The Equation of State of strongly interacting matter

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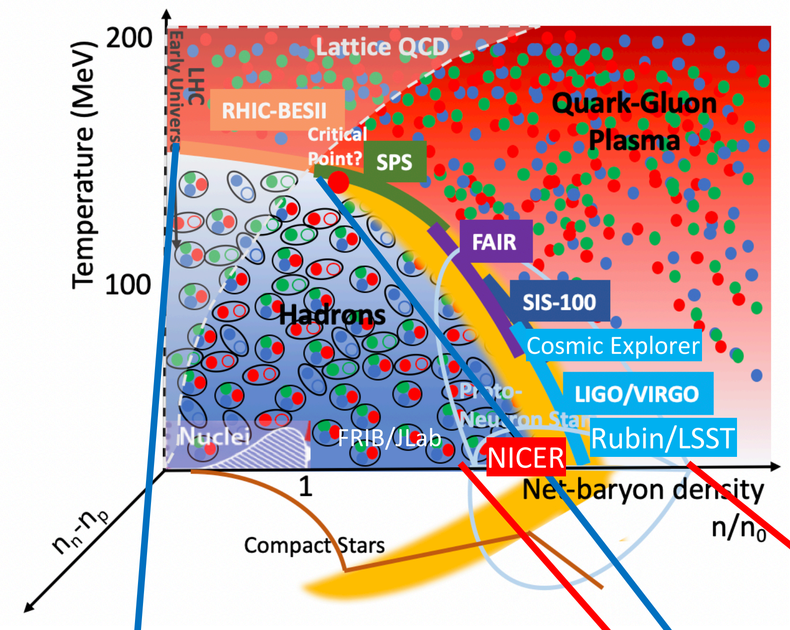
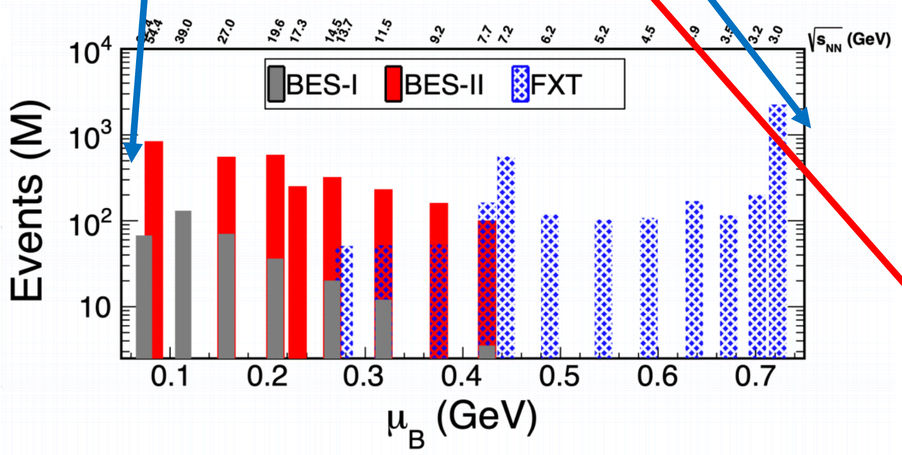
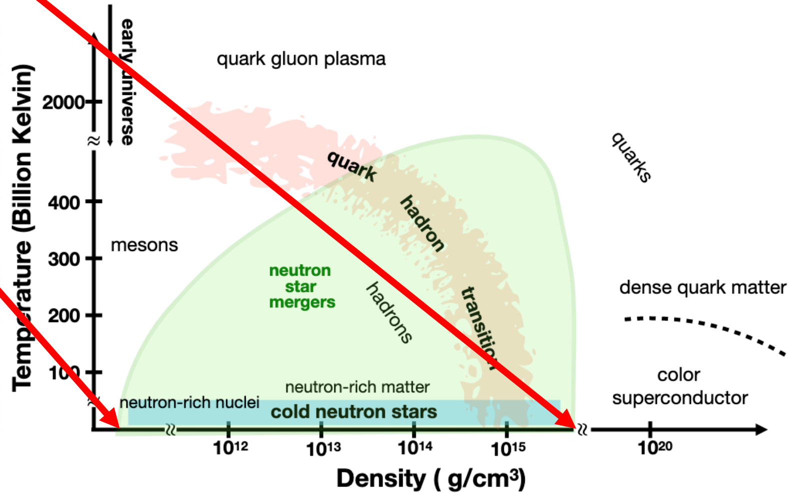
Motivating science goals

- Is there a critical point in the QCD phase diagram?
- What are the degrees of freedom in the vicinity of the phase transition?
- Where is the transition line at high density?
- What are the phases of QCD at high density?
- What is the nature of matter in the core of neutron stars?



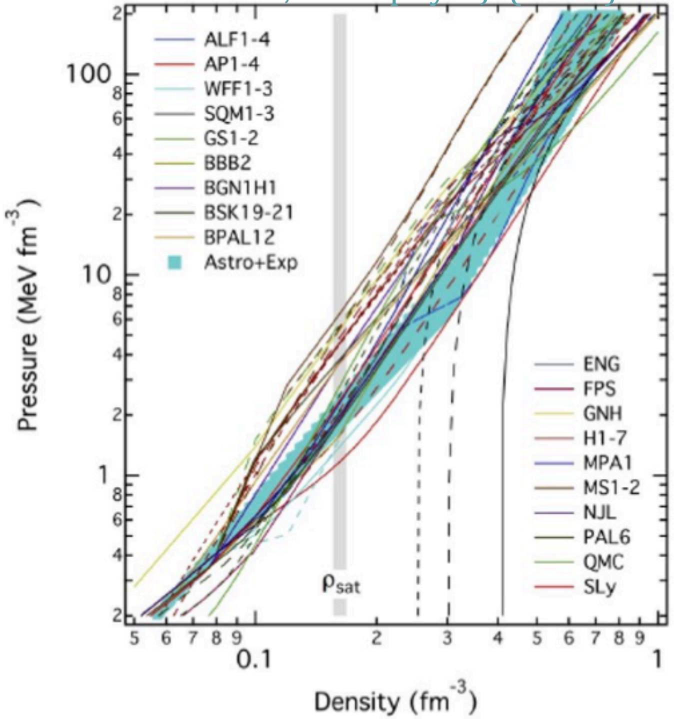
- Run 2019:
  - Collider: $\sqrt{s_{NN}}$=14.6, 19.6, 200 GeV
  - Fixed target: $\sqrt{s_{NN}}$=3.2 GeV
- Run 2020:
  - Collider: $\sqrt{s_{NN}}$=9.2, 11.5 GeV
  - Fixed target: $\sqrt{s_{NN}}$=3.5, 3.9, 4.5, 5.2, 6.2, 7.2, 7.7 GeV
- Run 2021:
  - Collider: $\sqrt{s_{NN}}$=7.7, 17.3 GeV
  - Fixed target: $\sqrt{s_{NN}}$=3.0, 9.2, 11.5, 13.7 GeV

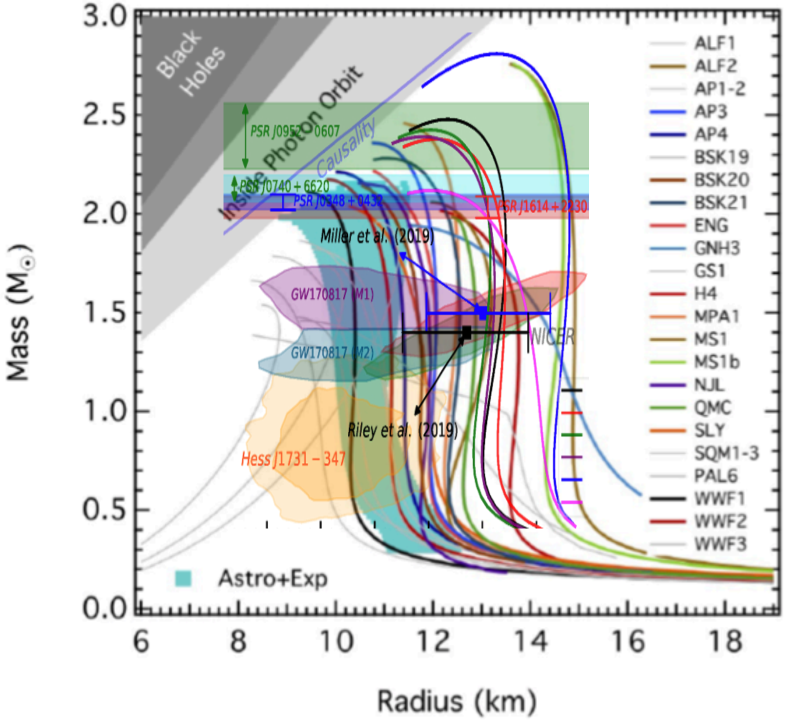




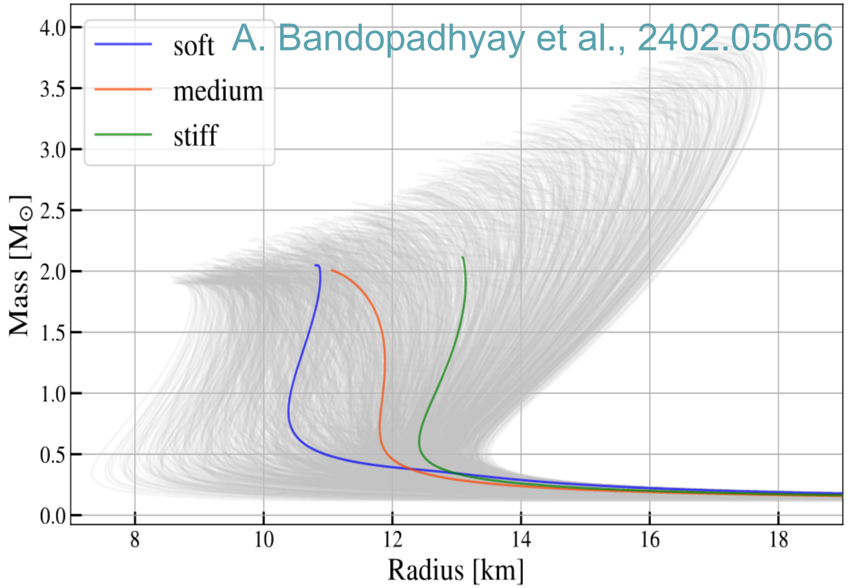
Neutron star mass/radius

F. Ozel et al., Astrophys. J. (2016)





A. Bandopadhyay et al., 2402.05056

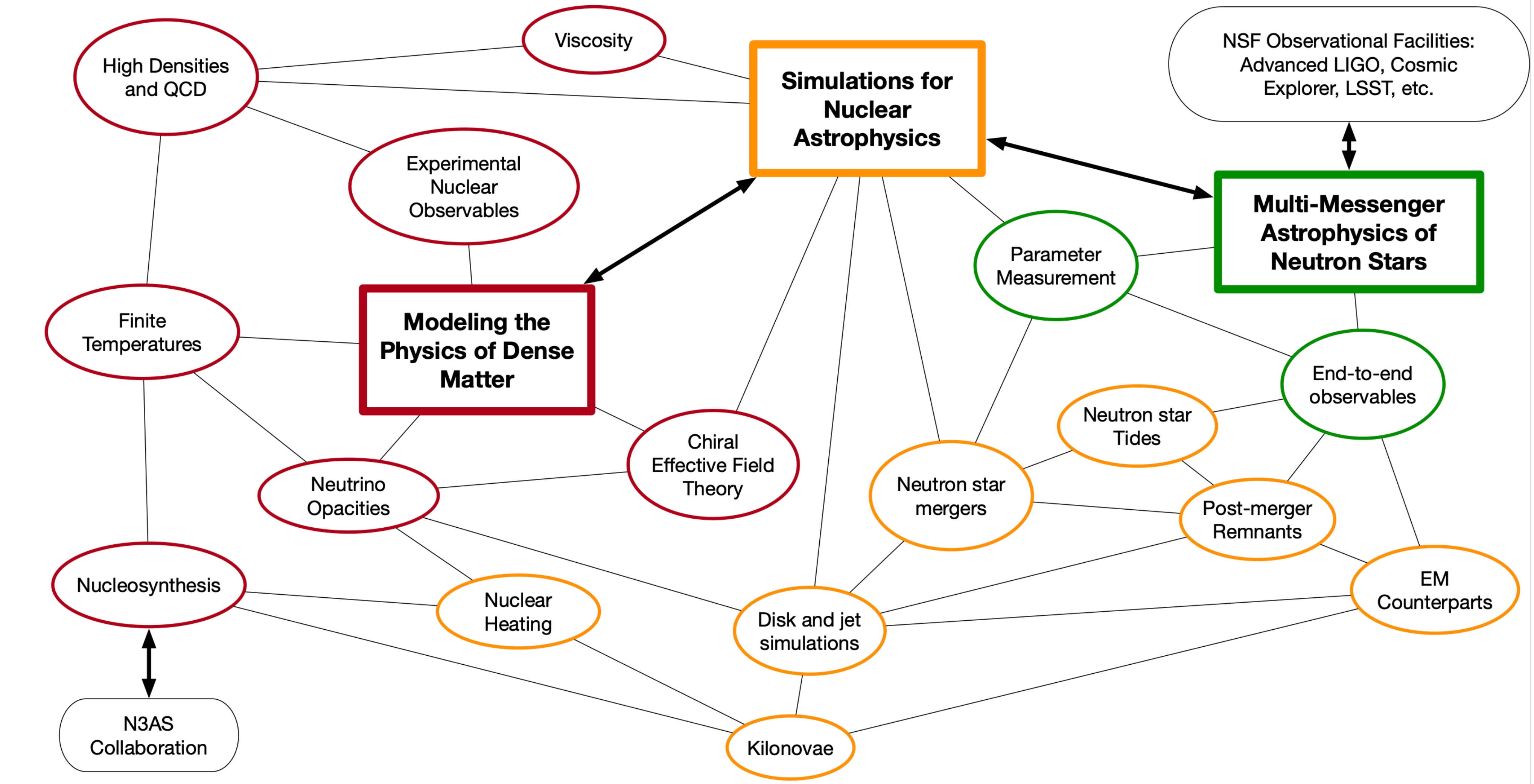


Detector network	Soft EoS	Medium EoS	Stiff EoS
LIGO-Virgo	$2e5^{+4e4}_{-4e4}$	$5e4^{+1e4}_{-1e4}$	7000^{+900}_{-900}
3 $A^\sharp$	300^{+50}_{-50}	100^{+40}_{-40}	20^{+4}_{-4}
CE20	21^{+10}_{-10}	15^{+7}_{-7}	3^{+1}_{-1}
CE40	12^{+3}_{-3}	8^{+1}_{-1}	$1^{+0.6}_{-0.6}$
CE40+2 $A^\sharp$	9^{+4}_{-4}	6^{+2}_{-2}	$0.4^{+0.2}_{-0.2}$
CE40+CE20+$A^\sharp$	5^{+2}_{-2}	3^{+1}_{-1}	$0.2^{+0.07}_{-0.07}$

- Current uncertainty on NS radius measurements are large
- CE network will achieve an uncertainty of 10 m very quickly
- Narrowing down the equation of state still requires understanding the underlying nuclear physics

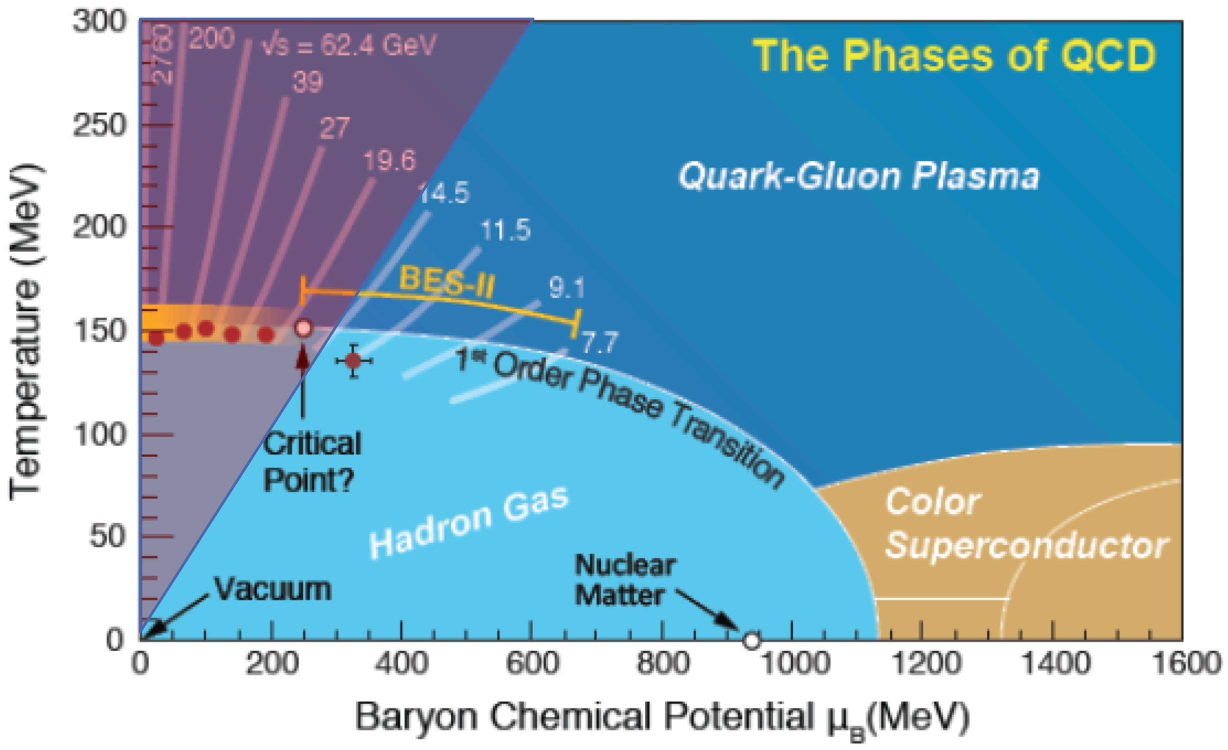
The Problem is Too Big For One Group

Progress needs a **close, coordinated, and sustained** collaboration across different research groups



Range of validity of Taylor-expanded equation of state from first principles

- The theory of strong interactions cannot be solved at finite chemical potential μ_B (sign problem)
- One can perform simulations at $\mu_B=0$ and expand them to finite density
- Taylor-expanded equation of state covers the range $\mu_B/T\leq 2$



Novel expansion method

WB: S. Borsanyi, C. R. et al, PRL (2021), PRD (2022)

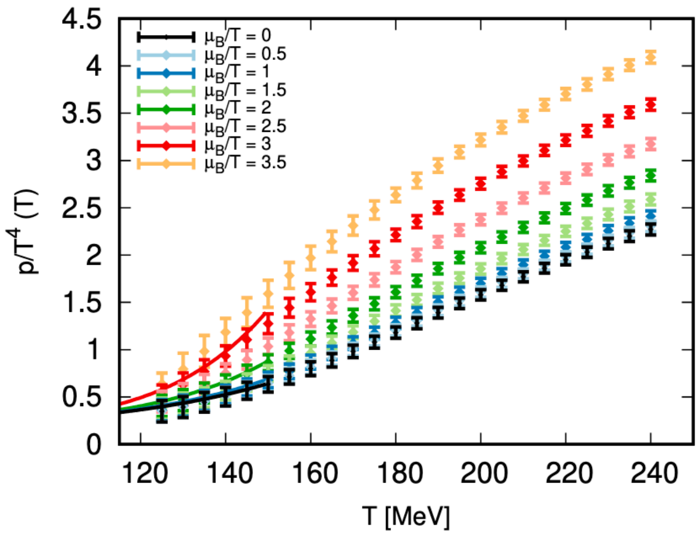
Observation: the temperature-dependence of baryonic density

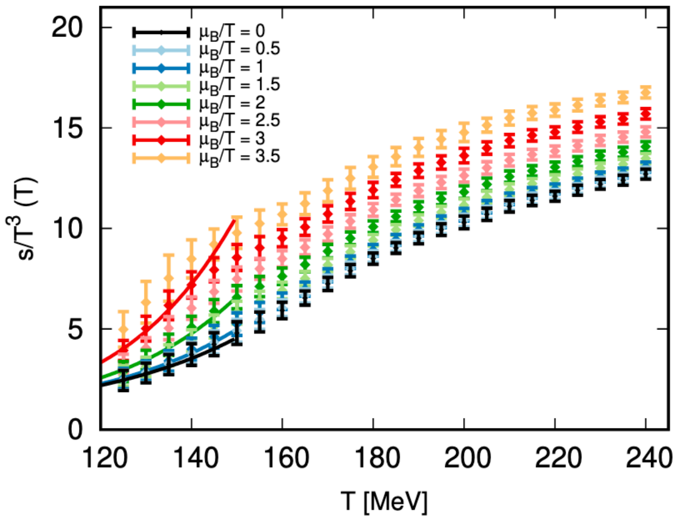
$$n_B(T)/\hat{\mu}_B = \chi_1^B(T,\hat{\mu}_B)/\hat{\mu}_B$$

at finite imaginary chemical potential is just a shift in temperature from the $\mu_B = 0$ results for χ_2^B :

$$\frac{\chi_1^B(T,\hat{\mu}_B)}{\hat{\mu}_B} = \chi_2^B(T',0) ,$$

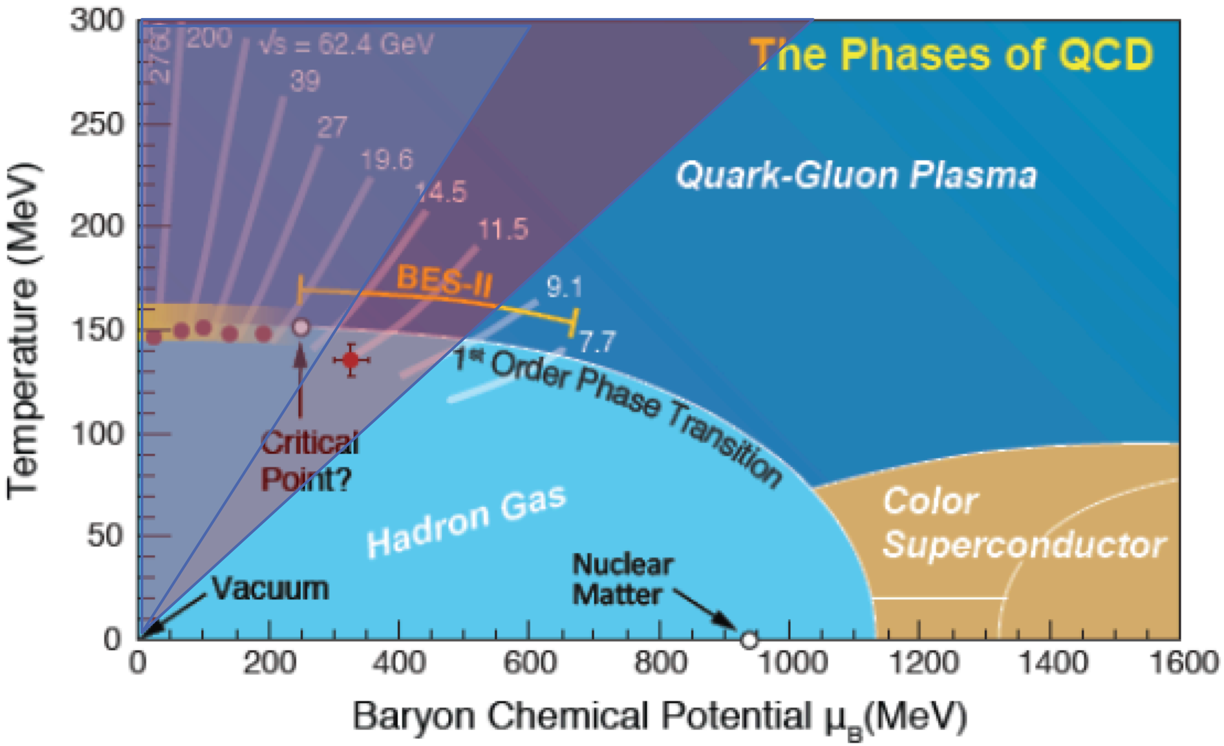
$$T'(T,\hat{\mu}_B) = T\left(1 + \kappa_2^{BB}(T)\hat{\mu}_B^2 + \kappa_4^{BB}(T)\hat{\mu}_B^4 + \mathcal{O}(\hat{\mu}_B^6)\right)$$





New range of validity of equation of state

- New expansion scheme provides the equation of state for $\mu_B/T \leq 3.5$

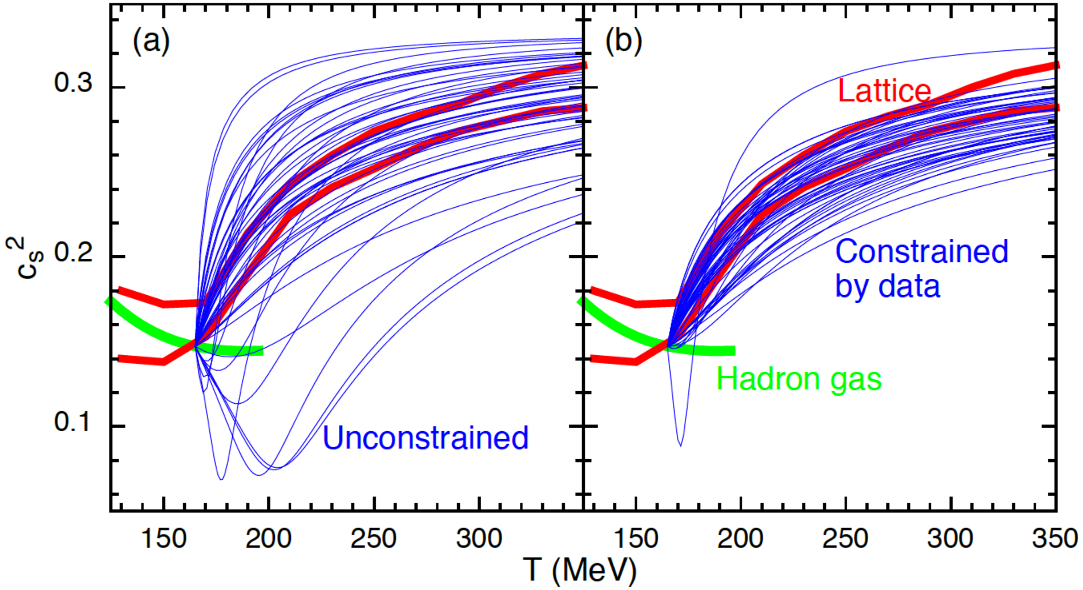


- This expansion scheme is now being extended to finite μ_S and μ_Q
- Results will be the state-of-the-art EoS from first principles
- Will be used to constrain models for high density matter

Lessons from heavy-ion collisions I

- Extract EoS from data through Bayesian analyses

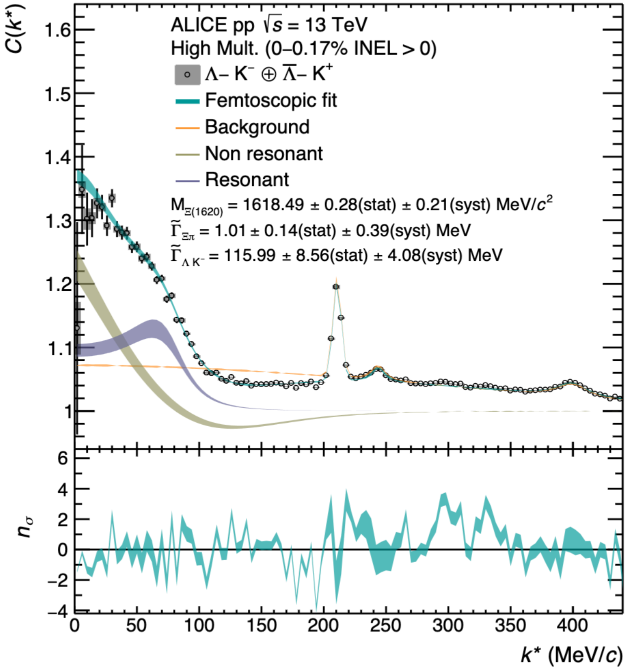
S. Pratt et al., PRL (2015)



- Comparison of data from HICs to theoretical models through Bayesian analysis
- The posterior distribution of EoS is consistent with the lattice QCD one

- Extract hadronic interactions from data

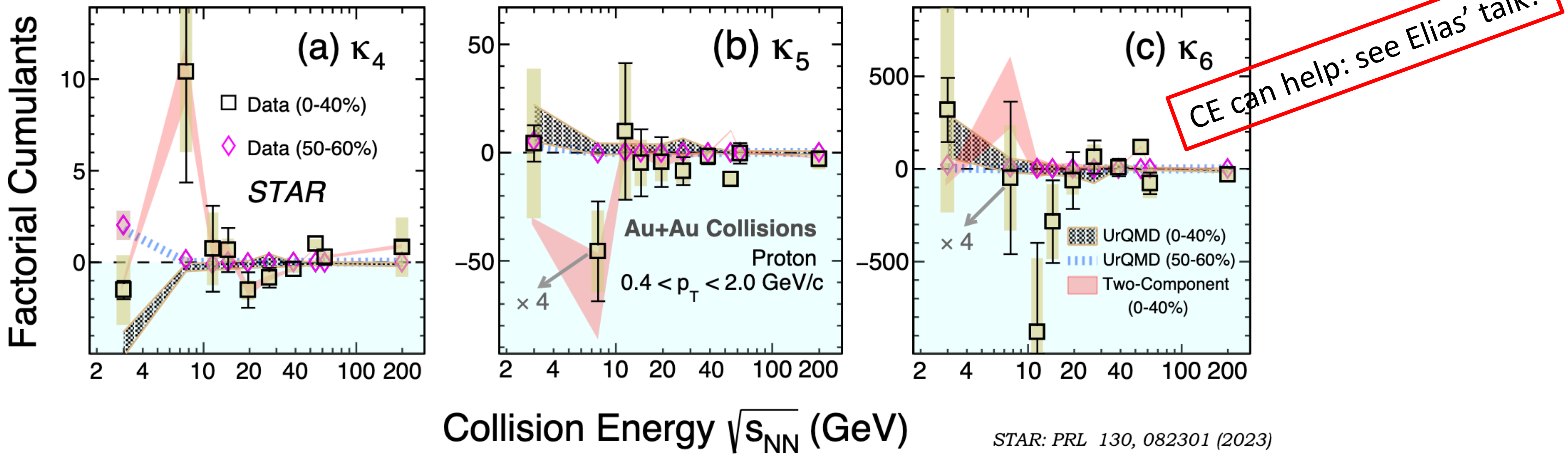
ALICE, PLB (2023)



- Access interaction between Λ and kaons with femtoscopy at the LHC

Lessons from heavy-ion collisions II

- Lowest collision energy at RHIC: 3 GeV in fixed target mode (μ_B~750 MeV)
- Results show that the system is purely hadronic



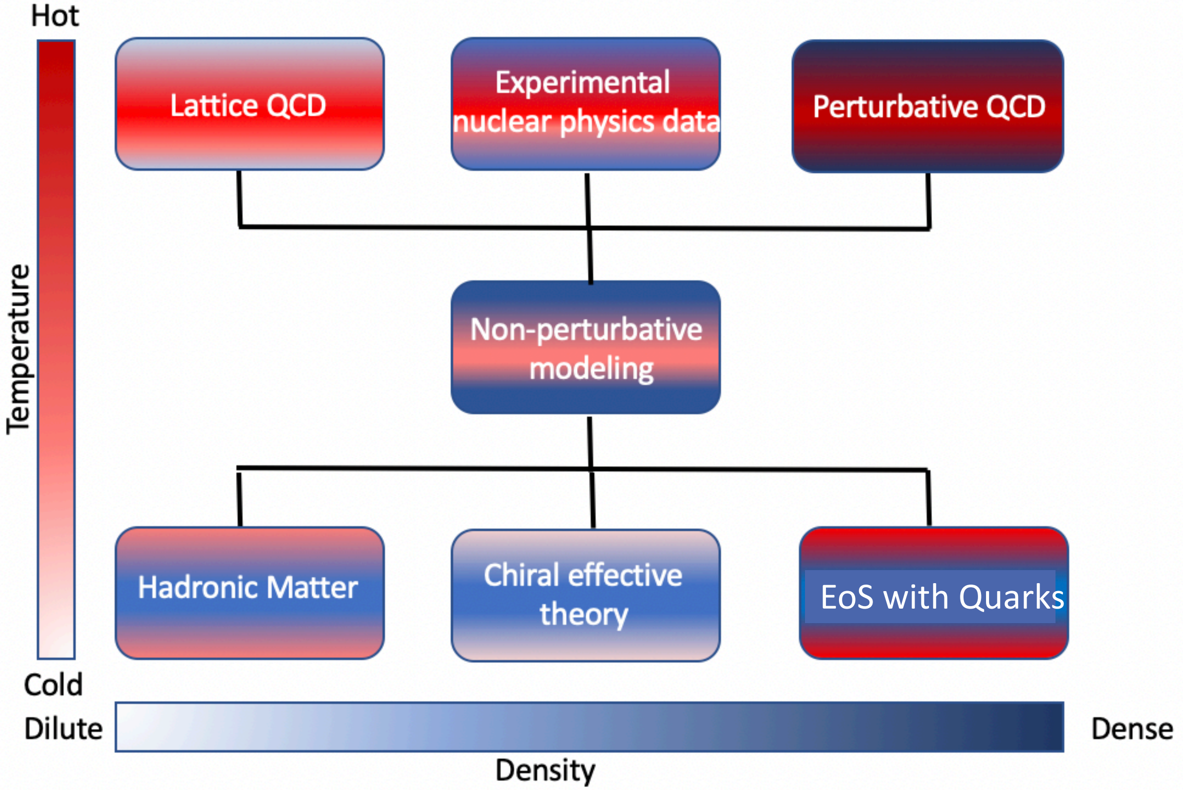
STAR: PRL 130, 082301 (2023)

- If the critical point sits at μ_B>750 MeV, it cannot be seen in terrestrial experiments

Connecting High and Low Temperature QCD

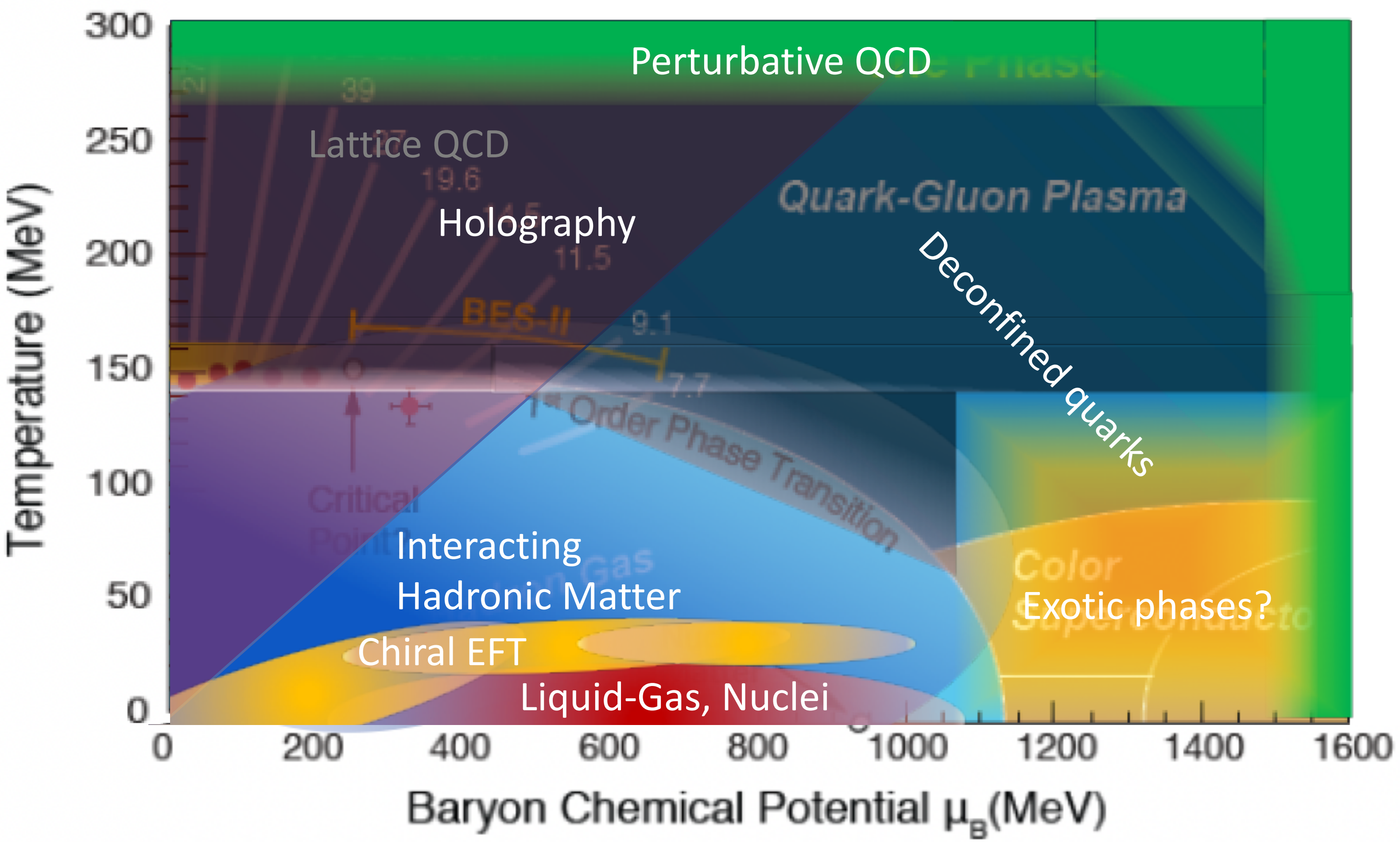
Using lessons learned from heavy-ion collisions

- Calculate lattice QCD equation of state, diagonal and off-diagonal fluctuations at small density
- Use them to constrain quantum many-body theory, accounting for quantum effects
- Apply these non-perturbative techniques in models with quark and gluon degrees of freedom, further constraining them with heavy-ion data



What happens at large densities?

- We need to merge the lattice QCD equation of state with other effective theories
- Careful study of their respective range of validity
- Constrain the parameters to reproduce known limits
- Test different possibilities and validate/exclude them

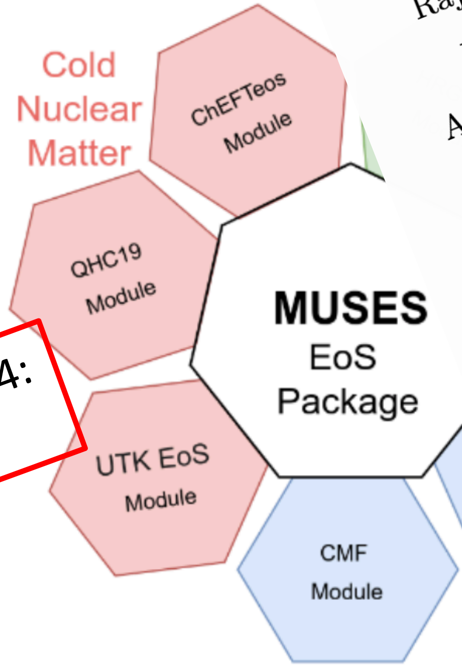


Lattice QCD: WB: PRL (2021)
Interacting HRG: V. Vovchenko et al., PRL (2017)
Liquid-gas, Nuclei: UTK EoS (Steiner)
Chiral EFT: see e.g. Holt, Kaiser, PRD (2017)
Holography: see e.g. J. Grefa et al., PRD (2021)

pQCD: Andersen et al., PRD (2002); Annala et al., Nat. Ph. (2020)
quarks: T-matrix approach (R. Rapp)
CMF model (V. Dexheimer)
Exotic phases: e.g. S. Sen and L. Sivertsen, Astrophys. J (2021)

MUSES goals and milestones

- CyberInfrastructure of interoperating tools and services wit
  - Upgrade of existing calculation tools to modern
  - **Equation of State (EoS) package** that co
  - **Web-based tools and services** th
  - **Job management system** tha
  - Scalable, high-availability **depl**



α-release in May 2024: stay tuned!

Theoretical and Experimental Constraints for the Equation of State of Dense and Hot Matter

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(MUSES Collaboration)

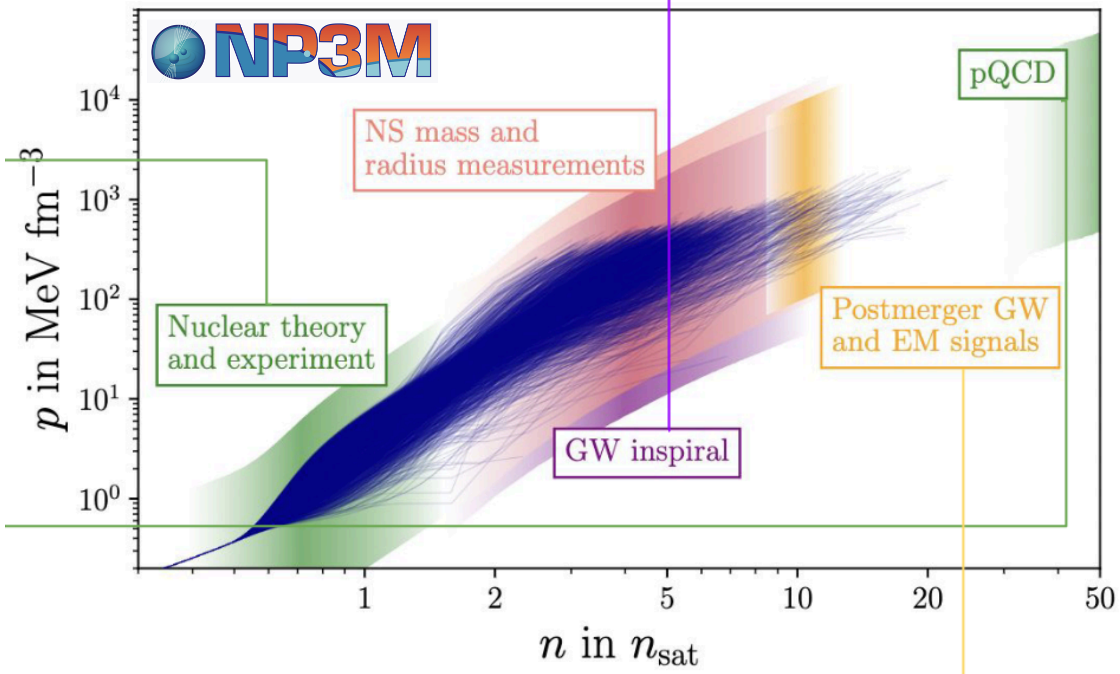
Accepted for publication on Living Reviews in Relativity

EoS constraints

Elias' talk!

- Neutron Star observations can constrain the EoS

Koehn et al., 'In preparation'



Somasundaram, Suleiman and Tews, in preparation