Neutron matter at finite temperature

Status report on part of project B05

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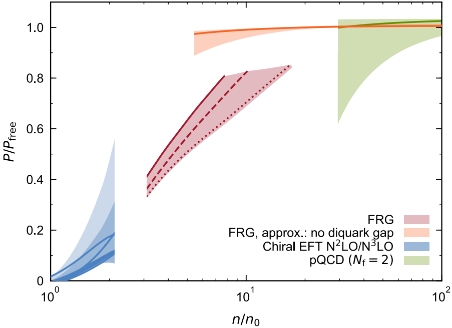
SFB Workshop, 25 March 2021

SFB 1245

Introduction

- Nuclear matter: idealized system on neutrons and protons in thermodynamic limit (no surface effects, ...)
- This talk: nuclear-density part from chiral EFT



Leonhardt at at., Phys. Rev. Lett. 125 (2020)

- So far EOS studied often for $T = 0$ for PNM or SNM
- Thermal effects matter for astro applications e.g. Yasin et al., Phys. Rev. Lett. 124 (2020)
- Astrophysical systems are neutron rich

$\longrightarrow$ Extend to finite temperatures (and asymmetric matter)

EOS calculation

Nuclear interaction
Chiral EFT: $H = H_0 + V_{NN} + V_{3N}$

↓

Grand-canonical potential
$\Omega(T, \mu) = -\frac{1}{\beta} \ln \mathrm{Tr} \left(e^{-\beta(H-\mu N)} \right)$

↓

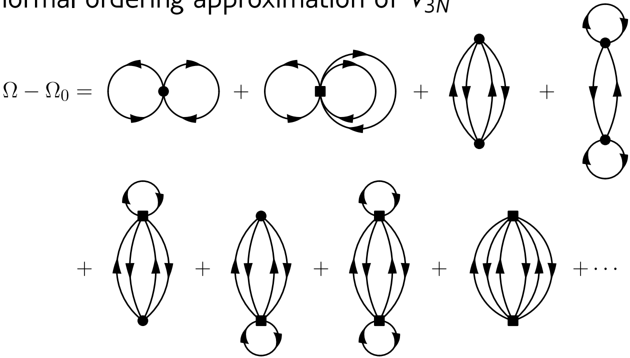
Approximation strategy
Many-body perturbation theory

↓

Equation of state (EOS)
$F(T, n), P(T, n), \ldots$

Many-body perturbation theory (MBPT)

- Expansion in V_{NN} and V_{3N} vertices
- No normal ordering approximation of V_{3N}

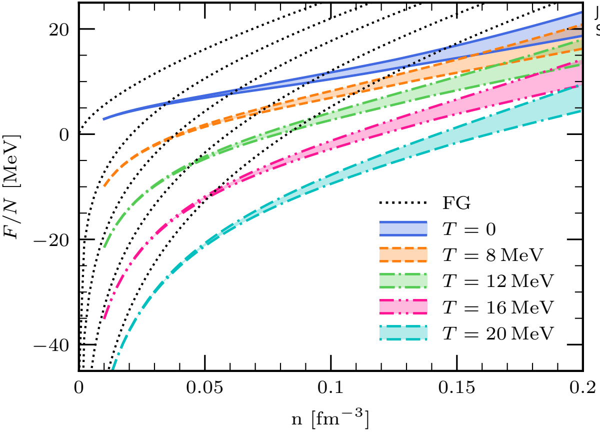


- Each line represents spin sums and momentum integral
- Additional anomalous diagrams
- Relevant potential is $F(T, n) = \Omega(T, \mu) + \mu\, n(T, \mu)$

Drischler, Hebeler, Schwenk, Phys. Rev. Lett. 122 (2019)

Free energy

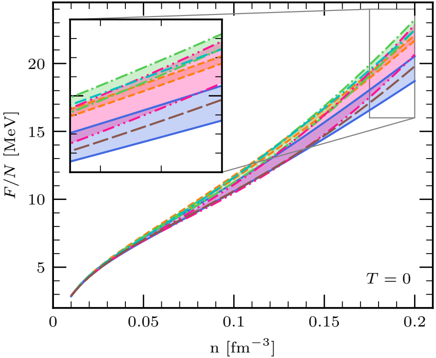
- Systematic study based on different nuclear interactions (bands)
- Large part of temperature dependence from free Fermi gas (FG)

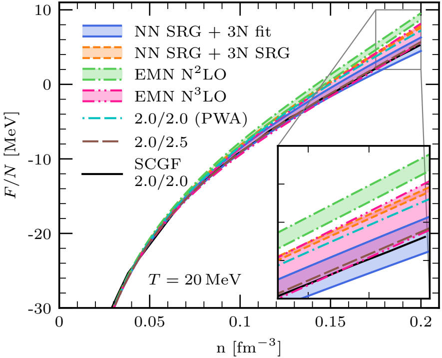


JK, Wellenhofer, Hebeler, Schwenk, arXiv:2011.05855

Free energy

- Bands display SRG ($\lambda_{SRG} = 1.8$ to $2.8\,\text{fm}^{-1}$) or cutoff variations ($\Lambda = 450$ to $500\,\text{MeV}$)
- Consistent with non-perturbative SCGF calculations
  Carbone, Schwenk, Phys. Rev. C 100 (2019)

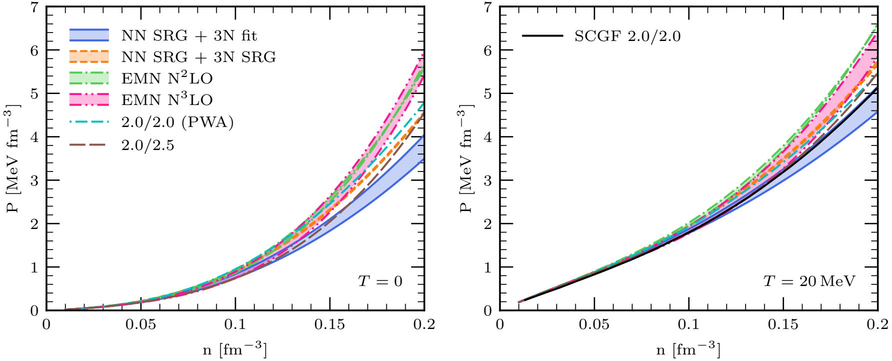




JK, Wellenhofer, Hebeler, Schwenk, arXiv:2011.05855

Pressure

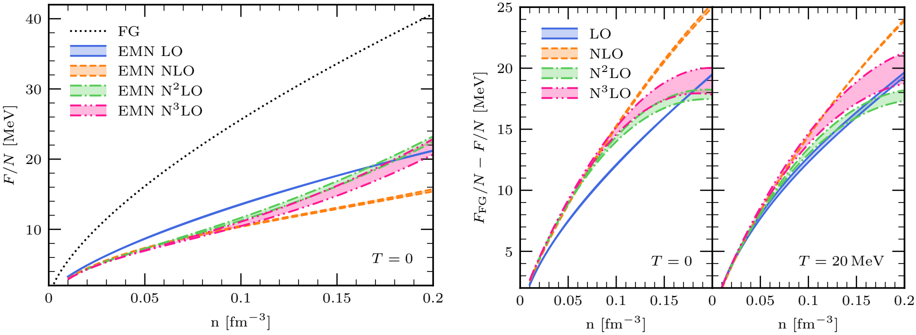
- Determined from free energy $P = \frac{\partial F}{\partial V} = n^2 \frac{\partial F}{\partial n}$



JK, Wellenhofer, Hebeler, Schwenk, arXiv:2011.05855

Chiral EFT convergence

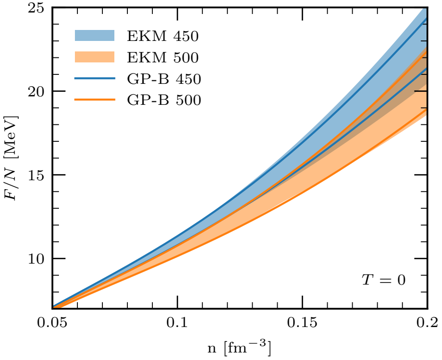
- From free Fermi gas (FG) to N^{3}LO interaction
- Qualitative difference starting at N^{2}LO from 3NF
- Convergence of expansion similar at $T > 0$

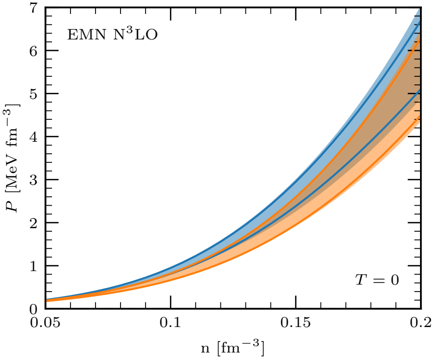


JK, Wellenhofer, Hebeler, Schwenk, arXiv:2011.05855

EFT uncertainties

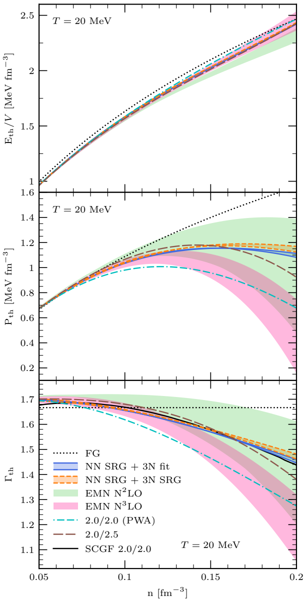
- Expansion in powers of $Q = \frac{p}{\Lambda_b}$
- Use order-by-order values to obtain uncertainty estimates
Epelbaum et al., Eur. Phys. J. A 51 (2015), Drischler et al., Phys. Rev. Lett. 125 (2020)





JK, Wellenhofer, Hebeler, Schwenk, arXiv:2011.05855

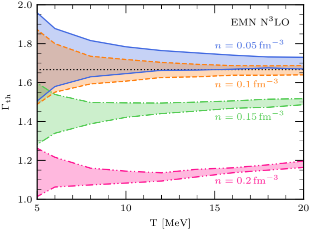
Thermal quantities



- Thermal part and thermal index

$$X_{th}(T,n) = X(T,n) - X(T=0,n)$$
$$\Gamma_{th}(T,n) = 1 + \frac{P_{th}(T,n)}{E_{th}(T,n)/V}$$

- For free gas: $\Gamma_{FG,th} = \frac{5}{3}$
- Thermal index is used to parameterize temperature dependence
  Bauswein et al., Phys. Rev. D 82 (2010)
- Weak temperature dependence

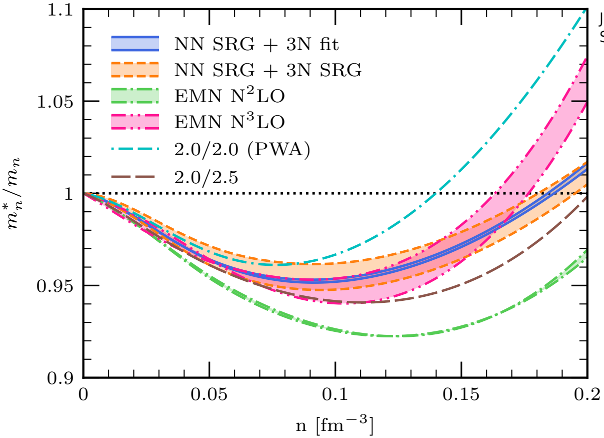


Effective mass approximation

- For ideal gas with density dependent effective mass $m_n^*(n)$

$$\Gamma_{th}(n) = \frac{5}{3} - \frac{n}{m_n^*}\frac{\partial m_n^*}{\partial n}$$

- Extracted from $\Gamma_{th}(T = 20\,\text{MeV})$
- Could be used in astro applications Huth et al., Phys. Rev. C 103 (2021)



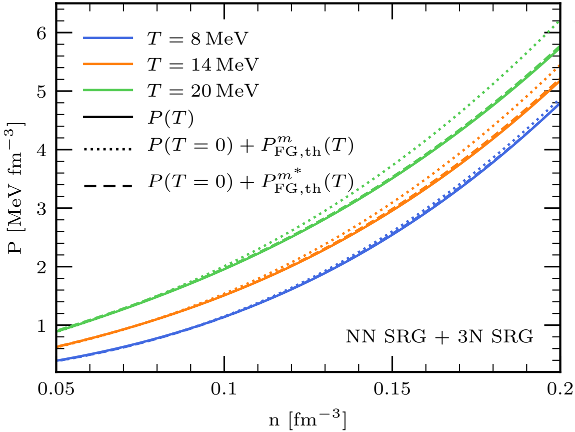
JK, Wellenhofer, Hebeler, Schwenk, arXiv:2011.05855

Pressure approximation

- Split into cold and hot part

$$P(T) = P(T = 0) + P_{th}(T)$$

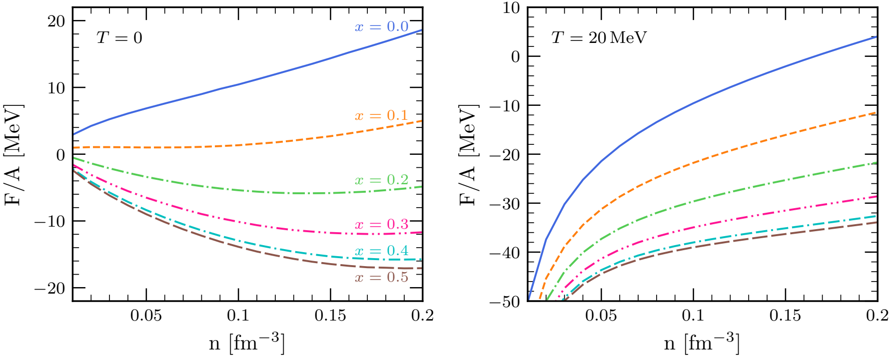
- Approximate $P_{th}(T)$ using free gas with m_n and m_n^*
- Good reproduction of thermal effects with effective mass



JK, Wellenhofer, Hebeler, Schwenk, arXiv:2011.05855

Asymmetric matter at finite temperature

- Extend to finte proton fractions $x = \frac{n_p}{n_n + n_p}$
- No quadratic approximation $F(\beta) = a_1 + a_2\beta^2 + \ldots$ with $\beta = \frac{n_n - n_p}{n_n + n_p}$
- First preliminary results for 1.8/2.0 interaction



Summary and outlook

Chiral EFT

- Calculations of EOS around saturation density using chiral EFT
- Extended previous calculations to $T > 0$
- Systematic study of neutron matter (interactions, EFT uncertainties)
- Studied temperature effects in detail for neutron matter
- Effective mass provides approximate temperature dependence

Outlook:

- Investigate asymmetric matter in detail at $T > 0$
- Compare calculations with FRG calculations (SFB project B05)

FRG

- Development of a new FRG regularization scheme for studies of dense relativistic matter Braun et al., arXiv:2008.05978
- New studies of dense QCD matter with dynamical hadronization techniques Braun and Schallmo, arXiv:2104.XXXXX; results for the gap are consistent with those from our previous studies Leonhardt at at., Phys. Rev. Lett. 125 (2020)
- Next step: include diquark fluctuation effects in the long-range limit and update of our present EOS results Leonhardt at at., Phys. Rev. Lett. 125 (2020)