KENT STATE UNIVERSITY

Center for Nuclear Research

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

Veronica Dexheimer

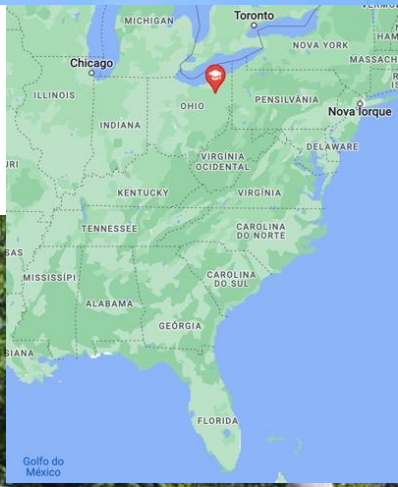
muses

NP3M

U.S. DEPARTMENT OF ENERGY

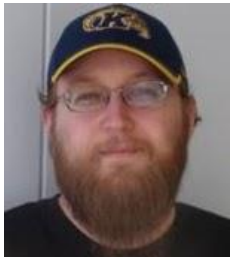
NSF

★ Kent State University



Astrophysics group

V. Dexheimer



J. Peterson

A. Clevinger

Center for Nuclear Research

R. Kumar

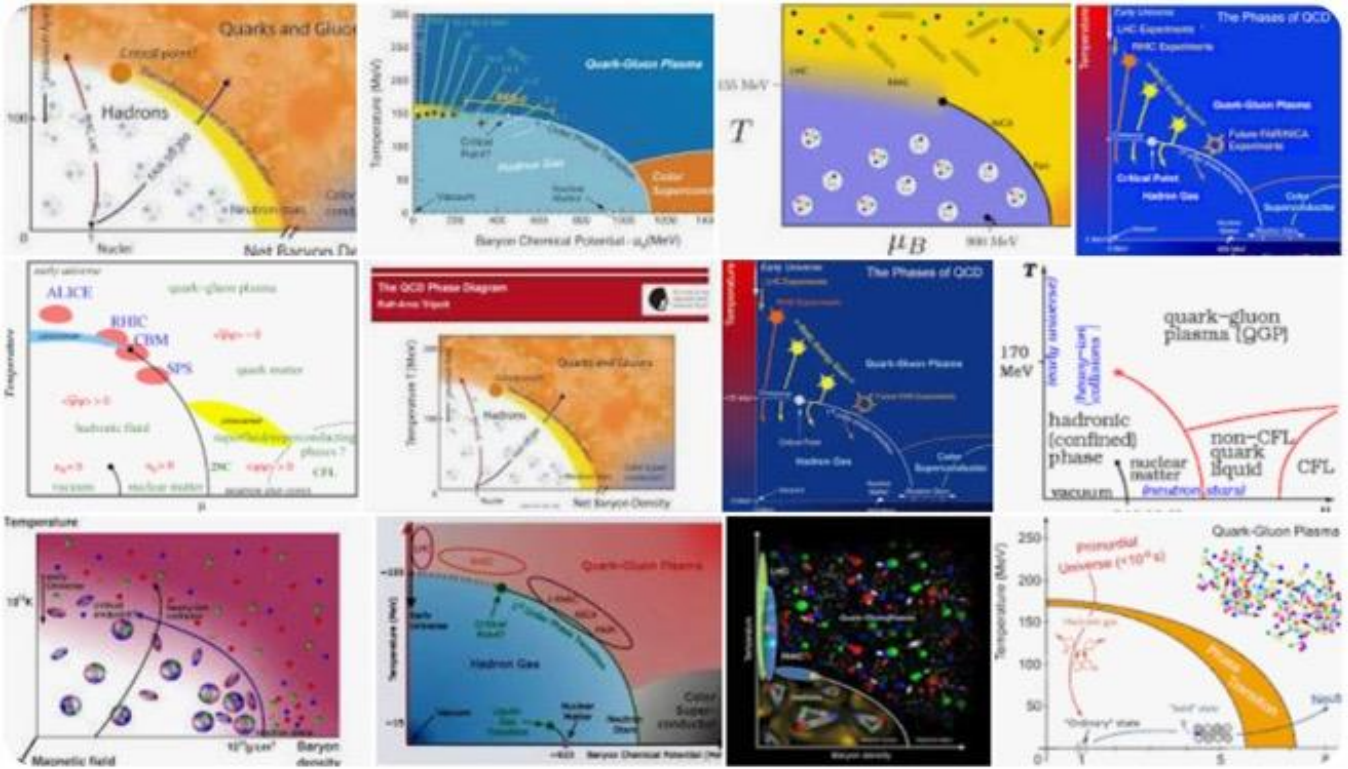
R. Jacobsen

Y. Wang

M. Pelicer

J. Grefa

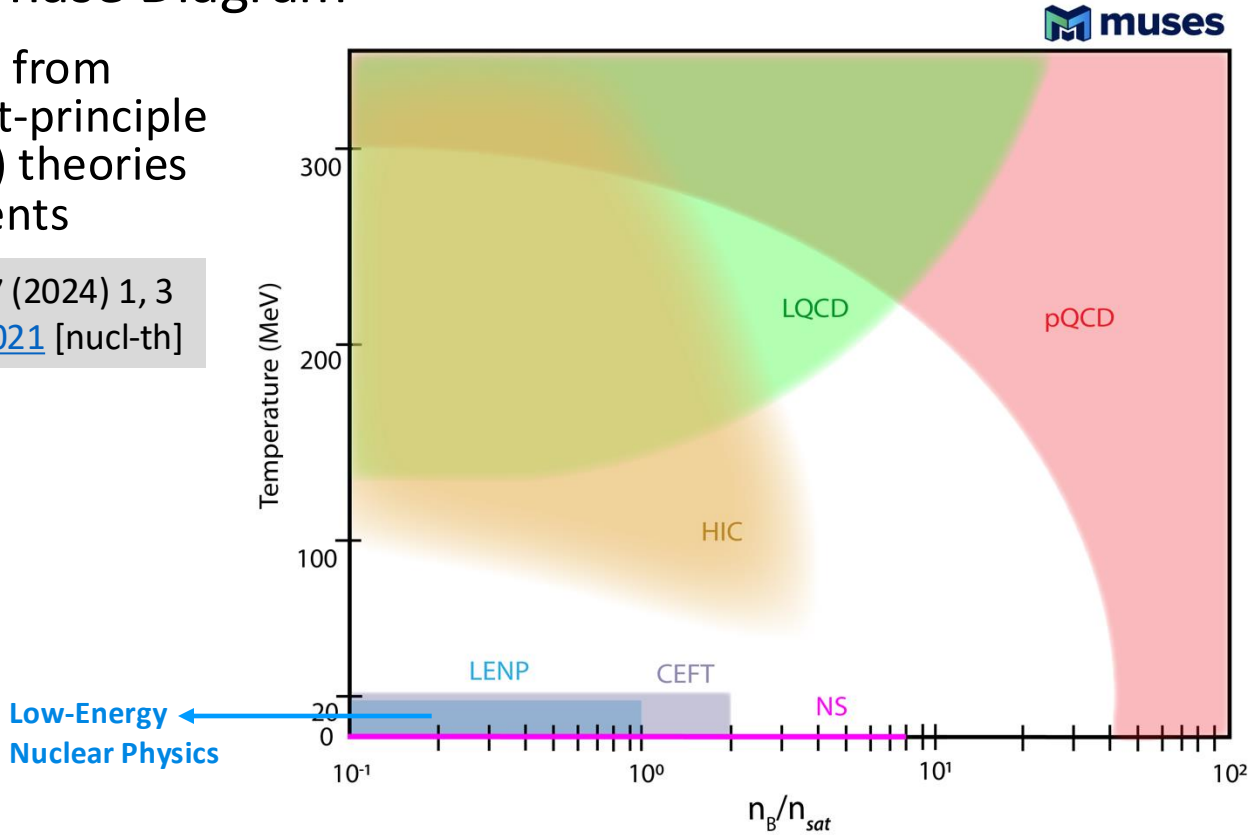
★ QCD Phase Diagrams



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 [nucl-th]



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
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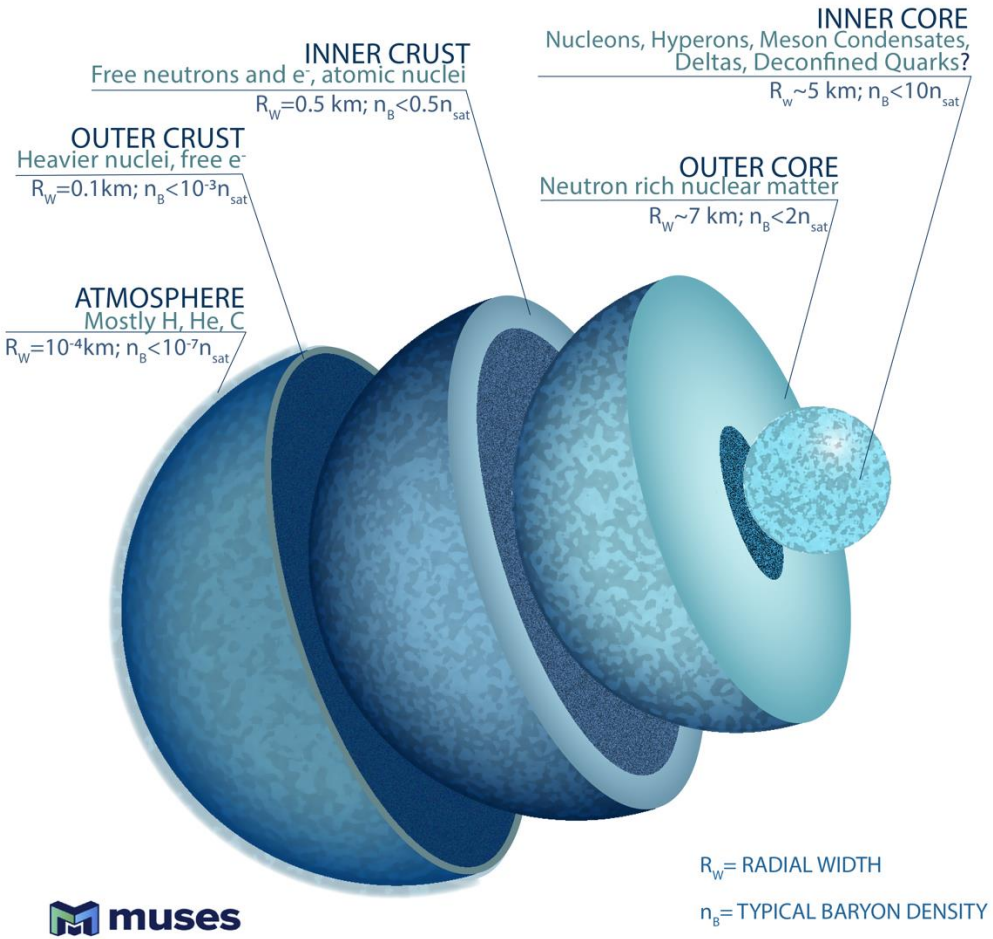

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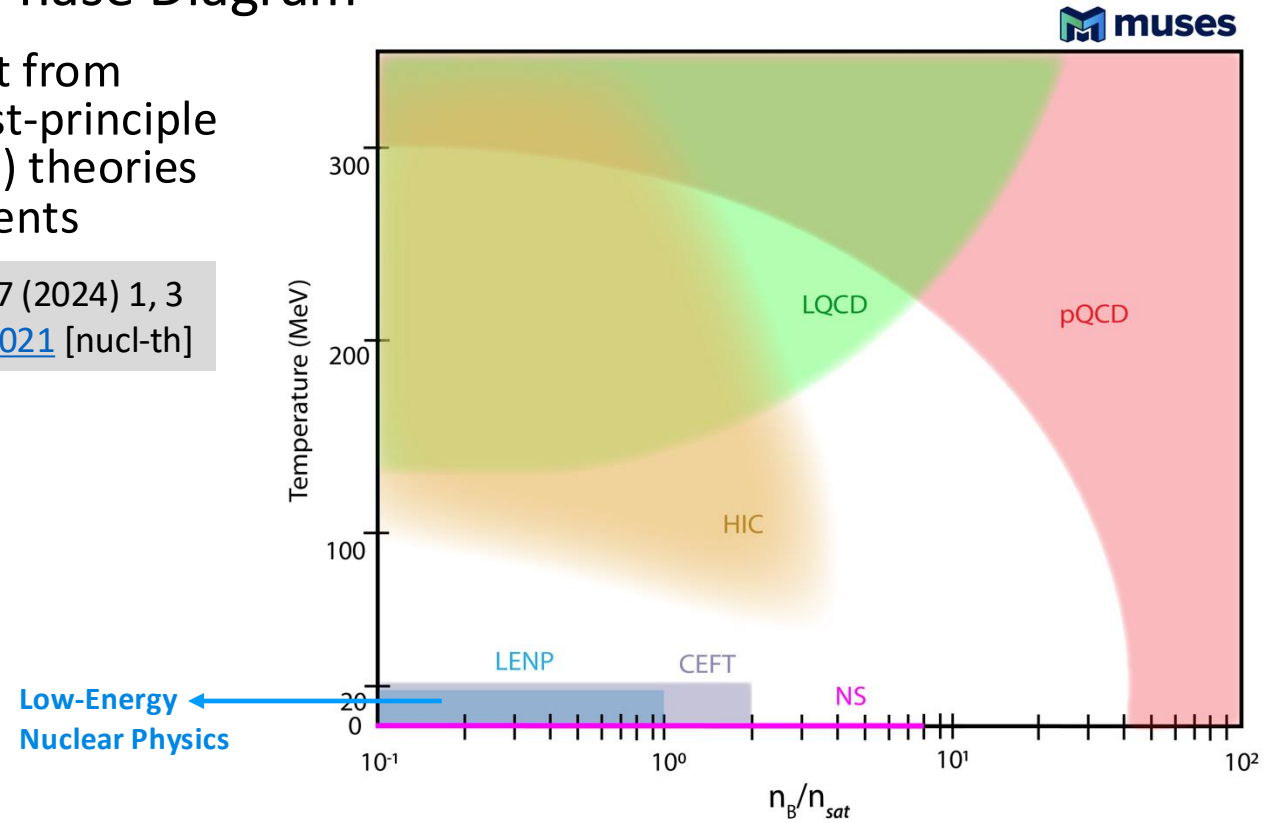
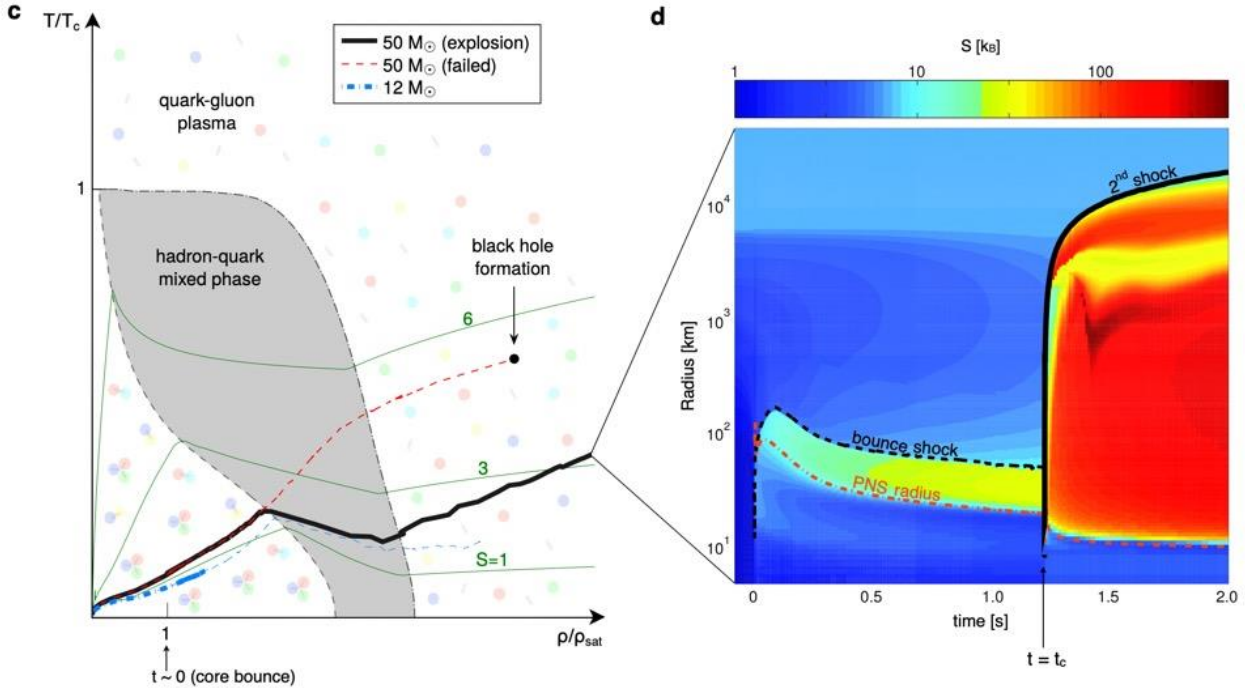


Supernovae

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

- 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 [astro-ph.HE]

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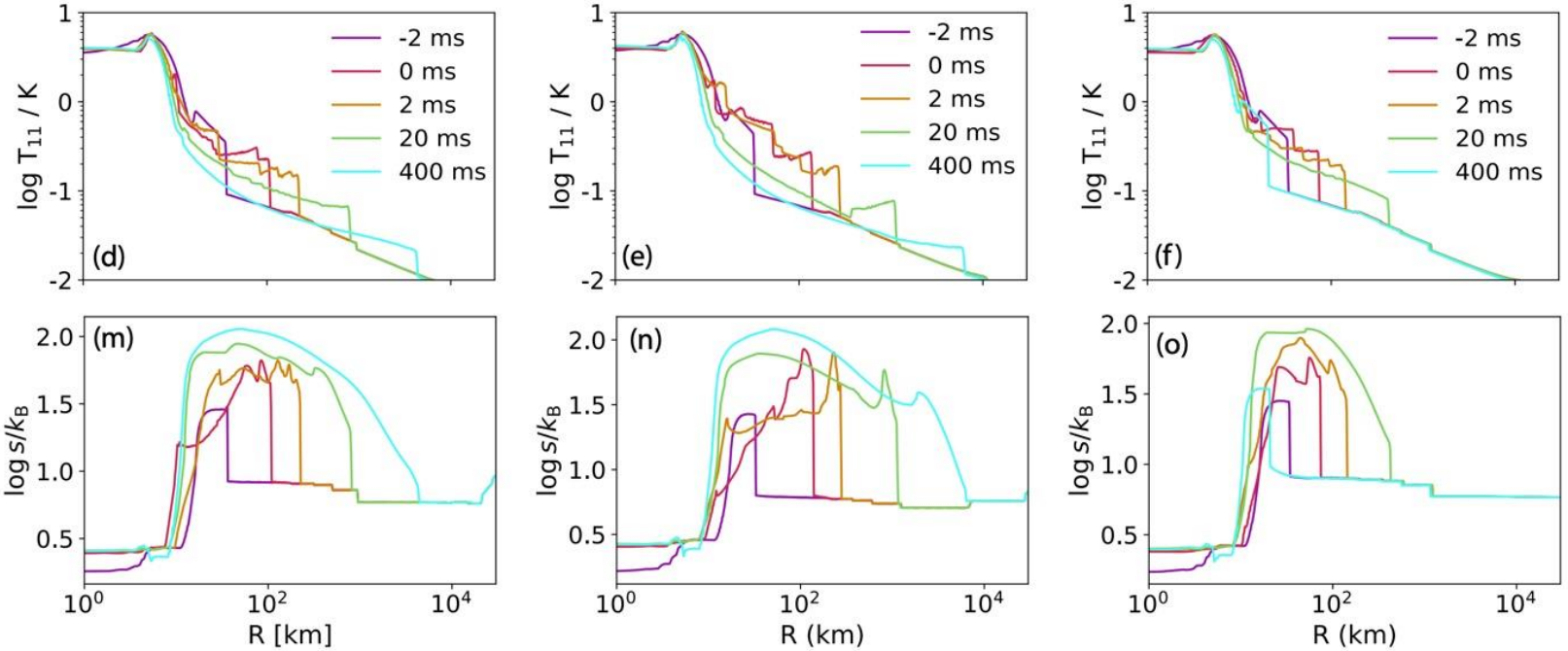
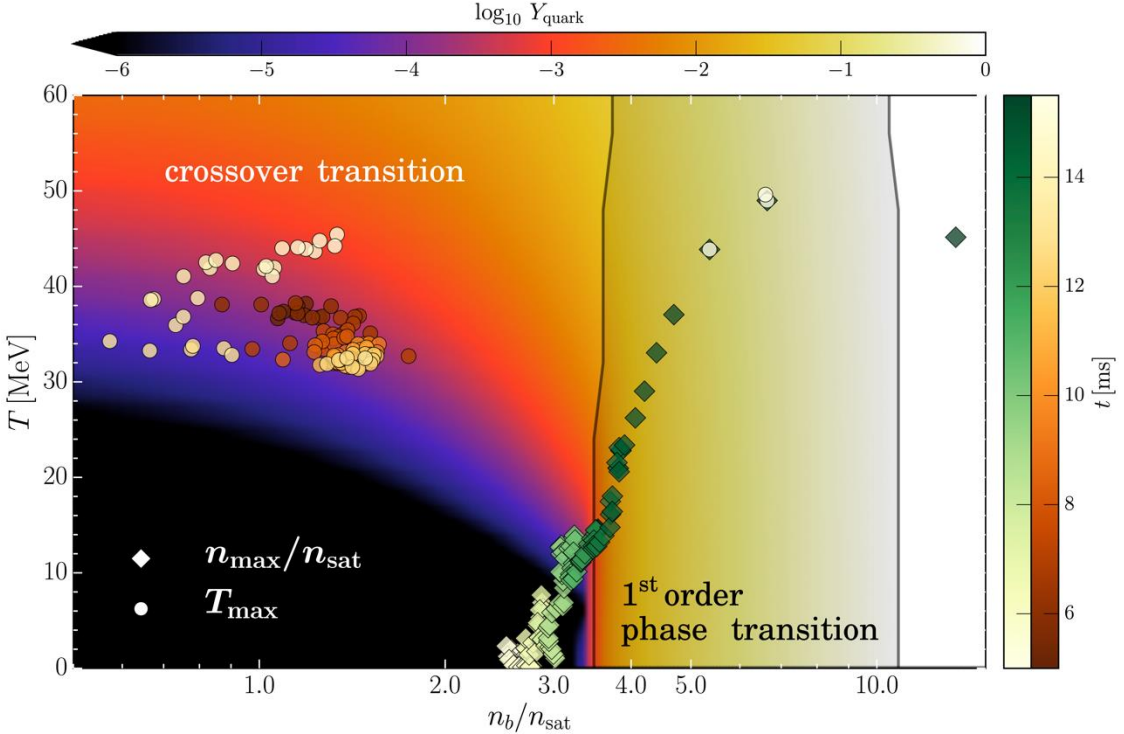


Neutron-Star Mergers

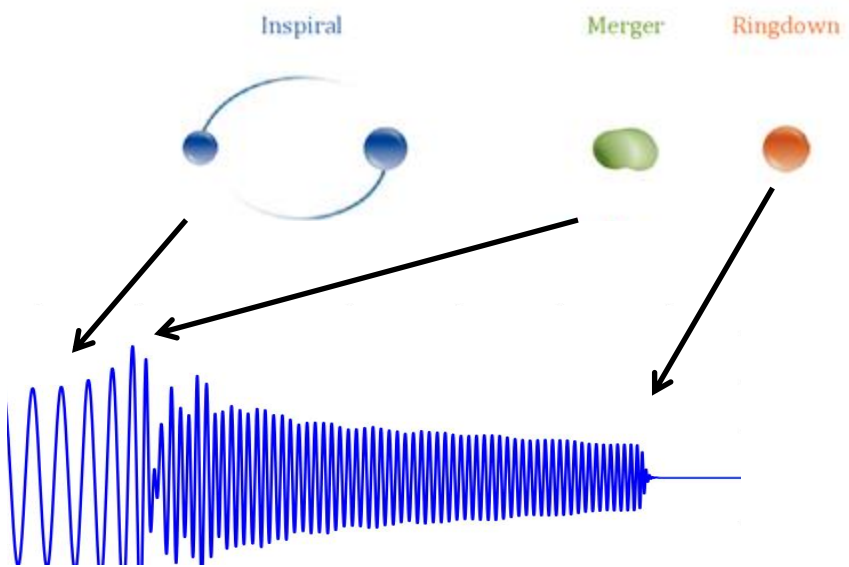
Phys.Rev.Lett. 122 (2019) 6, 061101 e-Print: 1807.03684

- Dense matter reaching temperatures of many tens of MeV



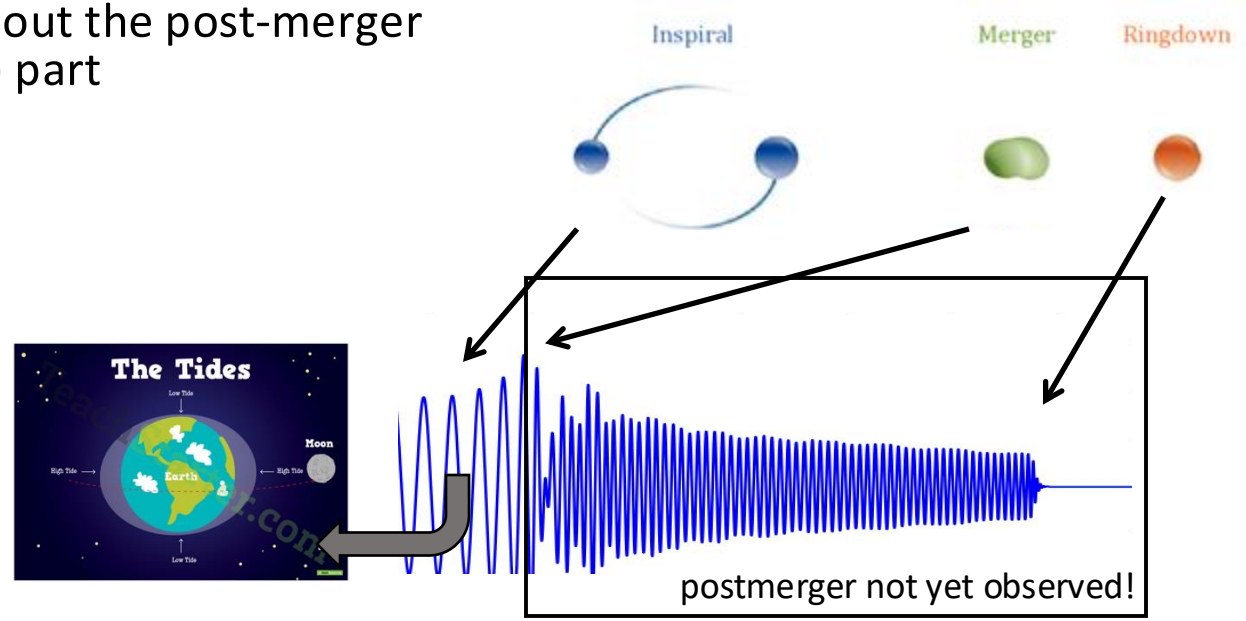
Gravitational Wave Data

- 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



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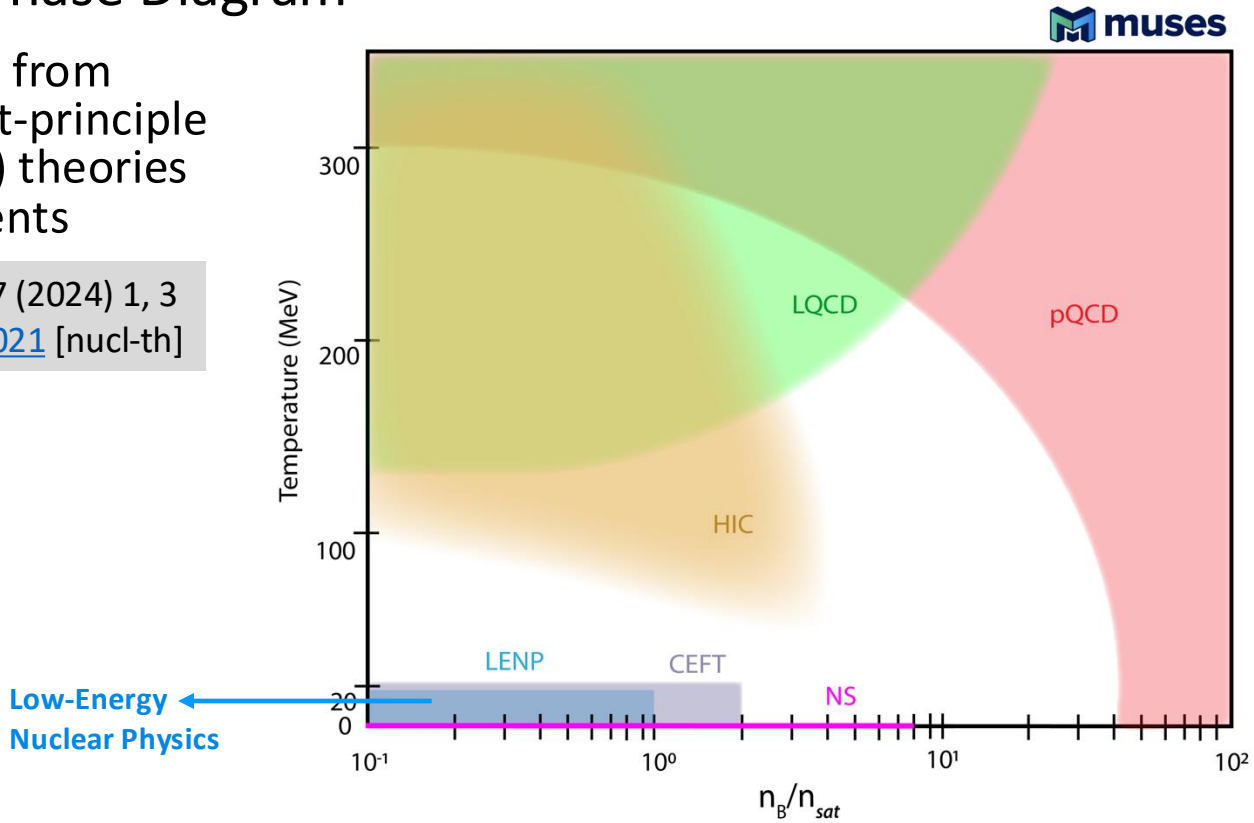


Astrophysics

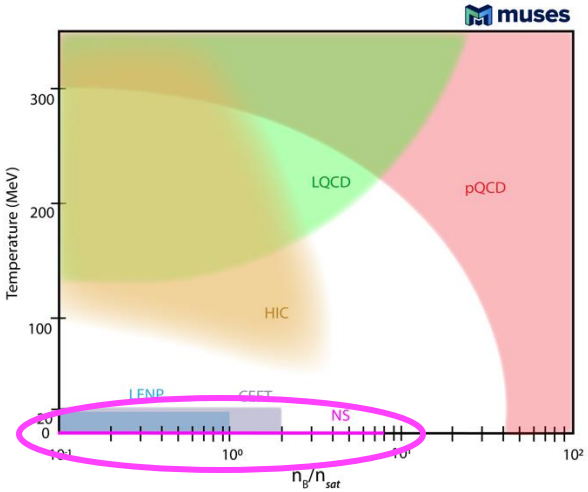
- Neutron-star maximum mass

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	$2.072^{+0.067}_{-0.066}$	$12.39^{+1.30}_{-1.98}$
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	$1.418^{+0.037}_{-0.037}$	$11.36^{+0.95}_{-0.63}$

→ $12.92 \pm ^{2.09}_{1.13}$



- 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
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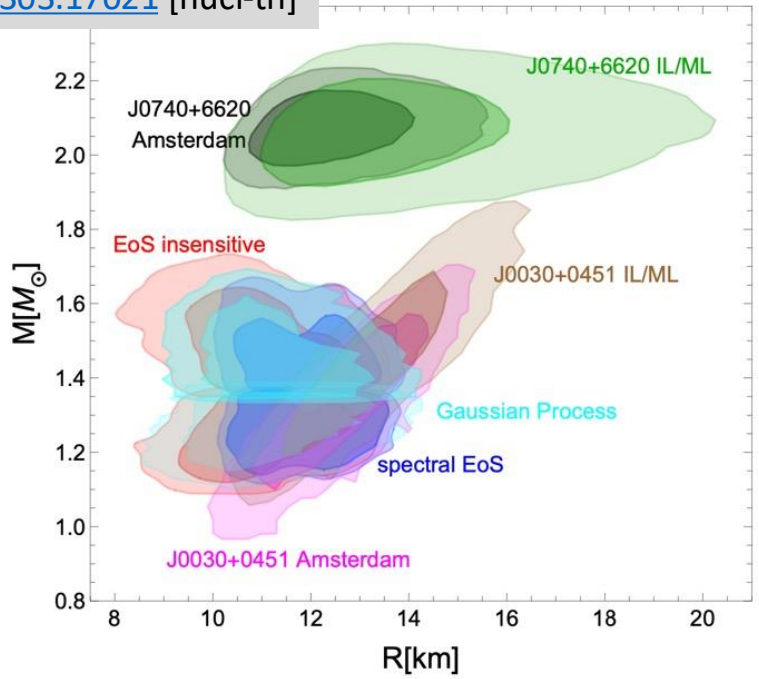

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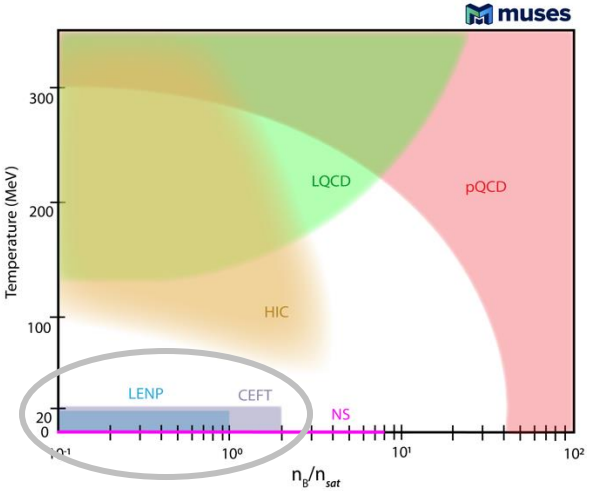
Chiral Effective Field Theory

- 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*

- 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*

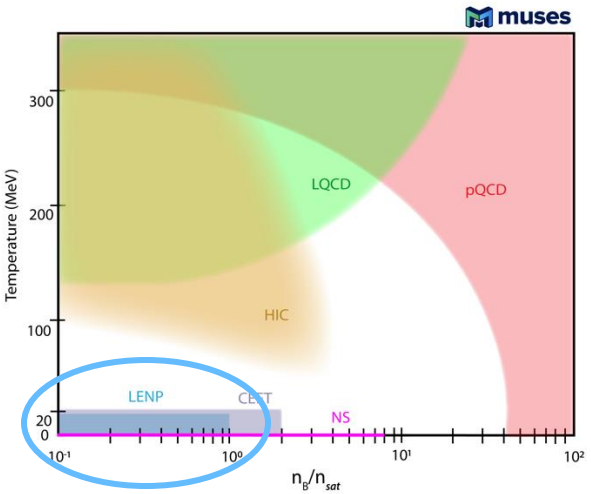


Low-Energy Nuclear Physics

- 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

Perturbative QCD

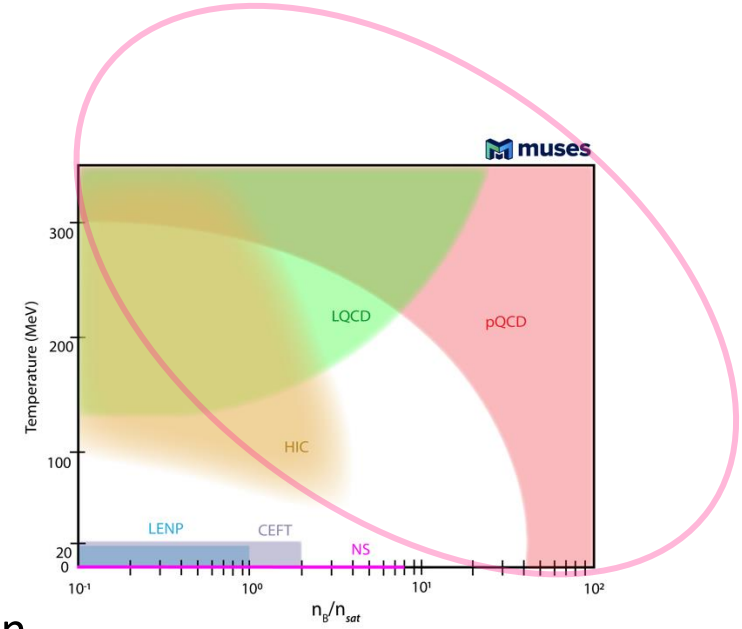
- Resummed perturbative QCD EoS calculated to N3LO using HTL perturbation theory in agreement with lattice for $T \gtrsim 2\ T_c$ at $\mu_B=0$

  JHEP 08 (2011) 053 e-Print: 1103.2528

- 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*

  (and extrapolations to lower densities)
- Transport coefficients at finite T and μ_B

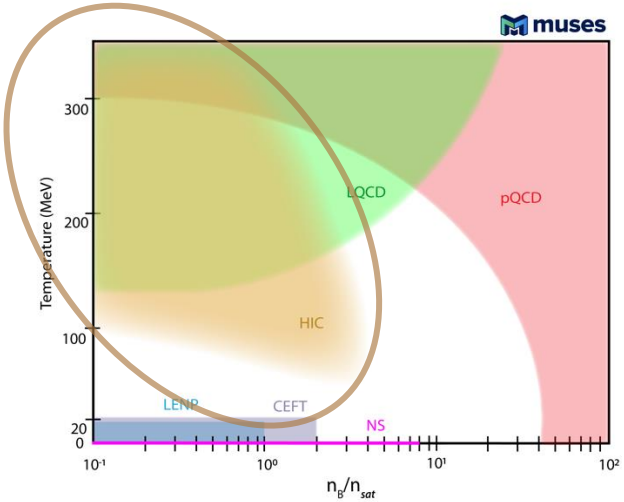


Heavy-Ion Collisions

- 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 below $\mu_B \sim 450$ MeV

  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

Lattice QCD

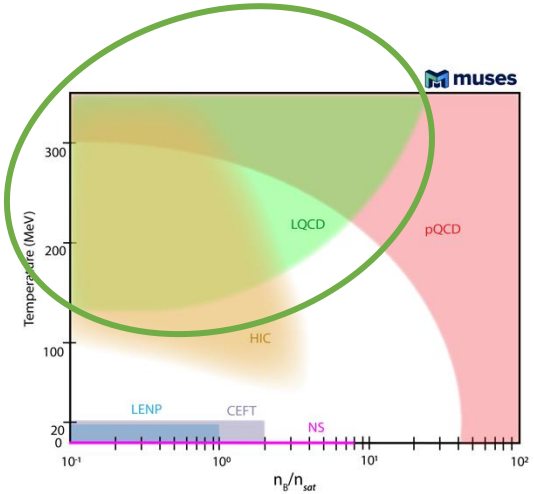
- EoS up to $\mu_B/T=3.5$ obtained from Taylor expansion

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

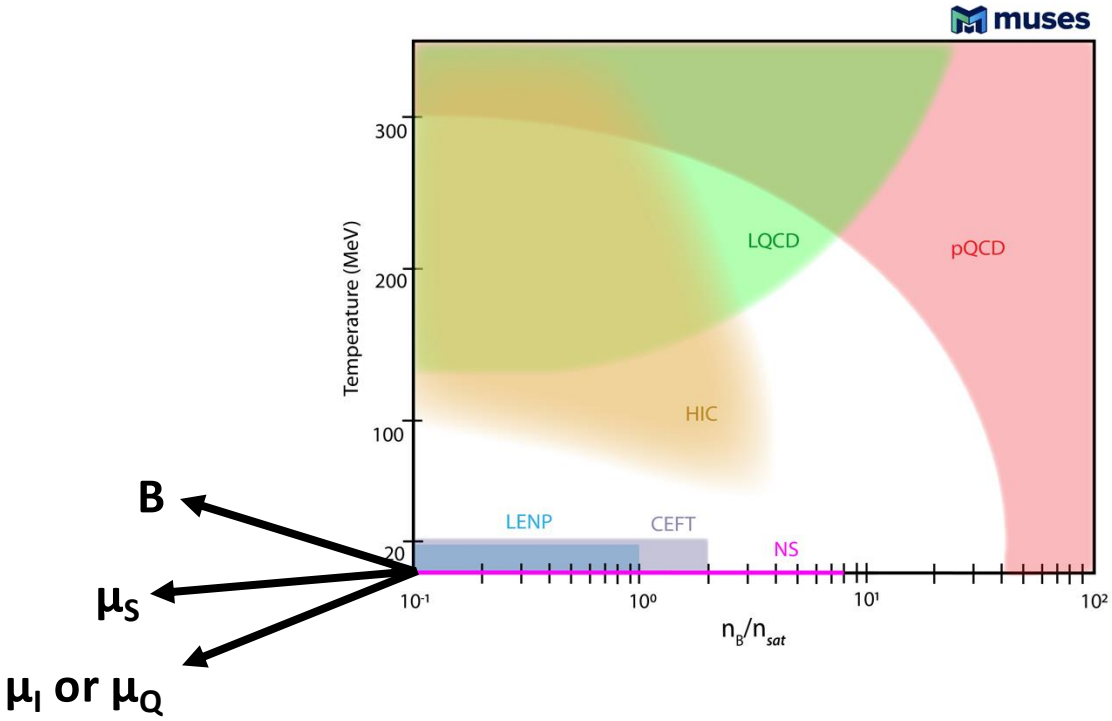
- BSQ susceptibilities
- Partial pressures (with hadronic phase treated as ideal resonance gas)
- Pseudo phase-transition line
- Limits on the critical point location $\mu_B \gtrsim 300$ MeV and $T_c \lesssim 132$ MeV.

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

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



What about More Dimensions?



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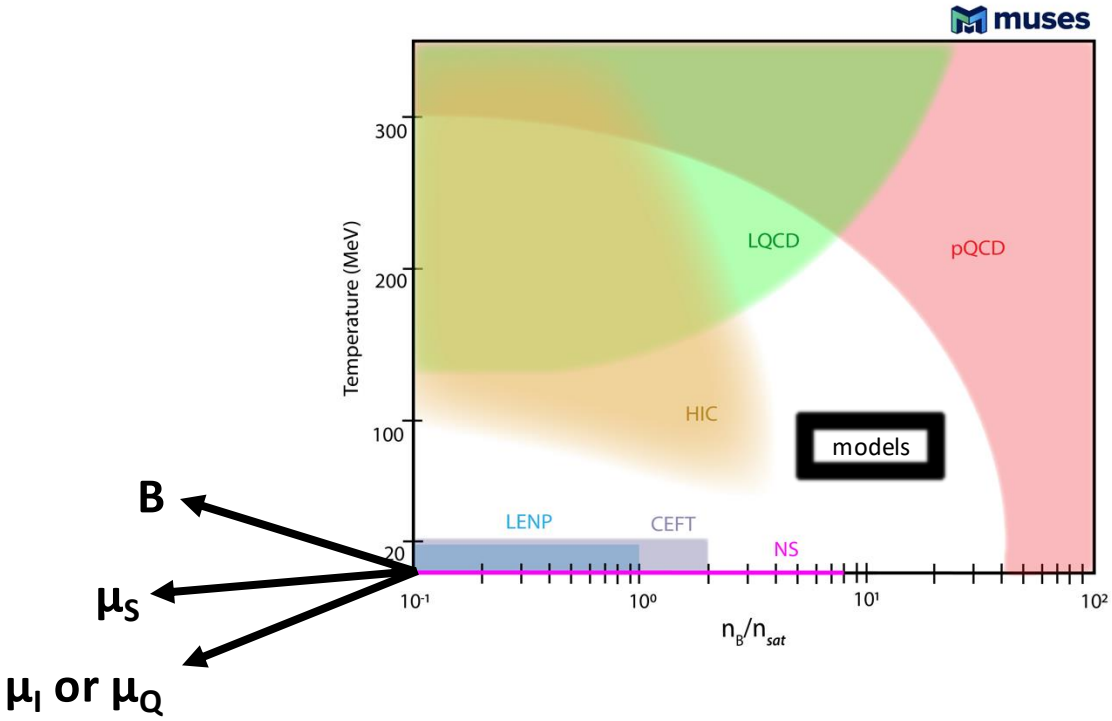
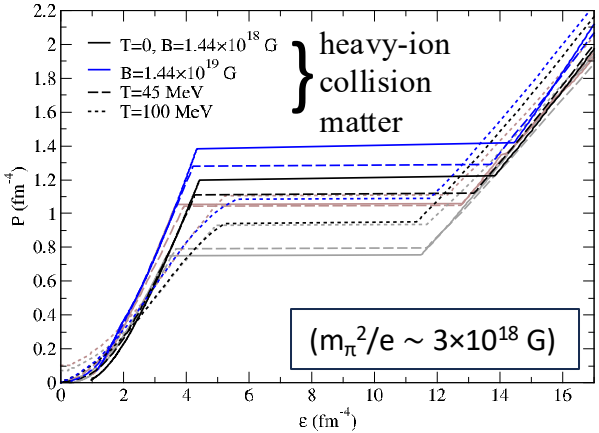


5D ~~Phase Diagrams~~ Curves

- Curves for the CMF model (with quark deconfinement)



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

- 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

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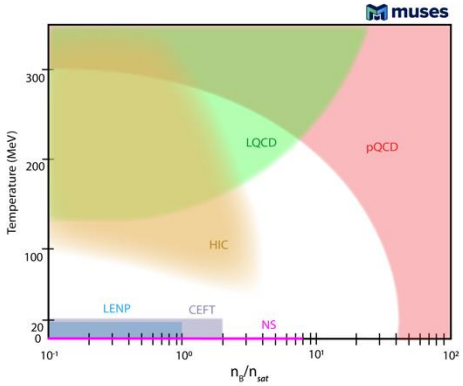

- Modular Unified Solver of the Equation of State
- Modular: while at low μ_B the EoS is known from 1st principles, at high μ_B there will be different theories and models for the user to choose from
- Unified: different modules will be merged together to ensure maximal coverage of the phase diagram
- Developers: physicists + computer scientists work together to develop the software that generates EoS's over large ranges of temperature and chemical potentials to cover the whole phase diagram
- Users: interested scientists from different communities, who provide input to the future open-source cyberinfrastructure

muses

PI and co-PIs

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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

1. Matias Carrasco Kind; National Center for Supercomputing Applications
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

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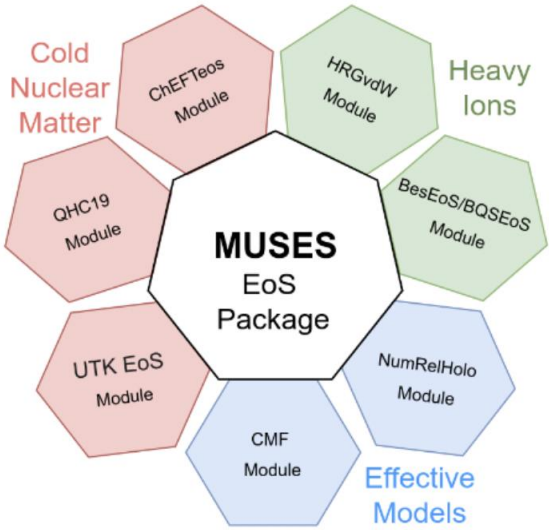
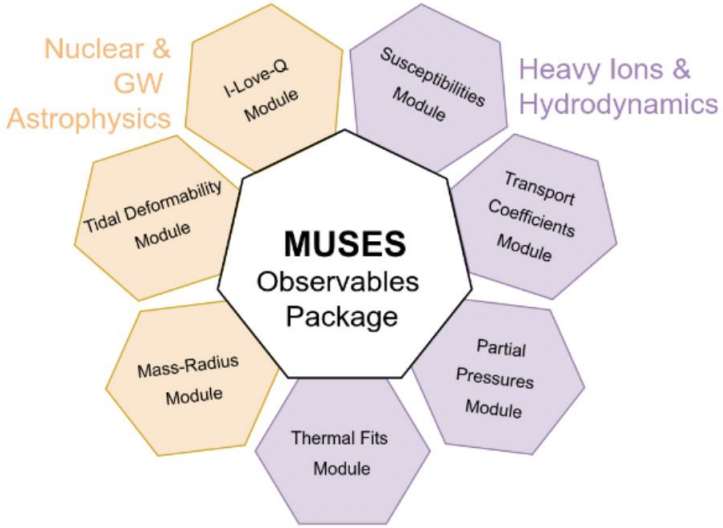
3. Katerina Chatziioannou; California Institute of Technology
4. Phillip Landry; California State University Fullerton
5. Reed Essick; Perimeter Institute
6. Rene Bellwied; University of Houston
7. David Curtin; University of Toronto
8. Michael Strickland; Kent State University
9. Matthew Luzum; University of Sao Paulo
10. Hajime Togashi; Kyushu University
11. Toru Kojo; Central China Normal University
12. Hannah Elfner; GSI/Goethe University Frankfurt

muses Modules





+ Lepton Module, Synthesis Module, Interpolator Module, …

muses Alpha-Release

- Target release: August 2024
- Includes a first set of modules
- Open-source, but still preliminary
- We invite interested people to test these modules and give us their feedback

- Alpha release online workshop
- Online tutorials tools …

Alpha-Release EoS

- 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
- CMF: 3D Chiral EoS with different orders for deconfinement
- CEFT: 2D EoS for interacting nucleons and pions
- UTK: 2D EoS including nuclei
- CompOSE compatible outputs

muses Alpha-Release Users

- Transport coefficients: thermal conductivity, baryon conductivity & diffusion, shear & bulk viscosities, …
- QLIMR module: quadrupole moment, tidal Love number, moment of inertia, mass, and radius of neutron star
- Flavor equilibration for weak β-equilibrium