Chiral Symmetry Restoration by Parity Doubling and the Structure of Neutron Stars

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Phys. Rev. D97 (2018) **3**, 036011
Phys. Rev. D98 (2018) **10**, 103021
Universe (2019) **5**, 180

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Uniwersytet Wrocławski

National Science Centre Poland

Common Approach to EoS

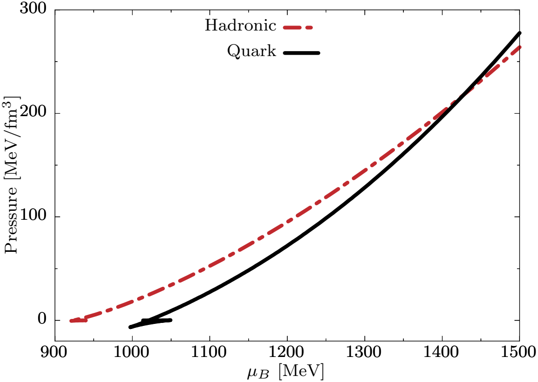
Hadronic EoS: p^+, n^+
(incomplete chiral physics)

$+$

Quark EoS
(chiral physics)

$\downarrow$

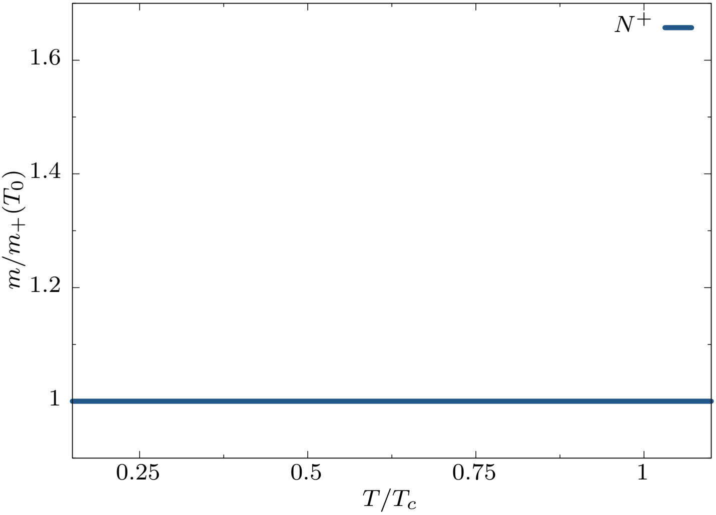
Maxwell Construction
(deconfinement)



Bastian, Blaschke, J. Phys. Conf. Ser. **668** (2016)

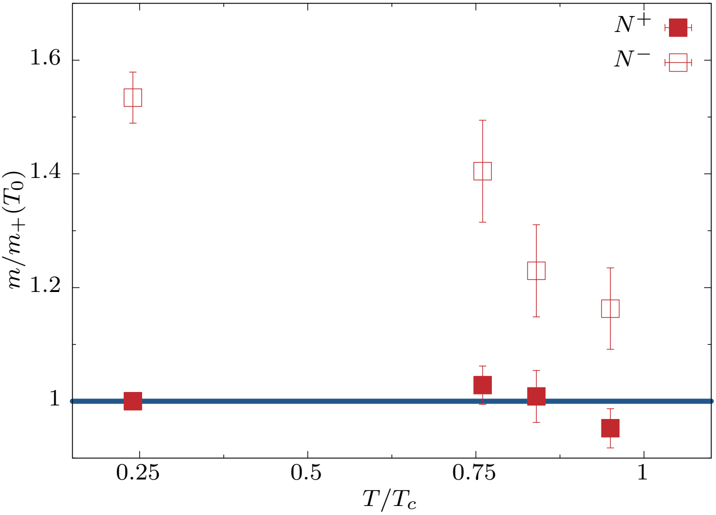
- Striking problem: No chiral physics in the resulting EoS

Common Approach to EoS



Parity Doubling in Lattice QCD

Aarts *et al*, JHEP **1706**, 034 (2017)



- Imprint of chiral symmetry restoration in the baryonic sector
- Expected to occur at low temperature

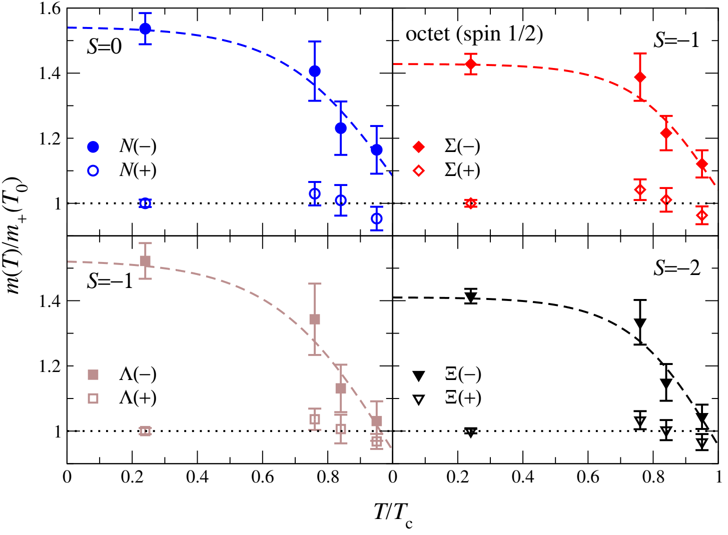
Particle Identification

p	$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: $****$
n	$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: $****$
$N(1535)\ 1/2^-$	$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: $****$

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019 update

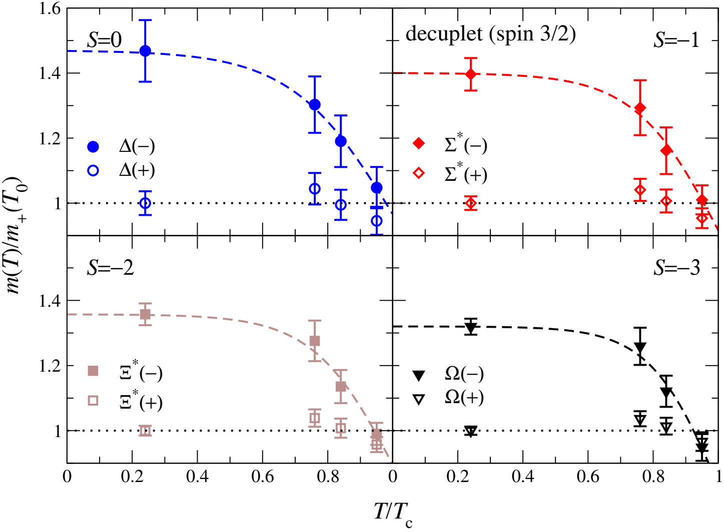
Parity Doubling for Light Baryons
Aarts *et al*, PRD **99** (2019)

Octect (spin $\frac{1}{2}$)



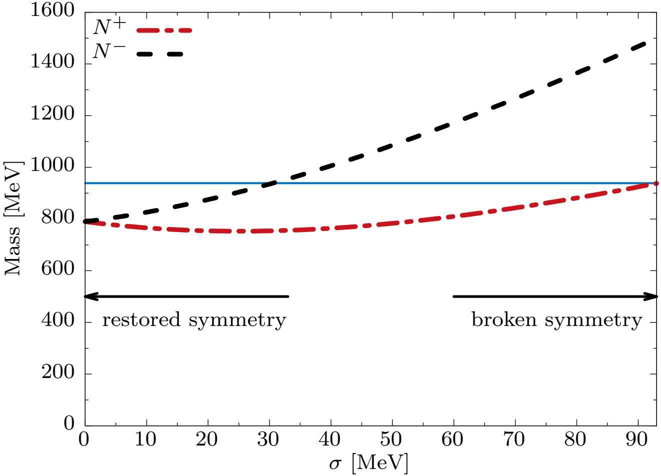
Parity Doubling for Light Baryons Aarts *et al*, PRD **99** (2019)

Decouplet (spin $\frac{3}{2}$)



Parity Doubling in SU(2) Chiral Models DeTar, Kunihiro PRD **39** (1989)

$$m^{\pm} = \frac{1}{2}\left[\sqrt{(g_1 + g_2)^2\,\sigma^2 + 4m_0^2} \mp (g_1 - g_2)\,\sigma\right] \xrightarrow{\sigma\to 0} m_0$$



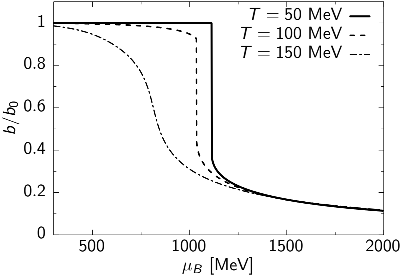
Hybrid Quark-Meson-Nucleon Model Benić, Mishustin, Sasaki, PRD **91** (2015)

Parity Doublet Model + Quark-Meson Coupling

$$\Downarrow$$

Statistical Confinement:

- UV cutoff for nucleons: $f_N \to \theta\left(\alpha^2 b^2 - \boldsymbol{p}^2\right) f_N$
- IR cutoff for quarks: $f_q \to \theta\left(\boldsymbol{p}^2 - b^2\right) f_q$
- α - model parameter



- b-field: Spontaneous Symmetry Breaking

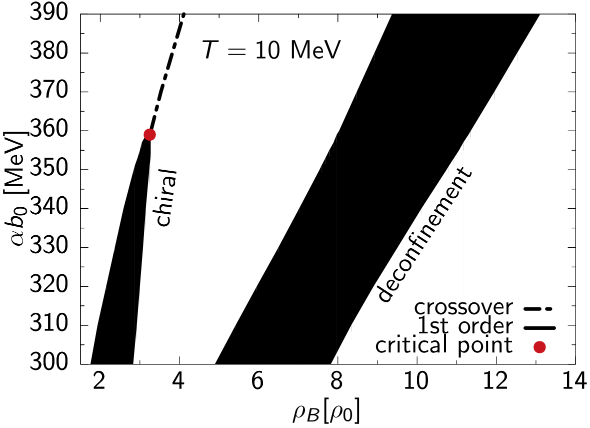
$$V_b = -\frac{1}{2}\kappa_b^2 b^2 + \frac{1}{4}\lambda_b b^4$$

$b(\mu_B = 0) > 0$ favors nucleons
$b(\mu_B \to \infty) = 0$ favors quarks

Phase Diagram for Isospin-Symmetric Matter

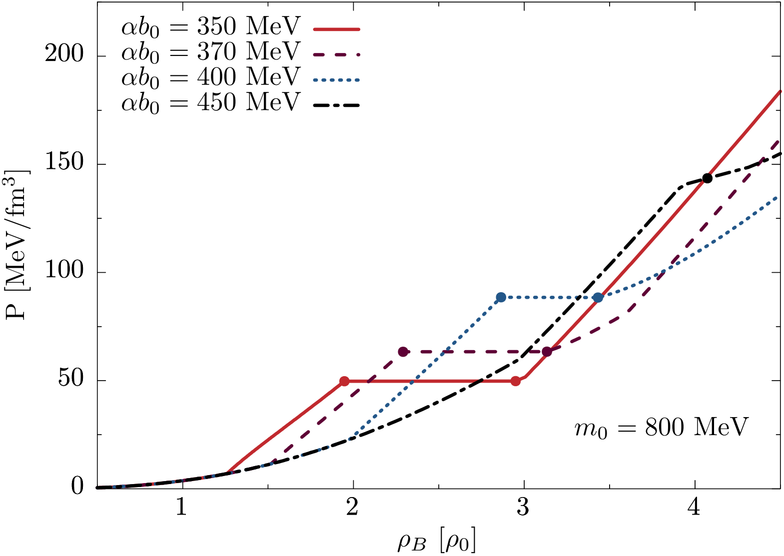
- Sequential phase transitions
- $\alpha \rightarrow$ Order of chiral transition

  (small α) 1st order $\rightarrow$ critical point $\rightarrow$ crossover (large α)



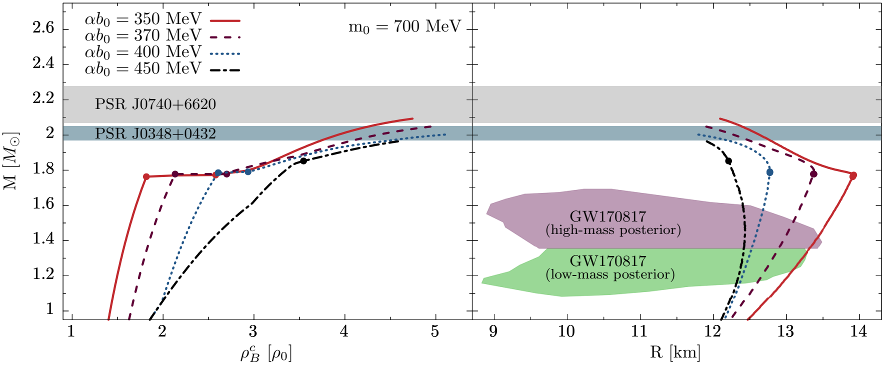
Equation of State Under NS Conditions

- $\alpha \rightarrow$ stiffening of EoS
- $\alpha \rightarrow$ strength of the chiral phase transition



Mass-Radius Relation

- chiral transition in high-mass part of the sequence
- $2M_\odot$ with chirally restored but confined core



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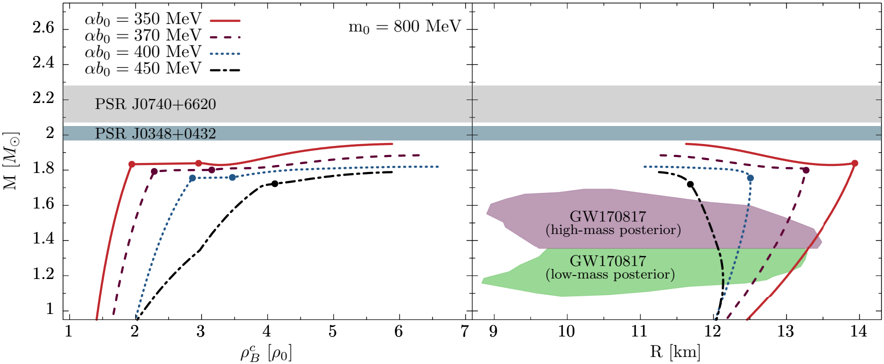
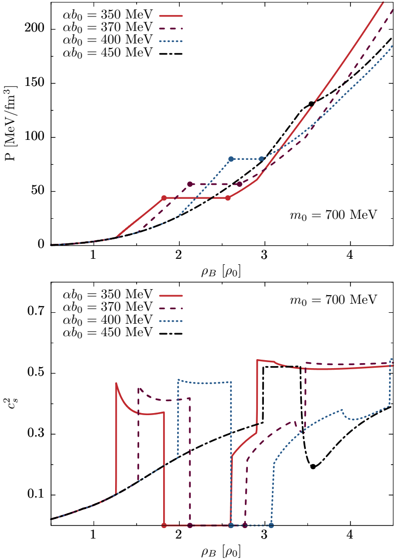


Speed of Sound



Threshold for Direct URCA
Lattimer, Pethick, Prakash, Haensel, PRL **66** (1991)

- Conventional Scenario
  - d.o.f.: p^+, n^+, e, μ
- Charge Neutrality

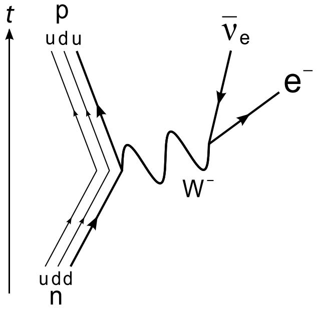
$$\rho_{p^+} = \rho_e + \rho_\mu$$

- Momentum Conservation

$$f_{n^+} \leqslant f_{p^+} + f_e$$

- Proton Fraction Threshold

$$\frac{1}{1 + (1 + \sqrt[3]{Y_e})^3} \Rightarrow 11\% - 15\%$$



Threshold for Direct URCA: Parity Doubling

- χ-Symmetry Broken
  - d.o.f.: p^+, n^+, e, μ
- Charge Neutrality

$$\rho_{p^+} = \rho_e + \rho_\mu$$

- Momentum Conservation

$$f_{n^+} \leqslant f_{p^+} + f_e$$

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Threshold for Direct URCA: Parity Doubling

- χ-Symmetry Broken
  - d.o.f.: p^+, n^+, e, μ
- Charge Neutrality

$$\rho_{p^+} = \rho_e + \rho_\mu$$

- Momentum Conservation

$$f_{n^+} \leqslant f_{p^+} + f_e$$

- Proton Fraction Threshold

$$\frac{1}{1 + (1 + \sqrt[3]{Y_e})^3} \Rightarrow 11\% - 15\%$$

- χ-Symmetry Restored
  - d.o.f.: p^+, n^+, p^-, n^-, e, μ
- Charge Neutrality

$$\rho_{p^+} + \rho_{p^-} = 2\rho_{p^+} = \rho_e + \rho_\mu$$

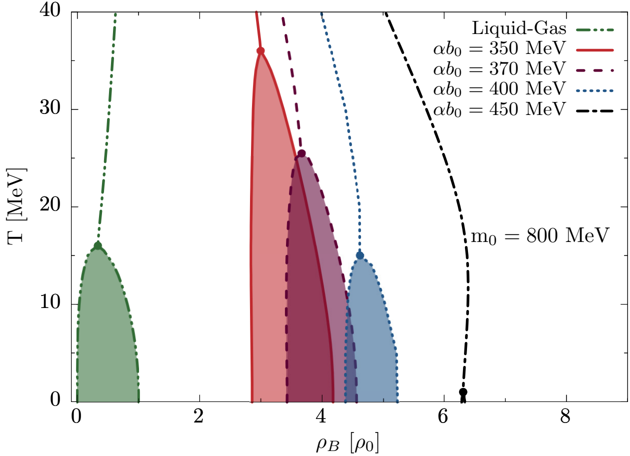
- Momentum Conservation

$$f_{n^+} \leqslant f_{p^+} + f_e$$

- Proton Fraction Threshold

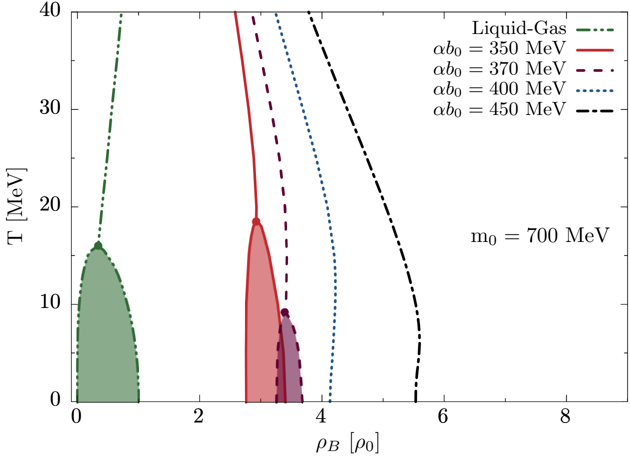
$$\frac{1}{1 + (1 + \sqrt[3]{Y_e})^3} \Rightarrow 8\% - 11\%$$

Prediction of the Symmetric-Matter Phase Diagram



- Astrophysical Constraints → CP at low T

Prediction of the Symmetric-Matter Phase Diagram



- Astrophysical Constraints → CP at low T or even absent!

Conclusions

Parity Doubling - implications for the physics of neutron stars:

- $2M_\odot$ with chirally restored but still confined core
- Parity doubling $\rightarrow$ modification of direct URCA threshold
  - possible impact on neutron-star cooling
- Astrophysical constraints $\rightarrow$ CP at low T or even absent

Thank You

Parity doubling in chiral models DeTar, Kunihiro Phys. Rev. D **39** 2805 (1989)

- Naive and mirror assignments under $SU(2)_L \times SU(2)_R$

$$\mathcal{L}_N = i\bar{\psi}_1 \partial\!\!\!/ \psi_1 + i\bar{\psi}_2 \partial\!\!\!/ \psi_2 + m_0 \left(\bar{\psi}_1 \gamma_5 \psi_2 - \bar{\psi}_2 \gamma_5 \psi_1 \right)$$

  For finite m_0, chiral symmetry is
  - explicitly broken under naive assignment
  - remains unbroken under mirror assignment
- Parity doublet model for cold and dense nuclear matter

  Hatsuda, Prakash, Phys.Lett. B **224** (1989) Zschiesche *et al*, Phys. Rev. C **75**, 055202 (2007)

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_M + \sum_{k=1,2} g_k \bar{\psi}_k \left(\sigma \pm i\gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi} \right) \psi_k - g_\omega \bar{\psi}_k \omega\!\!\!/ \psi_k$$

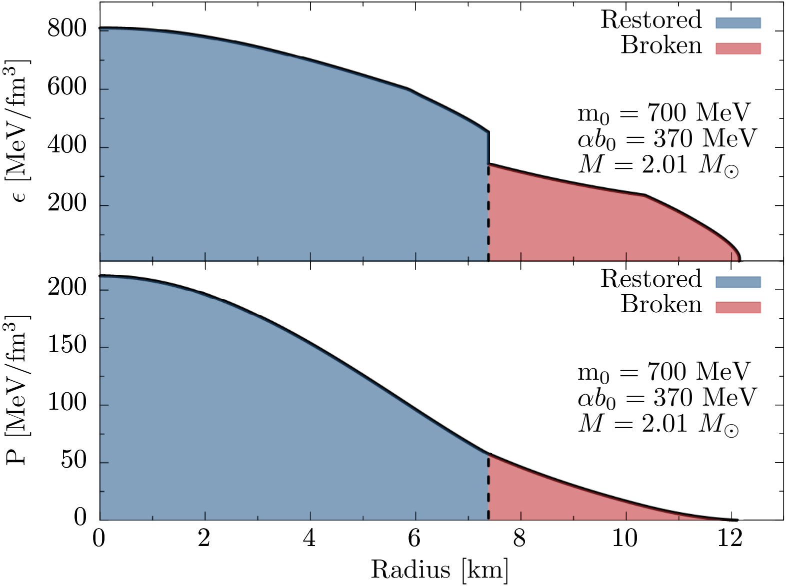
- Fermions coupled to bosons: σ, π, ω
- $\mathcal{L}_M \rightarrow$ Linear σ-model

Full HQMN model Lagrangian

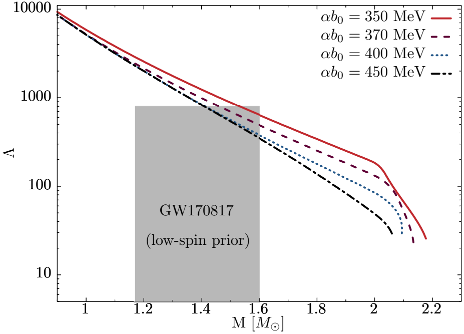
- $\mathcal{L} = \mathcal{L}_N + \mathcal{L}_M + \mathcal{L}_q$

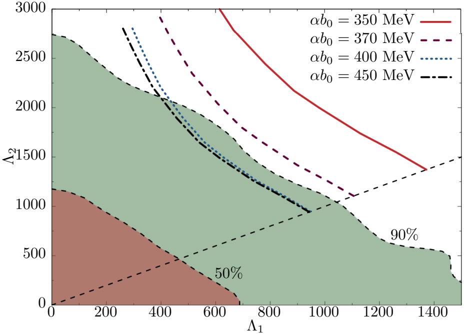
$$\mathcal{L}_N = \sum_{k=1,2} \bar{\psi}_k i\partial\!\!\!/ \psi_k + m_0 \left(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2\right) + \sum_{k=1,2} g_k\bar{\psi}_k \left(\sigma \pm i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\psi_k$$
$$- g_\omega\bar{\psi}_k \omega\!\!\!/ \psi_k - \frac{g_\rho}{2}\bar{\psi}_k\boldsymbol{\tau}\cdot\boldsymbol{\rho}\!\!\!/ \psi_k$$
$$\mathcal{L}_q = \bar{q}i\partial\!\!\!/ q + g_q\bar{q}\left(\sigma + i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)q$$
$$\mathcal{L}_M = \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\boldsymbol{\pi})^2 - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}\boldsymbol{\rho}_{\mu\nu}\boldsymbol{\rho}^{\mu\nu} - V_\sigma - V_\omega - V_b - V_\rho$$
$$V_\sigma = -\frac{\lambda_2}{2}\left(\sigma^2 + \boldsymbol{\pi}^2\right) + \frac{\lambda_4}{4}(\sigma^2 + \boldsymbol{\pi}^2)^2 - \epsilon\sigma$$
$$V_\omega = -\frac{1}{2}m_\omega^2\omega_\mu\omega^\mu$$
$$V_b = -\frac{1}{2}\kappa_b^2 b^2 + \frac{1}{4}\lambda_b b^4$$
$$V_\rho = -\frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu$$

2 $M_\odot$ Neutron Star Profile



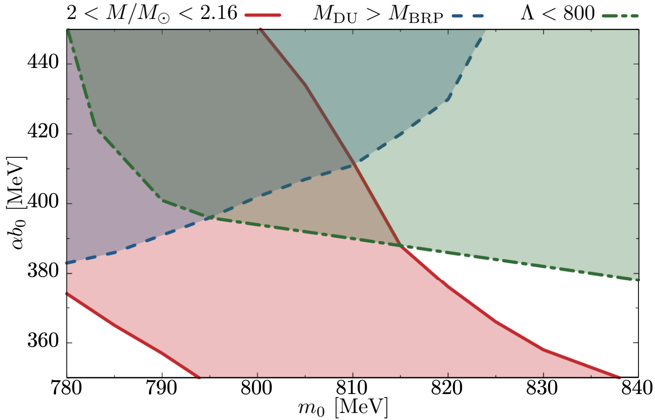
Constraints from GW170817





- $\Lambda = \frac{2}{3} k_2 C^{-5}$, where $C = M/R$ is compactness
- stiff EoS are rather excluded
- constraint on radius $R < 13.6$ km at 1.4 $M_\odot$

Compilation of All Constraints



- $2M_\odot \to$ stiff EoS
- Direct Urca $\to$ soft EoS
- Tidal Deformability $\to$ soft EoS