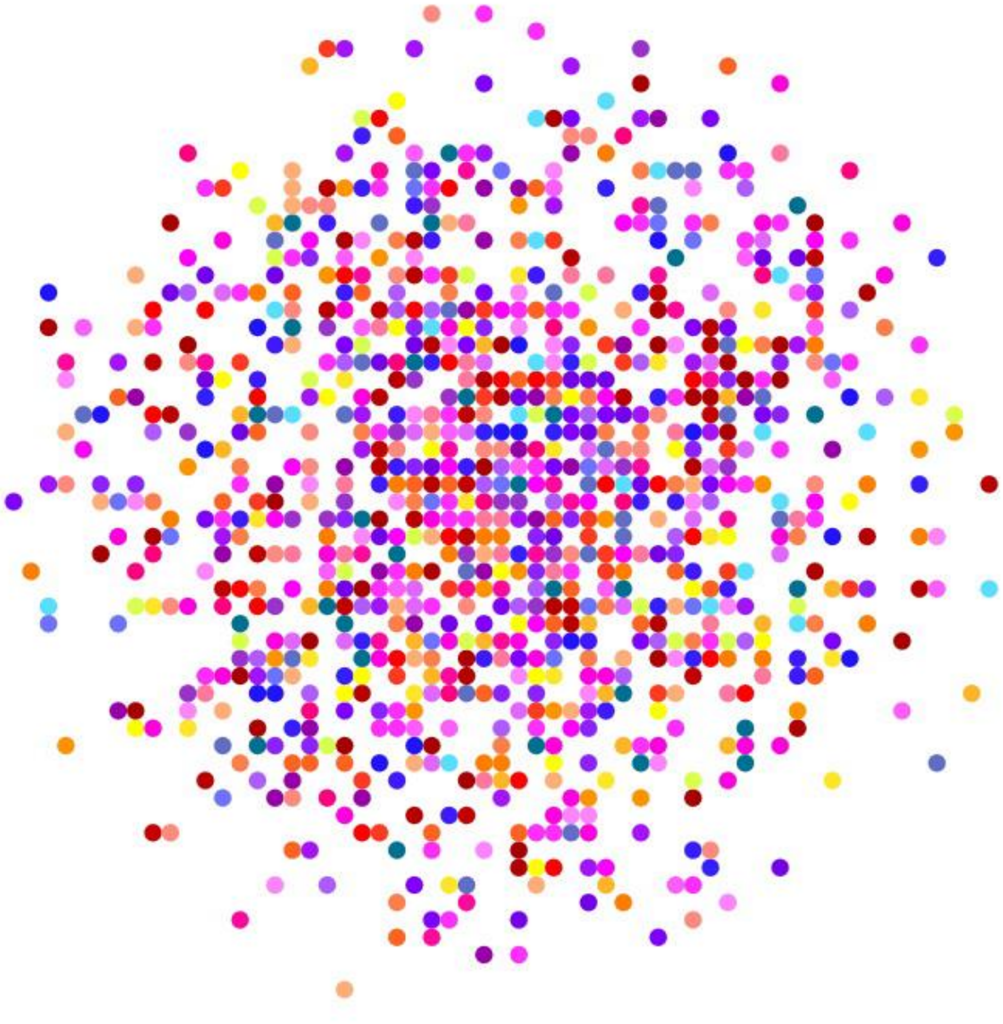
Energy-density-functional results for magic nuclei and the extrapolation to the neutron matter equation of state



NSCL

Alex Brown, LSTNT, Oct 7, 2019

Nuclear Physics A 627 (1997) 710–746

A Skyrme parametrization from subnuclear to neutron star densities

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$$\mathcal{H} = \mathcal{K} + \mathcal{H}_0 + \mathcal{H}_3 + \mathcal{H}_{\mathrm{eff}} + \mathcal{H}_{\mathrm{fin}} + \mathcal{H}_{\mathrm{so}} + \mathcal{H}_{\mathrm{sg}} + \mathcal{H}_{\mathrm{Coul}} \,,$$

$$\begin{aligned}
\mathcal{H}_0 &= \frac{1}{4} t_0 \left[(2 + x_0)\, \rho^2 - (2x_0 + 1)\left(\rho_{\mathrm{p}}^2 + \rho_{\mathrm{n}}^2\right)\right] \,, \\
\mathcal{H}_3 &= \frac{1}{24} t_3 \rho^{\sigma} \left[(2 + x_3)\, \rho^2 - (2x_3 + 1)\left(\rho_{\mathrm{p}}^2 + \rho_{\mathrm{n}}^2\right)\right] \,, \\
\mathcal{H}_{\mathrm{eff}} &= \frac{1}{8} \left[t_1 (2 + x_1) + t_2 (2 + x_2) \right] \tau \rho \\
&\quad + \frac{1}{8} \left[t_2 (2x_2 + 1) - t_1 (2x_1 + 1) \right] \left(\tau_{\mathrm{p}} \rho_{\mathrm{p}} + \tau_{\mathrm{n}} \rho_{\mathrm{n}} \right) \,, \\
\mathcal{H}_{\mathrm{fin}} &= \frac{1}{32} \left[3t_1 (2 + x_1) - t_2 (2 + x_2) \right] (\boldsymbol{\nabla} \rho)^2 \\
&\quad - \frac{1}{32} \left[3t_1 (2x_1 + 1) + t_2 (2x_2 + 1) \right] \left[(\boldsymbol{\nabla} \rho_{\mathrm{p}})^2 + (\boldsymbol{\nabla} \rho_{\mathrm{n}})^2 \right] \,, \\
\mathcal{H}_{\mathrm{so}} &= \frac{1}{2} W_0 \left[\boldsymbol{J} \cdot \boldsymbol{\nabla} \rho + \boldsymbol{J}_{\mathrm{p}} \cdot \boldsymbol{\nabla} \rho_{\mathrm{p}} + \boldsymbol{J}_{\mathrm{n}} \cdot \boldsymbol{\nabla} \rho_{\mathrm{n}} \right] \,, \\
\mathcal{H}_{\mathrm{sg}} &= -\frac{1}{16} (t_1 x_1 + t_2 x_2)\, \boldsymbol{J}^2 + \frac{1}{16} (t_1 - t_2) \left[\boldsymbol{J}_{\mathrm{p}}^2 + \boldsymbol{J}_{\mathrm{n}}^2 \right] \,.
\end{aligned}$$

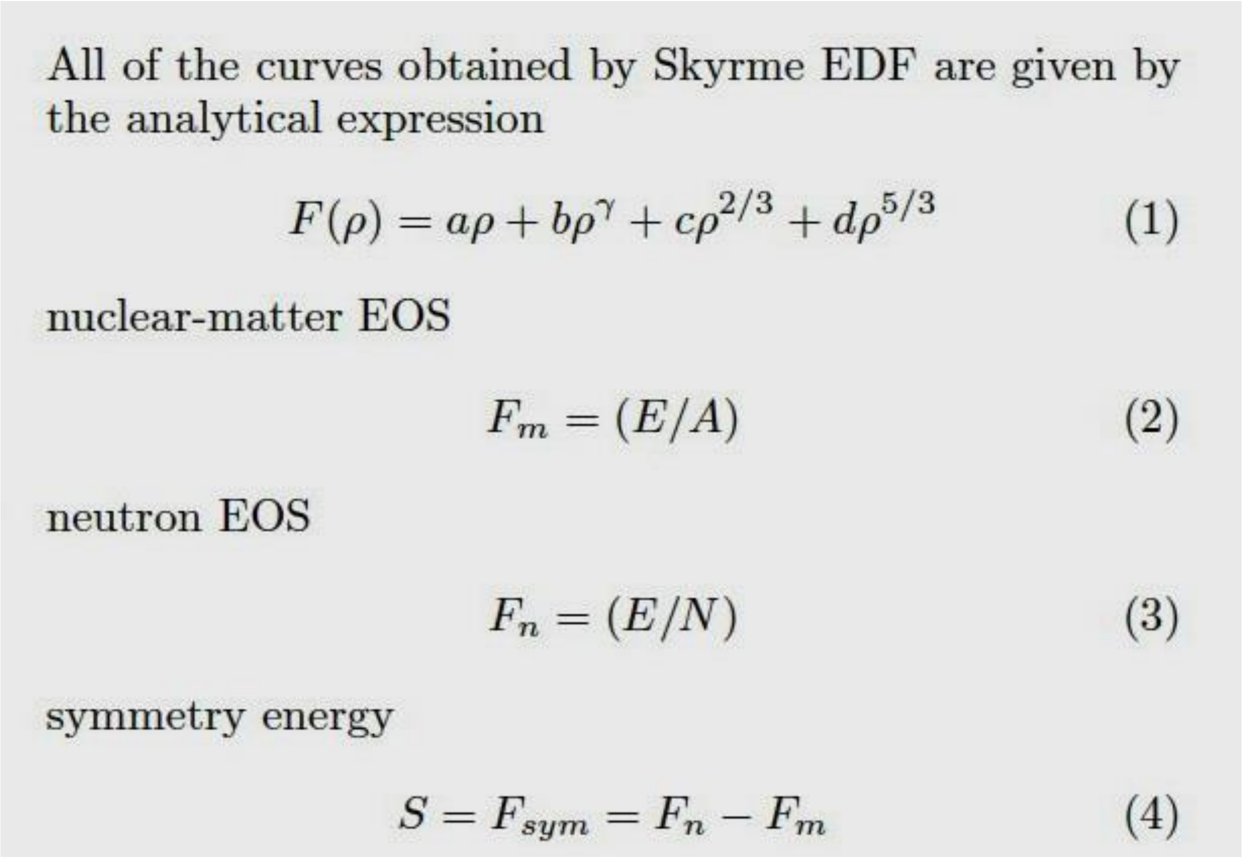
3.2. Asymmetric infinite nuclear matter

As function of $Y_\mathrm{p} = Z/A$ (or $I = (N - Z)/A$), we can use the density functional given by Eqs. (2.5), (2.6) to write the energy per particle of an asymmetric infinite nuclear matter:

$$
\begin{aligned}
\frac{E}{A}(Y_\mathrm{p} \text{ or } I, \rho) = {} & \frac{3}{5}\frac{\hbar^2}{2m}\left(\frac{3\pi^2}{2}\right)^{2/3} \rho^{2/3} F_{5/3} + \frac{1}{8} t_0 \rho \left[2\left(x_0 + 2\right) - \left(2x_0 + 1\right) F_2\right] \\
& + \frac{1}{48} t_3 \rho^{\sigma+1} \left[2\left(x_3 + 2\right) - \left(2x_3 + 1\right) F_2\right] \\
& + \frac{3}{40}\left(\frac{3\pi^2}{2}\right)^{2/3} \rho^{5/3} \Bigg\{ \left[t_1\left(x_1 + 2\right) + t_2\left(x_2 + 2\right)\right] F_{5/3} \\
& + \frac{1}{2}\left[t_2\left(2x_2 + 1\right) - t_1\left(2x_1 + 1\right)\right] F_{8/3} \Bigg\}, \qquad (3.18)
\end{aligned}
$$

with the following definition for the asymmetry factors:

$$
F_m(Y_\mathrm{p}) = 2^{m-1}\left[Y_\mathrm{p}^m + \left(1 - Y_\mathrm{p}\right)^m\right], \quad F_m(I) = \frac{1}{2}\left[(1 + I)^m + (1 - I)^m\right].
$$



All of the curves obtained by Skyrme EDF are given by the analytical expression

$$F(\rho) = a\rho + b\rho^{\gamma} + c\rho^{2/3} + d\rho^{5/3} \tag{1}$$

nuclear-matter EOS

$$F_m = (E/A) \tag{2}$$

neutron EOS

$$F_n = (E/N) \tag{3}$$

symmetry energy

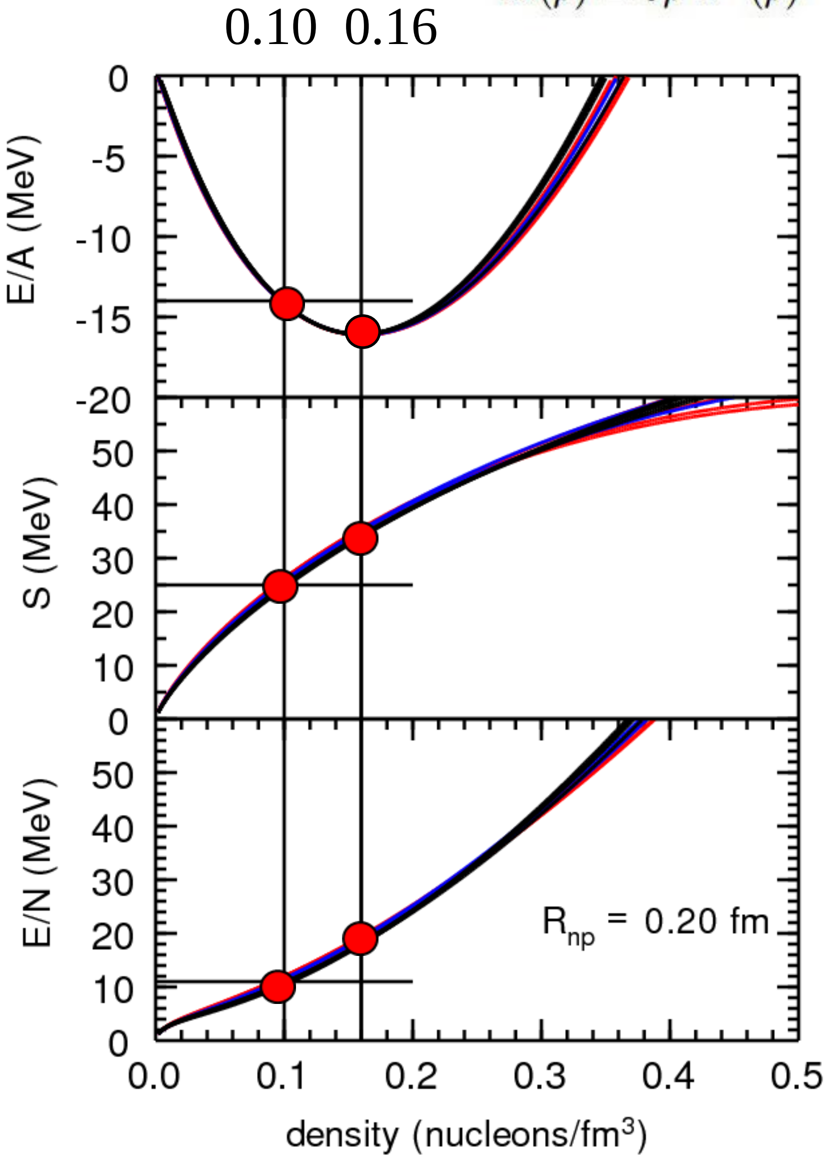
$$S = F_{sym} = F_n - F_m \tag{4}$$

ρ from s-wave
ρ^{γ} from density dependence $\gamma=(1+\sigma)$
$\rho^{2/3}$ from kinetic energy
$\rho^{5/3}$ from p-wave (effective mass)

$$J(\rho) = F(\rho)$$

$$L(\rho) = 3\rho F'(\rho)$$

$$K(\rho) = 9\rho^2 F''(\rho)$$



Typical values (MeV) at

	0.10	0.16	nucleons/fm^3
J_m	-14	-16	
L_m		0	
K_m		240	
J_s	25	34 = S_v	
L_s		68 = L	
K_s		-100	
J_n	11	18	
L_n		68	
K_n		140	

In terms of

$$\alpha = \frac{(\rho_n - \rho_p)}{(\rho_n + \rho_p)}$$

A more general EOS can be expanded in the form

$$\begin{aligned} \mathcal{E}(\rho,\alpha) =& \ \mathcal{E}(\rho,\alpha=0) + S_2(\rho)\,\alpha^2 + S_4(\rho)\,\alpha^4 \\ =& \ \mathcal{E}(\rho,\alpha=0) + \frac{1}{2}\left[\frac{\partial^2 \mathcal{E}(\rho,\alpha)}{\partial\alpha^2}\right]_{\alpha=0}\alpha^2 + \frac{1}{24}\left[\frac{\partial^4 \mathcal{E}(\rho,\alpha)}{\partial\alpha^2}\right]_{\alpha=0}\alpha^4 \end{aligned}$$

and for the symmetry energy

$$S(\rho) = S_2(\rho) + S_4(\rho)$$

The S_4 derived from nuclear properties has a very large uncertainty, e.g. an $(N-Z)^4$ term in the liquid drop model has a very large uncertainty.

With Skyrme we assume that this comes from a specific functional form.

PHYSICAL REVIEW C VOLUME 58, NUMBER 1 JULY 1998

New Skyrme interaction for normal and exotic nuclei

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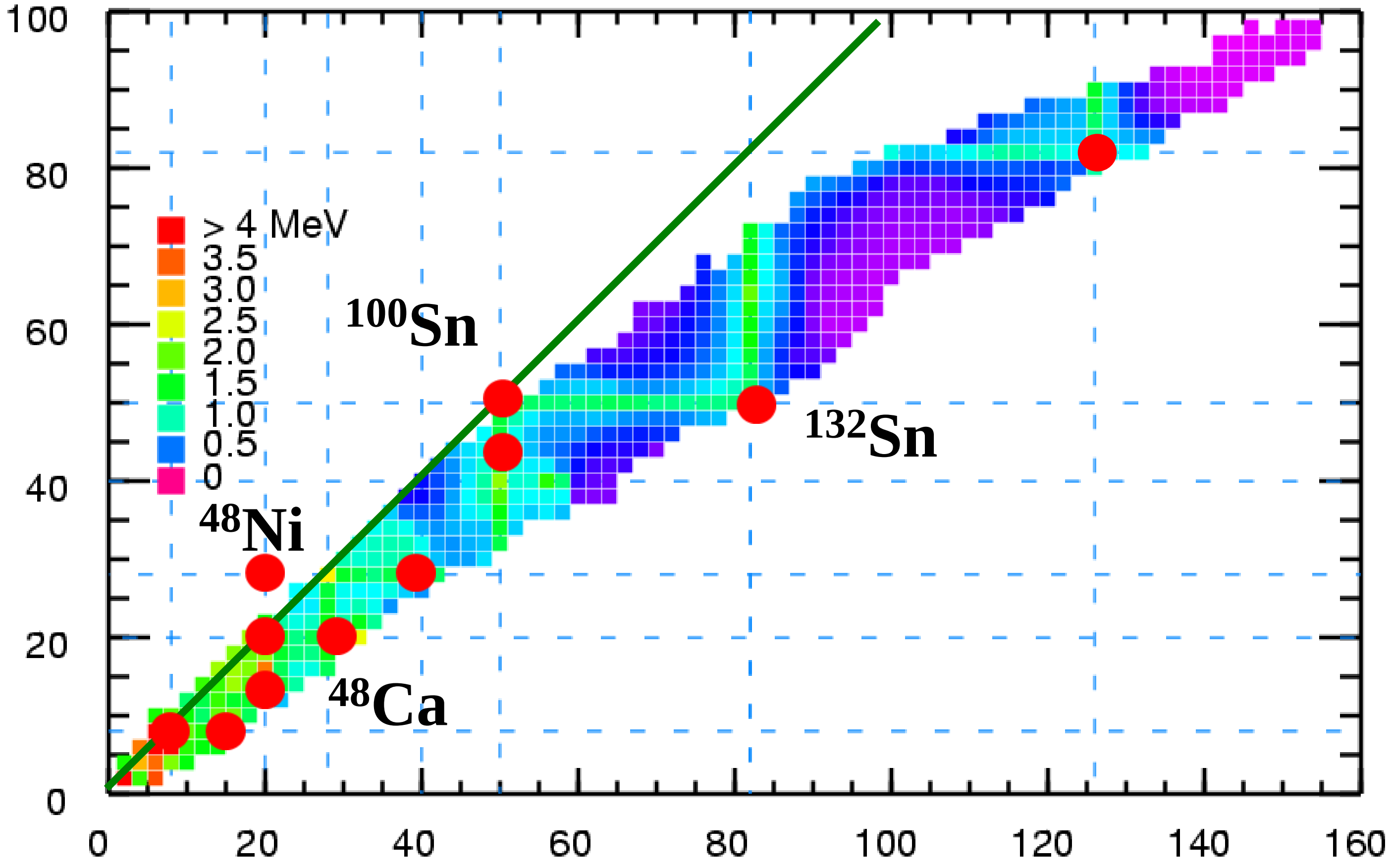
(Received 5 May 1997)



Nuclear data for the **Skx** the parameters

- Properties of "closed-shell" nuclei

  ^{16}O, ^{24}O, ^{34}Si, ^{40}Ca, ^{48}Ca, ^{48}Ni, ^{68}Ni, ^{88}Sr, ^{100}Sn, ^{132}Sn and ^{208}Pb

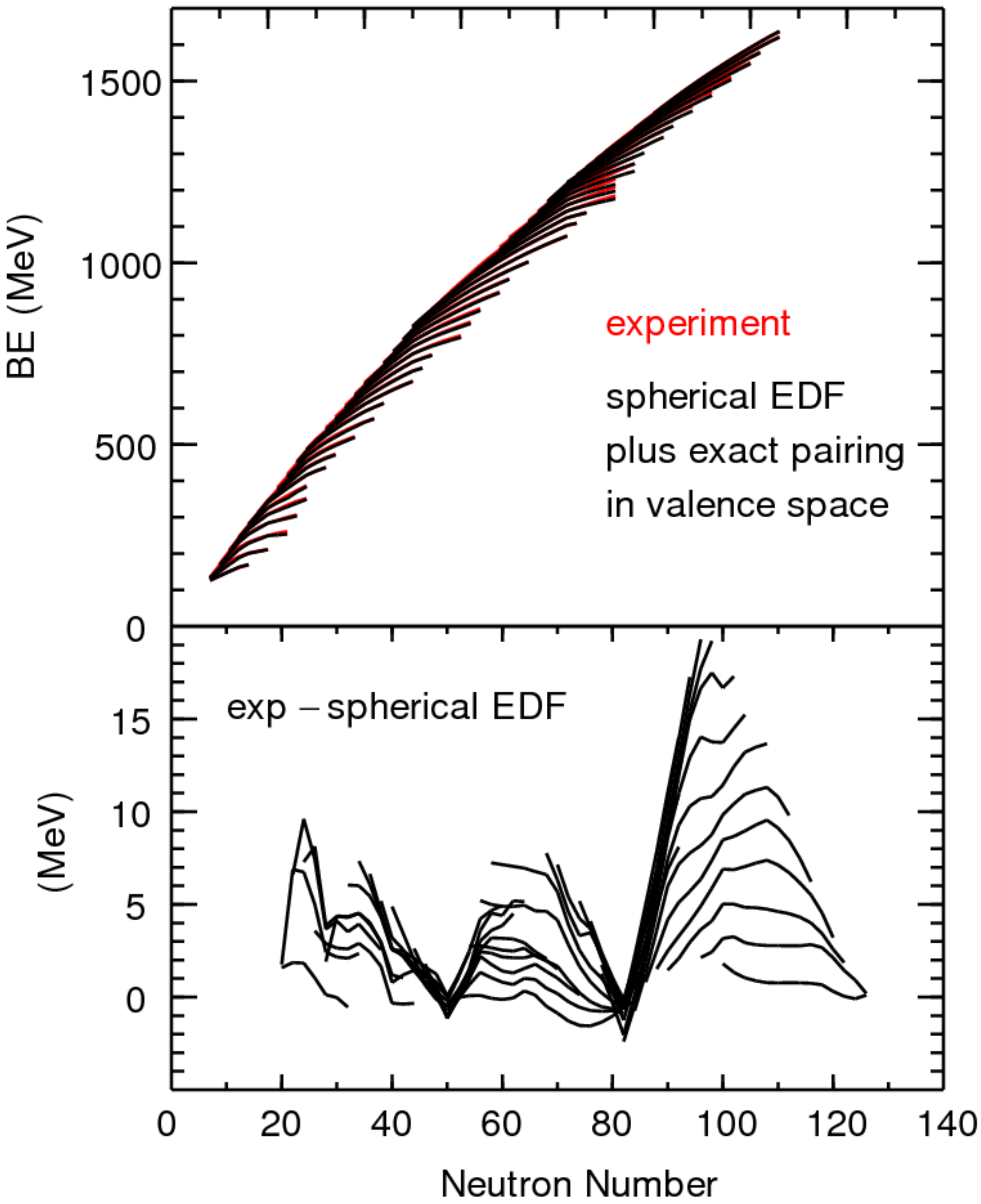
- Binding energies, [Z,N] [Z+1,N] [Z-1,N] [Z,N+1] [Z,N-1]

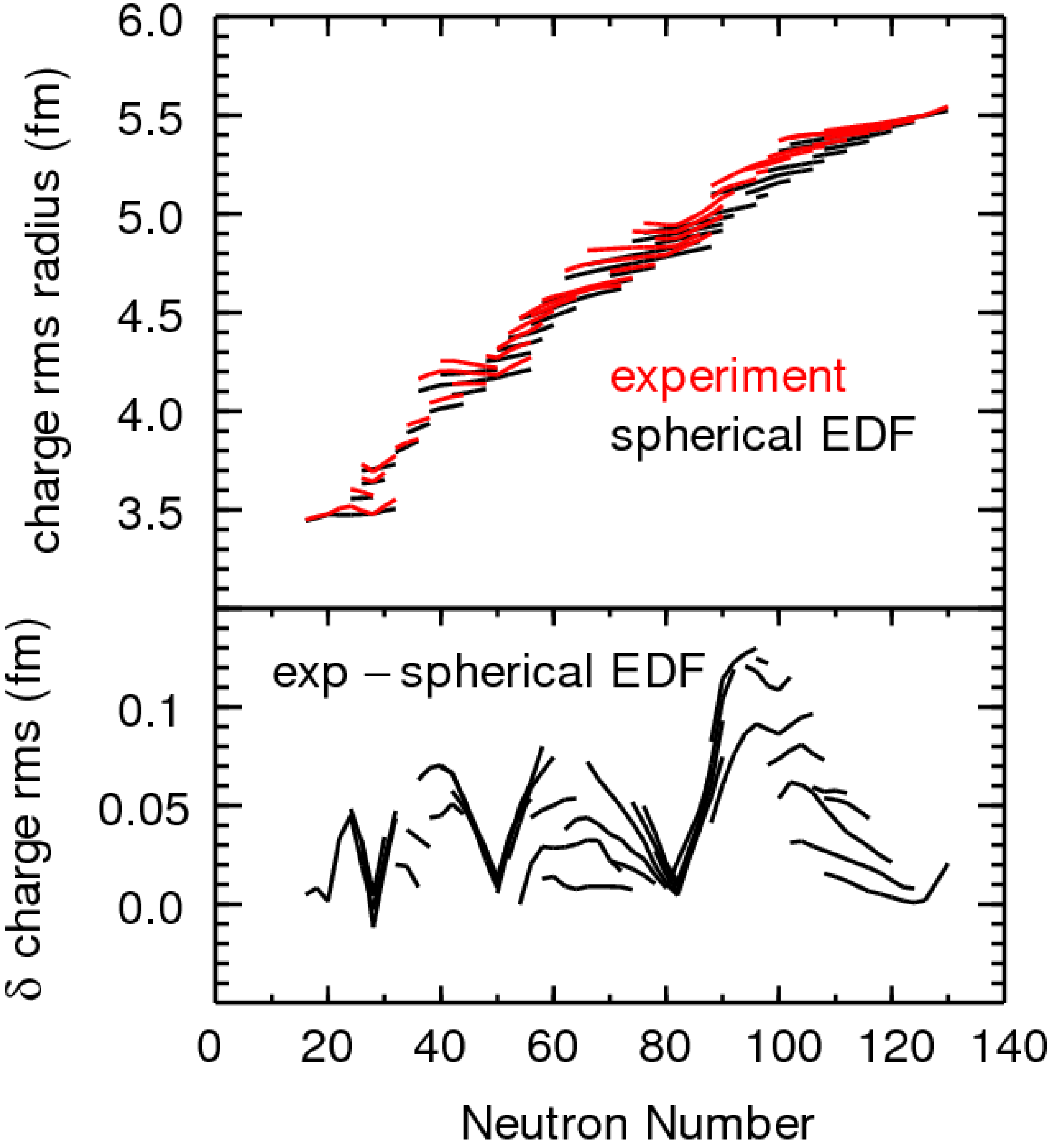
  fitted to within about 1 MeV

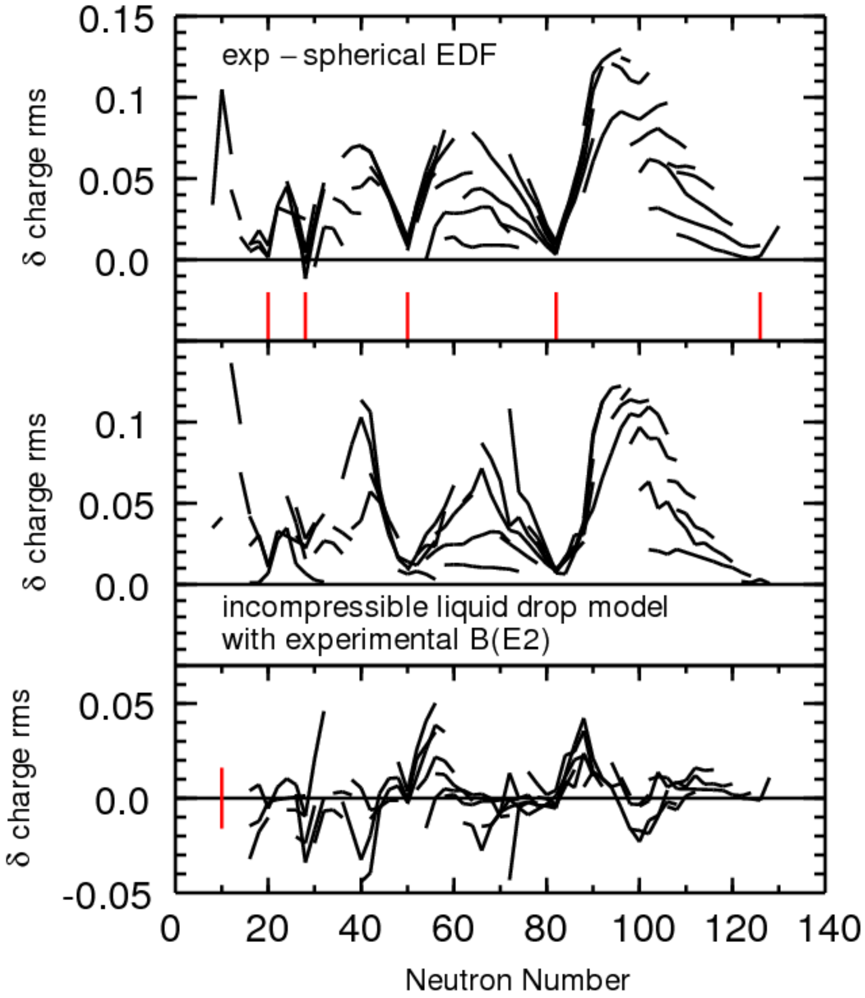
- rms charge radii

  fitted to within about 0.02 fm

- Some assumptions about the neutron equation of state


1500
1000
500
0
BE (MeV)
experiment
spherical EDF
plus exact pairing
in valence space
exp − spherical EDF
15
10
5
0
(MeV)
0
20
40
60
80
100
120
140
Neutron Number


charge rms radius (fm)
6.0
5.5
5.0
4.5
4.0
3.5
experiment
spherical EDF
δ charge rms (fm)
exp – spherical EDF
0.1
0.05
0.0
0
20
40
60
80
100
120
140
Neutron Number



$$\delta\langle r^2\rangle = \frac{B(E2\uparrow)}{(5/4\pi)\langle r_0^2\rangle(eZ)^2}.$$

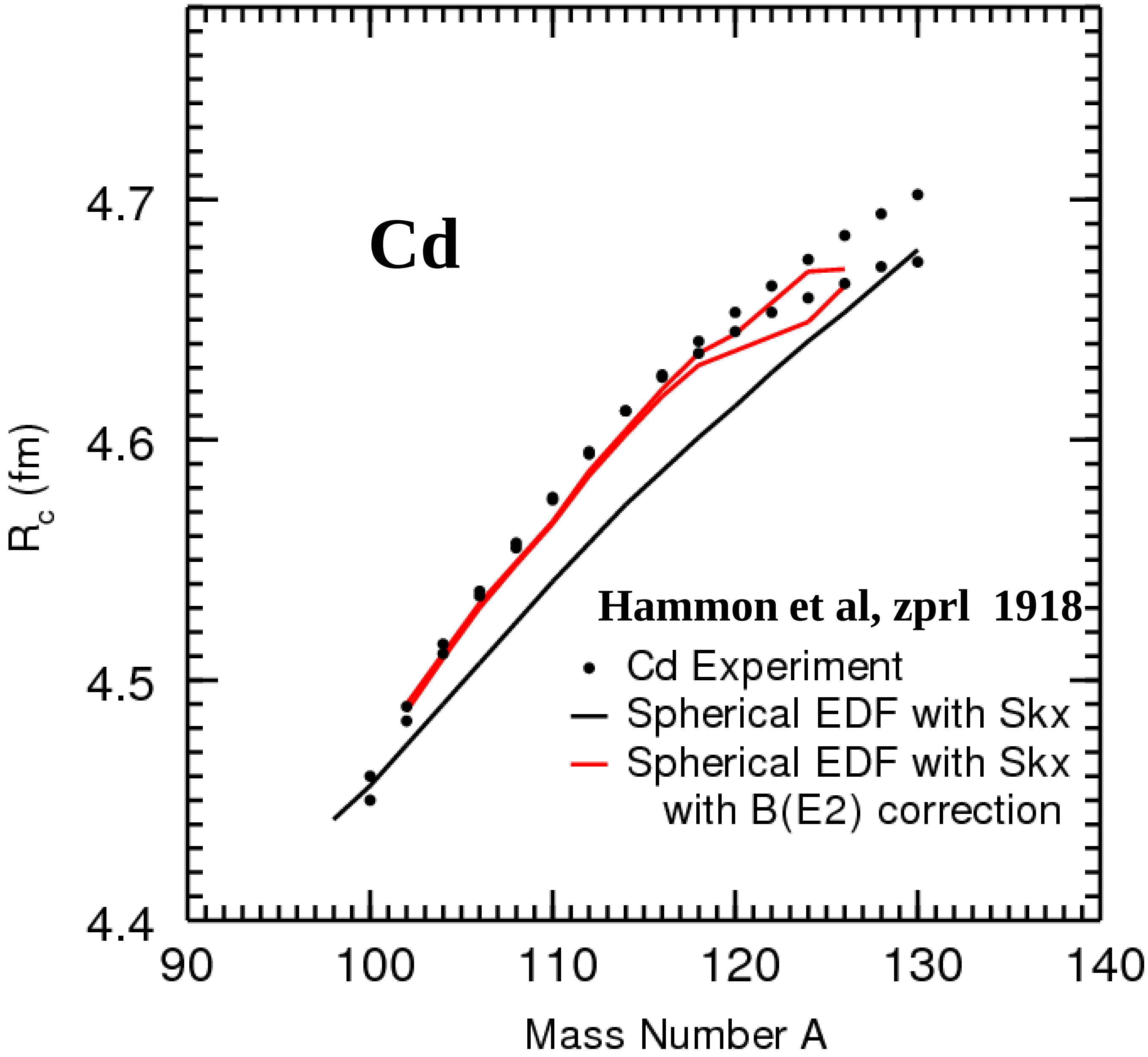
Except for the increase just after the magic numbers 28, 50, 82 and 126
the rms charge radii are understood to the level of about 0.02 fm

The “proton charge radius puzzle” (in fm)

0.879(11) from electron scattering
0.833(10) from atomic Lamb shift (Berginov et al., Science 365, 1007 (2019).
0.8409(4) from muon Lamb shift

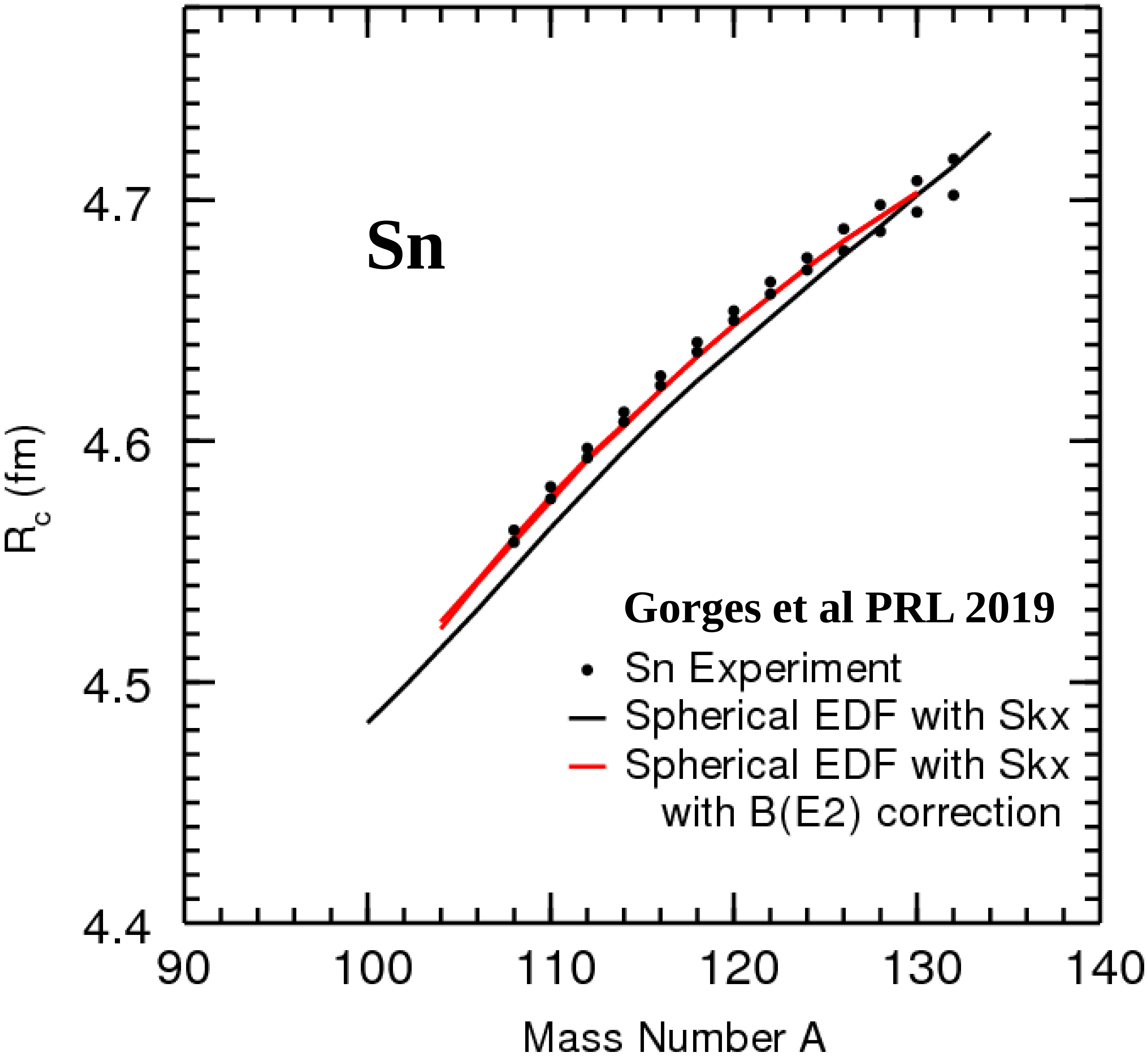
results differ 0.04 fm (7 σ)

NSCL



Cd

Hammon et al, zprl 1918


Sn
Gorges et al PRL 2019
● Sn Experiment
— Spherical EDF with Skx
— Spherical EDF with Skx with B(E2) correction
R_c (fm)
4.4
4.5
4.6
4.7
90
100
110
120
130
140
Mass Number A

PHYSICAL REVIEW C **81**, 014303 (2010)

Structure of even-even nuclei using a mapped collective Hamiltonian and the D1S Gogny interaction

J.-P. Delaroche,[1,*] M. Girod,[1] J. Libert,[2] H. Goutte,[1] S. Hilaire,[1] S. Péru,[1] N. Pillet,[1] and G. F. Bertsch[3,*]
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(Received 22 September 2009; published 13 January 2010)

5DCH   5 dimensional collective Hamiltonian

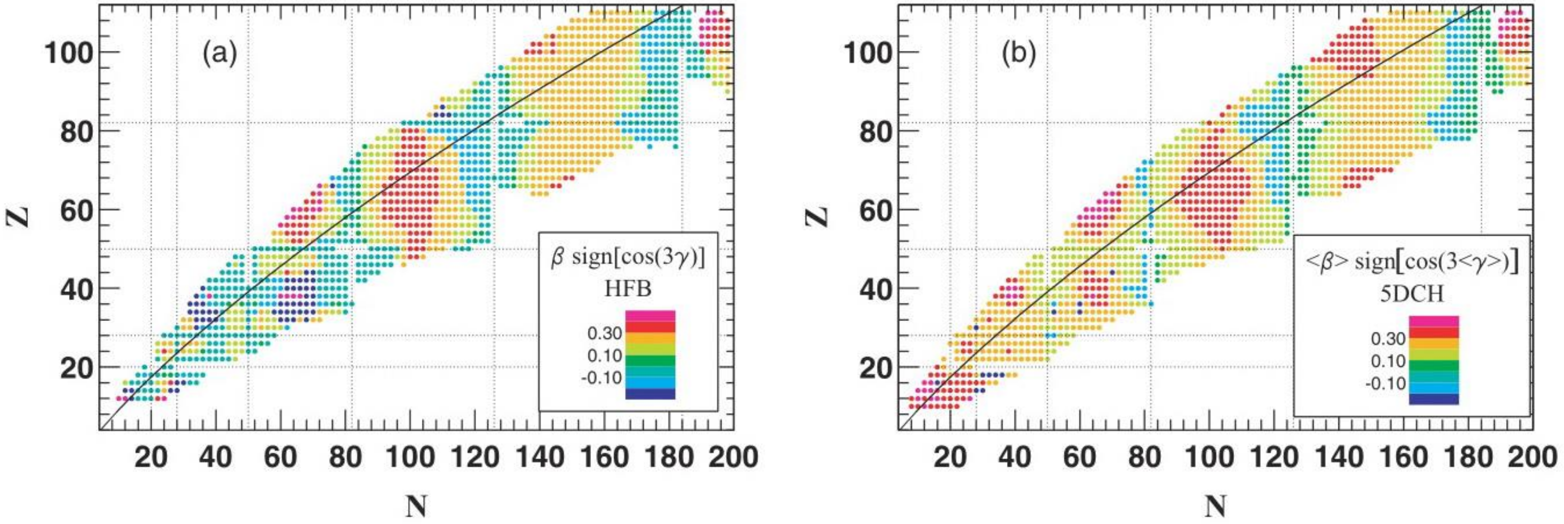
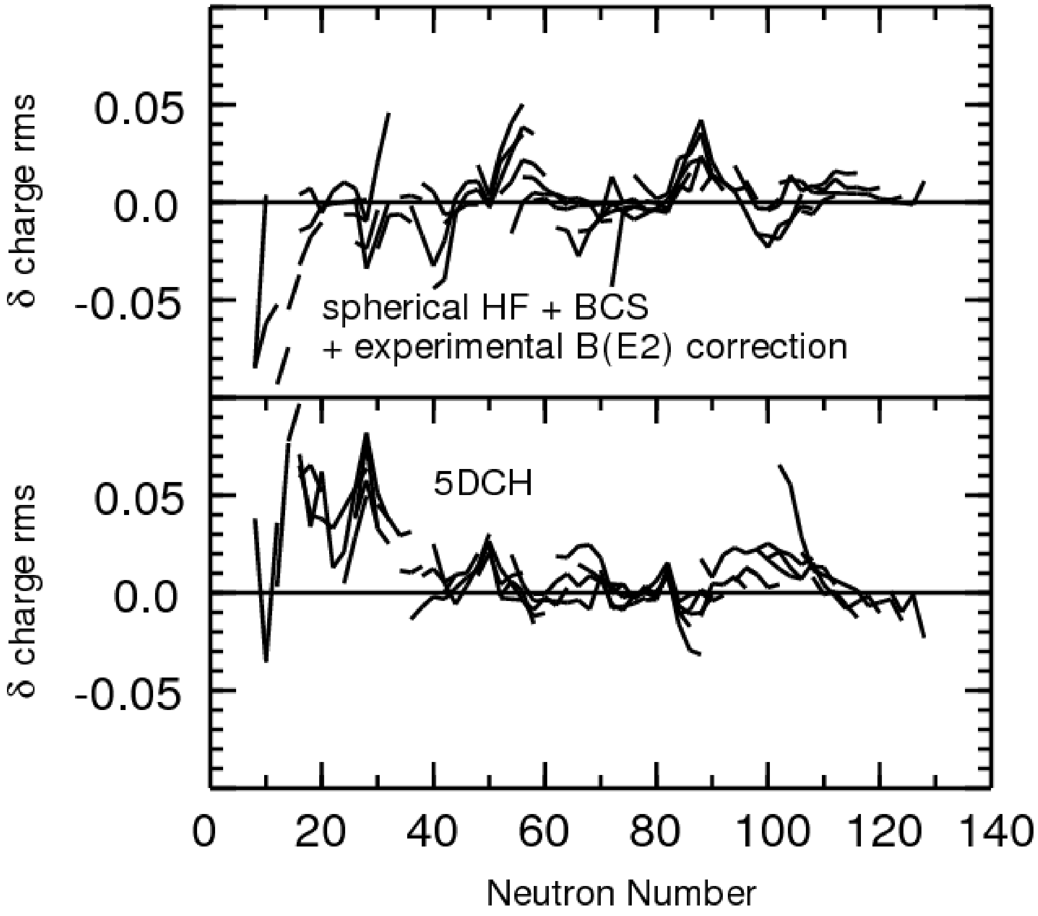


FIG. 3. (Color online) Chart of nuclides showing ground state deformations. (a) HFB minimum; (b) expectation value in the 5DCH ground state. The black curve shows the β-stability line.


δ charge rms
0.05
0.0
-0.05
spherical HF + BCS
+ experimental B(E2) correction
5DCH
0
20
40
60
80
100
120
140
Neutron Number

Question – how can we extrapolate the properties of nuclei to neutron matter and neutron stars?

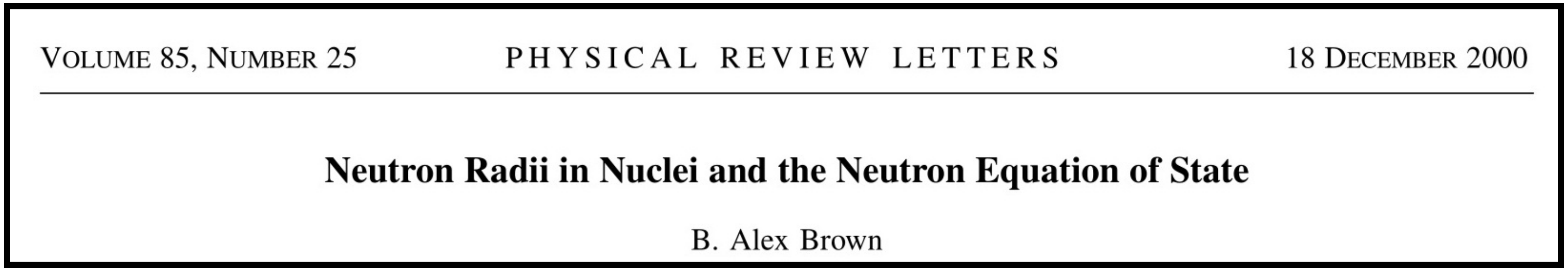
Path A - measure neutron skin or mirror charge radii differences

Path B - use low-density ab-initio theory neutron matter

Path C - use maximum mass of neutron stars

Remember the basic assumption that all of these are linked by the Skyrme EDF functional form

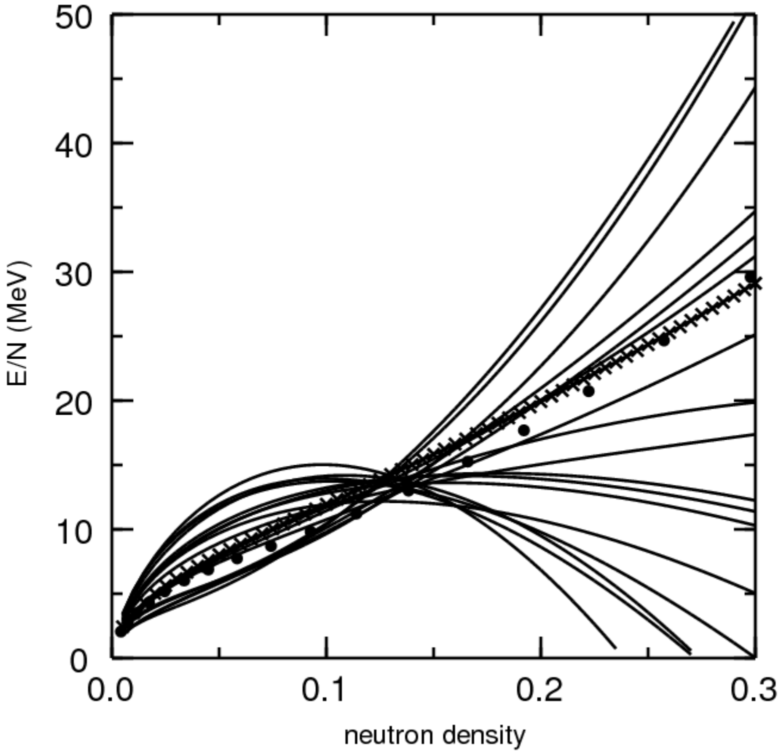
Path A



VOLUME 85, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 2000

Neutron Radii in Nuclei and the Neutron Equation of State

B. Alex Brown



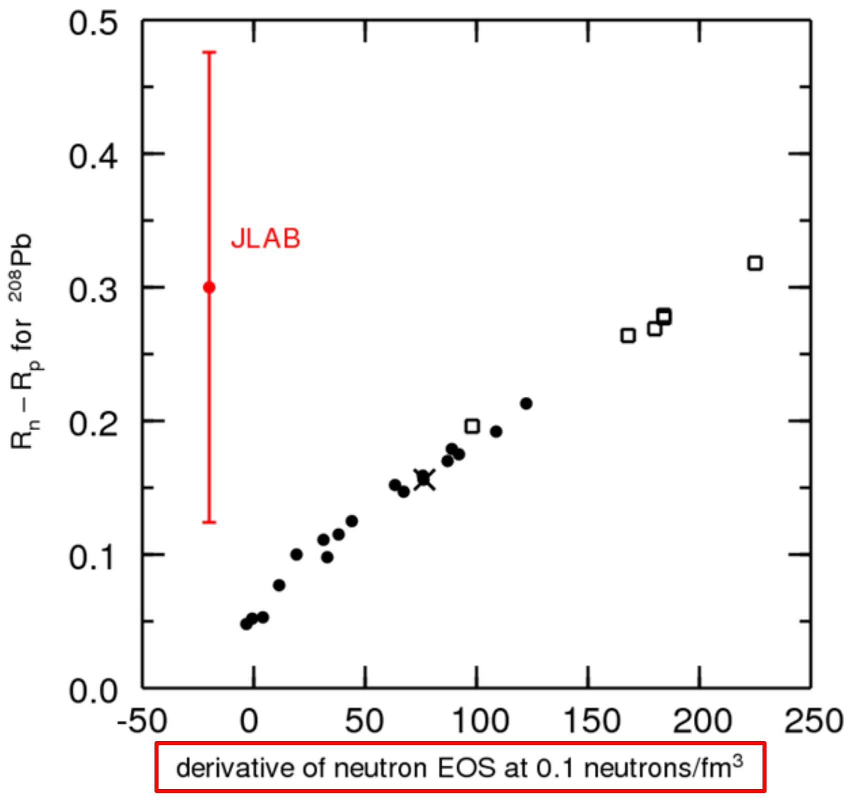
● Friedman-Pandharipanda

x Skx

lines – other Skyrme type functions that fit nuclear properties

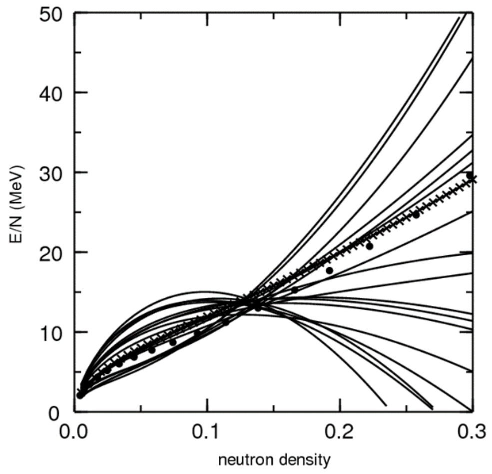
Path A

Question - what determines the size of the neutron skin in heavy nuclei like ^{208}Pb?



(circles) Skyrme-type EDF

(square) relativistic mean filed (RMF)



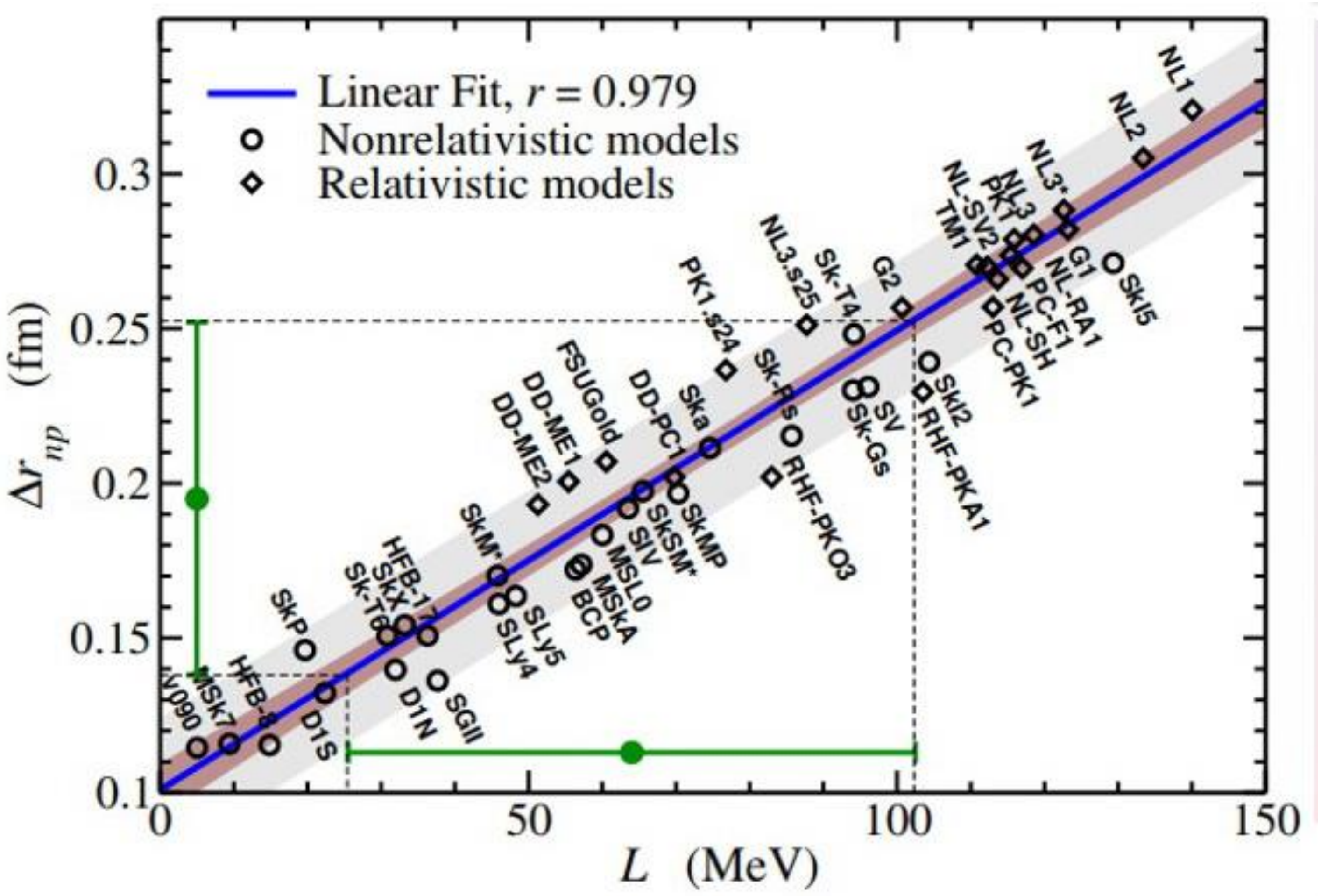
PHYSICAL REVIEW C, VOLUME 64, 027302

Neutron radii and the neutron equation of state in relativistic models

S. Typel and B. Alex Brown

Path A

One of the most complete versions from 2011 -
Note: it is the skin vs L (at 0.16 nucleons/fm^3)



Roca-Maza et al., PRL106,252501(2011)

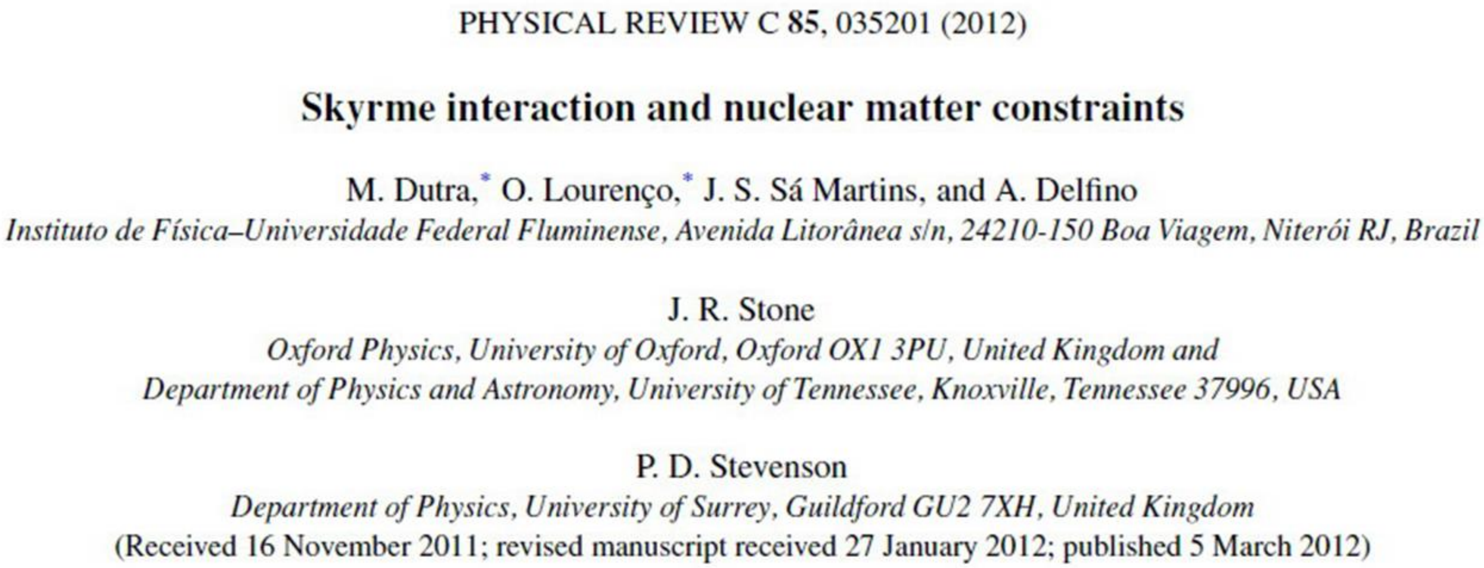
Path A


PRL **111,** 232502 (2013) PHYSICAL REVIEW LETTERS week ending 6 DECEMBER 2013

Constraints on the Skyrme Equations of State from Properties of Doubly Magic Nuclei

B. Alex Brown

Started with 12 Skyrme-type EDF - most from CSkP of Dutra et al. PRC 85, 035201 (2012).


PHYSICAL REVIEW C **85**, 035201 (2012)

Skyrme interaction and nuclear matter constraints

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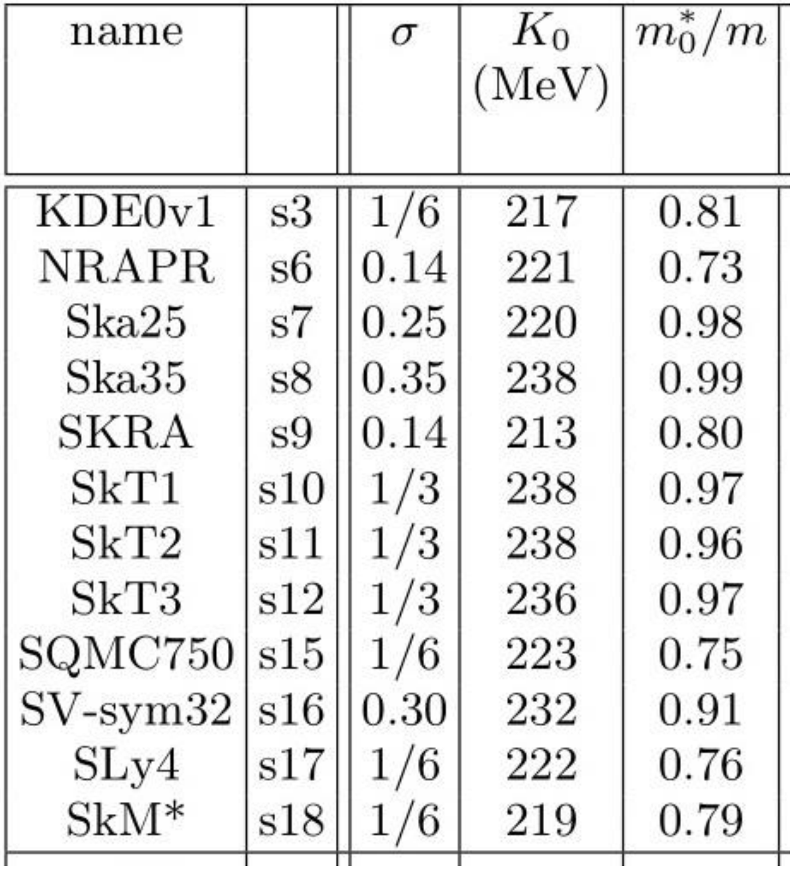
(Received 16 November 2011; revised manuscript received 27 January 2012; published 5 March 2012)

Path A



name		σ	K_0 (MeV)	m_0^*/m
KDE0v1	s3	1/6	217	0.81
NRAPR	s6	0.14	221	0.73
Ska25	s7	0.25	220	0.98
Ska35	s8	0.35	238	0.99
SKRA	s9	0.14	213	0.80
SkT1	s10	1/3	238	0.97
SkT2	s11	1/3	238	0.96
SkT3	s12	1/3	236	0.97
SQMC750	s15	1/6	223	0.75
SV-sym32	s16	0.30	232	0.91
SLy4	s17	1/6	222	0.76
SkM*	s18	1/6	219	0.79

incompressibility	effective mass	for nuclear matter
$K_m = 215 – 240$	$m^*/m = 0.70$ to 1.00	these are reasonable ranges

Path A

PRL **111,** 232502 (2013) PHYSICAL REVIEW LETTERS week ending 6 DECEMBER 2013

Constraints on the Skyrme Equations of State from Properties of Doubly Magic Nuclei

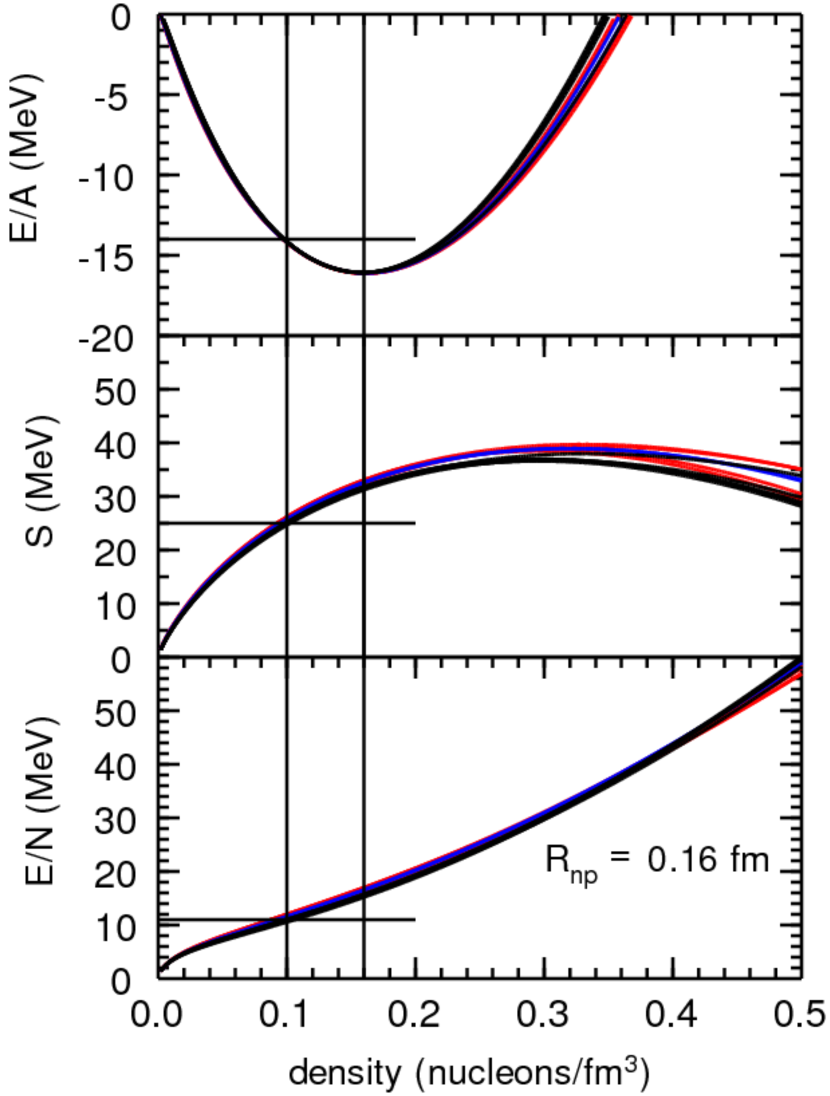
B. Alex Brown

Some combinations of parameters were refit to my SkX data set

But I also add a constraint to have fixed values for the neutron skin of ^{208}Pb

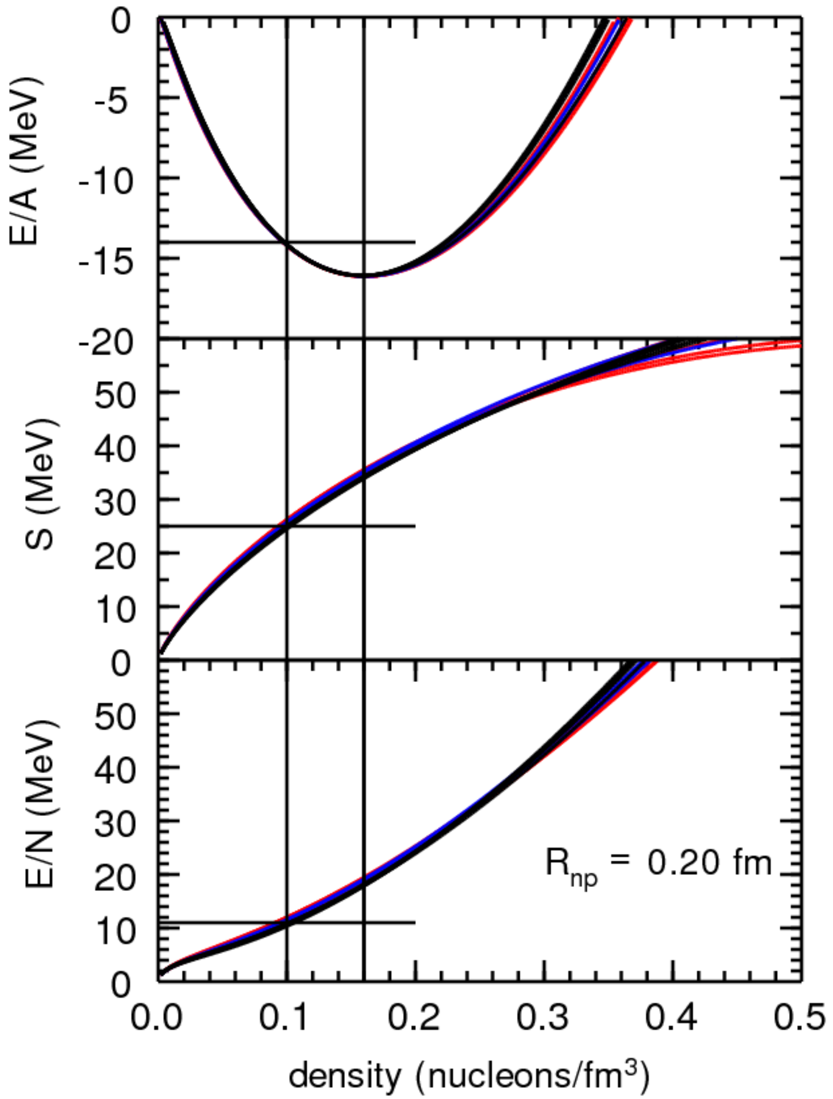
0.16, 0.20, 0.24 fm

Path A


E/A (MeV)
0
-5
-10
-15
-20
S (MeV)
50
40
30
20
10
0
E/N (MeV)
50
40
30
20
10
0
R_{np} = 0.16 fm
0.0
0.1
0.2
0.3
0.4
0.5
density (nucleons/fm^3)

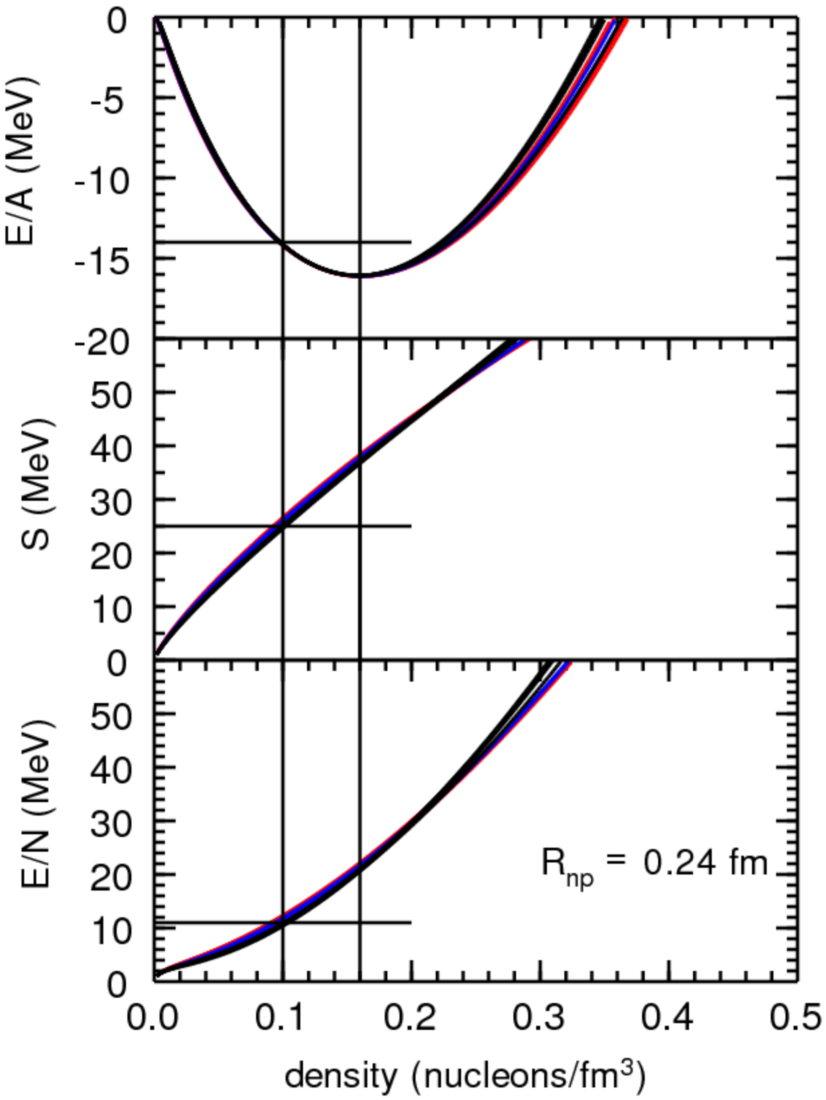
NSCL

Path A

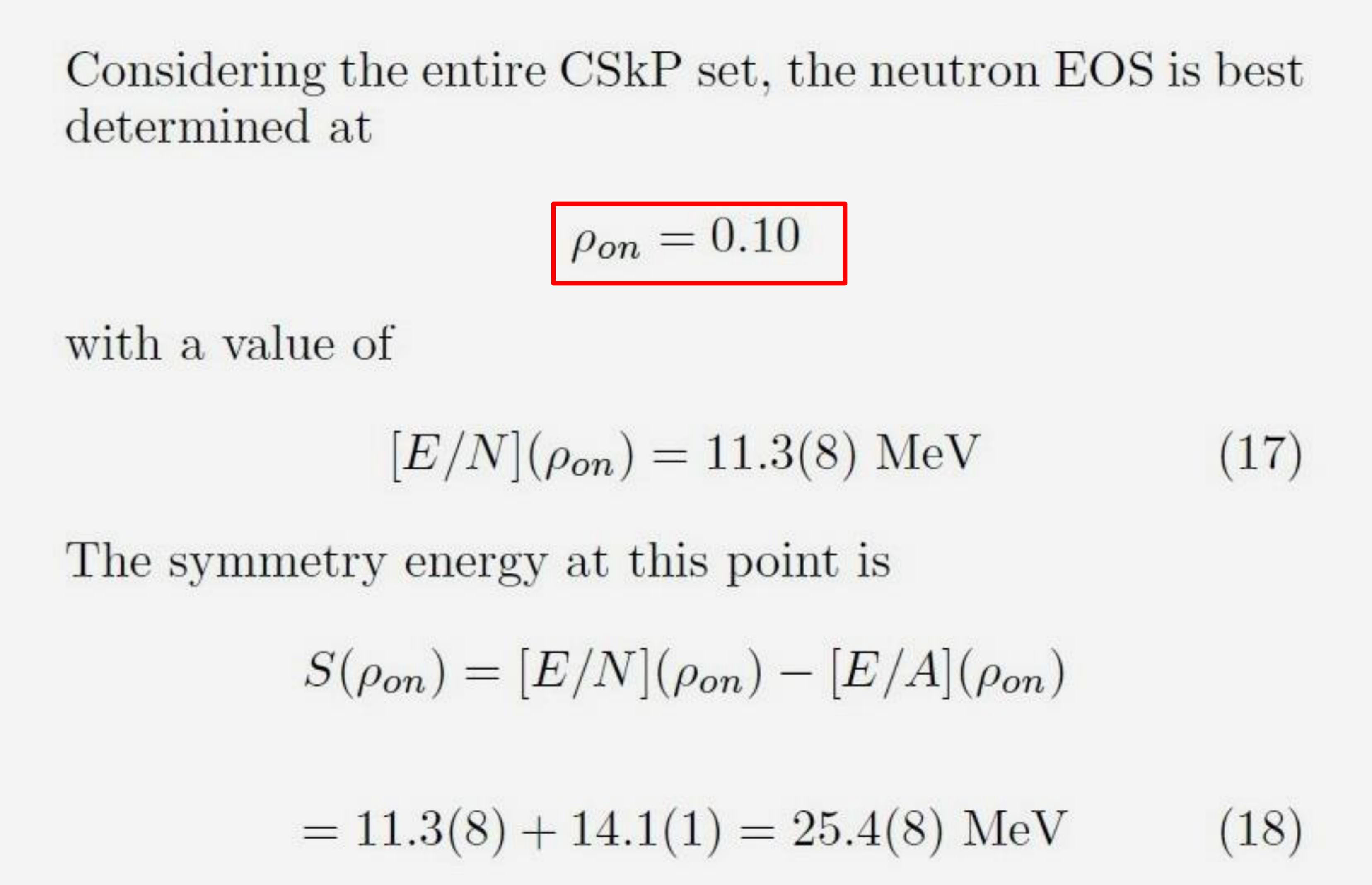


E/A (MeV)
0
-5
-10
-15
-20
S (MeV)
50
40
30
20
10
0
E/N (MeV)
50
40
30
20
10
0
R_{np} = 0.20 fm
0.0
0.1
0.2
0.3
0.4
0.5
density (nucleons/fm^3)

Path A


E/A (MeV)
0
-5
-10
-15
-20
S (MeV)
50
40
30
20
10
0
E/N (MeV)
50
40
30
20
10
0
R_{np} = 0.24 fm
0.0
0.1
0.2
0.3
0.4
0.5
density (nucleons/fm^3)

NSCL



Considering the entire CSkP set, the neutron EOS is best determined at

$$\boxed{\rho_{on} = 0.10}$$

with a value of

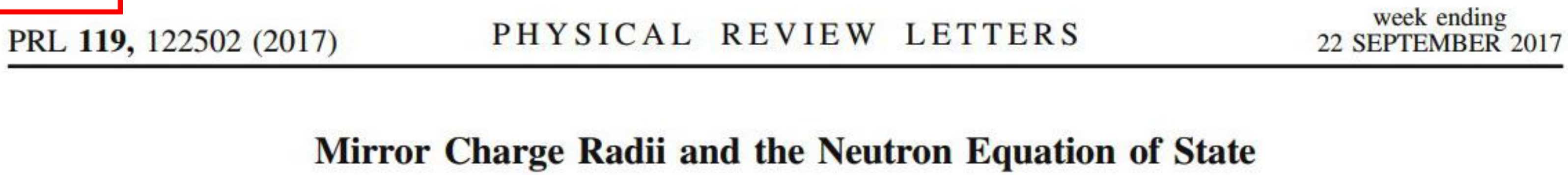
$$[E/N](\rho_{on}) = 11.3(8)\ \mathrm{MeV} \tag{17}$$

The symmetry energy at this point is

$$S(\rho_{on}) = [E/N](\rho_{on}) - [E/A](\rho_{on})$$

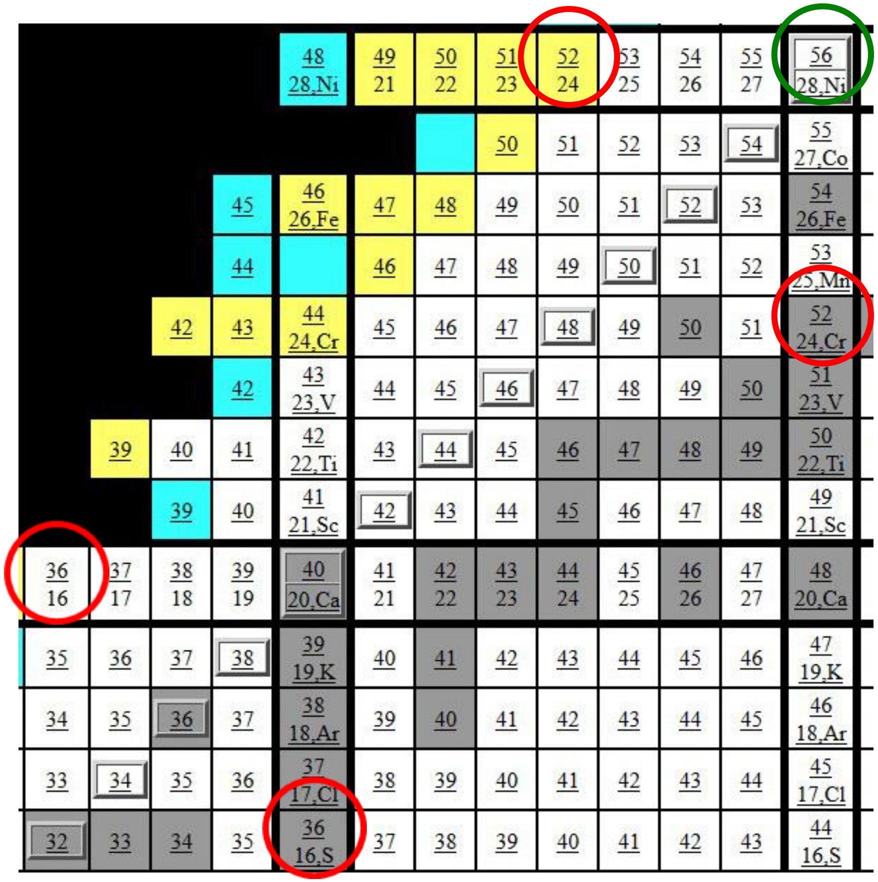
$$= 11.3(8) + 14.1(1) = 25.4(8)\ \mathrm{MeV} \tag{18}$$

Path A



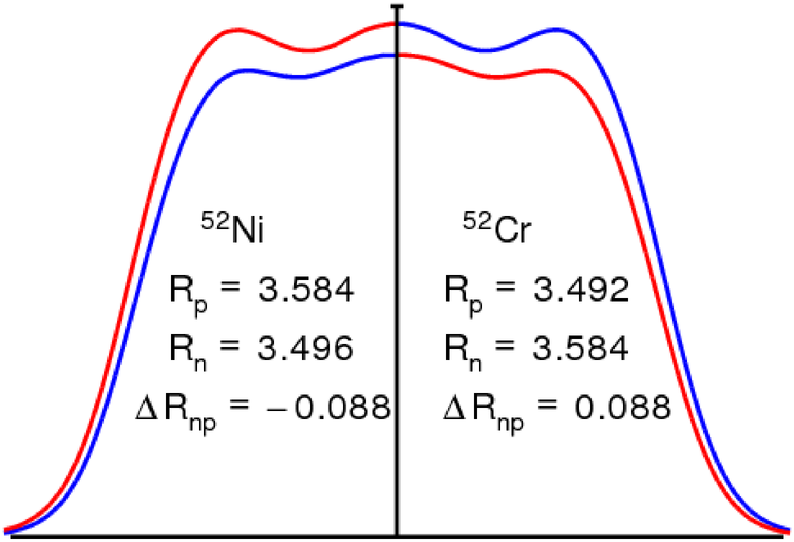
PRL **119,** 122502 (2017) PHYSICAL REVIEW LETTERS week ending 22 SEPTEMBER 2017

Mirror Charge Radii and the Neutron Equation of State

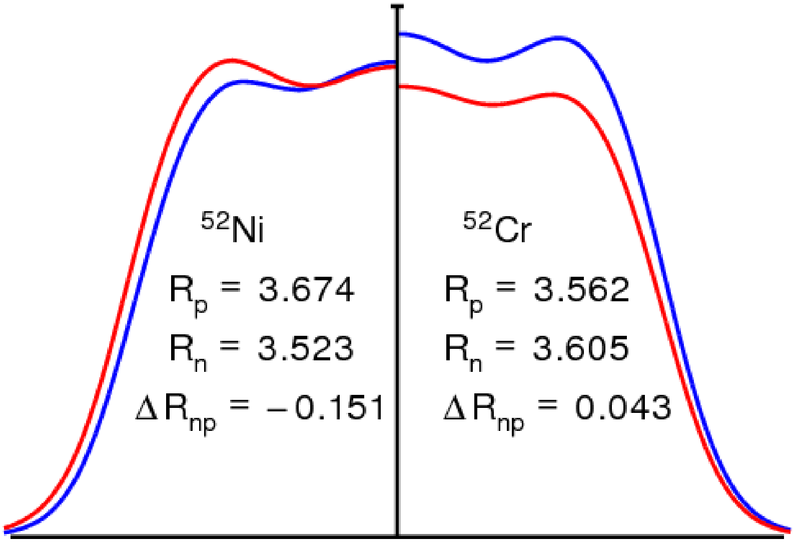


				48 28,Ni	49 21	50 22	51 23	52 24	53 25	54 26	55 27	56 28,Ni
							50	51	52	53	54	55 27,Co
			45	46 26,Fe	47	48	49	50	51	52	53	54 26,Fe
			44		46	47	48	49	50	51	52	53 25,Mn
		42	43	44 24,Cr	45	46	47	48	49	50	51	52 24,Cr
			42	43 23,V	44	45	46	47	48	49	50	51 23,V
	39	40	41	42 22,Ti	43	44	45	46	47	48	49	50 22,Ti
		39	40	41 21,Sc	42	43	44	45	46	47	48	49 21,Sc
36 16	37 17	38 18	39 19	40 20,Ca	41 21	42 22	43 23	44 24	45 25	46 26	47 27	48 20,Ca
35	36	37	38	39 19,K	40	41	42	43	44	45	46	47 19,K
34	35	36	37	38 18,Ar	39	40	41	42	43	44	45	46 18,Ar
33	34	35	36	37 17,Cl	38	39	40	41	42	43	44	45 17,Cl
32	33	34	35	36 16,S	37	38	39	40	41	42	43	44 16,S

Path A

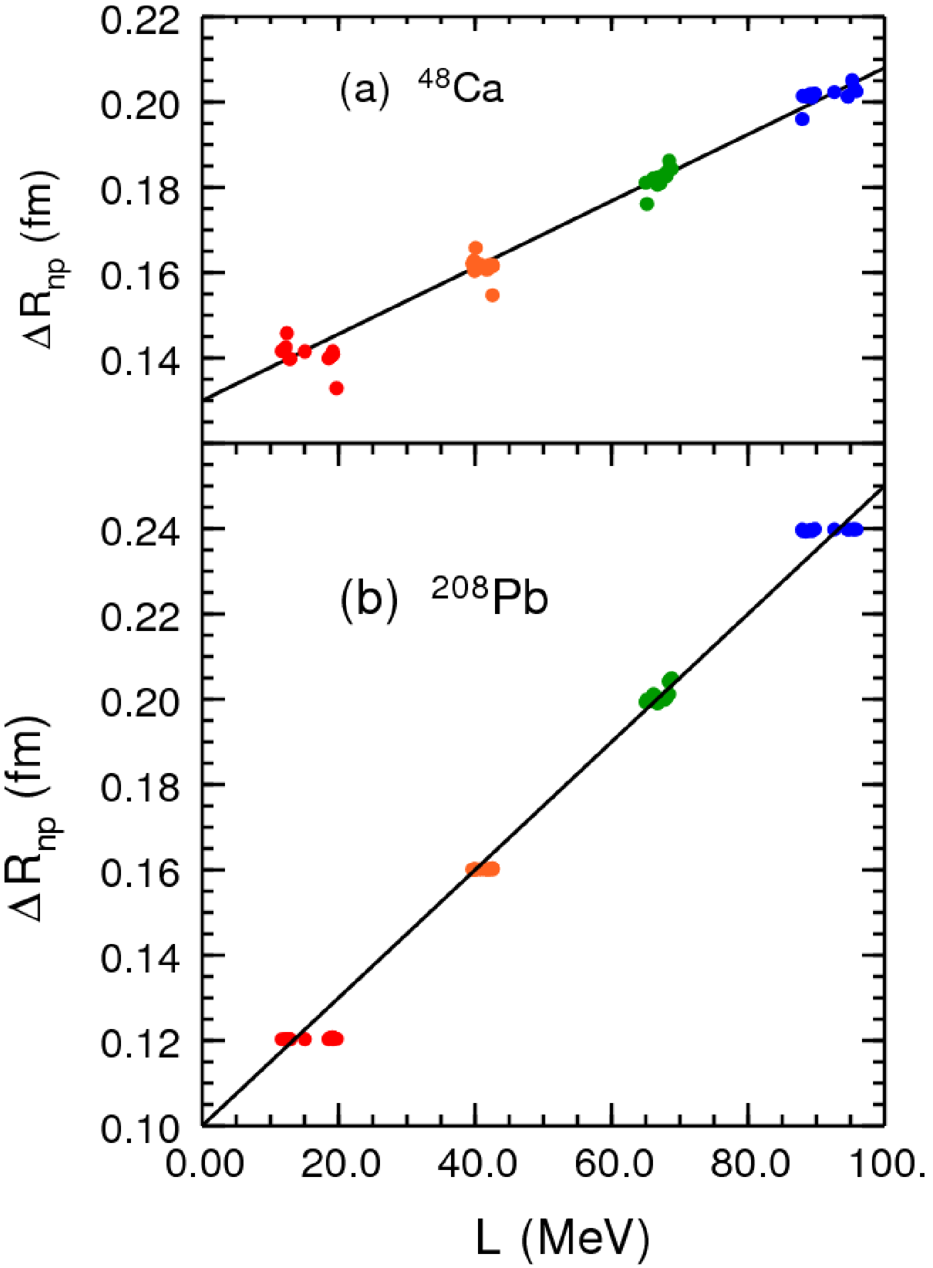


No Coulomb

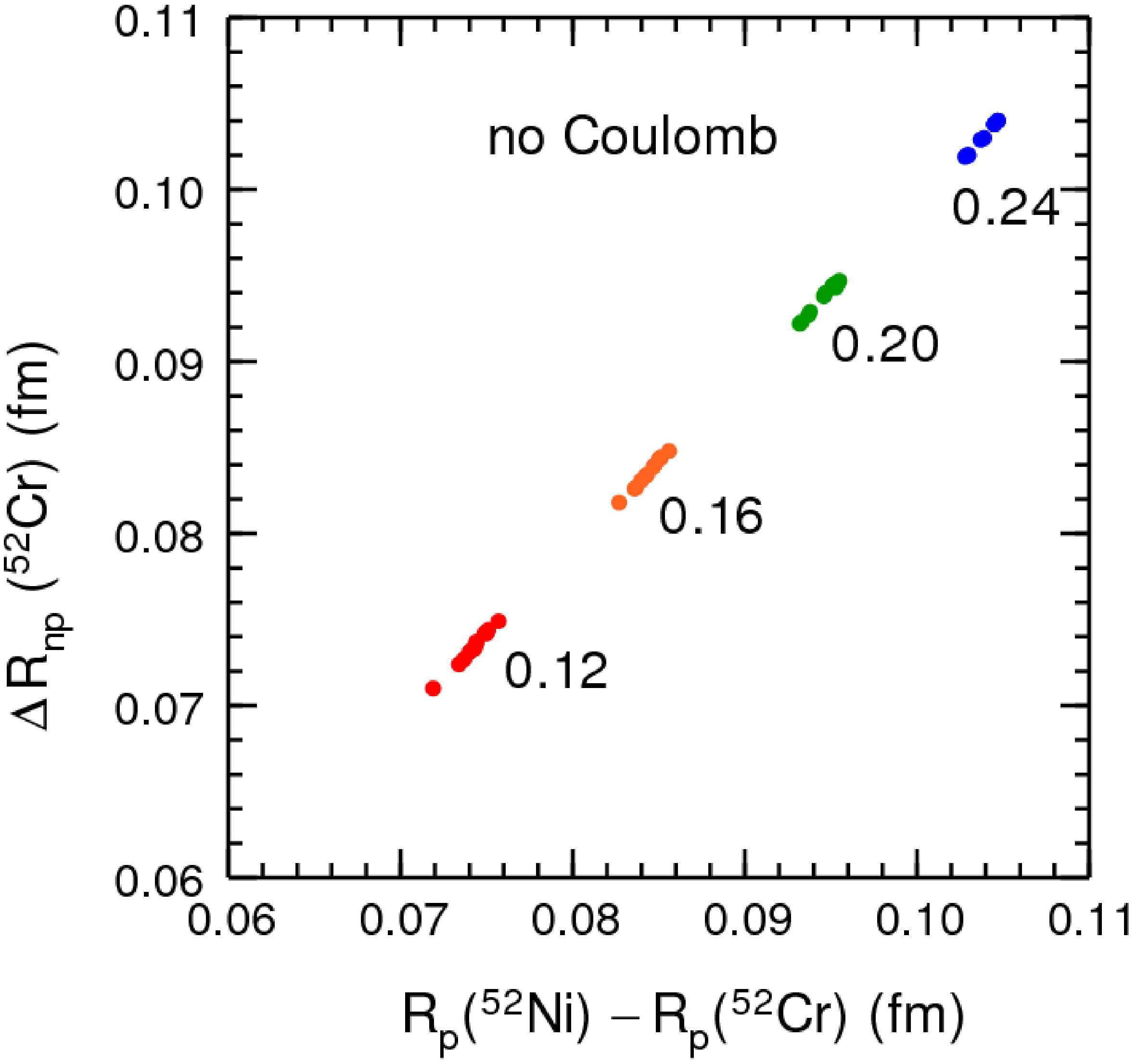


With Coulomb

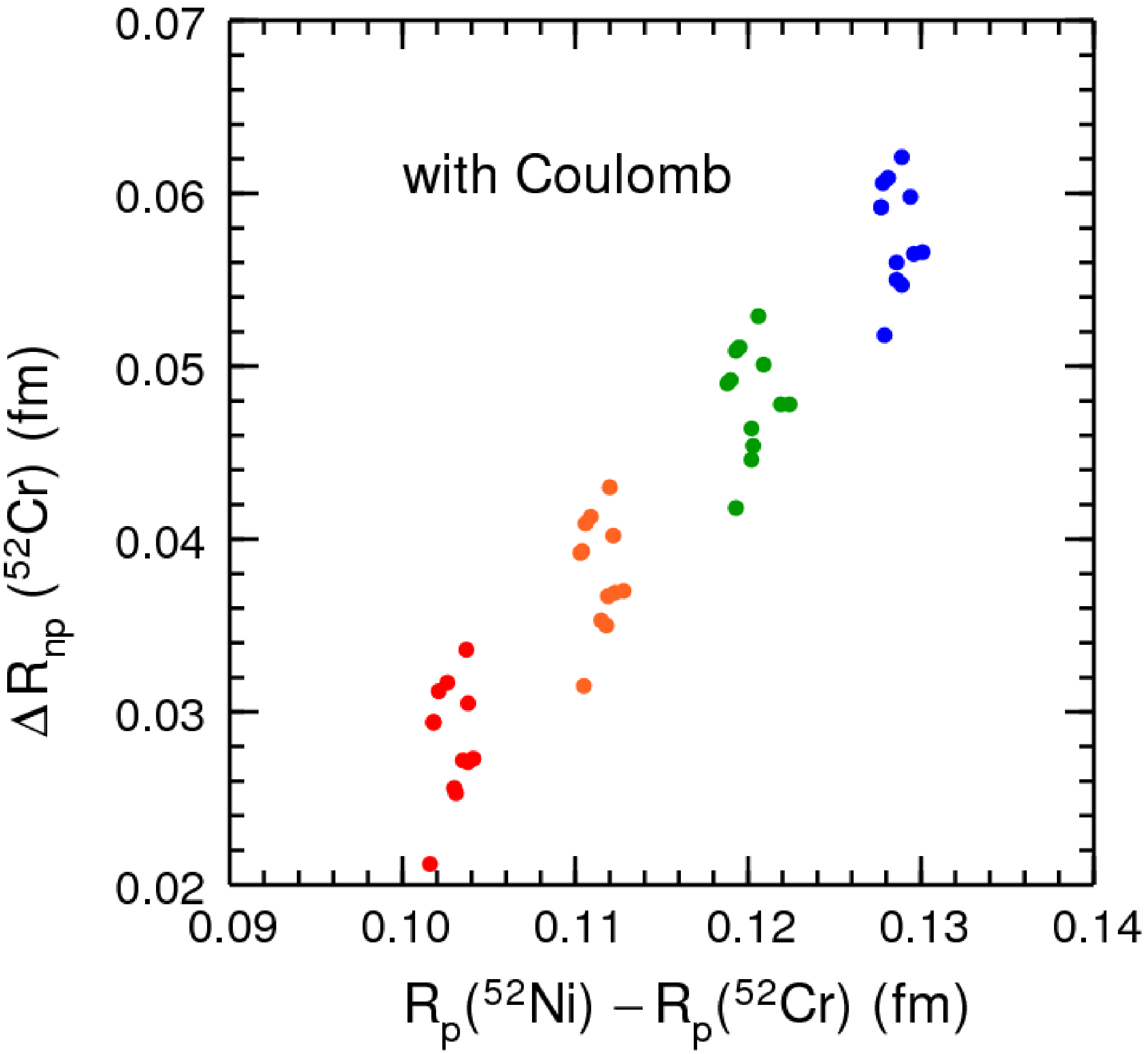
Path A


(a) ^{48}Ca
(b) ^{208}Pb
ΔR_{np} (fm)
0.22
0.20
0.18
0.16
0.14
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.00
20.0
40.0
60.0
80.0
100.
L (MeV)

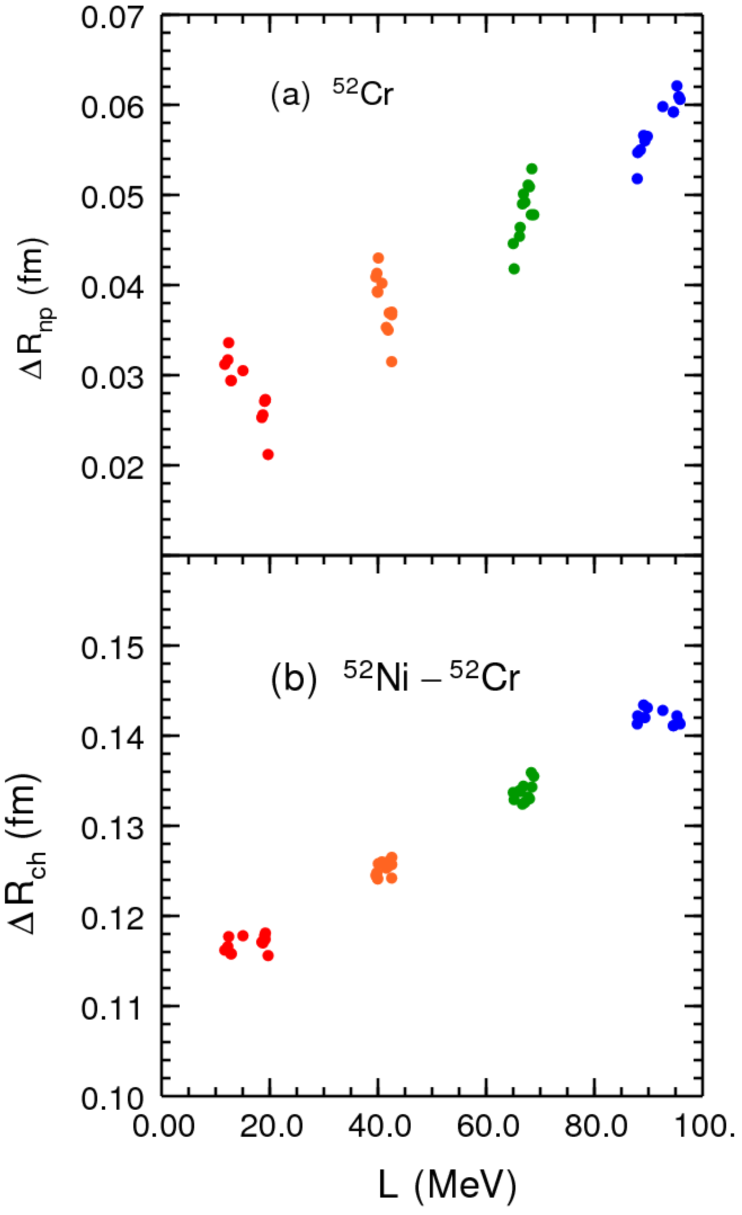
Path A


no Coulomb
0.24
0.20
0.16
0.12
0.06
0.07
0.08
0.09
0.10
0.11
ΔR_{np} (^{52}Cr) (fm)
$R_p(^{52}\mathrm{Ni}) - R_p(^{52}\mathrm{Cr})$ (fm)

Path A


with Coulomb
0.07
0.06
0.05
0.04
0.03
0.02
0.09
0.10
0.11
0.12
0.13
0.14
ΔR_{np} (^{52}Cr) (fm)
$R_p(^{52}\mathrm{Ni}) - R_p(^{52}\mathrm{Cr})$ (fm)

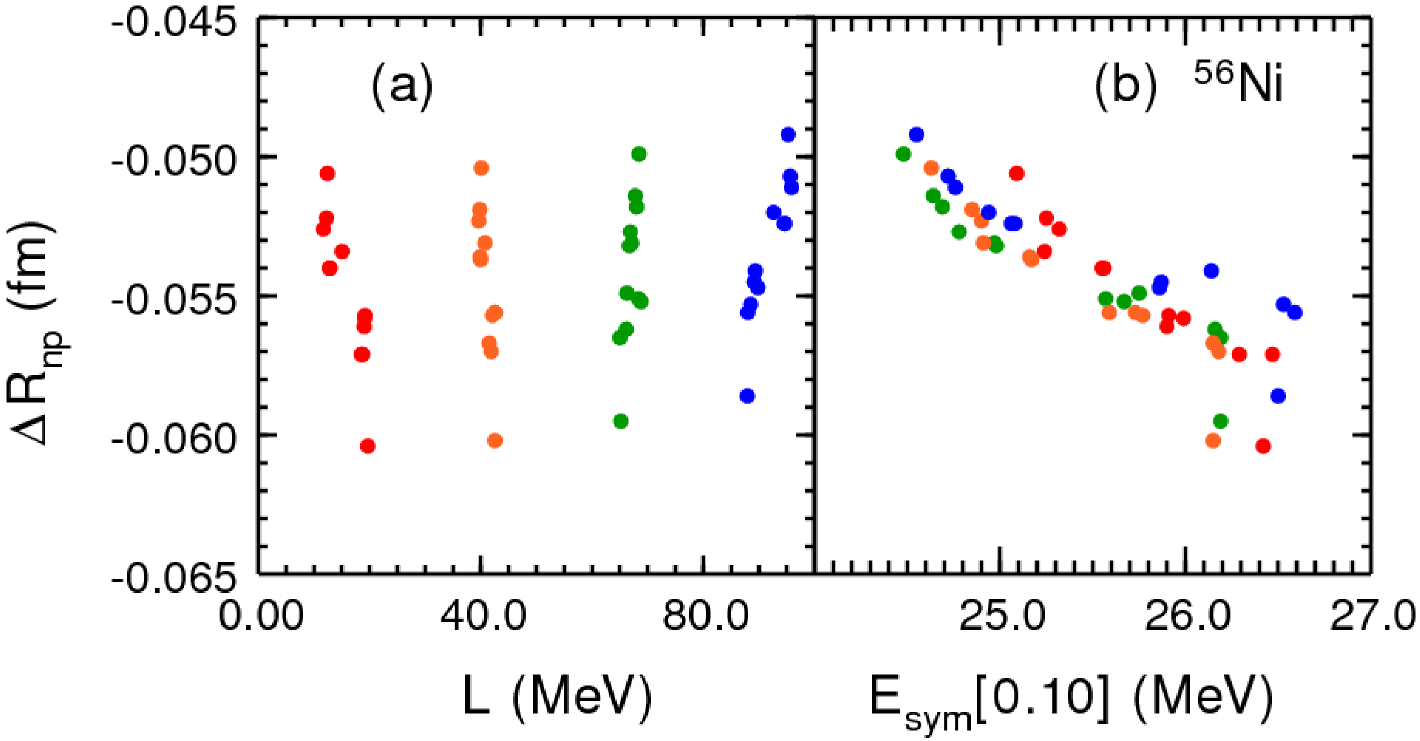
Path A



With Coulomb

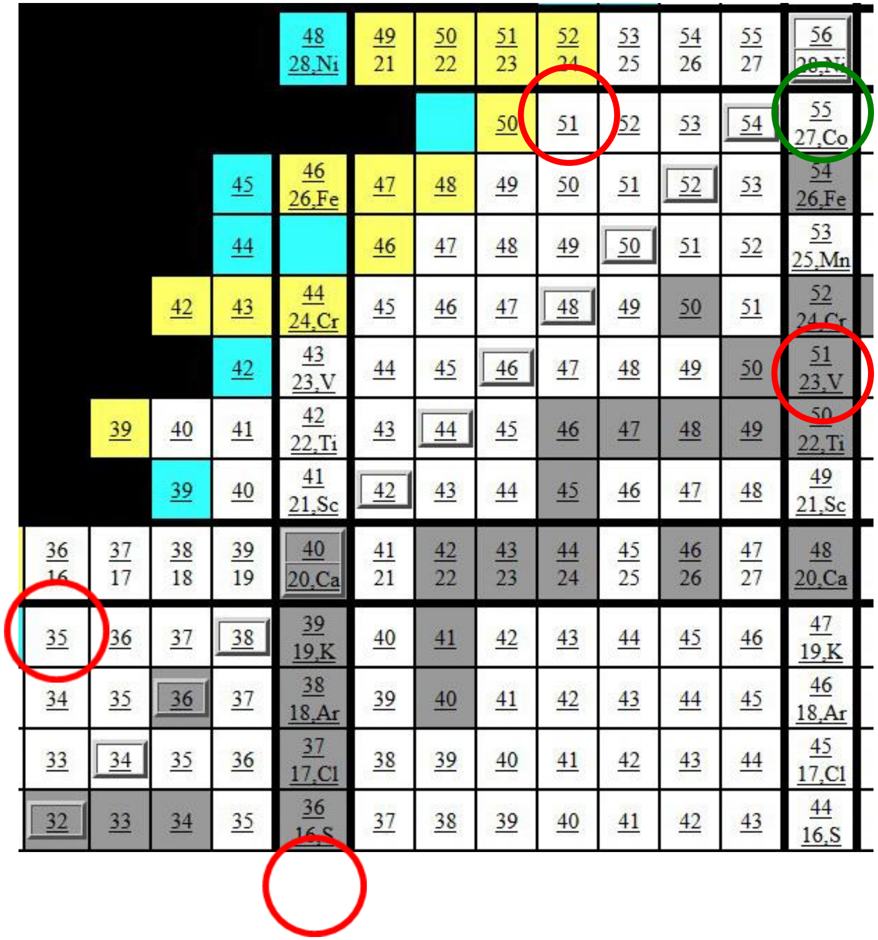
With Coulomb

Path A


(a)
(b) ^{56}Ni
-0.045
-0.050
-0.055
-0.060
-0.065
ΔR_{np} (fm)
0.00
40.0
80.0
L (MeV)
25.0
26.0
27.0
E_{sym}[0.10] (MeV)

NSCL

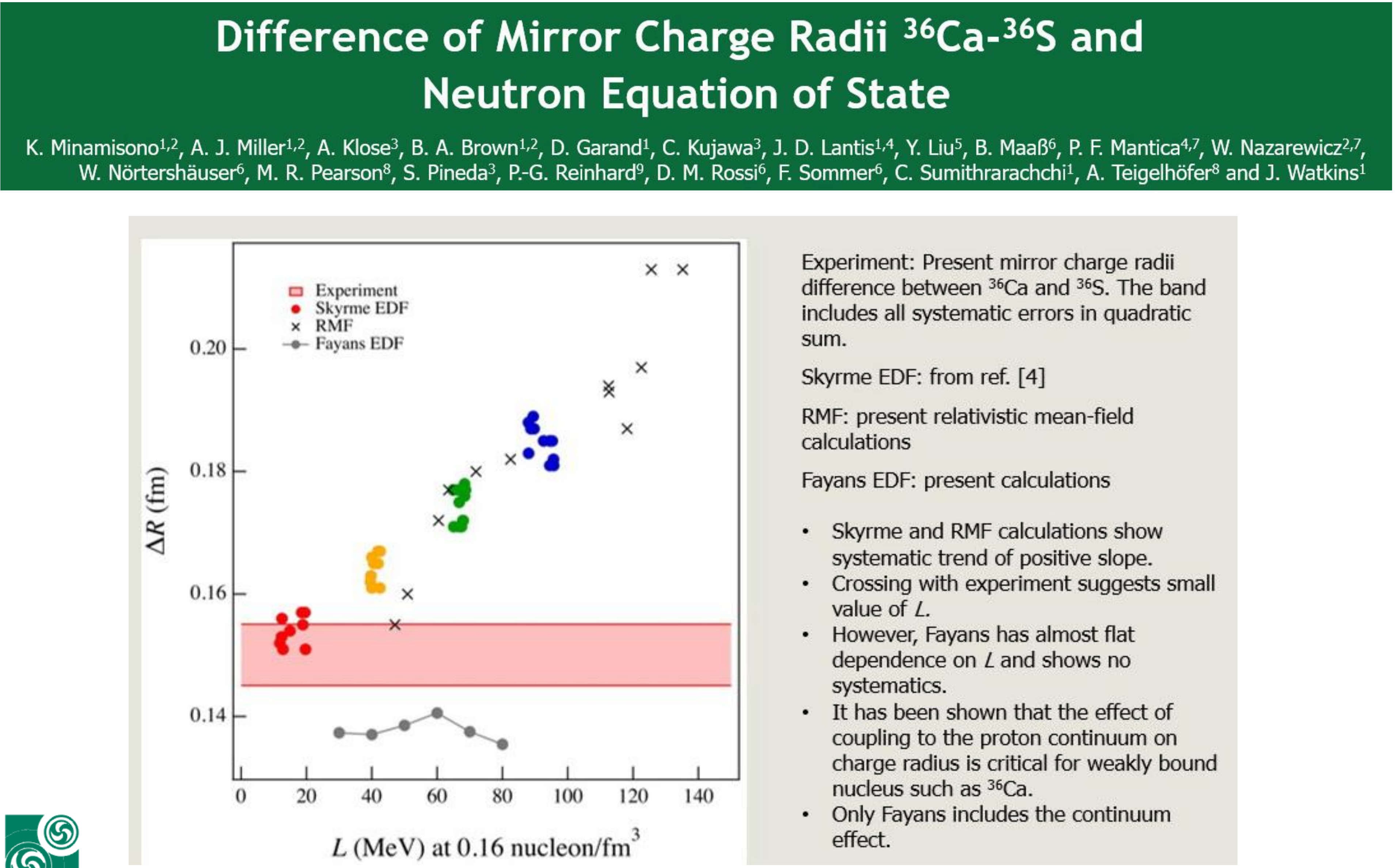
Path A



				48 28,Ni	49 21	50 22	51 23	52 24	53 25	54 26	55 27	56 28,Ni
							50	51	52	53	54	55 27,Co
			45	46 26,Fe	47	48	49	50	51	52	53	54 26,Fe
			44		46	47	48	49	50	51	52	53 25,Mn
		42	43	44 24,Cr	45	46	47	48	49	50	51	52 24,Cr
			42	43 23,V	44	45	46	47	48	49	50	51 23,V
	39	40	41	42 22,Ti	43	44	45	46	47	48	49	50 22,Ti
		39	40	41 21,Sc	42	43	44	45	46	47	48	49 21,Sc
36 16	37 17	38 18	39 19	40 20,Ca	41 21	42 22	43 23	44 24	45 25	46 26	47 27	48 20,Ca
35	36	37	38	39 19,K	40	41	42	43	44	45	46	47 19,K
34	35	36	37	38 18,Ar	39	40	41	42	43	44	45	46 18,Ar
33	34	35	36	37 17,Cl	38	39	40	41	42	43	44	45 17,Cl
32	33	34	35	36 16,S	37	38	39	40	41	42	43	44 16,S

Path A

Poster presented at NS2018



Difference of Mirror Charge Radii ^{36}Ca-^{36}S and Neutron Equation of State

K. Minamisono[1,2], A. J. Miller[1,2], A. Klose[3], B. A. Brown[1,2], D. Garand[1], C. Kujawa[3], J. D. Lantis[1,4], Y. Liu[5], B. Maaß[6], P. F. Mantica[4,7], W. Nazarewicz[2,7], W. Nörtershäuser[6], M. R. Pearson[8], S. Pineda[3], P.-G. Reinhard[9], D. M. Rossi[6], F. Sommer[6], C. Sumithrarachchi[1], A. Teigelhöfer[8] and J. Watkins[1]

Experiment: Present mirror charge radii difference between ^{36}Ca and ^{36}S. The band includes all systematic errors in quadratic sum.

Skyrme EDF: from ref. [4]

RMF: present relativistic mean-field calculations

Fayans EDF: present calculations

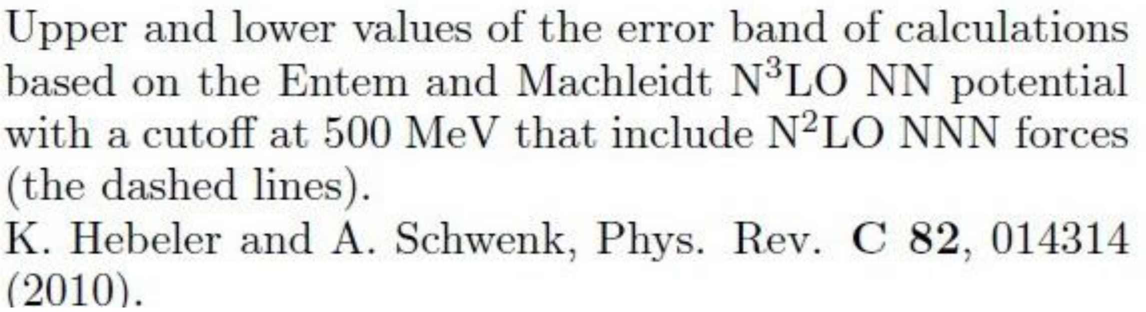
- Skyrme and RMF calculations show systematic trend of positive slope.
- Crossing with experiment suggests small value of *L*.
- However, Fayans has almost flat dependence on *L* and shows no systematics.
- It has been shown that the effect of coupling to the proton continuum on charge radius is critical for weakly bound nucleus such as ^{36}Ca.
- Only Fayans includes the continuum effect.

Path A

0.05 fm is a very small radius scale – we need to consider

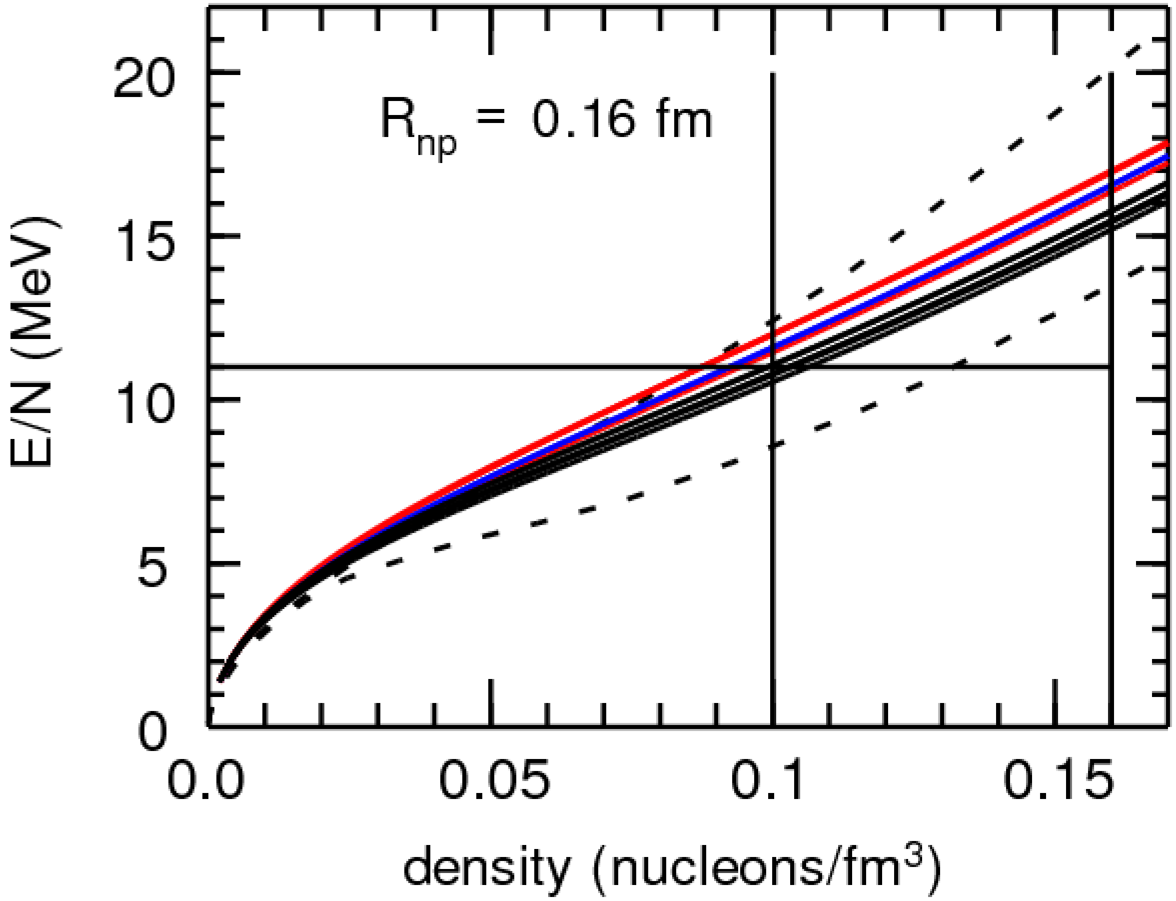
1) Proton size problem (0.04 fm)
2) Spin-orbit relativistic correction to the charge radius (0.02 fm)
3) Mirror asymmetry in the deformation, B(E2), correction (0.02 fm)
4) Near the proton continuum for proton-rich nuclei (?)

Path B

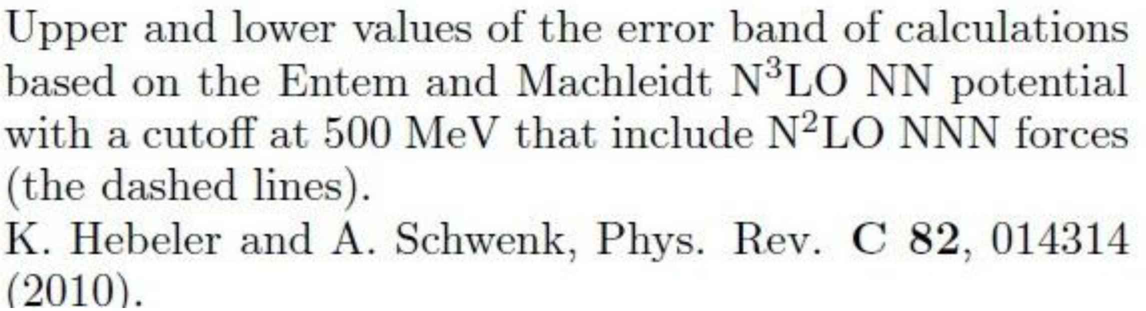


Upper and lower values of the error band of calculations based on the Entem and Machleidt N^3LO NN potential with a cutoff at 500 MeV that include N^2LO NNN forces (the dashed lines).

K. Hebeler and A. Schwenk, Phys. Rev. **C 82**, 014314 (2010).



Path B



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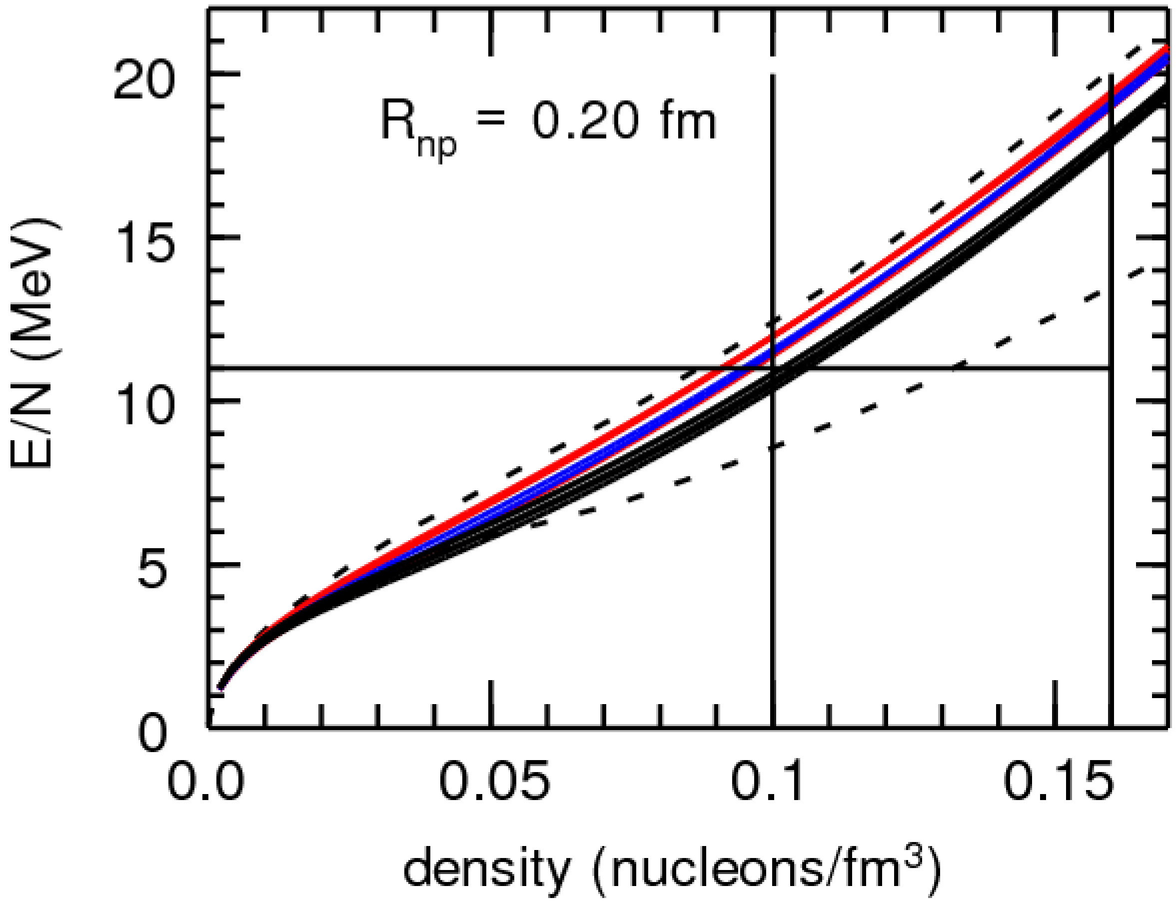
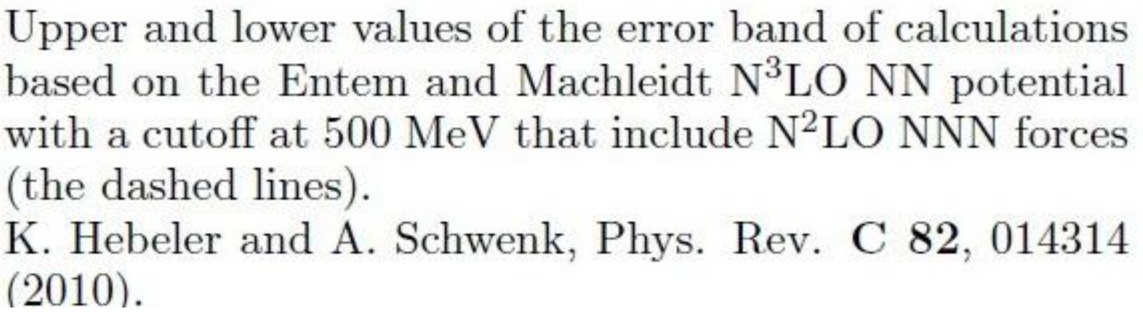


Path B



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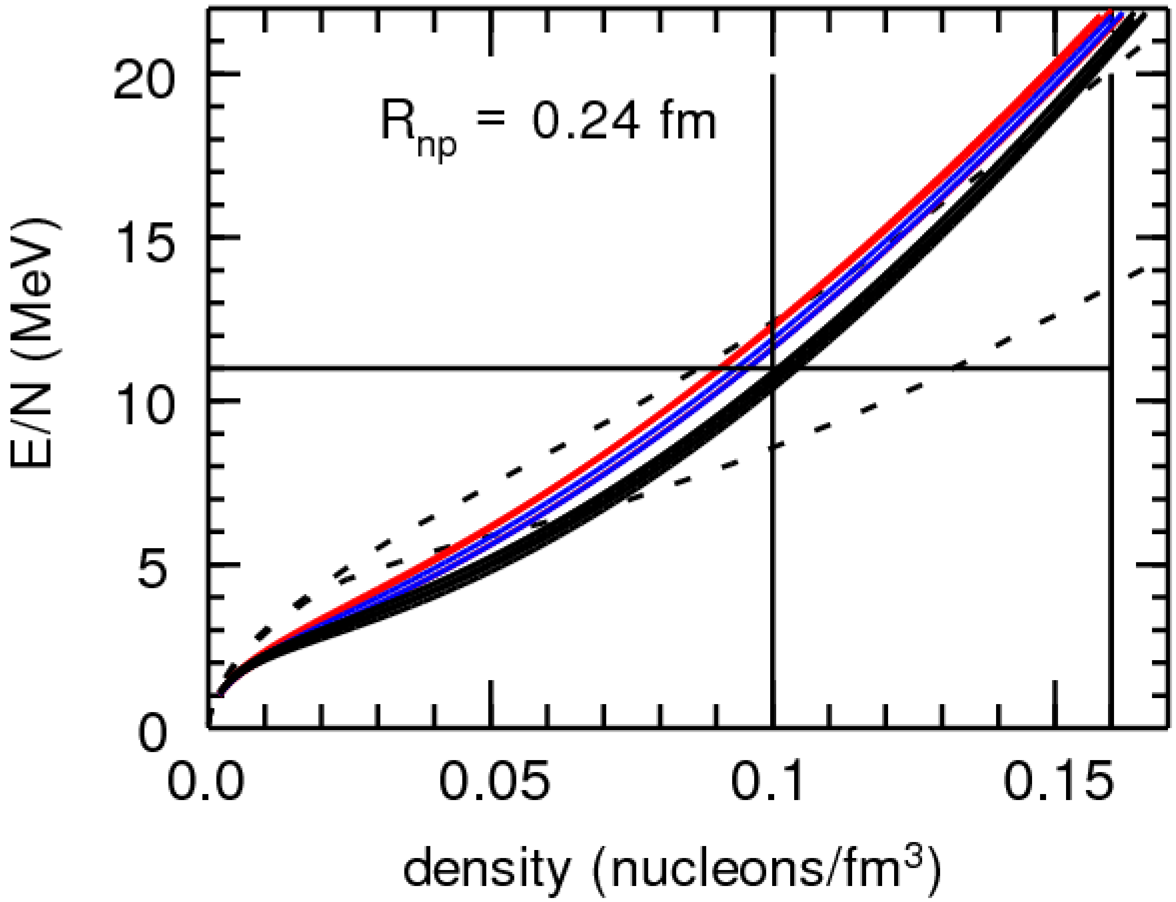

Path B

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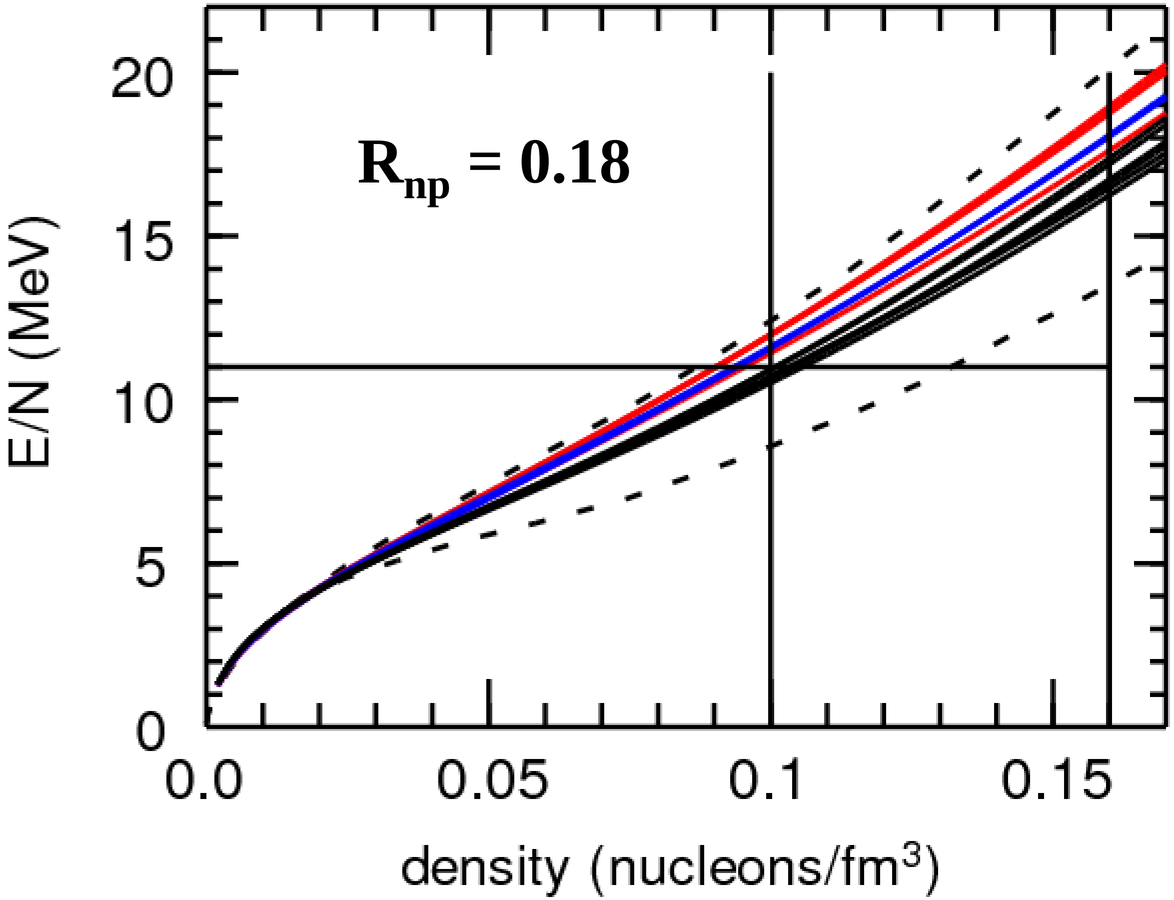


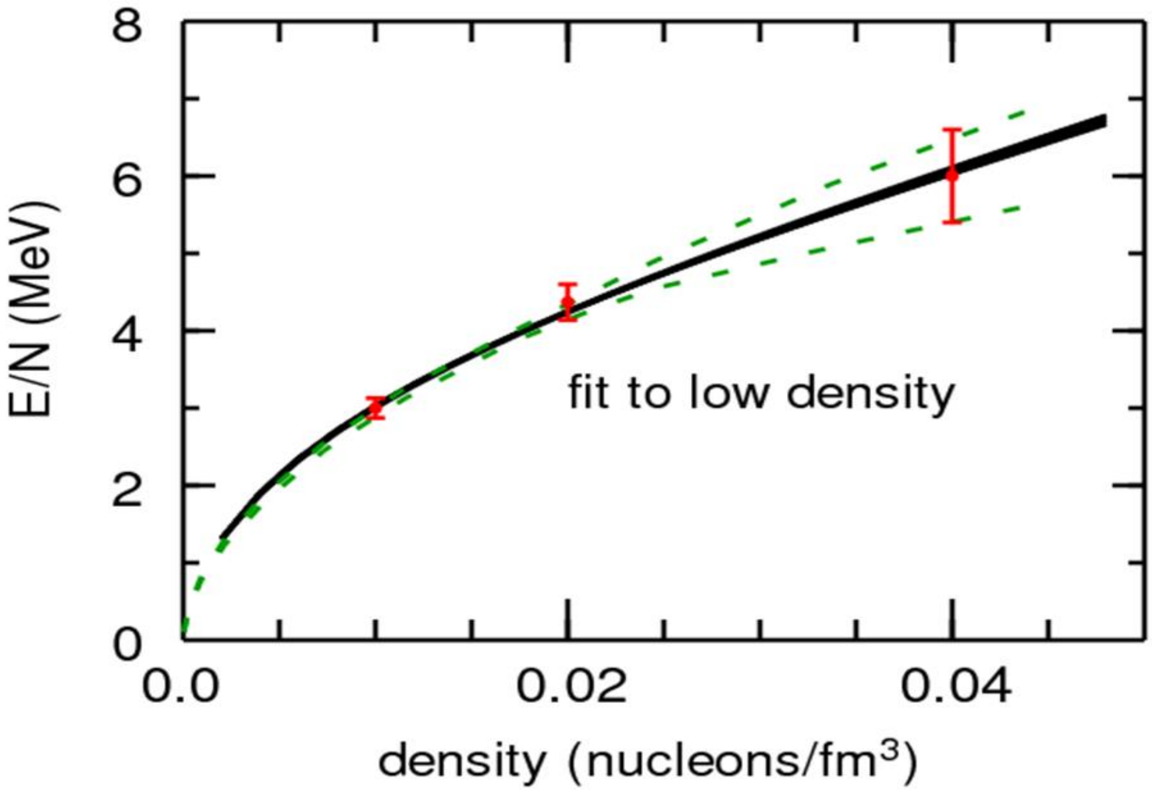
Path B

RAPID COMMUNICA

PHYSICAL REVIEW C **89**, 011307(R) (2014)

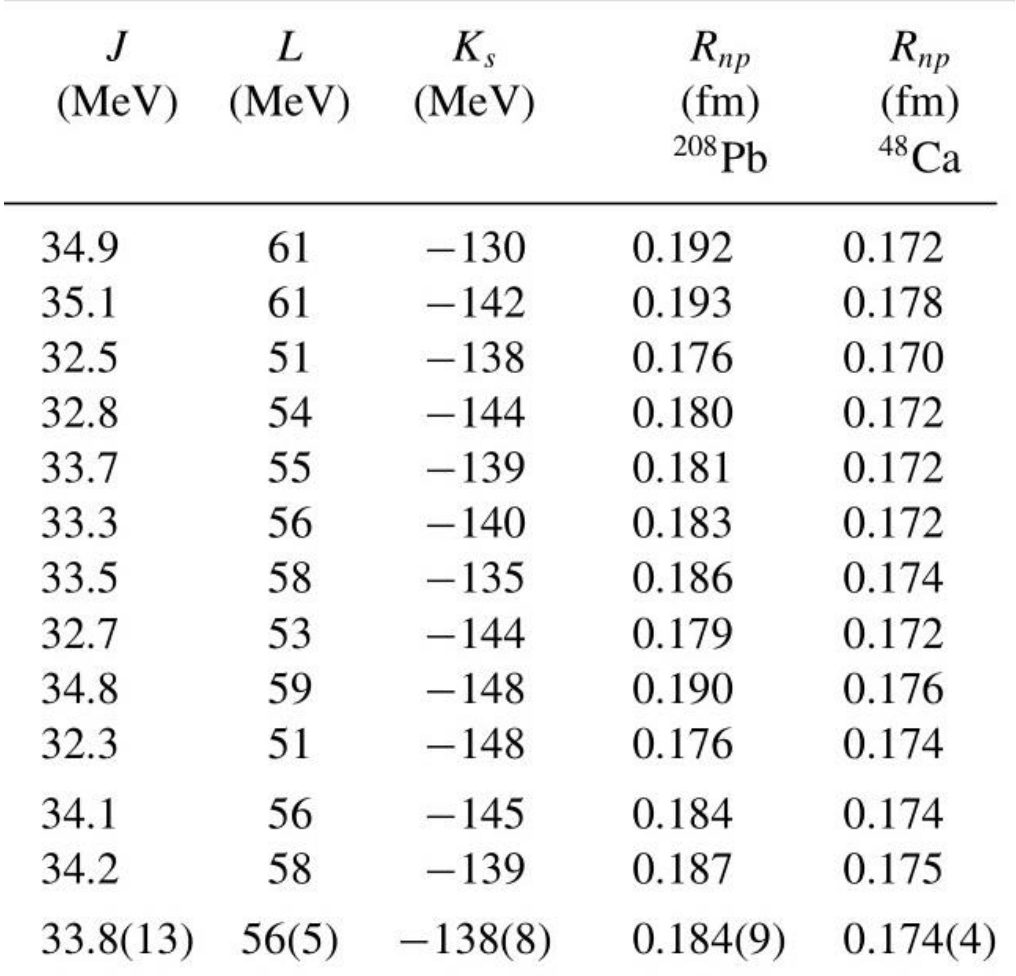
Constraints on Skyrme equations of state from properties of doubly magic nuclei and *ab initio* calculations of low-density neutron matter

B. Alex Brown[1] and A. Schwenk[2,3]



Path B

The low-density and nuclear fit was not sensitive to the neutron effective mass, and we assumed that $[m_n^*/m]$ (at 0.16 nucleons/fm3) = 0.85



J (MeV)	L (MeV)	K_s (MeV)	R_{np} (fm) ^{208}Pb	R_{np} (fm) ^{48}Ca
34.9	61	−130	0.192	0.172
35.1	61	−142	0.193	0.178
32.5	51	−138	0.176	0.170
32.8	54	−144	0.180	0.172
33.7	55	−139	0.181	0.172
33.3	56	−140	0.183	0.172
33.5	58	−135	0.186	0.174
32.7	53	−144	0.179	0.172
34.8	59	−148	0.190	0.176
32.3	51	−148	0.176	0.174
34.1	56	−145	0.184	0.174
34.2	58	−139	0.187	0.175
33.8(13)	56(5)	−138(8)	0.184(9)	0.174(4)

Path B

The result is that we predict !

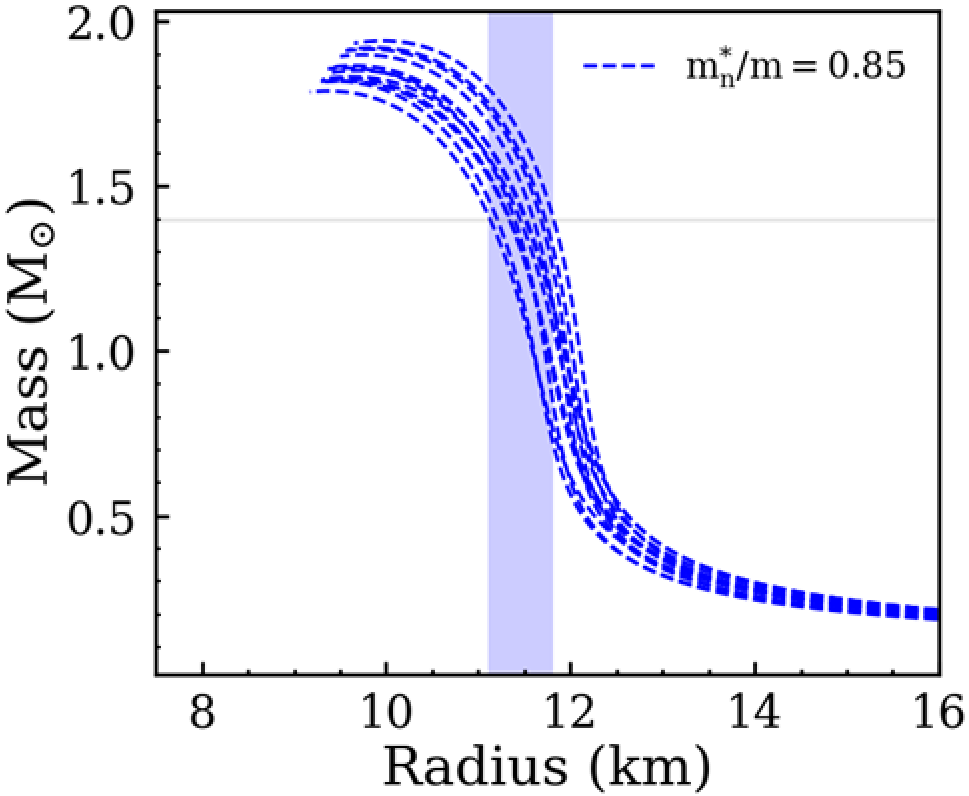
L_v = 56(5) MeV

$R_{np}(^{208}\mathrm{Pb})$ = 0.184(9) fm

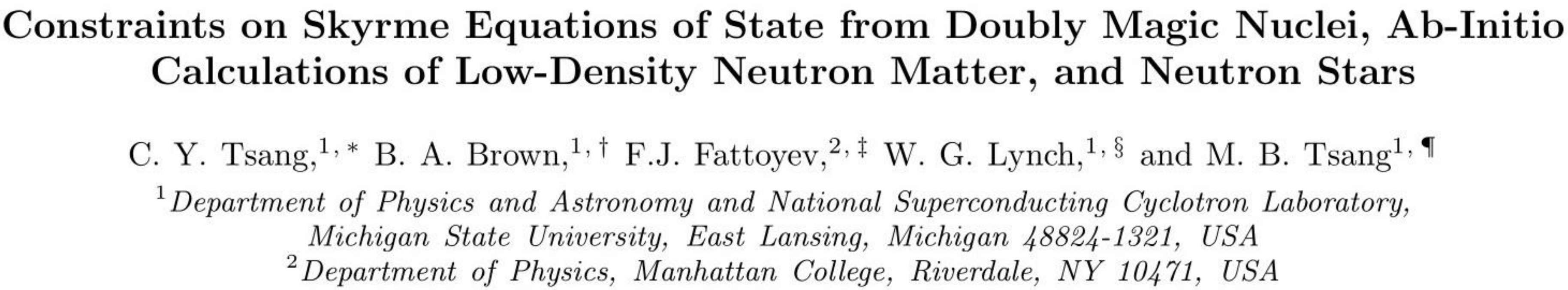
$R_{np}(^{48}\mathrm{Ca})$ = 0.173(4) fm

What if these turn out to be wrong? – then

1) The ab initio low-density neutron EOS is wrong
2) The Skyrme functional form is wrong


2.0
1.5
1.0
0.5
Mass ($M_\odot$)
8
10
12
14
16
Radius (km)
$m_n^*/m = 0.85$

Path C

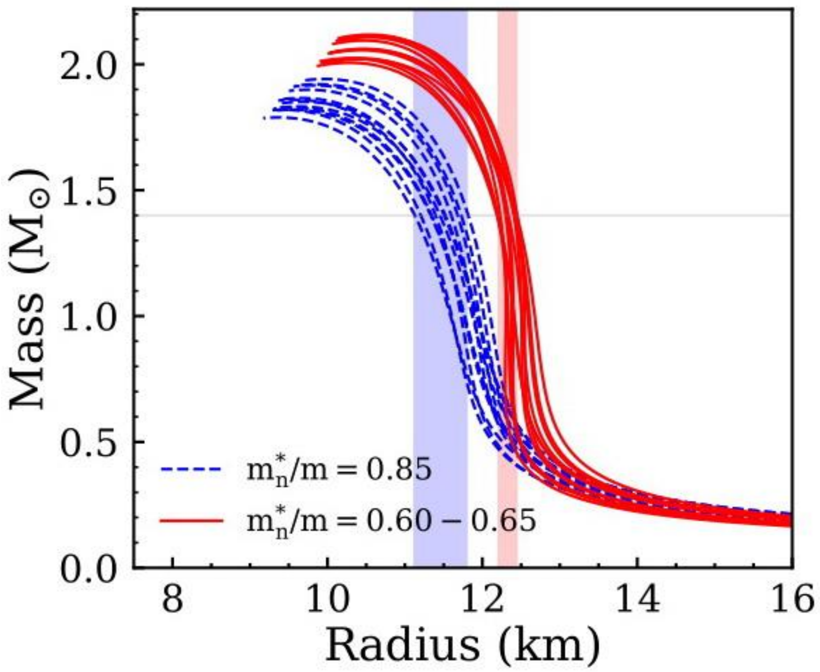


Constraints on Skyrme Equations of State from Doubly Magic Nuclei, Ab-Initio Calculations of Low-Density Neutron Matter, and Neutron Stars

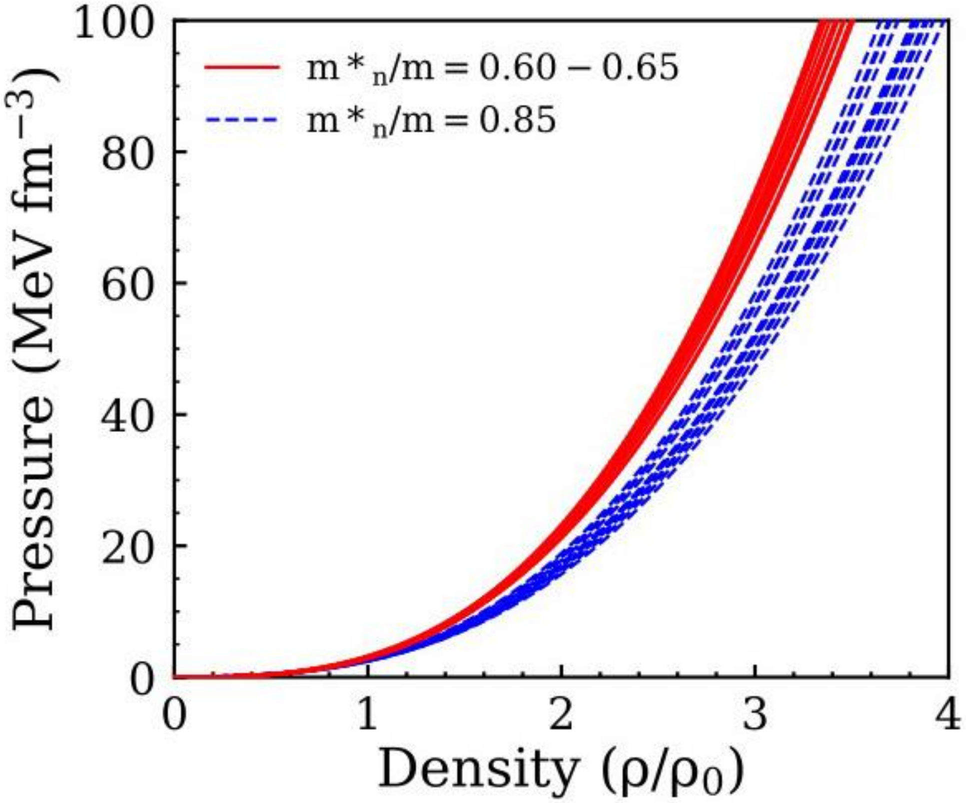
C. Y. Tsang,[1,*] B. A. Brown,[1,†] F.J. Fattoyev,[2,‡] W. G. Lynch,[1,§] and M. B. Tsang[1,¶]

[1] *Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321, USA*

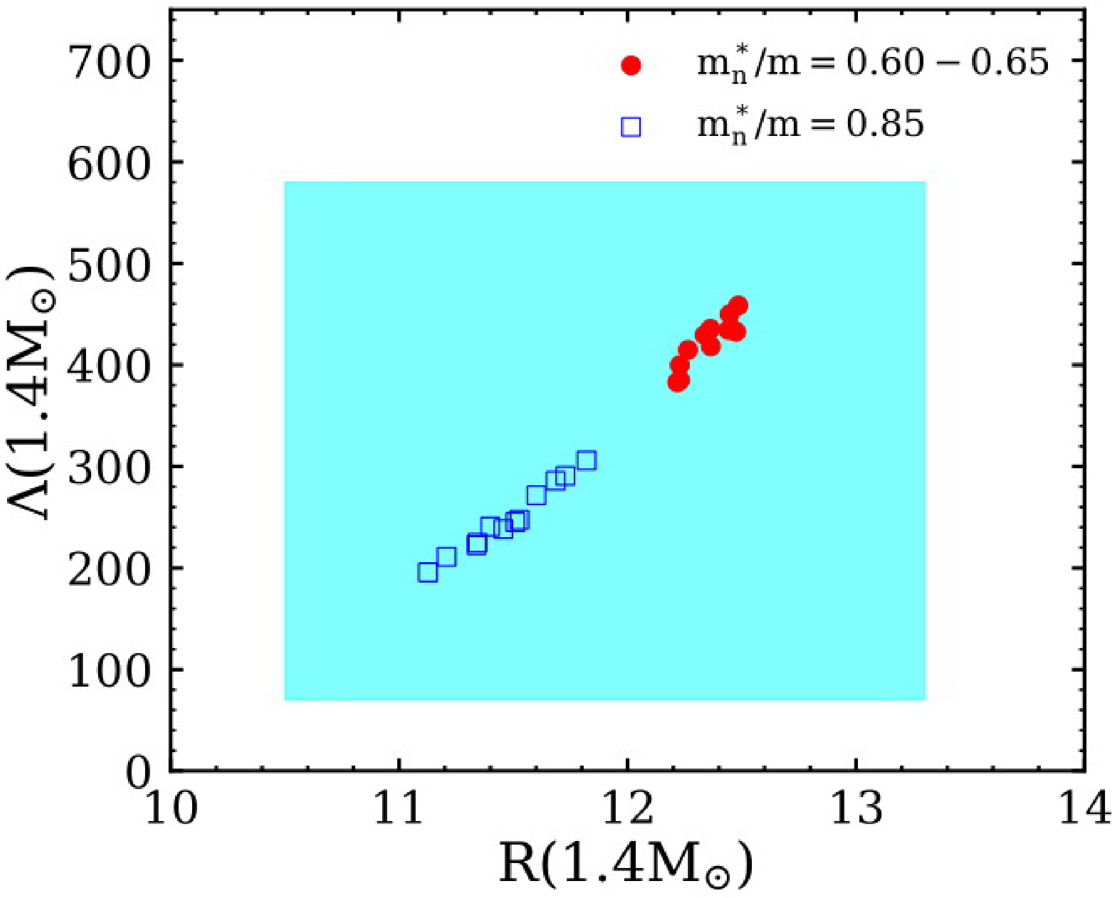
[2] *Department of Physics, Manhattan College, Riverdale, NY 10471, USA*



Path C


m*n/m = 0.60 – 0.65
m*n/m = 0.85
Pressure (MeV fm⁻³)
100
80
60
40
20
0
0
1
2
3
4
Density (ρ/ρ0)

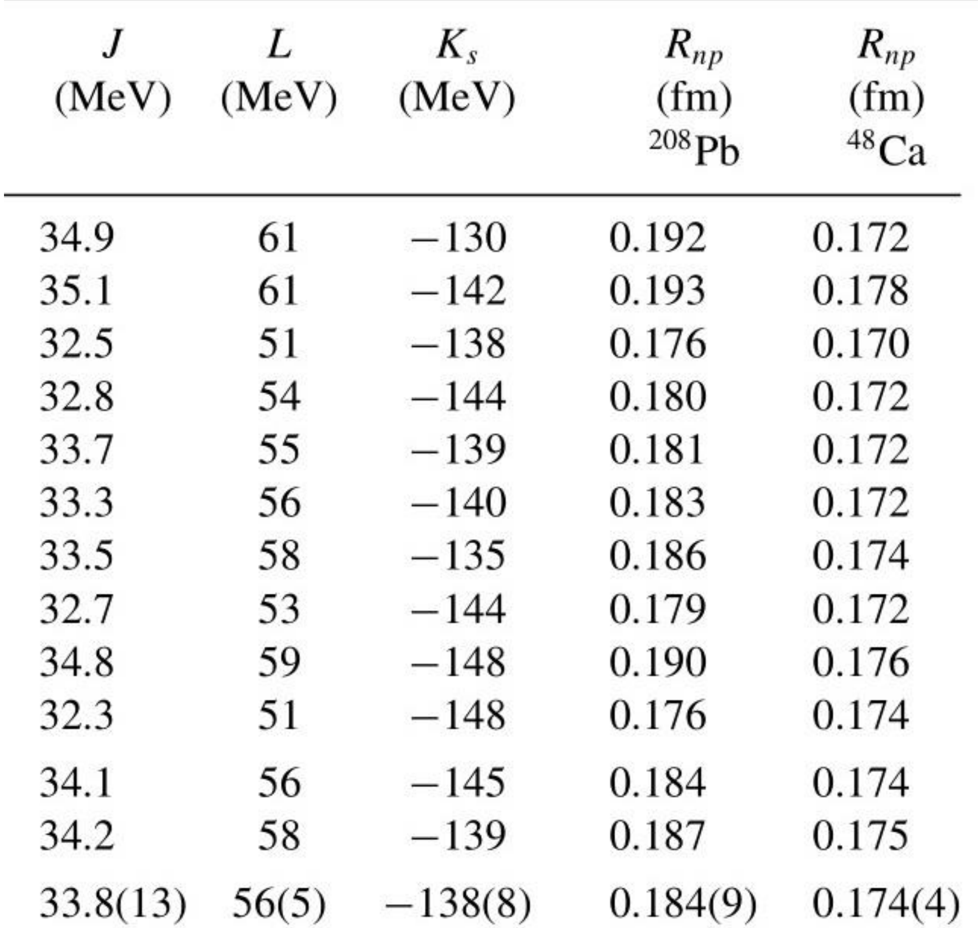
Path C



Blue area is the region allowed by the LIGO event GW170817

Path C

Max neutron star mass requires [m_n^*/m] (at 0.16 nucleons/fm3) = 0.60-0.65



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34.2	58	−139	0.187	0.175
33.8(13)	56(5)	−138(8)	0.184(9)	0.174(4)

Path C

Max neutron star mass requires [m_n*/m] (at 0.16 nucleons/fm3) = 0.60-0.65

This is determined from nuclear matter high 3-5 times normal nuclear matter

Maybe for high density Skyrme EDF it is just mocking up new physics

But at least Skyrme EDF is capable of provided a smooth parameterization for

1) ab-initio low-density neutron matter
2) BE and radii of nuclei
3) Max mass of neutron starts