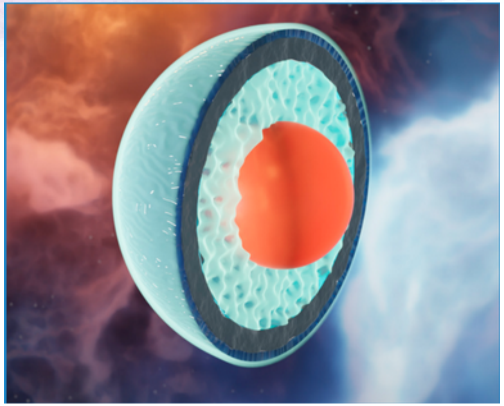
Quark Matter and Nuclear Astrophysics: recent developments

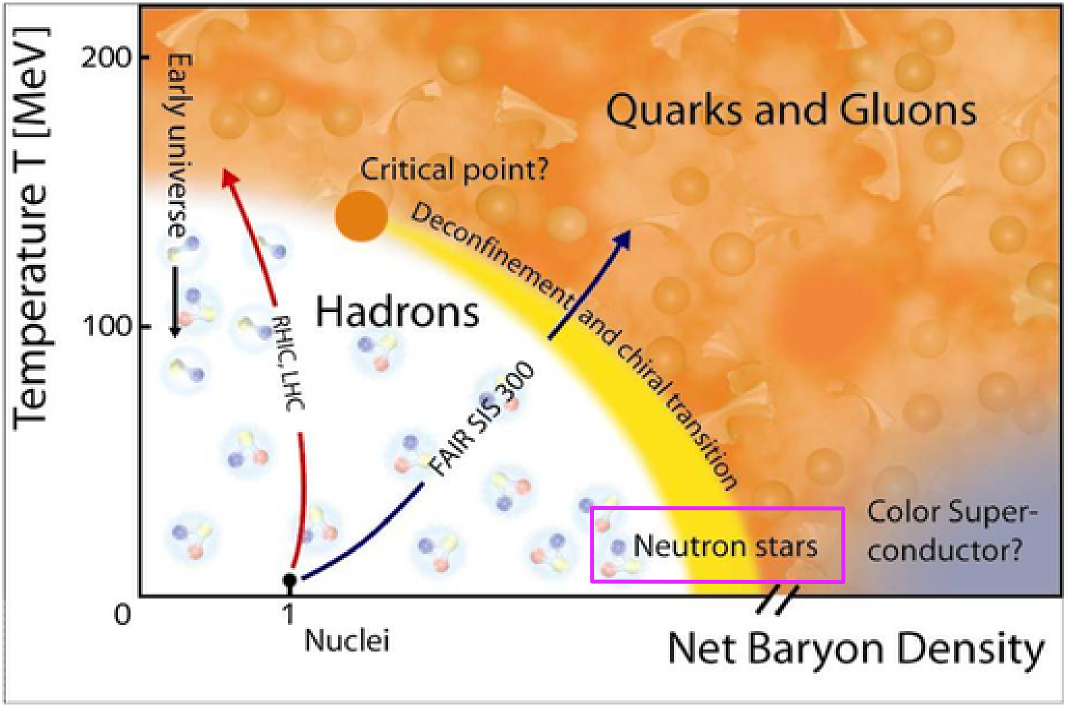


Zimányi Winter school, Budapest, Hungary

03 December 2024

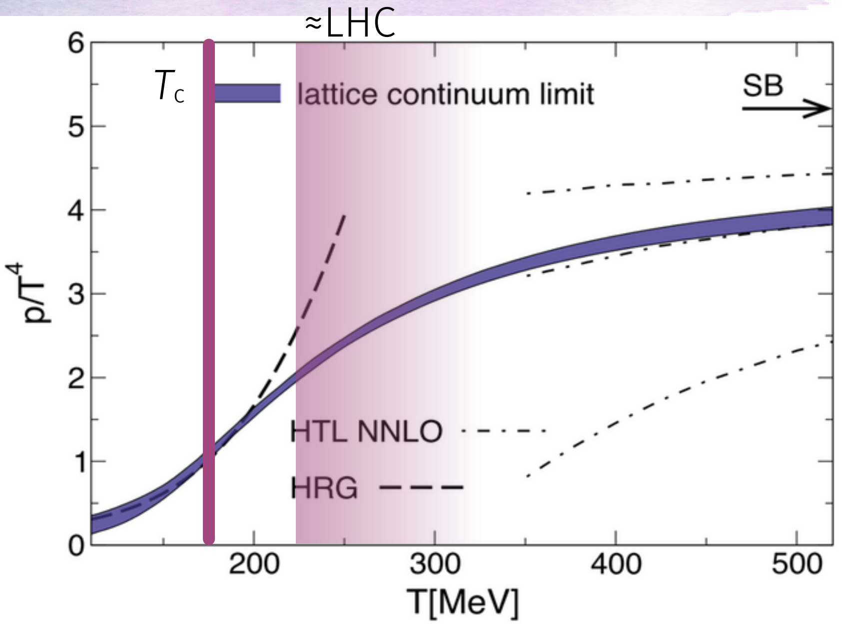
Tyler Gorda
Goethe University Frankfurt

Understanding the phase diagram of QCD

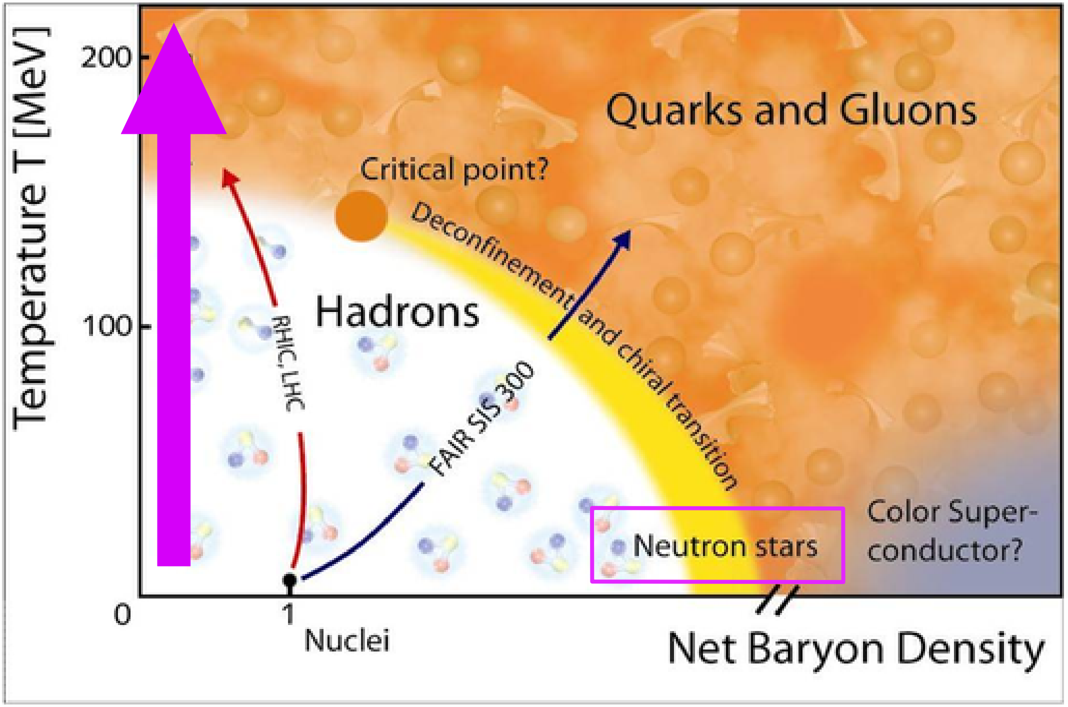


Compressed Baryonic Matter (CBM) experiment

Understanding the phase diagram of QCD



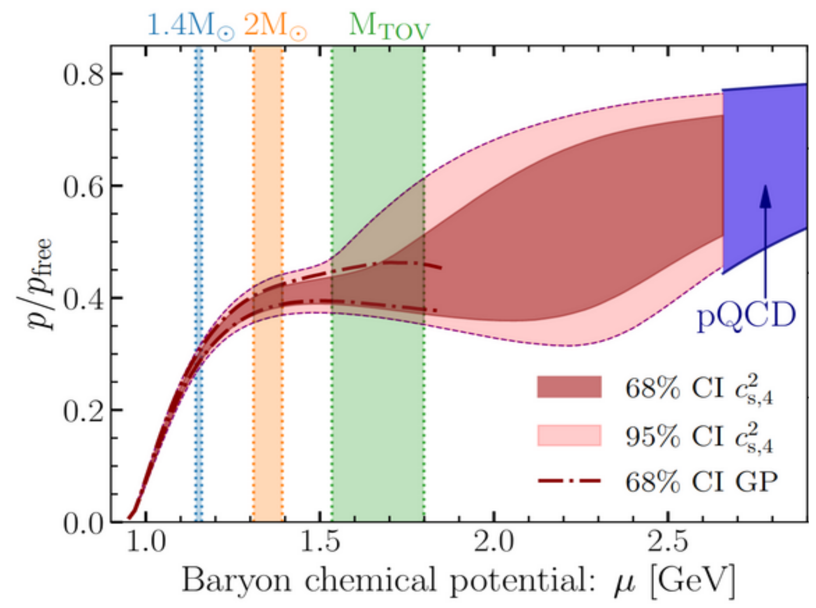
Borsanyi, Fodor, Hoelbling, Katz, Krieg, Szabo Phys. Lett. B 370 (2014), Gardim, Giacalone, Luzum, Ollitrault, Nature Physics 16, 615-619 (2020)



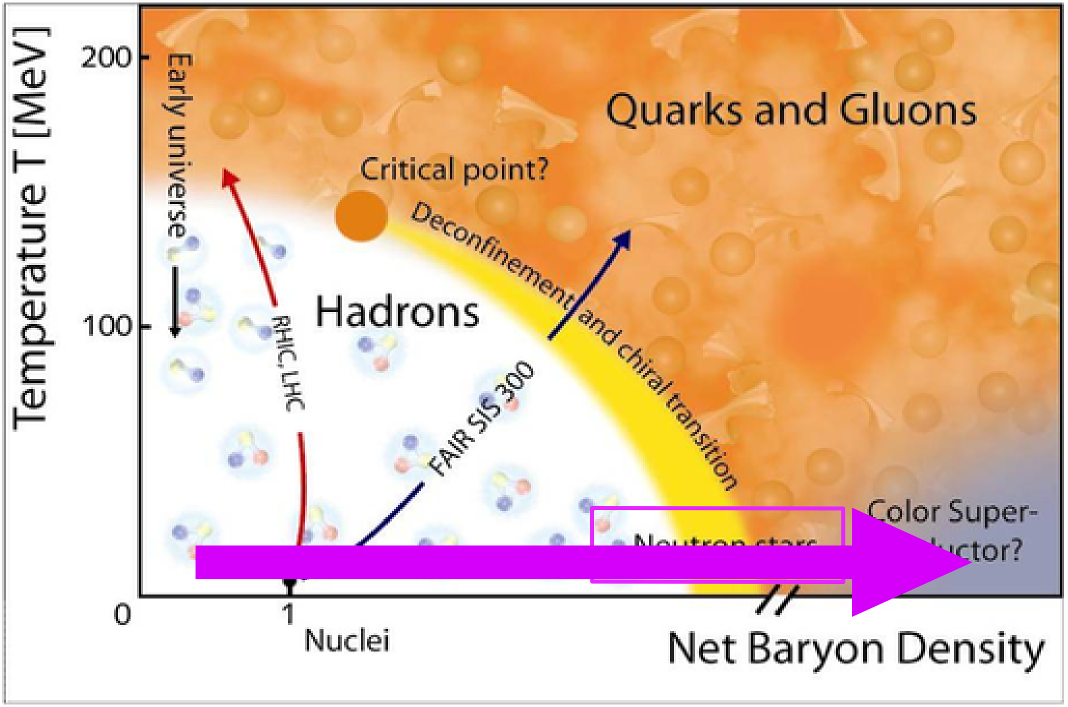
Compressed Baryonic Matter (CBM) experiment

Lattice calculations at high-T directly tell us the EoS; can compare to hadronic/partonic calculations

Understanding the phase diagram of QCD



Annala, TG, Hirvonen, Komoltsev, Kurkela, Nättilä, Vuorinen Nat. Comm. 14 (2023)

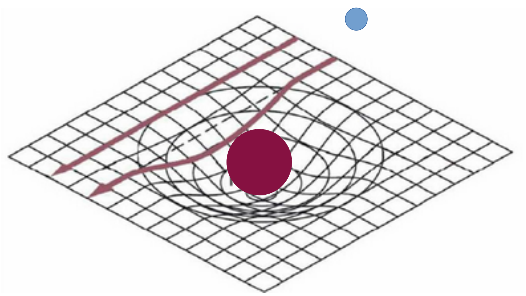


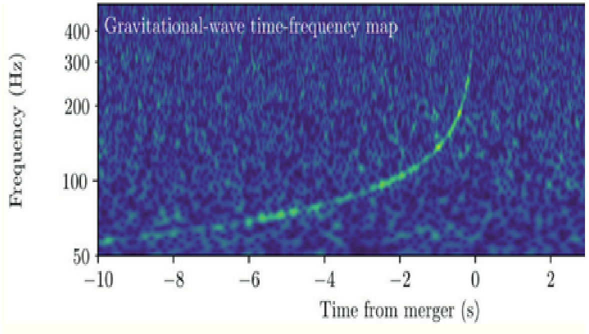
Compressed Baryonic Matter (CBM) experiment

At T = 0, no lattice, but we have astrophysics; and calculations in nuclear and particle theory

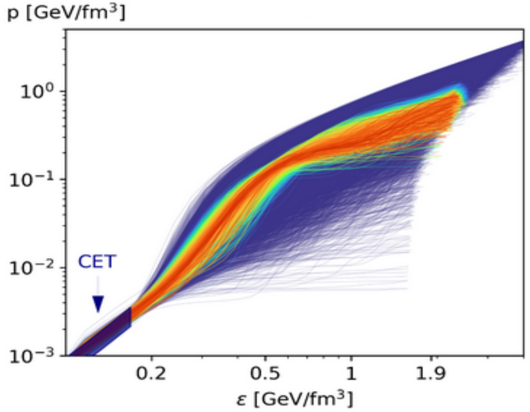
T = 0 is a synthesis of theory and experiment

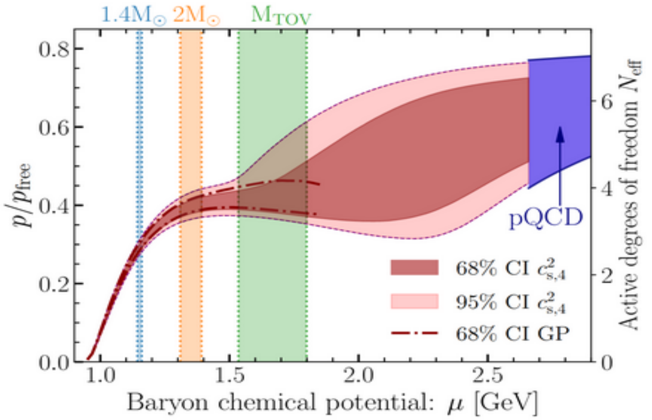
Astronomy +Astrophysics



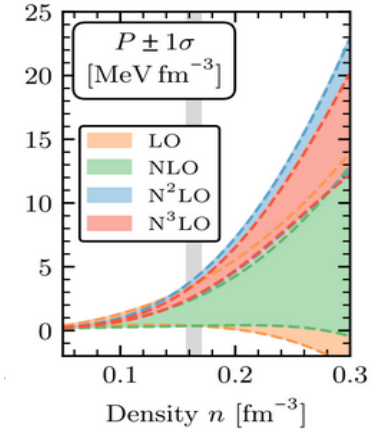


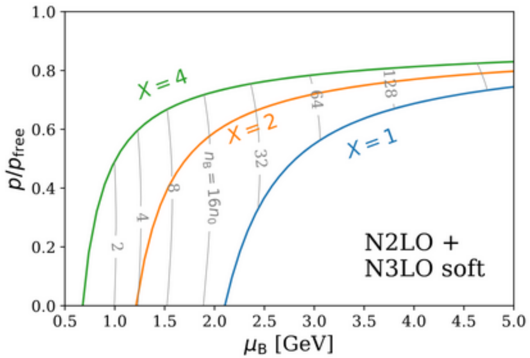
EoS Inference



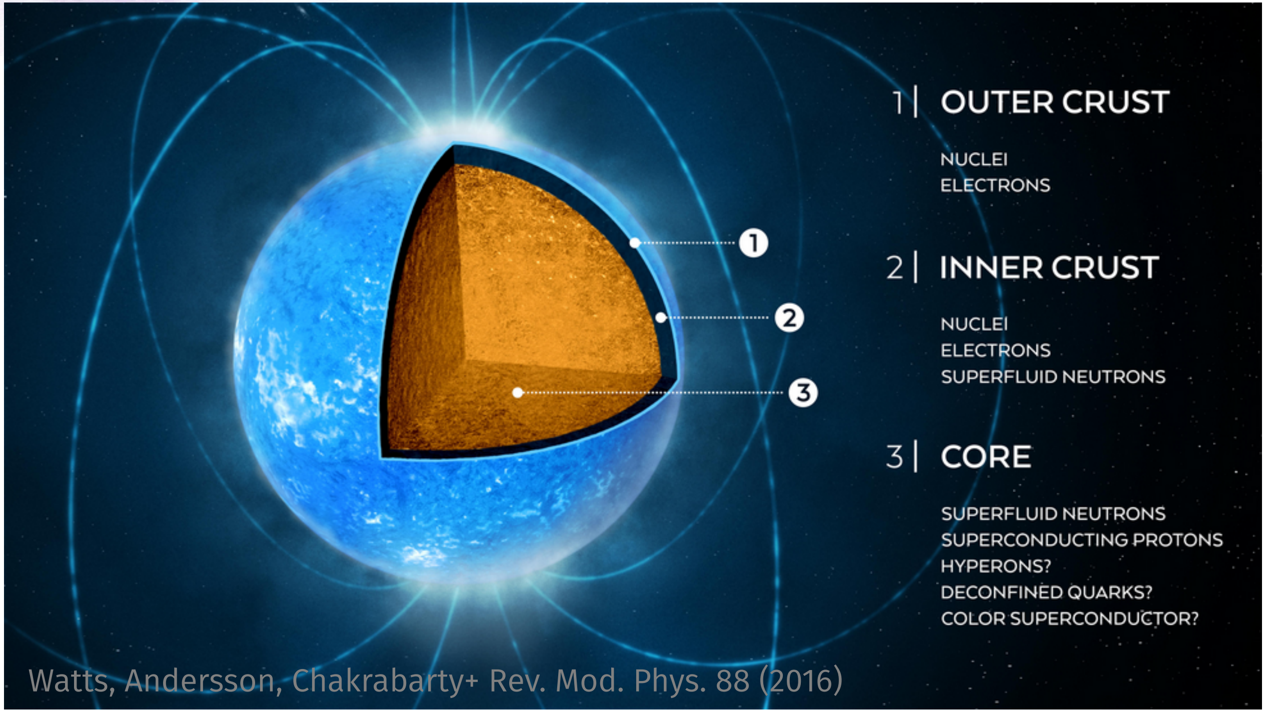


Nuclear + Particle Theory





What is a Neutron Star?

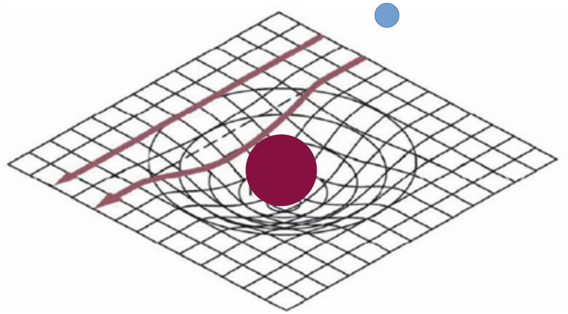


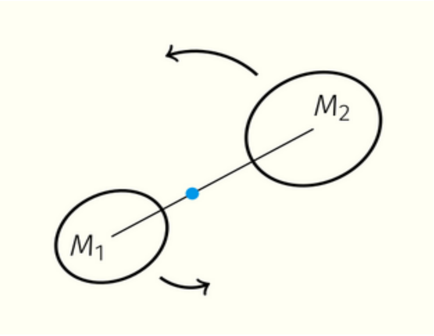
Collapsed remnant of dead stars, held from collapse by repulsive nuclear/QCD forces

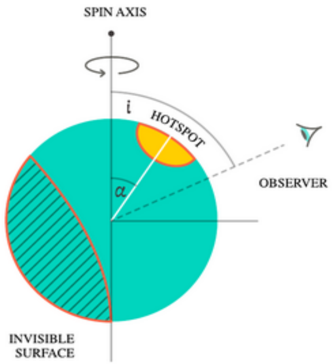
Cleanest probes of structure/bulk properties when they are in binary system with a companion

Mass $\lesssim 2M_\odot$, $11\text{ km} \lesssim R \lesssim 13\text{ km}$, $T \lesssim \text{keV} \sim 10^7\text{K}$.

Neutron stars in binaries tell us about structure







Masses

Demorest, Pennucci, Ransom, Roberts, Hessels. Nature 467 (2010) pp. 1081-1083;
Antoniadis+ Science 340 (2013) p. 6131;
Cromartie+ (NANOGrav). Nature Astron. 4.1 (2019).
E. Fonseca+ Astrophys. J. Lett. 915.1 (2021)

Deformabilities

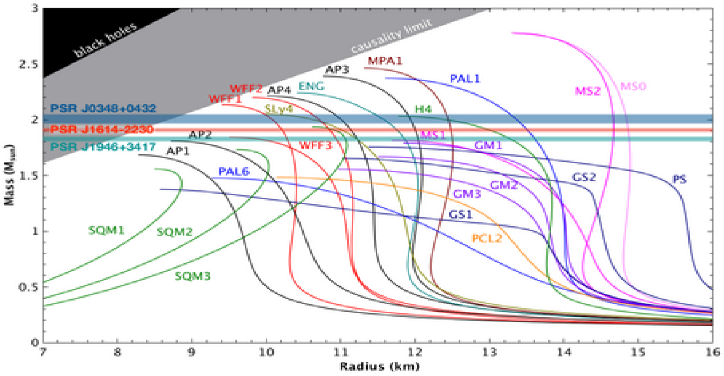
Abbott+ (LIGO Scientific, Virgo) PRL 119 (2017); PRL 121 (2018); PRX 9 (2019).

Radii, compactness

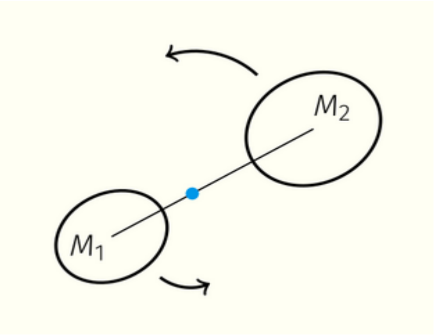
Miller+ Astrophys. J. Lett. 918.2 (2021), p. L28.
Riley+ Astrophys. J. Lett. 918.2 (2021) p. L27.

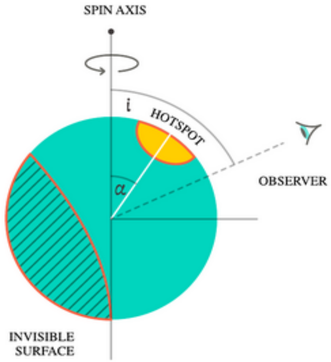
Neutron stars in binaries tell us about structure

$$M_{\text{TOV}} \geq \begin{cases} 1.97 \pm 0.04 M_\odot & \text{PSR J1614-2230} \\ 2.01 \pm 0.04 M_\odot & \text{PSR J0348+0432} \\ 2.08 \pm 0.07 M_\odot & \text{PSR J0740+6620} \end{cases}$$



Norbert Wex





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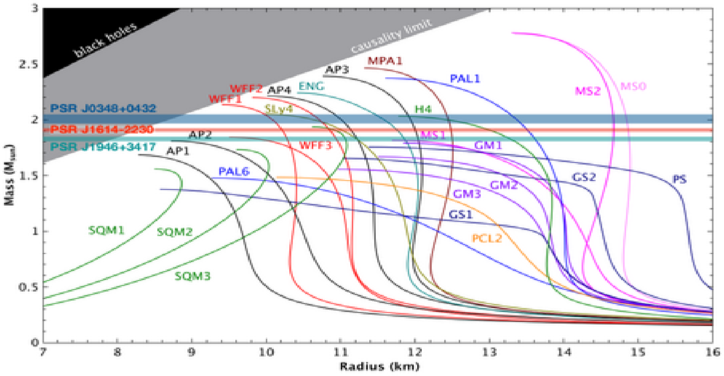
$$\Lambda(M) \equiv |Q_{ij}/\mathcal{E}_{ij}| M^5$$



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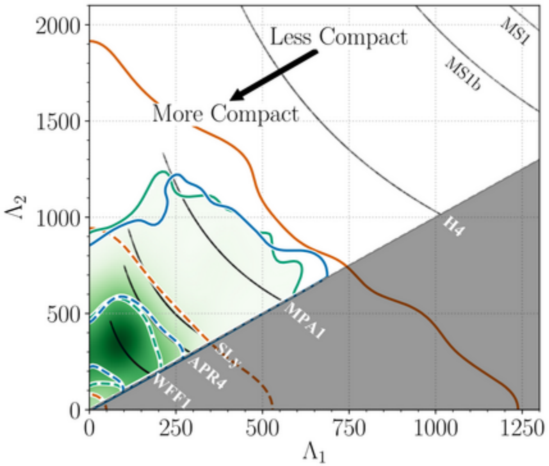

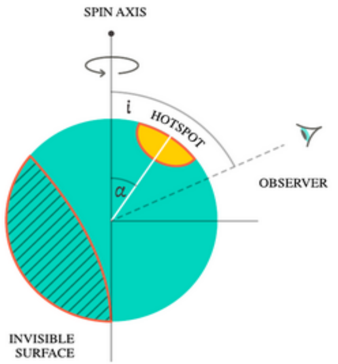

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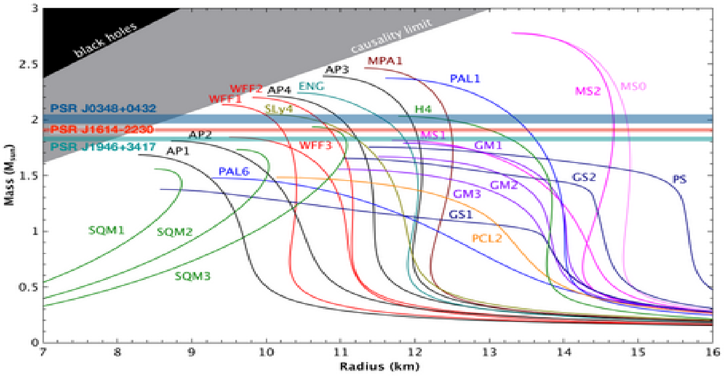

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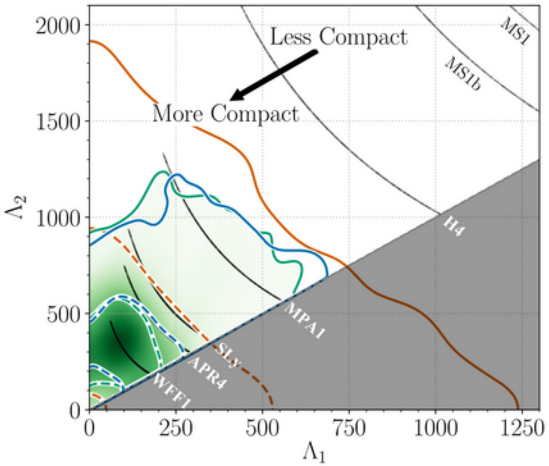

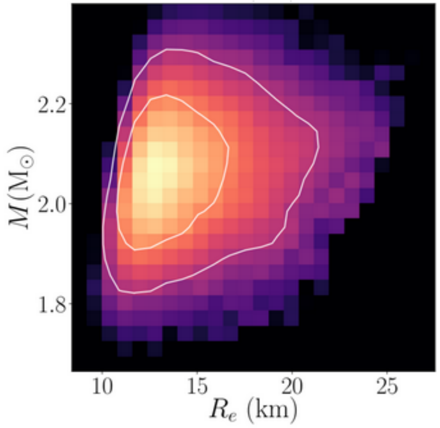

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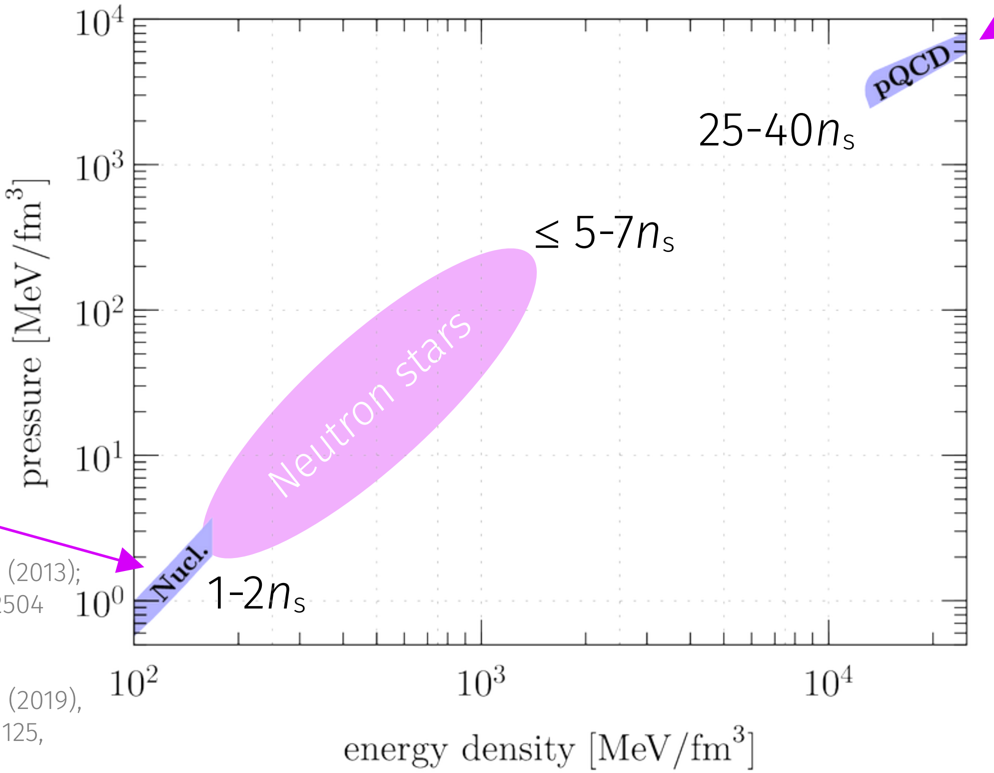
Riley+ Astrophys. J. Lett. 918.2 (2021) p. L27.

Use these data in place of lattice results

Different inputs constrain different parts of the EOS

Perturbative QCD

Kurkela, Romatschke, Vuorinen, PRD 81, 105021 (2010),
TG, Kurkela, Romatschke, Säppi, Vuorinen, PRL 121, 202701 (2018),
TG, Kurkela, Paatelainen, Säppi, Vuorinen, PRL 127, 162003 (2021), PRD 104, 074015 (2021),
TG, Paatelainen, Säppi, Seppänen PRL 131 (2023)



Chiral EFT

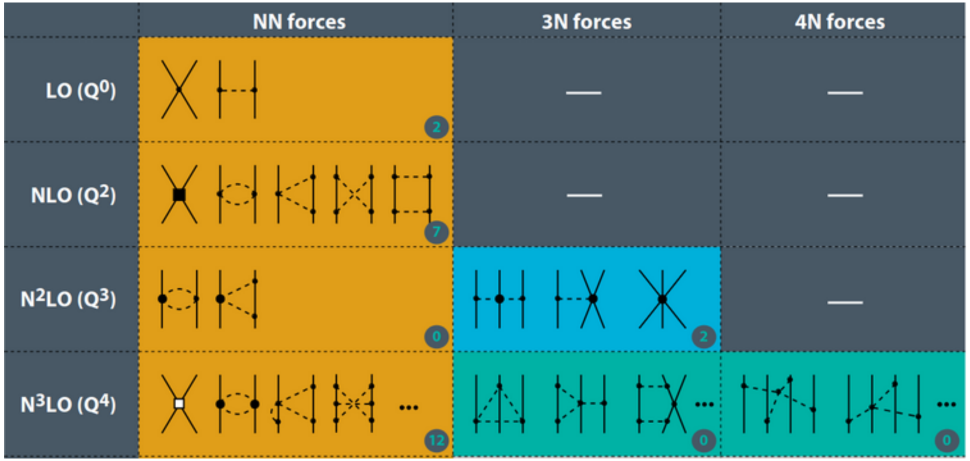
Hebeler, Lattimer, Pethick, Schwenk. ApJ. 773 (2013);
Tews, Krüger, Hebeler, Schwenk, PRL 110, 032504 (2013)
Lynn, Tews, Carlson+ PRL 116, 062501 (2016),
Drischler, Hebeler, Schwenk, PRL 122, 042501 (2019),
Drischler, Furnstahl, Melendez, Phillips, PRL 125, 202702 (2020),
Keller, Hebeler, and Schwenk, PRL 130, 072701 (2023).

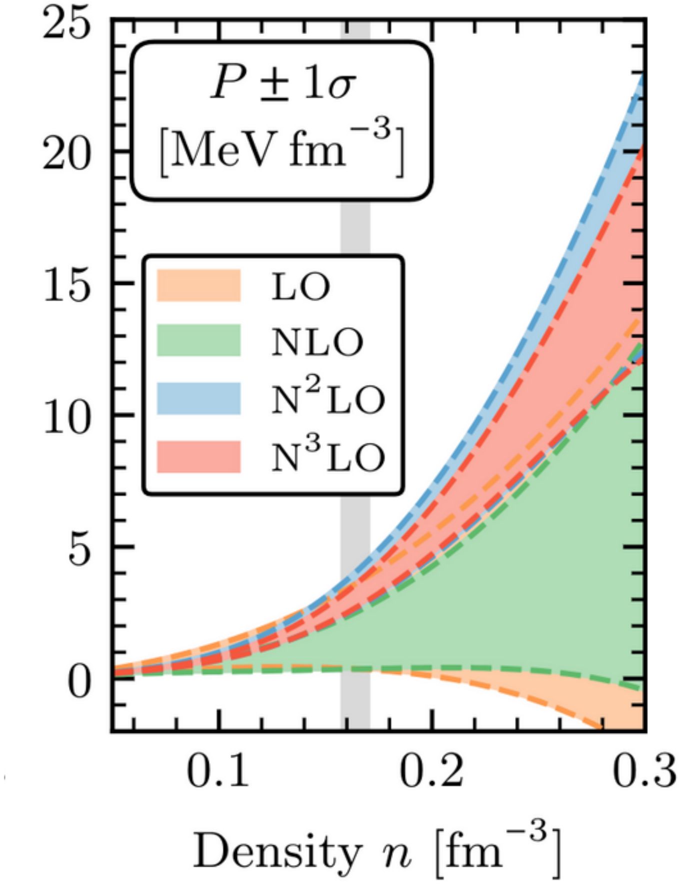
Hadronic matter: Chiral EFT

Describes massive nucleons interacting via pion exchange and contact interactions. EFT terms dictated by chiral symmetry

Calibrated by nuclear data

Uncertainty estimates by e.g. Gaussian process regression and naturalness arguments





Drischler, Holt, Wellenhofer, Ann.Rev.Nucl.Part.Sci. 71 (2021) 403-432
Drischler, Furnstahl, Melendez, Phillips PRL 125 (2020) 20, 202702

Quark matter: perturbative QCD (+recent developments)

Describes (nearly) massless quarks, gluons interacting. Quarks are approximately free, up to [O(20%)] perturbative corrections

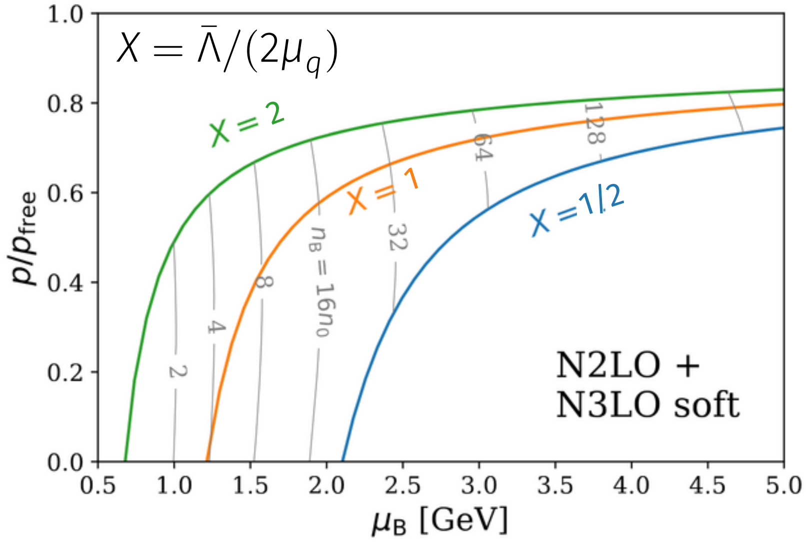
Freedman, McLerran, PRD 16 (1977)

$$\frac{p}{p_0} = 1 + a_1\alpha_s(\bar{\Lambda}) + a_2\alpha_s^2(\bar{\Lambda}) + a_3\alpha_s^3(\bar{\Lambda}) + \cdots$$

*free quark gas**

TG, Kurkela, Romatschke, Säppi, Vuorinen, PRL 121 (2018) – ongoing

Calibrated by collider data.



TG, Kurkela, Paatelainen, Säppi, Vuorinen, PRL 127, 162003 (2021), PRD 104, 074015 (2021)

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TG, Kurkela, Romatschke, Säppi, Vuorinen, PRL 121 (2018) – ongoing

Calibrated by collider data.

In last few years, the full structure of the N3LO pressure computation has been made clear

TG, Kurkela, Paatelainen, Säppi, Vuorinen, PRL 127, 162003 (2021), PRD 104, 074015 (2021),
TG, Paatelainen, Säppi, Seppänen PRL 131 (2023)

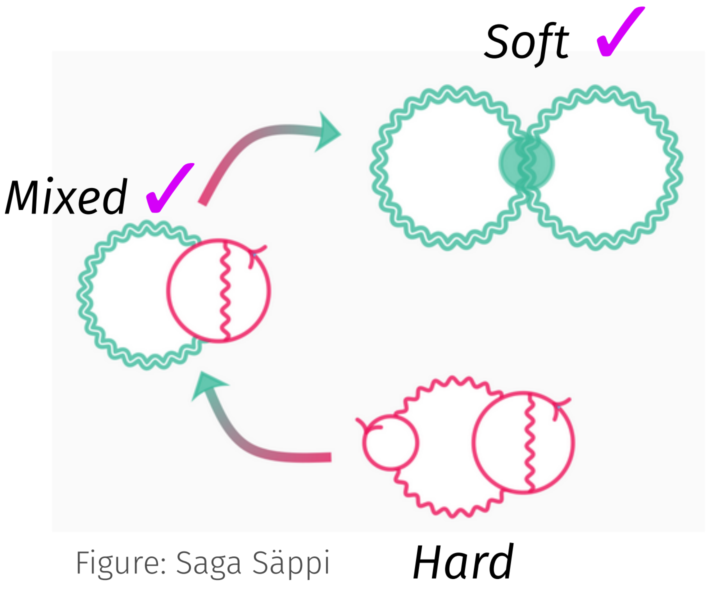
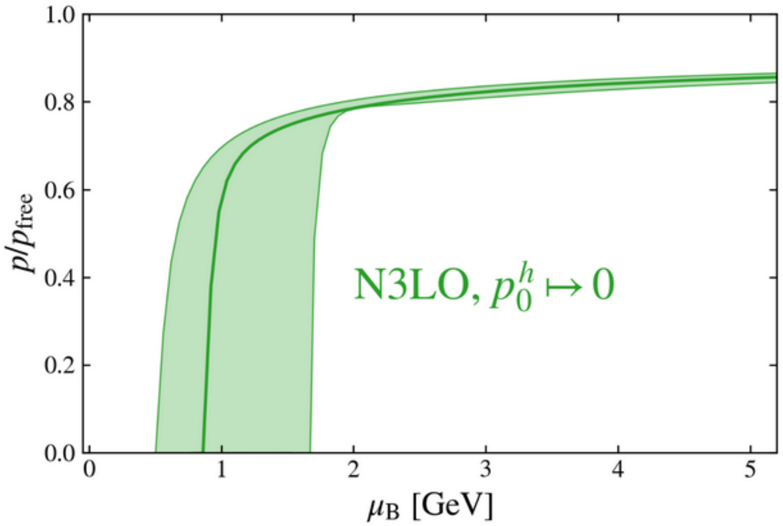


Figure: Saga Säppi

Soft: 2 interacting gluons **screened at LO**
Mixed: 1 gluon **screened at NLO**
Hard: gluons are **unscreened**

Quark matter: perturbative QCD (recent developments)



TG, Paatelainen, Säppi, Seppänen PRL 131 (2023)

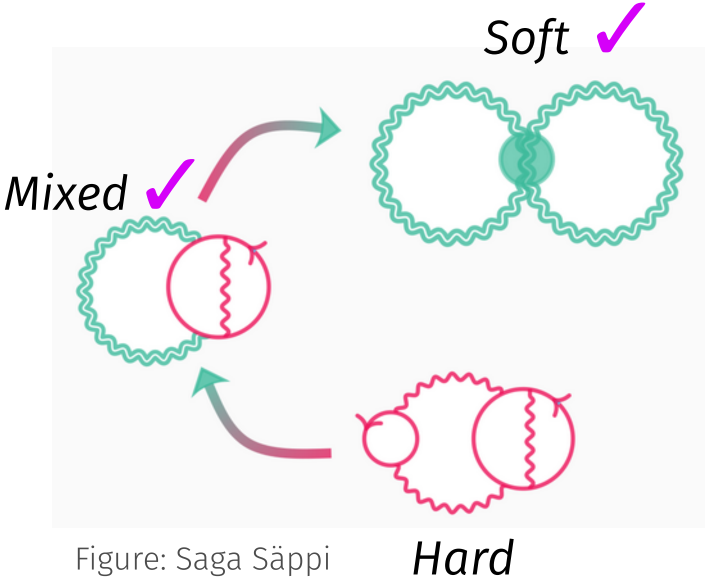


Figure: Saga Säppi

Soft and *Mixed* contributions now computed.
Result is extremely well converged

Soft: 2 interacting gluons **screened at LO**
Mixed: 1 gluon **screened at NLO**
Hard: gluons are **unscreened**

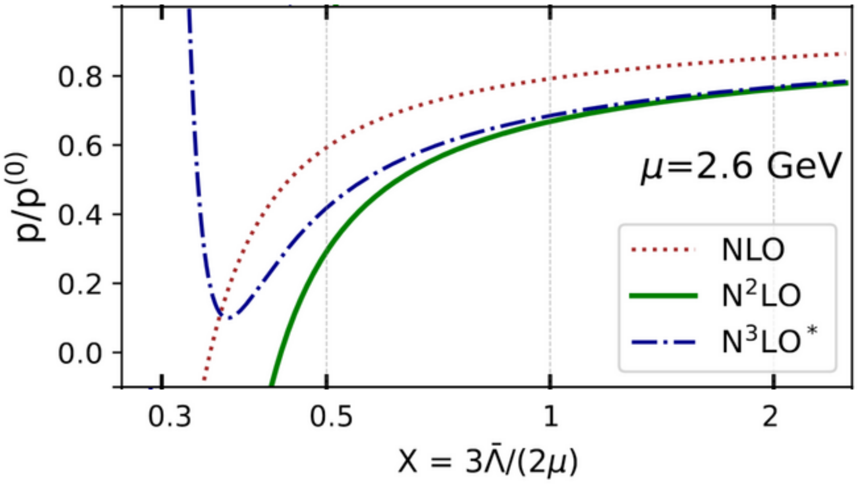
Quark matter: perturbative QCD (recent developments)

Recent Bayesian Uncertainty estimation

$$\frac{p}{p_0} = 1 + a_1\alpha_s(\bar{\Lambda}) + a_2\alpha_s^2(\bar{\Lambda}) + a_3\alpha_s^3(\bar{\Lambda}) + \cdots$$

Scale-variation uncertainty

Missing higher-order (truncation) uncertainty



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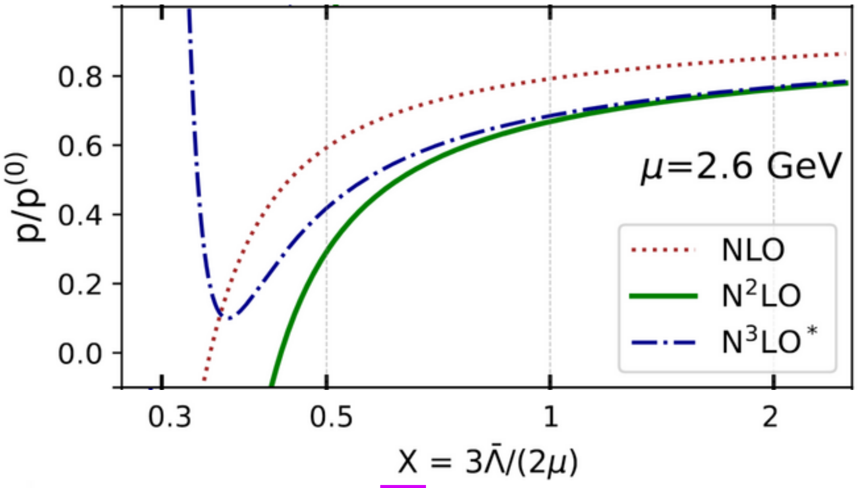
Scale-variation uncertainty

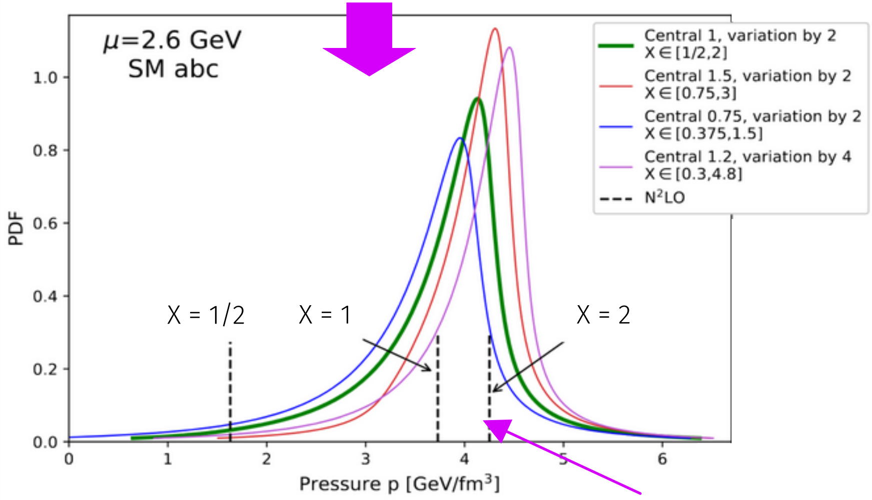
Missing higher-order (truncation) uncertainty

Machine-learning based Bayesian interpretation of these uncertainties. Perturbative series modeled as draws from a statistical model of convergent series, trained with available terms

Cacciari & Houdeau, JHEP 09, (2011), M. Bonvini, Eur. Phys. J. C 80, 989 (2020), Duhr, Huss, Mazeliauskas, Szafron, JHEP 122, (2021)

TG, Komoltsev, Kurkela, Mazeliauskas, JHEP 06 (2023)





Favors better converged X

Chiral EFT + pQCD + Thermodynamics constrain extreme EoSs

1. Stability

$$\partial_\mu^2 \Omega(\mu) \leq 0 \implies \partial_\mu n(\mu) \geq 0$$

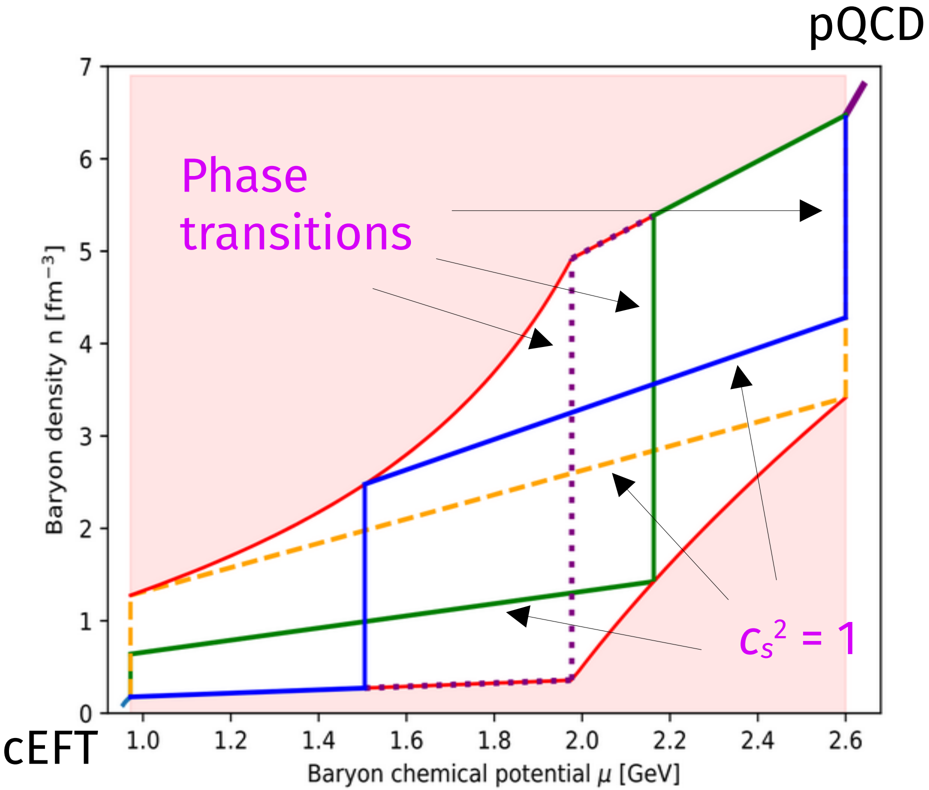
2. Causality

$$c_s^{-2} = \frac{\mu}{n}\frac{\partial n}{\partial \mu} \geq 1 \implies \partial_\mu n(\mu) \geq \frac{n}{\mu}$$

3. Consistency

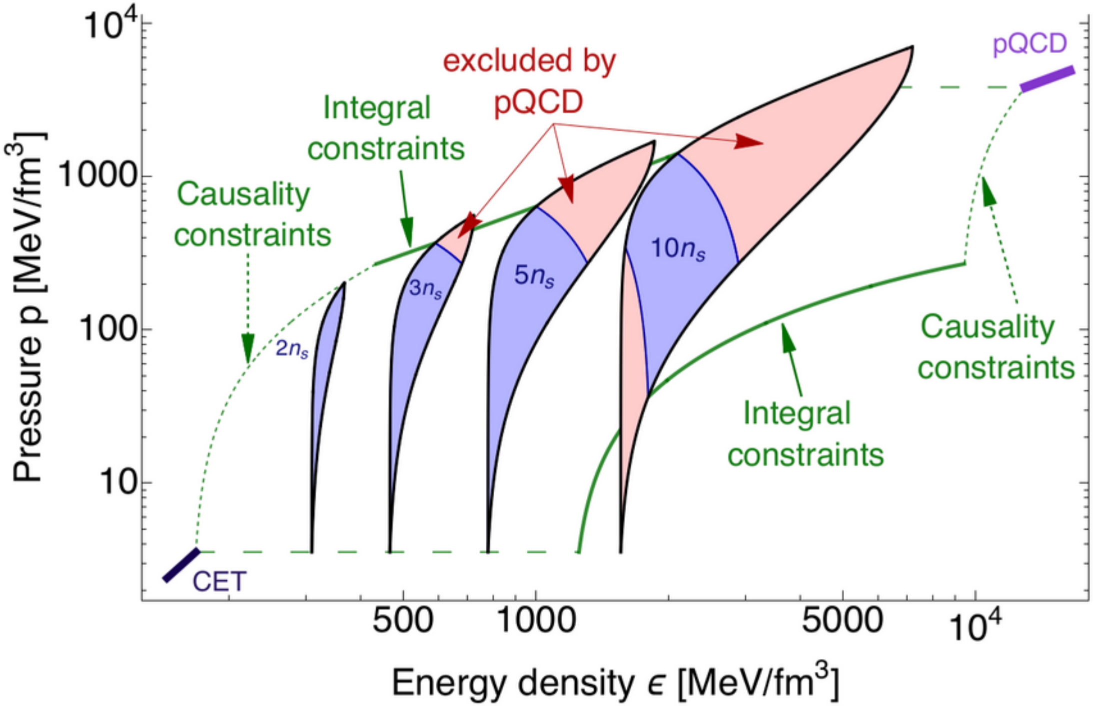
$$\int_{\mu_{\mathrm{CET}}}^{\mu_{\mathrm{QCD}}} \mathrm{d}\mu\, n(\mu) = p_{\mathrm{QCD}} - p_{\mathrm{CET}}$$ Fixed!

"integral constraints"



Komoltsev and Kurkela, PRL 128 (2022)

Chiral EFT + pQCD + Thermodynamics constrain extreme EoSs



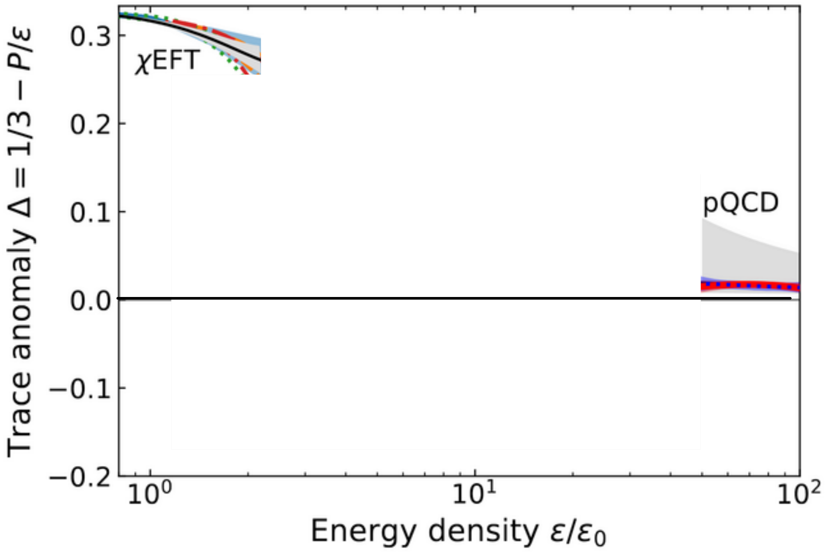
Region of (ε, p) at fixed n constrained by general principles

Komoltsev and Kurkela, PRL 128 (2022)

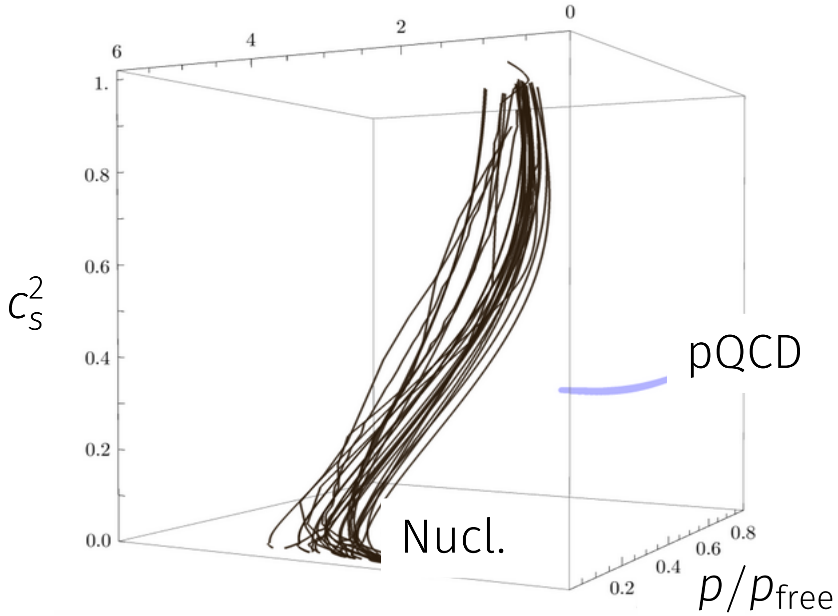
Hadronic and Quark matter are different

Quark matter is approximately conformal (scale-invariant), hadronic matter is non-conformal. This leads to different thermodynamics:

$$\gamma \equiv \frac{\mathrm{d}\ln p}{\mathrm{d}\ln \varepsilon}$$



ADAPTED from Fujimoto, Fukushima, McLerran, Praszalowicz, PRL 129 (2022) 25, 252702

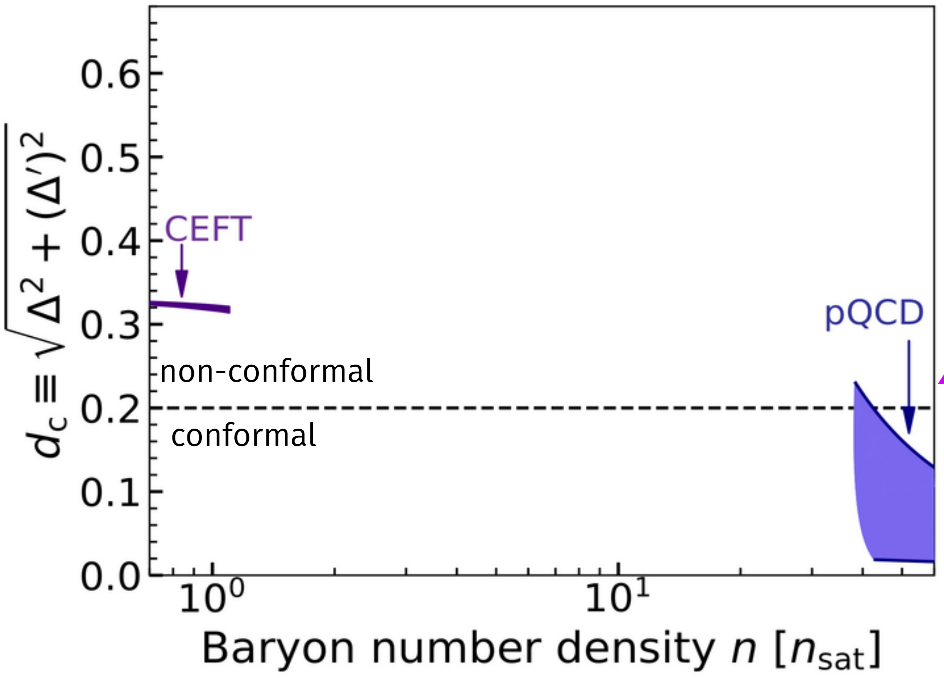


Annala, TG, Kurkela, Nättilä, Vuorinen Nat. Phys. 16 (2020)

A new measure of conformality

Δ and γ are both fixed for a conformal EoS, but for a non-conformal EOS they can still briefly pass through their conformal values.

Combine trace anomaly Δ and its rate of change $\Delta' \equiv \mathrm{d}\ln\Delta/\mathrm{d}\ln\varepsilon$, so not purely local measure



Average of chiral EFT and pQCD as dividing line

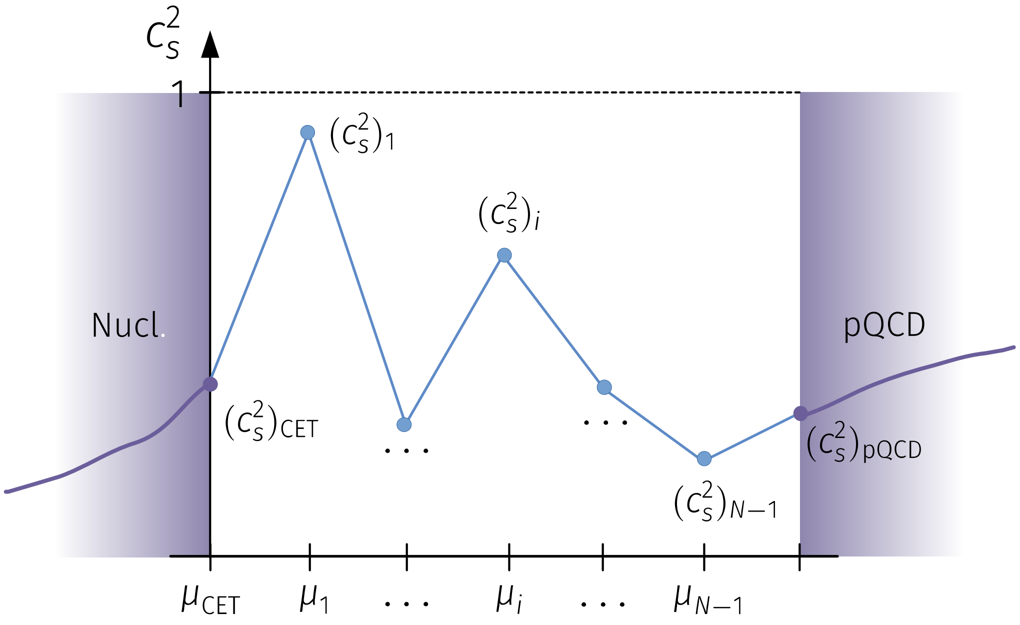
Annala, TG, Hirvonen, Komoltsev, Kurkela, Nättilä, Vuorinen Nat. Comm. 14 (2023)

Putting everything together…

Bayesian EoS inference setup

Posterior — Prior — Likelihood

$$P(\mathrm{EoS}\,|\,\mathrm{data}) = \frac{P(\mathrm{EoS})P(\mathrm{data}\,|\,\mathrm{EoS})}{P(\mathrm{data})}$$



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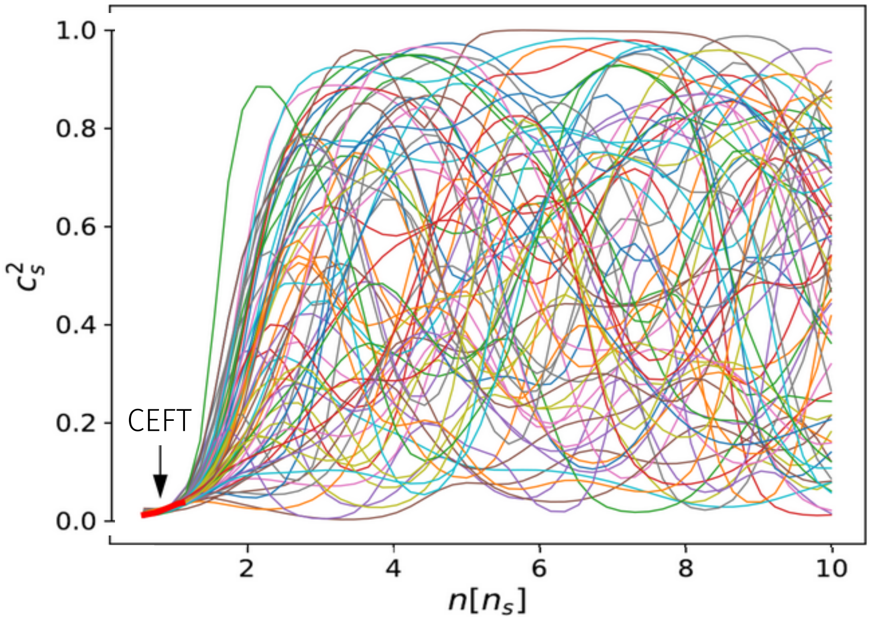

TG, Komoltsev, Kurkela, ApJ 950 (2023)

Bayesian EoS inference setup

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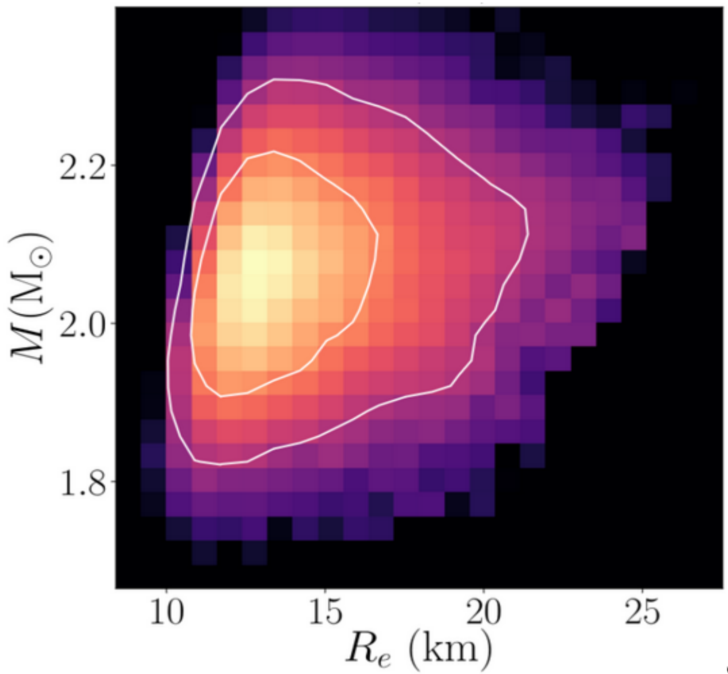
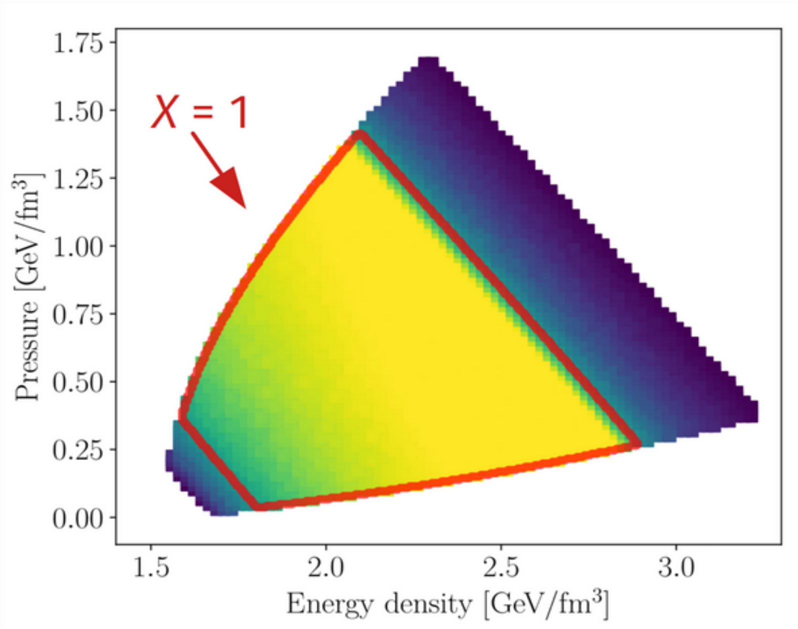
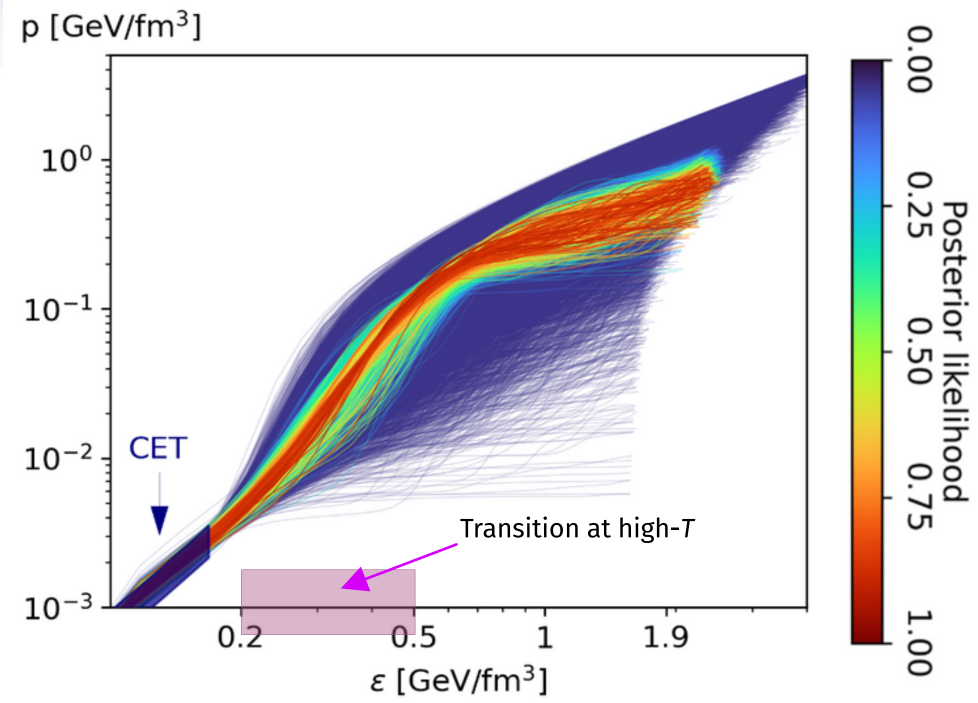


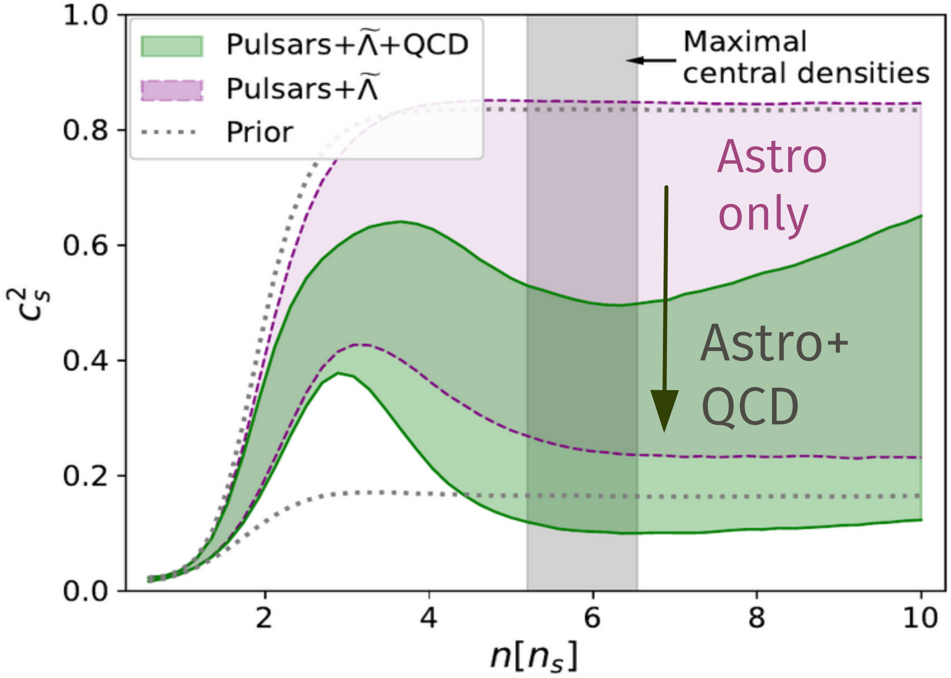
Weight of (ϵ, p) points at $n = 10n_s$



Stiff→soft transition, with softening driven by QCD input

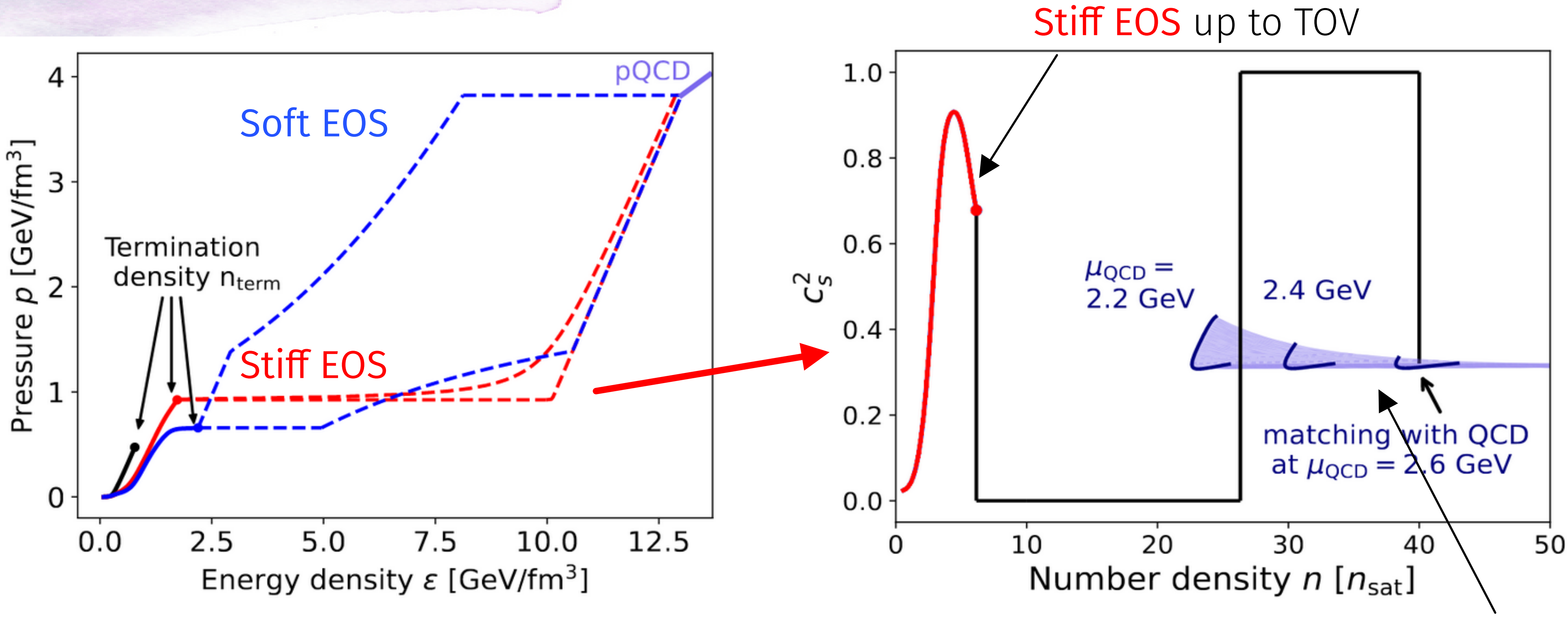


TG, Komoltsev, Kurkela, ApJ 950 (2023)



See also
Annala, TG, Kurkela, Nättilä, Vuorinen Nat. Phys. 16 (2020), Altiparmak, Ecker, Rezzolla, ApJ.Lett. 939 (2022); Ecker & Rezzolla, ApJ.Lett. 939 (2022); Fujimoto, Fukushima, McLerran, Praszalowicz, PRL 129 (2022); Marczenko, McLerran, Redlich, Sasaki, PRC 107 (2023);

Stiff EOSs at TOV inconsistent with pQCD at higher densities



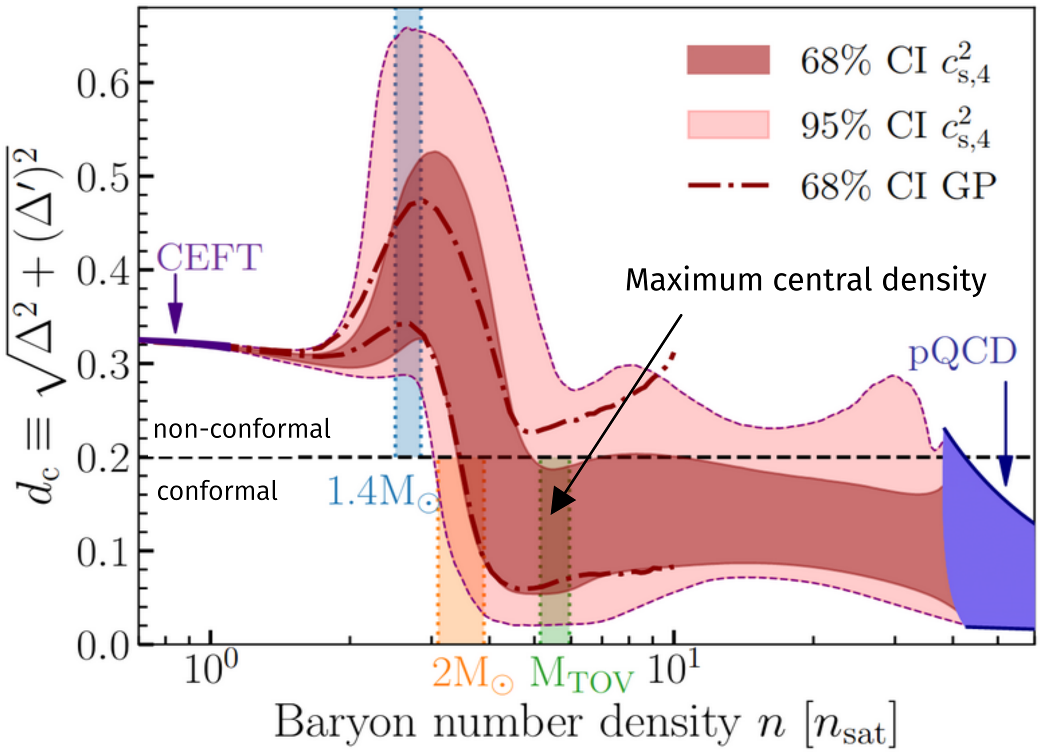
More informed QCD input yields robust posteriors

Inconsistent with pQCD at large densities

TG, Komaltsev, Kurkela, Margueron, Somasundaram, Tews PRD 109 (2024);

Public script: 10.5281/zenodo.10412734

Clear non-conformal→conformal transition within the cores of stable neutron stars



Annala, TG, Hirvonen, Komoltsev, Kurkela, Nättilä, Vuorinen Nat. Comm. 14 (2023)

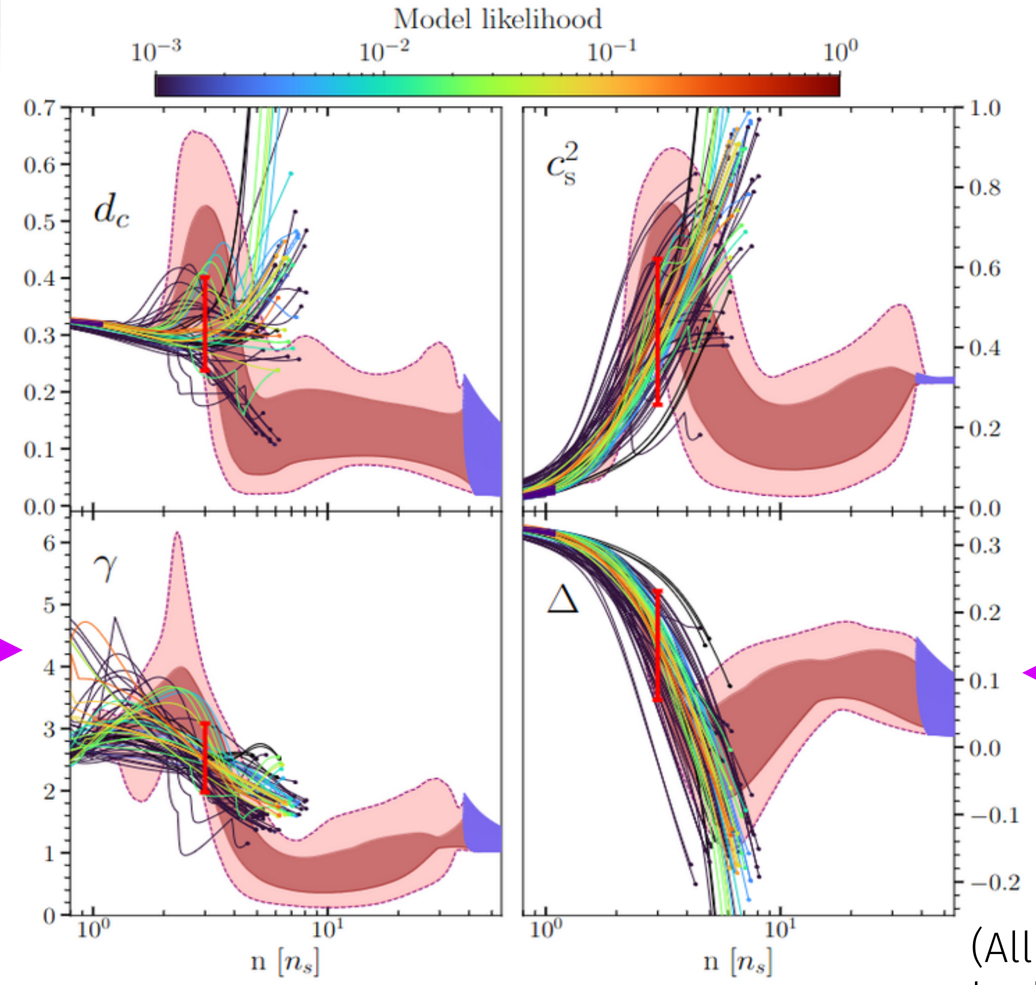
P(conformal) = 88% (75%) for the parametric (GP) approach, for maximally massive stars

Criterion is much stricter than older **γ analysis**. (Would have found 99.8% previously.)

See also: Han, Huang, Tang, Fan, Science Bulletin, 68, 9 (2023)

See also
Annala, TG, Kurkela, Nättilä, Vuorinen Nat. Phys. 16 (2020), Altiparmak, Ecker, Rezzolla, ApJ.Lett. 939 (2022);
Ecker & Rezzolla, ApJ.Lett. 939 (2022); Fujimoto, Fukushima, McLerran, Praszalowicz, PRL 129 (2022); Marczenko, McLerran, Redlich, Sasaki, PRC 107 (2023);

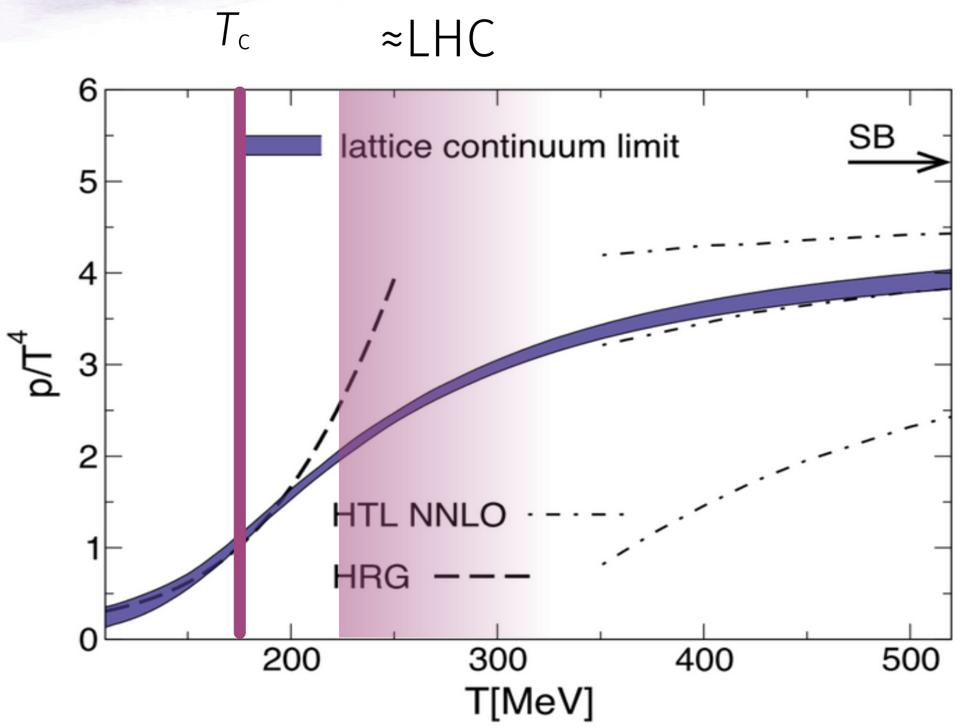
Nuclear models don't show conformal transition

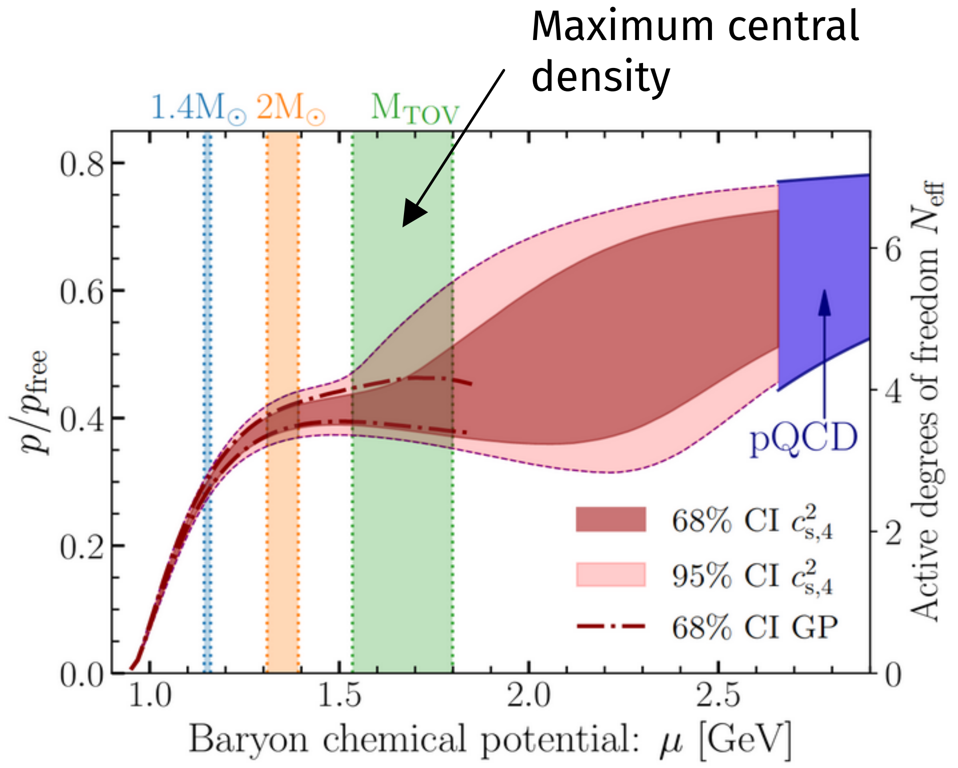


Δ, γ analyses alone not so clear!

(All T = 0, beta-equilibrated hadronic models from CompOSE)

Number of degrees of freedom consistent with deconfined quark matter





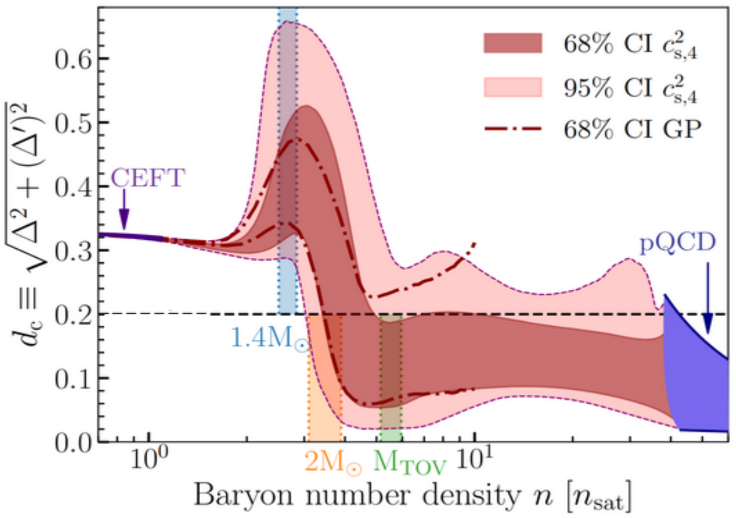
Annala, TG, Hirvonen, Komoltsev, Kurkela, Nättilä, Vuorinen Nat. Comm. 14 (2023)
Annala, TG, Kurkela, Nättilä, Vuorinen Nat. Phys. 16 (2020)

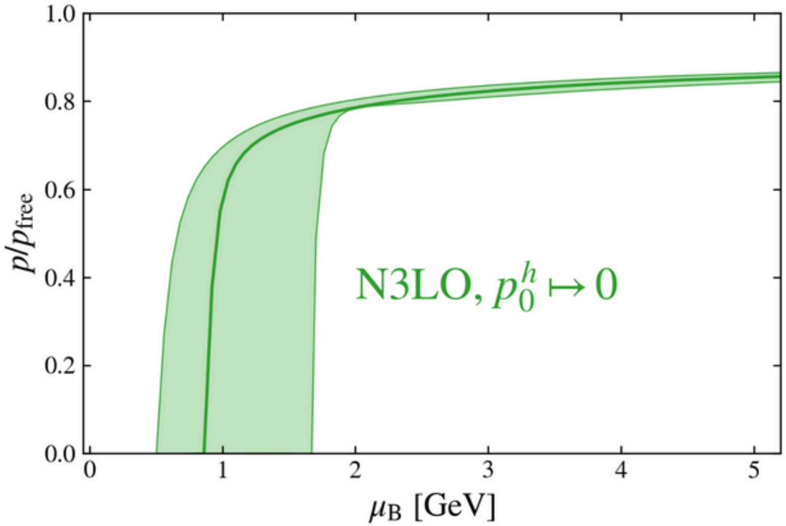
Takeaways

- ✔ Robust thermodynamic evidence for **hadronic→quark transition probed within the most massive neutron stars**.

  Evidence for cold quark matter created in nature.

- ✔ **Astrophysics + nuclear-theory + particle-theory input** are all essential in this conclusion





- ✔ Improvements in **pQCD calculations, analysis, and input in EOS inference**
  - Statistical analysis of pQCD truncation errors favors **higher pressures**, which are **better converged**
  - **Soft + mixed** pQCD EOS tightly converged; hard sector remains
  - Using **additional pQCD cs2 information** yields **robust EOS posteriors**

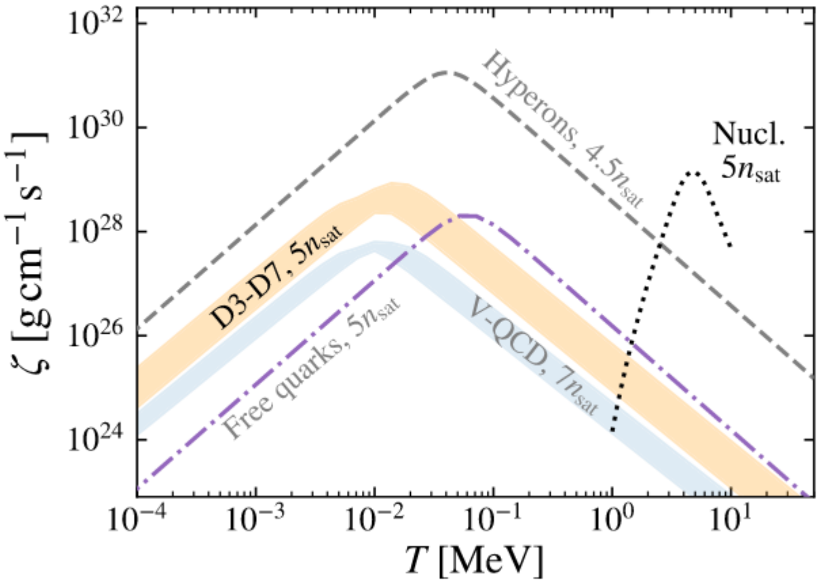
What's next?

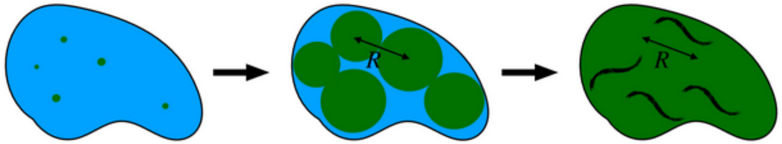
? Other lines of evidence of deconfined behavior?

- At high-T, thermodynamics is just one approach
- Recently improved transport calculations

Cruz Rojas, TG, Hoyos, Jokela, Järvinen, Kurkela, Paatelainen, Säppi, Vuorinen PRL 133 (2024); Hernandez, Manuel, Tolos PRD 109 (2024)

Bulk viscosity from weak processes





Casalderrey-Solana, Mateos, Sanchez-Garitaonandia 2210.03171

? Robust (post-)merger signals of deconfinement?

- MHz gravitation waves from bubble nucleation in remnant?

? Can similar analyses be performed at nonzero T, to apply statistical EoS inference throughout the phase diagram?

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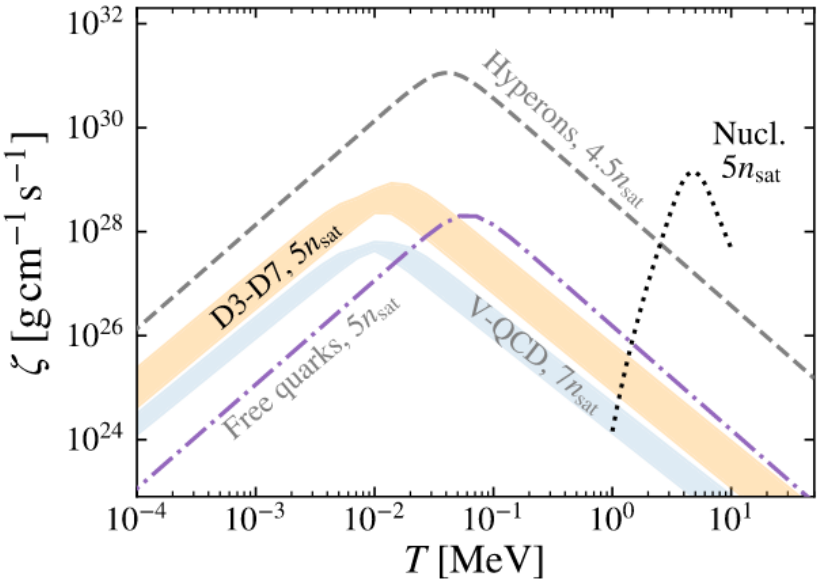

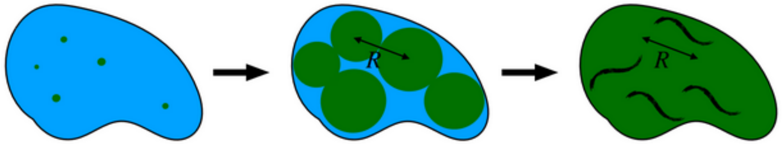

Casalderrey-Solana, Mateos, Sanchez-Garitaonandia 2210.03171

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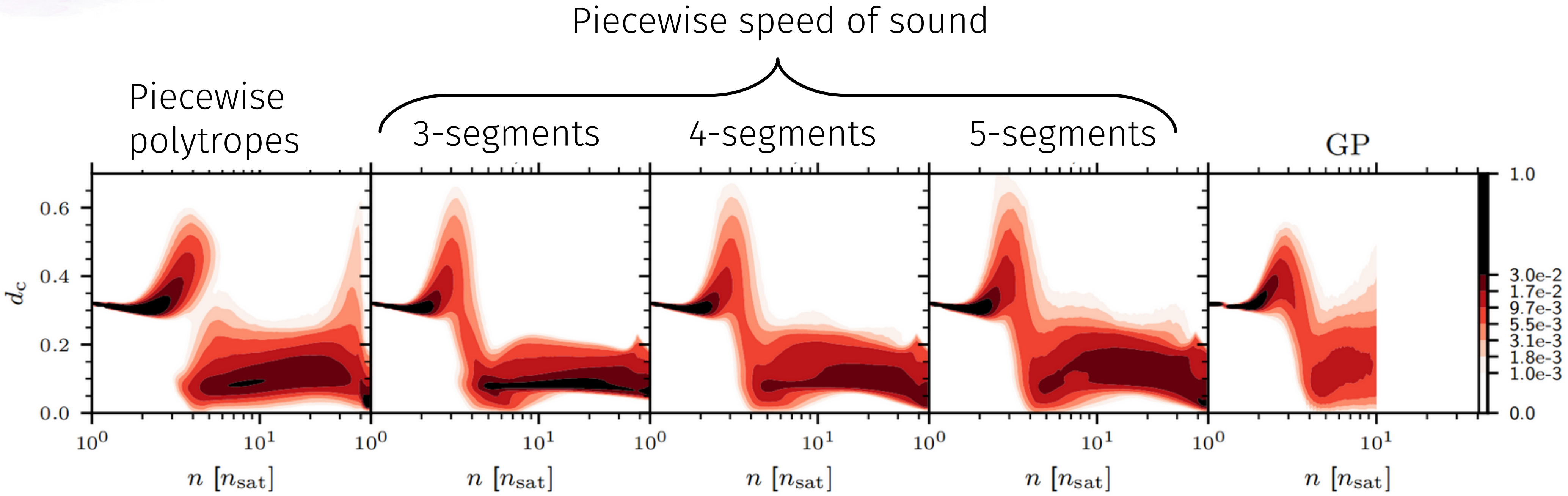
Thanks for your attention!

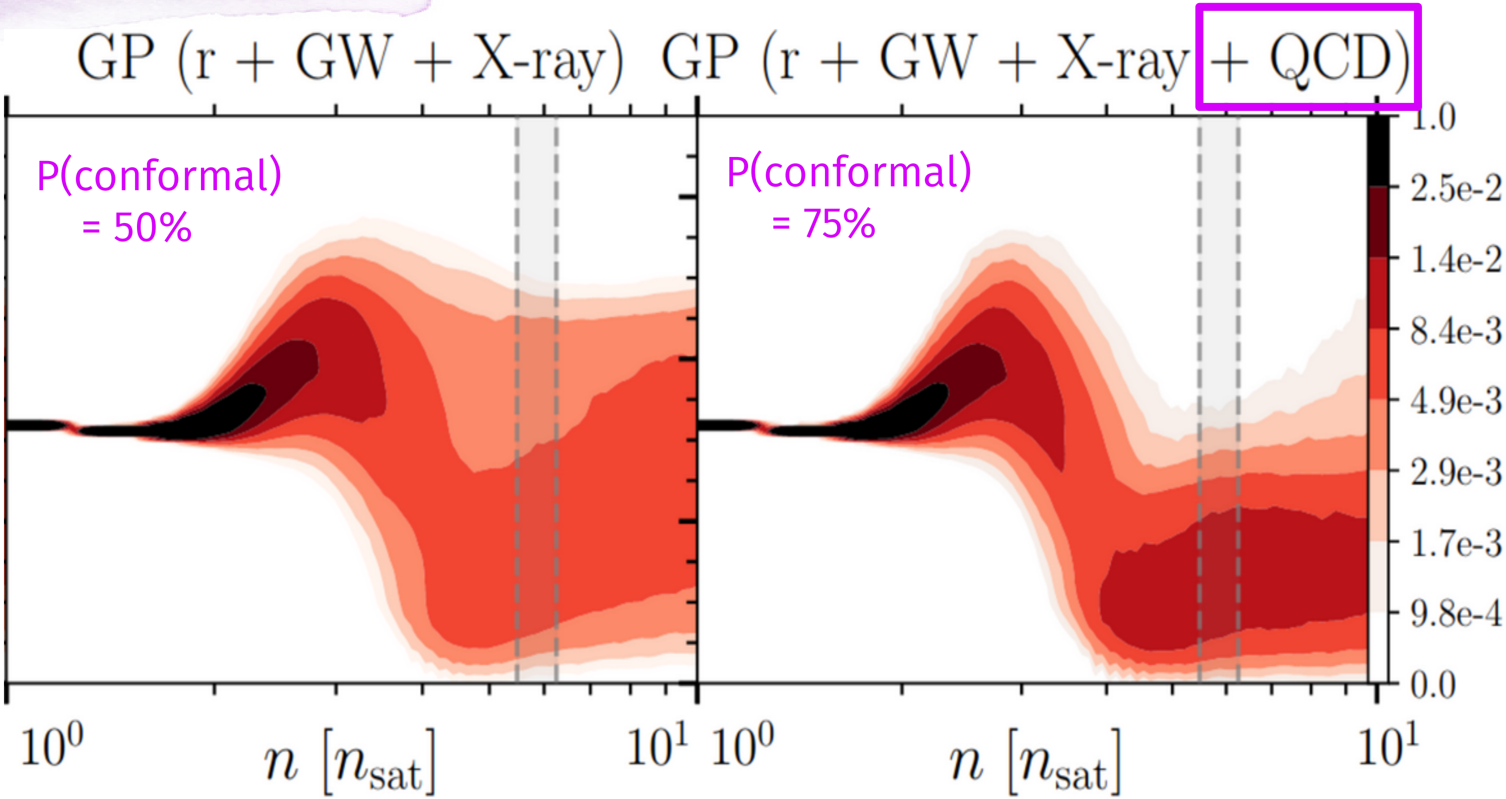
Here there be details…

Robust to interpolants



Annala, TG, Hirvonen, Komoltsev, Kurkela, Nättilä, Vuorinen
Nat. Comm. 14 (2023)

Effect from combined X-ray, QCD input



Annala, TG, Hirvonen, Komoltsev, Kurkela, Nättilä, Vuorinen
Nat. Comm. 14 (2023)

The *abc* model of convergent series

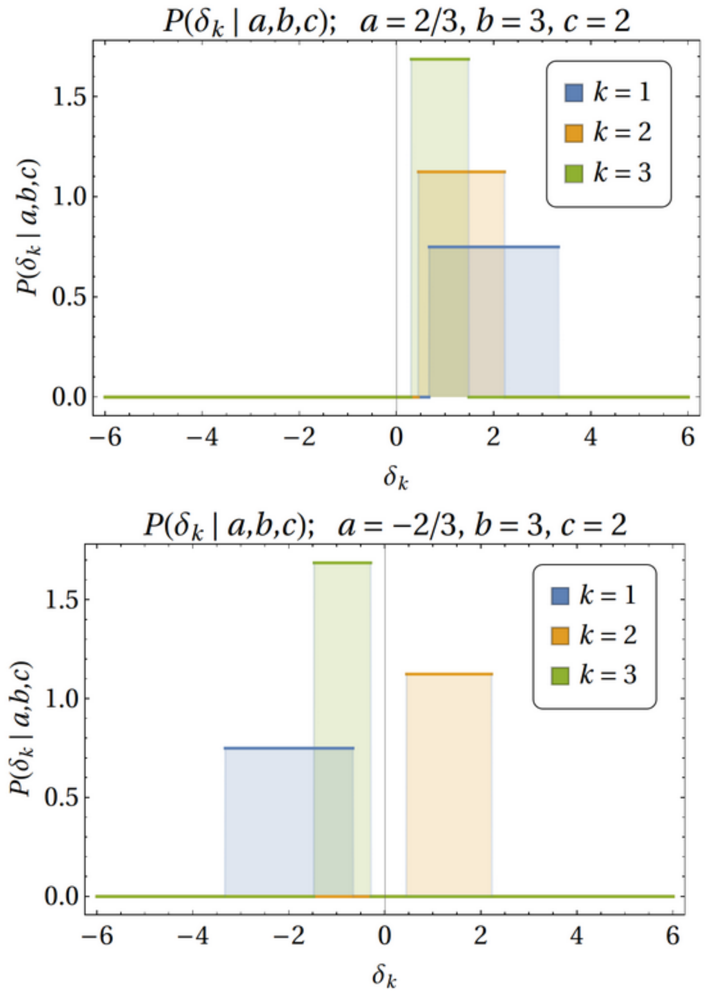
Normalize sequence by LO term

$$\delta_k \equiv \frac{\alpha^k O_k}{O_0} \quad (\delta_0 = 1)$$

Model assumes δ_k is bounded by some geometric series defined by (a, b, c)

$$(-c+b)a^k < |\delta_k| < (c+b)a^k,$$

Flat likelihoods taken for δ_k satisfying this inequality. (*Model also specifies a prior for *a*, *b*, *c* which favor smaller values of $|a|$, b, c)



Duhr, Huss, Mazeliauskas, Szafron, JHEP 09, 122 (2021)

The HARD diagrams

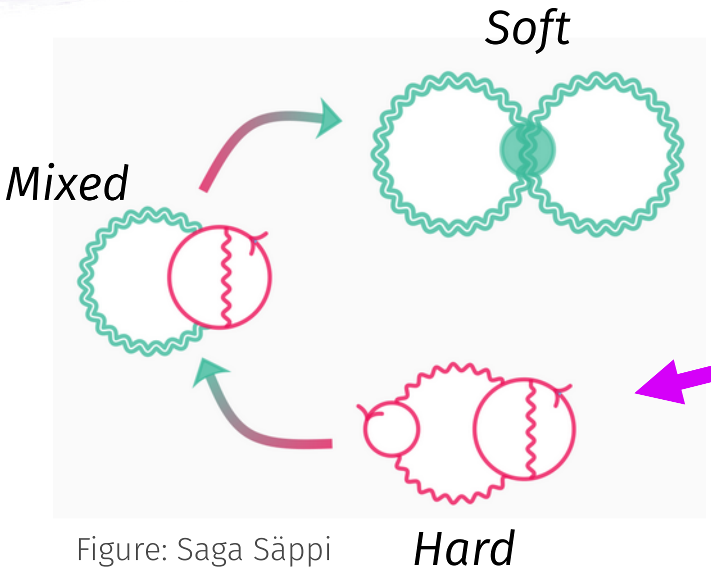
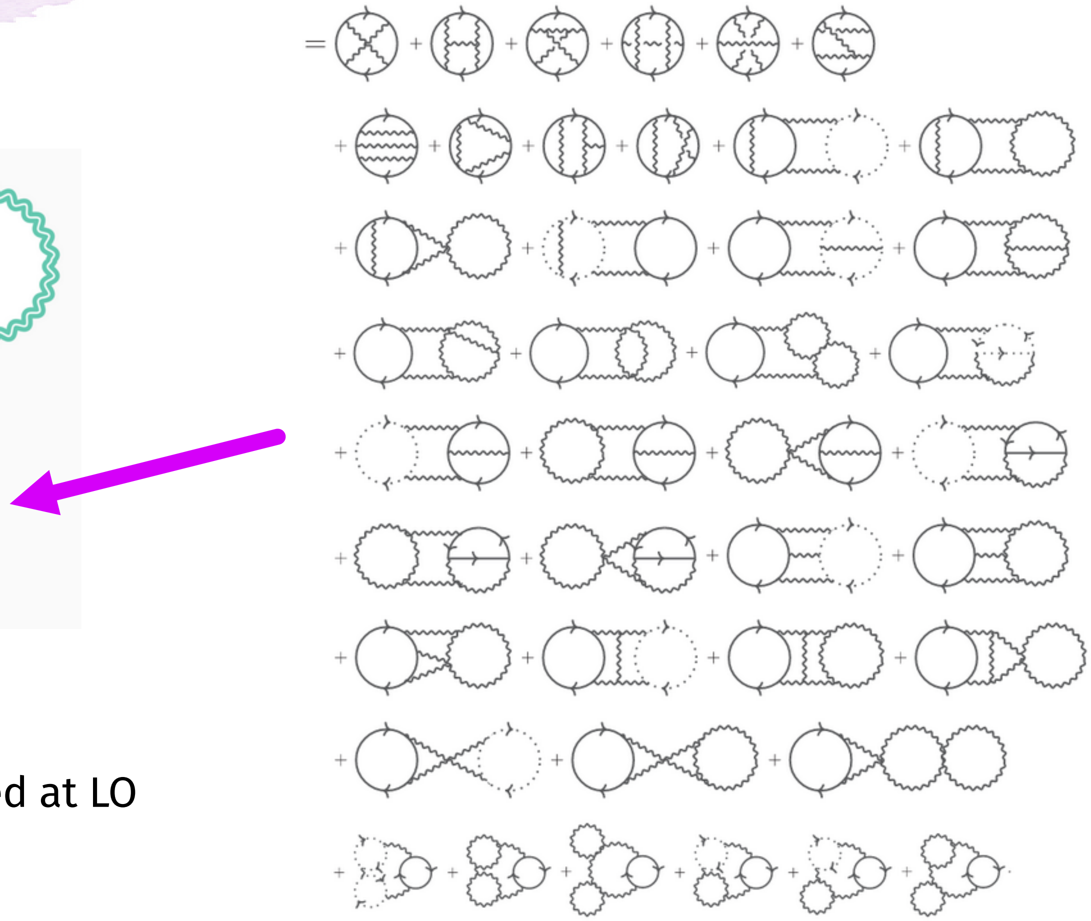


Figure: Saga Säppi



Soft: 2 interacting gluons **screened at LO**
Mixed: 1 gluon **screened at NLO**
Hard: gluons are **unscreened**

Gaussian Process regression priors

- Follow Landry & Essick Phys. Rev. D 99 (2019) and implement a Gaussian Process Regression in an auxiliary variable $\varphi(n) = -\ln\left(c_s^{-2}(n) - 1\right)$, but as function of n
- Use hierarchical model, for wide range of behavior

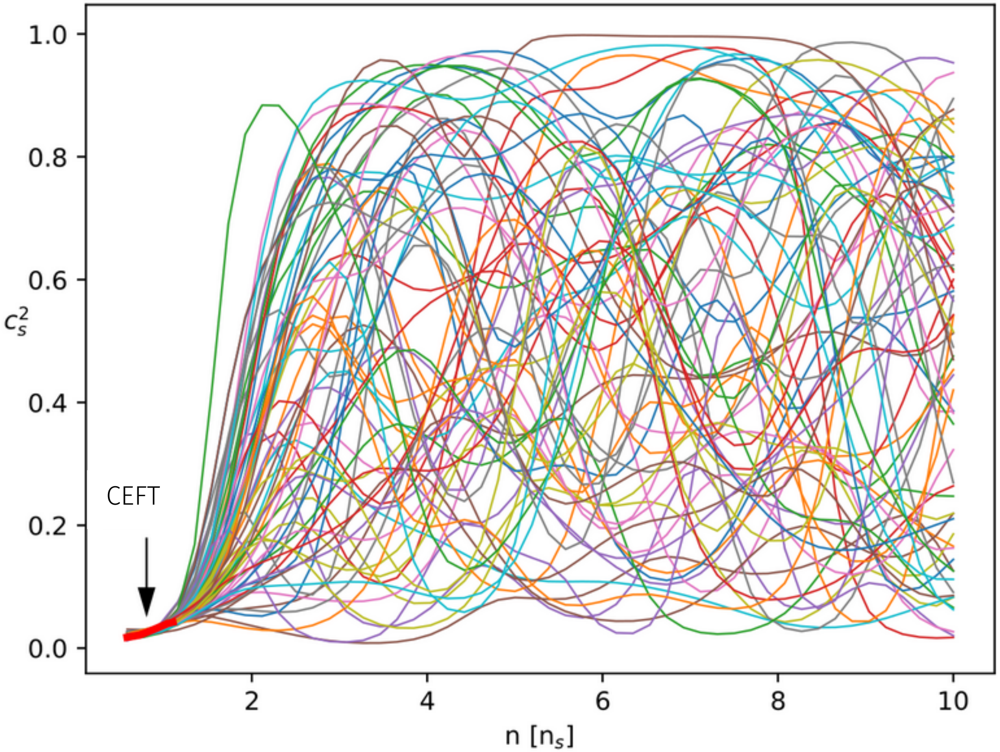
$$\varphi(n) \sim \mathcal{N}\left(-\ln\left(\bar{c}_s^{-2} - 1\right), K(n, n')\right),$$

$$K(n, n') = \eta e^{-(n-n')^2/2\ell^2}$$

$$\bar{c}_s^2 \sim \mathcal{N}(0.5, 0.25^2),$$

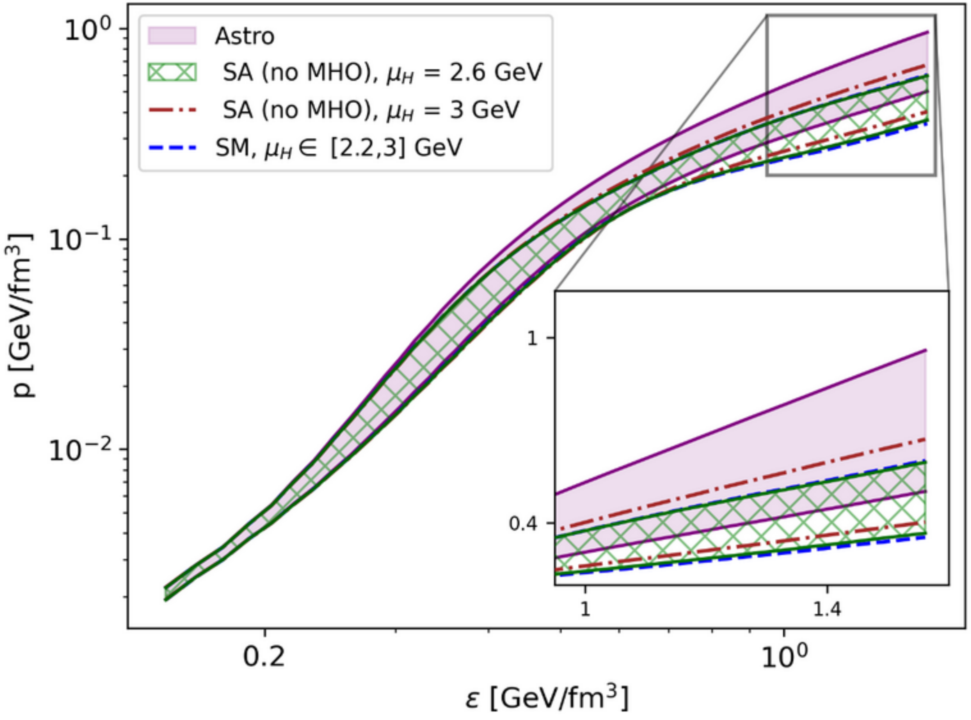
$$\ell \sim \mathcal{N}\left(1.0 n_s, (0.2 n_s)^2\right),$$

$$\eta \sim \mathcal{N}(1.25, 0.25^2).$$



TG, Komoltsev, Kurkela, ApJ 950 (2023)
https://github.com/OKomoltsev/QCD-likelihood-function

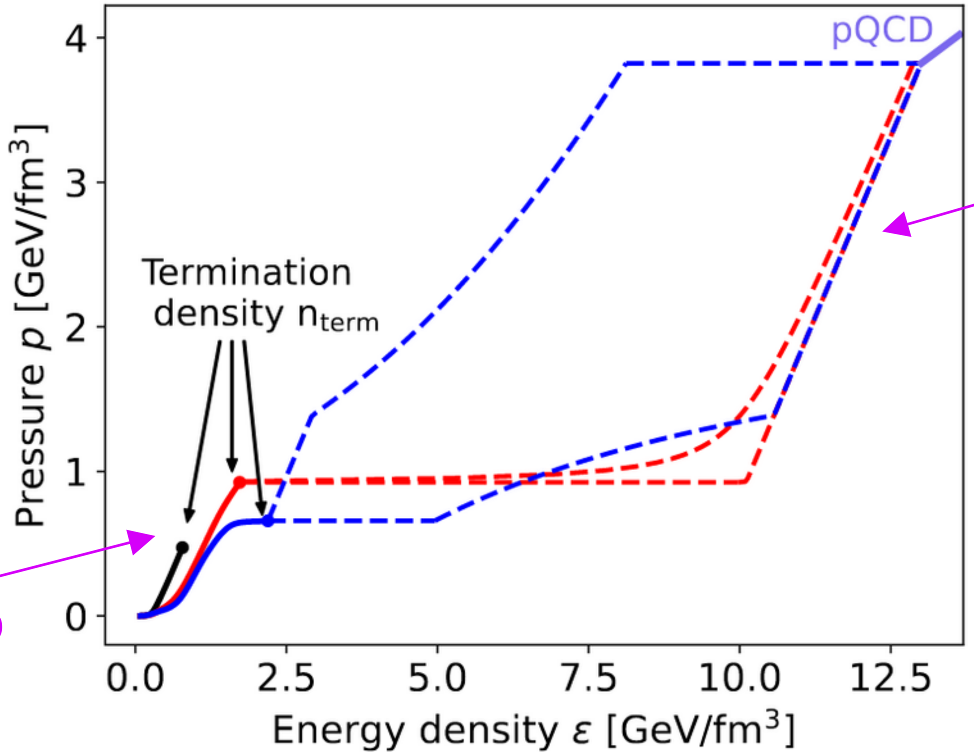
Details of statistical pQCD treatment don't affect NS inference



TG, Komoltsev, Kurkela, Mazeliauskas JHEP 06 (2023)

Quantifying the *tension* with perturbative QCD

Komoltsev, Somasundaram, TG, Kurkela, Margueron, Tews PRD 109 (2024)



Thermodynamics restricts EoS behavior beyond n_{term}

EoS modeled up to n_{term} using:

1. Gaussian process for c_s^2
2. Piecewise linear c_s^2

TG, Komoltsev, Kurkela, ApJ 950 (2023),
Somasundaram, Tews, Margueron PRC 107, L052801 (2023).

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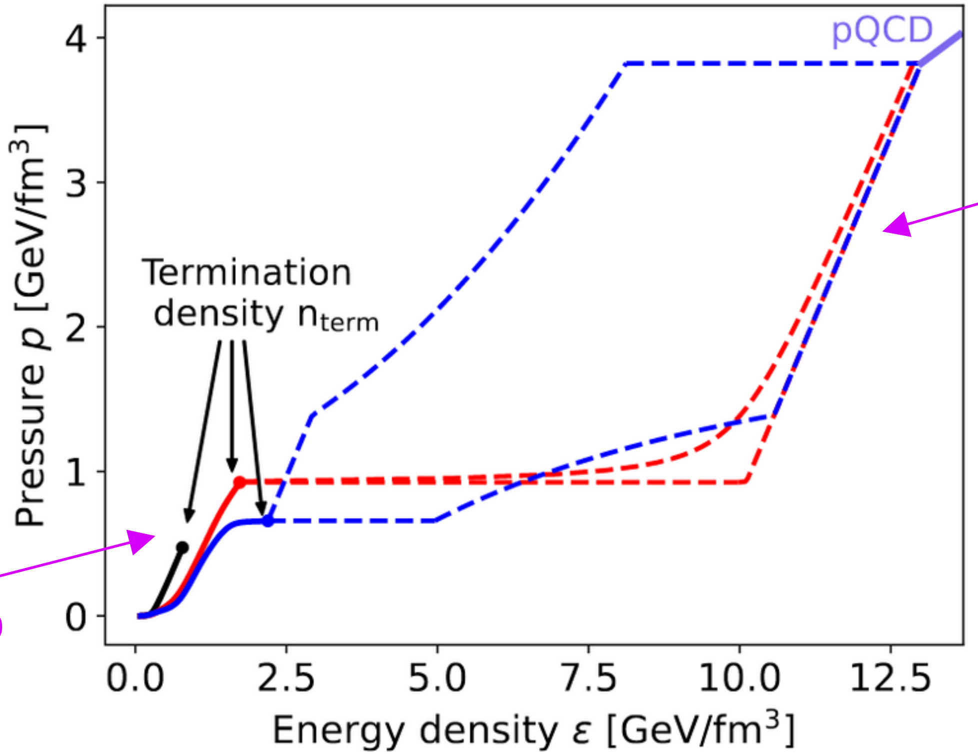

Thermodynamics restricts EoS behavior beyond n_{term}

Introduce pQCD tension index I_{pQCD} to quantify how close to excluded a point is:

$$0 \leq I_{pQCD} \equiv \frac{\Delta p - \Delta p_{min}}{\Delta p_{max} - \Delta p_{min}} \leq 1$$

(stiffer EOSs have larger I_{pQCD})

EoS modeled up to n_{term} using:

1. Gaussian process for c_s^2 TG, Komoltsev, Kurkela, ApJ 950 (2023),
2. Piecewise linear c_s^2 Somasundaram, Tews, Margueron PRC 107, L052801 (2023).

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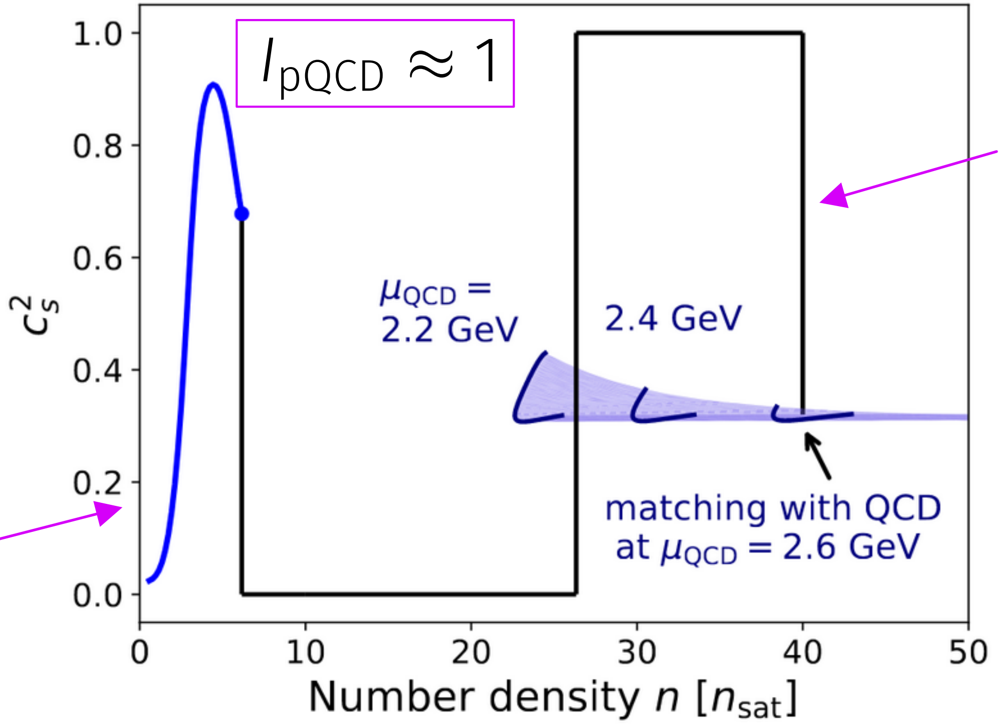

Thermodynamics restricts EoS behavior beyond $n_{\rm term}$

EoS modeled up to $n_{\rm term}$

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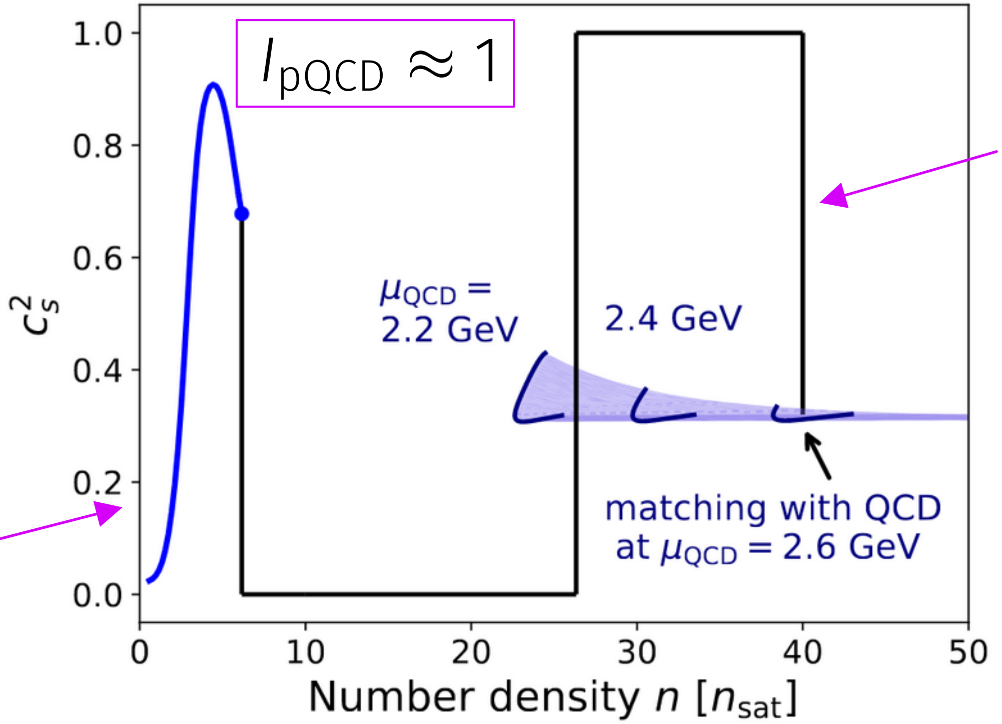
Komoltsev, Somasundaram, TG, Kurkela, Margueron, Tews PRD 109 (2024)



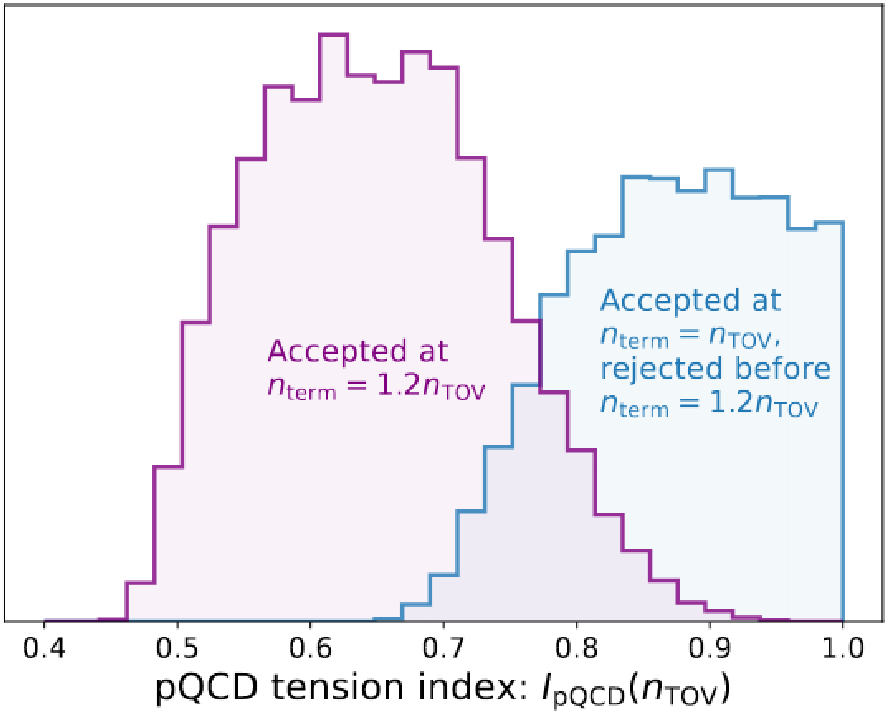
Thermodynamics restricts EoS behavior beyond n_{term}

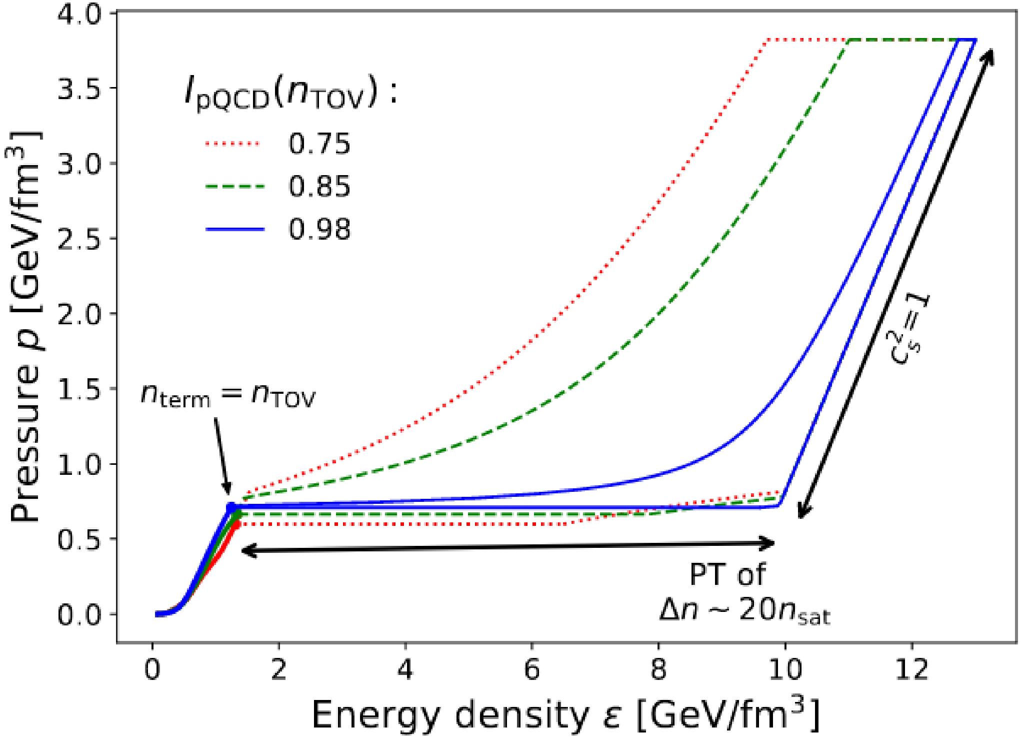
EoS modeled up to n_{term}

Observation: High pQCD tension index also inconsistent with well-converged pQCD c_s^2

Examining $n_{\text{term}} = n_{\text{TOV}}$: Many EOSs have high I_{pQCD}

Komoltsev, Somasundaram, TG, Kurkela, Margueron, Tews PRD 109 (2024)

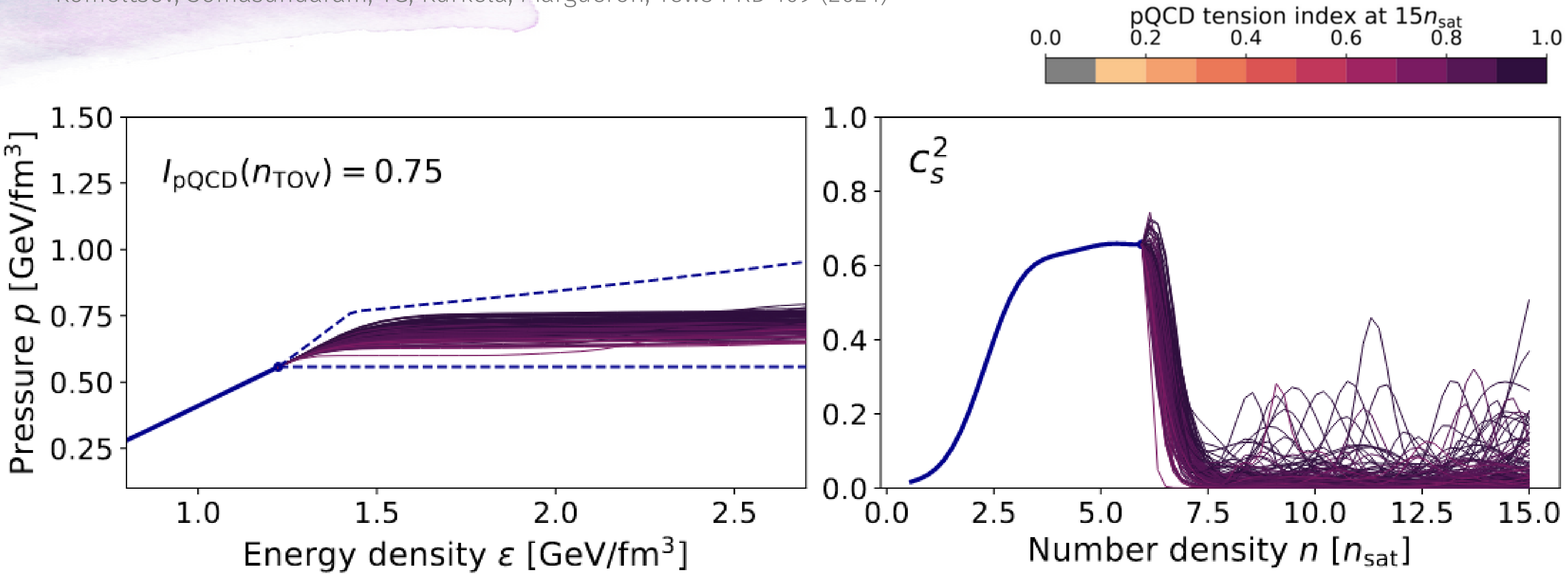




Allowed extensions for stiff EoSs have tightly constrained region beyond n_{TOV}

Extending stiff EoSs indeed show strong, prolonged softening

Komoltsev, Somasundaram, TG, Kurkela, Margueron, Tews PRD 109 (2024)



Takeaway: Softening before n_{TOV} **OR** Strong, prolonged softening just after, **followed by $c_s^2 \approx 1$**

EoS extensions for less extreme pressures

Komoltsev, Somasundaram, TG, Kurkela, Margueron, Tews PRD 109 (2024)