Neutron-star properties from chiral effective field theory, multimessenger observations and experiments

Ingo Tews, Theoretical Division (T-2)
Los Alamos National Laboratory

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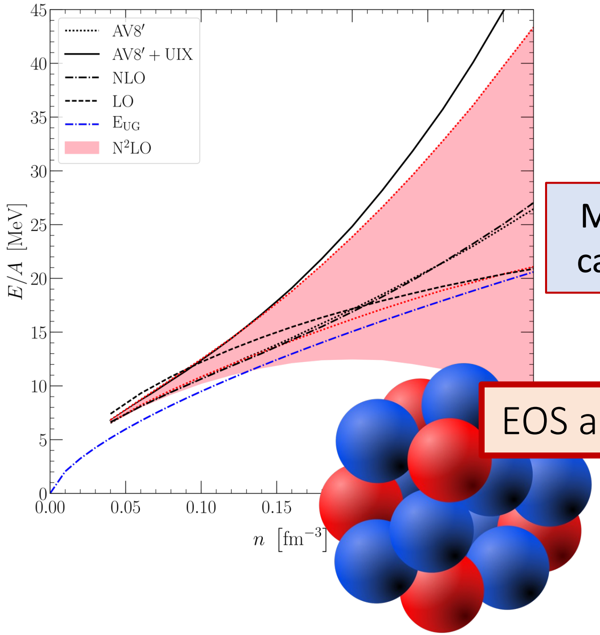
LA-UR-22-26729

Nuclear-physics Multi-Messenger Astrophysics (NMMA)



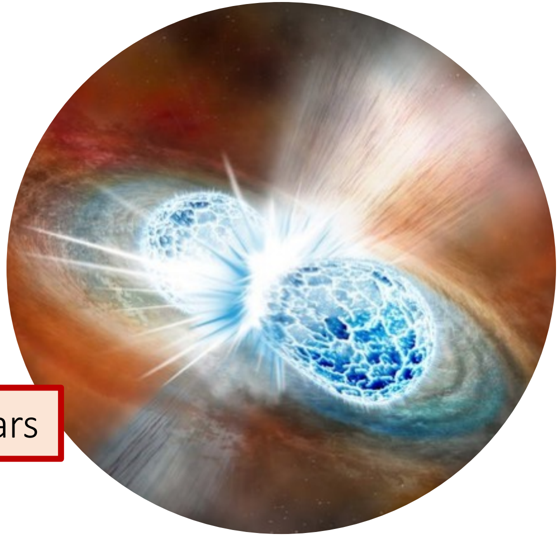
Nuclear forces & currents

Many-body calculations

EOS and nuclei

Neutron stars

Bayesian Inference of EOS from LIGO, NICER data



Quantum many-body studies of matter and nuclei offer an exciting opportunity to bridge different systems with same interactions and currents!

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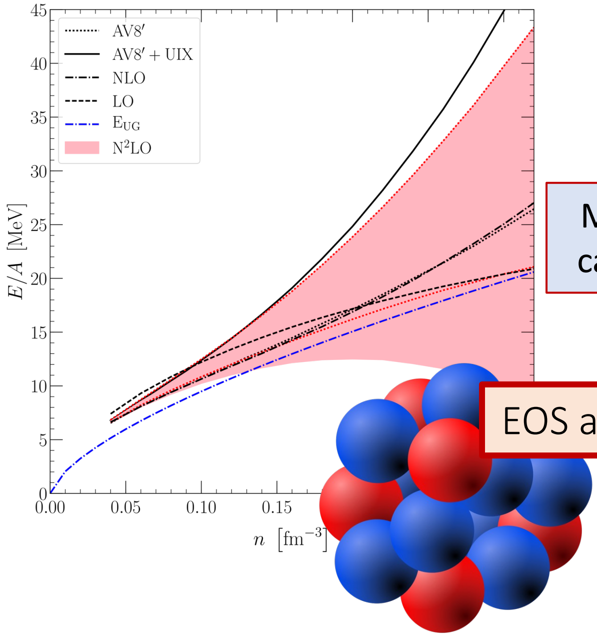

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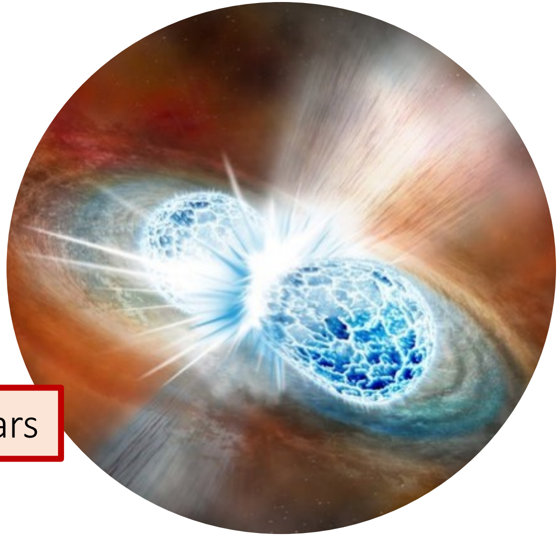
Bayesian Inference of EOS from LIGO, NICER data

+ Nuclear Experiment



Quantum many-body studies of matter and nuclei offer an exciting opportunity to bridge different systems with same interactions and currents!

Nuclear-physics Multi-Messenger Astrophysics (NMMA)

Same nuclear interactions among same constituents (nucleons) in the lab and in astrophysics.
A measurement or observation has immediate consequences for the other domain.

01

How can we describe microscopic interactions among nucleons?

- What are the fundamental interactions that govern strongly interacting matter?
- Chiral Effective Field Theory.
- How can we assess uncertainties?

02

What can we learn about neutron stars from nuclear theory?

- Constraints on mass-radius curve from microscopic calculations based on chiral EFT.

03

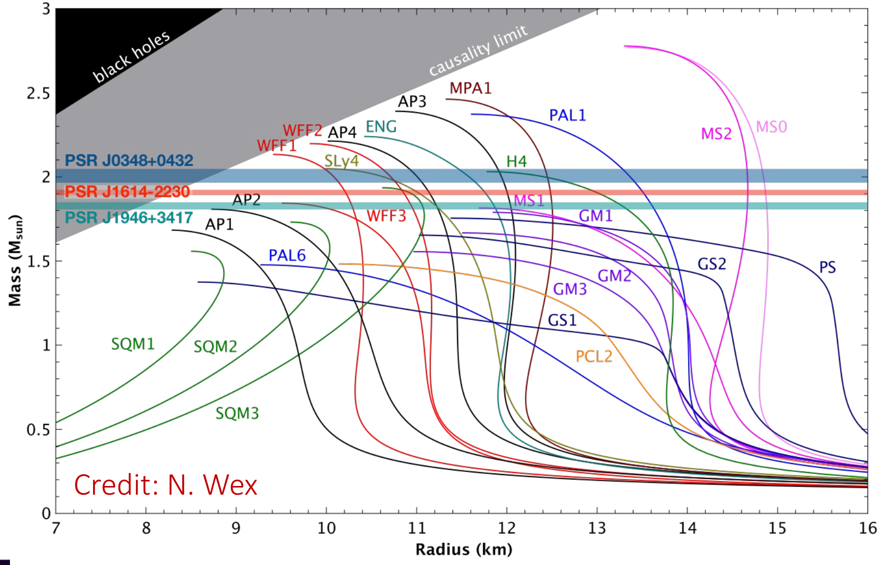
What do observations tell us about nuclear physics and nuclear interactions?

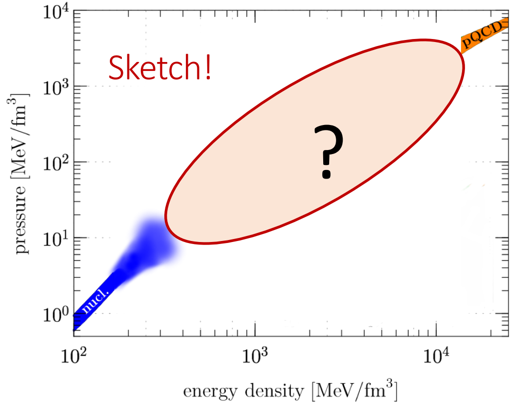
- Multi-messenger astrophysics as test for nuclear physis.
- Impact of experiments.

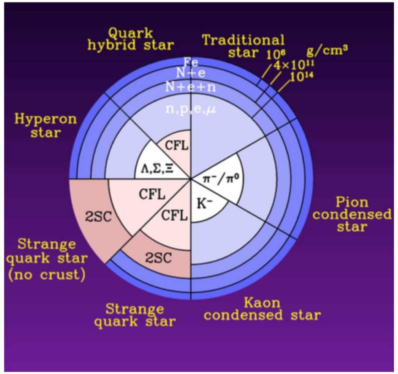
The equation of state

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:

- At low densities from **nuclear theory** 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 EOS but I will focus on **microscopic calculations**. We need:

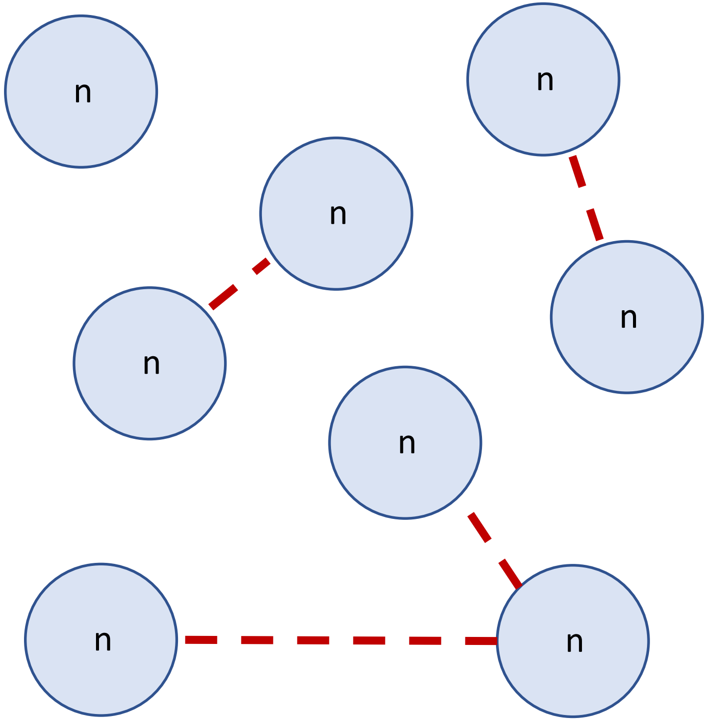
- A theory for the strong interactions among nucleons:

Chiral Effective Field Theory

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

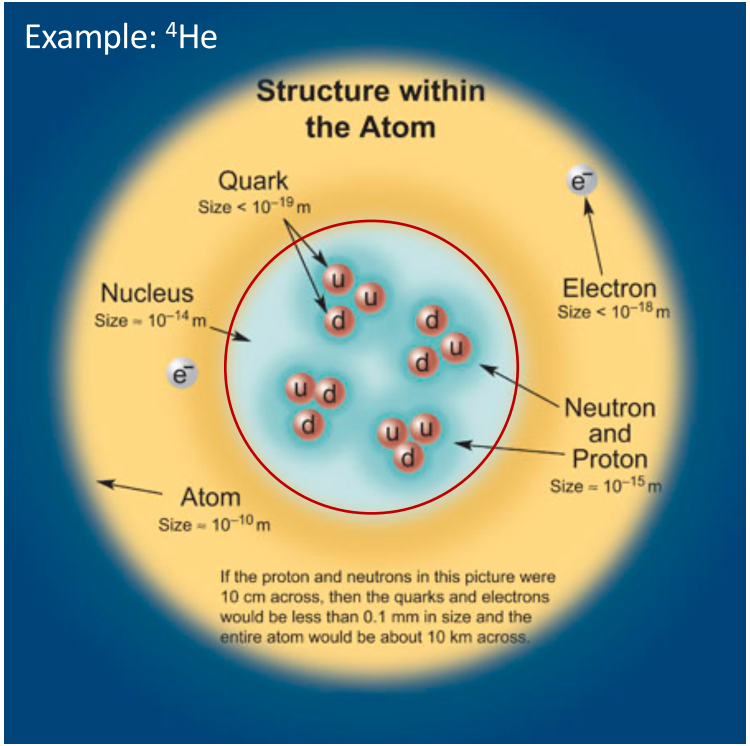
e.g., many-body perturbation theory, **quantum Monte Carlo**, coupled cluster, self-consistent Green's function, …

See also talk by J. Carlson



Chiral Effective Field Theory

- Atomic nucleus consists of strongly interacting matter.
- Made up by quarks and gluons (Quantum Chromodynamics).
- Extremely complicated to solve!



Chiral Effective Field Theory

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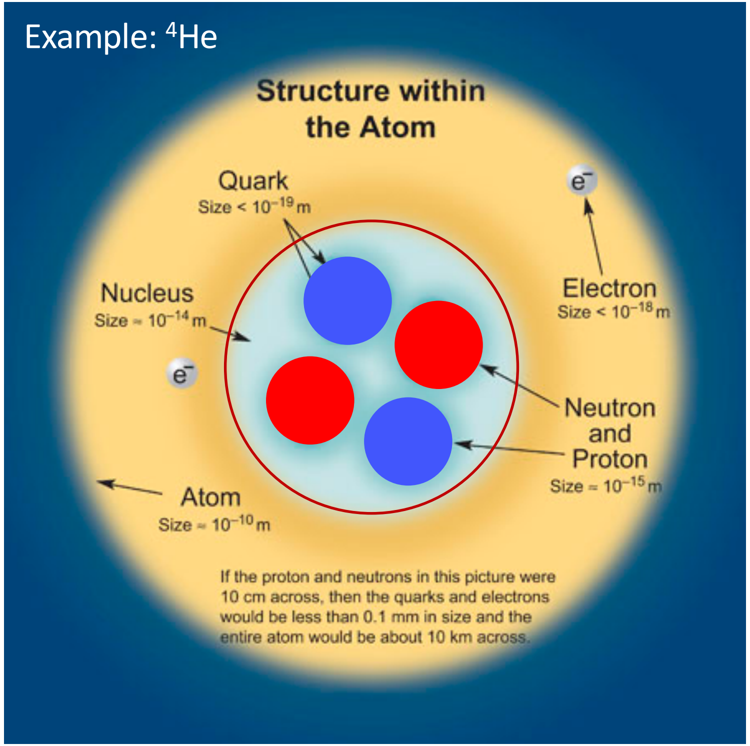
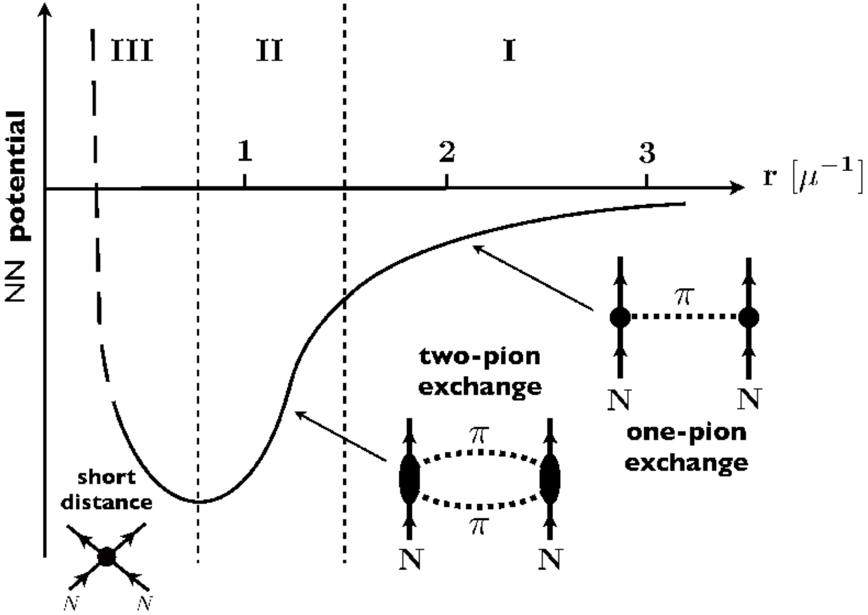
- Made up by quarks and gluons (Quantum Chromodynamics).
- Extremely complicated to solve!

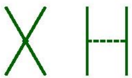
- Probing a nucleus at low energies does not resolve quark substructure of nucleons!
- We can describe the nucleus in terms of neutrons (udd) and protons (uud).



Chiral Effective Field Theory

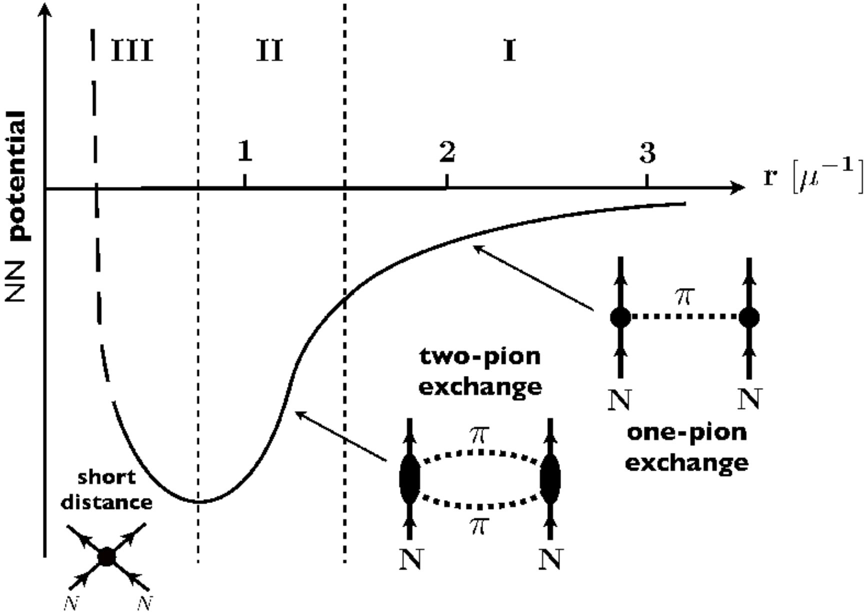


Holt et al., PPNP 73 (2013)

	NN	3N	4N
LO $\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$ (2 LECs)		—	—

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

Chiral Effective Field Theory



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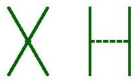
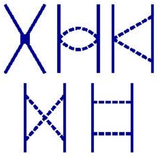
LO $\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$ (2 LECs)		—	—
NLO $\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$ (7 LECs)		—	—

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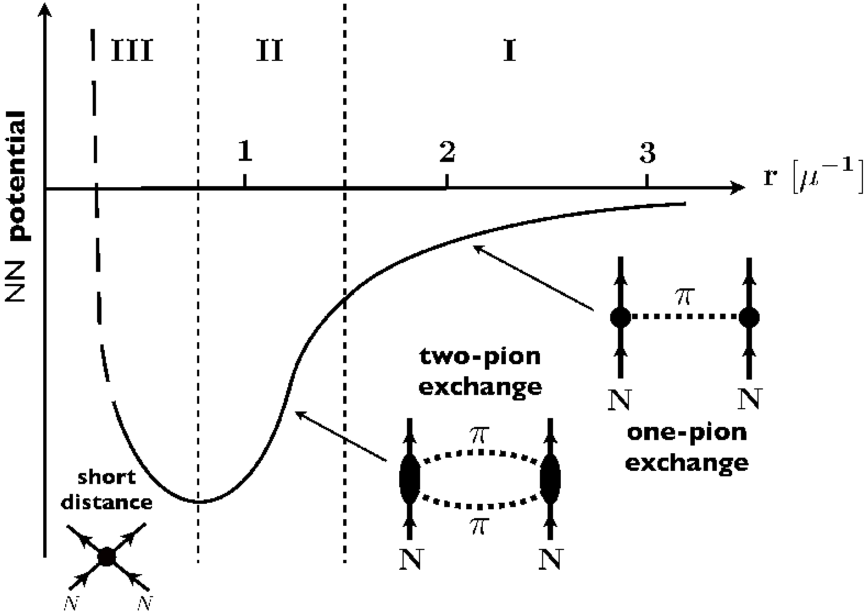

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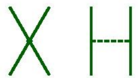
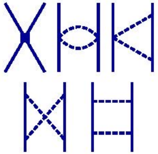
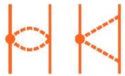
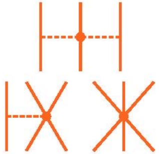
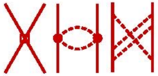
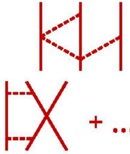
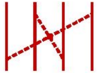
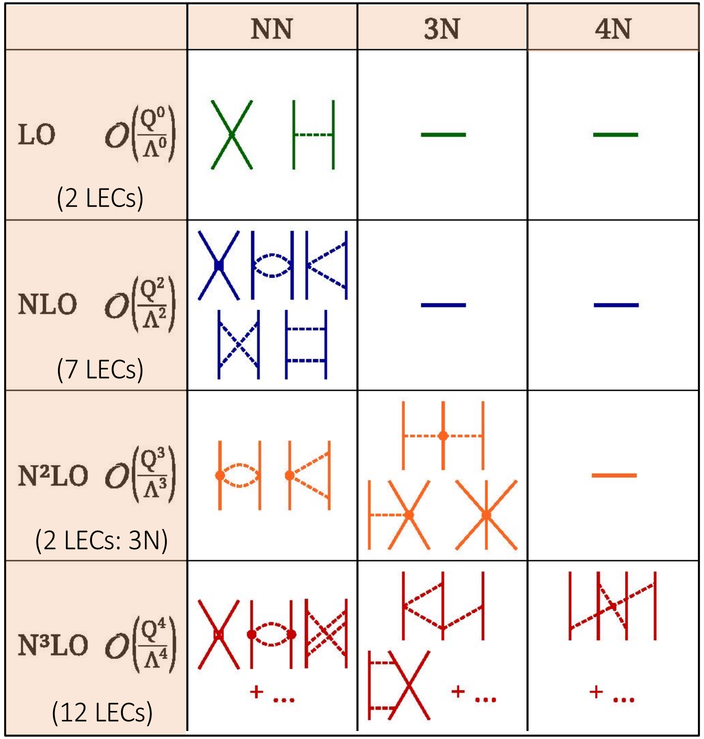
LO $\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$ (2 LECs)		—	—
NLO $\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$ (7 LECs)		—	—
N²LO $\mathcal{O}\left(\frac{Q^3}{\Lambda^3}\right)$ (2 LECs: 3N)			—
N³LO $\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$ (12 LECs)	 + ...	 + ...	 + ...

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 scattering), 3N forces in 3N/4N system (Binding energies, radii)



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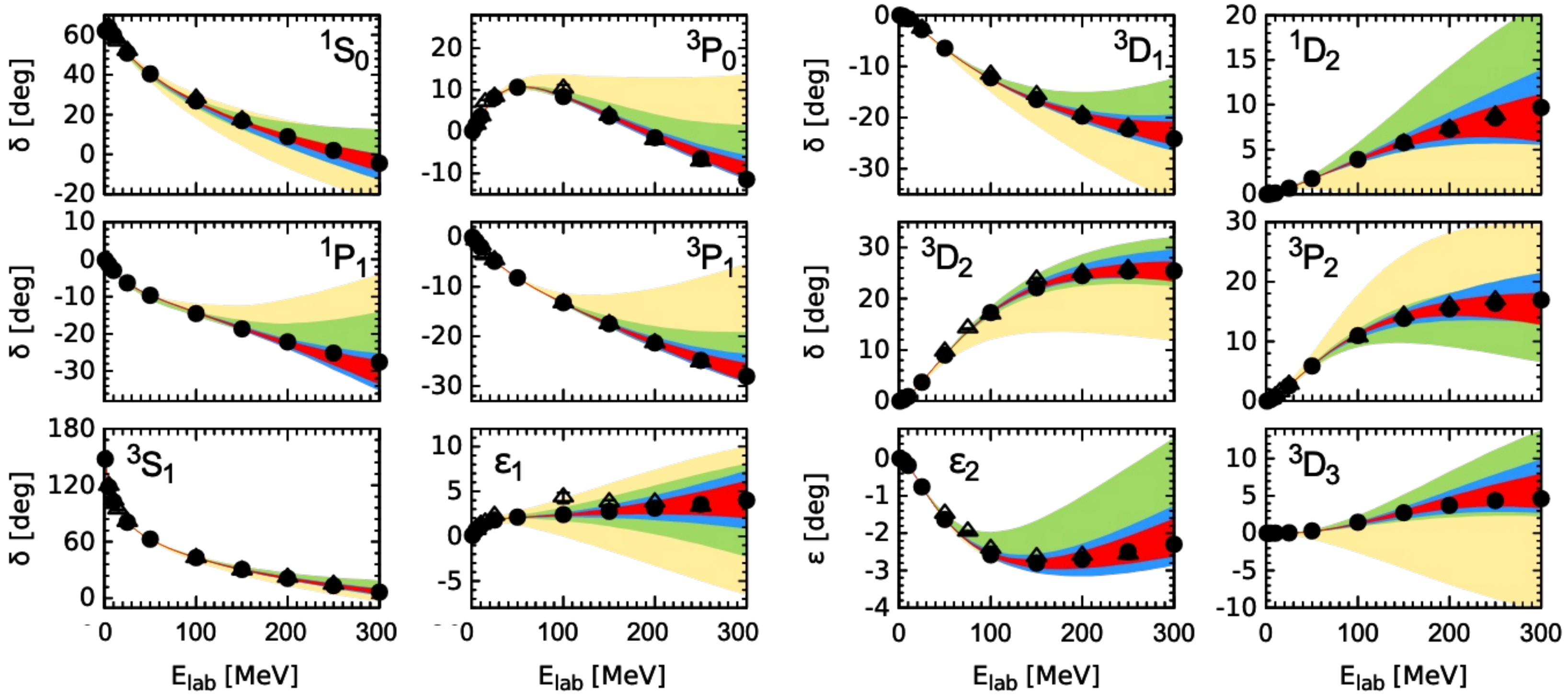
Neutron-proton scattering phase shifts

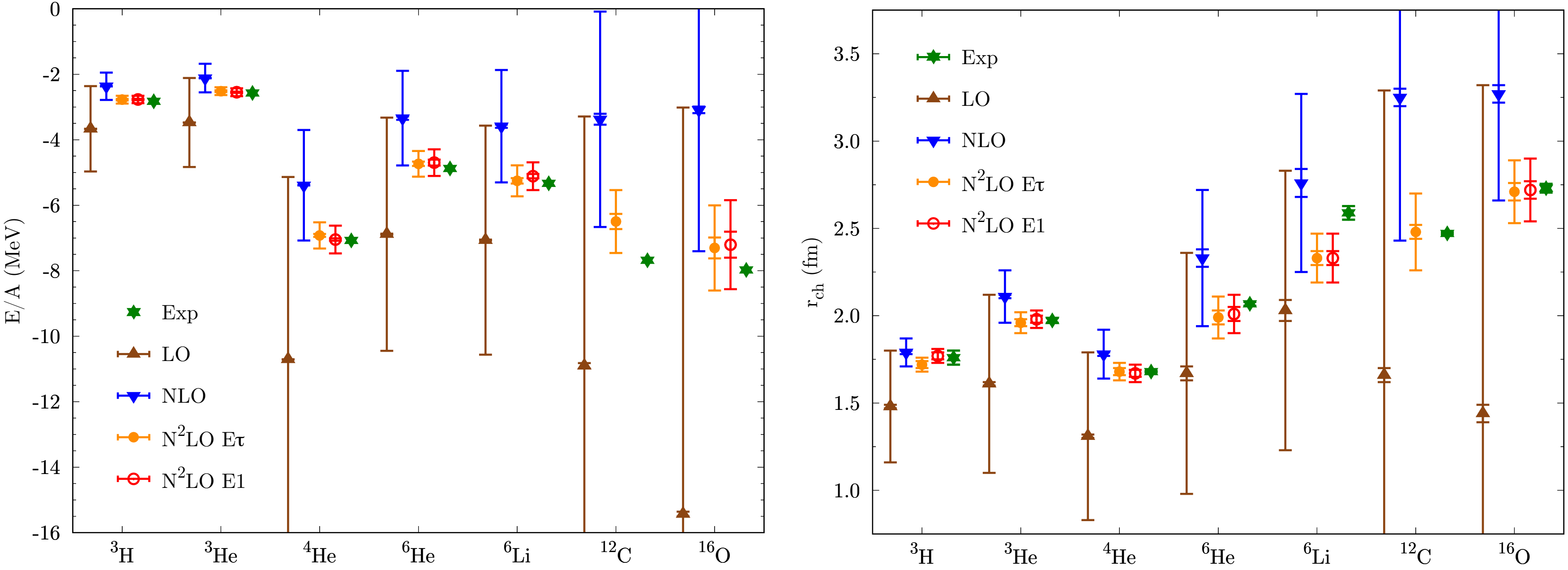


Can work to desired accuracy with error estimates!

Epelbaum et al., PRL (2015)
See also Carlsson et al. PRX (2016)

Results for nuclei

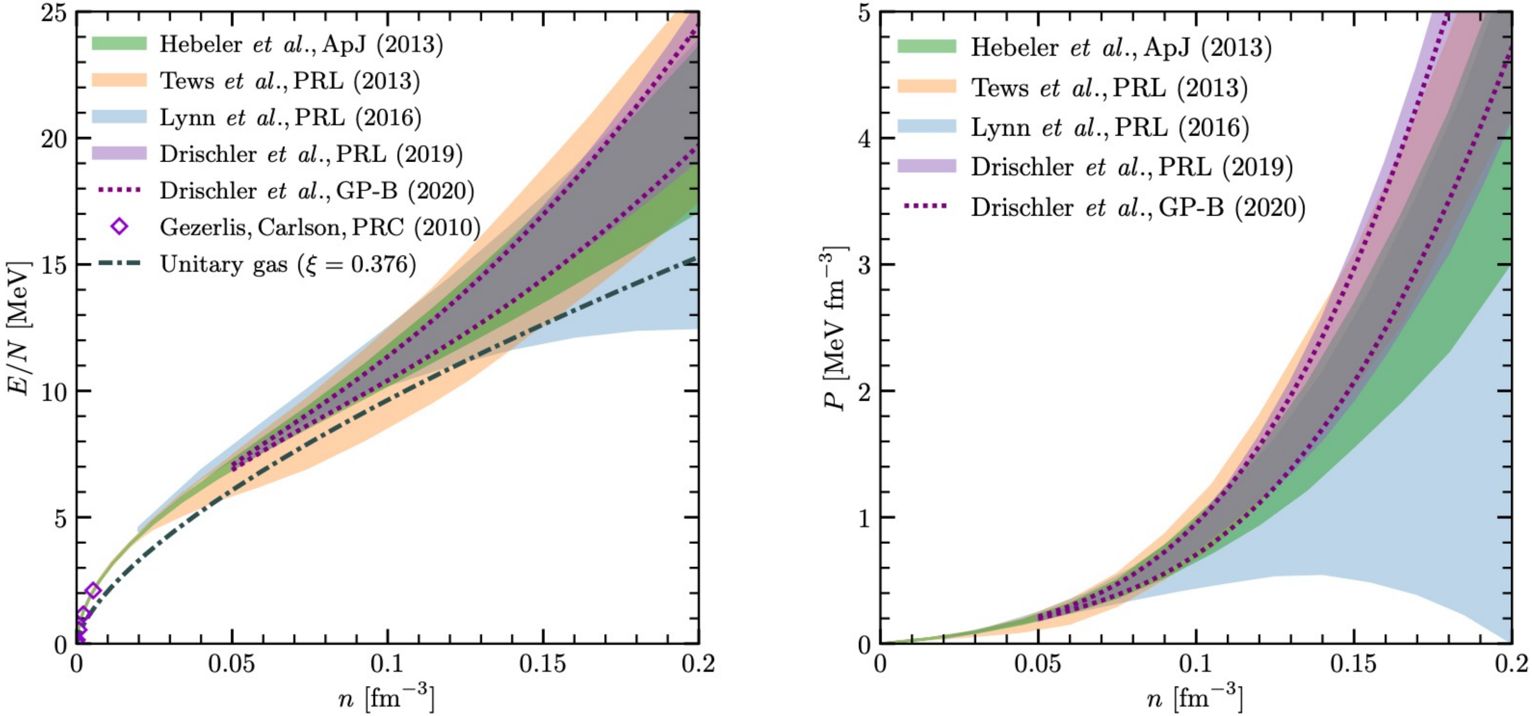
Results for chiral EFT calculations of nuclei with Quantum Monte Carlo (QMC) methods:



Excellent description of properties of nuclei up to the medium-mass region.

Lonardoni et al., PRL and PRC (2018)

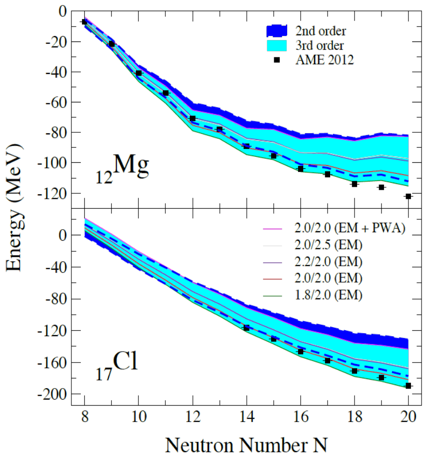
Results for neutron matter



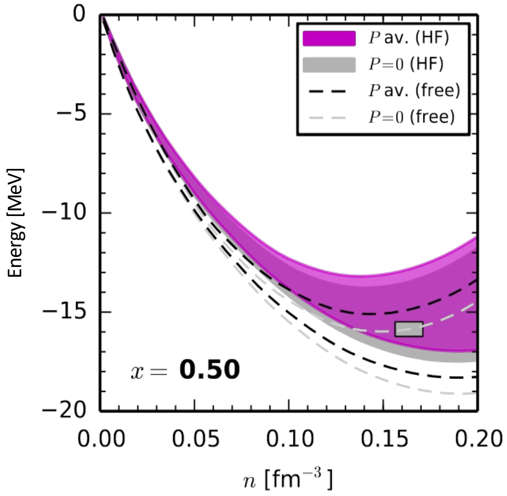
Huth et al., PRC (2021)

Excellent agreement for different many-body methods/EFT schemes!

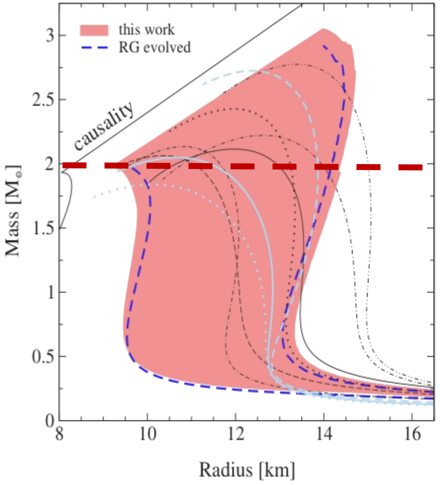
Uncertainty



Simonis et al., PRC (2016)



Drischler et al., PRC (2016)



Krueger, IT et al., PRC (2013)

Present theoretical predictions for nuclear systems are limited by:

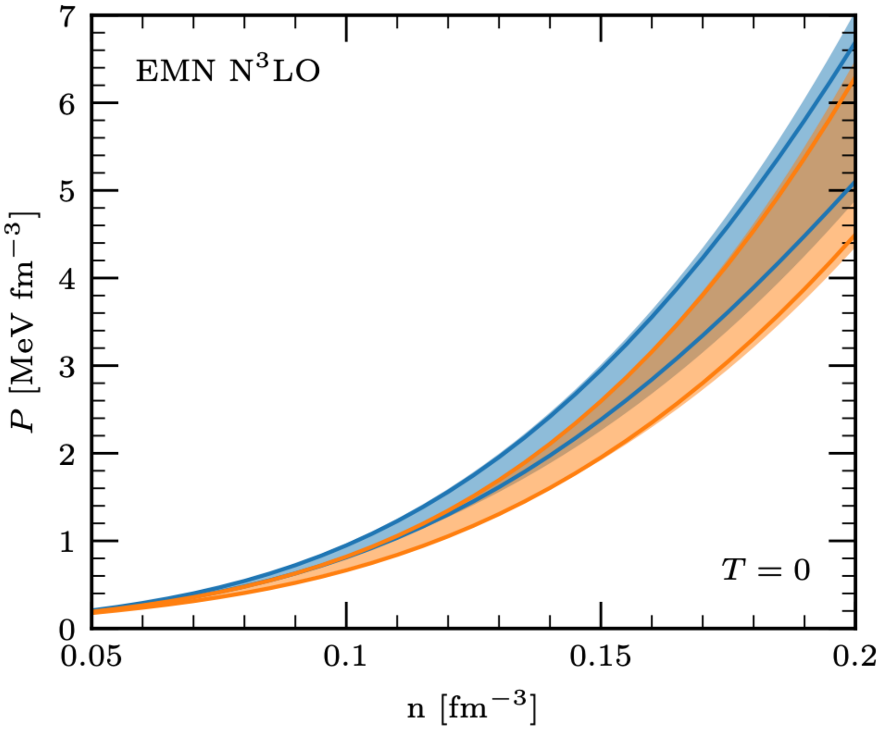
- our incomplete understanding of **nuclear interactions**,
- and our ability to **reliably calculate** these strongly interacting systems.

For nucleonic matter and nuclei, we need a **consistent approach** with:

- a systematic theory for strong interactions
- advanced many-body methods
- **controlled theoretical uncertainty estimates**.

Microscopic studies of nucleonic matter and nuclei using chiral EFT.

Truncation uncertainty



Keller et al., PRC (2021)

Estimated from order-by-order calculation:

$$\Delta X = X - X_0 \sum_{k=0}^{k_{\max}} c_k Q^k = X_0 \sum_{k=k_{\max}+1}^{\infty} c_k Q^k$$

- Using simple estimation **(bands)**:

Epelbaum, Krebs, Meißner, EPJ A (2015)

$$\Delta X^{\mathrm{N^2LO}} = \max\Big(Q^4\left|X^{\mathrm{LO}} - X^{\mathrm{free}}\right|, Q^2\left|X^{\mathrm{NLO}} - X^{\mathrm{LO}}\right|, Q\left|X^{\mathrm{N^2LO}} - X^{\mathrm{NLO}}\right|\Big)$$

$$Q = \frac{\max(p, m_\pi)}{\Lambda_b}$$

- Using Gaussian processes (**lines**).

Drischler et al., PRL (2020), see also talk by C. Drischler next week

Both approaches agree!

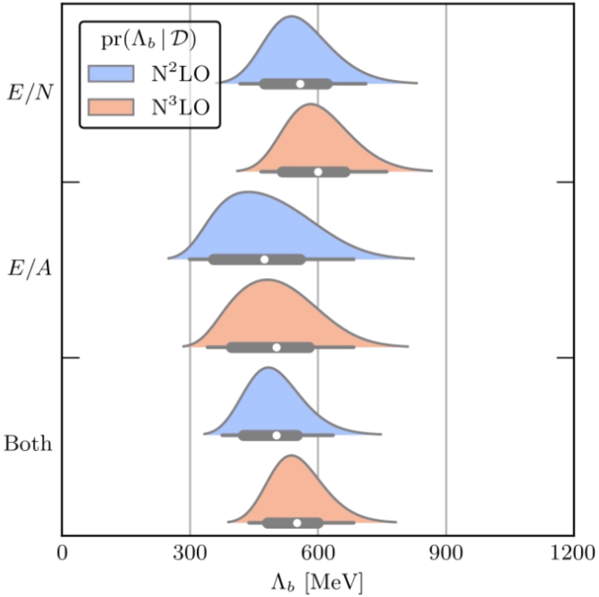
Use of emulators will allow to directly map LEC uncertainties to observables, e.g., nuclear matter.

See work by Ekstroem, Hagen et al., BuqEYE collaboration.

Chiral Effective Field Theory

However: There are still many open questions and problems!

- What is the **breakdown scale**? Does it change in the many-body system?



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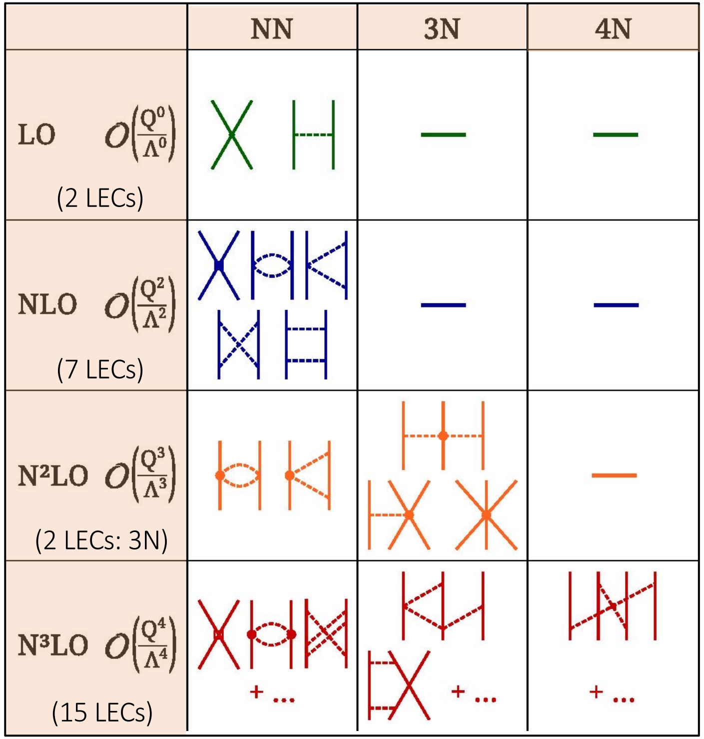

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meißner, Hammer ...

Chiral Effective Field Theory

However: There are still many open questions and problems!

- What is the **breakdown scale**? Does it change in the many-body system?
- How do results depend on the **regularization scheme** (explicit form of the interaction) **and scale** (cutoff necessary in many-body methods)?
- Does this series **converge** in the many-body system?
- How to best determine all **unknown coefficients**?

➢ Leads to **additional uncertainties** that have to be accounted for

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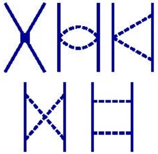
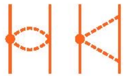
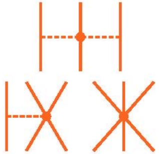
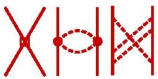
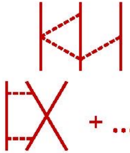
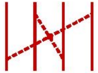
NLO $\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$ (7 LECs)		—	—
N²LO $\mathcal{O}\left(\frac{Q^3}{\Lambda^3}\right)$ (2 LECs: 3N)			—
N³LO $\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$ (15 LECs)	 + ...	 + ...	 + ...

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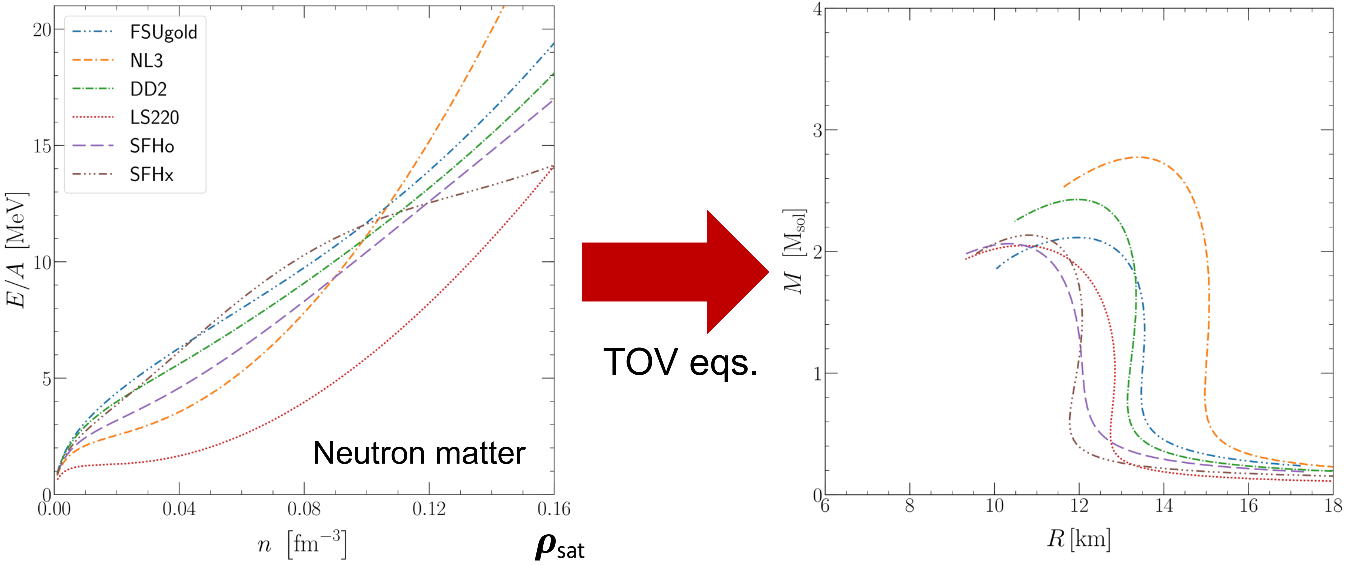
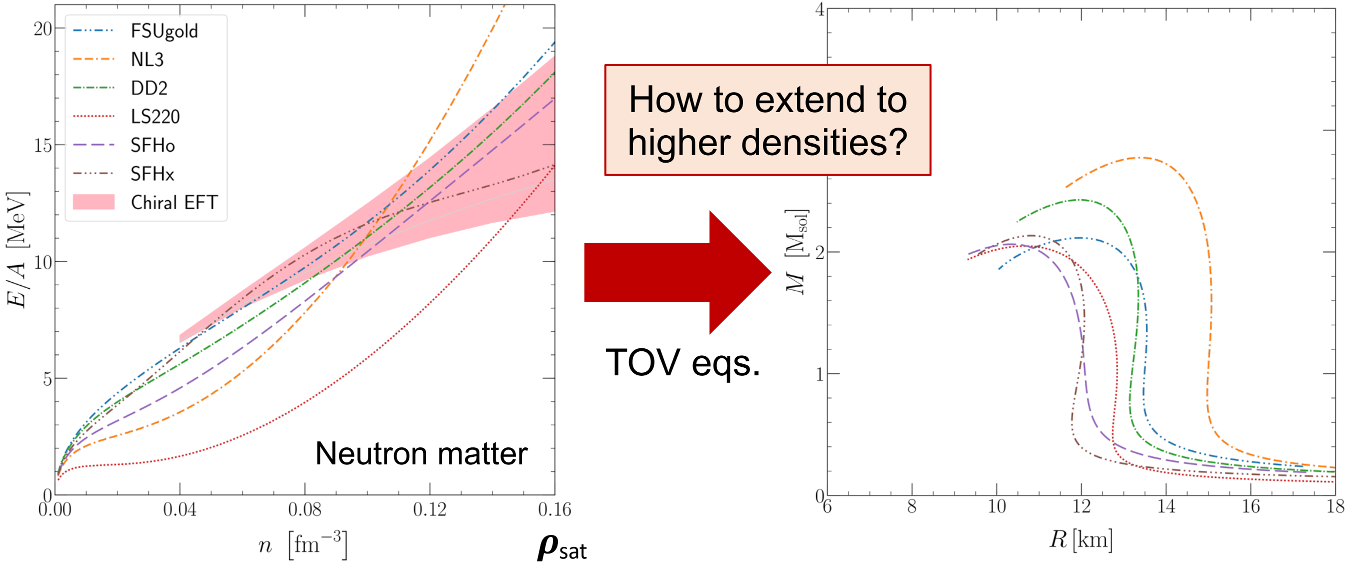
Chiral EFT and neutron stars



- Selection of a few EOS models that are used in astrophysics.

Chiral EFT and neutron stars

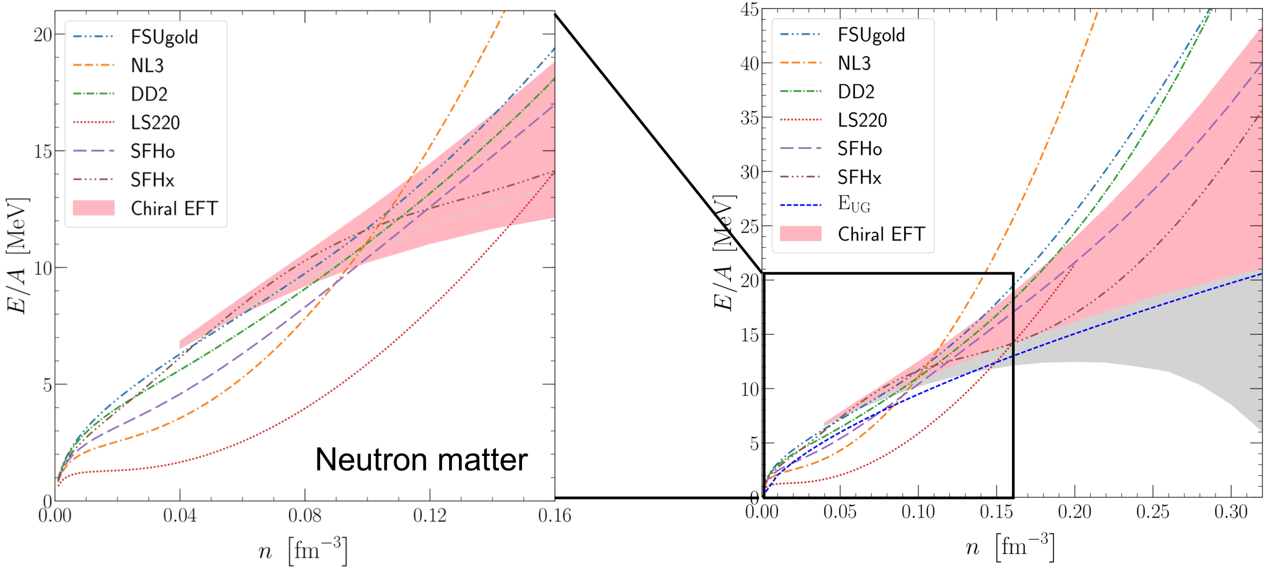


- Selection of a few EOS models that are used in astrophysics.

- Chiral EFT puts constraints on the EOS of neutron matter.
- Provides systematic and **reliable uncertainty estimates**!

Chiral EFT and neutron stars

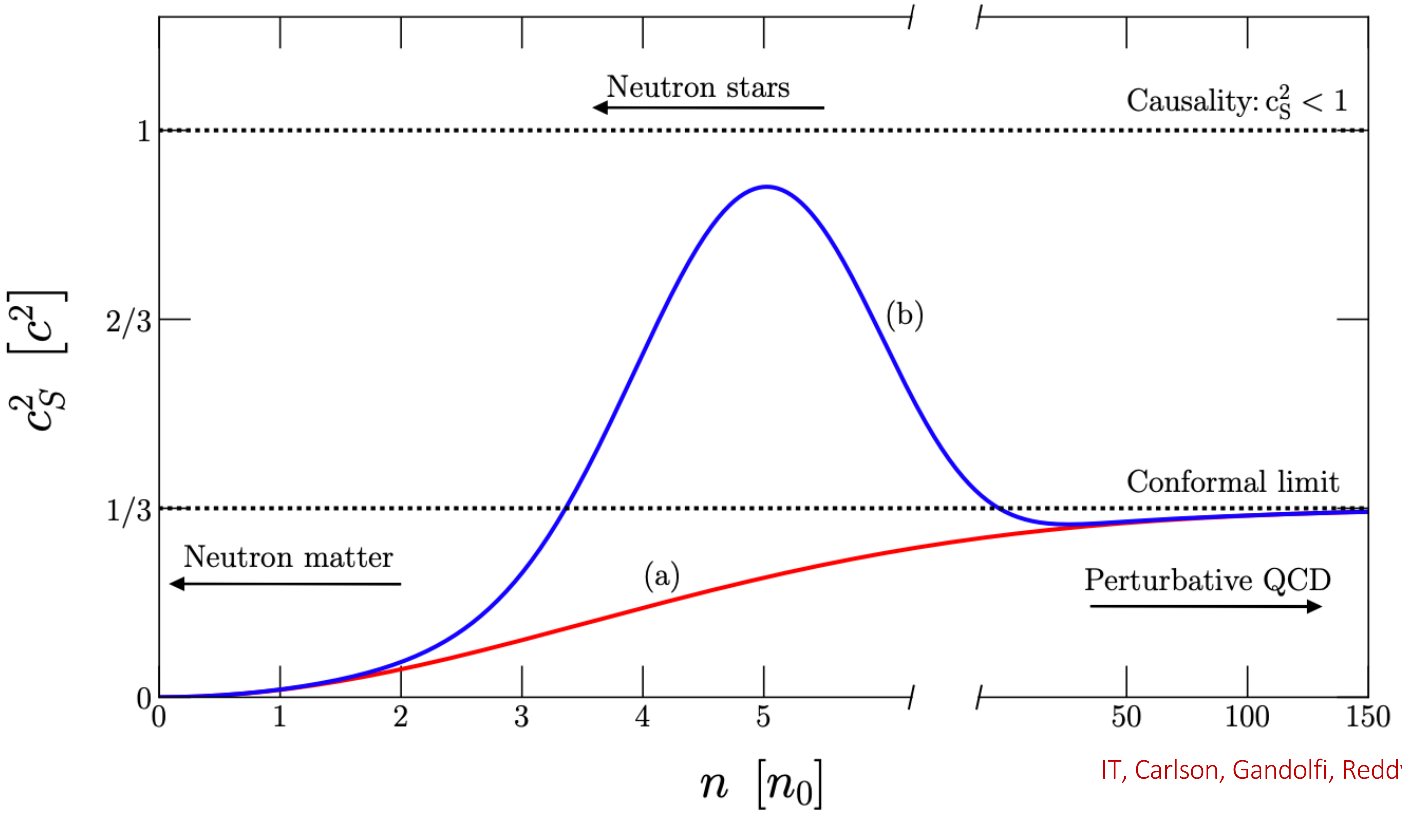
UG constraint: IT, Lattimer, Ohnishi, Kolomeitsev, APJ (2017)



- 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), but also other approaches e.g., Alford et al., arXiv:2205.10283

Chiral EFT and neutron stars



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

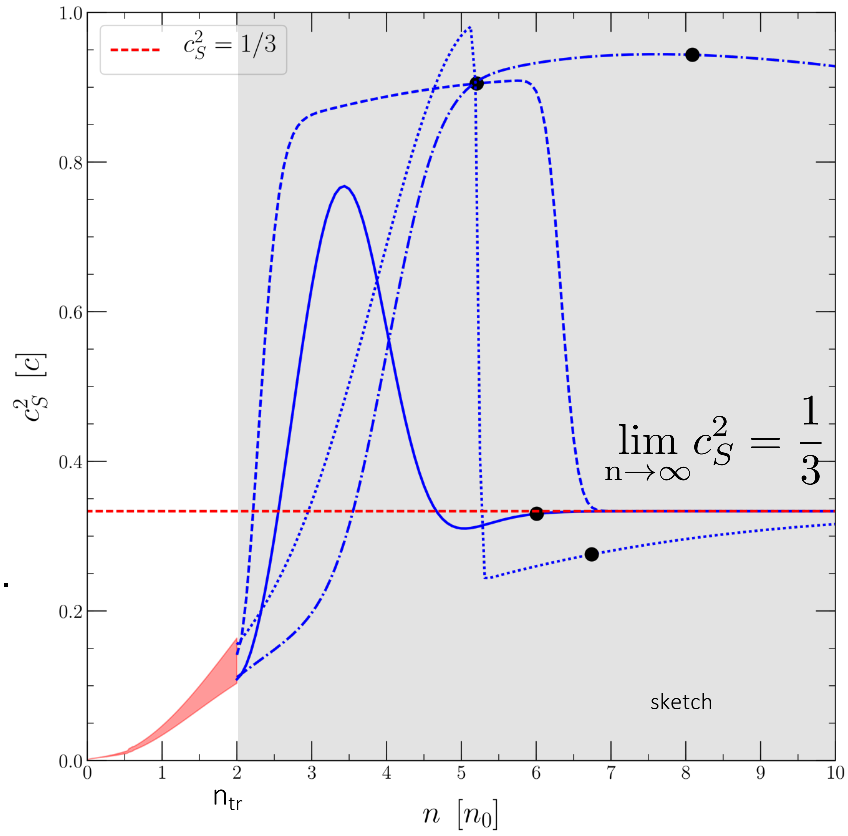
Chiral EFT and neutron stars

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

Speed of sound:

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

- Assume some general form for speed of sound above transition density, e.g., linear segments, etc.
- Sample many different curves in allowed region (gray band) and reconstruct EOS.
- Can easily include **phase transitions** and additional information on c_S.
- **Extend systematic uncertainties to higher densities!**



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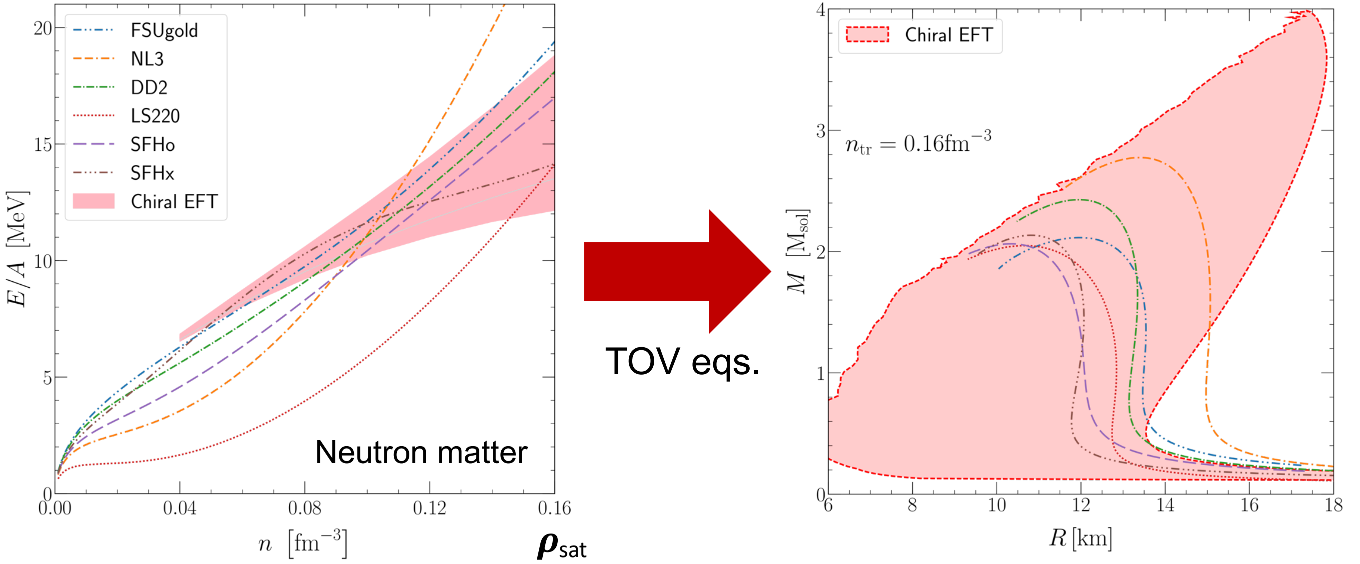
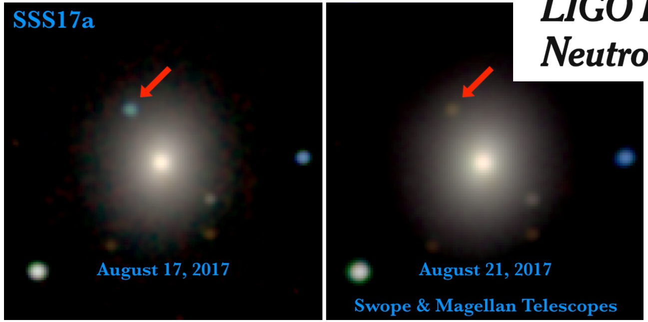


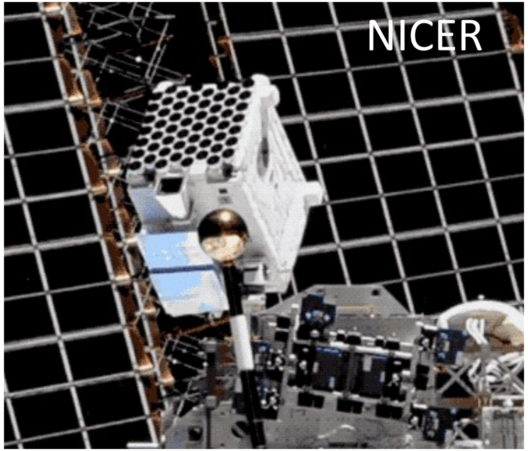
- Selection of a few EOS models that are used in astrophysics.

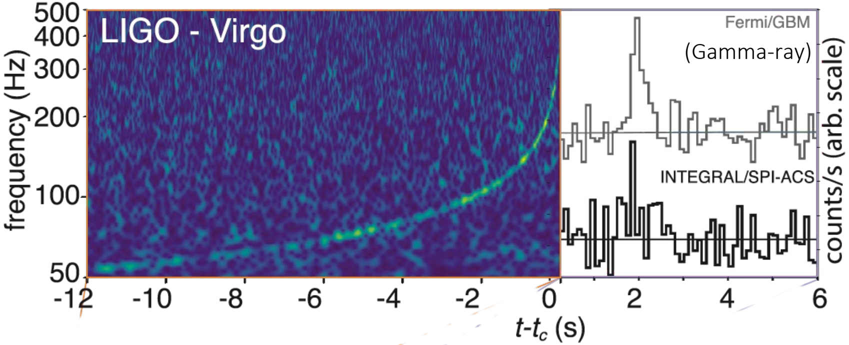
- Chiral EFT puts constraints on the EOS of neutron matter.
- Provides systematic and **reliable uncertainty estimates**!
- Uncertainty band can be extended to higher densities using general extension schemes.

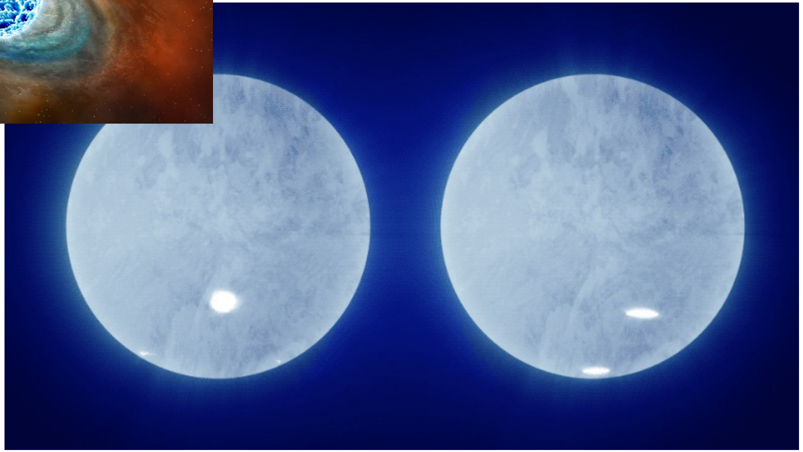
NS (multi-messenger) observations

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





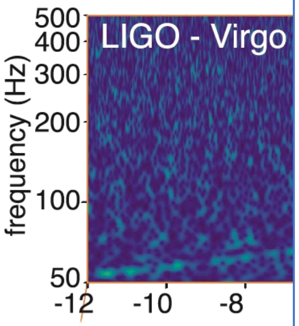


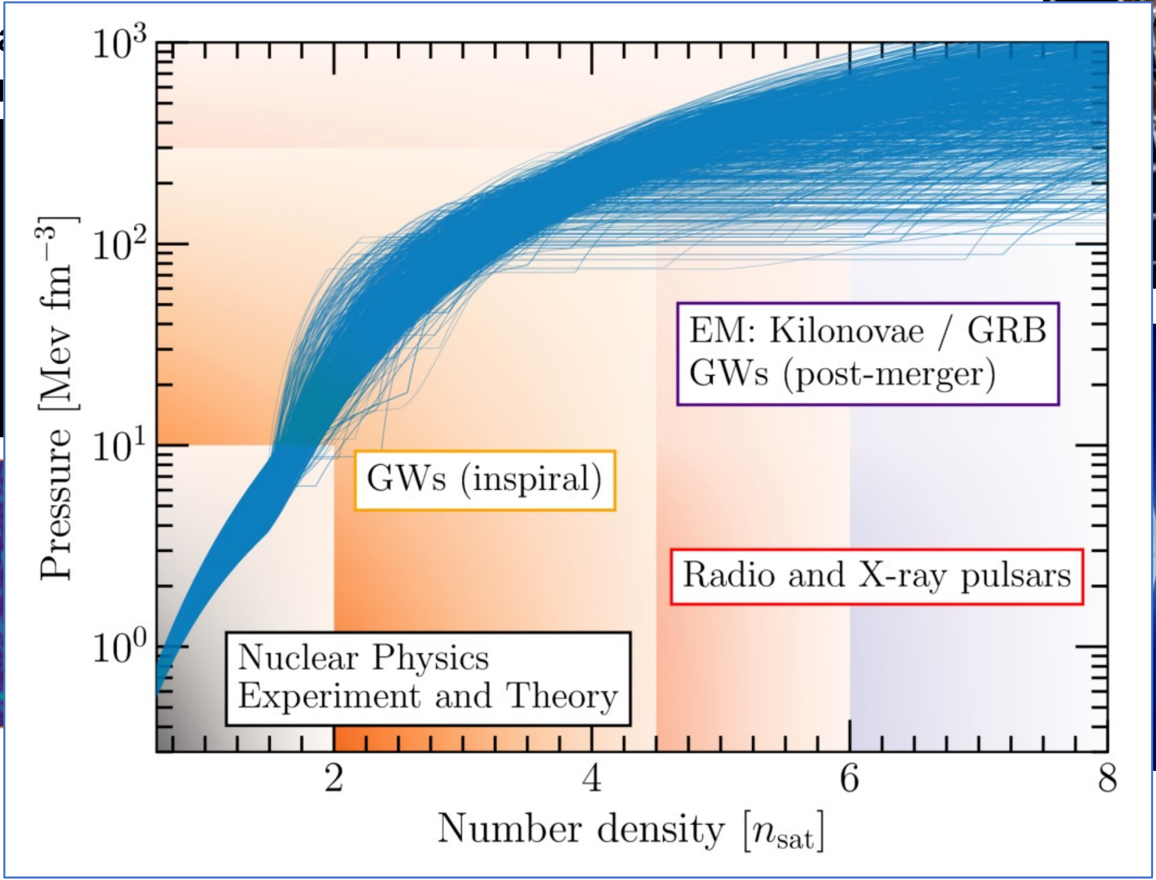


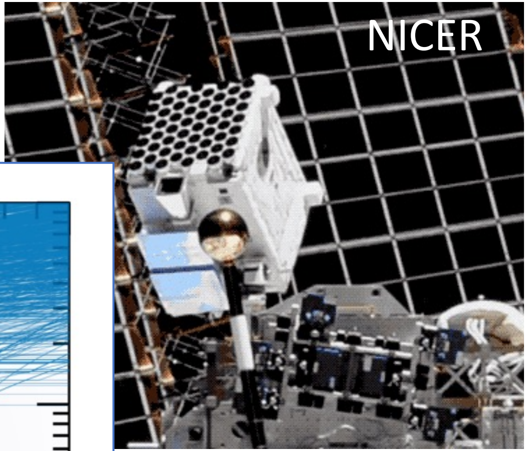
LIGO/VIRGO collaboration, ApJL 848, L12 (2017)

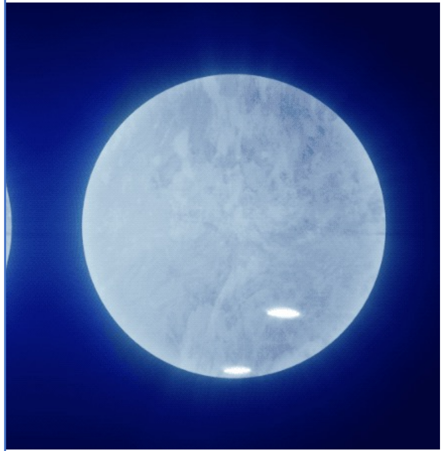
NS (multi-messenger) observations

First neutron-st
observed on Au





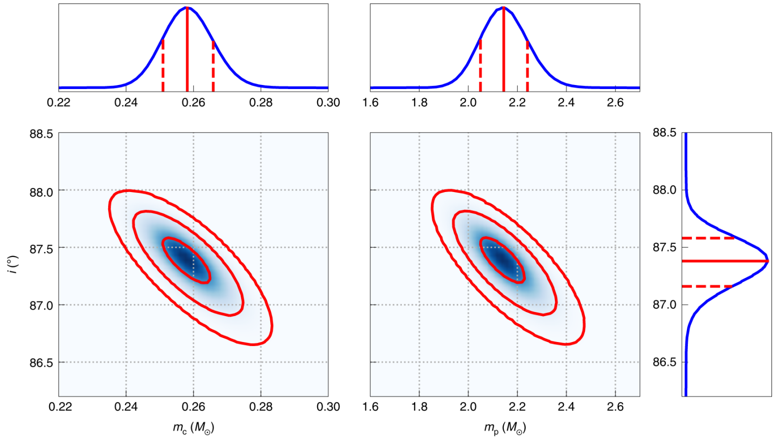


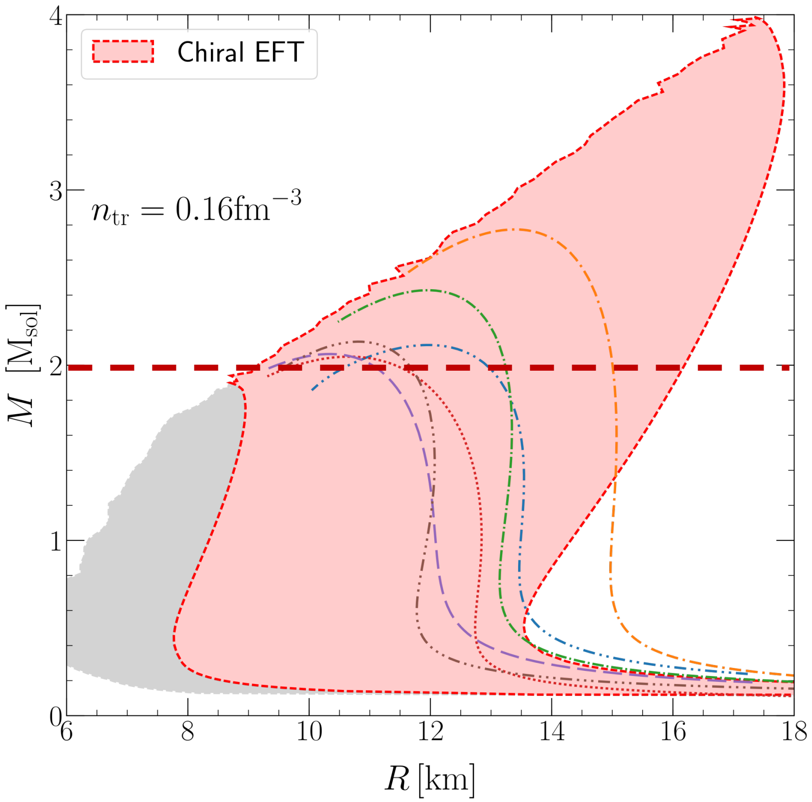


Pulsar mass observations

Since 2010, three pulsar-timing observations of heavy pulsars with masses close to 2 M_{sol}:

- PSR 1614-2230: 1.908(16) M_{sol}
  Demorest et al., Nature (2010), Arzoumanian et al., ApJS (2018)
- PSR J0348+0432: 2.01(4) M_{sol}
  Antoniadis et al., Science (2013)
- MSP J0740+6620: 2.08(7) M_{sol}
  Cromartie et al., Nat. Astron (2020), Fonseca et al., ApJ Lett. (2021)





Neutron-star EOS

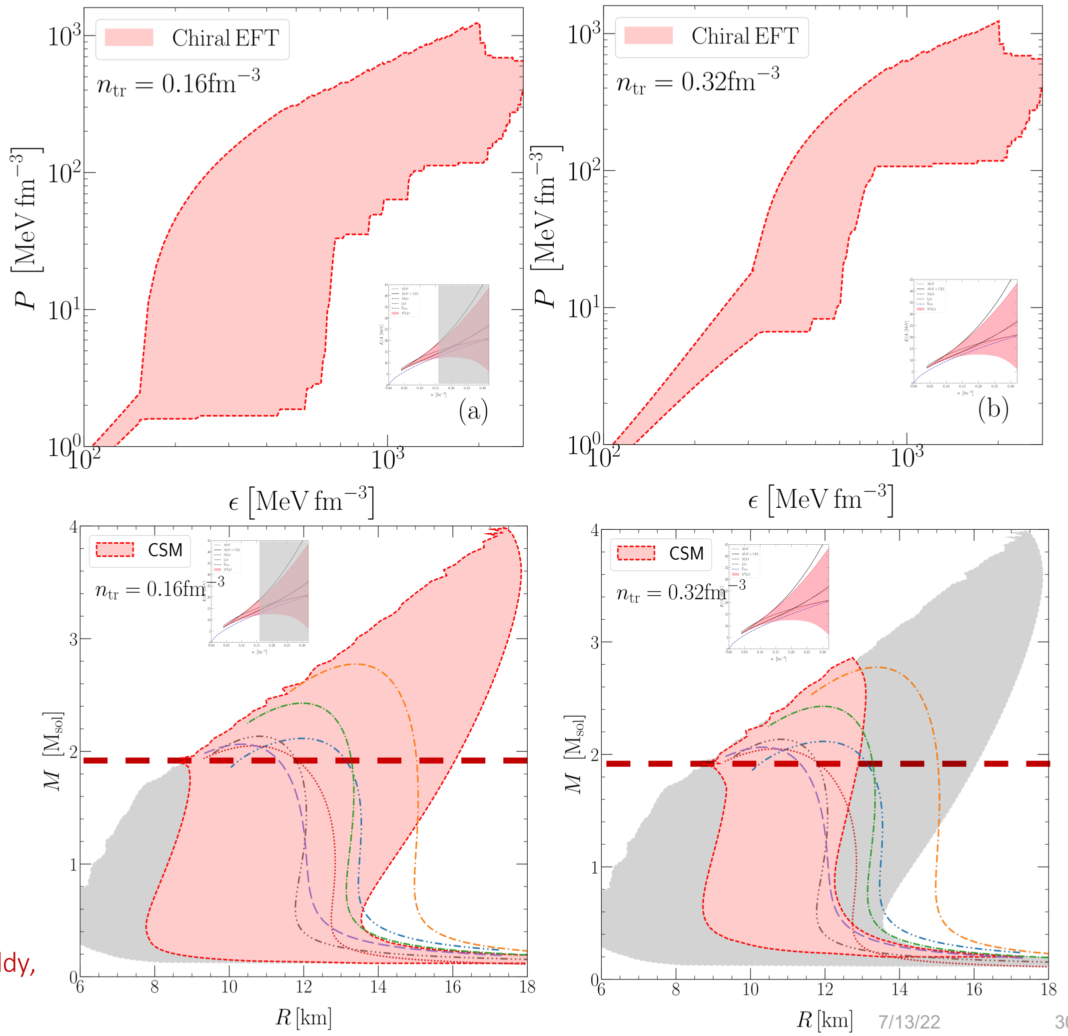
Envelopes around all EOS that:

- 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 (up to two different densities).
- Support at least **1.9 solar-mass** neutron stars.

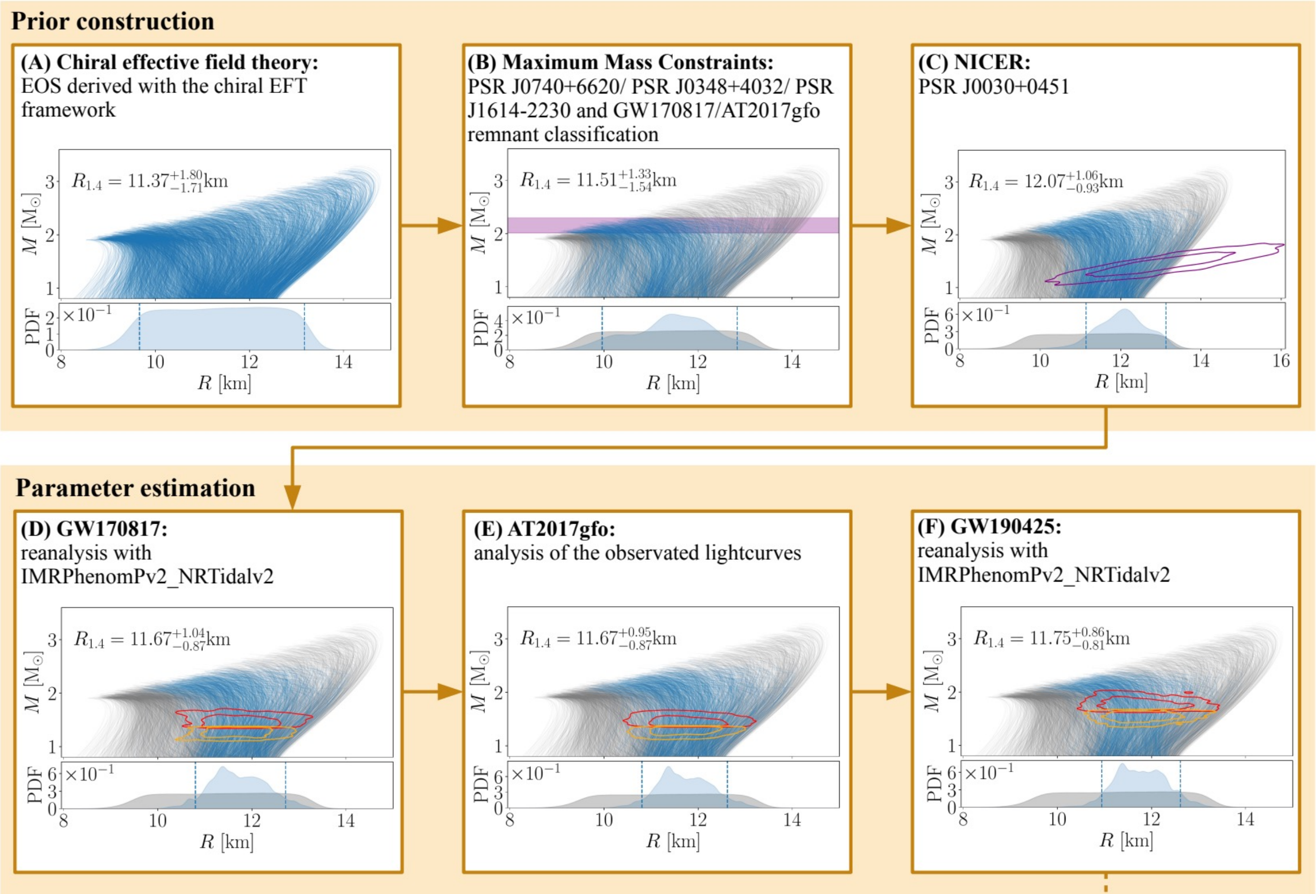
Current nuclear-physics uncertainties remain sizable!

Extract information from NS observations.

IT, Margueron, Reddy, EPJ A (2019)

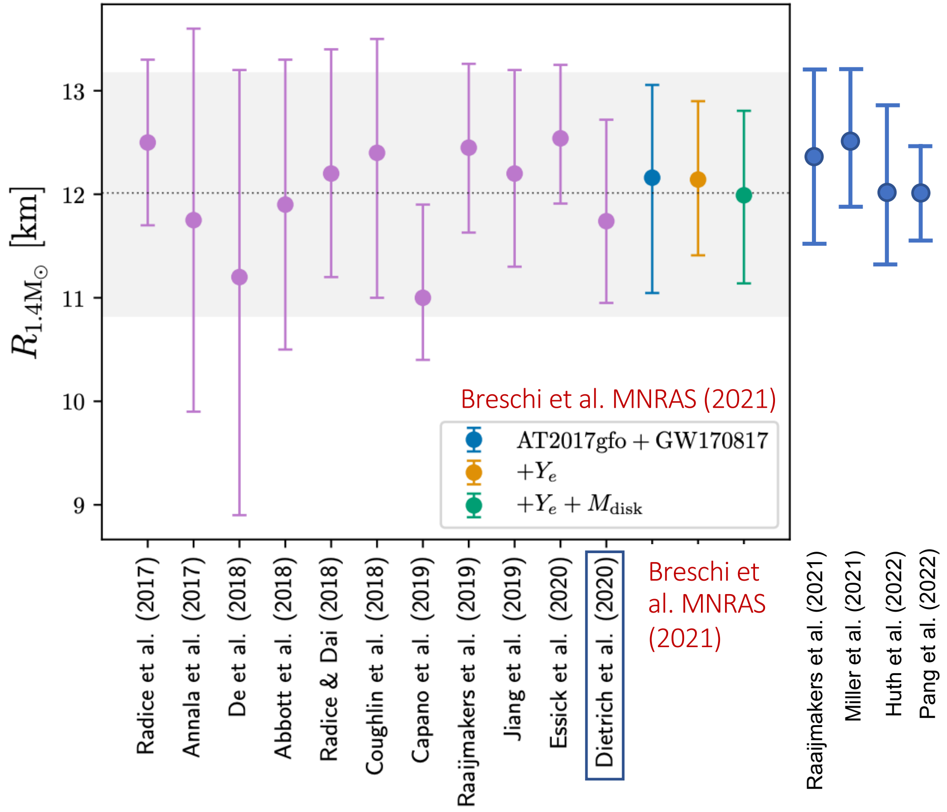


Nuclear-physics Multi-Messenger Astrophysics (NMMA)



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

Nuclear-physics Multi-Messenger Astrophysics (NMMA)



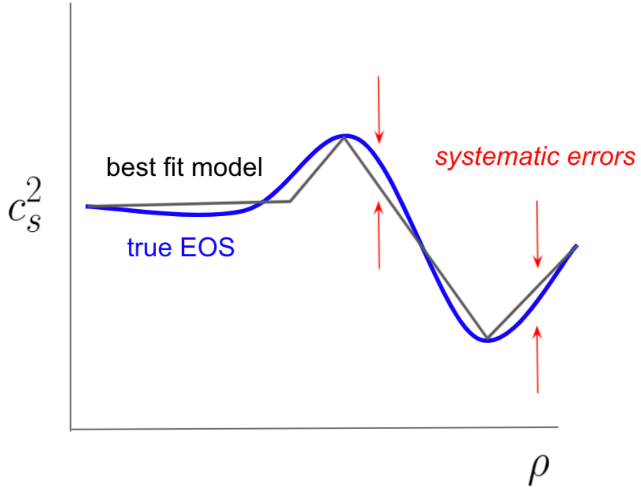
Analysis of gravitational-wave and electromagnetic signals constrain radius of typical neutron stars to be of the order of **12 km!**

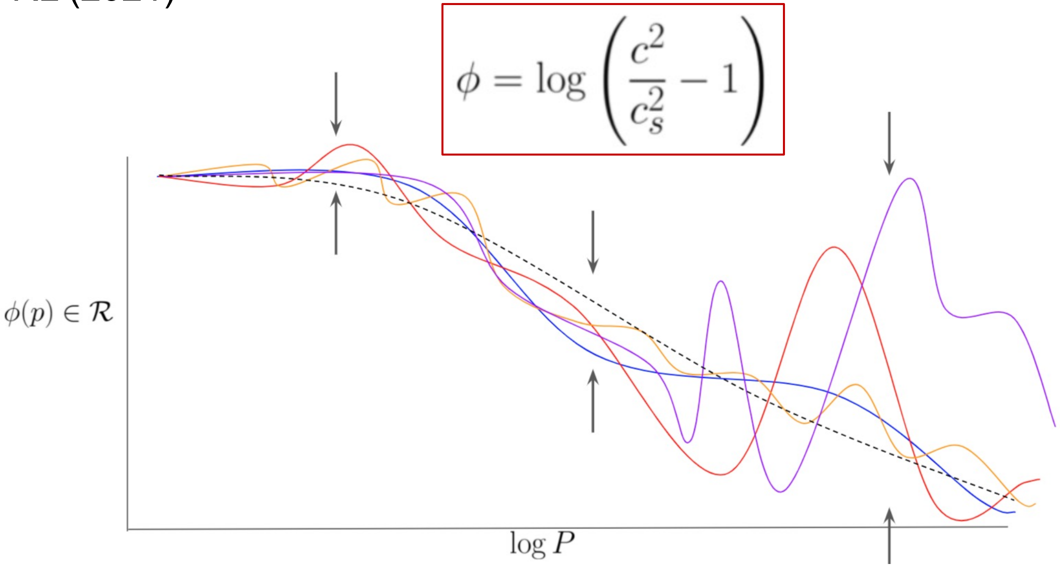
Chiral EFT calculations at low densities important input in many of them.

Consistent picture from many approaches with and without chiral EFT.

EOS inference with Gaussian processes

"*Astrophysical Constraints on the Symmetry Energy and the Neutron Skin of 208Pb with Minimal Modeling Assumptions*", Essick et al., PRL (2021)





Parametric EOS extensions:

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

Nonparametric EOS inference using Gaussian process in auxiliary variable

See talk by R. Essick next Monday!

EOS inference with Gaussian processes

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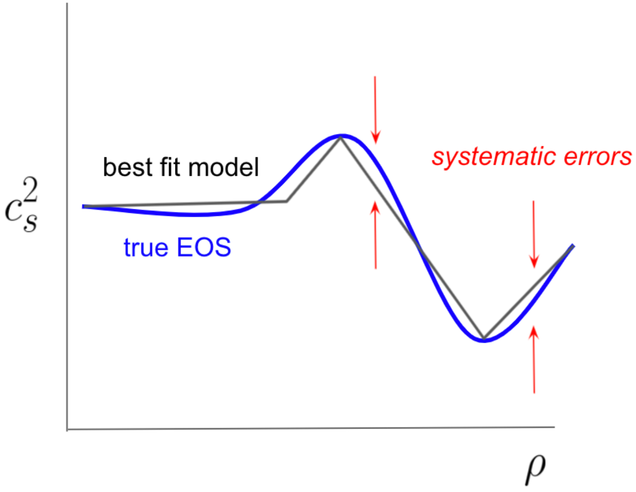

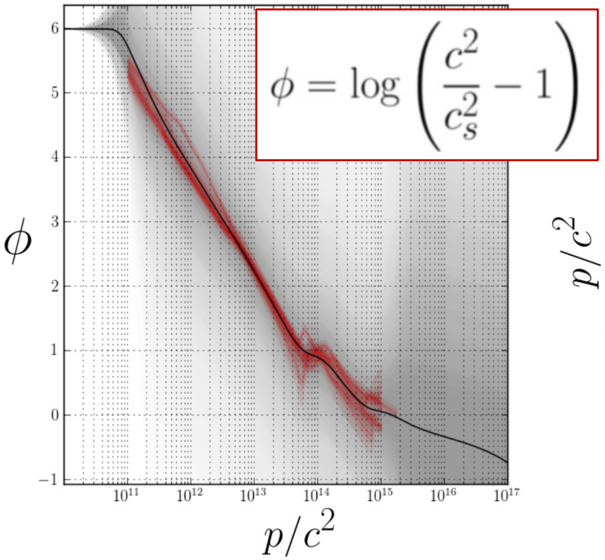

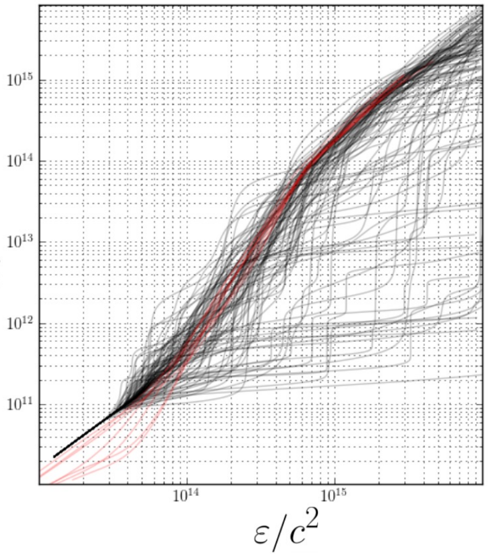

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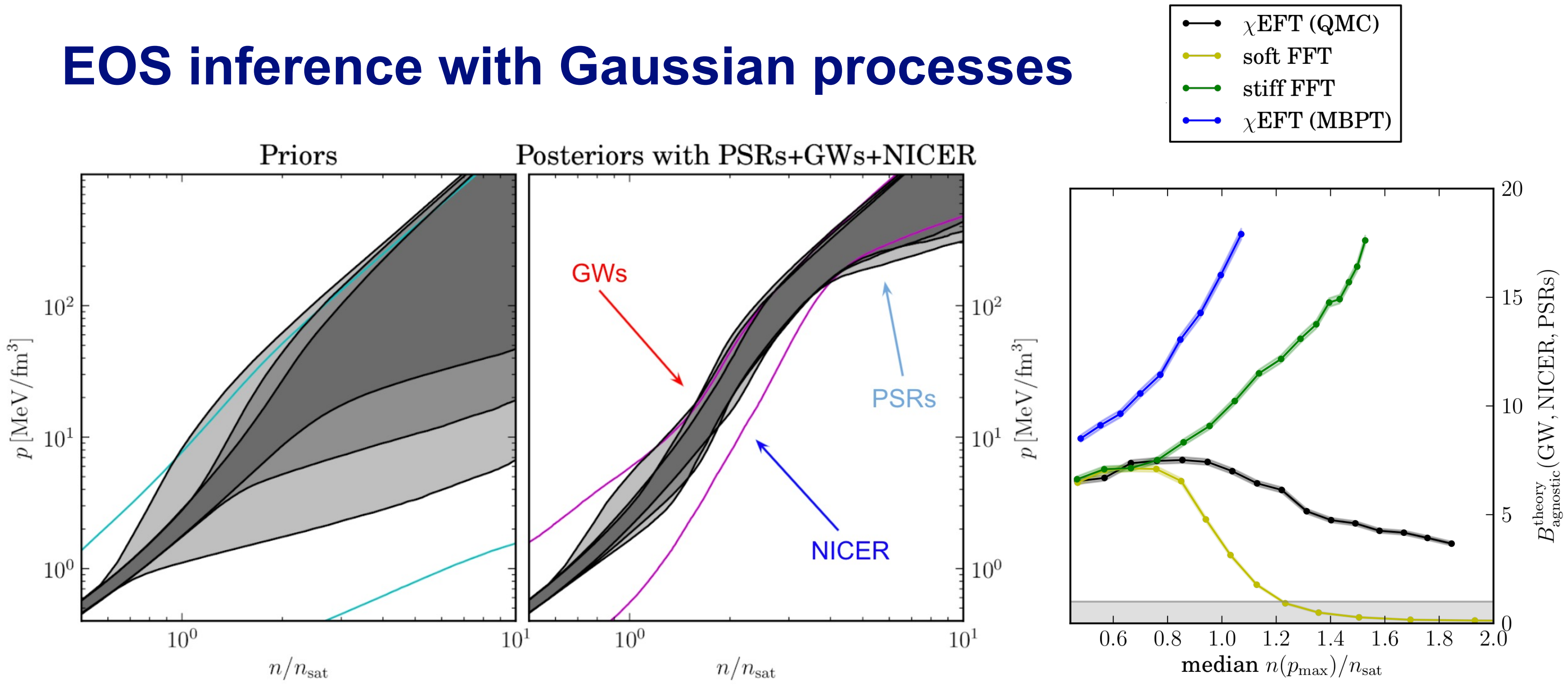
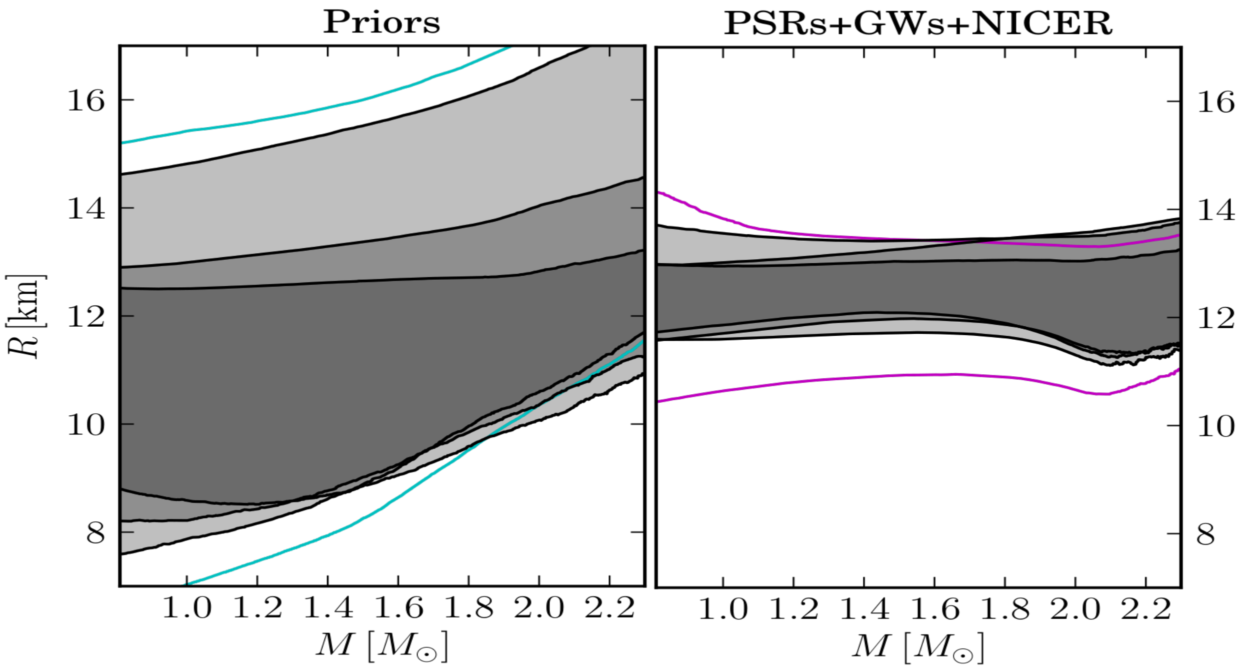
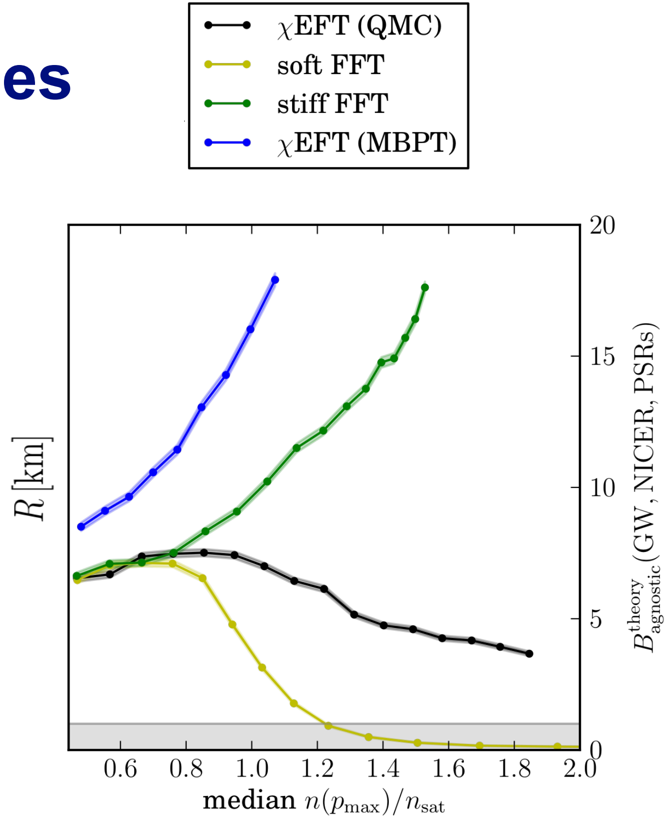


Essick et al., Phys. Rev. C 102, 055803 (2020)

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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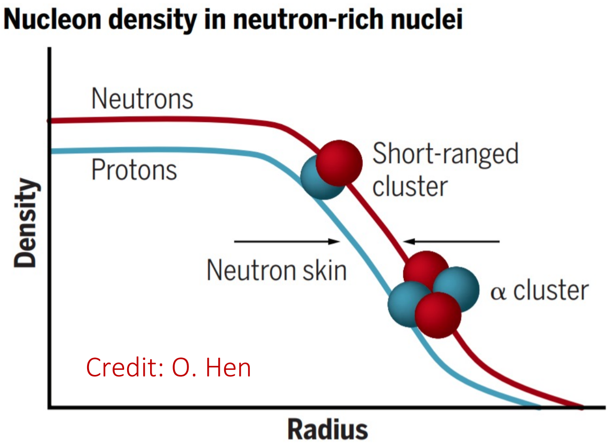
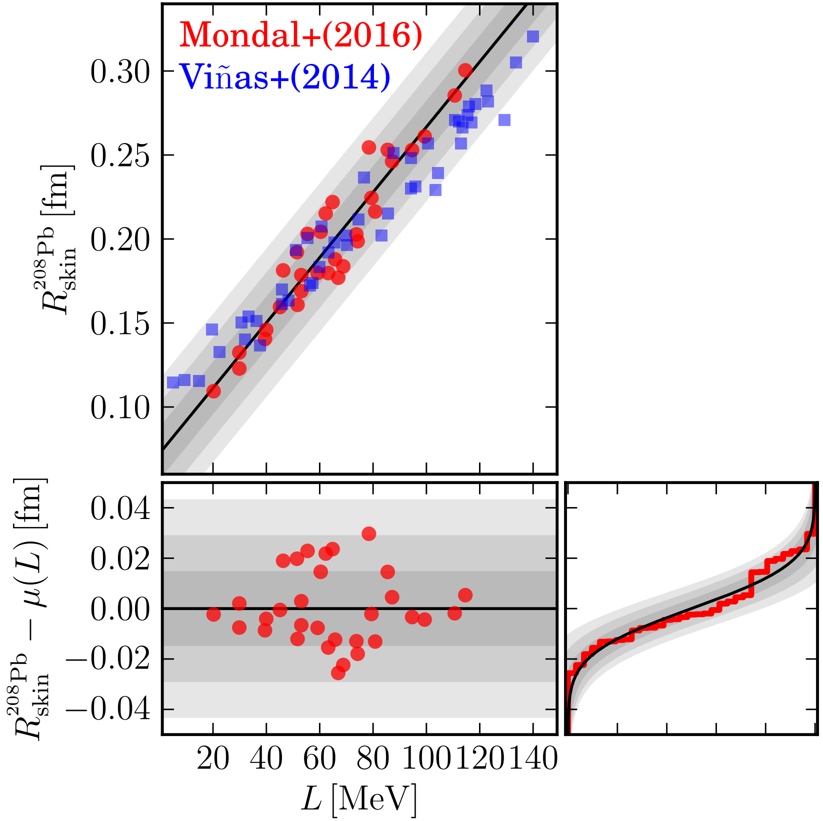
Connections to PREX-II



Neutron-skin thickness of ^{208}Pb inferred from PREX-II experiment, constraining EOS (but with large uncertainties):

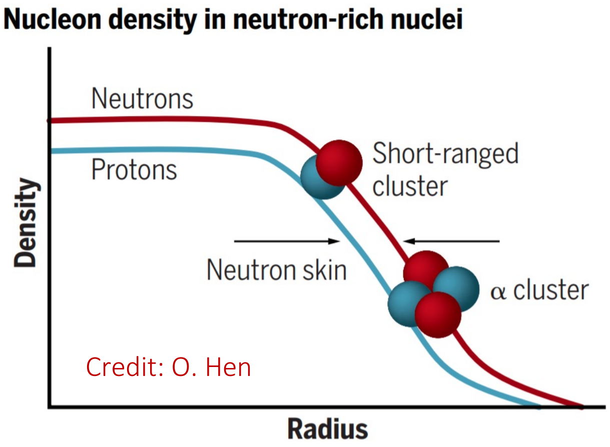
$$R_{skin} = 0.283 \pm 0.071 \text{ fm}$$
$$L = 106 \pm 37 \text{ MeV}$$

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)

Connections to PREX-II



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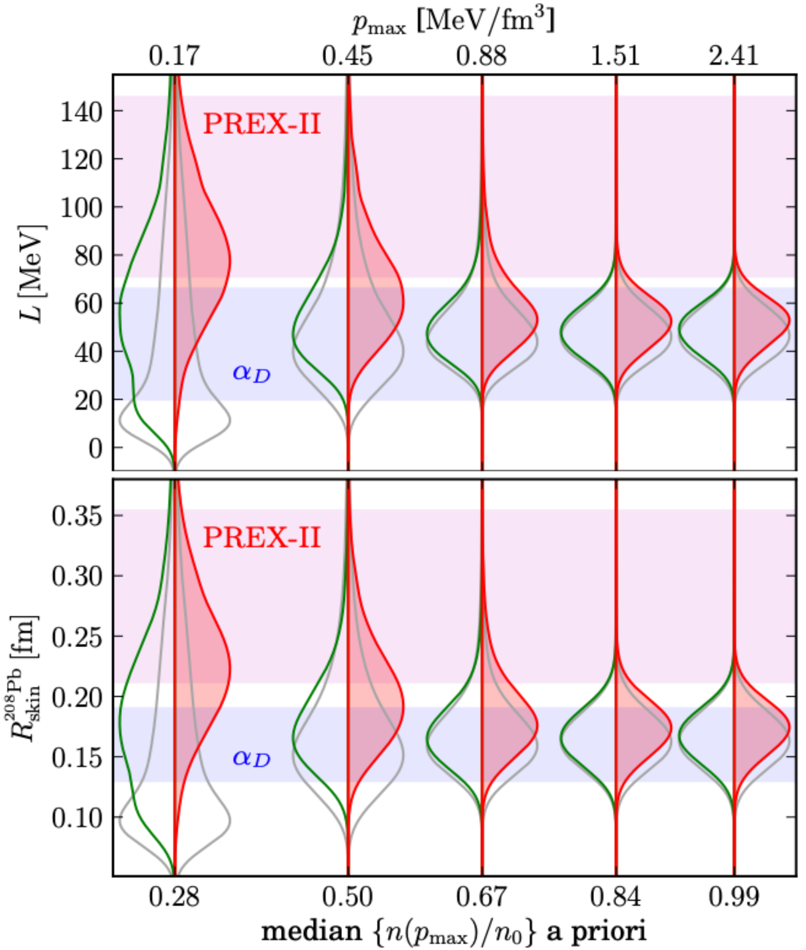

Adhikhari et al., PRL (2021)
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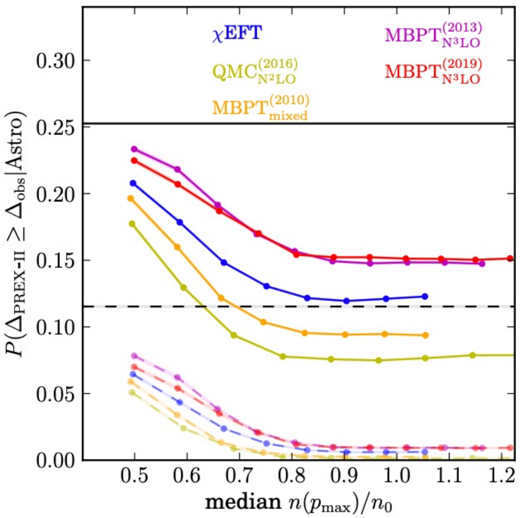
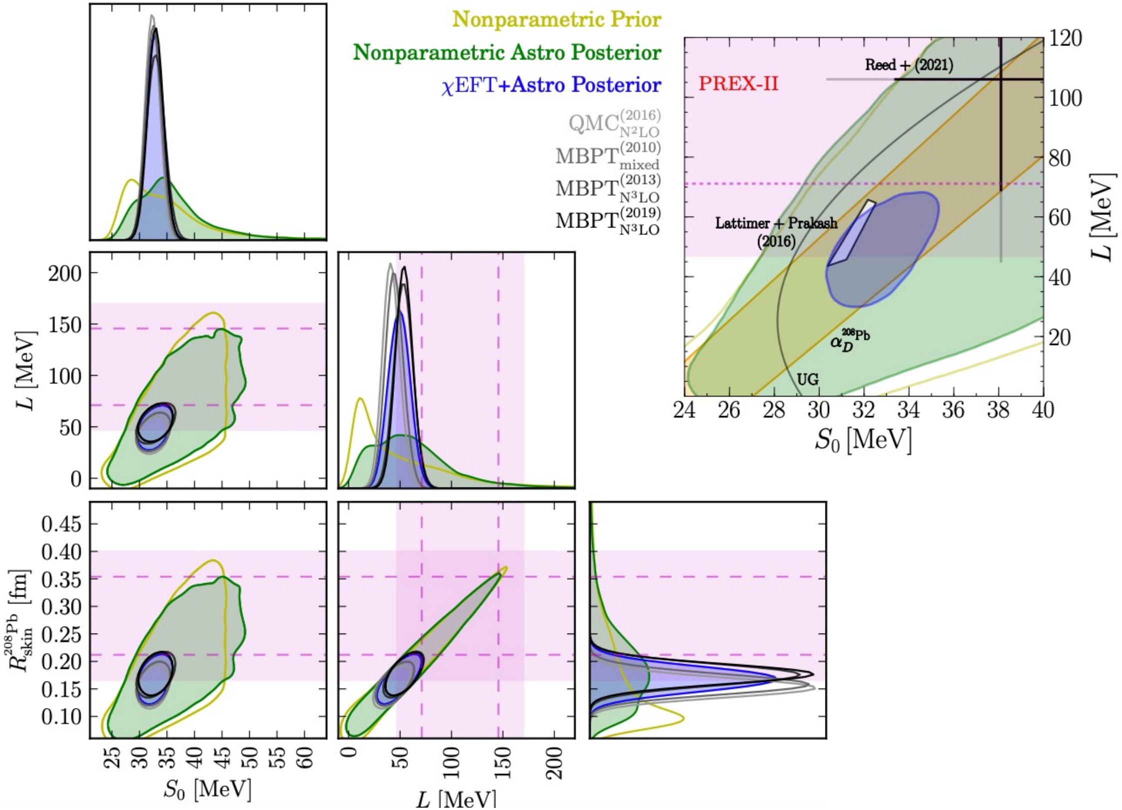
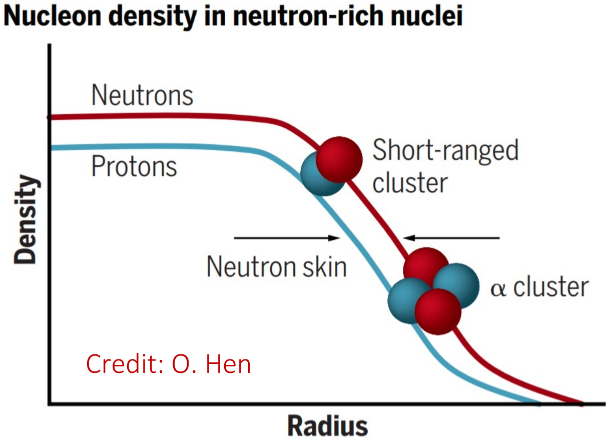




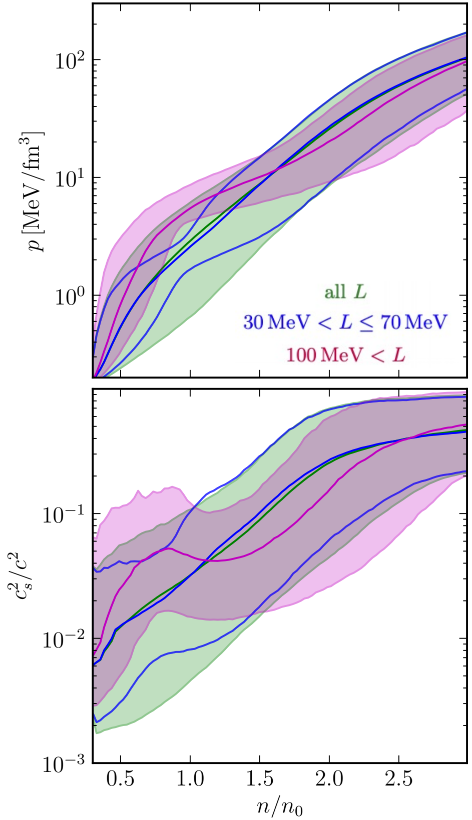
- Astrophysics data agrees with both nuclear theory and PREX, but posterior maximum in agreement with EFT.
- No significant tension between PREX and EFT calculations (p-value 13%).

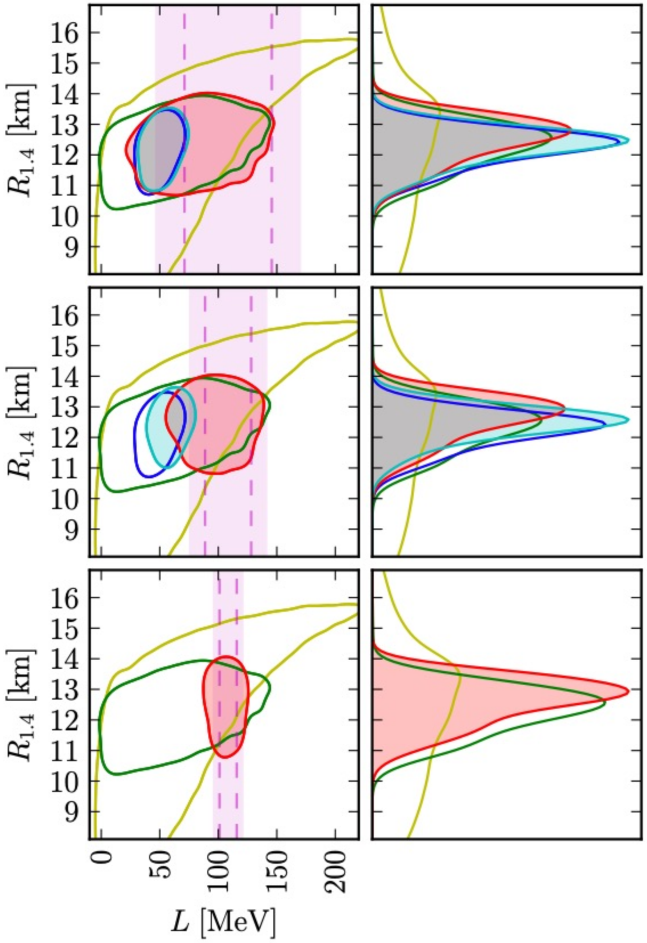
Essick, IT, Landry, and Schwenk, PRL (2021) and PRC (2021)

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, PRL (2021) and arxiv:2107.05528

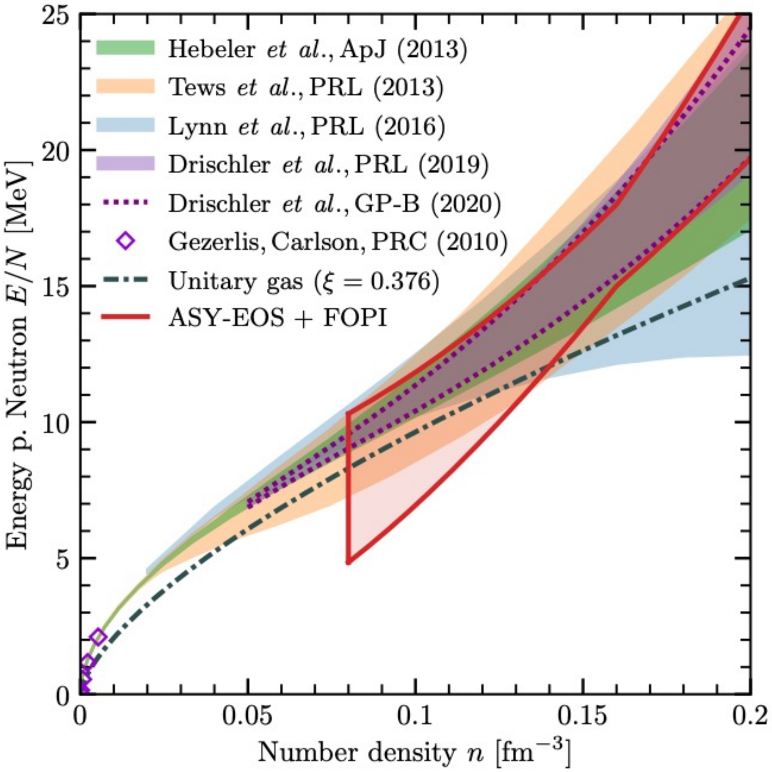
Including results from heavy-ion collisions

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 $n_{sat.}$

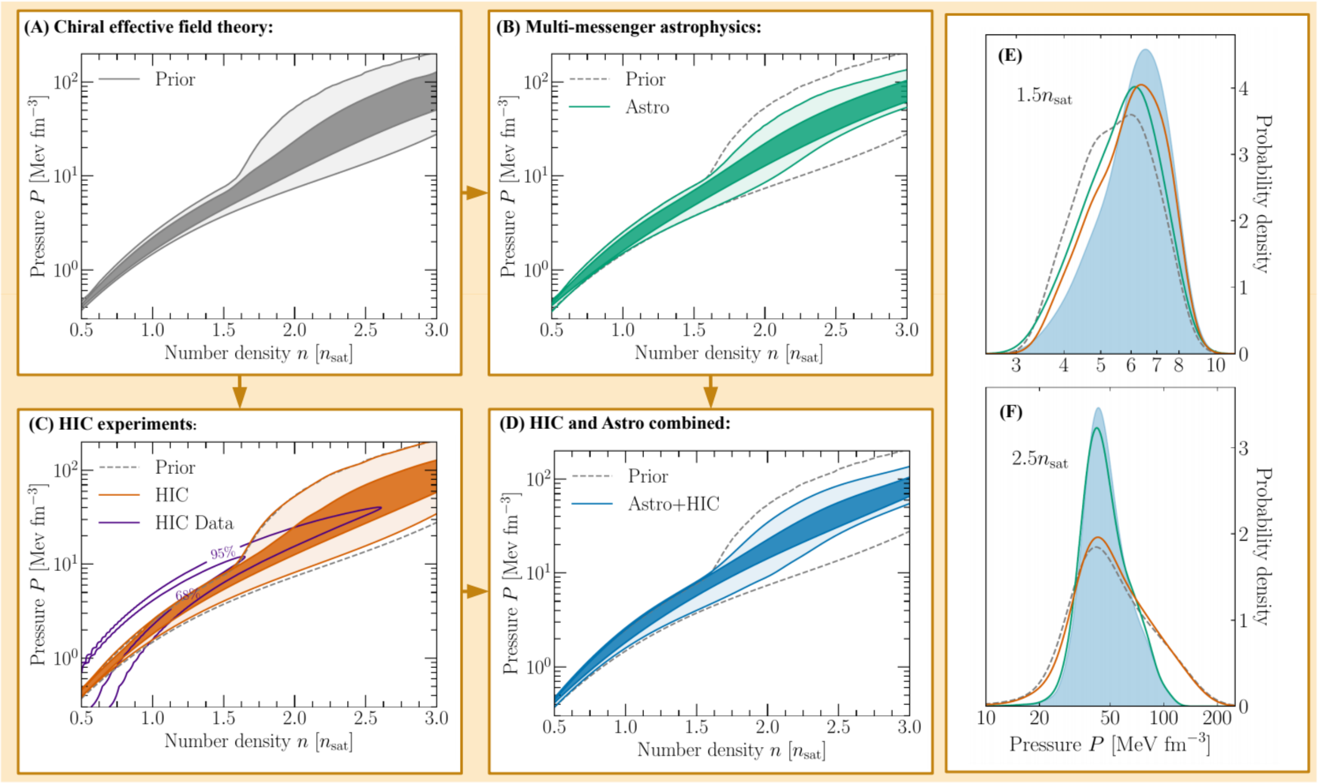


Huth, Pang et al., Nature (2022)

Including results from heavy-ion collisions

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

Excellent agreement with astrophysical observations.



Huth, Pang et al., Nature (2022)

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.

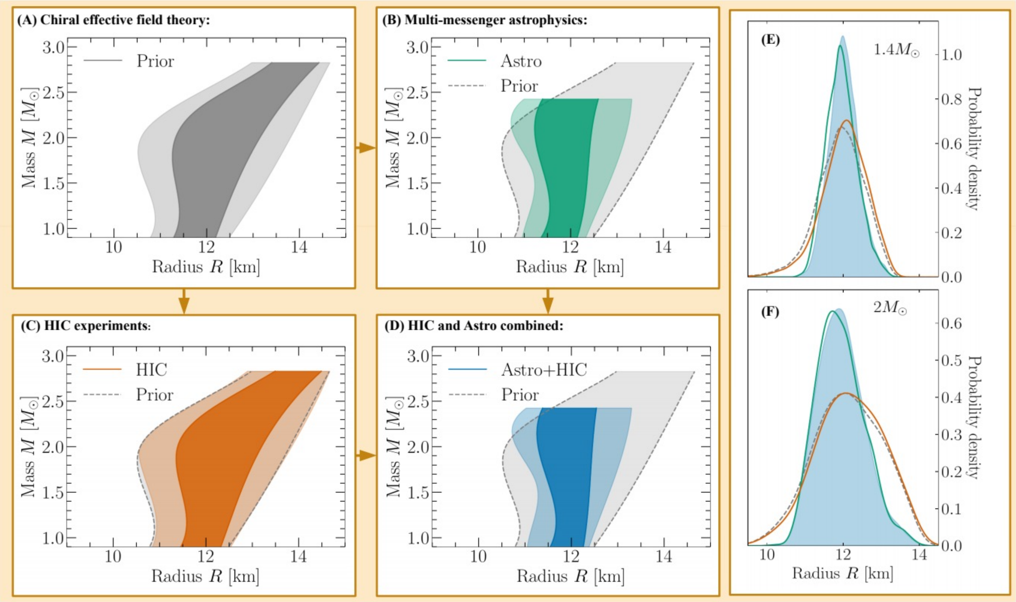


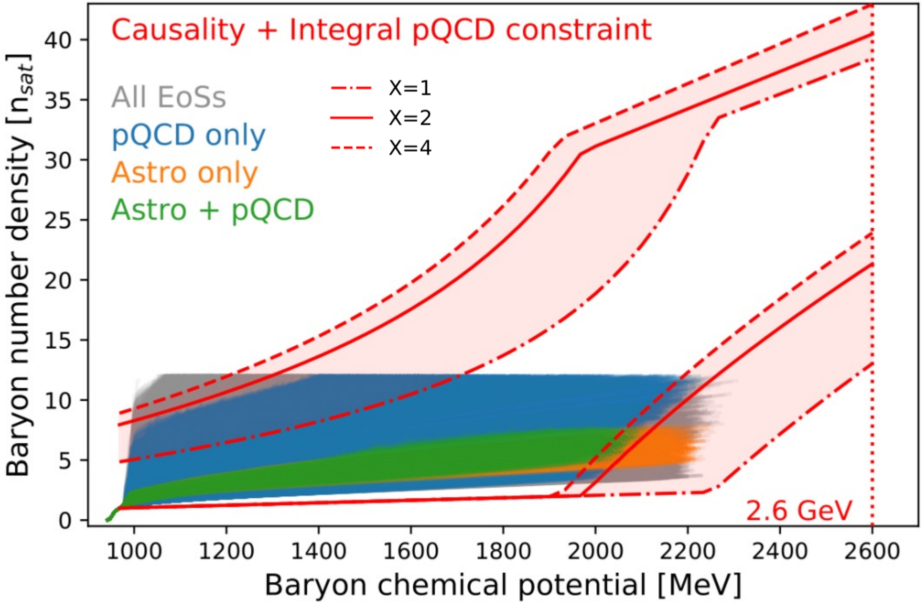
Table 1 | Final constraints on the pressure and the radius of neutron stars.

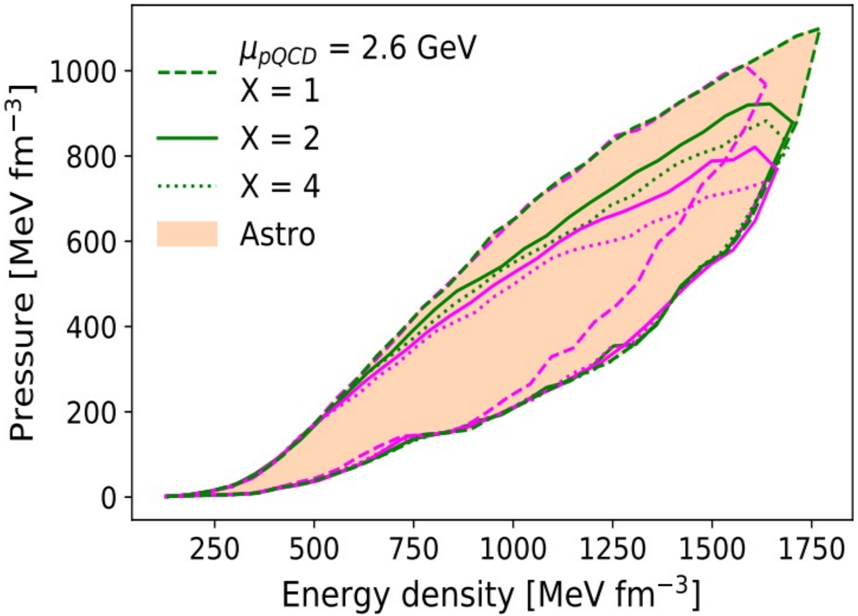
	Prior	Astro only	HIC only	Astro + HIC
$P_{1.5n_{sat}}$	$5.59^{+2.04}_{-1.97}$	$5.84^{+1.95}_{-2.26}$	$6.06^{+1.85}_{-2.04}$	$6.25^{+1.90}_{-2.26}$
$R_{1.4}$	$11.96^{+1.18}_{-1.15}$	$11.93^{+0.80}_{-0.75}$	$12.06^{+1.13}_{-1.18}$	$12.01^{+0.78}_{-0.77}$

Huth, Pang et al., Nature (2022)

See also Komoltsev and Kurkela, arXiv:2111.05350 & Gorda, Komoltsev, Kurkela, arXiv:2204.11877

Impact of perturbative QCD on the EOS





Given current uncertainties, pQCD does not significantly constrain EOS on top of astrophysical data.

Somasundaram, IT, Margueron, arXiv:2204.14039

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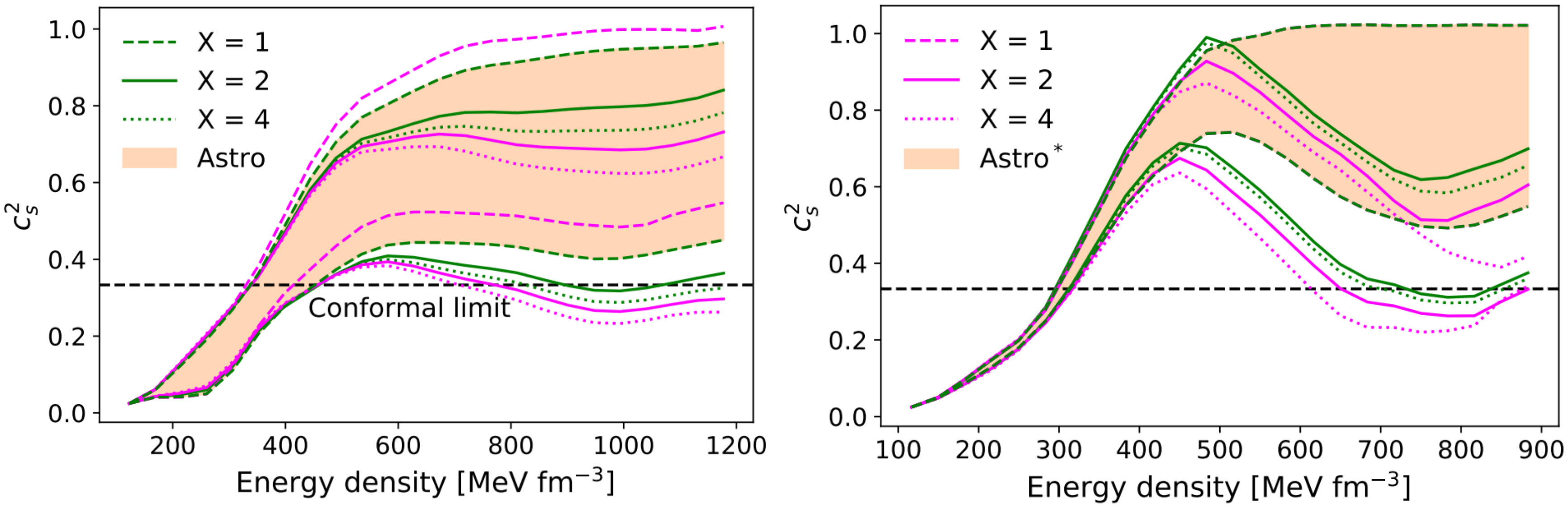


Given current uncertainties, pQCD does not significantly constrain EOS on top of astrophysical data.

BUT: - New Astro data preferring stiff EOS or improved pQCD constraints increase pQCD impact!
- Pushing EFT to higher densities might decrease pQCD impact.

Somasundaram, IT, Margueron, arXiv:2204.14039

Summary

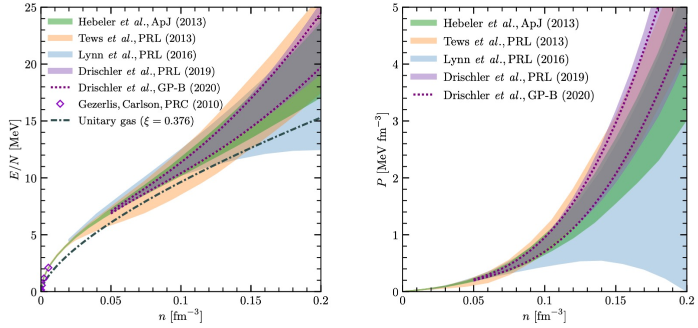
➢ Neutron stars represent ideal laboratories for nuclear physics and help to improve our understanding of nuclear interactions!

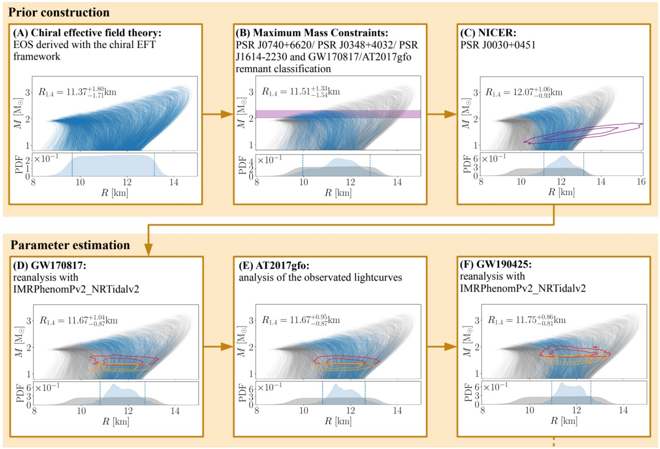
➢Uncertainty in neutron-star EOS can be reduced by

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

➢ GW observations favor softer, EM observations (kilonova and NICER) and nuclear experiments favor stiffer EOS, but have large uncertainties.

➢ HIC experiments have a similar impact as NICER at lower densities, give an opportunity to bridge theory calculations (below $2n_{sat}$) and astrophysical observations (above 3-4 n_{sat}).





Thanks

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J. Margueron, R. Somasundaram (IPN Lyon)
B. Margalit (UC Berkeley)
D. Brown (Syracuse University)
R. Essick (Perimeter Institute)
D. Holz (Kavli Institute)
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J. Heinzel (Carleton College)
S. Antier (APC Paris)

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NUCLEI Nuclear Computational Low-Energy Initiative

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Thank you for your attention!