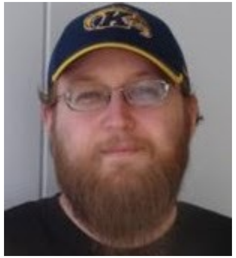
Neutron stars and Constraints for the Equation of State of Dense Matter + MUSES

Veronica Dexheimer

Astrophysics group

Center for Nuclear Research

V. Dexheimer



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muses

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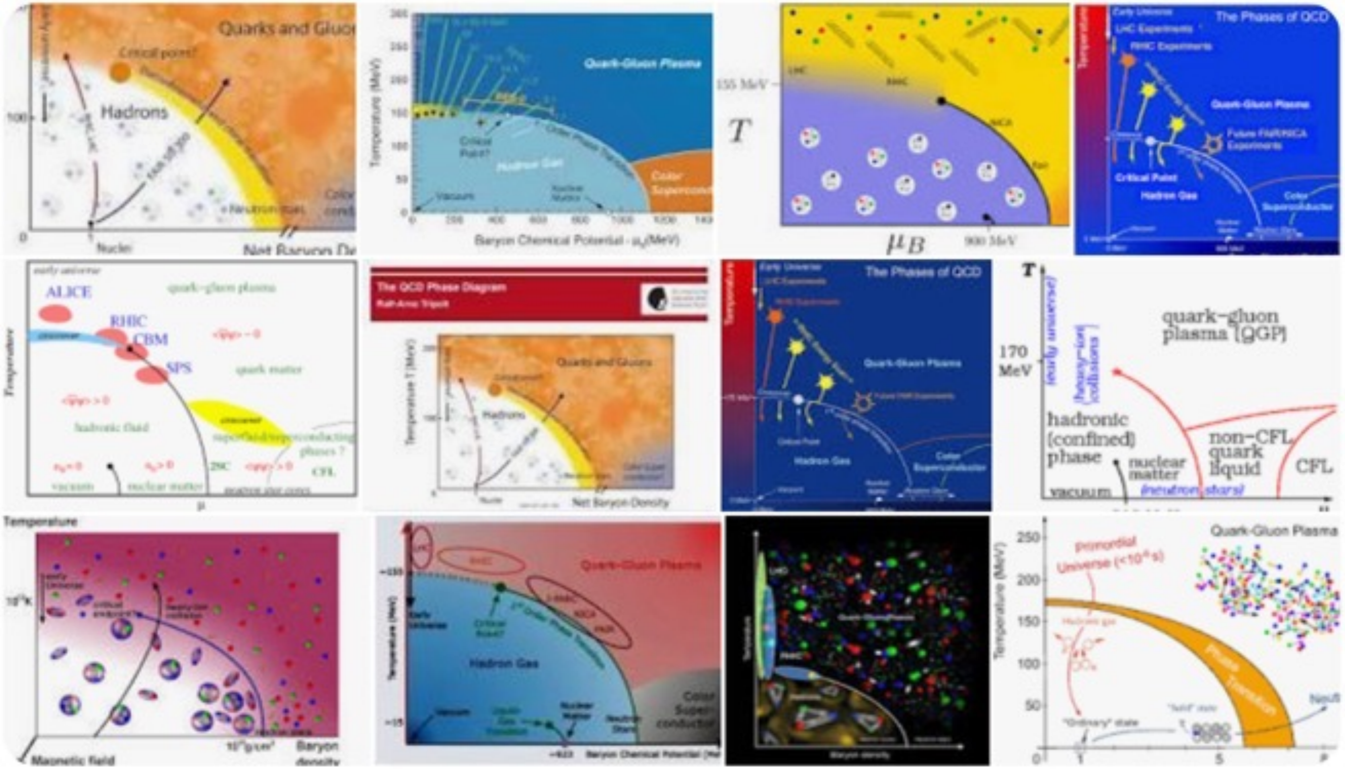
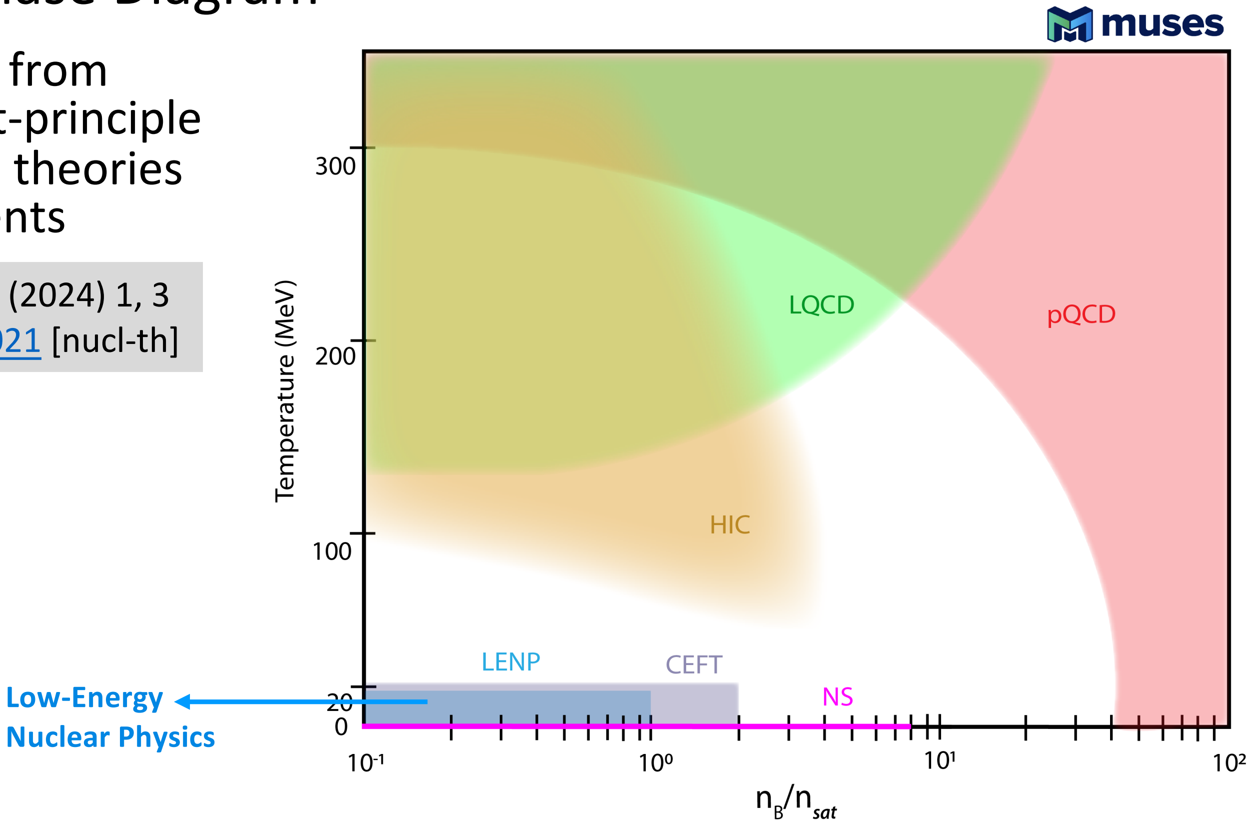
⭐ QCD Phase Diagrams



⭐ Our QCD Phase Diagram

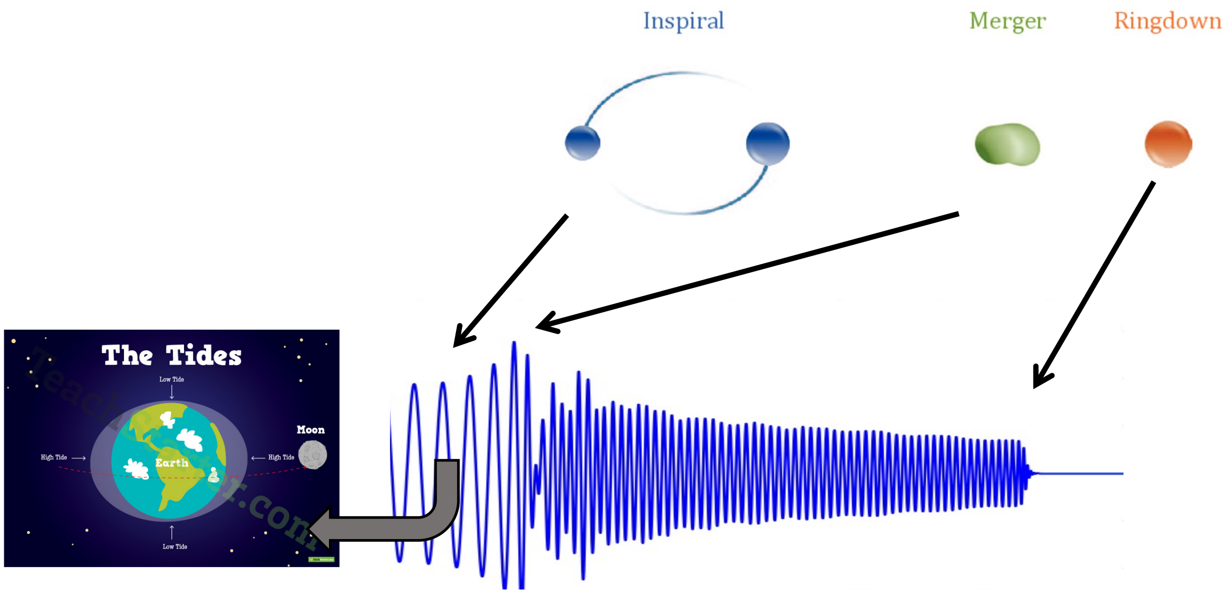
- Current input from different (first-principle and effective) theories and experiments

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



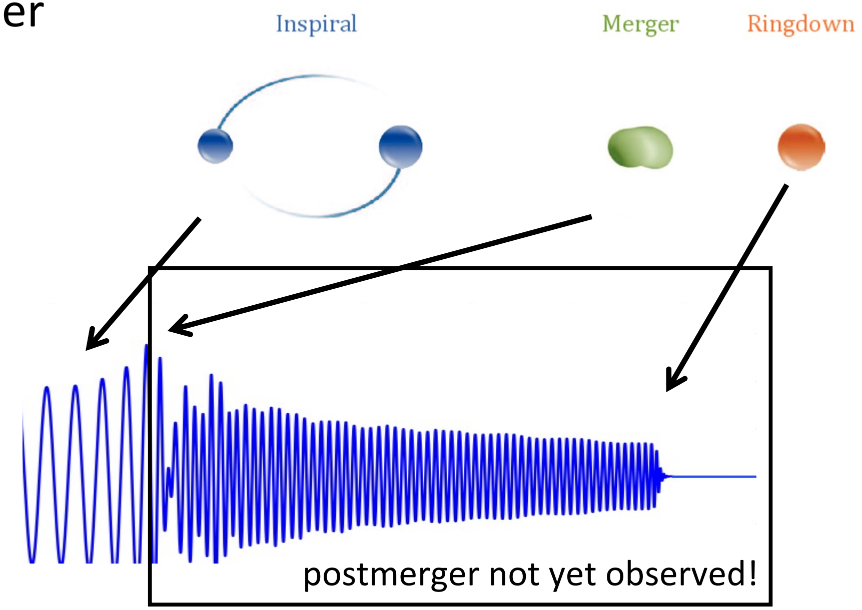
⭐ Gravitational Wave Data

- Several measurements from neutron-star mergers but only GW170817 provided electromagnetic counterparts and a relevant measurement of the tidal deformability



⭐ Gravitational Wave Data

- Several measurements from neutron-star mergers but only GW170817 provided electromagnetic counterparts and a relevant measurement of the tidal deformability
- Without the post-merger (hot) part



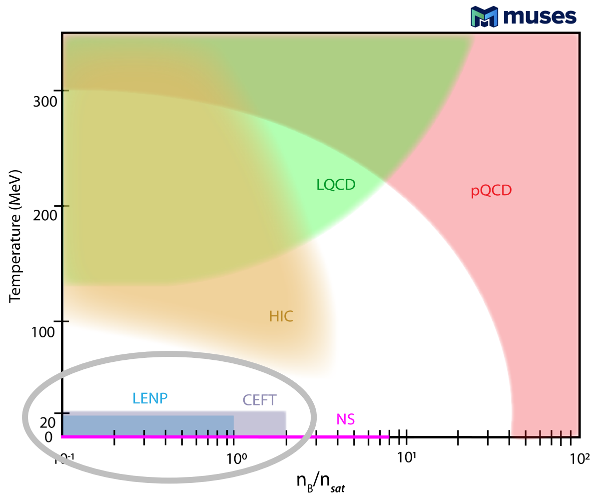
⭐ Chiral Effective Field Theory

- EoS computed up to N3LO in many-body perturbation theory (with three-body forces up to N2LO) for $n_B \lesssim 2n_{sat}$
- Provides E_{sym} and slope parameter L at n_{sat}

Ann.Rev.Nucl.Part.Sci. 71 (2021) 403-432
e-Print: [*2101.01709*](2101.01709)

- Can be used to study the liquid-gas phase transition for isospin-symmetric nuclear matter from a finite-temperature calculation up to T ~ 25 MeV

Phys.Rev.C 95 (2017) 3, 034326
e-Print: [*1612.04309*](1612.04309)



⭐ Lattice QCD

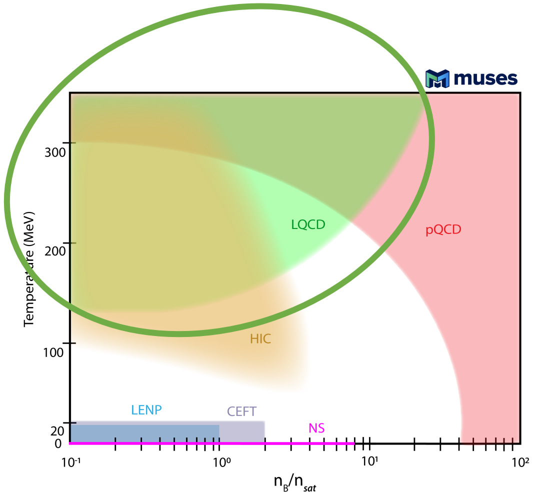
- EoS up to $\mu_B/T=3.5$ obtained from Taylor expansion

  Phys.Rev.Lett. 126 (2021) 23, 232001
  e-Print: [2102.06660](2102.06660)

- BSQ susceptibilities
- Partial pressures (with hadronic phase treated as ideal resonance gas)
- Pseudo phase-transition line
- Limits on the critical point location $\mu_B \gtrsim 300$ MeV and $Tc \lesssim 132$ MeV.

  Phys.Rev.Lett. 125 (2020) 5, 052001
  e-Print: [2002.02821](2002.02821)

  Phys.Rev.Lett. 123 (2019) 6, 062002
  e-Print: [1903.04801](1903.04801)



⭐ Perturbative QCD

- Resummed perturbative QCD EoS calculated to N3LO using HTL perturbation theory in agreement with lattice for $T \gtrsim 2\,T_c$ at μ_B=0

  JHEP 08 (2011) 053 e-Print: [1103.2528](1103.2528)

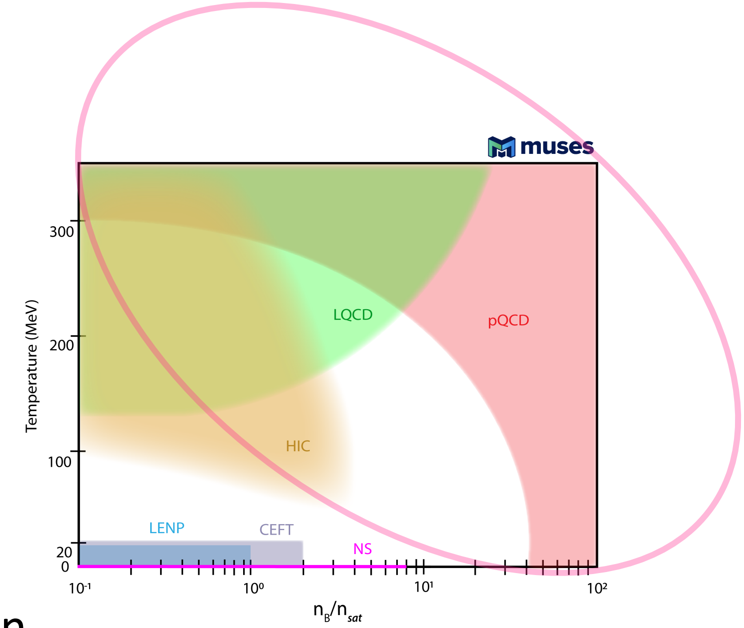
- The curvature of the QCD phase transition line

- Application at high density: starting at $n_B \sim 40\,n_{sat}$ from N3LO calculation

  Phys.Rev.D 104 (2021) 7, 074015 e-Print: [*2103.07427*](2103.07427)

  (and extrapolations to lower densities)

- Transport coefficients at finite T and μ_B

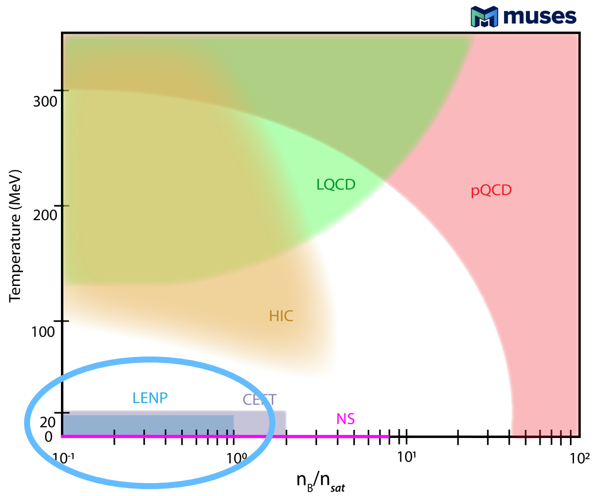


⭐ Low-Energy Nuclear Physics

- Isospin symmetric matter at n_{sat}

Saturation density, n_{sat} (fm^{-3})	0.17 ± 0.03
	0.148 - 0.185
	0.148 ± 0.0038
Binding energy per nucleon, B/A (MeV)	-15.677
	-16.24
Compressibility, K_∞ (MeV)	240 ± 20
	210 - 270
	251 - 315

Phys.Rev.C 89 (2014) 4, 044316
e-Print: 1404.0744



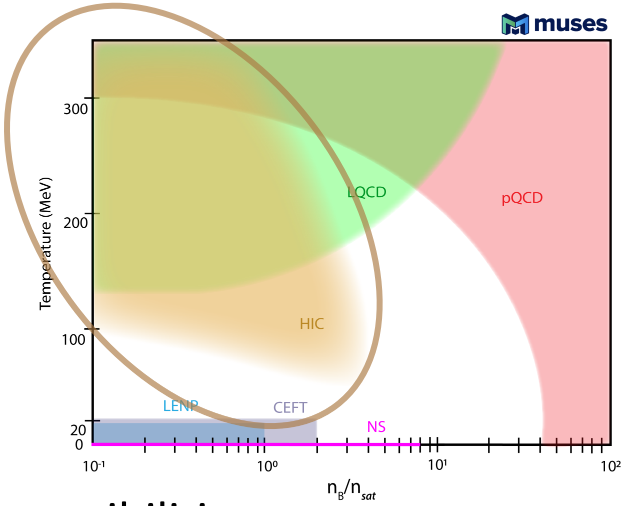
- Hyperon and Δ-baryon potentials at n_{sat}
- Symmetry energy E_{sym} and derivative L at ans around n_{sat}
- Heavy-ion collision measurements of neutron skin
- Liquid-gas critical point

⭐ Heavy-Ion Collisions

- Particle yields for $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$, $\Lambda/\bar{\Lambda}$, $\Xi^{-}/\bar{\Xi}^{+}$ and $\Omega^{-}/\bar{\Omega}^{+}$ … can indicate e.g. deconfinement

  Phys.Lett.B 728 (2014) 216-227 e-Print: 1307.5543

  Phys.Rev.C 77 (2008) 044908 e-Print: 0705.2511



- Fluctuation observables, such as cumulants of particle multiplicity distributions, can relate to thermodynamic susceptibilities, used to e.g. exclude a critical point until a given μ_B

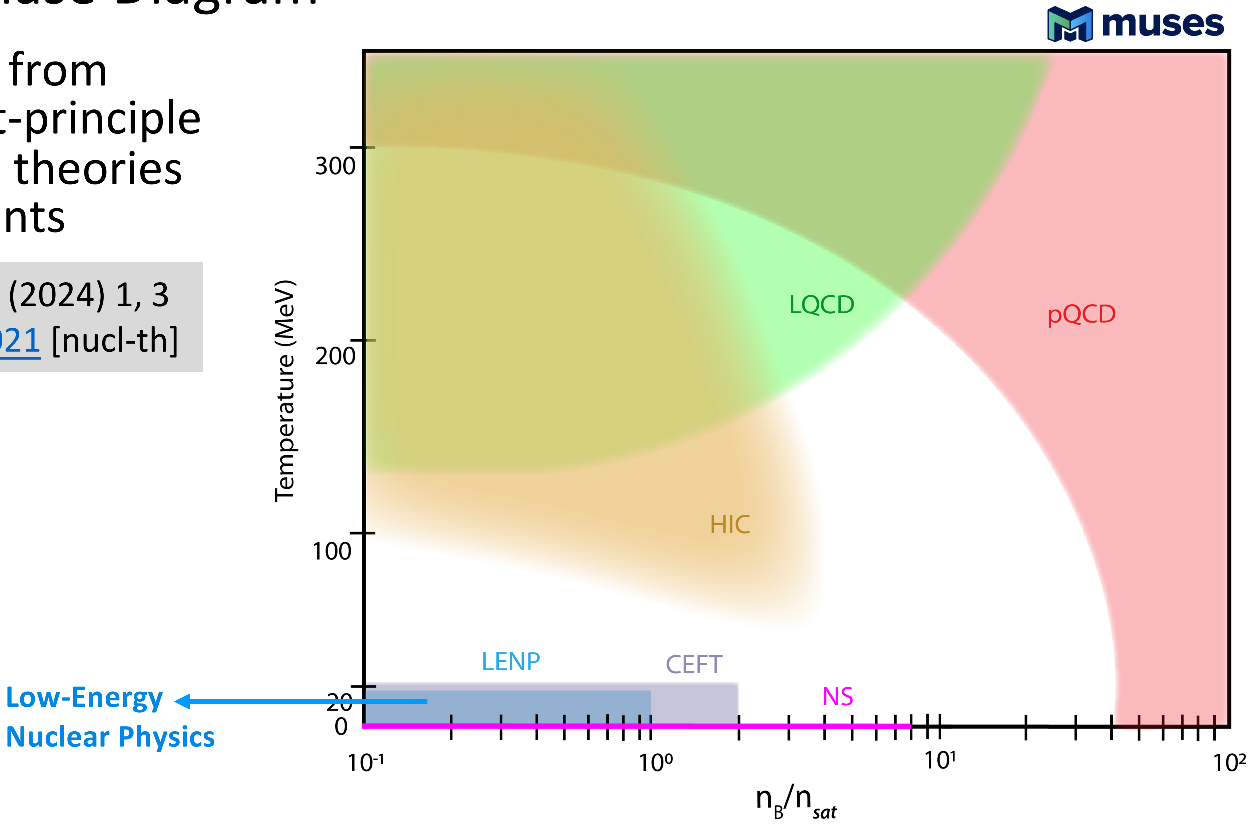
  PoS FACESQCD (2010) 017 e-Print: *1106.3887*

- Flow harmonics *Acta Phys.Polon.Supp.* 16 (2023) 1, 1-A48 e-Print: 2209.04957
- Hanbury Brown–Twiss (HBT) interferometry

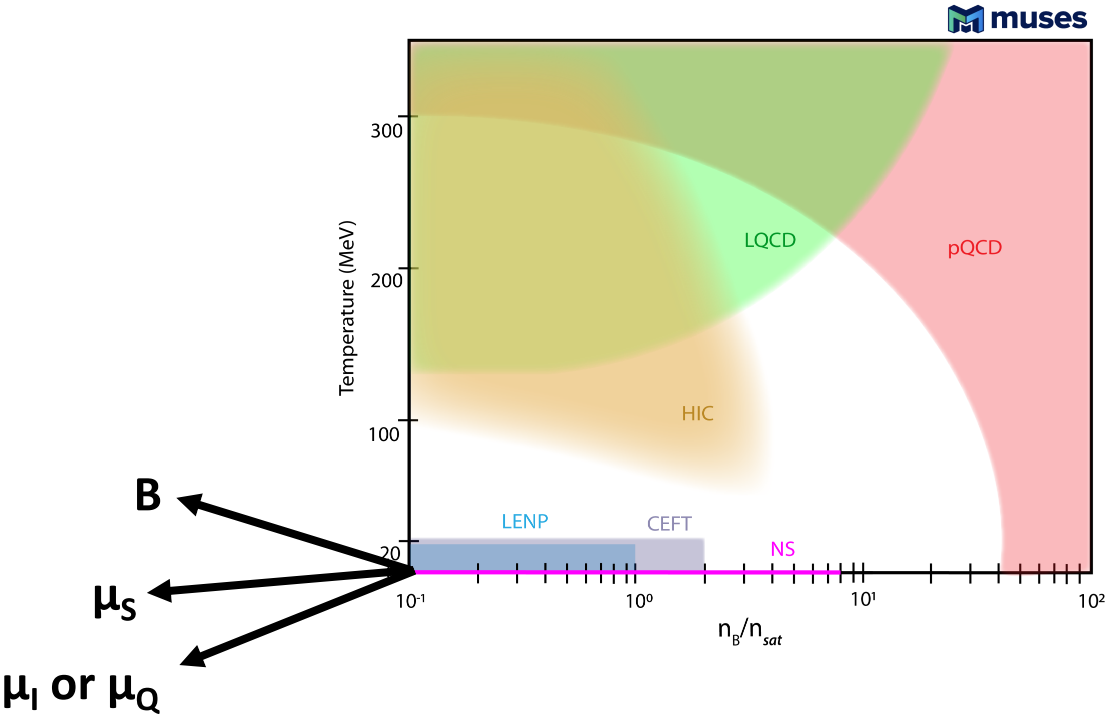
⭐ Our QCD Phase Diagram

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

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



⭐ What about More Dimensions?



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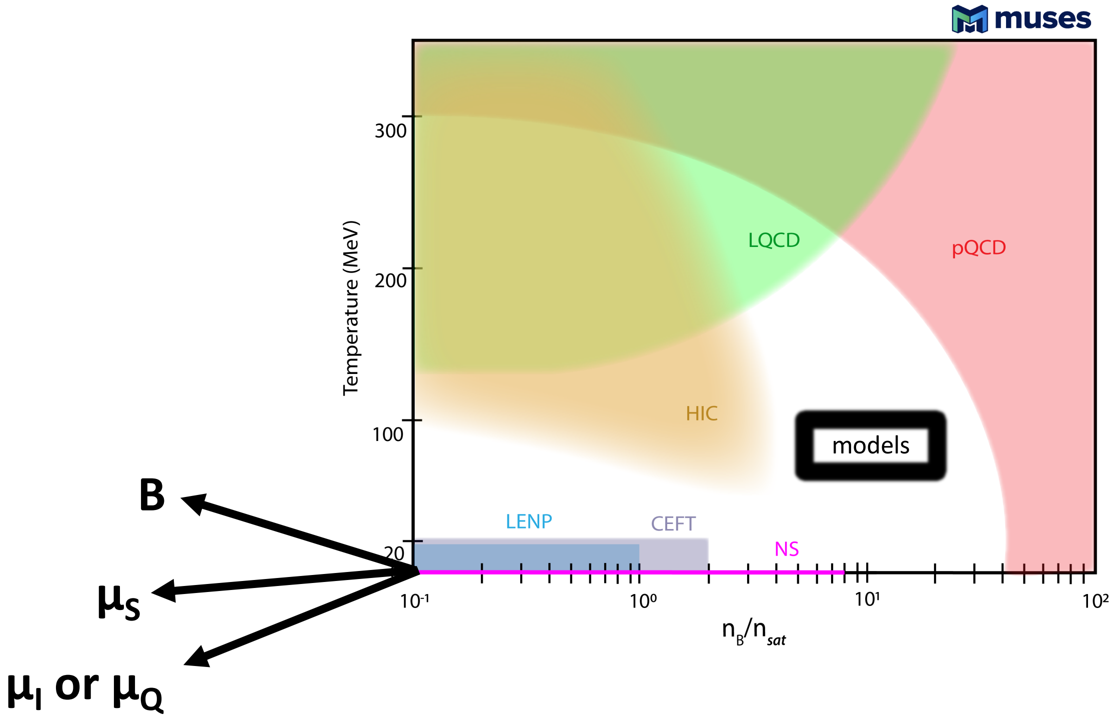
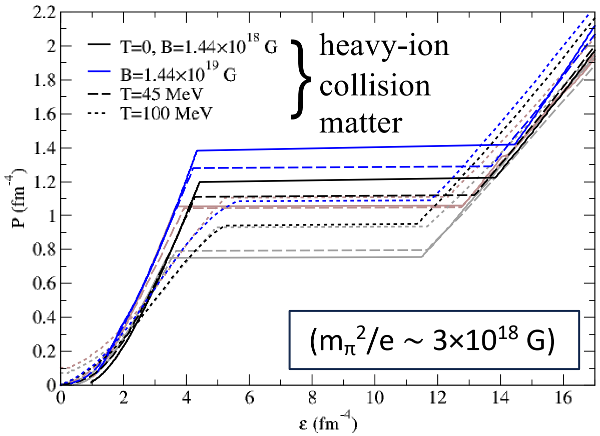


5D ~~Phase Diagrams~~ Curves

- Curves for the CMF model (with quark deconfinement)



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

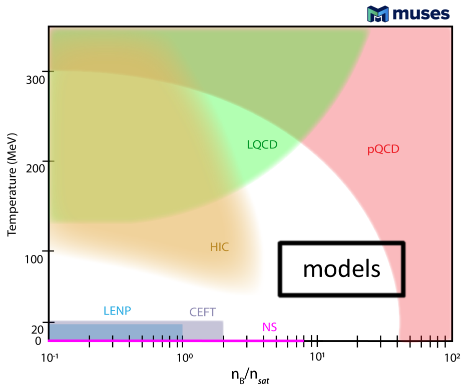
- Neutron-star matter also shown for comparison in different colors

B=1.44x10^18 G for neutron-star matter

B=1.44x10^19 G for neutron-star matter

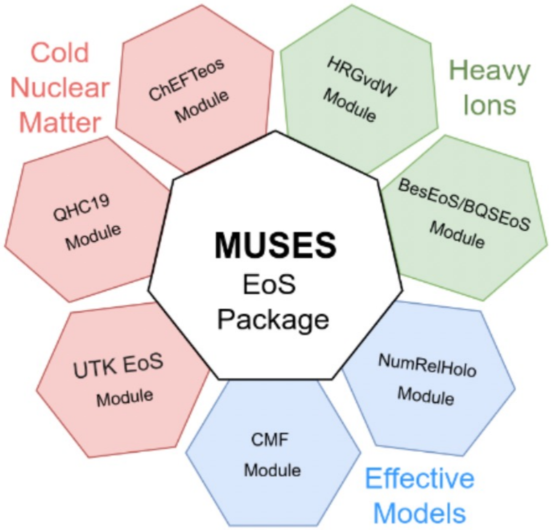
- (Stronger) phase transition takes place at larger ε and μ_B for larger B in CMF model
- (Weaker) phase transition takes place at lower μ_B for larger T
- Phase transition takes place at larger μ_B and is stronger for heavy-ion collision matter (for any **T** and **B**) in CMF model

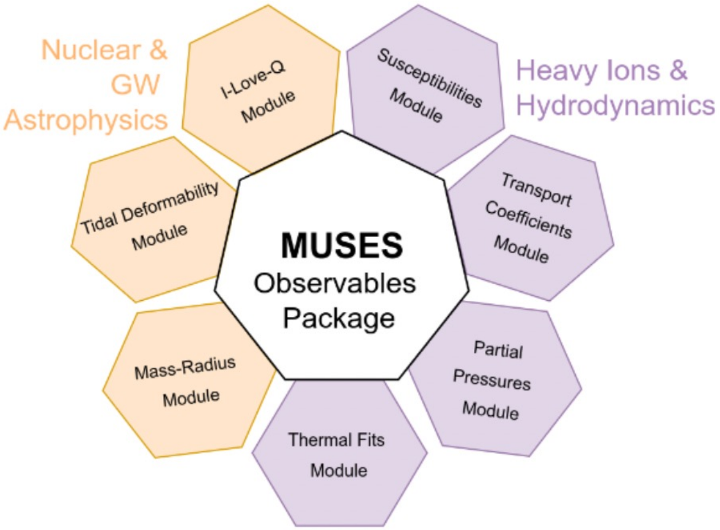
⭐ muses Cyberinfrastructure



- Modular Unified Solver of the Equation of State
- Modular: different theories/models (modules) for the user to pick from **and modify**
- Unified: different modules are merged together to ensure maximal coverage of the phase diagram
- Developers: physicists + computer scientists working together to develop optimized software that generates EoS's over large ranges of temperature and chemical potentials to cover the whole phase diagram, together with observables
- Users: interested scientists from different communities, who provide input to the cyberinfrastructure

muses Modules





+ Lepton Module, Synthesis Module, Interpolator Module, …

⭐ muses Alpha Release (September 2024)

- We invited interested people to test these modules and provide feedback
- Includes a first set of modules (open-source, but still preliminary)
- soon to be release to entire community …

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- ✶ Includes a first set of modules (open-source, but still preliminary)

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

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  - ✓ ISING-TEXS EOS: 2D Critical behavior into lattice QCD alternative expansion
  - ✓ NUMRELHOLO: 2D AdS/CFT correspondence based EoS

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

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  - ✓ Transport coefficients: thermal conductivity, baryon conductivity & diffusion, shear & bulk viscosities, …

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- ✶ Includes a first set of modules (open-source, but still preliminary)

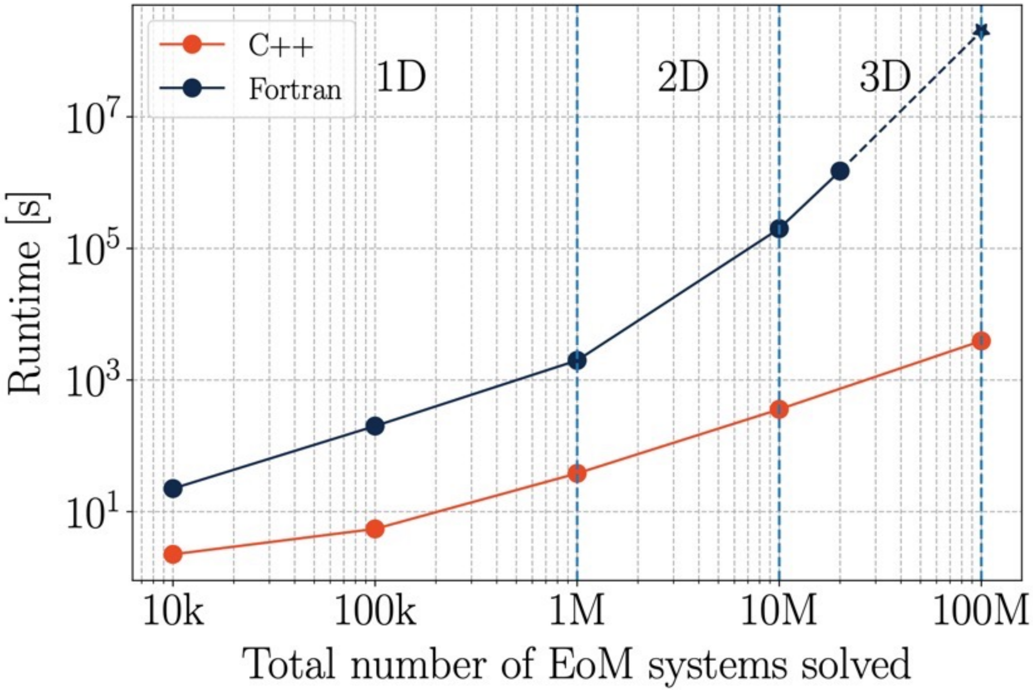
  - ✓ Transport coefficients: thermal conductivity, baryon conductivity & diffusion, shear & bulk viscosities, …
  - ✓ QLIMR module: quadrupole moment, tidal Love number, moment of inertia, mass, and radius of slowly rotating neutron star
  - ✓ Flavor equilibration for weak $\boldsymbol{\beta}$-equilibrium: Urca rates, relaxation rates, damping time, bulk viscosity.
  - ✓ Susceptibilities

⭐ muses Beta Release: October 2024

- ✶ After Beta release we will provide in-person/online workshops and schools
- ✶ Online tutorials tools …
- ✶ Stay tuned

- ✶ Coming in 2025: more dimensions for EoS’s, pasta phases, Thermal-FIST module, more interpolating functions, fully parametrized EoS’s …

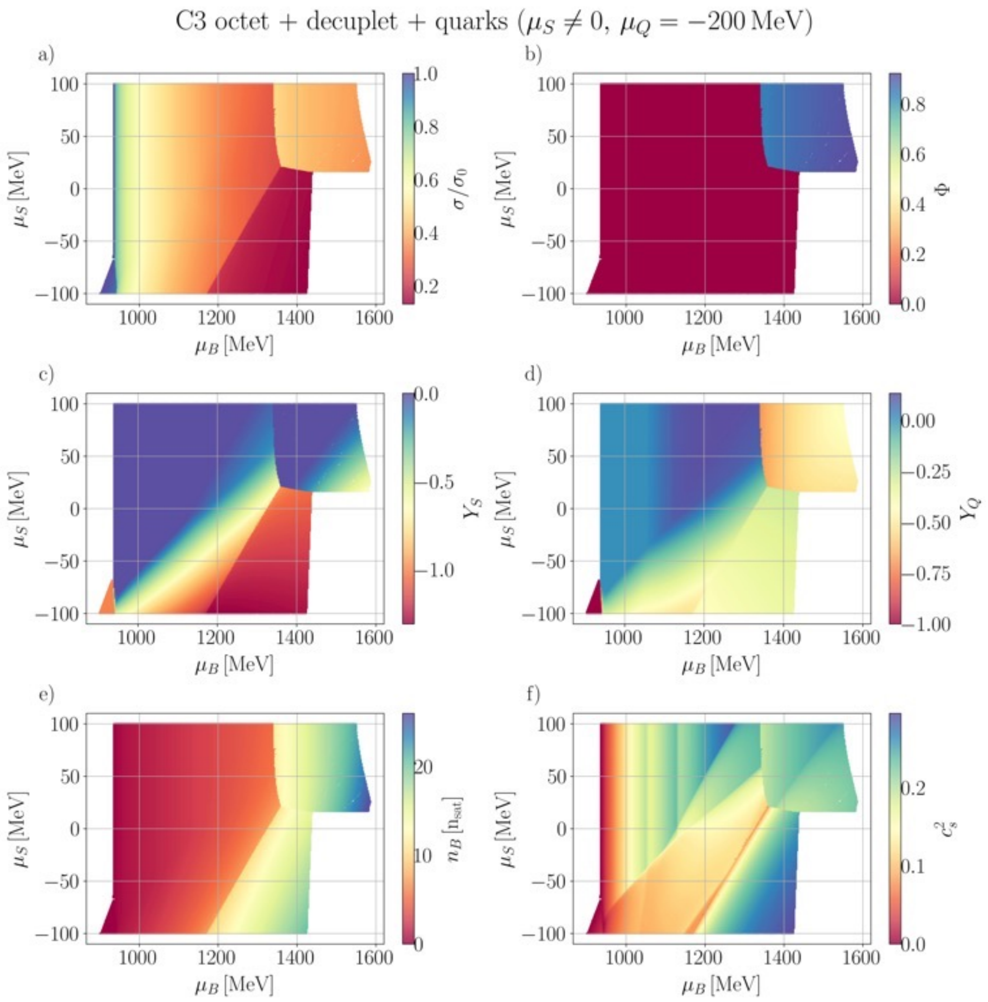
⭐ Results for CMF++



⭐ Results for CMF++

e-Print: [2409.06837](https://arxiv.org/abs/2409.06837)

a) scalar meson field σ normalized by vacuum
b) deconfinement field **Φ**
c) strangeness fraction
d) charge fraction
e) baryon density
f) speed of sound squared

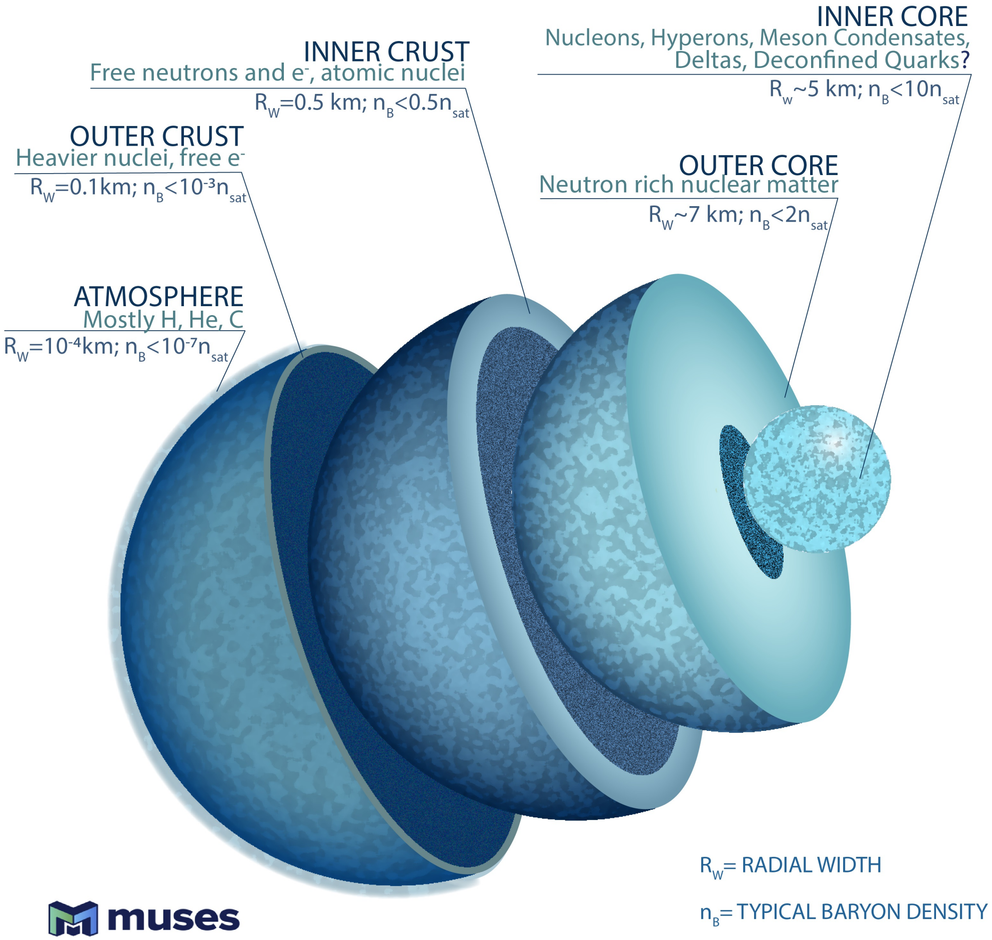


⭐ Additional Slides

⭐ Neutron Stars

- Mostly made up of dense matter (beyond saturation density)
- With inner core (beyond 2x saturation density) containing exotic matter

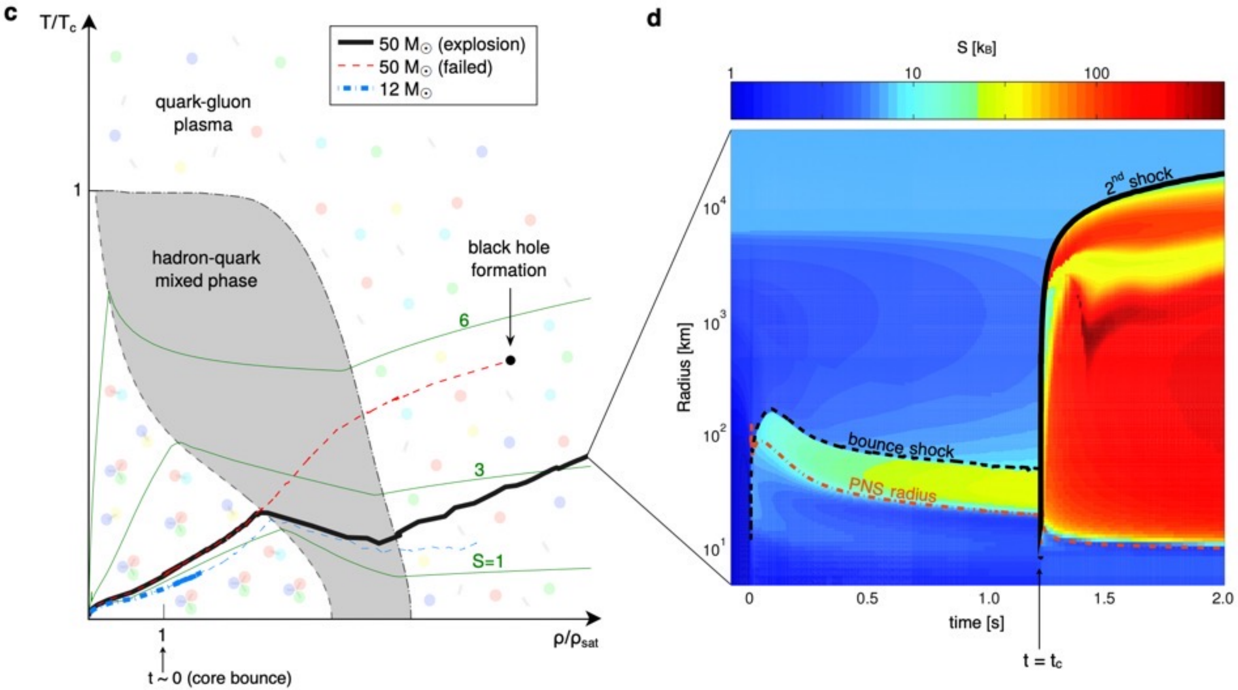
Living Rev.Rel. 27 (2024) 1, 3
e-Print: [2303.17021](https://arxiv.org/abs/2303.17021) [nucl-th]



Nature Astron. 2 (2018) 12, 980-986
e-Print: 1712.08788

⭐ Supernovae

- Dense matter reaching temperatures of few tens of MeV and S/B>2



⭐ Supernovae

Mon.Not.Roy.Astron.Soc. 516 (2022) 2, 2554-2574
e-Print: [2204.10397](2204.10397) [astro-ph.HE]

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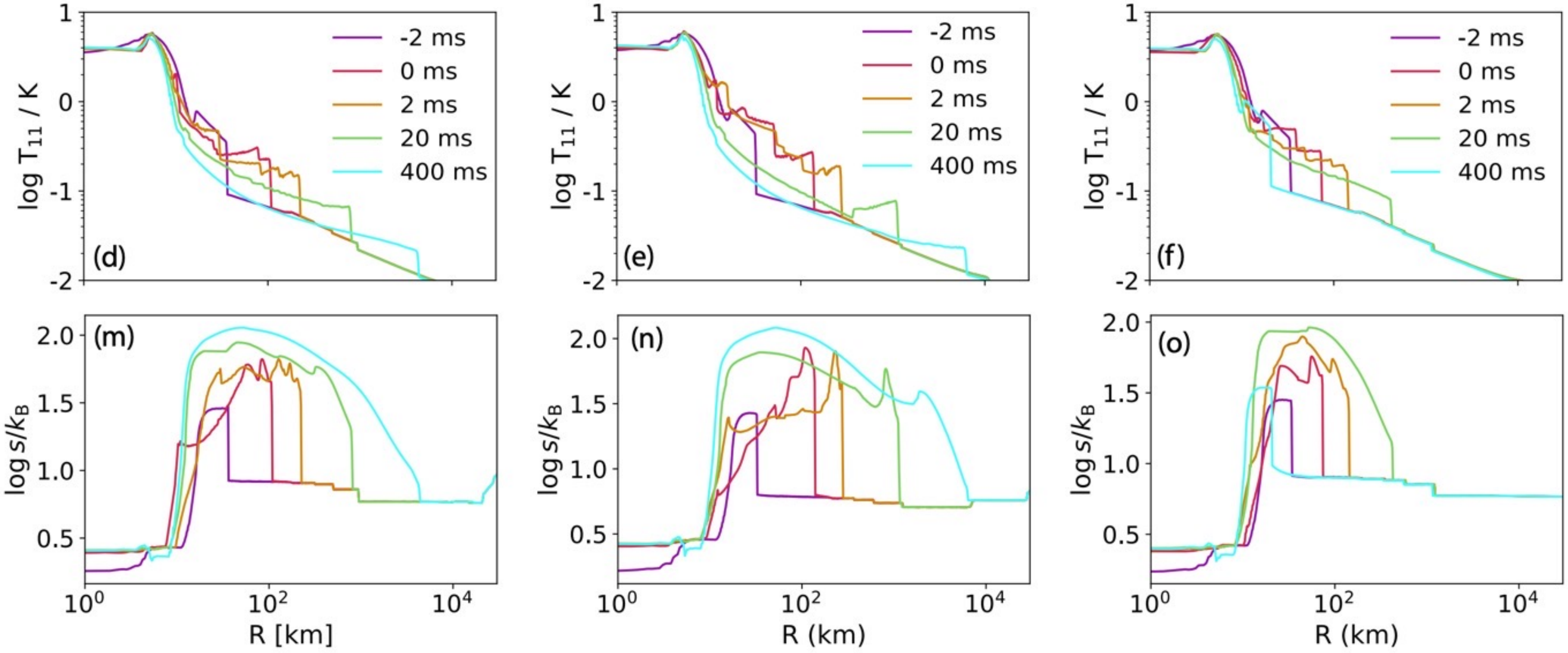
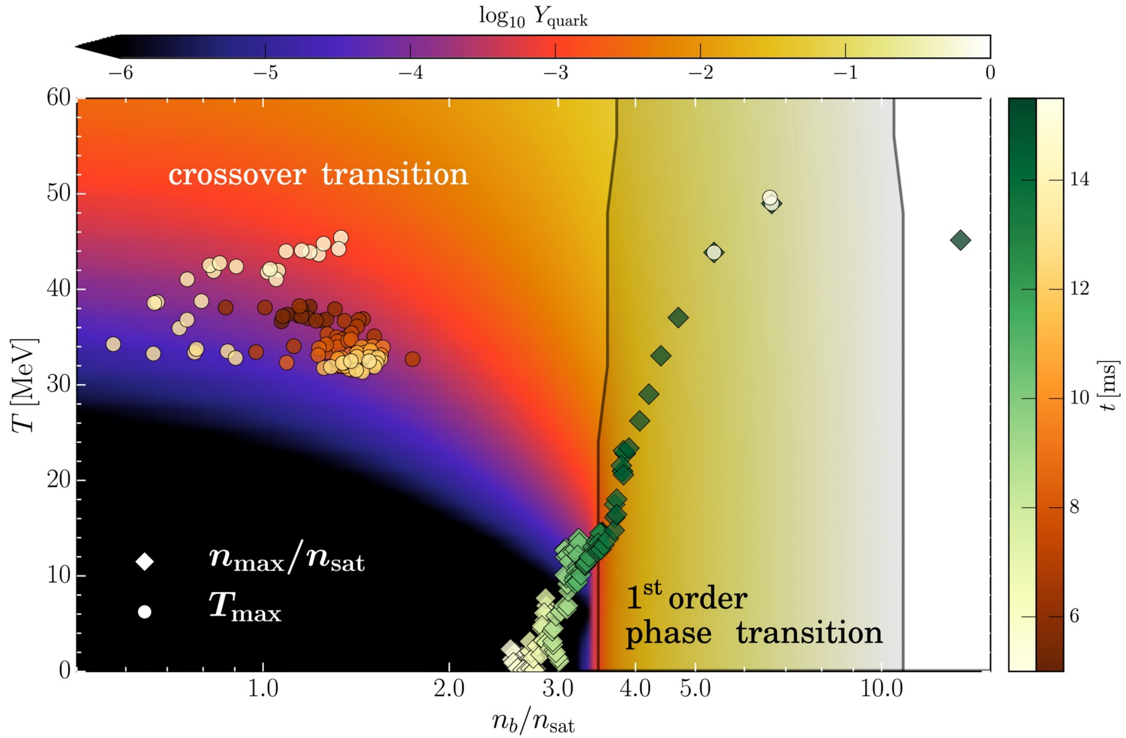


⭐ Neutron-Star Mergers

Phys.Rev.Lett. 122 (2019) 6, 061101 e-Print: [1807.03684]

✶ Dense matter reaching temperatures of many tens of MeV



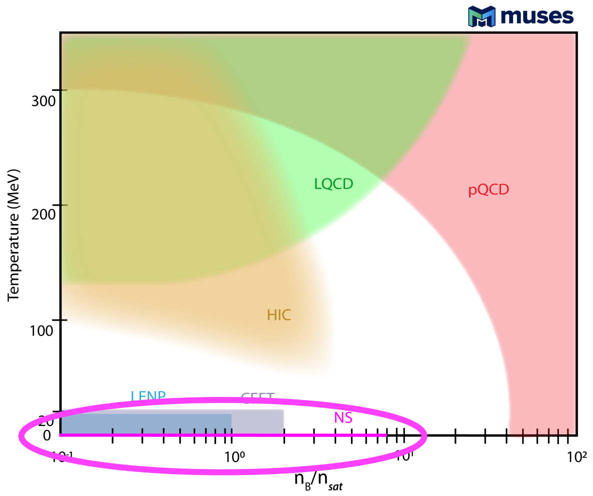
⭐ Astrophysics

- Neutron-star maximum mass

Neutron Star	M_{max} ($M_\odot$)
PSR J0740+6620	$\geq 2.08 \pm 0.07$
PSR J0348+0432	$\geq 2.01 \pm 0.04$

- Masses and radii from NICER

Neutron Star	M ($M_\odot$)	Radius (km)
PSR J0030+0451	$1.34^{+0.15}_{-0.16}$	$12.71^{+1.14}_{-1.19}$
PSR J0740+6620	$2.072^{+0.067}_{-0.066}$	$12.39^{+1.30}_{-1.98}$ → $12.92 \pm^{2.09}_{1.13}$
PSR J0030+0451	$1.44^{+0.15}_{-0.14}$	$13.02^{+1.24}_{-1.06}$
PSR J0740+6620	$2.08^{+0.07}_{-0.07}$	$13.7^{+2.6}_{-1.5}$
PSR J0437+4715	$1.418^{+0.037}_{-0.037}$	$11.36^{+0.95}_{-0.63}$



- More neutron star masses and radii (quiescent low-mass X-ray binaries), tidal deformability from gravitational waves, cooling data, …

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

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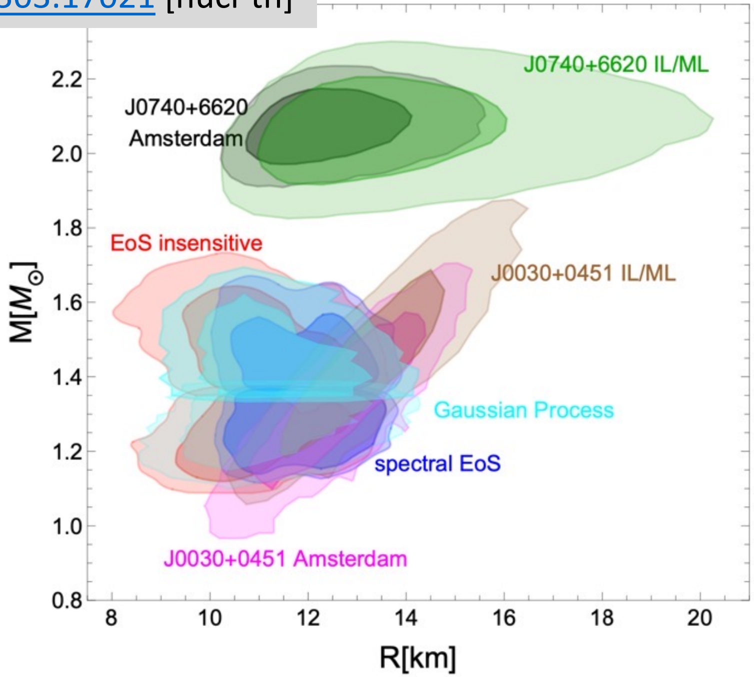

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MUSES EoS Module: Neutron Stars & Mergers

Theory/Model: Crust DFT, χEFT, CMF | α-release |

Details

- System has a long lifetime.
- Weak decay: $s \to u + W^-$.
- Strangeness is most likely not in equilibrium.
- Electrically neutral for stability $Y_Q + Y_{\mathrm{lep}} = 0$.

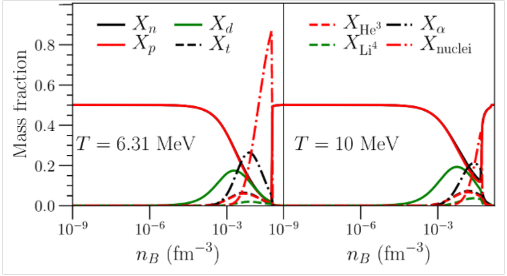
Needs

- Standard EoS: $(P, s, \varepsilon, \rho_B, c_s^2, \mu_i, Y_i)$.
- Lepton EoS.
- EoS at T=0 for neutron stars.
- EoS at finite-T for mergers.
- Ranges:
  $0 < n_B < 20?\ n_{\mathrm{sat}}$,
  $0 < T < 100?$ MeV.
- Variable proton fraction for mergers.

Crust DFT EoS Module (Holt's/Steiner's groups: Satyajit R., Zidu L.)

Range: $T \sim 0$ MeV; $\mu_B < 1000$ MeV; $10^{-12} < n_B(\mathrm{fm}^{-3}) < 2$ | α-release |

UTK or Crust density functional theory (DFT) EoS includes nuclei and nucleonic degrees of freedom based on a phenomenological fit of free energy density to nuclear experiments & astronomical observations.



X du, A. Steiner, J Holt, PRC 110 (2022)

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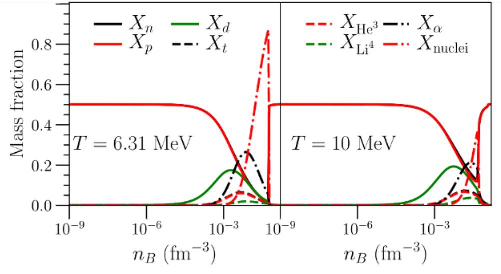
Outlook

- Addition of finite T EoS.
- Extension to strangeness degrees of freedom.
- Machine learned emulator.



X du, A. Steiner, J Holt, PRC 110 (2022)

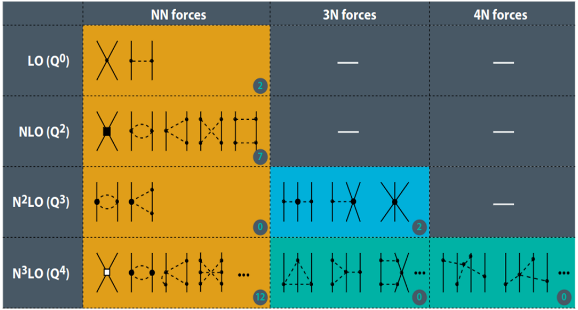
χEFT EoS Module (Holt's group: David F.)

Range: $T \sim 0$ MeV; $\mu_B < 1000$ MeV; $0<Y_p<0.5$ | α-release |

Interacting nucleons and pions within chiral effective field theory (χEFT) fitted to nucleon scattering data and boundstate potential.

Status before MUSES

- `Fortran` 77 proprietary code.
- Spaghetti code and not properly documented.
- Antique integration and interpolating routines.



J. Holt and N. Kaiser, PRC (2017)

χEFT EoS Module (Holt's group: David F.)

Range: $T \sim 0$ MeV; $\mu_B < 1000$ MeV; $0<Y_p<0.5$ | α-release |

Current status

- High resolution $T = 0$ that agrees with the `Fortran` code for 2D EoS (ρ_B and Y_I).
- Freedom to choose the underlying parameters which was hardcoded into the `Fortran` code.
- 3 times faster than legacy `Fortran` code.
- Able to incorporate multiple χ EFT potentials (currently uses N3LO-414 and N3LO-450).
- Execution via Docker and from Calculation Engine (tutorial notebook available).

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Outlook

- Add extension at finite-T (up to 30 MeV).
- Include a wider variety of χEFT potentials.
- Provide uncertainty quantification.

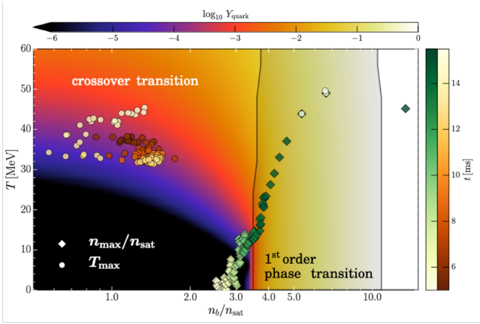
CMF EoS Module (Dexheimer's and Hostler's groups)

Nikolas C. C., Mateus R. P., Jeff P., Rajesh K. | α-release |

We created an open-source optimized modular modern `C++` code to compute multidimensional EoS tables using the Chiral Mean-field (CMF) model.

Status before MUSES

- `Fortran` 77 proprietary code.
- Spaghetti code between non- and magnetic cases, not properly documented.
- Antique root solving and integration routines.



E. Most, V. Dexheimer et al., PRL (2019)

CMF EoS Module (Dexheimer's and Hostler's groups:)

Nikolas C. C., Mateus R. P., Jeff P., Rajesh K. | α-release |

Current status

- High resolution zero temperature that agrees with the previous `Fortran` code for all particles.
- More thorough check for EoS stability in the new code.
- `CMF++` runtime is more than 4 orders of magnitude faster than legacy `Fortran`.
- Execution via Docker and from Calculation Engine (tutorial notebook available).

CMF EoS Module (Dexheimer's and Hostler's groups:)

Nikolas C. C., Mateus R. P., Jeff P., Rajesh K. | α-release |

Current status

- High resolution zero temperature that agrees with the previous `Fortran` code for all particles.
- More thorough check for EoS stability in the new code.
- `CMF++` runtime is more than 4 orders of magnitude faster than legacy `Fortran`.
- Execution via Docker and from Calculation Engine (tutorial notebook available).

Outlook

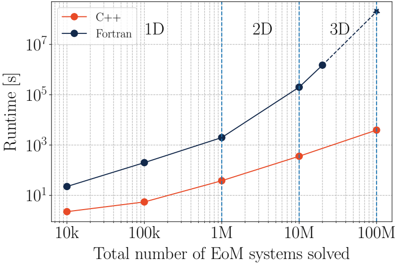
- Couple to flavor equilibration module.
- Zero temperature magnetic case.
- Finite temperature non- and magnetic case.
- Add thermal meson interactions.

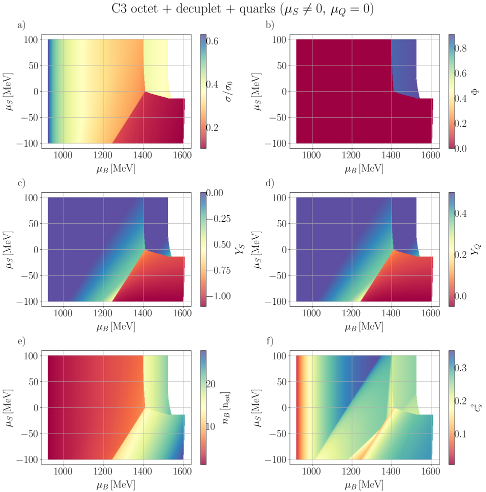
CMF Module: Preprint

Phase Stability in the 3-Dimensional Open-source Code for the Chiral mean-field Model

Highlights

- Improved run time.
- Extension to 3D (μ_B, μ_Q, μ_S).
- Stability analysis.





N. Cruz-Camacho, R.K. et al., arXiv:2409.06837

MUSES EoS Module: Heavy-ion Collisions

Theory/Model: HRG, BQS (lattice), 2D Ising T.Ex.S, 4D T.Ex.S, Holography

| α-release | except HRG, 4D T.Ex.S

Details

- System is described in terms of hydrodynamic simulations.
- Short lifetime, the system is not in equilibrium.
- Strangeness conserved $Y_S = 0$, charge fraction $Y_Q = 0.4$.

Needs

- To take into account local fluctuations, 4D EoS is needed.
- Free parameters: T, μ_B, μ_S, μ_Q, thermodynamic variables $(P, s, \varepsilon, n_B, c_s^2)$.
- 1st and 2nd order derivatives of pressure with respect to chemical potentials.
- Inclusion of critical point.
- Transport coefficients.

MUSES Observable Module: Neutron Stars & Mergers

QLIMR Module (Yunes's group: Carlos C.) | α-release |

Given an EoS, solves the Tolmann-Oppenheimer-Volkoff (TOV) equations

$$\frac{dp}{dr} = -\frac{G\varepsilon m}{c^2 r^2}\left[1 + \frac{p}{\varepsilon}\right]\left[1 + \frac{4\pi r^3 p}{mc^2}\right]\left[1 - \frac{2Gm}{c^2 r}\right]^{-1}$$

$$\frac{dm}{dr} = \frac{4\pi r^2 \varepsilon}{c^2}$$

plus Hartle Thorne method and computes:

- Q: quadrupole moment Q of NS
- L(Λ): tidal Love number (tidal deformability)
- I: moment of inertia
- M: mass of NS (+δM to correct for rotation)
- R: radius of NS (+δR to correct for rotation too)
- Local function $f(R)$

MUSES Observable Module: Neutron Stars & Mergers

(Alford/Dexheimer/Most/Yunes's groups: Mateus. R. P., Alexander H., Alexander C.)

Lepton module: β-equilibrium and charge neutral matter | α-release |

- Given an EoS, computes:
  - Charged lepton densities necessary to ensure charge neutrality

Flavor equilibration: β-equilibrium: $\mu_n - \mu_p - \mu_e = 0$ | α-release |

- Given an EoS, computes:
  - Urca rates $n \to p + e + \bar{\nu}_e; p + e \to n + \nu_e$, equilibrium charge fractions, relaxation rates, damping time, susceptibilities, bulk viscosity.

Adapter modules to obtain a standard EoS for NS & mergers simulation tools

- Compatibility with CompOSE to provide 1D/2D/3D EoS for NS.
- Ensuring compatibility with merger simulations.

MUSES Observable Module: Neutron Stars & Mergers

(Alford/Dexheimer/Most/Yunes's groups: Mateus. R. P., Alexander H., Alexander C.)

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  - Urca rates $n \to p + e + \bar{\nu}_e; p + e \to n + \nu_e$, equilibrium charge fractions, relaxation rates, damping time, susceptibilities, bulk viscosity.

Outlook:

- Nuclear structure (pasta phases).
- Testing more interpolation functions.

MUSES Observable Module: Heavy-ion Collisions

Susceptibilities & hadronic species contributions

- Susceptibilities from lattice QCD will be computable.
- Using HRG model, one can study the breakdown of different hadron families.
- Partial pressure and analogous relations for susceptibilities.

Transport coefficients from Holographic module

- Thermal conductivity, baryon conductivity & diffusion.
- Shear & bulk viscosities, HQ drag force & Langevin diffusion coefficients.
- Jet quenching parameter.

Freeze-out physics

- T and μ_B at chemical freeze-out can be fitted from exp. data with HRG.
- Will be incorporated with Thermal-FIST.

MUSES Equation of State Workflows in the Zero-Temperature Limit

M. R. Pelicer, R.K. et al., under preparation (preliminary) | α-release |