Nuclear symmetry energy and neutron skin thickness

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Piaski, 17-09-2011

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- Mario Centelles
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Outline:

- Introduction

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- Symmetry energy in nuclear matter and finite nuclei

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- Neutron skin and its impact on symmetry energy

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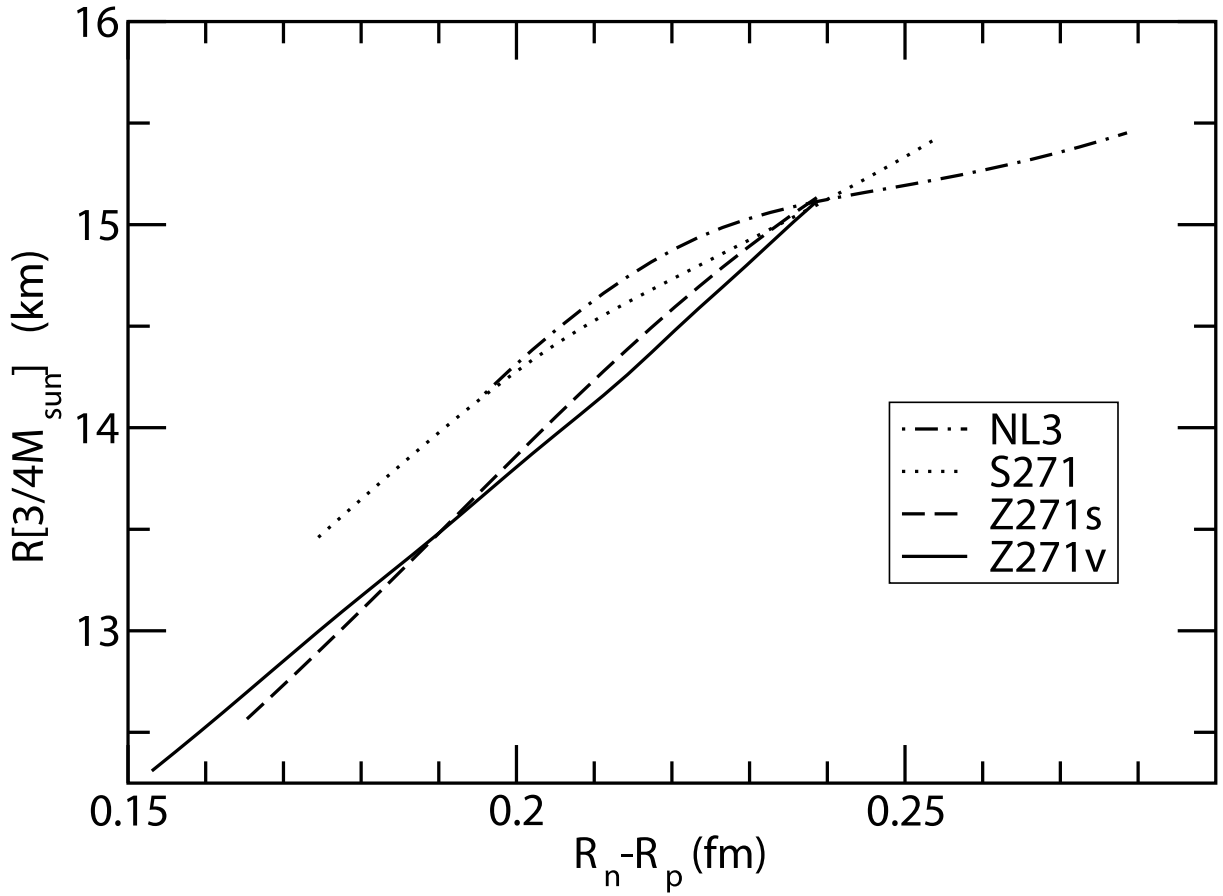
- Bulk and surface contributions to neutron skin
- PREX experiment
- Conclusions

Neutron star radius vs. neutron skin:



J. Carriere, C. J. Horowitz and J. Piekarewicz, Astr. J. 593 (2003) 463.

Implementations of nuclear symmetry energy

- Nuclear physics

  binding energy, drip lines, density distributions, neutron skin, giant resonances, HIC, isospin diffusion, multifragmentation

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Implementations of nuclear symmetry energy

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- Interdisciplinary areas

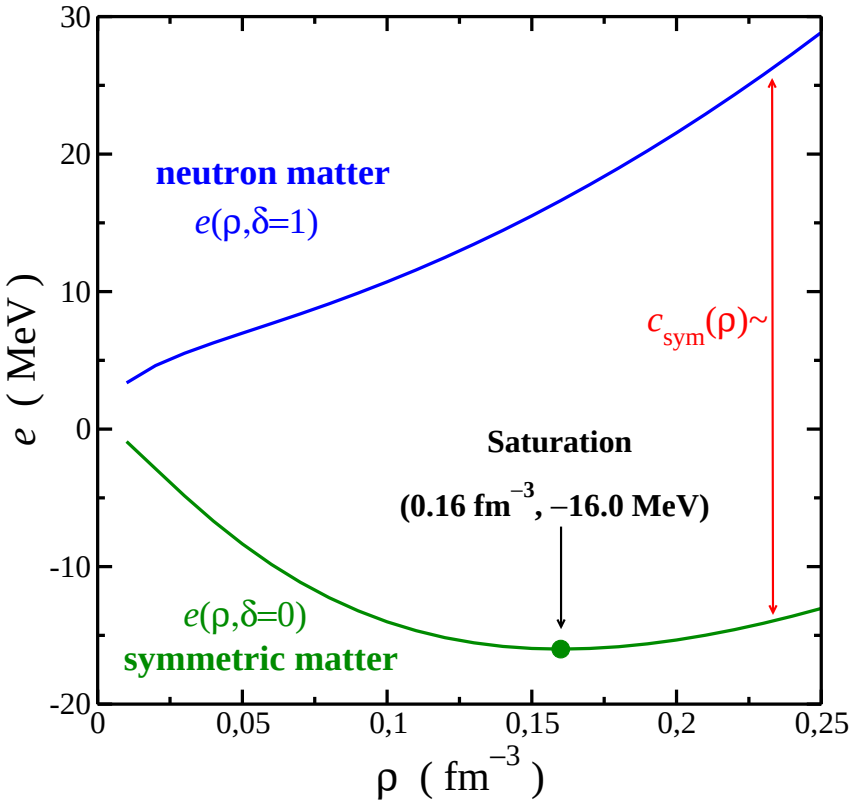
  parity non-conservation experiments

Symmetry energy of infinite nuclear matter

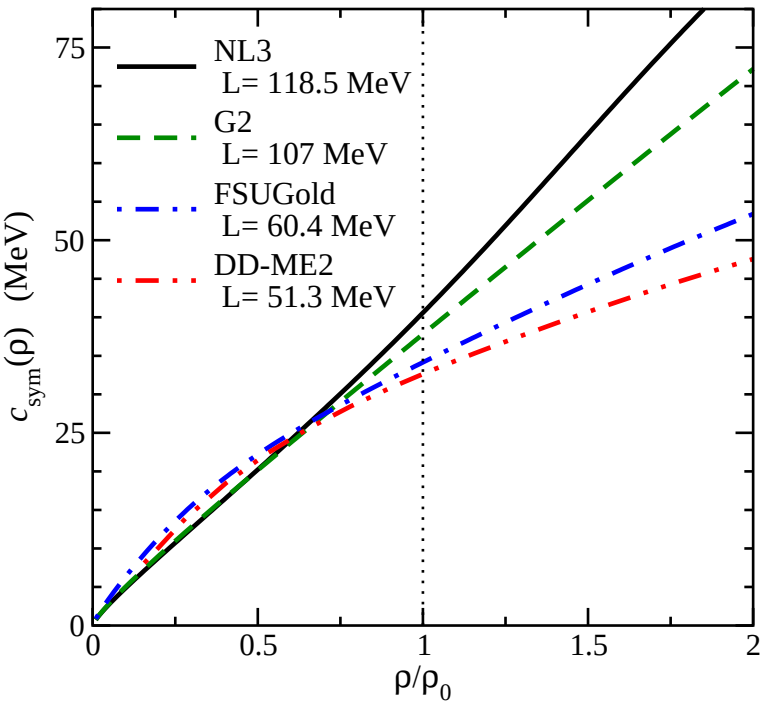
$$e(\rho,\delta) \approx e(\rho,\delta=0) + c_{sym}(\rho)\delta^2$$

$$c_{sym}(\rho) = J - L\epsilon + \frac{K_{sym}}{2}\epsilon^2 + O(\epsilon^3)$$

$$\delta = (\rho_n - \rho_p)/\rho$$
$$\epsilon = (\rho_0 - \rho)/3\rho_0$$



$$e_{sym}(\rho) = J - L\epsilon + \frac{K_{sym}}{2}\epsilon^2 + O(\epsilon^3)$$



Large L – stiff symmetry energy

Small L – soft symmetry energy

Symmetry energy at saturation

$J = e_{sym}(\rho_0) \approx 32$ MeV

Slope of symmetry energy

$$L = 3\rho_0 \left.\frac{\partial e_{sym}(\rho)}{\partial \rho}\right|_{\rho_0}$$

Curvature of symmetry energy

$$K_{sym} = 9\rho_0^2 \left.\frac{\partial^2 e_{sym}(\rho)}{\partial \rho^2}\right|_{\rho_0}$$

Symmetry energy in finite nuclei

$$E = E_{vol} + E_{surf} + E_{Coul} + E_{sym} + E_{pair}$$

$$E_{sym} = a_{sym}(A)(I - x_A I_C)^2 A \approx a_{sym} I^2 A$$

$$I = \frac{N-Z}{A} \qquad I_C = \frac{e^2 Z}{20 J r_0 A^{1/3}} \qquad x_A = \frac{9J}{4Q} A^{-1/3}$$

$$a_{sym}(A) = \frac{J}{1 + x_A}$$

Q - surface stiffness coefficient

W. D. Myers and W. J. Świątecki,

Ann. of Phys. (N.Y.) **55**, 395 (1969); Ann. of Phys. (N.Y.) **84**, 186 (1974)

How nuclear matter symmetry energy $c_{sym}(\rho)$
and symmetry energy in finite nuclei $a_{sym}(A)$ are related?

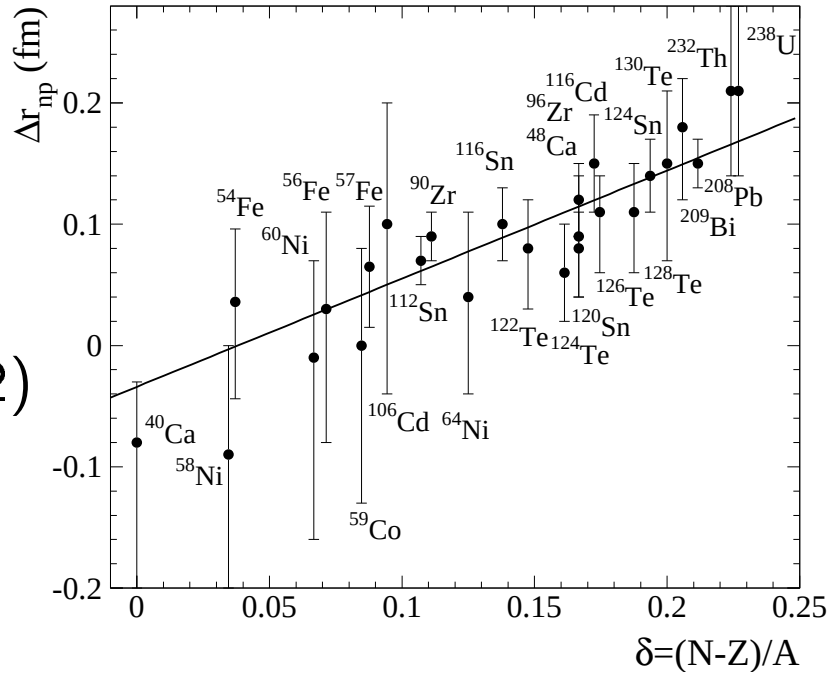
What can we learn about nuclear matter symmetry energy
from nuclear structure?

Neutron skin thickness:

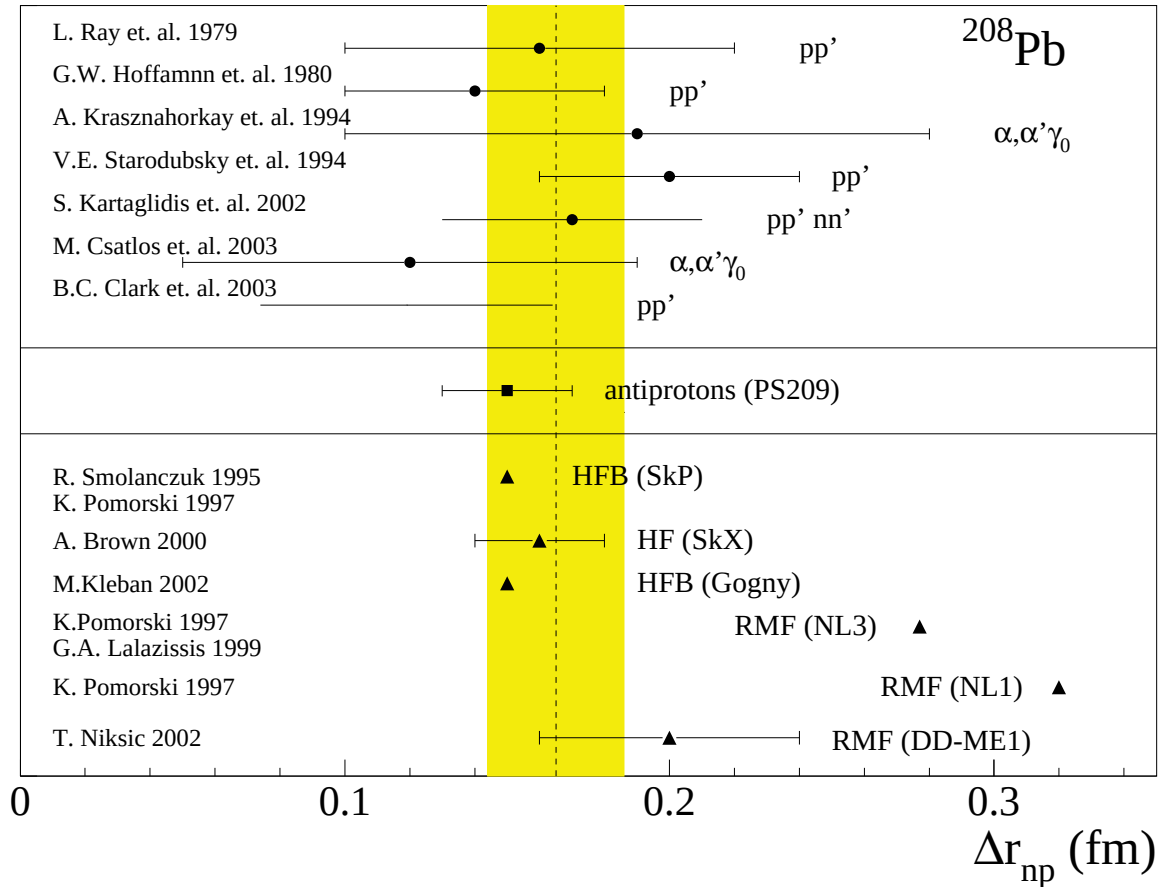
$$\Delta r_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}$$

$$\Delta R_{np} = (0.90 \pm 0.15) I + (-0.03 \pm 0.02)$$

Jastrzebski et al. Int. J. Mod. Phys. **E13**, 343 (2004).



Neutron skin thickness in ^{208}Pb:



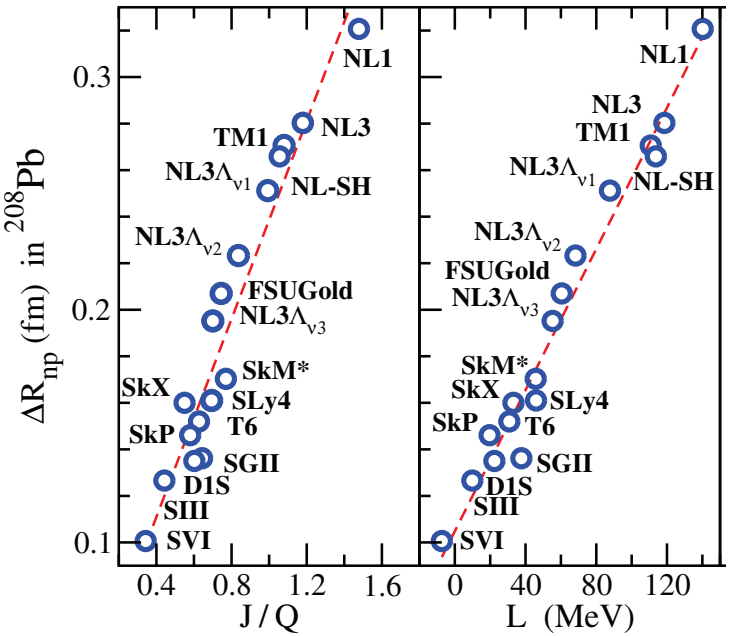
Jastrzbski et al. Int. J. Mod. Phys. **E13**, 343 (2004).

Droplet model:

$$\Delta R_{np} = \sqrt{\frac{3}{5}}\left[t - \frac{e^2 Z}{70J} + \frac{5}{2R}\left(b_n^2 - b_p^2\right)\right]$$

$$t = \frac{3}{2} r_0 \frac{J}{Q} \frac{I - I_C}{1 + x_A}$$

$$t = \frac{2r_0}{3J}\left[J - a_{\mathrm{sym}}(A)\right] A^{1/3}\left(I - I_C\right)$$



W. D. Myers and W. J. Świątecki,
Ann. of Phys. (N.Y.) 55, 395 (1969); Ann. of Phys. (N.Y.) 84, 186 (1974)

Brown PRL85, 5296; Brown, Typel PRC64, 027302

		$A = 208$		$A = 116$		$A = 40$	
Model	J	a_{sym}	ρ	a_{sym}	ρ	a_{sym}	ρ
NL3	37.4	25.8	0.103	24.2	0.096	21.1	0.083
NL-SH	36.1	25.8	0.105	24.6	0.099	21.3	0.086
FSUGold	32.6	25.4	0.098	24.2	0.090	21.9	0.075
TF - MS	32.6	24.2	0.093	22.9	0.085	20.3	0.068
SLy4	32.0	25.3	0.100	24.2	0.091	22.0	0.075
SkX	31.1	25.7	0.102	24.8	0.096	22.8	0.082
SkM*	30.0	23.2	0.101	22.0	0.093	19.9	0.078
SIII	28.2	24.1	0.093	23.4	0.088	21.8	0.077
SGII	26.8	21.6	0.104	20.7	0.096	18.9	0.082
AVERAGE			0.1		0.93		0.8

$$c_{sym}(\rho) = a_{sym}(A)$$

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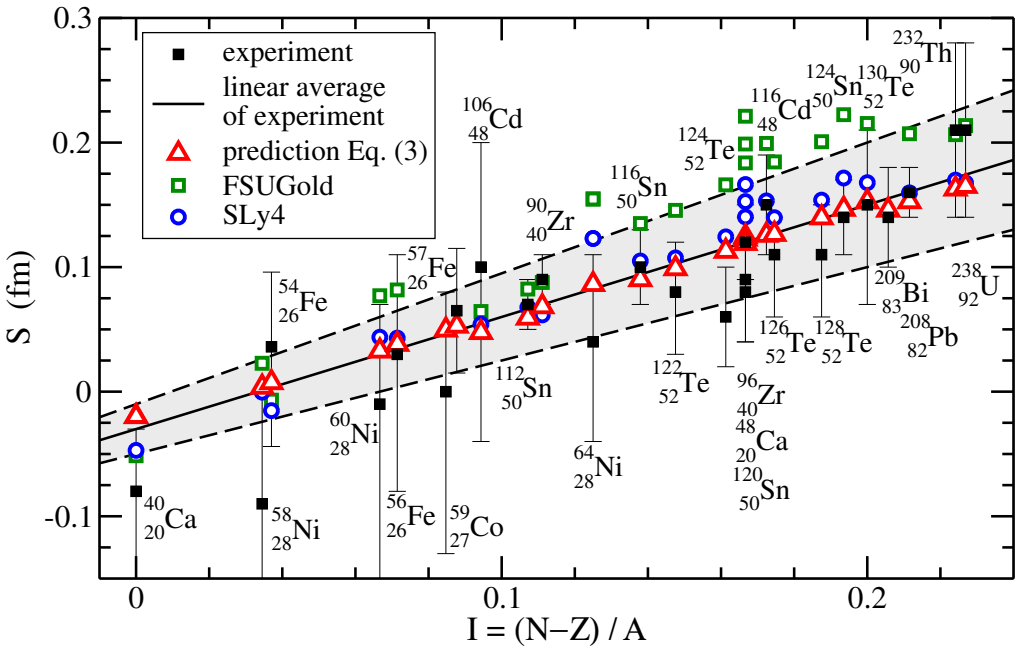
$$\rho_A = \rho_0 - \frac{\rho_0}{1 + cA^{1/3}}$$

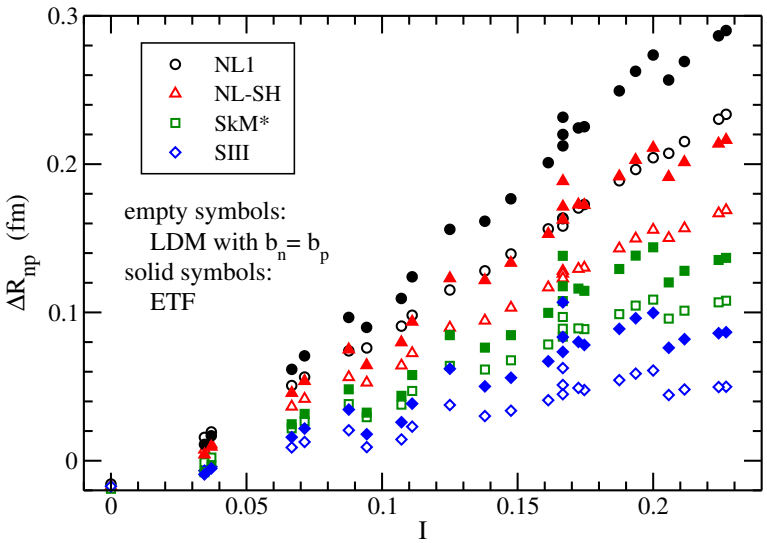
$$t = \frac{2r_0}{3J} L \left(1 - \epsilon \frac{K_{sym}}{2L}\right) \epsilon A^{1/3} (I - I_C).$$



$L = 75 \pm 25$ MeV – soft symmetry energy

Impact of surface distribution on neutron skin thickness

$$\Delta R_{np}^{sw} = \sqrt{\frac{3}{5}} \frac{5}{2R} (b_n^2 - b_p^2)$$



ETF – full symbols

LDM – empty symbols

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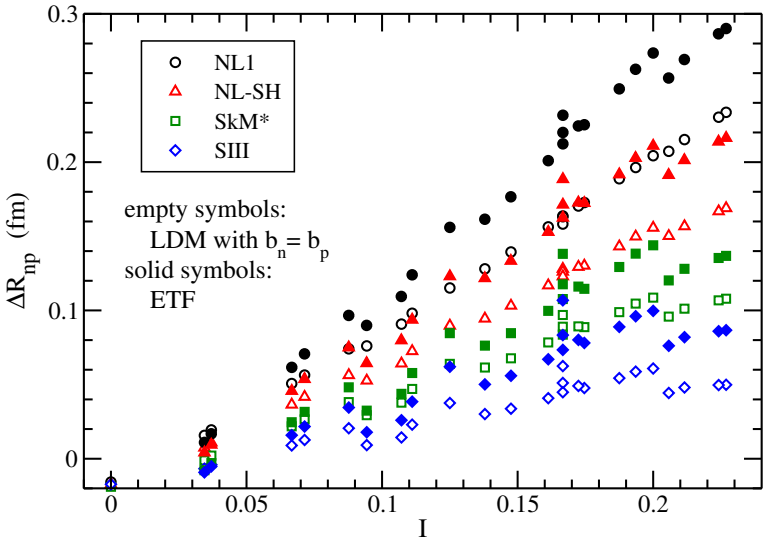
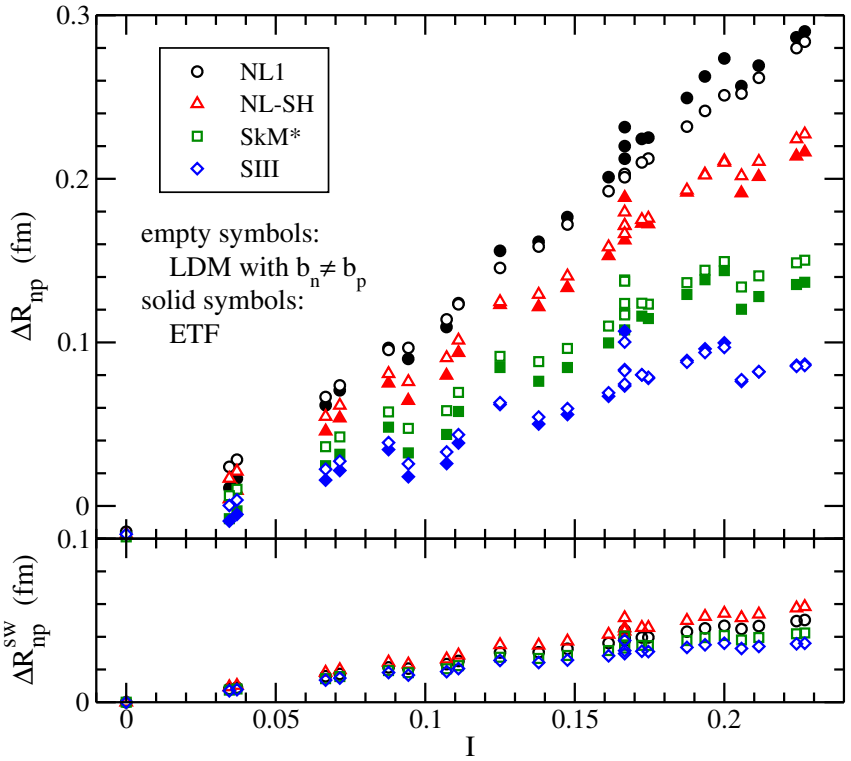




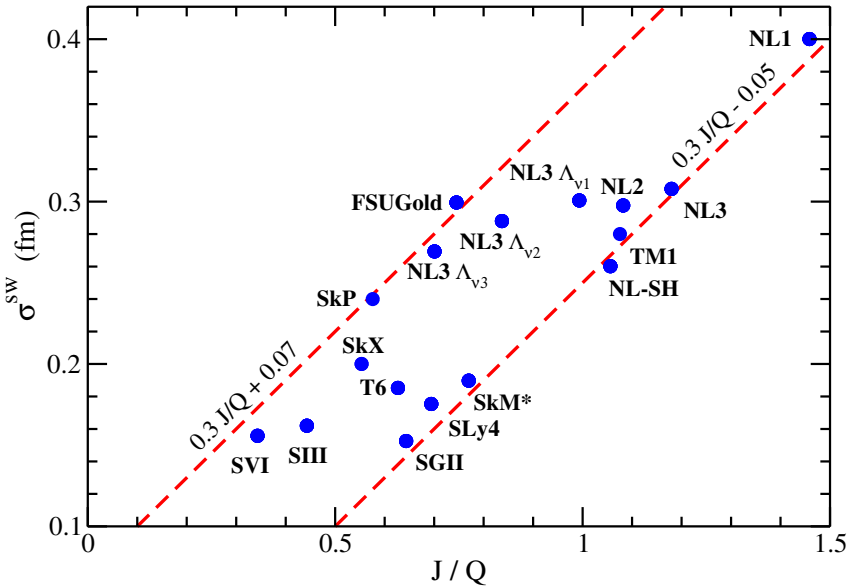
ETF – full symbols

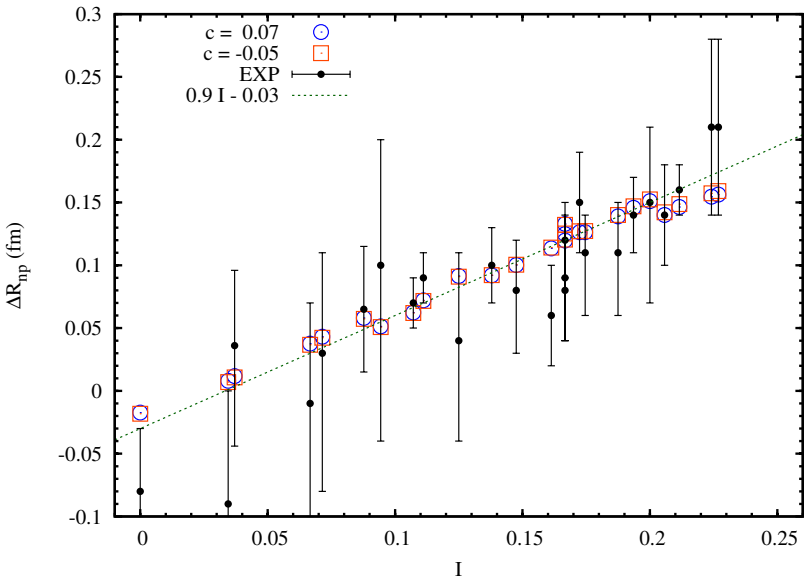
LDM – empty symbols

Slope of surface contribution:

$\sigma^{sw} = 0.3J/Q - 0.05$ fm

$\sigma^{sw} = 0.3J/Q + 0.07$ fm

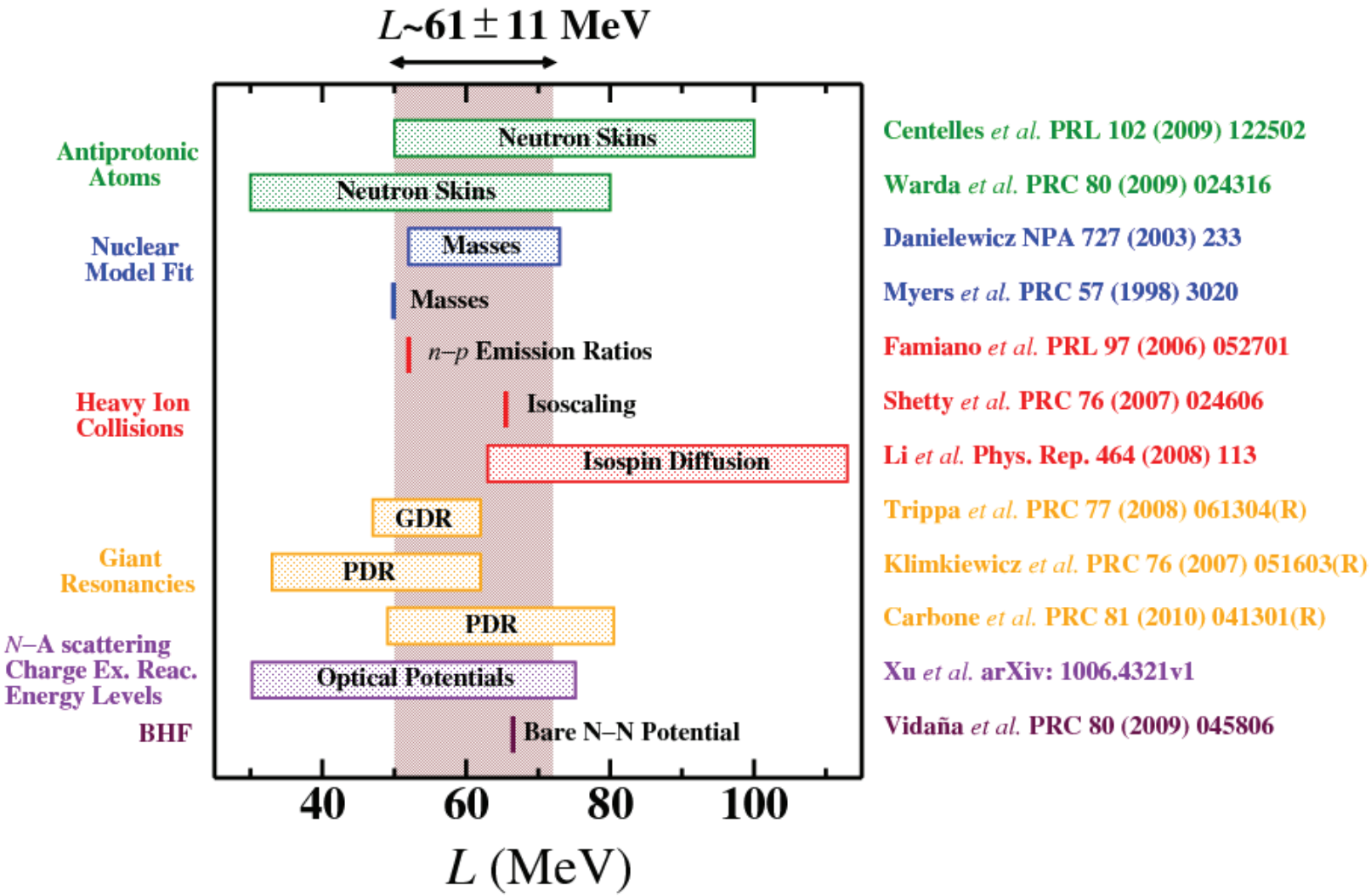




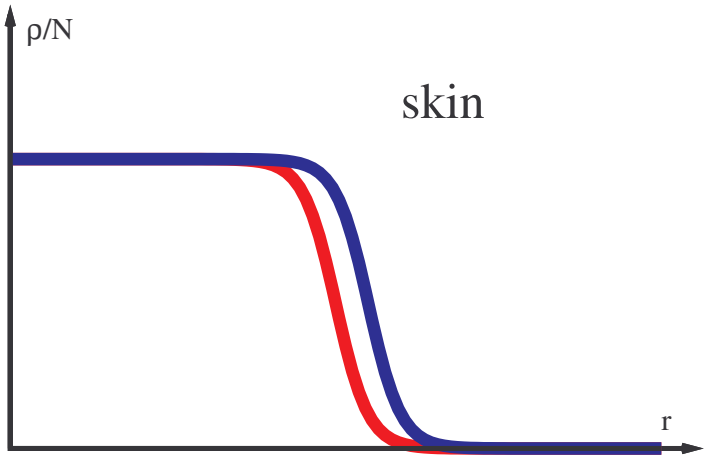
$$\Delta R_{np} = \sqrt{\frac{3}{5}}\left(t - \frac{e^2 Z}{70J}\right) + \left(0.3\frac{J}{Q} + c\right) I$$

$$L = 55 \pm 25 \text{ MeV}$$

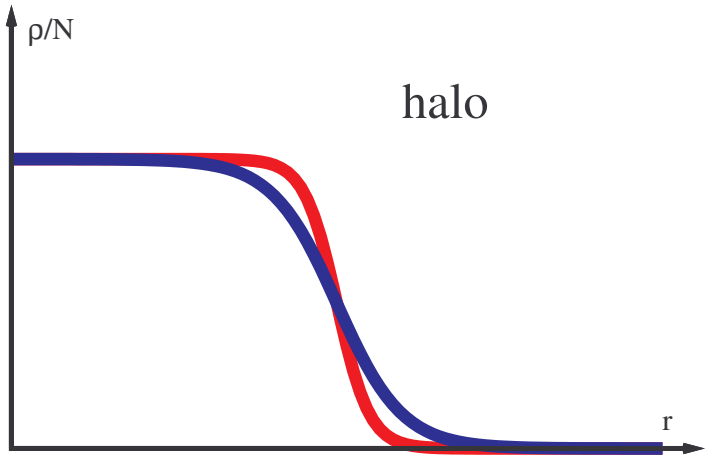
Recent constraints on the slope of the symmetry energy:



Origin of neutron skin



$a_n = a_p$



$C_n = C_p$

2-parameter Fermi density profile

$$\rho(r) = \frac{\rho_0}{1 + \exp\left[(r - C)/a\right]}$$

Which radius describes properly bulk properties?

Central radius C

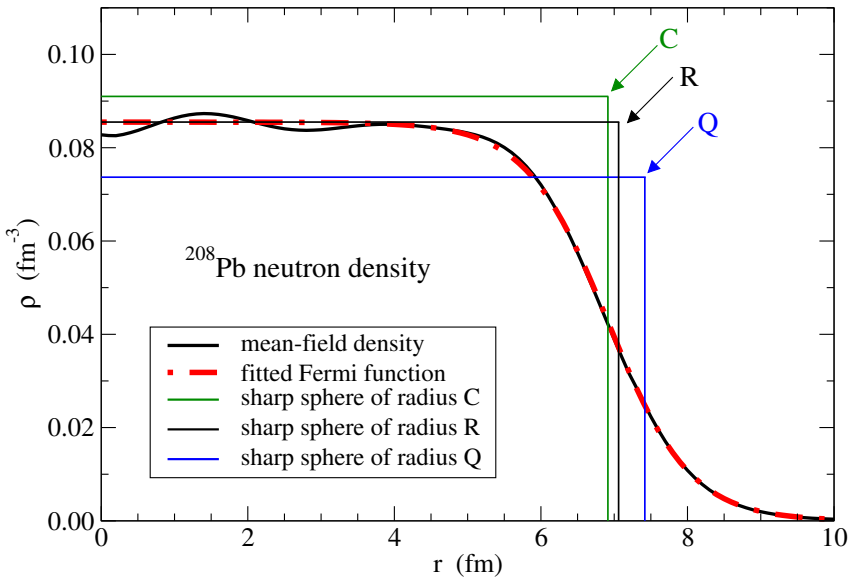
$$C = \frac{1}{\rho(0)} \int_0^\infty \rho(r) dr$$

Equivalent sharp radius R

$$\frac{4}{3}\pi R^3 \rho(\mathrm{bulk}) = 4\pi \int_0^\infty \rho(r) r^2 dr$$

Equivalent rms radius Q

$$\frac{3}{5} Q^2 = \langle r^2 \rangle$$



R. W. Hasse and W. D. Myers, *Geometrical relationships of macroscopic nuclear physics*

Bulk and surface contributions to neutron skin thickness

$$\Delta r_{np} = \sqrt{\frac{3}{5}}\,(Q_n - Q_p)$$

Bulk contribution

Consequence of difference in equivalent sharp radii R_n and R_p

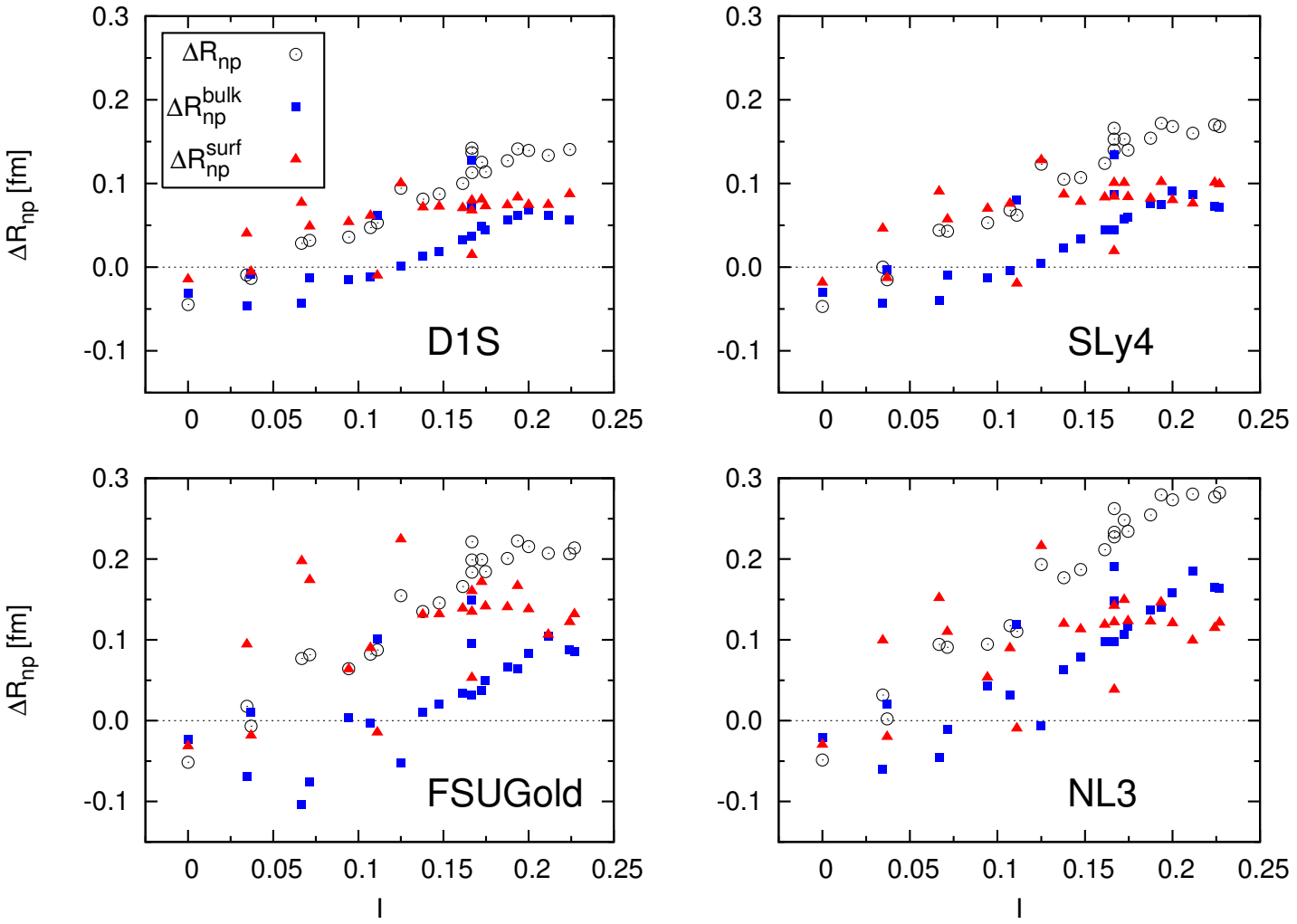
$$\Delta r_{np}^{\mathrm{bulk}} = \sqrt{\frac{3}{5}}\,(R_n - R_p) = \sqrt{\frac{3}{5}}\left[(C_n - C_p) + \frac{\pi^2}{3}\left(\frac{a_n^2}{C_n} - \frac{a_p^2}{C_p}\right)\right]$$

Surface contribution - all the rest

$$\Delta r_{np}^{\mathrm{surf}} = \Delta r_{np} - \Delta r_{np}^{\mathrm{bulk}}$$

$$\Delta r_{np}^{\mathrm{surf}} = \sqrt{\frac{3}{5}}\,\frac{5}{2}\left(\frac{b_n^2}{R_n} - \frac{b_p^2}{R_p}\right) = \sqrt{\frac{3}{5}}\,\frac{5\pi^2}{6}\left(\frac{a_n^2}{C_n} - \frac{a_p^2}{C_p}\right)$$

Bulk and surface contributions to neutron skin thickness



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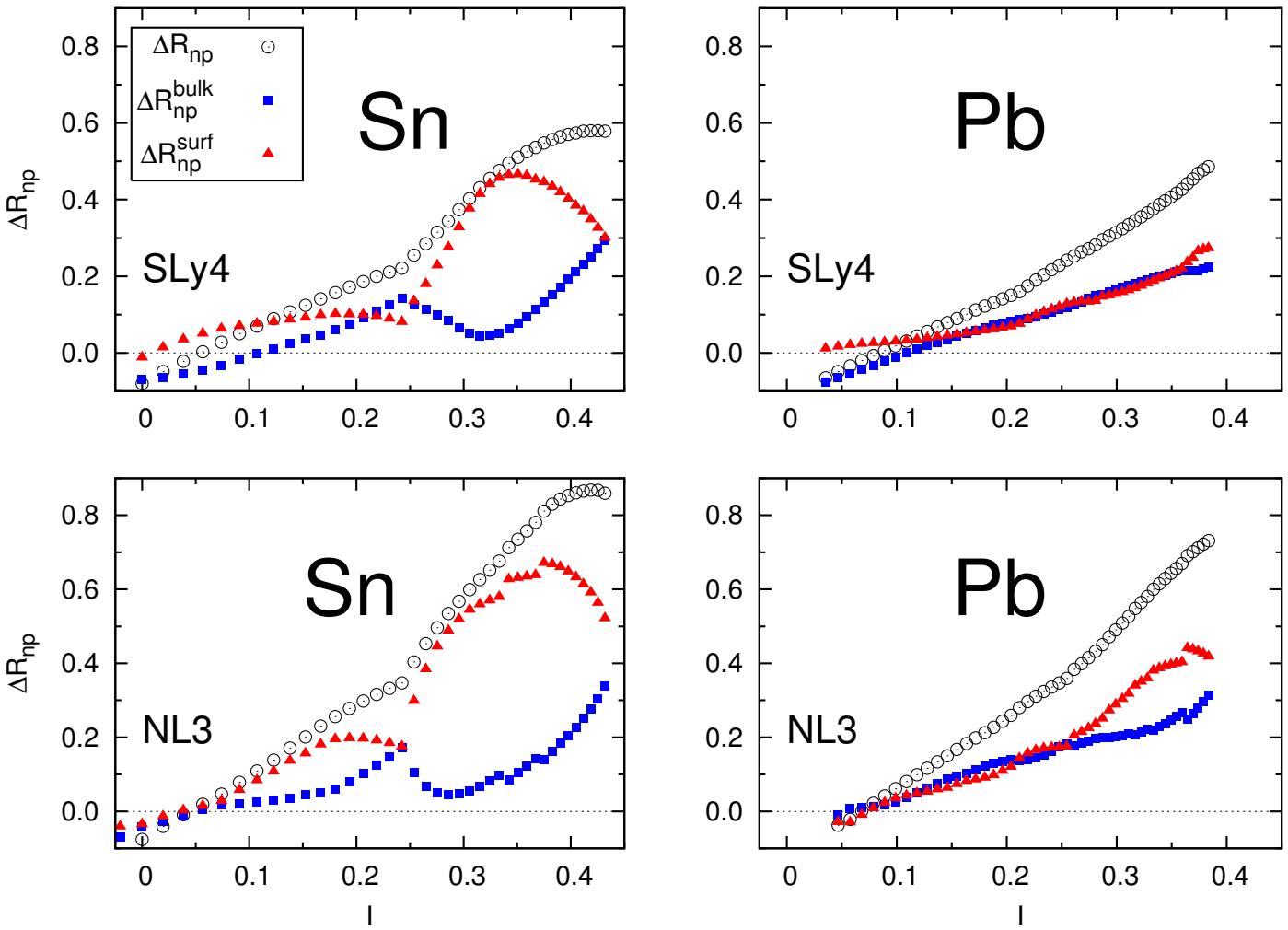
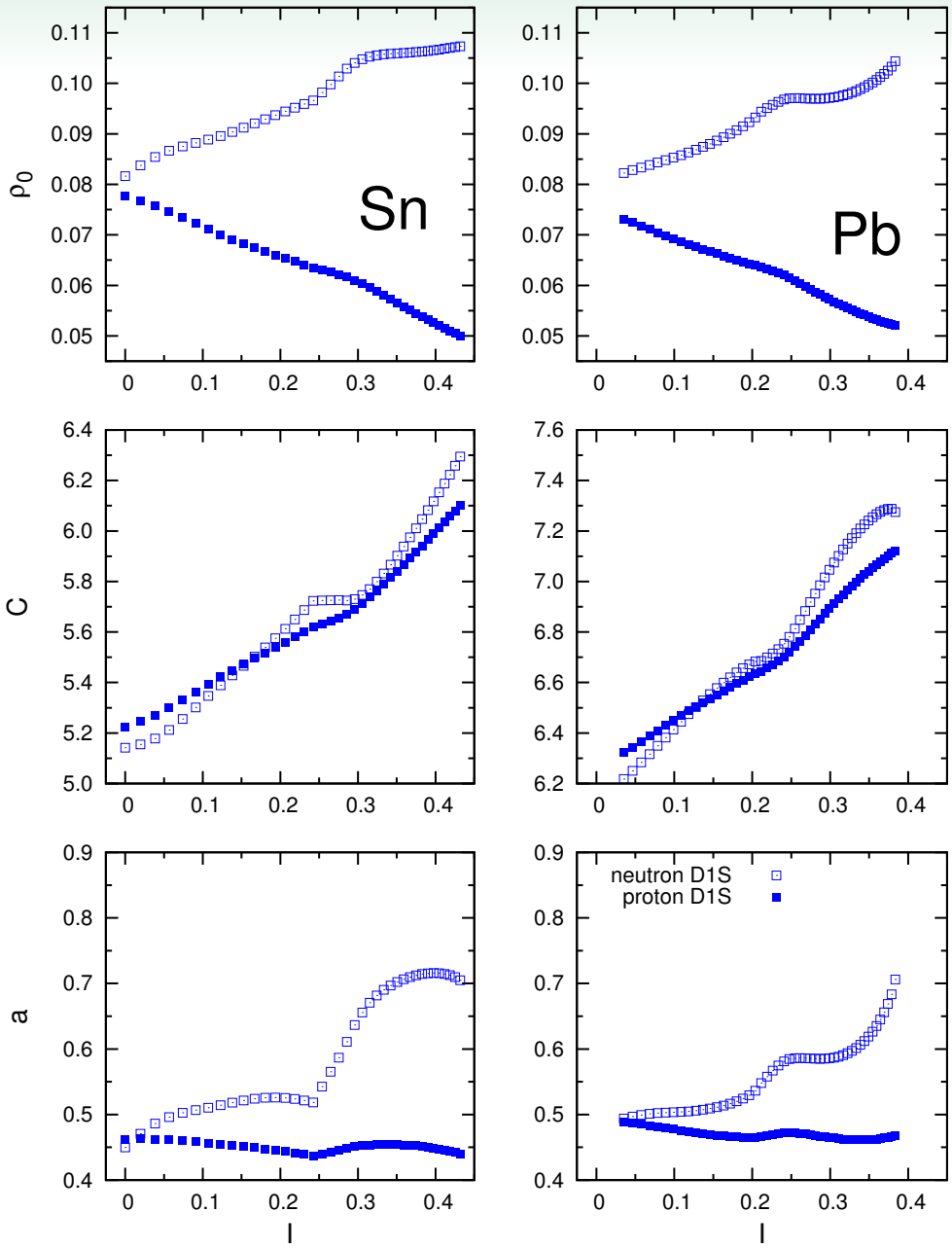
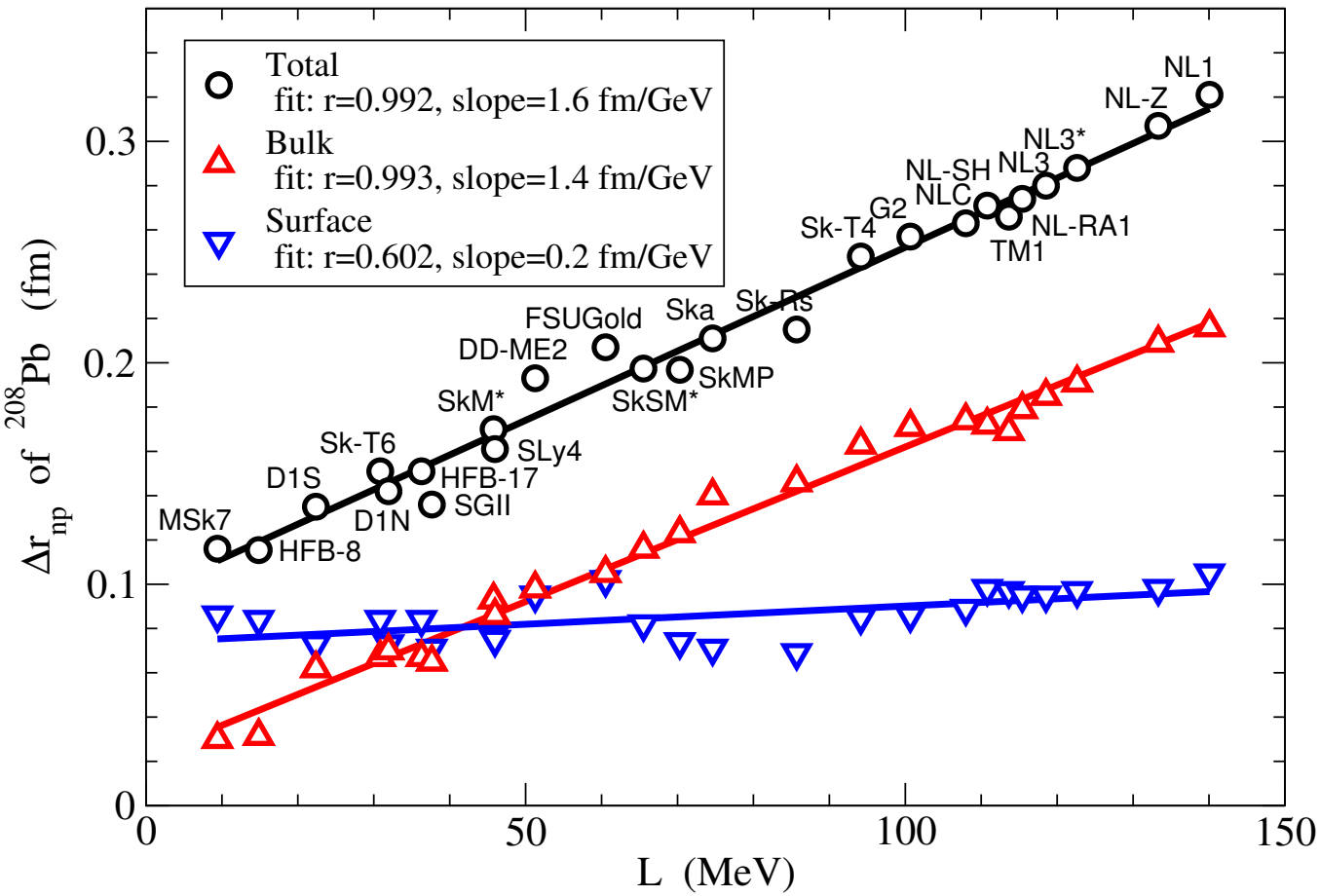



Sn
Pb
neutron D1S
proton D1S
ρ0
C
a
I
I

Bulk and surface contributions to neutron skin thickness in ^{208}Pb



PREX – Pb Radius Experiment @ Jefferson Lab

Parity Violating Electron Scattering on ^{208}Pb

Polarized electrons interact with a nucleus through electromagnetic field (γ - with protons) and weak field (Z_0 bozon - mainly with neutrons)

Asymmetry of left-handed and right-handed electrons is measured

Asymmetry is of the order of one particle per million

PREX @ JLab:
$E = 1.06$ GeV, $\theta = 5\,\mathrm{deg}$, $q_{lab} = 0.47$ fm^{-1}

http://hallaweb.jlab.org/parity/prex/

Horovitz et al. Phys. Rev. C63, 025501 (2001)

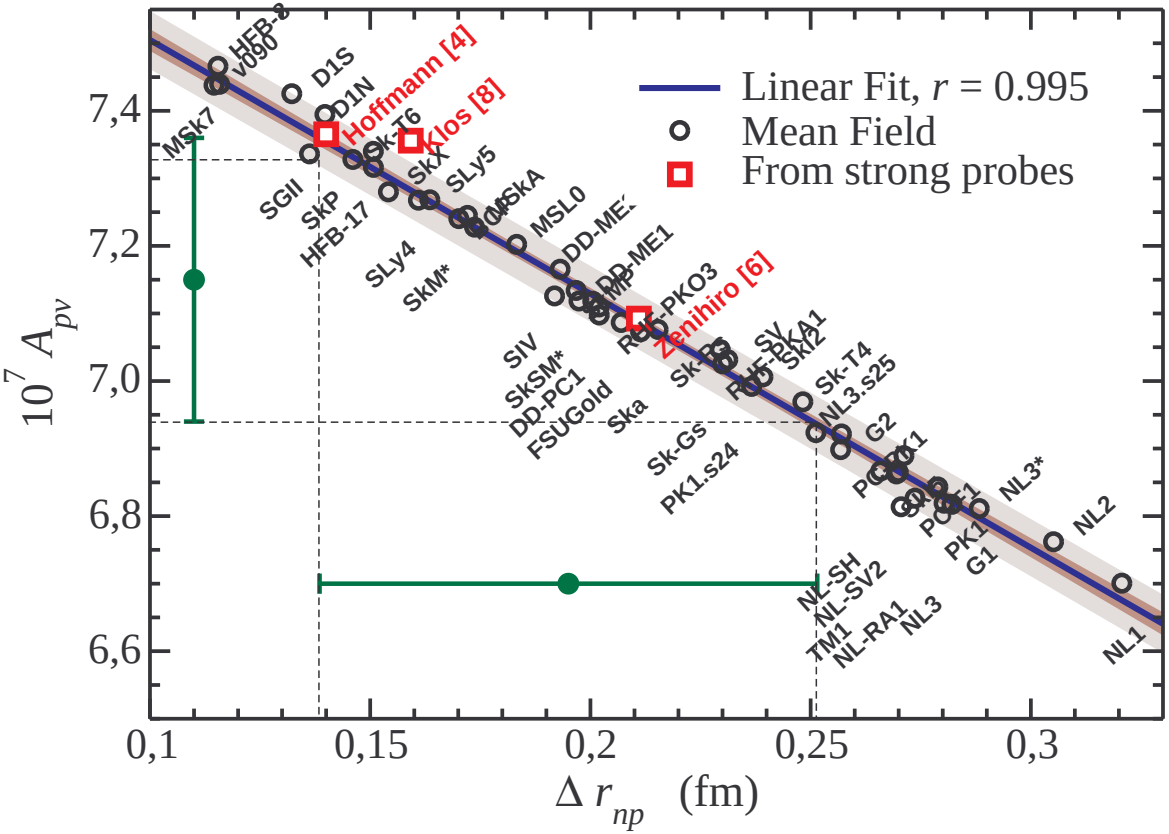
PREX – Pb Radius Experiment @ Jefferson Lab

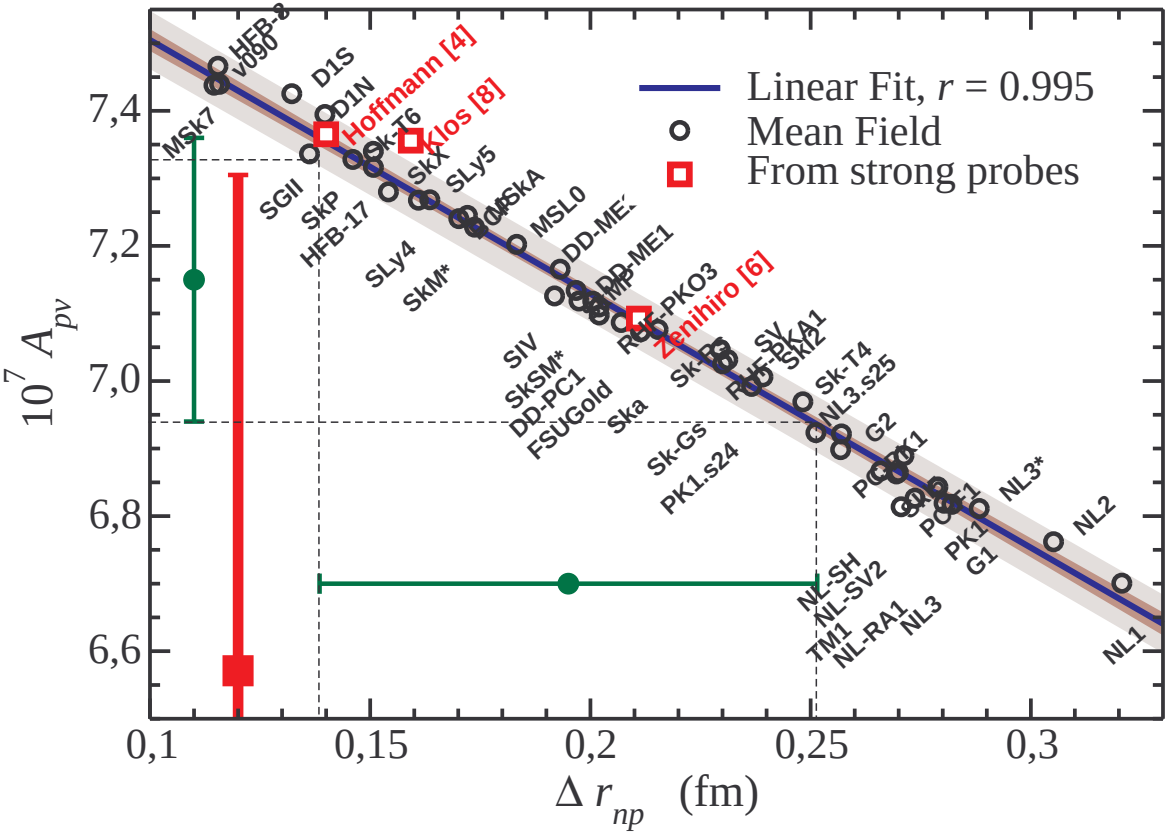
$$V_{\pm}(r) = V_{\mathrm{Coulomb}}(r) \pm V_{\mathrm{weak}}(r)$$
$$V_{\mathrm{weak}}(r) = \frac{G_F}{2^{2/3}}\left[(1 - 4\sin^2\theta_W)Z\rho_p(r) - N\rho_n(r)\right]$$

Parity violating asymmetry:

$$A_{PV} \equiv \frac{\frac{d\sigma_+}{d\Omega} - \frac{d\sigma_-}{d\Omega}}{\frac{d\sigma_+}{d\Omega} + \frac{d\sigma_-}{d\Omega}}$$

$$A_{PV}^{\mathrm{PWBA}} = \frac{G_F q^2}{4\pi\alpha\sqrt{2}}\left[4\sin^2\theta_W + \frac{F_n(q) - F_p(q)}{F_p(q)}\right]$$

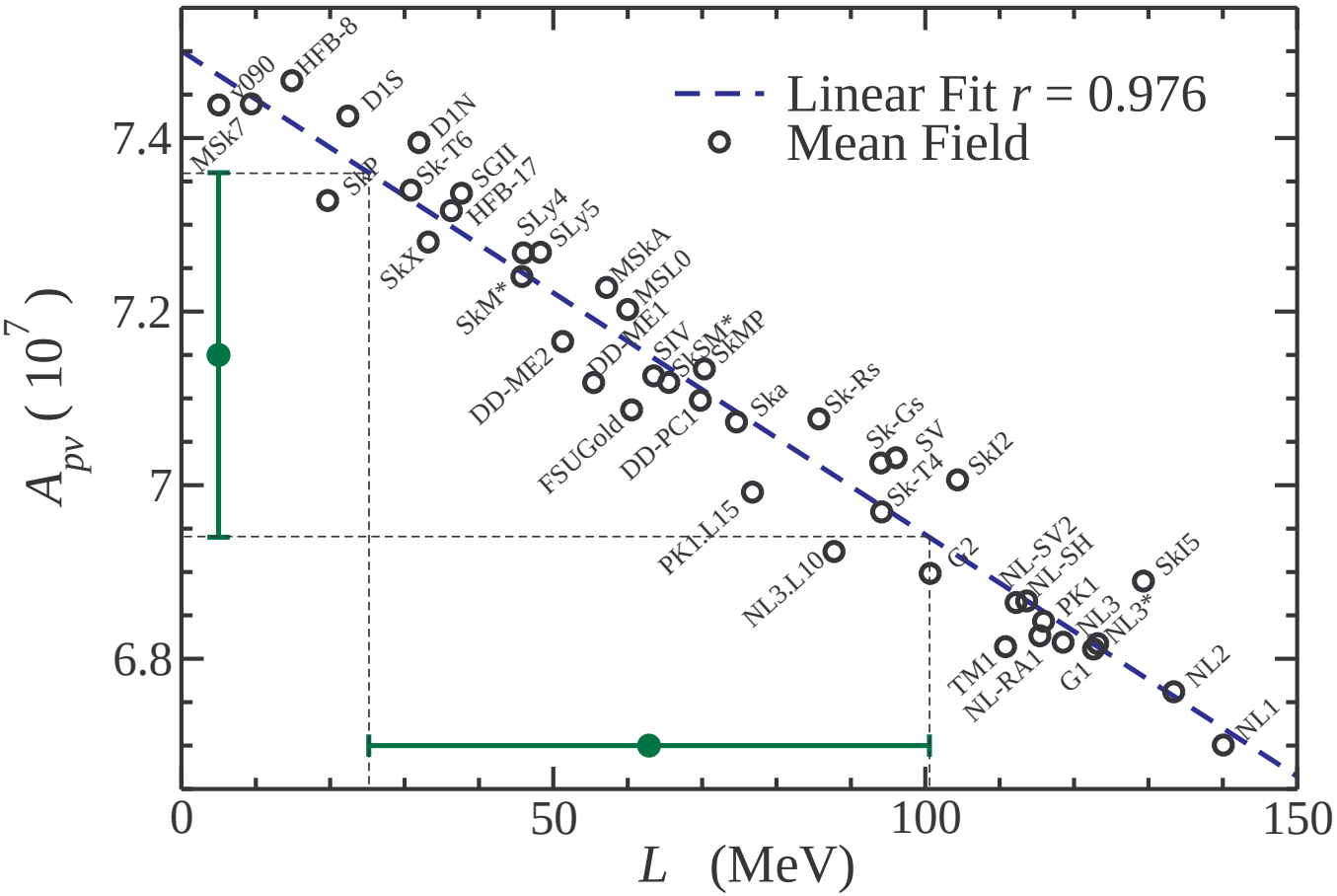

Linear Fit, r = 0.995
Mean Field
From strong probes
Hoffmann [4]
Klos [8]
Zenihiro [6]
HFB-8
v090
D1S
D1N
Sk-T6
SkX
SLy5
SkA
MSL0
DD-ME.
DD-ME1
MP
RHF-PKO3
RHF-PKA1
SV
SKI2
Sk-T4
NL3.s25
G2
PK1
NL3*
NL2
NL1
G1
NL-SH
NL-SV2
TM1
NL-RA1
NL3
Ska
Sk-Gs
PK1.s24
SIV
SkSM*
DD-PC1
FSUGold
SGII
SkP
HFB-17
SLy4
SkM*
MSK7
7,4
7,2
7,0
6,8
6,6
0,1
0,15
0,2
0,25
0,3
$10^7 A_{pv}$
Δr_{np} (fm)

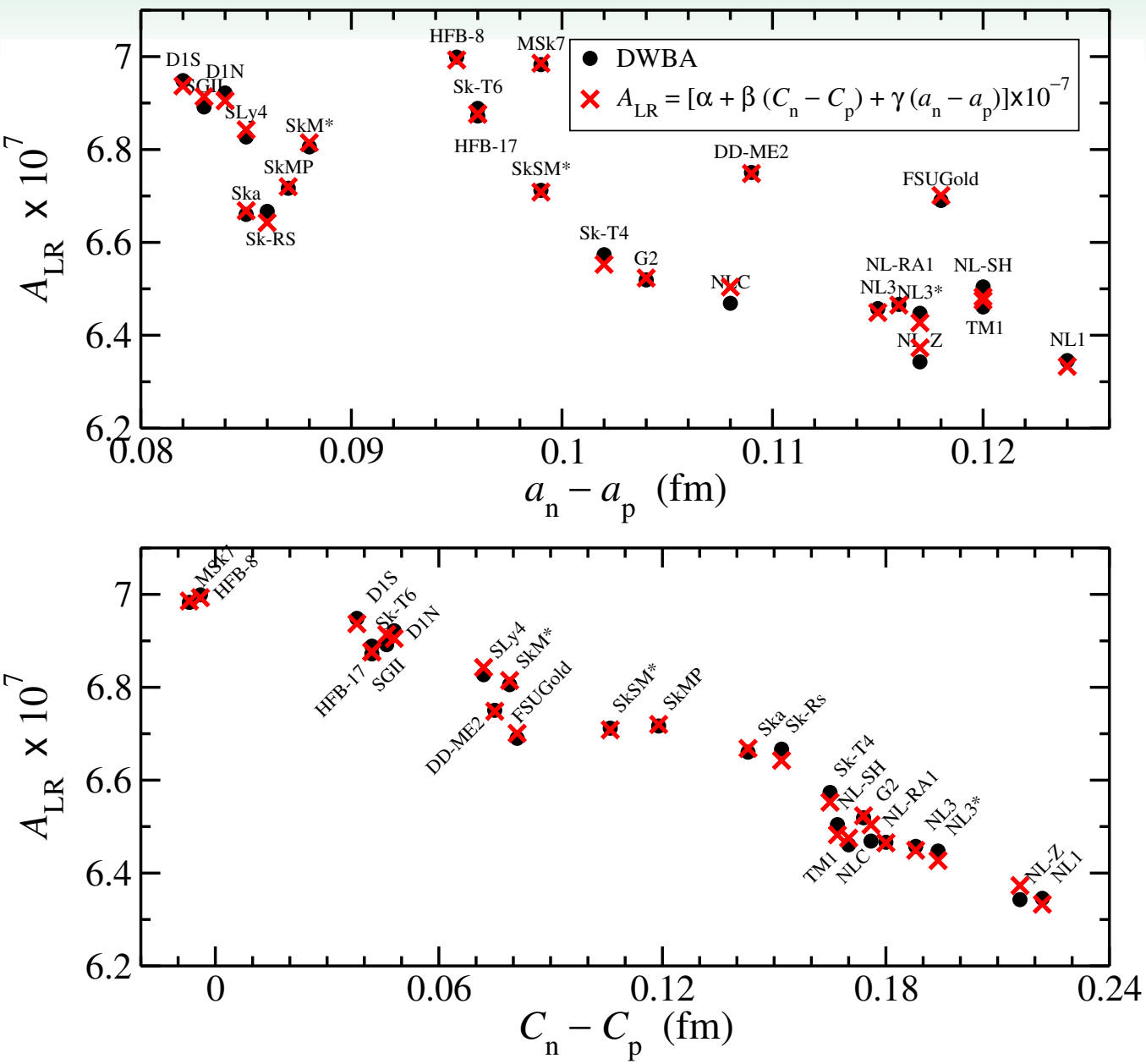


$$A_{PV}^{\mathrm{exp}} = 0.6571 \pm 0.0604(stat) \pm 0.0130(syst)$$

9% statistic error

2% systematic error


Linear Fit r = 0.976
Mean Field
A_{pv} (10^7)
L (MeV)
7.4
7.2
7
6.8
0
50
100
150
MSk7
X090
HFB-8
D1S
D1N
Sk-T6
SGII
HFB-17
SkP
SkX
SLy4
SLy5
SkM*
MSkA
MSL0
DD-ME1
DD-ME2
SIV
SkSM*
SkMP
FSUGold
DD-PC1
Ska
Sk-Rs
Sk-Gs
SV
Sk-T4
SkI2
PKDD
PKDD1
PK1
PK1L15
NL3L10
G2
NL-SV2
NL-SH
PK1
NL3
NL3*
SkI5
TM1
NL-RA1
G1
NL2
NL1


DWBA
$A_{LR} = [\alpha + \beta\,(C_n - C_p) + \gamma\,(a_n - a_p)]\times 10^{-7}$
A_{LR} x 10^7
$a_n - a_p$ (fm)
$C_n - C_p$ (fm)
D1S
D1N
SGII
SLy4
SkM*
SkMP
Ska
Sk-RS
HFB-8
MSk7
Sk-T6
HFB-17
SkSM*
DD-ME2
FSUGold
Sk-T4
G2
NLC
NL-RA1
NL3
NL3*
NL-SH
TM1
NL-Z
NL1
Sk-Rs

Conclusions:

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- Soft symmetry energy ($L = 55$ MeV) is predicted from neutron skin data
- Surface term should not be omitted in description of neutron skin
- Mixture of bulk and surface contributions is fund in numerous nuclei
- Prescription of calculating neutron skin from PREX is given

Published papers:

- M. Centelles, X. Roca-Maza, X. Viñas and M. Warda, Phys. Rev. Lett. 102, 122502 (2009)
- M. Warda, X. Viñas, X. Roca-Maza and M. Centelles, Phys. Rev. C 80, 024316 (2009)
- M. Warda, X. Viñas, X. Roca-Maza and M. Centelles, Phys. Rev. C 81, 054309 (2010)
- M. Centelles, X. Roca-Maza, X. Viñas and M. Warda, Phys. Rev. C 82, 054314 (2010)
- X. Roca-Maza, M. Centelles, X. Viñas and M. Warda, Phys. Rev. Lett. 106, 252501 (2011)