MICROSCOPIC EFFECTIVE INTERACTIONS IN NEUTRON-RICH MATTER

Plamen Krastev –TAMU-Commerce

F. Sammarruca – University of Idaho

Bao-An Li, Aaron Worley – TAMU-Commerce

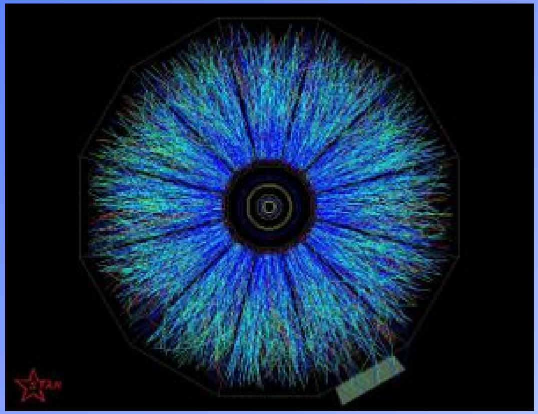
INT – Nuclear Many-Body Approaches For The 21st Century

Outline:

1. Introduction
2. Theoretical framework
3. Equation of state (EOS) of asymmetric nuclear matter
4. EOS of spin-polarized neutron matter
5. Astrophysical and cosmological applications
6. Summary

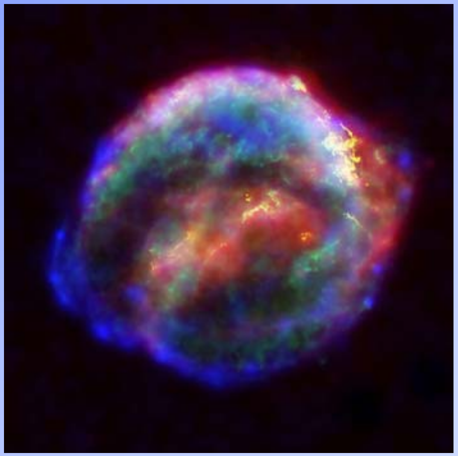
Introduction:

Equation of State (EOS) of dense neutron-rich matter



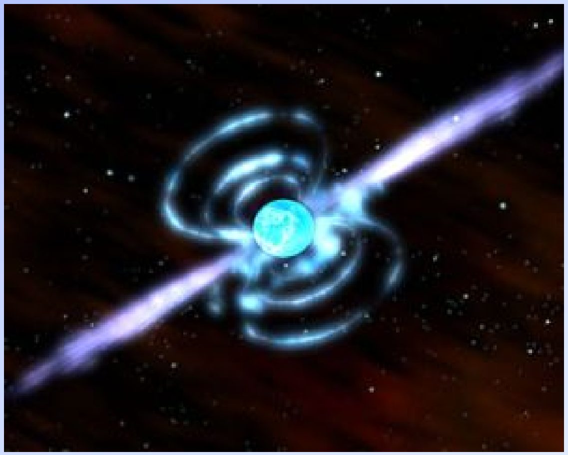
Dynamics of relativistic heavy-ion collisions

illustration credit: RHIC-Brookhaven National Laboratory



Supernova explosions and formation of heavy elements

illustration credit: NASA



Structure and properties of neutron stars

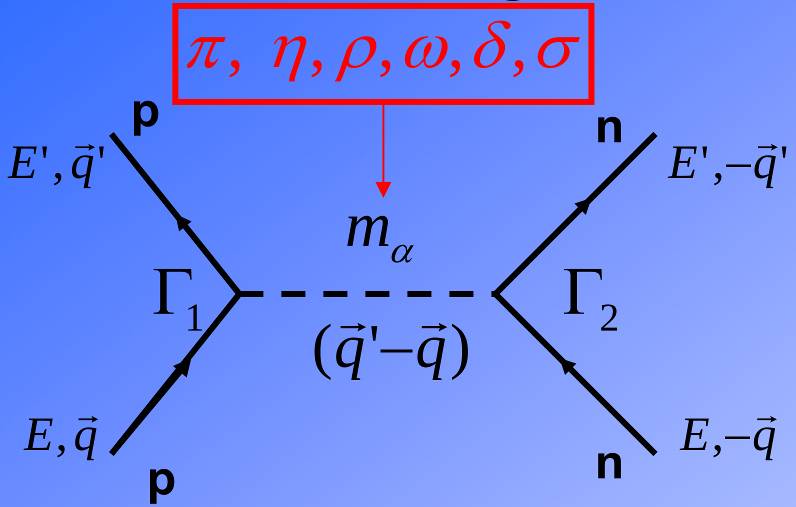
illustration credit: media.arstechnica.com

Theoretical framework:

1. Realistic Nucleon-Nucleon (NN) forces
2. Conventional Brueckner-Hartree-Fock (BHF) approach
3. Dirac-Brueckner-Hartree-Fock (DBHF) method

Realistic NN Forces:

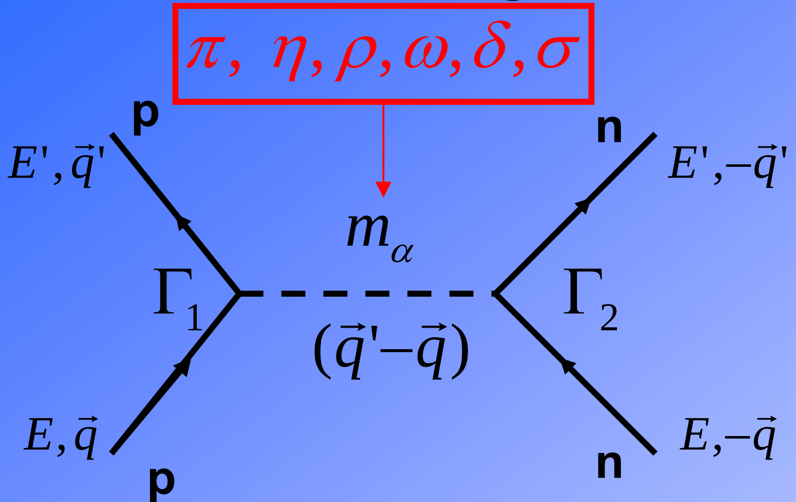
One-boson-exchange (OBE) model:



R. Machleidt, "The meson theory of nuclear forces and nuclear structure", Adv. Nucl. Phys. 19, 189-376 (1989).

Realistic NN Forces:

One-boson-exchange (OBE) model:



Nucleon-meson coupling Lagrangians:

$$\mathcal{L}_{p\upsilon} = -\frac{f_{ps}}{m_{ps}} \bar{\psi} \gamma^5 \gamma^\mu \psi \partial_\mu \phi^{(ps)}$$

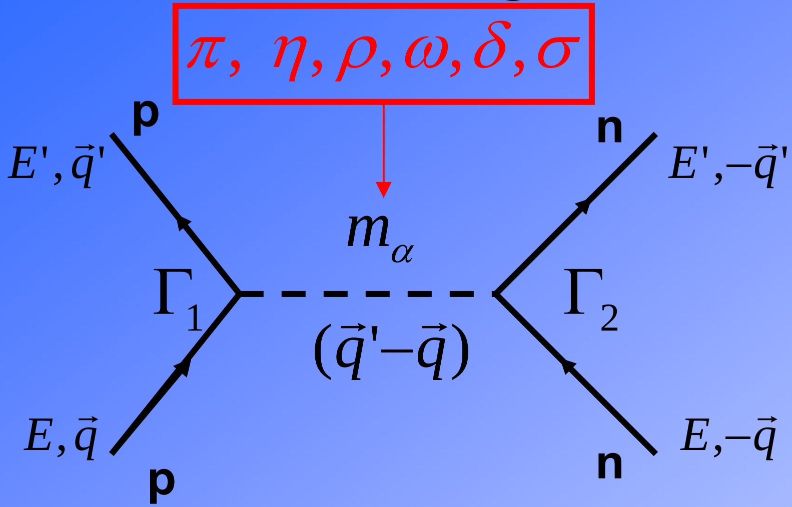
$$\mathcal{L}_s = g_s \bar{\psi} \psi \phi^{(s)}$$

$$\mathcal{L}_\upsilon = -g_\upsilon \bar{\psi} \gamma^\mu \phi_\mu^{(\upsilon)} - \frac{f_\nu}{4m} \psi \sigma^{\mu\nu} \psi (\partial_\mu \phi_\nu^{(\upsilon)} - \partial_\nu \phi_\mu^{(\upsilon)})$$

R. Machleidt, "The meson theory of nuclear forces and nuclear structure", Adv. Nucl. Phys. 19, 189-376 (1989).

Realistic NN Forces:

One-boson-exchange (OBE) model:



Nucleon-meson coupling Lagrangians:

$$\mathcal{L}_{p\upsilon} = -\frac{f_{ps}}{m_{ps}}\overline{\psi}\gamma^{5}\gamma^{\mu}\psi\partial_{\mu}\phi^{(ps)}$$

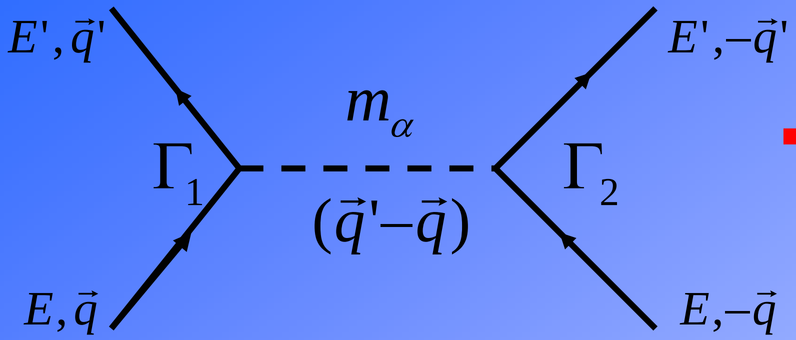
$$\mathcal{L}_{s} = g_{s}\overline{\psi}\psi\phi^{(s)}$$

$$\mathcal{L}_{\upsilon} = -g_{\upsilon}\overline{\psi}\gamma^{\mu}\phi_{\mu}^{(\upsilon)} - \frac{f_{\nu}}{4m}\psi\sigma^{\mu\nu}\psi(\partial_{\mu}\phi_{\nu}^{(\upsilon)} - \partial_{\nu}\phi_{\mu}^{(\upsilon)})$$

$$\mathrm{V}_{\mathrm{OBEP}} = \sum_{\alpha=\pi,\sigma,\rho,\omega,\eta,\delta,\ldots} \mathrm{V}_{\alpha}^{\mathrm{OBE}}$$

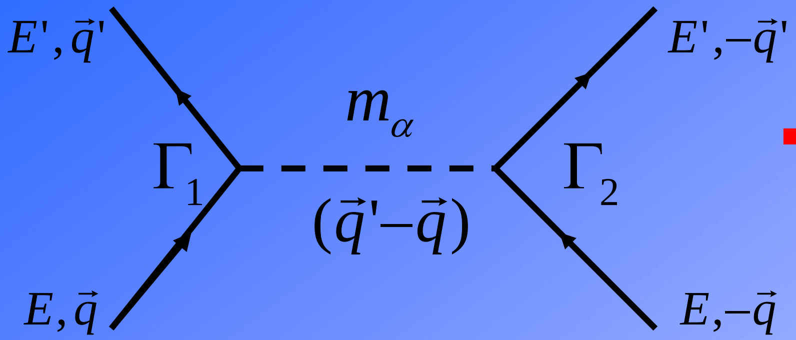
R. Machleidt, “The meson theory of nuclear forces and nuclear structure”, Adv. Nucl. Phys. 19, 189-376 (1989).

OBE amplitudes:



$$F_\alpha(q', q) = \frac{\bar{u}_1(q')\Gamma_1 u_1(q) P_\alpha \bar{u}_2(-q')\Gamma_2 u_2(-q)}{(q'-q)^2 - m_\alpha}$$

OBE amplitudes:



$$F_\alpha(q', q) = \frac{\bar{u}_1(q')\Gamma_1 u_1(q) P_\alpha \bar{u}_2(-q')\Gamma_2 u_2(-q)}{(q'-q)^2 - m_\alpha}$$

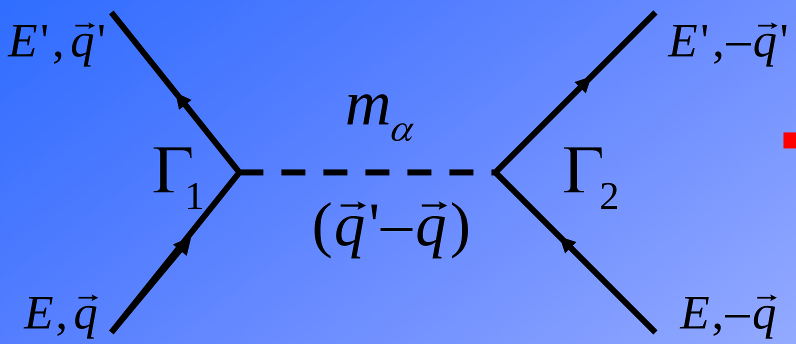
Example - OBE amplitudes for scalar mesons (σ, δ)

$$< q'\lambda_1'\lambda_2'|V_s^{OBE}|q\lambda_1\lambda_2 >= -g_s^2 \bar{u}(q', \lambda_1')u(q, \lambda_1)\bar{u}(-q', \lambda_2')u(-q, \lambda_2)\frac{(\mathcal{F}_s[(q'-q)^2])^2}{(q'-q)^2 + m_s^2}$$

$$\mathcal{F}_s[(q'-q)^2] = \frac{\Lambda_s^2 - m_s^2}{\Lambda_s^2 + (q'-q)^2}$$

Form-factor (of monopole type) to take care of the extended quark structure at short distances

OBE amplitudes:



$$F_\alpha(q',q)=\frac{\bar{u}_1(q')\Gamma_1 u_1(q)P_\alpha \bar{u}_2(-q')\Gamma_2 u_2(-q)}{(q'-q)^2-m_\alpha}$$

Example - <u>OBE amplitudes for scalar mesons</u> (σ,δ)

$$<q'\lambda_1'\lambda_2'|V_s^{OBE}|q\lambda_1\lambda_2>=-g_s^2\bar{u}(q',\lambda_1')u(q,\lambda_1)\bar{u}(-q',\lambda_2')u(-q,\lambda_2)\frac{(\mathcal{F}_s[(q'-q)^2])^2}{(q'-q)^2+m_s^2}$$

$$\mathcal{F}_s[(q'-q)^2]=\frac{\Lambda_s^2-m_s^2}{\Lambda_s^2+(q'-q)^2}$$

Form-factor (of monopole type) to take care of the extended quark structure at short distances

We apply the Bonn A, B, and C OBE potentials.

R. Machleidt, "The meson theory of nuclear forces and nuclear structure", Adv. Nucl. Phys. 19, 189-376 (1989).

Self-consistent evaluation of the single-particle spectrum (BHF):

$$G_{ij}(P;K,K_0) = V_{ij}(K,K_0) - \int \frac{d^3K'}{(2\pi)^3} V_{ij}(K',K_0) \frac{Q_{ij}(K';P,k_F)G_{ij}(P;K',K_0)}{\varepsilon^*_{ij}(P,K') - (\varepsilon^*_{ij})_0(P,K_0)}$$

$$U_i(p) = < p|U_i|p > = \mathcal{R}e\left[\sum_{q\le k_F^n} < pq|G_{in}|pq-qp > + \sum_{q\le k_F^p} < pq|G_{ip}|pq-qp >\right]$$

$$U_n = U_{nn} + U_{np}$$
$$U_p = U_{pp} + U_{pn}$$

Self-consistent evaluation of the single-particle spectrum (BHF):

$$G_{ij}(P;K,K_0) = V_{ij}(K,K_0) - \int \frac{d^3K'}{(2\pi)^3} V_{ij}(K',K_0) \frac{Q_{ij}(K';P,k_F)G_{ij}(P;K',K_0)}{\varepsilon^*_{ij}(P,K') - (\varepsilon^*_{ij})_0(P,K_0)}$$

$$U_i(p) = < p|U_i|p > = \mathcal{R}e\left[\sum_{q\le k_F^n} < pq|G_{in}|pq-qp > + \sum_{q\le k_F^p} < pq|G_{ip}|pq-qp >\right]$$

$$U_n = U_{nn} + U_{np}$$

$$U_p = U_{pp} + U_{pn}$$

Fails to predict the nuclear saturation!

Self-consistent evaluation of the single-particle spectrum (DBHF):

$$(\not{p}_i - m_i - U_i(p))u_i(\mathrm{p},s) = 0$$

$$u_i(\mathbf{p},s) = \left(\frac{E_i^*(p)+m_i^*}{2m_i^*}\right)^{1/2}\begin{pmatrix} 1 \\ \dfrac{\sigma.\mathbf{p}}{E_{p,i}^*+m_i^*}\end{pmatrix}\chi_S$$

$$U_i(p) = \mathcal{R}e\left[\sum_{q\le k_F^n}\frac{m_i^* m_n^*}{E_i^*(p)E_n^*(p)} < pq\,|\,g_{in}\,|\,pq-qp > + \sum_{q\le k_F^p}\frac{m_i^* m_p^*}{E_i^*(p)E_p^*(p)} < pq\,|\,g_{ip}\,|\,pq-qp >\right]$$

$$\mathrm{g_{ij}}(\mathrm{P;K,K_0}) = \upsilon_{ij}^*(\mathrm{K,K_0}) - \int\frac{\mathrm{d}^3K'}{(2\pi)^3}\upsilon_{ij}^*(\mathrm{K',K_0})\frac{m_i^* m_j^*}{E_i^* E_j^*}\frac{\mathrm{Q_{ij}}(\mathrm{K';P},k_F)\mathrm{g_{ij}}(\mathrm{P;K',K_0})}{\varepsilon_{ij}^*(\mathrm{P,K'}) - (\varepsilon_{ij}^*)_0(\mathrm{P,K_0})}$$

$$G_{ij} = \frac{m_i^*}{E_i^*}g_{ij}\frac{m_j^*}{E_j^*} \quad \text{and} \quad V_{ij}^* = \frac{m_i^*}{E_i^*}\upsilon_{ij}^*\frac{m_j^*}{E_j^*} \Rightarrow$$

$$G_{\mathrm{ij}}(\mathrm{P;K,K_0}) = V_{ij}^*(\mathrm{K,K_0}) - \int\frac{\mathrm{d}^3K'}{(2\pi)^3}V_{ij}^*(\mathrm{K',K_0})\frac{\mathrm{Q_{ij}}(\mathrm{K';P},k_F)G_{\mathrm{ij}}(\mathrm{P;K',K_0})}{\varepsilon_{ij}^*(\mathrm{P,K'}) - (\varepsilon_{ij}^*)_0(\mathrm{P,K_0})}$$

Self-consistent evaluation of the single-particle spectrum (DBHF):

$$(\not{p}_i - m_i - U_i(p))u_i(\mathrm{p},s) = 0$$

$$u_i(\mathbf{p},s) = \left(\frac{E_i^*(p)+m_i^*}{2m_i^*}\right)^{1/2}\begin{pmatrix} 1 \\ \dfrac{\sigma.\mathbf{p}}{E_{p,i}^* + m_i^*}\end{pmatrix}\chi_S$$

$$U_i(p) = \mathcal{R}e\left[\sum_{q\le k_F^n}\frac{m_i^* m_n^*}{E_i^*(p)E_n^*(p)} < pq \mid g_{in} \mid pq - qp > + \sum_{q\le k_F^p}\frac{m_i^* m_p^*}{E_i^*(p)E_p^*(p)} < pq \mid g_{ip} \mid pq - qp >\right]$$

$$\mathrm{g_{ij}}(\mathrm{P};\mathrm{K},\mathrm{K_0}) = \upsilon_{ij}^*(\mathrm{K},\mathrm{K_0}) - \int\frac{\mathrm{d}^3K'}{(2\pi)^3}\upsilon_{ij}^*(\mathrm{K'},\mathrm{K_0})\frac{m_i^* m_j^*}{E_i^* E_j^*}\frac{\mathrm{Q_{ij}}(\mathrm{K'};\mathrm{P},k_F)\mathrm{g_{ij}}(\mathrm{P};\mathrm{K'},\mathrm{K_0})}{\varepsilon_{ij}^*(\mathrm{P},\mathrm{K'}) - (\varepsilon_{ij}^*)_0(\mathrm{P},\mathrm{K_0})}$$

$$G_{ij} = \frac{m_i^*}{E_i^*}g_{ij}\frac{m_j^*}{E_j^*} \quad \text{and} \quad V_{ij}^* = \frac{m_i^*}{E_i^*}\upsilon_{ij}^*\frac{m_j^*}{E_j^*} \Rightarrow$$

$$G_{\mathrm{ij}}(\mathrm{P};\mathrm{K},\mathrm{K_0}) = V_{ij}^*(\mathrm{K},\mathrm{K_0}) - \int\frac{\mathrm{d}^3K'}{(2\pi)^3}V_{ij}^*(\mathrm{K'},\mathrm{K_0})\frac{Q_{\mathrm{ij}}(\mathrm{K'};\mathrm{P},k_F)G_{\mathrm{ij}}(\mathrm{P};\mathrm{K'},\mathrm{K_0})}{\varepsilon_{ij}^*(\mathrm{P},\mathrm{K'}) - (\varepsilon_{ij}^*)_0(\mathrm{P},\mathrm{K_0})}$$

Predicts correctly nuclear saturation properties!

Neutron-rich matter (definitions):

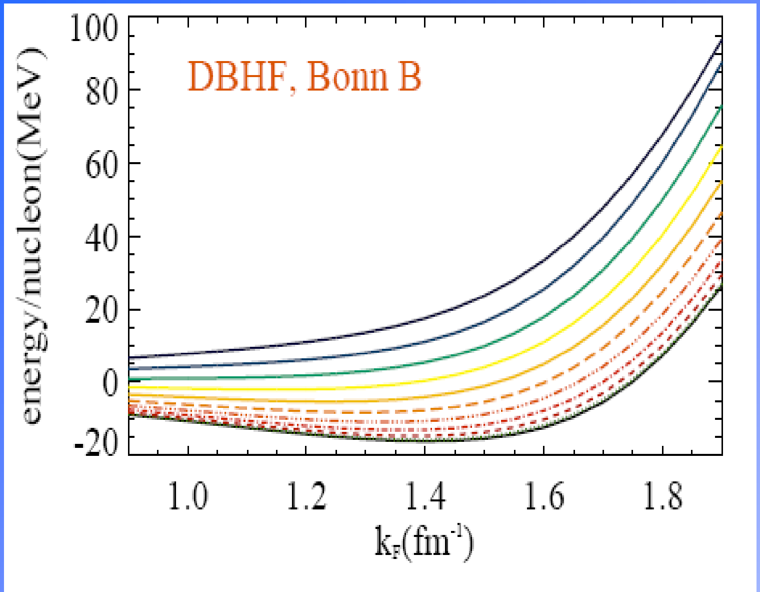
$$\rho = \frac{2k_F^3}{3\pi^2} \qquad \rho_n = \frac{(k_F^n)^3}{3\pi^2} \qquad \rho_p = \frac{(k_F^p)^3}{3\pi^2}$$

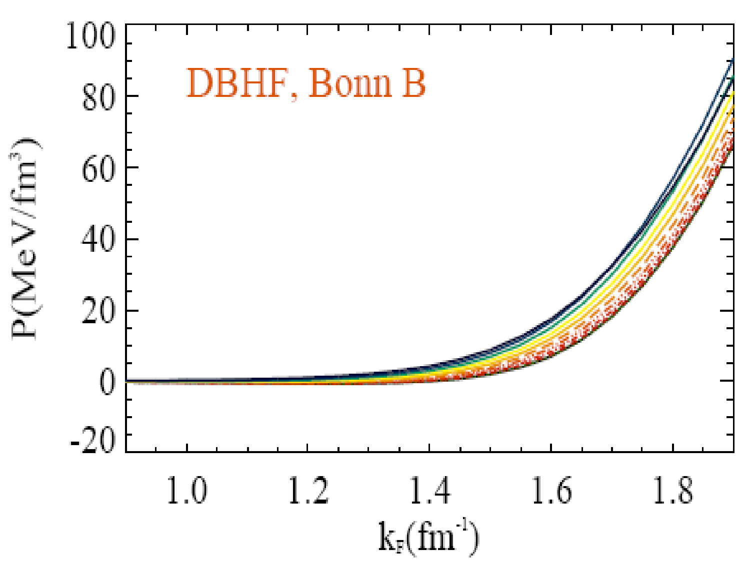
$$\rho = \rho_n + \rho_p \qquad \alpha = \frac{\rho_n - \rho_p}{\rho} \rightarrow \text{asymmetry parameter}$$

$$\alpha = 0 \quad \Rightarrow \quad \rho_p = \rho_n = \frac{\rho}{2} \qquad \text{symmetric nuclear matter}$$

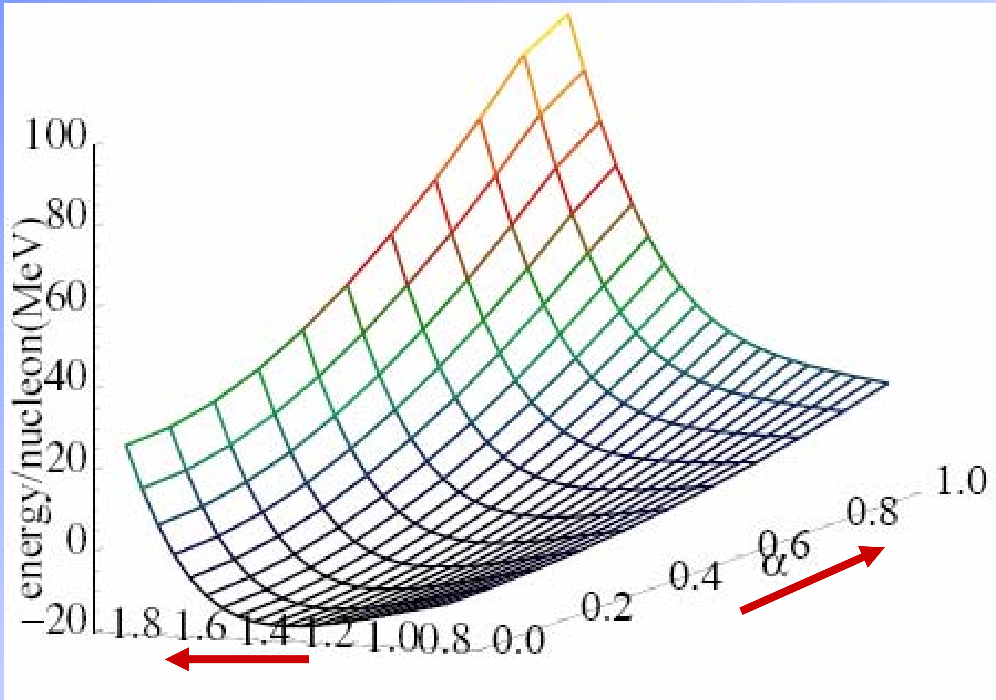
$$\alpha = 1 \quad \Rightarrow \quad \begin{cases} \rho_{\mathrm{n}} = \rho \\ \rho_p = 0 \end{cases} \qquad \text{neutron matter}$$

EOS of Neutron-Rich Matter:





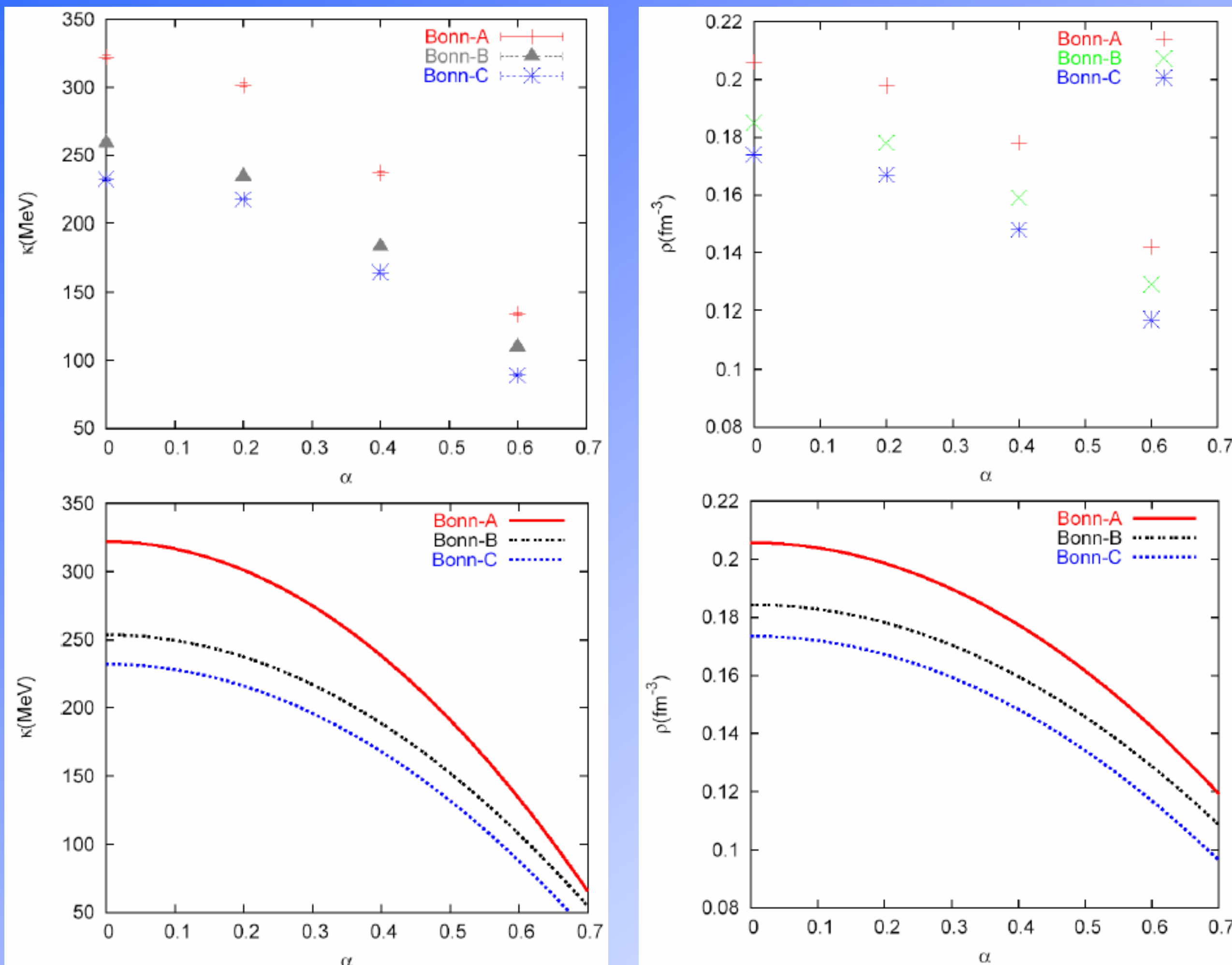
$$\bar{e}(\rho,\alpha)=\bar{e}(\rho,0)+e_{sym}(\rho)\alpha^2$$



$k_F\,(fm^{-1})$

D. Alonso and F. Sammarruca, PRC 67, 054301 (2003)

Nuclear compression modulus and saturation density:



$$\kappa = k_F \left. \frac{\partial^2 \bar{e}(k_F)}{\partial k_F^2} \right|_{k_F = k_F^{(0)}}$$

$$\kappa(\alpha) = \kappa_0 (1 - a\alpha^2)$$

$$\rho(\alpha) = \rho_0 (1 - b\alpha^2)$$

P. G. Krastev, Ph.D. dissertation, U. Idaho (2006)

Nuclear compression modulus and saturation density:

potential model	α	$\kappa(MeV)$	$k_F^{(0)}(fm^{-1})$	$\rho_0(fm^{-3})$
Bonn A	0.0	322.209	1.45	0.2059
	0.2	301.448	1.43	0.1975
	0.4	237.275	1.38	0.1775
	0.6	134.131	1.28	0.1417
Bonn B	0.0	259.043	1.40	0.1853
	0.2	234.408	1.38	0.1775
	0.4	183.926	1.33	0.1589
	0.6	109.938	1.24	0.1287
Bonn C	0.0	232.499	1.37	0.1737
	0.2	217.596	1.35	0.1662
	0.4	164.926	1.30	0.1484
	0.6	89.047	1.20	0.1167

$$\kappa = k_F \frac{\partial^2 \bar{e}(k_F)}{\partial k_F^2}\bigg|_{k_F = k_F^{(0)}}$$

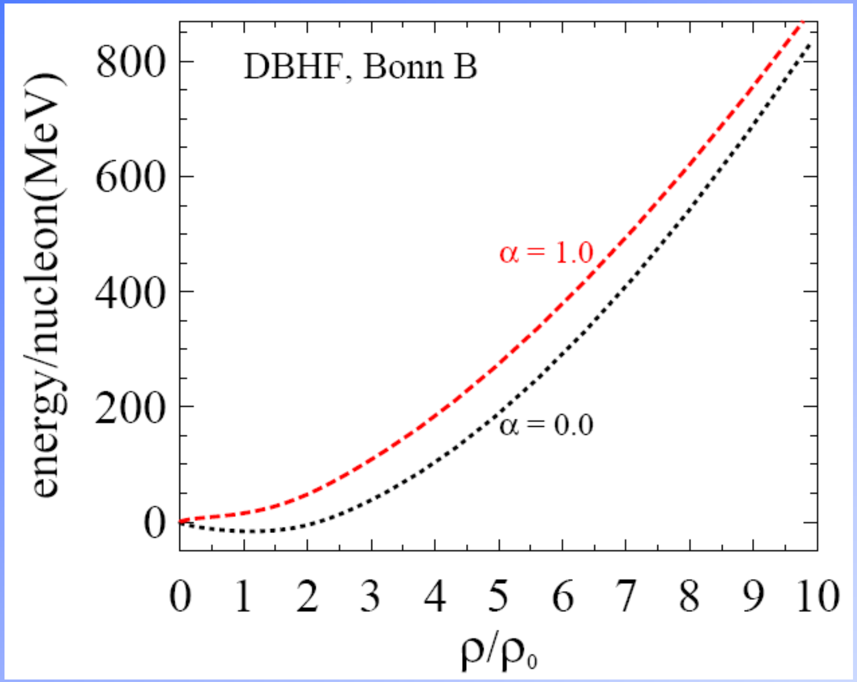
$$\kappa(\alpha) = \kappa_0(1 - a\alpha^2)$$
$$\rho(\alpha) = \rho_0(1 - b\alpha^2)$$

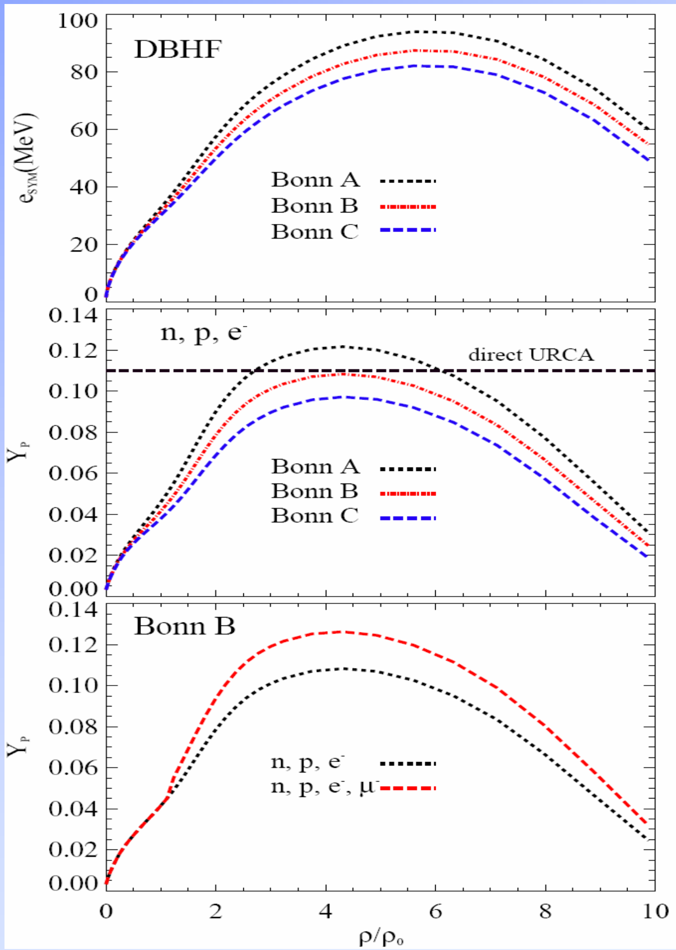
P. G. Krastev, Ph.D. dissertation, U. Idaho (2006)

Nuclear symmetry energy and proton fraction in beta equilibrium:

$$\bar{e}(\rho,\alpha) = \bar{e}(\rho,0) + e_{sym}(\rho)\alpha^2$$

$$e_{sym}(\rho) = \bar{e}(\rho,\alpha=1) - \bar{e}(\rho,\alpha=0)$$



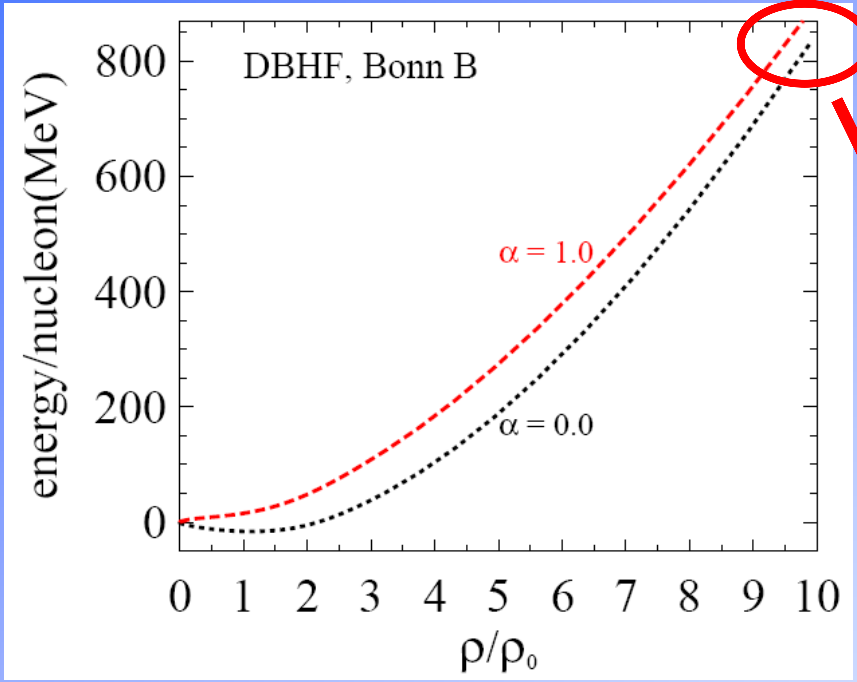


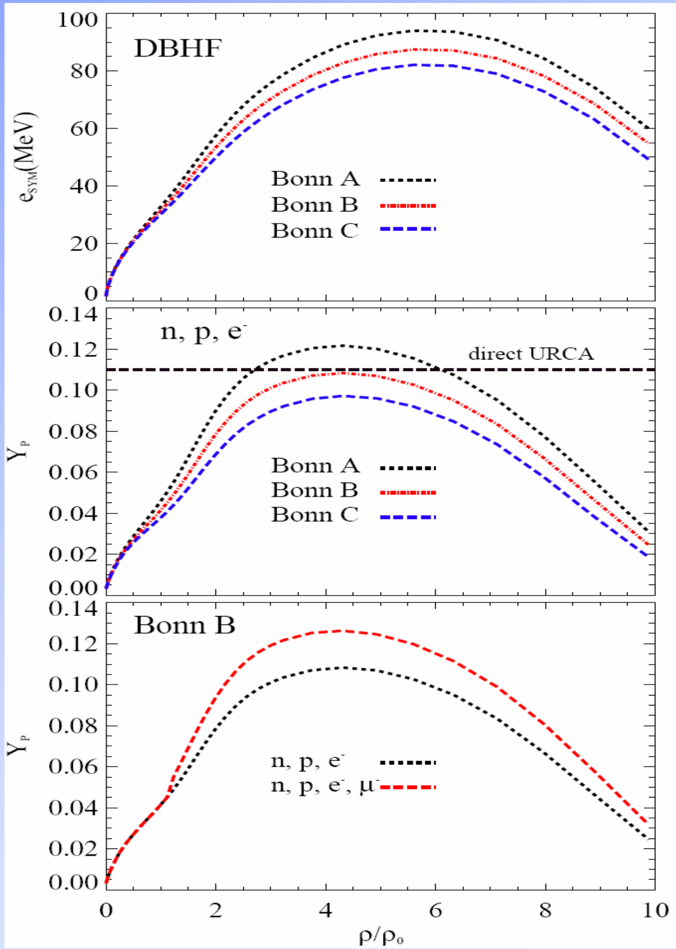
P. G. Krastev and F. Sammarruca, PRC 74, 025808 (2006)

Nuclear symmetry energy and proton fraction in beta equilibrium:

$$\bar{e}(\rho,\alpha) = \bar{e}(\rho,0) + e_{sym}(\rho)\alpha^2$$

$$e_{sym}(\rho) = \bar{e}(\rho,\alpha=1) - \bar{e}(\rho,\alpha=0)$$

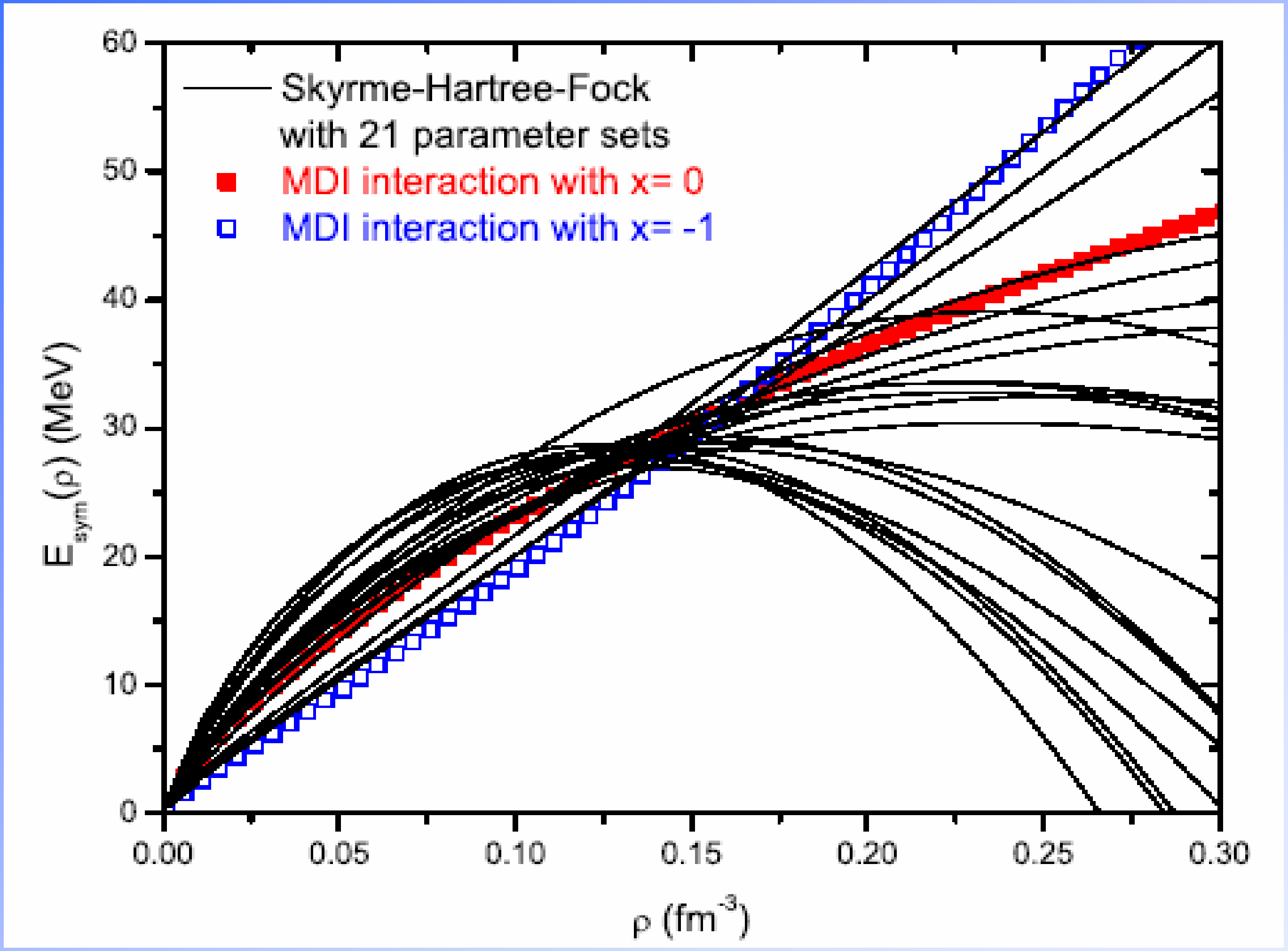




approaching "critical density"

P. G. Krastev and F. Sammarruca, PRC 74, 025808 (2006)

Nuclear symmetry energy, cont'd:



L.W. Chen, C.M. Ko and B.A. Li, Phys. Rev. C 72 064309 (2005)

EOS of Spin-Polarized Neutron Matter:

Studies of magnetic properties of dense matter are of great current interest in conjunction with physics of pulsars which are believed to be rotating neutron stars possessing huge surface magnetic fields.

F. Sammarruca and P. G. Krastev, Phys. Rev. C 75, 034315 (2007)

Brief description of the calculation:

$$U_u = U_{ud} + U_{uu}$$
$$U_d = U_{du} + U_{dd}$$

$$U_\sigma(\vec{p}) = \sum_{\sigma'=u,d} \sum_{q \le k_F^{\sigma'}} <\sigma,\sigma'|G(\vec{p},\vec{q})|\sigma,\sigma'>, \qquad (\sigma = u,d)$$

"u" – up

"d" – down

$$<\sigma,\sigma'|G(\vec{p},\vec{q})|\sigma,\sigma'> = \sum_{L,L',S,J,M,M_L} <\frac{1}{2}\sigma;\frac{1}{2}\sigma|S(\sigma+\sigma')><\frac{1}{2}\sigma;\frac{1}{2}\sigma|S(\sigma+\sigma')>$$
$$\times <LM_L;S(\sigma+\sigma')|JM><L'M_L;S(\sigma+\sigma')|JM>(i^{L'-L})Y^*_{L',M_L}(\hat{k}_{rel})Y_{L',M_L}(\hat{k}_{rel})<LSJ|G(k_{rel},K_{c.m.})|L'SJ>$$

$$\rho_d = \frac{(k_F^d)^3}{6\pi^2}, \quad \rho_u = \frac{(k_F^u)^3}{6\pi^2}, \quad k_F^u = k_F^n(1+\beta)^{1/3}, \quad k_F^d = k_F^n(1-\beta)^{1/3}$$

$$\beta = \frac{\rho_u - \rho_d}{\rho_u + \rho_d}$$

Polarization parameter

$$\beta = \begin{cases} \pm 1 \Rightarrow & \text{Completely polarized neutron matter} \\ 0 \Rightarrow & \text{Unpolarized neutron matter} \end{cases}$$

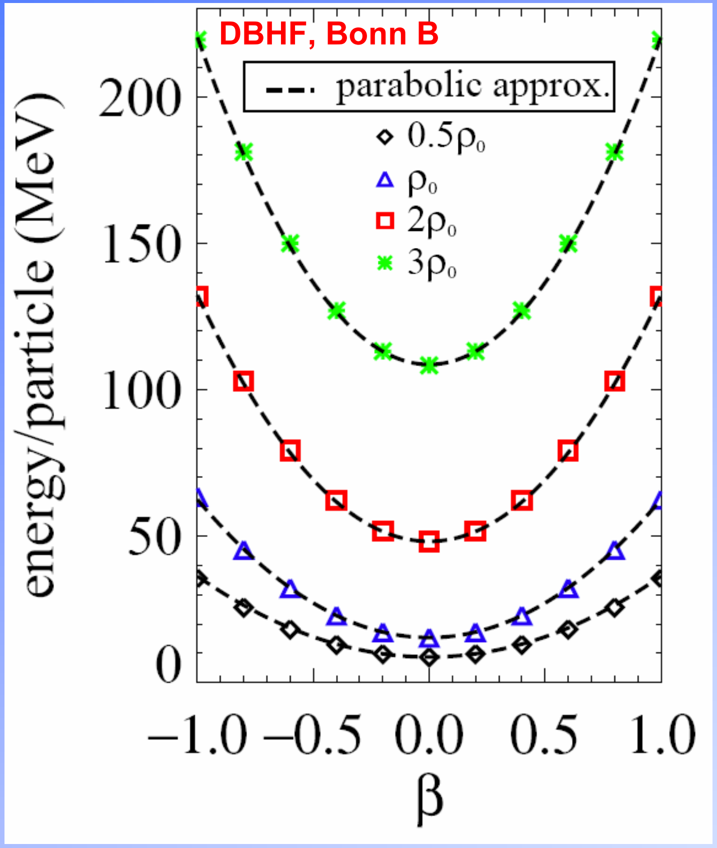
$$\bar{e}(\rho,\beta) = \bar{e}(\rho,\beta=0) + S(\rho)\beta^2$$

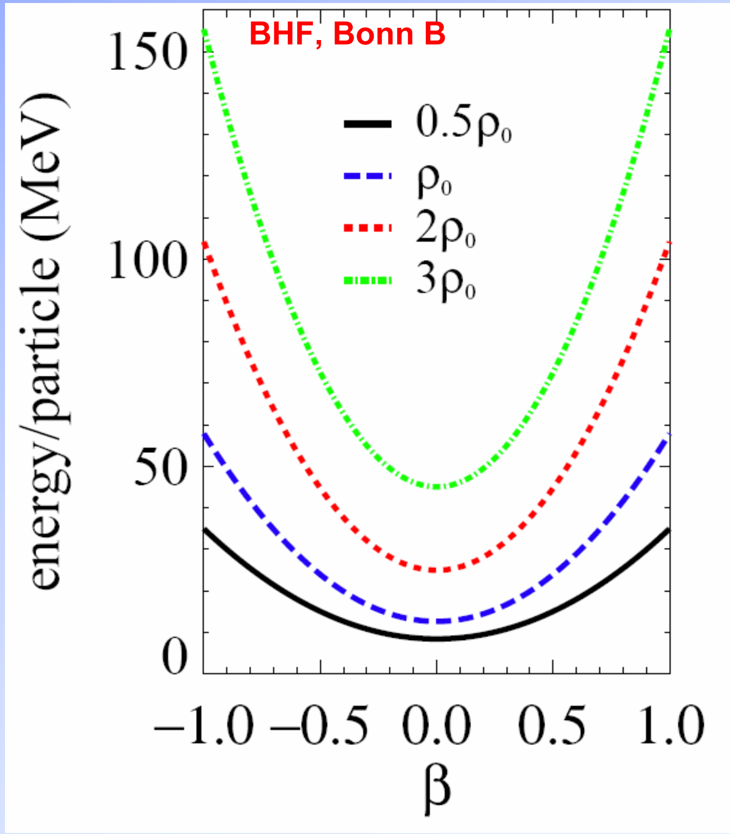
$$S(\rho) = \bar{e}(\rho,\beta=\pm1) - \bar{e}(\rho,\beta=0)$$

EOS of Spin-Polarized Neutron Matter – Spin Asymmetry Dependence:

$$\beta = \frac{\rho^{\uparrow} - \rho^{\downarrow}}{\rho^{\uparrow} + \rho^{\downarrow}}$$

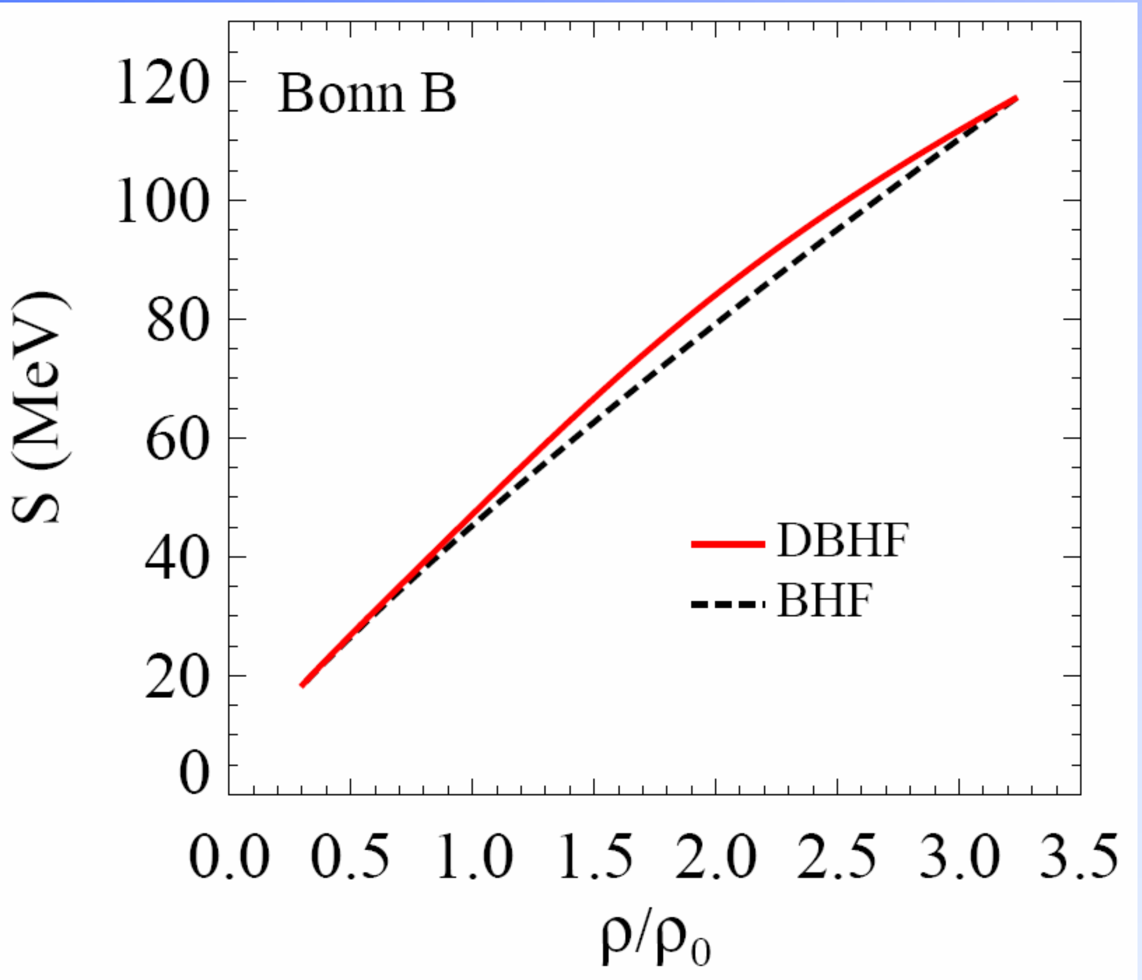
Spin-asymmetry parameter



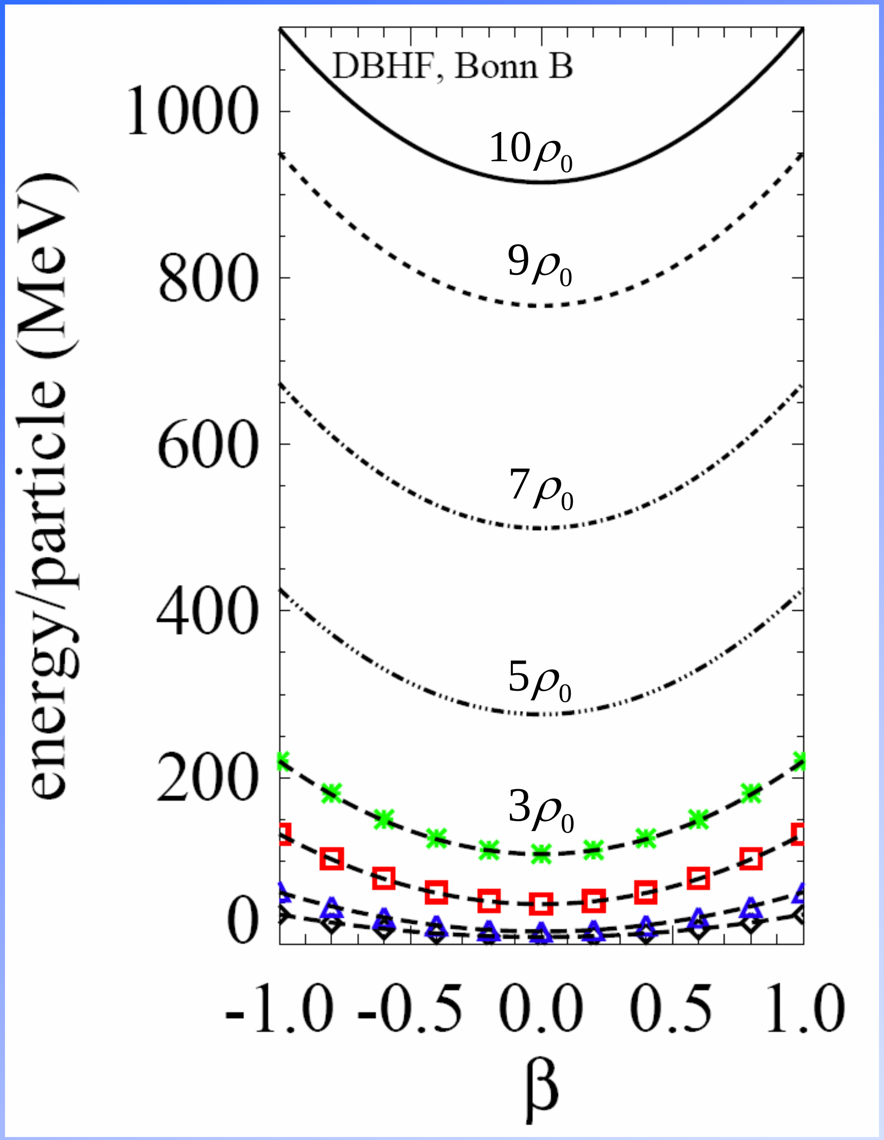


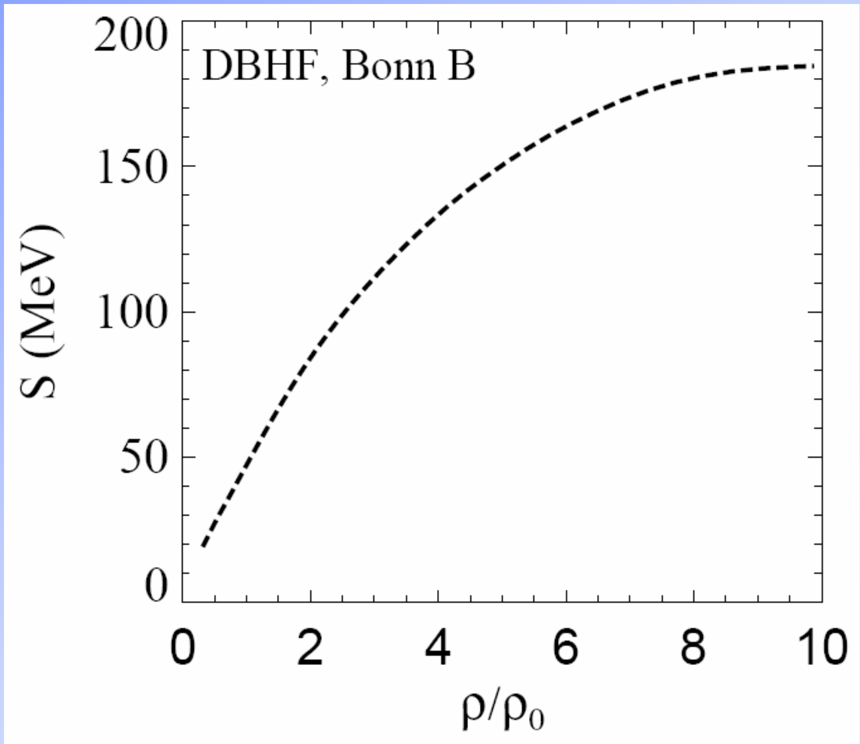
Spin-Symmetry Energy:

$$S(\rho) = \bar{e}(\rho, \beta = \pm 1) - \bar{e}(\rho, \beta = 0)$$



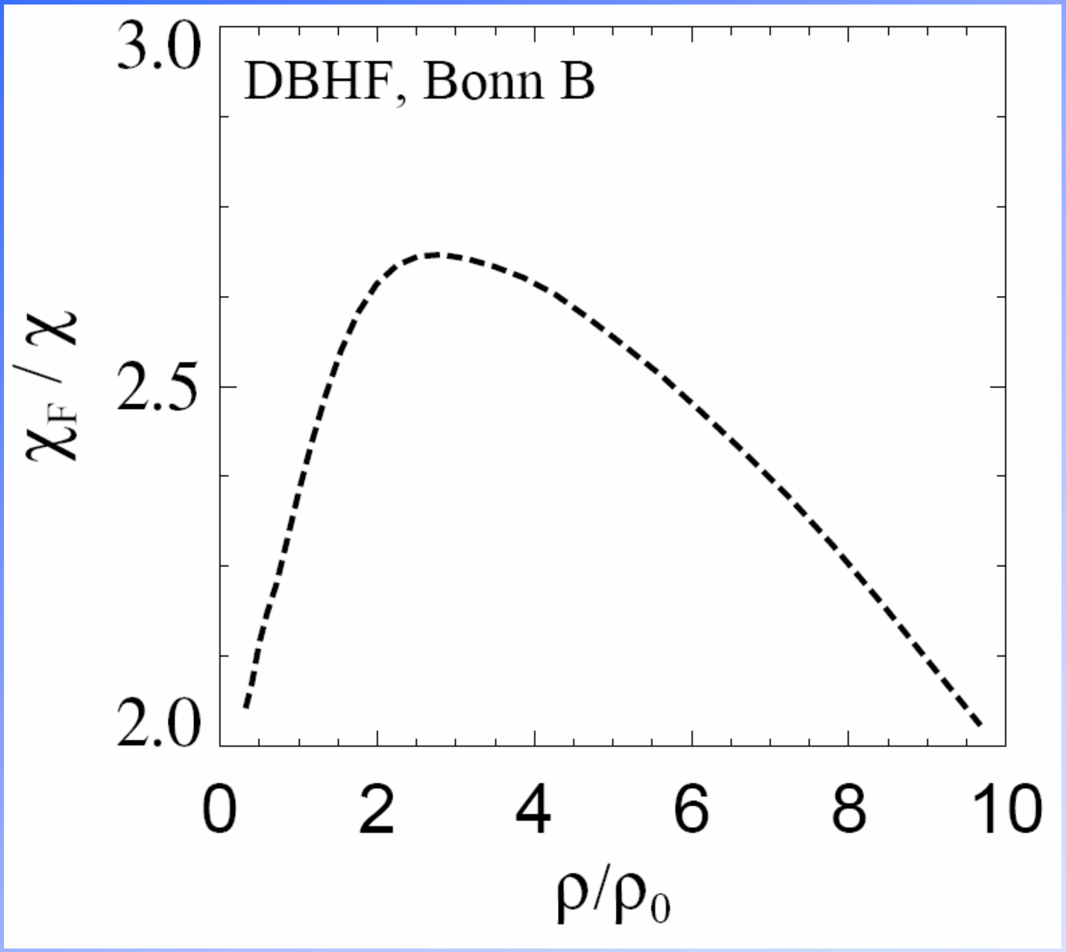
High-Density Regime:





Magnetic Susceptibility:

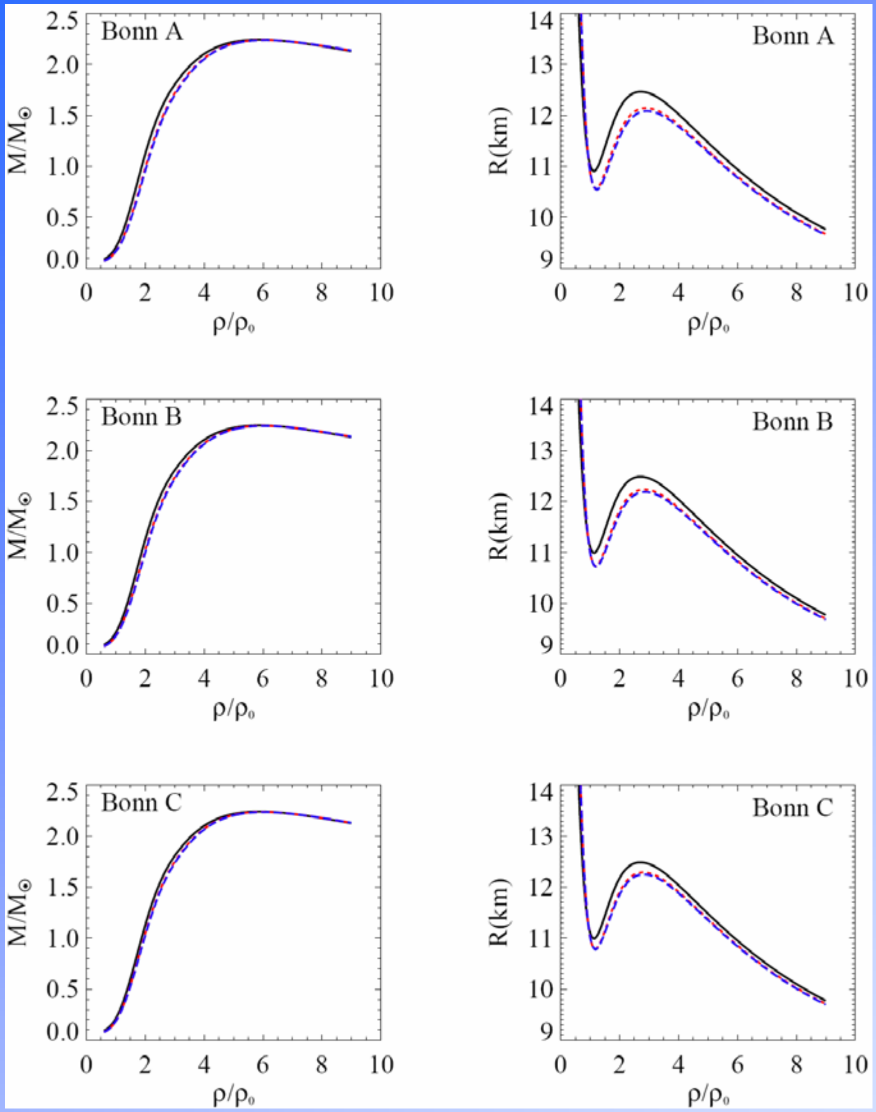
$$\chi(\rho) = \frac{\mu^2 \rho}{2S(\rho)}$$



$$\frac{1}{\chi} = 0$$

Onset of ferromagnetism

Masses and Radii of Static Neutron Stars:



Tolman-Oppenheimer-Volkoff (TOV):

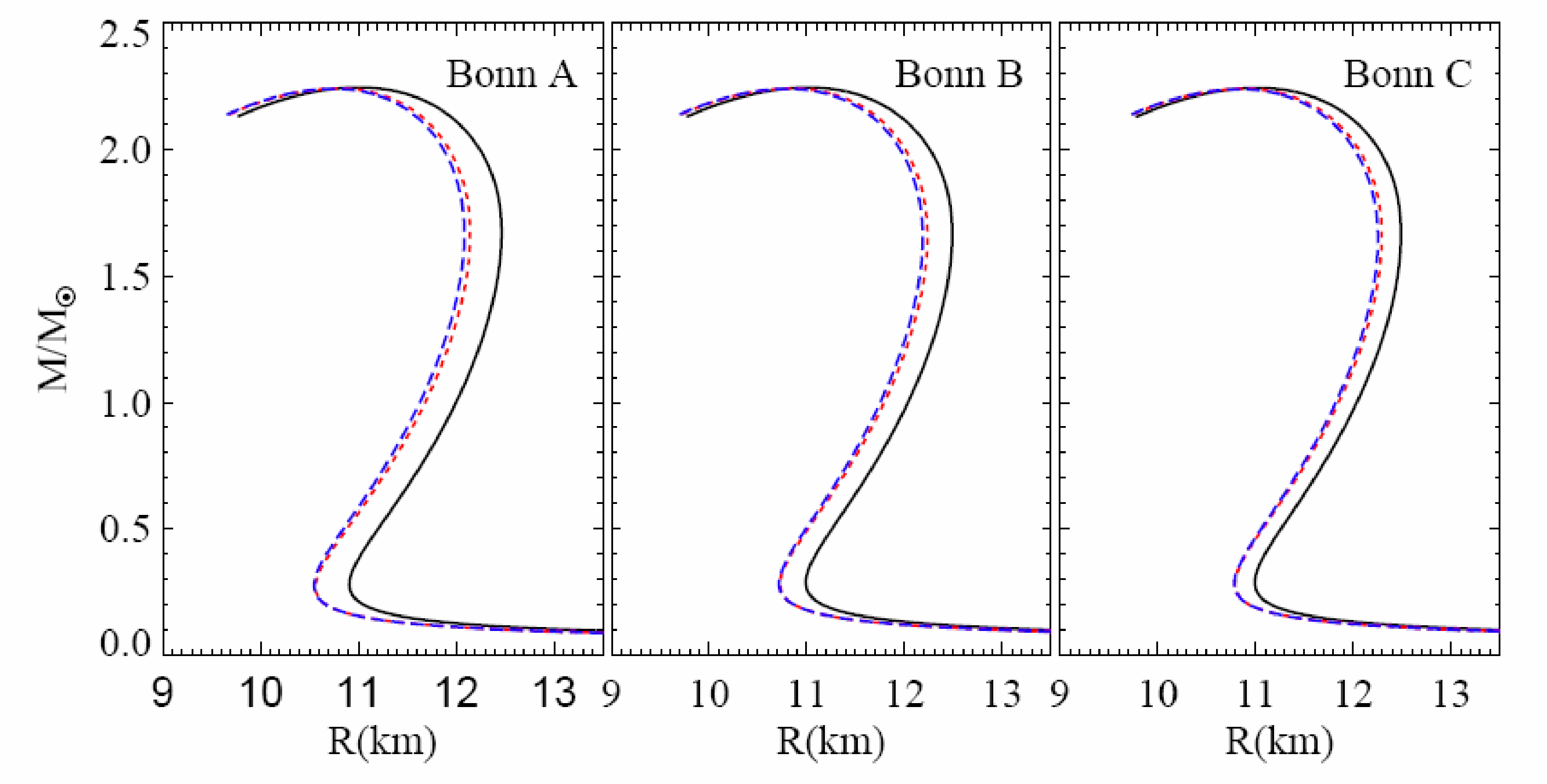
$$\frac{dP}{dr} = -\frac{\epsilon(r)m(r)}{r^2}\left[1+\frac{P(r)}{\epsilon(r)}\right] \times \left[1+\frac{4\pi r^3 P(r)}{m(r)}\right]\left[1-\frac{2m(r)}{r}\right]^{-1}$$

$$\frac{dm(r)}{dr} = 4\pi\epsilon(r)r^2 dr.$$

potential model	composition	$M_{max}(M_\odot)$	$R(km)$	$\rho_c(fm^{-3})$
Bonn A	n	2.2456	11.00	0.979
Bonn B	n	2.2453	11.01	0.979
Bonn C	n	2.2439	11.02	0.978
Bonn A	n,p,e^-	2.2414	10.78	1.007
Bonn B	n,p,e^-	2.2413	10.83	1.002
Bonn C	n,p,e^-	2.2399	10.87	0.998
Bonn A	n,p,e^-, μ^-	2.2401	10.74	1.013
Bonn B	n,p,e^-, μ^-	2.2399	10.79	1.008
Bonn C	n,p,e^-, μ^-	2.2384	10.83	1.003

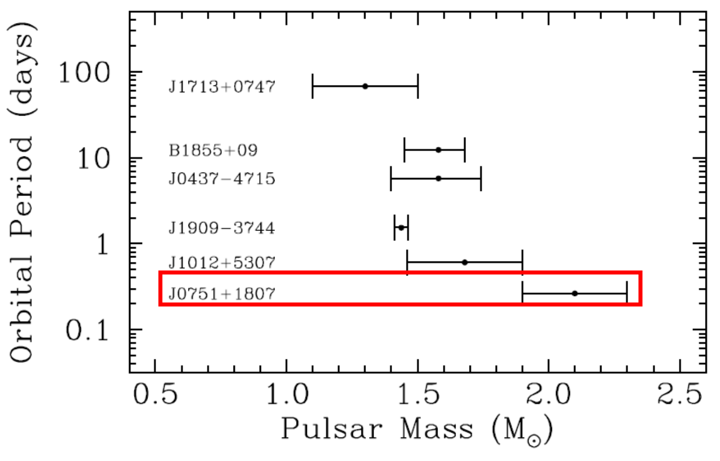
P. G. Krastev and F. Sammarruca, Phys. Rev. C 74, 025808 (2006).

Mass-Radius Relation (static NS):



Neutron-Star Latest Observations:

(1) PSR J0751−1807



D. J. Nice et. al., ApJ, 634: 1242-1249, 2005, December 1, [astro-ph/0508050]

(2) EXO 07482676

…..If this object is typical, then condensates and unconfined quarks do not exist in the centers of neutron stars.

$$M \geq 2.10 \pm 0.28 M_\odot \quad \text{and} \quad R \geq 13.8 \pm 1.8\,\text{km}$$

F. Özel, *Nature* 441, 1115-1117 (2006).

(3) PSR J1748−2446ad

We have discovered **a 716-HZ eclipsing binary radio PULSAR** in the globular cluster Terzan 5 using the Green Bank Telescope.…If the PULSAR has a mass less than 2 solar masses then its radius is constrained by the spin rate to be <16 km.

J. W. T. Hessels et. al., Science 31 March 2006: 1876-1877, [astro-ph/0601337]

(4) XTE J1739-285

…..We detected six X-ray type I bursts and found evidence for oscillations at 1122 ± 0.3 Hz in the brightest X-ray burst….. If the oscillations are confirmed, the oscillation frequency would suggest that XTE J1739-285 contains the fastest rotating neutron star yet found……

P. Kaaret et al, Astrophys. J. 657, L97-L100 (2007).

Modeling of Rapidly Rotating Neutron Stars:

Considerably more complicated than modeling of static (non-rotating) stars due to:

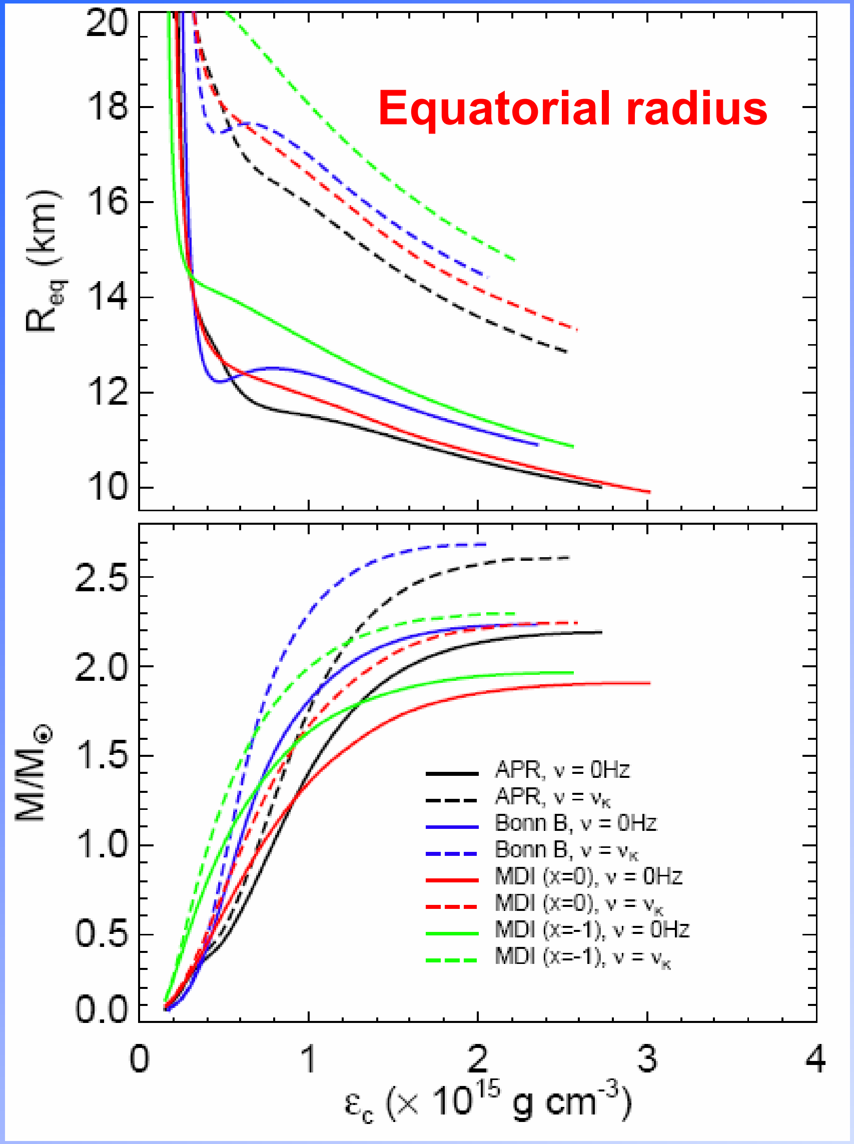
(1) Rotational deformations, i.e. flattening at the poles and bulging at the equatorial region. Lead to dependence of stellar metric on polar angle

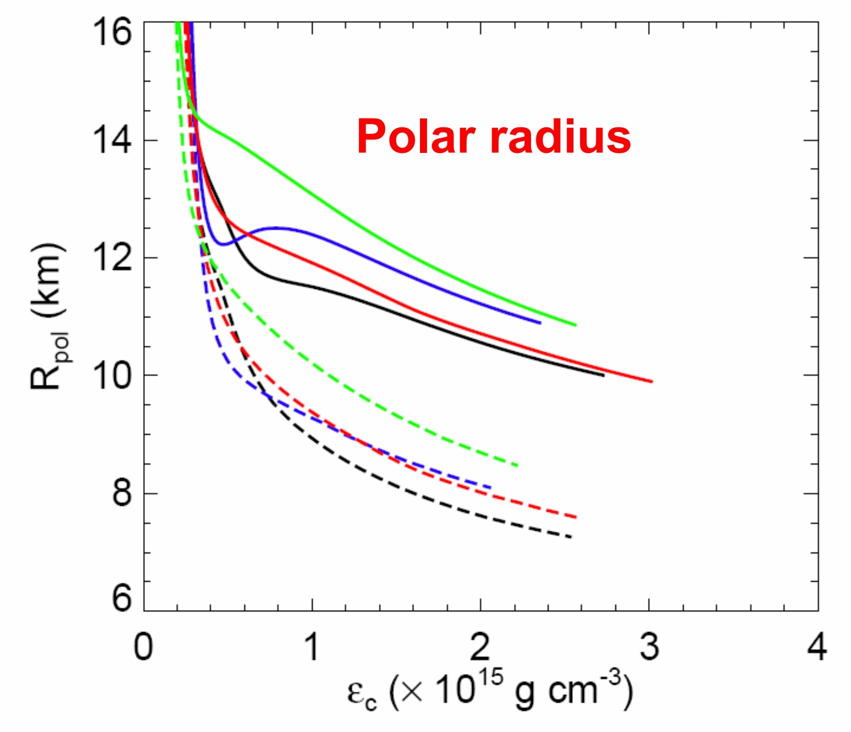
(2) Rotation stabilizes the star against gravitational collapse so the star can carry more mass. This, however, causes greater curvature of space-time. Leads to frequency dependence of metric functions

(3) General relativistic effect of dragging of local inertial frames. Imposes self-consistency condition on the stellar structure equations

The numerical computations are performed using the RNS code by Nikolaos Stergioulas (http://www.gravity.phys.uwm.edu/rns/)

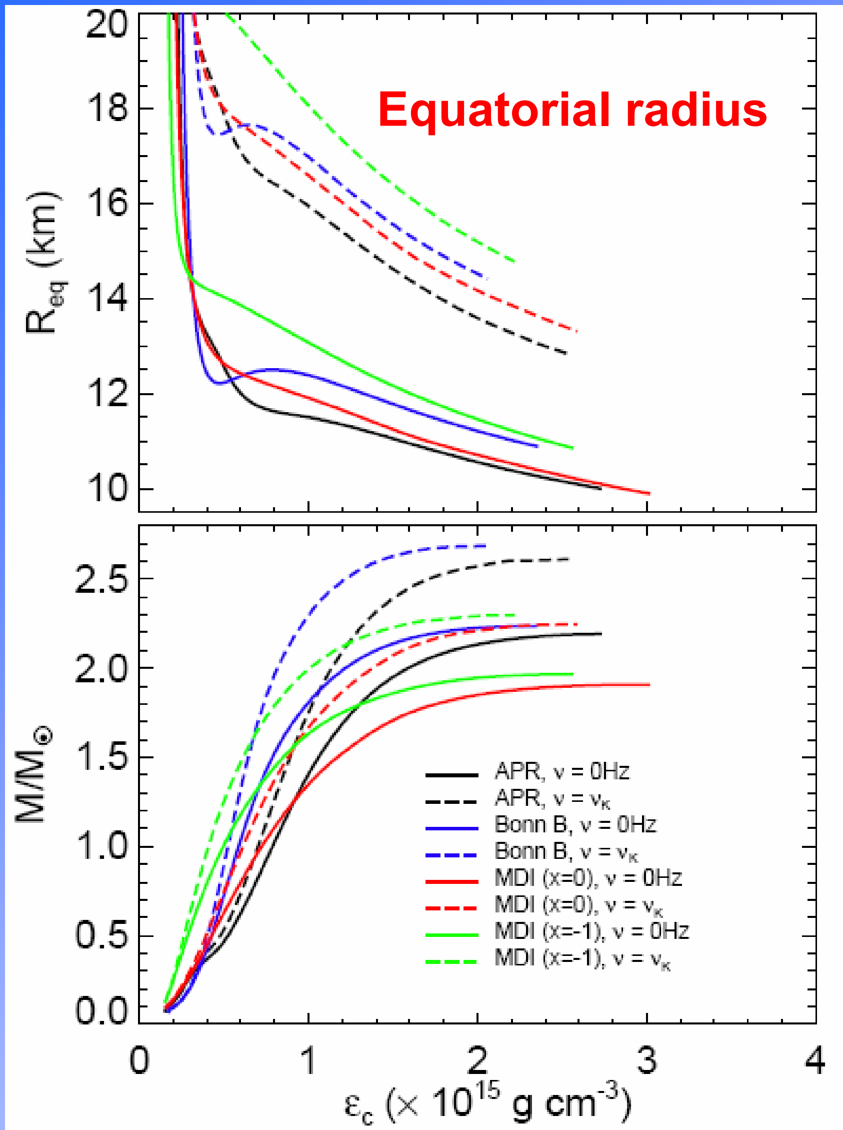
Static versus Rapidly Rotating Neutron Stars:

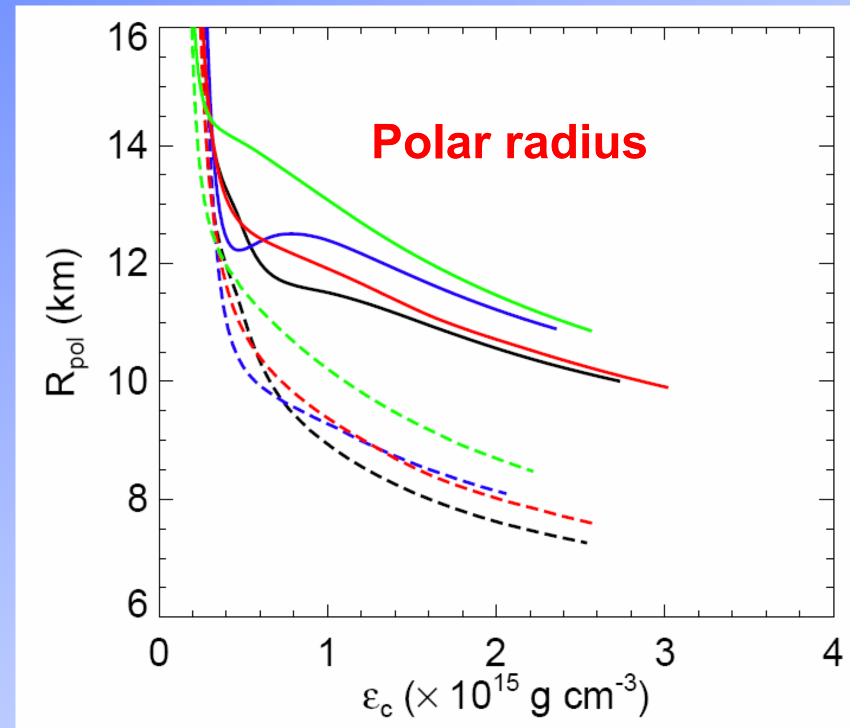


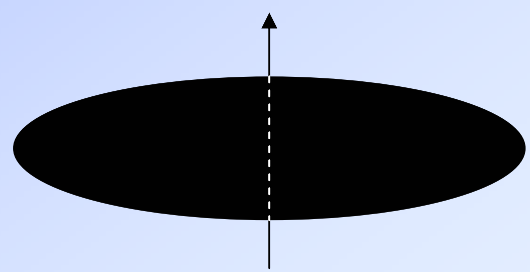


P. G. Krastev, A. Worley and Bao-An Li, Astrophys. Journal (submitted)

Static versus Rapidly Rotating Neutron Stars:

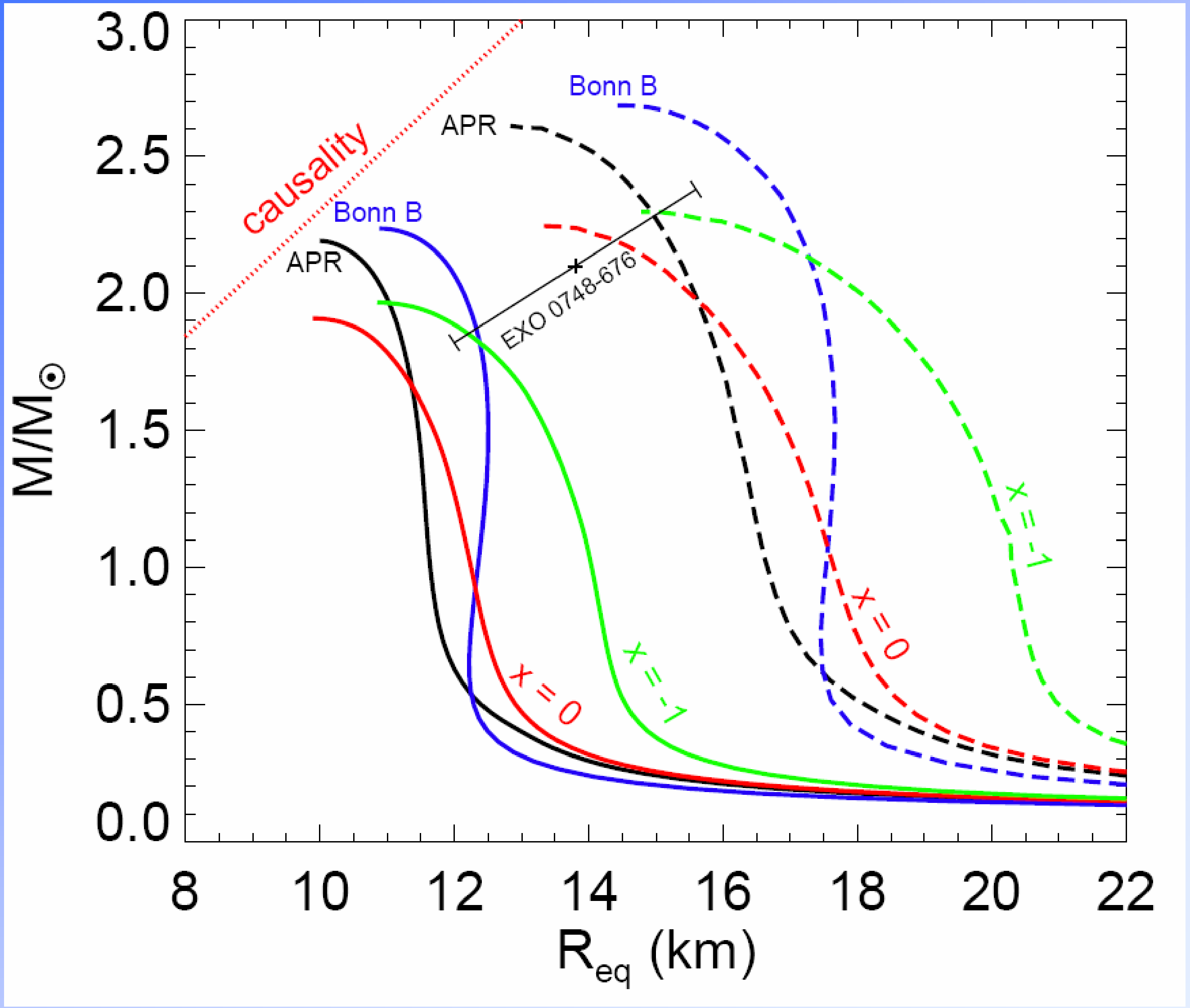






P. G. Krastev, A. Worley and Bao-An Li, Astrophys. Journal (submitted)

Mass-Radius Relation - static versus rapidly rotating N Stars:



Impact of rapid rotation on the upper mass limit:

Maximum-mass models (static stars)

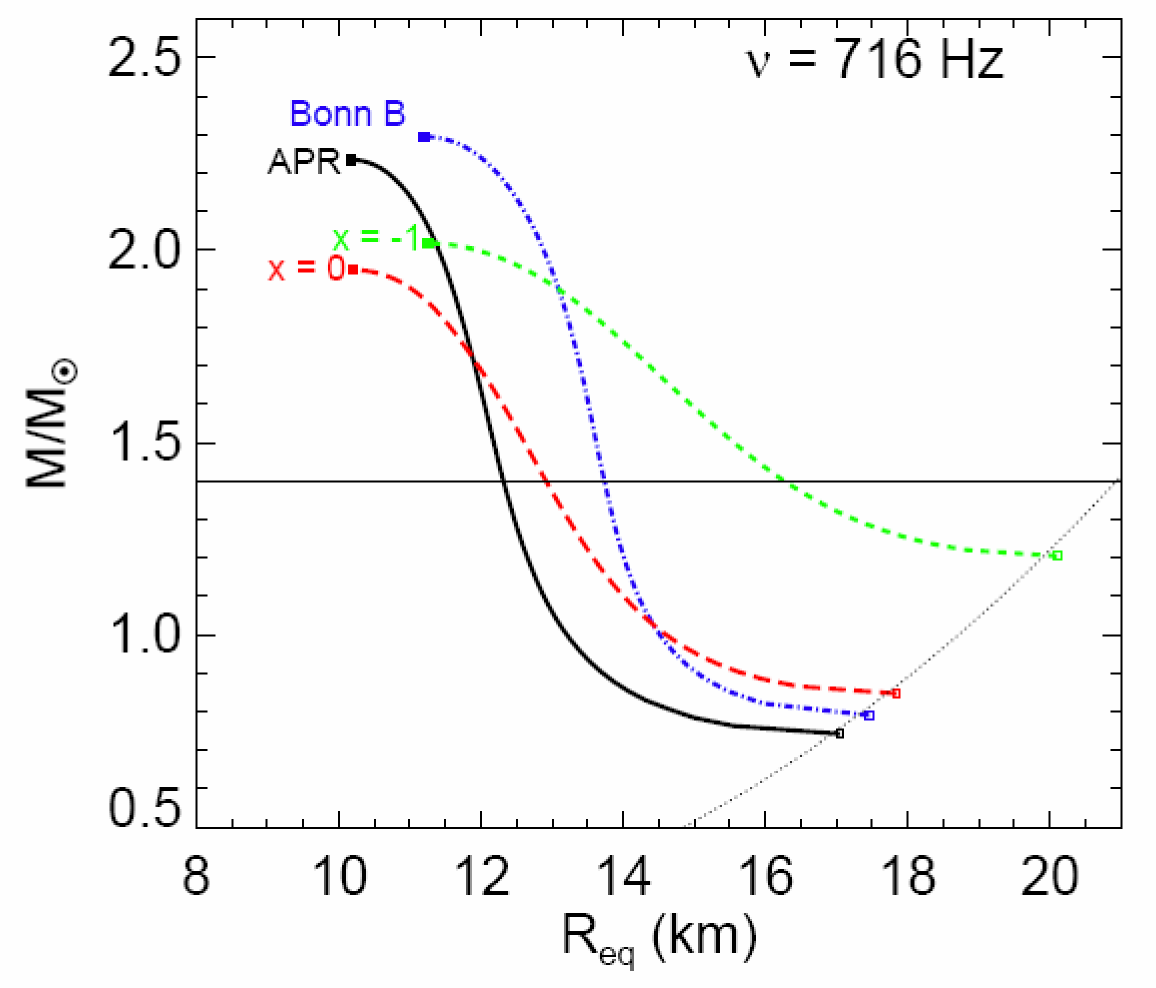
EOS	$M_{max}(M_{\odot})$	$R(km)$	$\epsilon_c(\times 10^{15} g/cm^3)$
MDI(x=0)	1.91	9.89	3.02
APR	2.19	9.98	2.73
MDI(x=-1)	1.97	10.85	2.57
Bonn B	2.24	10.88	2.36

Maximum-mass models (rapid rotation at the Kepler frequency)

EOS	$M_{max}(M_{\odot})$	Increase (%)	$\epsilon_c(\times 10^{15} g/cm^3)$	$\nu_k(Hz)$
MDI(x=0)	2.25	15	2.59	1742
APR	2.61	17	2.53	1963
MDI(x=-1)	2.30	14	2.21	1512
Bonn B	2.69	17	2.06	1685

P. G. Krastev, A. Worley and Bao-An Li, Astrophys. Journal (submitted)

Rotation at various frequencies-716Hz:

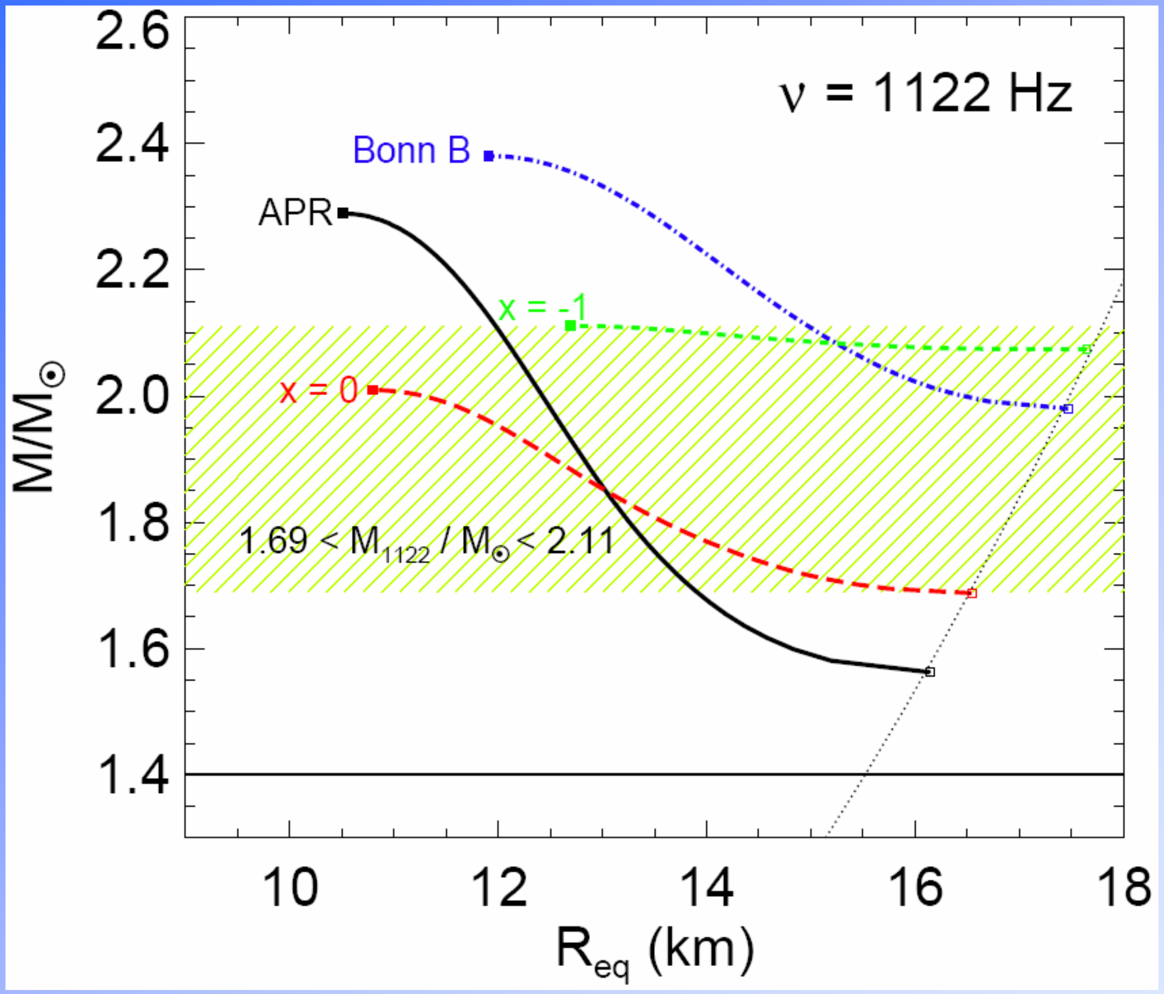


$$\frac{1}{2\pi}\left(\frac{GM}{R_{eq}^3}\right)^{1/2} = 716Hz$$

$$R_{\max} = 20.94\left(\frac{M}{1.4M_{SOL}}\right)^{1/2} km$$

Rotation at various frequencies-1122Hz:

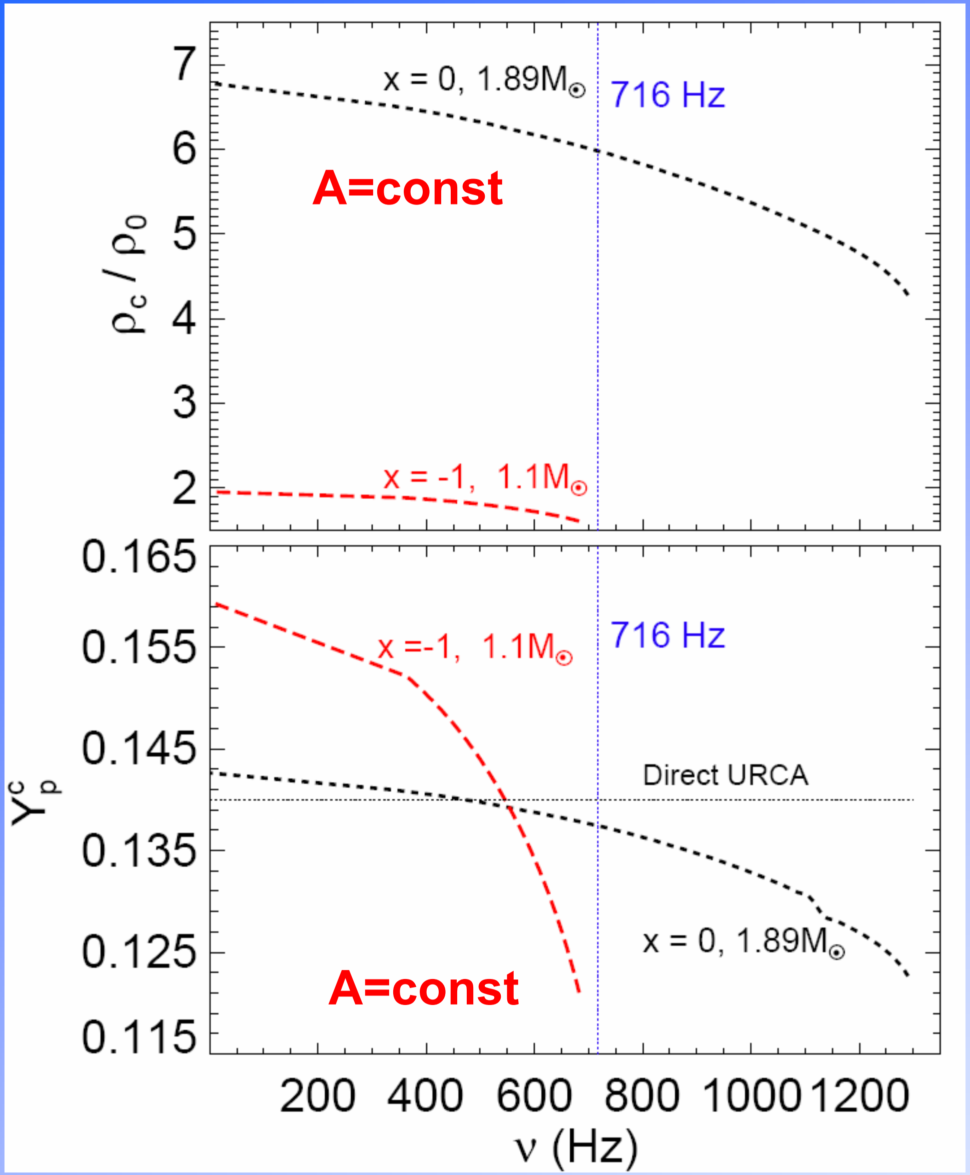
Constraint on the gravitational mass of the neutron star in the X-ray transient, XTE J1739-285

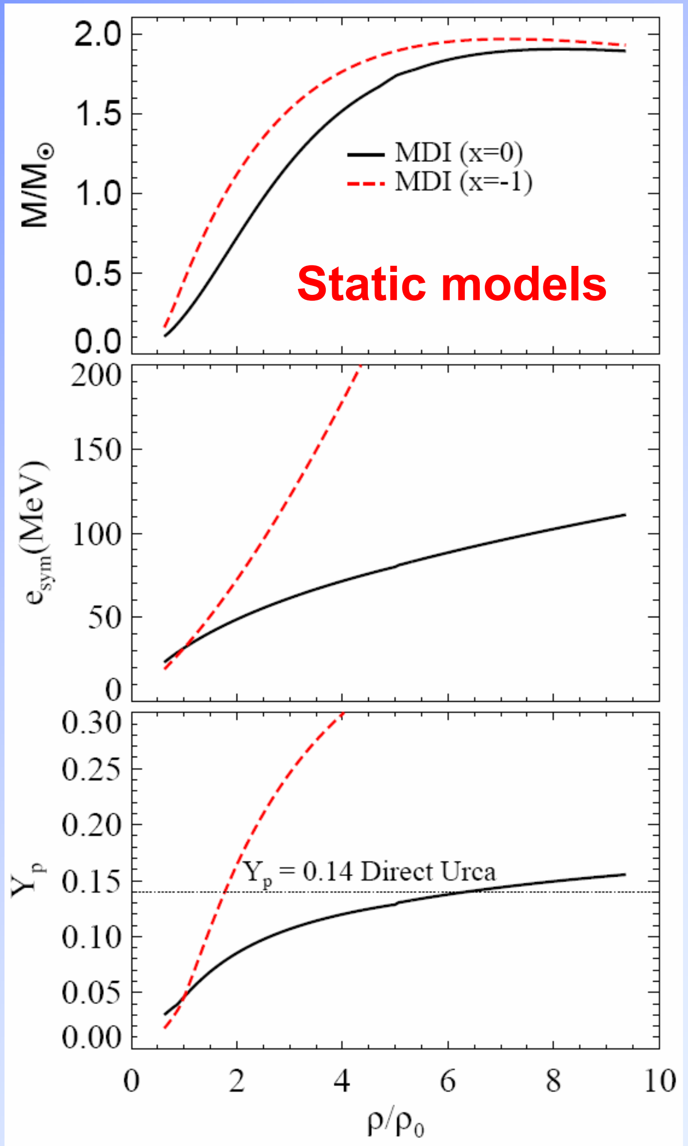


$$\frac{1}{2\pi}\left(\frac{GM}{R_{eq}^3}\right)^{1/2} = 1122 Hz$$

$$R_{\max} = 15.52\left(\frac{M}{1.4 M_{SOL}}\right)^{1/2} km$$

Impact of rotation on NS thermal evolution:





Constraining a possible time variation of the gravitational constant G with terrestrial nuclear laboratory data

Plamen G. Krastev and Bao-An Li

*Department of Physics, Texas A&M University – Commerce, Commerce, TX 75429, U.S.A**

(Dated: September 30, 2007)

Abstract

Testing the constancy of the gravitational constant G is a longstanding fundamental question in natural science. As first suggested by Jofré, Reisenegger and Fernández [1], Dirac's hypothesis of a decreasing gravitational constant G with time due to the expansion of the Universe would induce changes in the composition of neutron stars, causing dissipation and internal heating. Eventually, neutron stars reach their quasi-stationary states where cooling, due to neutrino and photon emissions, balances the internal heating. The correlation of surface temperatures and radii of some old neutron stars may thus carry useful information about the rate of change of G. Using the density dependence of the nuclear symmetry energy, constrained by recent terrestrial laboratory data on isospin diffusion in heavy-ion reactions at intermediate energies, and the size of neutron skin in ^{208}Pb, within the *gravitochemical heating* formalism developed by Jofré et al. [1], we obtain an upper limit for the relative time variation $|\dot{G}/G|$ in the range $(4.5-21)\times 10^{-12} yr^{-1}$.

P.G.Krastev and Bao-An Li, PRC (in press); nucl-th/0702080

Purpose / Relevance:

P. Dirac, Nature 139, 323 (1937)

Suggested that the gravitational force might be weakening with the expansion of the Universe

Contrary to most of the other fundamental constants, as the precision of the measurements increased, the disparity between the measured values of G also increased. This led the CODATA[11] in 1998 to raise the relative uncertainty for G from 0.013% to 0.15% (Gundlach and Merkowitz, 2000). The following constraints assume that the mass of stars and/or planets is kept constant.

J. P. Uzan, Rev. Mod. Phys. 75: 403, 2003

CODATA is the Committee on Data for Science and Technology, http://www.codata.org/

Upper bounds on $|\dot{G}/G|$

Method	$\lvert\dot{G}/G\rvert_{max}[10^{-12}yr^{-1}]$	Time scale [yr]	Reference
Big Bang Nucleosynthesis	0.4	1.4×10^{10}	C. Copi et al., PRL 92, 17 (2004)
Microwave Background	0.7	1.4×10^{10}	R. Nagata et al., PRD 69, 3512 (2004)
Gloubular Cluster Isochrones	35	10^{10}	S. Degl'Innocenti et al., A&A 312, 345 (1996)
Binary Neutron Star Masses	2.6	10^{10}	S. E. Thorsett, PRL 77, 1432 (1996)
Helioseismology	1.6	4×10^{9}	D. B. Guenther et al., AJ 498, 871 (1998)
Paleontology	20	4×10^{9}	W. Eichendorf and M. Reinhardt, (1977)
Lunar Laser Ranging	1.3	24	J. G. Williams et al., PRL 93, 261101-1-4 (2004)
Binary Pulsar Orbits	9	8	V. M. Kaspi et al., AJ 428, 713 (1994)
White Dwarf Oscillations	250	25	O. Benvenuto et al., PRD 69, 2002 (2004)

- (red) From the early Universe to present time
- (dark blue) Long timescales, 10^{9-10} *yr*, without reaching the early Universe
- (green) Short, “human”, timescales of years or few decades

Gravitochemical heating method-outline:

A change in G induces a variation in the internal composition of a neutron star, causing dissipation and internal heating. The comparison of the predicted surface temperature with the only available observation sets constraints on the variation of G.

P. Jofre, A. Reisenegger, and R. Fernandez, Phys. Rev. Lett. 97, 131102 (2006)

$$L_{\gamma,eq}^{\infty} = \tilde{\mathcal{D}} \left| \frac{\dot{G}}{G} \right|^{8/7}$$

$$L_{\gamma,eq}^{\infty} = 4\pi\sigma R_{\infty}^{2} (T_s^{\infty})$$

$$\longrightarrow T_s^{\infty}$$

To apply the *Gravitochemical* heating formalism one needs to know:

(1) The surface temperature of a neutron star

(2) That the star is certainly older than the time-scale necessary to reach a quasi-stationary state

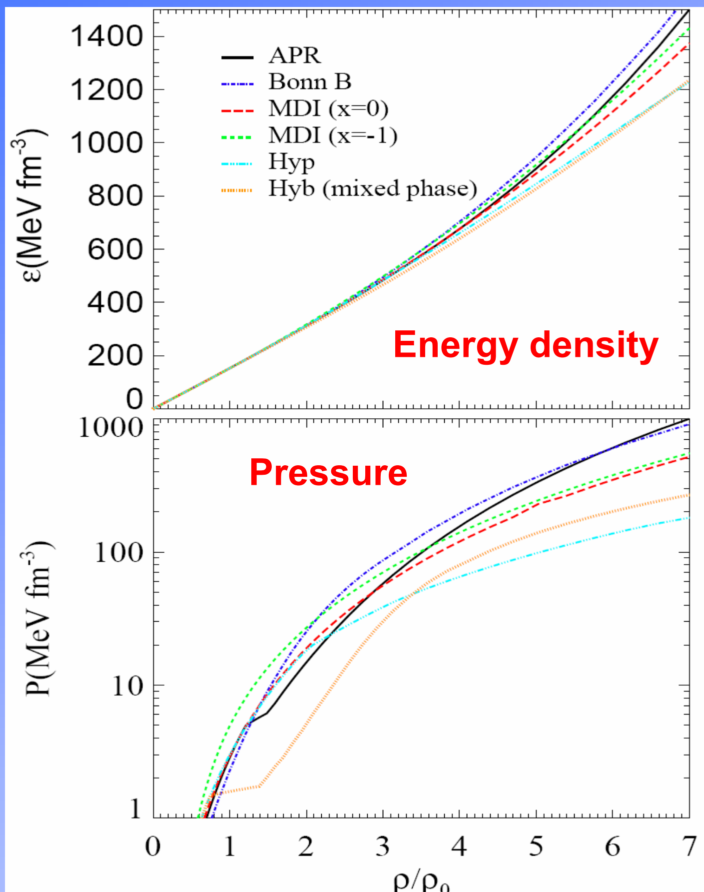
PSR J0437- 4715 – the closest millisecond pulsar

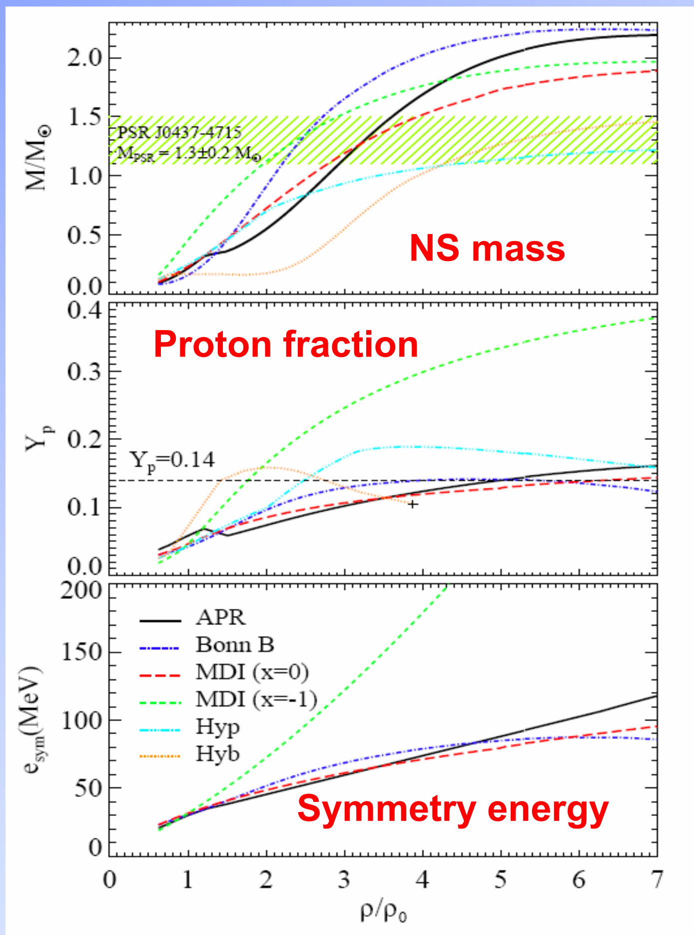
Surface temperature: By ultraviolet observations O. Kargaltsev et al., AJ 602, 327-335 (2004)

Mass: $1.3 \pm 0.2\, M_{SOL}$ A. W. Hotan et al., MNRAS 369, 15021520 (2006)

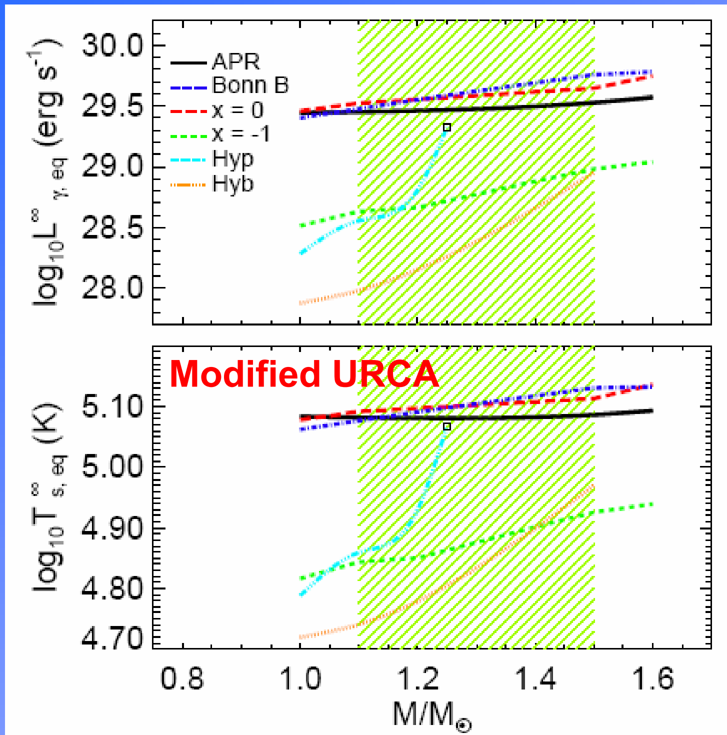
EOS and Neutron-Star Structure:

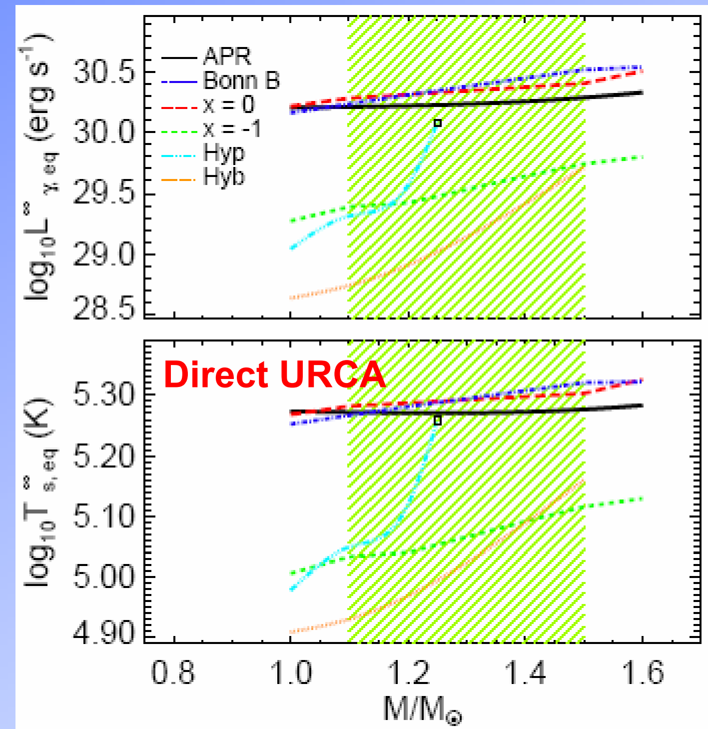
The idea: Using an equation of state (EOS) with symmetry energy constrained by terrestrial laboratory nuclear data from heavy-ion reactions, through the *Gravitochemical heating* method, to constrain the possible time variations of G.

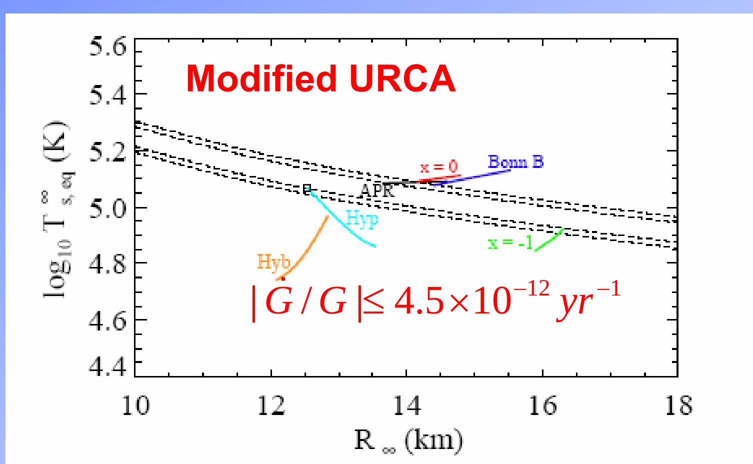


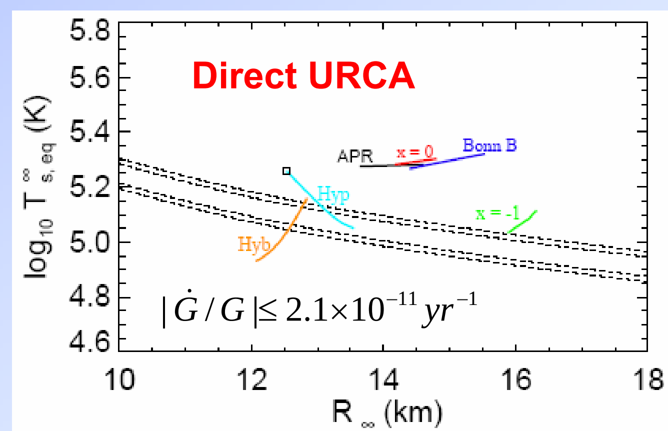


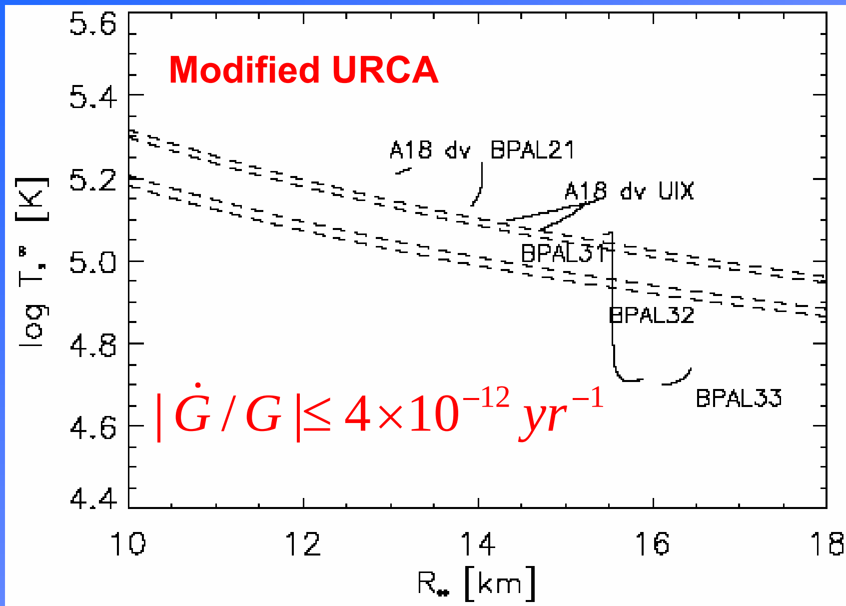
Photon luminosity and surface temperature:

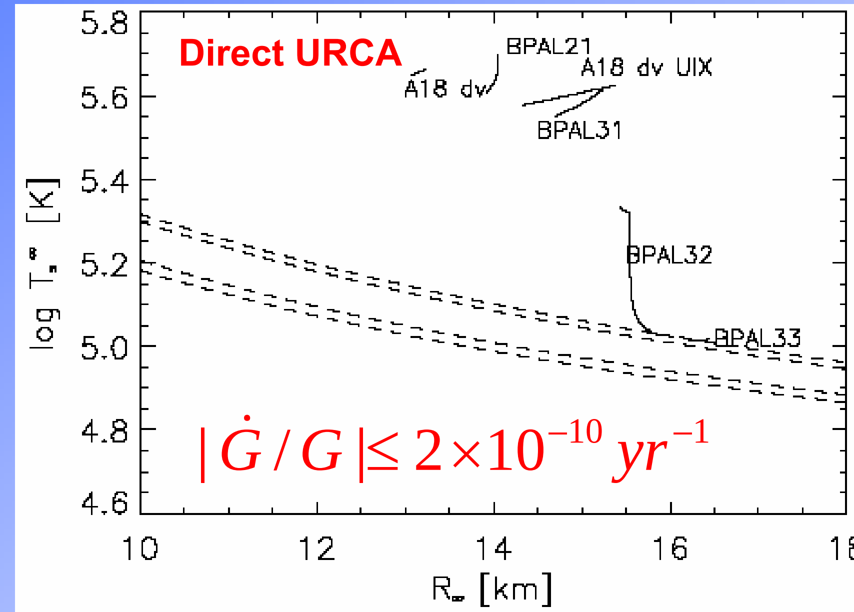




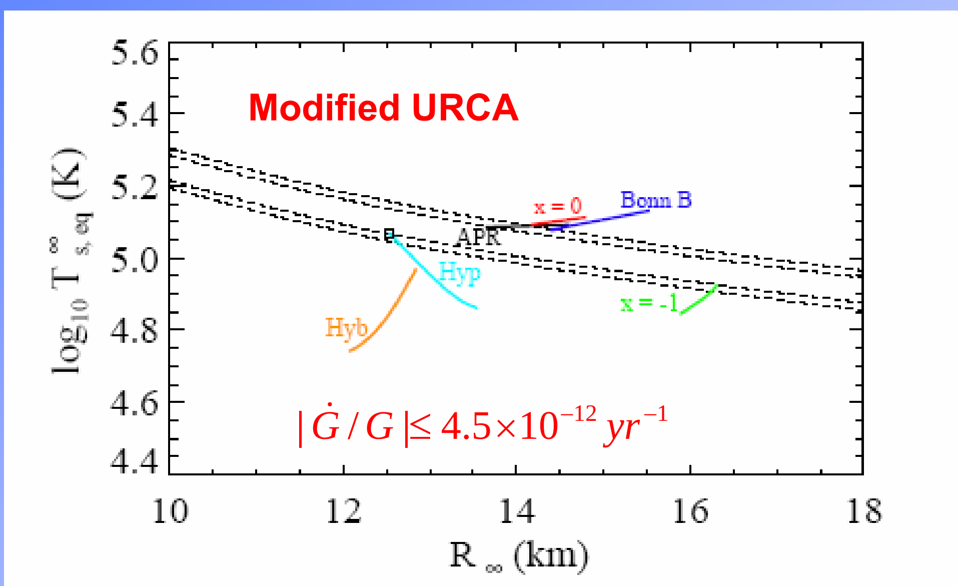


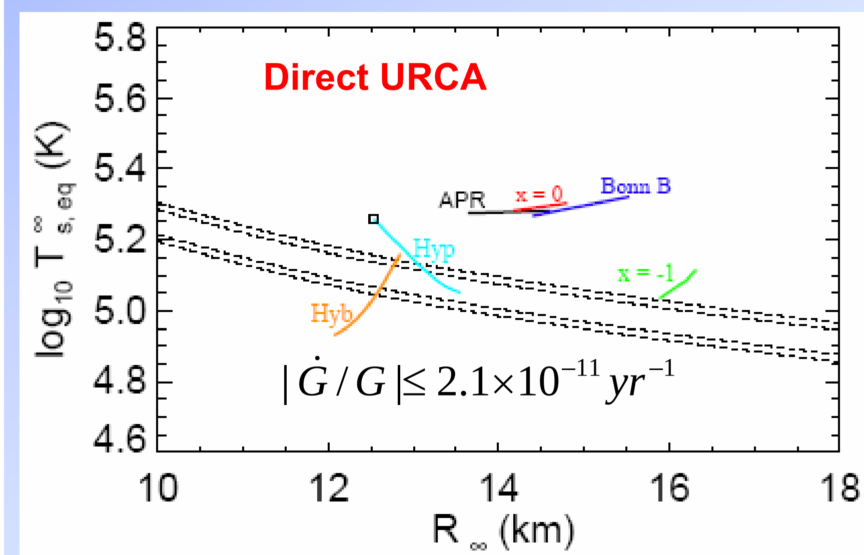






P. Jofre, A. Reisenegger, and R. Fernandez, Phys. Rev. Lett. 97, 131102 (2006)





P.G.Krastev and Bao-An Li, PRC (in press); nucl-th/0702080

Summary:

1) We have presented a study of effective interactions in dense and neutron-rich matter and their applications to:

- ✓ gravitational physics, and
- ✓ properties of static and rapidly rotating neutron stars

2) The ultimate goal is to study dense and exotic nuclear systems. This can be achieved through combining reliable models of the density dependence of the effective nuclear force with more stringent empirical constrains. Thus, systematic coherent effort from theory, experiments, and observations is necessary.

Acknowledgements:

Support from the U.S. Department of Energy under Grant No. DE-FG02-03ER41270 and the National Science Foundation under grant No. PHY0652548 is greatly acknowledged.

We would like to thank Rodrigo Fernandez and Andreas Reisenegger for helpful discussions and assistance with the numerics of the Gravitochemical heating formalism. We also thank Nikolaos Stergioulas for making the RNS code available.