CSQCD 2024, KYOTO

Constraining Quark Matter in Neutron Stars

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08/10/24: Yukawa Hall, YITP

IUCAA

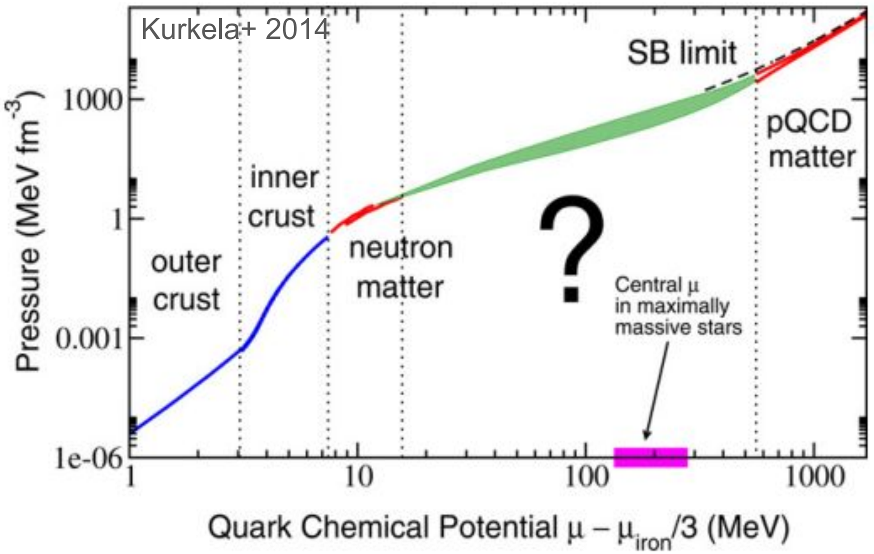
In collaboration with:
Suprovo Ghosh,
Prof. Debarati Chatterjee

LISC
LIGO–India Scientific Collaboration

LSC
LIGO Scientific Collaboration

GOAL

1) Constrain Quark Matter (QM) model and hybrid equation of state (EoS) using multi-disciplinary physics constraints



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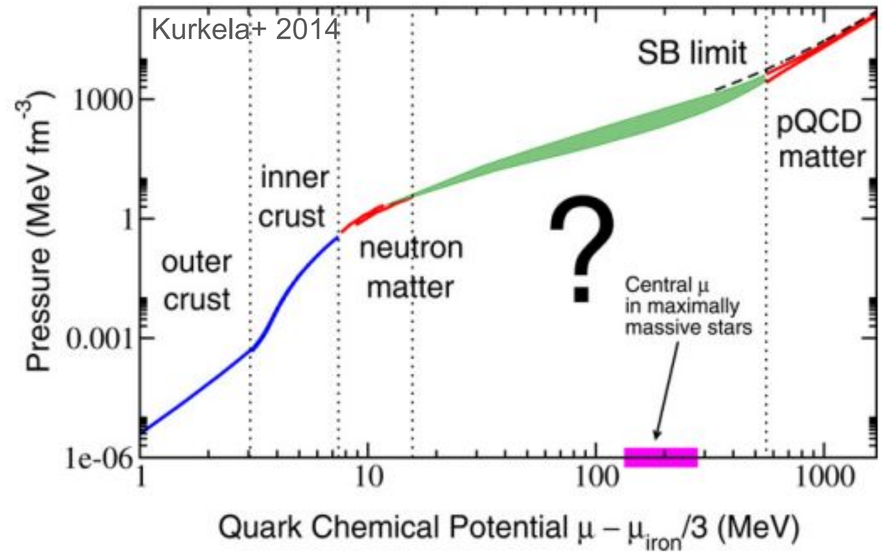

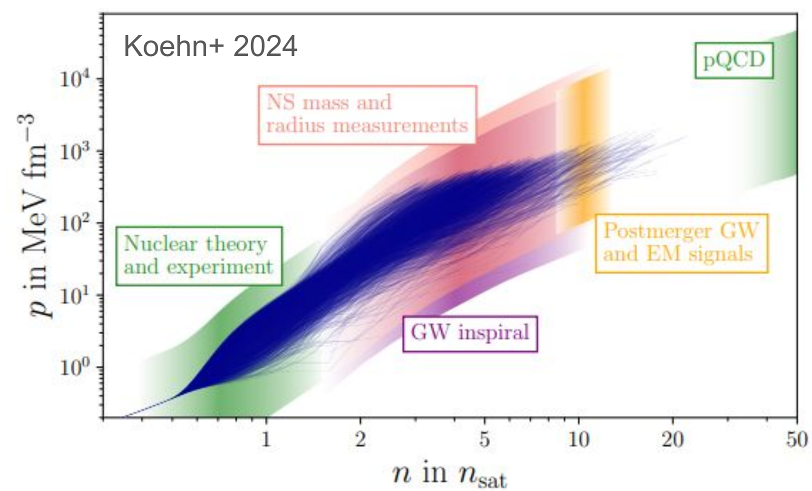

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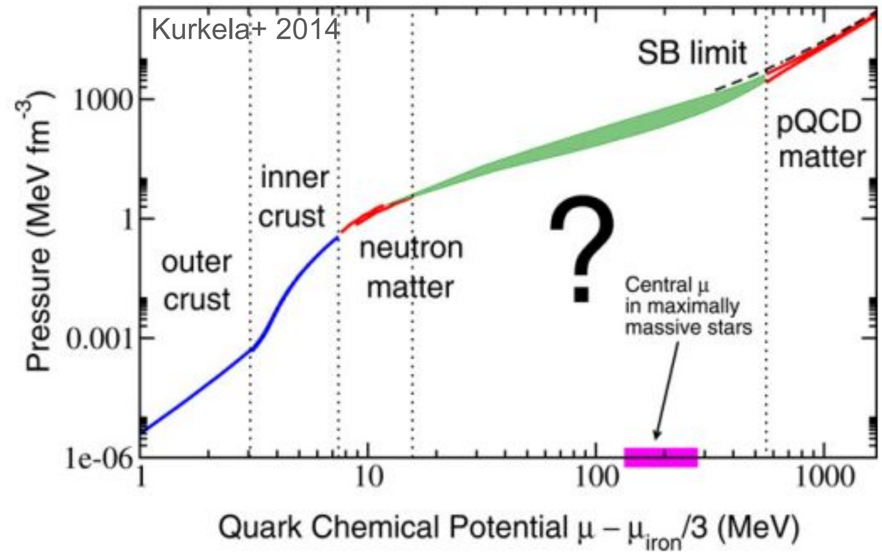
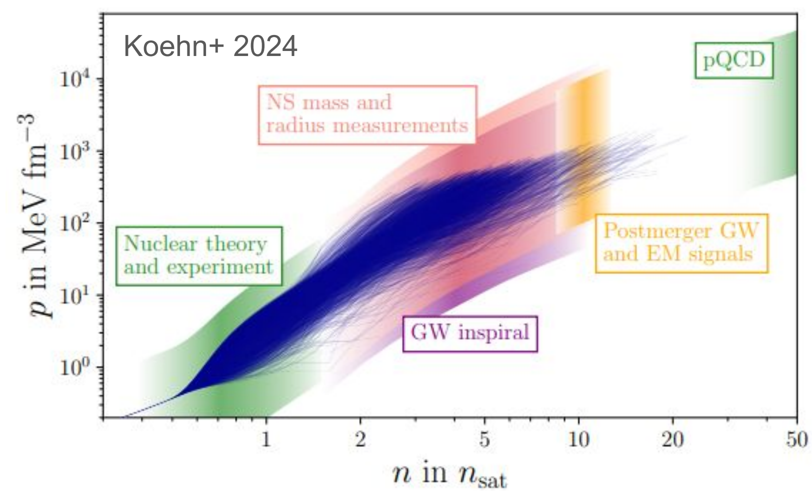
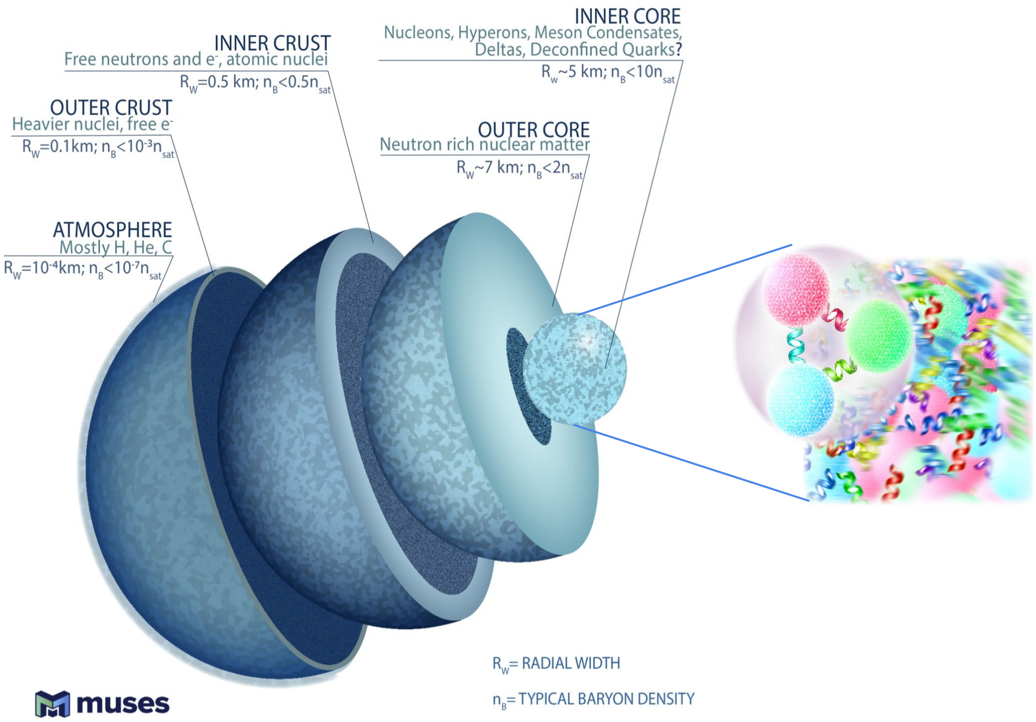
3) Probe the existence and phase of QM inside Neutron Stars





WHAT DO WE KNOW?

1) There might be a hadron-quark phase transition in NS cores



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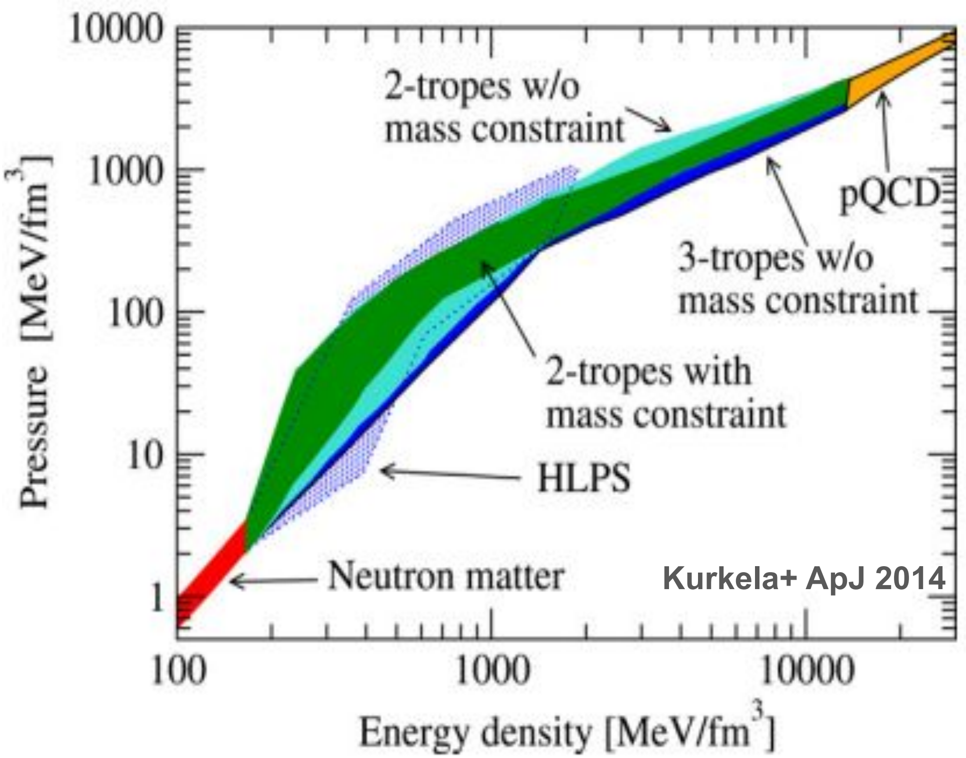

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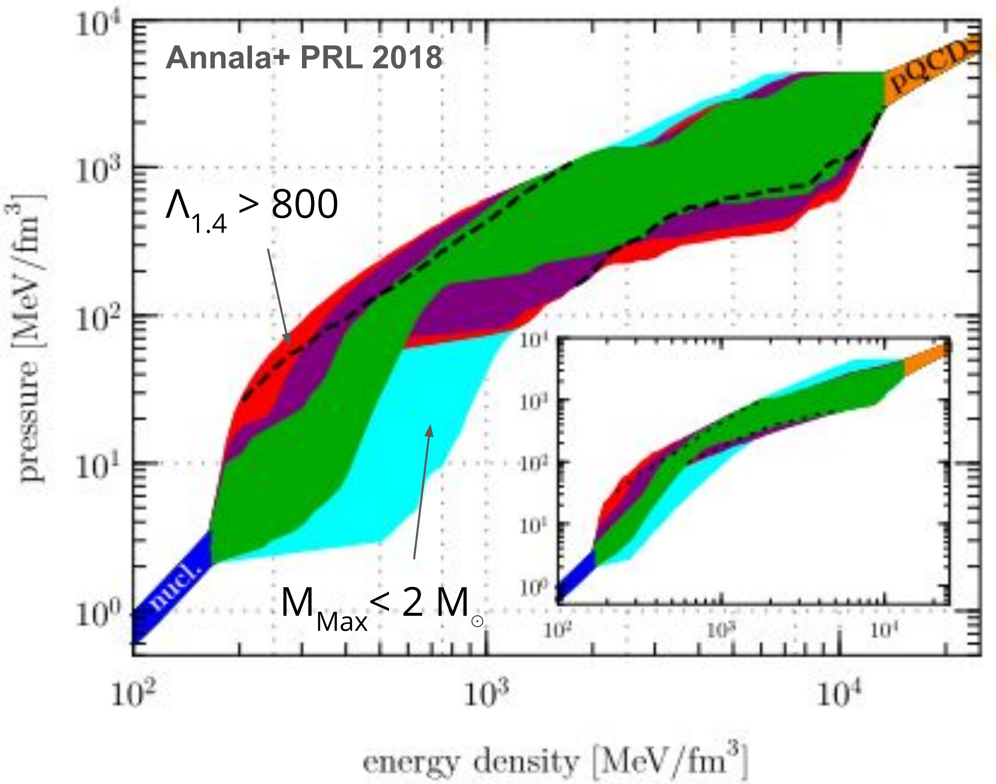

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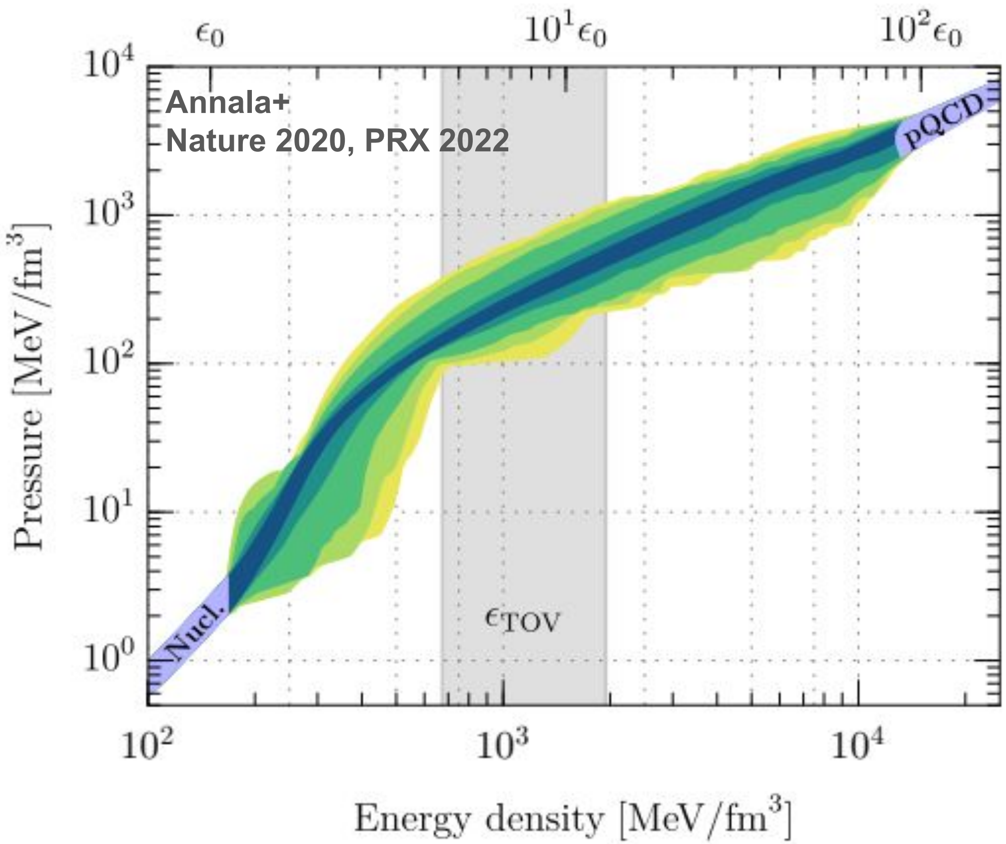
3) Observations: M_{max} and tidal deformability of GW170817 can constrain EoSs
4) Strong evidence of quark matter core in NSs



MOTIVATION

Many more works exist along the same line doing the same with different models

(too many to cite here!)

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However, most make use:

1) Parametric EOSs
    - Speed of sound parametrization, piecewise polytropes, interpolation methods for mixed phase, etc.
2) Select phenomenological EOSs / select parameters varied
3) Deploy maxwell construction with no mixed phase - (Mixed hadron-quark phase is allowed - Glendenning 1992)

WHAT WE DO

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MODEL

- **Hadronic Matter Phase:** Relativistic Mean-Field Model (RMF) [Hornick+ 2018]
  - Nucleons interacting via exchange of mesons

$$\mathcal{L}_{int} = \sum_N \bar{\psi}_N \left[g_\sigma \sigma - g_\omega \gamma^\mu \omega_\mu - \frac{g_\rho}{2} \gamma^\mu \boldsymbol{\tau} \cdot \boldsymbol{\rho}_\mu \right] \psi_N - \frac{1}{3} b m_N (g_\sigma \sigma)^3 - \frac{1}{4} c (g_\sigma \sigma)^4$$

$$+ \Lambda_\omega (g_\rho^2 \boldsymbol{\rho^\mu} \cdot \boldsymbol{\rho_\mu})(g_\omega^2 \omega^\nu \omega_\nu) + \frac{\zeta}{4!} (g_\omega^2 \omega^\mu \omega_\mu)^2$$

=0

Model parameters:
$\{n_{sat}, E_{sat}, K_{sat}, E_{sym}, L_{sym}, m^*/m\}$

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$\zeta = 0$

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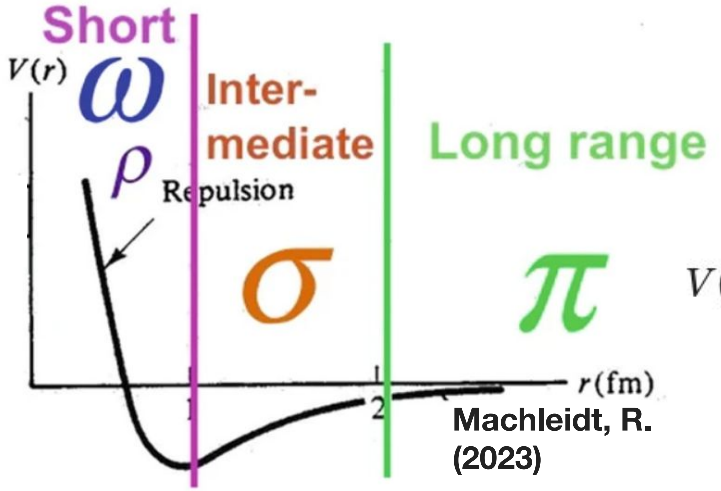
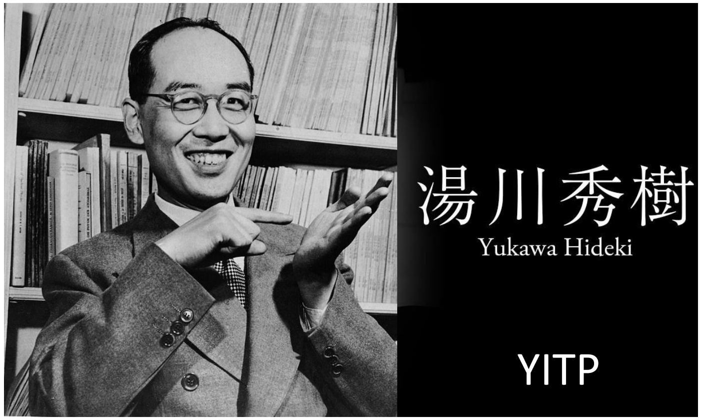


Machleidt, R. (2023)

$$V(r) = -\frac{g^2}{4\pi} \frac{e^{-mr}}{r}$$



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Model parameters: $\{n_{sat}, E_{sat}, K_{sat}, E_{sym}, L_{sym}, m^*/m\}$

- **Quark Matter Phase:** MIT Bag Model (with 1st order correction) [Farhi & Jaffe 1984, Glendenning 1997]

$$\Omega = \sum_{f=u,d,s} \Omega_f + \sum_{l=e,\mu} \Omega_{l,free} + B$$

$$\Omega_i = \Omega_{i,free} + \frac{1}{4\pi^2} \frac{2\alpha}{\pi} \Bigg[3 \left(\mu_i k_{F_i} - m_i^2 \ln \frac{\mu_i + k_{F_i}}{\mu_i} \right)^2 - 2k_{F_i}^2 - 3m_i^4 \ln^2 \frac{m_i}{\mu_i} + 6 \ln \frac{\tilde{\Lambda}}{\mu_i} \left(m_i^2 \mu_i k_{F_i} - m_i^4 \ln \frac{\mu_i + k_{F_i}}{m_i} \right) \Bigg]$$

$m_u = m_d = 5$ MeV, $m_s = 100$ MeV

$$1 - a_4 = \frac{2}{\pi} \alpha_s$$

Model parameters: $\{B, a_4\}$

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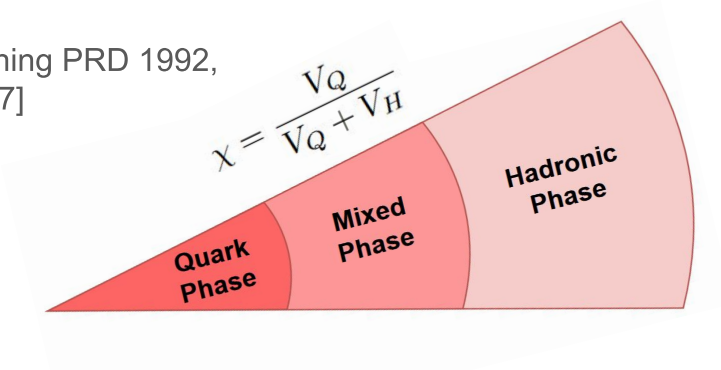
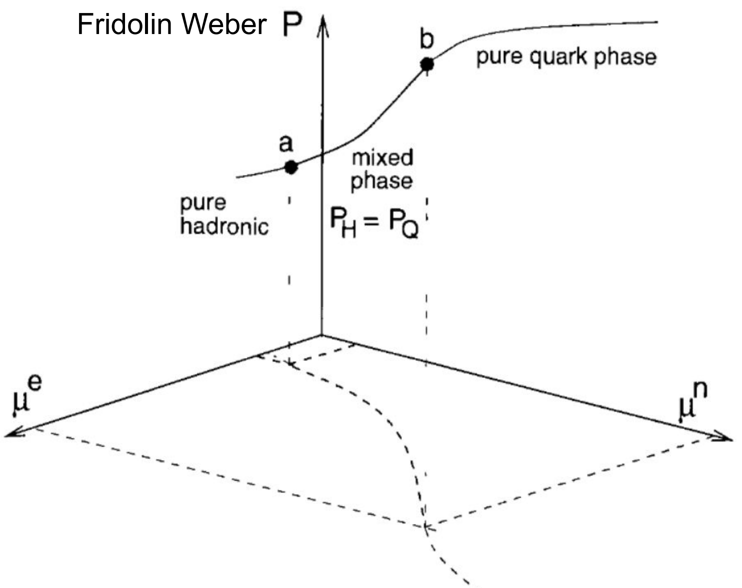
MODEL

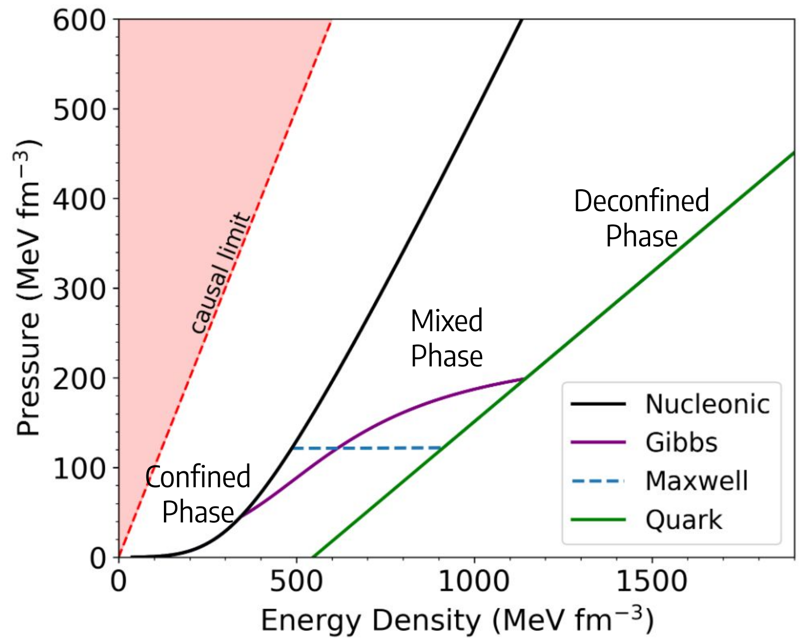
- **Phase transition:** Gibbs Construction [Glendenning PRD 1992, Book 1997]

$$\boxed{P_H(\mu_b, \mu_q) = P_Q(\mu_b, \mu_q)}$$

$$\chi q^Q + (1-\chi) q^H = 0,$$
$$\chi n^Q + (1-\chi) n^H = n_B$$







This is the case with zero surface and coulomb effects

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PRIORS & CONSTRAINTS

- **Range of parameters:** (Uniform Priors within their uncertainty ranges)

[Suprovo Ghosh+ EPJA 2022]

n_{sat} (fm^{-3})	E_{sat} (MeV)	K_{sat} (MeV)	E_{sym} (MeV)	L_{sym} (MeV)	m^*/m	a_4	$B^{1/4}$ (MeV)
0.14 - 0.17	-16.0 ± 0.2	200 - 300	28 - 34	40 - 70	0.55 - 0.75	0.4 - 1.0	100 - 300

We generate 100,000 equations of state!

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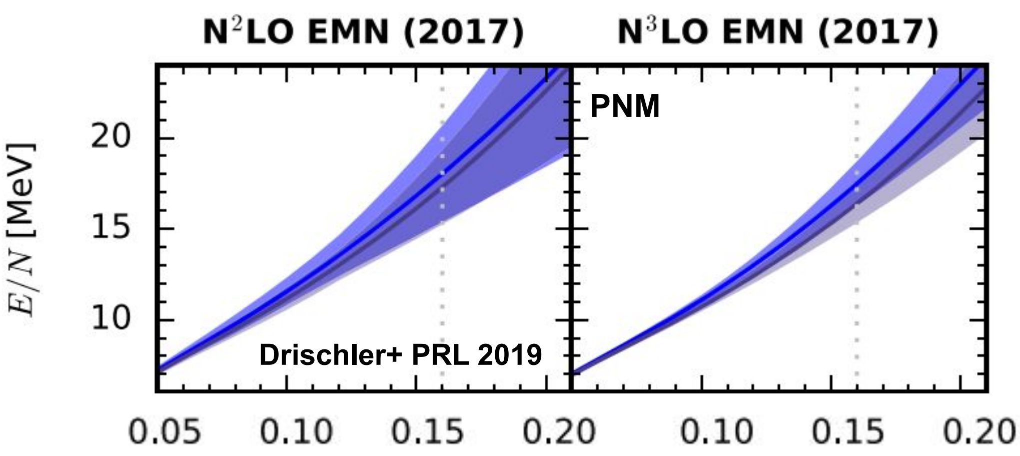

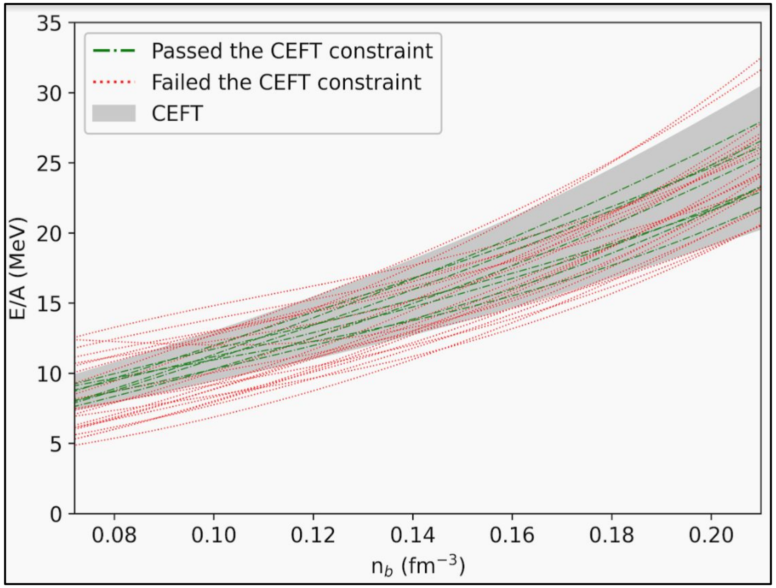

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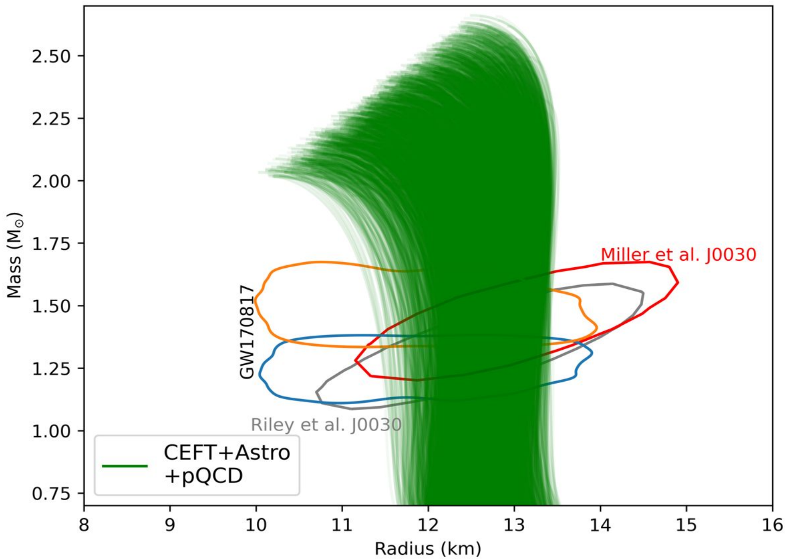

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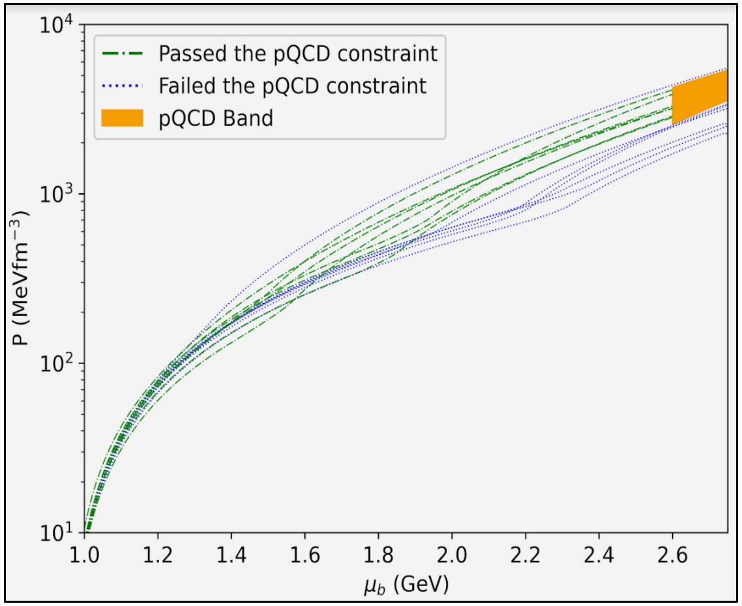
3. Very-high density: pQCD at μ_B= 2.6 GeV (Fraga+ ApJL 2014, Komoltsev+ PRL 2022)



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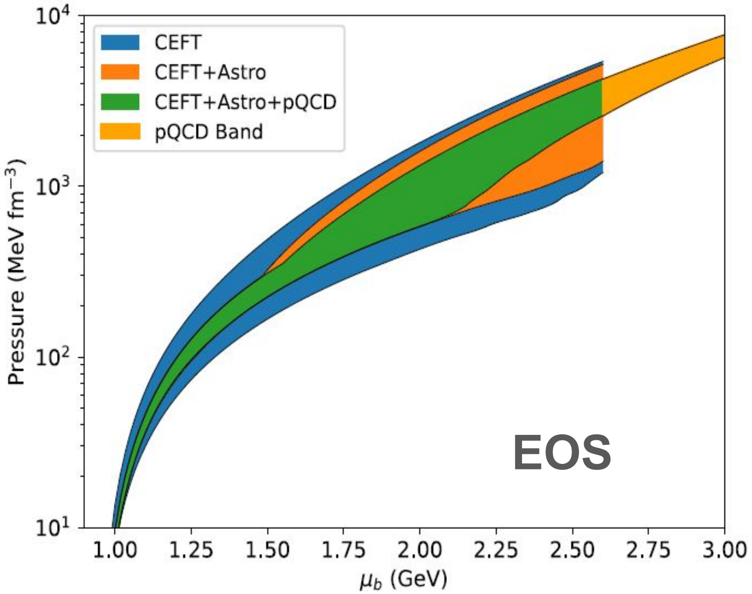
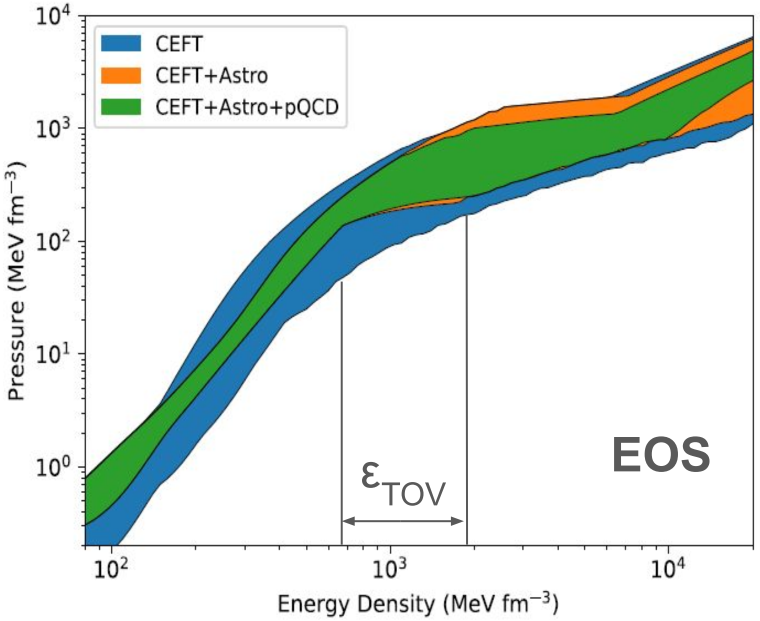
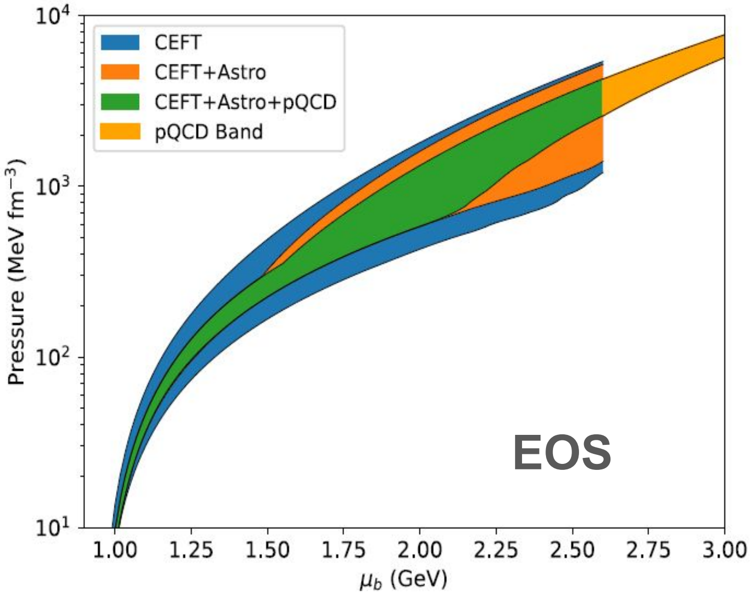
RESULTS





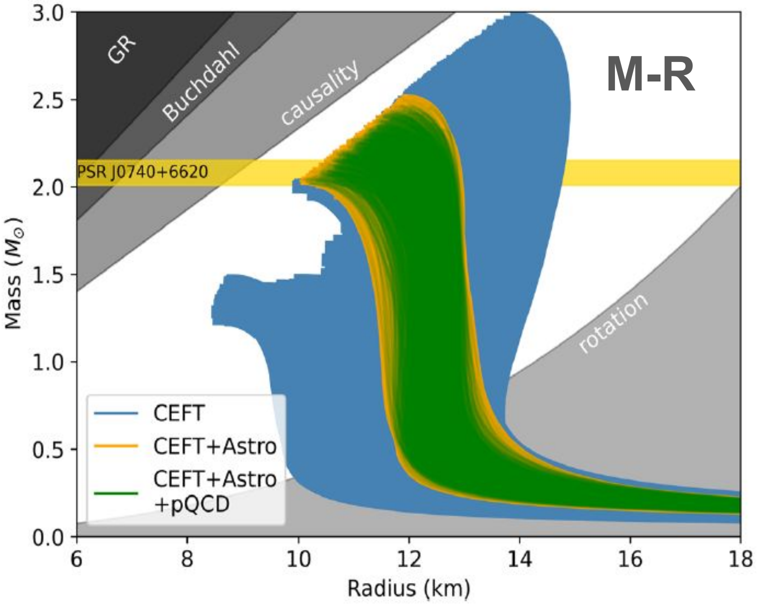
Side note: We also find a peak in speed of sound!

RESULTS



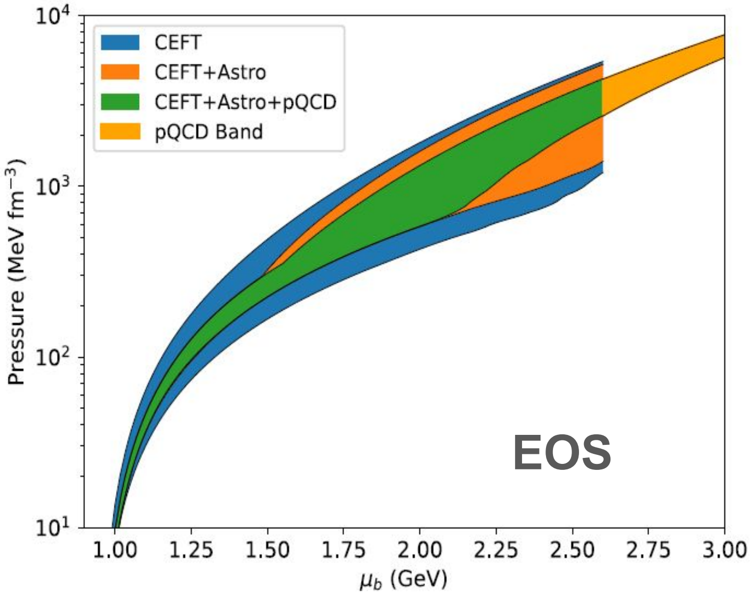
CEFT
CEFT+Astro
CEFT+Astro+pQCD
pQCD Band
Pressure (MeV fm^{-3})
10^4
10^3
10^2
10^1
1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00
μ_b (GeV)
EOS

TOV



M-R
GR
Buchdahl
causality
rotation
PSR J0740+6620
Mass ($M_\odot$)
3.0 2.5 2.0 1.5 1.0 0.5 0.0
CEFT
CEFT+Astro
CEFT+Astro +pQCD
6 8 10 12 14 16 18
Radius (km)

RESULTS



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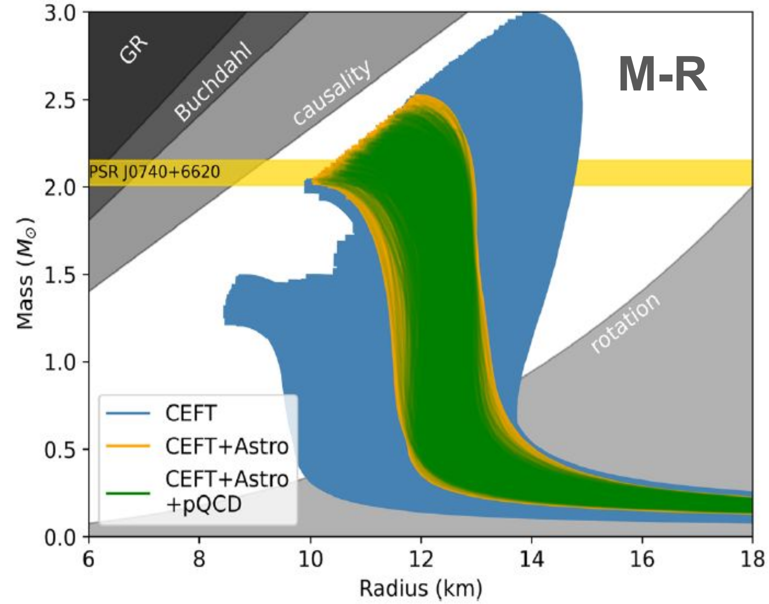
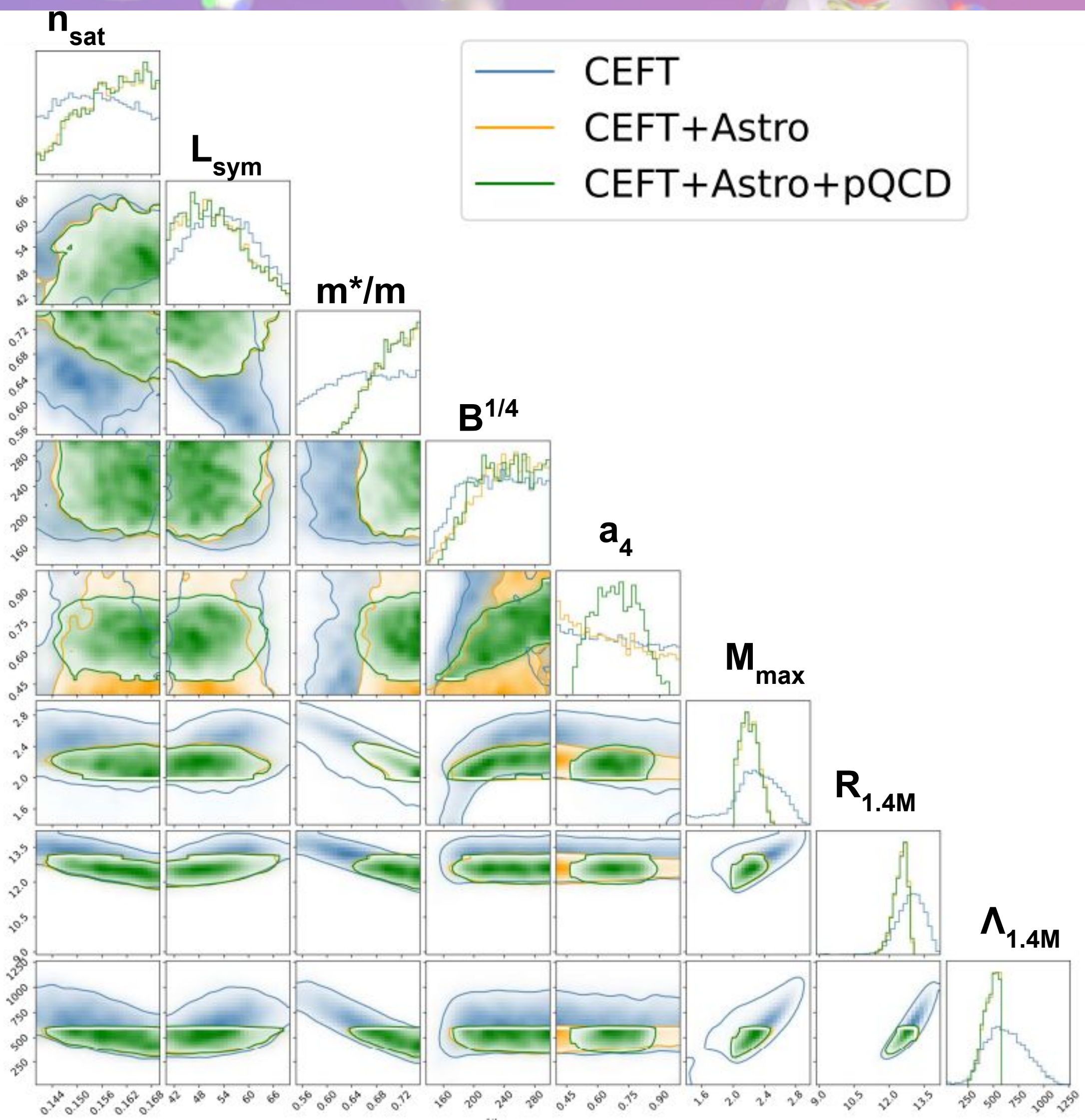


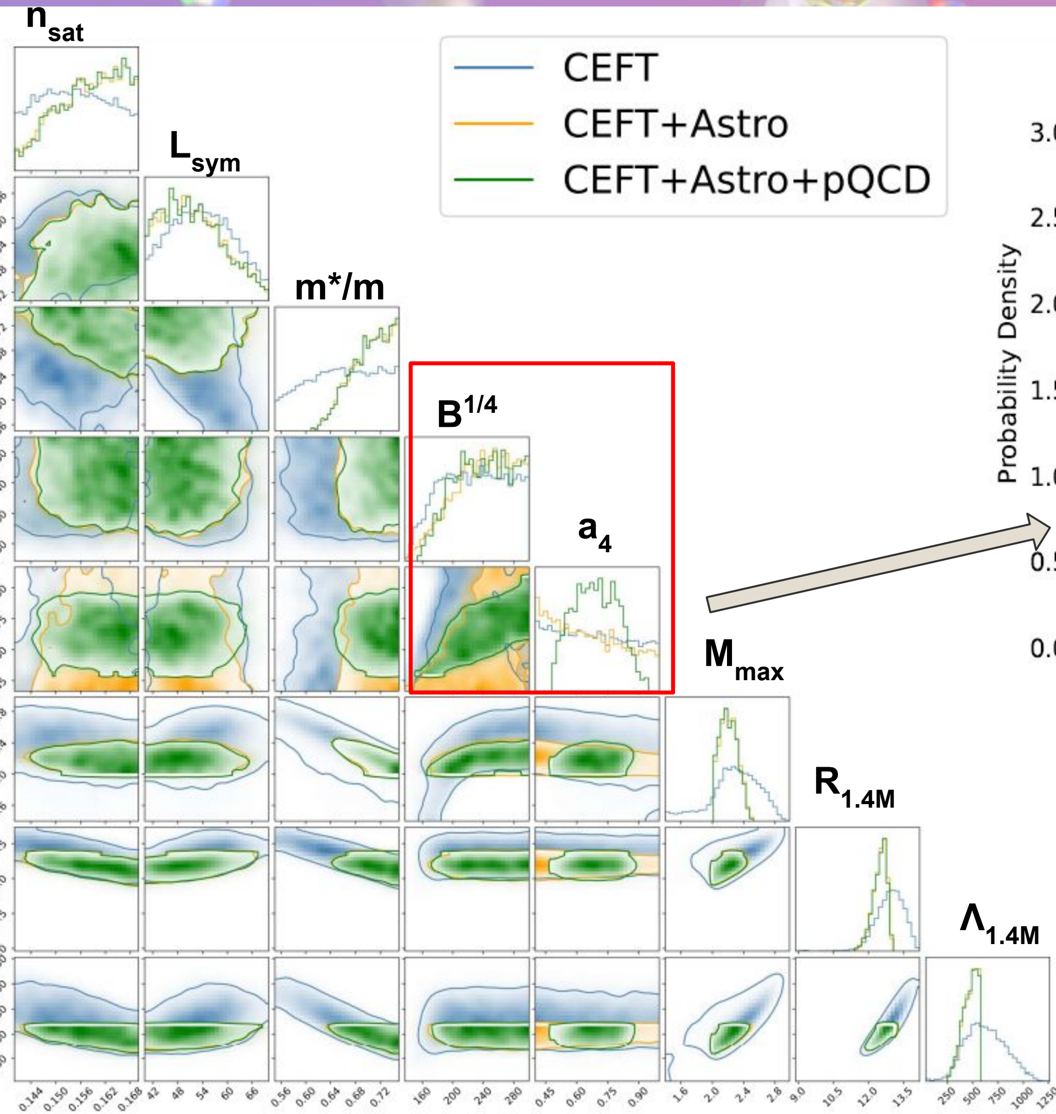
Posterior	n_{cen} (fm^{-3})	μ_{cen} (GeV)	M_{max} ($M_\odot$)	$R_{1.4M_\odot}$ (km)	$\Lambda_{1.4M_\odot}$
CEFT	0.54 - 1.77	1.13 - 1.98	1.04 - 2.99	8.8 - 14.2	33 - 1263
CEFT+Astro	0.76 - 1.23	1.38 - 1.97	2.01 - 2.53	11.3 - 13.1	247 - 580
CEFT+Astro+pQCD	0.76 - 1.23	1.39 - 1.96	2.01 - 2.52	11.4 - 13.1	247 - 580

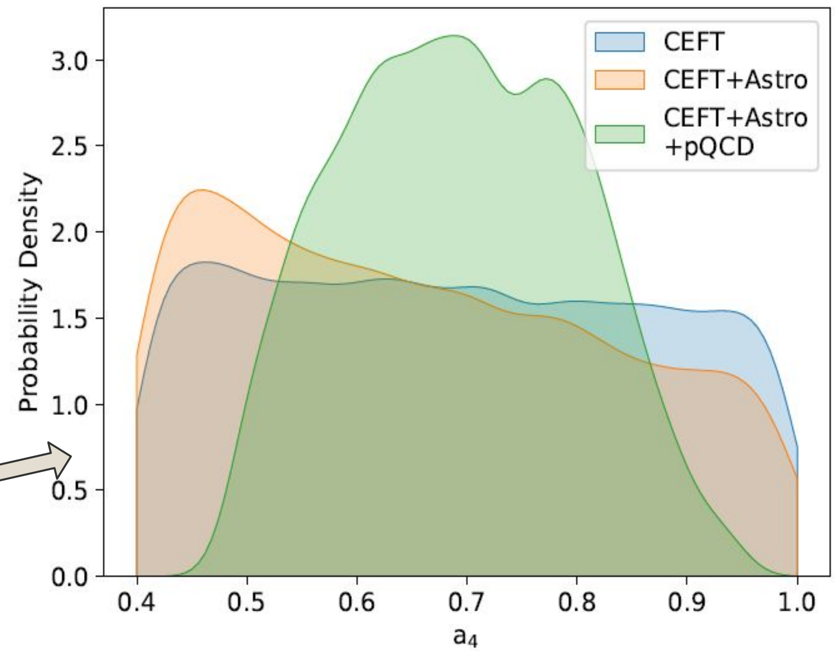
RESULTS



CEFT
CEFT+Astro
CEFT+Astro+pQCD
n_{sat}
L_{sym}
m^*/m
$B^{1/4}$
a_4
M_{max}
$R_{1.4M}$
$\Lambda_{1.4M}$

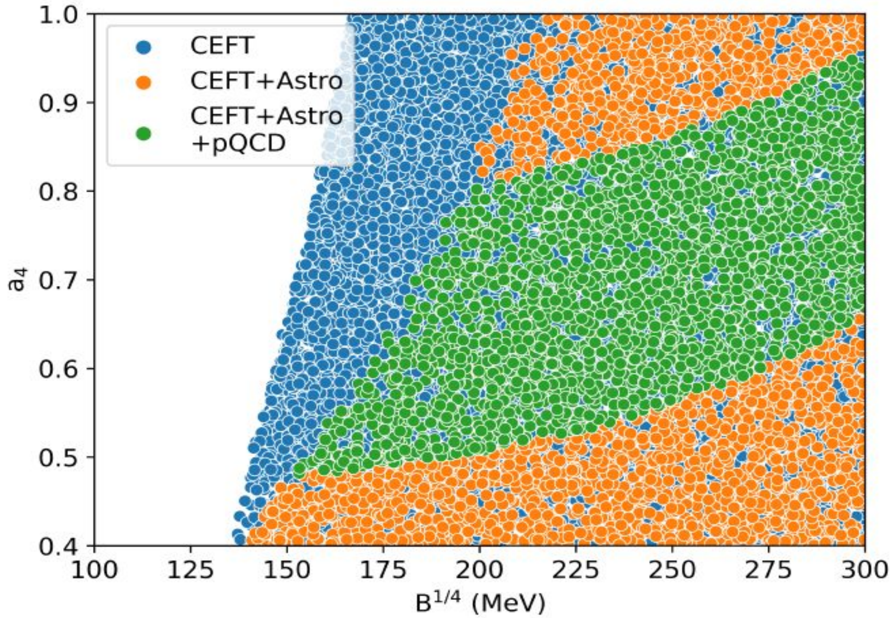
RESULTS

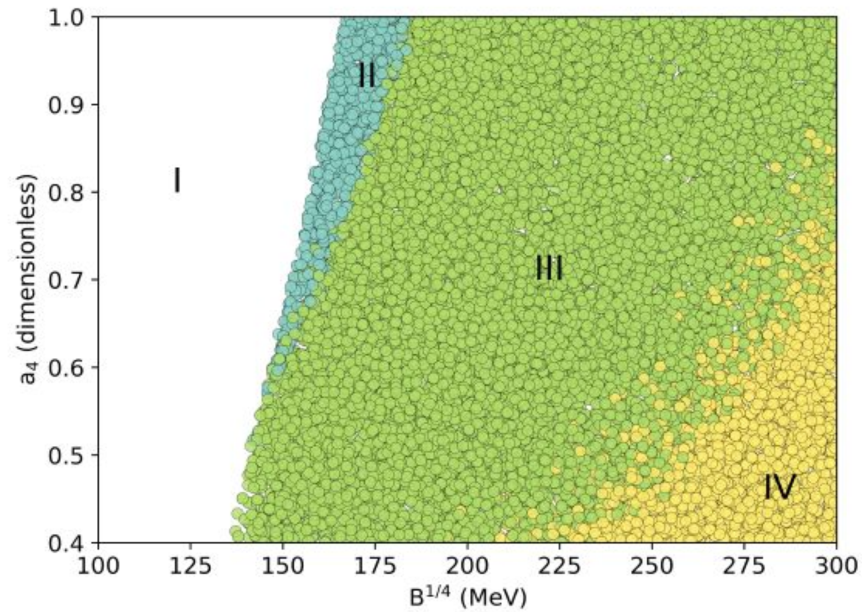




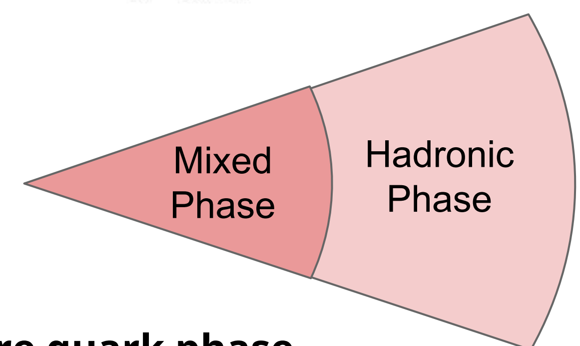
- pQCD significantly constraints the B-a_4 plane, in particular, a_4! (0.55-0.85)

RESULTS





- **a_4 > 0.48 $B^{1/4}$ > 153 MeV**
- **Region I:** No Hybrid Star solutions
- **Region II:** Pure Quark-Matter Core
- **Region III:** Mixed-Phase Core
- **Region IV:** No Phase Transition
- **Mixed-phase favoured** at the core of NSs and **not the pure quark phase**
- **Evidence for quark matter in NS core**



SUMMARY

- **Realistic** phenomenological RMF model (hadronic phase) and MIT Bag model (quark phase) via **Gibbs phase transition**
- **Vary all the parameters (100,000 EOSs!)**
- **Multi-disciplinary physics constraints**
  - CEFT
  - Multi-messenger astrophysical observations
  - pQCD

- **Constraints** on microscopic parameters, EoS and properties at the NS centre
- Study of **physical correlations** (can discuss later)

- pQCD + Astro filters significantly restricts B-a_4 quark parameter space
- pQCD constrains the QCD strong coupling constant (a_4/α_s)
- Astrophysical observations disfavour pure quark matter core in NSs
- pQCD calculation disfavours hadronic matter -> hadron-quark mixed-phase core in NSs is preferred (evidence for existence for hybrid stars)