Universal symmetry energy contribution to the neutron star equation of state

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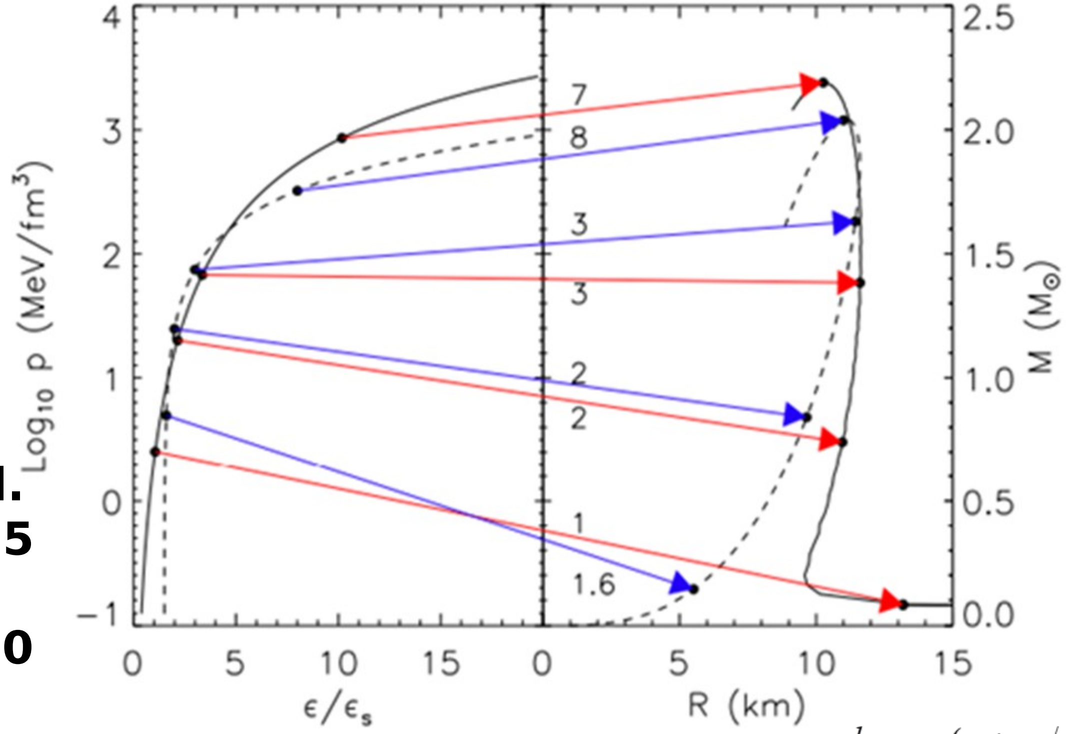
Outline

- Introduction to the neutron star equation of state.
- Relation between the symmetry energy and proton fraction.
- Generic examples for the symmetry energy.
- Results for the neutron star equation of state: direct Urca cooling and universal symmetry energy contribution.
- The neutron star radius and the symmetry energy

Key Questions

- What is the influence of the symmetry energy in the neutron star properties?
- Can we learn from neutron star observations about the symmetry energy?
- What is the role of the forbidden DUrca (fast) cooling for low mass stars in the equation of state?

Compact Star Sequences
(M-R ↔ EoS)



Lattimer, Annu. Rev. Nucl. Part. Sci. 62, 485 (2012) arXiv: 1305.3510

- TOV Equations
- Equation of State (EoS)

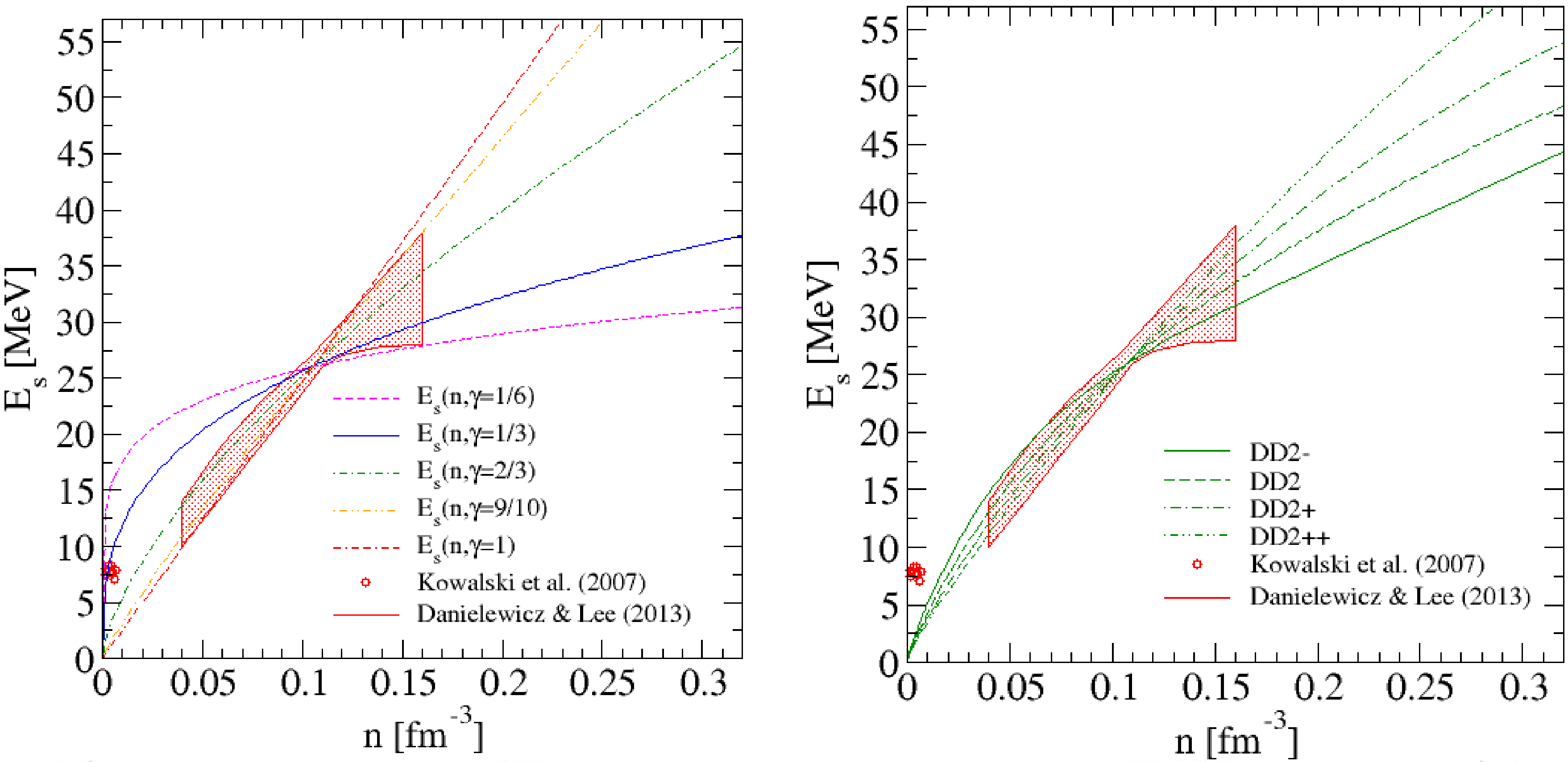
$$\frac{dp}{dr} = -\frac{(\varepsilon + p/c^2)G(m + 4\pi r^3 p/c^2)}{r^2(1 - 2Gm/rc^2)}$$

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

$$E(n) = E_0(n) + (1 - 2x(n))^2 E_s(n)$$

$$p(\varepsilon)$$

MDI-type and DD2-based E_s



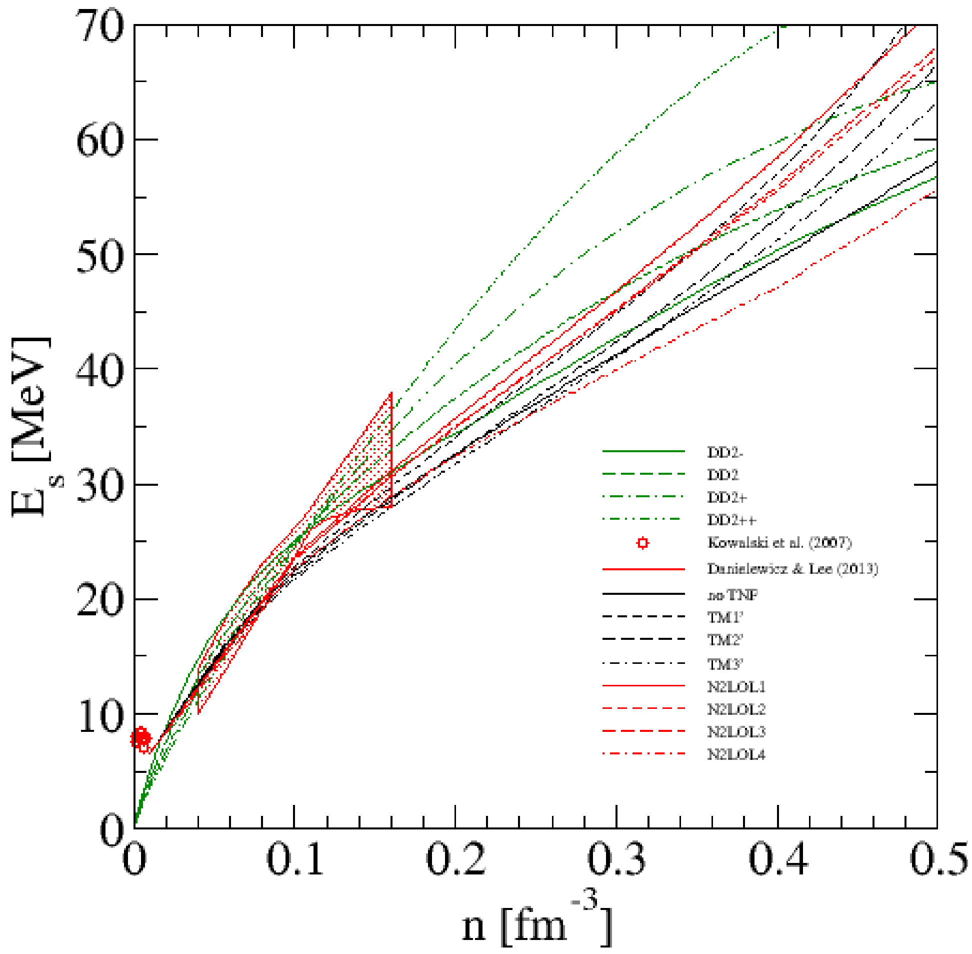
$$E_s(n) = A^*(n/n^*)^{2/3} + B^*(n/n^*)^{\gamma} = A(n/\mathrm{fm}^{-3})^{2/3} + B(n/\mathrm{fm}^{-3})^{\gamma}$$

$$where\ A = 42.4\ MeV\ and\ B = 16.5/(0.105)^{\gamma}\ MeV$$

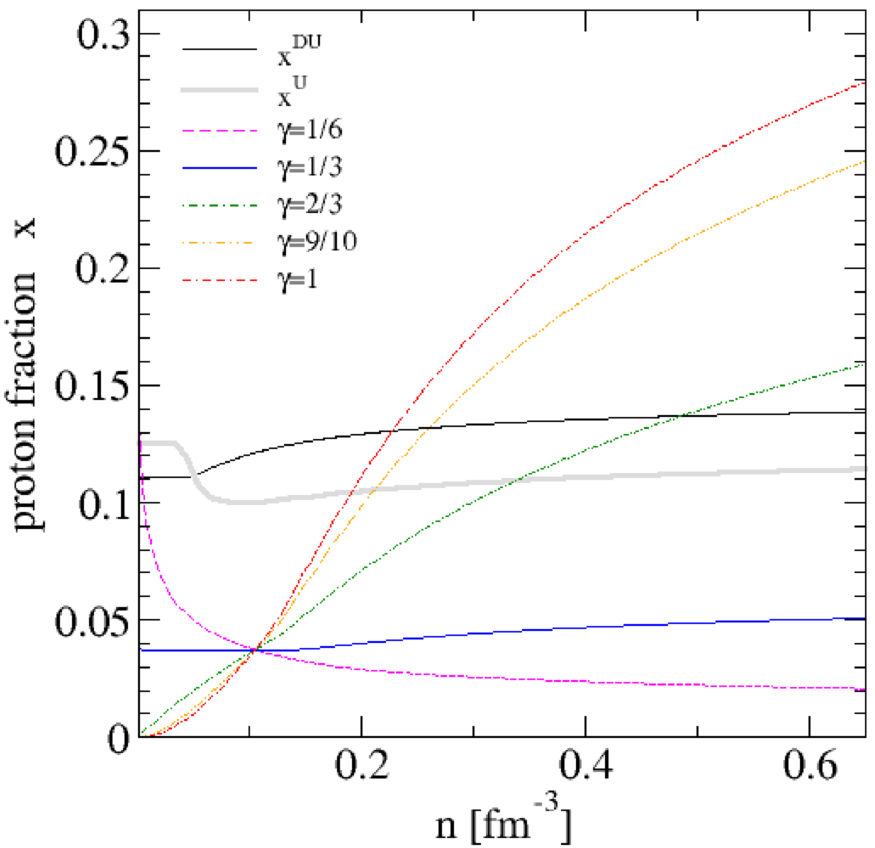
Table 1: Symmetry energy parameters.

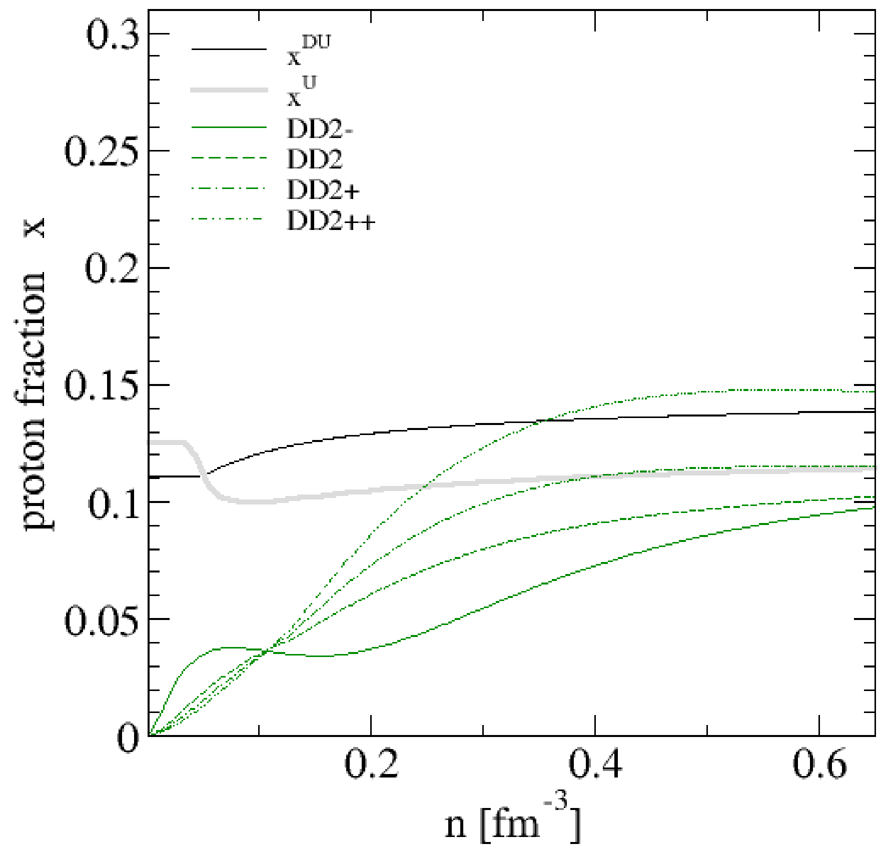
model	S	L	K_{sym}
1/6	27.8909	13.9454	-34.8672
1/3	29.9192	29.9192	-59.8438
1/2	32.0951	48.1426	-72.2194
2/3	34.4292	68.8584	-68.8627
8/10	36.4182	87.4036	-52.4449
9/10	37.9849	102.559	-30.7692
1	39.619	118.857	0
DD2-	31.055	41.7502	-42.3486
DD2	32.9878	56.8036	-92.6091
DD2+	34.6673	72.7921	-99.8584
DD2++	36.2663	89.5635	-73.6083

Symmetry energies



Direct Urca process constraint





Quark substructure effects in baryonic matter

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Excluded volume mechanism in the context of RMF models

Consider nucleons as hard spheres of volume $V_{\rm nuc}$, the available volume V_{av} for the motion of nucleons is only a fraction $\Phi = V_{av}/V$ of the total volume V of the system. We introduce

$$\Phi = 1 - v \sum_{i=n,p} n_i \ ,$$

with nucleon number densities n_i and volume parameter $v = \frac{1}{2}\frac{4\pi}{3}(2r_{\rm nuc})^3 = 4V_{\rm nuc}$ and identical radii $r_{\rm nuc} = r_n = r_p$ of neutrons and protons. The total hadronic pressure and energy density are:

$$\begin{aligned} p_{\rm tot}(\mu_n,\mu_p) &= \frac{1}{\Phi}\sum_{i=n,p} p_i + p_{\rm mes} \ , \\ \varepsilon_{\rm tot}(\mu_n,\mu_p) &= -p_{\rm tot} + \sum_{i=n,p} \mu_i n_i \ , \end{aligned}$$

with contributions from nucleons and mesons depending on μ_n and μ_p. The nucleonic pressure

$$p_i = \frac{1}{4}\left(E_i n_i - m_i^* n_i^{(s)}\right) \ ,$$

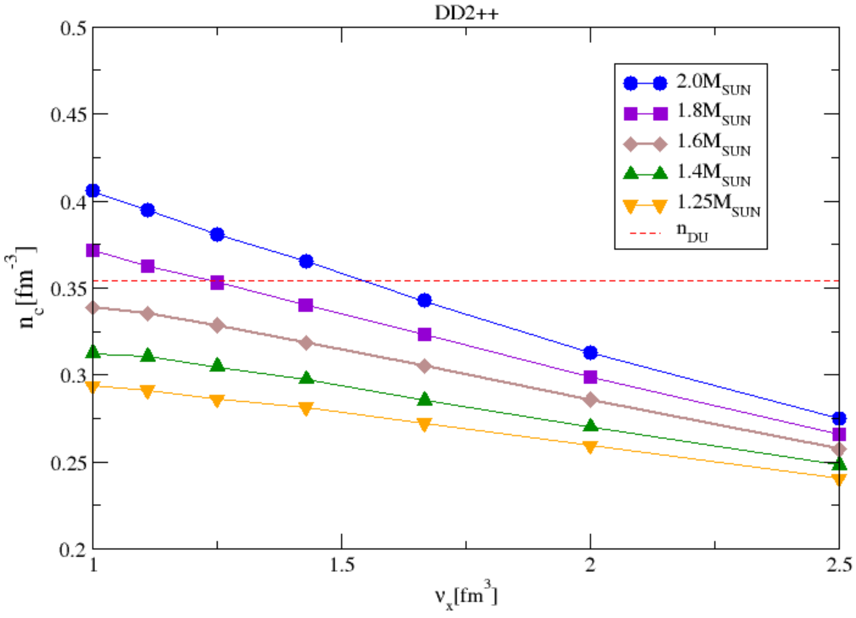
contains the nucleon number densities, scalar densities and energies:

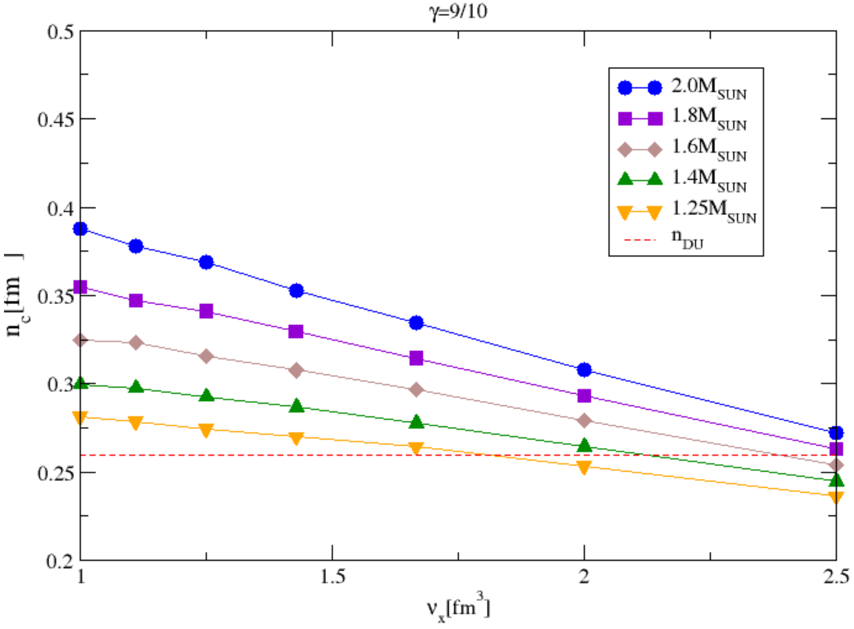
$$n_i = \frac{\Phi}{3\pi^3} k_i^3, \quad n_i^{(s)} = \frac{\Phi m_i^*}{2\pi^2}\left[E_i k_i - (m_i^*)^2 \ln \frac{k_i + E_i}{m_i^*}\right], \quad E_i = \sqrt{k_i^2 + (m_i^*)^2} = \mu_i - V_i - \frac{v}{\Phi}\sum_{j=p,n} p_j,$$

as well as Fermi momenta k_i and effective masses $m_i^* = m_i - S_i$. The vector V_i and scalar S_i potentials and the mesonic contribution $p_{\rm mes}$ to the total pressure have the usual form of RMF models with density-dependent couplings.

Benic, Blaschke, Alvarez-Castillo, Fischer, Typer, A&A 577, A40 (2015)

Excluded Volume





Symmetry energy Conjecture

Kaehn et al. PhysRev C74 (2006) PHYSICAL REVIEW C **74**, 035802 (2006)

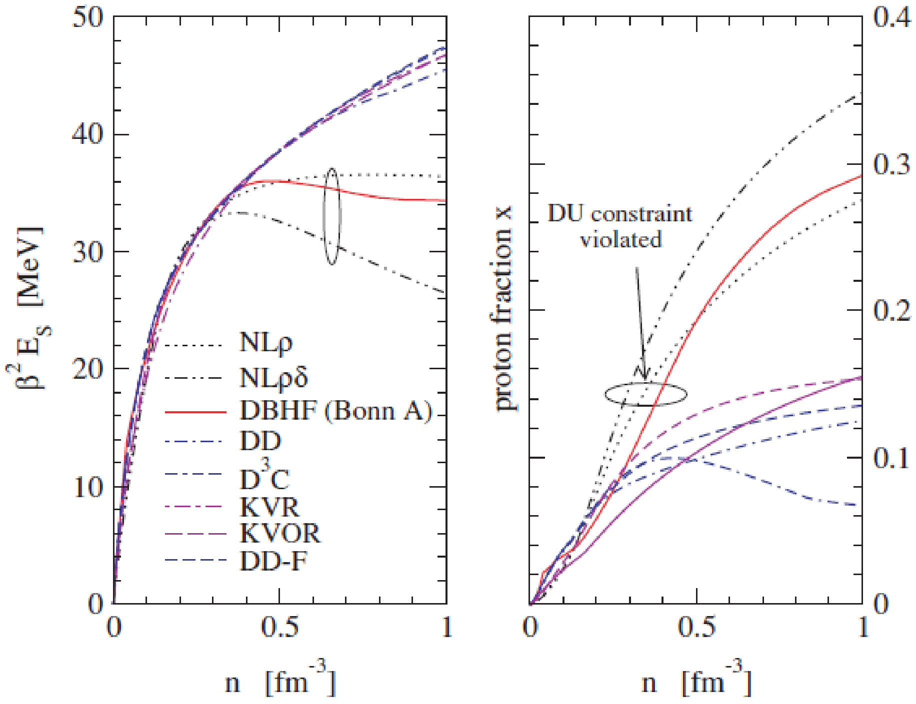
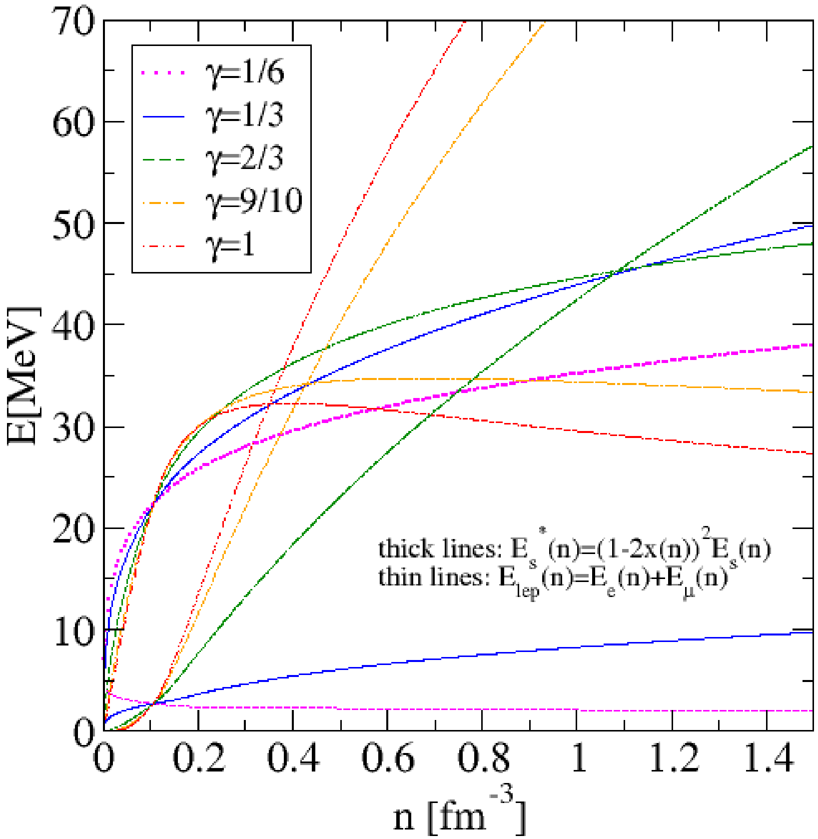
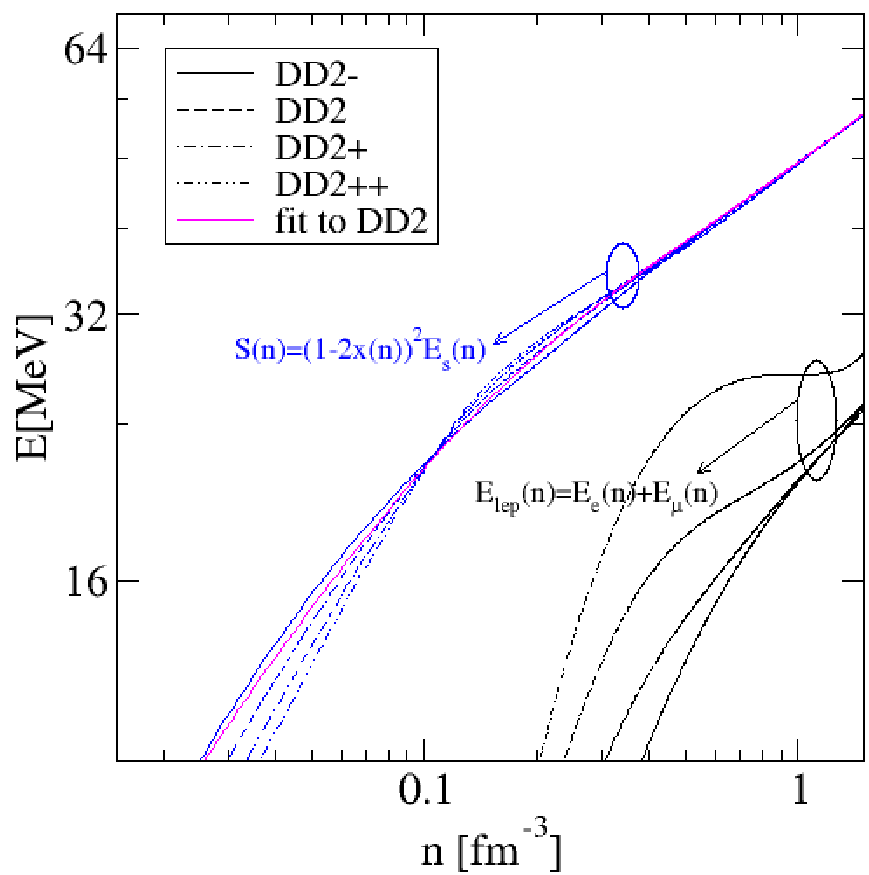


FIG. 7. (Color online) Density dependence of the asymmetry contribution to the energy per particle (left panel) and of the proton fraction (right panel) in NSM. Encircled curves correspond to EoSs that violate the DU-constraint.

Universal symmetry energy contribution





The symmetry energy contribution to the neutron star EoS behaves universal!

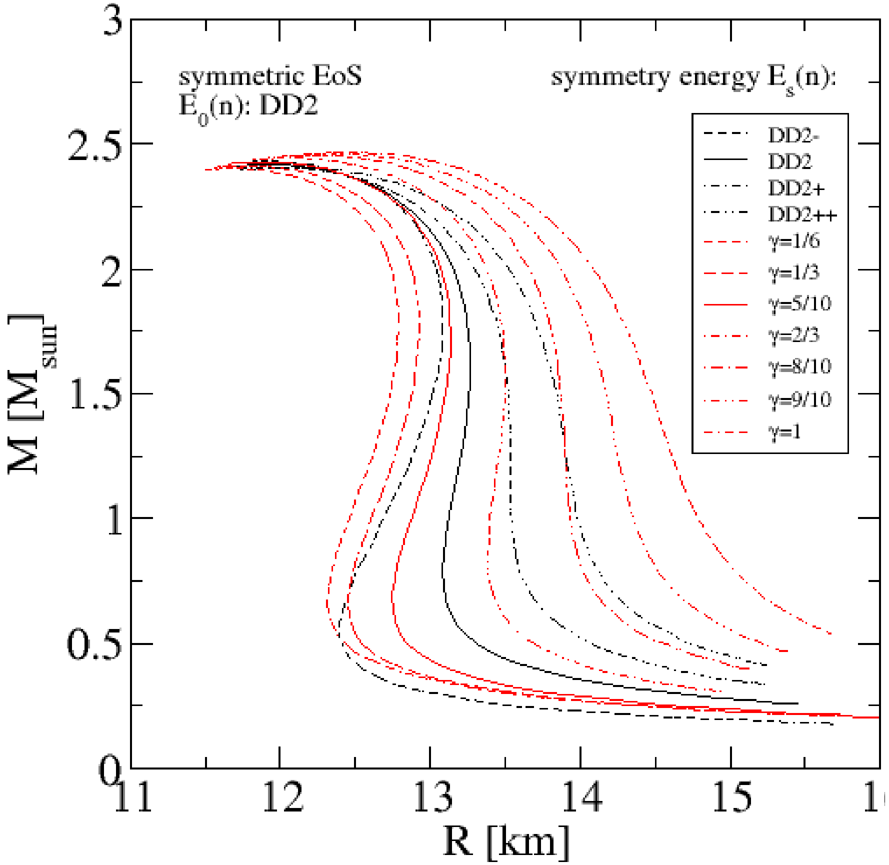
Universal symmetry energy contribution

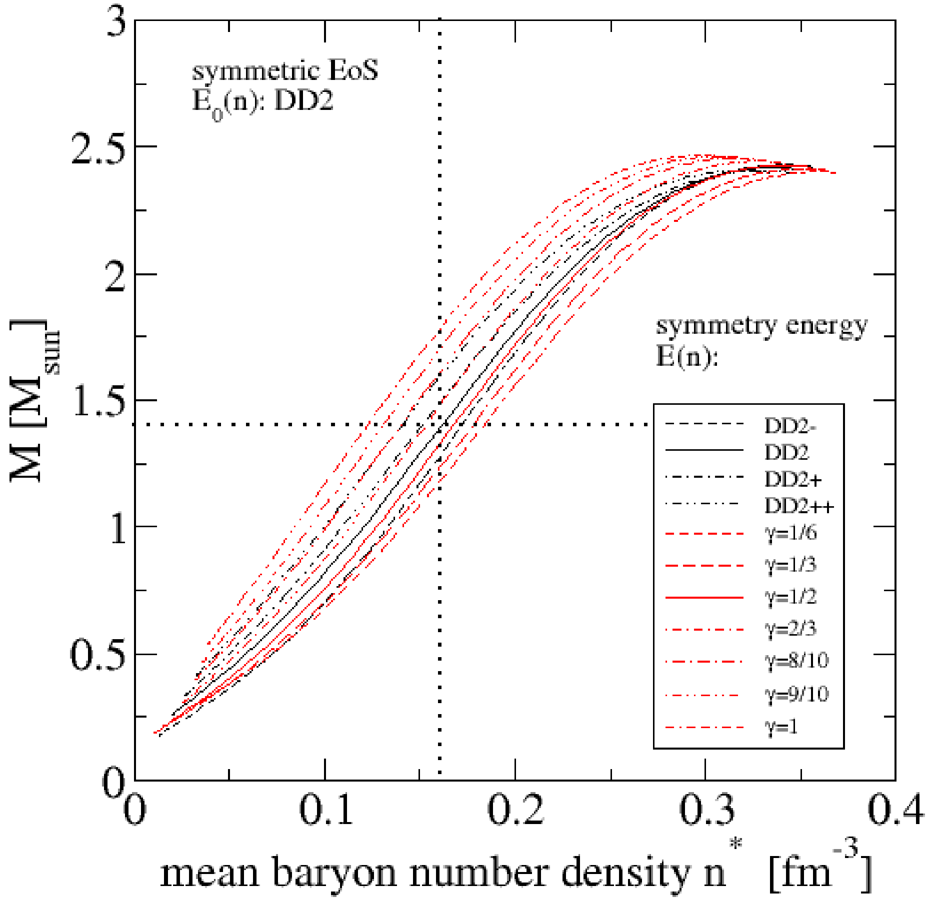
$$S^U(n) = 44\ \mathrm{MeV}\left(\frac{n}{\mathrm{fm}^{-3}}\right)^{0.25} + 3.5\ \mathrm{MeV}\left(\frac{n}{\mathrm{fm}^{-3}}\right) - 10\ \mathrm{MeV}\exp\left[-10\left(\frac{n}{\mathrm{fm}^{-3}}\right)\right] . \qquad ($$

The symmetry energy contribution to the neutron star EoS behaves universal!

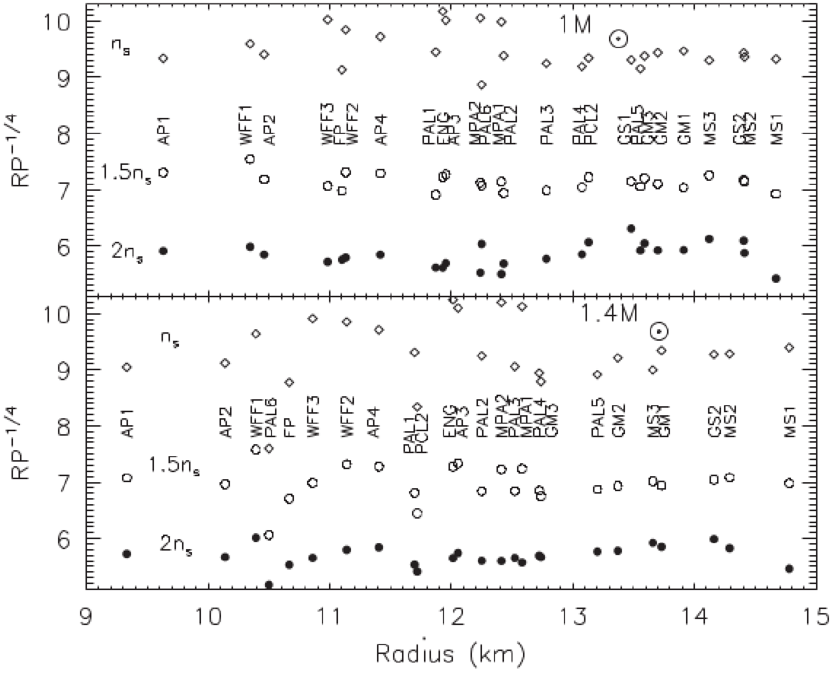
Neutron Stars

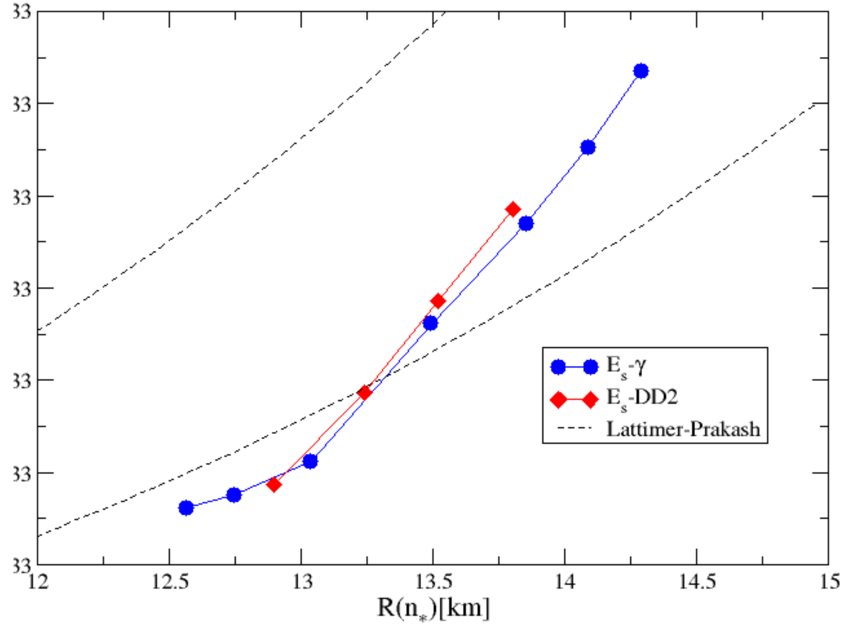
$$n^* = \frac{\int_0^R n dV}{\int_0^R dV}$$





Radius constraint

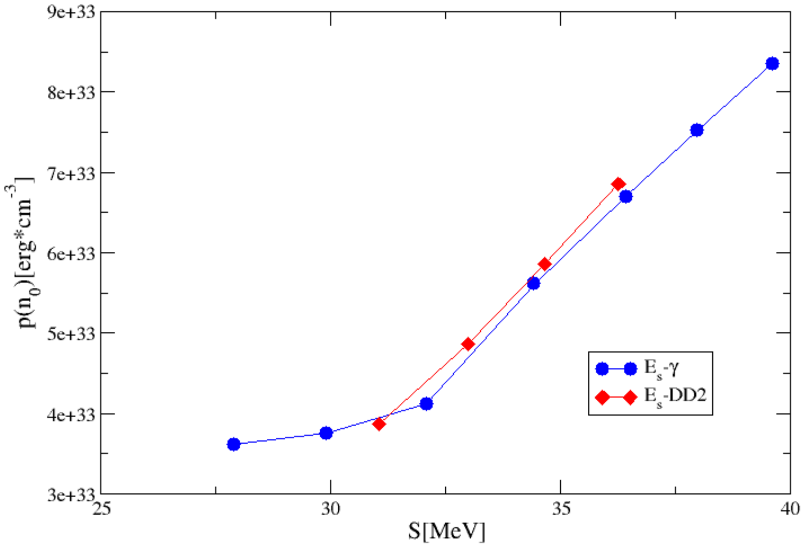


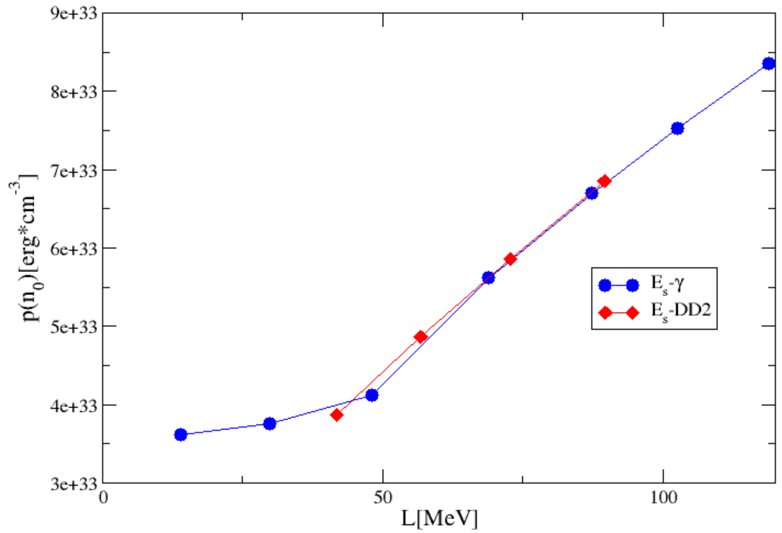


Empirical demonstration of the constancy of $Rp_{*}^{1/4}$

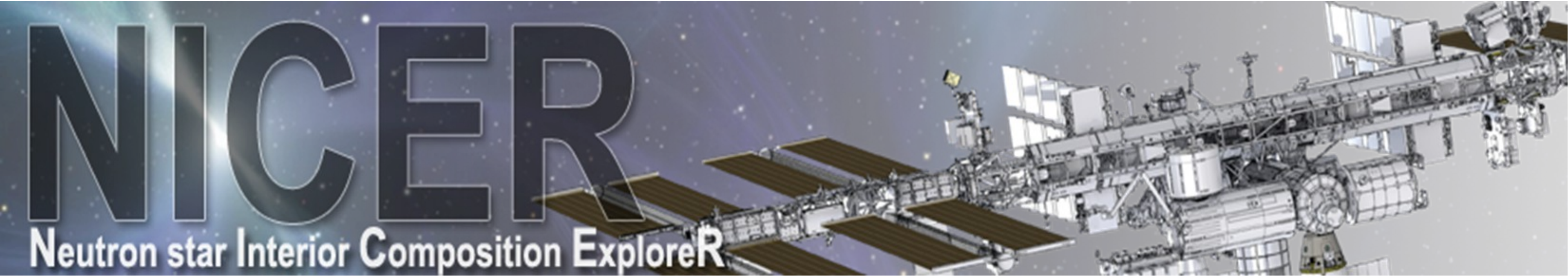
J.M. Lattimer, M. Prakash, Astrophys. J. 550 (2001) 426

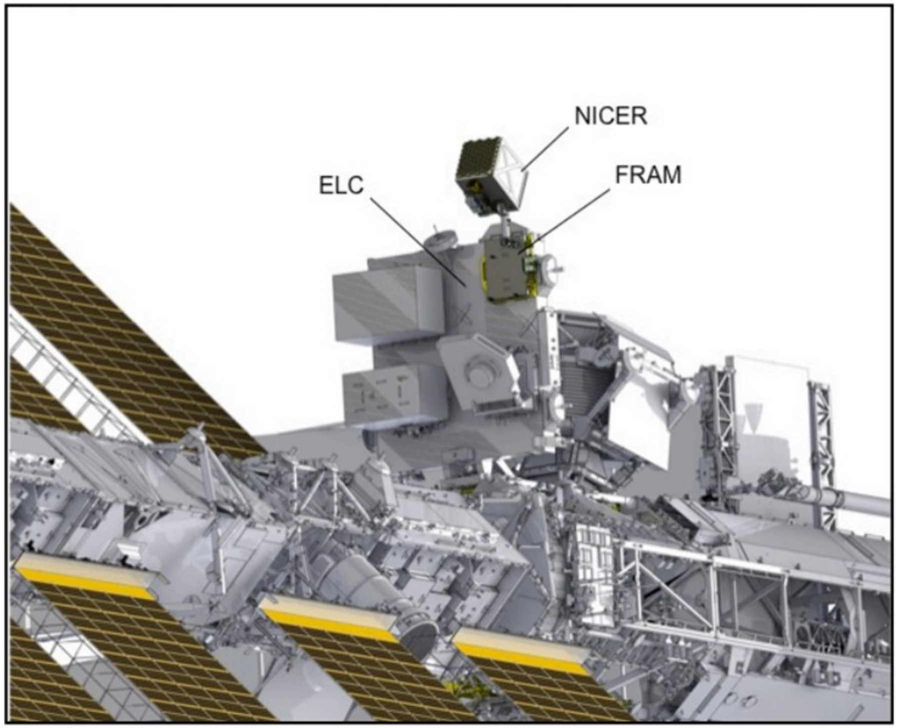
Neutron Star Radius

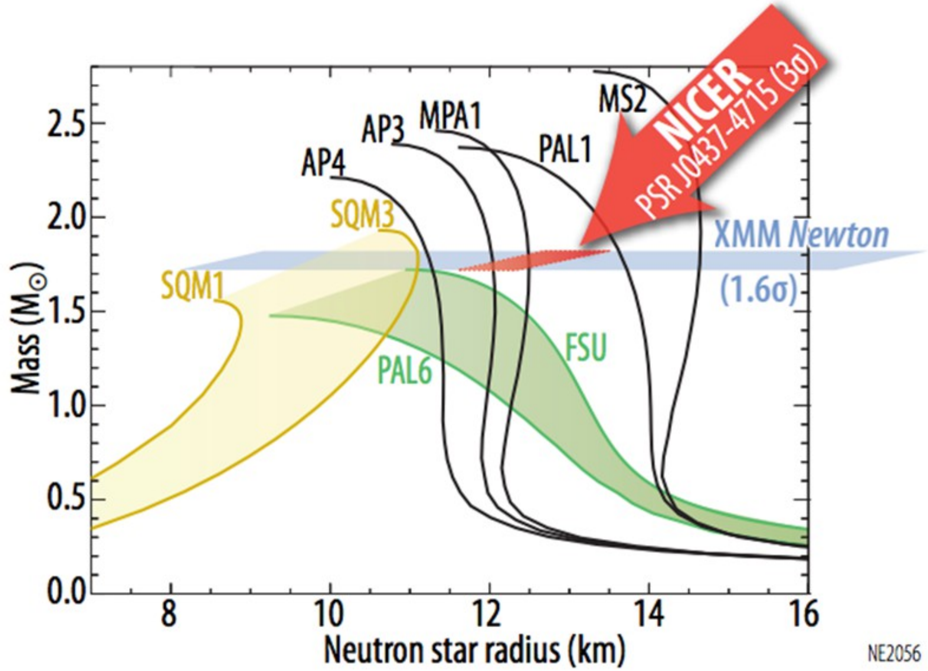




$$P = n^2 d/dn(E_t ot(n))|_{n0} = n_0^2 dS^U(n)/dn|_{n0} + n_0^2 dE_l ep(n)/dn|_{n0}$$







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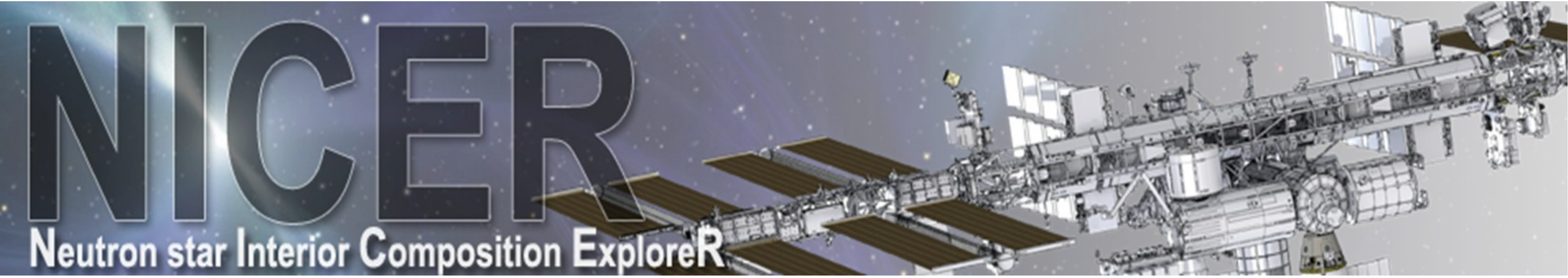
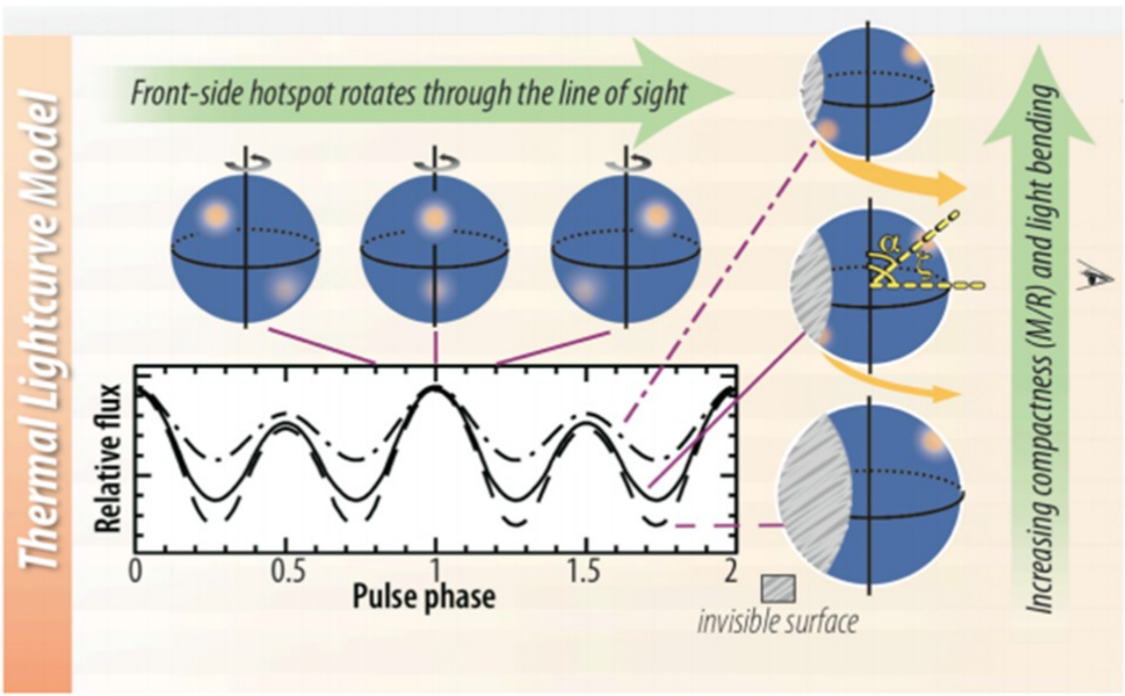
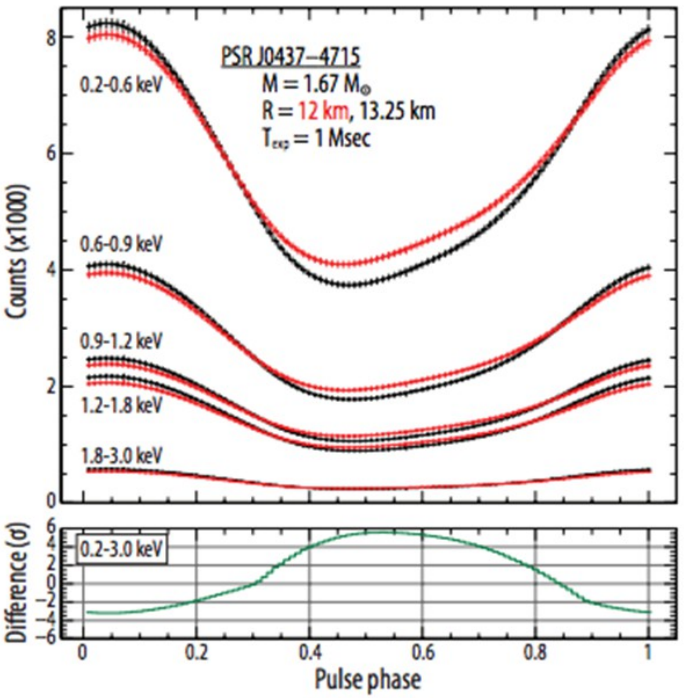
endreau, K. C., Arzoumanian, Z., & Okajima, T. 2012, Proc. SPIE, 8443, 8443







Hot Spots

endreau, K. C., Arzoumanian, Z., & Okajima, T. 2012, Proc. SPIE, 8443, 8443

Conclusions

- There exists a universal symmetry energy contribution to the equation of state for certain class of functionals, in particular those respecting the DUrca constraint.

- Excluded volume effects can also prevent the DUrca cooling for very stiff equations of state and also influence the mass and radius properties.

- The Prakash - Lattimer relation allows to constraint the radius.

The symmetry energy parameters at saturation directly influence the neutron star radius: $P(n_0) \sim L$.

- Precise determination of the gamma, S and L parameters is desirable for NS studies. In the contrary, mass radius measurements might help to constraint those values.

Gracias