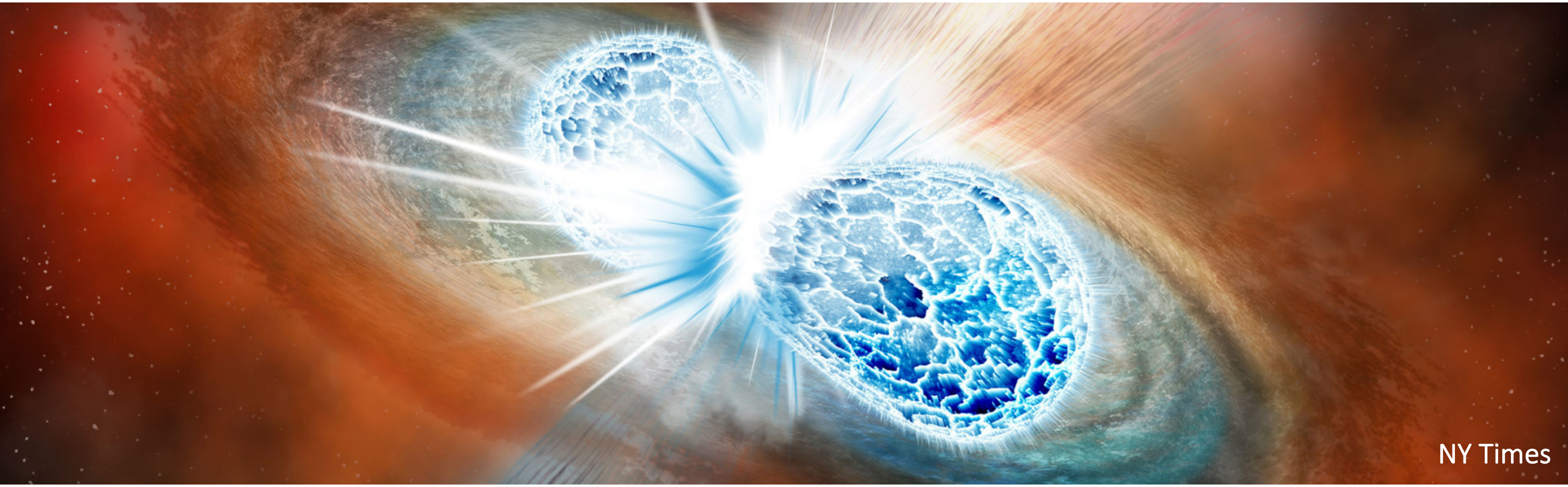
Chiral EFT and neutron-star structure from crust to core



Ingo Tews

In collaboration with J. Margueron, S. Reddy, J. Carlson, S. Gandolfi

INT Workshop: Astro-solids, dense matter, and gravitational waves,
April 16-20, 2018,
Institute for Nuclear Theory, Seattle

JINA–CEE

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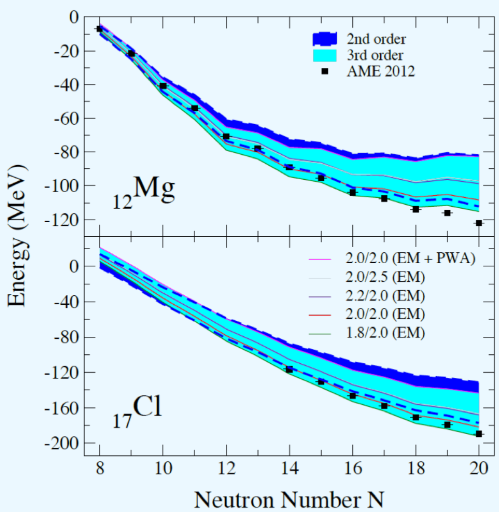
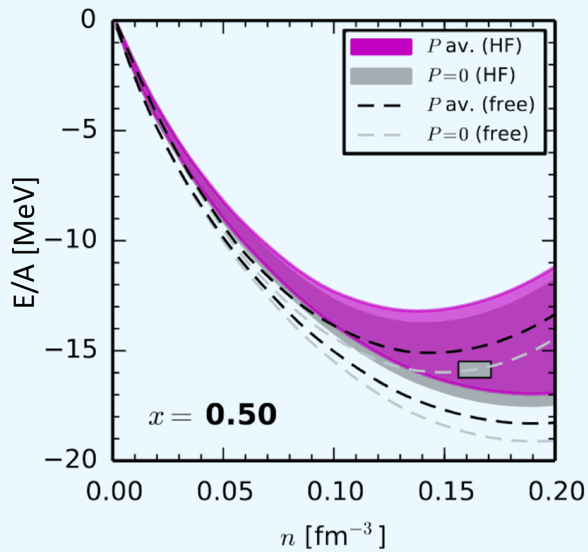
Motivation

Present theoretical predictions for nuclear systems are limited by:

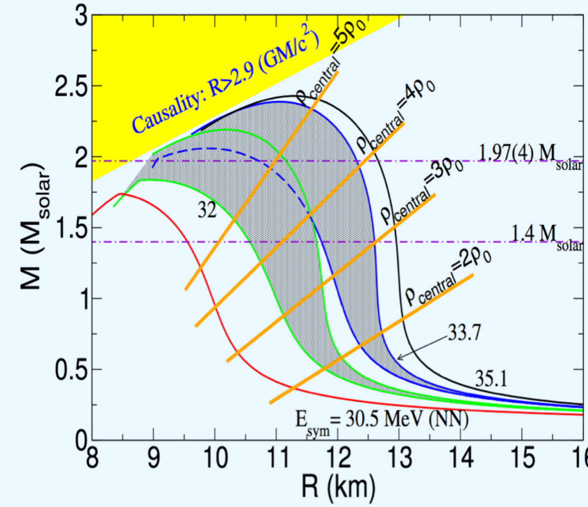
- our understanding of nuclear interactions,
- and our ability to reliably calculate these strongly interacting systems.



Simonis et al., PRC (2016)



Drischler et al.,PRC (2016)



Gandolfi, Carlson, Reddy, PRC (2012)

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.

Outline

- What are the fundamental interactions that govern strongly interacting matter?

  Chiral effective field theory: e.g. Epelbaum *et al.*, PPNP (2006) and RMP (2009)
  - Systematic basis for nuclear forces, naturally includes many-body forces.

  Quantum Monte Carlo methods.

- How does subatomic matter organize itself?

  Results of Quantum Monte Carlo calculations with chiral interactions
  - for neutron matter,
  - for light to medium-mass nuclei.

- How can we understand astrophysical phenomena?

  Results for astrophysical applications:.
  - Neutron-star equation of state and structure.
  - Neutron-star mergers

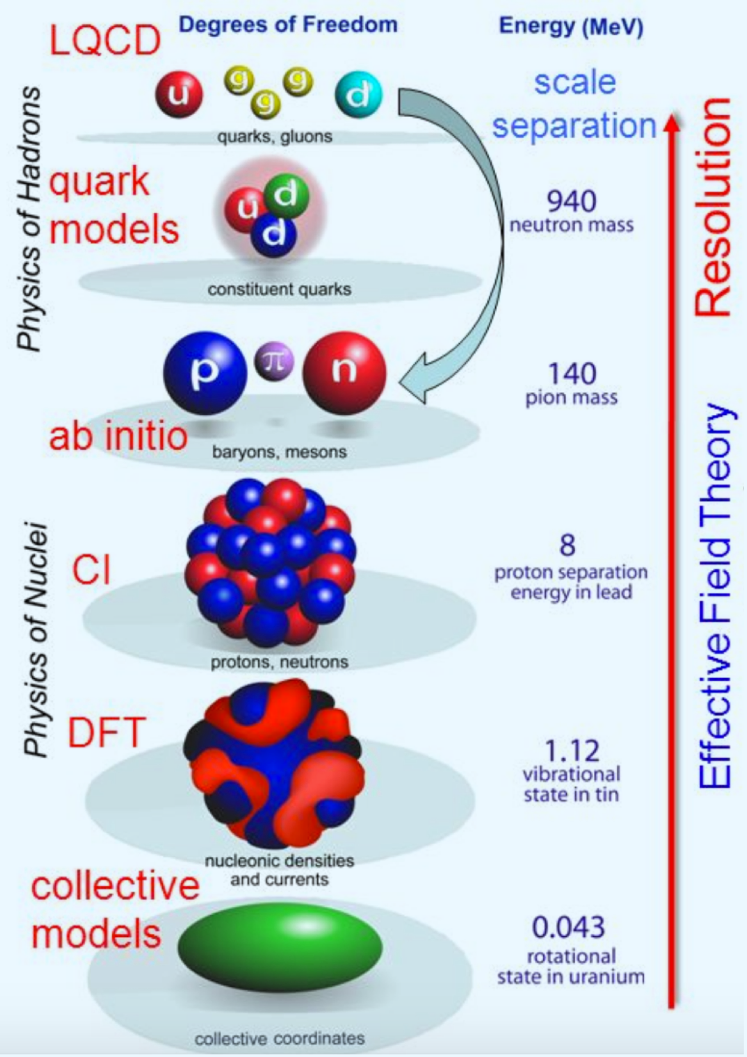
- Summary

Chiral effective field theory for nuclear forces

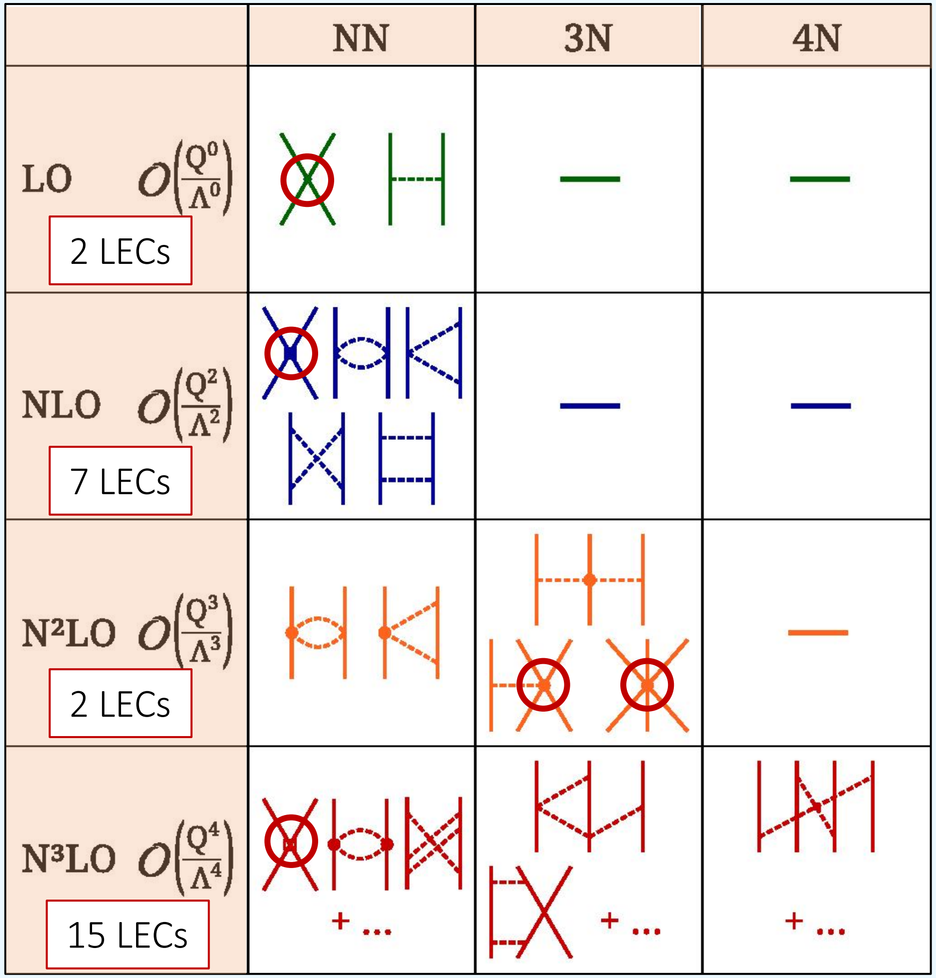
Quantum Chromodynamics (QCD)

↓

Nuclear Physics (EOS, nuclei)



Chiral effective field theory for nuclear forces

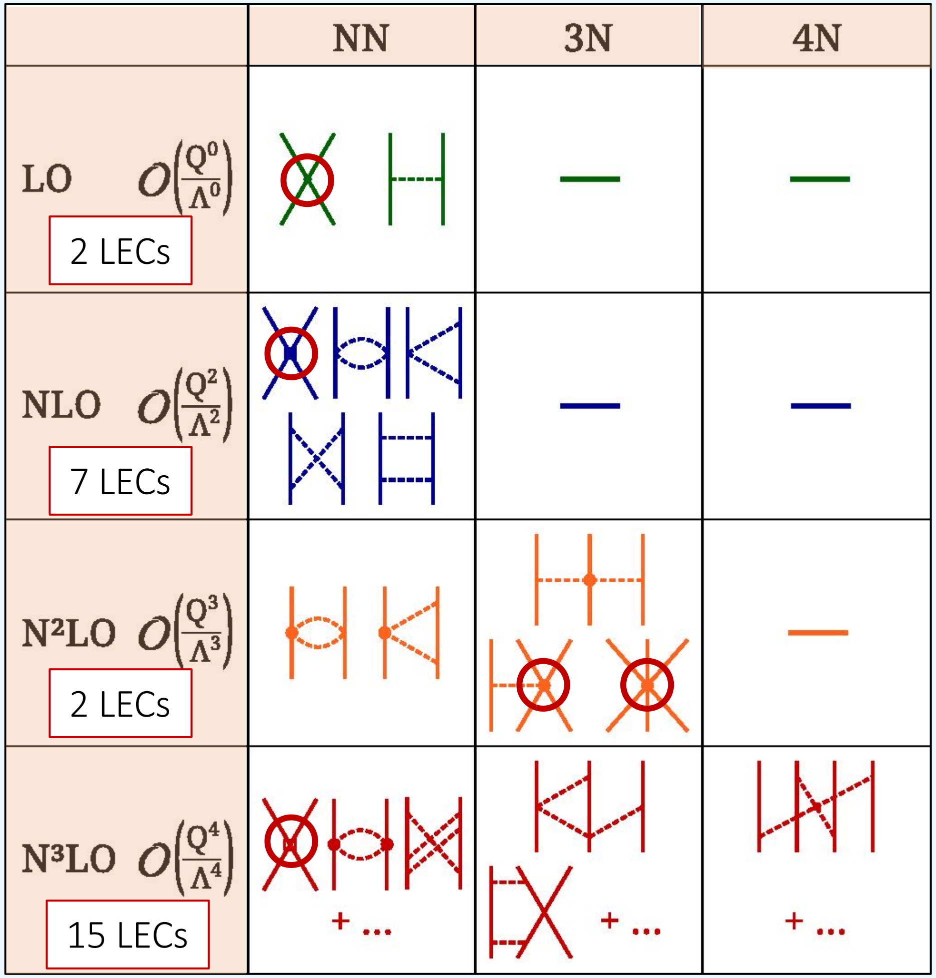


Systematic expansion of nuclear forces:

- Pions and nucleons as relevant degrees of freedom
- Power counting scheme
- Operators constrained by symmetries of QCD, short-range physics captured in set of low-energy couplings
- Natural hierarchy of nuclear forces
- Can work to desired accuracy with systematic error estimates
- Fitting: NN forces in NN system (NN phase shifts), 3N forces in 3N/4N system (Binding energies, radii)

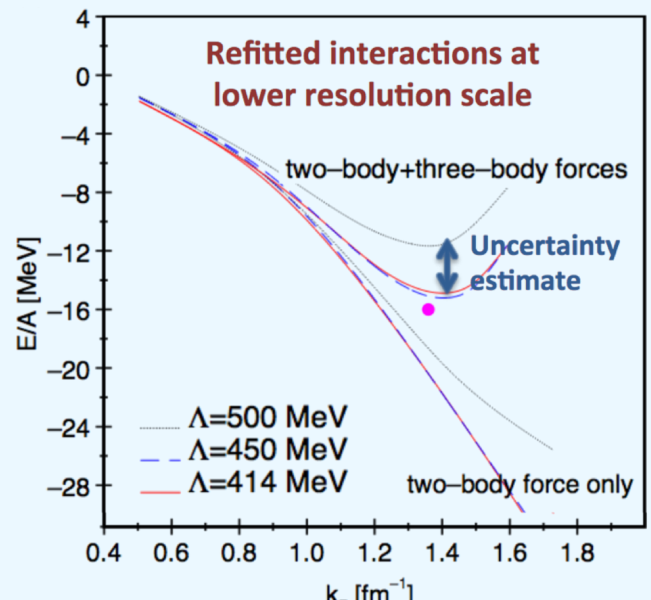
Weinberg, van Kolck, Kaplan, Savage, Wise,
Epelbaum, Kaiser, Machleidt, Meißner, Hammer ...

Chiral effective field theory for nuclear forces



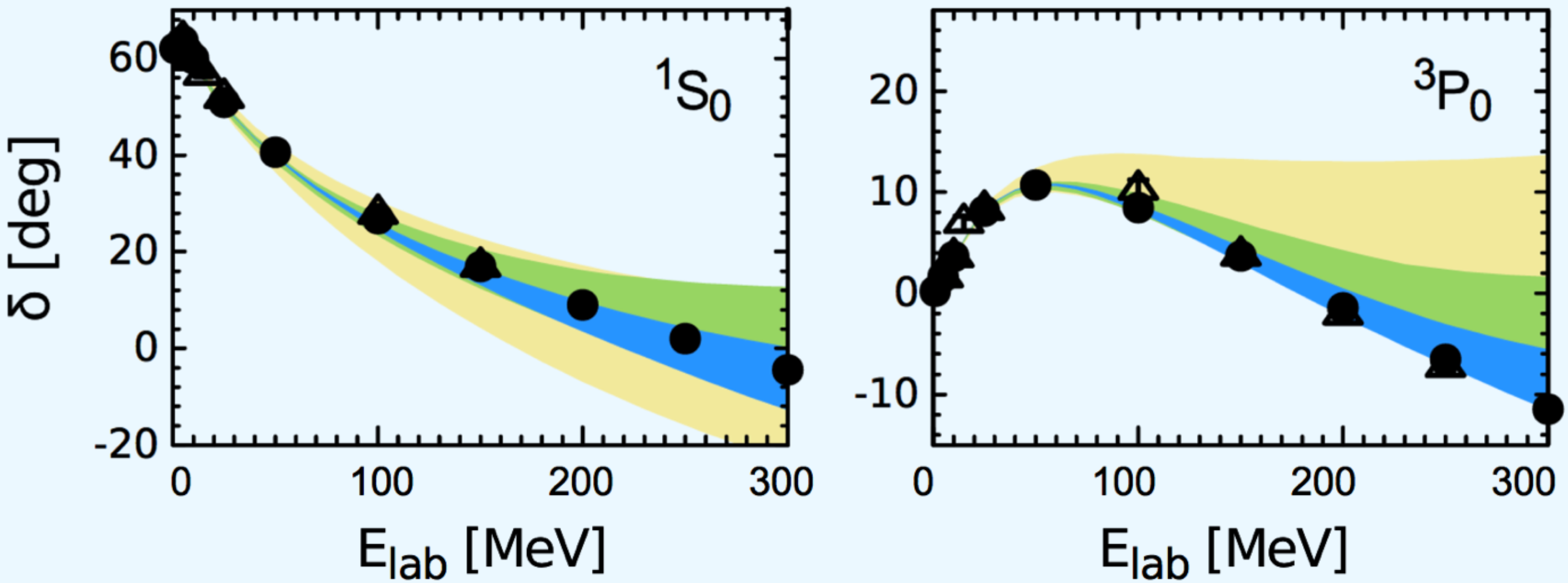
Many-body forces:

- Natural hierarchy of nuclear forces
- Crucial for nuclear physics
- Consistent interactions: Same couplings for two-nucleon and many-body sector



Coraggio, Holt, Itaco, Machleidt, Marcucci, Sammarruca, PRC (2014)

Chiral effective field theory for nuclear forces



Epelbaum *et al.*, Eur. Phys. J (2015)

Systematic expansion of the nuclear forces:

- Can work to desired accuracy
- Can obtain systematic error estimates

Quantum Monte Carlo method

Cast many-body Schrödinger equation as diffusion equation:

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

Basic steps:

- Choose trial wavefunction which overlaps with the ground state

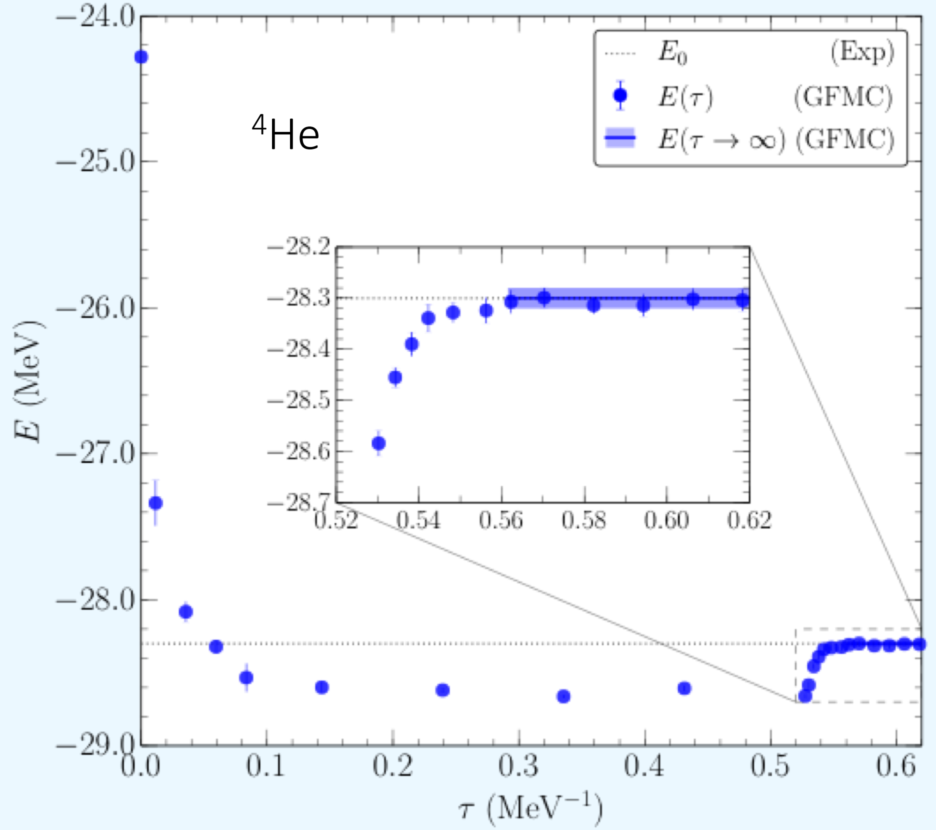
$$|\psi(R,0)\rangle = |\psi_T(R,0)\rangle = \sum_i c_i|\phi_i\rangle \to \sum_i c_i e^{-(E_i-E_0)\tau}|\phi_i\rangle$$

- Evaluate propagator for small timestep $\Delta\tau$, in practice only for local potentials
- 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

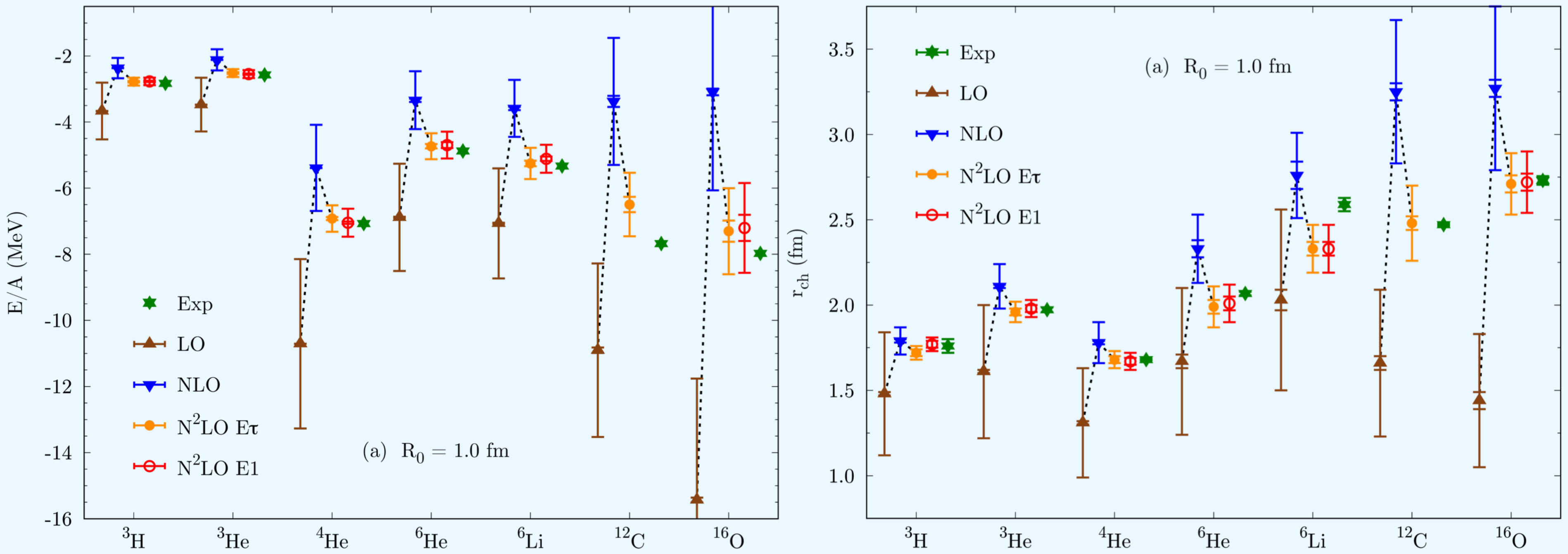


Lynn, IT, Carlson, Gandolfi, Gezerlis, Schmidt, Schwenk, PRC (2017)

- Very precise method for strongly interacting systems.
- Many-body uncertainty is statistical.

Results

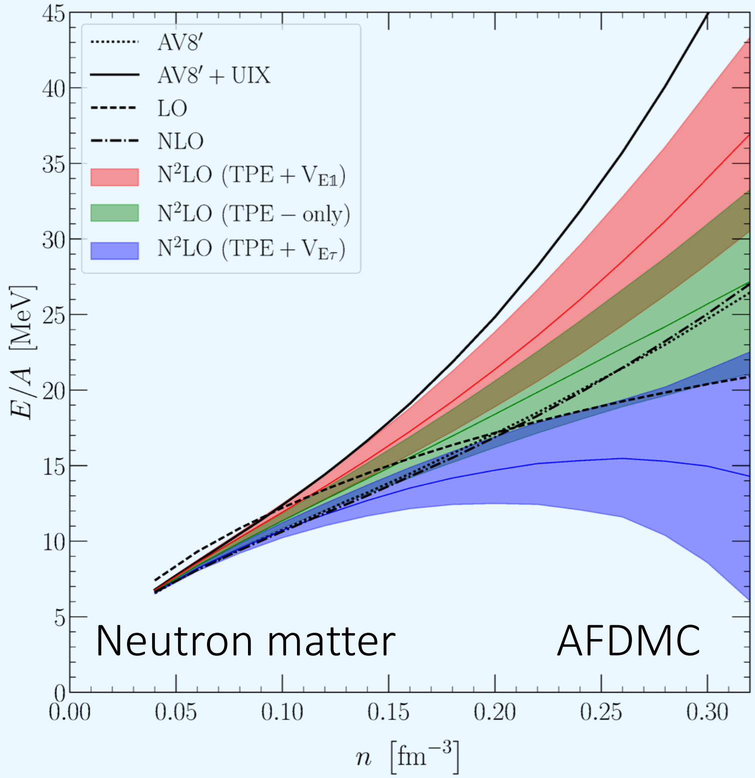
Recent results for Quantum Monte Carlo calculations of nuclei:



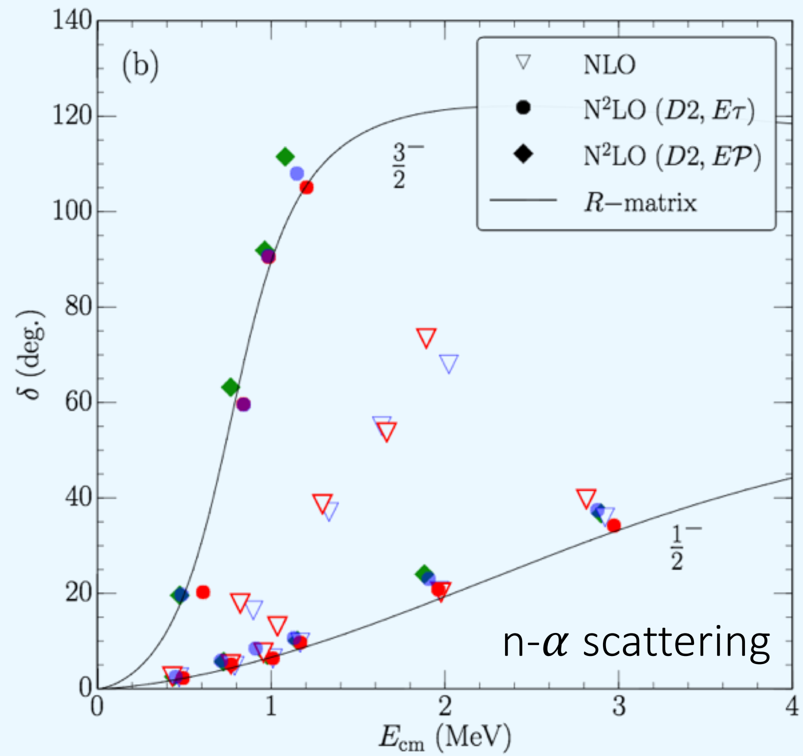
Excellent description of binding energies and charge radii for A ≤16.

Lonardoni et al., arXiv:1709.09143 and 1802.08932

Results



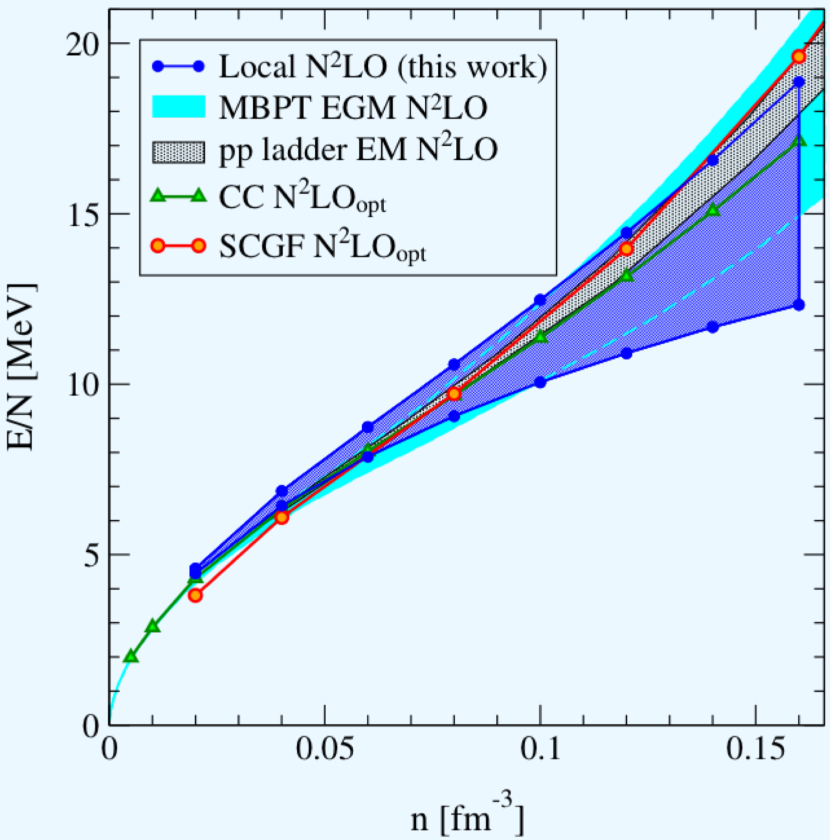
IT, Carlson, Gandolfi, Reddy, arXiv:1801.01923

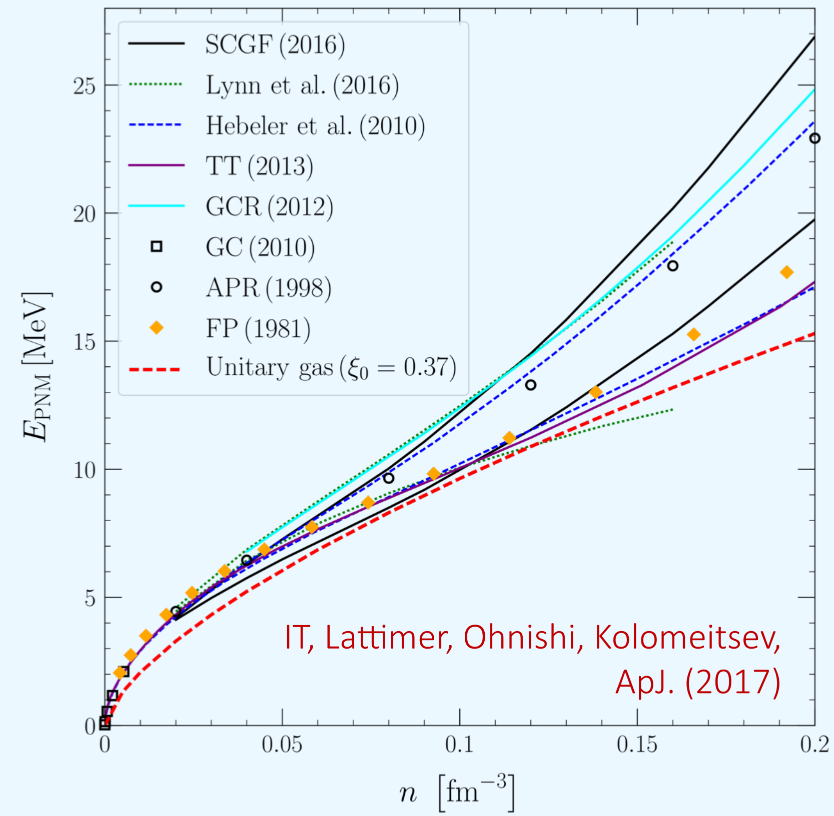


Lynn, IT, et al., PRL (2016)

- Chiral interactions at N^2LO simultaneously reproduce the properties of A≤16 systems and of neutron matter (uncertainty estimate as in E. Epelbaum et al, EPJ (2015)).
- Uncertainty from nuclear interactions grows fast with density and limits applicability of nuclear ab initio calculations.

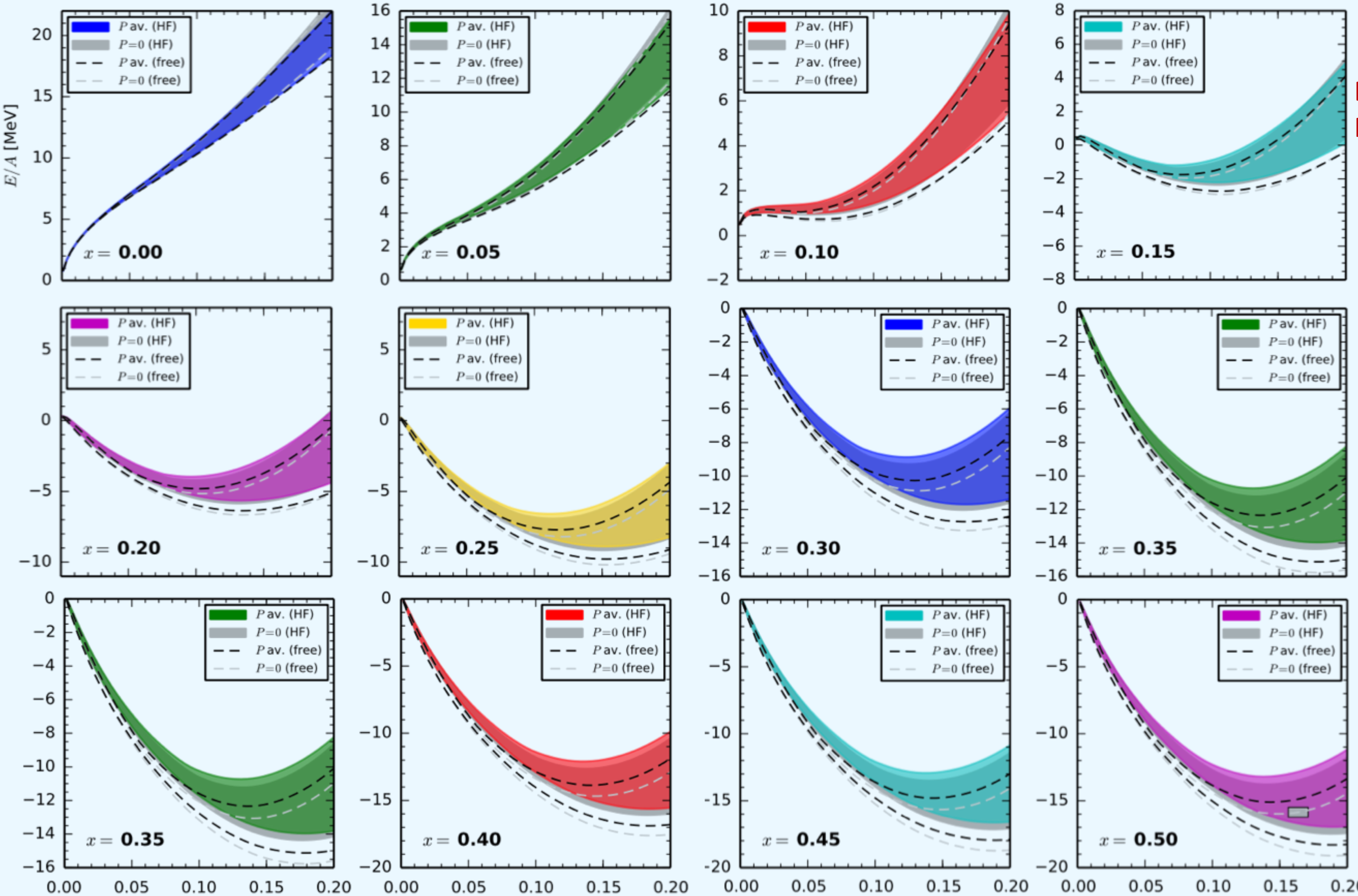
Results





- Good agreement between various microscopic approaches to neutron matter.
- Uncertainty originates mainly in many-body interactions.

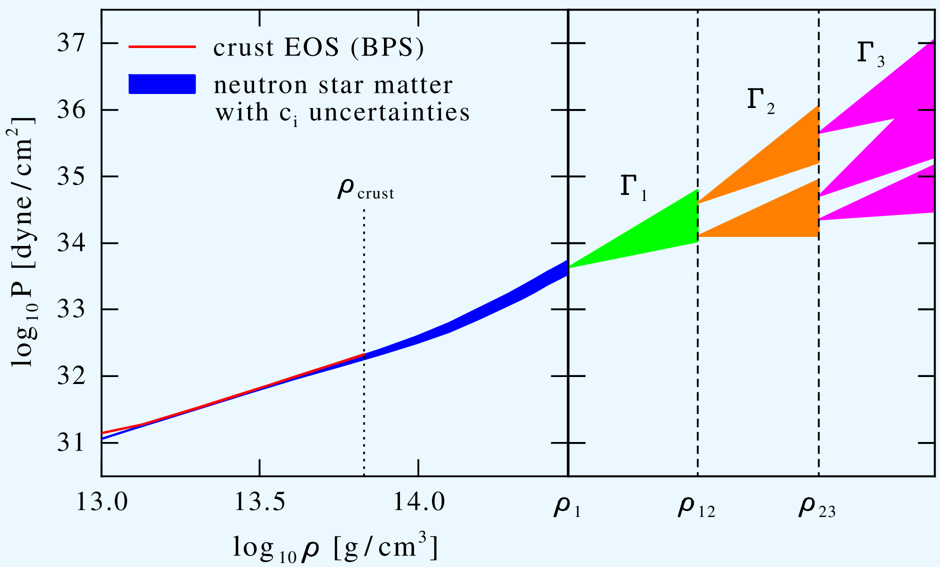
EOS for asymmetric matter



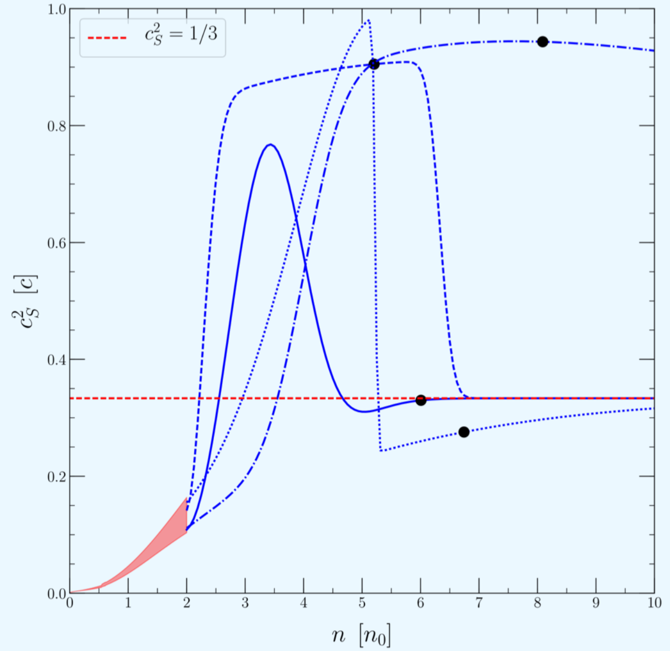
MBPT

Drischler et al., PRC (2016)

Neutron Star EOS



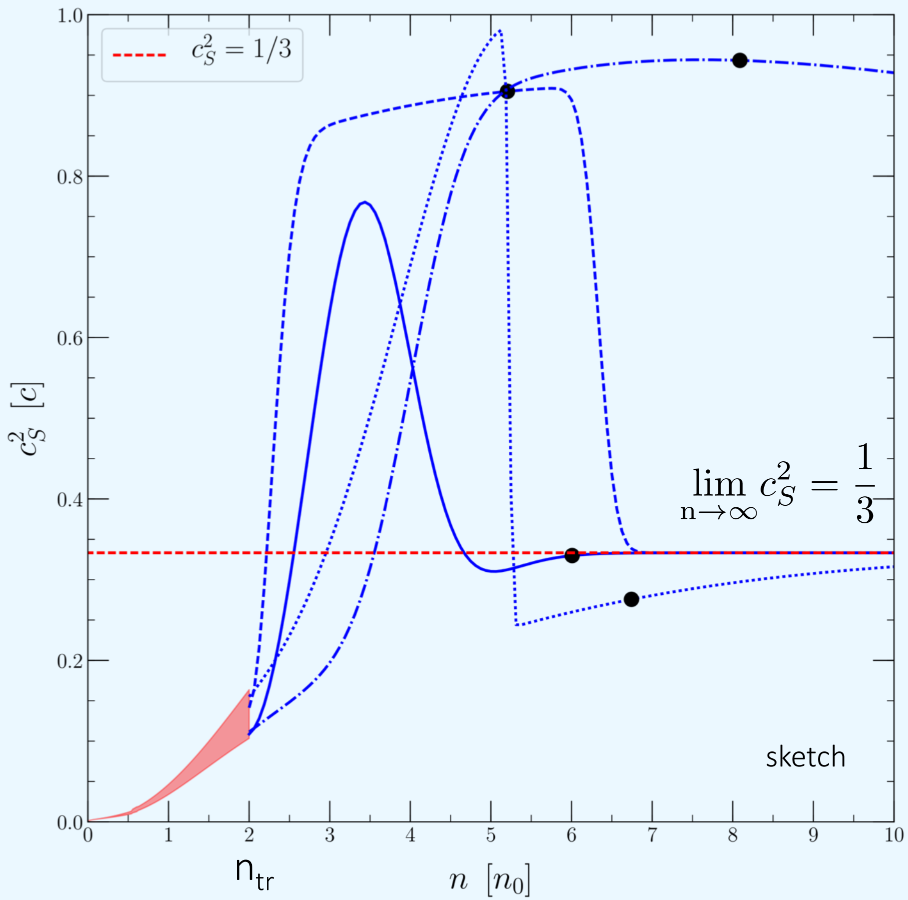
Hebeler et al., ApJ (2013)



IT, Carlson, Gandolfi, Reddy, arXiv:1801.01923

- 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, arXiv:1801.01923
  - Meta-EOS based on empirical parameters Margueron et al., PRC 97, 025805 & 025806 (2018)

Extension using speed of sound



IT, Carlson, Gandolfi, Reddy, arXiv:1801.01923

Use the speed of sound to extend EOS:

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. Gaussians, linear segments, etc.
- Sample many different curves and reconstruct EOS.
- Can easily include phase transitions.
- Loose information on degrees of freedom.

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

Meta-EOS based on the nuclear empirical parameters (MM)

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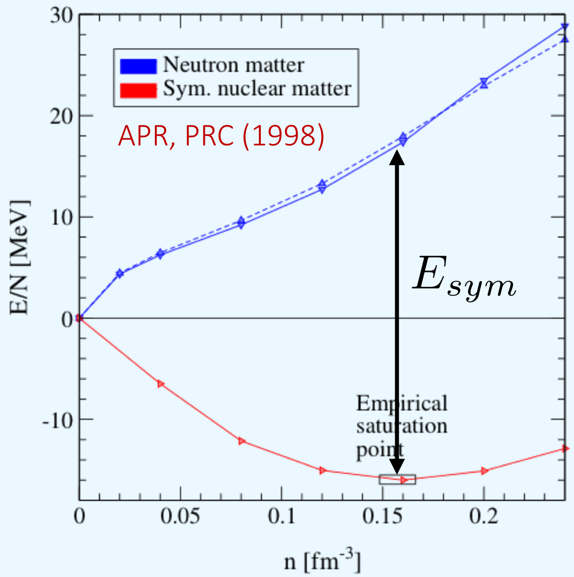

Typically, extrapolation to asym. nucl. matter from sym. nucl. matter:

$$\frac{E}{A}(n,\delta) \approx e_{sat}(n) + e_{sym}(n)\delta^2 + e_{sym,4}(n)\delta^4 + \ldots$$

with

$$e_{sat}(n) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{6}Q_{sat}x^3 + \frac{1}{24}Z_{sat}x^4 + \ldots$$

$$e_{sym}(n) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \ldots$$

P_α	E_{sat} MeV	E_{sym} MeV	n_{sat} fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500
σ_{P_α}	±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000

Small uncertainties ← → (Esat … Ksat) Large uncertainties ← → (Ksym … Zsym)

Some empirical parameters are not well constrained by nuclear physics experiments:

- Generate uncertainties in the extrapolation to high density and large isospin asymmetry.
- The impact of these uncertainties on the nuclear EOS are determined from a meta-modelling.

Margueron, Casali, Gulminelli, PRC 97, 025805 & 025806 (2018)

Assumptions

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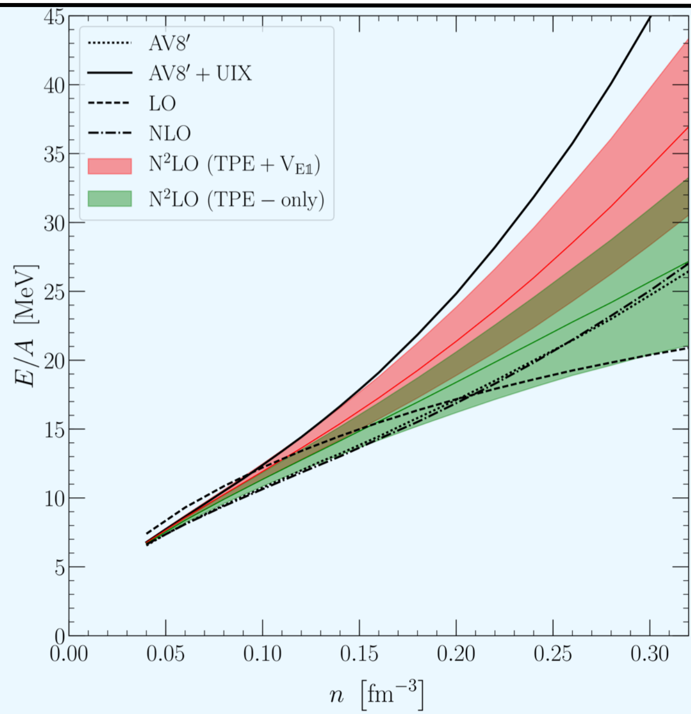


IT, Carlson, Gandolfi, Reddy, arXiv:1801.01923

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5] (2010)

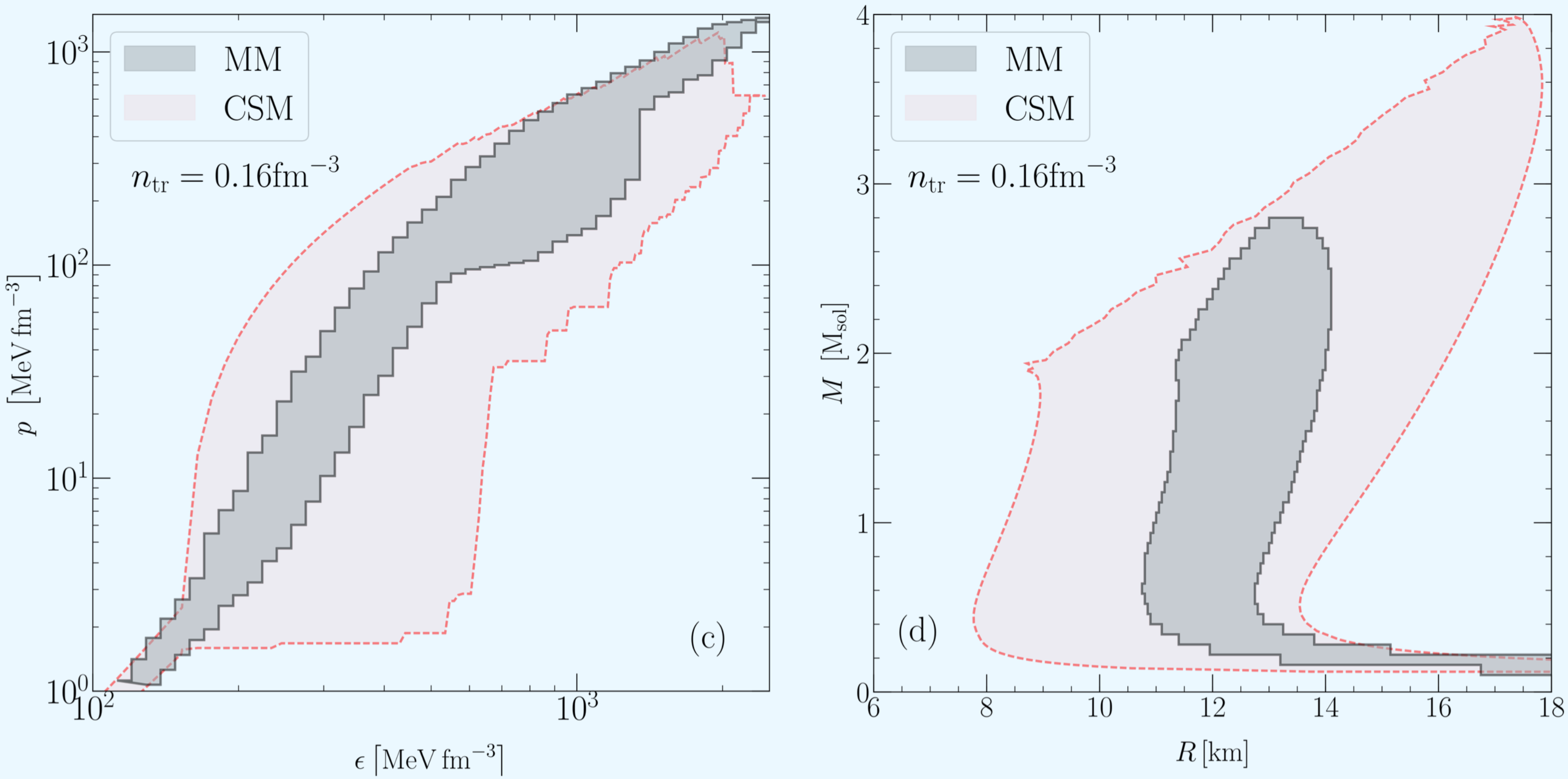
A Massive Pulsar in a Compact Relativistic Binary (2013)

John Antoniadis,* Paulo C. C. Freire, Norbert Wex, Thomas M. Tauris, Ryan S. Lynch, Marten H. van Kerkwijk, Michael Kramer, Cees Bassa, Vik S. Dhillon, Thomas Driebe, Jason W. T. Hessels, Victoria M. Kaspi, Vladislav I. Kondratiev, Norbert Langer, Thomas R. Marsh, Maura A. McLaughlin, Timothy T. Pennucci, Scott M. Ransom, Ingrid H. Stairs, Joeri van Leeuwen, Joris P. W. Verbiest, David G. Whelan

Generate thousands of EOSs that:

- Are consistent with low-density results from chiral effective field theory up to 1-2 n_0.
- Are causal ($c_S^2 \leq 1$) and stable ($c_S \geq 0$ inside neutron stars).
- Support 1.9 solar-mass neutron stars.

Comparison of models: $n_{tr}=n_0$

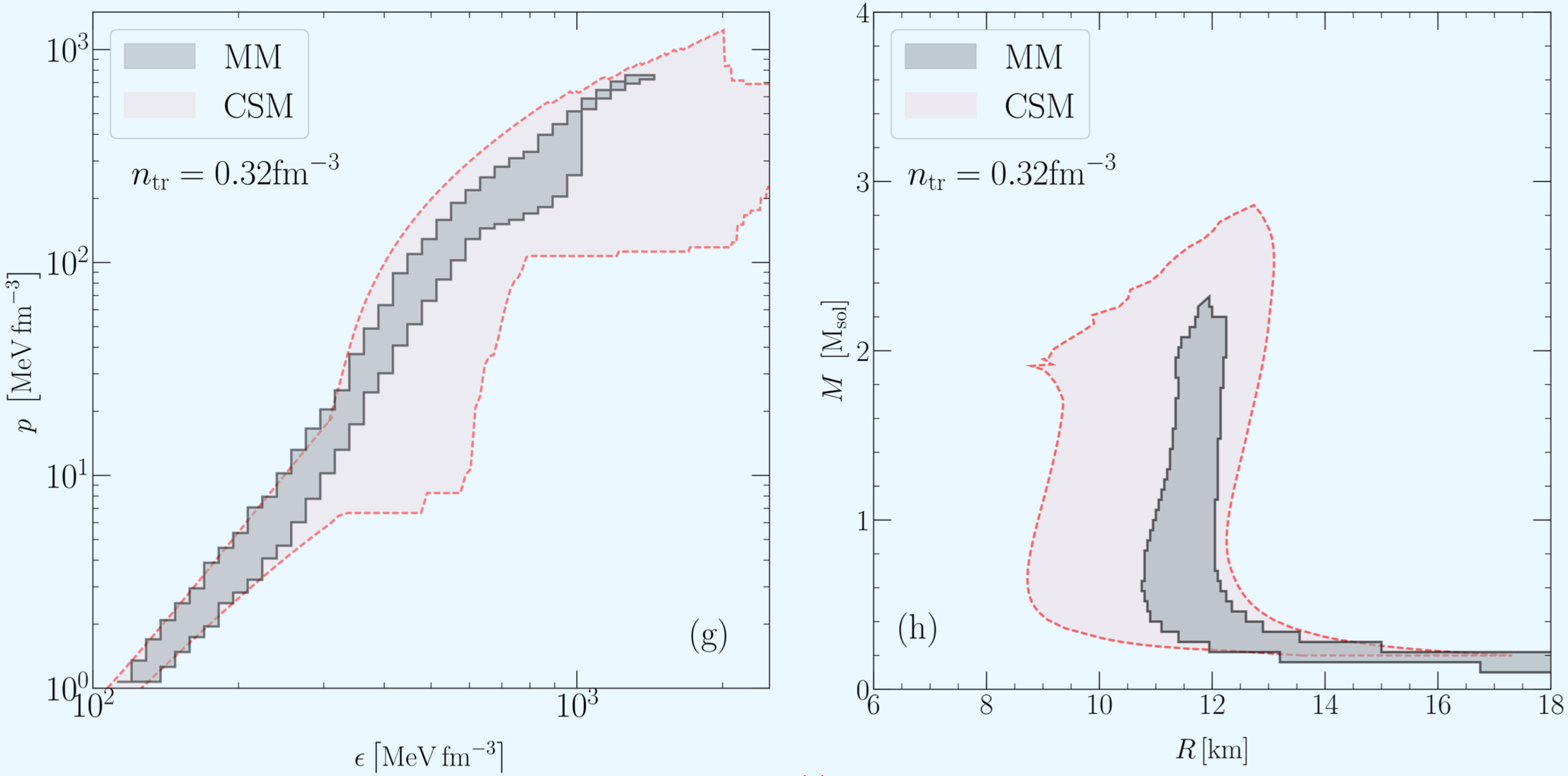


IT, Margueron, Reddy, arXiv:1804.0273

Chiral EFT constraint up to saturation density:

- Good agreement of different models!
- Different degrees of generalization: from nuclear degrees of freedom (black band) up to very general model with regions of softening and phase transition, etc.

Comparison of models: $n_{tr} = 2n_0$



IT, Margueron, Reddy, arXiv:1804.0273

Chiral EFT constraint up to two times saturation density:

- Good agreement of different models!
- Different degrees of generalization: from nuclear degrees of freedom (black band) up to very general model with regions of softening and phase transition, etc.

Extension using speed of sound

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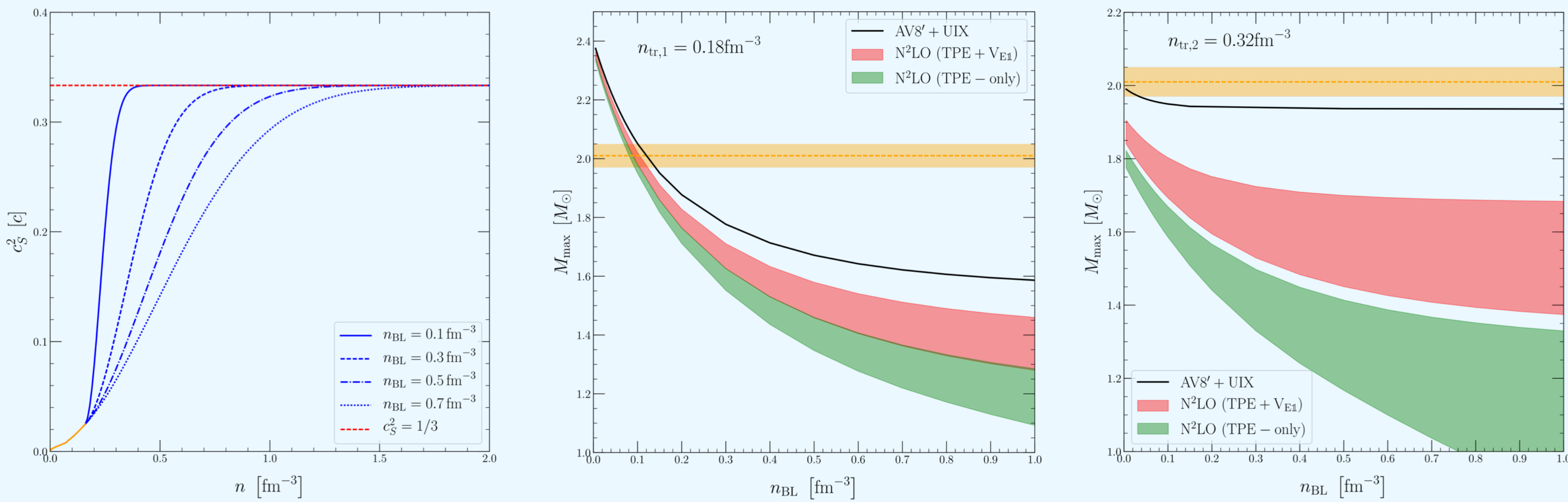
Varying transition density n_{tr} and using for $n > n_{tr}$:

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

(c_1 & c_2 fit at n_{tr})

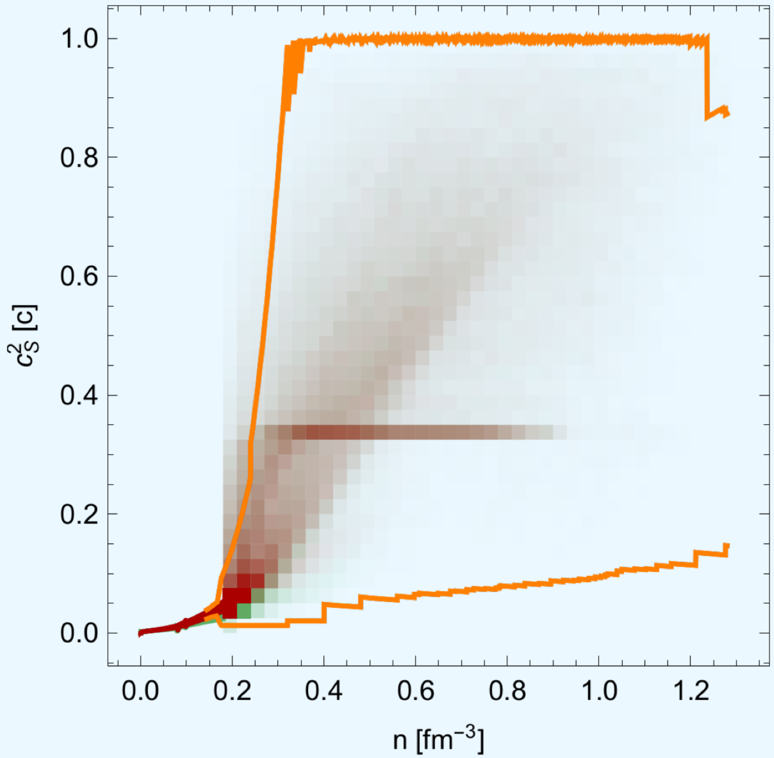


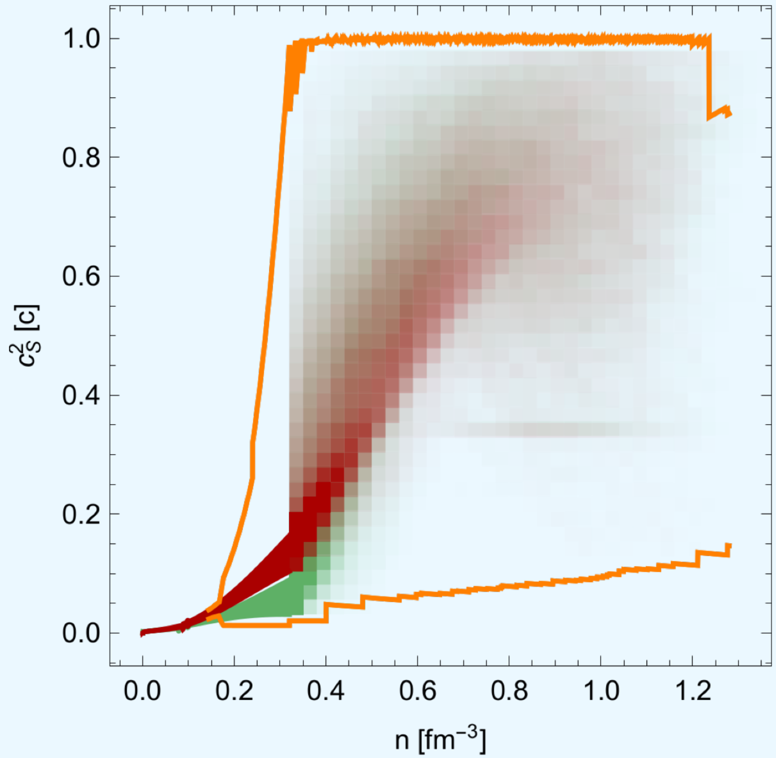
IT, Carlson, Gandolfi, Reddy, arXiv:1801.01923

See also Bedaque & Steiner (2015)

Extension using speed of sound

Allow speed of sound to vary between 0 and 1:

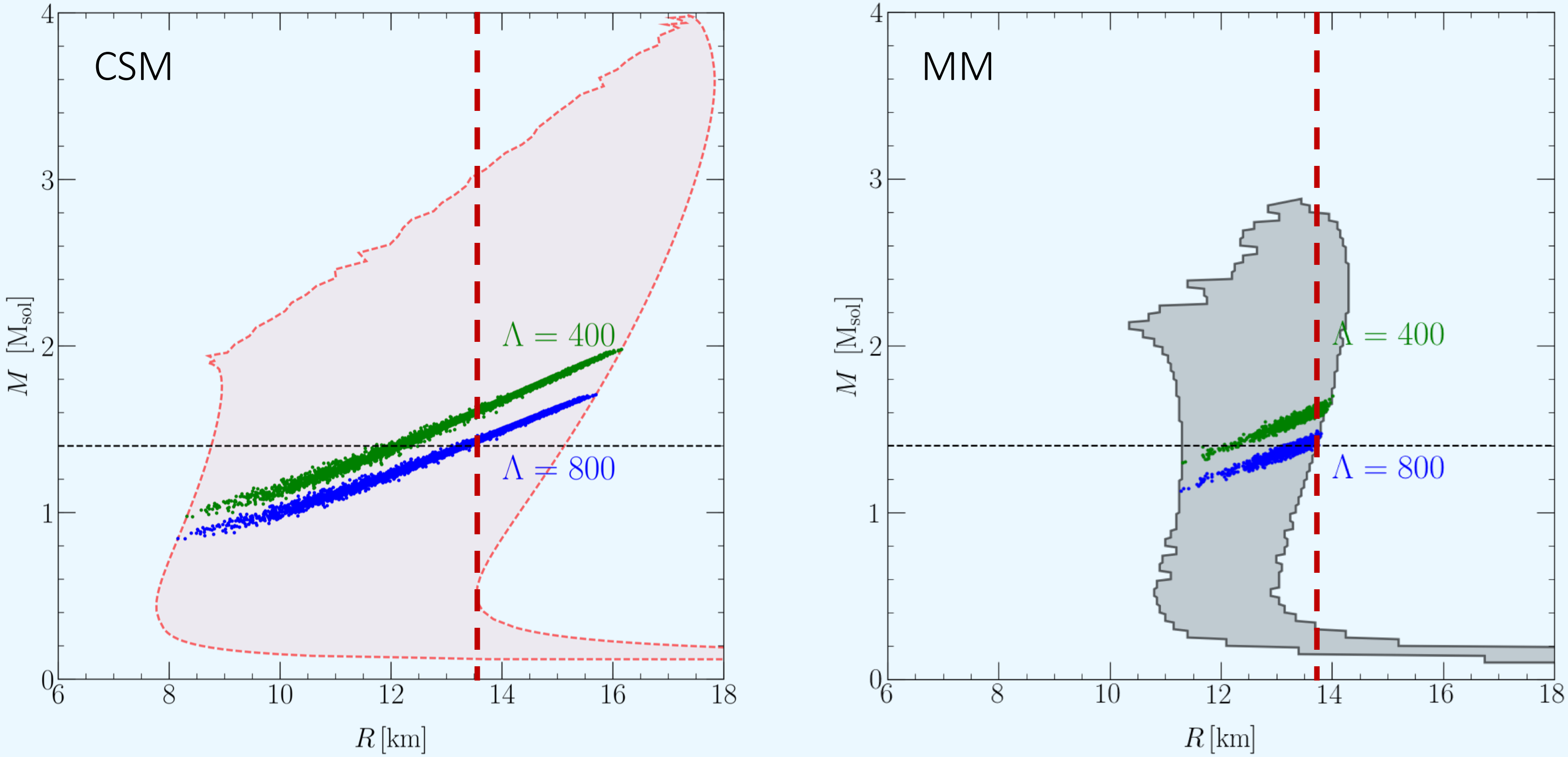




IT, Carlson, Gandolfi, Reddy, arXiv:1801.01923

See also Bedaque & Steiner (2015)

Constraint from GW170817



GW170817 provides constraints on the tidal polarizability ($n_{tr} = n_0$):

- Constrains the radius of a typical neutron star to be less than 13.6 km.

See also Annala et al., Most et al.

Predictions based on GW170817 posterior for NS masses

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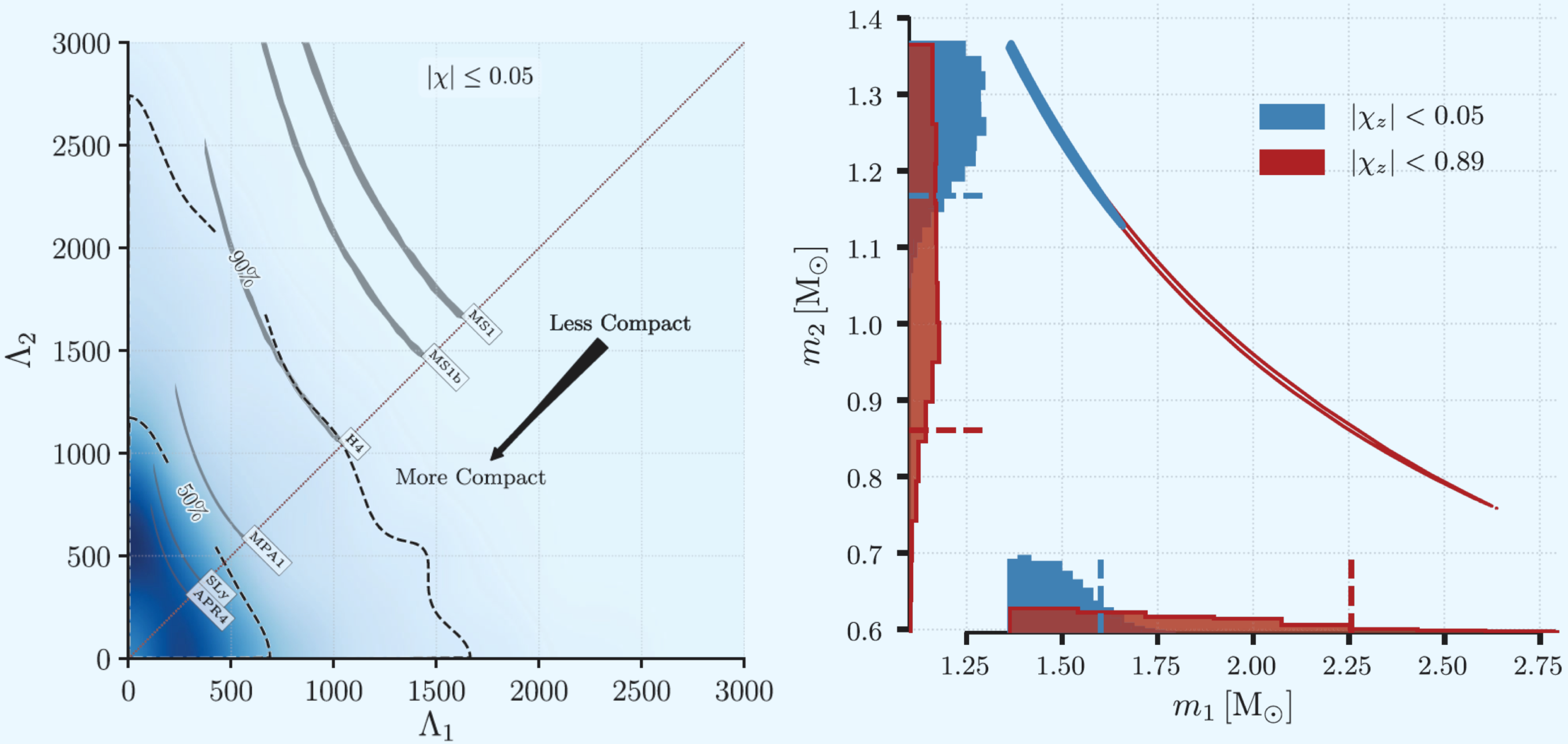
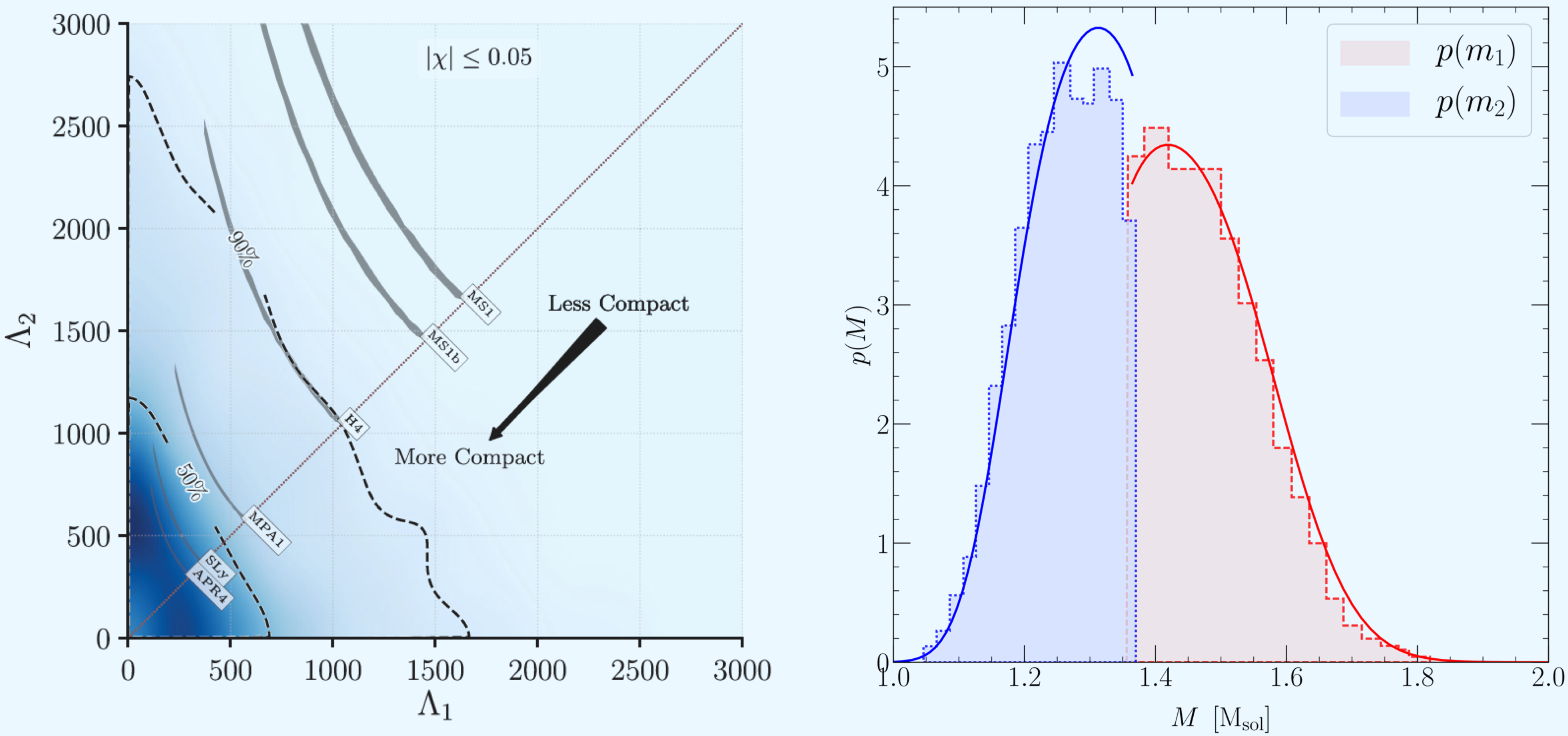


LIGO/VIRGO collaboration, PRL (2017)

Study GW170817:

- Obtain tidal polarizabilities using mass distributions of GW170817.
- We do not include prior on $\overline{\Lambda}$ from LIGO observation!

Predictions based on GW170817 posterior for NS masses



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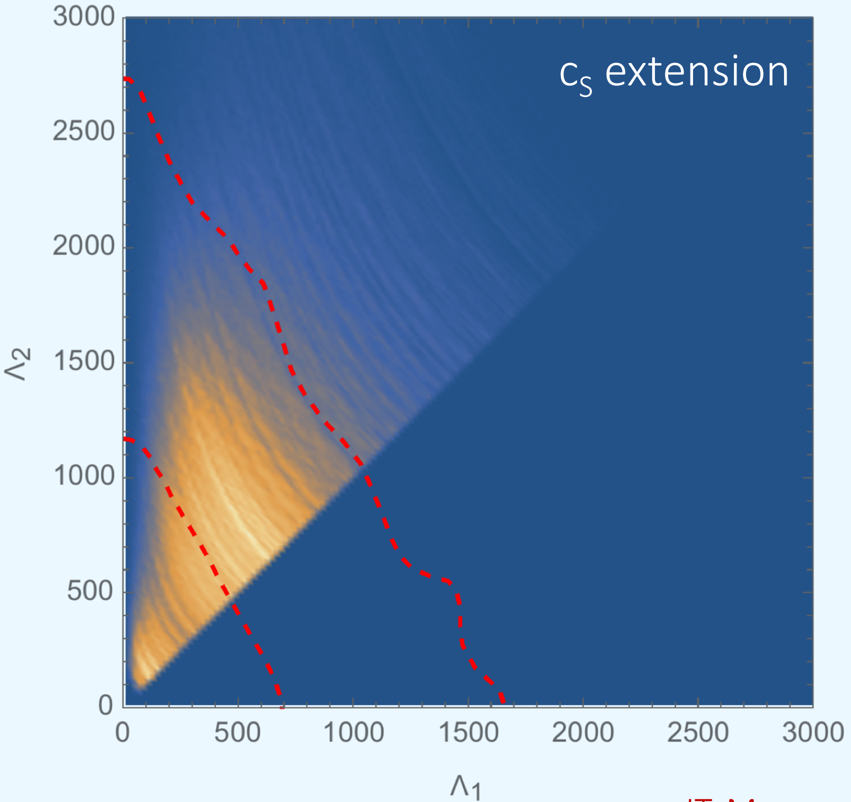
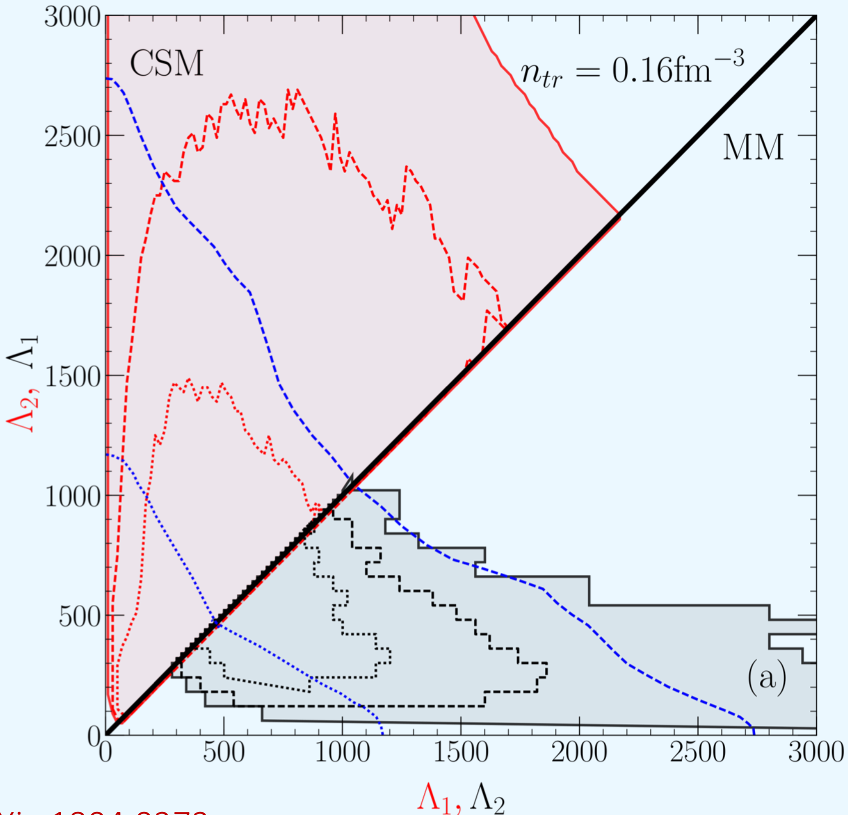
Predictions based on GW170817 posterior for NS masses: $n_{tr}=n_0$





IT, Margueron, Reddy, arXiv:1804.0273

'Trust' nuclear physics up to saturation density:

- Large range of tidal polarizabilities allowed, depending on freedom in high-density models: 60-2170 (CSM) and 260-1060 (MM)
- In this case, GW170817 provides constraints for the EOS.

Predictions based on GW170817 posterior for NS masses: $n_{tr}=n_0$

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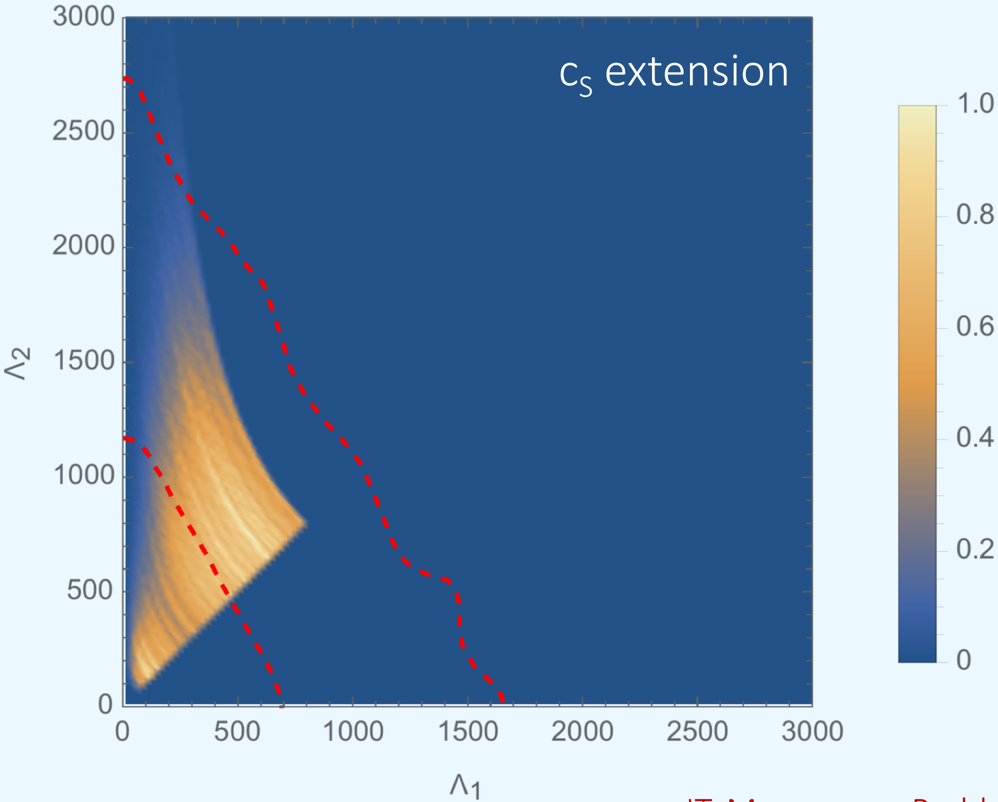
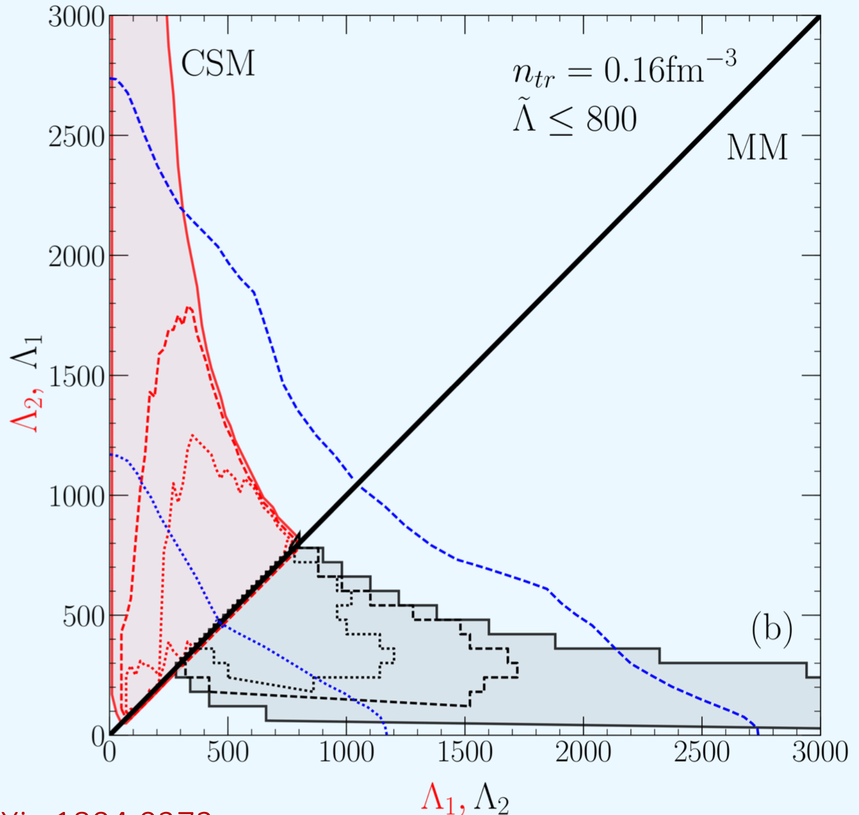


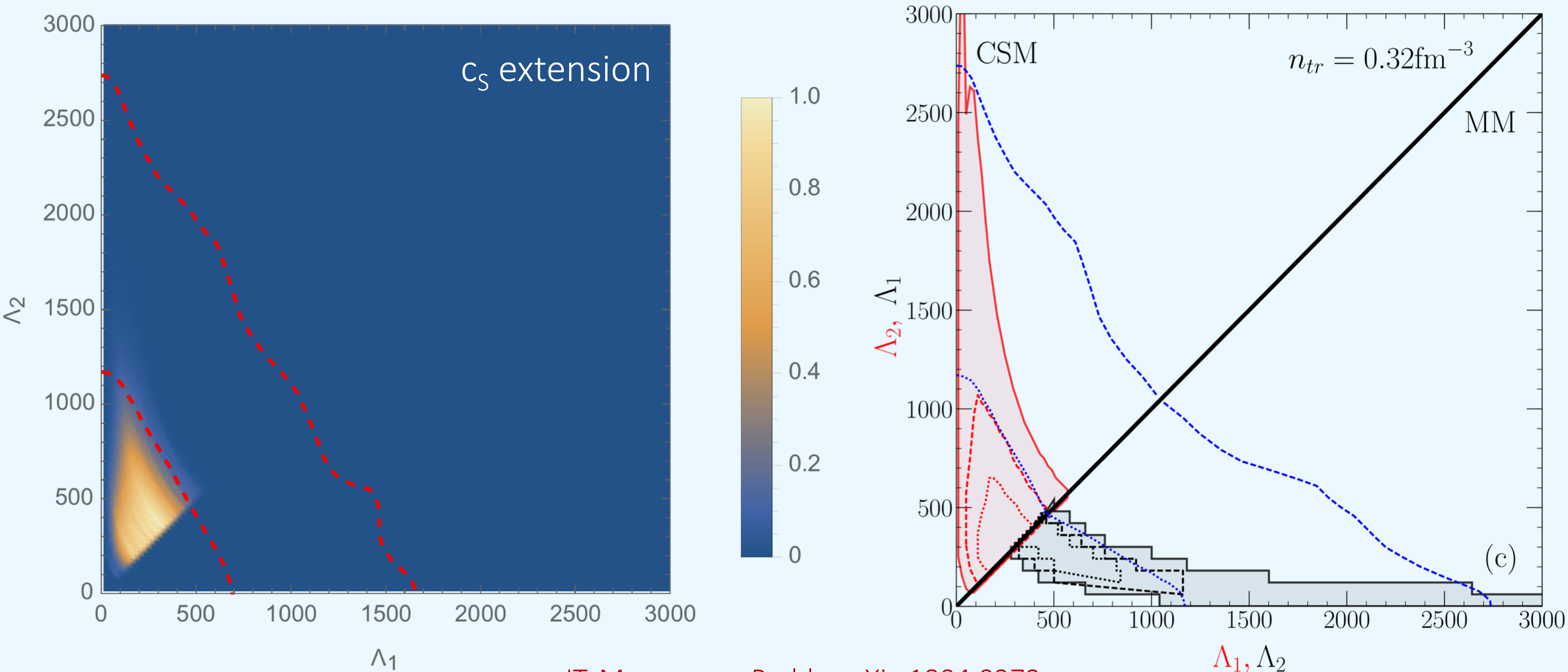


IT, Margueron, Reddy, arXiv:1804.0273

'Trust' nuclear physics up to saturation density and enforce $\tilde{\Lambda} \leq 800$:

- Large range of tidal polarizabilities allowed, depending on freedom in high-density models
- In this case, GW170817 provides constraints for the EOS.

Predictions based on GW170817 posterior for NS masses: $n_{tr}=2n_0$



IT, Margueron, Reddy, arXiv:1804.0273

'Trust' nuclear physics up to two times saturation density:

- Range of tidal polarizabilities drastically reduced, consistent for different high-density models: 80-570 (CSM) and 260-500 (MM)
- EOSs fully consistent with GW170817 without information on Λ.

Predictions based on GW170817 posterior for NS masses: $n_{tr}=2n_0$

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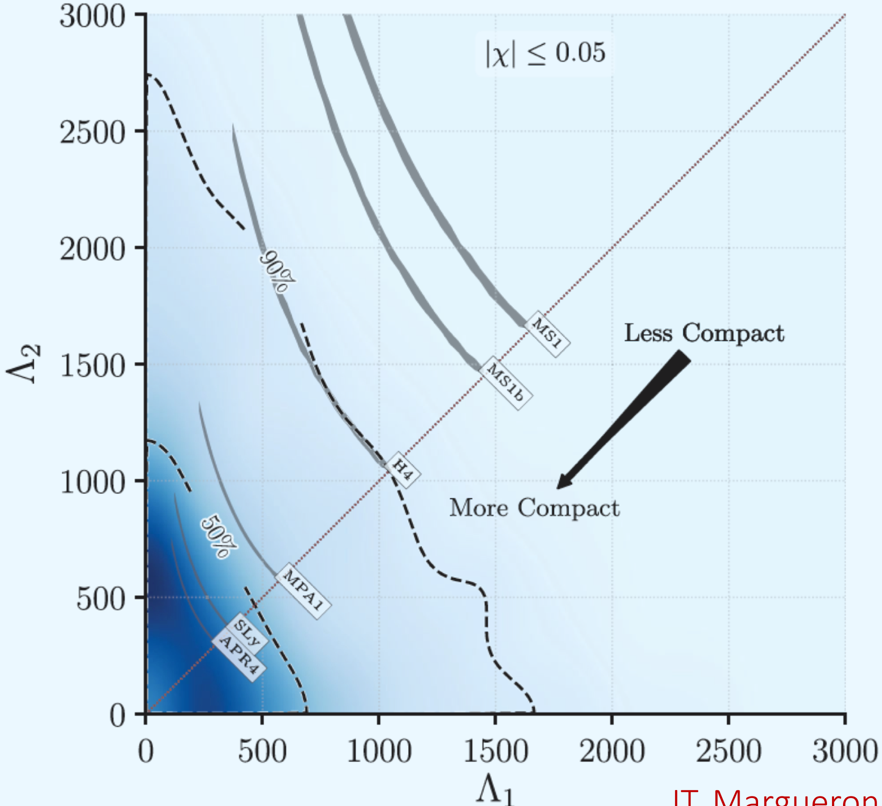

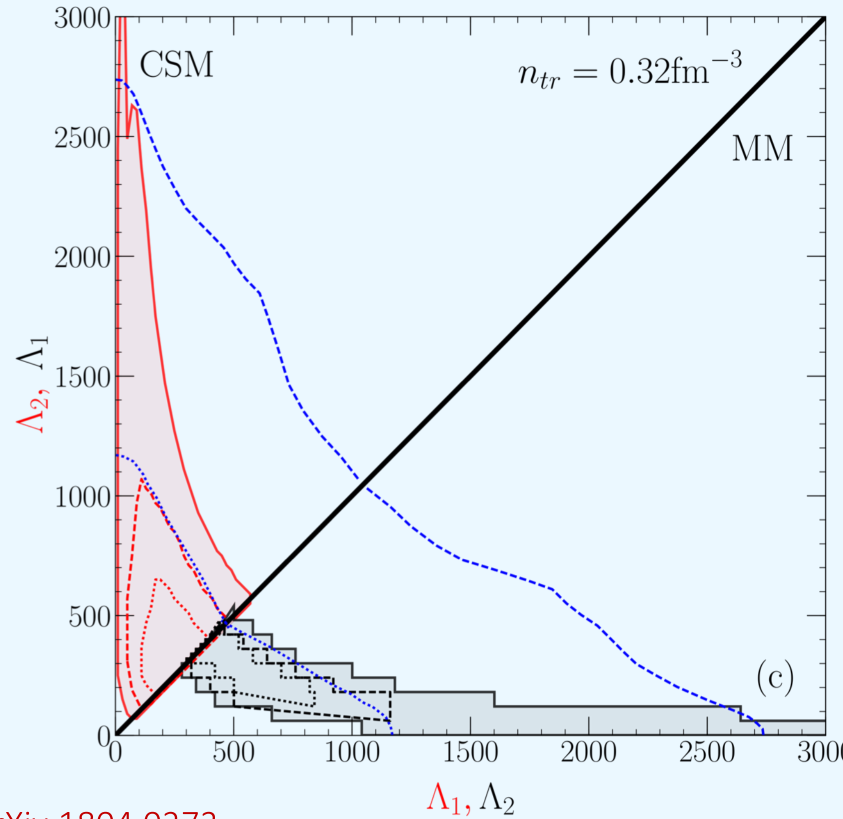

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Maximum mass vs. tidal polarizability

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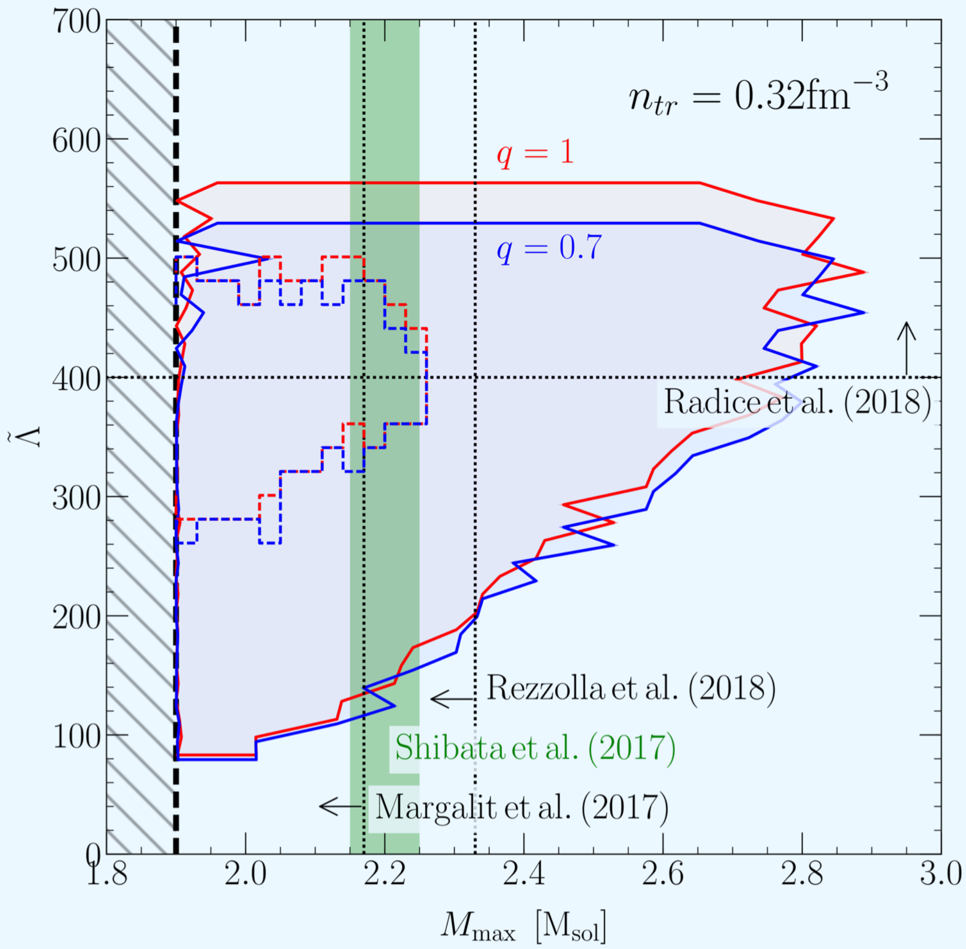
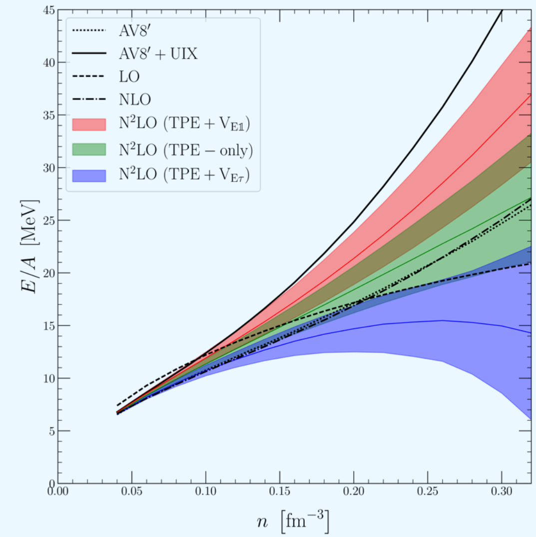
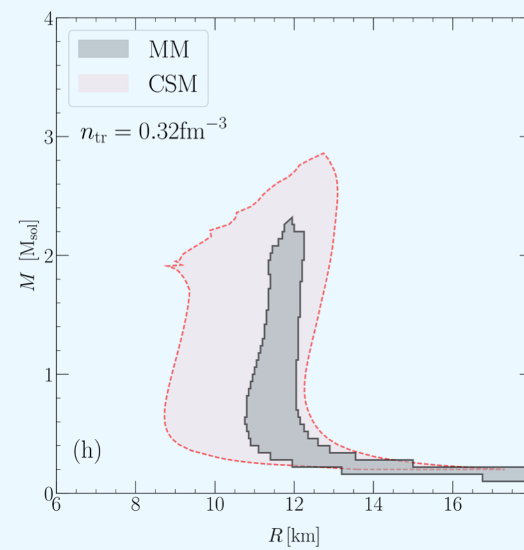


Maximum mass of the EOS vs. combined tidal polarizability.

Summary

- QMC calculations of matter and nuclei with local chiral potentials including NN and 3N forces are a versatile and systematic approach to *ab initio* calculations of nuclei and matter.
- Chiral interactions at N^2LO simultaneously reproduce the properties of A≤16 systems and of neutron matter, commonly used phenomenological 3N interactions fail.
- There is a sizable uncertainty for nuclear interactions.
- Systematic high-density extension needed for reliable study of astrophysical phenomena:
- Nuclear physics input between 1-2 n_0 will be directly probed in merger observations.
- Further improvements necessary to calculate nuclei and neutron-matter EOS with improved uncertainties.





Thanks

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- Stony Brook: J. Lattimer
- Yukawa Institute Kyoto: A. Ohnishi

Thank you for your attention.