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The Fayans functional.
New constraints from the equations of state.

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NUCLEAR EQUATION OF STATE

The nuclear EOS is of paramount importance for nuclear physics and nuclear astrophysics.

At ISOSPIN ASYMMETRY PARAMETER $\delta = (\rho_p - \rho_n) / \rho = 0$ ***symmetric nuclear matter (SNM)****, the EOS defines*

- *the global properties of atomic nuclei and nuclear saturation density -* ρ_0 *;*
- *the dipole polarizability, the giant dipole resonance energy, neutron skin* $R_{np} = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$*.*

At ISOSPIN ASYMMETRY $\rightarrow 1$ ***pure neutron matter*** *(PNM), the nuclear EOS determines the properties of neutron stars.*

THE SCOPE

*Fine tuning of the Fayans functional DF3-a by varying previously unused parameter **h_{-2}** of the isovector volume component of EDF.*

Constraints for fitting :

a) *keeping the fit quality (masses, εs.p, <Rch> …)*
b) *adding condition on max. of E1 resonance 208Pb.*

The aim:

- *To find an impact of h_{-2} on EOS of the SNM and PNM, as well as on S(ρ) , L (ρ).*
- *Would varying the $h-_{2-}$ allow one to meet the constraints on the EOS parameters ?*

$J=S(\rho_0)$, $L=L(\rho_0)$ and Rnp (neutron skin)

derived from nuclear masses, PREX-II experiments, "ab initio" χETF calculations

and astrophysical observations: NS radii, gravitational observations: LIGO, VIRGO, NICER e.t.c.

EOS for sub-nuclear matter, nuclei , symmetric nuclear matter (SNM), pure neutron matter (PNM) :

$$E(\rho_p + \rho_n ,\ \delta) / A$$

density dependence of total energy / per nucleon

$\rho = \rho_p + \rho_n$ – total barionic density, $\delta = (\rho_p - \rho_n) / \rho$ - *isospin asymmetry*

SNM ($\delta = 0$) → PNM ($\delta = 1$)

- *EOS can be constructed in empirical form (Weiszeker)*

or microscopically : e.g. from Energy -Density Functional or χEFT…

- *In micro-approach an equilibrium state of dense matter (if any) is found selfconsistently (for each density ρ) by minimization*

$$E(\rho_0)/A \rightarrow \min \{ \varepsilon (\rho, \delta)\}$$

For uniform system few useful EOS parametrization exist.
The simplest one is a quadratic expansion on δ^2 .

Valid at $\delta \ll 1$, $\rho < 2\rho$, ρ_0 = 0.164(7) fm-3 – equilibrium density

$$E(\rho,\delta)/A = E_{SNM}(\rho,0)/A + S(\rho)\delta^2 + \cdots$$

$$S(\rho) = \frac{1}{2}\frac{\partial^2 E(\rho,\delta)/A}{\partial\delta^2}\Big|_{\delta=0}$$

$$E_{sym}(\rho) = E(\rho,1)/N - E(\rho,0)/A$$

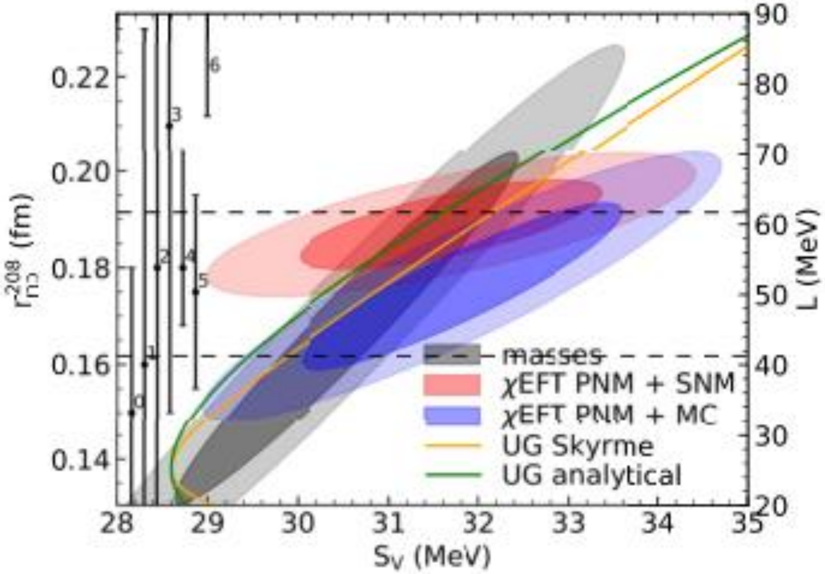
For comparing different EOS it is convinient to use the expansion parameters J, L near equilibrium density ρ_0

$J = S(\rho_0)$ - symmetry energy coefficient,

$L = 3\rho \frac{\partial}{\partial\rho} Esym(\rho)\,|_{\rho 0}$ - slope parameter ~ ΔRnp - neutron skin

J, L are derived from the nuclear properties and astrophisical measurements . An accuracy is still insufficient.

Constraints on J, L , ΔRnp: masses+EFT+ astro e.t.c.



L = 59 ± 16 MeV
ΔRnp (208Pb) = 0.19 ± 0.07fm

J.M. Lattimer, The Modern Physics of Compact Stars and Relativistic Gravity 2021 Yerevan, Armenia, Sep. 27 - 30, 2021

L = 106 ± 37 MeV ΔRnp (^{208} Pb) = 0.283 ± 0.071 fm

Parity violating (e,e') Jefferson Lab exp. PREX-II :

D.Adhikari et al. (PREX), Phys. Rev. Lett. 126, 172502 (2021).

Non-parametric EOS :

PREX-II, Heavy pulsar masses, LIGO/Virgo, NICER + χEFT(2021)

L = 49+14-15 MeV, ΔRnp(208) =0.17 ± 0.004 fm, J = 32.7+1.9-1.8

R.Essick , I. Tews , P. Landry , A. Schwenk Phys.Rev.Lett 127, 192701 (2021).

Volume part of the Fayans functional : DF3

$$\mathcal{E} = \frac{3}{5}\varepsilon_p(\rho_p)\rho_p + \frac{3}{5}\varepsilon_n(\rho_n)\rho_n +$$

$$+\frac{C_0}{4}\left[a_+ \frac{1-h_1^+(\rho/\rho_0)^\sigma}{1+h_2^+(\rho/\rho_0)^\sigma}\rho^2 + a_- \frac{1-h_1^-\rho/\rho_0}{1+h_2^-\rho/\rho_0}\rho^2\delta^2\right].$$

$$E_{sym}(\rho) = E(\rho,1)/N - E(\rho,0)/A = \varepsilon_{0\mathrm{F}}\left\{\frac{3}{5}\left(2^{2/3}-1\right)\left(\frac{\rho}{\rho_0}\right)^{2/3} + \frac{1}{3}a_- \frac{1-h_1^-(\rho/\rho_0)}{1+h_2^-(\rho/\rho_0)}\left(\frac{\rho}{\rho_0}\right)\right\}. \quad (7)$$

$a^{+,-}$ $h^{+,-}_{1,2}$, σ – iso-scalar (-vector) parameters of volume part of E/A

Previously, $h_{2,-} = h_{2,+}$ (reducing the number of parameters)

Now, $h_{2,-}$ released to be a free parameter.

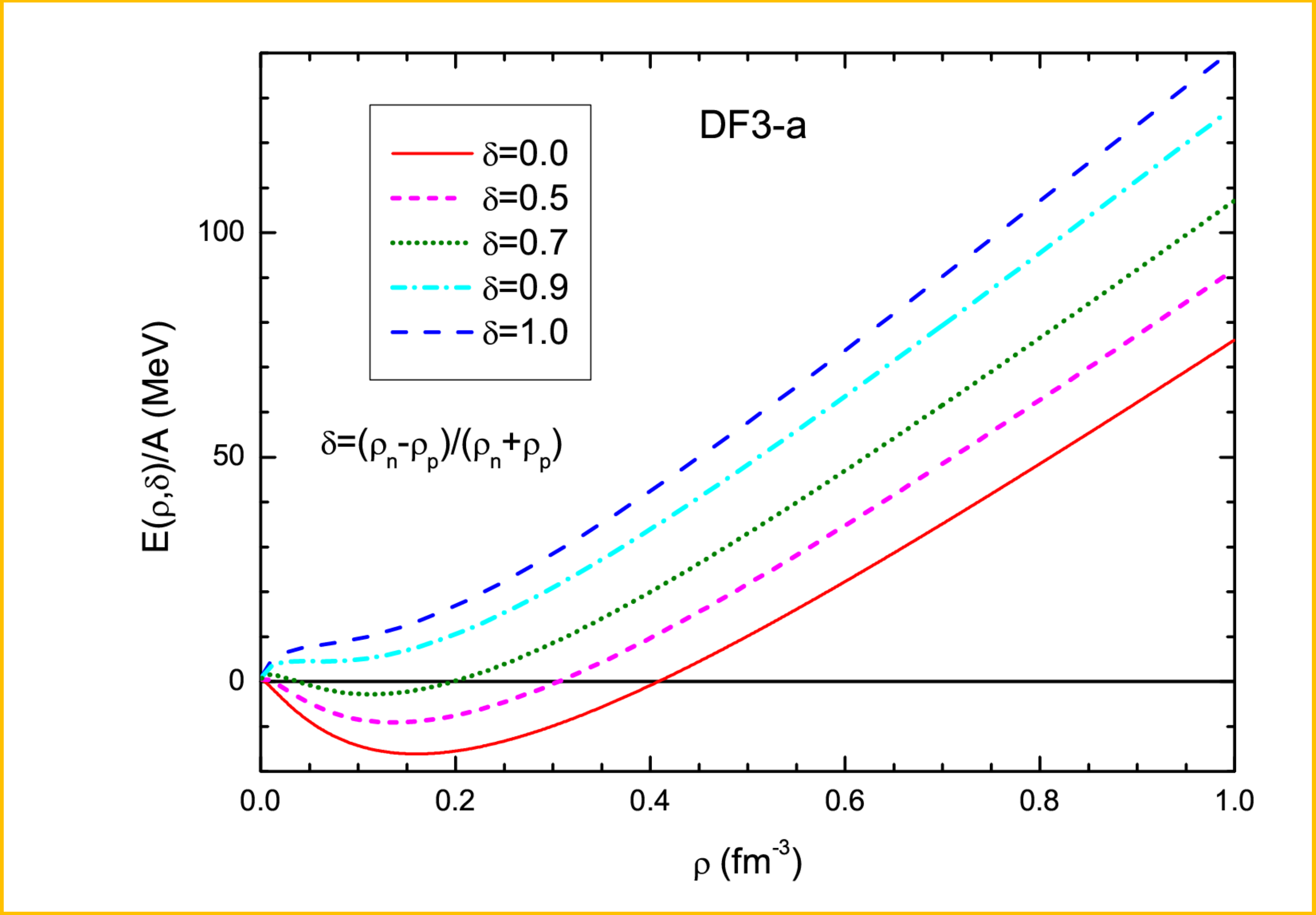
Are there $h_{2,-}$ consistent with :

- PREX-II EOS parameters:

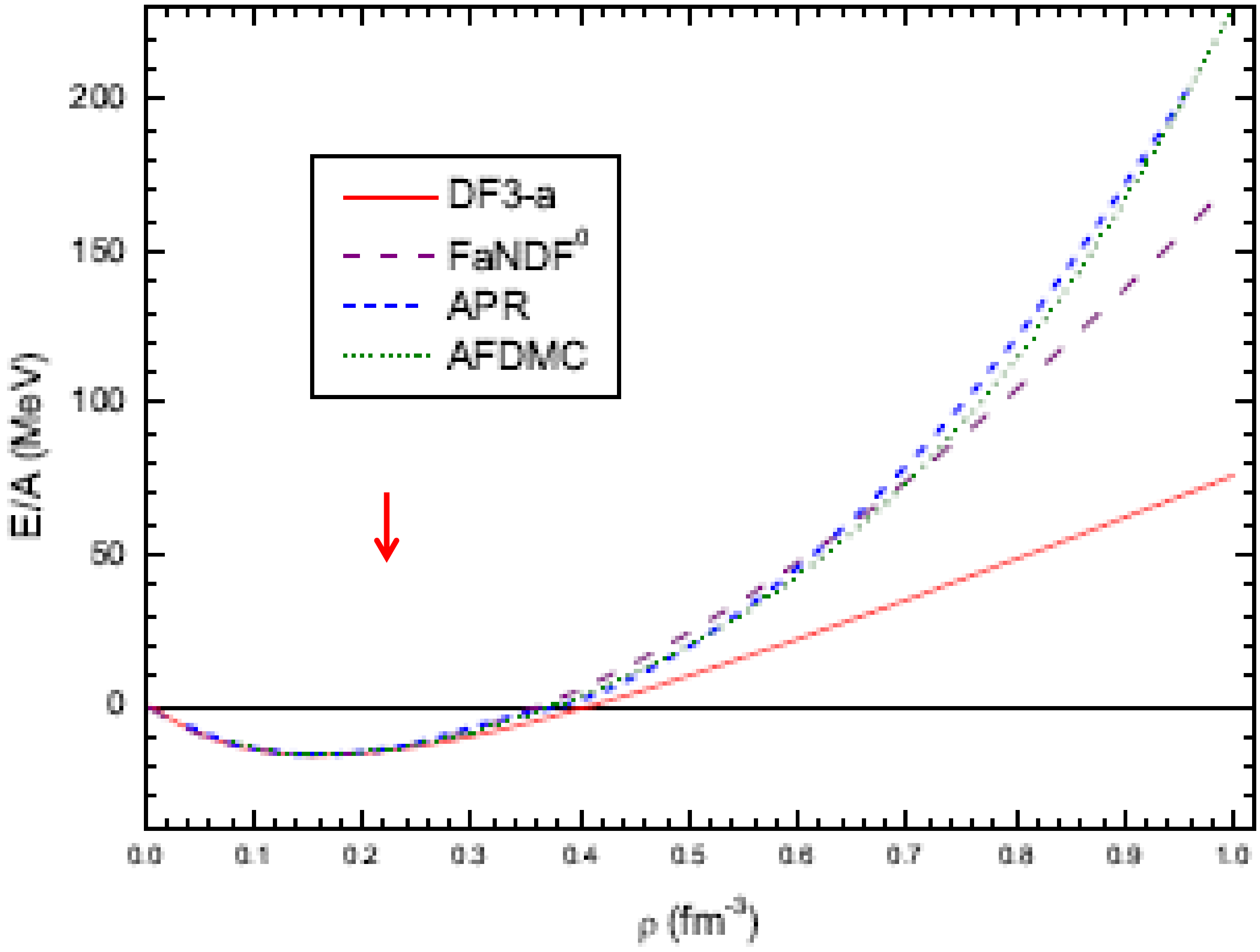
J, L = 106 ± 37 MeV and ΔRnp (208Pb PREX-II) = 0.283 ± 0.071 fm ?

- with additional condition on E1 GR max energy in 208Pb

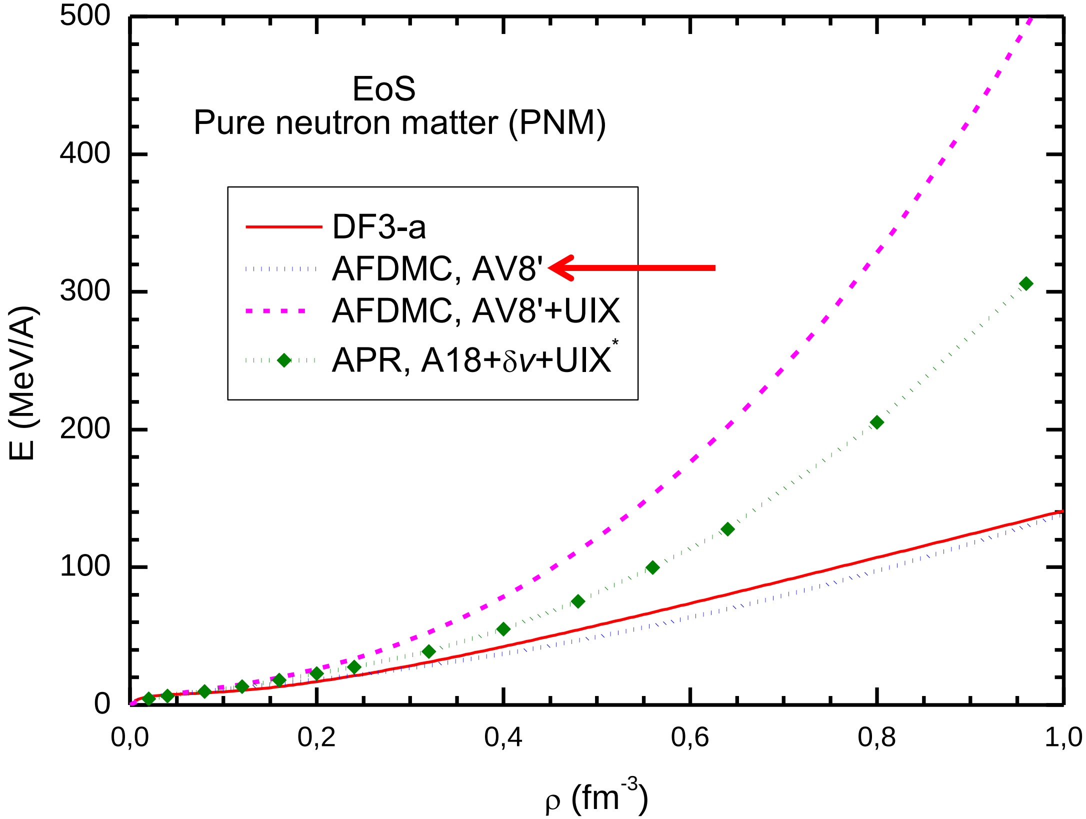
$E/A(\rho,\delta)$ Fayans functional : DF3-a



E/A(ρ)   Fayans functional : DF3-a

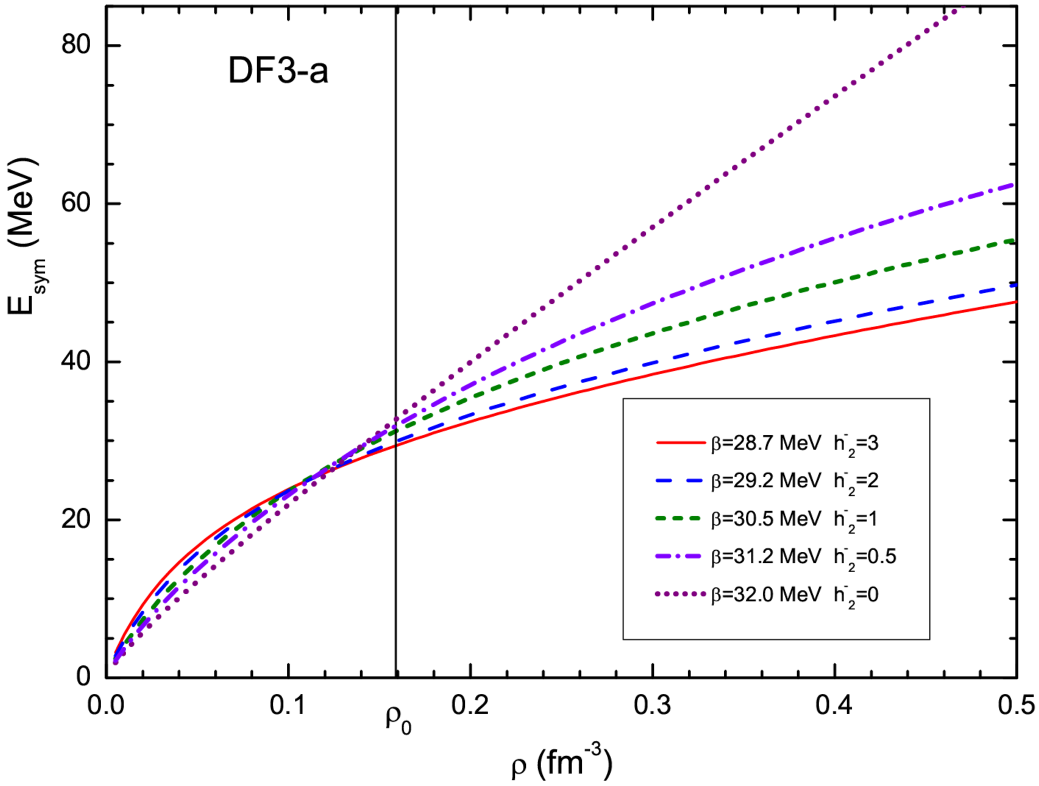


1. *Fayans S.A. JETP Letters 68 169 (1998)*
2. *Akmal, V. R. Pandharipande, and D. G. Ravenhall, Phys. Rev. C **58,** 1804 (1998).*
3. *D. Lonardoni, I. Tews, S. Gandolfi, and J. Carlson, arXiv:1912.09411 [nucl-th] (2019).*



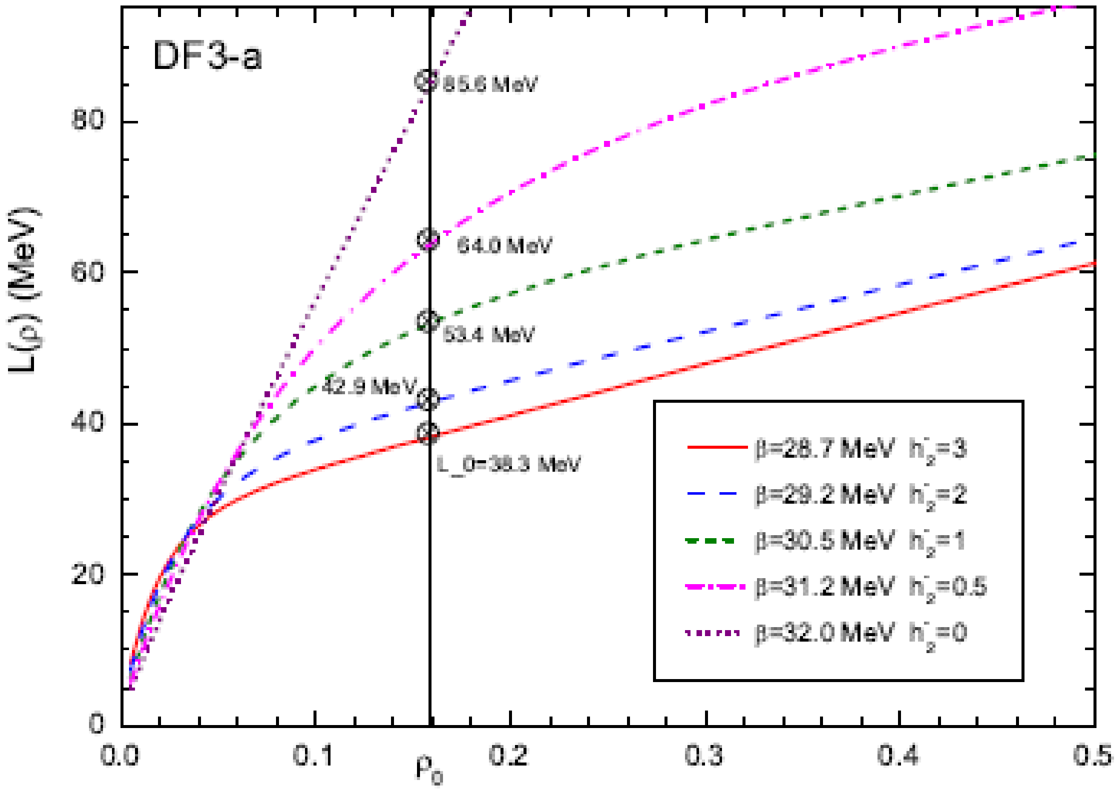
Akmal, V. R. Pandharipande, and D. G. Ravenhall, Phys. Rev. C ***58,*** *1804 (1998).*
S. Gandolfi, A. Yu. Illarionov, K. E. Schmidt, F. Pederiva, and S. Fantoni, Phys. Rev. C ***79***, *054005 (2009).*

Esym (ρ,h_2-)   Fayans functional : DF3-a



DF3-a: J=S(ρ_0) ~ 30.5 MeV   → irrespective to h_{2-}

Esym (ρ, h2-)   Fayans functional : DF3-a



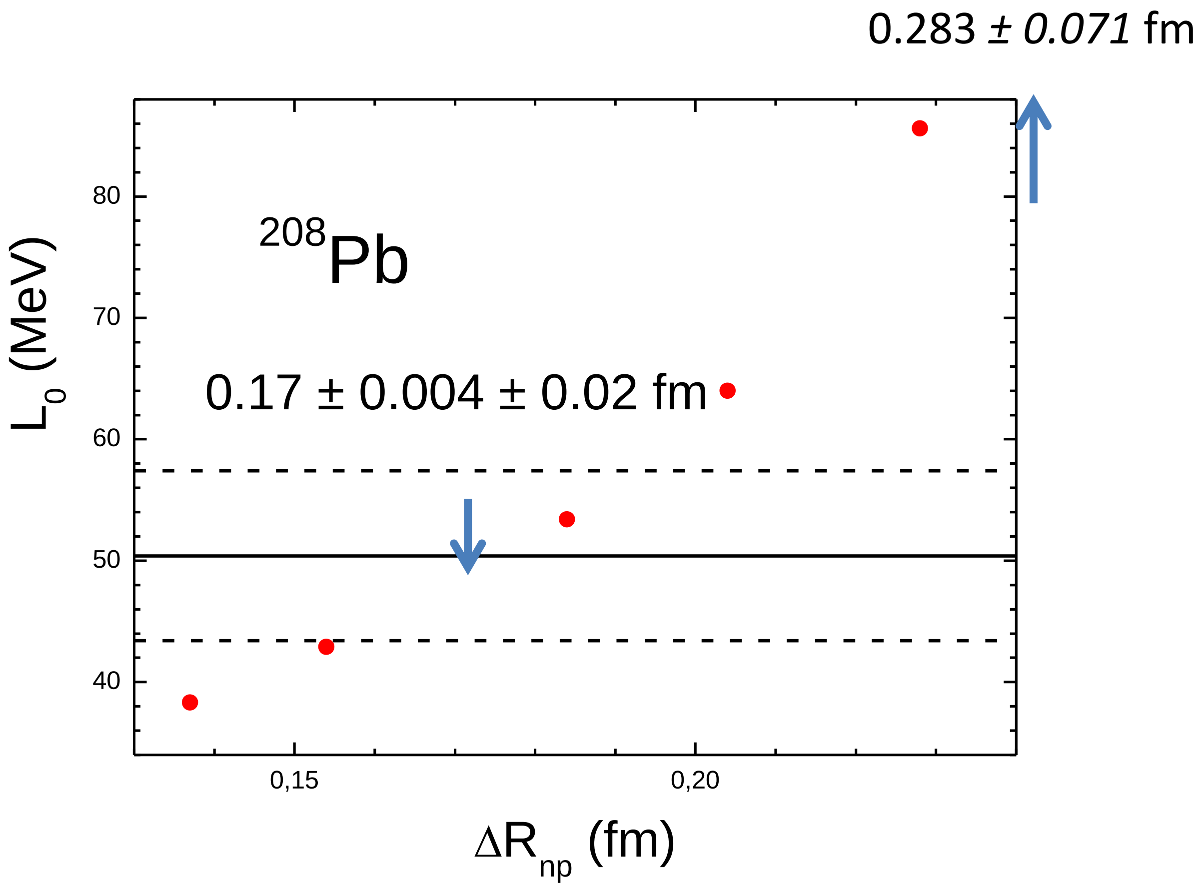
J = 32 ± 3 MeV   L =59 ± 16 MeV   → ***h = 0.5 -2.0***

S(ρ_0) =30.5 MeV , L(ρ_0) = L = 49+14-15 MeV   → ***h >0***

J. Lattimer in "Nuclear Matter Symmetry Energy From Experiment, Theory and Observation", S@INT 2021.

R.Essick , I. Tews , P. Landry , A. Schwenk Phys.Rev.Lett 127, 192701 (2021)

L (ρ, h2-)   Fayans functional : DF3-a



*ΔRnp (PREX I and II) = 0.283 ± 0.071 fm - **no match***

J = 32 ± 3 MeV   L =59 ± 16 MeV

ΔRnp (PREX+Astro+χETF) = 0.17 ± 0.004 ± 0.02 fm

*can be met at **2.0 > h_{2-} >0.5***

Impact of h_{2-} variation on ω_{GDR} and ΔRnp in 208Pb

Таблица I: Расчет с функционалом DF3 для различных значений параметра h_2^-.

$\omega_{GDR} = \sqrt{m_3/m_1}$, m_1, m_1 — первый и третий моменты силовой функции GDR.

h_2^-	β (MeV)	f_{in}^-	f_{ex}^-	f_{surf}^-	ω_{GDR} (^{208}Pb) (MeV)	$L(\rho_0)$ (MeV)	Δr_{np} (^{208}Pb) (fm)
0	32.0	0.808	0.808	0.808	12.80	85.6	0.228
0.5	31.2	0.775	1.163	0.969	13.37	64.0	0.204
1	30.5	0.747	1.494	1.115	13.73	53.4	0.184
2	29.2	0.694	2.080	1.387	14.11	42.9	0.154
3	28.7	0.673	2.693	1.687	14.41	38.3	0.137

~~*ΔRnp (PREX I and II) = 0.283 ± 0.071 fm*~~

ΔRnp (PREX+Astro+ETF) = 0.17 ± 0.004 fm

L= 49+14-15 MeV

as well as J = 32 ± 3 MeV L =59 ± 16 MeV

are met within ***h_{2}-~ 1.0 – 1.5***

Conclusions

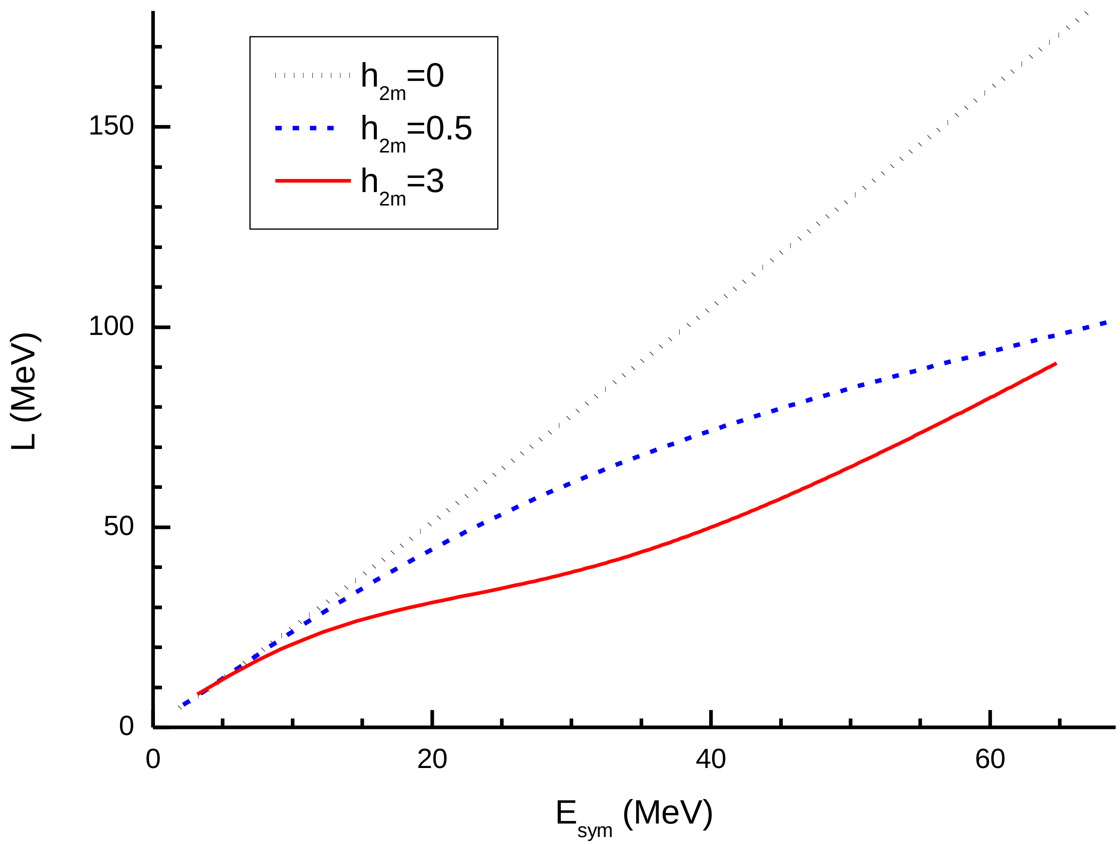
- *For the Fayans energy functional DF3-a, (previously unused) parameter of the isovector volume component h_{2-}^{-} is varied.*

- *Additional condition is set for the maximum energy of the giant dipole resonance. The quality of the DF 3-a fit to nuclear densities, nuclear masses, single-particle levels and charge radii has been preserved.*

- *The impact is studied of h_2^- parameter on the EOS of symmetric nuclear matter (SNM), pure neutron matter (PNM), and on the density dependence of symmetry energy S(p) and its derivative L(p).*

- *The value of the neutron skin ΔRnp (208Pb), found in the PREX I, II experiments, is not described simultaneously with the EOS SNM parameters: J =S(p0) and L(p0).*

- *EOS parameters {J, L, ΔRnp} by R.Essick at.al PHYS.REV.LETT.127, 192701 (2021) based on PREX-II + astrophysical constrains + chiral EFT calculations*
  can be described in DF3-a within fairly narrow range of the h_{-2} parameter.



h2m=0
h2m=0.5
h2m=3
L (MeV)
0
50
100
150
0
20
40
60
Esym (MeV)

EOS for DF3 functional

$$E(\rho,\delta)/A = \mathcal{E}(\rho_p,\rho_n)/\rho\,,$$

$$E(\rho,\delta)/A = \varepsilon_{0\mathrm{F}} \left\{ \frac{3}{10}\left(\frac{\rho}{\rho_0}\right)^{2/3} \left[(1-\delta)^{5/3} + (1+\delta)^{5/3}\right] + \right.$$

$$\left. + \frac{1}{3}a_+ \frac{1-h_1^+(\rho/\rho_0)^\sigma}{1+h_2^+(\rho/\rho_0)^\sigma}\left(\frac{\rho}{\rho_0}\right) + \frac{1}{3}a_- \frac{1-h_1^-(\rho/\rho_0)}{1+h_2^-(\rho/\rho_0)}\left(\frac{\rho}{\rho_0}\right)\delta^2 \right\}.$$

E O S : symmetric nuclear matter (SNM) - δ= $(\rho_p - \rho_n)/\rho = 0$

$$E_{SNM}(\rho)/A = E(\rho,0)/A = \varepsilon_{0\mathrm{F}} \left[\frac{3}{5}\left(\frac{\rho}{\rho_0}\right)^{2/3} + \frac{1}{3}a_+ \frac{1-h_1^+(\rho/\rho_0)^\sigma}{1+h_2^+(\rho/\rho_0)^\sigma}\left(\frac{\rho}{\rho_0}\right) \right].$$

E O S : pure neutron matter (PNM) - δ= $(\rho_p - \rho_n)/\rho = 1$

$$E_{PNM}(\rho)/N = E(\rho,1)/N = \varepsilon_{0\mathrm{F}} \left\{ \frac{3}{5}2^{2/3}\left(\frac{\rho}{\rho_0}\right)^{2/3} + \right.$$

$$\left. + \frac{1}{3}a_+ \frac{1-h_1^+(\rho/\rho_0)^\sigma}{1+h_2^+(\rho/\rho_0)^\sigma}\left(\frac{\rho}{\rho_0}\right) + \frac{1}{3}a_- \frac{1-h_1^-(\rho/\rho_0)}{1+h_2^-(\rho/\rho_0)}\left(\frac{\rho}{\rho_0}\right) \right\}$$

One-neutron separation energies 208Pb