Neutron-Star Mergers as Probes for Nuclear Physics

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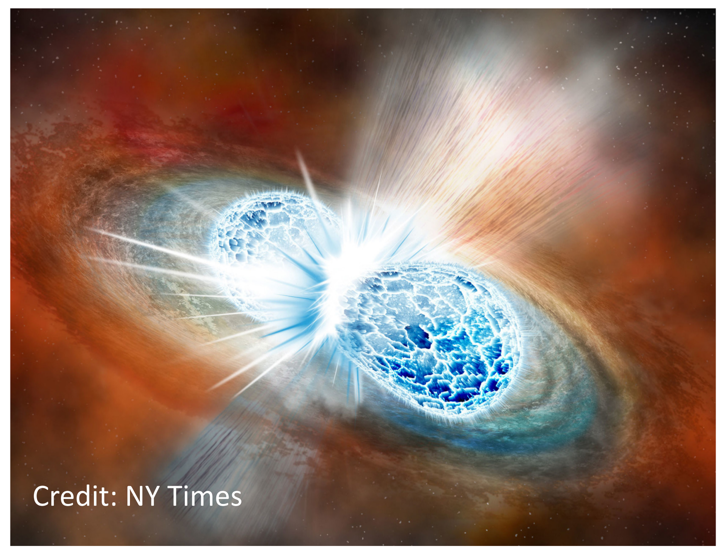
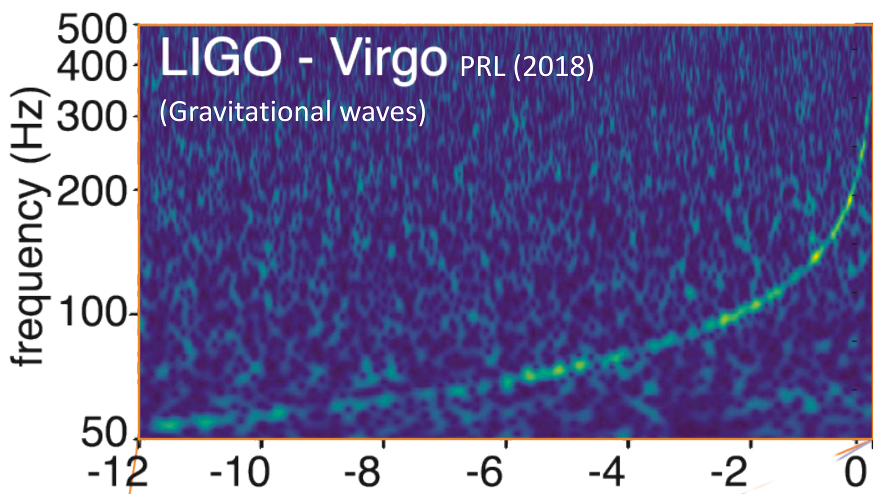
Neutron Stars

- Neutron stars (NS) are remnants of core-collapse supernovae and stabilized against gravitational collapse by nuclear interactions.
- A typical NS has a mass of 1.4 M_{sol} but a radius of less than 15 km!
- Hence, NS contain the densest form of matter we know to exist in the cosmos and are ideal laboratories for theories of nuclear interactions. They are probed in astrophysical observations.

A Groundbreaking Discovery



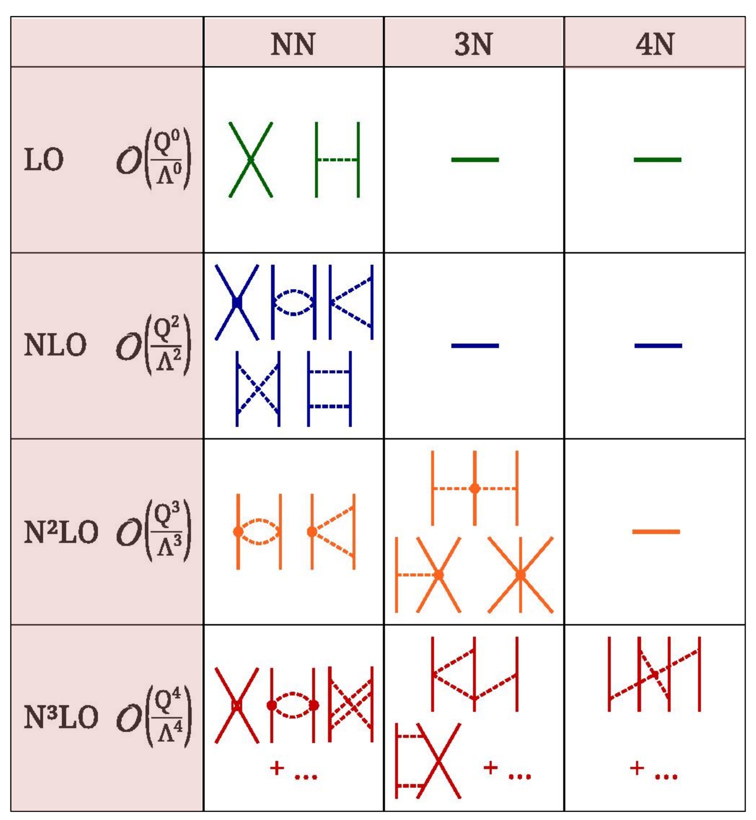


- The LIGO-Virgo collaboration (LVC) observed gravitational waves from a binary neutron-star merger for the first time on Aug 17, 2017. The event was called GW170817.
- Gravitational waves probe NS radii and, hence, the equation of state (EOS) and nuclear forces.
- Light curves of the ejecta from the associated explosion (kilonova) probe ejecta composition and nucleosynthesis (r-process pathway).
- To reliably interpret these events, we need precise many-body methods in combination with a systematic theory for nuclear forces. We perform controlled calculations with systematic theoretical error estimates using chiral effective field theory (EFT) and advanced Quantum Monte Carlo methods.

Chiral Effective Field Theory

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

- Pions and nucleons as degrees of freedom.
- Power counting scheme.
- Can work to desired accuracy with systematic error estimates.
- Provides natural hierarchy of nuclear forces.
- Consistent interactions: Same couplings for two-nucleon and many-body sector.



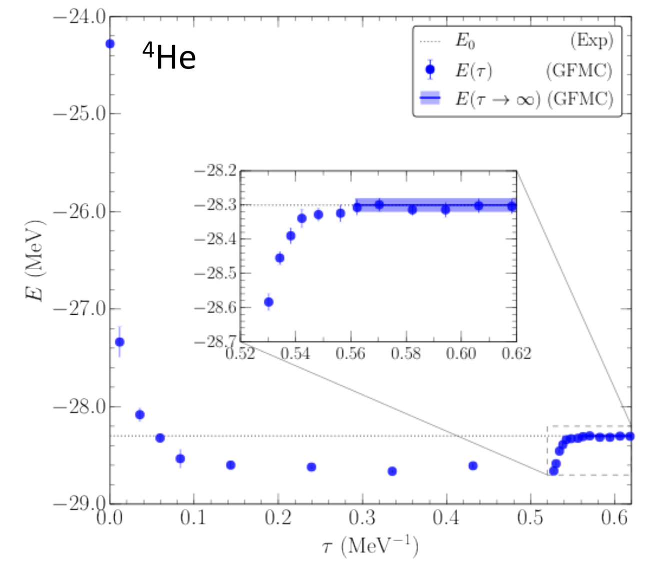
- Fitting: Two-nucleon (NN) forces in NN system (phase shifts), three-nucleon forces (3N) in A=3,4 systems (Binding energies, radii).

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

Quantum Monte Carlo Method

Quantum Monte Carlo (QMC) method to solve the many-body Schroedinger equation:

- Choose trial wavefunction that overlaps with the ground state of the system.
- Evaluate imaginary-time propagator for small timestep $\Delta\tau$.
- Make consecutive small time steps using Monte Carlo techniques to project out ground state:



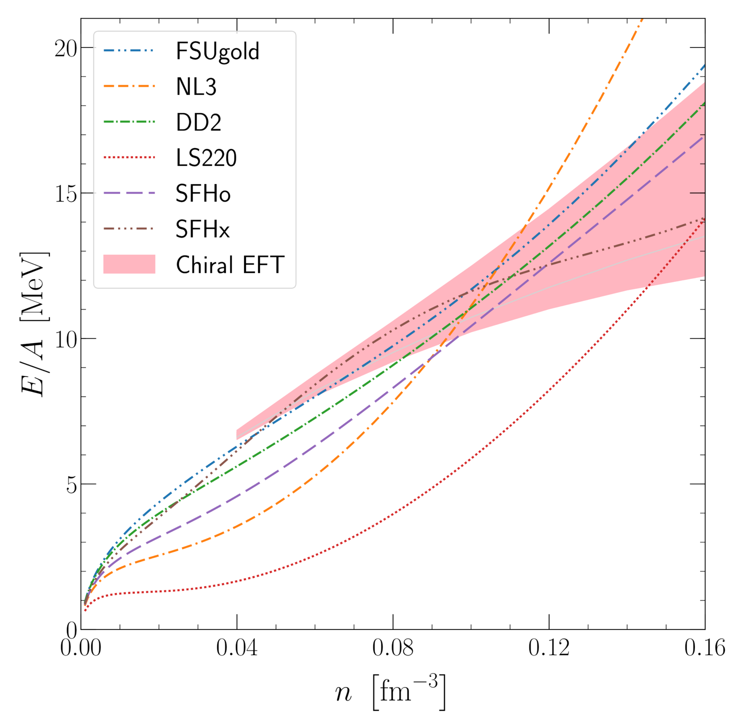
$$|\psi(R,0)\rangle = |\psi_T(R,0)\rangle = \sum_i c_i|\phi_i\rangle \to \sum_i c_i e^{-(E_i-E_0)\tau}|\phi_i\rangle$$

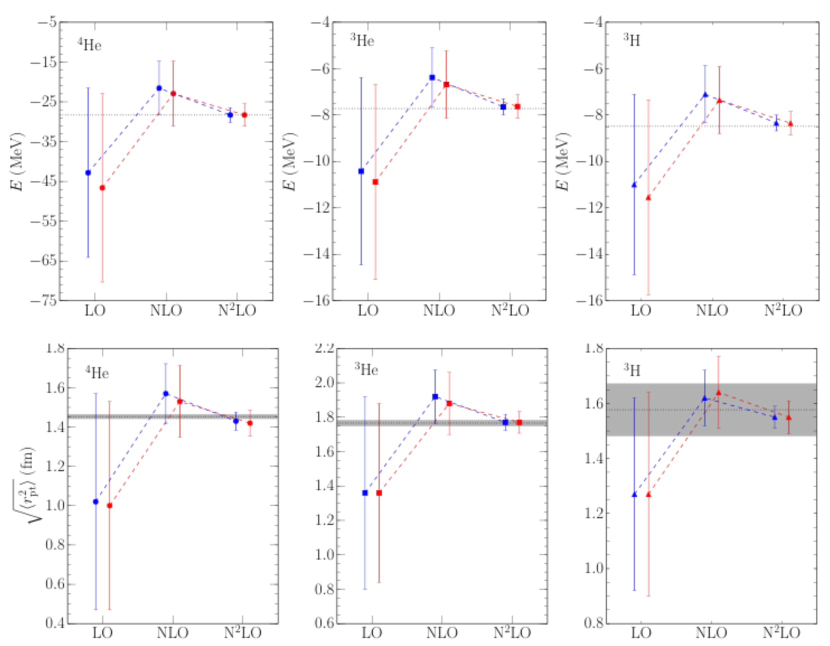
$$|\psi(R,0)\rangle \to |\phi_0\rangle \quad \text{for} \quad \tau\to\infty$$

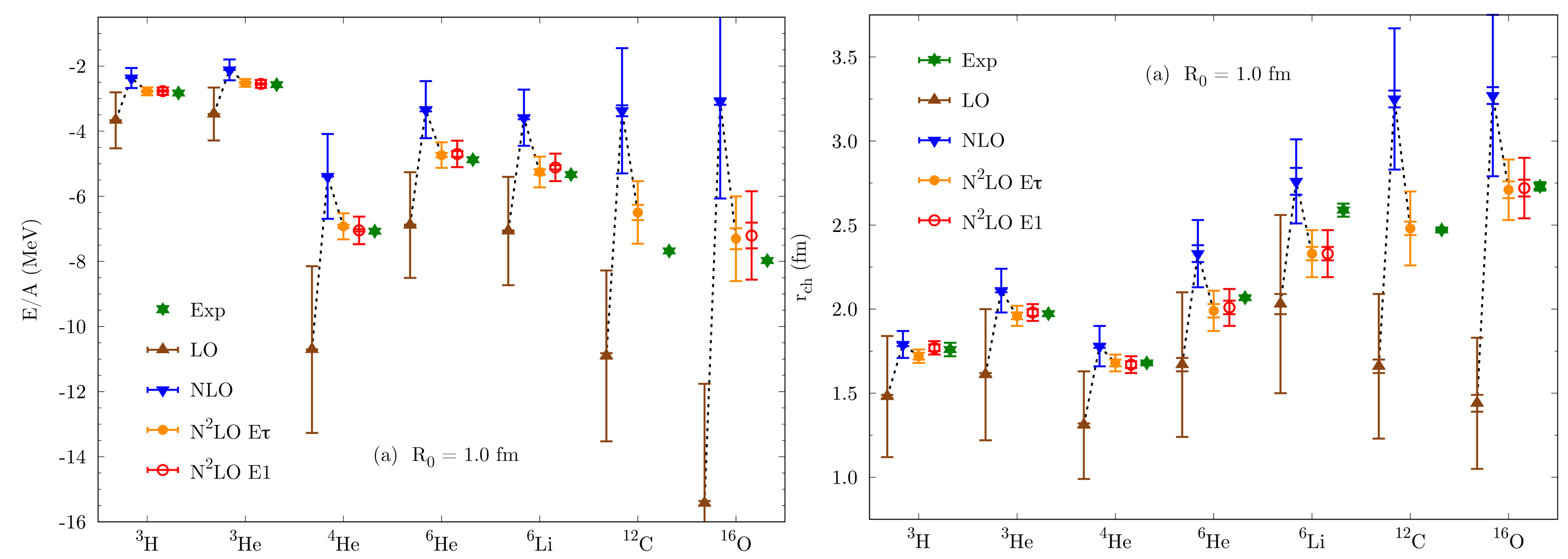
- With transient estimates, QMC methods are stochastically exact.
- We perform large-scale QMC simulations of atomic nuclei and nuclear matter relevant for astrophysics.

More details:
Carlson, Gandolfi, Pederiva, Pieper, Schiavilla, Schmidt, Wiringa, RMP (2015)

Results: Equation of State and Atomic Nuclei



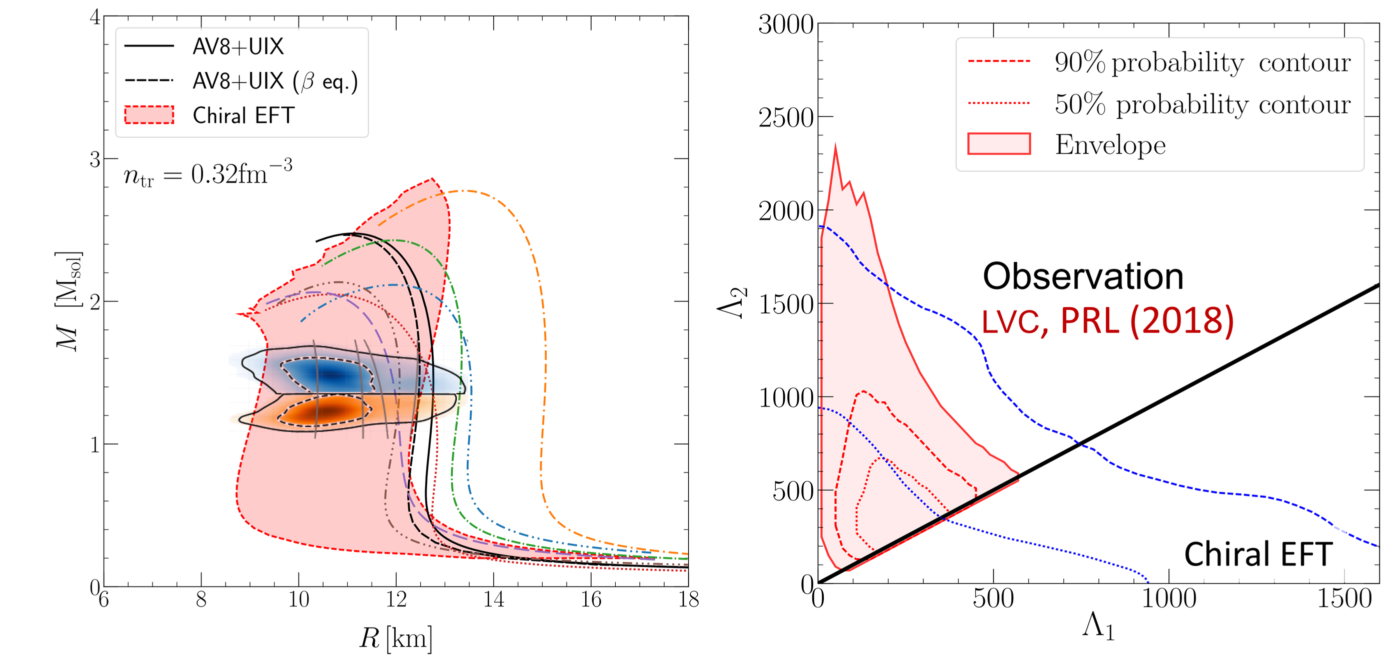




Lonardoni et al., PRL and PRC (2018)

- Chiral interactions at N^{2}LO simultaneously reproduce the properties of A ≤ 16 systems and of neutron matter.
- Commonly used phenomenological 3N interactions fail for neutron matter [Sarsa, Fantoni, Schmidt, Pederiva, PRC (2003)].

Results: Neutron-Star Mergers



- Tidal polarizabilities relate NS deformation Q_{ij} with partner's gravitational field E_{ij}. They are given by (with love number k_2):

$$Q_{ij} = -k_2\frac{2R^5}{3G}E_{ij} = \lambda E_{ij}, \qquad \Lambda = \lambda/M^5$$

- With a EOS extension to high densities using the speed of sound, we find that GW170817 constrains the radius of a 1.4 $M_\odot$ NS:

$$\mathrm{R}_{1.4} \leq 13.6\,\mathrm{km}$$

- However, systematic calculations show that currently nuclear-physics input is more constraining than first merger observation:

$$8.7\,\mathrm{km} \leq \mathrm{R}_{1.4} \leq 12.6\,\mathrm{km}$$

Conclusions & Outlook

- The combination of chiral EFT and advanced QMC methods is a versatile and systematic approach to atomic nuclei and nuclear matter with relevance for astrophysics, e.g., neutron-star mergers.
- Nuclear physics is directly probed in neutron-star mergers. Future gravitational-wave observations will reduce the observational uncertainties, and allow precision tests of nuclear forces.

References

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