Model-independent approach to the NS-matter equation of state

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Hot problems in Strong Interactions

9 November 2020

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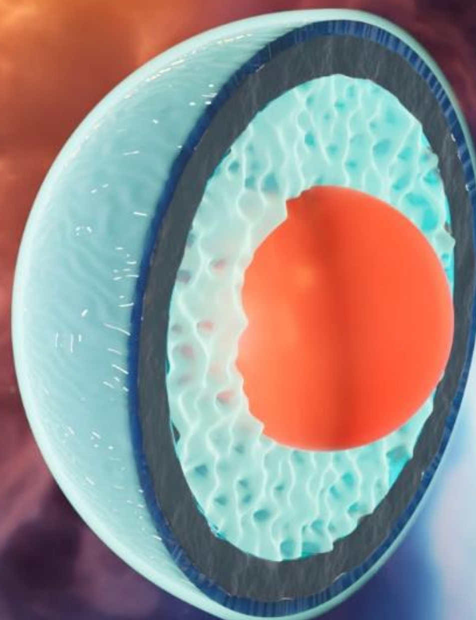
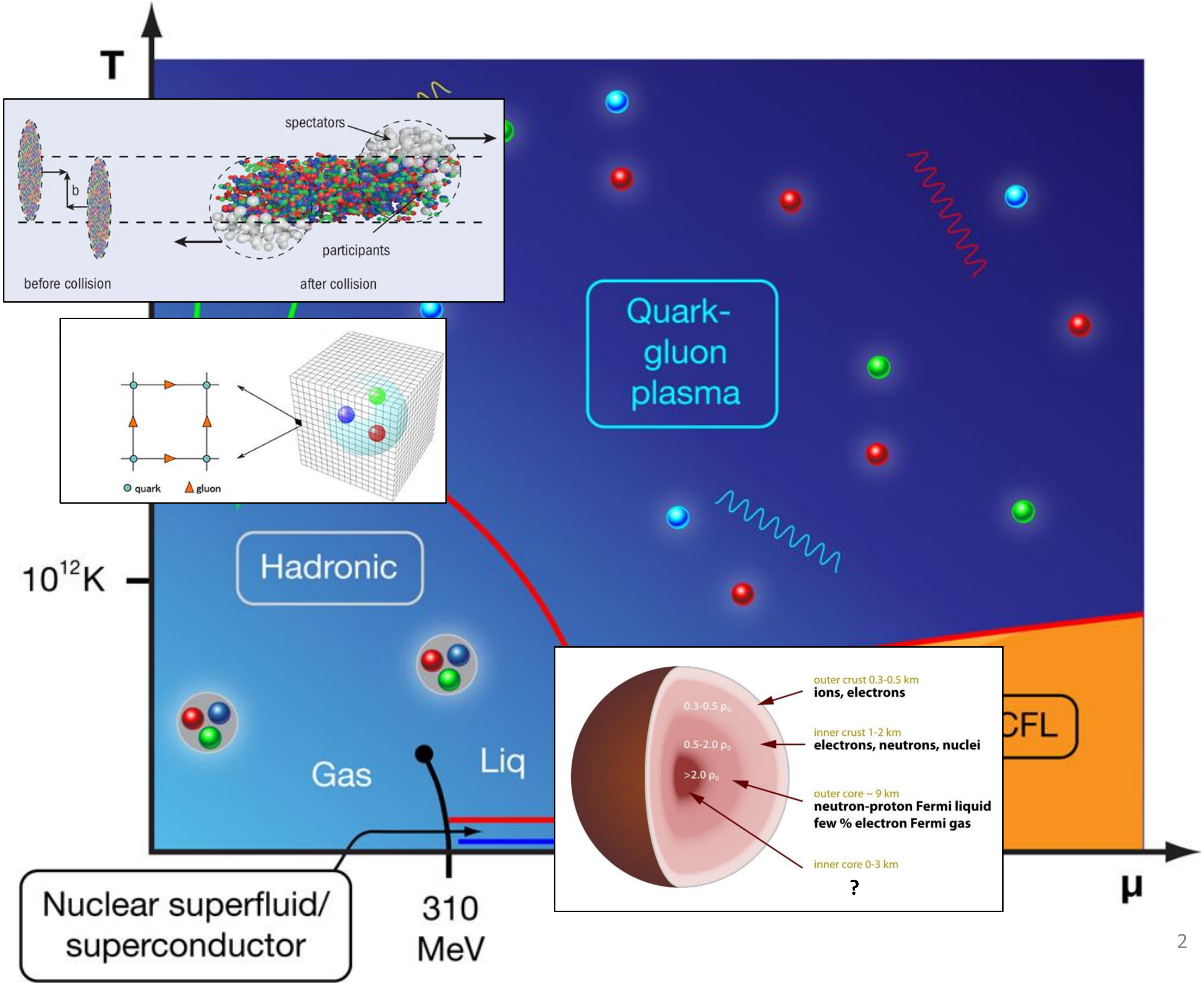
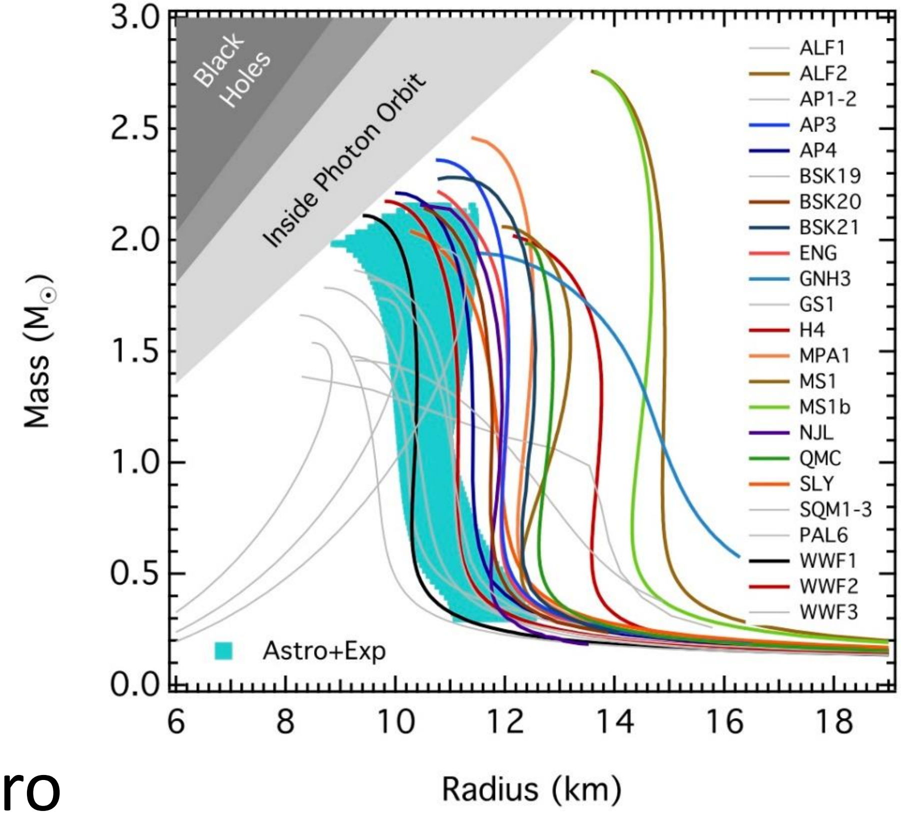


Main references:

1) Annala, Gorda, Kurkela, AV, PRL 120 (2018), 1711.02644
2) Gorda, Kurkela, Romatschke, Säppi, AV, PRL 121 (2018), 1807.04120
3) **Annala, Gorda, Kurkela, Nättilä, AV, Nature Phys. (2020), https://www.nature.com/nphys/**


T
10^{12}K
μ
spectators
b
participants
before collision
after collision
quark
gluon
Quark-gluon plasma
Hadronic
Gas
Liq
CFL
Nuclear superfluid/ superconductor
310 MeV
outer crust 0.3-0.5 km
ions, electrons
inner crust 1-2 km
electrons, neutrons, nuclei
outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas
inner core 0-3 km
?
0.3-0.5 ρ_0
0.5-2.0 ρ_0
>2.0 ρ_0

Underlying challenge with NSs: *Can we determine the properties of cold & dense QCD matter using only first principles field theory tools and robust observational data on neutron stars?*



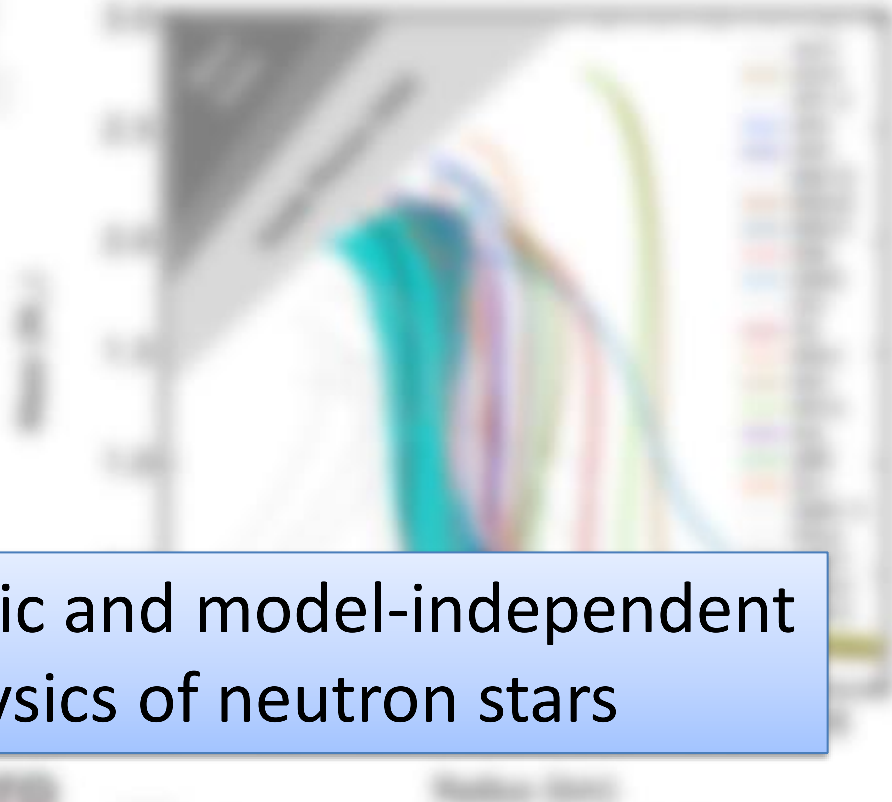
Ozel et al., ApJ 820 (2016)

Link between micro and macro from GR (non-rotating TOV-eqs.):

$$\begin{aligned}\frac{dM(r)}{dr} &= 4\pi r^2 \varepsilon(r),\\ \frac{dp(r)}{dr} &= -\frac{G\varepsilon(r)M(r)}{r^2}\frac{\left(1+p(r)/\varepsilon(r)\right)\left(1+4\pi r^3 p(r)/M(r)\right)}{1-2GM(r)/r}\end{aligned}$$

$$\varepsilon(p) \Rightarrow M(R)$$

Underlying challenge with NSs: *Can we determine the properties of cold & dense QCD matter using only first principles field theory tools*



Özel et al., ApJ 820 (2016)

Clear need for a systematic and model-independent approach to the microphysics of neutron stars

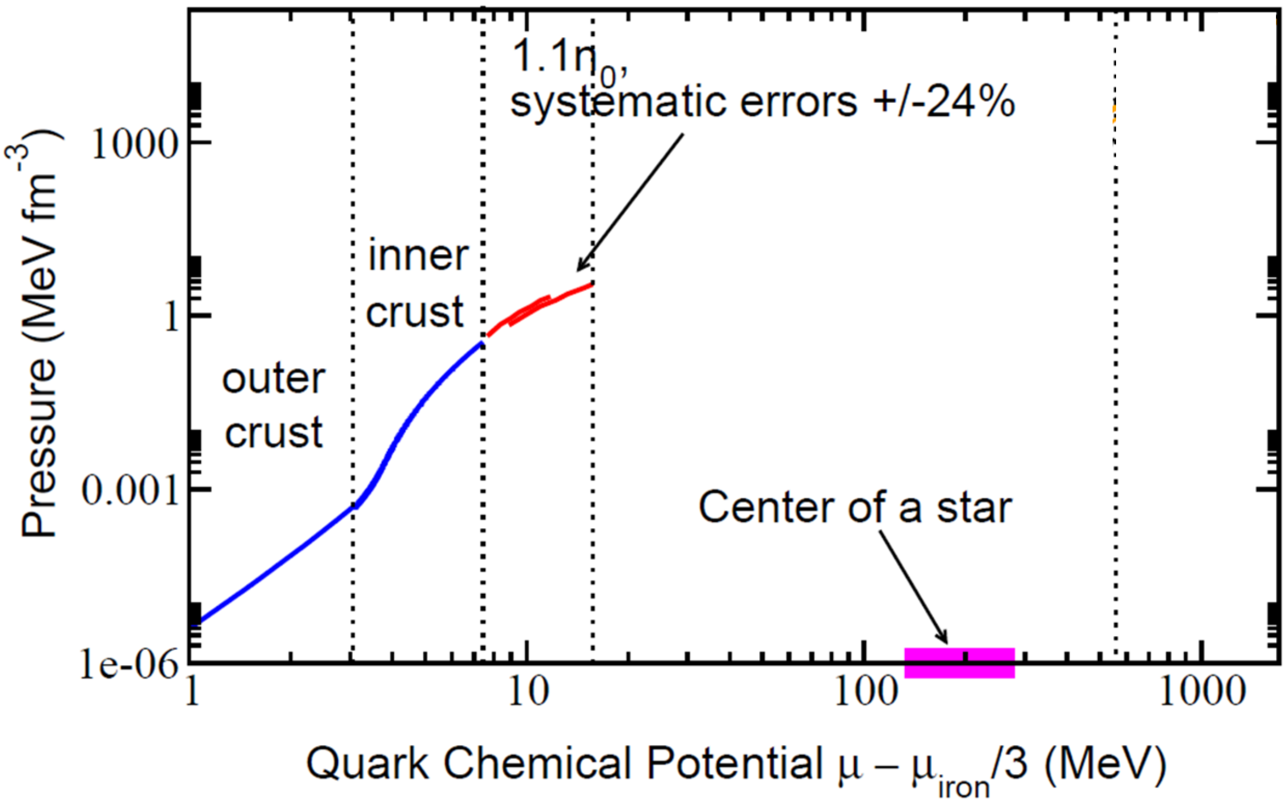
Link between micro and macro from GR (non-rotating TOV eqs.)

$$\frac{dM(r)}{dr} = 4\pi r^2 \epsilon(r),$$

$$\frac{dp(r)}{dr} = -\frac{G\epsilon(r)M(r)}{r^2}\frac{[1+p(r)/\epsilon(r)][1+4\pi r^3 p(r)/M(r)]}{1-2GM(r)/r}$$

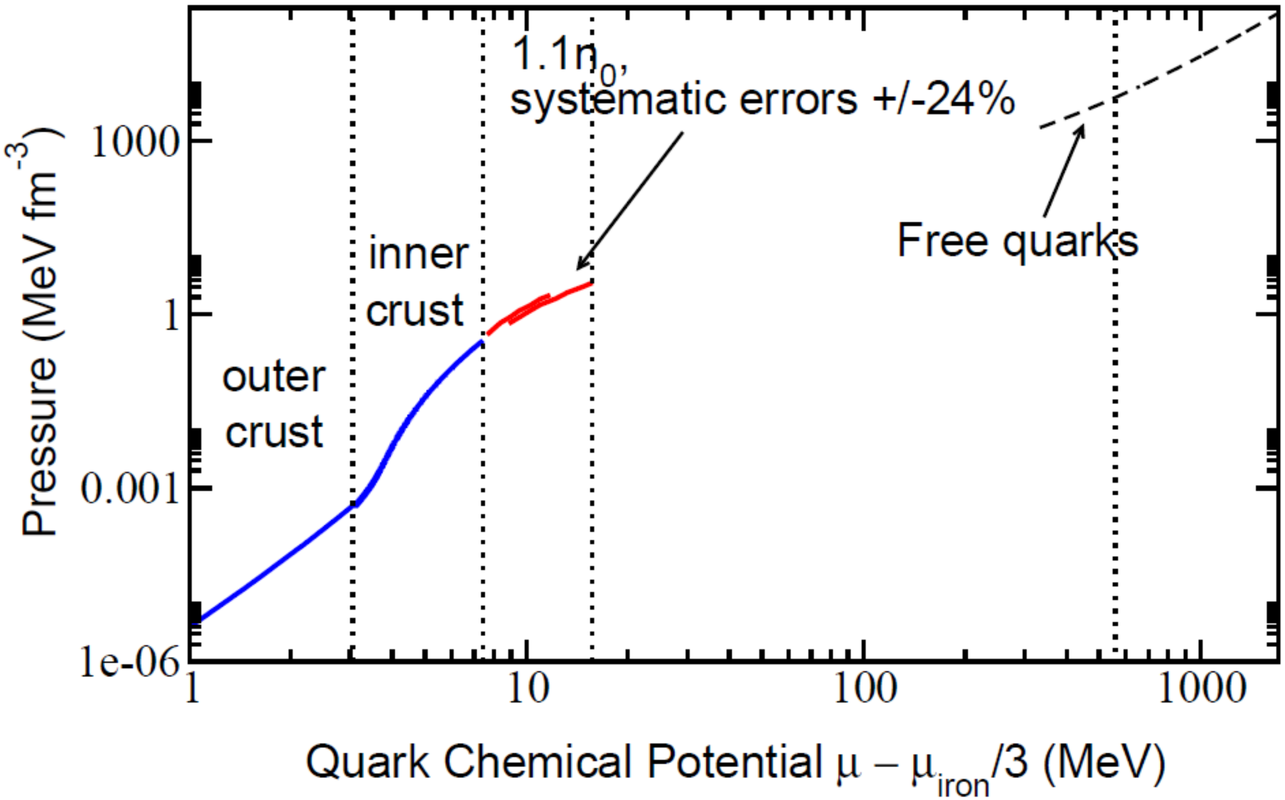
$$\epsilon(p) \Leftrightarrow M(R)$$

NS matter EoS – robust theoretical limits



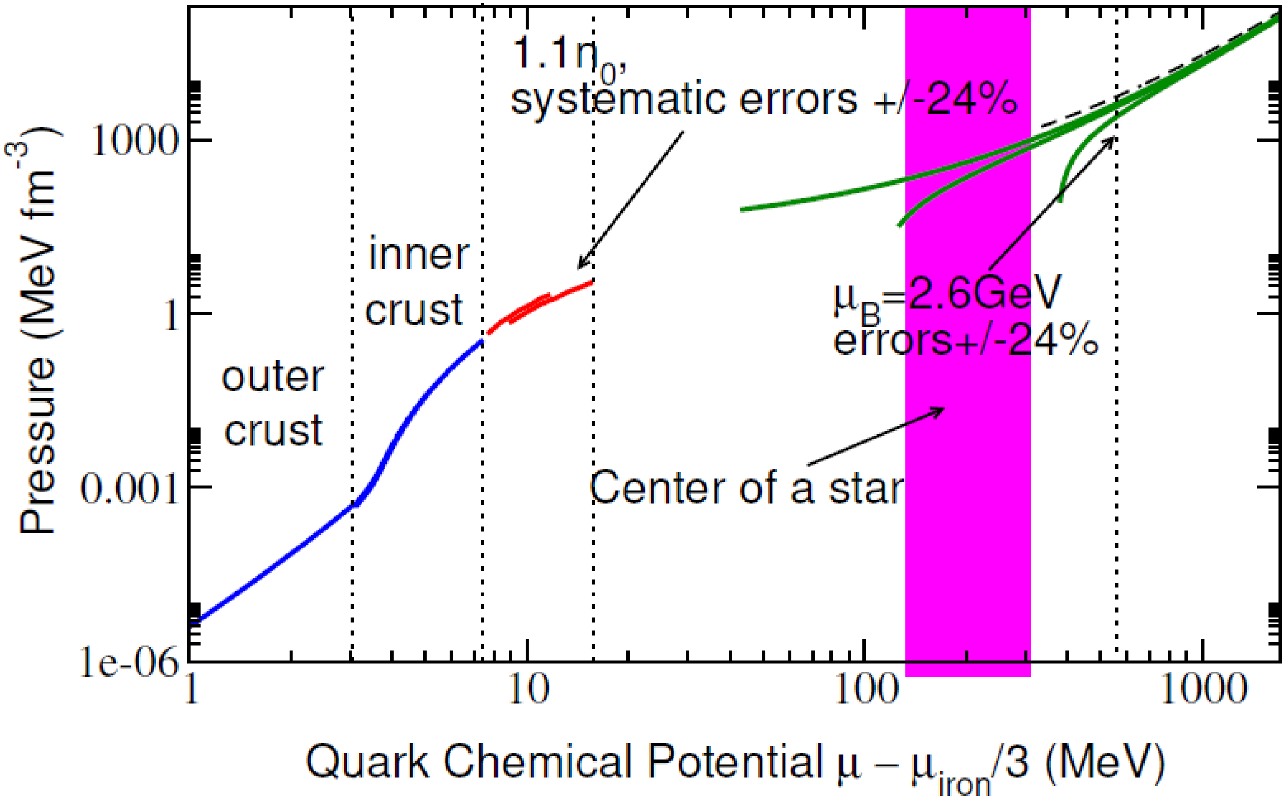
Low-density behavior of EoS well known from nuclear theory side. Challenges begin close to saturation density:

- At $1.1n_s$, current errors in Chiral Effective Theory EoS $\pm 24\%$ - mostly due to uncertainties in effective theory parameters
- State-of-the-art EoS NNNLO in chiral perturbation theory power counting [Tews et al., PRL 110 (2013), Hebeler et al., ApJ 772 (2013)]



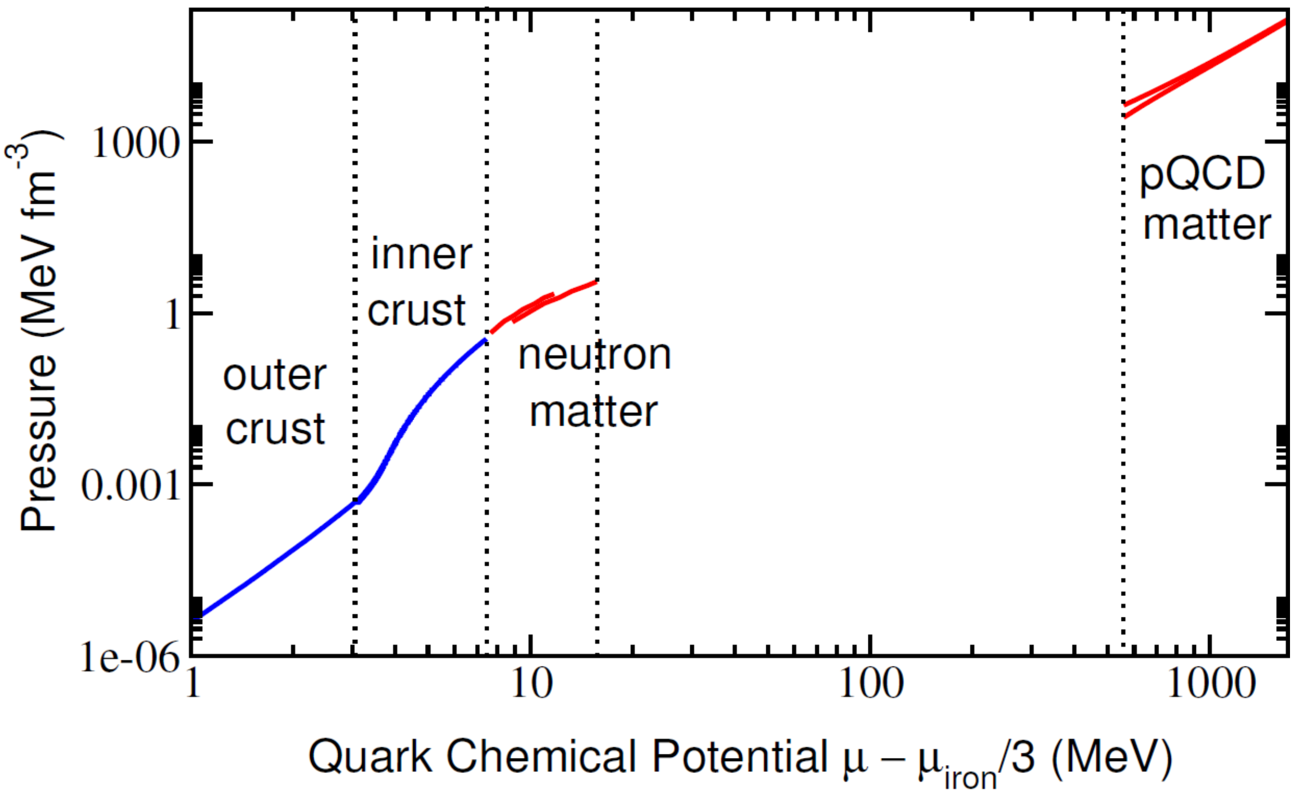
Asymptotic freedom of QCD ⇒ High-density limit from a non-interacting theory. However,…

- For practical applications, need to know also how rapidly this limit is approached
- At interesting densities $(1-10)n_s$ system clearly strongly coupled and no nonperturbative methods available



State-of-the-art in pQCD: three loops at $m_q \neq 0$; towards four loops at $m_q = 0$ [Kurkela, Romatschke, Vuorinen, PRD 81 (2009); Gorda, Kurkela, Romatschke, Säppi, AV, PRL 121 (2018);...]

- Uncertainty in the result at $\pm 24\%$ level around $40 n_s$
- Main source of uncertainty: renormalization scale dependence
- Pairing contributions to EoS subdominant at perturbative densities



Conclusion: Sizable no man's land extending from outer core to densities not realized inside physical neutron stars

Options: Use models, novel nonperturbative techniques, or interpolate between the limits using observational data

What do we know from observations?

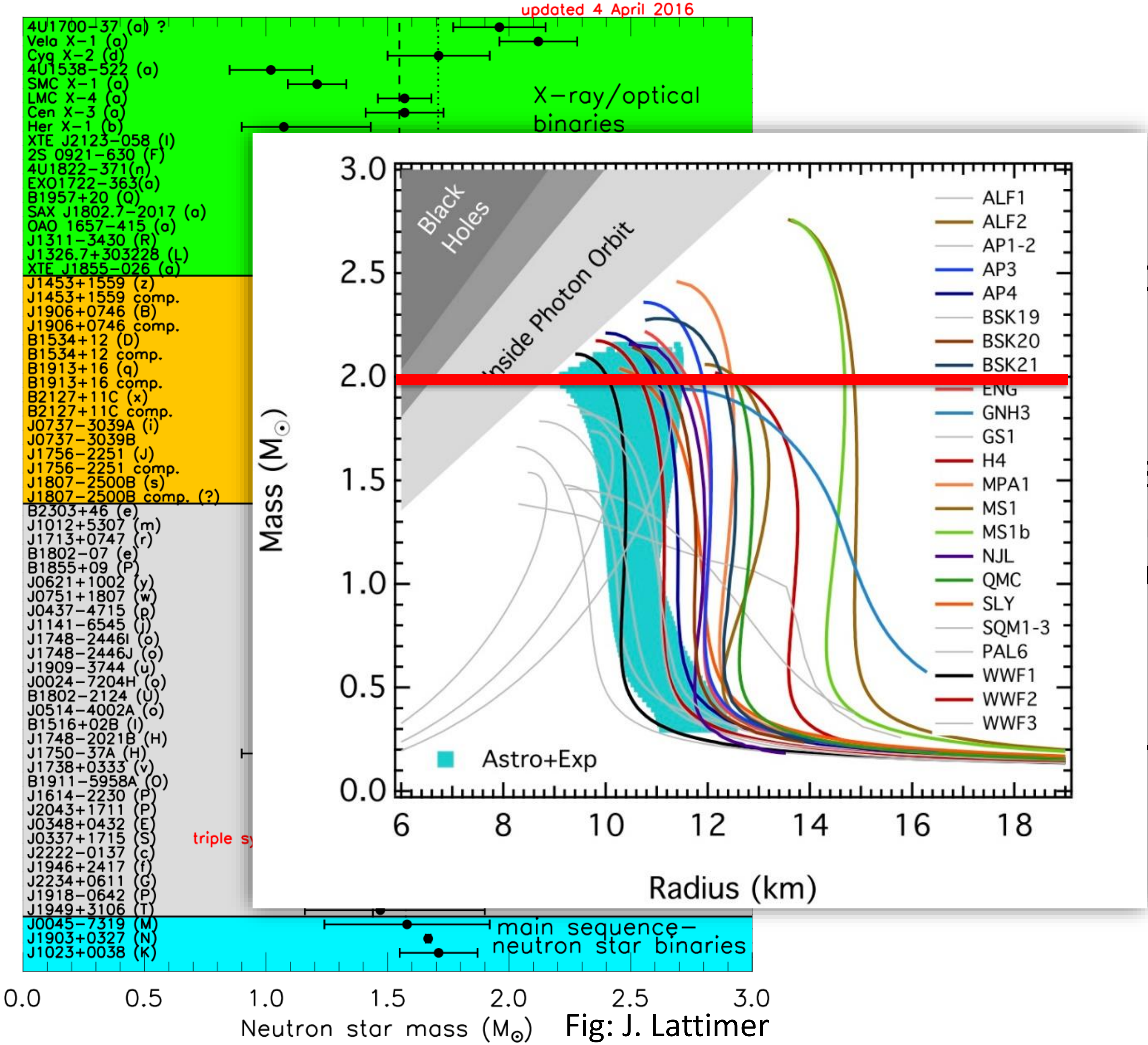


Fig: J. Lattimer

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s:

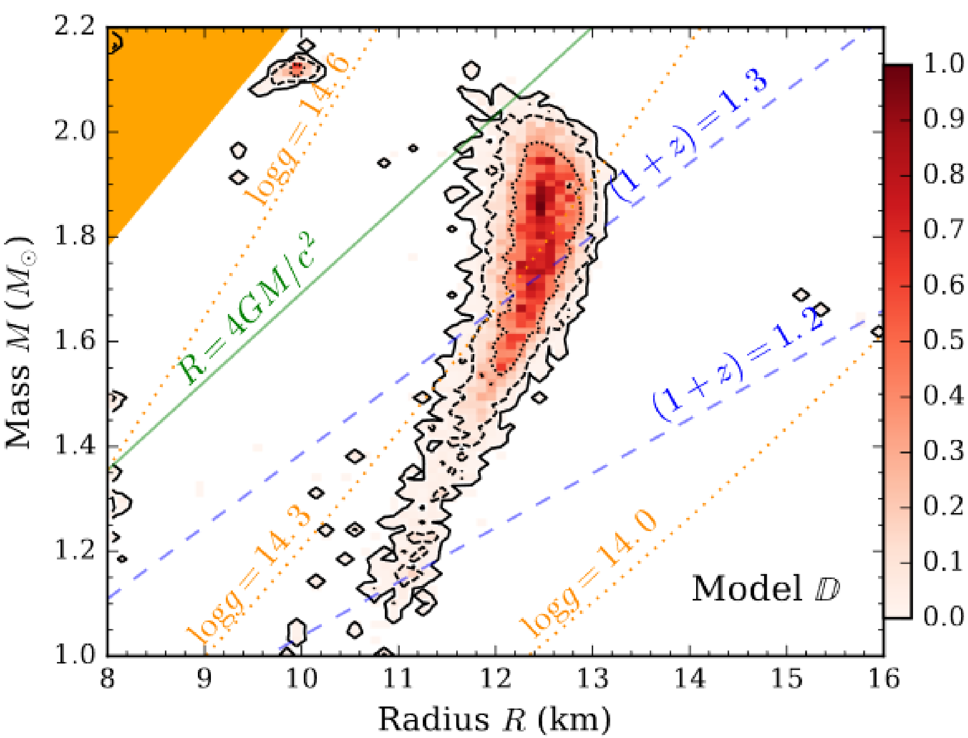
re 467 (2010)

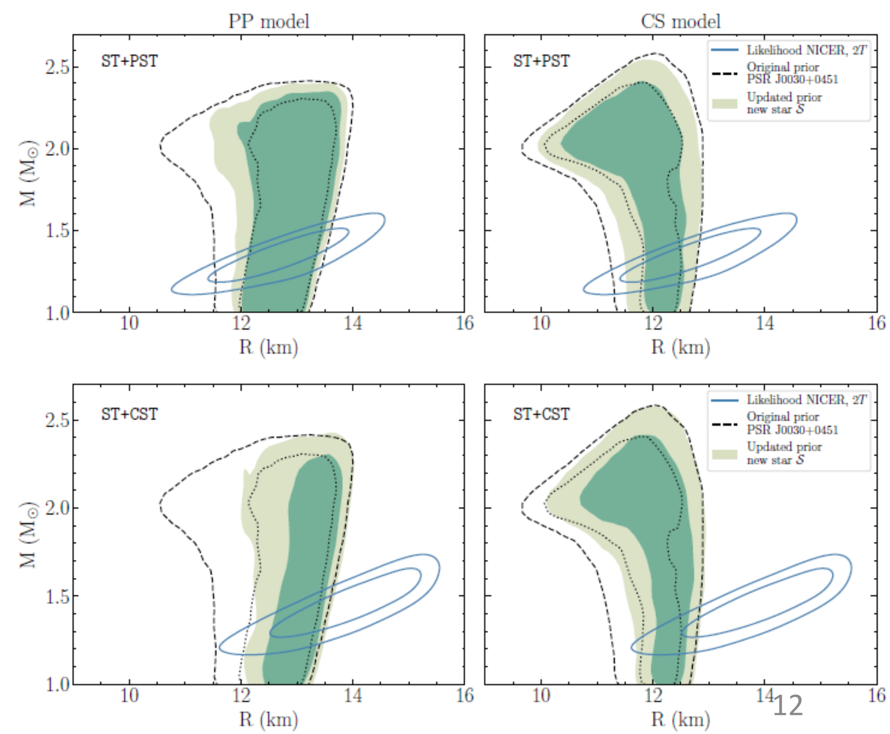
nce 340

$2M_\odot$

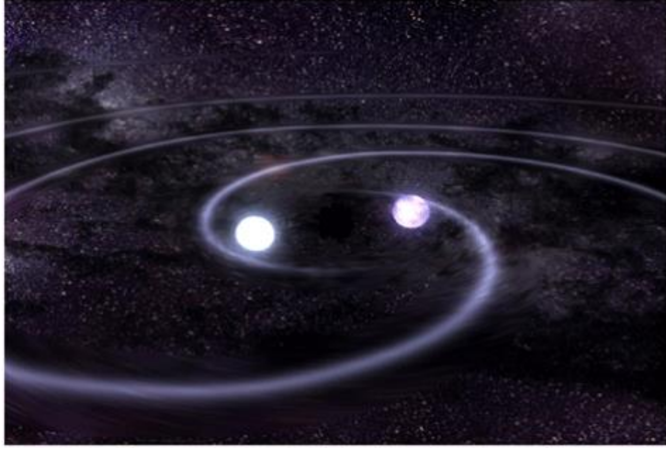
Radius measurements more problematic, but progress through observation of X-ray emission:

- Cooling of thermonuclear X-ray bursts provide radii to $\sim \pm 400$m [Nättilä et al., Astronomy & Astrophysics 608 (2017), …]
- Pulse profiling (NICER) has provided a robust radius measurem. for one NS so far [Raaijmakers et al., Astr.J.Lett. 887 (2019)]



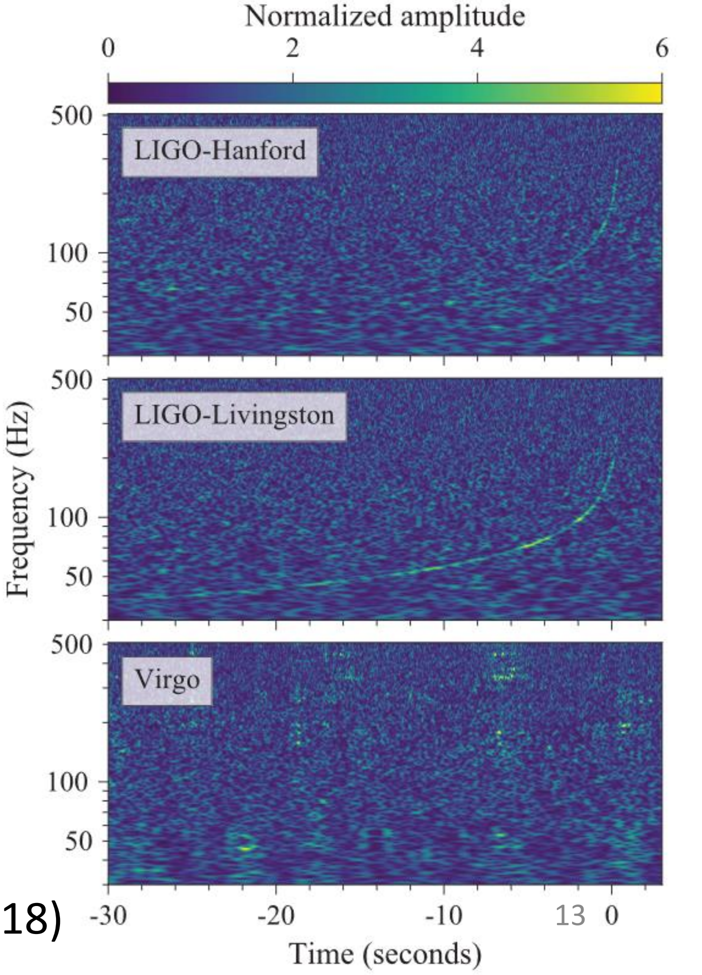


Gravitational wave breakthrough: First observed NS merger by LIGO & Virgo in 2017 (any many since then)



Three types of potential inputs:

1) Tidal deformabilities of the NSs during inspiral – good measure of stellar compactness
2) EM signatures – present if no immediate collapse to a BH
3) Ringdown pattern – sensitive to EoS (also at $T \neq 0$), but freq. too high for LIGO/Virgo

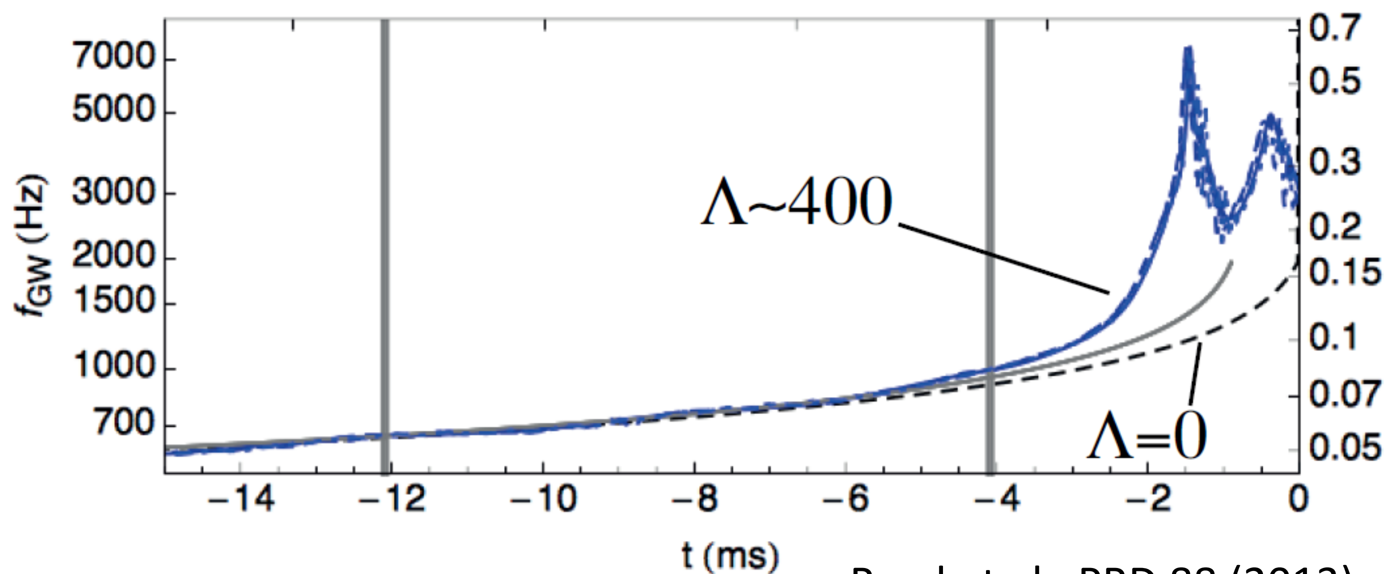


LIGO and Virgo collaborations, PRL 119 (2017), PRL 121 (2018)

Tidal deformability: How large of a quadrupolar moment a star's gravitational field develops due to an external quadrupolar field

$$Q_{ij} = -\Lambda \mathcal{E}_{ij}$$

Substantial effect on observed GW waveform during inspiral phase

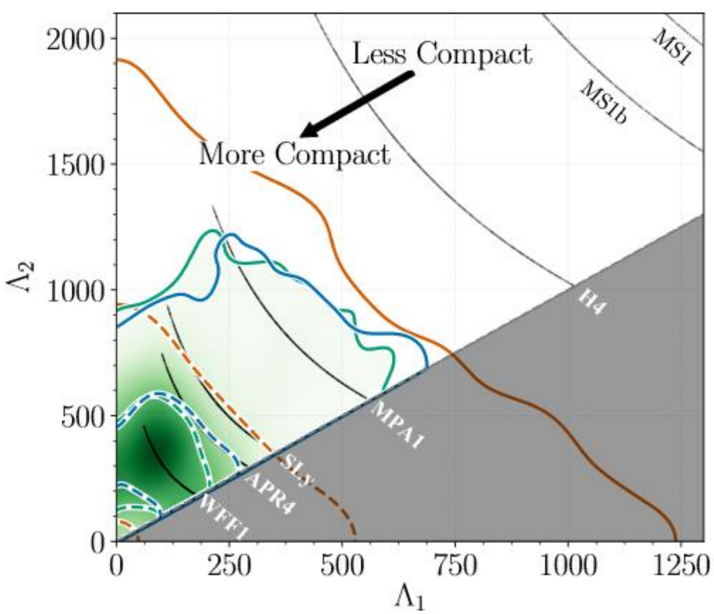


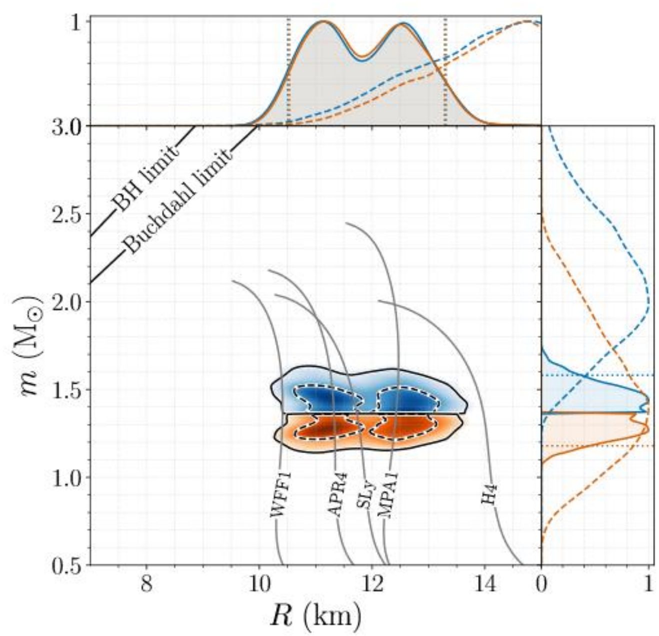
Read et al., PRD 88 (2013)

Tidal deformability: How large of a quadrupolar moment a star's gravitational field develops due to an external quadrupolar field

$$Q_{ij} = -\Lambda \mathcal{E}_{ij}$$

LIGO & Virgo bound $70 < \Lambda(1.4 M_{\odot}) < 580$ at 90% credence using low spin prior [LIGO and Virgo, PRL 121 (2018)]





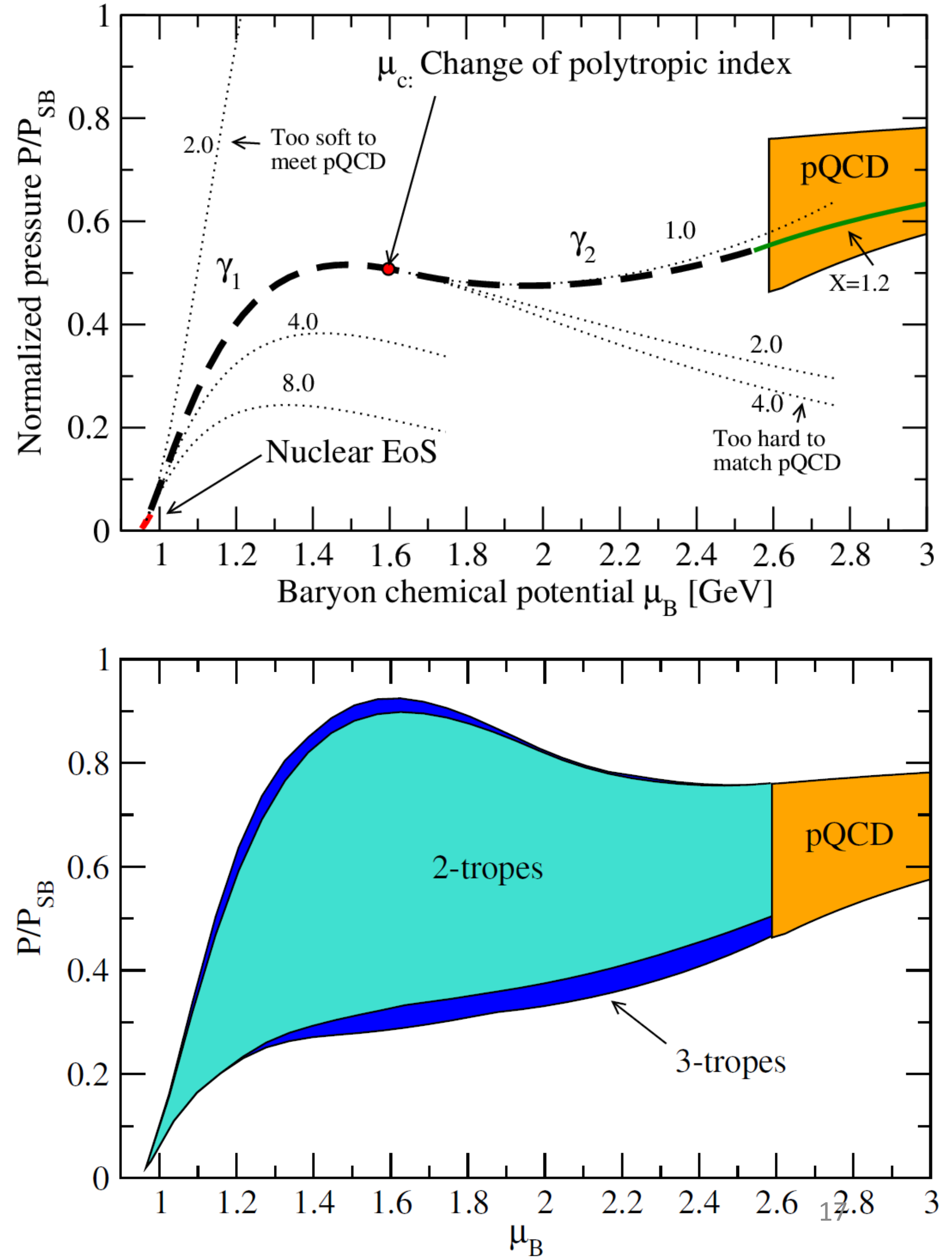
Interpolation – or how to optimally combine theoretical and observational insights

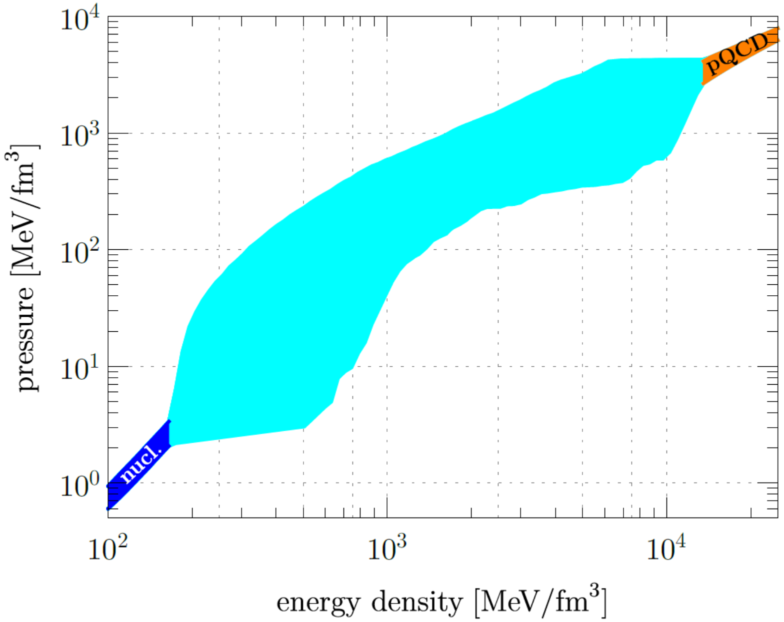
Allow all possible EoS behaviors by interpolating it over the no man's land using one's favorite (often piecewise) basis functions

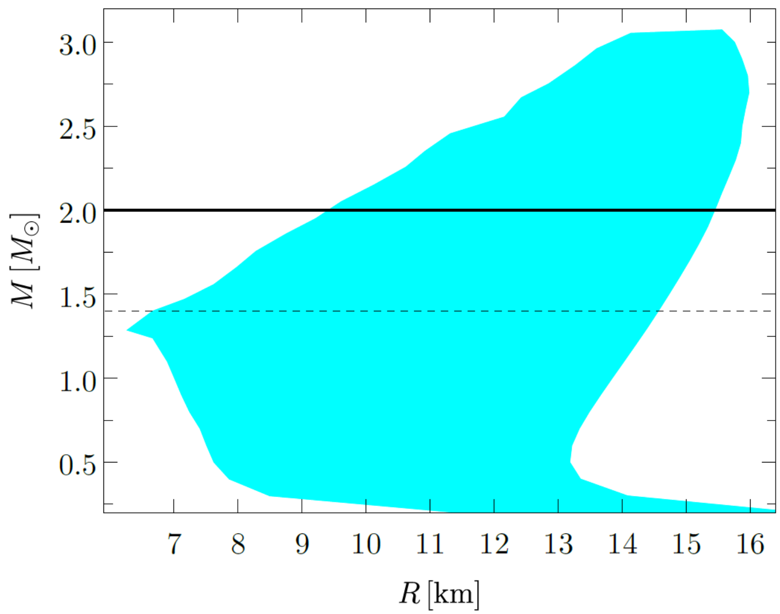
Require:

1) Smooth matching to nuclear and quark matter EoSs
2) Continuity of p and n – with at most one exception (1st order transition)
3) Subluminality
4) Optional: astrophysical constraints

[Kurkela et al., ApJ 789 (2014)]





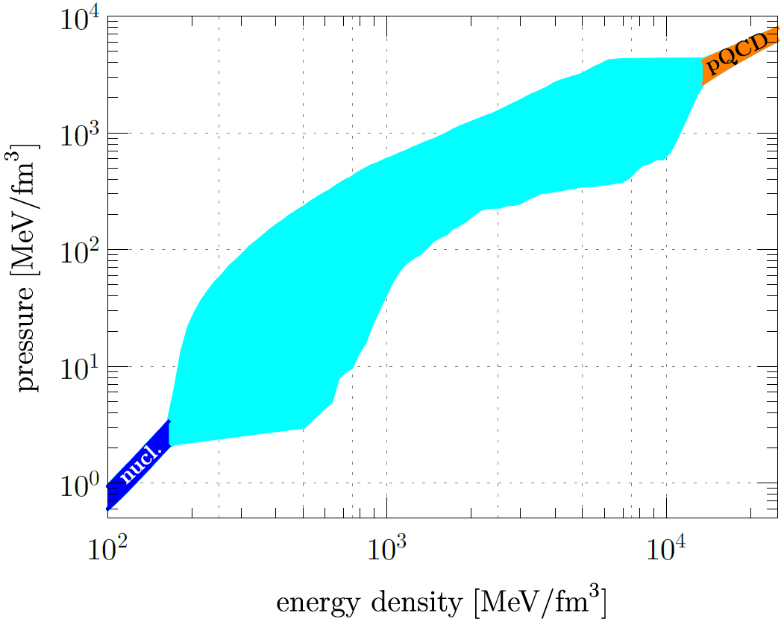


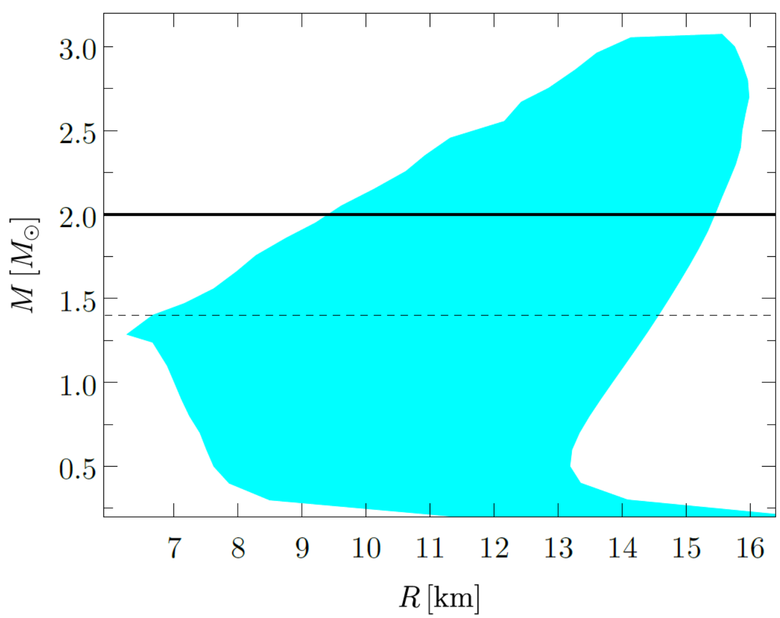
Using polytropes, generate ensemble of 200.000 viable EoSs.

Assumption here and in the following: All stars considered main seq. NSs

- Excluded: twin stars [e.g. Alvarez-Castillo, Blaschke, PRC96 (2017)], strange quark stars [e.g. Weber et al., IAU 291 (2013)]

[Annala, Gorda, Kurkela, AV, PRL 120 (2018), 1711.02644]

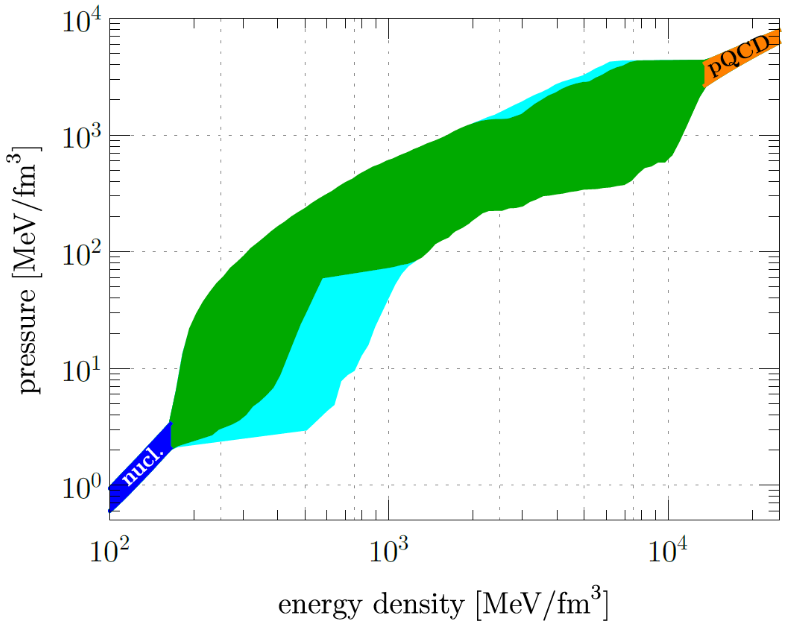


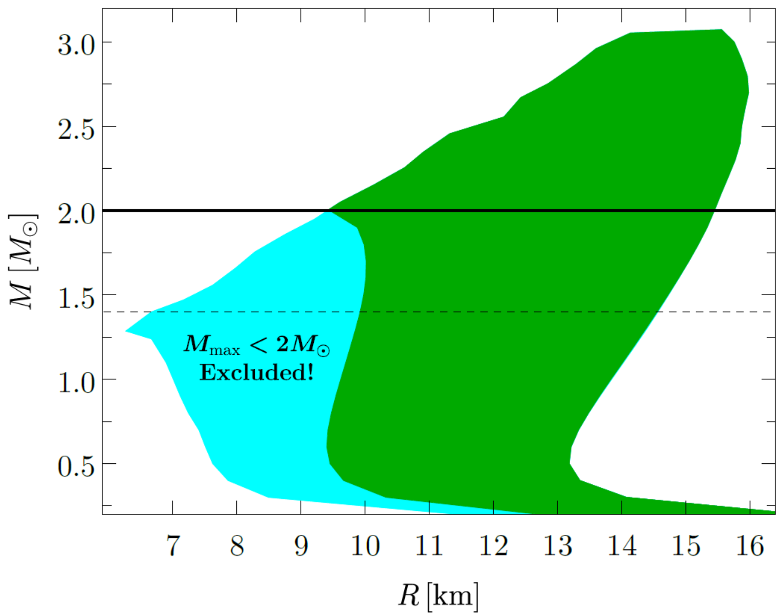


Using polytropes, generate ensemble of 200.000 viable EoSs.

Additionally take into account:

[Annala, Gorda, Kurkela, AV, PRL 120 (2018), 1711.02644]



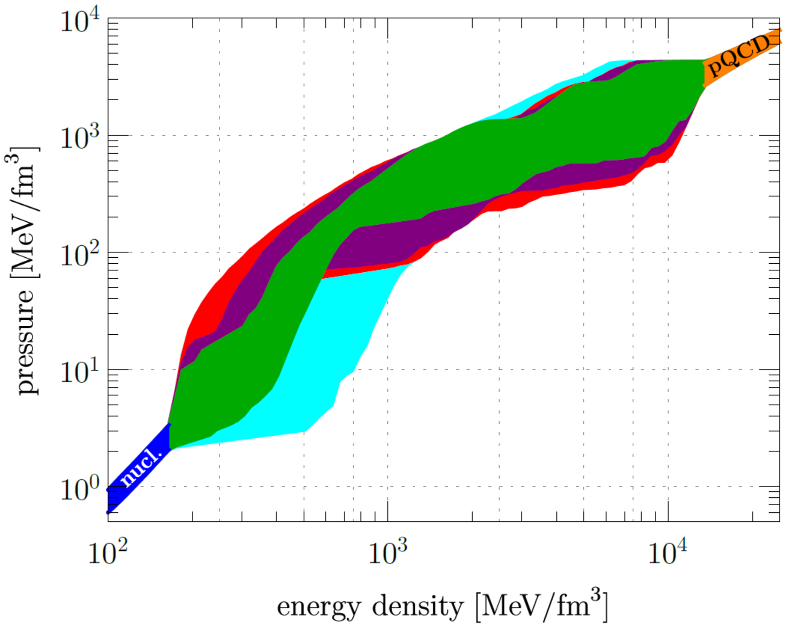


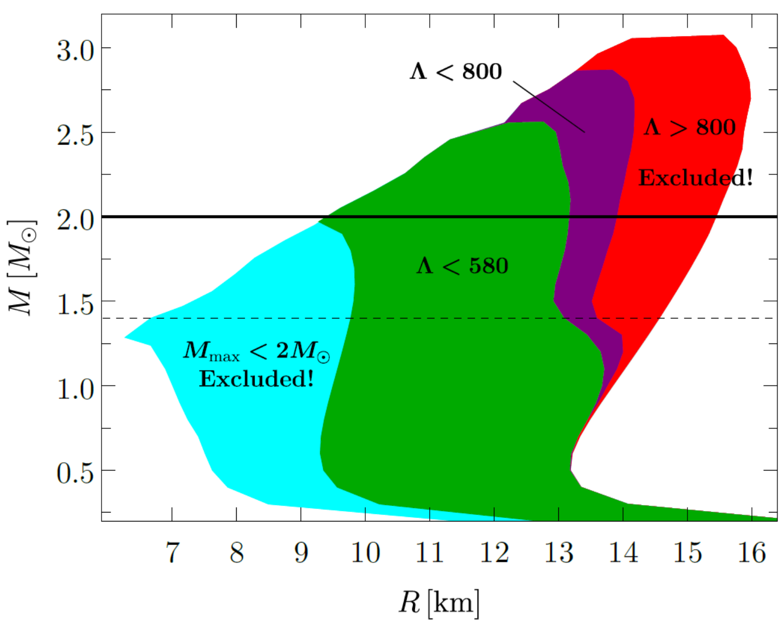
Using polytropes, generate ensemble of 200.000 viable EoSs.

Additionally take into account:

- Existence of $2M_\odot$ NSs $\Rightarrow$ Very soft EoSs ruled out, $R(1.4M_\odot) \geq 10\text{km}$

[Annala, Gorda, Kurkela, AV, PRL 120 (2018), 1711.02644]



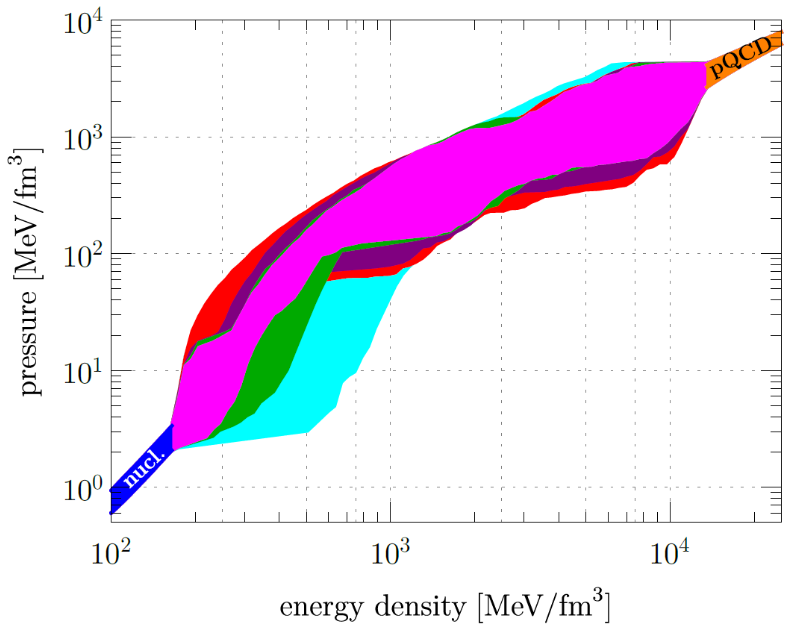


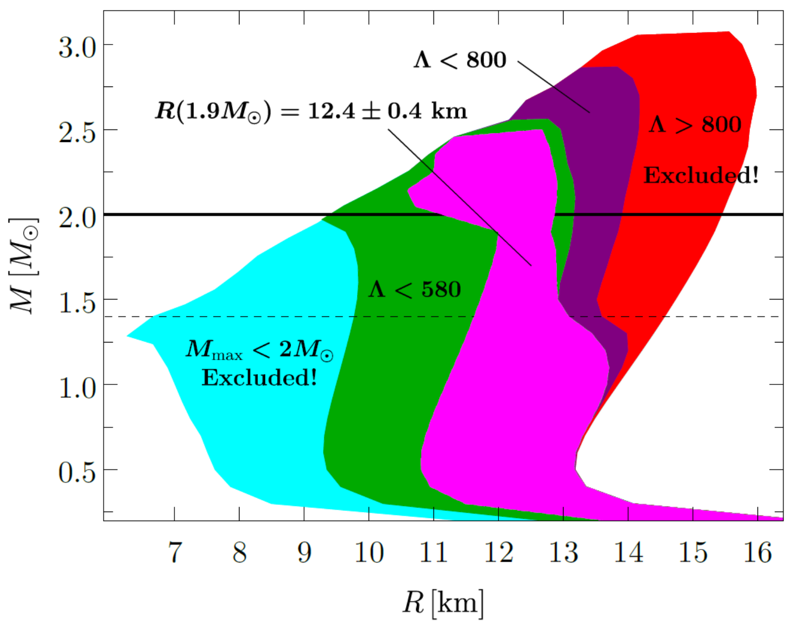
Using polytropes, generate ensemble of 200.000 viable EoSs.

Additionally take into account:

- Existence of $2M_\odot$ NSs ⇒ Very soft EoSs ruled out, $R(1.4M_\odot) \geq 10\text{km}$
- Tidal deformability limits ⇒ EoS cannot be overly stiff, $R(1.4M_\odot) \leq 13\text{km}$

[Annala, Gorda, Kurkela, AV, PRL 120 (2018), 1711.02644]





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- Tidal deformability limits $\Rightarrow$ EoS cannot be overly stiff, $R(1.4M_\odot) \leq 13\text{km}$
- Accurate R measurements (here assuming accurately determined mass)

[Annala, Gorda, Kurkela, AV, PRL 120 (2018), 1711.02644]

How about quark matter?

Recent work: Implement interpolation starting from speed of sound, and classify results in terms of max(c_s^2) and the latent heat of the deconfinement transition

[Annala, Gorda, Kurkela, Nättilä, Vuorinen, Nature Physics (2020)]

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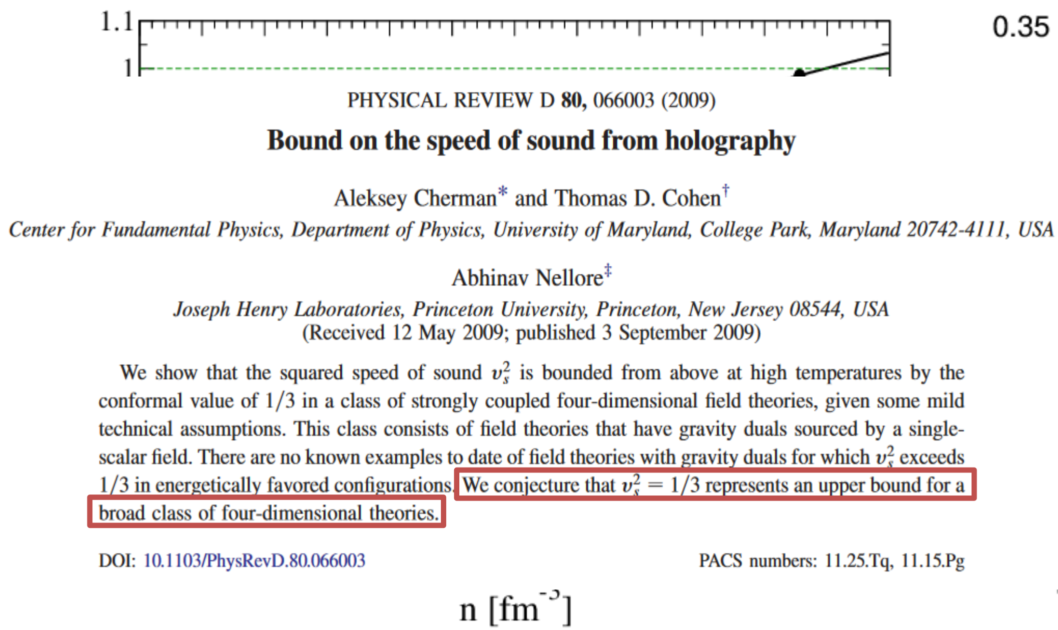
[Annala, Gorda, Kurkela, Nättilä, Vuorinen, Nature Physics (2020)]

Interesting because of tension between standard lore in nuclear physics and experience from other contexts



PHYSICAL REVIEW D **80,** 066003 (2009)

Bound on the speed of sound from holography

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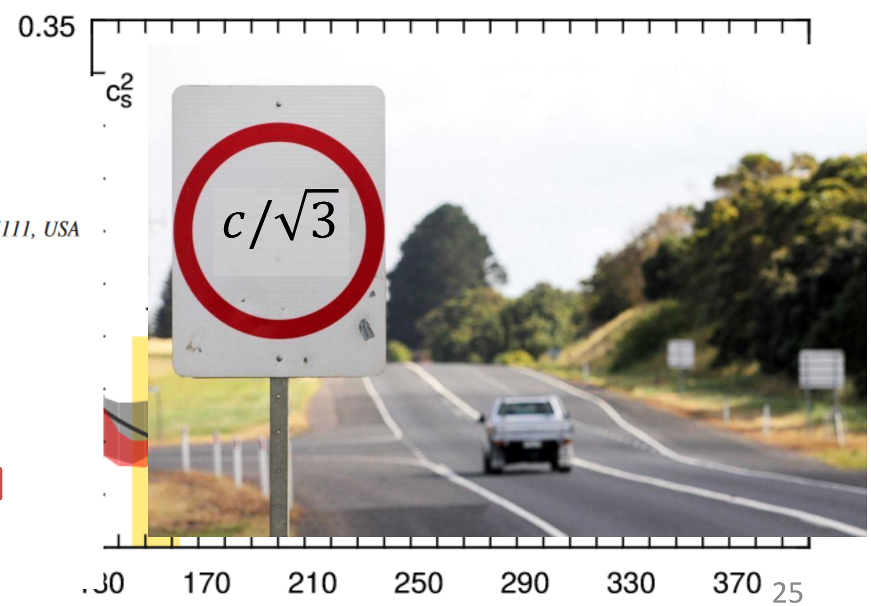
Abhinav Nellore‡

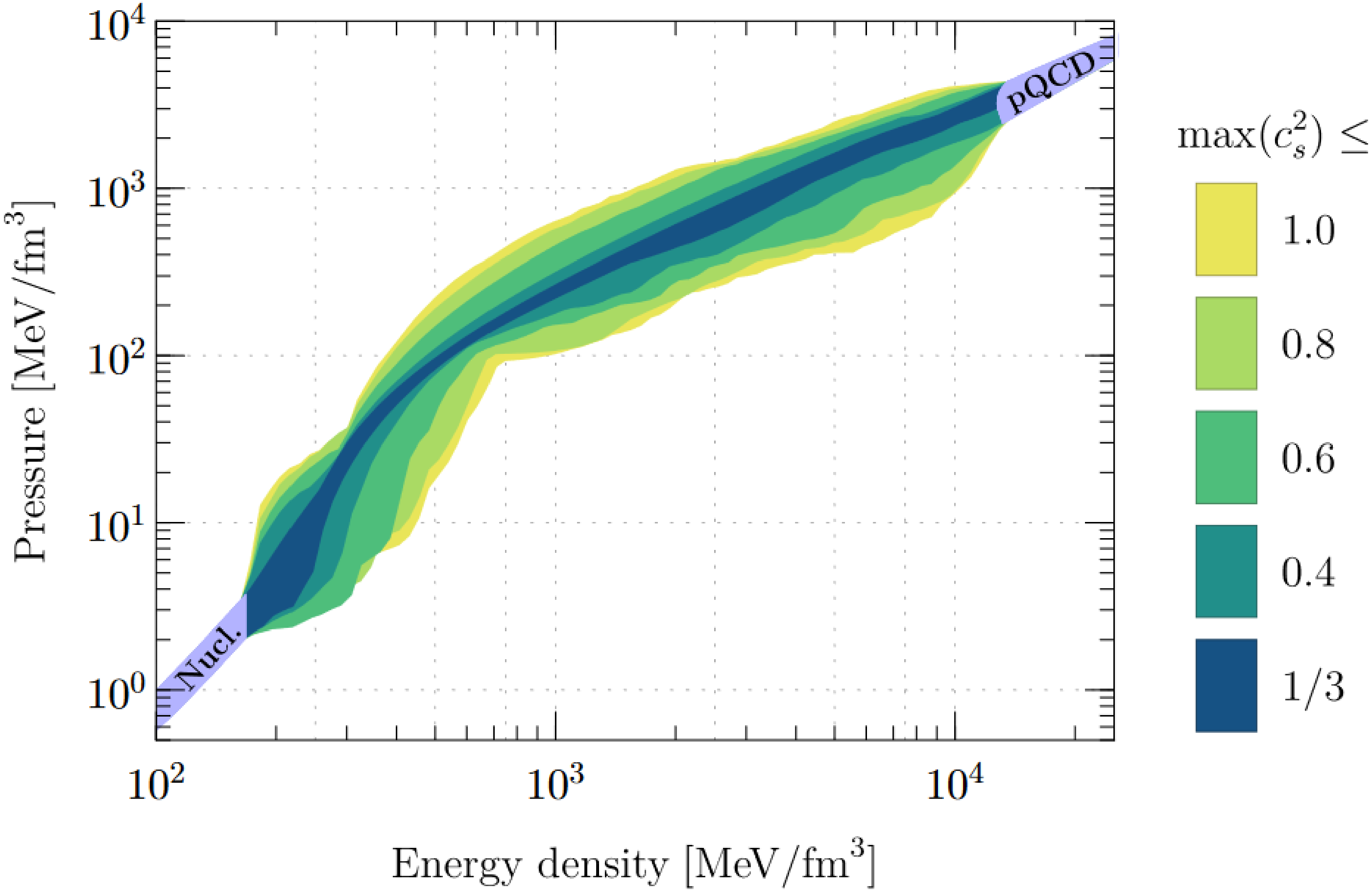
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544, USA

(Received 12 May 2009; published 3 September 2009)

We show that the squared speed of sound v_s^2 is bounded from above at high temperatures by the conformal value of $1/3$ in a class of strongly coupled four-dimensional field theories, given some mild technical assumptions. This class consists of field theories that have gravity duals sourced by a single-scalar field. There are no known examples to date of field theories with gravity duals for which v_s^2 exceeds $1/3$ in energetically favored configurations. We conjecture that $v_s^2 = 1/3$ represents an upper bound for a broad class of four-dimensional theories.

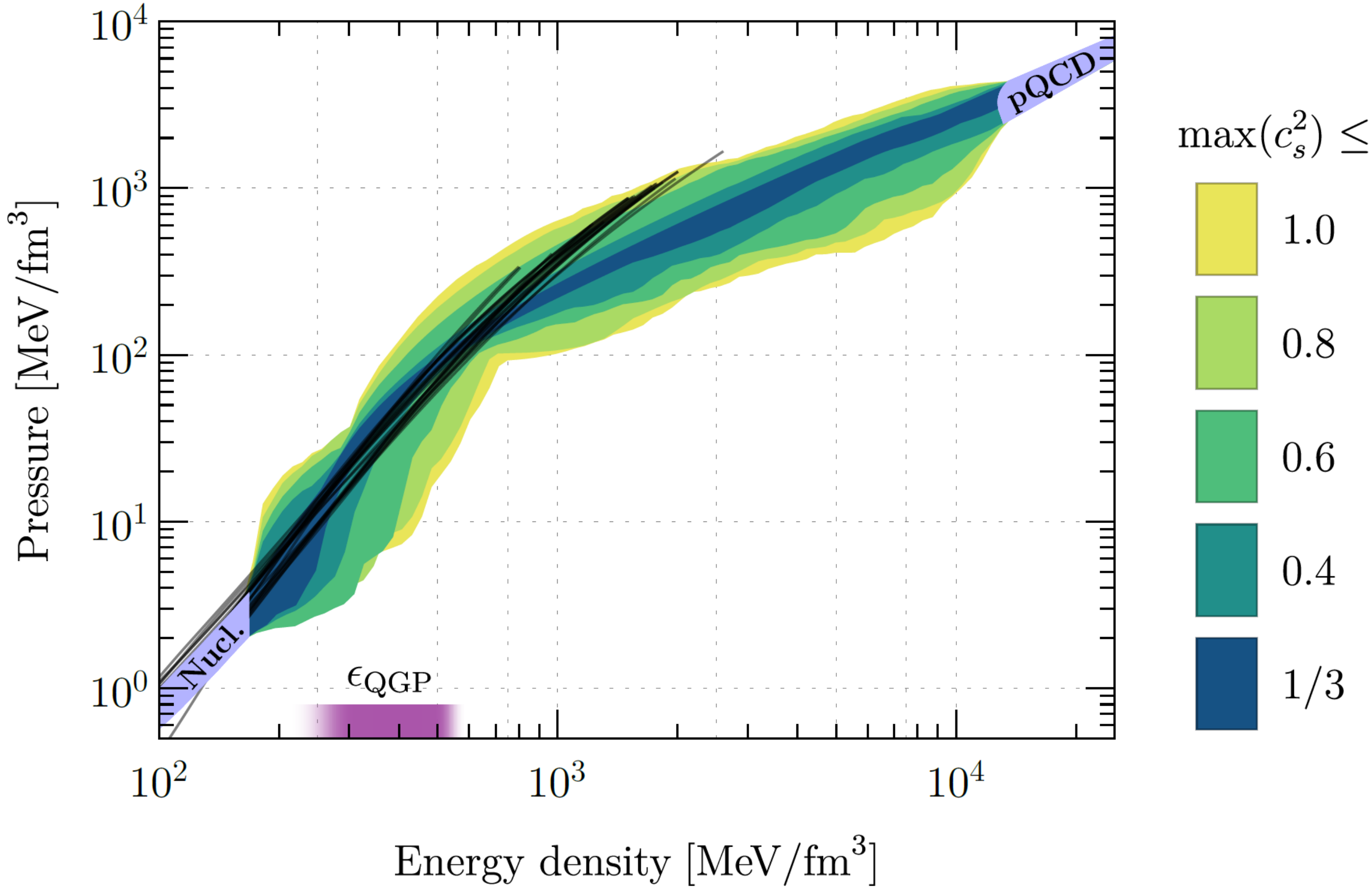
DOI: 10.1103/PhysRevD.80.066003 PACS numbers: 11.25.Tq, 11.15.Pg





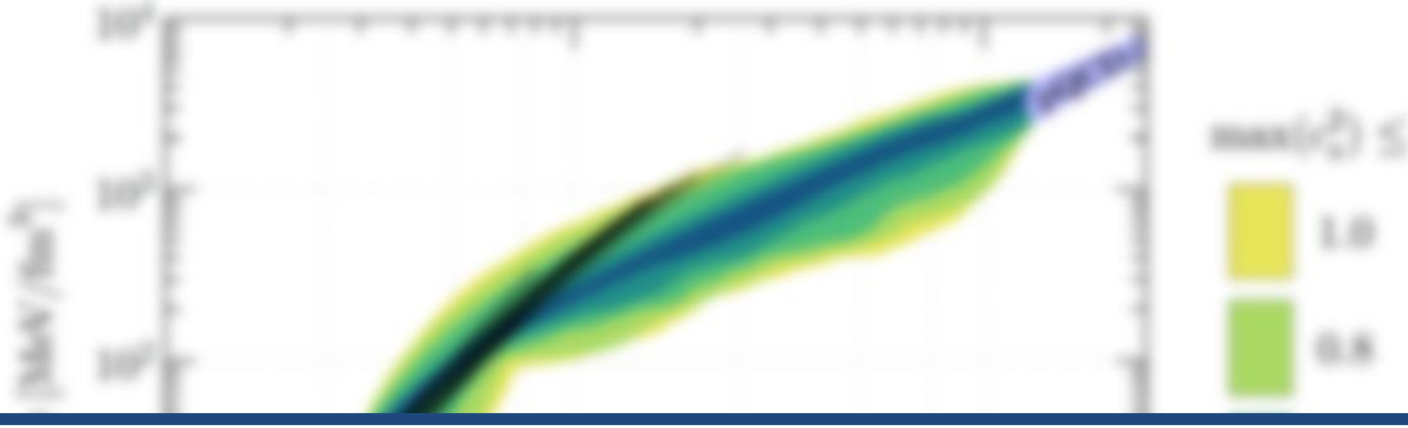
Setting nontrivial upper limits for speed of sound leads to increasingly constrained results; contrary to common lore, even sub-conformal ($c_s^2 < 1/3$) EoSs viable

Low-c_s EoSs suggest two-phase structure of the EoS band



Comparison with viable NM EoSs and QGP critical region strengthens link between bend and deconf. transition

Distinguishing feature between phases: slope $\gamma \equiv \dfrac{d\ln p}{d\ln \epsilon} \approx$ 1 in nearly conformal QM, ~2.5 in sub-n_s nuclear matter



Obvious questions:

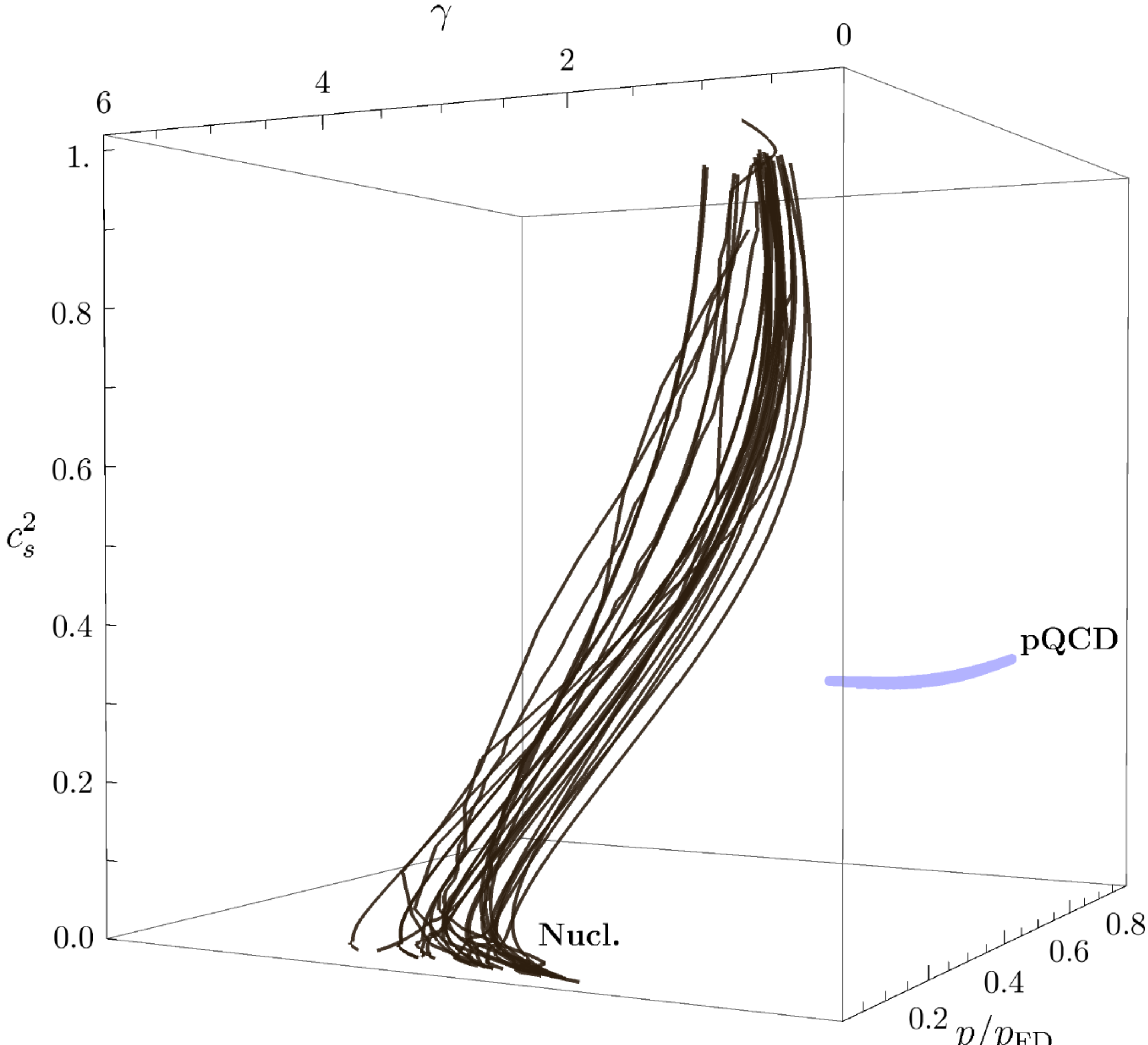
1) Is the two-slope structure only a property of the band, or does it persist more differentially – and for larger values of max(c_s^2)?
2) Where do the centers of NSs with different masses lie, i.e. does quark matter exist inside NSs?

strengthen link between bend and deconf. transition

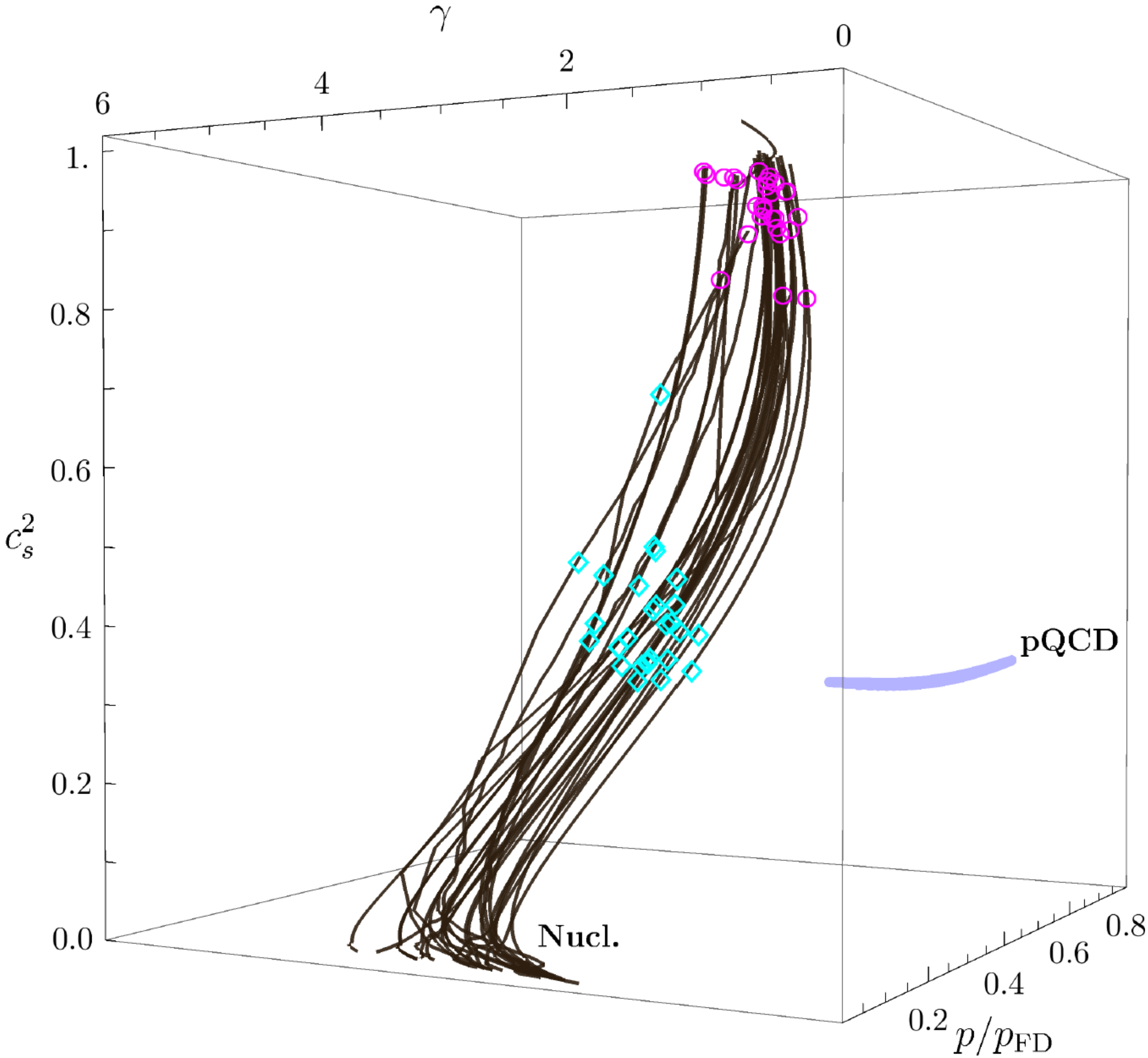
Distinguishing feature between phases: slope $\gamma \equiv \frac{d \ln p}{d \ln \epsilon} \approx$ 1 in nearly conformal QM, 2.5 in sub-n_s nuclear matter

Plan for investigation:

1) Generate a large ($\sim$500.000) ensemble of viable EoSs with speed-of-sound method, allowing for 1st order transitions with arbitrary latent heats $\Delta\epsilon$
2) Compare behaviors of three key quantities – γ, c_s^2, and p/p_{FD} – to all viable hadronic EoSs available
3) Identify approximative criterion for the onset of QM and quantify conditions for its presence and amount inside NSs of different masses



γ
0
2
4
6
1.
0.8
0.6
0.4
0.2
0.0
c_s^2
pQCD
Nucl.
0.2
0.4
0.6
0.8
p/p_{FD}



γ
6
4
2
0
c_s^2
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0.8
0.6
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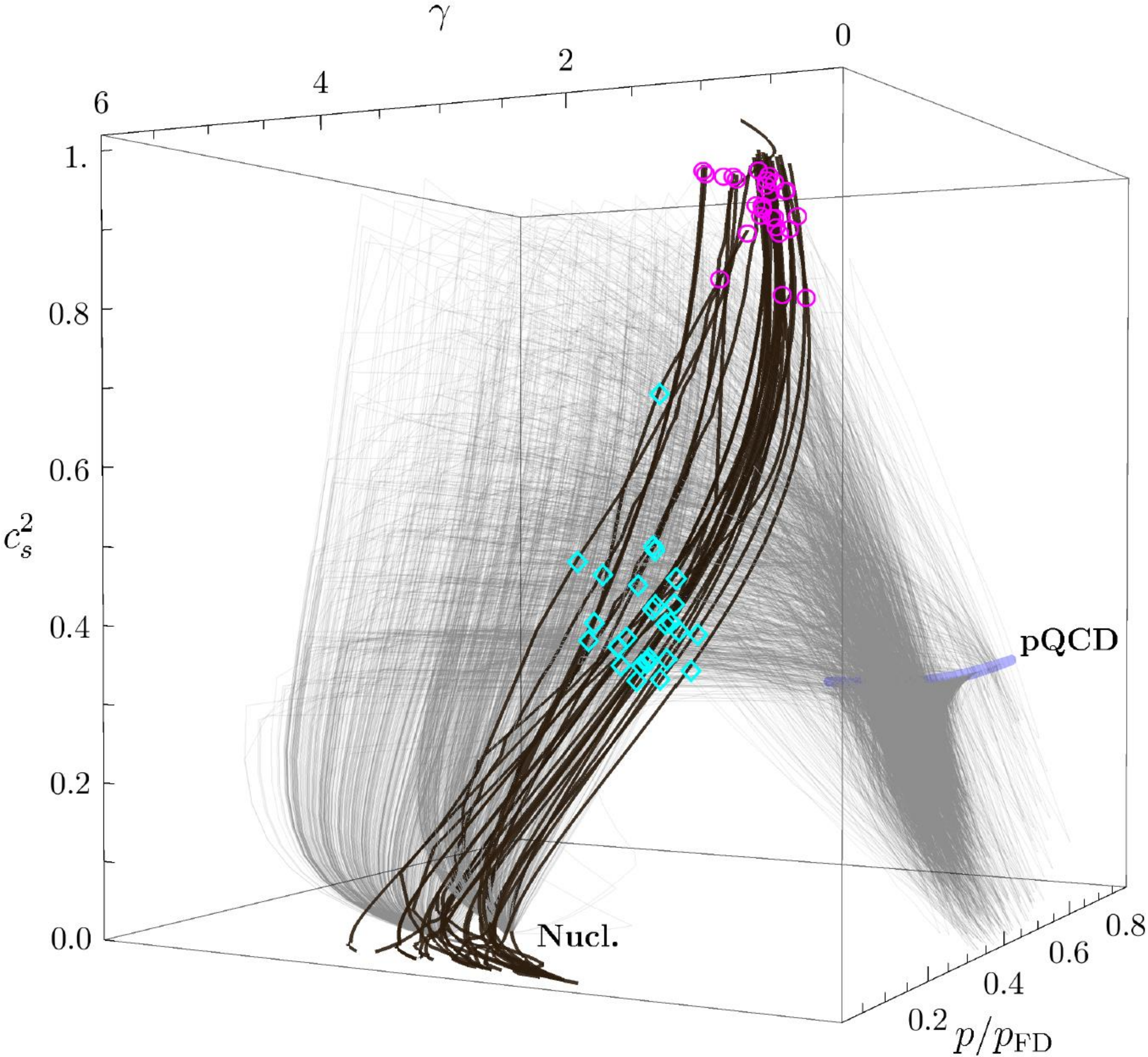
pQCD
Nucl.
0.2
0.4
0.6
0.8
$p/p_{\rm FD}$



γ
0
2
4
6
1.
0.8
0.6
0.4
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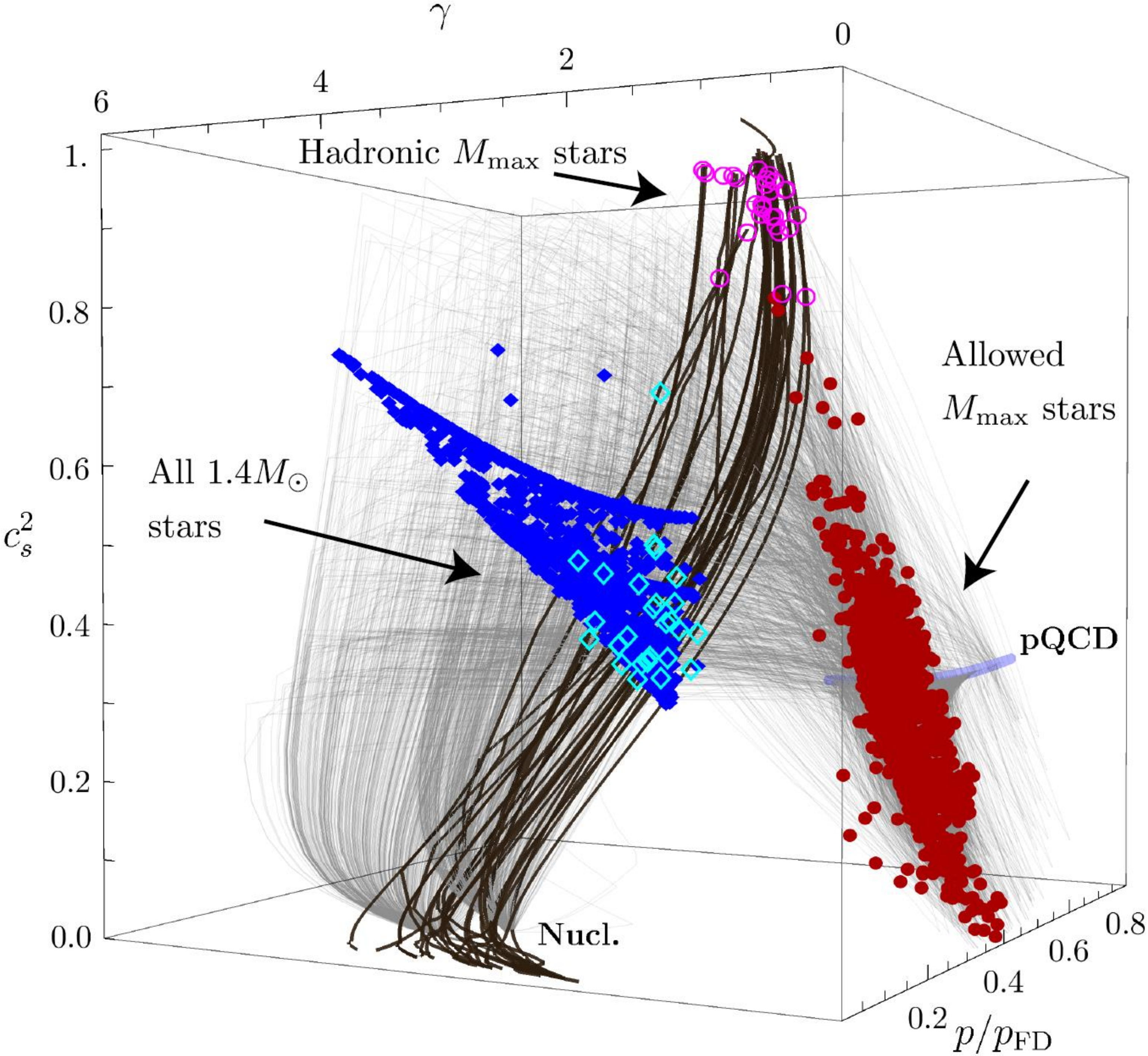
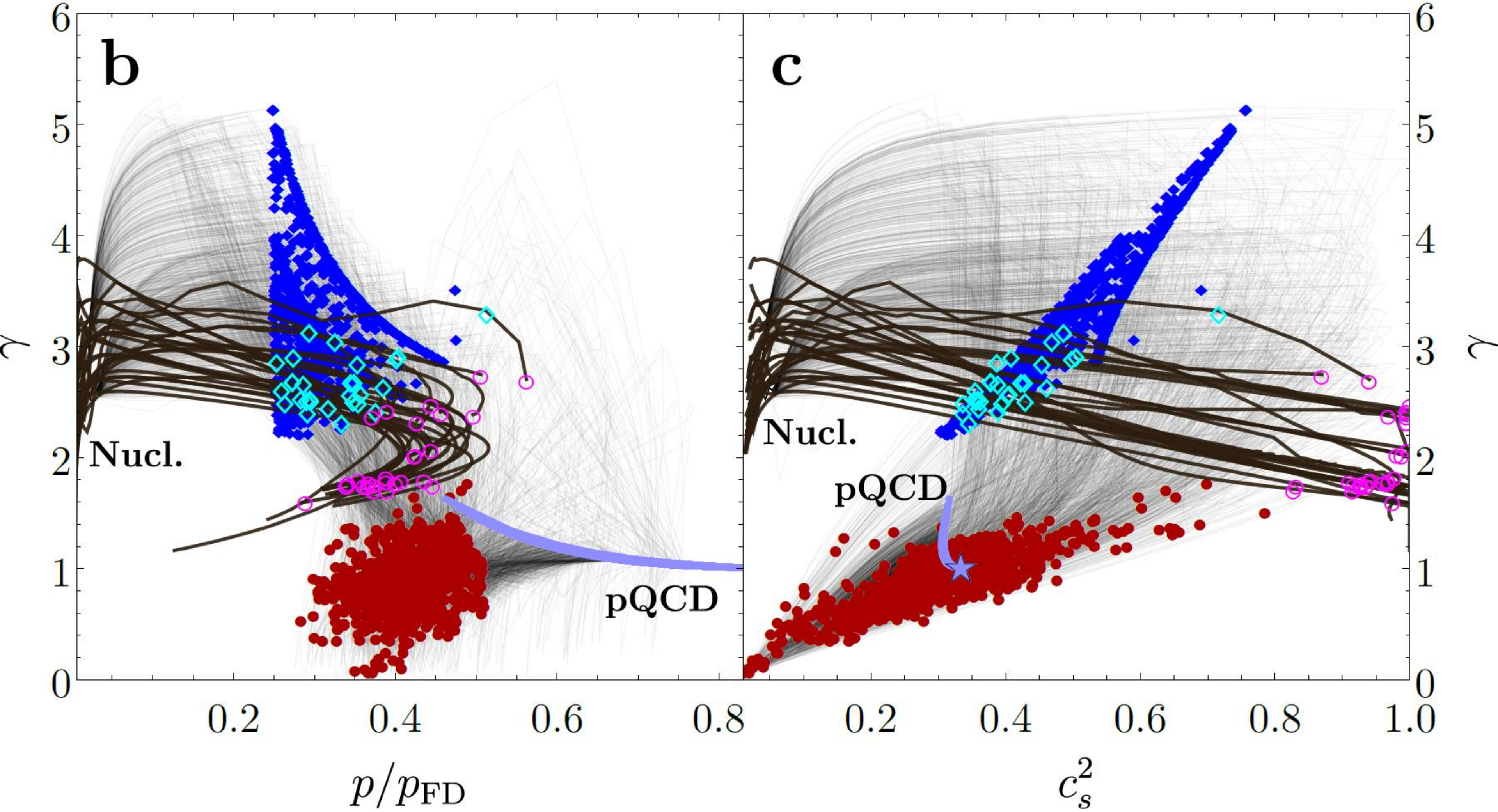
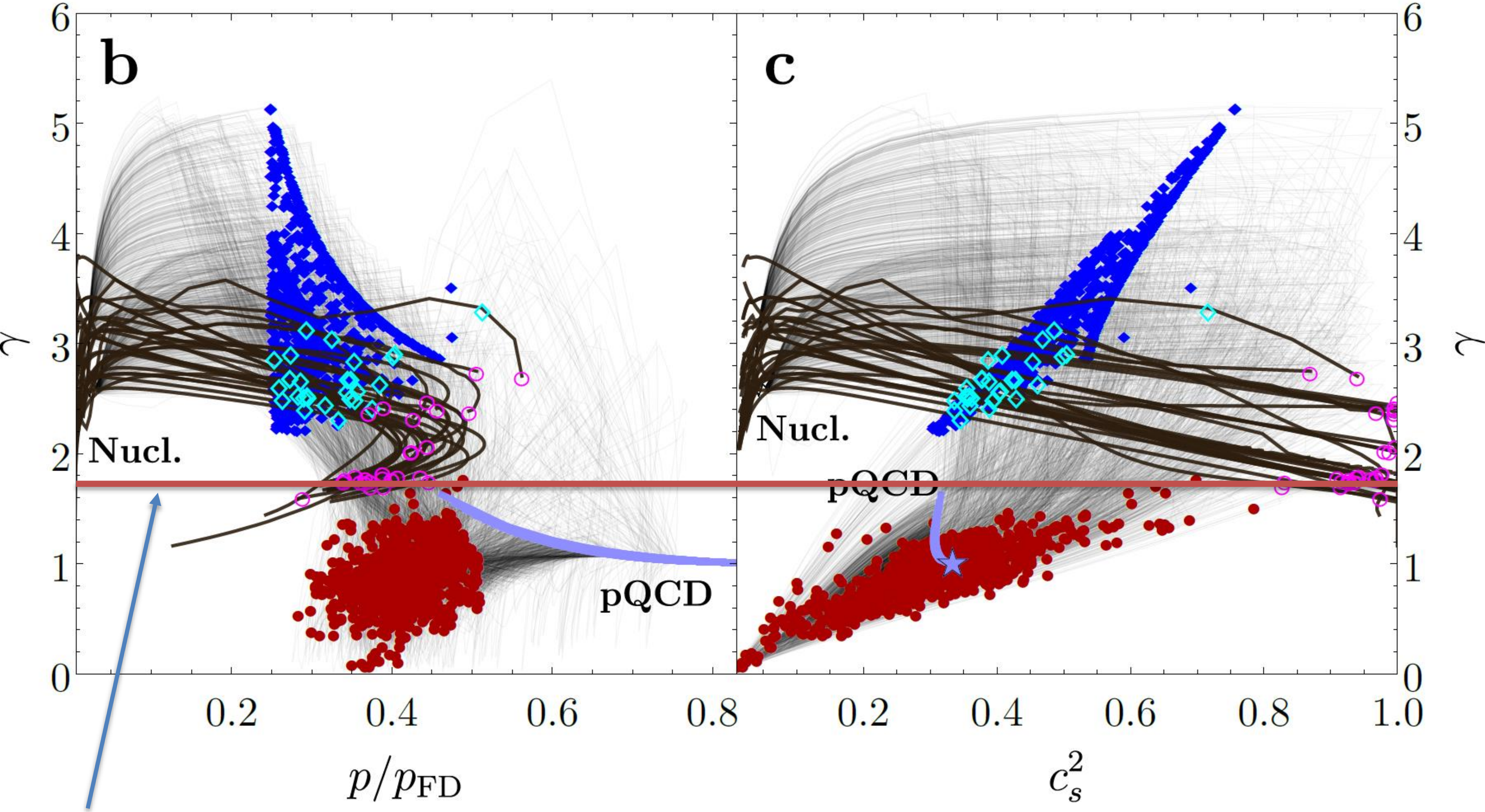
c_s^2
pQCD
Nucl.
0.2
0.4
0.6
0.8
$p/p_{\rm FD}$



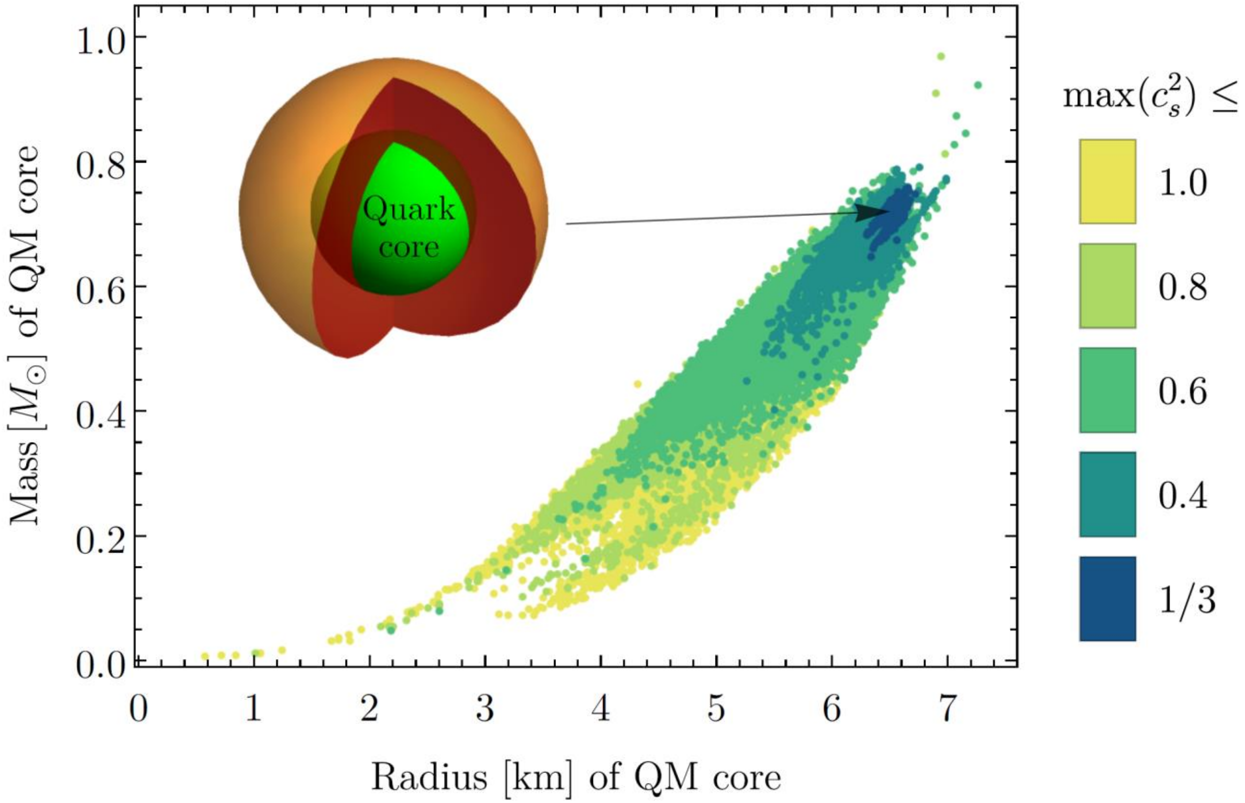
γ
0
2
4
6
Hadronic $M_{\max}$ stars
1.
0.8
0.6
0.4
0.2
0.0
c_s^2
All $1.4M_\odot$ stars
Allowed $M_{\max}$ stars
pQCD
Nucl.
0.2
0.4
0.6
0.8
$p/p_{\rm FD}$



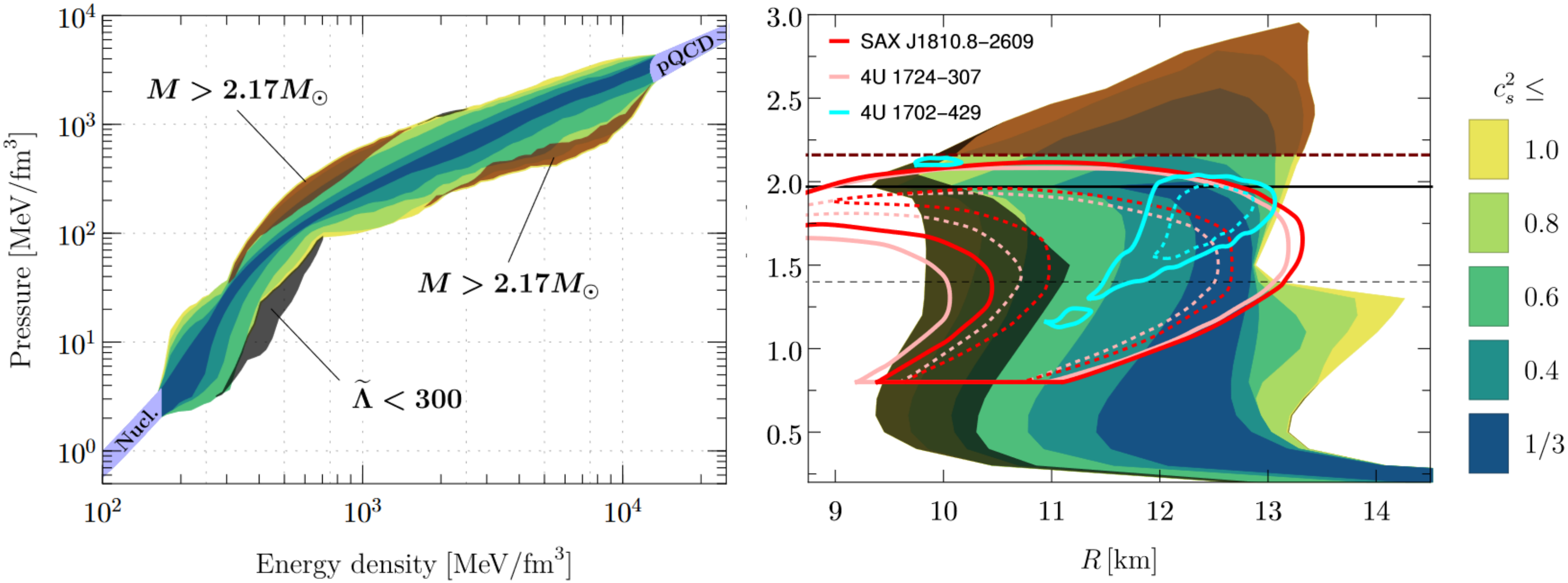
b
c
Nucl.
pQCD
γ
p/p_{FD}
c_s^2



Approximative criterion for the onset of QM



- In maximal-mass stars, quark core is present in a vast majority of stars – and always sizable if $\max(c_s^2) \lesssim 0.5$
- Purely hadronic NSs possible only if $\max(c_s^2) \gtrsim 0.7$ **and** transition first order
  - ✓ If transition a crossover, quark cores inevitable!



Recent simultaneous MR-measurements [1] and limits drawn from EM counterparts of GW170817 [2] in excellent agreement with low-c_s EoSs

[1] Nättilä et al., Astronomy & Astrophysics 608 (2017)
[2] Margalit and Metzger, Astrophys. Journal 850 (2017); Radice and Dai, Eur. Phys. J. A55 (2019)

Final thoughts

- How to remedy for the absence of lattice methods at high density?

- How to optimally exploit observational info on NSs?

- Do QM cores exist inside NSs, and if so, in which stars?

- How to remedy for the absence of lattice methods at high density?
  - No single method available everywhere; tools such as CET & pQCD useful but in separated regimes
- How to optimally exploit observational info on NSs?
  - Model-independent interpolation of the EoS offers systematic framework for including observations
- Do QM cores exist inside NSs, and if so, in which stars?
  - For massive enough stars, matter in their cores apprears to have characteristics resembling QM