Stringent constraints on neutron-star radii from neutron-star mergers and chiral effective field theory

Ingo Tews

Los Alamos National Laboratory (LANL)

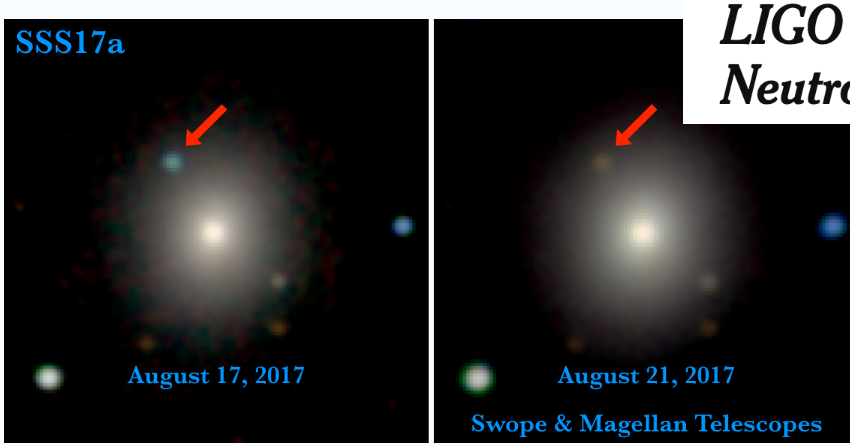
In collaboration with:

S. Brown, D. Brown, C. Capano, J. Carlson, S. De, S. Gandolfi, K. Hebeler, D. Lonardoni, B. Krishnan, S. Kumar, J. Lynn, B. Margalit, J. Margueron, S. Reddy, A . Schwenk

LA-UR-20-20236

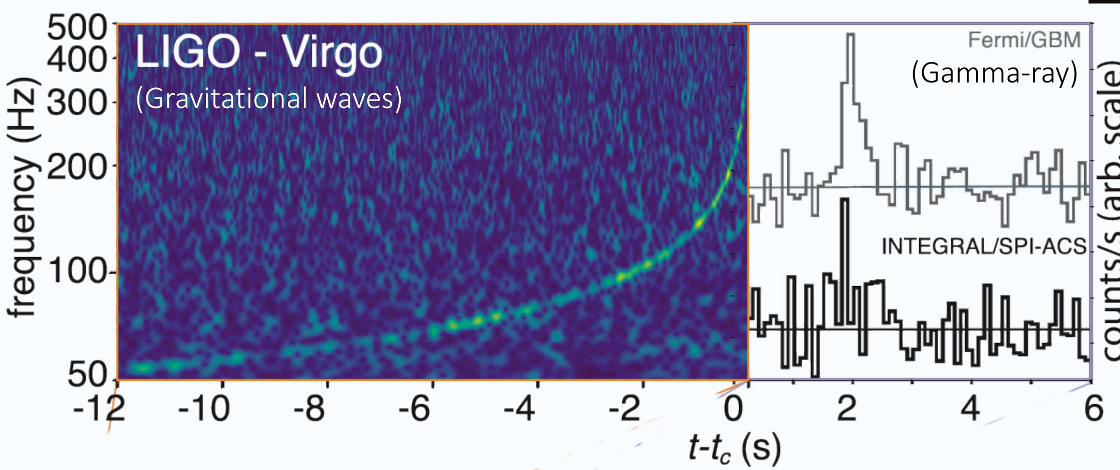
Motivation

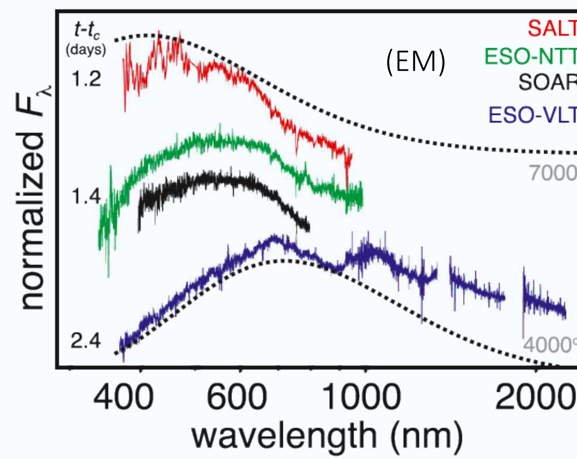
First neutron-star merger observed on **Aug 17, 2017** :



The New York Times

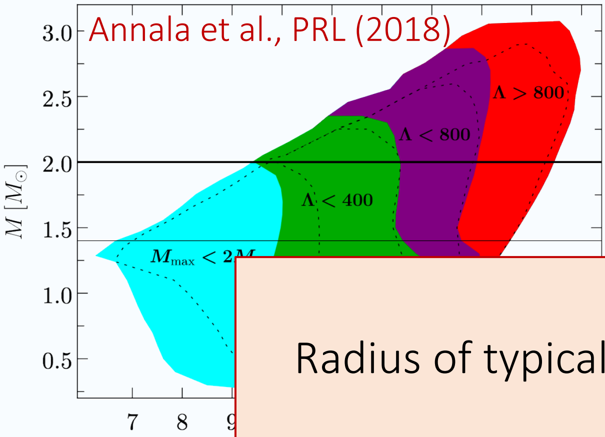
LIGO Detects Fierce Collision of Neutron Stars for the First Time

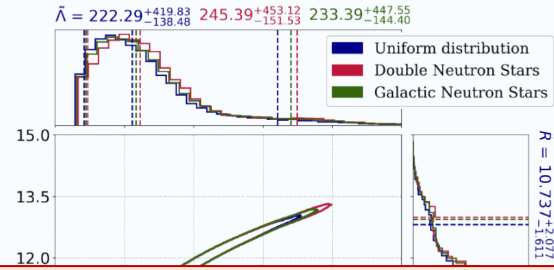


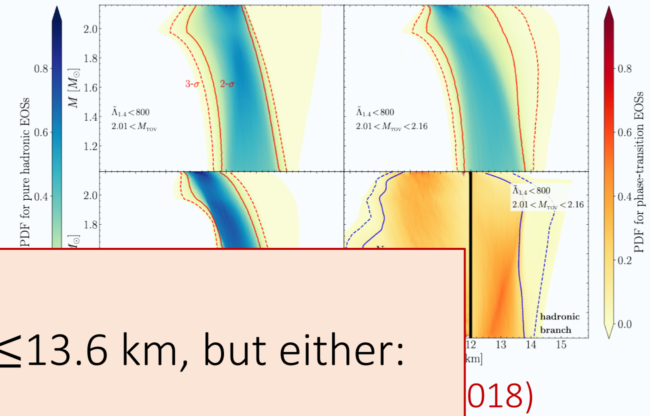


LIGO/VIRGO collaboration, ApJL 848, L12 (2017)

Motivation

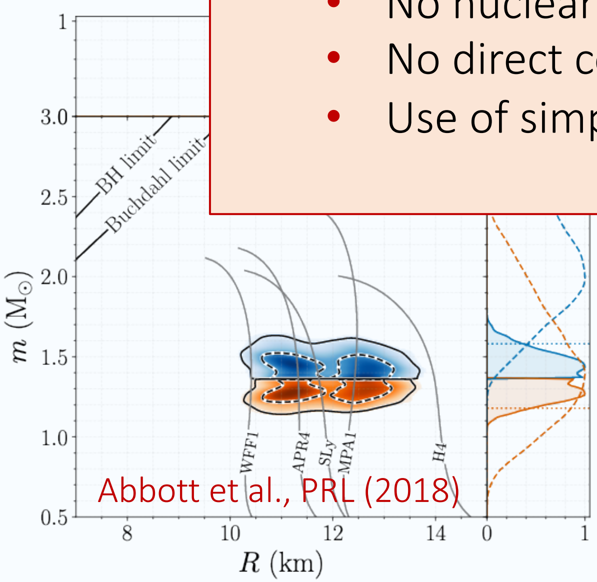


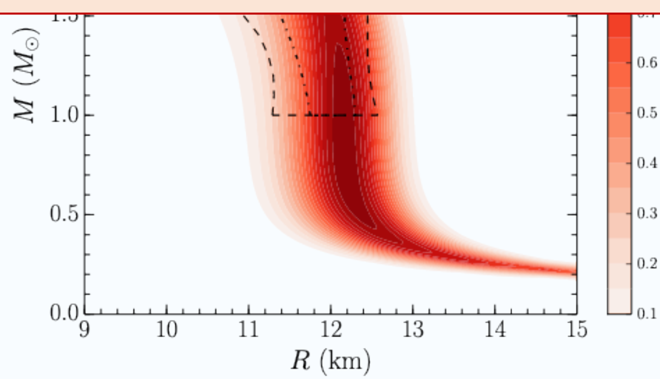


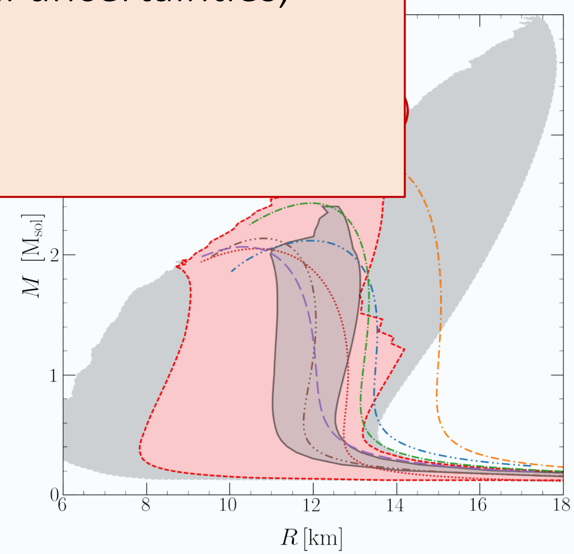


Radius of typical neutron-star constrained to be ≤13.6 km, but either:

- No nuclear physics constraints with theoretical uncertainties,
- No direct comparison to data,
- Use of simple parametrizations.







Outline

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In this work, we employ a strategy to overcome these deficiencies.

- Nuclear physics approach:
  - Chiral EFT as a systematic basis for nuclear forces that accounts for density-dependent theoretical uncertainties.
  - Quantum Monte Carlo methods.
  - Equation-of-state extension to higher densities.

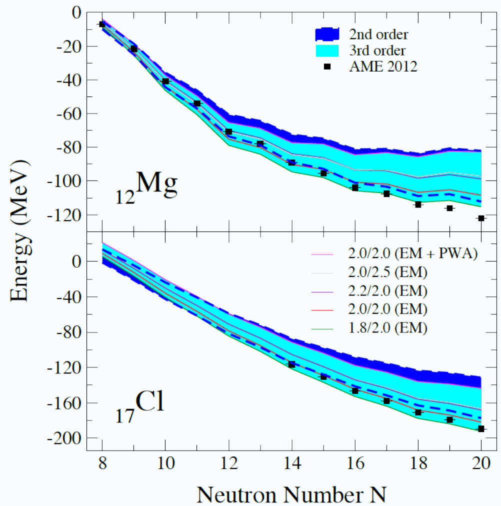
- Analysis of multimessenger observations of GW170817:
  - Gravitational-wave analysis, see talk **by S. De**
  - Analysis of electromagnetic observations

- Results for the neutron-star radius

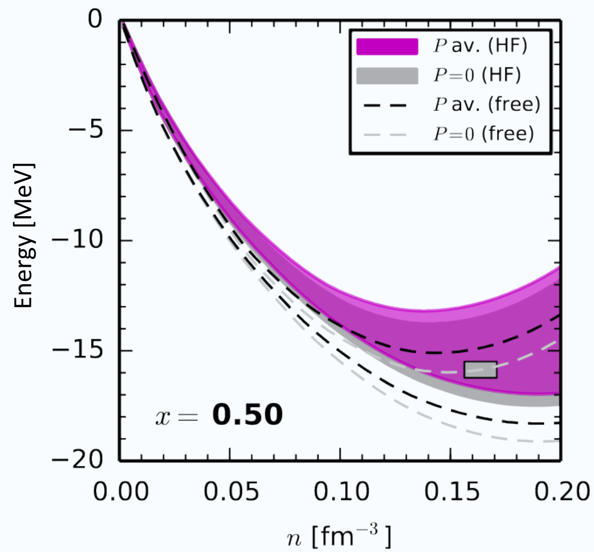
Nuclear-physics approach

Present theoretical predictions for nuclear systems are limited by:

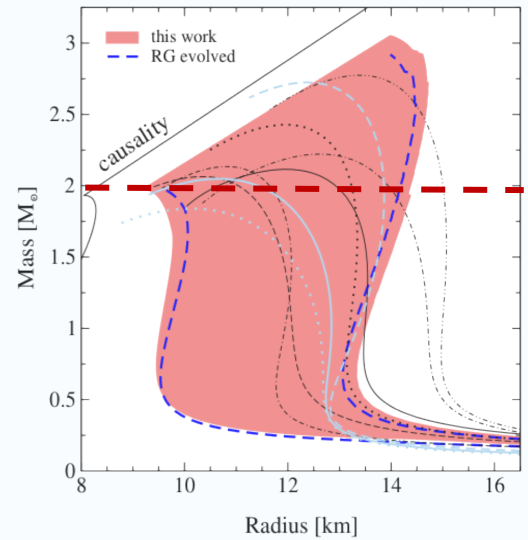
- our understanding of nuclear interactions,
- and our ability to reliably calculate these strongly interacting systems.



Simonis et al., PRC (2016)



Drischler et al.,PRC (2016)



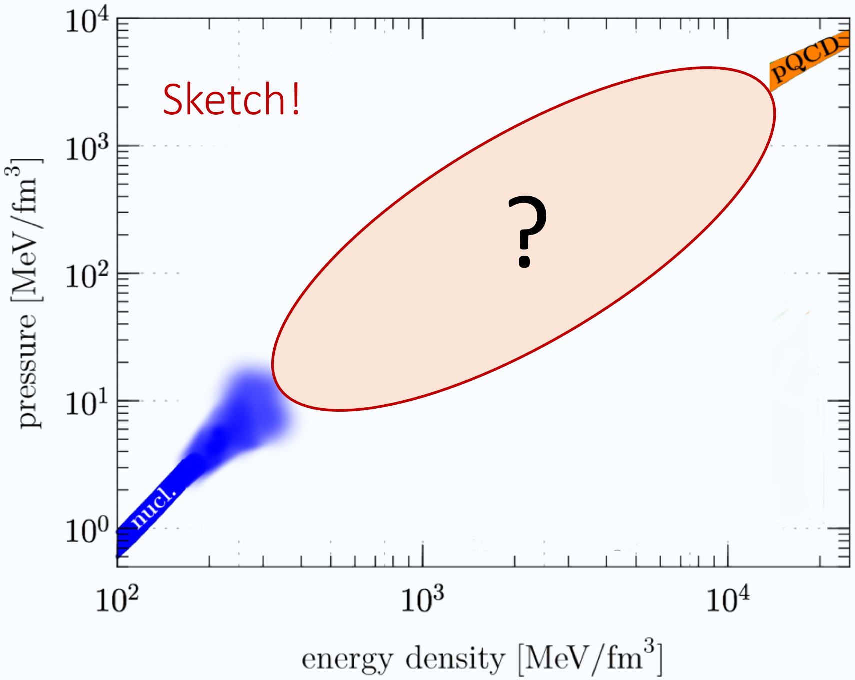
Krueger, IT et al.,PRC (2013)

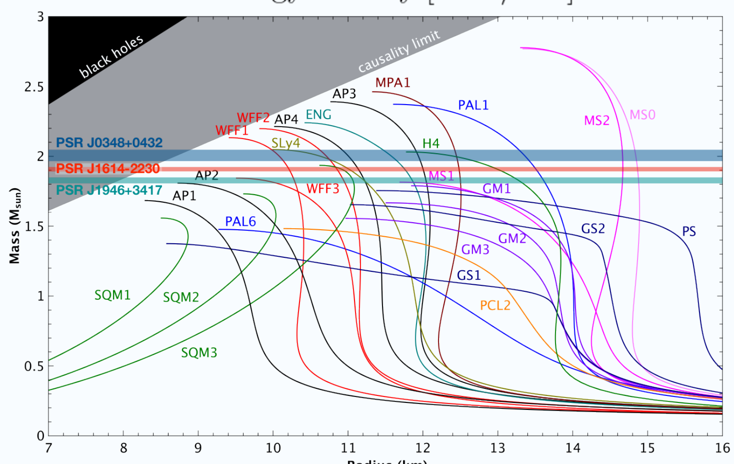
For nucleonic matter and nuclei, we need a consistent approach with:

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

Precision studies of nucleonic matter and nuclei using QMC and chiral EFT.

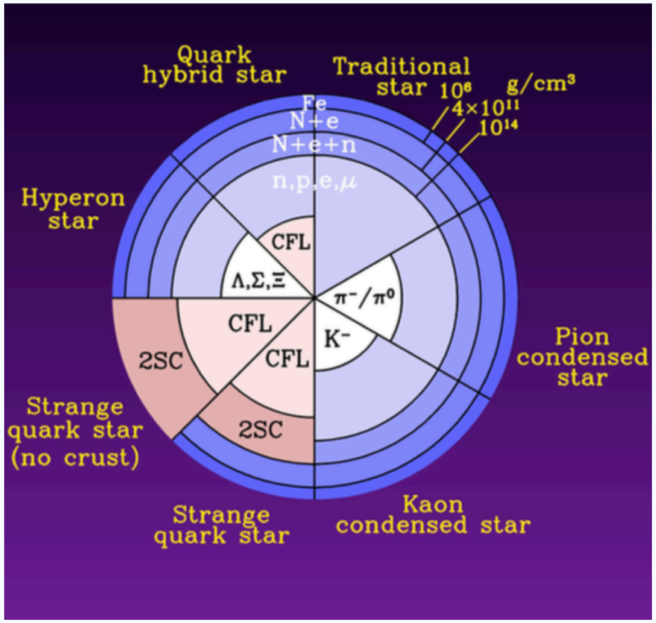
Nuclear-physics approach



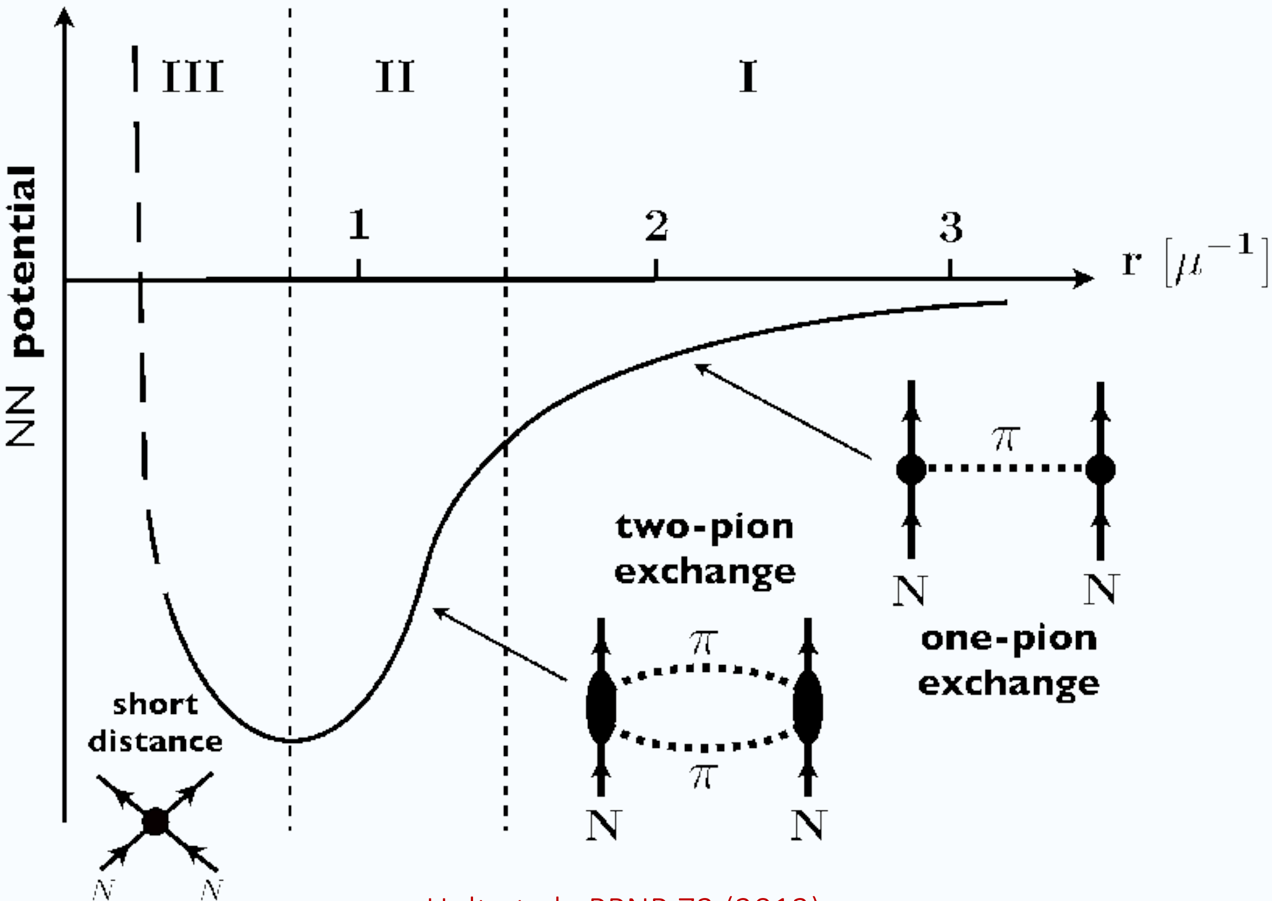


Constraints:

- 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!

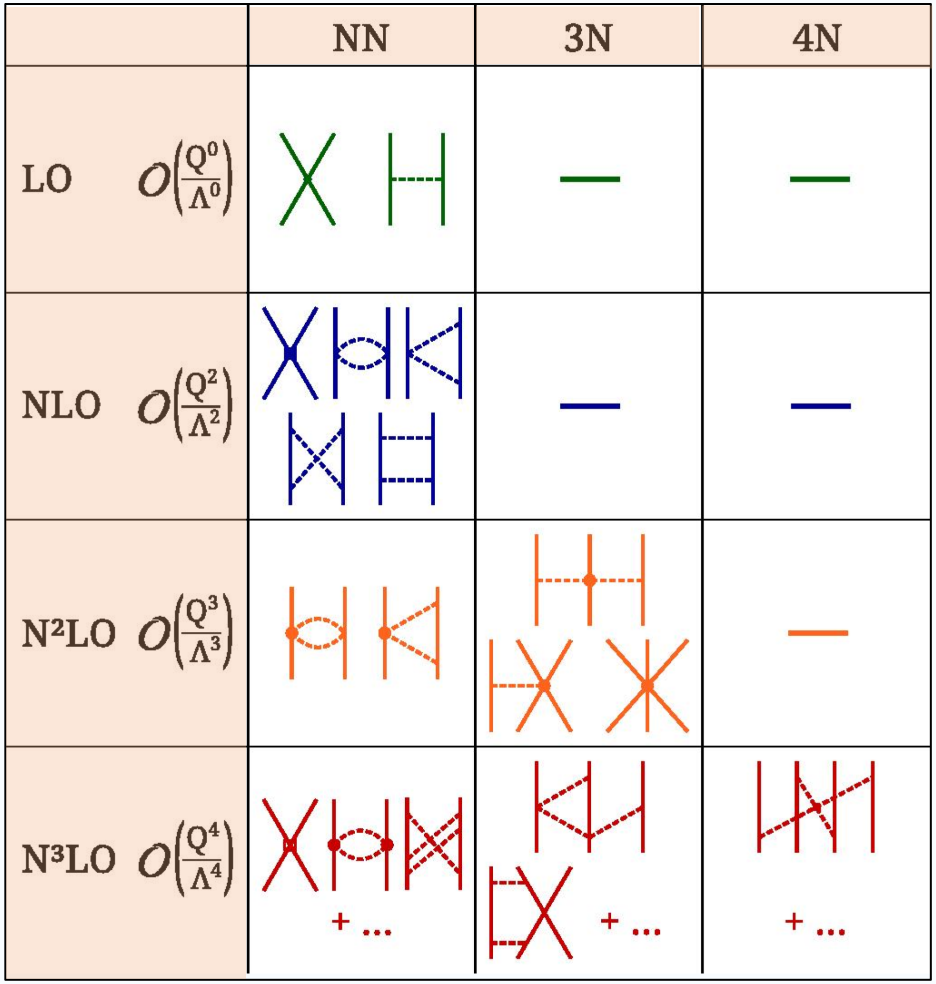


Chiral effective field theory for nuclear forces



Holt et al., PPNP 73 (2013)

Chiral effective field theory for nuclear forces

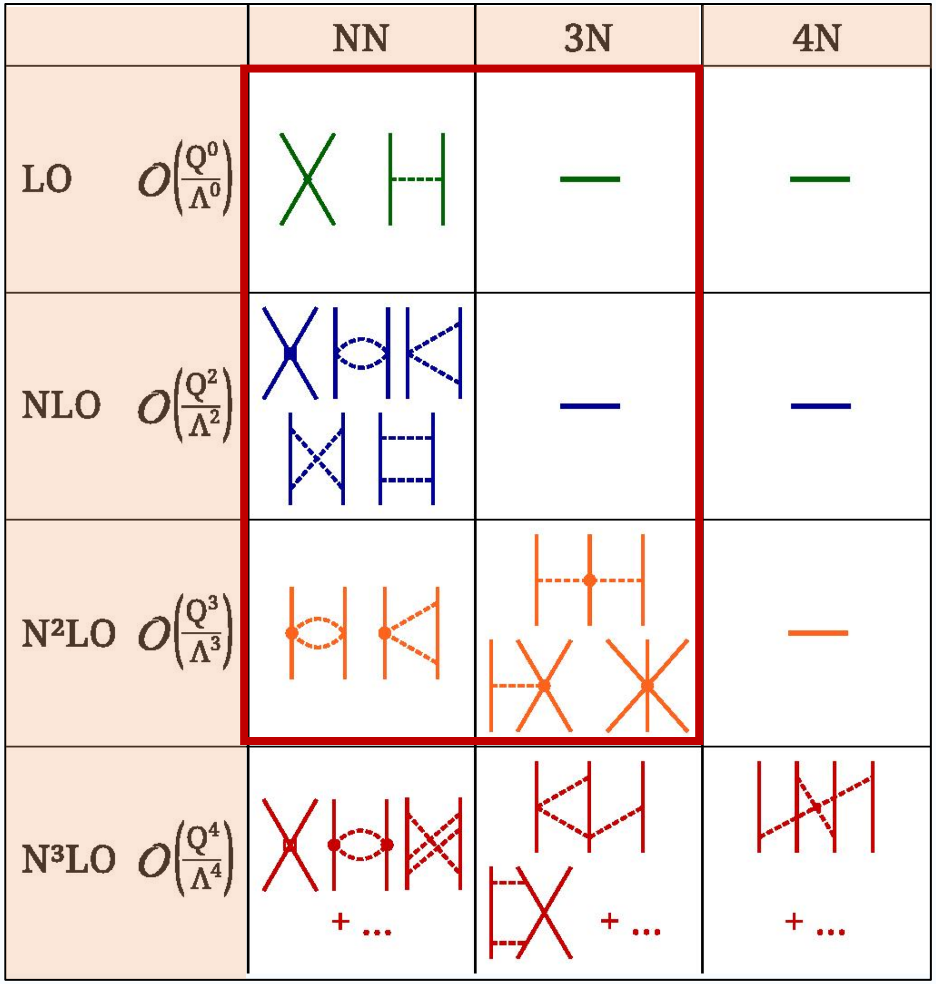


Weinberg, van Kolck, Kaplan, Savage, Wise,
Epelbaum, Kaiser, Machleidt, Meißner, Hammer ...

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

- Based on symmetries of QCD
- Pions and nucleons as explicit degrees of freedom
- Power counting scheme
- Can work to desired accuracy with systematic error 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)

Chiral effective field theory for nuclear forces



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

- We use local chiral potentials up to N^2LO.
  Gezerlis, IT, et al., PRL (2013)
  Gezerlis, IT, et al., PRC (2014)

- Two-body LECs fit to nn scattering phase shifts.

- 3N LECS fit to uncorrelated observables:
  - Probe properties of light nuclei: ^4He $E_{B,}$
  - Probe spin-orbit physics: n-α scattering.

  Lynn, IT, et al., PRL (2016)

- Improvement of local interactions ongoing
  Huth, IT, et al., PRC (2017) & PRC (2018),
  Lonardoni, IT, et al., in preparation.

Quantum Monte Carlo method

- Method to solve for the ground state of a many-body system.
- Treat many-body Schrödinger equation as diffusion in imaginary time:

$$\lim_{\tau \to \infty} e^{-H\tau} |\Psi_T\rangle \to |\Psi_0\rangle$$

Basic steps:

- Choose trial wavefunction which overlaps with the ground state:

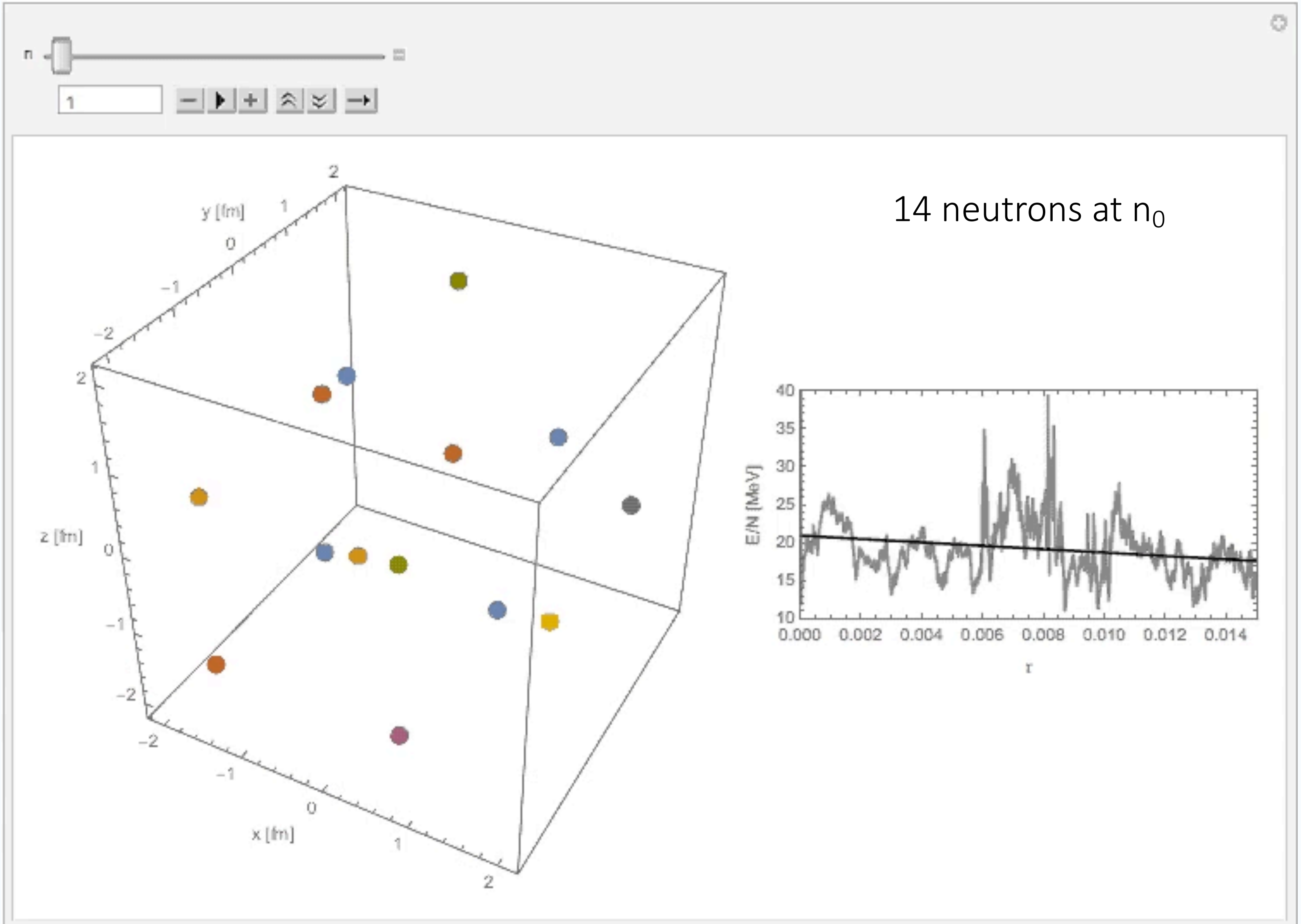
$$|\psi(R,0)\rangle = |\psi_T(R,0)\rangle = \sum_i c_i |\phi_i\rangle \to \sum_i c_i e^{-(E_i - E_0)\tau} |\phi_i\rangle$$

- Evaluate propagator for small timestep **$\Delta\tau$**
- Make consecutive small time steps using Monte Carlo techniques to project out ground state

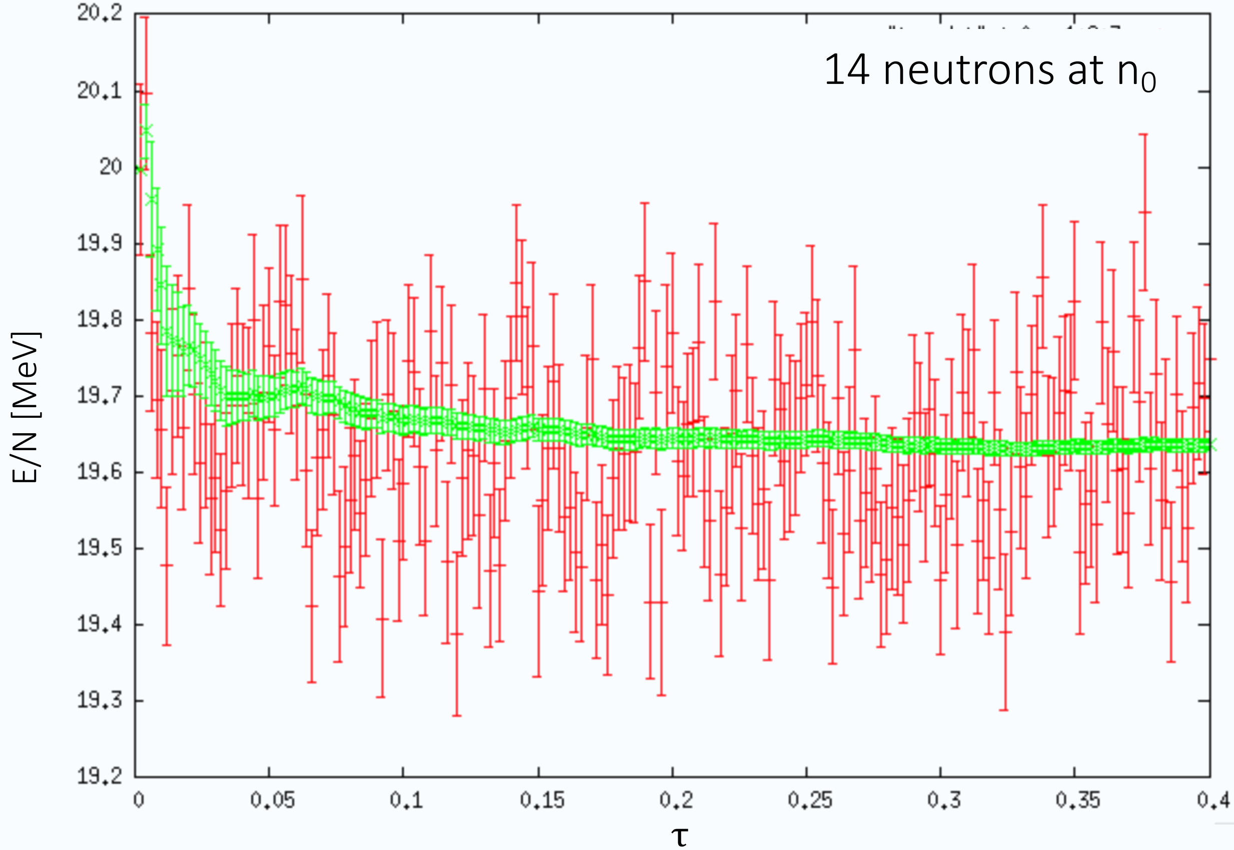
$$|\psi_T(R,\tau)\rangle \to |\phi_0\rangle \quad \text{for} \quad \tau \to \infty$$

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

Quantum Monte Carlo method



Quantum Monte Carlo method



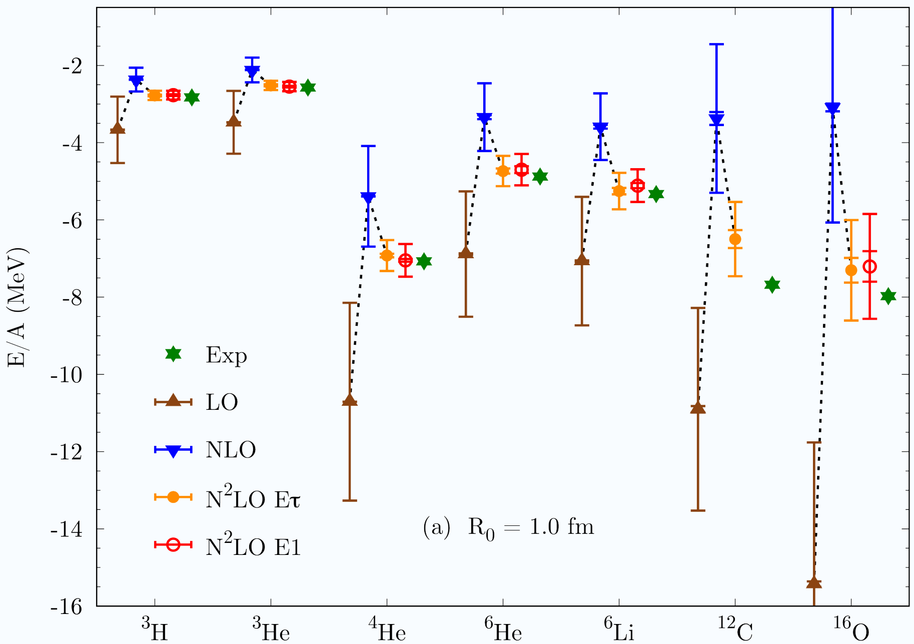
Credit: Diego Lonardoni

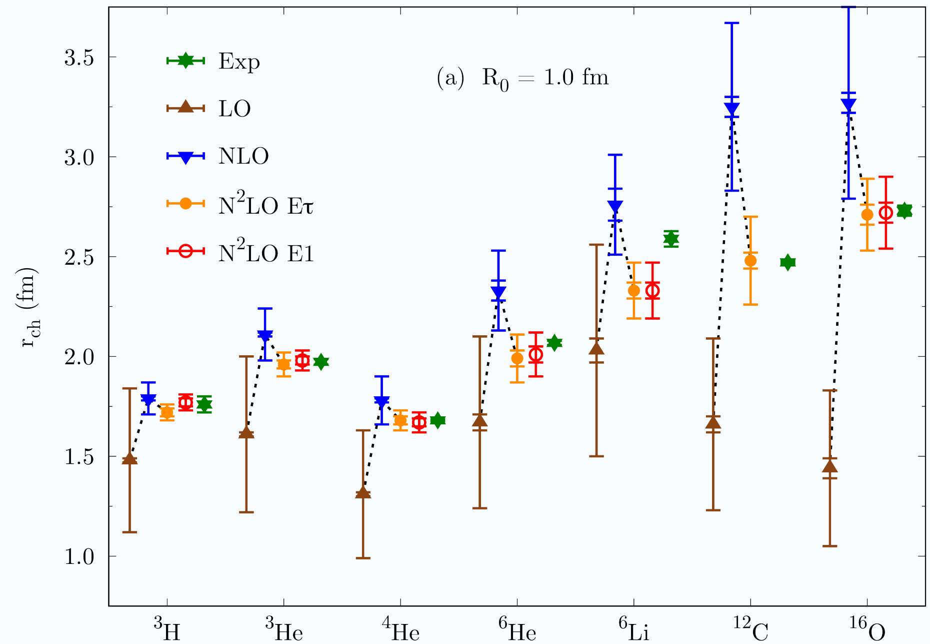
- Very precise method for strongly interacting systems.
- With transient estimates, stochastically exact.

QMC for nuclei

Results for AFDMC calculations of nuclei up to ^{16}O (R_0 = 1.0 fm):

Lonardoni et al., PRL and PRC (2018)

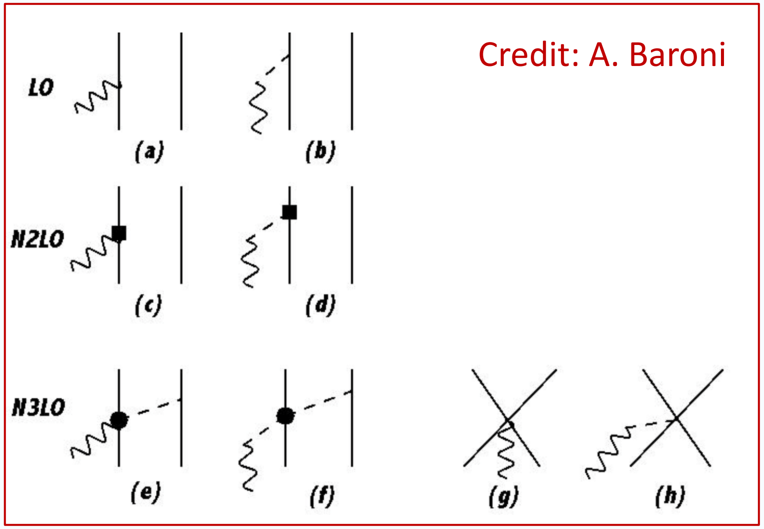




Excellent description of binding energies and charge radii for A ≤16!

Beta decays (in progress)

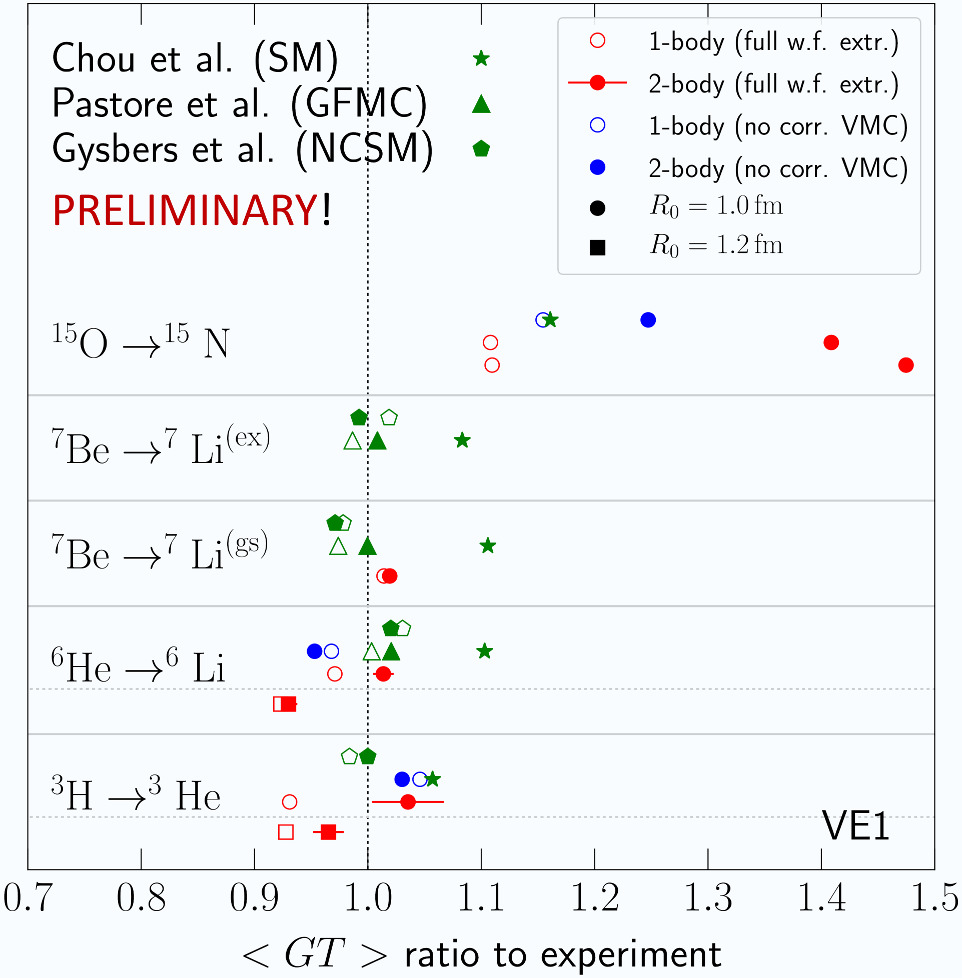
Neutrino interactions with nucleons also described within chiral EFT:



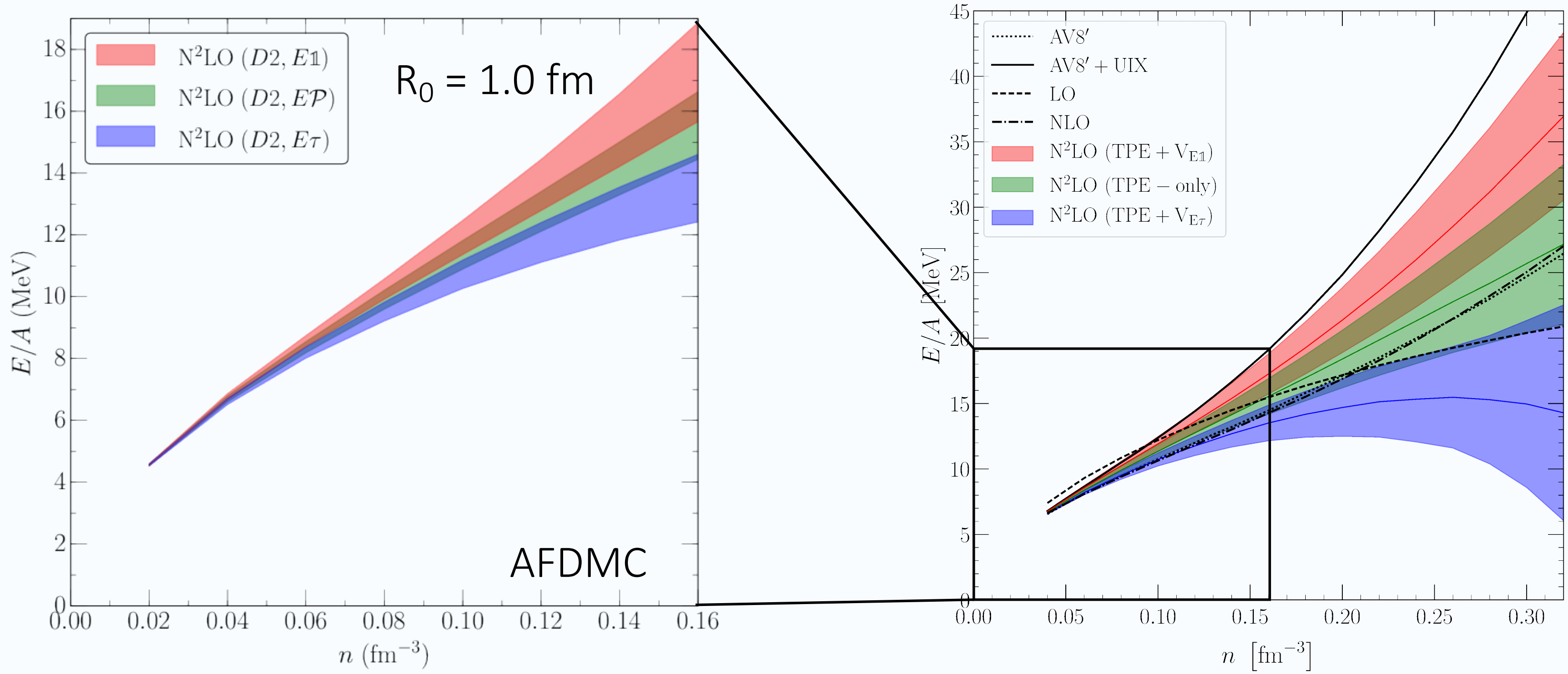
We have implemented neutrino interactions consistent with nuclear part.

Currently, testing these in nuclei.

Disagreement for ^{15}O decay.



QMC for neutron matter



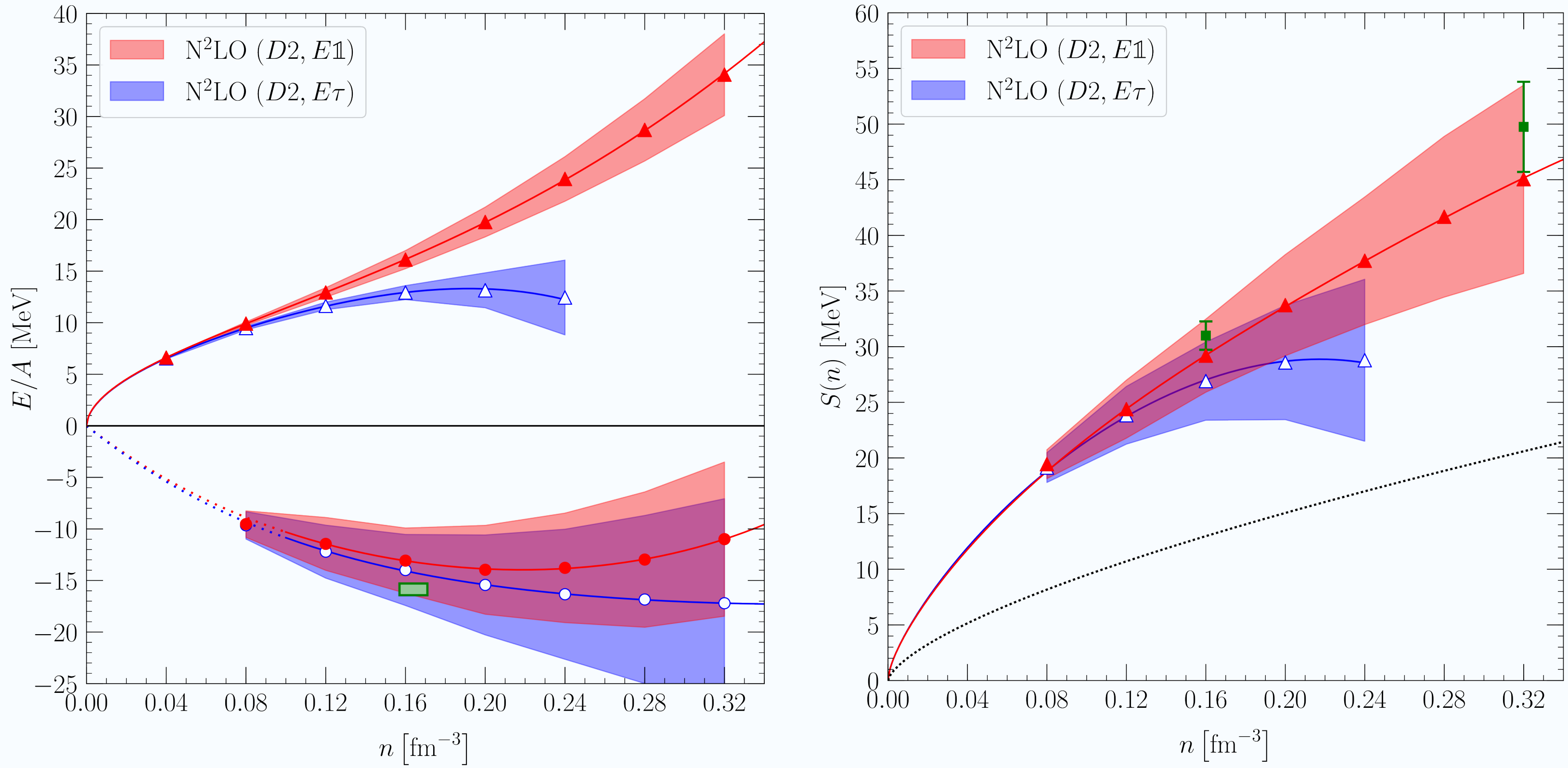
Lynn, IT, et al., PRL (2016)

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

QMC calculations of nuclei and matter show:

- Chiral interactions at N^{2}LO simultaneously reproduce the properties of A≤16 systems and of neutron matter with systematic uncertainty estimates

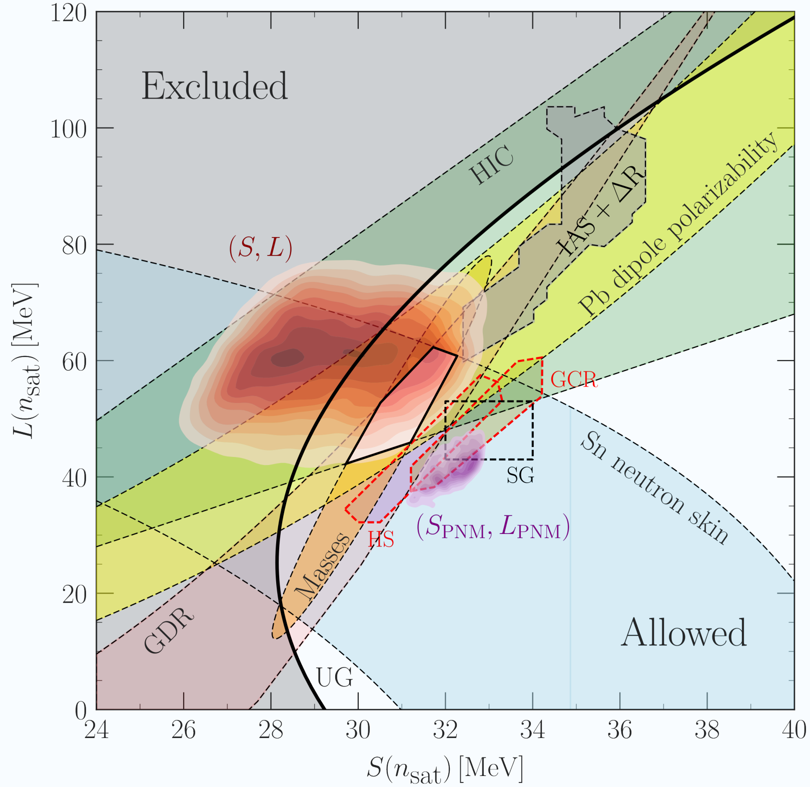
Nuclear matter

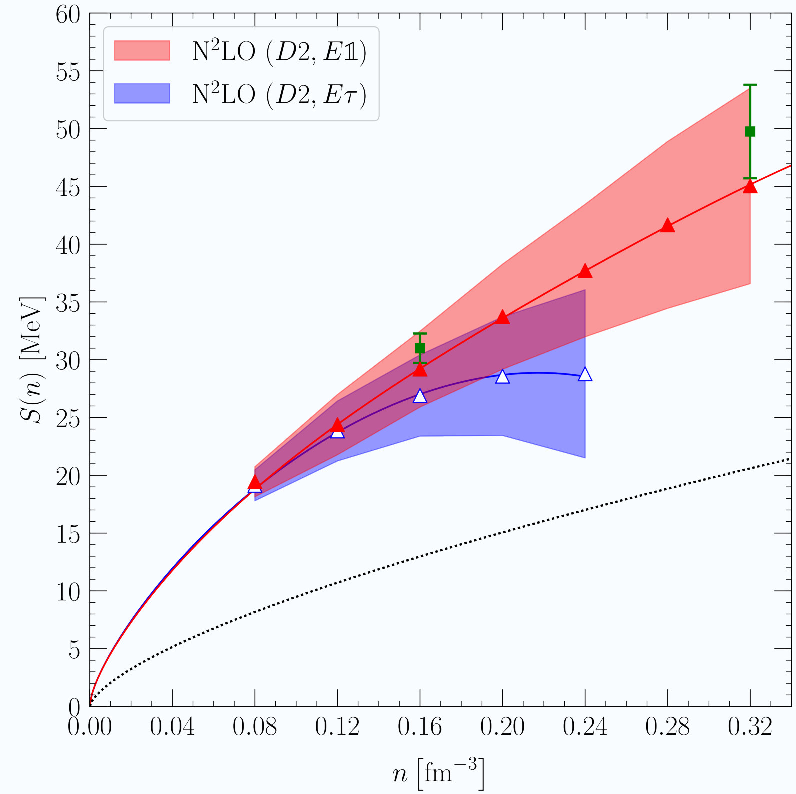


Lonardoni et al., arXiv:1912.09411

- First AFDMC calculations of symmetric nuclear matter with chiral interactions.
- Theoretical uncertainty estimates for symmetry energy.

Nuclear matter

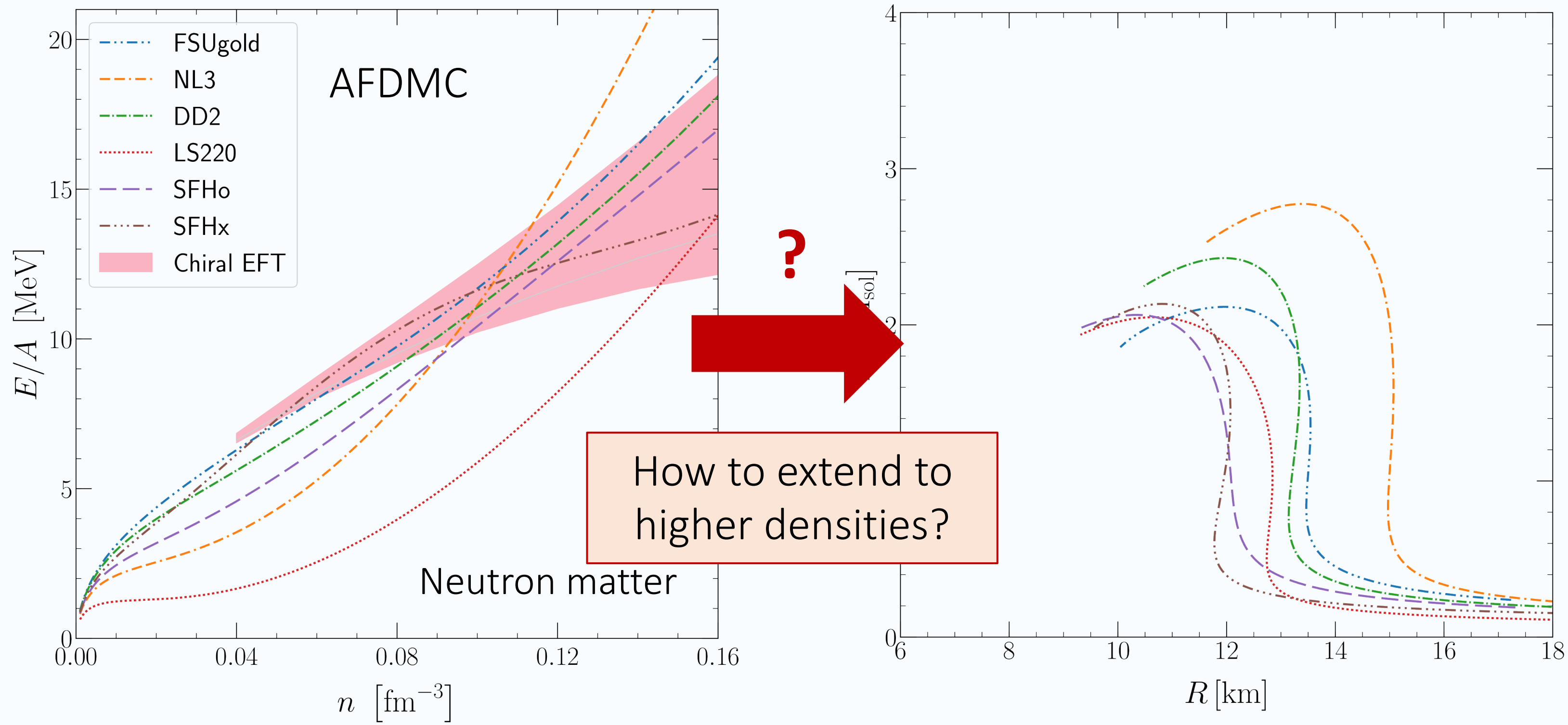




Lonardoni et al., arXiv:1912.09411

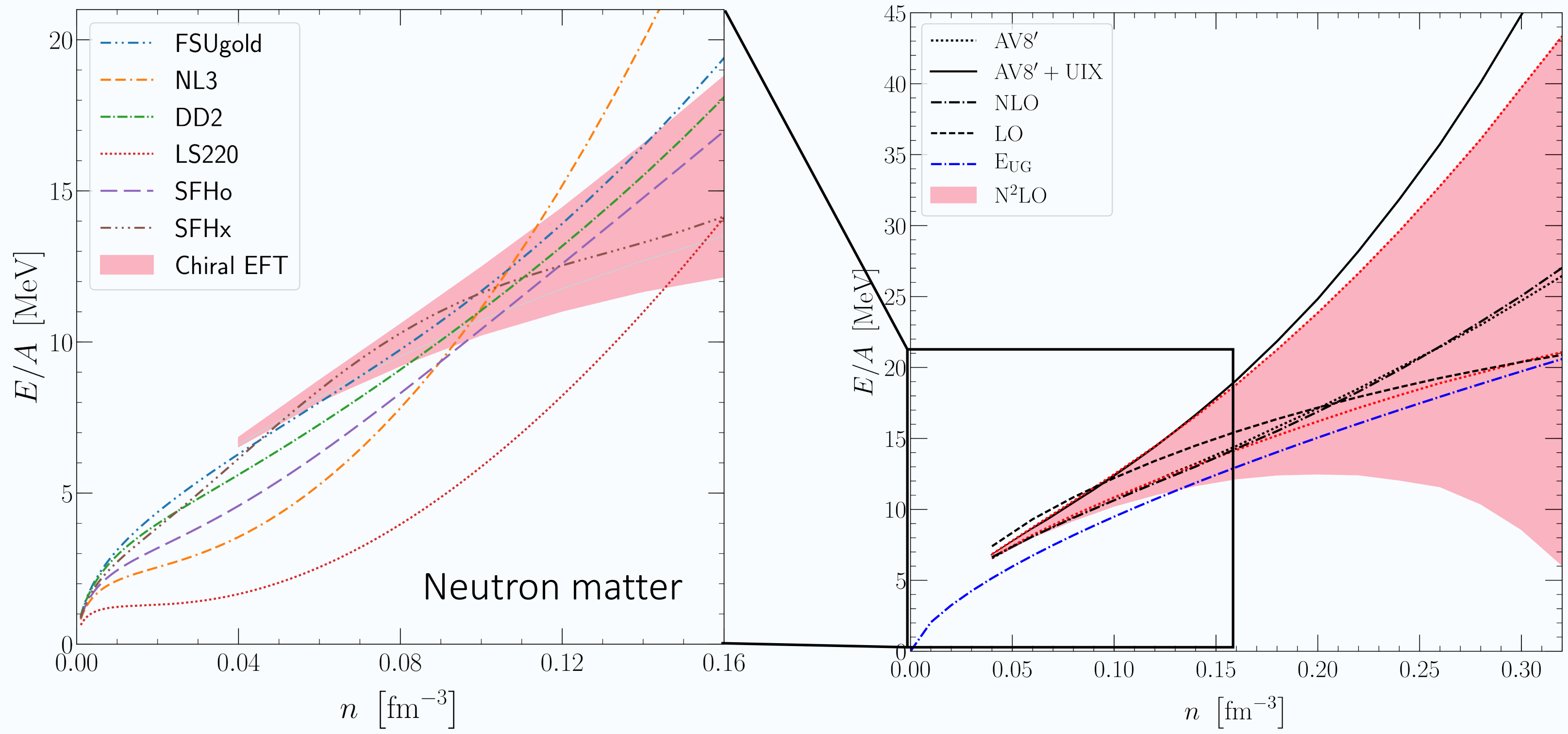
- First AFDMC calculations of symmetric nuclear matter with chiral interactions.
- Theoretical uncertainty estimates for symmetry energy.
- Ab initio calculations put constraints on S_0 and its density dependence L.

Results for neutron matter



- 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!

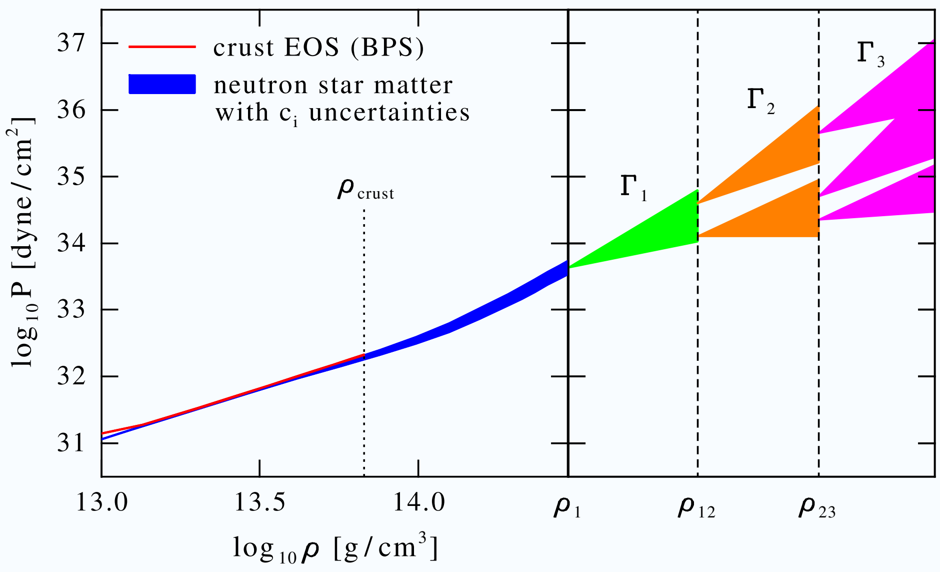
Neutron matter and EOS



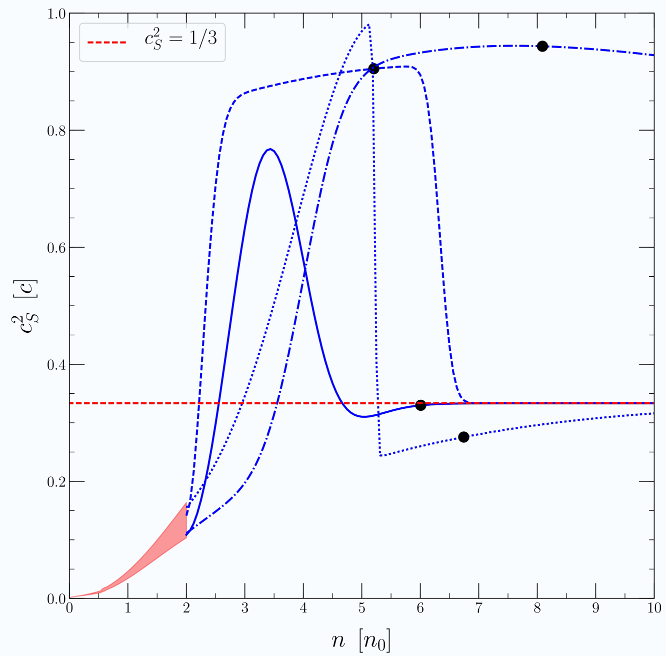
Chiral interactions are limited in range of applicability due to breakdown of the theory.:

- Extend results to higher densities using model-agnostic, general approach (e.g., polytropes, speed-of-sound extension, meta EOS)!

Neutron-star EOS



Hebeler et al., ApJ (2013)



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

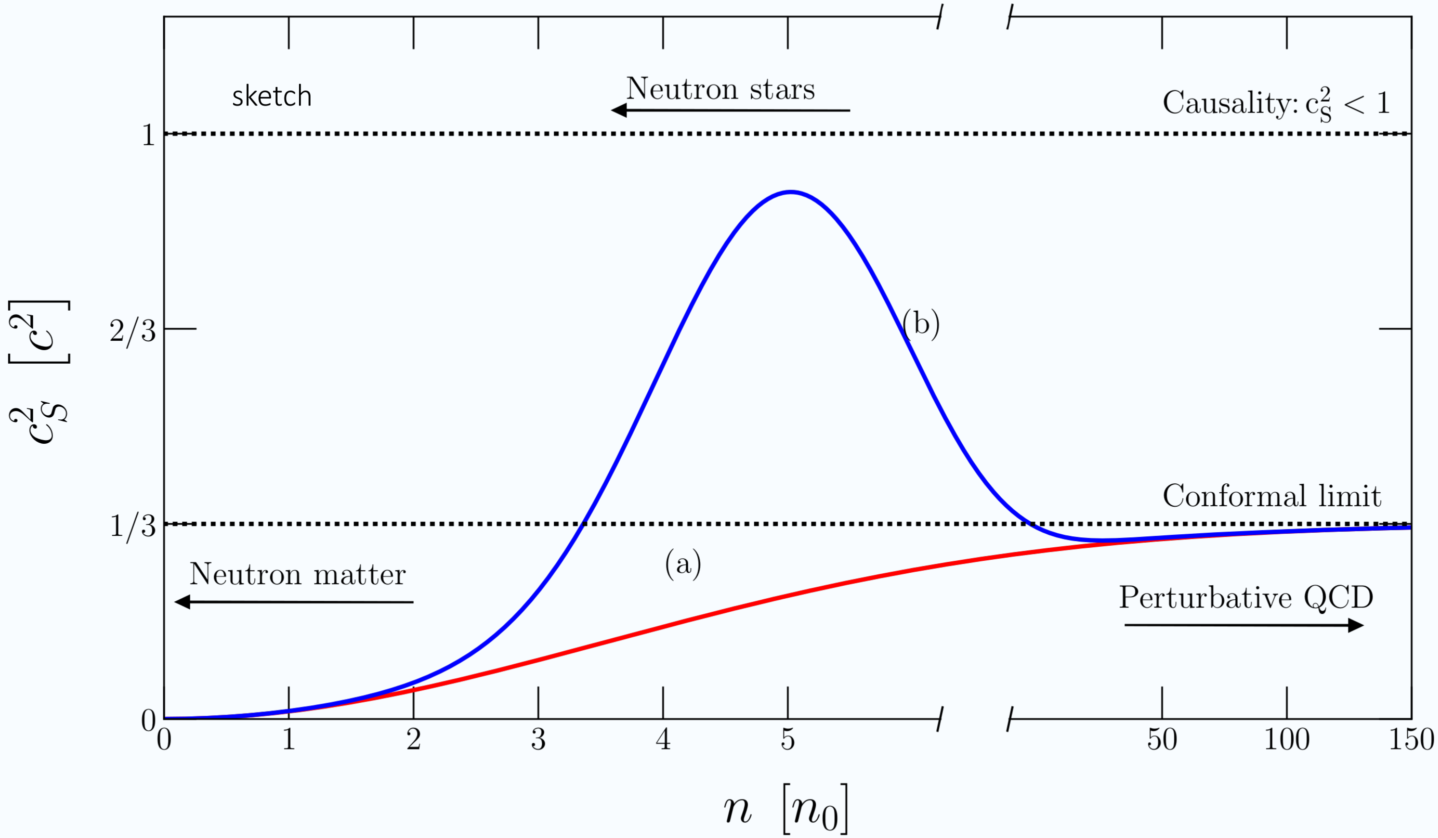
- Extend results to beta equilibrium (small $Y_{e,p}$) and include crust EOS
- Extend to higher densities, e.g.,
  - using piecewise polytropic expansion Hebeler et al., PRL (2010) and APJ (2013)
  - using speed-of-sound IT, Carlson, Gandolfi, Reddy, ApJ (2018)
  - Meta-EOS based on empirical parameters Margueron et al., PRC 97, 025805 & 025806 (2018)

Extension using speed of sound

Speed of sound:
$$c_S^2 = \frac{\partial p(\epsilon)}{\partial \epsilon}$$

Use the speed of sound to extend EOS:

- Information at low densities (chiral EFT) and from pQCD
- High-n behavior cannot be distinguished at neutron-star densities



$$\lim_{n\to\infty} c_S^2 = \frac{1}{3}$$

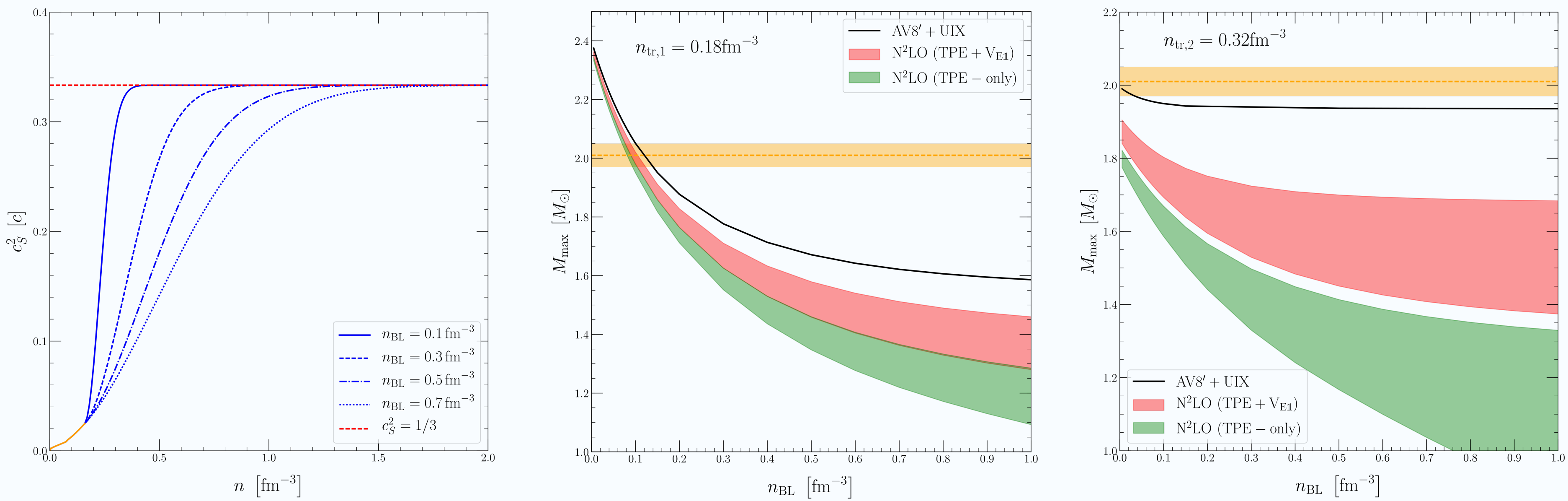
Kurkela et al. (2010)
Bedaque & Steiner (2015)

Extension using speed of sound (a)

Varying transition density n_{tr} and using for $n > n_{tr}$:

$$c_S^2 = \frac{1}{3} - c_1 \exp\left(-\frac{(n-c_2)^2}{n_{\rm BL}^2}\right)$$

(c_1 & c_2 fit to n_{tr})

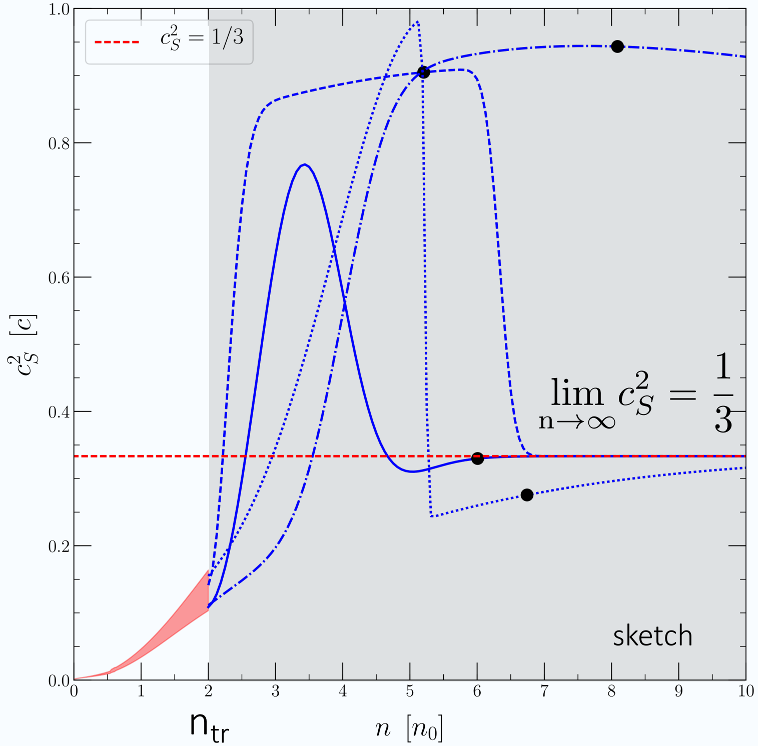


IT, Carlson, Gandolfi, Reddy, ApJ (2018)

See also Bedaque & Steiner (2015)

Neutron-Star EOS

- Extend results to beta equilibrium (small $Y_{e,p}$) and include crust EOS.
- Extend to higher densities using speed of sound.



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

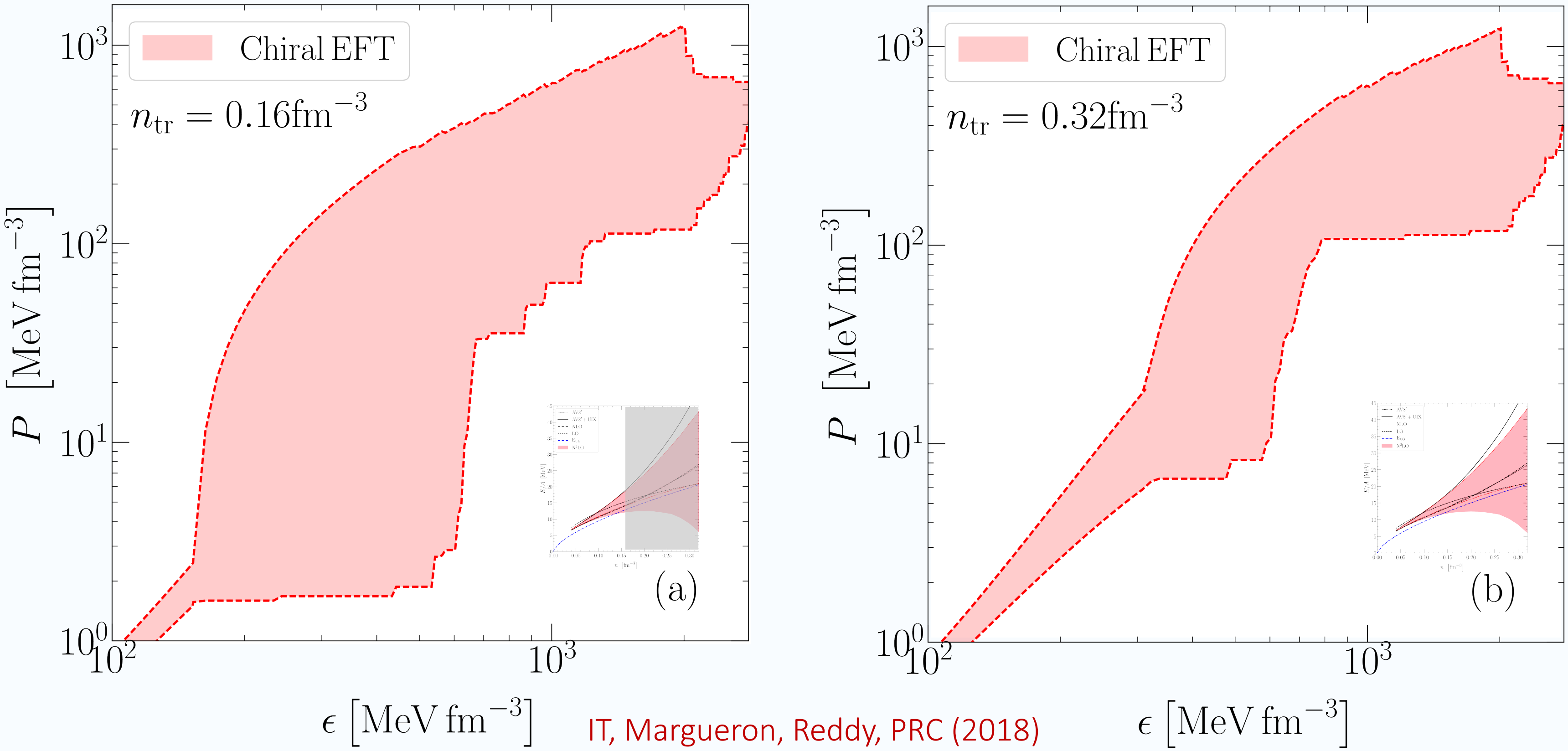
Speed of sound:

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

- 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!

Kurkela et al. (2010), Bedaque & Steiner (2015)

Neutron-star EOS

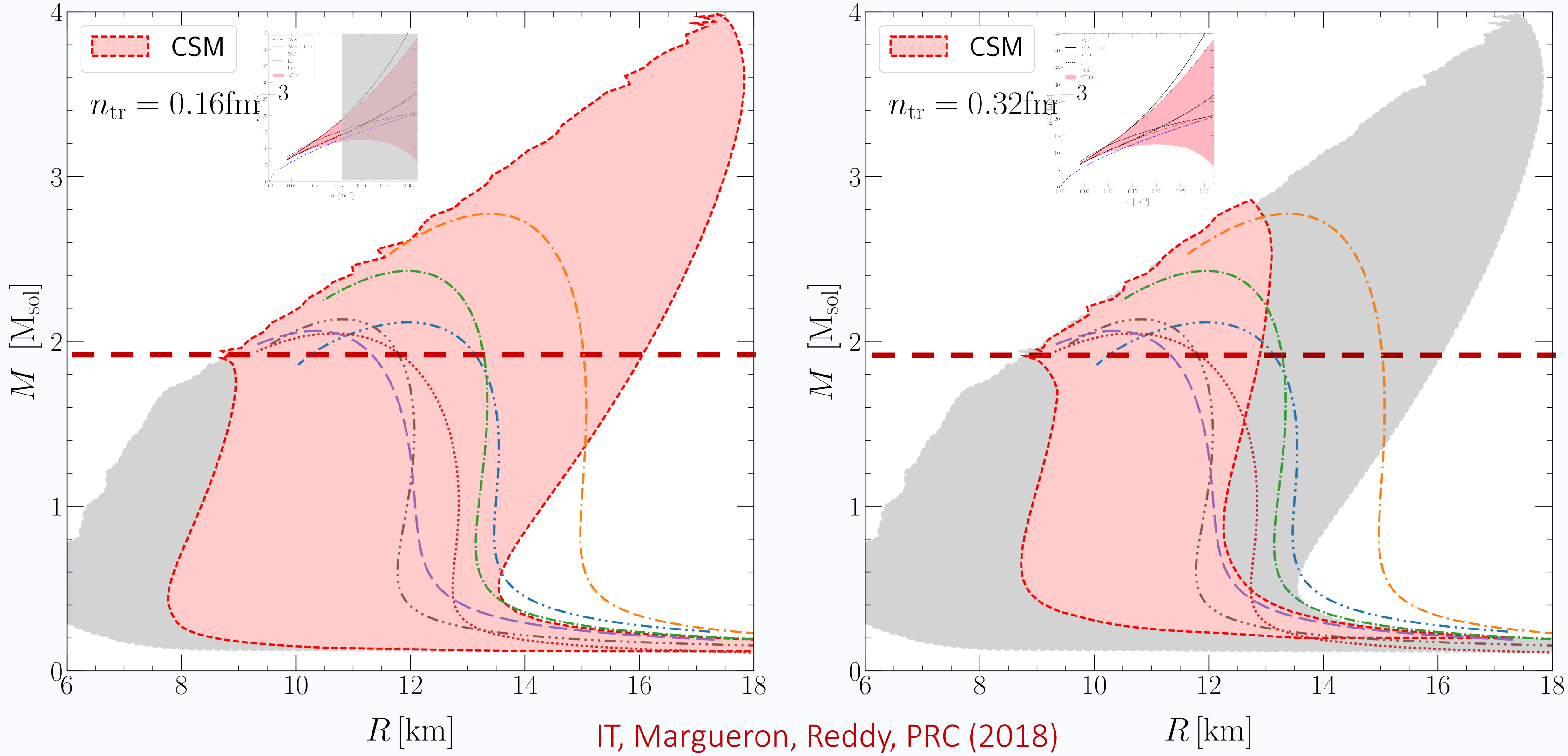


IT, Margueron, Reddy, PRC (2018)

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 1.9 solar-mass neutron stars.

Neutron-star EOS



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Neutron-star mergers

Gravitational waves from inspiral phase of neutron-star merger offer possibility to "measure" the neutron-star radius!

LIGO/VIRGO:

- During merger, neutron stars deform under gravitational field of partner.
- This deformation is measured as "tidal polarizability" from gravitational waveform during inspiral phase of neutron-star merger, and probes radius.

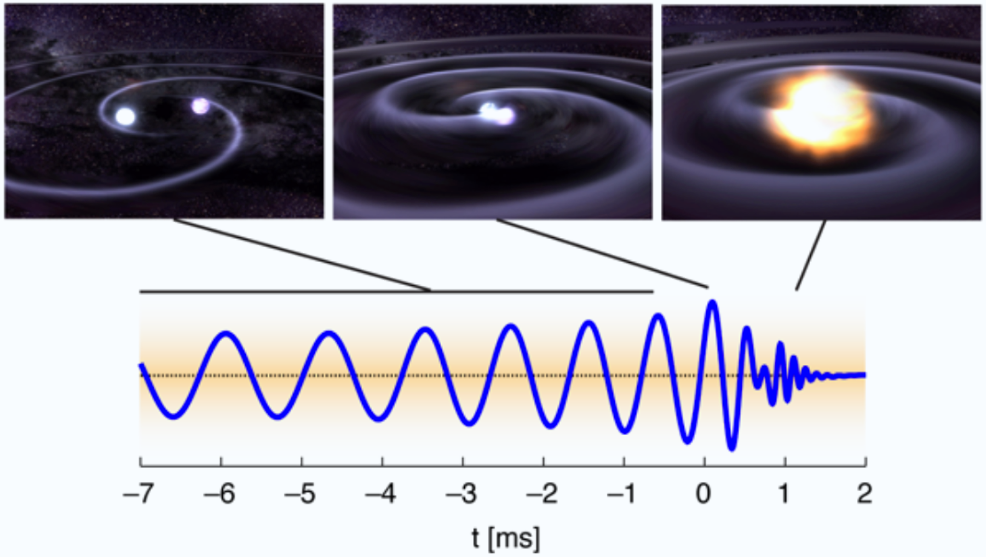
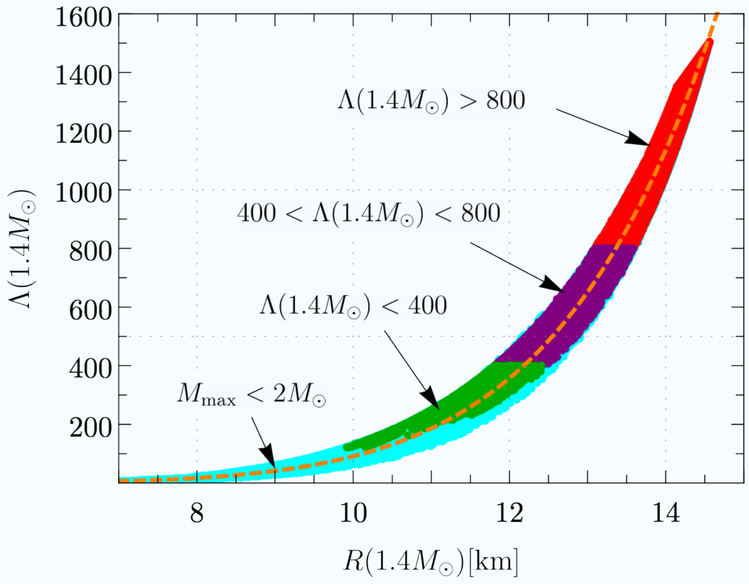
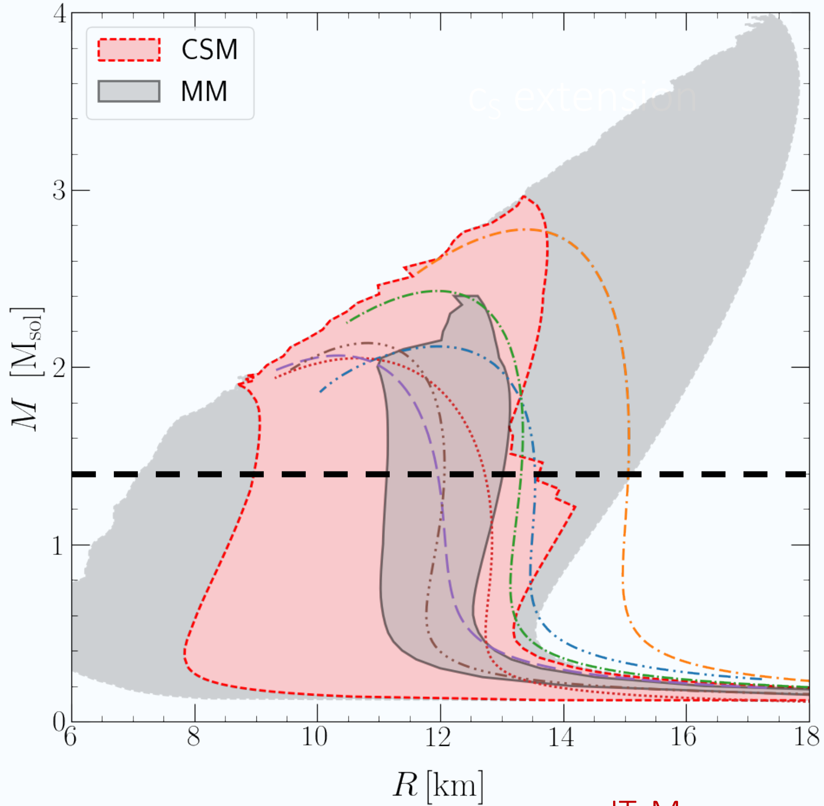


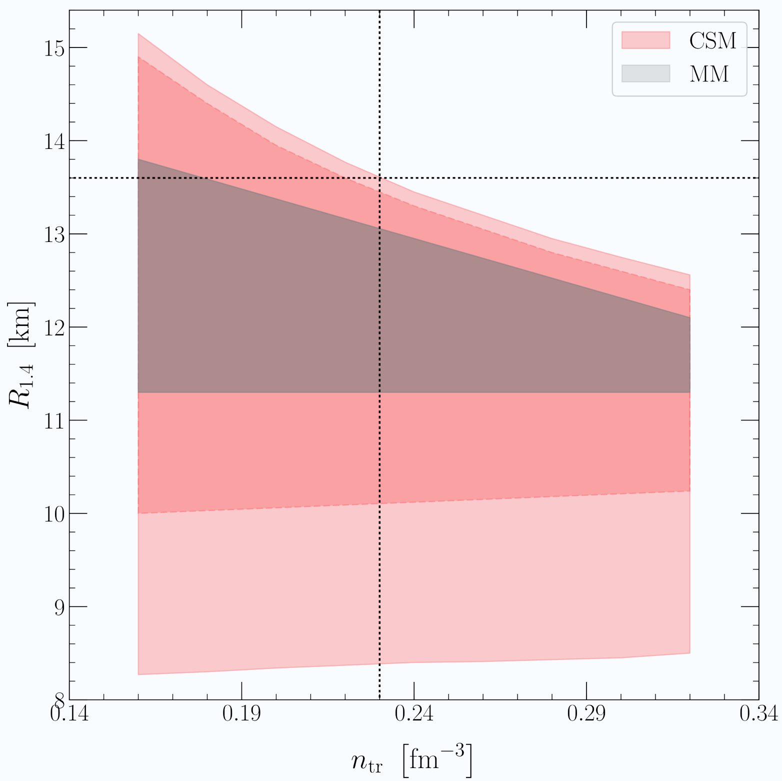
Illustration: (Top) NASA; (Bottom), Alan Stonebreaker



Annala et al., PRL (2018)

Predictions based on GW170817

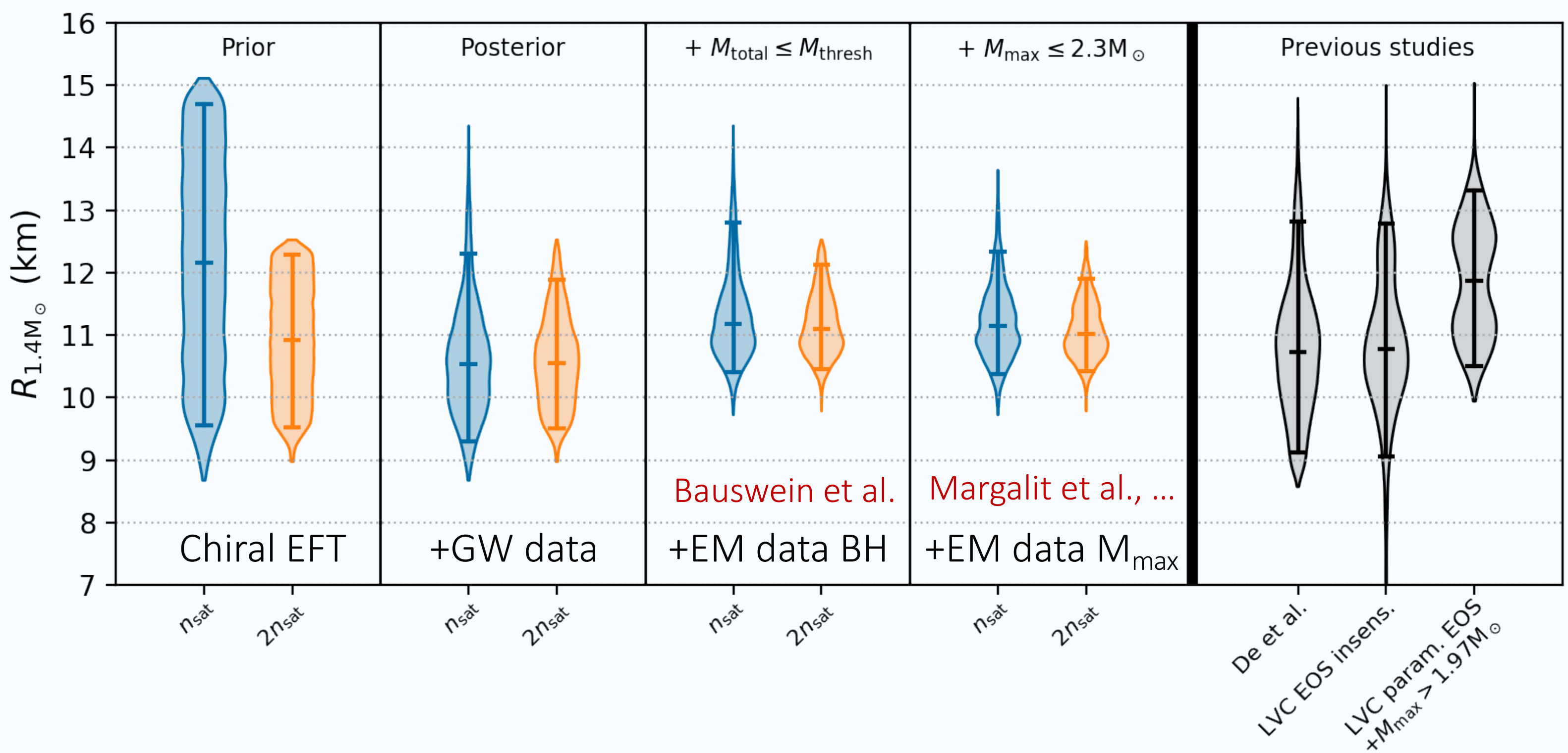




IT, Margueron, Reddy, PRC (2018)

- First observation of neutron-star merger: $70 \leq \tilde{\Lambda} \leq 720$
- LIGO observation implies $R_{1.4}$ < 13.6 km:
  - Chiral EFT input becomes compatible with GW170817 at n_{tr}=0.23 fm^{-3} (k_F=1.9 fm^{-1})

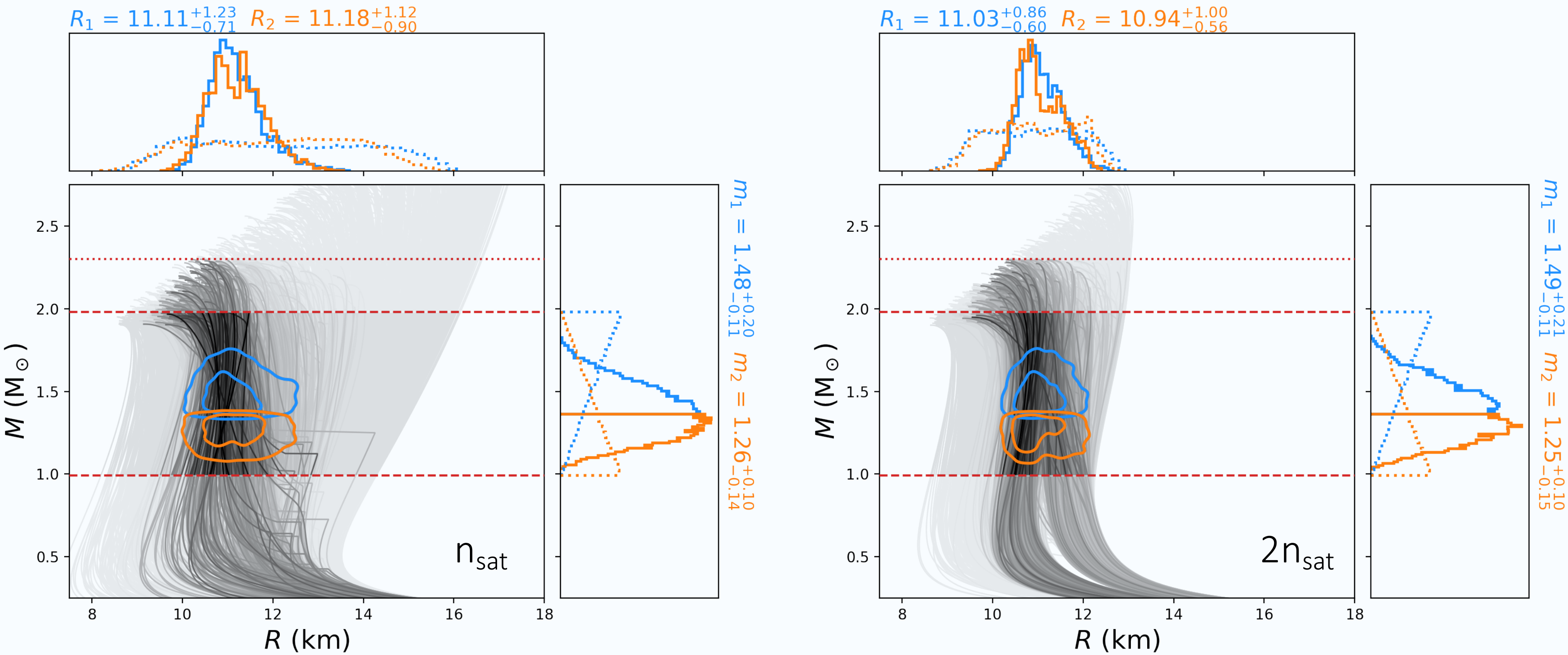
Measure the EOS directly from GW data



- We want to consistently combine constraints from low-energy nuclear theory, gravitational-wave observations and electromagnetic observations.
- Use Bayesian methods to determine probability so that the tidal polarizability of GW170817 is consistent with a specific equation of state in our sets.
- Stringent constraints on NS radii: $R_{1.4M_\odot} = 11.0^{+0.9}_{-0.6}\,\mathrm{km}$

Capano, IT, et al. , arXiv:1908.10352

Measure the EOS directly from GW data



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Capano, IT, et al. , arXiv:1908.10352

Summary

- Neutron stars represent ideal laboratories for nuclear physics!
- There is a large uncertainty for the EOS, but this uncertainty can be reduced by:
  - Nuclear physics constraints at low densities.
  - Observational constraints from neutron-star mergers.
- Already the first neutron-star merger event, GW170817, has provided EOS constraints.
- Constraints from GW signal have large uncertainties, but definitely rule out stars with $R_{1.4} > 13.6$ km. An updates analysis rules out stars with $R_{1.4} > 11.9$ km.
- Constraints from EM signal depend on information from simulations with limited number of EOS! More EOS need to be explored.
- Much work to do on theory side: additional constraints at low densities reduce uncertainty considerably. IT, Margueron, Reddy, PRC (2018)
- Even if can obtain EOS, we need to understand it (exotic matter?).

Outlook

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GraceDB — Gravitational-Wave Candidate Event Database

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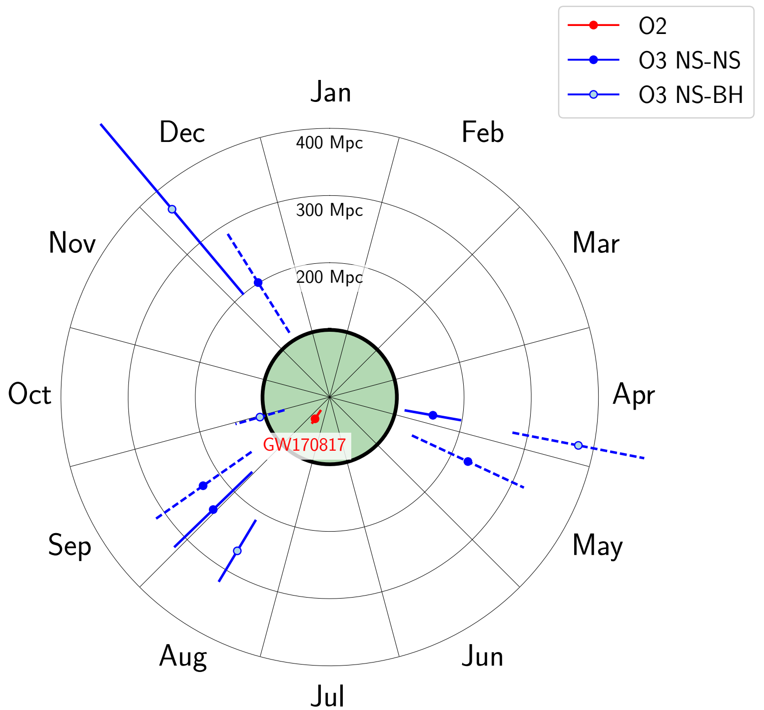
Latest — as of 9 September 2019 22:44:52 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.



Additional Observations:
GW190910d: NS-BH (632 ± 186 Mpc)
GW190923ly: NS-BH (438 ± 133 Mpc)

Observing run O3 since April 01: 30-40 events

		t_start	t_0	t_end	FAR (Hz)	UTC Created
		1251415878.837767	1251415879.837767	1251415880.838844	7.027e-09	2019-09-01 23:31:24 UTC
		1251147973.281494	1251147974.283940	1251147975.283940	5.151e-09	2019-08-29 21:06:19 UTC
		1251010526.884921	1251010527.886557	1251010528.913573	4.629e-11	2019-08-28 06:55:26 UTC
		1251009262.739486	1251009263.756472	1251009264.796332	8.474e-22	2019-08-28 06:34:21 UTC
		1250472616.589125	1250472617.589203	1250472618.589203	6.145e-18	2019-08-22 01:30:23 UTC
		1249995888.757789	1249995889.757789	1249995890.757789	1.436e-08	2019-08-16 13:05:12 UTC
		1249852255.996787	1249852257.012957	1249852258.021731	2.033e-33	2019-08-14 21:11:18 UTC
		1249338098.496141	1249338099.496141	1249338100.496141	3.366e-08	2019-08-08 22:21:45 UTC
		1248331527.497344	1248331528.546797	1248331529.706055	2.527e-23	2019-07-28 06:45:27 UTC
		1248242630.976288	1248242631.985887	1248242633.180176	1.378e-10	2019-07-27 06:03:51 UTC
		1247616533.703127	1247616534.704102	1247616535.860840	3.801e-09	2019-07-20 00:08:53 UTC
		1247495729.067865	1247495730.067865	1247495731.067865	3.648e-08	2019-07-18 14:35:34 UTC
		1246527223.118398	1246527224.181226	1246527225.284180	5.265e-12	2019-07-07 09:33:44 UTC
		1246487218.321541	1246487219.344727	1246487220.585938	1.901e-09	2019-07-06 22:26:57 UTC
		1246048403.576563	1246048404.577637	1246048405.814941	1.916e-08	2019-07-01 20:33:24 UTC
		1245955942.175325	1245955943.179550	1245955944.183184	1.435e-13	2019-06-30 18:52:28 UTC
		1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51 UTC
		1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30 UTC
		1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
		1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
		1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04 UTC
		1242242376.474609	1242242377.474609	1242242380.922655	1.004e-08	2019-05-18 19:19:39 UTC
		1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
		1241816085.736106	1241816086.869141	1241816087.869141	3.734e-13	2019-05-13 20:54:48 UTC
		1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42 UTC
		1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
		1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
		1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
		1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

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