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

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[arXiv: 1711.02644]

Outline

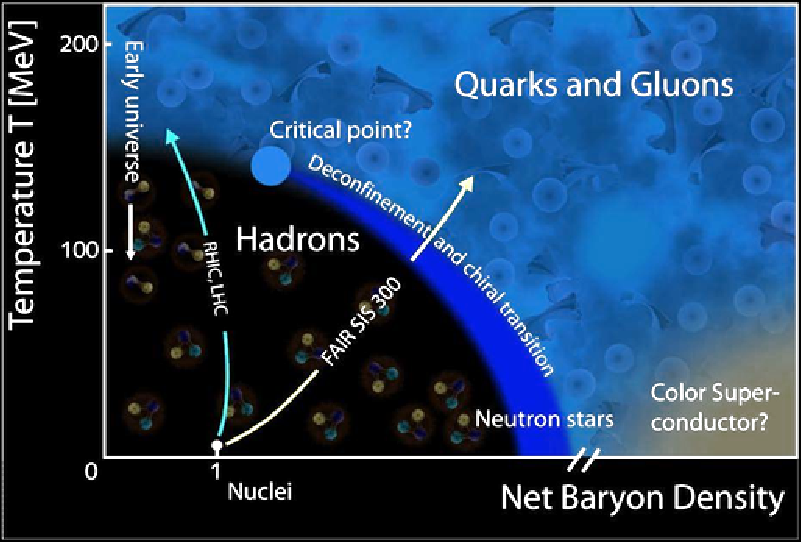
1. Matching EoSs: the idea

2. cEFT-pQCD EoS band

   Theory + Observations

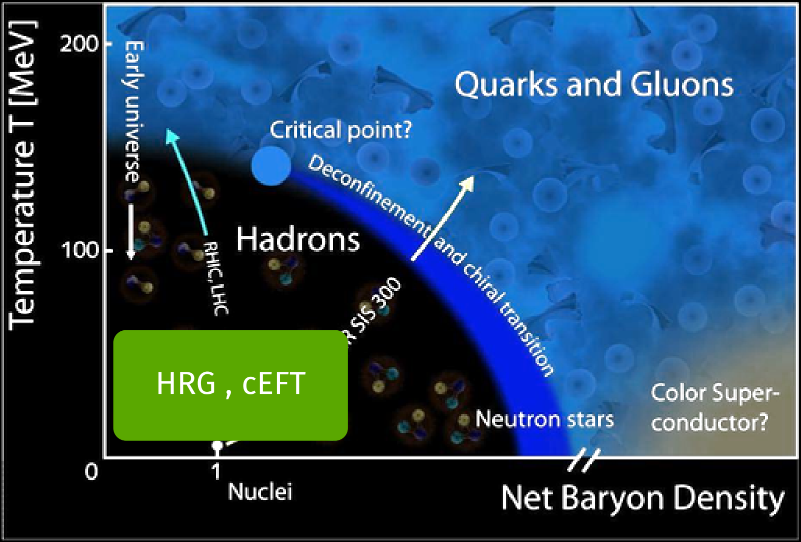
3. Results: Plots

Matching: the idea



Source: Compressed Baryonic Matter (CBM) experiment

QCD MATTER



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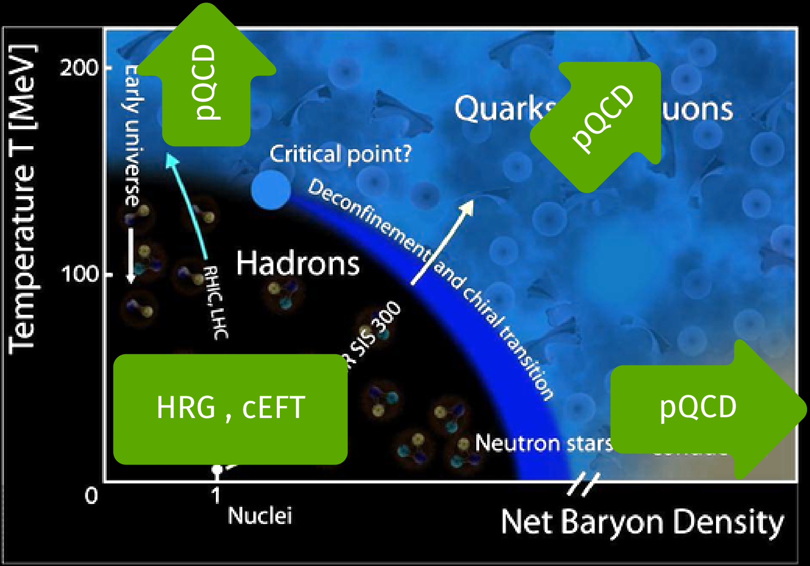

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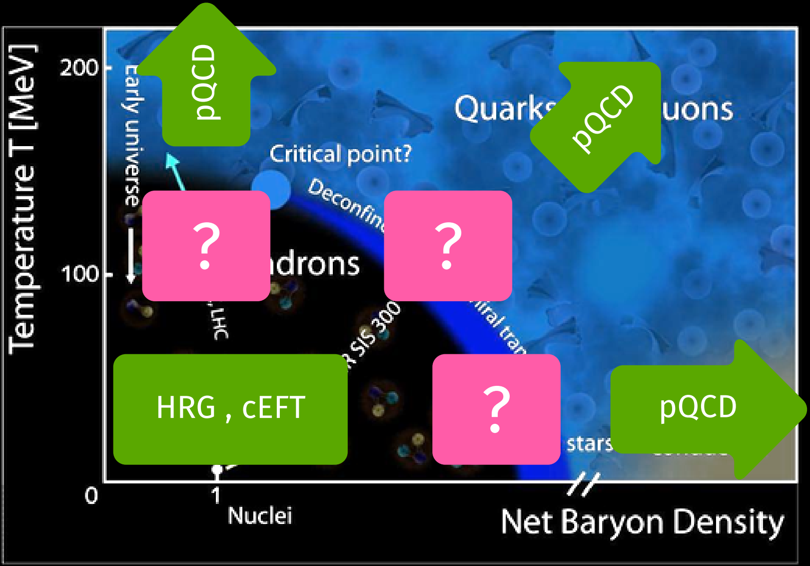

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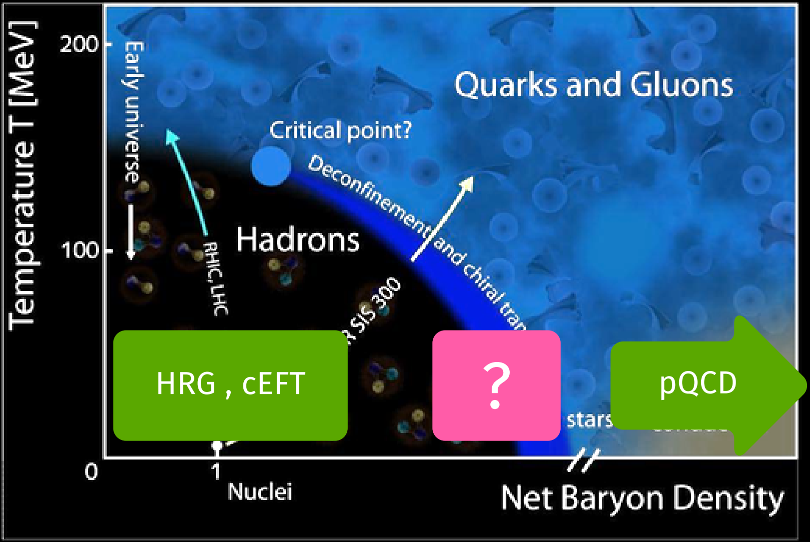

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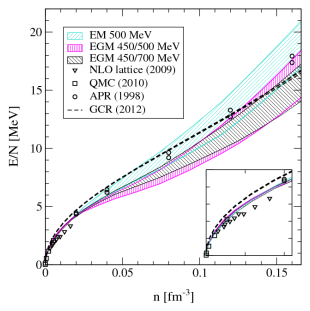
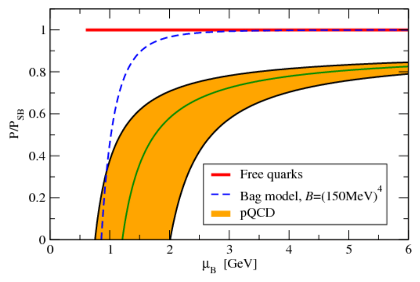
- Observations can further improve these conclusions.

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: $p_i(n) = \kappa_i n^{\gamma_i}$:





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nuclear: h/s —— μ_{nucl} ———— μ_{pQCD} —— pQCD: $X \in [1, 4]$

cEFT-pQCD EoS band: theory

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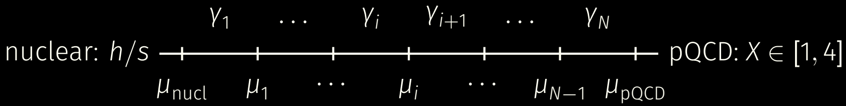
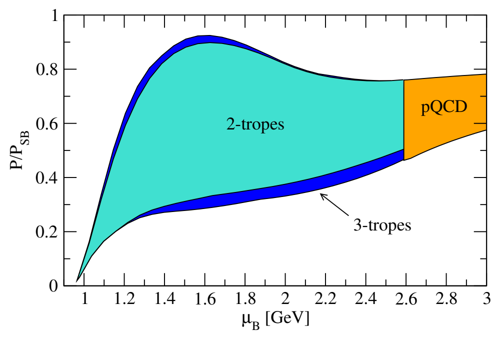


$2N - 3$ free parameters per polytropic EoS, plus nuclear & pQCD parameters.

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.,



Kurkela et al. [arXiv:1402.6618], Fraga et al. [arXiv:1508.05019]

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 ($\gamma_i \in [0, 15]$, $\mu_i \in [\mu_{\mathrm{nucl}}, \mu_{\mathrm{pQCD}}]$, 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.

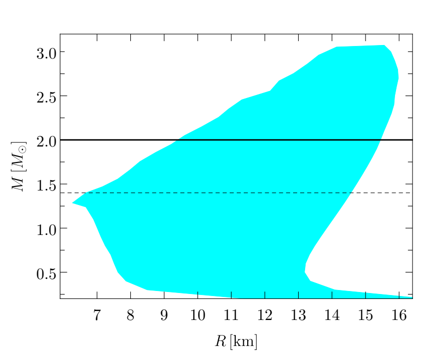
Annala, TG, Kurkela, Vuorinen [arXiv:1711.02644]

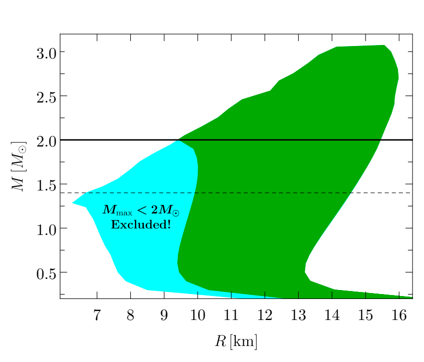
Observations

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

Results: Plots

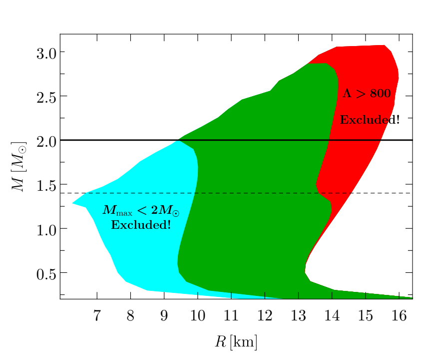
Mass-Radius cloud



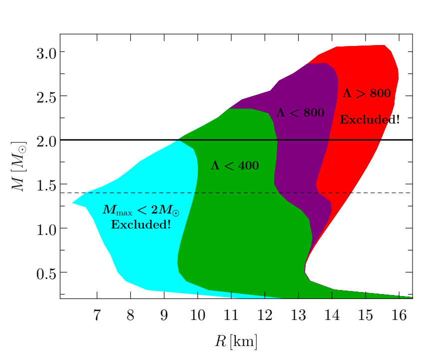


- $2M_\odot$ constraint removes small stars.

Mass-Radius cloud



- $2M_\odot$ constraint removes small stars.
- LIGO/Virgo constraint removes largest stars.
- Bounds:
  $9.9 \text{ km} < R(1.4M_\odot) < 13.6 \text{ km}$
  $2.0M_\odot < M_{max} < 3.0M_\odot$



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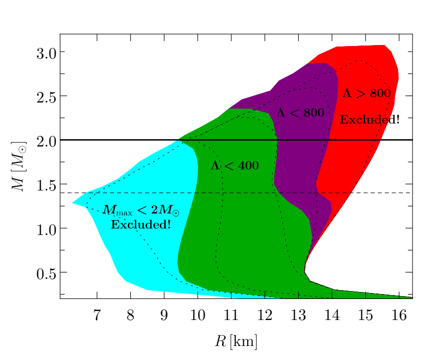

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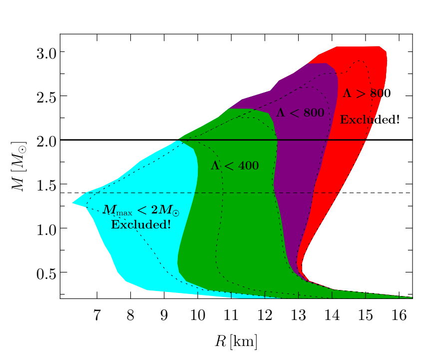

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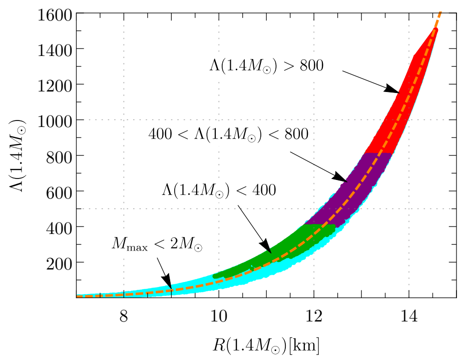
- Constraint on $0.6 \le \gamma_1 \le 6.7$, if first polytrope required to last until $1.5n_s$.

Tidal deformabilities



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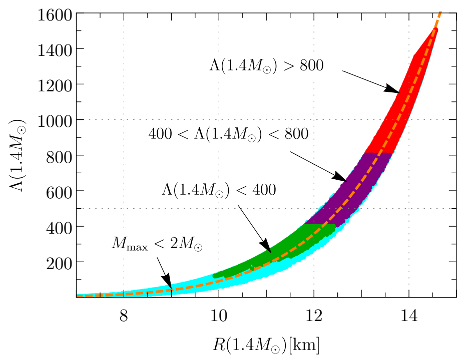
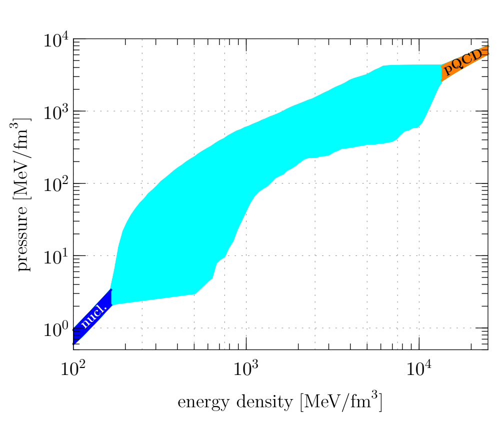


- $\Lambda(R) = 2.88 \times 10^{-6}(R/\text{km})^{7.5}$ approximates well.
- $2M_\odot$ constraint gives $\Lambda(1.4M_\odot) > 120$.

ENERGY DENSITY VS. PRESSURE



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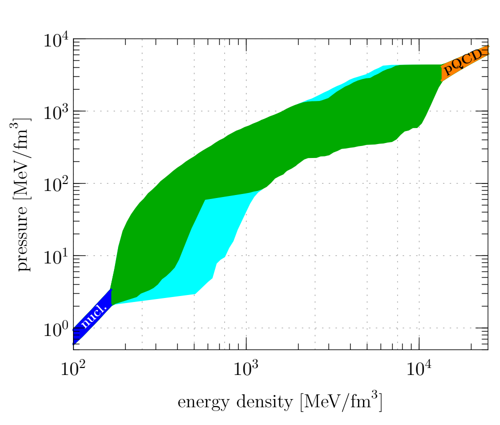

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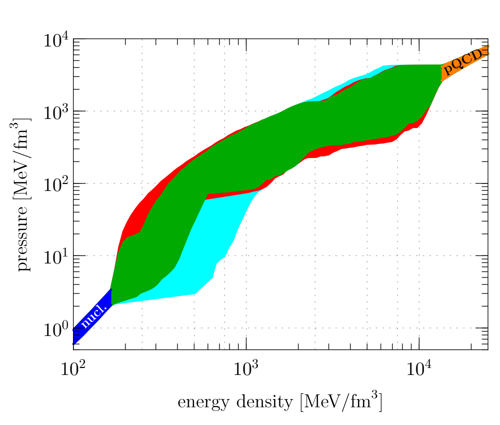

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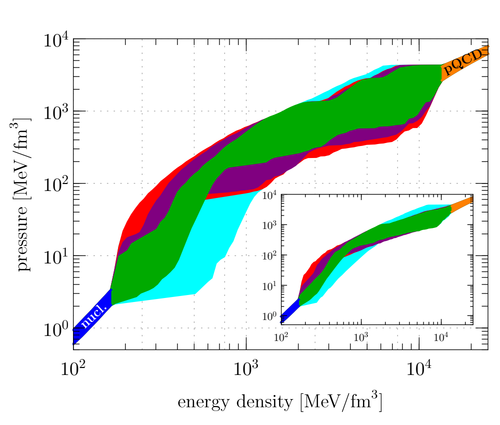

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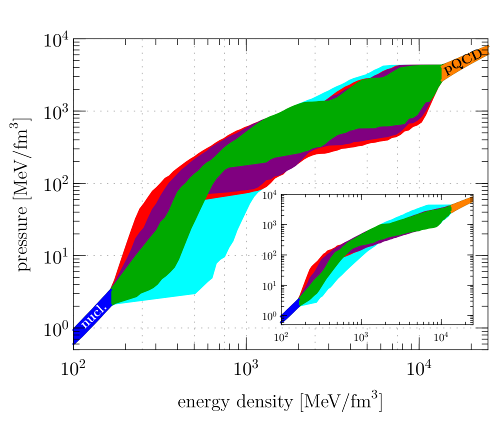
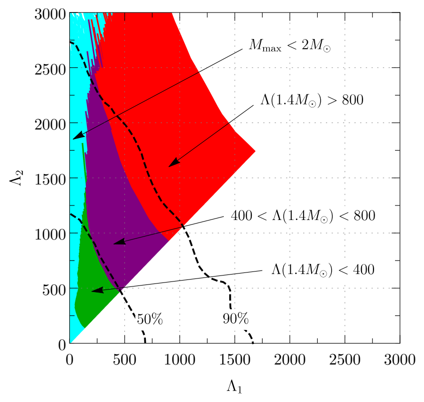


Λ_1 vs. Λ_2 of LIGO/Virgo measurment



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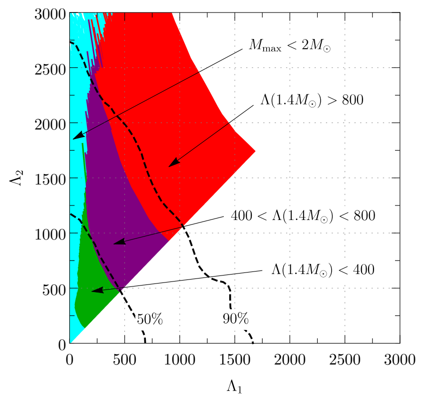
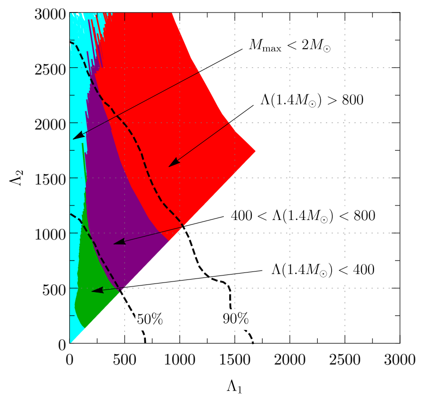


- Good qualitative agreement with 90% contour: a different way to measure credence level.



- Good qualitative agreement with 90% contour: a different way to measure credence level.
- Using 90% curve here instead:
  9.9 km $< R(1.4M_\odot) <$ 13.8km
  $2.0M_\odot < M_{\max} < 3.0M_\odot$
  Robust.

Summary

- No **fully first-principles** approach to the QCD EoS currently exists to apply to NSs.
- Matching cEFT to pQCD + observations provides constraints

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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:
    $9.9\text{ km} < R(1.4M_\odot) < 13.6\text{ km}$, $2.0M_\odot < M_{\text{max}} < 3.0M_\odot$
  - Observational astronomy now providing stringent bounds on the collective properties of dense QCD matter.

Thank you!