Using Neutron Stars to Understand Fundamental Physics

Liam Brodie

Washington University in St. Louis

Collaboration with: Mark G. Alford, Alexander Haber, and Ingo Tews

arXiv: 2205.10283, 2302.02989, and 2304.07836

Where are we going? Part 1 of 4

1. Compact stars and the **phase diagram** of nature
2. New models for neutron star **phenomenology**
3. Studying the **lightest** observed compact star
4. Some possible directions of **future work**

Where are we going? Part 1 of 4

1. Compact stars and the **phase diagram** of nature

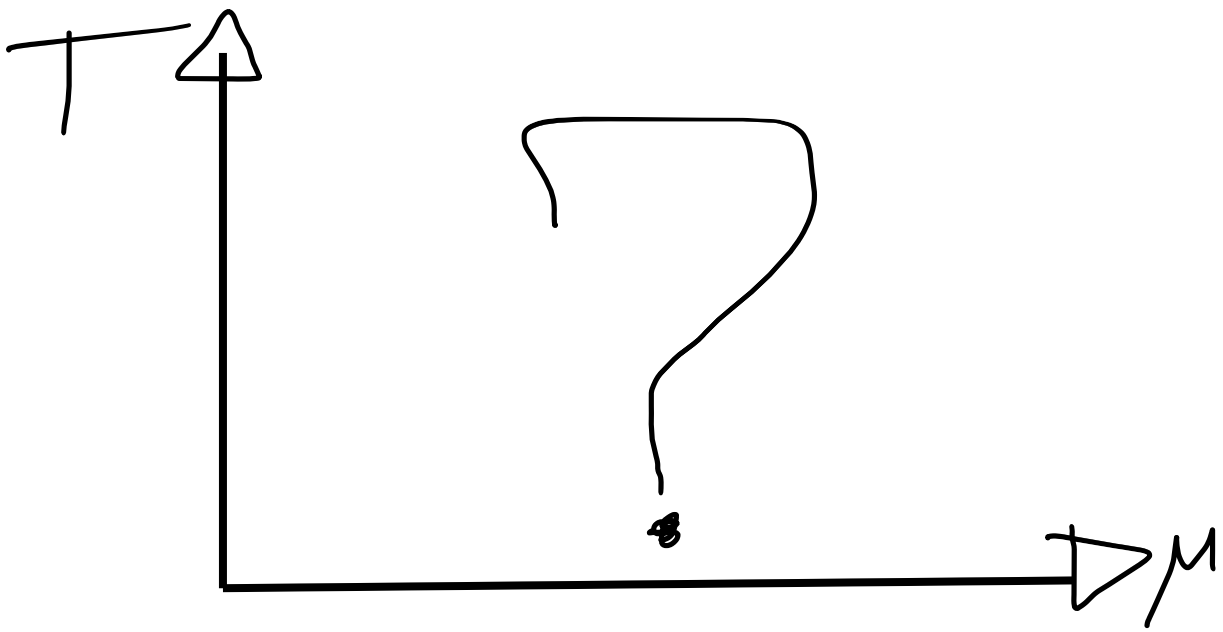
2. New models for neutron star **phenomenology**

3. Studying the **lightest** observed compact star

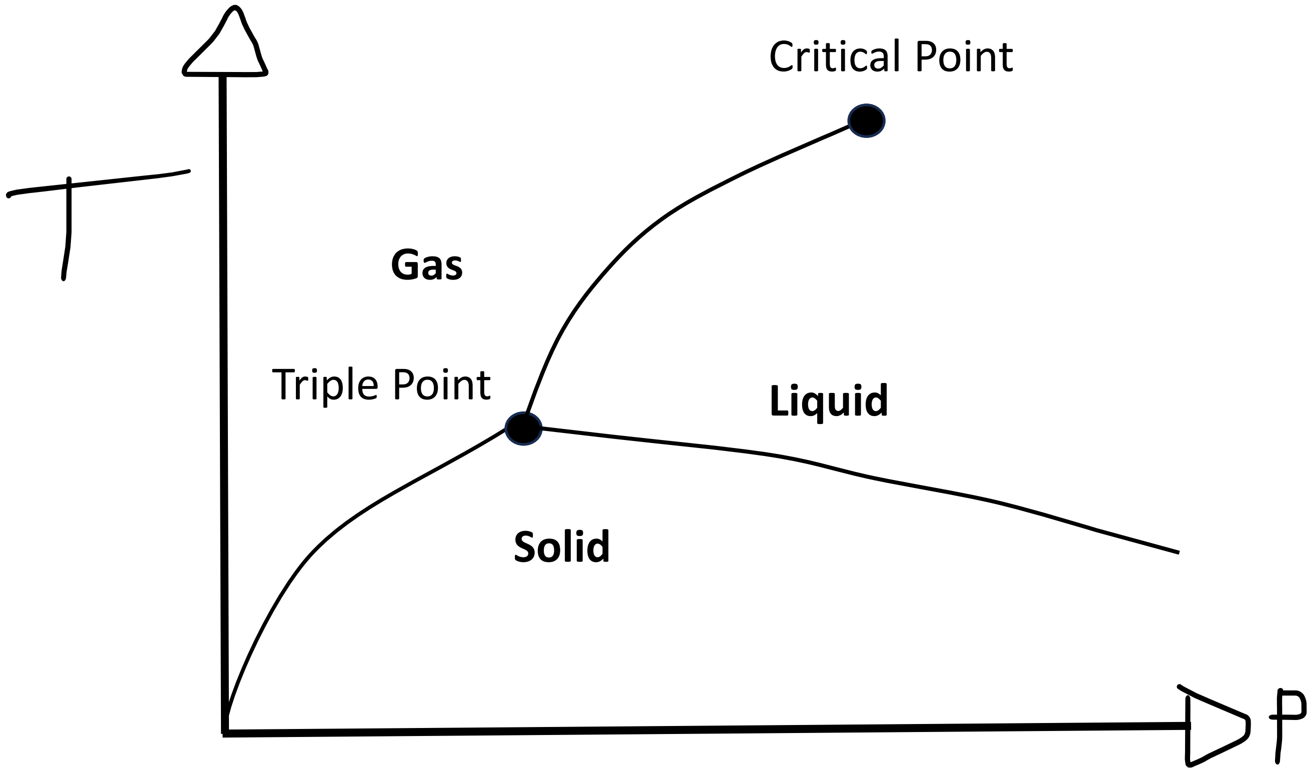
4. Some possible directions of **future work**

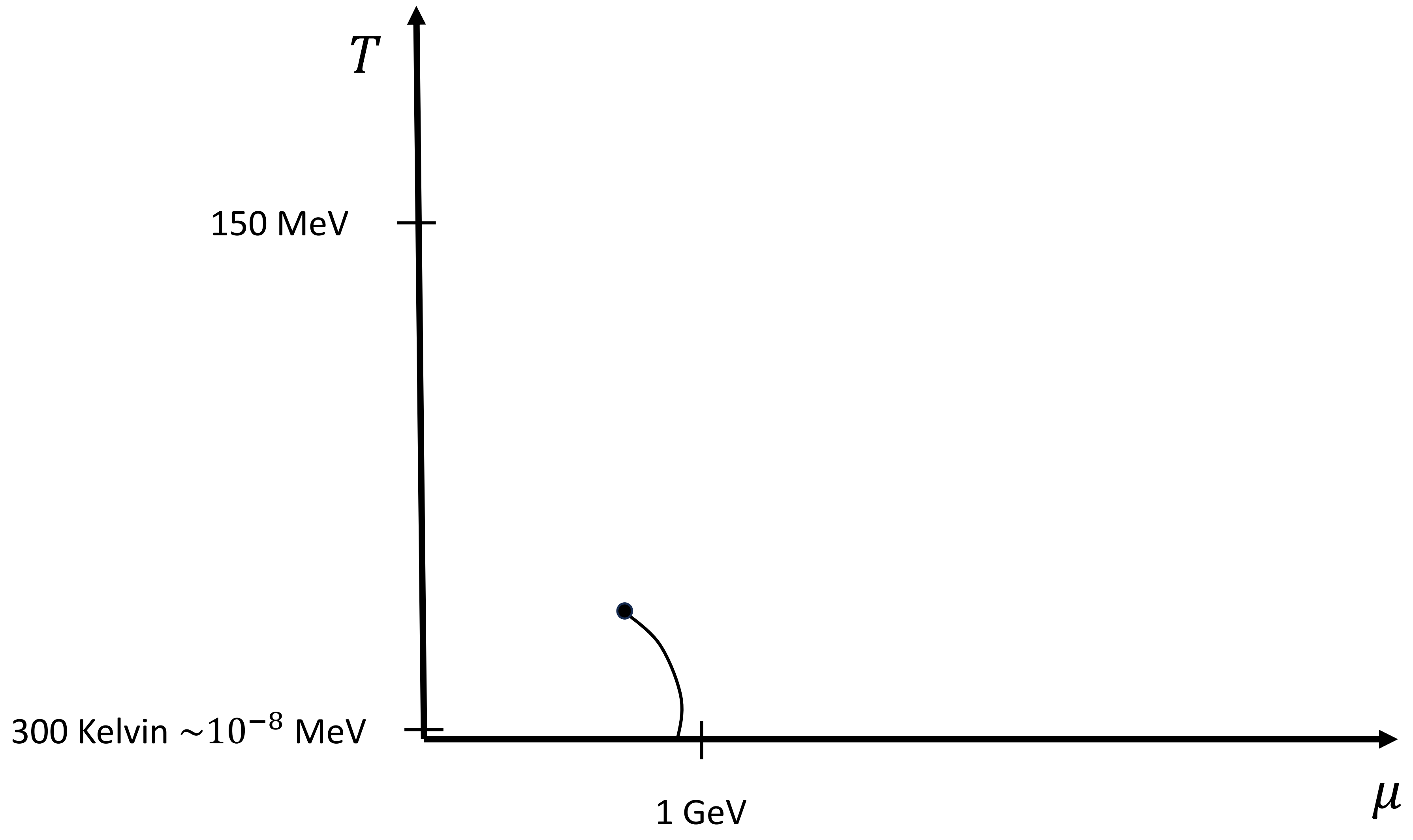
Fundamental Forces

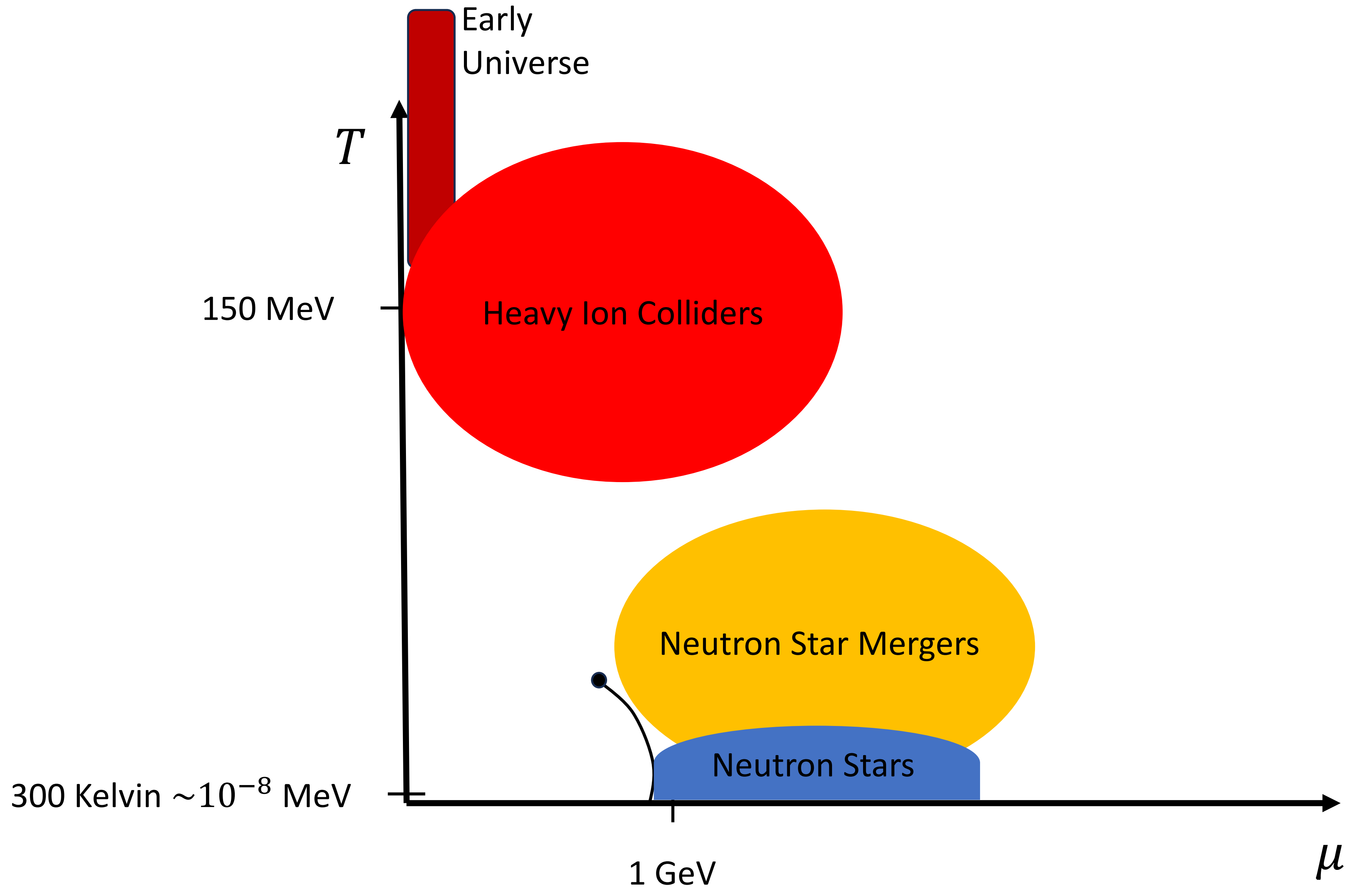
Gravity Electroweak Strong

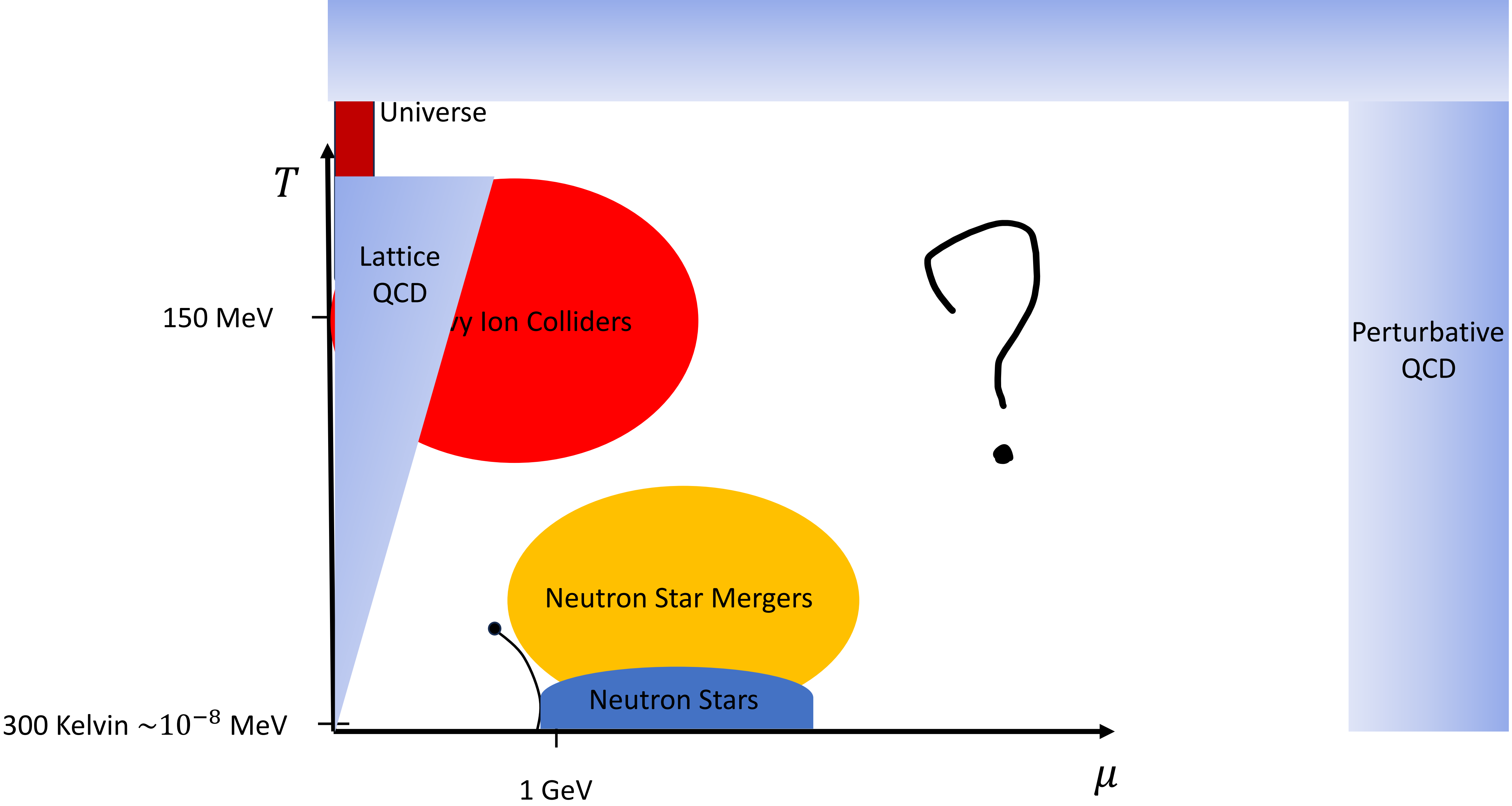


Earthly Matter: Water




T
150 MeV
300 Kelvin $\sim 10^{-8}$ MeV
1 GeV
μ


Early
Universe
T
150 MeV
Heavy Ion Colliders
Neutron Star Mergers
Neutron Stars
300 Kelvin $\sim 10^{-8}$ MeV
1 GeV
μ



Universe
T
Lattice
QCD
vy Ion Colliders
150 MeV
Perturbative
QCD
Neutron Star Mergers
Neutron Stars
300 Kelvin ~10^-8 MeV
1 GeV
μ

Why else are neutron stars interesting?

All fundamental forces are relevant!

Strong

Stabilizes star against gravity

Gravity

Second most **dense** object in the universe ($\sim 10^{15} \mathrm{g/cm^3}$)

Gravitational waves from merger

Electromagnetism

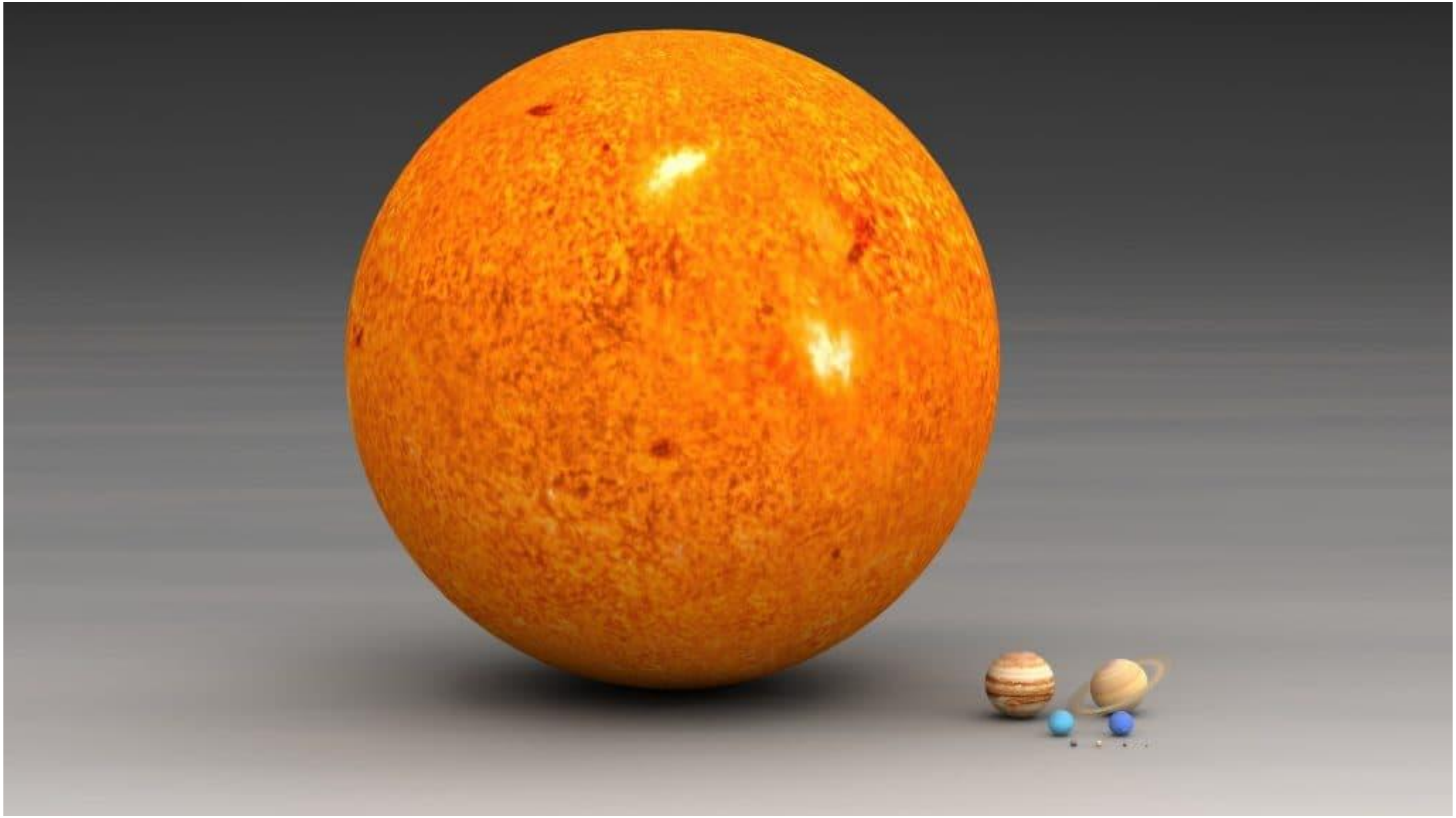
Strongest **magnetic fields** in the universe

Charge **neutrality**

Weak

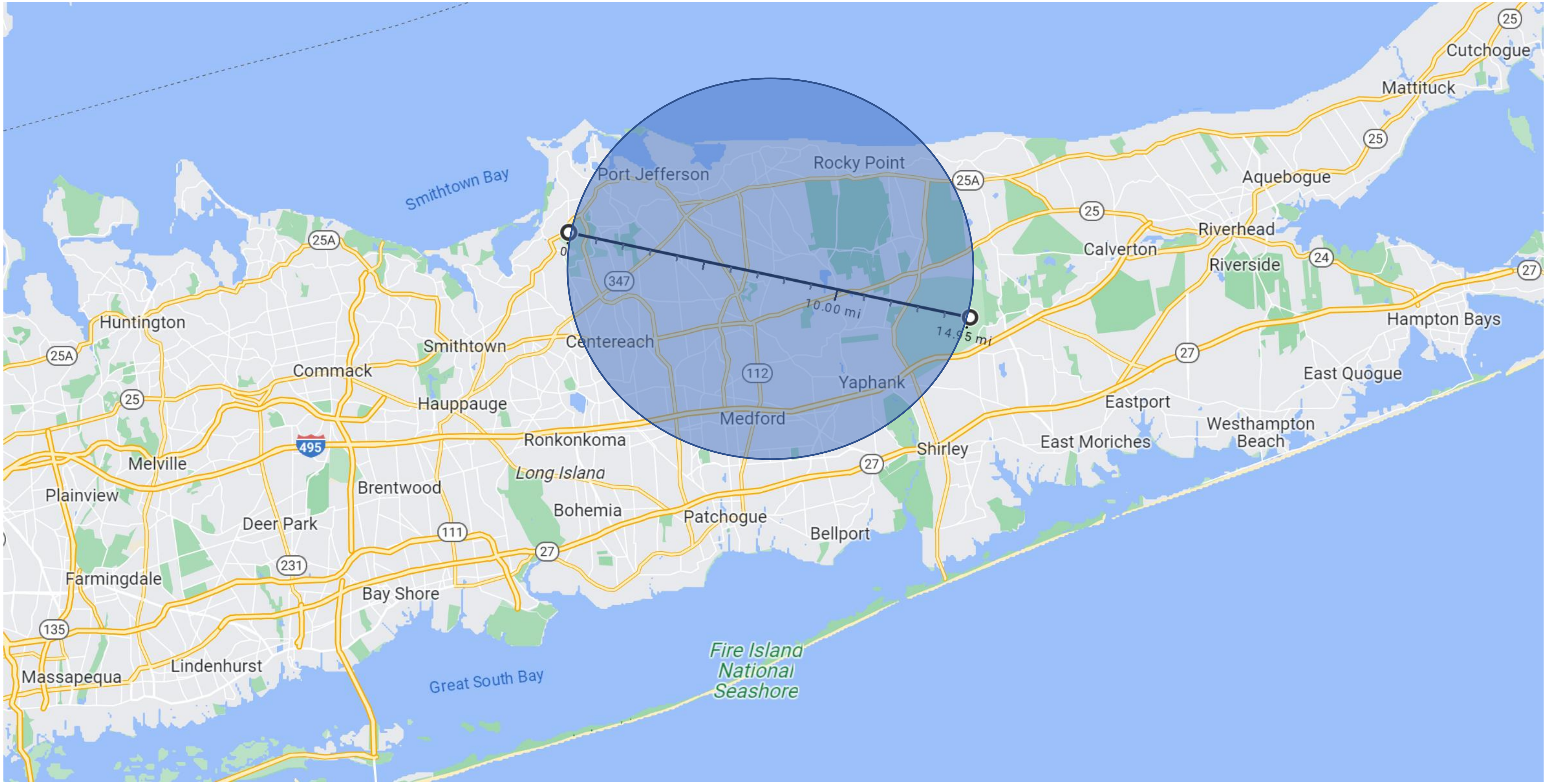
Isospin **equilibration**
→ Bulk viscosity

Nucleosynthesis



https://nineplanets.org/questions/how-big-is-the-sun/

10^{14} times smaller than the Sun



Google Maps

Conclusions: Part 1 of 4

- Neutron stars are…
  - **extremely** compact
  - used as a “laboratory” to explore some region of the **phase diagram** of matter
  - **cool** and **dense** (μ/T large)

- QCD **cannot** be solved exactly → **phenomenological** models needed

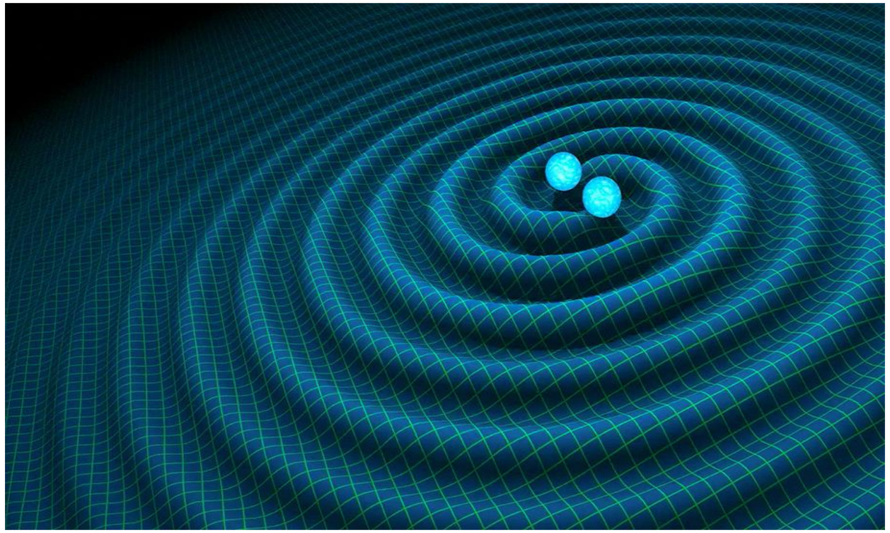
Where are we going? Part 2 of 4

1. Compact stars and the **phase diagram** of nature
2. New models for neutron star **phenomenology**
3. Studying the **lightest** observed compact star
4. Some possible directions of **future work**

Why develop new phenomenological models?

- Neutron star mergers probe regions of **neutron-rich** matter

- Most **equations of state** are calibrated to isospin-symmetric matter (**50% neutrons**) and **extrapolated** to ~90% neutron matter



R. HURT/CALTECH-JPL

- Let's calibrate models to neutron-rich matter!

Summary: Part 2 of 4

- Want **better** microscopic models of nuclear matter that are constrained by:
  - Properties of **neutron matter** (how?)
  - Saturation properties of **isospin-symmetric** nuclear matter
  - Observations of **neutron star** structure

Relativistic Mean-Field Theory (RMFT)

Advantages	**Limitations**
Relativistic theory (e.g., $v_{sound} < c$) ☺	Not a controlled approximation ☹
Tractable calculations ☺	Reasonable to about 6 times nuclear saturation density (~$1\mathrm{fm}^{-3}$) ☺ ☹
Finite temperature and out of equilibrium physics included ☺	No phase transition to deconfined quarks ☹
Microscopic information available ☺	Coupling constants need to be fit to something ☺☹

$$\mathcal{L} = \mathcal{L}_{\mathrm{N}} + \mathcal{L}_{\mathrm{M}} + \mathcal{L}_{l}$$

$$\mathcal{L}_{\mathrm{N}} = \bar{\psi}\left[i\gamma^{\mu}\partial_{\mu} - m_N + g_{\sigma}\langle\sigma\rangle - g_{\omega}\langle\omega_0\rangle - \frac{g_{\rho}}{2}\tau_3\langle\rho_{03}\rangle\right]\psi$$

$$\mathcal{L}_M = -\frac{1}{2}m_{\sigma}^2\langle\sigma\rangle^2 - b\frac{M}{3}(g_{\sigma}\langle\sigma\rangle)^3 - \frac{c}{4}(g_{\sigma}\langle\sigma\rangle)^4 + \frac{1}{2}m_{\omega}^2\langle\omega_0\rangle^2 + \frac{1}{2}m_{\rho}^2\langle\rho_{03}\rangle^2 + \Lambda(g_{\rho}\langle\omega_0\rangle\langle\rho_{03}\rangle)^2$$

$$\mathcal{L}_l = \bar{\psi}_e\left(i\gamma^{\mu}\partial_{\mu} - m_e\right)\psi_e$$

$$\mathcal{L} = \mathcal{L}_{\mathrm{N}} + \mathcal{L}_{\mathrm{M}} + \mathcal{L}_l$$

$$\mathcal{L}_{\mathrm{N}} = \bar{\psi}\left[i\gamma^{\mu}\partial_{\mu} - m_N + g_{\sigma}\langle\sigma\rangle - g_{\omega}\langle\omega_0\rangle - \frac{g_{\rho}}{2}\tau_3\langle\rho_{03}\rangle\right]\psi$$

$$\mathcal{L}_M = -\frac{1}{2}m_{\sigma}^2\langle\sigma\rangle^2 - b\frac{M}{3}(g_{\sigma}\langle\sigma\rangle)^3 - \frac{c}{4}(g_{\sigma}\langle\sigma\rangle)^4 + \frac{1}{2}m_{\omega}^2\langle\omega_0\rangle^2 + \frac{1}{2}m_{\rho}^2\langle\rho_{03}\rangle^2 + \Lambda(g_{\rho}\langle\omega_0\rangle\langle\rho_{03}\rangle)^2$$

$$\mathcal{L}_l = \bar{\psi}_e\left(i\gamma^{\mu}\partial_{\mu} - m_e\right)\psi_e$$

Nuclear Physics Data to Constrain Our Model

Fit relativistic mean-field theory to **symmetric** and **neutron** matter

- Isospin-Symmetric Matter
  - Binding energy
  - Pressure
  - Incompressibility

- Neutron Matter

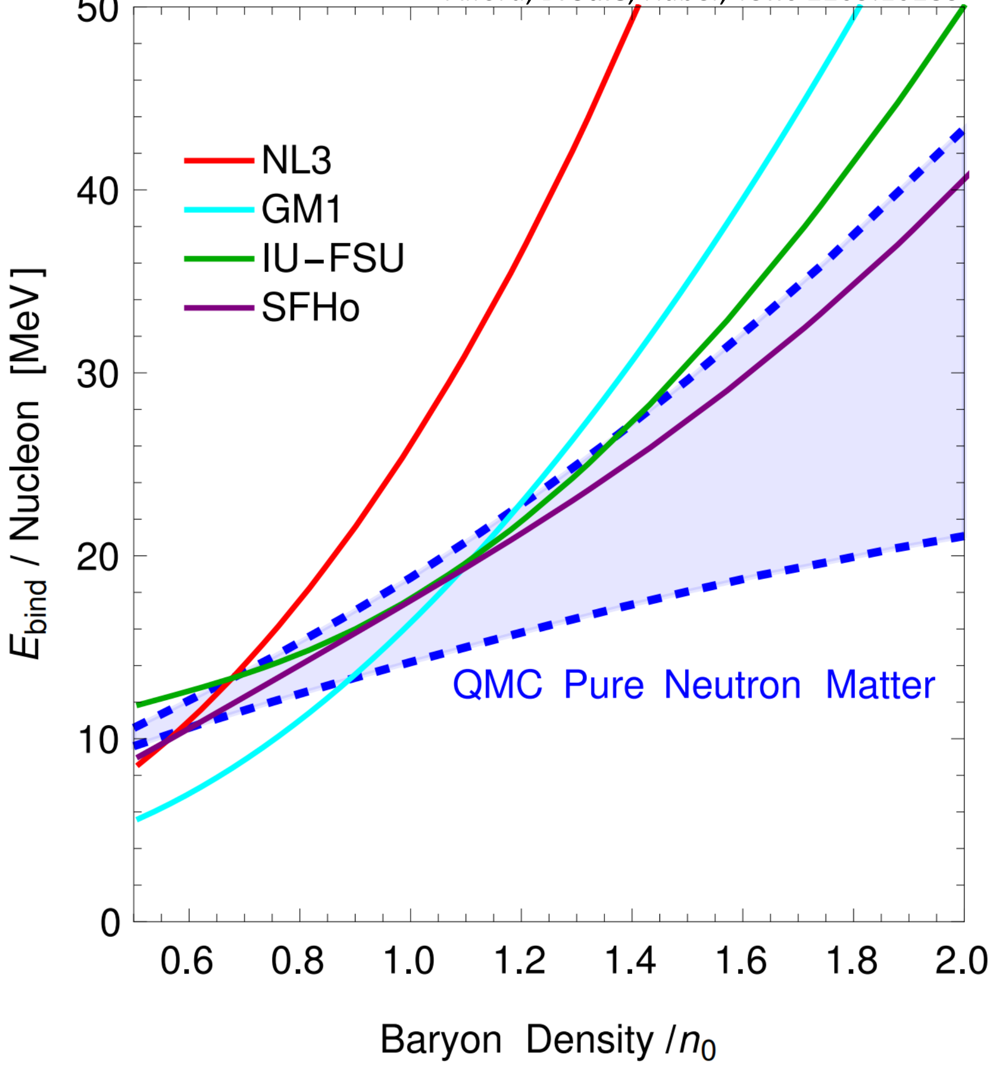
  →Chiral Effective Field Theory

Chiral Effective Field Theory (ChiEFT)

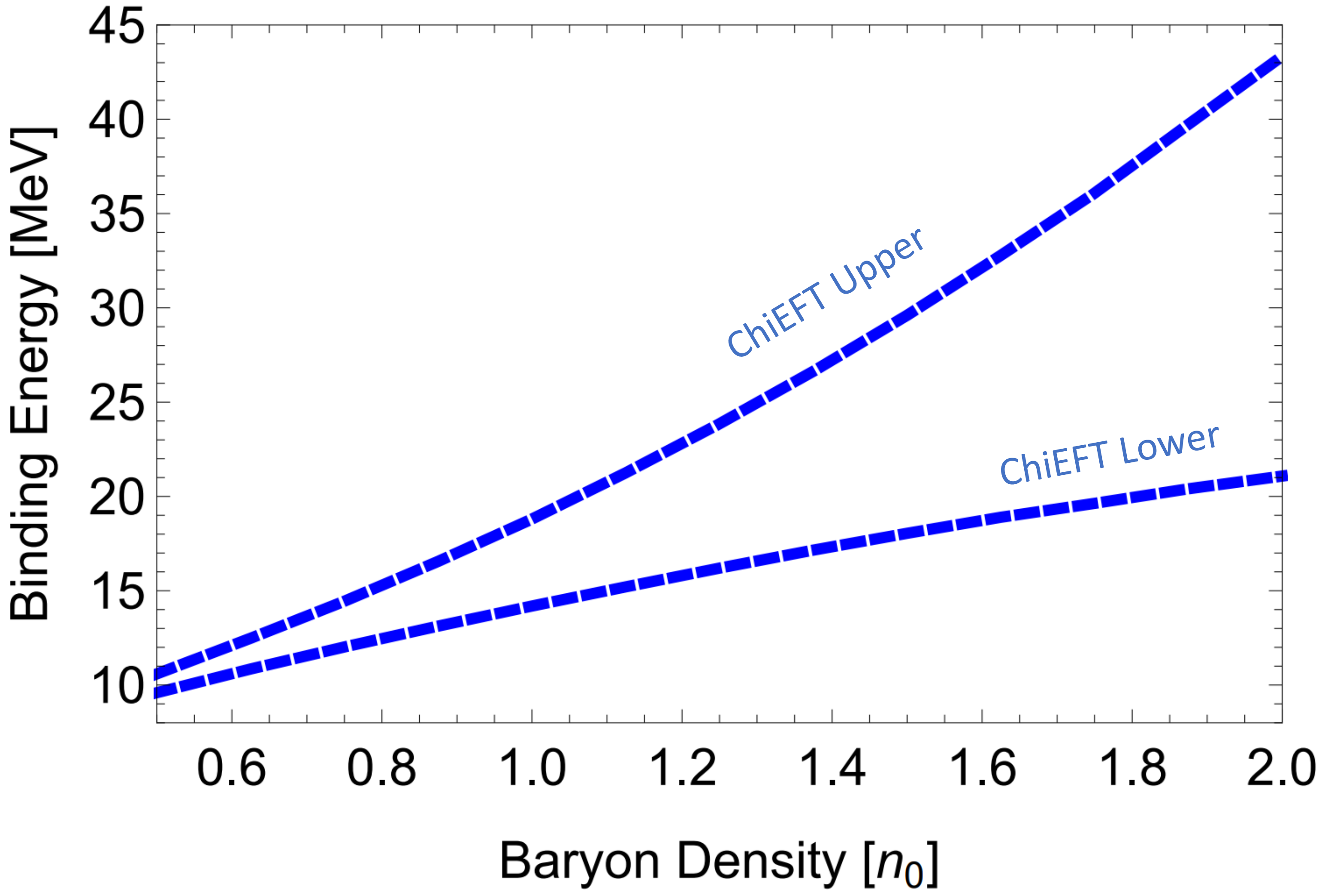
- Based on the <u>symmetries</u> of QCD with nucleon and pion degrees of freedom
- <u>Controlled</u> approximation to QCD valid at low densities
- Theory fitted to data from scattering <u>experiments</u>

Commonly used relativistic mean-field theories are **inconsistent** with ChiEFT for neutron matter

Alford, **Brodie**, Haber, Tews 2205.10283

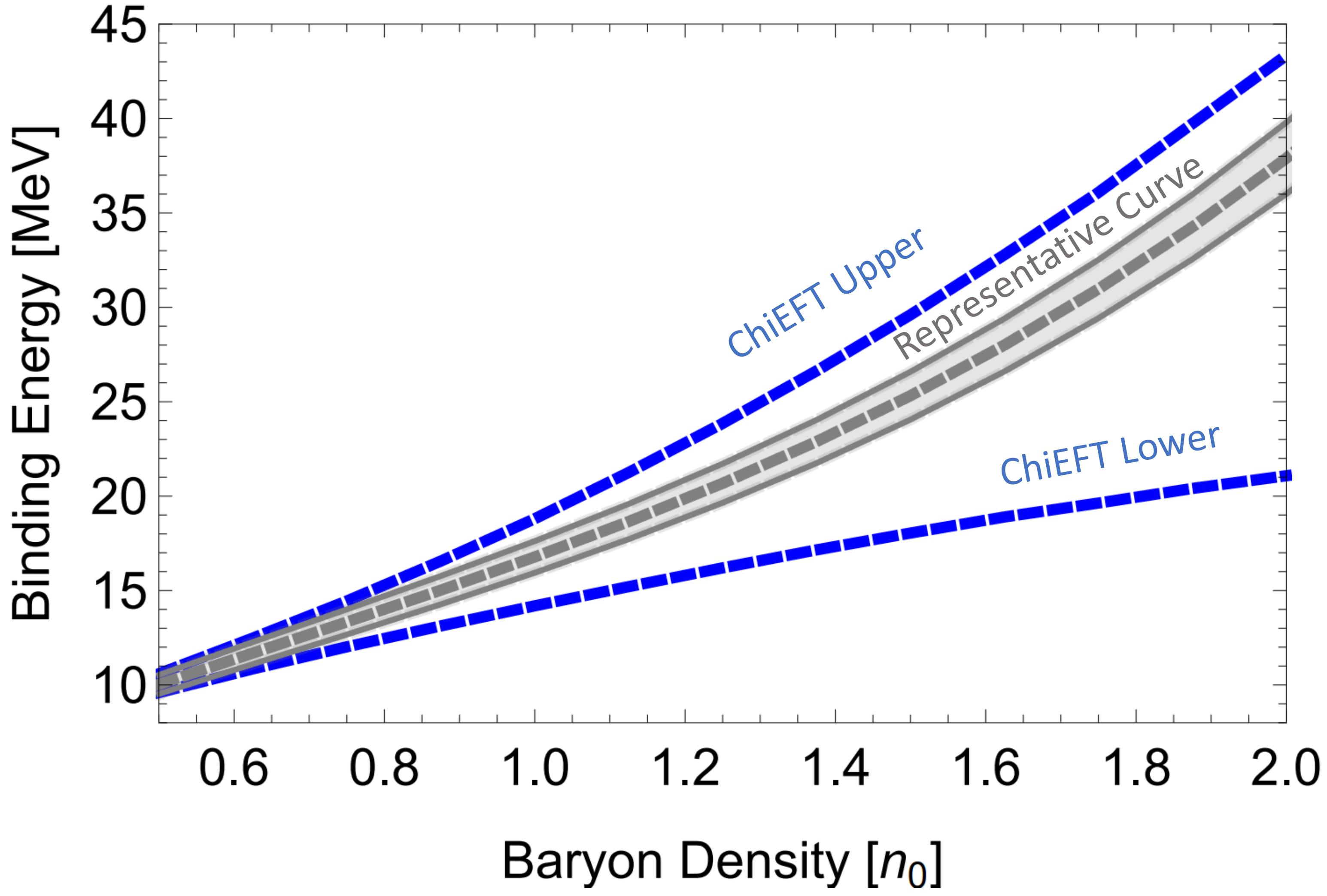


Uncertainty in Chiral Effective Field Theory



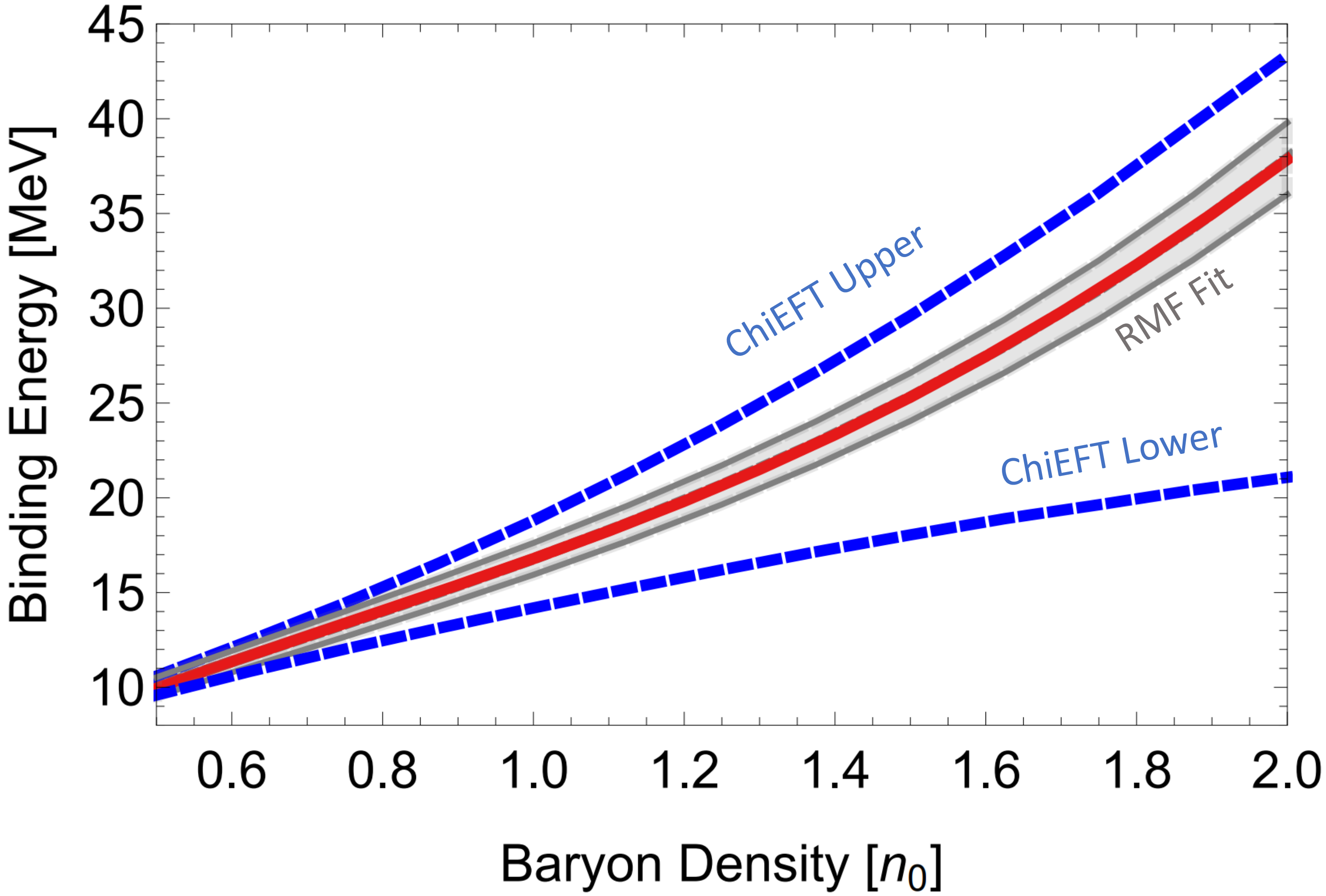
ChiEFT data from Tews et al. (arXiv:1801.01923)

Uncertainty in Chiral Effective Field Theory



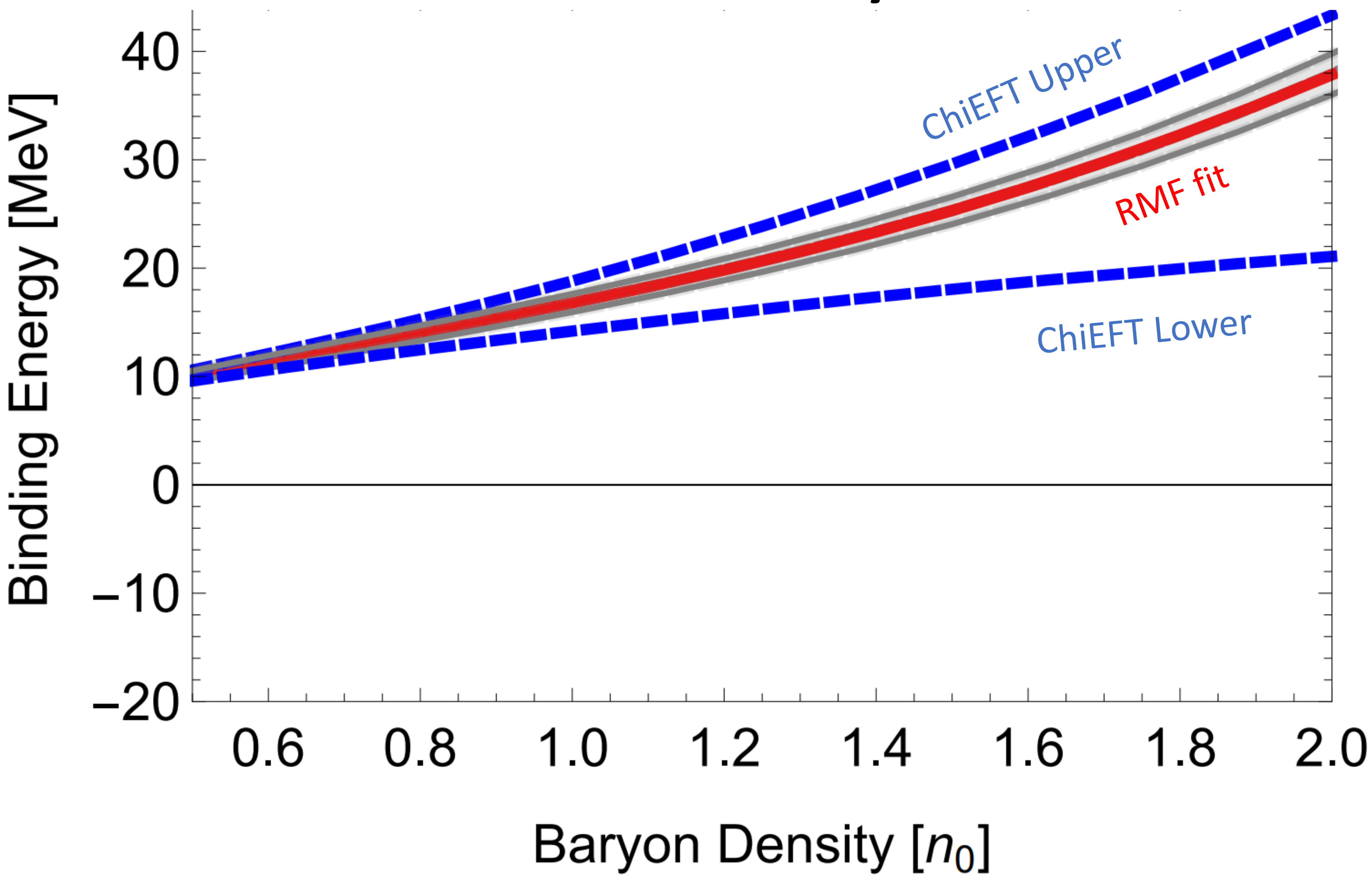
ChiEFT data from Tews et al. (arXiv:1801.01923)

Uncertainty in Chiral Effective Field Theory

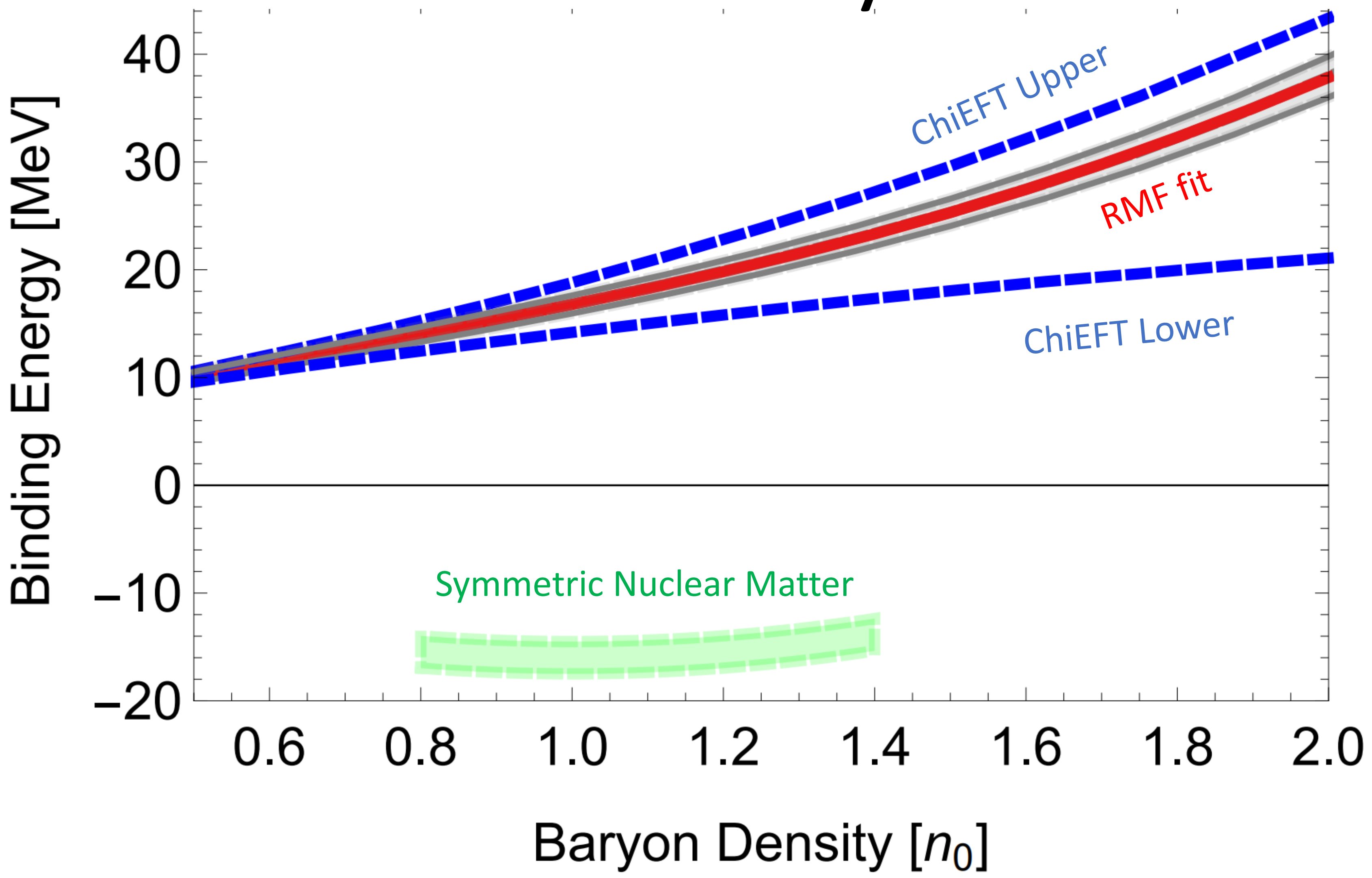


ChiEFT data from Tews et al. (arXiv:1801.01923)

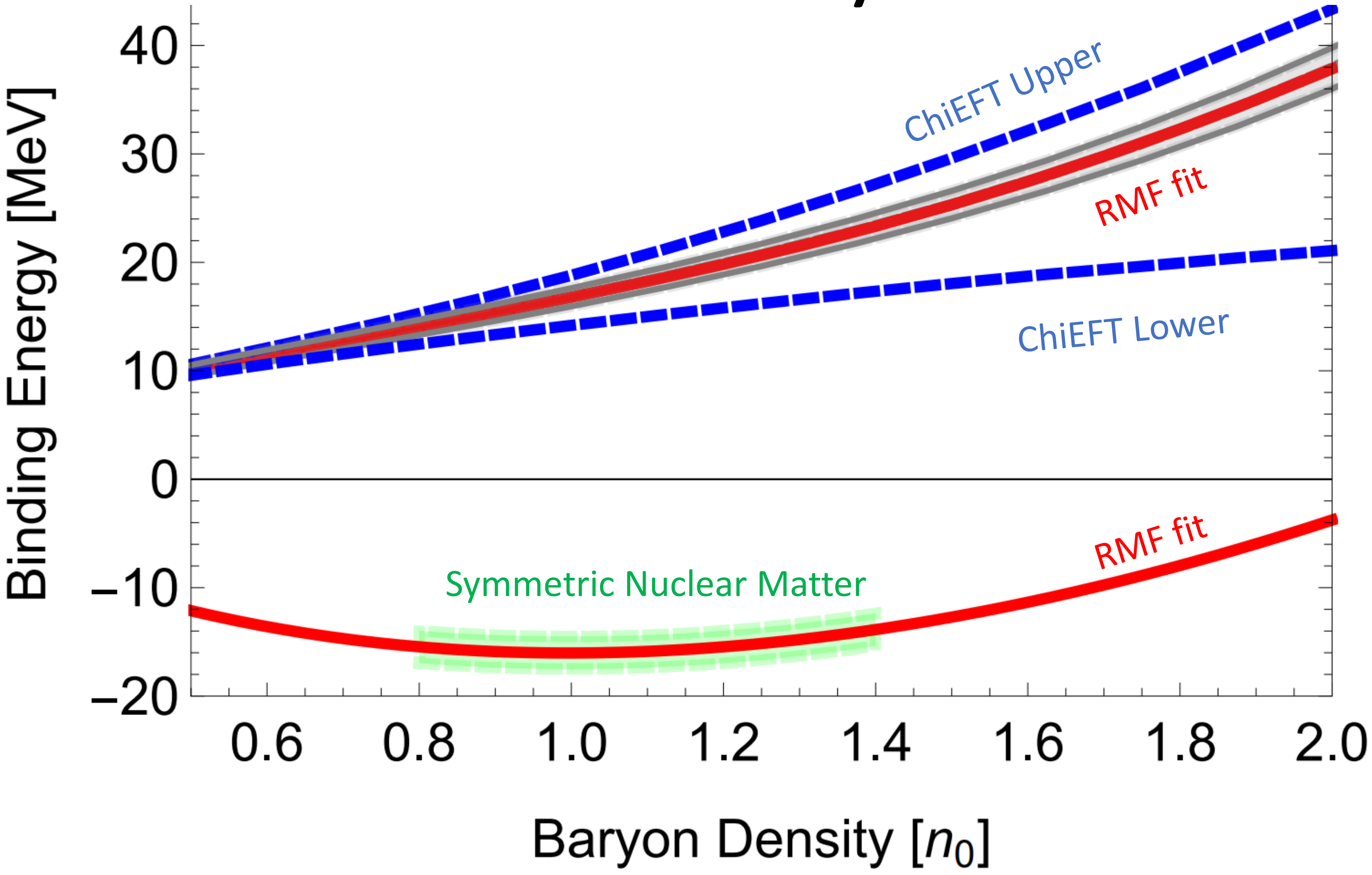
Simultaneous Nuclear Physics Constraints



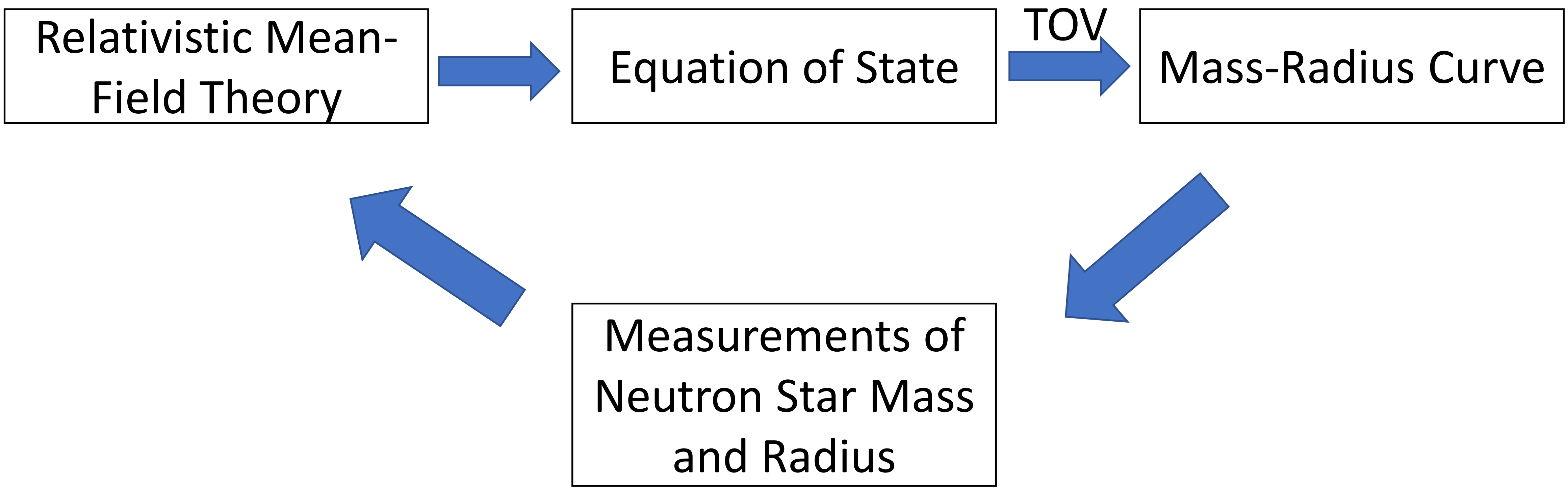
Simultaneous Nuclear Physics Constraints



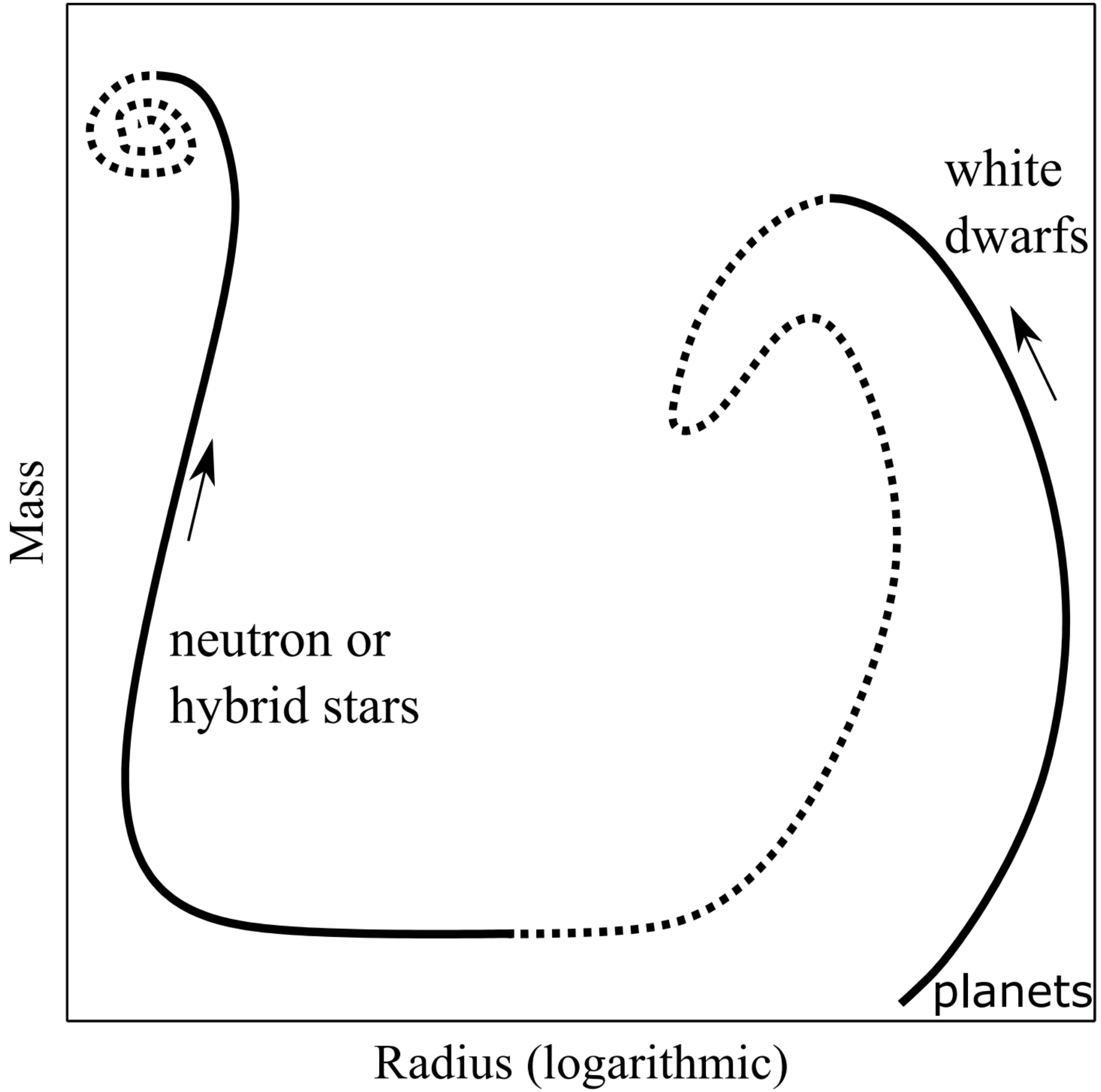
Simultaneous Nuclear Physics Constraints



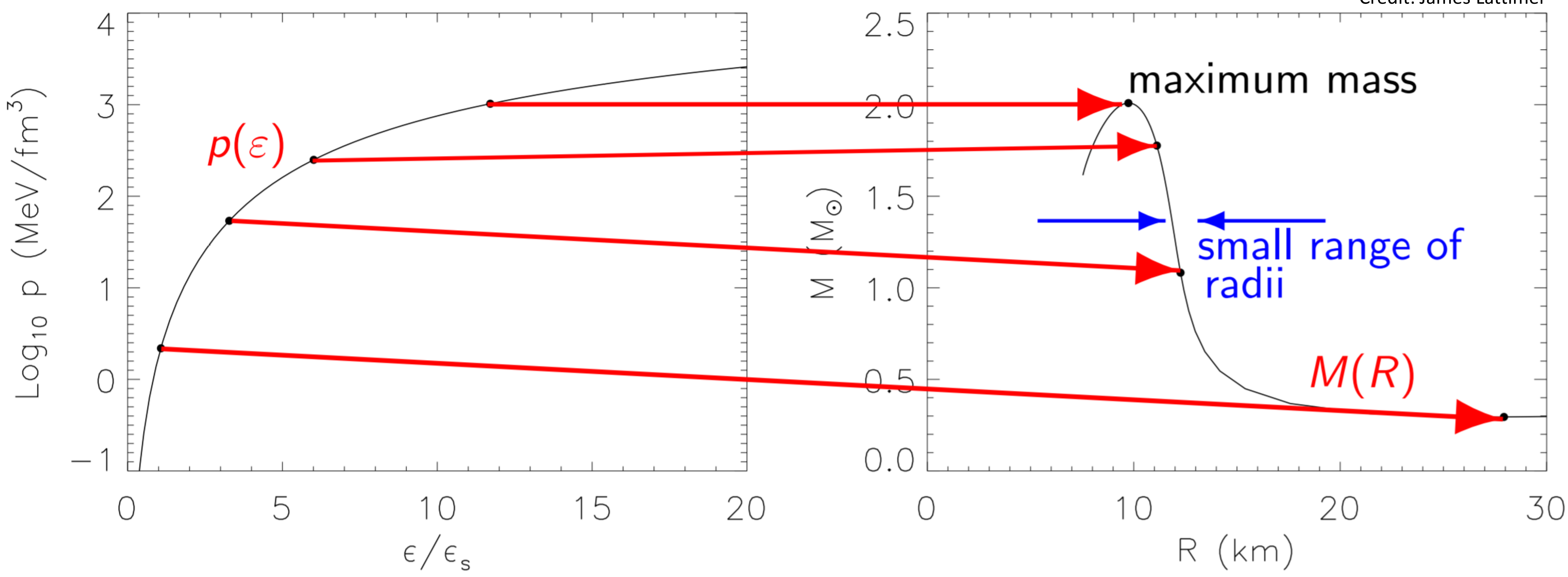
How can neutron stars constrain our model?



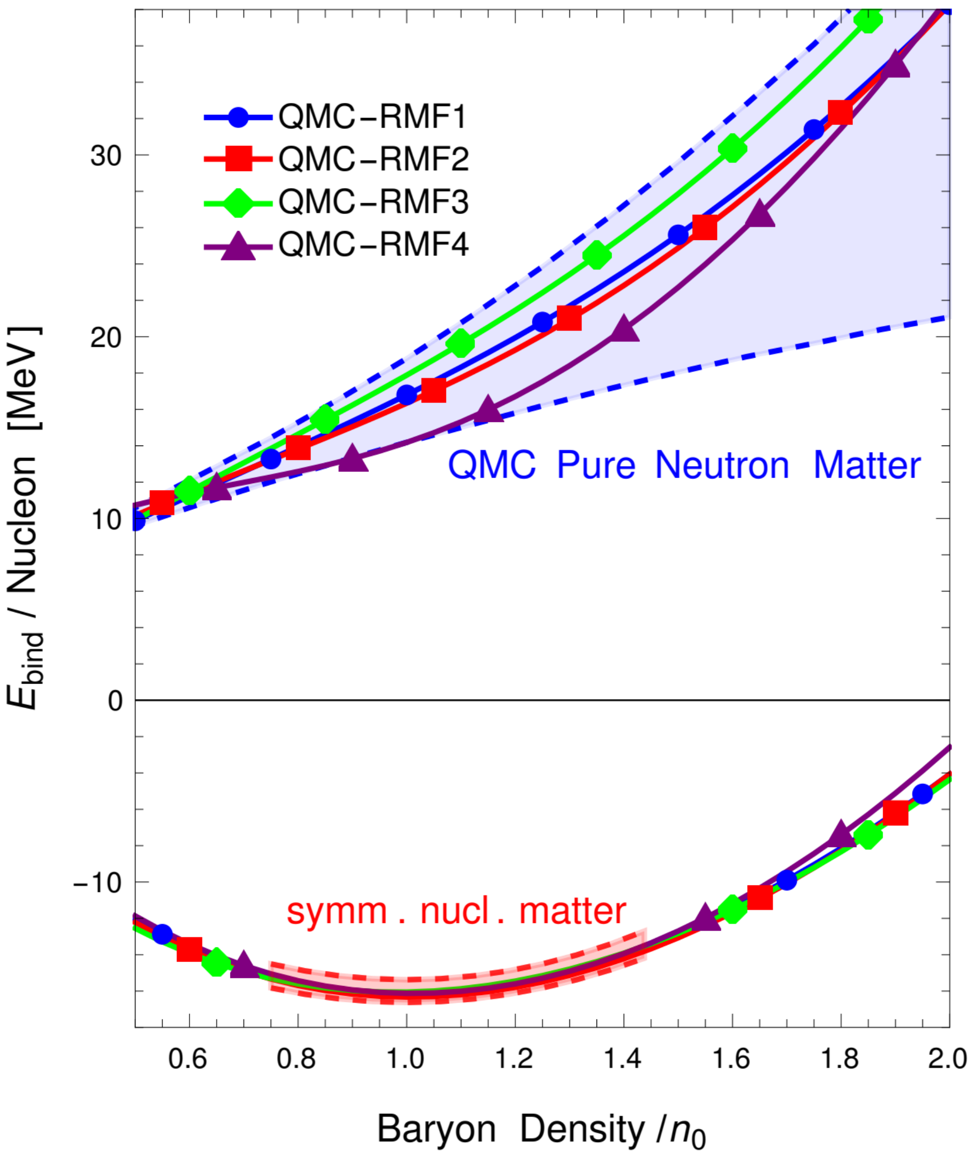
Alford et al. 1705.09880

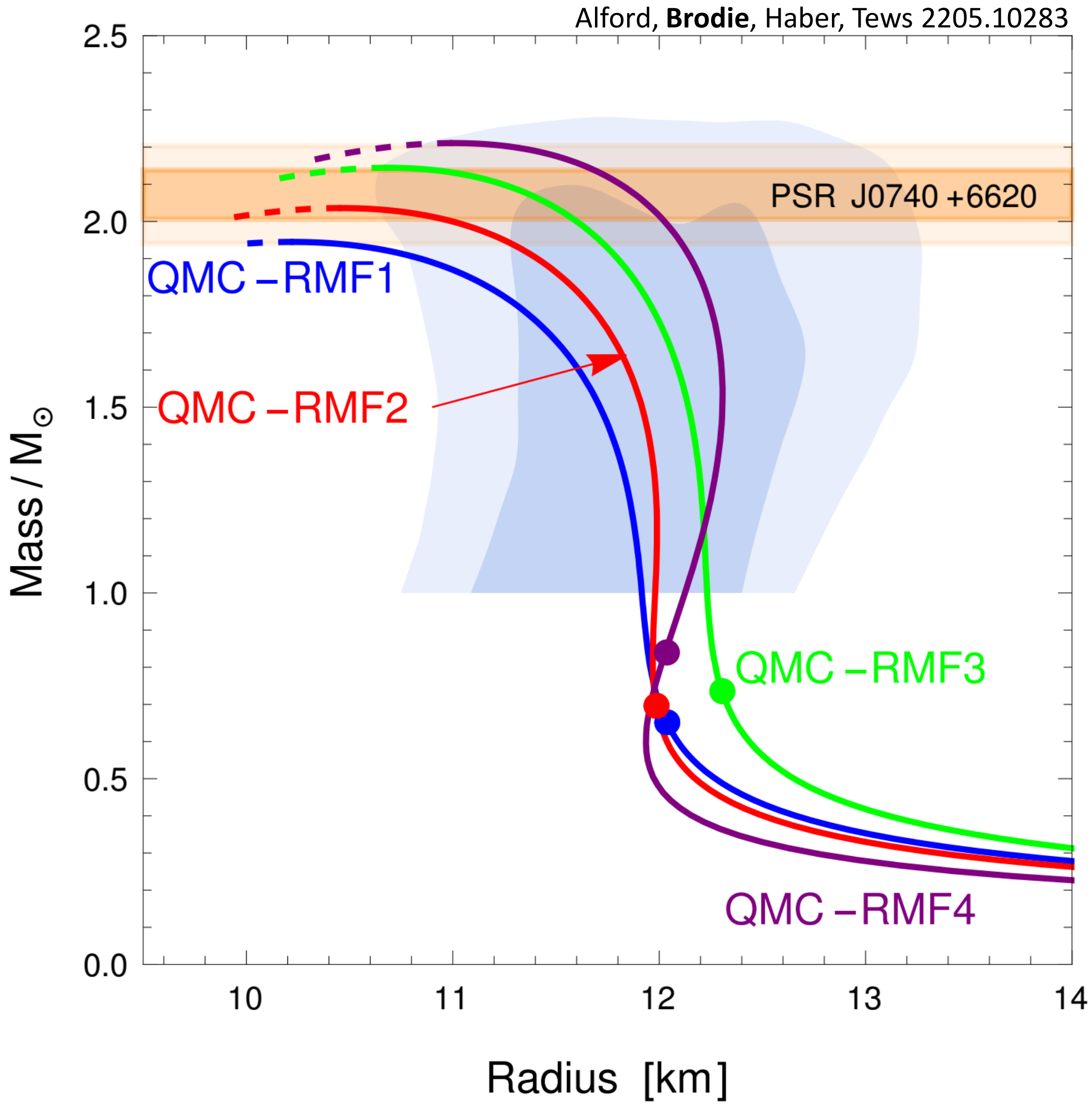


Credit: James Lattimer



Equation of State ← Observations


QMC−RMF1
QMC−RMF2
QMC−RMF3
QMC−RMF4
QMC Pure Neutron Matter
symm . nucl . matter
$E_{\rm bind}$ / Nucleon [MeV]
Baryon Density / n_0
30
20
10
0
−10
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0


Alford, **Brodie**, Haber, Tews 2205.10283
PSR J0740 +6620
QMC −RMF1
QMC −RMF2
QMC −RMF3
QMC −RMF4
Mass / $M_\odot$
Radius [km]
2.5
2.0
1.5
1.0
0.5
0.0
10
11
12
13
14

Conclusions: Part 2 of 4

Developed **QMC-RMF1,2,3,4**: models of nuclear matter that are constrained by isospin-symmetric and neutron matter and by observations of neutron star structure

Ready for use in neutron star merger simulations: **compose.obspm.fr/eos/297**

- Tabulated over a range of temperatures, densities, and proton fractions
- Provides an equation of state (p,ε,s,μ,…)
- Provides particle dispersion relations and effective masses

Where are we going? Part 3 of 4

1. Compact stars and the **phase diagram** of nature
2. New models for neutron star **phenomenology**
3. Studying the **lightest** observed compact star
4. Some possible directions of **future work**

nature astronomy

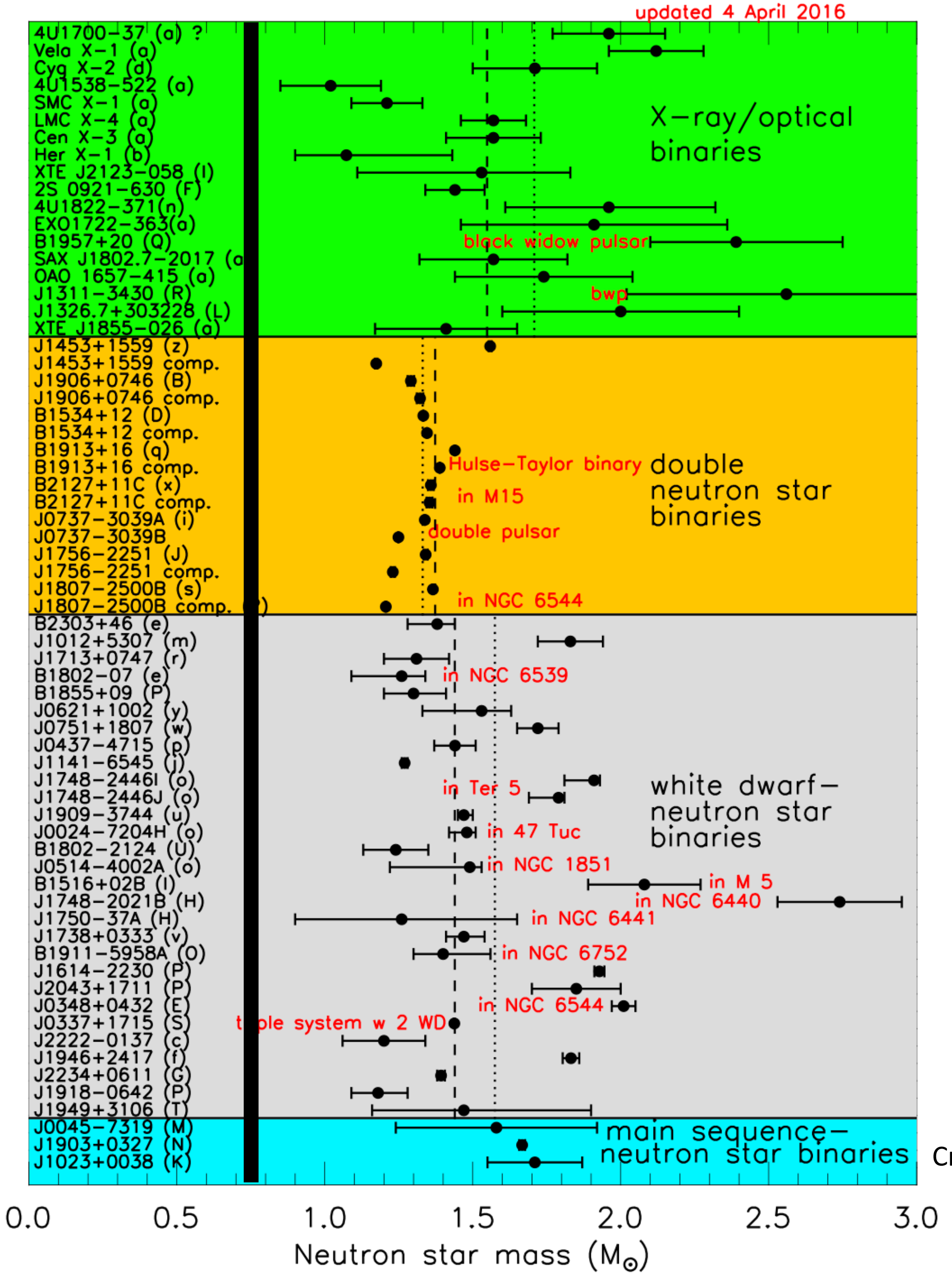
Article

Doroshenko et al., 2022

A strangely light neutron star within a supernova remnant

$$M = 0.77^{+0.20}_{-0.17}\ \mathrm{M_\odot}$$

$$R = 10.4^{+0.86}_{-0.78}\ \mathrm{km}$$



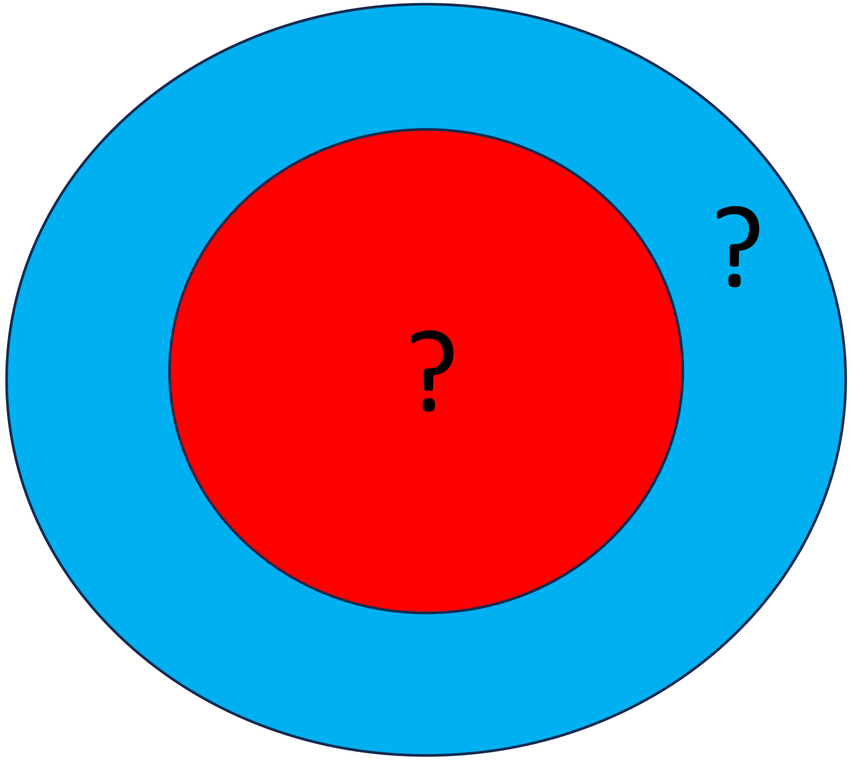
Credit: Lattimer, Prakash

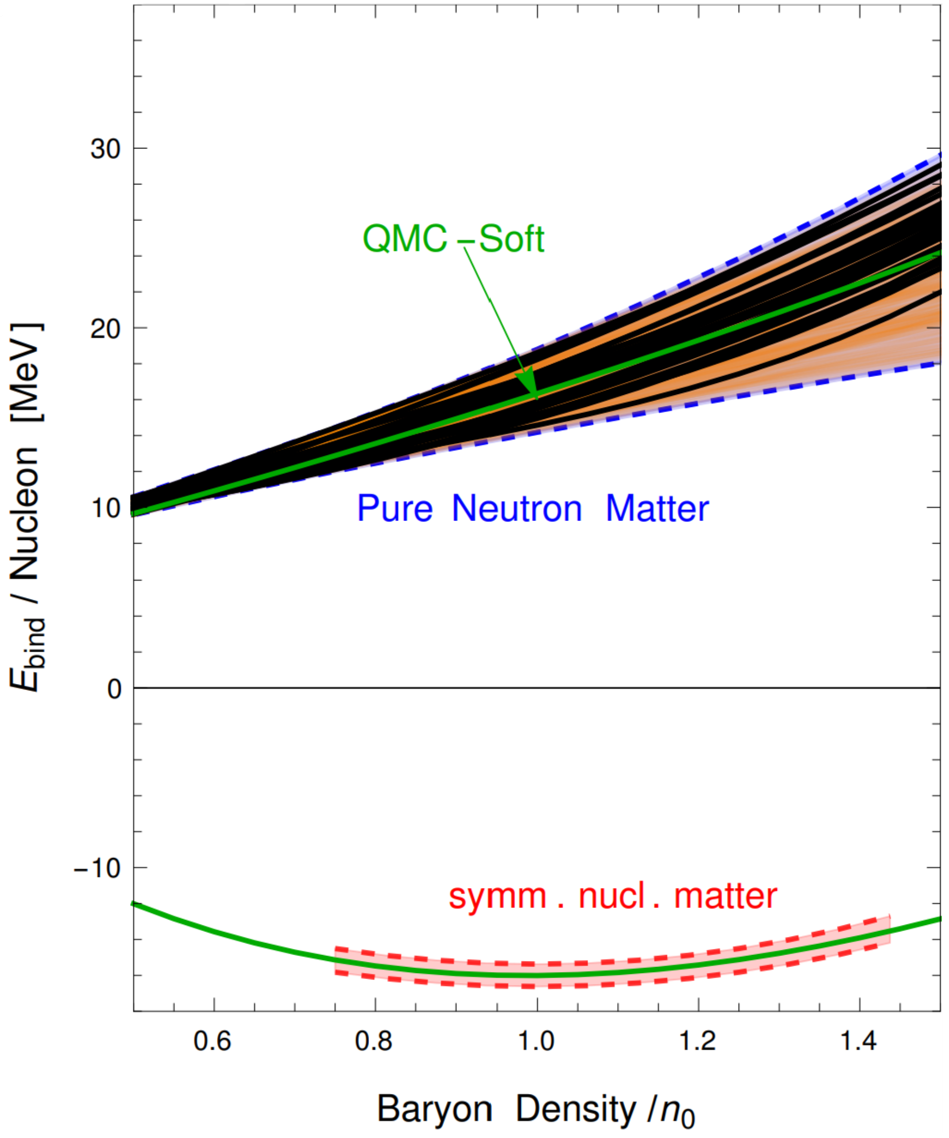
Studying the Lightest Compact Star

$$M = 0.77^{+0.20}_{-0.17}\ \mathrm{M}_\odot \qquad R = 10.4^{+0.86}_{-0.78}\ \mathrm{km}$$

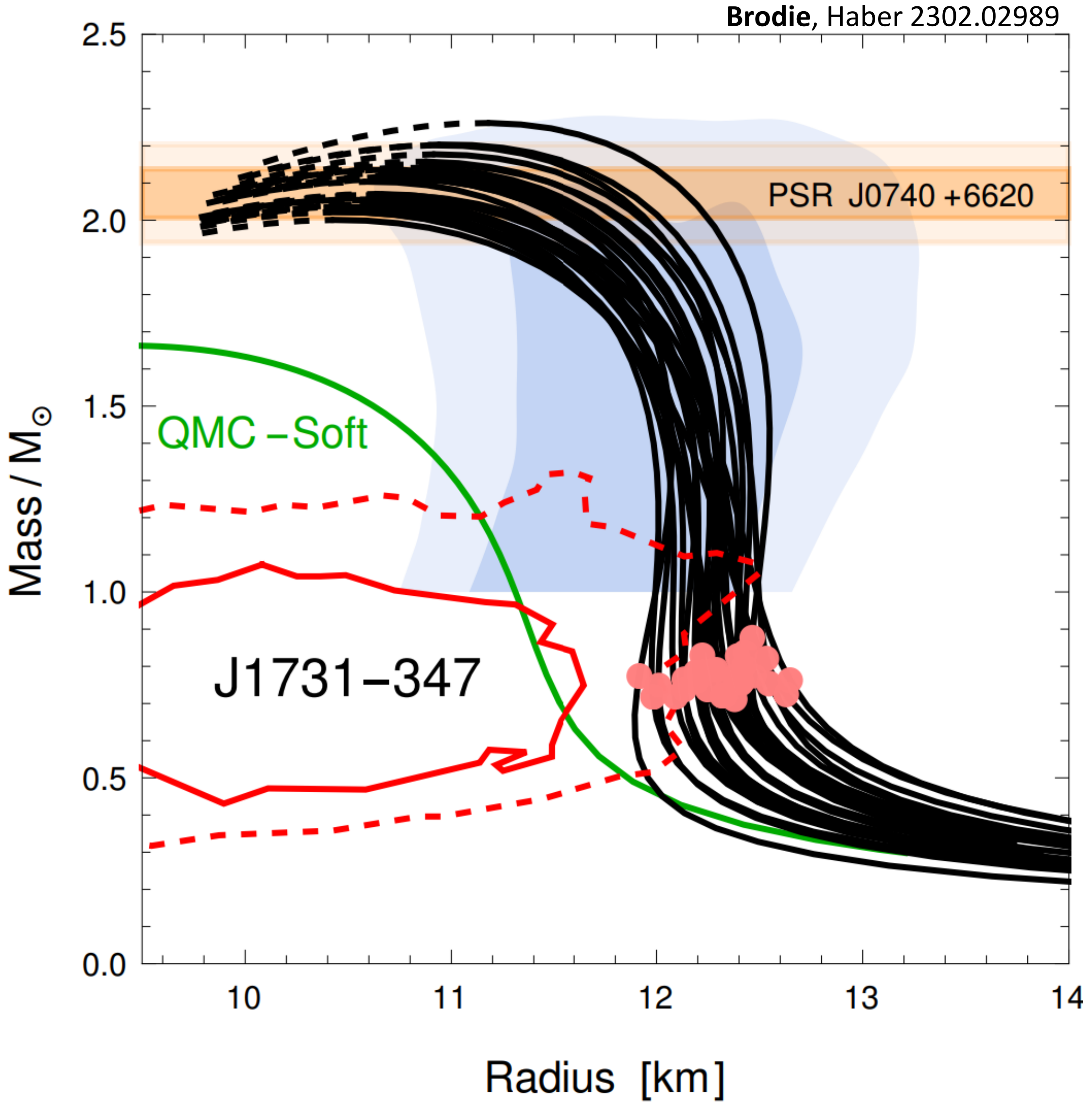
- Caution: Parameter estimation & formation mechanism

- What is the **composition** of this star?
  - Quark star
  - Neutron star
  - Hybrid star
  - Etc…





30
20
10
0
−10
QMC −Soft
Pure Neutron Matter
symm . nucl . matter
E_{bind} / Nucleon [MeV]
0.6
0.8
1.0
1.2
1.4
Baryon Density / n_0

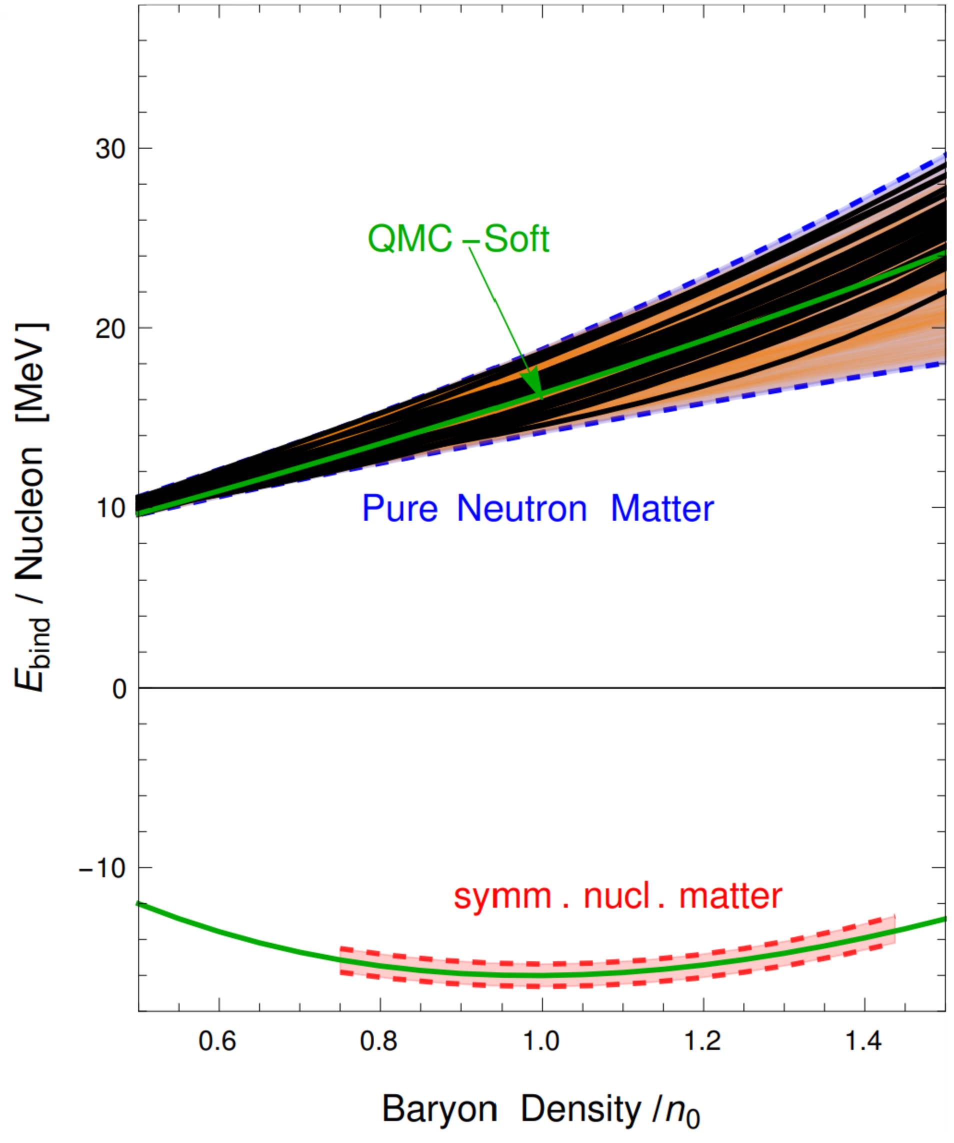


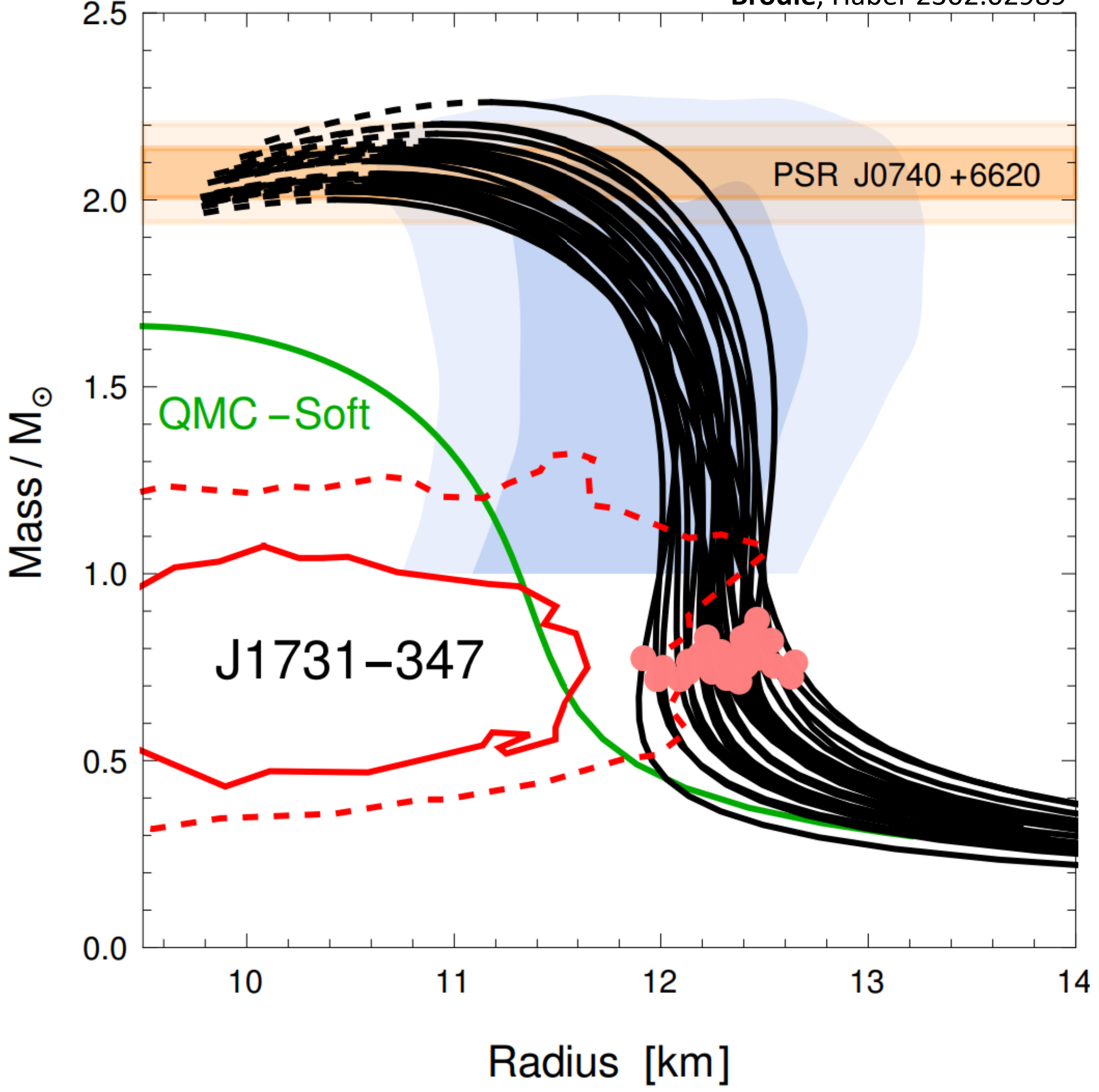
Brodie, Haber 2302.02989
2.5
2.0
1.5
1.0
0.5
0.0
PSR J0740 +6620
QMC −Soft
J1731−347
Mass / $M_\odot$
10
11
12
13
14
Radius [km]

Nuclear models only reach 2σ consistency with the HESS J1731-347 measurement

- Possibly because:
  - Measurement uncertainties **underestimated**
  - **Additional** nuclear physics not included in the family of RMFs used
  - Nucleons are not the only relevant **degree of freedom**

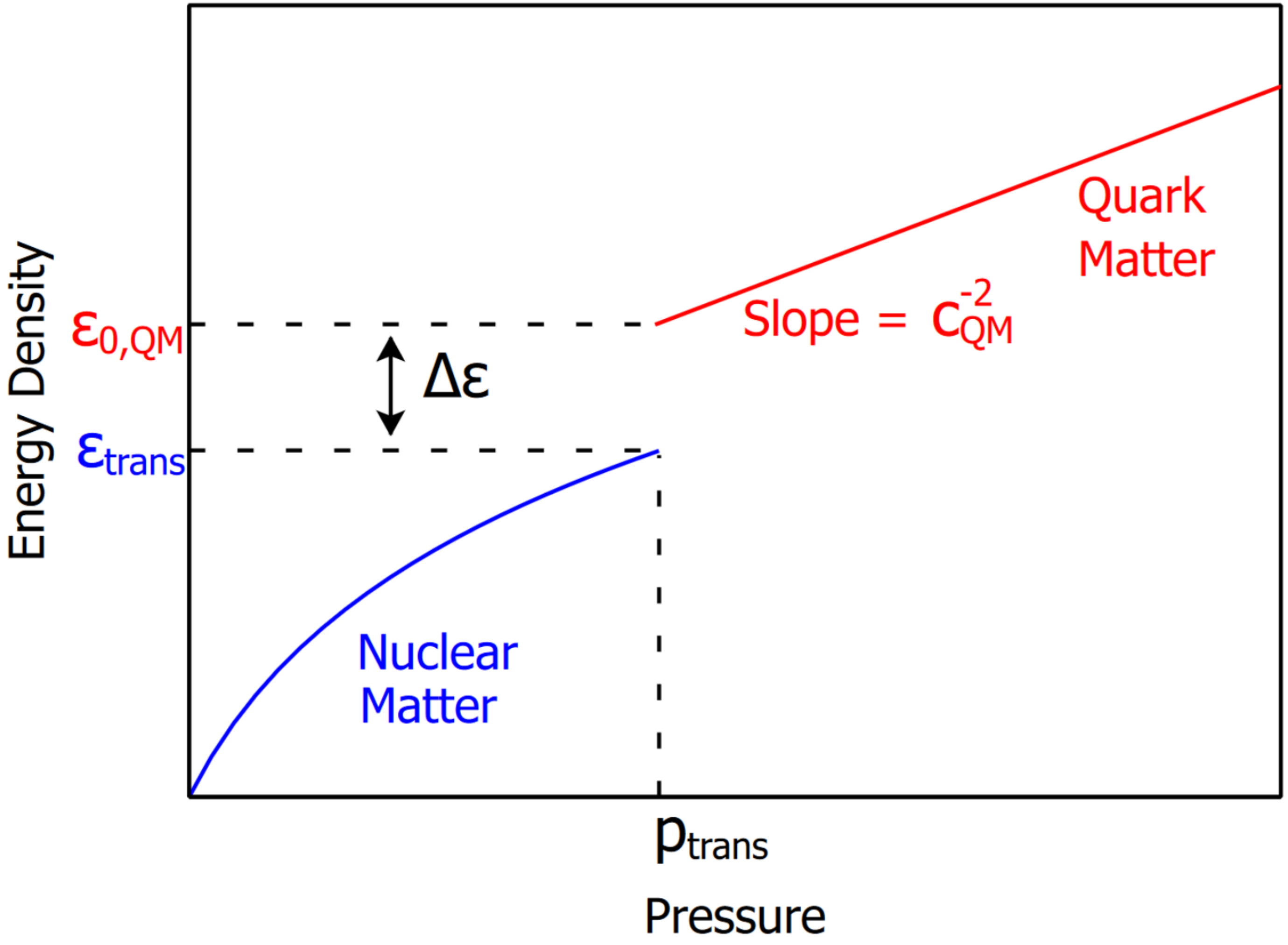
Brodie, Haber 2302.02989

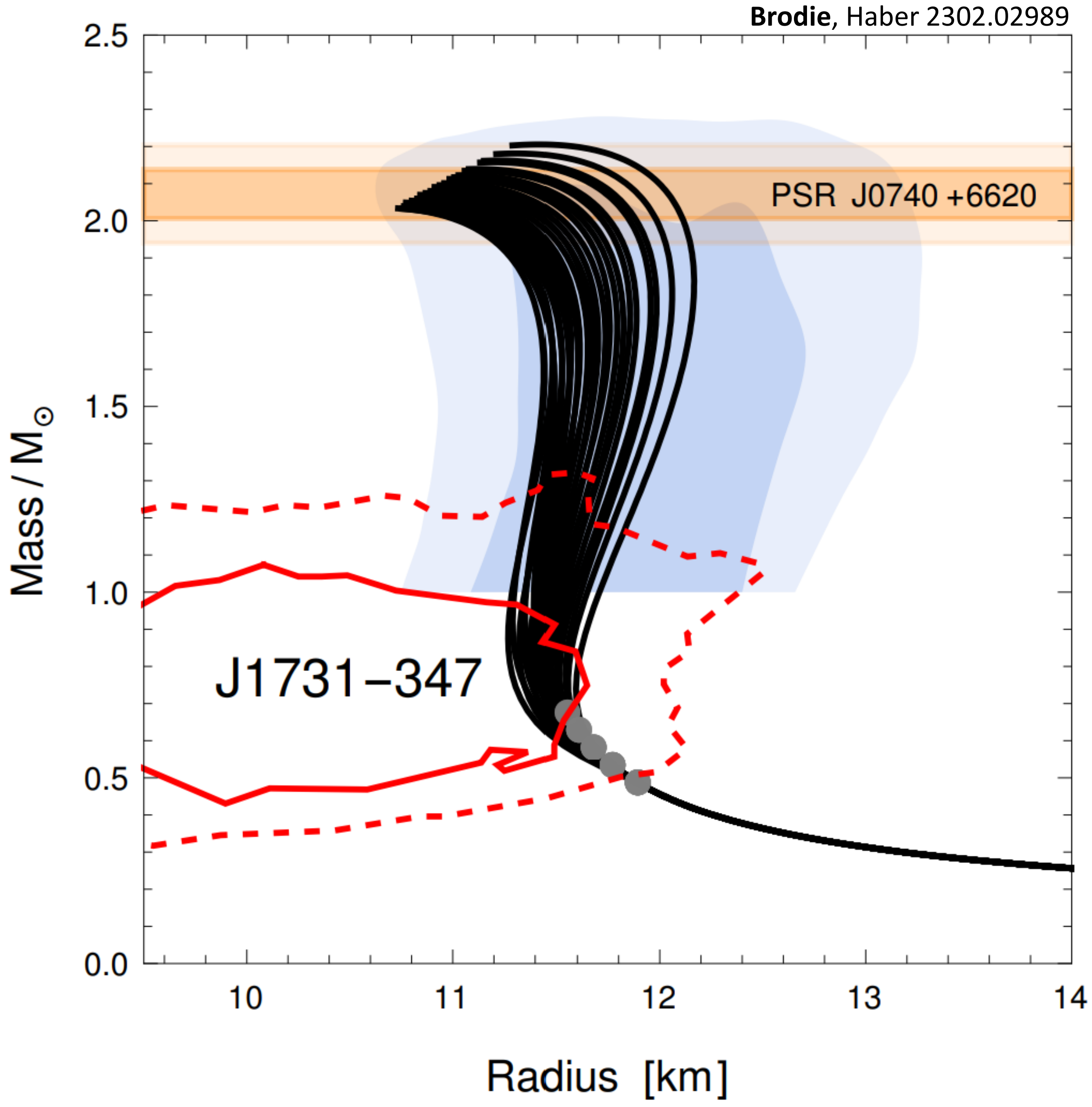




Hybrid Equation of State

Alford, Han, Prakash 1302.4732





$$c_{QM}^2 = 0.48$$

$$n_{tr} \in \{2n_0, 2.4n_0\}$$

$$\frac{\Delta\epsilon}{\epsilon} \in \{0.004, 0.151\}$$

Conclusions: Part 3 of 4

If HESS J1731-347 measurement is credible

- **Most** compact stars could be **hybrid stars** with a nuclear matter “mantle” and a quark matter “core”
- Nuclear models **do not** have to be as “stiff”
- Future observations could help **constrain** low-energy nuclear theory

Parts 1-3 Conclusions

- Neutron stars can be used as a “laboratory” to explore part of the **phase diagram** of matter
- Developed **new** models for neutron stars constrained by nuclear physics and astrophysics
- **Most** compact stars could be **hybrid stars** with a nuclear matter “mantle” and a quark matter “core”

Where are we going? Part 4 of 4

1. Compact stars and the **phase diagram** of nature
2. New models for neutron star **phenomenology**
3. Studying the **lightest** observed compact star
4. Some possible directions of **future work**

Future work

- Weak interaction transport properties
  - Urca processes with arbitrary neutrino distribution
  - Strangeness equilibration in quark matter at merger temperatures

- Interested in the rest of the phase diagram of matter
  - Is there is a critical endpoint?
  - Is chiral symmetry restored at deconfinement?
  - Other phases of matter?