Constraints on braneworld from compact stars[†]

Daryel Manreza Paret, ICN-UNAM
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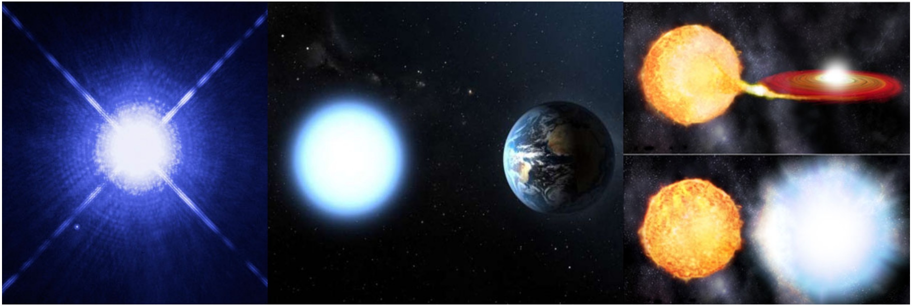
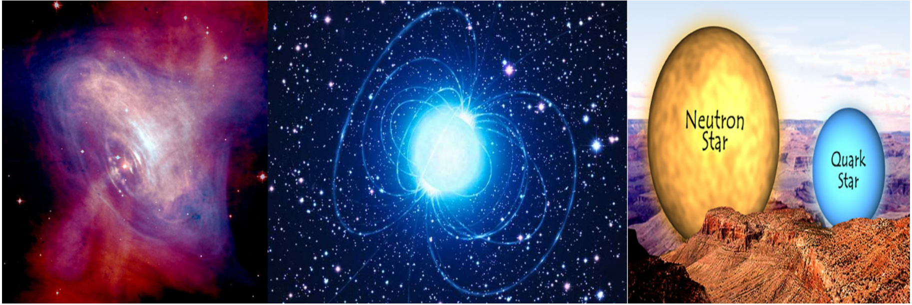
Ricardo. González Felipe, ISEL, Portugal

[†] R. Gonzales Felipe, D. Manreza Paret and A. Perez Martinez, Eur. Phys. J. C (2016) 76:337 (arXiv:1601.01973)

Introduction. Compact Stars.

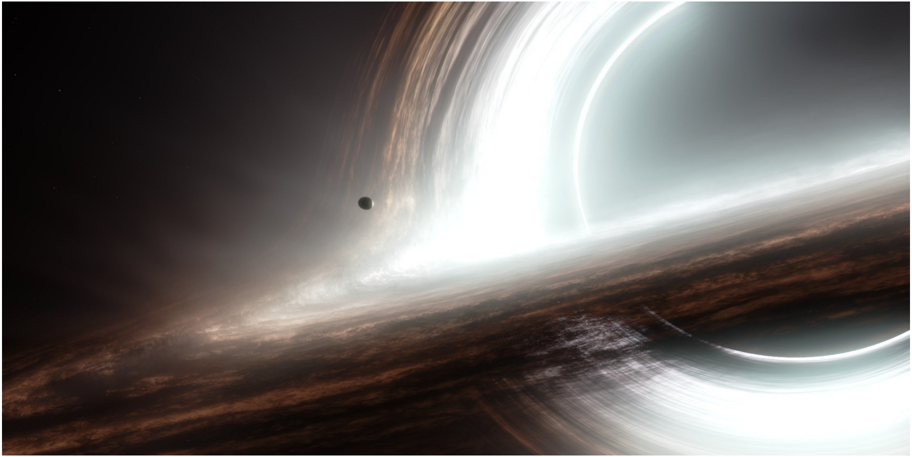


White Dwarfs⇑ Neutron Stars/Strange Stars⇓



Introduction. Compact Stars.

Third type of Compact Object:
Black Holes



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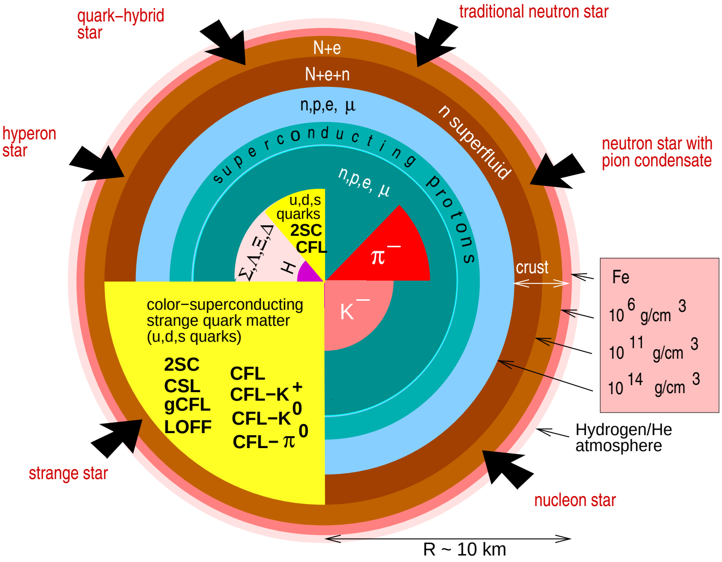
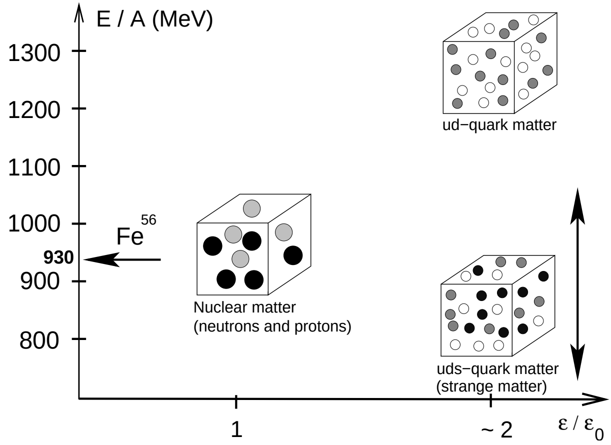


†F. Weber. Progress in Particle and Nuclear Physics, 54:193-288 (2005).

Introduction. Compact Stars.

Quark Stars. Bodmer-Witten-Terazawa conjeture[‡]

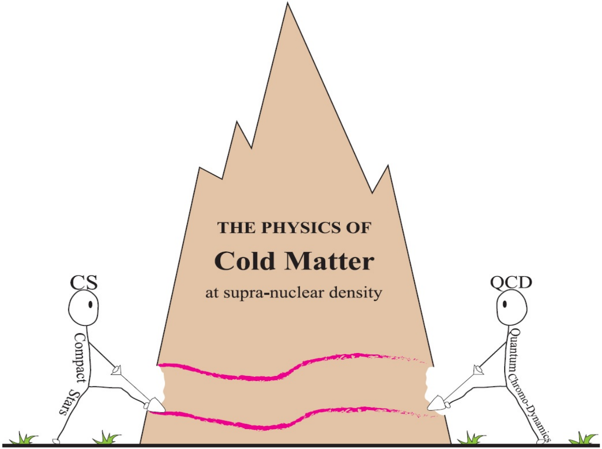


[†] Picture from: F. Weber. Progress in Particle and Nuclear Physics, 54:193-288 (2005).

[‡] A. R. Bodmer. Phys. Rev. D,(1971). E. Witten. Phys. Rev. D (1984). H. Terazawa. Journal of the Physical Society of Japan, (1989)

Introduction. Compact Stars.

Neutron Stars: Natural Laboratories



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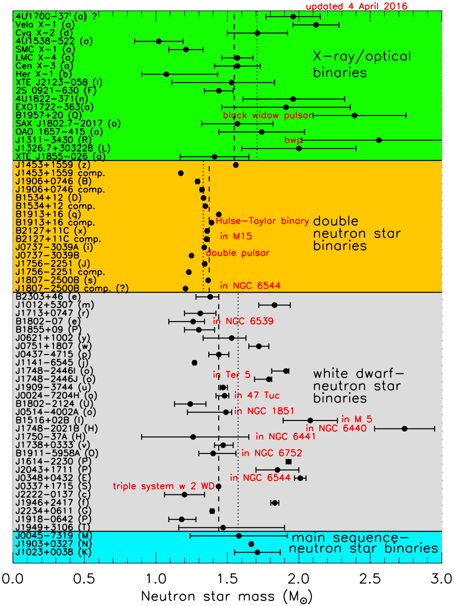
† Renxin Xu. J. Phys. G: Nucl. Part. Phys. 36 (2009) 064010 (9pp).

Introduction. Compact Stars.



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† http://stellarcollapse.org/nsmasses. Accedido 26-01-2017.

Tolman-Oppenheimer-Volkoff equations

The static, structure equations for a spherical symmetric relativistic star are found by solving Einsteint's equation

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \kappa^2 T_{\mu\nu}. \tag{1}$$

For a spherically symmetric star, the metric is given by

$$ds^2 = -e^{2\Phi(r)} dt^2 + e^{2\Lambda(r)} dr^2 + r^2 \left(d\theta^2 + \sin^2\theta \, d\phi^2\right). \tag{2}$$

and the energy momentum tensor

$$T_{\mu\nu} = \rho u_\mu u_\nu + p \left(g_{\mu\nu} + u_\mu u_\nu\right) \tag{3}$$

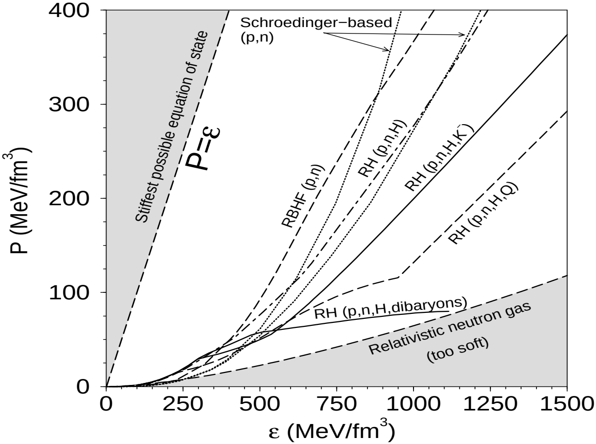
Tolman–Openheimer–Volkof (TOV):

$$\begin{aligned} \frac{dm}{dr} &= 4\pi r^2 \rho, \\ \frac{dp}{dr} &= -G \frac{(\rho + p)(m + 4\pi p r^3)}{r^2 - 2Grm}, \end{aligned}$$

with initial conditions $m(0) = 0$, $p(0) = p_c$ and at stellar surface $p(R) = 0$.

Tolman-Oppenheimer-Volkoff equations

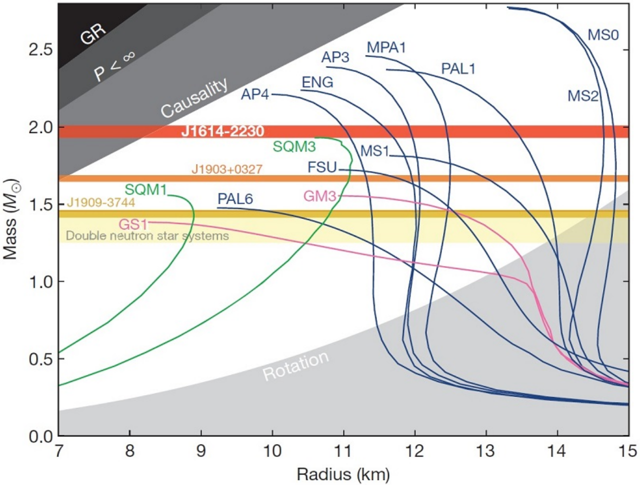
Equations of state



[†] F. Weber. Progress in Particle and Nuclear Physics, 54:193-288 (2005).

Tolman-Oppenheimer-Volkoff equations

Mass-Radius diagram



[†] P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts, and J. W. T. Hessels. Nature, 467:10811083 (2010).

Tolman-Oppenheimer-Volkoff equations

Theoretical constrains

- GR: $R > \dfrac{2GM}{c^2}$.
- $P < \infty$: $R > \dfrac{9}{4}\dfrac{GM}{c^2}$
- Causality: A sound signal cannot propagate faster than the speed of light $v < \sqrt{dp/d\rho} \leq c \Rightarrow R > 2.9\dfrac{GM}{c^2}$
- Rotation: $R > R_{\text{max}}$ excluded by the 716 Hz pulsar J1748-2446ad from the empirical result[†]

$$R < 10.4\left(\frac{1000\ \text{Hz}}{\nu}\right)^{2/3}\left(\frac{M}{M_\odot}\right)^{1/3}\ \text{km}.$$

[†] J. M. Lattimer, M. Prakash, Science 304, 536 (2004)

Tolman-Oppenheimer-Volkoff equations

Observational constraints

- For neutron star radii

$$7.6\,\mathrm{km}^{\dagger} \leq R \leq 13.9\,\mathrm{km}^{\ddagger}, \tag{4}$$

- For neutron star masses

$$1.08 M_{\odot}^{\S} \leq M \leq 2.05 M_{\odot}^{\dagger\dagger}, \tag{5}$$

[†] S. Guillot, M. Servillat, N.A. Webb, R.E. Rutledge, Astrophys. J. 772, 7 (2013)

[‡] K. Hebeler, J.M. Lattimer, C.J. Pethick, A. Schwenk, Phys. Rev. Lett. 105, 161102 (2010).

[§] F. Ozel, D. Psaltis, R. Narayan, A.S. Villarreal, Astrophys. J. 757, 55 (2012).

[††] J. Antoniadis et al., Science 340, 6131 (2013).

Brane World Models

From a classical point of view brane world models can be realised via the localization of matter and radiation fields on the brane, with gravity propagating in the bulk.

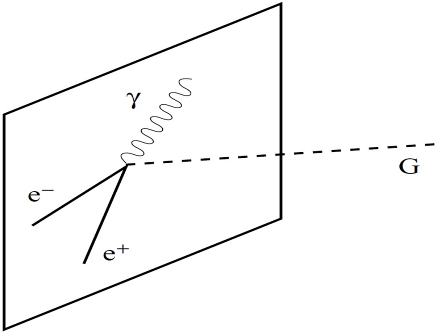


Image from: Cavaglia, M., Int. J. Mod.Phys. A, 18, 1843-1882, (2003). [hep-ph/0210296].

Brane World Models

Randall–Sundrum Brane-Worlds

- The bulk is a portion of a 5-D anti-de Sitter (AdS$_5$) spacetime (extra dimension is curved rather than flat).

- What prevents gravity from leaking into the extra dimension at low energies is a negative bulk cosmological constant $\Lambda_5 = -6/l^2$ where l is the curvature radius.

- The brane gravitates with self-gravity in the form of a brane tension λ.

[†] Randall&Sundrum PRL 1999; Maartens, PRD 2000; Shiromizu et al PRD 2000.

TOV equations on the brane

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \kappa^2 T_{\mu\nu} + \frac{6\kappa^2}{\lambda}\mathcal{S}_{\mu\nu} - \mathcal{E}_{\mu\nu}\,, \tag{6}$$

where

$$T_{\mu\nu} = \rho u_\mu u_\nu + p\left(g_{\mu\nu} + u_\mu u_\nu\right) \tag{7}$$

and

$$\mathcal{S}_{\mu\nu} = \frac{1}{12}\,\rho^2 u_\mu u_\nu + \frac{1}{12}\,\rho(\rho + 2p)(g_{\mu\nu} + u_\mu u_\nu), \tag{8}$$

where u^μ is the four-velocity of the fluid. The tensor $\mathcal{E}_{\mu\nu}$ reduces to the form

$$\mathcal{E}_{\mu\nu} = -\frac{6}{\kappa^2\lambda}\left[\mathcal{U}u_\mu u_\nu + \mathcal{P}r_\mu r_\nu + \frac{1}{3}(\mathcal{U} - \mathcal{P})\left(g_{\mu\nu} + u_\mu u_\nu\right)\right], \tag{9}$$

- $\mathcal{U}$ y $\mathcal{P}$ are dark energy and pressure respectively.
- $\mathcal{S}_{\mu\nu}$ local correction term.
- $\mathcal{E}_{\mu\nu}$ non-local correction term.
- When $\lambda \to \infty$, we recover GR.

TOV equations on the brane

$$\begin{aligned}
\frac{dm}{dr} &= 4\pi r^2 \rho_{\rm eff}\,, && (10)\\
\frac{dp}{dr} &= -(\rho + p)\frac{d\Phi}{dr}, && (11)\\
\frac{d\Phi}{dr} &= \frac{2Gm + \kappa^2 r^3 \left[p_{\rm eff} + (4\mathcal{P})/(\kappa^4\lambda)\right]}{2r(r-2Gm)}, && (12)\\
\frac{d\mathcal{U}}{dr} &= -\frac{1}{2}\kappa^4(\rho + p)\frac{d\rho}{dr} - 2\frac{d\mathcal{P}}{dr} - \frac{6}{r}\mathcal{P} - (2\mathcal{P} + 4\mathcal{U})\frac{d\Phi}{dr}\,, && (13)
\end{aligned}$$

where

$$\rho_{\rm eff} = \rho_{\rm loc} + \frac{6}{\kappa^4\lambda}\mathcal{U}\,, \quad p_{\rm eff} = p_{\rm loc} + \frac{2}{\kappa^4\lambda}\mathcal{U}\,. \tag{14}$$

and,

$$\rho_{\rm loc} = \rho + \frac{\rho^2}{2\lambda}\,, \quad p_{\rm loc} = p + \frac{p\rho}{\lambda} + \frac{\rho^2}{2\lambda}\,, \tag{15}$$

We need $p(\rho)$ y $\mathcal{P}(\mathcal{U})$ and initial conditions: $m(0) = 0$, y $p(0) = p_c$. At stellar surface $p(R) = 0 \Rightarrow m(R) = M$. For the dark component $\mathcal{U}$, we shall assume $\mathcal{U}(0) = 0$.

TOV equations on the brane

Equations of state

- In our analysis, the non-local dark components are modelled via the simple linear proportionality relation $\mathcal{P} = w\mathcal{U}$ between the dark energy $\mathcal{U}$ and dark pressure $\mathcal{P}$.
- For dense nuclear matter, we shall consider the analytical representation for the unified Brussels-Montreal EoS models[†], which are based on the nuclear energy-density functional theory with generalized Skyrme effective forces.
- For quark matter, we shall employ the simple phenomenological parametrisation[‡] which includes QCD and strange-quarkmass corrections.
- Hybrid EoS to study hybrid stars, i.e., stars with a hadronic outer region surrounding a quark (or mixed hadron-quark) inner core.

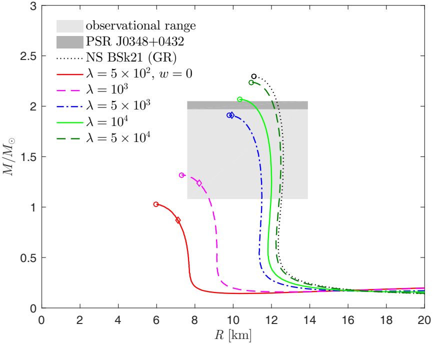
[†] A.Y. Potekhin, A.F. Fantina, N. Chamel, J.M. Pearson, S. Goriely, Astron. Astrophys. 560, A48 (2013).

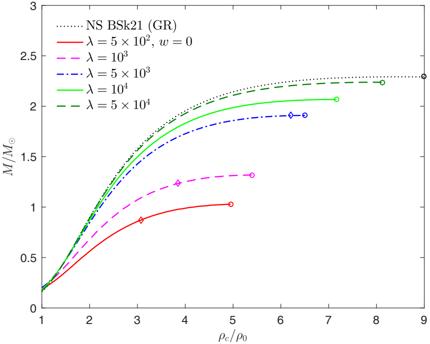
[‡] M. Alford,M. Braby,M.W. Paris, S. Reddy, Astrophys. J. 629, 969 (2005).

TOV equations on the brane

Results: Neutron Stars

- Requiring agreement with observational constraints leads to a lower bound on the brane tension, $\lambda \gtrsim 8 \times 10^2$ MeV/fm^3.
- The star radii lie in the range 8–13 km.

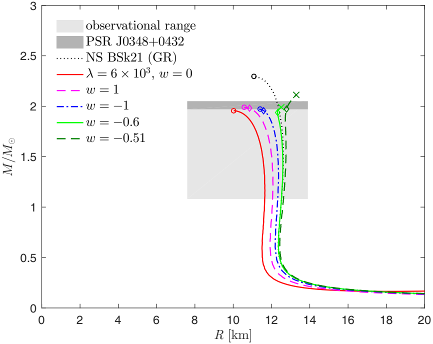


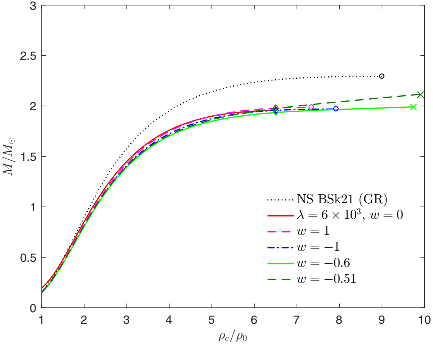


TOV equations on the brane

Results: Neutron Stars

- Mass-radius curves bend clockwise for $w = -0.6$ and $w = -0.51$.
- We have indicated with crosses $(\times)$ the mass-radius configuration at which the GR causality condition $v_s \leq 1$ is violated in such cases.

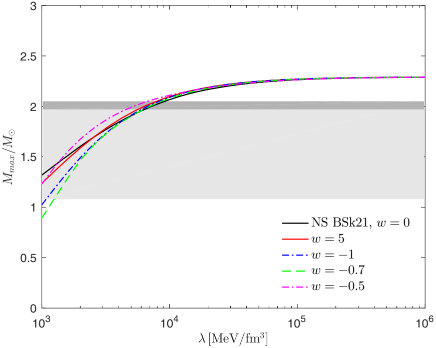


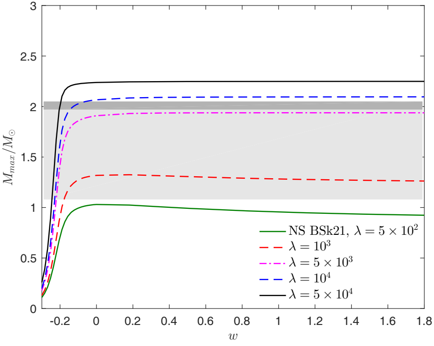


TOV equations on the brane

Results: Neutron Stars

- The maximum star mass predicted for this type of EoS is compatible with observations provided that $\lambda \gtrsim 6 \times 10^2$ MeV/fm^3.
- For $w \gtrsim -0.1$, the value of M_{max} remains practically constant with the variation of w, depending only on the value of λ.
- For $-0.3 < w < -0.1$, the maximum mass is quite sensitive to w.

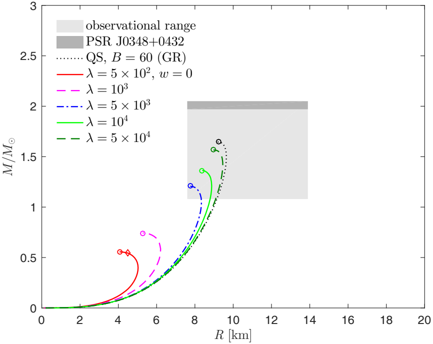


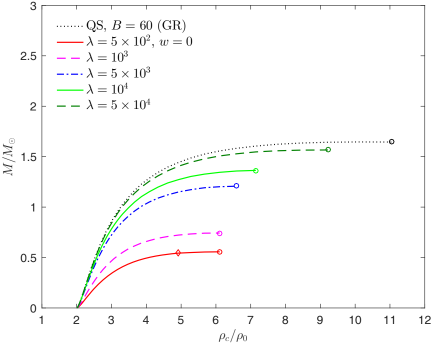


TOV equations on the brane

Results: Quark Stars

- Agreement with observational constraints imposes the lower bound $\lambda \gtrsim 4 \times 10^3$ MeV/fm^3, for $w = 0$
- The star radii lie in the range 8–10 km.

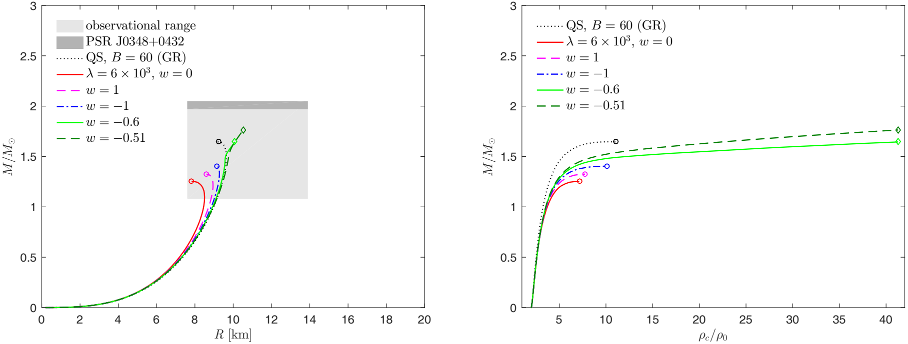




TOV equations on the brane

Results: Quark Stars

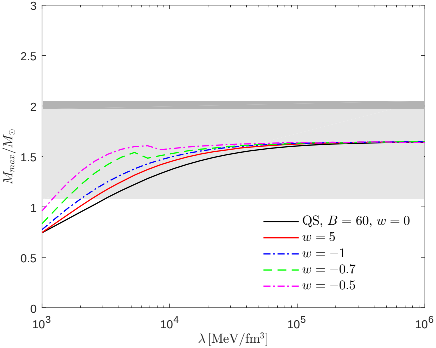
- For certain negative values of w the mass-radius curves bend clockwise, reaching the maximum mass at relatively high central densities, $\rho_c \sim 40\rho_0$, bounded by the requirement of subluminality of the EoS.

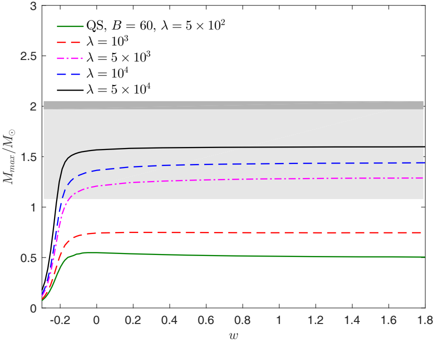


TOV equations on the brane

Results: Quark Stars

- The maximum star mass predicted for this type of EoS is compatible with observations provided that $\lambda \gtrsim 10^3$ MeV/fm^3.
- For $w \gtrsim -0.1$, the value of M_{max} remains practically constant with the variation of w, depending only on the value of λ.
- For $-0.3 < w < -0.1$, the maximum mass is quite sensitive to w.

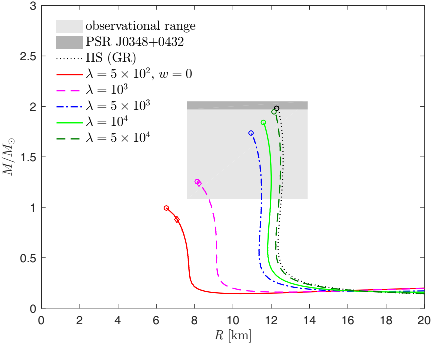


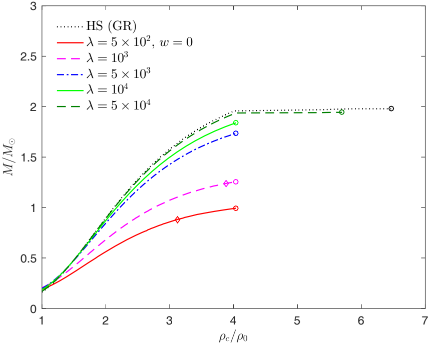


TOV equations on the brane

Results: Hybrid Stars

- Requiring agreement with observational constraints leads to a lower bound on the brane tension, $\lambda \gtrsim 8 \times 10^2$ MeV/fm^3.
- The maximum mass $M \sim 1.98 M_\odot$ is obtained for GR, and this value is consistent with the observational range of the pulsar PSR J0348+0432.

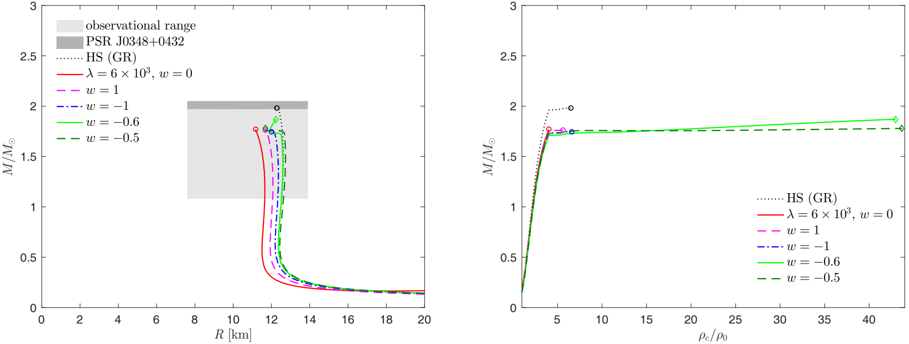




TOV equations on the brane

Results: Hybrid Stars

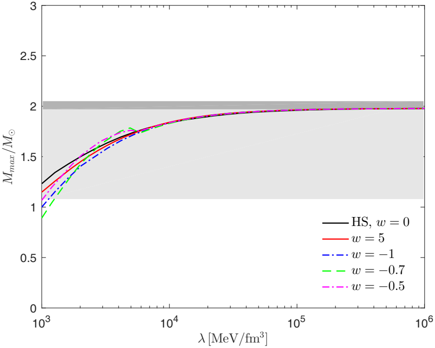
- As in the case of quark stars,we notice that the clockwise bending of the mass-radius curves persists for certain negative values of w, reaching the maximum mass at relatively high central densities,$\rho_c \sim 45\rho_0$

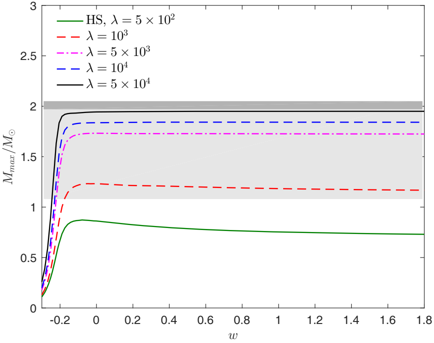


TOV equations on the brane

Results: Hybrid Stars

- The maximum star mass predicted for this type of EoS is compatible with observations provided that $\lambda \gtrsim 10^3$ MeV/fm^3.
- For $w \gtrsim -0.1$, the value of M_{max} remains practically constant with the variation of w, depending only on the value of λ.
- For $-0.3 < w < -0.1$, the maximum mass is quite sensitive to w.





Conclusions

1. Compact Stars are natural laboratories to test new theories.

2. In all the three EOS cases, the maximum mass and the corresponding star radius decrease as λ decreases.
   Furthermore, the central energy density ρ_c required to achieve the maximum mass configuration is always less than that of GR
    - $\rho_c \lesssim 7\rho_0$ for pure neutron stars and quark stars
    - slightly lower for hybrid stars, $\rho_c \lesssim 4.5\rho_0$

   The star radii lie in the ranges
    - 8–12 km for pure neutron stars,
    - 8–11 km for quark stars
    - 9–14 km for hybrid stars.

3. The maximum star mass as a function of λ and w was also studied for the three families of stars. Requiring agreement with observational constraints leads to a lower bound on the brane tension, $\lambda \gtrsim 10^3$ MeV/fm^3 for all three types of stars.

Muchas Gracias

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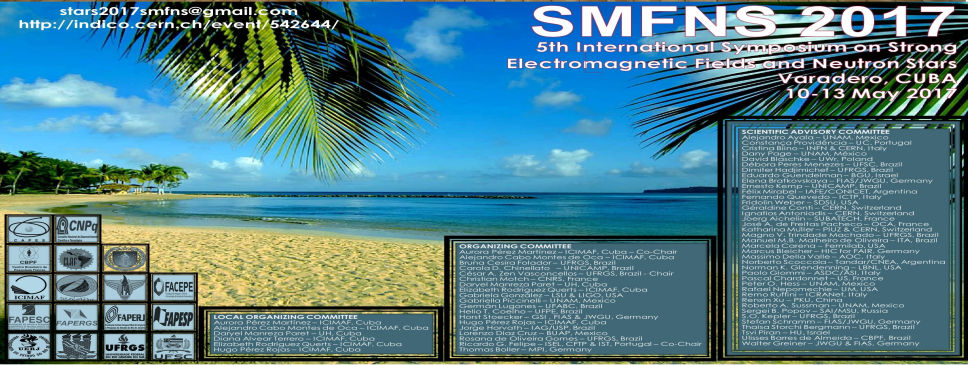

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