Improving Nuclear Theory Input for Next-Generation Gravitational-Wave Detectors

Ingo Tews

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

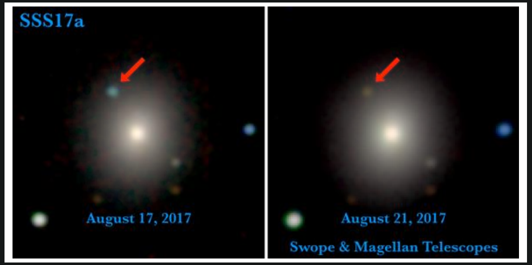
INT Workshop: EOS Measurements with Next-Generation GW Detectors
September 2, 2024

LA-UR-24-29308

Los Alamos
NATIONAL LABORATORY

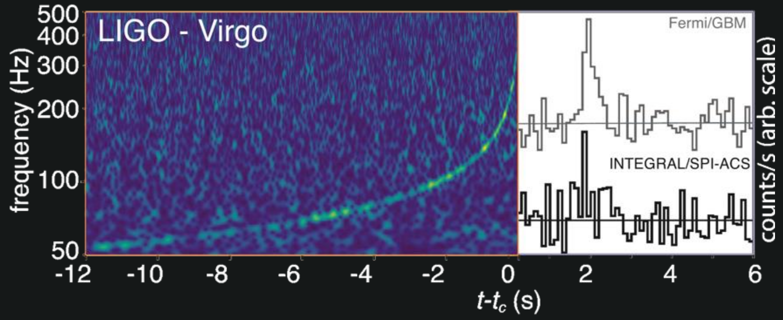
NS (multi-messenger) observations

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



(Gamma-ray)

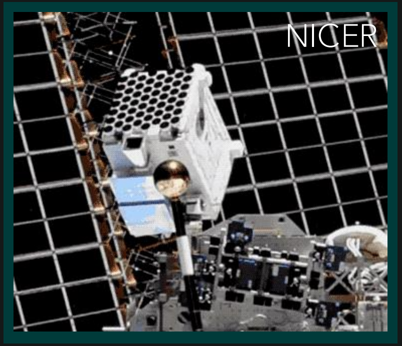
LIGO/VIRGO collaboration, ApJL 848, L12 (2017)



The New York Times

LIGO Detects Fierce Collision of Neutron Stars for the First Time

NICER observations:



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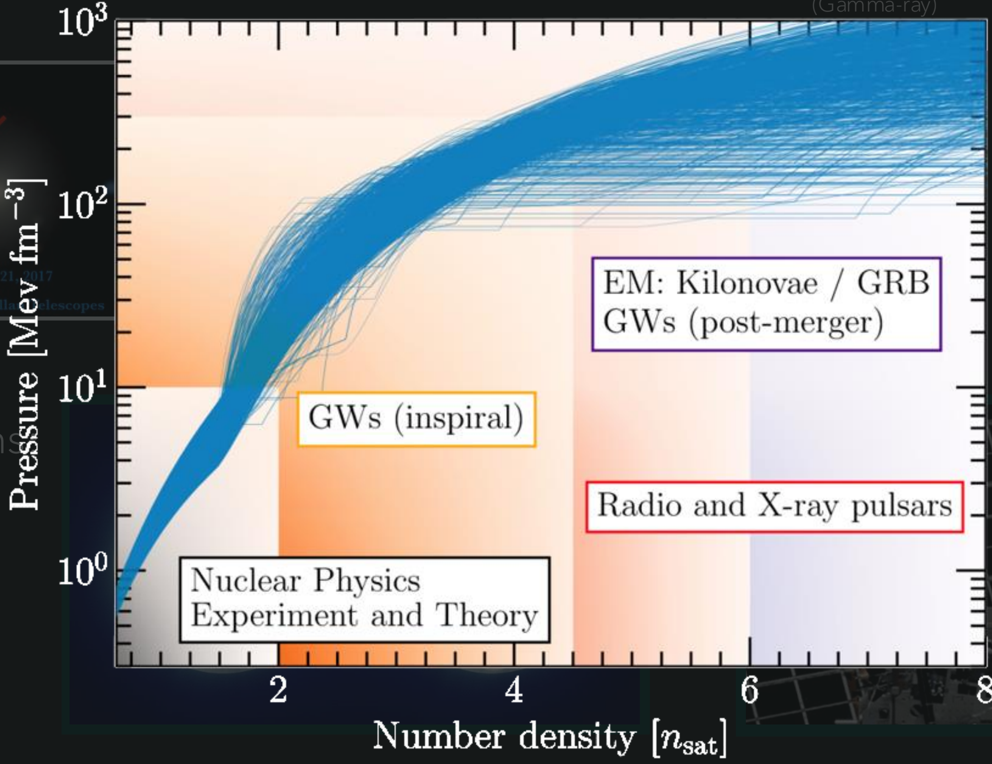

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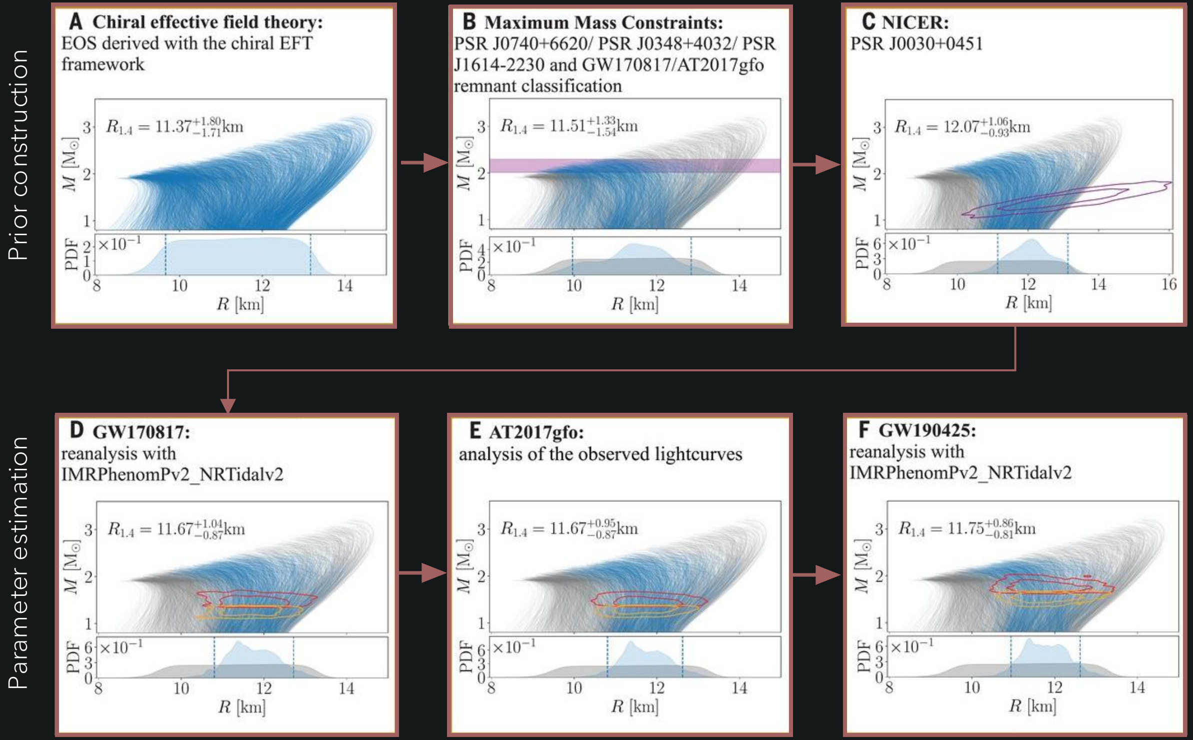

Dietrich, Coughlin, Pang, Bulla, Heinzel, Issa, **IT**, Antier, **Science** (2020)

Pang et al., **Nature Communications** (2024)

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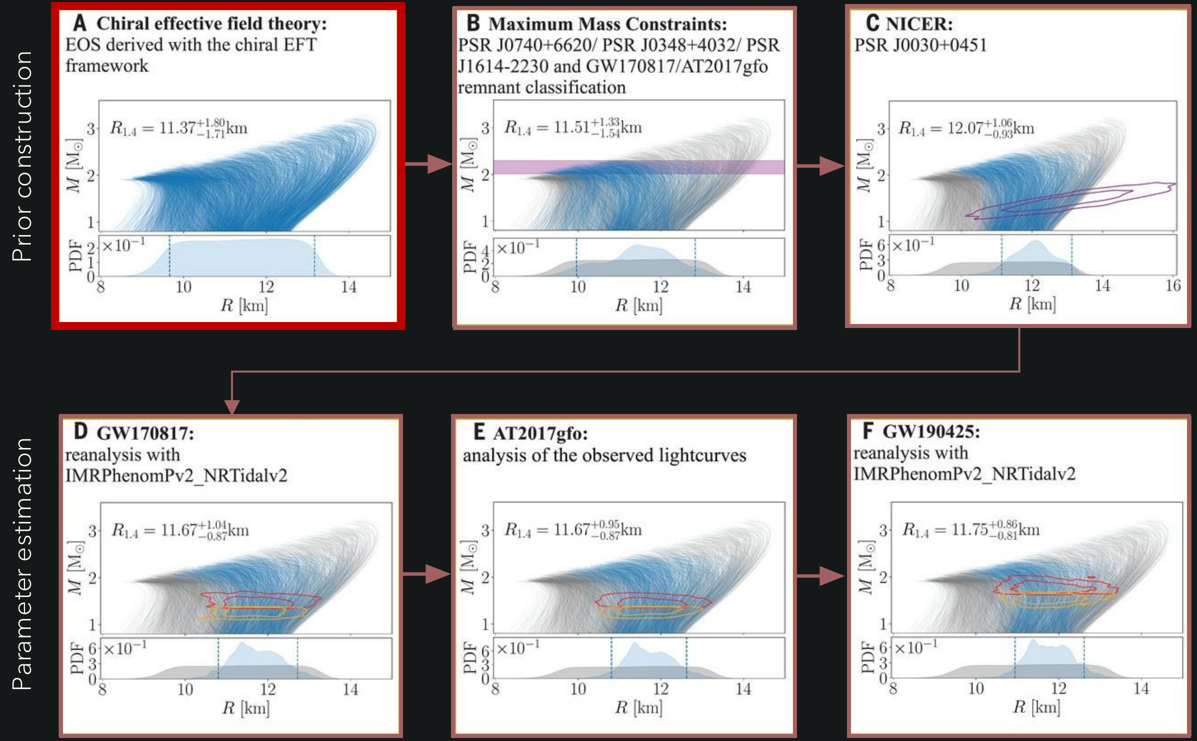

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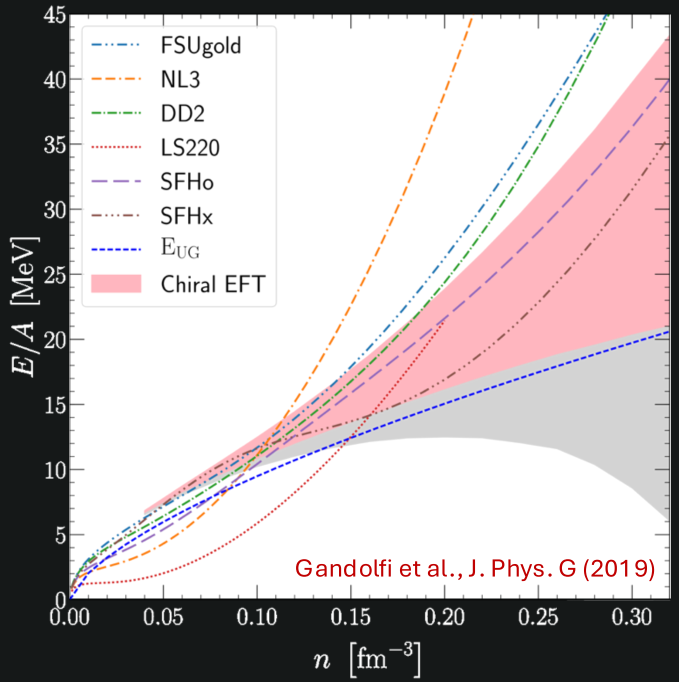
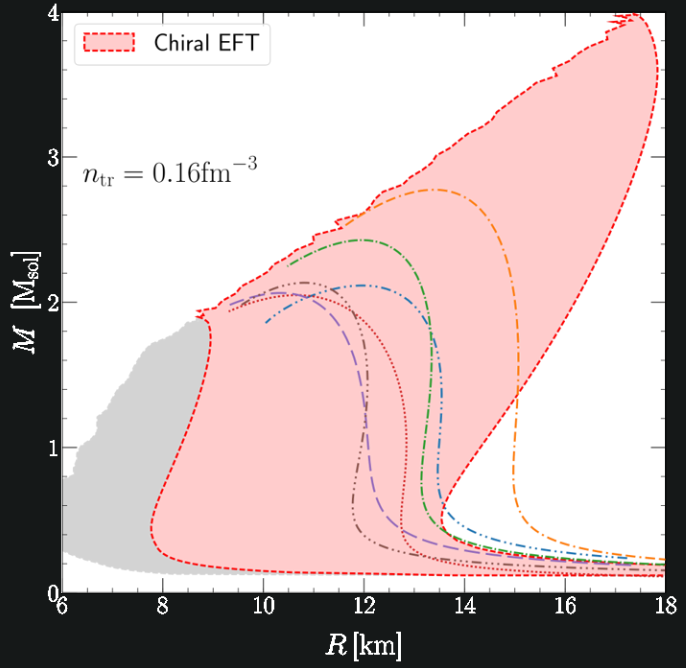
Current Input



Gandolfi et al., J. Phys. G (2019)

TOV equations



- Chiral EFT calculations (left) have large uncertainties, that grow with density.
- This leads to sizable uncertainties for neutron-star masses and radii.

Nuclear Interactions and EOS

Many different approaches to calculate $\frac{E}{A}(n,x)$ but I will focus on **microscopic calculations** where we solve

$$\boxed{\mathcal{H}}\,|\psi\rangle \boxed{=} E\,|\psi\rangle$$

We need:

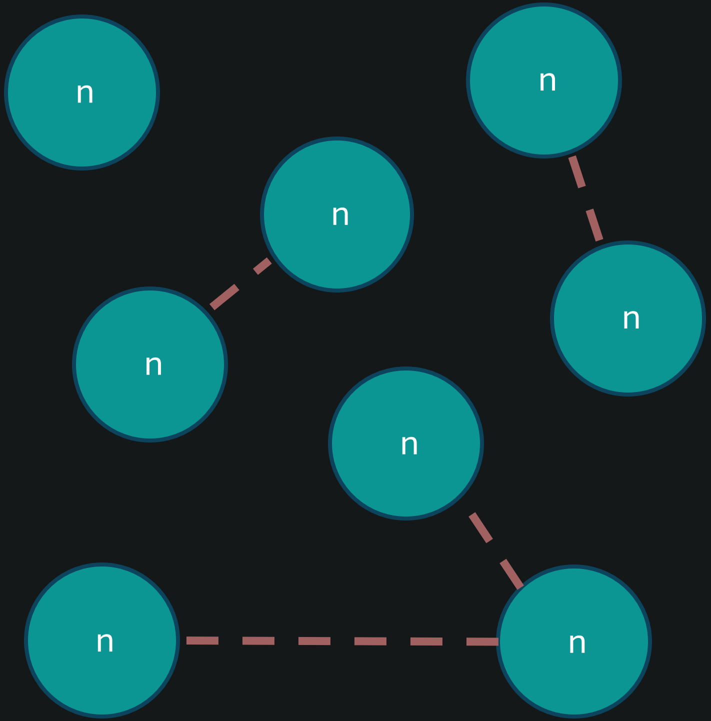
☐ A theory for the strong interactions among nucleons

Chiral Effective Field Theory

$$\mathcal{H} = \sum_{i} \mathcal{T}_i + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \cdots$$

☐ A computational method to solve the many-body Schrödinger equation:

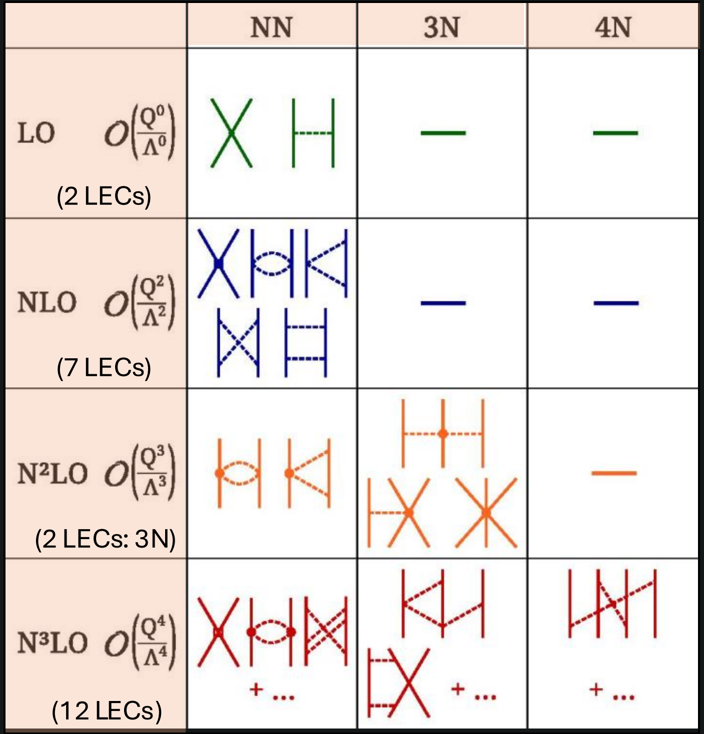
e.g., many-body perturbation theory, **quantum Monte Carlo**, coupled cluster, self-consistent Green’s function, in-medium SRG…



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, beta decay)



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LO $\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$ (2 LECs)			
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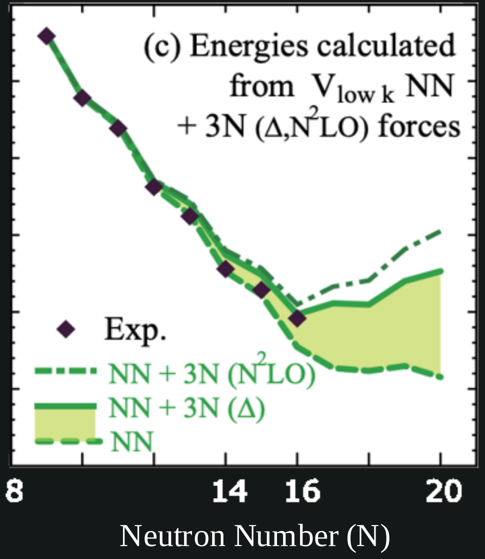
N³LO $\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$ (12 LECs)	+ ...	+ ...	+ ...

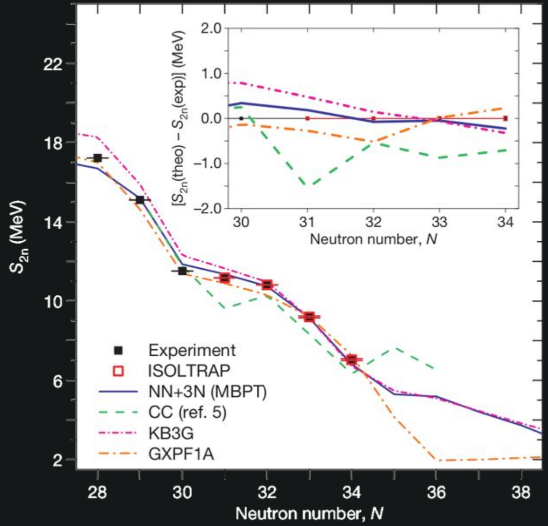
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meißner, Hammer …

Chiral Effective Field Theory - Successes



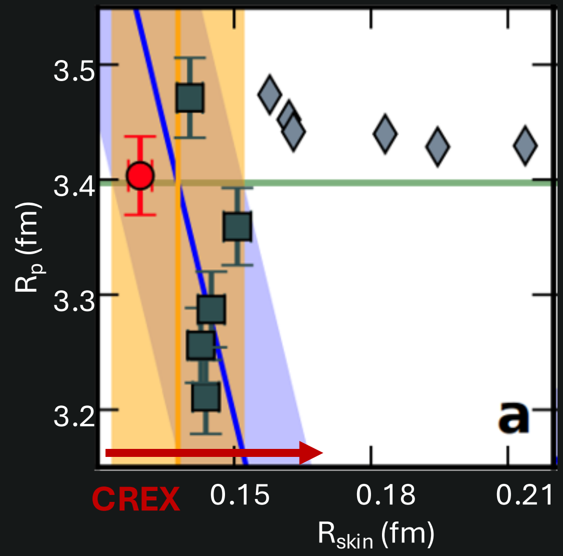
Oxygen anomaly explained

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)

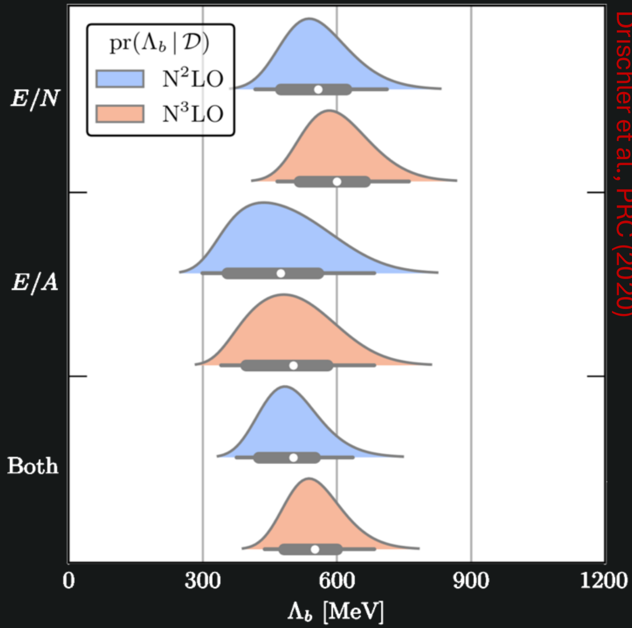
Remember: Fits (only) to light systems!

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

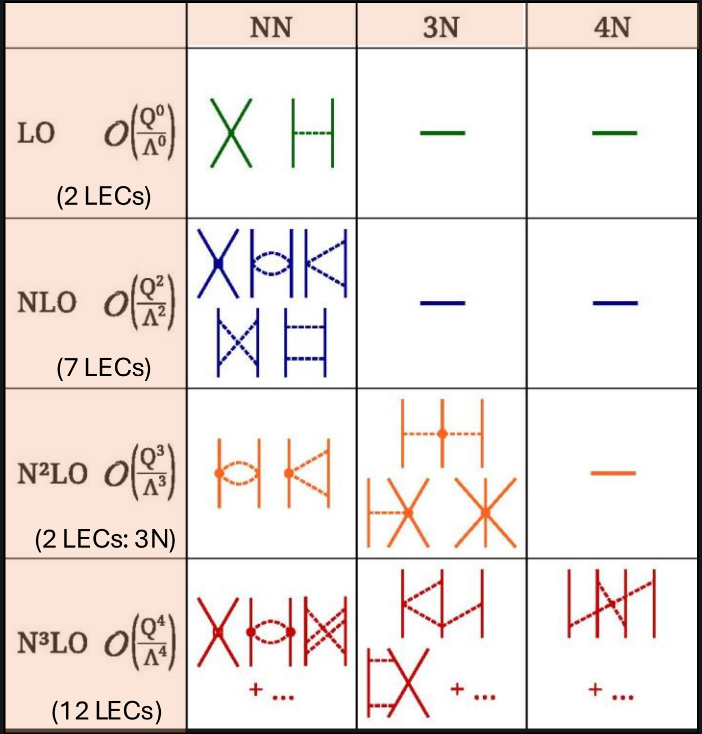
Chiral Effective Field Theory

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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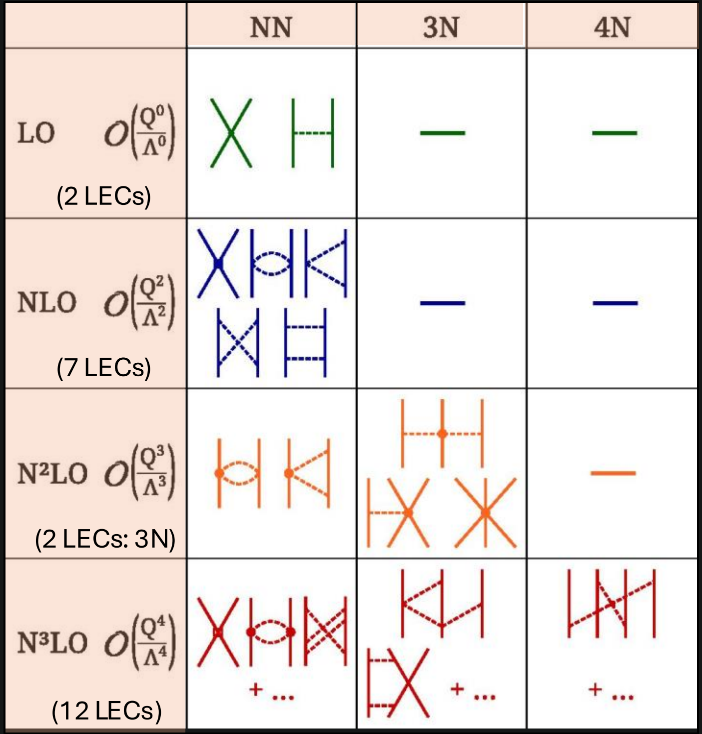
Chiral Effective Field Theory

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 scale** (cutoff necessary in many-body methods)?
- At which densities does this series **converge** in the many-body system (nuclear matter)?
- How to best determine all **unknown coefficients** (see Rahul’s talk)?



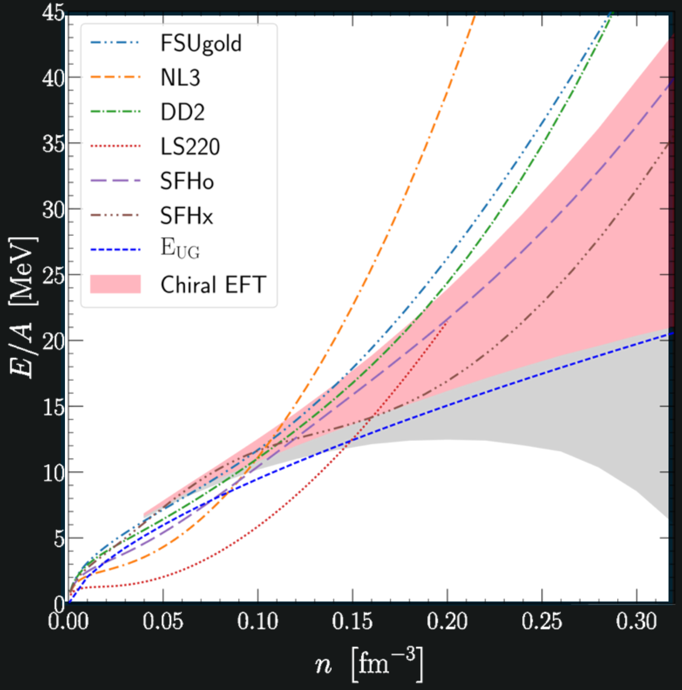
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meißner, Hammer …

How To Address These Questions?

To study these questions, we need new approaches to EFT calculations:

- We need to study observables at a range of values for the regularization scale (cutoff). This is especially important for matter.
- We need properly quantified uncertainties, ideally by propagating LEC uncertainties directly to the observables.
- For the latter, we need accelerated nuclear-physics calculations.

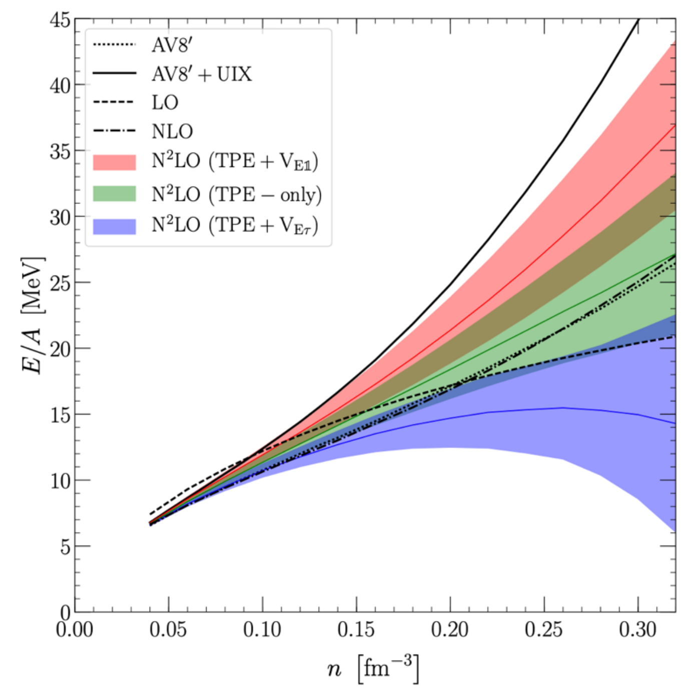
High-Cutoff Interactions



Gandolfi et al., J. Phys. G (2019)

- Regulator and truncation of EFT introduce uncertainties that grow fast with density!

High-Cutoff Interactions



Lynn et al., PRL (2016)

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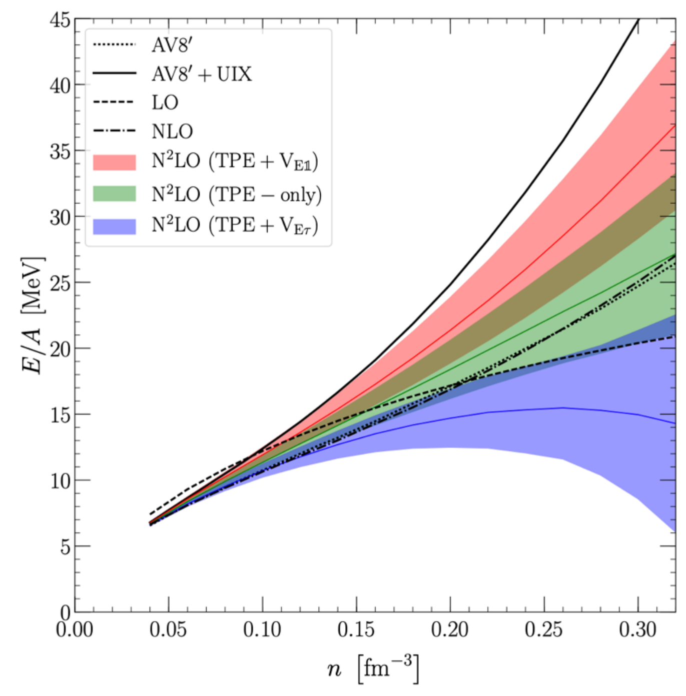
- Uncertainty band consists of different Hamiltonians that explore these uncertainties.

High-Cutoff Interactions



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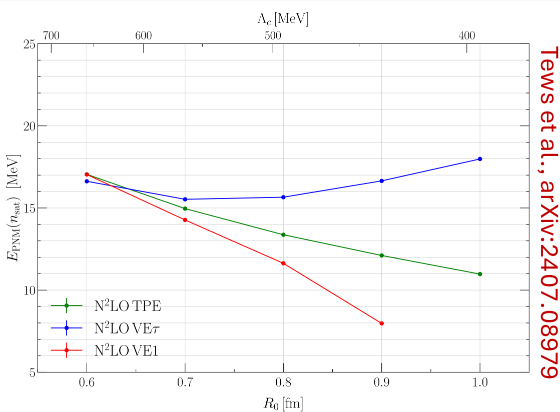
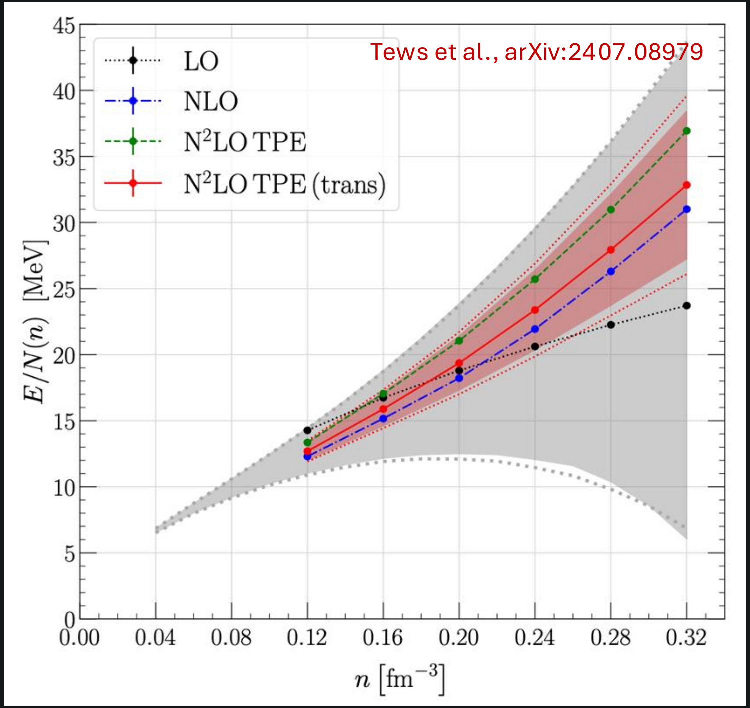
- Regulator uncertainty goes as 1/cutoff^{2n}!
- New interactions at high cutoffs allow us to reduce these uncertainties!



Tews et al., arXiv:2407.08979

High-Cutoff Interactions



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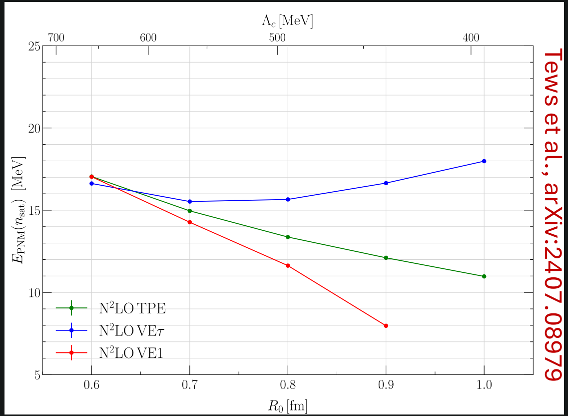
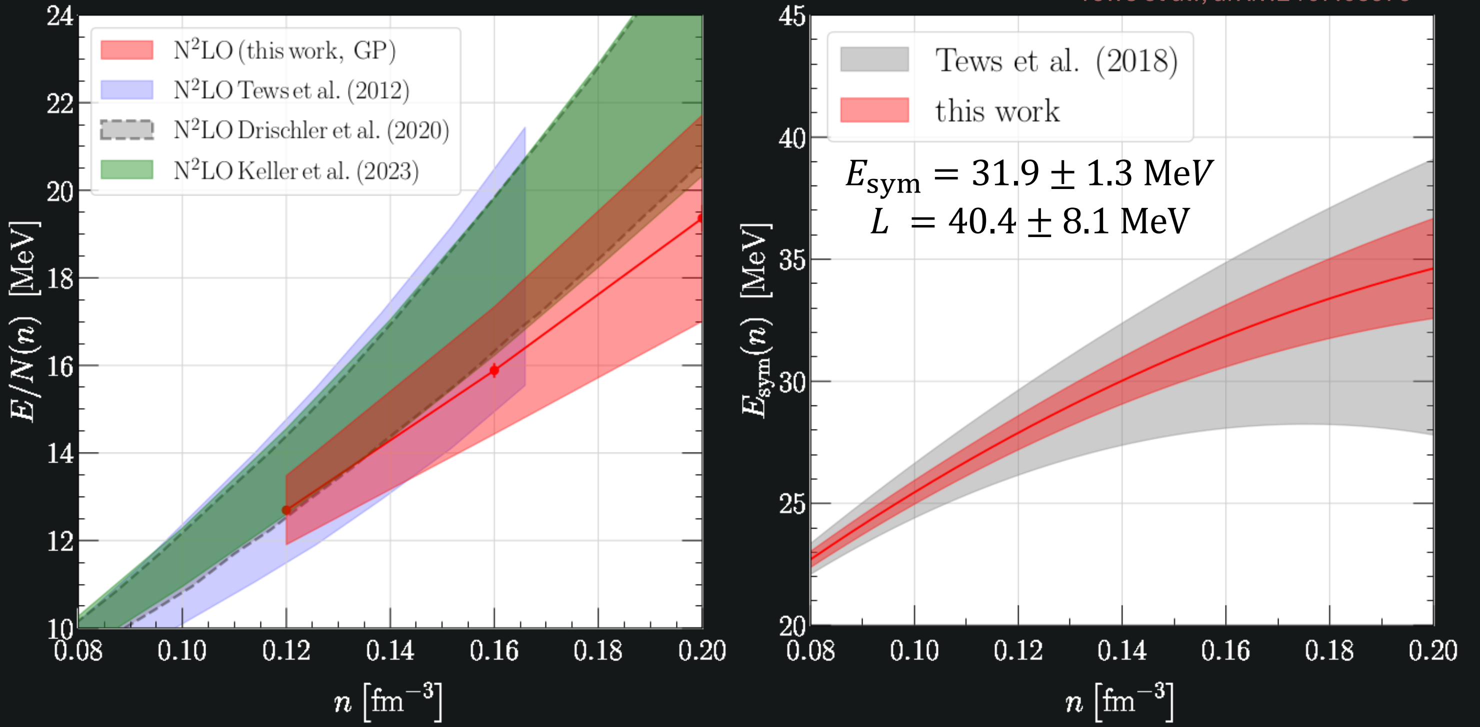


This allows us to reduce uncertainties by factor 3 already at N^{2}LO!
Improvement at N^{3}LO expected to be even better.

High-Cutoff Interactions

Tews et al., arXiv:2407.08979



$$E_{\text{sym}} = 31.9 \pm 1.3 \text{ MeV}$$
$$L = 40.4 \pm 8.1 \text{ MeV}$$

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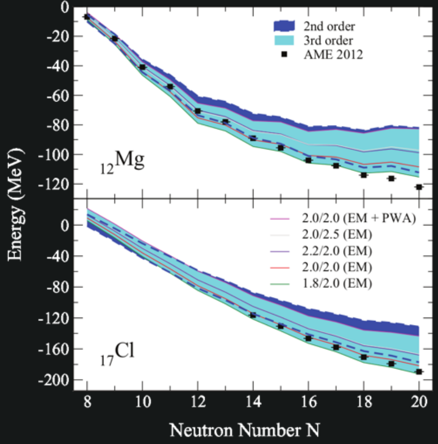
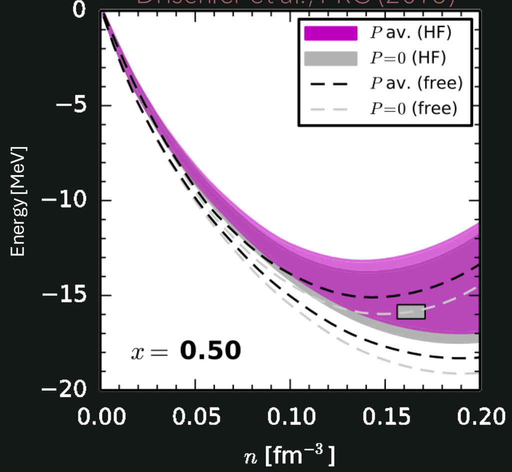
Uncertainty

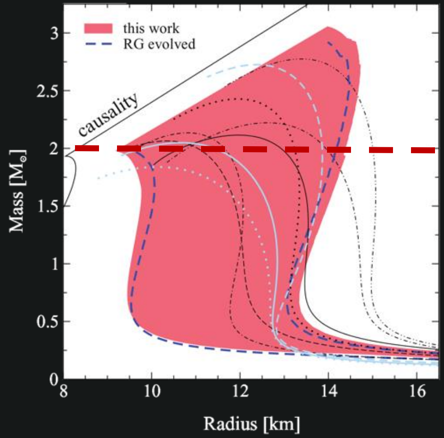
Simonis et al., PRC (2016)



Drischler et al., PRC (2016)



Krueger, IT et al., PRC (2013)



All theoretical predictions for nuclear systems are limited by:

- our incomplete understanding of **nuclear interactions** (dominating),
- and our ability to **reliably calculate** these strongly interacting systems (under control).

Uncertainties of observables are currently estimated a posteriori (see Christian's talk).

We would like to **propagate** uncertainties from interaction directly to observable.

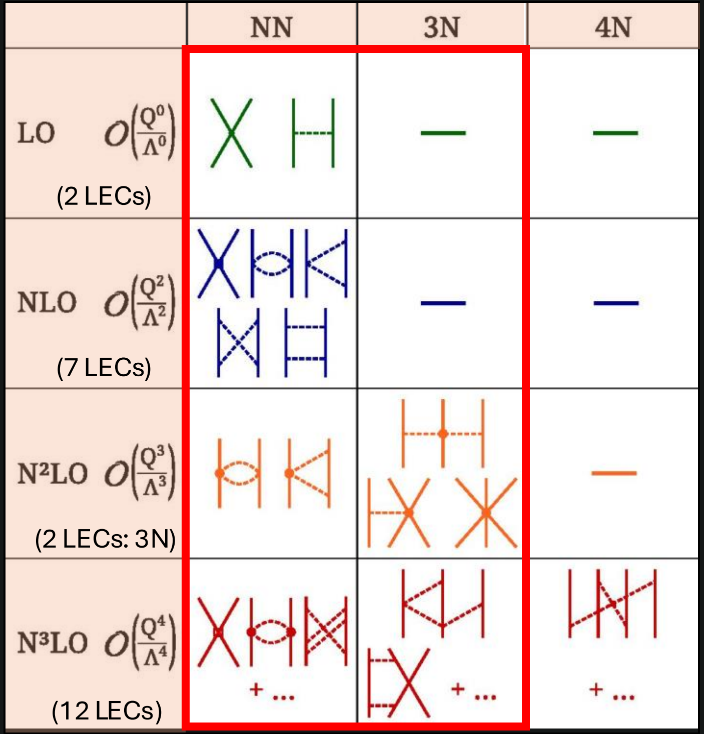
Chiral Effective Field Theory

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

Previous results were shown up to N^{2}LO.

Next, go to N^{3}LO, which is typically employed in the community.

Continue to employ large cutoffs to better resolve high-momentum physics.



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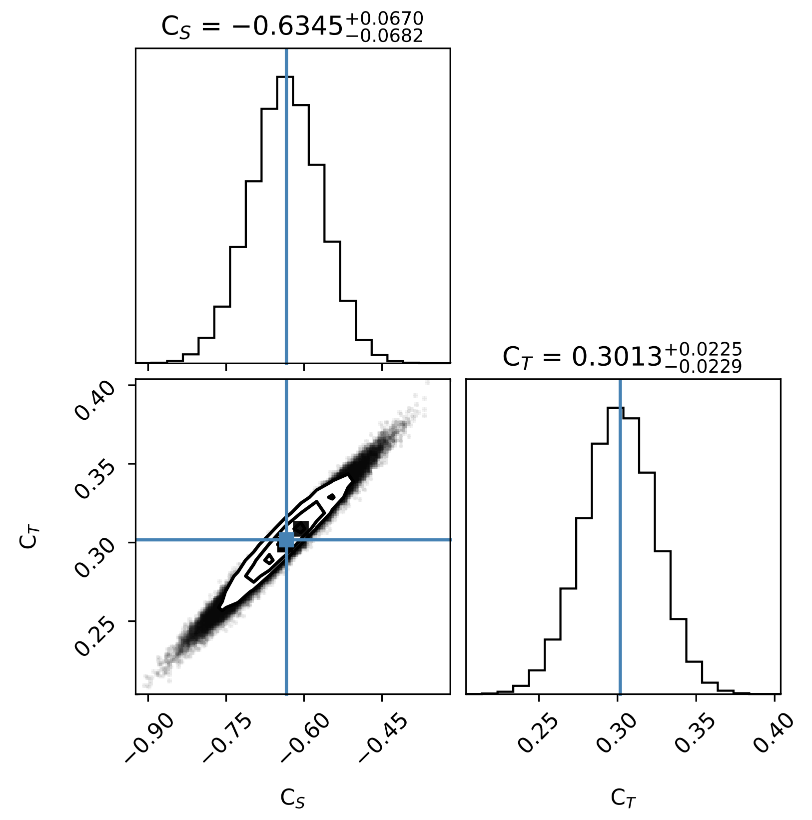
New Interactions at N^{3}LO

- Two-nucleon interactions:
  - 12 new coupling constants need to be fit to scattering data.
  - Developed new fitting algorithm using Bayesian inference to estimate errors.
  - Fit local interactions to N^{3}LO.
  - Cutoff variation from 400-700 MeV, all results last week at lower cutoff scales.
  - Excellent reproduction of NN data even up to high momenta!
- Three-nucleon interactions:
  - Parameter-free at N^{3}LO and local.
- Band from full Bayesian posteriors on LECs

Somasundaram et al., PRC (2024).



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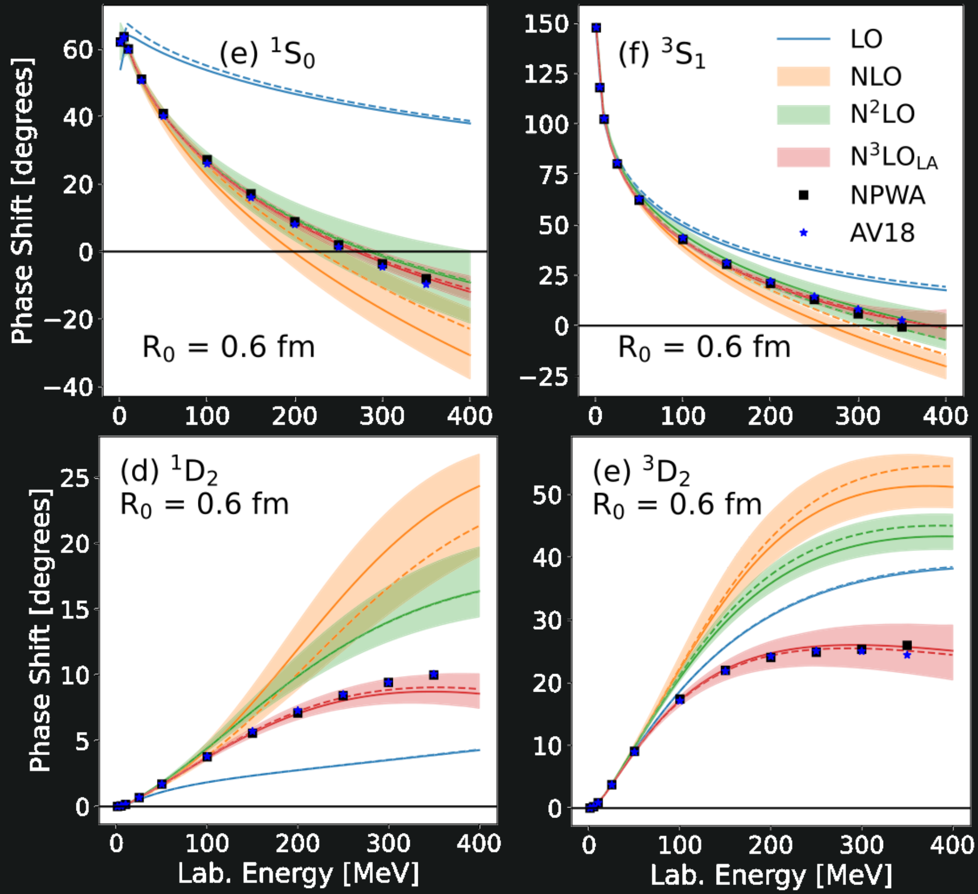
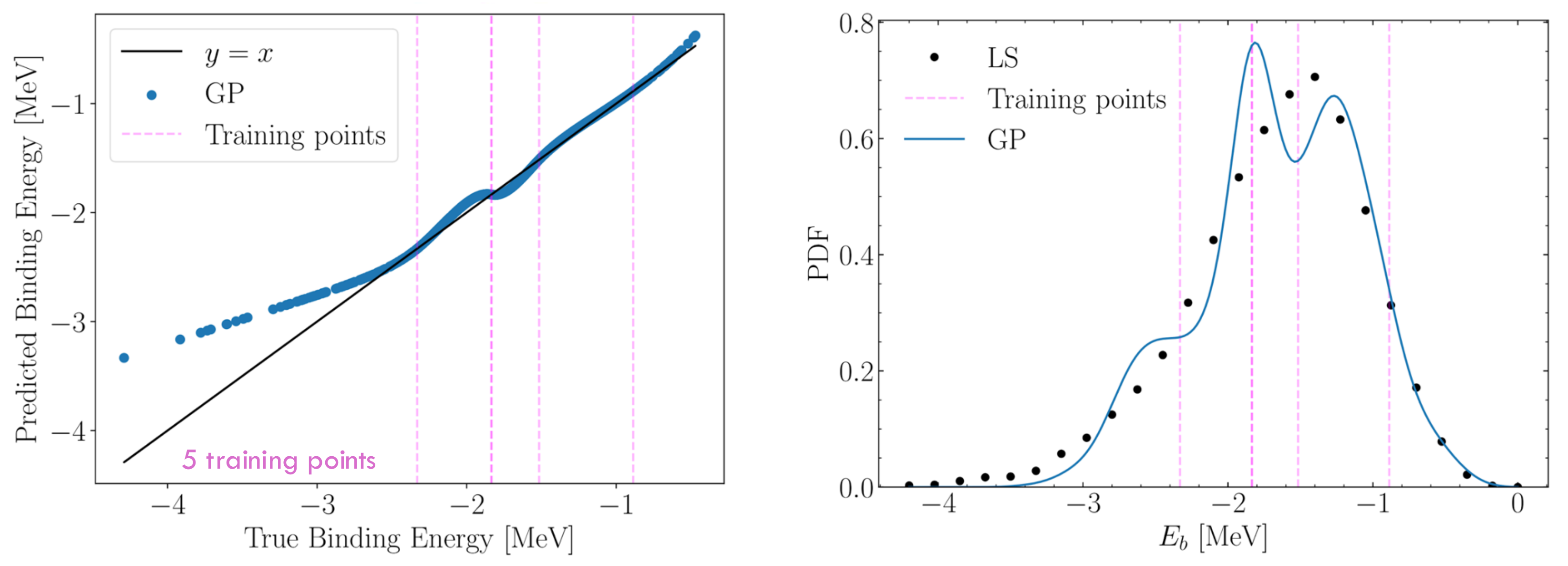


Somasundaram et al., PRC (2024).

Emulators to Propagate Interaction Uncertainty

We have studied different emulators for QMC calculations: Gaussian processes (GP)

Leading-order interactions in the deuteron:



Somasundaram et al., arXiv:2404.11566

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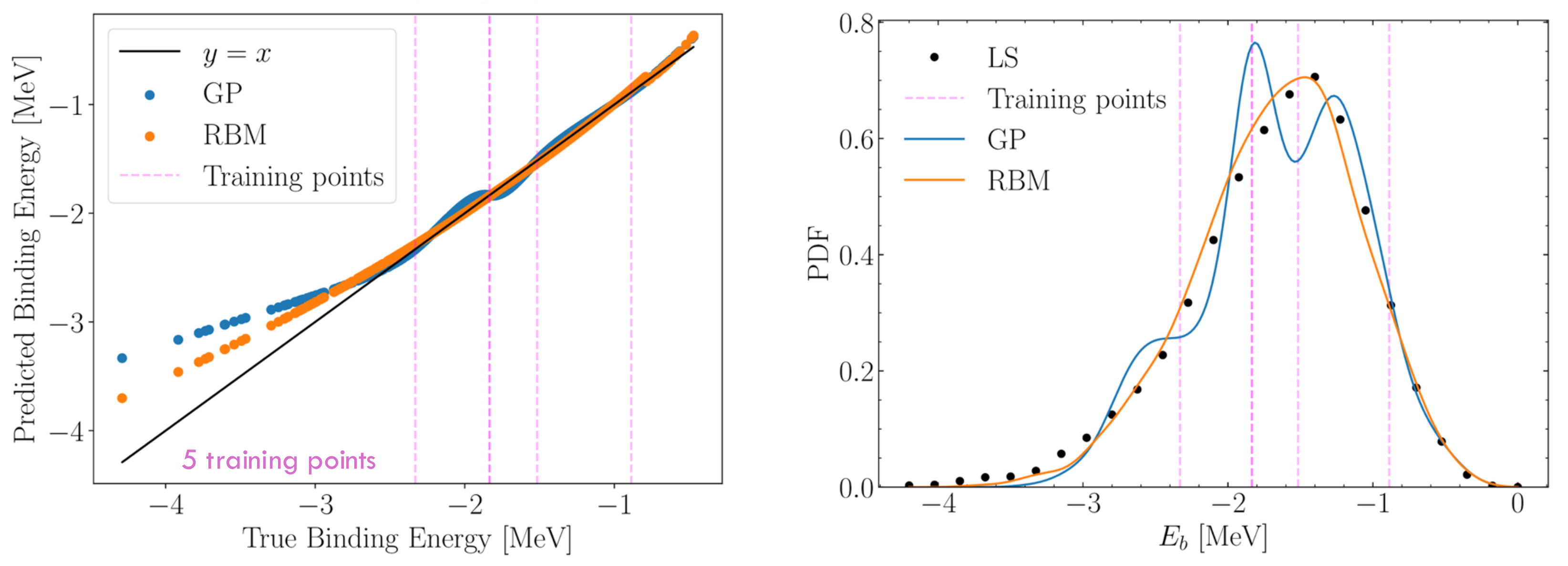

5 training points

Somasundaram et al., arXiv:2404.1566

Emulators to Propagate Interaction Uncertainty

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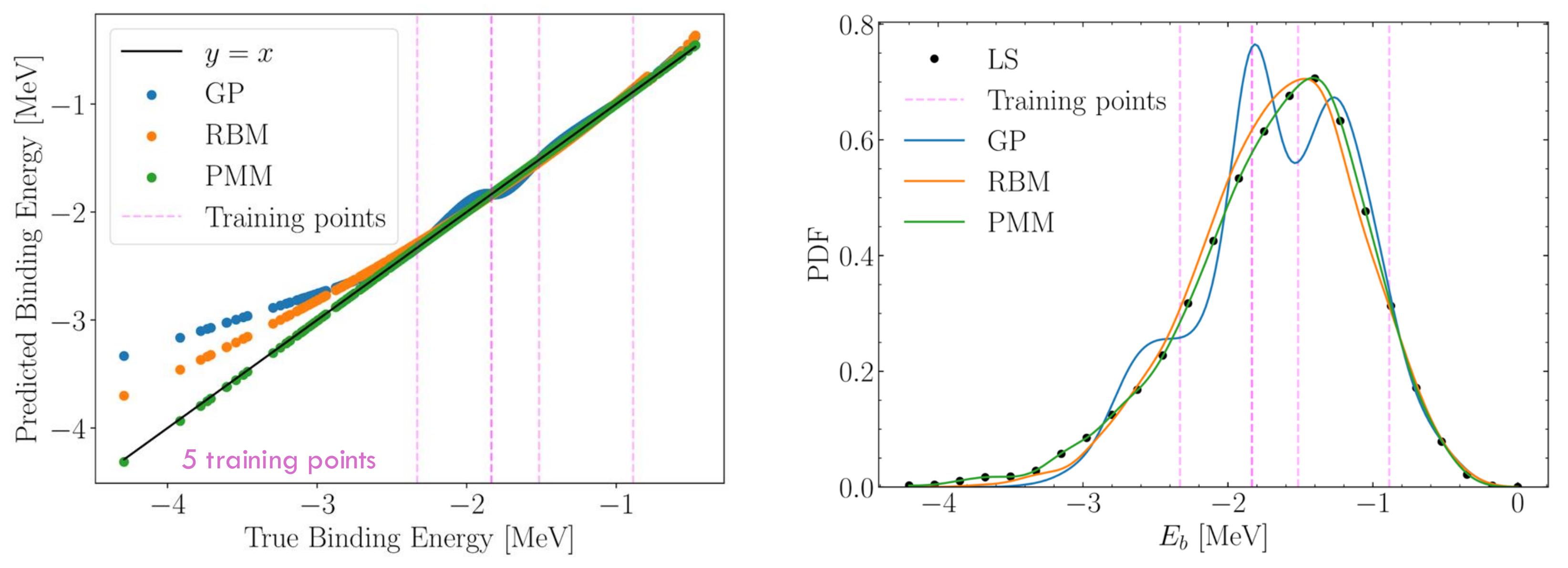

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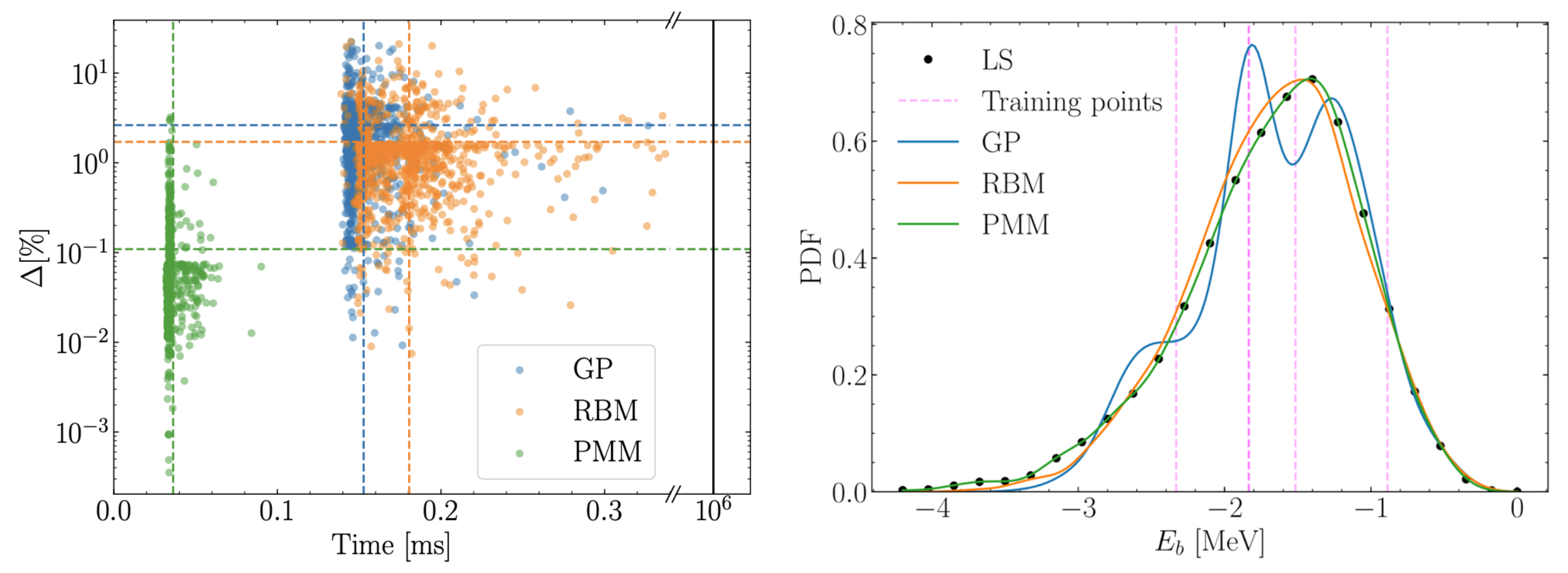

Somasundaram et al., arXiv:2404.11566

Emulators to Propagate Interaction Uncertainty

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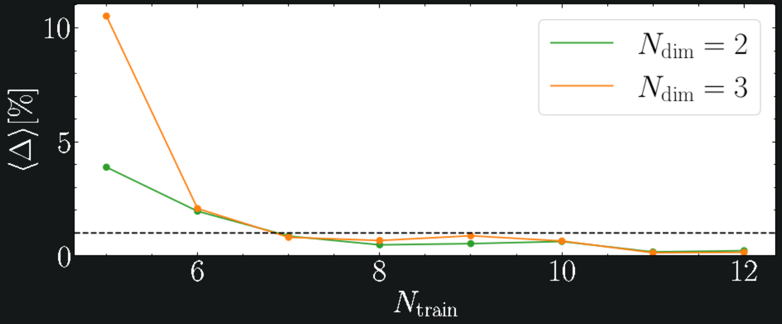
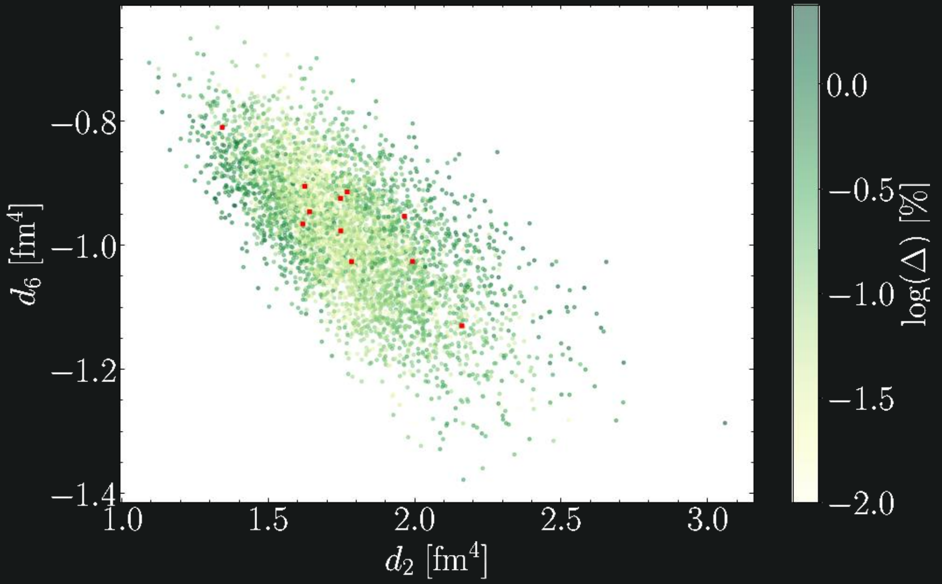
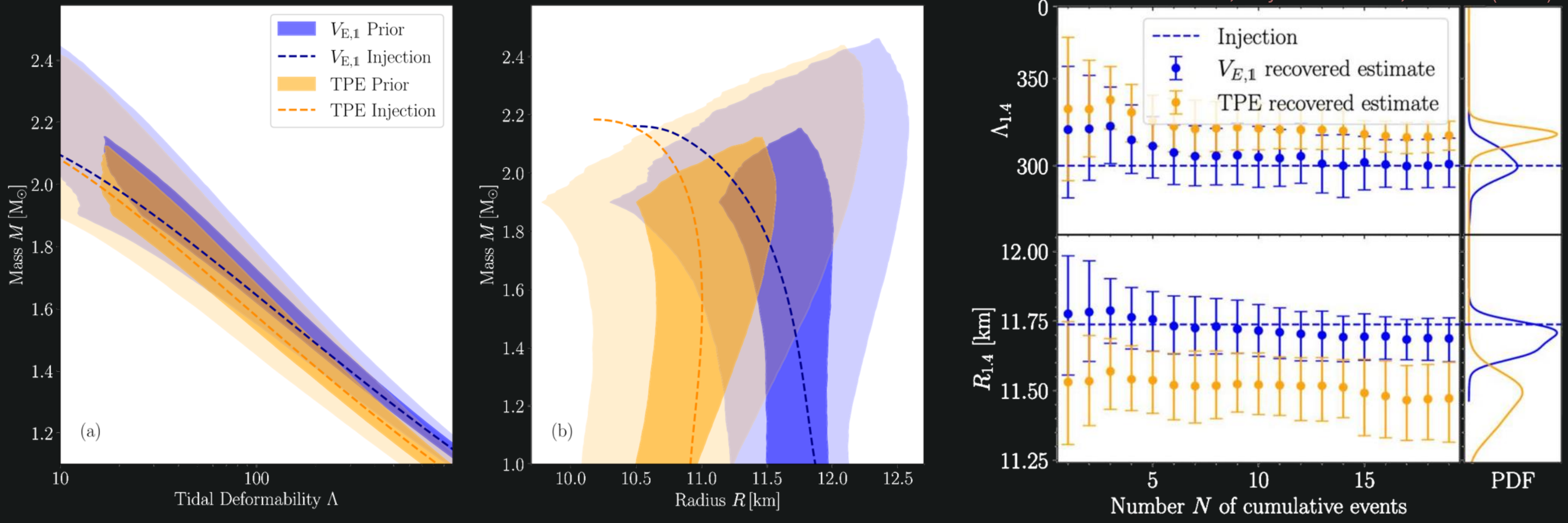
Next-to-next-to-leading-order interactions in the deuteron:





Somasundaram et al., arXiv:2404.11566

Fit Chiral EFT Hamiltonians with Next-Gen GW Detectors



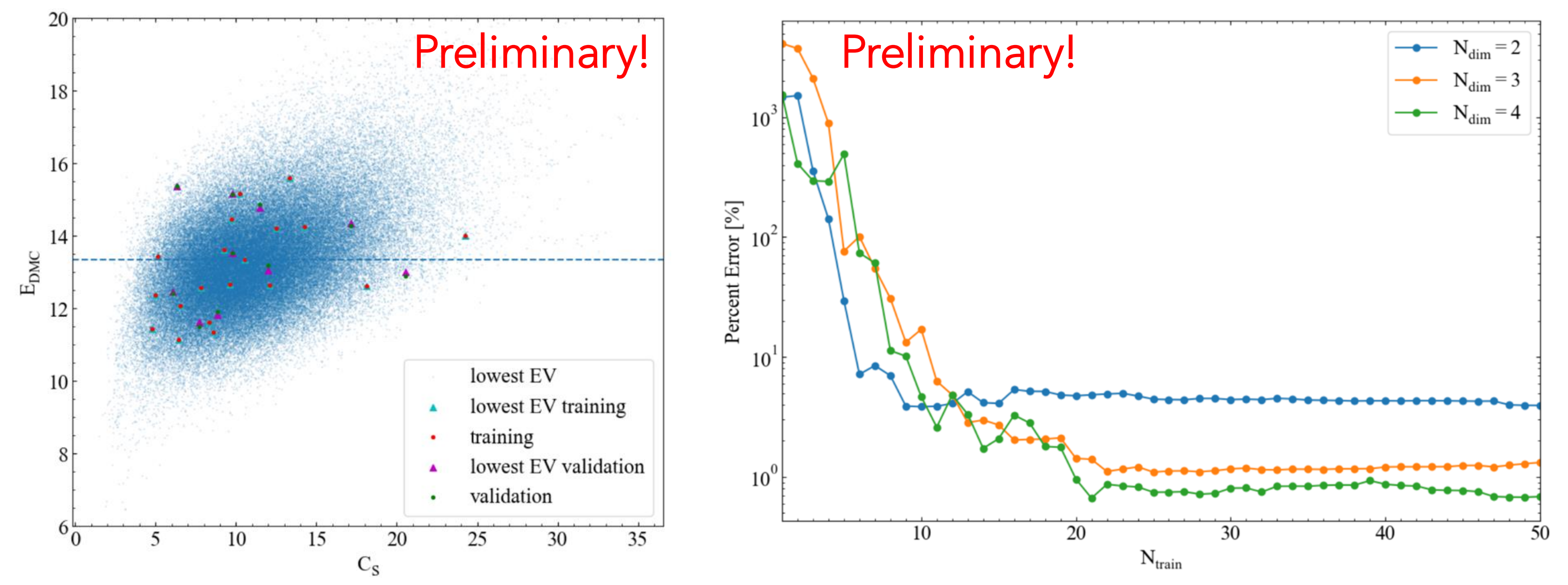
Rose et al., Phys Rev. C 108, 025811 (2023).

Current GW detectors are not sensitive enough to distinguish nuclear Hamiltonians with different three-nucleon forces.

However, 3rd-generation detectors can be used to fit these parts of the Hamiltonian.

Emulators to Propagate Interaction Uncertainty

We explore the parametric matrix model (PMM) in pure neutron matter:



Armstrong et al., in preparation.

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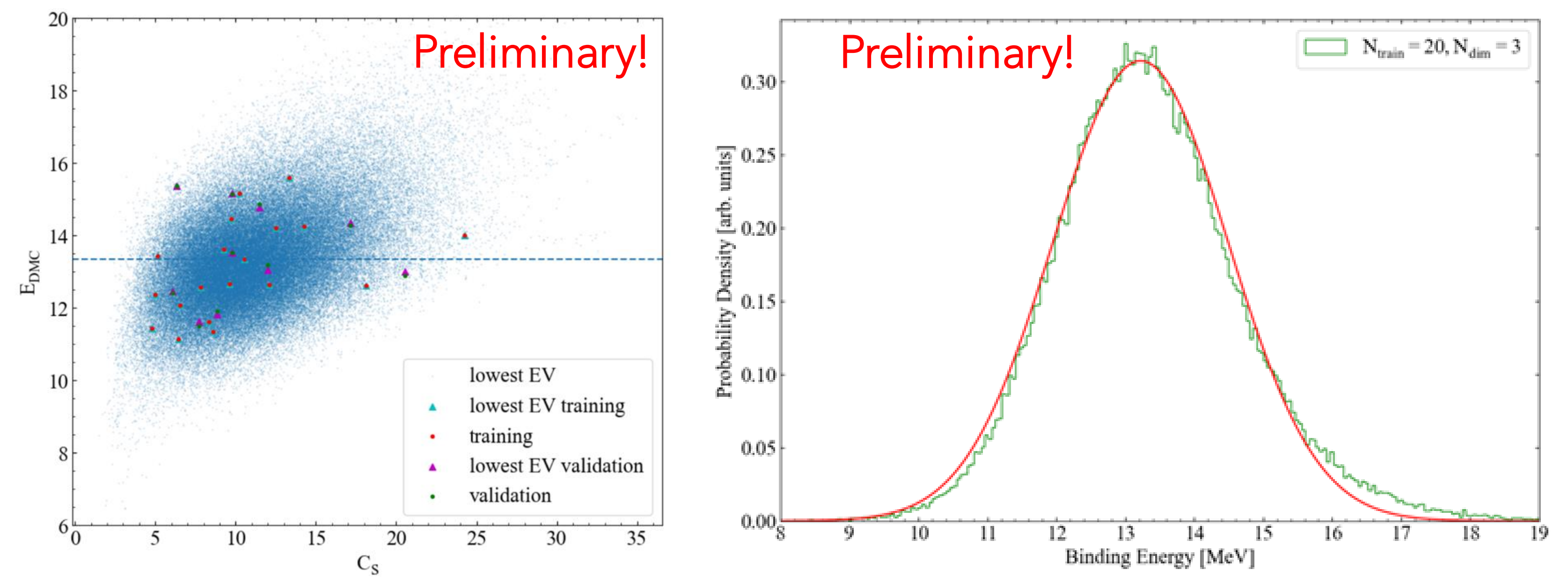


Armstrong et al., in preparation.

Summary

- Development of new local chiral EFT interactions up to fourth order (N^3LO) with high cutoffs.
- New way of fitting using Bayesian statistics to account for theoretical uncertainties on parameter level.
- Already at N^2LO, reduction in uncertainty in EOS by factor of 3 due to increased cutoffs for new interactions.
- Implementation into AFDMC in progress, then calculations of EOS properties at N^3LO.
- New machine-learning tools to propagate uncertainties from parameters directly to observables.

Thanks for your attention!

Thanks

C. Armstrong, J. Carlson, S. De, S. Gandolfi, D. Lonardoni, B. Reed, R. Somasundaram (LANL)

K. Hebeler, H. Goettling, A. Schwenk (TU Darmstadt)

A. Le Fevre, W. Trautmann (GSI Darmstadt)

K. Lund, S. Reddy (INT Seattle)

J. Margueron (IPN Lyon & MSU)

K. Godbey, P. Giuliani (MSU)

D. Brown, C. Capano (Syracuse University)

R. Essick, P. Landry (CITA)

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

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

M. Coughlin (University of Minnesota)

M. Bulla (Ferrara University)

S. Antier (Université Côte d'Azur)

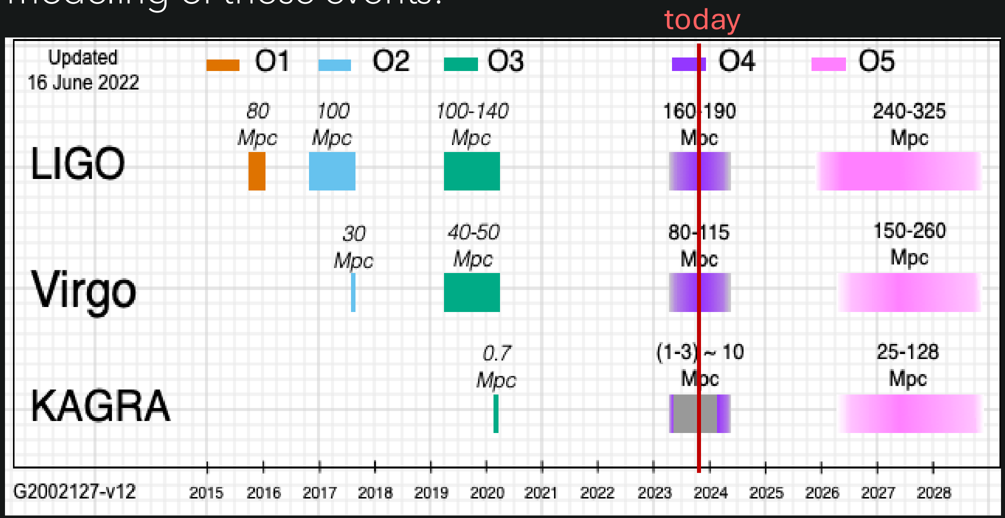
Thank you for your attention!

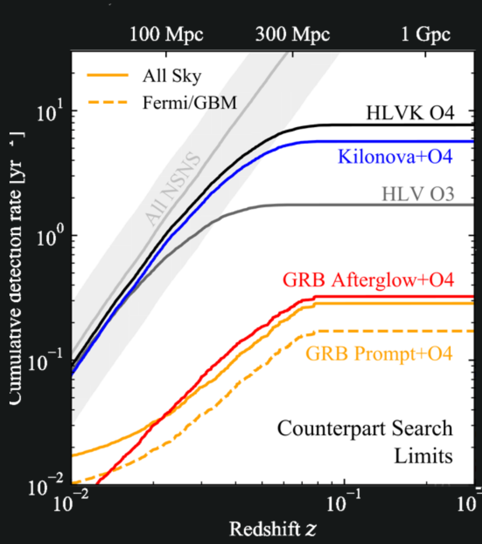
Backup Slides

LIGO: Next Observing Runs

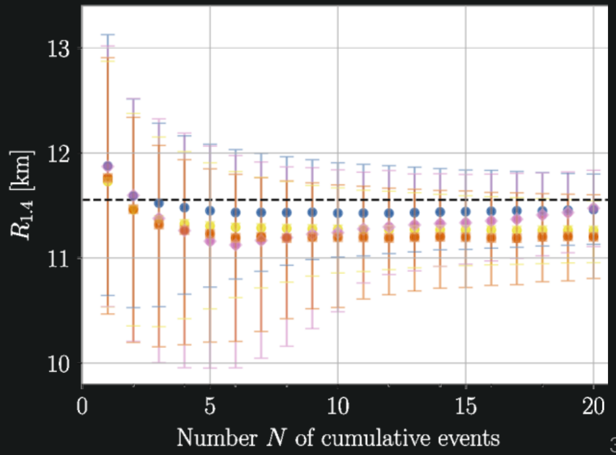
Fourth observing run started in May, up to 7-ish BNS expected, so far nothing reported.

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



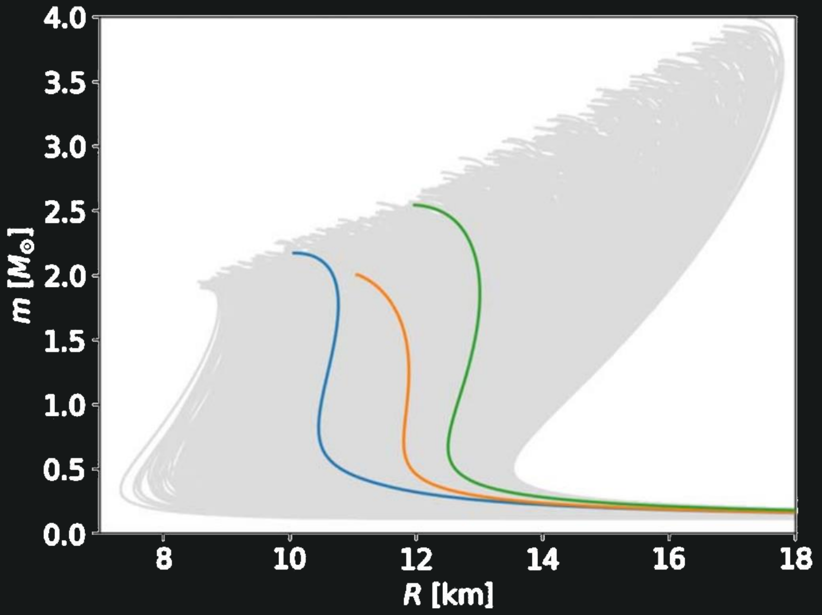


Colombo et al., ApJ (2022)

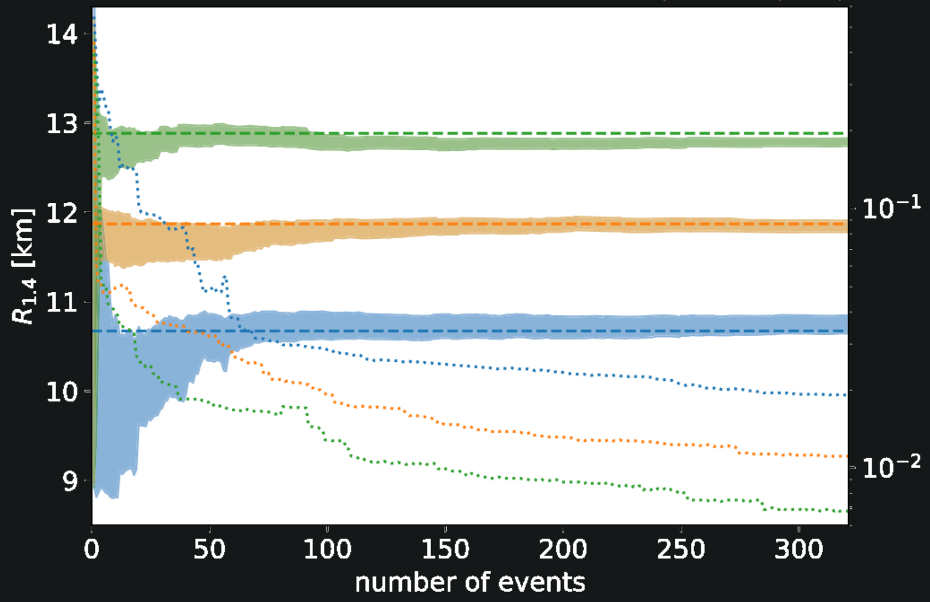


Adapted from Kunert et al. PRD (2022)

LIGO: Next Observing Runs

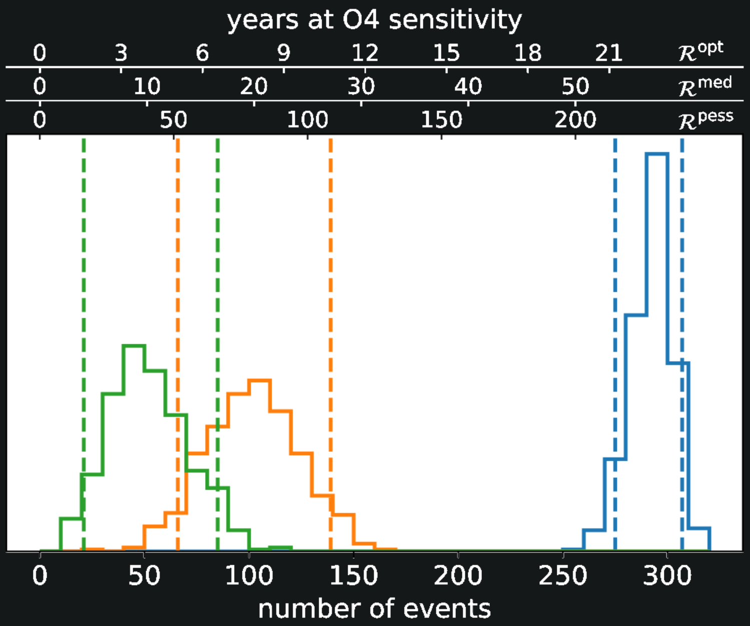


Finstad et al., ApJ 995, 45 (2023)

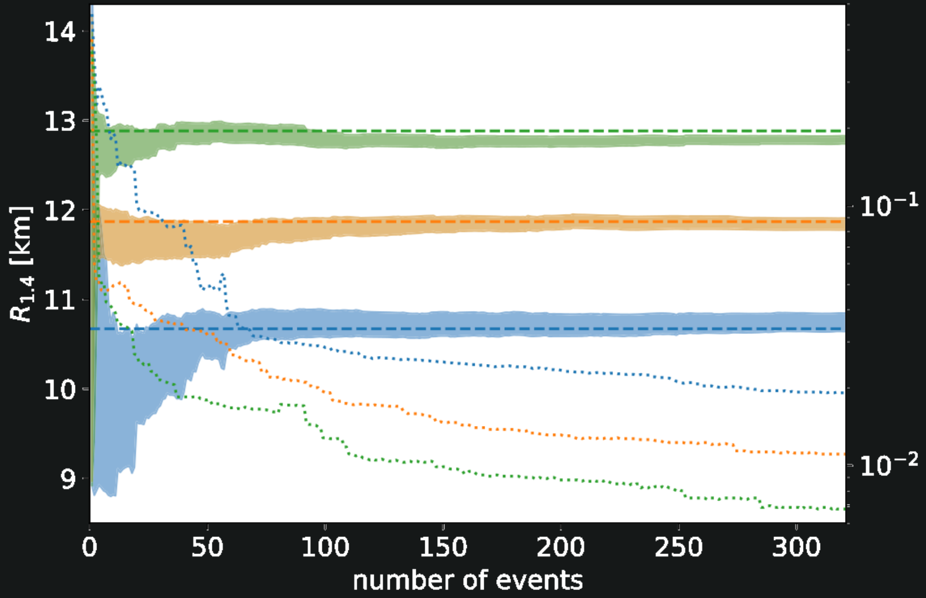


For nuclear physics, we would like to know the EOS/radii to 1% accuracy.
This required several 100 events at current sensitivity!

LIGO: Next Observing Runs



Finstad et al., ApJ 995, 45 (2023)



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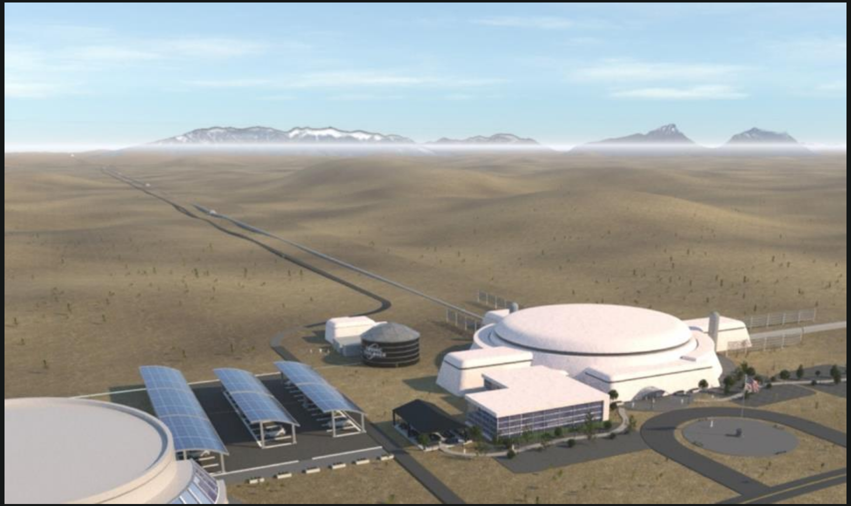
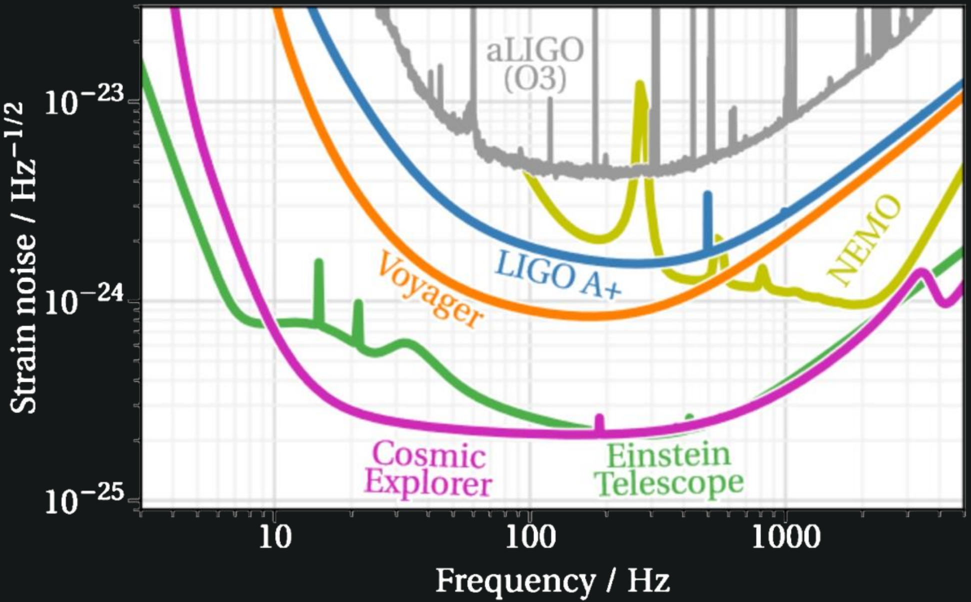
The Future: Cosmic Explorer (CE)

Source: CE consortium

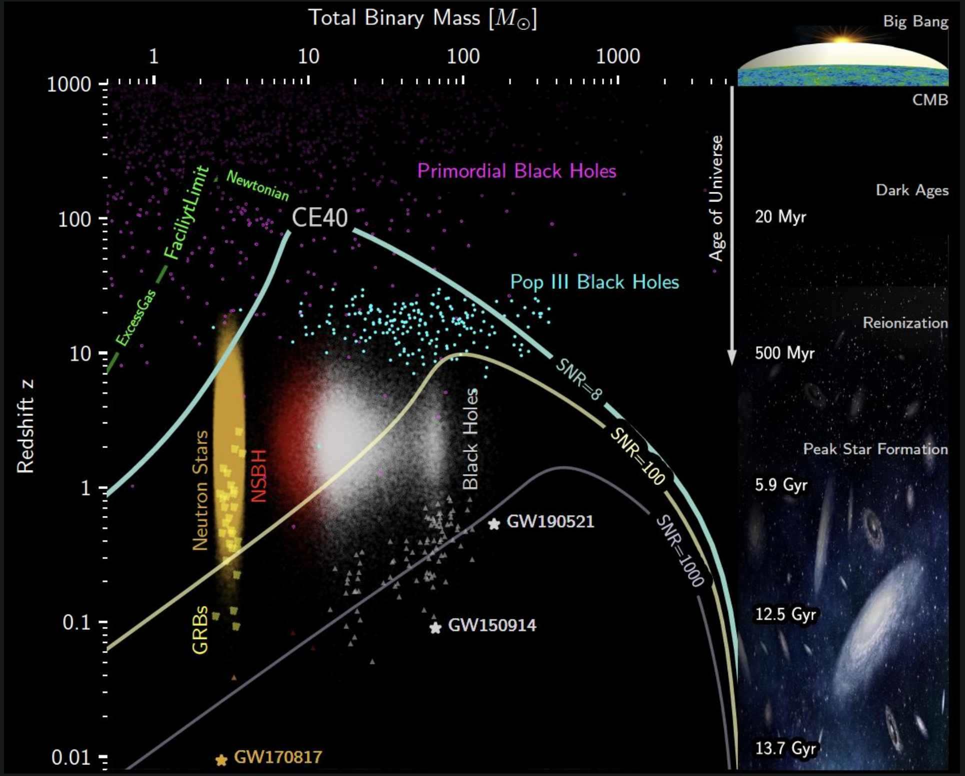




3rd generation Gravitational-Wave Detectors will increase sensitivity by at least factor of 10

US-proposal: Cosmic Explorer EU-proposal: Einstein Telescope

The Future: Cosmic Explorer (CE)

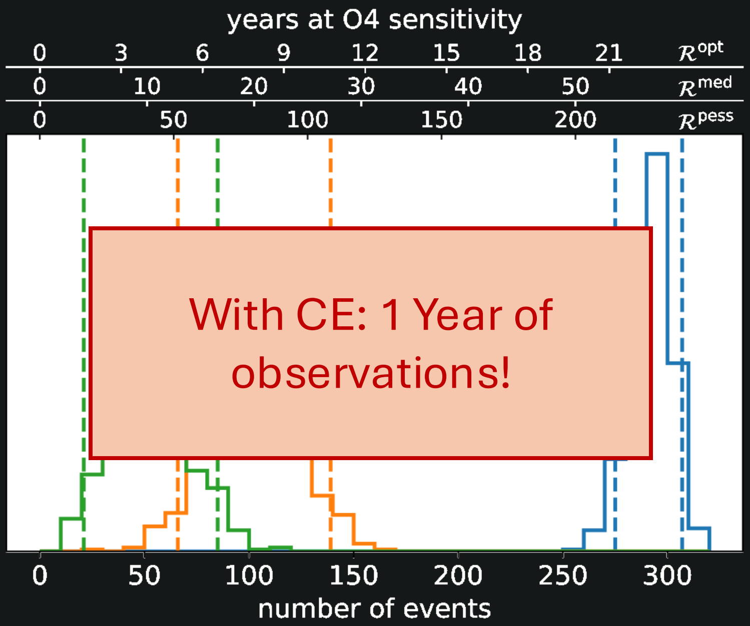


Evans et al., arXiv:2306.13745

CE will detect the majority of neutron-star mergers in the universe!

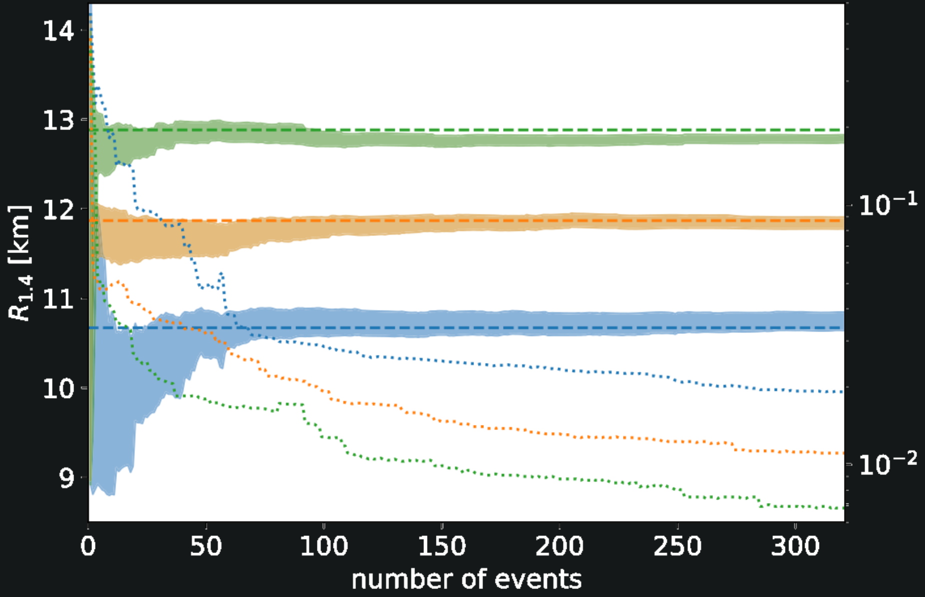
GW170817 would have been observed with an SNR 100 times higher.

The Future: Cosmic Explorer (CE)



With CE: 1 Year of observations!

Finstad et al., ApJ 995, 45 (2023)



For nuclear physics, we would like to know the EOS/radii to 1% accuracy.
This required several 100 events at current sensitivity.
In the worst case, this means we need to **wait 200 years!**