Interacting mesons as degrees of freedom in a chiral model

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+ muses collaboration

+ NP3M collaboration


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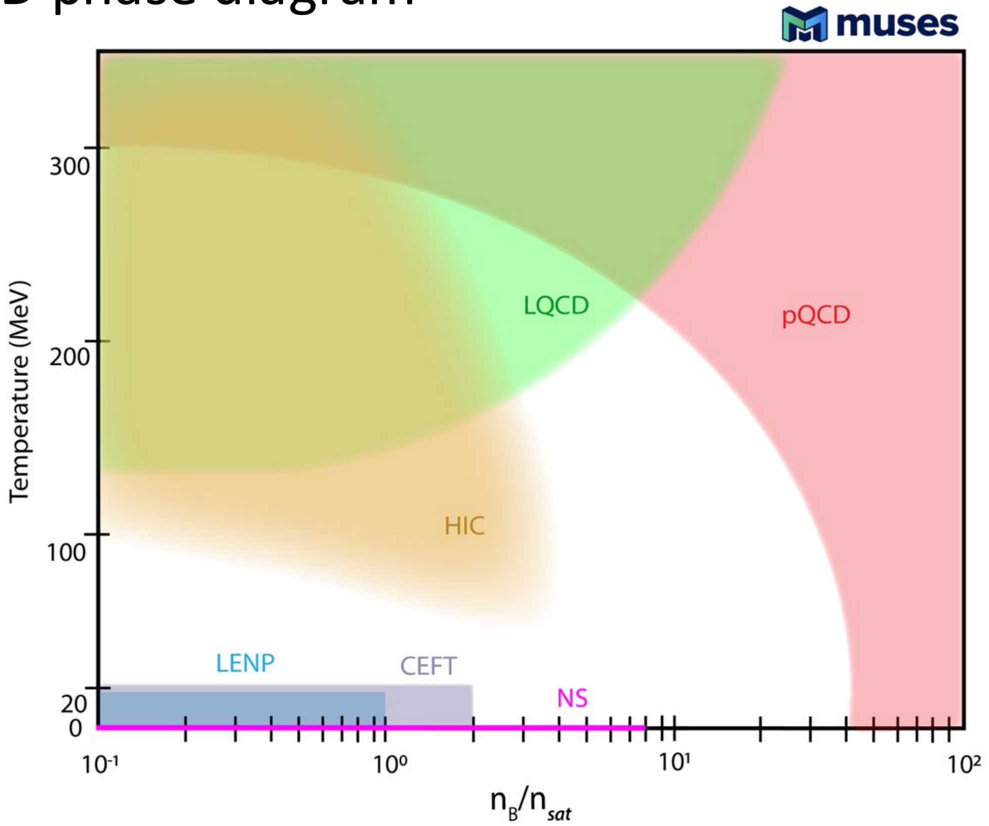
⭐ Dense matter in the QCD phase diagram

- ✶ Current input from different (first-principle and effective) theories and experiments

  Living Rev.Rel. 27 (2024) 1, 3
  e-Print: 2303.17021

- ✓ Perturbative QCD
- ✓ Lattice QCD (T' expanded)
- ✓ Chiral Effective Field Theory
- ✓ Heavy-ion Collisions
- ✓ Neutron Stars
- ✓ Low-energy Nuclear Physics



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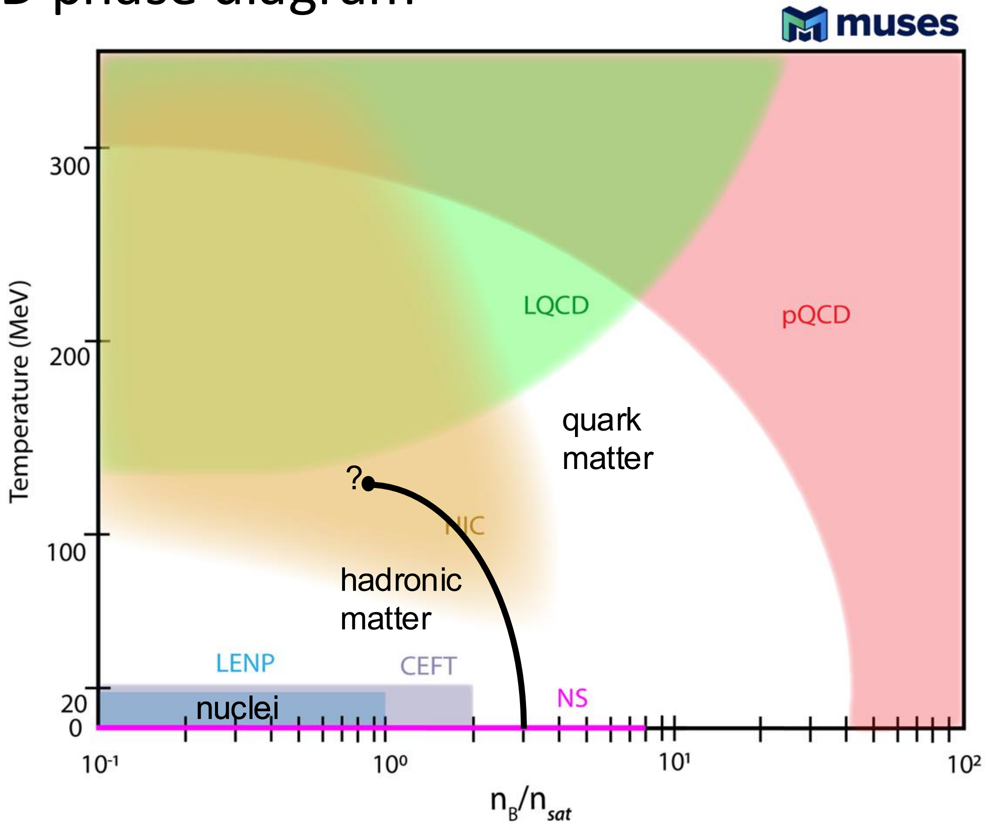

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- Current input from different (first-principle and effective) theories and experiments

  Living Rev.Rel. 27 (2024) 1, 3
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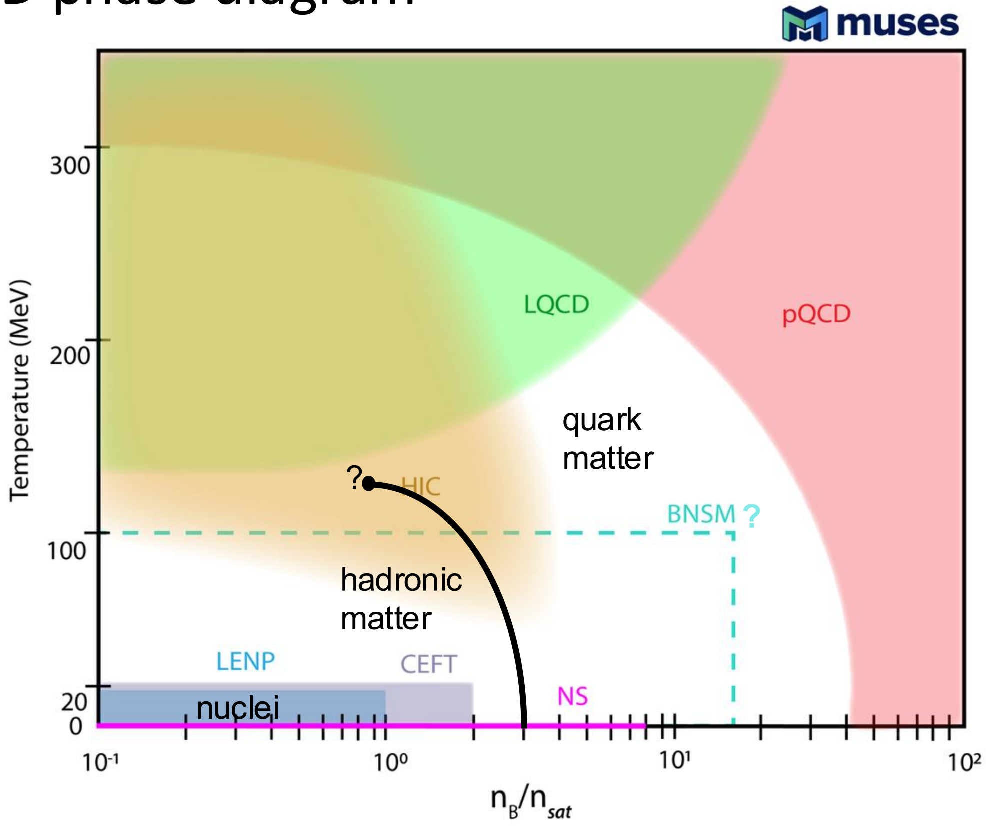
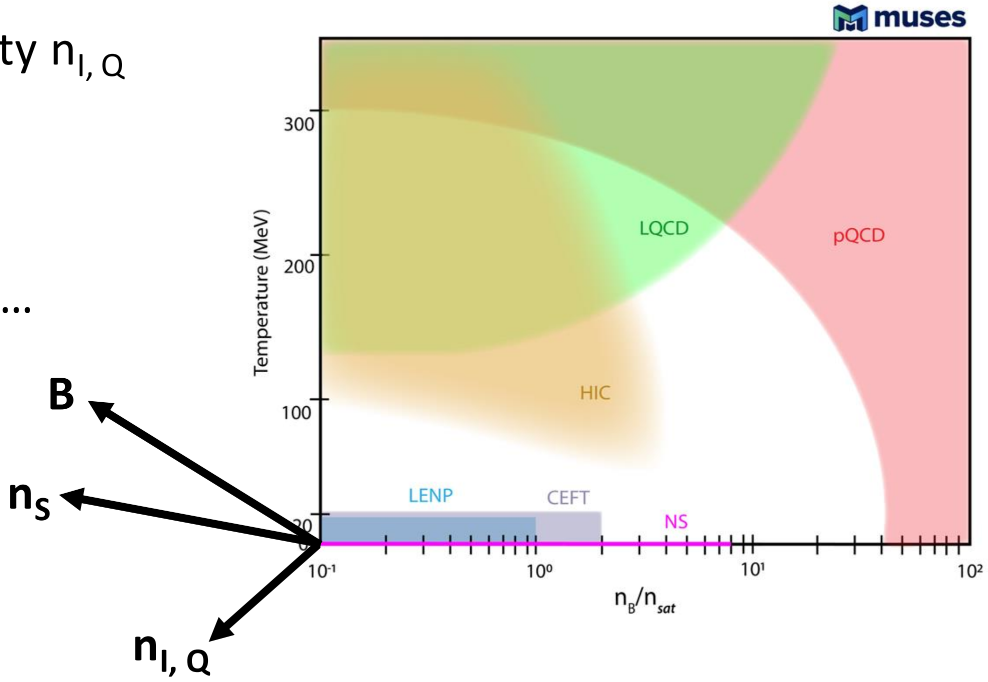
- Astrophysics input only at T~0 for now …

  but finite T input is coming



⭐ Dense matter in the QCD phase diagram

- Temperature T
- Baryon (net) density n_B or chemical potential μ_B
- Isospin/electric charge density $n_{I,\,Q}$ or chemical potential $\mu_{I,\,Q}$
- Strangeness density n_S or chemical potential μ_S
- Magnetic field, size, vorticity…



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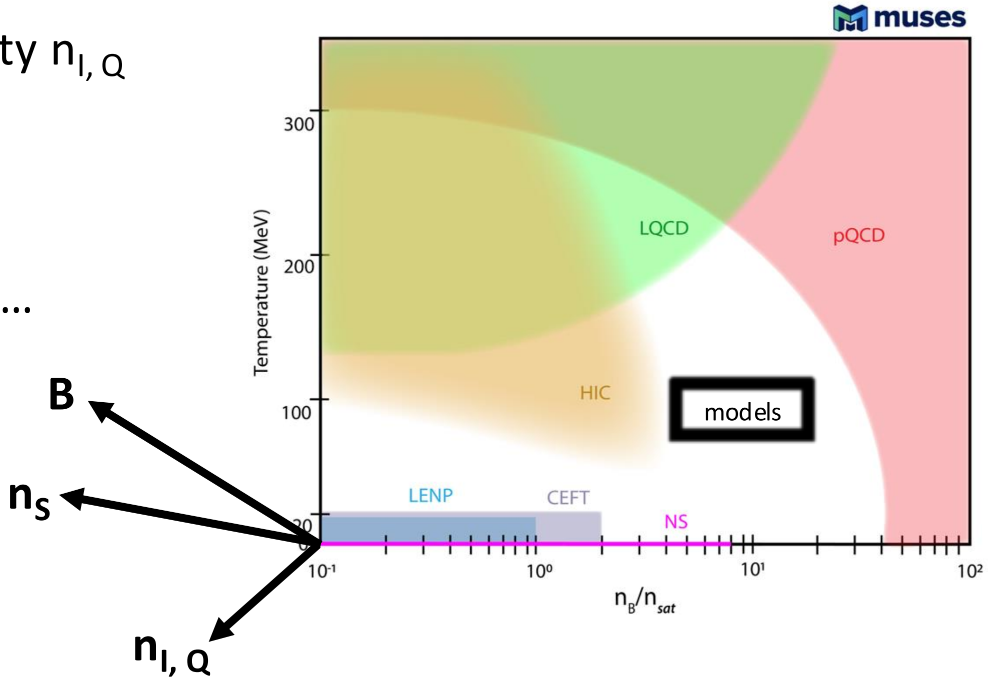
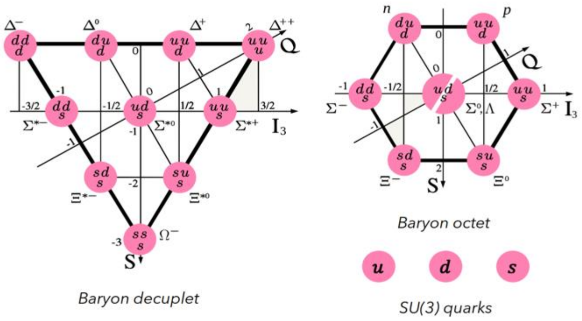


☆ Chiral Mean Field model (CMF)

- Microscopic relativistic mean-field model for baryon octet, decuplet, quarks, free leptons, and **free** thermal mesons

Phys.Rev.C 81 (2010) 045201 e-Print: [0901.1748]

Phys.Rev.D 109 (2024) 7, 074008 e-Print: [2401.12944]



Baryon decuplet

Baryon octet

SU(3) quarks

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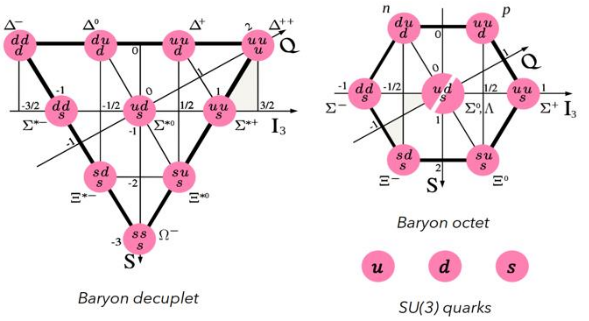
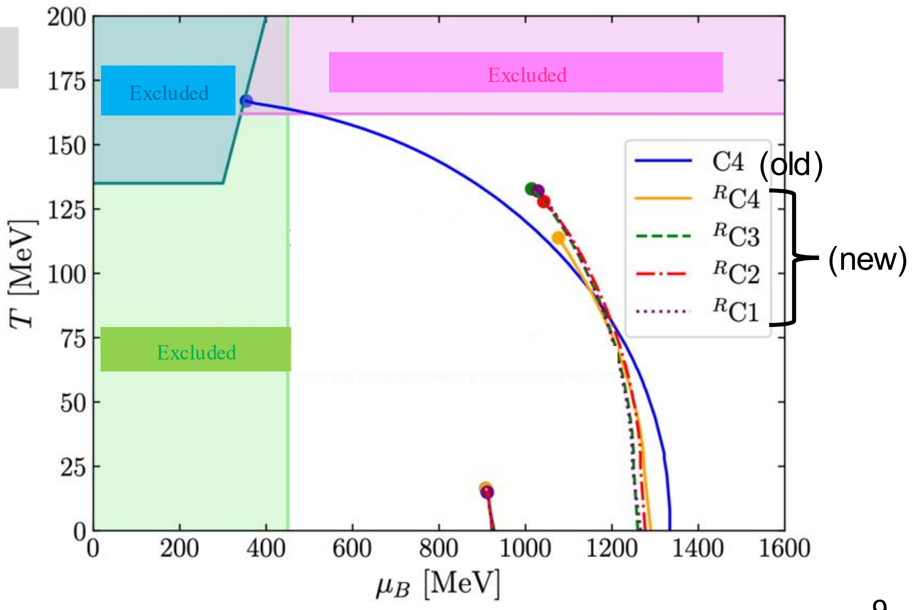
Phys.Rev.C 81 (2010) 045201 e-Print: [0901.1748](0901.1748)

Phys.Rev.D 109 (2024) 7, 074008 e-Print: [2401.12944](2401.12944)

- Reproduces liquid-gas, and (crossover or 1st-order) chiral/deconfinement transitions
- In agreement with nuclear physics, astrophysics, pQCD, and lattice QCD





⭐ Chiral Mean Field model <u>with improved meson description</u> (**mCMF**)

- ✶ In-medium masses of pseudoscalar and vector mesons need to be calculated <u>before</u> mean field approximation
- ✶ In-medium meson contributions generate feedback term to equations of motion which modify equation of state
- ✶ Results provide good agreement with HRG and lattice-QCD T' expansion

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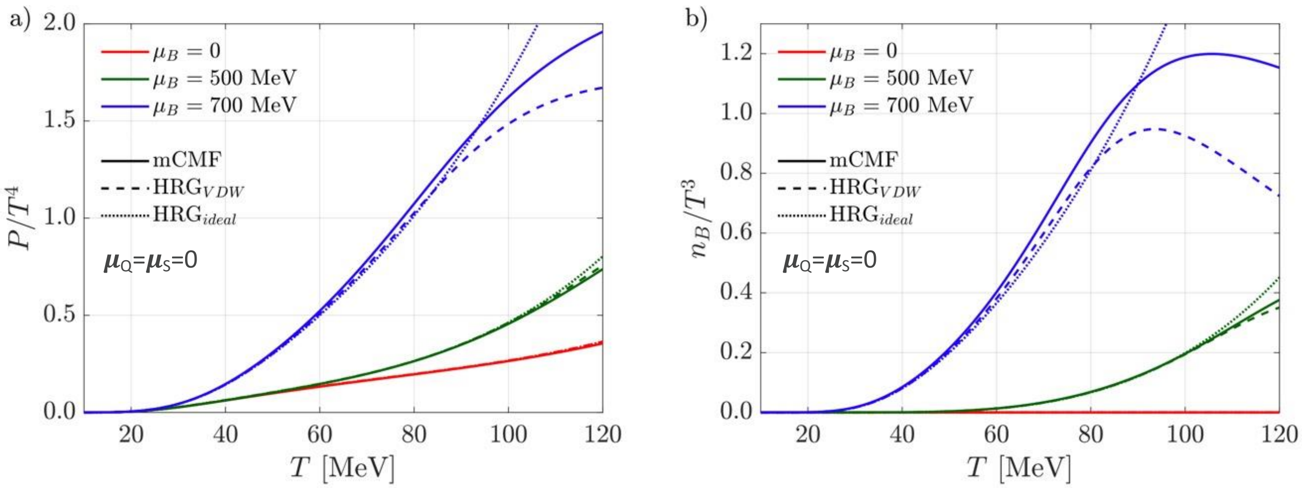
lower energy (hadrons only)

Phys.Rev.D 111 (2025) 7, 074029
e-Print: 2503.03057



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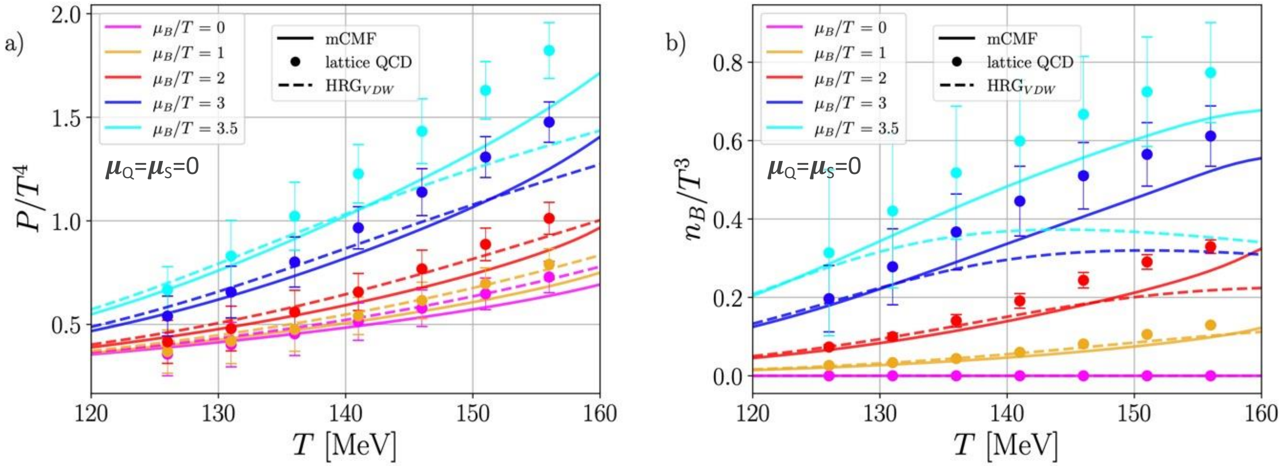


⭐ Chiral Mean Field model with improved meson description (**mCMF**)

- Heavy-ion collisions STAR Ru+Ru and Zr+Zr isobar data combined with Bayesian thermal analysis of hadron yields provides T, μ_B, μ_Q, and μ_S

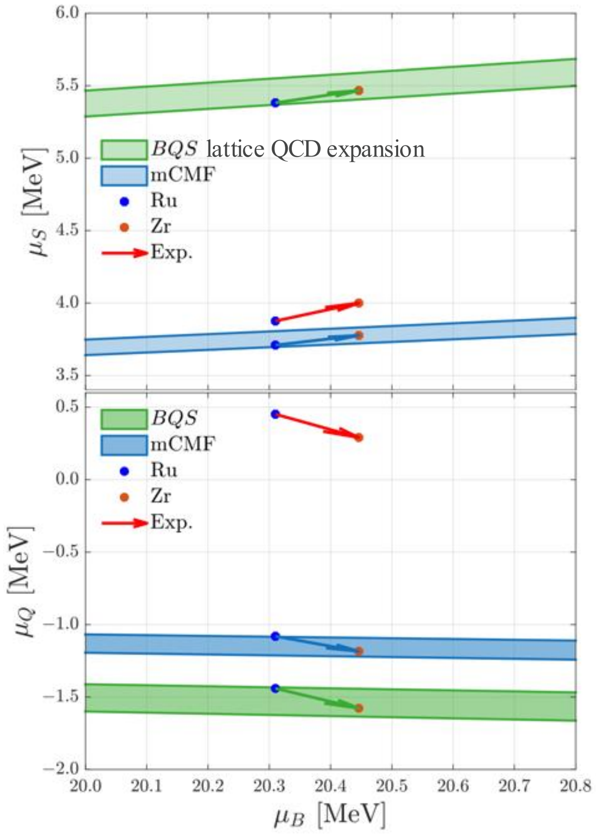
Accepted Nature (2026)
e-Print: 2408.15441

- mCMF results closer to heavy-ion collisions than lattice QCD expansion for small μ_Q and μ_S and

$$\langle Y_S \rangle = \left\langle \frac{n_S}{n_B} \right\rangle = 0, \qquad \langle Y_Q \rangle = \left\langle \frac{n_Q}{n_B} \right\rangle = \frac{Z}{A}\alpha\,,$$

e-Print: 2601.21232

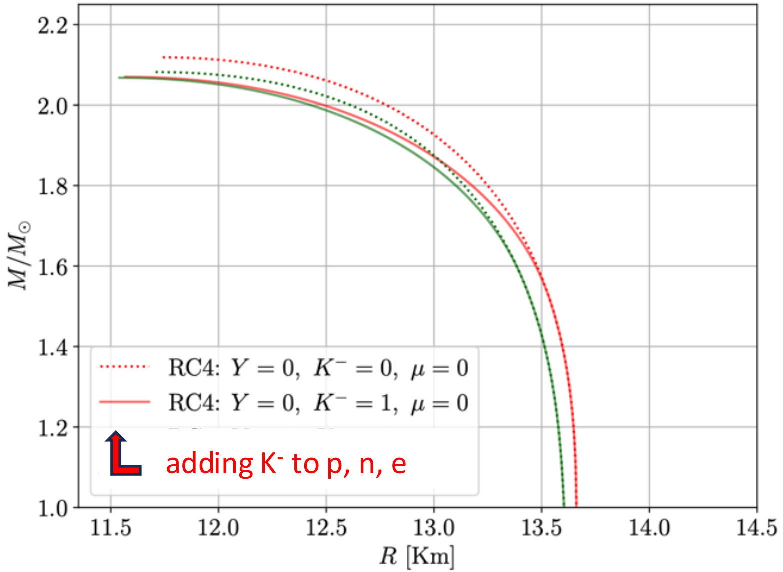
where in CMF isospin and strangeness are constrained only to nuclear physics and astrophysics



Chiral Mean Field model with improved meson description (**mCMF**)

- For large μ_Q mesons condense and require different formalism
- S wave kaon condensation for T=0 investigated in mCMF model for neutron stars
- Reproduce realistic neutron stars

e-Print: 2603.22164

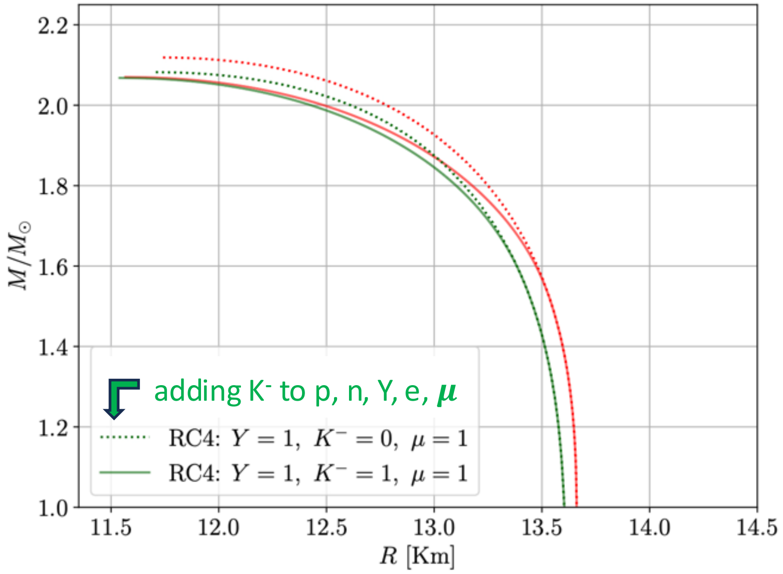


Chiral Mean Field model with improved meson description (**mCMF**)

- For large μ_Q mesons condense and require different formalism
- S wave kaon condensation for T=0 investigated in mCMF model for neutron stars
- Reproduce realistic neutron stars with hyperons (Y) and muons (μ)

e-Print: 2603.22164

- Hyperons push kaon condensation to large densities
- Results depend on kaon scattering lengths



☆ CMF in muses

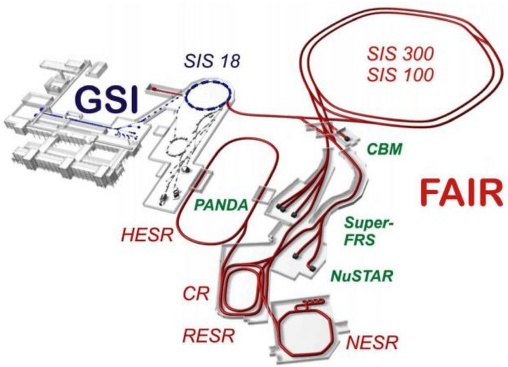
- Modular Unified Solver of the Equation of State
- Free and open-source Calculation Engine that lets you run and combine a growing library of modules
  https://musesframework.io/
- MUSES EoS and observable modules can be used to study nuclear physics, compact stars, and heavy-ion collisions
- CMF was part of 2025 beta release (EoS modules combined at T=0)

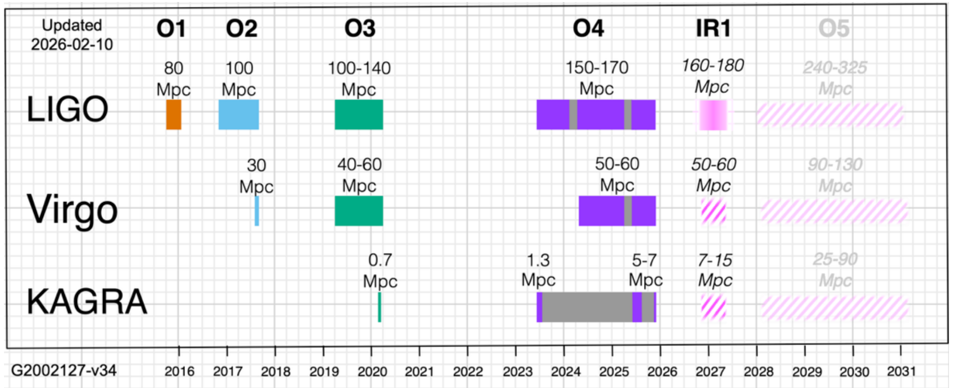
  Phys.Rev.D 111 (2025) 10, 103037
  e-Print: 2502.07902
- CMF finite-T will come with (or after) Caliope release coming this summer…

  e-Print: 2606.26326

Conclusions

- Modeling dense matter is still necessary
- We are slowly constraining the dense-matter from all sides
- Much more data expected in coming years





☆ Chiral Mean Field (CMF) Lagrangian density

Phys.Rev.D 111 (2025) 9, 094030
e-Print: 2409.06837 [nucl-th]

- The CMF Lagrangian density can be organized as

$$\mathcal{L}_{\rm CMF} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm int} + \mathcal{L}_{\rm scal} + \mathcal{L}_{\rm vec} + \mathcal{L}_{\rm esb} + \mathcal{L}_{m_0} - U_\Phi \,.$$

$$\mathcal{L}_{\rm int} = -\sum_{i\in B} \bar{\psi}_i \left[\gamma_0 (g_{i\omega}\omega + g_{i\rho}\rho + g_{i\phi}\phi) \boxed{+ g_{i\sigma}\sigma + g_{i\zeta}\zeta + g_{i\delta}\delta \right] \psi_i ,}$$

mass term

$$\mathcal{L}_{m_0} = -\sum_{i\in B} \bar{\psi}_i m_0 \psi_i .$$

$$\mathcal{L}_{\rm esb}^u = -\left[m_\pi^2 f_\pi \sigma + \left(\sqrt{2} m_K^2 f_K - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi \right) \zeta \right] .$$

$$\mathcal{L}_{\rm pot}^H = -\sum_{i\in H} \left[\bar{\psi}_i m_3^H \left(\sqrt{2}(\sigma - \sigma_0) + (\zeta - \zeta_0) \right) \psi_i \right] .$$

$$\begin{aligned}\mathcal{L}_{\rm scal} = &-\frac{1}{2} k_0 \chi_0^2 (\sigma^2 + \zeta^2 + \delta^2) + k_1 (\sigma^2 + \zeta^2 + \delta^2)^2 \\ &+ k_2 \left[\frac{\sigma^4 + \delta^4}{2} + \zeta^4 + 3(\sigma\delta)^2 \right] + k_3 \chi_0 (\sigma^2 - \delta^2)\zeta \\ &+ \frac{\epsilon}{3} \chi_0^4 \ln \left[\frac{(\sigma^2 - \delta^2)\zeta}{\sigma_0^2 \zeta_0} \right] , \end{aligned} \qquad (2)$$

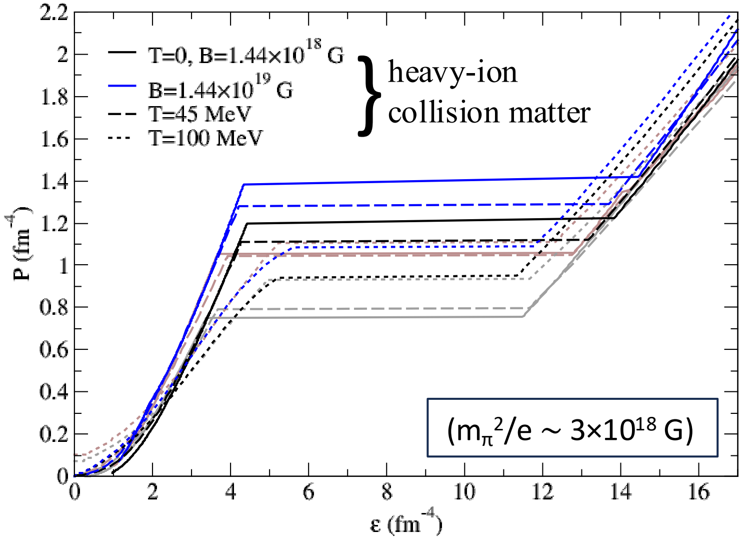
$$\mathcal{L}_{\rm vec}^{\rm SI,C4} = g_4 \left(\omega^4 + \frac{\phi^4}{4} + 3\omega^2\phi^2 + 2\sqrt{2}\omega^3\phi + \sqrt{2}\omega\phi^3 \right) .$$

$$\begin{aligned} U_\Phi = &\left(a_0 T^4 + a_1 \mu_B^4 + a_2 T^2 \mu_B^2 \right) \Phi^2 \\ &+ a_3 T_0^4 \ln \left(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4 \right) , \end{aligned}$$

CMF in 5 dimensions: magnetic field

- Temperature, magnetic fields, isospin, and strangeness have comparable effects!

  … but code takes too long to run



- Neutron-star matter shown for comparison in different colors

$B=1.44\times10^{18}$ G for neutron-star matter

$B=1.44\times10^{19}$ G for neutron-star matter

Phys.Rev.D 108 (2023) 6, 063011
e-Print: 2304.02454

☆ muses CMF++

- Optimized and documented new 3D (T=0) CMF code

Phys.Rev.D 111 (2025) 9, 094030
e-Print: [2409.06837]

a) chiral condensate

b) deconfinement field **Φ**

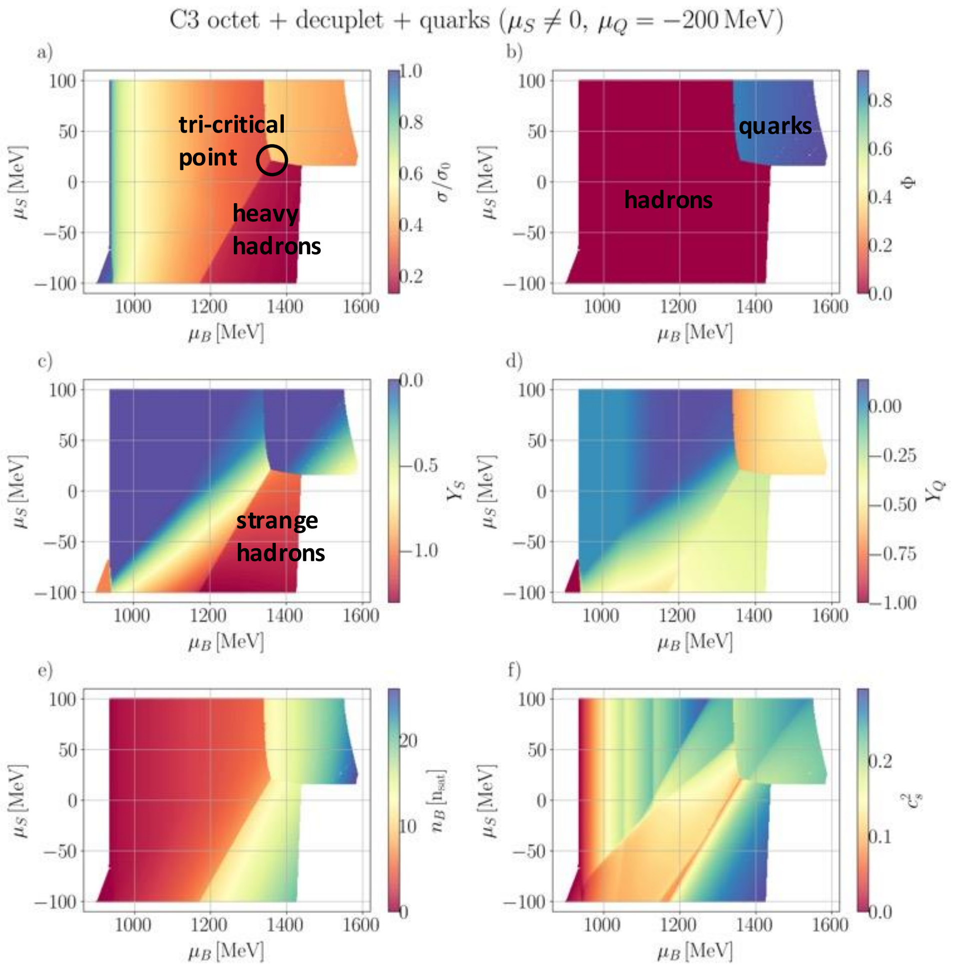
c) strangeness fraction

d) charge fraction

d) baryon density

e) speed of sound squared

with high order susceptibilities



☆ muses beta release (Feb 2025)

Phys.Rev.D 111 (2025) 10, 103037
e-Print: 2502.07902

- We publicly released the alpha release modules
- We invite everyone to test these modules and provide feedback
- Includes a first set of modules (free and open-source) but still preliminary

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finite T

- ✓ BQS EOS: 4D lattice QCD with alternative expansion scheme in μ_B
- ✓ ISING-TEXS EOS: 2D Critical behavior into lattice QCD alternative expansion
- ✓ NUMRELHOLO: 2D AdS/CFT correspondence based EoS

T ~ 0

- ✓ CMF: 3D Chiral EoS with different orders for deconfinement
- ✓ CEFT: 2D EoS for interacting nucleons
- ✓ UTK or Crust DFT: 2D EoS including nucleons and nuclei
- ✓ Lepton module, Synthesis module, CompOSE outputs

EoSs

☆ muses beta release (Feb 2025)

Phys.Rev.D 111 (2025) 10, 103037
e-Print: [2502.07902](2502.07902)

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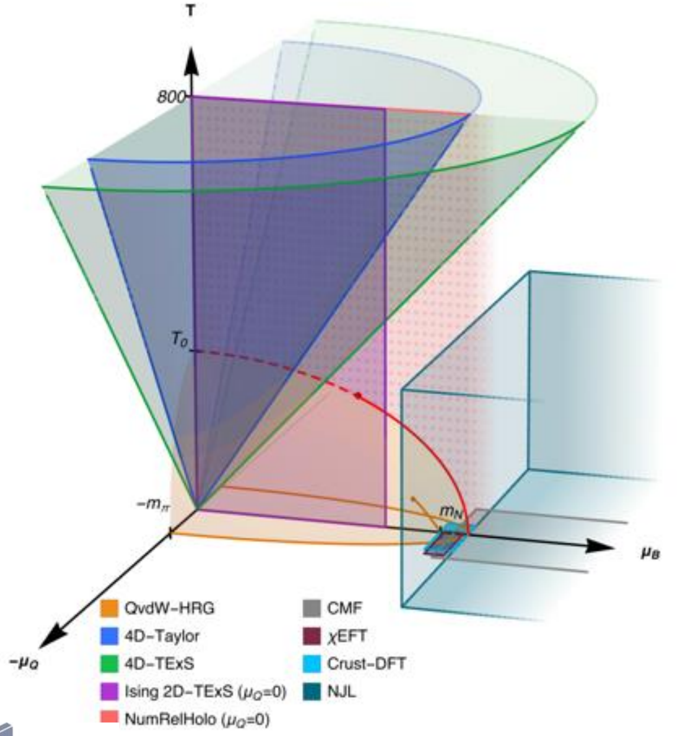
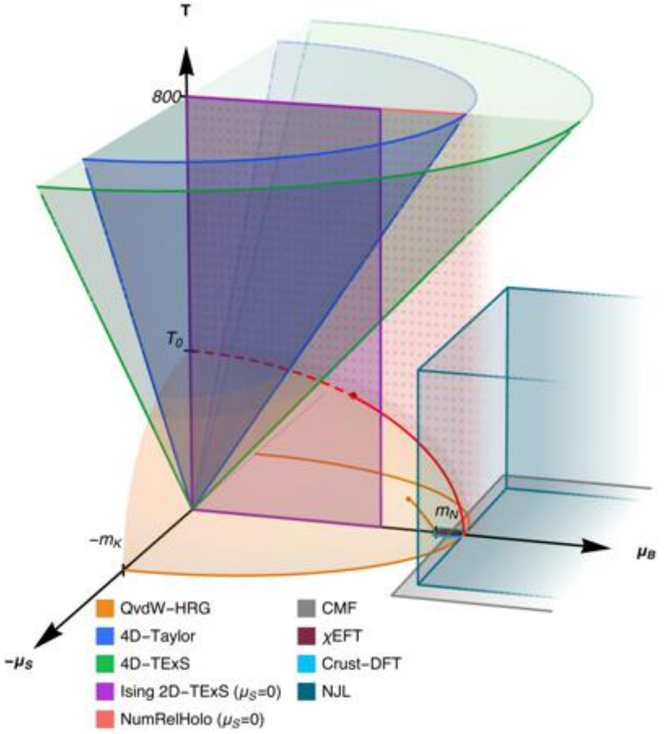
$T \sim 0$

- ✓ QLIMR module: quadrupole moment, tidal Love number, moment of inertia, mass, and radius of static and slowly rotating neutron stars (including universal relations)
- ✓ Flavor equilibration for weak β-equilibrium: Urca rates, relaxation rates, damping time, bulk viscosity

Observables

muses Caliope release (Summer 2026) e-Print: 2606.26326





+ PQCD (T=0)

+ metamodel (T=0)

+ partial pressures

+ holographic transport coefficients

+ synthesis (T≠0)

+ EoS inverter