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Symmetry Energy and Equations of States for Nuclear Matter

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Soongsil University, Seoul, Korea

Heavy Ion Meeting (HIM), Korea University, May 24, 2013

Contents

Science program with tentative beam schedule

Beam schedule	Science program	Exp. facility♯	Beam species on exp. target: Day1†	Beam species on exp. target: Extra 2 Years	Beam Intensity on exp. target (pps) (required/expected)
2017.June.1 ~ from SCL1 (<18.5 MeV/u)	Nuclear structure SHE search, rp-process, Spin physics	RS	^{58}Fe	^{64}Ni, ^{26m}Al (^{28}Si), ^{25}Al (^{28}Si), ^{44}Ti (^{42}Ca), ^{14,15}O (^{15}N)	^{15}N, ^{58}Fe ($<10^{9-10}$) ^{28}Si, ^{42}Ca, ^{64}Ni ($<10^{7}$) ^{25}Al, ^{26m}Al, ^{44}Ti, ^{14,15}O: (10^{5-6})
	Pigmy dipole resonance	LAS-L	^{58}Ni	^{40}Ca, ^{112}Sn	(10^{6-8} / $<10^{9-10}$)
	Biological effects	BM	^{12}C		($<10^{12}$ / $>10^{12}$)
2017.July.1 ~ from ISOL (~5 keV/u)	Fine structure, mass measurement	AT/LS	^{132}Sn	$^{130-135}$Sn	^{132}Sn ($<10^{5}$ / 10^{7})
2018.Jan.1 ~ ISOL-SCL3 (<18.5 MeV/u)	r-process	RS	^{132}Sn	$^{130-135}$Sn	^{132}Sn (10^{6} / 10^{7}), $^{130-135}$Sn (10^{3-6} / 10^{3-7})
	Pigmy dipole resonance	LAS-L	^{132}Sn	$^{60+n}$Ni, $^{130-135}$Sn	^{65,66}Ni (10^{6-8} / 10^{6-7})
SCL1-SCL2 (~ hundreds MeV/u)	New materials	μSR	Muon by (p, πx)→μ		p ~full intensity, μ (10^{8}/10^{9})
	Biological effects	BM	^{12}C		($<10^{12}$ / $>10^{12}$)
	Baseline experiments, Spin physics	LAS-H	^{40}Ca	^{58}Ni, ^{112}Sn, ^{132}Xe	(10^{6}~10^{8} /$<10^{9-11}$)
SCL1-SCL2(X) (~ tens MeV/u)	New material, Polarized beam	β-NMR	^{8}Li by (d,α)	^{11}Be	p, d ~full intensity, n ($<10^{12}$ / 10^{12}) ^{8}Li (10^{8} / 10^{9}), ^{11}Be(10^{7} / 10^{8})
	Neutron cross section	NSF	n by (p,n) (d,n)		
2018.Mar.1 ~ SCL1-SCL2-IF (~ hundreds MeV/u)	Nuclear structure	ZDS & HRS	^{128}Sn	^{132}Sn, ^{18}O	^{128}Sn (10^{6-8} / 10^{7}), ^{132}Sn (10^{6-8} / 10^{6})‡
	Symmetry energy	LAS-H	^{128}Sn	^{132}Sn, $^{44+n}$Ca, $^{60+n}$Ni, ^{144}Xe	
2018.Sep.1 ~ ISOL-SCL3-SCL2-IF(X) (~ hundreds MeV/u)	Nuclear structure	ZDS & HRS	^{132}Sn		^{132}Sn (10^{6-8} / 10^{7}), ^{144}Xe (10^{6-8} / 10^{6})
	Symmetry energy	LAS-H	^{132}Sn	^{144}Xe	

♯ RS: Recoil Spectrometer, LAS: Large Acceptance Spectrometer, BM: Bio & Medical, AT/LS: Atom Trap & Laser Spectrometer, NSF: Neutron Science Facility, ZDS: Zero Degree Spectrometer, HRS: High Resolution Spectrometer

† Beam purity >50 % from ISOL, Beam species : SI(black), RI(Blue)

‡ Beam available on 2018 Sep.

ibS Institute for Basic Science

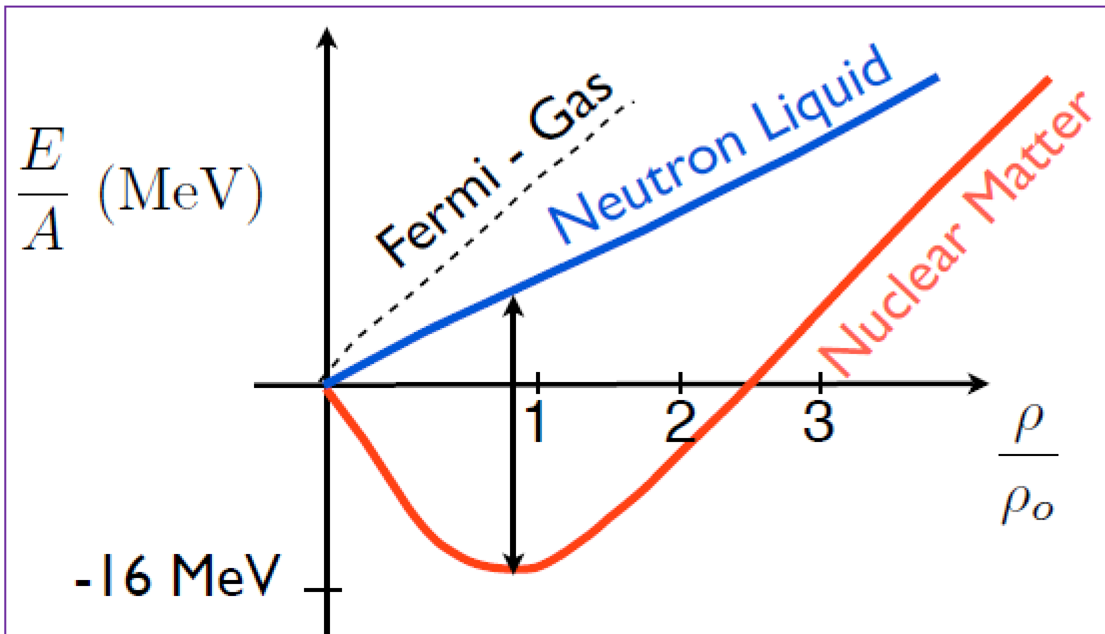
Symmetry Energy　Definition by Energy per nucleon

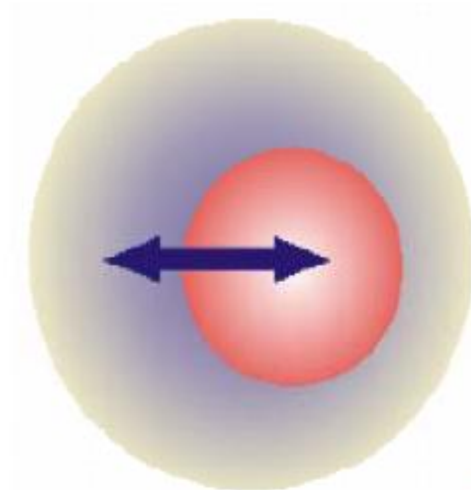
PHYSICAL REVIEW C **79**, 054311 (2009)

Incompressibility of neutron-rich matter

J. Piekarewicz[1,*] and M. Centelles[2,†]

$$E/A(\rho,\alpha) - M \equiv \mathcal{E}(\rho,\alpha) = \mathcal{E}_{\rm SNM}(\rho) + \alpha^2 \mathcal{S}_2(\rho) + \alpha^4 \mathcal{S}_4(\rho) + \cdots$$





$\mathcal{S}_2(\rho) \equiv \mathcal{S}(\rho)$, is known as the symmetry energy.

$$\mathcal{E}_{\rm PNM}(\rho) \equiv \mathcal{E}(\rho, \alpha = 1) \approx \mathcal{E}_{\rm SNM}(\rho) + \mathcal{S}(\rho).$$

Sym. Energy is given by the difference of the SNM and PNM energy !!

S. Energy, Pressure and Incompressbility

Sym. Energy at sat. density

Sym. (in)compressbility

$$\mathcal{S}(\rho) = J + Lx + \frac{1}{2}K_{\rm sym}x^2 + \frac{1}{6}Q_{\rm sym}x^3 + \cdots, \qquad x \equiv \frac{(\rho - \rho_0)}{3\rho_0}$$

Sym. Pressure

$$L = \left(\frac{\partial \mathcal{S}}{\partial x}\right)_{x=0} \qquad P_0 = \frac{1}{3}\rho_0 L. \qquad K_{\rm sym} = \left(\frac{\partial^2 \mathcal{S}}{\partial x^2}\right)_{x=0}$$

$$\mathcal{S}(\rho) = \mathcal{S}_0\left(\frac{\rho}{\rho_0}\right)^{\gamma} = J(1+3x)^{\gamma}$$

$$L = \left(\frac{\partial \mathcal{S}}{\partial x}\right)_{x=0} = 3J\gamma,$$

$$K_{\rm sym} = \left(\frac{\partial^2 \mathcal{S}}{\partial x^2}\right)_{x=0} = 9J\gamma(\gamma - 1)$$

$$P_0 = \rho_0 J\gamma.$$

intermediate-energy heavy-ion

$\gamma \sim 0.69$–1.05 Transport model simulations

$\gamma \sim 0.5 \pm 0.15$

$P_0 = 2.3 \pm 0.8$ MeV/fm^3 and $J = 32 \pm 1.8$ MeV

from pygmy dipole resonances

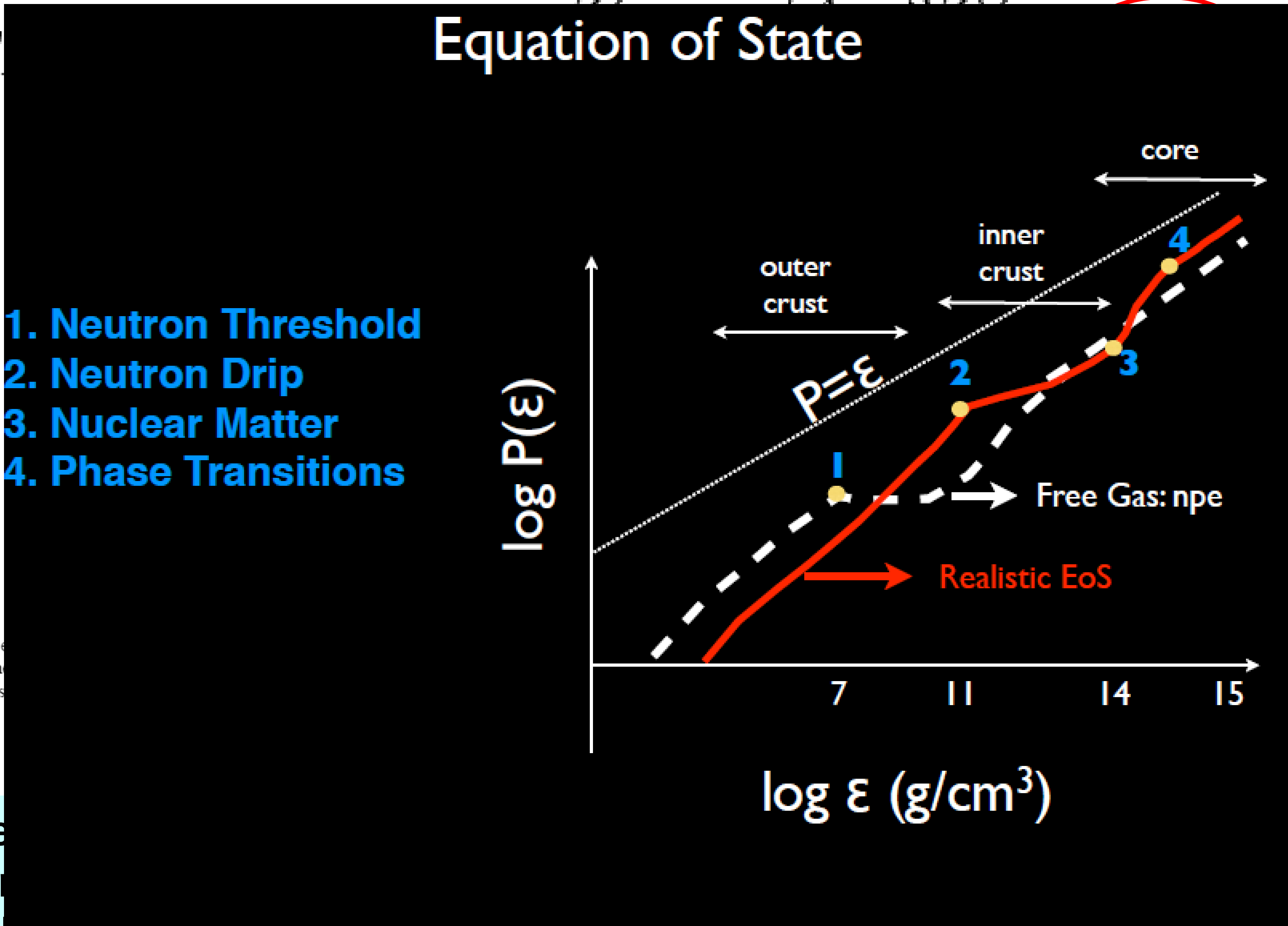
$\gamma \sim 0.5$–0.65

$23.3 < \mathcal{S}(\rho = 0.1\ \text{fm}^{-3}) < 24.9$ MeV

the giant dipole resonance in ^{208}Pb

Sym. Energy has still some ambiguities !!
More refined values may be obtained from the Low Energy Reactions ? !!

Why Pairing Energy in Sym. Energy ?



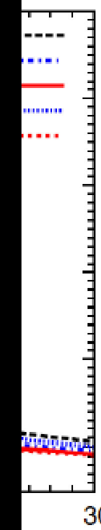
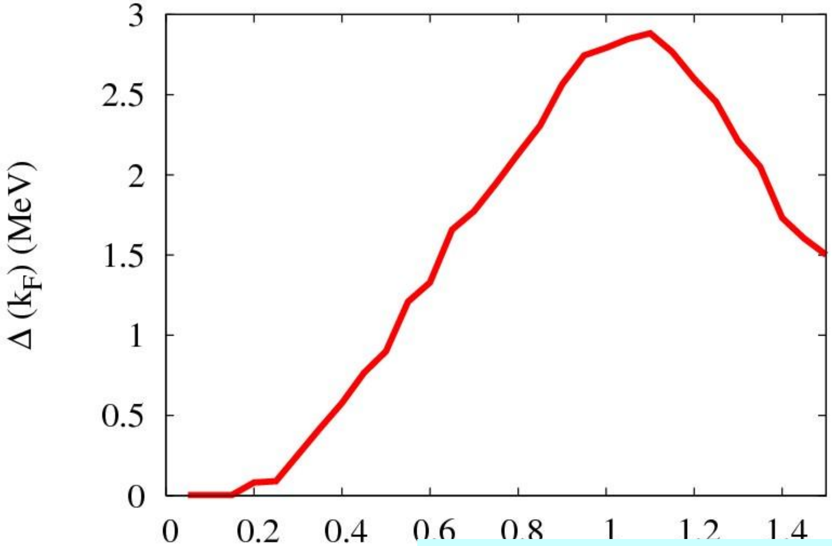


Fig. 1. Mass
nuclei and th
plotted versus

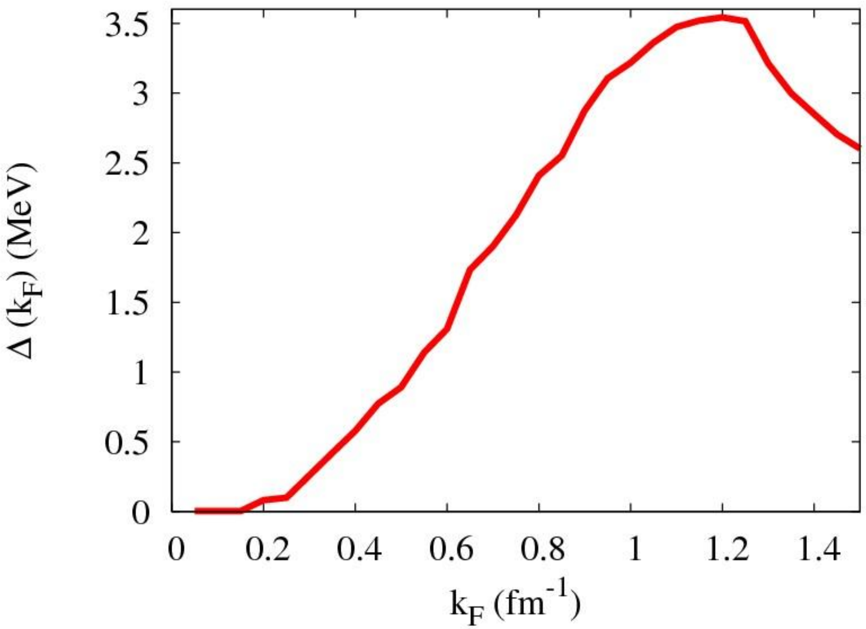
Since
depe
should be considered !!

clei,
the

Pairing gap in symmetric matter

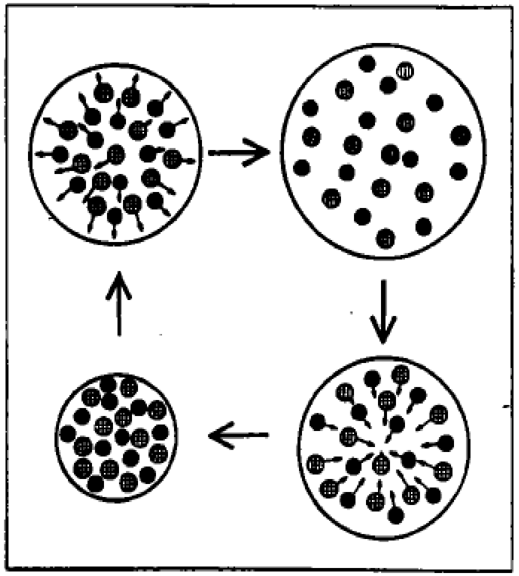


Pairing gap in neutron matter



Pairing Gaps by the CD Bonn potentials are reproduced to some extent in our RMF model !!
The Urca process is in progress !!

Iso-scalar GMR (Breathing Mode)



compressibility (K_A)

$$K_A = K_{Vol} + K_{Surf} A^{-1/3} + K_{Sym}\left(\frac{N-Z}{A}\right)^2 + K_{Coul}\frac{Z^2}{A^{4/3}} + \ldots$$

$$\frac{K_A}{m < r^2 >} = E_0^2 + 3\left(\frac{\Gamma}{2.35}\right)^2$$

Figure 18 Shematic illustration of the monopole resonance in nuclei.

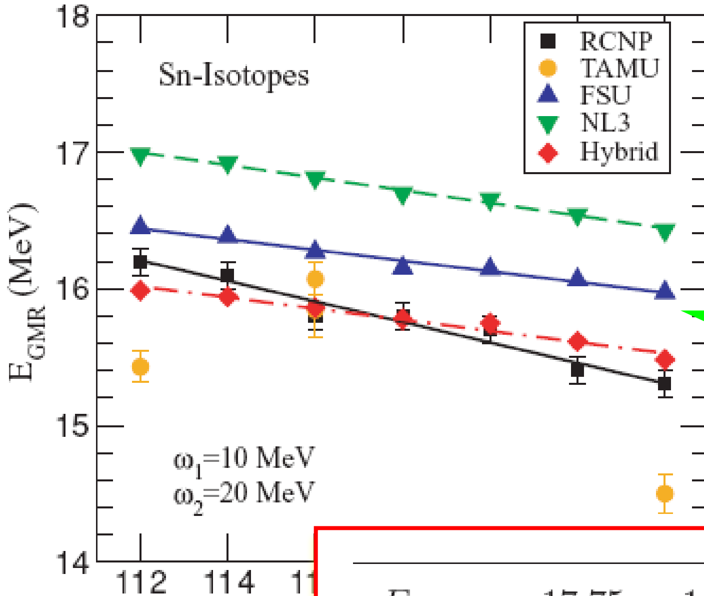
$$E_0 = m_1/m_0 \qquad m_k = \int E^k S(E)\,dE \qquad S(E) = \sum_n \left|\langle n|F^{\mathrm{IS}}_{\mathrm{monopole}}|0\rangle\right|^2 \delta(E - E_n).$$

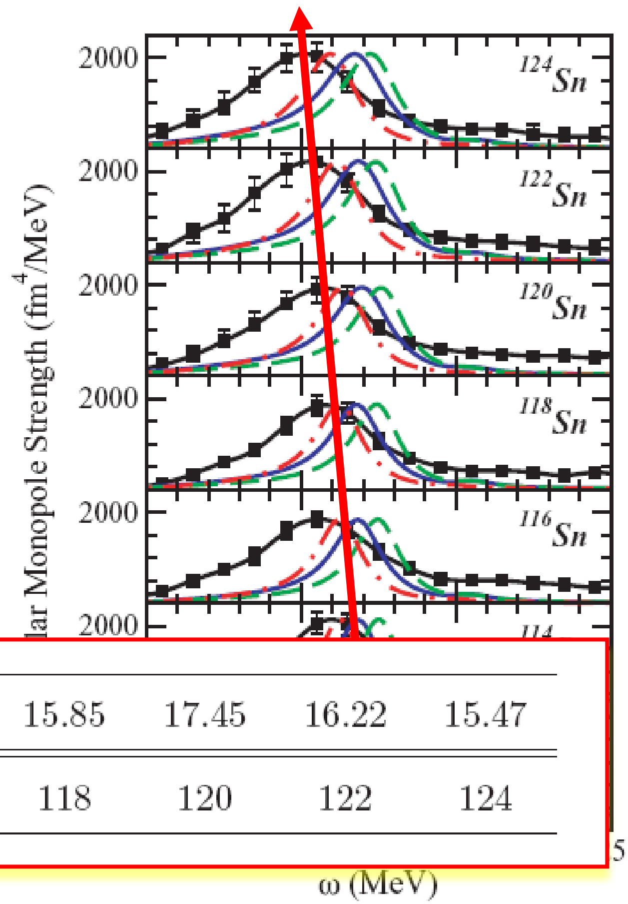
$$F^{\mathrm{IS}}_{\mathrm{monopole}} = \sum_{i=1}^{A} r_i^2$$

The larger K_A, which can be calculated by the EWSR of the GMR, the stiffer is the nucleus !!

Iso-scalar GMR in Sn Isotopes

Why is tin so soft?





E_{GMR}	17.75	14.47	13.25	15.85	17.45	16.22	15.47
Sn	112	114	116	118	120	122	124

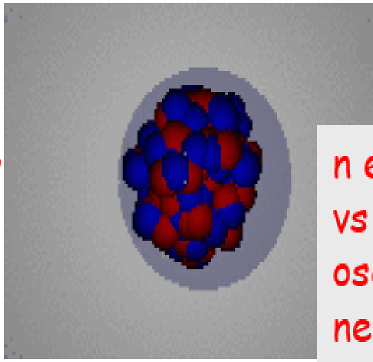
FIG. 8. (Color online) Con... energies (m_1/m_0) in all neutron... from experiment [6,7] (black solid squares) and the theo... predictions of the FSUGold (blue up-triangles), NL3 (green ... triangles), and hybrid (red dot-dashed line) models. Also ... (filled gold circles) are experime... [30,36,37]

FIG. 7. (Color online) Comparison between the distribution of isoscalar monopole strength in all neutron-even ^{112}Sn-^{124}Sn isotopes ... and the ... L3 (green

Our results show, the heavier Sn, the softer is the incompressbility !! Detailed micoroscopic understanding is in progress !!

$$E_{GMR} = \frac{m_1}{m_0} = \ldots$$

Iso-vector GDR and PDR

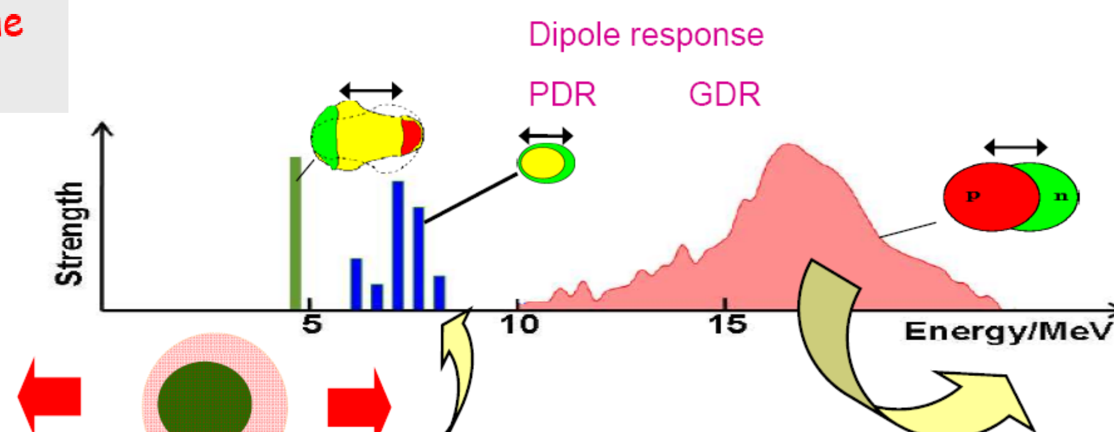


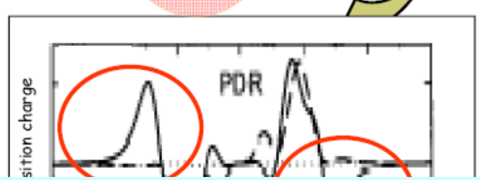
n excess
vs inert core :
oscillation of the
neutron skin

$$E_{GDR} = 31.2A^{-1/3} + 20.6A^{-1/6}\ (MeV)$$

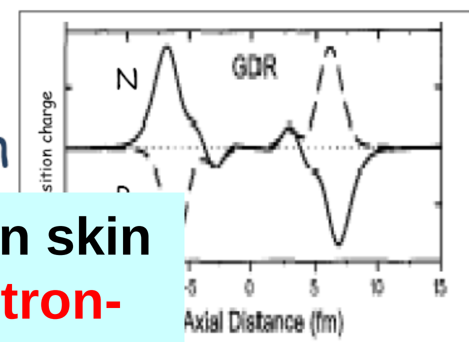
$$E_{GDR} \approx 80A^{-1/3}\ (MeV)$$

Electric Dipole response in Nuclei





Average
Transition



PDR is the resonance between the neutron skin and the symmetric core, in particular, neutron-rich and neutron halo nuclei !!

$$\hat{Q}^{T=1}_{1\mu} = \frac{N}{N+Z}\sum_{p=1}^{Z} r_p Y_{1\mu} - \frac{Z}{N+Z}\sum_{n=1}^{N} r_n Y_{1\mu}$$

2.3. Description of CC and NC reactions

Under the second quantization, matrix elements of any transition operator $\hat{\mathcal{O}}_\lambda$ between a ground state and an excited state $|\omega; JM\rangle$ can be factored as follows:

$$\langle QRPA\|\hat{\mathcal{O}}_\lambda\|\omega; JM\rangle = [\lambda]^{-1}\sum_{ab}\langle a\|\hat{\mathcal{O}}_\lambda\|b\rangle\langle QRPA\|\left[c_a^+\tilde{c}_b\right]_\lambda\|\omega; JM\rangle. \quad (14)$$

Here, the first factor $\langle a\|\hat{\mathcal{O}}_\lambda\|b\rangle$ can be calculated independently of nuclear models for a given single particle basis [29]. Ground and excited states developed in the previous subsection are exploited for the second factor with the quasi boson approximation (QBA). By using the phonon operator $Q^{+,m}_{JM}$ in equation (8), we obtain the following expressions for NC and CC neutrino reactions. For NC reactions,

$$\begin{aligned}\langle QRPA\|\hat{\mathcal{O}}_\lambda\|\omega; JM\rangle = \sum_{a\alpha' b\beta'} [&\mathcal{N}_{a\alpha' b\beta'}\langle a\alpha'\|\hat{\mathcal{O}}_\lambda\|b\beta'\rangle[u_{pa\alpha'}v_{pb\beta'}X_{a\alpha' b\beta'} + v_{pa\alpha'}u_{pb\beta'}Y_{a\alpha' b\beta'}]\\ &-(-)^{j_a+j_b+J}\mathcal{N}_{b\beta' a\alpha'}\langle b\beta'\|\hat{\mathcal{O}}_\lambda\|a\alpha'\rangle[u_{pb\beta'}v_{pa\alpha'}X_{a\alpha' b\beta'} + v_{pb\beta'}u_{pa\alpha'}Y_{a\alpha' b\beta'}]]\\ &+(p\to n),\end{aligned} \quad (15)$$

where the normalization factor is given as $\mathcal{N}_{a\alpha' b\beta'}(J) = \sqrt{1-\delta_{ab}\delta_{\alpha'\beta'}(-1)^{J+T}}/(1+\delta_{ab}\delta_{\alpha'\beta'})$.

Without the np pairing correlation, this expression can be easily reduced to the following simple form:

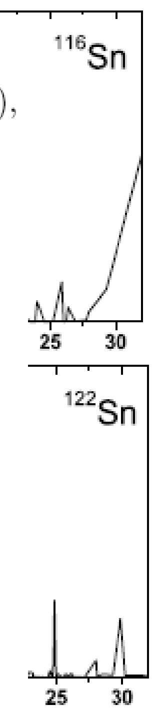
$$\begin{aligned}\langle QRPA\|\hat{\mathcal{O}}_\lambda\|\omega; JM\rangle = \sum_{ab}[&\mathcal{N}_{apbp}\langle ap\|\hat{\mathcal{O}}_\lambda\|bp\rangle[u_{pa}v_{pb}X_{apbp} + v_{pa}u_{pb}Y_{apbp}]\\ &-(-)^{j_a+j_b+J}\mathcal{N}_{bpap}\langle bp\|\hat{\mathcal{O}}_\lambda\|ap\rangle[u_{pb}v_{pa}X_{apbp} + v_{pb}u_{pa}Y_{apbp}]] + (p\to n),\end{aligned} \quad (16)$$

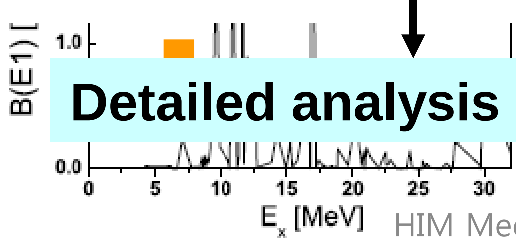
Results of GDR and PDR by QRPA

Table. I: Various moments of the IVGDR through the energy weighted sum rule (EWSR), $m_k = \int E^k S(E) dE$, with the strength functions of the GDR and PDR

A	PDR		GDR			PDR/GDR		
	m_0	m_1	E_c	m_0	m_1	E_c	m_0 (%)	m_1 (%)
112	0.42	3.05		4.58	93.4		3.26	9.28
114	0.52	3.62		6.16	122.4		2.95	8.50
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]
118	1.61	13.9		12.3	213.6		6.49	13.1
120	1.15	9.86		12.66	226.3		4.35	9.09
122	2.92	26.4		13.61	213.8		12.4	21.4
124	3.29	31.9		14.99	230.8		13.8	23.3

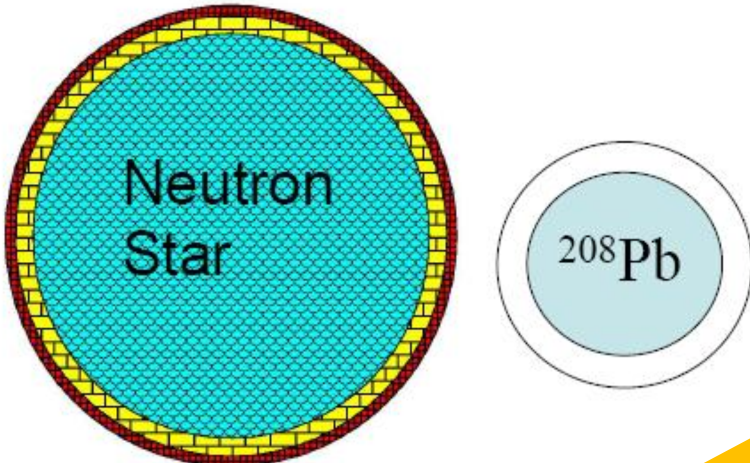
PDR is increased with the heavier Sn isotopes !!





Detailed analysis for the K value are in progress !!

Neutron Star Crust vs ^{208}Pb Neutron Skin



- Neutron star has solid cr… (yellow) over liquid c…
- Nucleus has n…
- Both neutron … NS crust are made … of neutron rich matter at similar densities.
- Common unknown is EOS at subnuclear densities.

PHYSICAL REVIEW C **82**, 014314 (2010)

Chiral three-nucleon forces and neutron matter

K. Hebeler[1,*] and A. Schwenk[1,2,3,†]

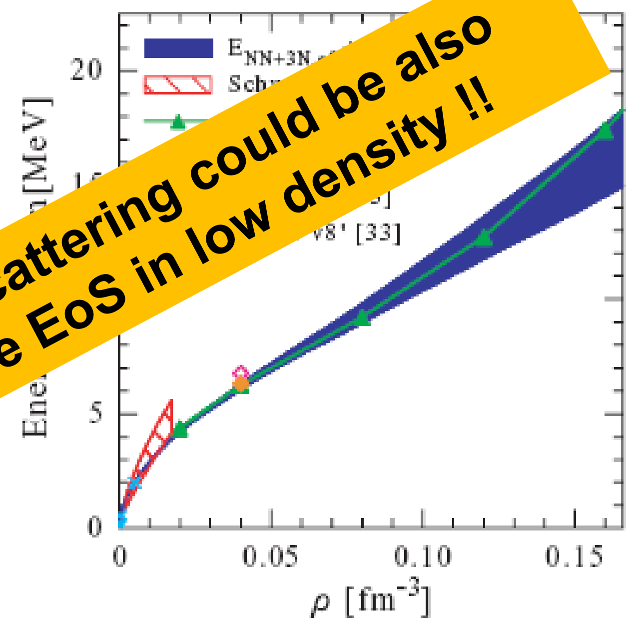


FIG. 9. (Color online) Comparison of the second-order energy with the c_i uncertainty band of Fig. 8 to other neutron matter results (see text for details).

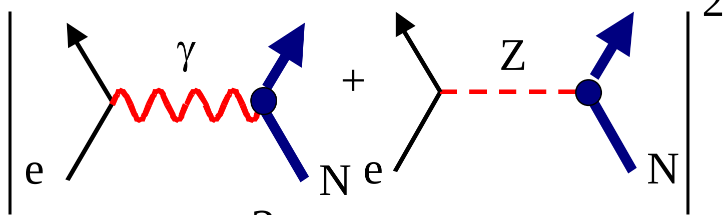
Parity Violating Electron Scattering could be also the alternative to study the EoS in low density !!

Matter Distribution PV electron and Neutrino scattering

K. S. Kim and MKC, JSPJ 82(2013), 024201

How to Measure the Neutral weak form factors **(matter radius) ???**

$\sigma \propto$



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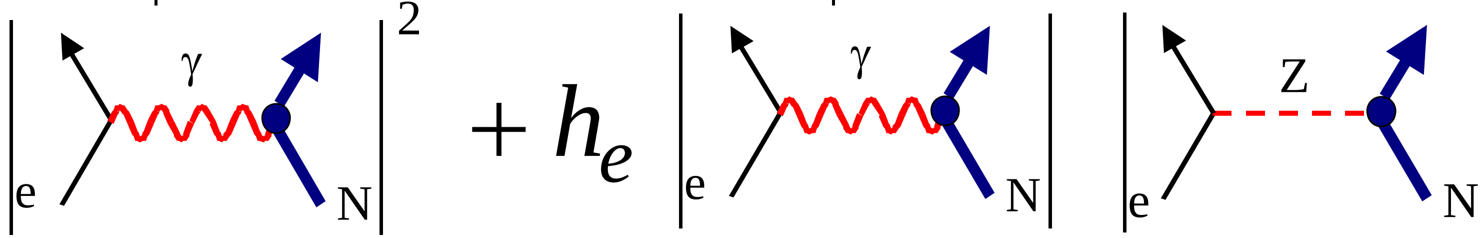
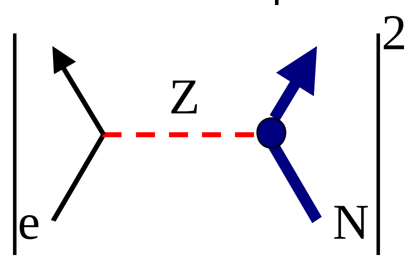
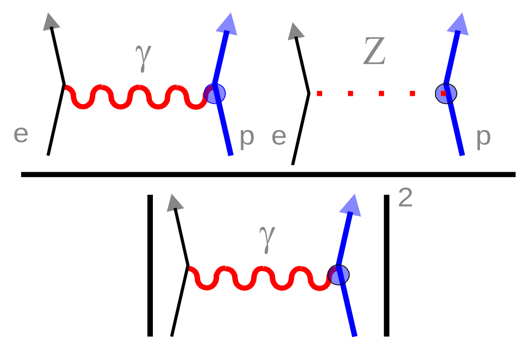


$\vec{e} + N$
(elastic scattering)

$+$



$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto$$

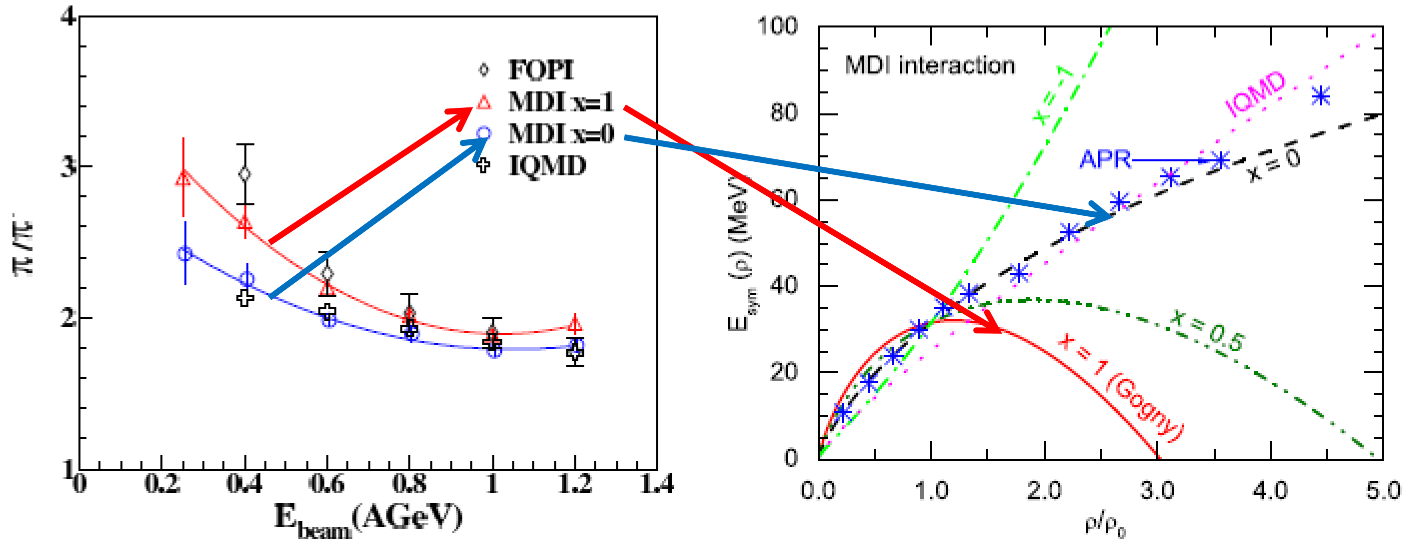


$$= \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \right] \times (\text{form factors}) \approx 10^{-5} \sim 10^{-6}$$

Data from FOPI HIC exp.

Access to $S(\rho)$ at $\rho > \rho_0$?

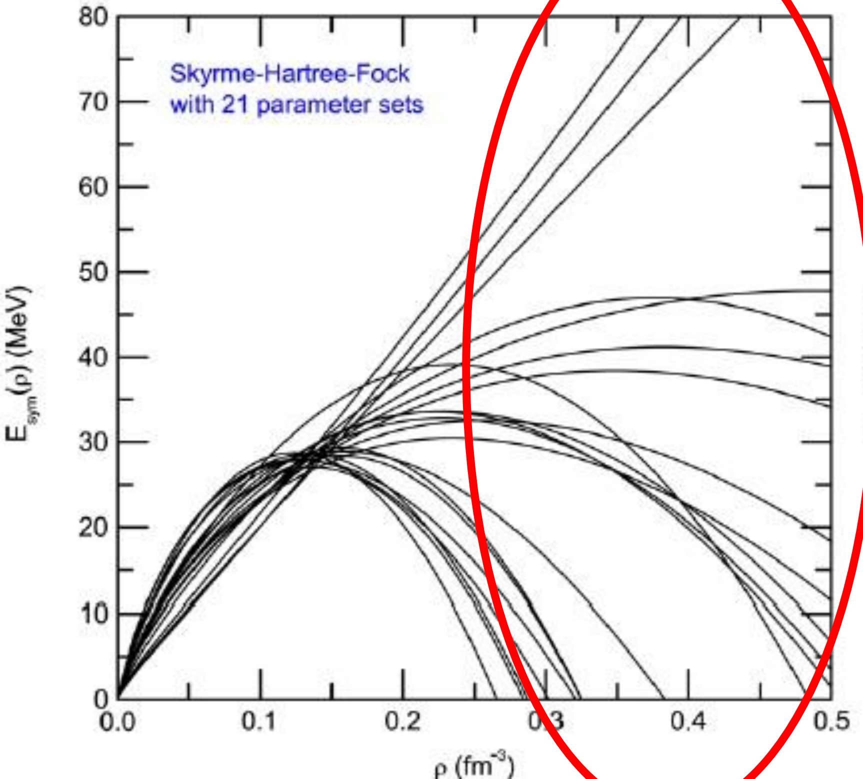
π^-/π^+ ratio data: Reisdorf *et al*, NPA781(07)459

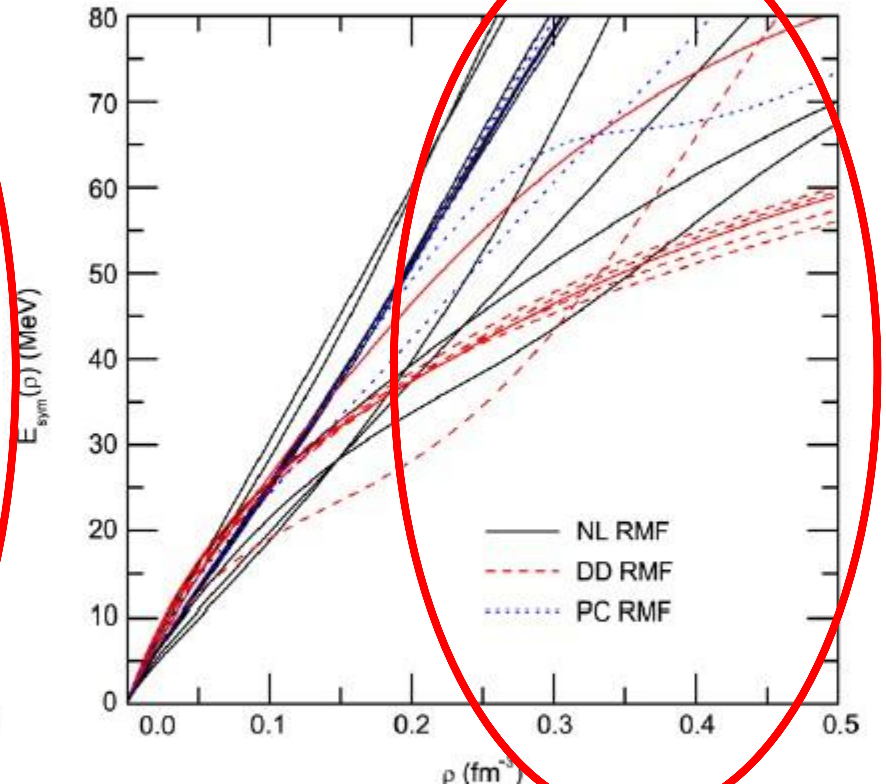


IBUU04 calculations: Xiao, Li *et al*, PRL102(09)062502

Evidence for a suprasoft $S(\rho)$ at $\rho > \rho_0$??

But, NS may collapse by the super-soft EOS !!!
There is a new analysis.
One needs more experimental data !!!





Physics Reports 464 (2008) 113–281

Bao-An Li[a,*], Lie-Wen Chen[b], Che Ming Ko[c]

Symmetry energy is still uncertain at high densities !!
And it strongly depends on given models.

Eq. of State　Results by RMFs in SU(3)

T. Miyatsu, MKC et.al, arXiv:1304-1871[astro-ph]

$$\mathcal{L}_{int} = -g_8\sqrt{2}\left[\alpha \mathrm{Tr}\left(\left[\bar{B}, M_8\right] B\right) + (1-\alpha)\mathrm{Tr}\left(\left\{\bar{B}, M_8\right\} B\right)\right] - g_1\frac{1}{\sqrt{3}}\mathrm{Tr}\left(\bar{B}B\right)\mathrm{Tr}\left(M_1\right), \quad (23)$$

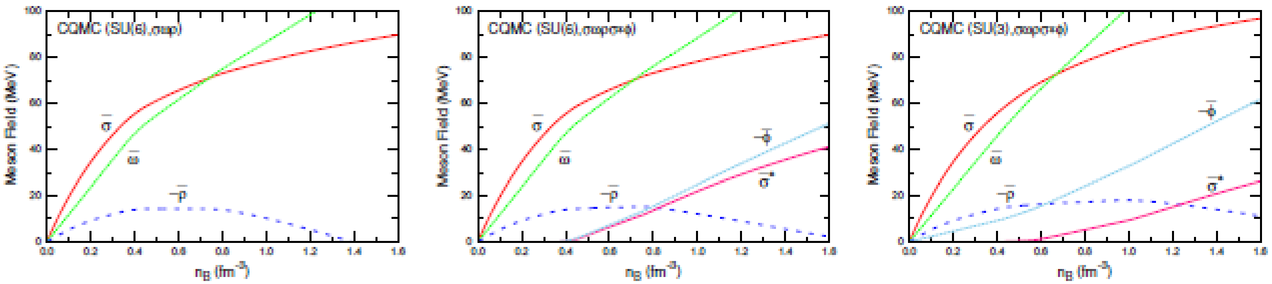
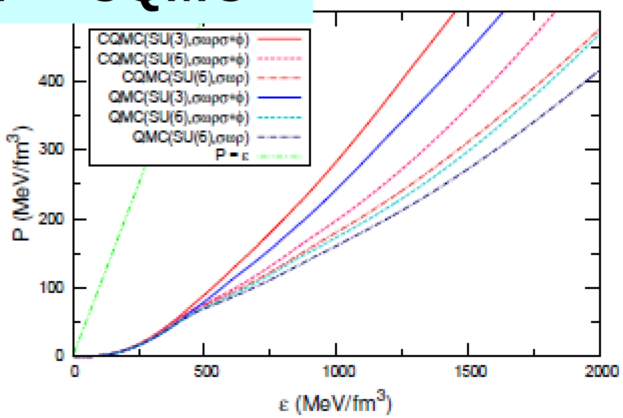


FIG. 2. Meson fields in the CQMC model for the same cases as Fig. 1.

RMF + CQMC



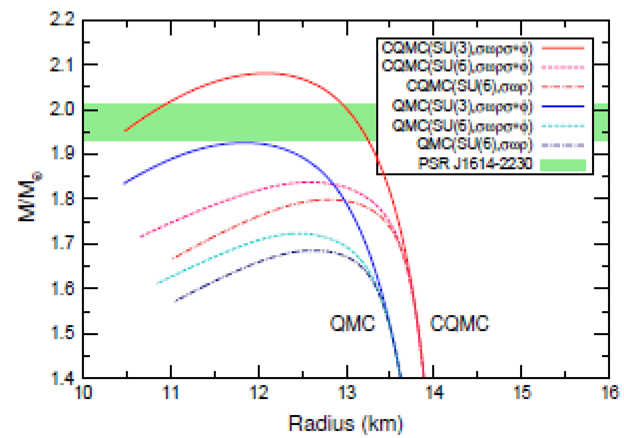


FIG. 4. Mass-radius relations in the QMC and CQMC models.

FIG. 3. Equations of state by QMC an

SU(3) extension may lead to massive NS about 2.0 Solar Mass, even with hyperons !! ??

Results by RMFs in SU(3)

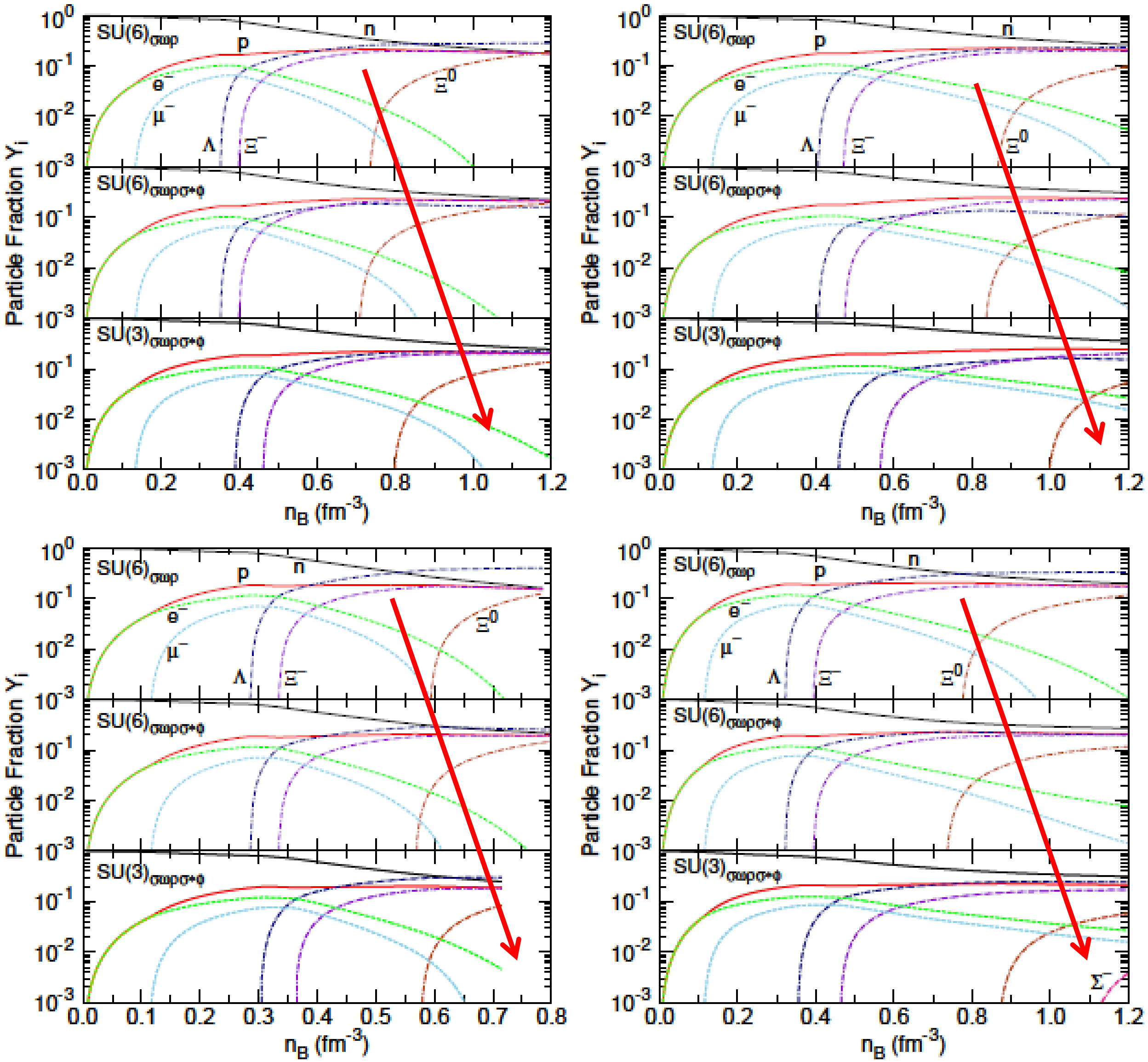


FIG. 2. Particle fractions, Y_i, in the GM1, GM3, NL3 and TM1 models (upper left: GM1, upper right: GM3, lower left: NL3, lower right: TM1).

Eq. of State Results by the MTOV from modified Gravity

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\,f(R) + S_{\rm matter} \qquad f(R) = R + \alpha h(R) + \mathcal{O}(\alpha^2)$$

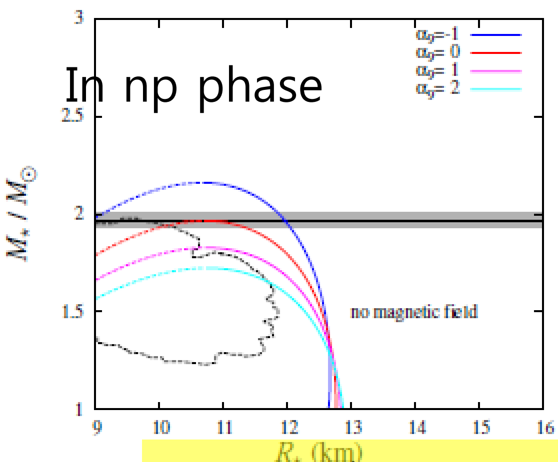
Modified TOV

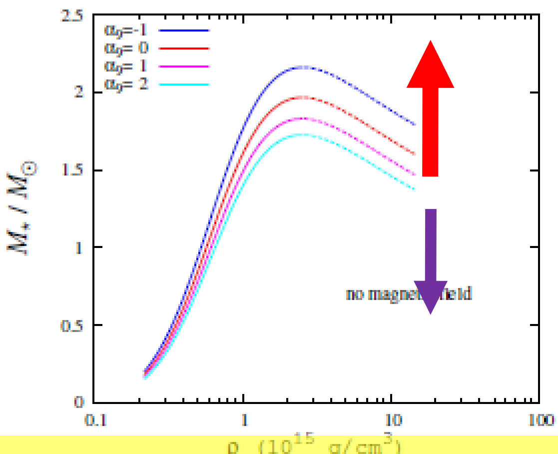
$$\frac{dP_\alpha}{dr} = -(\rho_\alpha + P_\alpha)\frac{d\phi_\alpha}{dr}.$$

$$2(r - M_\alpha)\frac{d\phi_\alpha}{dr} = 8\pi r^2 P_\alpha + \frac{M_\alpha}{r} - \alpha h_R \left[\begin{array}{l} 8\pi r^2 P + \frac{r^2}{2}(\frac{h}{h_R} - R) \\ +(2r - \frac{3}{2}M + 4\pi P r^3)\frac{h'_R}{h_R} \end{array} \right]$$

★ the parameter α depend heavily on the length scale considered.
related to the Yukawa correction to the Newtonian potential, $\frac{G}{3}\ \exp(-r/\lambda) \qquad \lambda = \sqrt{6\alpha}$

In np phase





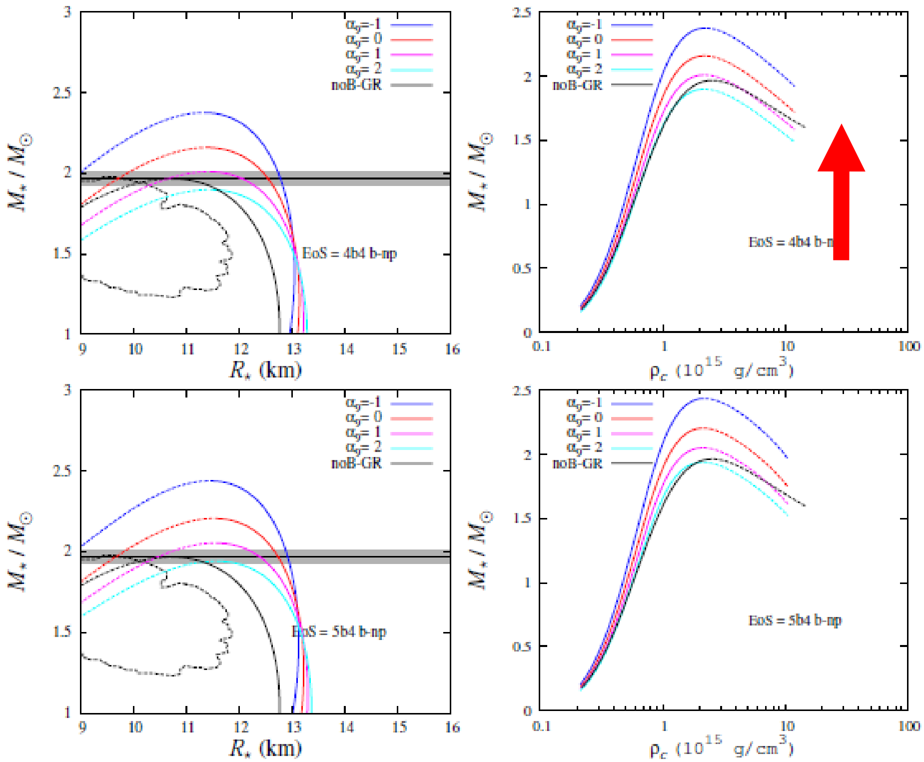
For alpha = -1**(+1)**, more steeper (softer) EOS and more massive (light) Masses !!

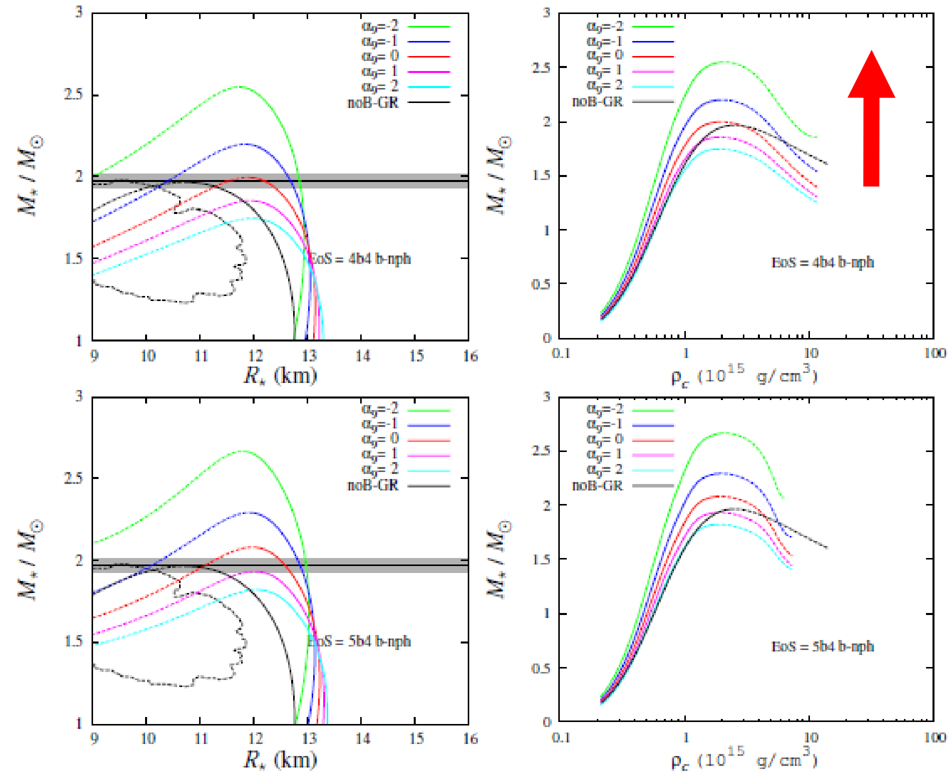
Hyperonic NS may go to 2.0 solar mass by the modified gravity with reasonable magnetic field **without any modification in RMF** !!

Results by MTOV and Magnetic fields

MKC et.al, arXiv:1304-1871[astro-ph]

In np and nph phase with stronger magnetic field





$\alpha_9 \equiv \alpha/10^9\,\mathrm{cm}^2 = -2, -1, 0, 1, 2$ in the $f(R) = R + \alpha R^2$ gravity.

the Kaluza–Klein action expands into:

$$\mathcal{R} \to f(R) = R - \alpha |F|^2 \; ,$$

For stronger m. field, we obtain more stiffer EOS and more massive Masses !! May **compensate modified gravity (alpha >0).**

Eq. of State

Results by DDRMF

If we divide the symmetry energy into kinetic and potential terms as

$$S(\rho)_{\delta=1} = T_{\rm sym} + V_{\rm sym}, \tag{18}$$

the kinetic term reads

$$T_{\rm sym} = \frac{\Delta E_{\rm kin}}{\rho} = \frac{(k_F^N)^2}{6\sqrt{(k_F^N)^2 + (m_N^*)^2}}, \tag{19}$$

where k_F^N is the Fermi momentum of the nucleon in symmetric nuclear matter. The potential part is then written as

$$V_{\rm sym} = \frac{\Gamma_{\rho N}^2}{8m_\rho^2}\rho. \tag{20}$$

As mentioned in the Introduction, the polytropic formula of the potential term is written as

$$V_{\rm sym}(\rho) = \frac{C_{s,p}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma_i} \tag{21}$$

where $C_{s,p} = 35.2$ MeV and the symmetry energy at saturation density is $S_0 = 30.1$ MeV in Ref. [1]. Therefore, $\Gamma_{\rho N}$ can be obtained from this formula for given γ_i. In this work, we test $\gamma_i = 0.5, 1$ and 2.

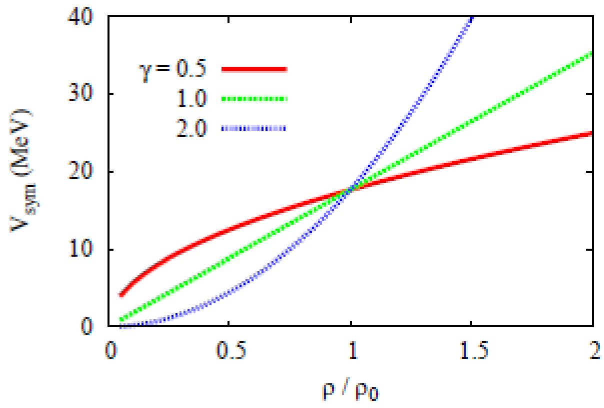


FIG. 1: (color online). The potential part in symmetry energy.

$$\Gamma_{ib}(\rho) = g_{ib} f_i(n), \tag{12}$$

where $n = \rho/\rho_0$ with ρ_0 the saturation density. It is assumed that $f_i(1) = 1$, so g_{ib} denotes the coupling constant at the saturation density. Density-dependent part $f_i(n)$ is given by

$$f_i(n) = a_i \frac{1 + b_i(n + d_i)^2}{1 + c_i(n + d_i)^2}. \tag{13}$$

Meson(i)	g_{iN}	a_i	b_i	c_i	d_i
σ	10.87854	1.365469	0.226061	0.409704	0.901995
ω	13.29015	1.402488	0.172577	0.344293	0.983955

TABLE I: Parameters of the density-dependent coupling constants in Typel & Wolter [7] fitted to the saturation density $\rho_0 = 0.153\,\mathrm{fm}^{-3}$, binding energy per nucleon 16.247 MeV, and the compression modulus $K_0 = 240$ MeV. Masses of mesons are used as $m_\sigma = 550$ MeV and $m_\omega = 783$ MeV.

Gamma factors from experiments may be exploited in RMF and predict EoS and MR relations of Neutrons Stars !!

Eq. of State | Results by DDRMF with mag. field

C-Y. Ryu and MKC, submitted for publication

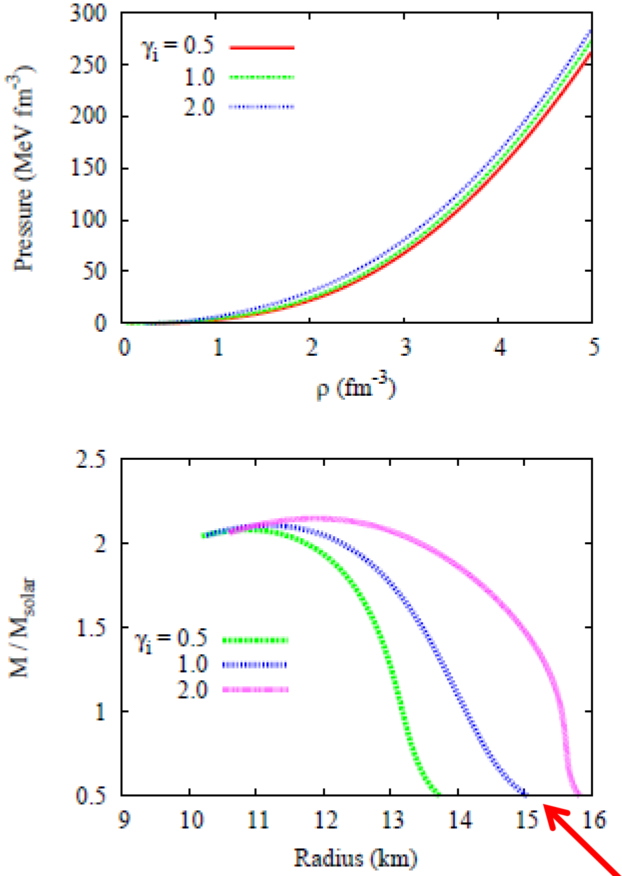


FIG. 3: (color online). The equation of state and mass-radius relation for various γ_i and $B^* = 1 \times 10^4$ for all calculations is used.

Gamma_i = 0.69

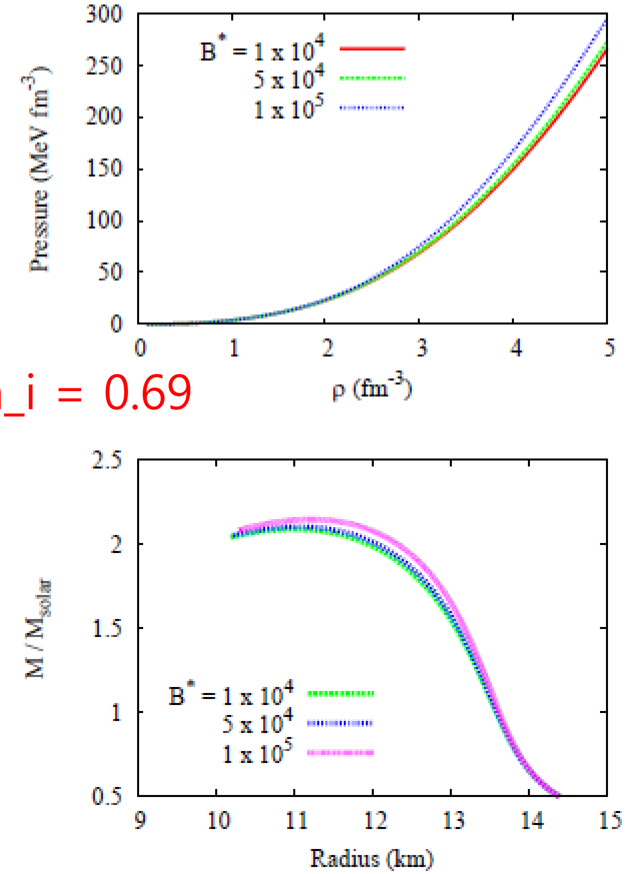


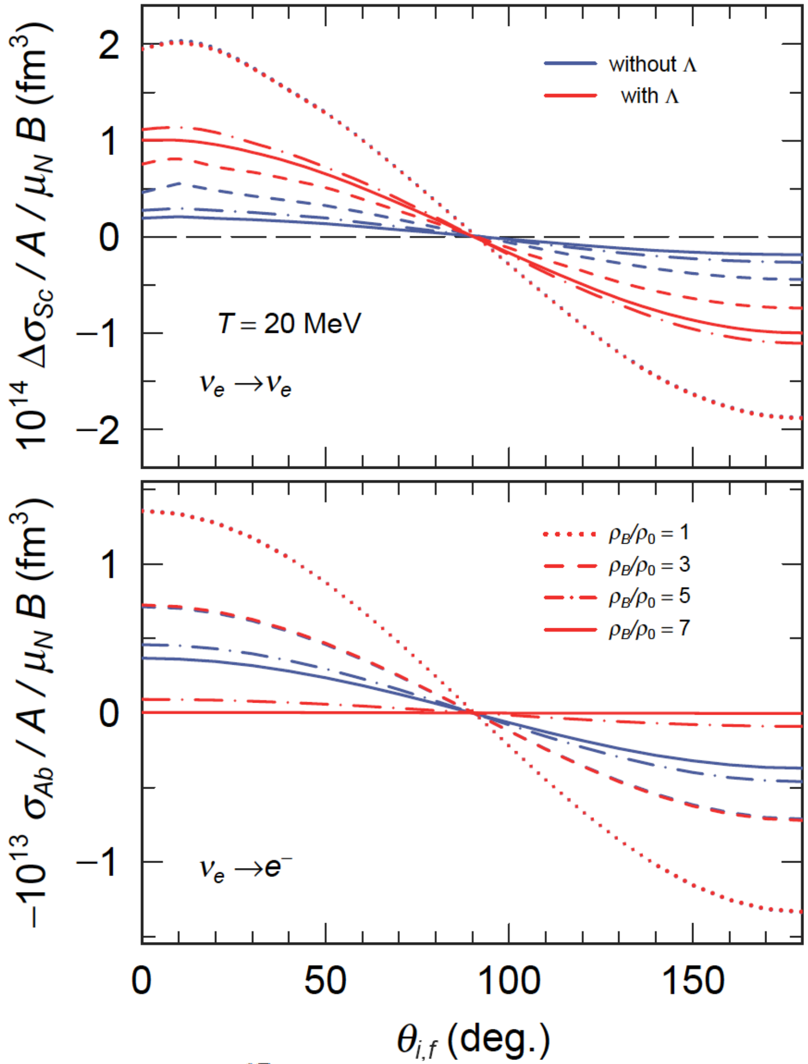
FIG. 4: (color online). The equation of state and mass-radius relation for magnetic fields. $\gamma_i = 0.69$ is used.

Mass-radius relation of neutron stars may depend heavily on the gamma factor in the Symmetry energy !!!

Application of EoS — Pulsar Kick and Spin Decce. in N-Star

T. Maruyama, MKC et.al, PRD 86(2012), 123003; PRD 83 081303(2011)

Asymmetry of neutrino emission in SN explosion



$B = 2 \times 10^{17}$ G. This gives $\mu_N B = 0.63$ MeV

Full Relativistic

Nuclear Matter ⇒ RMF Approach

Different Mean-Field for p, n & Λ

Fermi Motion, Mom.Dep.-Spin Vector, EoS

Neutrino Reactions and Transport by Boltzmann Eq.

Magnetic-Field is treated perturbatively

$$\sigma = \sigma_0 + \Delta\sigma \ \ (\Delta\sigma \propto B)$$

Magnetic Field increases neutrinos emitted in the direction parallel to the magnetic field and decreases that in its opposite direction

Summary and Conclusion

1. Symmetry energy and equations of state for nuclear (finite and infinite) matter systems are one of the main goals in RAON physics.
2. Pairing gaps leading to the BCS phase are to be studied in detail for the symmetry energy research.
3. For finite nuclei, we tested our nuclear model (QRPA and DQRPA) for GMR and PDR data and deduce the information for the symmetry energy.
4. For the information in intermediate density, heavy ion scattering could be vital for the EoS. For high density, observational data of neutrons stars may constrain the EoS. But many ambiguities still remained.
5. For a consistent model for finite and infinite matter, we are developing the RMF with the nucleon structure, the pairing, the density dependence and the deformation.

Thanks for your Attention !!

Collaborators

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T. Maruyama (Nihon Univ.), T. Hayakawa, S. Chiba (JAEA)

C. Deliduman... (Turkey)
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Backup Files

Main Research Subjects

Nuclear Science	Nuclear Astrophysics & Nucleosynthesis	- Direct measurements of proton and alpha capture reactions - Search for Super Heavy Elements beyond Z=113
	Nuclear Structure & Matter	- RI nuclear structure of neutron rich nuclei near N=126, 80<A<140 - Symmetry energies at sub-saturation density
	Nuclear Data	- Neutron capture cross section measurements by using n-TOF
	Nuclear Theory	- Development of RI nuclear theories
Atomic & Molecular Science	Precision Mass Measurement & Laser Spectroscopy	- Hyperfine structure and characteristics of element and nuclei
Material Science	RI Material Research	- Search for new material and its properties with β-NMR/μSR and RI beam
Medical & Bio Science	Medical & Bio application	- Development of new cancer therapy - Biological effect of tissue and DNA by RI beam

Associated EOS quantities

Nuclear matter EOS

Symmetric matter EOS

Symmetry energy S

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta=0) + S(\rho)\,\delta^2$$

where $\delta = (\rho_n - \rho_p)/\rho$.

$$\begin{aligned} S(\rho_0) &= J \\ S'(\rho_0) &= L/3\rho_0 \\ S''(\rho_0) &= K_{sym}/9\rho_0^2 \end{aligned}$$

The density dependence of the symmetry energy is poorly constrained and one would like to know the key

L slope parameter K_{sym} curvature pa

$E(\rho,\delta) = E_0(\rho,\delta=0) + S(\rho)\delta^2 + o(\delta^2)$

$S(\rho) = J + L/3\,(\rho-\rho_0)/\rho_0 + K_{sym}((\rho-\rho_0)$

Expa

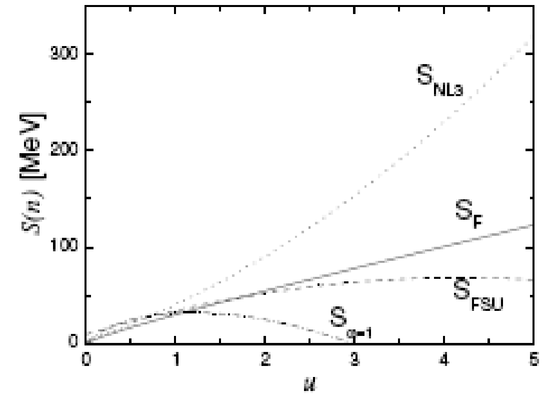
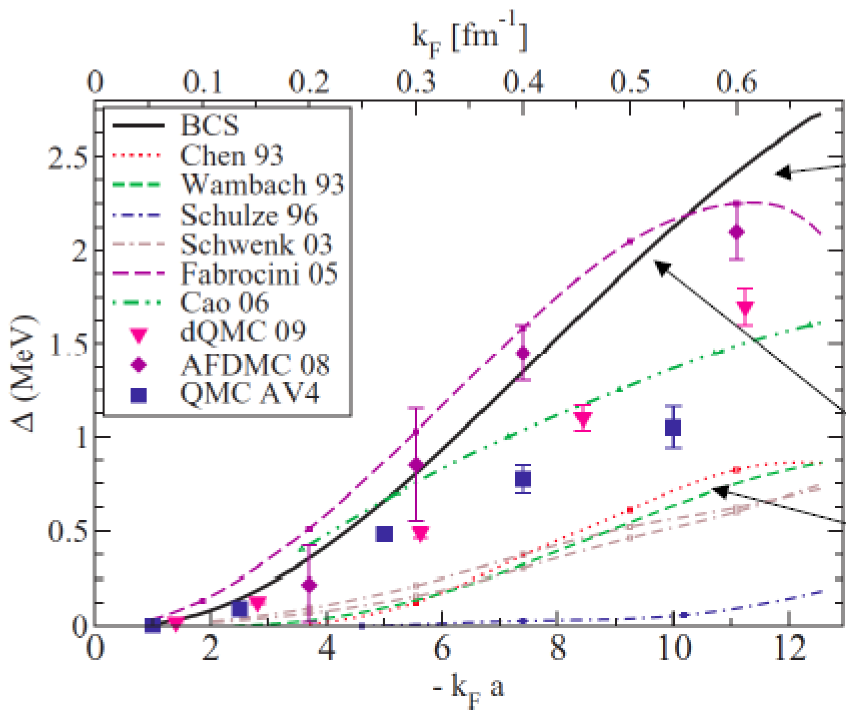


Figure 2: The density dependencies of $S(n)$'s for different models.

$^1S_0$ Pairing in uniform matter



BCS

We assume two models for pairing:
Strong (max at 3 MeV),
Weak (max at 1 MeV).

Gezerlis, Carlson, Phys. Rev. C 81 (2010)

Lombardo, Schulze, Lect. Notes Phys. 578 (2001)

Pairing Energy in Nuclear Matter

For nuclear matter, RHB equations are:

$$\begin{pmatrix} \epsilon(k)-\lambda & \Delta(k) \\ \Delta(k) & -\epsilon(k)+\lambda \end{pmatrix}\begin{pmatrix} u(k) \\ v(k) \end{pmatrix} = e(k)\begin{pmatrix} u(k) \\ v(k) \end{pmatrix}$$

Where: $\epsilon(k) = V + E^*(k)$ with $E^*(k) = \sqrt{k^2+m^{*2}}$

$$m^* = m + g_\sigma \sigma$$

$$\lambda = V + \sqrt{k_F^2 + m^{*2}}$$

$$V = g_\omega \omega_0 + g_\rho \tau_3 \cdot \rho_{0.3}.$$

$$e(k) = \sqrt{(\epsilon(k)-\lambda)^2 + \Delta^2(k)}$$

$$v^2(k) = \frac{1}{2}\left(1 - \frac{\epsilon(k)-\lambda}{\sqrt{(\epsilon(k)-\lambda)^2+\Delta^2(k)}}\right)$$

Pairing gap equation:

$$\Delta(k) = -\frac{1}{8\pi^2}\int_0^\infty v_{pp}(k,p)\frac{\Delta(p)}{\sqrt{(\epsilon(p)-\lambda)^2+\Delta^2(p)}}p^2 dp.$$

Where $v_{pp}(k,p)$ is pairing interaction matrix elements:

$$v_{pp}(k,\ p) = v_{pp}^\sigma(k,\ p) + v_{pp}^\omega(k,\ p) + v_{pp}^\rho(k,\ p)$$

$$v_{pp}^\sigma(p,x) = \frac{g_\sigma^2}{2E^*(k)E^*(p)}\left\{\frac{(E^*(p)-E^*(k))^2 + m_\sigma^2 - 4M^{*2}}{4pk}\ln\frac{(k+p)^2+m_\sigma^2}{(k-p)^2+m_\sigma^2} - 1\right\}$$

$$v_{pp}^\omega(p,k) = \frac{g_\omega^2}{E^*(k)E^*(p)}\frac{2E^*(k)E^*(p)-M^{*2}}{2pk}\ln\frac{(k+p)^2+m_\omega^2}{(k-p)^2+m_\omega^2},$$

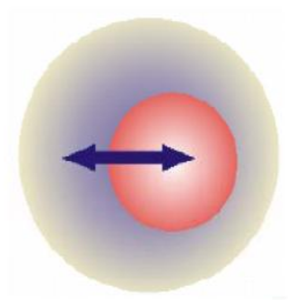
$$v_{pp}^\rho(p,k) = \frac{g_\rho^2}{E^*(k)E^*(p)}\frac{2E^*(k)E^*(p)-M^{*2}}{2pk}\ln\frac{(k+p)^2+m_\rho^2}{(k-p)^2+m_\rho^2}.$$

GMR and PDR

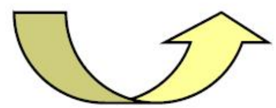
Iso-vector GDR and PDR

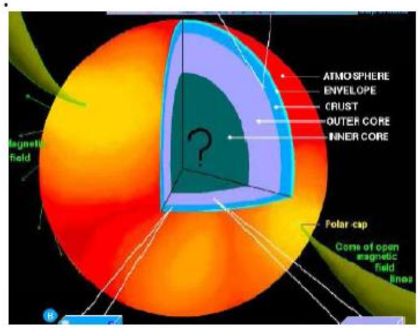
Why the Pygmy Resonance is important ?

There is an extrapolation of 18 orders of magnitude from the neutron radius of a nucleus (from 5-6 fm to 10 km radius) of a neutron star.

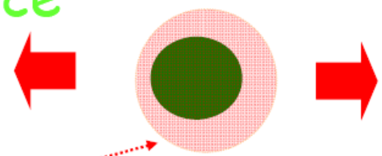


Yet both radii depend on the knowledge of equation of state of neutron rich matter.





From the pygmy dipole resonance



One can derive:

- ❑ Nuclear symmetry energy

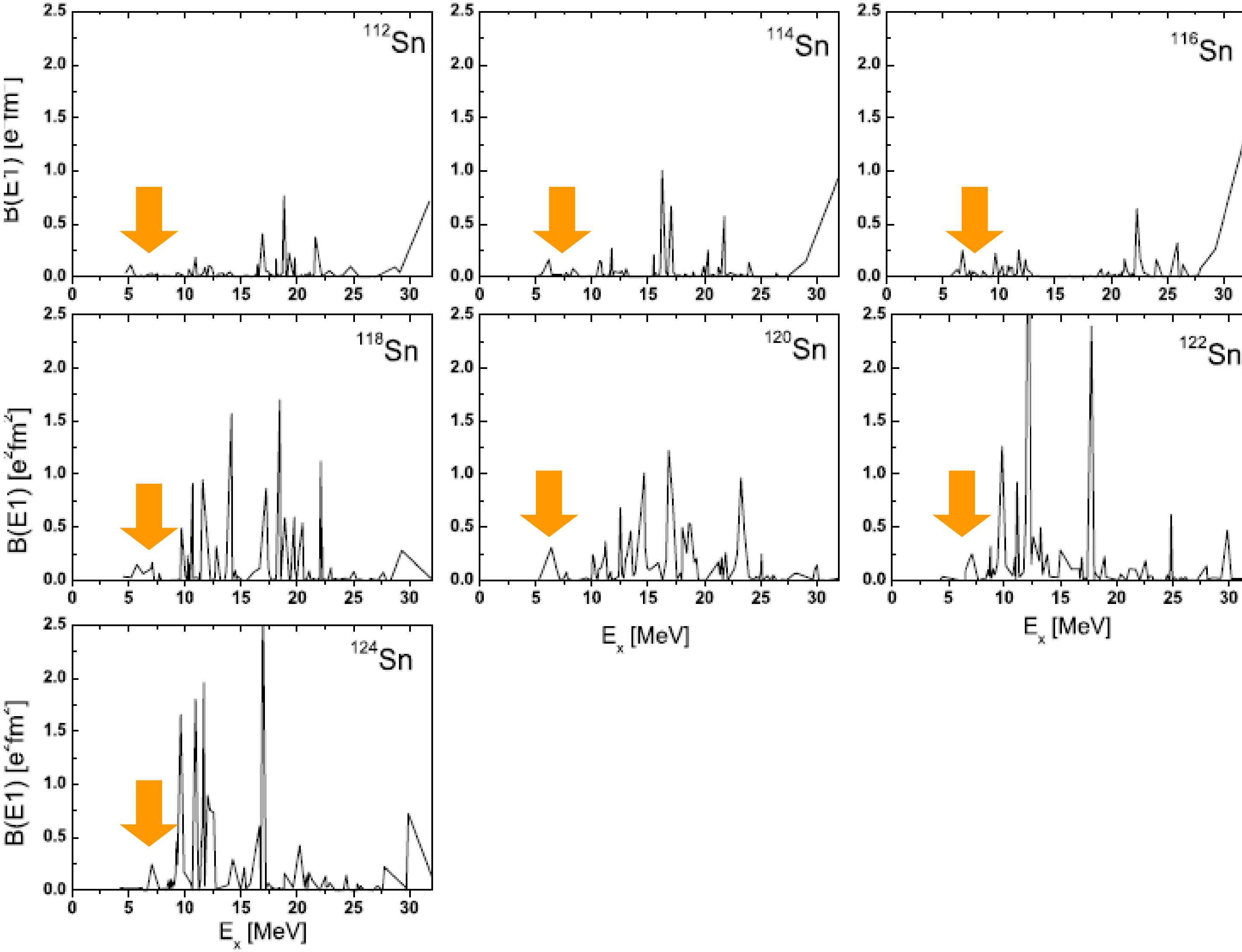
- ❑ Neutron skin

Data on neutron rms radius constrain the isospin-asymmetric part of the Equation of state of nuclear matter

- ❑ Relation between neutron skin and neutron stars :

both are built on neutron rich nuclear matter so that one-to-one correlations can be drawn

Results of GDR and PDR by QRPA



Eq. of State High Density from Neutron Stars

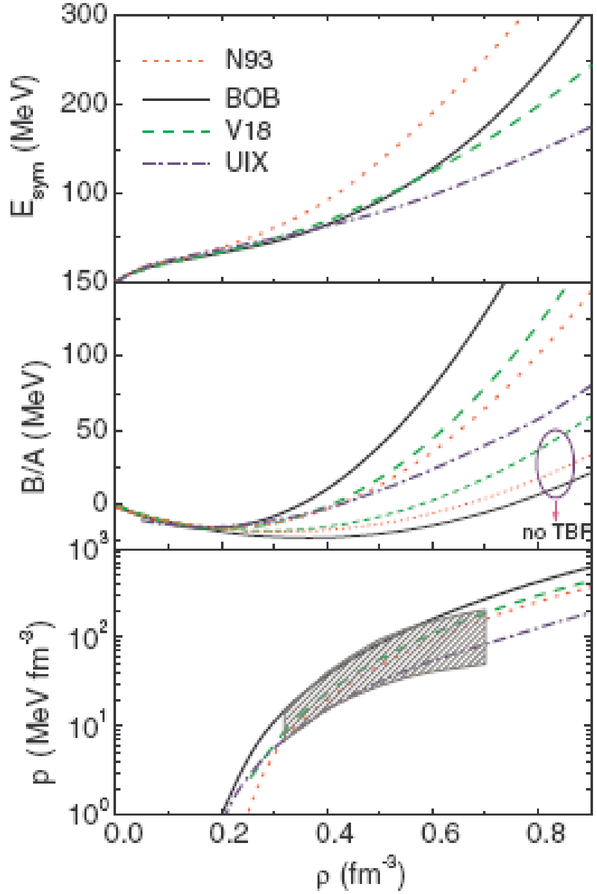
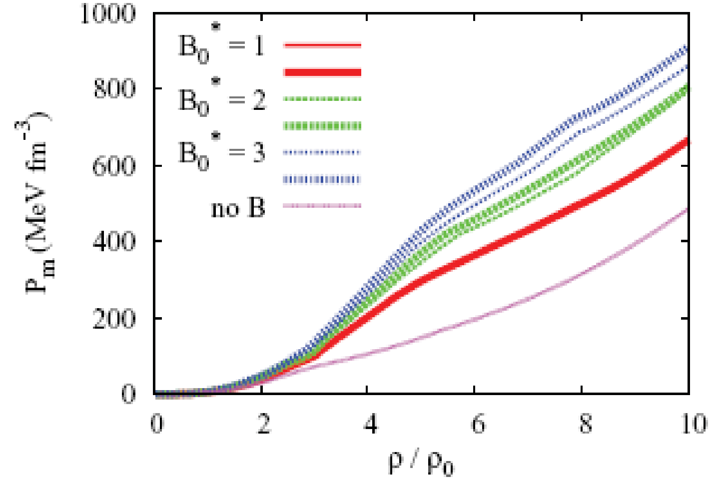
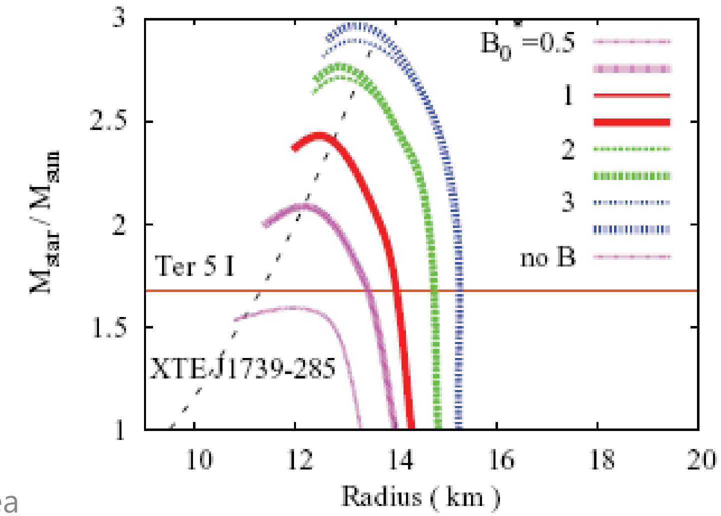


FIG. 2. (Color online) Symmetry energy (upper panel), binding energy per nucleon of symmetric nuclear matter (central panel), and pressure of symmetric matter (lower panel), employing different interactions. The shaded region indicates the constraints of Ref. [28].

PHYSICAL REVIEW C **82**, 025804 (2010)





Motivation 2: Modified Gravity

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

JCAP07(2011)020

Constraints on perturbative $f(R)$ gravity via neutron stars

Savaş Arapoğlu,[a] Cemsinan Deliduman[b] and K. Yavuz Ekşi[a]

$$\boxed{R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}\,R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4}T_{\mu\nu}}$$

The current accelerated expansion of the universe

Although the cosmological constant is arguably the simplest explanation and the best fit to all observational data, its theoretical value predicted by quantum field theory is many orders of magnitude greater than the value to explain the current acceleration of the universe. This

categories, both of them introducing new degrees of freedom [9]: The first approach is to add some unknown energy-momentum component to the right hand side of Einstein's equations with an equation of state $p/\rho \approx -1$, dubbed *dark energy*. In the more radical second

approach, the idea is to modify the left hand side of Einstein's equations, so-called *modified gravity*. Trying to explain such perplexing observations by modifying gravity rather than postulating an unknown dark energy has been an active research area in the last few years and in this paper we adopt this path.

Modified TOV equations of $f(R)$ gravity

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}f(R) + S_{\text{matter}}$$

$$\alpha \lesssim 5 \times 10^{15}\ \text{cm}^2$$

$$f(R) = R + \alpha h(R) + \mathcal{O}(\alpha^2)$$

How will be the modified gravity effect in the stellar scale ???

Motivation 2-1 : Yukawa Potential + Newtonian Gravity

We investigate the nonrelativistic limit by taking the $\mathcal{O}(1)$ part of Eq. (45). Considering each particle as a test particle in the field of the other ones, we replace the potentials U and W by their self-energy free parts. The equations of motion for the test particle then read

$$\frac{dv_n^i}{dt} = G\sum_{k\neq n}\frac{\partial}{\partial x_n^i}\left(\frac{m_k}{|\mathbf{x}_n - \mathbf{x}_k|}\left(1 + \frac{1}{3}e^{-\alpha|\mathbf{x}_n - \mathbf{x}_k|}\right)\right). \quad (49)$$

$\alpha^2 := 1/(6a)$

This is the analogue of the Newtonian equations of motion for a purely gravitating set of point particles.

PHYSICAL REVIEW D 81, 104003 (2010)

On the $1/c$ expansion of $f(R)$ gravity

Joachim Näf* and Philippe Jetzer

$$f(R) = -2\Lambda + R + aR^2, \qquad a \neq 0,$$

While the laboratory bound from the Eöt-Wash experiment provides the small bound $a \lesssim 10^{-10}\ \mathrm{m}^2$, the results from Gravity Probe B imply the much larger limit $a \lesssim 5\times 10^{11}\ \mathrm{m}^2$. The measurements of the precession of the pulsar B in the PSR J0737-3039 system provide instead the limit $a \lesssim 2.3\times 10^{15}\ \mathrm{m}^2$. Even for these large values of a the quadratic term in (5) still induces a small correction of GR.

Theoretical Frameworks 1 : Standard TOV

Standard TOV

$$\frac{dP(r)}{dr} = -\frac{G}{r^2}\left[\rho(r) + \frac{P(r)}{c^2}\right]\left[M(r) + 4\pi r^3 \frac{P(r)}{c^2}\right]\left[1 - \frac{2GM(r)}{c^2 r}\right]^{-1}$$

If $1/c^2$ terms go to 0, Newtonian Gravity

Solution of the Einstein eq. for a given time independent and spherical symmetric metric

$$ds^2 = e^{\nu(r)} c^2 dt^2 - (1 - 2GM(r)/rc^2)^{-1} dr^2 - r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$\frac{d\nu(r)}{dr} = -\left(\frac{2}{P(r) + \rho(r)c^2}\right)\frac{dP(r)}{dr}$$

With a boundary
conditions on a
boundary
and continuous metric

$\exp[\nu(r)] = 1 - 2GM(r)/rc^2$

$$ds^2 = (1 - 2GM_0/rc^2)c^2 dt^2 - (1 - 2GM_0/rc^2)^{-1} dr^2 - r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$\frac{8\pi G}{c^4} T_{11} = G_{11}$$

Theoretical Frameworks 2: Modified TOV by M. Gravity

Modified Action

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}f(R) + S_{\text{matter}} \qquad f(R) = R + \alpha h(R) + \mathcal{O}(\alpha^2)$$

Modified E. Equation

$$(1+\alpha h_R)G_{\mu\nu} - \frac{1}{2}\alpha(h - h_R R)g_{\mu\nu} - \alpha(\nabla_\mu\nabla_\nu - g_{\mu\nu}\Box)h_R = 8\pi T_{\mu\nu}$$

$$G_{\mu\nu} = R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} \qquad h_R = \frac{dh}{dR}$$

$$ds^2 = -e^{2\phi_\alpha}dt^2 + e^{2\lambda_\alpha}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2).$$

$$\phi_\alpha = \phi + \alpha\phi_1 + \dots \qquad \lambda_\alpha = \lambda + \alpha\lambda_1 + \dots \qquad M_\alpha = M + \alpha M_1 + \dots$$

$$\rho_\alpha = \rho + \alpha\rho_1 + \dots \qquad P_\alpha = P + \alpha P_1 + \dots$$

If alpha dep. terms go to 0, Standard Gravity

Modified TOV

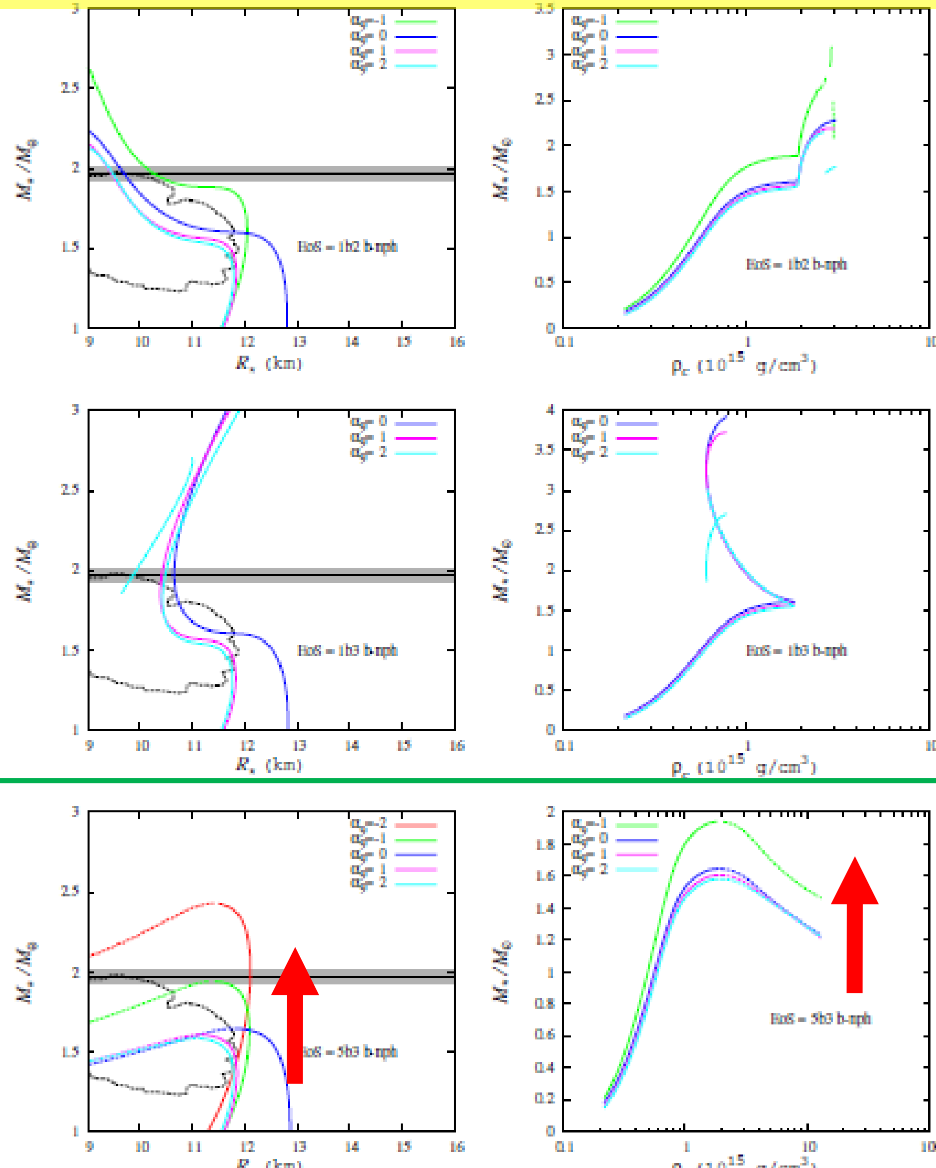
$$\frac{dP_\alpha}{dr} = -(\rho_\alpha + P_\alpha)\frac{d\phi_\alpha}{dr}.$$

$$2(r - M_\alpha)\frac{d\phi_\alpha}{dr} = 8\pi r^2 P_\alpha + \frac{M_\alpha}{r} - \alpha h_R\left[\begin{array}{l} 8\pi r^2 P + \frac{r^2}{2}\left(\frac{h}{h_R} - R\right) \\ +\left(2r - \frac{3}{2}M + 4\pi P r^3\right)\frac{h_R'}{h_R} \end{array}\right]$$

Hyperonic NS may go to 2.0 solar mass by the modified gravity with reasonable magnetic field without any modification in RMF !!

In nph phase

For alpha = -1 and stronger m. field,
more steeper
EOS and
more massive Masses !!



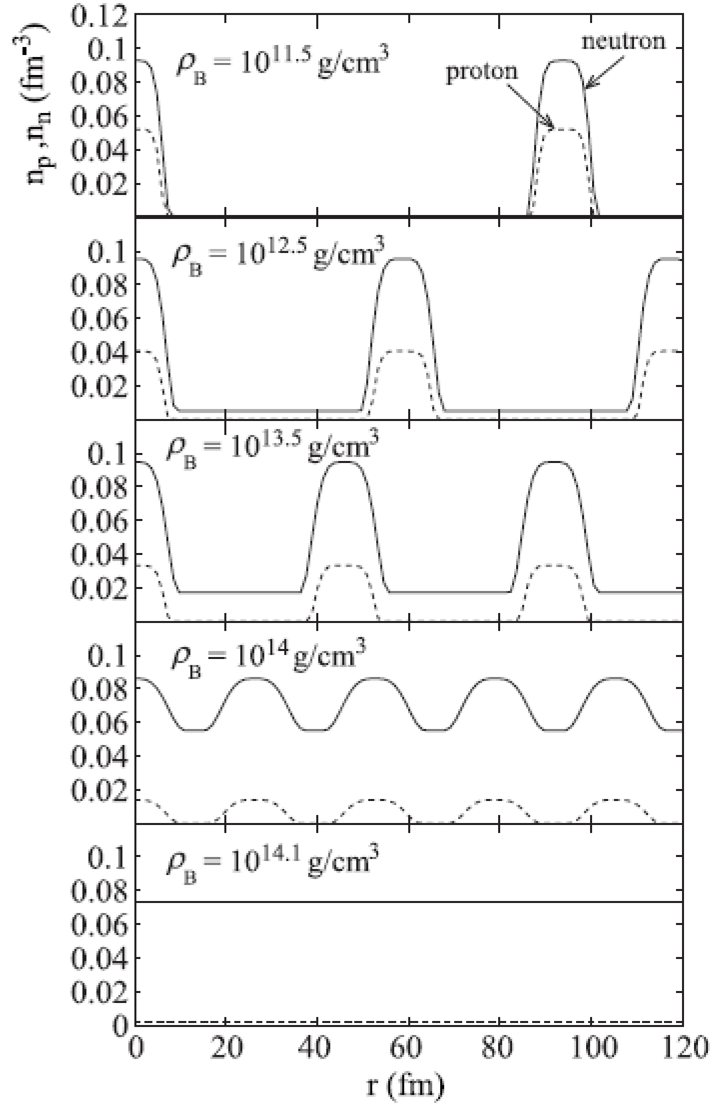


FIG. 3: The neutron distribution (solid) and proton distribution (dashed) along the straight line joining the centers of the nearest nuclei in the bcc lattice. The plots correspond, from top to bottom, to the cases at the baryon mass density $\rho_B = 10^{11.5}$, $10^{12.5}$, $10^{13.5}$, $10^{14.0}$ and $10^{14.1}$ g cm^{-3} ($n_B = 1.90 \times 10^{-4}$, 1.90×10^{-3}, 1.90×10^{-2}, 6.02×10^{-2}, 7.58×10^{-2} fm^{-3} in baryon number