Quark matter in sight: neutron-star cores as a laboratory for particle physics

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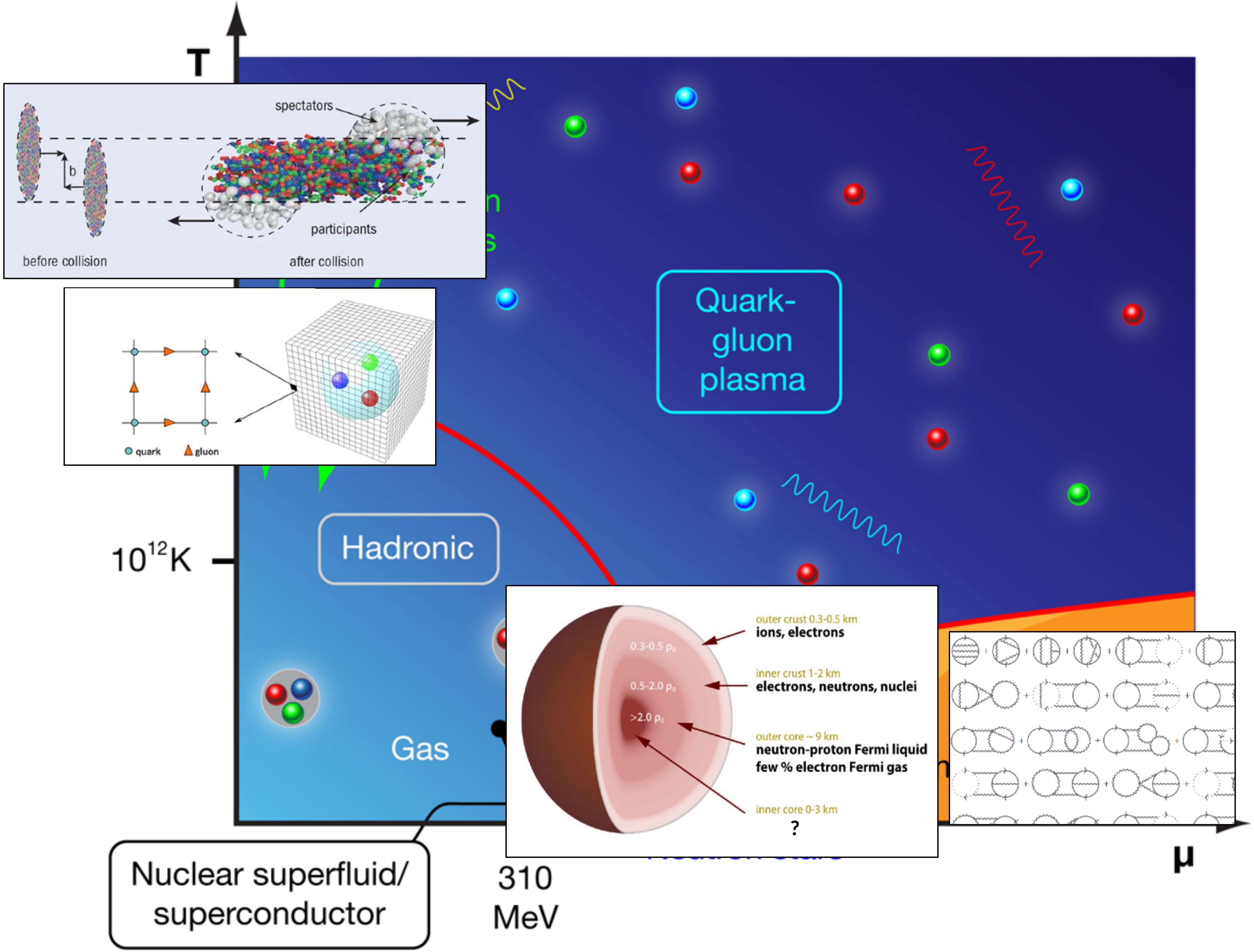
University of Helsinki & Helsinki Institute of Physics

Theory seminar at T.D. Lee Institute

14 November 2022

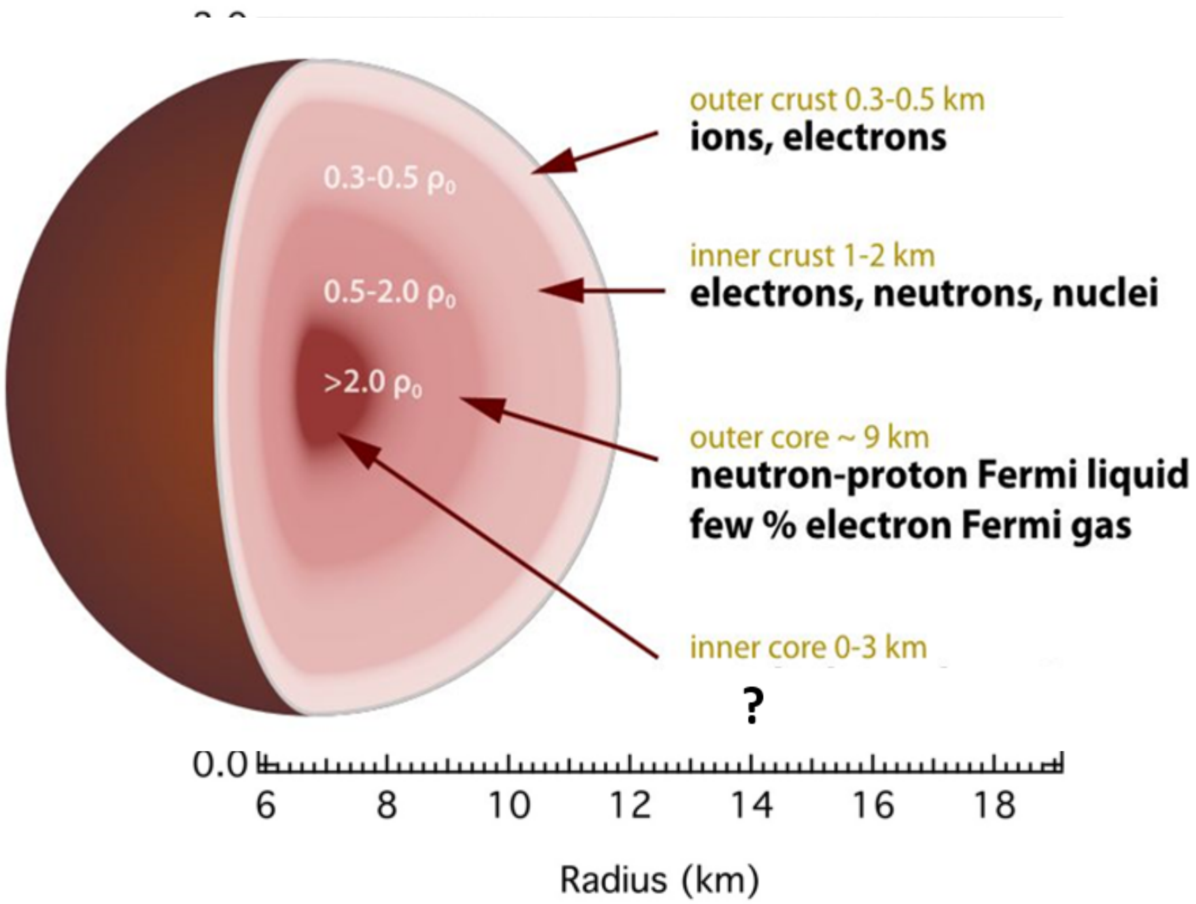
1) Annala, Gorda, Kurkela, Nättilä, AV, Nature Phys. (2020), 1903.09121
2) Annala, Gorda, Katerini, Kurkela, Nättilä, Paschalidis, AV, PRX 12 (2022), 2105.05132
3) Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, In preparation



T
10^{12}K
μ
Quark-gluon plasma
Hadronic
Gas
Nuclear superfluid/ superconductor
310 MeV
spectators
b
participants
before collision
after collision
quark
gluon
$0.3\text{-}0.5\ \rho_0$
$0.5\text{-}2.0\ \rho_0$
$>2.0\ \rho_0$
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
?

Dense QCD challenge: can we understand the composition and macroscopic properties of NSs using only first-principles field theory tools and robust observational data?

Link between micro and macro from GR and **Equation of State (EoS)**:



[Ozel et al., ApJ 820 (2016)]

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

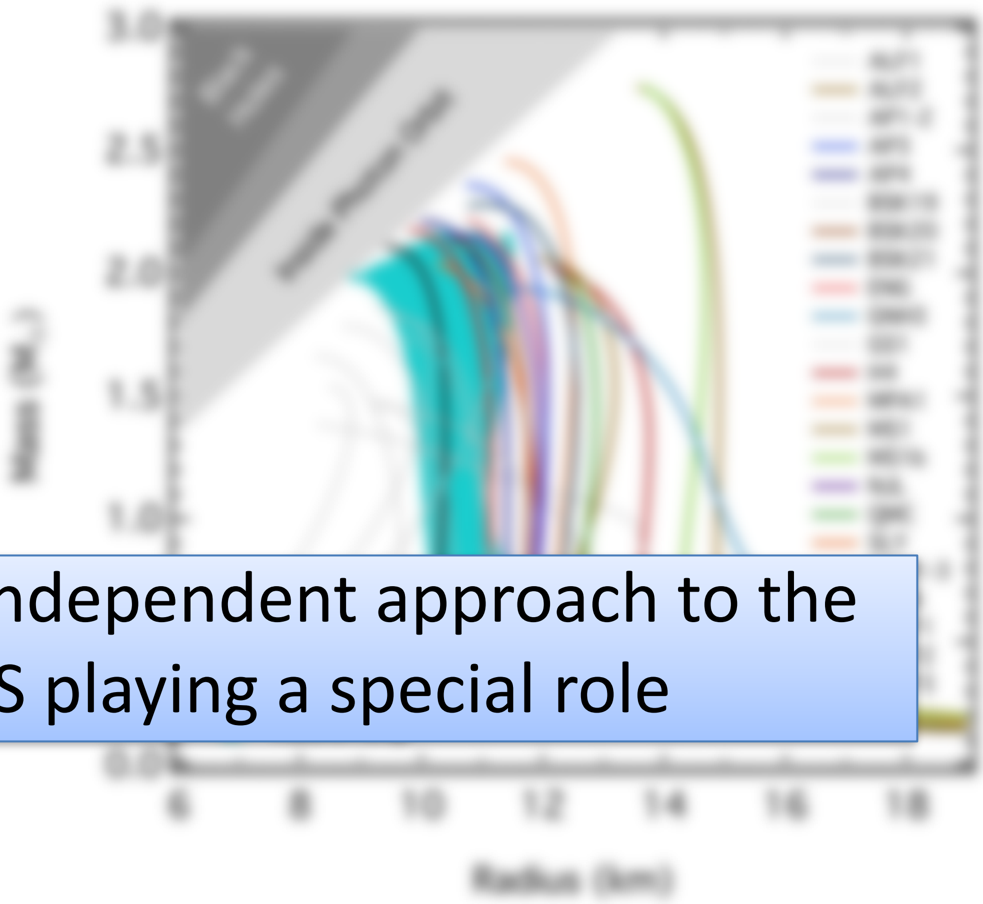
$$\frac{dp(r)}{dr} = -\frac{G\varepsilon(r)M(r)}{r^2}\frac{(1+p(r)/\varepsilon(r))\left(1+4\pi r^3 p(r)/M(r)\right)}{1-2GM(r)/r}$$

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

Dense QCD challenge: can we understand the composition and macroscopic properties of NSs using only first-principles field theory tools and robust observational data?

Clear need for systematic and model-independent approach to the microphysics of neutron stars, with EoS playing a special role

Link … GR … equation of state (EoS):



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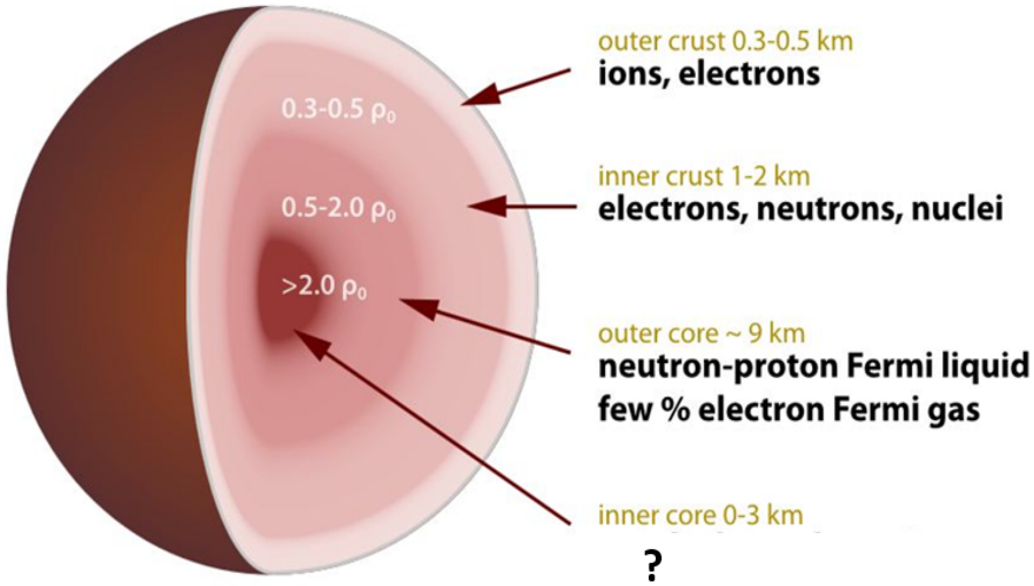
NS matter: from dilute crust to ultradense core

Proceeding inwards from the crust:

- μ_B increases gradually, starting from $\mu_{\rm Fe}$
- 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: $T \approx 0 \approx n_Q$



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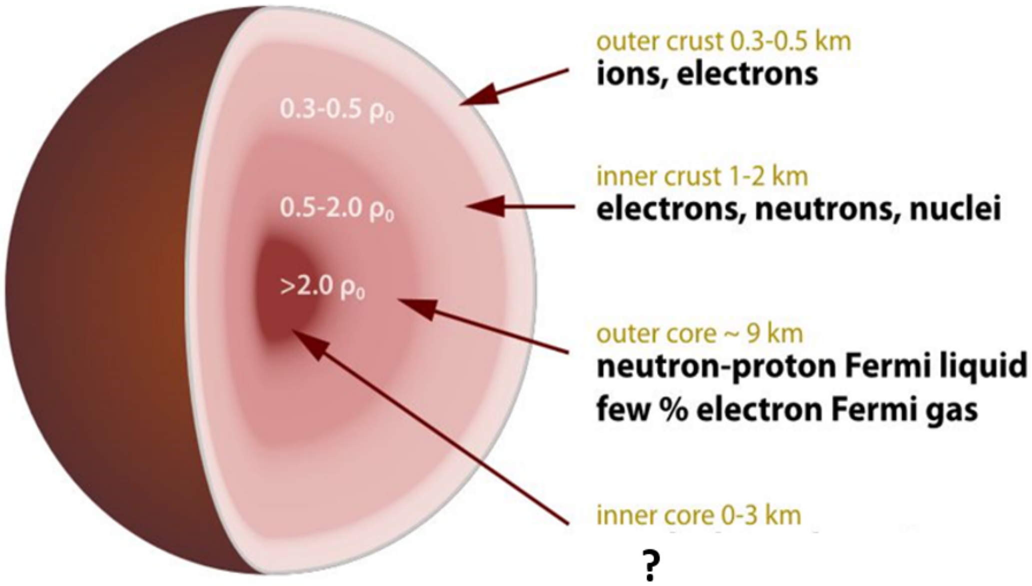
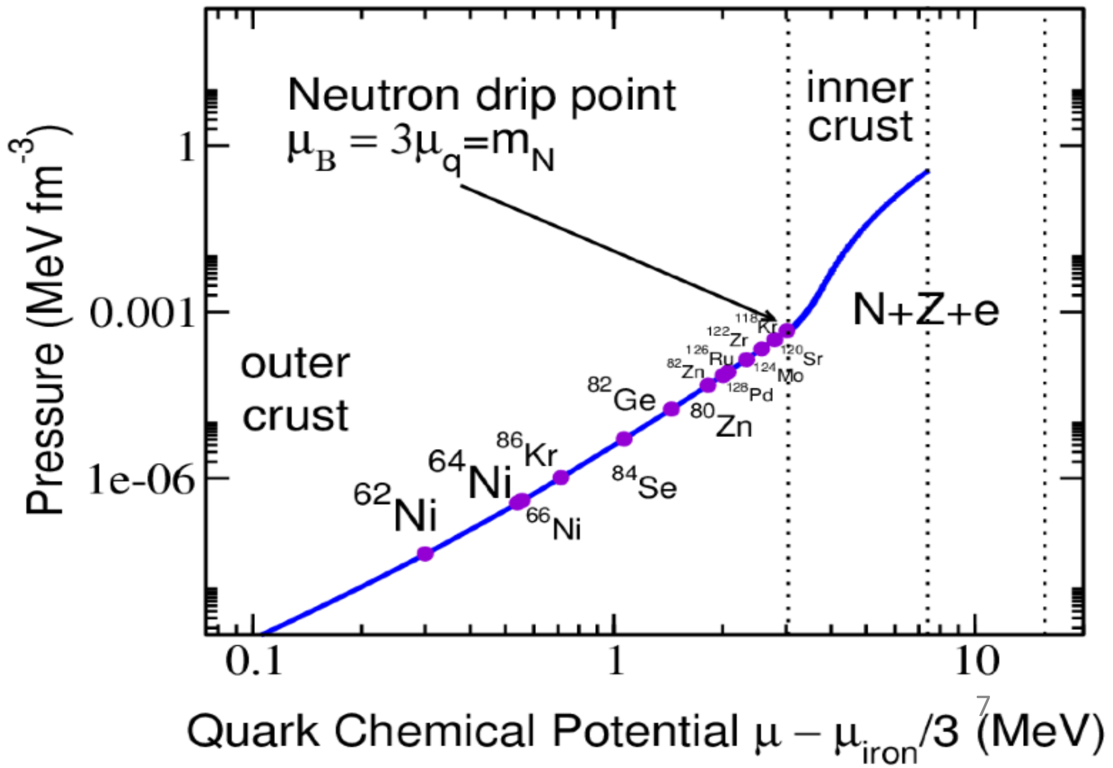
Beyond neutron drip point NN interactions important; then 3Ns, boost corrections, etc.





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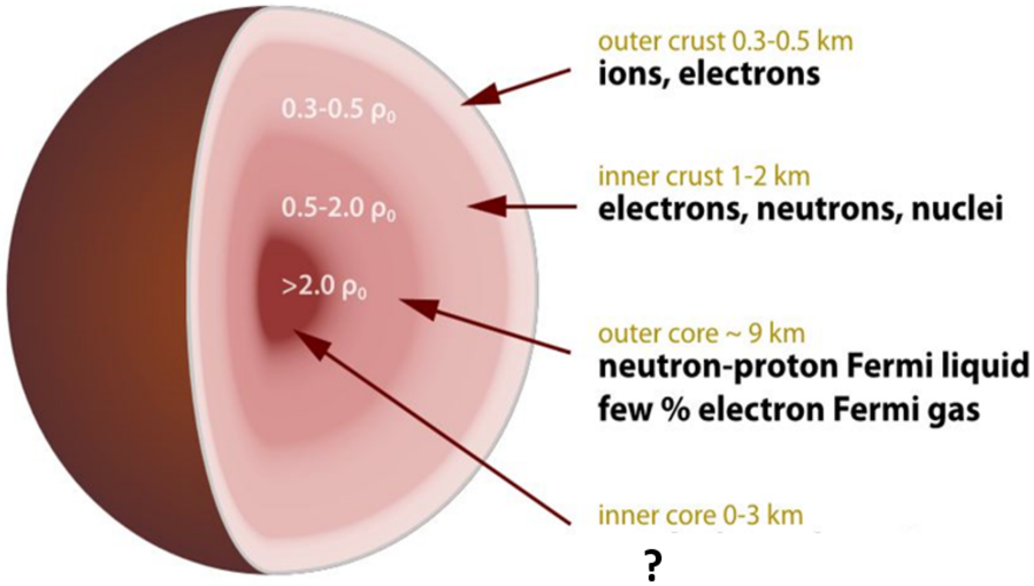

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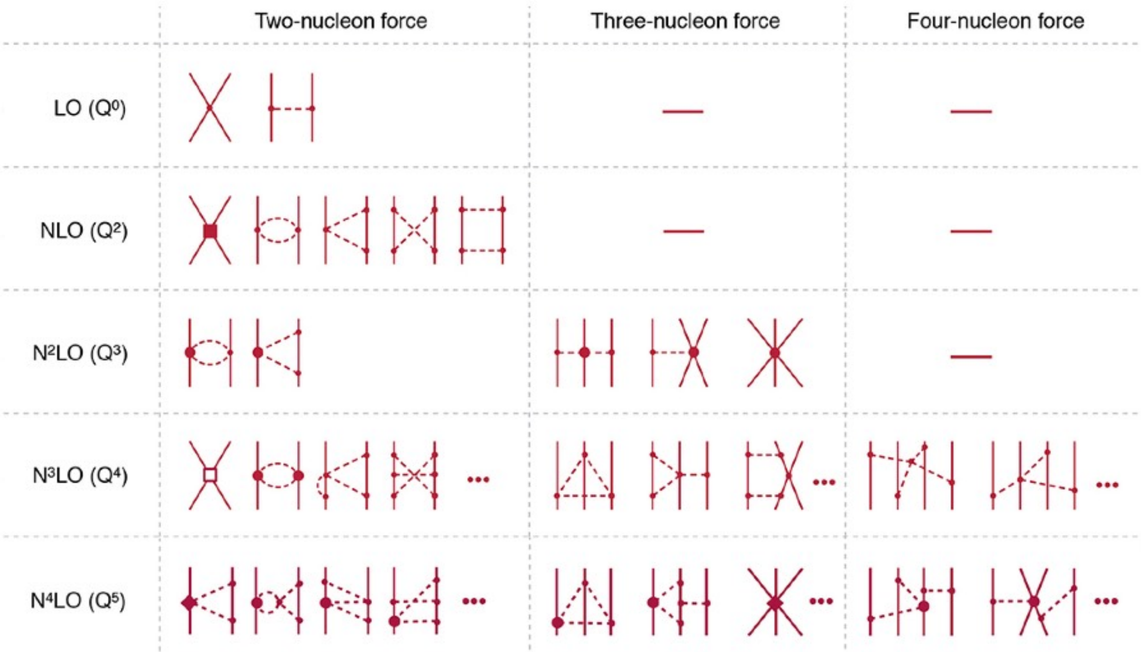
- Systematic effective theory framework: Chiral Effective Theory (CET)



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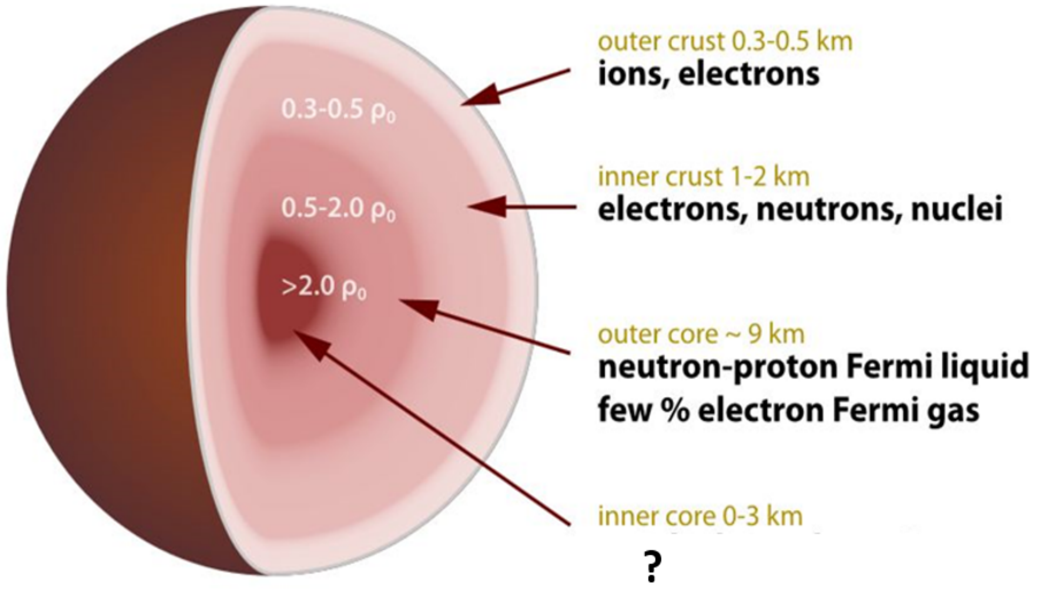
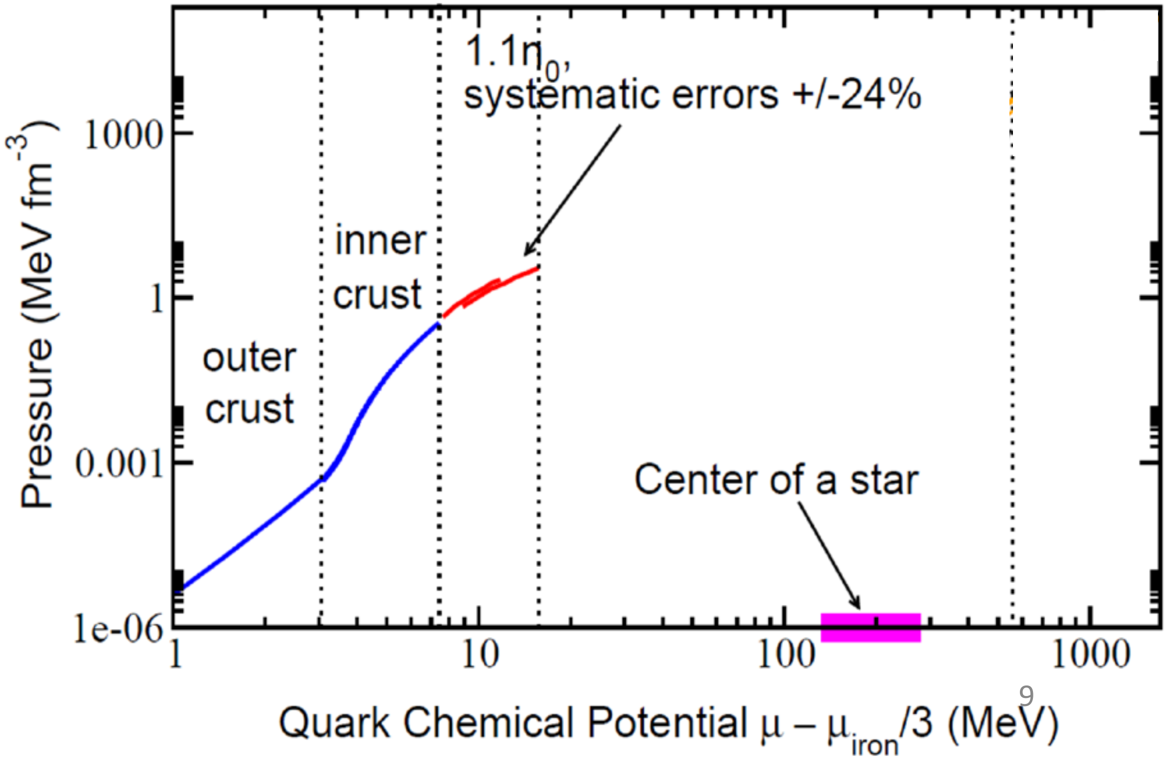


Beyond neutron drip point NN interactions important; then 3Ns, boost corrections, etc.

- 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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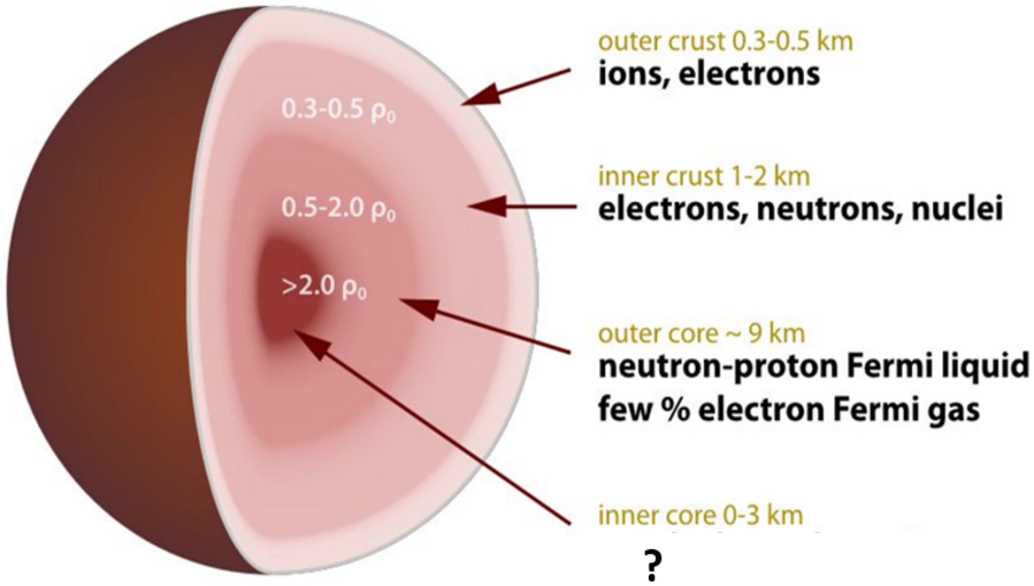
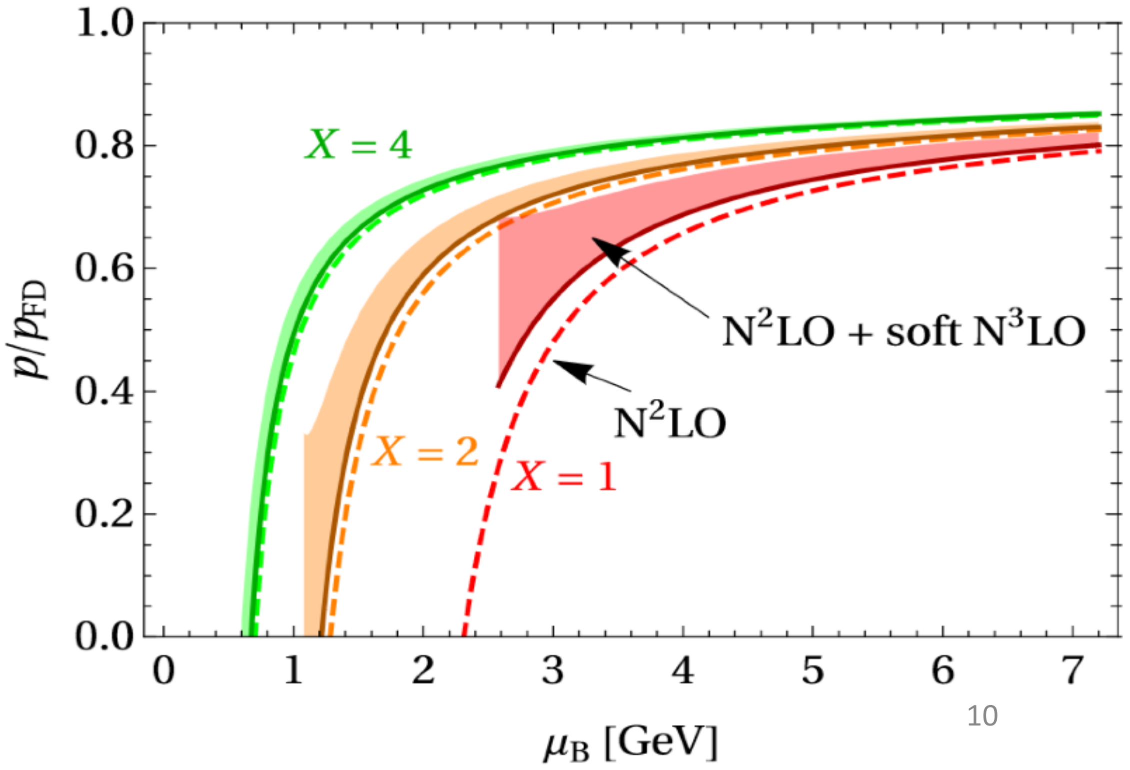
At high density, asymptotic freedom ⇒ weakening coupling and deconfinement

- State-of-the-art pQCD EoS at partial NNNLO, with purely soft sector fully determined [Gorda et al., PRL 127 (2021)]





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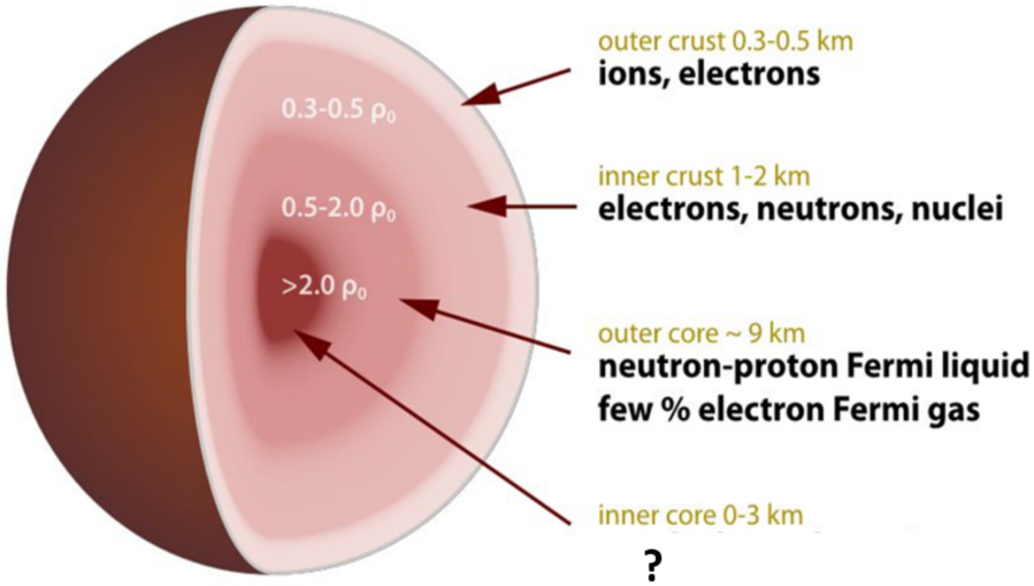

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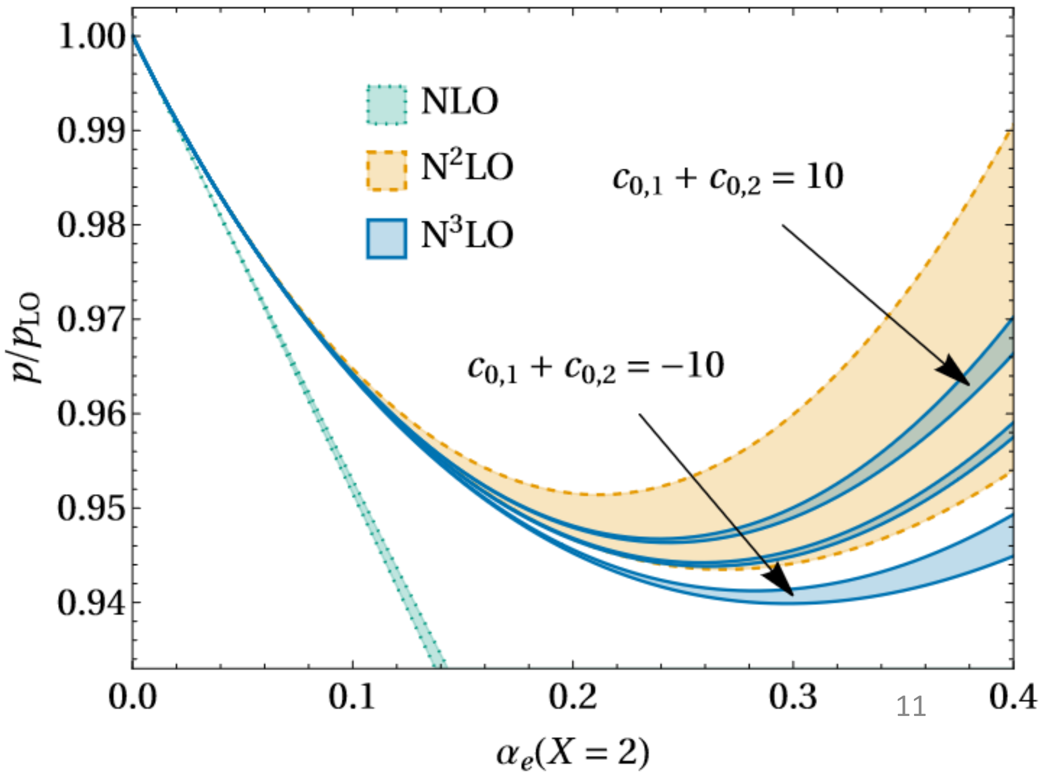
- State-of-the-art pQCD EoS at partial NNNLO, with purely soft sector fully determined [Gorda et al., PRL 127 (2021)]
- QED calculations indicate qualitatively improved convergence at full α_s^3 order



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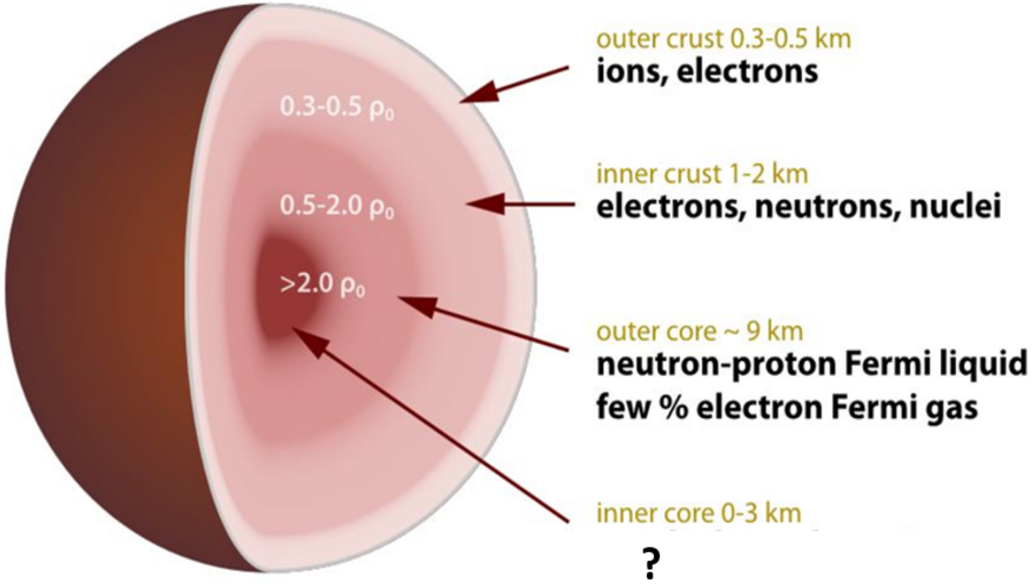
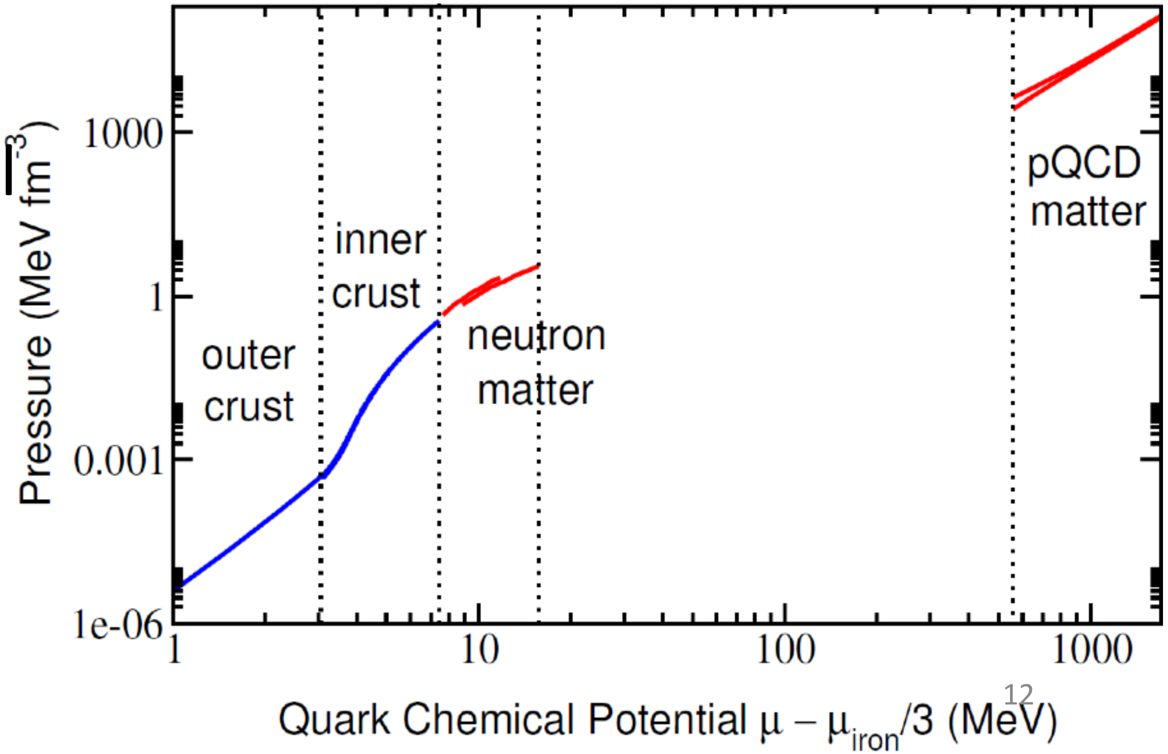
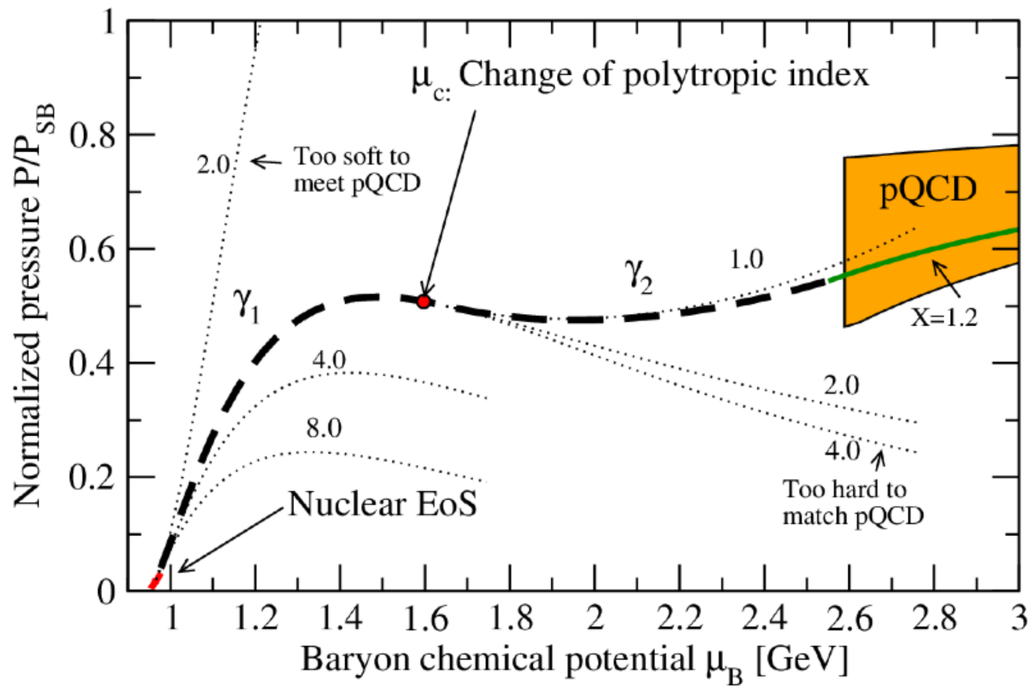
∴ Low- and high-density limits under control but extensive no-man's land at intermed. densities. Have to work with:

1) Astrophysical observations: masses, radii, tidal deformabilities,…
2) Thermodynamic relations
3) Subluminality: $c_s \leq 1$





Possible way to proceed: build large ensembles of randomly generated interpolators with piecewise basis functions

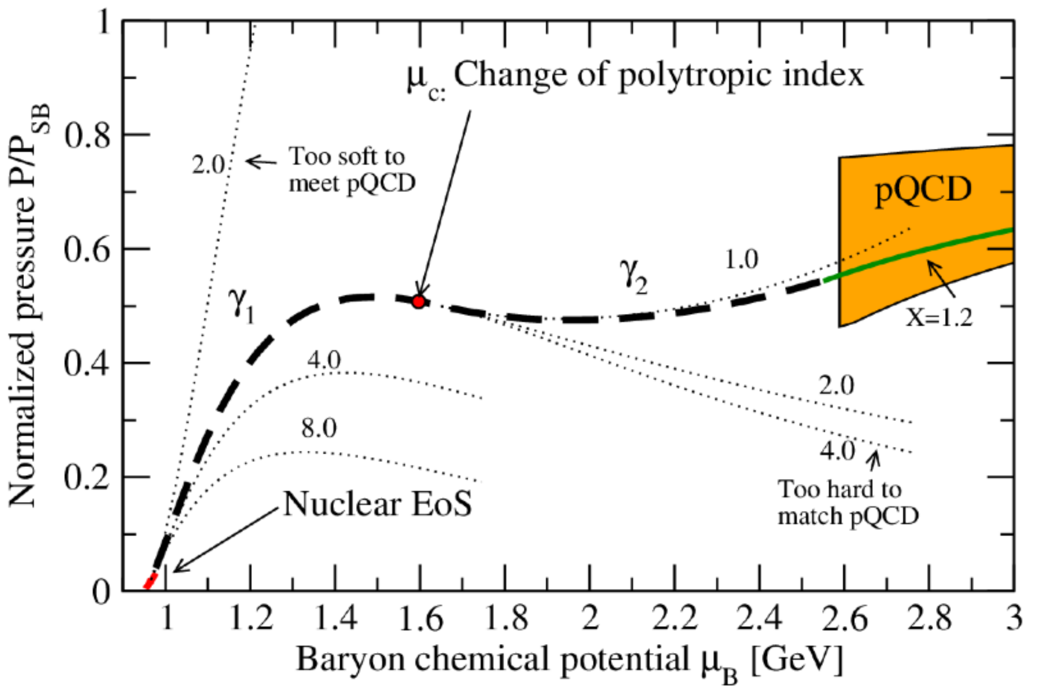


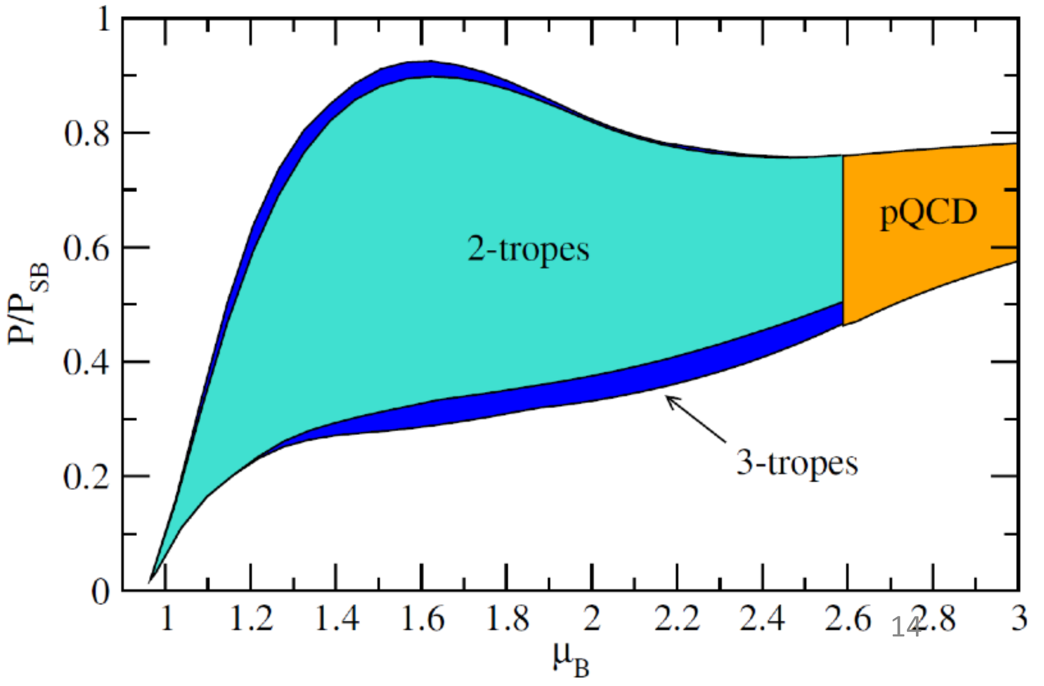
Possible way to proceed: build large ensembles of randomly generated interpolators with piecewise basis functions

Require for all individual EoSs:

1) Smooth matching to nuclear and quark matter EoSs
2) Continuity of p and n_B with at most one exception (1st order transition)
3) Subluminality: $c_s < 1$
4) Stellar models constructed with interpolated EoSs agree with robust measurements of NS properties

[Kurkela et al., ApJ 789 (2014), Gorda et al., PRL 120 (2018); etc.]





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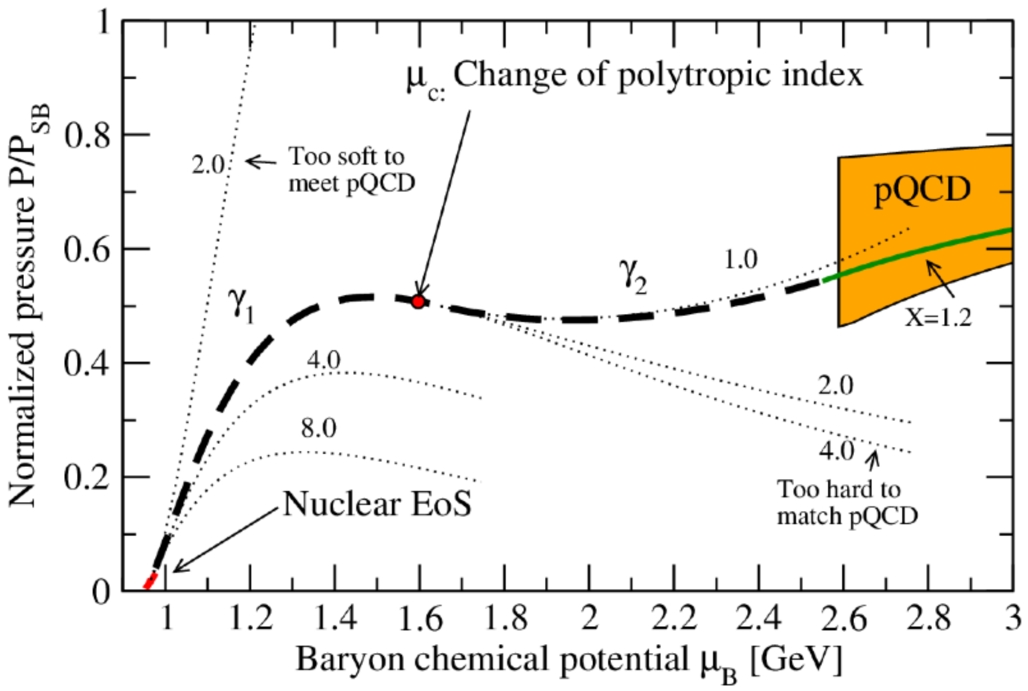
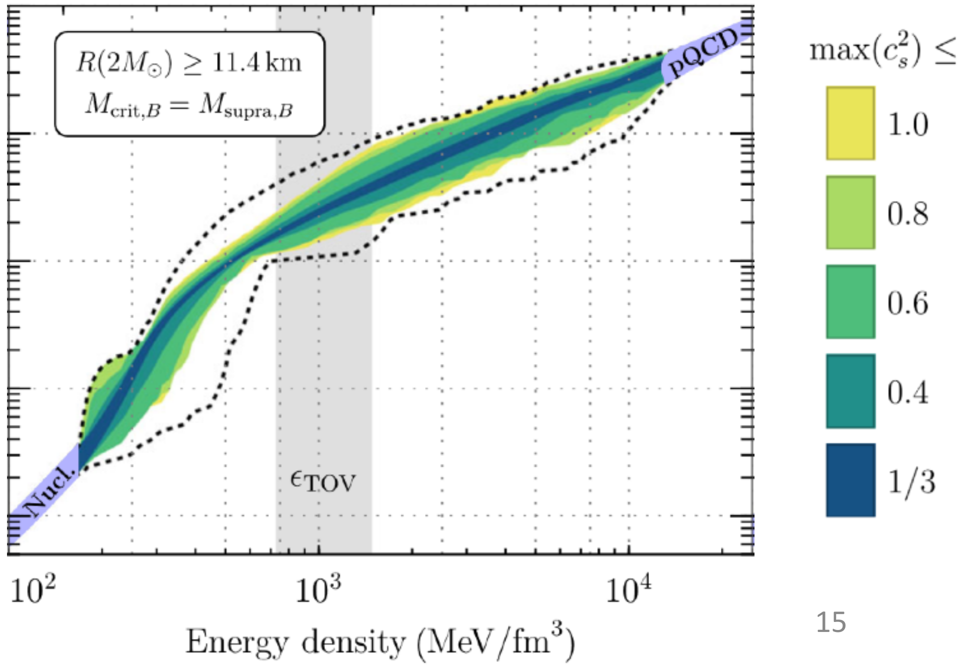
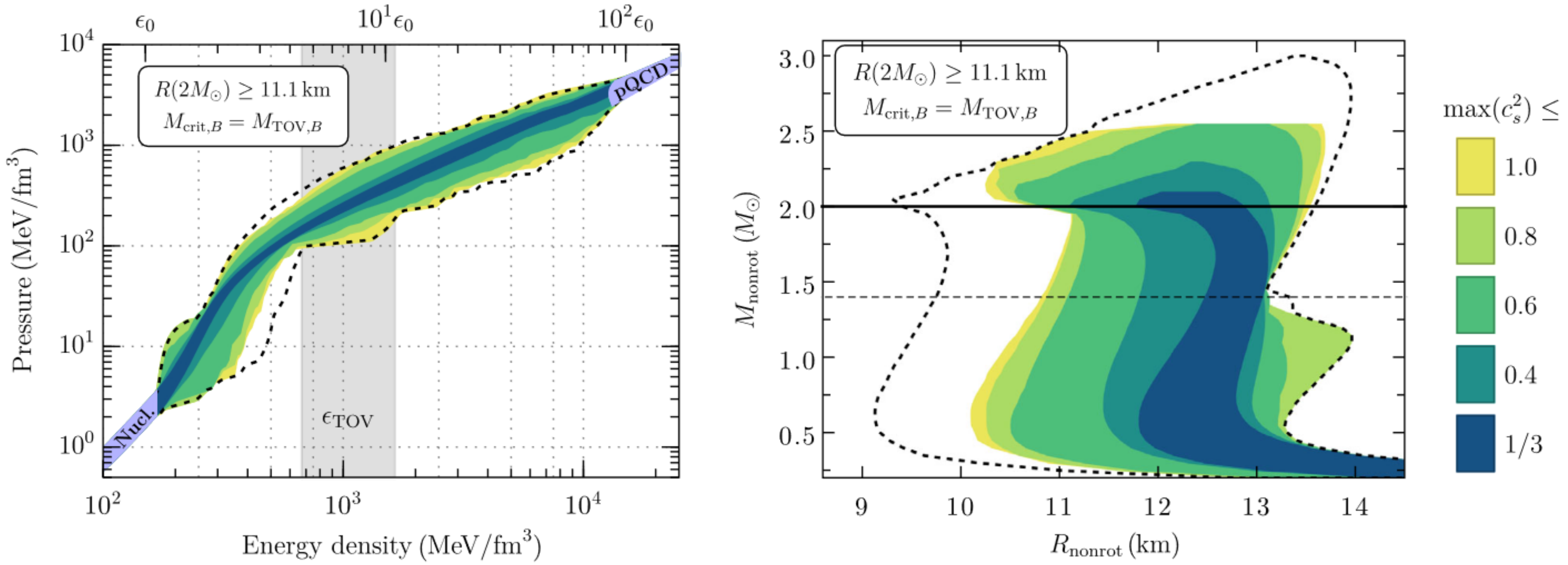


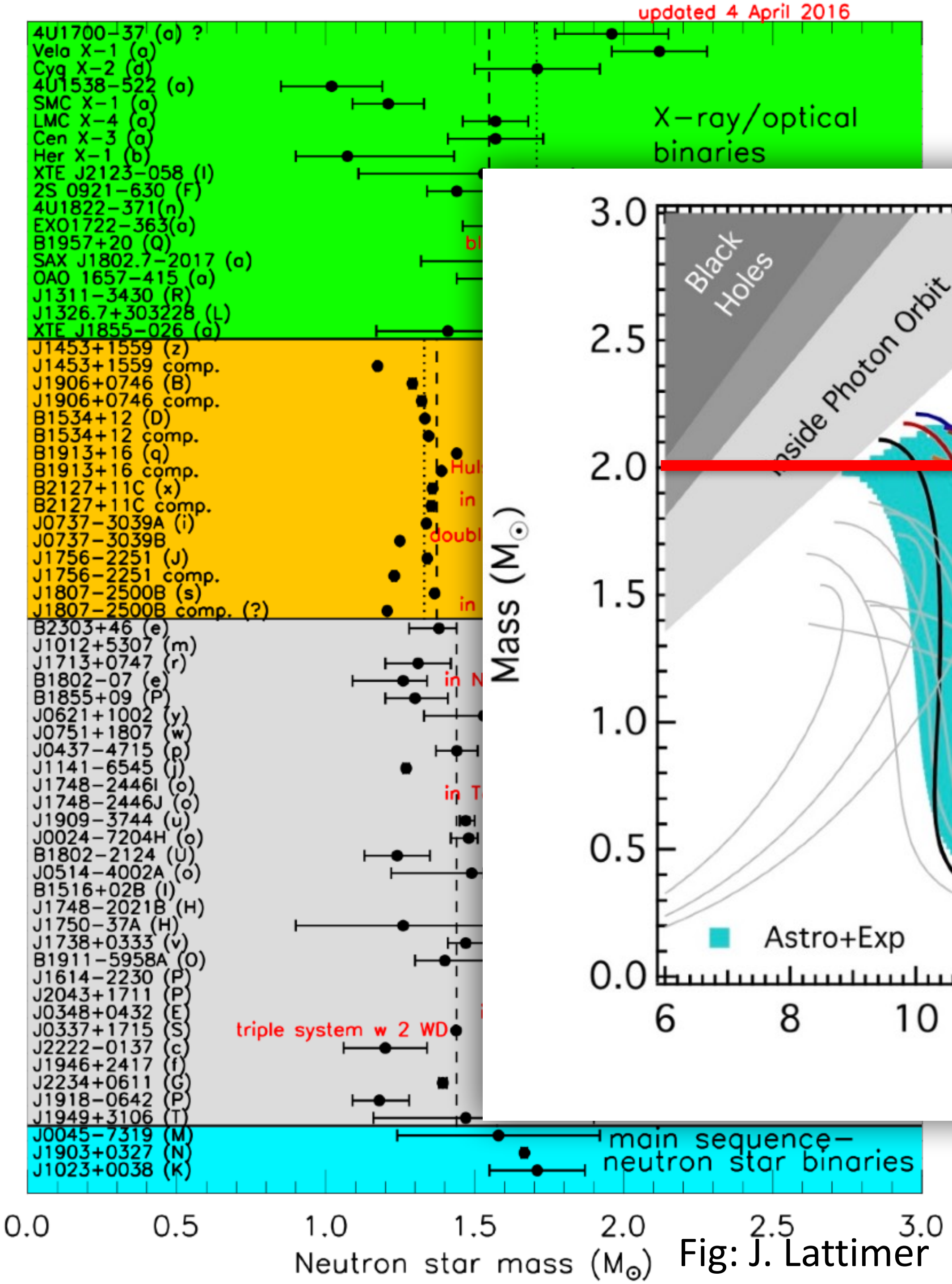




In the remainder of this talk, 3 brief topics:

1) What are the most useful astrophysical measurements for EoS determination?
2) How well do current interpolation studies constrain the EoS?
3) What can we say about the phase of matter inside NS cores?

What do we know from NS observations?



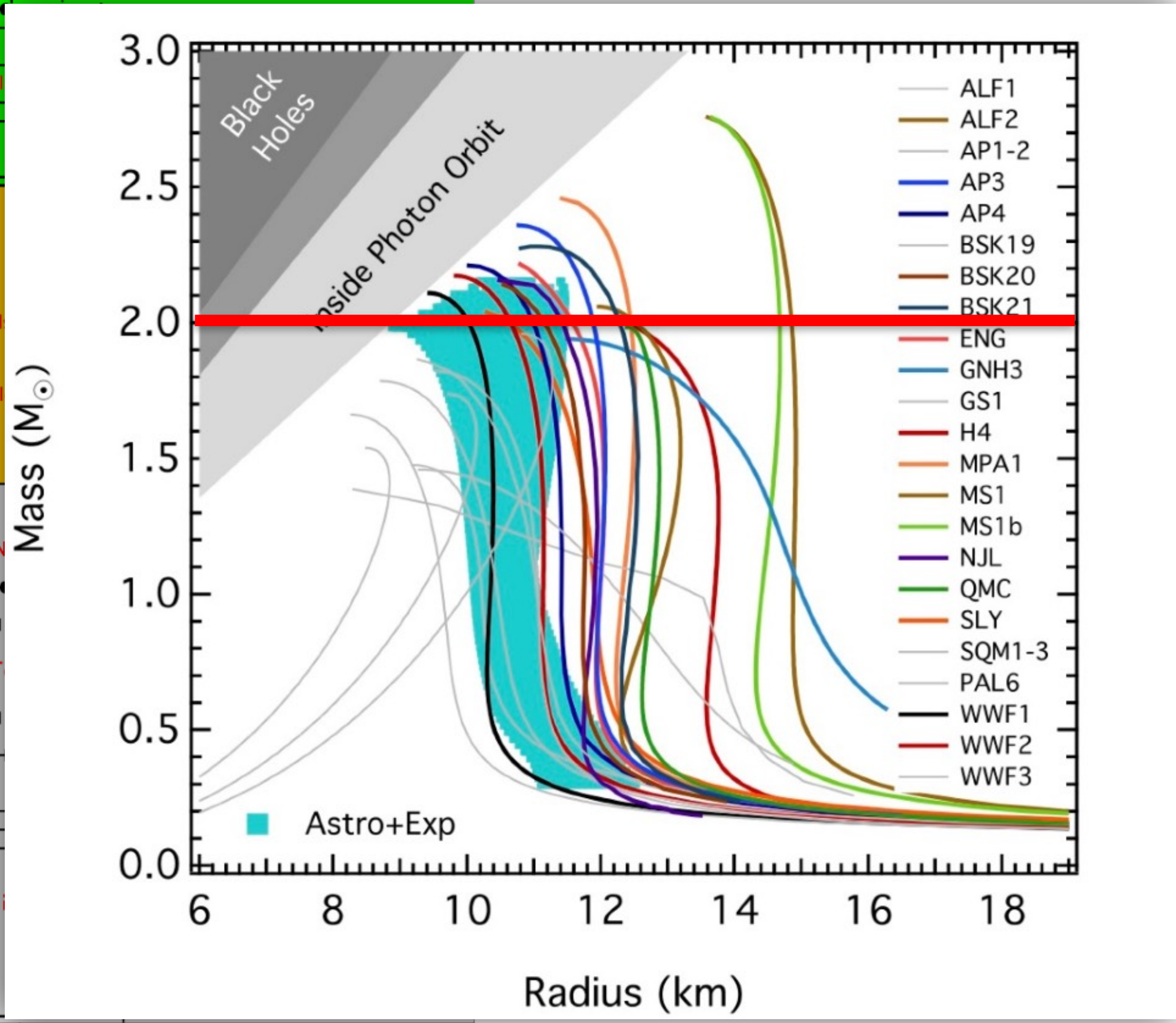


Fig: J. Lattimer

ate Shapiro delay

vo-solar-mass

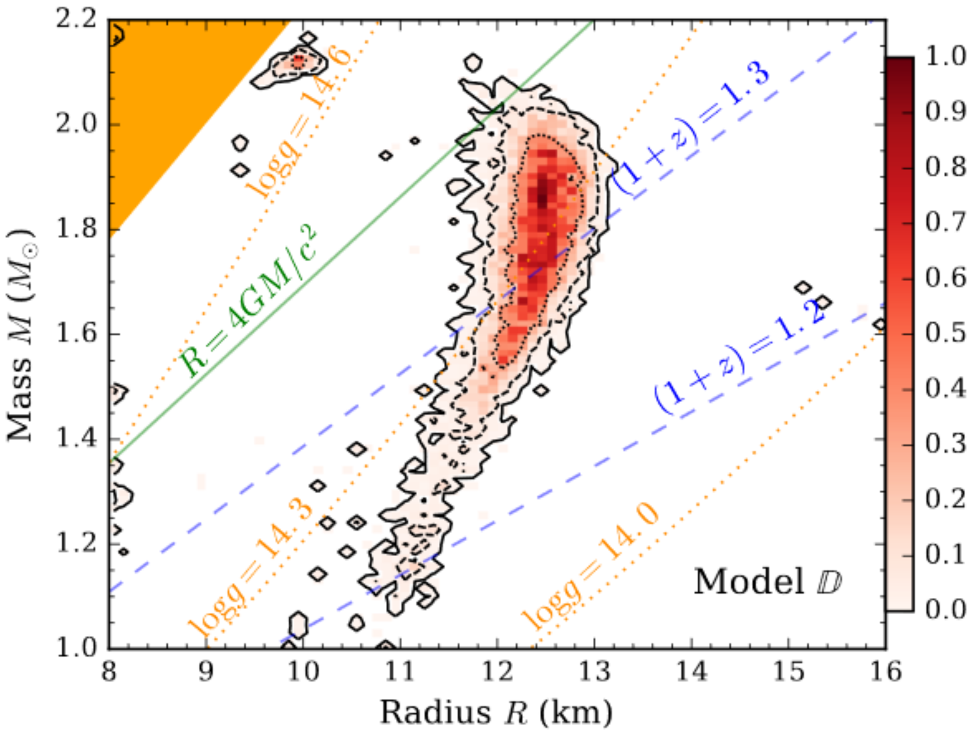
(2010)

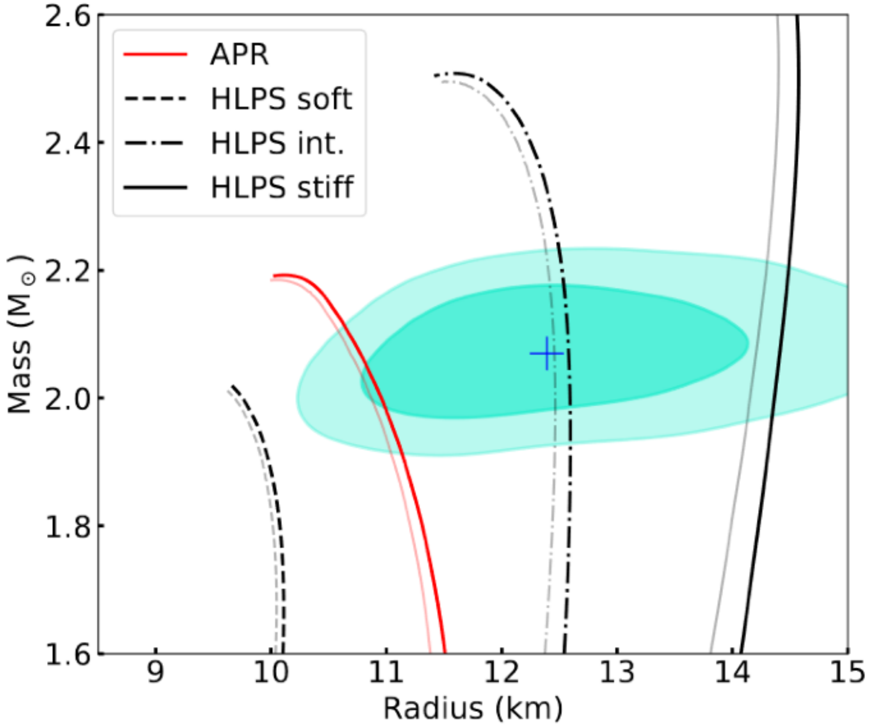
0 (2013)

ronomy 4 (2019)

Radius (and combined MR) measurements more problematic, but recently important progress through X-ray observations:

- Cooling of thermonuclear X-ray bursts provide radii to ~ ± 400m [Nättilä et al., Astronomy & Astrophysics 608 (2017), …]
- Pulse profiling (NICER) ⇒ nontrivial lower bounds for two stellar radii, including PSR J0740+6620 with $M \gtrsim 2M_\odot$ [Miller et al., Astrophysical Journal Letters 918 (2021), …]



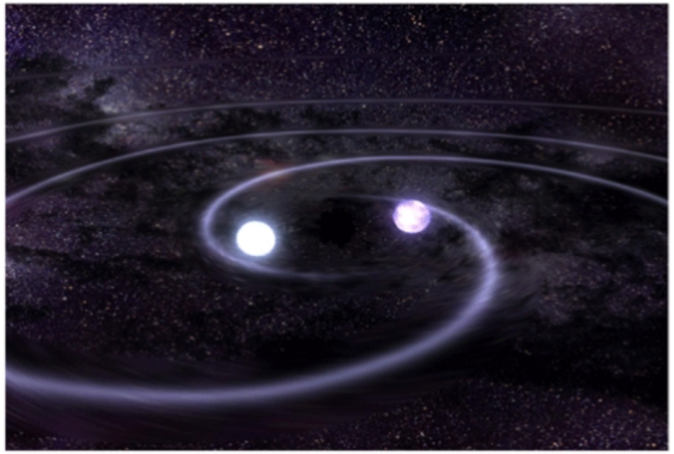


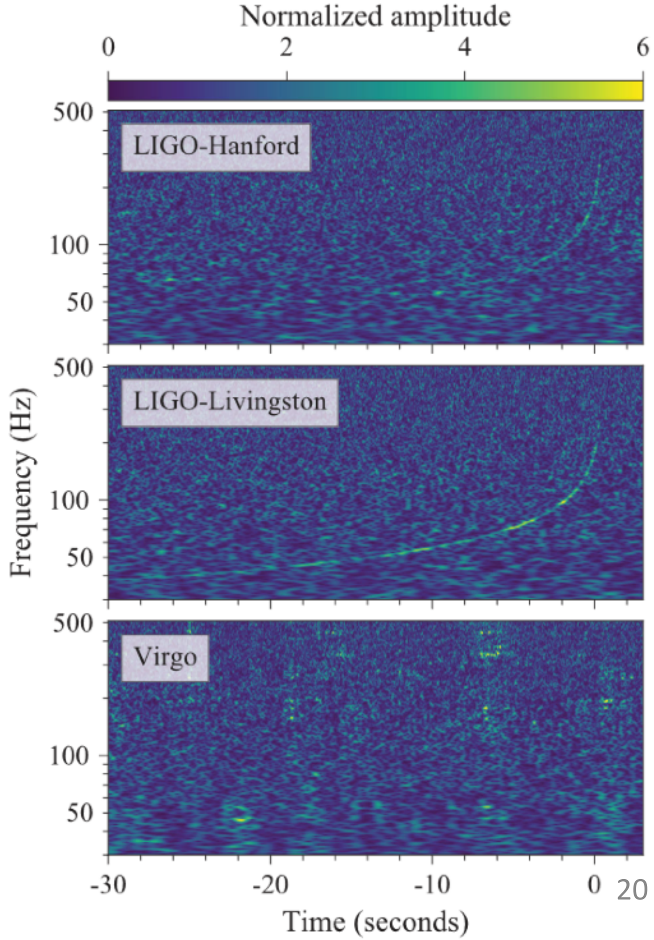
Gravitational wave breakthrough: First observed binary NS merger GW170817 by LIGO & Virgo in 2017 (and many since then)

Three types of potential inputs:

1) Tidal deformabilities of the NSs during inspiral – good measure of stellar compactness
2) Ringdown pattern – sensitive to EoS (also at $T \neq 0$), but frequency too high for LIGO/Virgo
3) EM counterpart: indirect information on merger product

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

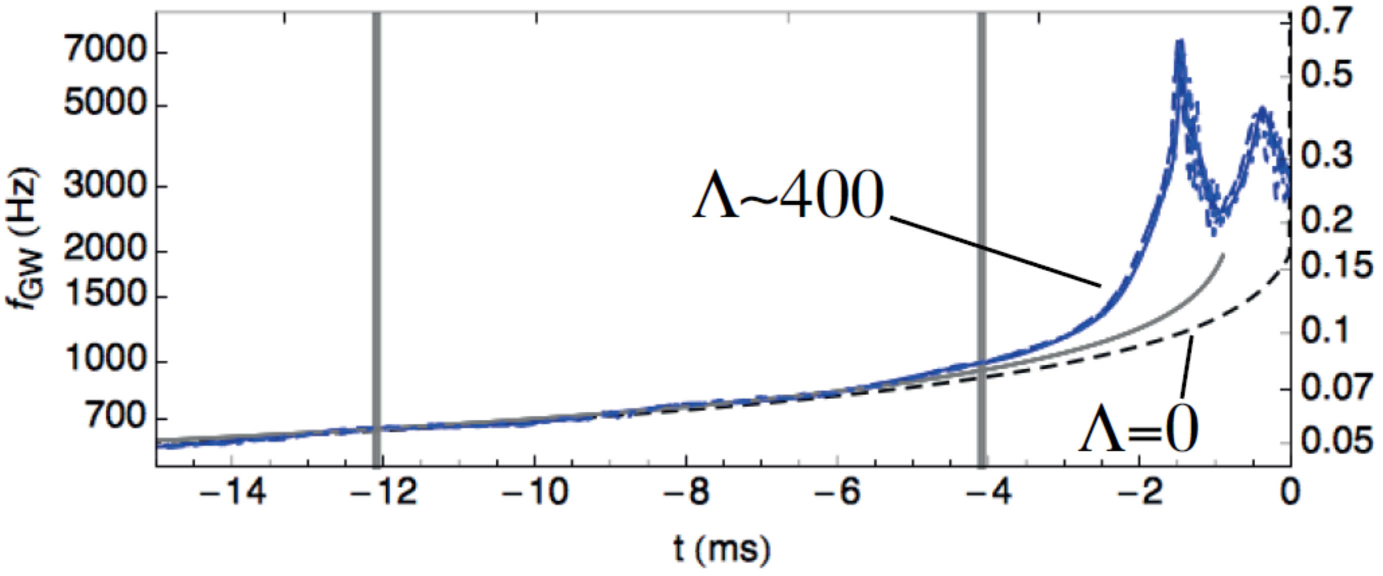




Tidal deformability: How large of a quadrupolar moment a star's gravitational field develops due to an external quadrupolar field

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

Substantial effect on observed GW waveform during inspiral phase



[Read et al., PRD 88 (2013)]

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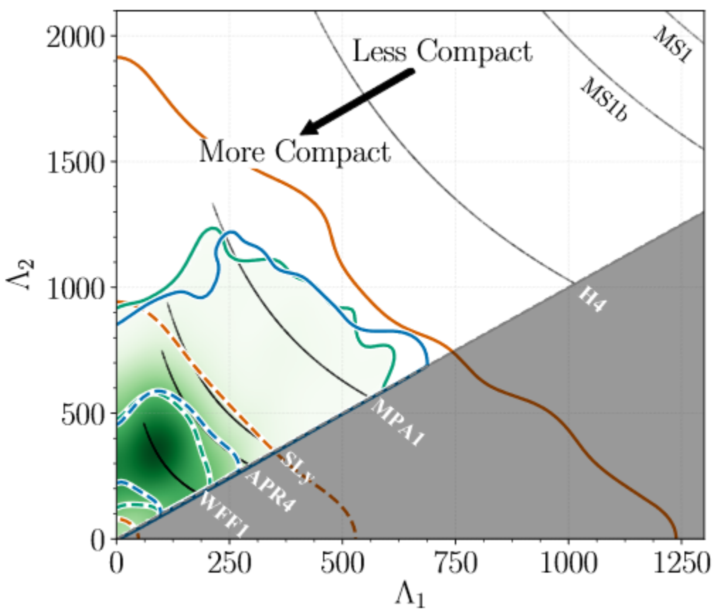
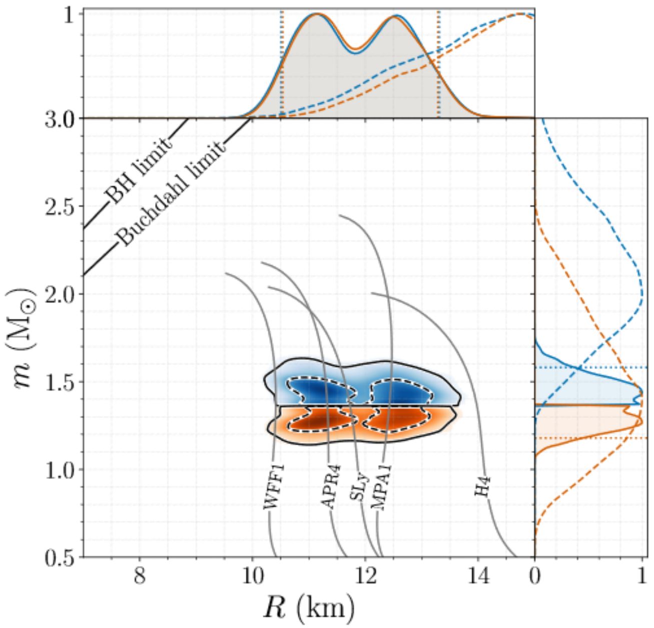
$$Q_{ij} = -\Lambda \mathcal{E}_{ij}$$

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





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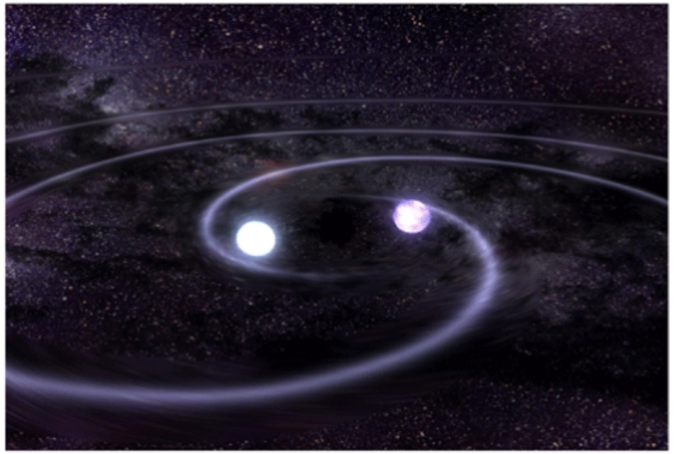
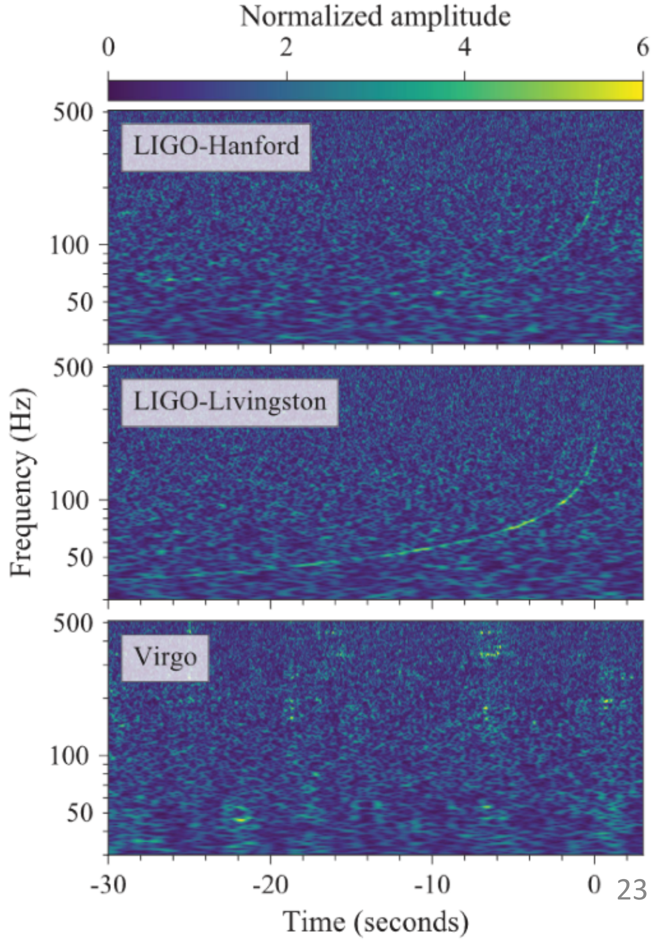




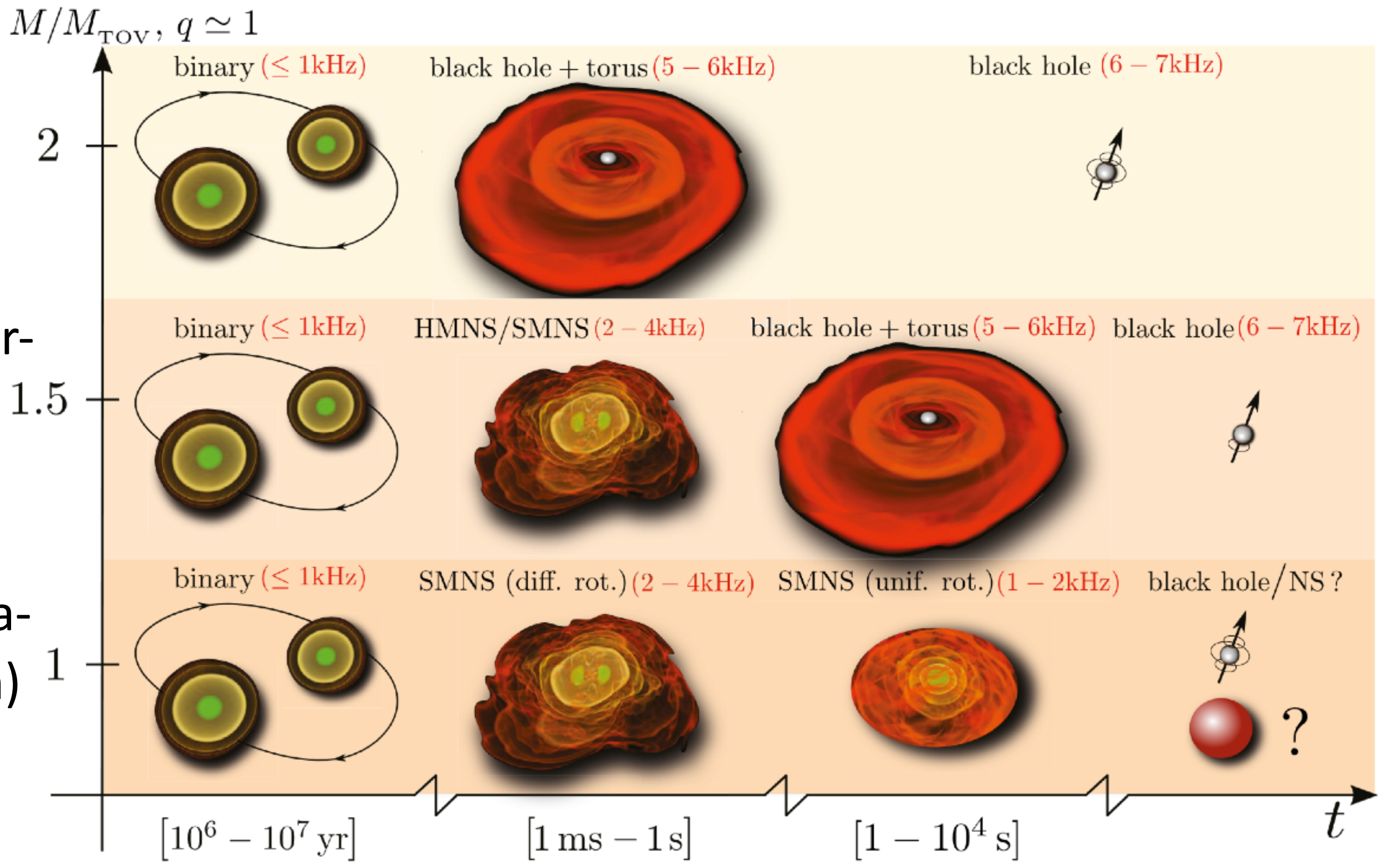
Ringdown pattern: Unlike in BH mergers, binary NS mergers expected to feature complex period of relaxation characterized by GW spectrum sensitive to both initial NS masses and the EoS

Scenario 1: prompt collapse

Scenario 2: collapse during hyper-massive phase (differential rotation)

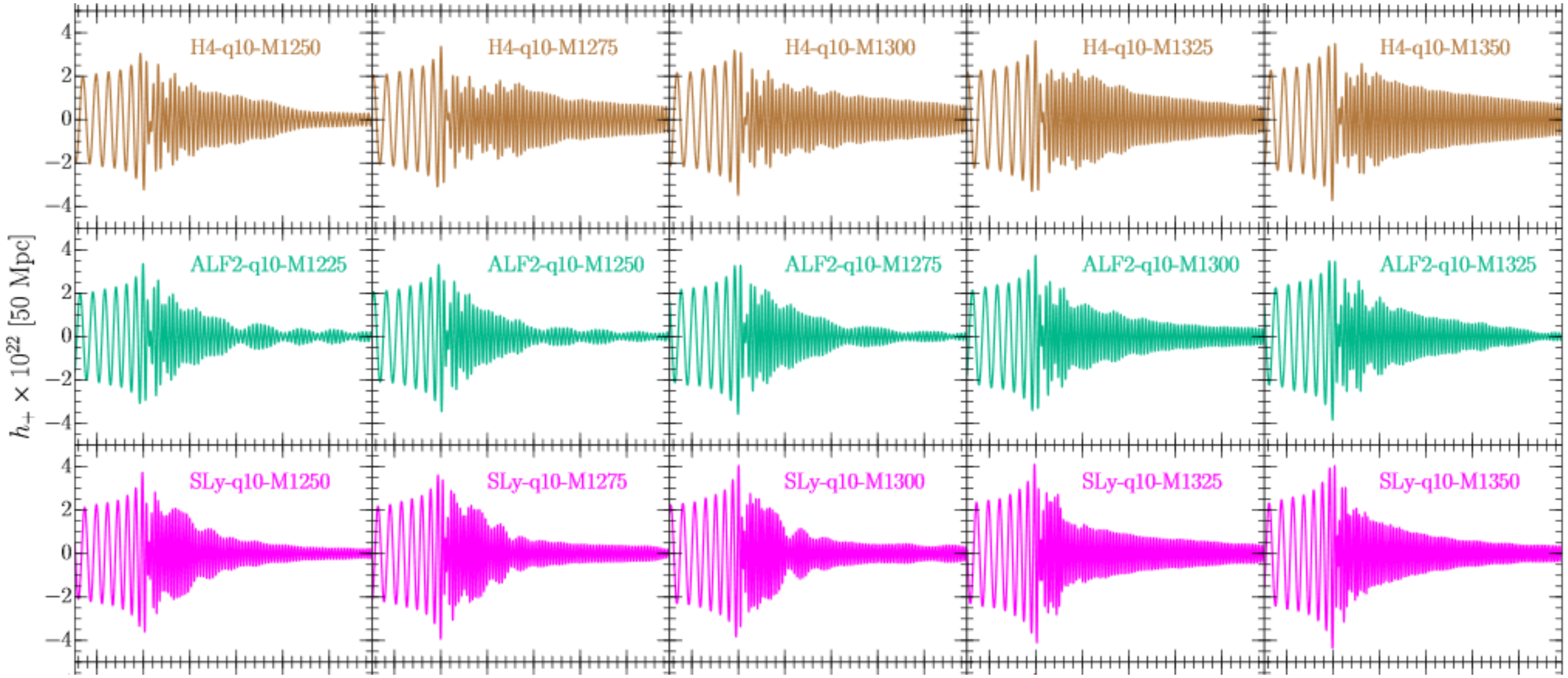
Scenario 3: collapse during supra-massive phase (uniform rotation)

Scenario 4: no collapse



[Baiotti, Rezzolla, Rept.Prog.Phys. 80 (2017)]

Post-merger dynamics can be studied with relativistic hydrodynamics simulations, showing marked sensitivity to first-order phase transitions, but frequency range (currently) too high for LIGO and Virgo



[Takami, Rezzolla, Baiotti, PRD 91 (2015)]

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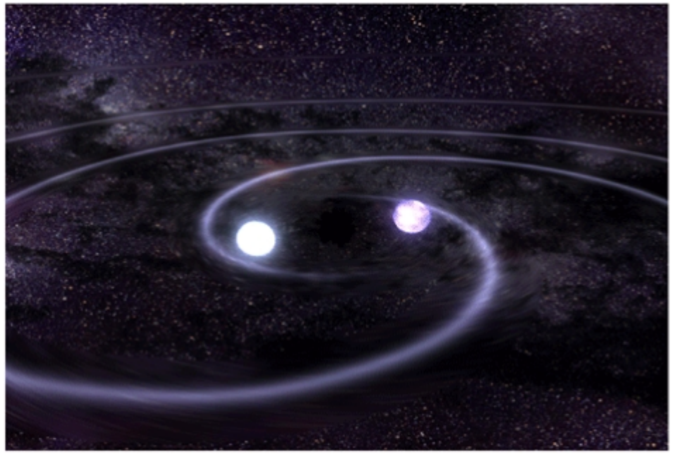

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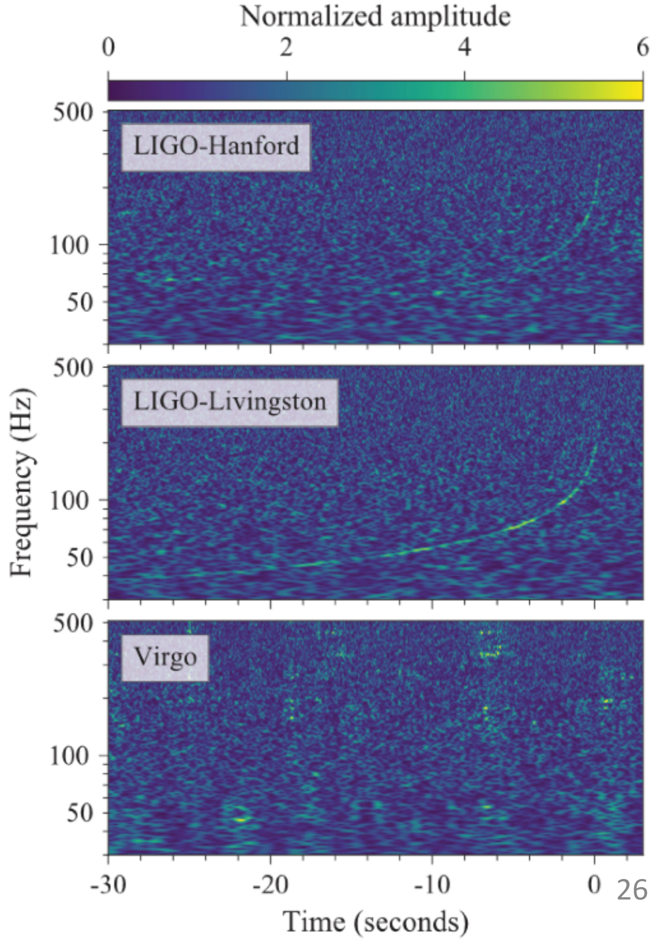
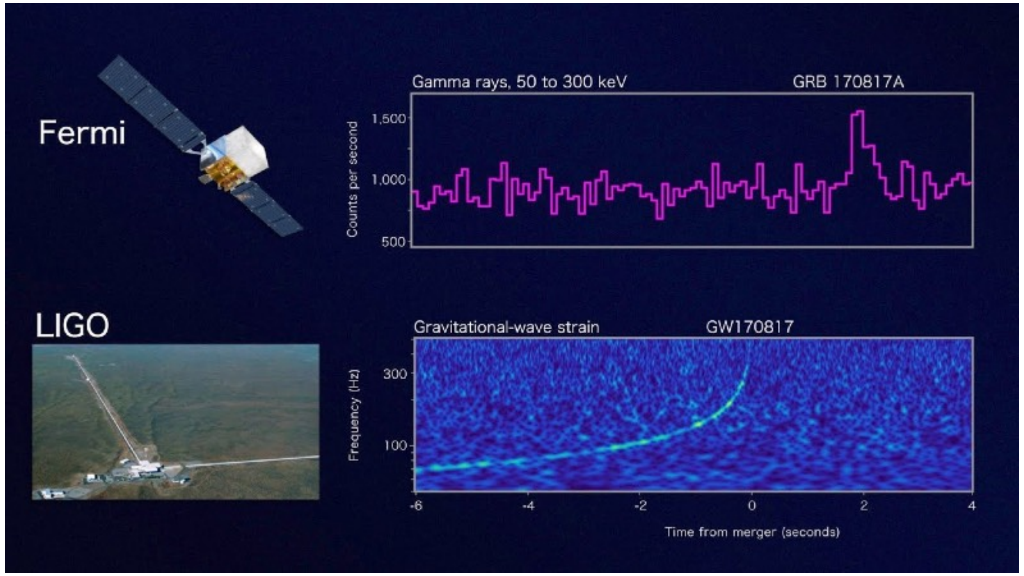
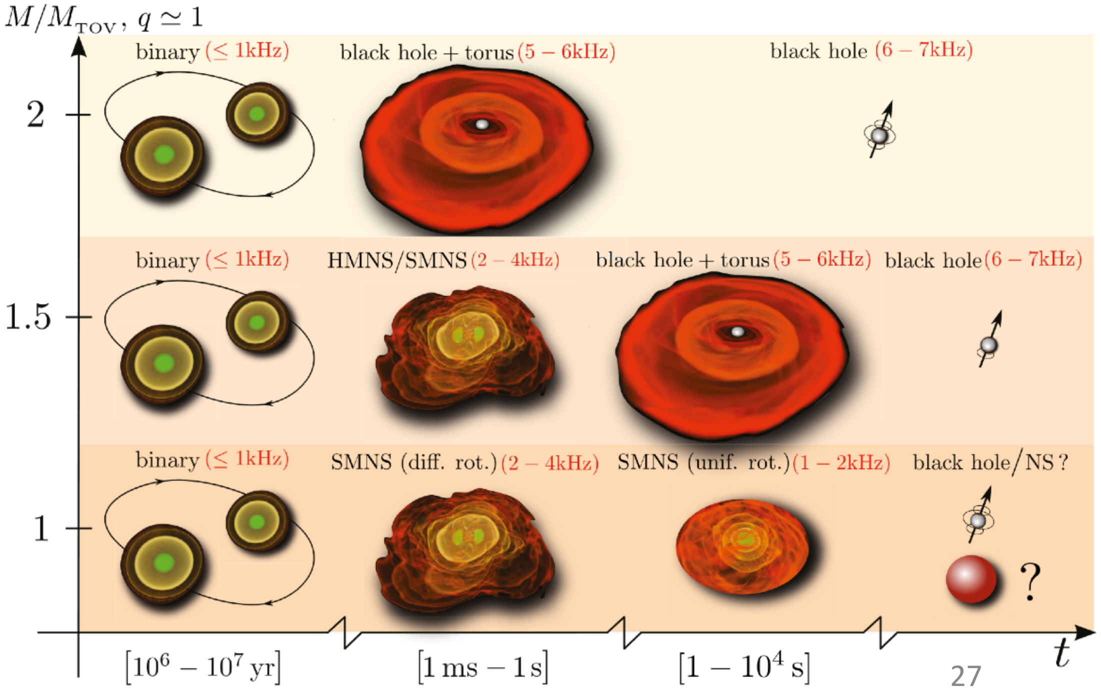


In GW170817, short gamma-ray burst 1.7s after GWs, followed by optical signal: Delayed collapse to a BH





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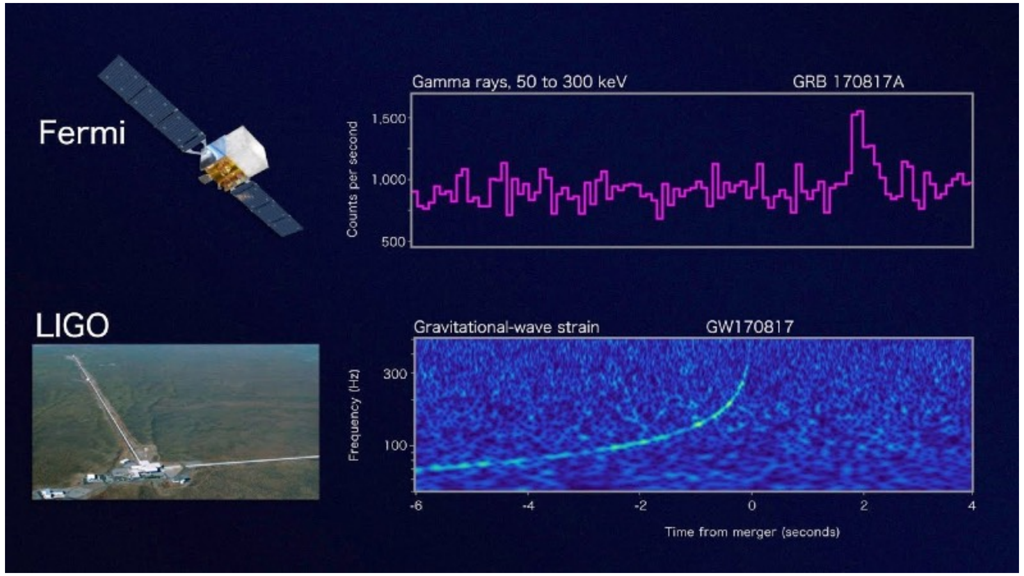
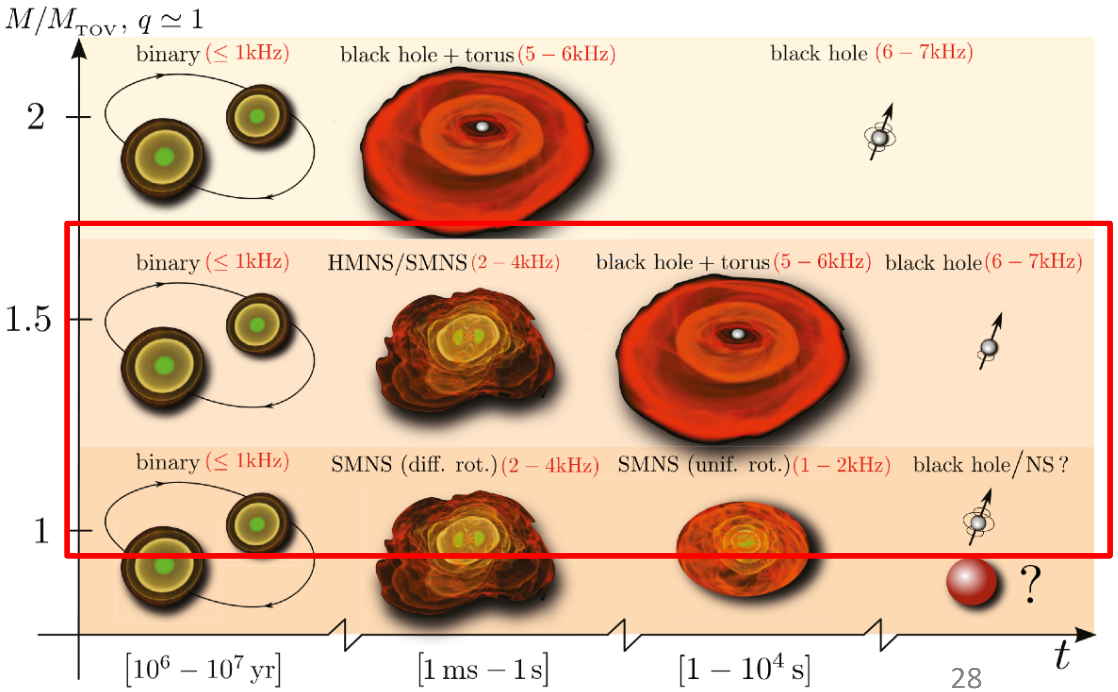


Constraints for maximal (TOV) mass of stable NSs from scenarios 2 and 3:

2) Differentially-rotating hypermassive NS: $M_{\rm remnant} \geq M_{\rm crit} = M_{\rm supra}$ (HMNS-hyp below)
3) Uniformly-rotating supramassive NS: $M_{\rm remnant} \geq M_{\rm crit} = M_{\rm TOV}$ (BH-hyp)



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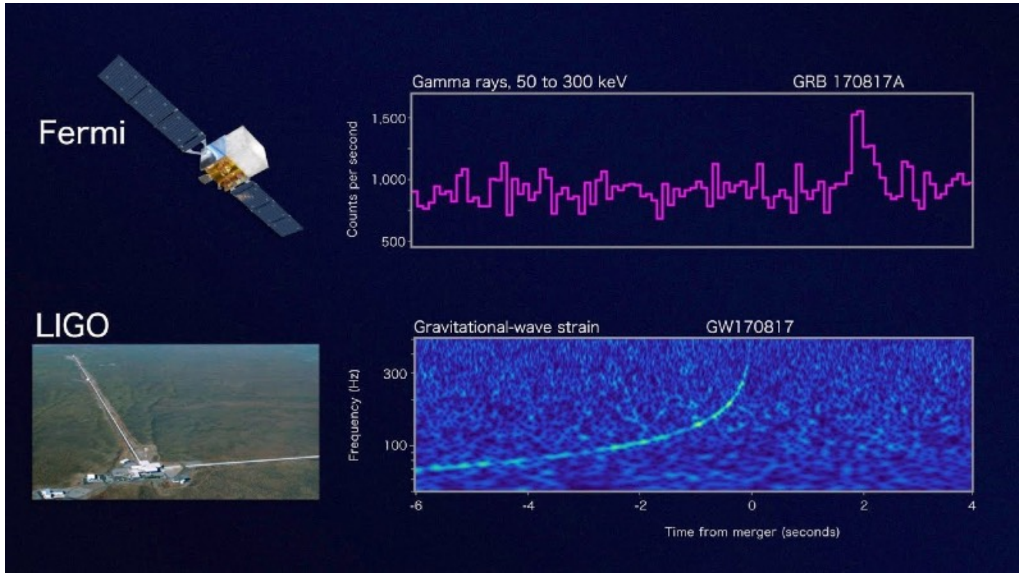

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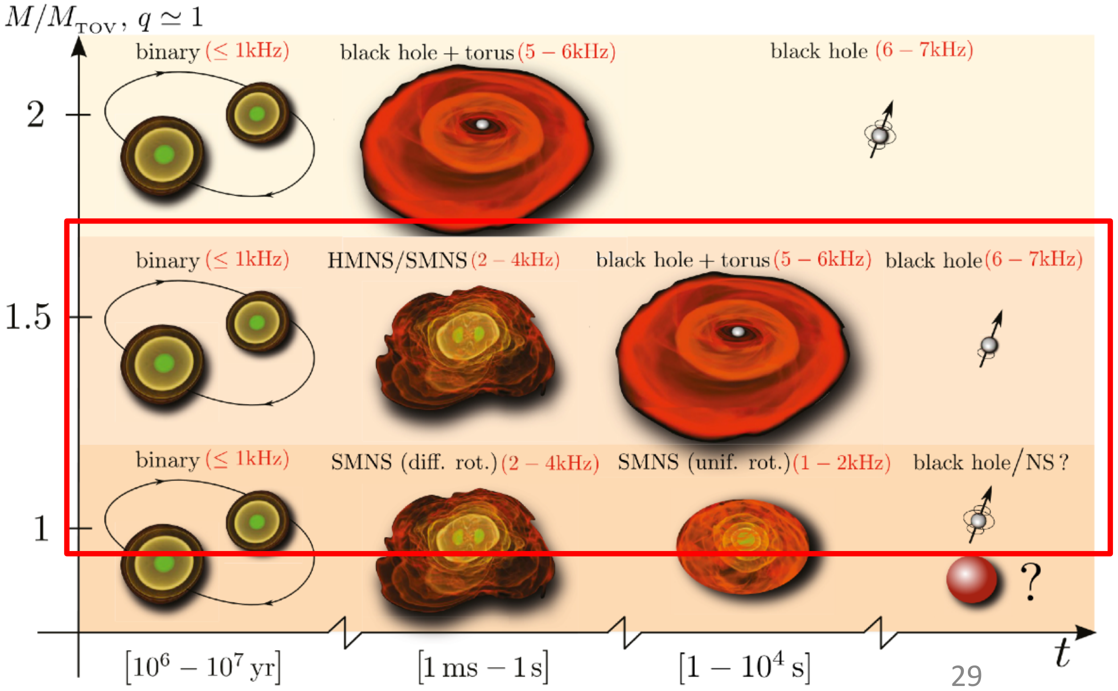
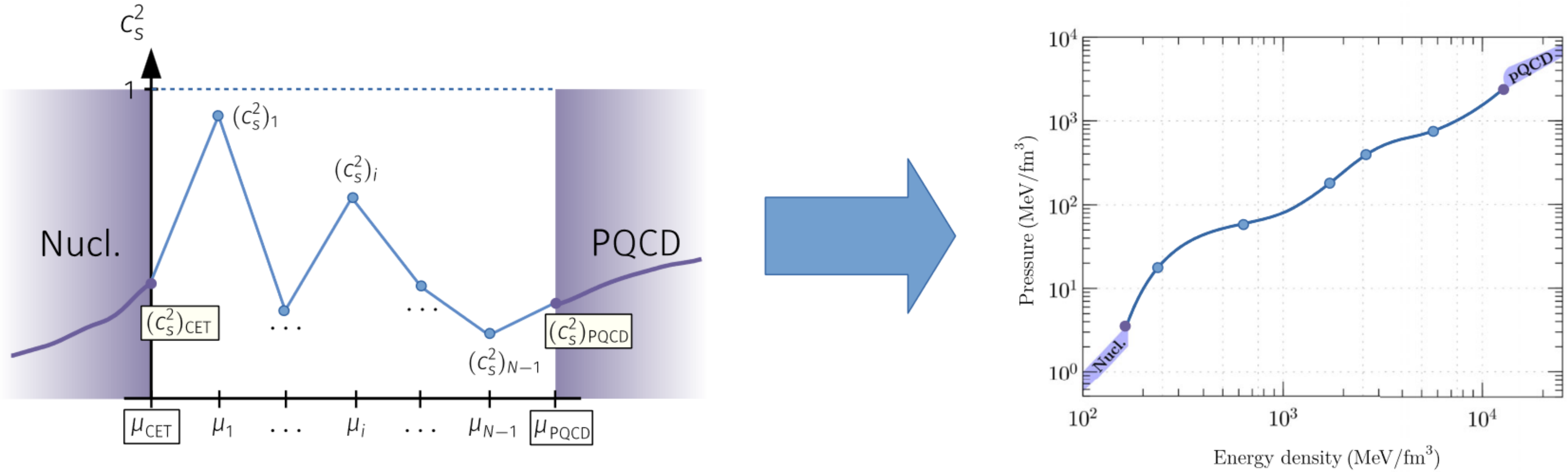
HMNS-scenario more likely due to short delay between GW and EM signals; gives stronger constraints [Rezzolla et al, ApJ 852 (2018)]



Interpolation: combining all available information, what can we say about the EoS?

Useful strategy: Implement interpolation starting from speed of sound and classify results in terms of maximal value c_s^2 reaches at any density [Annala et al., Nature Physics (2020) and PRX (2022)]



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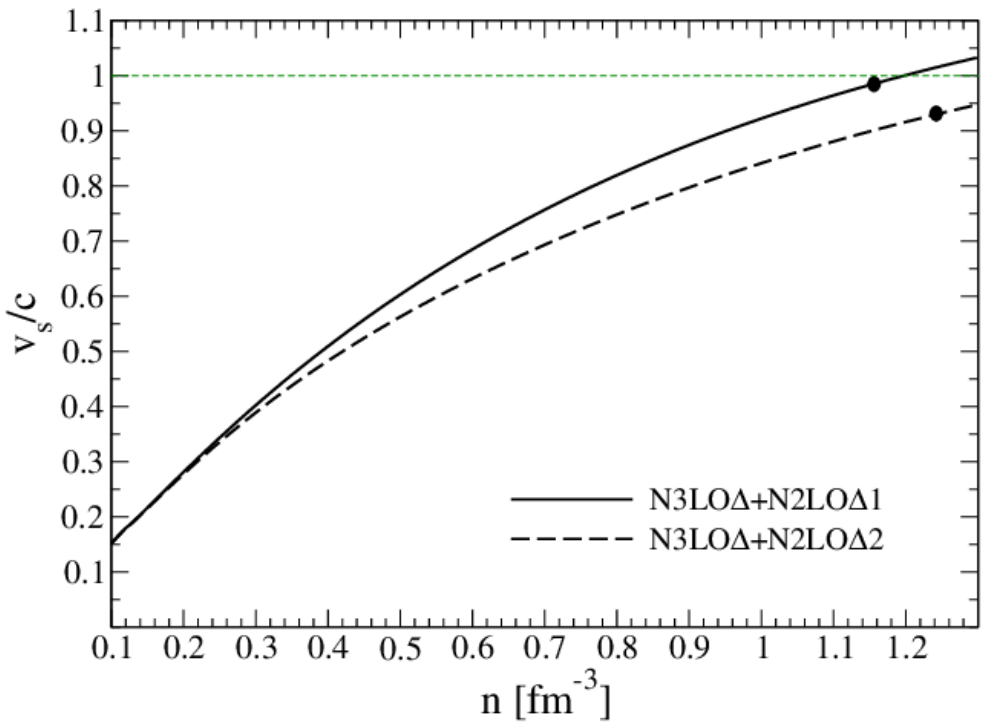
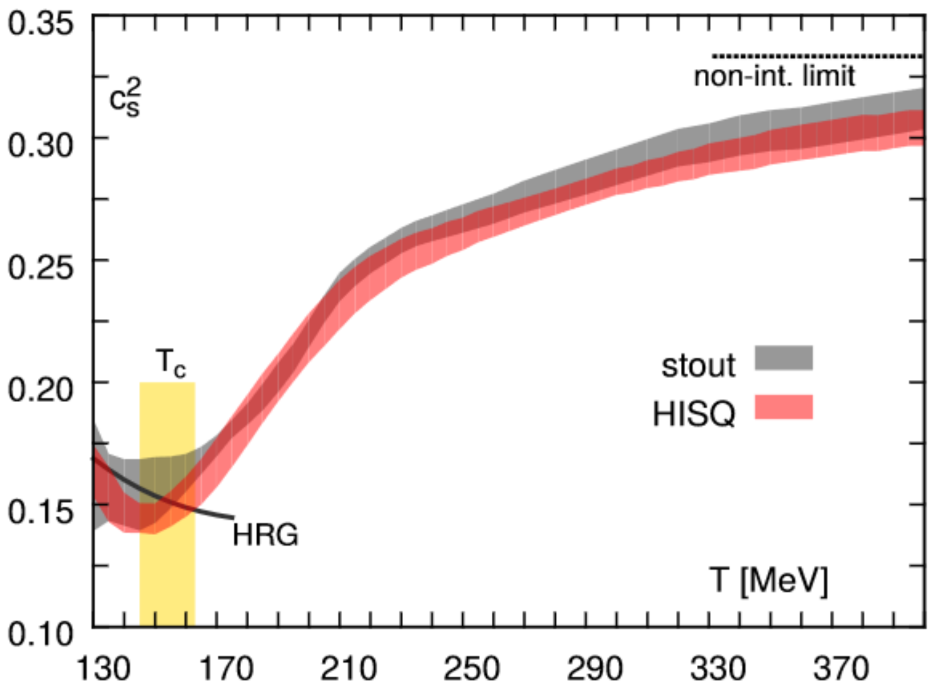
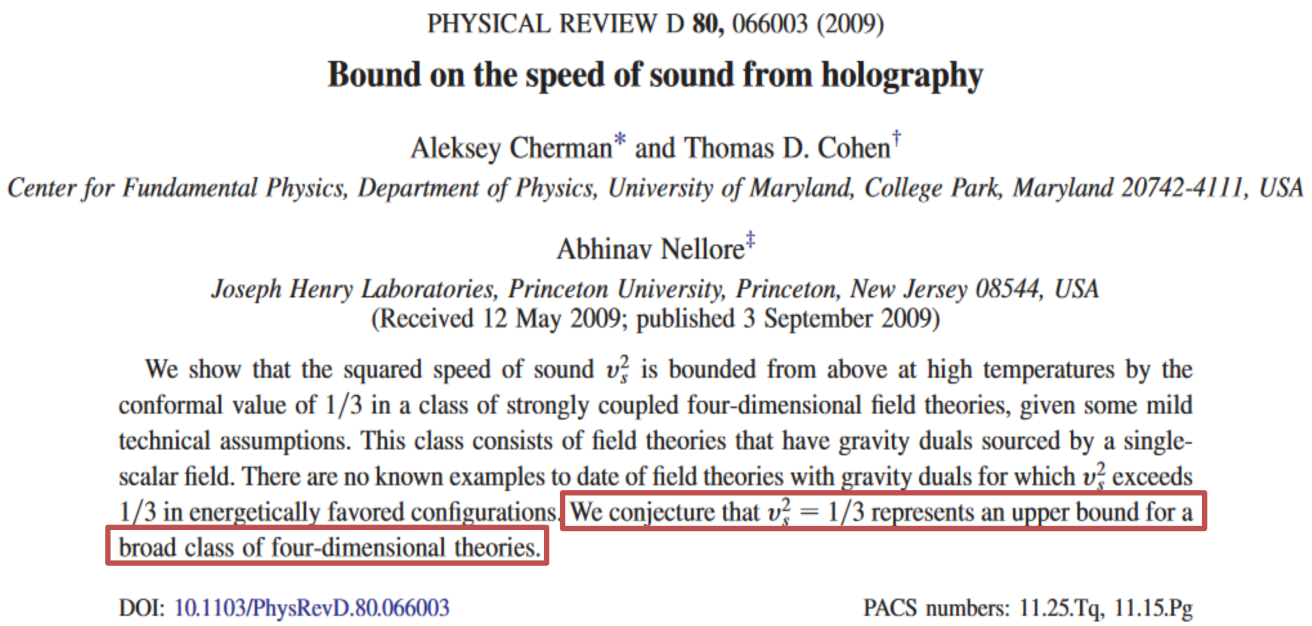
Interesting because of tension between standard lore in nuclear physics and experience from other contexts





Useful strategy: Implement interpolation starting from speed of sound and classify results in terms of maximal value c_s^2 reaches at any density [Annala et al., Nature Physics (2020) and PRX (2022)]

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

Aleksey Cherman* and Thomas D. Cohen†

Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, Maryland 20742-4111, USA

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(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.

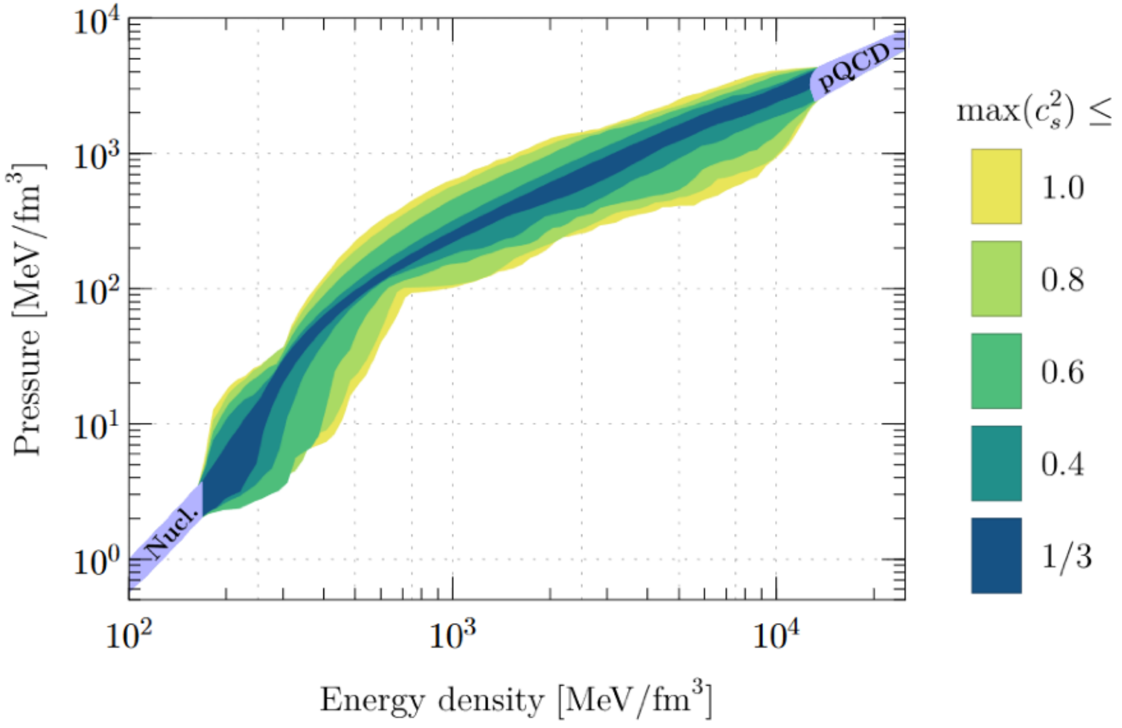
DOI: 10.1103/PhysRevD.80.066003

PACS numbers: 11.25.Tq, 11.15.Pg

In addition to the usual low- and high-density limit, always require:

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

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



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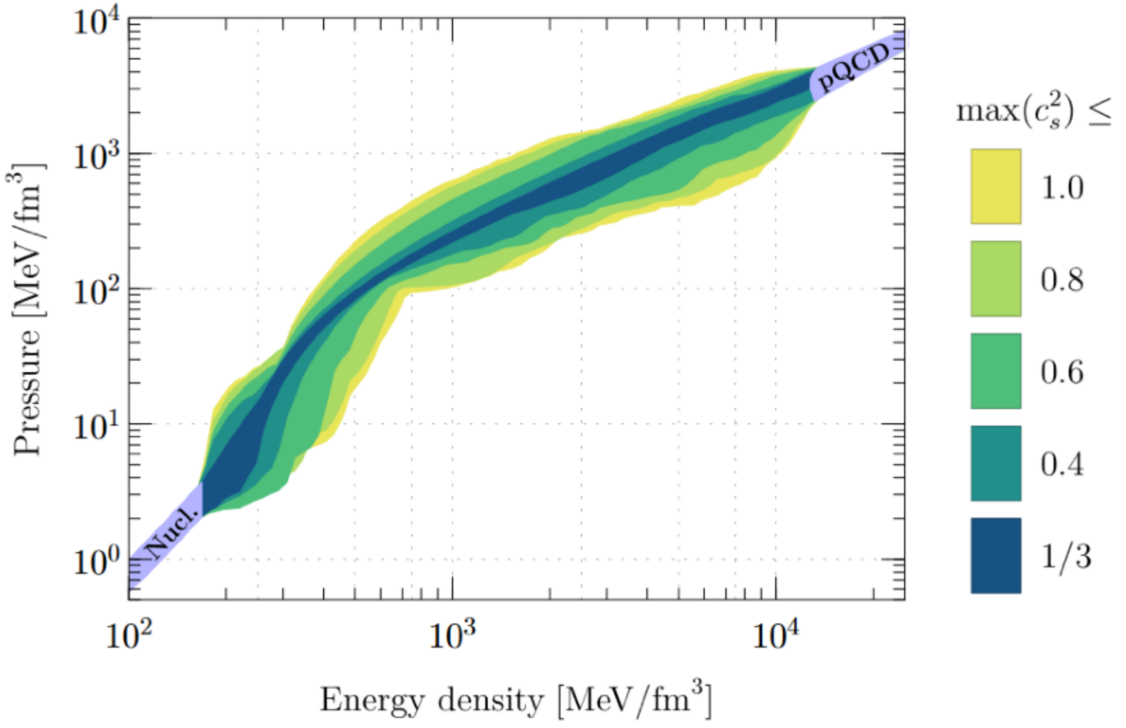

In recent work, also take into account:

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

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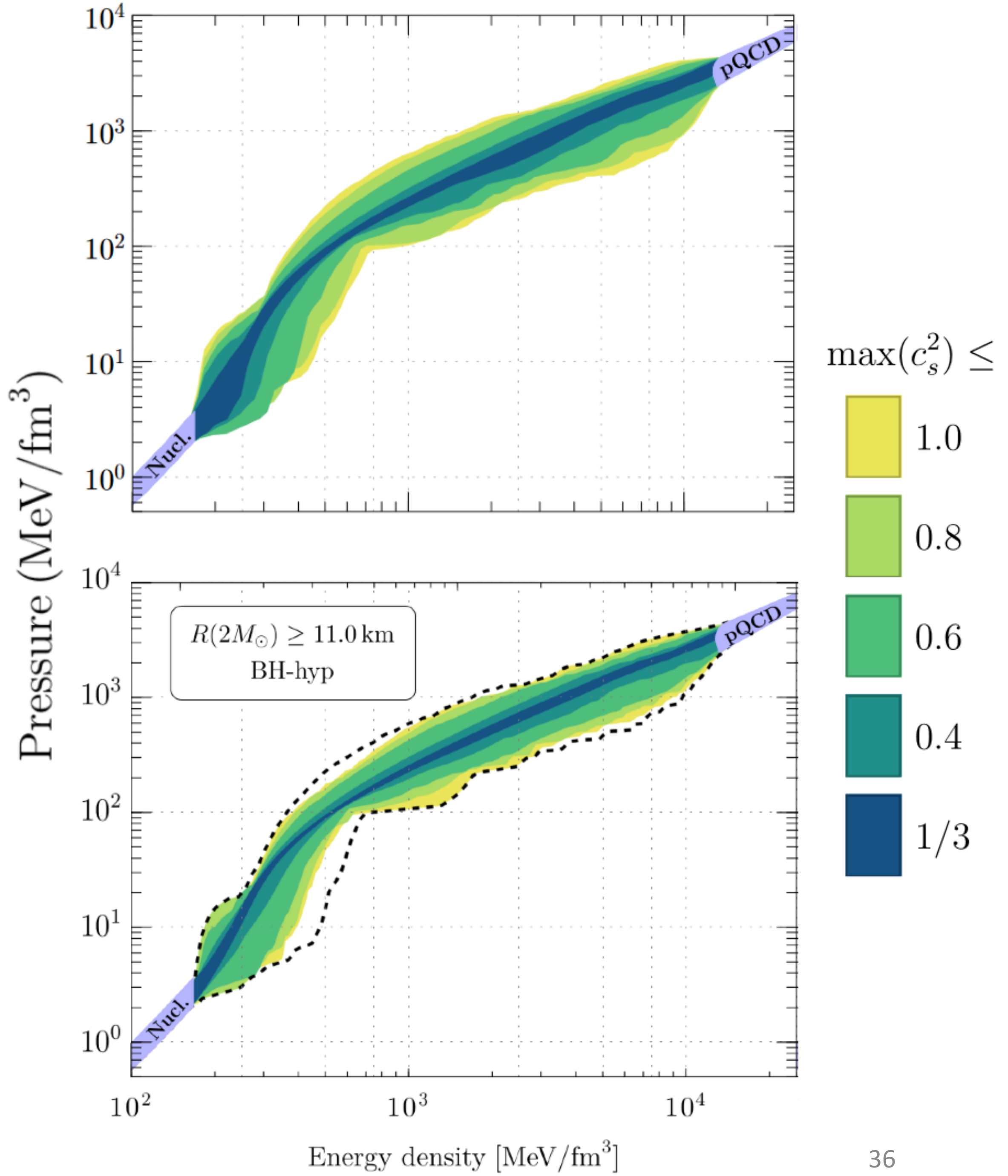

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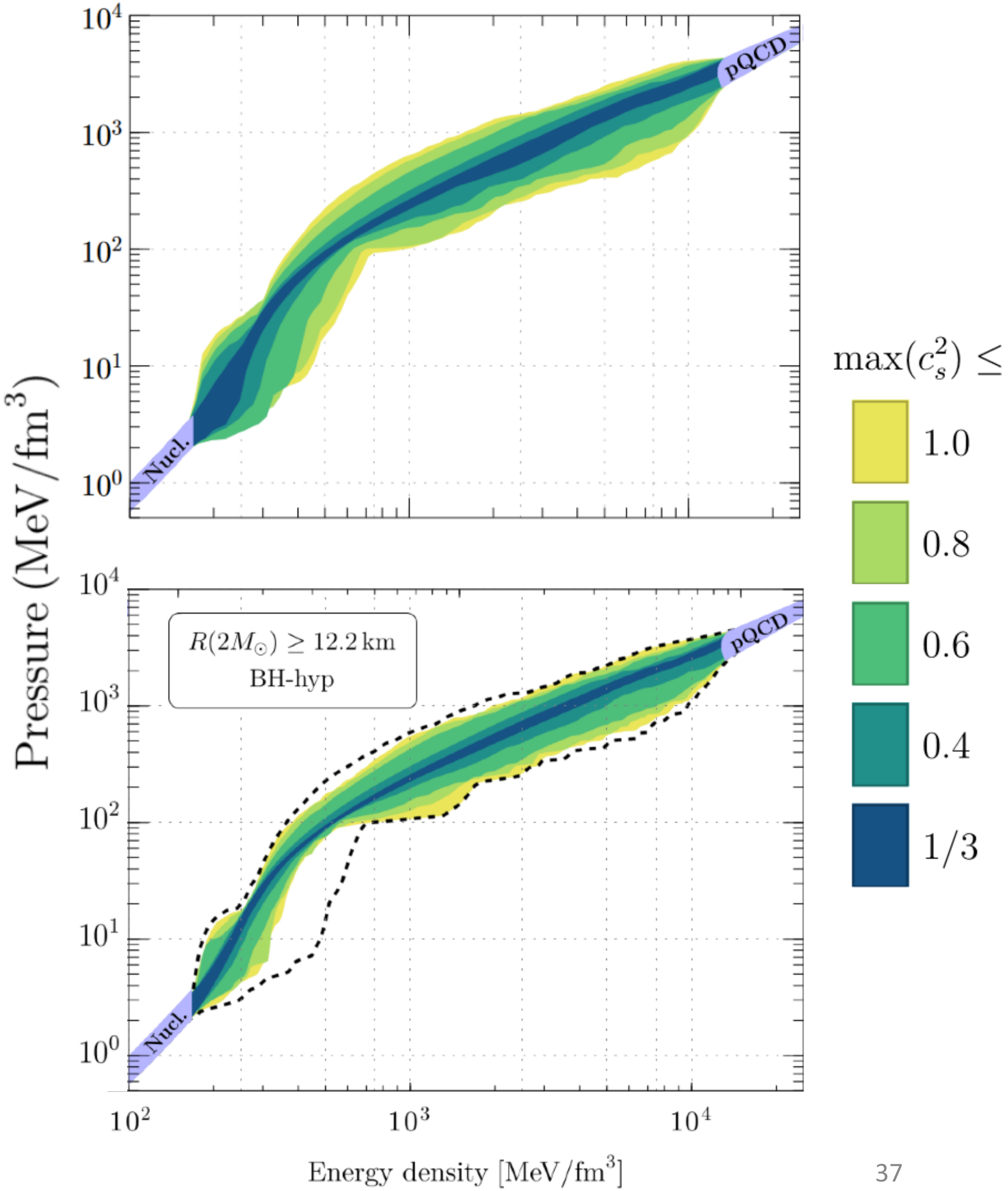

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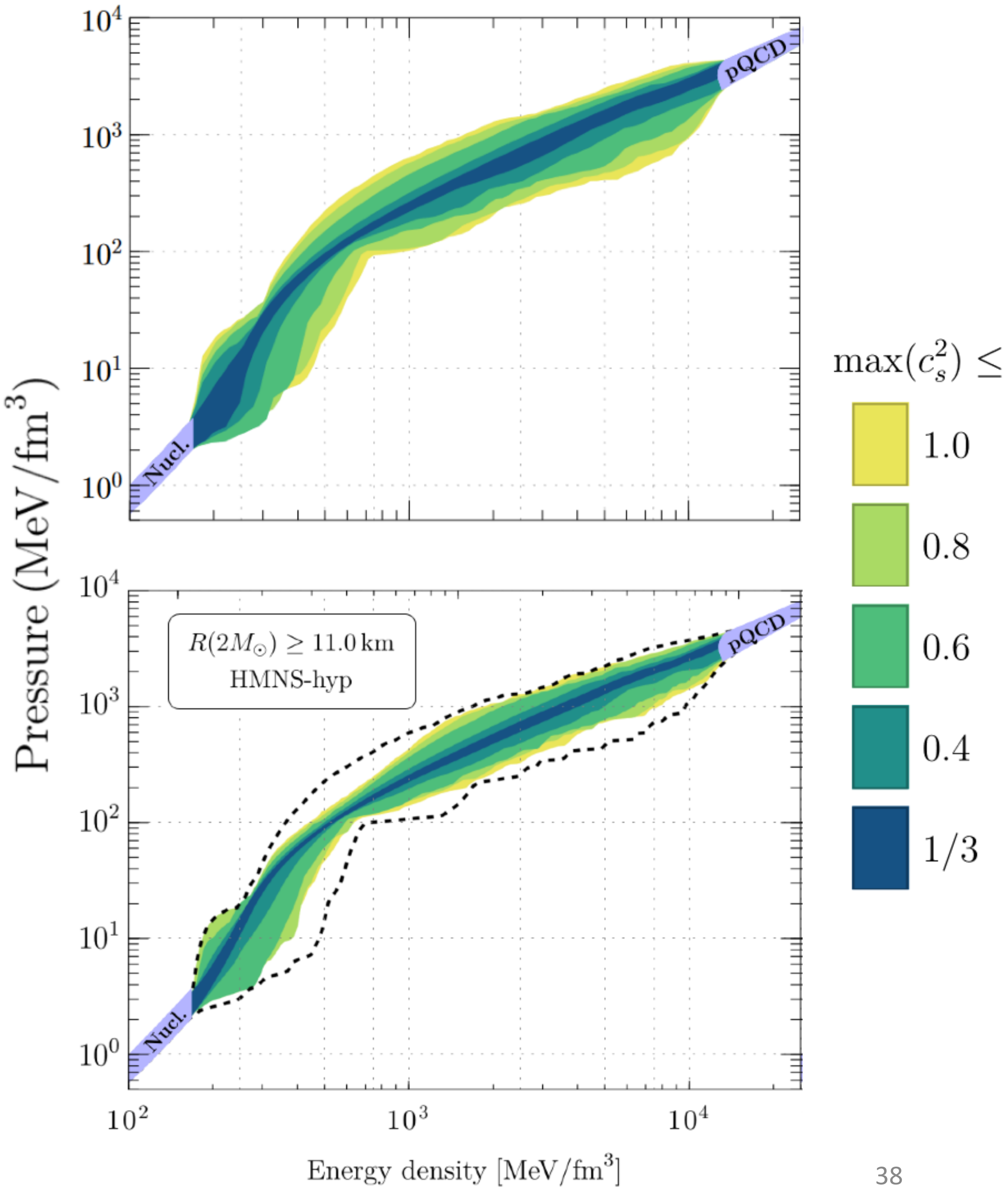

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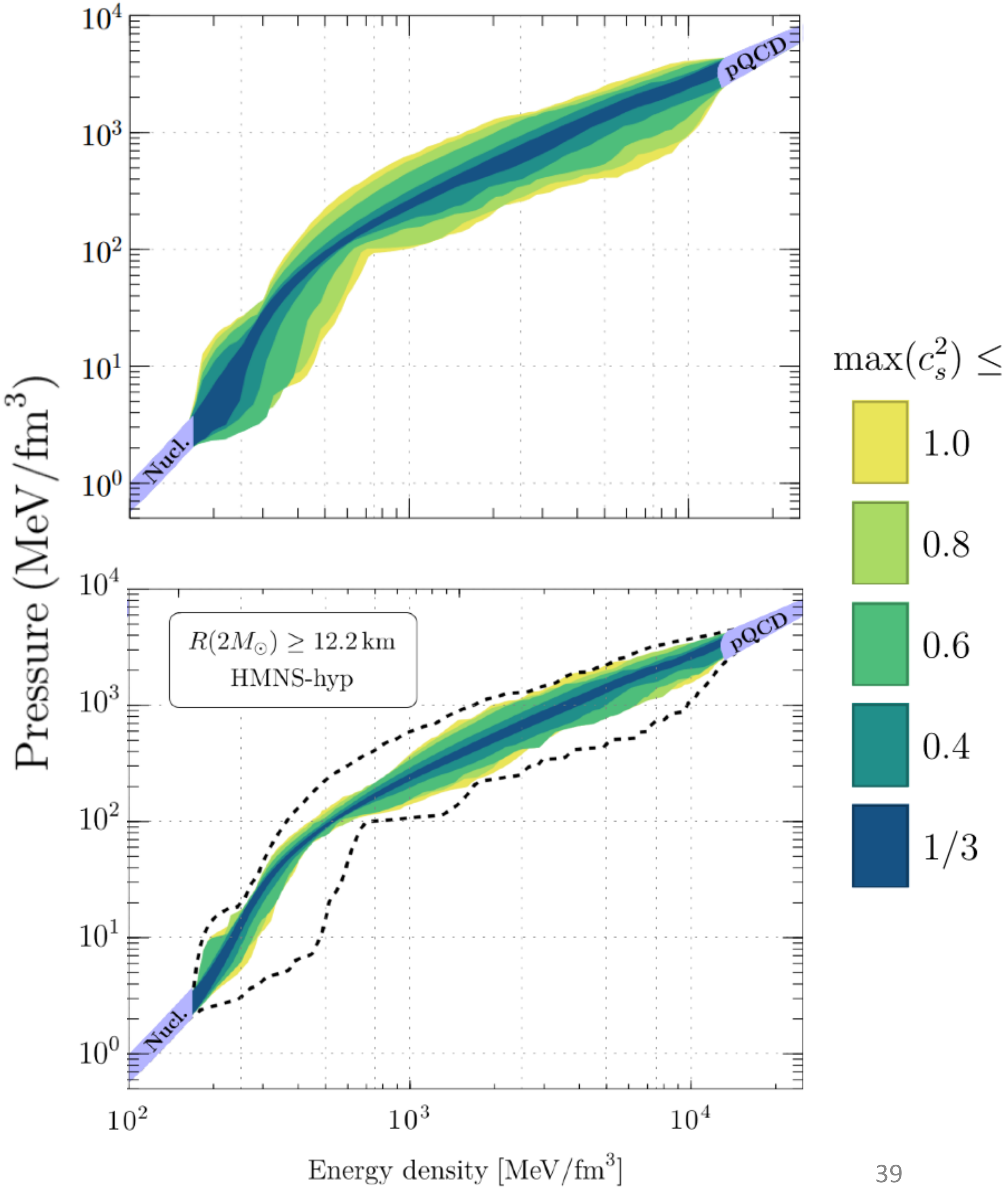
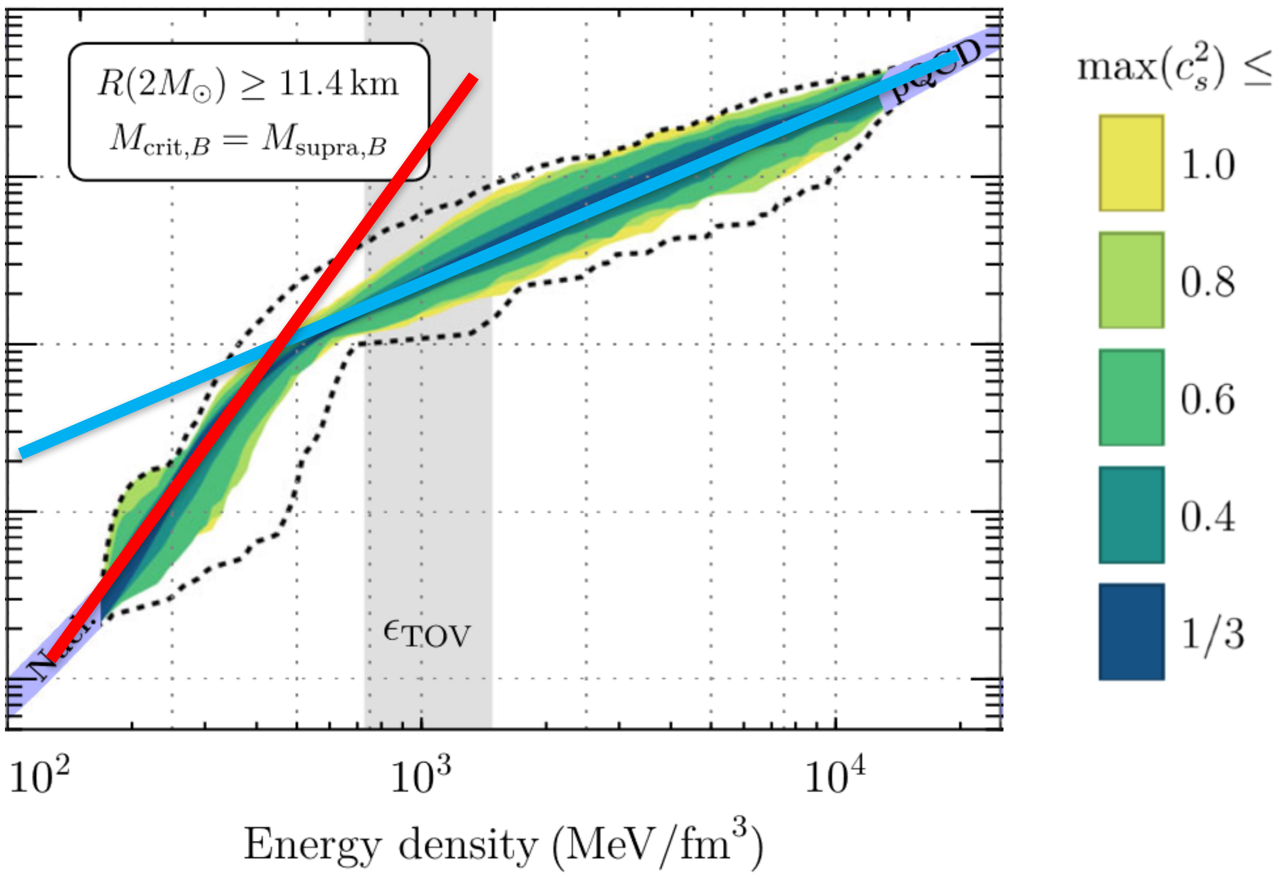


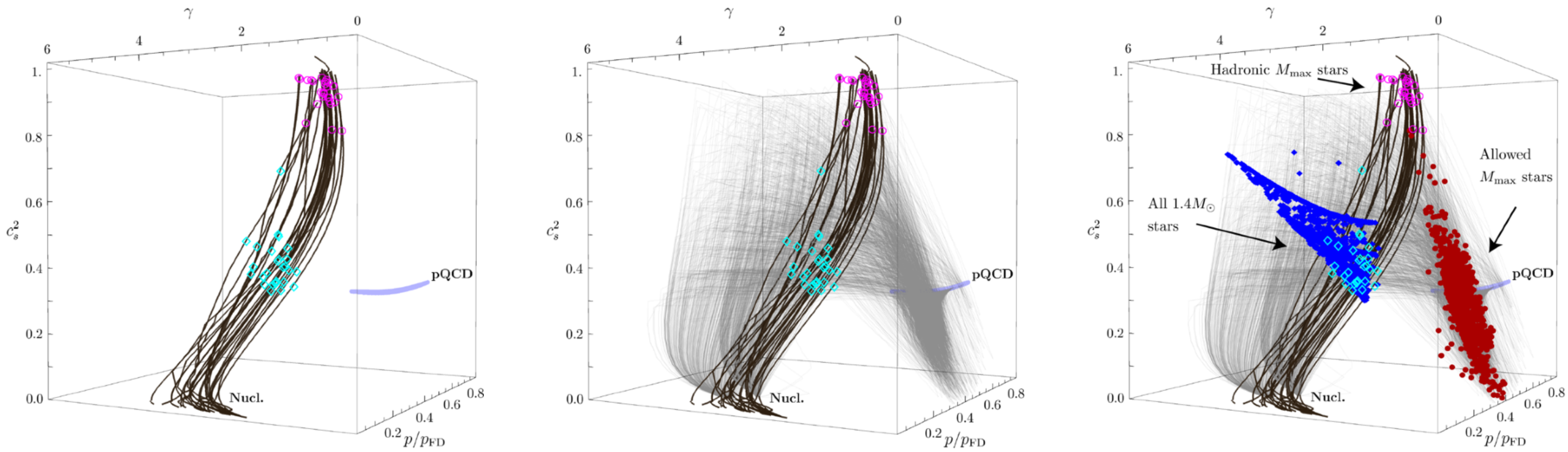


In particular the low-c_s EoSs strongly suggest a two-phase structure

Distinguishing feature between phases: polytropic index (logarithm. slope)

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

What about the phase of matter: can we make the EoS observation more quantitative and robust?



Detailed comparison of interpolated EoSs with nuclear matter models and pQCD limit reveals M_{max} centres to reside closer to quark than nuclear-matter limit. Large QM-like cores for moderate latent heats and max(c_s^2).

This conclusion was significantly strengthened by new data in our 2022 PRX.

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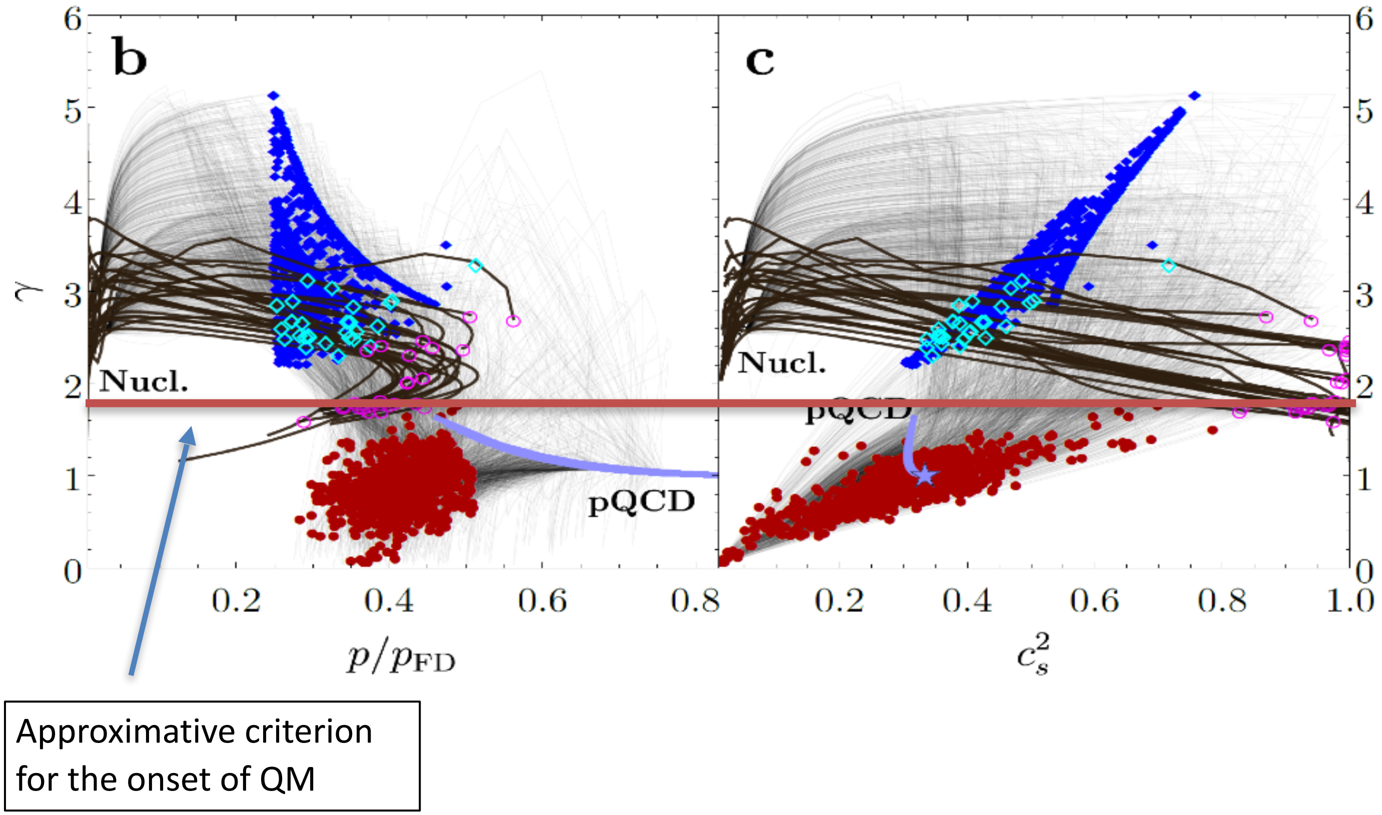

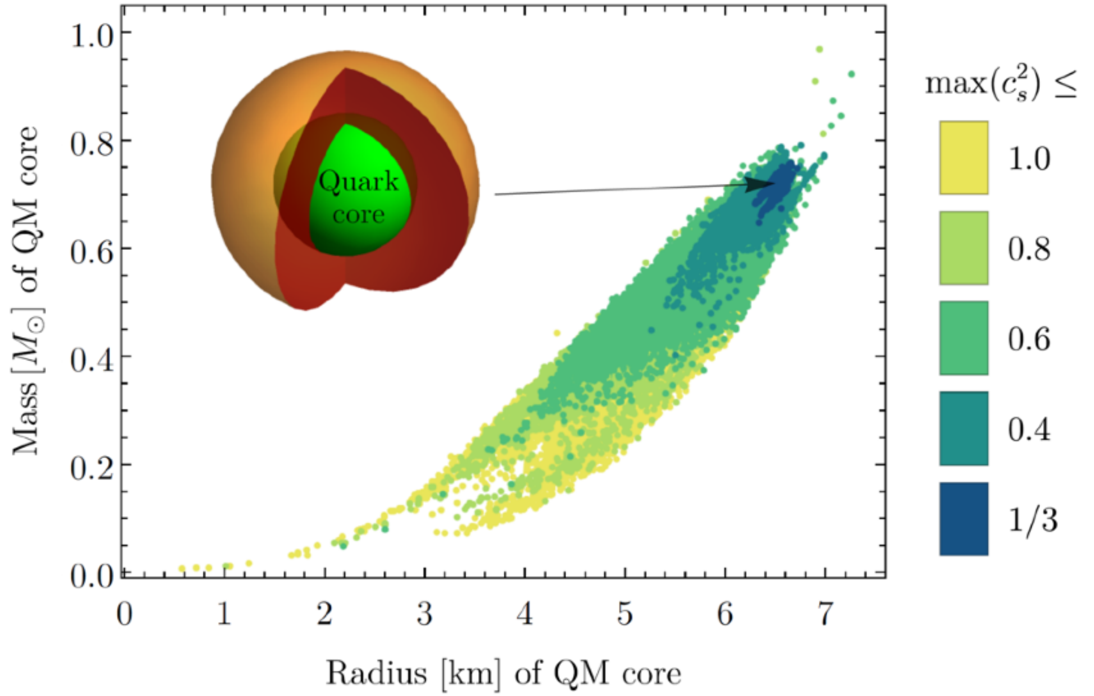

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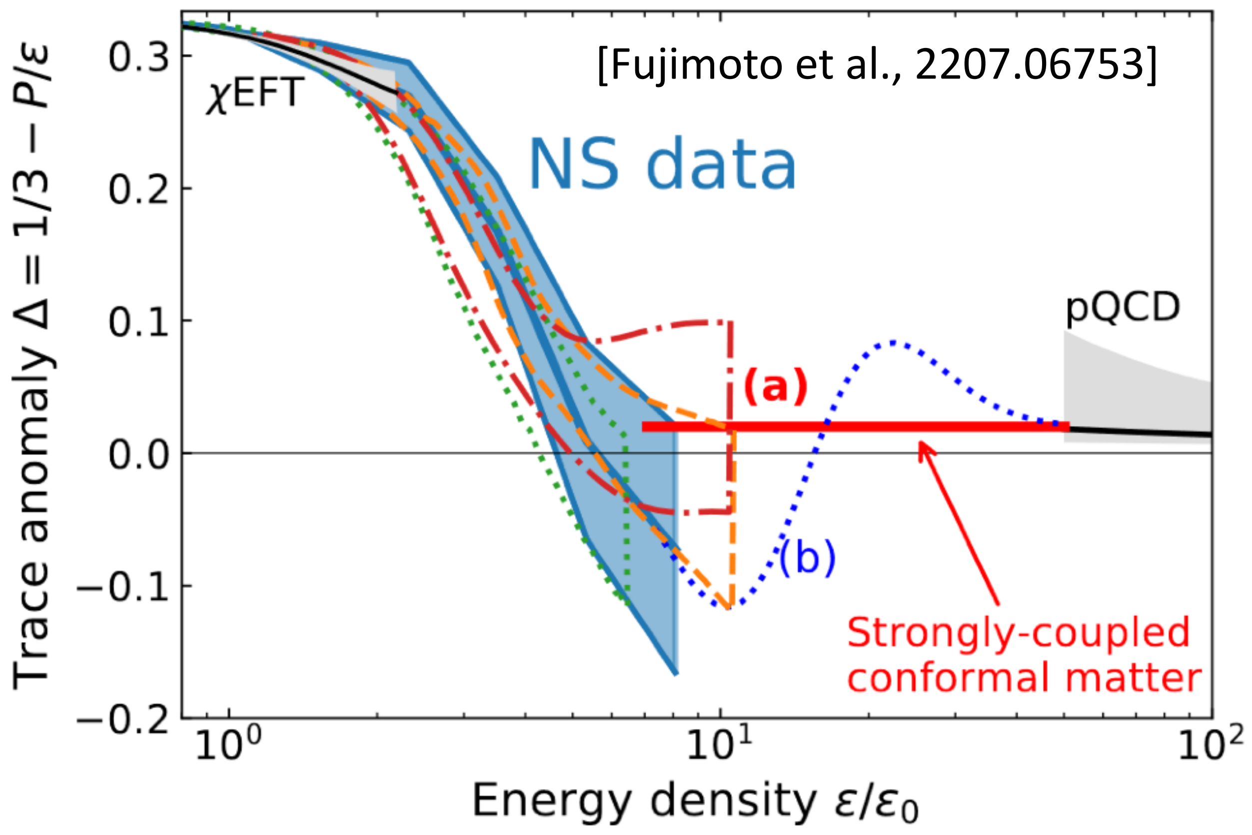
To improve further, must-do's:

1) Elevate studies from hard cutoffs to Bayesian framework, enabling usage of more observational data
2) In addition to interpolation, also apply nonparametric methods
3) Improve QM definition using also trace anomaly $\Delta \equiv \dfrac{\epsilon - 3p}{3\epsilon}$, useful measure of conformality



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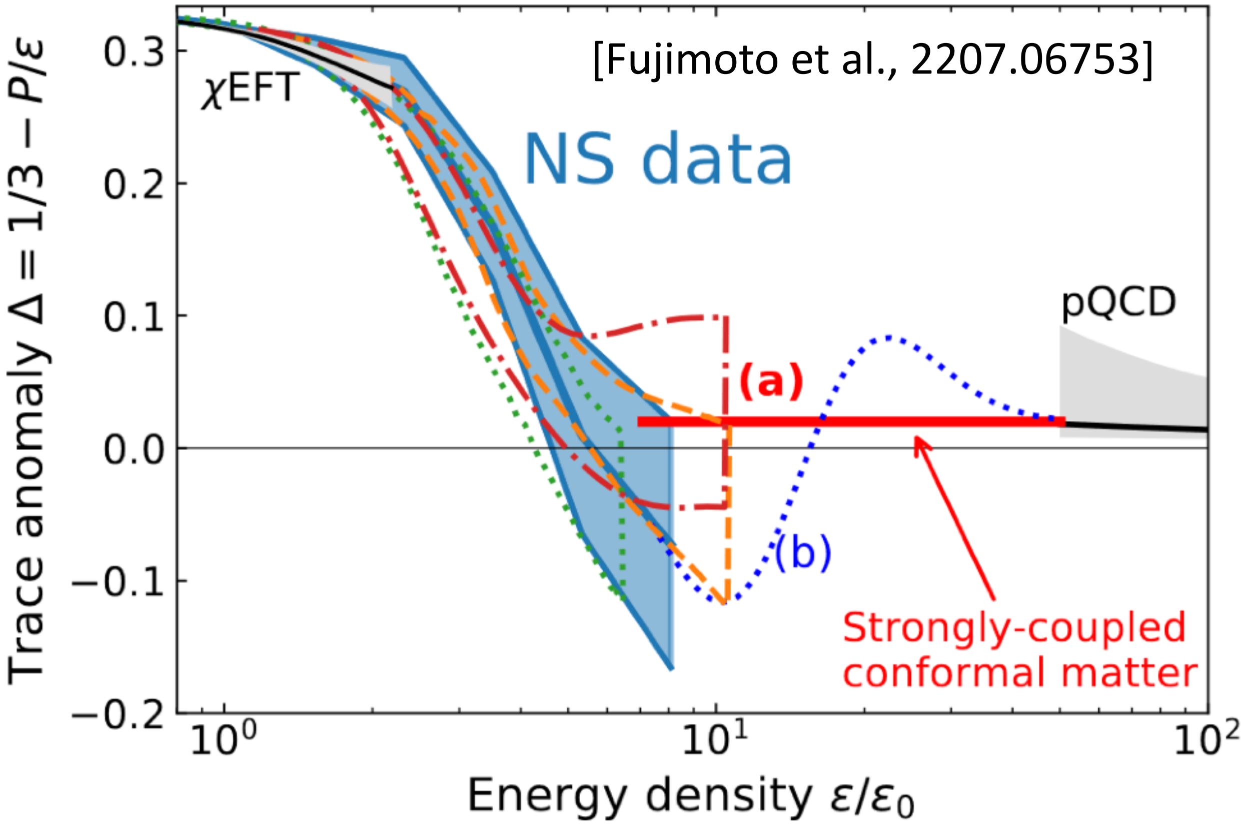
For near-conformal QM, demand:

- $0.2 < \gamma < 1.75$ (to exclude PTs)
- $|\Delta| < 1/6$ (again halfway point)

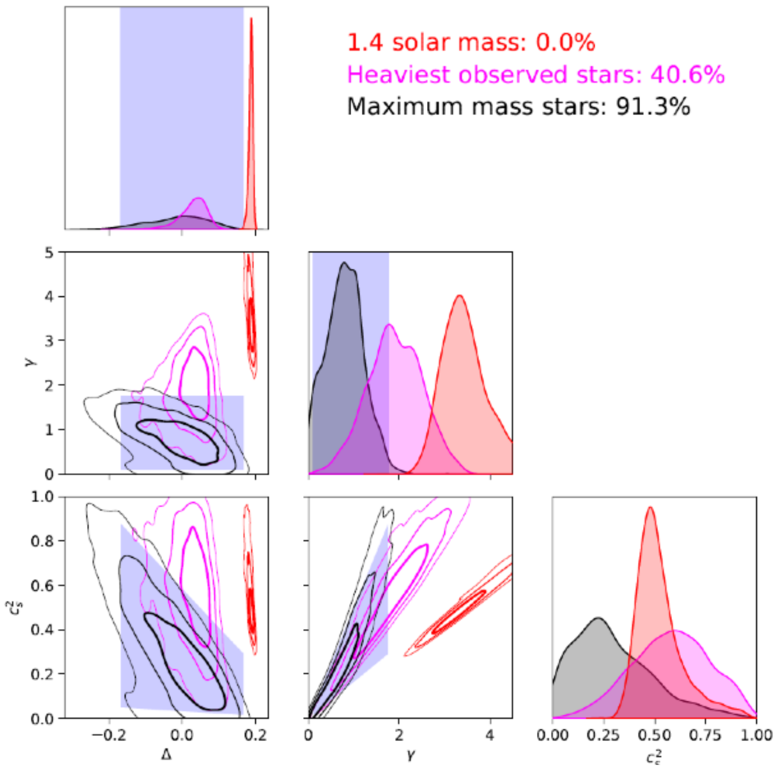


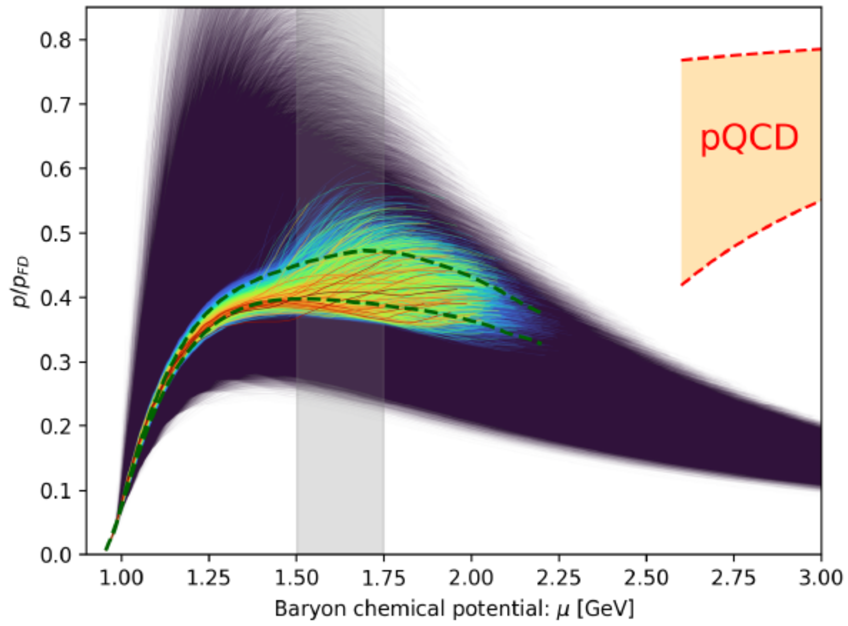
	Chiral EFT	Dense NM	CFTs	Pert. QM
Δ	$\approx 1/3$	$0.15 \cdots 0.3$	0	$0 \cdots 0.15$
γ	≈ 2.5	$\gtrsim 2$	1	$1 \cdots 1.7$
c_s^2	$\ll 1$	≈ 1	$1/3$	$\lesssim 1/3$
$p/p_{\rm FD}$	$\ll 1$	$0.2 \cdots 0.5$	Anything	$0.5 \cdots 1$

Preliminary results:

- Very likely existence of QM cores in maximal-mass stars, with extra assumption of $\Delta > 0$ taking likelihood close to 100%
- Perfect agreement between parametric interpol. and non-parametric Gaussian process method
- Effect of pQCD constraint important: softening of EoS at high densities, implying near-certain BH creation in GW170817 [Gorda et al, 2204.11877]
- Remaining caveat w/ QM cores (also at $\Delta > 0$): destabilizing strong first-order transition

[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, In preparation]





Future directions?

In near future, expect major advances from multiple fronts:

- Within CET, impressive efforts towards $2n_s$ limit
- In pQCD studies of cold QM, qualitative improvement from higher-order calculations and resummations in sight
- Astrophysical observations coming up:
  - GW observatory KAGRA operational since 2020; complemented by Einstein Telescope in 2030s
  - On X-ray front NICER to be complemented by eXTP ca. 2025
- Yet, no ab-initio methods for densities between 2 and $20n_s$
  - Transport and out-of-equilibrium dynamics major challenges; input needed from novel approaches such as holography