Constraining the microscopic properties of high-density QCD

Gravity Seminar, Southampton
11 May 2023

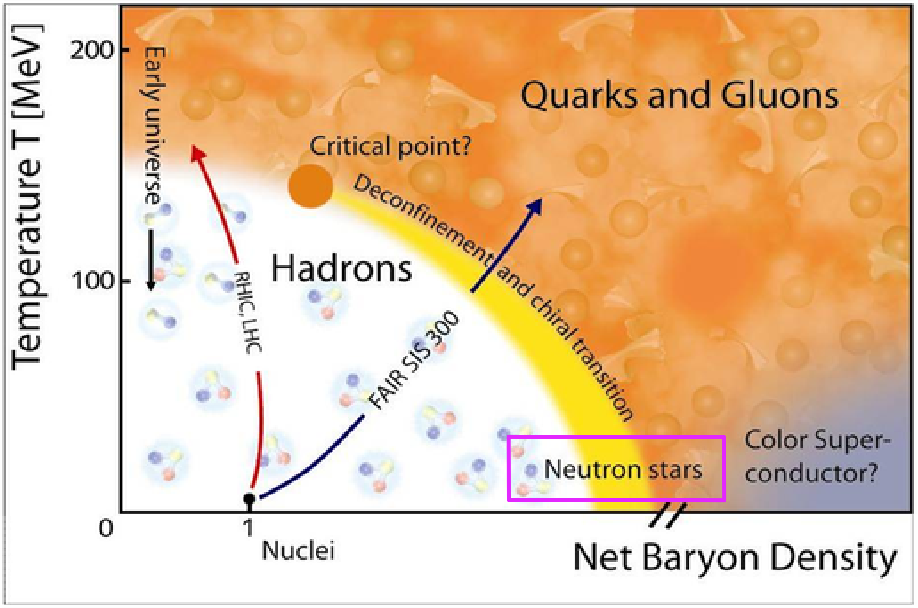
Based on 2303.11356, 2303.02175

In collaboration with
E. Annala, J. Hirvonen, O. Komoltsev, A. Kurkela,
A. Mazeliauskas, J. Nättilä and A. Vuorinen

Tyler Gorda
TU Darmstadt

How to study strongly interacting matter using NSs

- Strongly interacting matter at high density cannot be studied from first principles

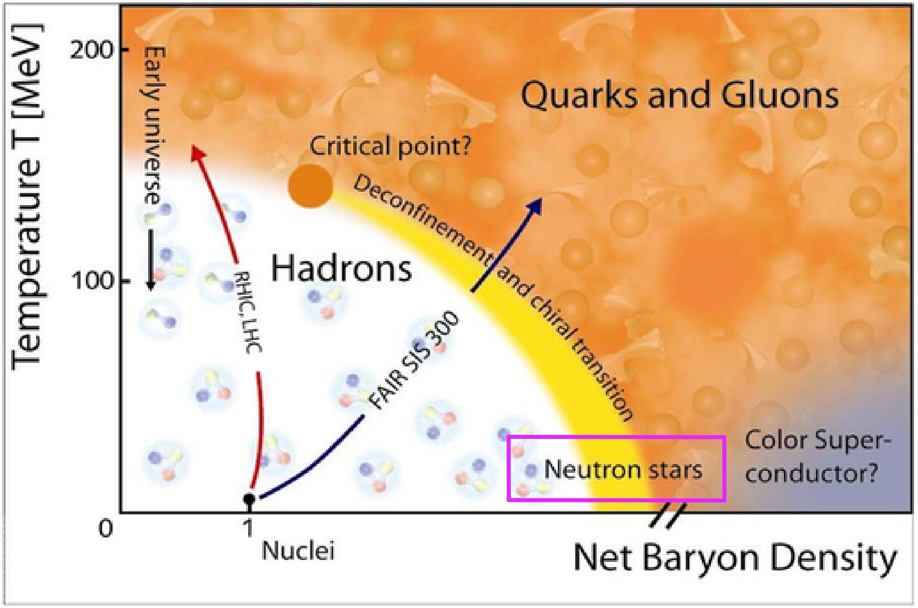


Compressed Baryonic Matter (CBM) experiment

How to study strongly interacting matter using NSs

- Strongly interacting matter at high density cannot be studied from first principles

High-T lattice + experiment have identified a crossover deconfinement transition

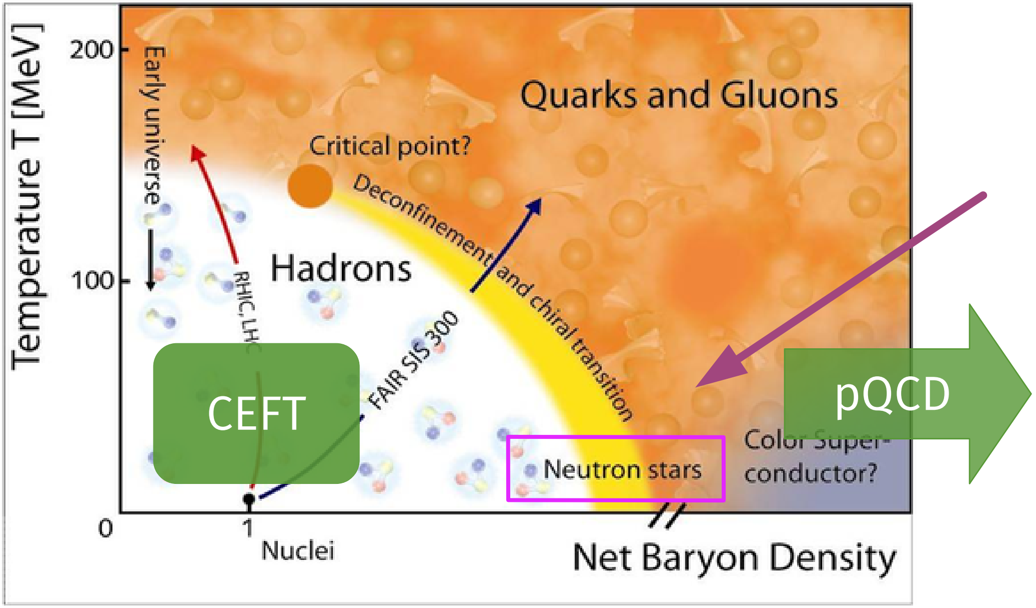


Compressed Baryonic Matter (CBM) experiment

How to study strongly interacting matter using NSs

- Strongly interacting matter at high density cannot be studied from first principles

High-T lattice + experiment have identified a crossover deconfinement transition



Compressed Baryonic Matter (CBM) experiment

At high density and low T, have robust input only from **CEFT**, **pQCD** and **NS observables**

Combine all these to determine properties of dense matter

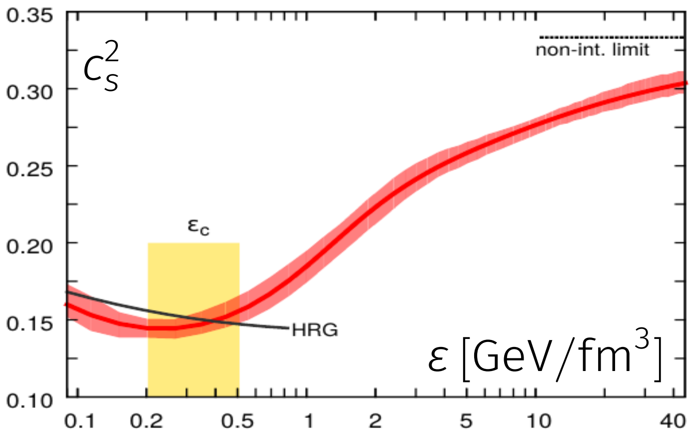
Objective: Search for change in thermodynamic behavior

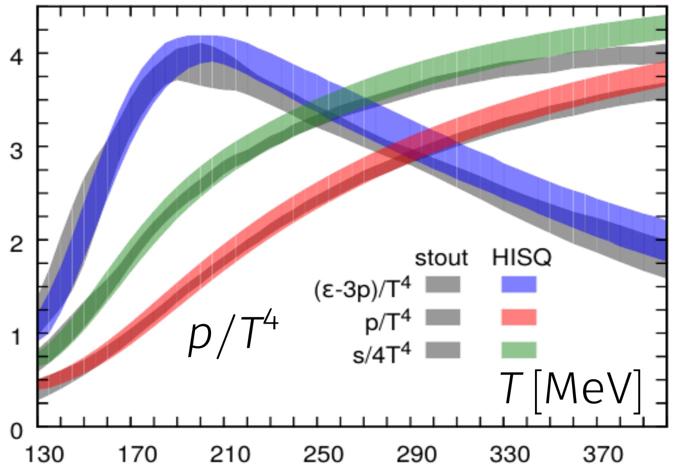
- *Strategy:*
  Identify where/if EoS changes physical properties from hadronic → quark

  Want to be model agnostic

- Similar to isolating change in behavior of lattice results at high *T*.

- Identify change in phase from ***change in physical properties*** of matter

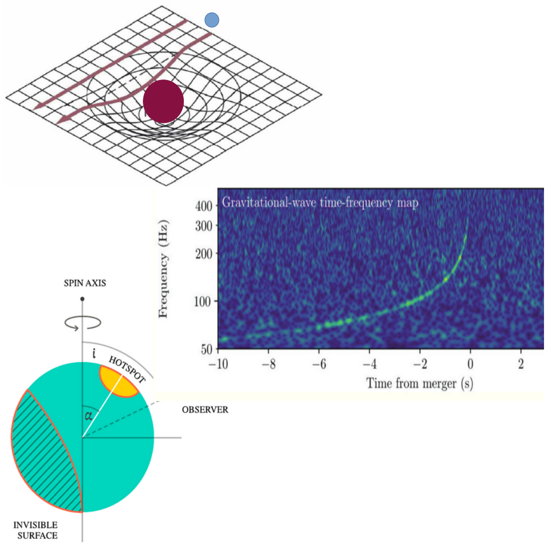




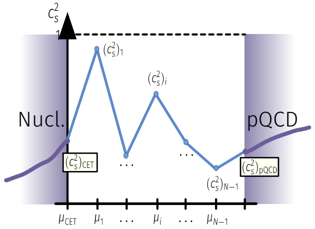
HotQCD Phys.Rev.D 90 (2014), Borsanyi+ Phys. Lett. B 370 (2014)

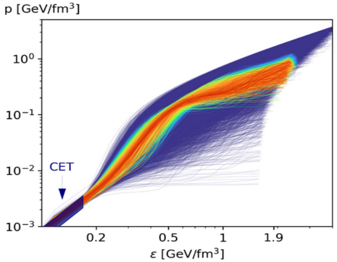
Workflow

NS observations

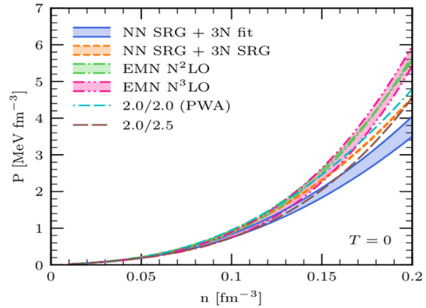


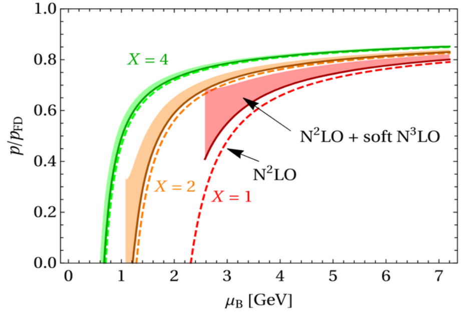
EoS Inference



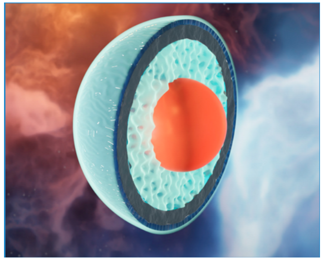


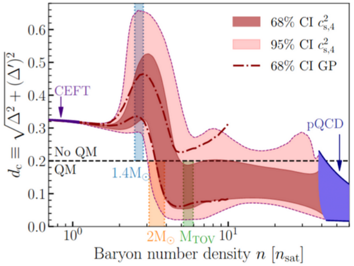
Theoretical Calculations:





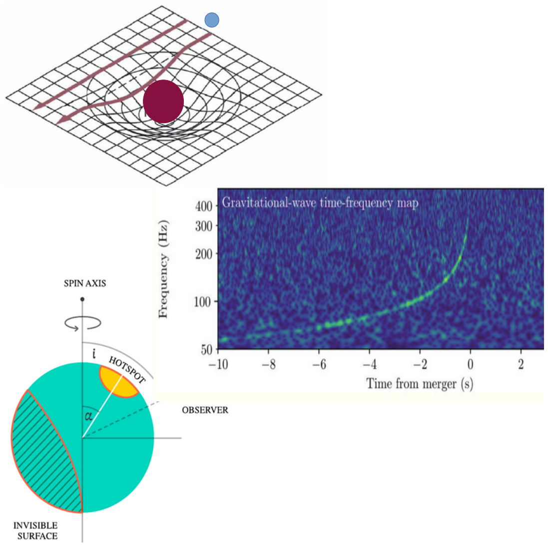
Behavior of Dense QCD



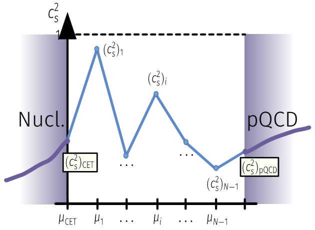


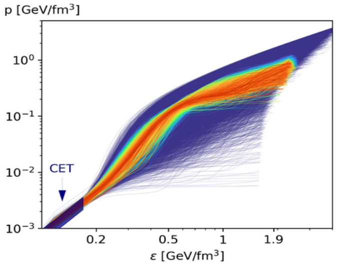
What do we know from theory?

NS observations

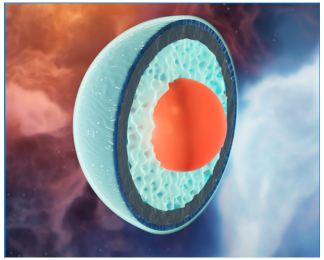


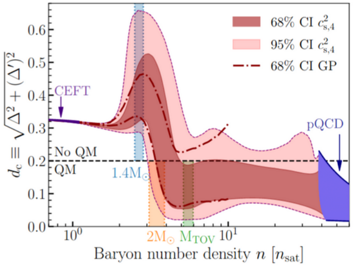
EoS Inference



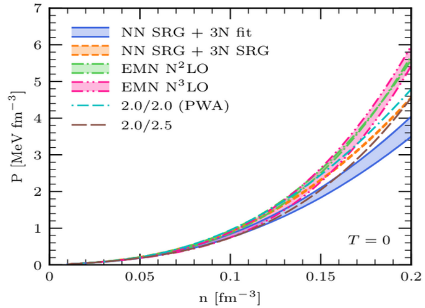


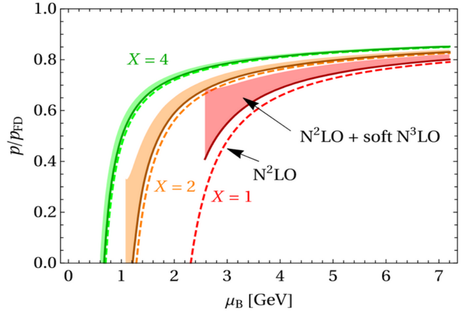
Behavior of Dense QCD





Theoretical Calculations:

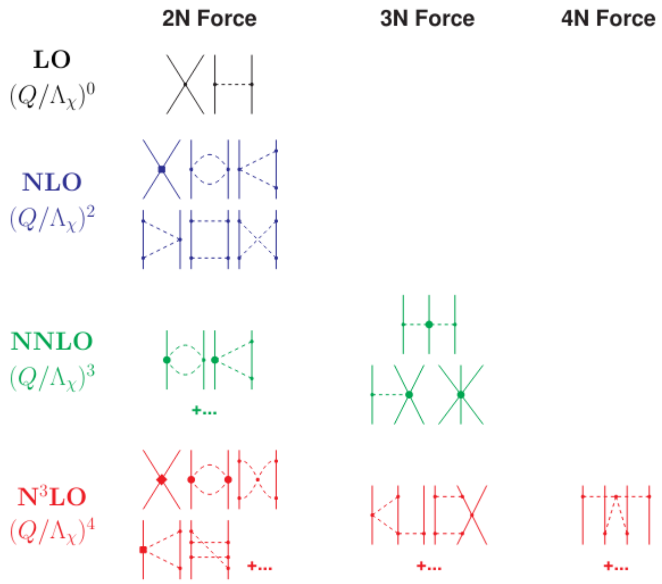




Theory predicts EoS at low and high Density

Chiral EFT

Describes interactions between *(massive) nucleons*, via pion exchange and contact interactions, in a hierarchical manner



Perturbative QCD

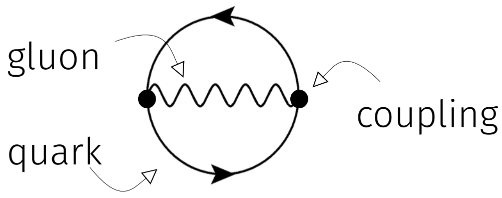
Describes interactions between *massless quarks and gluons*. Quarks are approximately free, up to [O(20%)] perturbative corrections

$$p = \underbrace{p_{\mathrm{FD}}}_{\textit{free quark gas}^*} + p_1\alpha_s + p_2\alpha_s^2 + \cdots$$

$^*(p_{\mathrm{FD}} \propto \mu^4, \quad p_{\mathrm{pairing}} \propto \mu^2\Delta^2)$

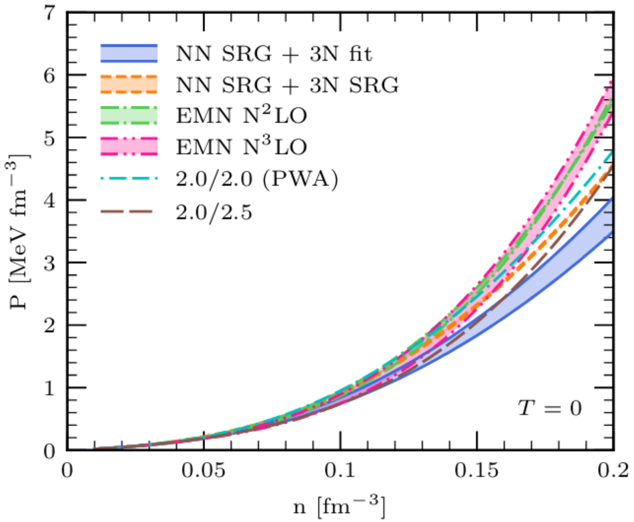
Alford+, Rev. Mod. Phys. 80, 1455 (2008)

Language for this expansion is *Feynman diagrams*



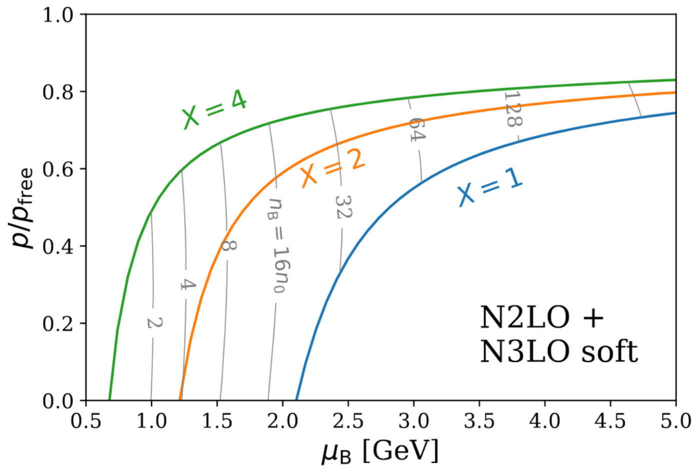
Theory predicts EoS at low and high Density

Chiral EFT



Hebeler, Lattimer, Pethick, Schwenk. Astrophys. J. 773 (2013);
Tews, Krüger, Hebeler, Schwenk, PRL 110, 032504 (2013)
Lynn, Tews, Carlson, et al., 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).

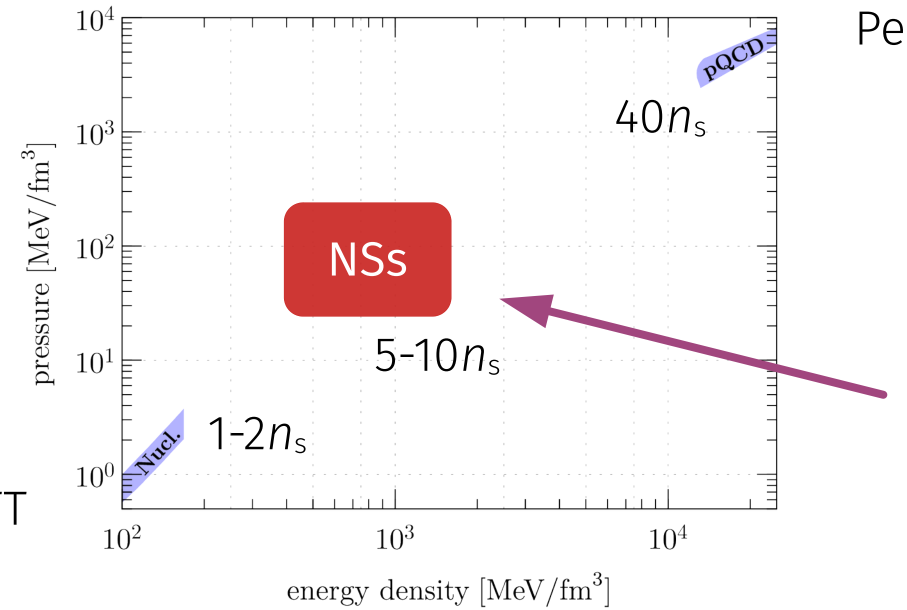
Perturbative QCD



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

Theory predicts EoS at low and high Density

Perturbative QCD

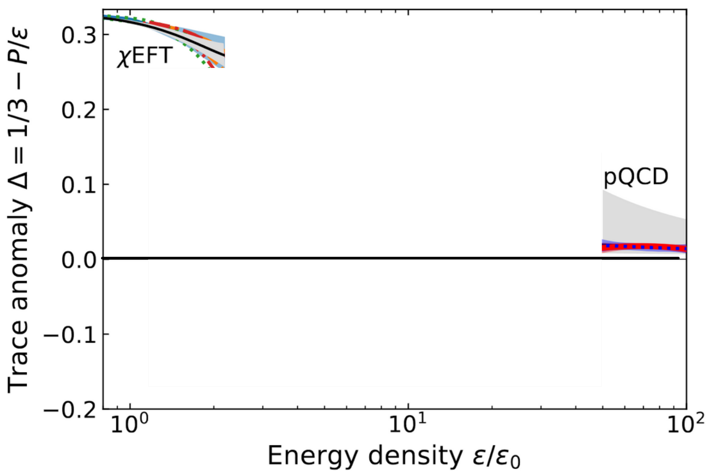


Chiral EFT

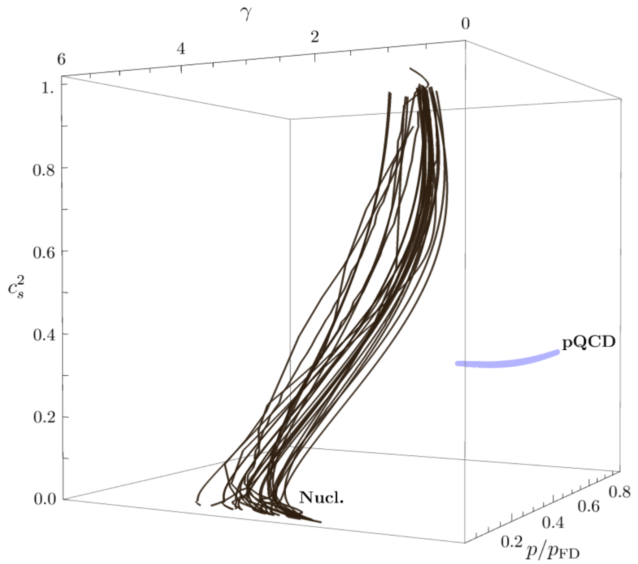
Intermediate EoS must be constrained by interpolation / regression

Hadronic and Quark matter are different

QM has different physical properties than hadronic matter, in particular, it is approximately ***conformal***, with many implications. One consequence is a vanishing trace of the energy-momentum tensor, $\Delta \equiv T^{\mu}_{\mu}/(3\varepsilon) = (\varepsilon - 3p)/(3\varepsilon)$



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



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

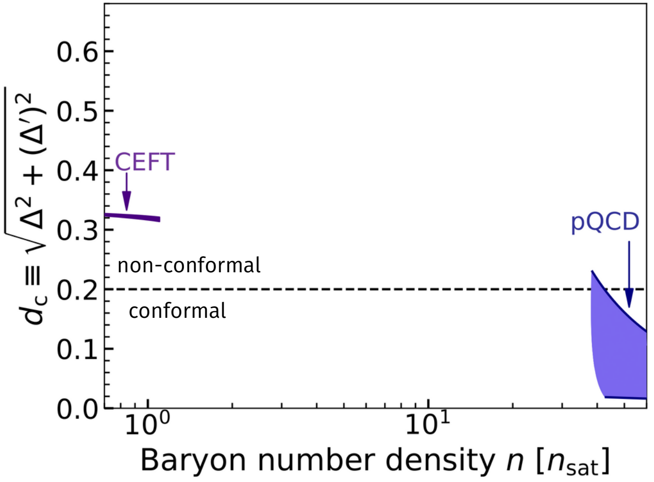
Hadronic and Quark matter are different

QM has different physical properties than hadronic matter, in particular, it is approximately ***conformal***, with many implications. One consequence is a vanishing trace of the energy-momentum tensor, $\Delta \equiv T^{\mu}_{\mu}/(3\varepsilon) = (\varepsilon - 3p)/(3\varepsilon)$

For our recent work, we use a combination of the normalized trace anomaly and its derivative: $\Delta' \equiv \mathrm{d}\ln\Delta/\mathrm{d}\ln\varepsilon$

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

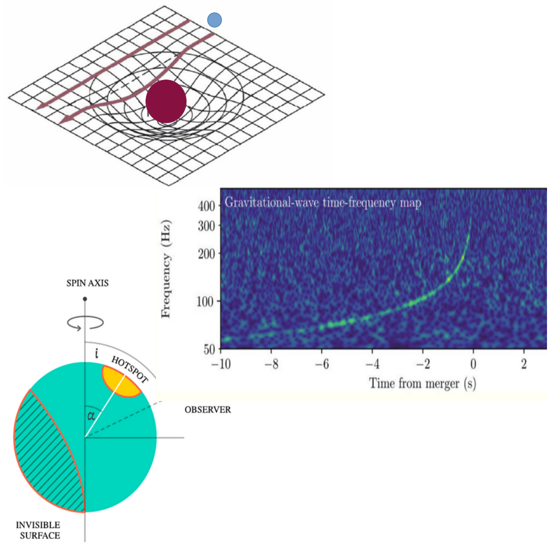
This quantity is sensitive to the local trace anomaly and how quickly trace anomaly is changing



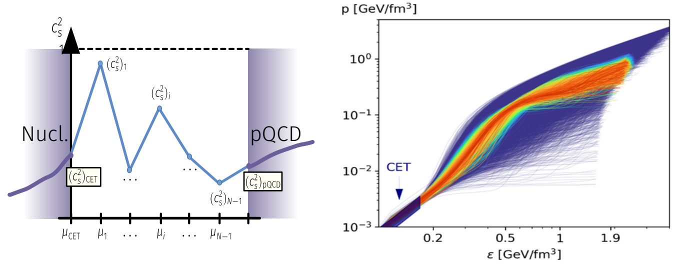
Annala, TG, Hirvonen, Komoltsev, Kurkela, Nättilä, Vuorinen 2303.11356

What do we know from observations?

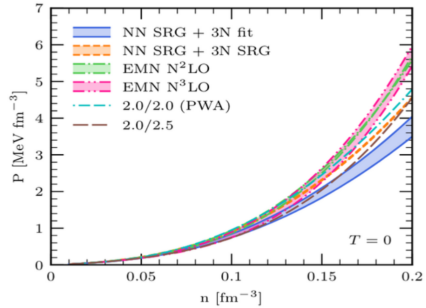
NS observations

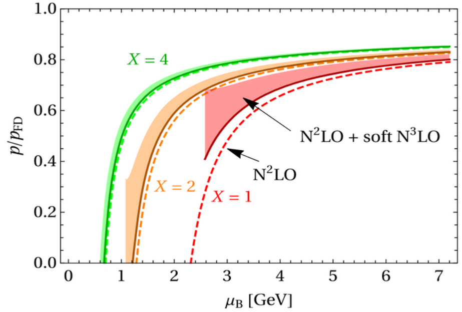


EoS Inference

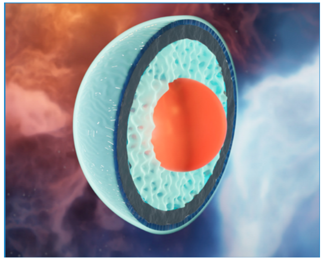


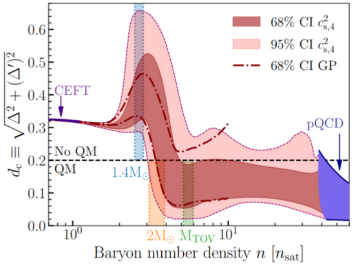
Theoretical Calculations:



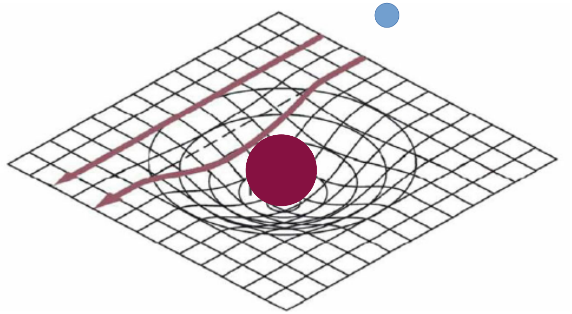


Behavior of Dense QCD



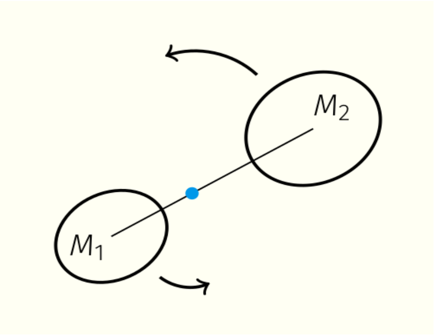


Observations tell us about:



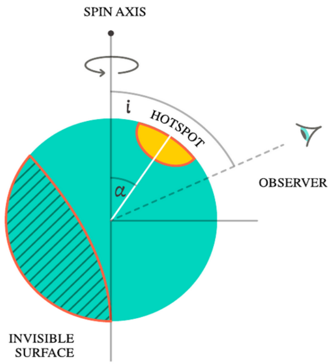
Masses

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



Deformabilities

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

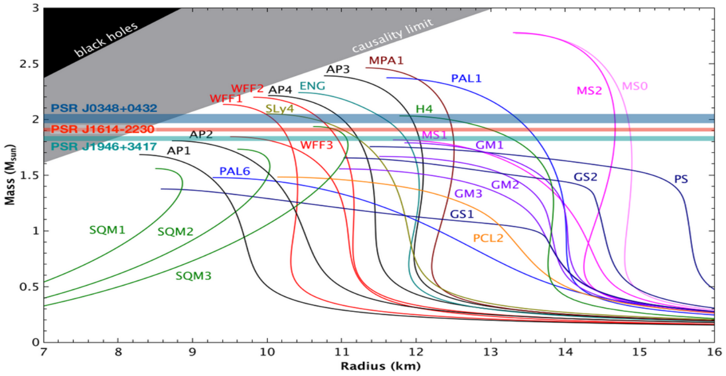


Radii, compactness

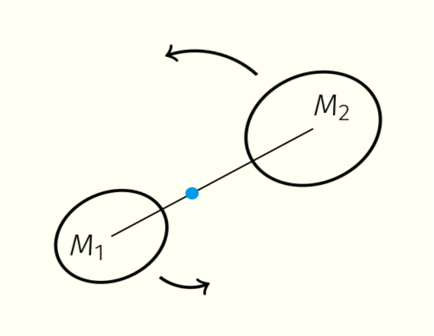
Miller et al. Astrophys. J. Lett. 918.2 (2021), p. L28. Riley et al. Astrophys. J. Lett. 918.2 (2021) p. L27.

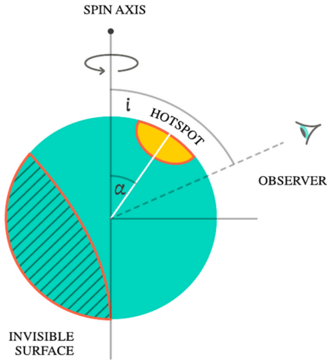
Observations tell us about:

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



Norbert Wex





Masses

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

Deformabilities

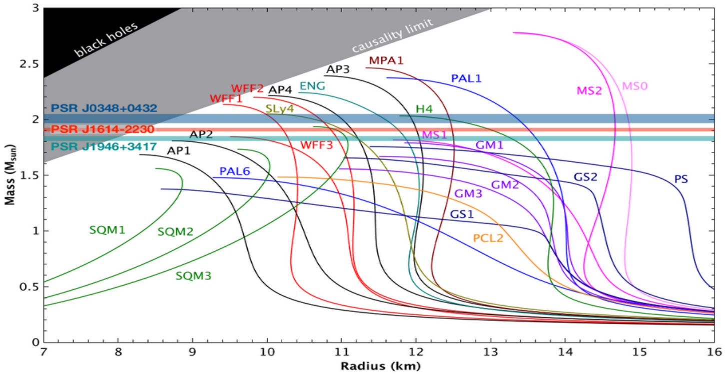
Abbott et. al (LIGO Scientific, Virgo) PRL 119 (2017); PRL 121 (2018); PRX 9 (2019).

Radii, compactness

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

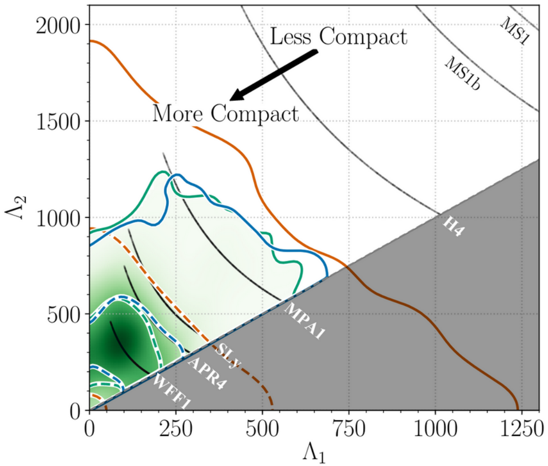
Observations tell us about:

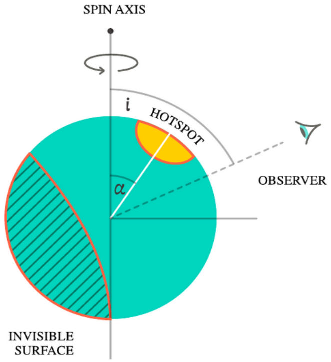
$$M_{\text{TOV}} \geq \begin{cases} 1.97 \pm 0.04 M_\odot & \text{PSR J1614-2230} \\ 2.01 \pm 0.04 M_\odot & \text{PSR J0348+0432} \\ 2.08 \pm 0.07 M_\odot & \text{PSR J0740+6620} \end{cases}$$



Norbert Wex

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





Masses

Deformabilities

Radii, compactness

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

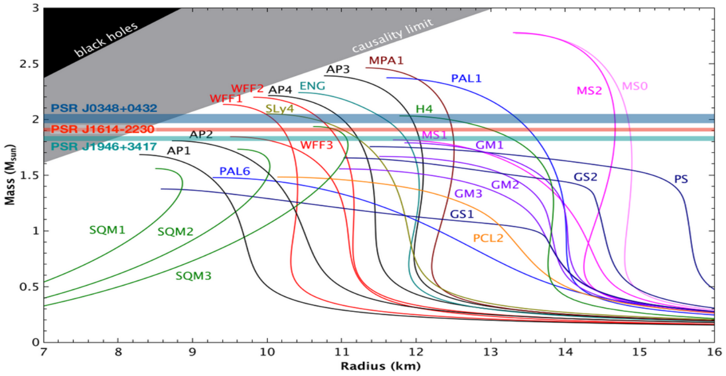
Abbott et. al (LIGO Scientific, Virgo) PRL 119 (2017); PRL 121 (2018); PRX 9 (2019).

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

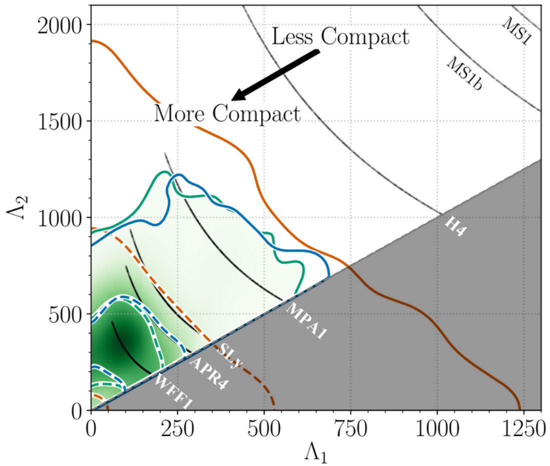
Observations tell us about:

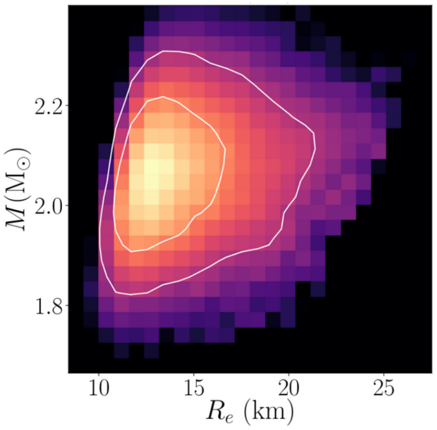
$$M_{\mathrm{TOV}} \geq \begin{cases} 1.97 \pm 0.04 M_\odot & \text{PSR J1614-2230} \\ 2.01 \pm 0.04 M_\odot & \text{PSR J0348+0432} \\ 2.08 \pm 0.07 M_\odot & \text{PSR J0740+6620} \end{cases}$$

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



Norbert Wex





Masses

Deformabilities

Radii, compactness

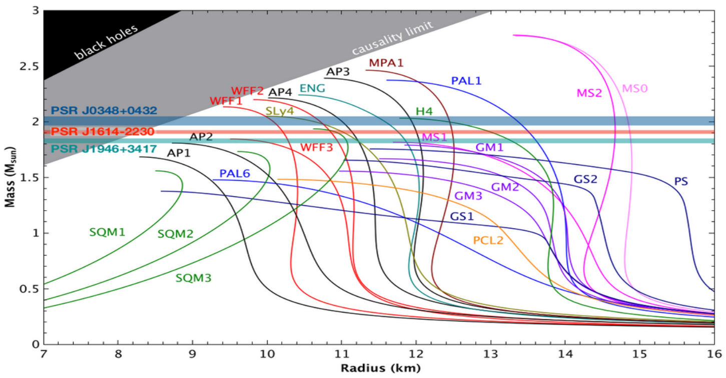
Demorest, Pennucci, Ransom, Roberts, Hessels. Nature 467 (2010) pp. 1081-1083;
Antoniadis et al. Science 340 (2013) p. 6131;
Cromartie et al. (NANOGrav). Nature Astron. 4.1 (2019).
E. Fonseca at al. Astrophys. J. Lett. 915.1 (2021)

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

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

Observations tell us about:

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



Norbert Wex

Masses

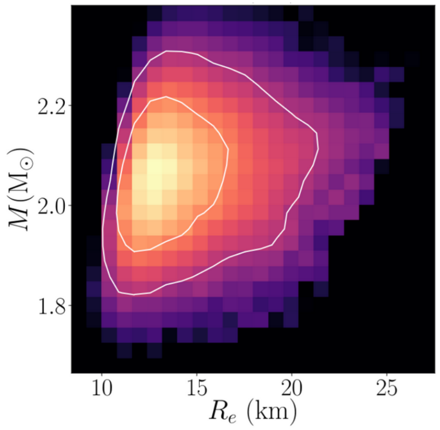
Demorest, Pennucci, Ransom, Roberts, Hessels. Nature 467 (2010) pp. 1081-1083;
Antoniadis et al. Science 340 (2013) p. 6131;
Cromartie et al. (NANOGrav). Nature Astron. 4.1 (2019).
E. Fonseca at al. Astrophys. J. Lett. 915.1 (2021)

* EM counterpart evidence for collapse to BH (BH-hyp)

Margalit & Metzger. ApJ. Lett. 850.2 (2017);
Rezzolla, Most, Weih. ApJ 852.2 (2018);
Shibata+ PRD 96.12 (2017);

Deformabilities

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

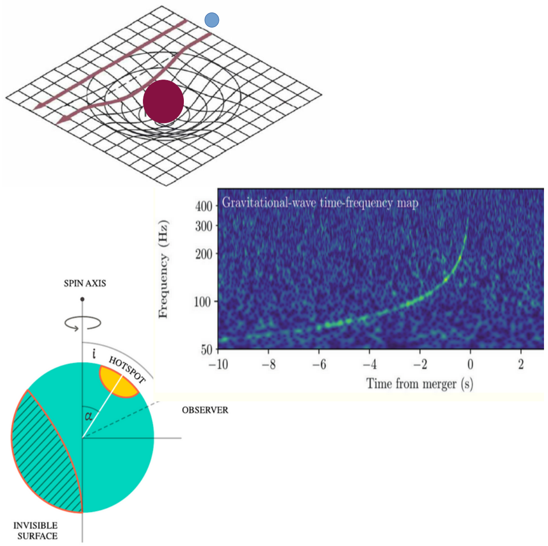


Radii, compactness

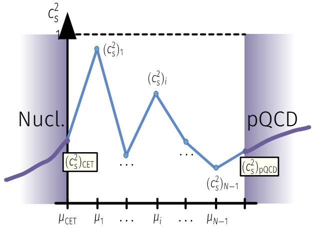
Miller et al. Astrophys. J. Lett. 918.2 (2021), p. L28. Riley et al. Astrophys. J. Lett. 918.2 (2021) p. L27.

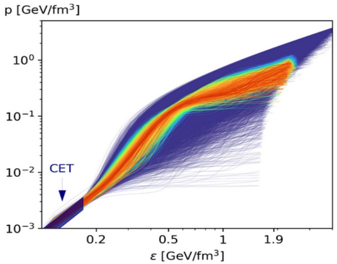
How do we synthesize?

NS observations

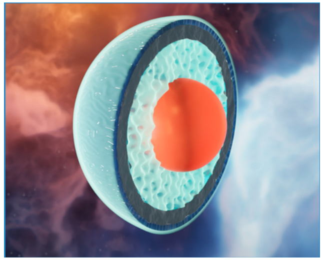


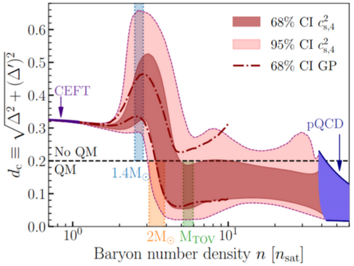
EoS Inference



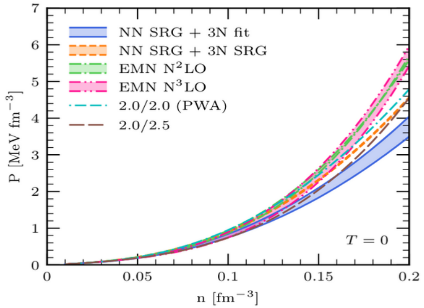


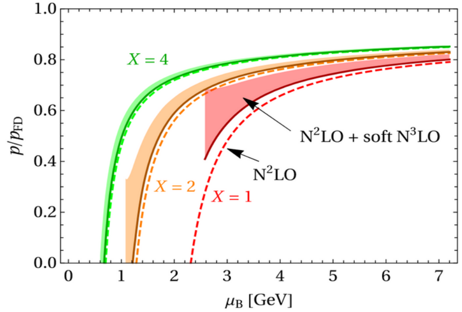
Behavior of Dense QCD





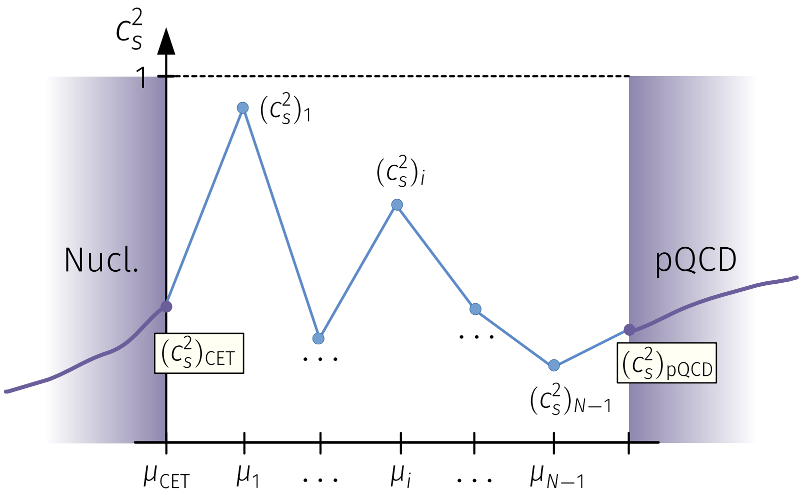
Theoretical Calculations:





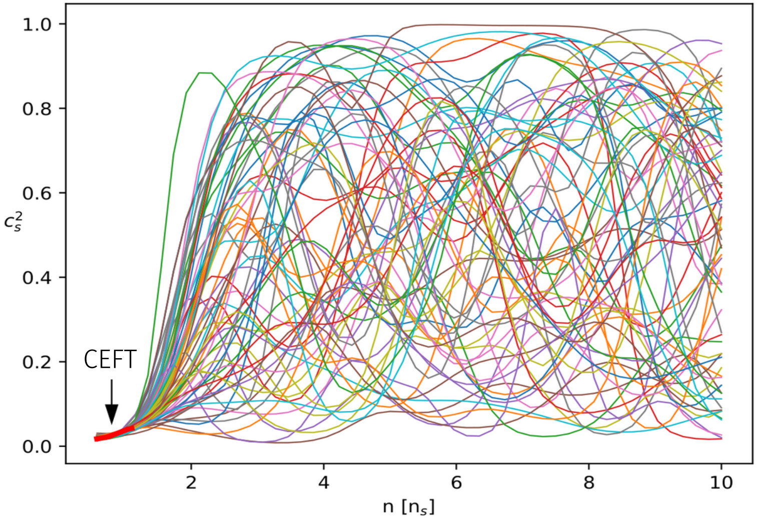
Two approaches to EoS Inference

Parametric interpolation



Annala, TG, Kurkela, Nättilä, Vuorinen. Nature Phys. 16.9 (2020)
Annala, TG, Katerini, Kurkela, Nättilä, Paschalidis, Vuorinen. PRX 12.1 (2022)

Gaussian process regression

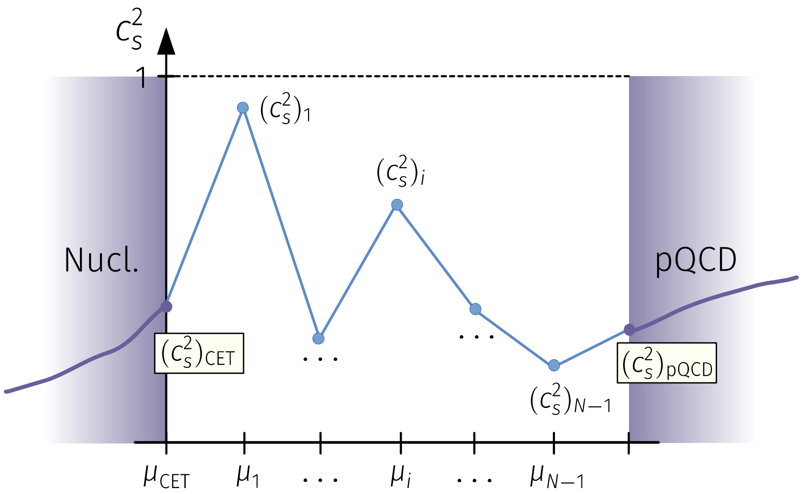


Following Landry & Essick Phys. Rev. D 99 (2019)

TG, Komoltsev, Kurkela, 2204.11877, accepted to ApJ

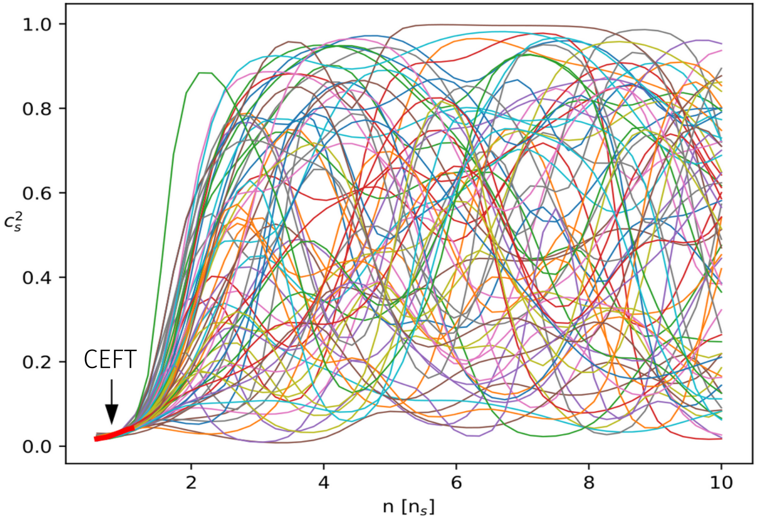
Two approaches to EoS Inference

Parametric interpolation



Cons: Lose many parameters interpolating from 10-40n_s.

Gaussian process regression

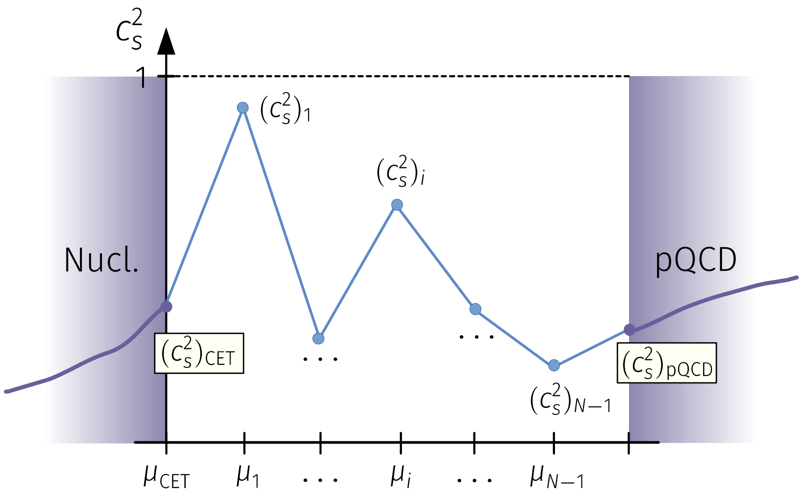


Following Landry & Essick Phys. Rev. D 99 (2019)

TG, Komoltsev, Kurkela, 2204.11877, accepted to ApJ

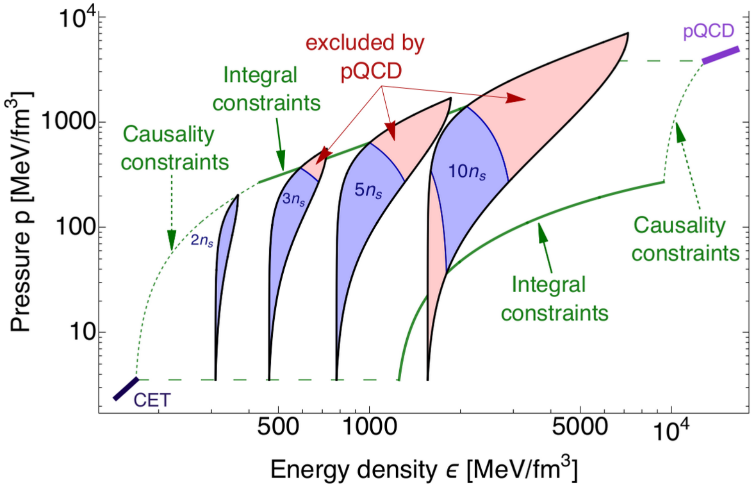
Two approaches to EoS Inference

Parametric interpolation



Cons: Lose many parameters interpolating from 10-40n_s.

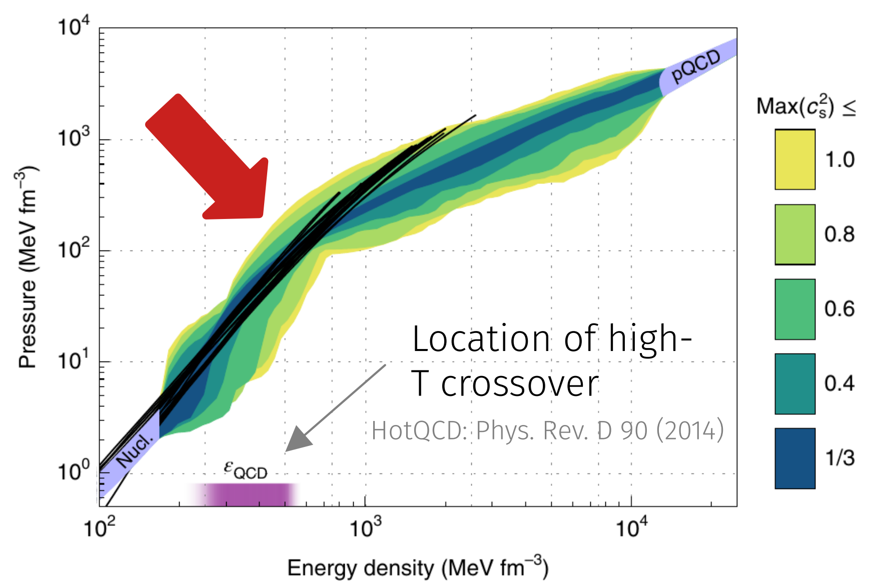
Gaussian process regression

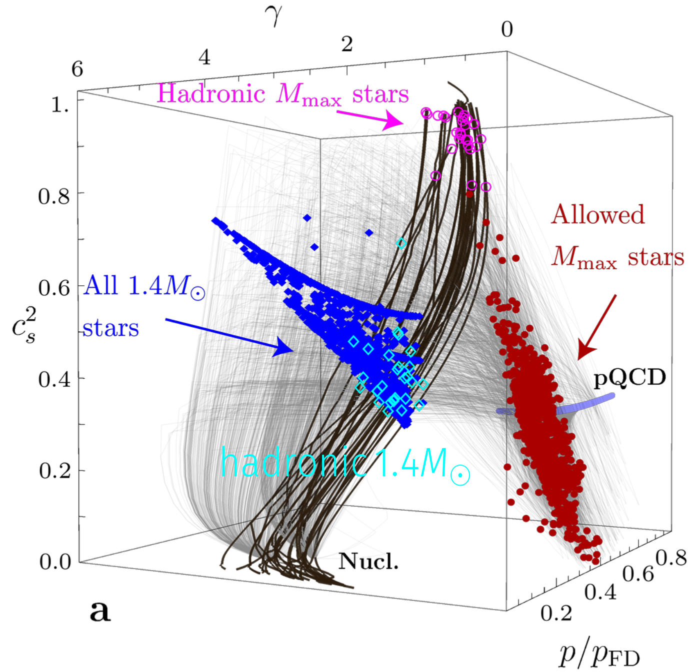


Use Komoltsev and Kurkela, PRL 128 (2022) to impose most general ε,p region consistent with pQCD at 10n_s.

Using hard cuts gave evidence for transition

Annala, TG, Kurkela, Nättilä, and Vuorinen. Nature Phys. 16.9 (2020)





Previous evidence for non-conformal to conformal transition, based on $\gamma \equiv \mathrm{d}\ln p/\mathrm{d}\ln \varepsilon$

Also indicated by recent analysis of trace anomaly in Fujimoto, Fukushima, McLerran, Praszałowicz. PRL 129 (2022); Marczenko, McLerran, Redlich, Sasaki PRC 107 (2023)

- $1.4M_\odot$ stars ***consistent*** with cores of hadronic $1.4M_\odot$
- (most) $M_{\rm max}$ stars ***inconsistent*** with centers of hadronic $M_{\rm max}$

Full Bayesian analysis quantifies P(conformal)

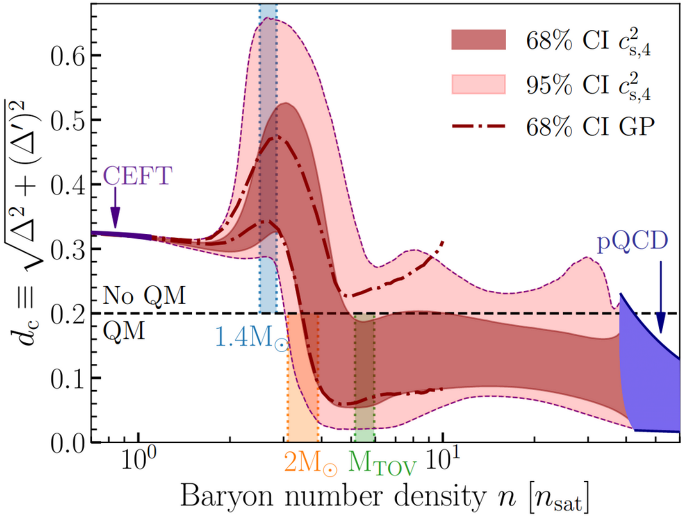
Annala, TG, Hirvonen, Komoltsev, Kurkela, Nättilä, Vuorinen 2303.11356

After folding in measurements of high-mass pulsars, GW observations, and X-ray observations, the new conformal measure d_c shows striking behavior inside neutron stars.

P(conformal) = 88% (75%) for the parametric (GP) approach, for TOV stars. (GP without pQCD is 50%).

Criterion is much stricter than previous work. (Would have found 99.8% previously.)

See also: Han, Huang, Tang, Fan+ arXiv:2207.13613



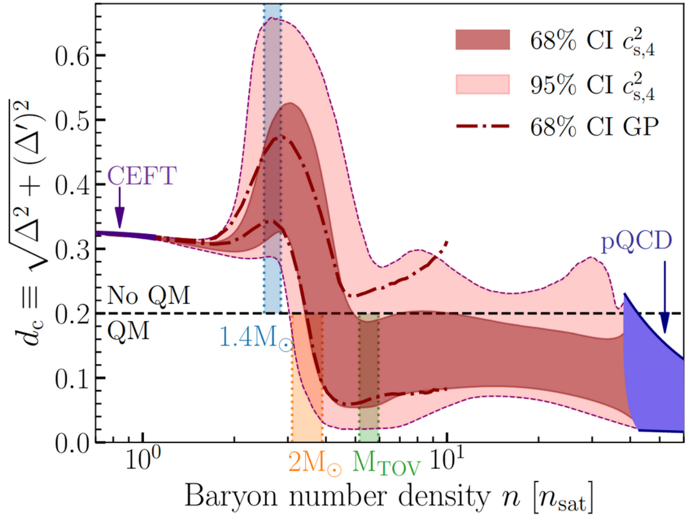
Full Bayesian analysis quantifies P(conformal)

Annala, TG, Hirvonen, Komoltsev, Kurkela, Nättilä, Vuorinen 2303.11356

After folding in measurements of high-mass pulsars, GW observations, and X-ray observations, the new conformal measure d_c shows striking behavior inside neutron stars.

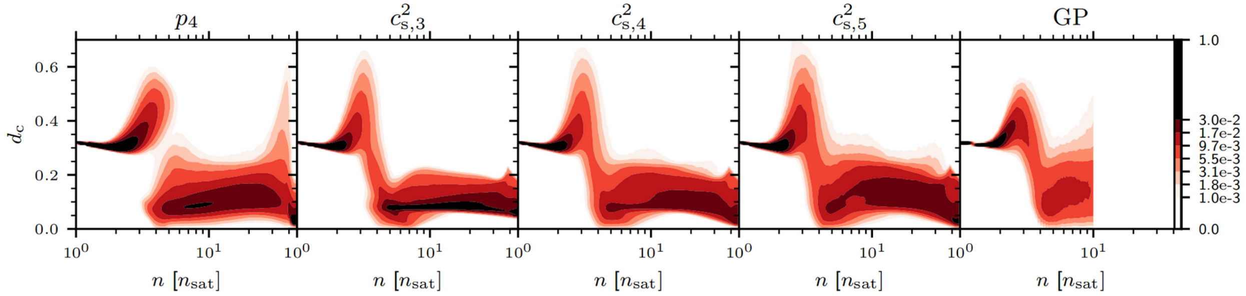
P(conformal) = 88% (75%) for the parametric (GP) approach, for TOV stars. (GP without pQCD is 50%).

Criterion is much stricter than previous work. (Would have found 99.8% previously.)



See also: Han, Huang, Tang, Fan+ arXiv:2207.13613

Robust to interpolants:

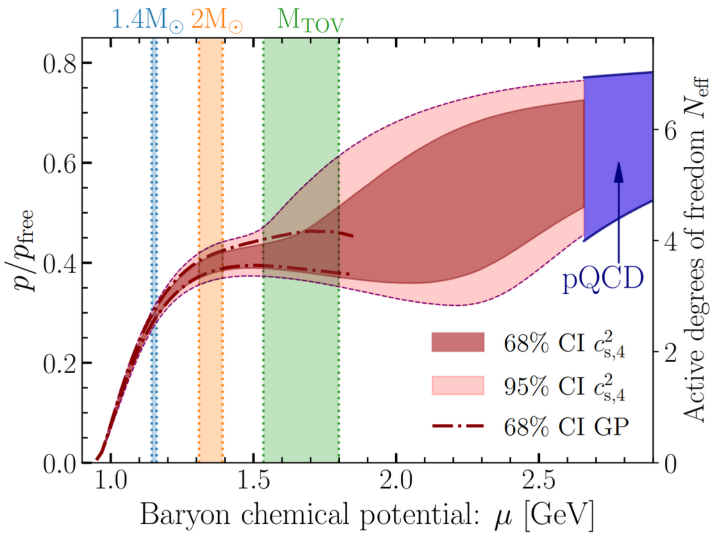


Is it Quark matter?

Annala, TG, Hirvonen, Komoltsev, Kurkela, Nättilä, Vuorinen 2303.11356

Active degrees of freedom N_{eff} comparable to number in quark matter at high density (roughly 2/3) – **suggests: Yes, QM**

“It is, however, interesting to ask whether the slightly reduced value of the quantity within maximally massive NSs may signal that matter in these stellar cores features strongly-coupled characteristics.”

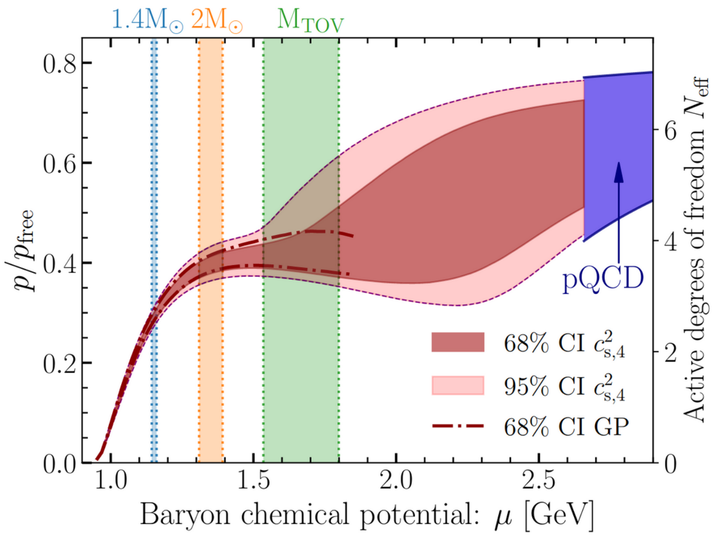


Is it Quark matter?

Annala, TG, Hirvonen, Komoltsev, Kurkela, Nättilä, Vuorinen 2303.11356

Active degrees of freedom N_{eff} comparable to number in quark matter at high density (roughly 2/3) – **suggests: Yes, QM**

"It is, however, interesting to ask whether the slightly reduced value of the quantity within maximally massive NSs may signal that matter in these stellar cores features strongly-coupled characteristics."



Also desirable to find other observables, arguments that support or contradict this EoS evidence for deconfined matter

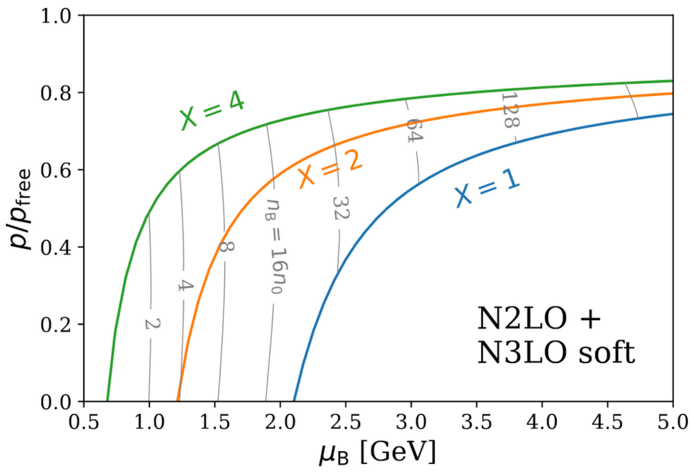
Statistical treatment of pQCD errors

TG, Komoltsev, Kurkela, Mazeliauskas 2303.02175

Estimates of truncation errors in pQCD

TG, Komoltsev, Kurkela, Mazeliauskas 2303.02175

Heretofore have estimated pQCD errors by varying renormalization scale $X = \bar{\Lambda}/\mu_B$, but this is just a proxy



Estimates of truncation errors in pQCD

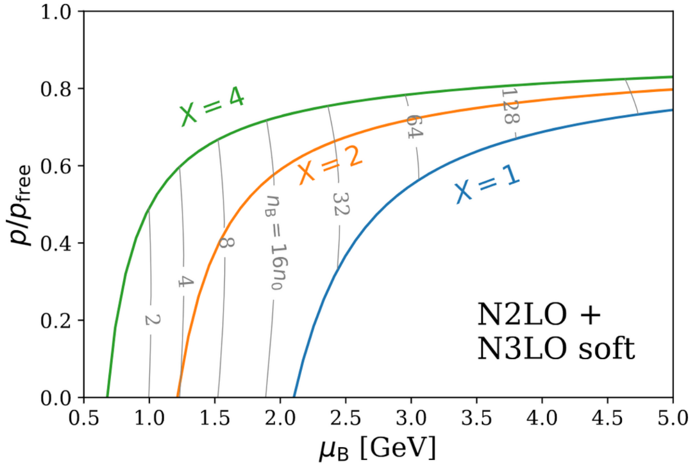
TG, Komoltsev, Kurkela, Mazeliauskas 2303.02175

Heretofore have estimated pQCD errors by varying renormalization scale $X = \overline{\Lambda}/\mu_B$, but this is just a proxy

Decided to investigate using a Bayesian framework, **assuming the perturbative coefficients are independent draws from distributions of a statistical model of convergent series**.

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

Performing Bayesian inference on the known orders constrains the model parameters and returns a probability distribution for the next term in the series.



The *abc* model of convergent series

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

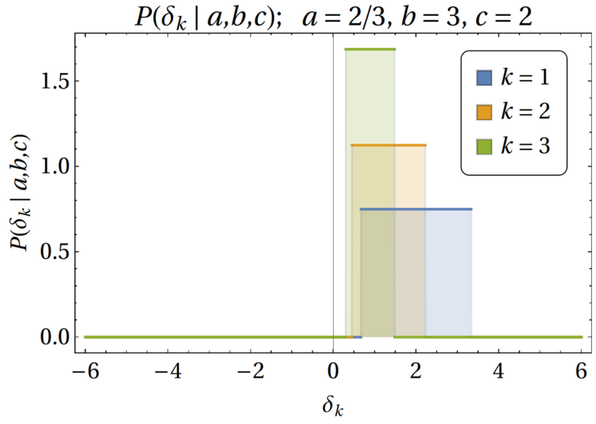
Consider a perturbative sequence, normalized by the LO term

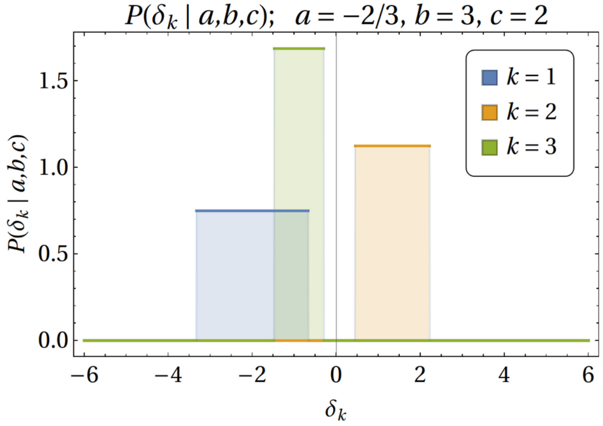
$$\delta_k \equiv \frac{\alpha^k O_k}{O_0} \quad (\delta_0 = 1)$$

The model assumes that these δ_k are bounded by some geometric series defined by (a, b, c)

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

Take flat likelihoods on all δ_k satisfying this equation. (*also specify a prior for *a, b, c* which favor smaller values of $|a|$, b, c)





*geo model defined by 2 parameters, with $c = 0$

Bayesian inference of the next term in the pressure

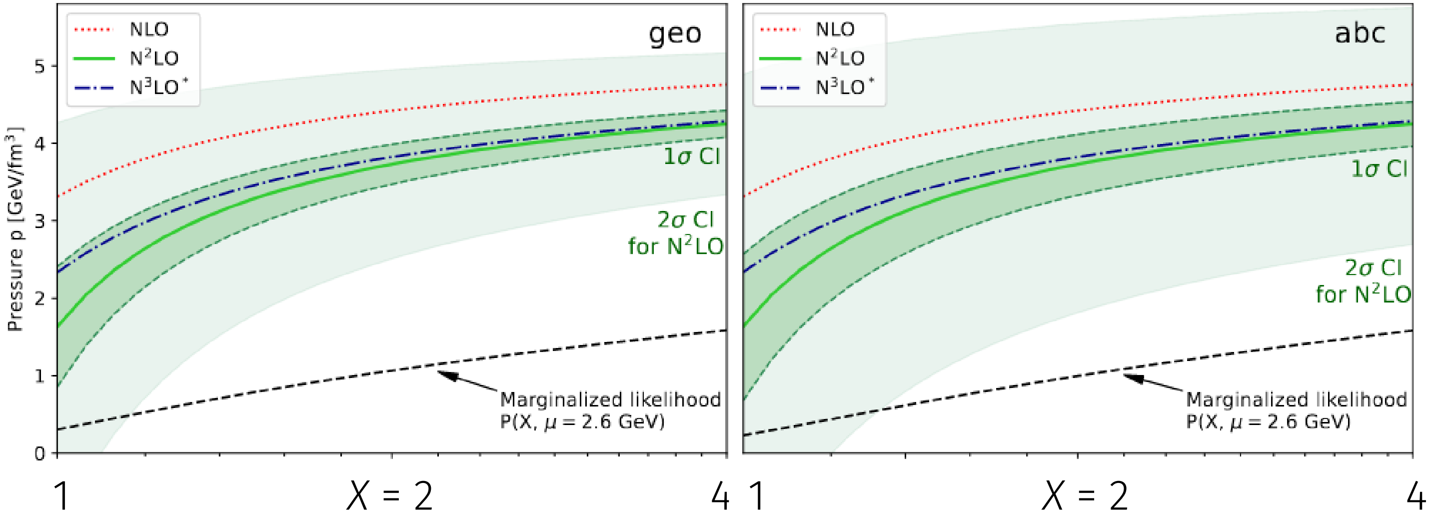
1. $P(\vec{\delta}_k|abc) = \prod_{n=0}^{k} P(\delta_n|abc)$ (What is the likelihood of the current terms?)

2. $P(\vec{\delta}_k) \equiv \int dadbdc P(\vec{\delta}_k|abc) P_0(abc)$ (marginal likelihood / evidence)

3. $P(abc|\vec{\delta}_k) = \frac{P(\vec{\delta}_k|abc) P_0(abc)}{P(\vec{\delta}_k)}$ (Bayes theorem; posterior of model parameters)

4. $P(\delta_{k+1}|\vec{\delta}_k) \equiv \int dadbdc P(\delta_{k+1}|abc) P(abc|\vec{\delta}_k) = \frac{P(\vec{\delta}_{k+1})}{P(\vec{\delta}_k)}$ (Prediction for next term)

Bayesian inference of the next term in the pressure



Posteriors for p for different perturbative orders, as function of X, with $\mu_B = 2.6$ GeV

Incorporating the scale dependence

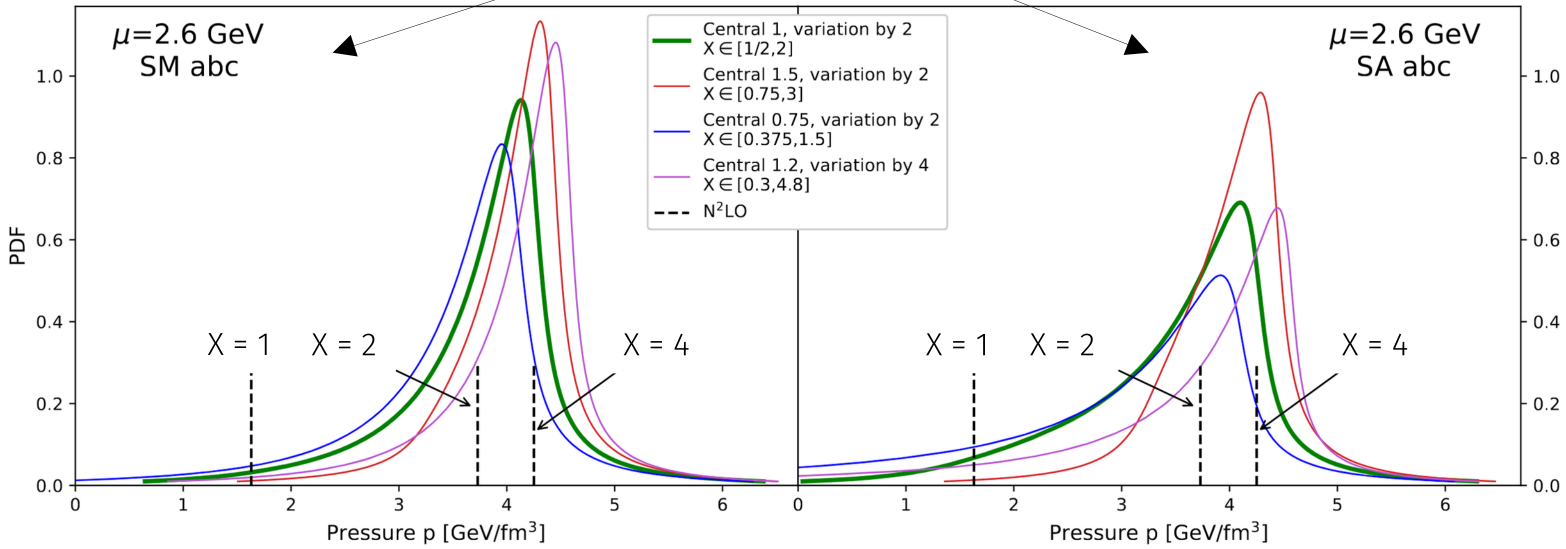
1. **Scale Averaging** :

Treat all log(X) in some interval as equally likely

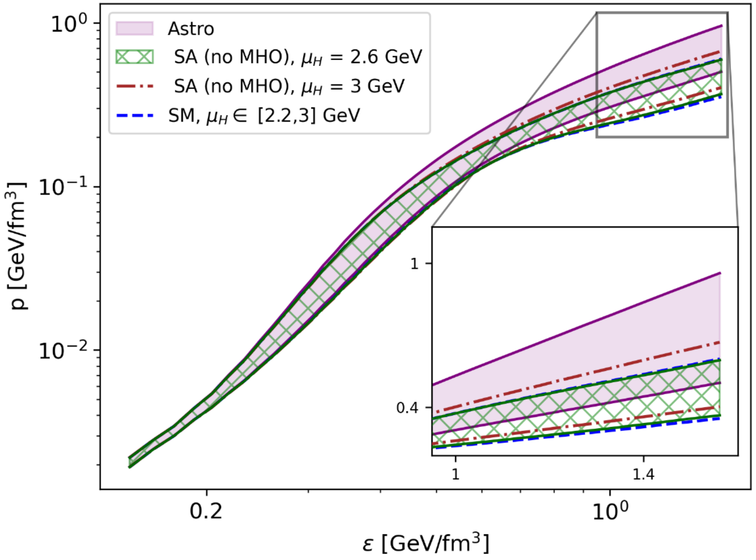
We used this in Gorda, Komoltsev, Kurkela 2204.11877 (accepted to ApJ)

2. **Scale Marginalization** :

Weight different X by likelihood of X



In the end, the effect on the NS EoS inference is small



Takeaway: Impact of pQCD input insensitive to the exact treatment of the X dependence (and even the matching μ_{pQCD})

Outlook and future directions

Ongoing work to improve pQCD to full N3LO

TG, Paatelainen, Säppi, Seppänen (Ongoing work)

Organized the N3LO into kinematic sectors:

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

Soft computed in 2021, and now the gluon screening at NLO was computed last month

TG, Kurkela, Paatelainen, Säppi, Vuorinen, PRL 127, 162003 (2021)
TG, Paatelainen, Säppi, Seppänen, 2304.09187.

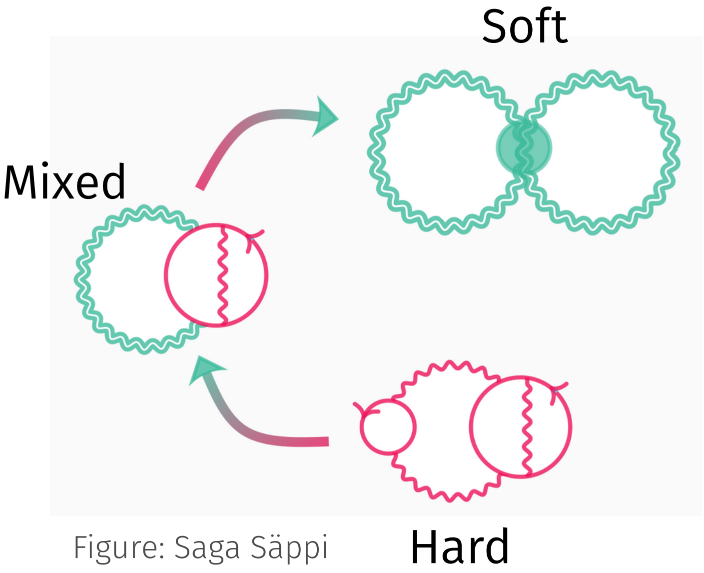


Figure: Saga Säppi

Mixed contribution is on overleaf :)

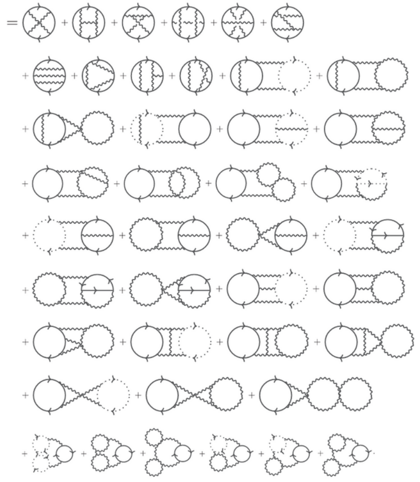
Ongoing work to improve pQCD to full N3LO

TG, Paatelainen, Säppi, Seppänen (Ongoing work)

$$\frac{p}{p_{\rm free}} = 1 - 2\left(\frac{\alpha_s}{\pi}\right) - \left(\frac{\alpha_s}{\pi}\right)^2 \left[3\ln\left(6\frac{\alpha_s}{\pi}\right) + 9\ln\frac{\overline{\Lambda}}{2\mu} + 12.9268\right]$$
$$+ \left(\frac{\alpha_s}{\pi}\right)^3 \left[c_{3,2}\ln^2\left(6\frac{\alpha_s}{\pi}\right) + c_{3,1}(\overline{\Lambda})\ln\left(6\frac{\alpha_s}{\pi}\right) + c_{3,0}(\overline{\Lambda})\right] + O(\alpha_s^4),$$

TG, Kurkela, Romatschke, Säppi, Vuorinen Phys. Rev. Lett. 121 (2018)

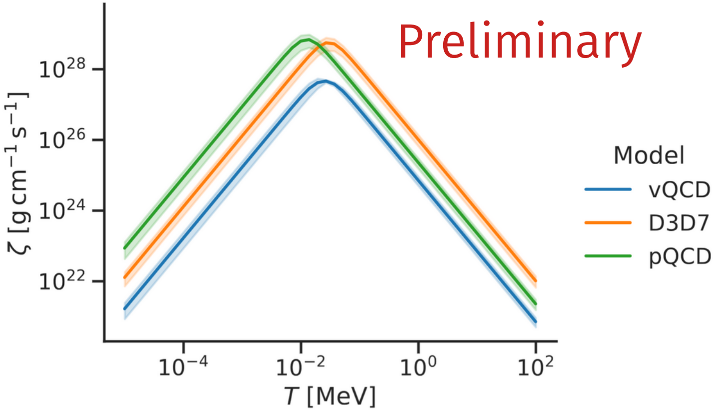
Overleaf :) Looks surprisingly big



Clearly requires sophisticated techniques

Ongoing/Future directions

Transport Properties

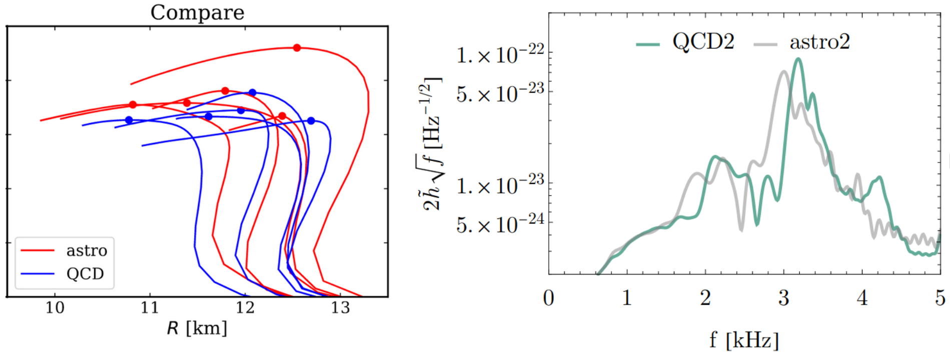


Bulk viscosity in unpaired quark matter

Ongoing work with Cruz Rojas, TG Hoyos, Jokela, Järvinen, Kurkela, Paatelainen, Säppi, Vuorinen

Impact of the pQCD input on postmerger dynamics

Preliminary



Representative “astro” and “astro+QCD” EOSs, effects on waveforms etc.

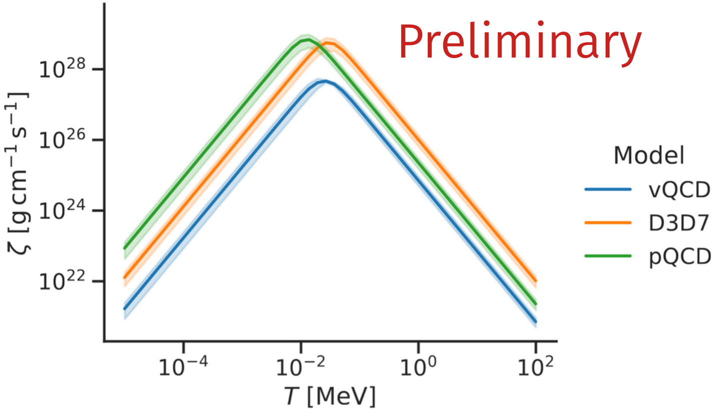
Ongoing work with Ecker, Kurkela, Rezzolla

Ongoing/Future directions

Also looking into pairing effects in pQCD

Ongoing work with Braun, Geissel

Transport Properties

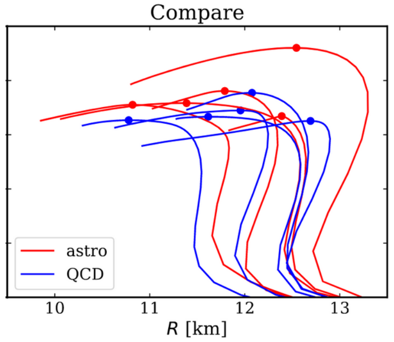


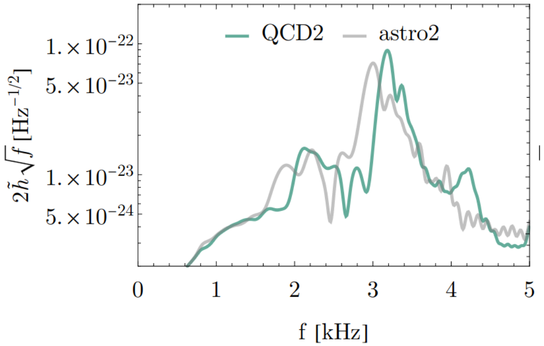
Bulk viscosity in unpaired quark matter

Ongoing work with Cruz Rojas, TG Hoyos, Jokela, Järvinen, Kurkela, Paatelainen, Säppi, Vuorinen

Impact of the pQCD input on postmerger dynamics

Preliminary





Representative "astro" and "astro+QCD" EOSs, effects on waveforms etc.

Ongoing work with Ecker, Kurkela, Rezzolla

Summary…

- Bayesian EOS analysis suggests conformal matter in the cores of massive NSs is likely, number of DOF points to quark matter.

  Other observables / arguments to support (or contradict!) this evidence? (Transport properties…?)

- Have completed a **statistical analysis of the truncation errors** of the pQCD input—**find that they do not strongly affect the NS-EOS analysis**

And outlook…

- Ongoing work to improve pQCD, pushing to full N3LO pressure

- Working on finite-*T*, dynamic regime, for applications to merger simulations, and the post-merger phase, and thinking about pairing effects in pQCD

Summary…

- **Bayesian EOS analysis suggests conformal matter in the cores of massive NSs is likely, number of DOF points to quark matter.**

  Other observables / arguments to support (or contradict!) this evidence? (Transport properties…?)

- Have completed a **statistical analysis of the truncation errors** of the pQCD input—**find that they do not strongly affect the NS-EOS analysis**

And outlook…

- Ongoing work to improve pQCD, pushing to full N3LO pressure

- Working on finite-*T*, dynamic regime, for applications to merger simulations, and the post-merger phase, and thinking about pairing effects in pQCD

Thanks for your attention!