Strong-interaction matter at nuclear densities and beyond

TECHNISCHE UNIVERSITÄT DARMSTADT

Status report and future plans of project B05: Nuclear matter equation of state for astrophysical applications

Kai Hebeler and Jens Braun

CRC 1245 Workshop
Darmstadt, 2019

SFB 1245

QCD phase diagram:
Neutron stars and the dense EoS

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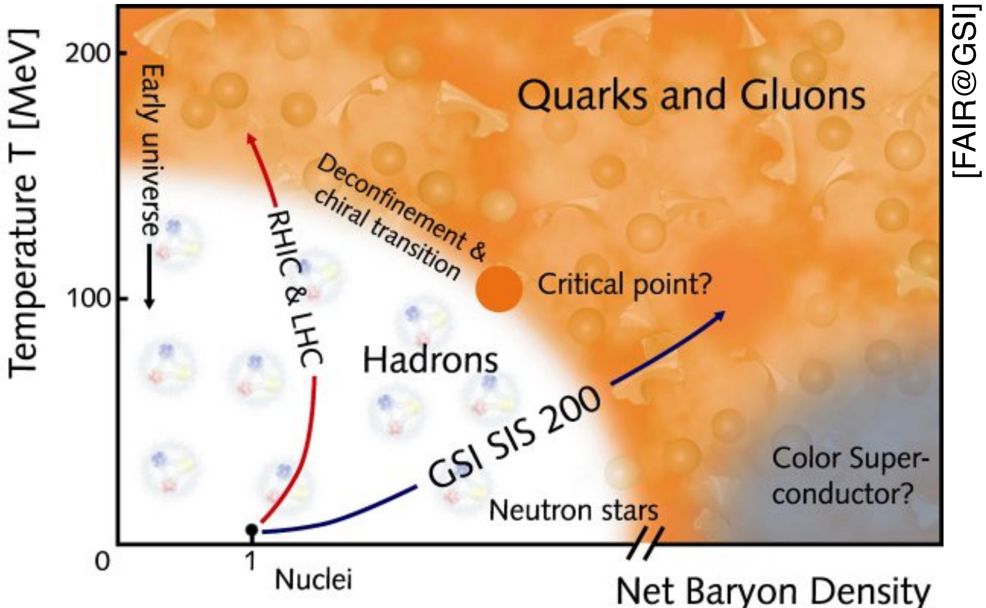
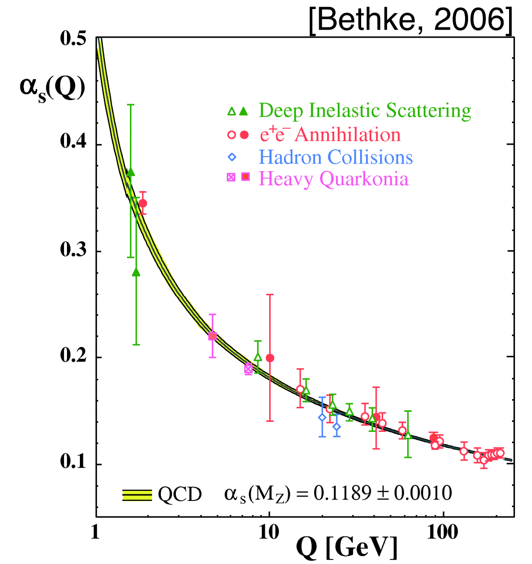


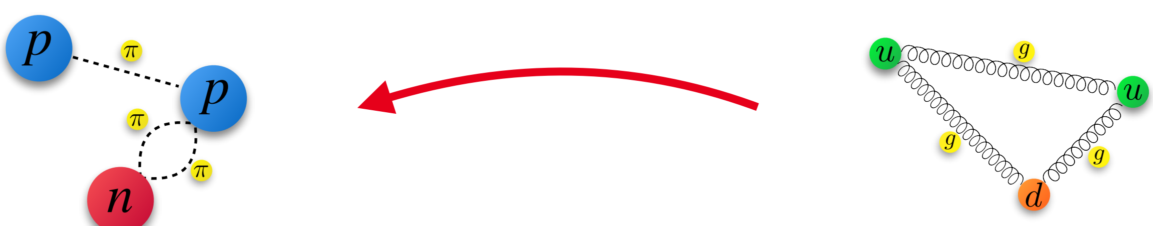


$\lesssim 60\rho_{\mathrm{sat}}$ [Kurkela et al., 2014]

Low-energy effective theories

Functional methods

Perturbative methods



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Outline

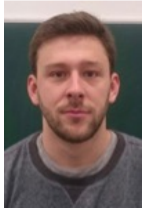
- Chiral effective field theory (at lower densities)
  - Systematic incorporation of NN, 3N, … interactions
  - EoS from MBPT: Order-by-order convergence
  - Calculation of most advanced 3N interactions
- Functional renormalization group (at higher densities)
  - Dynamic generation of Fierz complete four-quark self-interactions by gauge degrees of freedom
  - Connecting to low-energy regime and results on the EoS and the speed of sound
- Summary and plans for next funding period


Christian Drischler


Corbinian Wellenhofer

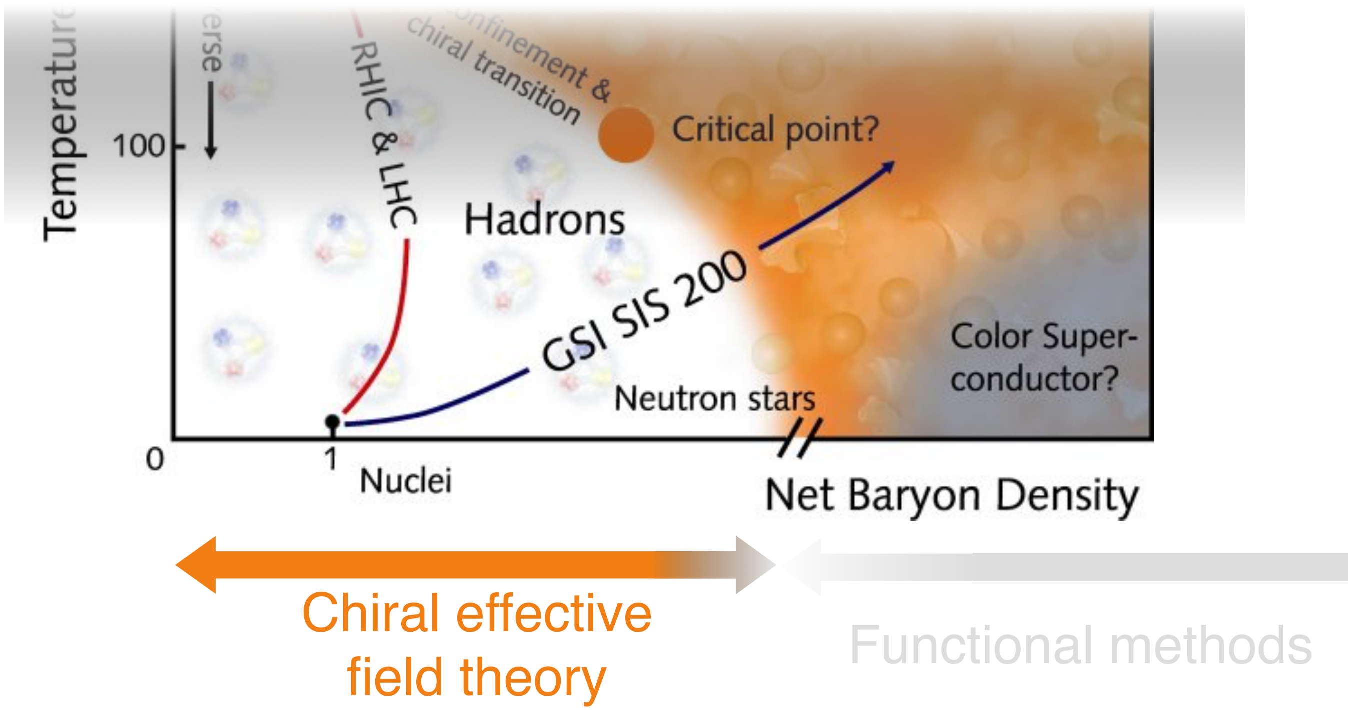

Marc Leonhardt

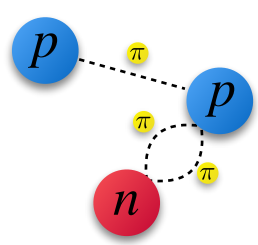

Martin Pospiech

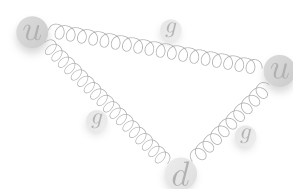

Benedikt Schallmo


Sebastian Töpfel

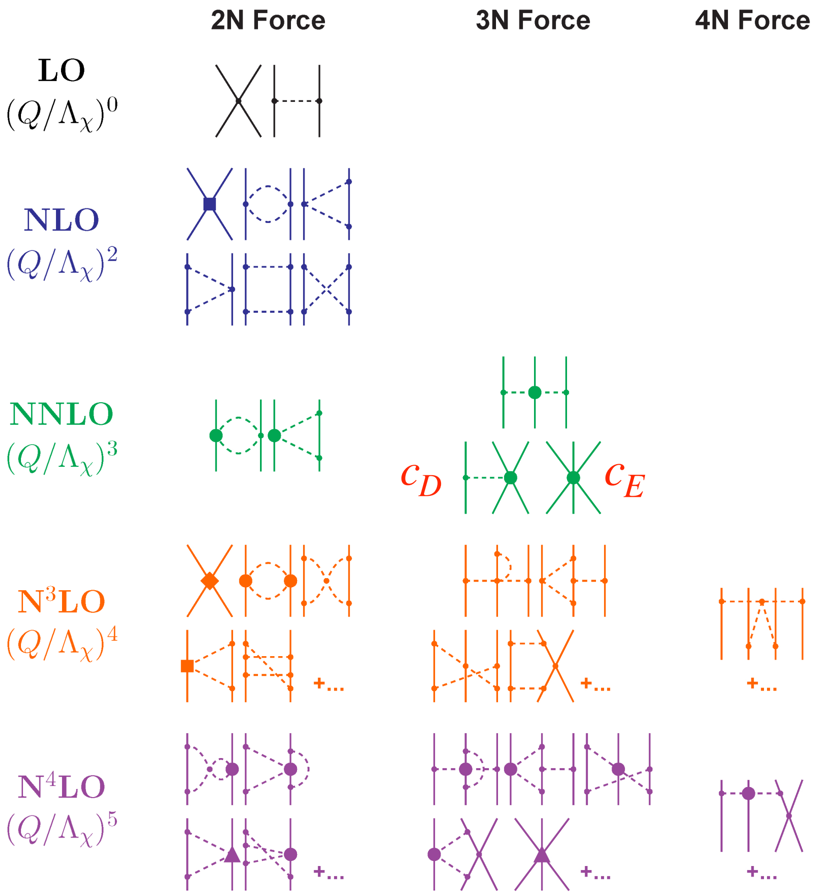
QCD phase diagram:
Neutron stars and the cold dense EoS







Chiral effective field theory of nuclear interactions



- Nuclear potentials V_{NN}, V_{3N}, … (Λ), with LECs fitted to NN, 3N, … data
- MBPT calculations, predictions for nuclear matter EoS

Chiral effective field theory of nuclear interactions

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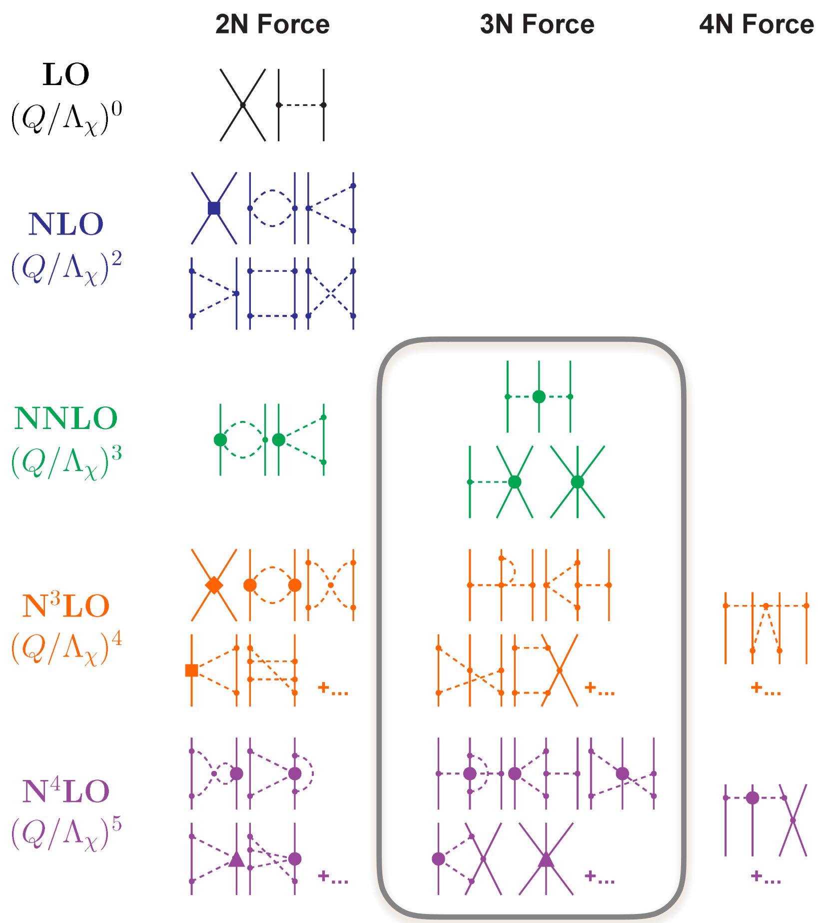

calculation of state-of-the-art 3N interactions for applications to matter and nuclei

[Hebeler et al. PRC 91 (2015)]

A02 A04 B05

- Nuclear potentials V_{NN}, V_{3N}, … (Λ), with LECs fitted to NN, 3N, … data
- MBPT calculations, predictions for nuclear matter EoS

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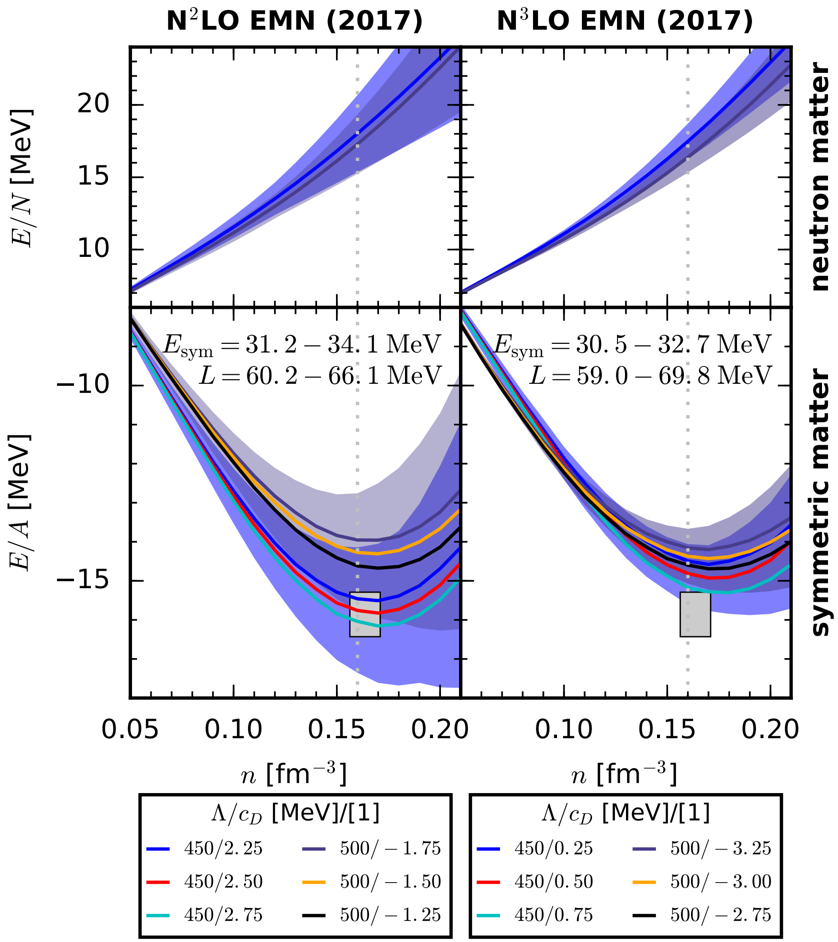
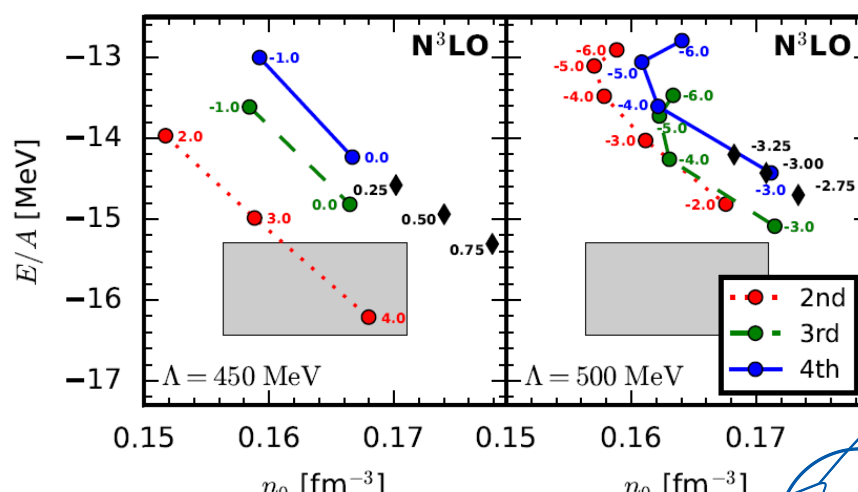
Efficient Monte-Carlo framework for MBPT calculations with chiral interactions



[Drischler, Hebeler, Schwenk, PRL122 (2019)]

- Improved studies of many-body uncertainties
  MBPT at high orders via automatic code generation, here: up to 4th order; 5th, 6th order in progress

- Constrain LECs using empirical nuclear matter saturation region
  here: fit 3N LECs c_D, c_E to ^{3}H and saturation point



Very low densities (dilute Fermi gas): pionless EFT

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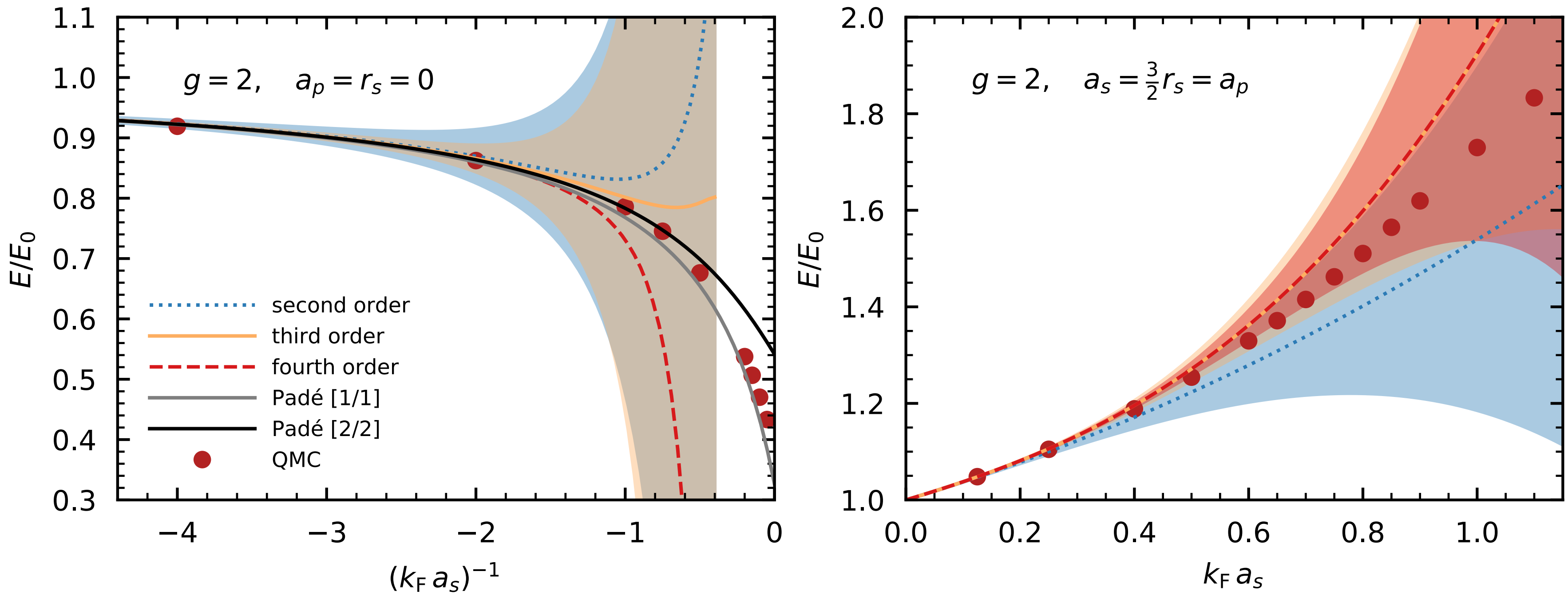
MPBT calculation of ground-state energy = expansion in $k_F a_s$

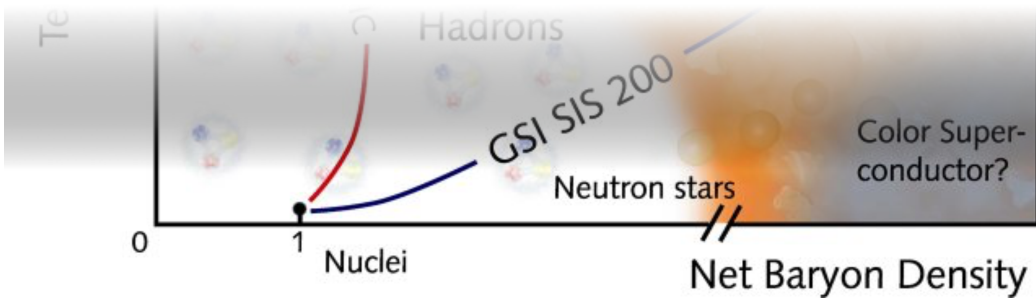


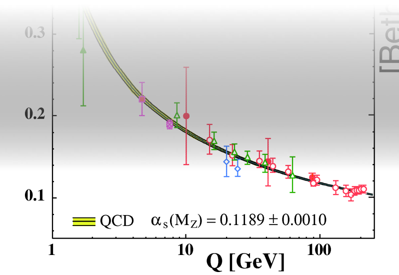
$$E/E_0 = 1 + 0.357\, k_F a_s + 0.186\, (k_F a_s)^2 + 0.03\, (k_F a_s)^3$$ [Bishop, Ann.Phys.77 (1972)]

$$-0.05\, (k_F a_s)^4 + \ldots$$ [Wellenhofer, Drischler, Schwenk (2018)]

Comparison with QMC calculations [Gandolfi et al. ARNPS 65 (2015), Pilati et al. PRL 105]

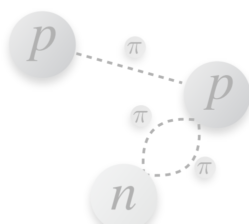
QCD phase diagram:
Neutron stars and the cold dense EoS





$\lesssim 60\rho_{\rm sat}$ [Kurkela et al., 2014]

Chiral effective field theory



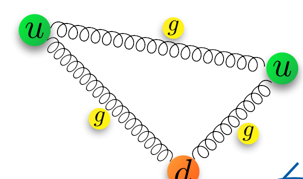
Functional methods

Strongly correlated matter at intermediate densities: variety of condensates as non-perturbative phenomena

- Stiffness of EoS
- Non-equilibrium processes, e.g. transport properties, cooling rate
- …

Perturbative methods

- Quarks and gluons as only dofs
- Weak coupling expansion



Functional renormalization group (FRG): From high to low energies in QCD

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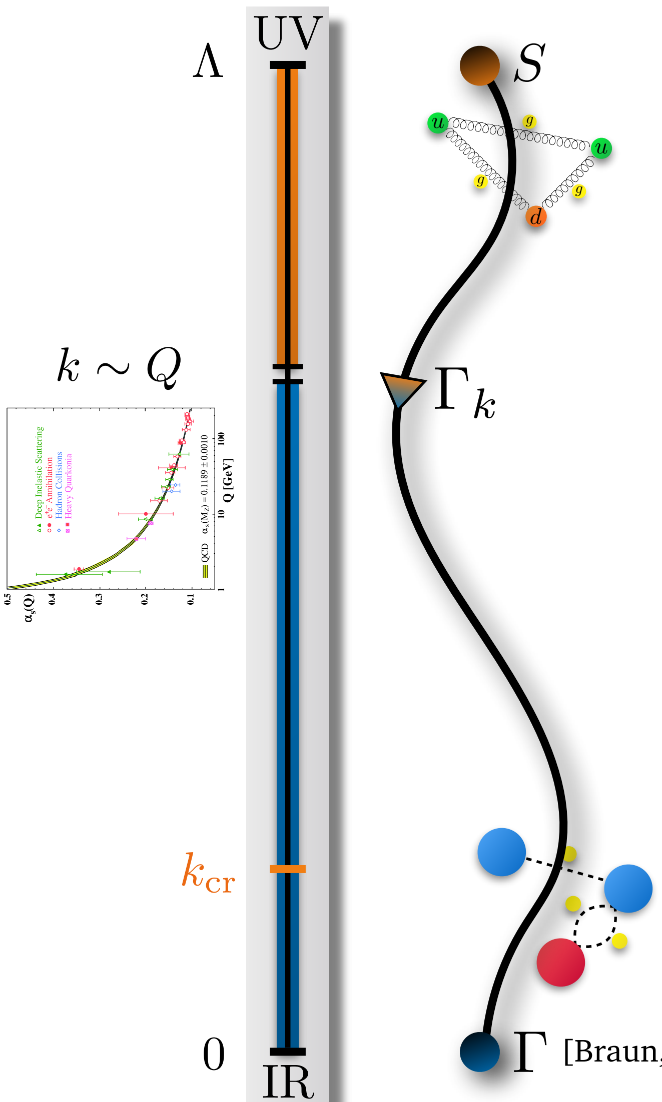
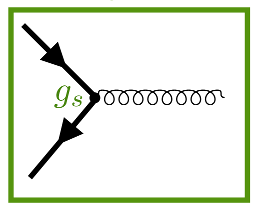
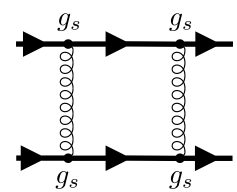


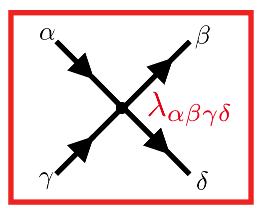
Gluodynamics



Input parameter: strong coupling $g_s(\Lambda)$



Four-quark interactions



Fierz-completeness
$\leftrightarrow$
variety of condensates

- chiral condensate
- diquark condensate
- …

[Braun, Leonhardt, Pospiech, PRD **96**, 076003(2017) [Editor's suggestion]; Braun, Leonhardt, Pospiech, PRD **97**, 076010 (2018)]

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First results for the equation of state of symmetric nuclear matter

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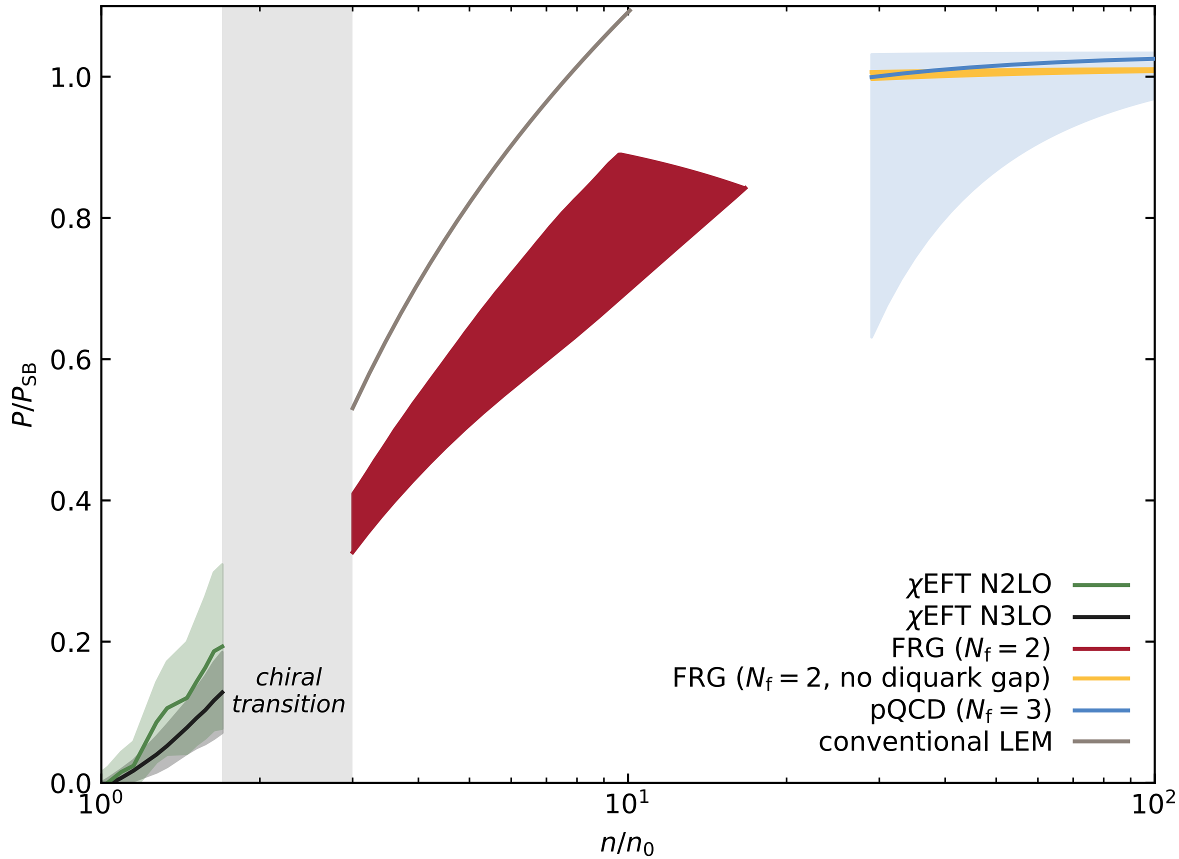

[pQCD results (no diquark gap!) from E. S. Fraga, A. Kurkela, and A. Vuorinen (2015)]

- Diquark gap is generated for all densities above the chiral transition
- Good consistency with χEFT results!

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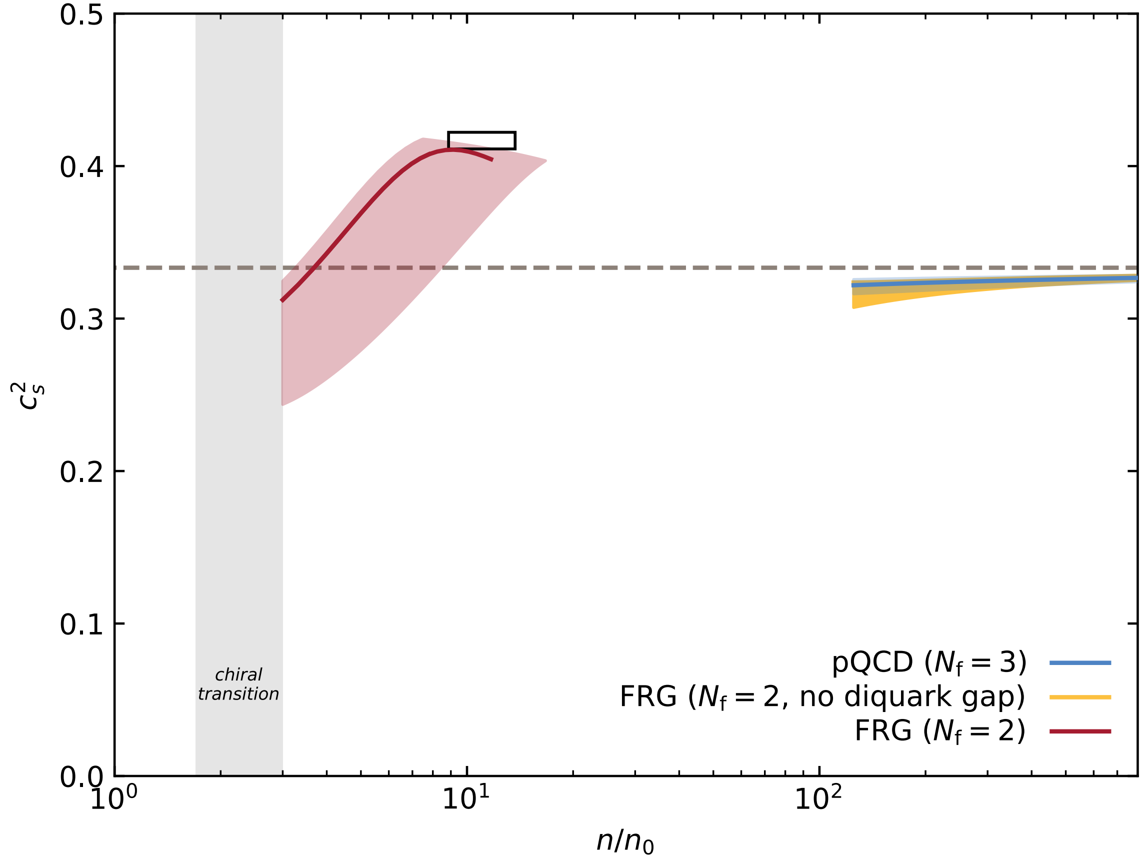
Speed of sound of symmetric nuclear matter



[pQCD results (no diquark gap!) from E. S. Fraga, A. Kurkela, and A. Vuorinen (2015)]

- Speed of sound exhibits a maximum (open box: uncertainty estimate)
- Emergence of a diquark gap is crucial for the appearance of a maximum

Speed of sound of symmetric nuclear matter

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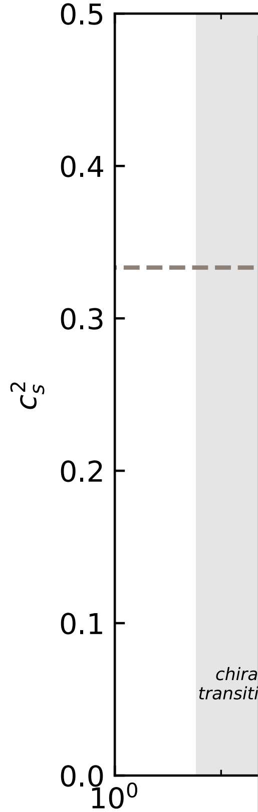

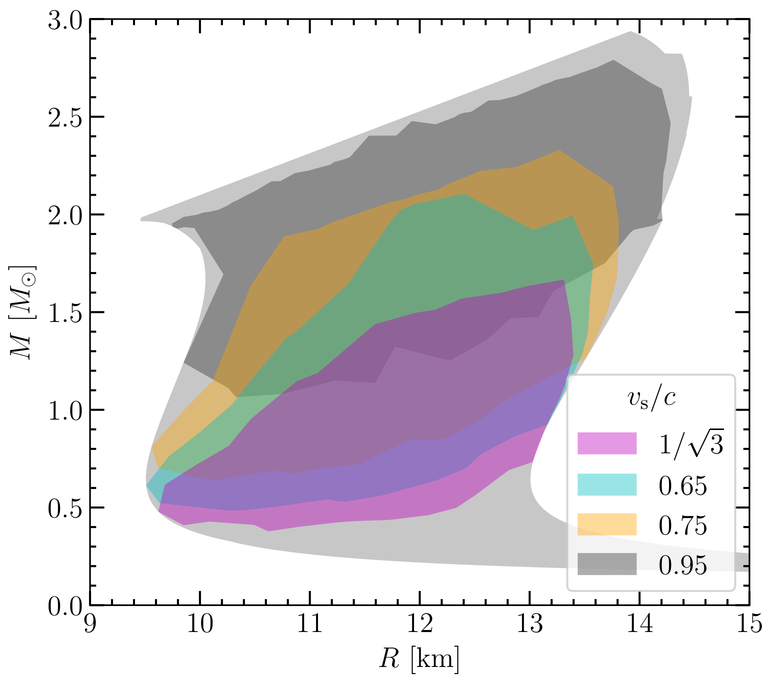

[Greif, Hebeler, Lattimer, Pethick, Schwenk, in preparation]
[Greif, Raaijmakers, Hebeler, Schwenk, Watts, MNRAS (2019)]

existence of maximum consistent with constraints from neutron star masses

[pQCD results (no diquark gap!) fror

- Speed of sound exhibits a
- Emergence of a diquark gap is crucial for the appearance of a maximum

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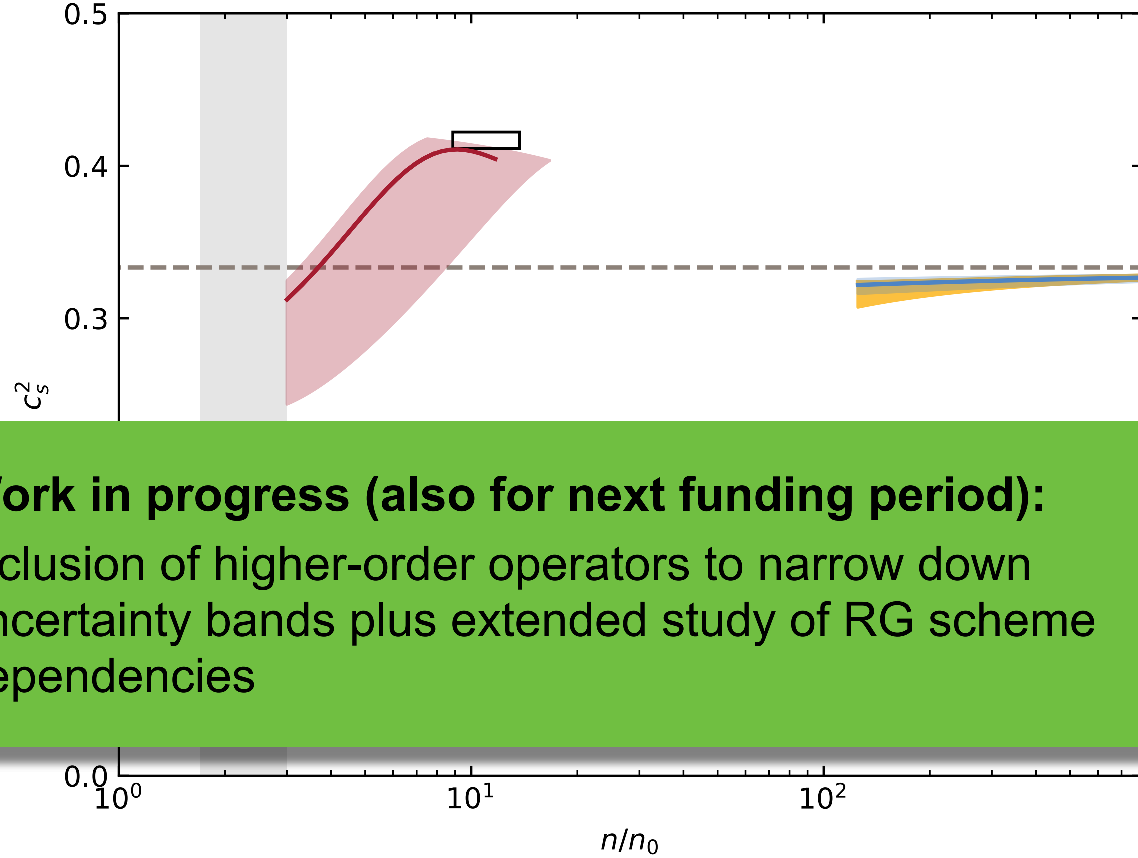
Speed of sound of symmetric nuclear matter



Work in progress (also for next funding period):
Inclusion of higher-order operators to narrow down uncertainty bands plus extended study of RG scheme dependencies

[pQCD results (no diquark gap!) from E. S. Fraga, A. Kurkela, and A. Vuorinen (2015)]

- Speed of sound exhibits a maximum (open box: uncertainty estimate)
- Emergence of a diquark gap is crucial for the appearance of a maximum

Summary

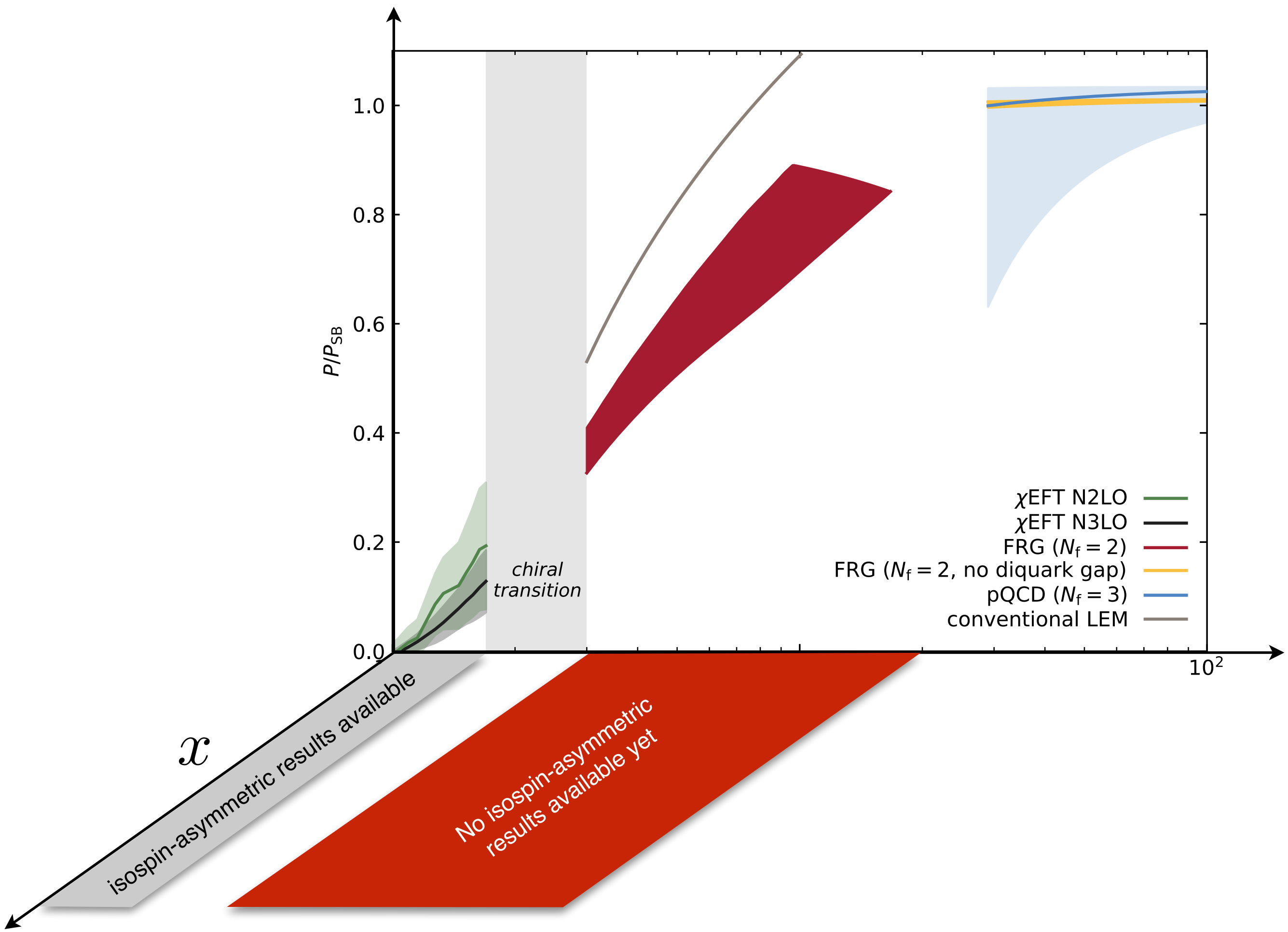
- Number of published articles: 17 (based on SFB webpage)
- Number of articles currently under review: 2
- Highlight publications:
  - C. Drischler, K. Hebeler, and A. Schwenk, Phys. Rev. Lett. 122, 042501 (2019)
  - J. Braun, M. Leonhardt, and M. Pospiech, Phys. Rev. D **96**, 76003 (2017) [Editor's suggestion]
  - M. Leonhardt, M. Pospiech, J. Braun, C. Drischler, K. Hebeler, A. Schwenk, *QCD constraints on the dense matter equation of state (in preparation)*
- Additional articles in preparation:
  - J. Braun, M. Leonhardt, M. Pospiech, *Gluon-induced symmetry breaking patterns at high density*

Summary

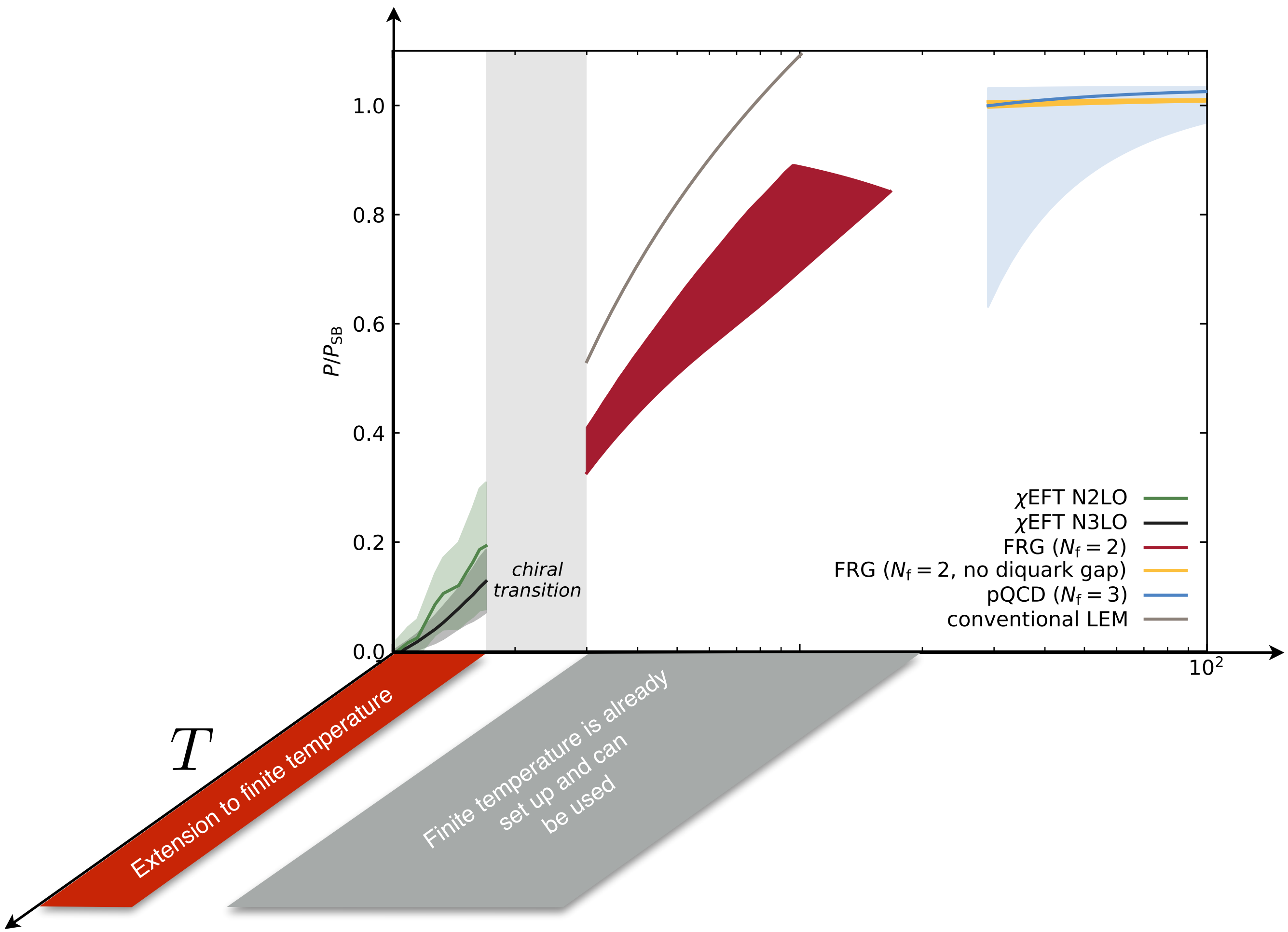
- Major successes of the young researchers:
  - **M. Leonhardt**: Travel prize of CRC 1245 (2018)
  - **M. Leonhardt**: Best-poster prize, workshop on “From Correlation Functions to QCD Phenomenology”, Bad Honnef (2018)
  - **C. Drischler**: PostDoc at Berkeley, Feodor Lynen stipend (since Fall 2017)
  - **C. Drischler**: Internship at Ohio State University (January 2017)

- (Co-)Organization of workshops:
  - *Functional Methods in Strongly Correlated Systems*, Hirschegg, Austria, March 31 - April 7, 2019

Plans for upcoming period



Plans for upcoming period



Towards improved QCD constraints for neutron-rich matter at high densities

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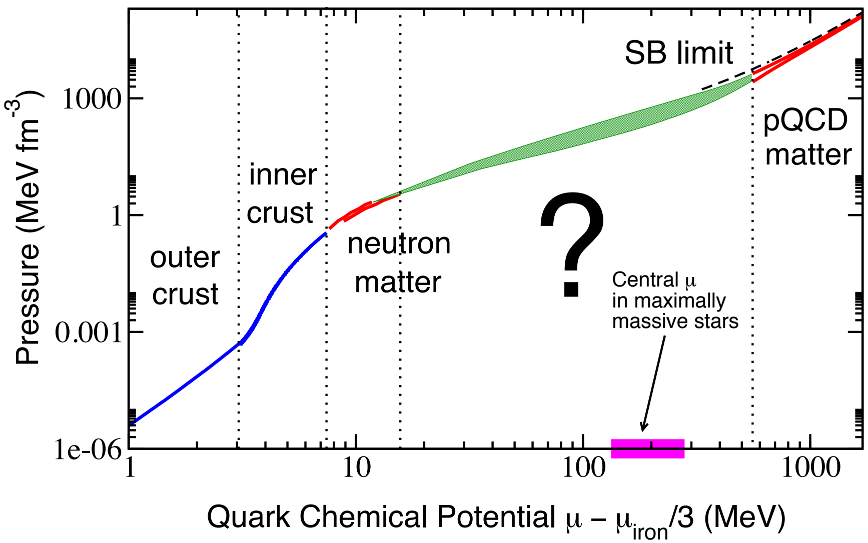
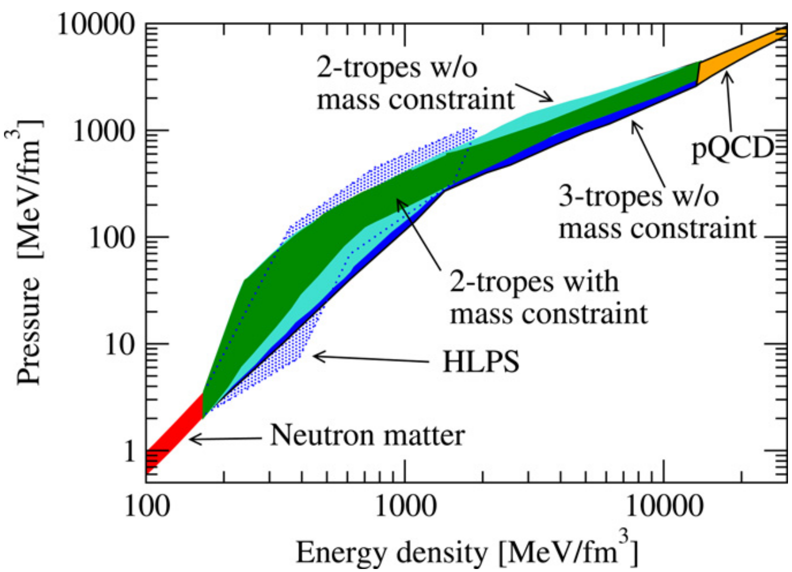
Current status:





[Kurkela, Fraga, Schaffner-Bielich, Vuorinen, ApJ 789 (2014)]

[Hebeler, Lattimer, Pethick, Schwenk, ApJ 773 (2013)]

Generalization of fRG framework to isospin-asymmetric and pure neutron systems can significantly improve constraints

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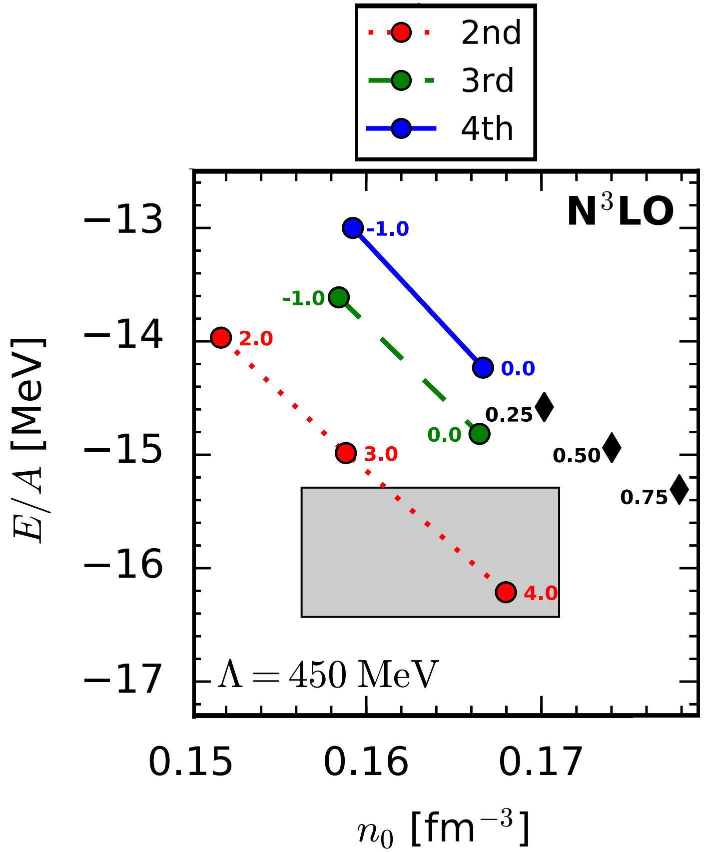
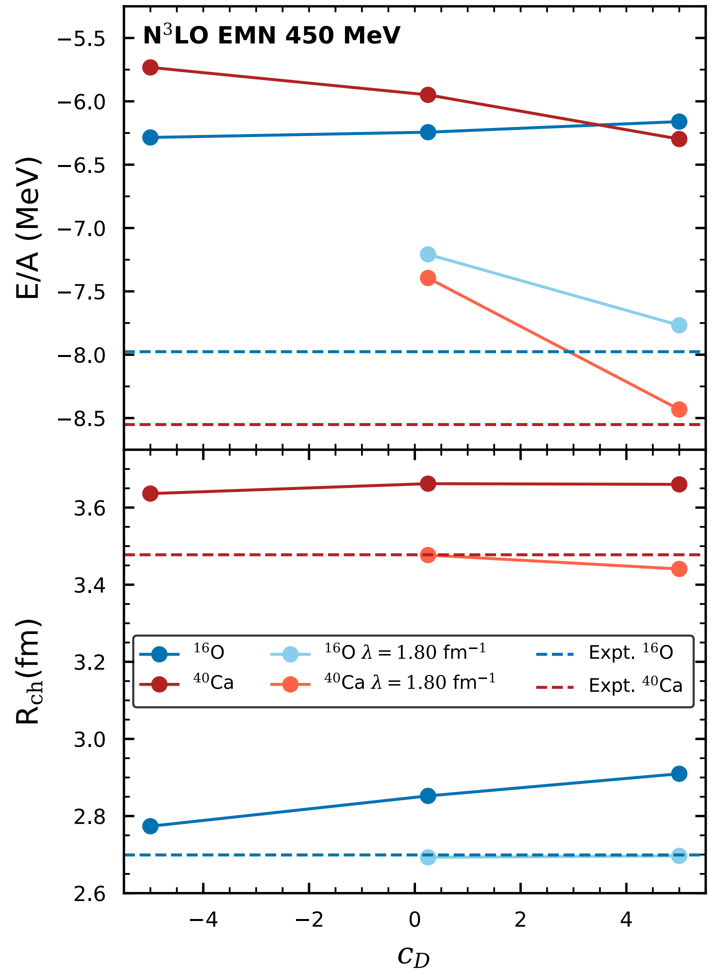
Challenge: Understanding the connection between nuclear matter and nuclei (A04)



[Drischler, Hebeler, Schwenk, PRL122 (2019)]



[Hoppe, Drischler, Hebeler, Schwenk, Simonis, in preparation]

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Challenge: Understanding the connection between nuclear matter and nuclei (A04)

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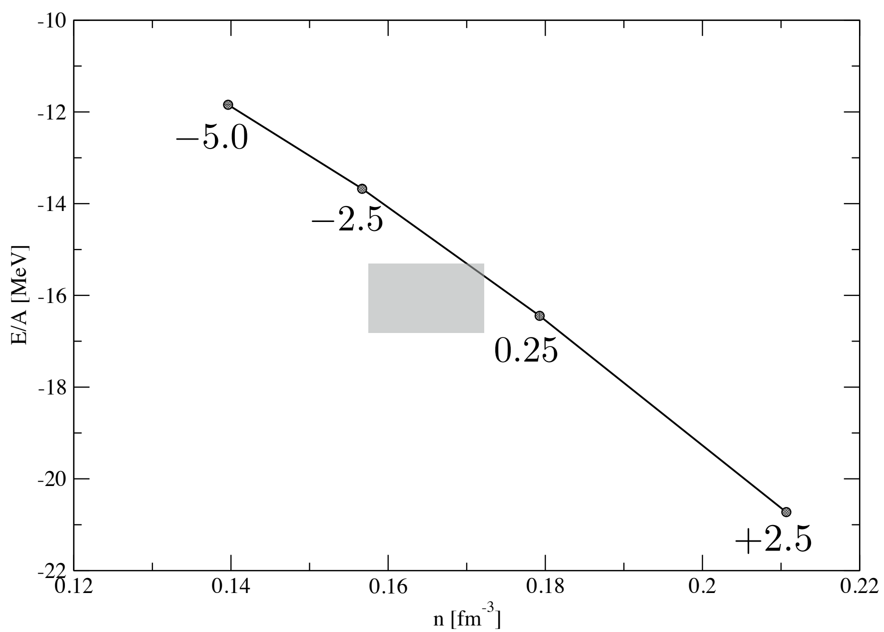

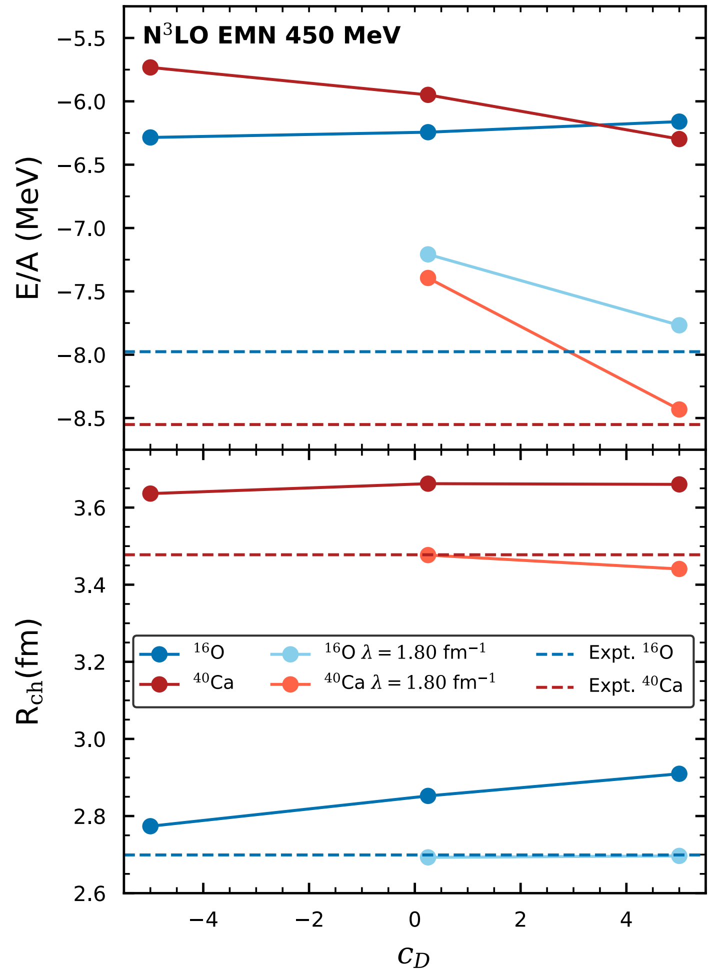

quantitative connection still puzzling

[Hoppe, Drischler, Hebeler, Schwenk, Simonis, in preparation]

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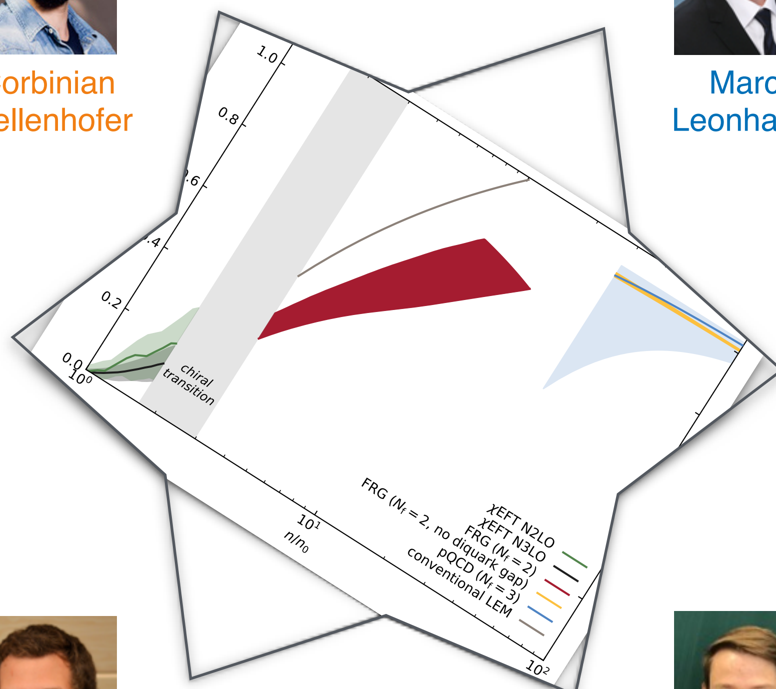
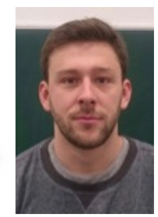
Thanks to the crew!

Corbinian Wellenhofer

Marc Leonhardt

Christian Drischler





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Backup

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Chiral effective field theory at lower densities

- Efficient Monte-Carlo framework for MBPT (automatic code generation; 4th order)
- Improve fits of LECs for development of improved nuclear interactions guided by empirical nuclear saturation properties
- Possible to generalize framework to finite temperature

Functional renormalization group at higher densities

- Dynamical generation of four-quark interactions by gluodynamics, importance of Fierz-completeness at high density and low temperature
- Connecting to low-energy dynamics by utilizing RG flow of gluon-induced four-quark couplings at high densities
- Studies with diquark gap taken to be zero agree with perturbative calculations at hight density; however, gap plays an important role at intermediate densities
- Equation of state: consistent with perturbative calculations at high density and χEFT at low density

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