Quark matter cores in massive neutron stars

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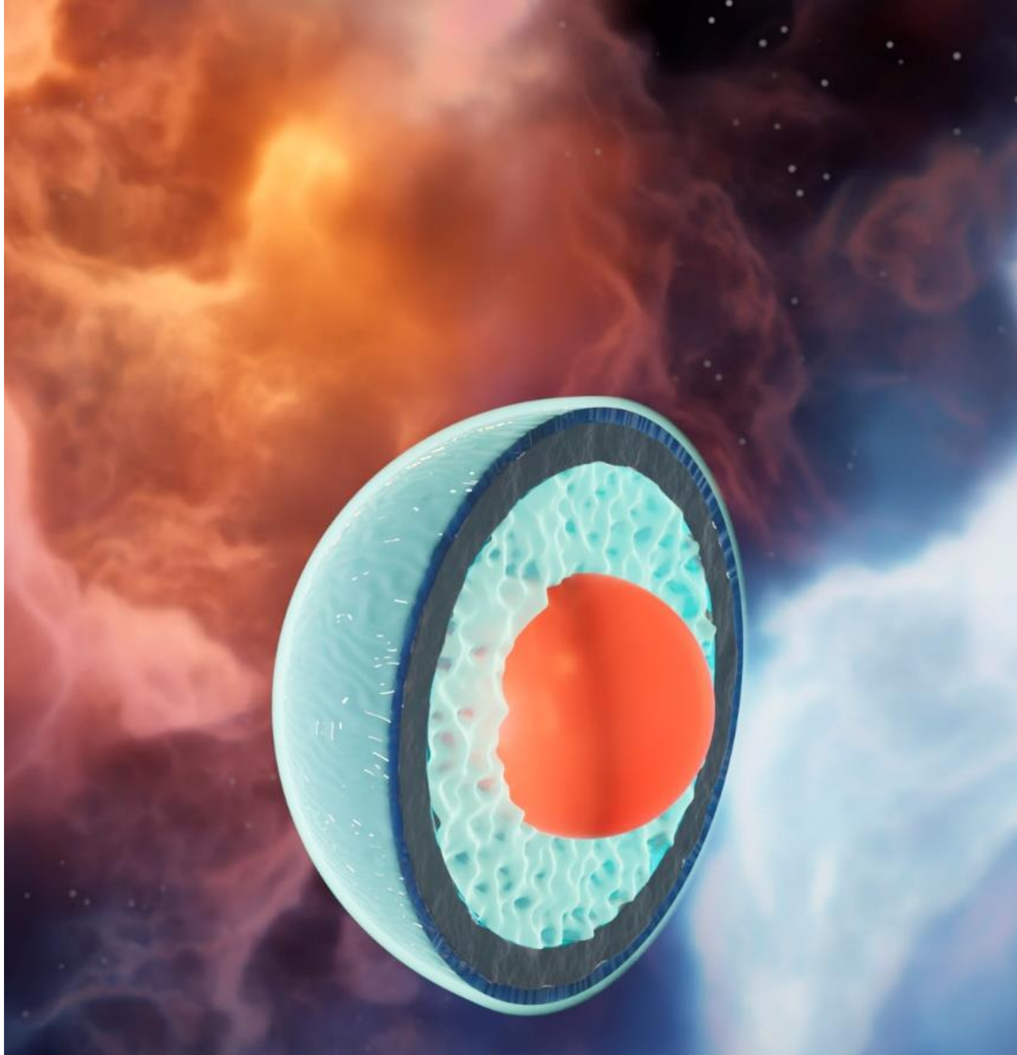
Compact stars and QCD

21 August 2020



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/**

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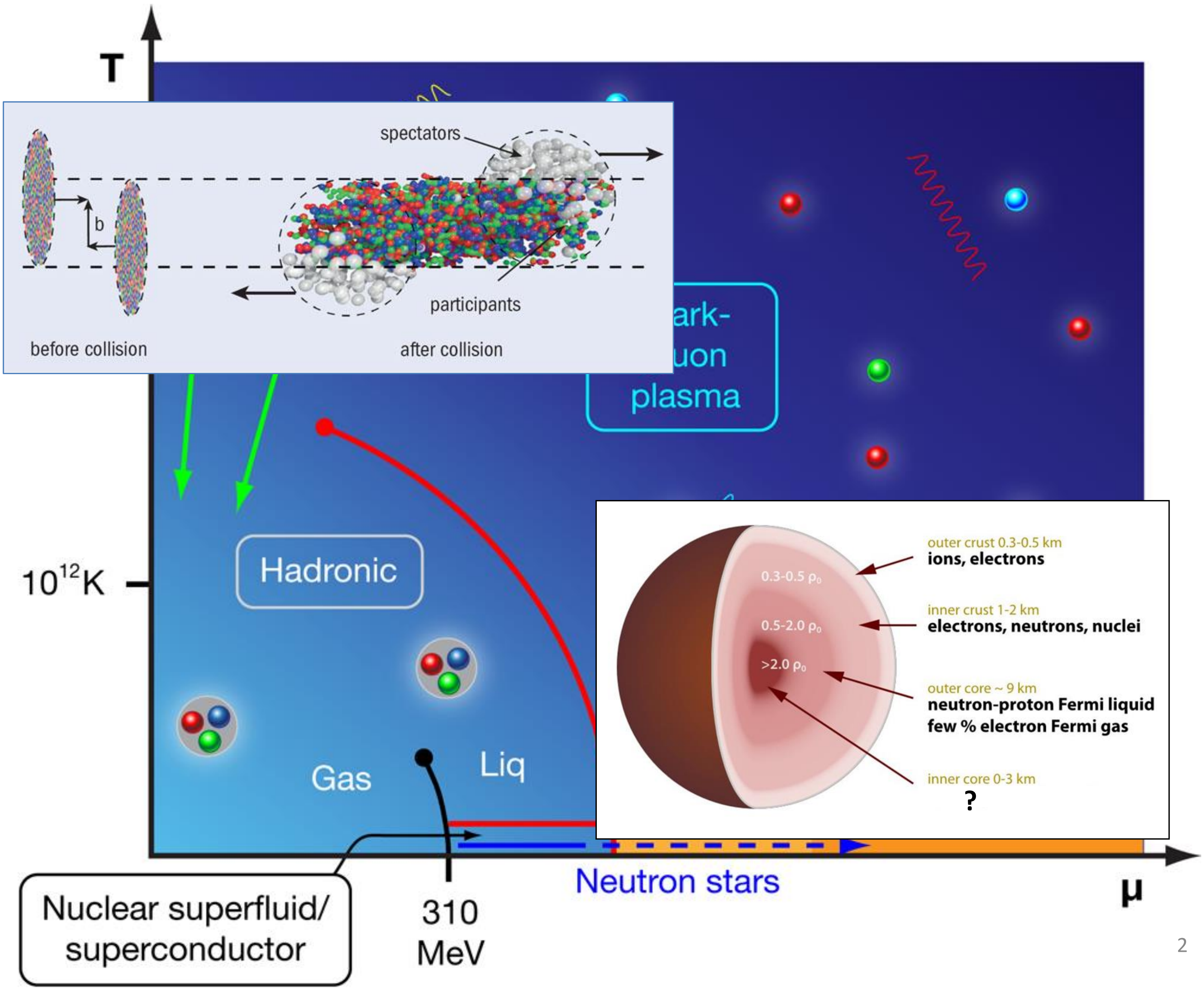
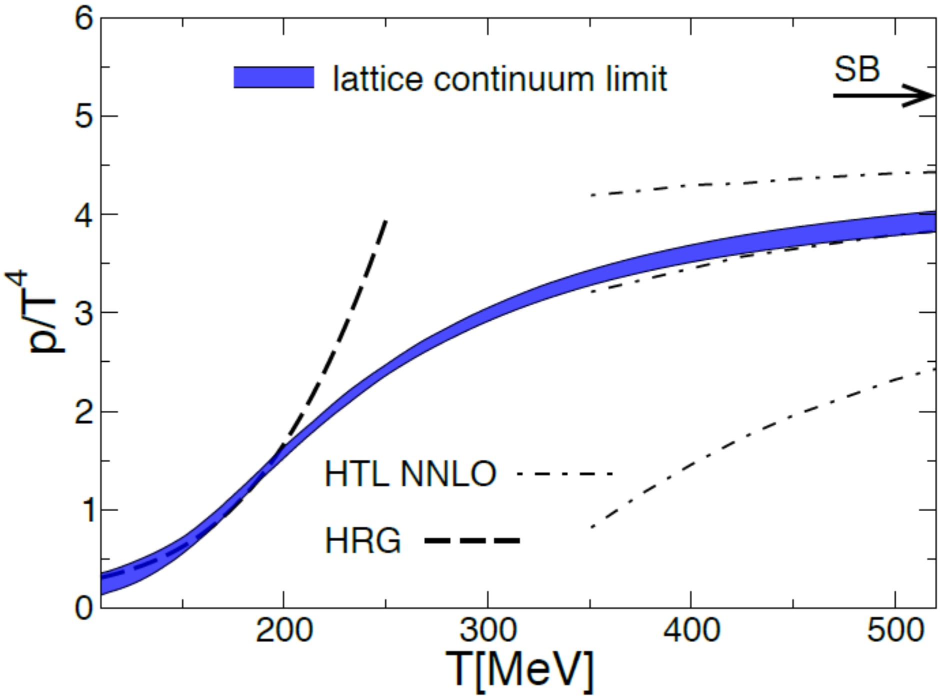
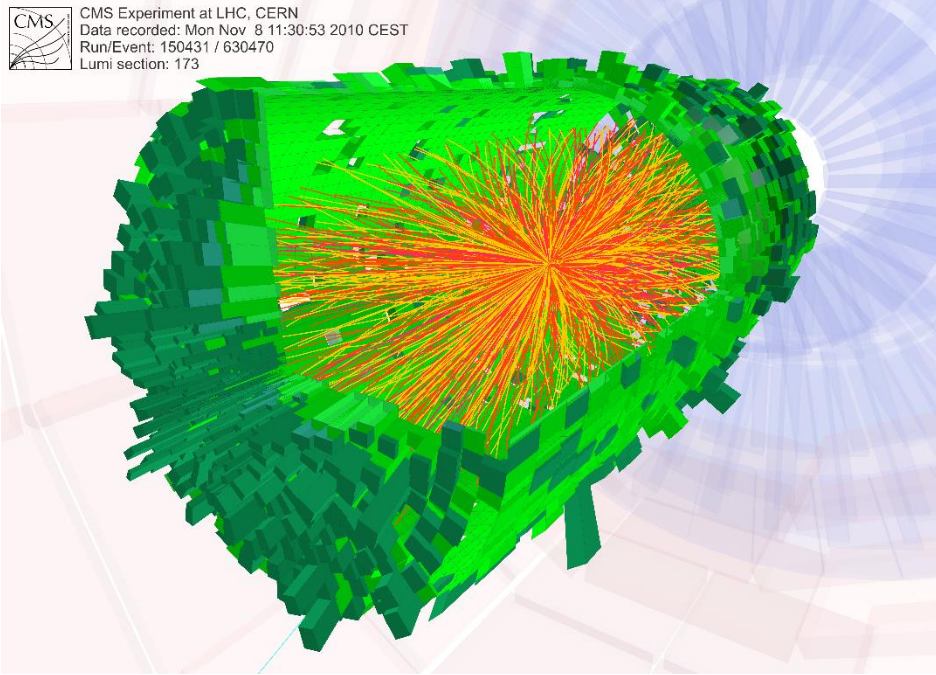

T
spectators
b
participants
before collision
after collision
ark-
uon
plasma
Hadronic
10^{12}K
Gas
Liq
outer crust 0.3-0.5 km
ions, electrons
0.3-0.5 ρ_0
inner crust 1-2 km
electrons, neutrons, nuclei
0.5-2.0 ρ_0
>2.0 ρ_0
outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas
inner core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

Heavy ion collisions vs. neutron stars

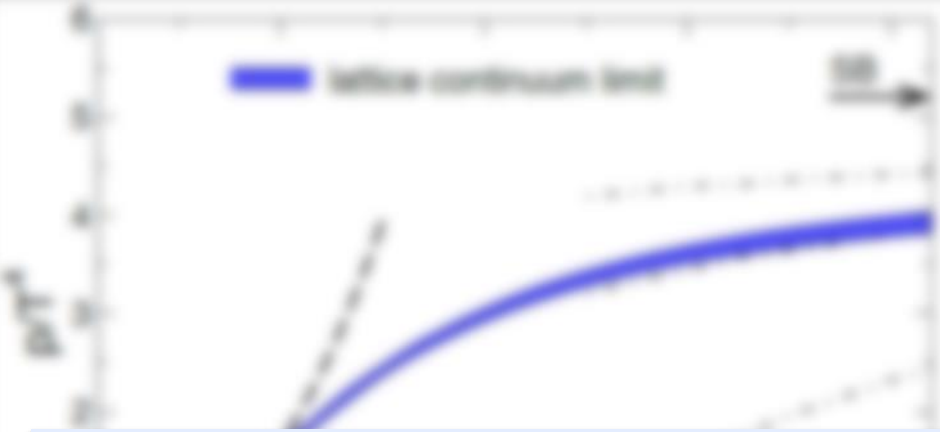
- Only existing systems of QCD matter with energy densities of order or above 1 GeV/fm^3
- Interest in both equilibrium properties and equilibration dynamics
- First-principles theoretical description challenging – need observational input for optimal progress
- Ultimate goals: Discover deconfined matter, measure its properties, and map the phase diagram

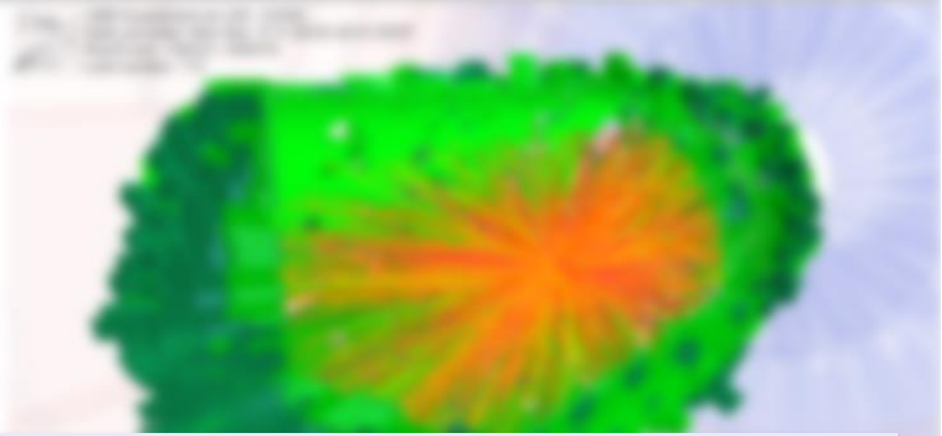




Main lessons from heavy ion experiments & lattice studies:

1) Crossover deconf. transition at $T \sim 150$ MeV, $\epsilon \sim 400$ MeV/fm^3
2) Soon thereafter rapid but smooth approach towards conformal behavior: $\gamma \equiv \frac{d \ln p}{d \ln \epsilon} \approx 1$, $c_s^2 \lesssim 1/3$, $p/T^4 \sim N_{\text{dof}}$
3) Although strong coupling machinery useful in understanding transport & thermalization, bulk thermo of hot QGP consistent with resummed perturbation theory from $T \sim$2-3T_c onwards



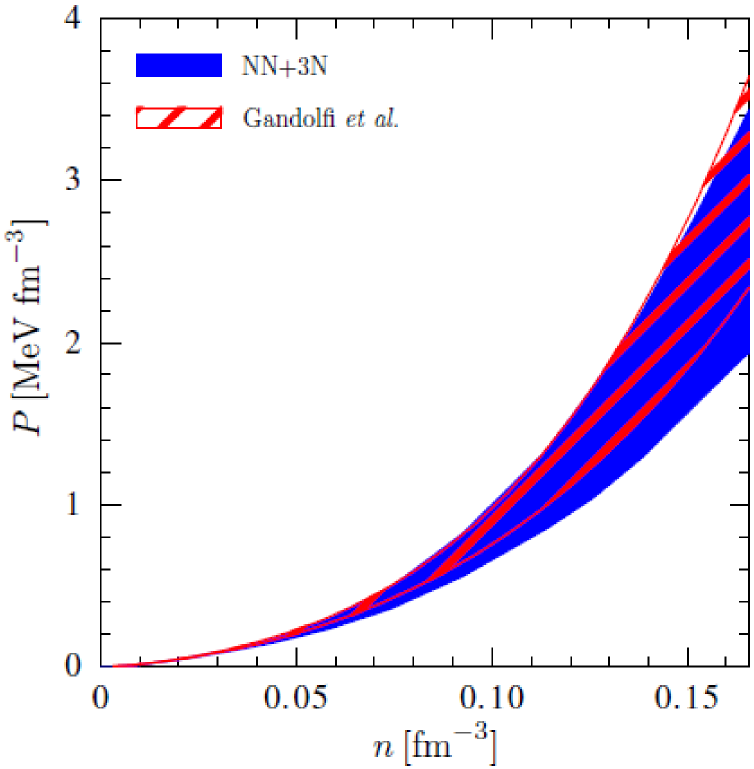


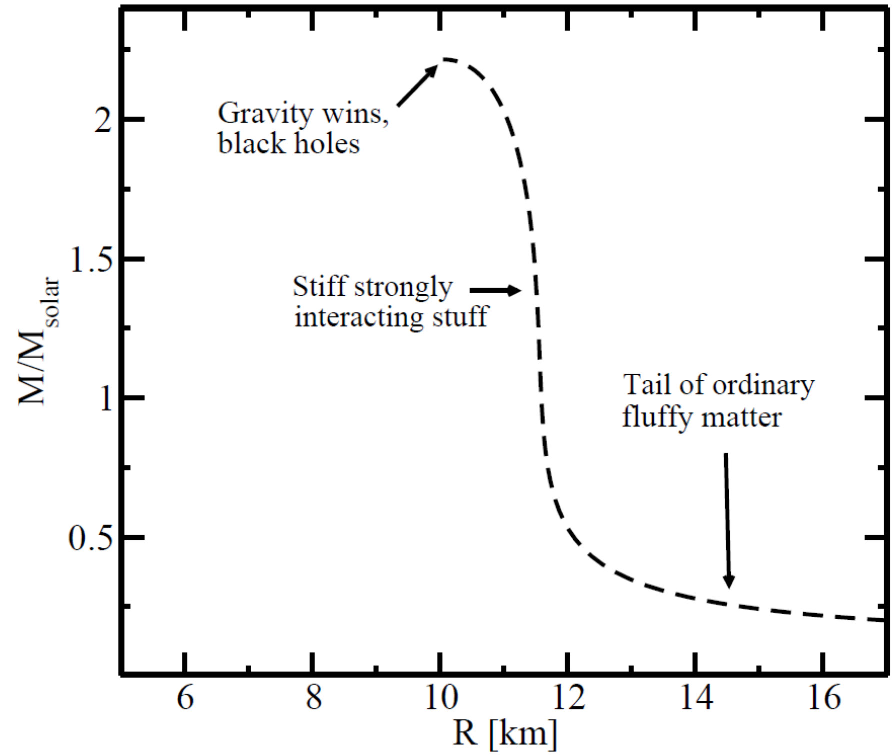
Main question for the remainder of this talk: how does all this generalize to neutron stars

- How to remedy for the absence of lattice methods (Sign Problem) at high density?
- How to optimally exploit observational info on NSs?
- Do QM cores exist, and if so, where?

2) Soon thereafter rapid but smooth approach towards conformality: $\gamma \equiv \frac{d \ln p}{d \ln \epsilon} \approx 1, c_s^2 \leq 1/3, p/T^4 \sim N_{dof}$
3) Main features of hot QGP consistent with predictions of resummed perturbation theory from $T \sim 2\text{-}3T_c$ onwards

NS matter EoS – robust theoretical limits



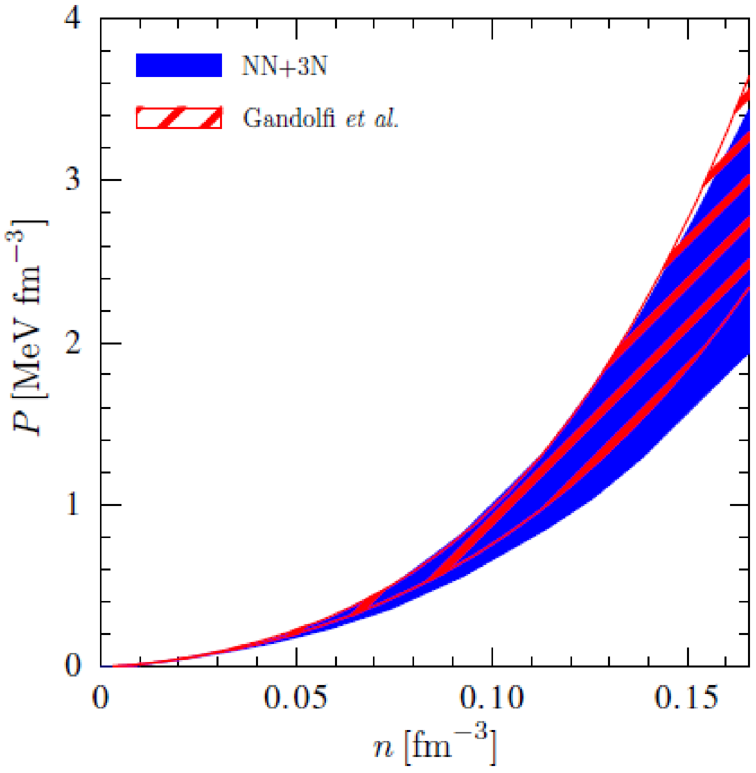


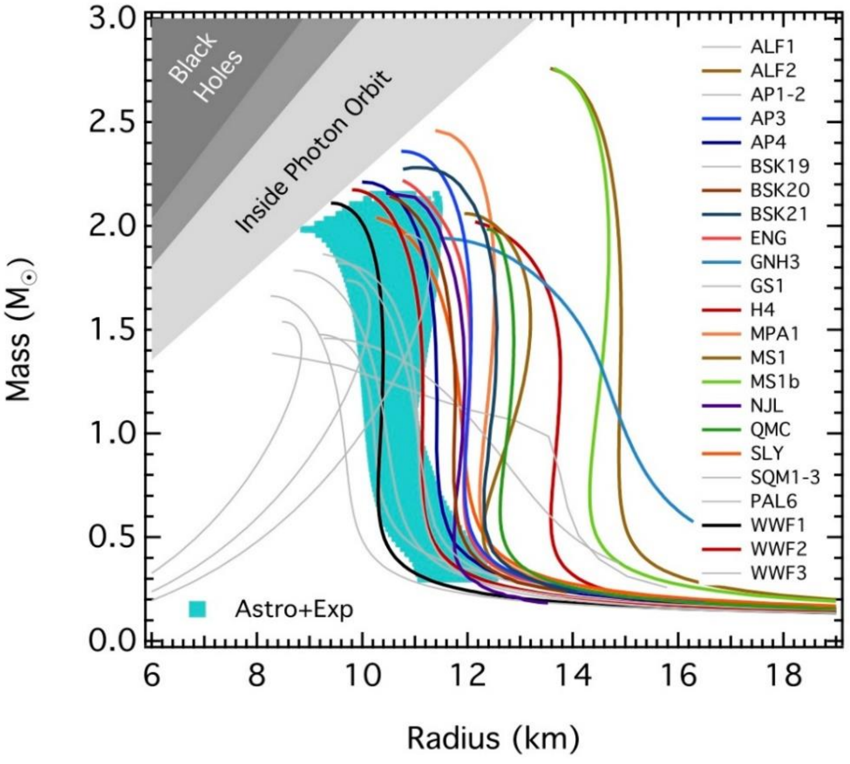
Key quantity connecting micro to macro: Equat. of State:

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

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

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





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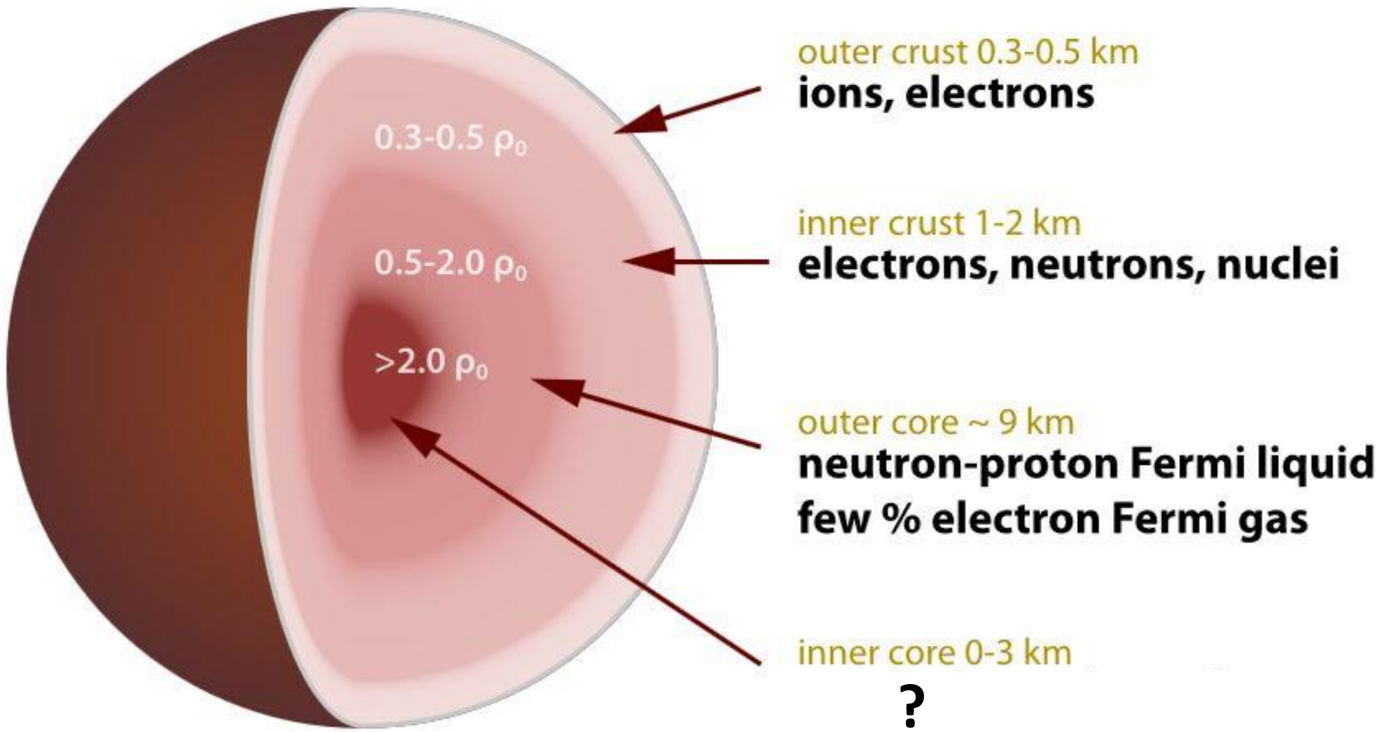
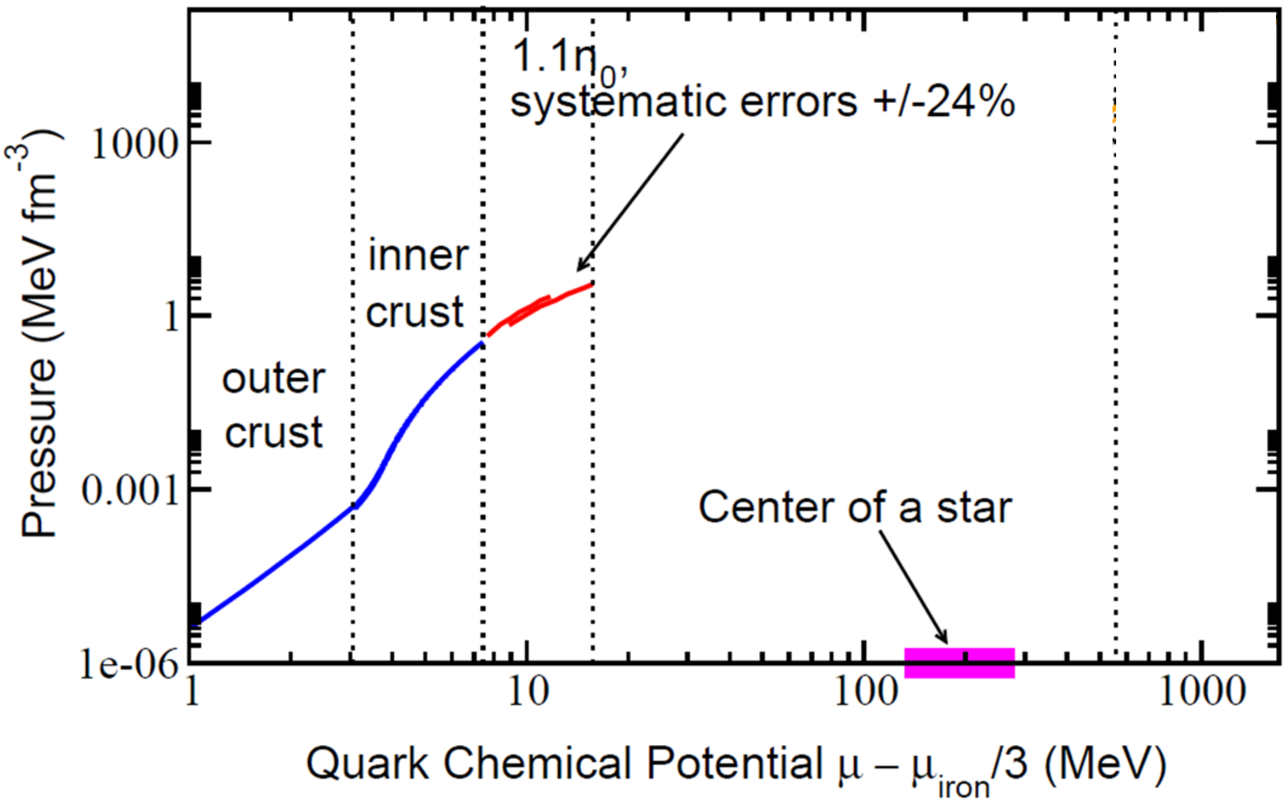


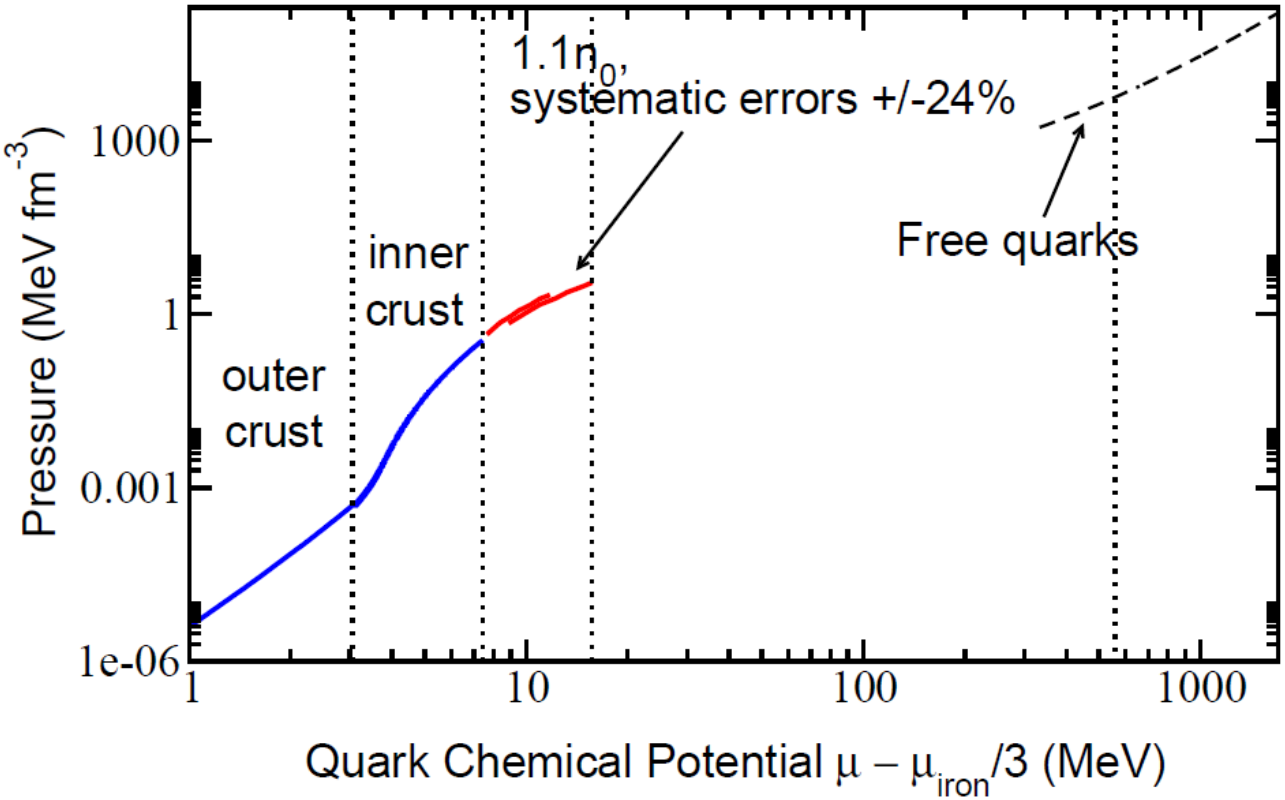
Proceeding inwards from the crust:

- μ_B increases gradually, starting from μ_{Fe}
- Baryon/mass density increase from 0 to beyond $n_s \equiv \rho_0 \approx 0.16/\mathrm{fm}^3 \approx 2 \times 10^{14}\mathrm{g/cm}^3$
- Composition of matter changes dramatically



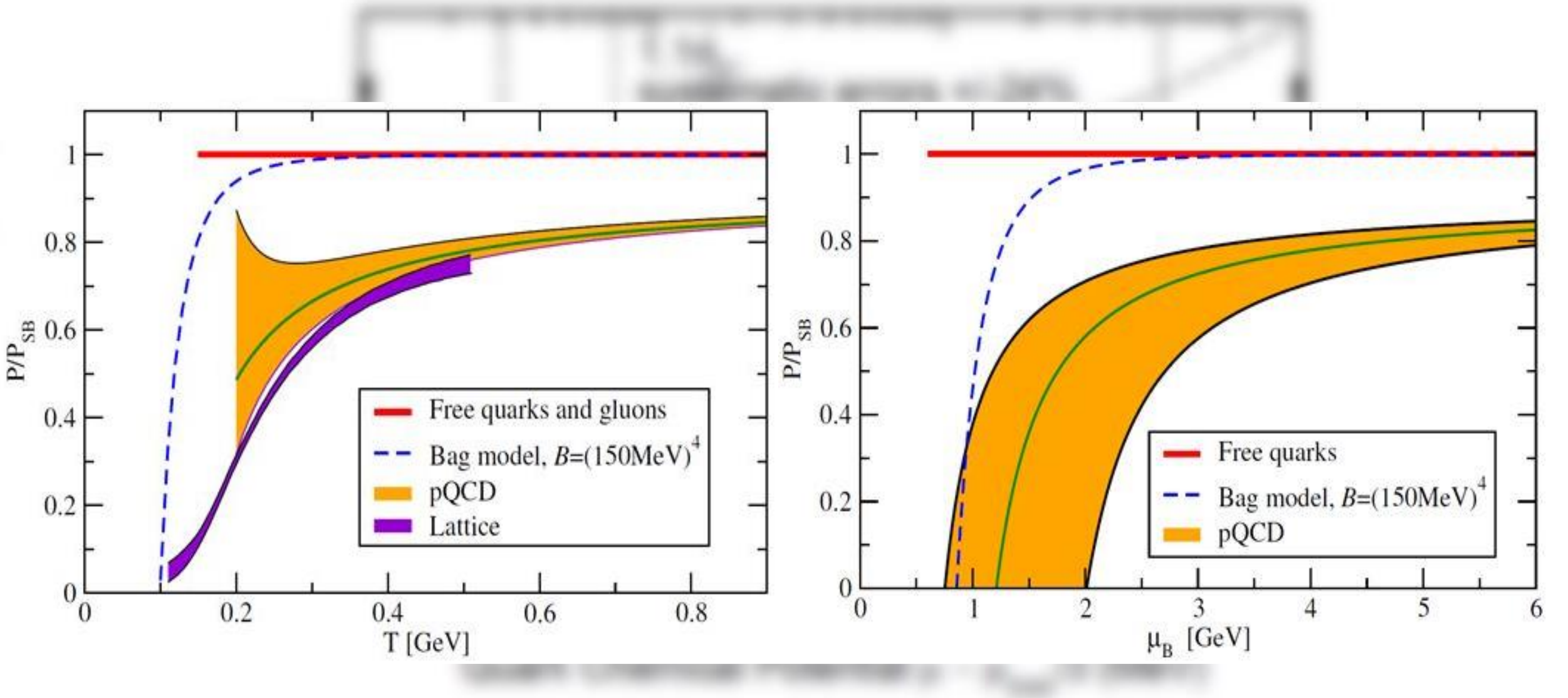
Low-density behavior of EoS well known from nuclear theory side. Challenges begin close to saturation density:

- At $1.1 n_s$, 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)]



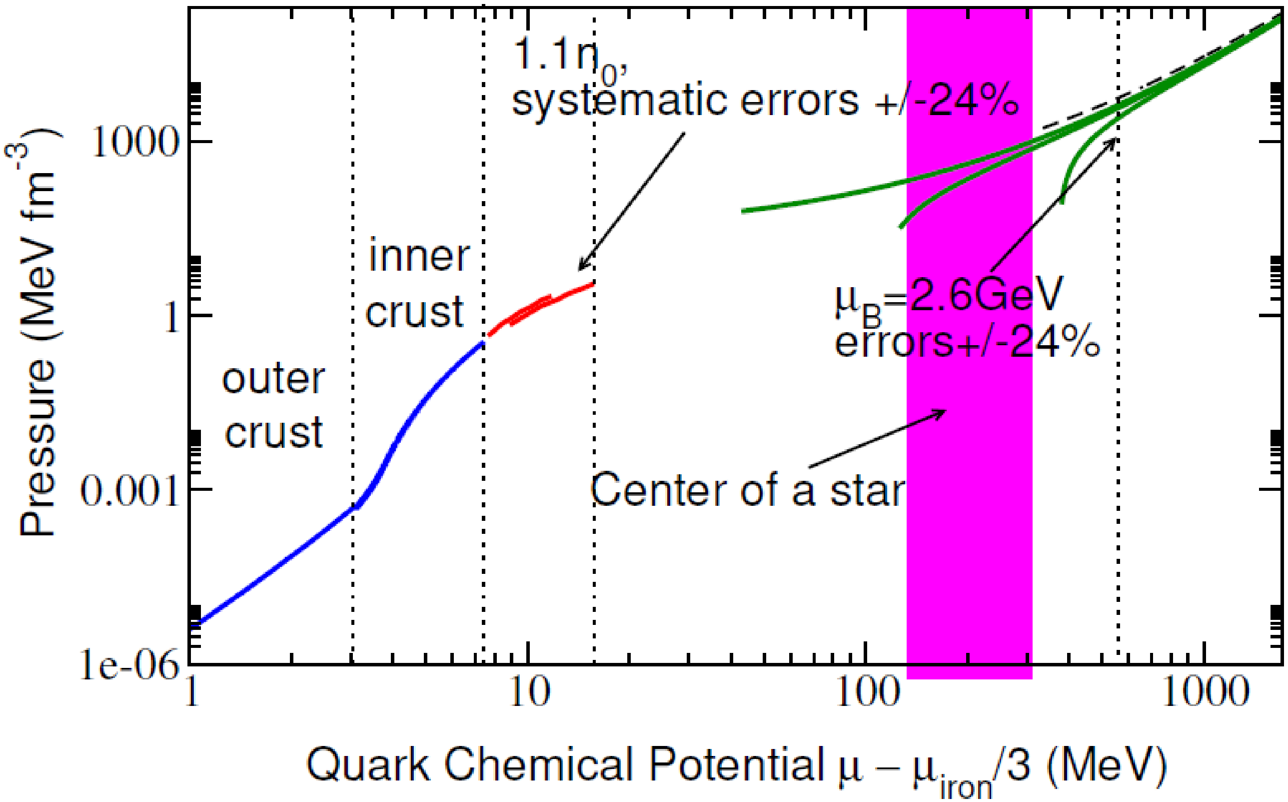
Asymptotic freedom of QCD ⇒ High-density limit from a non-interacting theory. However,…

- At interesting densities $(1-10)n_s$ system strongly interacting but no nonperturbative methods available
- Naïve expectation: Weak coupling methods only useful at very high densities



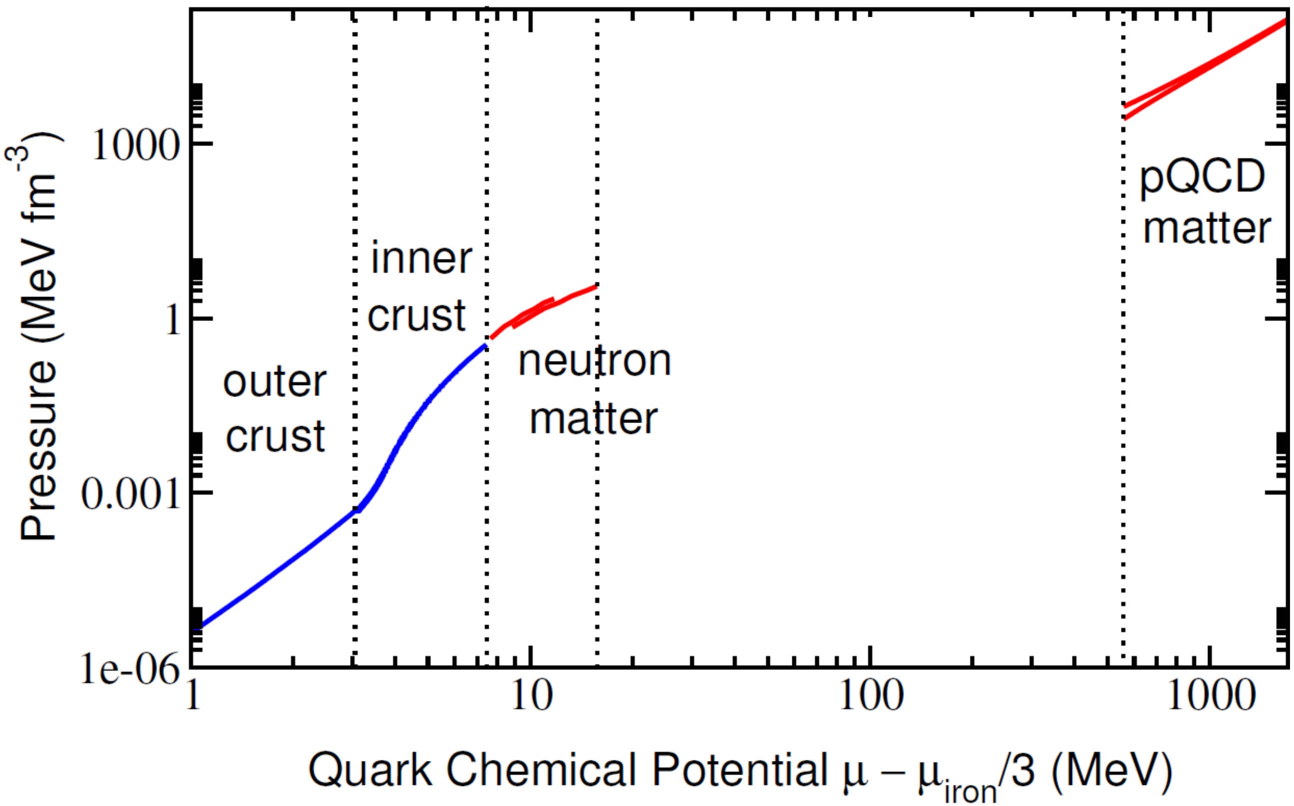
Recent improvement: First part of four-loop $T = 0$ pressure derived: $p_{4-\text{loop}} \ni -\frac{11}{12}\frac{N_c d_A}{(2\pi)^3}\alpha_s m_\infty^4 \ln^2 \alpha_s$ [Gorda, Kurkela, Romatschke, Säppi, AV, PRL 121 (2018), 1807.04120]

Linear log term also almost there and full α_s^3 order underway [work with Gorda, Kurkela, Paatelainen, Säppi; recently also Schicho, Seppänen, Österman]



Three-loop result with nonzero quark masses [Kurkela, Romatschke, Vuorinen, PRD 81 (2009)]

- Uncertainty of result at $\pm 24\%$ level around $40n_s$
- Main uncertainty from renormalization scale dependence
- Pairing contributions to EoS subdominant at relevant densities (see, however, also: Cherman, Sen, Yaffe, PRD 100 (2019))



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?

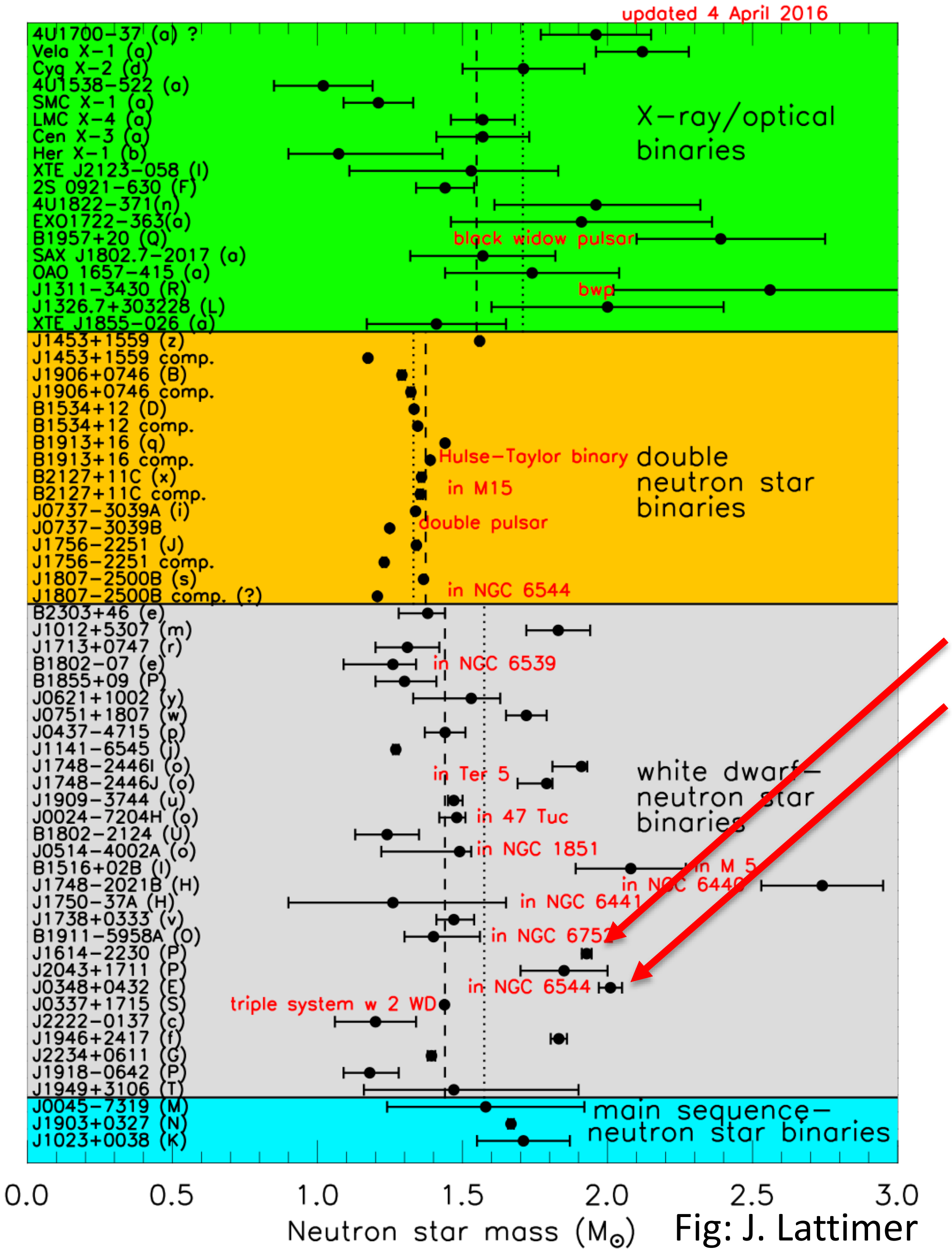


Fig: J. Lattimer

By now, two accurate Shapiro delay measurements of two-solar-mass stars:

Demorest et al., Nature 467 (2010)

Antoniadis et al., Science 340 (2013)

$$\therefore \quad M_{\max} > 2M_\odot$$

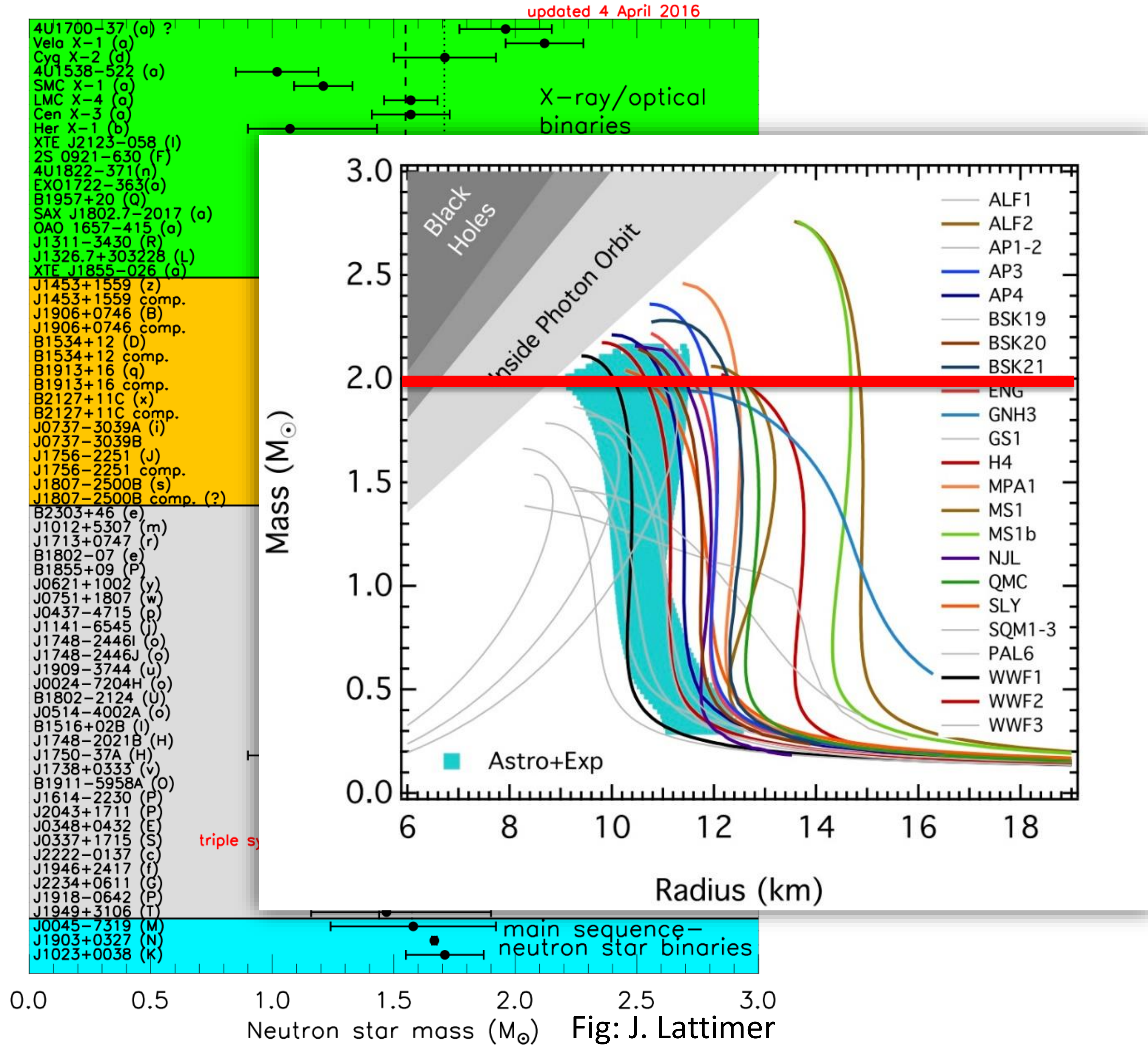


Fig: J. Lattimer

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s:

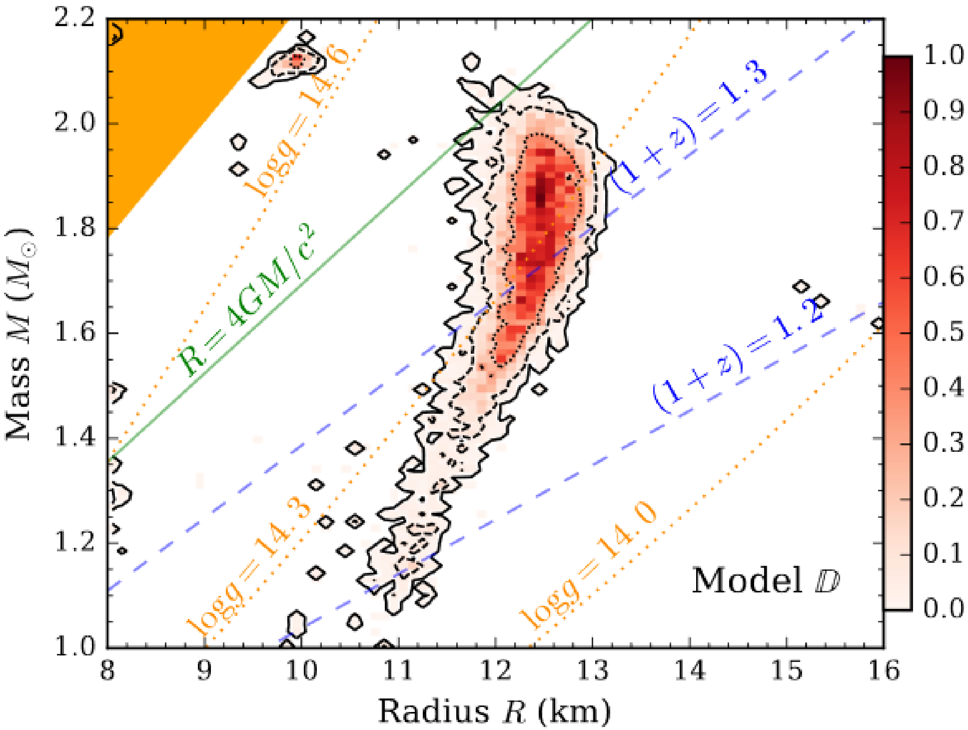
re 467 (2010)

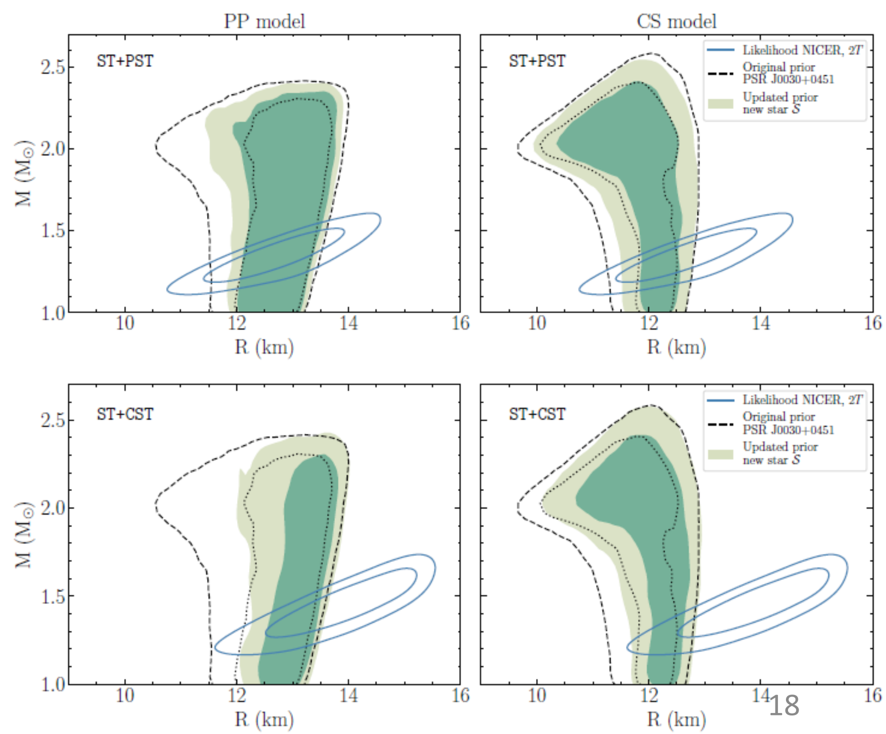
nce 340

$2M_\odot$

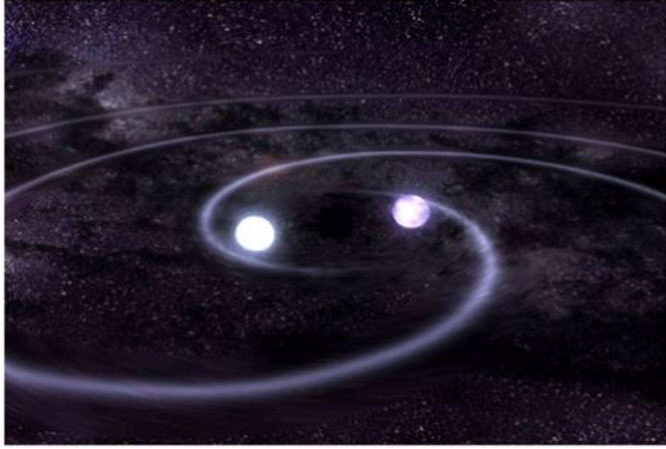
Radius measurements more problematic, but progress through observation of X-ray emission:

- Cooling of thermonuclear X-ray bursts provide radii to $\sim\pm 400\text{m}$ [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)]



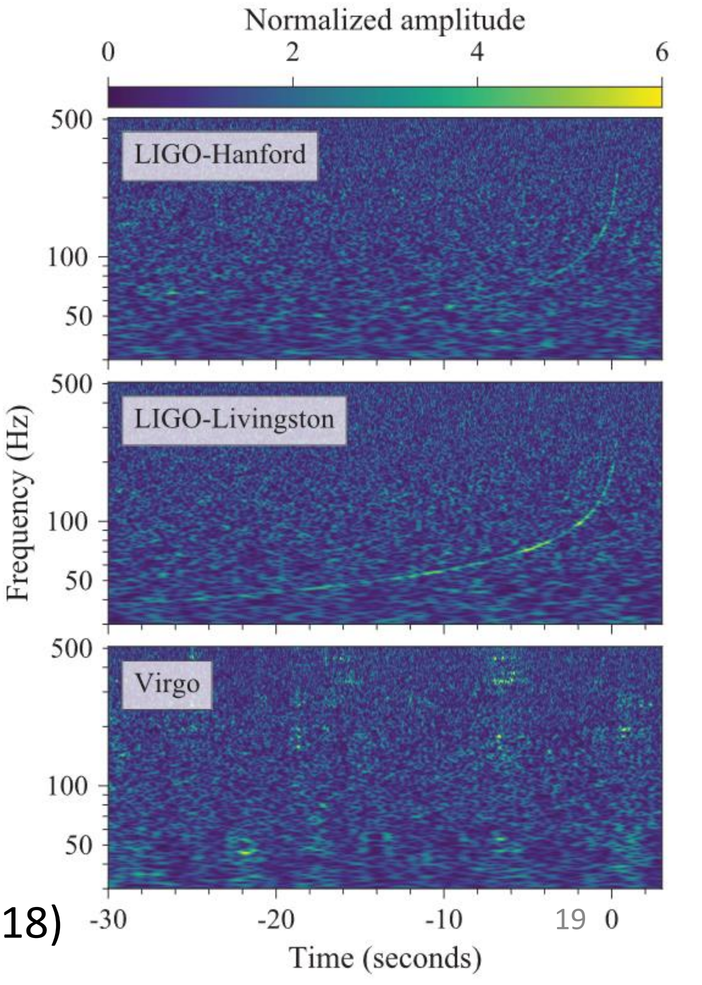


Gravitational wave breakthrough: First observed NS merger by LIGO & Virgo in 2017 (any many since then)



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

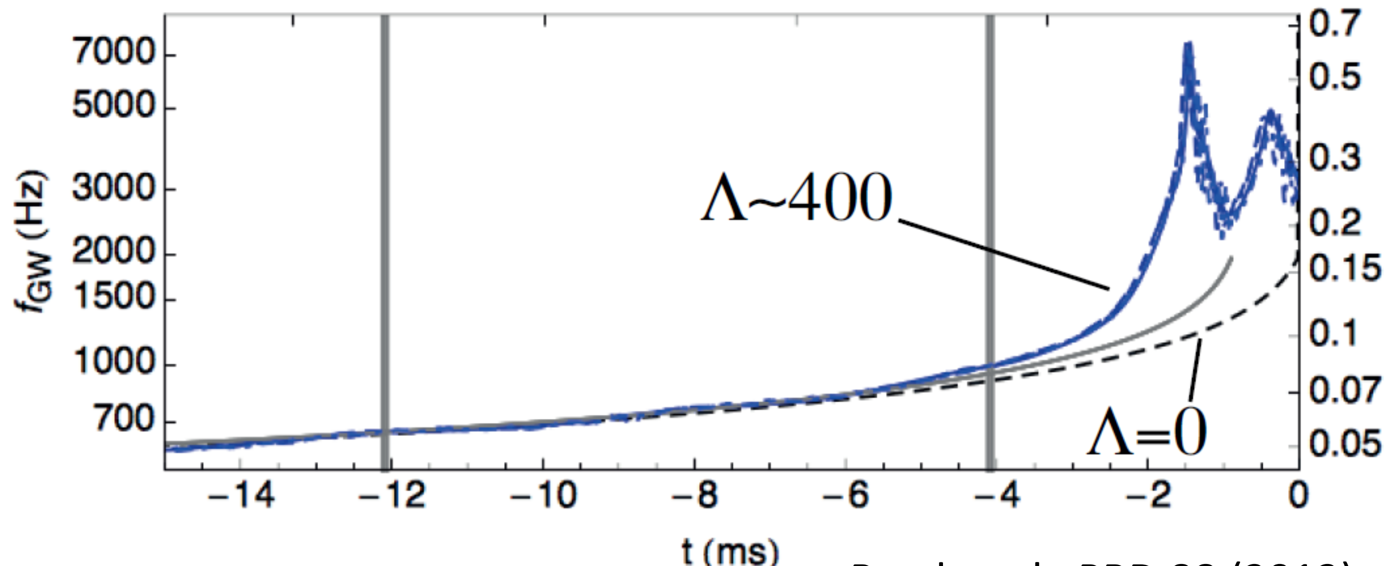


LIGO and Virgo collaborations, PRL 119 (2017), PRL 121 (2018)

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

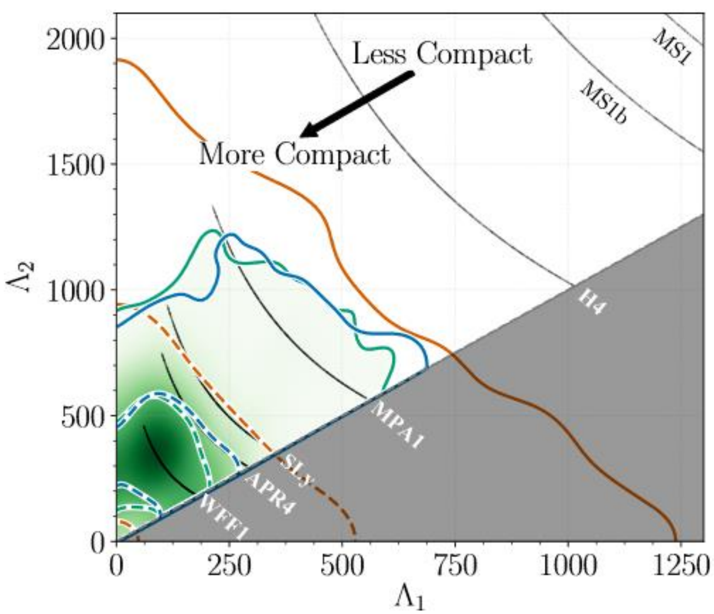


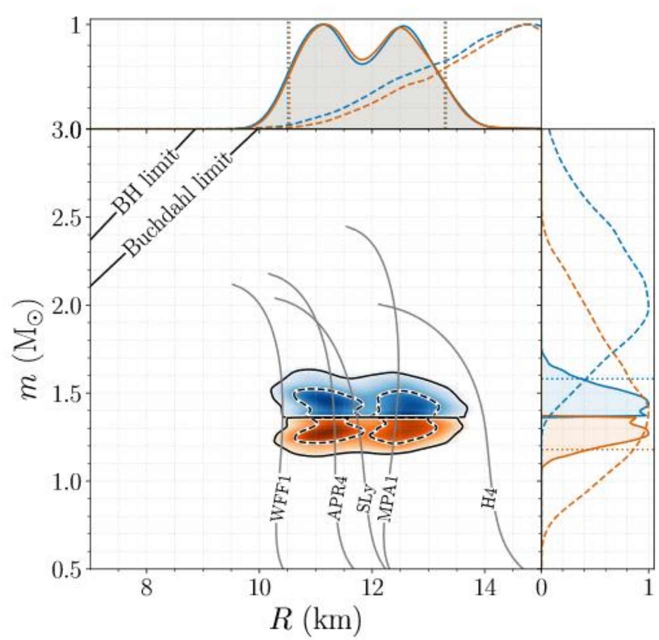
Read et al., PRD 88 (2013)

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)]





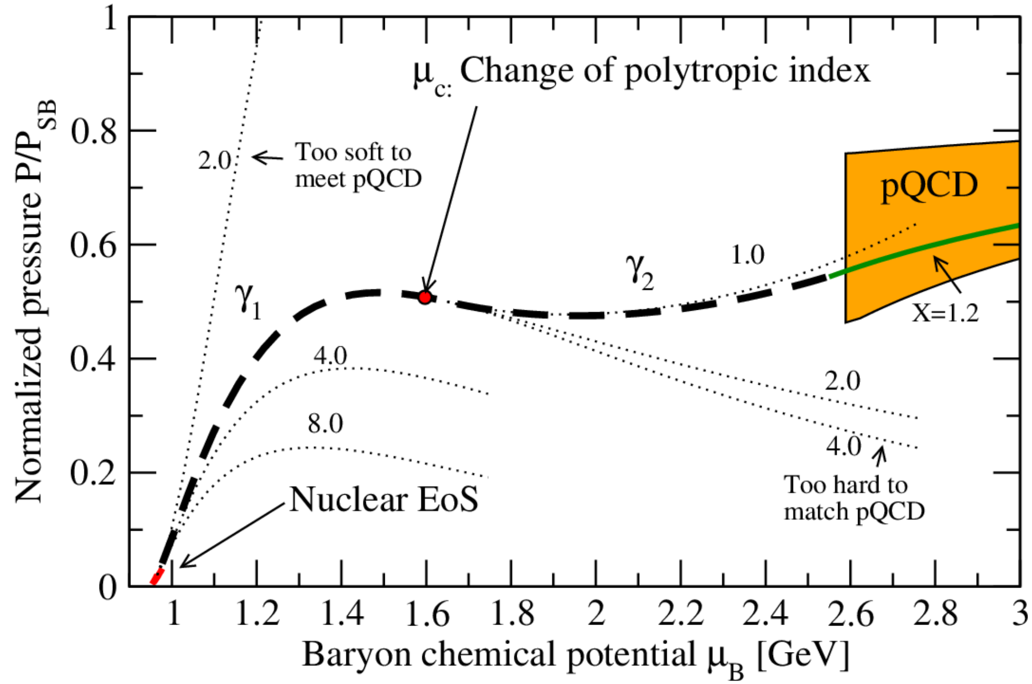
Interpolation – or how to optimally combine theoretical and observational insights

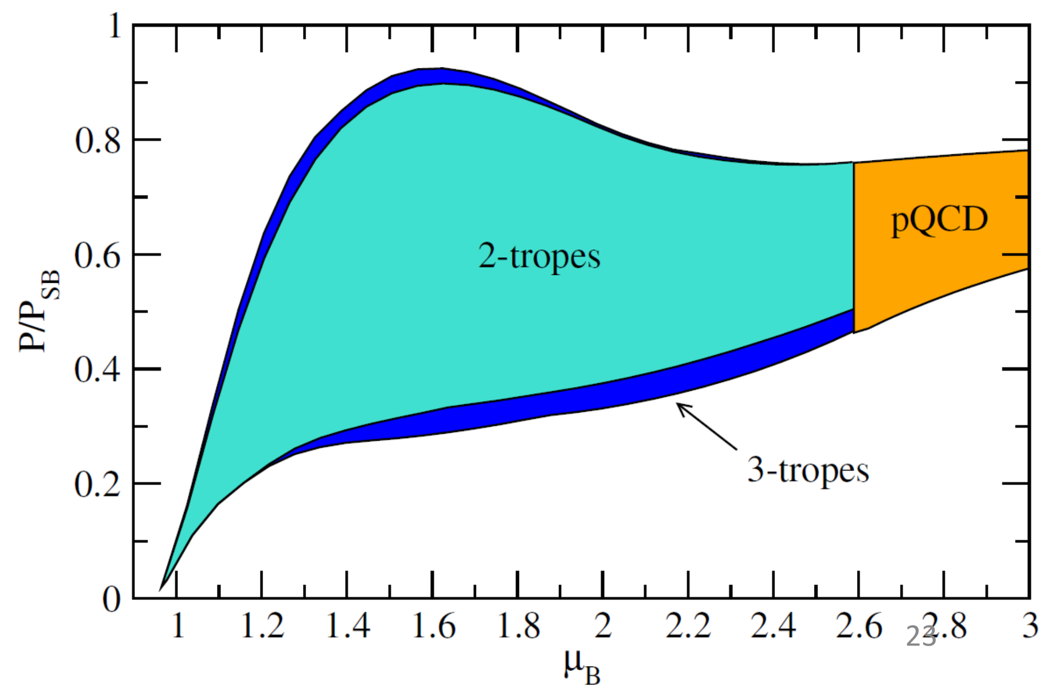
Allow all possible EoS behaviors by interpolating it over the no man's land using one's favorite (often piecewise) basis functions

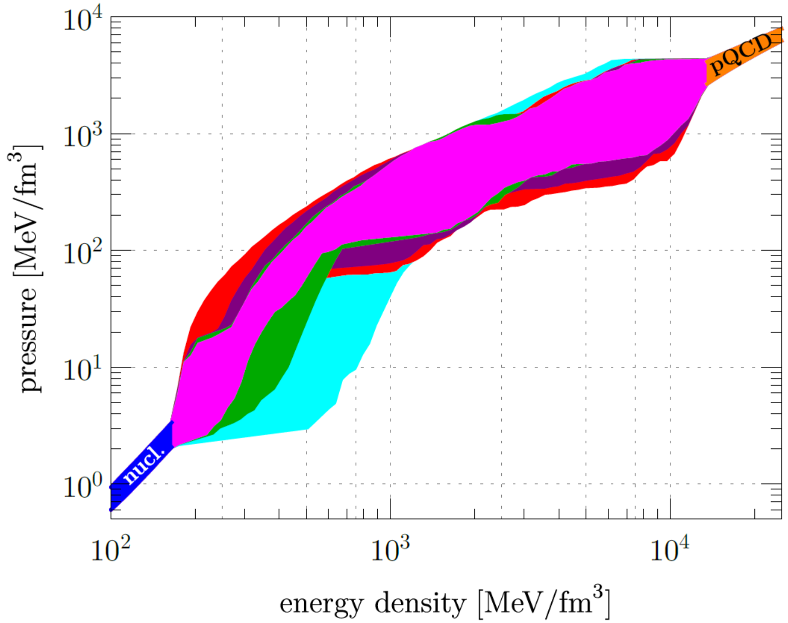
Require:

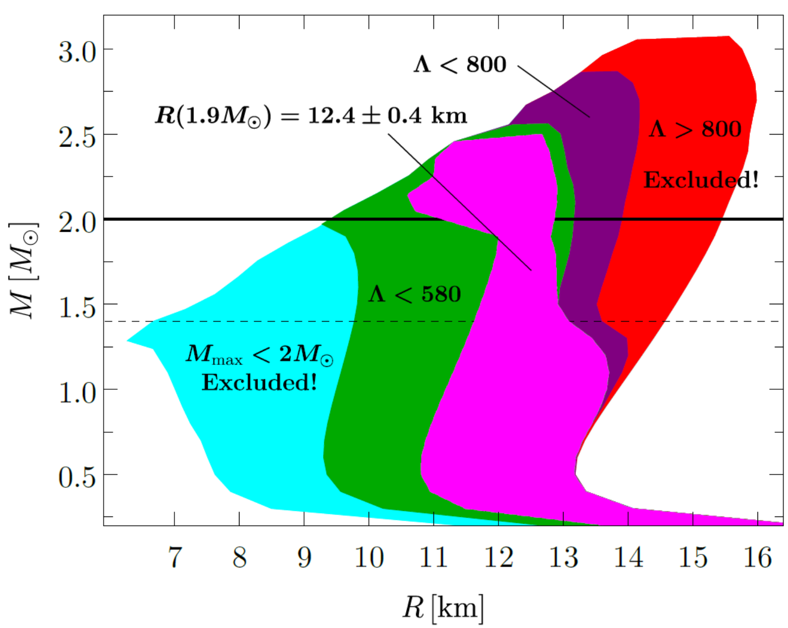
1) Smooth matching to nuclear and quark matter EoSs
2) Continuity of p and n – with at most one exception (1st order transition)
3) Subluminality
4) Optional: astrophysical constraints

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









Using 4-tropes, generate ensemble of 200.000 viable EoSs.

Additionally take into account:

- Existence of $2M_\odot$ NSs ⇒ Very soft EoSs ruled out, $R(1.4M_\odot) \geq 10$km
- Tidal deformability limits ⇒ EoS cannot be overly stiff, $R(1.4M_\odot) \leq 13$km
- Accurate R measurements (here assuming accurately determined mass)

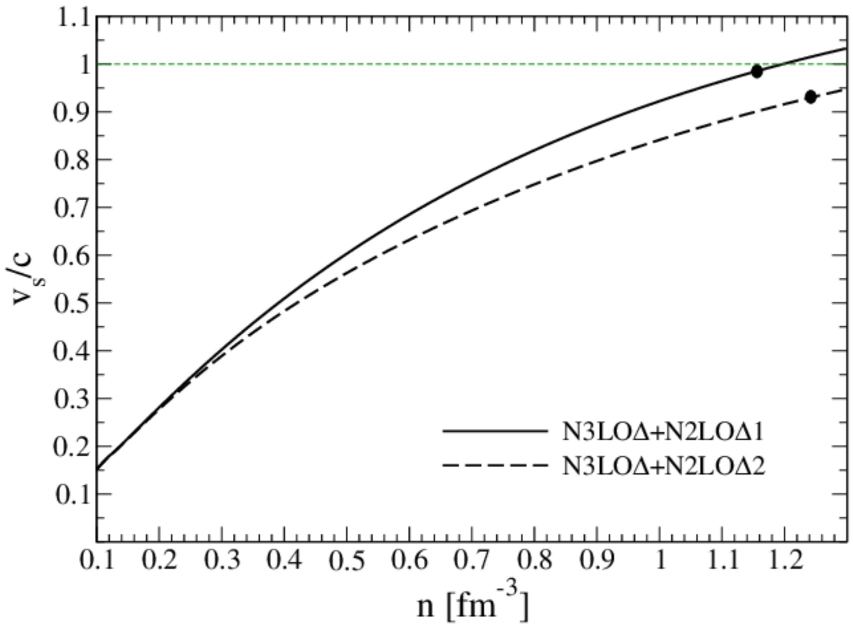
[Annala, Gorda, Kurkela, AV, PRL 120 (2018), 1711.02644]

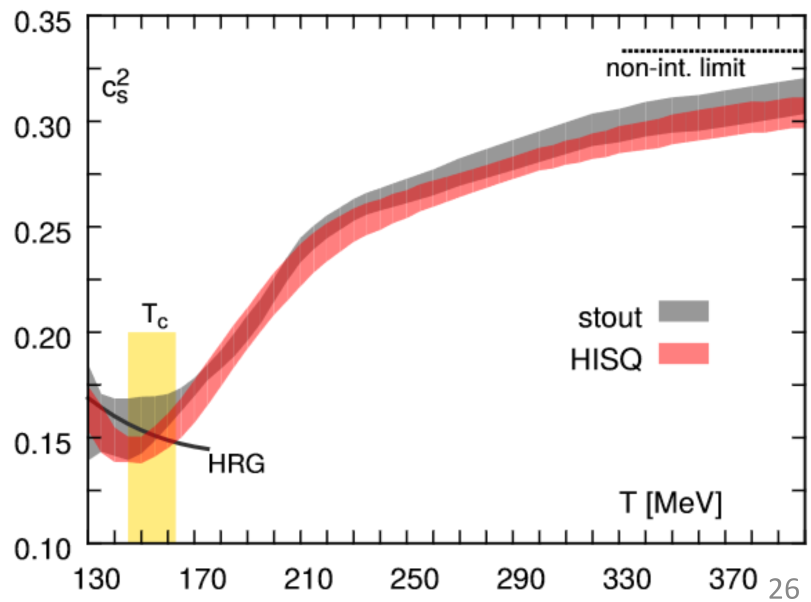
How about quark matter?

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)]

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





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

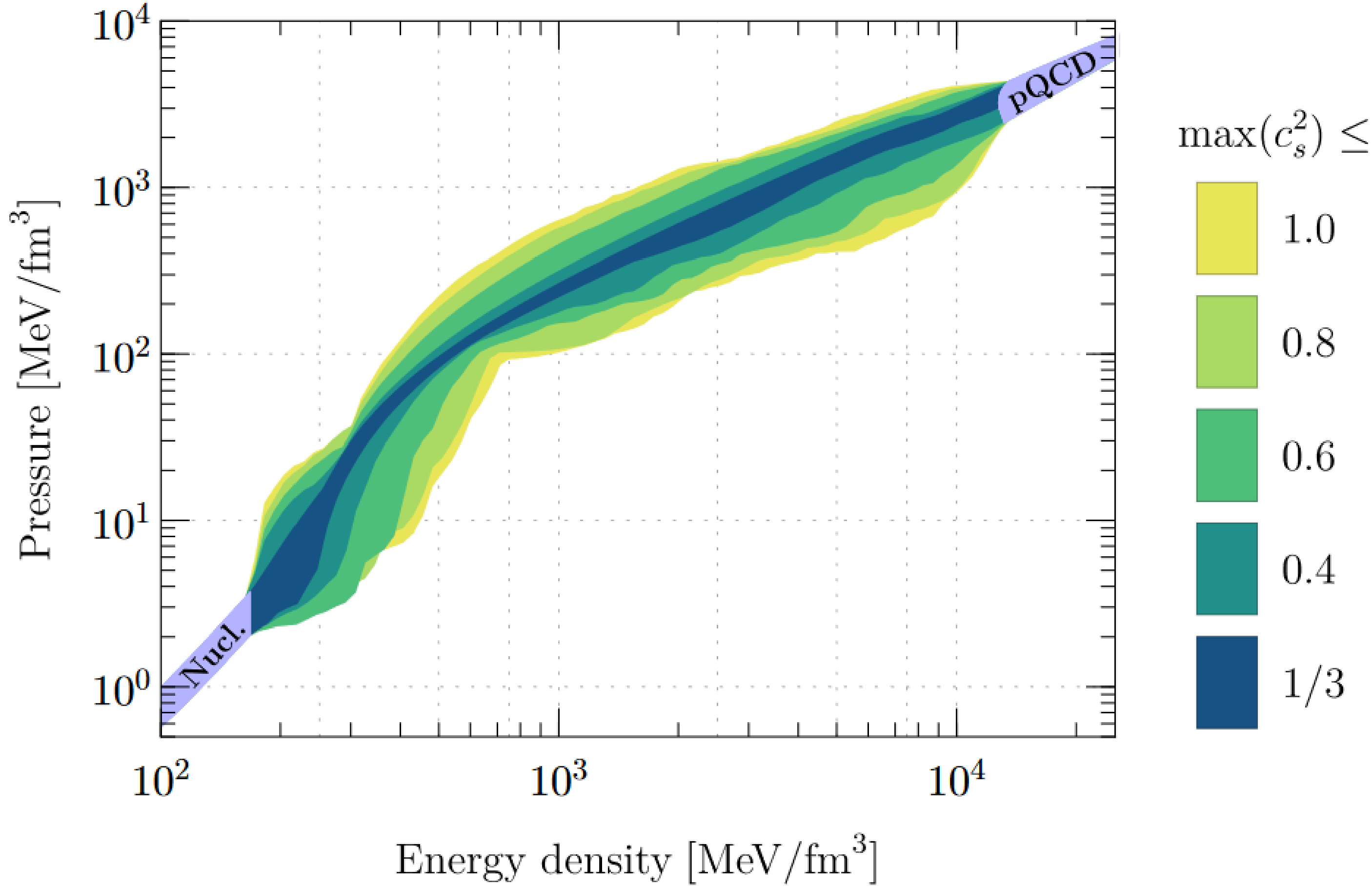
Bound on the speed of sound from holography

Aleksey Cherman* and Thomas D. Cohen†
Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, Maryland 20742-4111, USA

Abhinav Nellore‡
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544, USA
(Received 12 May 2009; published 3 September 2009)

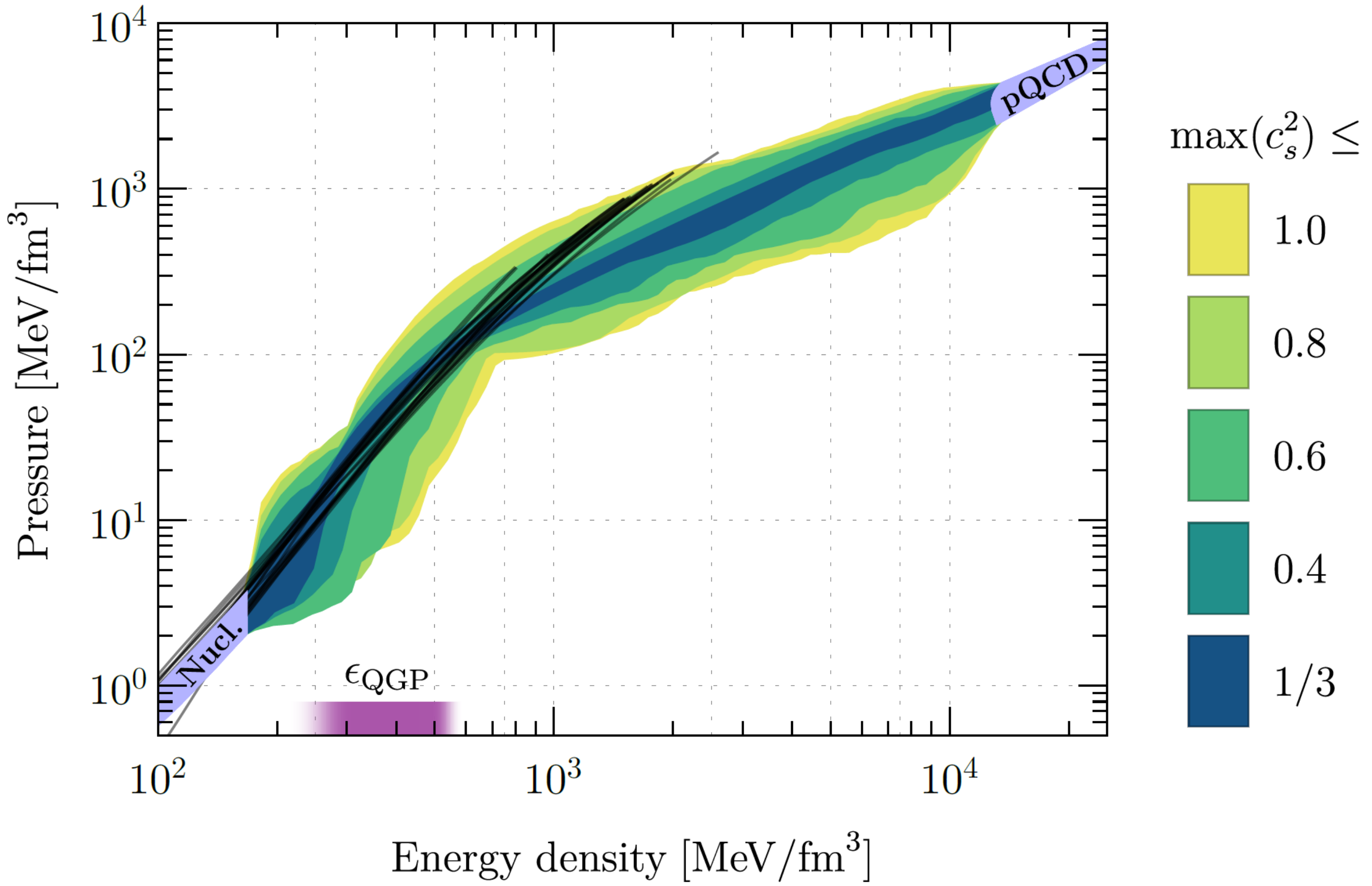
We show that the squared speed of sound v_s^2 is bounded from above at high temperatures by the conformal value of $1/3$ in a class of strongly coupled four-dimensional field theories, given some mild technical assumptions. This class consists of field theories that have gravity duals sourced by a single-scalar 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



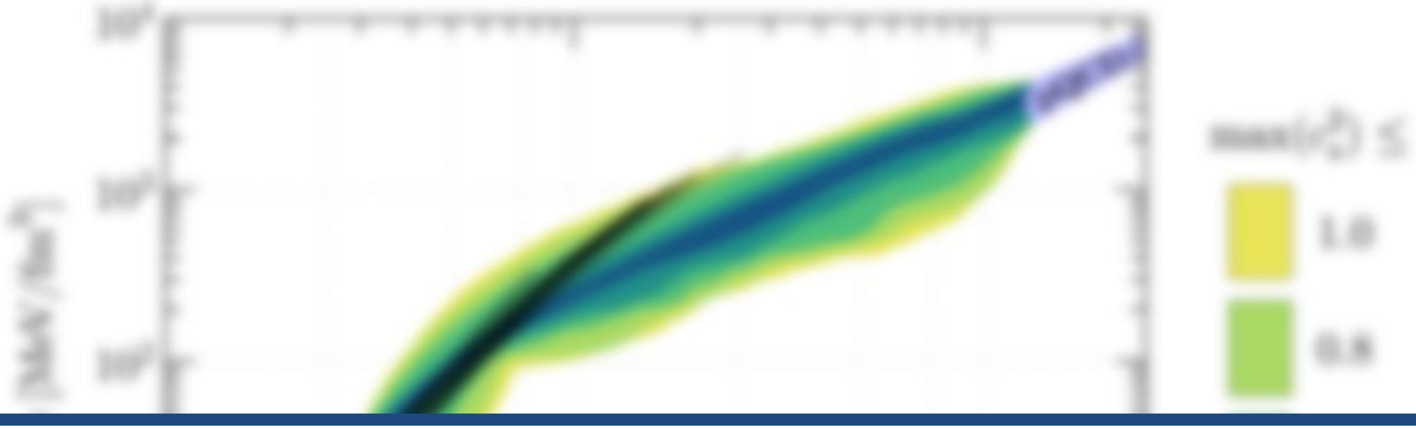
Setting nontrivial upper limits for speed of sound leads to increasingly constrained results; contrary to common lore, even sub-conformal ($c_s^2 < 1/3$) EoSs viable

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 $\gamma \equiv \frac{d \ln p}{d \ln \epsilon} \approx 1$ in nearly conformal QM, ~2.5 in sub-n_s nuclear matter



Obvious questions:

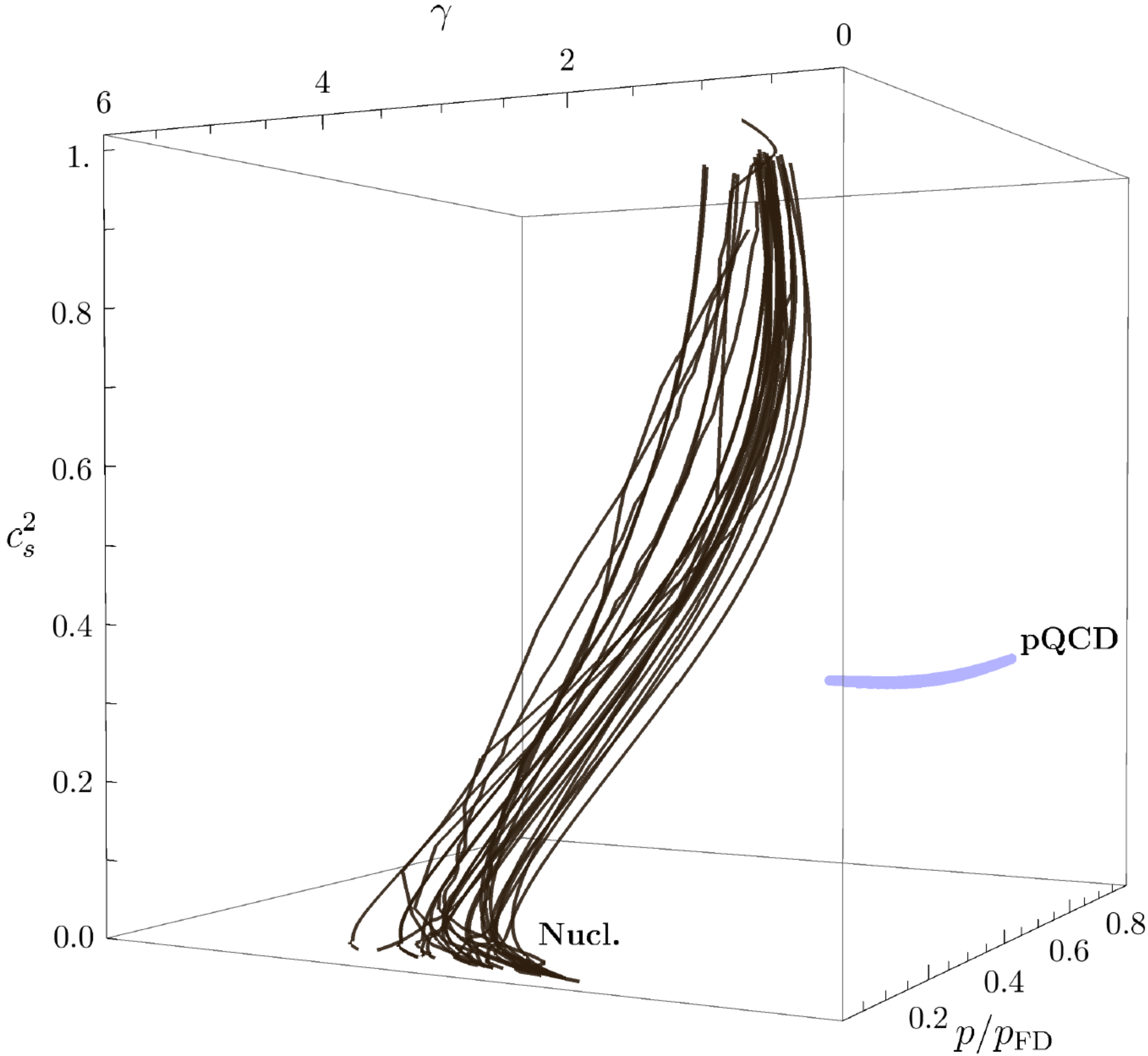
1) Is the two-slope structure only a property of the band, or does it persist more differentially – and for larger values of max(c_s^2)?
2) Where do the centers of NSs with different masses lie, i.e. does quark matter exist inside NSs?

strengthen link between bend and deconf. transition

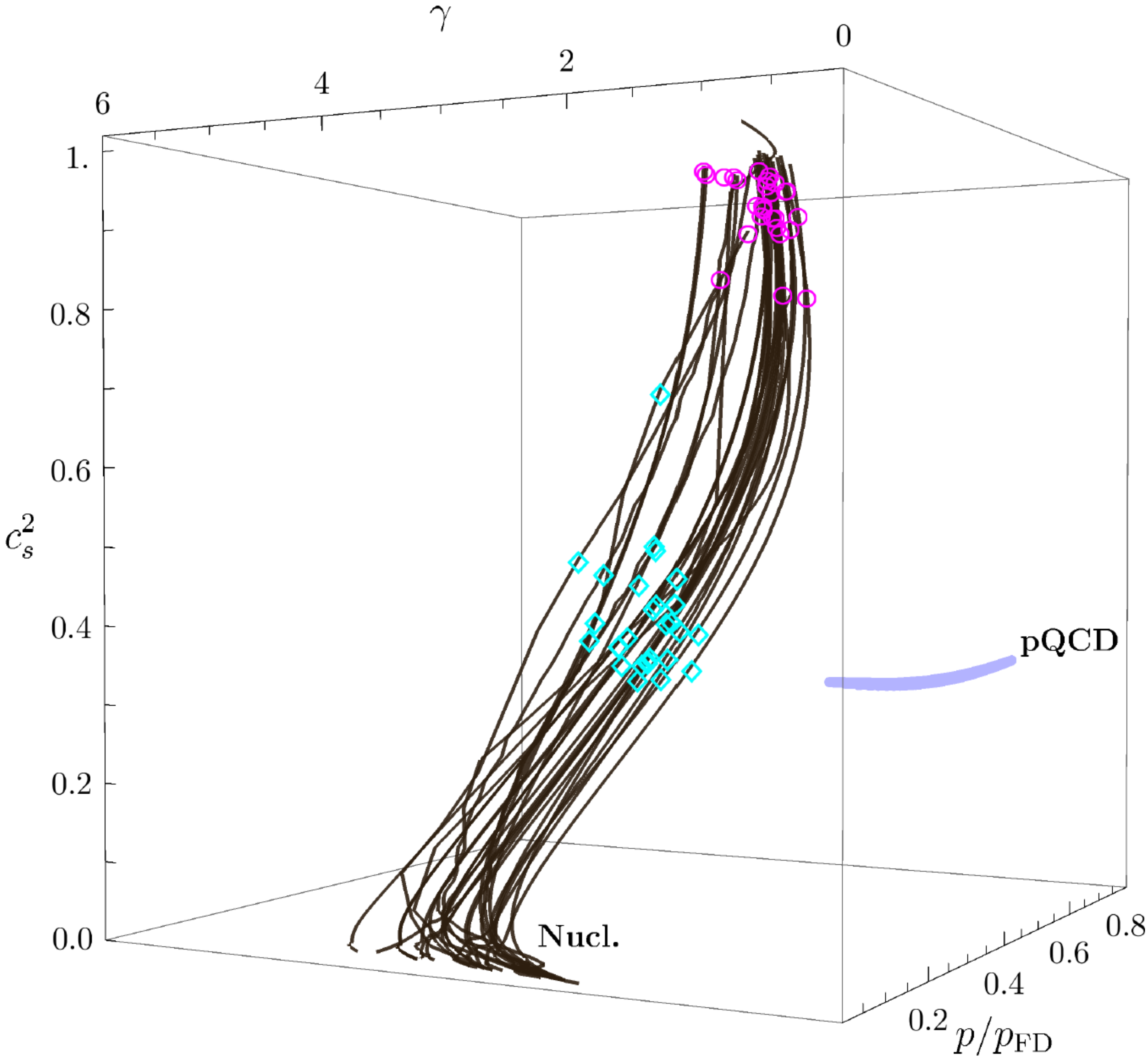
Distinguishing feature between phases: slope $\gamma \equiv \frac{d \ln p}{d \ln \epsilon} \approx$ 1 in nearly conformal QM, 2.5 in sub-n_s nuclear matter

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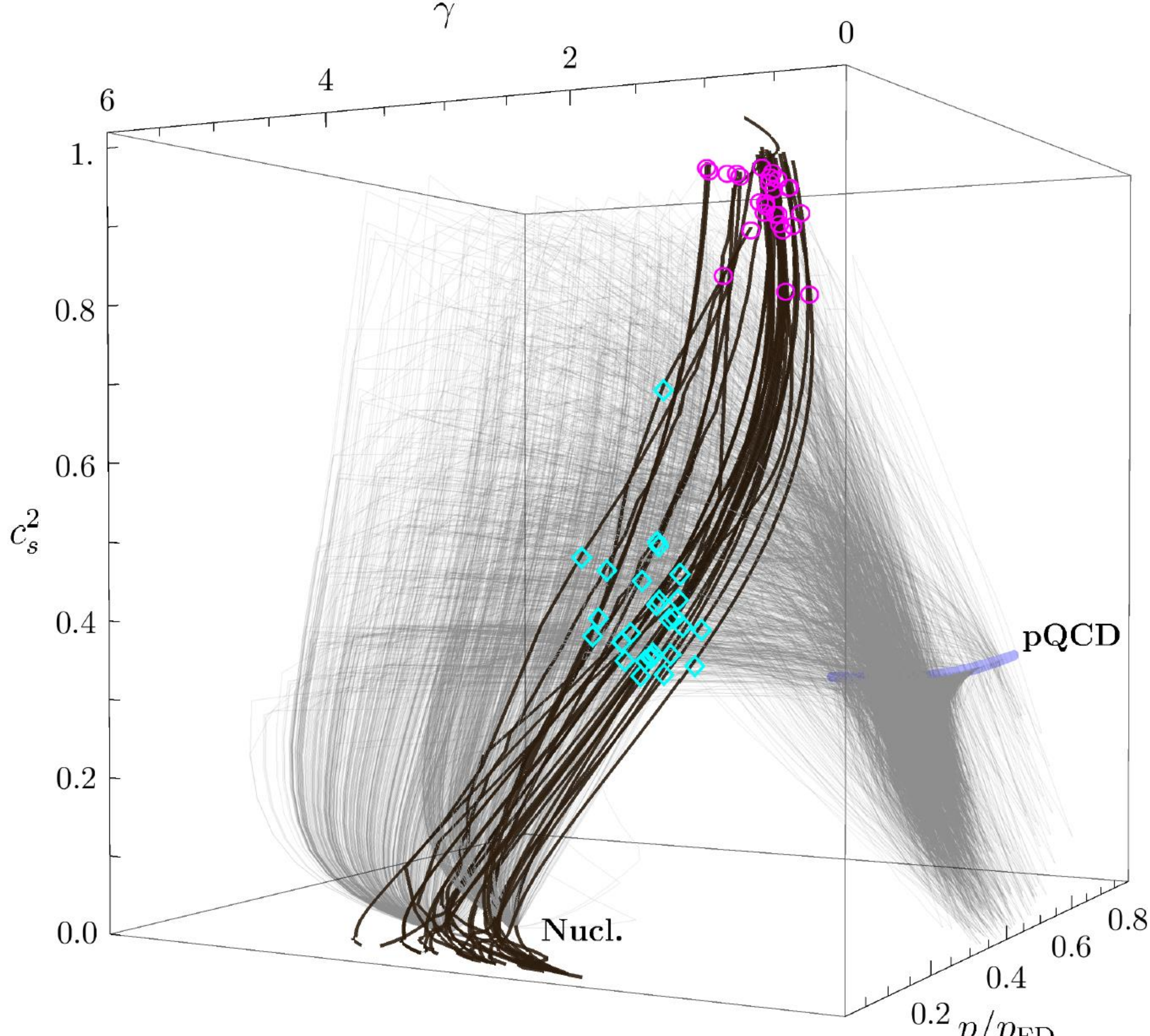
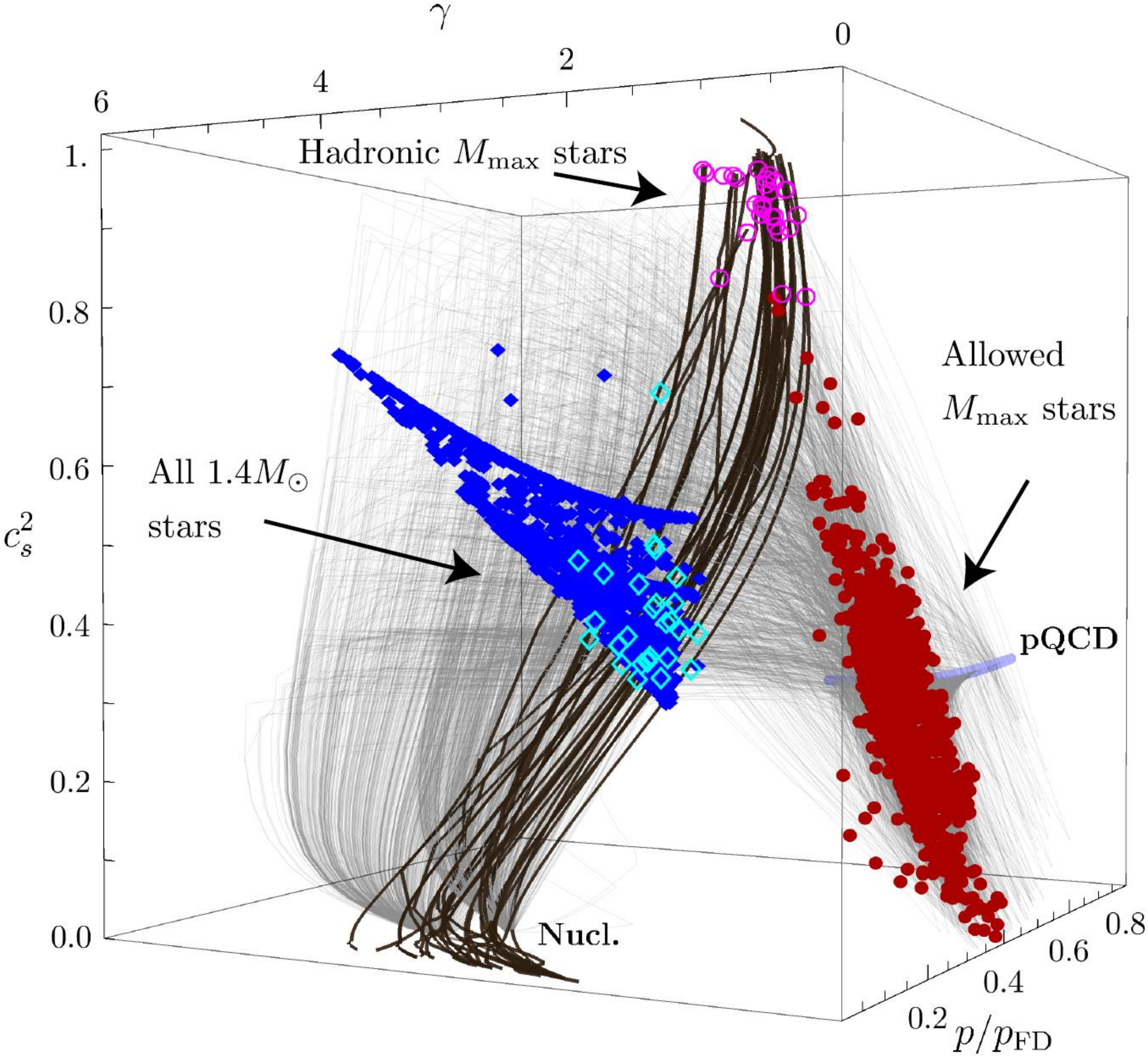
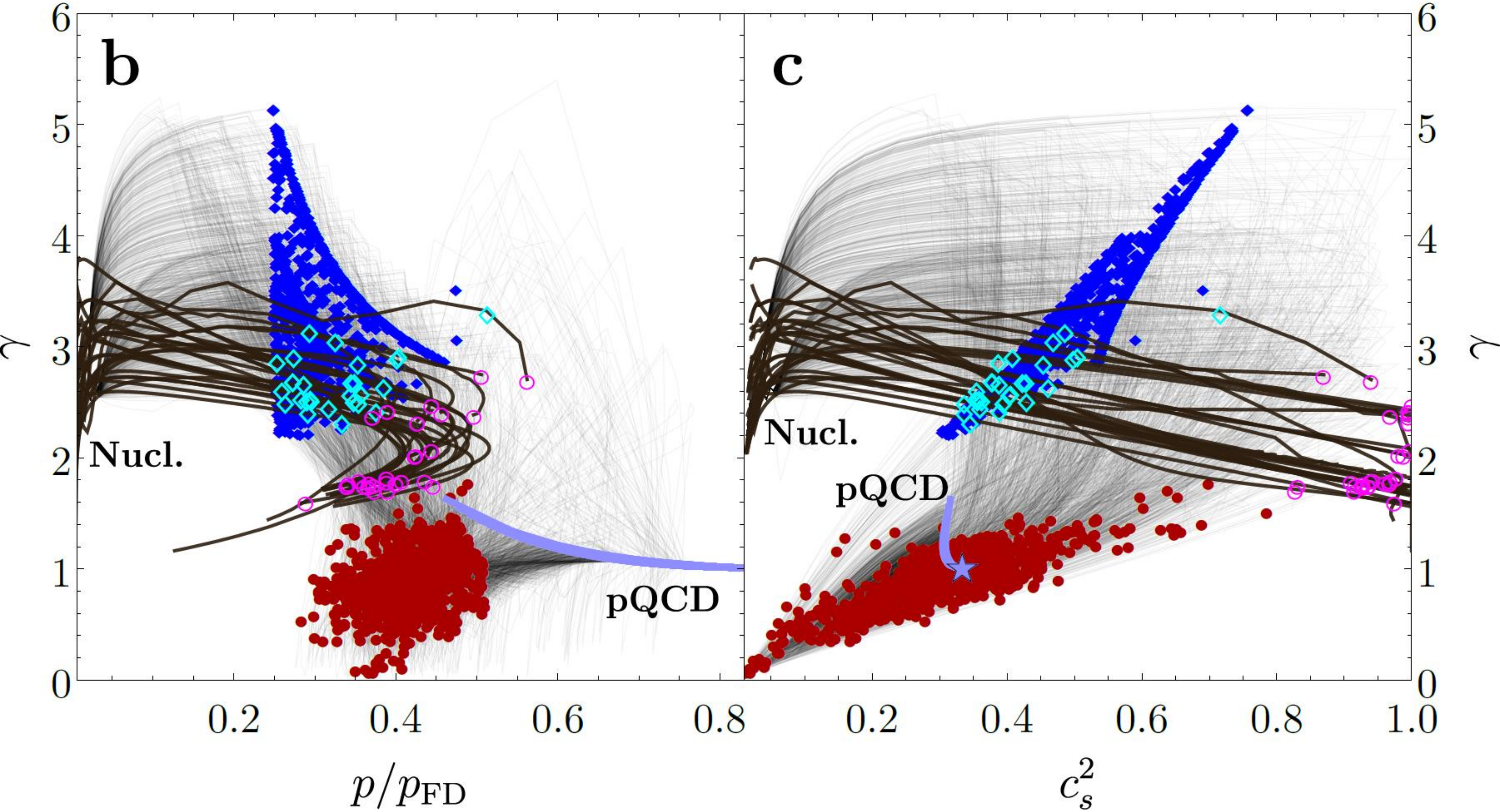
c_s^2
pQCD
Nucl.
0.2
0.4
0.6
0.8
$p/p_{\rm FD}$



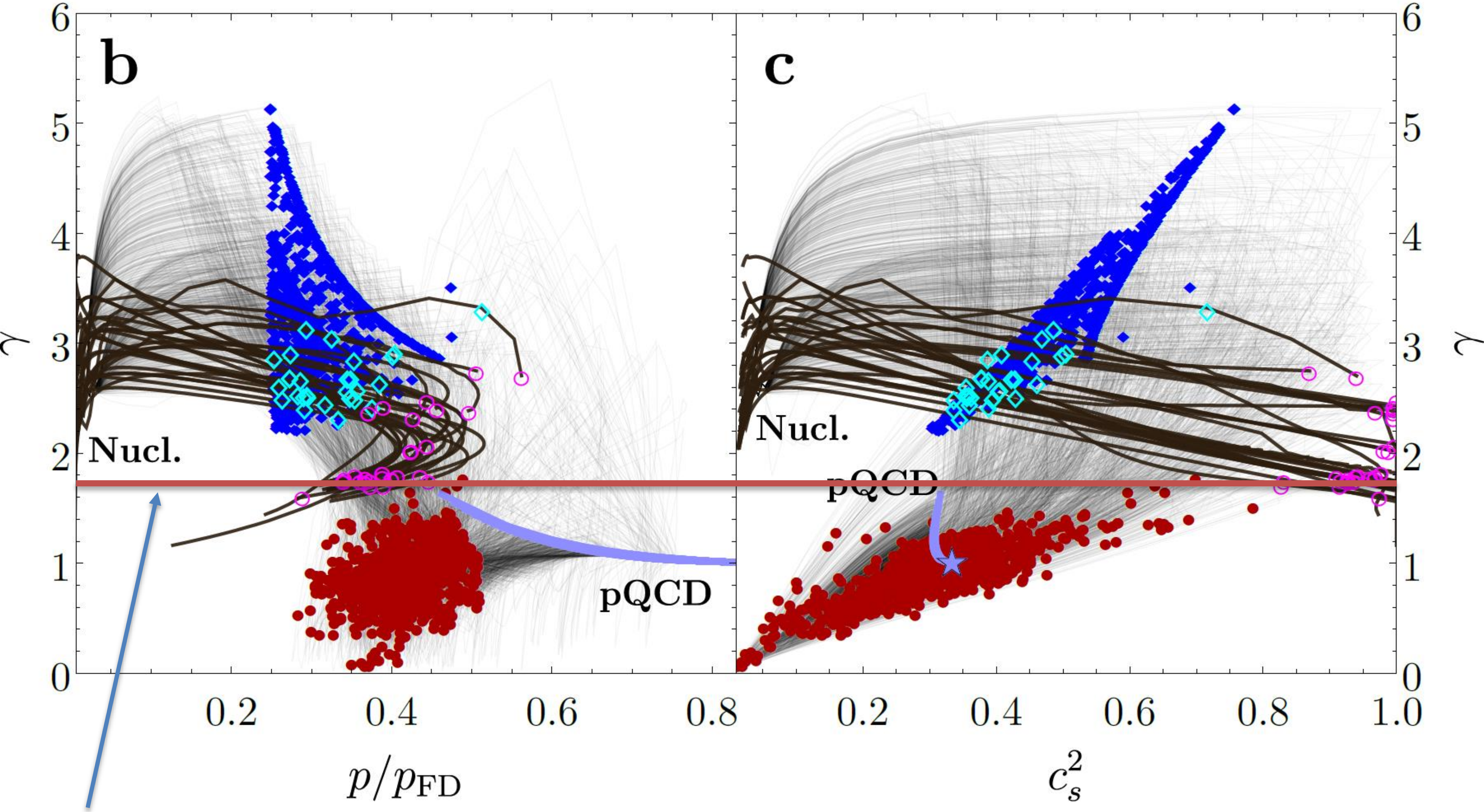
γ
0
2
4
6
1.
0.8
0.6
0.4
0.2
0.0
c_s^2
pQCD
Nucl.
0.2
0.4
0.6
0.8
$p/p_{\rm FD}$



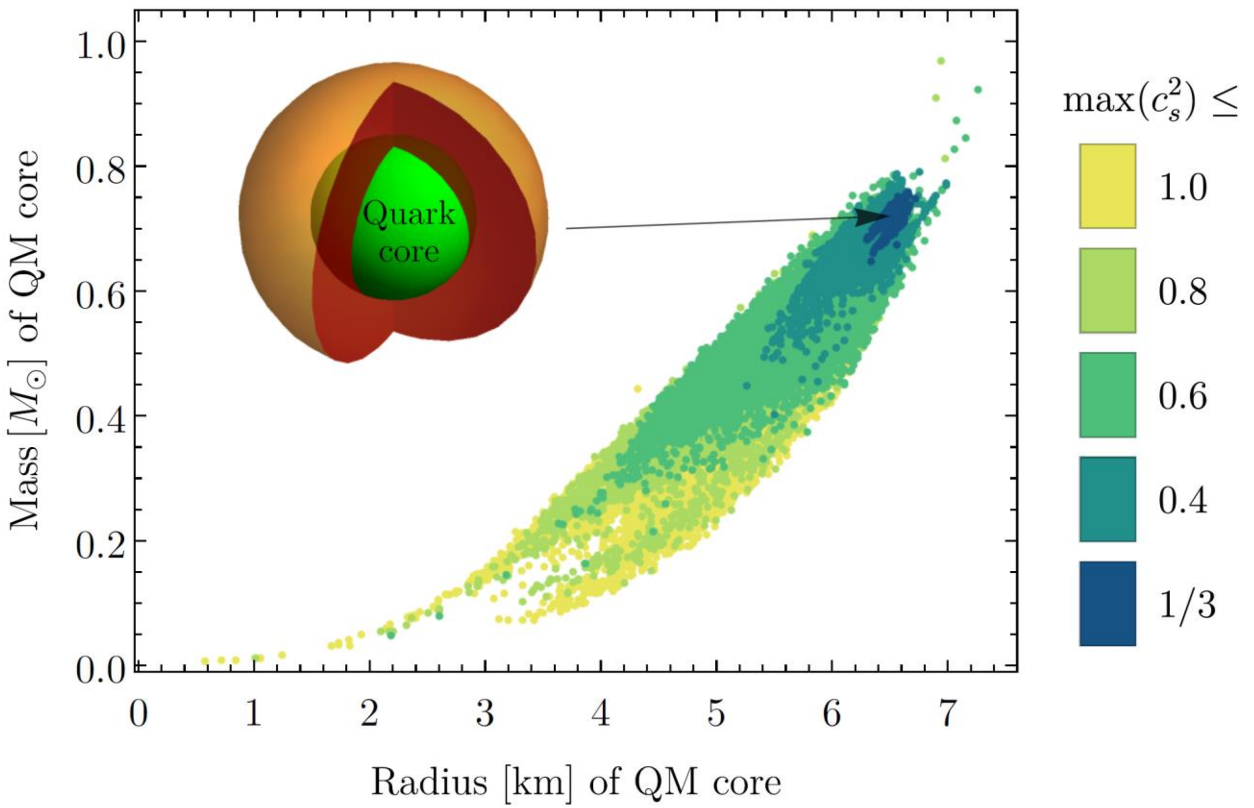
γ
0
2
4
6
Hadronic $M_{\max}$ stars
1.
0.8
0.6
0.4
0.2
0.0
c_s^2
All $1.4M_\odot$ stars
Allowed $M_{\max}$ stars
pQCD
Nucl.
0.2
0.4
0.6
0.8
$p/p_{\rm FD}$



b
c
Nucl.
Nucl.
pQCD
pQCD
γ
γ
$p/p_{\rm FD}$
c_s^2
0
1
2
3
4
5
6
0.2
0.4
0.6
0.8
1.0

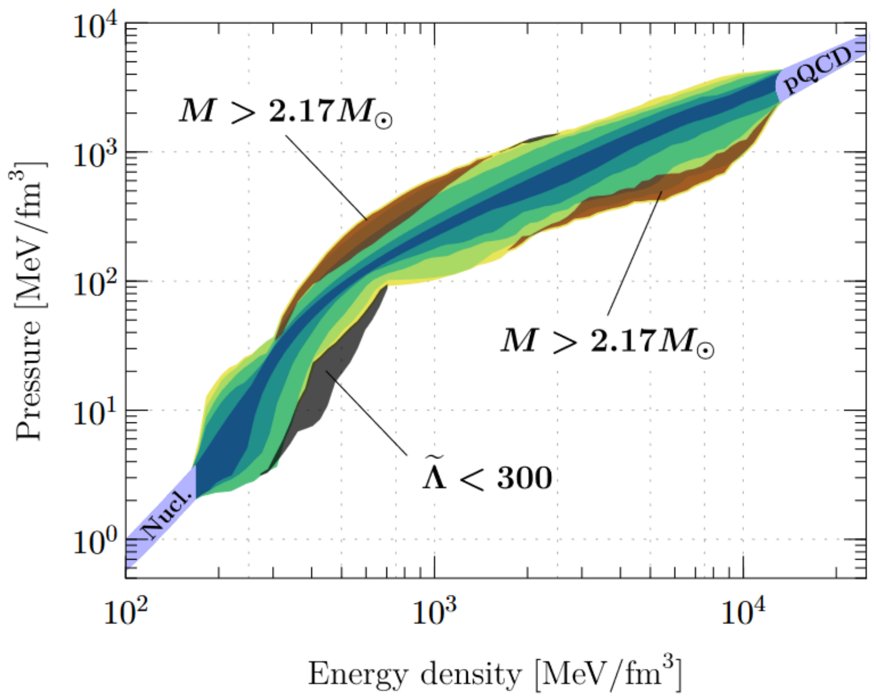


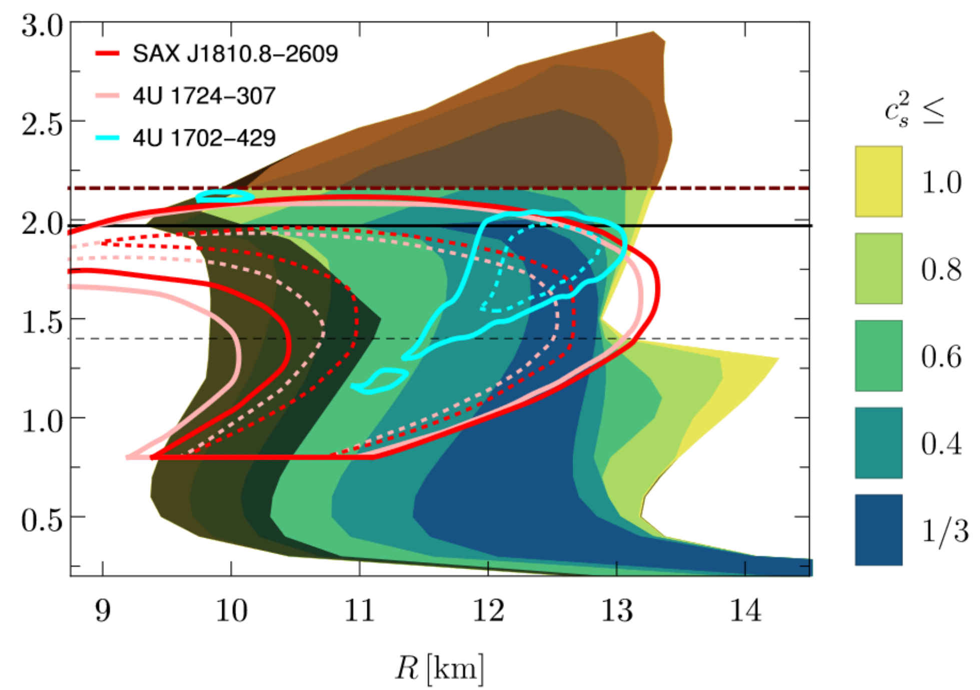
Approximative criterion for the onset of QM



- 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

- First-principles description of dense QCD matter is difficult, and no nonperturbative solution applicable everywhere in sight
  - Large no man’s land between low and high densities
- Efficient combination of ab-initio microphysics results and neutron-star observations is providing increasingly robust results for the Equation of State
- New model-independent study points towards centers of massive NSs behaving in a way reminiscent of QM
  - Caveats remain, but key quantities for identified: speed of sound & latent heat of transition – reason for optimism