Neutron star interiors: model-independent lessons and unsolved problems

Aleksi Vuorinen

University of Helsinki & Helsinki Institute of Physics

Holography for Astrophysics and Cosmology

Nordita, 21 October 2022

Perturbative QCD at high density:

1) Gorda, Kurkela, Paatelainen, Säppi, AV, PRL 127 (2021), 2103.05658

2) Gorda, Kurkela, Österman, Paatelainen, Säppi, Schicho, Seppänen, AV, 2204.11893

Neutron-star applications:

3) Annala, Gorda, Kurkela, Nättilä, AV, Nature Phys. (2020), 1903.09121

4) Annala, Gorda, Katerini, Kurkela, Nättilä, Paschalidis, AV, PRX 12 (2022), 2105.05132

+ Ongoing work with AGKN & Hebeler, Hirvonen, Komoltsev, Schwenk

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

HELSINKI INSTITUTE OF PHYSICS

ACADEMY OF FINLAND

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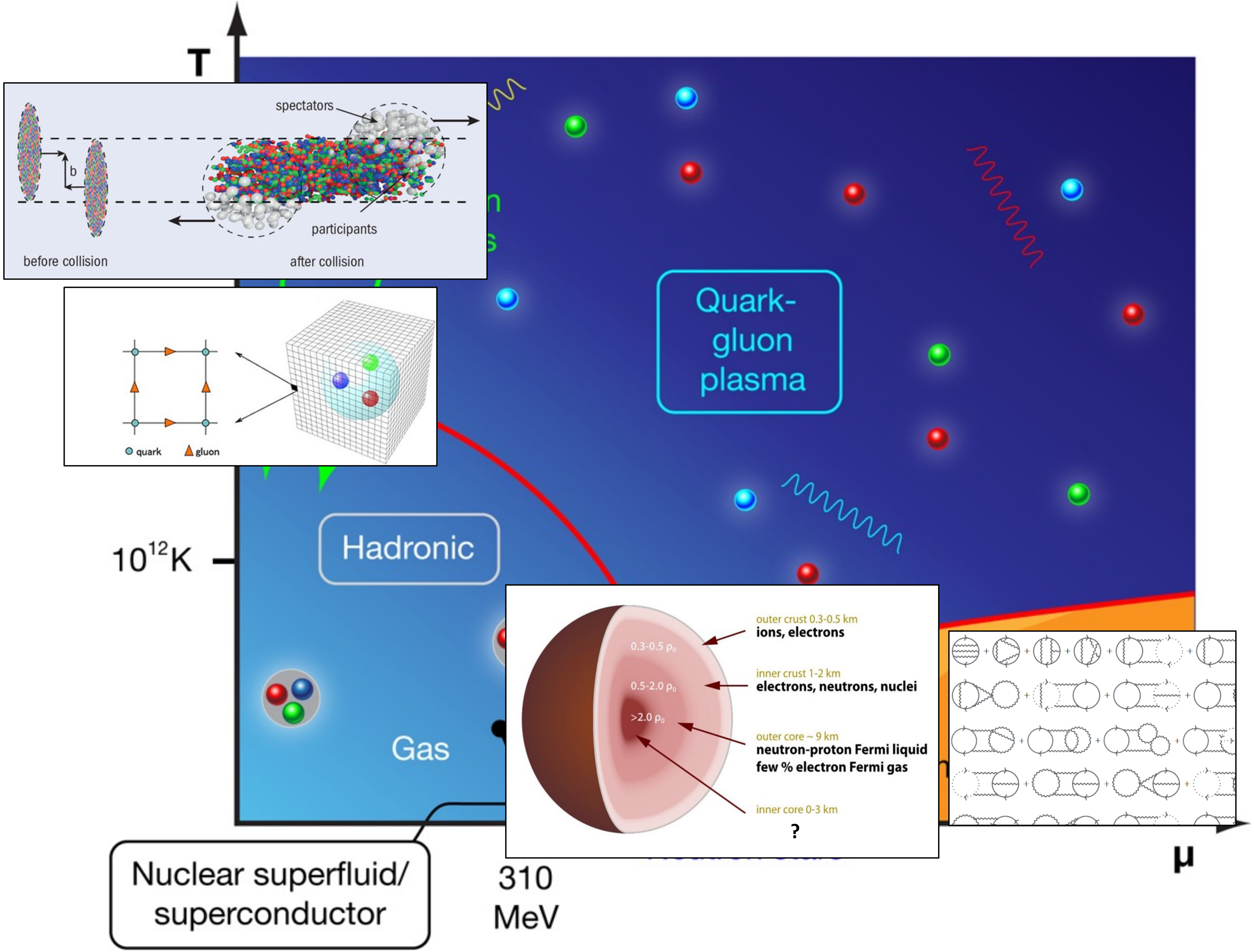
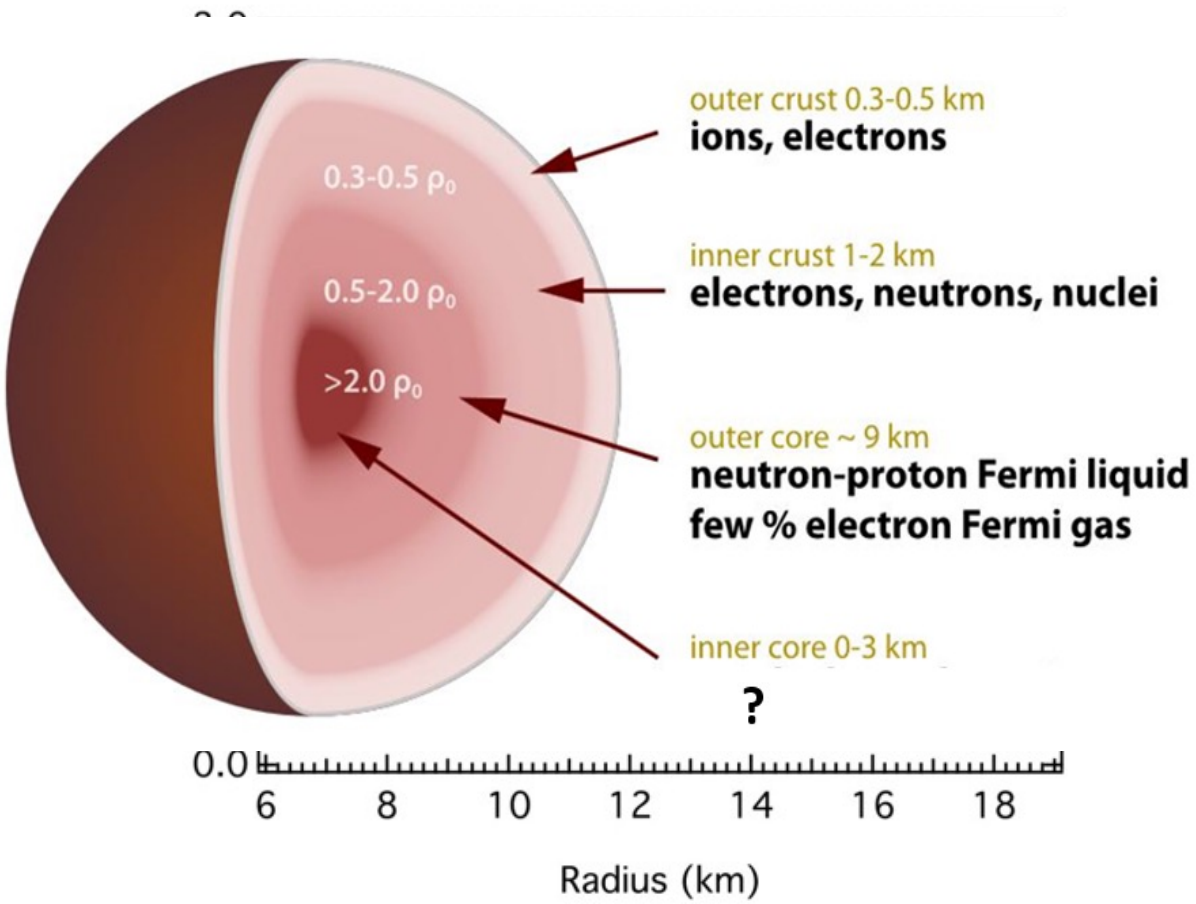

T
spectators
b
participants
before collision
after collision
quark
gluon
Quark-
gluon
plasma
10^{12}K
Hadronic
Gas
outer crust 0.3-0.5 km
ions, electrons
0.3-0.5 ρ_0
inner crust 1-2 km
electrons, neutrons, nuclei
0.5-2.0 ρ_0
>2.0 ρ_0
outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi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

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)]

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

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

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

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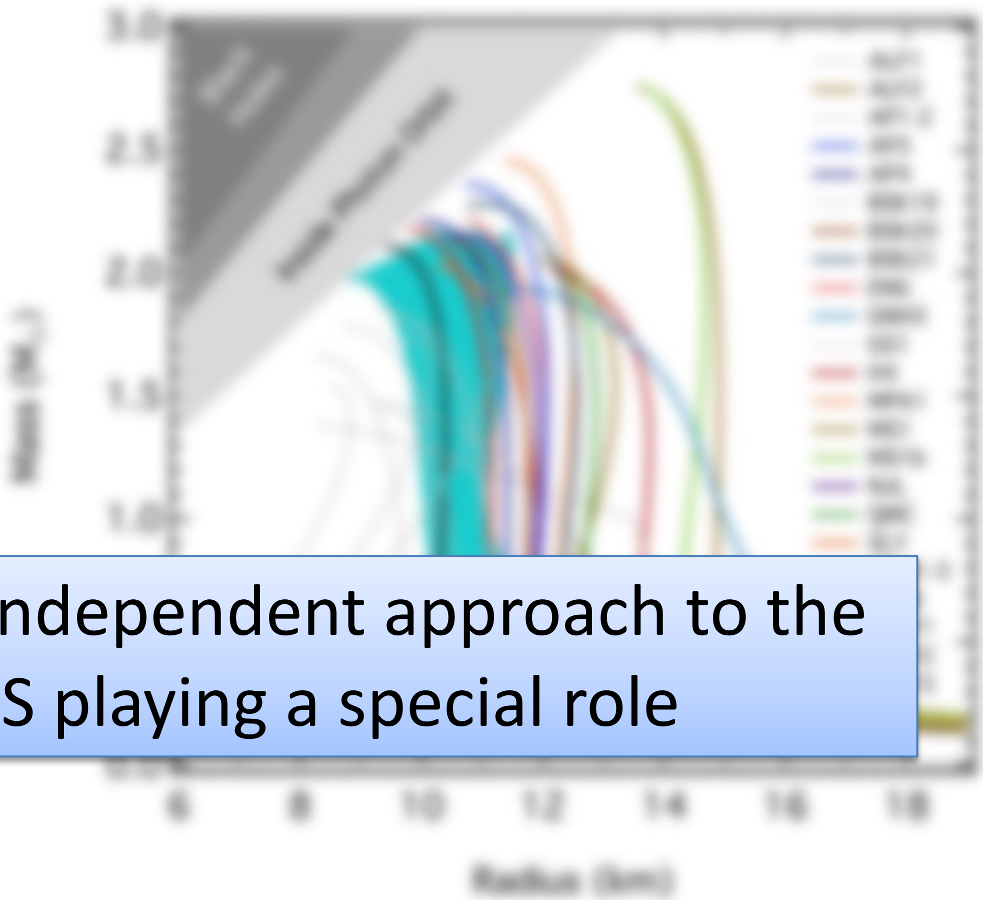

[Özel et al., ApJ 820 (2016)]

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

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

Rest of the talk:

I. NS matter basics: what do we know about the composition of NSs from nuclear physics?
II. Lessons from (ultra)high density: what can pQCD do for you?
III. NS observations: from masses and radii to NS mergers
IV. Putting it all together: how far can model-independent approaches take us right now?
V. Future directions: what is to be expected in near future?

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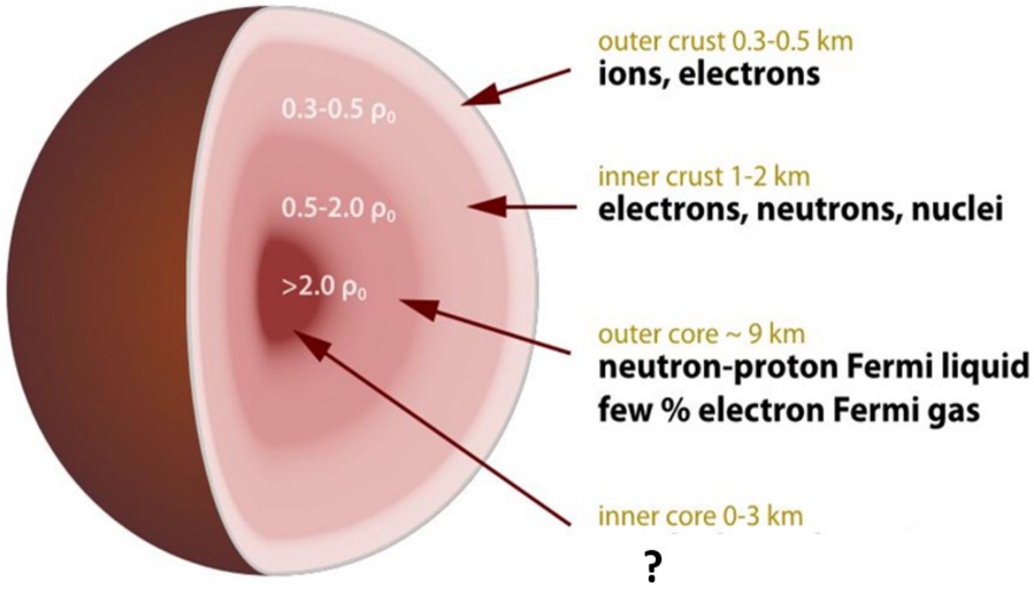
Recurring theme: where can holography make a difference?
Please interrupt with questions and comments!

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: $T \approx 0 \approx n_Q$



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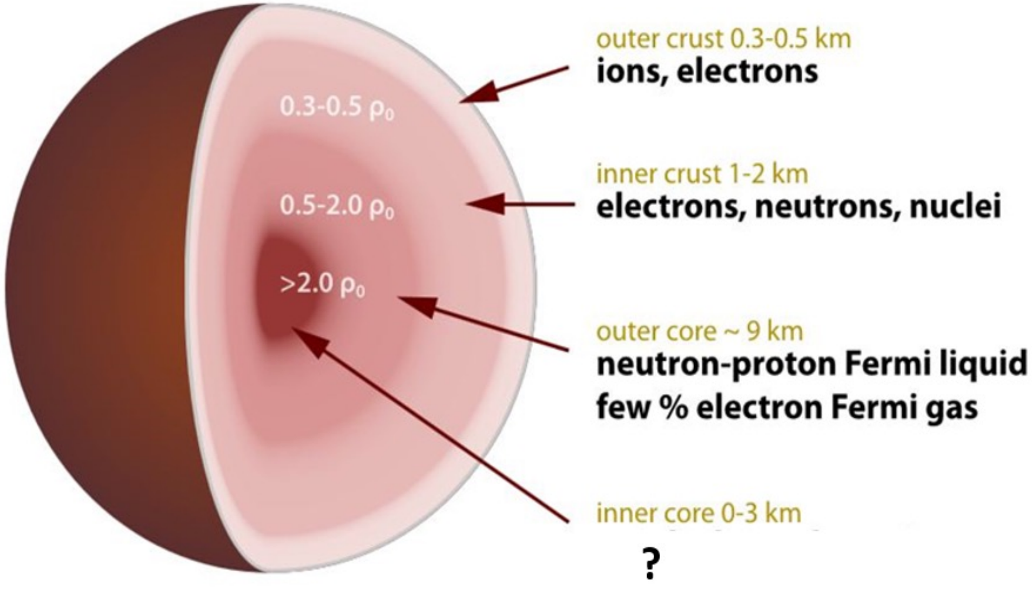
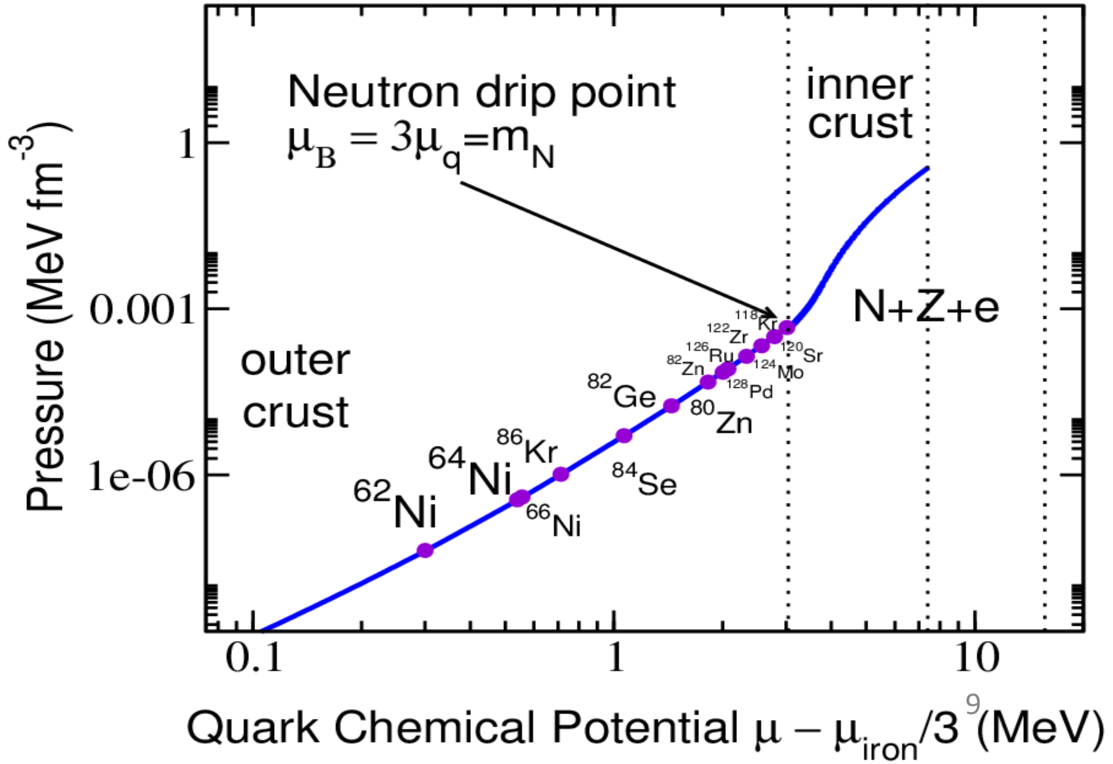
Beyond neutron drip point NN interactions important; then 3Ns, boost corrections, etc.





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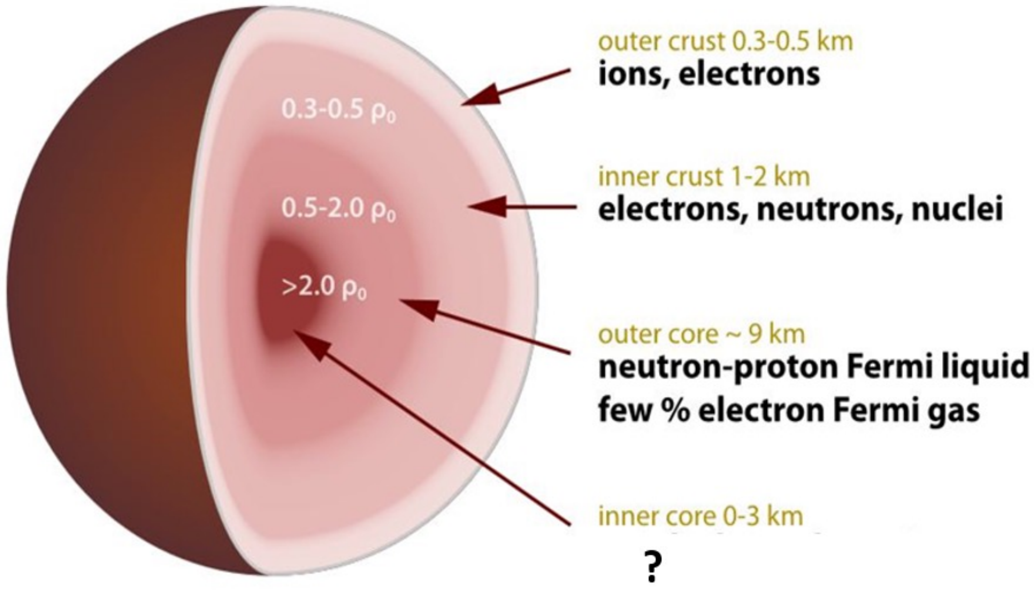

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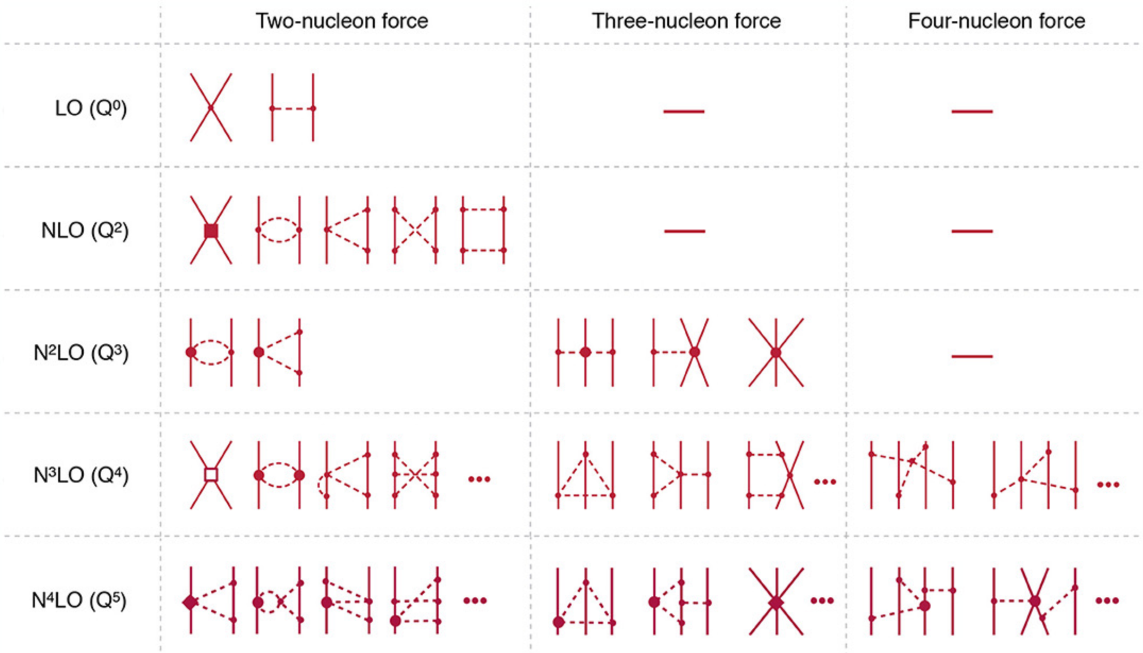
- Systematic effective theory framework: Chiral Effective Theory (CET)



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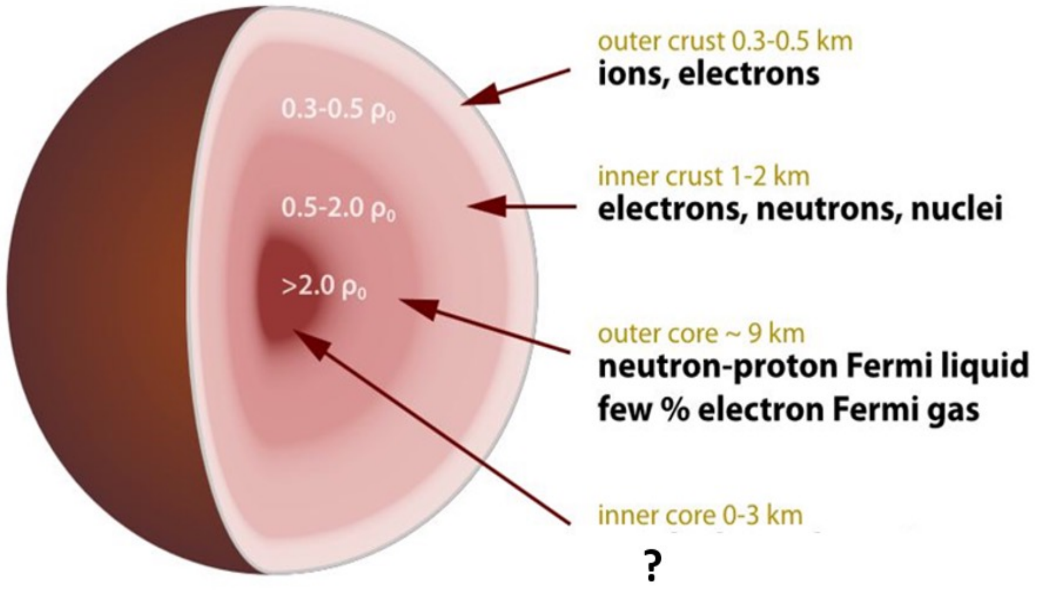
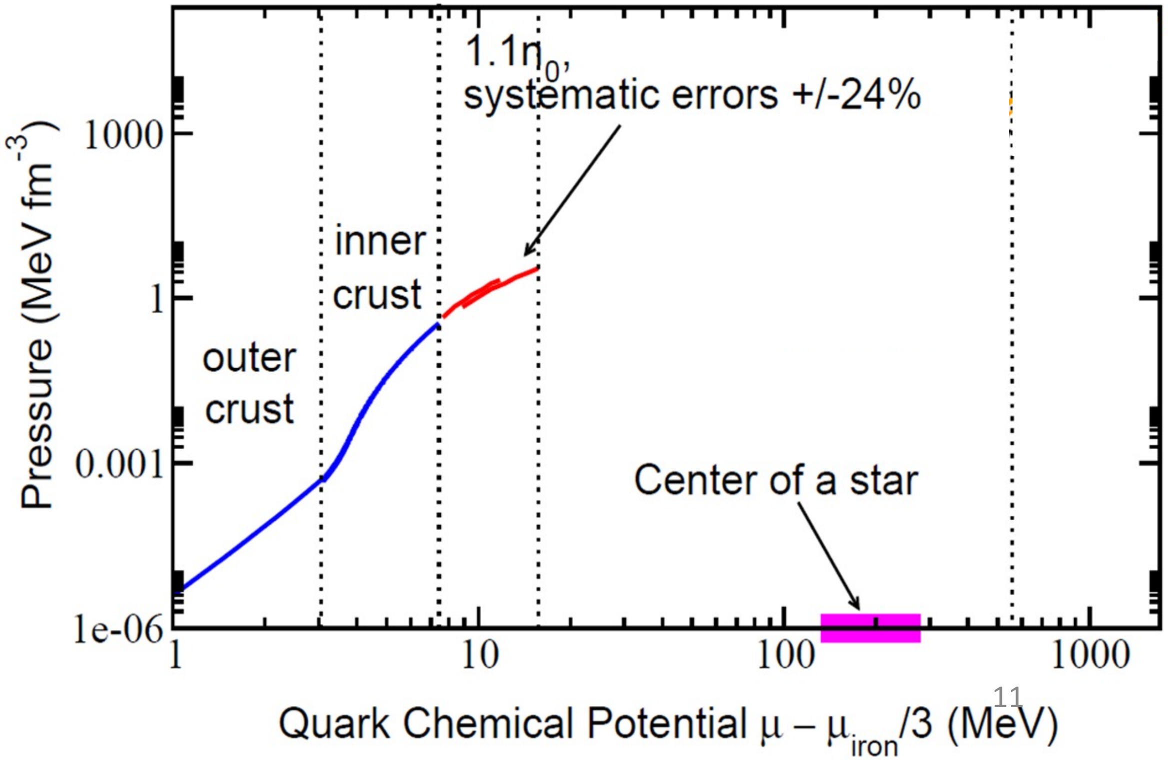


Beyond neutron drip point NN interactions important; then 3Ns, boost corrections, etc.

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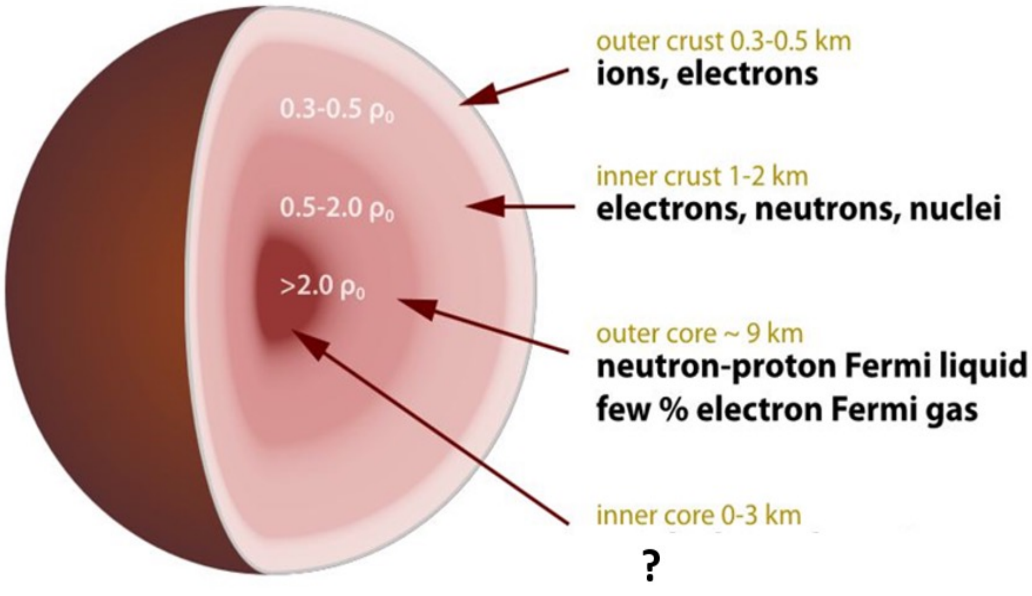
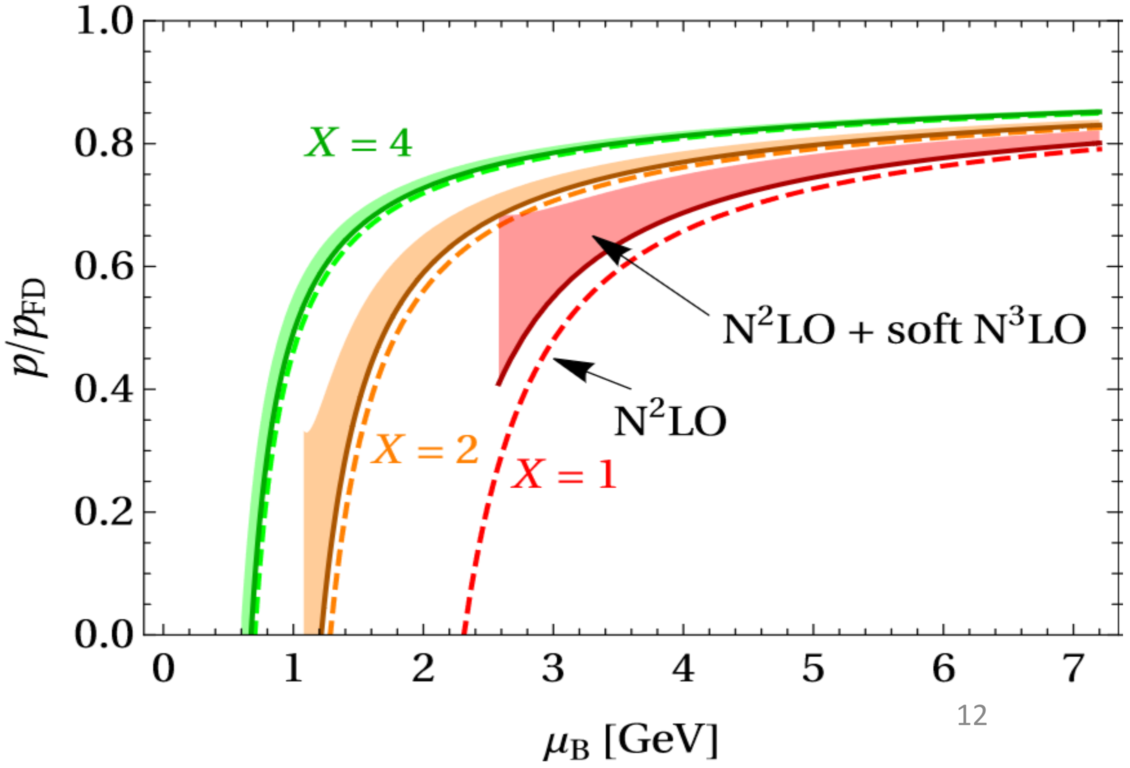
At high density, asymptotic freedom ⇒ weakening coupling and deconfinement

- State-of-the-art pQCD EoS at partial NNNLO, with purely soft sector fully determined [Gorda et al., PRL 127 (2021)]
- Still remaining from full α_s^3 result: “purely hard” and “mixed” contributions





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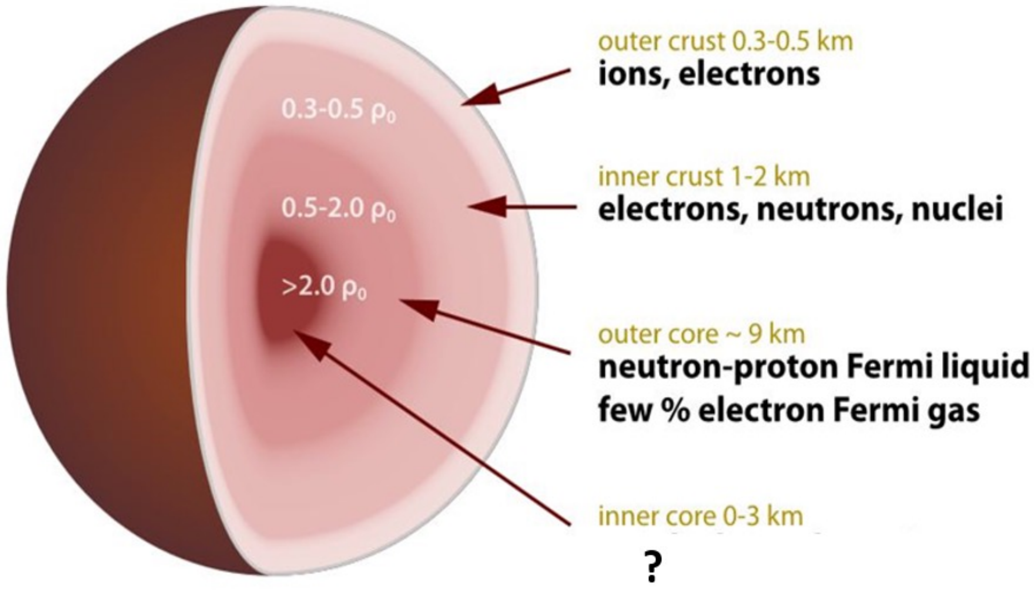
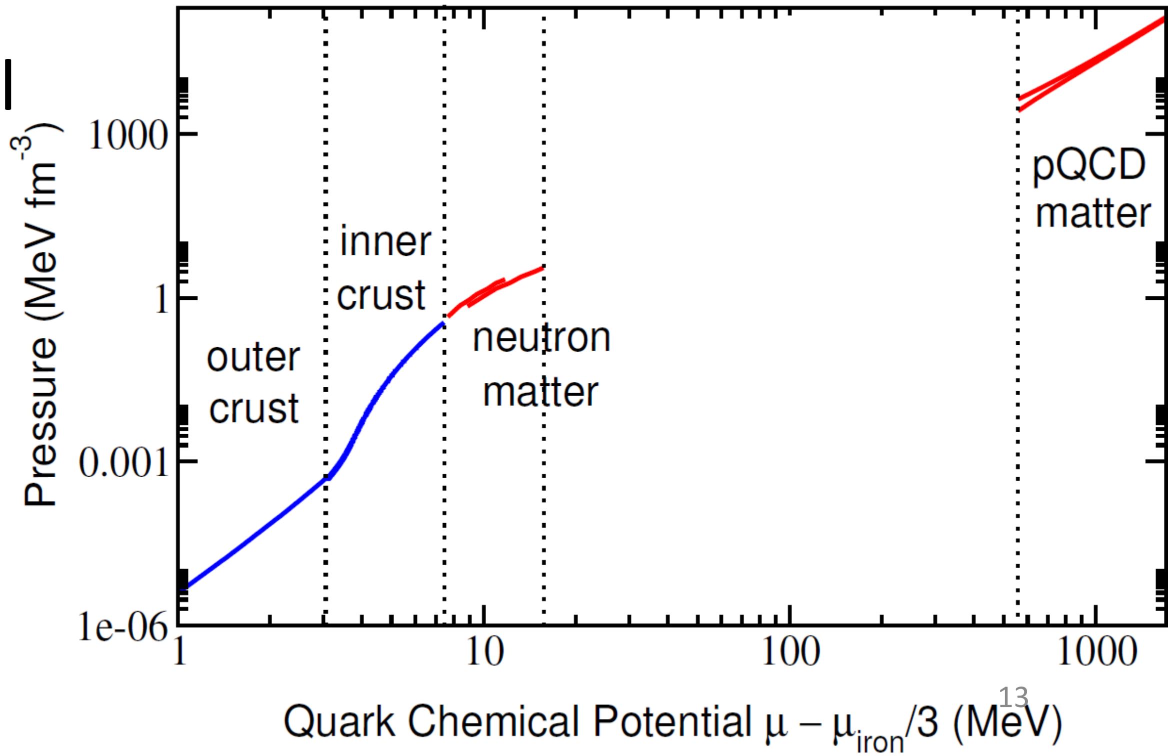
∴ Low- and high-density limits under control but extensive no-man's land at intermed. densities. Have to work with:

1) Astrophysical observations
2) Thermodynamic relations
3) Subluminality: $c_s \leq 1$





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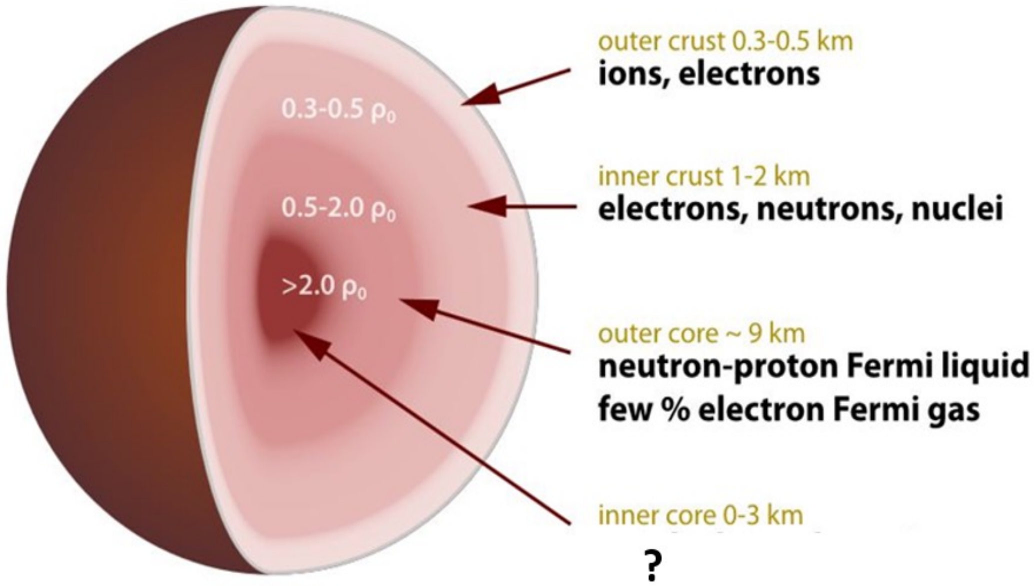
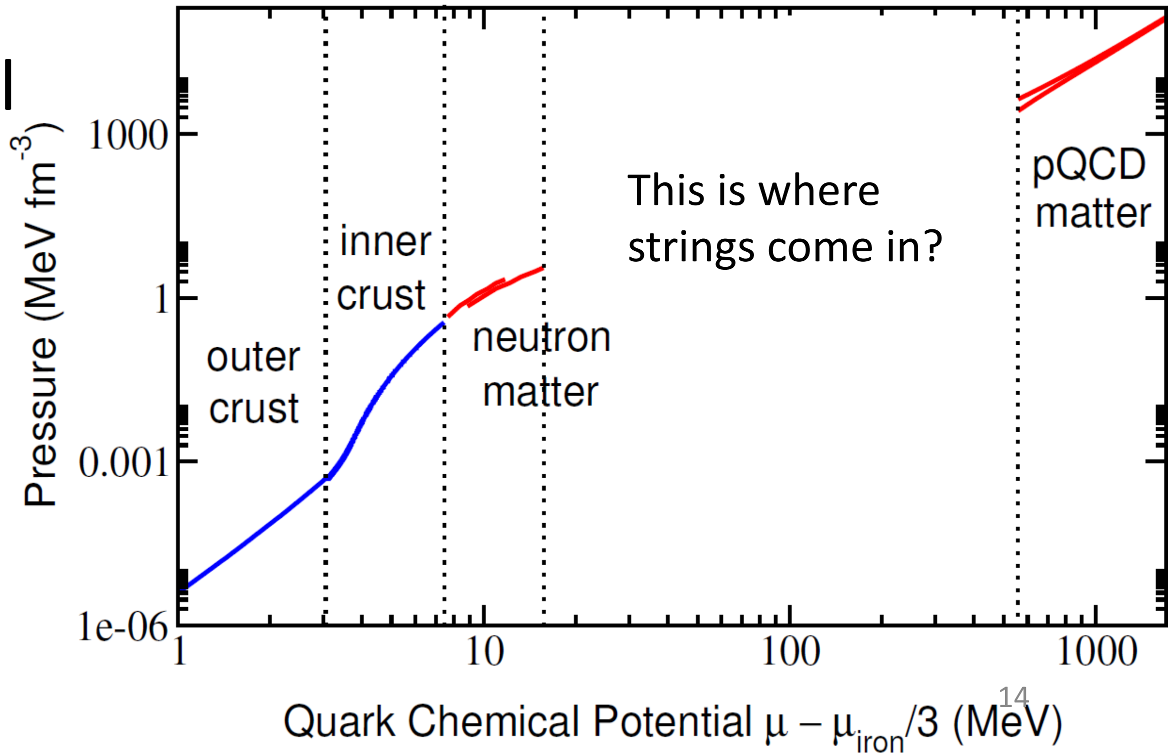
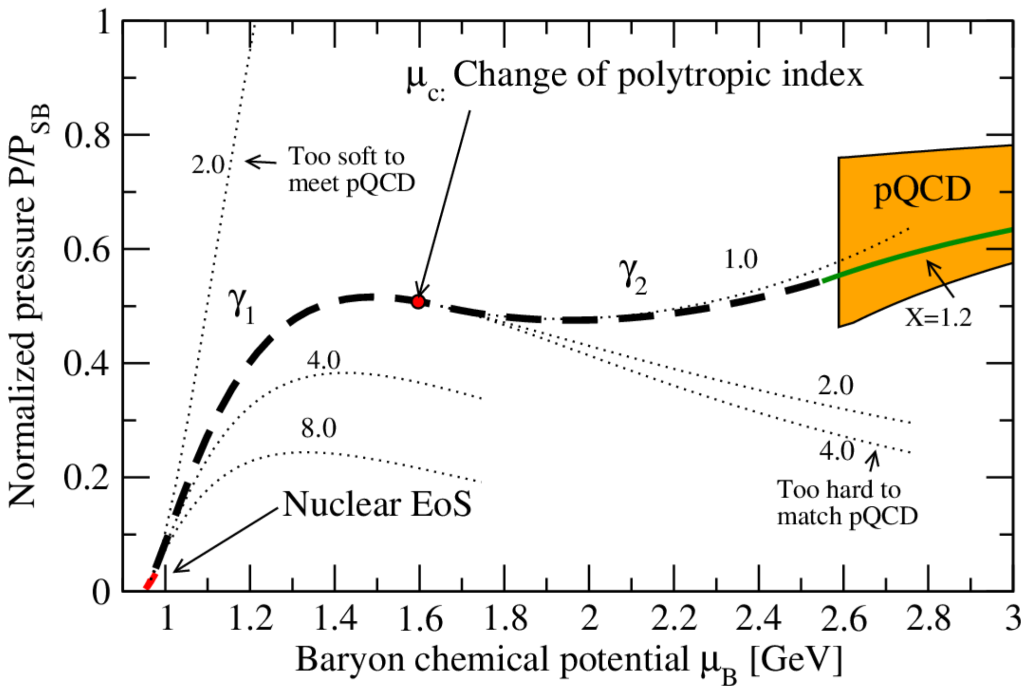
Barring of course a new ab-initio approach!





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



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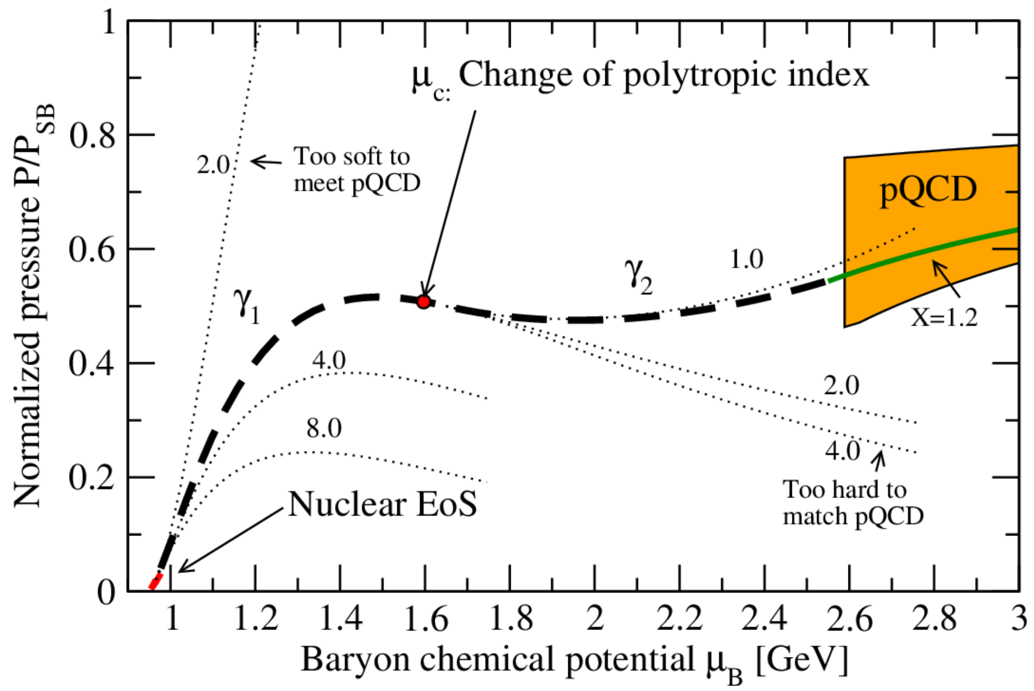
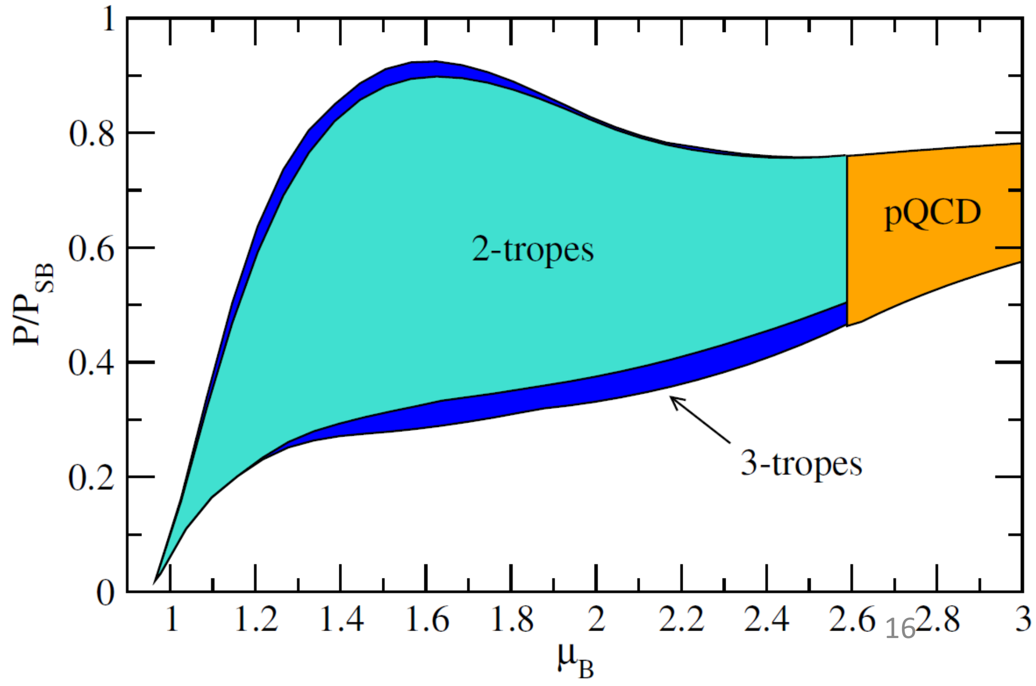
Require for all individual EoSs:

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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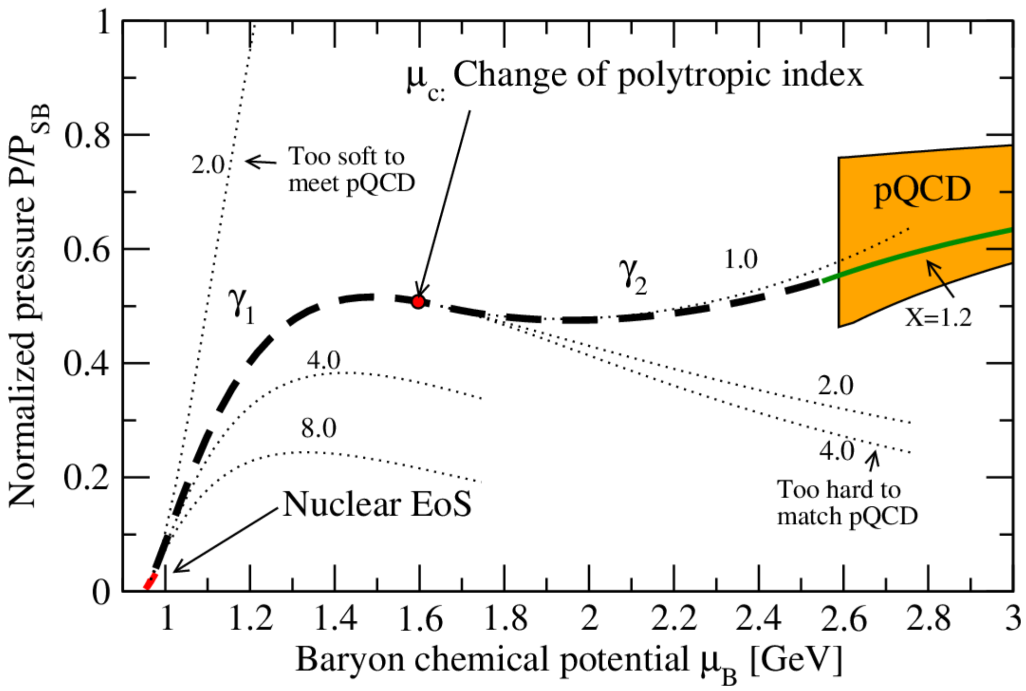
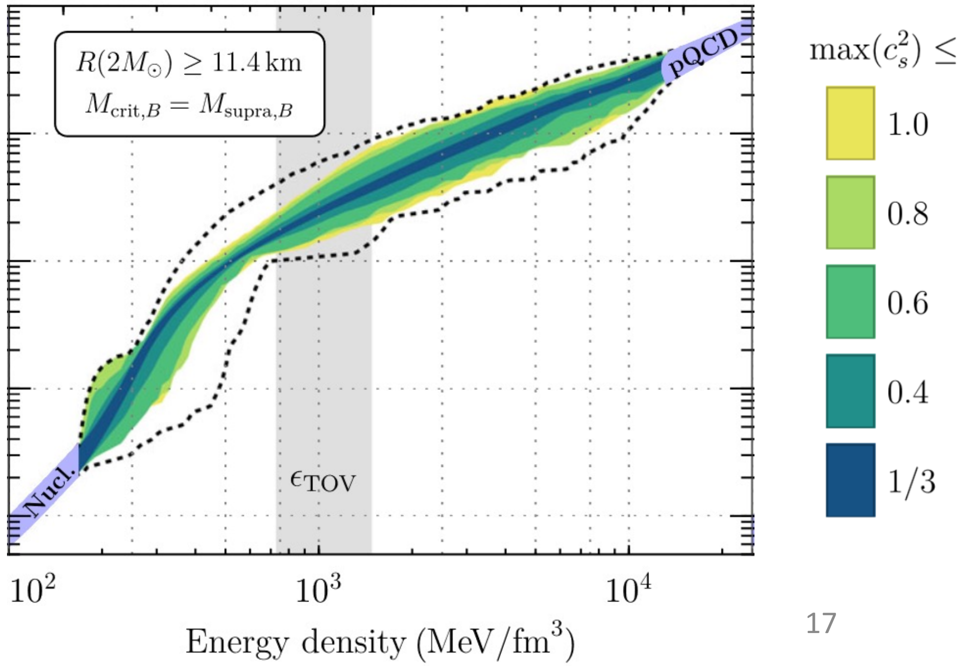
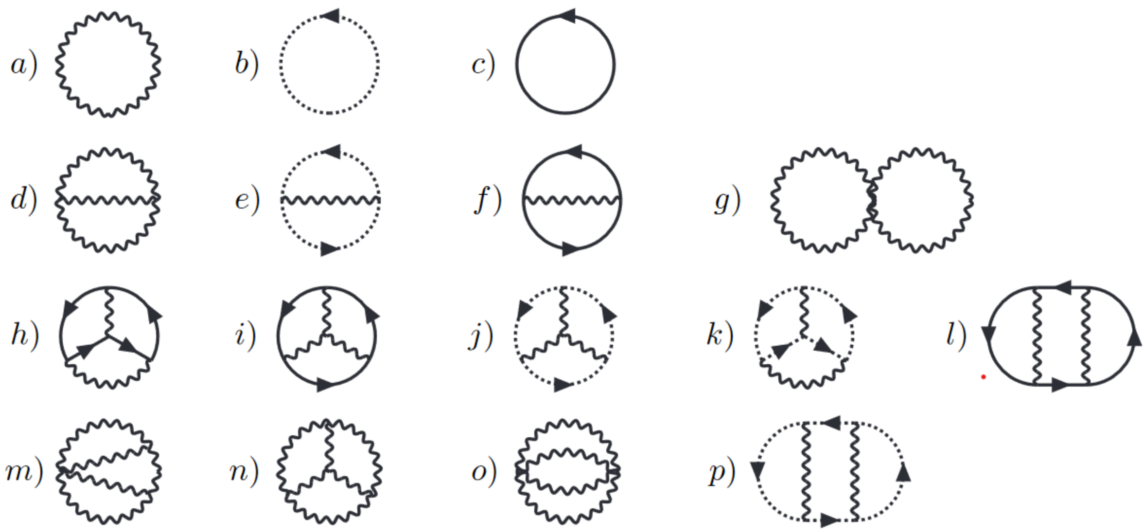


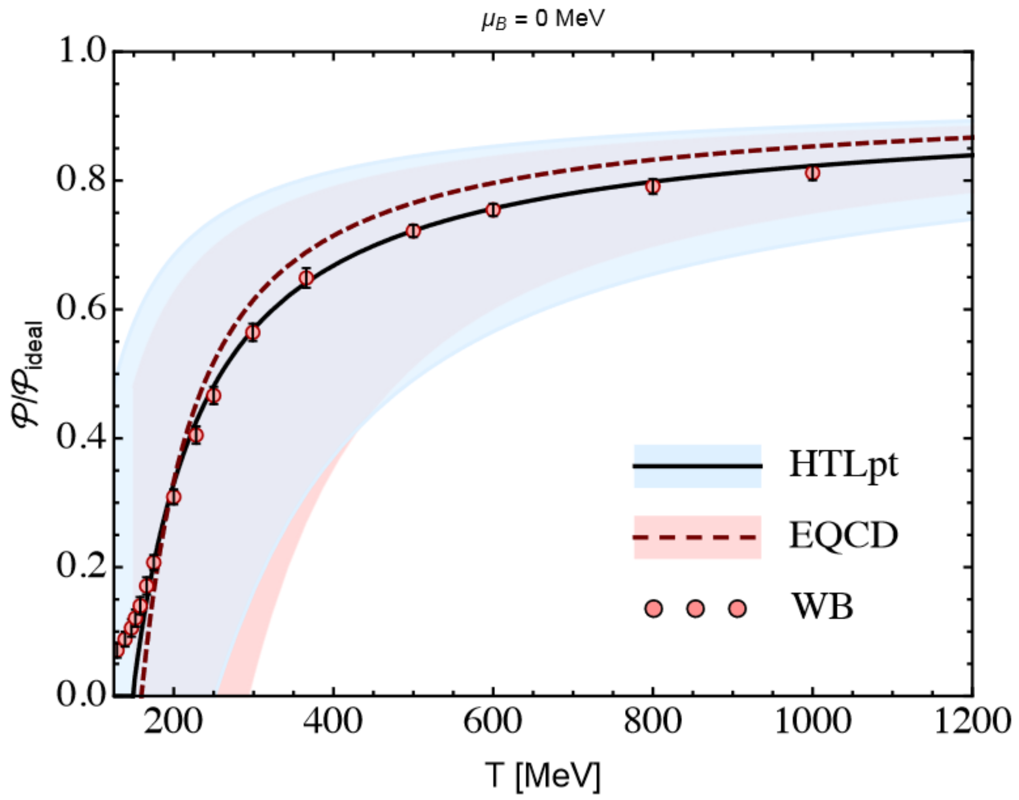


pQCD at high density and zero temperature: Hard (but not really) Thermal Loops

$$\Omega(T,\mu_u,\mu_d,\mu_s,m_s) = -T\log\int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A_\mu e^{-\int d^3x\int_0^{1/T}d\tau\mathcal{L}_{\rm QCD}},$$

$$\mathcal{L}_{\rm QCD} = \frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu} + \bar{\psi}_i(\gamma_\mu D_\mu + m_i - \mu_i\gamma_0)\psi_i$$





+ proper resummation of static bosonic modes (at nonzero T)

Andersen, Strickland, Su, JHEP 08 (2011)
Ghiglieri, Kurkela, Strickland, AV, Phys. Rept. 880 (2020)

$$\begin{aligned}\Omega(T,\mu_u,\mu_d,\mu_s,m_s) &= -T\log\int\mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A_\mu e^{-\int d^3x\int_0^{1/T}d\tau\mathcal{L}_{\rm QCD}},\\ \mathcal{L}_{\rm QCD} &= \frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu}+\bar{\psi}_i(\gamma_\mu D_\mu+m_i-\mu_i\gamma_0)\psi_i\end{aligned}$$

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- Sum-integrals get replaced by four-dimensional continuous integrals, with fermionic $p_0 \to p_0 - i\mu$
  - Simplification from vanishing of diagrams with no fermion loops
  - Technical challenge: how to deal with fermionic p_0 integrals in a systematic manner?

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  - Correct effective theory for IR modes: Hard Thermal Loops (HTL)

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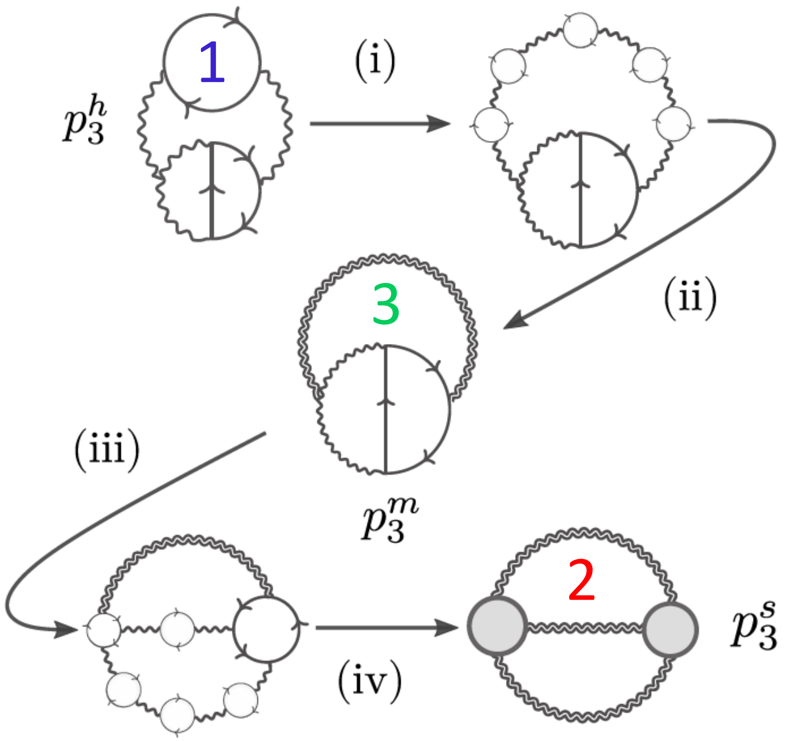
- No correct answer from lattice!

Up to state-of-the-art $O(\alpha_s^3)$, three types of contributions to the pressure:

1) Hard modes (scale μ_B) and their interactions: naïve loop expansion up to and including four loops
2) Soft modes (scale $m_E \sim g\mu_B$) and their interactions: one- and two-loop graphs in HTL effective theory
3) Mixing of soft and hard modes



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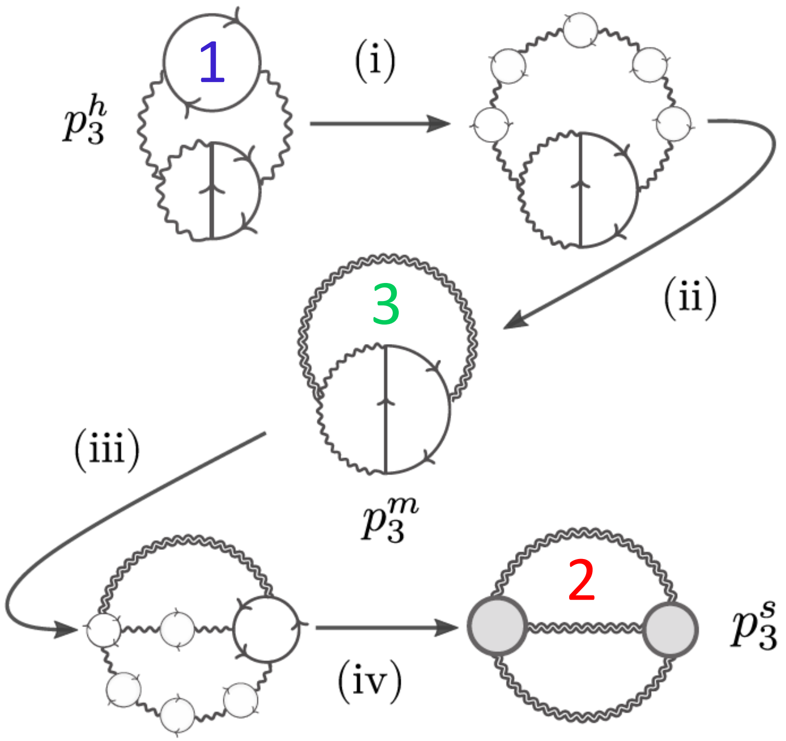

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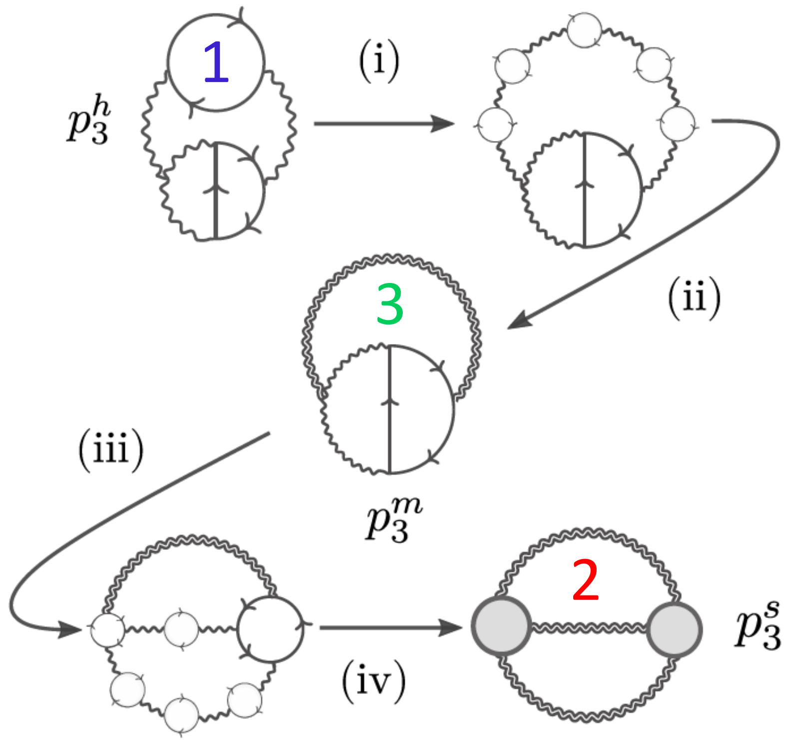

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Known since 1970's [Freedman, McLerran, PRD 16 (1977)]

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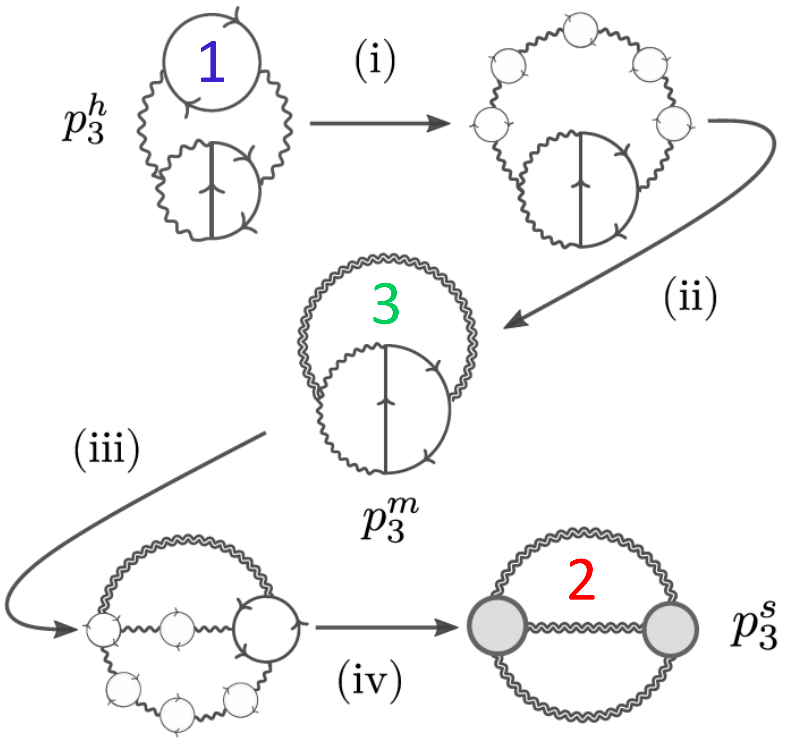

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Leading log from Gorda, Kurkela, Romatschke, Säppi, AV, PRL 121 (2018)

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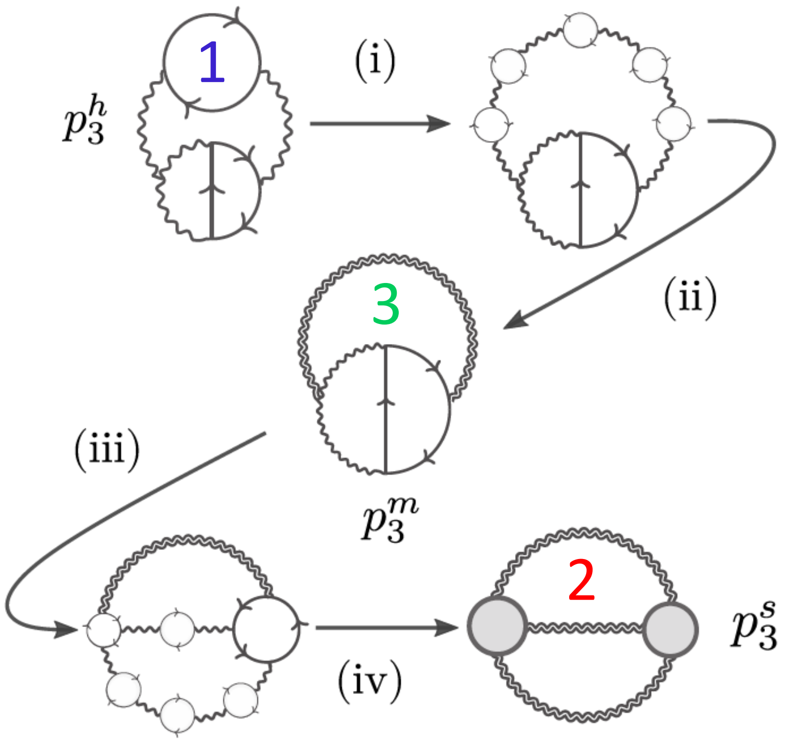

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Gorda, Kurkela, Paatelainen, Säppi, AV, PRL 127 (2021); Fernandez, Kneur, 2109.02410

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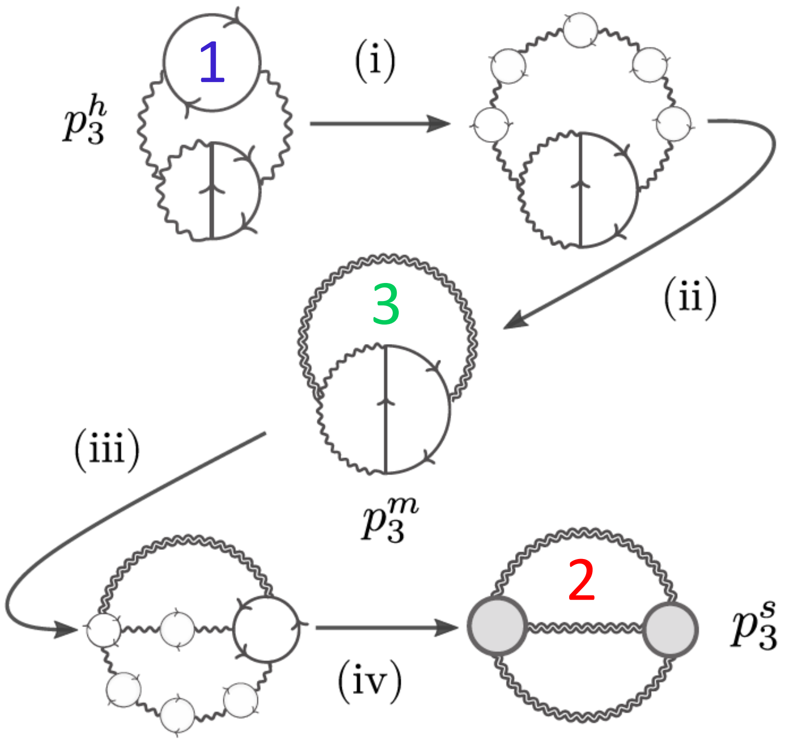

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QED: Gorda, Kurkela, Österman, Paatelainen, Säppi, Seppänen, Schicho, AV, 2204.11893
QCD: Underway; results in 2022

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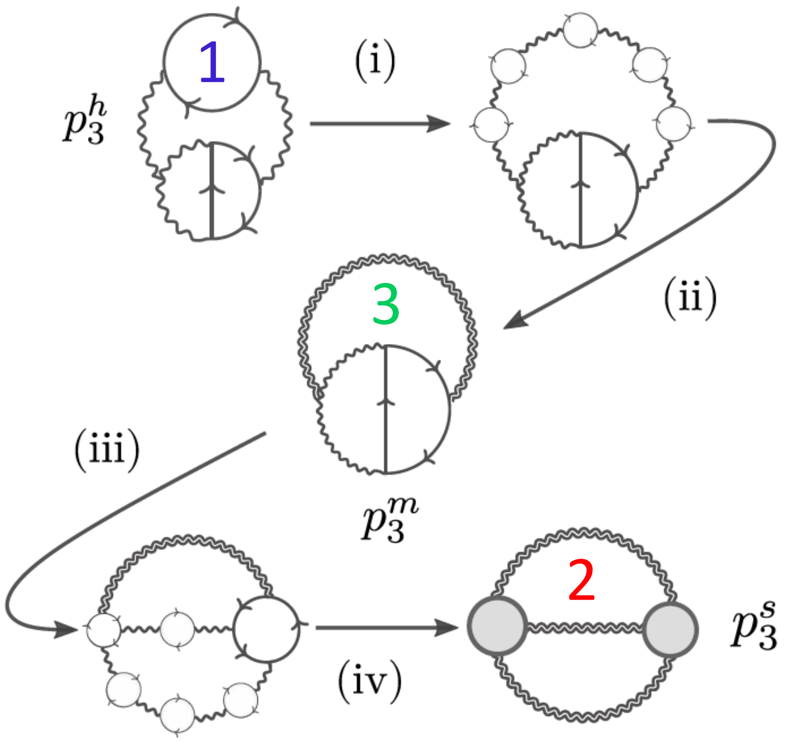

Also underway; no concrete promises of timescale

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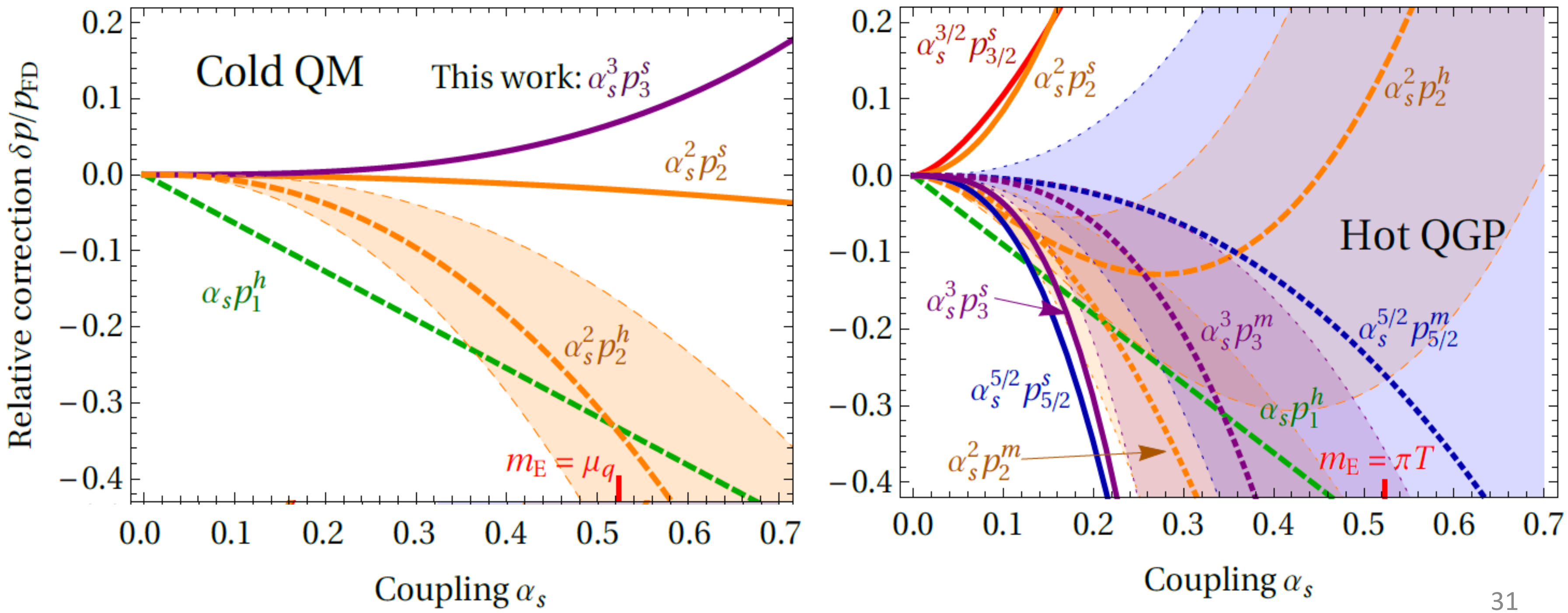
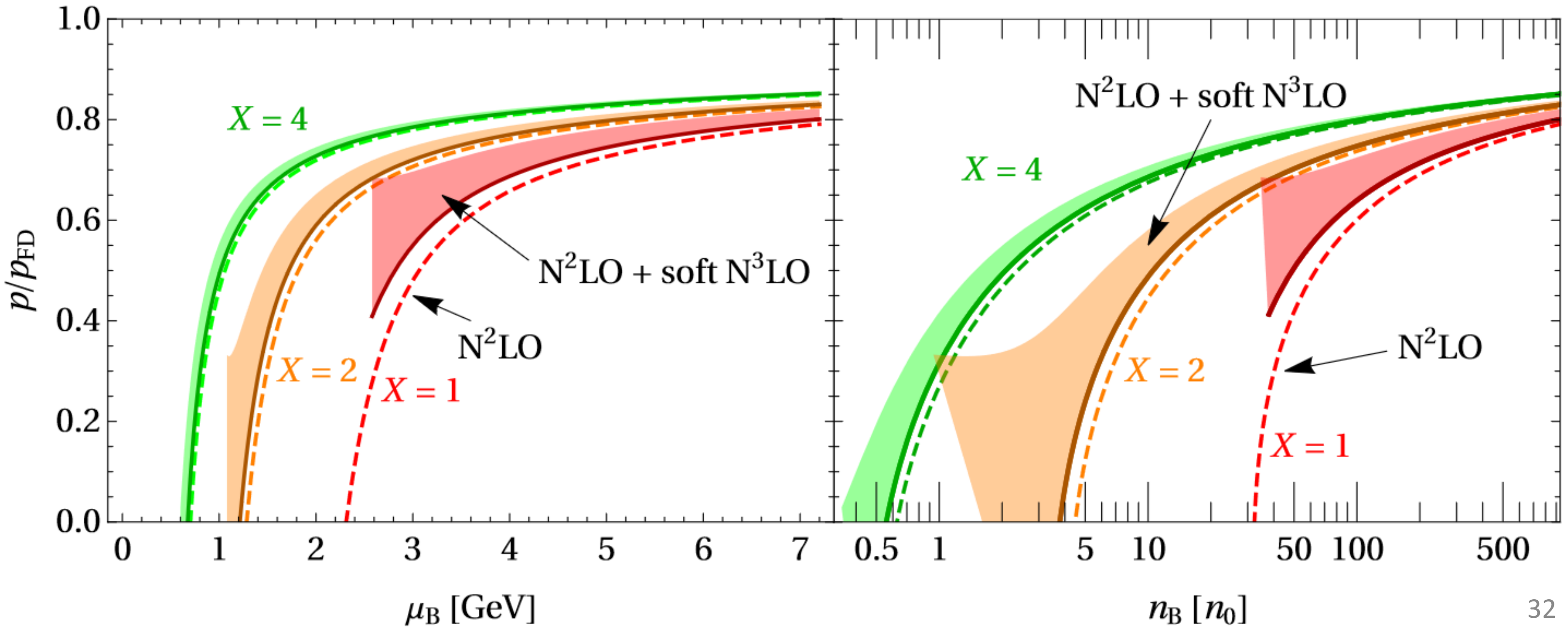
Comparison of convergence at zero vs. high temperature:



Up to state-of-the-art $O(\alpha_s^3)$, three types of contributions to the pressure:

1) Hard modes (scale μ_B) and their interactions: naïve loop expansion up to and including four loops
2) Soft modes (scale $m_E \sim g\mu_B$) and their interactions: one- and two-loop graphs in HTL effective theory
3) Mixing of soft and hard modes

Effect of soft contributions on the EoS:



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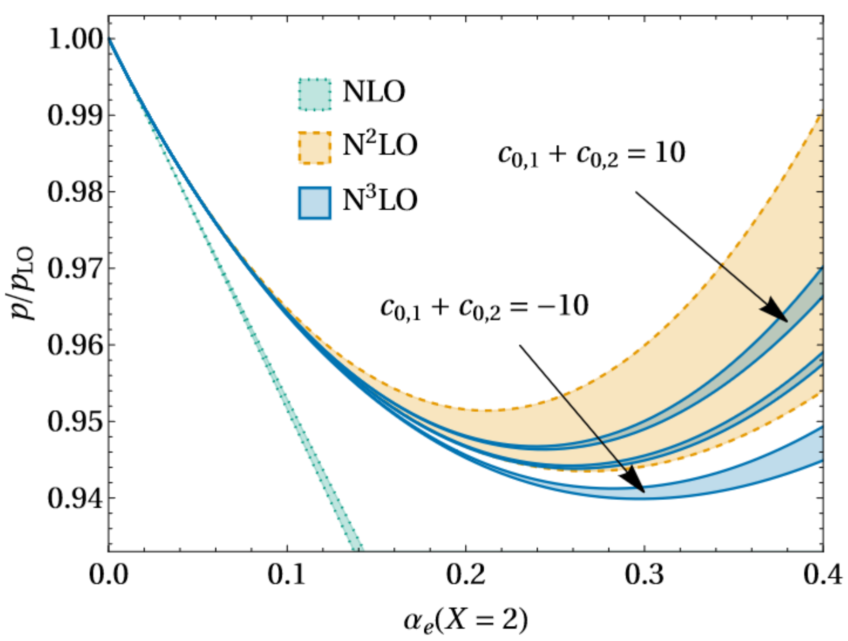
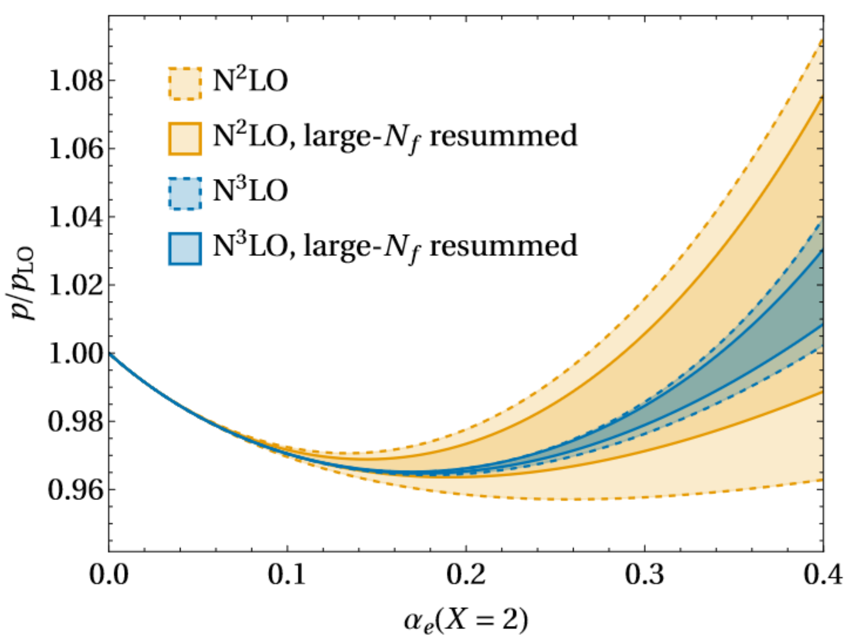
Effect of mixed contributions and large-N_f resummation on EoS of cold and dense QED:





What do we know from NS observations?

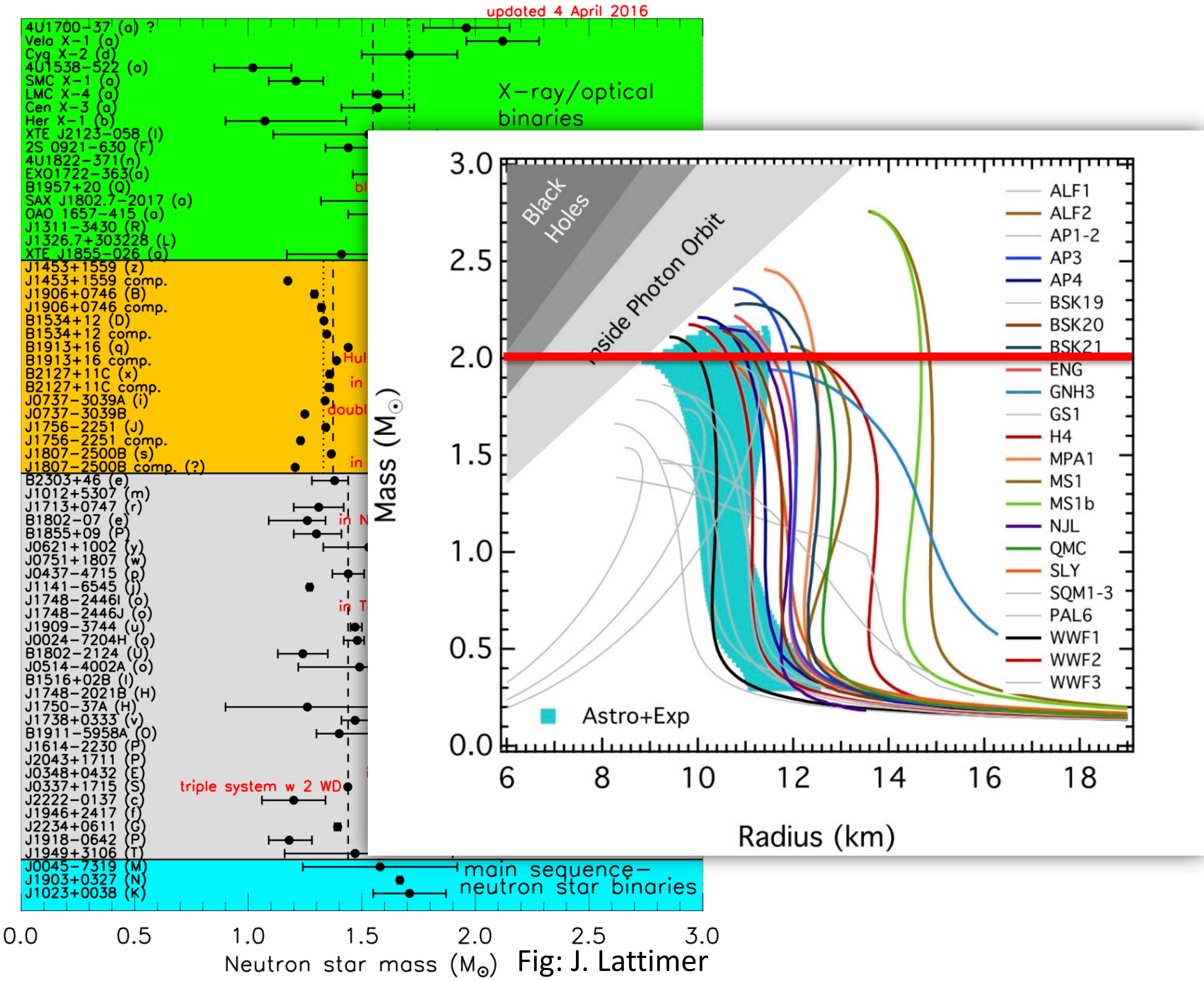


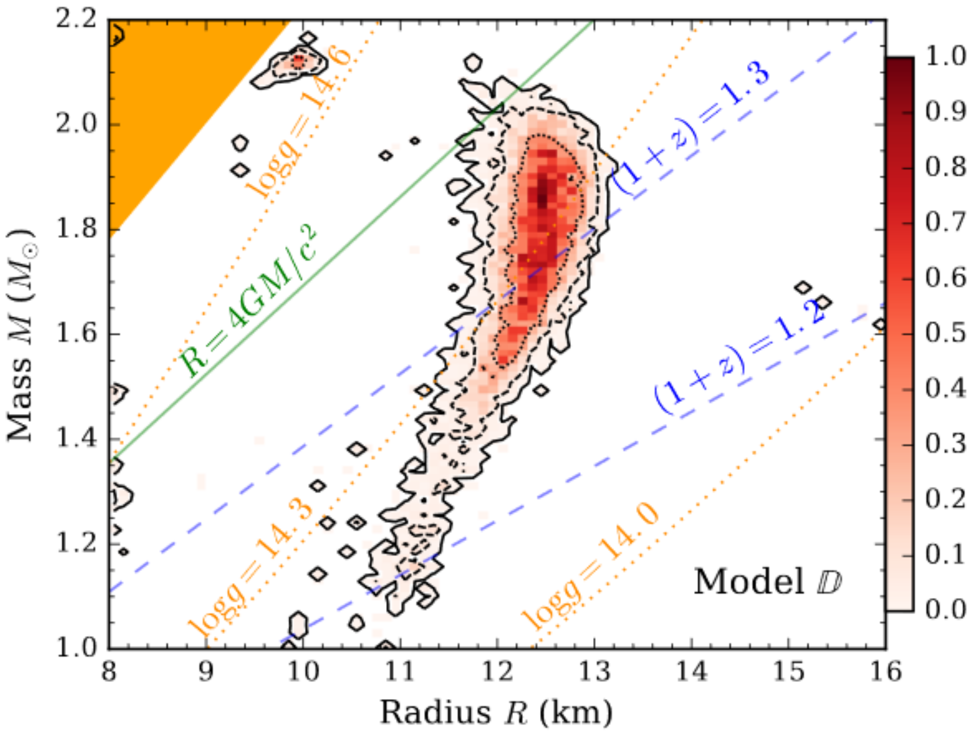
Fig: J. Lattimer

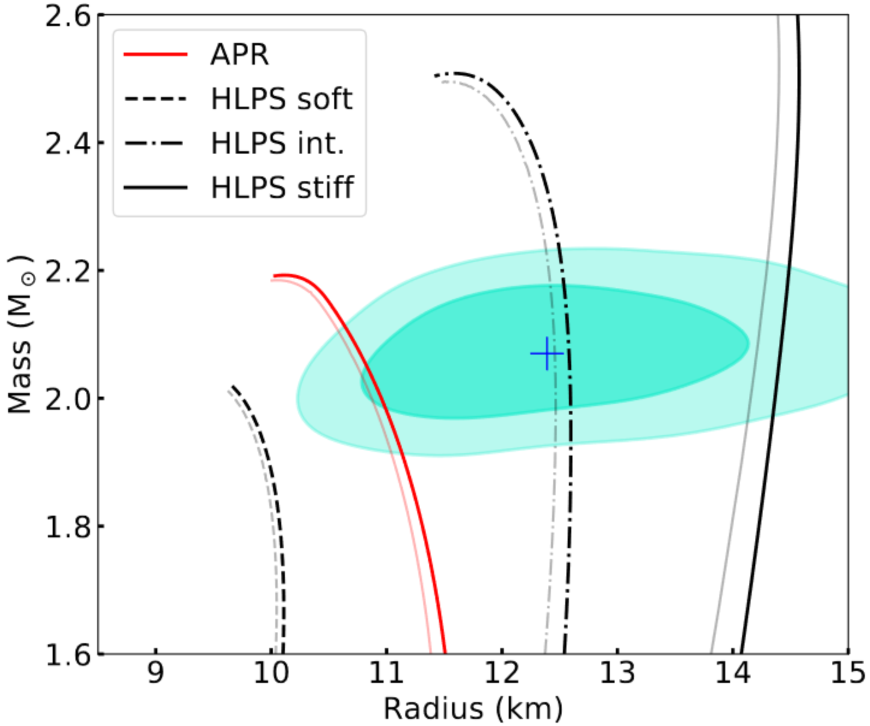
ate Shapiro delay
vo-solar-mass

(2010)
0 (2013)
ronomy 4 (2019)

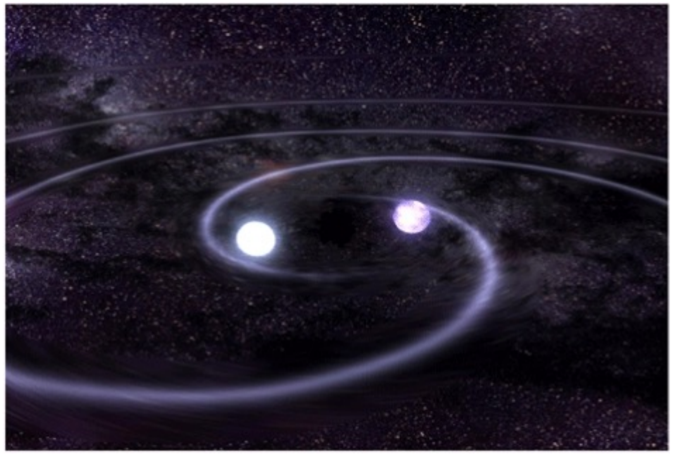
Radius (and combined MR) measurements more problematic, but recently important progress through X-ray observations:

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



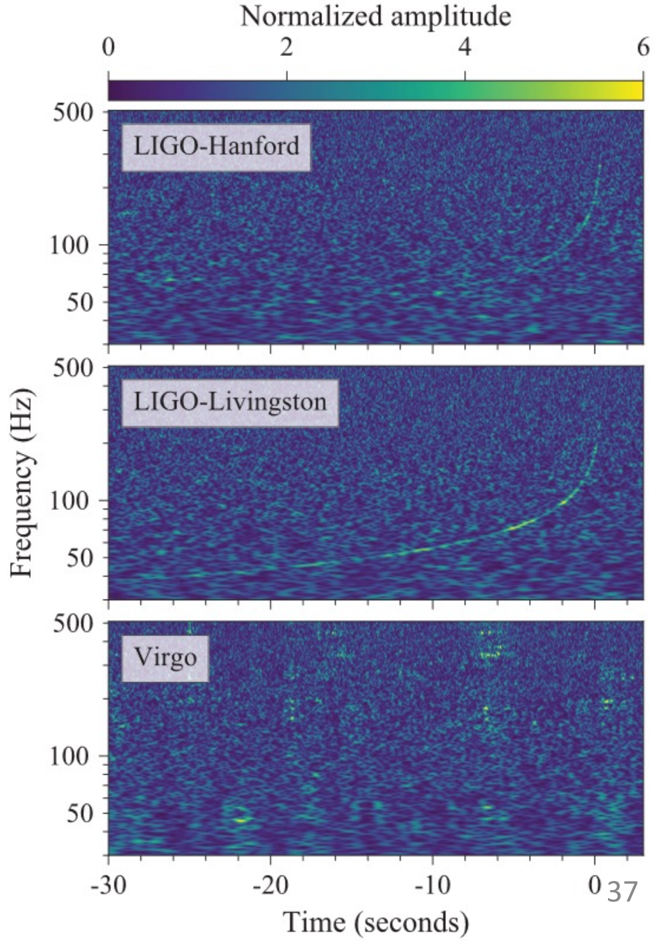


Gravitational wave breakthrough: First observed binary NS merger GW170817 by LIGO & Virgo in 2017 (and many since then)



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

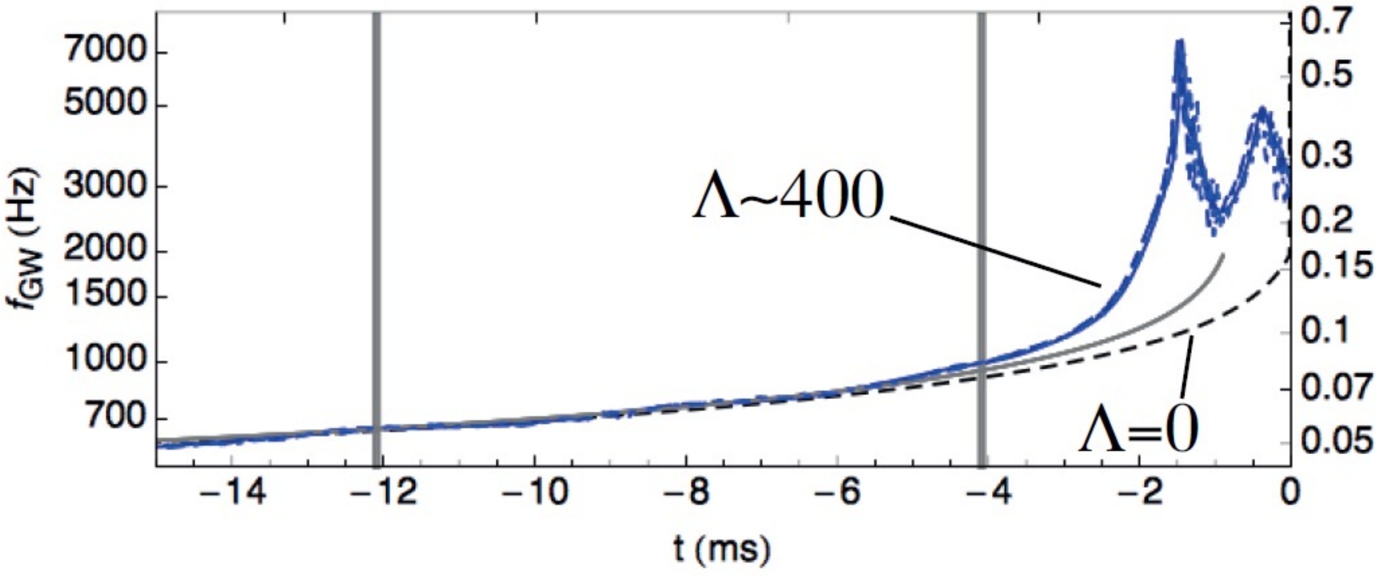


[LIGO and Virgo collaborations, PRL 119 (2017), PRL 121 (2018)]

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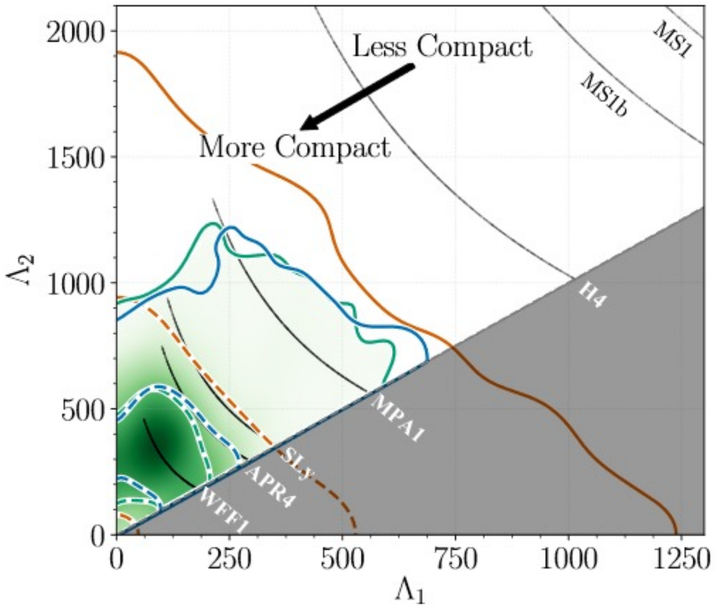
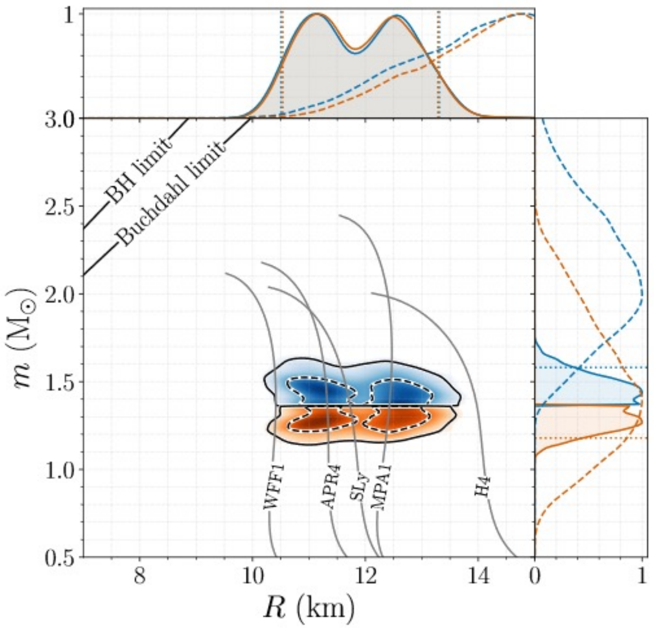
$$Q_{ij} = -\Lambda \mathcal{E}_{ij}$$

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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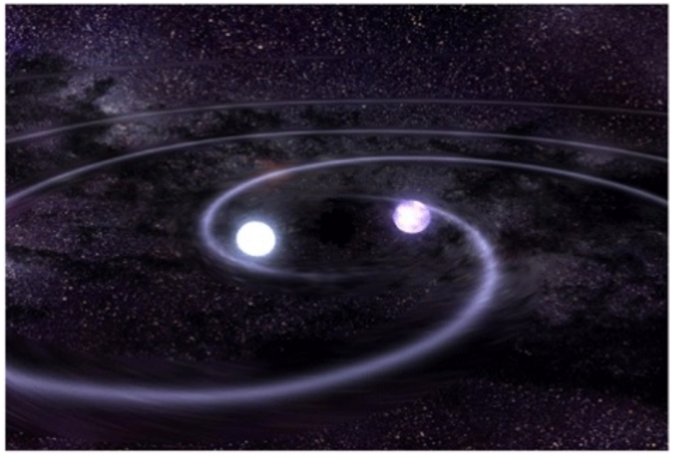

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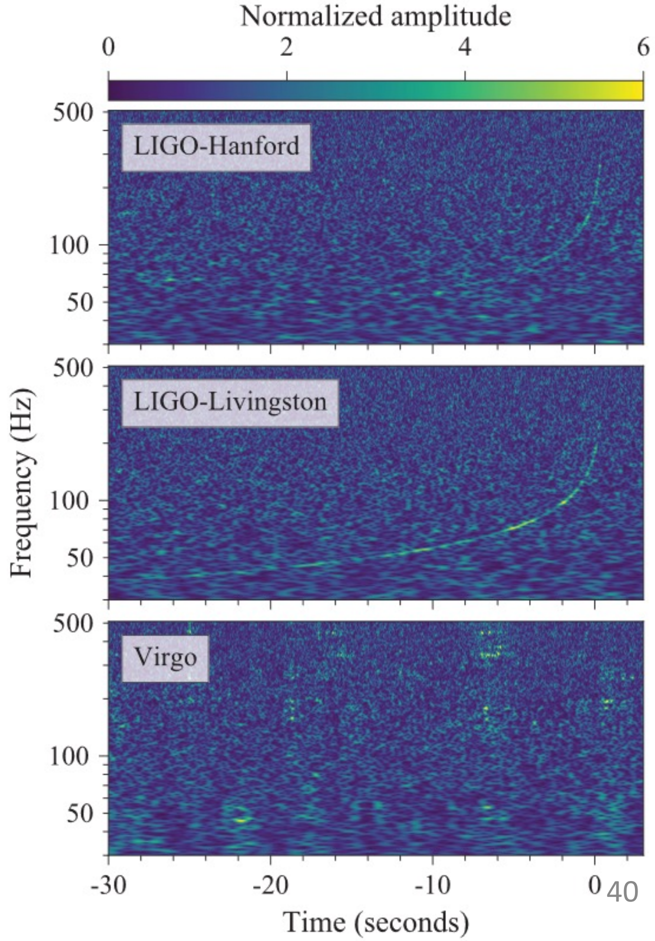


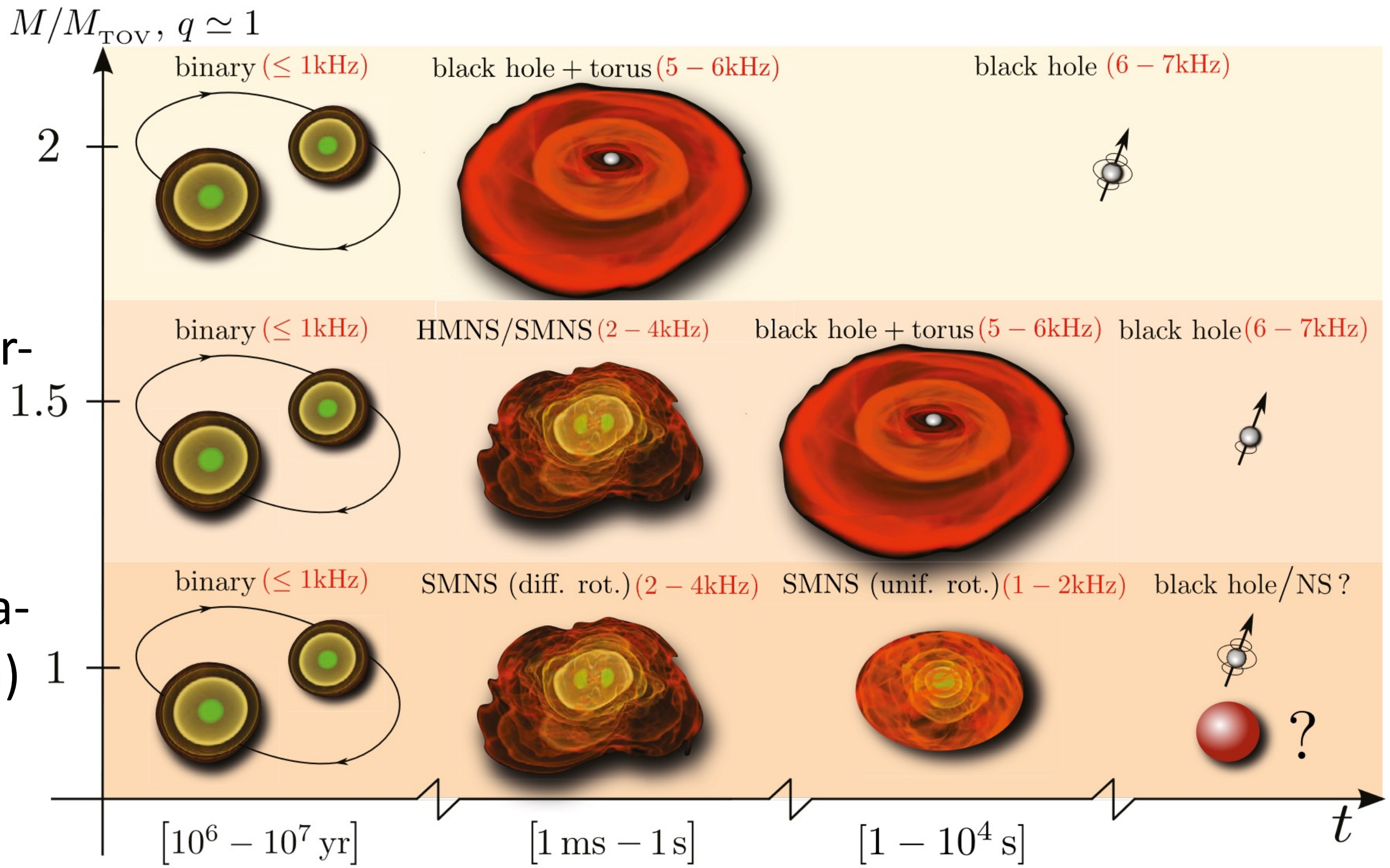
Ringdown pattern: Unlike in BH mergers, binary NS mergers expected to feature complex period of relaxation characterized by GW spectrum sensitive to both initial NS masses and the EoS

Scenario 1: prompt collapse

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

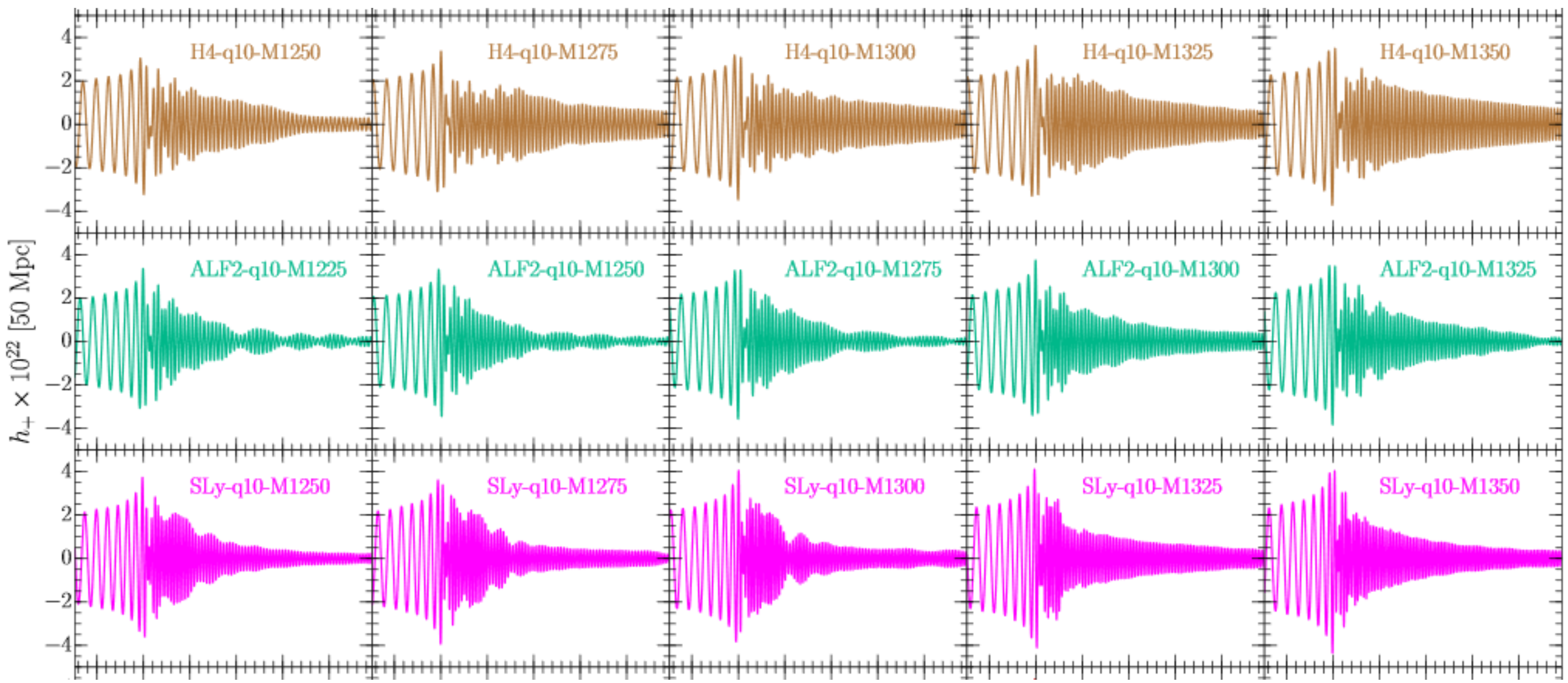
Scenario 3: collapse during supra-massive phase (uniform rotation)

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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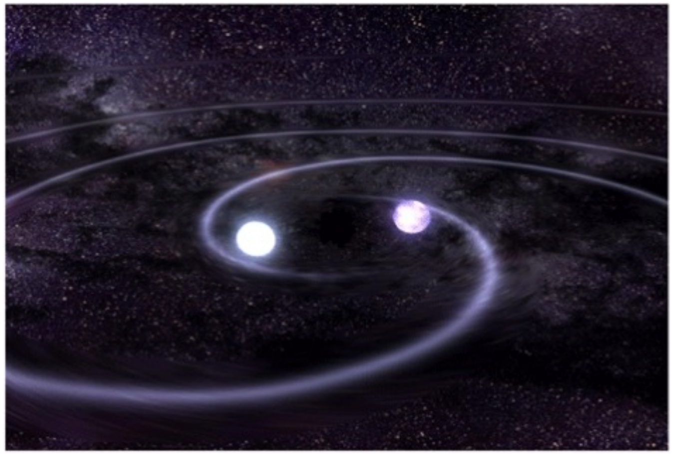

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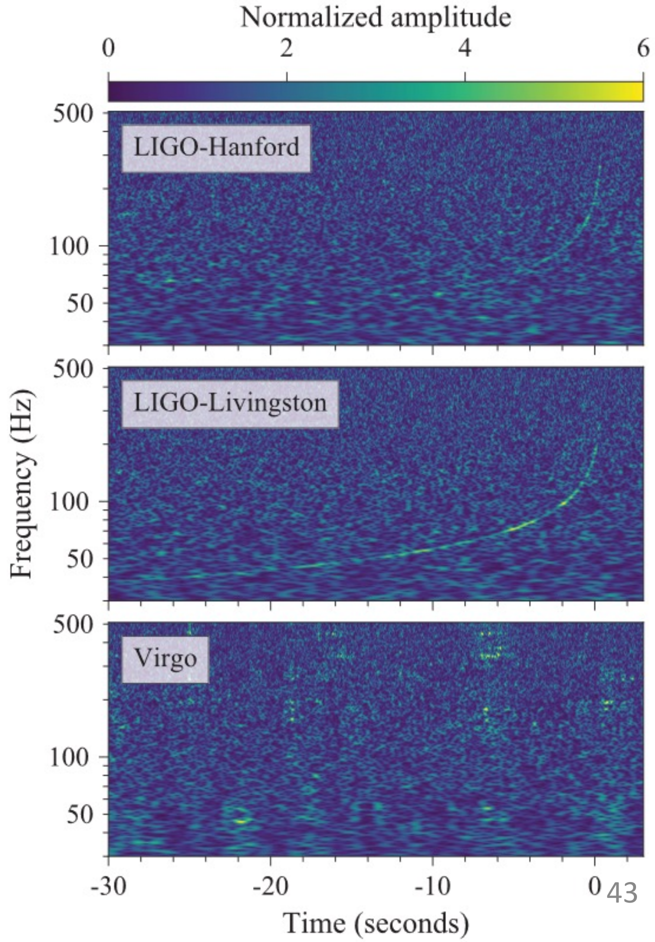
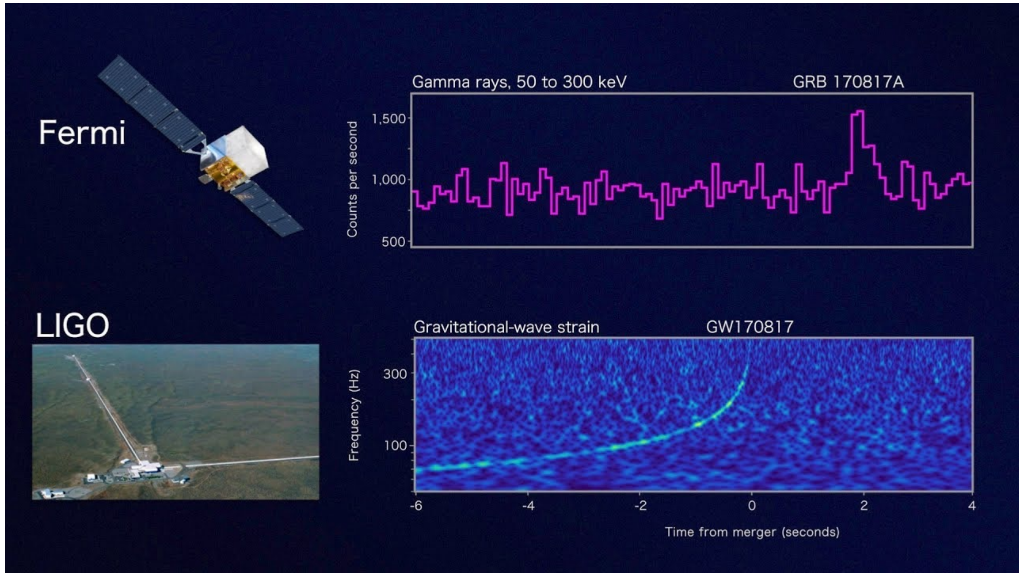
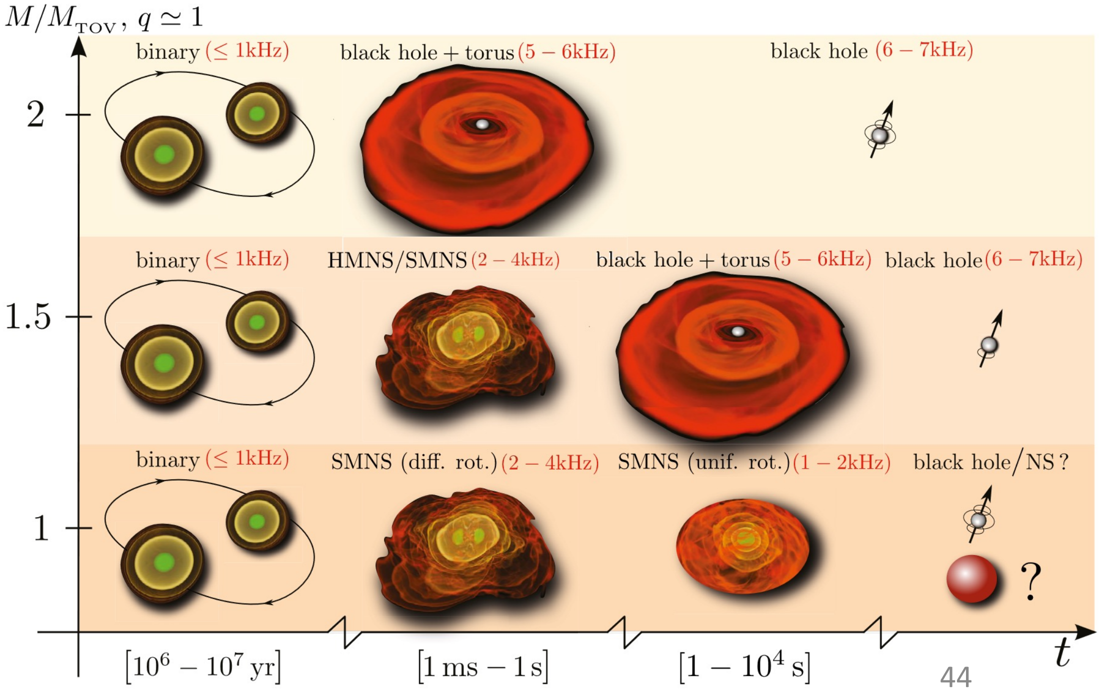


In GW170817, short gamma-ray burst 1.7s after GWs, followed by optical signal: Delayed collapse to a BH





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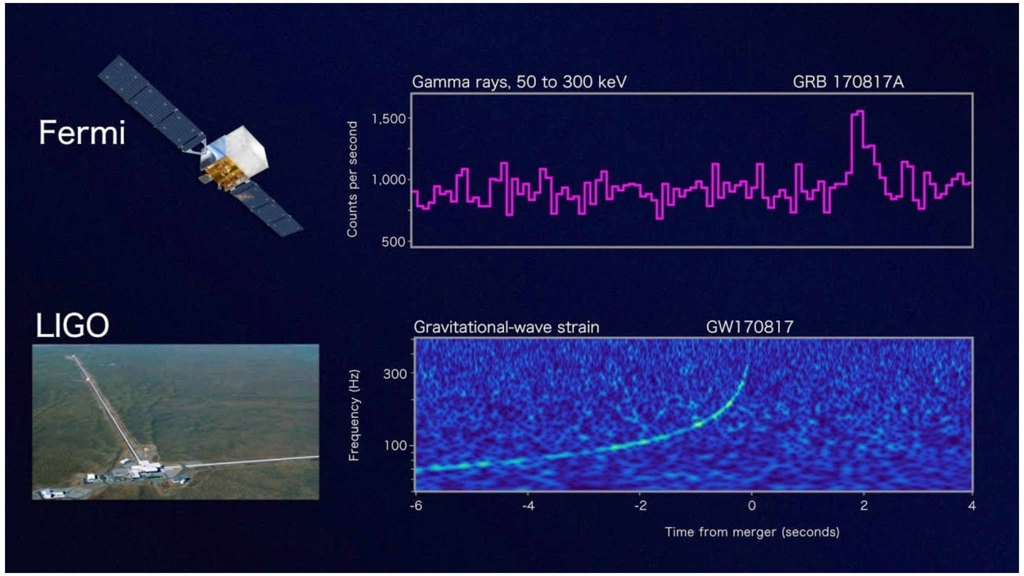
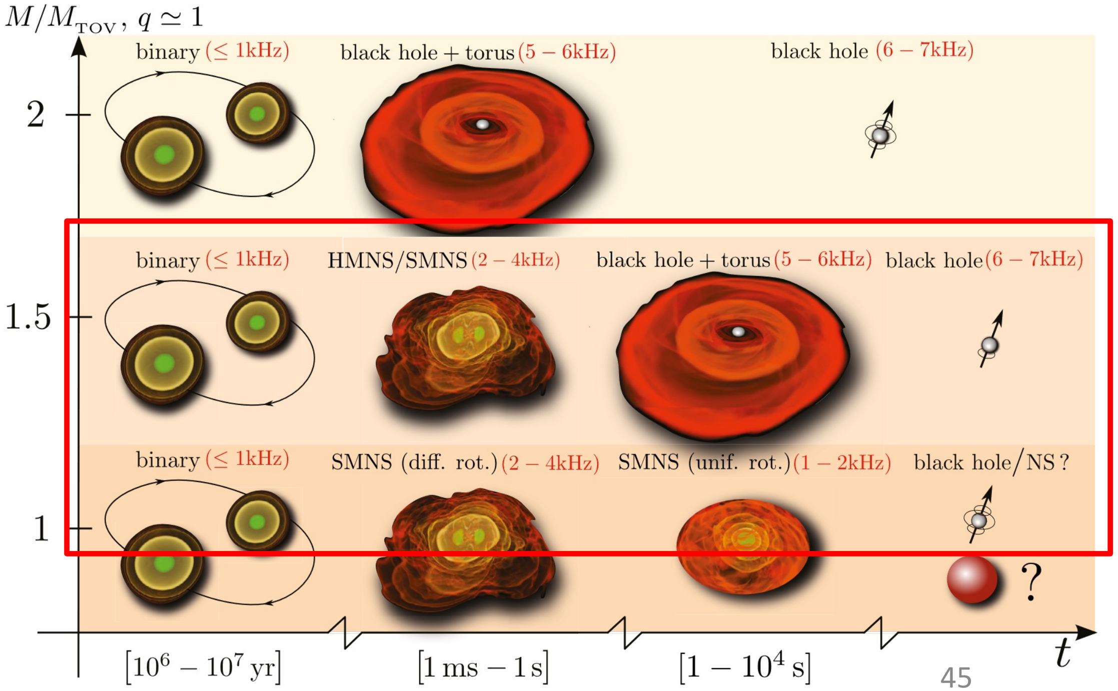
Constraints for maximal (TOV) mass of stable NSs from scenarios 2 and 3:

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





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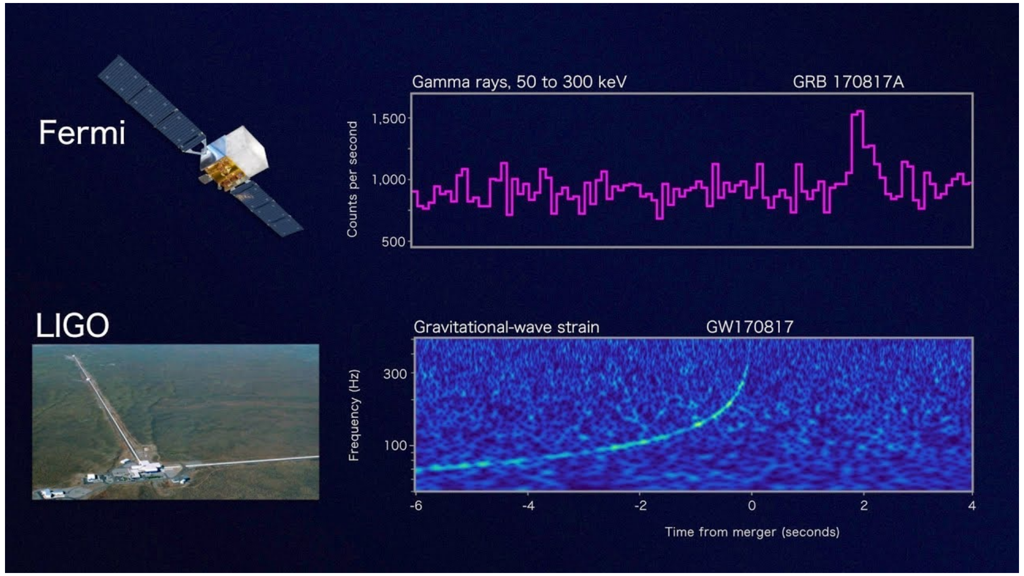
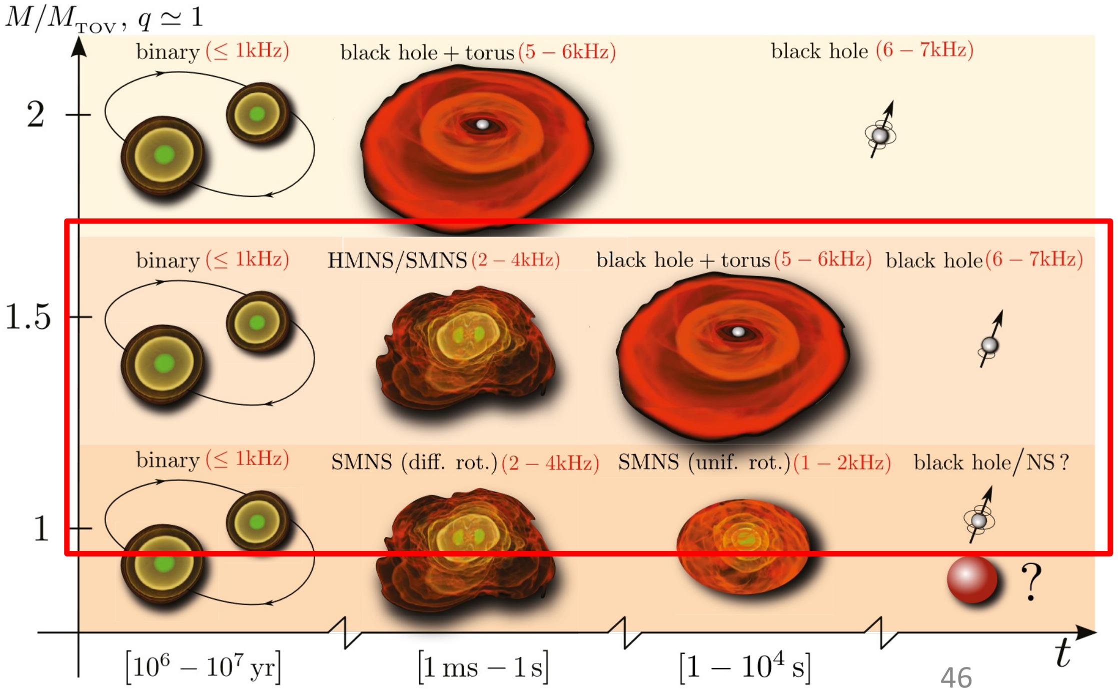
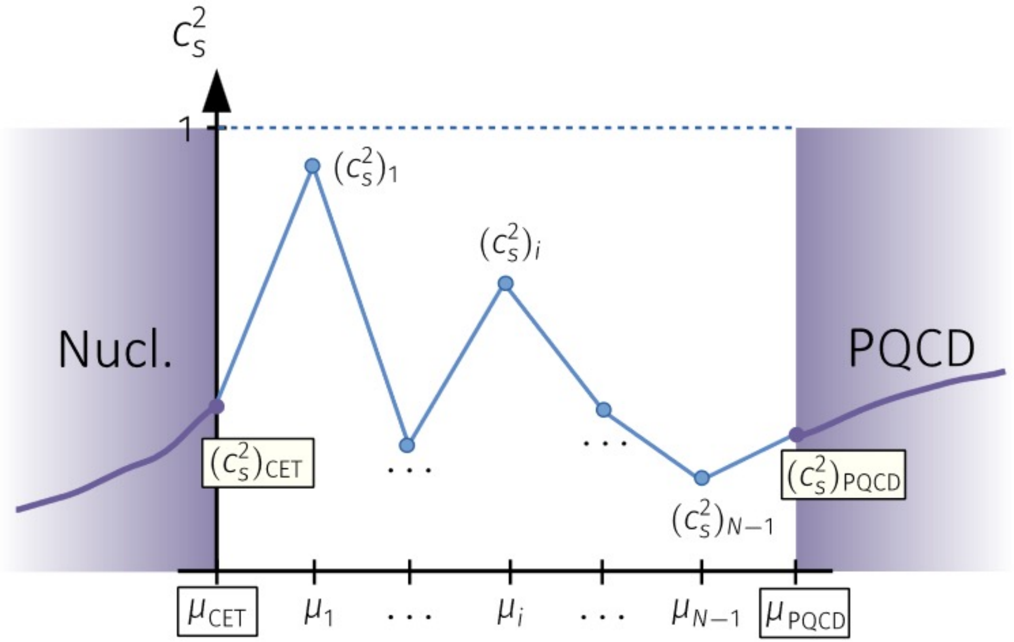
HMNS-scenario more likely due to short delay between GW and EM signals; gives stronger constraints [Rezzolla et al, ApJ 852 (2018)]

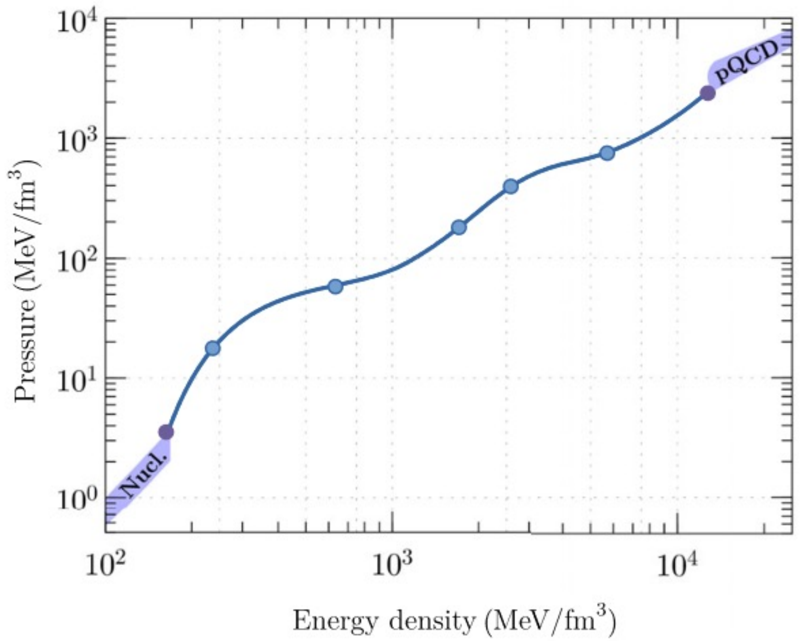




Interpolation: combining all available information, what can we say about the EoS and the composition of massive NSs?

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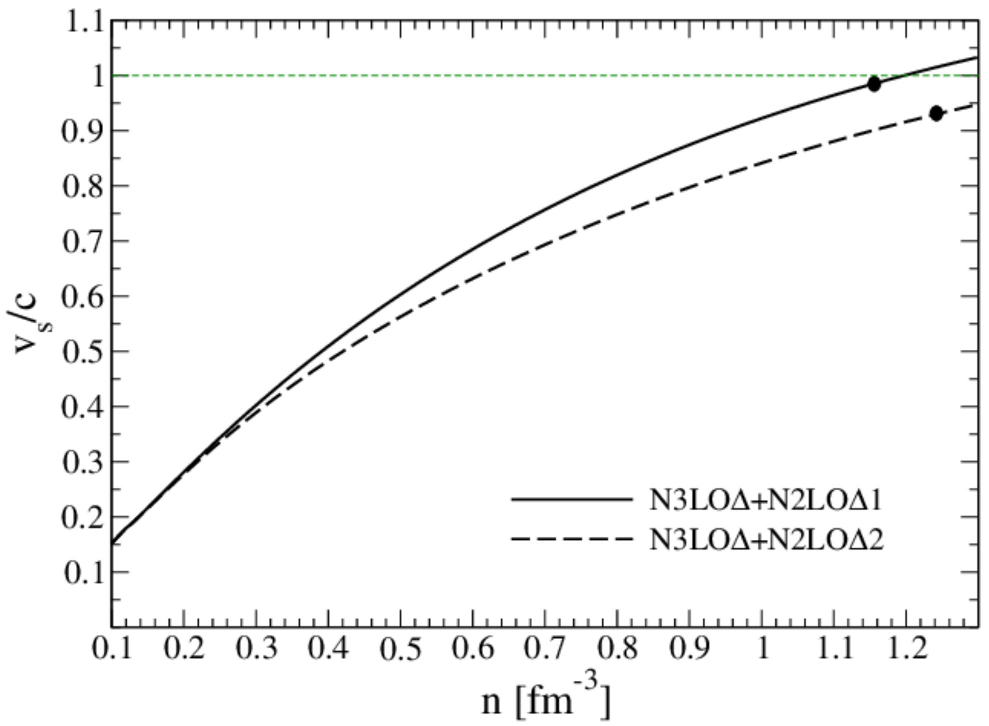
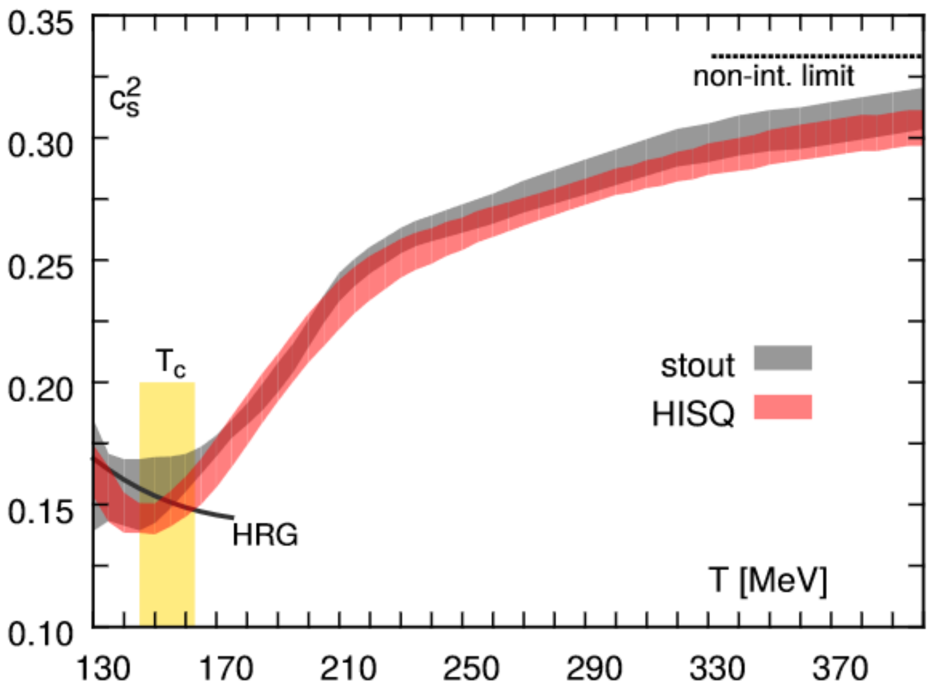
Interesting because of tension between standard lore in nuclear physics and experience from other contexts





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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.

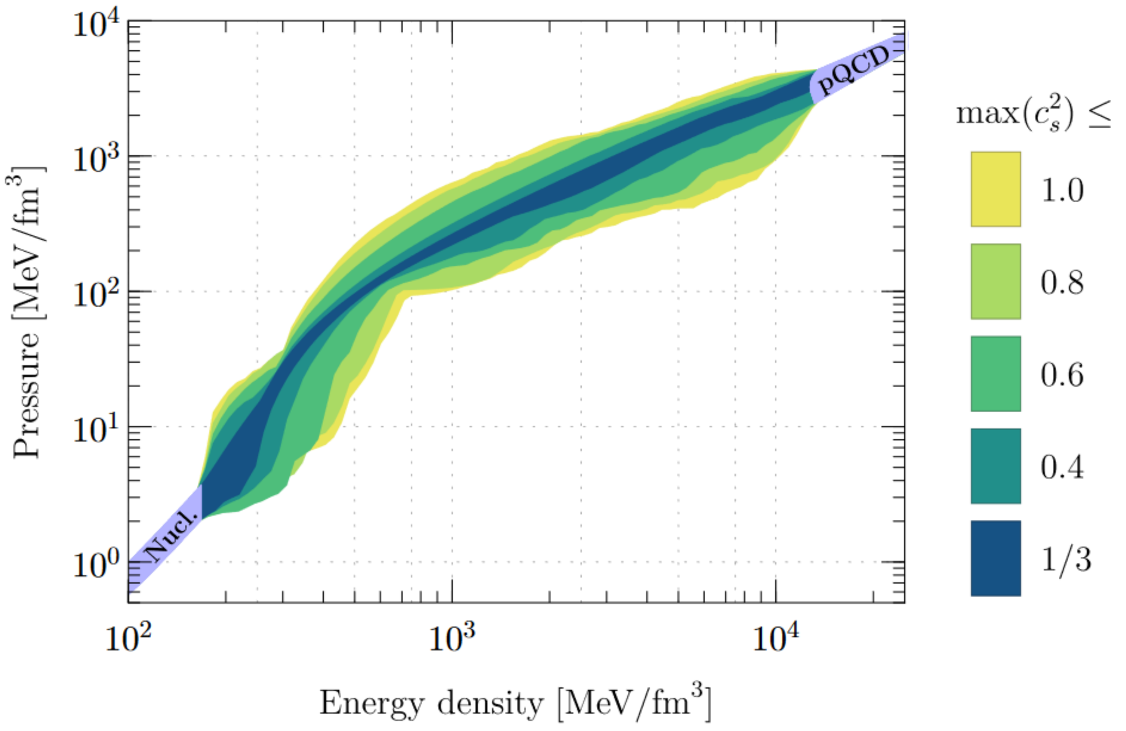
DOI: 10.1103/PhysRevD.80.066003

PACS numbers: 11.25.Tq, 11.15.Pg

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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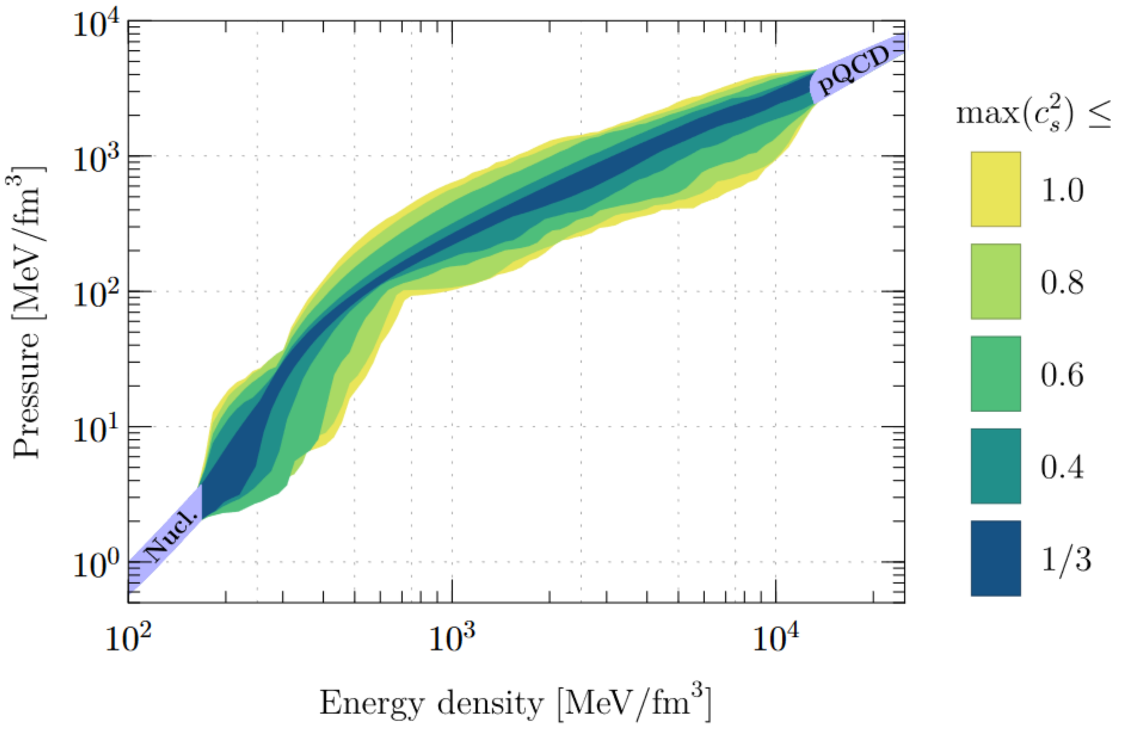

In recent work, also take into account:

- 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

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

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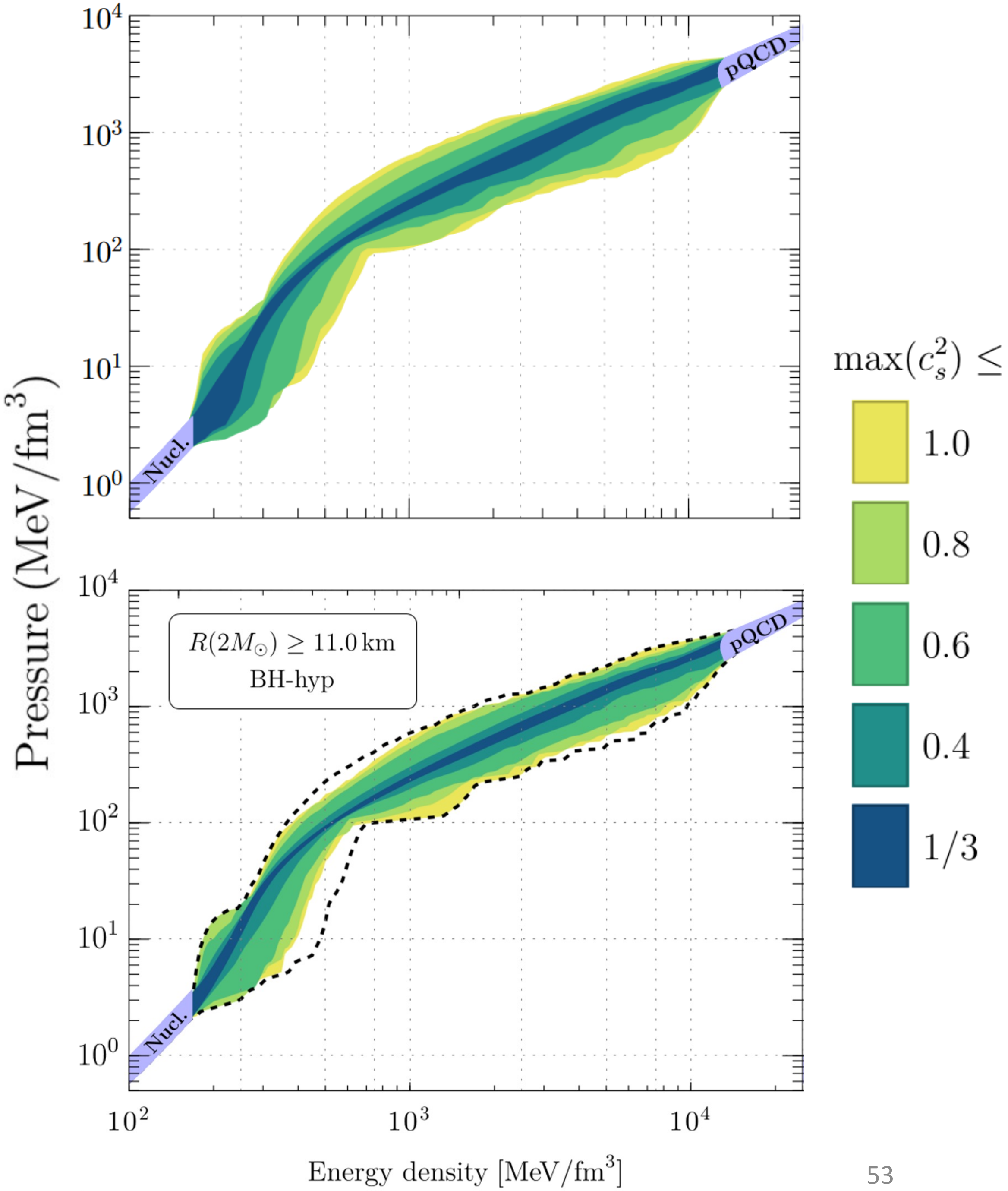

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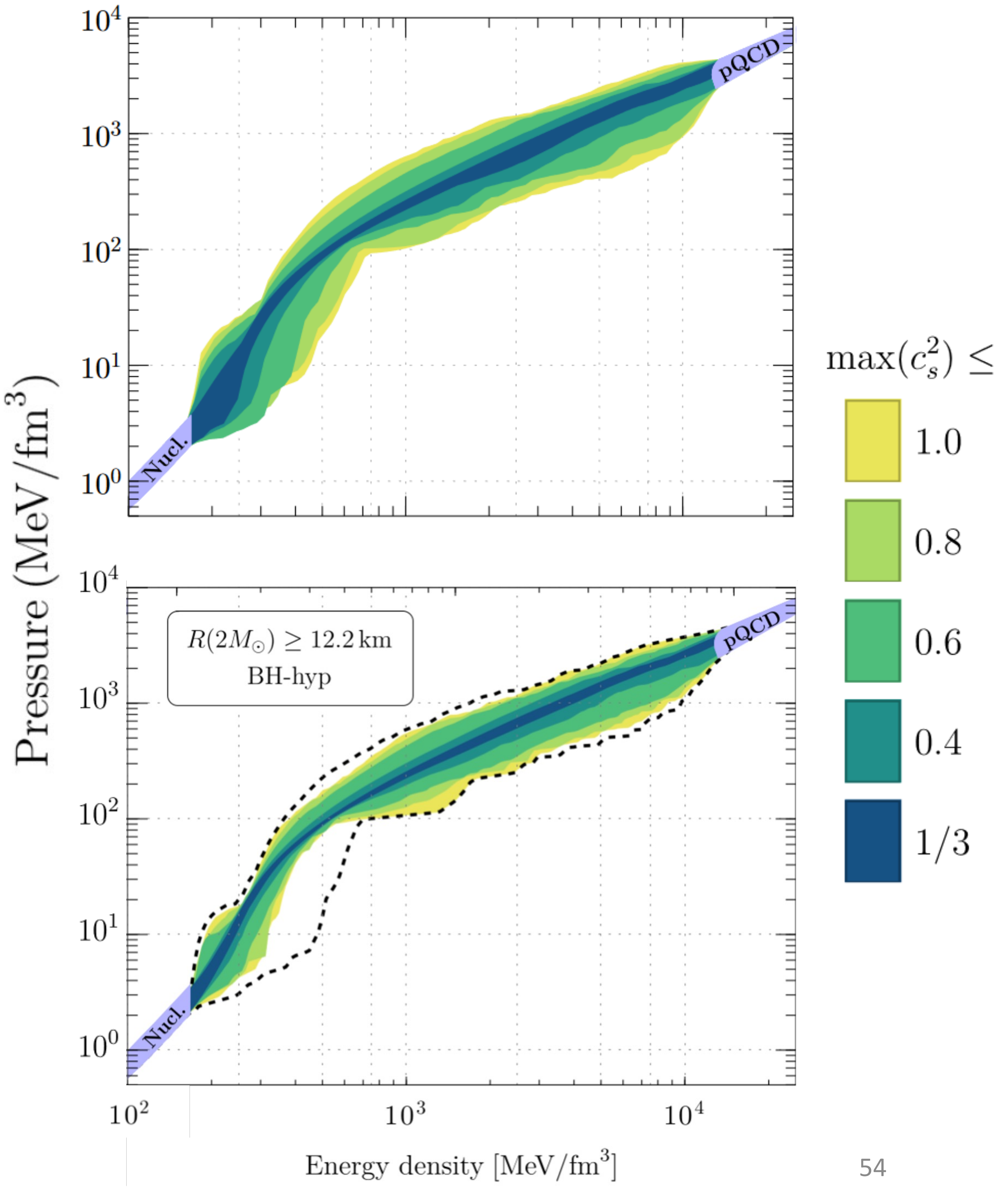

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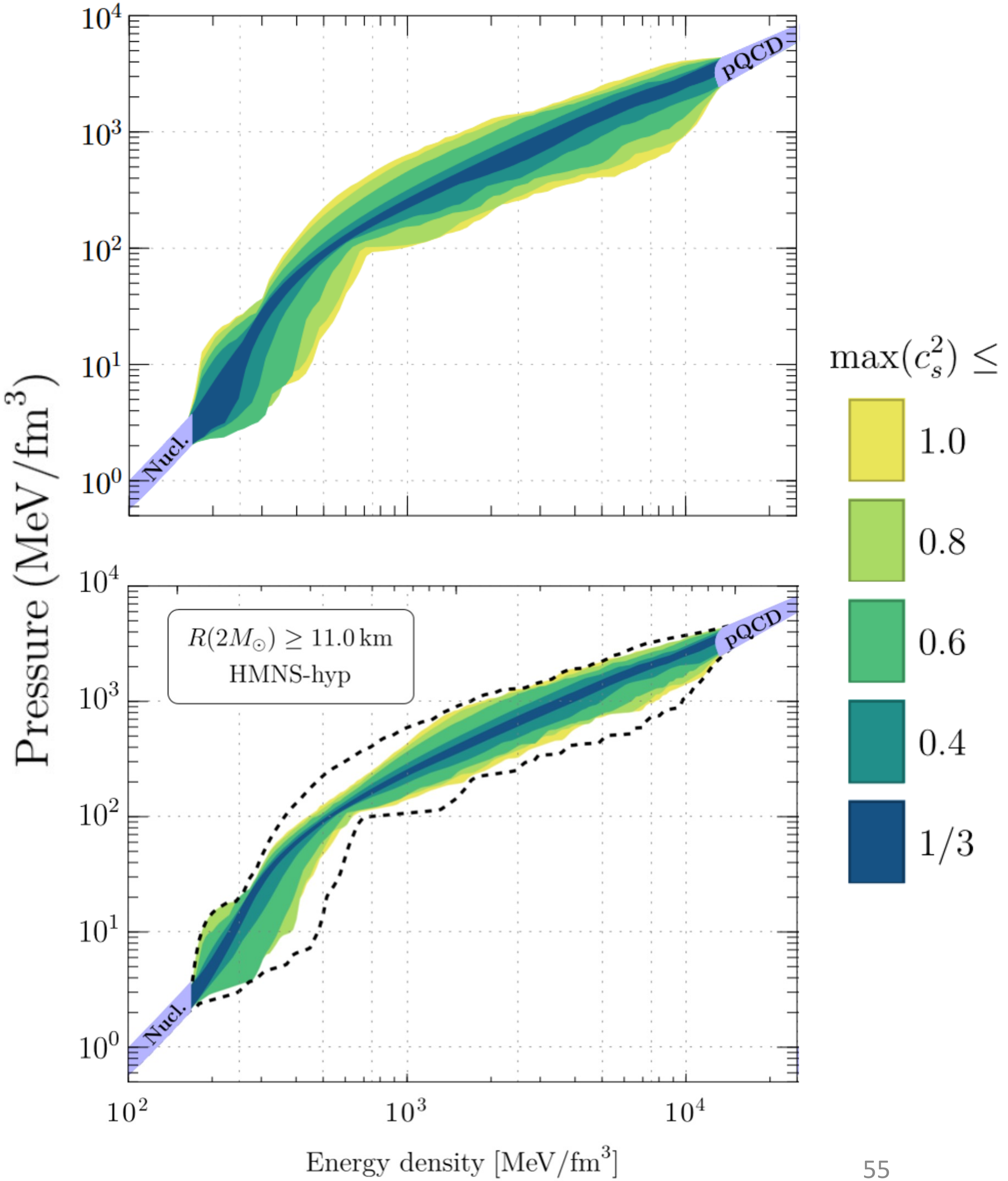

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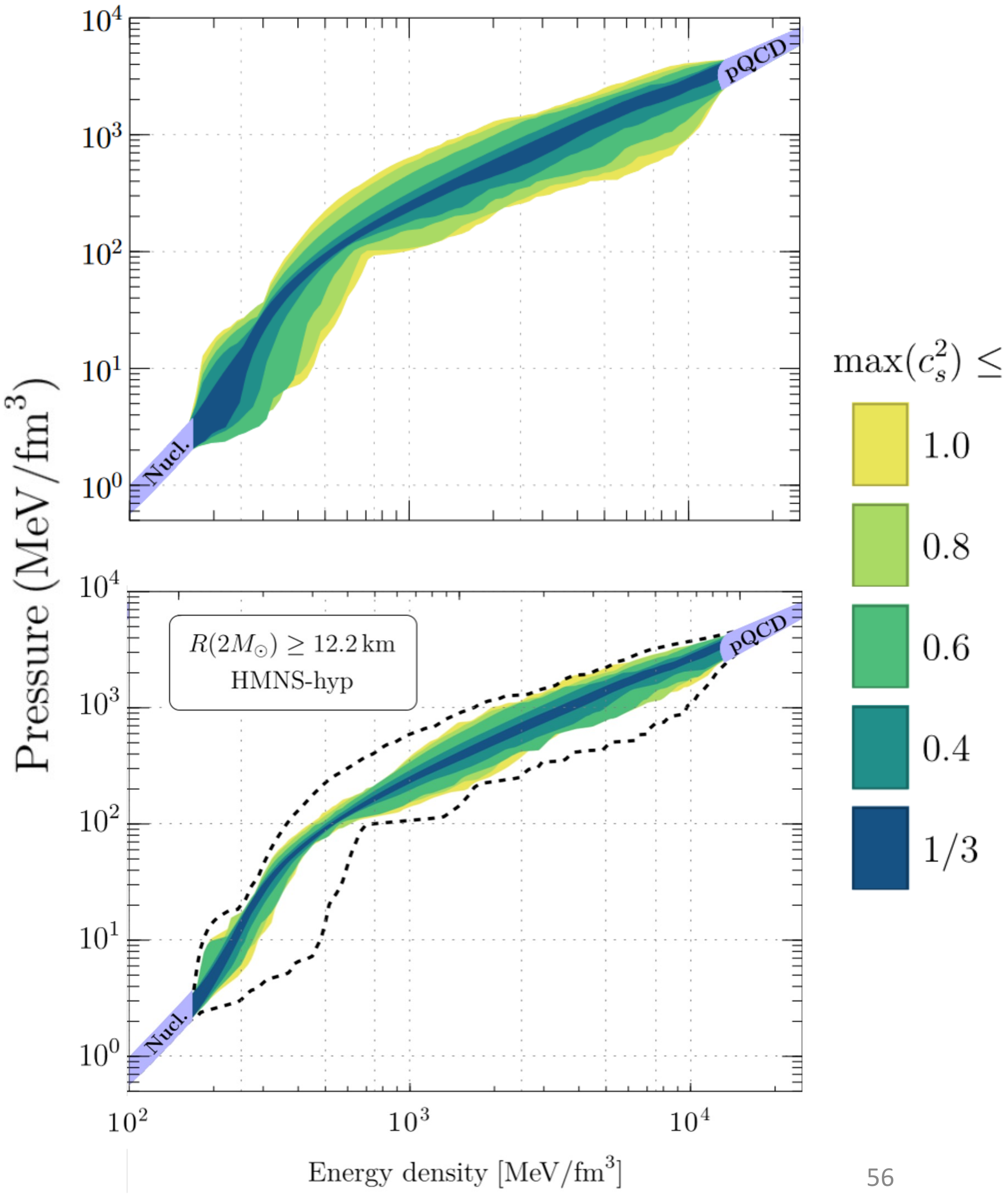
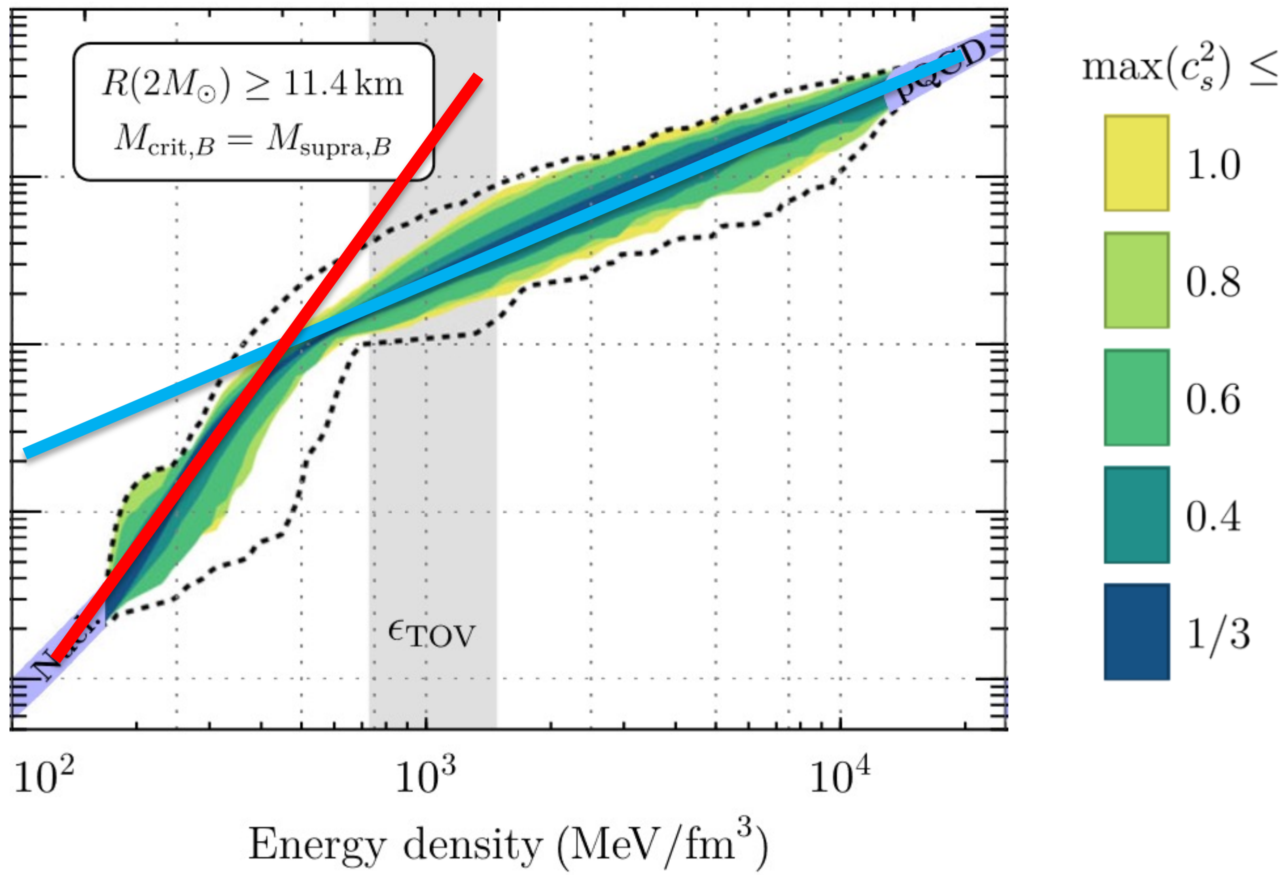
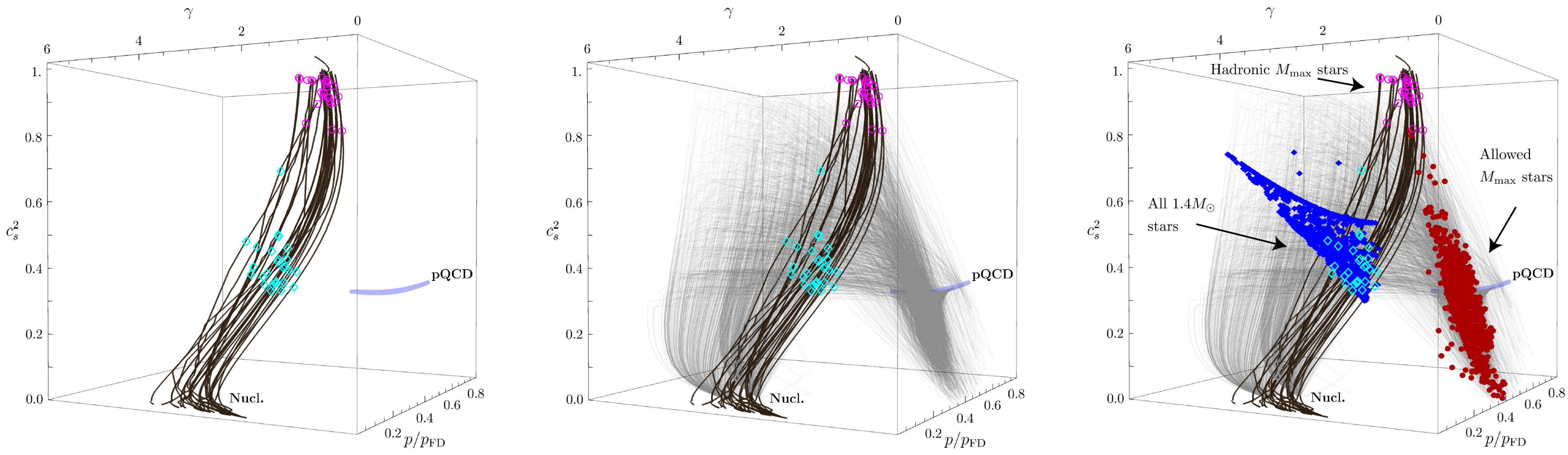




In particular the low-c_s EoSs suggest a two-phase structure

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

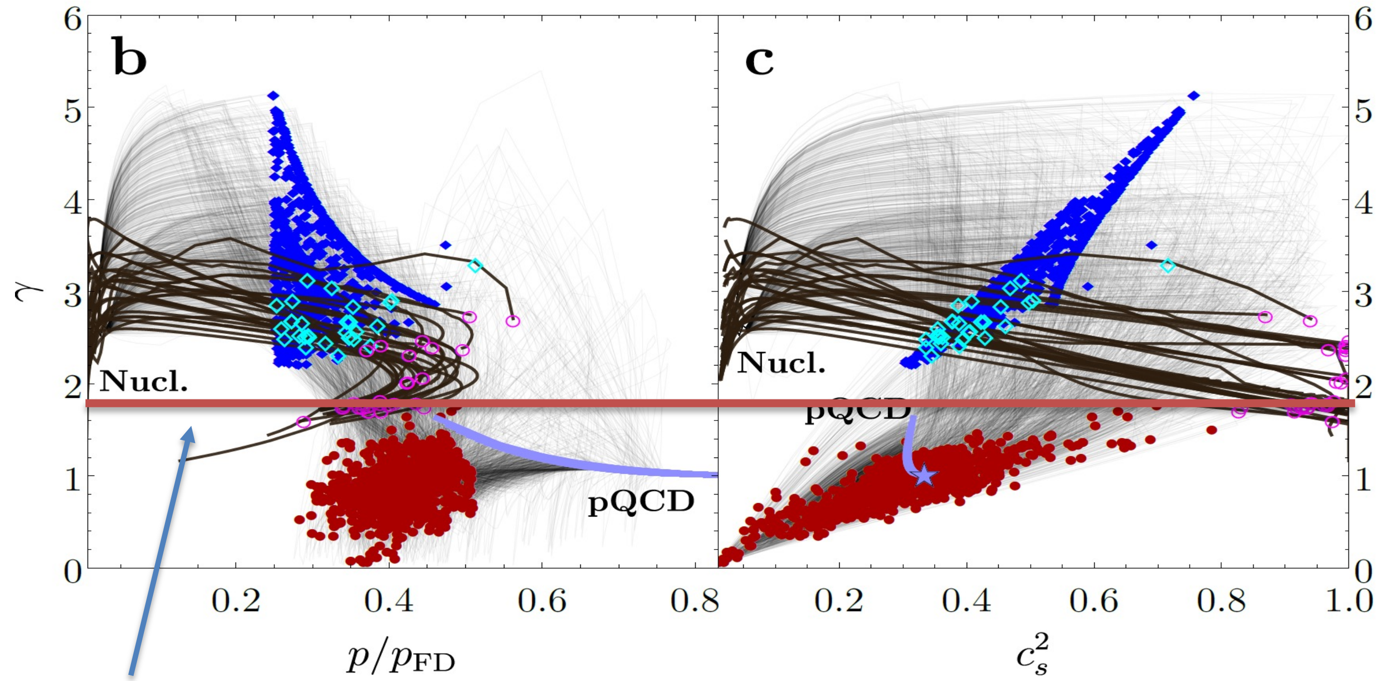
$\gamma \equiv \frac{d \ln p}{d \ln \epsilon} \approx 1$ in nearly conformal QM, ~2.5 in sub-n_s nuclear matter



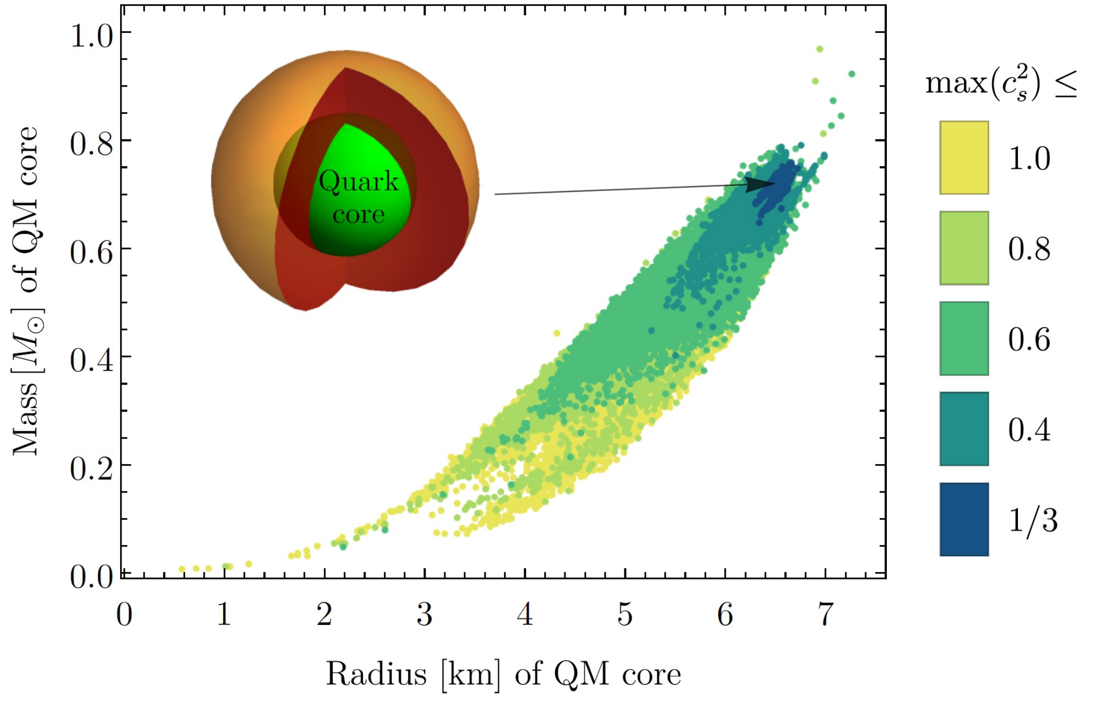
Detailed comparison of interpolated EoSs with nuclear matter models and pQCD limit reveals $M_{\max}$ centres to reside closer to quark than nuclear-matter limit. Large QM-like cores for moderate latent heats and max(c_s^2).

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

[Annala et al., Nature Physics (2020); Annala et al., PRX 12 (2022)]



Approximative criterion for the onset of QM



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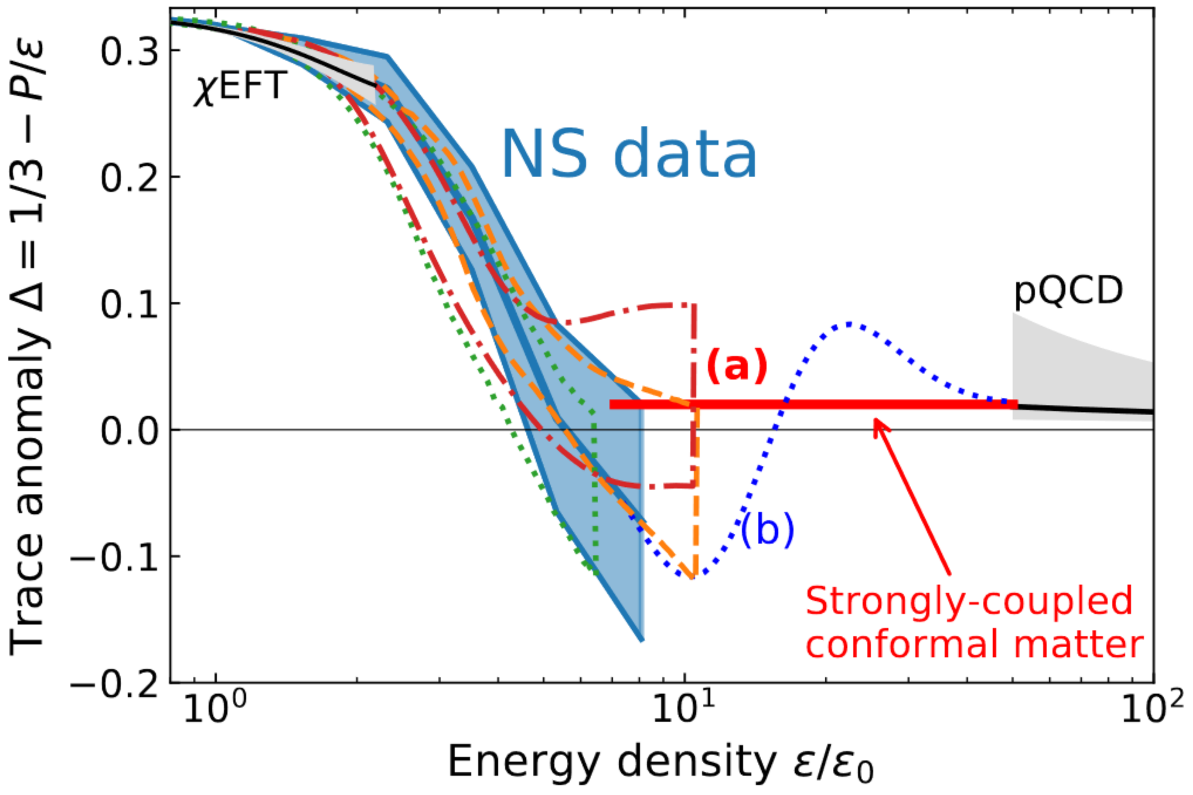

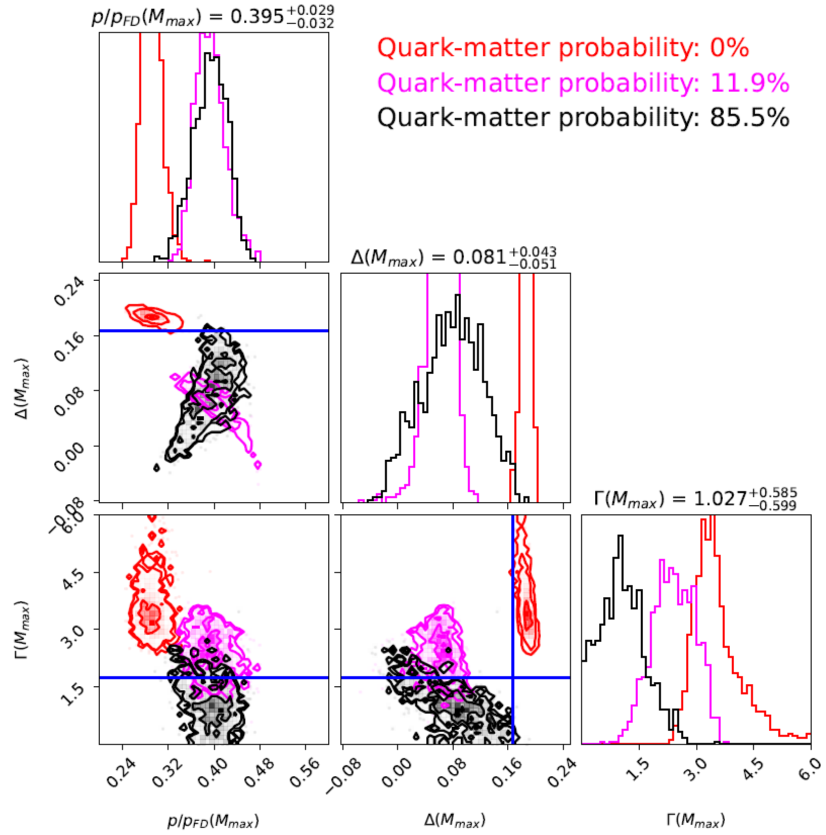

In addition to γ and c_s^2, normalized trace anomaly $\Delta \equiv \frac{\epsilon - 3p}{3\epsilon} = \frac{1}{3} - \frac{p}{\epsilon}$ has been suggested as useful measure of conformality. [Fujimoto et al., 2207.06753]

To be conservative, demand that in QM $\gamma < 1.75$, $p/p_{\mathrm{free}} > 0.4$ & $|\Delta| < 1/6$. Even then, likelihood of QM cores in M_{max} stars currently ~ 0.9!

[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 progress from inclusion of mixed contributions and resummations
- Astrophysical observations coming up:
  - GW observatory KAGRA started in 2020; Einstein Telescope in 2030s
  - On X-ray front NICER, to be complemented by eXTP around 2025
- Model-independent EoS studies:
  - Bayesian studies, enabling use of many more measurements
  - Incorporating explicit first-order transitions
- Yet, no ab-initio method with realistic chances between 2 and $20n_s$
  - Transport, out-of-equilibrium dynamics particular challenges