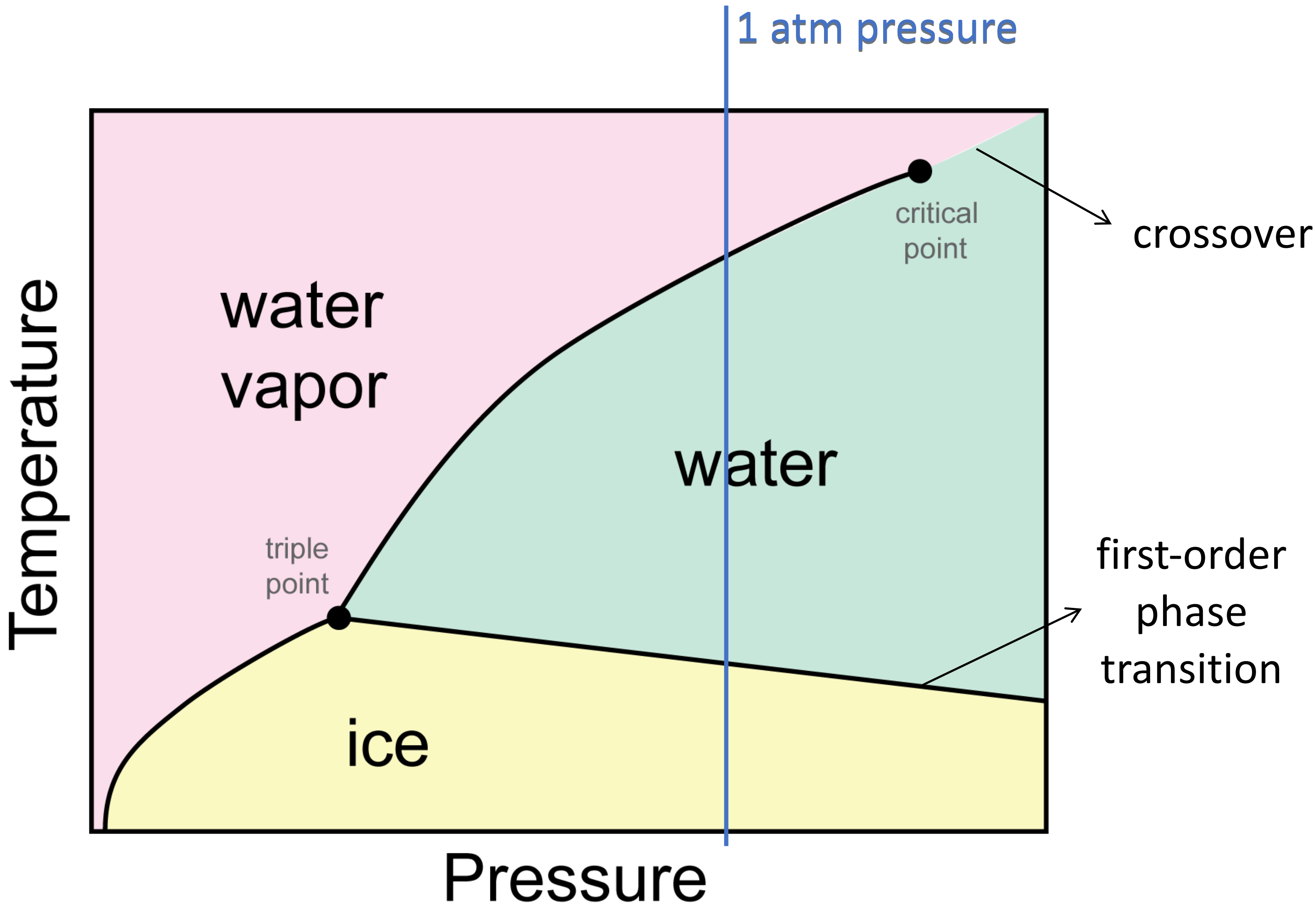
How much of the QCD phase diagram is still uncharted?

Veronica Dexheimer

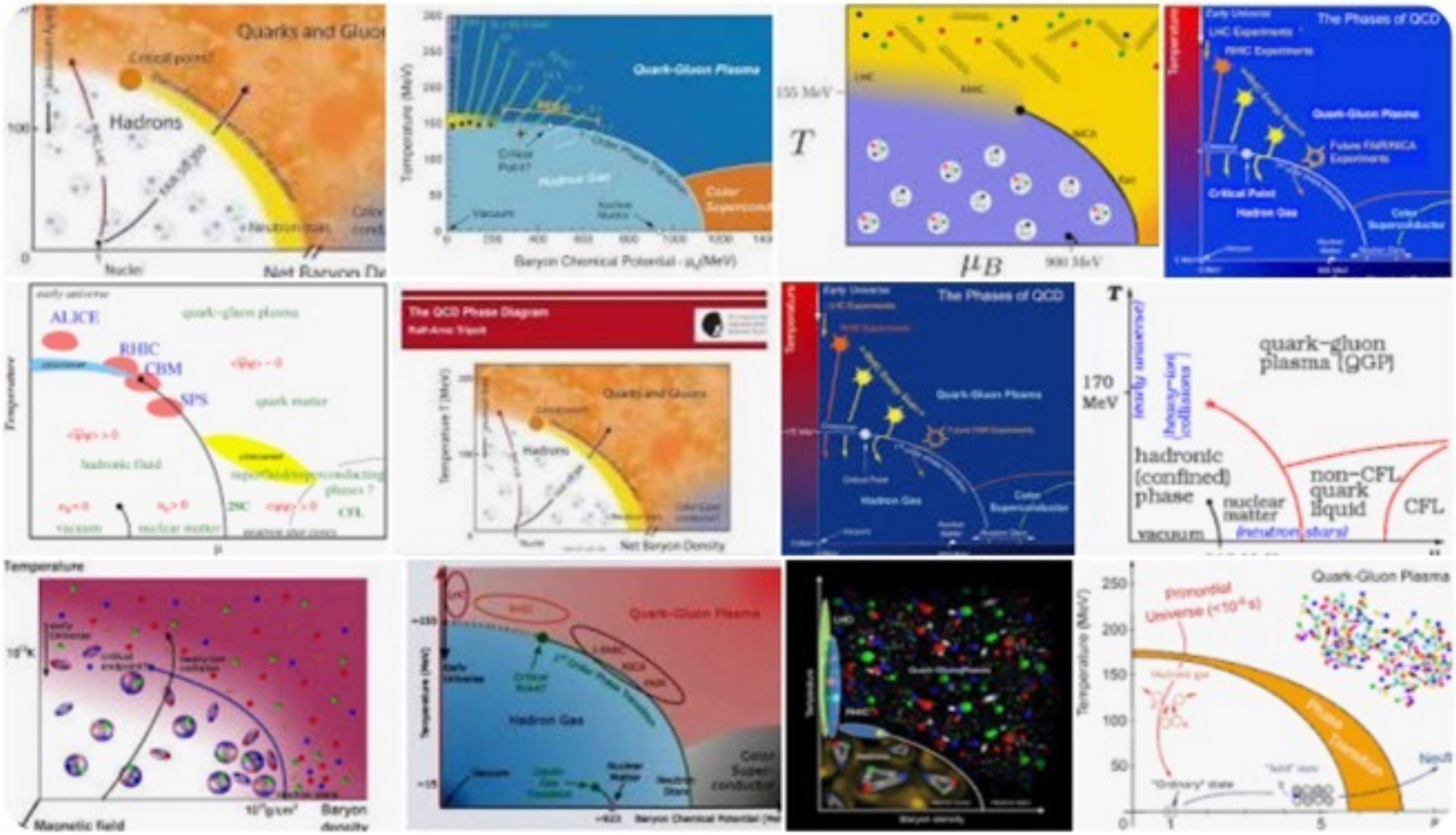
Center for Nuclear Research

KENT STATE UNIVERSITY

Phase Diagram for Water



QCD Phase Diagrams

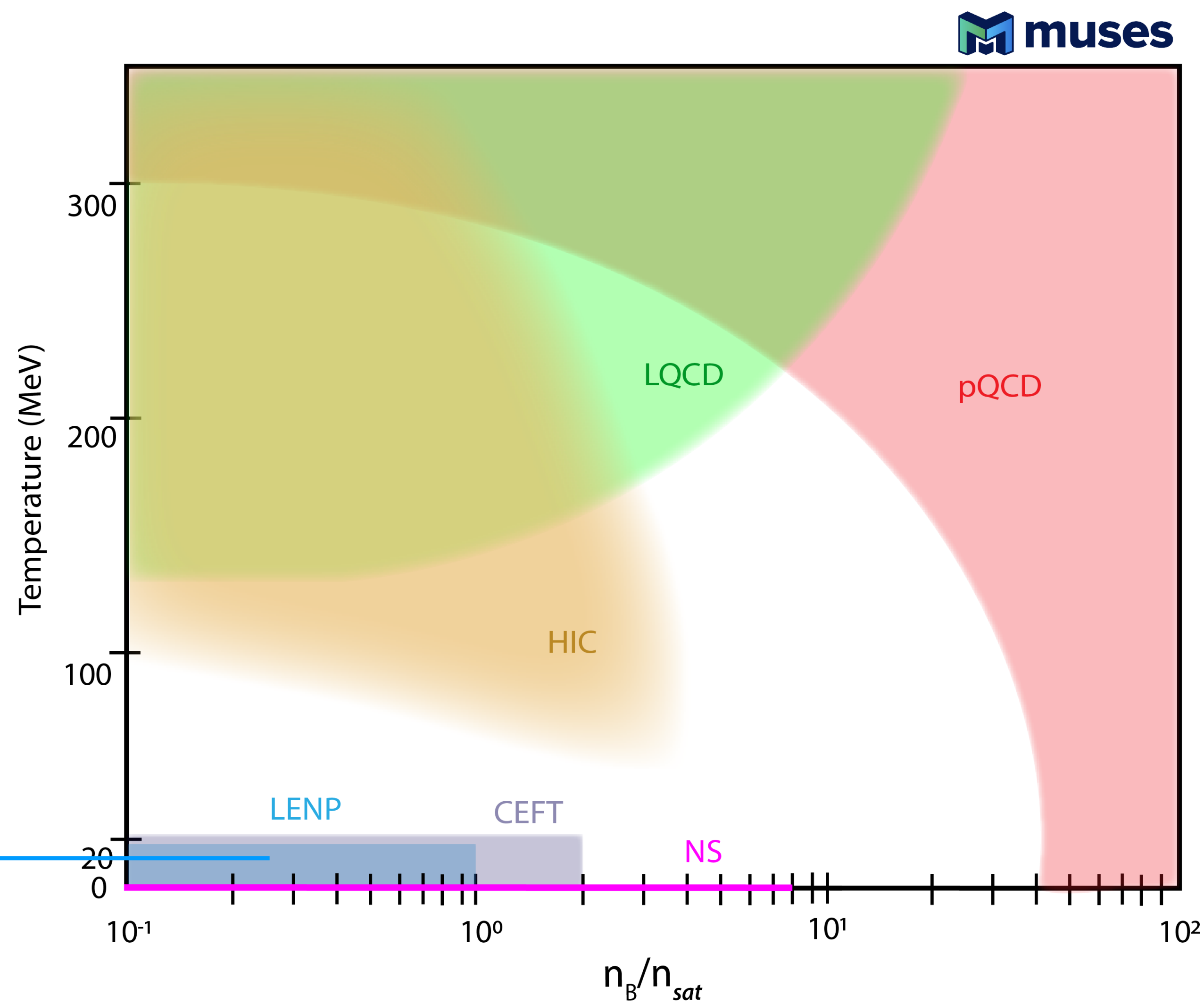


Data in the QCD Phase Diagram

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

e-Print: [2303.17021](https://arxiv.org/abs/2303.17021) [nucl-th]

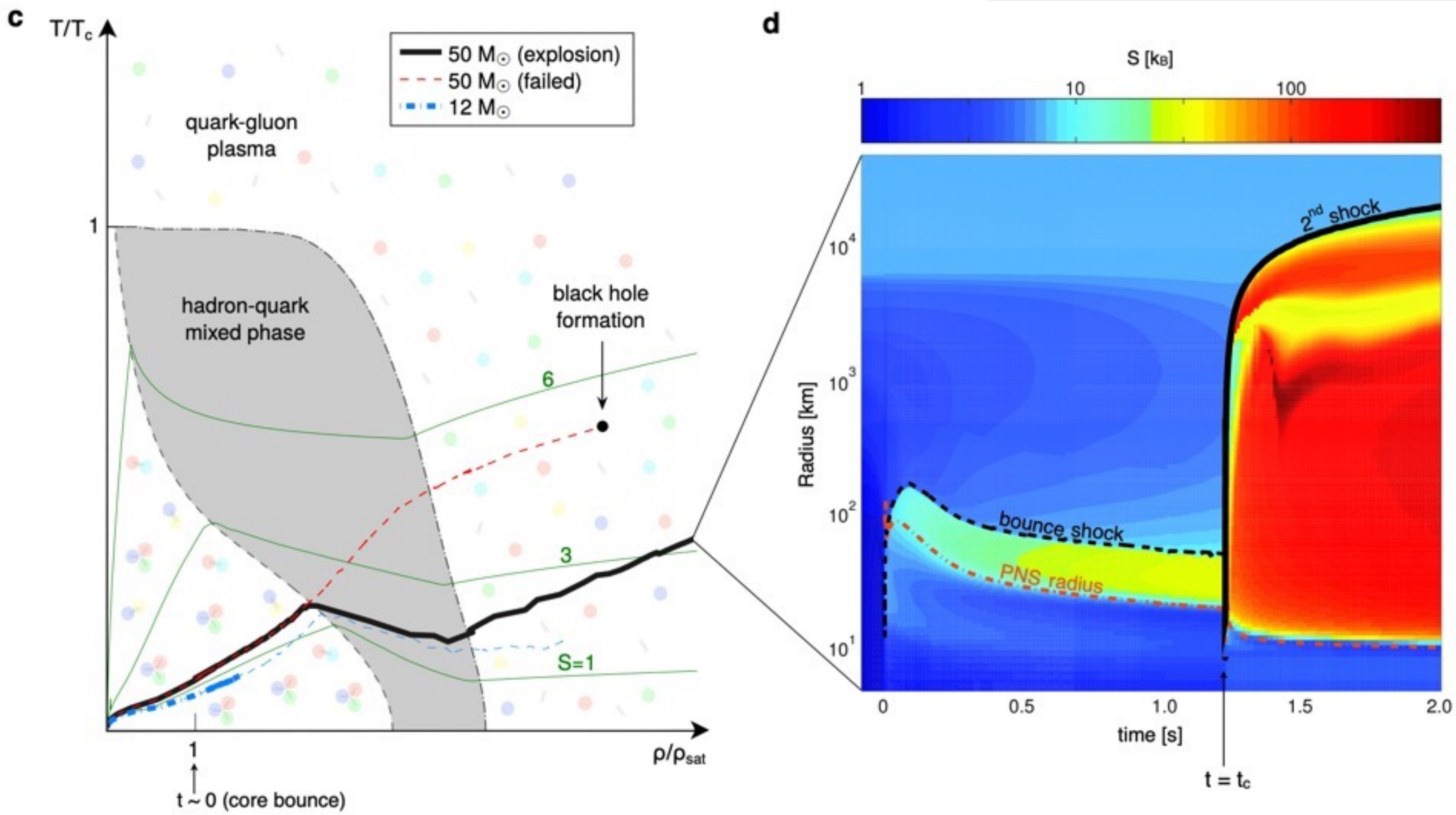
Low-Energy Nuclear Physics



Supernovae

- Dense matter reaching temperatures of a few tens of MeV

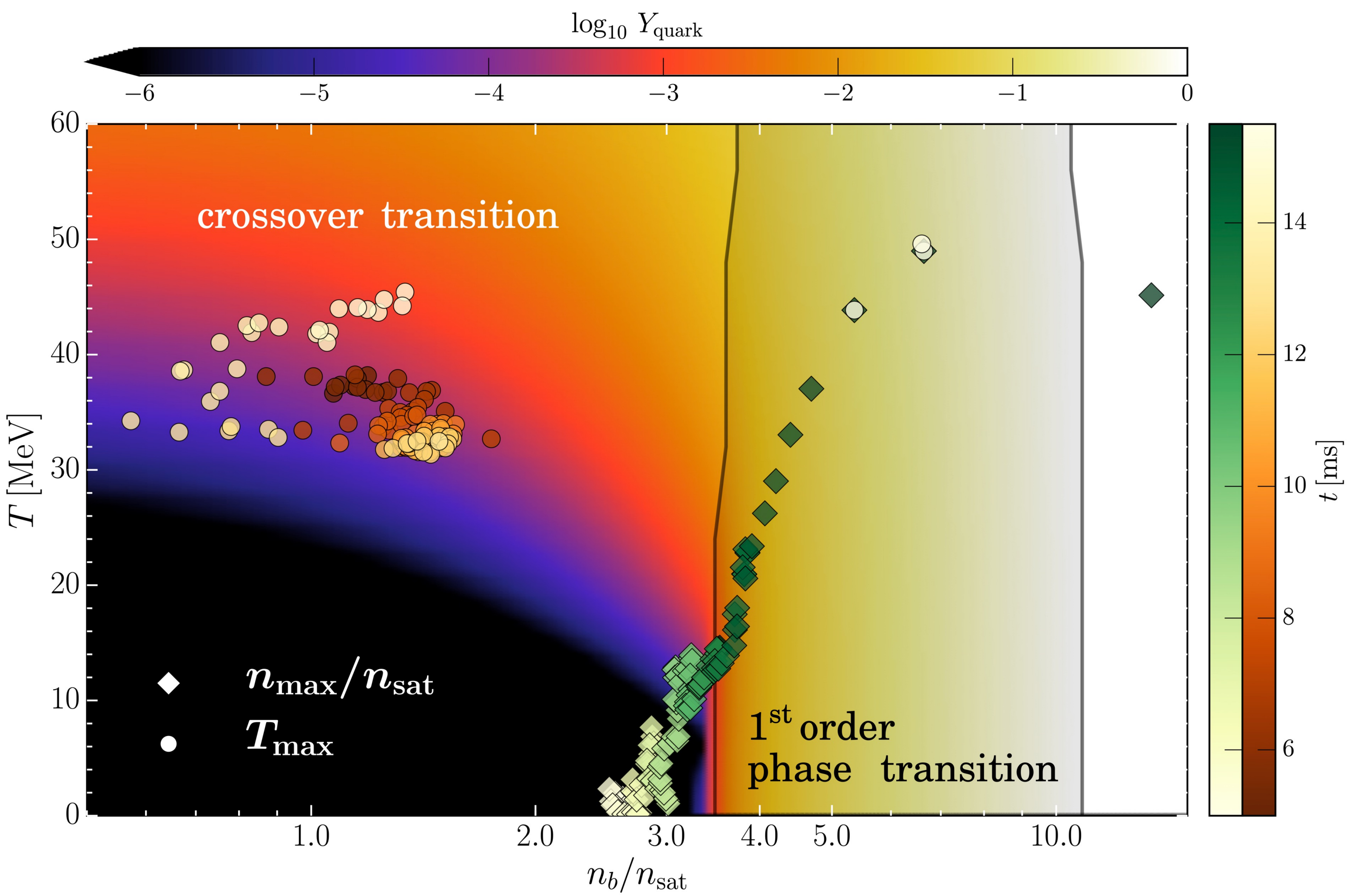
Nature Astron. 2 (2018) 12, 980-986
e-Print: 1712.08788



Neutron-Star Mergers

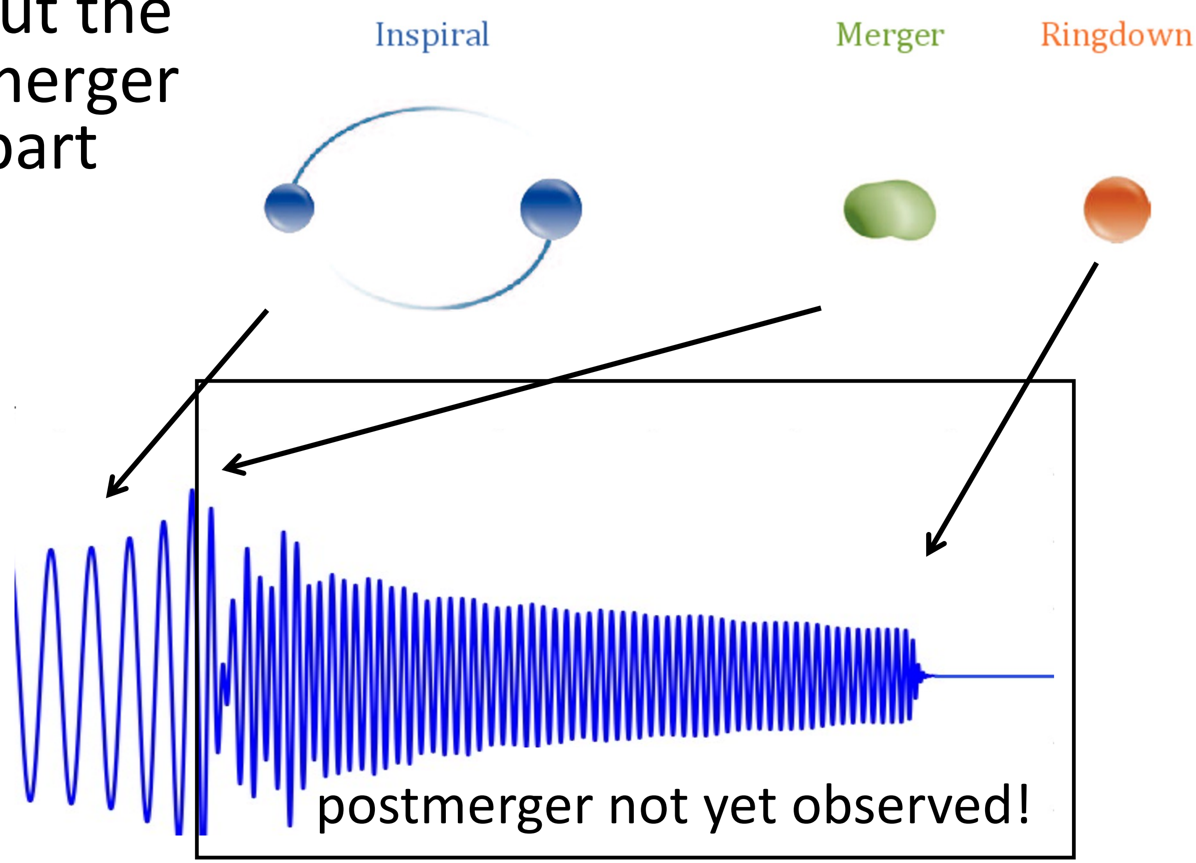
- Dense matter reaching temperatures of many tens of MeV

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



Gravitational Wave Data

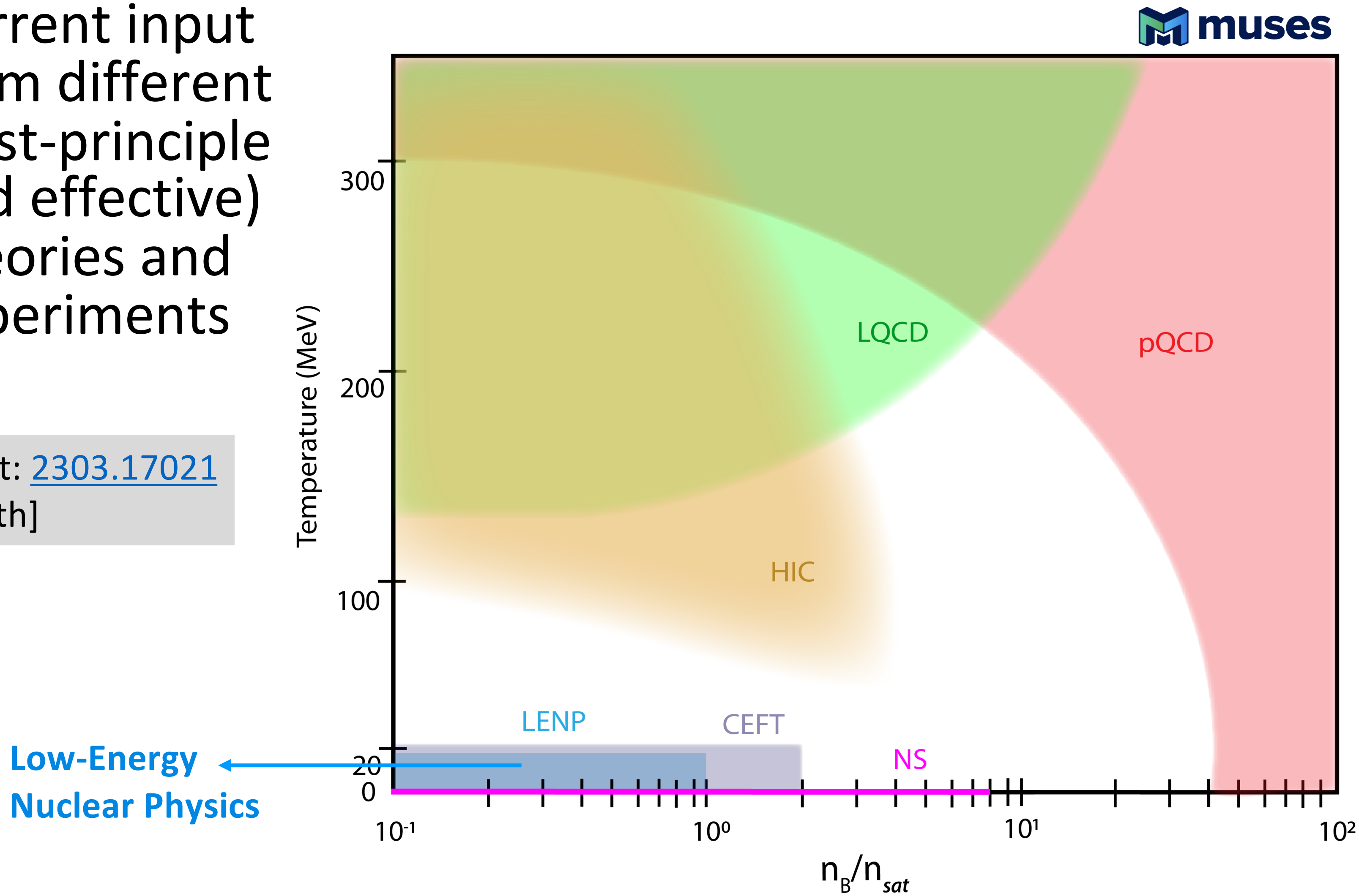
- Several measurements from neutron-star mergers but only GW170817 provided electromagnetic counterparts and a relevant measurement of the tidal deformability
- Without the post-merger (hot) part



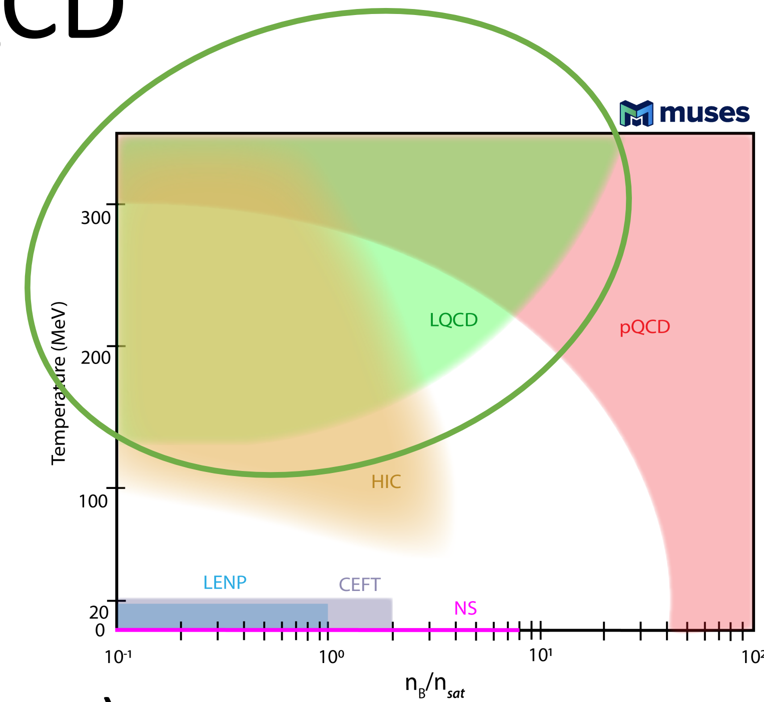
Data in the QCD Phase Diagram

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

e-Print: [2303.17021](https://arxiv.org/abs/2303.17021) [nucl-th]



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.

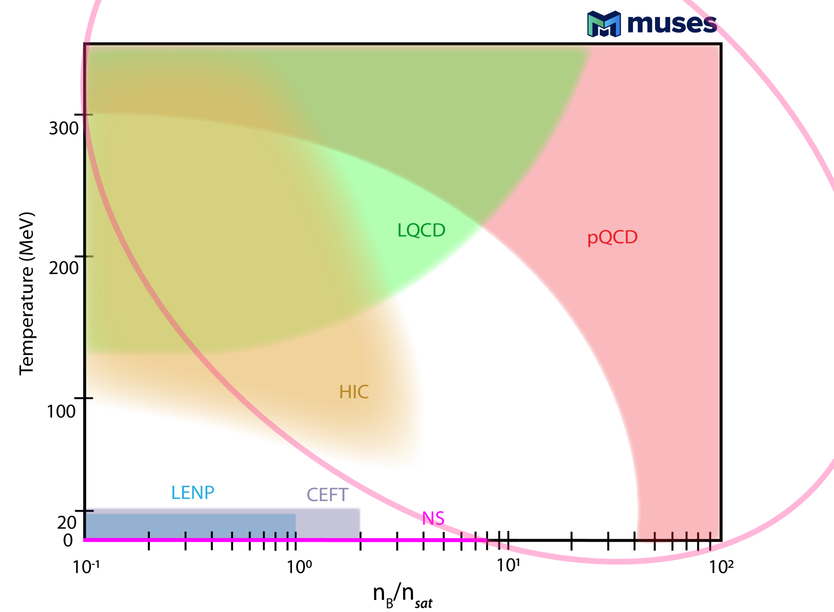
Phys.Rev.Lett. 125 (2020) 5, 052001
e-Print: [2002.02821](2002.02821)

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



- 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*

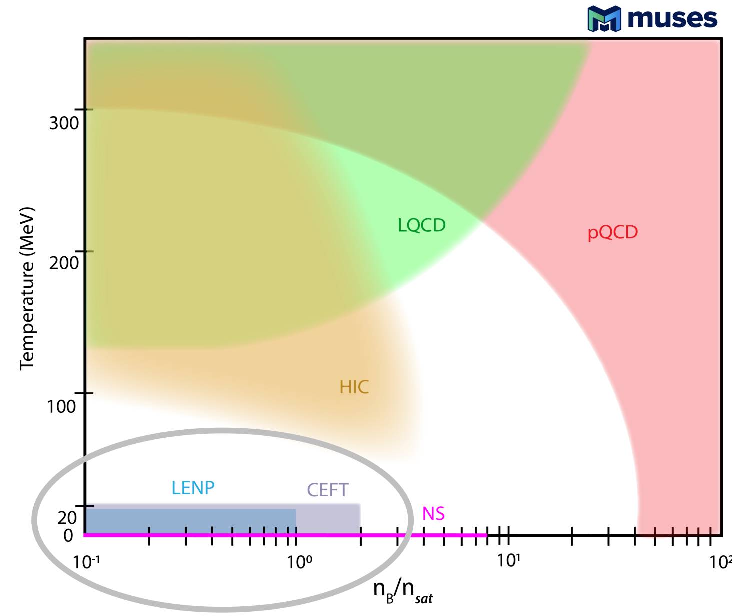
(and extrapolations to lower densities)

- Transport coefficients at finite T and μ_B

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}

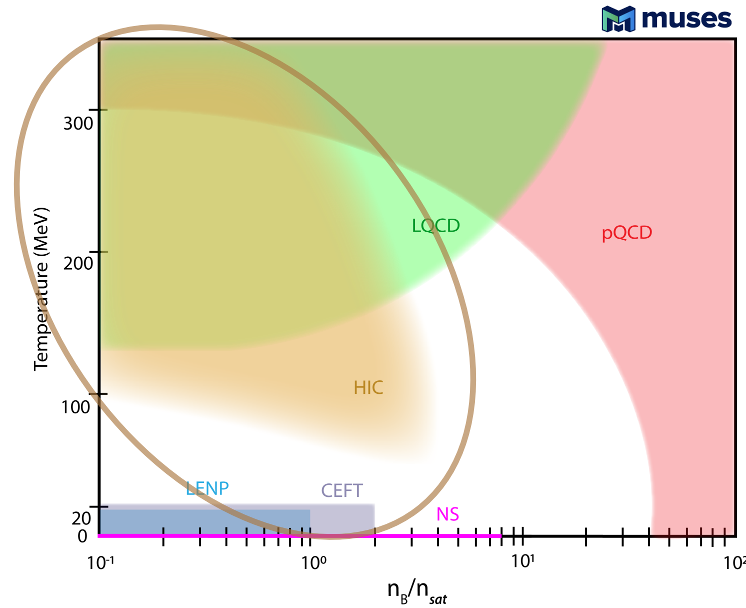
Ann.Rev.Nucl.Part.Sci. 71 (2021) 403-432
e-Print: [2101.01709](2101.01709)



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

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

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*

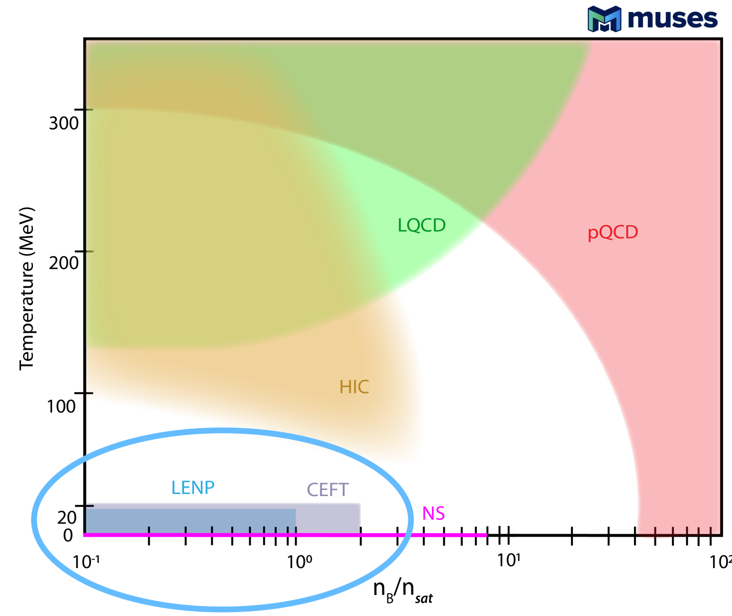
- Flow harmonics e-Print: 2209.04957
- Hanbury Brown–Twiss (HBT) interferometry

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

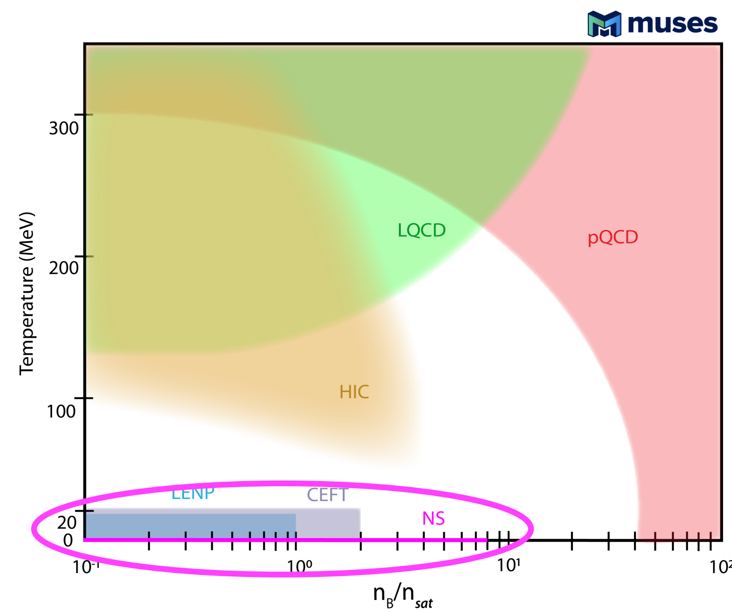
Astrophysics

* Neutron-star maximum mass

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

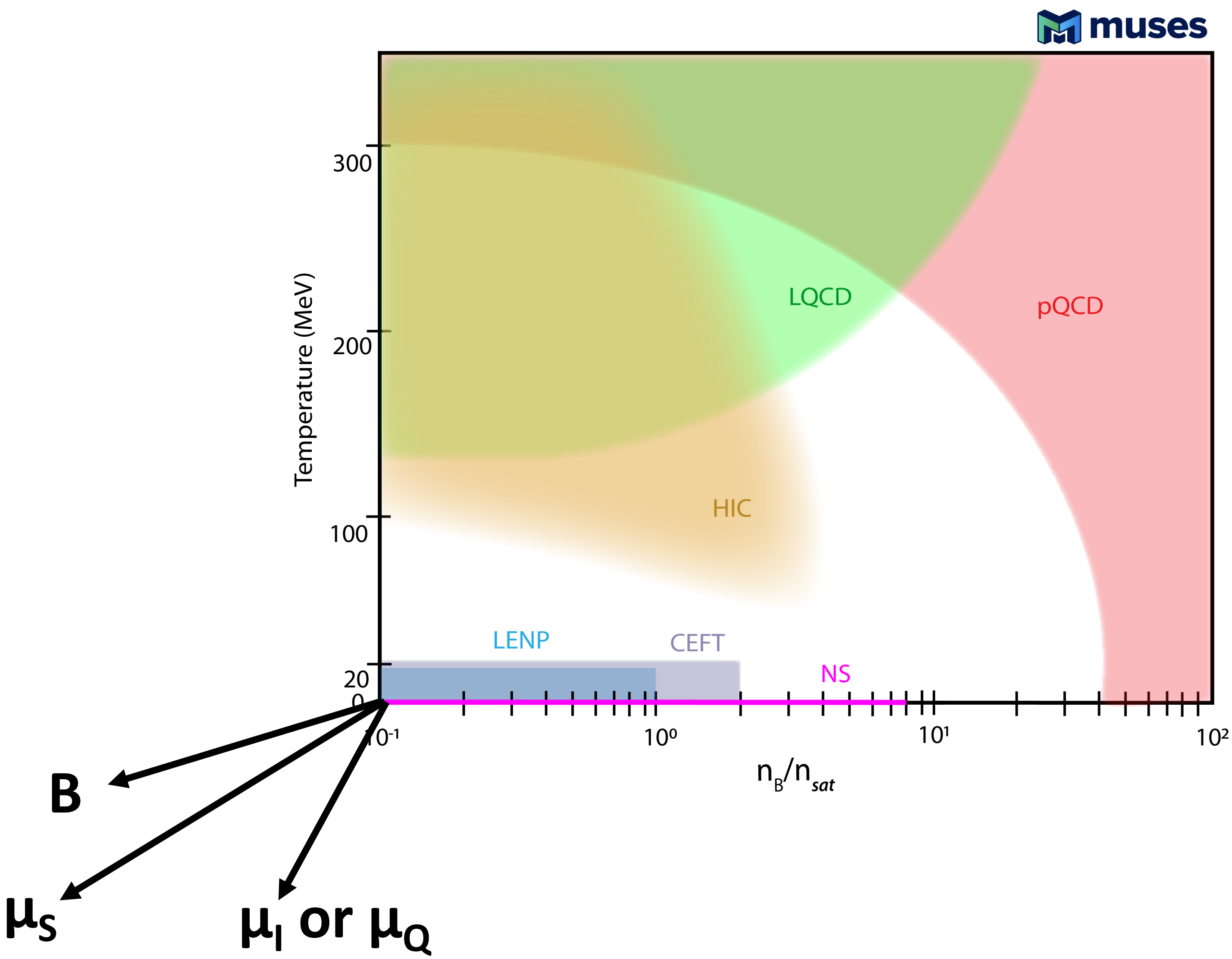
* Masses and radii from NICER

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	$2.08^{+0.07}_{-0.07}$	$13.7^{+2.6}_{-1.5}$

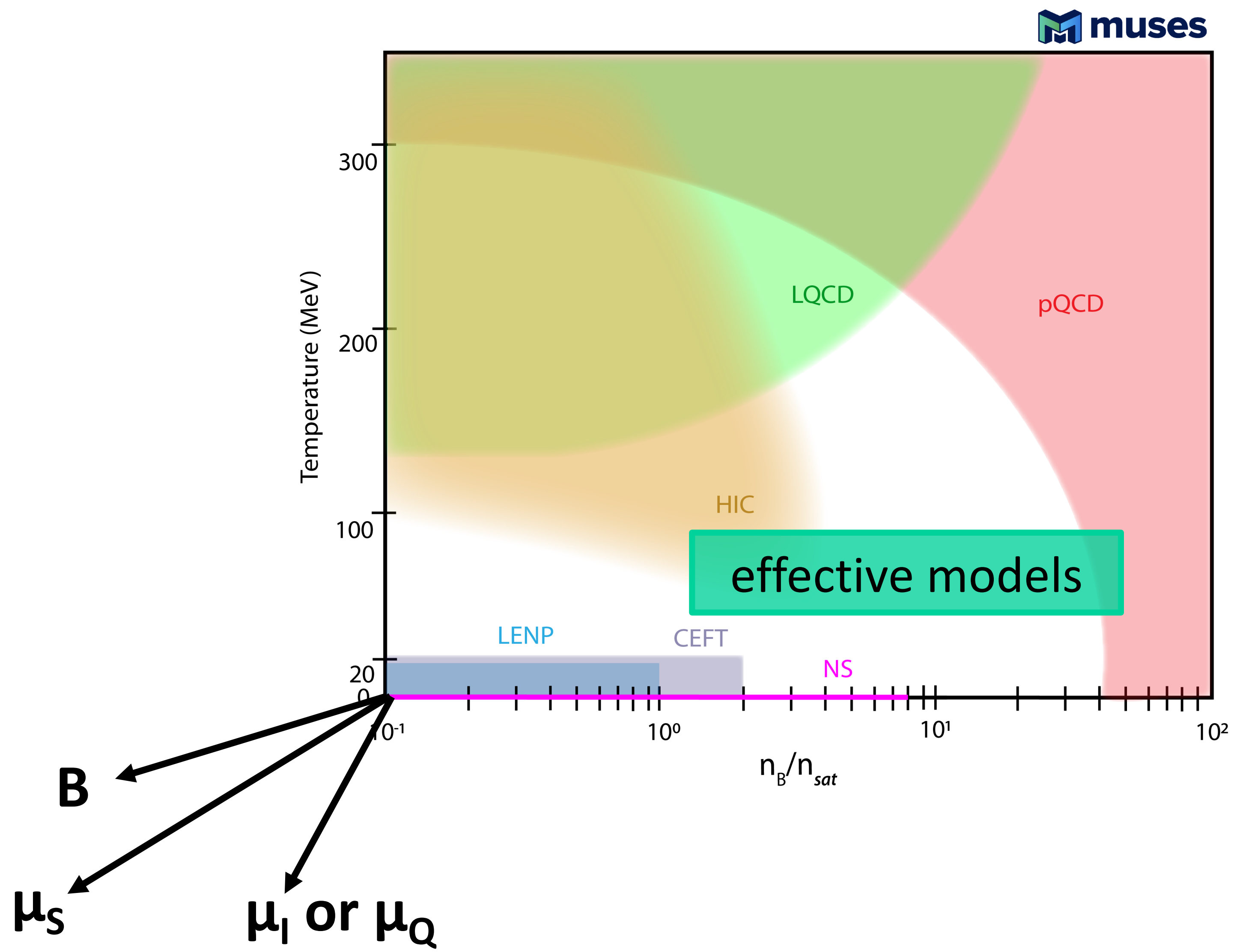


* Other observational constraints on neutron star masses and radii (quiescent low-mass X-ray binaries ...)
* Neutron-star tidal deformability from gravitational waves

What about More Dimensions?

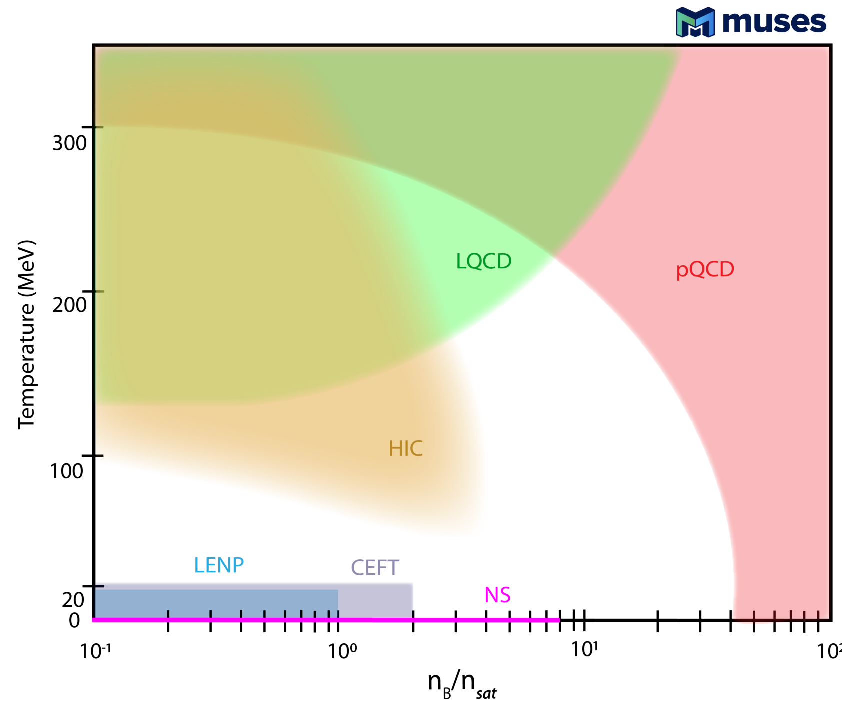


What about More Dimensions?



Outlook

- ✶ Neutron-star mergers will soon inform us about dense and hot matter (while also strange and highly isospin asymmetric)
- ✶ Overlap with heavy-ion collisions will help us to understand the middle of the phase diagram



- ✶ Multidimensional phase diagrams are much more complicated
- ✶ MUSES cyberinfrastructure https://muses.physics.illinois.edu/

muses

- 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 models for the user to choose
- Unified: different modules will be merged together to ensure maximal coverage of the phase diagram
- Developers: physicists + computer scientists will 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

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

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

1. Helvi Witek; University of Illinois at Urbana-Champaign
2. Stuart Shapiro; University of Illinois at Urbana-Champaign
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