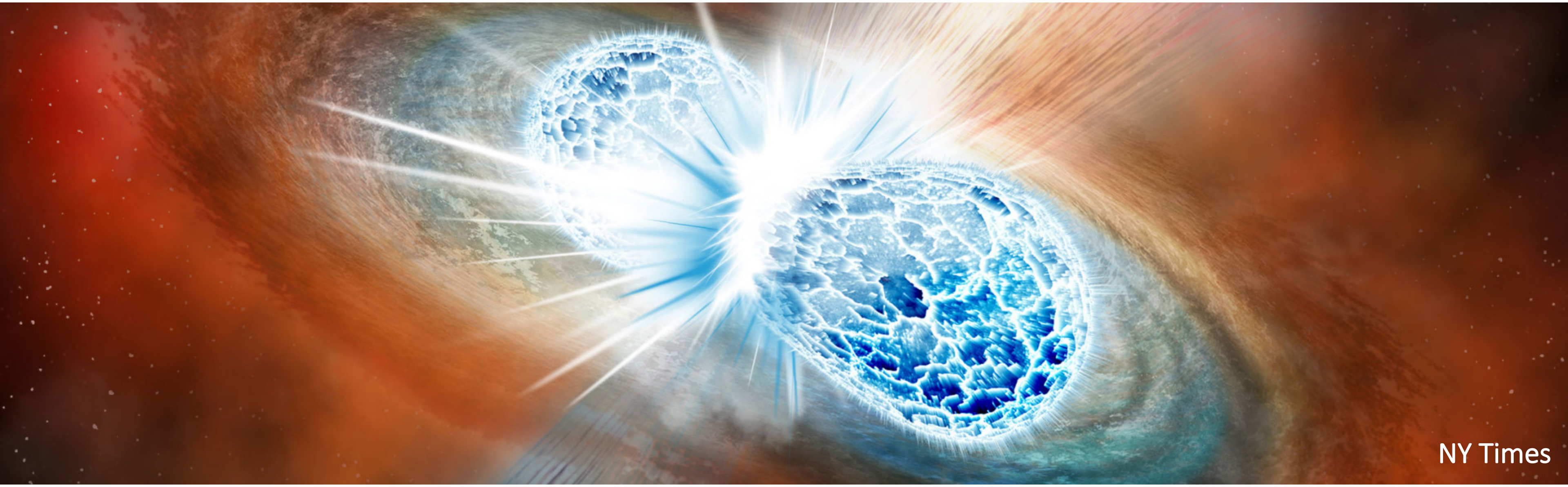
The neutron-star equation of state from chiral EFT and constraints from gravitational waves from neutron-star mergers



Ingo Tews

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

INT-JINA Symposium: First multi-messenger observations of a neutron star merger and its implications for nuclear physics,

March 12-14, 2018,
Institute for Nuclear Theory, Seattle

JINA–CEE

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Chiral effective field theory for nuclear forces

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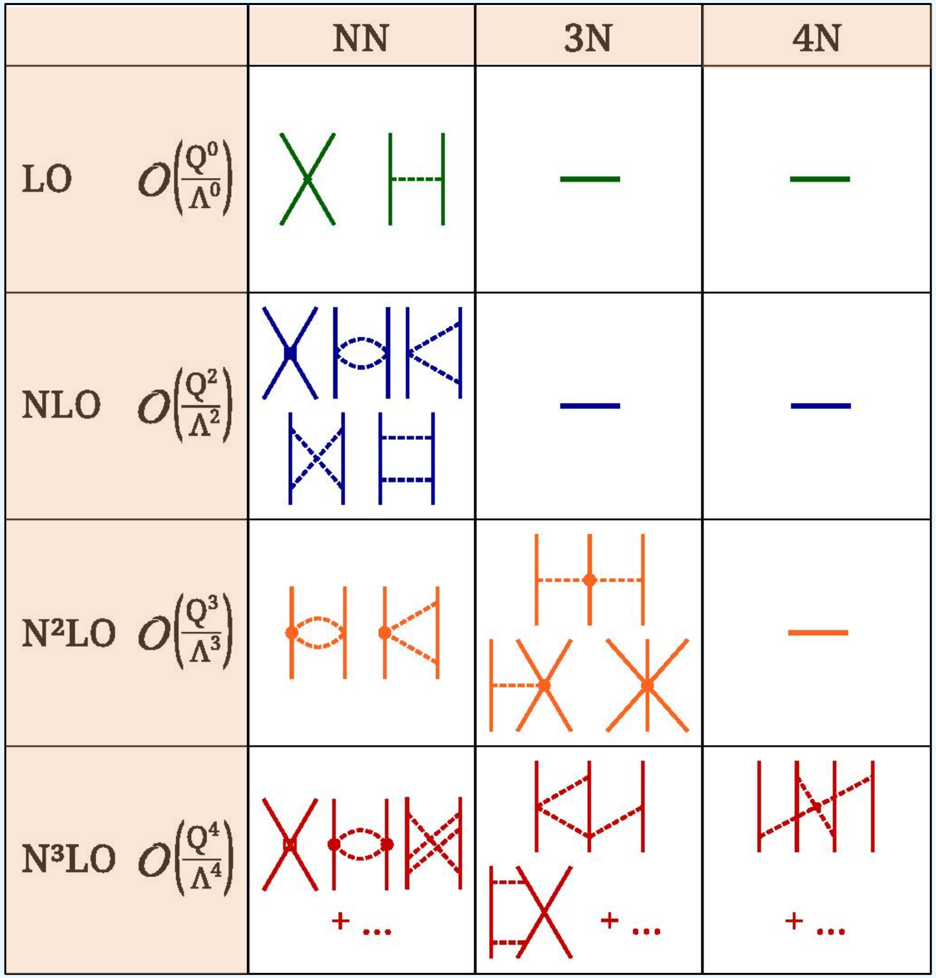


See talks by Kai Hebeler, Stefano Gandolfi.

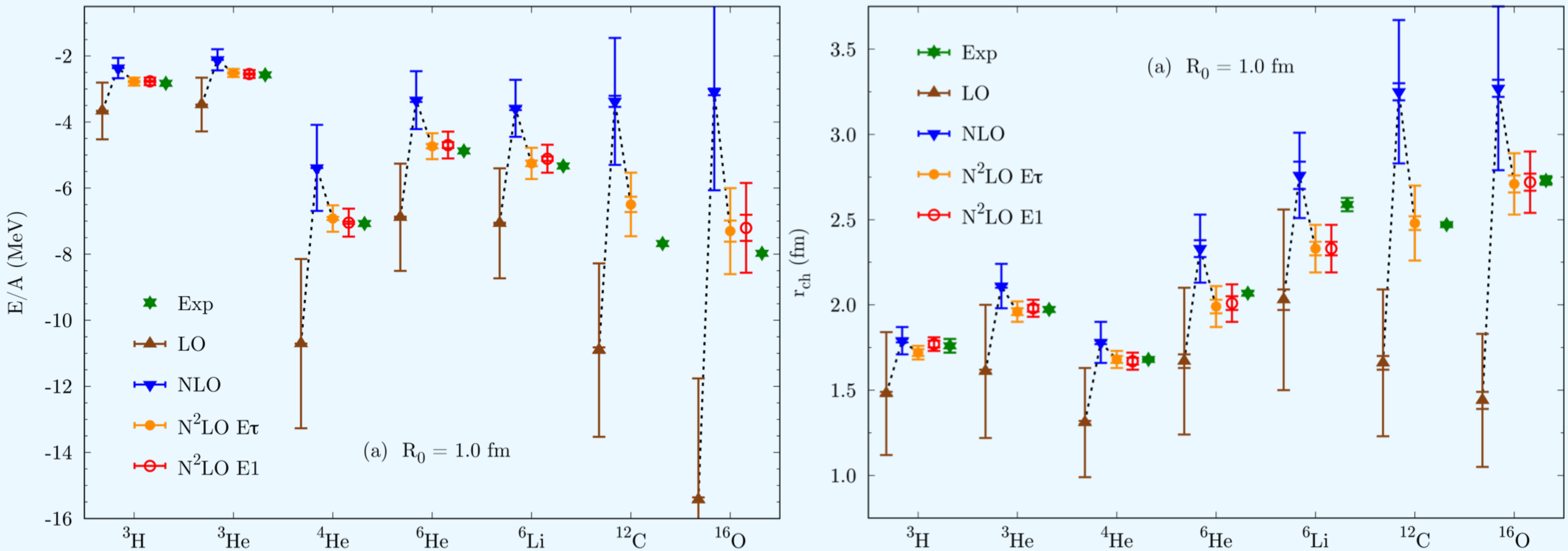
Systematic expansion of nuclear forces:

- 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)

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

Results

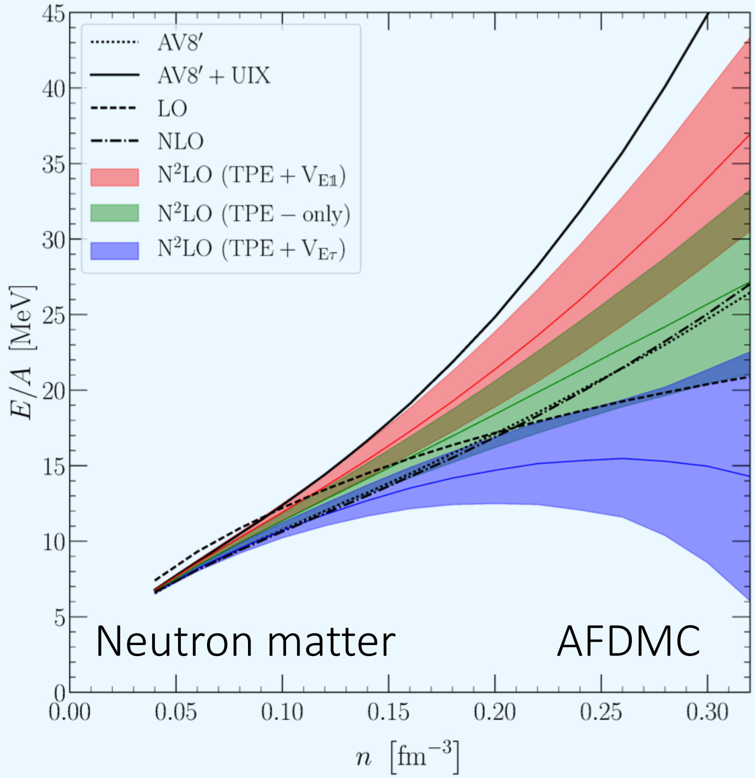
Recent results for Quantum Monte Carlo calculations of nuclei:



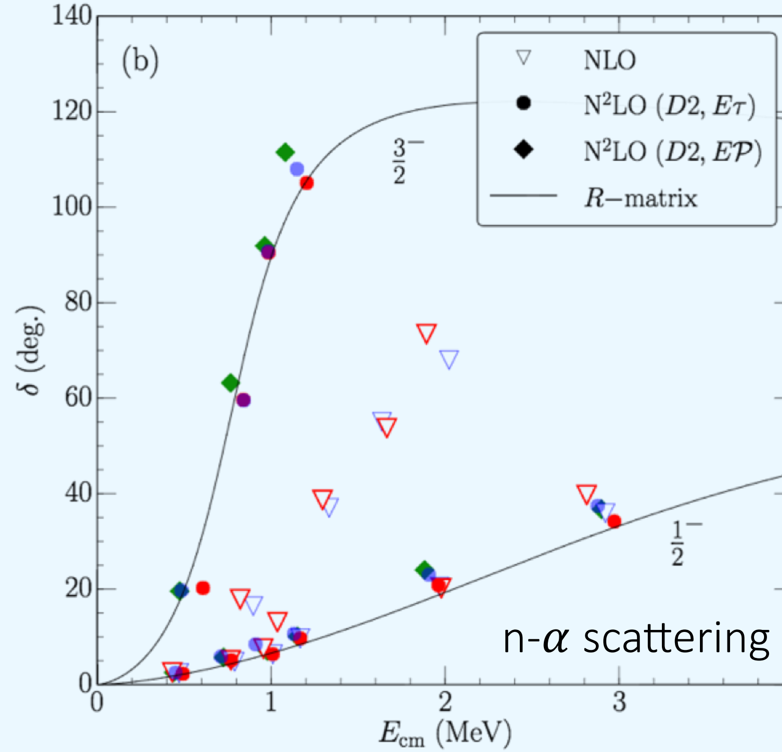
Excellent description of binding energies and charge radii for A ≤16.

Lonardoni et al., arXiv:1709.09143 and 1802.08932

Results



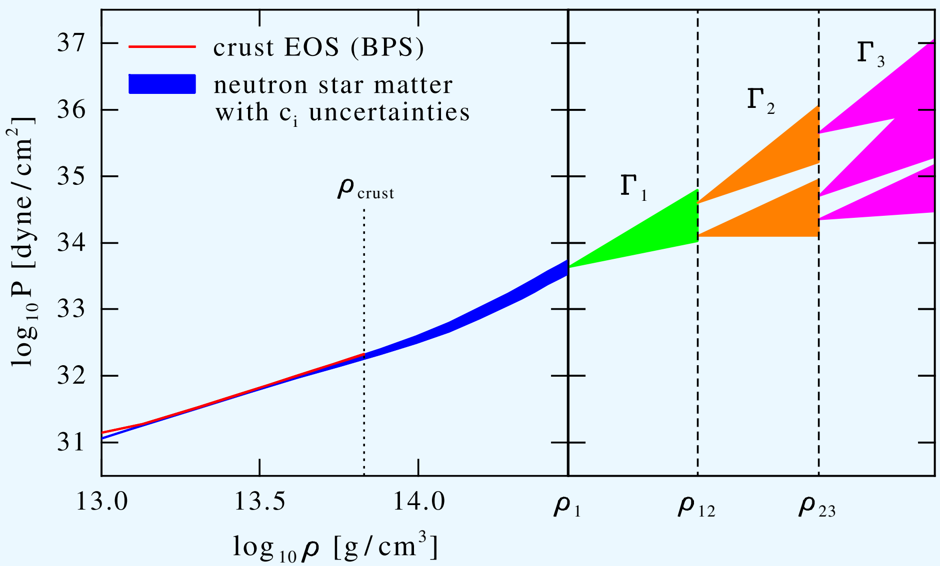
IT, Carlson, Gandolfi, Reddy, arXiv:1801.01923



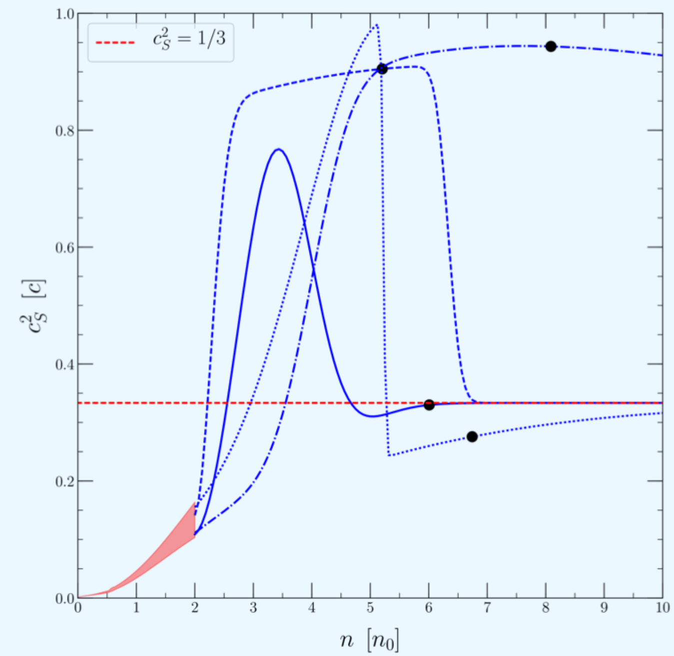
Lynn, IT, et al., PRL (2016)

- 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.

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

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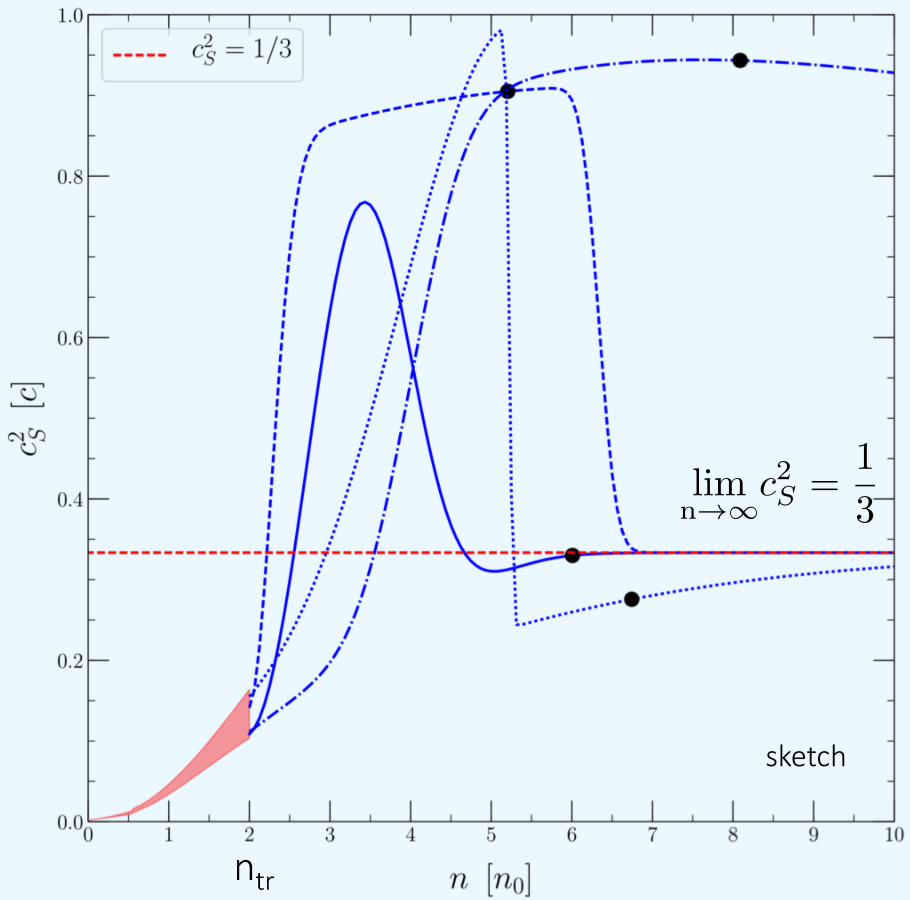


IT, Carlson, Gandolfi, Reddy, arXiv:1801.01923

Use the speed of sound to extend EOS:

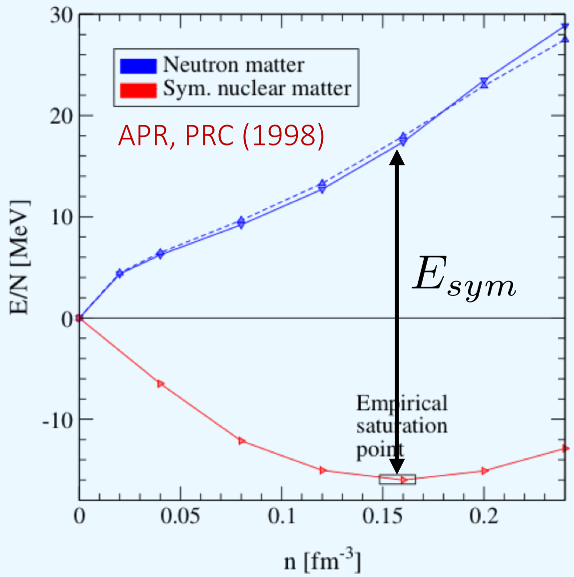
Speed of sound:

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

- 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-EP)



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 ⟷ Large uncertainties

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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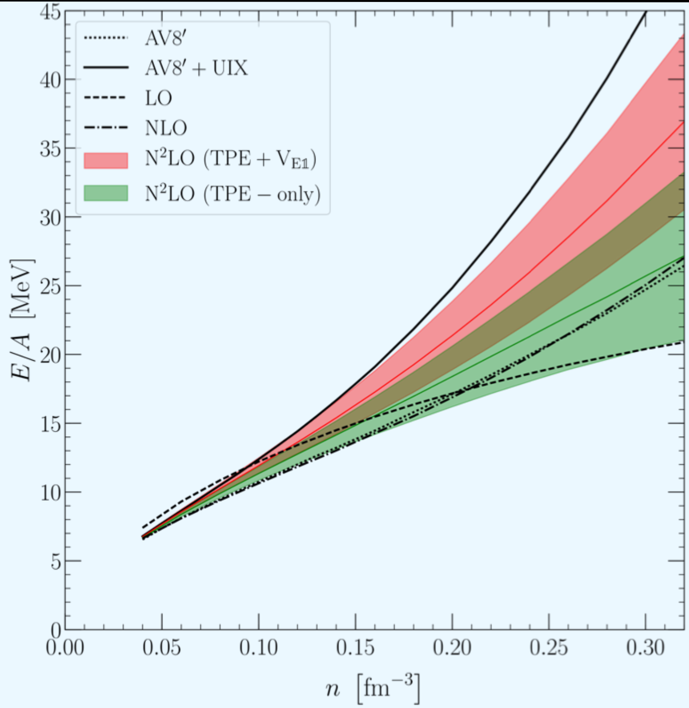


IT, Carlson, Gandolfi, Reddy, arXiv:1801.01923

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

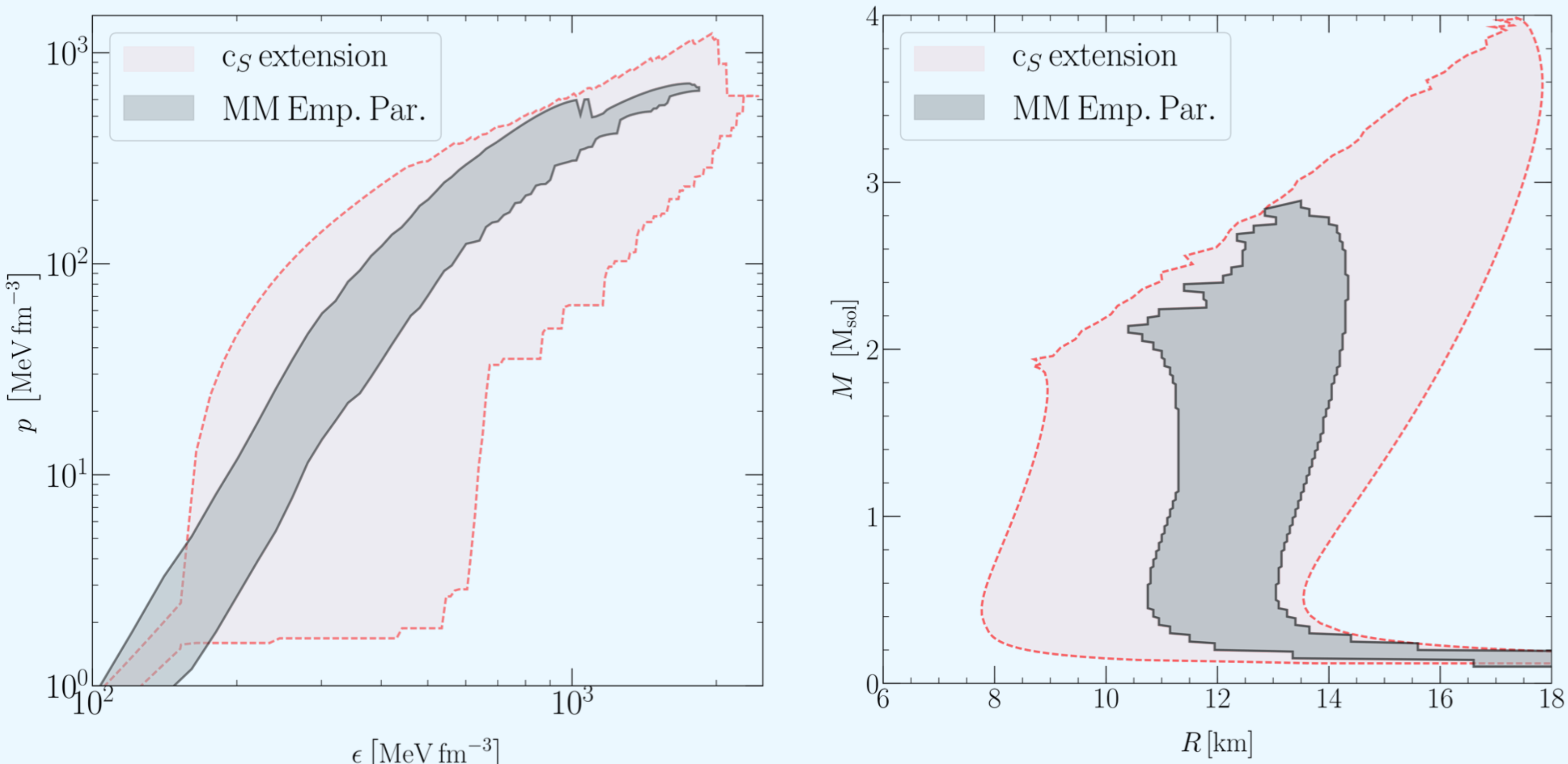
(2013)

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: $n_{tr}=n_0$

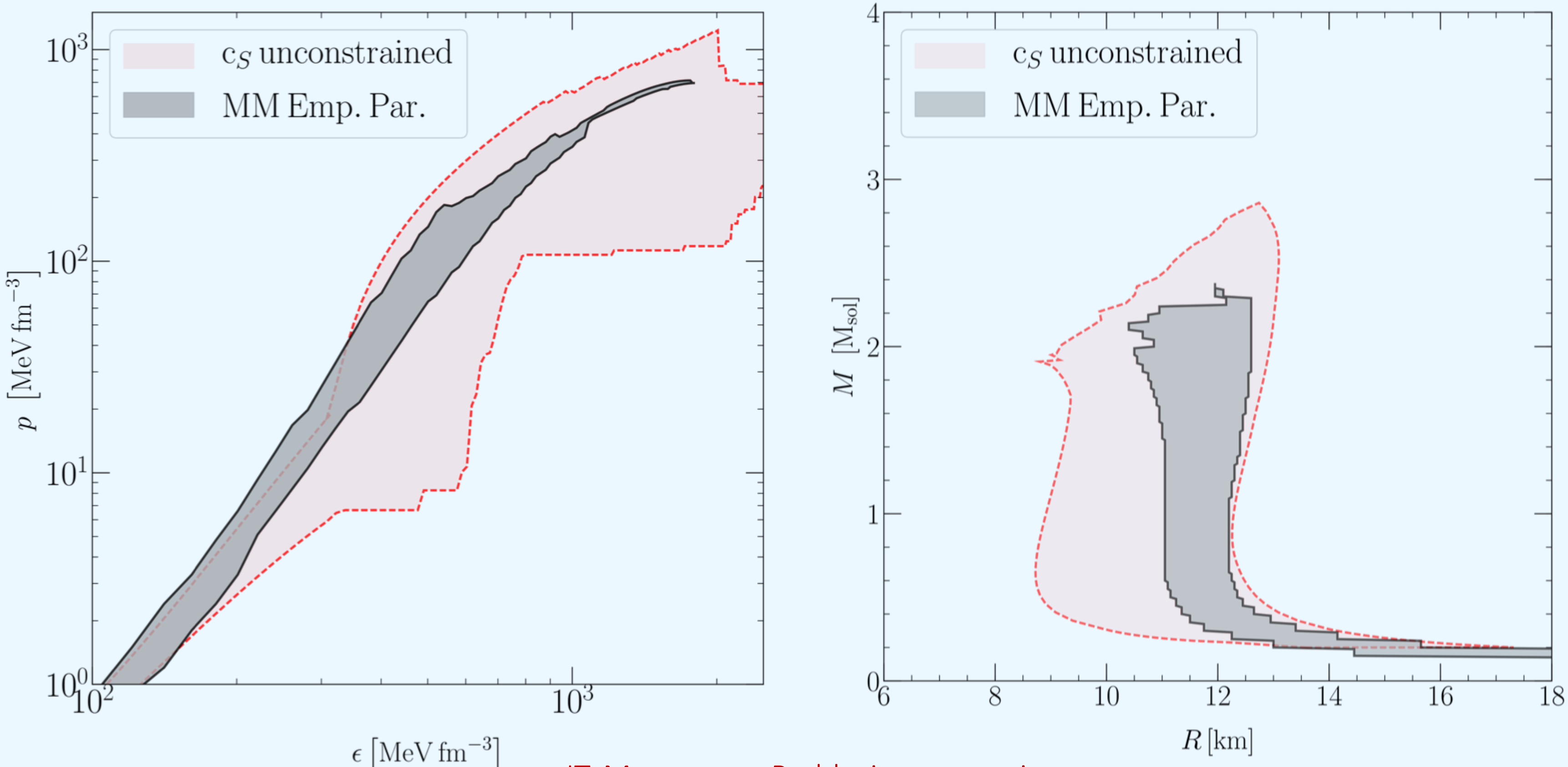


IT, Margueron, Reddy in preparation.

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: $n_{tr} = 2n_0$



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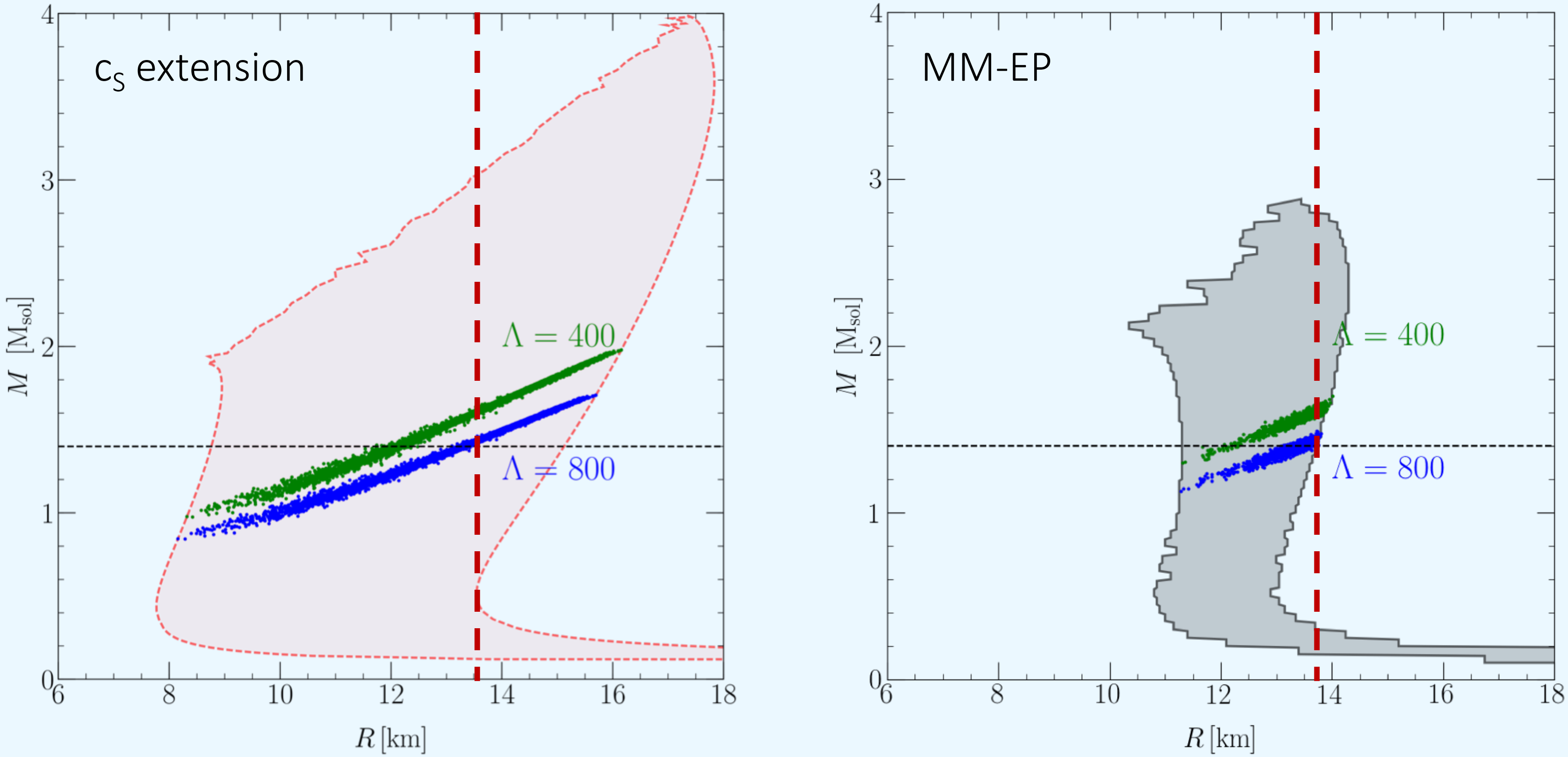
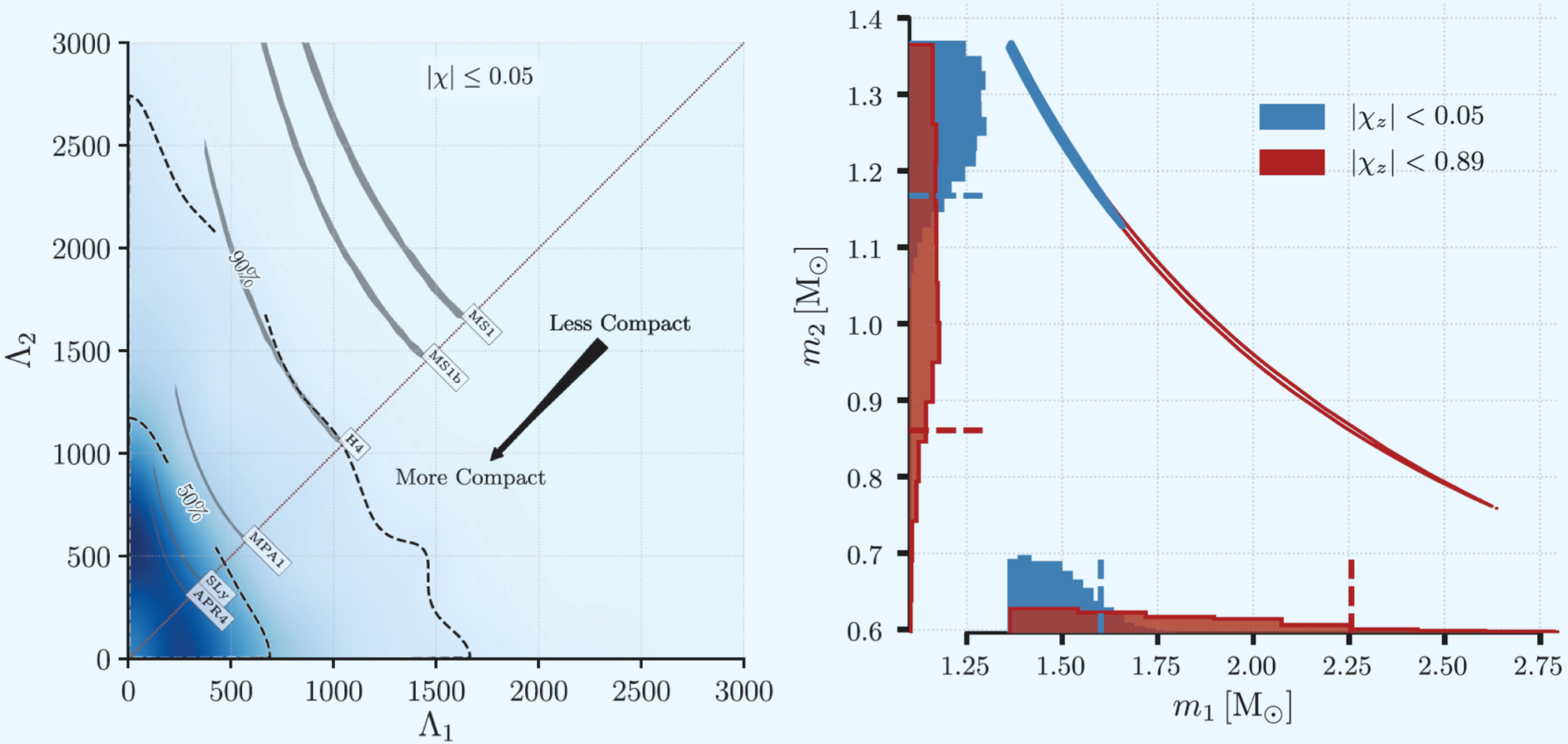
Constraint from GW170817



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

- Constrains the radius of a typical neutron star to be less than 13.5 km.
  See talks by K. Hebeler, J. Lattimer

Predictions based on GW170817 posterior for NS masses

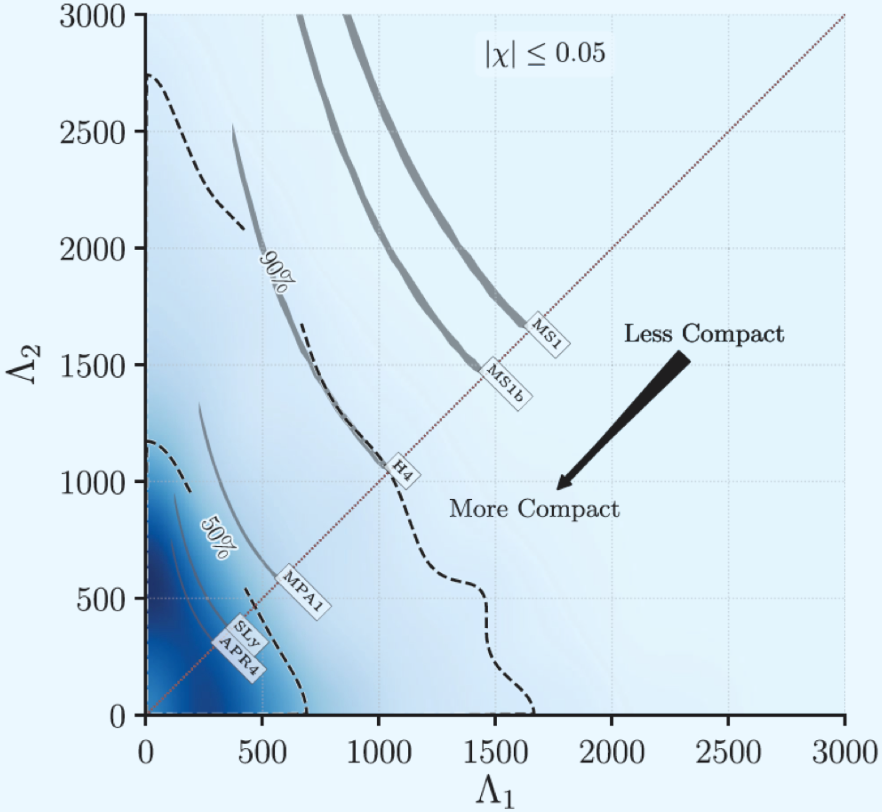


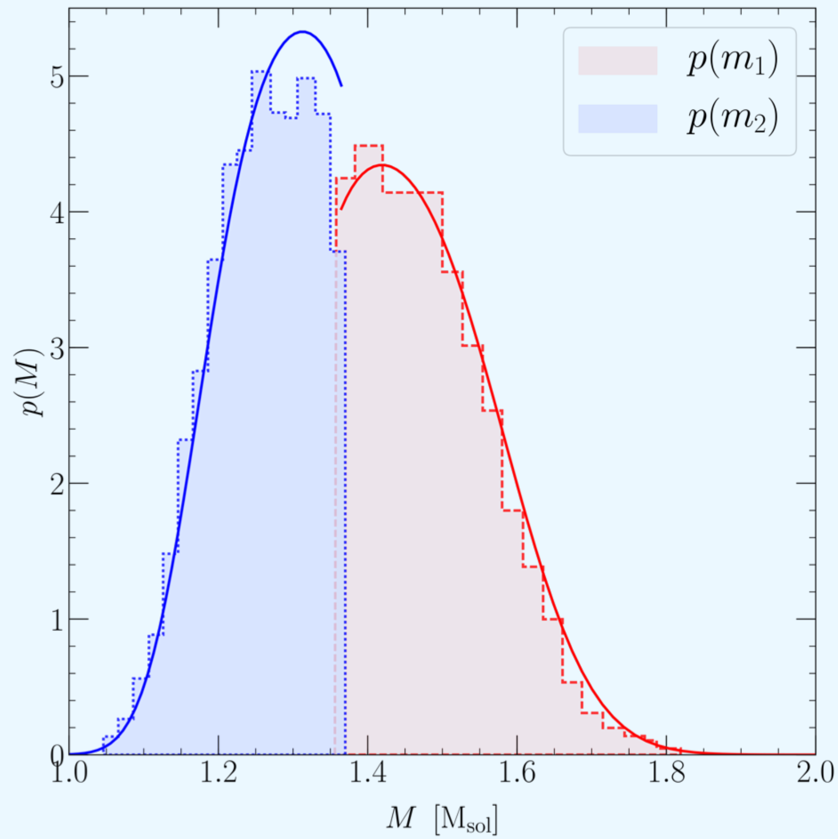
LIGO/VIRGO collaboration, PRL (2017)

Study GW170817:

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

Predictions based on GW170817 posterior for NS masses





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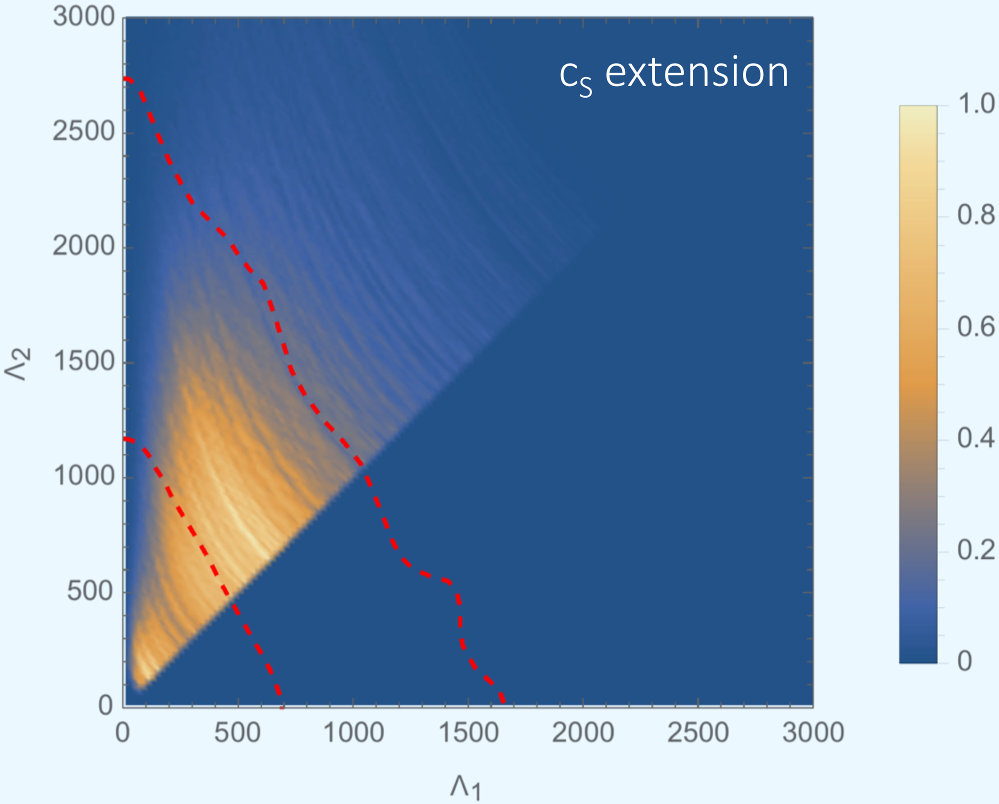
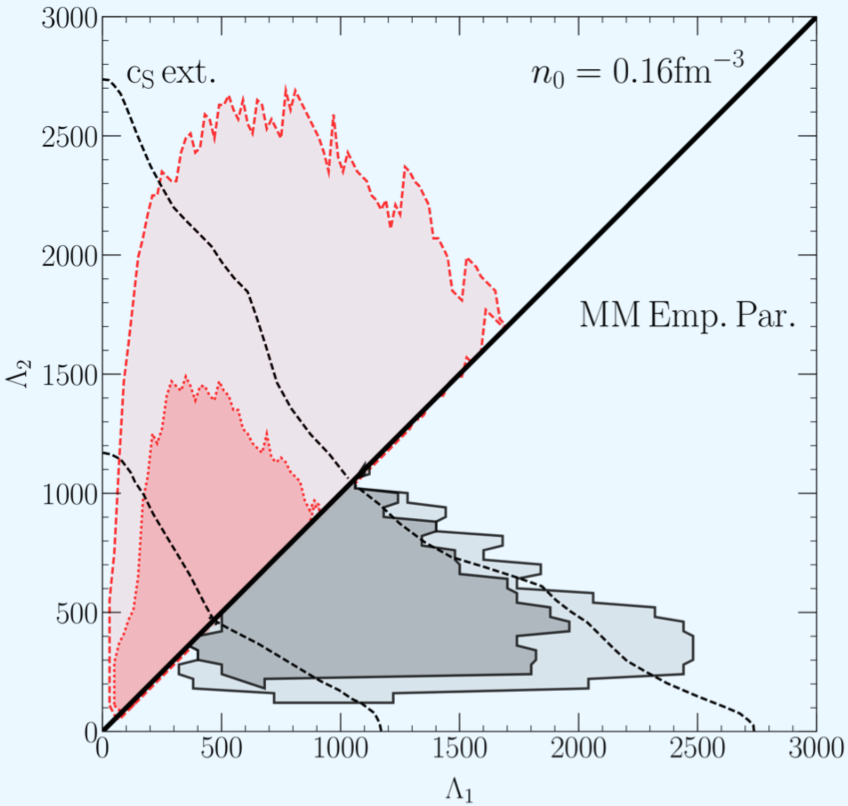
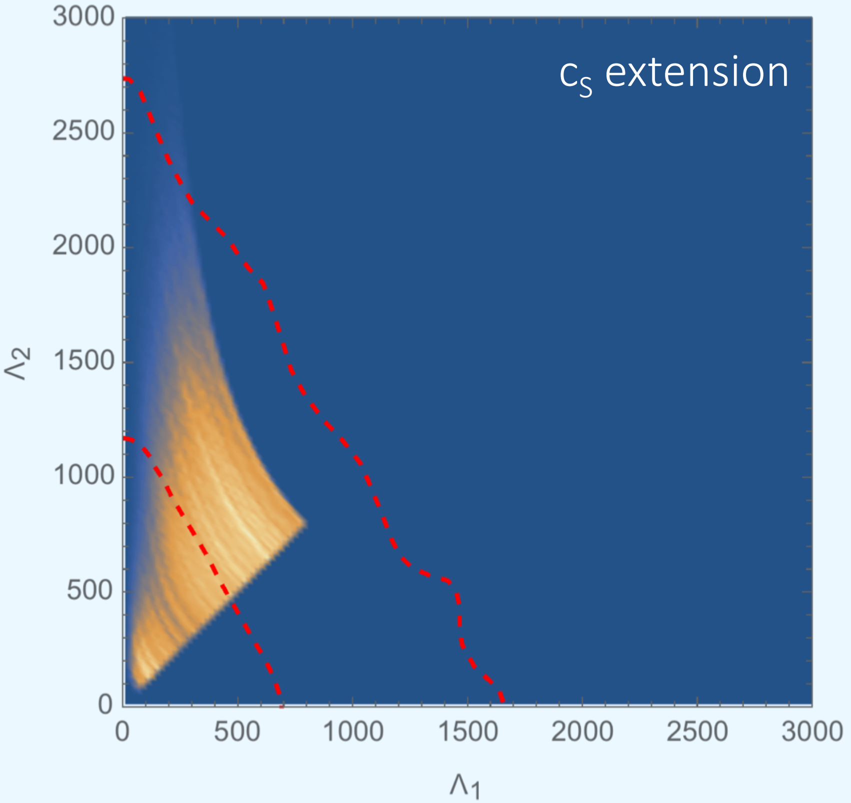


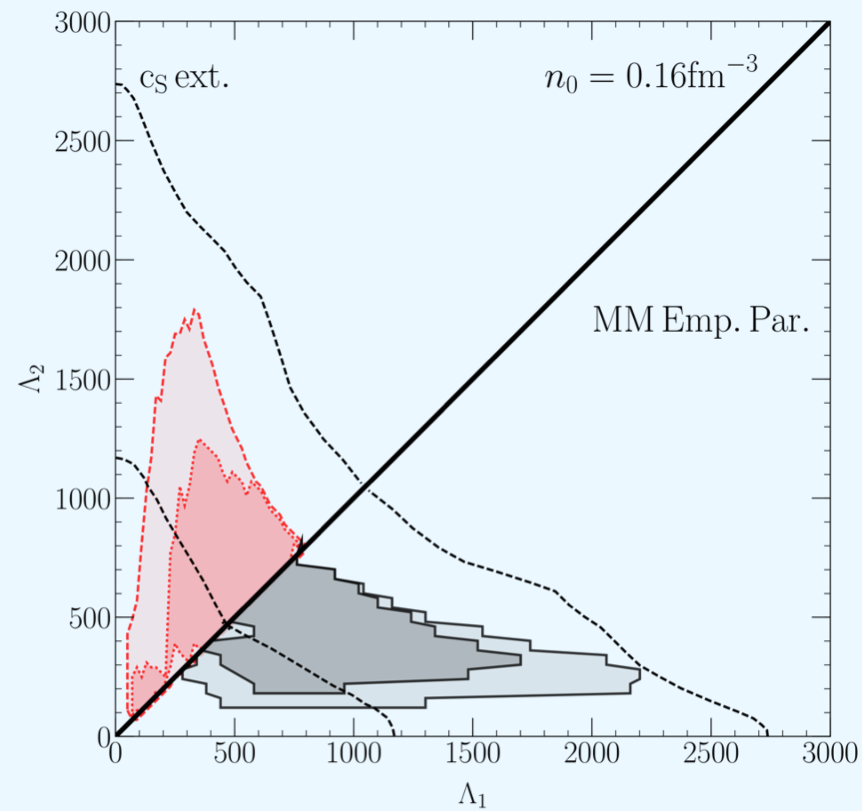


‘Trust’ nuclear physics up to saturation density:

- 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: $n_{tr}=n_0$

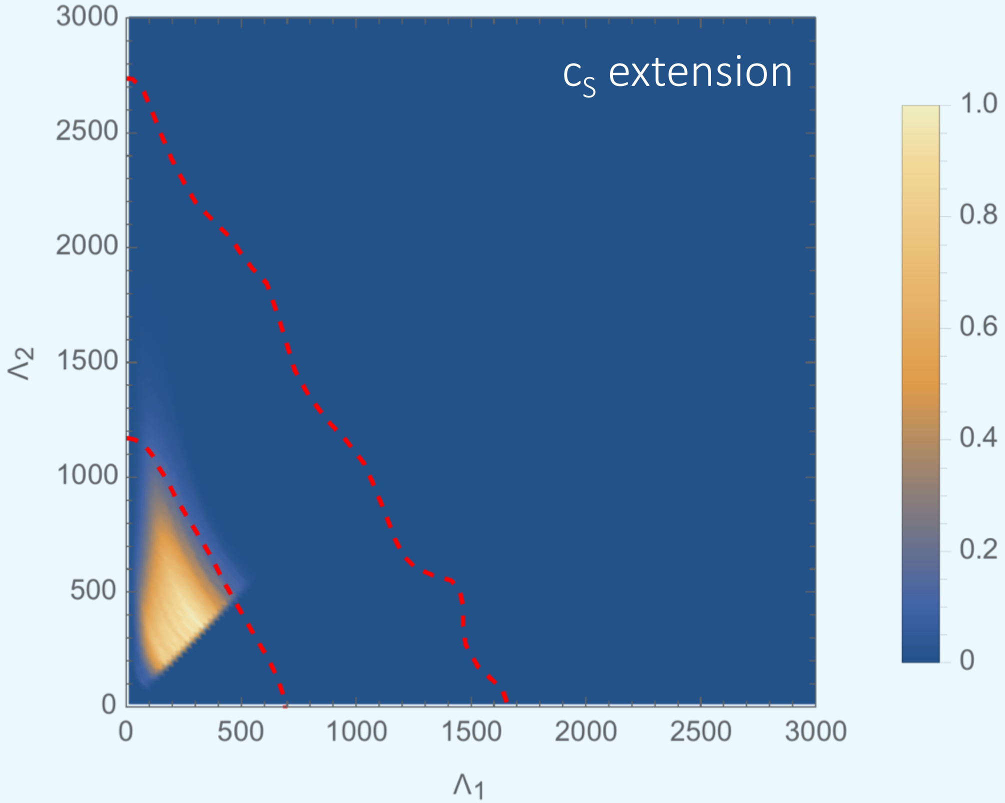


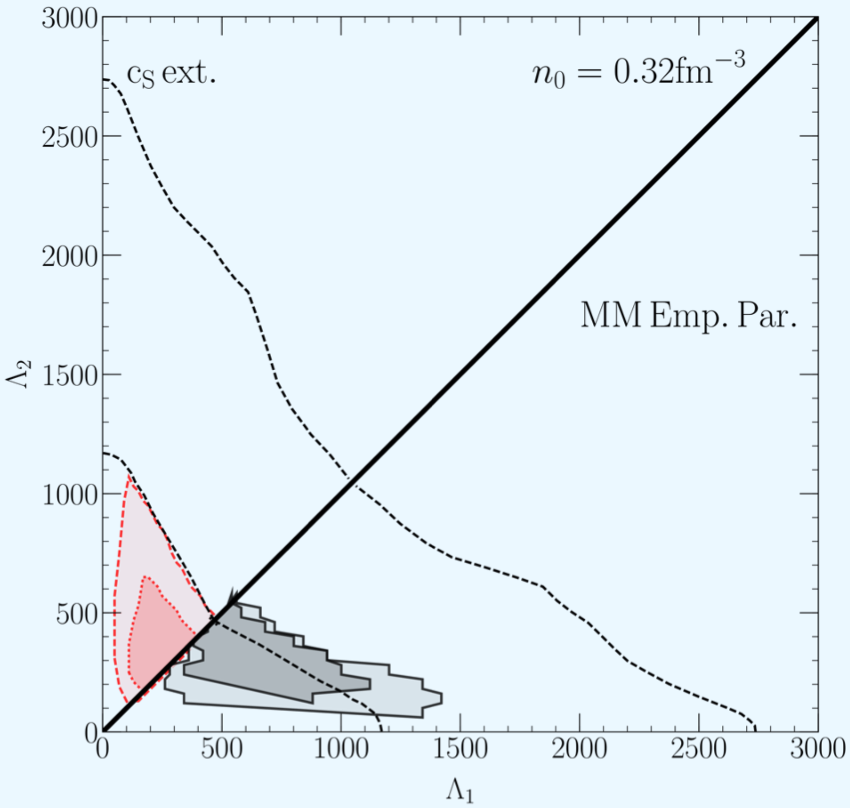


'Trust' nuclear physics up to saturation density and enforce $\tilde{\Lambda} \leq 800$:

- 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: $n_{tr}=2n_0$

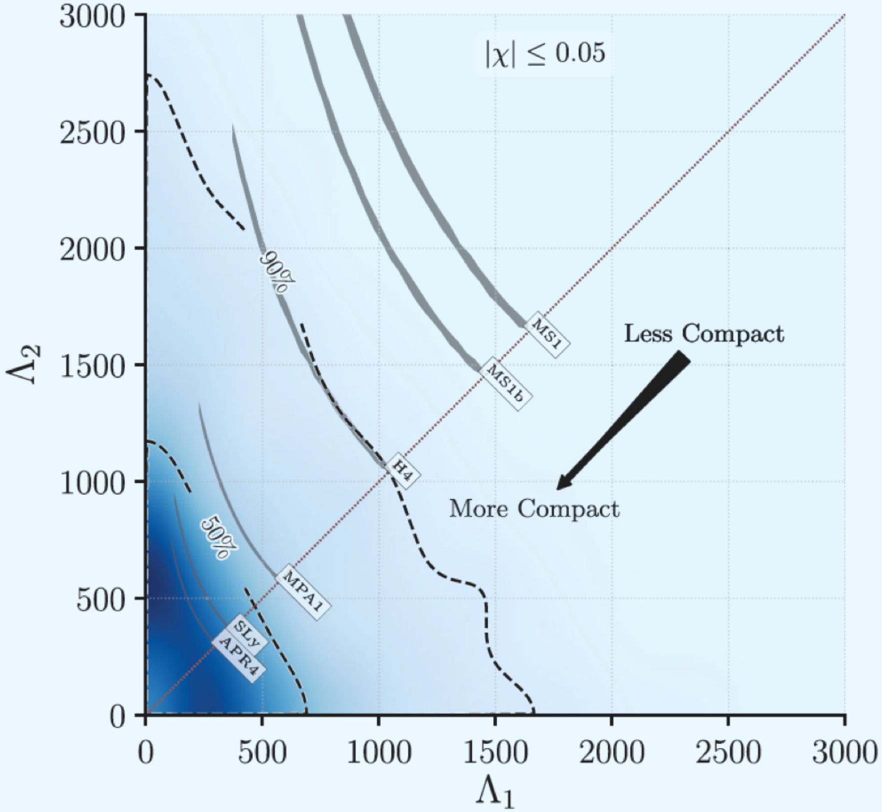


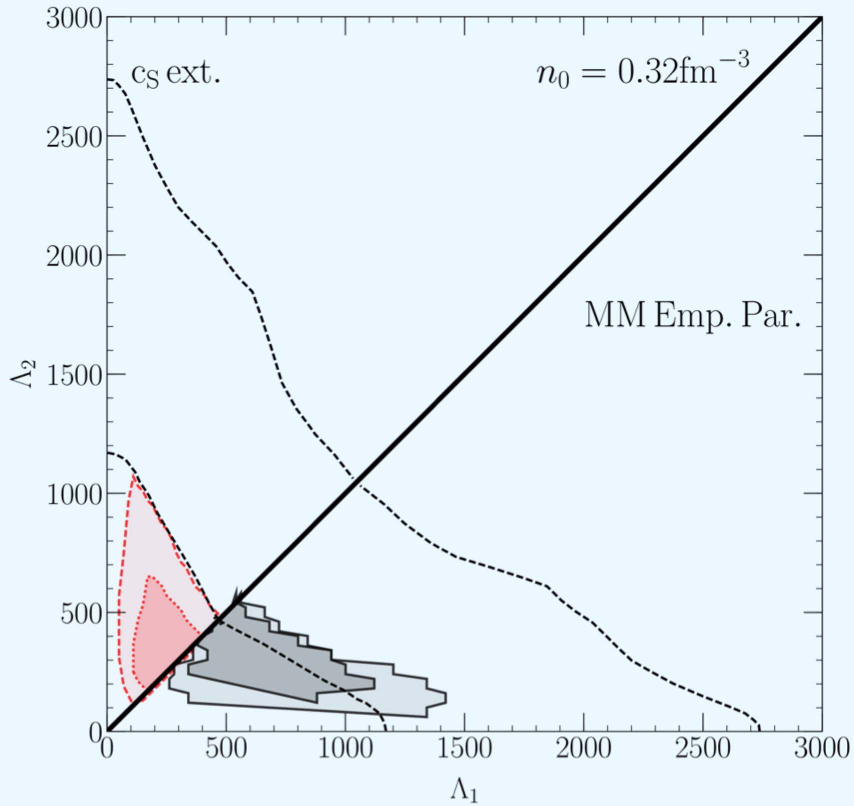


'Trust' nuclear physics up to twice saturation density:

- Range of tidal polarizabilities drastically reduced, consistent for different high-density models.
- 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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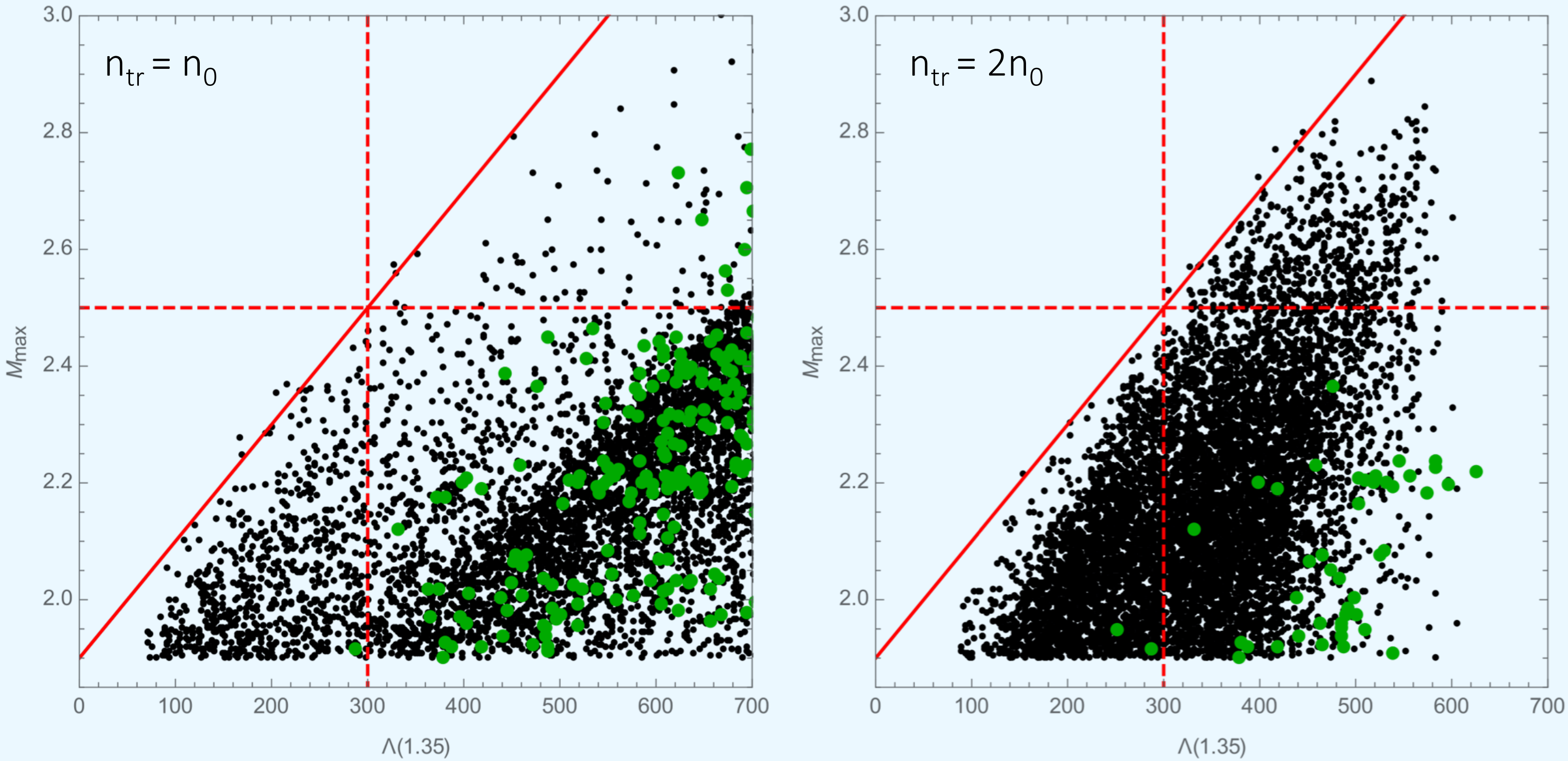
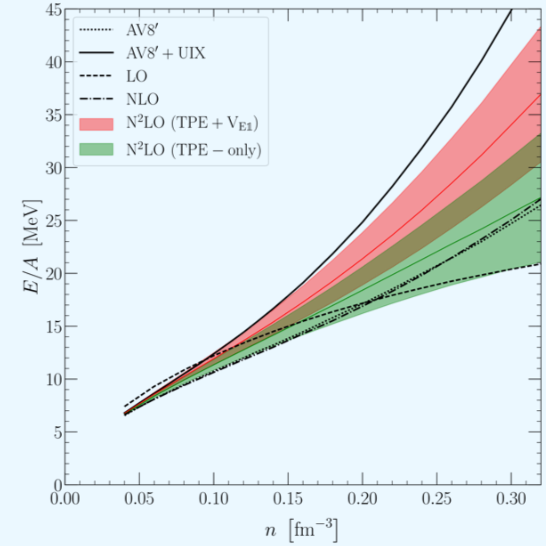
Maximum mass vs. tidal polarizability

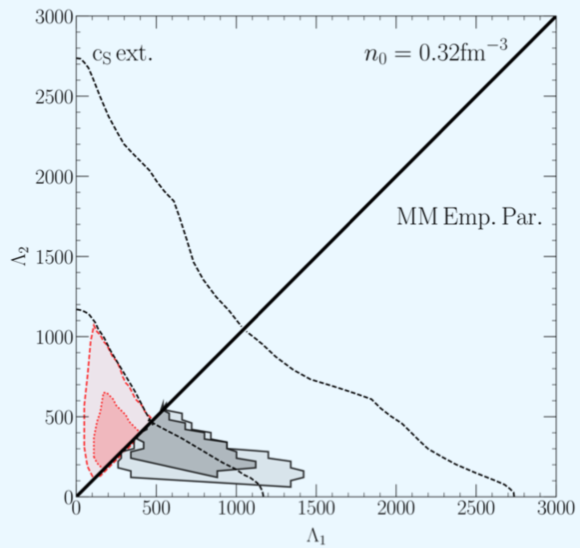


Maximum mass of the EOS vs. tidal polarizability of 1.35 solar mass star.

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.
- Systematic high-density extension needed for reliable study of astrophysical phenomena:
  - We studied extension based on the speed of sound and sampling of the empirical parameters.
- There is a sizable uncertainty for nuclear interactions.
- Nuclear physics input between 1-2 n_0 will be directly probed in merger observations. We need tighter constraints on $\tilde{\Lambda}$.
- We live in exciting times!





Thanks

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- INT Seattle: S. Reddy
- Technische Universität Darmstadt:
  K. Hebeler, J. Lynn, A. Schwenk
- Universität Bochum: E. Epelbaum
- Los Alamos National Laboratory: J. Carlson, S. Gandolfi
- University of Guelph: A. Gezerlis
- Forschungszentrum Jülich: A. Nogga
- Matej Bel University: E. Kolomeitsev
- Stony Brook: J. Lattimer
- Yukawa Institute Kyoto: A. Ohnishi

Thanks to FZ Jülich for computing time and NIC excellence project.

JINA–CEE

erc European Research Council Established by the European Commission

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Thank you for your attention.

Backup

Results

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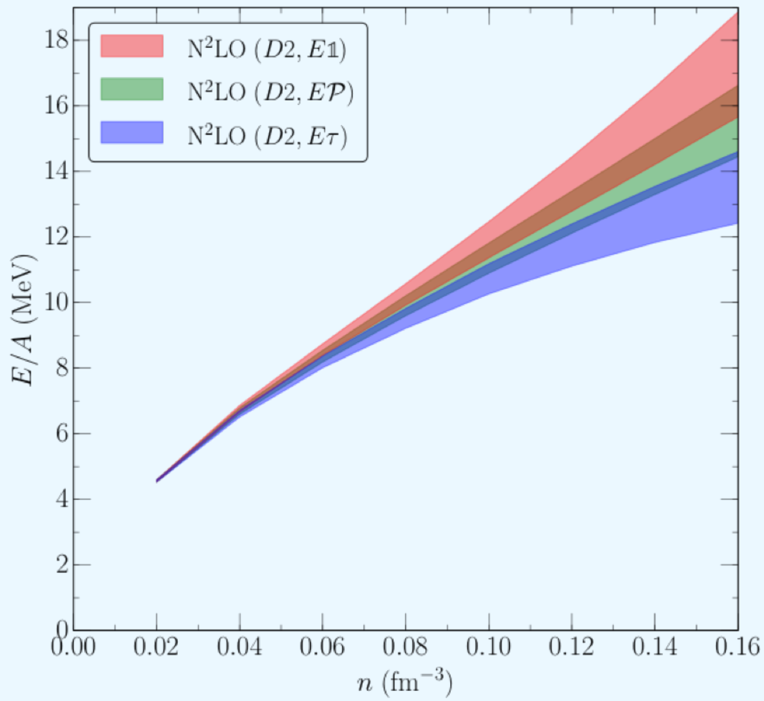
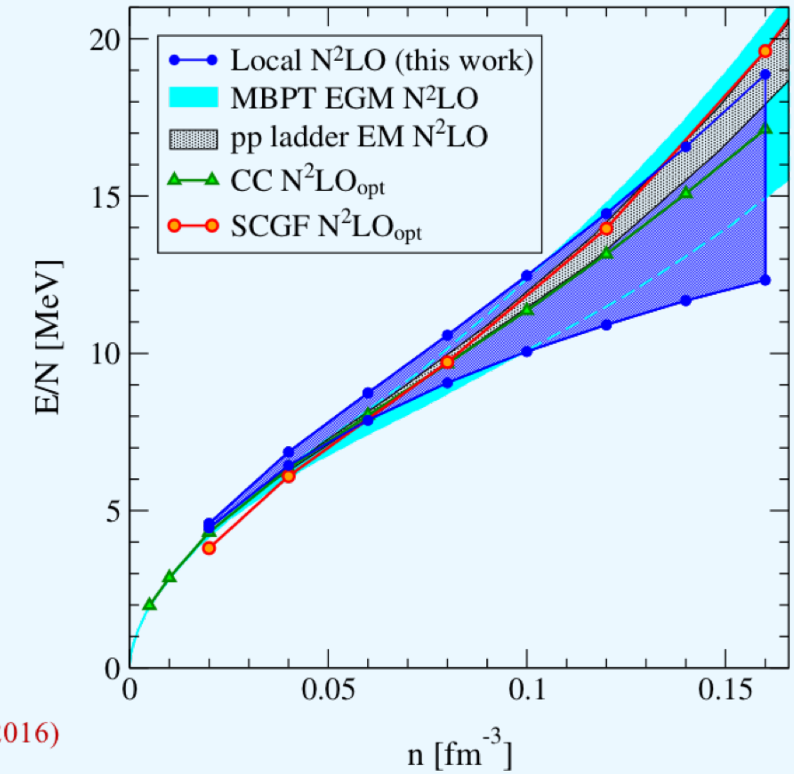


Lynn, IT, Carlson, Gandolfi, Gezerlis, Schmidt, Schwenk, PRL (2016)

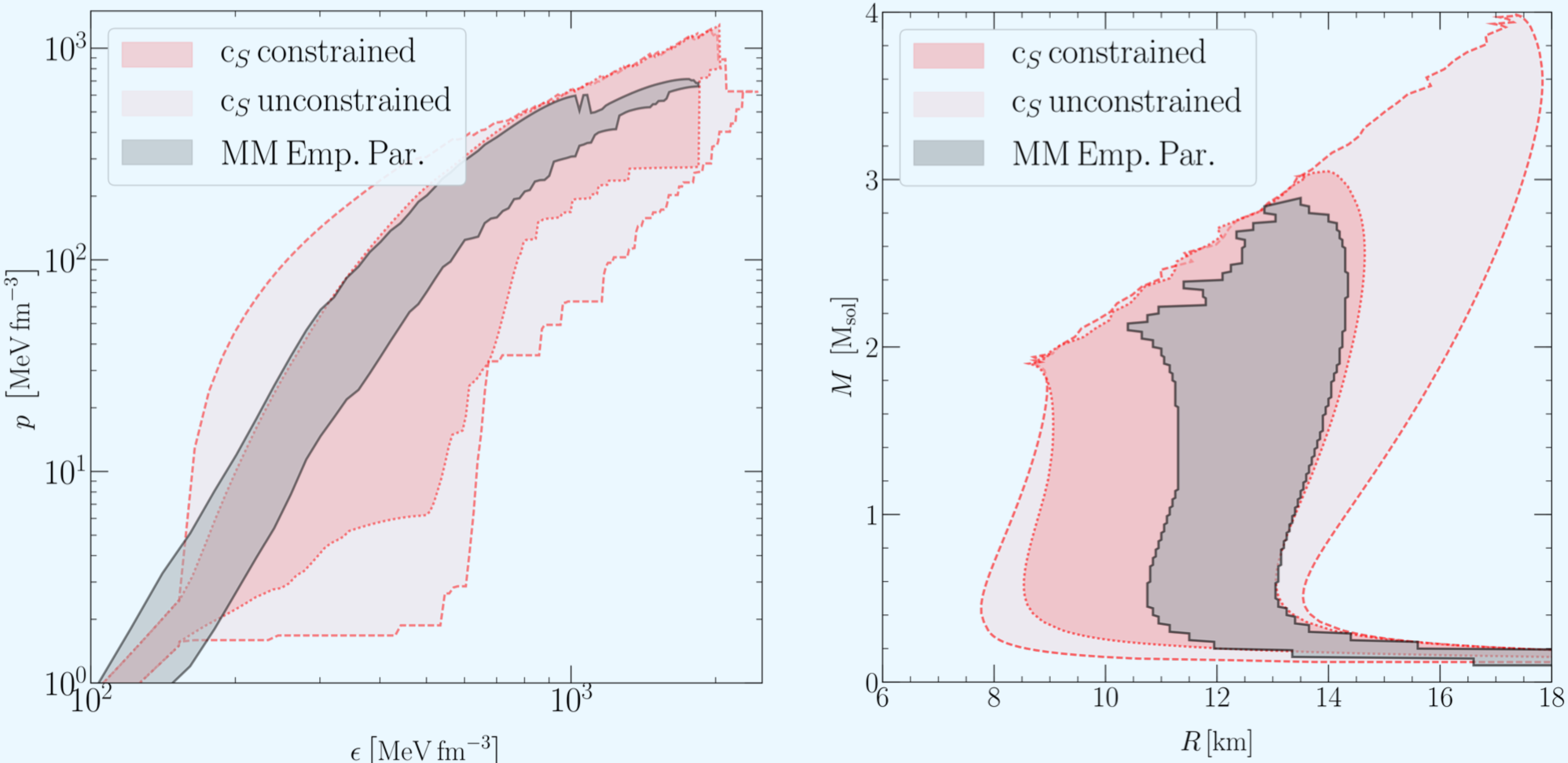


- Additional contributions due to shorter-range 3N forces
- Agreement between various approaches

  (different way of uncertainty estimate, see EKM, PRC 2015)

- Ambiguity in short-range structure leads to additional uncertainty.

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



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