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Nuclear-Physics Multi-messenger Constraints on the Equation of State of Neutron Stars

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A Virtual Tribute to Quark Confinement and the Hadron Spectrum

August 2, 2021

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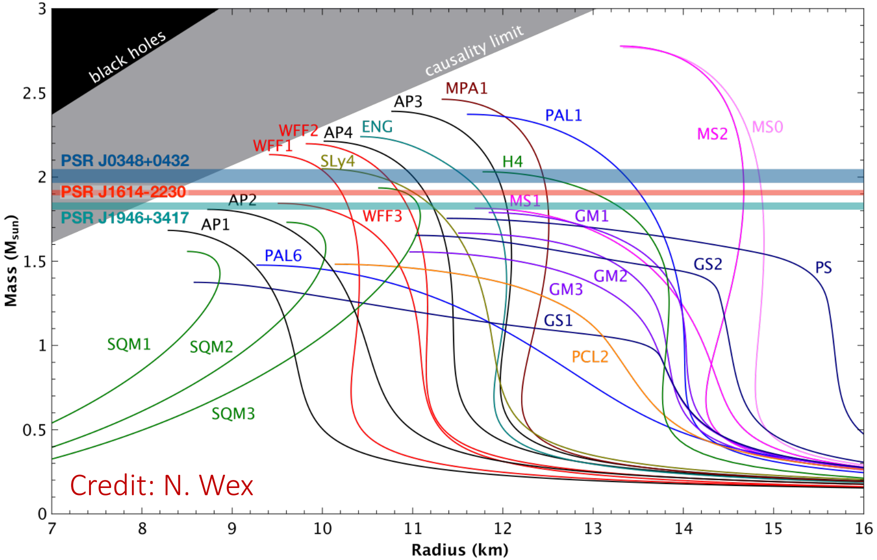
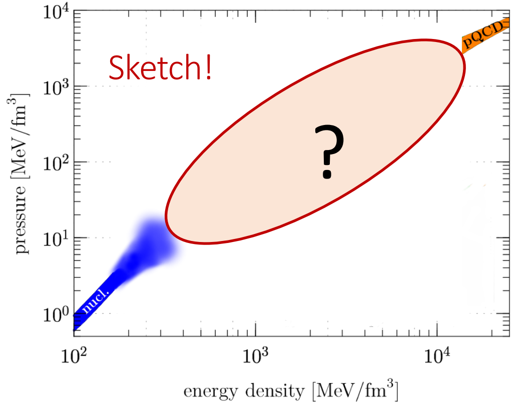
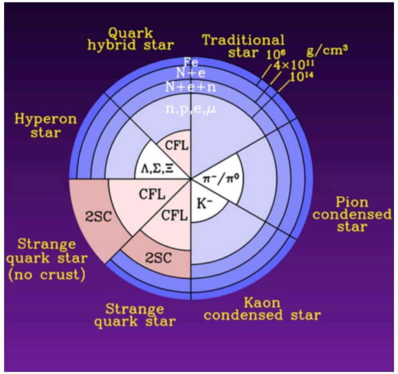
The equation of state

Large number of neutron-star equations of state available in the literature, but which ones are "good"?

- They do **not provide any theoretical uncertainty** estimates.
- They are not constructed based on some fundamental guiding principle; hence, it is **not clear how to improve them** systematically.







Constraints:

- <u>At low densities from **nuclear theory**</u> and experiment.
- At very high density from pQCD.
  see, e.g., Kurkela, Vuorinen et al.
- No robust constraints at intermediate densities from nuclear physics!

The equation of state

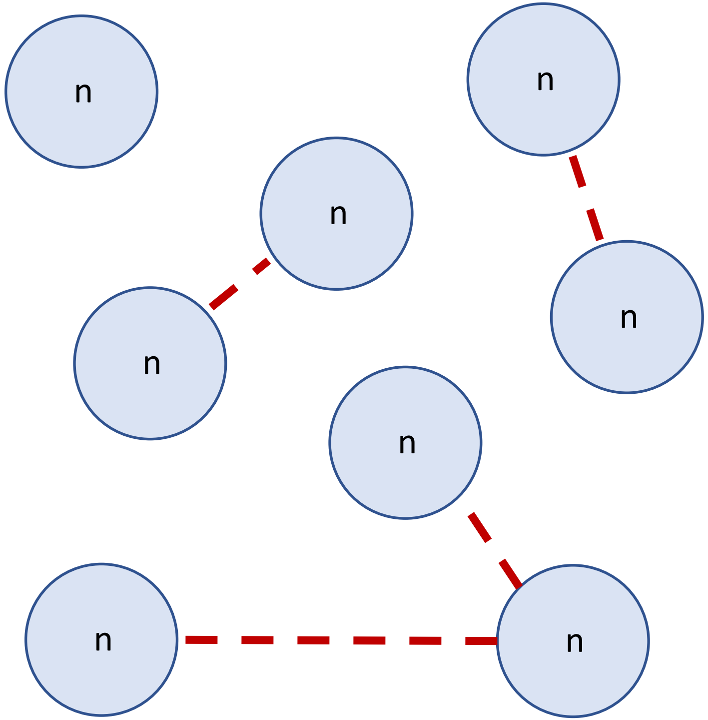
Many different approaches to calculate $\frac{E}{A}(n, x)$ but I will focus on **microscopic calculations**. We need:

- A theory for the strong interactions among nucleons

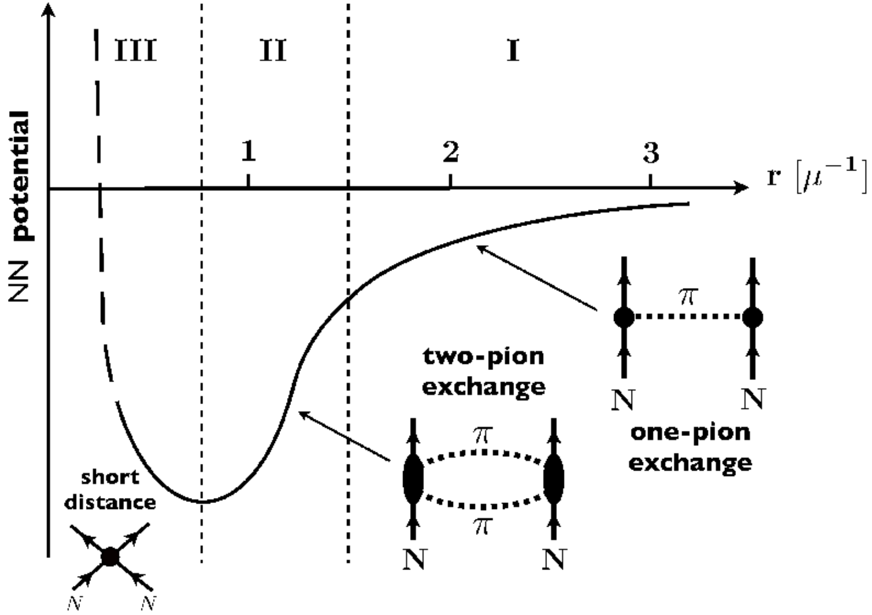
Chiral Effective Field Theory

- A computational method to solve the many-body Schrödinger equation.

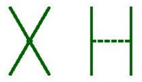
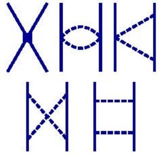
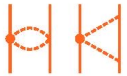
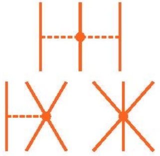
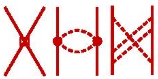
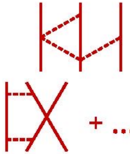
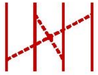
e.g., many-body perturbation theory, quantum Monte Carlo, coupled cluster, self-consistent Green's function, …



Chiral Effective Field Theory



Holt et al., PPNP 73 (2013)

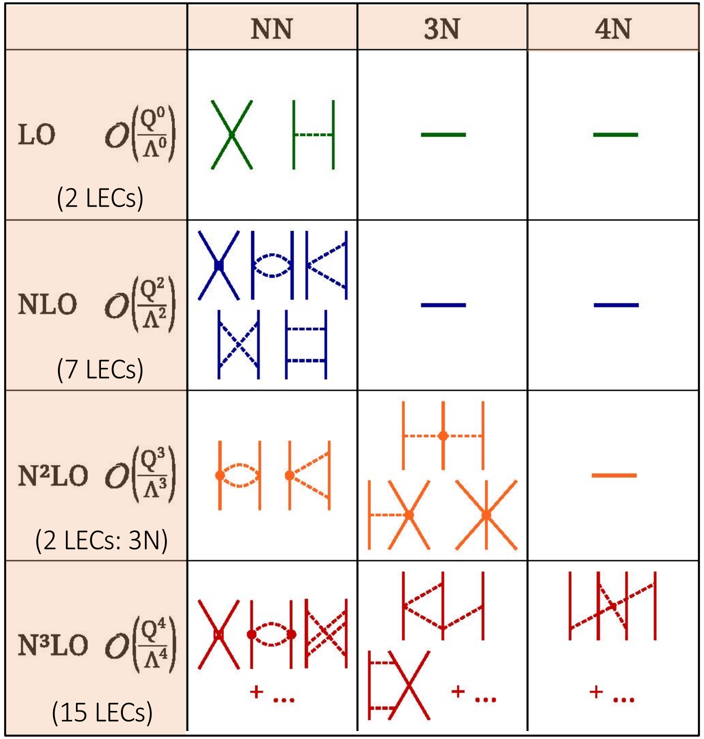
	NN	3N	4N
LO $\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$ (2 LECs)		—	—
NLO $\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$ (7 LECs)		—	—
N²LO $\mathcal{O}\left(\frac{Q^3}{\Lambda^3}\right)$ (2 LECs: 3N)			—
N³LO $\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$ (15 LECs)	 + ...	 + ...	 + ...

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meißner, Hammer ...

Chiral Effective Field Theory

Systematic expansion of nuclear forces in momentum Q over breakdown scale Λ_b :

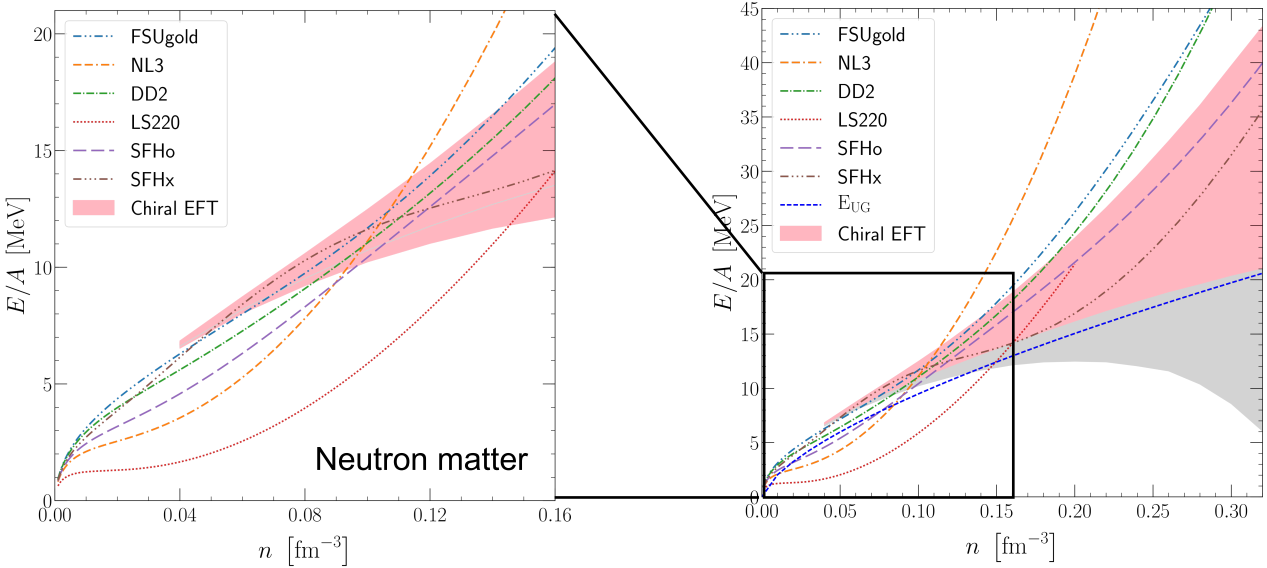
- Based on symmetries of QCD
- Pions and nucleons as explicit degrees of freedom
- Power counting scheme results in systematic expansion, **enables uncertainty estimates!**
- Natural hierarchy of nuclear forces
- **Consistent interactions**: Same couplings for two-nucleon and many-body sector
- Fitting: NN forces in NN system (NN phase shifts), 3N forces in 3N/4N system (Binding energies, radii)



Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meißner, Hammer ...

UG constraint: IT, Lattimer, Ohnishi, Kolomeitsev, APJ (2017)

Chiral EFT and neutron stars



- Chiral EFT interactions limited in range of applicability due to breakdown of the theory, rapid increase of theoretical uncertainty.

- Extend results to neutron-star densities using **general approach without strong model assumptions** (e.g., polytropes, speed-of-sound extension, meta-EOS, nonparametric inference)!

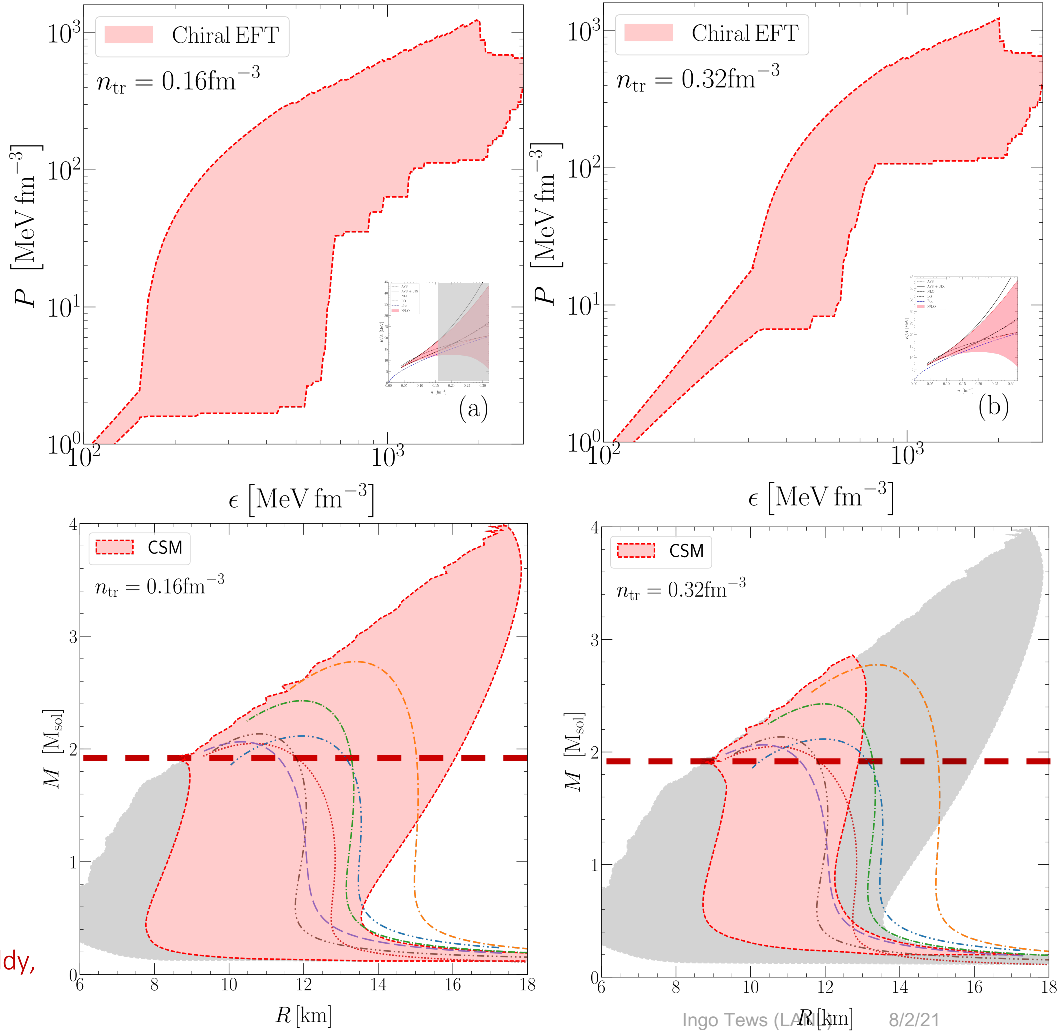
Neutron-star EOS

Generate thousands of EOSs that:

- Are **causal** ($c_S^2 \leq 1$) and **stable** ($c_S \geq 0$ inside NS).
- Are **consistent with low-density results** from chiral effective field theory.
- Support observed **1.9 solar-mass** neutron stars.

Current nuclear-physics uncertainties remain sizable!

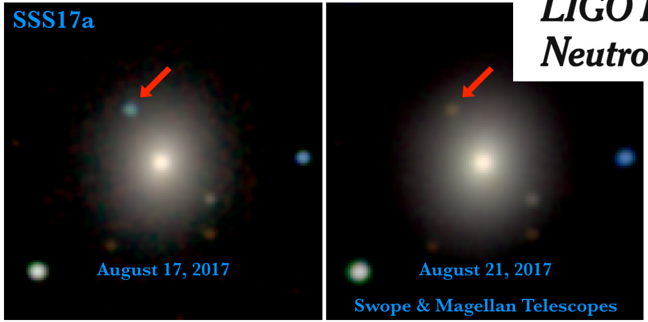
Extract information from NS observations.

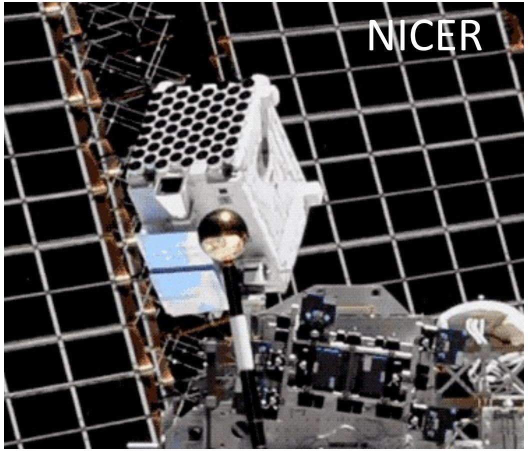


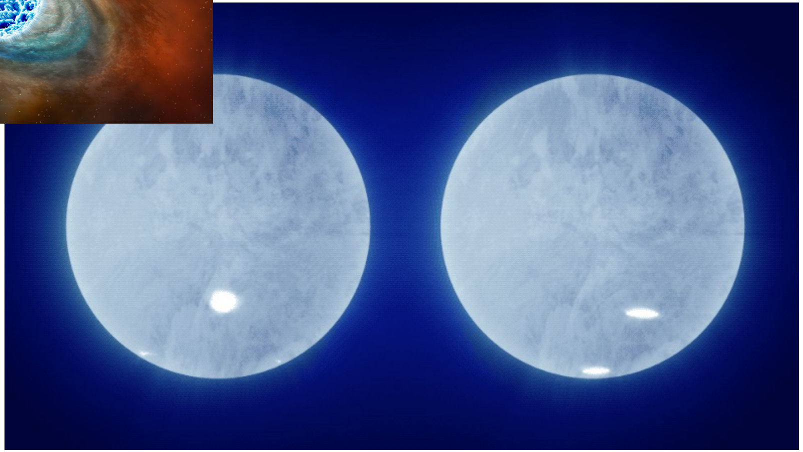
IT, Margueron, Reddy, EPJ A (2019)

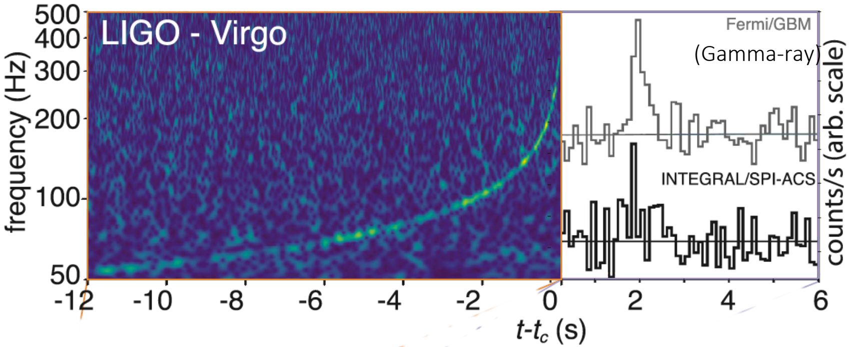
NS (multi-messenger) observations

First neutron-star merger observed on Aug 17, 2017 :









LIGO/VIRGO collaboration, ApJL 848, L12 (2017)

NS (multi-messenger) observations

First neutron-star
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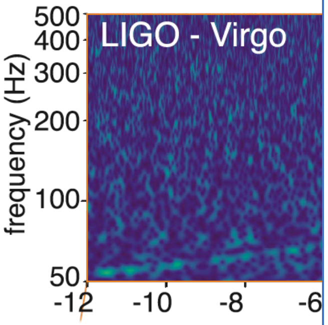
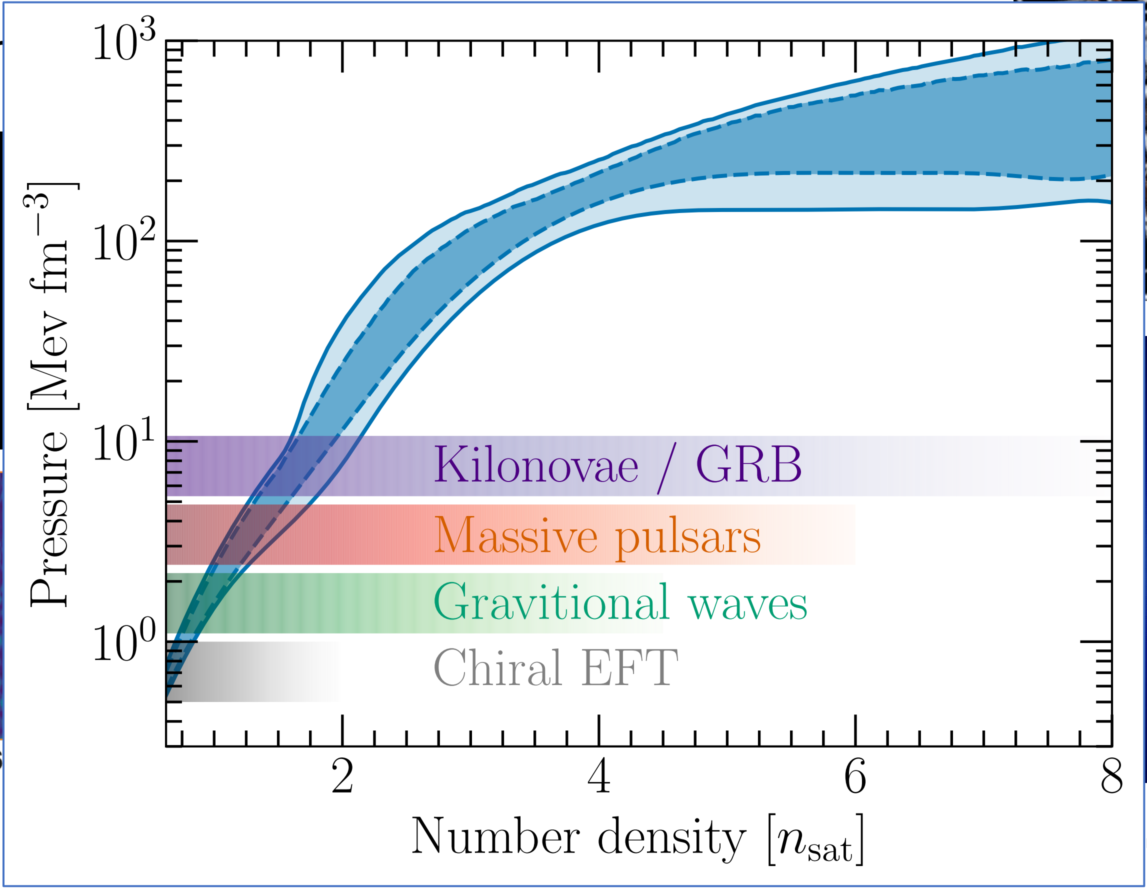
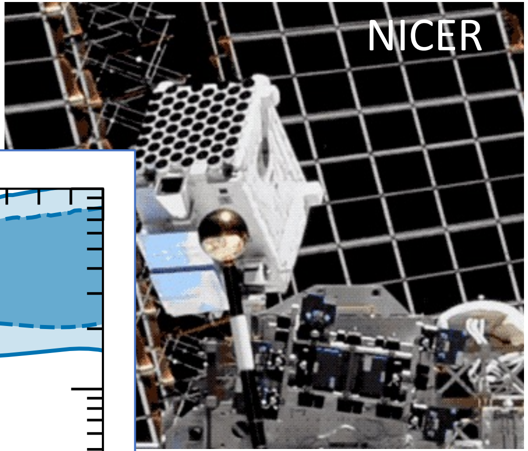
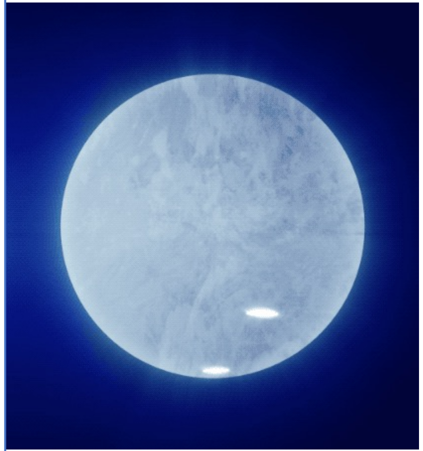








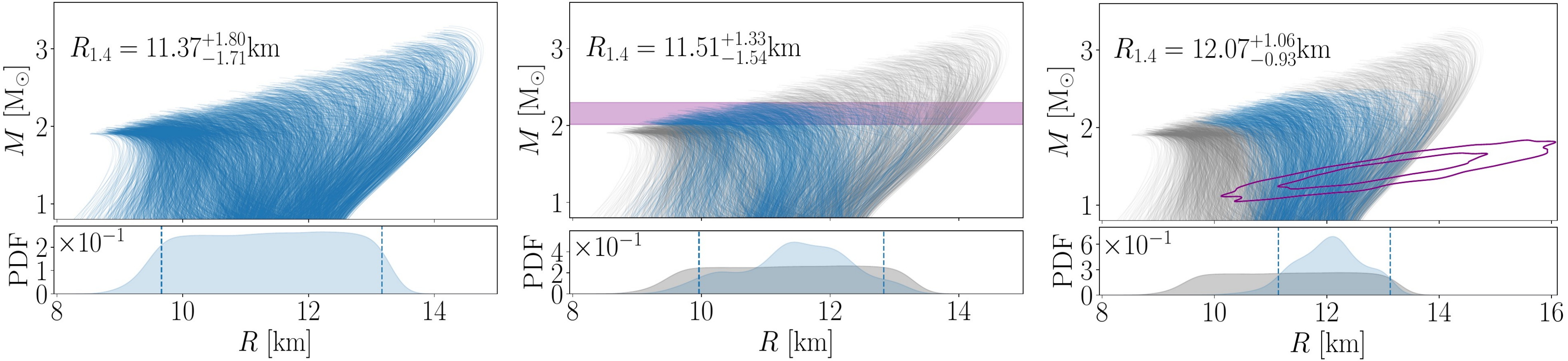
Multi-step analysis of NS observations

Consistently combine constraints from low-energy nuclear theory, gravitational-wave observations and electromagnetic observations using Bayesian methods.

(A) Starting point:
Discreet EOS samples constrained by EFT results at low densities

(B) Maximum-mass constraints:
Add information from pulsar mass measurements and GW170817 remnant classification

(C) NICER constraints:
Add information from pulsar J0030+0451 mass-radius measurement



Dietrich, Coughlin, Pang, Bulla, Heinzel, Issa, IT, Antier, Science (2020)

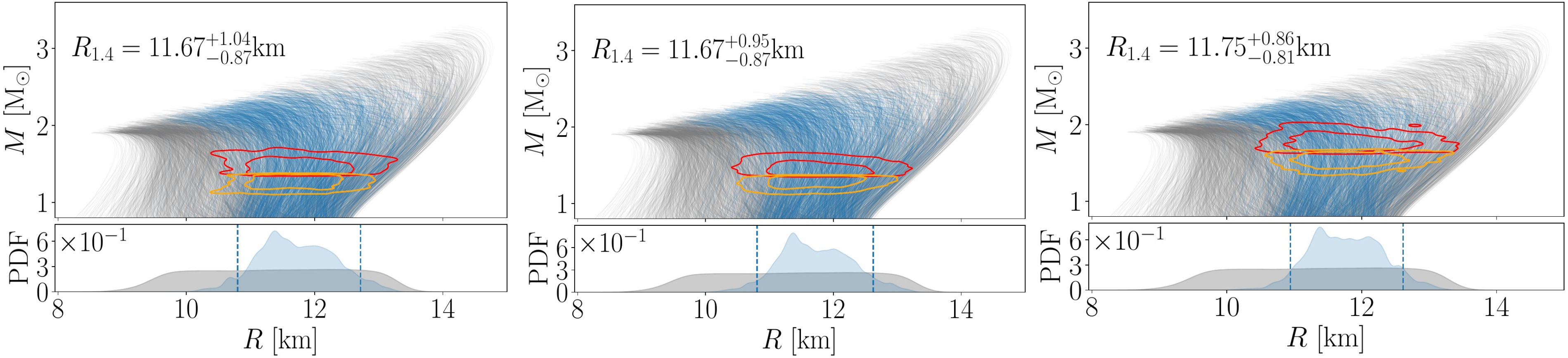
Multi-step analysis of NS observations

Consistently combine constraints from low-energy nuclear theory, gravitational-wave observations and electromagnetic observations using Bayesian methods.

(D) GW constraints:
Parameter Estimation of data from GW170817 (IMRPhenomPv2_NRTidalv2)

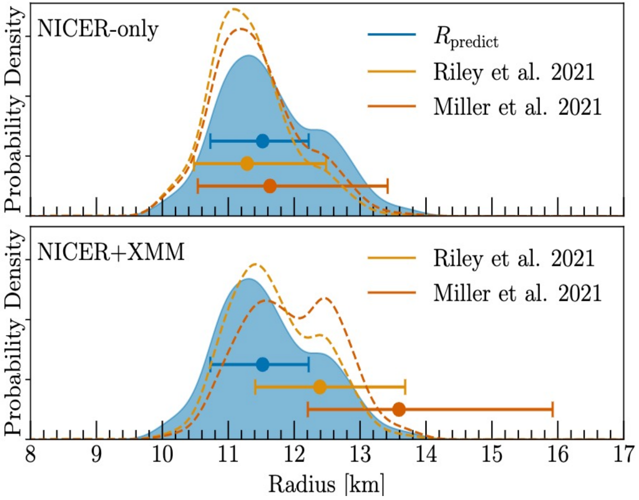
(E) Kilonova constraints:
Add information extracted from modeling the observed lightcurves of associated kilonova AT2017gfo

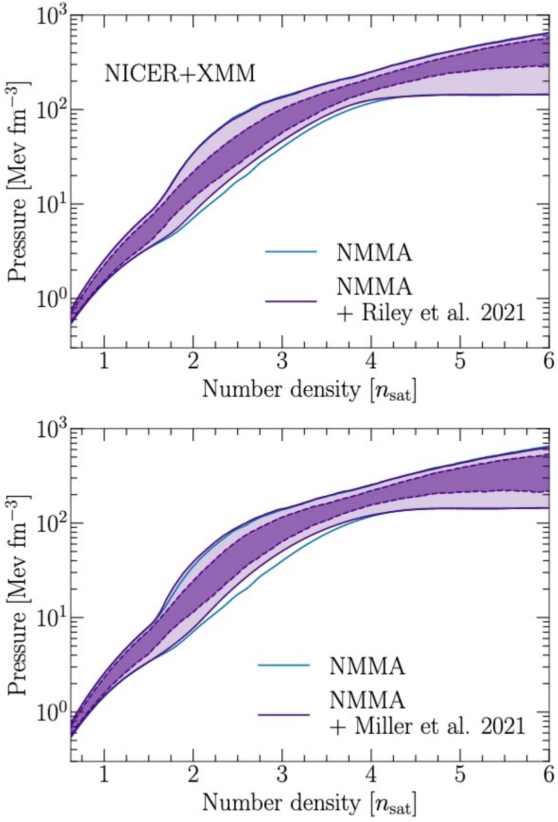
(F) GW constraints:
Add information from GW190425 (IMRPhenomPv2_NRTidalv2)

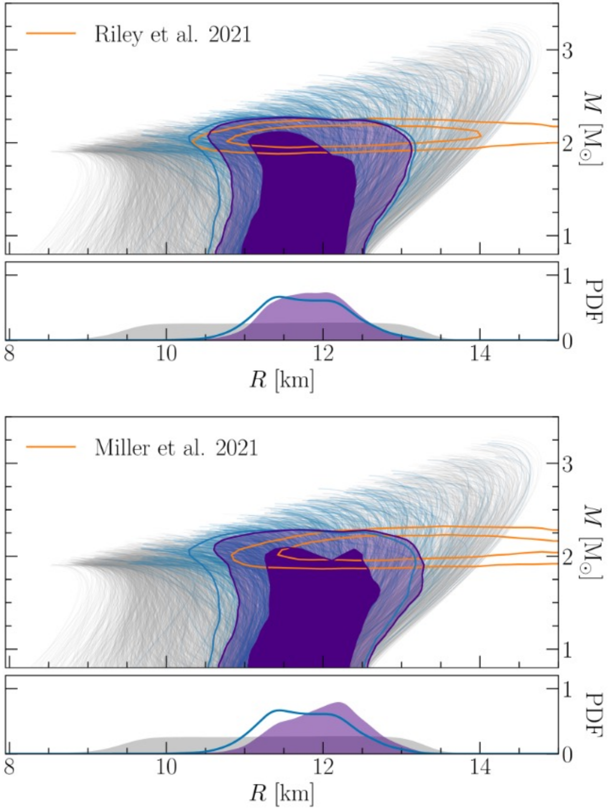


Dietrich, Coughlin, Pang, Bulla, Heinzel, Issa, IT, Antier, Science (2020)

New NICER results for PSR J0740+6620 (2.1 M_{sol})



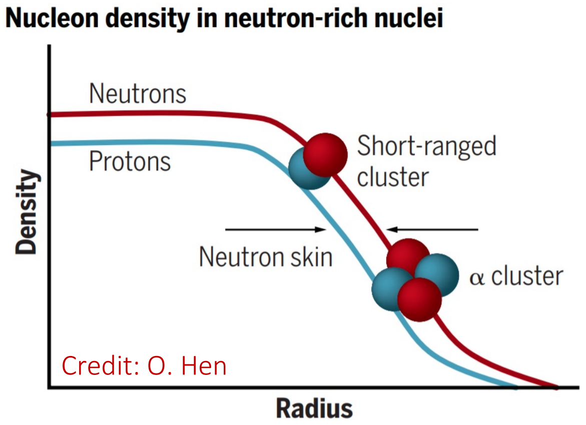




Quantity	NMMA	NMMA + Combined Miller & Riley et al. 2021
$R_{1.4}$	$11.75^{+0.86}_{-0.81}$km	$11.59^{+0.83}_{-0.76}$km $(11.94^{+0.76}_{-0.87}$km$)$
$M_{\max}$	$2.18^{+0.14}_{-0.13}M_\odot$	$2.15^{+0.15}_{-0.12}M_\odot$ $(2.18^{+0.16}_{-0.13}M_\odot)$
$\mathcal{B}^{\rm PT}_{\rm NPT}$	0.27 ± 0.01	0.29 ± 0.01 (0.23 ± 0.01)

Pang, IT, et al., arXiv:2105.08688, accepted in ApJ

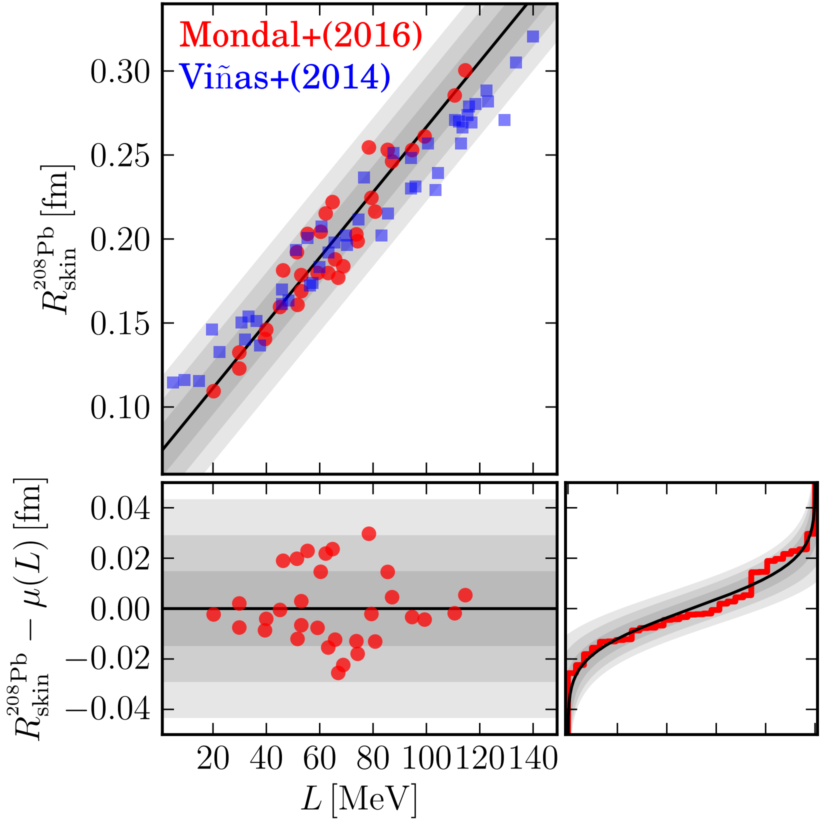
Connections to PREX-II



- PREX-II measured neutron-skin thickness of ^{208}Pb, constraining EOS but with large uncertainties:

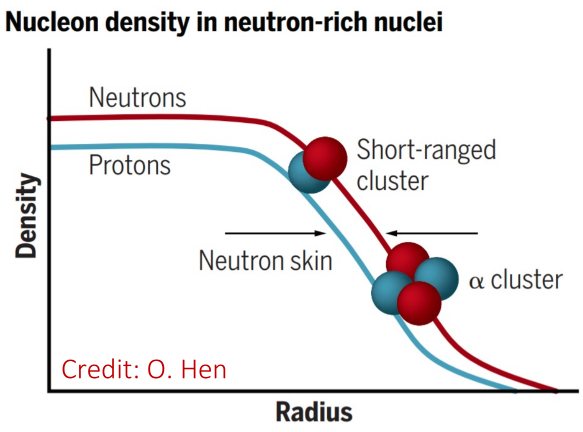
$$R_{skin} = 0.283 \pm 0.071 \text{ fm}$$
$$L = 106 \pm 37 \text{ MeV}$$

Adhikhari et al., PRL (2021)
Reed et al., PRL (2021)
Roca-Maza et al., PRC (2015)

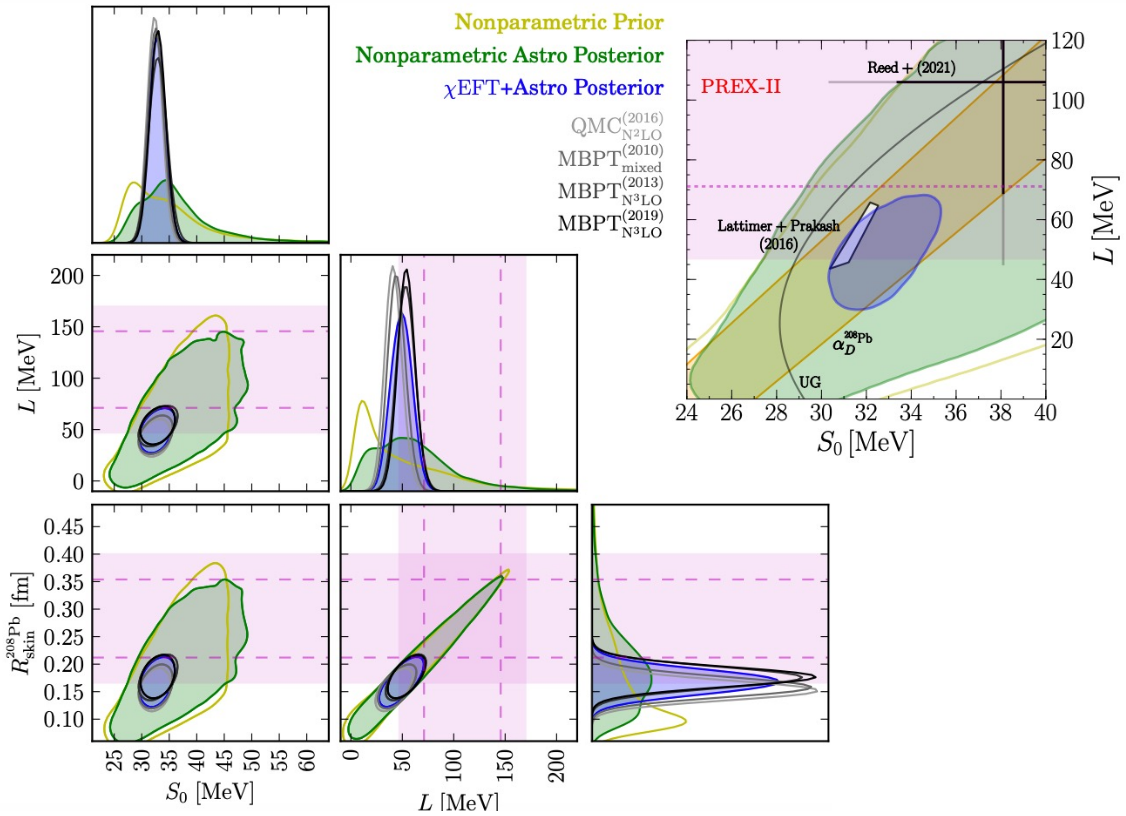


Essick, IT, Landry, and Schwenk, arXiv:2107.05528

Connections to PREX-II

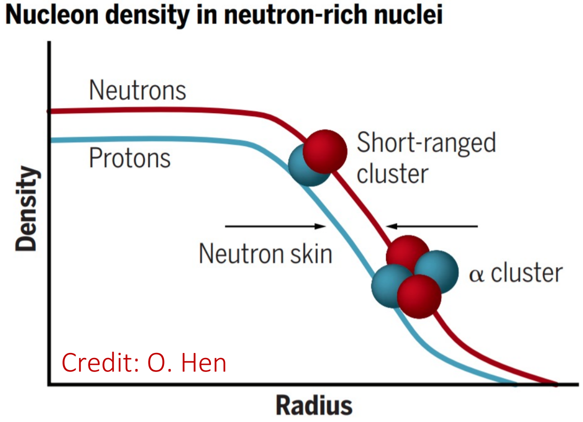


- Astrophysics data agrees with both nuclear theory and PREX, but posterior maximum of agnostic nonparametric analysis
- No significant tension between PREX and EFT calculations.

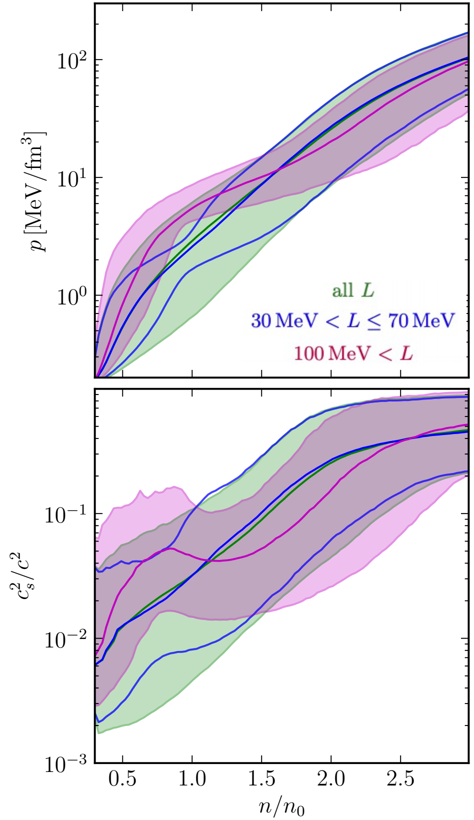


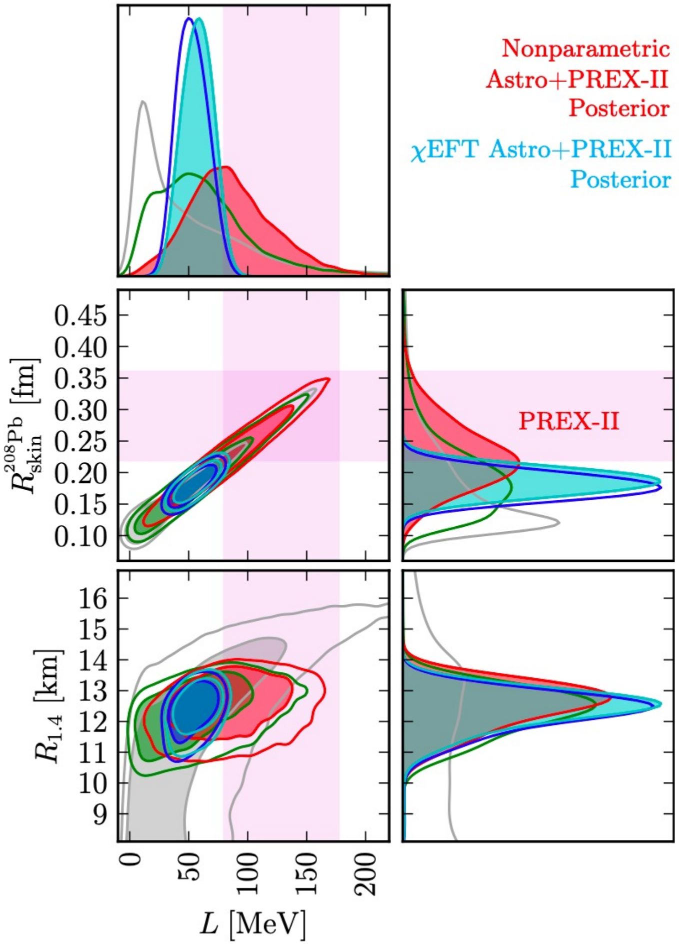
Essick, IT, Landry, and Schwenk, arXiv:2102.10074 and in preparation

Connections to PREX-II



- Large L would require interesting behavior in the speed of sound
- Radius prediction for typical neutron star does not change if PREX-II is included, correlation of L and R weak





Essick, IT, Landry, and Schwenk, arXiv:2102.10074 and in preparation

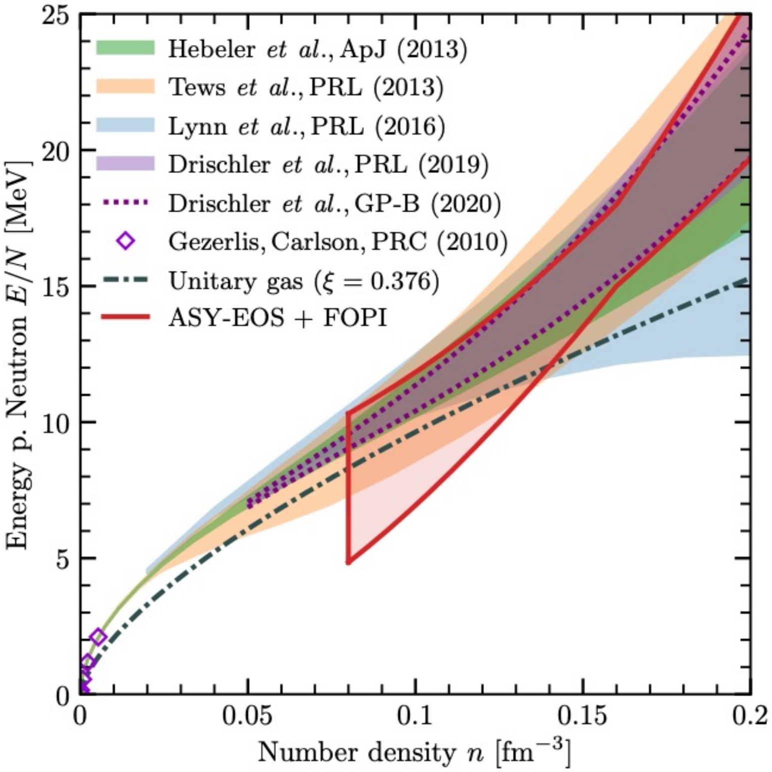
Including results from heavy-ion collisions

Including experimental data from heavy-ion collision experiments:

- ASY-EOS and FOPI experiments at GSI from ^{197}Au+^{197}Au collisions, constraints between 1-2 n_{sat}
- Constraints at higher densities from Danielewicz et al.

P. Danielewicz, R. Lacey, and W. G. Lynch, Science **298**, 1592 (2002), nucl-th/0208016.
A. Le Fèvre, Y. Leifels, W. Reisdorf, J. Aichelin, and C. Hartnack, Nucl. Phys. A **945**, 112 (2016), arXiv:1501.05246 [nucl-ex].
P. Russotto *et al.*, Phys. Rev. C **94**, 034608 (2016), arXiv:1608.04332 [nucl-ex].

Experiments prefer stiff EOS between 1-2 $n_{sat.}$

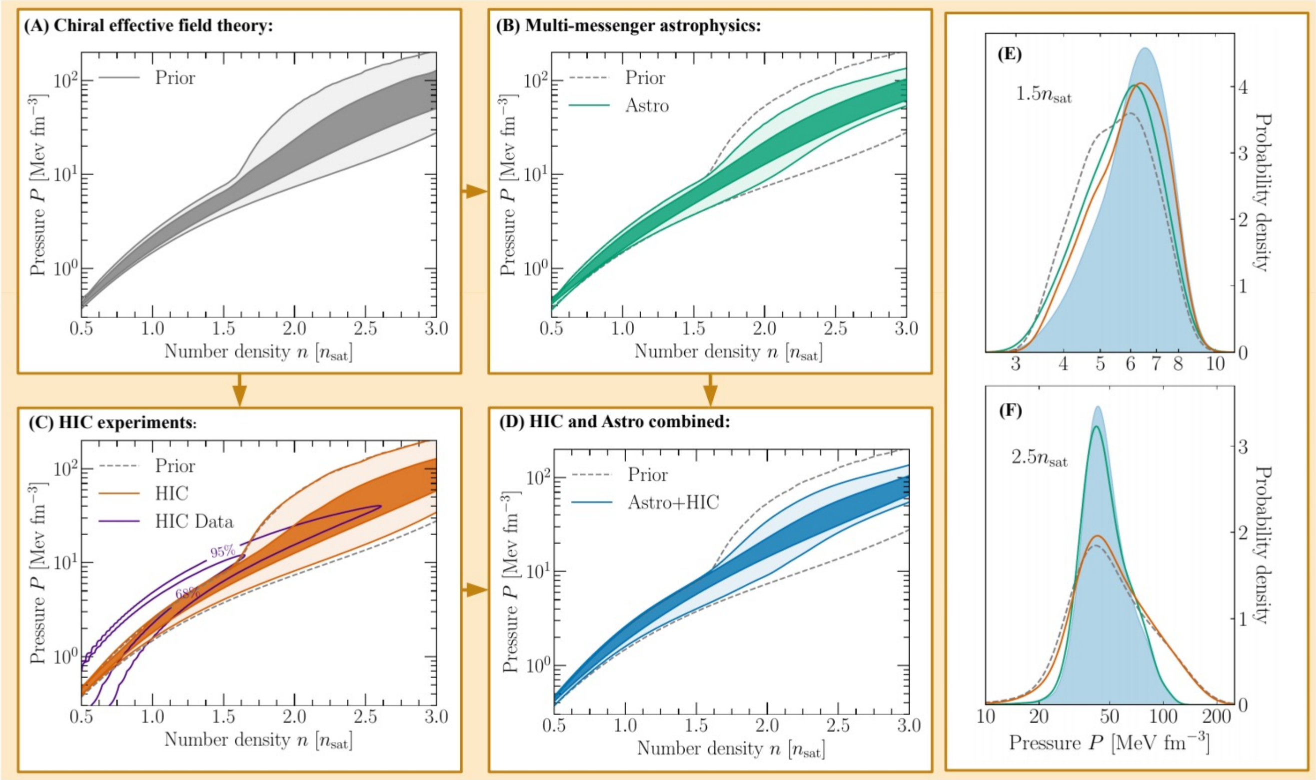


Huth, Pang et al., arXiv:2107.06229

Including results from heavy-ion collisions

Experiments prefer stiff EOS between 1-2 $n_{sat.}$

Excellent agreement with astrophysical observations.



Huth, Pang et al., arXiv:2107.06229

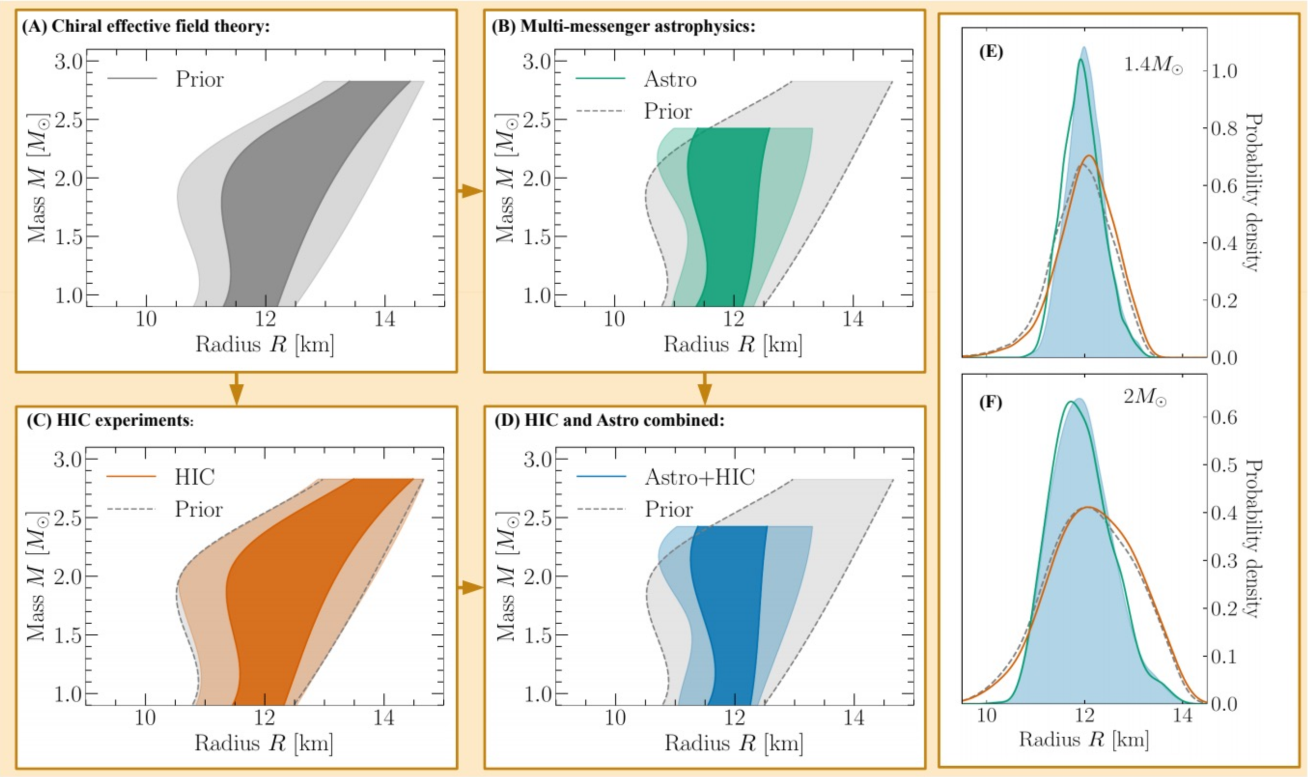
Including results from heavy-ion collisions

Experiments prefer stiff EOS between 1-2 $n_{sat.}$

Excellent agreement with astrophysical observations.

Impact on neutron-star radii for low-mass stars.

Possibility to bridge EOS between density ranges where theory and observations provide answers.



Huth, Pang et al., arXiv:2107.06229

Summary

- ➢ Neutron stars represent ideal laboratories for nuclear physics and help to improve our understanding of nuclear interactions!

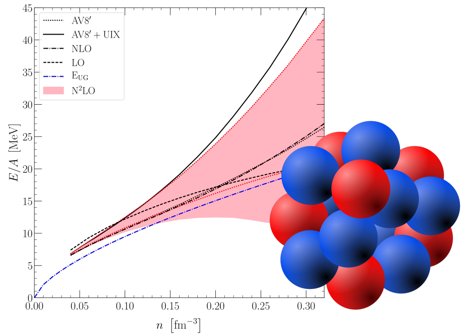
- ➢ Uncertainty in neutron-star EOS can be reduced by
  - Nuclear-physics constraints at low densities.
  - Multimessenger observations of NS and NS mergers.

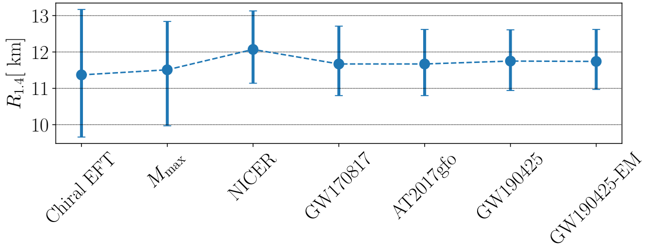
- ➢ Multimessenger constraints and nuclear theory find

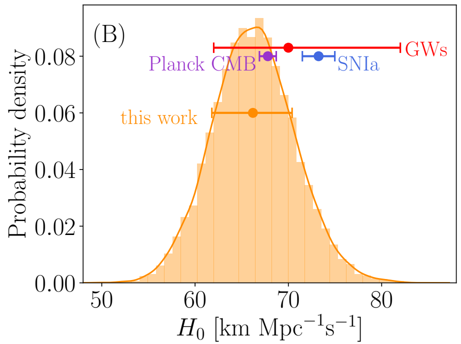
$$R_{1.4} = 11.8 \pm 0.8 \text{ km (90\% confidence)},$$
$$H_0 = 66 \pm 4 \text{ km Mpc}^{-1}\text{ s}^{-1}$$

- ➢ GW observations favor softer, EM observations (kilonova and NICER) favor stiffer EOS, but have large uncertainties, also systematic (depend on information from simulations with limited number of EOS, more EOS need to be explored).

- ➢ Even if can obtain EOS, we need to understand it (exotic matter?).







Thanks

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S. Antier (APC Paris)

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NUCLEI Nuclear Computational Low-Energy Initiative

NERSC

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Thank you for your attention!