The state-of-the-art perturbative EoS at all T and μ

"Cool Quark Matter" Phys.Rev.Lett. 117 (2016) no.4, 042501

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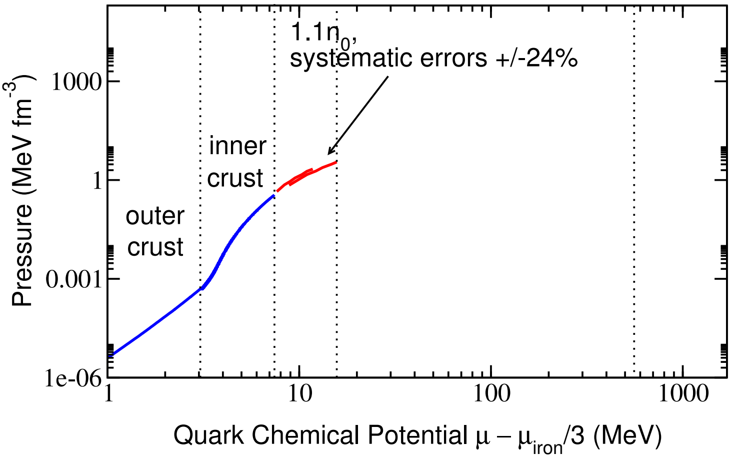
QM2017, Chicago

What: Properties of neutron stars during binary mergers

How: Using state-of-the-art resummed perturbation theory

New: Full $\mathcal{O}(g^5)$ computation of EOS at all T and μ.

Motivation: Perturbation theory and Neutron Stars



Low density EoS: Negele & Vautherin Nucl.Phys. A207 (1973) 298-320; Baym et al. Nucl.Phys. A207 (1973) 298-320; Tews et al. Phys.Rev.Lett. 110 (2013) 032504; Hebeler et al. Astrophys.J. 773 (2013) 11

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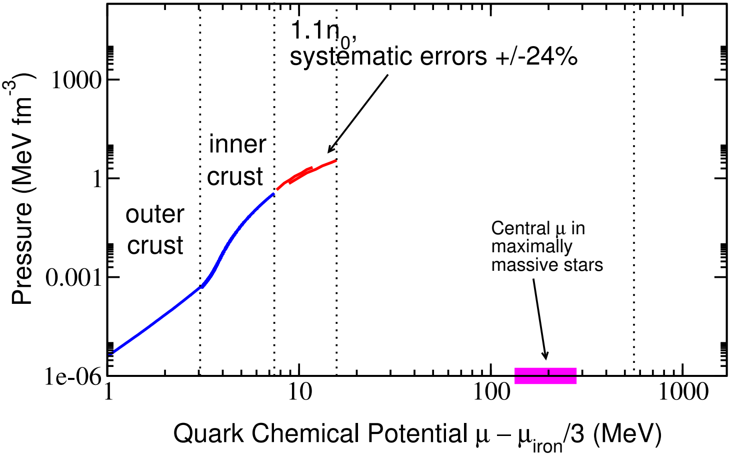

Central densities $n_{\text{center}} \in [3.7, 14.3]n_0$

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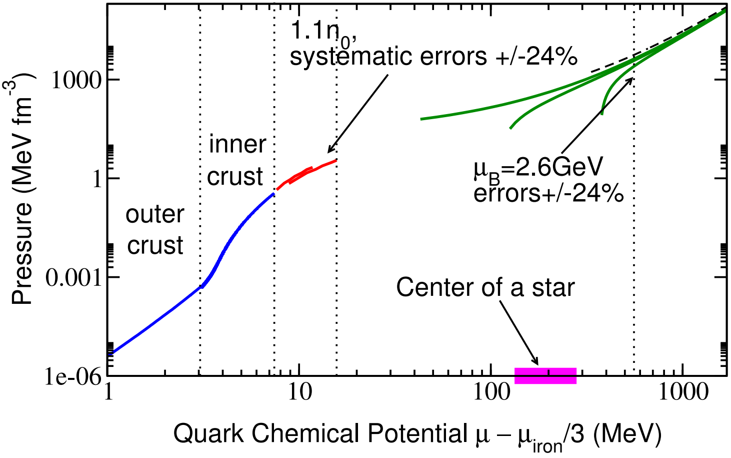
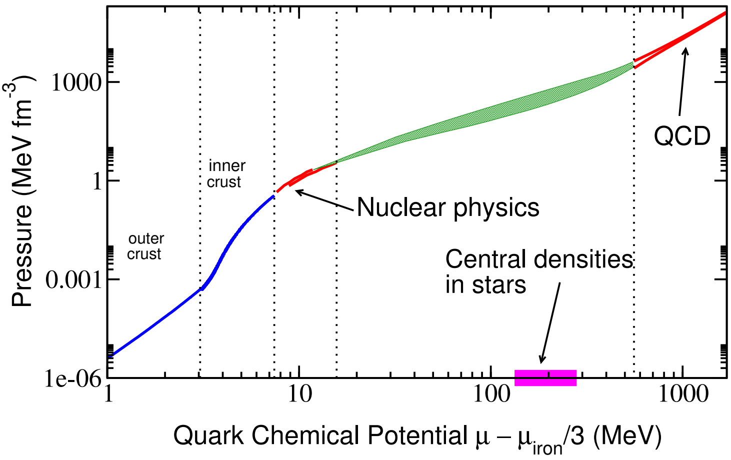


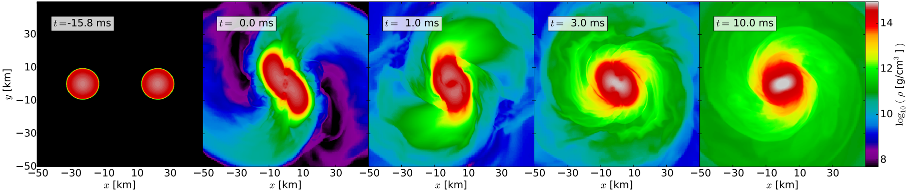
AK, Romatschke, Vuorinen Phys.Rev. D81 (2010) 105021: Full NNLO, g^4 with $m_s \neq 0$

Motivation: Perturbation theory and Neutron Stars



AK, Fraga, Schaffner-Bielich, Vuorinen, Astrophys.J. 789 (2014) 127

Motivation: Gravitational waves from neutron star mergers

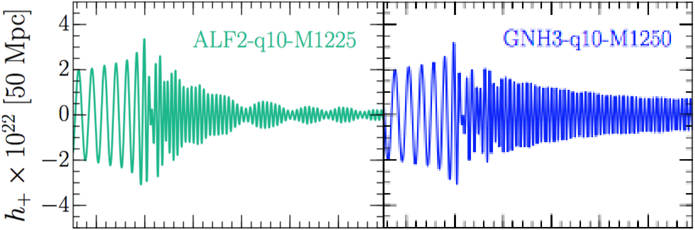


Takami et al. PRD91 (2015) no.6, 064001

- Potential detection of Hypermassive neutron star (HMNS) ringdown in the near future

LIGO, VIRGO, KAGRA, ...

Motivation: Gravitational waves from neutron star mergers



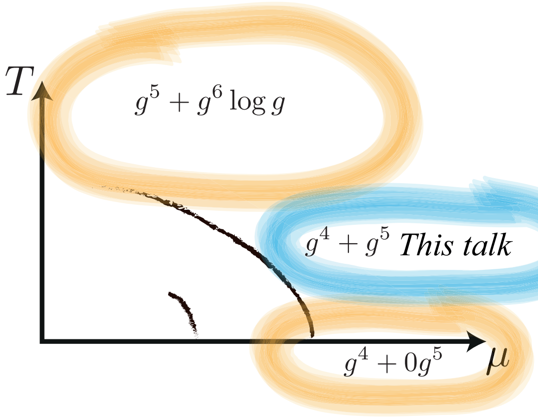
Takami et al. PRD91 (2015) no.6, 064001

- Ringdown sensitive to EoS up to

$$T \lesssim 100\text{MeV}$$

Shen et al, Nucl. Phys. A 637 (1998) 435

State of the art in perturbation theory

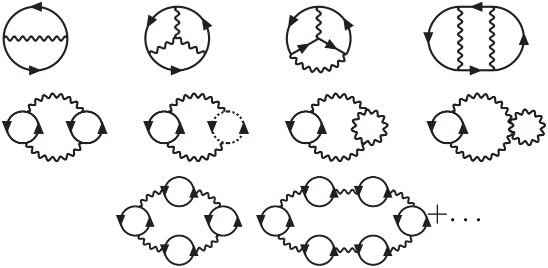


$T > 0, \quad \mu < gT: \quad g^5 + g^6 \log g$, Kajantie et al PRD67 (2003) 105008, Vuorinen PRD68 (2003) 054017

$T = 0, \quad \mu > 0: \quad g^4 + 0g^5$ Freedman & McLerran PRD16 (1977) 1169; AK et al. PRD81 (2010) 105021

Calculation:

- Bubble diagrams up to desired order in g:



$+\dots$

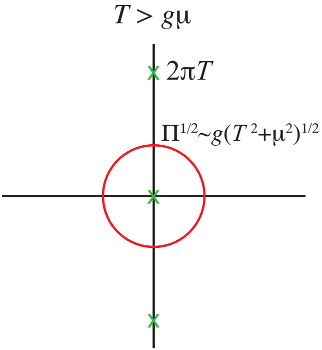
- Discrete Matsubara modes:

$$\int \frac{d\omega}{(2\pi)} \to T \sum_{\omega_n}, \qquad \omega_n \begin{cases} 2n\pi Ti \\ (2n+1)\pi Ti + \mu \end{cases}$$

- Medium modification to propagators: and similarly vertices

$$G^{-1} \sim -\omega_n^2 + \mathbf{p}^2 \to -\omega_n^2 + \mathbf{p}^2 + \Pi$$

Calculation:

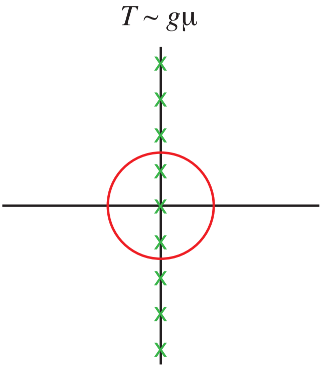


$$G^{-1} \sim \underbrace{-\omega_n^2}_{(2\pi n T)^2} + \mathbf{p}^2 + \underbrace{\Pi}_{g^2(T^2+\mu^2)}$$

- Only ω_0-mode nonperturbatively affected by medium
- Effective theory for the ω_0 sufficient: EQCD

Appelquist & Pisarski Phys. Rev. D 23 (1981) 2305, Kajantie et al Nucl. Phys. B 458 (1996) 90
Braaten & Nieto Braaten & Nieto, Phys. Rev. D 51 (1995) 6990

Calculation:

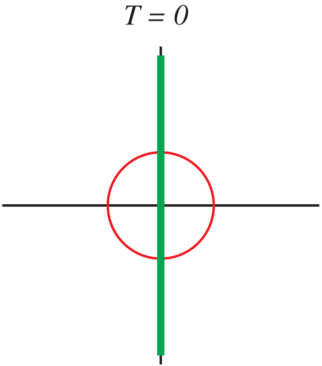


$$G^{-1} \sim \underbrace{-\omega_n^2}_{(2\pi n T)^2} + \mathbf{p}^2 + \underbrace{\Pi}_{g^2(T^2+\mu^2)}$$

- Many modes affected by medium, EQCD not sufficient
- Existing results with laborious explicit resummations

Ipp et al PRD74 (2006) 045016

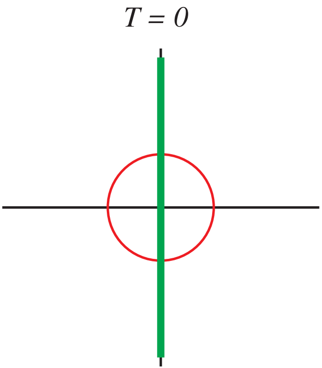
Calculation:



$$G^{-1} \sim -\omega^2 + \mathbf{p}^2 + \underbrace{\Pi}_{g^2(T^2+\mu^2)}$$

- At $T = 0$, continuous Euclidean frequency

Calculation:



$$G^{-1} \sim -\omega^2 + \underbrace{\mathbf{p}^2}_{\sim\Pi} + \underbrace{\Pi}_{g^2(T^2+\mu^2)}$$

- Even at $T = 0$, only modes with $\mathbf{p} \sim \Pi^{1/2}$ need to resummed
  Kinematic simplification $\rightarrow$ Hard Loop Theory.
  Braaten & Pisarski Nucl. Phys. B 337 (1990) 569, Blaizot et al. Phys.Rev. D63 (2001) 065003

New strategy

Reorganization of the perturbation theory:

- Treat soft modes ($\mathbf{p} \sim \Pi^{1/2}, \omega \sim \Pi^{1/2}$) in Hard Loop Theory
- Optionally treat ω_0 in EQCD
- All the rest in unresummed PT

All these contributions already known in literature up to g^5:

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$$p_{QCD} = \delta p^{hard} + \delta p^{HTL} + \delta p^{EQCD}$$

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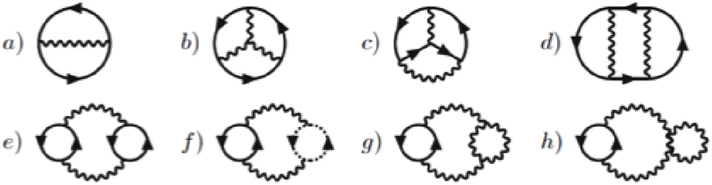

IR divergence due to mistreatment of soft sector

Vuorinen PRD68 (2003) 054017

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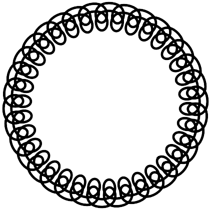


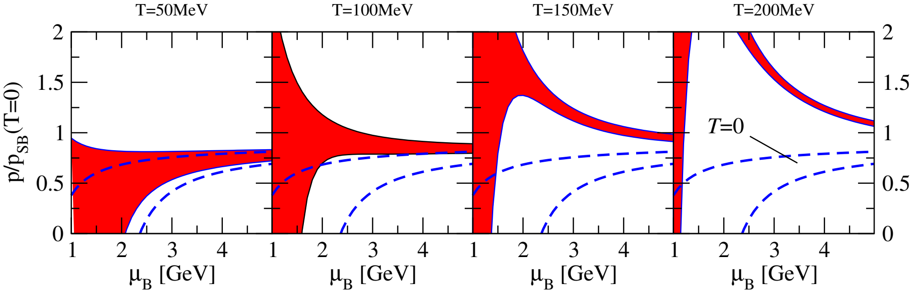
UV divergence due to mistreatment of hard sector cancel the IR divergence of hard sector

Andersen et al. , Phys. Rev. D 61 (2000) 014017, Blaizot et al. PRD63 (2001) 065003

Kajantie et al. JHEP 0304 (2003) 036

Result:

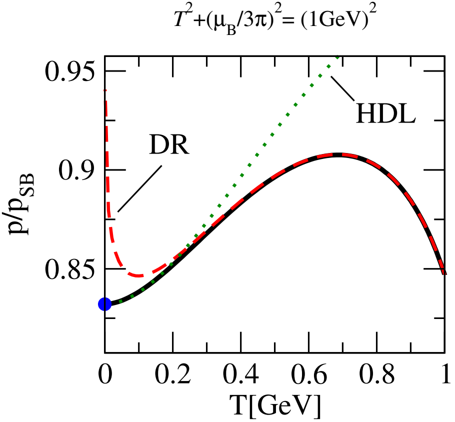
Full $\mathcal{O}(g^5)$ EOS valid at all μ and T:

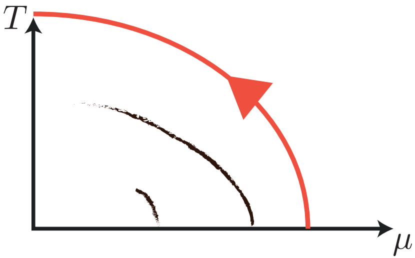


AK, Vuorinen PRL. 117 (2016) no.4, 042501

Result:

Smooth interpolation between zero density and zero temperature





AK, Vuorinen PRL. 117 (2016) no.4, 042501

Comparison to HTLpt:

- Many computations in "HTLpt"
  Andersen et al. PRD93 (2016) no.5, 054045, JHEP 1405 (2014) 027, PRD89 (2014) no.6, 061701, JHEP 1108 (2011) 053, PLB696 (2011) 468-472, PRD70 (2004) 045001, PRD61 (2000) 074016, ...

- In HTLpt, use the resummed propagators and vertices all the way to UV.
  - UV divergences removed through renormalization.

- Here: UV divergences due to kinematical simplifications, automatically match with IR divergences of the hard mode contribution.
  - Benefit: Significantly simpler HTL computations needed for given order in g

Conclusions:

- New state-of-the-art in strict perturbative EoS now up to and including $\mathcal{O}(g^5)$ at all temperatures and densities.
  - No new calculations were needed, novel view on the soft sector.
  - Underway: extend $\mathcal{O}(g^6 \log g + g^6 \log^2 g)$ at $T = 0$
    Ghisoiu, Gorda, AK, Romatschke, Vuorinen
- Result being implemented to constraining neutron star EoS in Supernova and NS binary merger simulations.
- Constrain the EoS for beam energy scan and fragmentation region
  Kapusta and Li, PRC95 (2017) no.1, 011901