Quantifying the likelihood of quark-matter cores in massive neutron stars

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EoS measurements with next-generation GW detectors

Institute for Nuclear Theory, 2 Sept 2024

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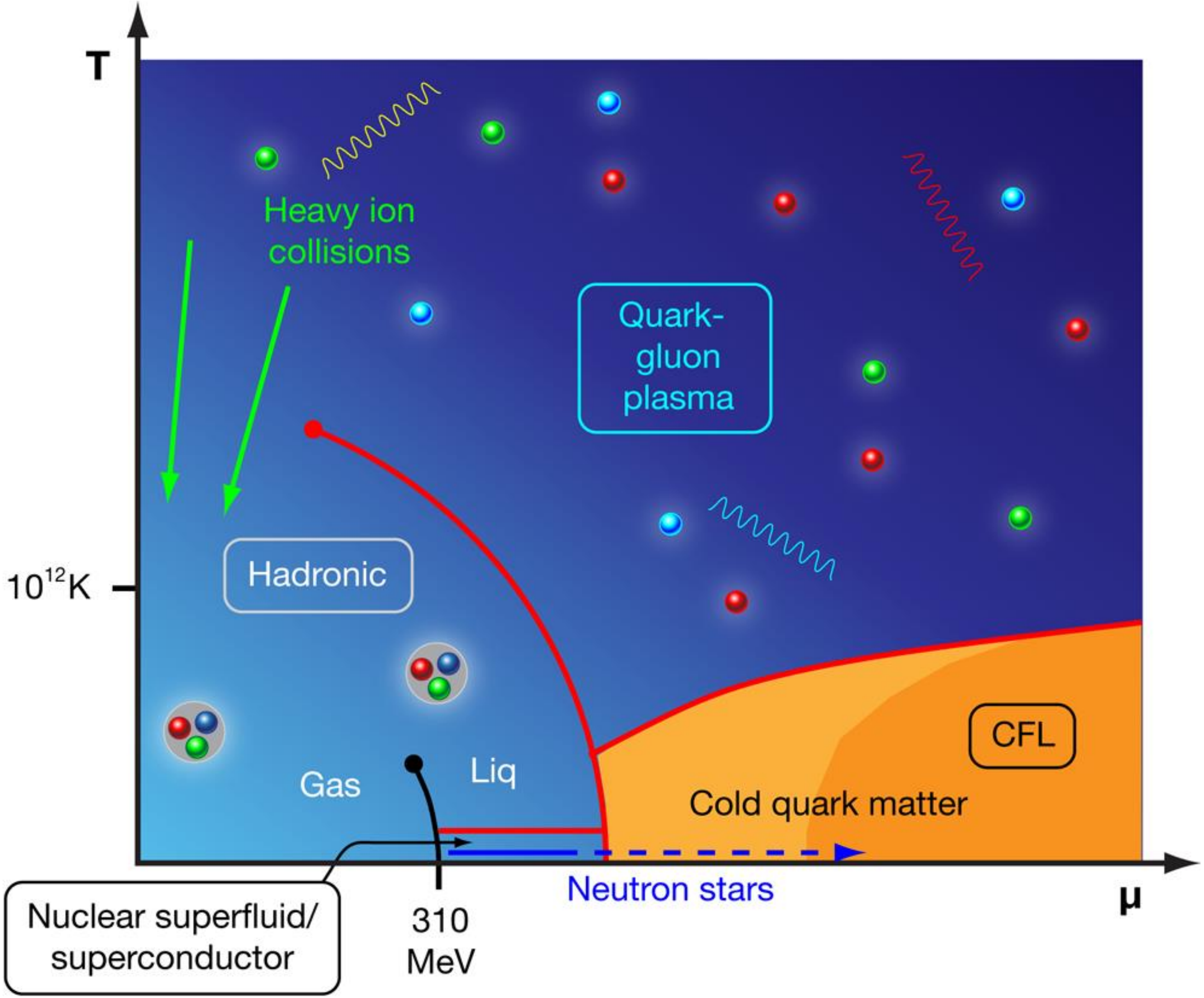
pQCD at high density:

1) Gorda, Kurkela, Paatelainen, Säppi, AV, PRL 127, 2103.05658
2) Gorda, Paatelainen, Seppänen, Säppi, PRL 131, 2307.08734

Applications to neutron-star physics:

1) Annala et al. (incl. AV), Nature Phys. (2020), 1903.09121
2) Annala et al. (incl. AV), PRX 12 (2022), 2105.05132
3) **Annala et al. (incl. AV), Nature Comm. (2023), 2303.11356**

Lecture notes: AV, Acta Phys. Polon. B 55 (2024), 2405.01141


T
Heavy ion
collisions
Quark-
gluon
plasma
10^12K
Hadronic
Gas
Liq
CFL
Cold quark matter
Neutron stars
μ
Nuclear superfluid/
superconductor
310
MeV

Parallels and differences between heavy-ion collisions and NS cores:

- Both feature strongly interacting matter at high energy densities – up to and exceeding 1 GeV/fm^3
    - At these energy densities, QCD *strongly coupled* → need to account for non-perturbative effects in some fashion
- At high T, lattice simulations have found a *crossover* deconfinement transition at $T{\sim}155$ MeV, $\epsilon{\sim}400$ MeV/fm^3, while at high n_B order and location of transition unknown (lattice results not available)
    - Need alternative (experimental?) access to non-perturbative physics
- In heavy-ion physics, creation of deconfined matter confirmed *indirectly* through presence of a near-thermal medium with $T > T_c$
    - Can this be repeated in NS context, perhaps through EoS inference?

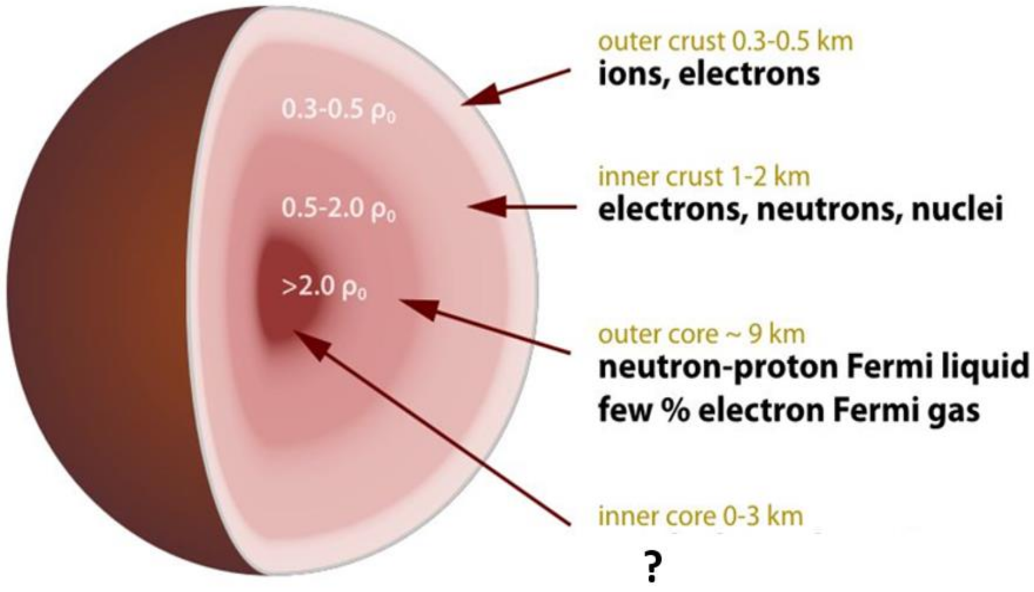
NS matter: from dilute crust to ultradense core

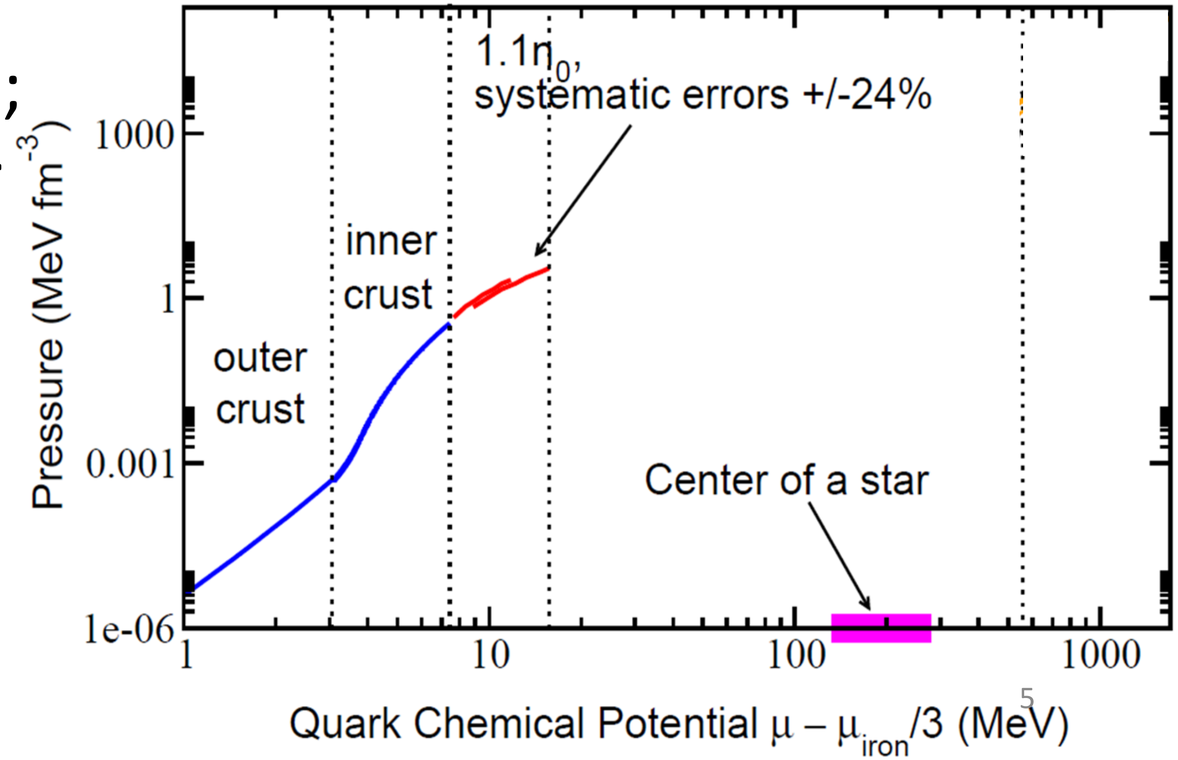
Proceeding inwards from the crust:

- μ_B increases gradually, starting from μ_{Fe}
- Baryon/mass density increase beyond saturation density $\approx 0.16/\mathrm{fm}^3$
- Composition changes from ions to nuclei to neutron liquid and beyond
- Good approximations: $T \approx 0 \approx n_Q$

Low-density EoS constrained by experiment; after neutron drip point interactions matter

- Systematic effective theory framework: Chiral Effective Theory (CET)
- State-of-the-art CET EoSs NNNLO in χPT power counting but still long way from stellar centers [e.g. Tews et al., PRL 110 (2013)]





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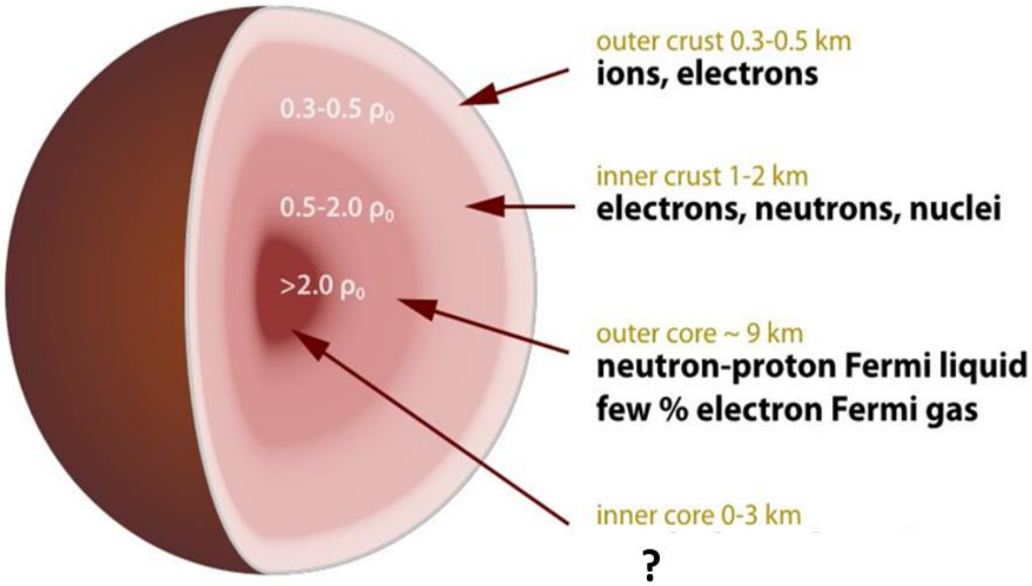
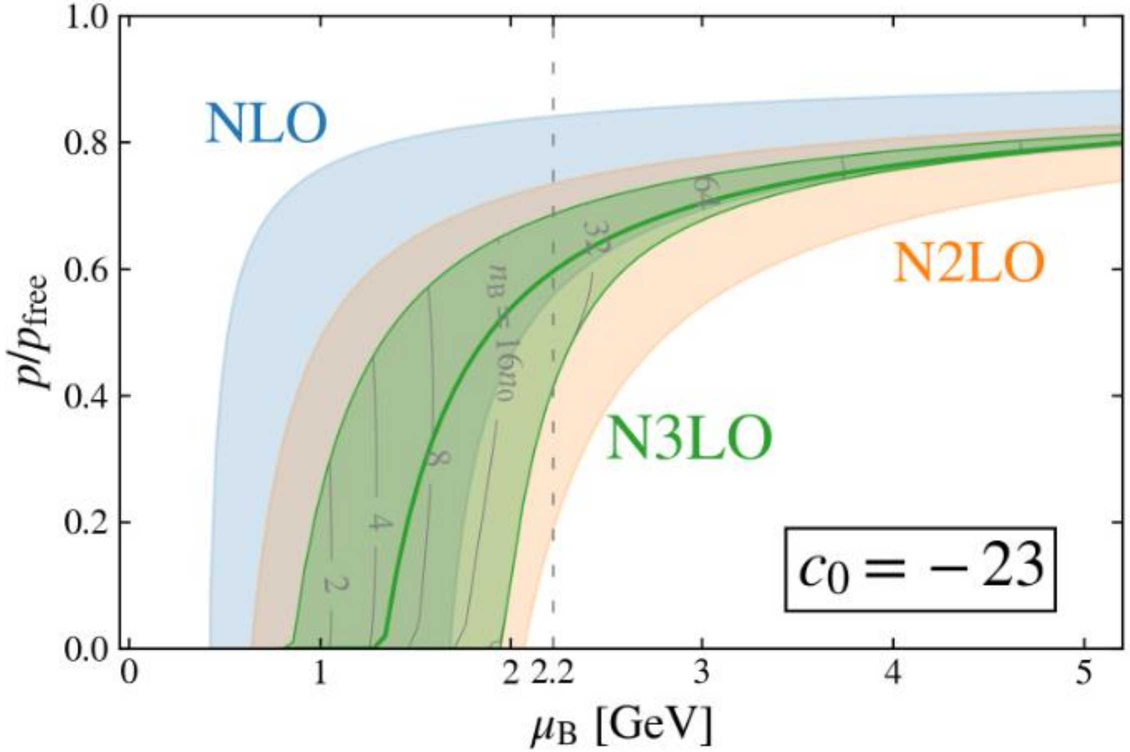


At high density, asymptotic freedom ⇒ weakening coupling and deconfinement

- State-of-the-art pQCD EoS at partial NNNLO, with purely soft and mixed sectors fully determined [Gorda et al., PRL 127 (2021); PRL 131 (2023)]
- Missing hard contribution shown to bring dramatic improvements in accuracy



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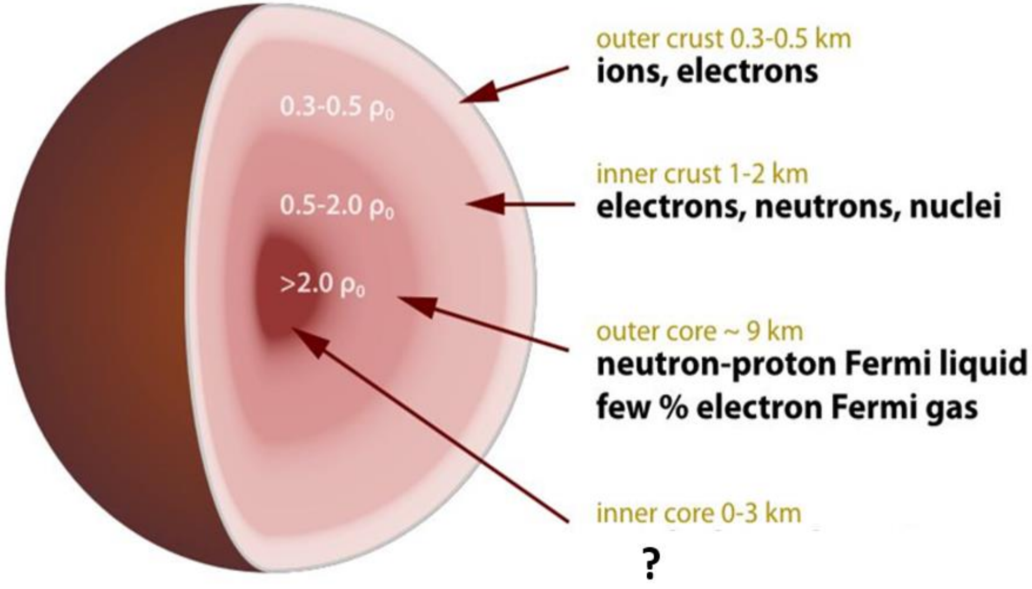
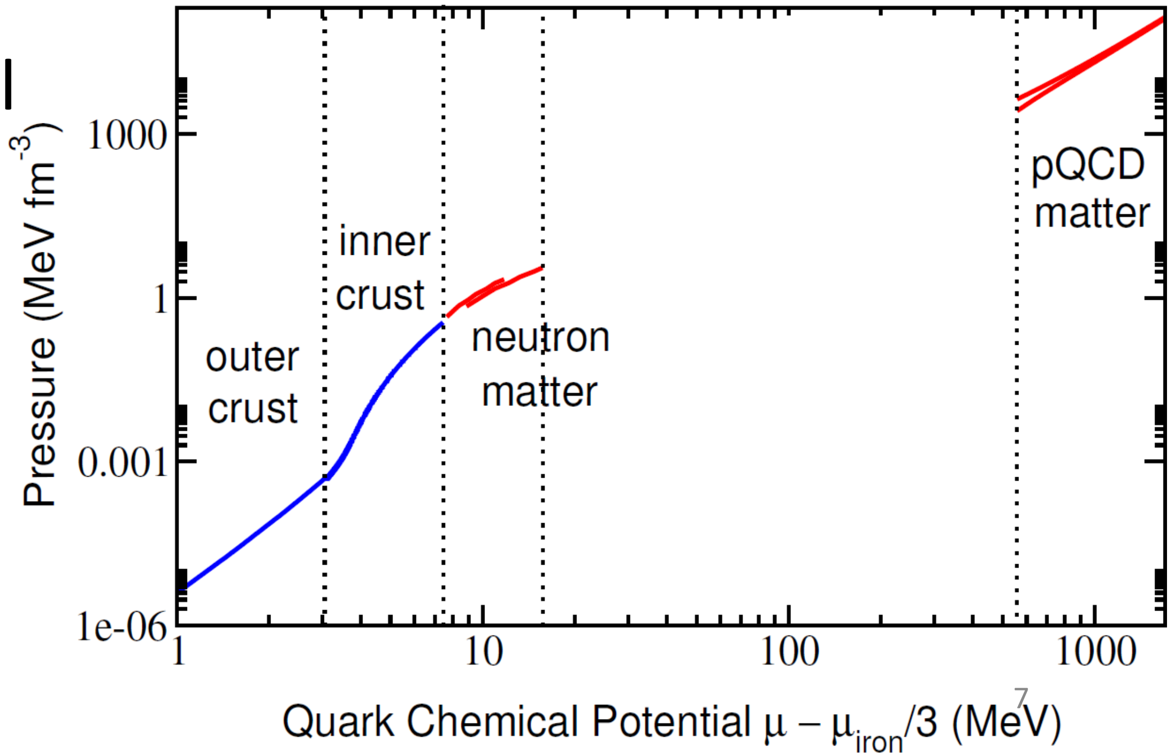
∴ Low- and high-density limits under control but extensive no-man's land at intermed. densities. Possibilities for proceeding:

1) Solve the sign problem of lattice QCD
2) Use phenomenological models for nuclear and quark matter
3) Allow all possible behaviors for the EoS





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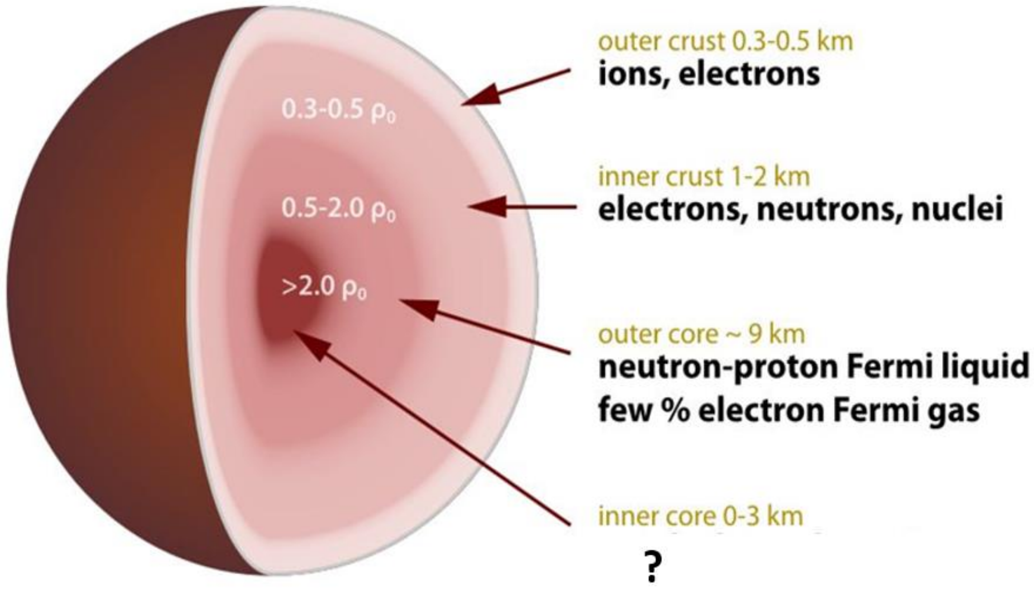
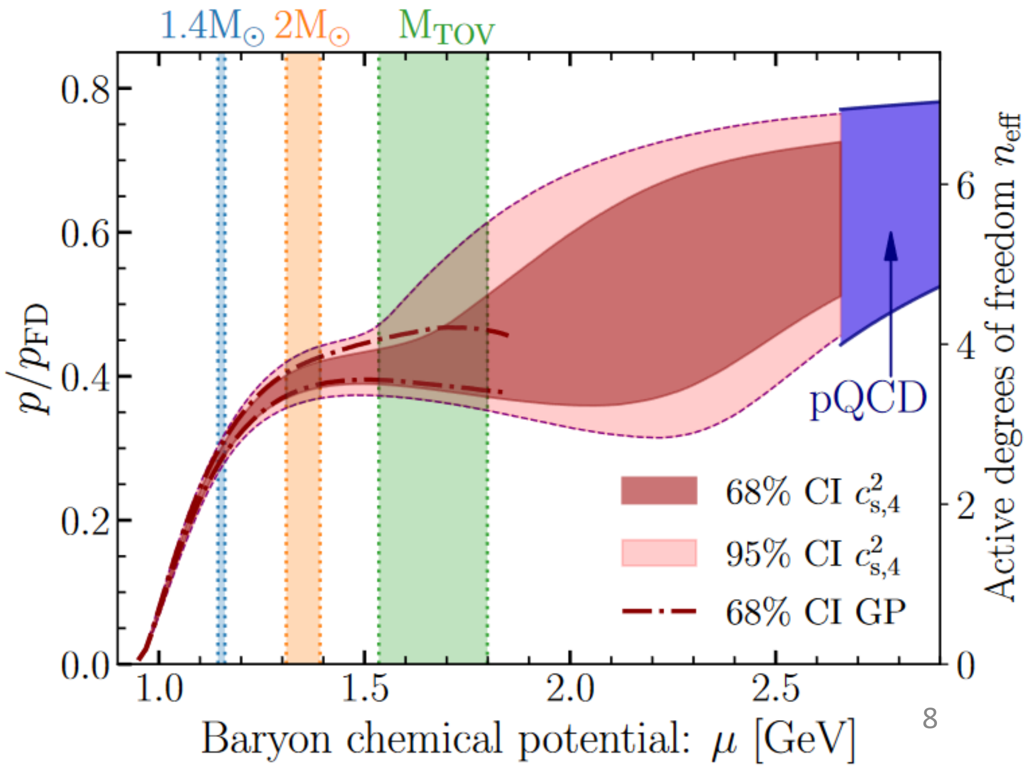
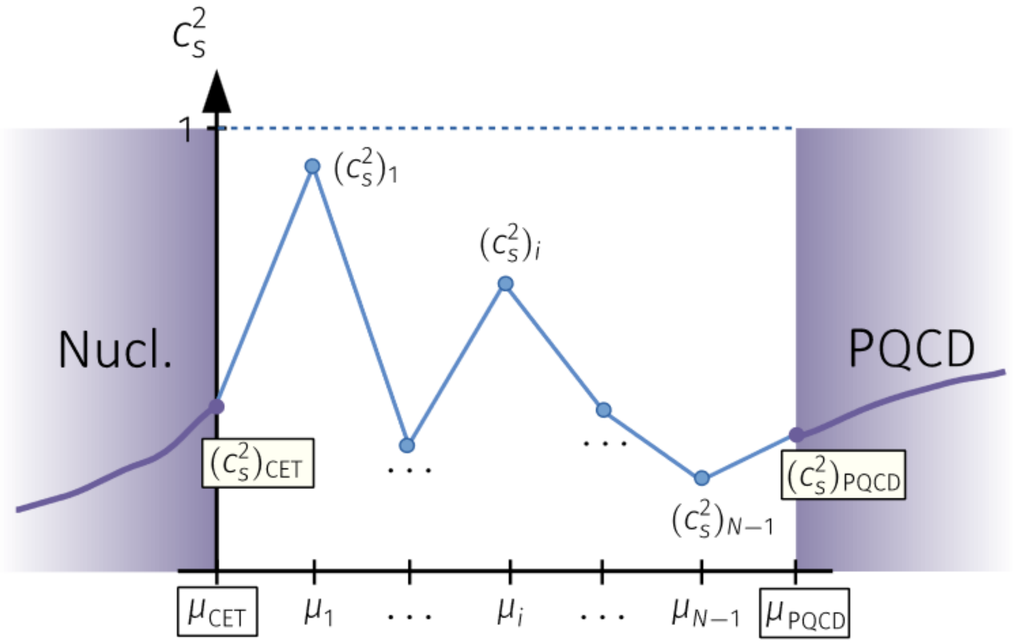
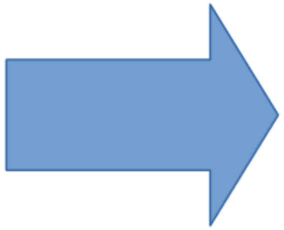


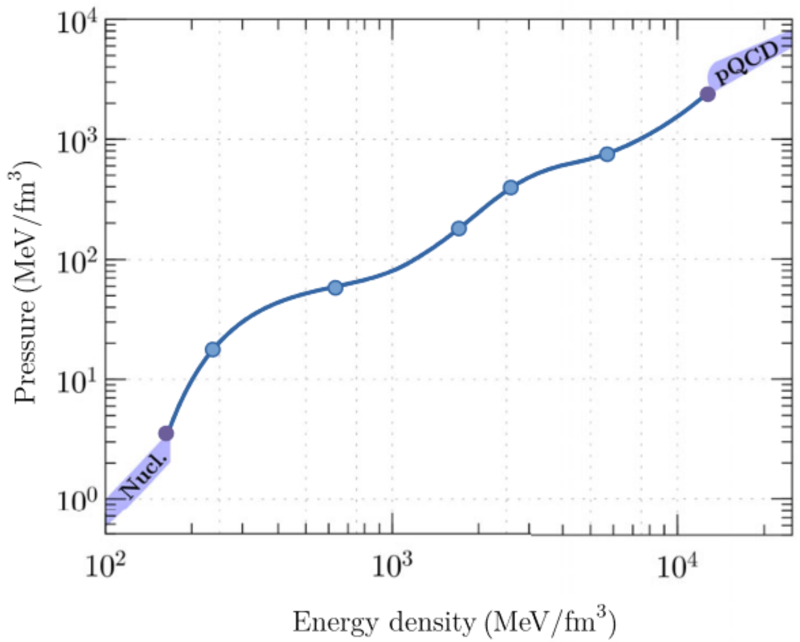


NS-matter EoS: model-independent interpolation

Useful strategy: First interpolate speed of sound between CET and pQCD limits, then integrate to obtain the pressure and other thermodynamic quantities [Annala et al., Nature Physics (2020) and PRX (2022)]







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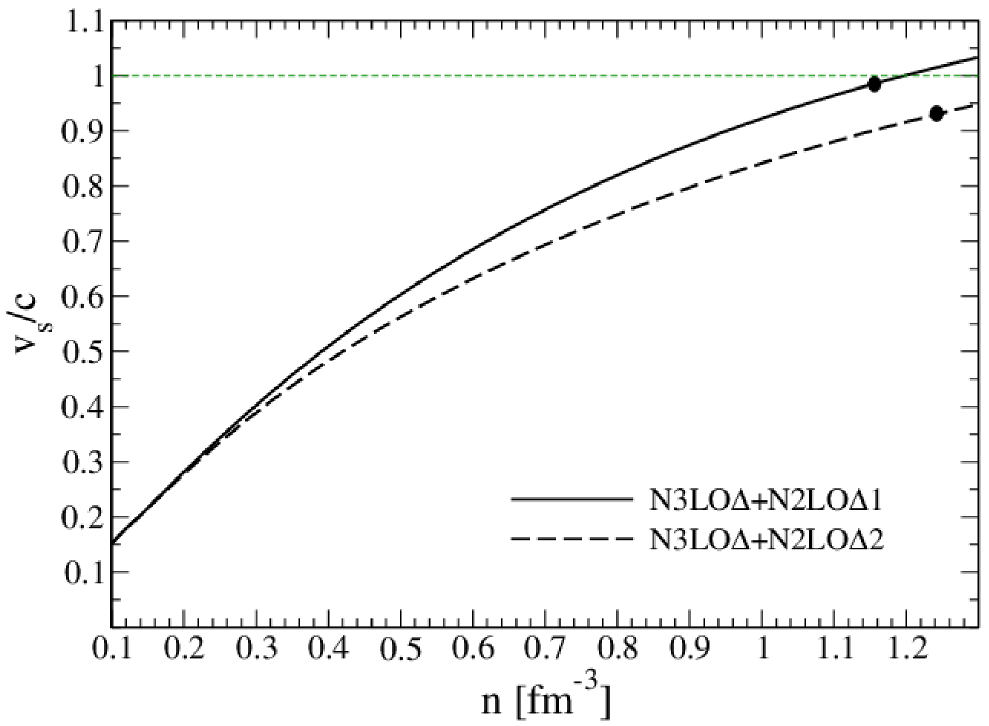
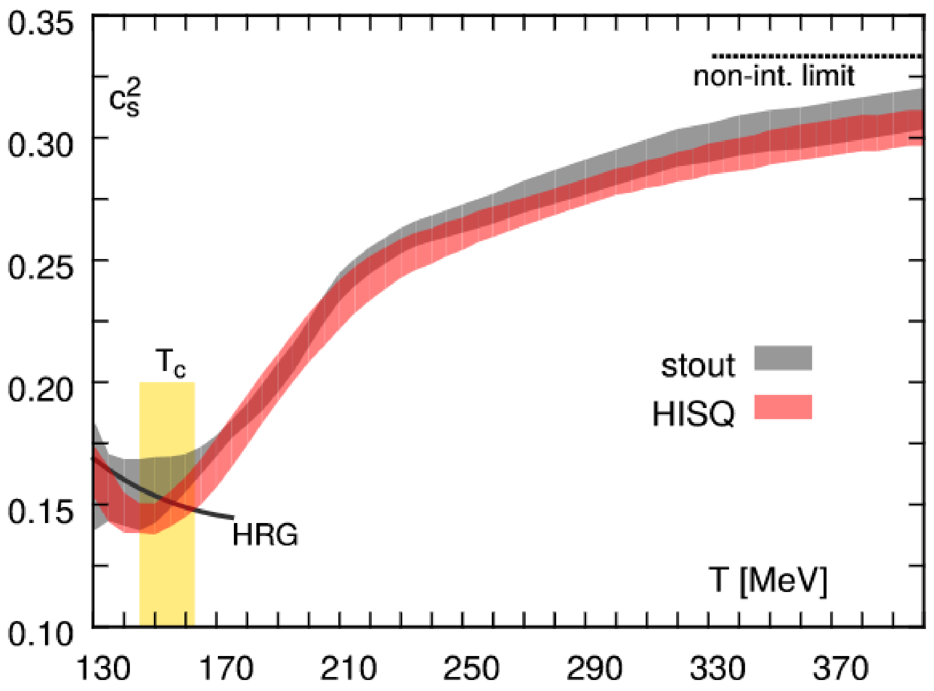
Allows accurate tracking of c_s^2 – an interesting quantity with tension between expectations from nuclear theory and experience from other contexts





On top of the usual low- and high-density limits, always require:

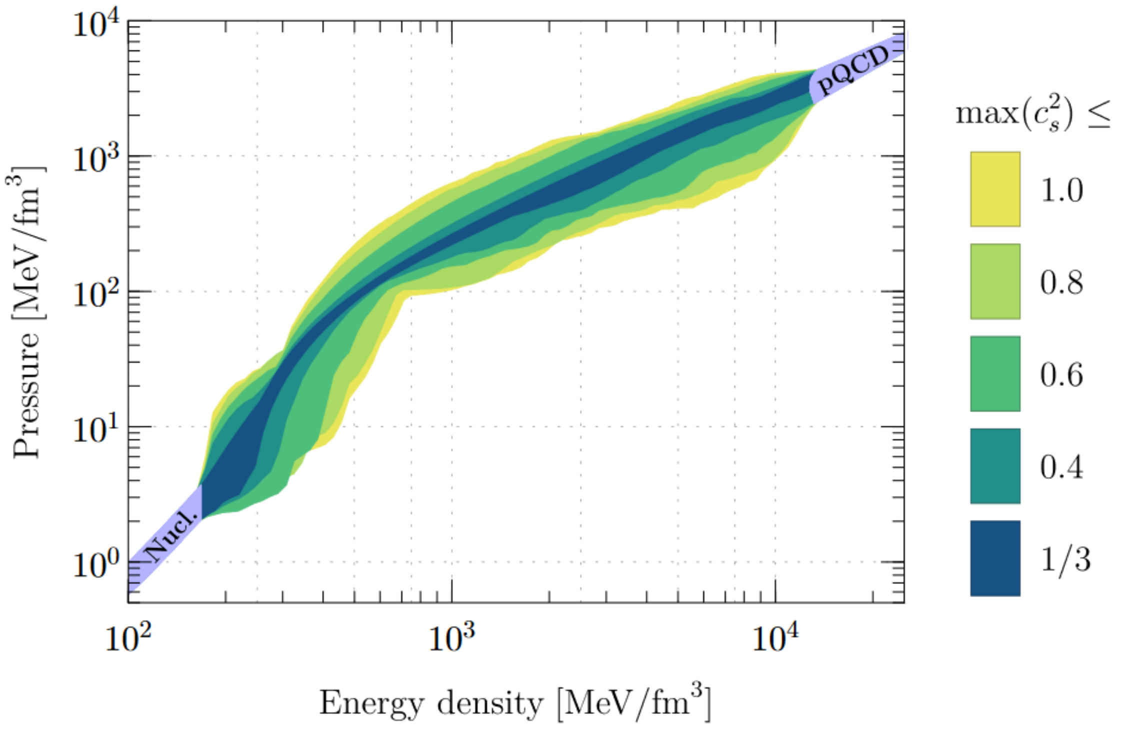
- EoS must support $2M_\odot$ stars
- LIGO/Virgo 90% tidal deformability limit must be satisfied

[Annala et al., Nature Physics (2020)]

In addition, can also take into account:

- NICER data for PSR J0740+6620:
  - $R(2M_\odot) > 11.0\text{km}$ (95%)
  - $R(2M_\odot) > 12.2\text{km}$ (68%)
- BH formation in GW170817 via
  - Supramassive or hypermassive NS

[Annala et al., PRX 12 (2022)]



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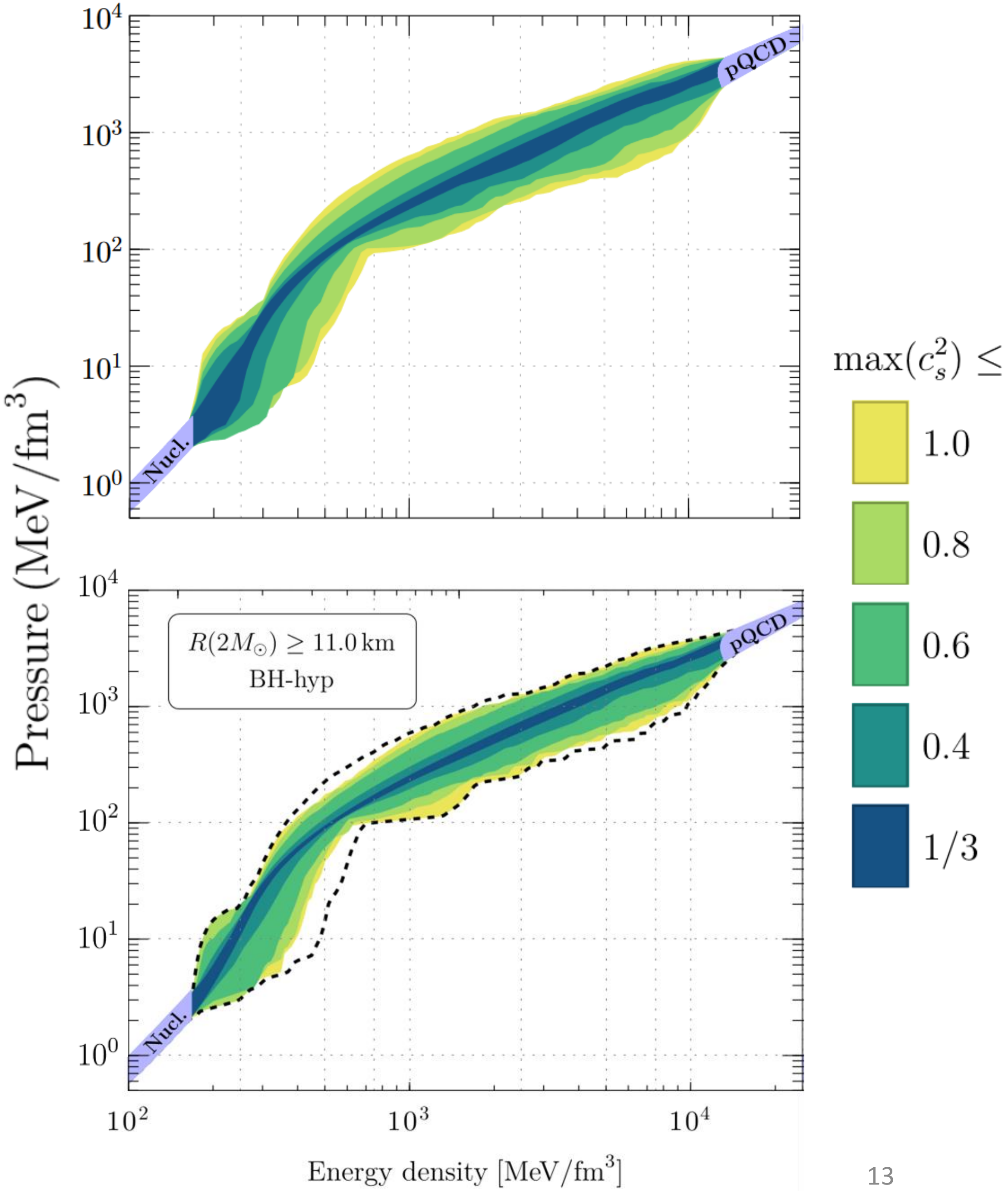

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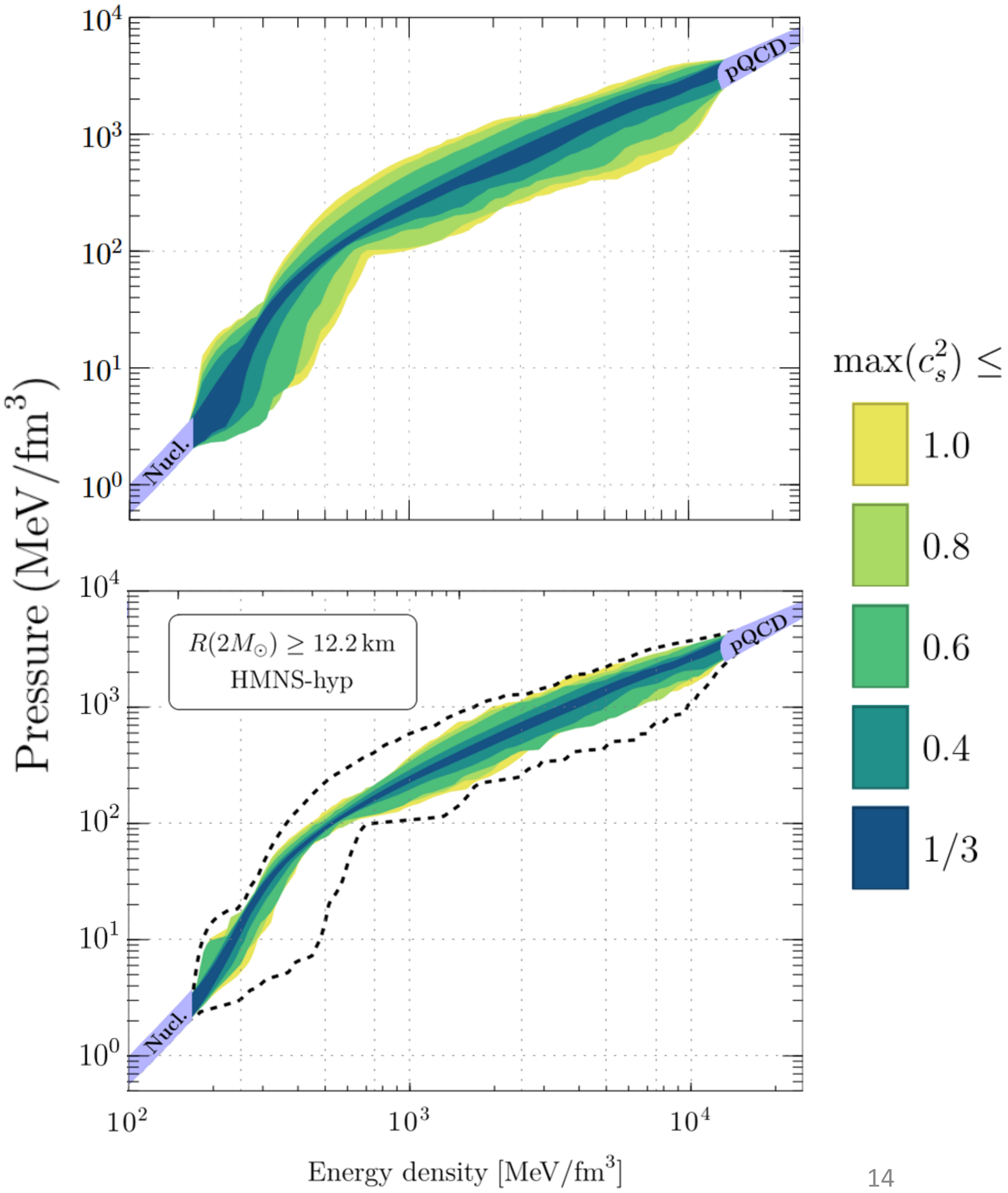
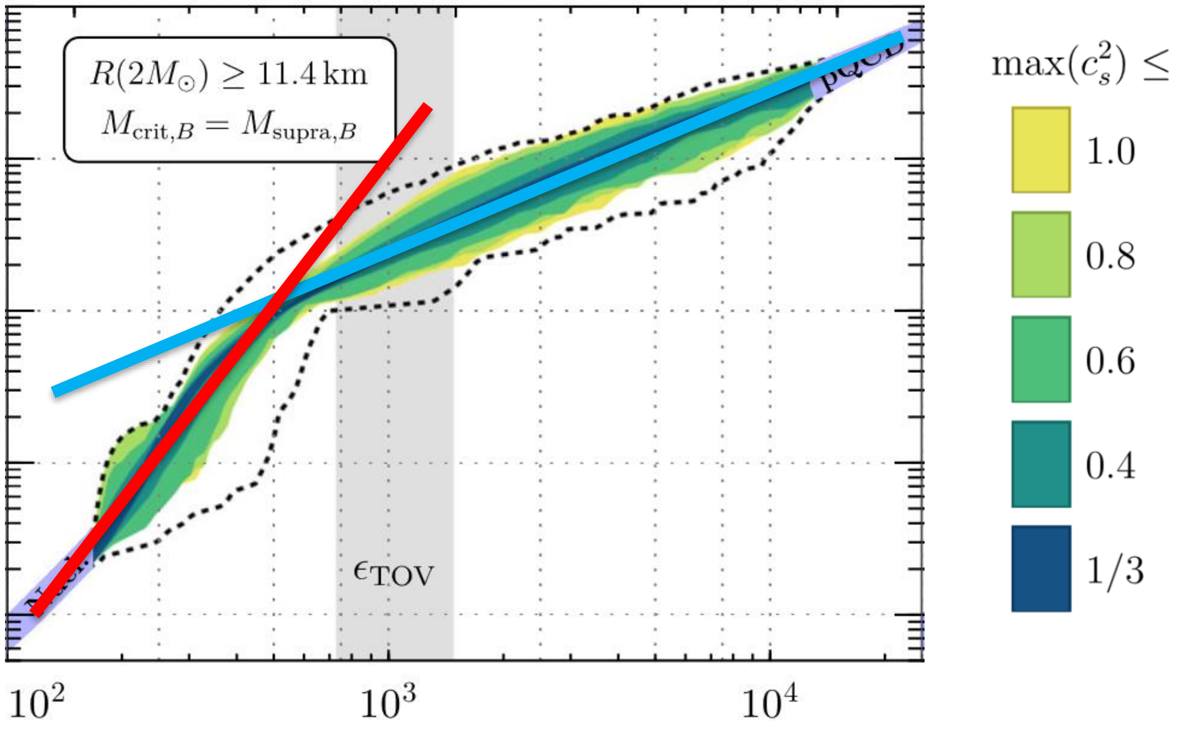


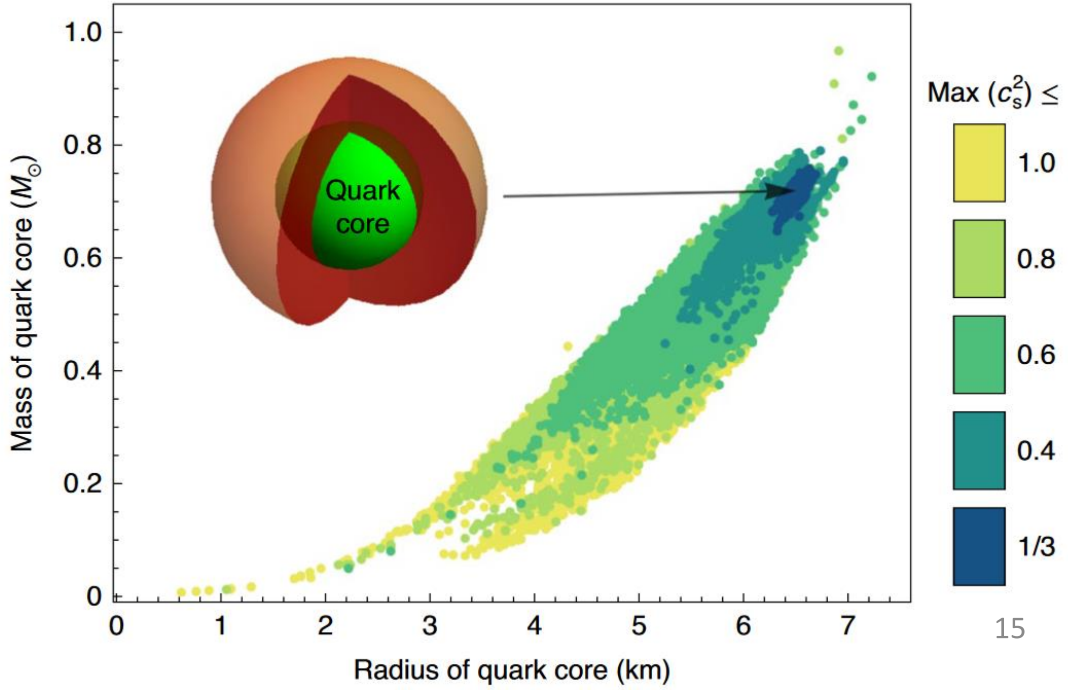
The EoS band features clear two-phase structure, with polytropic index $\gamma \equiv \frac{d \ln p}{d \ln \epsilon}$ transitioning from hadronic ($\gamma \gtrsim 2$) to near-conformal ($\gamma \approx 1$) behavior below TOV densities: evidence for QM cores

[Annala et al., Nature Physics (2020)]



However, open questions remain:

1) Do other quantities display similar signs of conformalization?
2) Does conformalization necessarily imply onset of deconfinement?
3) How likely are QM cores in TOV stars?
4) What is the role of the pQCD limit?



NS-matter EoS: recent Bayesian results

Improvements in recent work:

- Factor in measurement uncertainties ⇒ ability to utilize many more observations in the analysis
- Track also conformal anomaly and its log derivative $\Delta \equiv \frac{\epsilon - 3p}{3\epsilon}$, $\Delta' \equiv \frac{d\Delta}{d \ln \epsilon}$
- For comparison, construct EoSs with non-parametric Gaussian Process regression

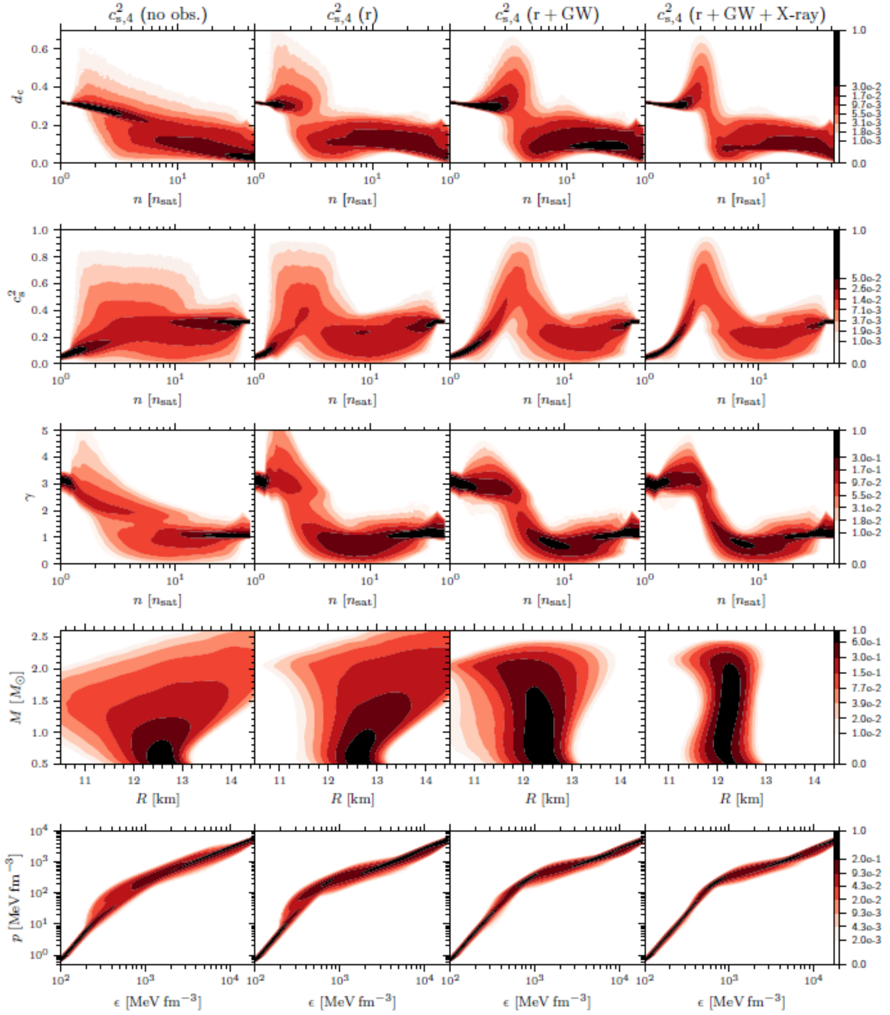
Ultimate goal: Approx. likelihoods of various scenarios (QM core, destabilizing FOPT,…)

Tools: MCMC utilizing Bayesian inference:

$$P(\mathrm{EoS}|\mathrm{data}) = \frac{P(\mathrm{data}|\mathrm{EoS})P(\mathrm{EoS})}{P(\mathrm{data})}$$

[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, Nature Comm. 14 (2023)]

	CEFT	Dense NM	Pert. QM	CFTs	FOPT
c_s^2	$\ll 1$	$[0.25, 0.6]$	$\lesssim 1/3$	$1/3$	0
Δ	$\approx 1/3$	$[0.05, 0.25]$	$[0, 0.15]$	0	$1/3 - p_{\mathrm{PT}}/\epsilon$
Δ'	≈ 0	$[-0.4, -0.1]$	$[-0.15, 0]$	0	$1/3 - \Delta$
d_c	$\approx 1/3$	$[0.25, 0.4]$	$\lesssim 0.2$	0	$\geq 1/(3\sqrt{2})$
γ	≈ 2.5	$[1.95, 3.0]$	$[1, 1.7]$	1	0
p/p_{free}	$\ll 1$	$[0.25, 0.35]$	$[0.5, 1]$	—	$p_{\mathrm{PT}}/p_{\mathrm{free}}$



Main results:

1) All quantities studied – $\gamma, c_s^2, \Delta, \Delta'$ – consistently approach their conformal limits close to (but below) the central densities of M_{TOV} stars

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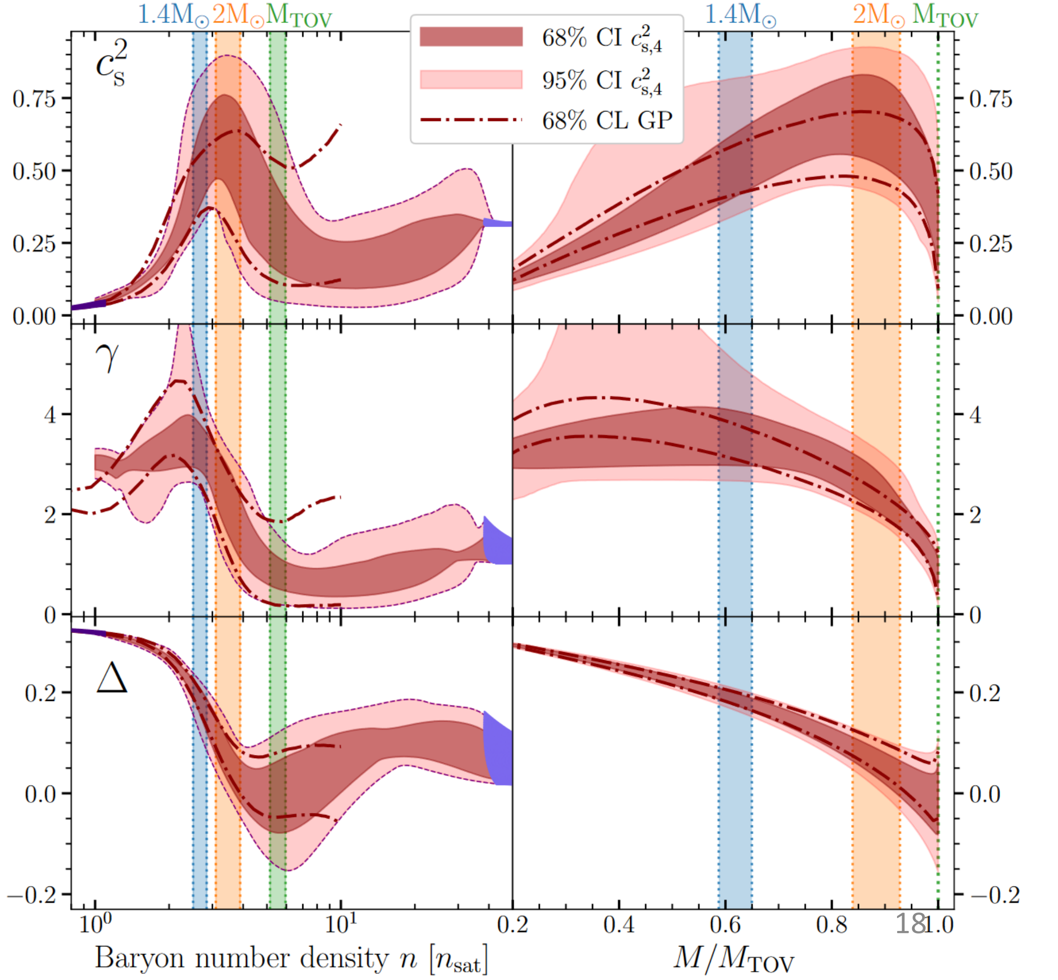

[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, Nature Comm. 14 (2023)]

Main results:

2) Optimal quantity to track: "conformal distance" $d_c \equiv \sqrt{\Delta^2 + (\Delta')^2}$
   - Its conformalization ensures that of all other quantities considered
   - Values in dense NM and perturbative QM sufficiently far apart
   - In FOPTs $d_c \geq 1/(3\sqrt{2}) \approx 0.24$

∴ Our intentionally conservative criterion for near-conformality: $d_c < 0.2$

[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, Nature Comm. 14 (2023)]

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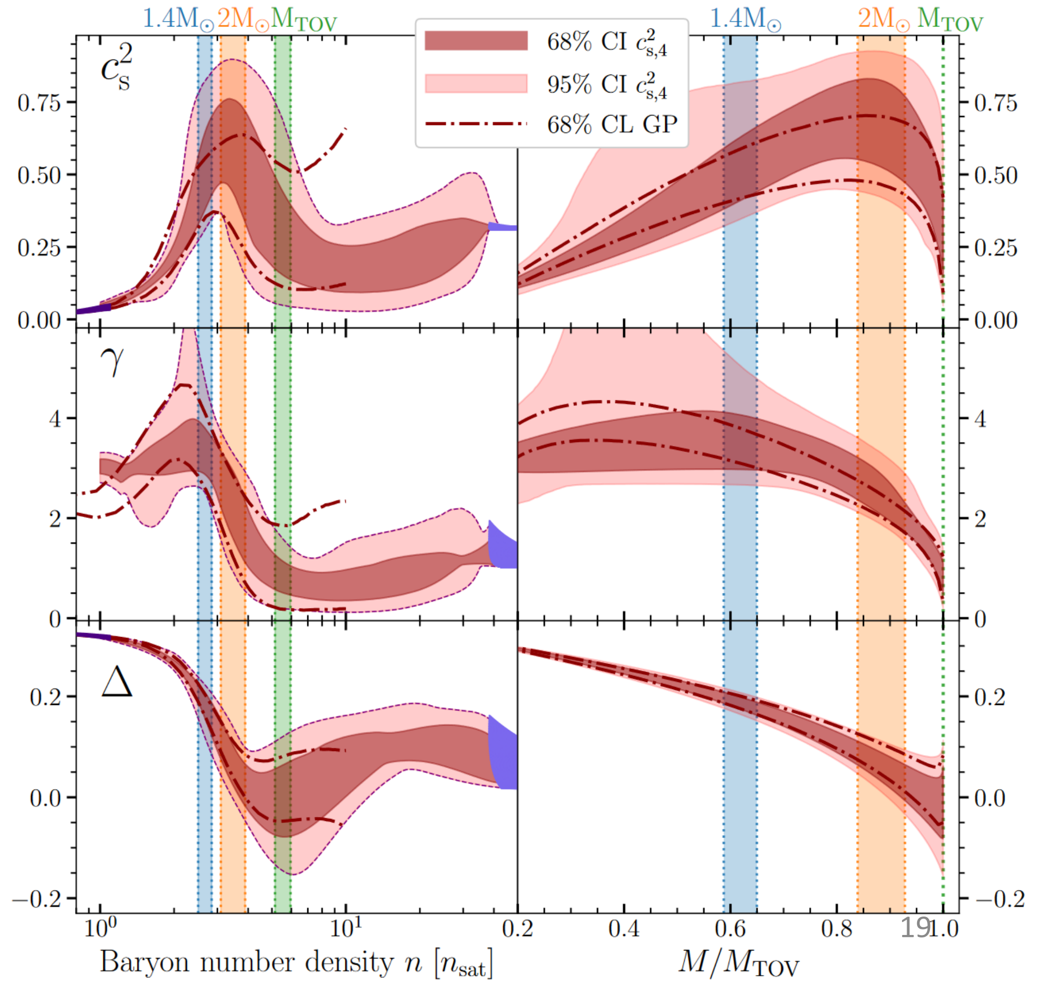
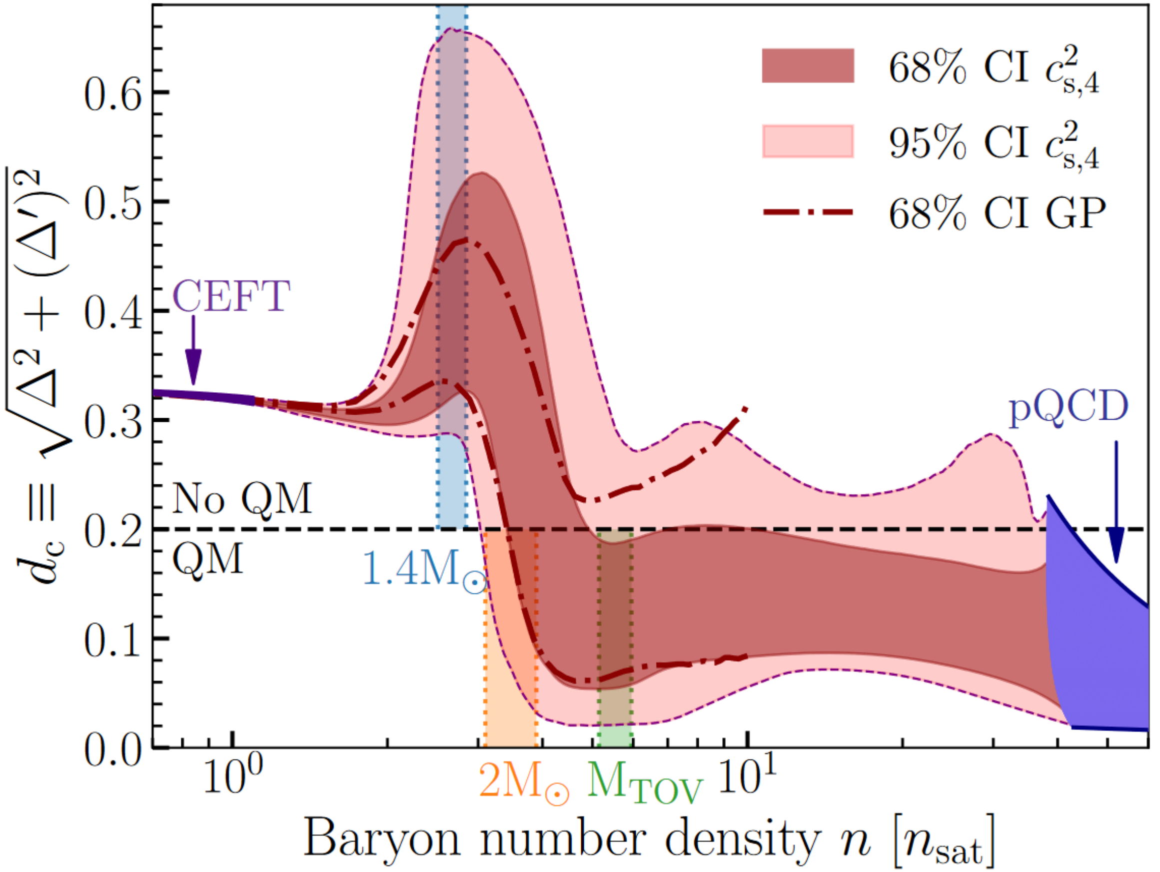


Main results:

3) Likelihood of conformalized matter in centers of

- $1.4 M_\odot$ NSs: 0%
- $2.0 M_\odot$ NSs: 11%
- M_{TOV} NSs: 88%



New criterion **very** conservative: with old criterion ($\gamma < 1.75$) from our 2020 Nat. Phys., the above 88% would be 99.8%.

For remaining 12% of TOV-star centers, all EoSs feature FOPT-like behavior.

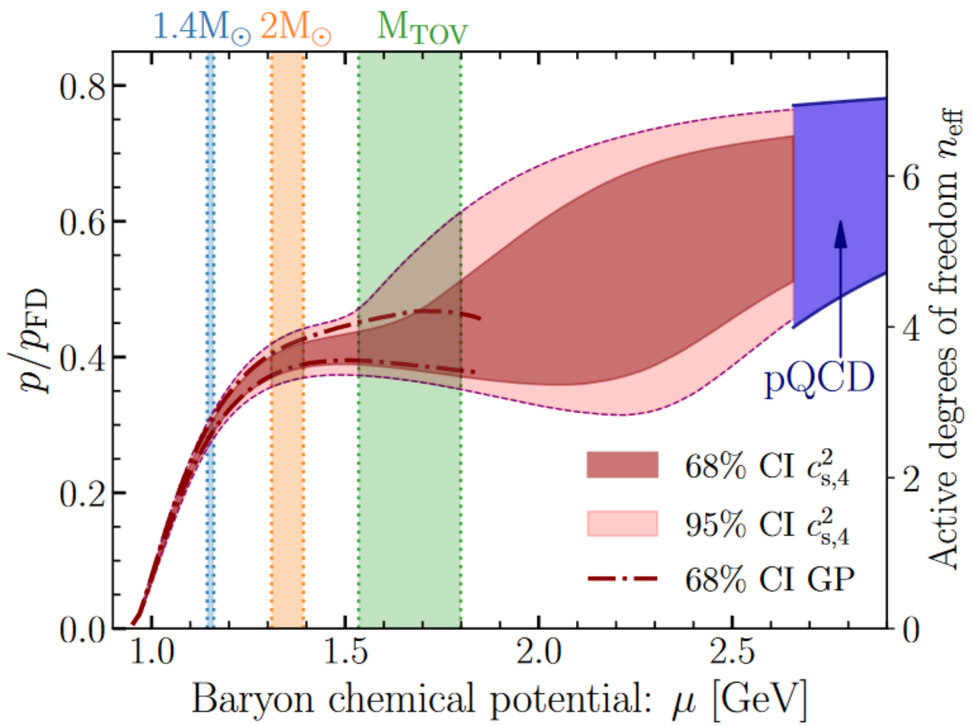
[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, Nature Comm. 14 (2023)]

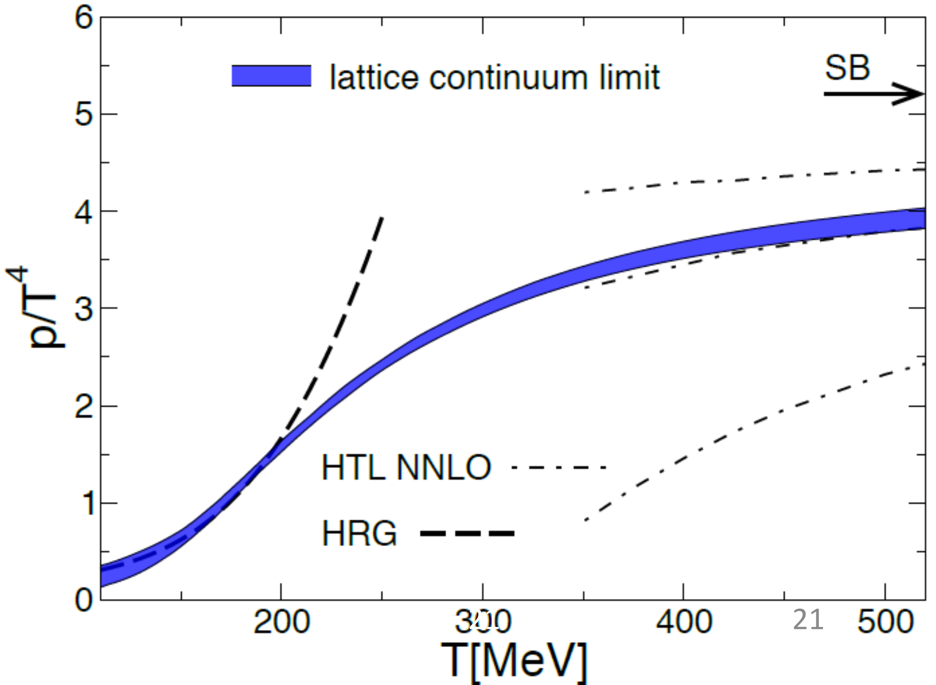
Main results:

4) For weak coupling and CFTs, normalized pressure ∝ number of active degrees of freedom.
In centers of TOV stars, p/p_{FD} at approx. 2/3 of its value in pQCD, while at high T crossover transition from hadron gas to QGP at much smaller values of p/p_{SB}.

∴ “Near-conformal“ very likely implies “deconfined”.

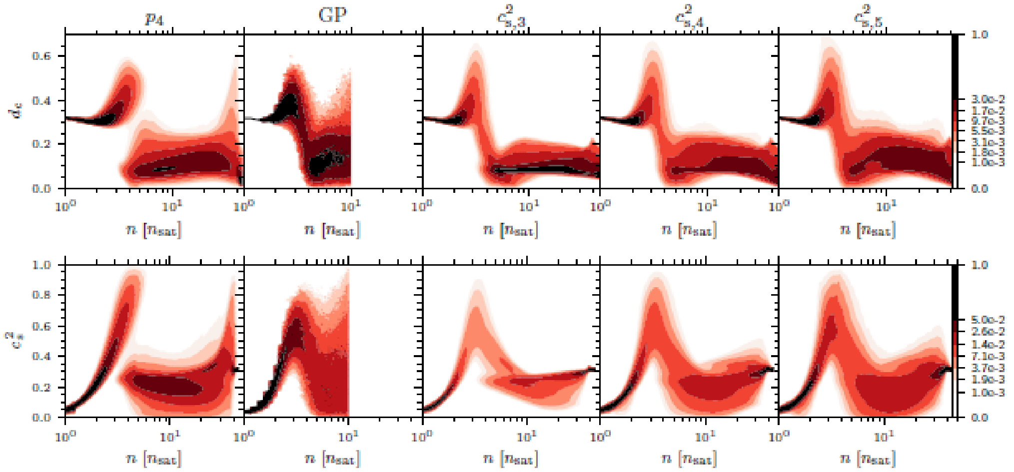
[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, Nature Comm. 14 (2023)]



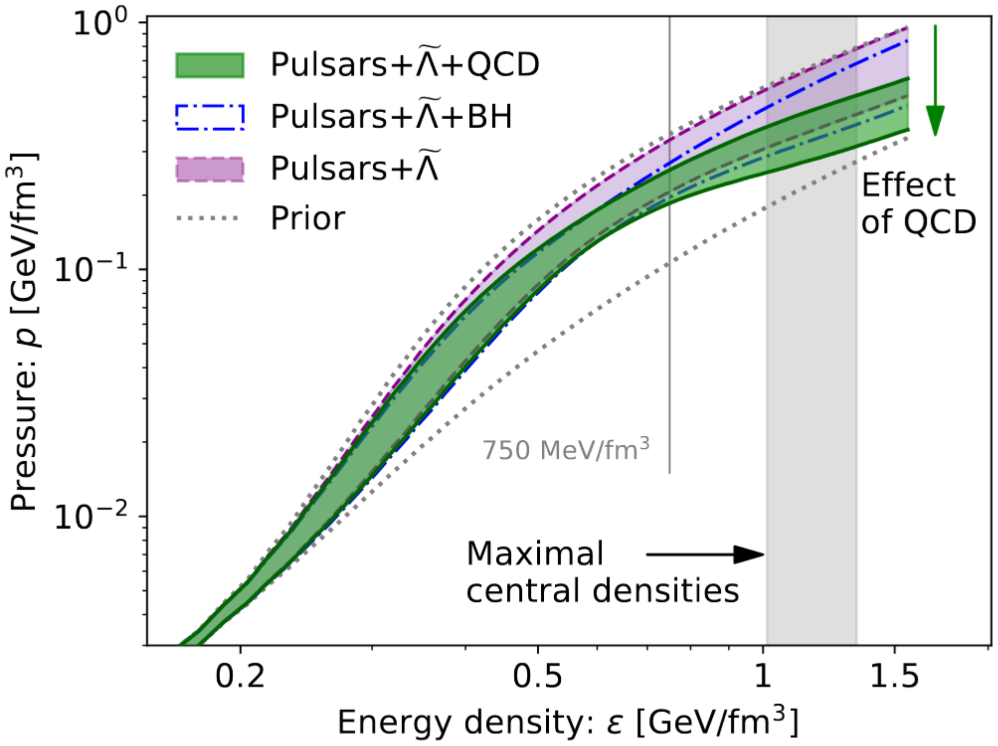


Main results:

5) Results independent of the details of interpolation, with those from non-parametric Gaussian Process regression well in line with c_s^2 ones.



With GP method, possible to show that it is precisely the pQCD constraint that softens the EoS in the cores of TOV stars.



[Gorda, Komoltsev, Kurkela, Astrophys. J. 950 (2023)]

[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, Nature Comm. 14 (2023)]

Remaining caveat: strong first-order PTs

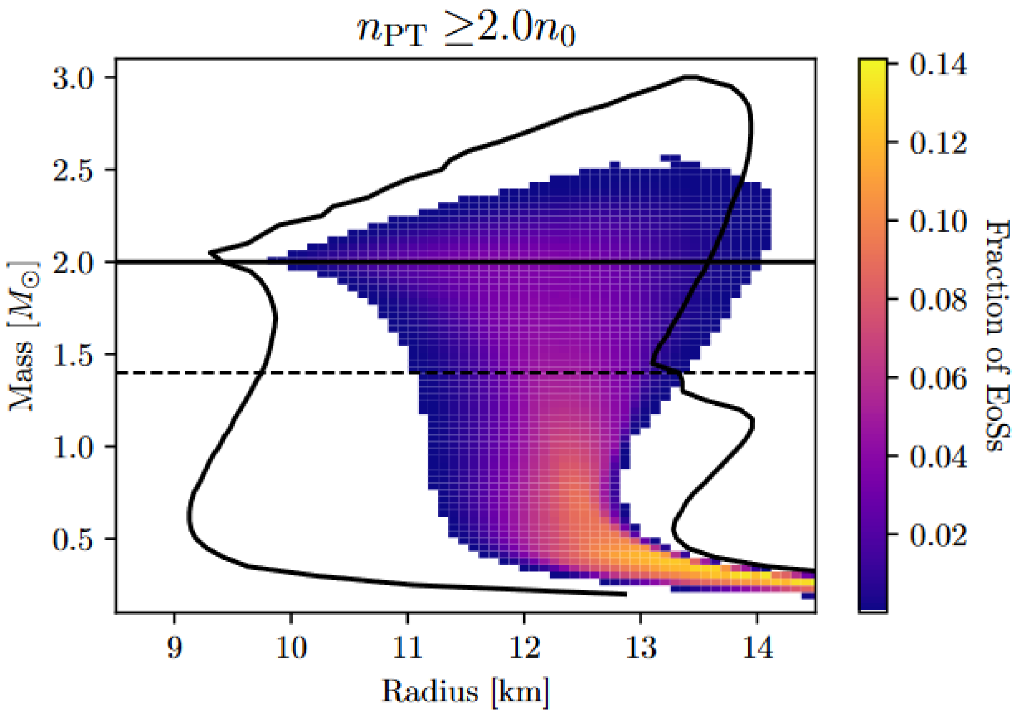
Most current results approximate PTs as rapid crossovers, but some preliminary results with discontinuous transitions exist:

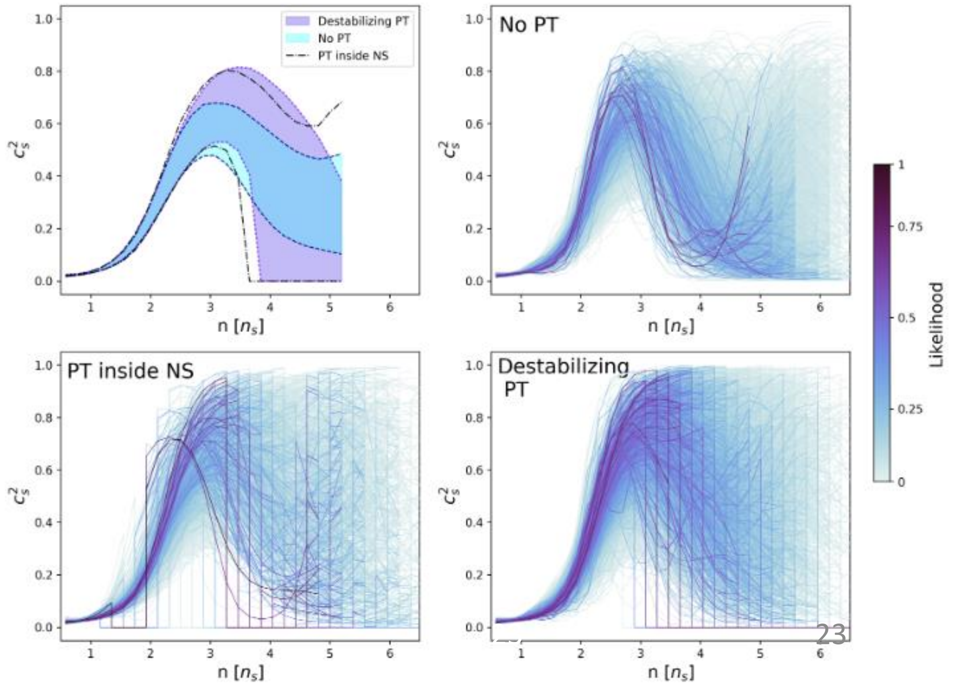
- In hard-limit setups, possible to exit EoS bounds based on rapid crossovers
    - Destabilizing solutions often extreme, but not unreasonably so
- Implications for likelihood of QM cores inconclusive so far

[Gorda, Hebeler, Kurkela Schwenk, AV, Astrophys. J. 955 (2023)]

[Komoltsev, arXiv:2404.05637]

[Blomqvist, Ecker, Gorda, AV, In preparation]





Conclusions

Main takeaways:

1) Strong evidence for rapid conformalization of matter near central densities of TOV stars, *identifiable as onset of deconfinement*
2) Only remaining alternative to QM cores: strong destabilizing first-order phase transition, responsible for the value of M_{TOV}
   - Can this transition be constrained with postmerger GW signal?
3) In near future, dramatic improvements expected from pQCD calculations and observations (perhaps also from CET?), bringing **robust discovery of QM cores within sight**