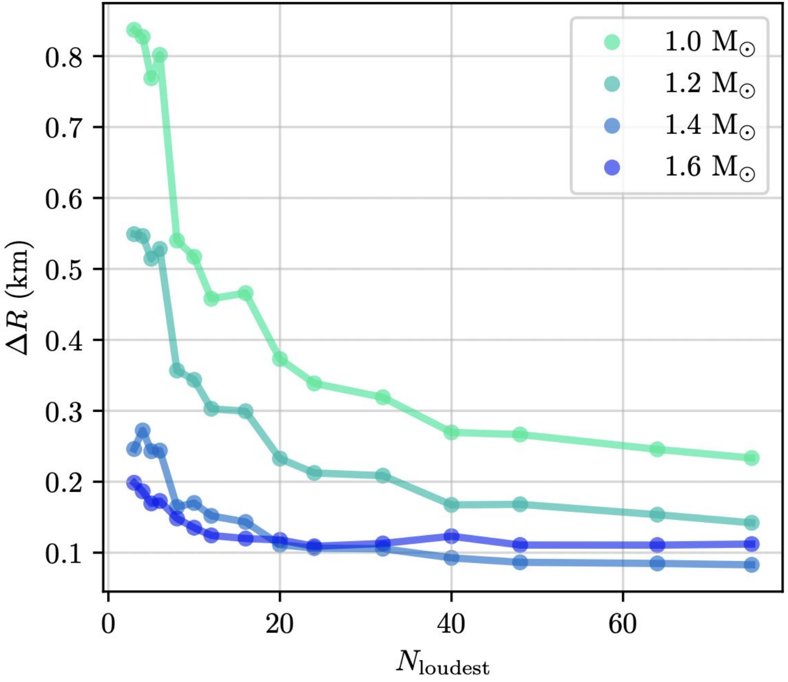
Inferring chiral three-nucleon forces from third-generation gravitational-wave detectors

Rahul Somasundaram
Los Alamos National Laboratory and Syracuse University

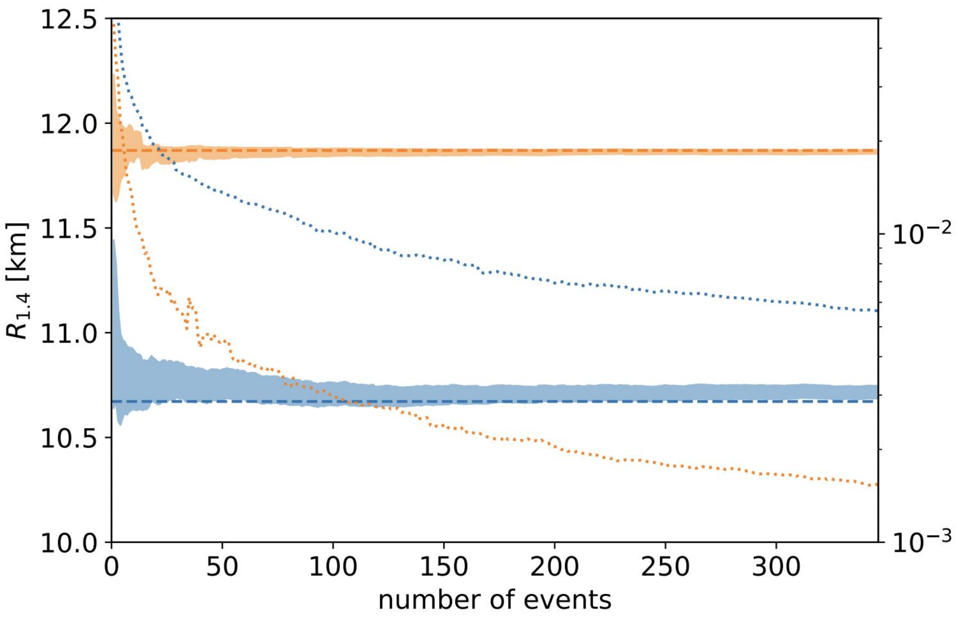
Collaborators: Isak Svensson, Philippe Landry, Ingo Tews, Duncan Brown, Achim Schwenk, Soumi De, Andrew Deneris, Yannick Dietz, Brendan Reed, Pablo Giuliani, Cassandra Armstrong

08/30/2024, INT Workshop: EOS Measurements with Next-Generation GW Detectors

High precision measurements of the EOS from next-generation detectors



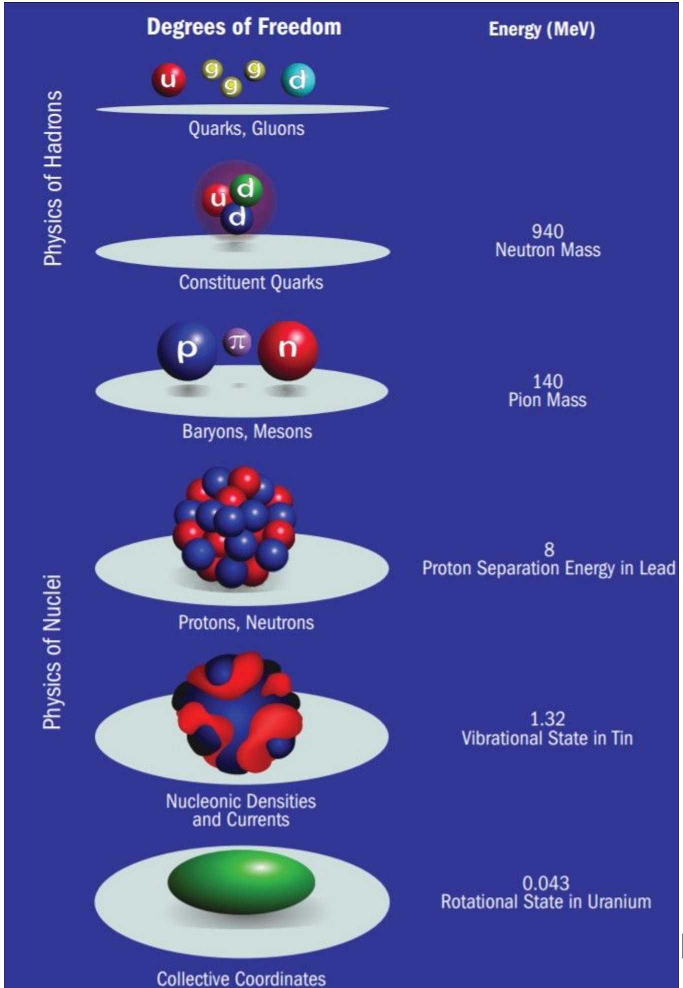
Walker et al., arXiv:2401.02604

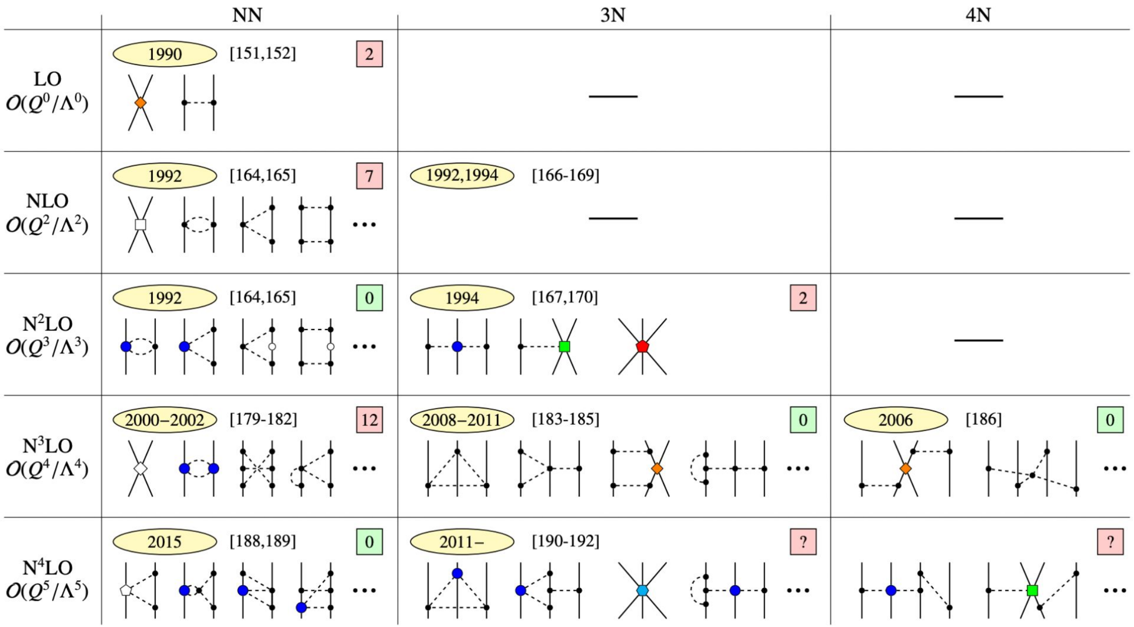


Finstad et al., Astrophys.J. 955 (2023) 1, 45

But can we go beyond the EOS? What can we learn about the underlying nuclear interactions?

Chiral Effective Field theory



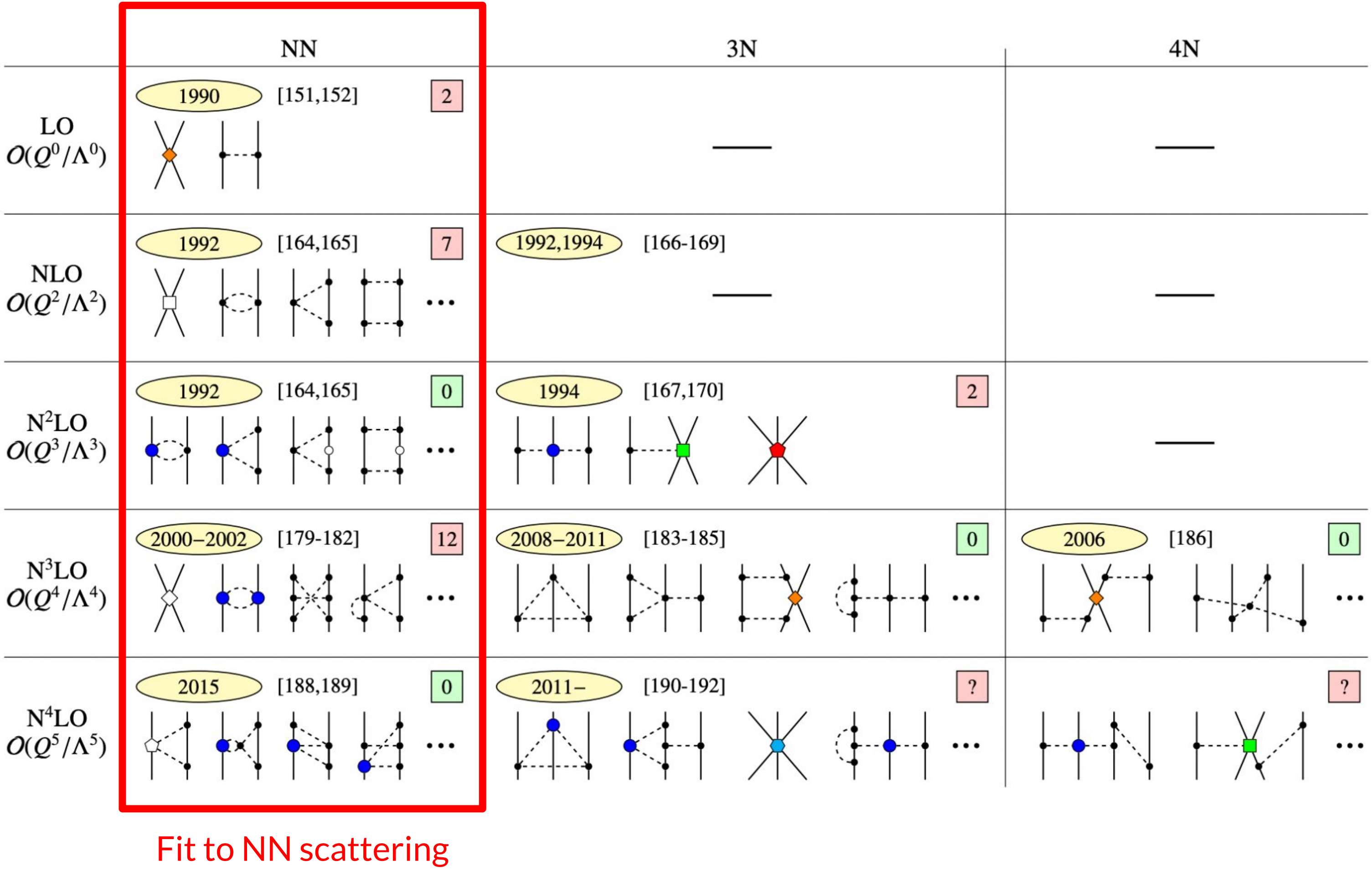


Hebeler, Phys.Rept. 890 (2021) 1-116

Bertsch et al., United States: N. p., 2007. Web.

Chiral Effective Field theory

Hebeler, Phys.Rept. 890 (2021) 1-116



Chiral Effective Field theory

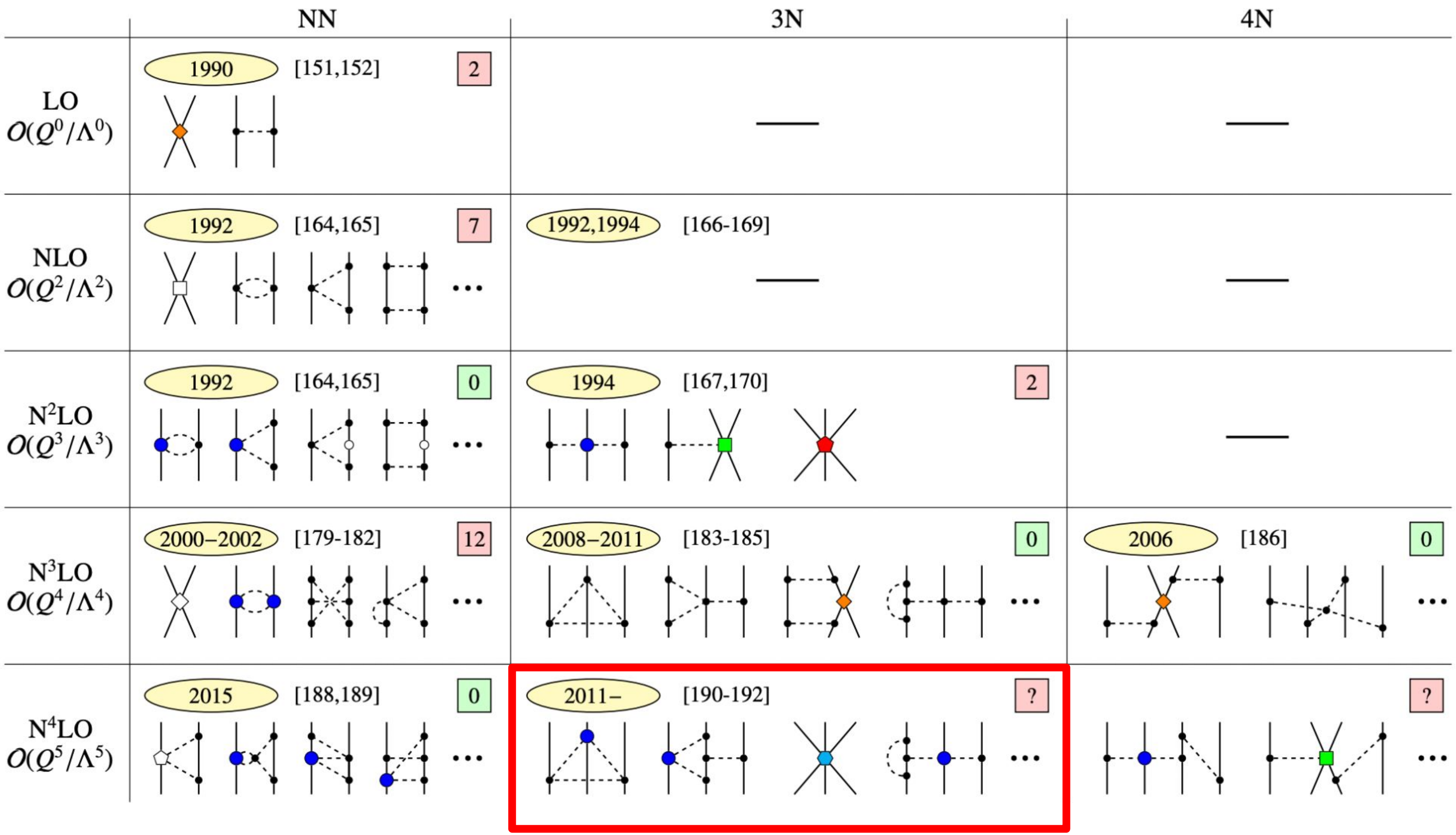
Hebeler, Phys.Rept. 890 (2021) 1-116

	NN	3N	4N
LO $\mathcal{O}(Q^0/\Lambda^0)$	1990 [151,152] 2	—	—
NLO $\mathcal{O}(Q^2/\Lambda^2)$	1992 [164,165] 7 …	1992,1994 [166-169] —	—
N^2LO $\mathcal{O}(Q^3/\Lambda^3)$	1992 [164,165] 0 …	1994 [167,170] 2	—
N^3LO $\mathcal{O}(Q^4/\Lambda^4)$	2000–2002 [179-182] 12 …	2008–2011 [183-185] 0 …	2006 [186] 0 …
N^4LO $\mathcal{O}(Q^5/\Lambda^5)$	2015 [188,189] 0 …	2011– [190-192] ? …	? …

Fit to A ~ 3 nuclei

Chiral Effective Field theory

Hebeler, Phys.Rept. 890 (2021) 1-116



Fit to ???
Astrophysical NS observations?

Chiral Effective Field theory

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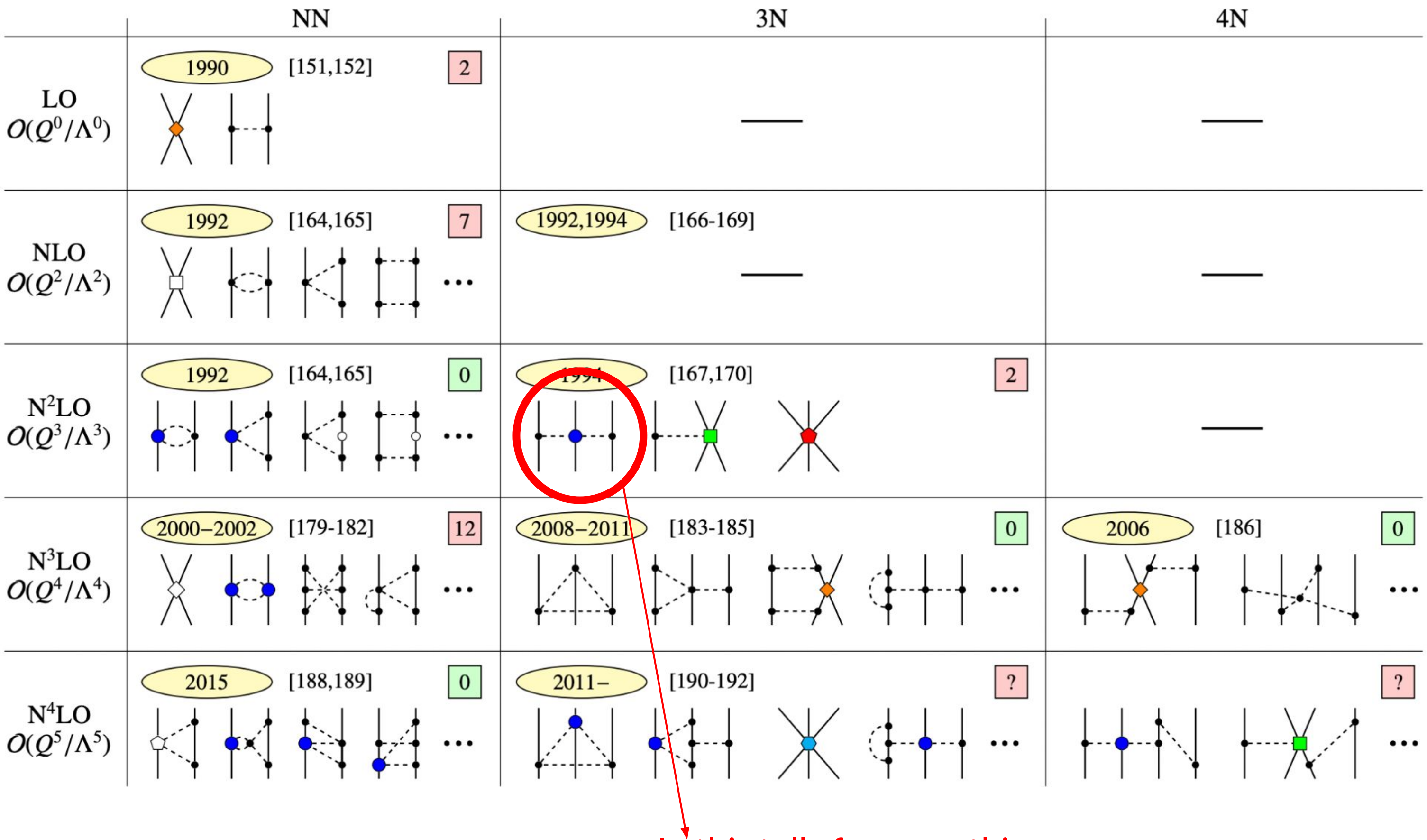
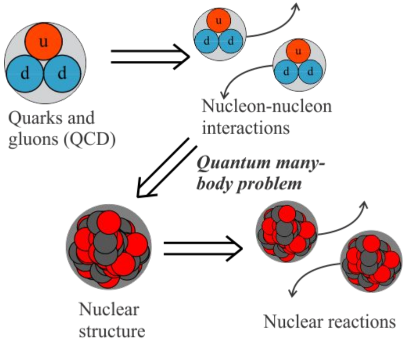
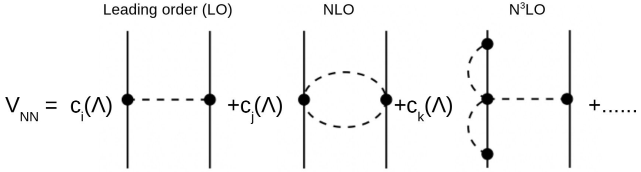


In this talk, focus on this

In principle, how would we do this?

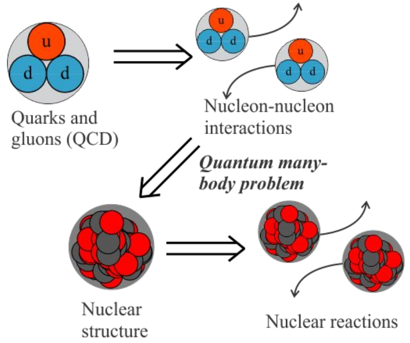
Model for interaction between particles

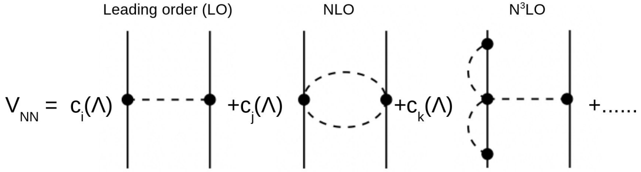


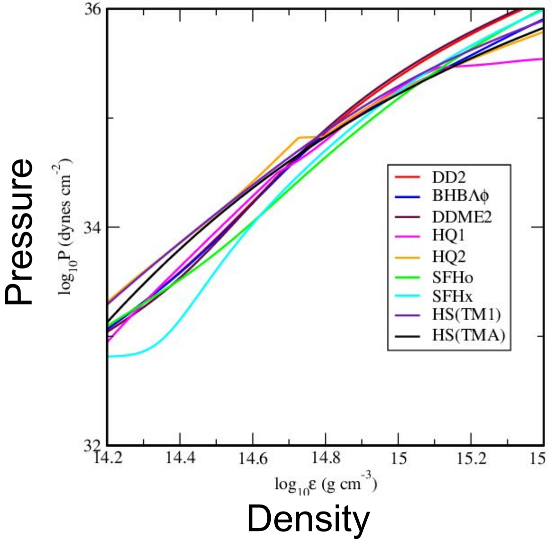


In principle, how would we do this?

Model for interaction between particles $H|\psi\rangle = E|\psi\rangle$ → The Equation of State







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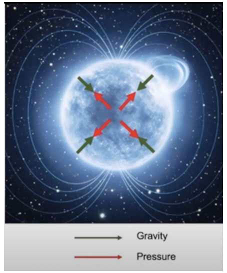
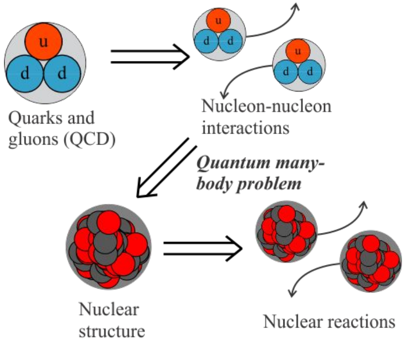
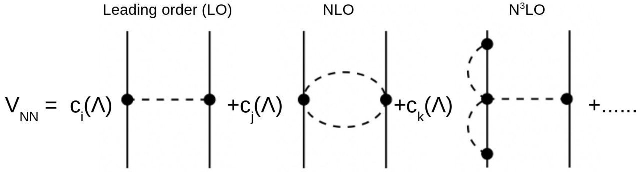
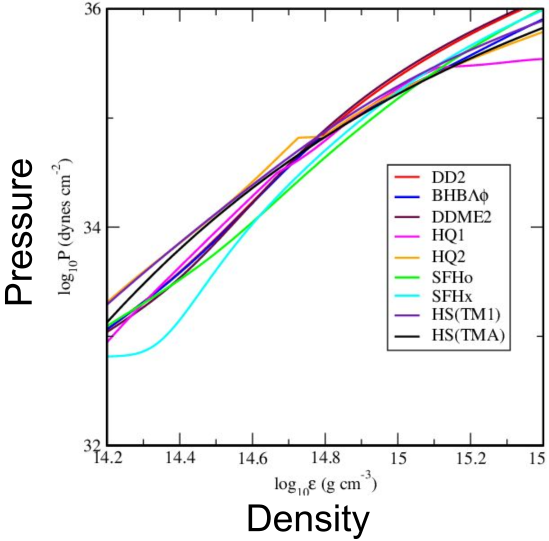


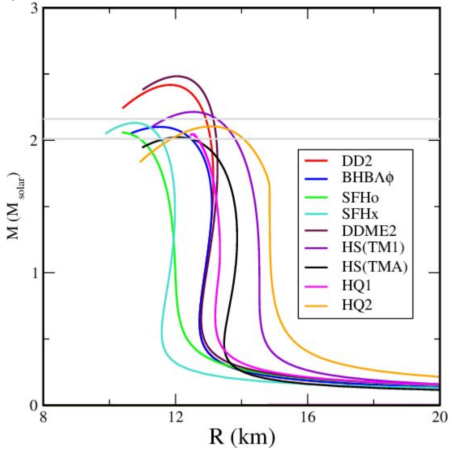
Tolman–Oppenheimer–Volkoff (TOV) equation

Model for interaction between particles → $H|\psi\rangle = E|\psi\rangle$ → The Equation of State → $G^{\mu\nu} = \kappa T^{\mu\nu}$ → Neutron star observables



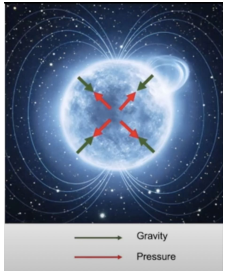






In principle, how would we do this?

Bayesian inference requires ~10^7 model evaluations



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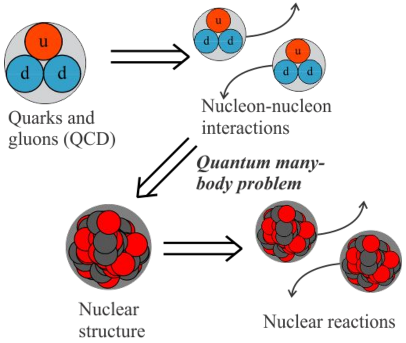
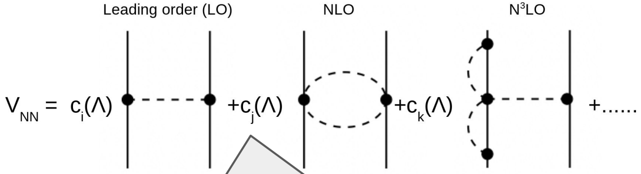
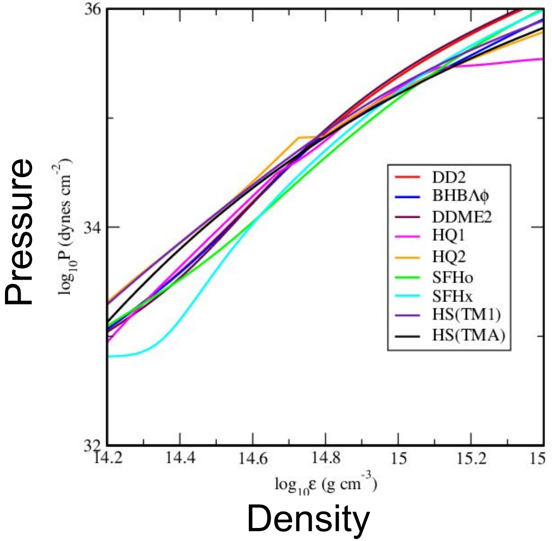
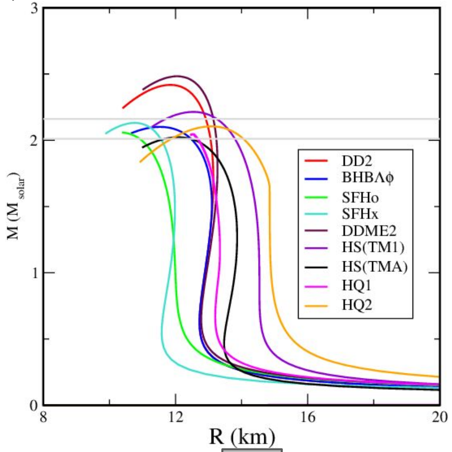




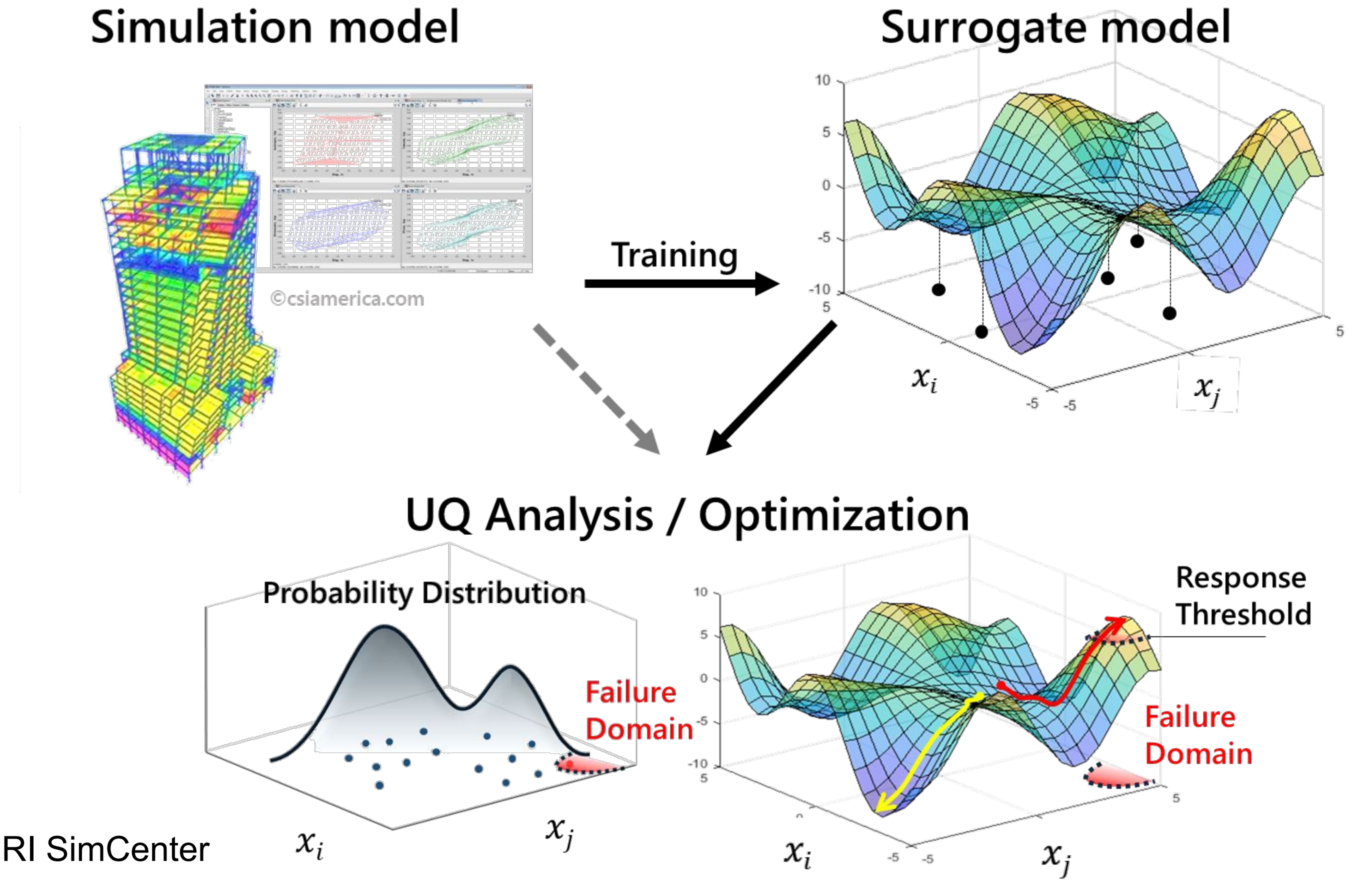




Bayesian Parameter Estimation

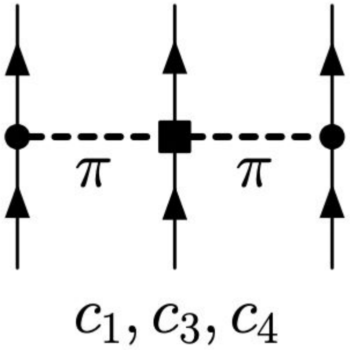
The solution: Use emulators to accelerate calculations

Emulators mimic the behaviour of the full-scale model at a small fraction of its computational cost



Credits: NHERI SimCenter

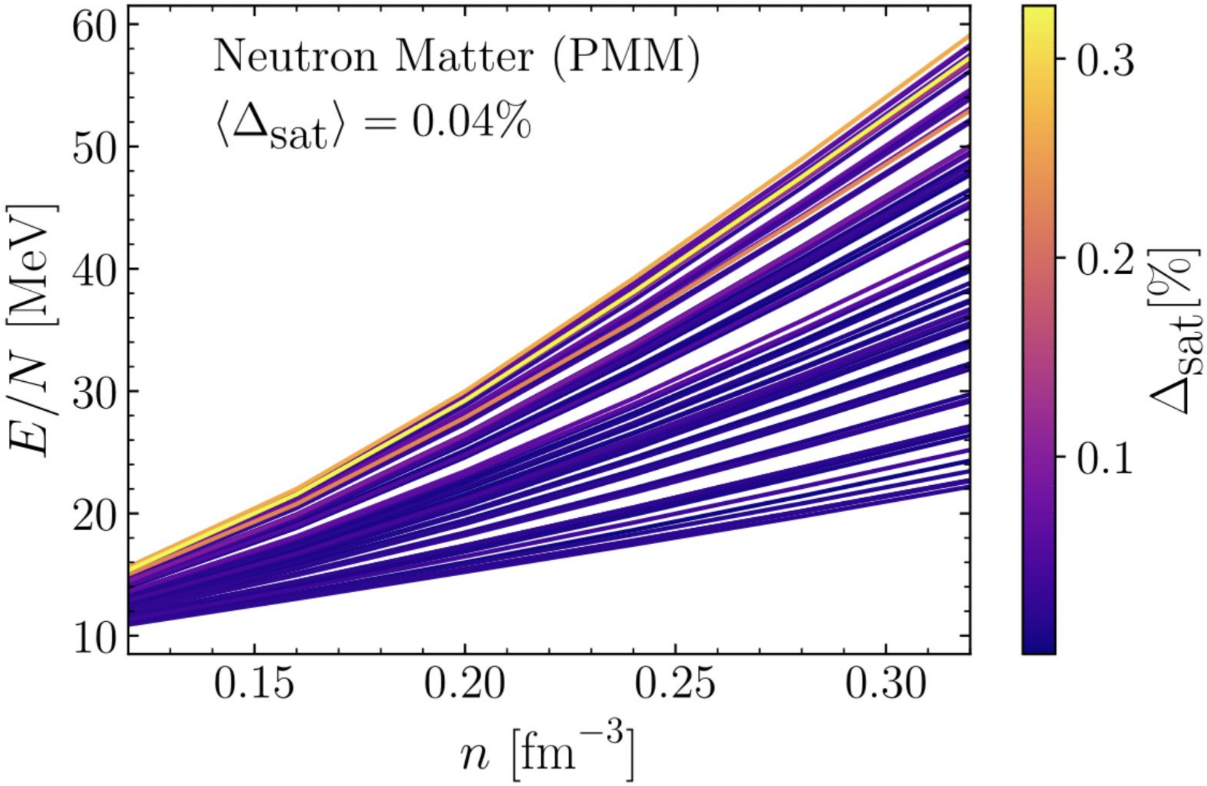
Emulators for neutron matter calculations



- Use Many-Body Perturbation Theory (MBPT) as ‘High Fidelity Model’

- Approximate MBPT predictions with lowest eigenvalue of a 2x2 matrix

$$M = M_0 + c_1 M_1 + c_3 M_3$$

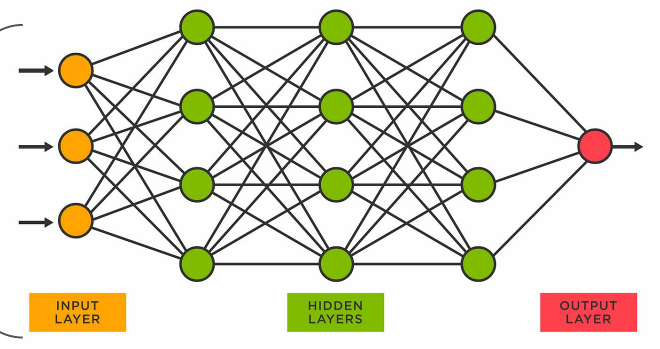


RS et al., In preparation

Emulators for the TOV equations

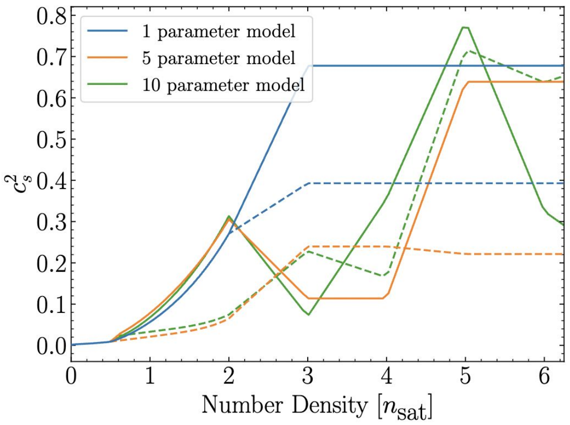
We use an ensemble of feedforward neural networks to emulate solutions to the TOV equations

Equation of State parameters

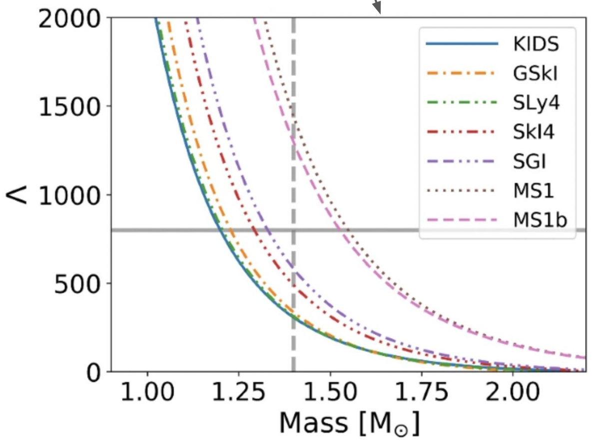


The neutron star tidal deformability

(x100)

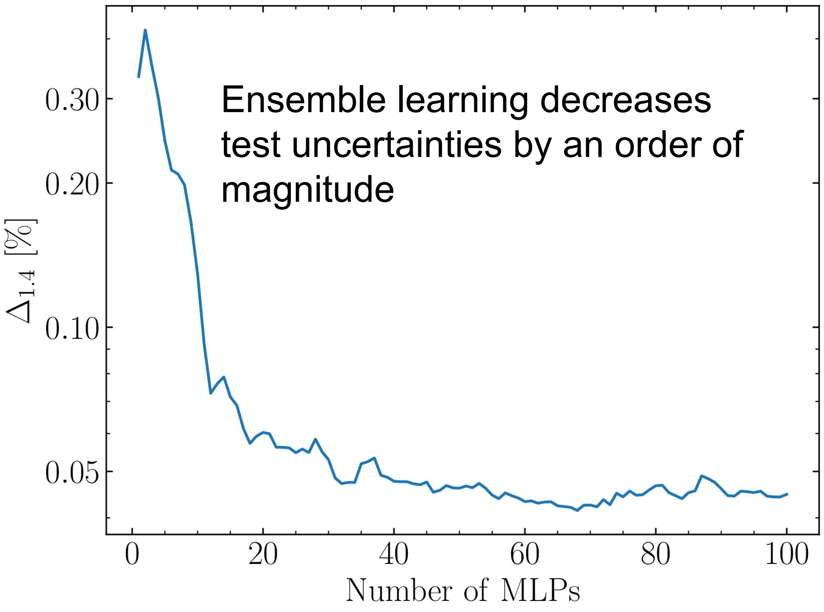


We generated 200K samples, randomly split into training and test data

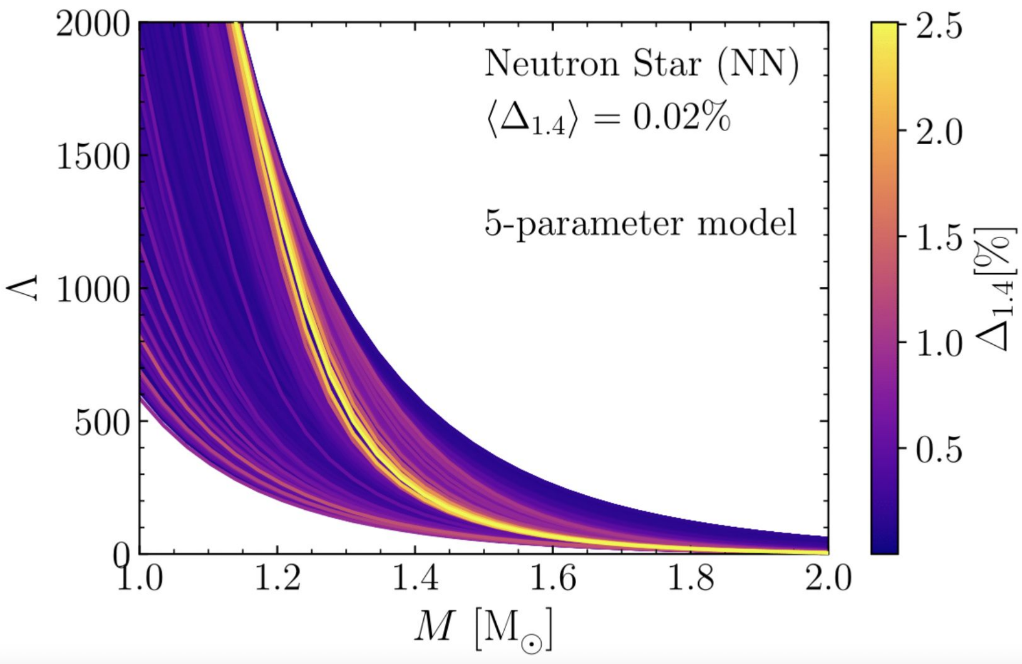


Reed, **RS**, et al., arXiv:2405.20558

Emulators for the TOV equations



$$\Delta[\%] = \left| \frac{\Lambda_{\mathrm{TOV}} - \Lambda_{\mathrm{NN}}}{\Lambda_{\mathrm{TOV}}} \right| \times 100$$



- Average uncertainty on test samples is 0.02 %
- 0.01% of test samples are outliers (uncertainty > 2%)

Reed, **RS**, et al., arXiv:2405.20558

RS, et al., In preparation

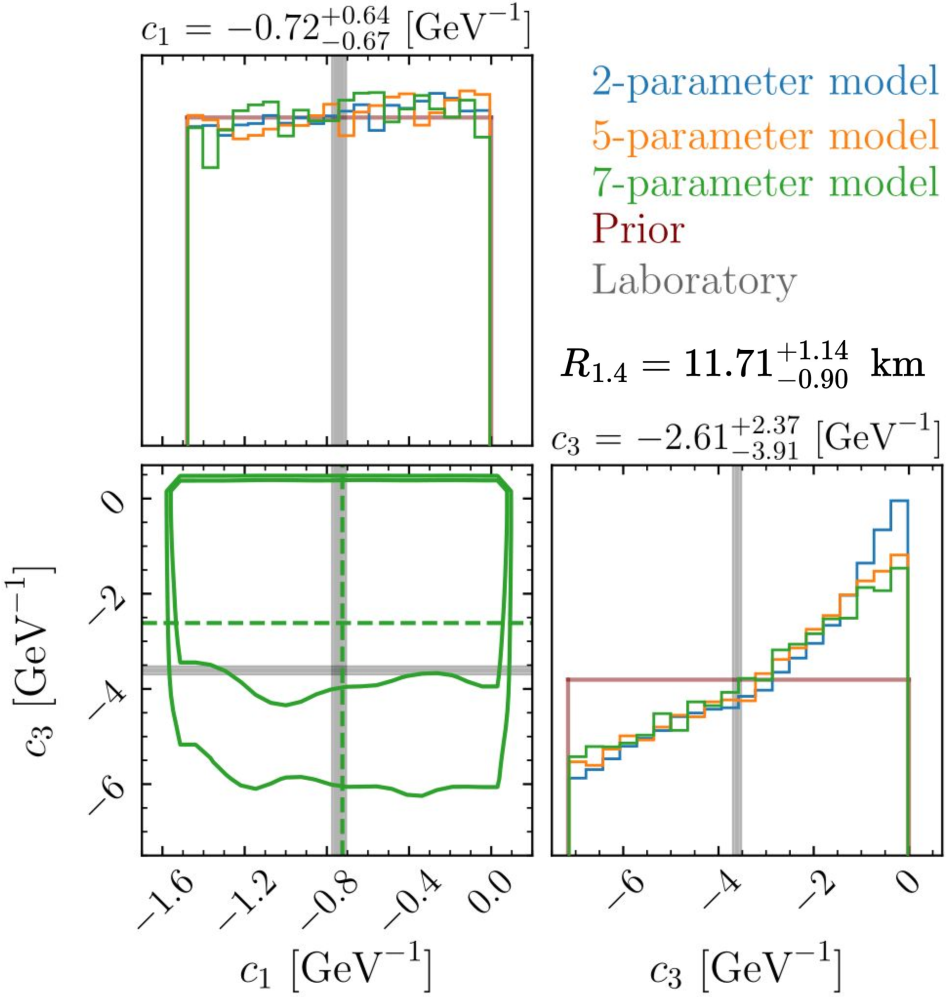
Putting everything together

$$p(\theta|d, H) = \frac{p(d, H|\theta)p(\theta|H)}{p(d|H)}$$

Estimate the posterior using MCMC; Use emulators to evaluate Likelihood

For the data, we use:

- GW170817 + 2 M_{solar} constraint



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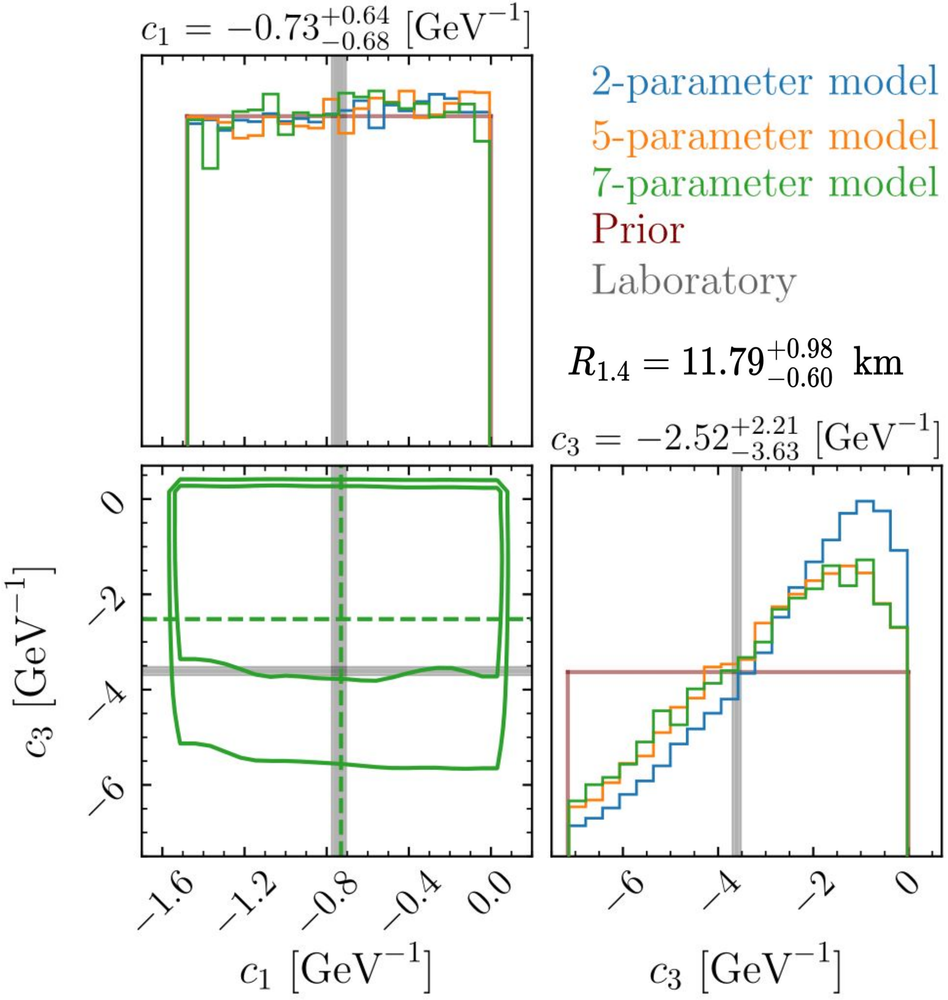
- + NICER’s J0030 observation
- + NICER’s J0740 observation
- + NICER’s J0437 observation

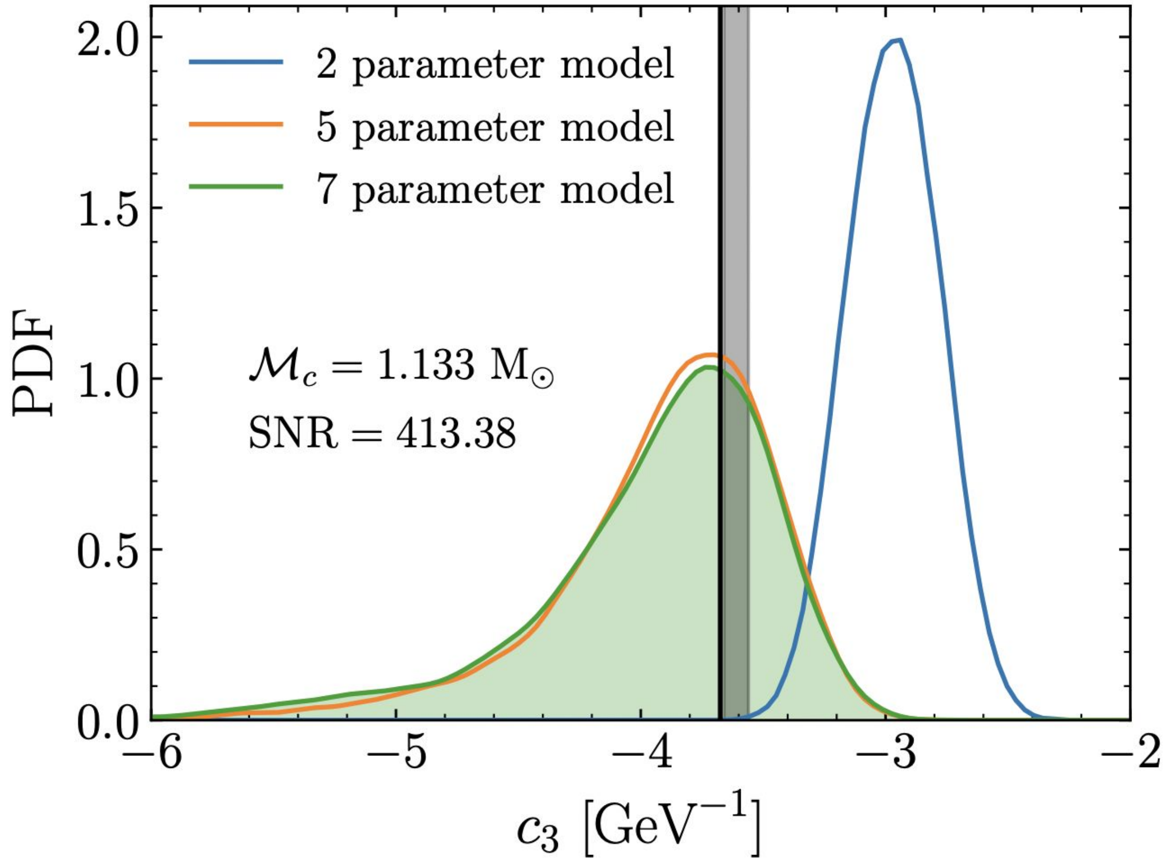


We can do much better with next-generation detectors!

Simulation with CE-40, CE-20, and ET for 1 year's worth of observation

For source population, assume uniform distribution on component masses with random pairing into binaries

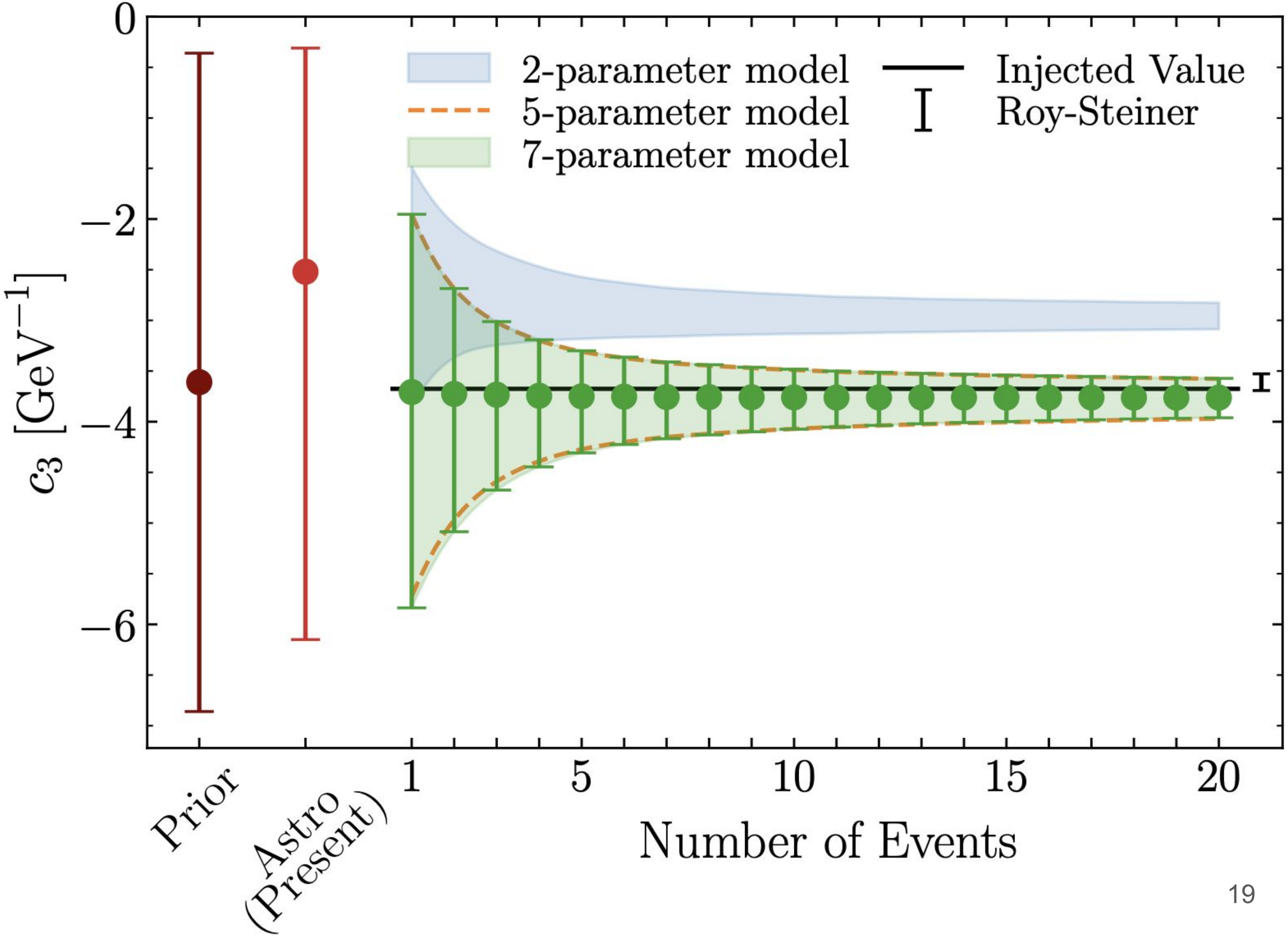
From the generated 427 events, select the 20 loudest events; SNR > 225. Analyse each event within the Fisher Matrix approximation



We can do much better with next-generation detectors!

Within 1 year, next-generation observatories can measure c_3 at a level comparable with laboratory data.

Marginalization over high-density EOS necessary to avoid systematic uncertainties



Conclusion and Outlook

We have demonstrated how to use astrophysical NS observations, especially next-generation observations, to constrain microphysical parameters governing the nuclear interaction

Future work:

- Improved nuclear interactions at higher orders in the EFT expansion
- Explore EFTs with heavier degrees of freedom, such as the Delta resonance
- Going beyond the Fisher Matrix approximation: Implement emulators in GW analysis pipelines such as PyCBC
- Incorporate systematics carefully: Waveform modeling, High density EOS extrapolations, emulator uncertainties, etc.

NP3M

Thank You!