High-density constraints for matter inside neutron-star cores

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HELSINGIN YLIOPISTO
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HELSINKI INSTITUTE OF PHYSICS

ACADEMY OF FINLAND

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pQCD and EFT at high density:

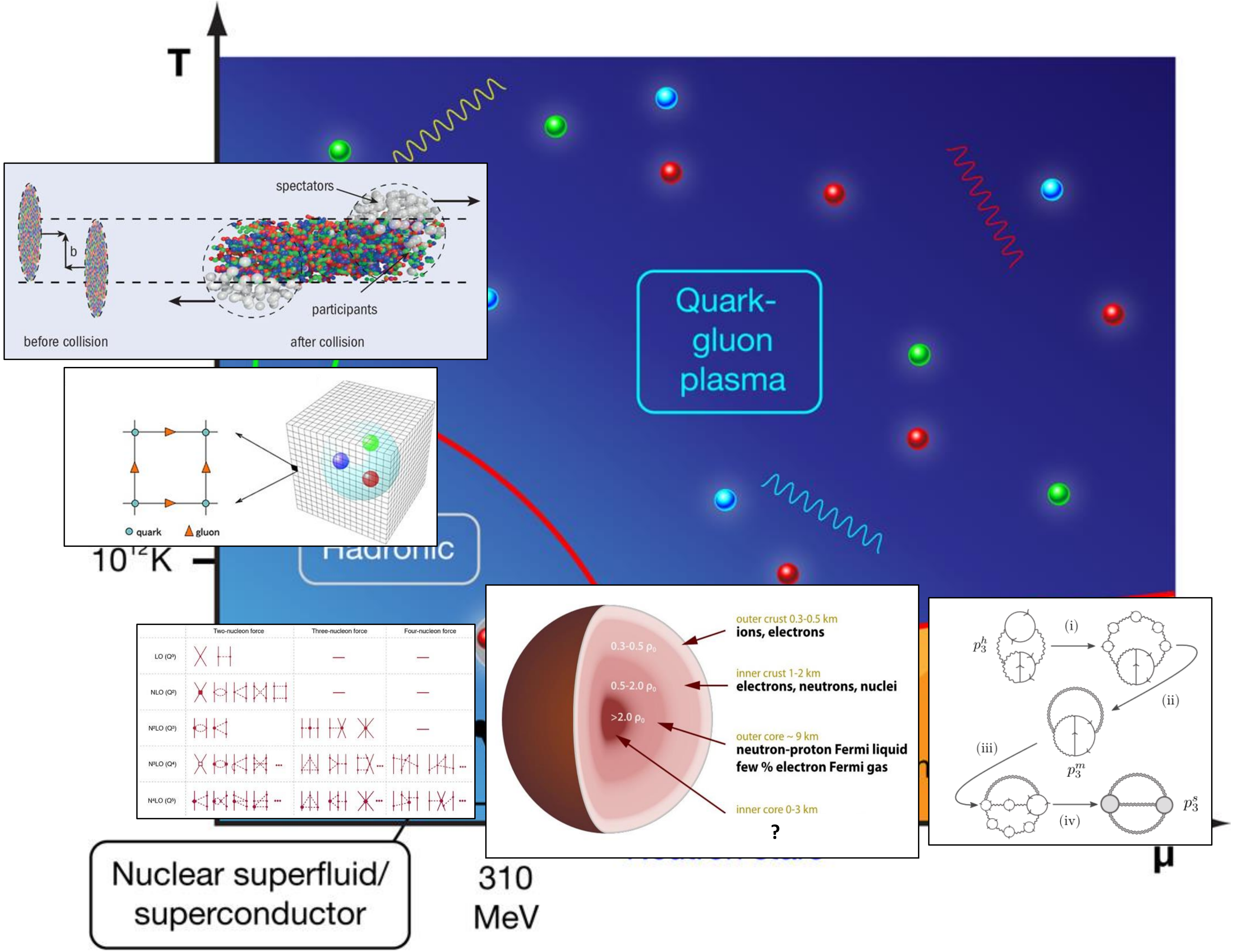
1) Laine, AV, Lect. Notes. Phys. 925, 1701.01554
2) Gorda, Kurkela, Paatelainen, Säppi, AV, PRL 127, 2103.05658

Applications to neutron-star physics:

1) Annala et al., Nature Phys. (2020), 1903.09121
2) Annala et al., PRX 12 (2022), 2105.05132
3) Annala et al., 2303.11356

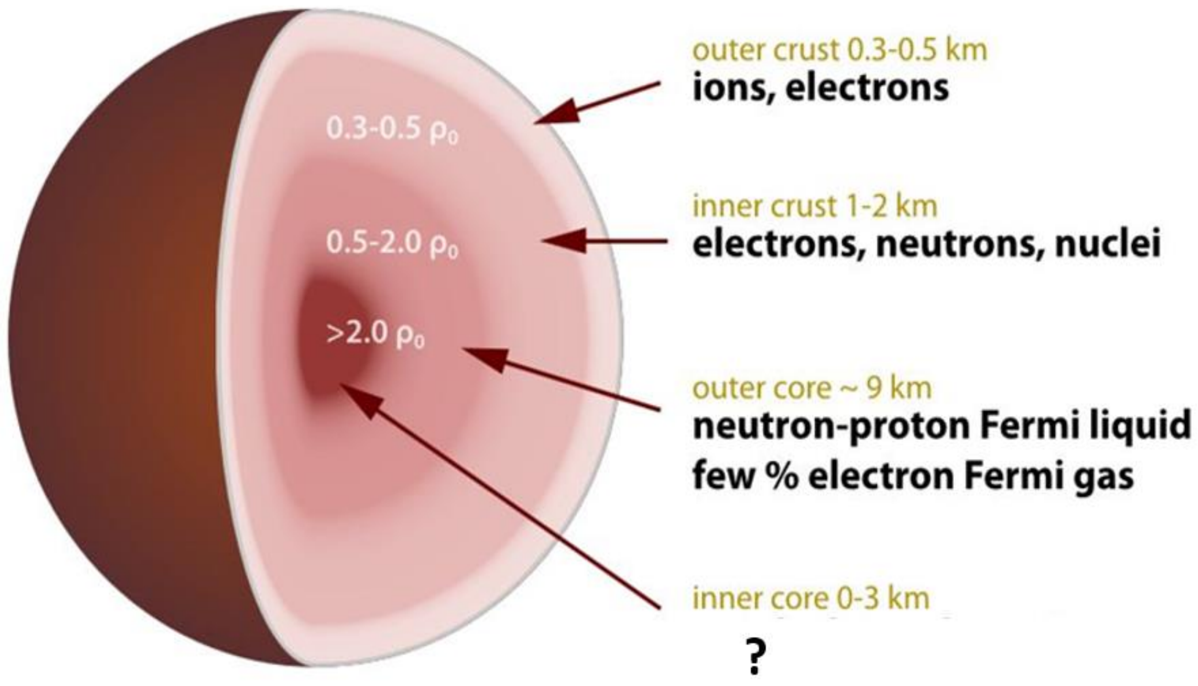
Role of pQCD constraint in NS-matter EoS inference:

1) Gorda, Komoltsev, Kurkela, APJ 950 (2023), 2204.11877



T
Quark-gluon plasma
Hadronic
10^12 K
310 MeV
μ
Nuclear superfluid/ superconductor
spectators
b
participants
before collision
after collision
quark
gluon
Two-nucleon force
Three-nucleon force
Four-nucleon force
LO (Q^0)
NLO (Q^2)
N^2LO (Q^3)
N^3LO (Q^4)
N^4LO (Q^5)
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
?
p3h
(i)
(ii)
(iii)
p3m
(iv)
p3s

Dense QCD challenge: can we solve NS properties and composition using only first-principles theory tools and robust observational data? **Do some NS cores contain deconfined matter?**



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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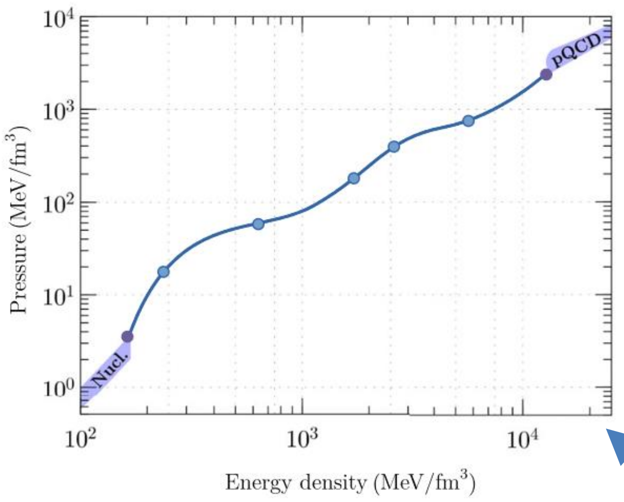

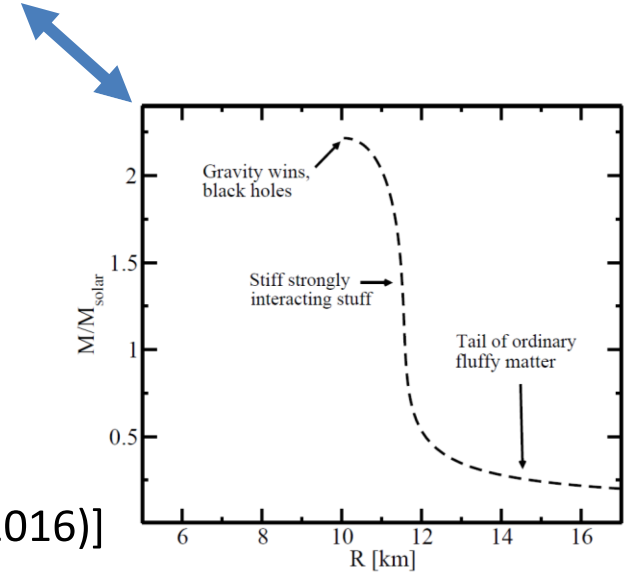

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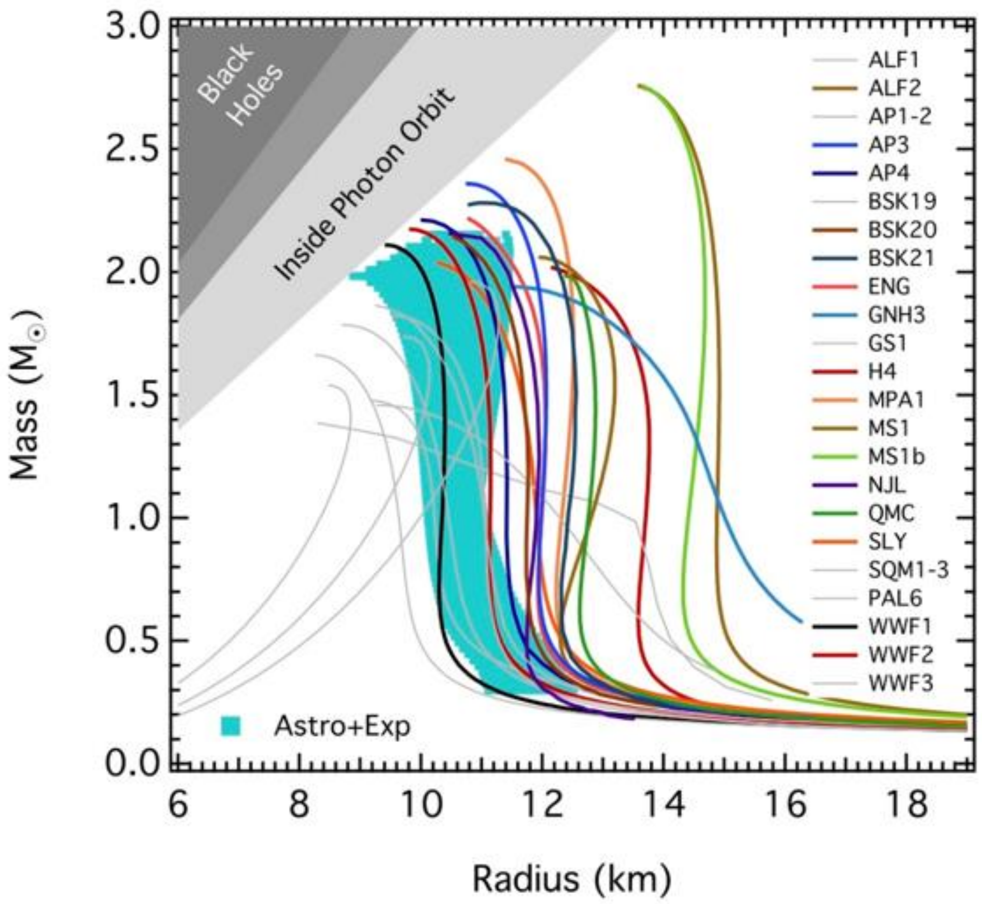

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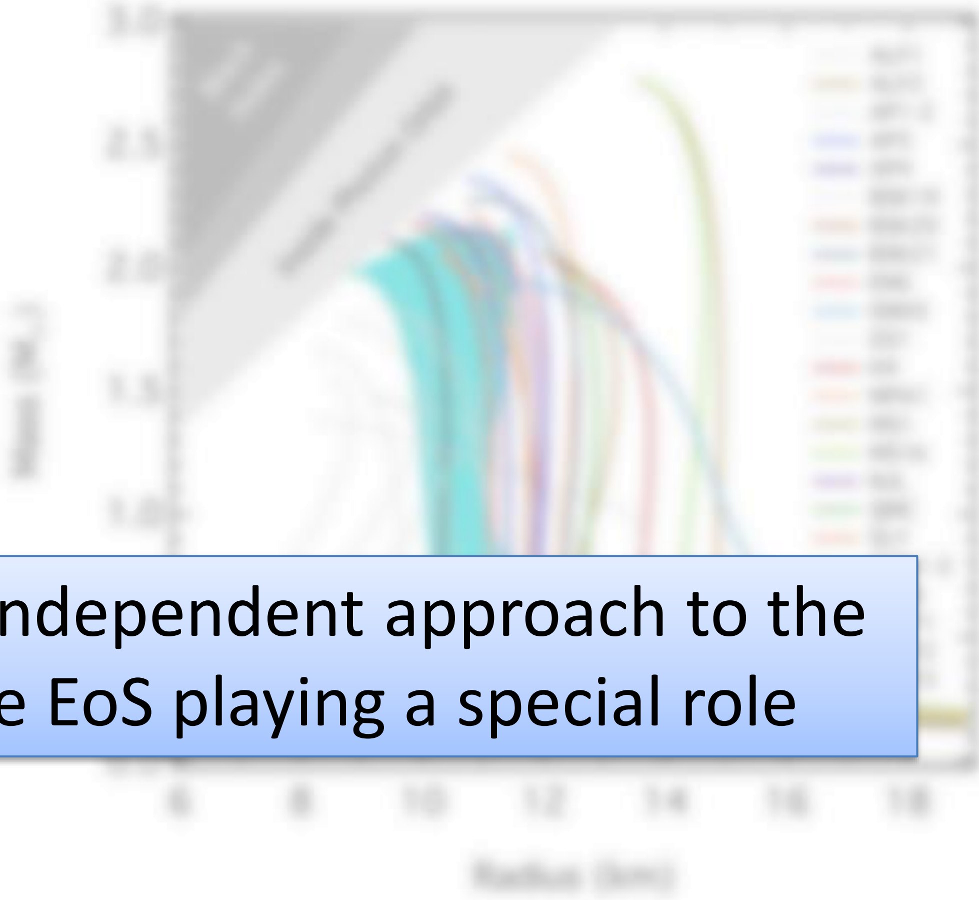

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Clear need for systematic and model-independent approach to the microphysics of neutron stars, with the EoS playing a special role

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Plan of the lectures:

I. Basics of neutron stars and their interiors: main properties and theoretical tools

II. Effective field theory at (ultra)high baryon density: Hard Thermal Loops and beyond

III. Fitting all the pieces together: what can we robustly say about NS cores?

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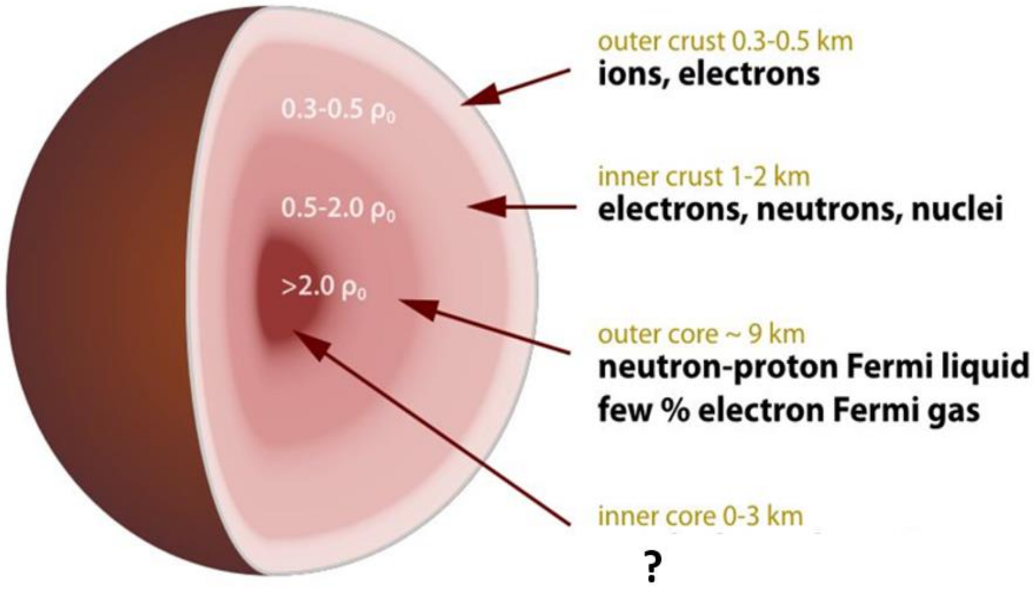
NS matter: from dilute crust to ultradense core

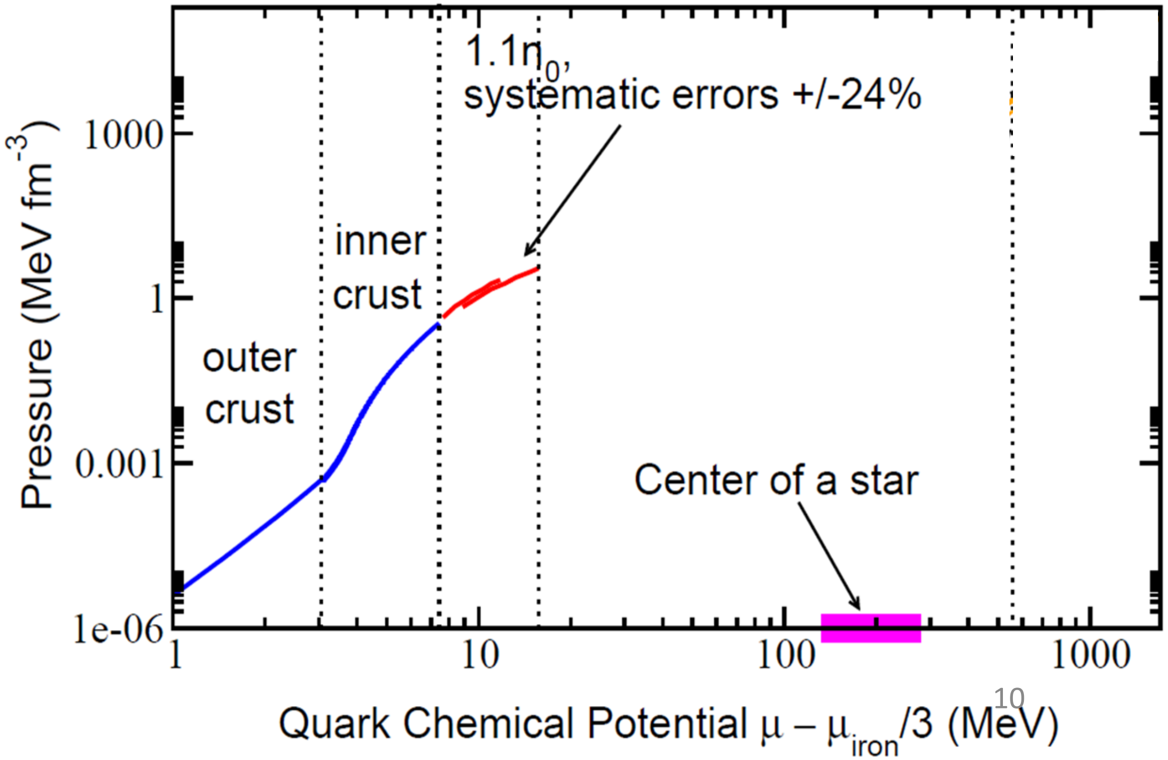
Proceeding inwards from the crust:

- μ_B increases gradually, starting from μ_{Fe}
- Baryon/mass density increase beyond saturation density $\approx 0.16/\mathrm{fm}^3$
- 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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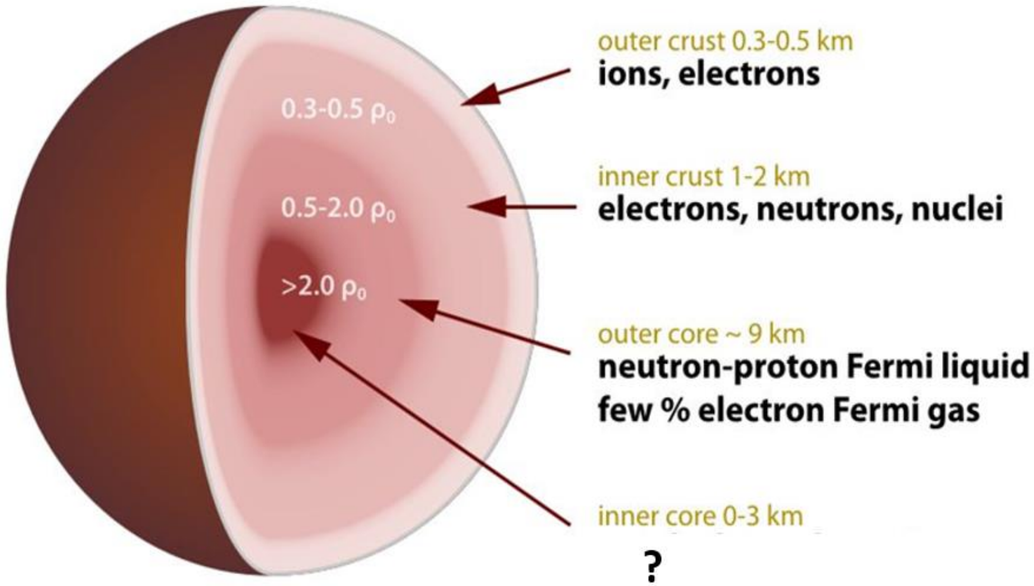
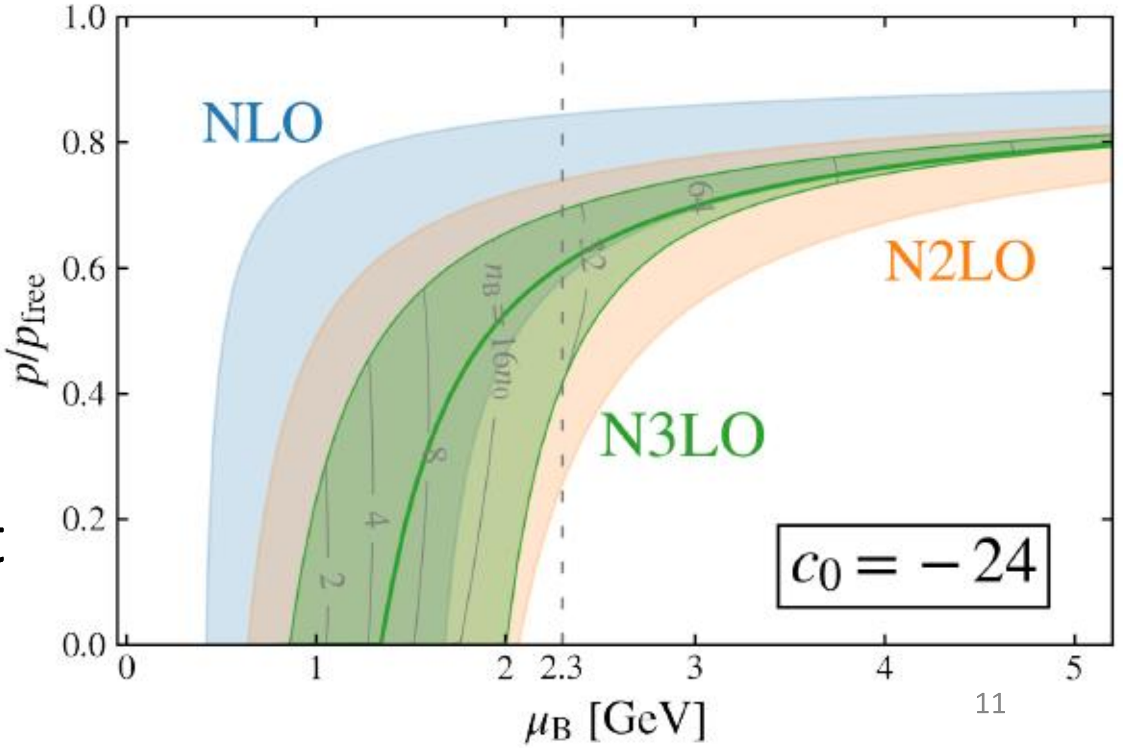
At high density, asymptotic freedom ⇒ weakening coupling and deconfinement

- State-of-the-art pQCD EoS at partial NNNLO, with soft and mixed sectors fully determined [Gorda et al., PRL 127 (2021)]
- New results display marked improvement at full α_s^3 order [Gorda et al., 2307.08734]





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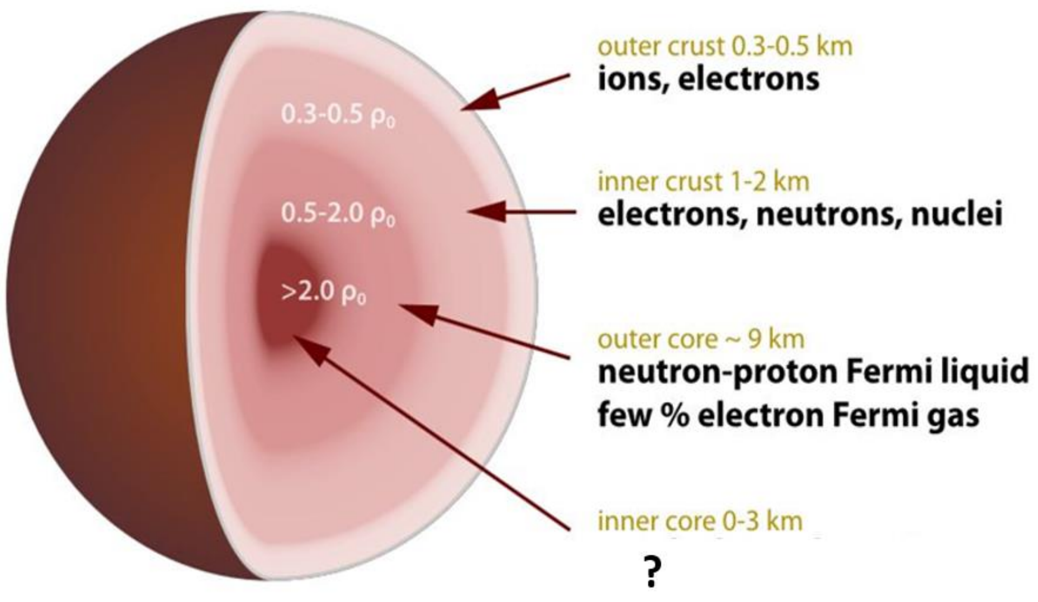
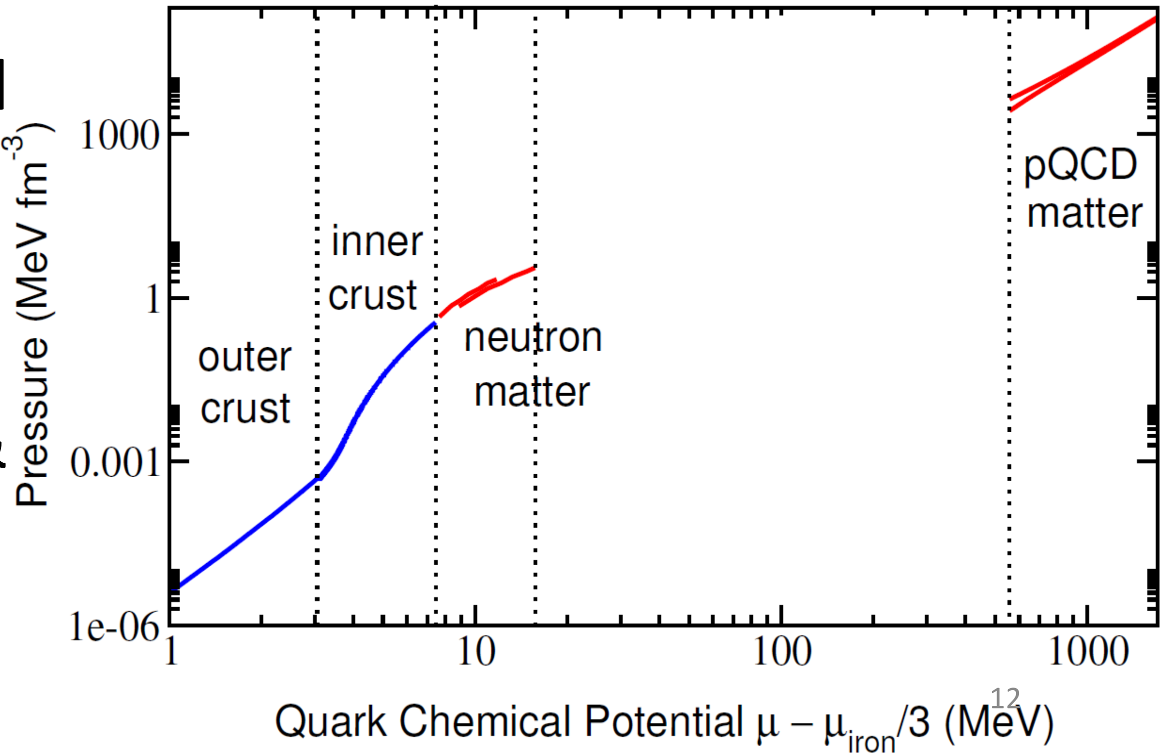
∴ Low- and high-density limits under control but extensive no-man's land at intermed. densities. Possibilities for proceeding:

1) Solve the sign problem of lattice QCD
2) Use phenomenological models for NM & QM at intermediate densities
3) Allow all possible behaviors for the EoS



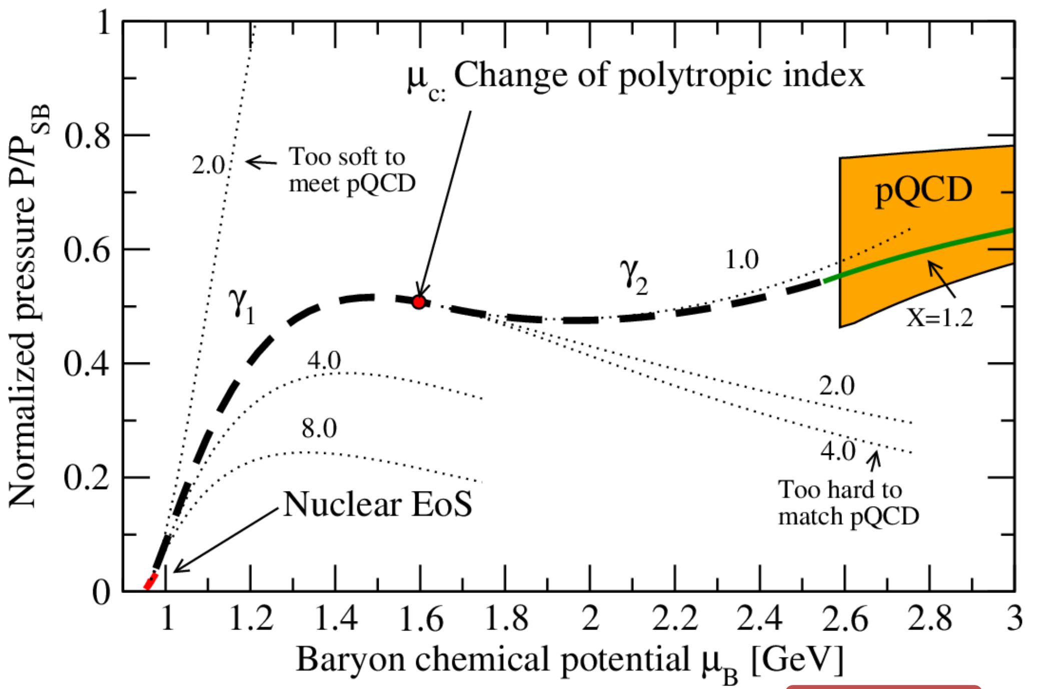


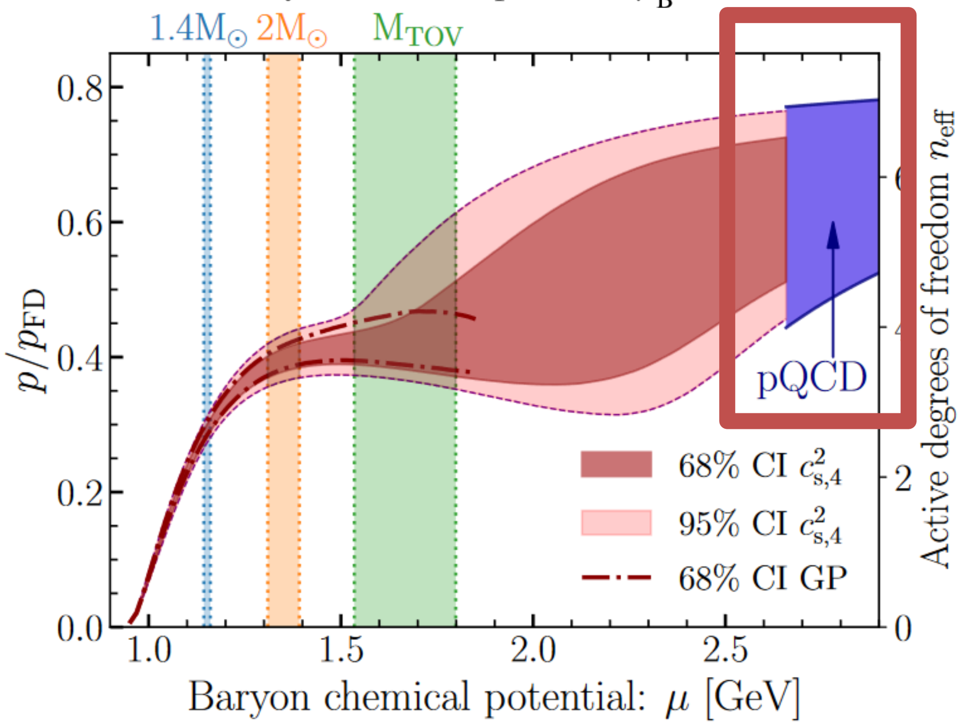
Possible way to proceed: build huge ensembles of randomly generated interpolators with piecewise basis functions – or use nonparametric Gaussian Process regression

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); Gorda et al., ApJ 950 (2023), 2204.11877, Annala et al., 2303.11356]





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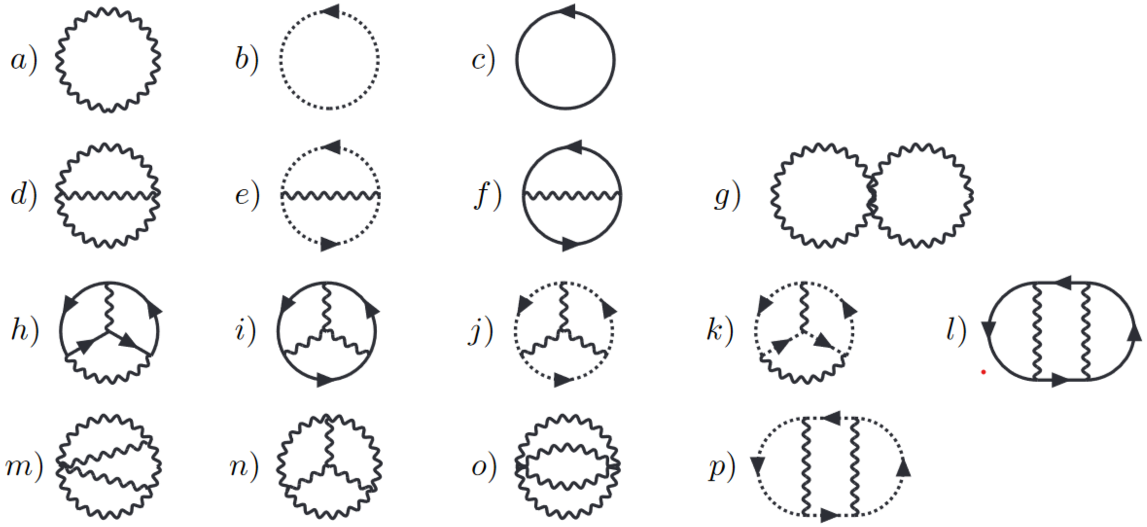
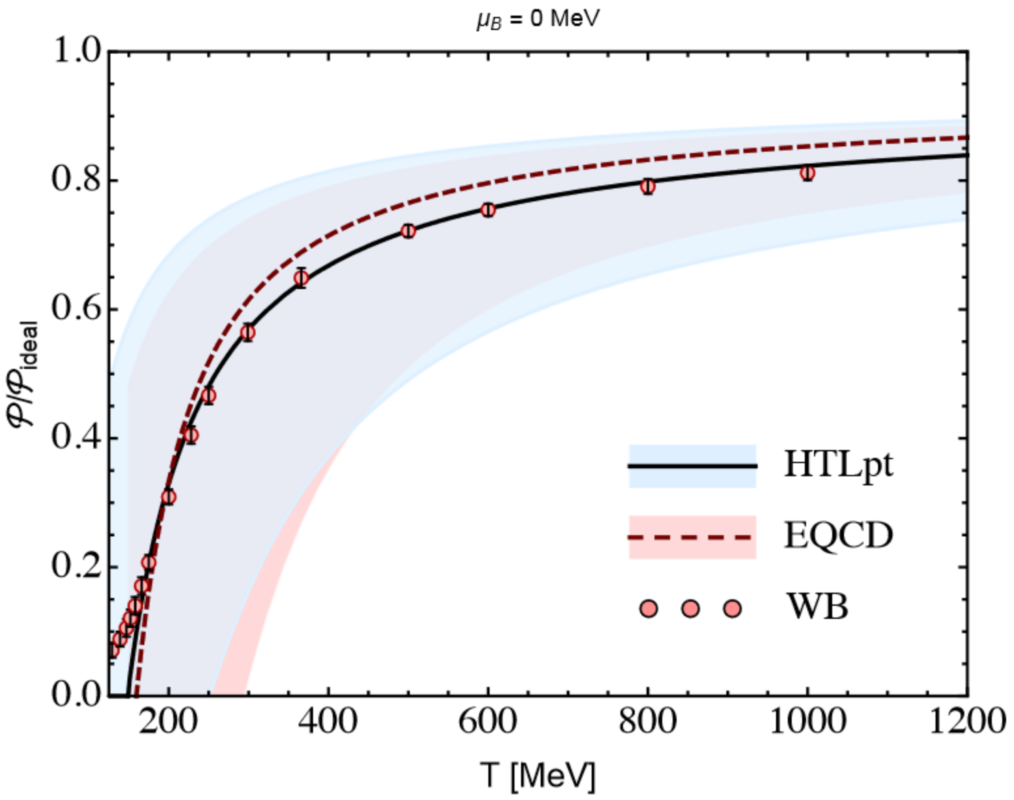
pQCD at high densities and low temperatures: concepts and tools

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

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





+ proper resummation of soft bosonic dof's, resolving IR problems

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

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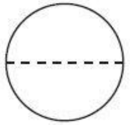
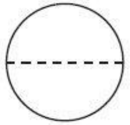
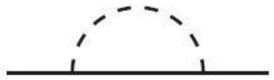
But what happens at high μ and $T = 0$?

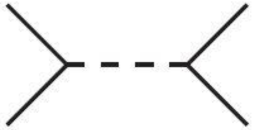
1) Sum-integrals get replaced by four-dimensional continuous integrals, with fermionic $p_0 \to p_0 - i\mu$
   - Simplification from vanishing of diagrams with no fermion loops
   - Technical challenge: how to deal with fermionic p_0 integrals in a systematic manner?
2) IR sensitive modes no longer 3d: all bosonic (Euclidean) four-momenta satisfying $|P| \lesssim m_E \sim g\mu_B$ need special treatment
   - What is the correct EFT?

1) From sum-integrals to 4d integrals:

At strict $T = 0$ limit, advantageous to first perform p_0 integrals using the Residue theorem. Proceduce can be automatized via “cutting rules”:

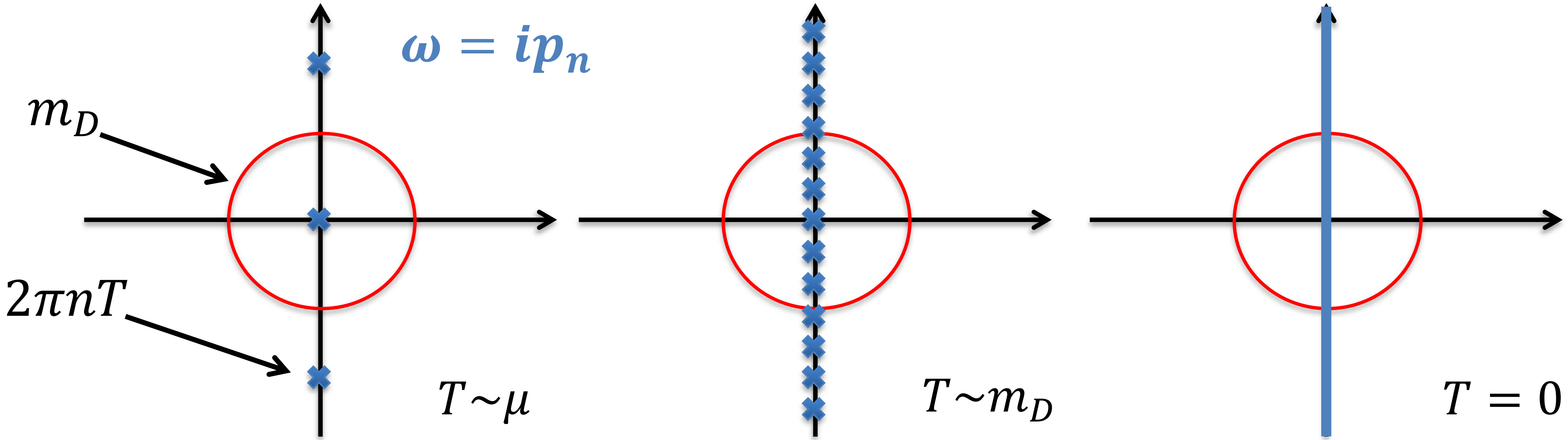
I. For $i = 0$ to $i = \#$ of fermionic loop momenta, perform all possible cuts of i fermion lines
II. Place cut line on shell and integrate the generated amplitude over three-momenta p with measure $\int \frac{d^3p}{(2\pi)^3} \frac{\theta\left(\mu - E(p)\right)}{2E(p)}$, $E(p) \equiv \sqrt{p^2 + m^2}$
III. Sum over i and all topologies

 $\rightarrow$  $- 2\int \frac{d^3\vec{p}}{(2\pi)^3} \frac{\theta(\mu - E(\vec{p}))}{2E(\vec{p})}$ 

$+ \int \frac{d^3\vec{p}}{(2\pi)^3} \frac{\theta(\mu - E(\vec{p}))}{2E(\vec{p})} \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{\theta(\mu - E(\vec{q}))}{2E(\vec{q})}$ 

2) Differences between (static) EFTs at high and low T:

	$T \gg m_E \sim g\sqrt{T^2+\mu^2}$	$T \lesssim m_E \sim g\sqrt{T^2+\mu^2}$
IR sensitive modes	$n=0$ Matsubara modes of bosonic fields: A_0 & A_i	All soft bosonic fields: separation of $n = 0$ modes meaningless



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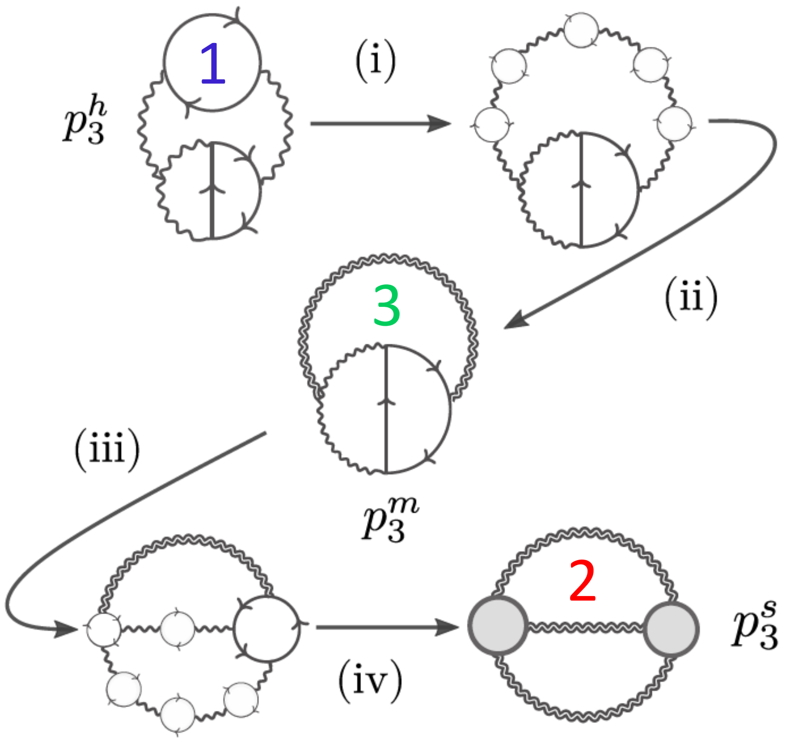
Simplest EFT construction	Dimensional reduction: 3d effective theories for scales gT (EQCD, A_0 & A_i) and g^2T (MQCD, only A_i)	Soft limit of gluonic amplitudes: Hard Thermal Loops (HTL), valid for momenta $P \lesssim m_E$
Source of LO non-analyticity in α_s	LO pressure of a 3d SFT for A_0 field: $p_{\mathrm{EQCD}} \sim T\int d^3p \ln(p^2+m_E^2)$	LO pressure at T ≈ 0: $p_{\mathrm{HTL}} \sim \int d^4P \ln\left(P^2+\Pi_{\mathrm{HTL}}^{L/T}(P)\right)$
Higher-order soft contributions	Weak-coupling expansion within EQCD and 3d lattice determination of p_{MQCD}	Weak-coupling expansion within extended HTL effective theory
First soft terms in EoS expansion	$\frac{p}{T^4} \sim 1+\alpha_s+\alpha_s^{\frac{3}{2}}+\alpha_s^2\ln\alpha_s+\alpha_s^2+\alpha_s^{\frac{5}{2}}$ $+\alpha_s^3\ln\alpha_s+\alpha_s^3+\cdots$	$\frac{p}{\mu^4} \sim 1+\alpha_s+\alpha_s^2\ln\alpha_s+\alpha_s^2$ $+\alpha_s^3\ln^2\alpha_s+\alpha_s^3\ln\alpha_s+\alpha_s^3+\cdots$

Blue = hard, red = soft, green = both

Quark matter pressure to four loops: how do we account for all contributions?

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



$$p = p_{\rm FD} + p_1^h \alpha_s + p_2^h \alpha_s^2 + p_3^h \alpha_s^3 + p_2^s \alpha_s^2 + p_3^s \alpha_s^3 + p_3^m \alpha_s^3$$

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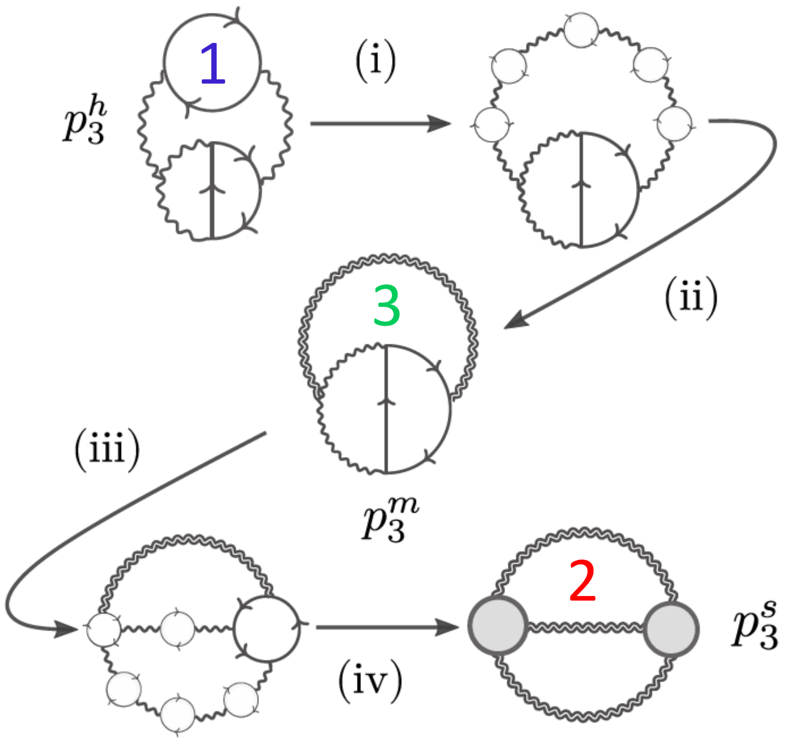

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Known since 1970's [Freedman, McLerran, PRD 16 (1977)]

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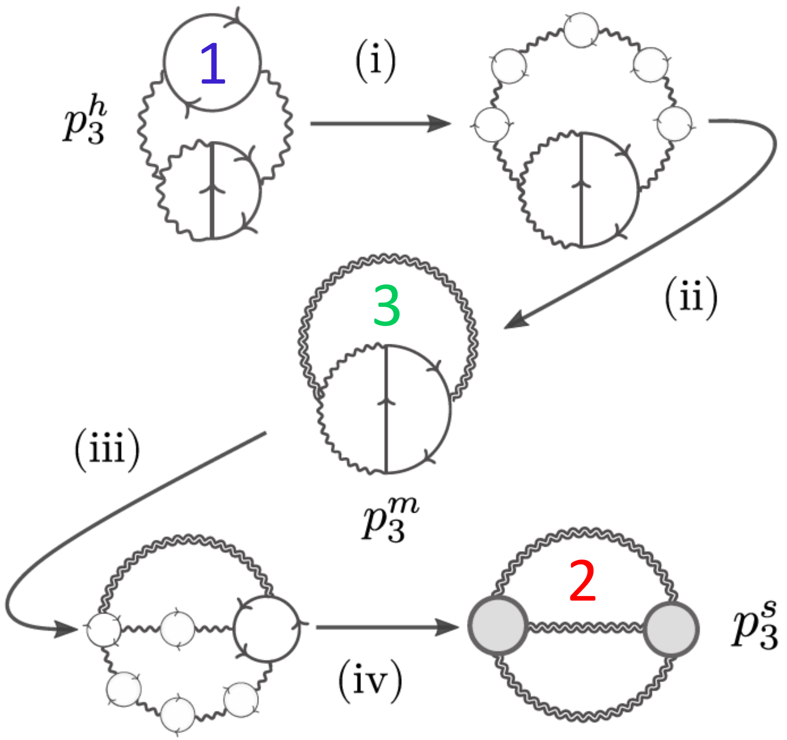

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Leading log from Gorda, Kurkela, Romatschke, Säppi, AV, PRL 121 (2018)

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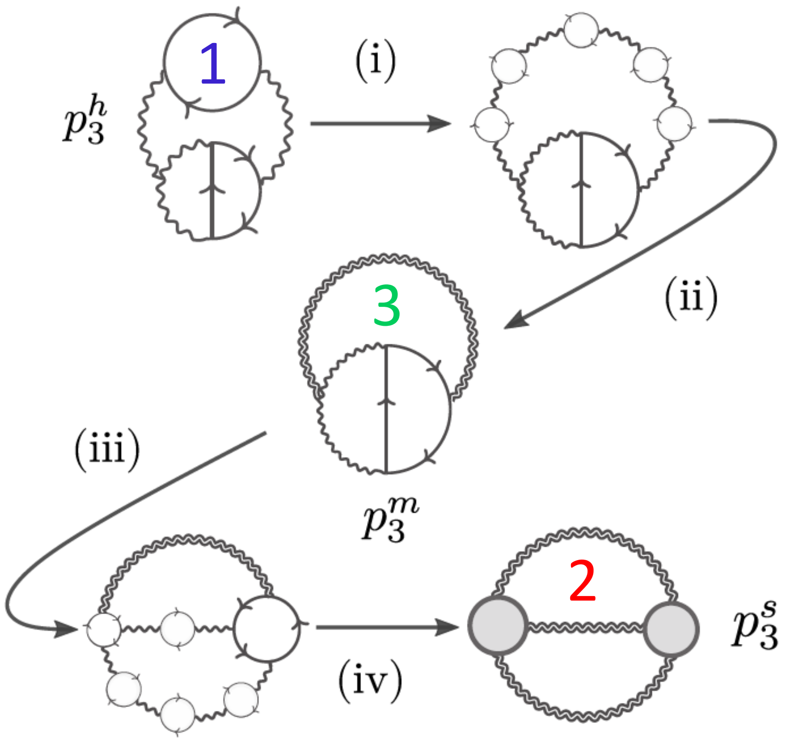

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Gorda, Kurkela, Paatelainen, Säppi, AV, PRL 127 (2021); Fernandez, Kneur, 2109.02410

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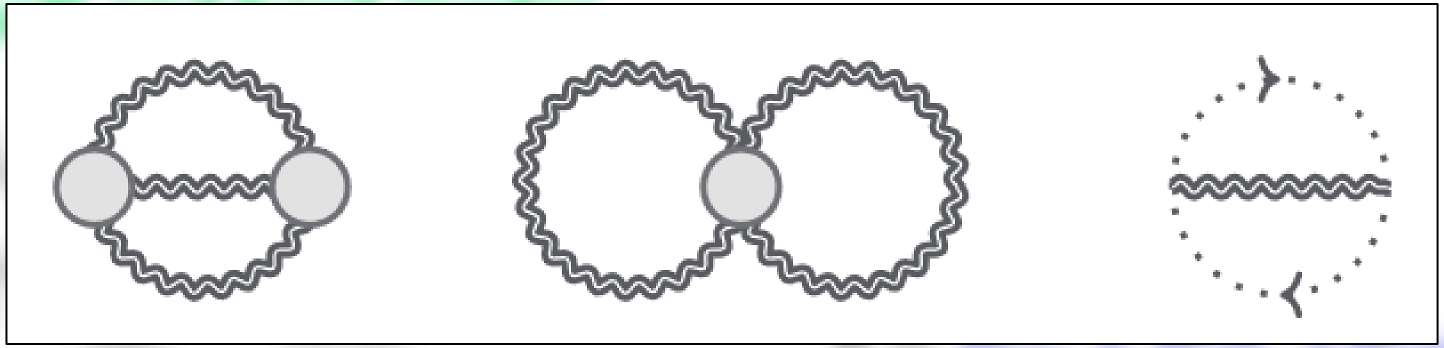

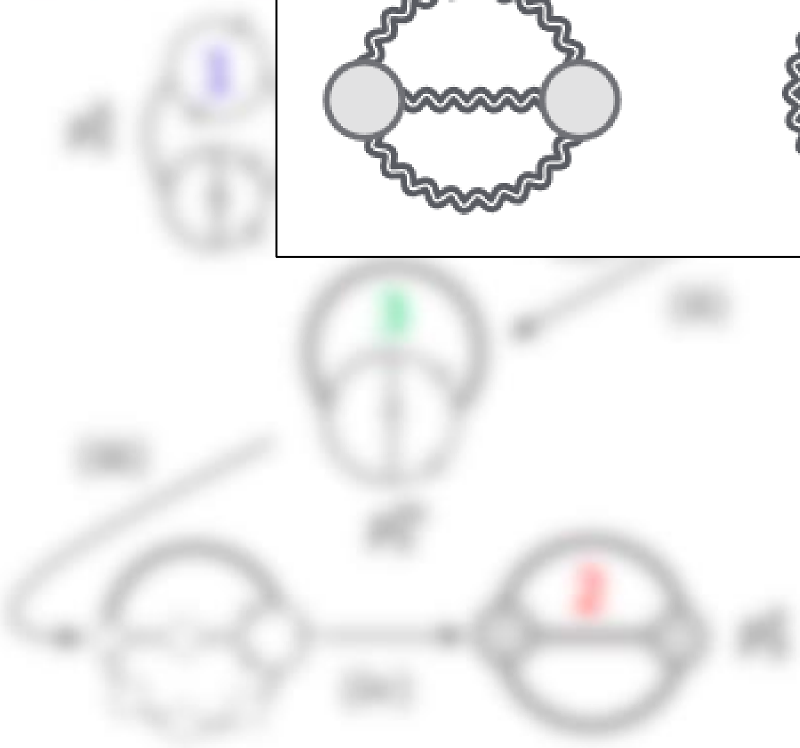

$$p = p_0 + p_1\alpha_s + p_2\alpha_s^2 + p_3^h\alpha_s^3 + p_2^s\alpha_s^2 + p_3^s\alpha_s^3 + p_3^m\alpha_s^3$$

Gorda, Kurkela, Paatelainen, Säppä, Vuorinen, PRL 127 (2021); Fernandez, Kneur, 2109.02410

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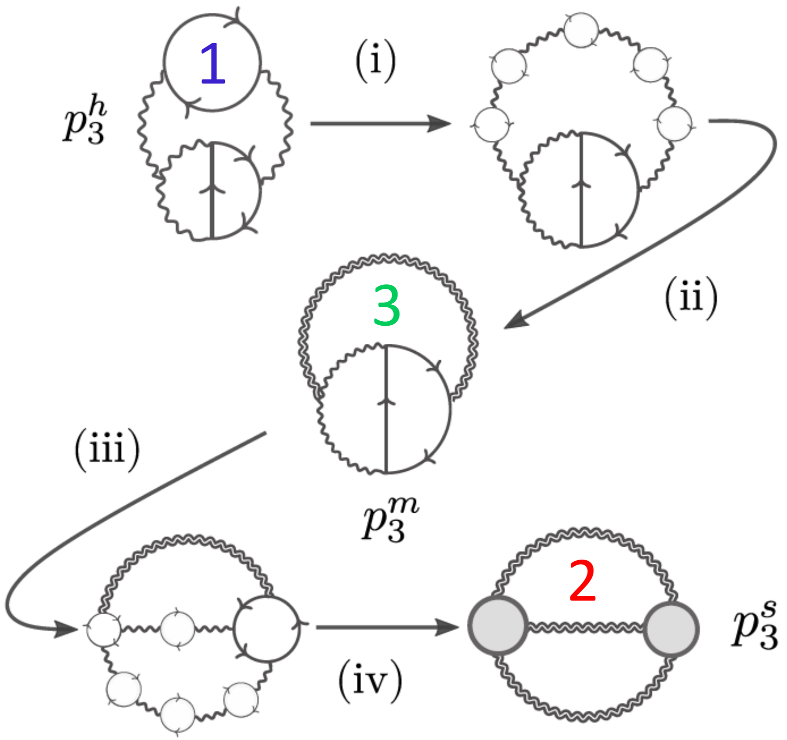

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QED: Gorda, Kurkela, Österman, Paatelainen, Säppi, Seppänen, Schicho, AV, 2204.11893

QCD: Gorda, Paatelainen, Säppi, Seppänen, 2307.11877

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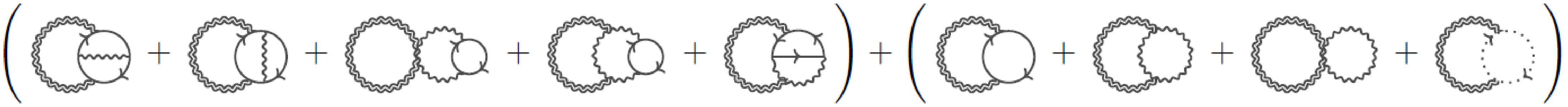
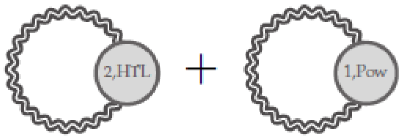
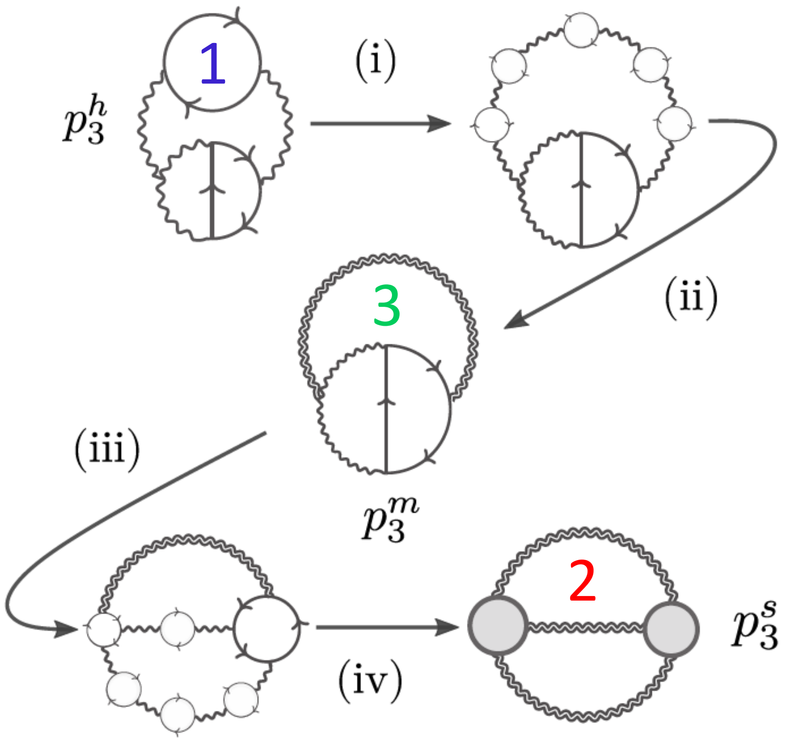
$p^m =$ 

$=$  $= -\frac{\alpha_s m_E^2 d_A}{8\pi} \int_K \mathrm{Tr}\left\{ G_{\mathrm{LO}}(K) \left[\Pi^{2,\mathrm{HTL}}(K) + \frac{K^2}{m_E^2} \Pi^{1,\mathrm{Pow}}(K) \right] \right\}.$

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



Underway by Navarrete, Paatelainen, Seppänen et al.; huge undertaking so no concrete promises on timescale

$$p = p_{\rm FD} + p_1^h \alpha_s + p_2^h \alpha_s^2 \boxed{+ p_3^h \alpha_s^3} + p_2^s \alpha_s^2 + p_3^s \alpha_s^3 + p_3^m \alpha_s^3$$

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

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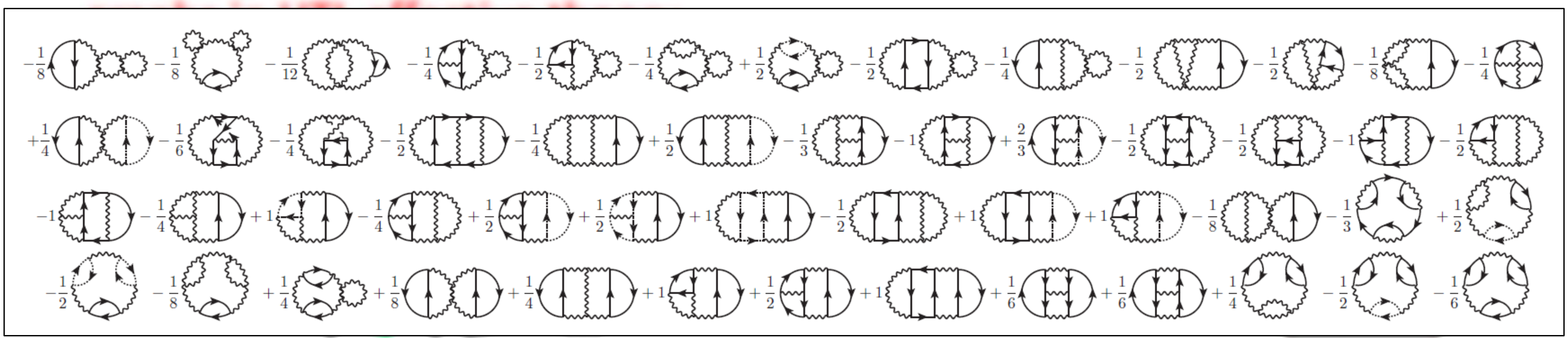

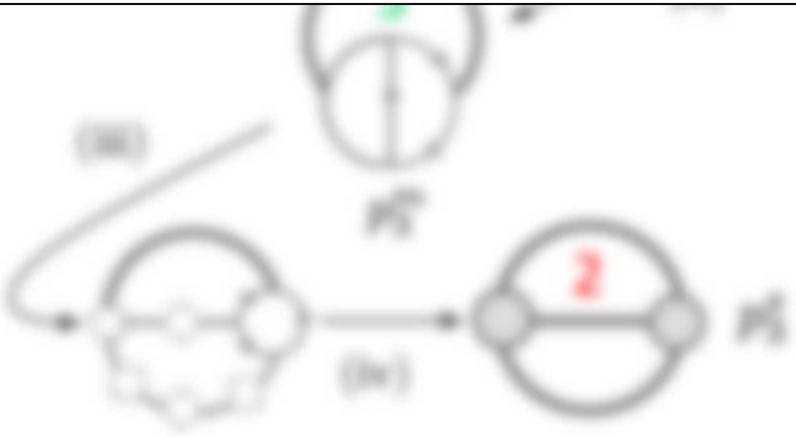

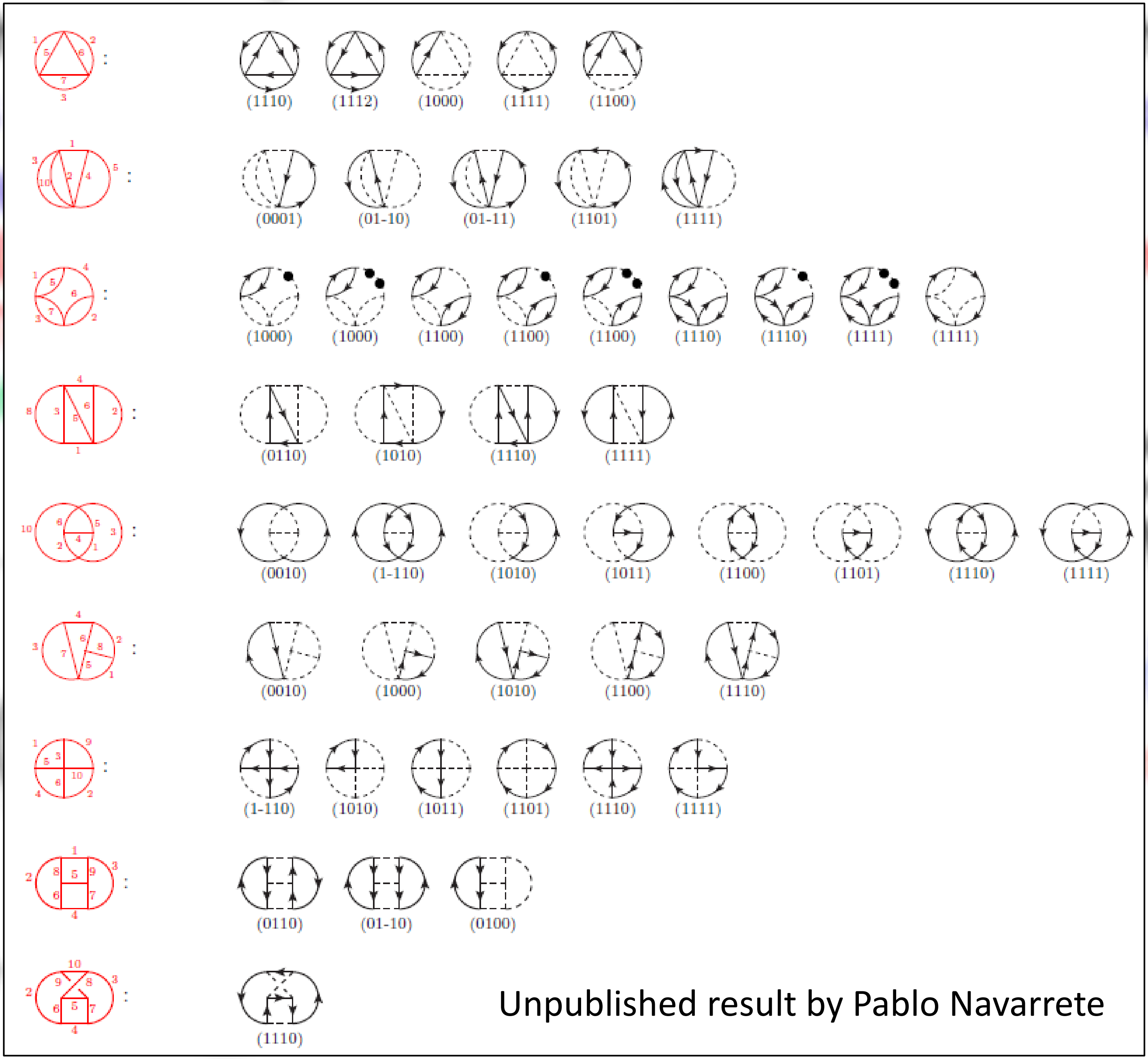

Unpublished result by Pablo Navarrete

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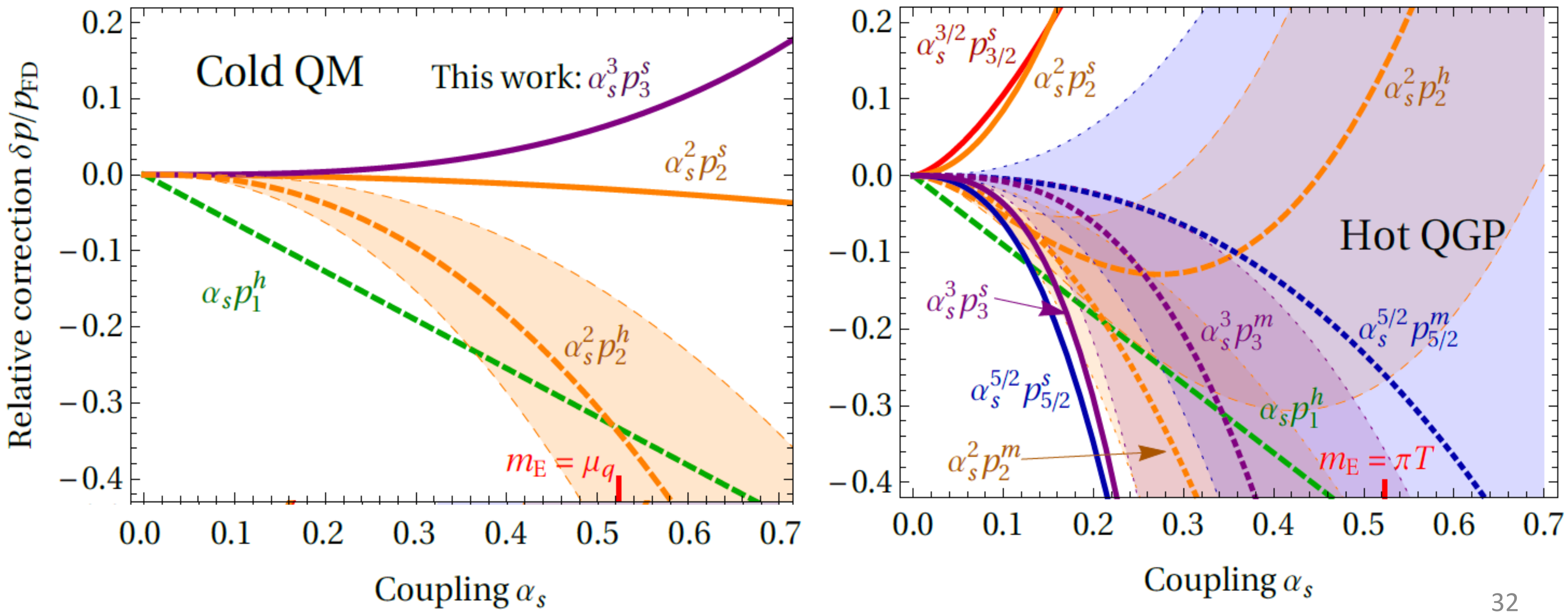
Comparison of convergence at zero vs. high temperature

[Gorda, Kurkela, Paatelainen, Säppi, AV, PRL 127 (2021)]:



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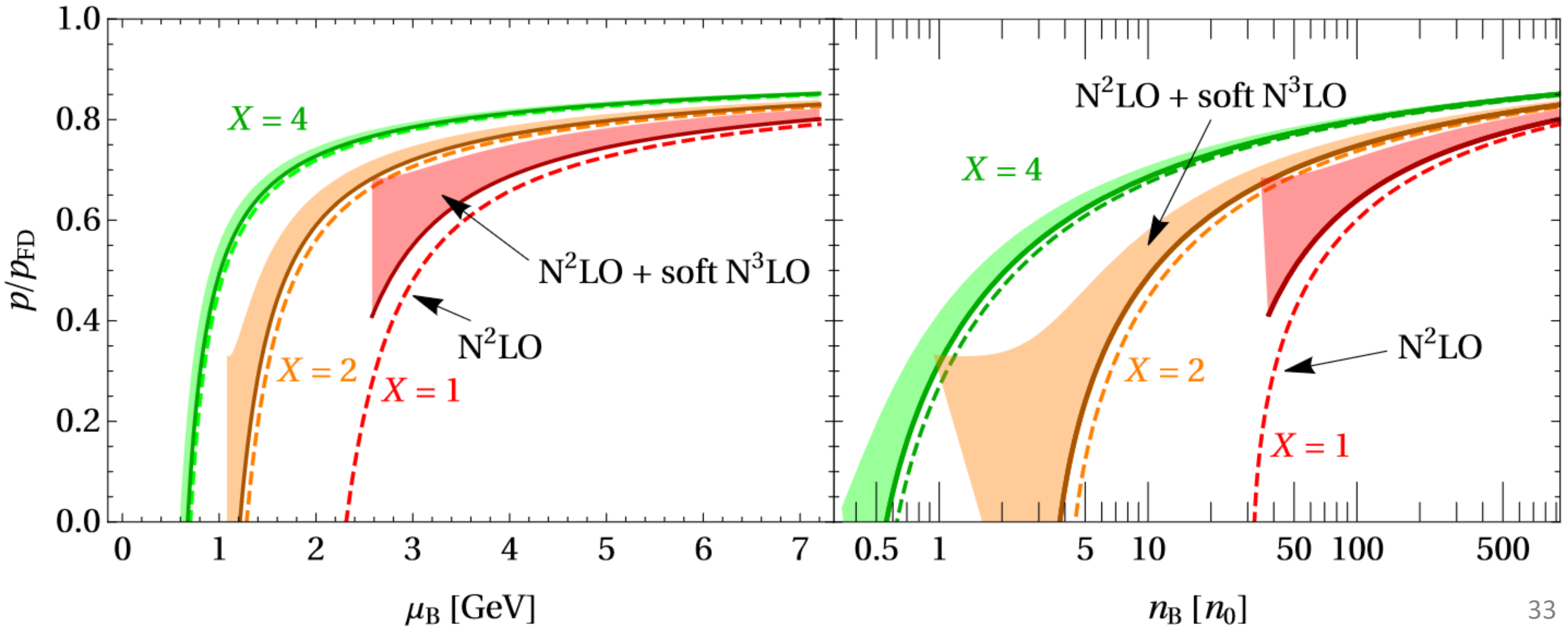
3) Mixing of soft and hard modes

Effect of soft contributions on the EoS [Gorda, Kurkela, Paatelainen, Säppi, AV, PRL 127 (2021)]:



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

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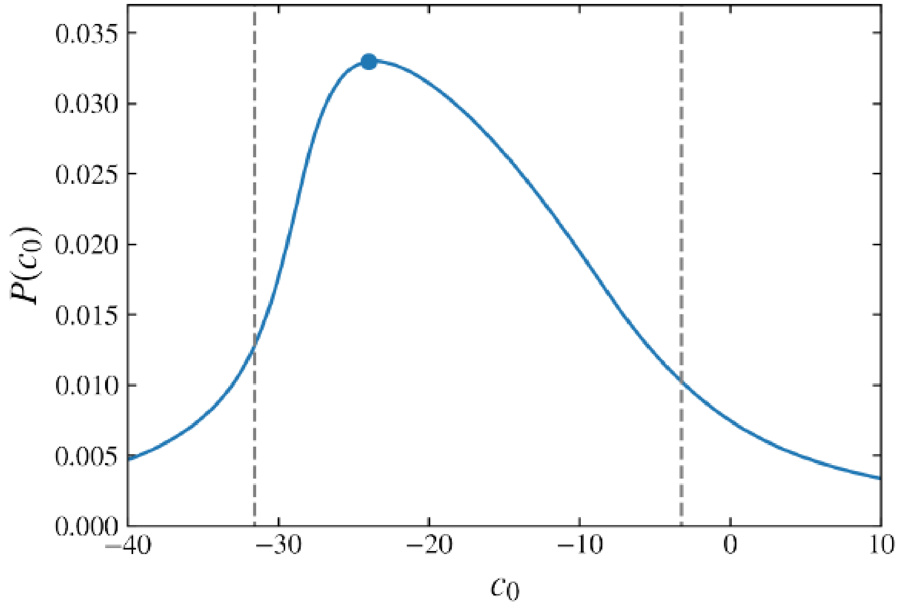
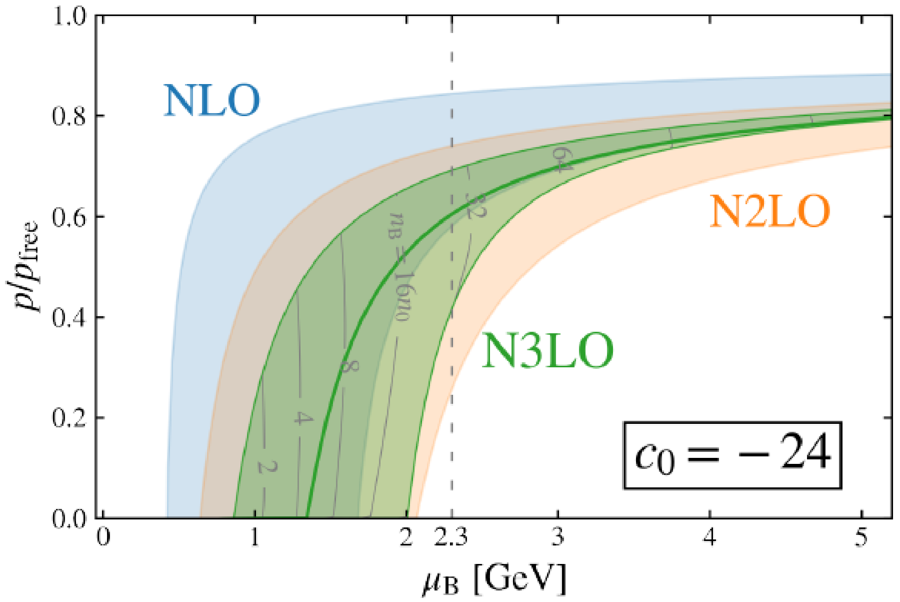
3) Mixing of soft and hard modes

Effect of mixed contributions in QCD [Gorda, Paatelainen, Säppi, Seppänen, 2307.11877]:





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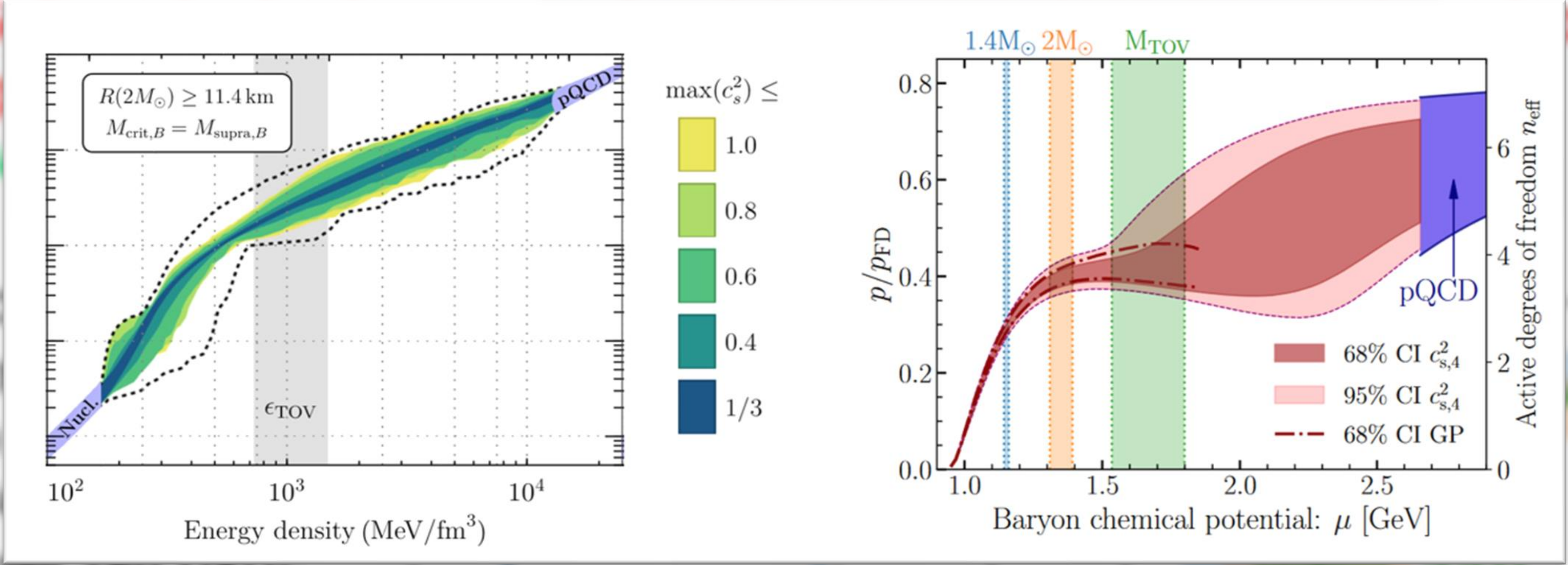


Plan of the lectures:

I. Basics of neutron stars and their interiors: main properties and theoretical tools

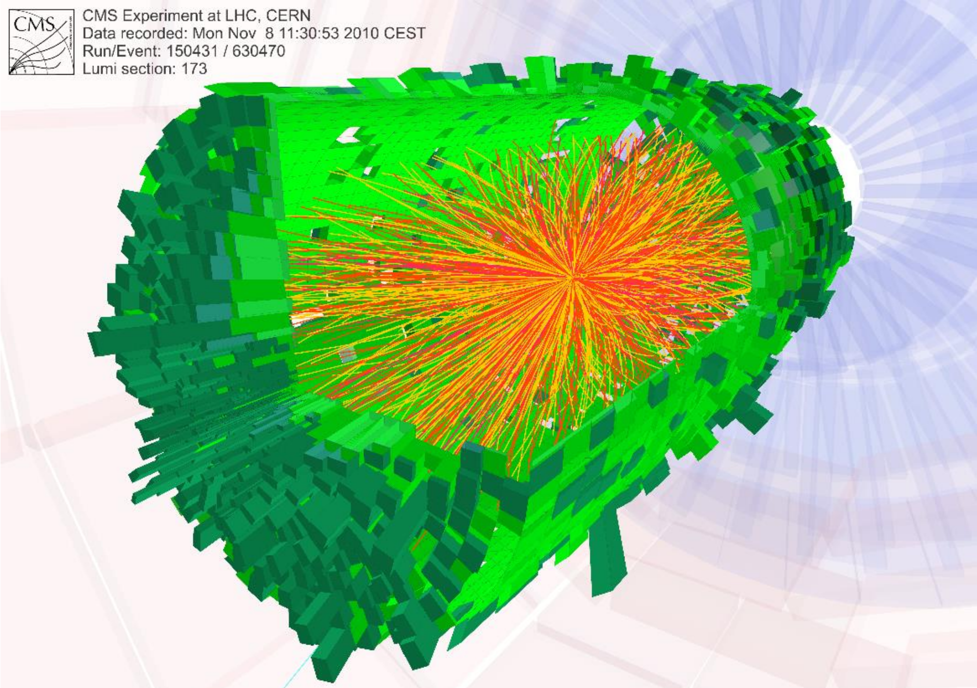
II. Effective field theory at (ultra)high baryon density: Hard Thermal Loops and beyond

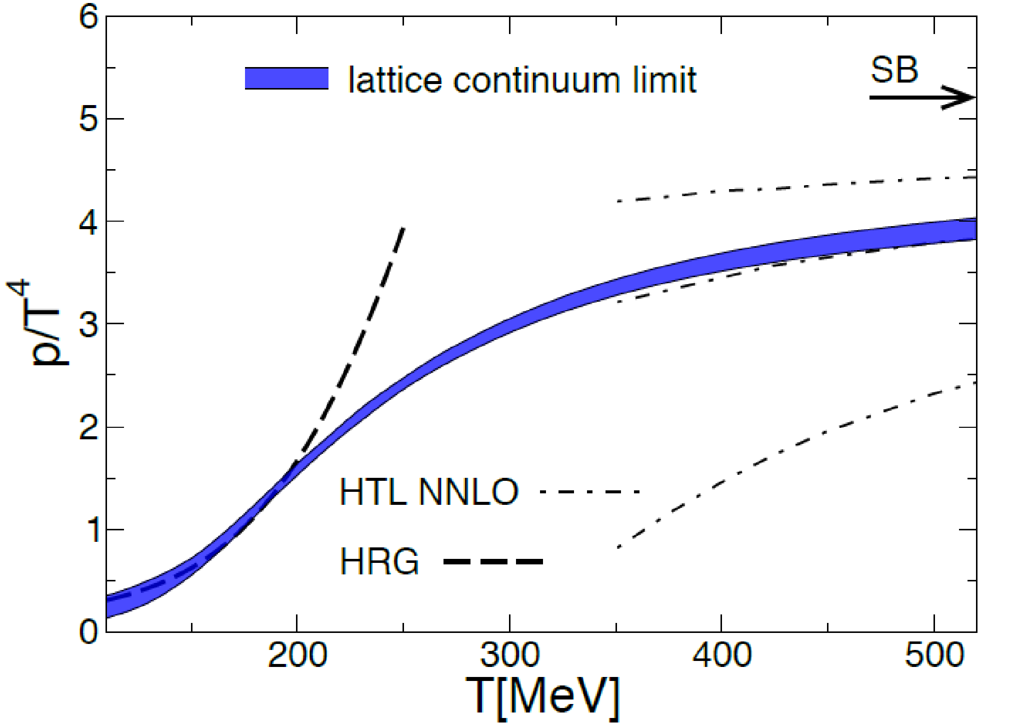
III. Fitting all the pieces together: what can we robustly say about NS cores?

Lessons from heavy-ion physics

Some lessons from heavy-ion experiments & lattice studies of hot QGP:

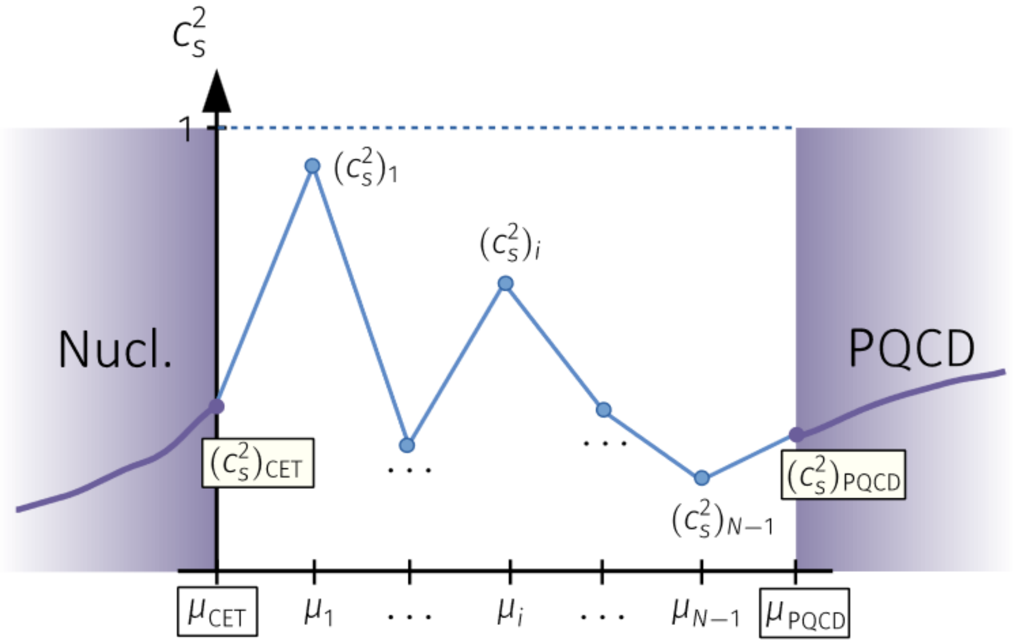
1) In dilute limit, deconfinement transition a *crossover* at $T \sim 155$ MeV, $\epsilon \sim 400$ MeV/fm^3
2) Soon thereafter rapid but smooth approach towards conformal behavior: $\gamma \equiv \frac{d \ln p}{d \ln \epsilon} \approx 1$, $c_s^2 \lesssim 1/3$
3) Strong coupling machinery useful for transport & dynamics, but *bulk thermo-dynamic properties of hot QGP consistent with resummed pQCD from $T \sim 2.5 T_c$*
4) Creation of deconfined matter confirmed *indirectly* through presence of a near-thermal medium with $T > T_c$

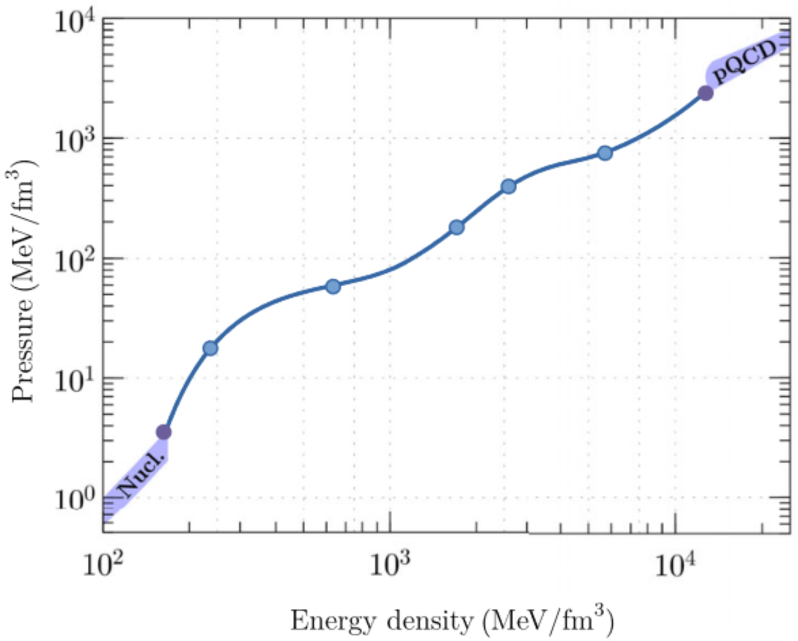




NS-matter EoS: robust hard limits

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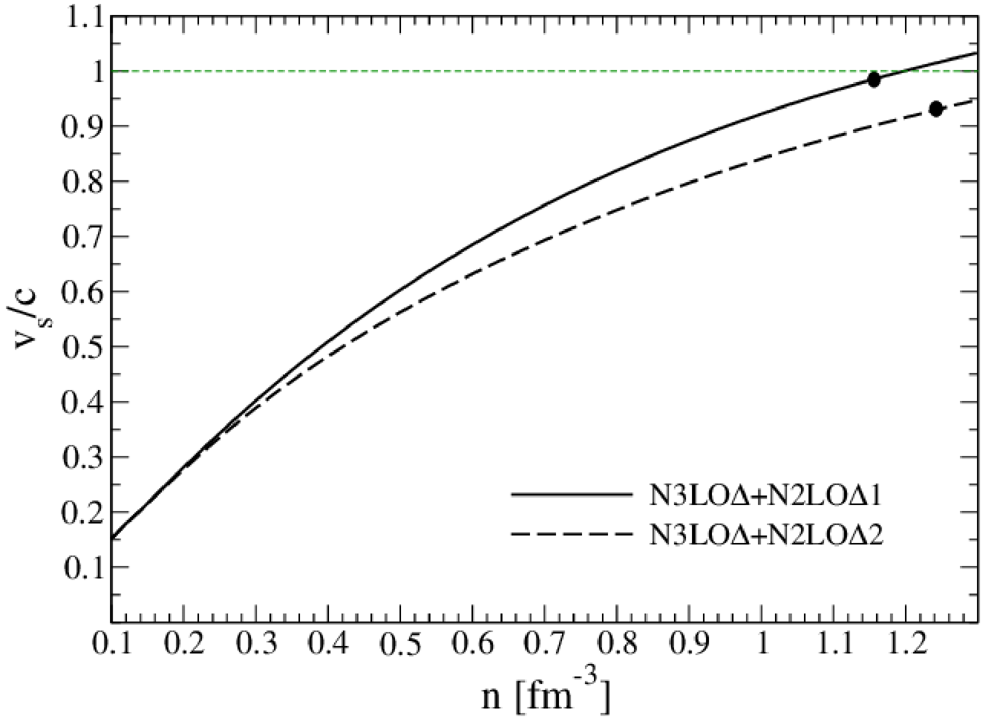
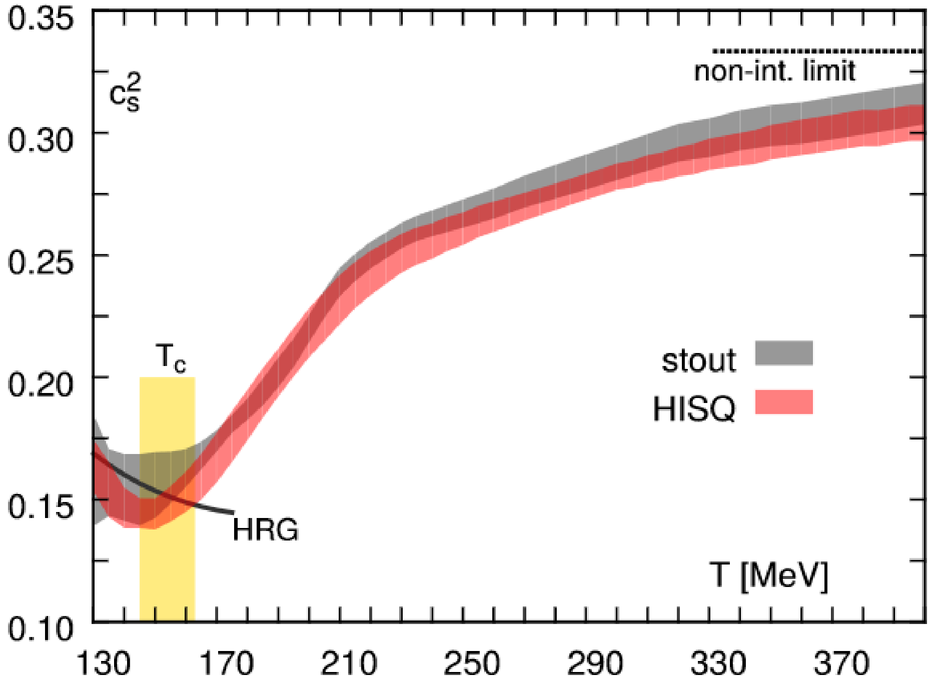
Interesting because of tension between standard lore in nuclear physics and experience from other contexts





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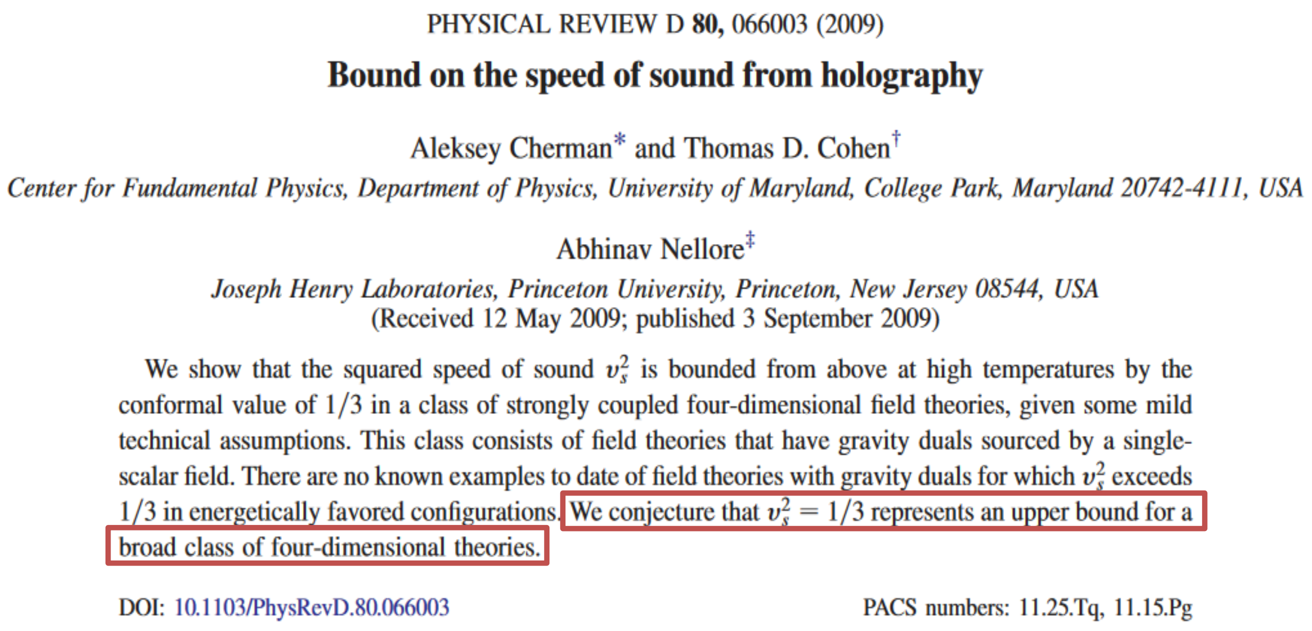


PHYSICAL REVIEW D **80,** 066003 (2009)

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)

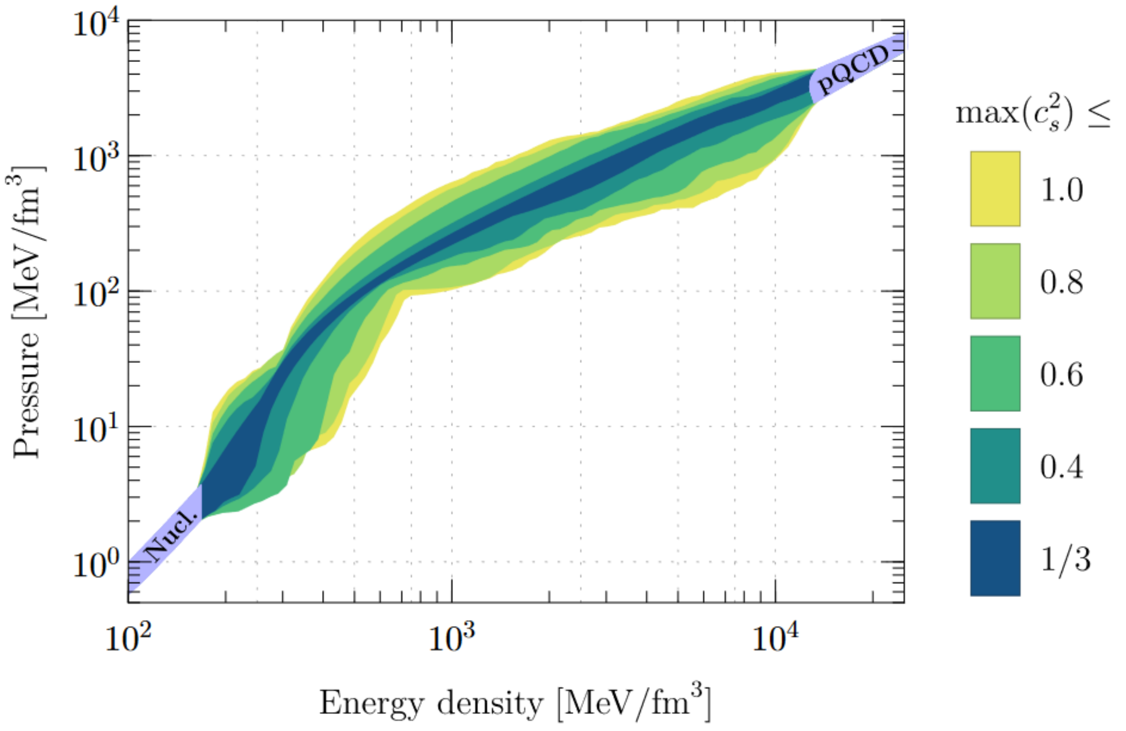
We show that the squared speed of sound v_s^2 is bounded from above at high temperatures by the conformal value of 1/3 in a class of strongly coupled four-dimensional field theories, given some mild technical assumptions. This class consists of field theories that have gravity duals sourced by a single-scalar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



Additional robust observational info:

- 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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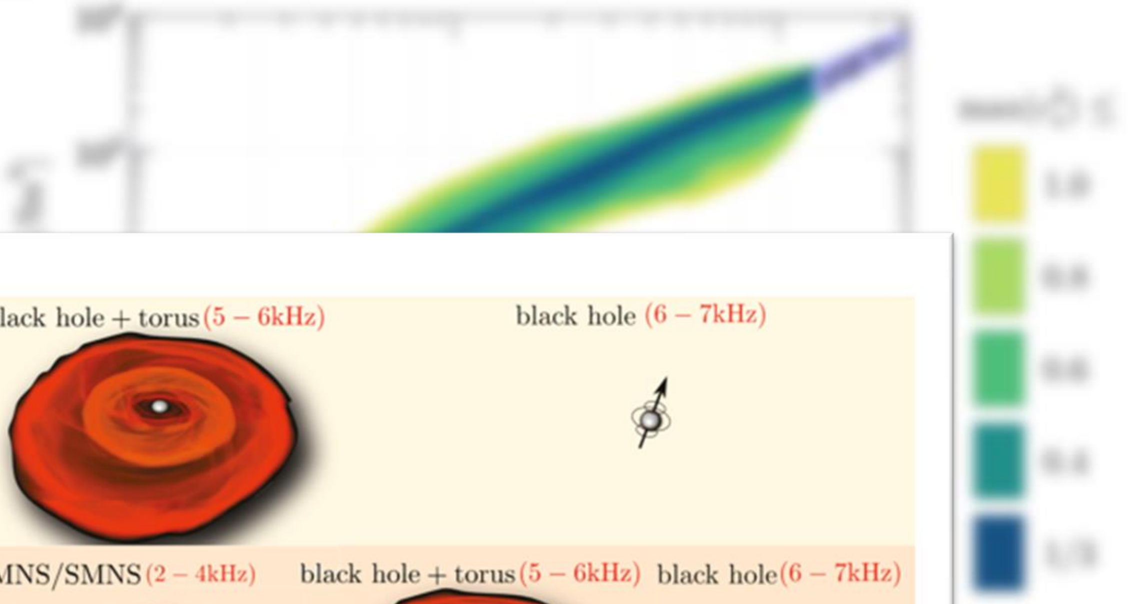
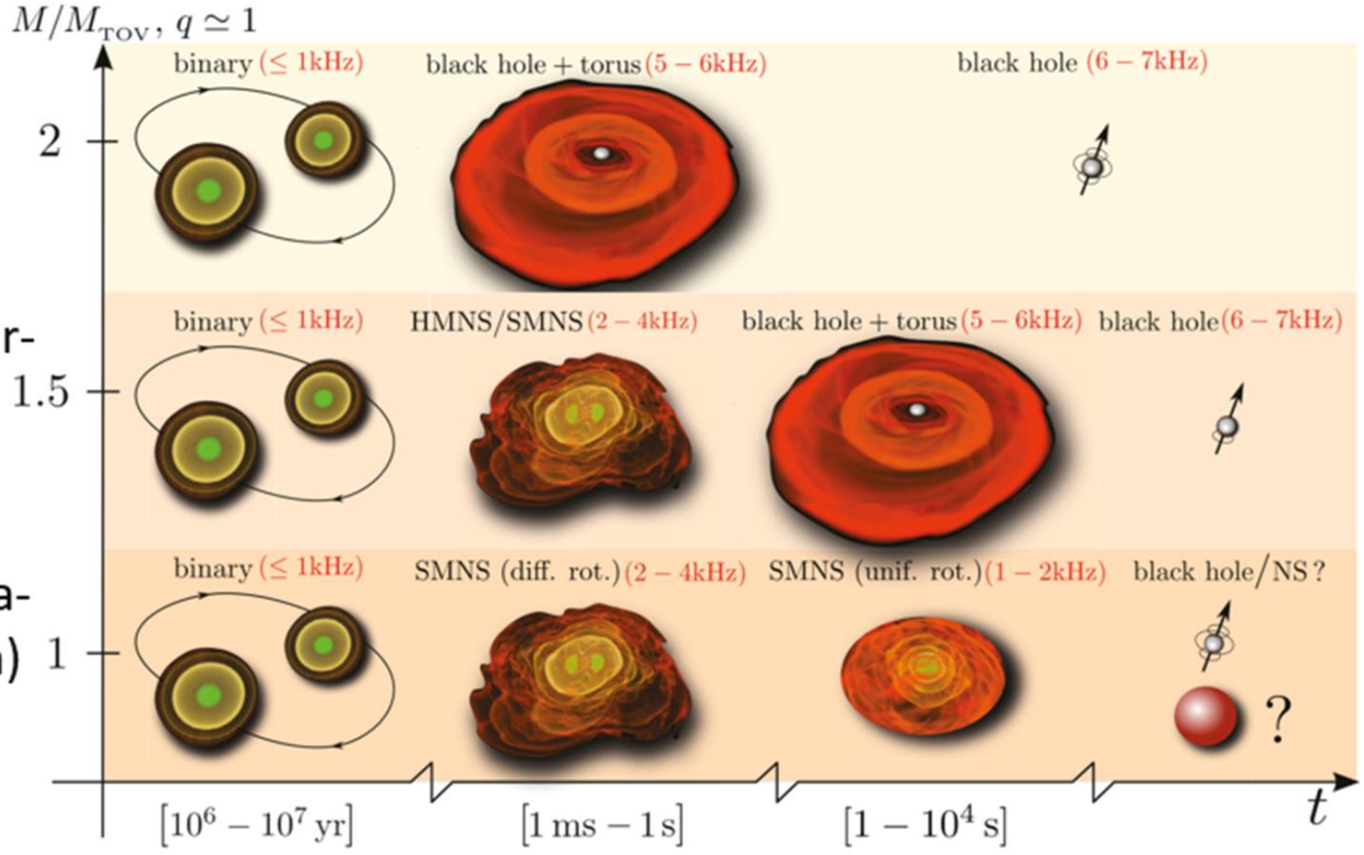


Scenario 1: prompt collapse

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)]

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

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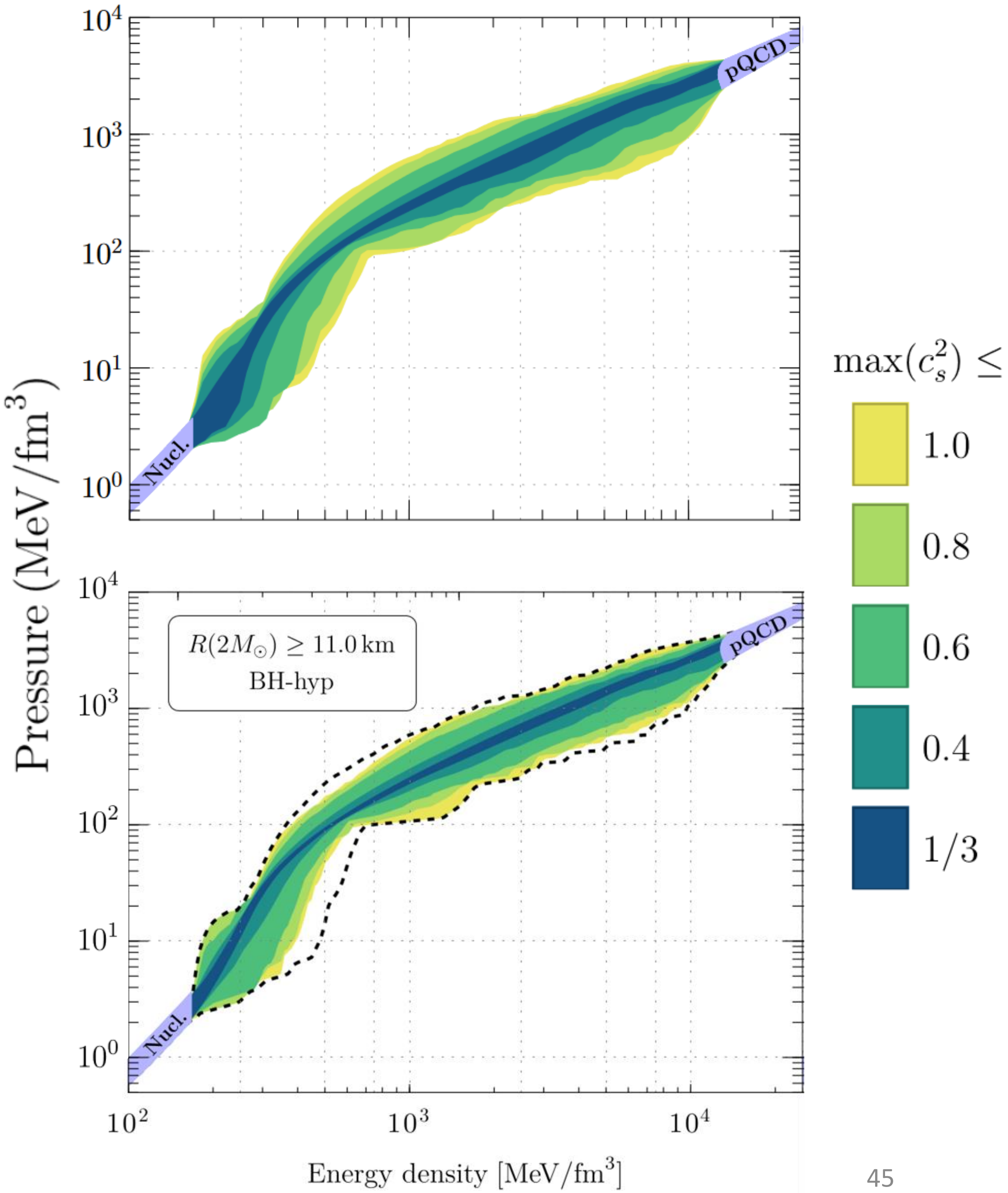

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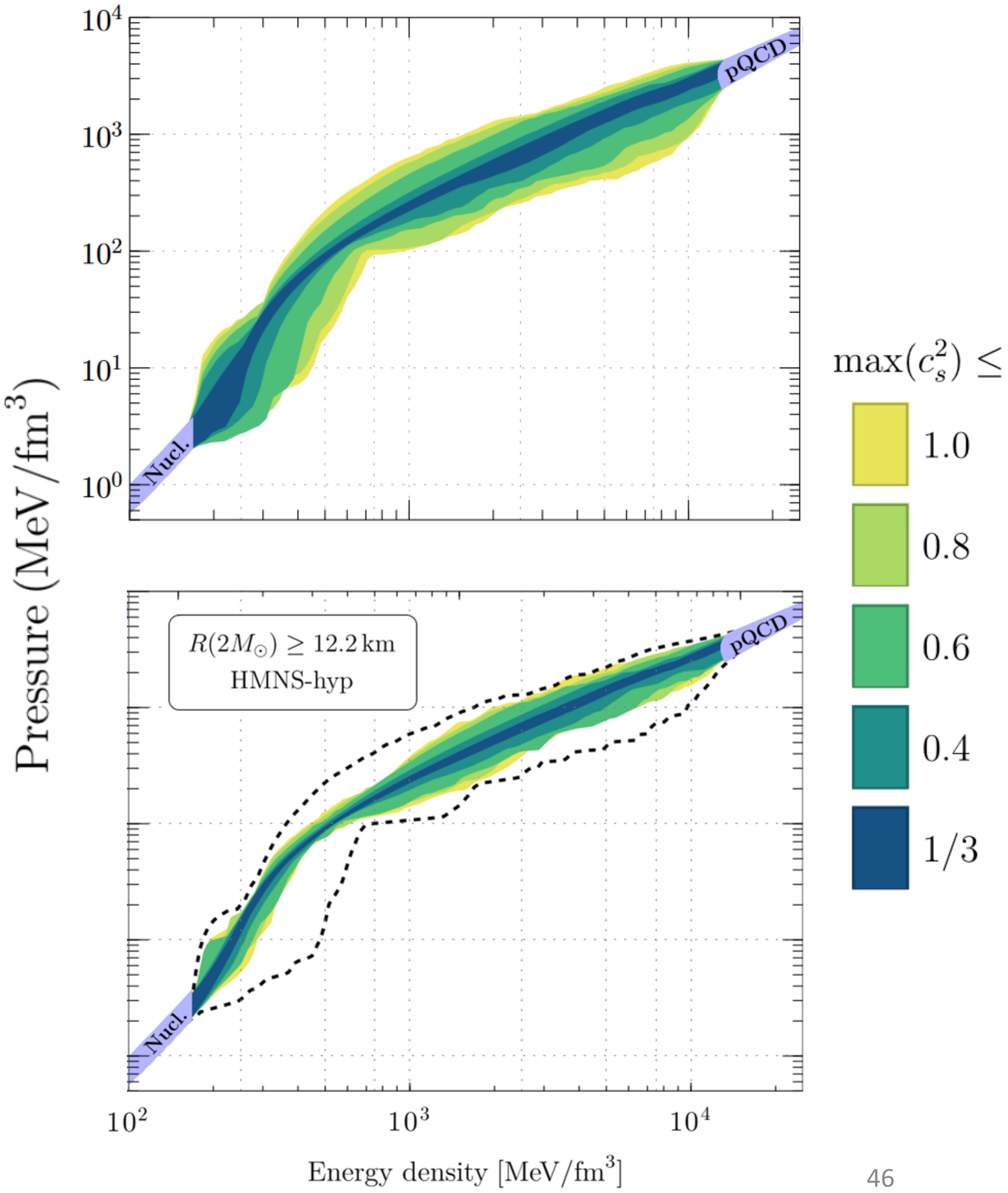
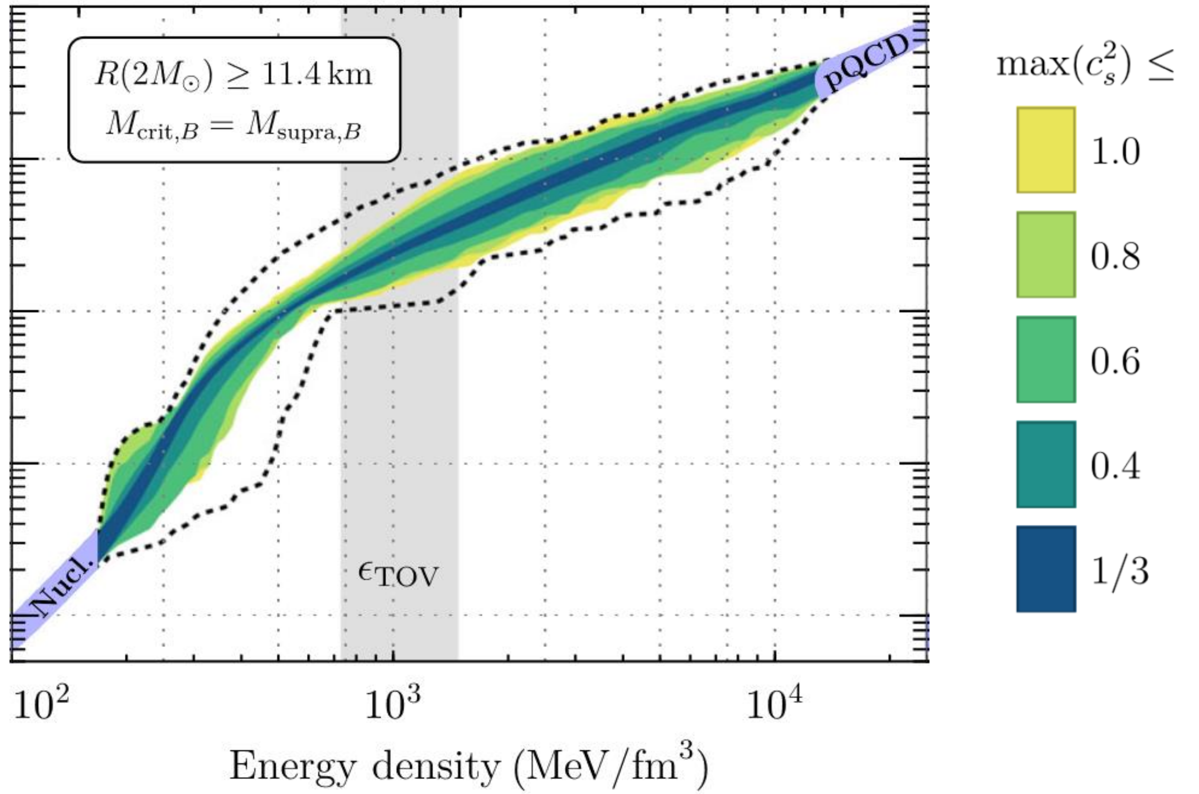


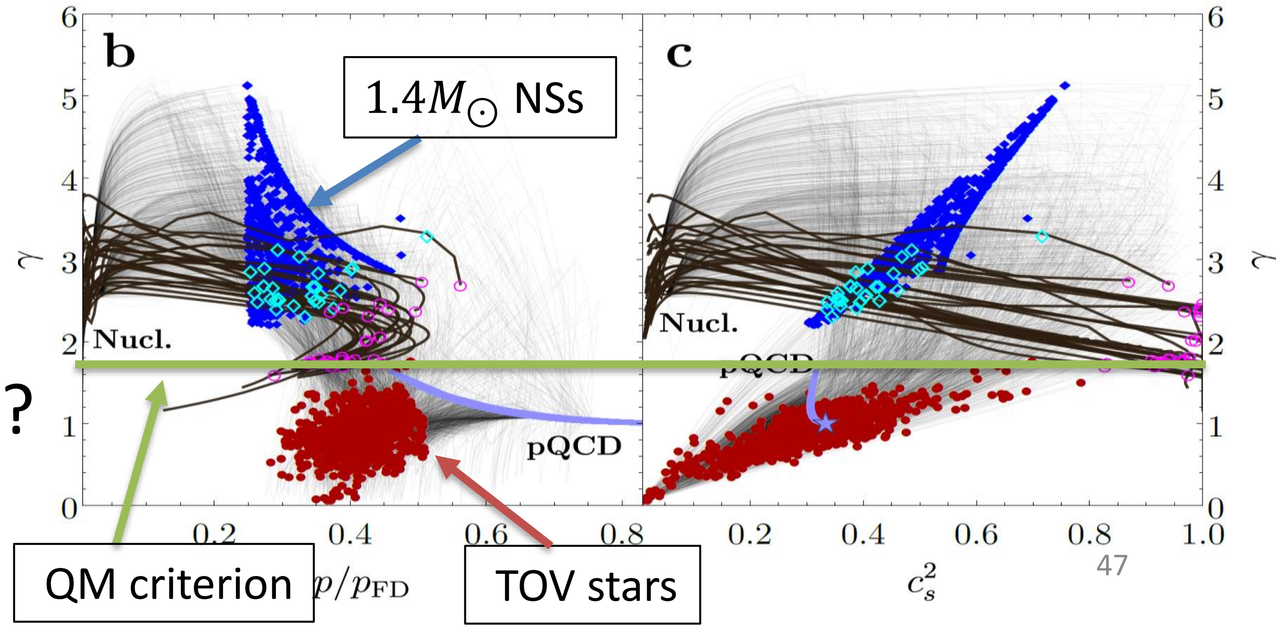
The EoS band features clear two-phase structure, with polytropic index $\gamma \equiv \frac{d \ln p}{d \ln \epsilon}$ transitioning from hadronic ($\gamma \gtrsim 2$) to near-conformal ($\gamma \approx 1$) behavior below TOV densities: evidence for QM cores

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



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?



Quark cores and probabilities: Bayesian approach

Improvements in recent work:

- Instead of placing hard limits, consider measurement uncertainties ⇒ ability to factor in many more observations
- 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: Estimate likelihood of various scenarios (QM core, destabilizing FOPT,...)

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

[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, 2303.11356]

System	Mass prior [$M_\odot$]	Model	Ref.
NICER pulsars			
PSR J0030+0451	$\mathcal{U}(1.0, 2.5)$	ST+PST	[51, 52]
PSR J0740+6620	$\mathcal{N}(2.08, 0.07^2)$	N+XMM+calib.	[17, 45, 53]
qLMXB systems			
M13	$\mathcal{U}(0.8, 2.4)$	H	[48]
M28	$\mathcal{U}(0.5, 2.8)$	He	[49]
M30	$\mathcal{U}(0.5, 2.5)$	H	[49]
ω Cen	$\mathcal{U}(0.5, 2.5)$	H	[49]
NGC 6304	$\mathcal{U}(0.5, 2.7)$	He	[49]
NGC 6397	$\mathcal{U}(0.5, 2.0)$	He	[49]
47 Tuc X7	$\mathcal{U}(0.5, 2.7)$	H	[49]
X-ray bursters			
4U 1702−429	$\mathcal{U}(1.0, 2.5)$	D	[50]
4U 1724−307	$\mathcal{U}(0.8, 2.5)$	SolA001	[84]
SAX J1810.8−260	$\mathcal{U}(0.8, 2.5)$	SolA001	[84]

	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	$1/3 - p_{\mathrm{PT}}/\epsilon$
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_{free}	$\ll 1$	$[0.25, 0.35]$	$[0.5, 1]$	—	$p_{\mathrm{PT}}/p_{\mathrm{free}}$

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

This is consistent with earlier findings of, e.g., Fujimoto et al., PRL 129 (2022)

	CEFT	Dense NM	Pert. QM	CFTs	FOPT
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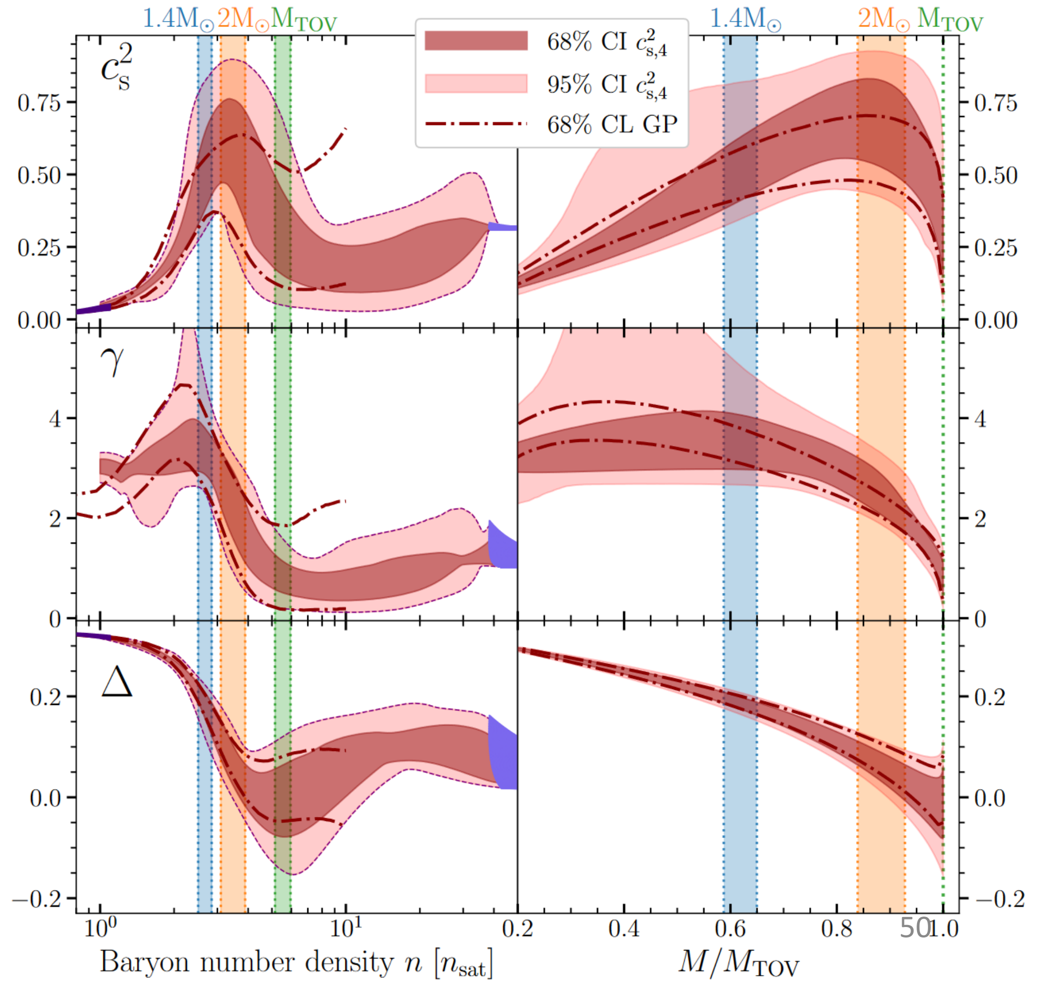

[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, 2303.11356]

Main results:

2) Given that $\Delta = \frac{1}{3} - \frac{c_s^2}{\gamma}$ and $\Delta' = c_s^2 \left(\frac{1}{\gamma} - 1\right)$ we track the "conformal distance"

$$d_c \equiv \sqrt{\Delta^2 + (\Delta')^2}$$

- Its conformalization ensures conformal. for all other quantities considered
- Values in dense NM and perturbative QM sufficiently separated
- 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, 2303.11356]

	CEFT	Dense NM	Pert. QM	CFTs	FOPT
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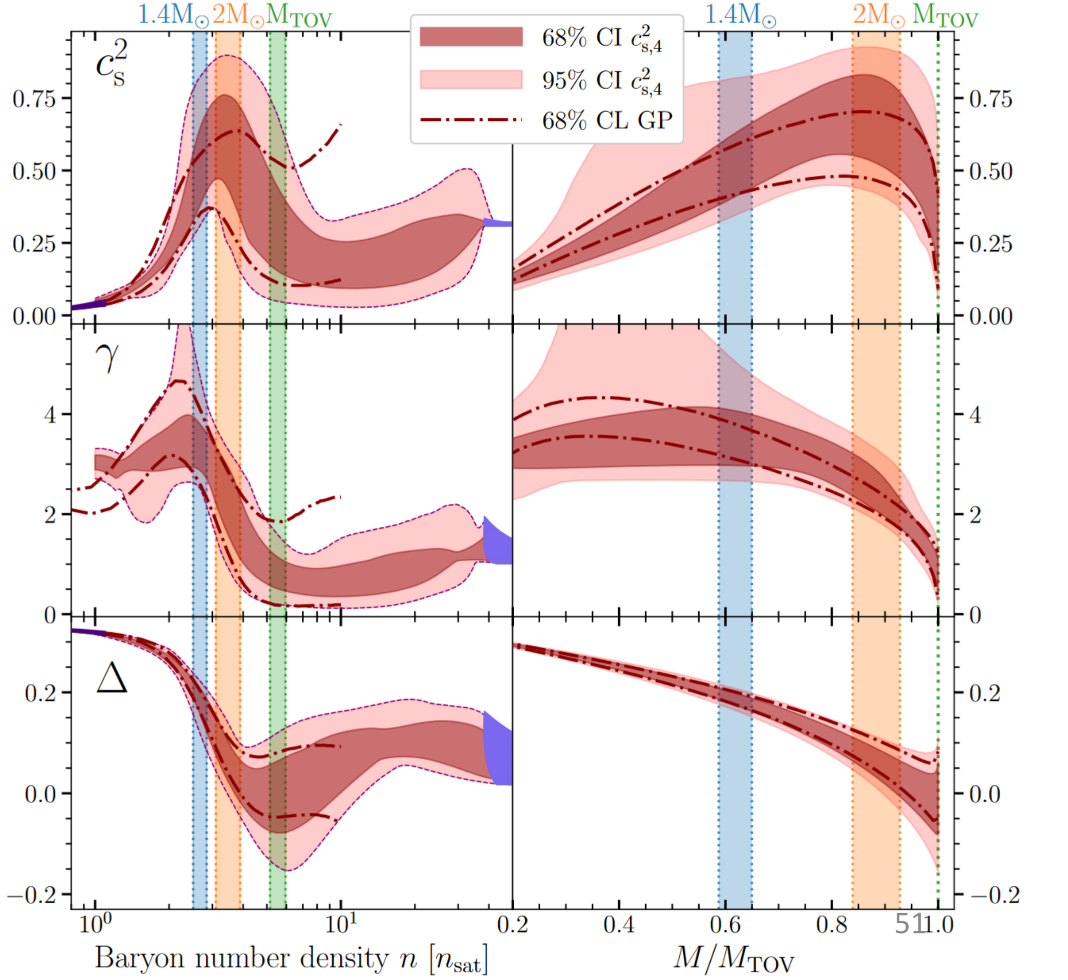


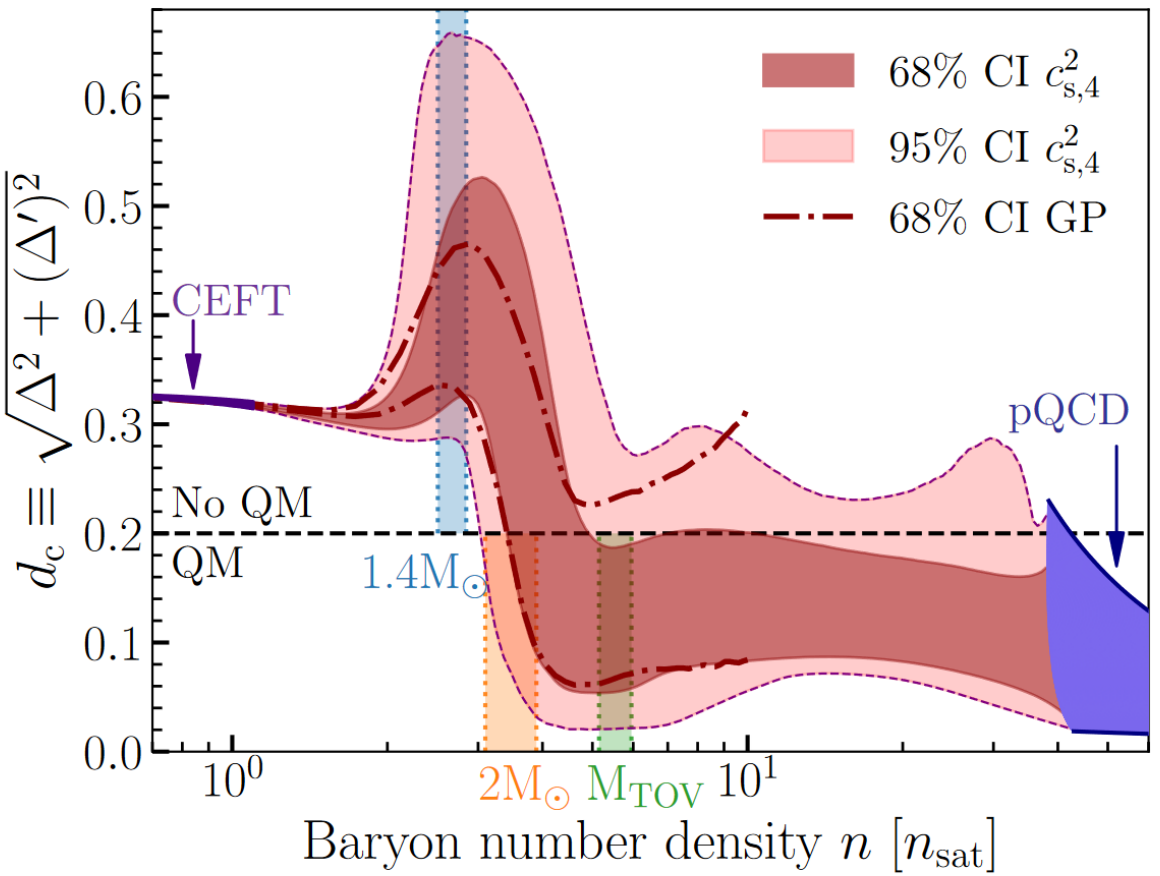
Main results:

3) According to cs4 interpolation, likelih. of conformalized matter in centers of

- $1.4M_\odot$ NSs: 0%
- $2.0M_\odot$ NSs: 11%
- M_{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, all EoSs feature FOPT-like behavior.

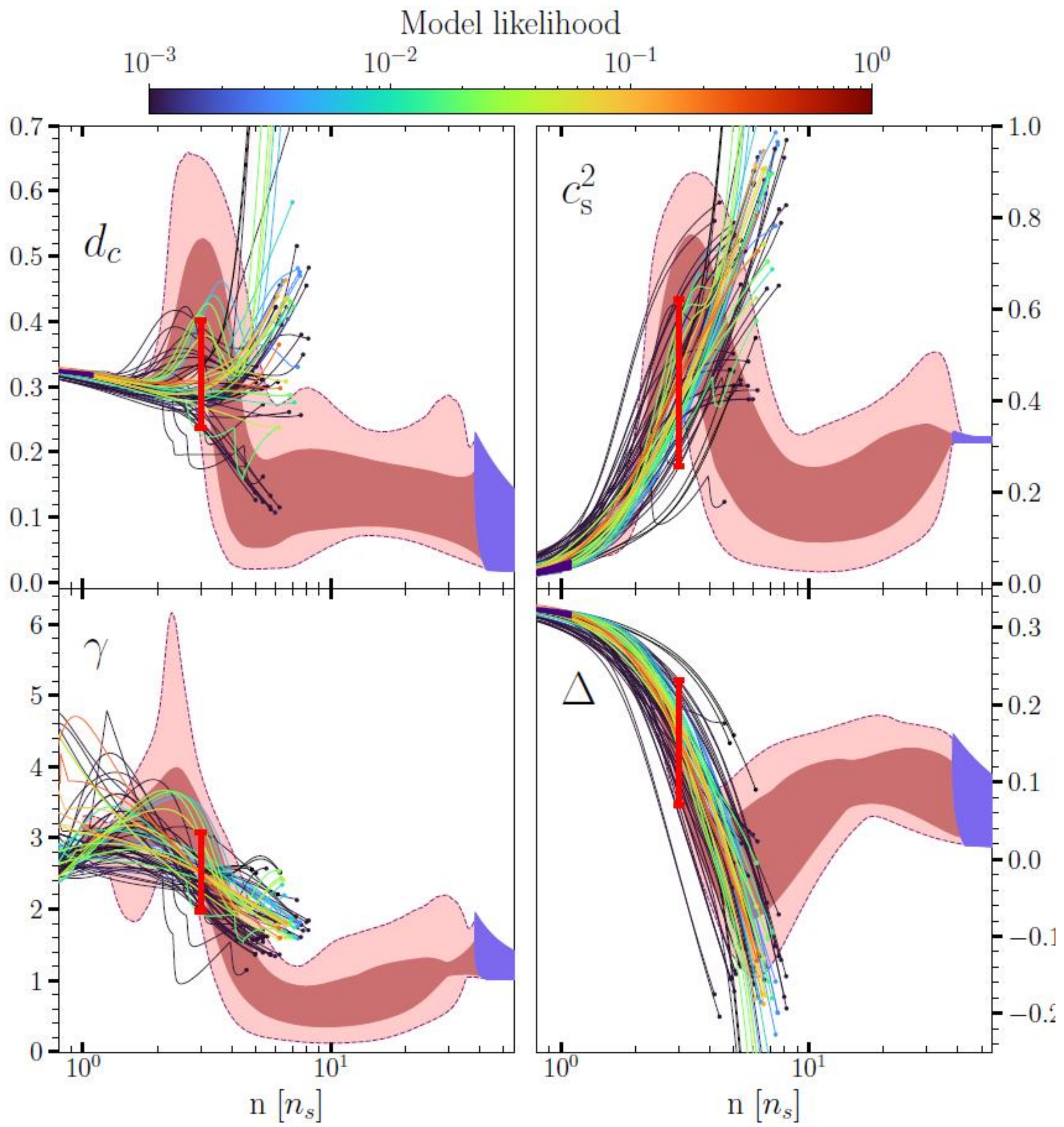


[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, 2303.11356]

Main results:

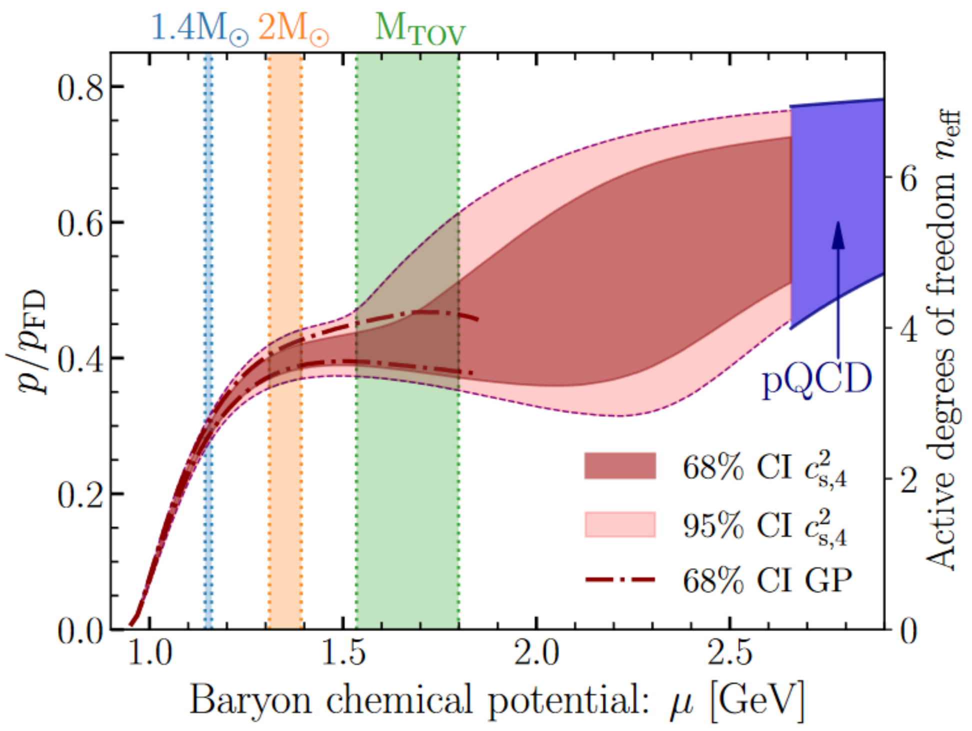
4) Comparison with all available hadronic models available on ComPOSE reveals no viable hadronic model consistent with our findings.

As long as even qualitative agreement exists between different hadronic models, their properties are highly non-conformal.

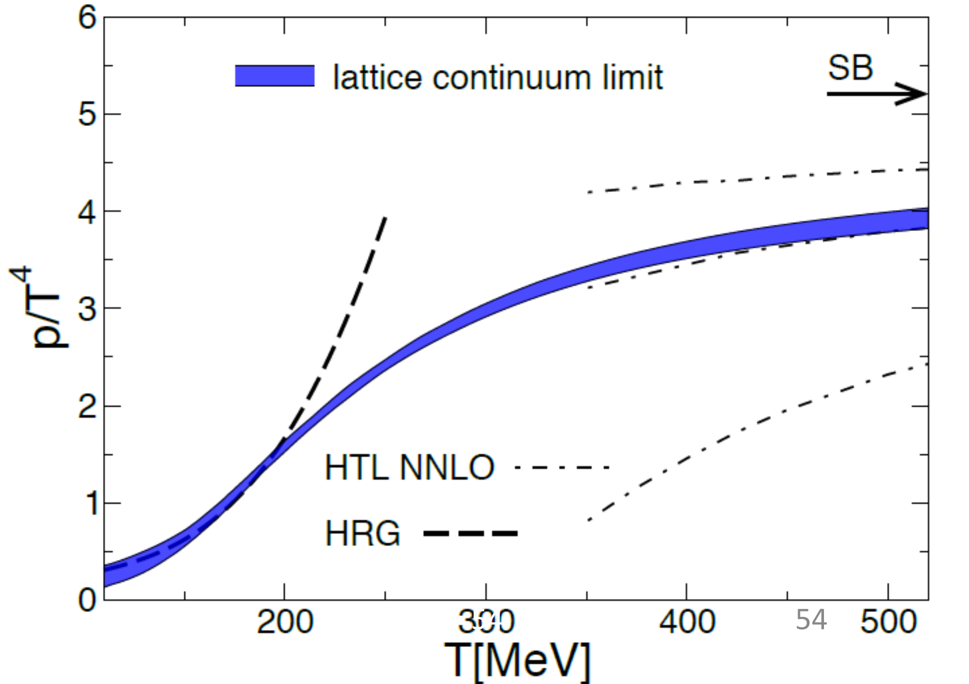


Main results:

5) For weak coupling and some CFTs, the normalized pressure directly proportional to number of active degrees of freedom. In centers of TOV stars, p/p_{FD} at approx. 2/3 of its perturbative value and close to 1/2 of free limit. To this end, the leap from "conformal" to "deconfined" plausible.



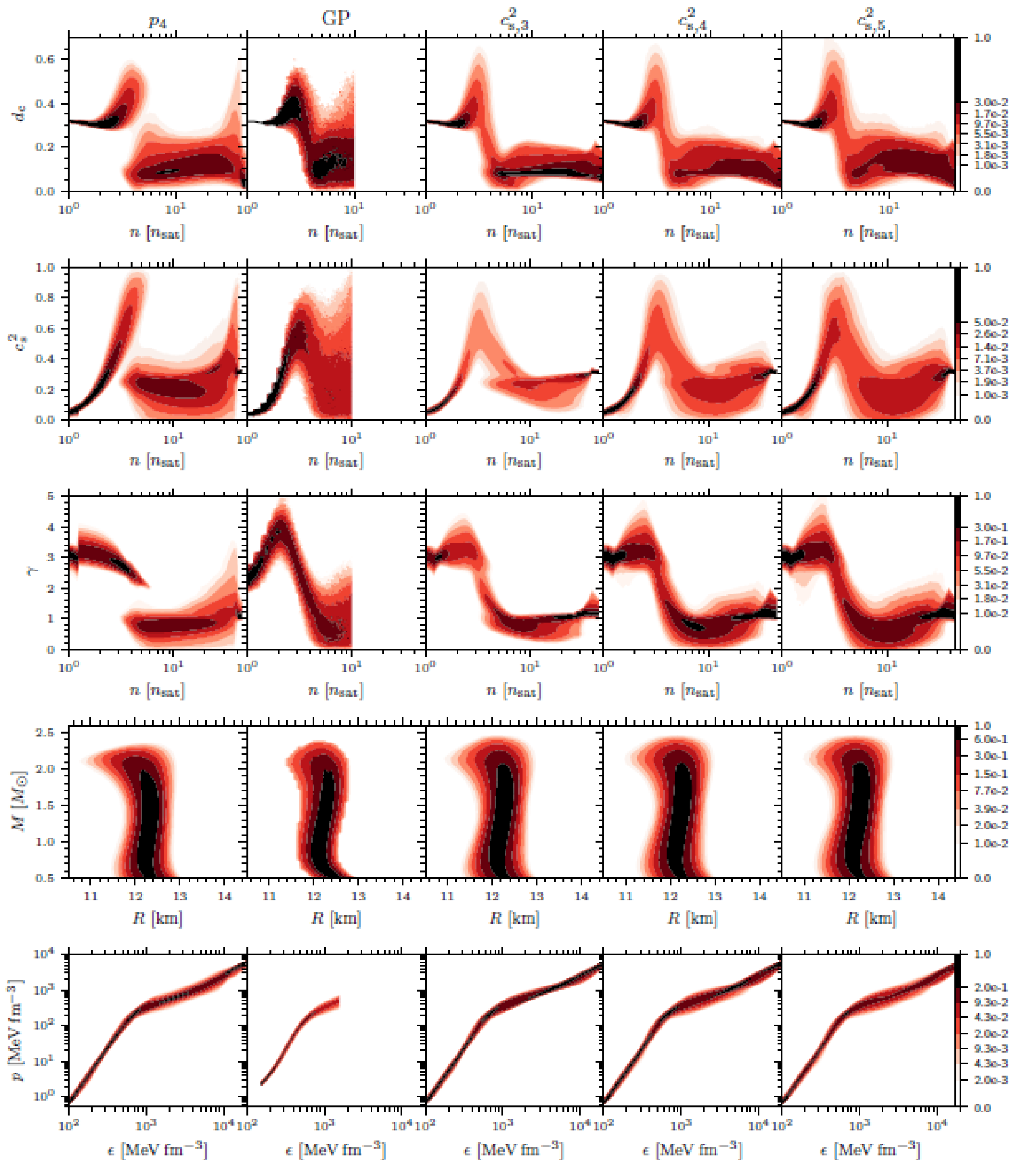
In comparison, the high-T crossover transition from a hadron gas to quark-gluon plasma takes place at much smaller values of p/p_{SB}.



[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, 2303.11356]

Main results:

6) Presented results highly independent of the details of interpolation, with results from separate nonparametric Gaussian Process regression calculation also well in line although likelihood of QM cores slightly lower (75%).



[Gorda, Komoltsev, Kurkela, APJ 950 (2023)]

[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, 2303.11356]

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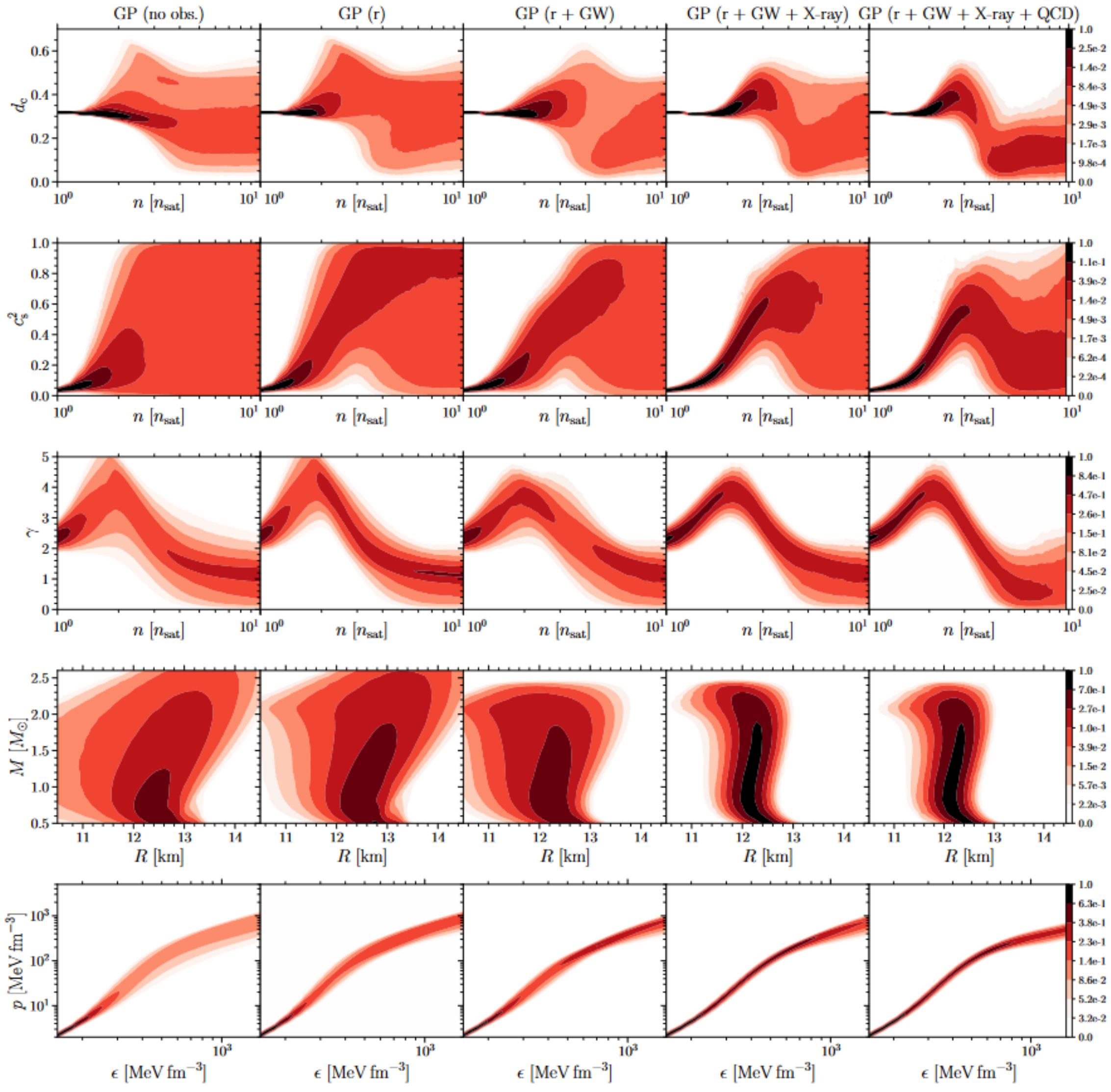
With GP method, possible to show that it is precisely the pQCD limit that softens the EoS inside cores of TOV stars.



[Gorda, Komoltsev, Kurkela, APJ 950 (2023)]

[Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, AV, 2303.11356]

Conclusions

Where are we now?

- Advances in observational astrophysics have turned NS physics a precision science: new laboratory for ultradense QCD matter
- Accurate understanding of quark-matter thermodynamics plays a demonstrably crucial role, with pQCD the main field theory tool
- To obtain a well-behaved weak-coupling expansion, EFT treatment of the soft scale $m_E \sim g\mu_B$ via HTL necessary
  - All soft and mixed contributions now under control – only the hard part (full theory four-loop diagrams) remains
- Quark matter cores in massive NSs appear likely, but caveats remain ⇒ more work (both theoretical & observational) needed!