Testing chiral EFT in nuclear matter with neutron-star observations (and nuclear experiments)

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1/17/2022, Hirschegg 2023: ‘Effective Field Theories for Nuclei and Nuclear Matter’

LA-UR-23-20382

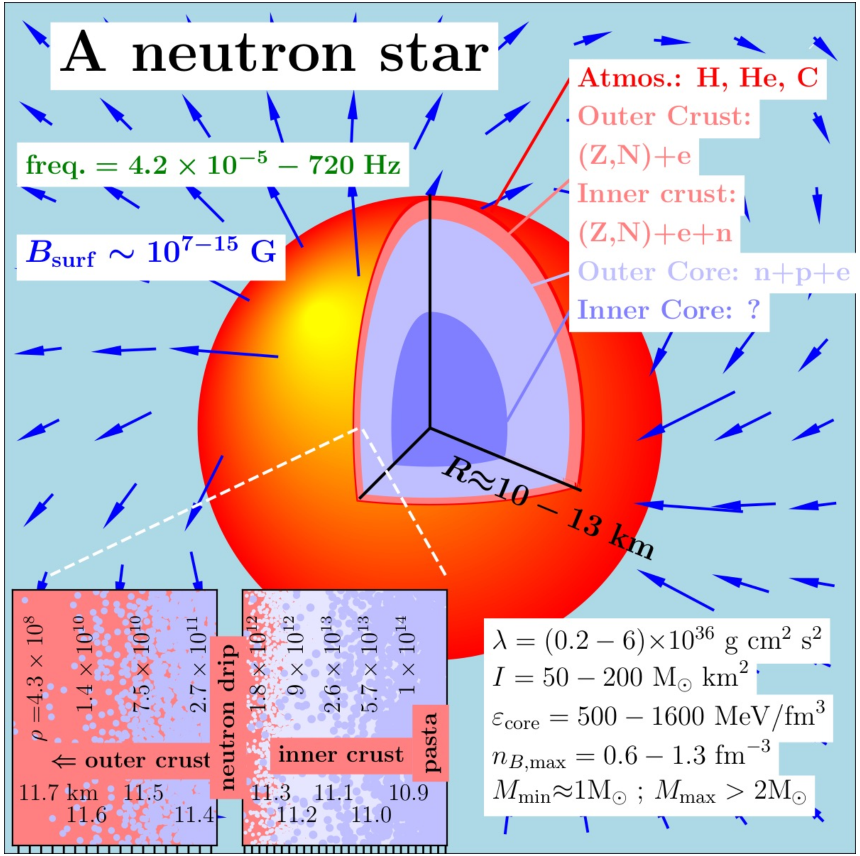
Neutron Stars

- Remnants of core-collapse supernovae with typical masses of 1.4 M_{sol} and typical radii of only $\mathcal{O}(10)$ km.
- Described by equation of state (EOS).
- Extreme densities, magnetic fields, spin frequencies, gravity, …

Neutron-star mergers:

- Coalescence of two neutron stars can be detected in gravitational-wave and EM spectrum (Multi-Messenger Astrophysics).
- Densest stellar systems in the Cosmos!

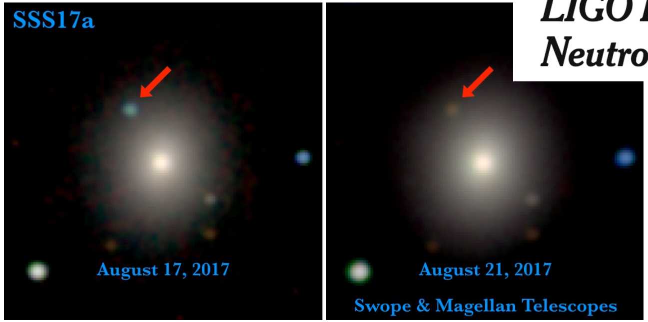
Ideal laboratories for **strongly interacting matter**, may exhibit exotic phases of matter in the core

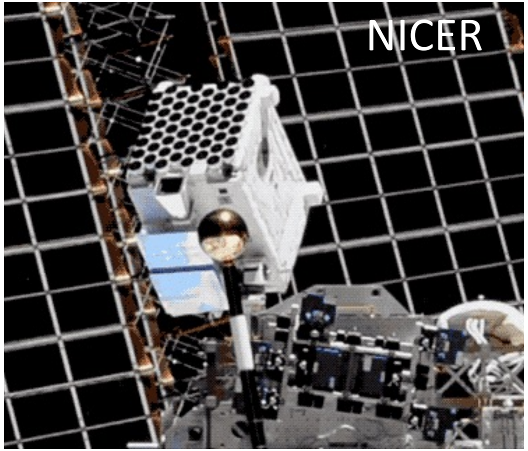


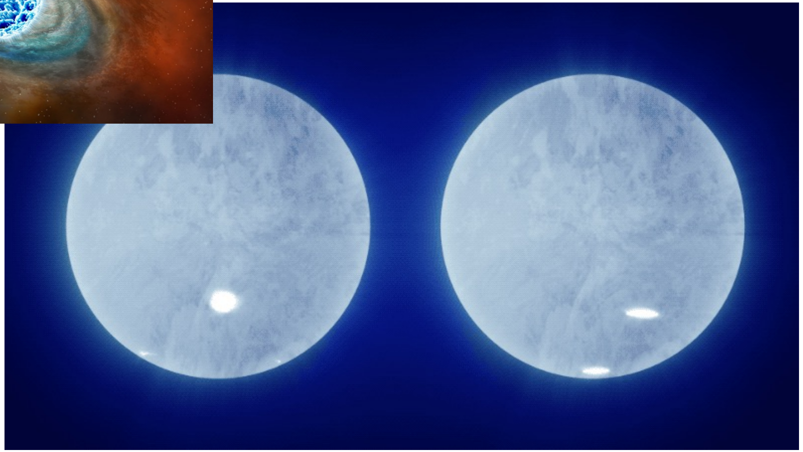
Gandolfi, Lippuner, Steiner, IT et al., J. Phys. G (2019)

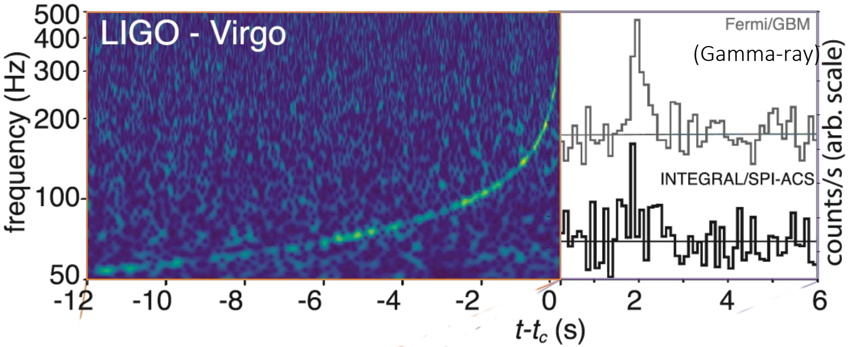
NS (multi-messenger) observations

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



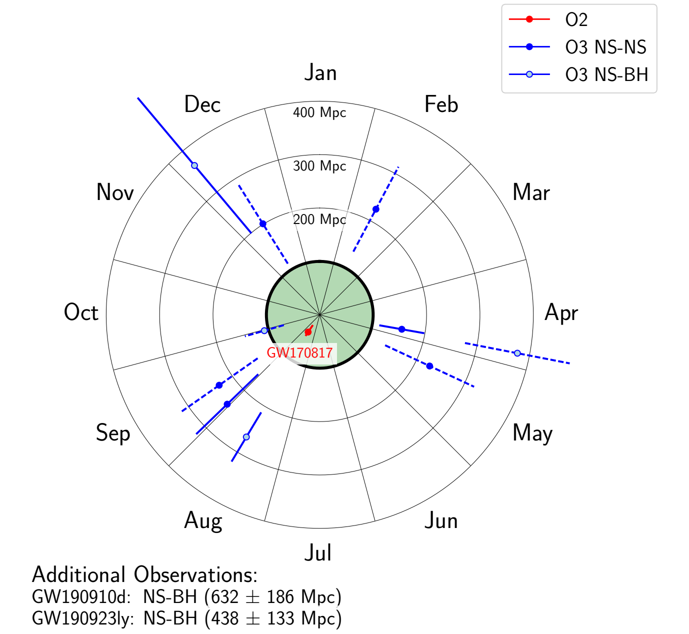






LIGO/VIRGO collaboration, ApJL 848, L12 (2017)

Observing run O3 complete: 50-60 events!



Credit: ESO/L. Calçada

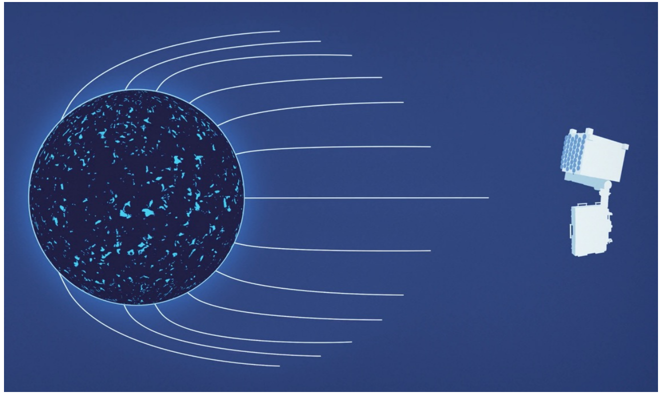
Exciting observations to date:

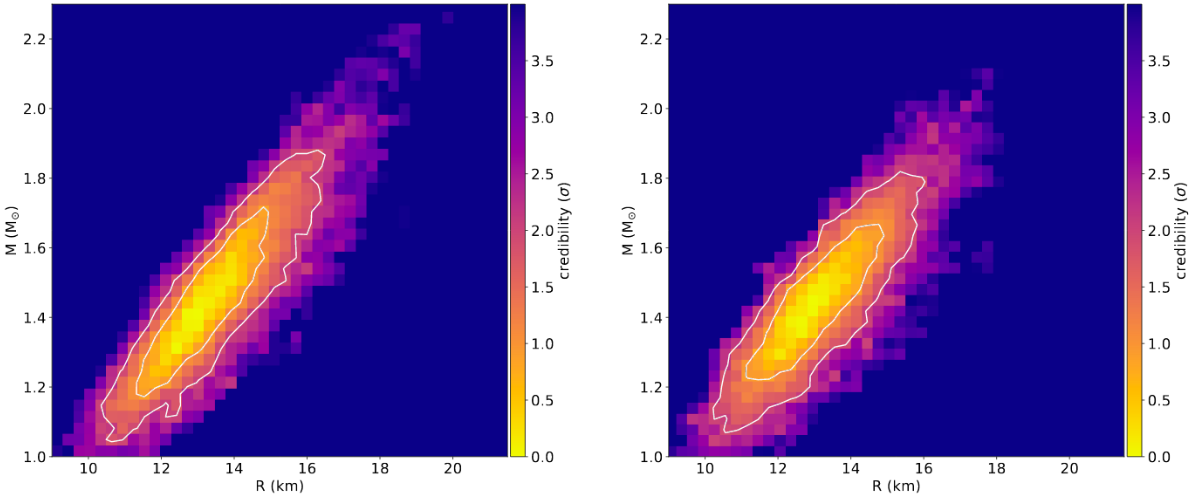
- Gravitational waves (GW) and EM observations from GW170817, loudest binary NS event to date.
- Second binary NS merger with intermediate SNR and larger total mass, GW190425.

Neutron-Star Black-hole mergers:

- Several NS-BH candidates (but low SNR).
- GW190814: 2.6 M_{sol} compact object merged with 23 M_{sol} black hole

NICER: Mass-radius measurement





Miller et al., ApJL (2019)

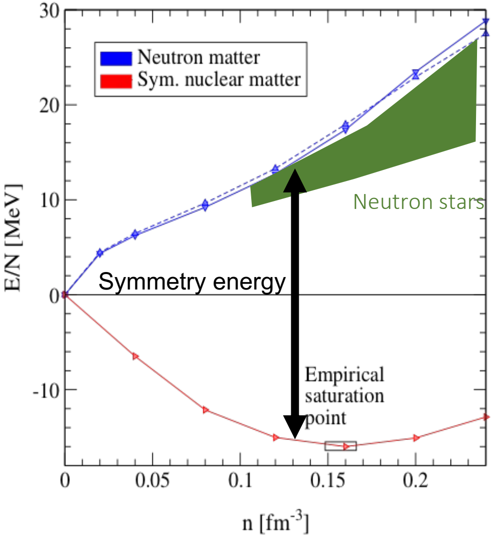
Recent mass-radius measurements of pulsars PSR J0030+0451 and PSR J0740+6620 by Neutron star Interior Composition Explorer (NICER) X-ray telescope:

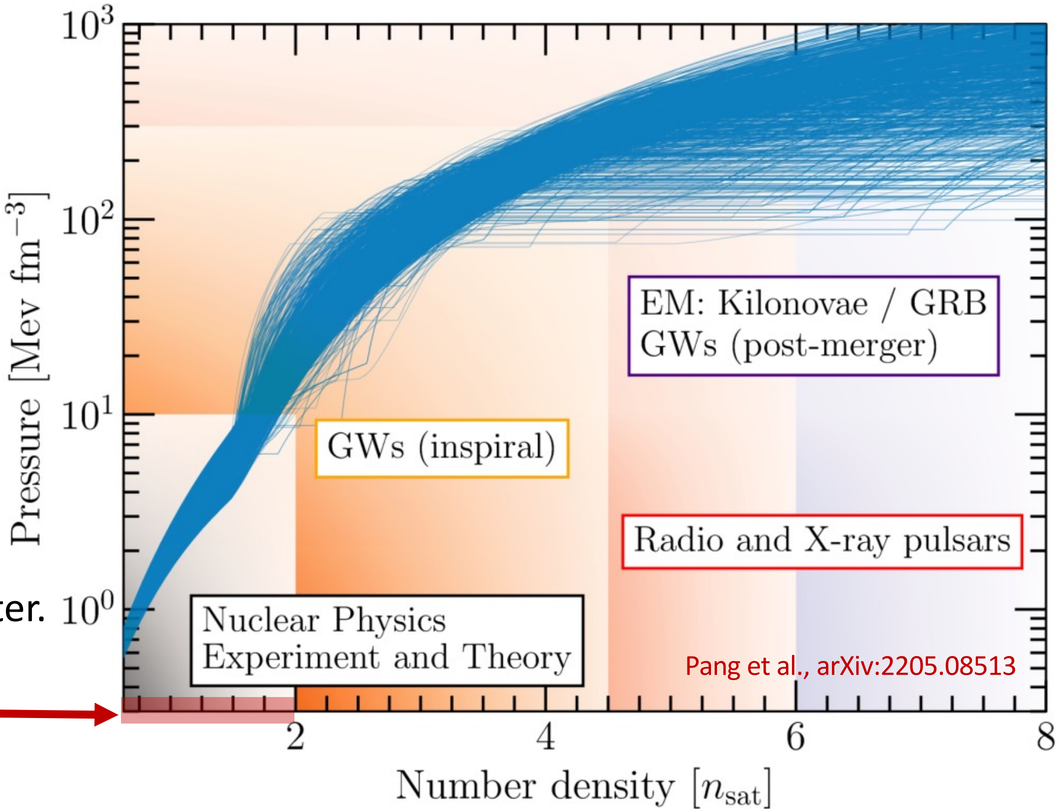
$$R_{0030} = 13.02^{+1.24}_{-1.06}\text{km}, \quad M_{0030} = 1.44^{+0.15}_{-0.14} M_\odot$$ [Miller et al., ApJL (2019)]

$$R_{0740} = 13.7^{+2.6}_{-1.5}\text{km}, \quad M_{0740} = 2.08 \pm 0.07 M_\odot$$ [Miller et al., ApJL (2021)]

Still large uncertainties because of unknown number and properties of hot spots and low statistics -> **more data expected soon, as NICER mission extended.**

Equation of state





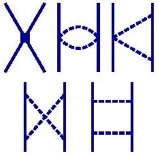
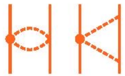
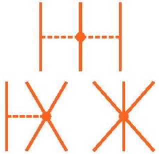
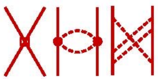
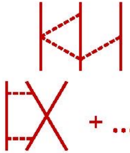
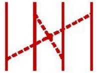
- EOS describes relation between pressure, density, energy, temperature in dense matter.
- Density range between (1-2)n_{sat}: **Theory, experiment and observations overlap.**

See Huth et al., Nature 606, 276 (2022)

Chiral effective field theory for nuclear forces

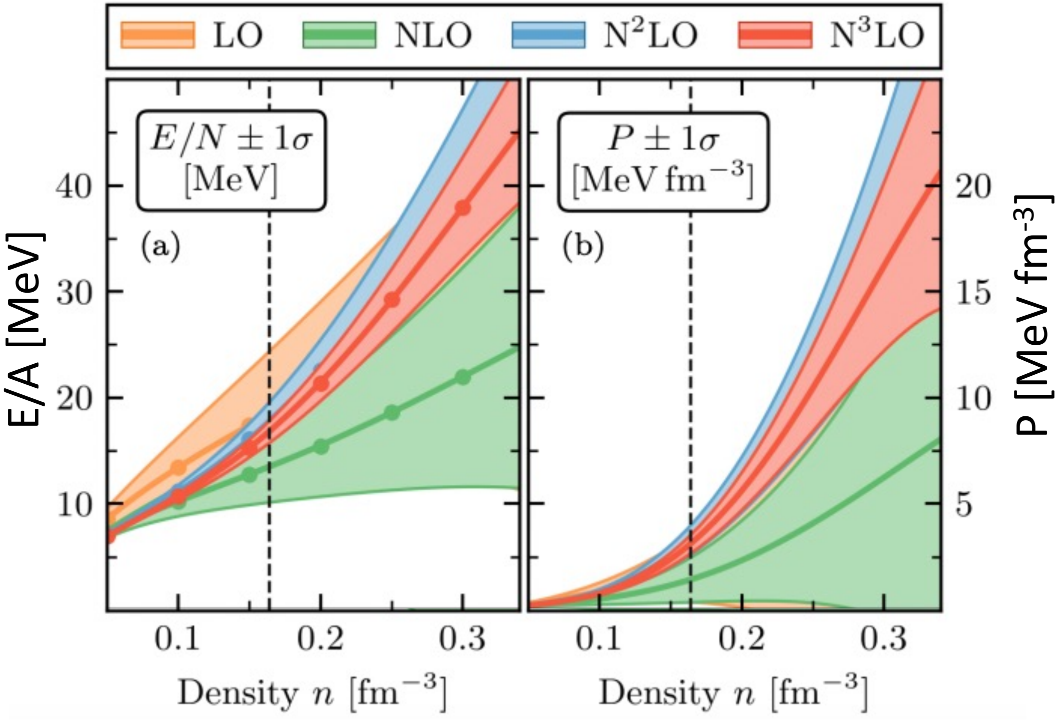
Systematic expansion of nuclear forces in momentum Q over breakdown scale Λ_b :

- 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)

	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 ...

Results for neutron matter



Drischler et al., PRL (2020)

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

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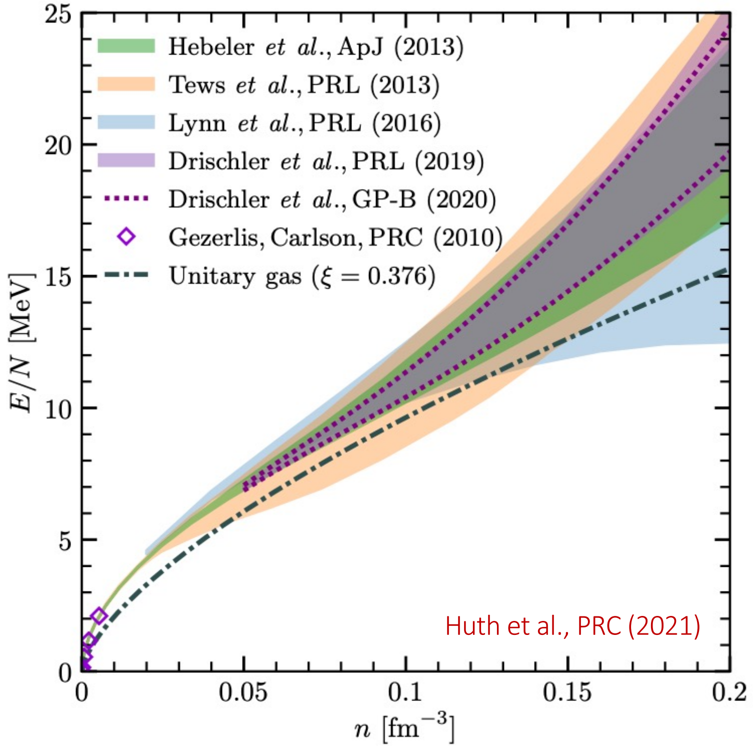
Results for neutron matter



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Weinberg, van Kolck, Kaplan, Savage, Wise,
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Excellent agreement for different many-body methods/EFT schemes!

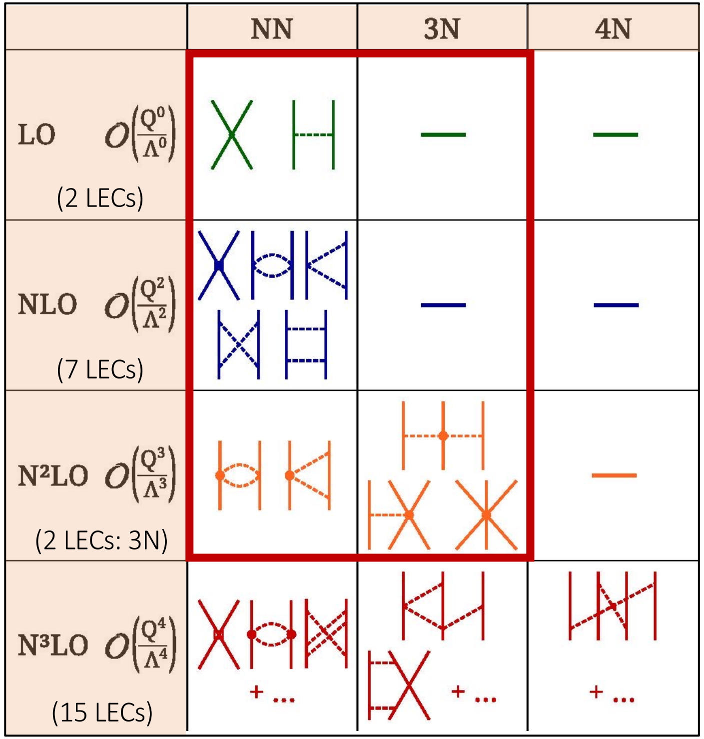
Chiral effective field theory for quantum Monte Carlo methods

- In the following, we use local chiral potentials up to **N²LO** for **QMC methods**.

  Gezerlis, IT, et al., PRL (2013)
  Gezerlis, IT, et al., PRC (2014)
  Lynn, IT, et al., PRL (2016)

- Two-body LECs fit to NN scattering phase shifts.
- **3N LECS** fit to uncorrelated observables:
  - Probe properties of light nuclei: ^{4}He E_B,
  - Probe spin-orbit physics: n-α scattering.
- Improvement of local interactions ongoing.

  Huth, IT, et al., PRC (2017) & PRC (2018),
  IT, Lonardoni, et al., in preparation,
  Somasundaram, IT, et al., in preparation.

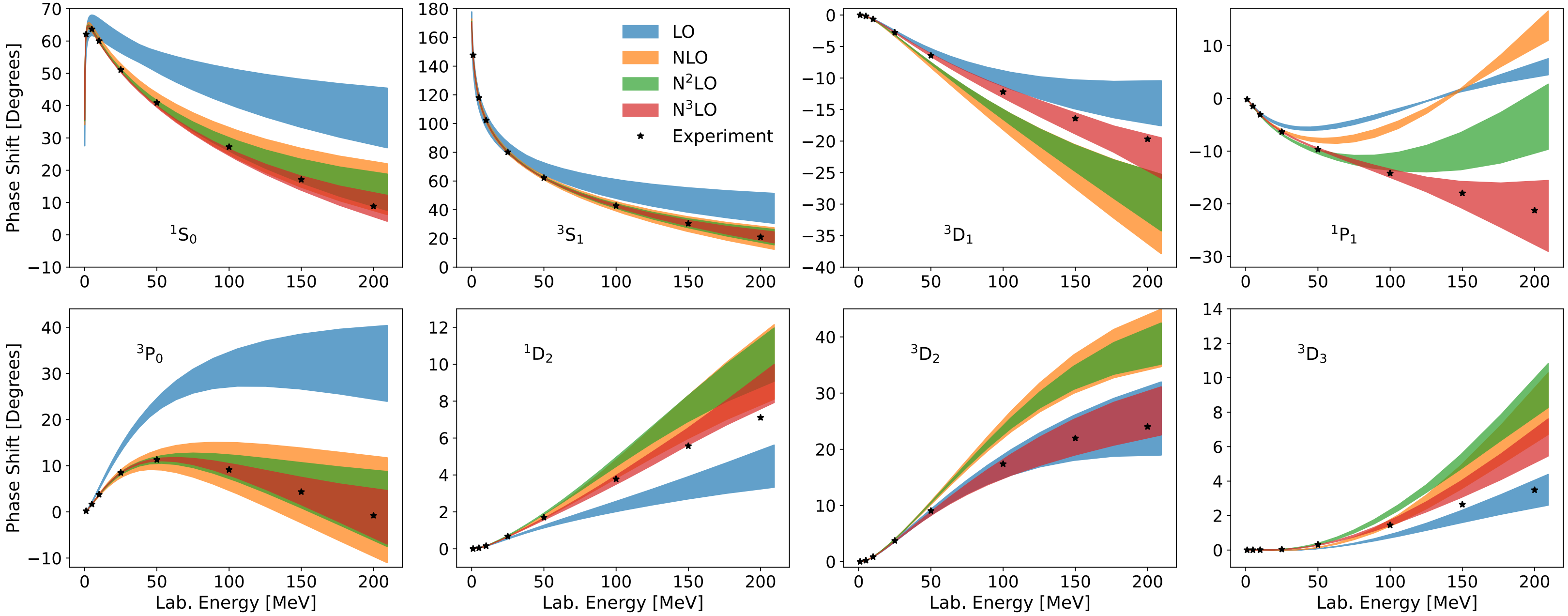


Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meißner, Hammer ...

Chiral EFT for quantum Monte Carlo methods

PRELIMINARY!

$R_0 = 0.9\,\mathrm{fm}$



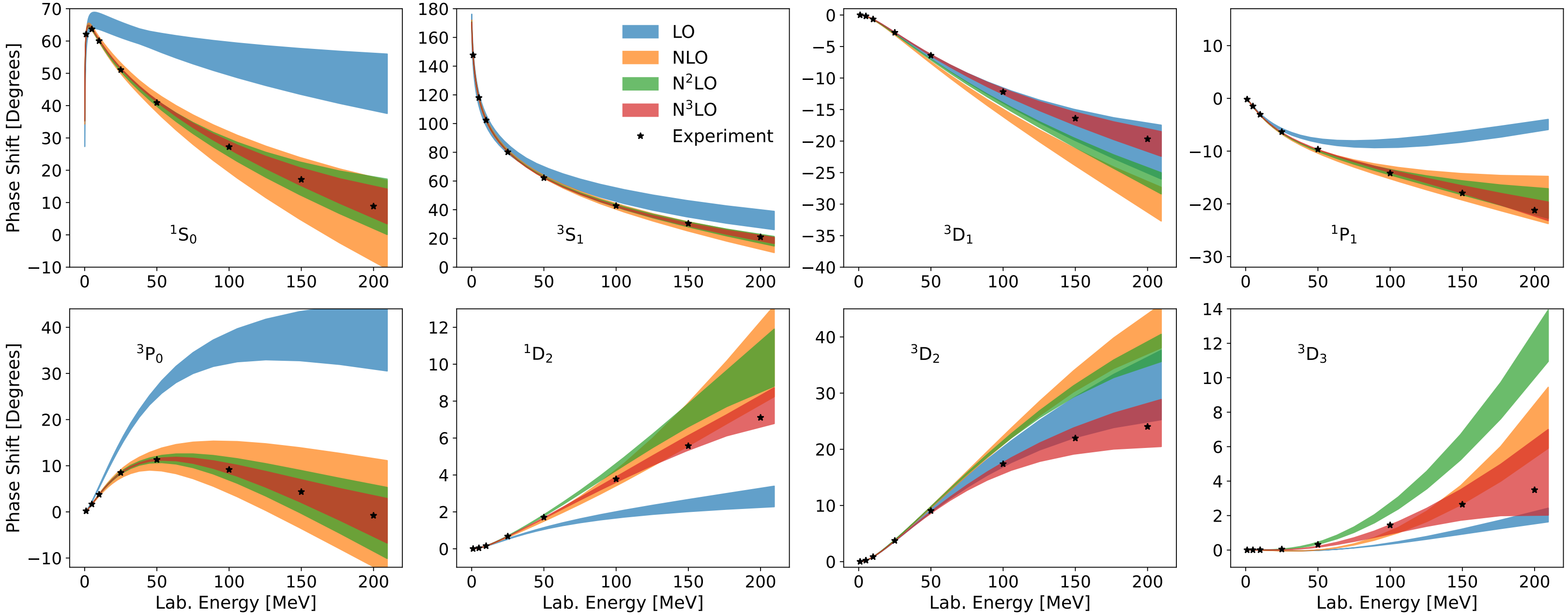
Constructing family of maximally-local interactions at N^{3}LO and various cutoffs.

Somasundaram, IT, et al., in preparation.

Chiral EFT for quantum Monte Carlo methods

PRELIMINARY!

$R_0 = 0.6\,\mathrm{fm}$



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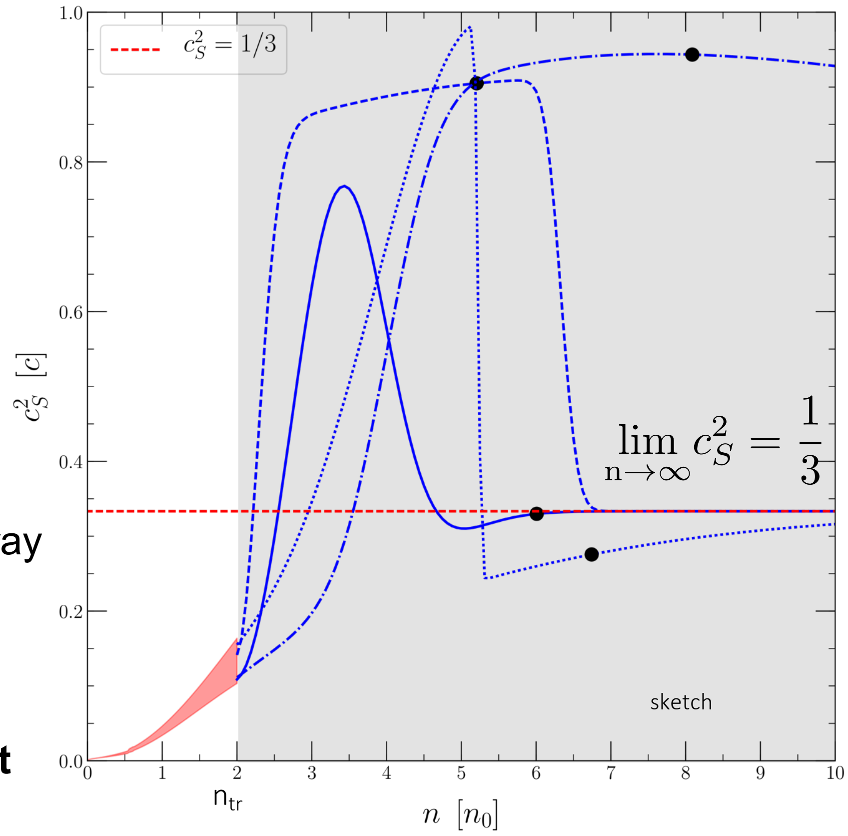
Neutron-star EOS

- Extend results to beta equilibrium (small $Y_{e,p}$) and include crust EOS.
- Extend to higher densities using general parametrization, e.g., in **speed of sound:**

Speed of sound:

$$c_S^2 = \frac{\partial p(\epsilon)}{\partial \epsilon}$$

- Sample many different curves in allowed region (gray band) and reconstruct EOS.
- Can easily include phase transitions and additional information on c_S.
- **Extend uncertainties to higher densities without strong assumptions!**



IT, Carlson, Gandolfi, Reddy, ApJ (2018)

Neutron-star EOS

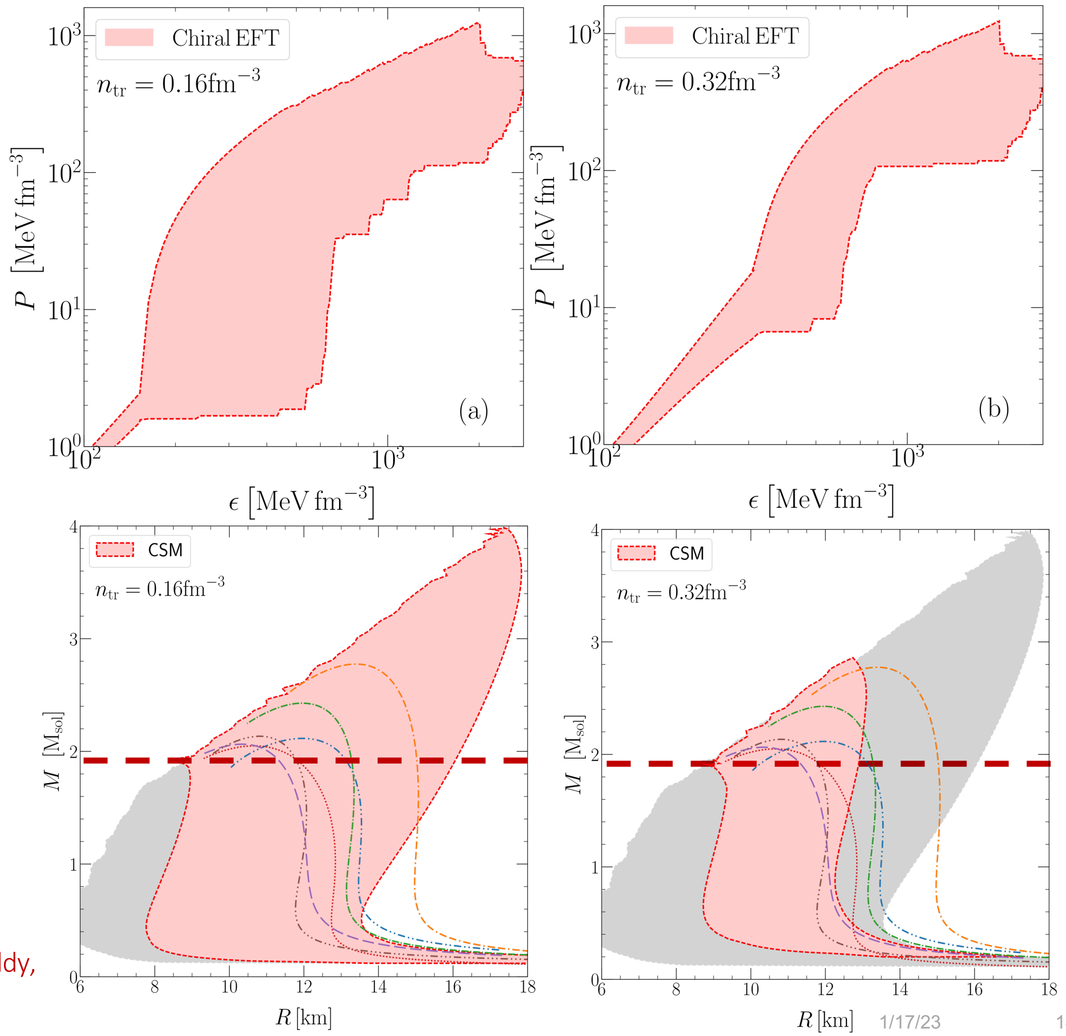
Generate large groups of EOSs that:

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

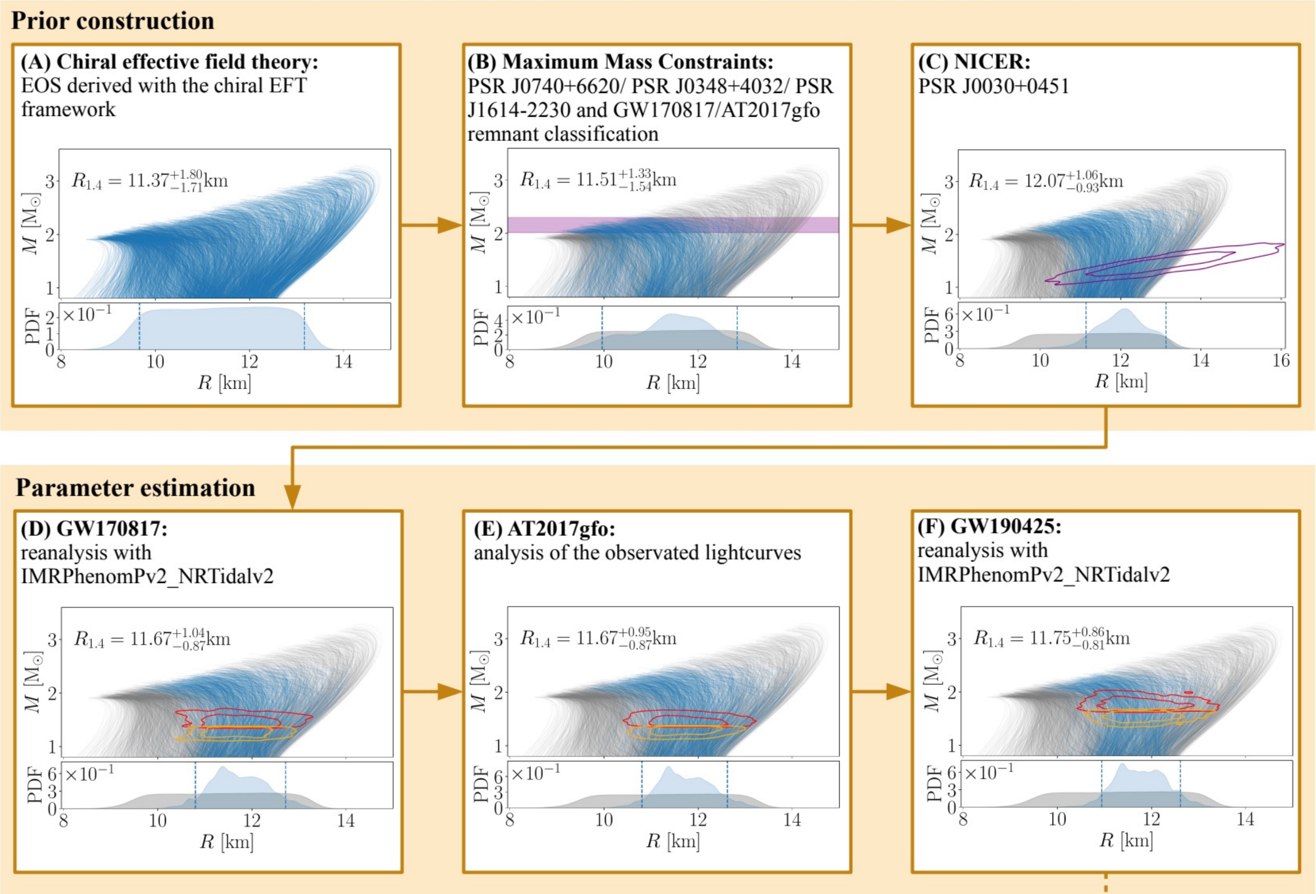
Current nuclear-physics uncertainties remain sizable **but EFT input critical!**

Extract information from NS observations and experiments.

IT, Margueron, Reddy, EPJ A (2019)



Nuclear-physics Multi-Messenger Astrophysics (NMMA)



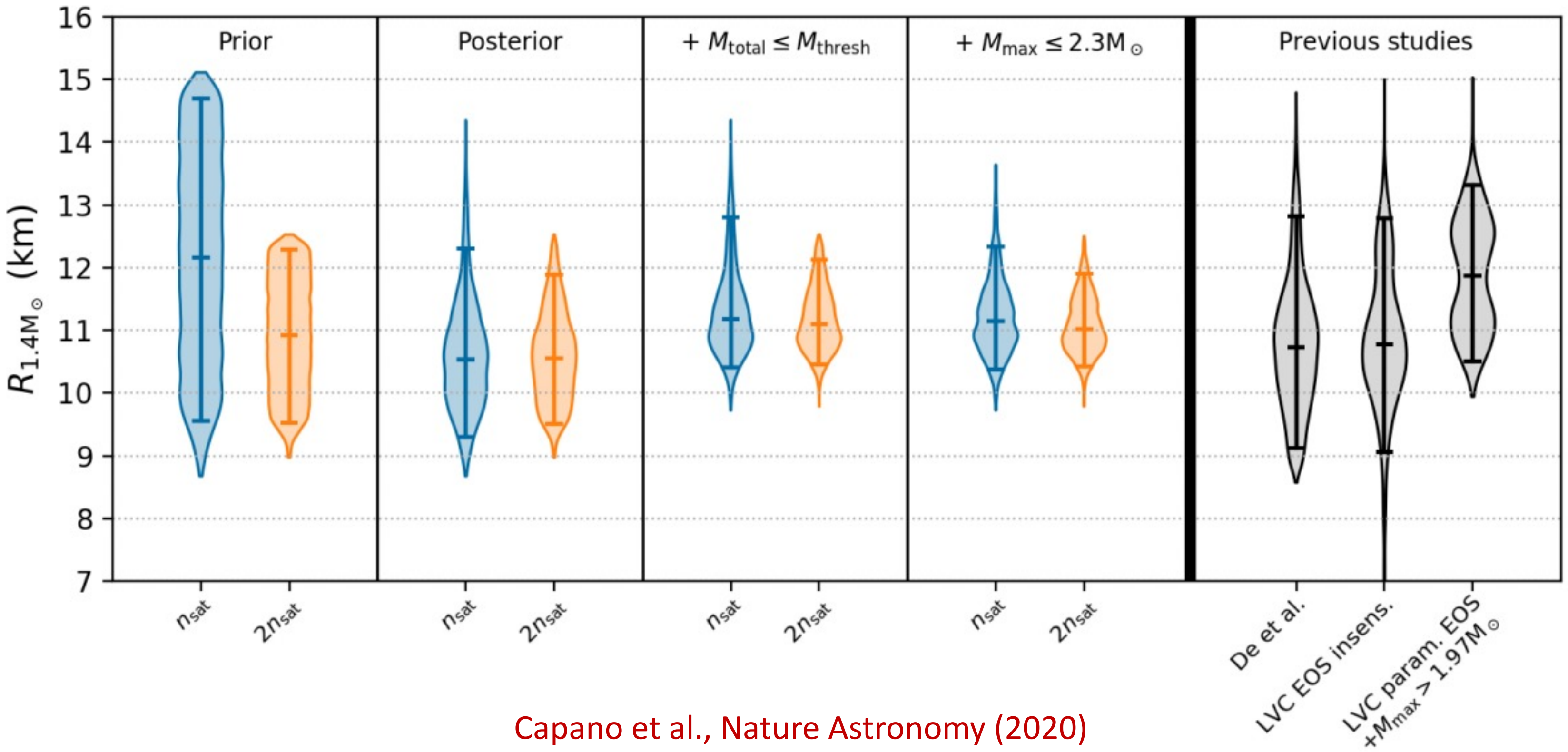
NMMA framework:

Pang et al., arXiv:2205.08513

- EOS consistent with theory
- Masses and NICER via published posteriors
- Simultaneous full GW and KN analyses
- Available online.

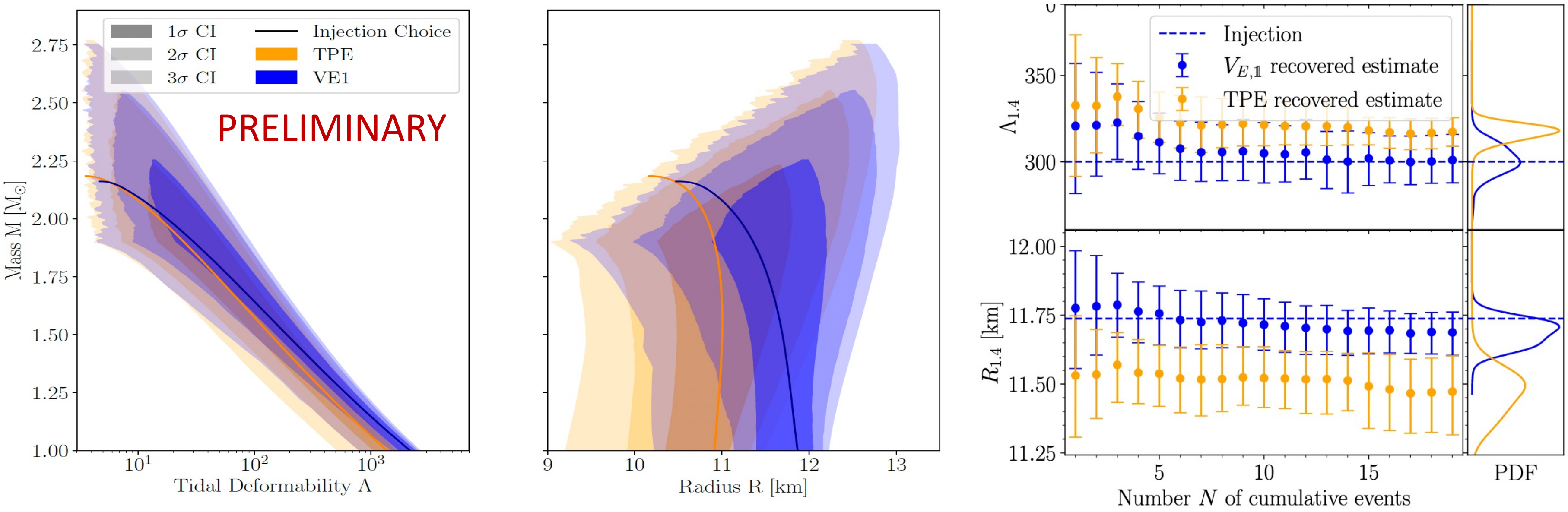
Dietrich, Coughlin, Pang, Bulla, Heinzel, Issa, **IT**, Antier, **Science** (2020)

Only GW170817 data and heavy NS



Capano et al., Nature Astronomy (2020)

Test chiral Hamiltonians with next-generation detectors

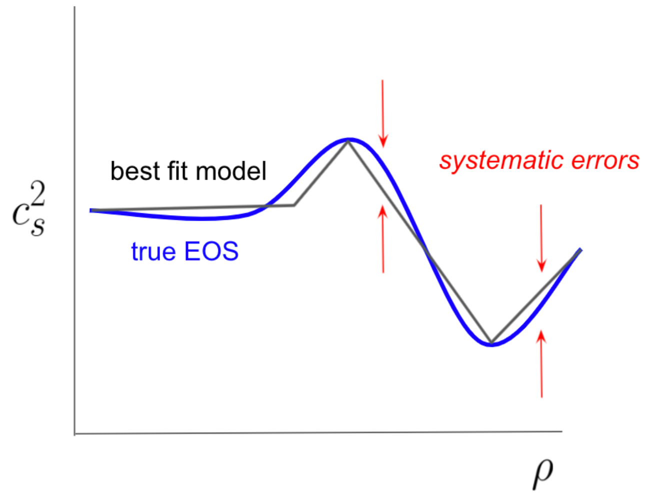


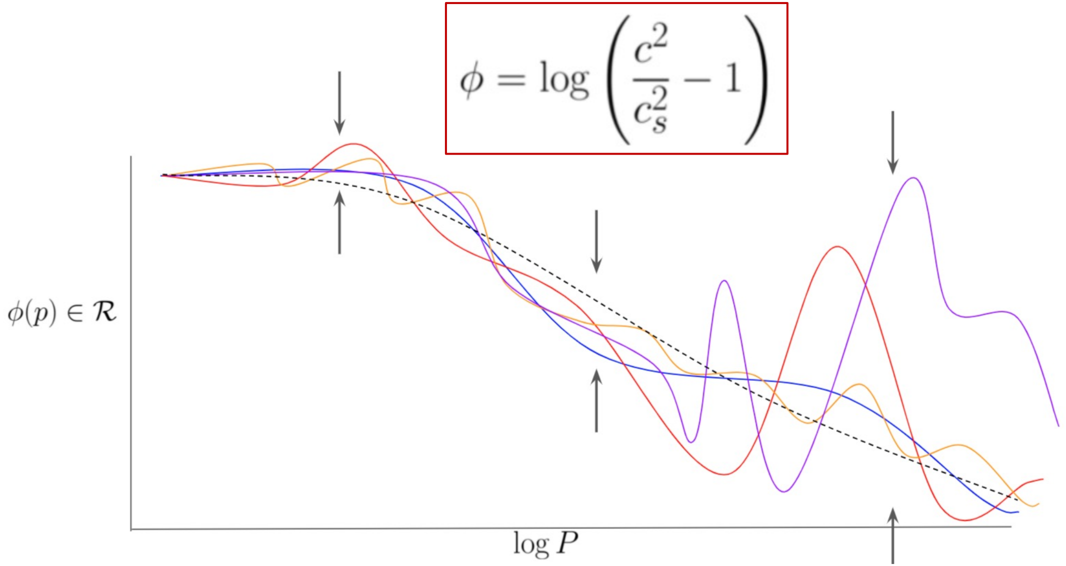
Kunert, Rose et al., in preparation

Current GW detectors are not sensitive enough to distinguish different nuclear Hamiltonians, but 3rd-generation detectors (Einstein Telescope) are well-suited for this.

EOS inference with Gaussian processes

Essick, Landry et al.





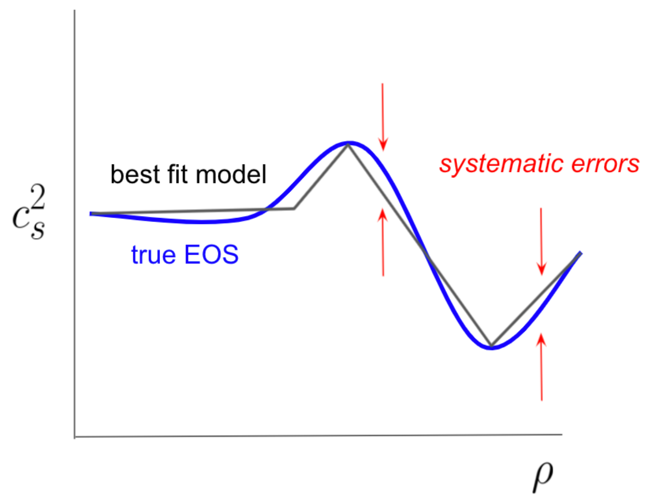
Parametric EOS extensions:

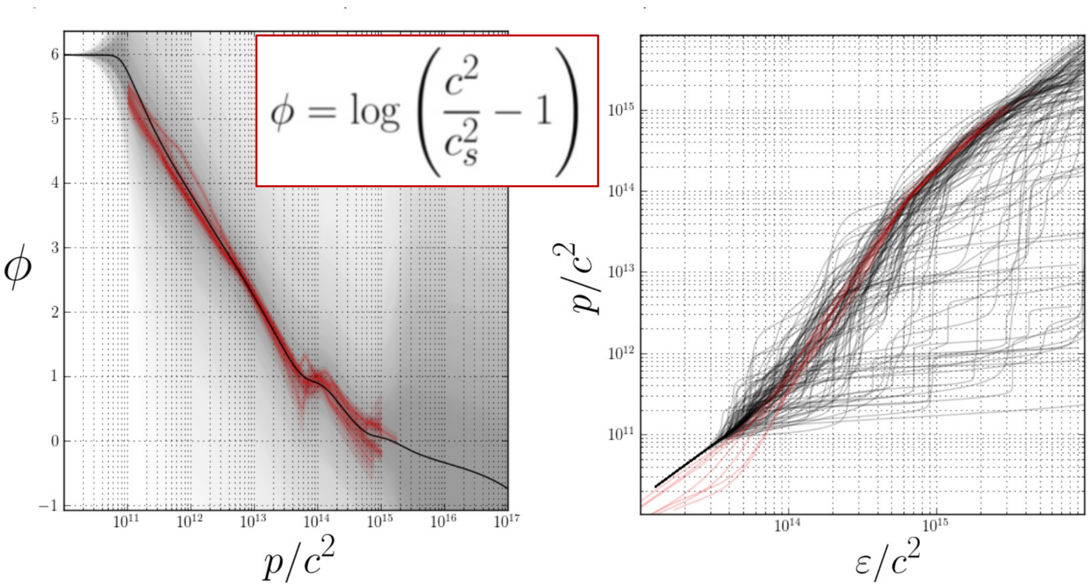
- only allow for certain types of behavior,
- true EOS might never be exactly recovered

Nonparametric EOS inference using Gaussian process in auxiliary variable

EOS inference with Gaussian processes

Essick, Landry et al.





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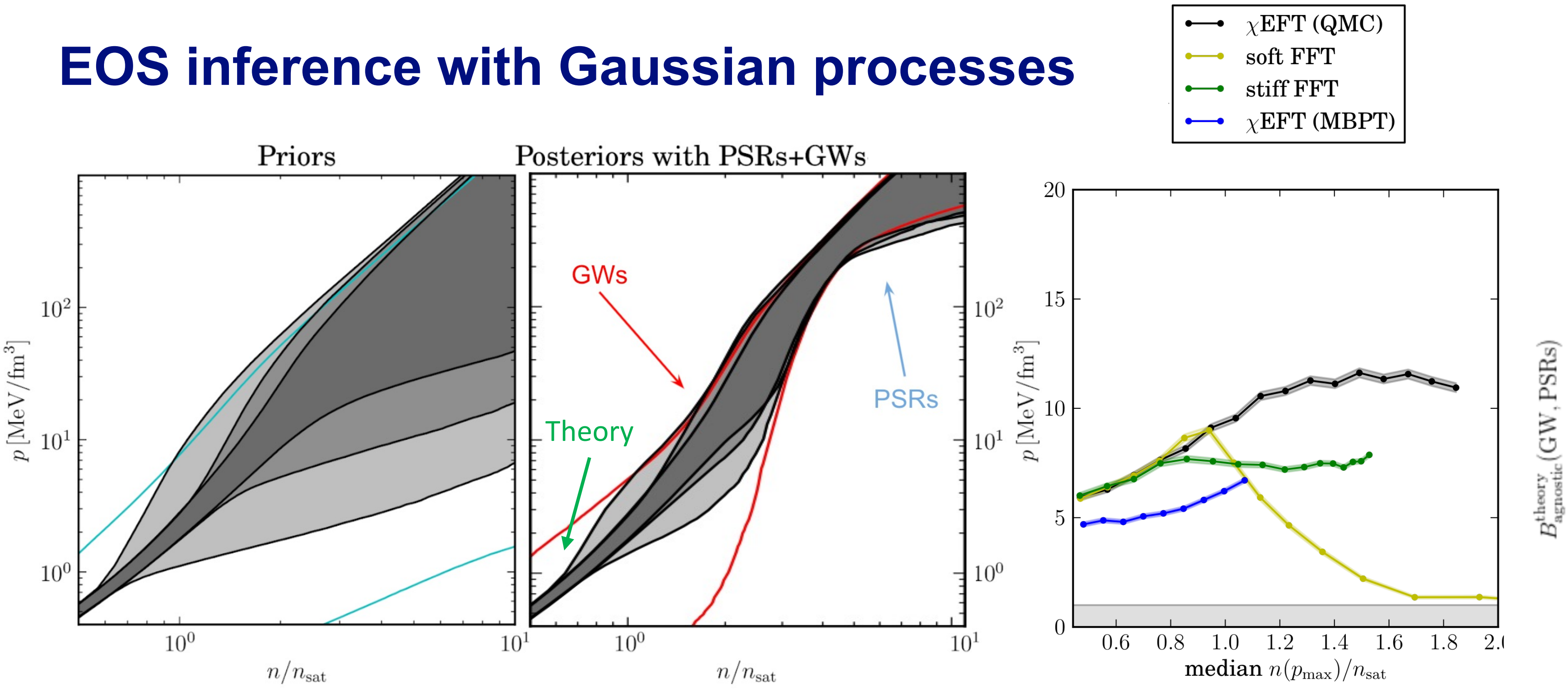
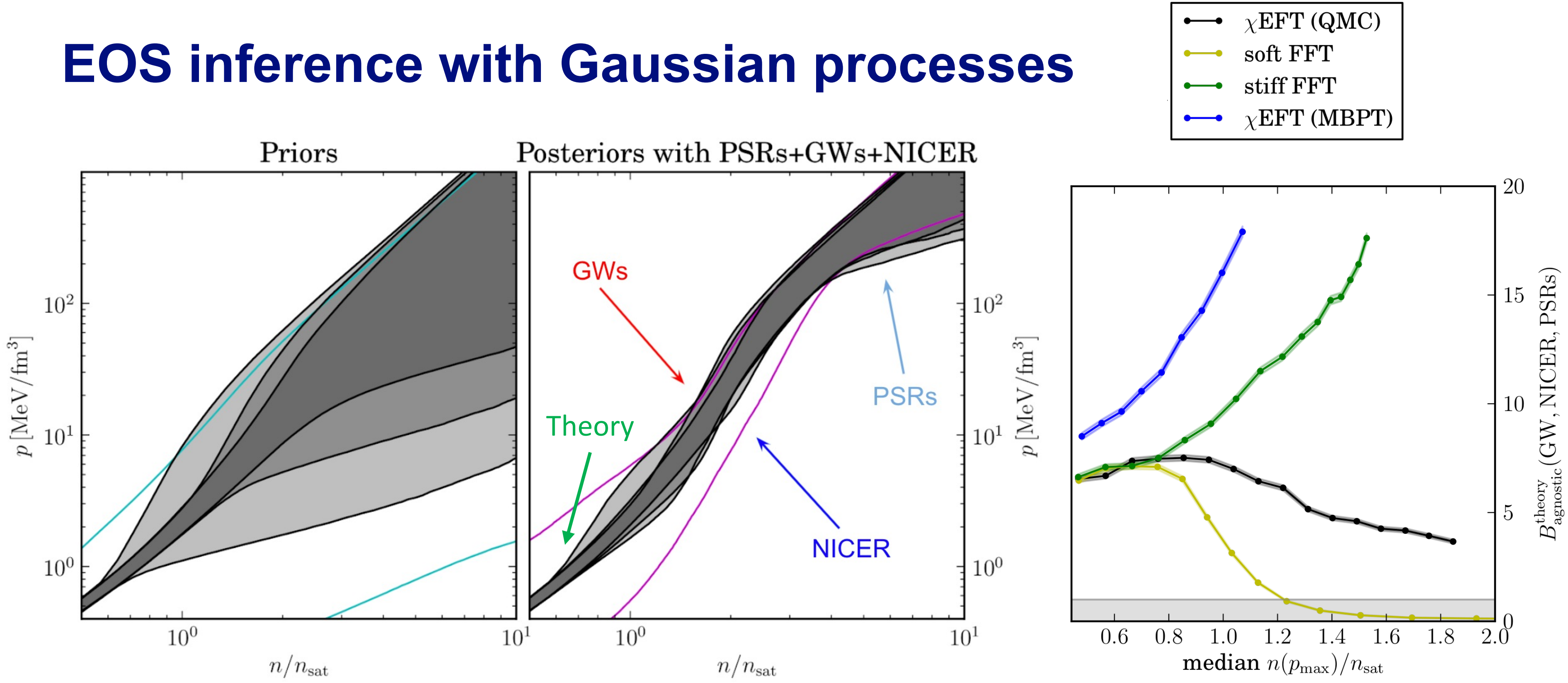


Essick et al., Phys. Rev. C 102, 055803 (2020)

Condition GP on nuclear-theory input up to $n_{sat}/2$, n_{sat}, 2 n_{sat}.

EOS inference with Gaussian processes



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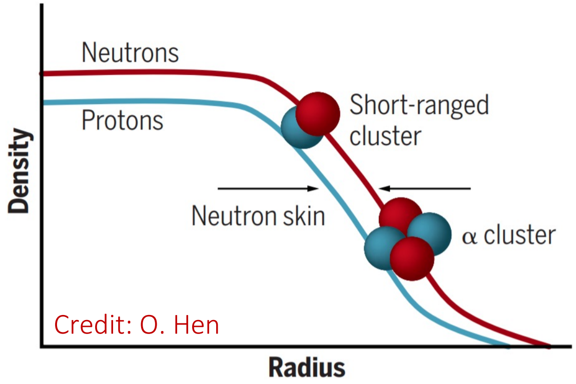
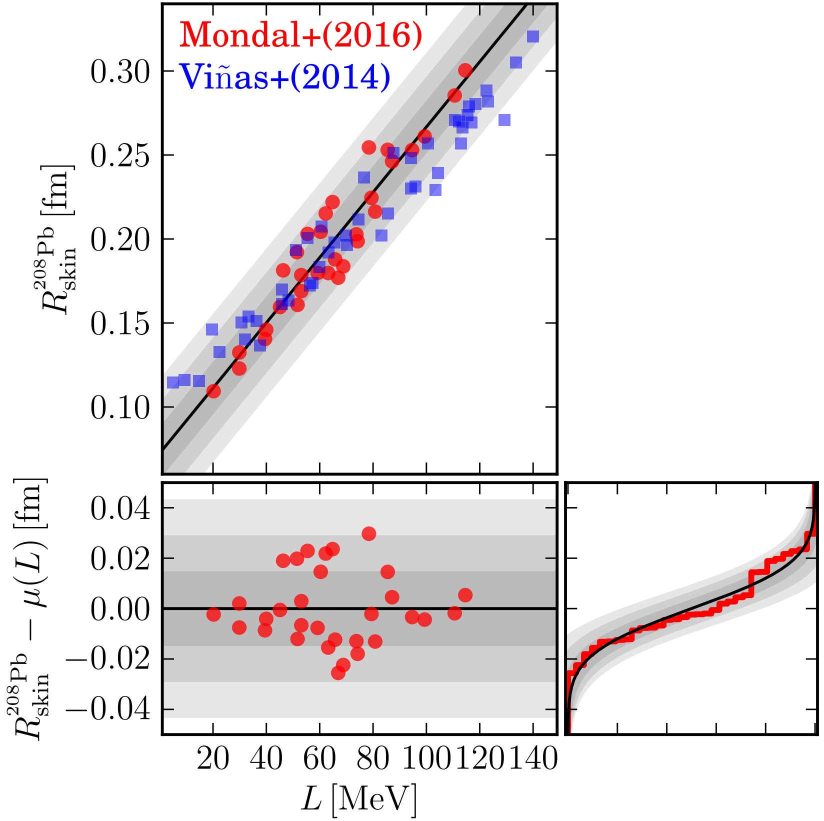
Connections to PREX-II



Neutron-skin thickness of ^{208}Pb inferred from PREX-II experiment, 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, PRL (2021) and PRC (2021)

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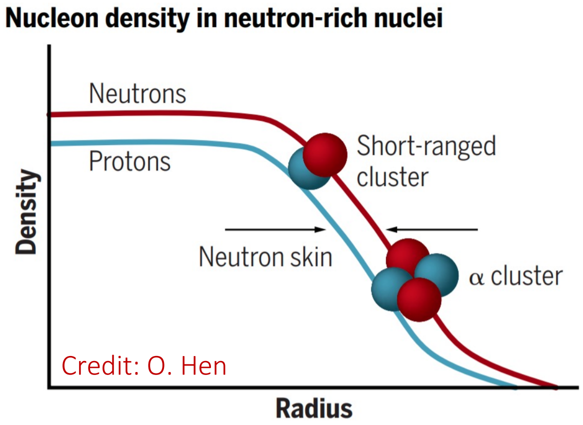
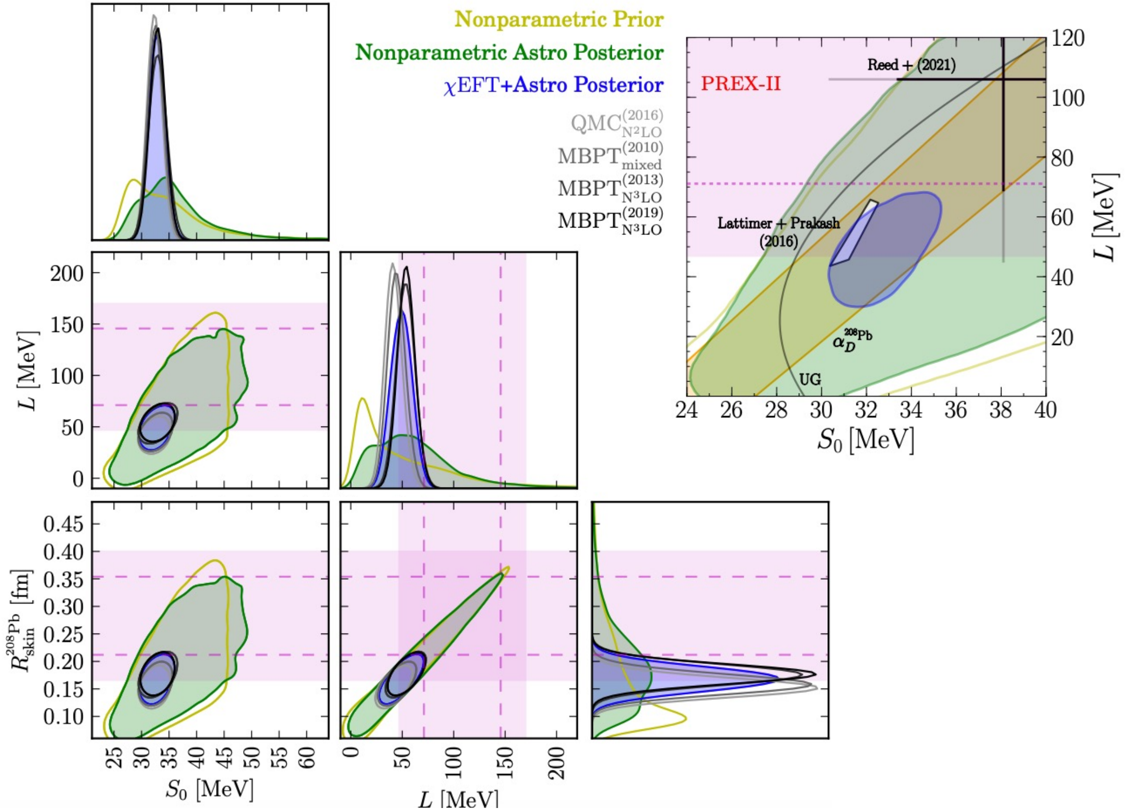
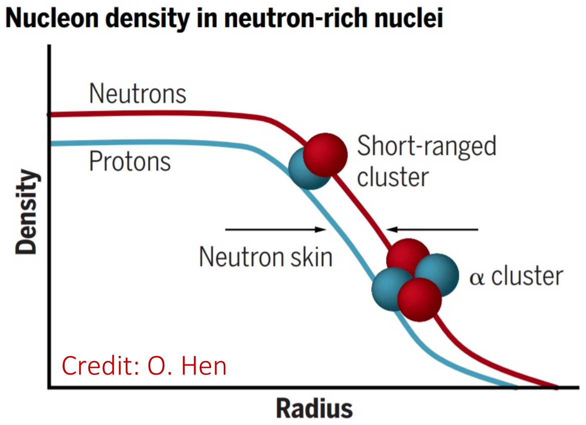




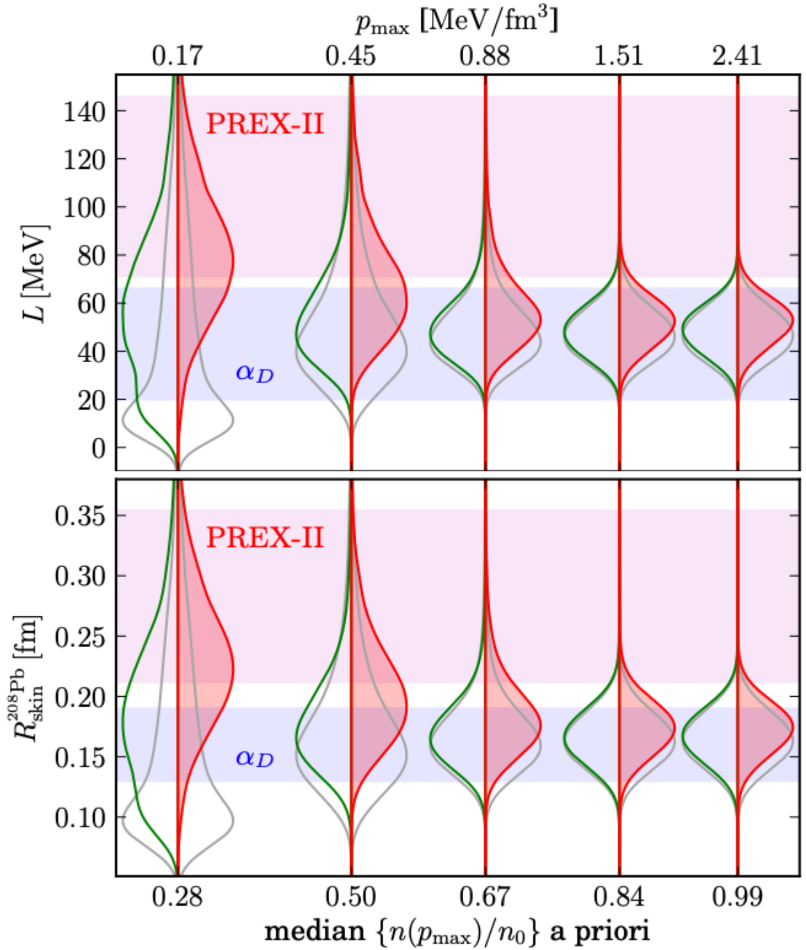
- Astrophysics data agrees with both nuclear theory and PREX, posterior maximum coincides with EFT prediction
- No significant tension between PREX and EFT calculations.

Essick, IT, Landry, and Schwenk, PRL (2021) and PRC (2021)

Connections to PREX-II



- Astrophysics data agrees with both nuclear theory and PREX, posterior maximum coincides with EFT prediction
- No significant tension between PREX and EFT calculations.
- Chiral EFT provides most stringent constraints



Essick, IT, Landry, and Schwenk, PRL (2021) and PRC (2021)

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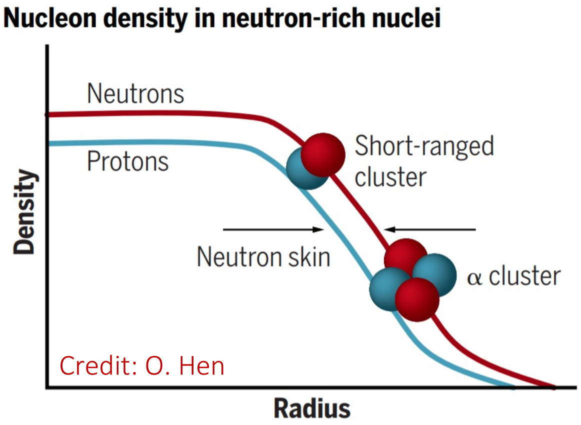
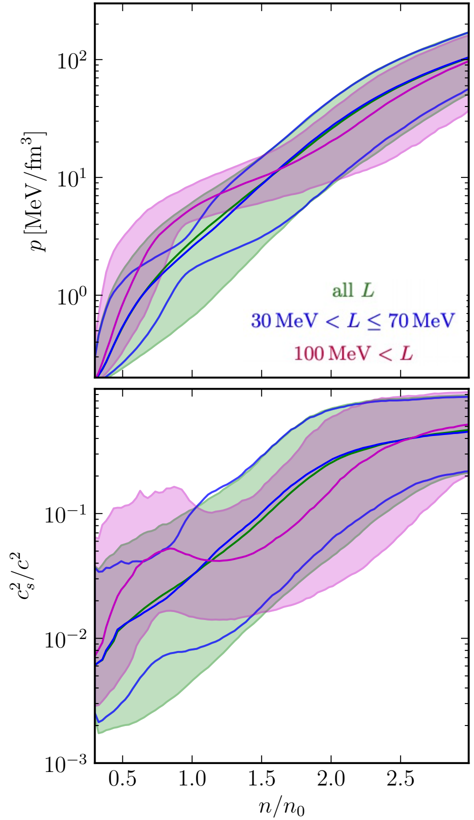
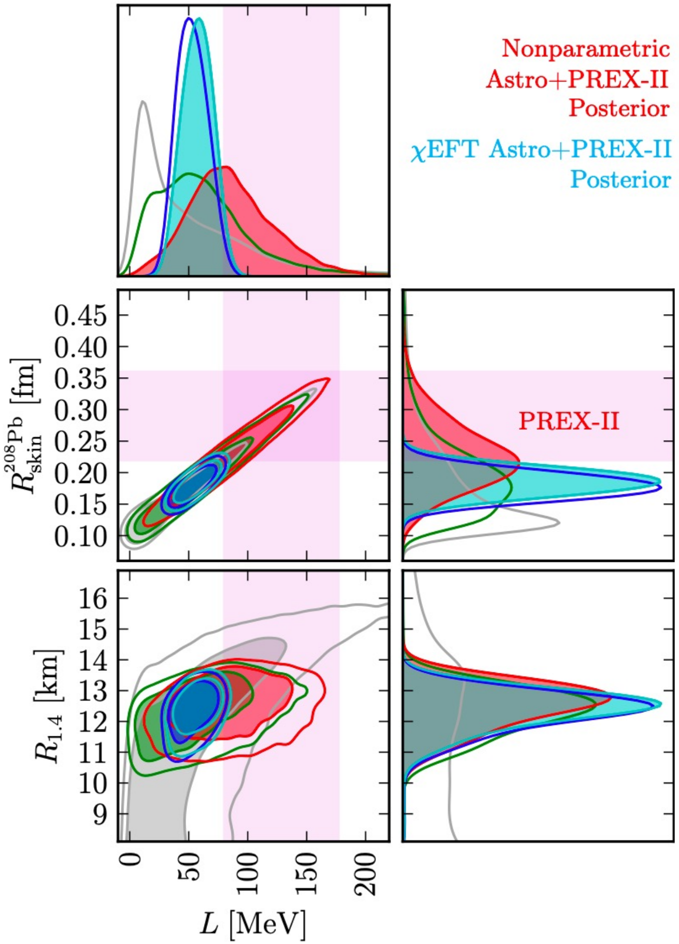


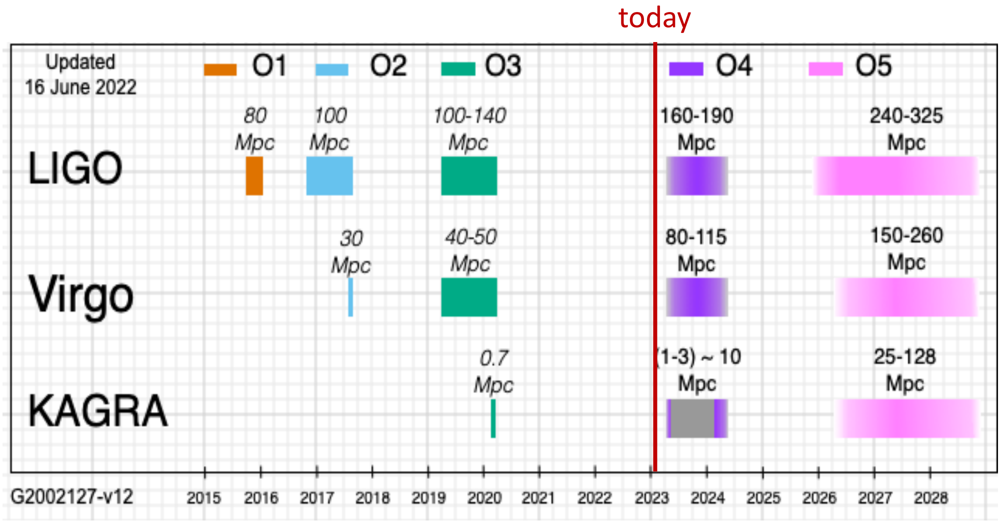
- Large L would require interesting behavior in the speed of sound
- Radius prediction for typical neutron star does not change if PREX-II is included, correlation of L and R weak

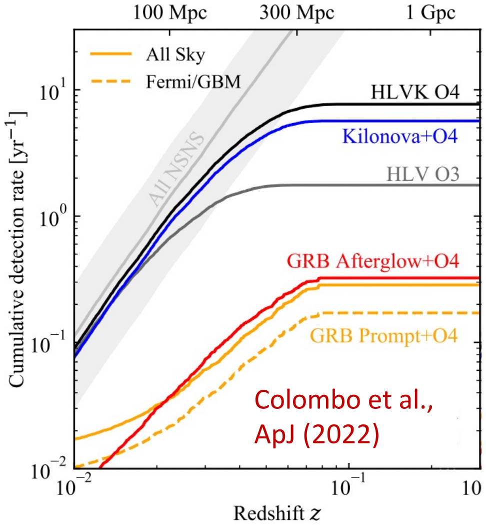


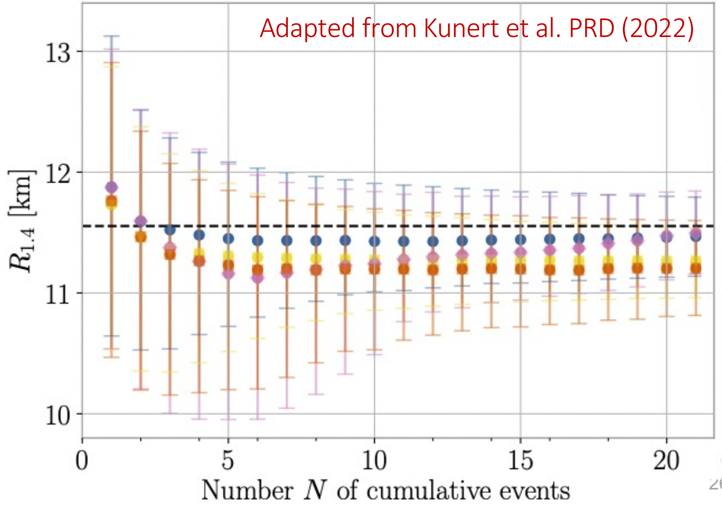


Essick, IT, Landry, and Schwenk, PRL (2021) and PRC (2021)

LIGO: Next observing runs







Next observing run starting in May, up to 7-ish BNS expected

Electromagnetic observations: Kilonova observations are crucial to probe physics at highest densities (without postmerger GW signal), we need detailed astrophysical modeling of these events.

Summary

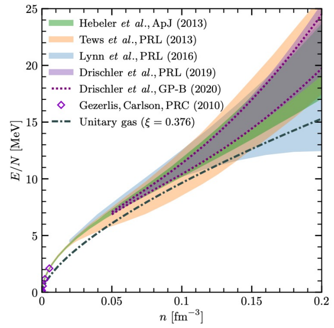
➢ Neutron stars represent ideal laboratories for nuclear physics and help to improve our understanding of nuclear interactions!

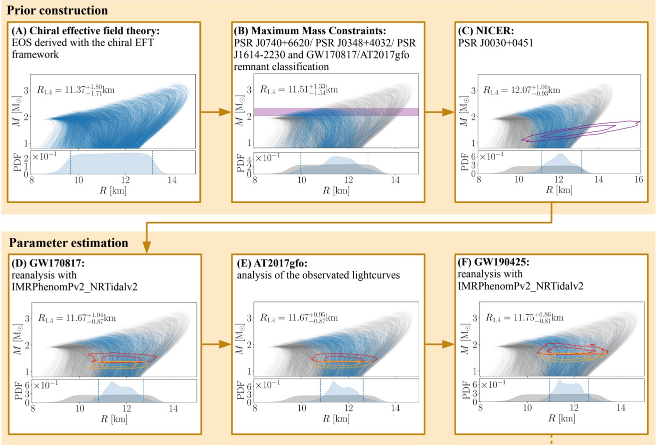
➢Uncertainty in neutron-star EOS can be reduced by

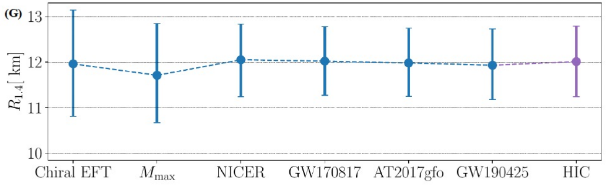
- Improved nuclear-physics calculations using chiral EFT,
- Multimessenger observations of NS and NS mergers,
- Experiments in the laboratory.

➢ GW observations favor softer, EM observations (kilonova and NICER) and nuclear experiments favor stiffer EOS but still large uncertainties. Upcoming years will provide exciting new data.

➢ Crucial to estimate breakdown density of EFT in neutron-rich matter to fully capitalize on future data, and test EFT.







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S. Reddy (INT Seattle)

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J. Margueron (IPN Lyon)

B. Margalit (UC Berkeley)

D. Brown (Syracuse University)

R. Essick (Perimeter Institute)

D. Holz (Kavli Institute)

P. Landry (Cal State Fullerton)

T. Dietrich, N. Kunert, H. Rose (University of Potsdam)

P. Pang, C. van den Broeck (Nikhef)

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Thank you for your attention!