Constraining the nuclear EOS with theory, observations, and experiment

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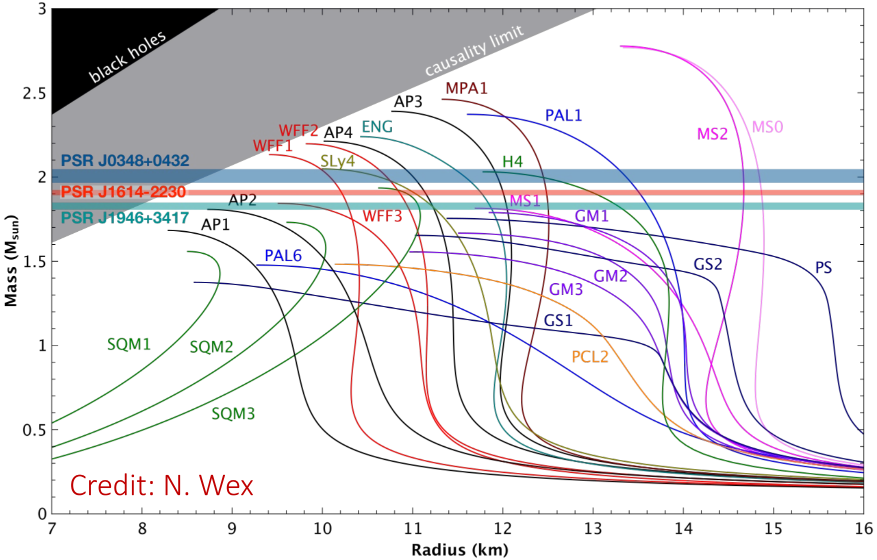
LA-UR-22-32682

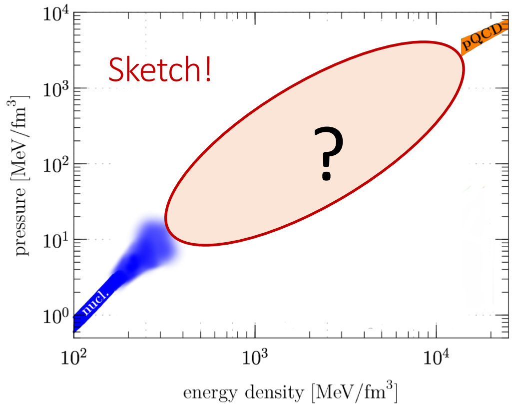
Motivation

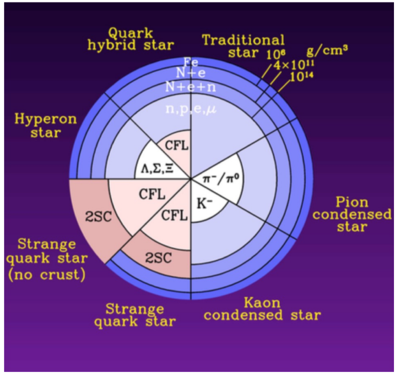
Large number of neutron-star EOS available in the literature, but:

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



Credit: N. Wex



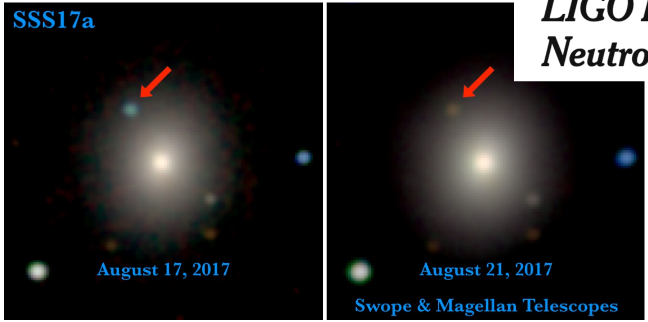


Constraints possible:

- At low densities from nuclear theory (chiral effective field theory) and experiment.
- At asymptotically high density from pQCD.
  see, e.g., Kurkela, Vuorinen, Gorda et al.
- Robust constraints at intermediate densities from astrophysics!

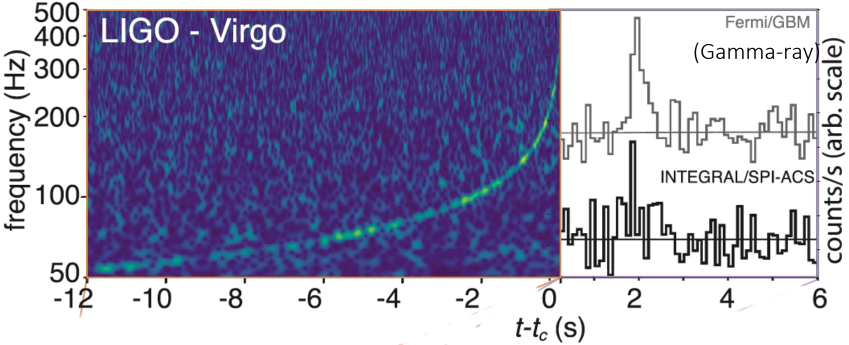
NS (multi-messenger) observations

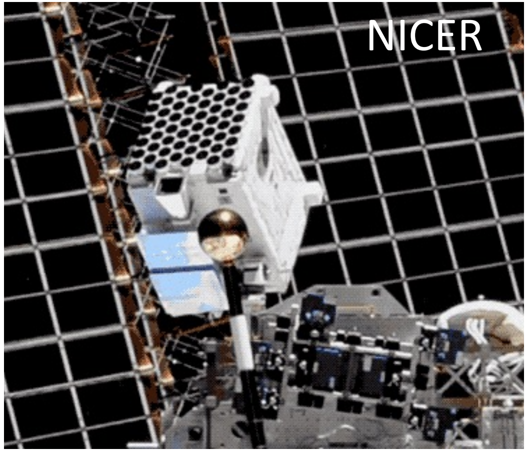
First neutron-star merger observed on Aug 17, 2017 :

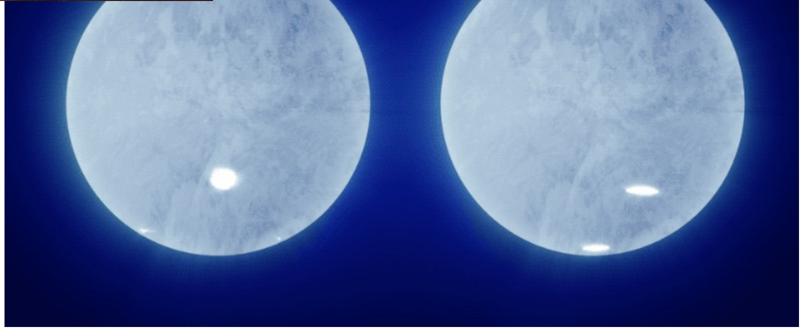


The New York Times

LIGO Detects Fierce Collision of Neutron Stars for the First Time



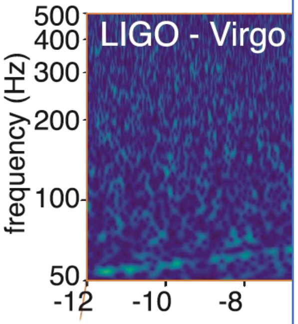


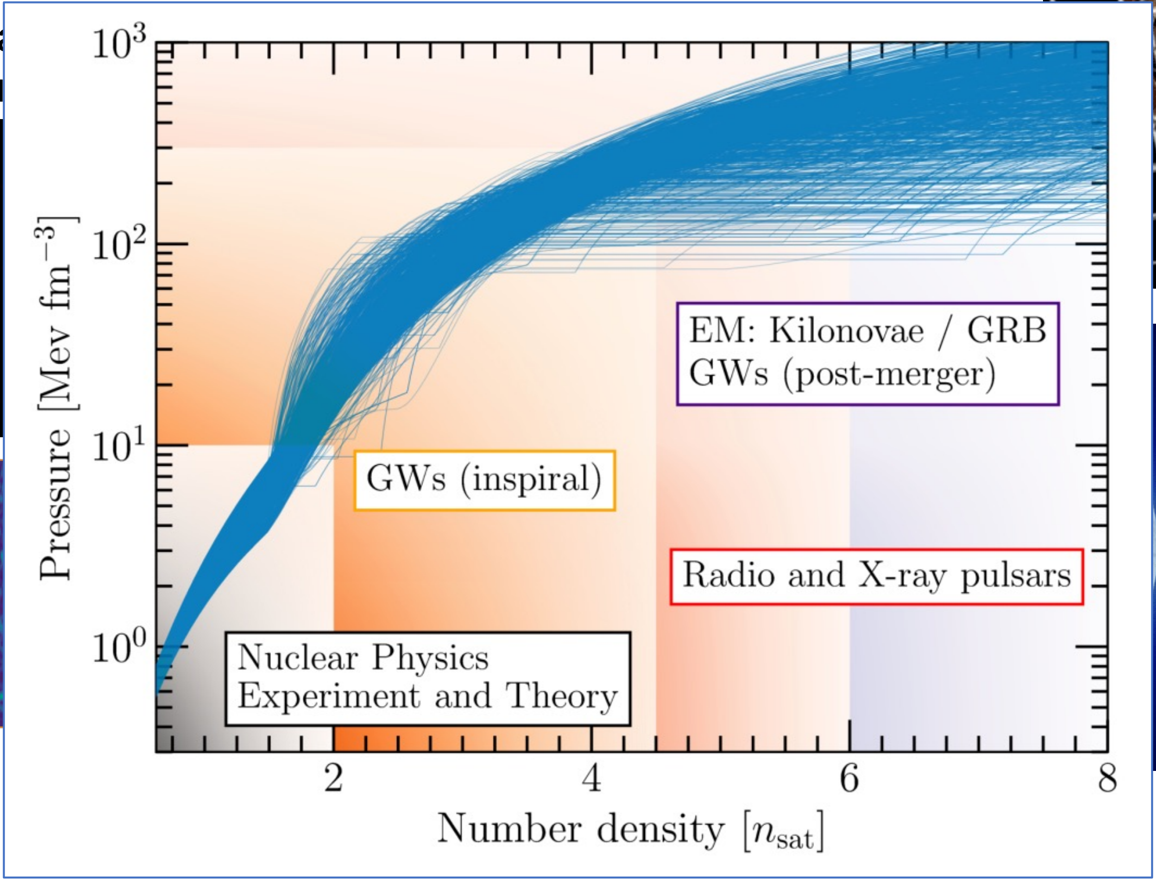


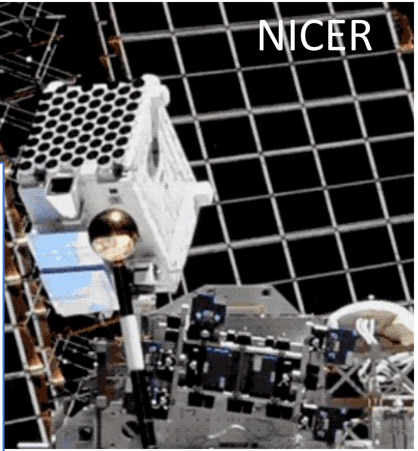
LIGO/VIRGO collaboration, ApJL 848, L12 (2017)

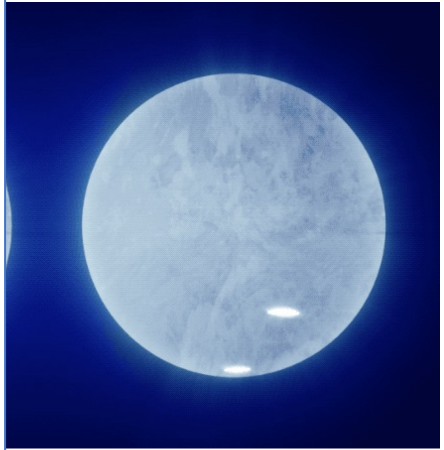
NS (multi-messenger) observations

First neutron-st
observed on Au

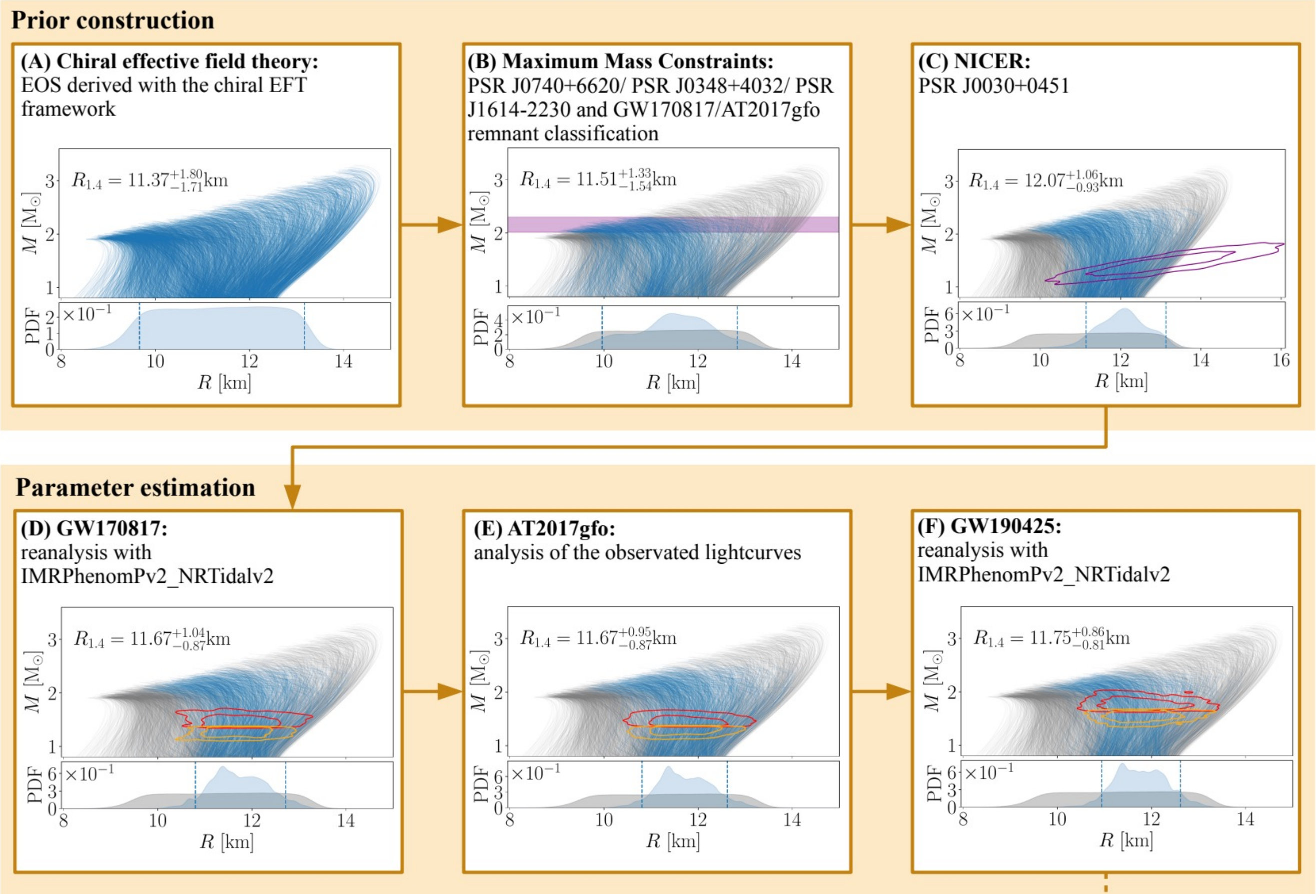








Nuclear-physics Multi-Messenger Astrophysics (NMMA)



Prior construction

(A) Chiral effective field theory: EOS derived with the chiral EFT framework

(B) Maximum Mass Constraints: PSR J0740+6620/ PSR J0348+4032/ PSR J1614-2230 and GW170817/AT2017gfo remnant classification

(C) NICER: PSR J0030+0451

Parameter estimation

(D) GW170817: reanalysis with IMRPhenomPv2_NRTidalv2

(E) AT2017gfo: analysis of the observed lightcurves

(F) GW190425: reanalysis with IMRPhenomPv2_NRTidalv2

NMMA framework:

Pang et al., arXiv:2205.08513

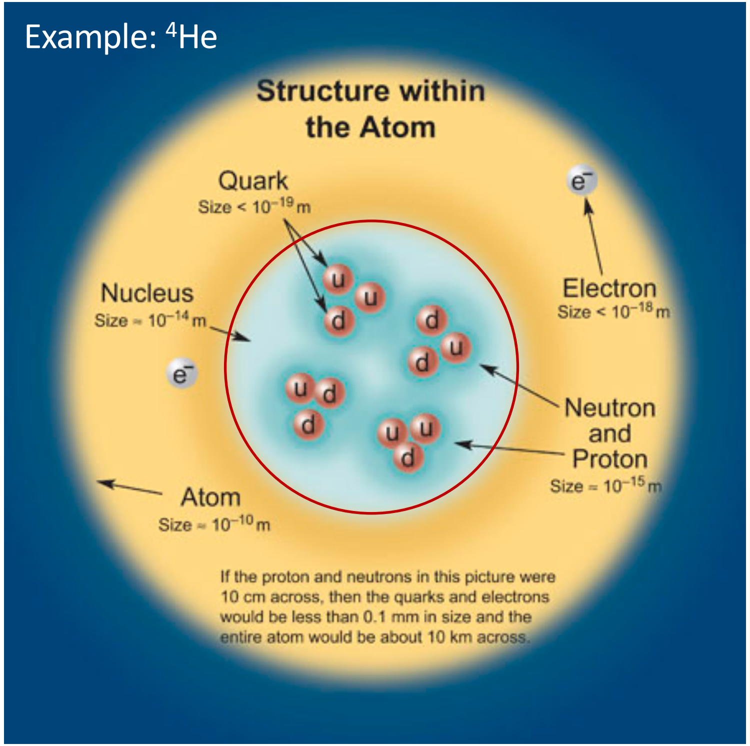
- EOS consistent with theory
- Masses and NICER via published posteriors
- Full GW analysis
- Full KN analysis

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

Low-energy QCD

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

Example: ^4He

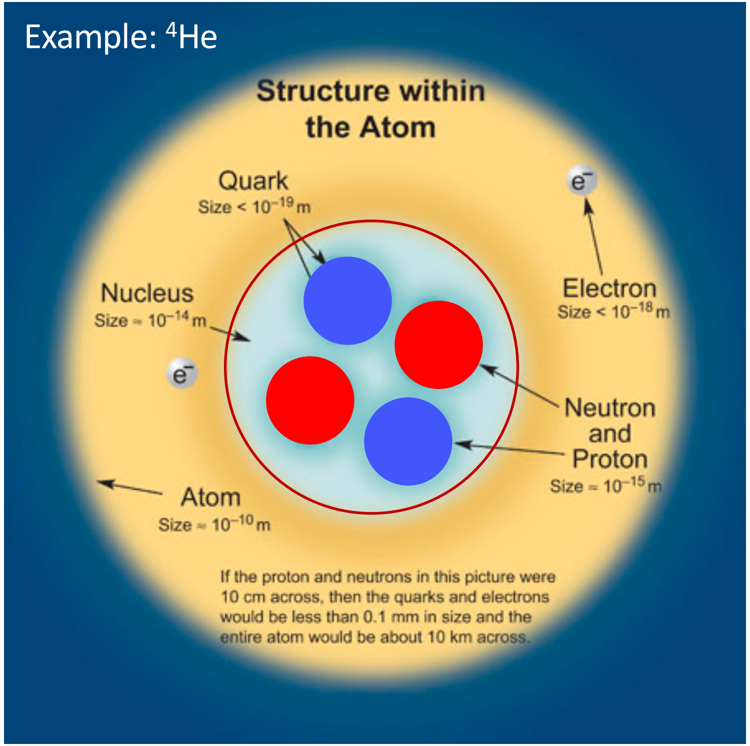


Low-energy QCD

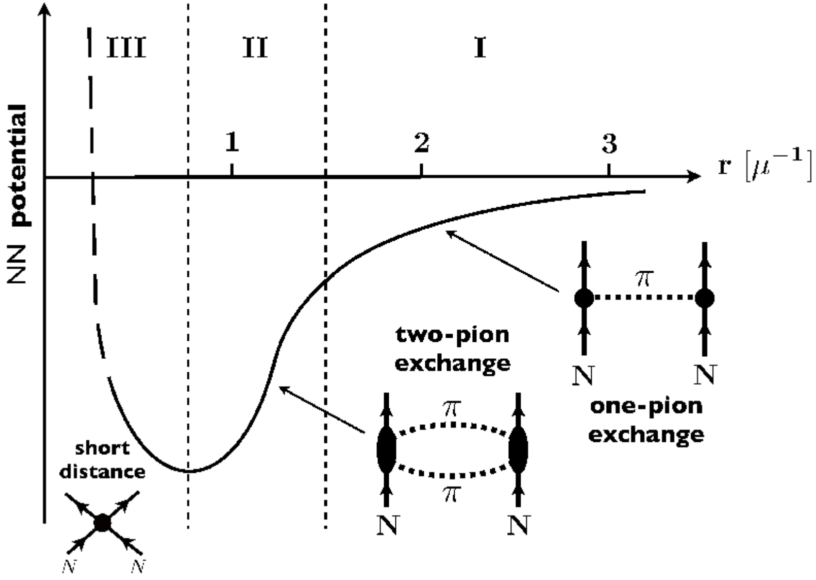
- Atomic nucleus consists of strongly interacting matter.
- Made up by quarks and gluons (Quantum Chromodynamics).
- Extremely complicated to solve!

- 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).

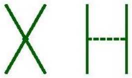
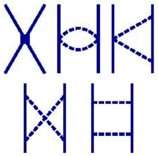
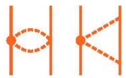
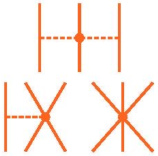
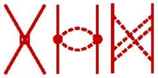
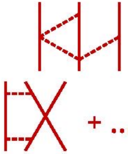
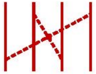
Example: ^{4}He



Chiral effective field theory for nuclear forces



Holt et al., PPNP 73 (2013)

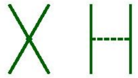
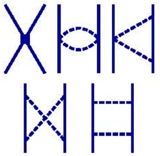
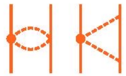
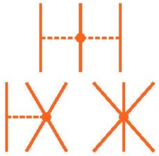
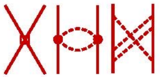
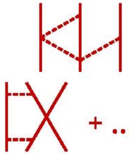
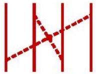
	NN	3N	4N
LO $\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$ (2 LECs)		—	—
NLO $\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$ (7 LECs)		—	—
N²LO $\mathcal{O}\left(\frac{Q^3}{\Lambda^3}\right)$ (2 LECs: 3N)			—
N³LO $\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$ (15 LECs)	 + ...	 + ...	 + ...

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

Chiral effective field theory for nuclear forces

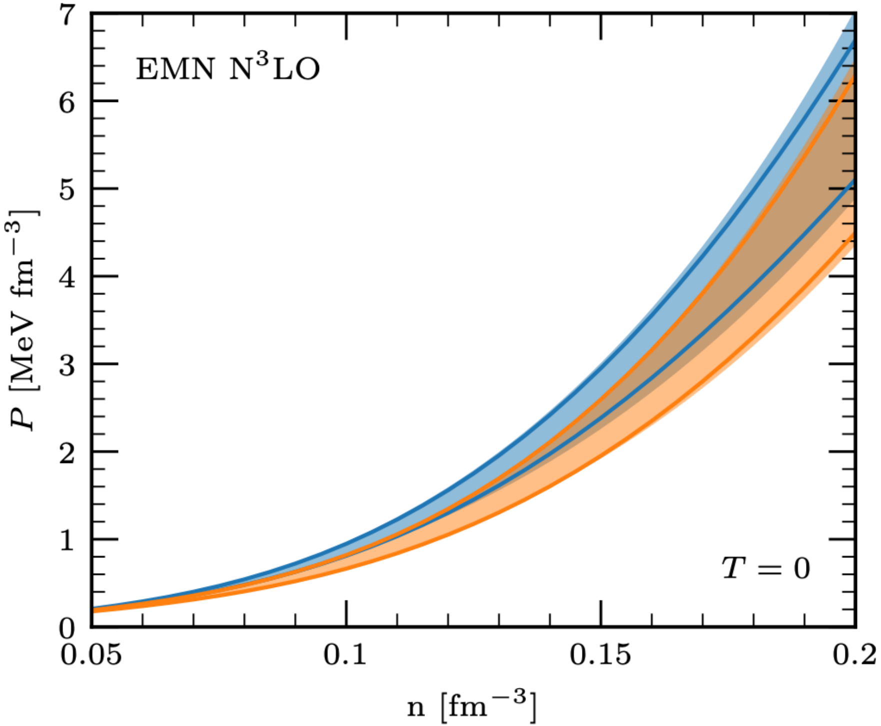
Systematic expansion of nuclear forces in momentum Q over breakdown scale Λ_b :

- 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 …

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**).

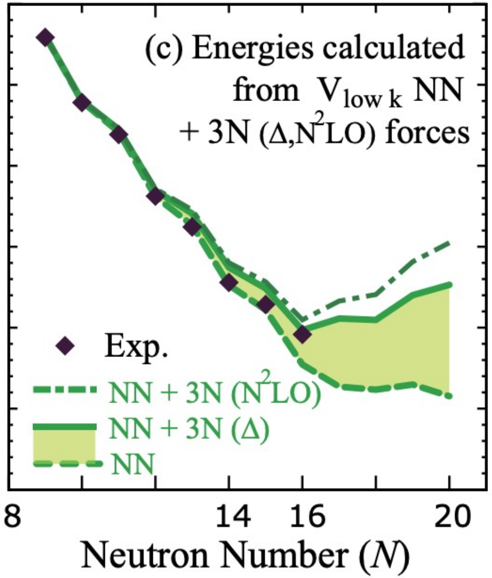
Drischler et al., PRL and PRC (2020)

Both approaches agree!

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

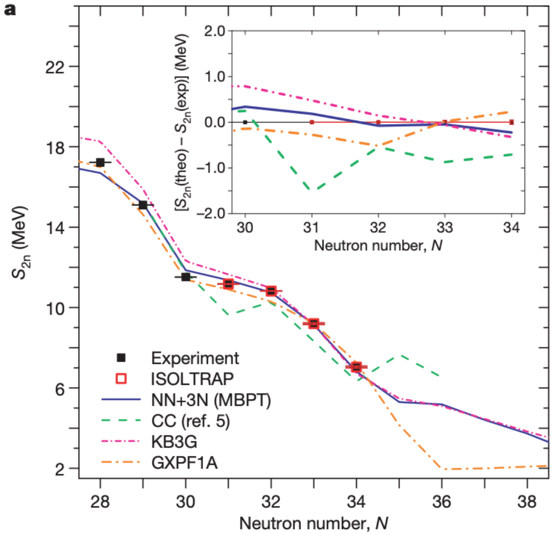
See work by Ekstroem, Hagen et al., BuqEYE collaboration.

Chiral Effective Field Theory - Successes



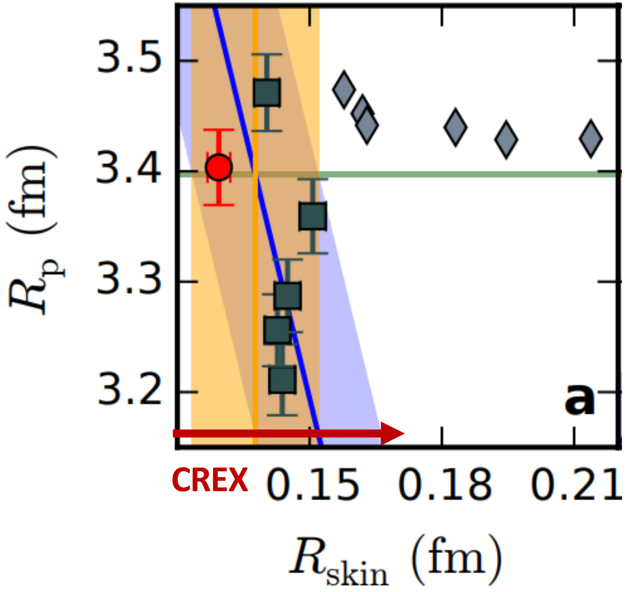
Oxygen anomaly explained

Otsuka et al., PRL 105 (2010)



Calcium 2n separation energies

Wienholtz et al., Nature 498 (2013)



Neutron skin of ^{48}Ca

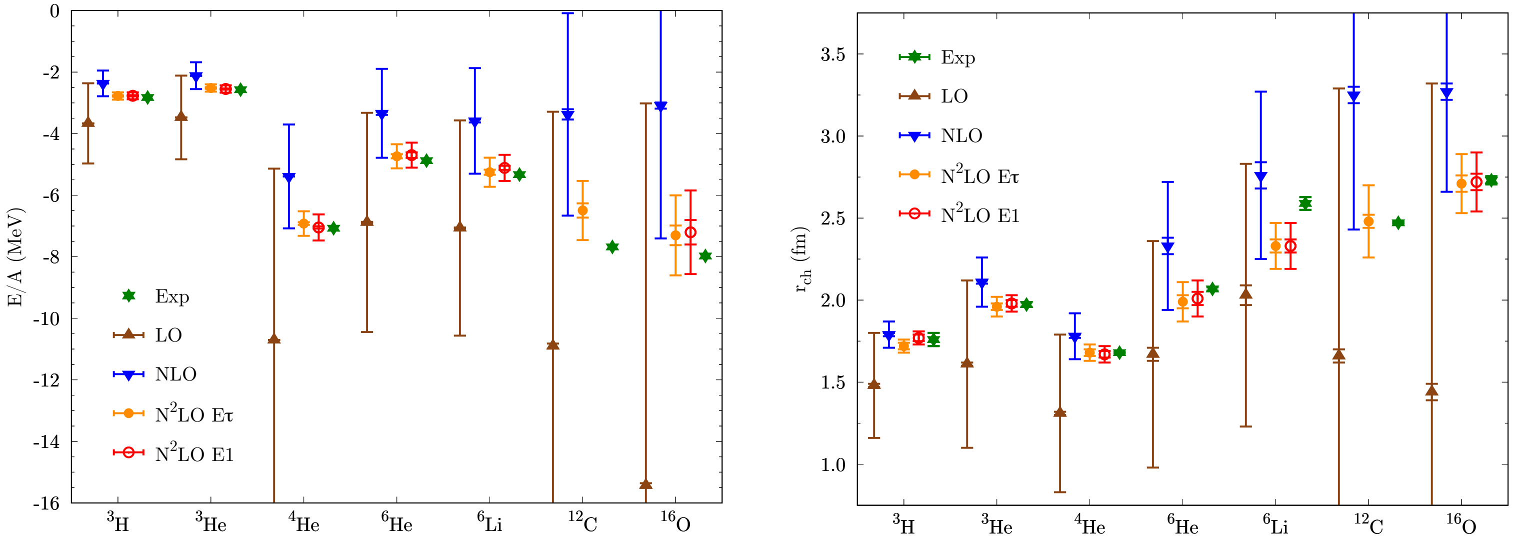
Hagen et al., Nature Physics (2015)

Remember: Fits (only) to light systems!

See works by many others in the community, e.g., Hergert, Roth, Bogner, Holt, Stroberg and many more…

Results for nuclei

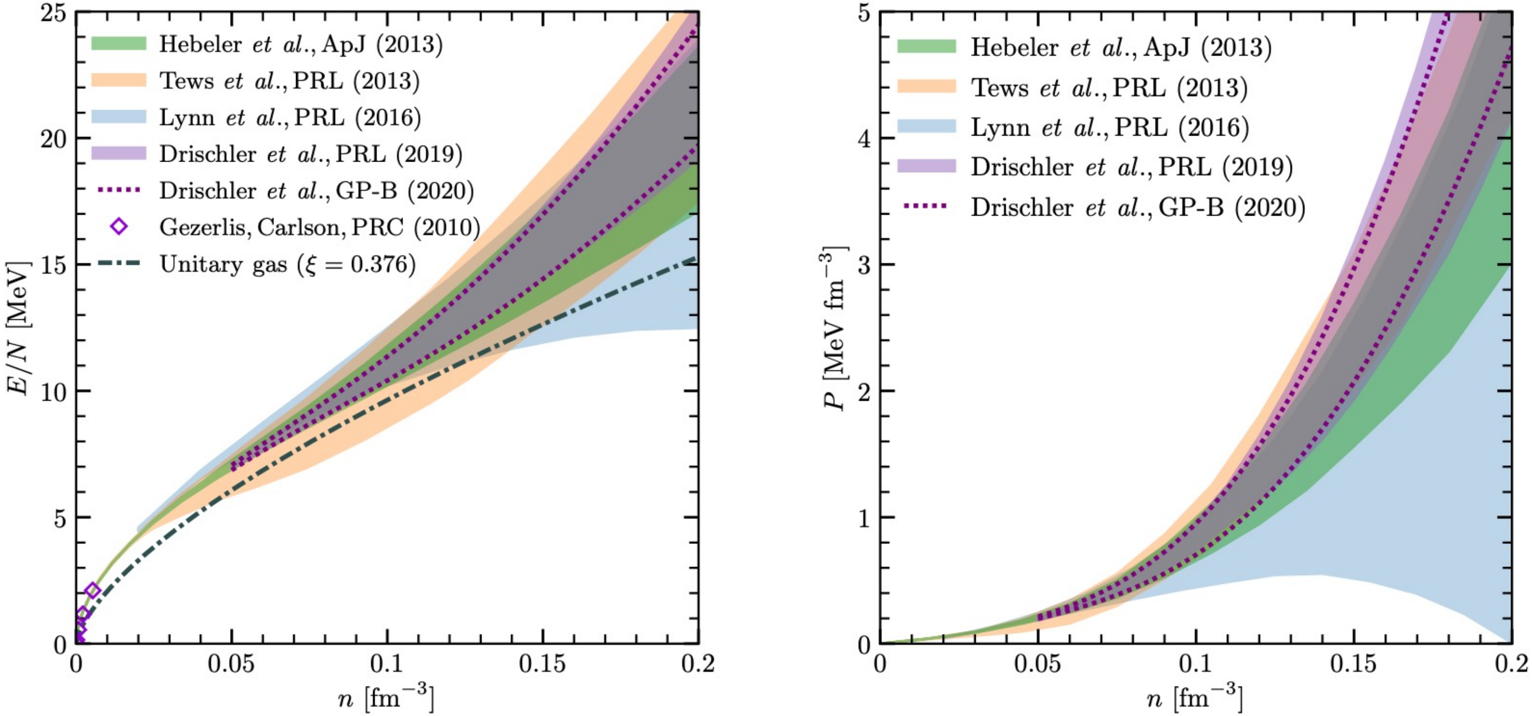
Results for quantum Monte Carlo (QMC) calculations of nuclei up to ^{16}O:
(Local chiral interactions at N^{2}LO with R_0 = 1.0 fm [ca. 500 MeV])



Lonardoni et al., PRL and PRC (2018)

Excellent description of binding energies and charge radii for A ≤16!

Results for neutron matter

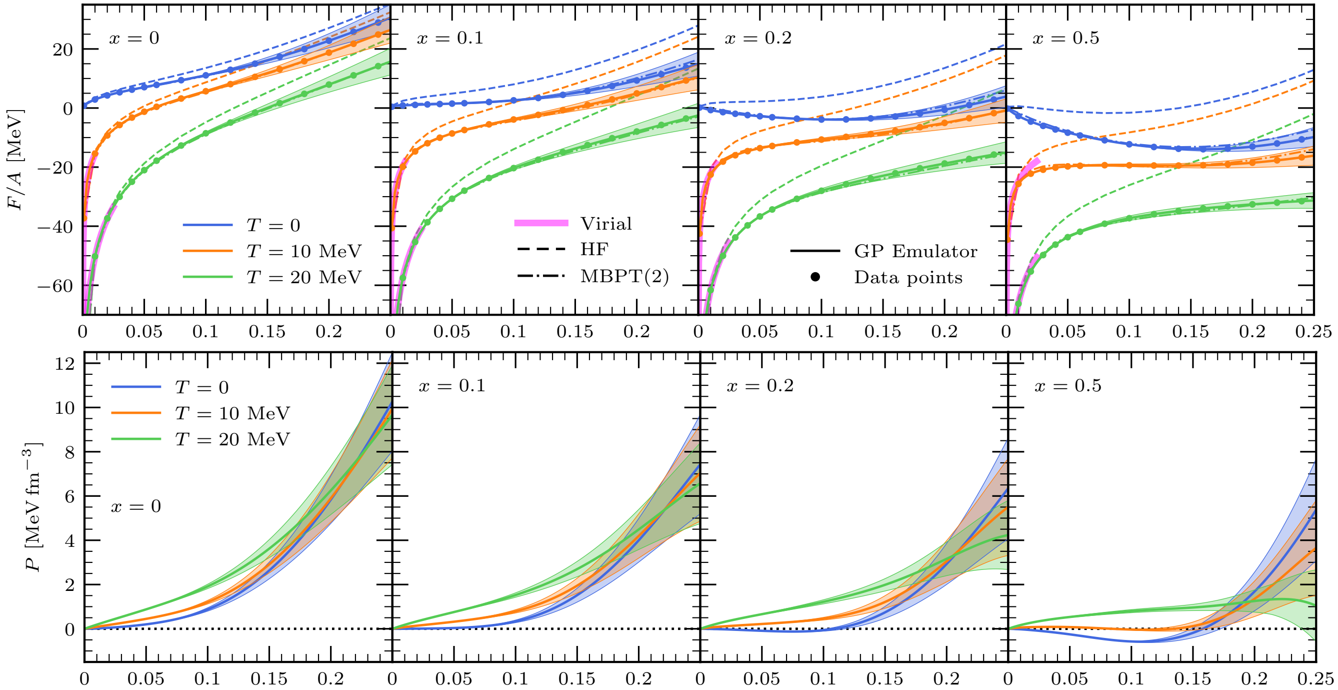


Huth et al., PRC (2021)

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

Results for arbitrary proton fraction and temperature

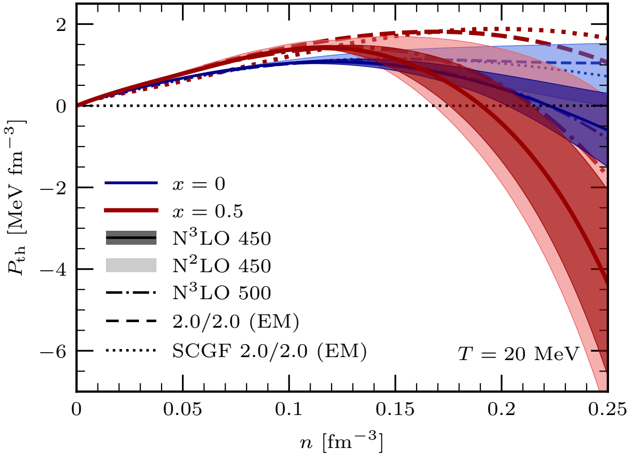
- Train a Gaussian process emulator on many-body perturbation theory calculations of chiral EFT NN and 3N interactions to N^3LO (EMN 450)
- EFT uncertainties as before, many-body uncertainties small

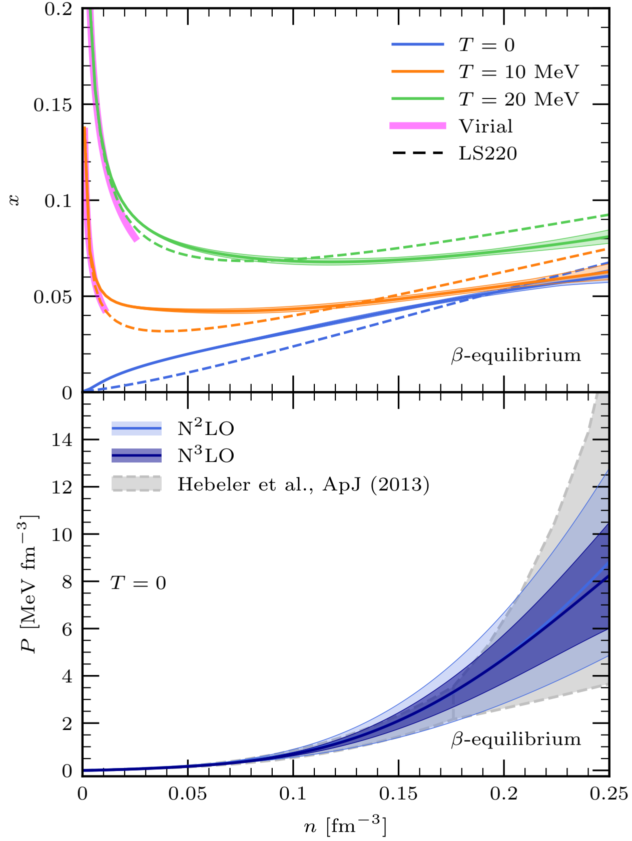


Keller et al., arXiv:2204.14016

Results for arbitrary proton fraction and temperature

- Thermal pressure decreases with density, observed for different chiral orders, cutoffs and interactions





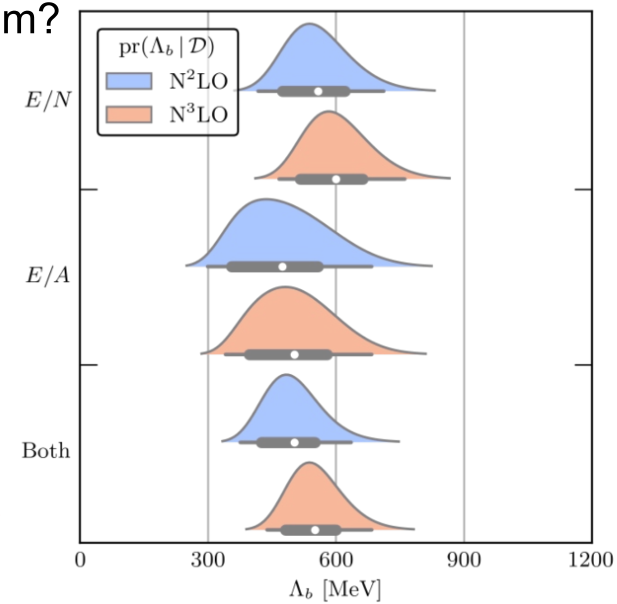
- Use of Gaussian process emulator to directly access matter in beta equilibrium.
- EOS of neutron star matter at N2LO and N3LO shows no indication of EFT breakdown.
- Bands prefer slightly higher pressures than older calculations.

Keller et al., arXiv:2204.14016

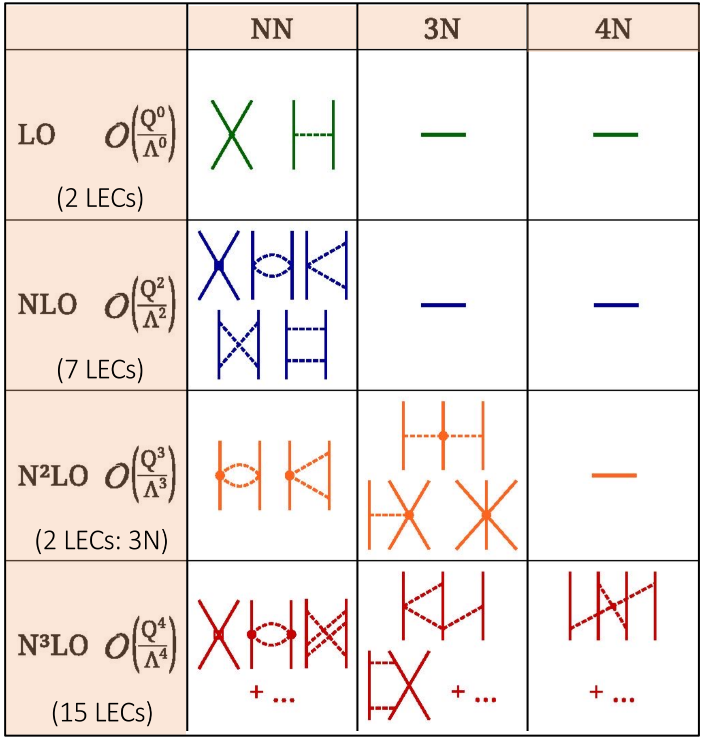
Chiral effective field theory for nuclear forces

BUT: There are still many open questions and problems!

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



Drischler et al., PRC (2020)



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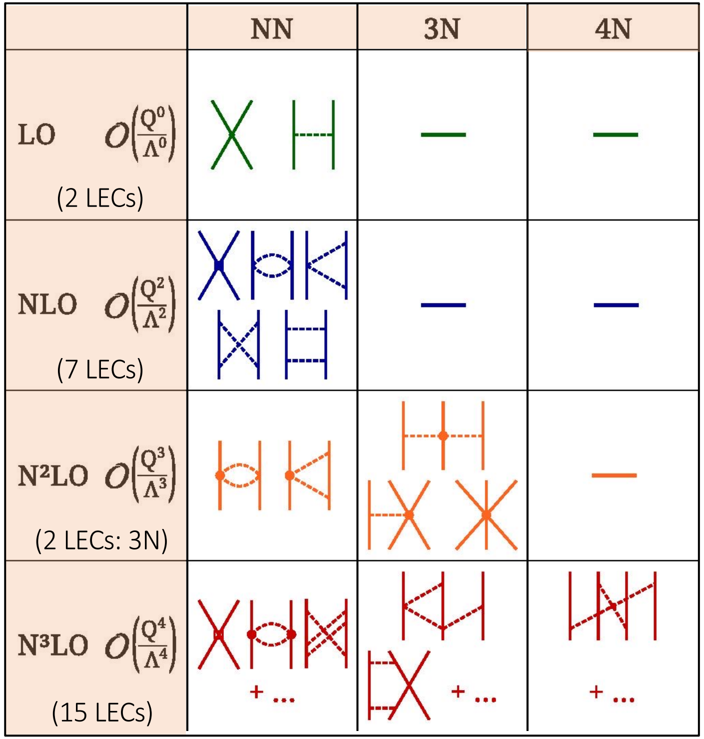
N³LO $\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$ (15 LECs)	+ ...	+ ...	+ ...

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

Chiral effective field theory for nuclear forces

BUT: 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**?



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

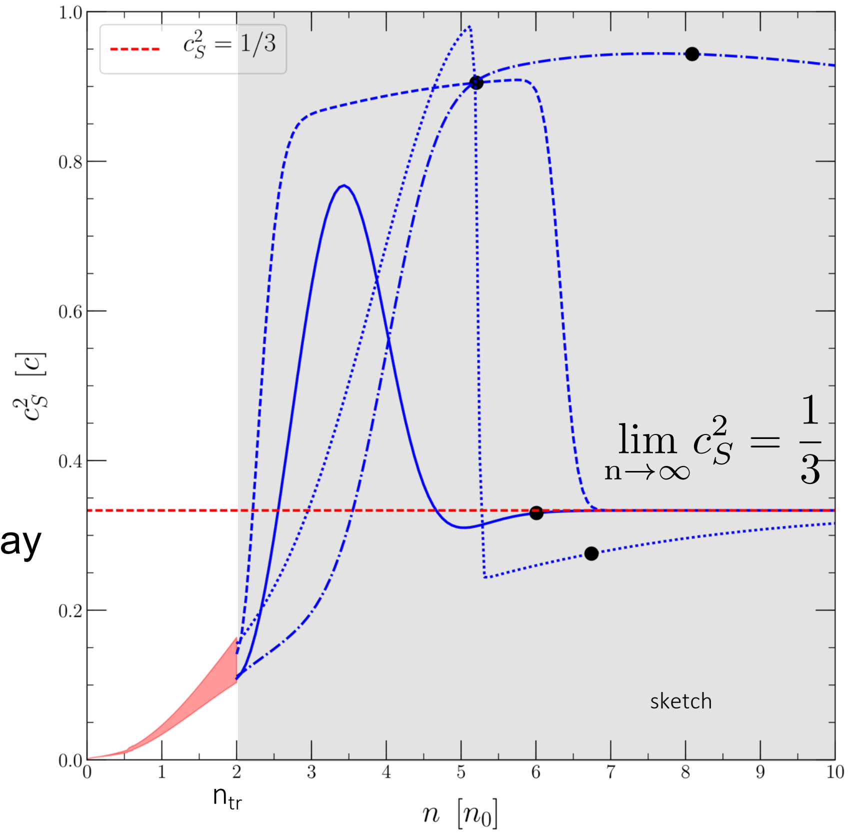
Neutron-star EOS

- 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 systematic uncertainties to higher densities!**



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

Neutron-star EOS

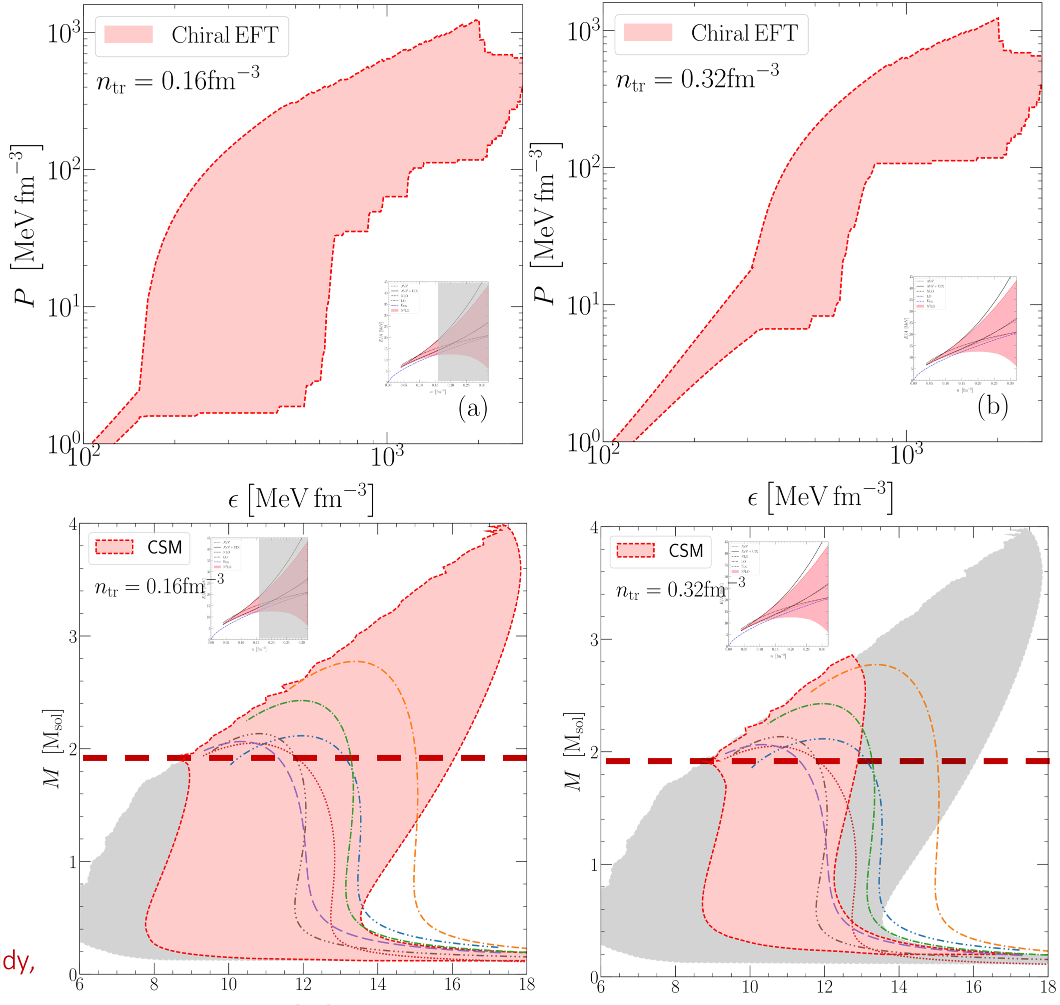
Generate thousands of EOSs that:

- 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.

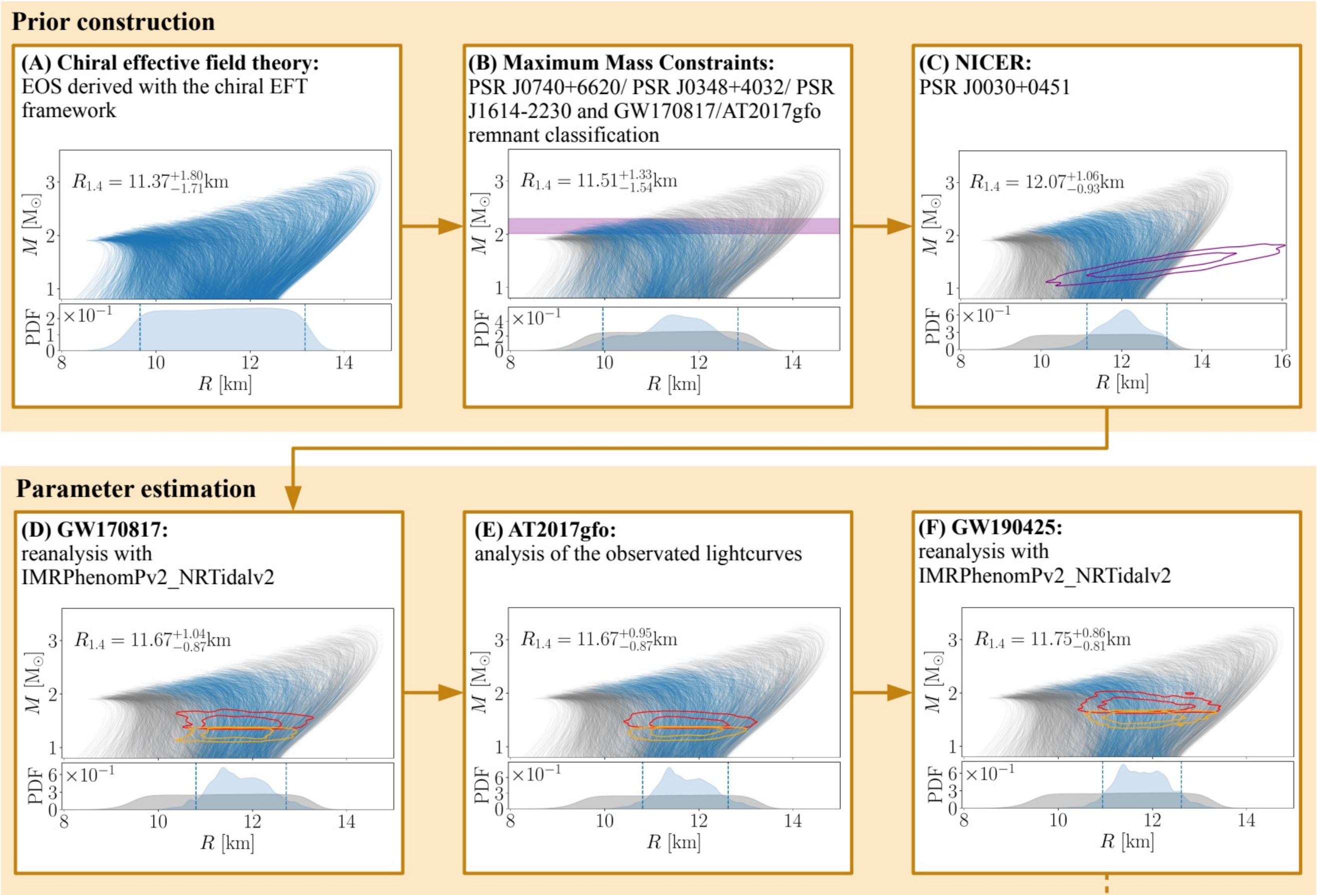
Current nuclear-physics uncertainties remain sizable **but EFT input critical!**

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 chiral EFT
- Masses and NICER via published posteriors
- Full GW analysis
- Full KN analysis

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

Including results from heavy-ion collisions

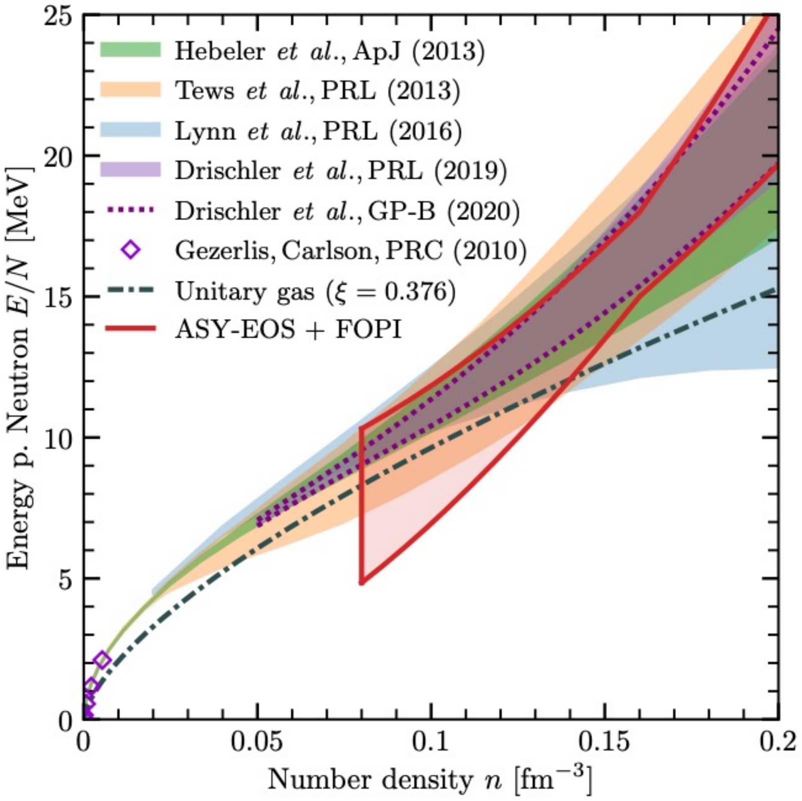
Including experimental data from heavy-ion collision experiments:

- 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].

- Initial asymmetry of Au-Au system makes expansion of collision region sensitive to the symmetry energy.

- Flow ratio of particles with large isospin difference most sensitive.



Huth, Pang et al., Nature (2022)

Including results from heavy-ion collisions

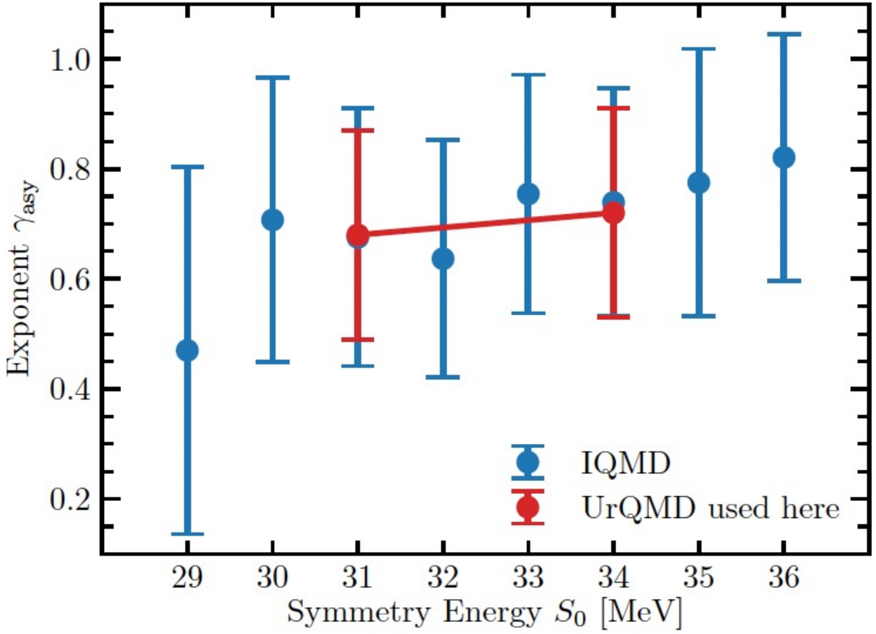
HIC data (elliptic flow ratio) is analyzed using transport models, describe EOS as

$$\frac{E}{A}(n,\delta) \approx \boxed{\frac{E}{A}(n,0)} + \boxed{S(n)\delta^2}$$

The symmetric-matter part is constrained by FOPI, the symmetry energy by ASY-EOS assuming

$$S(n) = E_{\mathrm{kin},0}\left(\frac{n}{n_{\mathrm{sat}}}\right)^{2/3} + E_{\mathrm{pot},0}\left(\frac{n}{n_{\mathrm{sat}}}\right)^{\gamma_{\mathrm{asy}}} .$$

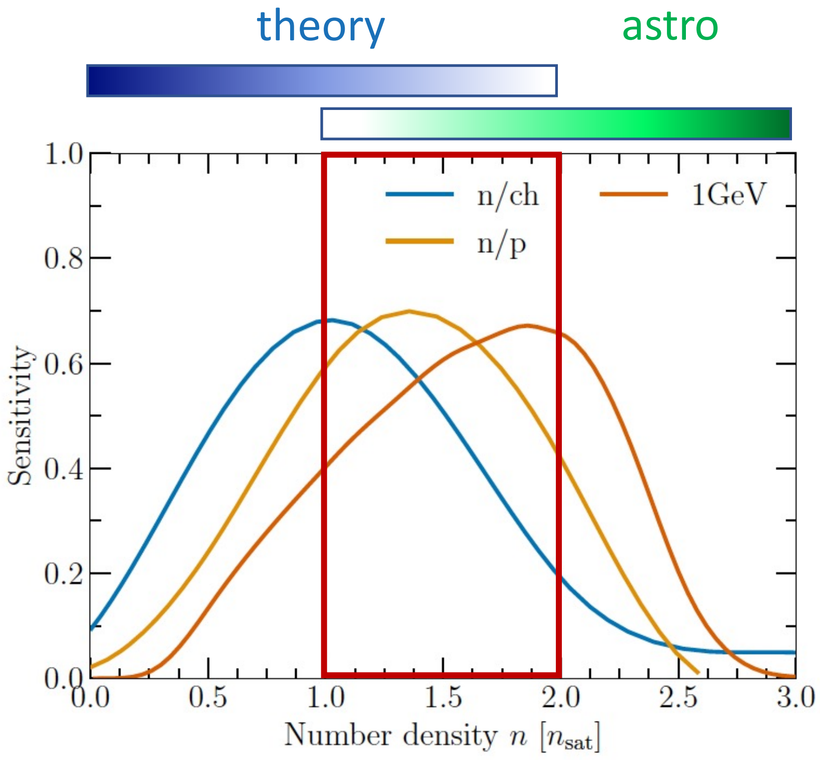
Two transport models (UqQMD and IQMD) give similar results and a linear dependence of gamma.



Huth, Pang et al., Nature (2022)

Including results from heavy-ion collisions

- To implement HIC constraint in Bayesian analysis, we need to know in which density range the constraint can be applied.
- Use neutron-over-charged-particle sensitivity curve for the elliptic flow ratio (n/ch).
- We have compared with neutron-over-proton (n/p) at estimated sensitivity at 1 GeV/nucleon collisions.
- The higher the sensitivity at large n, the stronger the constraint, as experiment probes more and more in Astro domain.



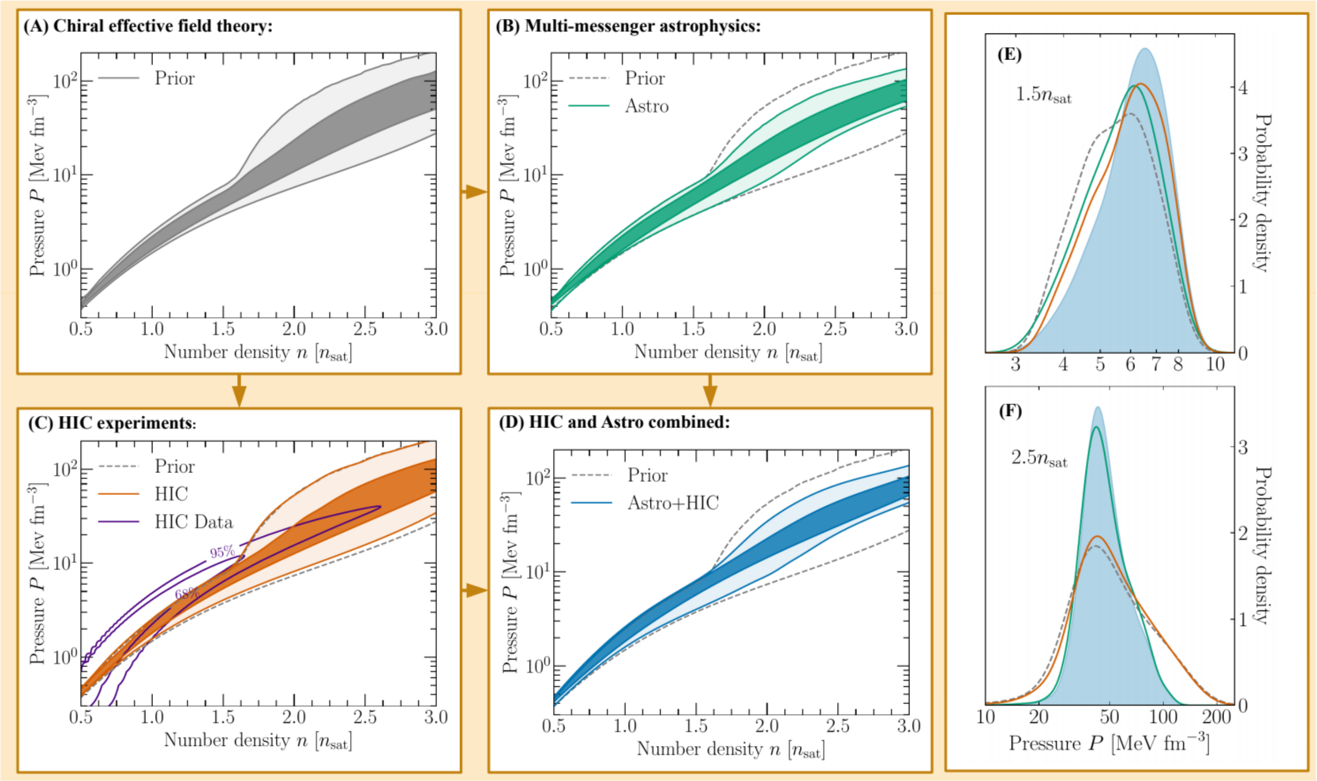
Huth, Pang et al., Nature (2022)

Including results from heavy-ion collisions

In Bayesian analysis, vary n_{sat}, E_{sat}, K_{sat}, S_0, γ within uncertainties.

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

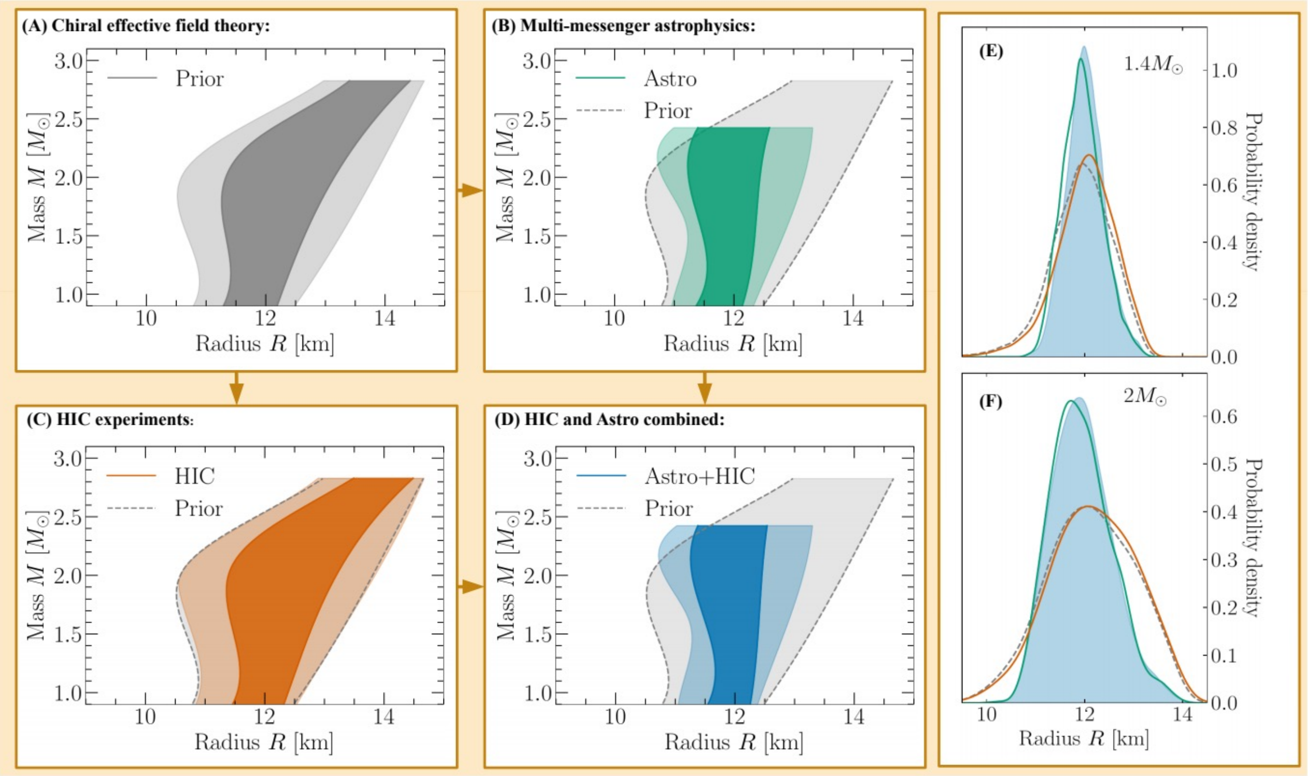
In Bayesian analysis, vary n_{sat}, E_{sat}, K_{sat}, S_0, γ within uncertainties.

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

Excellent agreement with astrophysical observations.

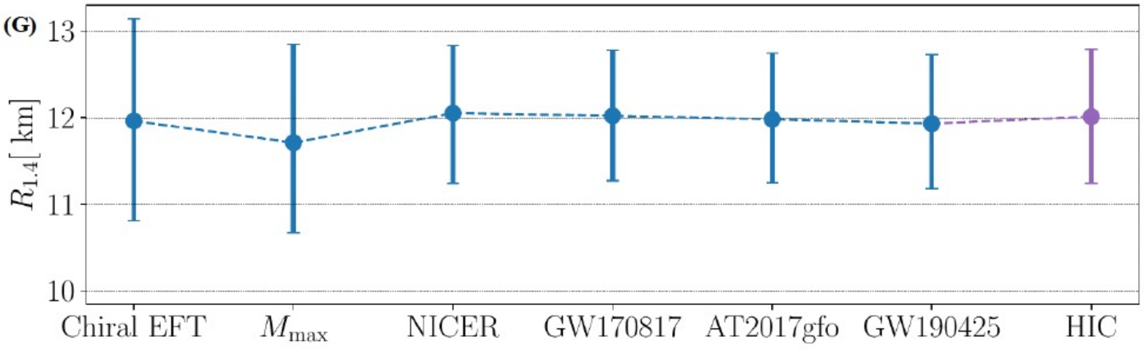
Impact on neutron-star radii for low-mass stars.

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



Huth, Pang et al., Nature (2022)

Including results from heavy-ion collisions

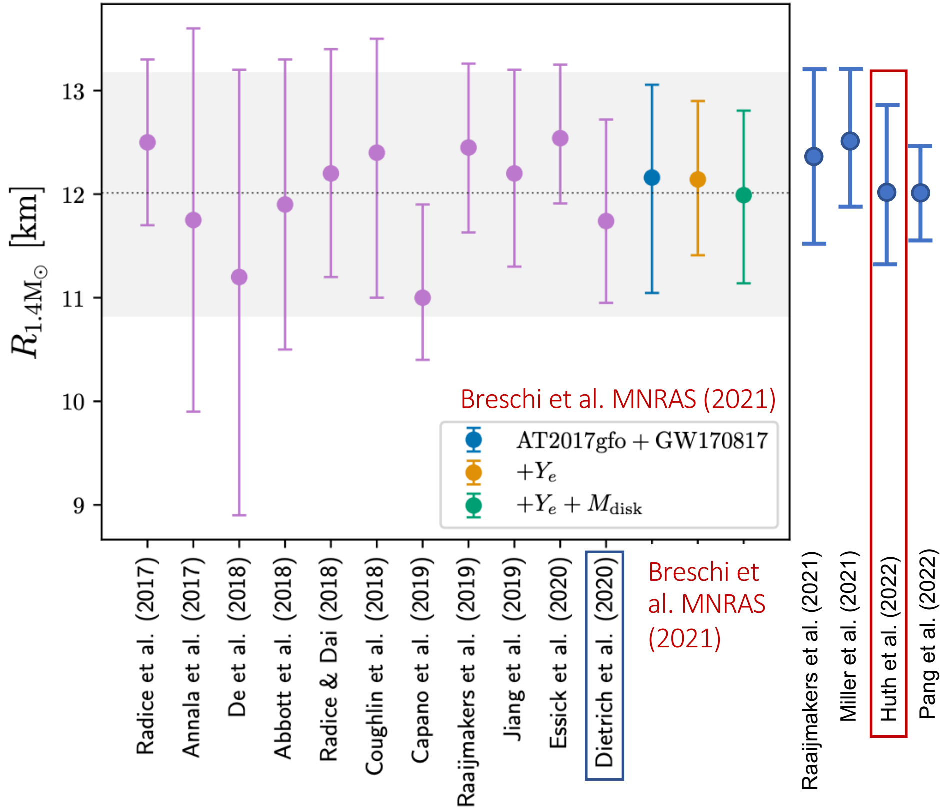


Huth, Pang et al., Nature (2022)

Constraint on radius of typical neutron star seems to converge at about 12km if available theoretical, observational, and experimental data is considered.

Most important: Density range between 1-2 n_{sat} is where theory, experiment, and astrophysics overlap. This will allow future tests of theories against data.

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.

Results are consistent with heavy-ion collision experiments (large uncertainties).

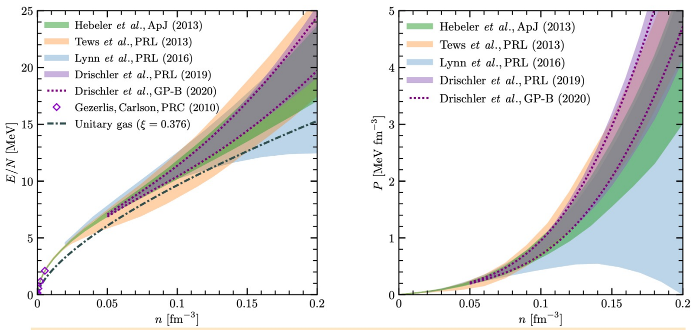
Summary

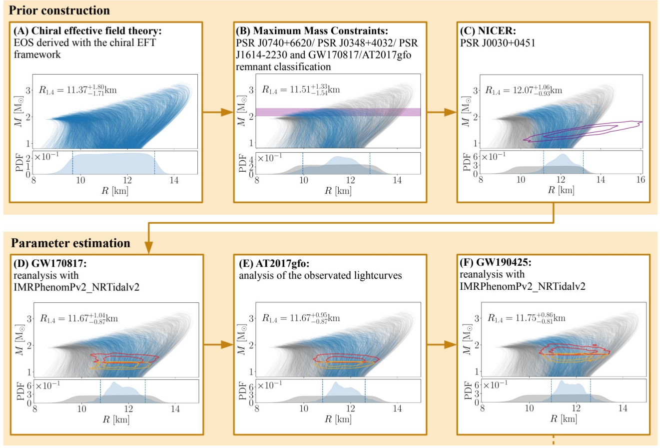
- ➢ Neutron stars represent ideal laboratories for nuclear physics and help to improve our understanding of nuclear interactions!

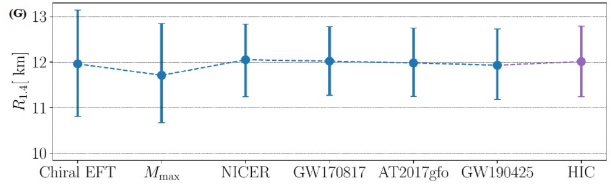
- ➢Uncertainty in neutron-star EOS can be reduced by
  - Improved nuclear-physics calculations using chiral EFT,
  - Multimessenger observations of NS and NS mergers
  - Experiments in the laboratory

- ➢ GW observations favor softer, EM observations (kilonova and NICER) and nuclear experiments favor stiffer EOS but all 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}).







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Thank you for your attention!