The role of neutron stars in constraining the QCD equation of state (The QCD equation of state from CMF)

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⭐ Astrophysics group


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muses

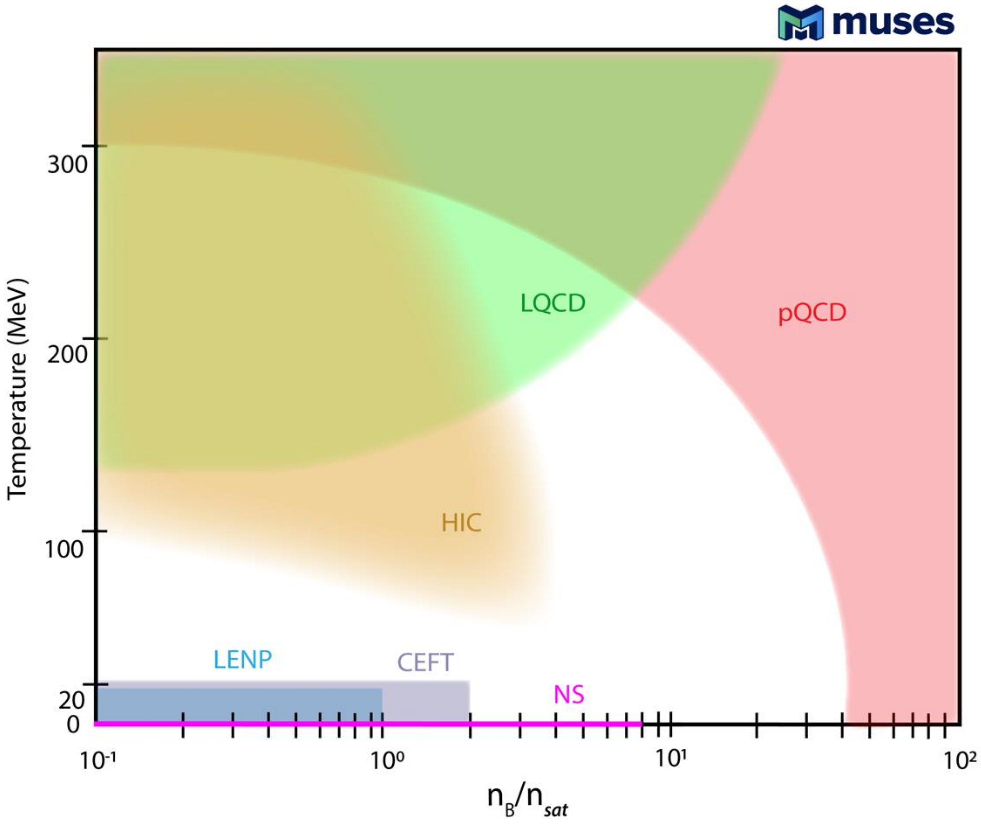
NP3M

NSF

⭐ 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)



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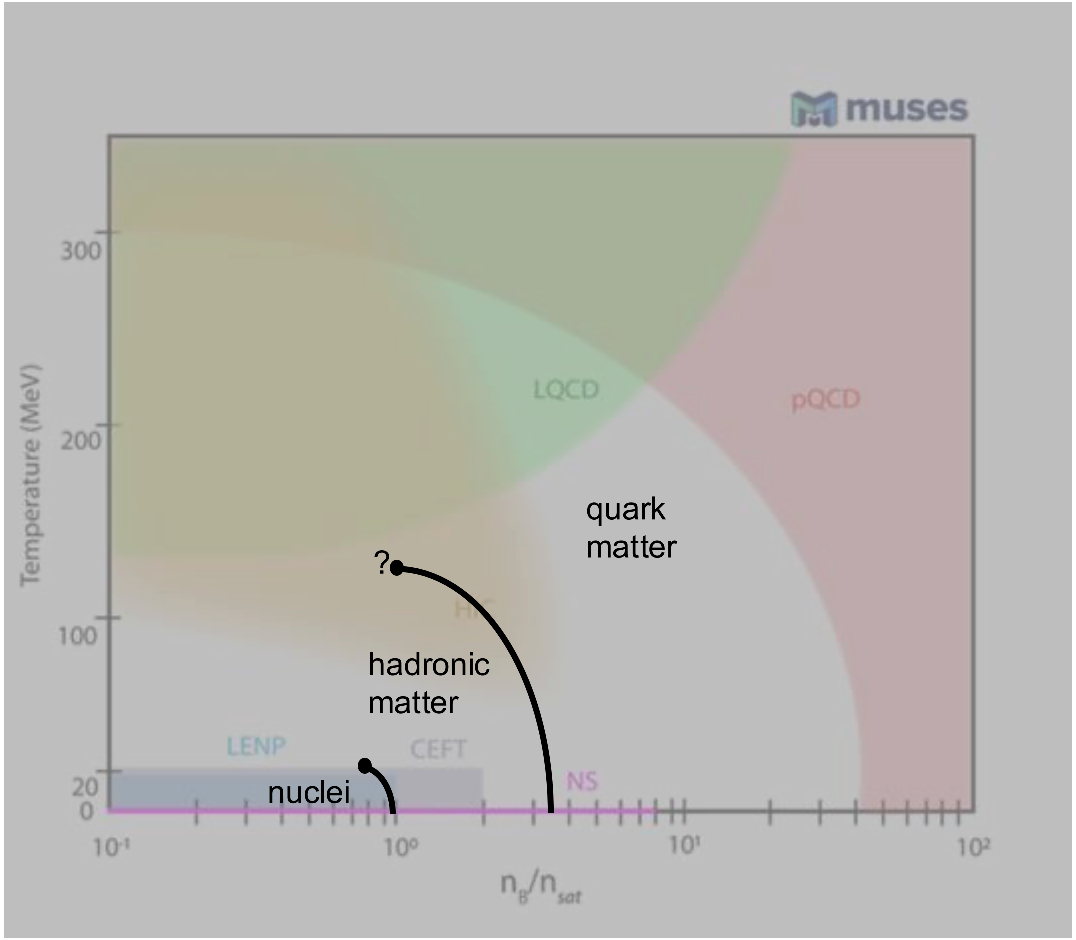

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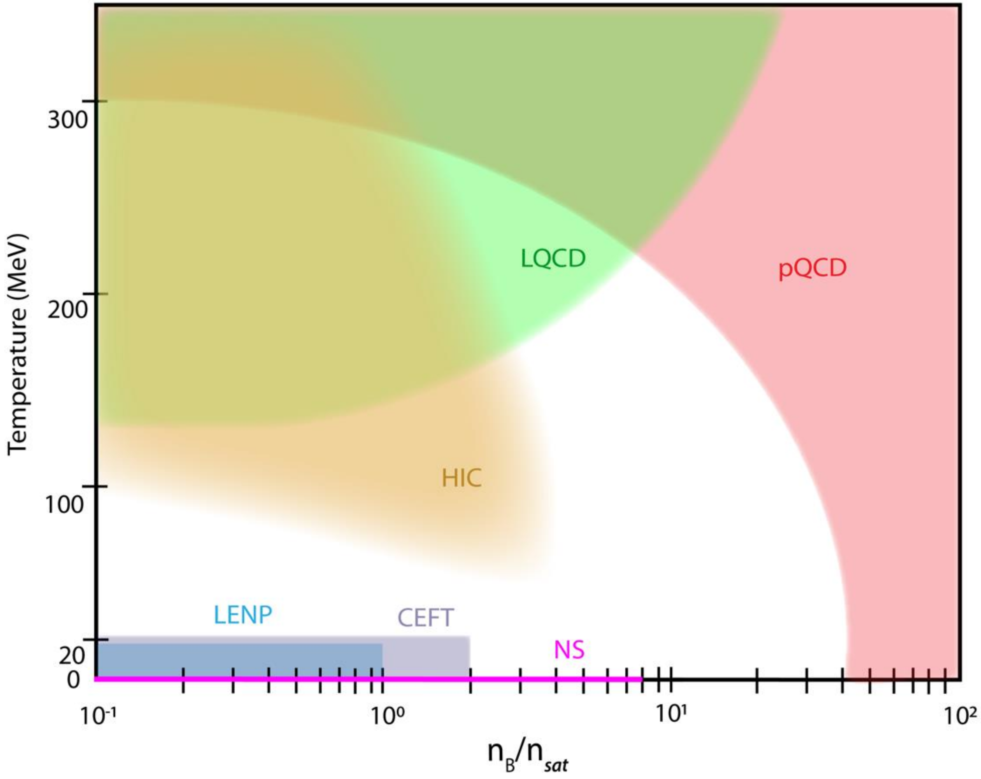
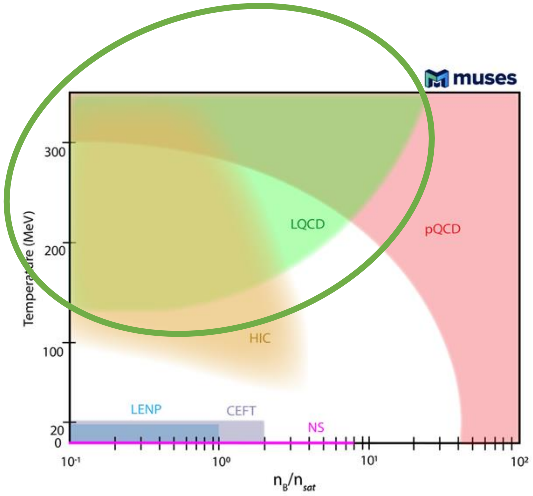


⭐ Lattice QCD

- 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 $\mu_B=0$

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

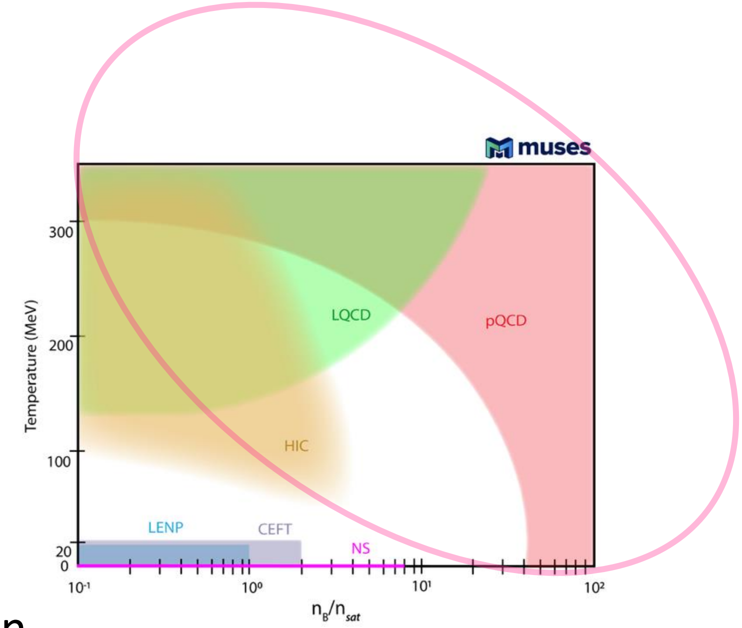
- The curvature of the QCD phase transition line

- 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



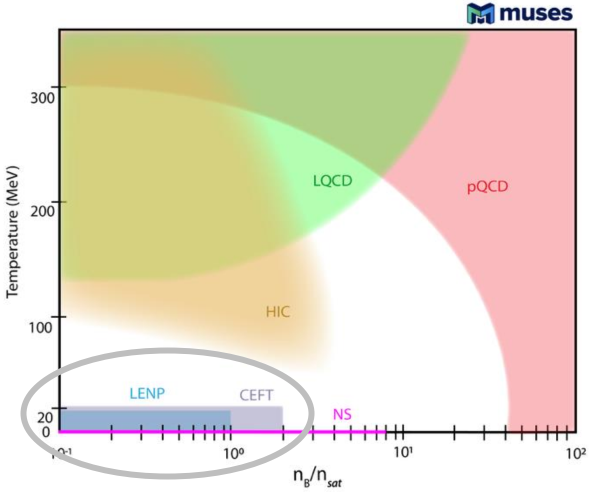
⭐ Chiral Effective Field Theory

- 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)

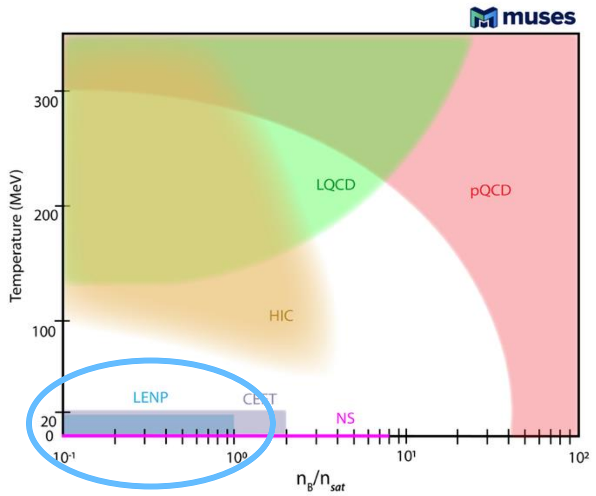


⭐ Low-energy nuclear physics

- 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 and around n_{sat}
- Heavy-ion collision measurements of neutron skin
- Liquid-gas critical point

⭐ QCD phase diagram

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

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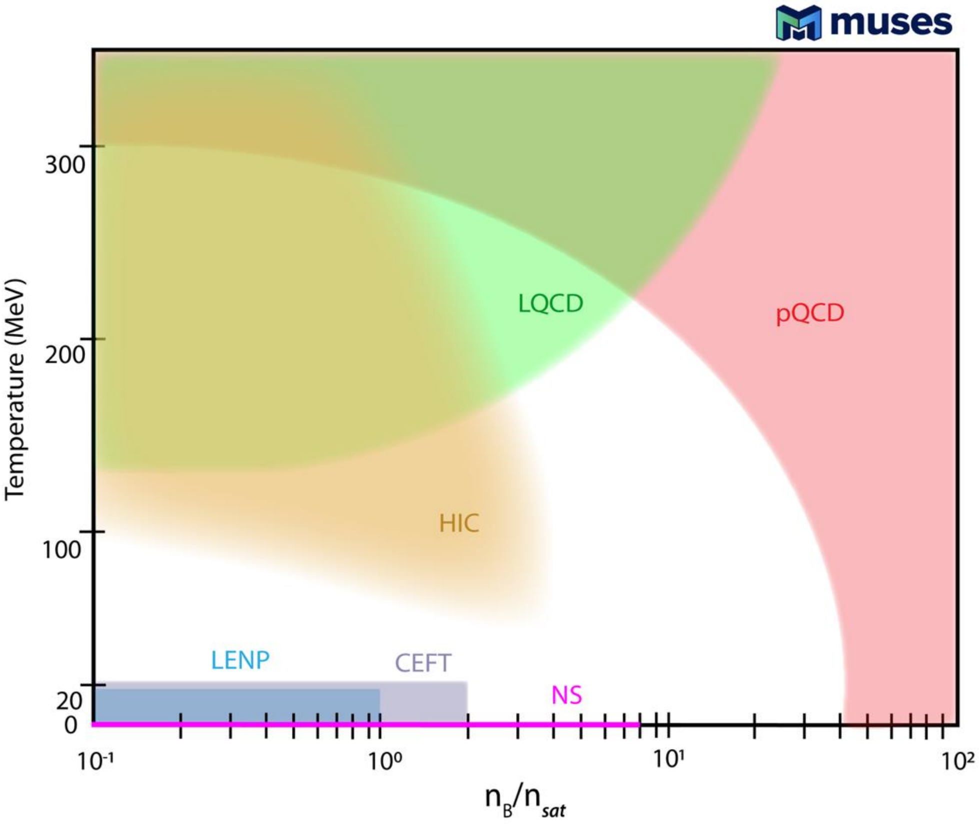
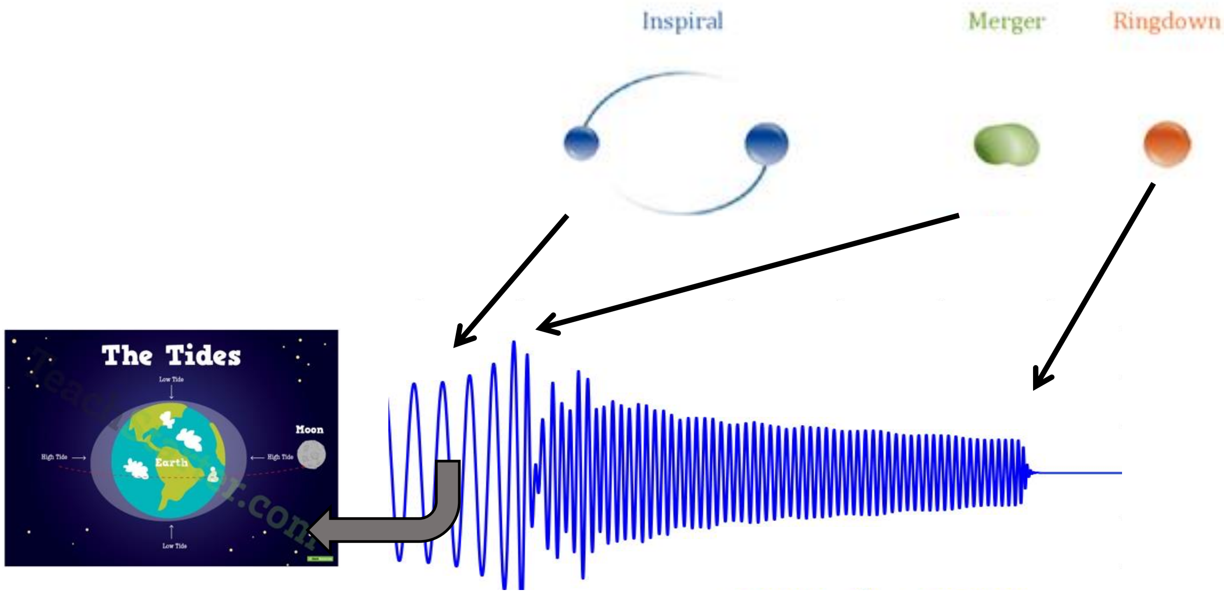
e-Print: [2303.17021](2303.17021)

- Astrophysics input only at T~0 …



Gravitational wave data

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



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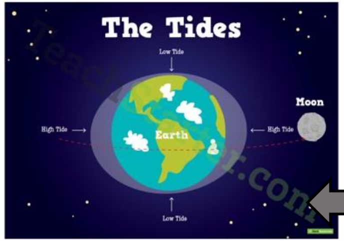

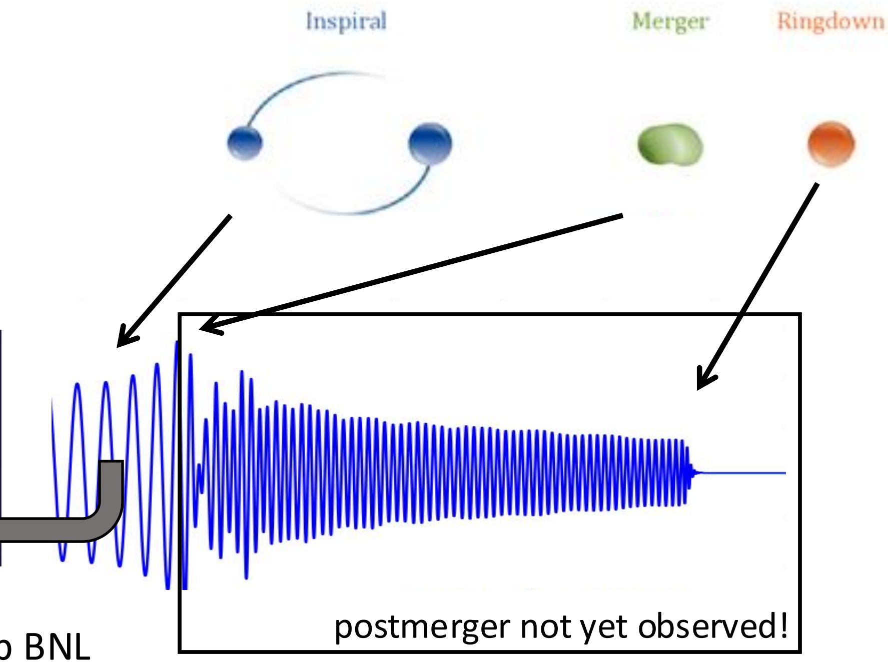

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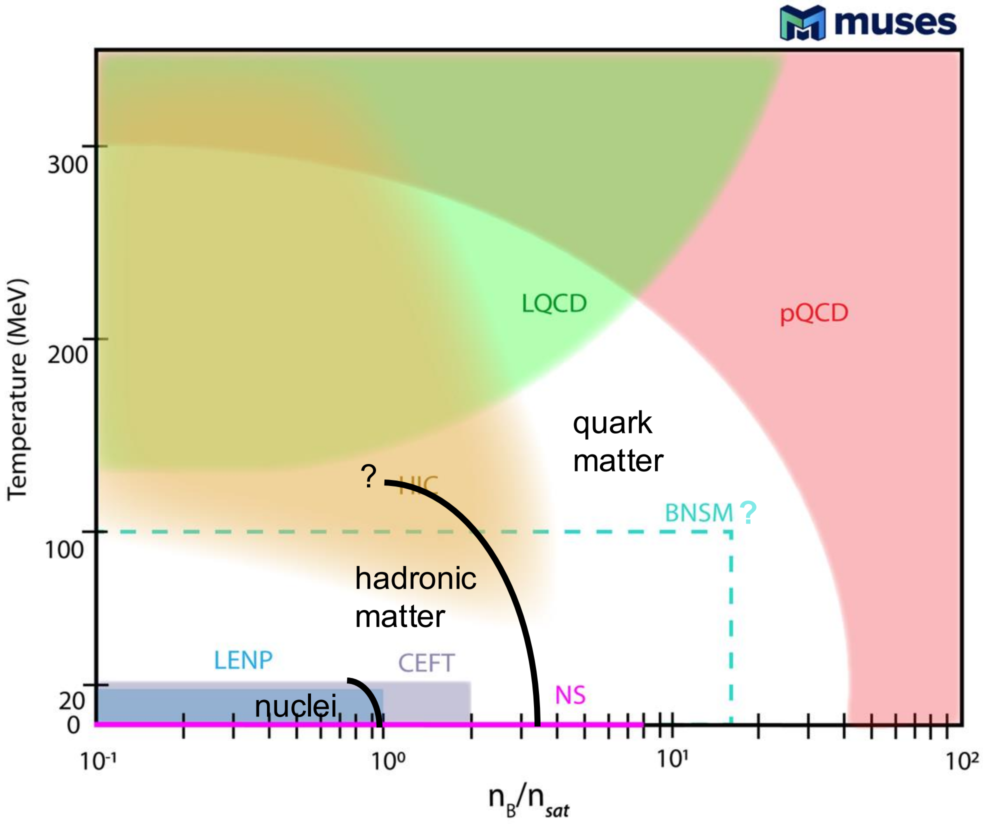
- Current input from different (first-principle and effective) theories and experiments

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

- Astrophysics input only at T∼0 for now
- But finite T input is coming soon



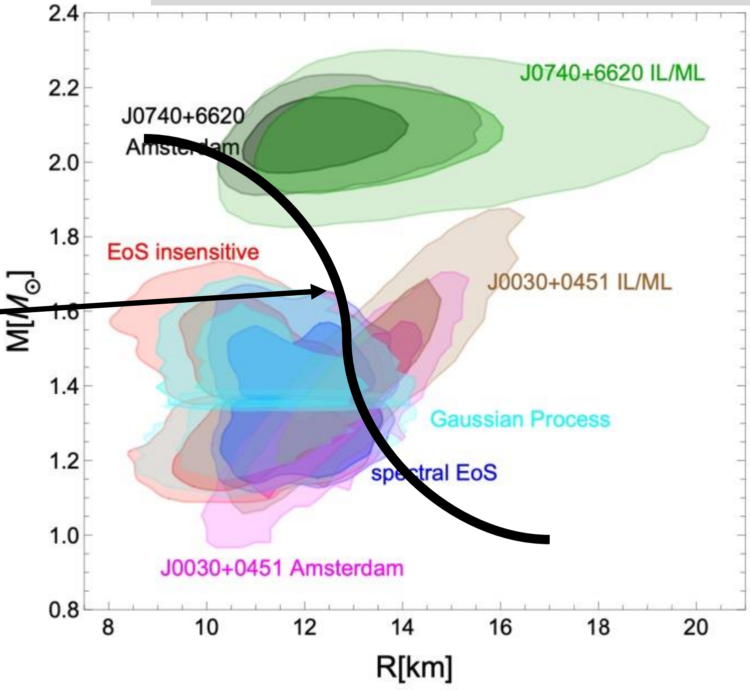
⭐ Astrophysics: mass-radius diagram

PRD 105 (2022) 2, 023018 e-Print: [2106.03890](2106.03890)

- Equation of state (EoS): P (ε)
- Einstein's equations: Tolman–Oppenheimer–Volkoff (TOV) equation
- Mass-radius for neutron stars (for many central densities)
- How can we invert the mass-radius diagram to obtain the EoS? Start from

  - microscopic models
  - interpolations
  - parametric EoSs …

and check if they match data!



⭐ Astrophysics data

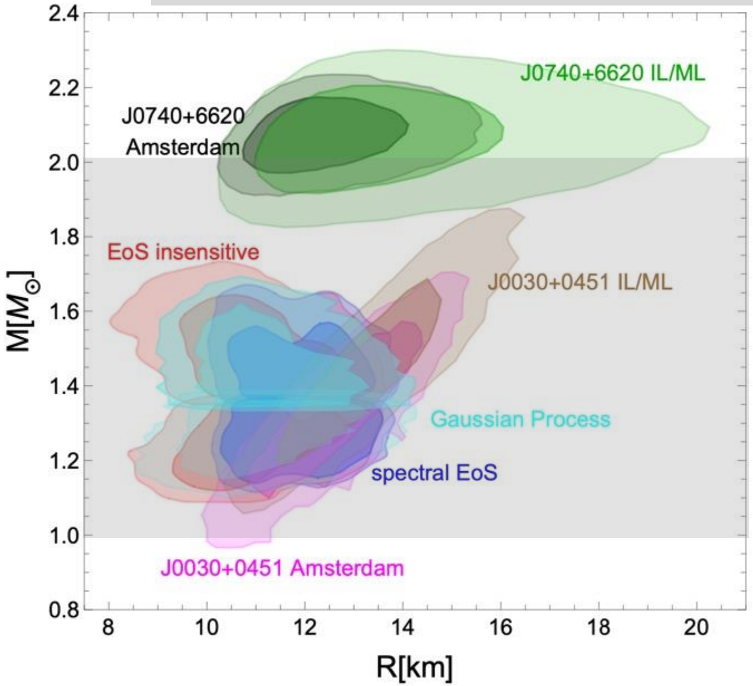
- Neutron-star maximum mass

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	$1.418\ ^{+0.037}_{-0.037}$	$11.36\ ^{+0.95}_{-0.63}$

PRD 105 (2022) 2, 023018 e-Print: [2106.03890](2106.03890)



- More neutron star radii and masses, cooling data, …

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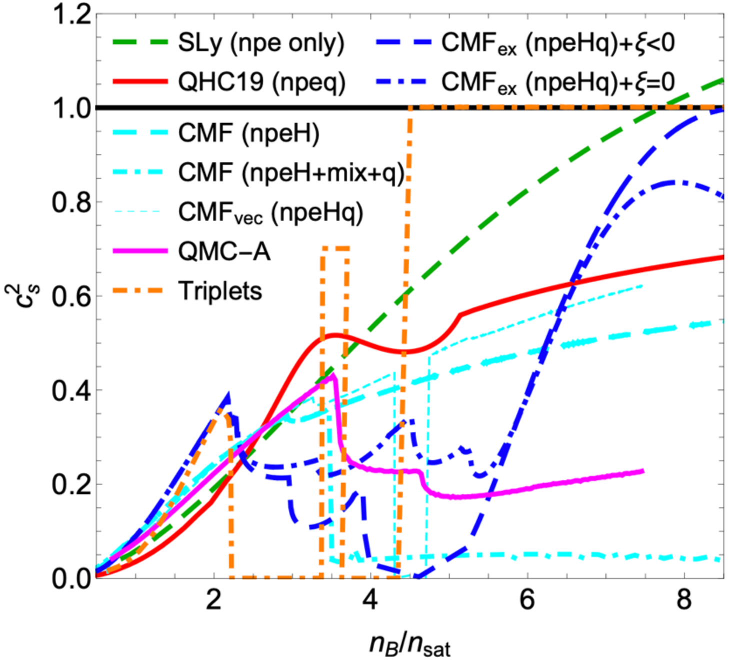
e-Print: [2303.17021](2303.17021)

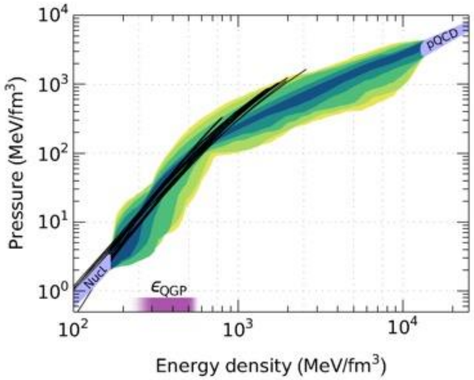
⭐ Speed of sound of dense matter

- ✶ Structure associated with different particles, interactions, phase transitions, …

PRD 105 (2022) 2, 023018 e-Print: [2106.03890](2106.03890)



- ✶ Structure needed to reproduce nuclear + astrophysics data



Nature Phys. 16 (2020) 9, 907-910
e-Print: [1903.09121](1903.09121)

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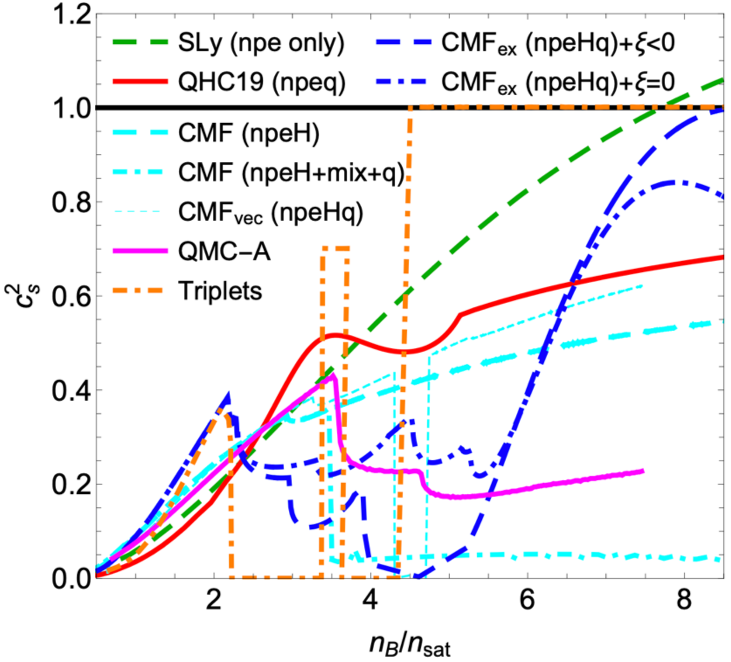
PRD 105 (2022) 2, 023018 e-Print: [2106.03890](2106.03890)

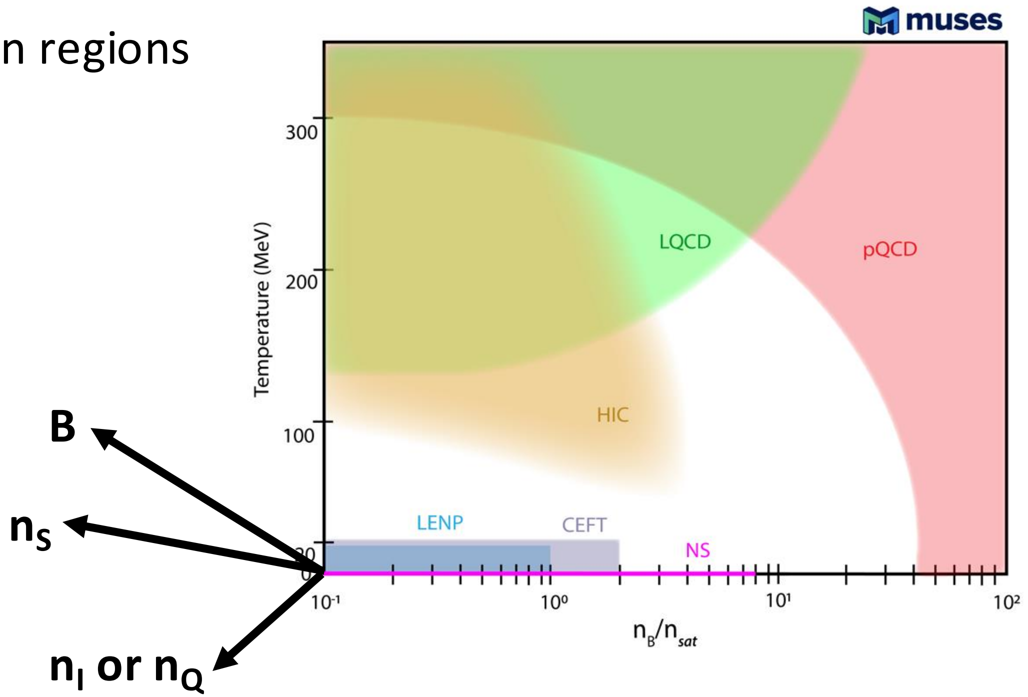


- See Nanxi Yao's talk for connections with heavy-ion collisions

Phys.Rev.C 109 (2024) 6, 065803
e-Print: [2311.18819](2311.18819)

⭐ QCD phase diagram with more dimensions

- Strangeness, isospin, magnetic fields, …
- Large unknown regions

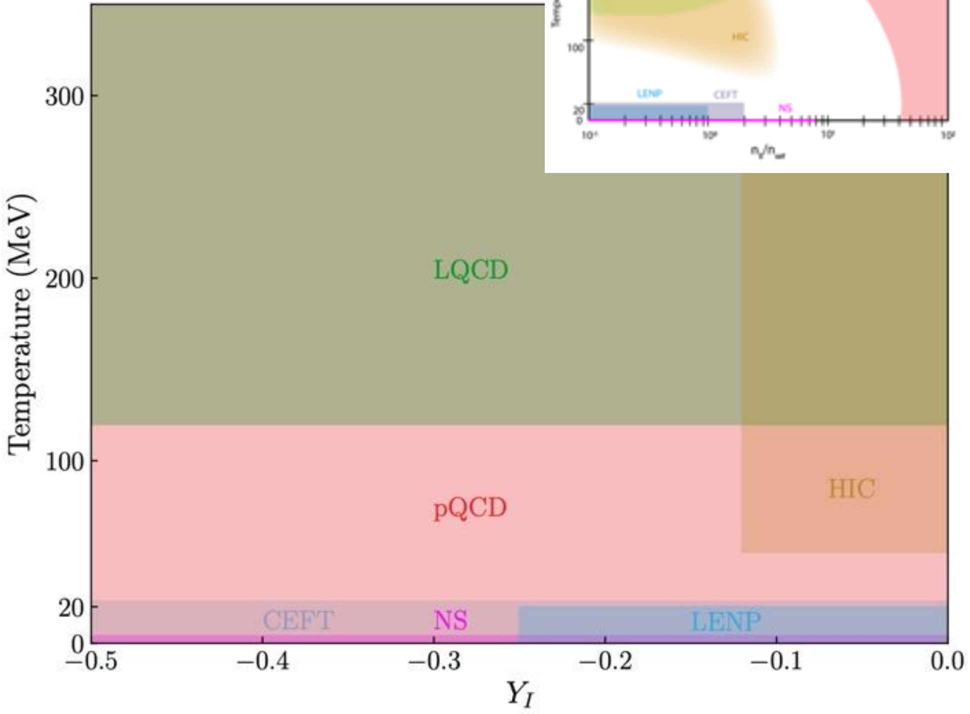


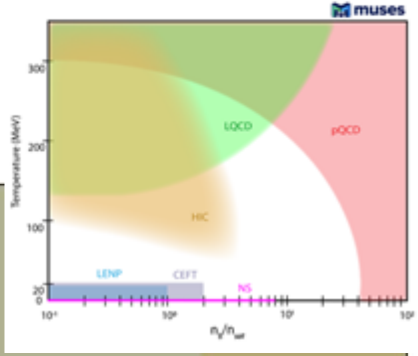
⭐ QCD phase diagram at finite isospin

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

e-Print: [2503.23413](2503.23413)

Region	Isospin Fraction (Y_I)
PQCD	−0.5 to 0
LQCD	−0.5 to 0
CEFT	−0.5 to 0
NS	−0.5 to 0
LENP	(−0.5), −0.25 to 0
HIC	−0.12 to 0





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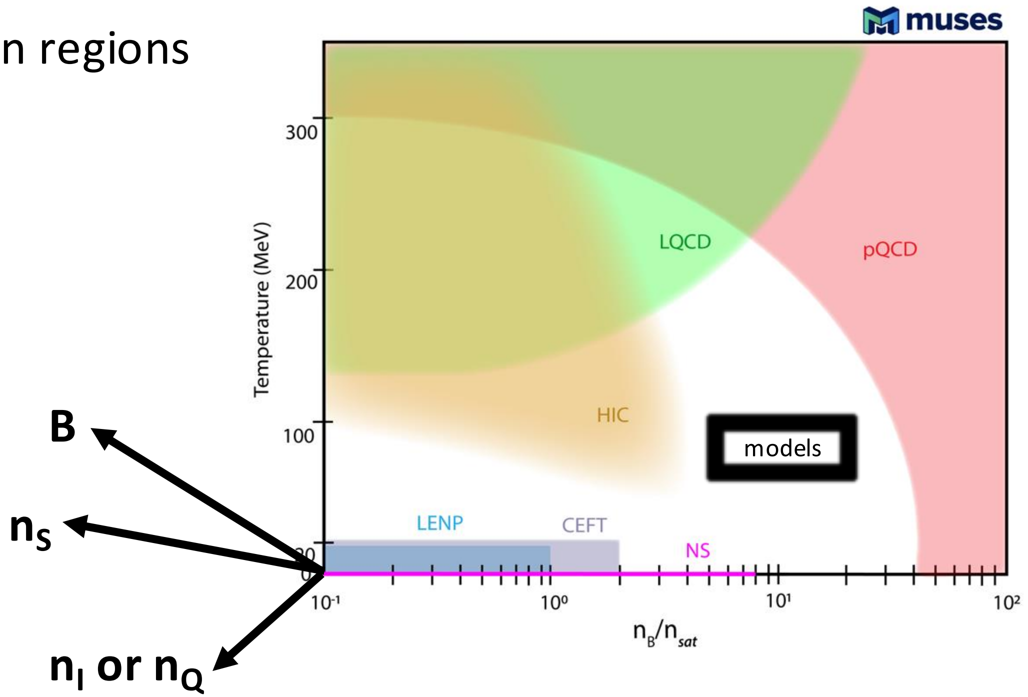
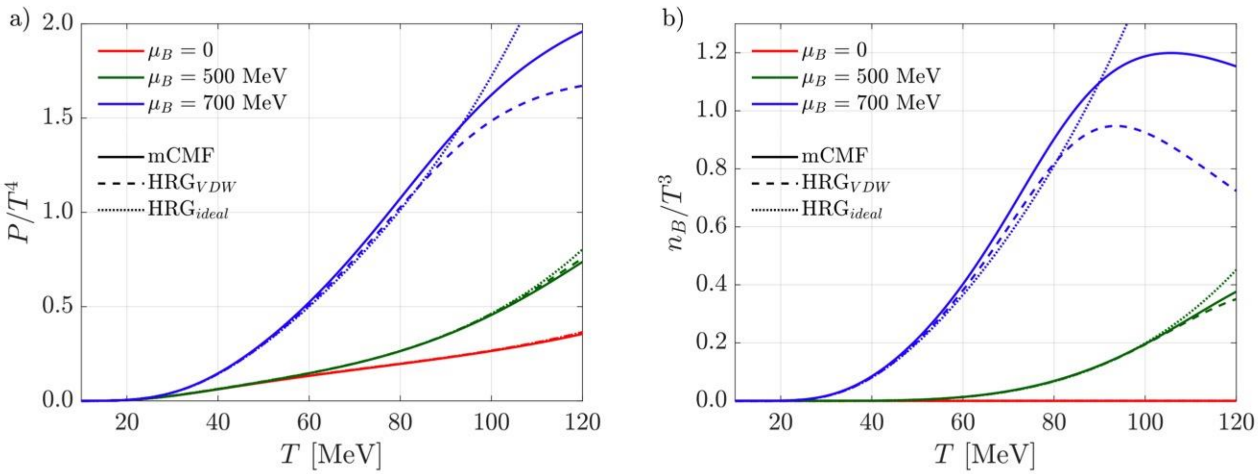


Chiral Mean Field (CMF) model

- microscopic model with chiral symmetry restoration and quark deconfinement
- reproduces liquid-gas, and crossover/1st-order phase transition for deconfinement
- in agreement with nuclear physics, astrophysics, and lattice QCD
- now with improved meson description (**mCMF**) for $\boldsymbol{\mu}_Q=\boldsymbol{\mu}_S=0$

low energy

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



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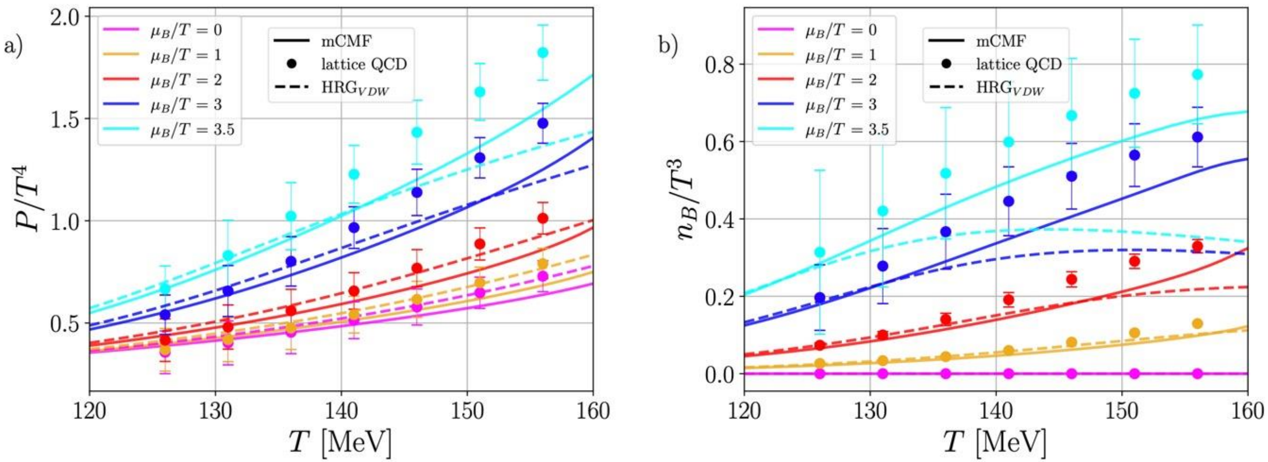
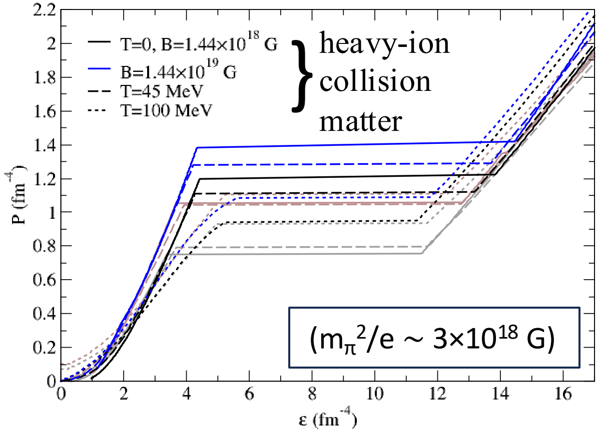
Phys.Rev.D 111 (2025) 7, 074029
e-Print: 2503.03057



CMF in more dimensions

- CMF can be extended in 5 dimensions



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

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

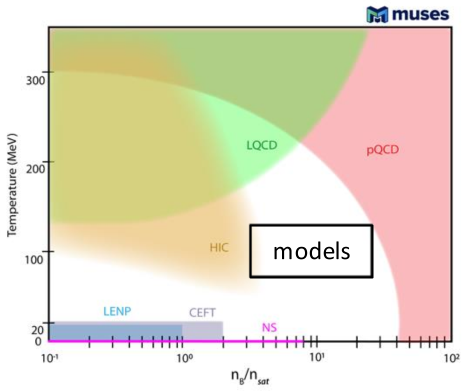
B=1.44x10^18 G for neutron-star matter

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

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

… but code takes too long to run

☆ muses cyberinfrastructure



- **M**odular **U**nified **S**olver of the **E**quation of **S**tate (EoS)
- Modular: different theories/models (modules) for the user to pick from **and modify**
- Unified: different modules are combined in different ways to ensure maximal coverage of the phase diagram
- Web-based tools and services that provide interactive interfaces to the Calculation Engine
- Job management system and a deployment system that can be reproduced in other computing environments
- EoS description modules and observable modules that link to experiments
- Developers: physicists + computer scientists working together to develop optimized software in modern programing languages + Users

☆ muses

PI and co-PIs

1. Nicolas Yunes; University of Illinois at Urbana-Champaign; **PI**
2. Jacquelyn Noronha-Hostler; University of Illinois at Urbana-Champaign; co-PI
3. Jorge Noronha; University of Illinois at Urbana-Champaign; co-PI
4. Claudia Ratti; University of Houston; co-PI and **spokesperson**
5. Veronica Dexheimer; Kent State University; co-PI

Senior investigators

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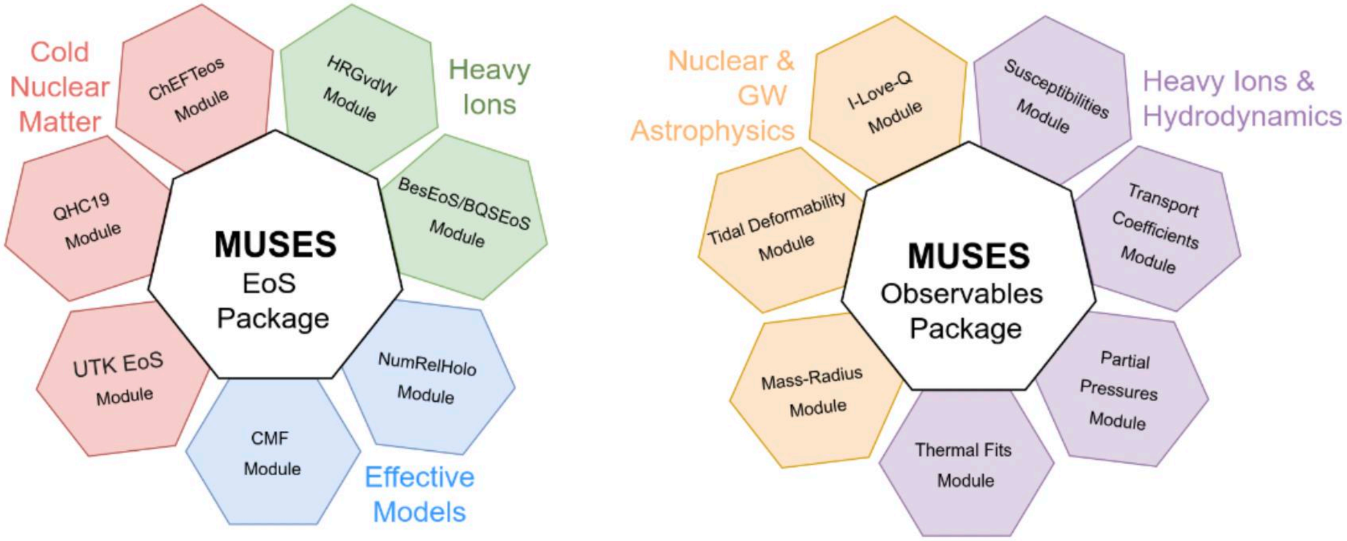
2. Roland Haas; National Center for Supercomputing Applications
3. Timothy Andrew Manning; National Center for Supercomputing Applications
4. Andrew Steiner; University of Tennessee, Knoxville
5. Jeremy Holt; Texas A&M University
6. Gordon Baym; University of Illinois at Urbana-Champaign
7. Mark Alford; Washington University in Saint Louis
8. Elias Most; Princeton University

External collaborators

Now we have 91+ collaborators

muses Modules



+ Lepton Module, Synthesis Module, Interpolator Module, …

☆ muses beta release (February 2025)

- Includes a first set of modules (free and open-source) but still preliminary
- We invite <u>everyone</u> to test these modules and provide feedback

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

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

T ~ 0
- ✓ QLIMR module: quadrupole moment, tidal Love number, moment of inertia, mass, and radius of static and slowly rotating neutron stars
- ✓ Flavor equilibration for weak **β**-equilibrium: Urca rates, relaxation rates, damping time, bulk viscosity

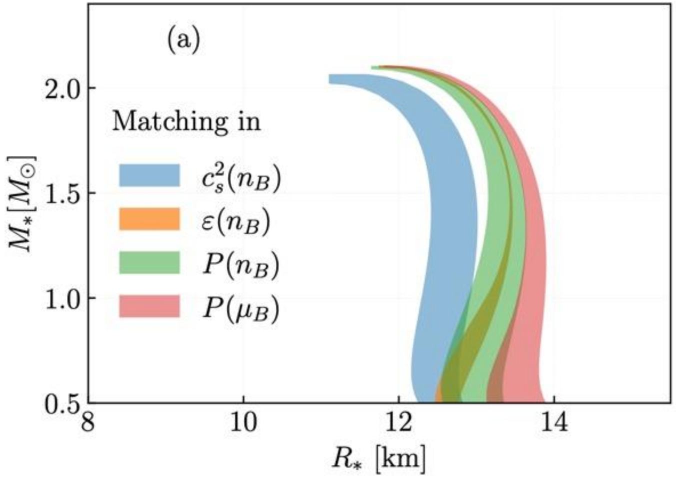
both
- ✓ Susceptibilities

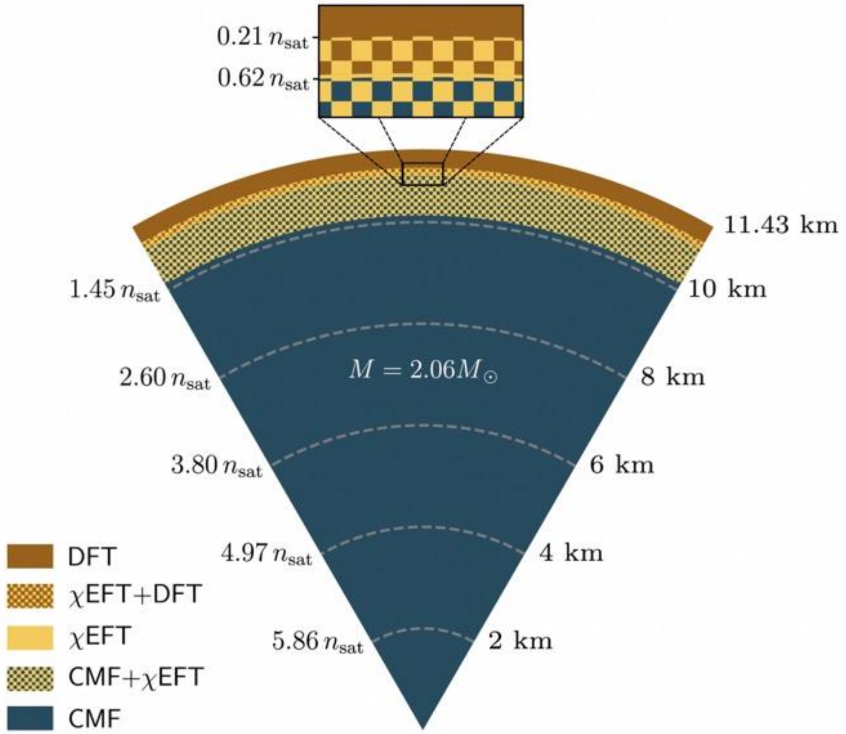
Observables

Results for a neutron-star

- Crust-DFT + χEFT + CMF
- Smooth matching using speed of sound

e-Print: [2502.07902](2502.07902)





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- Seminar series: https://musesframework.io/seminar/
- Publications: https://musesframework.io/publications/
- Forum discussions: https://forum.musesframework.io/
- Code documentation and links to module source : https://ce.musesframework.io/docs/