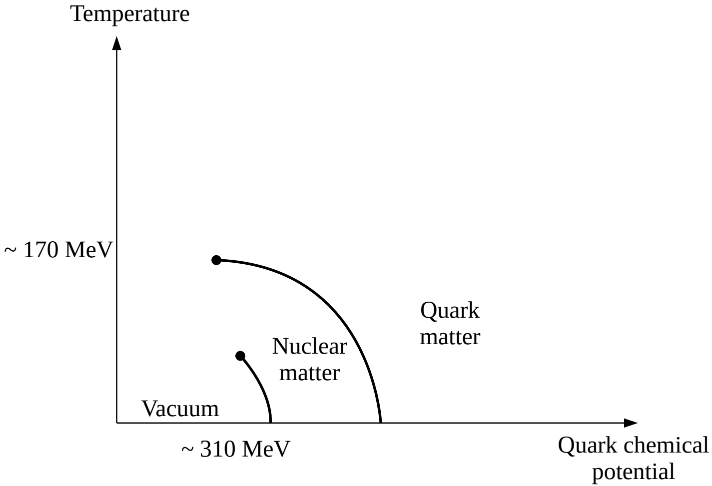
Exploring the Phase Diagram of QCD with Neutron Star Mergers

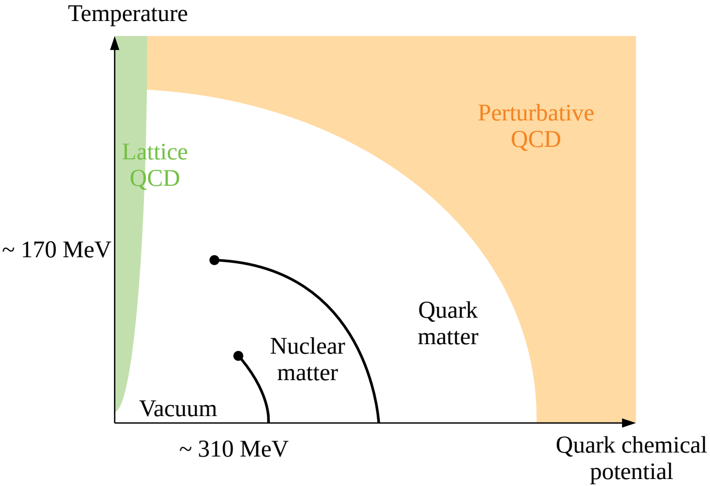
Christian Ecker

Based on work with
S. Tootle, K. Topolski, T. Demircik, M. Järvinen, L. Rezzolla

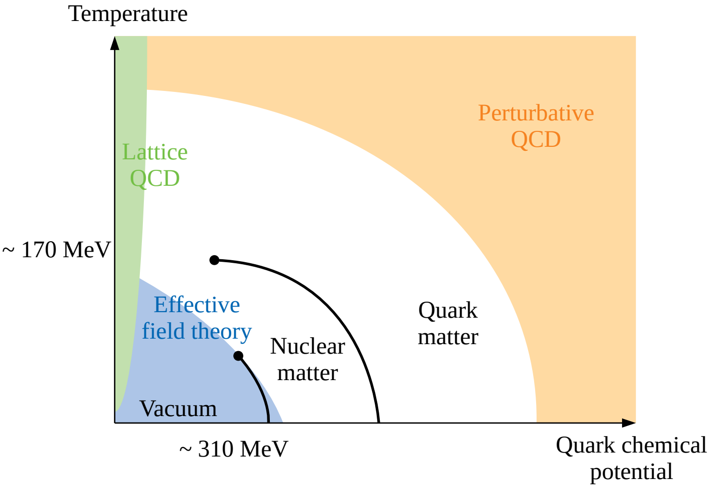
What we (don't) known about QCD



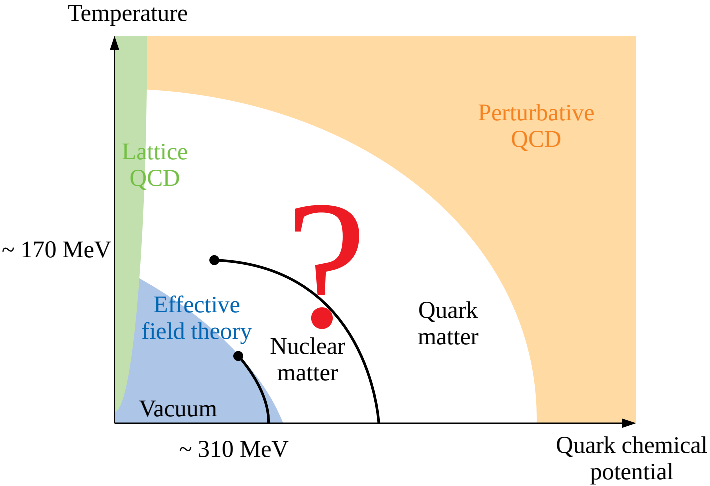
What we (don't) known about QCD



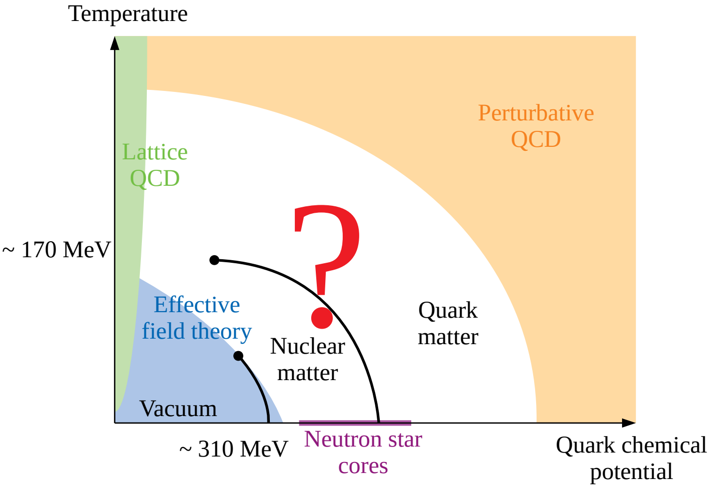
What we (don't) known about QCD



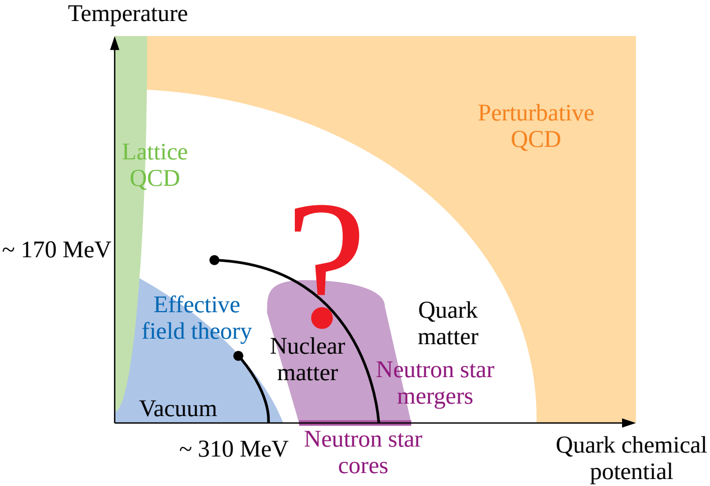
What we (don't) known about QCD



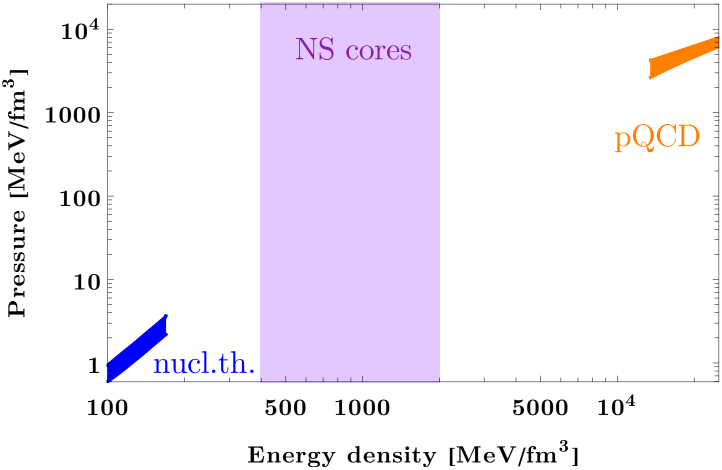
What we (don't) known about QCD



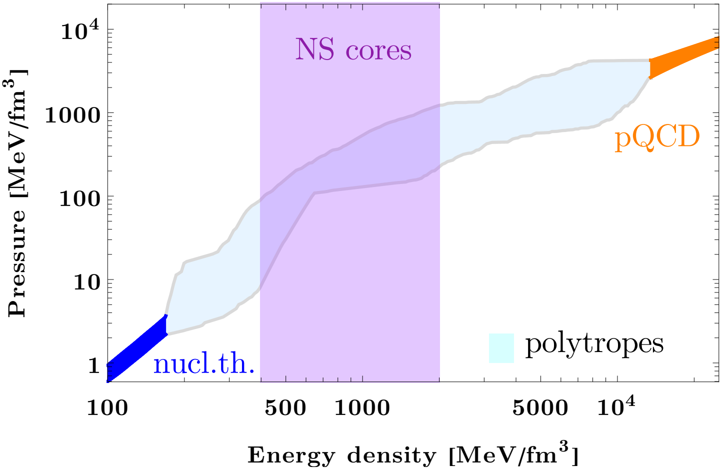
What we (don't) known about QCD



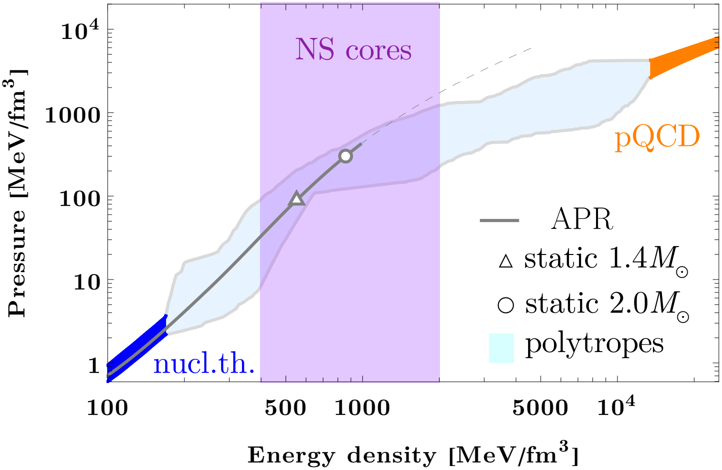
The Equation of State

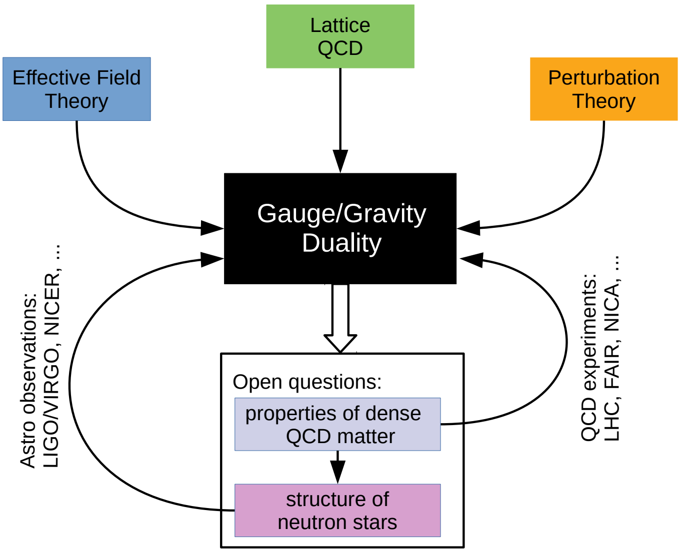


The Equation of State



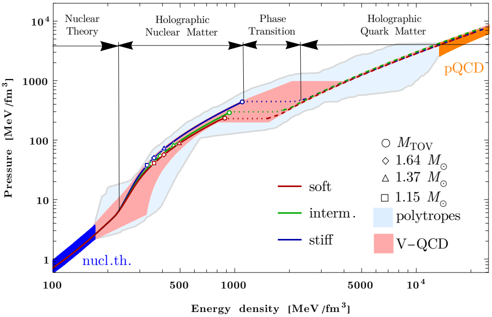
The Equation of State

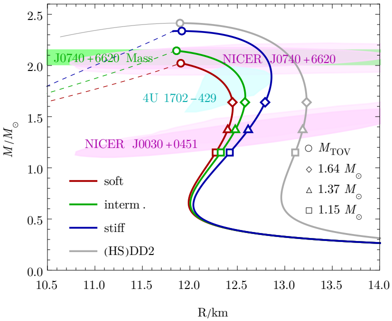



Lattice QCD
Effective Field Theory
Perturbation Theory
Gauge/Gravity Duality
Astro observations:
LIGO/VIRGO, NICER, ...
QCD experiments:
LHC, FAIR, NICA, ...
Open questions:
properties of dense QCD matter
structure of neutron stars

Cold V-QCD Hybrid Equation of State

- Holographic V-QCD model for dense baryonic and quark matter.
- By construction consistent with nuclear theory and pQCD.
- Constrained by neutron star observations.

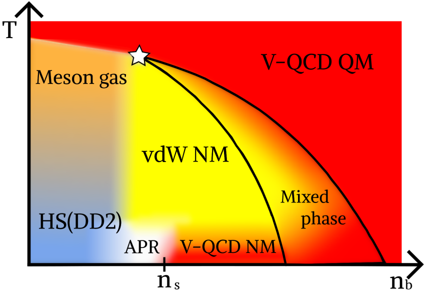


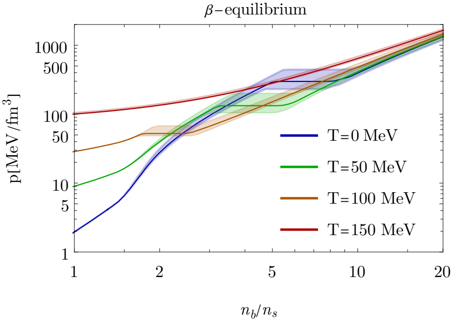


Ecker, Järvinen, Nijs, van der Schee arXiv:1908.03213
Demircik, Ecker, Järvinen arXiv:2112.12157

Extending to finite T

- Finite T extension of V-QCD baryons via van der Waals model.
- Predictions for location of critical point in QCD phase diagram.
- 3 versions (soft, interm., stiff) in tabulated CompOSE format.

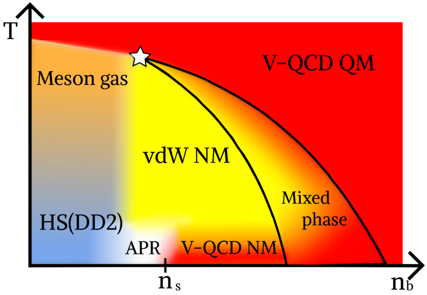


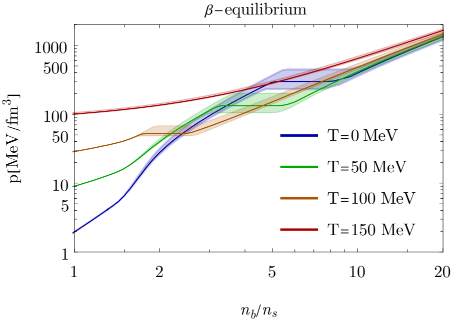


Demircik, Ecker, Järvinen arXiv:2112.12157

Hot V-QCD Hybrid Equation of State

- Finite T extension of V-QCD baryons via van der Waals model.
- Predictions for location of critical point in QCD phase diagram.
- 3 versions (soft, interm., stiff) in tabulated CompOSE format.





Demircik, Ecker, Järvinen arXiv:2112.12157

Simulating Binary Neutron Star Mergers

- 3+1D General Relativistic Hydrodynamics:

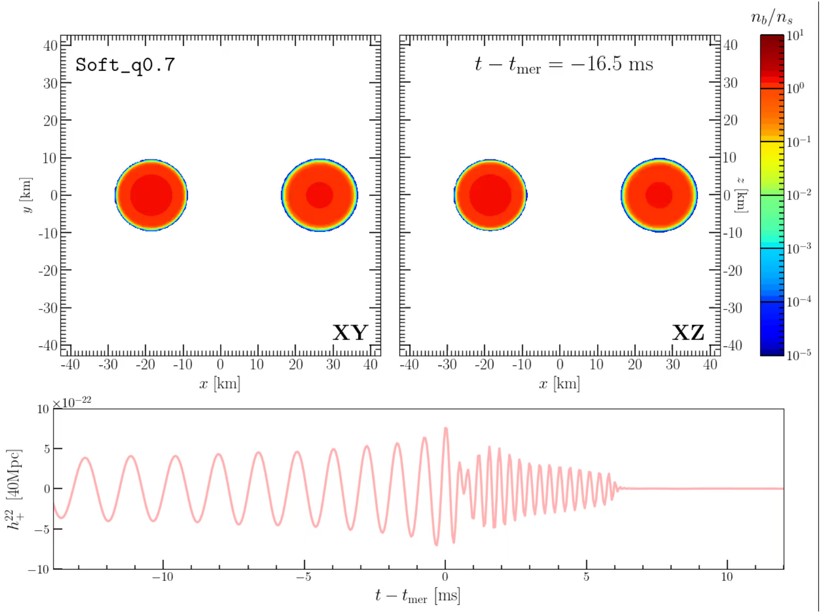
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G_N T_{\mu\nu}\,, \quad \nabla_\mu T^{\mu\nu} = 0\,, \quad \nabla_\mu J^\mu = 0\,.$$

- Equation of State (EoS) $p = p(n_b, T, Y_e)$ as input required.
- Pseudo spectral code Frankfurt University/Kadath (FUKA) for initial data. [Papenfort, Tootle, Grandclément, Most, Rezzolla arXiv:2103.09911]
- Frankfurt/Illinois (FIL) code for binary evolution with tabulated EoS. [Most, Papenfort, Rezzolla arXiv:1907.10328]
- Implemented in the Einstein Toolkit framework. [https://einsteintoolkit.org/]

High-Performance Computing Center Stuttgart

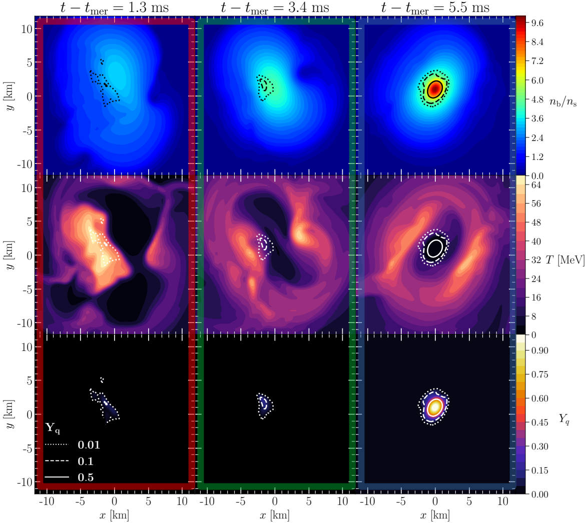
- Project BNSMIC with 100 million core-hours on HAWK.

Picture Copyright: Ben Derzian for HLRS



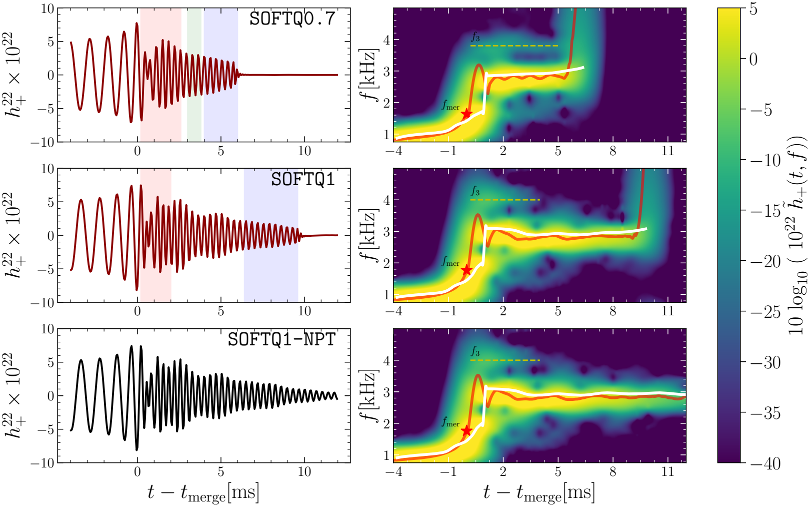
Movie by K. Topolski

Hot, Warm and Cold Quarks



Tootle, Ecker, Topolski, Demircik, Järvinen, Rezzolla

Work in progress: Imprint on Gravitational Waves



Tootle, Ecker, Topolski, Demircik, Järvinen, Rezzolla

Summary

Complete:

- Hot V-QCD EoS with deconfinement phase transition.
- Three tabulated versions in CompOSE format.
- Predictions for the QCD critical point.
  [Demircik, Ecker, Järvinen arXiv:2112.12157]

In progress:

- Neutron star merger simulations with V-QCD EoS.
- Identified 3 different stages in HMNSs: hot, warm, cold quark matter.
- Smoking-gun signature in waveform?
  [Tootle, Ecker, Topolski, Demircik, Järvinen, Rezzolla]

Future:

- Study models with color superconducting phases.
- Study dark matter in neutron star mergers.