Symmetry Energy Constraints From Neutron Stars and Experiment

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Hirschegg 2012
Facets of Strong-Interaction Physics

Outline

- Nuclear Symmetry Energy
- Neutron Star Structure
  - Mass Measurements and Constraints
  - Neutron Star Radii and Relation to Symmetry Energy
  - Measuring Neutron Star Radii
  - The Universal Mass-Radius Relation and the Neutron Star EOS
- Nuclear Experimental Constraints
  - Masses
  - Neutron Skin Thickness
  - Isospin Diffusion in Heavy Ion Collisions
  - Giant Dipole Resonances
  - Dipole Polarizabilities
  - Pygmy Dipole Resonances
- Neutron Matter Calculations

Nuclear Symmetry Energy

Two definitions:

1. Difference between energies of pure neutron matter and symmetric nuclear matter

$$S(\rho) = E(\rho, x = 0) - E(\rho, x = 1/2)$$

2. Expansion around saturation density and symmetric matter

$$E(\rho, x) = E(\rho, x = 1/2) + (1 - 2x)^2 E_{sym}(\rho)$$

$$E_{sym}(\rho) = \left[S_v + \frac{L}{3} \frac{\rho - \rho_s}{\rho_s} + \frac{K_{sym}}{18} \left(\frac{\rho - \rho_s}{\rho_s} \right)^2 \right] + \ldots$$

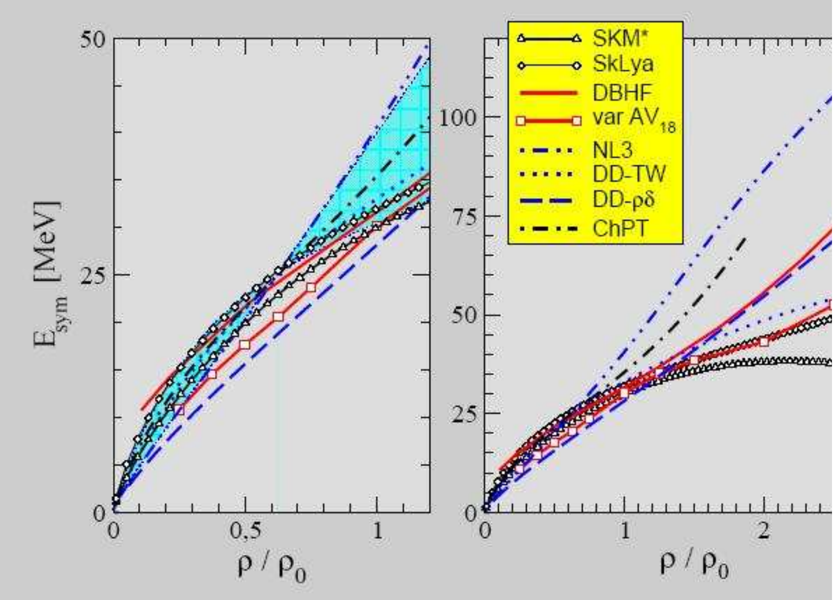
$$S_v = \frac{1}{8} \frac{\partial^2 E}{\partial x^2} \bigg|_{\rho_s, 1/2}, \quad L = \frac{3}{8} \frac{\partial^3 E}{\partial \rho \partial x^2} \bigg|_{\rho_s, 1/2}, \quad K_{sym} = \frac{9}{8} \frac{\partial^4 E}{\partial \rho^2 \partial x^2} \bigg|_{\rho_x, 1/2}$$

Thus, $E_{sym}(\rho) \simeq S(\rho)$, but

$$S(\rho_s) = E_N(\rho_s) + B \neq S_v$$

$$p_N(\rho_s) \neq L\rho_s/3$$

The Uncertain $E_{sym}(n)$



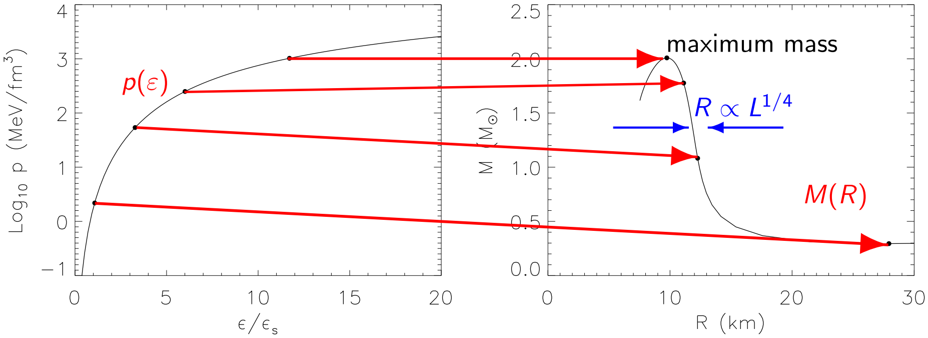
C. Fuchs, H.H. Wolter, EPJA 30(2006) 5

Neutron Star Structure

Tolman-Oppenheimer-Volkov equations

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

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



Equation of State ⟵ Observations

Mass-Radius Diagram and Theoretical Constraints

GR:

$R > 2GM/c^2$

$P < \infty$:

$R > (9/4)GM/c^2$

$M < M_{max}$

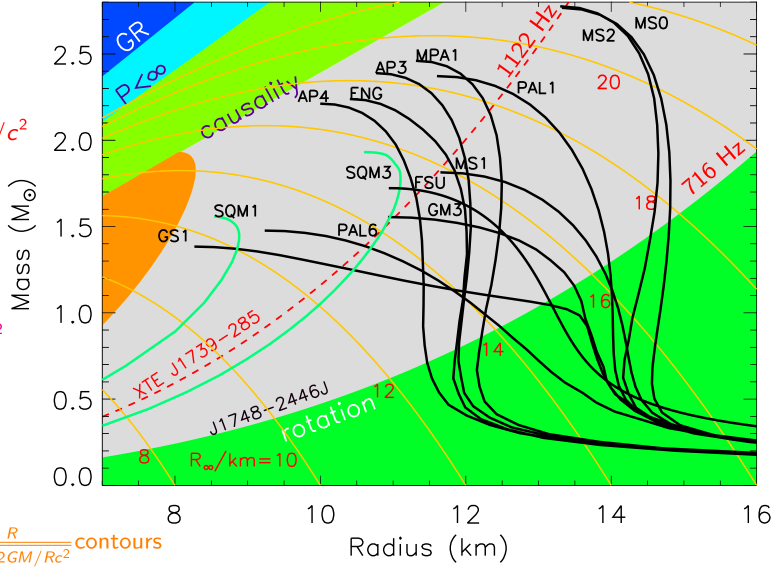
causality:

$R \gtrsim 2.9GM/c^2$

— normal NS

— SQS

— $R_\infty = \frac{R}{\sqrt{1-2GM/Rc^2}}$ contours



Neutron Star Matter Pressure and the Radius

$p \simeq K n^\gamma$

$\gamma = d \ln p / d \ln \;\; n \sim 2$

$R \propto K^{1/(3\gamma-4)} M^{(\gamma-2)/(3\gamma-4)}$

$R \propto p_f^{1/2} n_f^{-1} M^0$

$(1 < n_f/n_s < 2)$

Wide variation:

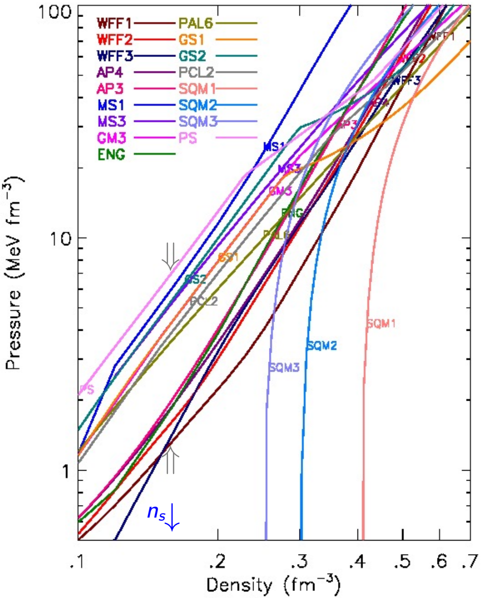
$1.2 < \frac{p(n_s)}{\mathrm{MeV\ fm^{-3}}} < 7$

GR phenomenological result

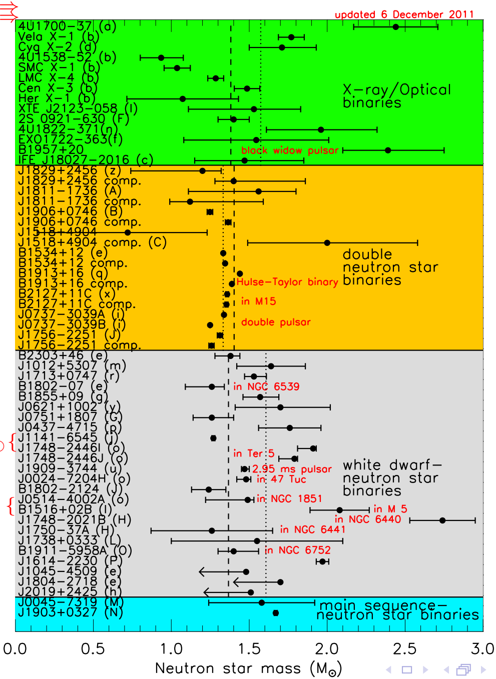
(Lattimer & Prakash 2001)

$R \propto p_f^{1/4} n_f^{-1/2}$

$p_f \simeq n^2 dS/dn$



Black hole?
Firm lower mass limit?



$M > 1.68\ M_\odot$ { **95% confidence**

Freire et al. 2007 {

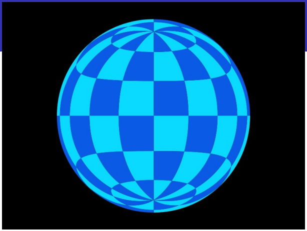
Although simple average mass of w.d. companions is 0.27 $M_\odot$ larger, weighted average is 0.08 $M_\odot$ smaller

} **w.d. companion? statistics?**

Demorest et al. 2010

Champion et al. 2008

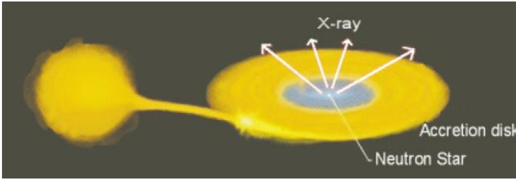
Measuring Neutron Star Radii



- The measurement of flux and temperature yields an apparent angular size (pseudo-BB):

$$\frac{R_\infty}{D} = \frac{R}{D}\frac{1}{\sqrt{1-2GM/Rc^2}}$$

- Observational uncertainties include distance, interstellar absorption (UV and X-rays), atmospheric composition

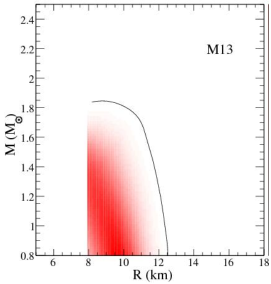


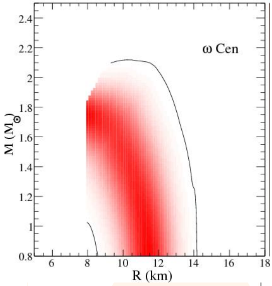
Best chances for accurate radius measurement:

- Nearby isolated neutron stars with parallax
- Quiescent X-ray binaries in globular clusters (reliable distances, low B H-atmospheres)
- Bursting sources with peak fluxes close to Eddington (where gravity balances radiation pressure)

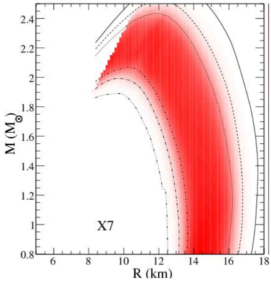
$$F_{Edd} = \frac{cGM}{\kappa D^2}$$

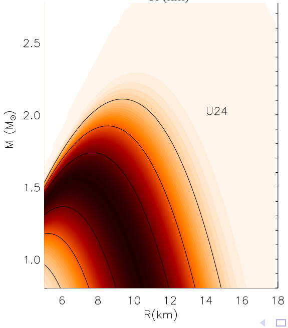
Inferred M-R Probability Distributions – Thermal Sources

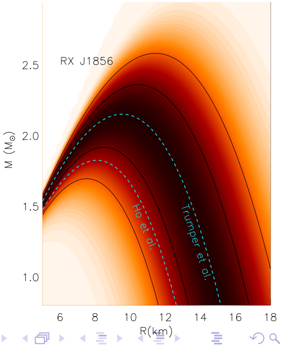




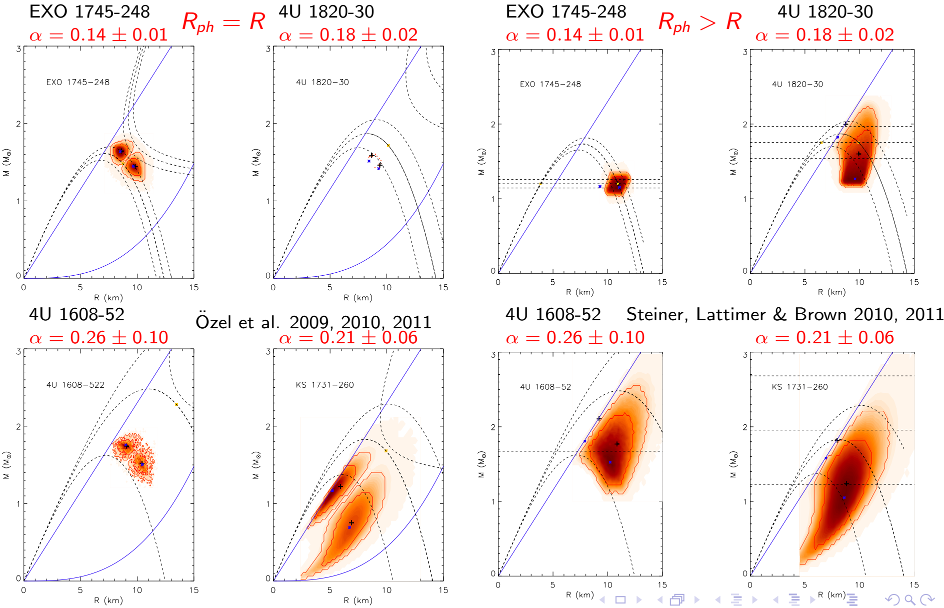
Steiner, Lattimer & Brown 2010





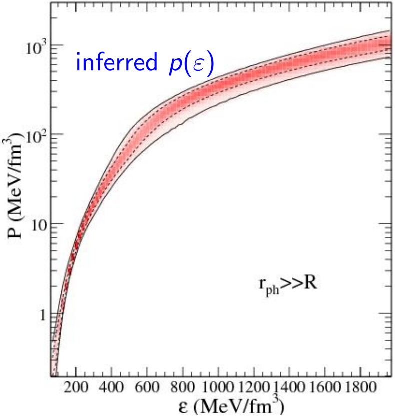


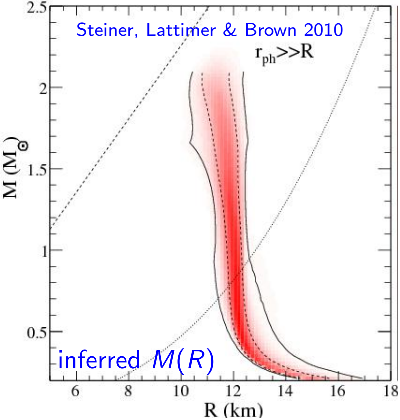
$M - R$ Probability Estimates from PRE Bursts



Bayesian TOV Inversion

- $\varepsilon < 0.5\varepsilon_0$: Known crustal EOS
- $0.5\varepsilon_0 < \varepsilon < \varepsilon_1$: EOS parametrized by K, K', S_v, γ
- Polytropic EOS: $\varepsilon_1 < \varepsilon < \varepsilon_2$: n_1; $\varepsilon > \varepsilon_2$: n_2
- EOS parameters $K, K', S_v, \gamma, \varepsilon_1, n_1, \varepsilon_2, n_2$ uniformly distributed
- $M_{max} \geq 1.97$ M$_\odot$, causality enforced
- All stars equally weighted





Nuclear Binding Energy

$E_{sym}(N,Z) = I^2(S_vA - S_sA^{2/3})$

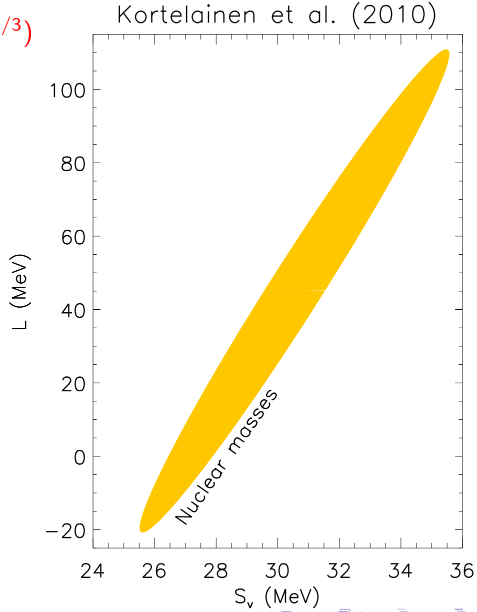
$\chi^2 = \sum_i (E_{ex,i} - E_{sym,i})^2/\mathcal{N}$
$\chi_{vv} = \frac{2}{\mathcal{N}} \sum_i I_i^4 A_i^2$
$\chi_{ss} = \frac{2}{\mathcal{N}} \sum_i I_i^4 A_i^{4/3}$
$\chi_{vs} = \frac{2}{\mathcal{N}} \sum_i I_i^4 A_i^{5/3}$

$\sigma_{S_v} = \sqrt{\frac{2\chi_{ss}}{\chi_{vv}\chi_{ss} - \chi_{sv}^2}}$
$\sigma_{S_s} = \sqrt{\frac{2\chi_{vv}}{\chi_{vv}\chi_{ss} - \chi_{sv}^2}}$

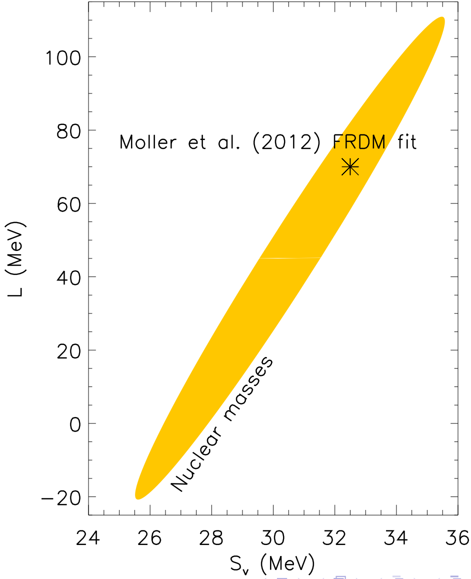
$\alpha = \frac{1}{2}\tan^{-1}\frac{2\chi_{vs}}{\chi_{vv} - \chi_{ss}}$
$r_{vs} = -\frac{\chi_{vs}}{\sqrt{\chi_{vv}\chi_{ss}}}$

$S_s \approx 0.95 S_v + 0.57 L$

$E_{sym}(N,Z) = \frac{S_v A I^2}{1 + (S_s/S_v)A^{-1/3}}$



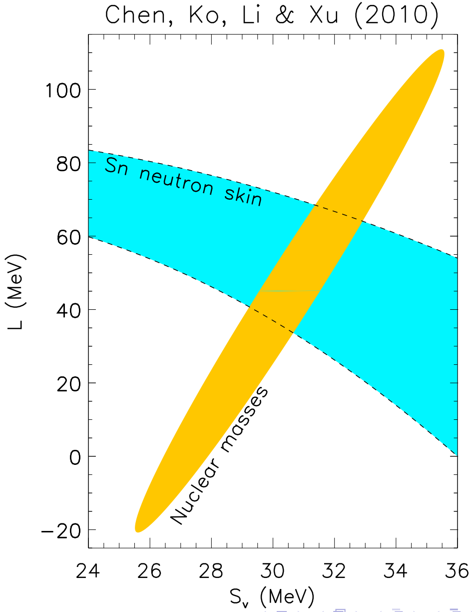
Nuclear Binding Energy



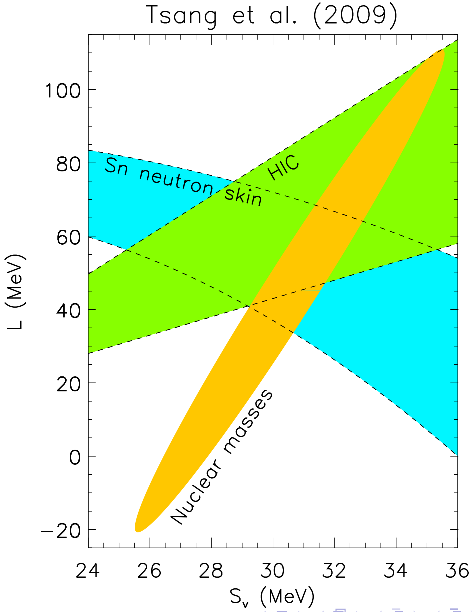
Neutron Skin Thickness

$$R_n - R_p \simeq \sqrt{3/5} t_{np}$$

$$t_{np} = \frac{2r_o}{3} \frac{S_s I}{S_v + S_s A^{-1/3}}$$



Heavy Ion Collisions

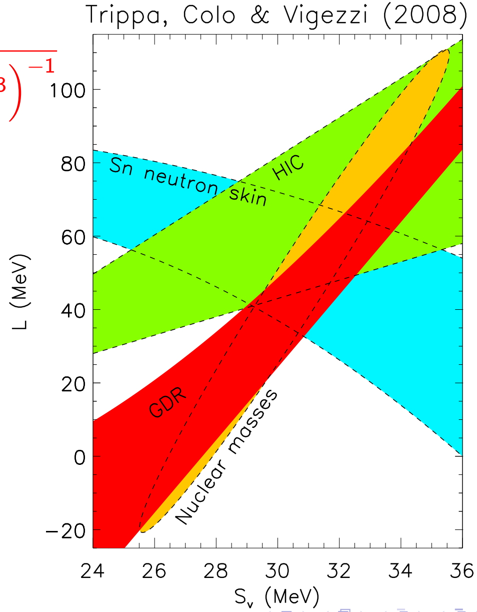


Giant Dipole Resonances

$$E_{-1} \propto \sqrt{S_v \left(1 + \frac{5S_s}{3S_v} A^{-1/3}\right)^{-1}}$$

Correlation between E_{-1} and E_{sym} maximized when

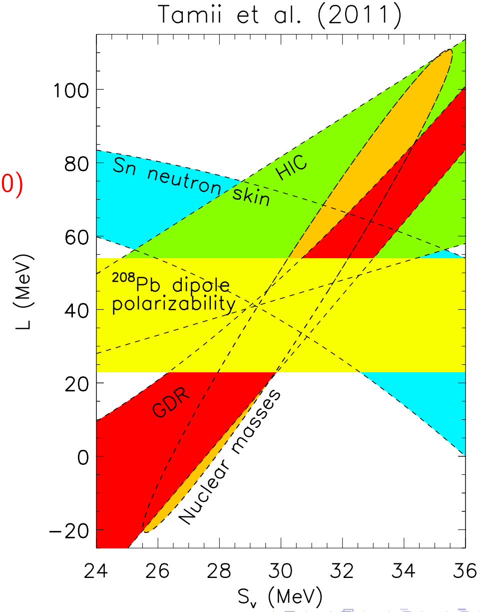
$$E_{sym,208}/AI^2 = \frac{S_v}{1+(S_s/S_v)A^{-1/3}} \simeq S(\rho = 0.1)$$



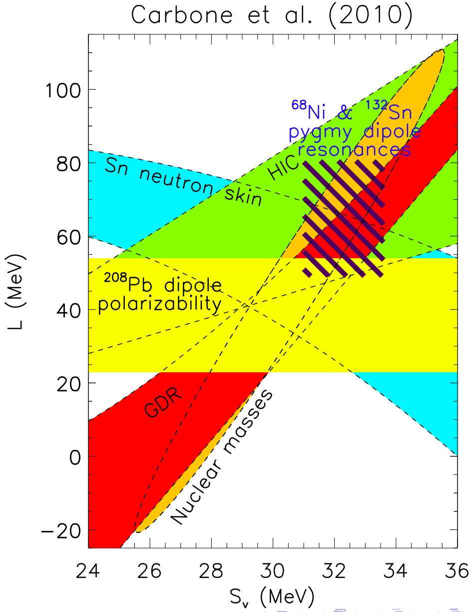
Dipole Polarizability

α_D and $R_n - R_p$ in ^{208}Pb are 98% correlated

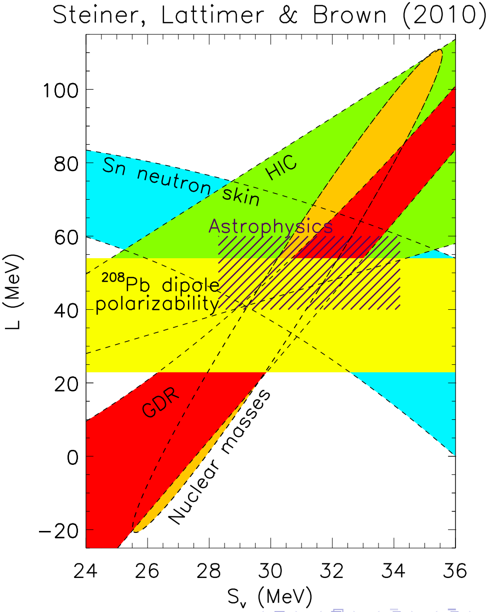
Reinhard & Nazawericz (2010)



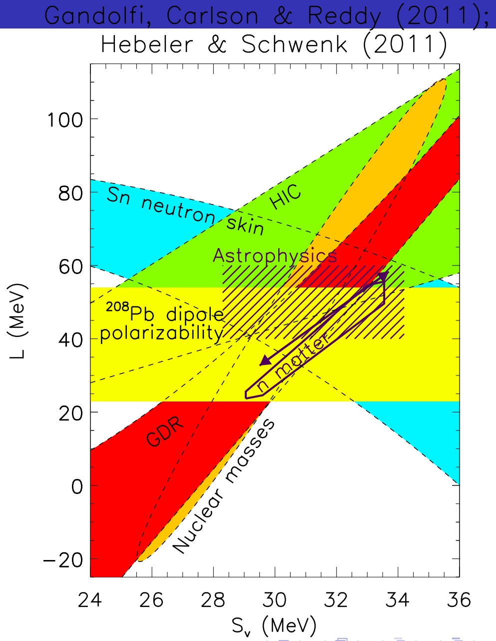
Pygmy Dipole Resonances



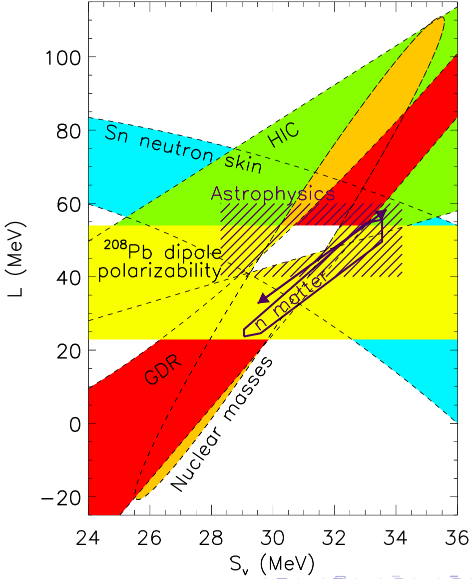
Astronomical Observations



Neutron Matter



Combined Constraints



Astrophysical Consistency with Neutron Matter and Heavy-Ion Collisions