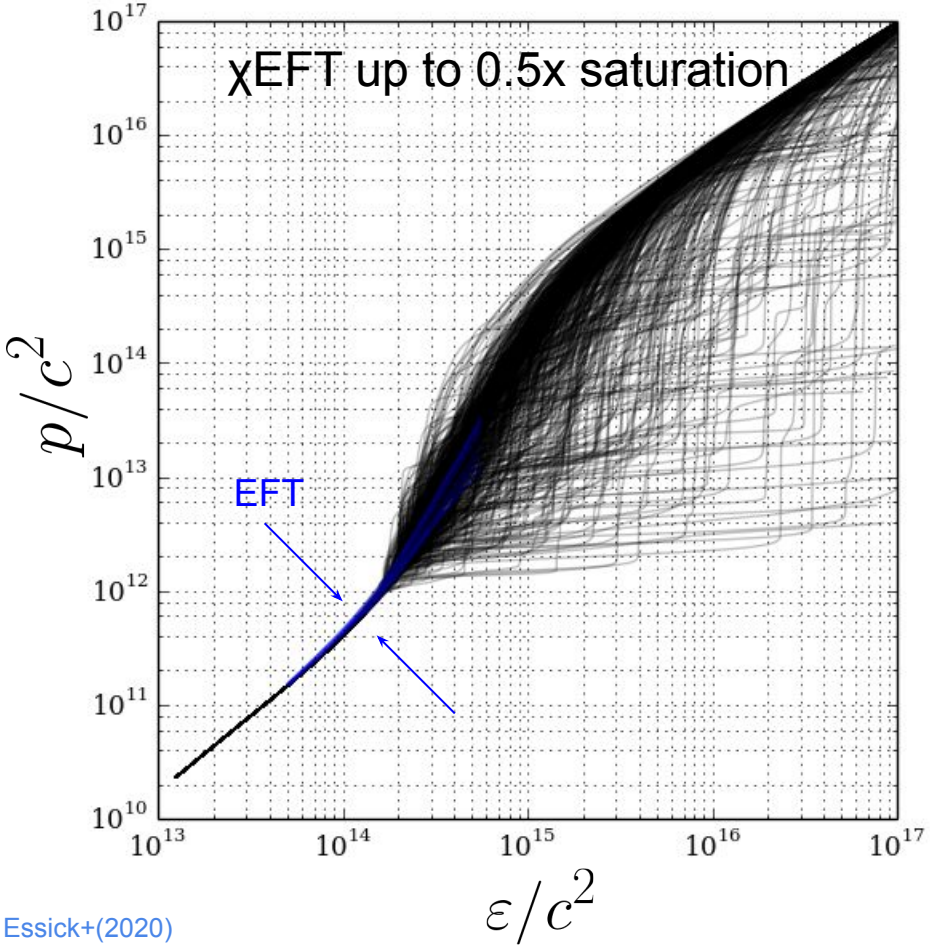
Comparisons with Terrestrial Nuclear Experiments and *ab initio* Theory

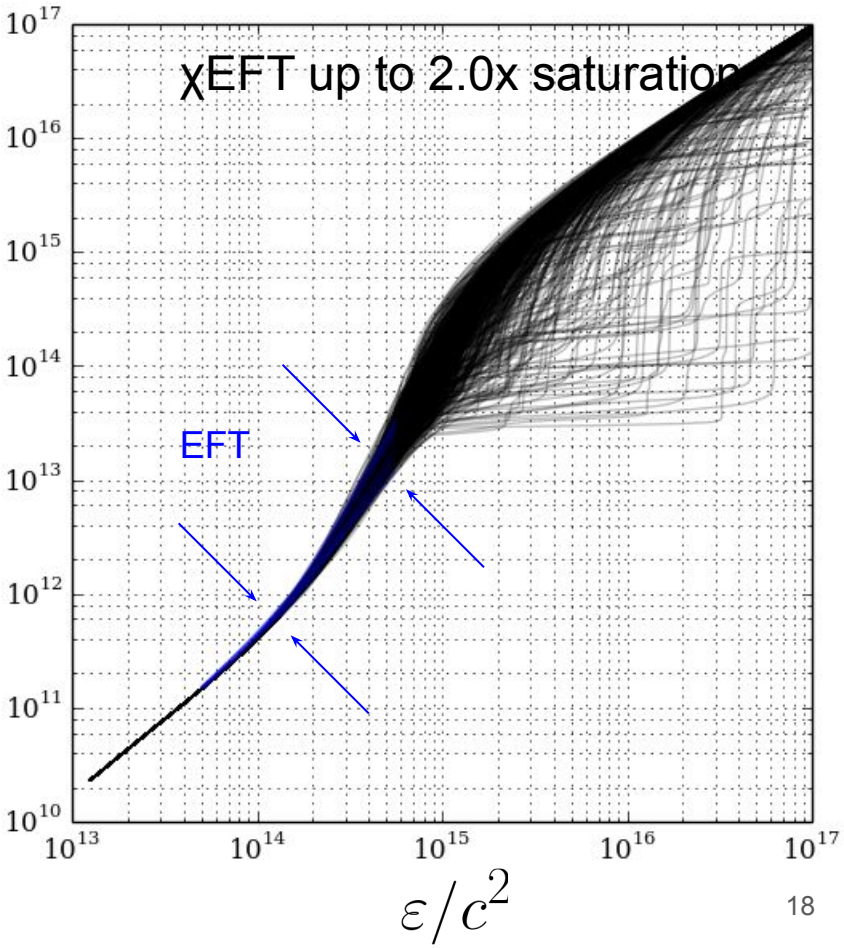
R. Essick, I. Tews, P. Landry, S. Reddy, D. E. Holz, *Direct Astrophysical Tests of Chiral Effective Field Theory at Supranuclear Densities*, PRC 102, 055803 (2020)

R. Essick, I. Tews, P. Landry, A. Schwenk, *Astrophysical Constraints on the Symmetry Energy and the Neutron Skin of* ^{208}Pb *with Minimal Modeling Assumptions*, PRL 127, 192701 (2021).

R. Essick, I. Tews, P. Landry, A. Schwenk, *A Detailed Examination of Astrophysical Constraints on the Symmetry Energy and the Neutron Skin of* ^{208}Pb *with Minimal Modeling Assumptions*, PRC 104, 065804 (2021)

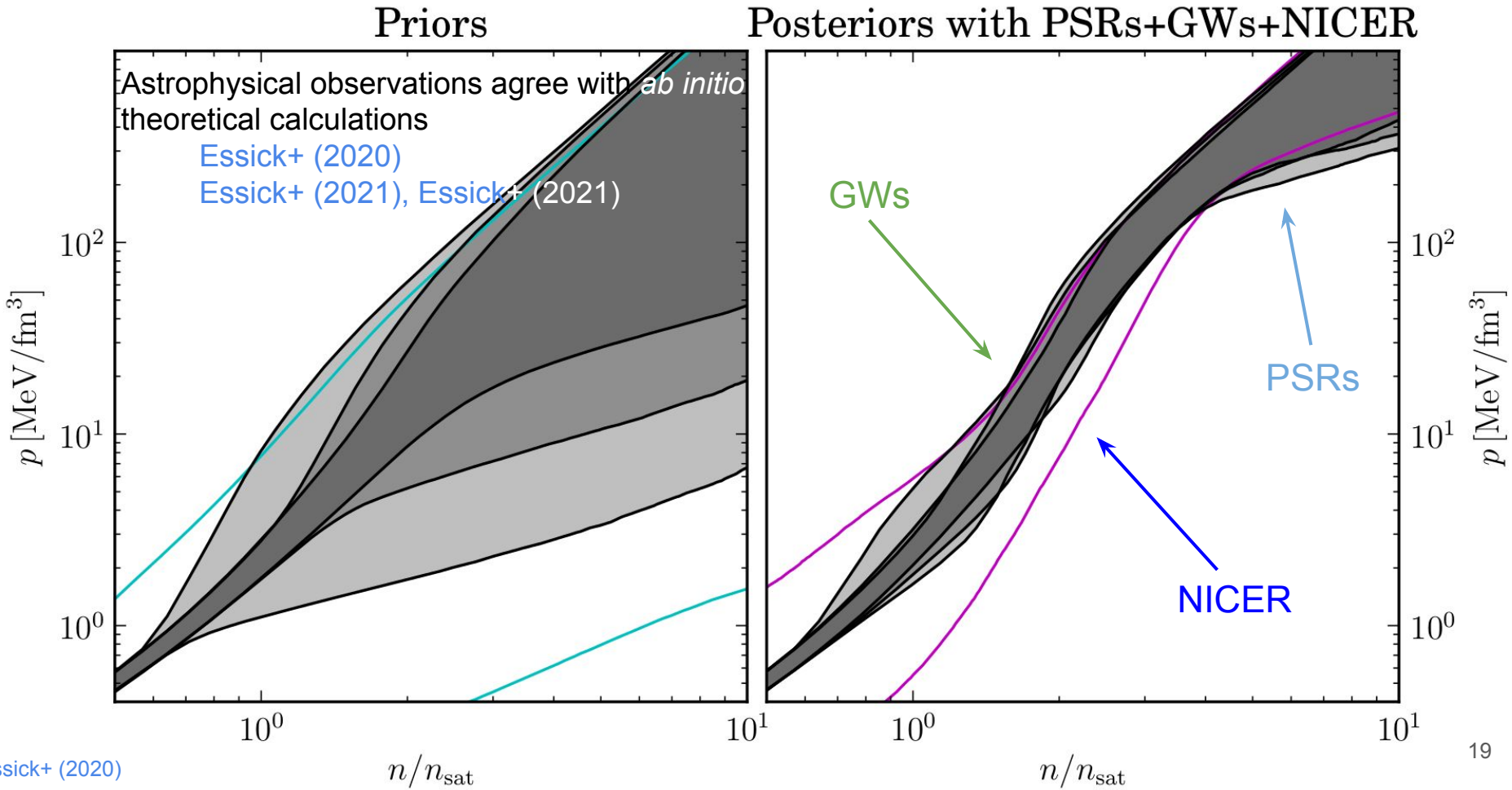
Comparisons with Terrestrial Nuclear Experiments and *ab initio* Theory





Essick+(2020)

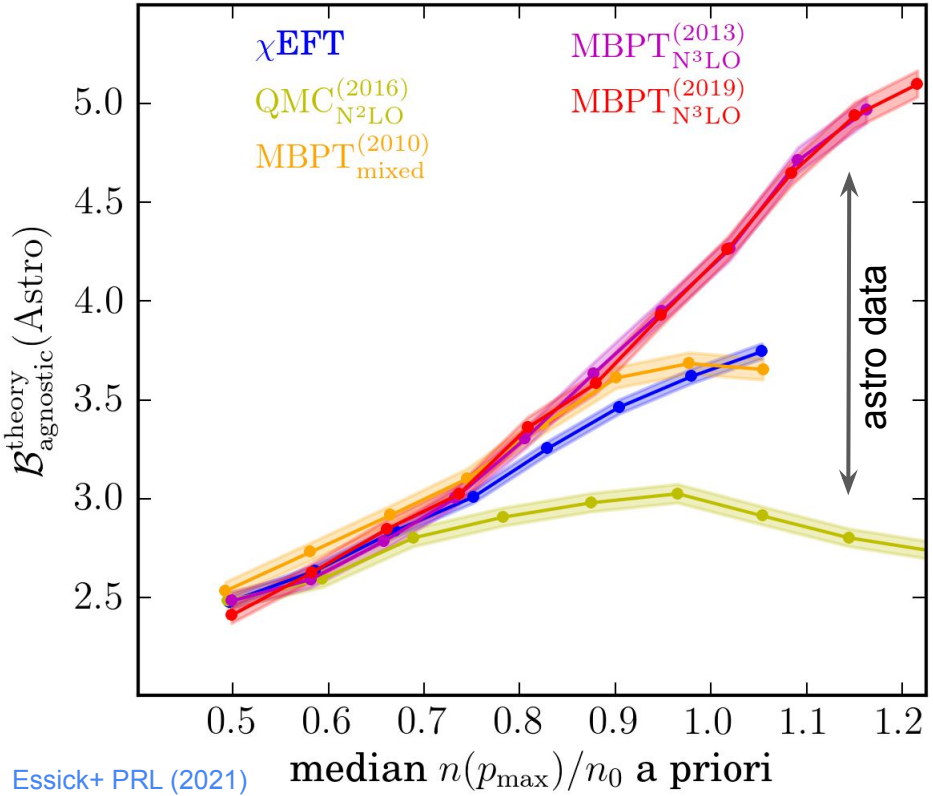
Comparisons with Terrestrial Nuclear Experiments and *ab initio* Theory



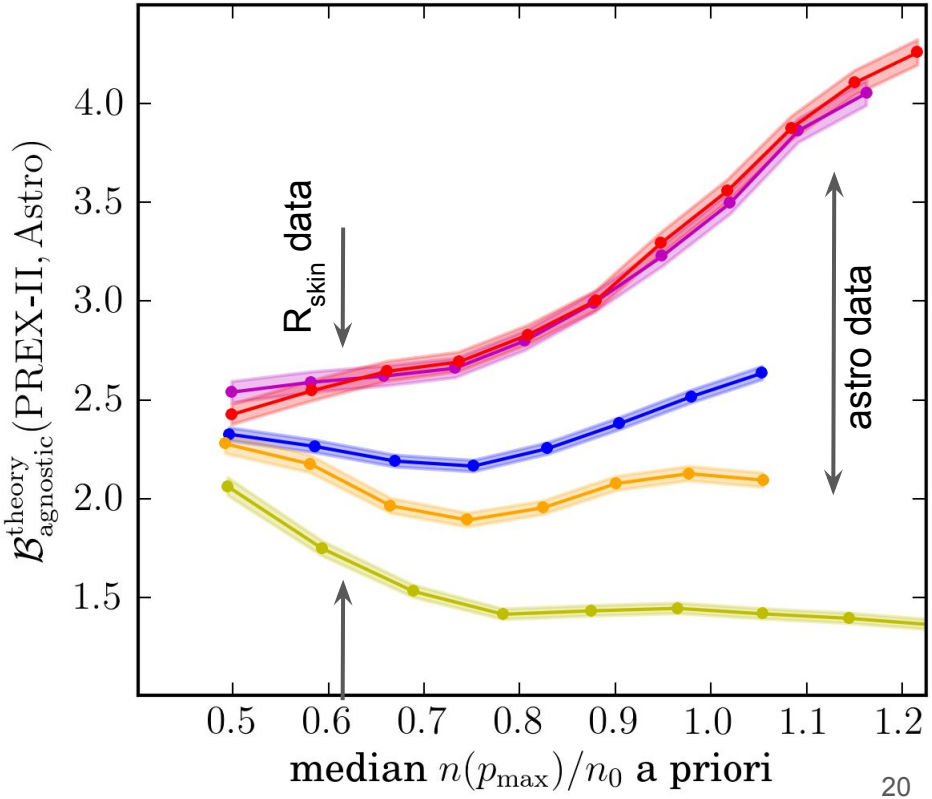
Essick+ (2020)

Comparisons with Terrestrial Nuclear Experiments and *ab initio* Theory

astro data can distinguish between nuclear theories at high densities



nuclear experiments probe lower densities



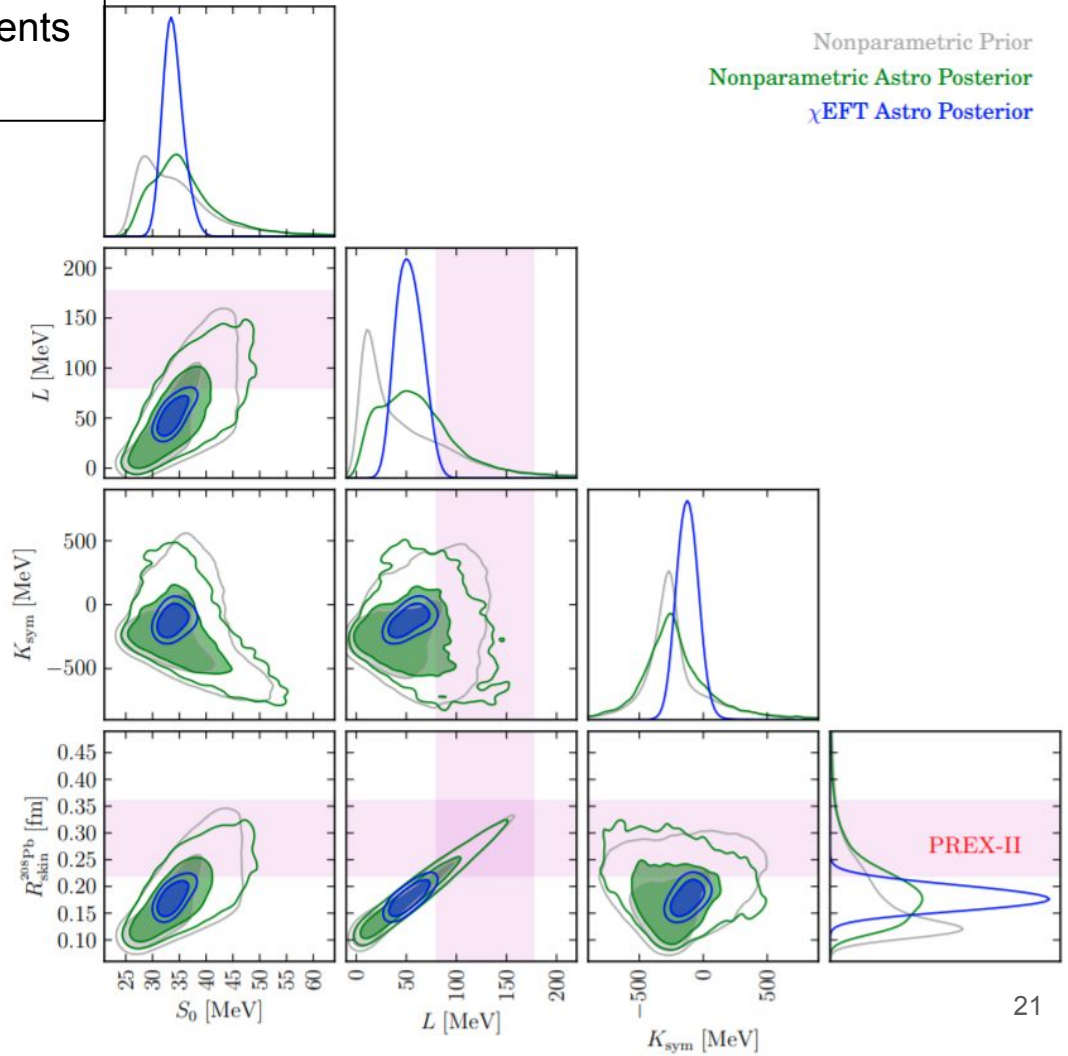
Essick+ PRL (2021)
Essick+ PRC (2021)

Comparisons with Terrestrial Nuclear Experiments and *ab initio* Theory

Comparison to "theory marginalized" χEFT calculations and (preliminary) PREX-II measurement

- χEFT calculations fall near the maximum *a posteriori* of our agnostic nonparametric analysis
- Incorporating PREX (Gaussian) likelihood shifts posteriors towards larger $R_{n\text{-}p}$, L.
- ***No significant tension between PREX, χEFT, and/or agnostic astrophysical posterior***

Reed+(2021) suggest there might be some tension. We find this is because they use a single model class (RMF) to high densities, which may not be warranted.



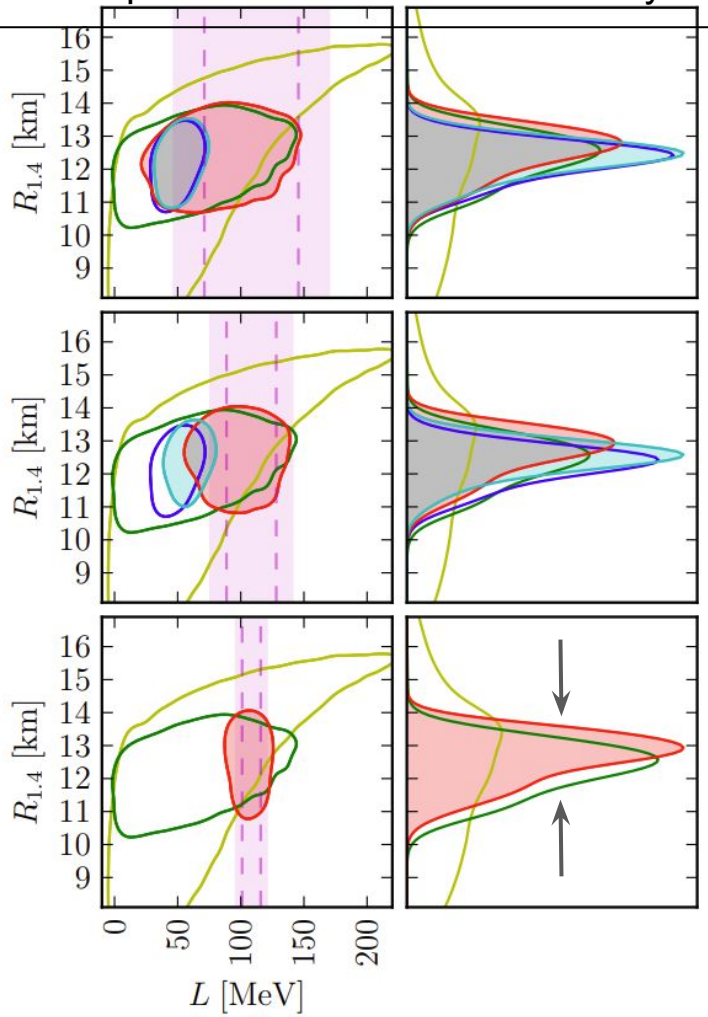
Essick+ PRL (2021)
Essick+ PRC (2021)

Comparisons with Terrestrial Nuclear Experiments and *ab initio* Theory

current R_{skin} uncertainty

R_{skin} uncertainty improved by a factor of 2

hypothetical perfect R_{skin} measurement



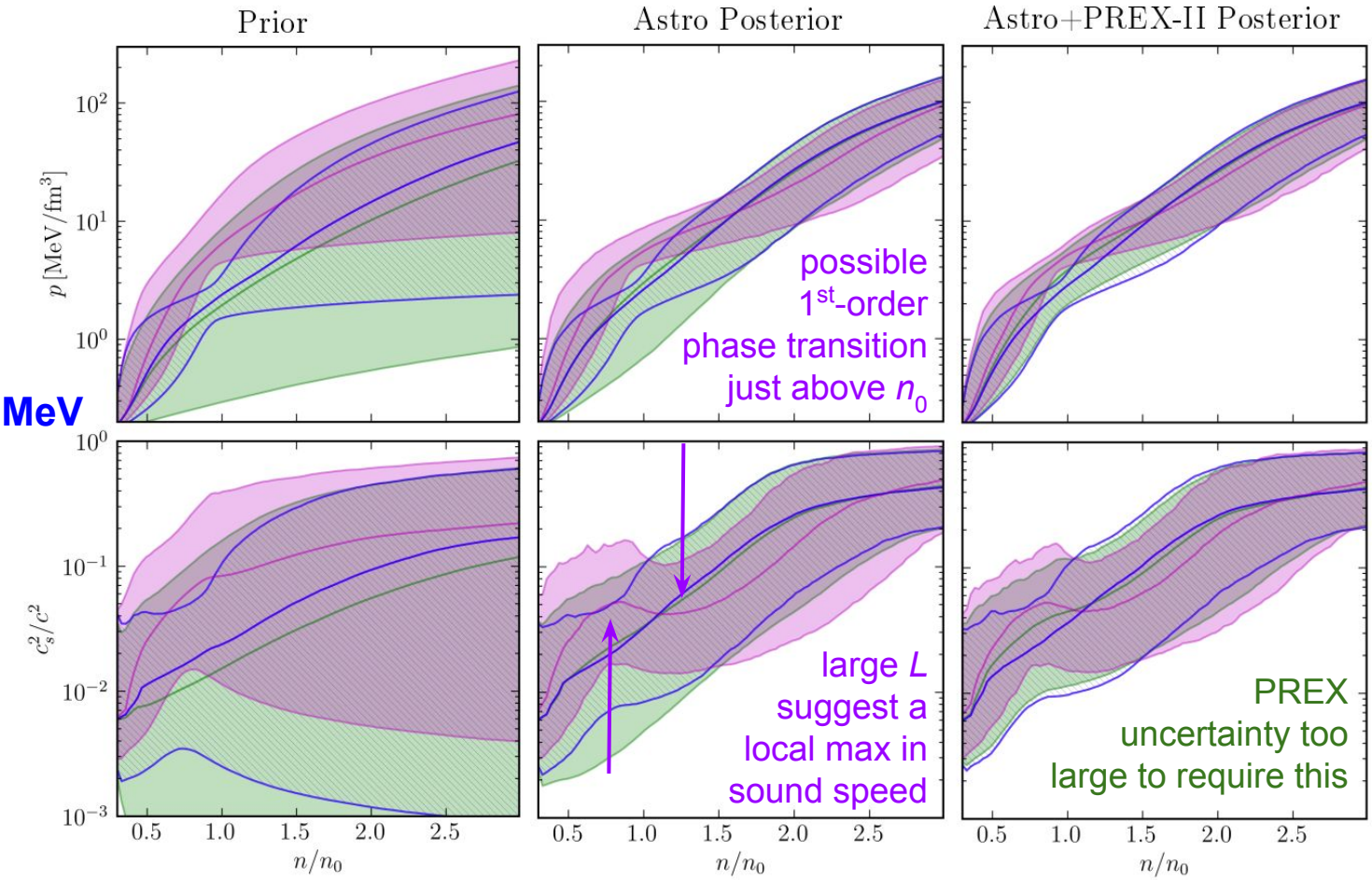
nonparametric prior
nonparametric astro-only posterior
χEFT+astro posterior
nonparametric astro+R_{skin} posterior
χEFT+astro+R_{skin} posterior

improved precision in nuclear experiments is unlikely to affect our knowledge of NS radii without improved theoretical calculations

Essick+ PRL (2021)
Essick+ PRC (2021)

Comparisons with Terrestrial Nuclear Experiments and *ab initio* Theory

100 MeV < *L*
30 MeV < *L* < 70 MeV
All *L*



Essick+ PRL (2021)
Essick+ PRC (2021)

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