QCHS-XV Round Table 3: Constraints on the neutron star EoS: from multi-messenger observations & from pQCD ?

0) David Blaschke (convener) Questions:

The present information about neutron star radii and masses imply that the EOS should not be too stiff around densities corresponding to the hyperon (and/or Delta) onset at 1.4 M_sun, but should then stiffen in order to reach (and exceed) masses of 2.0 M_sun at radii of about 12 km or larger.

Is such a pattern compatible with a purely hadronic EOS? Or does it imply an early, strong deconfinement transition to quark matter that stiffens with increasing density?

As the maximum energy density reached in the very core of massive neutron stars is below about 2 GeV/fm^3, a factor 20 below the range where perturbative QCD is applicable, how can pQCD nevertheless constrain the neutron star EoS?

What constraints for the hadron-to-quark matter transition can be derived from NS observations? How likely is a crossover transition at low temperatures which could imply a second critical endpoint or even a crossover-all-over in the QCD phase diagram?

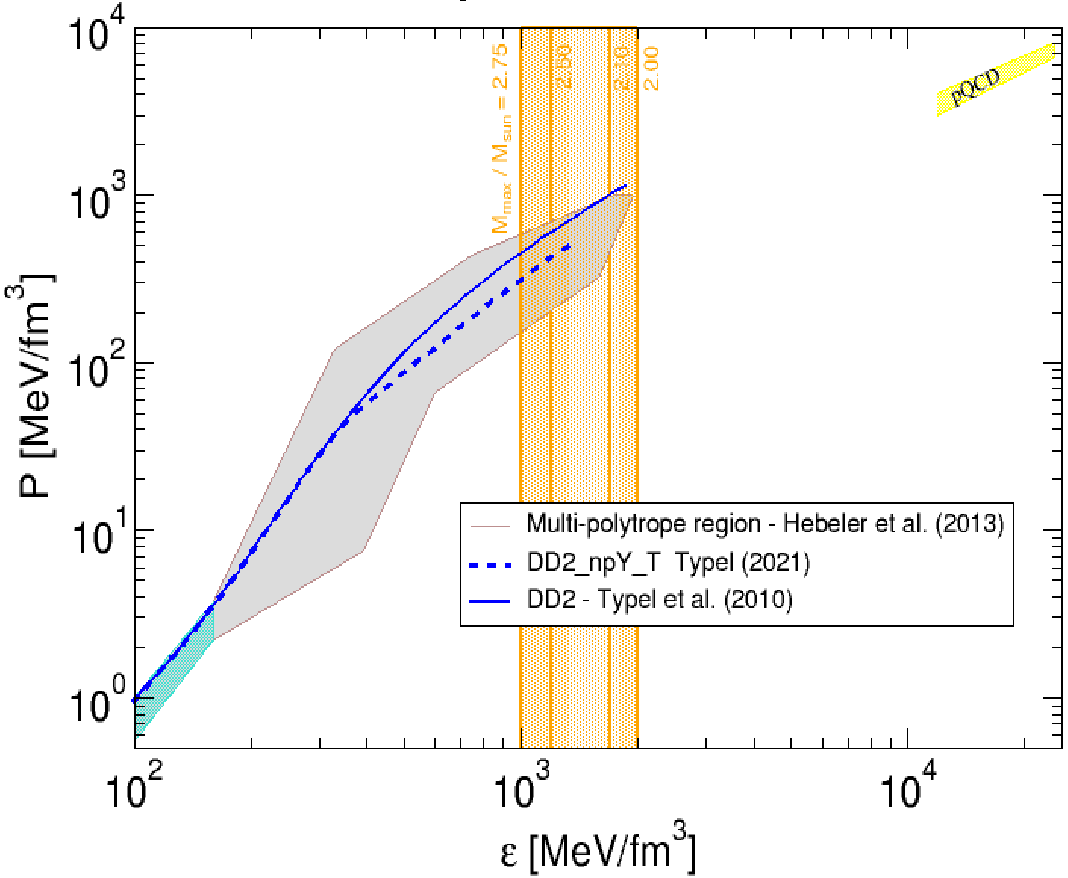
These are questions to be discussed by the panelists together with the audience of QCHS-XV.

1) Michael Coughlin:
The multi-messenger constraints on R_1.4 and R_2.0 and their implications for the NS-EOS
2) Aleksi Kurkela:
Constraints on the NS EOS from pQCD
3) Kenji Fukushima:
Quark deconfinement in NS: first-order vs. crossover
4) Nicolas Chamel:
Are there “realistic” hadronic EoS that are compatible with all multi-messenger constraints?

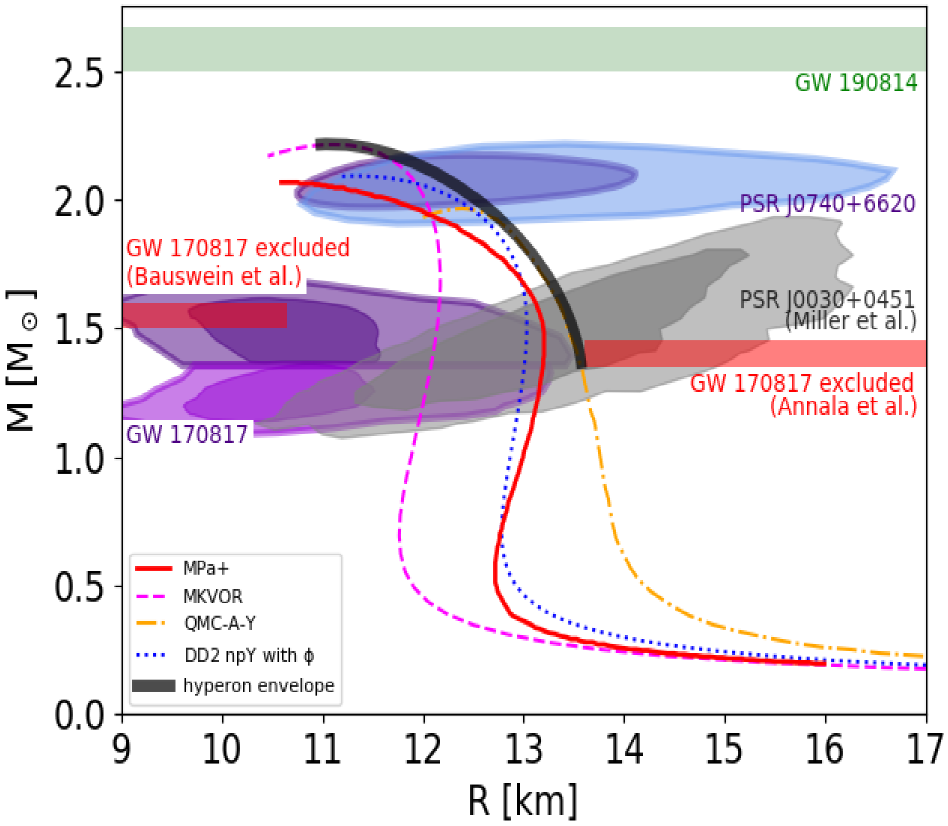
XVth Quark Confinement and the Hadron Spectrum Conference
2022 - University of Stavanger

0) Teaser questions …

In high-density nuclear matter hyperons (and Δ's) occur above ~2 ρ_0 and soften the EoS, so ...

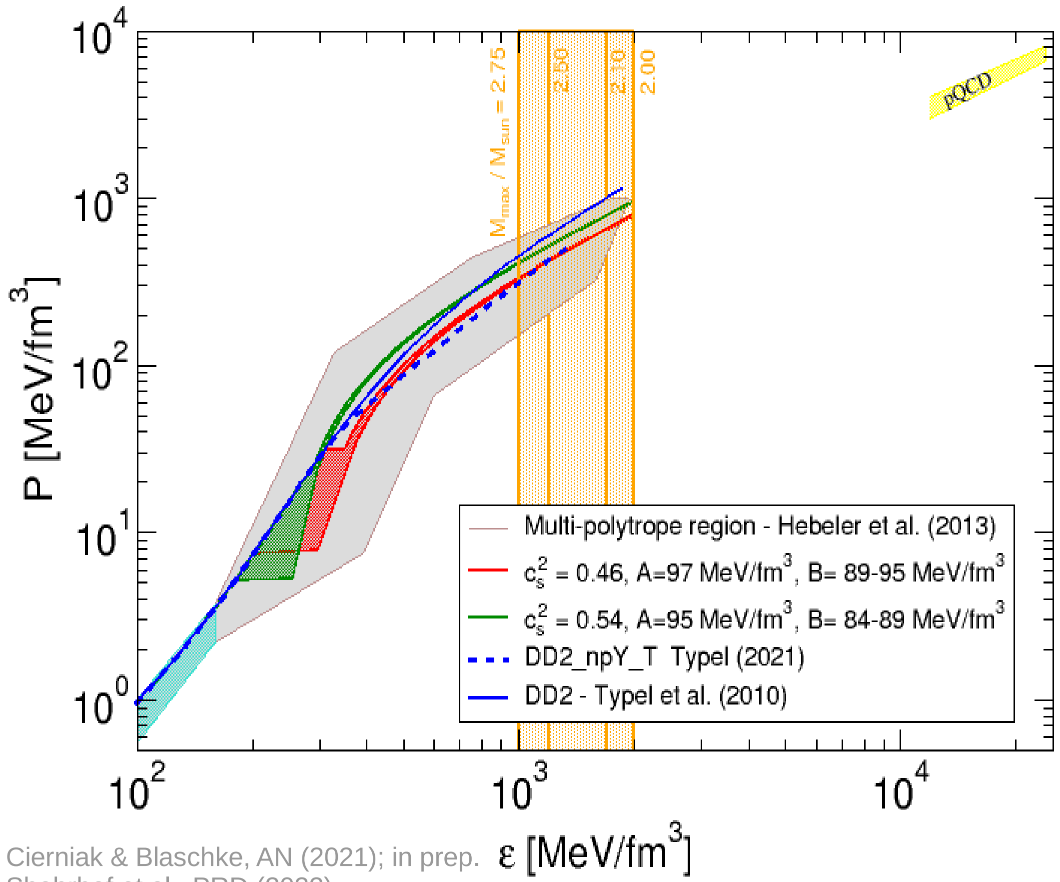


… is there a "Berlin Wall" (bold black line) for realistic hadronic equations of state?



If yes, then ...

Then …



Cierniak & Blaschke, AN (2021); in prep.
Shahrbaf et al., PRD (2022)

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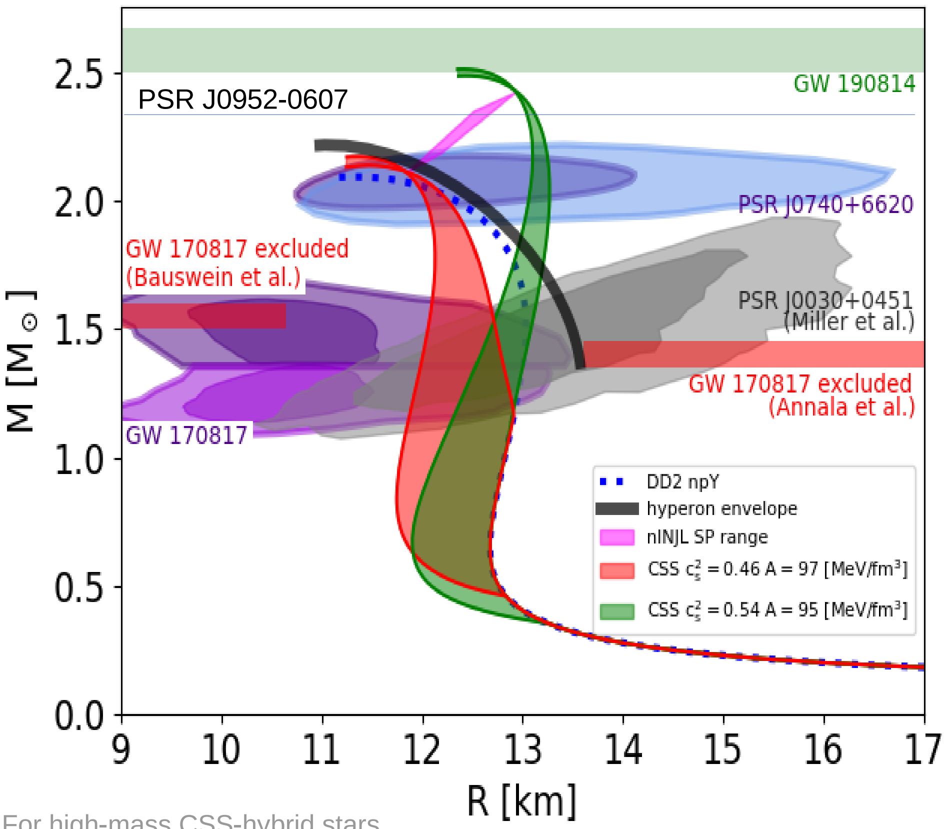
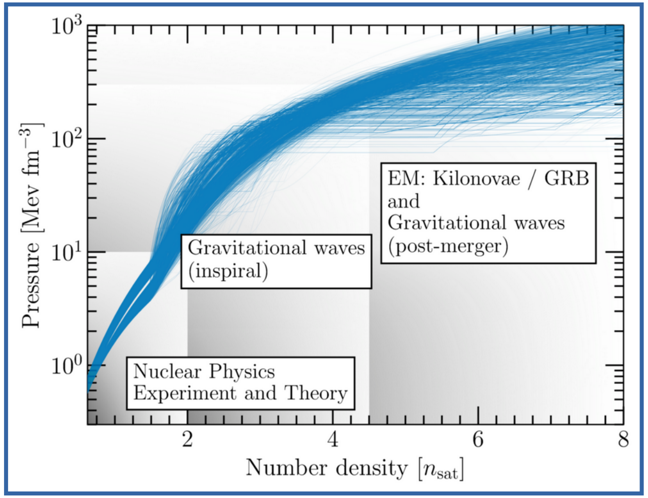


For high-mass CSS-hybrid stars,
see Somasundaram & Margueron, EPL (2022); Ivanytskyi & Blaschke, PRD (2022)

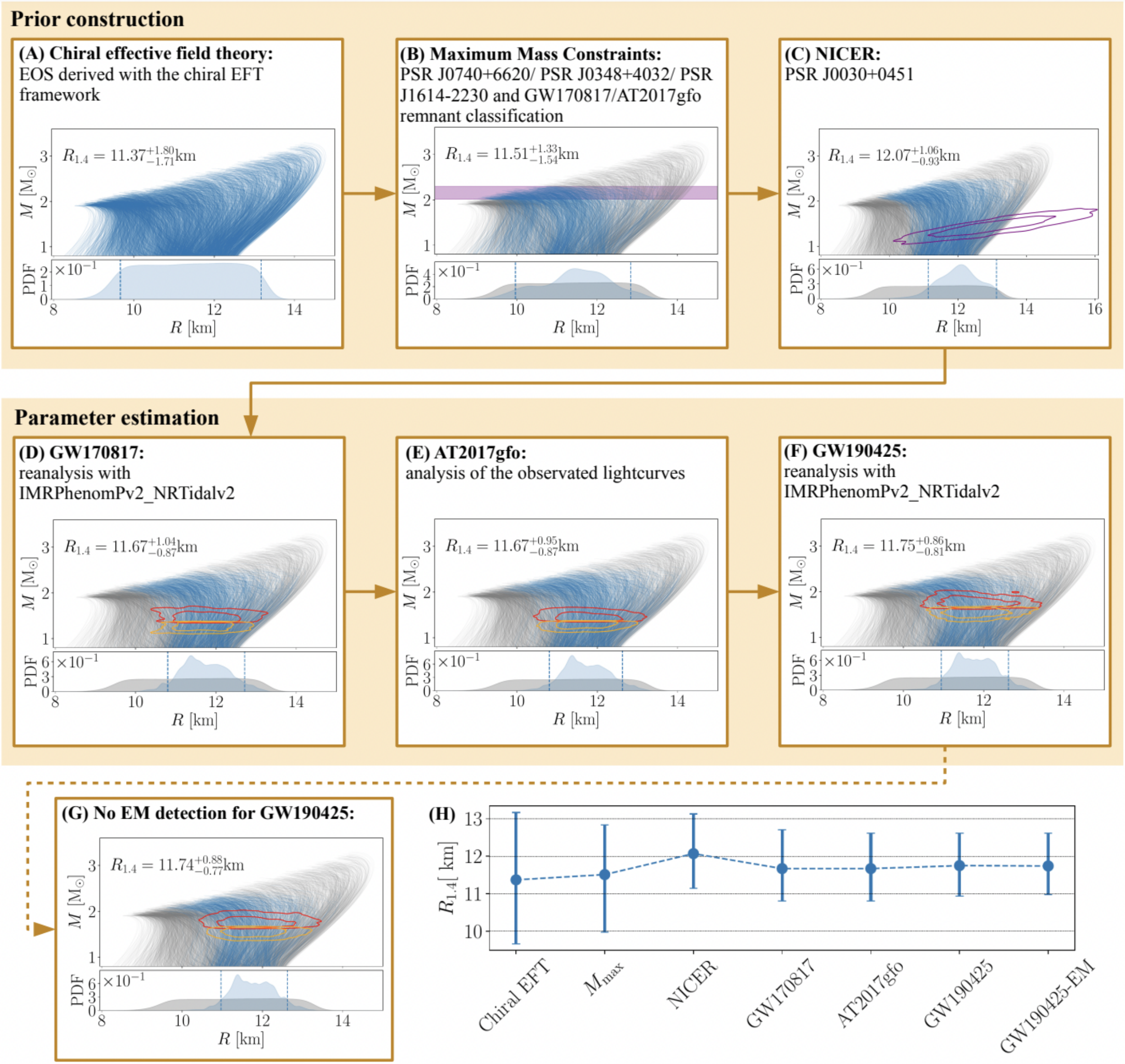
… measuring mass (and radius) on the other side of the wall would prove deconfinement !

1) Multi-messenger Astronomy combining:

-chiral effective-field theory
-pulsar mass measurements
- X-ray measurements with NICER
- gravitational-wave inference of GW170817 and GW190425
- Inference of AT2017gfo and the missing / kilonova for GW190425

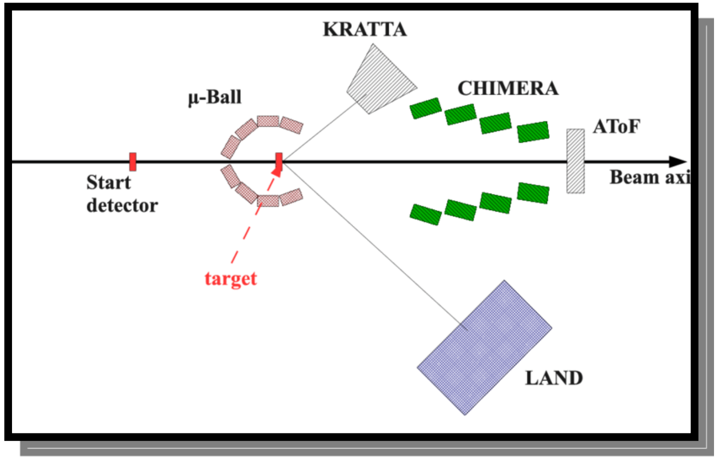


Pang et al., arxiv: 2205.08513

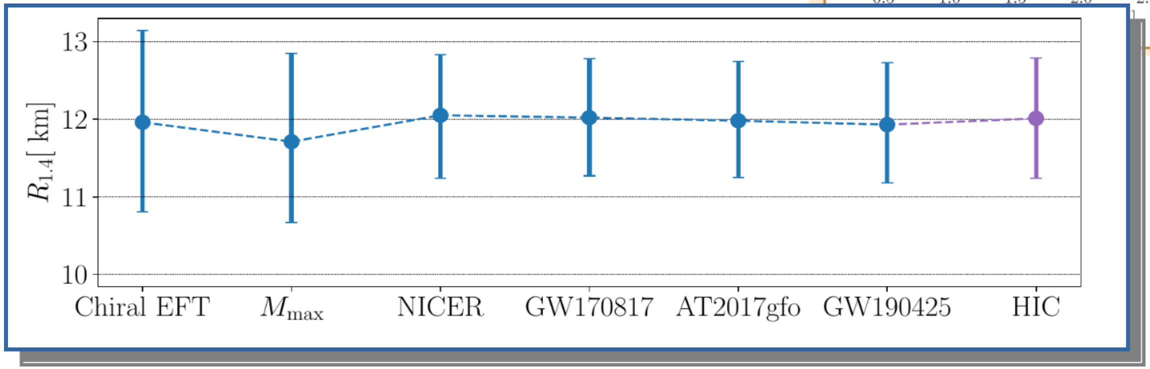


Dietrich et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Incorporating HIC information

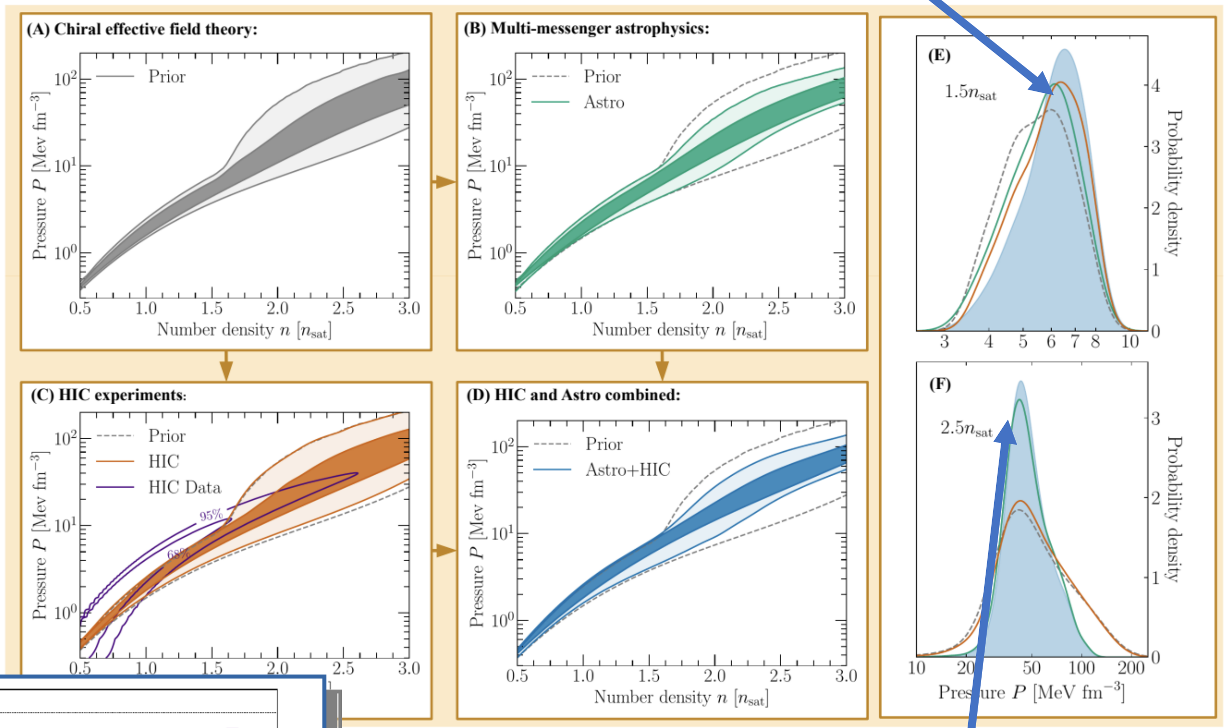


Russotto et al., J.Phys.Conf.Ser. 420 (2013)



Huth et al., Nature 606 (2022) 276-280

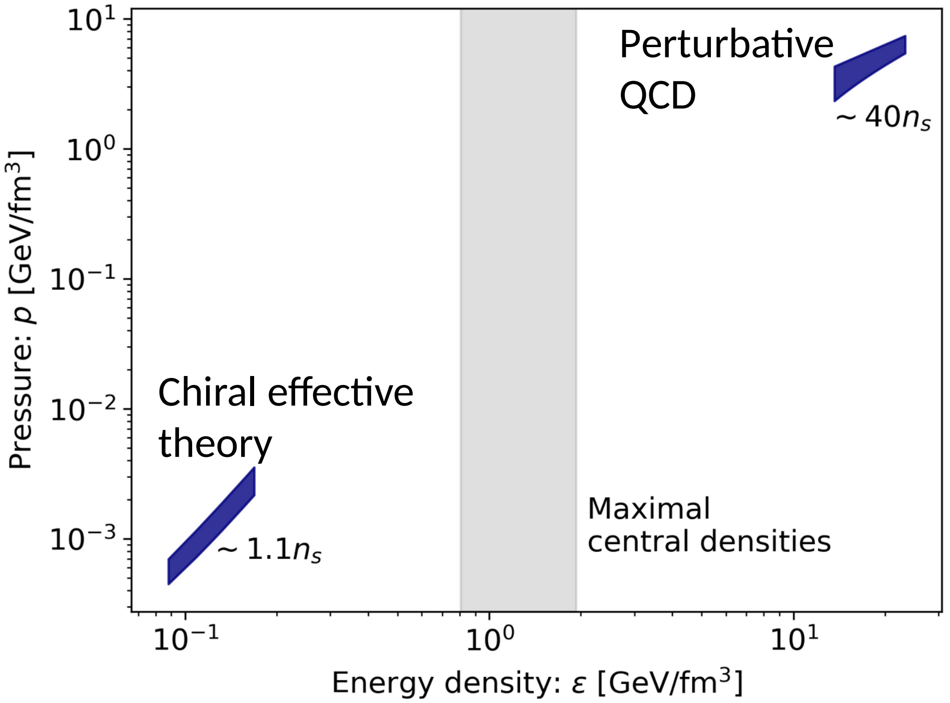
Good agreement between macroscopic and microscopic collisions



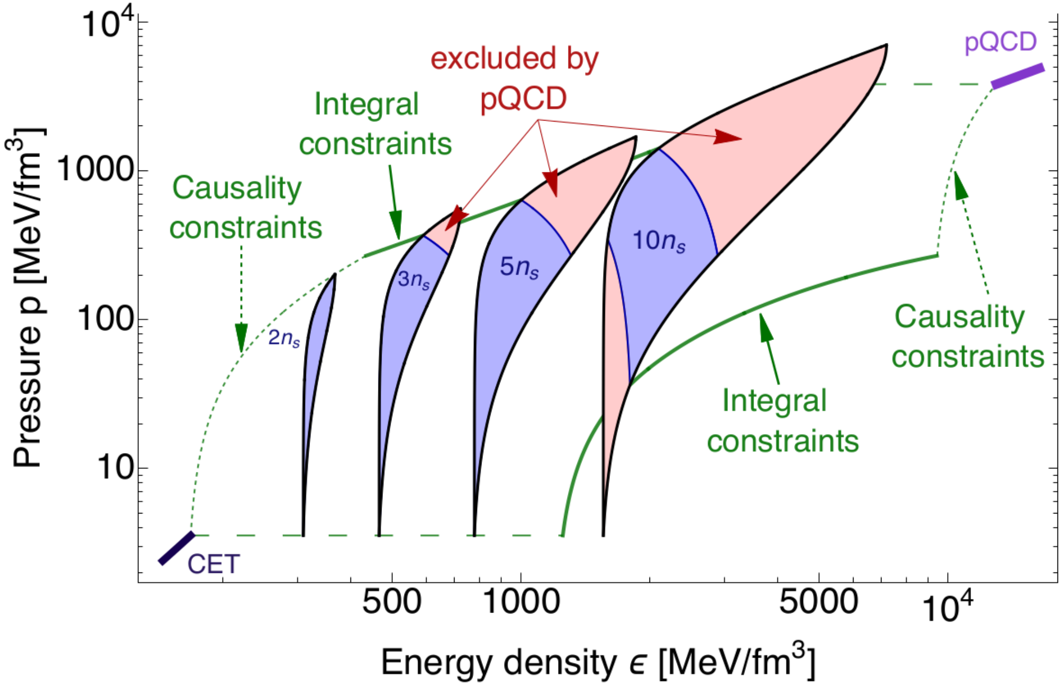
high-density information from astrophysical studies

2) Constraints on the NS EOS from pQCD

Equation of State can be computed in **perturbative QCD** around **40 n_s**

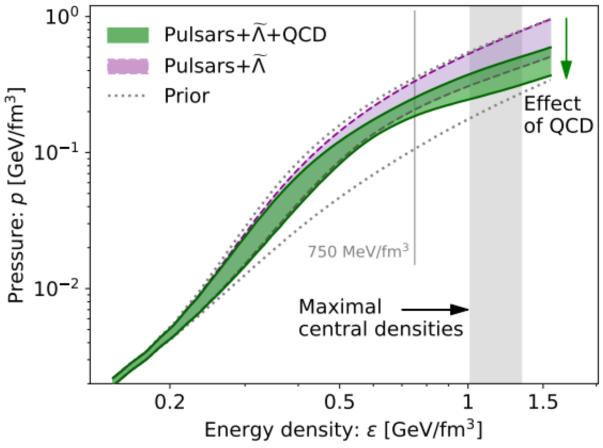


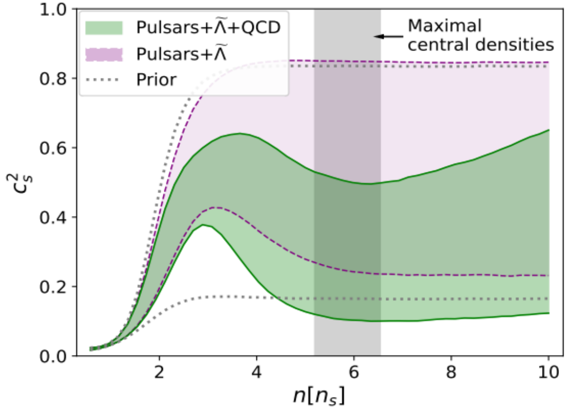
pQCD with **causality** and **stability** constrain the Equation of state at **Neutron-Star densities**



Komoltsev & Kurkela PRL128 (2022)

The QCD input makes the EoS **soften** at highest NS densities.

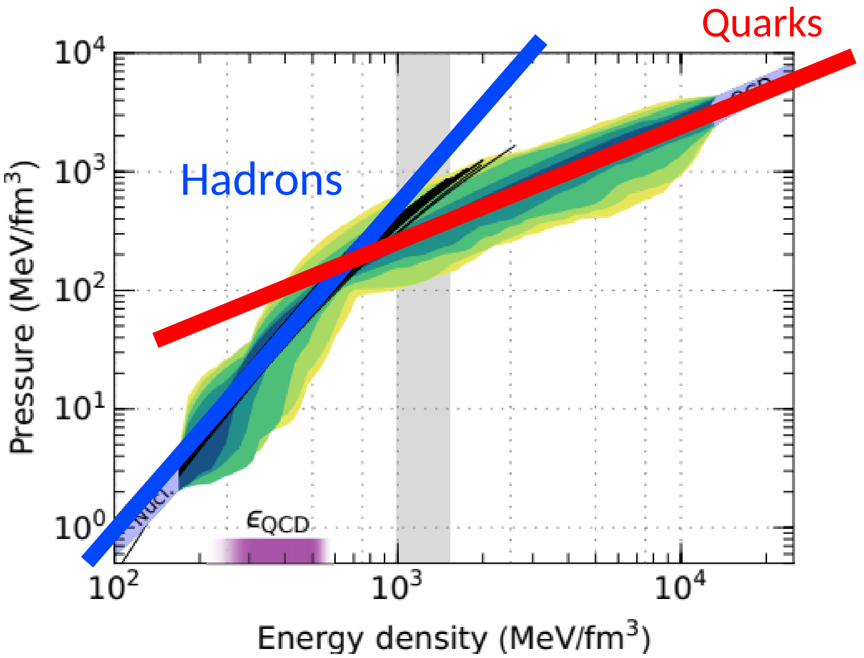




Gorda, Komoltsev & Kurkela 2204.11877
Also: Annala et al. PRX 12 (2022), Altiparmak, Ecker, Rezzolla 2203.14974,
Han, Huang, Tang & Yi-Zhong Fan 2207.13613,
Marczenko, McLerran, Redlich & Sasaki 2207.13059, …

Properties of the EoS reflect the **phase structure** of the matter.

The cores of most massive NSs consistent with **deconfined, nearly conformal Quark Matter**.



Annala, Gorda, Kurkela, Nätttilä, Vuorinen Nature Physics 16 (2020) 9
Also: Fujimoto, Fukushima, McLerran, Praszalowicz 2207.06753,
Kojo PRD 104, …

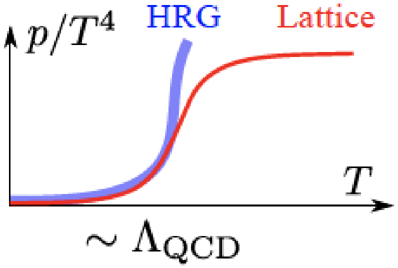
What observations/calculations needed to reliably establish the Quark Matter cores?

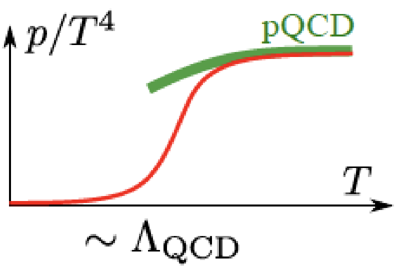
3) First-order vs. Crossover — Underlying physics of deconfinement at high density ?

*** Very good and still controversial questions ***

— What is the theoretical *definition* of "quark matter" ?

For high-T matter how did we define a QGP?

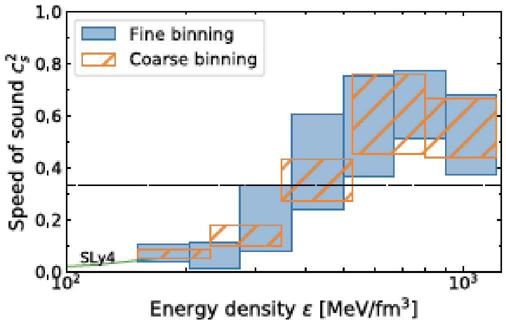


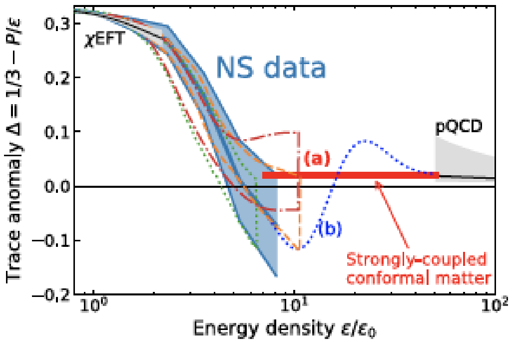


QM '14 (KF)

— How to understand *deconfinement*; percolation? quarkyonic?
strongly-coupled conformal matter?

Is there a peak in the sound velocity? A high-density analogue of the sQGP?



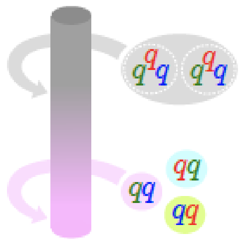


First-order vs. Crossover — underlying physics of deconfinement at high density ?

* Very good and still controversial questions *

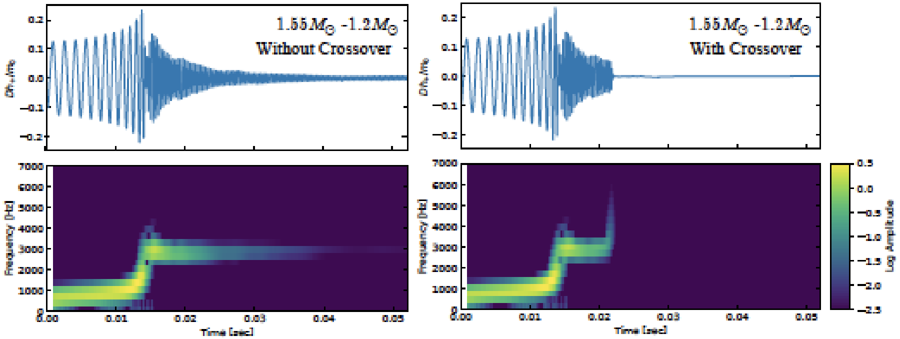
— **Can we theorize distinction between nuclear and quark matter?**
Quark-hadron duality (in favor of crossover)
vs. Discontinuous change with higher-form symmetry (in favor of 1st-order)

0-form symmetries can be exactly matched, but not for extended operators…?



U(1) flux in a superfluid vortex
seems to have a discontinuous change?
(Cherman-Sen-Yaffe 2018)

— **Can we distinguish different scenarios from the gravitational wave signals?**



Crossover looks very similar
to the 1st-order case.

"Softening" could be quantified,
enough to conclude anything?

4) Are there realistic hadronic EoS compatible with all multimessenger constraints?

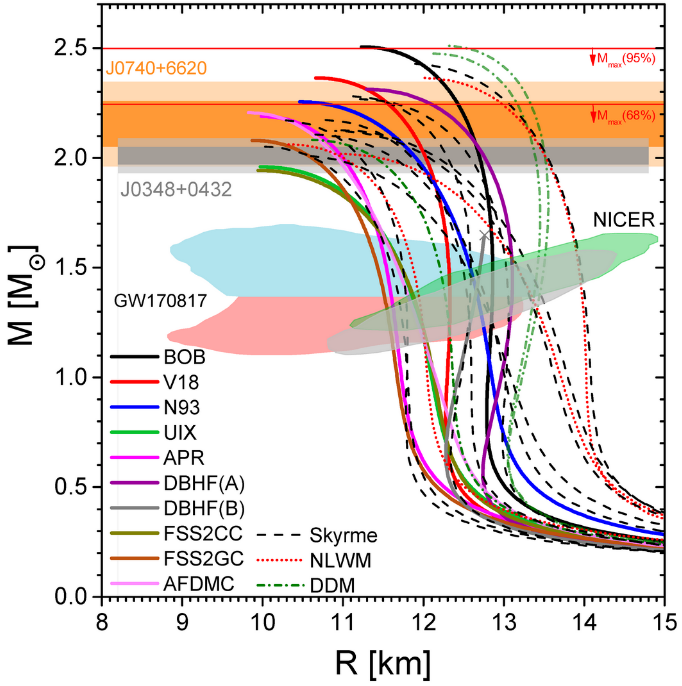
Phenomenological approaches

- nonrelativistic mean field: Skyrme, Gogny, EDF
- relativistic mean field: nonlinear, density-dependent

Ab initio approaches

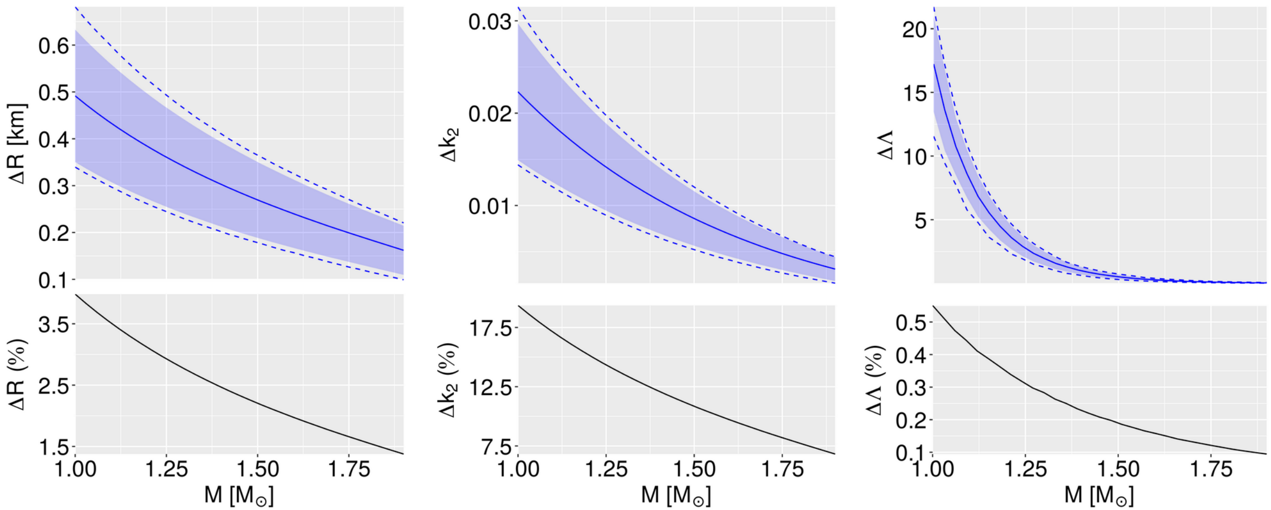
- diagrammatic : (D)BHF, SCGF
- Variational
- *quantum Monte Carlo, chiral EFT* ($\rho \lesssim 2\,\rho_0$)

There are purely <u>nucleonic</u> EoS compatible with all multimessenger constraints:



Burgio et al., Prog. Part. Nucl. Phys. 120, 103879 (2021)

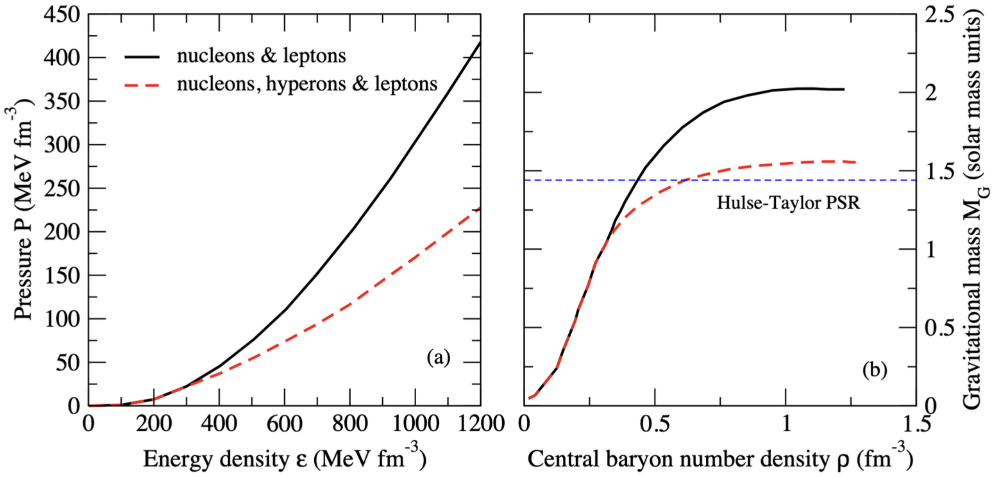
Very few EoS are unified with same model for crust and core: BSk, Sly, BCPM, D1M*. Matching errors may become an issue for future observations:

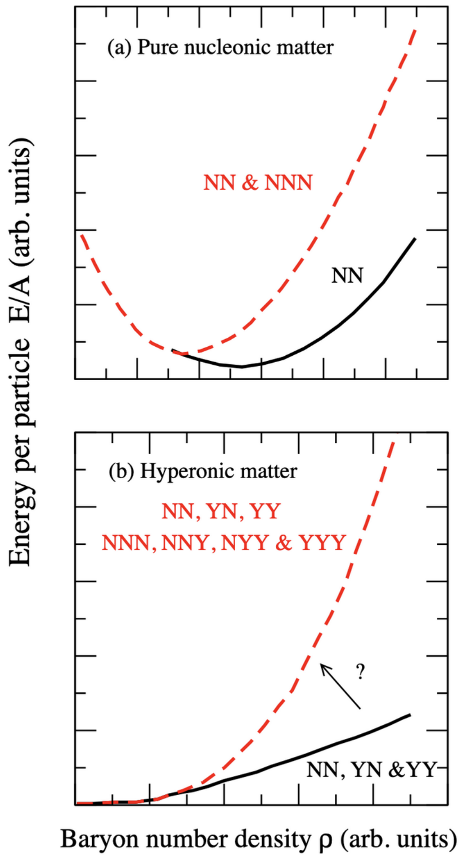


Ferreira & Providencia, Universe 6(11), 220 (2020)

4) Are there realistic hadronic EoS compatible with all multimessenger constraints?

✗ **Many hadronic EoS with <u>hyperons</u> are ruled out by observations of massive NS due to strong softening:**





Scarce or no experimental data on YN, YY, YNN, YYY interactions

Hyperon puzzle can be solved with suitable adjustments of phenomenological models. Less clear with ab initio approaches.

Additional softening due to meson condensates, Δ isobars, dibaryons d*…

Blaschke&Chamel, Astrophys. Space Sci. Lib. 457, eds L. Rezzolla, P. Pizzochero, D. I. Jones, N. Rea, I. Vidaña p. 337-400 (Springer, 2018)

Chatterjee & Vidana, Eur. Phys. J. A 52, 29 (2016)