Microphysics of neutron stars: first-principles approaches to open problems

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Holography and dense matter

Paris, 11 June 2024

pQCD at high density:

1) Gorda, Kurkela, Paatelainen, Säppi, AV, PRL 127, 2103.05658
2) Gorda, Paatelainen, Säppi, Seppänen, PRL 131, 2307. 08734

Applications to neutron-star physics:

1) Annala et al., Nature Phys. 16 (2020), 1903.09121
2) Annala et al., Nature Comm. 14 (2023), 2303.11356

Transport via pQCD and holography:

1) Cruz et al., 2402.00621

Recent lecture notes (on all of the above):

1) AV, Acta Phys. Polon. B 55 (2024), 2405.01141

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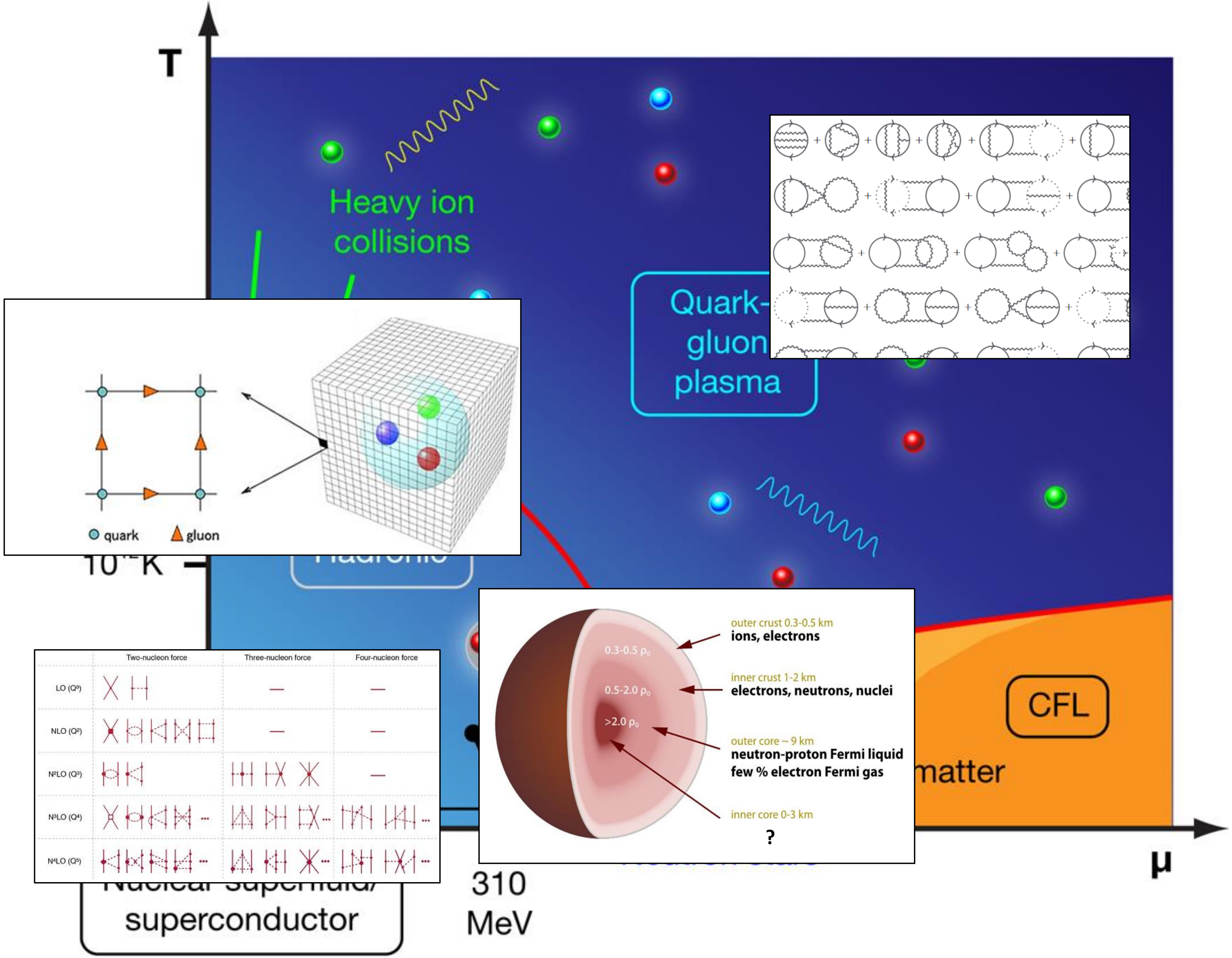
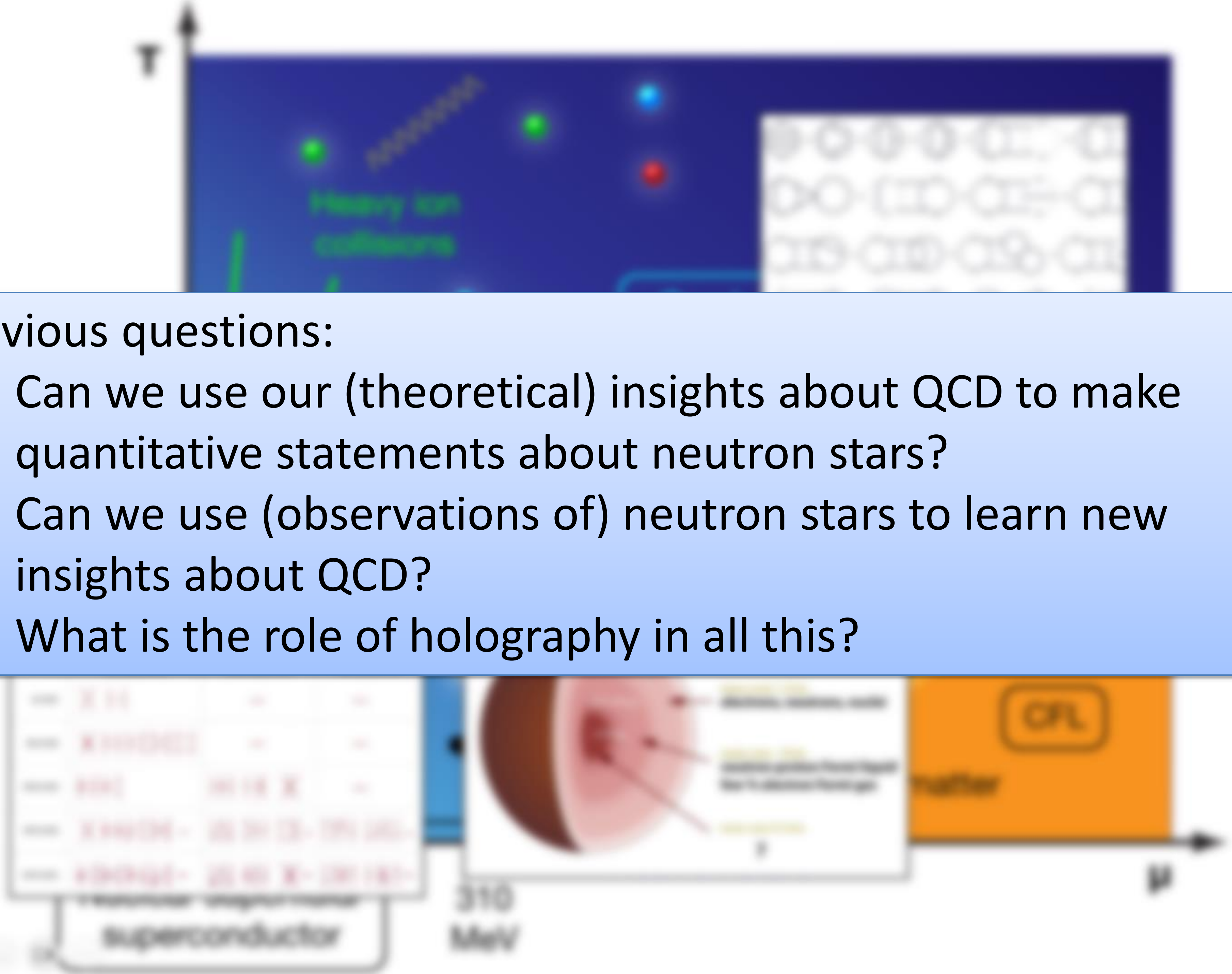

T
Heavy ion collisions
Quark-gluon plasma
quark
gluon
Two-nucleon force
Three-nucleon force
Four-nucleon force
LO (Q⁰)
NLO (Q²)
N²LO (Q³)
N³LO (Q⁴)
N⁴LO (Q⁵)
0.3-0.5 ρ₀
0.5-2.0 ρ₀
>2.0 ρ₀
outer crust 0.3-0.5 km
ions, electrons
inner crust 1-2 km
electrons, neutrons, nuclei
outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas
inner core 0-3 km
?
CFL
matter
μ
310 MeV
superconductor



Obvious questions:

1) Can we use our (theoretical) insights about QCD to make quantitative statements about neutron stars?
2) Can we use (observations of) neutron stars to learn new insights about QCD?
3) What is the role of holography in all this?

Plan of the talk:

I. Equilibrium thermodynamics of dense QCD matter: interplay of theory and observations
II. From the EoS to the phases of QCD: do massive stars host quark-matter cores?
III. Transport and dissipation: bulk viscosity from pQCD and holography

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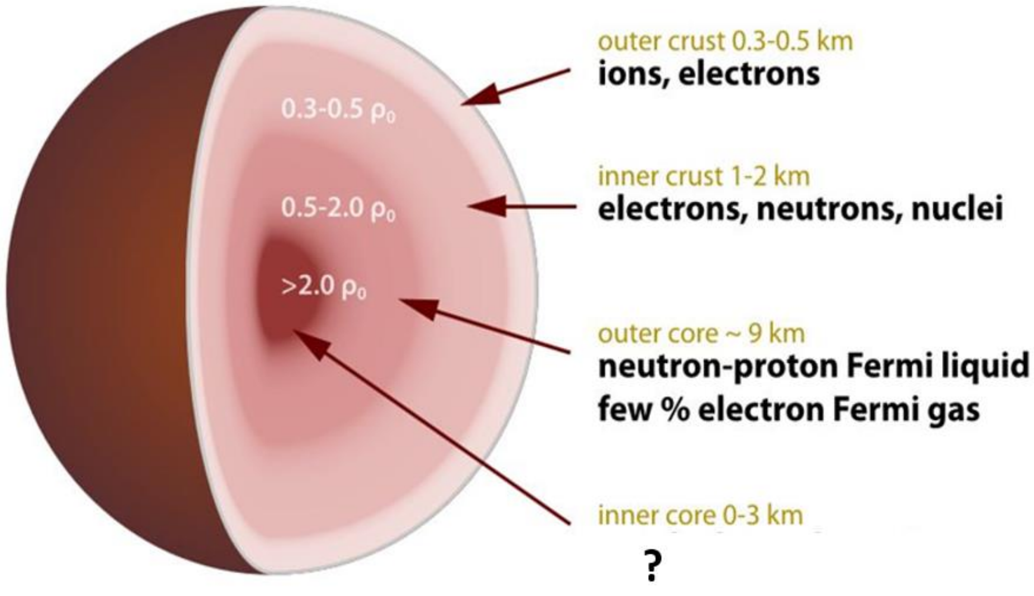
NS matter: from dilute crust to ultradense core

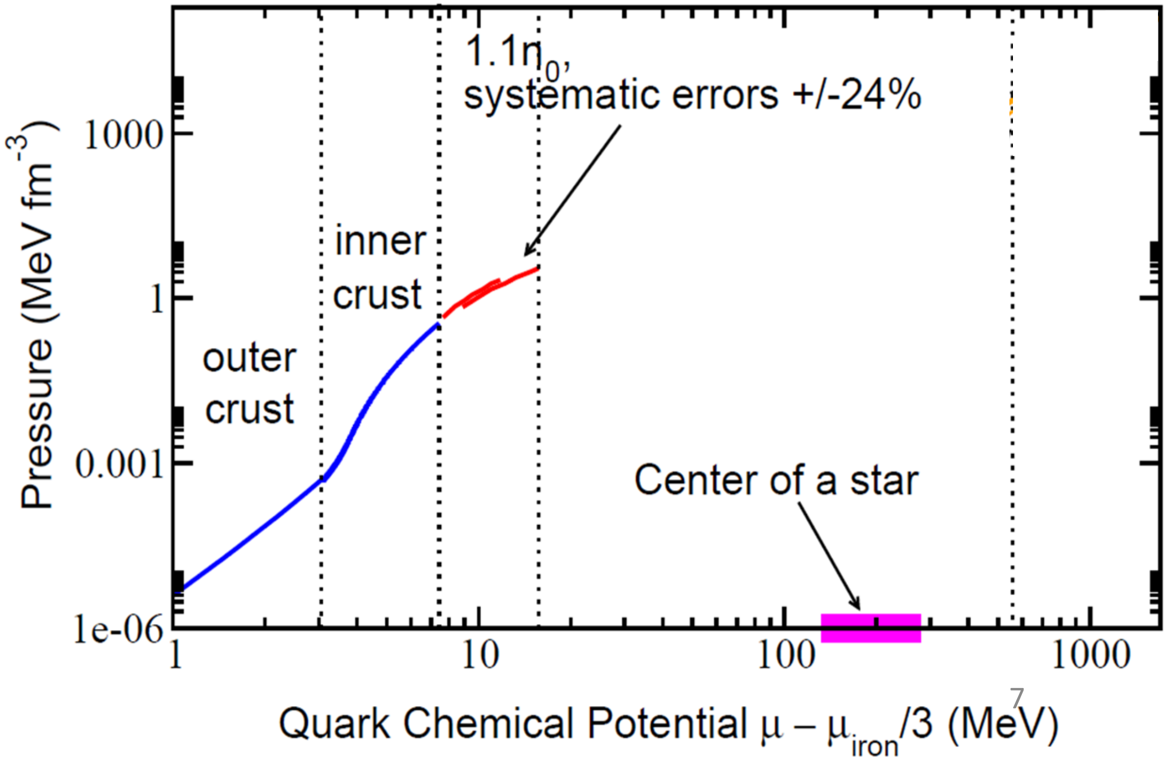
Proceeding inwards from the crust:

- μ_B increases gradually, starting from μ_{Fe}
- Baryon/mass density increase beyond saturation density $\approx 0.16/\text{fm}^3$
- Composition changes from ions to nuclei to neutron liquid and beyond
- Good approximations: $T \approx 0 \approx n_Q$



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

- Systematic effective theory framework: Chiral Effective Field 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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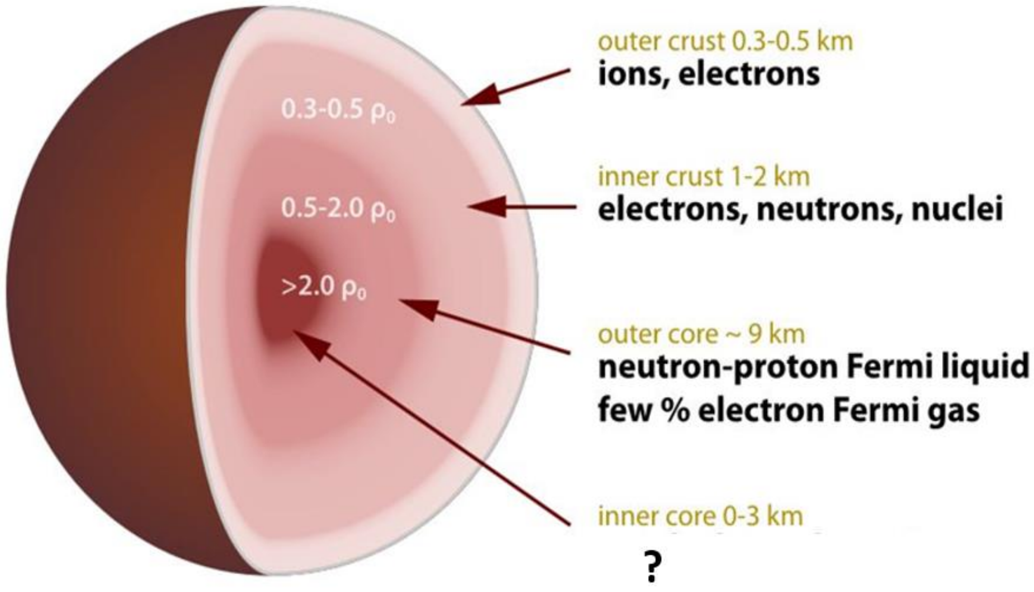
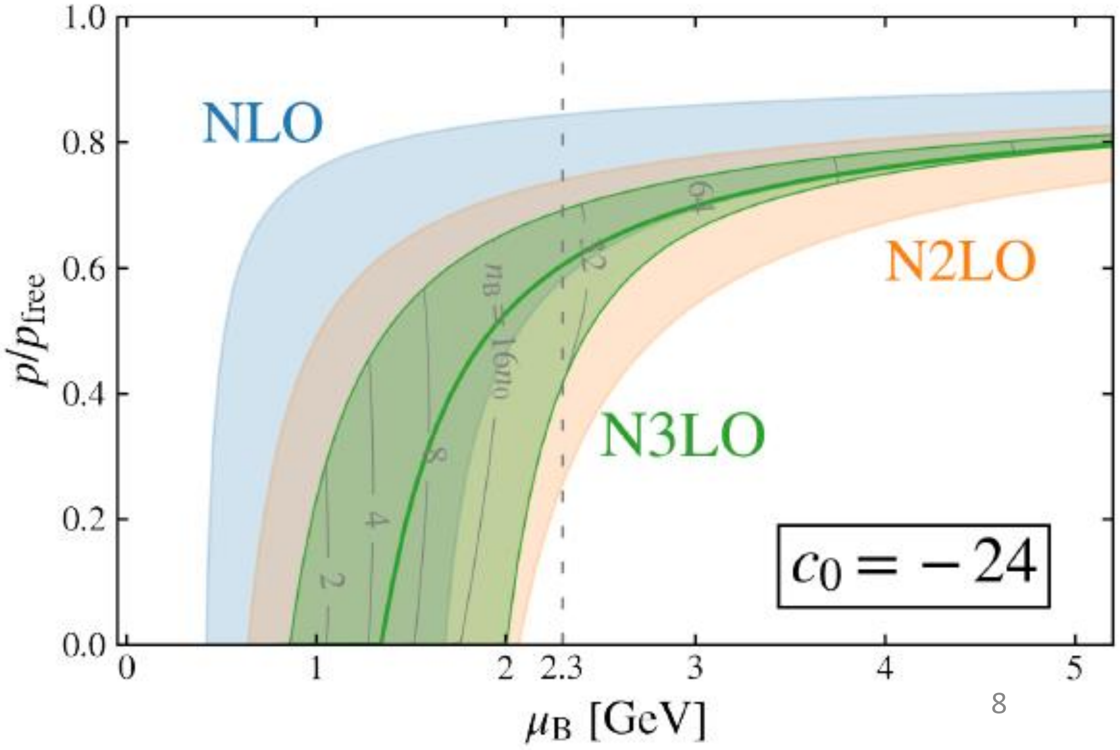
At high density, asymptotic freedom ⇒ weakening coupling and deconfinement

- State-of-the-art pQCD EoS at partial NNNLO, with soft and mixed sectors fully determined [Gorda et al., PRL 127 (2021)]
- New results hint at marked improvement at upcoming α_s^3 order [Gorda et al., PRL 131 (2023)]





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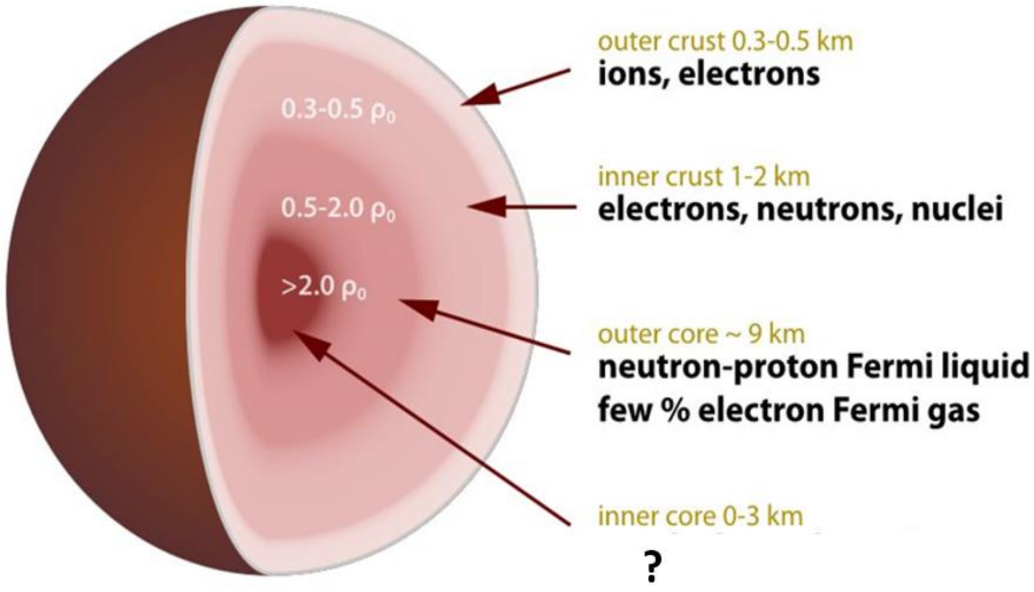
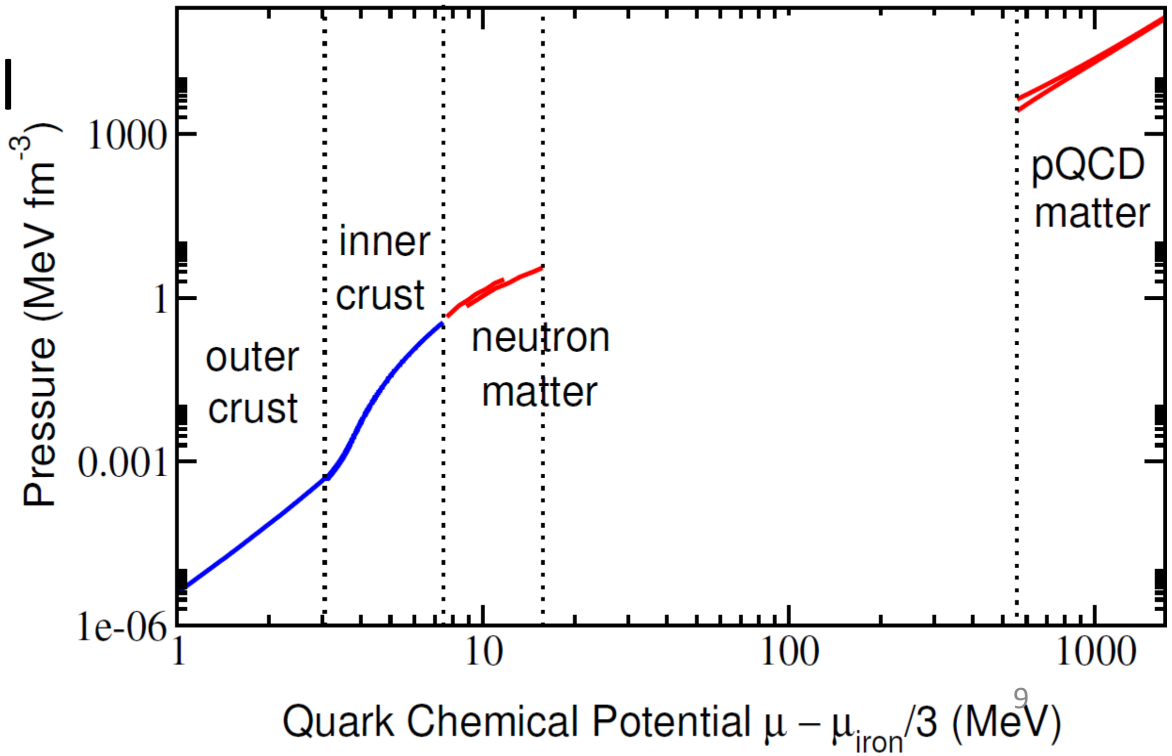


∴ Low- and high-density limits under control but extensive no man's land at intermed. densities. Possibilities for proceeding:

1) Solve the sign problem of lattice QCD
2) Use phenomenological models
3) Allow all possible behaviors for the EoS, perhaps aided by holographic insights

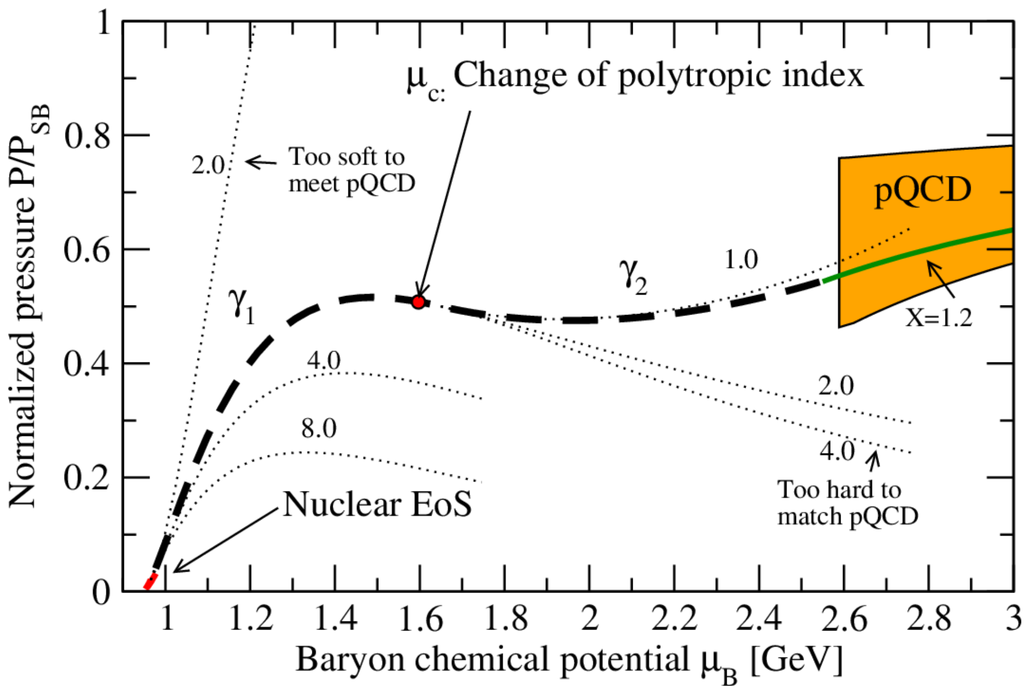


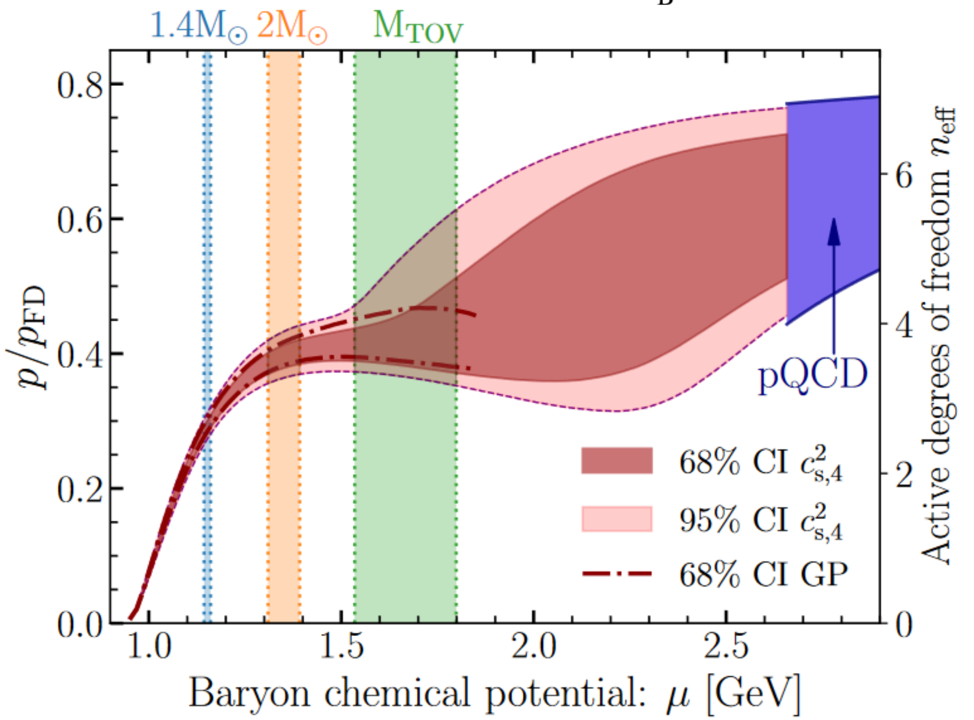
Possible way to proceed: build huge ensembles of randomly generated interpolators with piecewise basis functions – or use nonparametric Gaussian Process regression

Require for all interpolated EoSs:

1) Smooth matching to nuclear and quark matter EoSs
2) Continuity of p – and of n_B except at possible first-order phase transitions
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); Annala et al., Nature Phys. 16 (2020), Nature Comm. 14 (2023)]





What do we know from NS observations?

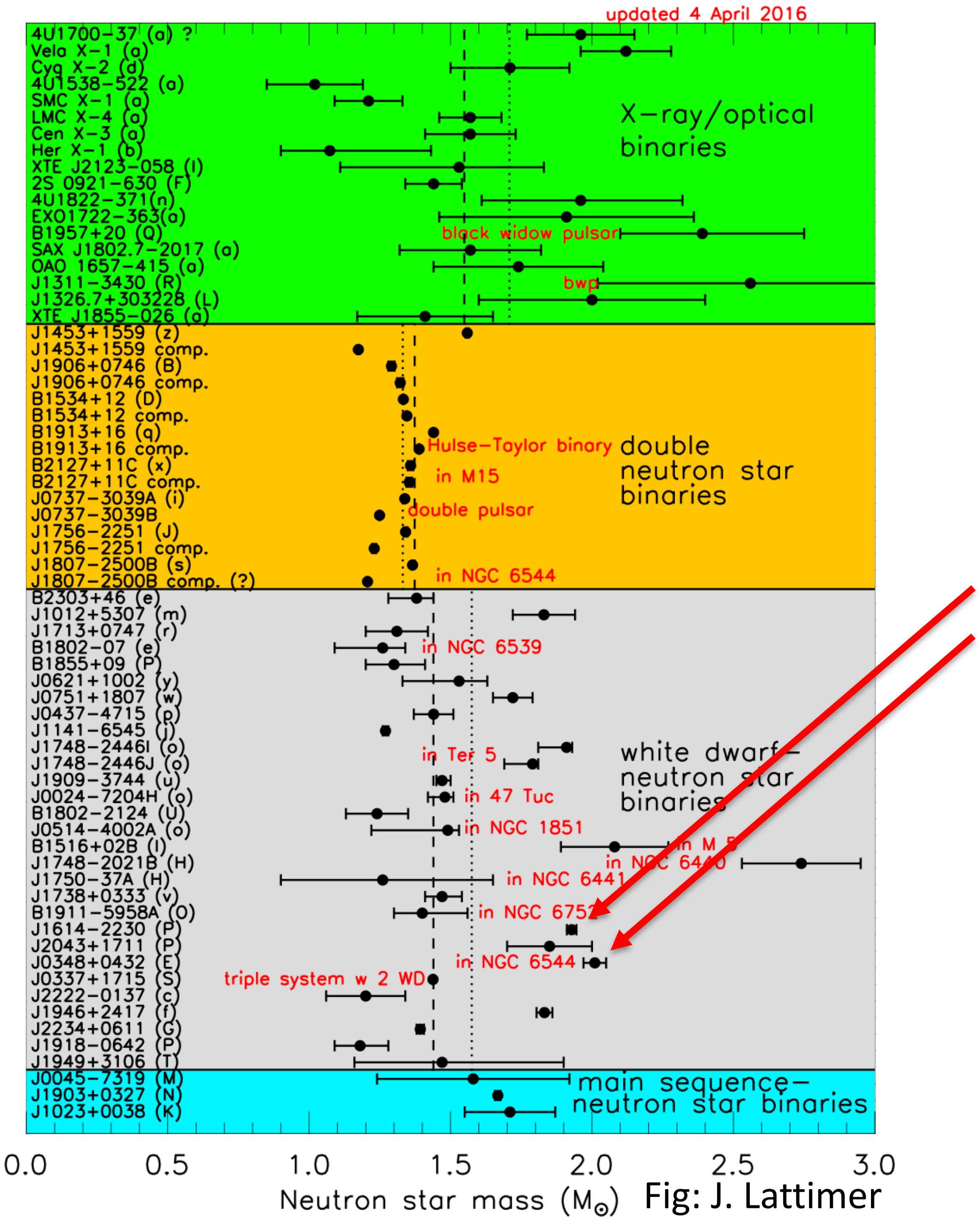
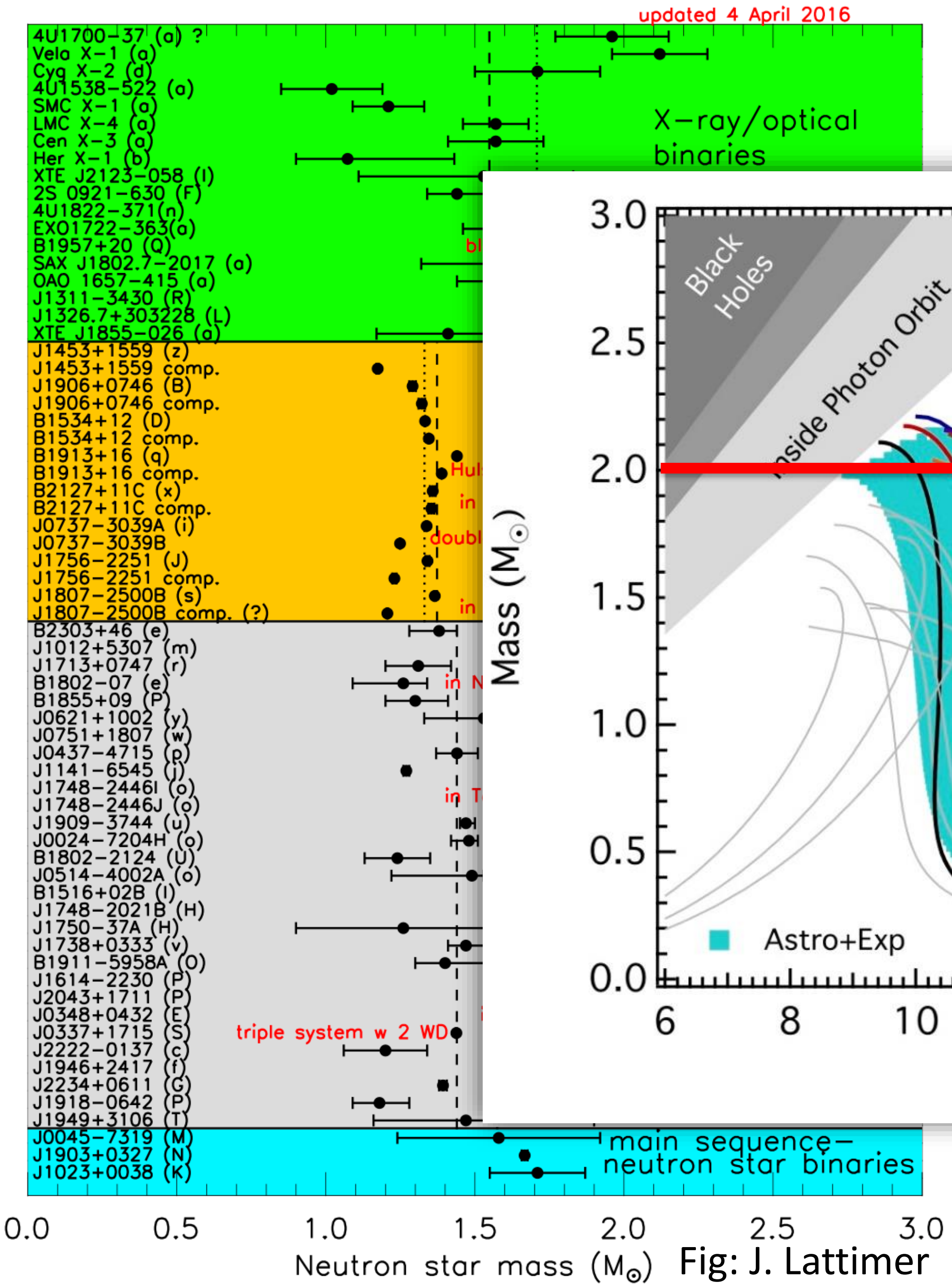


Fig: J. Lattimer

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

Demorest et al., Nature 467 (2010)
Antoniadis et al., Science 340 (2013)
Cromartie et al., Nature Astronomy 4 (2019)

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



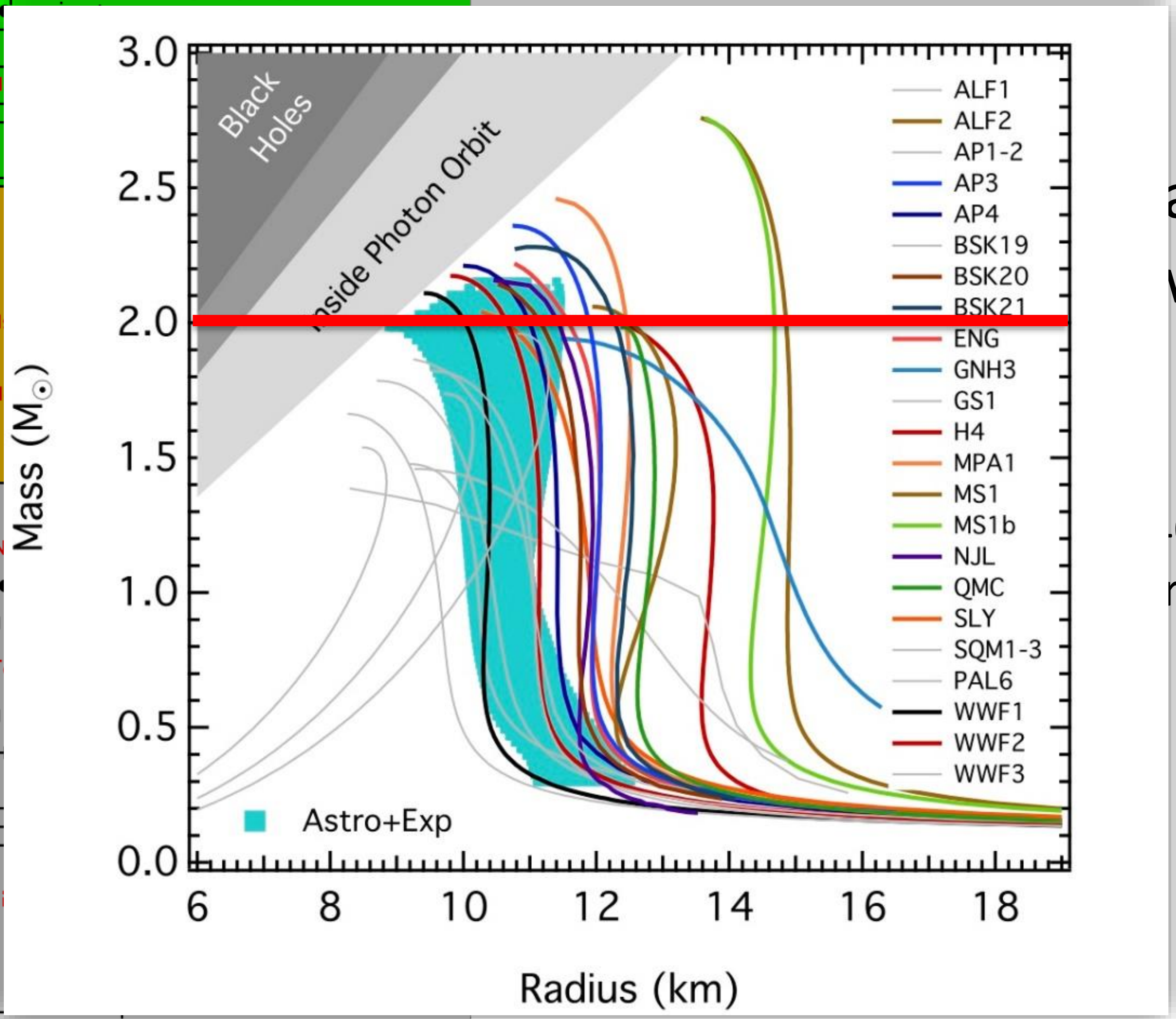


Fig: J. Lattimer

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(2010)
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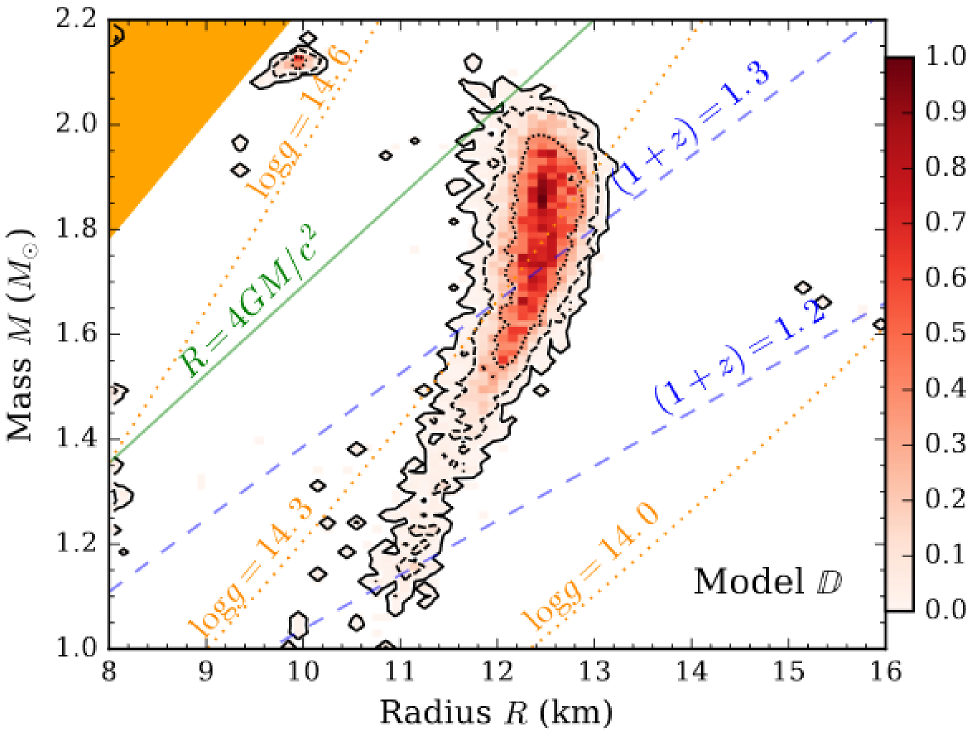
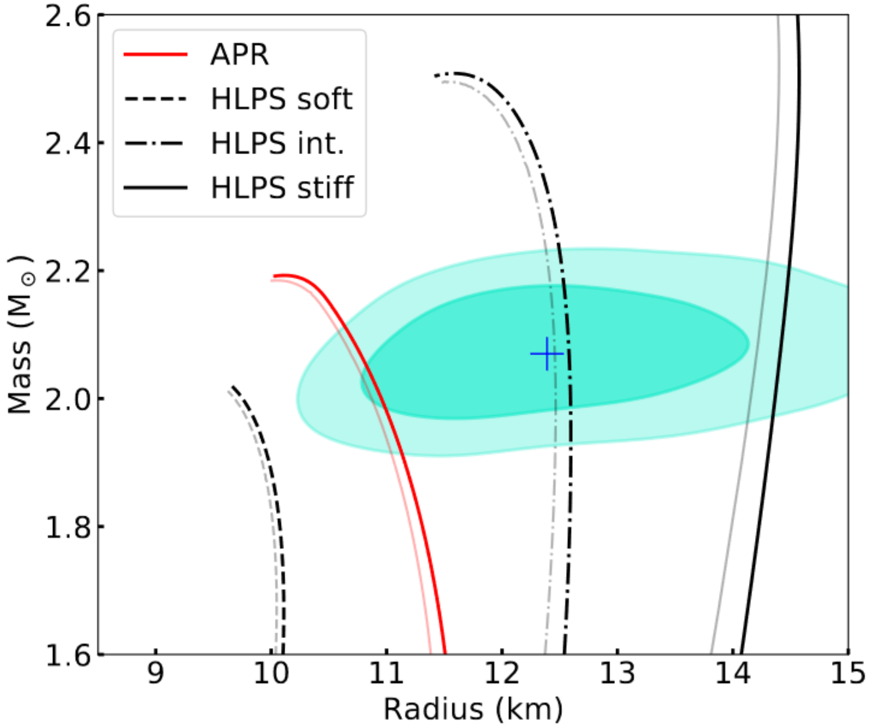
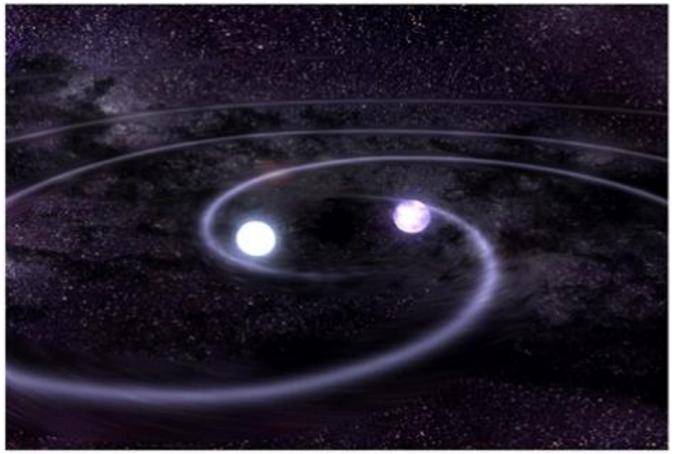
Radius (and combined MR) measurements more problematic, but recently important progress through X-ray observations:

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





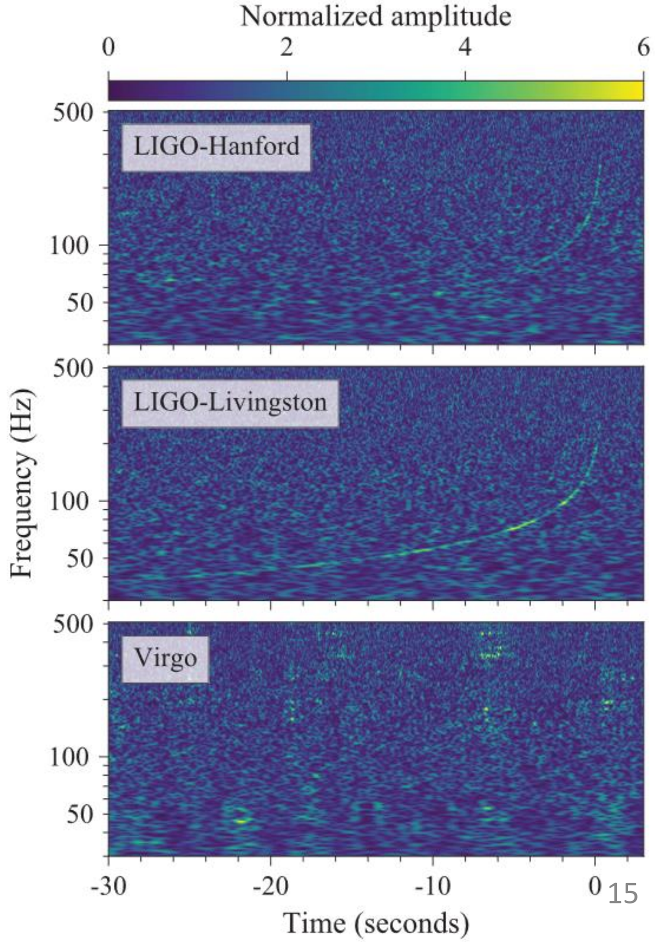
Gravitational wave breakthrough: First observed binary NS merger GW170817 by LIGO & Virgo in 2017 (and many since then)



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

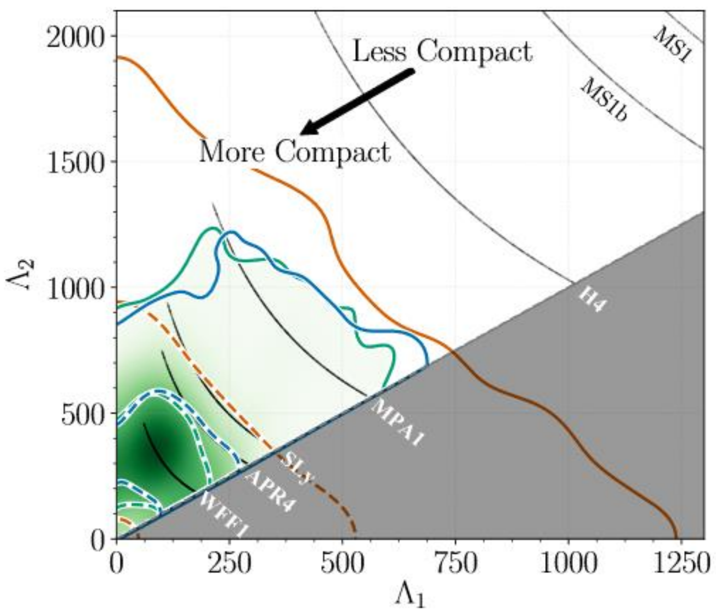
[LIGO and Virgo collaborations, PRL 119 (2017), PRL 121 (2018)]

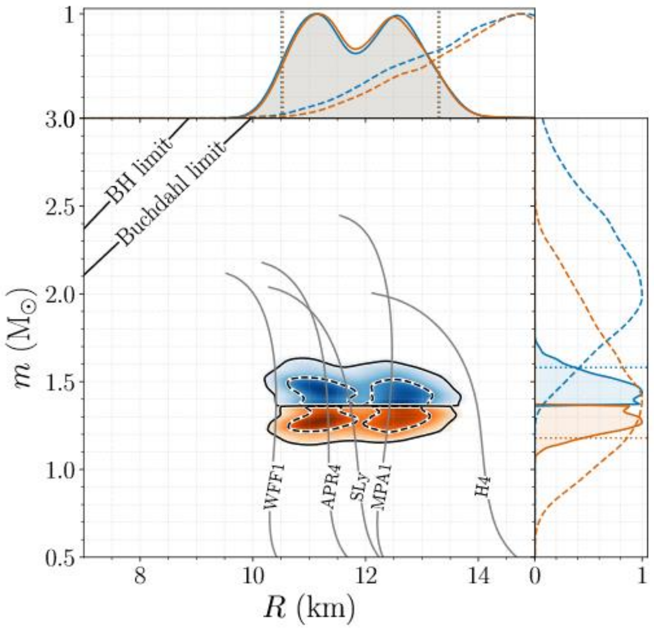


Tidal deformability: How large of a quadrupolar moment a star's gravitational field develops due to an external quadrupolar field

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

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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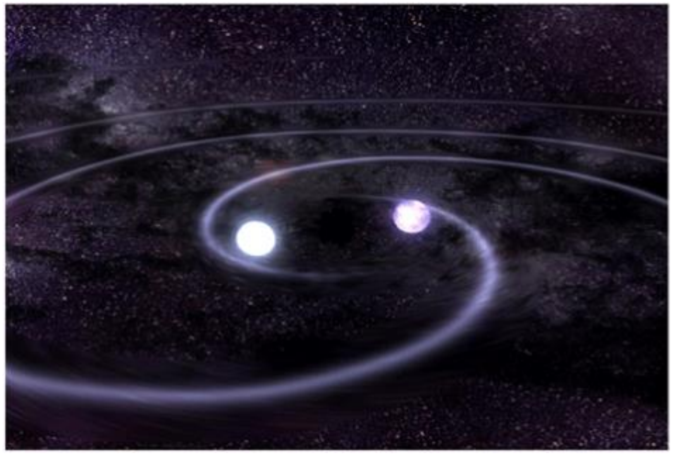

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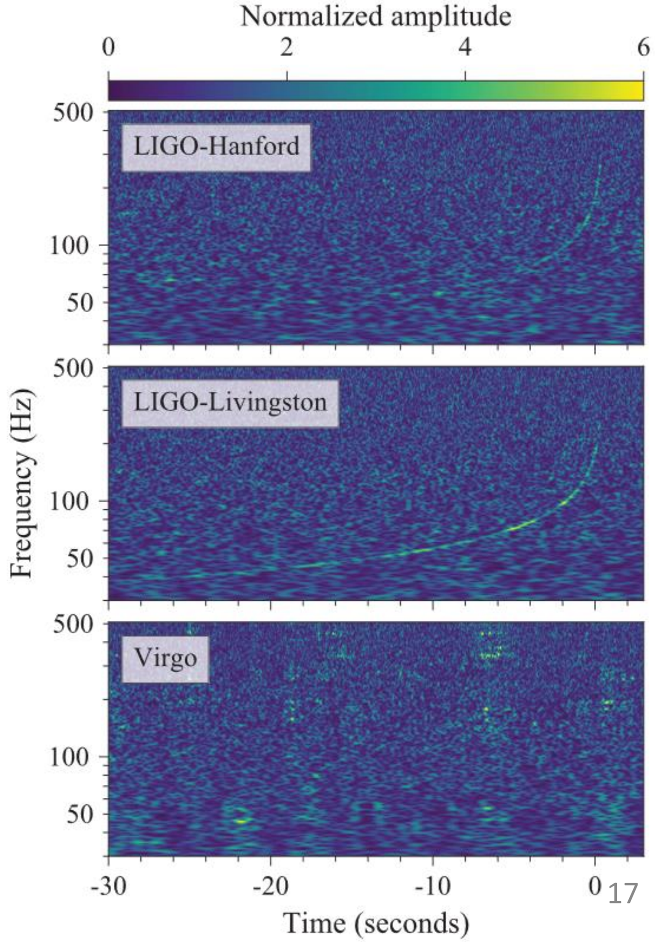


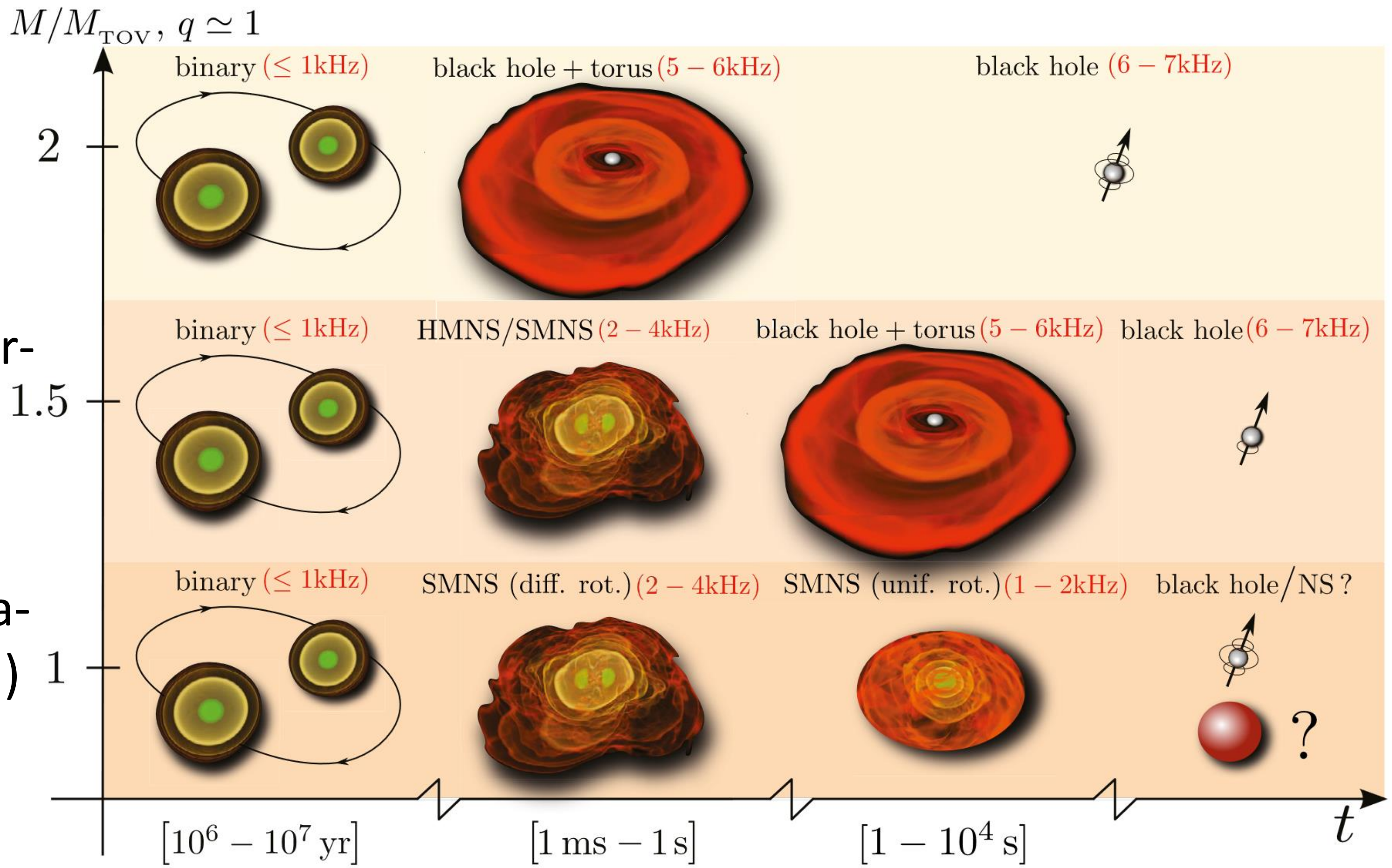
Ringdown pattern: Unlike in BH mergers, binary NS mergers expected to feature complex period of relaxation characterized by GW spectrum sensitive to both initial NS masses and the EoS

Scenario 1: prompt collapse

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

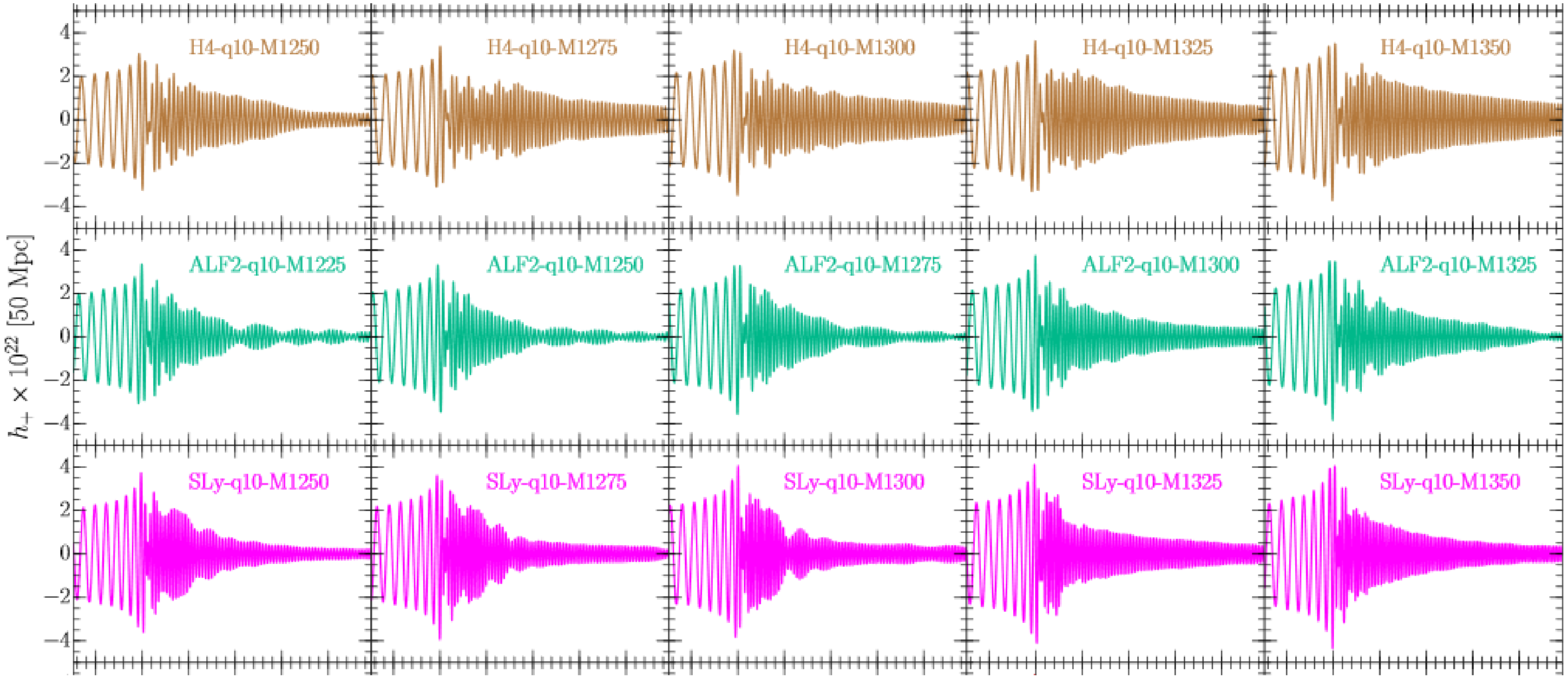
Scenario 3: collapse during supra-massive phase (uniform rotation)

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 too high for current observatories



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

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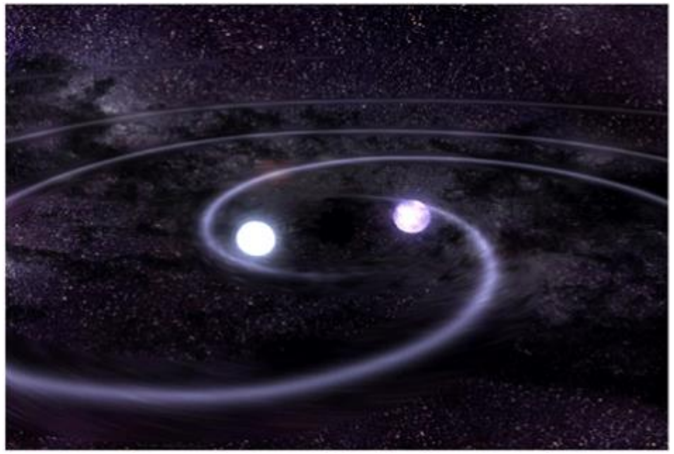
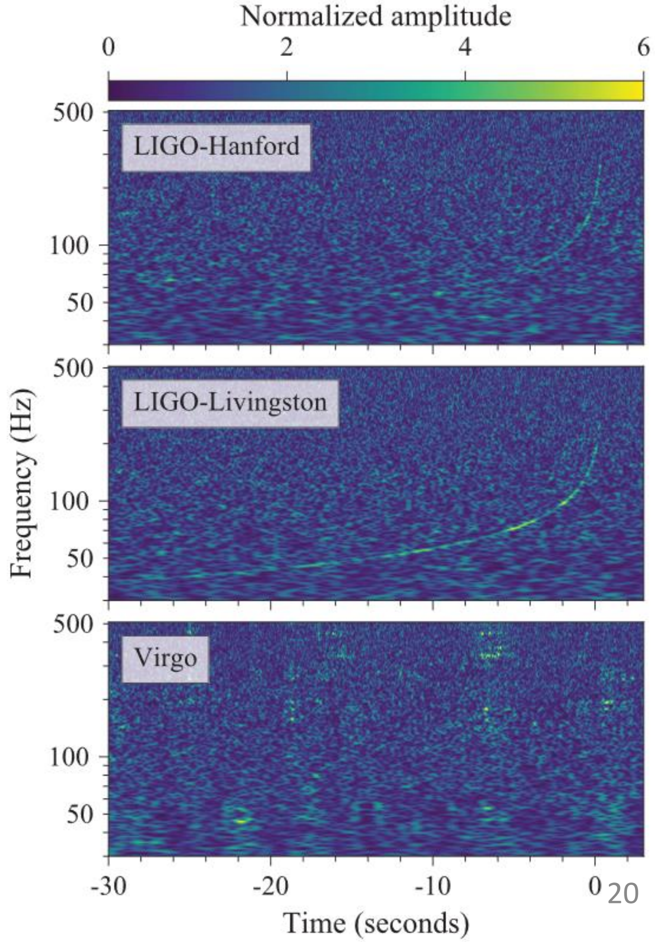
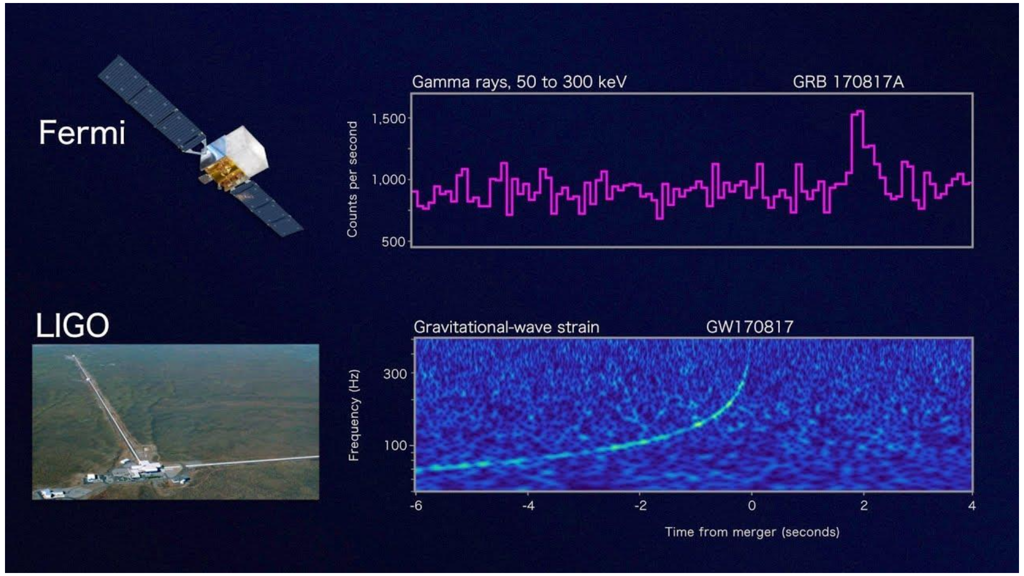




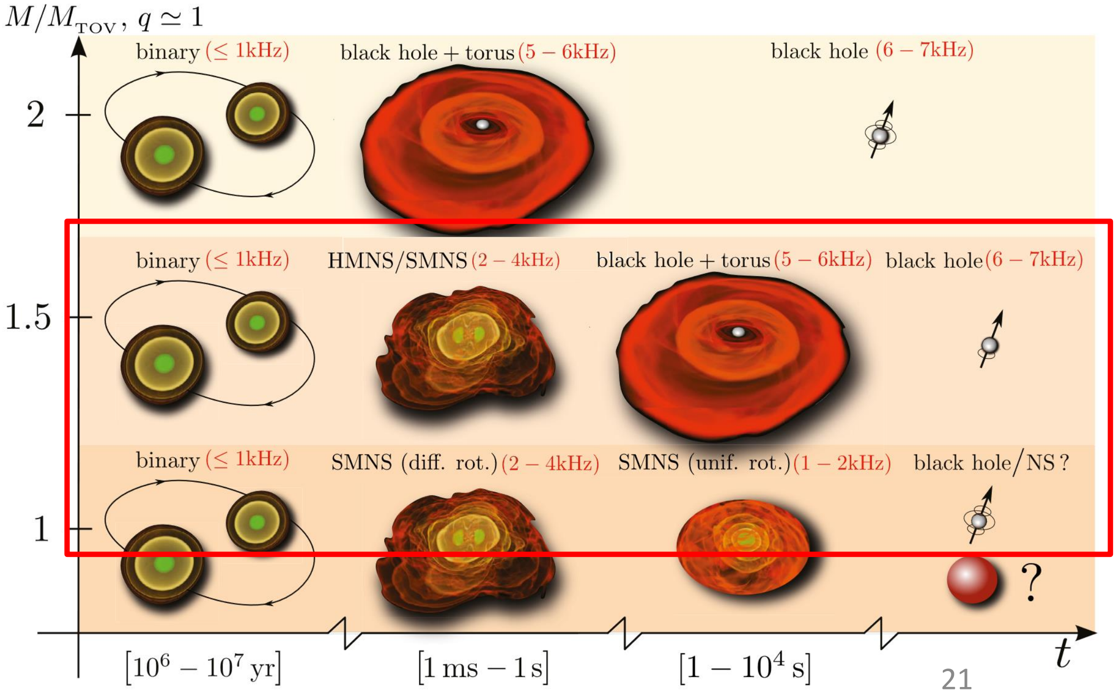
In GW170817, short gamma-ray burst 1.7s after GWs, followed by optical signal: Delayed collapse to a BH



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)

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



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NS-matter EoS: model-independent interpolation

On top of the usual low- and high-density limits, always require:

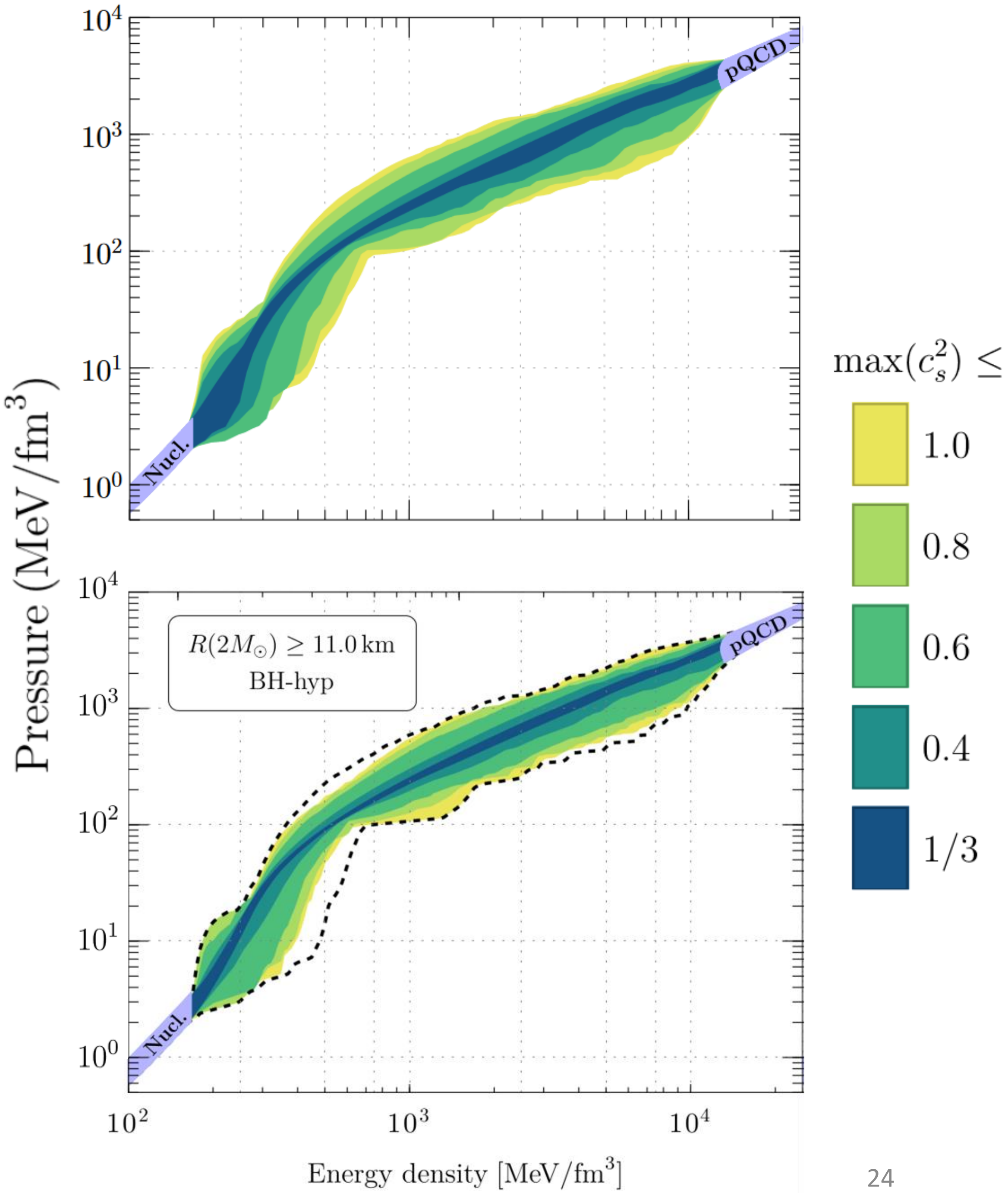
- EoS must support $2M_{\odot}$ stars
- LIGO/Virgo 90% tidal deformability limit must be satisfied

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

In addition, can also take into account:

- NICER data for PSR J0740+6620:
  - $\boldsymbol{R(2M_{\odot}) > 11.0}$**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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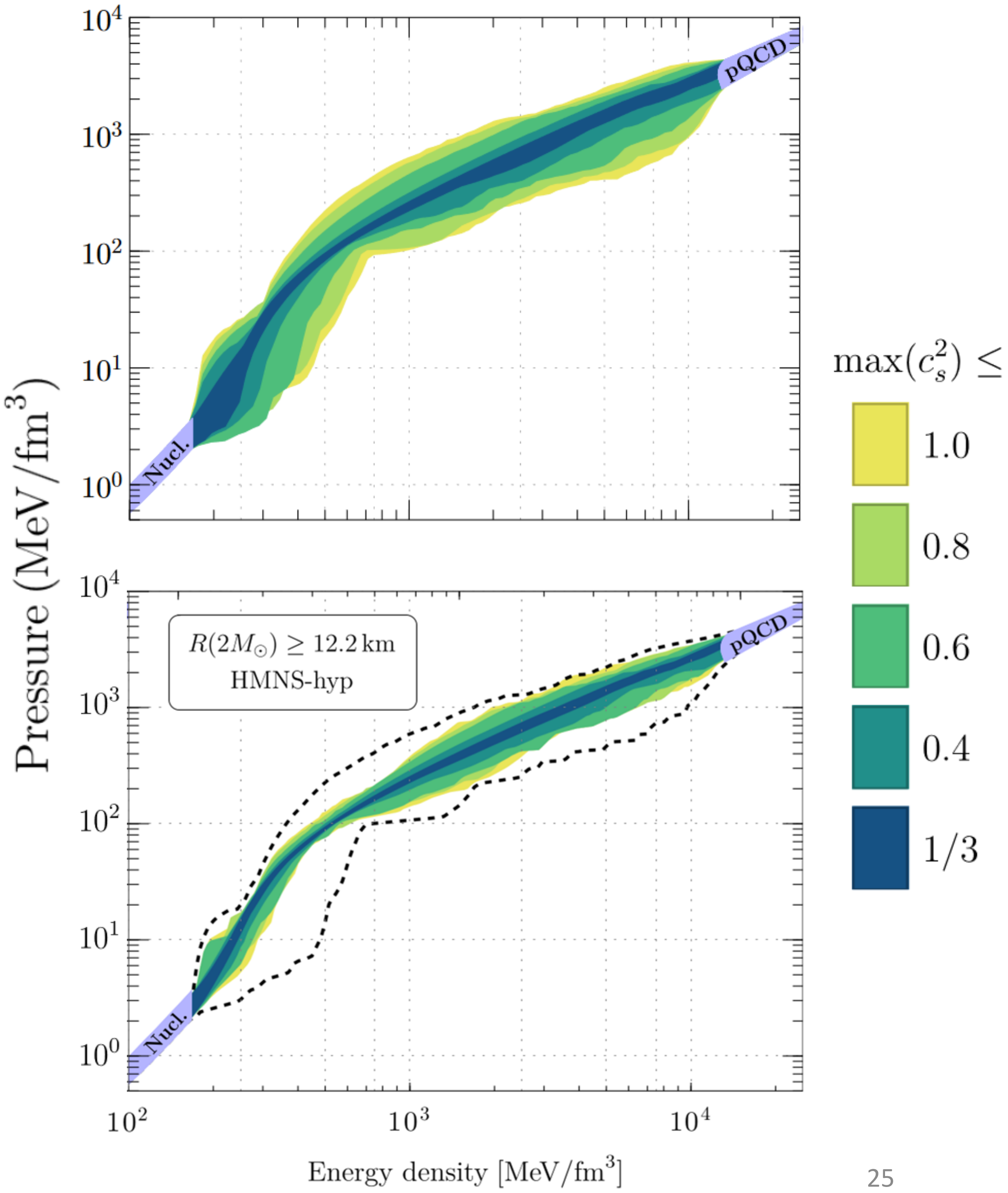
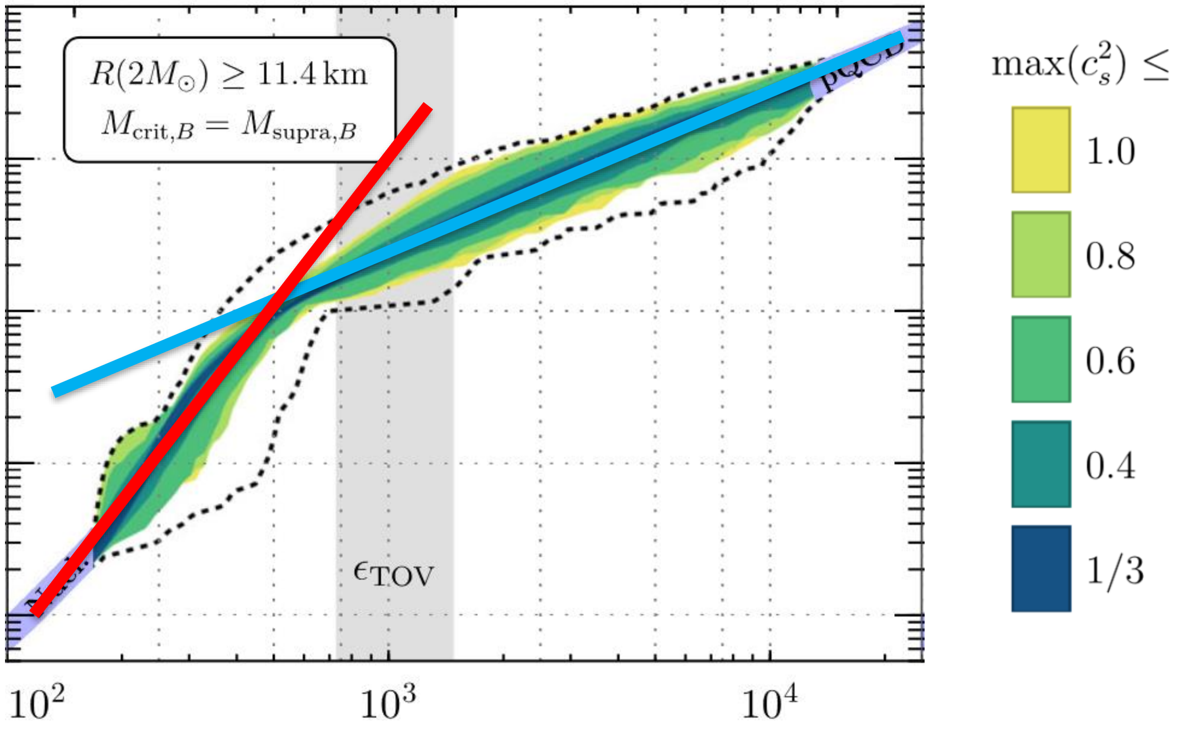


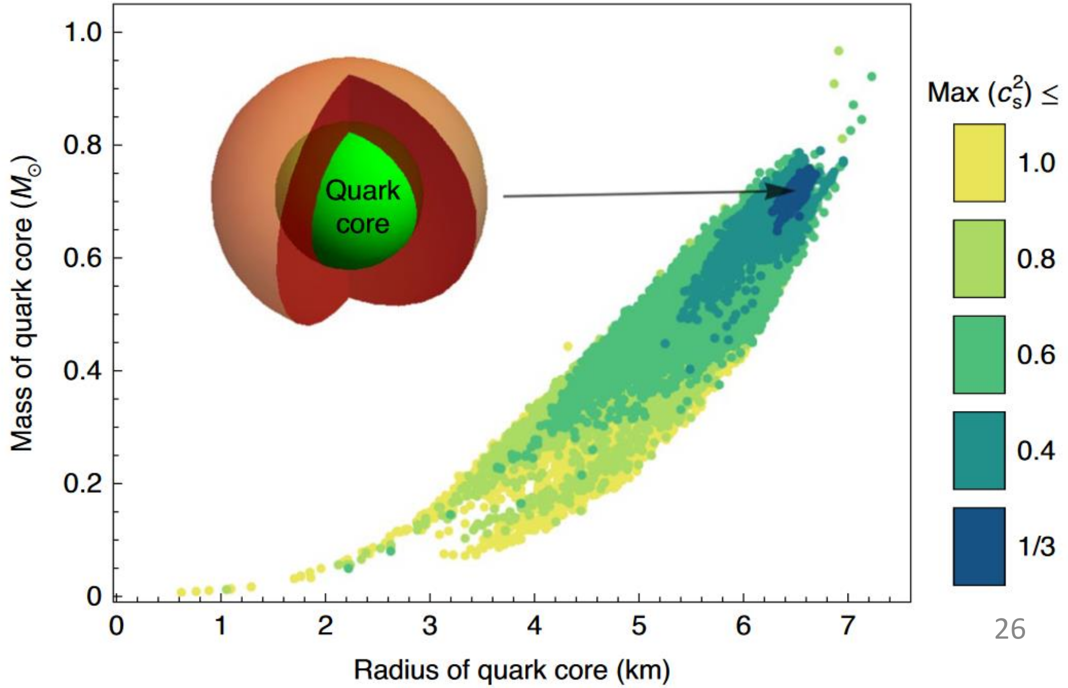
The EoS band features clear two-phase structure, with polytropic index $\gamma \equiv \dfrac{d \ln p}{d \ln \epsilon}$ transitioning from hadronic ($\gamma \gtrsim 2$) to near-conformal ($\gamma \approx 1$) behavior below TOV densities: evidence for QM cores

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



However, open questions remain:

1) Do other quantities display similar signs of conformalization?
2) Does conformalization necessary imply phase transition to QM?
3) How likely are QM cores in TOV stars?
4) What is the role of the pQCD limit?



NS-matter EoS: recent Bayesian results

Improvements in recent work:

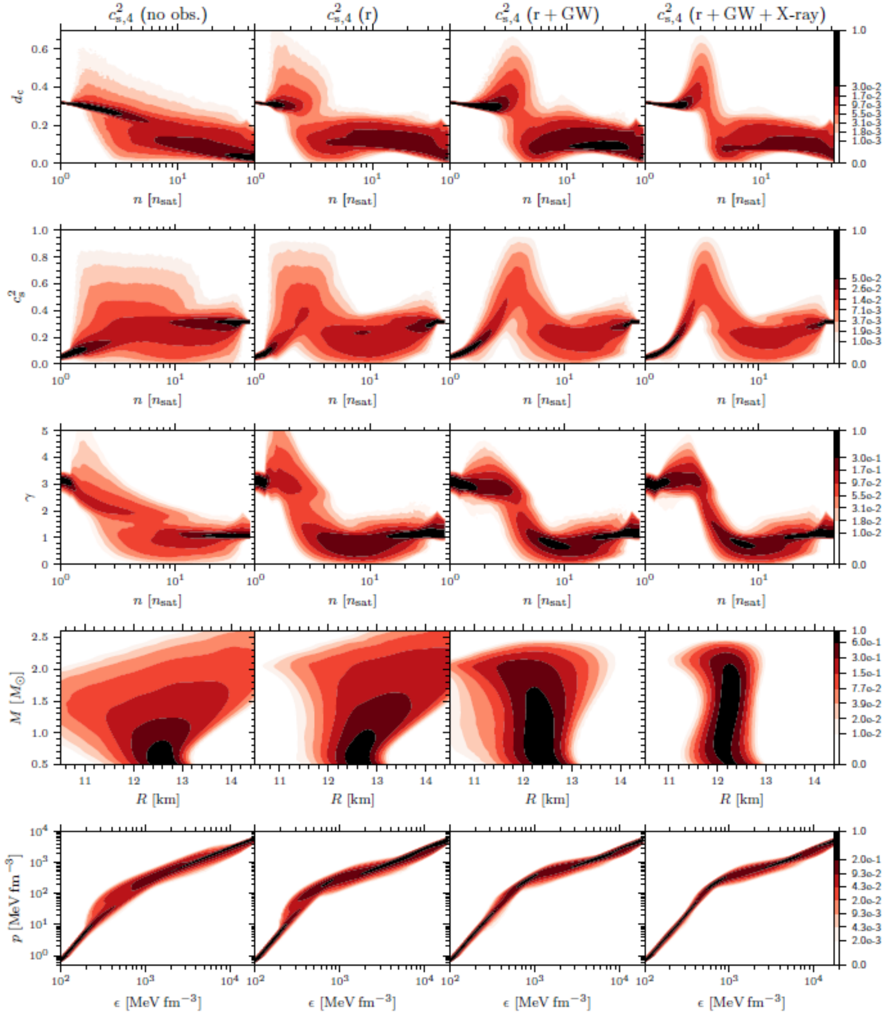
- Factor in measurement uncertainties ⇒ ability to utilize many more observations in the analysis
- Track also conformal anomaly and its rate of change $\Delta \equiv \frac{\epsilon - 3p}{3\epsilon}$, $\Delta' \equiv \frac{d\Delta}{d\ln\epsilon}$
- For comparison, construct EoSs also with nonparam. Gaussian Process regression

Ultimate goal: Approx. likelihoods of various scenarios (QM core, destabilizing FOPT,…)

Tool: Bayes' thm. $P(\text{EoS}|\text{data}) = \frac{P(\text{data}|\text{EoS})P(\text{EoS})}{P(\text{data})}$, MCMC simulations, and ab-initio limits

[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, Nature Comm. 14 (2023)]

	CEFT	Dense NM	Pert. QM	CFTs	FOPT
c_s^2	$\ll 1$	$[0.25, 0.6]$	$\lesssim 1/3$	$1/3$	0
Δ	$\approx 1/3$	$[0.05, 0.25]$	$[0, 0.15]$	0	$1/3 - p_{\rm PT}/\epsilon$
Δ'	≈ 0	$[-0.4, -0.1]$	$[-0.15, 0]$	0	$1/3 - \Delta$
d_c	$\approx 1/3$	$[0.25, 0.4]$	$\lesssim 0.2$	0	$\geq 1/(3\sqrt{2})$
γ	≈ 2.5	$[1.95, 3.0]$	$[1, 1.7]$	1	0
$p/p_{\rm free}$	$\ll 1$	$[0.25, 0.35]$	$[0.5, 1]$	—	$p_{\rm PT}/p_{\rm free}$



Main results:

1) All quantities studied – $\gamma, c_s^2, \Delta, \Delta'$ – consistently approach their conformal limits close to (but below) the central densities of M_{TOV} stars

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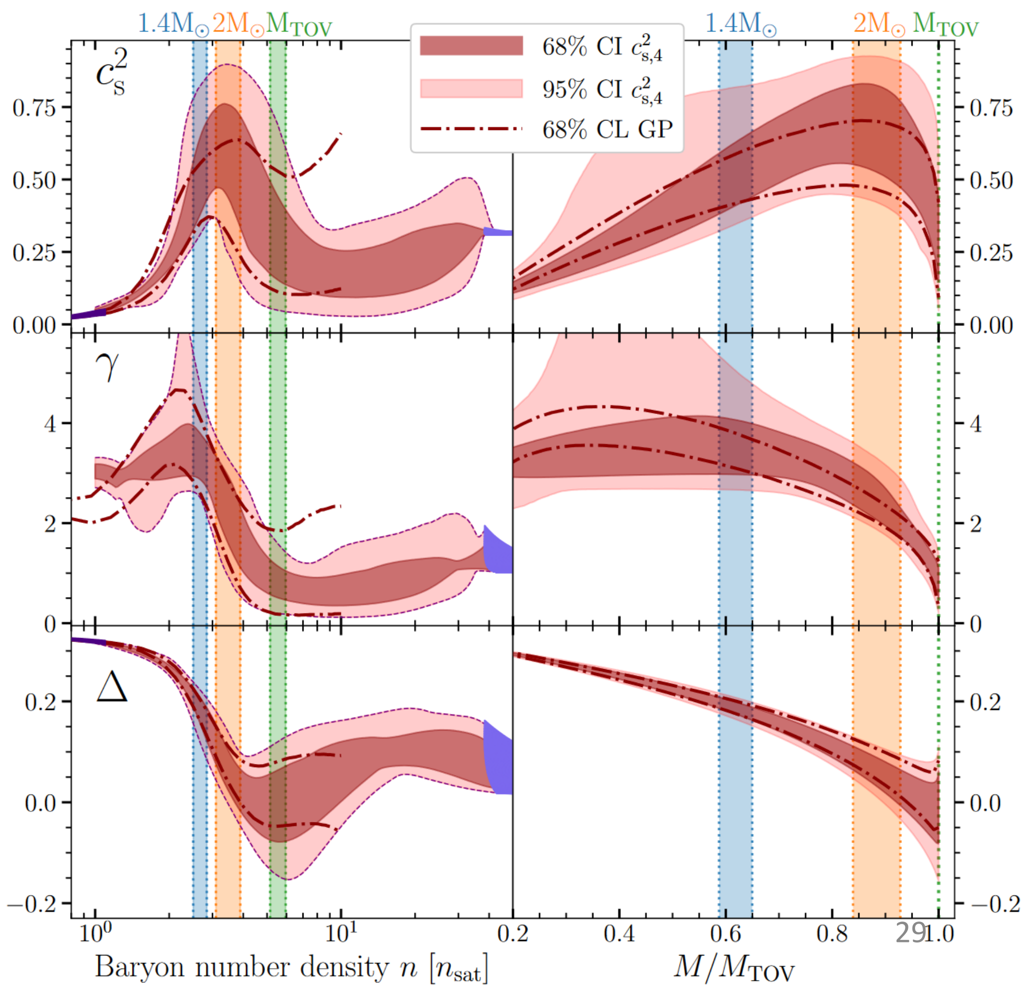

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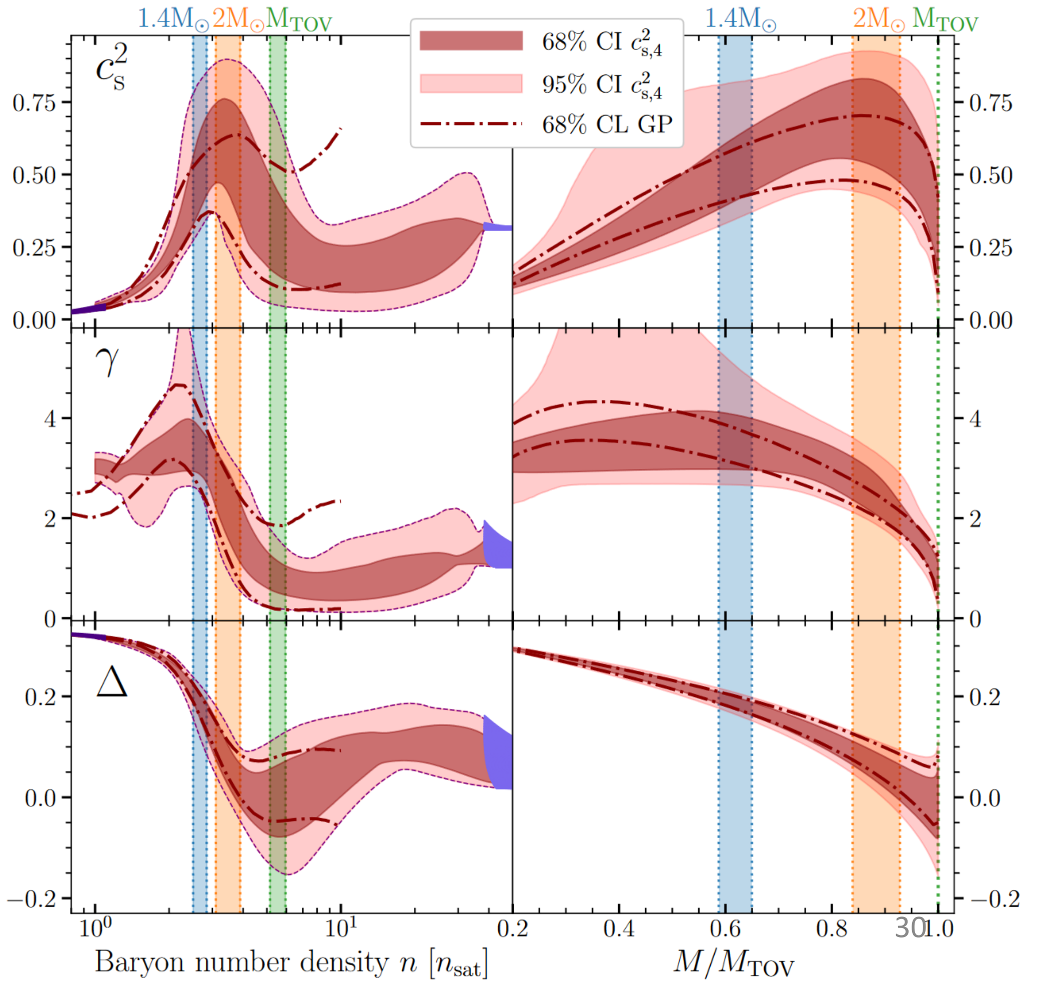
$p/p_{\rm free}$	$\ll 1$	$[0.25, 0.35]$	$[0.5, 1]$	—	$p_{\rm PT}/p_{\rm free}$

Main results:

2) Optimal quantity to track: "conformal distance" $d_c \equiv \sqrt{\Delta^2 + (\Delta')^2}$
   - Its conformalization ensures that of all other quantities considered
   - Values in dense NM ($\gtrsim 0.4$) and perturbative QM ($\lesssim 0.2$) far apart
   - In FOPTs $d_c \geq 1/(3\sqrt{2}) \approx 0.24$

∴ Our (intentionally conservative) criterion for near-conformality: $d_c < 0.2$



[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, Nature Comm. 14 (2023)]

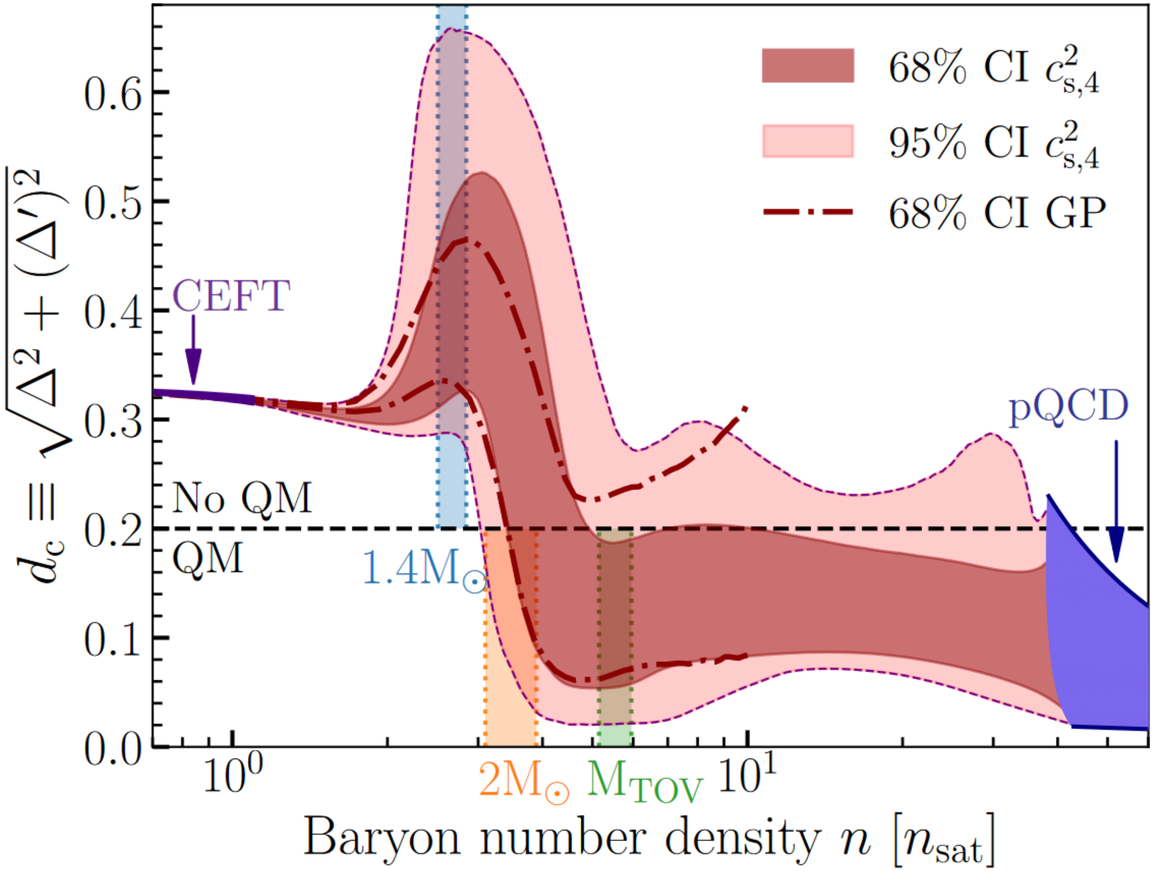
Main results:

3) Probability of conformalized matter in centers of

- $1.4M_\odot$ NSs: 0%
- $2.0M_\odot$ NSs: 11%
- $M_{\rm TOV}$ NSs: 88%

New criterion **very** conservative: with old criterion ($\gamma < 1.75$) from our 2020 Nat. Phys., the above 88% would be 99.8%.

For remaining 12% of TOV-star centers, nearly all EoSs feature FOPT-like behavior.



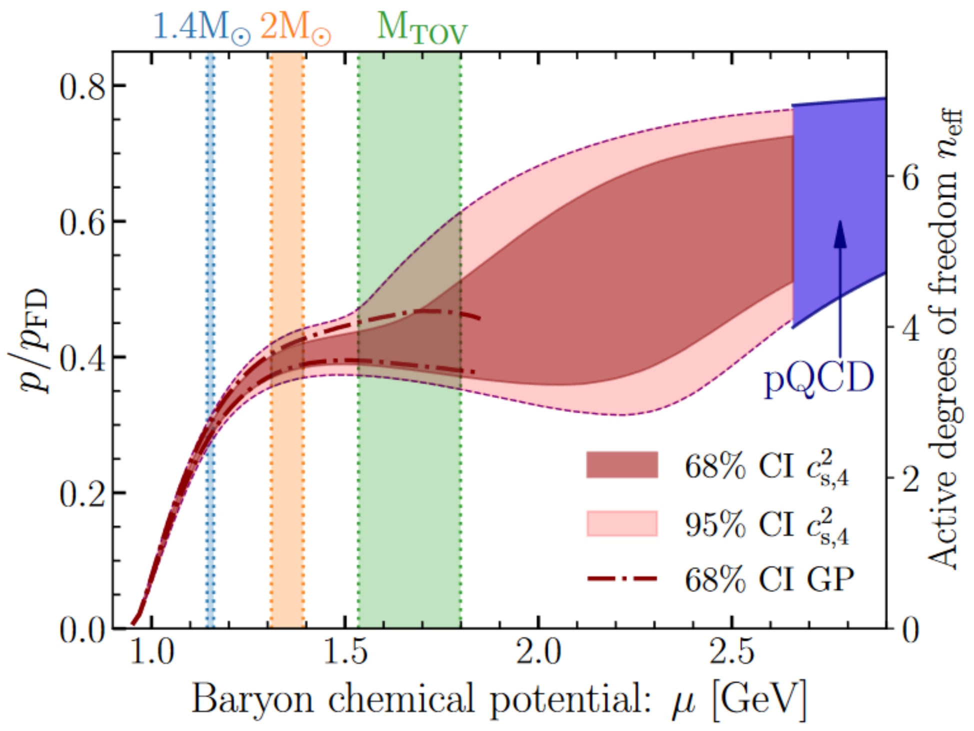
[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, Nature Comm. 14 (2023)]

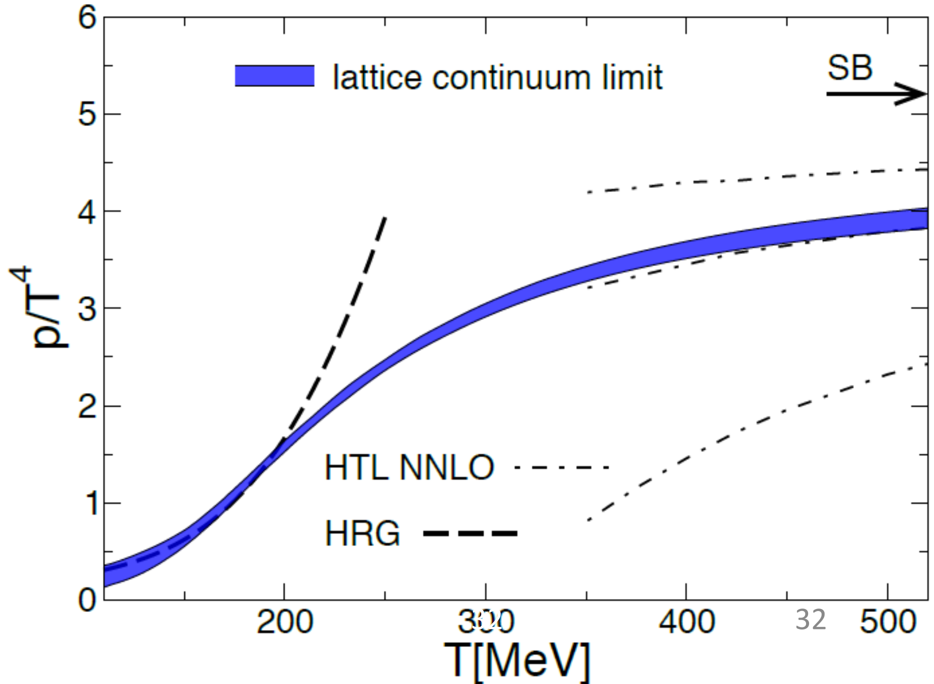
Main results:

4) For weak coupling and CFTs, normalized pressure ∝ number of active degrees of freedom.
In centers of TOV stars, p/p_{FD} at approx. 2/3 of its value in pQCD, while at high T crossover transition from hadron gas to QGP at much smaller values of p/p_{SB}.

∴ "Near-conformal" very likely implies "deconfined".

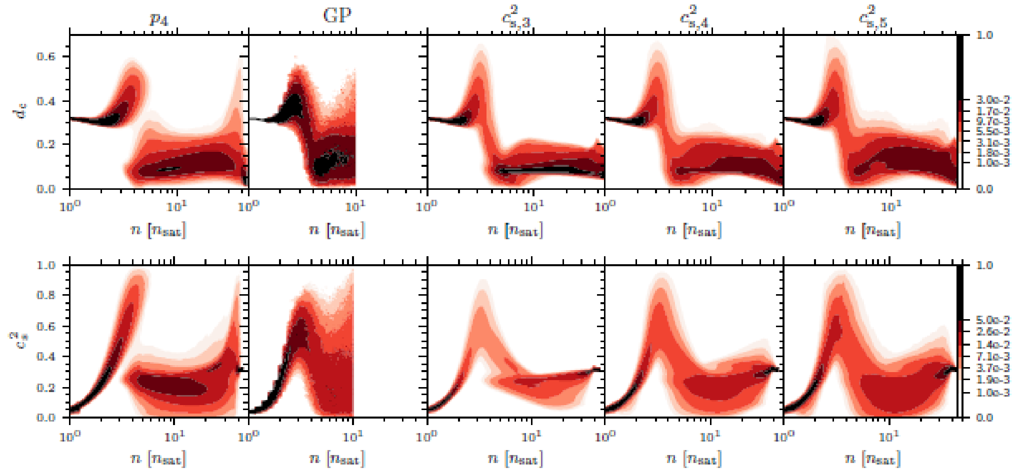
[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, Nature Comm. 14 (2023)]



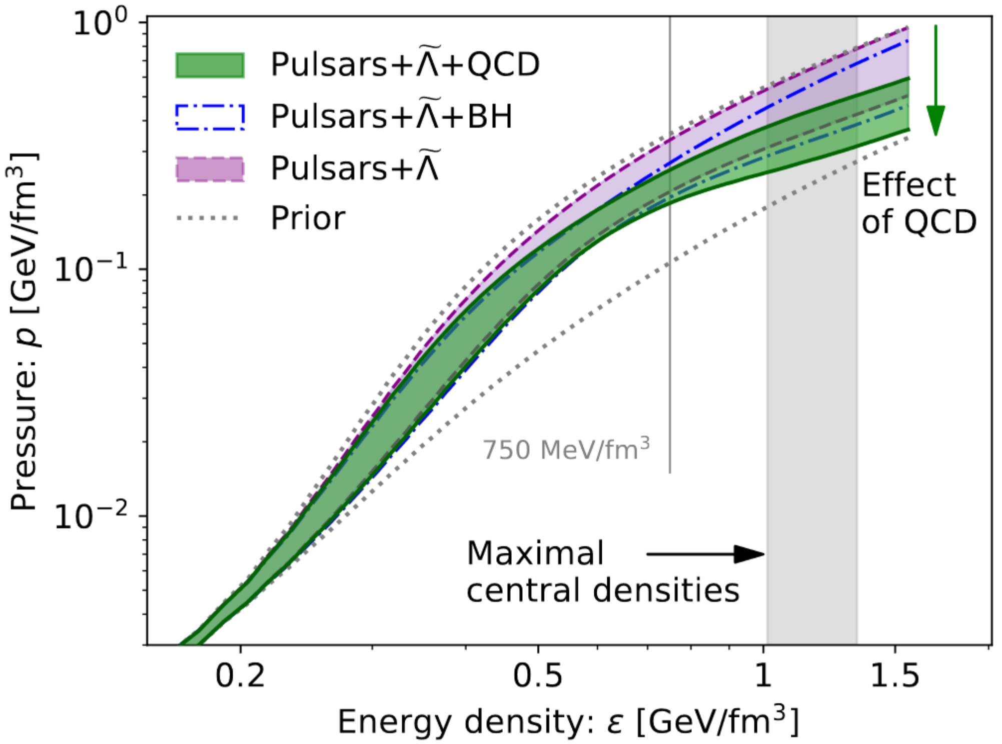


Main results:

5) All results independent of the details of interpolation, with results from non-parametric Gaussian Process regression well in line.



With GP method, also possible to show that it is precisely the pQCD constraint that softens the EoS in the cores of TOV stars.



[Gorda, Komoltsev, Kurkela, Astrophys. J. 950 (2023)]

[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, Nature Comm. 14 (2023)]

Remaining caveat: strong first-order PTs

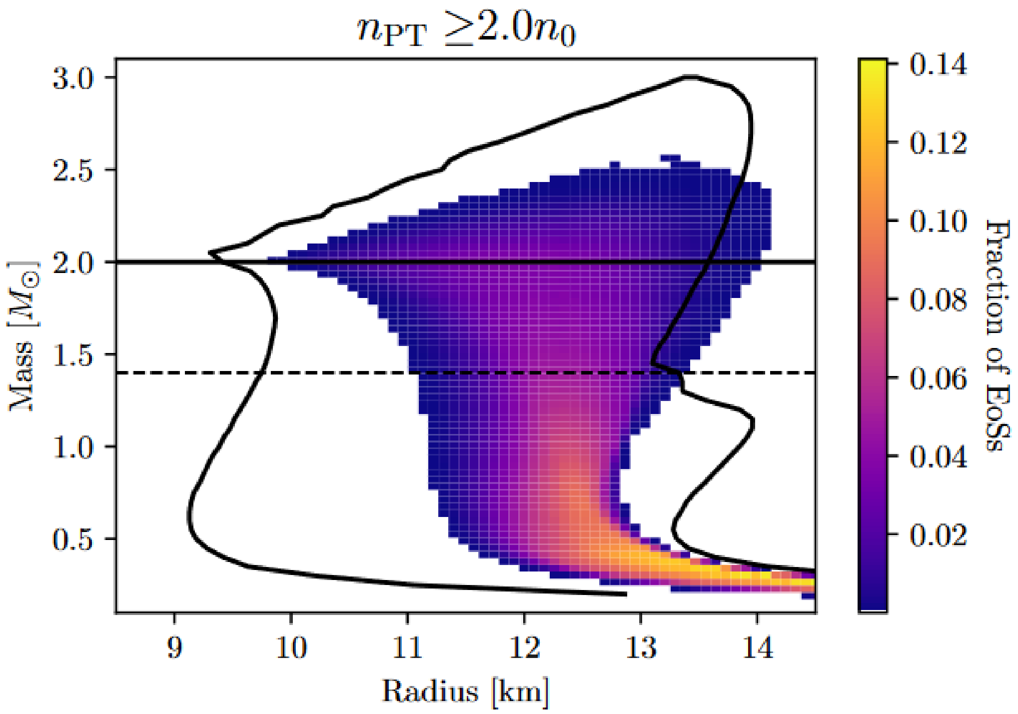
Few systematic studies of first-order PTs, but some preliminary results exist:

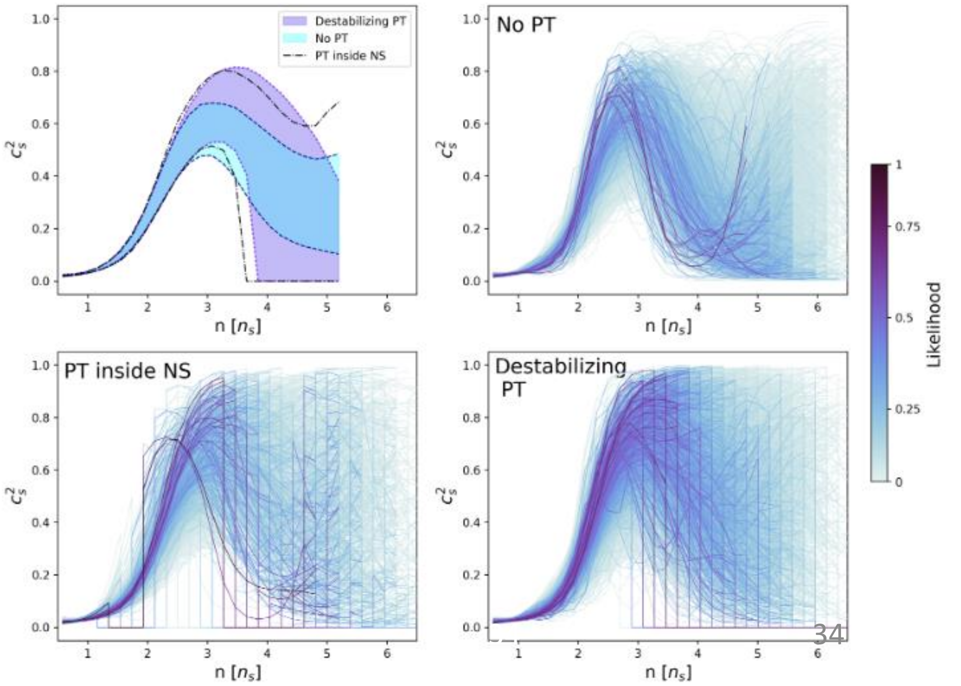
- In hard-limit setups possible to exit earlier bounds if early-onset strong 1st order PTs allowed
- Destabilizing solutions often extreme, but not unreasonable
- Implementing 1st order transitions to a Bayesian setting nontrivial but possible; existing results inconclusive

[Gorda, Hebeler, Kurkela Schwenk, AV, Astrophys. J. 955 (2023)]

[Komoltsev, arXiv:2404.05637]

[Blomqvist, Ecker, Gorda, AV, In preparation]

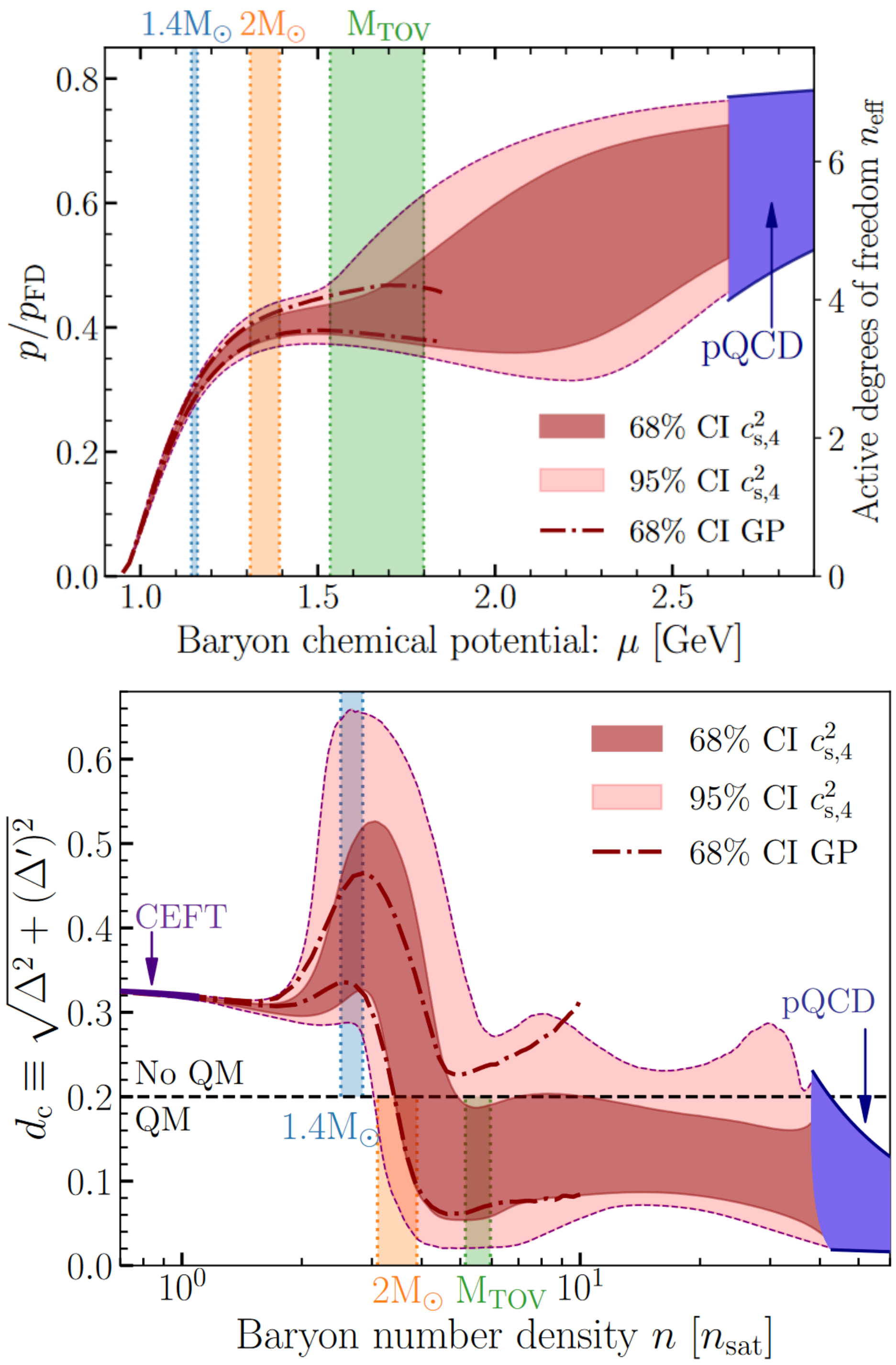




Challenge for holography / topic for later discussion:

At the most problematic densities where the deconfinement transition is expected to take place and where stellar cores lie, QCD is strongly coupled and we must rely on interpolation and observational constraints.

Can holography say anything **universal** about the equilibrium properties of strongly coupled fundamental matter at high density that could be used to **robustly constrain** the EoS here: order of transition, possible range of latent heat, positivity of trace anomaly,…?



Plan of the talk:

I. Equilibrium thermodynamics of dense QCD matter: interplay of theory and observations

II. From the EoS to the phases of QCD: do massive stars host quark-matter cores?

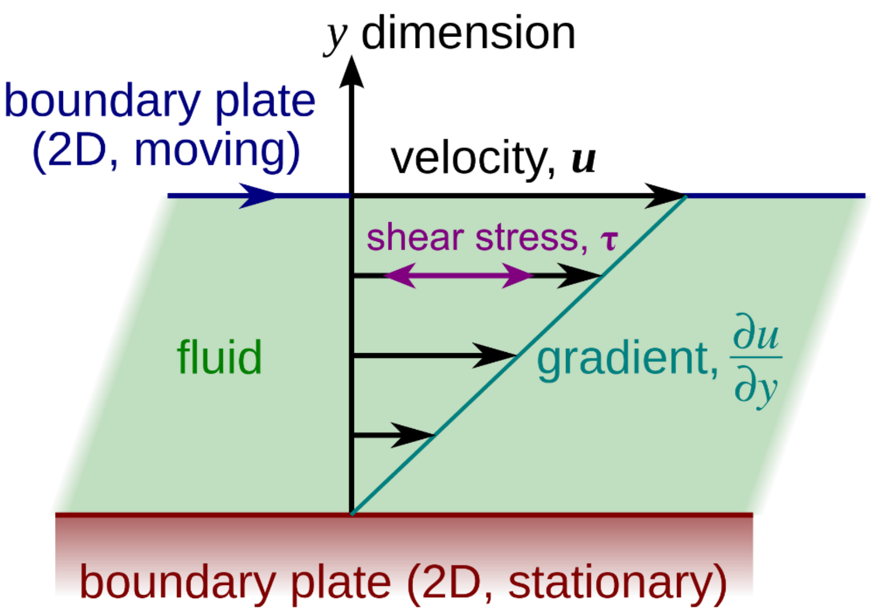
III. Transport and dissipation: bulk viscosity from pQCD and holography

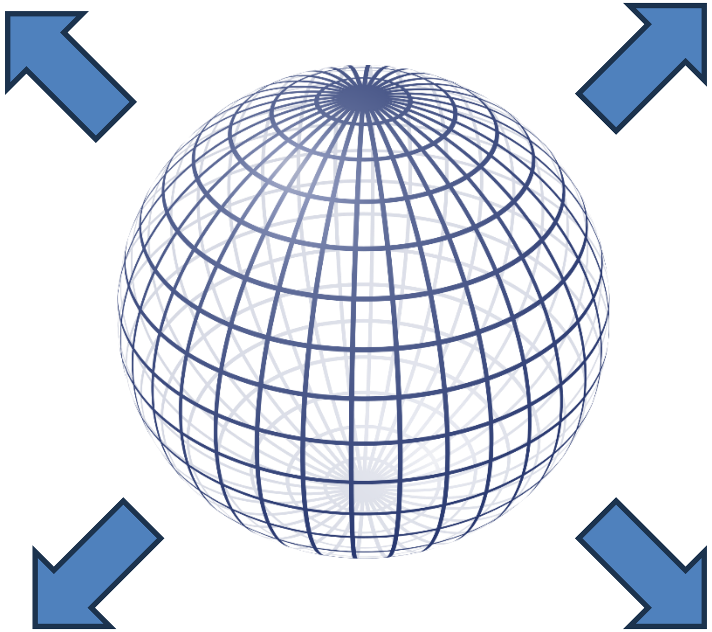
Stepping away from equilibrium: transport in QM

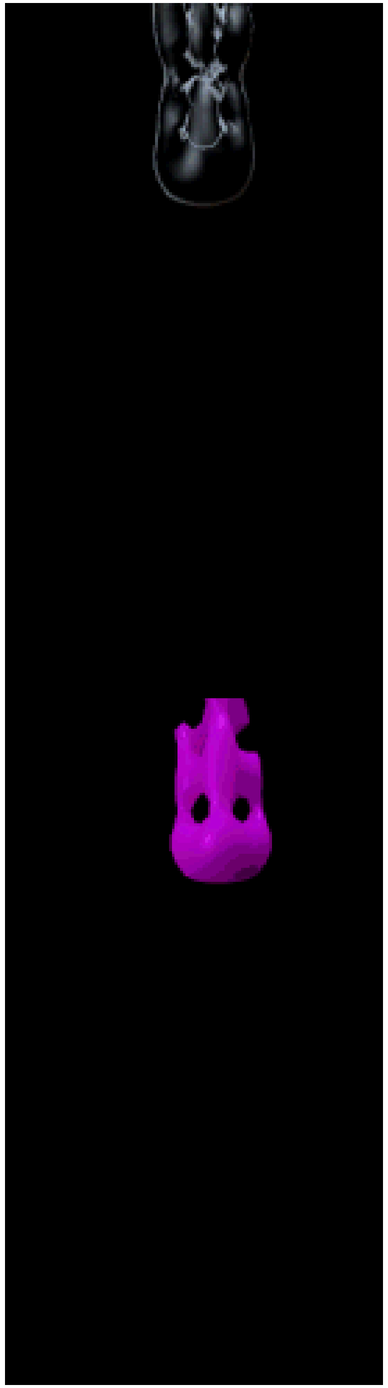
Away from thermal equilibrium, need to account for energy dissipation & transport of momentum, heat, and charge:

- Fluid dynamics: shear η and bulk ζ viscosities

$$\rho\left(\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v}\right) = -\nabla p + \eta\nabla^2\boldsymbol{v} + \boldsymbol{F} + \left(\frac{\eta}{3} + \zeta\right)\nabla(\nabla\cdot\boldsymbol{v})$$







Source: Wikipedia

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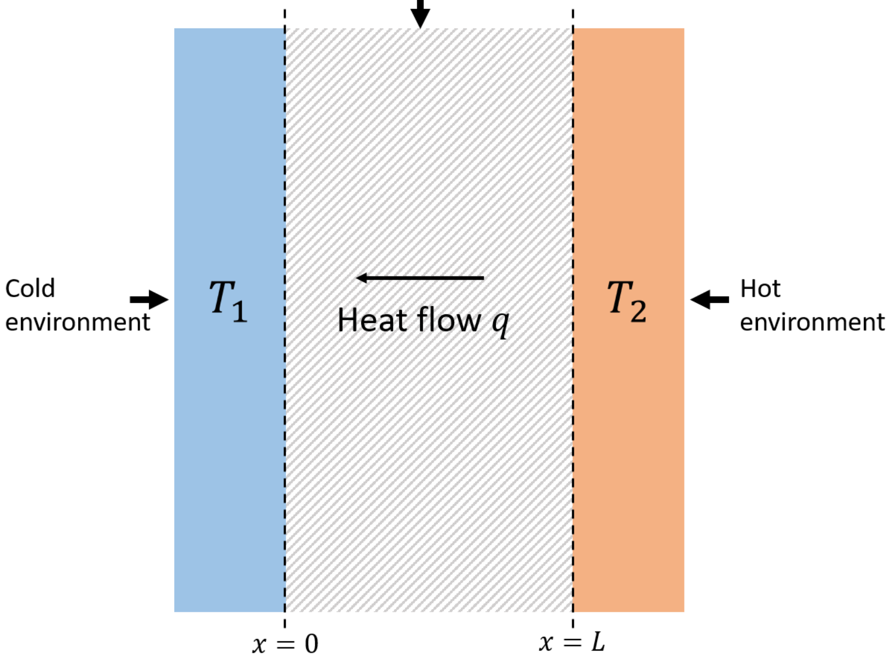
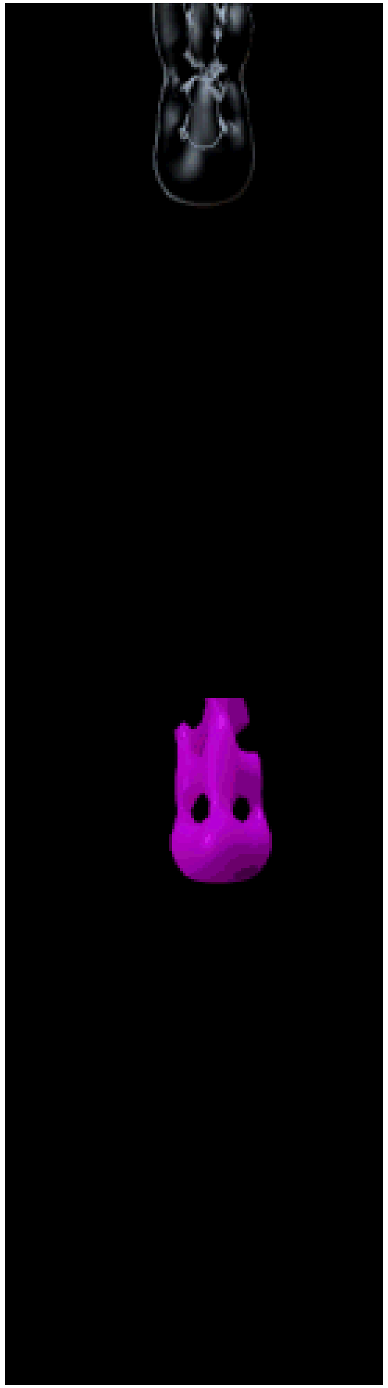
- Thermal conductivity κ: $\boldsymbol{Q} = -\kappa\nabla T$
- Electrical conductivity σ: $\boldsymbol{J} = \sigma\boldsymbol{E}$





Source: Wikipedia

But which of these effects are important in a strongly off-equilibrium high-density setting such as a binary NS merger?

At low/moderate temperatures ($T \lesssim 10$ MeV) in nuclear matter, answer appears to be "bulk viscosity alone" – i.e. the quantity least known at strong coupling [Alford, Bovard, Hanauske, Rezzolla, Schwenzer, PRL 120 (2018)]:

> Inferring the properties of dense matter is one of the most exciting prospects from the measurement of gravitational waves from neutron star mergers. However, it will require reliable numerical simulations that incorporate viscous dissipation and energy transport if these can play a significant role within the survival time of the post-merger object. We calculate timescales for typical forms of dissipation and find that thermal transport and shear viscosity will not be important unless neutrino trapping occurs, which requires temperatures above about 10 MeV and gradients over lengthscales of 0.1 km or less. On the other hand, if direct-Urca processes remain suppressed, leaving modified-Urca processes to establish flavor equilibrium, then bulk viscous dissipation could provide significant damping to density oscillations observed right after the merger. When comparing with data from a state-of-the-art merger simulation we find that the bulk viscosity takes values close to its resonant maximum in a typical neutron-star merger, motivating a more careful assessment of the role of bulk viscous dissipation in the gravitational-wave signal from merging neutron stars.

Bulk viscosity of unpaired quark matter: preliminaries

In quiescent NSs, matter close to β equilibrium and local charge neutrality:

- $u + d \leftrightarrow u + s,\ u + e \leftrightarrow d/s + \nu_e \Longrightarrow \mu_s = \mu_d, \mu_u = \mu_d - \mu_e$
- $\frac{2}{3} n_u - \frac{1}{3} n_d - \frac{1}{3} n_s = n_e \Longrightarrow \mu_e = \mu_e(\mu_d)$

When the system is taken out of chemical equilibrium at low or moderate T, the non-leptonic flavor-changing process $u + d \leftrightarrow u + s$ tries to restore equilibrium with a rate

$$\lambda_1 \approx \frac{64}{5\pi^3} G_F^2 \sin^2\theta_c \cos^2\theta_c\, \mu_d^5 T^2$$

so that

$$\frac{dn_d}{dt} \approx \lambda_1(\mu_s - \mu_d).$$

The bulk viscosity parametrizes the dissipation of energy in a radially pulsating system, for which we can write $n(t) = n_0 + \Delta n \sin \omega t$. Then

$$\langle \dot{E}_{\mathrm{diss}} \rangle = -\frac{\zeta \omega^2}{2} \left(\frac{\Delta n}{n_0} \right)^2 .$$

The same dissipation can also be related to work done in a compression-decompression cycle, so that

$$\langle \dot{E}_{\mathrm{diss}} \rangle \approx \frac{n_0}{\tau} \int_0^\tau \mathrm{d}t \, p(t) \frac{d\big(1/n(t)\big)}{dt} .$$

For QCD, expanding the pressure in densities and susceptibilities and using $\frac{dn_d}{dt} \approx \lambda_1(\mu_s - \mu_d)$, this equality can be used to derive an expression for ζ

The result reads

$$\zeta = \frac{\lambda_1 A_1^2}{\omega^2 + (\lambda_1 C_1)^2}, \text{ with}$$

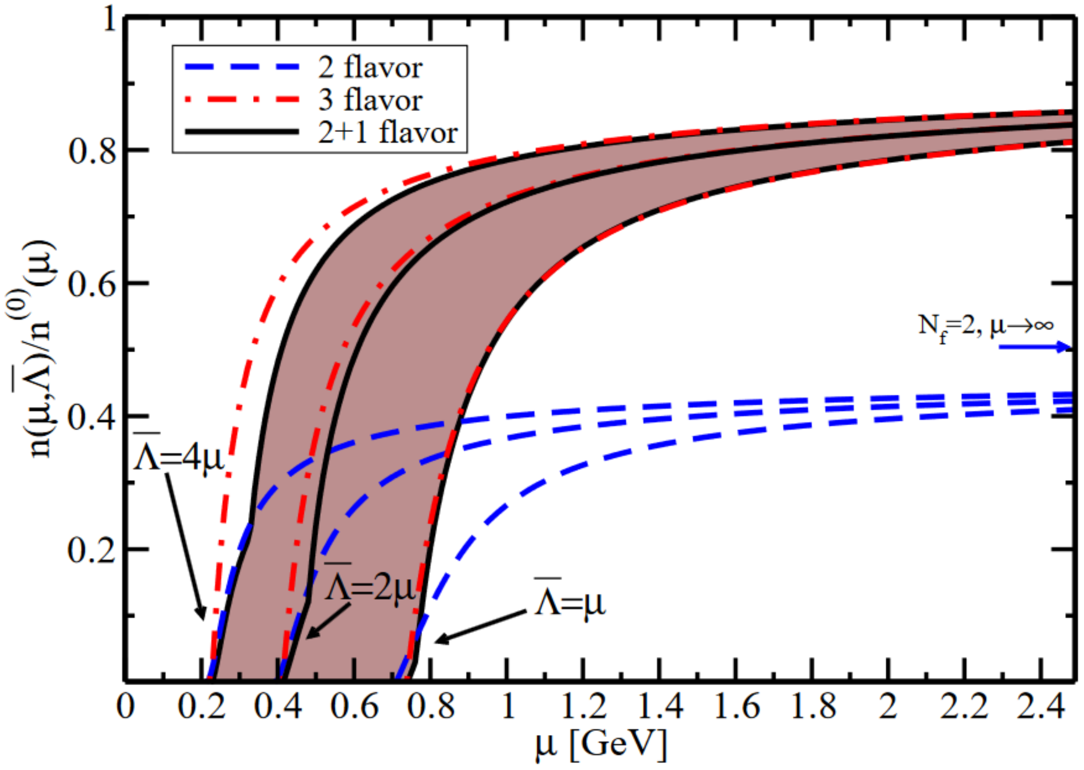
$$\begin{aligned} A_1 &\equiv H_p^{-1}\Big\{ n_s \left[\chi_{uu}\left(\chi_{dd}+\chi_{ds}\right) - \chi_{du}\left(\chi_{ud}+\chi_{us}\right)\right] \\ &\quad - n_d \left[\chi_{uu}\left(\chi_{ss}+\chi_{sd}\right) - \chi_{su}\left(\chi_{ud}+\chi_{us}\right)\right] \\ &\quad + n_u \left[\chi_{ud}\left(\chi_{ss}+\chi_{sd}\right) - \chi_{us}\left(\chi_{dd}+\chi_{ds}\right)\right]\Big\} \\ C_1 &\equiv H_p^{-1}\left[(\chi_{ud}+\chi_{us})^2 - \chi_{uu}(\chi_{dd}+2\chi_{ds}+\chi_{ss})\right] \end{aligned}$$

and $H_p \equiv \det \frac{\partial^2 p}{\partial \mu_i \partial \mu_j}$

∴ The evaluation of ζ reduces to that of quark densities and susceptibilities!

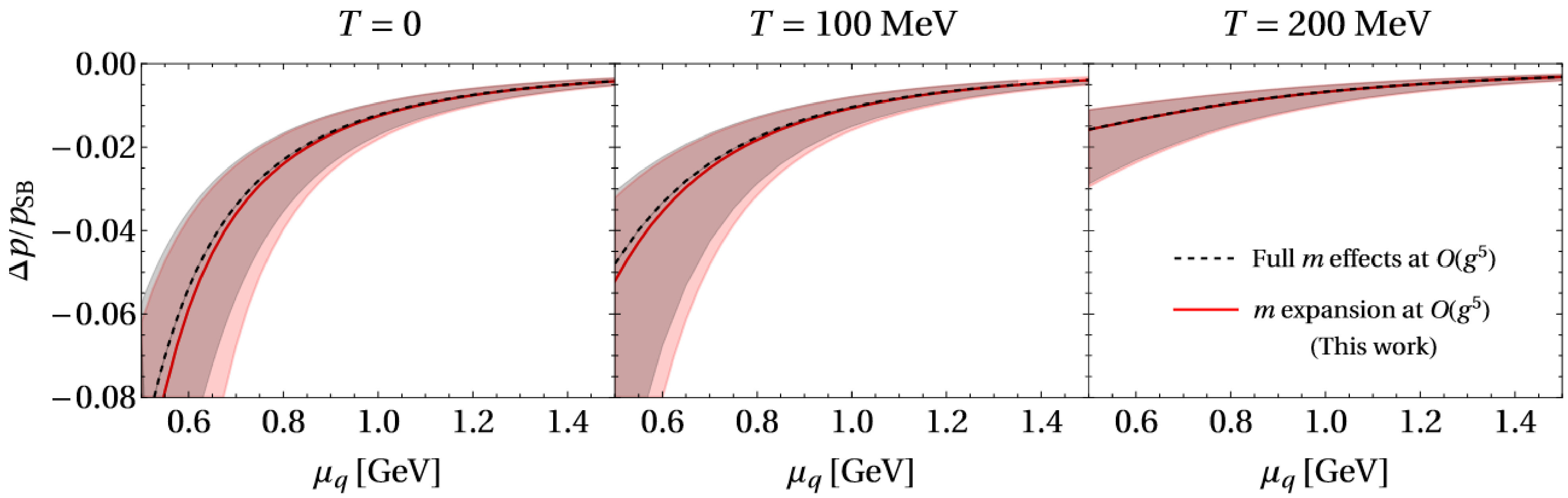
Important catch: realistic description of s quark mass effects in thermod. quantities imperative as A_1 vanishes for mass-degenerate quarks!

Easier said than done: for the pQCD pressure of $T = 0$ QM, massless 3-loop result from 1977 [Freedman, McLerran, PRD 16 (1977)] and massive from 2010 [Kurkela, Romatschke, AV, PRD 81 (2010)]!



In the new work [Cruz et al., 2402.00621], we used three different approaches:

1) pQCD: Mass-expansion scheme of [Gorda, Säppi, PRD 106 (2022)], where m_s treated as $O(g\mu)$ perturbation, enables analytic finite-m computations



In the new work [Cruz et al., 2402.00621], we used three different approaches:

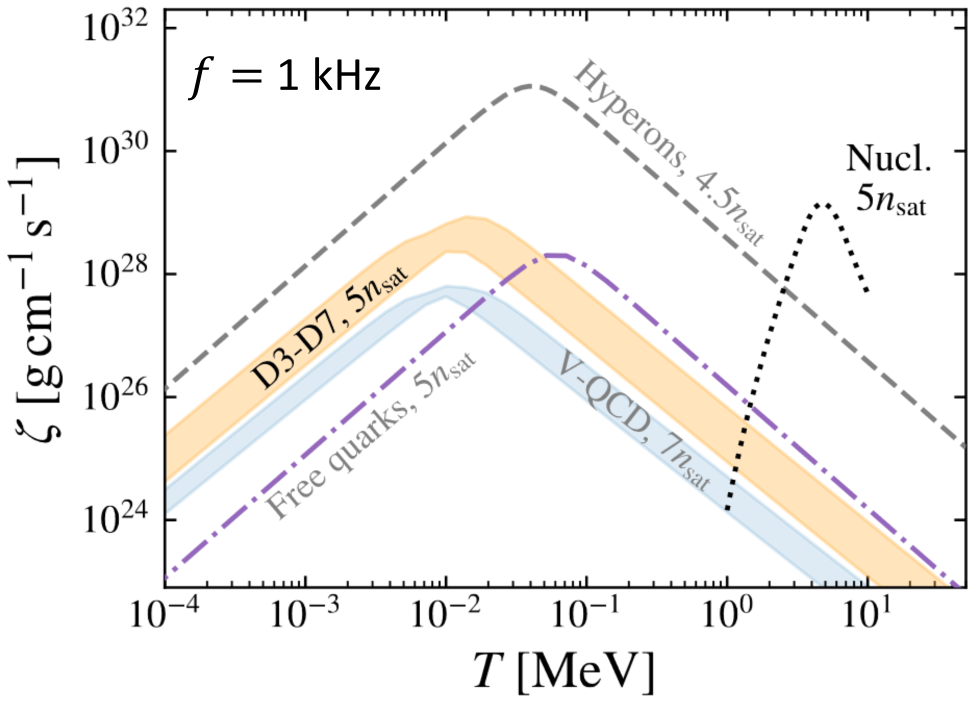
1) pQCD: Mass-expansion scheme of [Gorda, Säppi, PRD 106 (2022)], where m_s treated as $O(g\mu)$ perturbation, enables analytic finite-m computations
2) D3-D7 top-down model: constituent quark masses fixed by making sure quark densities agree with pQCD predictions at $\mu_d = 1$ GeV → relative difference between *u,d* and *s* quark masses only tens of MeV's
3) V-QCD bottom-up model: treats quarks unquenched, with *u,d* massless and m_s value fixed to kaon and eta masses in vacuum
   - Caveat: this procedure appears to *underestimate* mass effects at nonzero T & μ, so that V-QCD predictions should be viewed as lower limits for quantities that vanish when $m_s = 0$ – such as the bulk viscosity

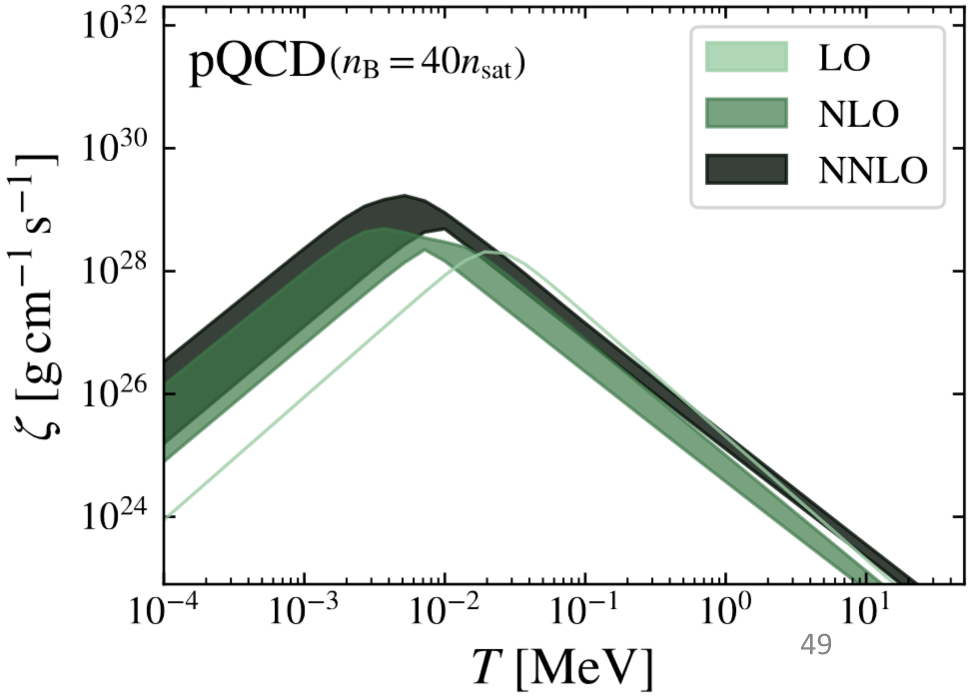
Bulk viscosity of unpaired quark matter: results

Observation 1: pQCD and D3-D7 predictions for thermodynamic quantities that enter ζ well in line but V-QCD appears to underestimate A_1

Observation 2: The same trend continues for ζ but all predictions for the QM bulk viscosity similar and far from hadronic results

Observation 3: Interactions important: even at $n_B = 40n_s$, where pQCD converges well, marked differences between LO, NLO and NNLO (new work) results





Observation 4: Nearly all T-dependence of ζ originates from the weak rate

$$\lambda_1 \approx \frac{64}{5\pi^3} G_F^2 \sin^2\theta_c \cos^2\theta_c \, \mu_d^5 T^2$$

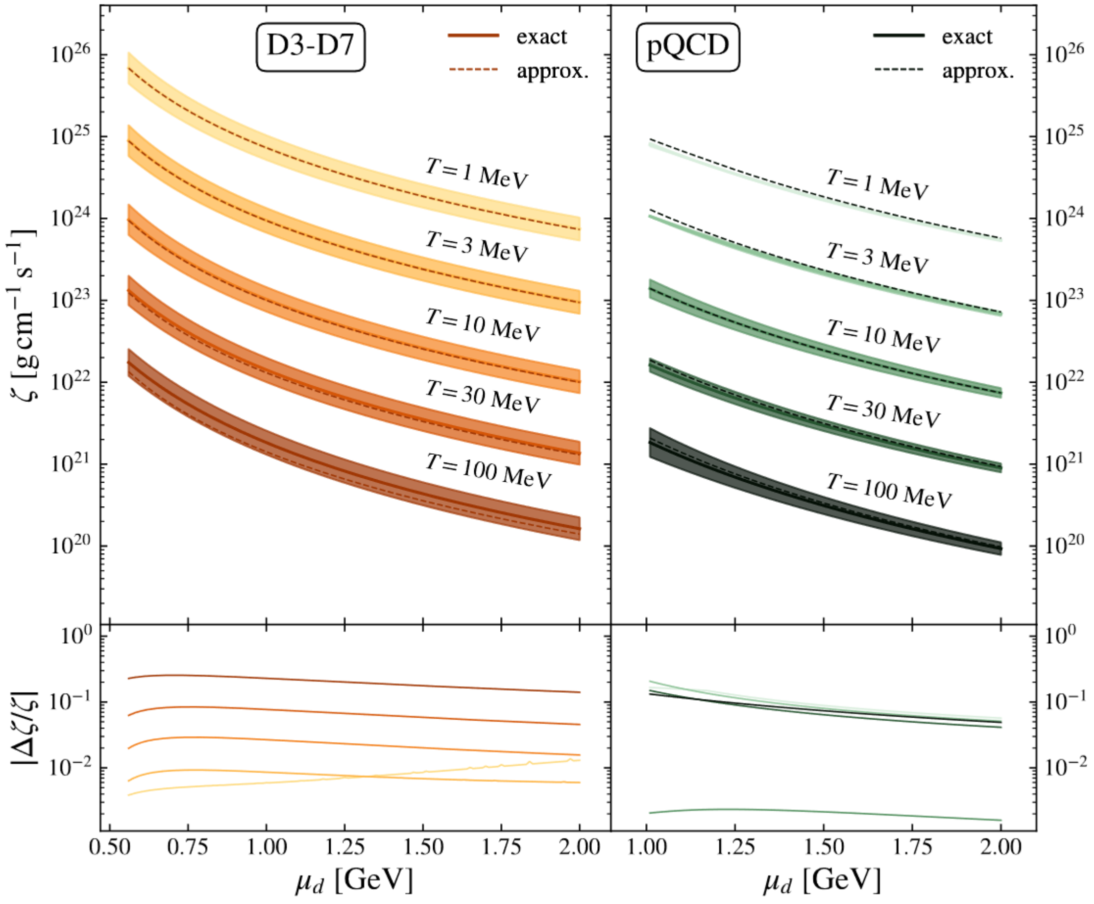
$\Rightarrow$ we can set $T = 0$ in the QCD input A_1, C_1

In this approximation, the D3-D7 result – that appears to extrapolate pQCD nicely to lower densities – reduces to a pocket formula,

$$\zeta \approx \frac{4\lambda_1 \mu_d^6 \left(M_s^2 - M_d^2\right)^2}{K_d^2 K_s^2 \omega^2 + \pi^4 \lambda_1^2 (K_d + K_s)^2}, K_i \equiv 3\mu_d^2 - M_i^2,$$

our main result for unpaired quark matter!

$f = 1$ kHz



Conclusions

Main takeaways:

1) Active interplay between particle & nuclear theory and observational astrophysics is currently leading to a rapid unraveling of the mysteries of NS cores
2) Strong evidence for rapid conformalization of matter near TOV-star centers, identifiable as onset of deconfinement. A destabilizing transition, however, remains as viable alternative.
3) To improve from present interpolation studies and asymptotic pQCD results, need insights from nonperturbative approaches such as holography. Especially valuable contributions: universal patterns and/or particularly complicated quantities.