Gravitational-wave constraints on the neutron-star-matter Equation of State

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Outline

1. Matching EoSs: the idea

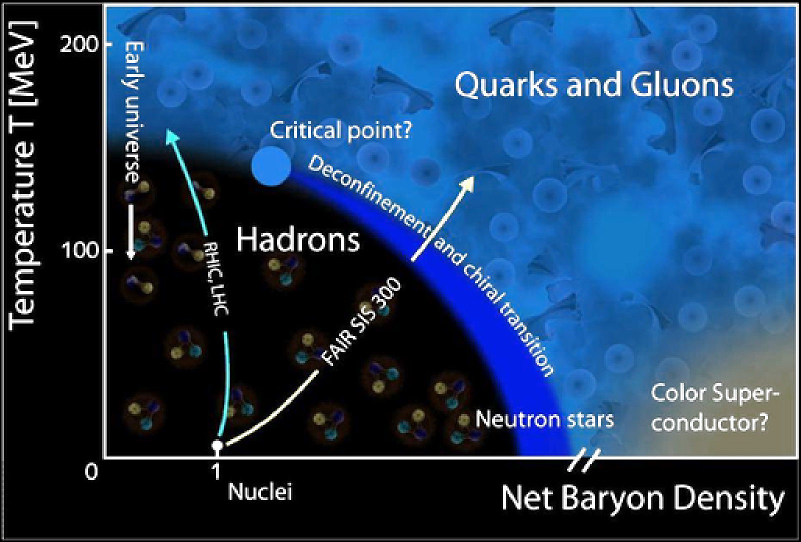
2. cEFT-pQCD EoS band with May 2018 LIGO/Virgo updates

   Theory + Observations

3. Results: Plots

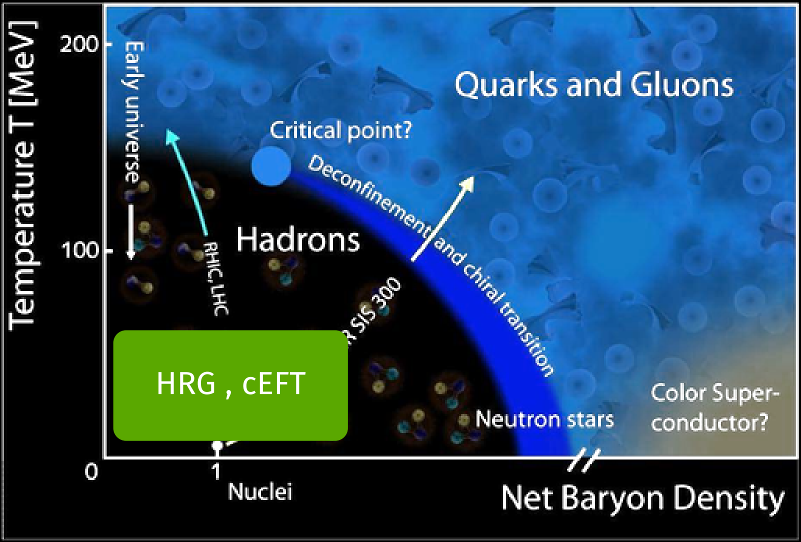
Matching: the idea

QCD MATTER



Source: Compressed Baryonic Matter (CBM) experiment

QCD MATTER



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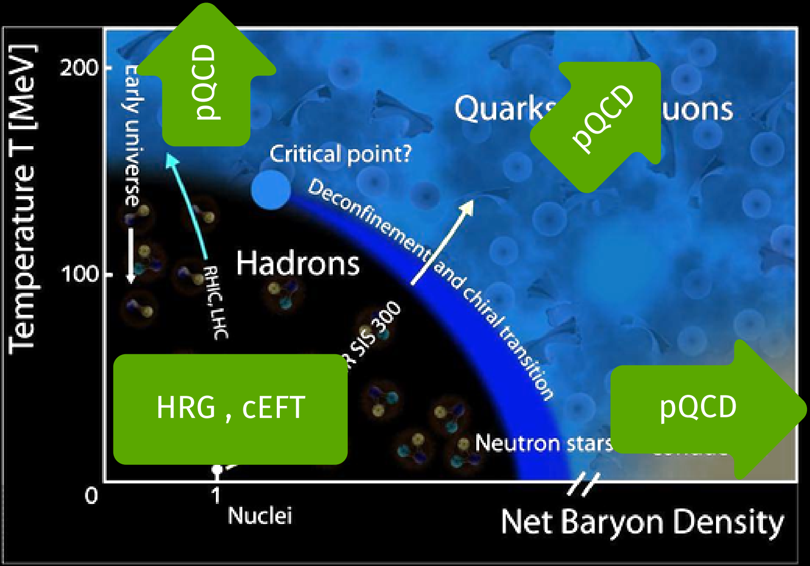

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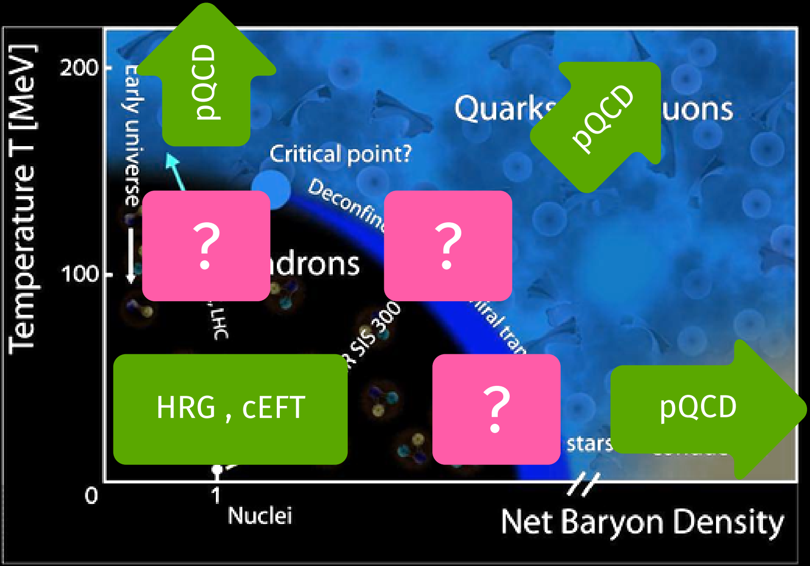

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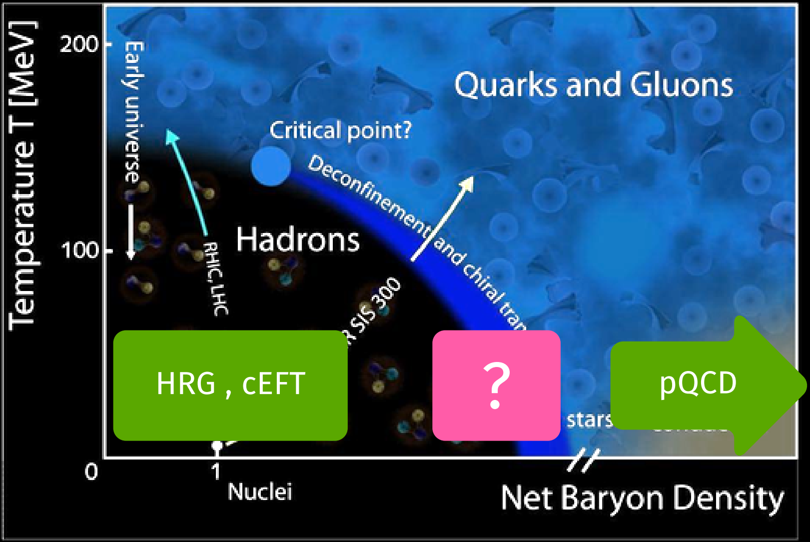

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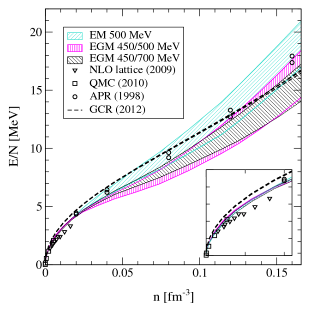
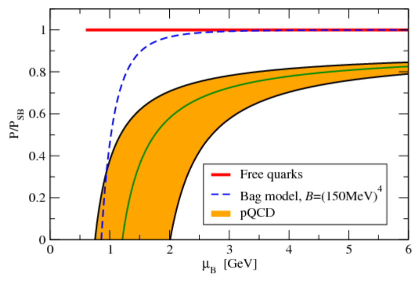
- This philosophy, applied to the QCD phase diagram at $T = 0$ can shed light on NSs and their properties.

- Observations can further improve these conclusions.

cEFT-pQCD EoS band

We follow Kurkela et al. 2014 and match **cEFT** (Tews et al. 2013) to **pQCD** (Fraga et al. 2014, Kurkela et al. 2010) with N interpolating polytropes: $p_i(n) = \kappa_i n^{\gamma_i}$:





cEFT-pQCD EoS band: theory

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nuclear: h/s —— pQCD: $X \in [1, 4]$

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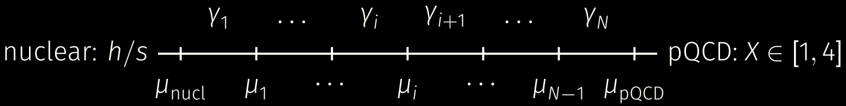
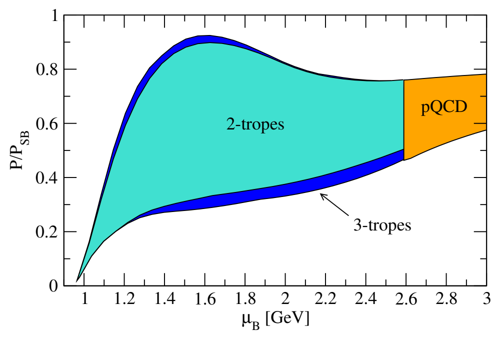


$2N - 3$ free parameters per polytropic EoS, plus nuclear & pQCD parameters.

Tews et al. arXiv:1206.0025, Kurkela et al. arXiv:1402.6618, Fraga et al. arXiv:1508.05019

Thermodynamic consistency, subluminality, matching to nuclear & pQCD, place stingent constraints on values of γ_i, μ_i.

In past, $N = 2, 3$ taken to be sufficient: e.g.,



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Our current procedure: Generate 90,000 3-trope and 170,000 4-trope matched EoSs that are

- thermodynamically consistent
- subluminal ($c_s^2 < 1$) everywhere

Take no constraints on the parameters ($\gamma_i \in [0, 15]$, $\mu_i \in [\mu_{\text{nucl}}, \mu_{\text{pQCD}}]$, and $X \in [1, 4]$.) $\therefore$ effectively allow for 1st order phase transitions.

We find EoSs to be roughly uniformly distributed in γ_i, μ_i and X so the entire parameter space is satisfactorily covered.

Annala, TG, Kurkela, Vuorinen arXiv:1711.02644

Observations

1. Old: existence of $1.97 M_\odot$ star (Demorest et al. 2010, Antoniadis et al. 2013)
2. New: LIGO/Virgo GW constraint on tidal deformability: $\Lambda(1.4 M_\odot) < 800$:

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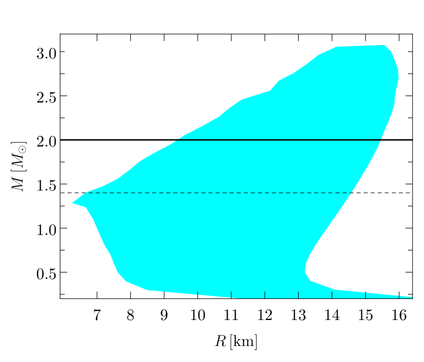
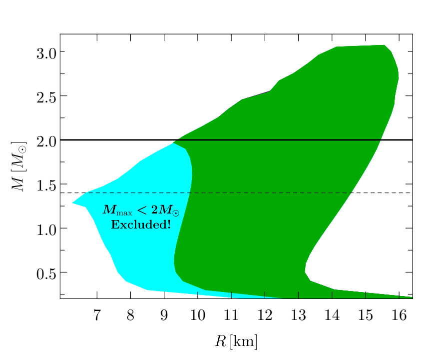
2. New: LIGO/Virgo GW constraint on tidal deformability: ~~$\Lambda(1.4M_\odot) < 800$:~~ $70 < \Lambda(1.4M_\odot) < 580$ (May 2018)

Demorest et al. arXiv:1010.5788, Antoniadis et al. arXiv:1304.6875, LIGO/Virgo arXiv:1710.05832, arXiv:1805.11581

Results: Plots

Mass-Radius cloud





- $1.97 M_\odot$ constraint removes small stars.

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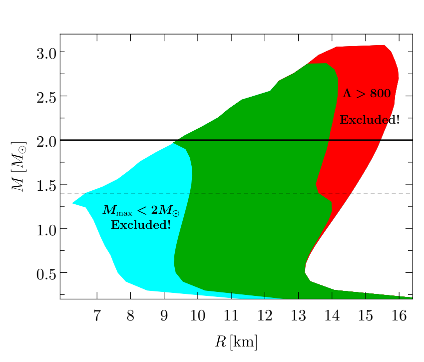
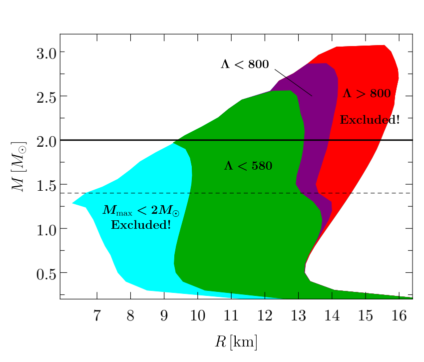


- $1.97 M_\odot$ constraint removes small stars.
- LIGO/Virgo constraint removes largest stars.
- Bounds:
  $9.7\text{ km} < R(1.4 M_\odot) < 13.6\text{ km}$
  $1.97 M_\odot < M_{\rm max} < 3.0 M_\odot$

Mass-Radius cloud



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  9.7 km $< R(1.4 M_\odot) <$ 13.1 km
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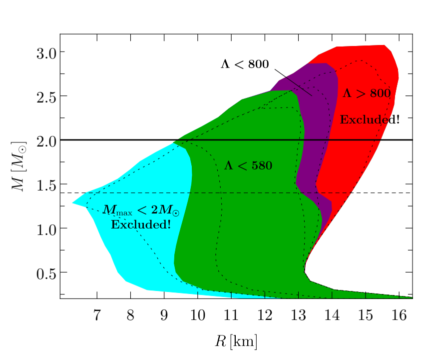

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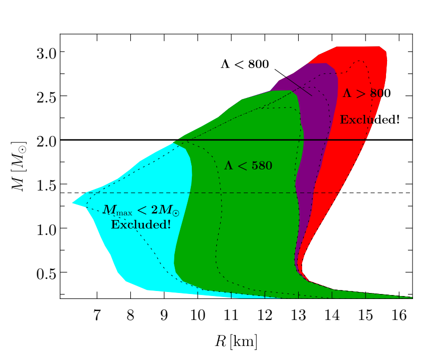

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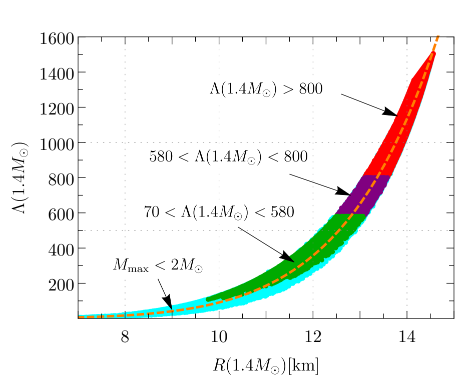
- Constraint on $0.4 \leq \gamma_1 \leq 5.8$, if first polytrope required to last until $1.5n_s$.

Tidal deformabilities



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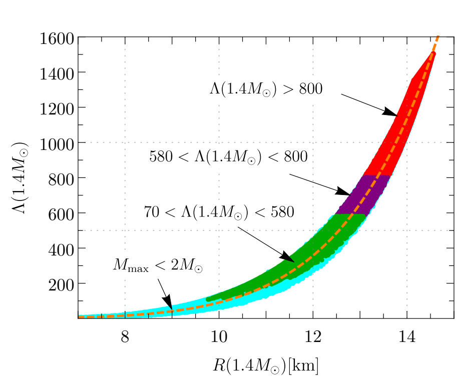
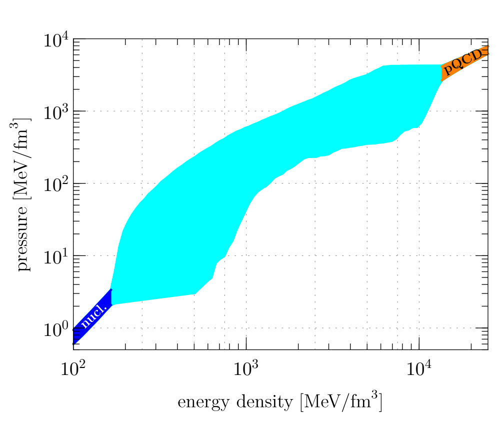


- $\Lambda(R) = 2.88 \times 10^{-6}(R/\mathrm{km})^{7.5}$ approximates well.
- $2M_\odot$ constraint gives $\Lambda(1.4M_\odot) > 107$.

ENERGY DENSITY VS. PRESSURE



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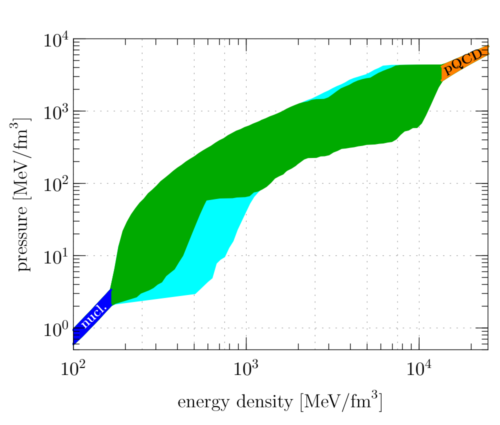

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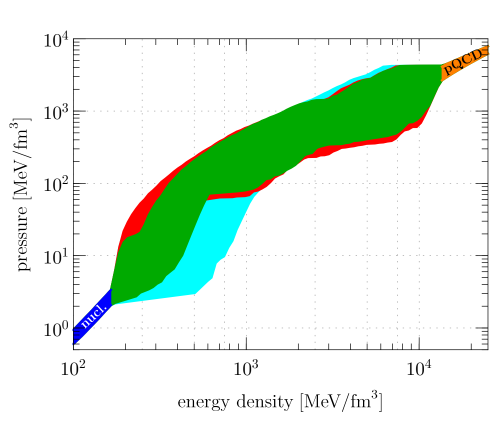

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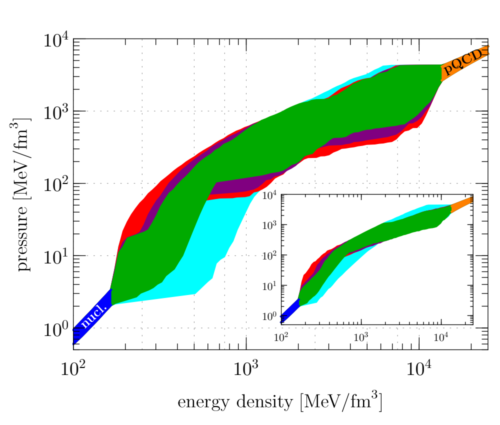

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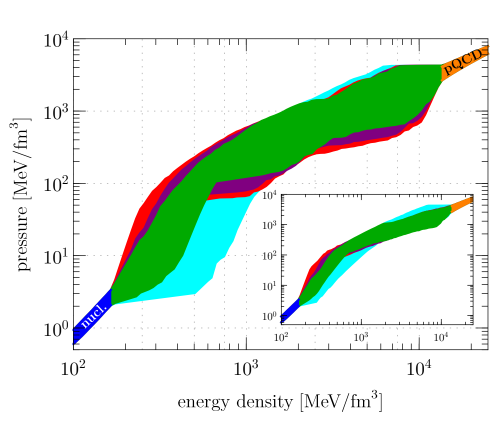

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Current work

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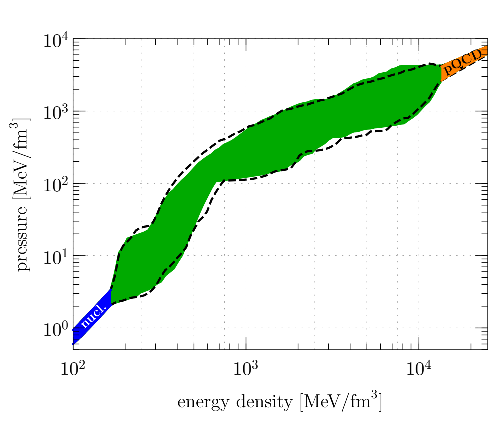

Allowed region robust against parametrization.

Summary

- No **fully first-principles** approach to the QCD EoS currently exists to apply to NSs.
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- No **fully first-principles** approach to the QCD EoS currently exists to apply to NSs.

- Matching cEFT to pQCD + observations provides constraints
  - Bounds from $2M_\odot$ and LIGO/Virgo:
    $9.7\ \text{km} < R(1.4M_\odot) < 13.1\ \text{km}$,
    $1.97M_\odot < M_{\text{max}} < 2.7M_\odot$
  - Region robust.
  - Observational astronomy now providing stringent bounds on the collective properties of dense QCD matter.

Thank you!