Quark matter cores in massive neutron stars

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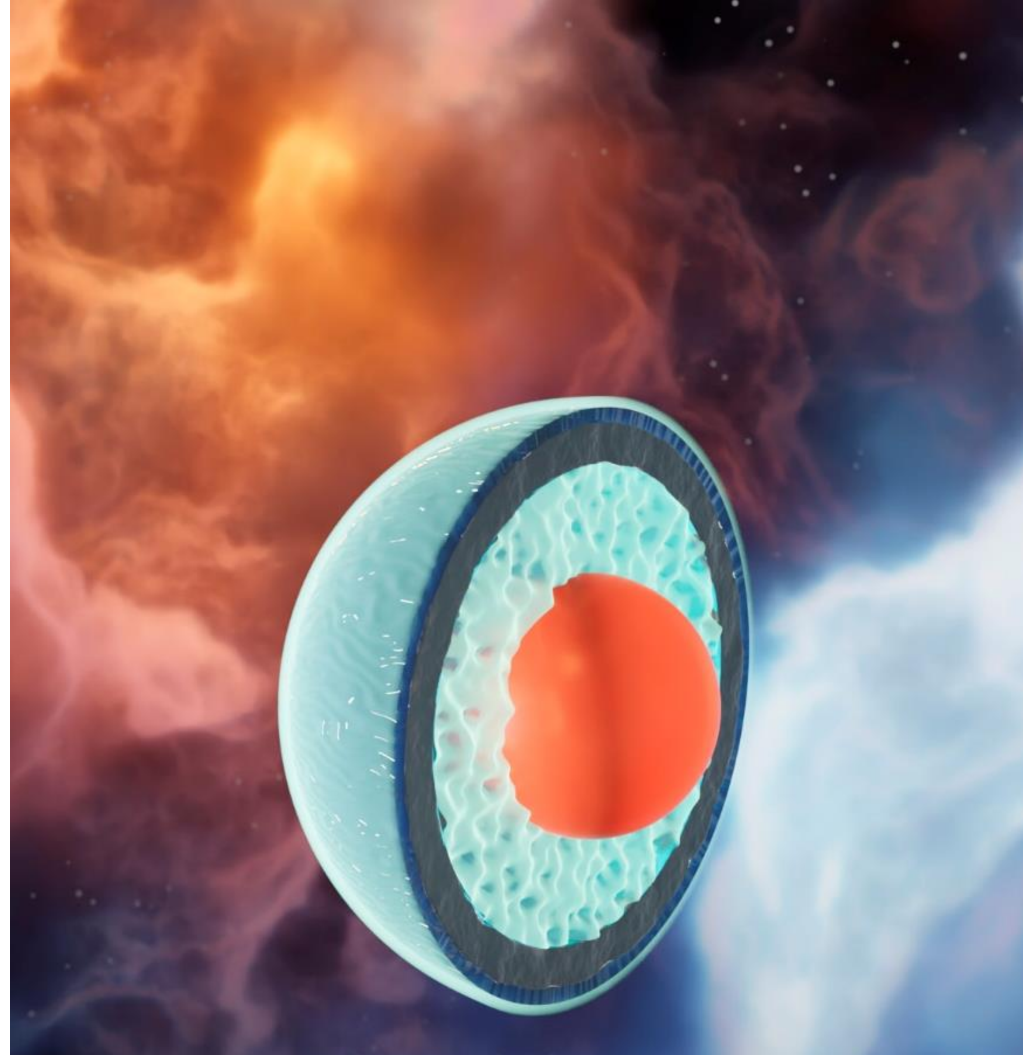

Main references:

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/**

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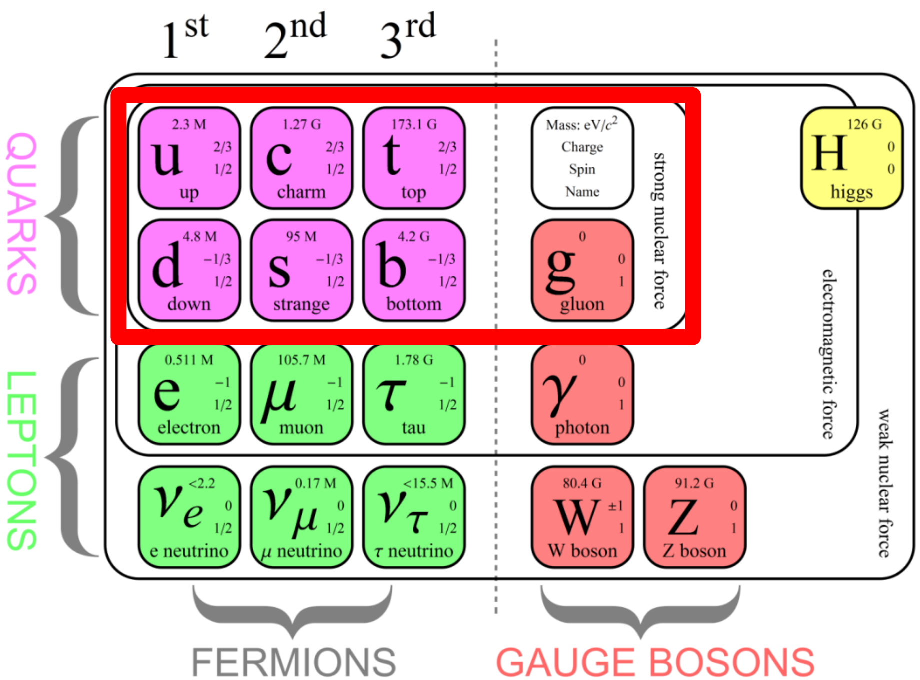
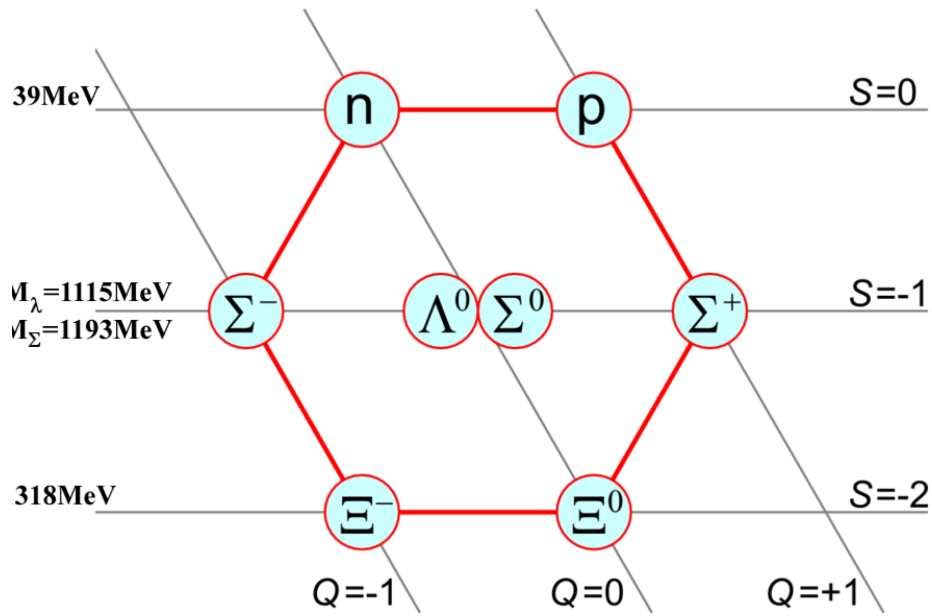
$$\mathcal{L}_{\mathrm{QCD}} = \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \sum_f \bar{\psi}_f (\gamma_\mu D_\mu + m_f) \psi_f$$





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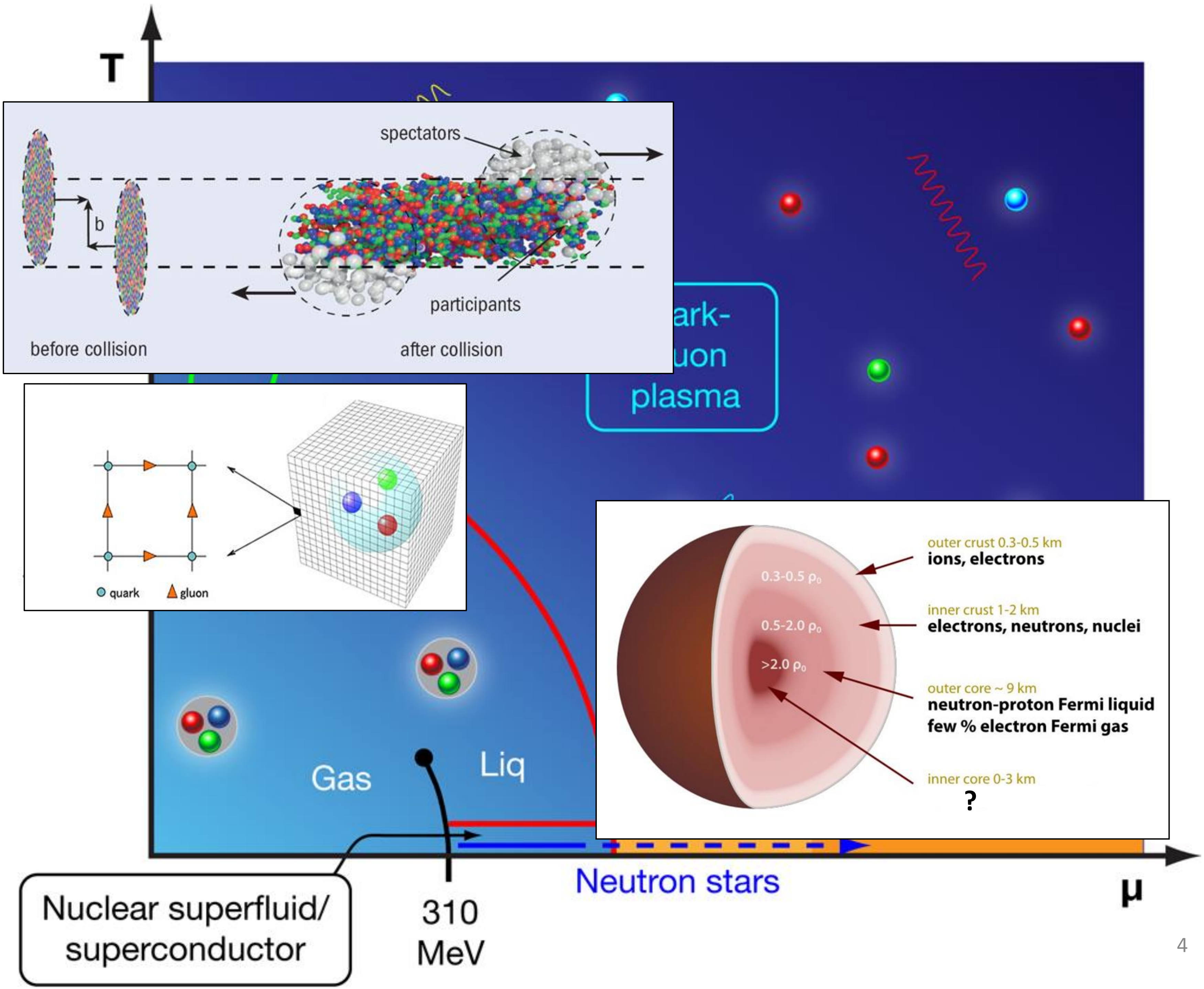
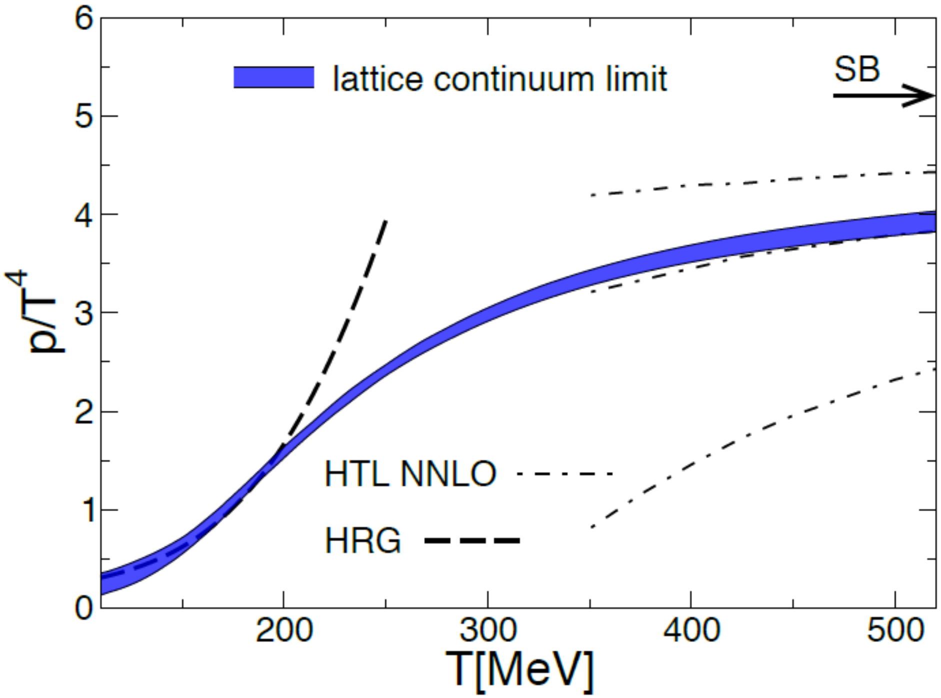
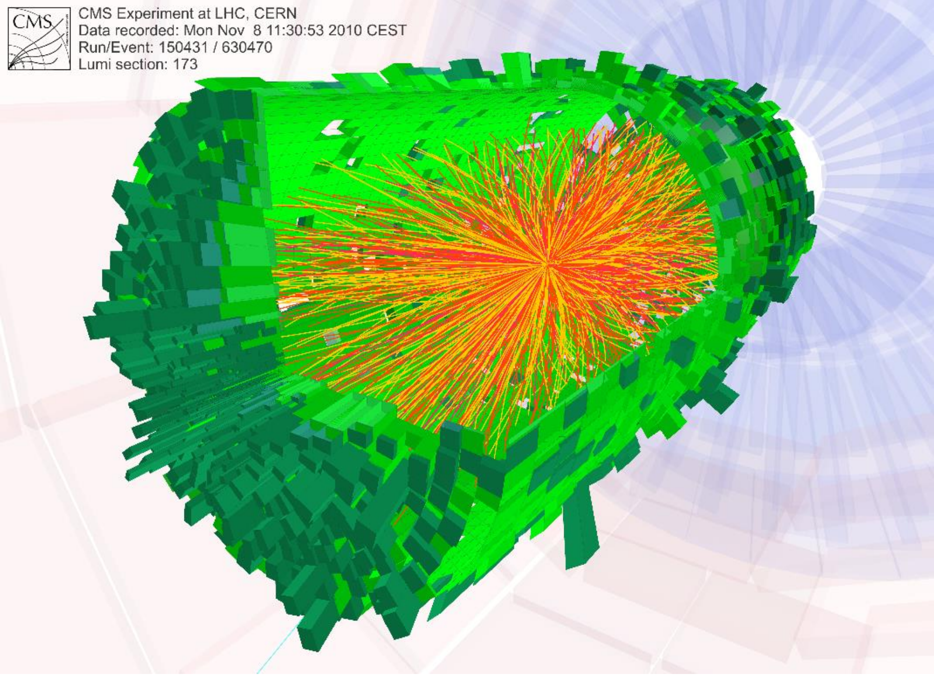
Fundamental prediction from the theory: Due to its asymptotic freedom, at high enough energy densities one enters the deconfined phase, with quarks and gluons as the degrees of freedom



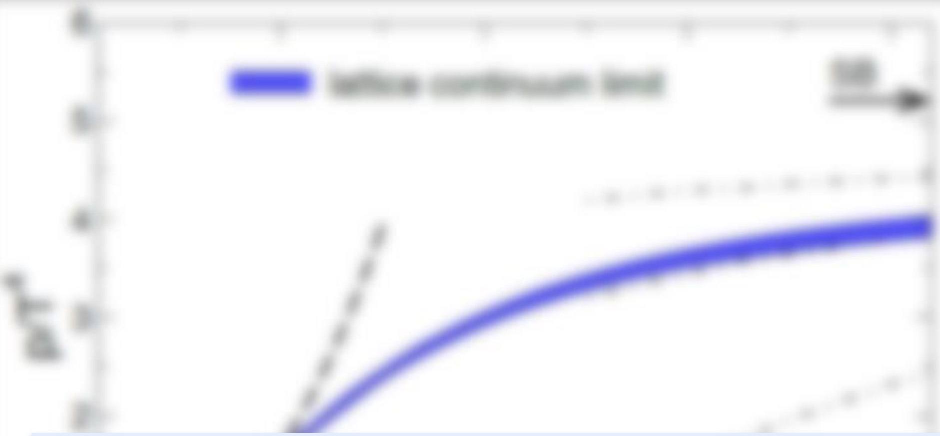
T
spectators
b
participants
before collision
after collision
ark-
uon
plasma
quark
gluon
outer crust 0.3-0.5 km
ions, electrons
0.3-0.5 ρ_0
inner crust 1-2 km
electrons, neutrons, nuclei
0.5-2.0 ρ_0
>2.0 ρ_0
outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas
inner core 0-3 km
?
Gas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

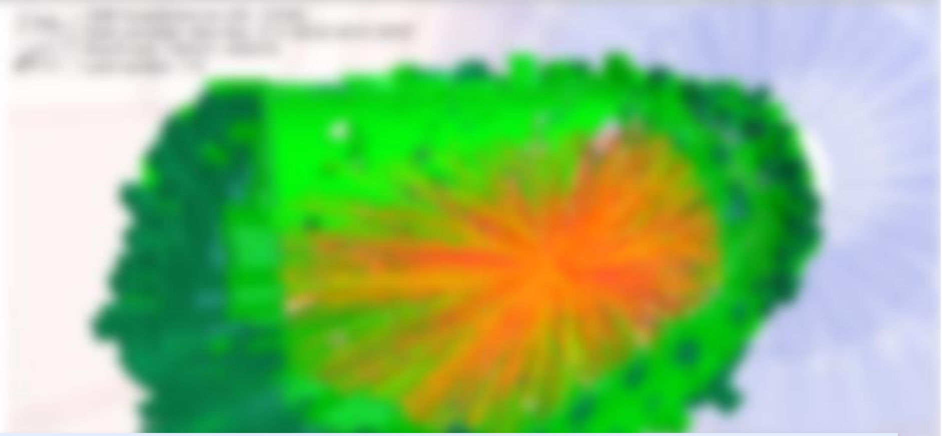




Some lessons from heavy ion experiments & lattice studies:

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: $\gamma \equiv \frac{d \ln p}{d \ln \epsilon} \approx 1$, $c_s^2 \lesssim 1/3$, $p/T^4 \sim N_{\mathrm{dof}}$
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



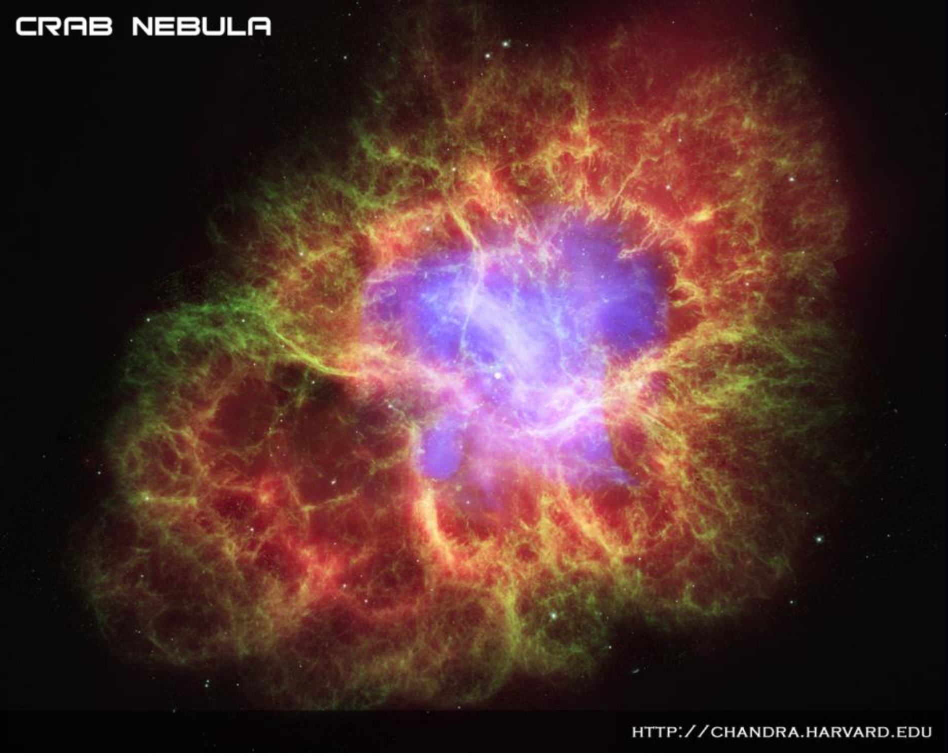


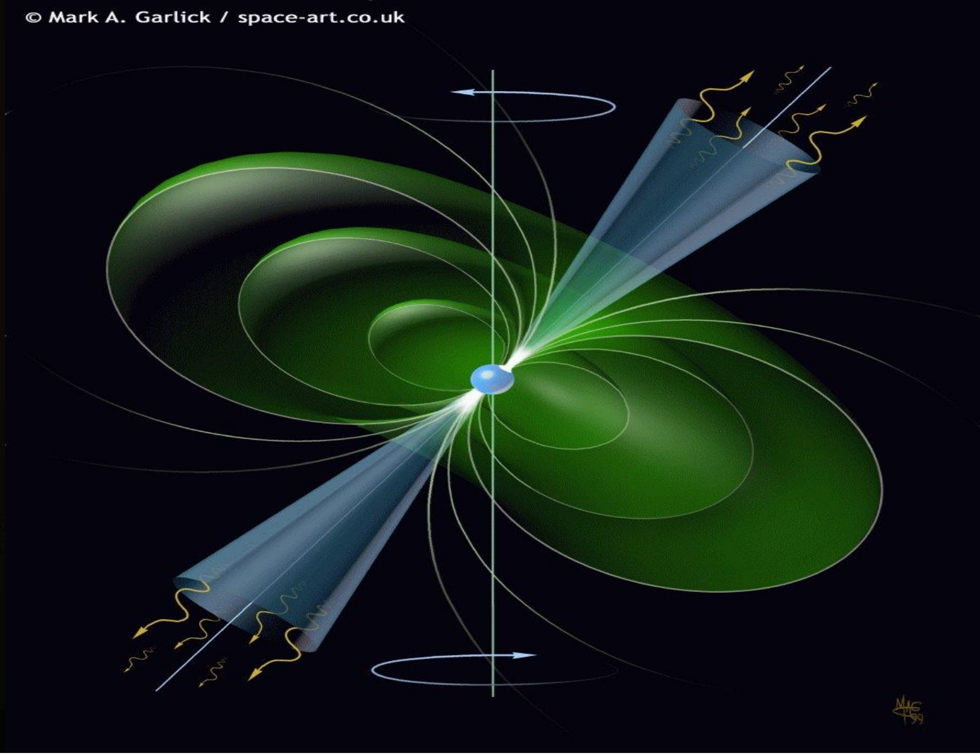
Main question for the remainder of this talk: how does all this generalize to neutron stars

- 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 inside NSs, and if so, in which stars?

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

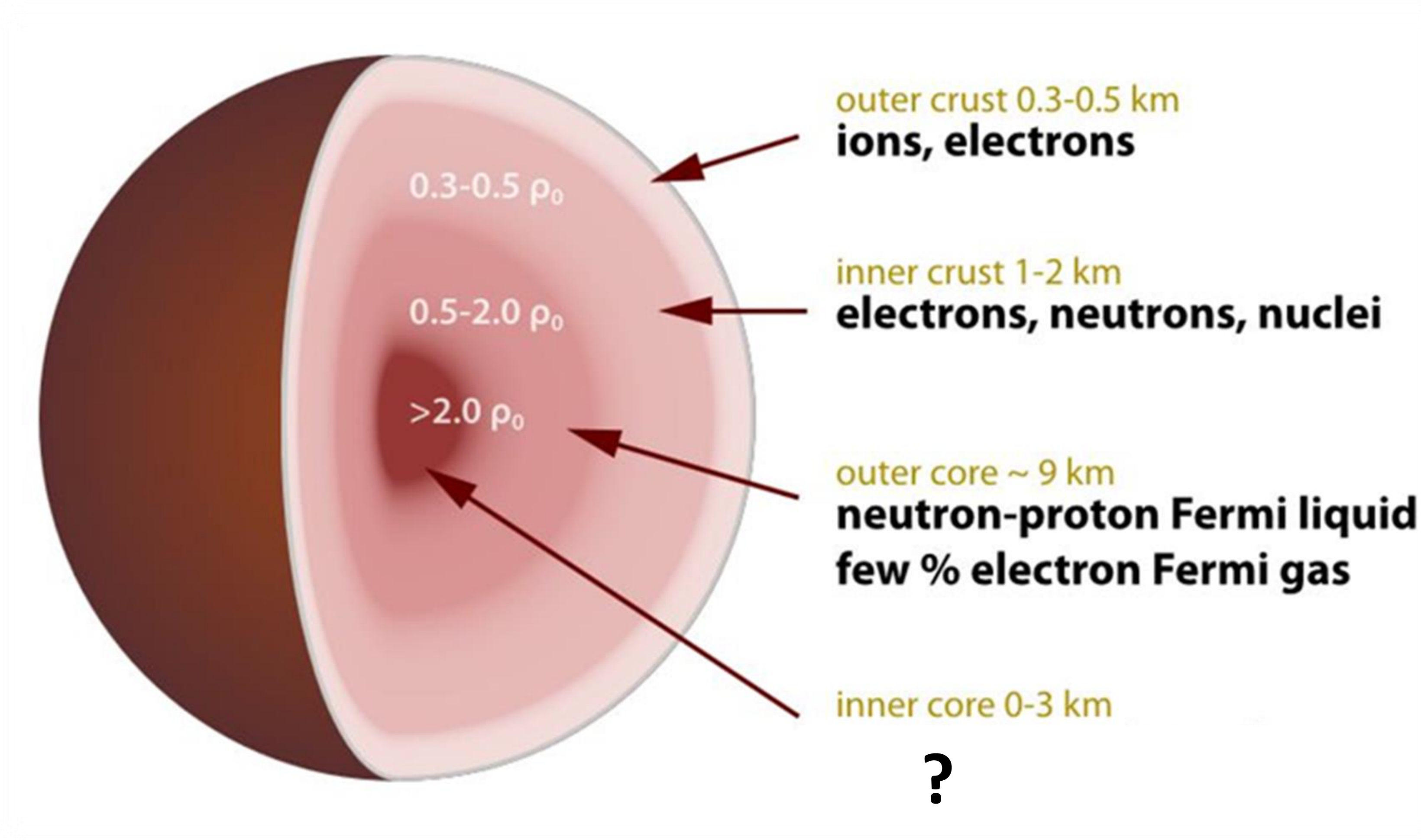
Neutron stars: goals and challenges



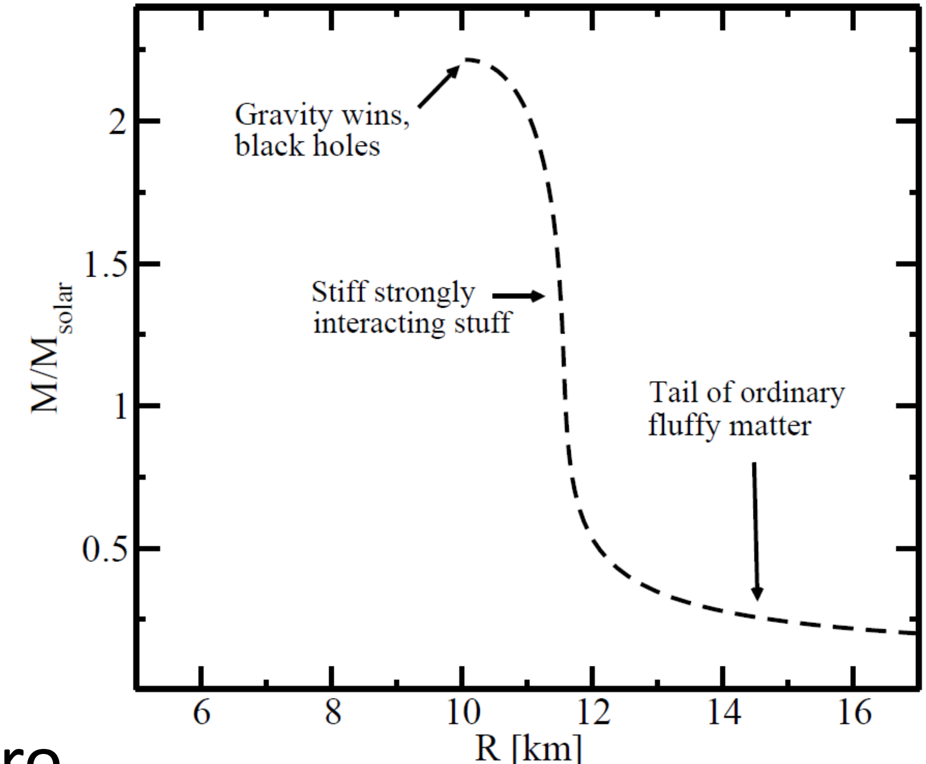


When a hydrogen burning star runs out of fuel:

- $\mathrm{M} \lesssim 9M_{\mathrm{sun}}$ ⇒ White dwarf
- $\mathrm{M} \gtrsim 9M_{\mathrm{sun}}$ ⇒ Supernova explosion
    - $\mathrm{M} \gtrsim 20M_{\mathrm{sun}}$ ⇒ Gravitational collapse into BH
    - $\mathrm{M} \lesssim 20M_{\mathrm{sun}}$ ⇒ Gravitational collapse into…


0.3-0.5 ρ_0
0.5-2.0 ρ_0
>2.0 ρ_0
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
?

Underlying challenge:
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.):

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

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

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

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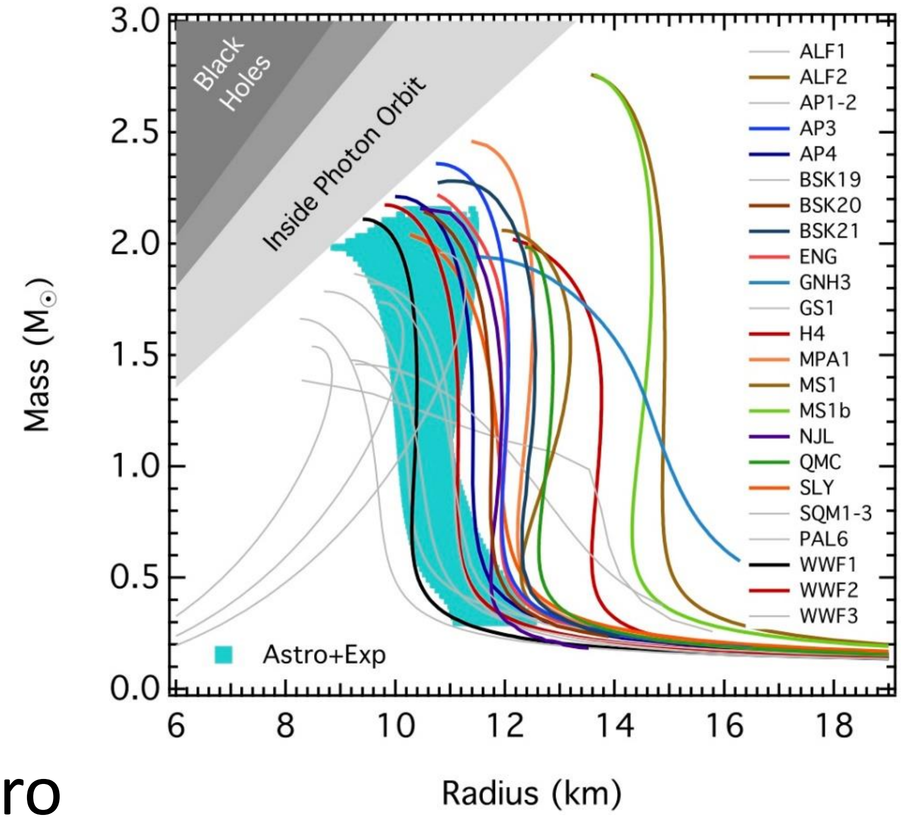

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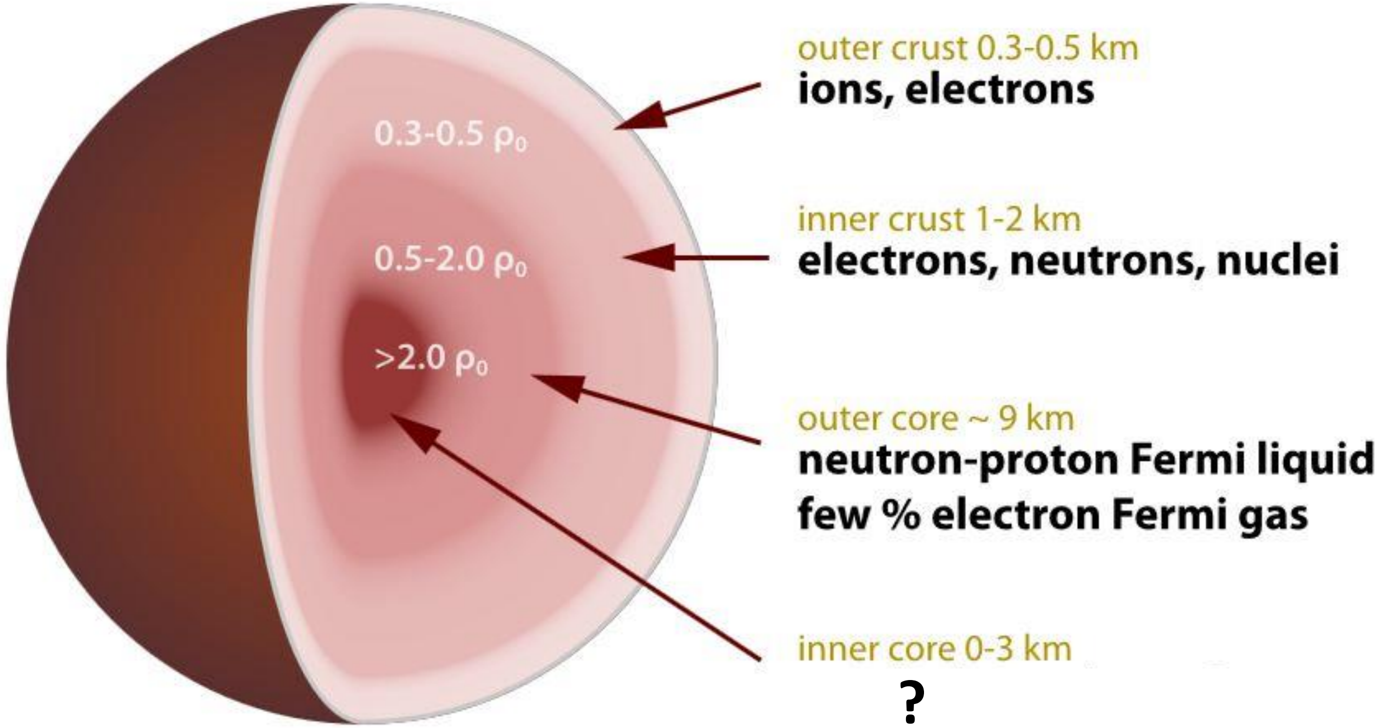
$$\varepsilon(p) \Rightarrow M(R)$$

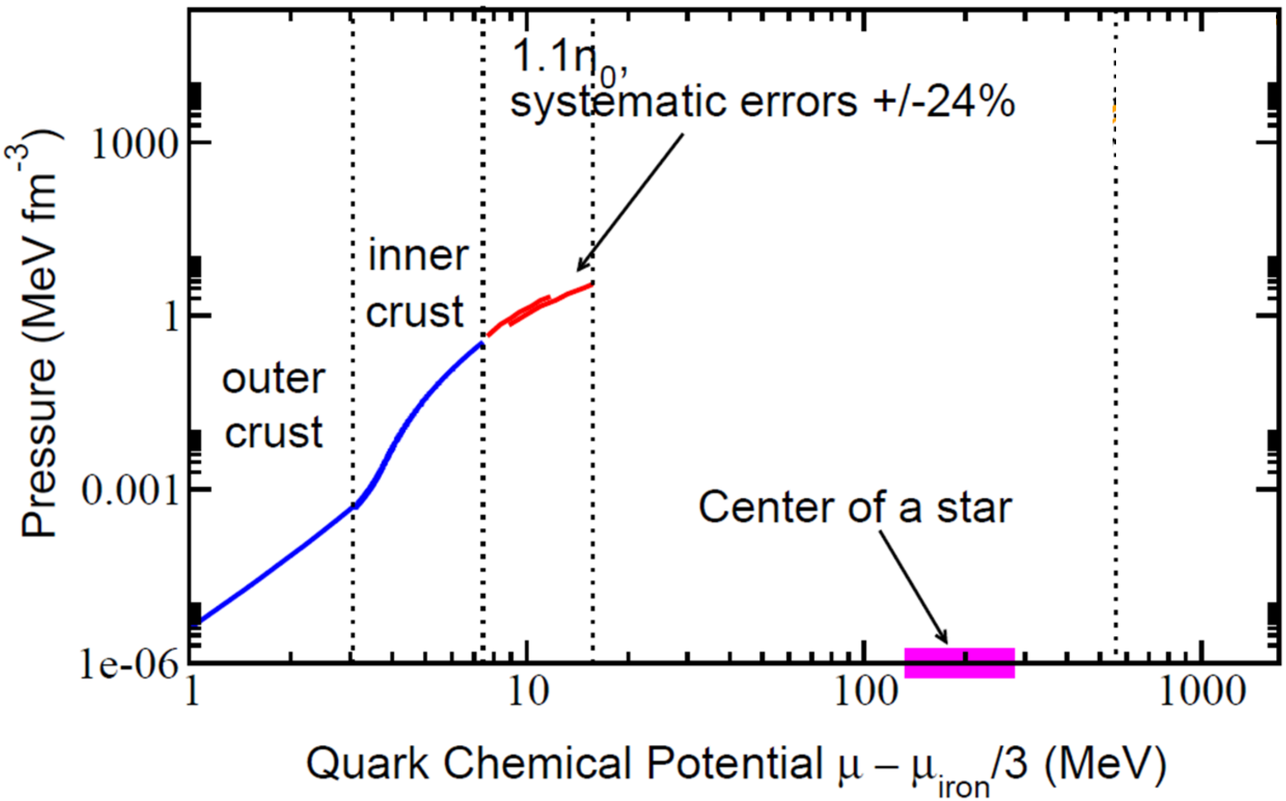
Clear need for a systematic and model-independent approach to the microphysics of neutron stars

NS matter EoS – robust theoretical limits



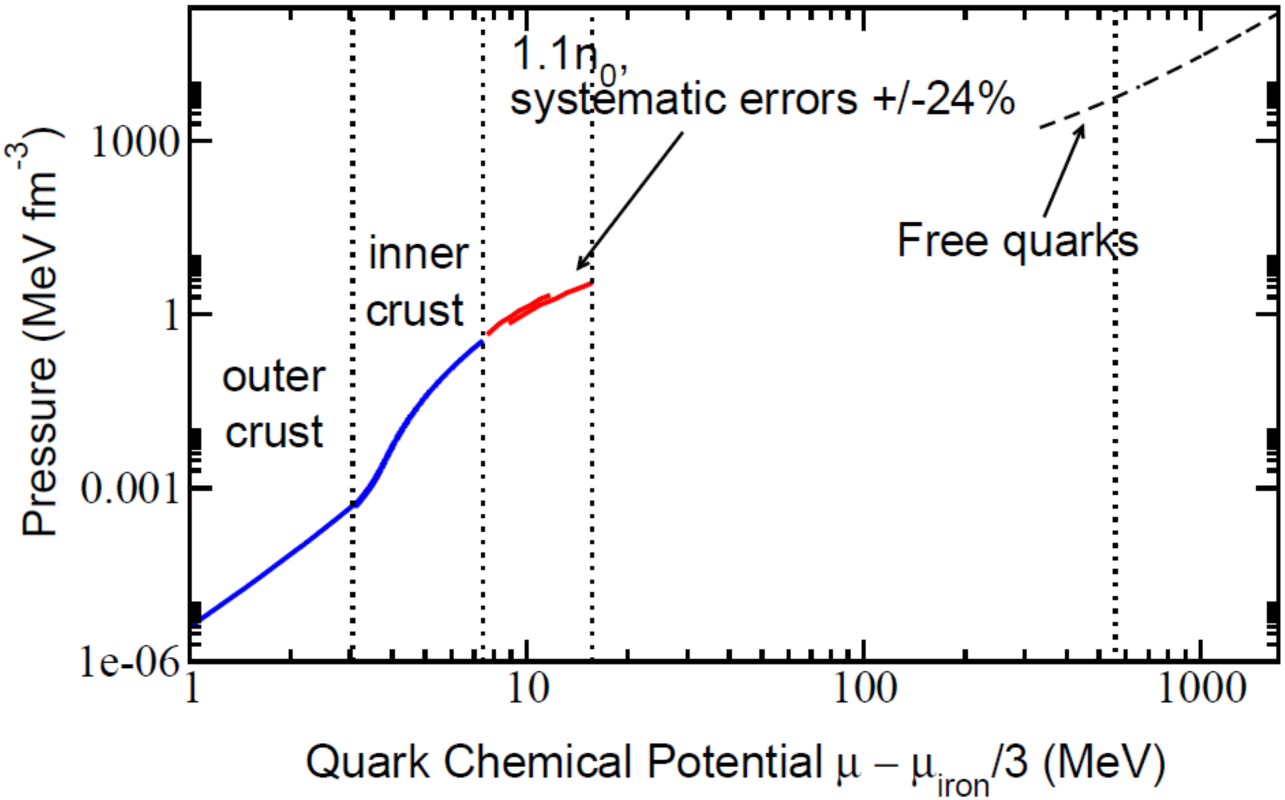
Proceeding inwards from the crust:

- 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



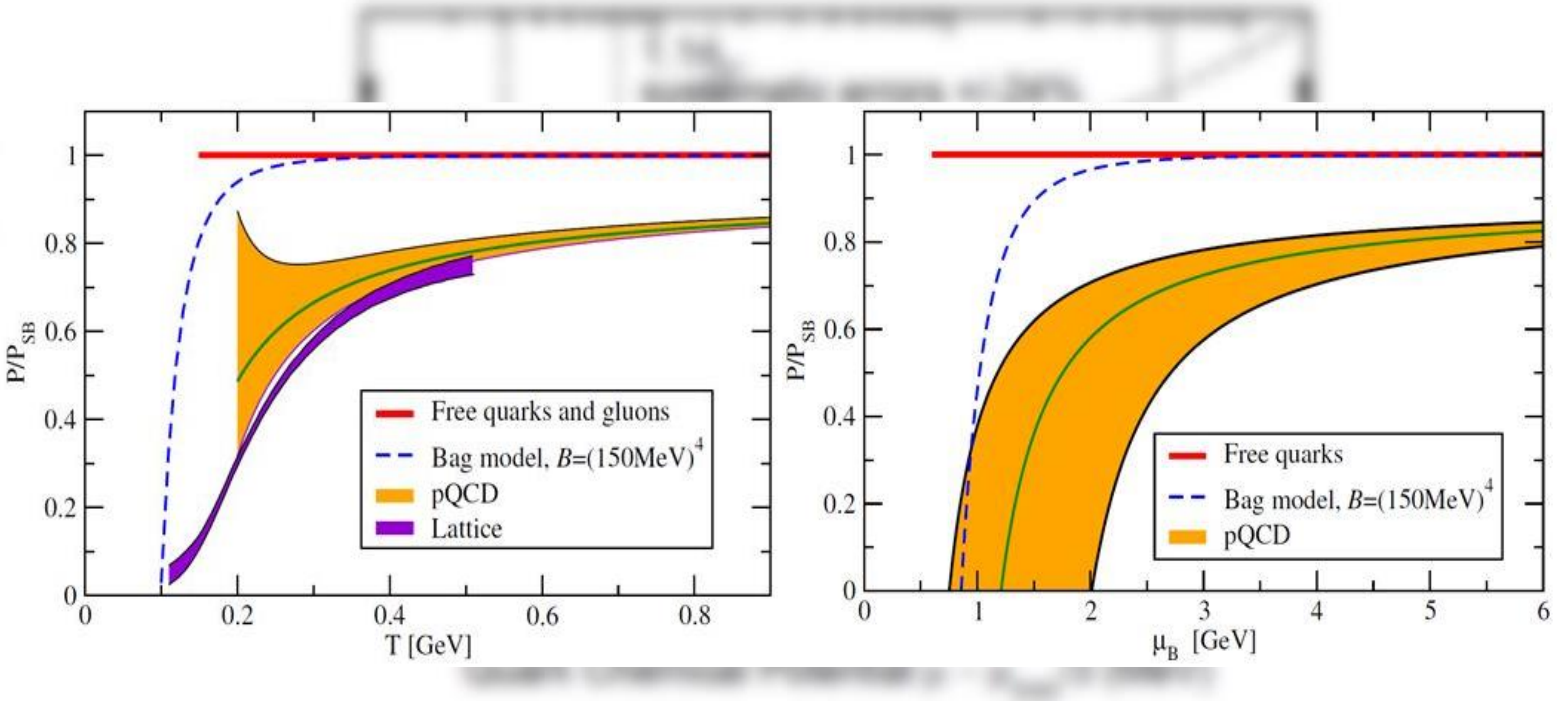
Low-density behavior of EoS well known from nuclear theory side. Challenges begin close to saturation density:

- At $1.1n_s$, 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)]



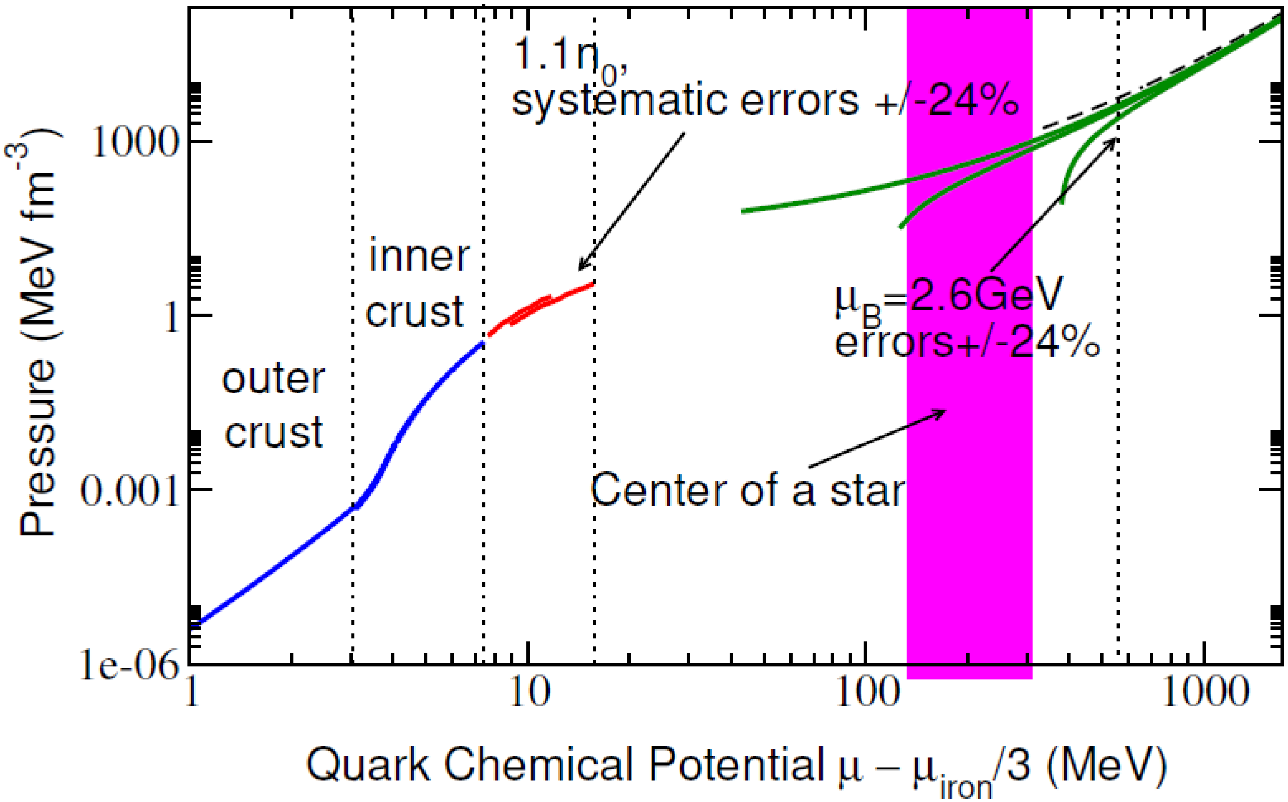
Asymptotic freedom of QCD ⇒ High-density limit from a non-interacting theory. However,…

- 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



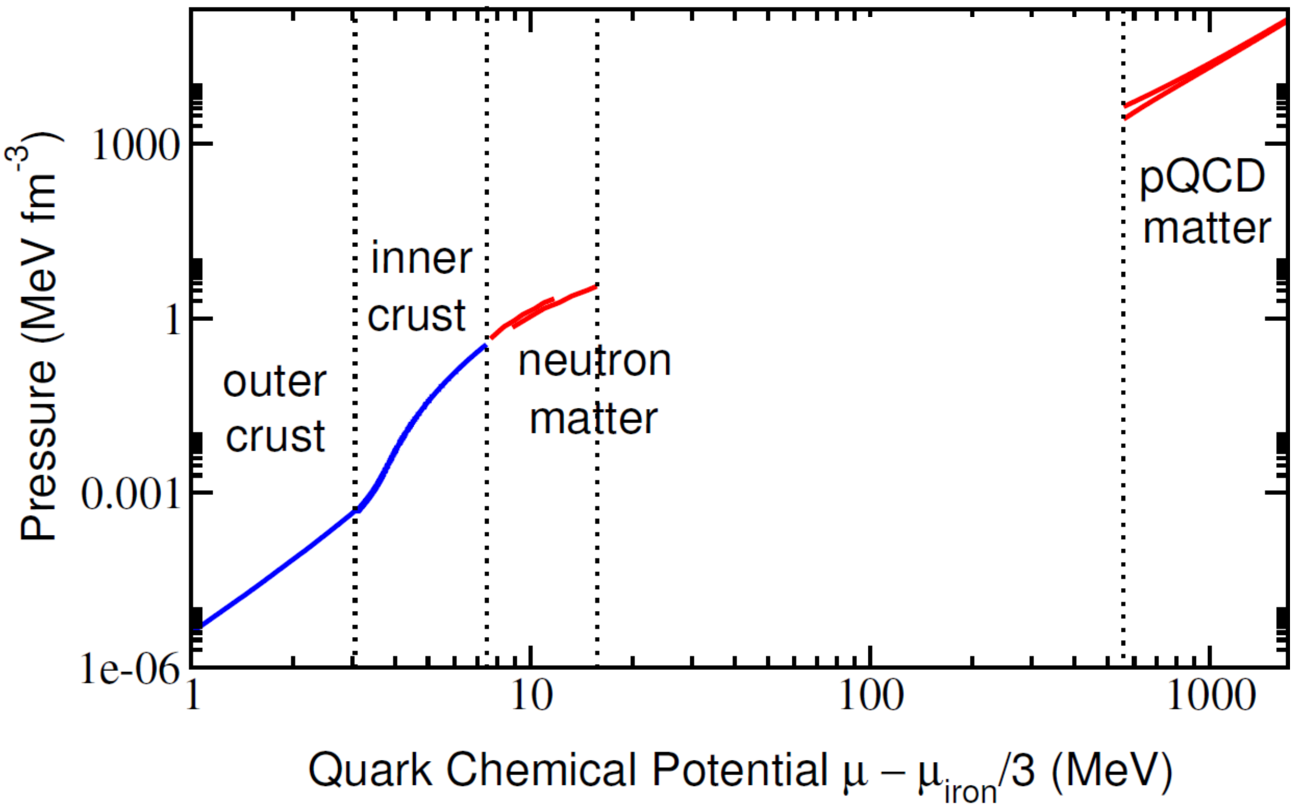
Recent improvement: First part of four-loop $T = 0$ pressure derived: $p_{4-\mathrm{loop}} \ni -\frac{11}{12}\frac{N_c d_A}{(2\pi)^3}\alpha_s m_\infty^4 \ln^2\alpha_s$ [Gorda, Kurkela, Romatschke, Säppi, AV, PRL 121 (2018), 1807.04120]

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?

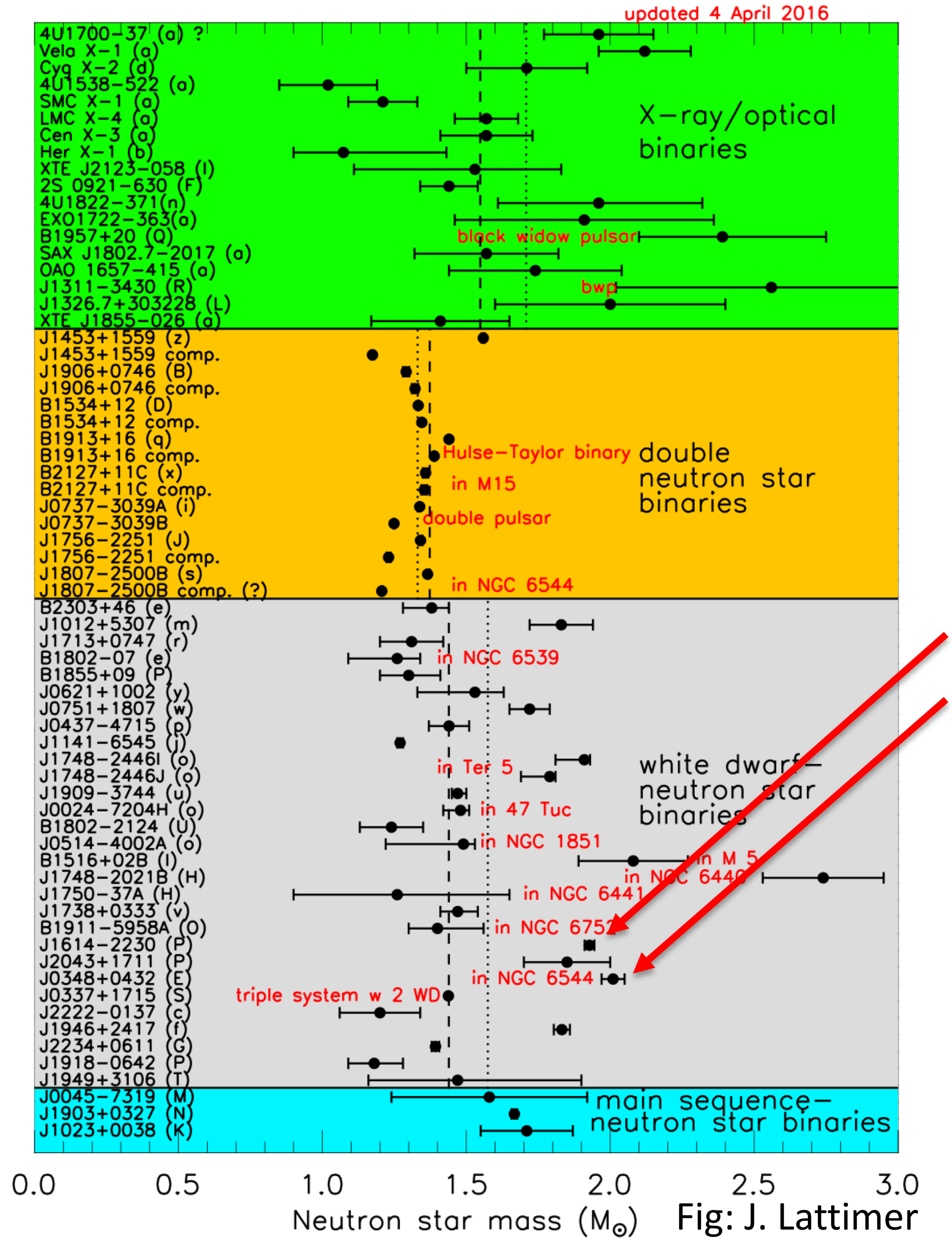


Fig: J. Lattimer

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

Demorest et al., Nature 467 (2010)

Antoniadis et al., Science 340 (2013)

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

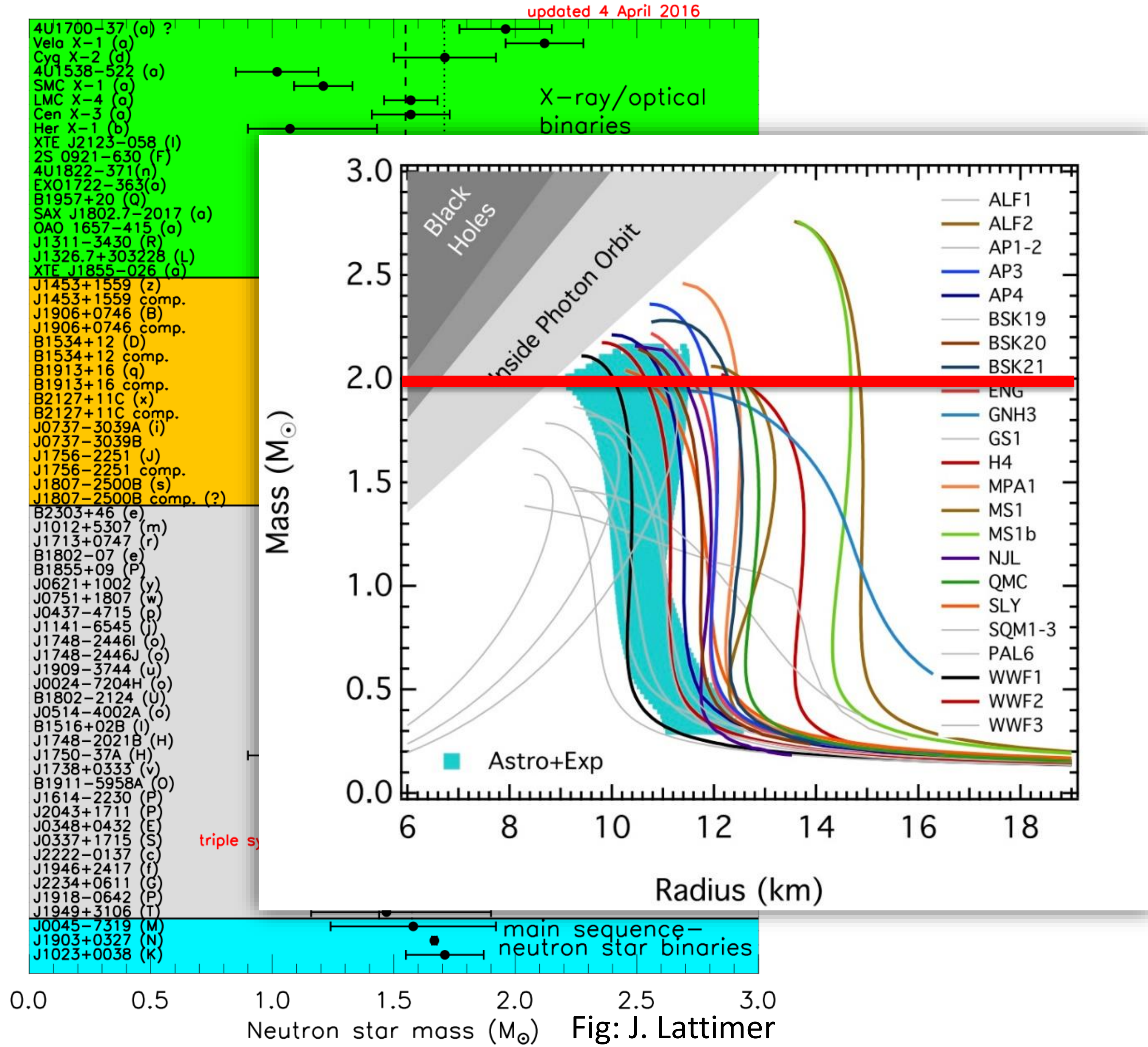


Fig: J. Lattimer

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s:

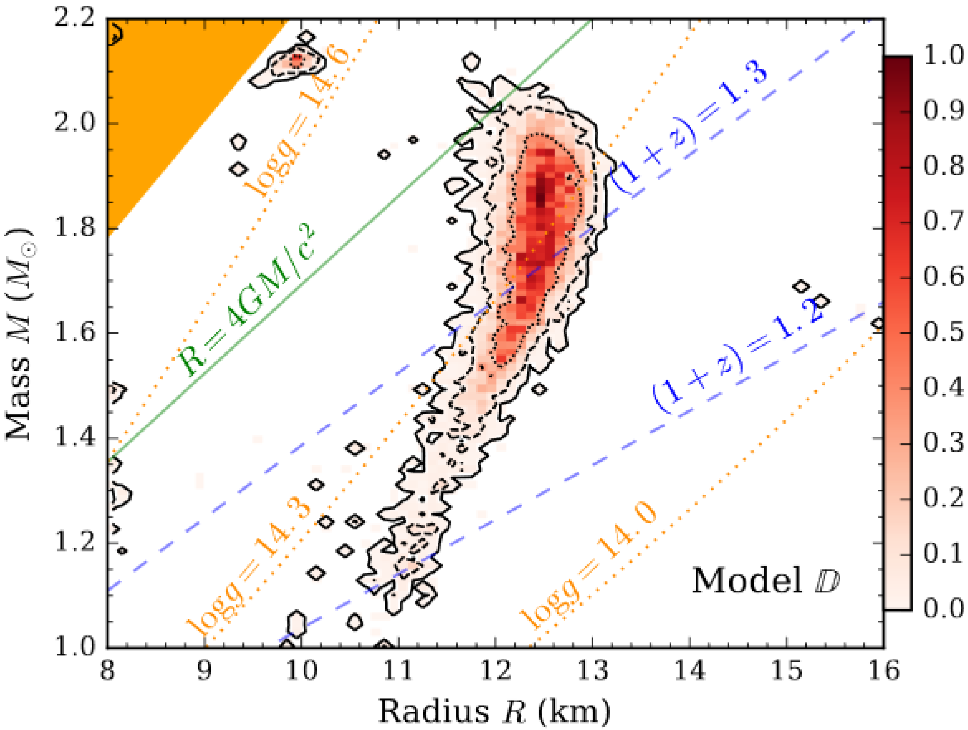
re 467 (2010)

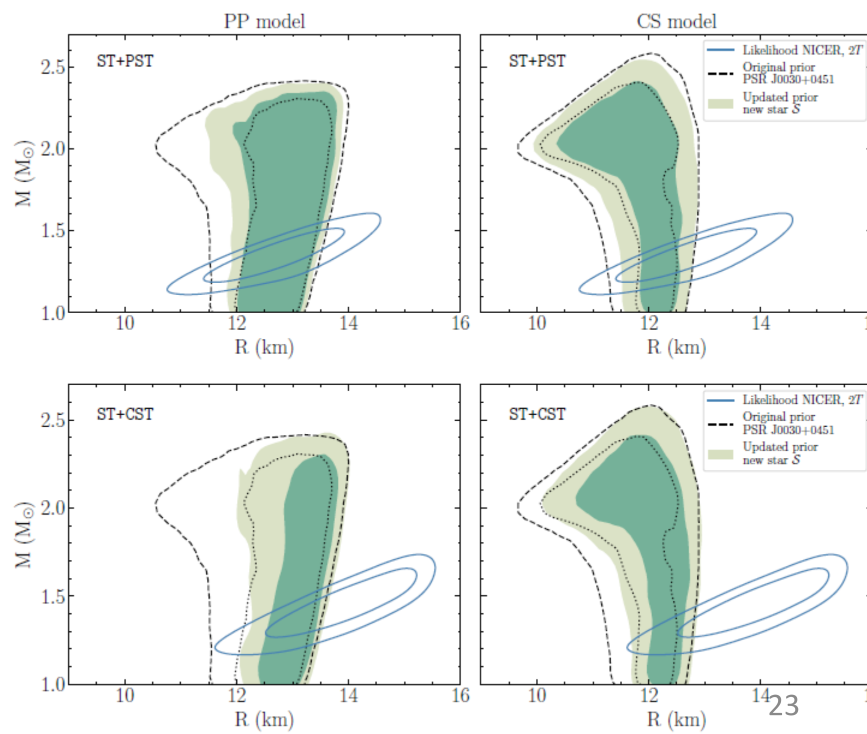
nce 340

$2M_\odot$

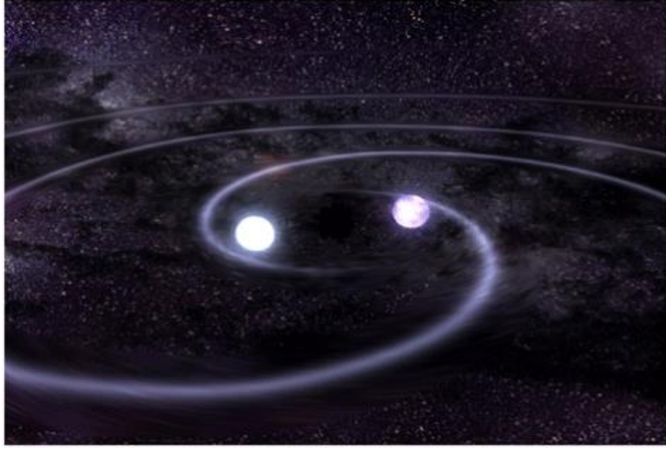
Radius measurements more problematic, but progress through observation of X-ray emission:

- Cooling of thermonuclear X-ray bursts provide radii to $\sim \pm 400$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)]



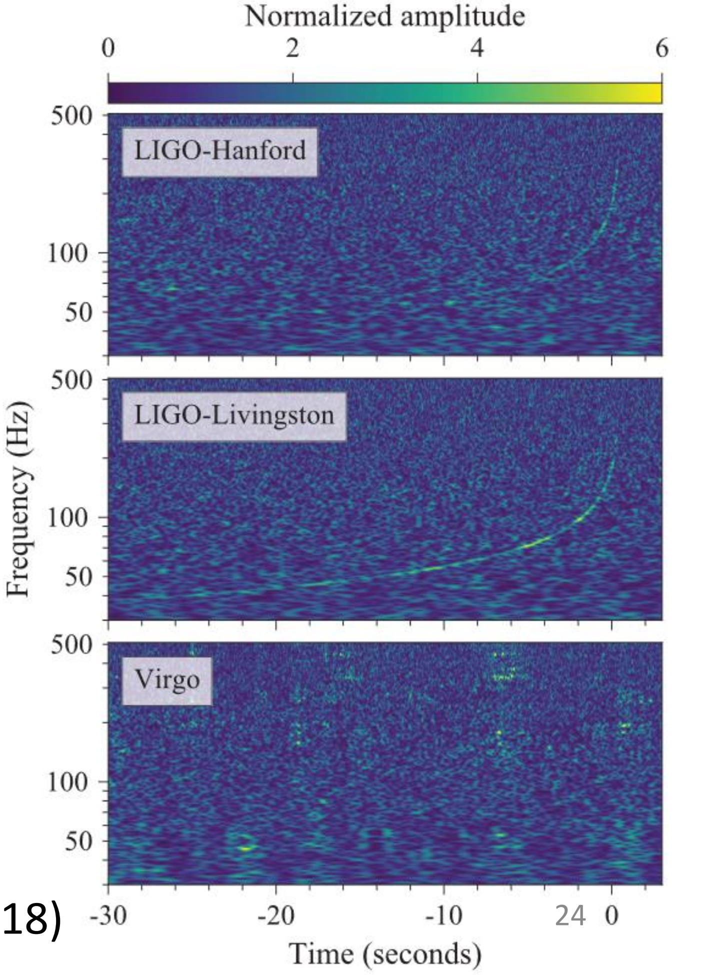


Gravitational wave breakthrough: First observed NS merger by LIGO & Virgo in 2017 (any many since then)



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

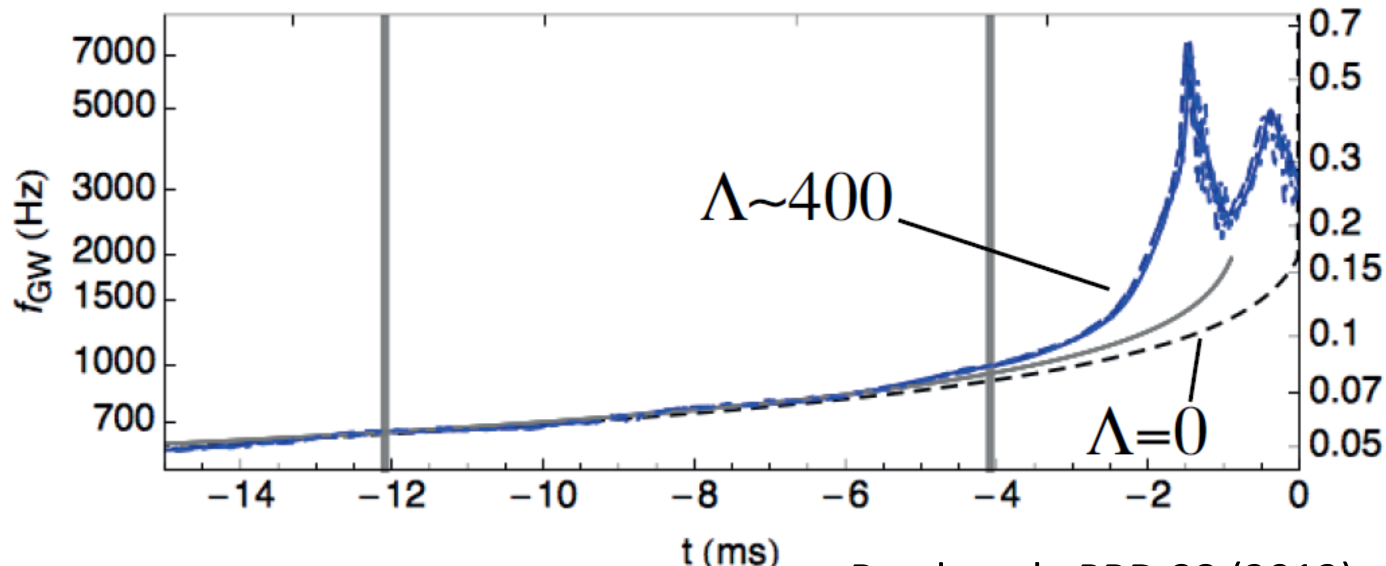


LIGO and Virgo collaborations, PRL 119 (2017), PRL 121 (2018)

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

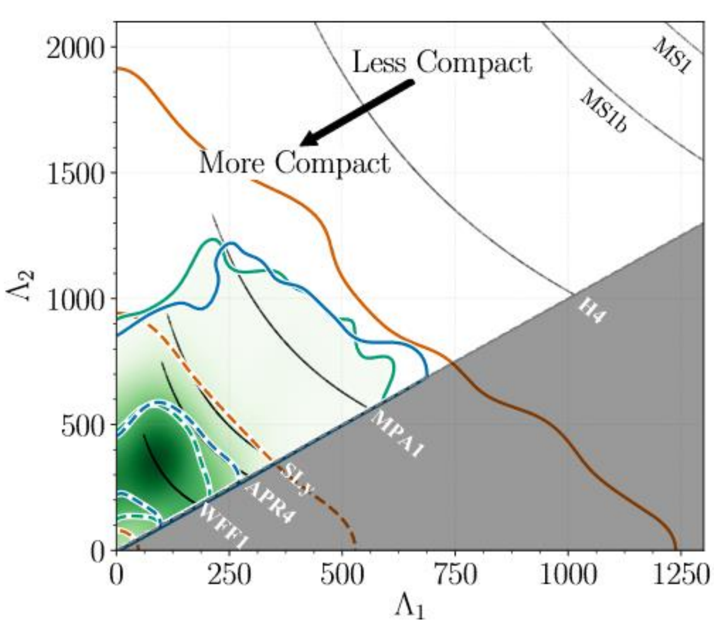


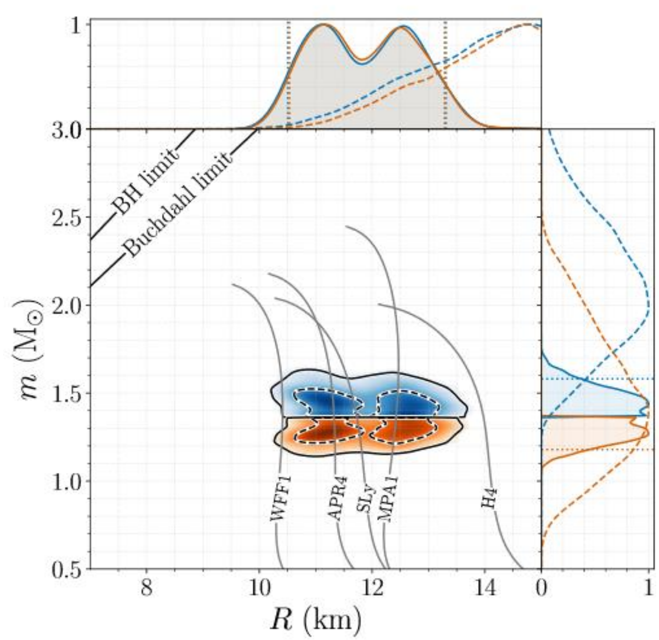
Read et al., PRD 88 (2013)

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)]





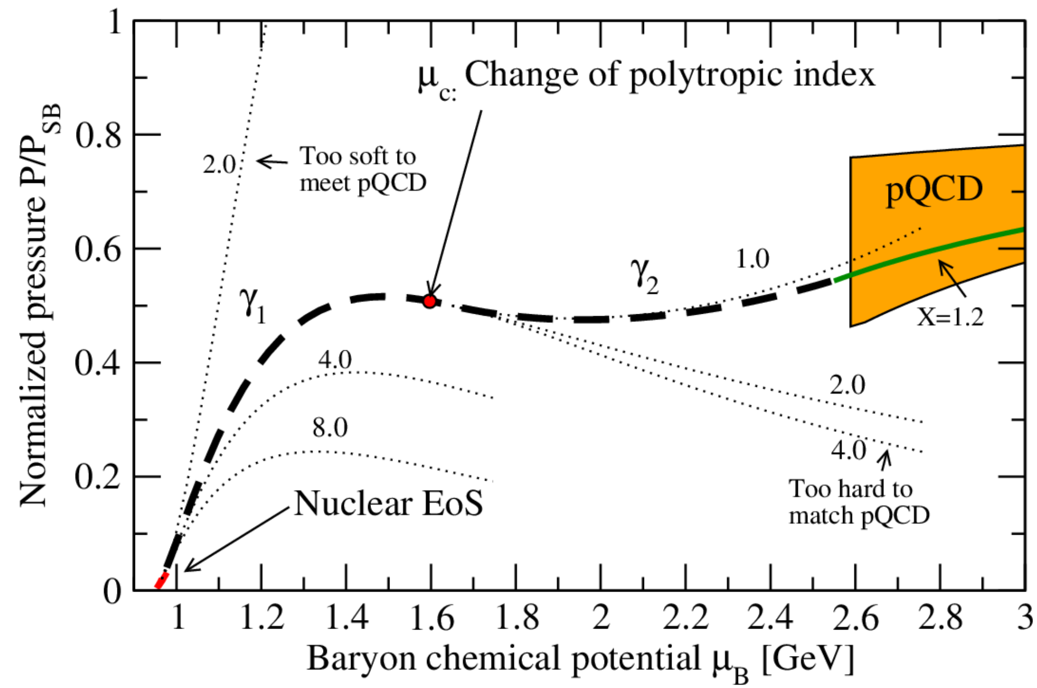
Interpolation – or how to optimally combine theoretical and observational insights

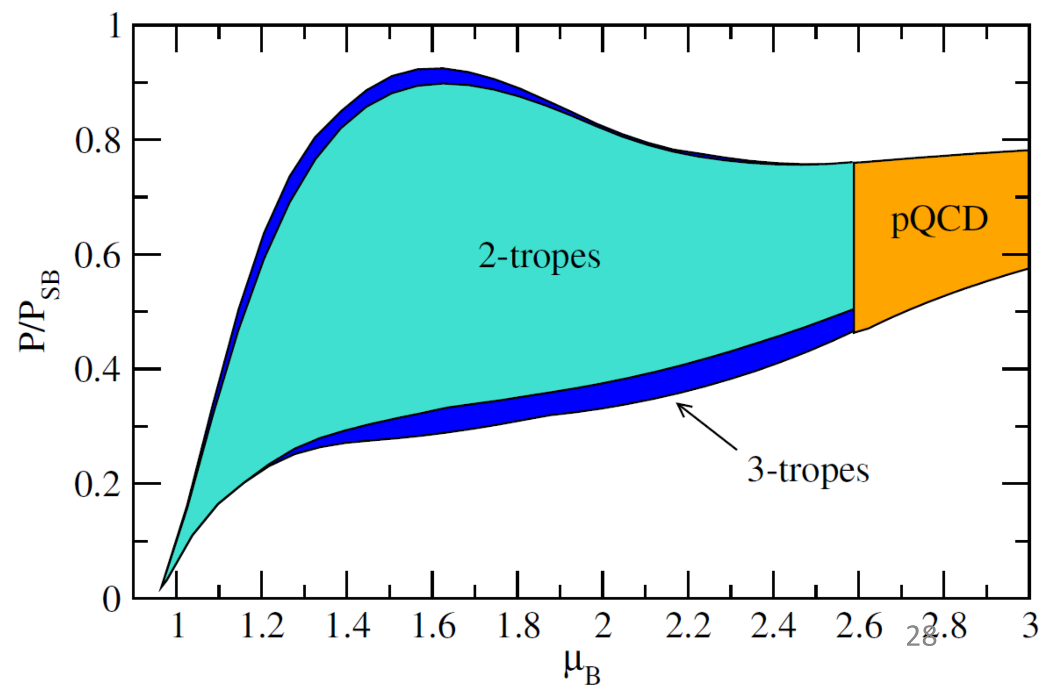
Allow all possible EoS behaviors by interpolating it over the no man's land using one's favorite (often piecewise) basis functions

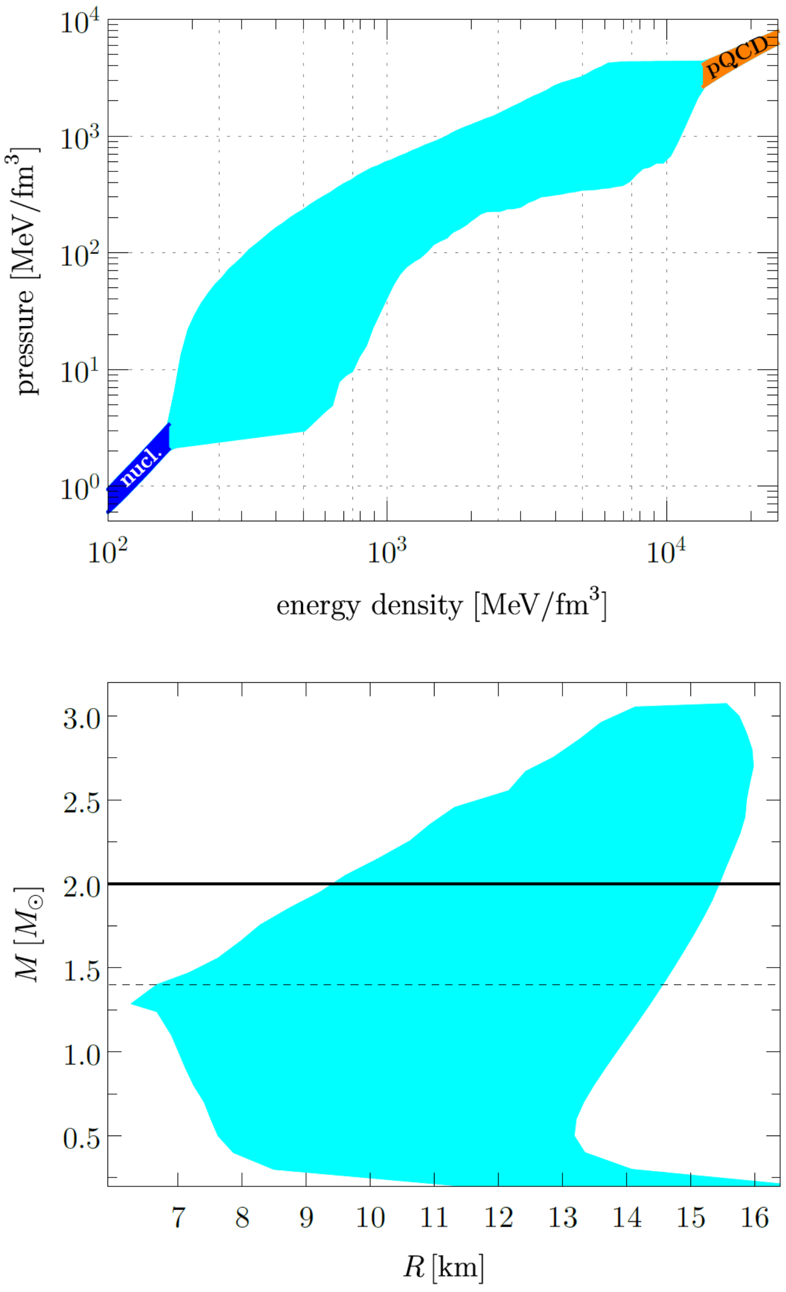
Require:

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)]

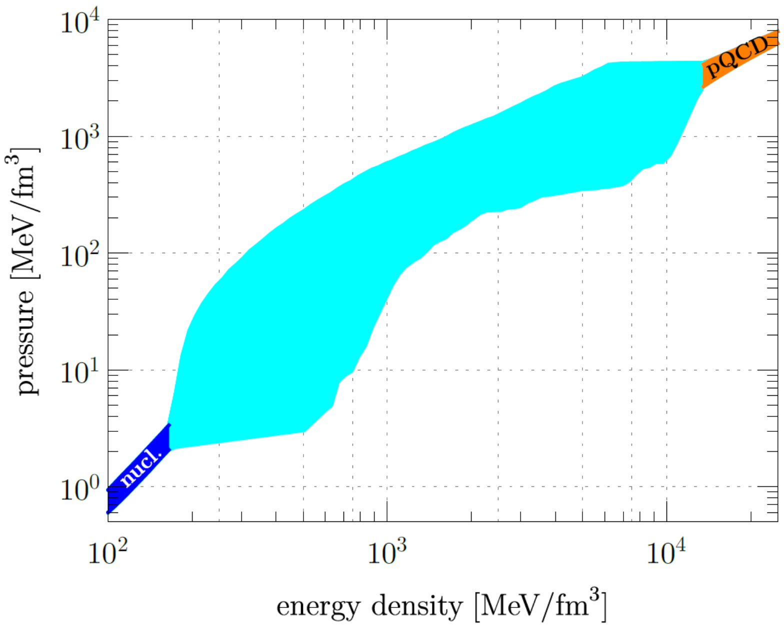


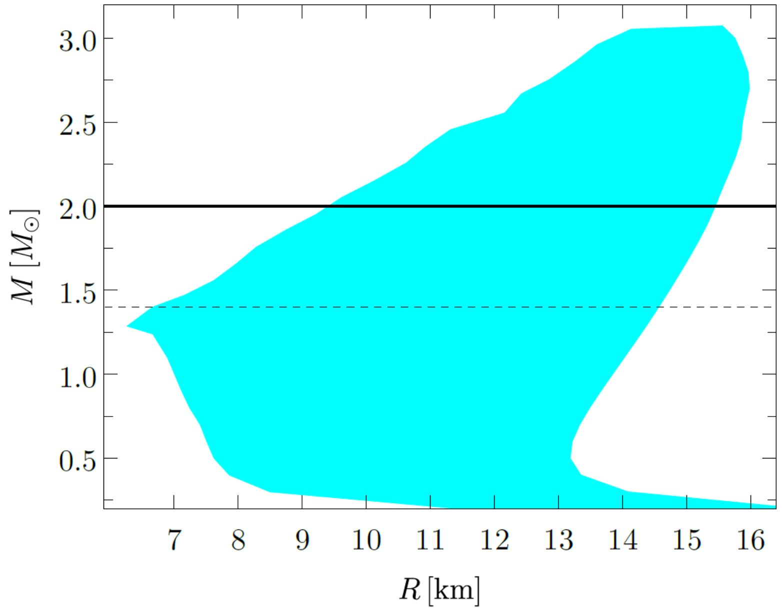




Using polytropes, generate ensemble of 200.000 viable EoSs.

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





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Additionally take into account:

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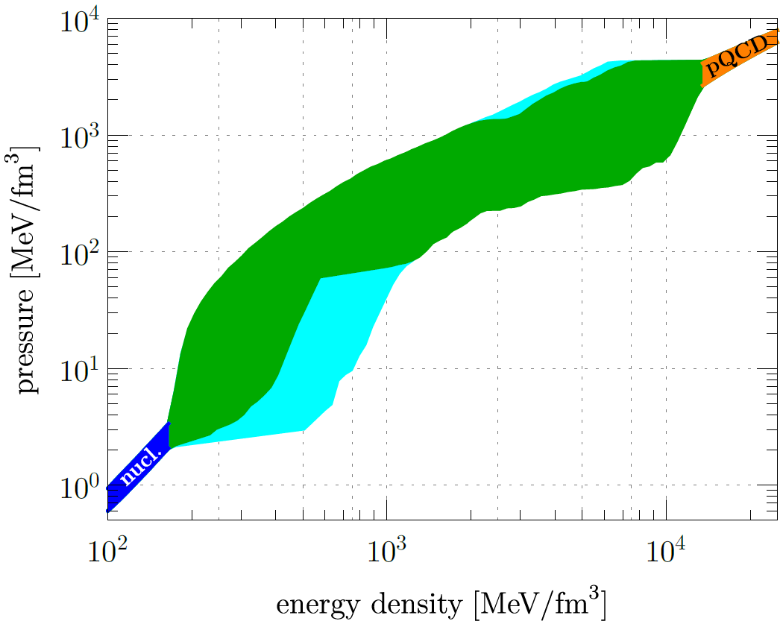

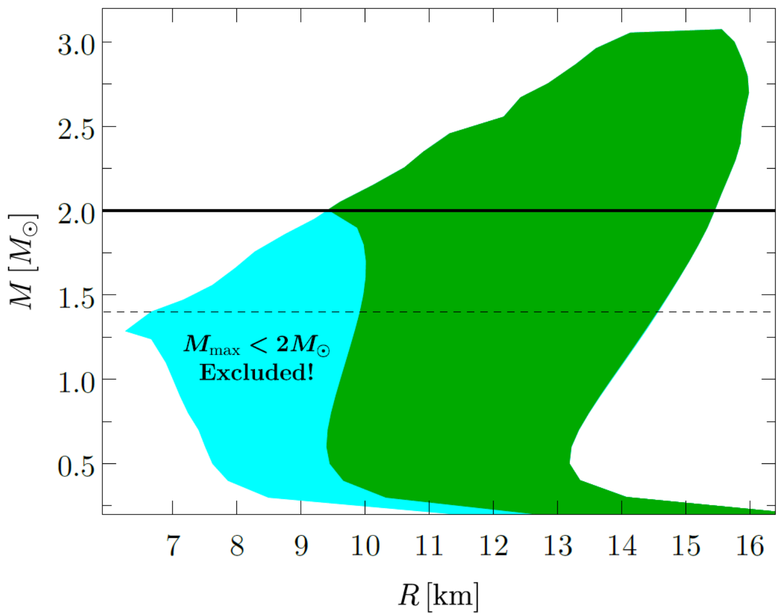

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Additionally take into account:

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

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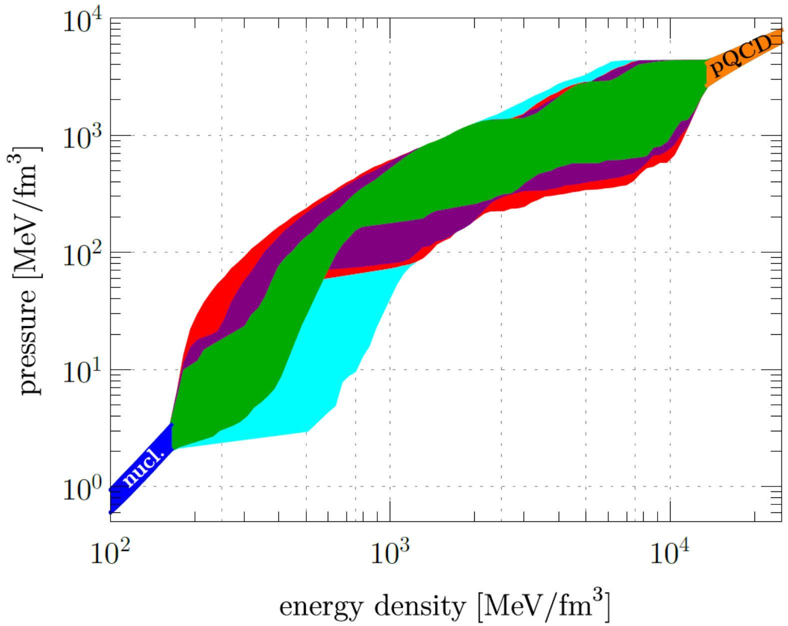

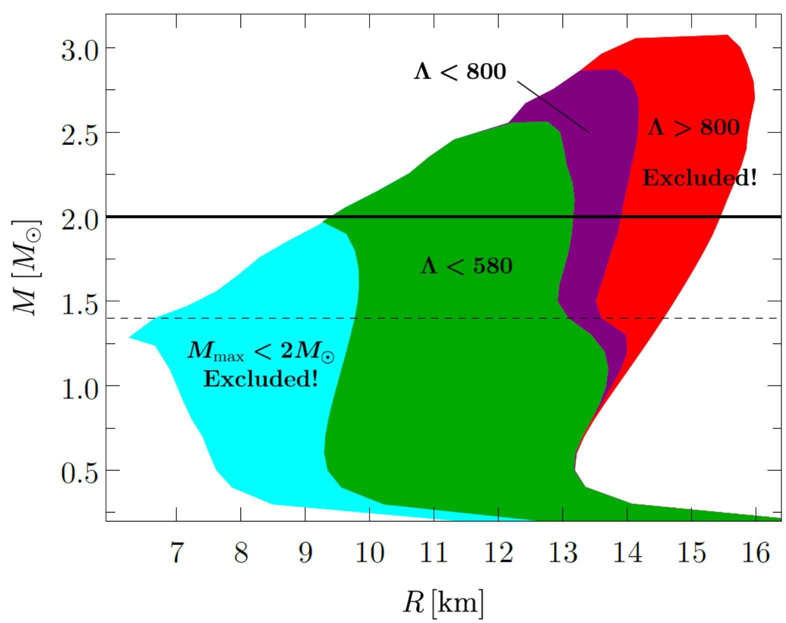

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Additionally take into account:

- 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, $R(1.4M_\odot) \leq 13\text{km}$

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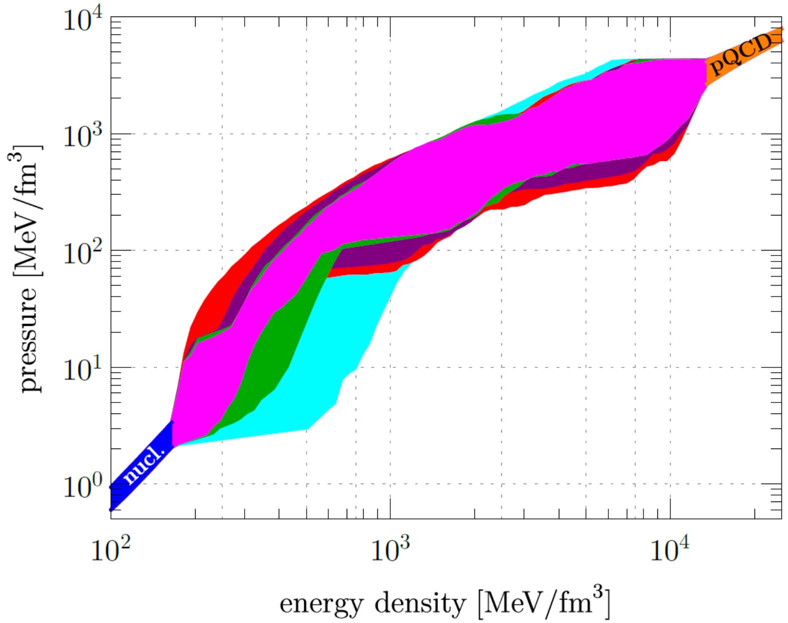

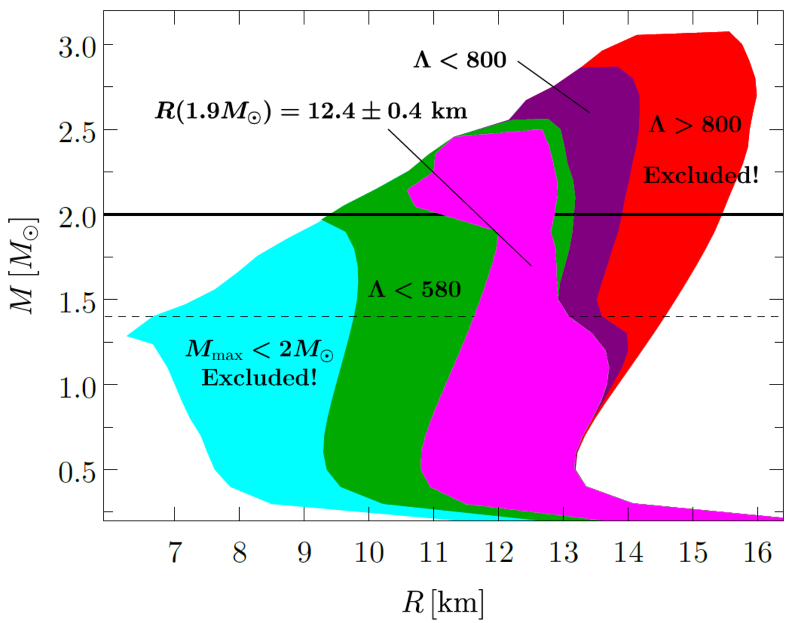

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- Accurate R measurements (here assuming accurately determined mass)

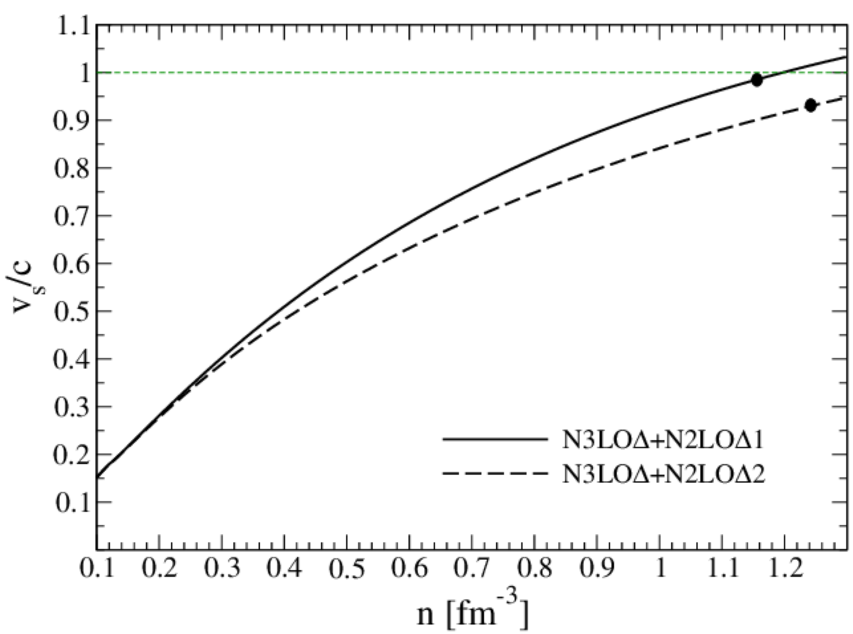
[Annala, Gorda, Kurkela, AV, PRL 120 (2018), 1711.02644]

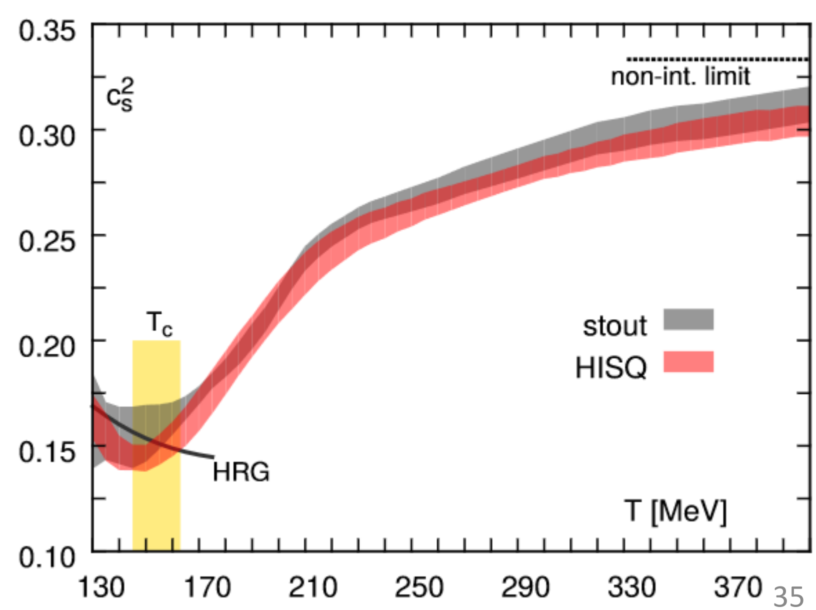
How about quark matter?

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)

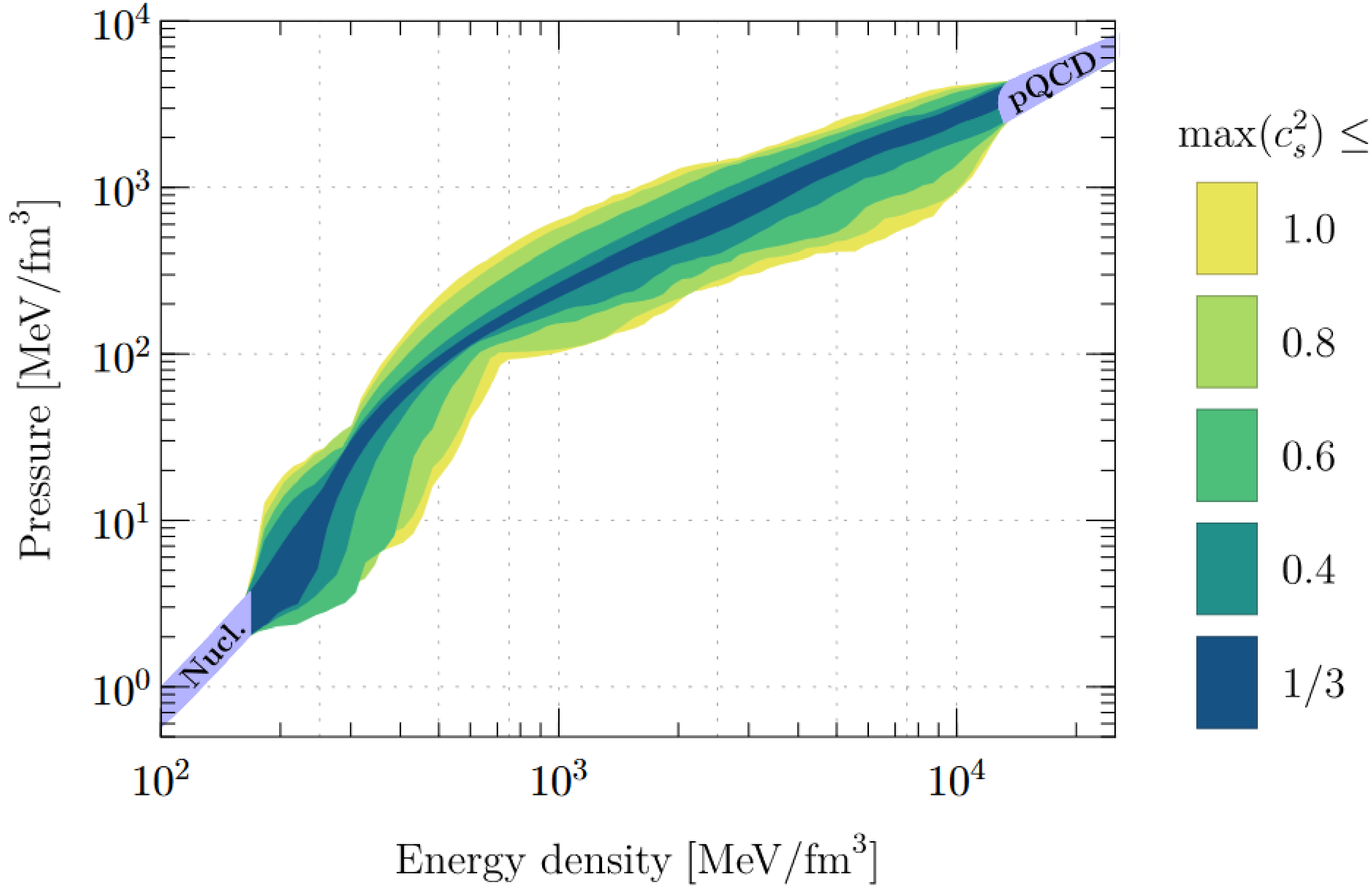
Bound on the speed of sound from holography

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)

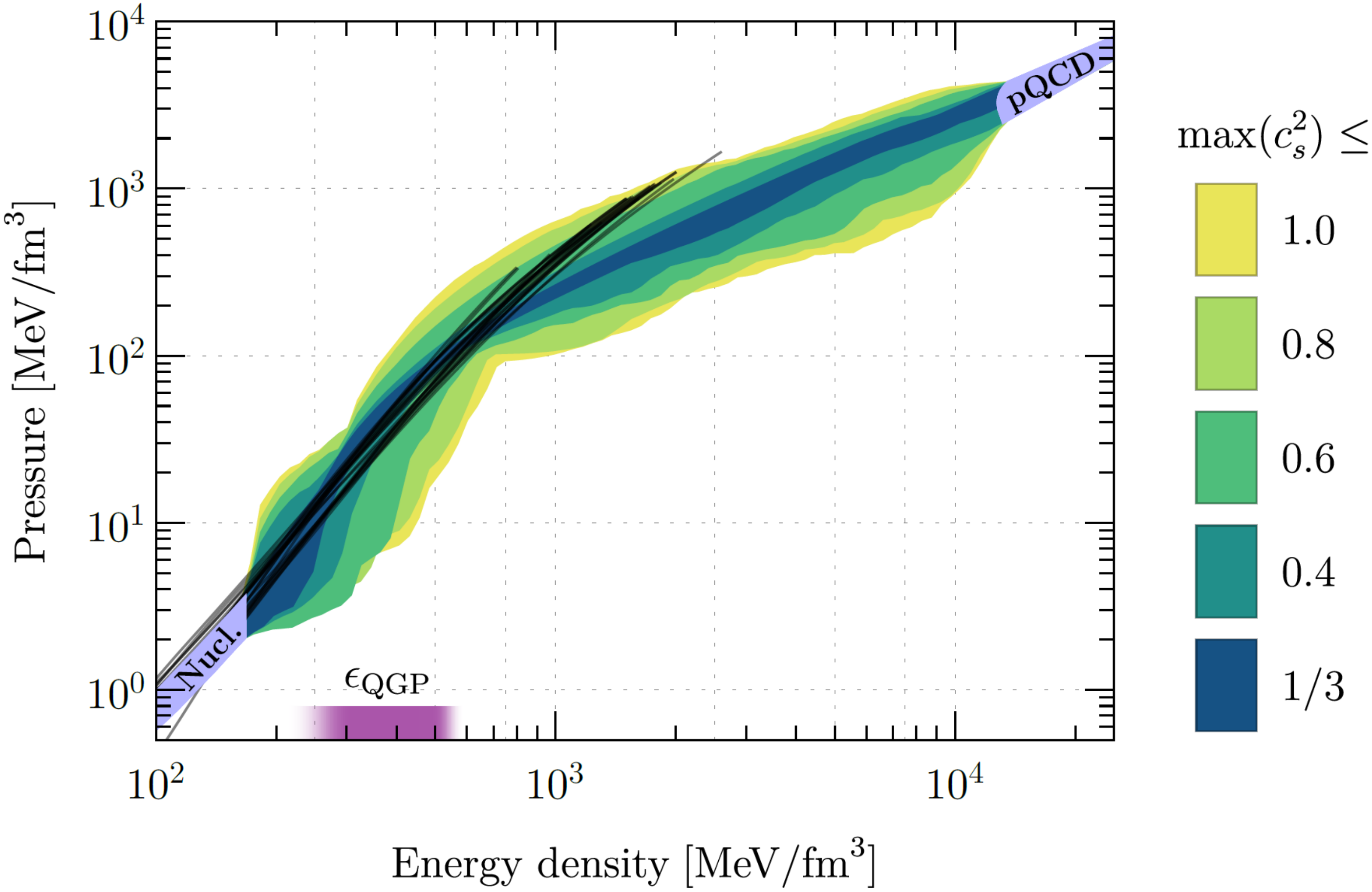
We show that the squared speed of sound v_s^2 is bounded from above at high temperatures by the conformal value of $1/3$ in a class of strongly coupled four-dimensional field theories, given some mild technical assumptions. This class consists of field theories that have gravity duals sourced by a single-scalar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



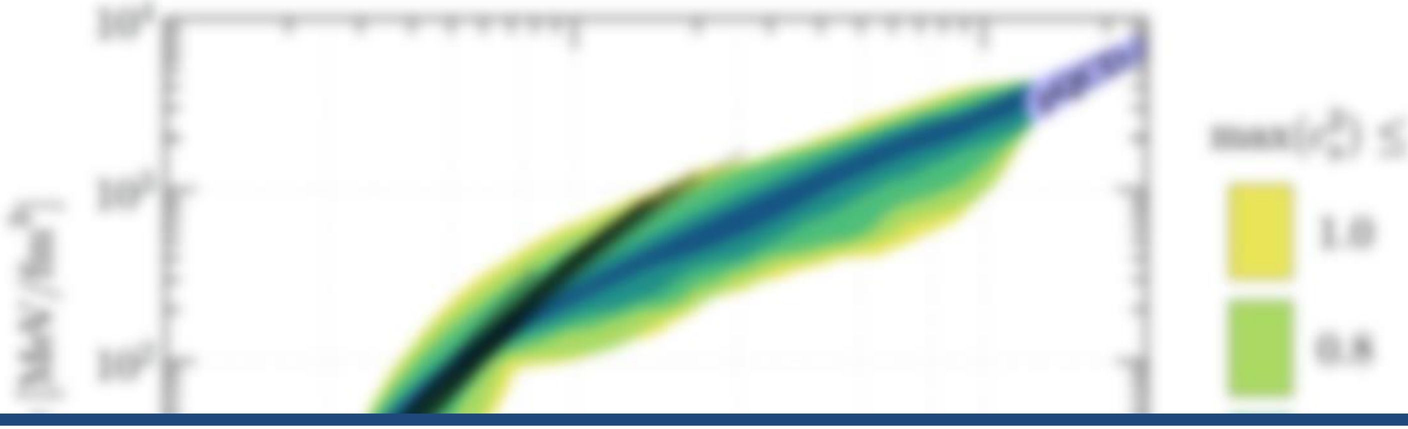
Setting nontrivial upper limits for speed of sound leads to increasingly constrained results; contrary to common lore, even sub-conformal ($c_s^2 < 1/3$) EoSs viable

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:

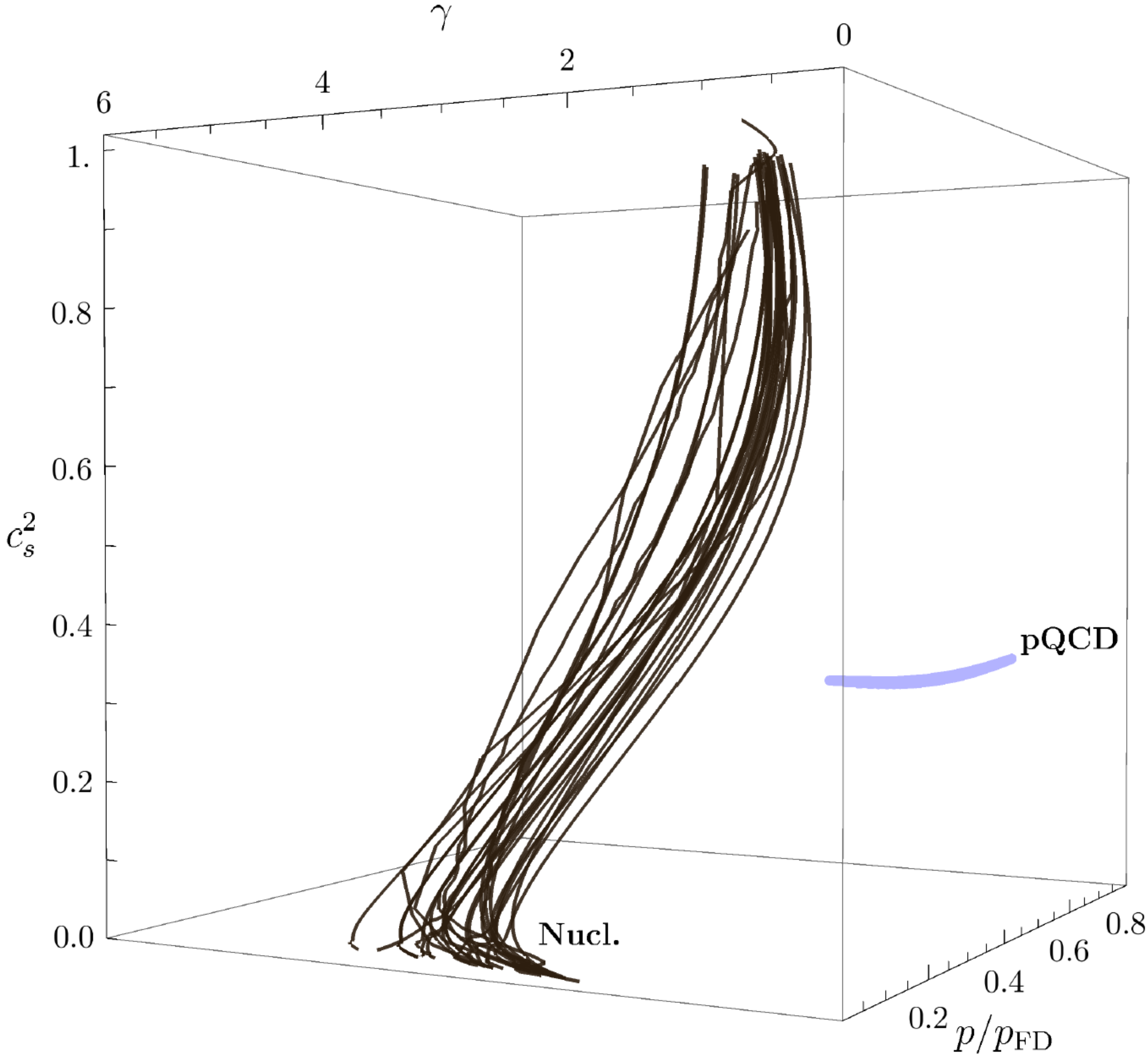
1) Is the two-slope structure only a property of the band, or does it persist more differentially – and for larger values of $\max(c_s^2)$?
2) Where do the centers of NSs with different masses lie, i.e. does quark matter exist inside NSs?

strengthen link between bend and deconf. transition

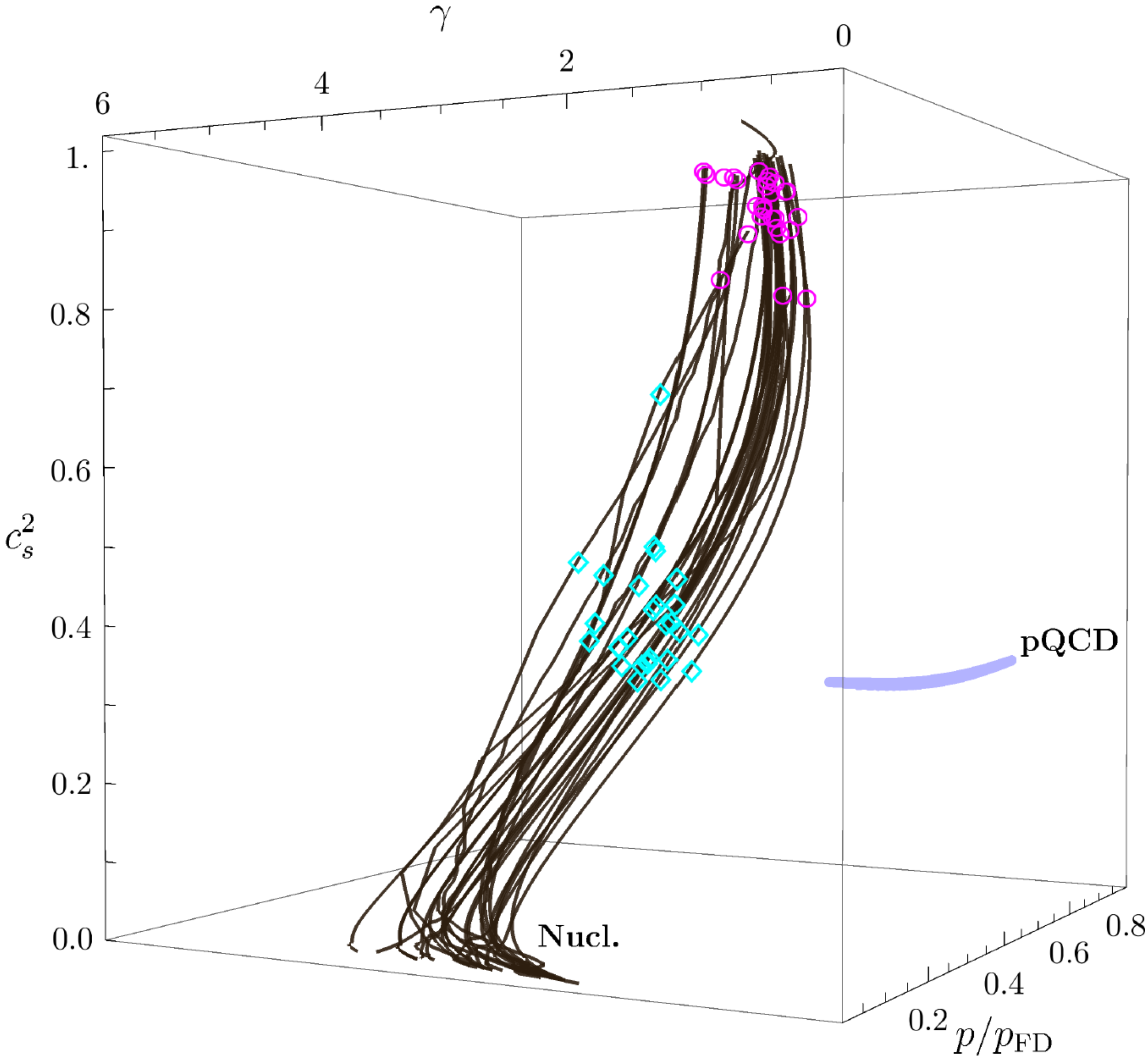
Distinguishing feature between phases: slope $\gamma \equiv \frac{d \ln p}{d \ln \epsilon} \approx$ 1 in nearly conformal QM, 2.5 in sub-n_s nuclear matter

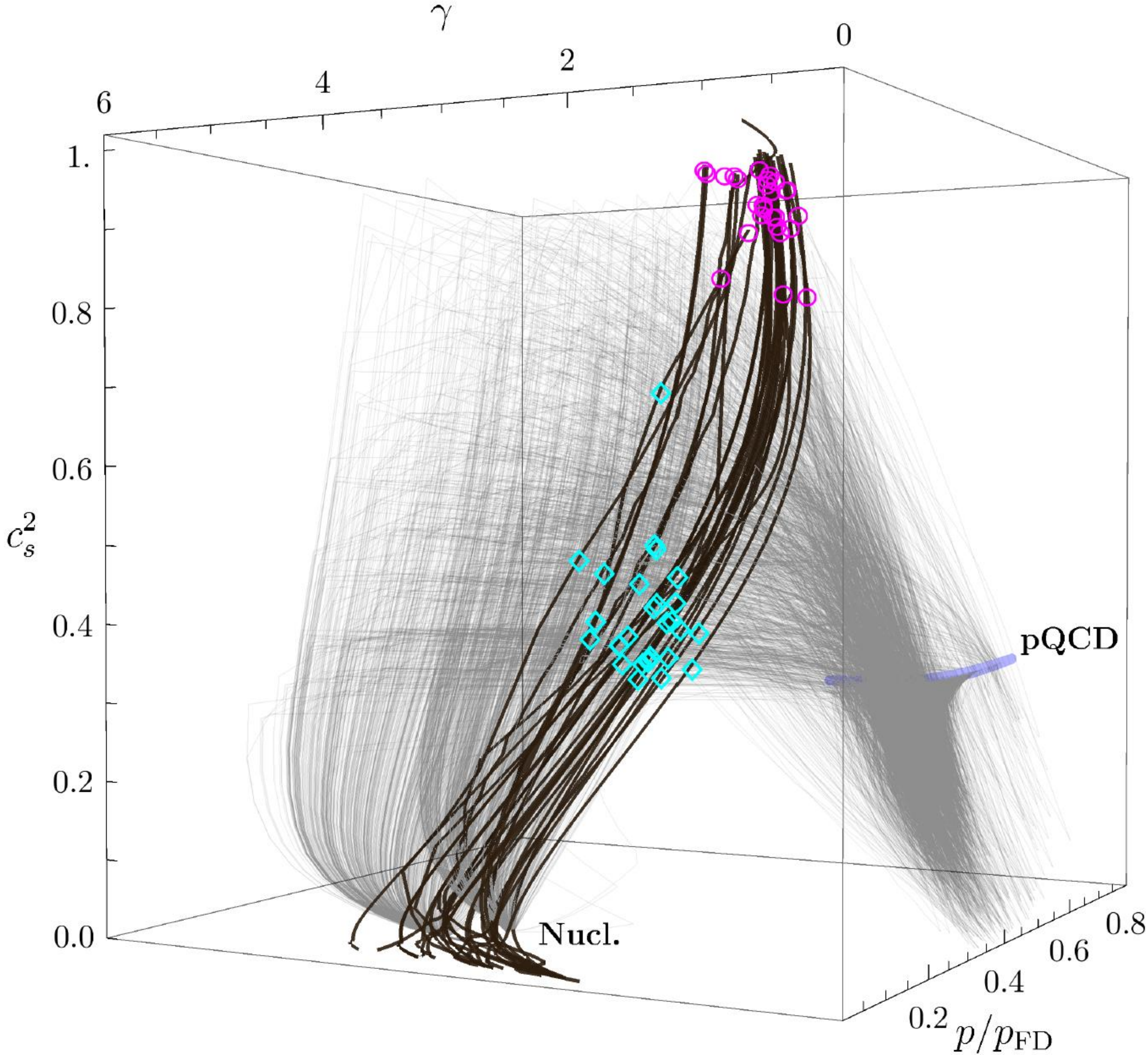
Plan for investigation:

1) Generate a large (∼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

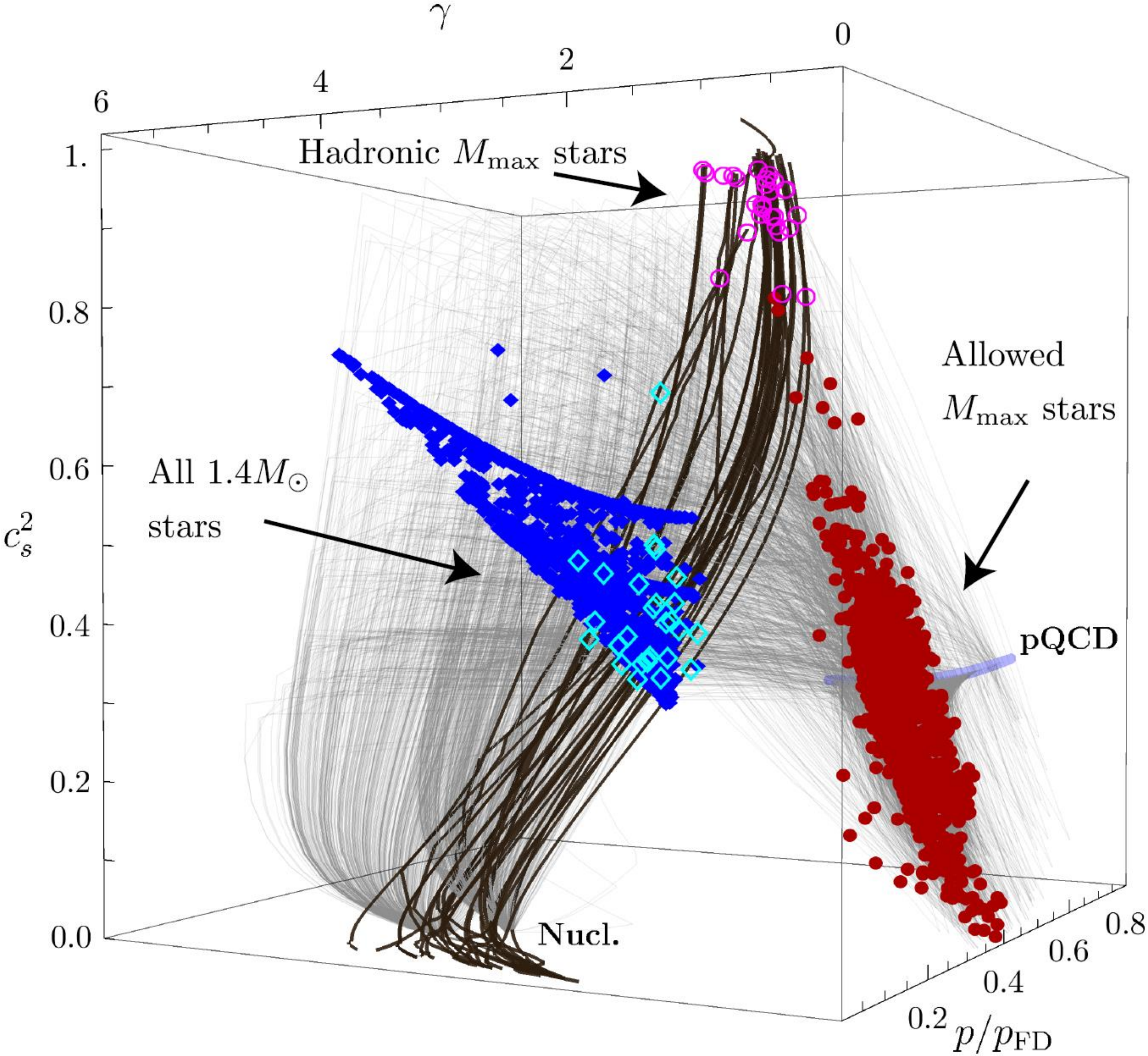


γ
6
4
2
0
1.
0.8
0.6
0.4
0.2
0.0
c_s^2
pQCD
Nucl.
0.2
0.4
0.6
0.8
$p/p_{\rm FD}$

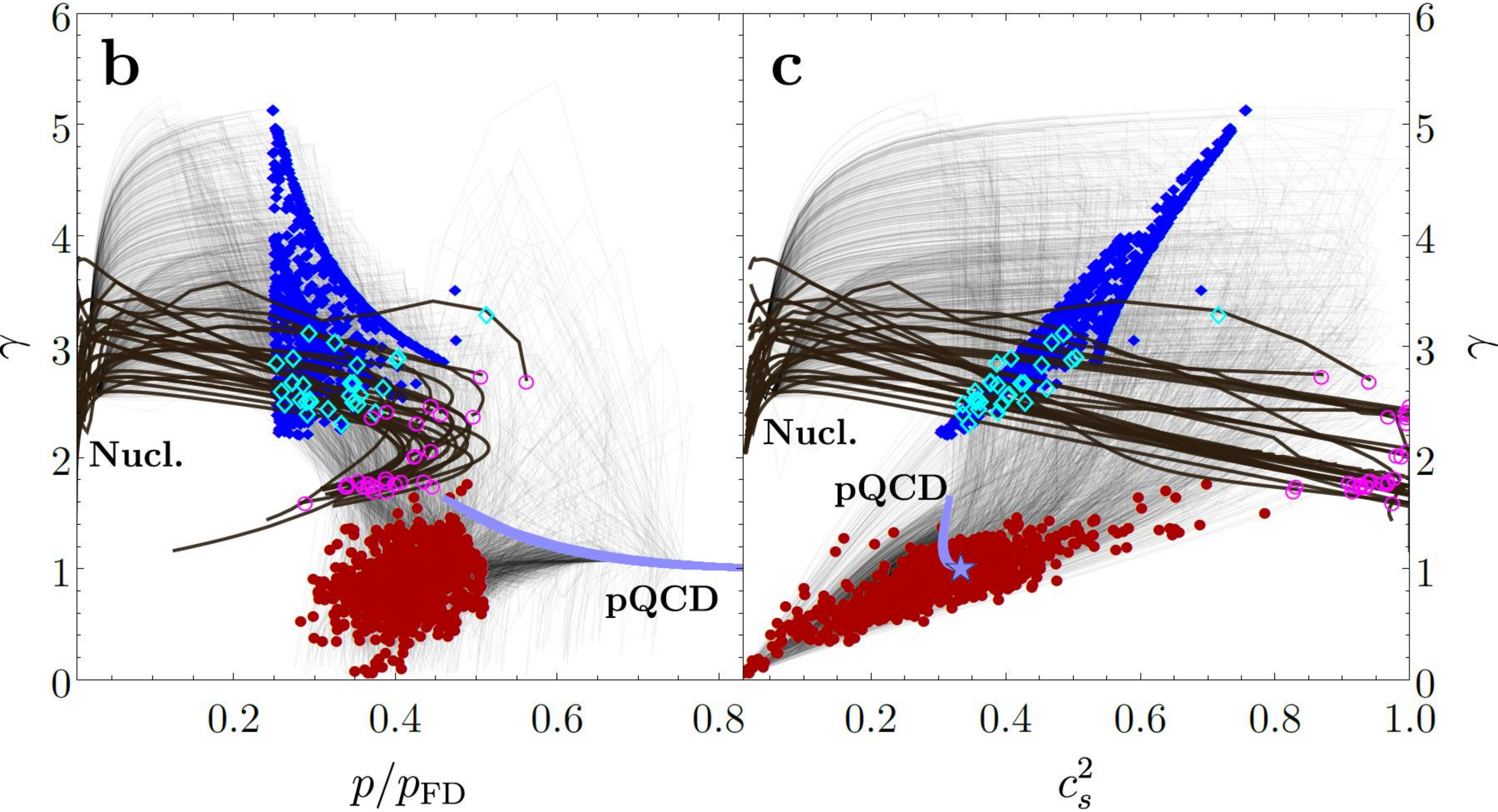

γ
6
4
2
0
1.
0.8
0.6
c_s^2
0.4
0.2
0.0
pQCD
Nucl.
0.2
0.4
0.6
0.8
$p/p_{\rm FD}$



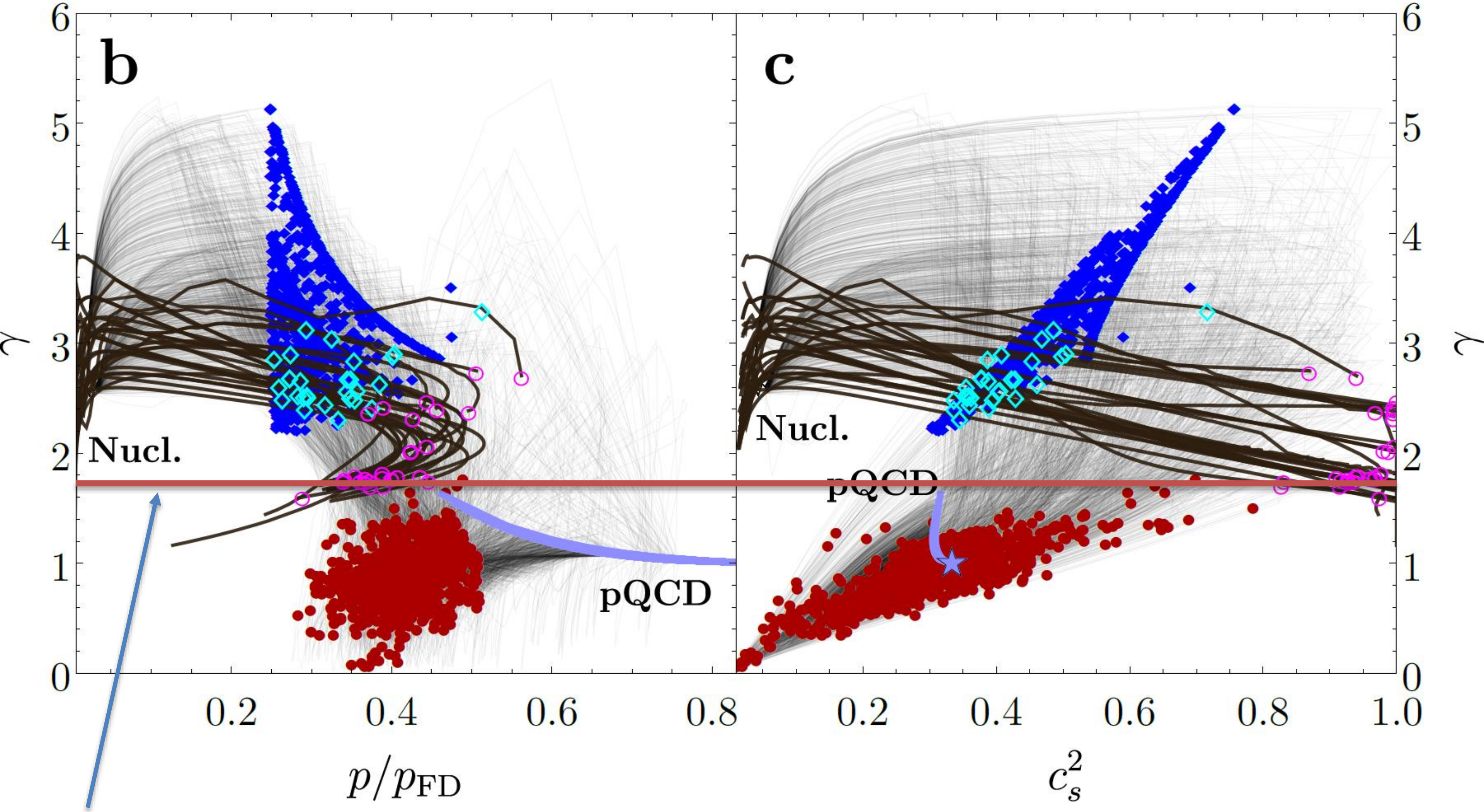
γ
0
2
4
6
1.
0.8
0.6
0.4
0.2
0.0
c_s^2
pQCD
Nucl.
0.2
0.4
0.6
0.8
$p/p_{\rm FD}$



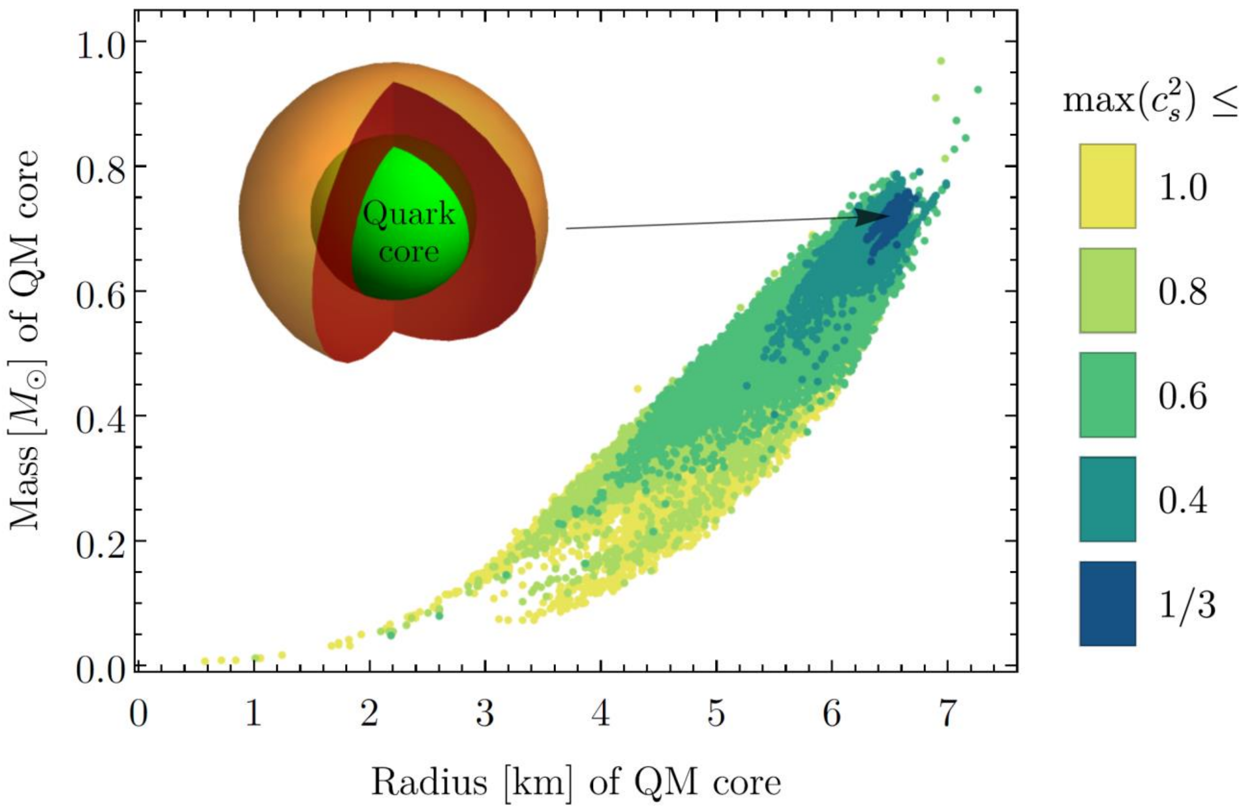
γ
0
2
4
6
1.
0.8
0.6
0.4
0.2
0.0
c_s^2
Hadronic $M_{\max}$ stars
Allowed
$M_{\max}$ stars
All $1.4M_\odot$
stars
pQCD
Nucl.
0.2
0.4
0.6
0.8
$p/p_{\rm FD}$



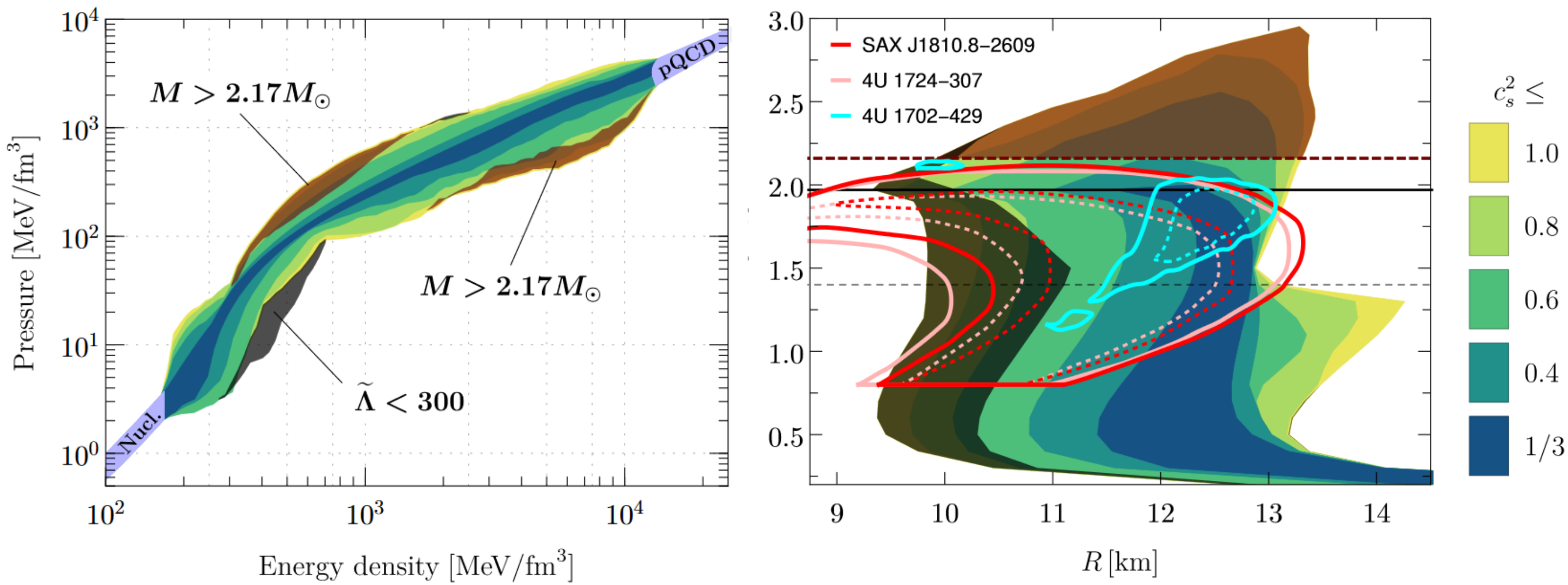
b
c
Nucl.
pQCD
Nucl.
pQCD
γ
γ
$p/p_{\rm FD}$
c_s^2
0
1
2
3
4
5
6
0.2
0.4
0.6
0.8
1.0



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

- 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