Strong-interaction matter at nuclear densities and beyond

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Status report on project B05:
Nuclear matter equation of state for astrophysical applications

Corbinian Wellenhofer and Marc Leonhardt

with

Martin Pospiech and Jens Braun,
Christian Drischler and Kai Hebeler

3rd CRC 1245 Workshop
Schloss Waldthausen, 2018

Heisenberg-Programm DFG Deutsche Forschungsgemeinschaft

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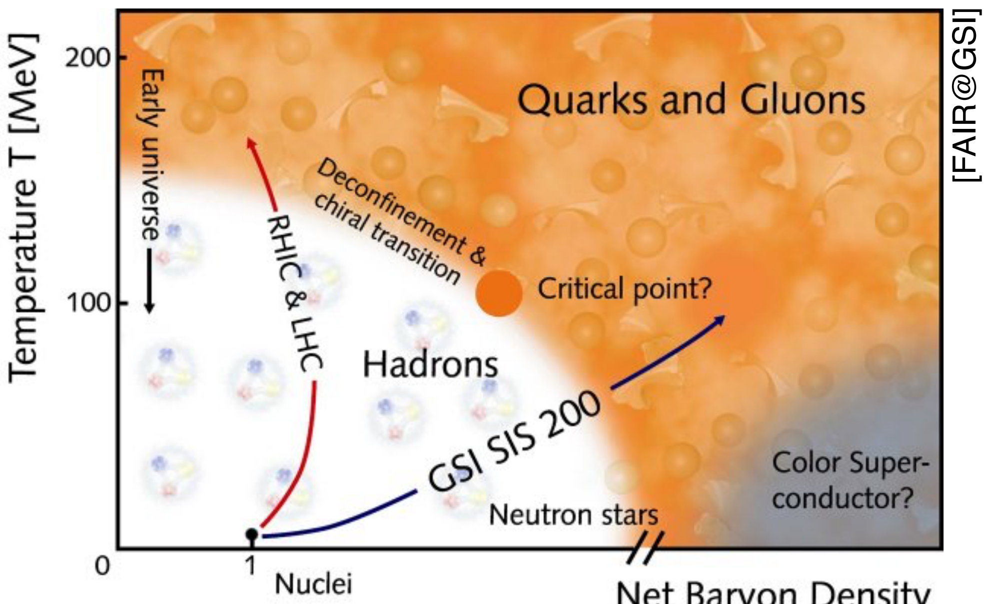
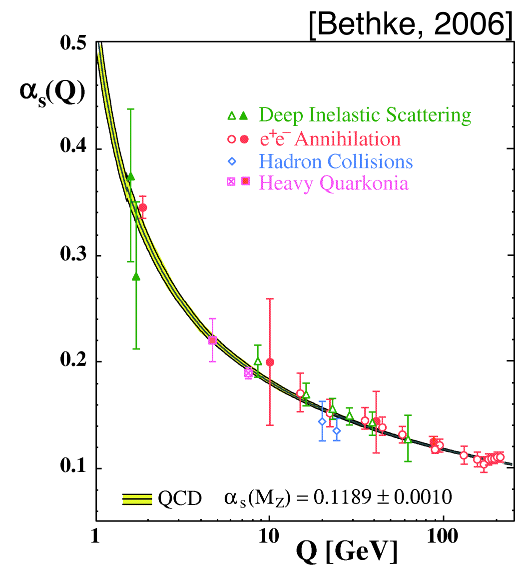
HIC for FAIR Helmholtz International Center

QCD phase diagram:
Neutron stars and the dense EoS



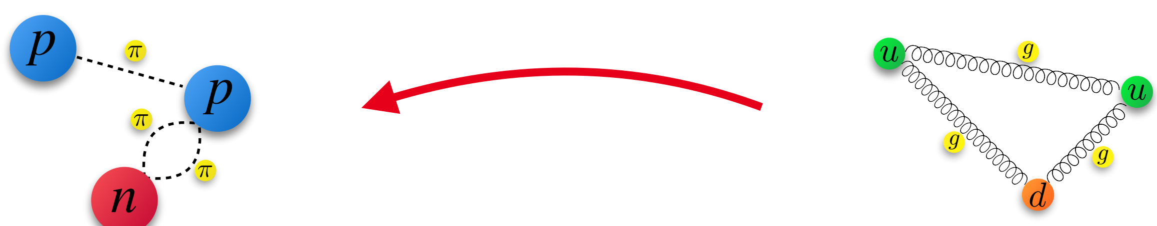


$\lesssim 35\,\rho_{\rm sat}$ [Kurkela et al., 2014]

Low-energy effective theories

Functional methods

Perturbative methods



Outline

- Chiral effective field theory (at lower densities)
  - Systematic description of NN, 3N, … interactions
  - RG evolution to low-momentum scales
  - EoS from MBPT:
    Order-by-order convergence, finite temperature
- Functional renormalization group (at higher densities)
  - Dynamic generation of Fierz complete four-quark self-interactions by gauge degrees of freedom
  - Connecting to low-energy effective model and first results on the EoS
- Conclusions and outlook


Christian Drischler


Corbinian Wellenhofer


Martin Pospiech


Marc Leonhardt

[Drischler, Hebeler, Schwenk, arXiv:1710.08220]
[Wellenhofer, arXiv:1804.03040]

[Braun, ML, Pospiech, PRD **96**, 076003 (2017)]
[Braun, ML, Pospiech, PRD **97**, 076010 (2018)]
[Braun, ML, Pawlowski, arXiv:1806.04432]
[Braun, Drischler, Hebeler, ML, Pospiech, Schwenk, in prep.]

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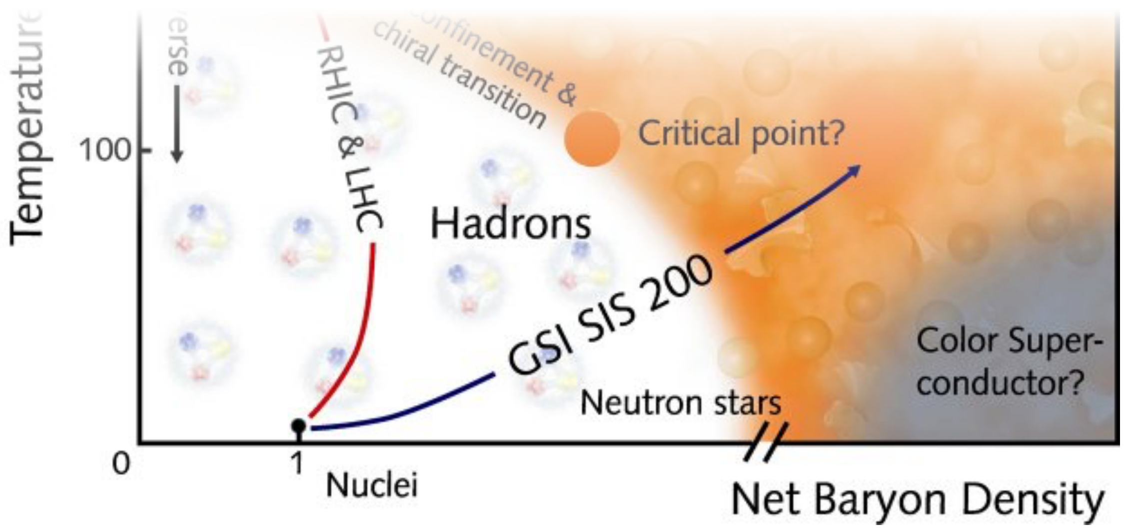
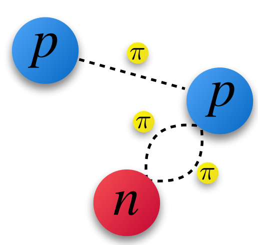
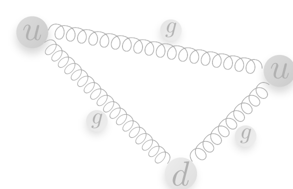
QCD phase diagram:
Neutron stars and the cold dense EoS



Chiral effective field theory

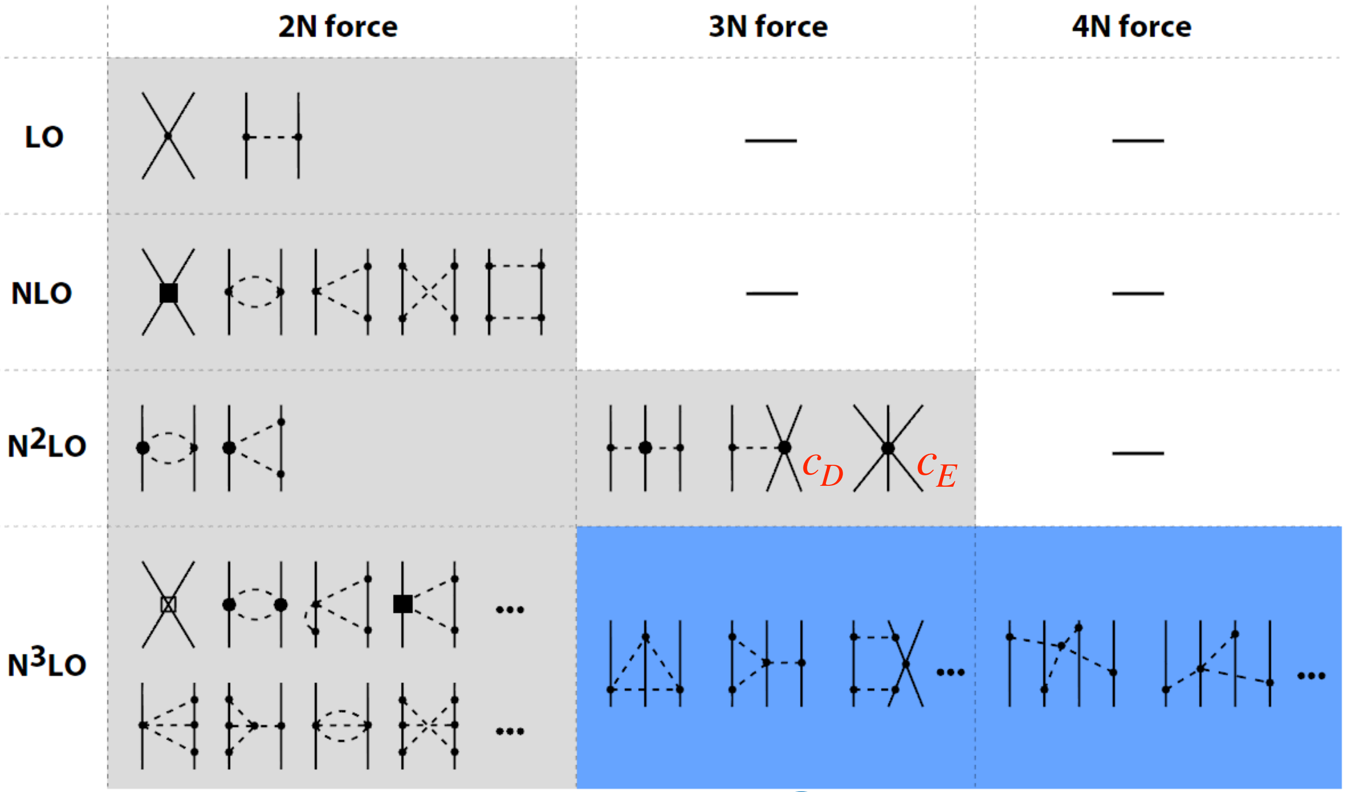
Functional methods





Chiral effective field theory of nuclear interactions

Systematic hierarchy in terms of Q/Λ_B



... and ongoing work at N⁴LO, N⁵LO, ...

➡ Nuclear potentials V_{NN}, V_{3N}, … (Λ), with LECs fitted to NN, 3N, … data

➡ MBPT calculations, predictions for nuclear matter EoS

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

Efficient Monte-Carlo framework for MBPT calculations with chiral interactions

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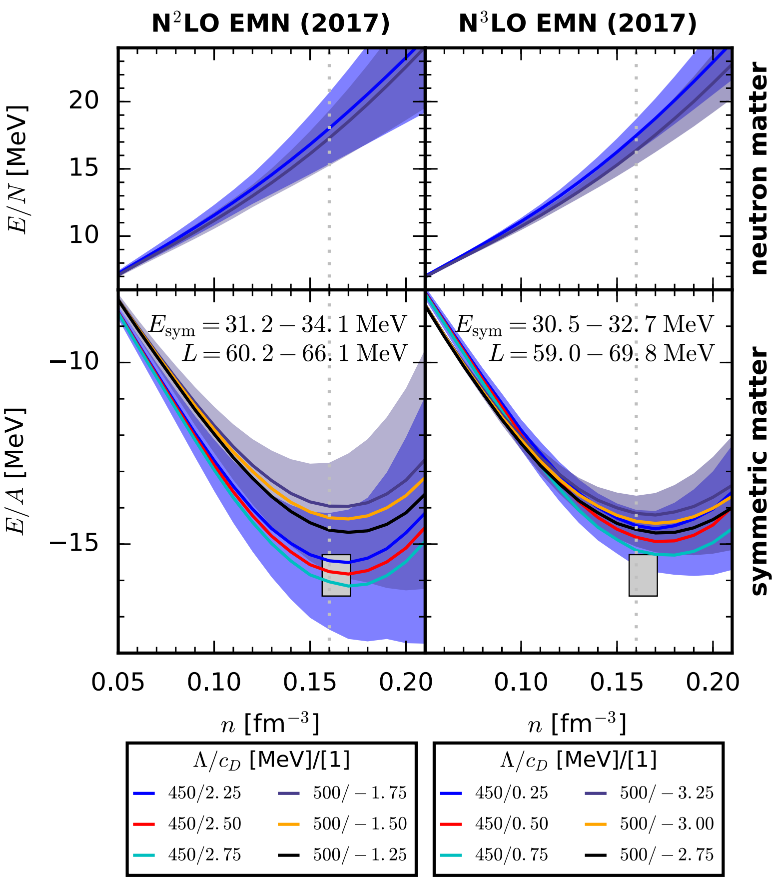
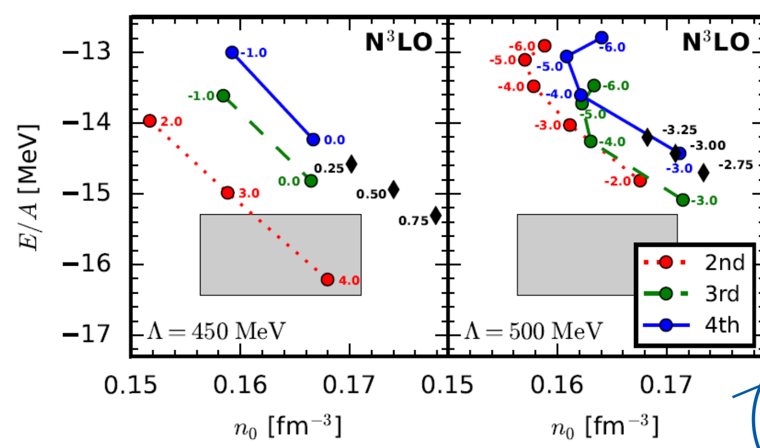


- Explore Many-Body Uncertainties
  →MBPT at high orders: **automatic code generation**
  here: 4th order; 5th, 6th order in progress

- Efficient treatment of 3N, 4N @ N^{3}LO, …
  analytical expressions instead of PW

- Constrain LEC fits in terms of nuclear saturation
  here: fit 3N LECs c_D, c_E to ^{3}H and study saturation



[Drischler, Hebeler, Schwenk, arXiv:1710.08220]

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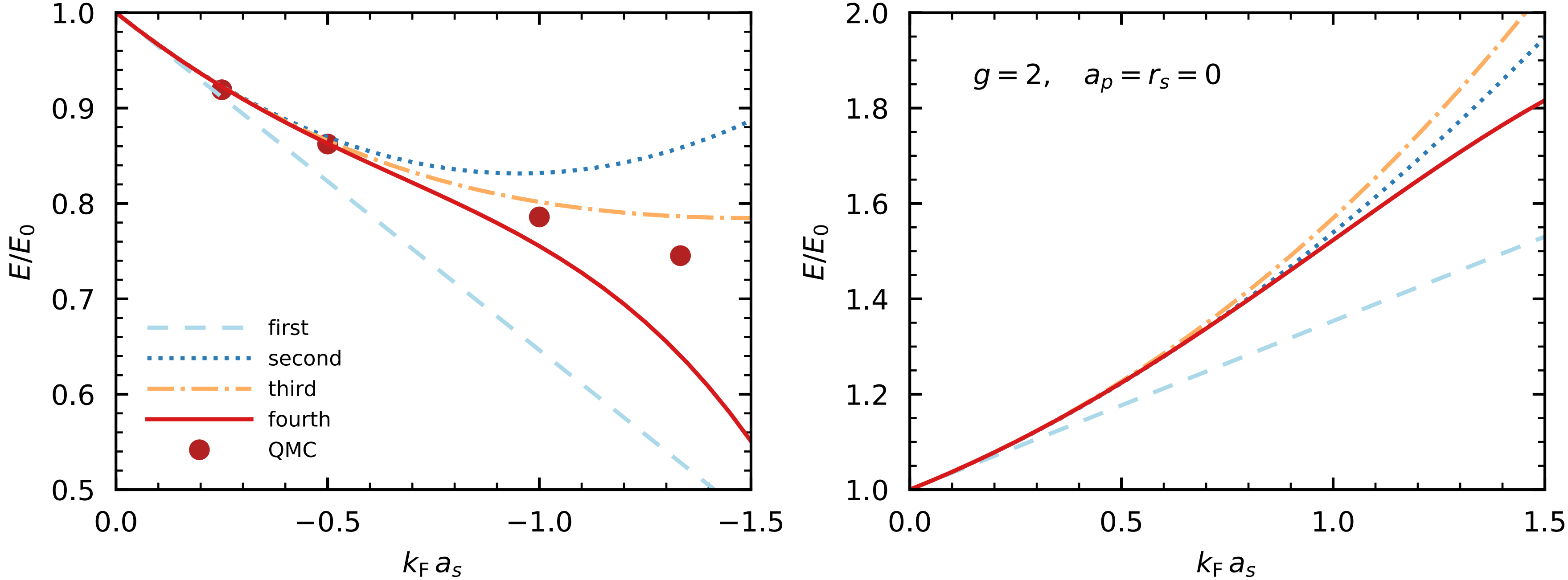
Very low densities (dilute Fermi gas): pionless EFT

LECs matched to low-energy T-matrix: $T(k) \sim a_s - \mathrm{i}ka_s^2 + \ldots$

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, in preparation (2018)]

Comparison with QMC calculations [Gandolfi, Gezerlis, Carlson, arXiv:1501.05675]

Current work: extend framework, with focus on astrophysical applications

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- Generalize MBPT framework consistently to finite T
  Energy denominator poles $\sim n_i n_j (1-n_k)(1-n_l)/(e_i+e_j-e_k-e_l)$
  → sum over cyclic permutations, cancels poles

- Statistical quasiparticles in higher-order MBPT [Wellenhofer, arXiv:1804.03040]
  → Fermi-liquid phenomenology, improved EoS parametrizations

- Generate EoS tables for astrophysical applications
  → Efficient MC framework to treat large parameter space (T, ρ, Y_p)

- Extension of EoS to higher densities → functional RG methods

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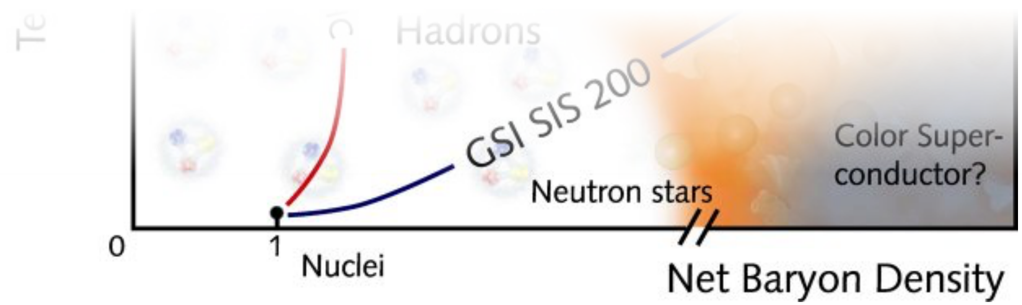
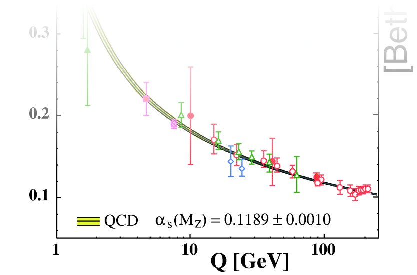
QCD phase diagram: Neutron stars and the cold dense EoS





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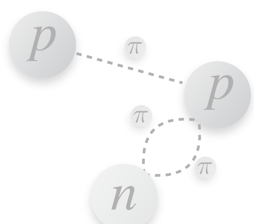
Chiral effective field theory



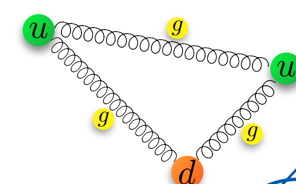
Functional methods

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
- …

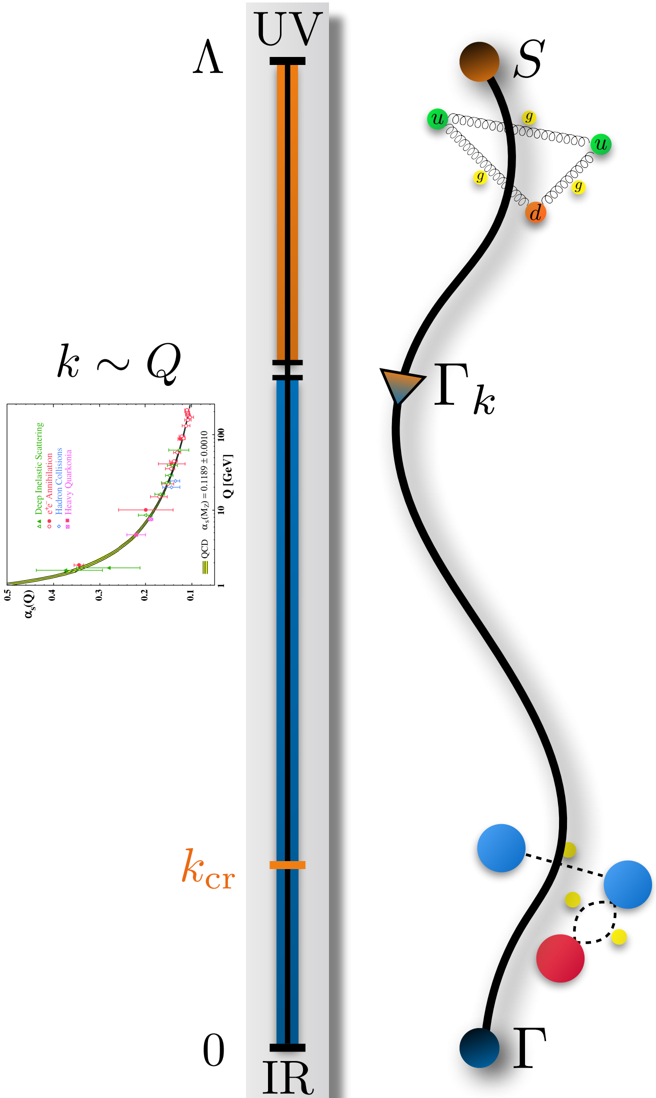
Perturbative methods

- Quarks and gluons as only dofs
- Weak coupling expansion



Functional renormalization group (FRG)

From high to low energies in QCD



[Braun, ML, Pospiech, PRD **97**, 076010 (2018)]

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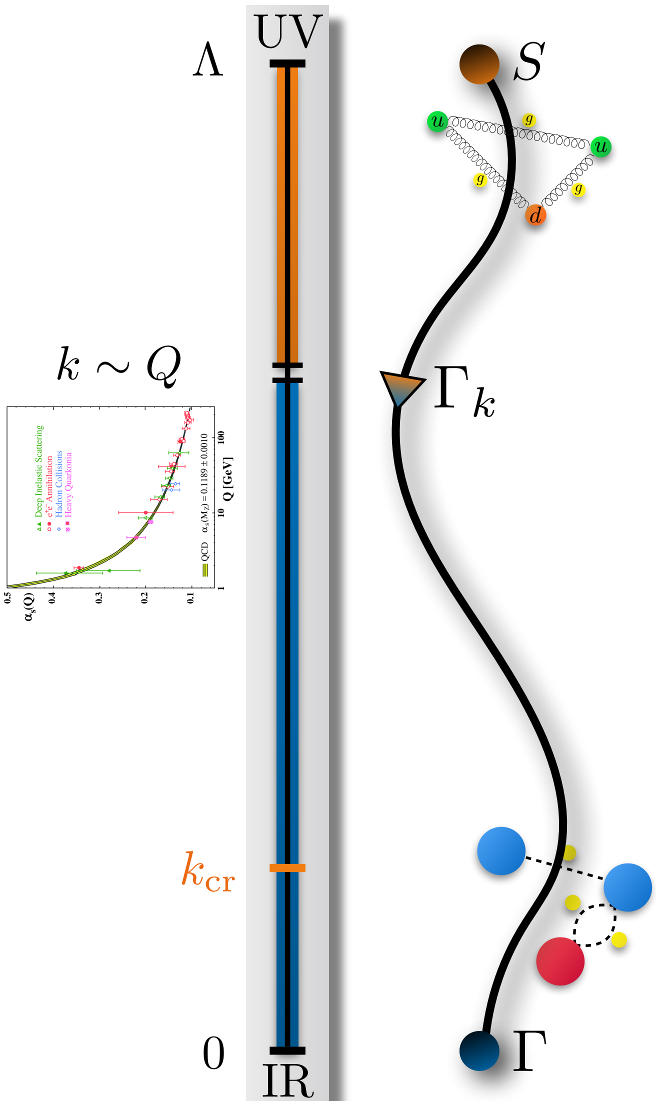
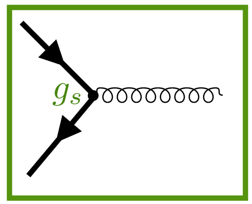


Gluodynamics



Strong coupling $g_s(\Lambda)$ only parameter!

$g_s(\Lambda)$ at Λ = 10 GeV within exp. error [Bethke, 2006]

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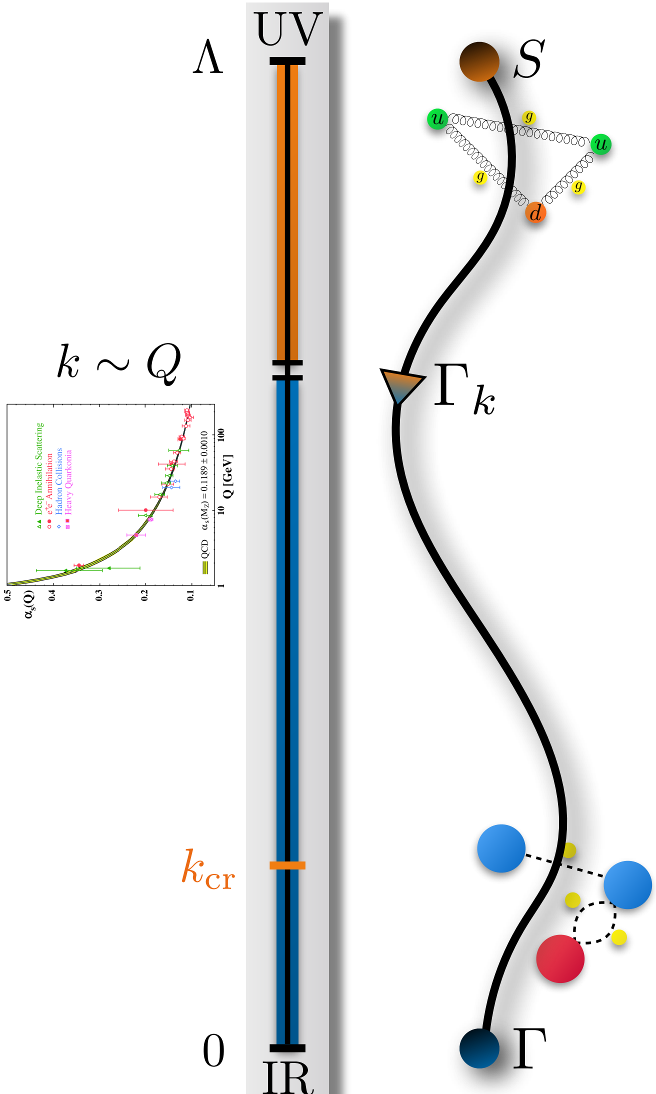

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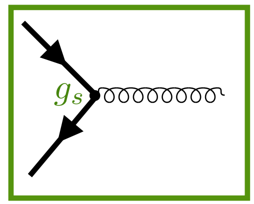

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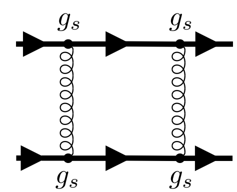
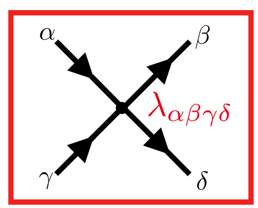


Four-quark interactions

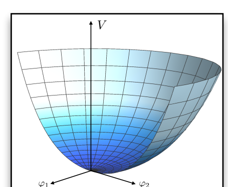


Fierz-completeness

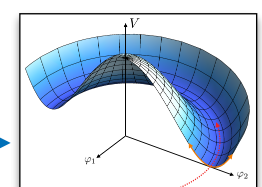
$\leftrightarrow$

variety of condensates

- chiral condensate
- diquark condensate
- …



$$\frac{1}{\bar{\lambda}_{(\sigma\text{-}\pi)}}\bigg|_{k_{\mathrm{cr}}} \longrightarrow 0$$



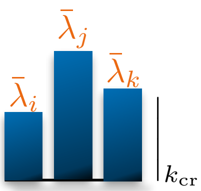
[Braun, ML, Pospiech, PRD **97**, 076010 (2018)]

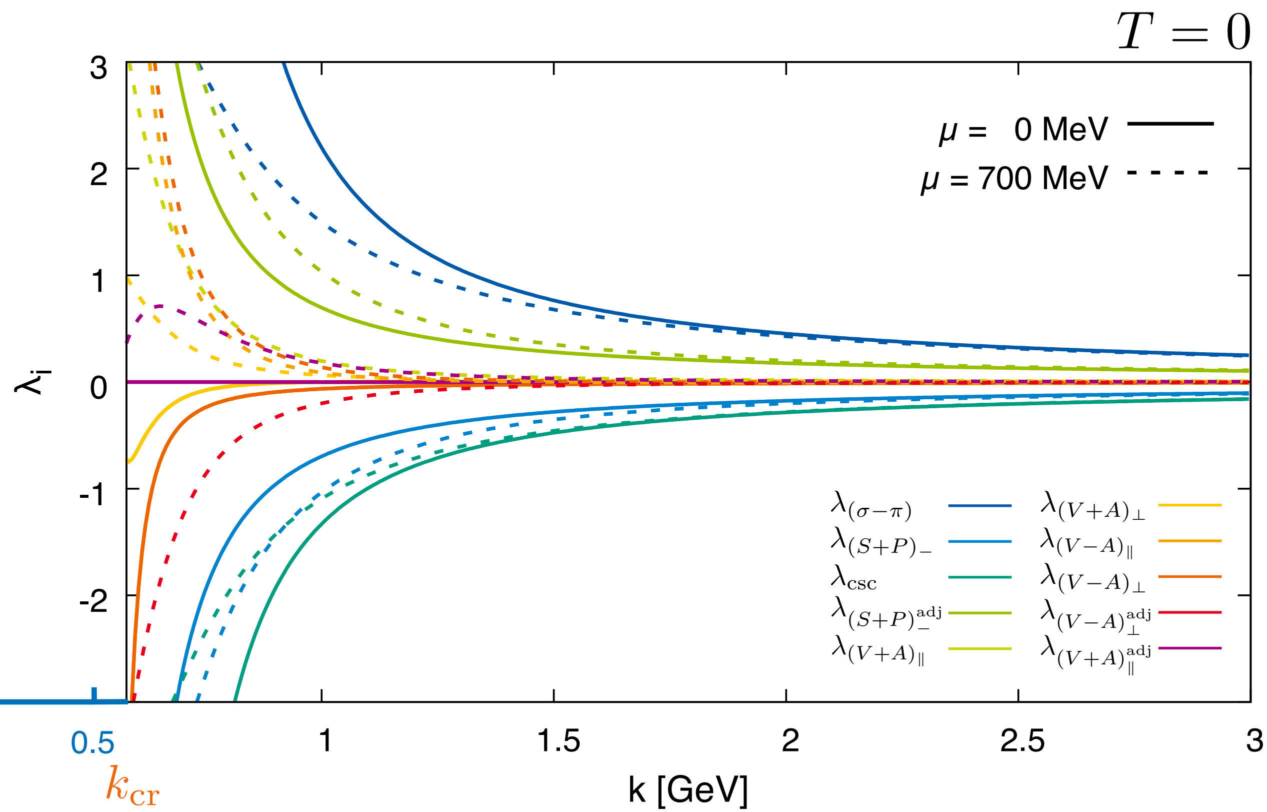
RG flow of four-quark interactions

Illustration of the RG flow at zero temperature

- Diverging coupling signals onset of condensate formation

- Assessing relative interactions strengths
  → Formation of specific condensates





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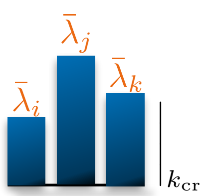

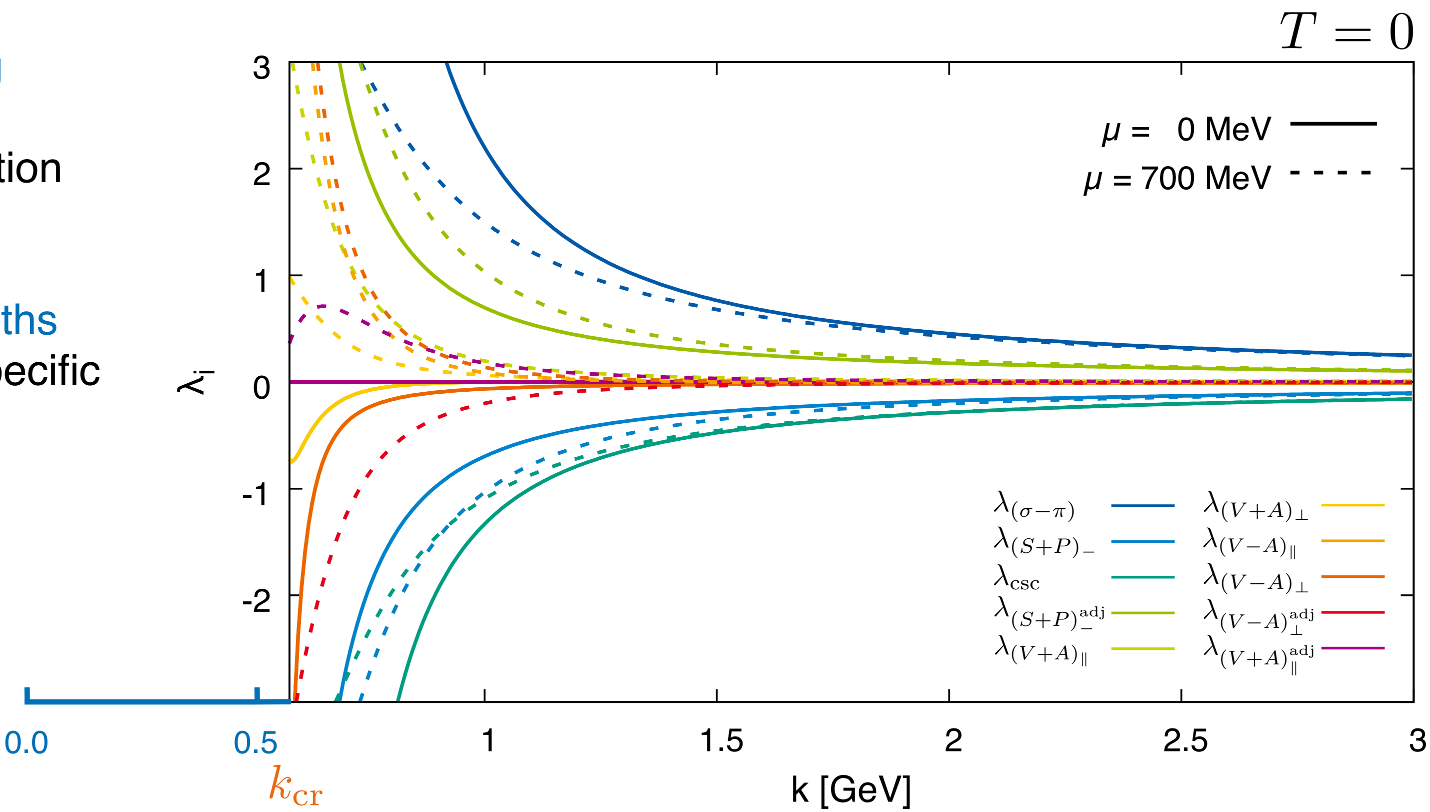

customized ansatz for low energy part → chiral fields φ / diquark fields Δ

now: two most dominant channels

[Braun, ML, Pospiech, (2018) in preparation]

Connecting to low-energy dynamics

Determining parameters at high densities

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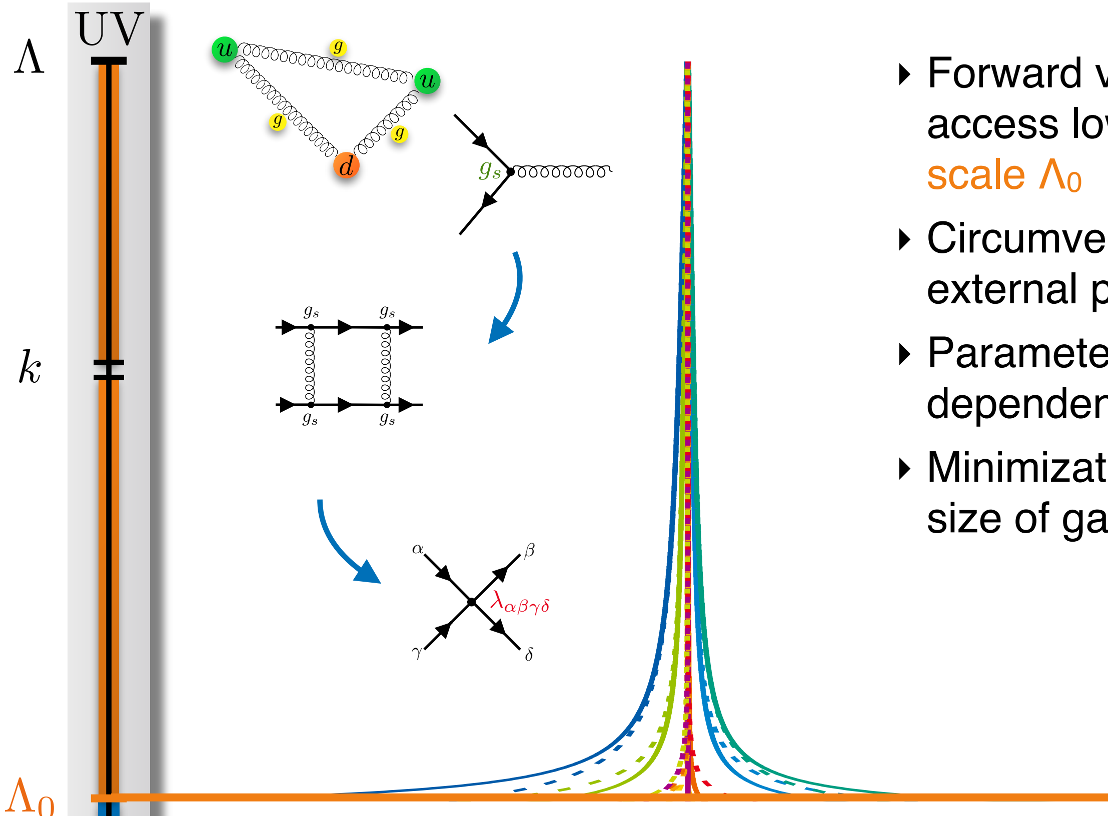
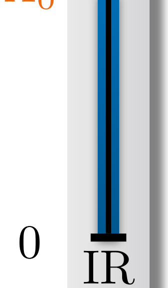


- Forward value of four-quark couplings to access low-energy dynamics at transition scale Λ_0
- Circumvent limit of accessible range of external parameters
- Parameters temperature and density dependent
- Minimization of thermodynamic potential: size of gaps, pressure, density, …

$$\mathcal{Z} \sim \int_{p<\Lambda_0} \mathcal{D}q\,\mathcal{D}\bar{q}\,\mathcal{D}\varphi\,\mathcal{D}\Delta\;\mathrm{e}^{-S(\lambda_{(\sigma-\pi)},\lambda_{\mathrm{csc}})}$$



↳ Thermodynamic potential $\Omega\,(\varphi,\Delta)\Big|_{\lambda_{(\sigma-\pi)},\lambda_{\mathrm{csc}}} = -\frac{T}{V}\log\mathcal{Z}$

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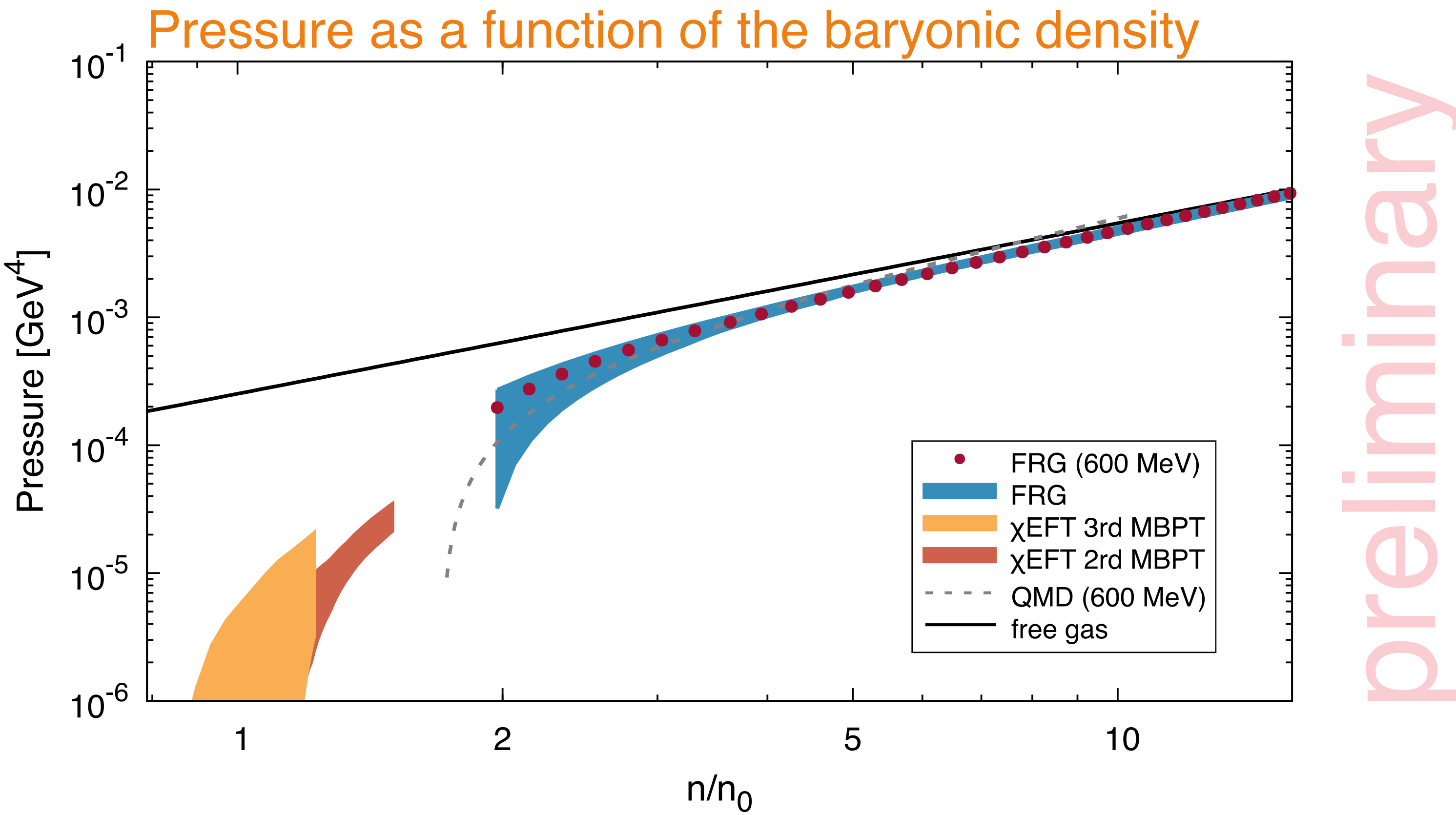
Implications on the equation of state

Connecting to the quark-meson-diquark model



[χEFT data by C. Drischler, K. Hebeler and A. Schwenk]

- Compatible to pQCD [E. S. Fraga, A. Kurkela, and A. Vuorinen, 2015]
- Degrees of freedom at smaller densities

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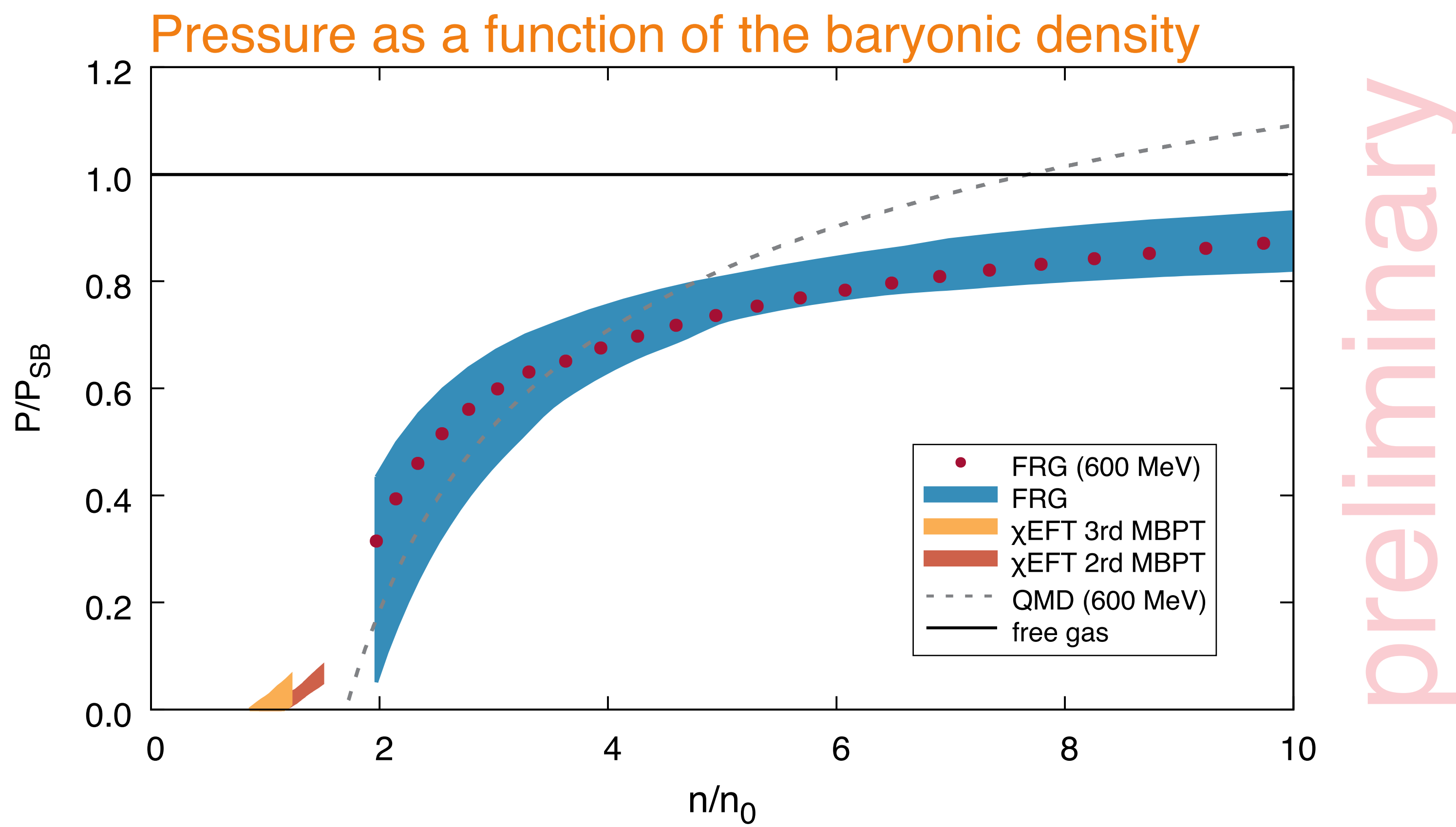

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Conclusions and outlook

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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 by guiding in terms of nuclear saturation
- Consistent generalisation to finite temperature

Outlook Nuclear equation of state for astrophysical applications, statistical quasiparticles

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 four-quark couplings to fix parameters at high densities
- Equation of state: connects to free gas pressure at asymptotically large densities; compatibility with χEFT results appears to be improved

Outlook Improve connection between high- and low-energy regime by employing dynamical hadronization techniques

[H. Gies, and C. Wetterich, 2002; J. Braun et al., 2014]

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Travel prize

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PHYSICAL REVIEW D **96,** 076003 (2017)

Fierz-complete NJL model study: Fixed points and phase structure at finite temperature and density

Jens Braun,[1,2] Marc Leonhardt,[1] and Martin Pospiech[1]

[1]*Institut für Kernphysik (Theoriezentrum), Technische Universität Darmstadt, D-64289 Darmstadt, Germany*
[2]*ExtreMe Matter Institute EMMI, GSI, Planckstraße 1, D-64291 Darmstadt, Germany*

(Received 22 May 2017; published 6 October 2017)

Nambu–Jona-Lasinio-type models are frequently employed as low-energy models in various research fields. With respect to the theory of the strong interaction, this class of models is indeed often used to analyze the structure of the phase diagram at finite temperature and quark chemical potential. The predictions from such models for the phase structure at finite quark chemical potential are of particular interest as this regime is difficult to access with lattice Monte Carlo approaches. In this work, we consider a Fierz-complete version of a Nambu–Jona-Lasinio model. By studying its renormalization group flow, we analyze in detail how Fierz-incomplete approximations affect the predictive power of such model studies. In particular, we investigate the curvature of the phase boundary at small chemical potential, the critical value of the chemical potential above which no spontaneous symmetry breaking occurs, and the possible interpretation of the underlying dynamics in terms of difermion-type degrees of freedom. We find that the inclusion of four-fermion channels other than the conventional scalar-pseudoscalar channel is not only important at large chemical potential but also leaves a significant imprint on the dynamics at small chemical potential as measured by the curvature of the finite-temperature phase boundary.

DOI: 10.1103/PhysRevD.96.076003

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