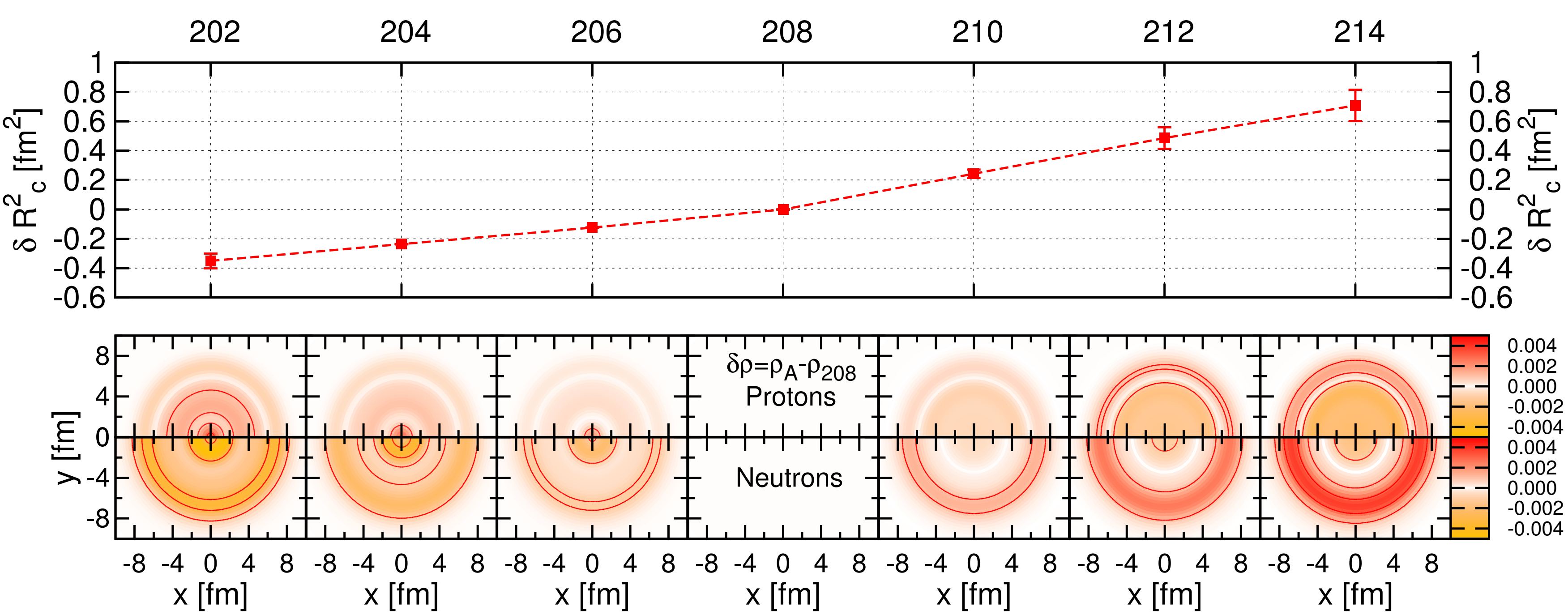
Why is lead so kinky?

Charge Radius Isotope Shift Across the N=126 Shell Gap



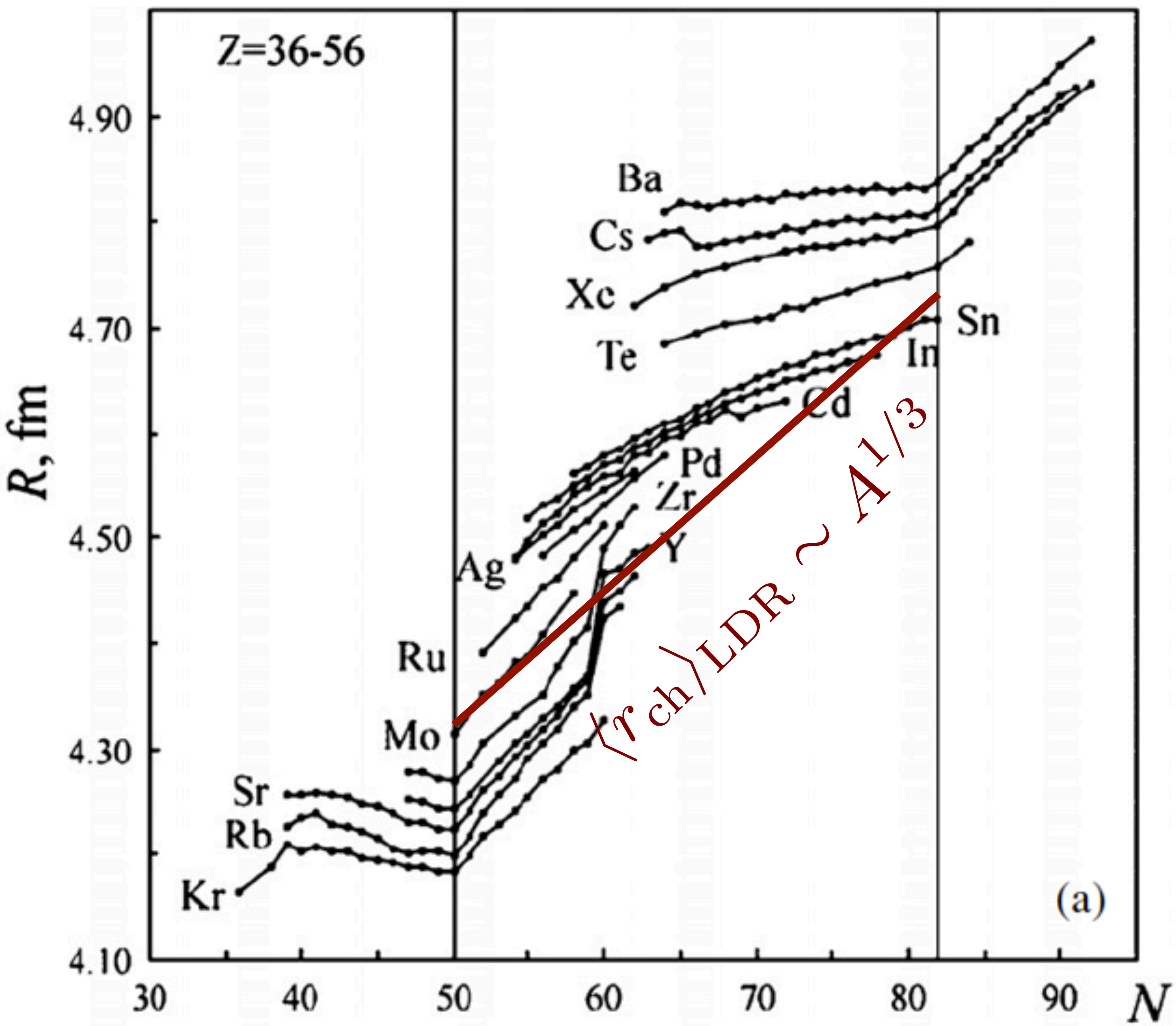
P. Goddard, P. Stevenson & A.R., *Phys. Rev. Lett.* **110**, 032503 (2013)

Arnau Rios Huguet
STFC Advanced Fellow
Department of Physics
University of Surrey

INT Program on Medium Mass nuclei (15 April 2013)

Nuclear radii

Medium mass nuclei systematics



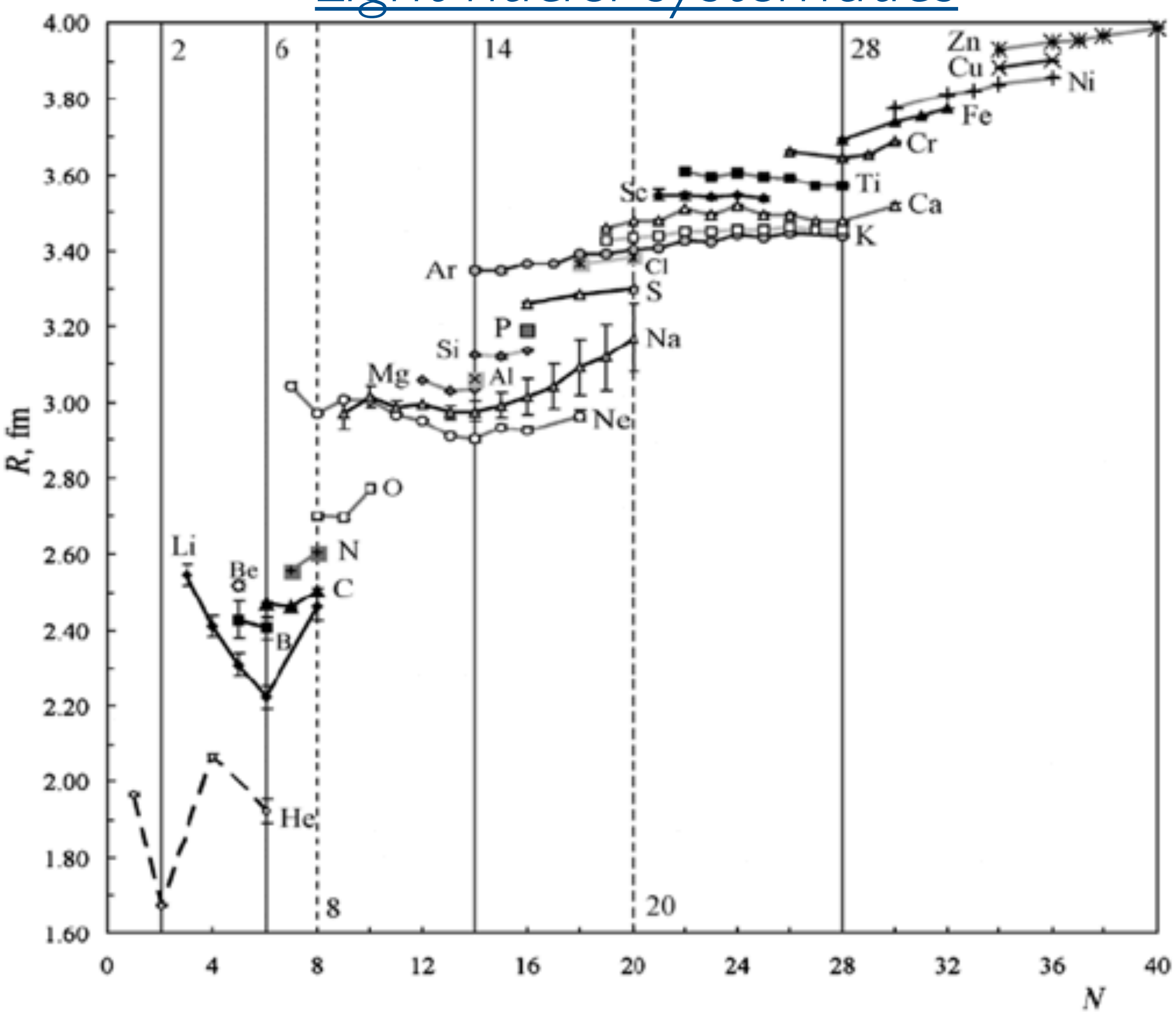
- Kinks are ubiquitous
- Shell effects influence radii
- 1/3 power valid in specific cases

$$\langle r_{\rm ch} \rangle_{\rm emp} \sim A^{0.003Z}$$

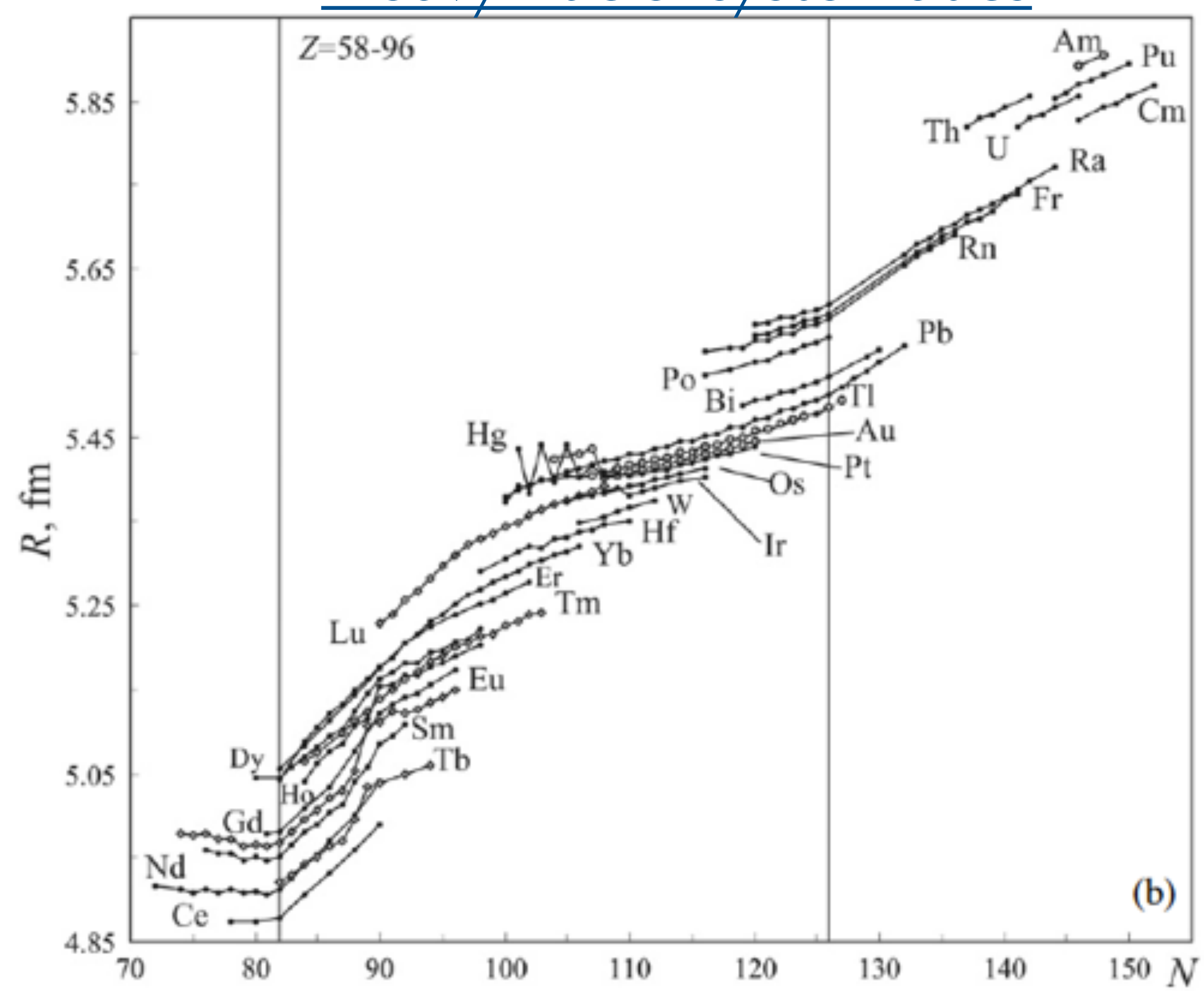
Angeli et al., *J. Phys. G: Nucl. Part. Phys.* **36** 085102 (2009)

Nuclear radii
Experiments

Light nuclei systematics



Heavy nuclei systematics



$$\langle r_{\rm ch}\rangle_{\rm RMS} \sim A^{1/3}?$$

Isotope shift in droplet model

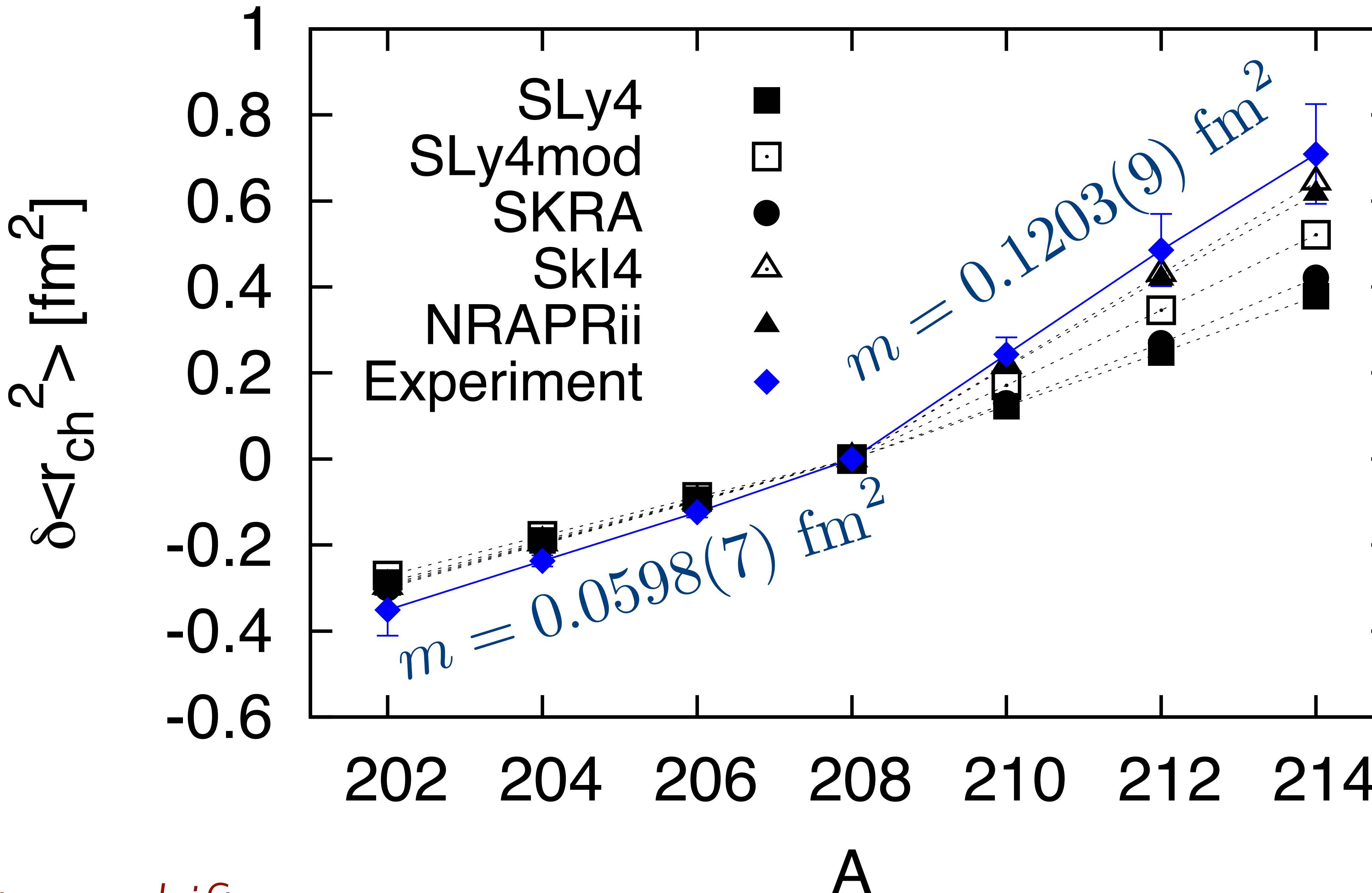
$$\delta\langle r^2_{\rm ch}\rangle = \langle r^2_{\rm ch}\rangle_A - \langle r^2_{\rm ch}\rangle_{A'} \sim 0.575\frac{\delta A}{A^{1/3}}$$

Angeli et al., *J. Phys. G: Nucl. Part. Phys.* ***36*** 085102 (2009)

A deeper look

UNIVERSITY OF SURREY

Isotope shifts in lead isotopes: theory vs experiment



Isotope shifts

$$\delta\langle r^2_{\rm ch}\rangle = \langle r^2_{\rm ch}\rangle_A - \langle r^2_{\rm ch}\rangle_{208} = m(A-208)$$

$$m_{\rm LDR} = 0.0972\ \mathrm{fm}^2$$

Nuclear radii: experiments

4 methods to extract radii from experiments:

Angeli et al., *J. Phys. G: Nucl. Part. Phys.* **36** 085102 (2009)

1. Transition energies in muonic atoms

$$a_\mu = \frac{\hbar}{m_\mu c \alpha} = \frac{m_e}{m_\mu} a_0 \sim 200 \text{ fm}$$

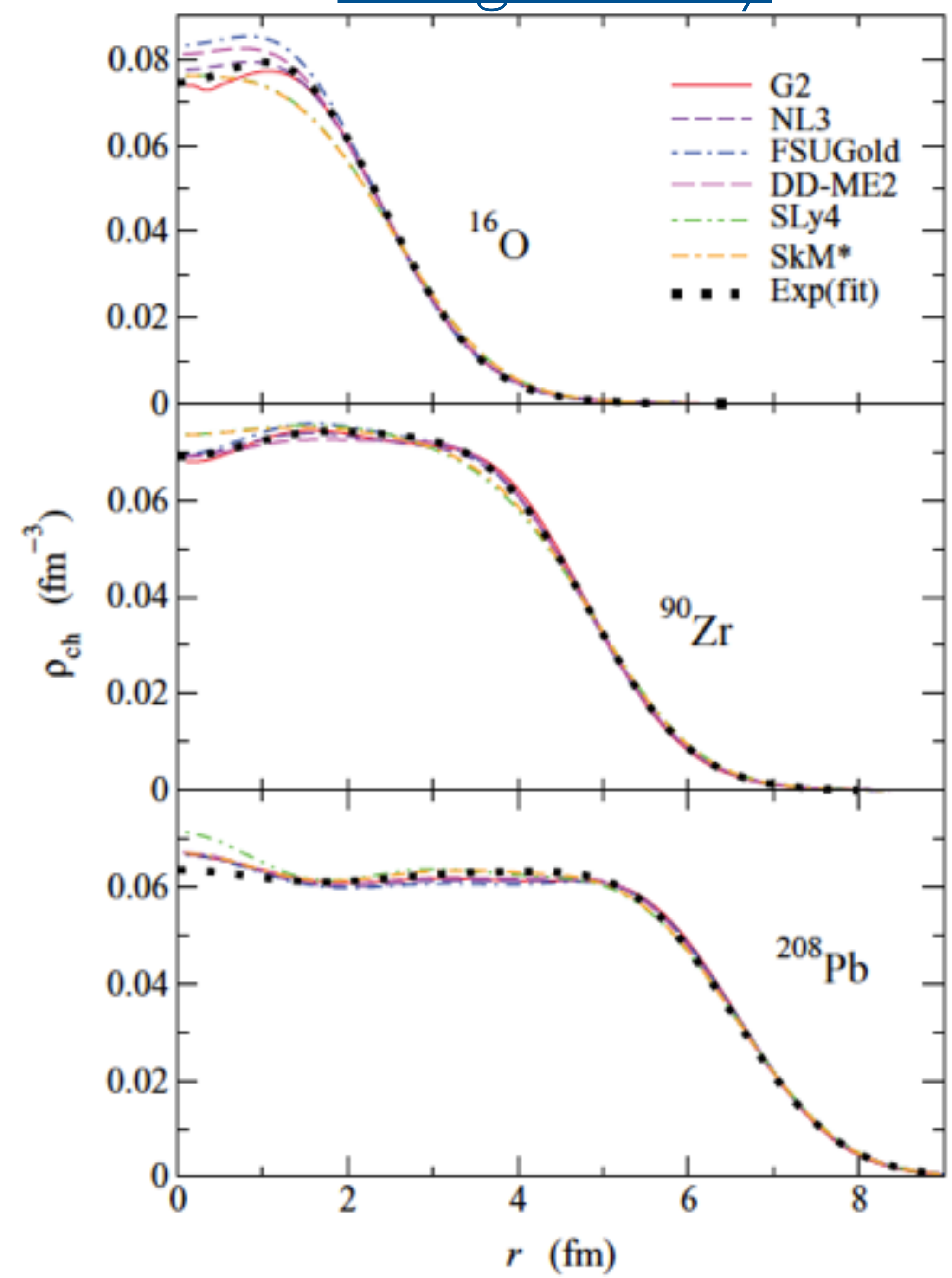
$$E \sim B_{k,\alpha} = \int dr\, r^k \rho(r) e^{-\alpha r}$$

2. Elastic electron scattering

$$\langle r^2_{\rm ch} \rangle = \frac{\int dr\, r^4 \rho_{\rm ch}(r)}{\int dr\, r^2 \rho_{\rm ch}(r)}$$

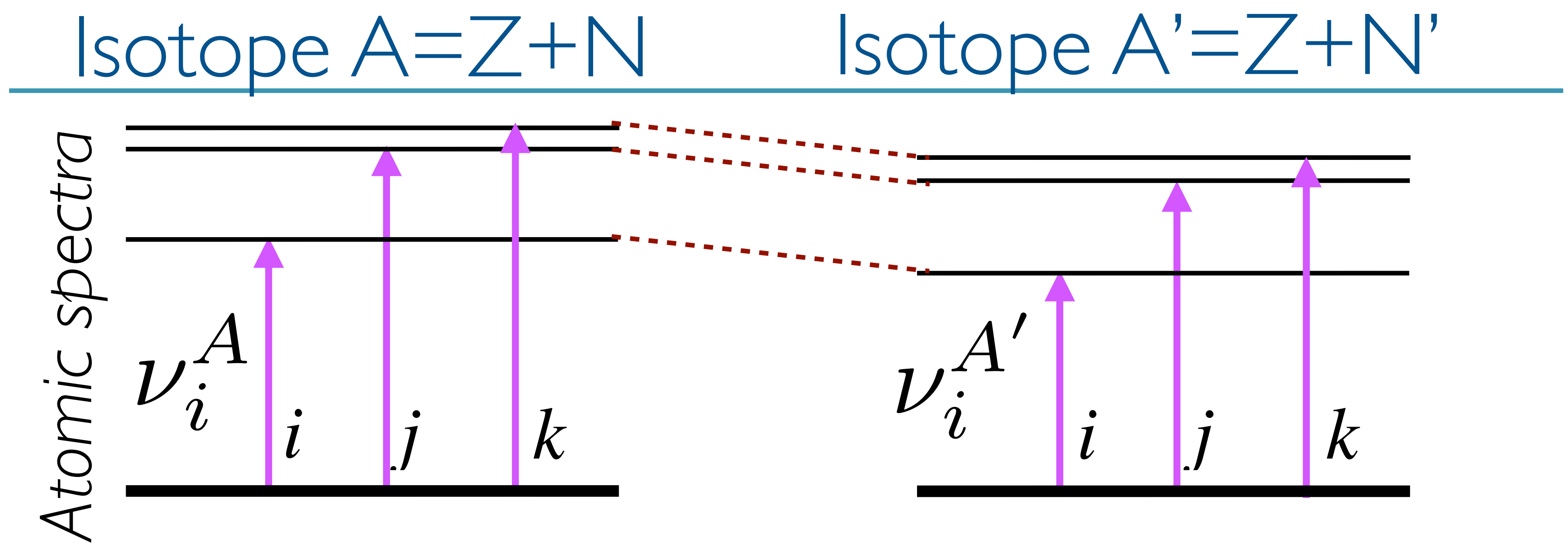
3. X-ray isotope shifts
4. Optical isotope shifts

Charge density



Roca-Maza et al., *Phys. Rev. C* **78** *044332* (2008)

Isotope shifts
Atoms meet nuclei



Isotope shifts

$$\delta\nu_i^{A,A'} = M_i \frac{A'-A}{AA'} + F_i \delta\langle r^2\rangle^{A,A'}$$

- Mass, M_i, and field, F_i, shifts obtained theoretically or empirically
- Isotope shift separation is possible ⇒ proliferation issues

Cheal, Cocolios & Fritzsche, *Phys. Rev. A* **86**, 042501 (2012)

Laser spectroscopy in unstable beams

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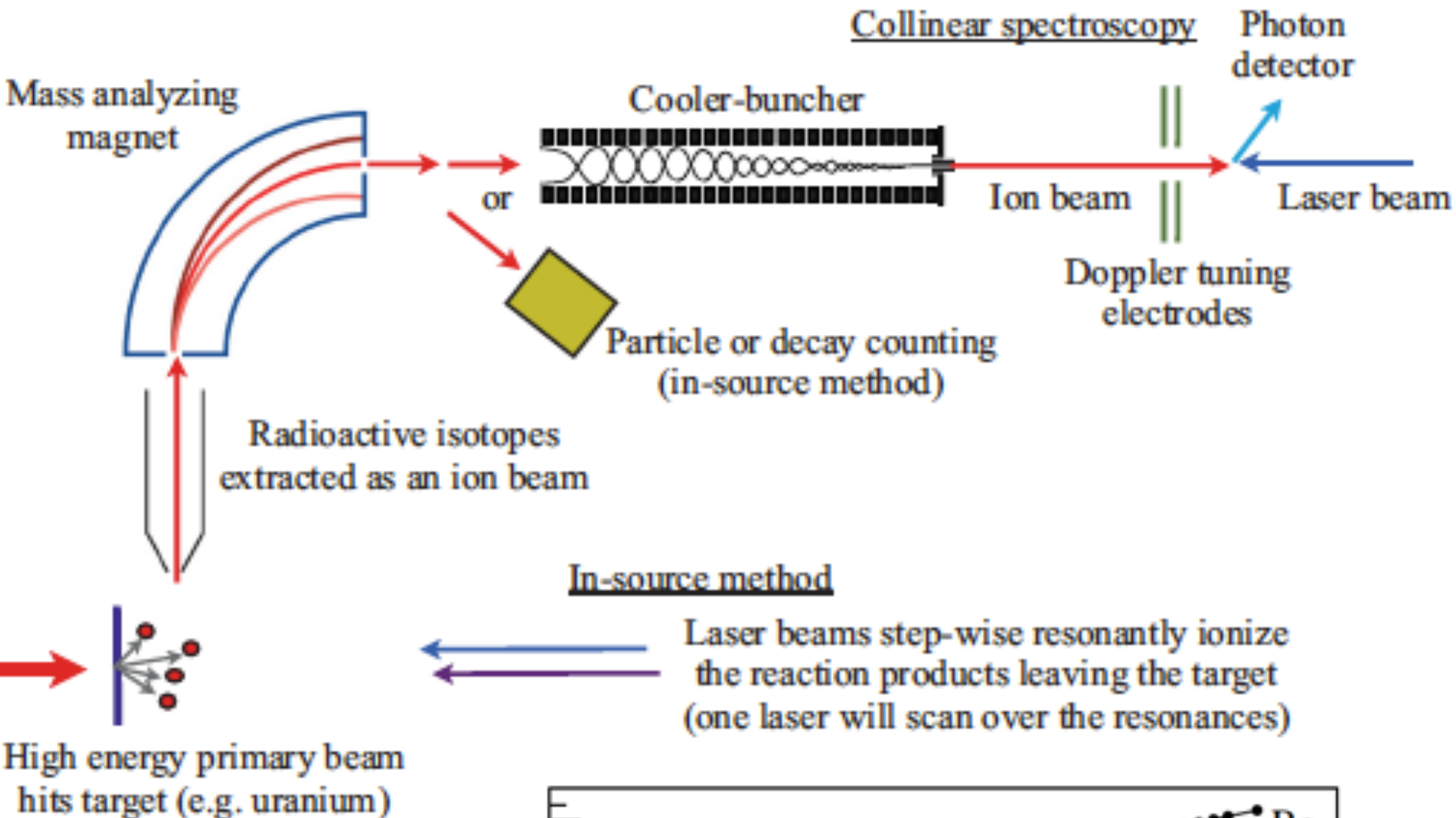
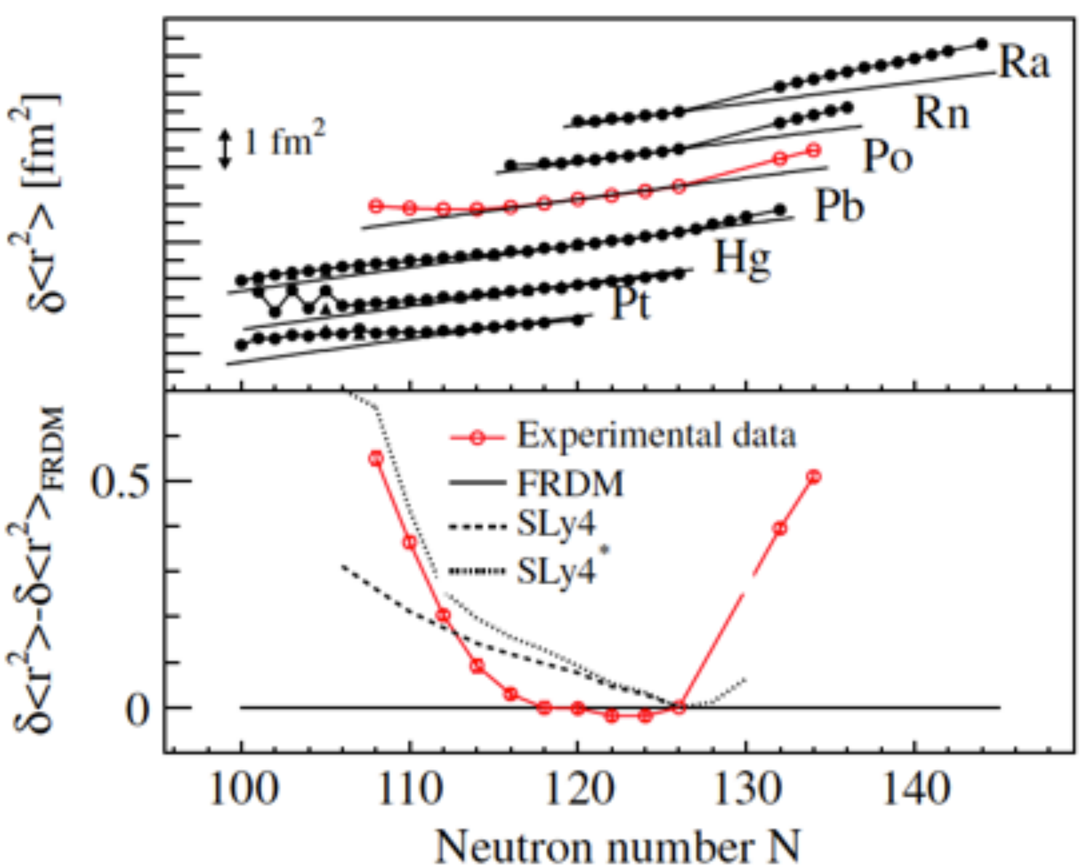
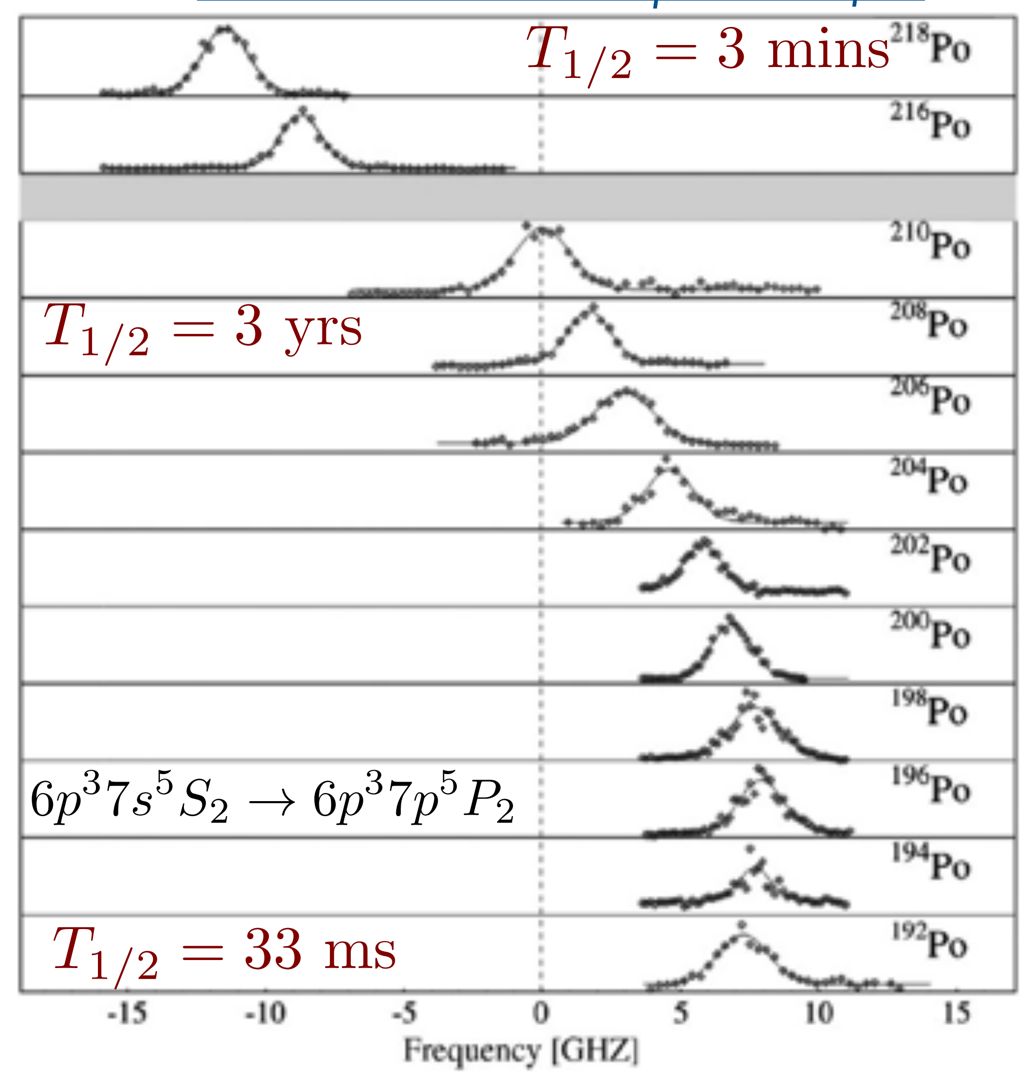




Polonium isotopic shifts



Cocolios et al., *Phys. Rev. Lett.* **106**, 052503 (2011)

Quadrupole correlations?

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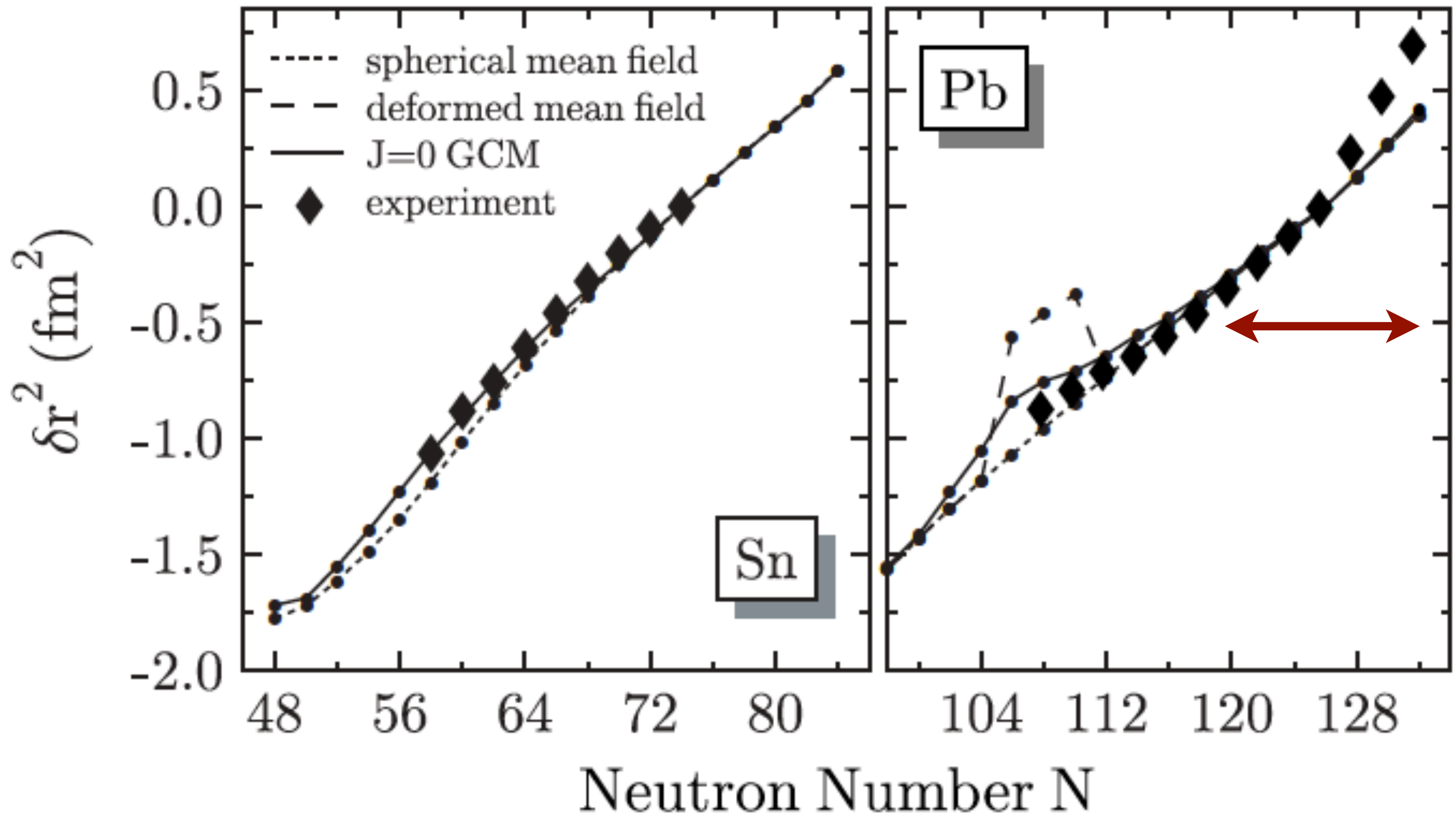
Beyond mean-field calculations of isotope shifts



Observation: correlations do not affect kink mass region

Bender, Bertsch & Heenen, *Phys. Rev. C* ***73*** *034322* (2006)

Previous proposal

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- Skyrme force yields neutron spin-orbit term:

$$W_{\mathrm{SHF}} = b_4(\nabla\rho + \nabla\rho_n)$$

- Relativistic EDF yields:

$$W_{\mathrm{RMF}} = \frac{\hbar^2}{(2m - C\rho)^2} C\nabla\rho$$

- Different isospin dependence?

- Try richer alternative in Skyrme:

$$W_{\mathrm{SHF}} = b_4\nabla\rho + b_4'\nabla\rho_n$$

Reinhard & Flocard, *Nucl. Phys. A* **584** 467 (1995)

Previous proposal II

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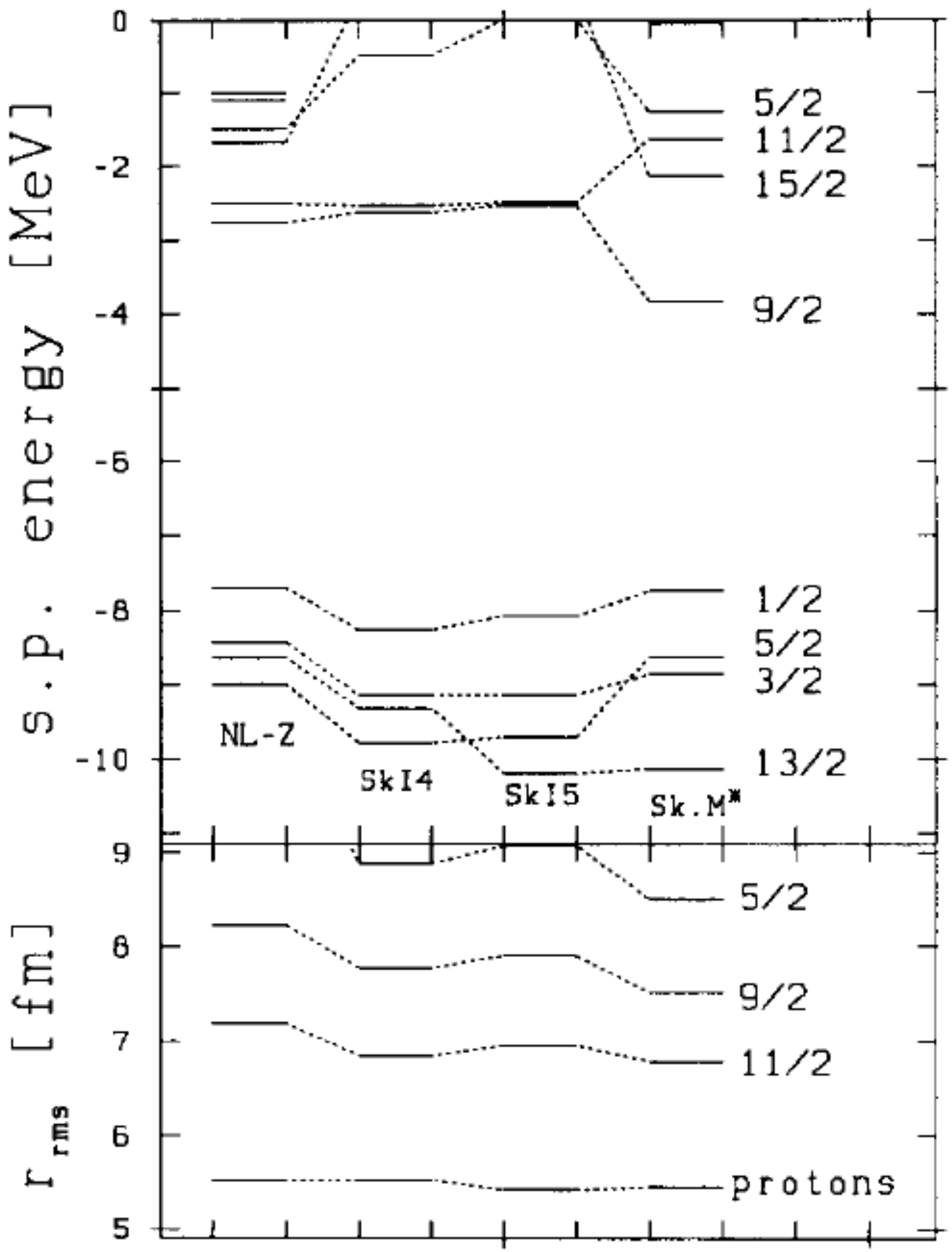

- Position of $2g_{9/2}$ relevant
- This state is affected by SO
- When less bound, sp radius is larger
- Pull on protons (via symmetry energy) should be larger
- Charge radius larger when $2g_{9/2}$ less bound

Reinhard & Flocard, *Nucl. Phys. A* **584** 467 (1995)

A deeper look

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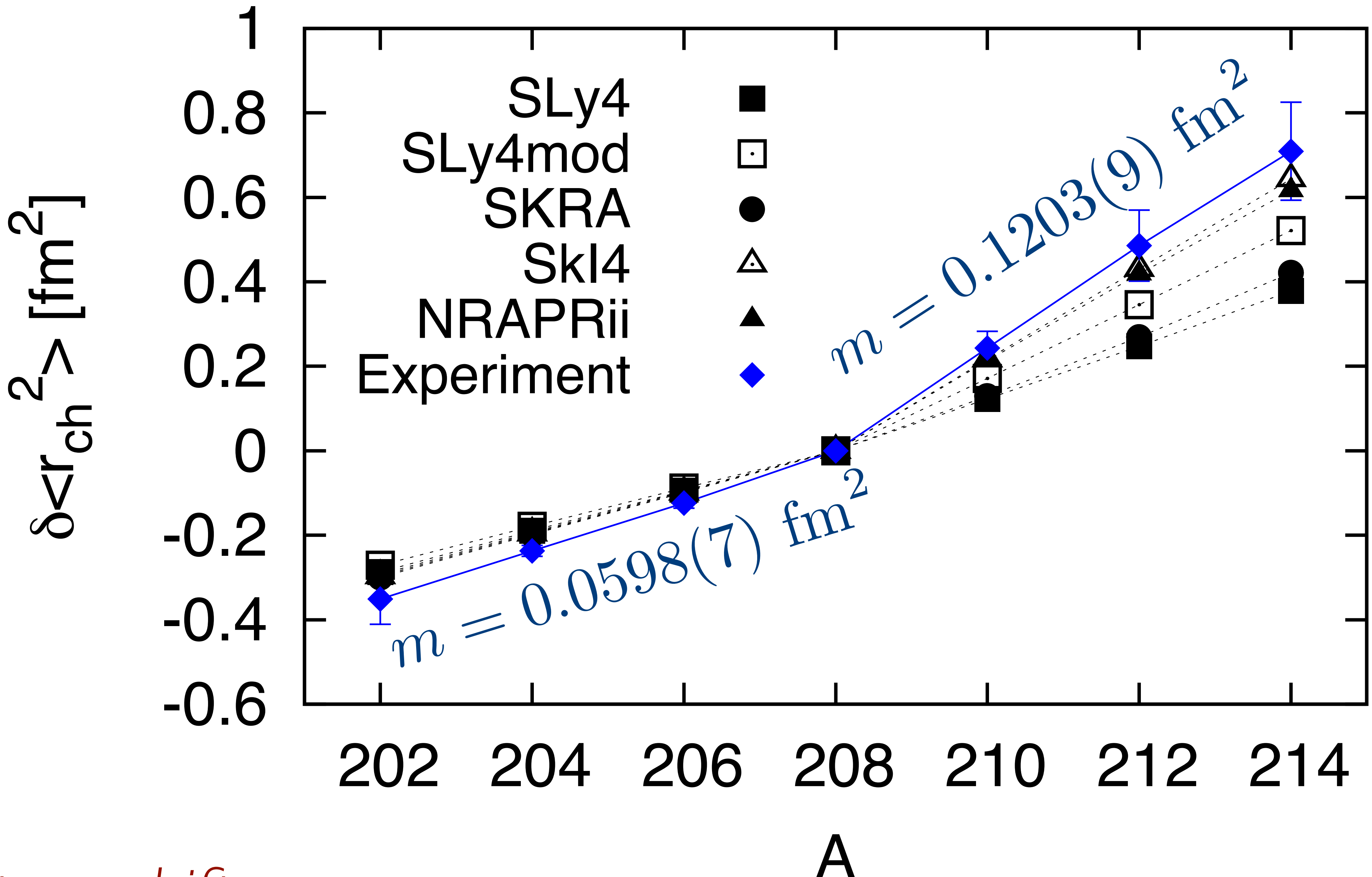
Isotope shifts in lead isotopes: theory vs experiment



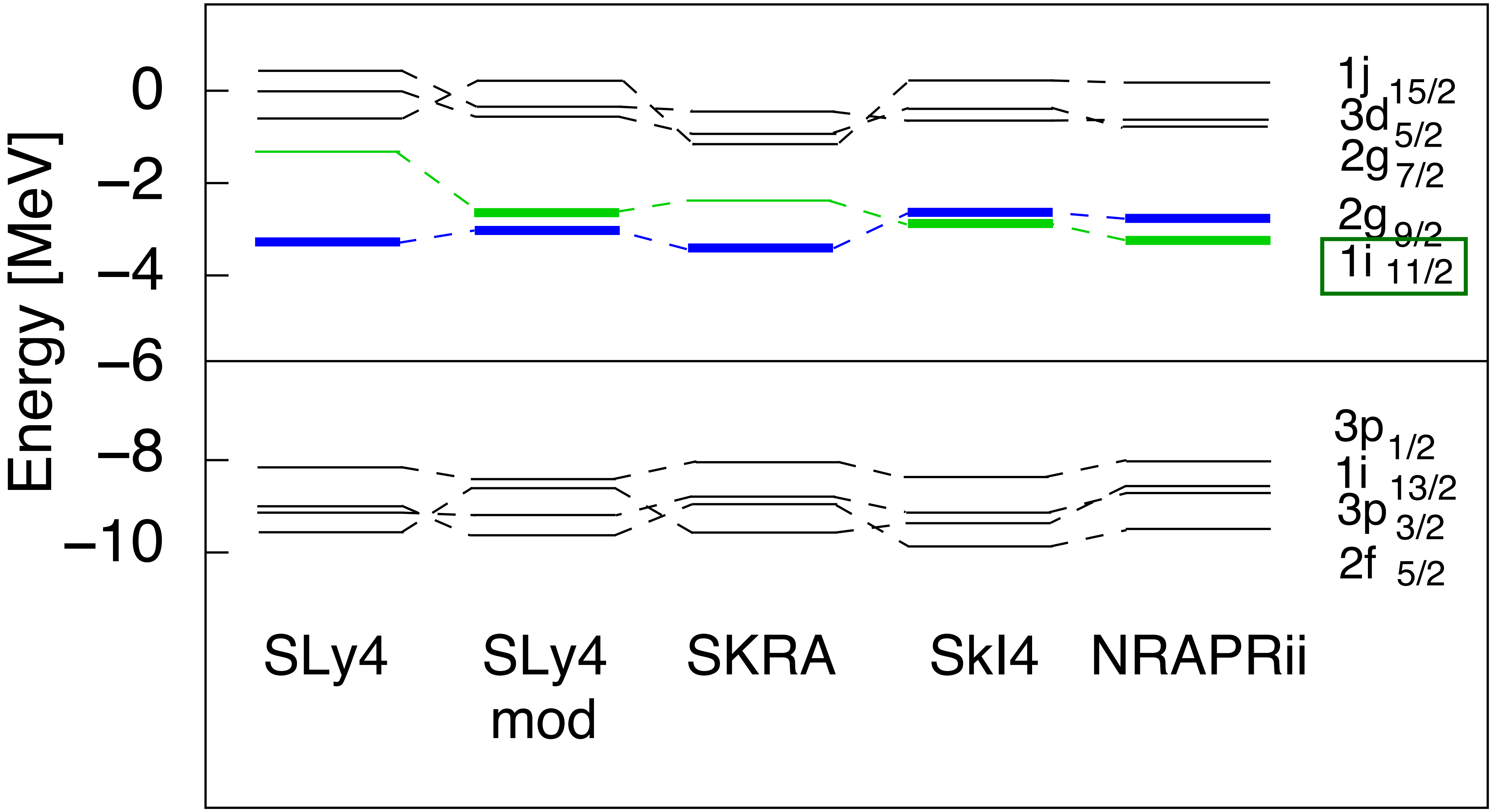
Isotope shifts

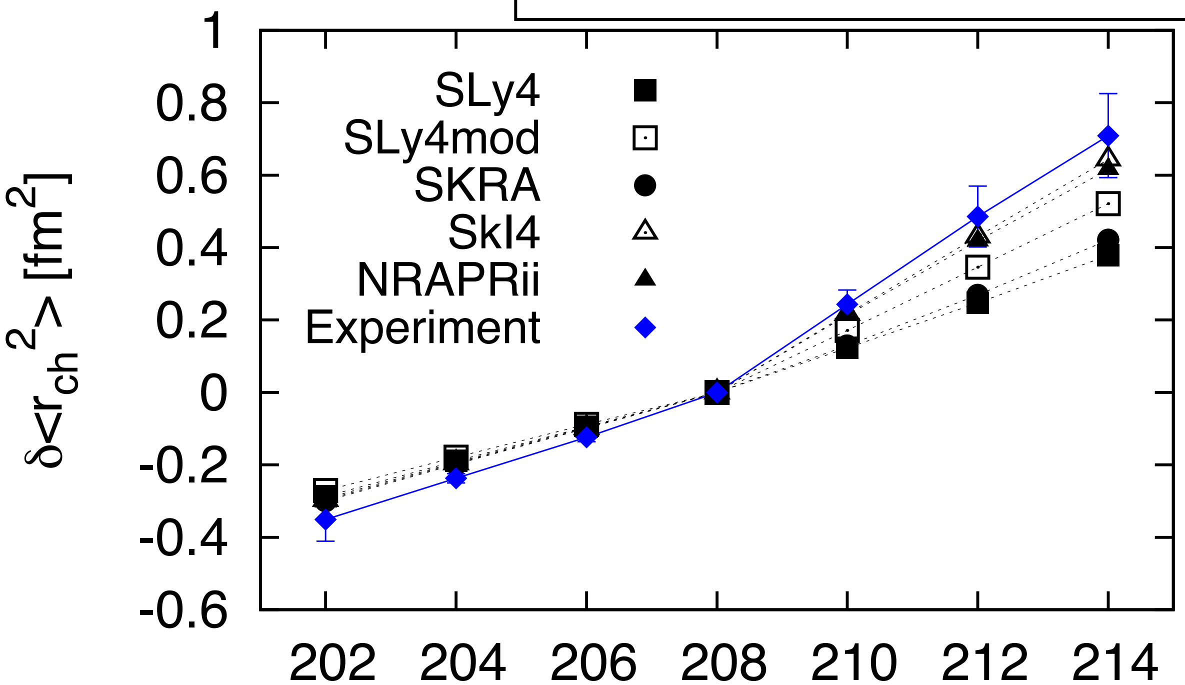
$$\delta\langle r_{\mathrm{ch}}^2\rangle = \langle r_{\mathrm{ch}}^2\rangle_A - \langle r_{\mathrm{ch}}^2\rangle_{208} = m(A-208)$$

$$m_{\mathrm{LDR}} = 0.0972 \text{ fm}^2$$

Spectra

Single-particle spectrum of ^{210}Pb around Fermi surface





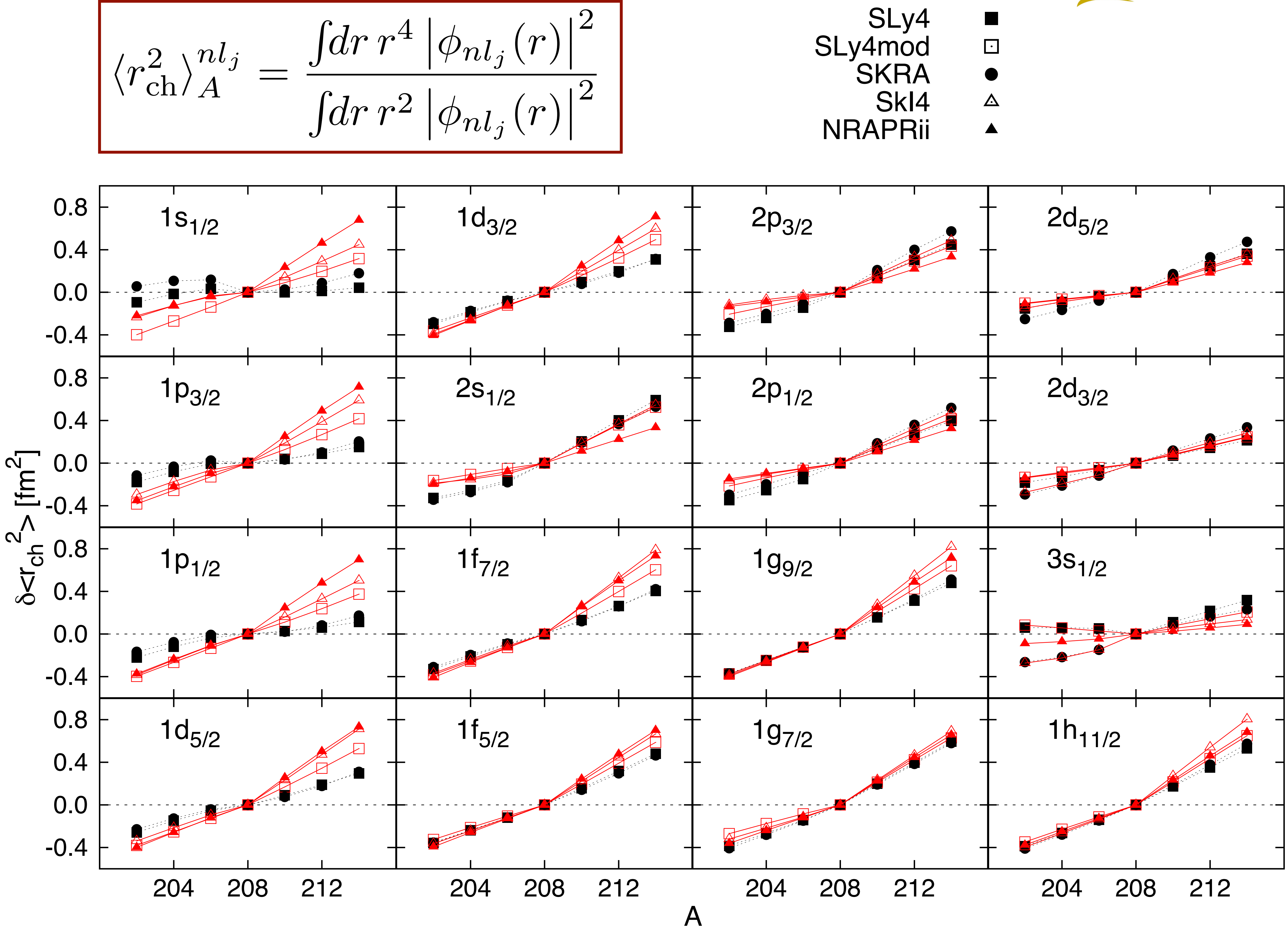
NRAPRii has $b_4 = b_4'$

SLy4mod has $b_4 \neq b_4'$

$1i_{11/2}$ plays an important role!

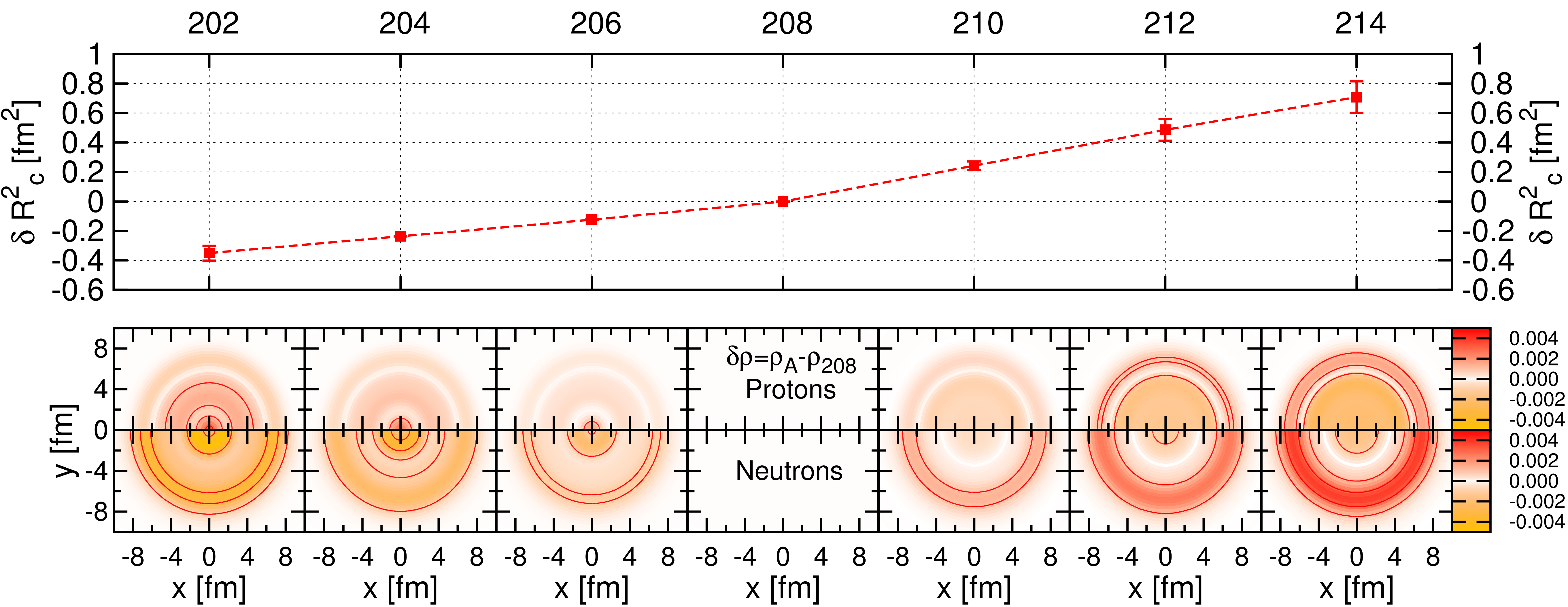
Single-particle isotope shifts

$$\langle r_{\rm ch}^2 \rangle_A^{nl_j} = \frac{\int dr\, r^4 \left|\phi_{nl_j}(r)\right|^2}{\int dr\, r^2 \left|\phi_{nl_j}(r)\right|^2}$$



Kink in deeply bound states ⇔ $1i_{11/2}$ is occupied

Further proof



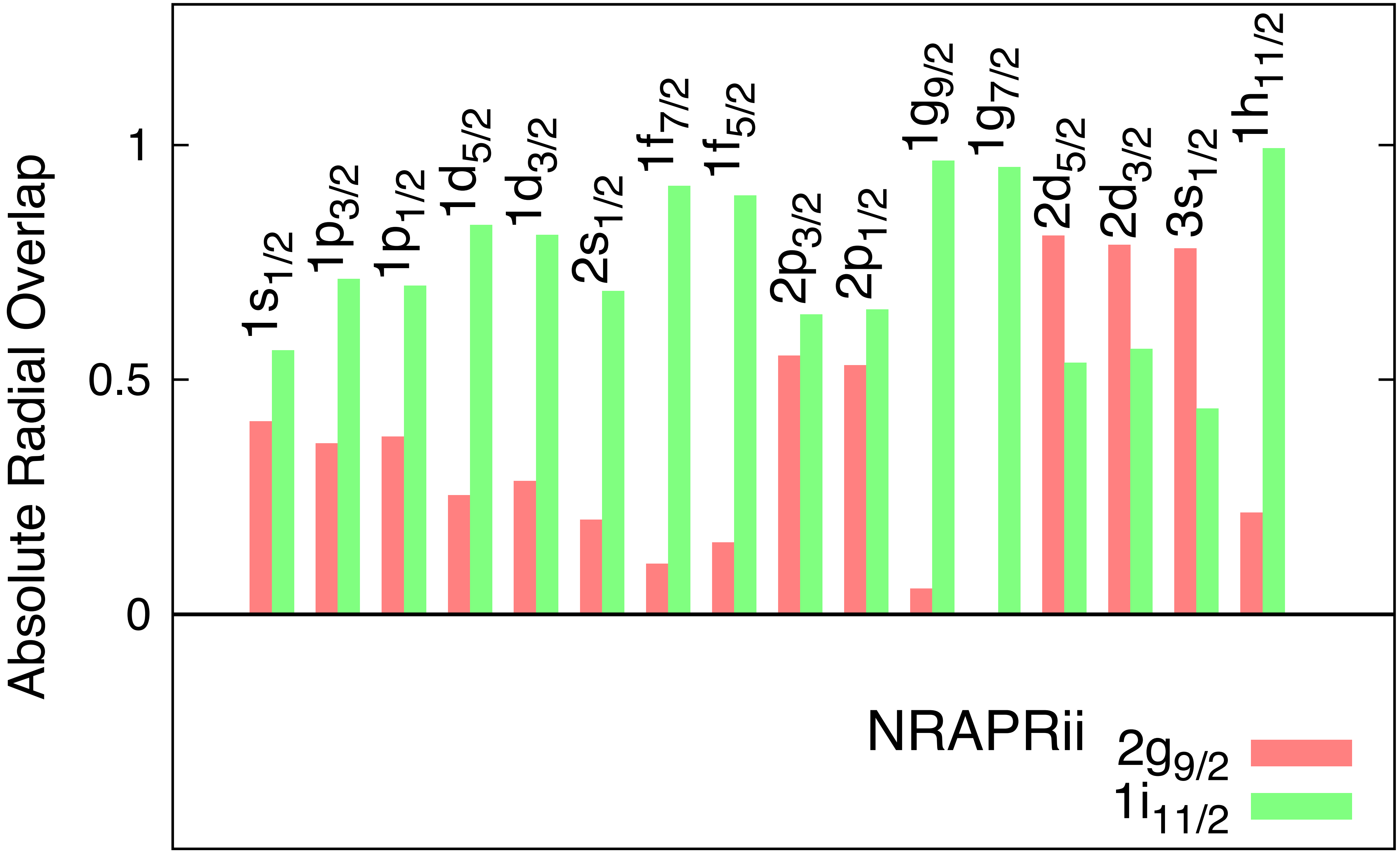
- Neutron density changes mostly at surface
- Proton density change also has interior component
- But $1i_{11/2}$ is ~1 fm more bound than $2i_{9/2}$

Definite proof

Radial overlaps

$$\langle \pi, nl_j | \nu, 1i_{11/2} \rangle = \int dr\, r^2 \phi^*_{nl_j}(r) \phi_{1i_{11/2}}(r)$$

Proton-neutron overlaps in ^{208}Pb



Same thing in Polonium!

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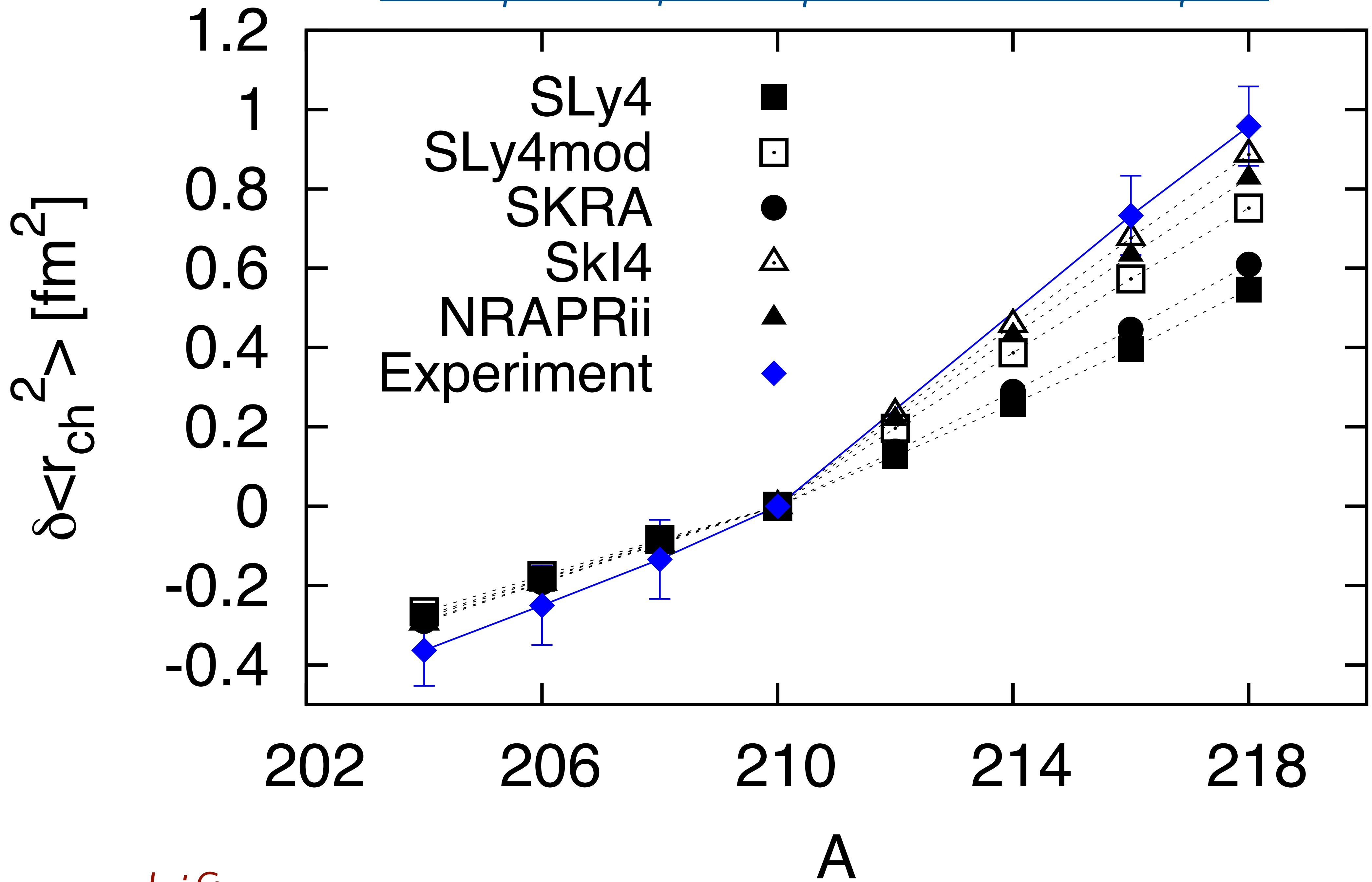
Isotope shifts in polonium isotopes

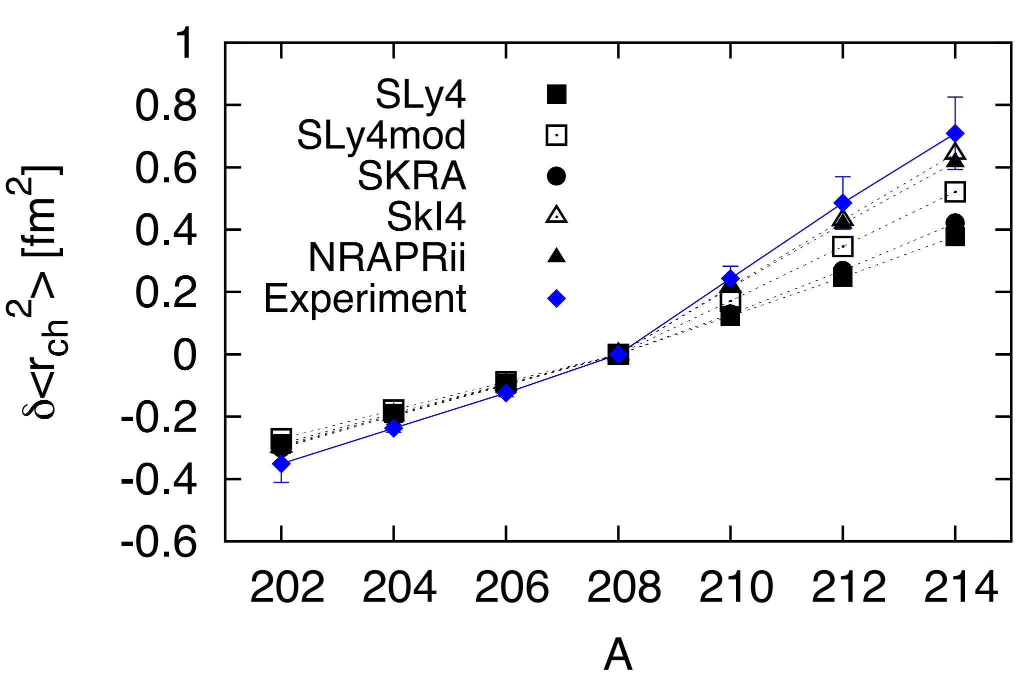


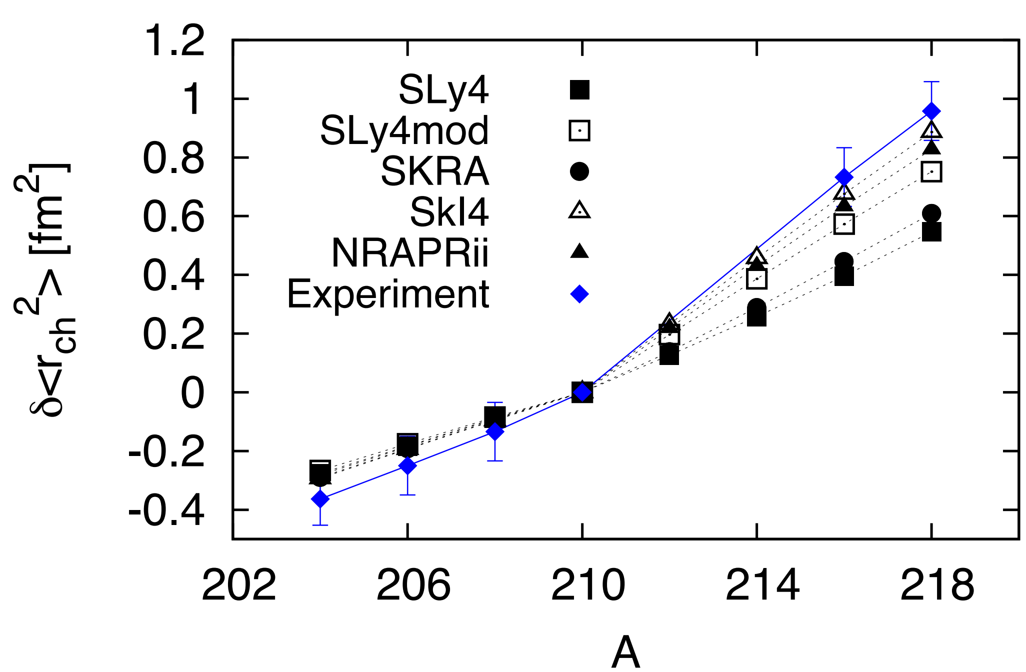
Isotope shifts

$$\delta\langle r_{\rm ch}^2\rangle = \langle r_{\rm ch}^2\rangle_A - \langle r_{\rm ch}^2\rangle_{210}$$

Conclusions

- Reproduction of isotope shift by and large determined by occupation of $1i_{11/2}$ neutron orbital
- This n=1 orbital has larger overlap with deeply bound proton orbitals
- Provides larger pull to protons via symmetry energy
- Mechanism general around N=126





Future work

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- Why is $1i_{11/2}$ occupied?
  - Spin-orbit? Tensor? Correlations?
- Experimental spectrum vs postulated $1i_{11/2}$ population?
- Explore other mass regions and kinks:
  - Tensor in Ca isotopes?
  - Deformation in Hg?
  - Isotone shifts?
- Phil's thesis: dipole response with TDHF

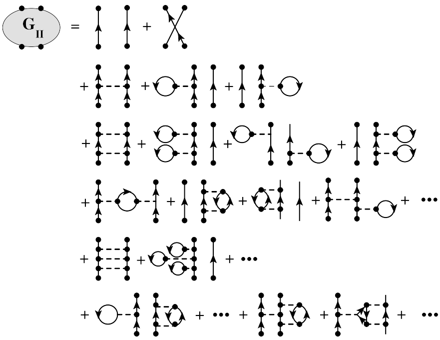
Nuclear & neutron matter

Beyond a quasi-particle approach

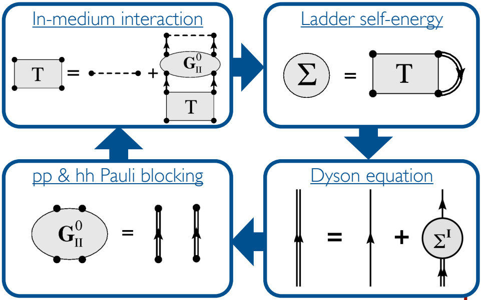
Arnau Rios Huguet
STFC Advanced Fellow
Department of Physics
University of Surrey

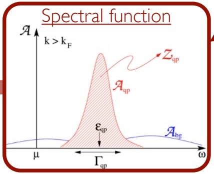
INT Program - Medium mass nuclei
Seattle, 16 April 2013

Self-consistent Green's functions



Ladder approximation within SCGF





One-body properties
Momentum distribution
Thermodynamics & EoS
Transport

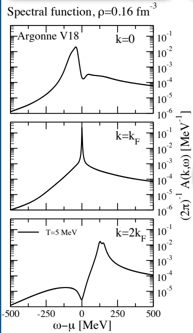
Ramos, Polls & Dickhoff, NPA **503** 1 (1989)
Alm *et al.*, PRC **53** 2181 (1996)
Dewulf *et al.*, PRL **90** 152501 (2003)
Frick & Müther, PRC **68** 034310 (2003)
Rios, PhD Thesis, U. Barcelona (2007)
Somà & Bożek, PRC **78** 054003 (2008)

- Self-consistency, pp+hh & full off-shell effects

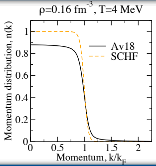
Self-consistent Green's functions

Microscopic properties

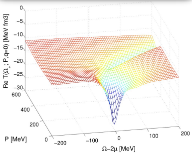
Spectral function



Momentum distribution

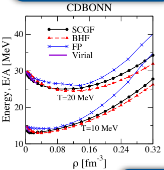


In-medium interaction

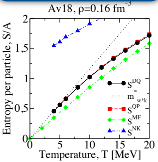


Bulk properties

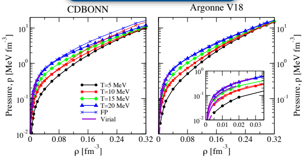
Total Energy



Entropy



Equation of State

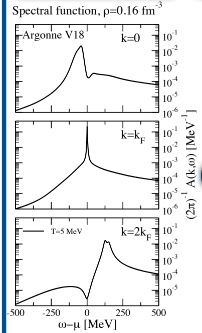


- Self-consistency, pp+hh & full off-shell effects

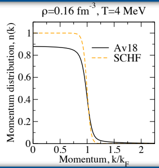
Self-consistent Green's functions

Microscopic properties

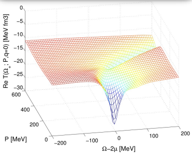
Spectral function



Momentum distribution



In-medium interaction



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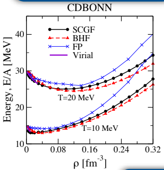
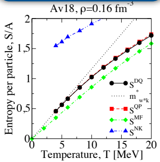
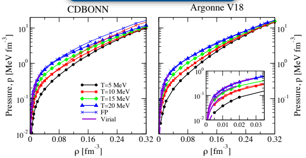


Entropy



Equation of State



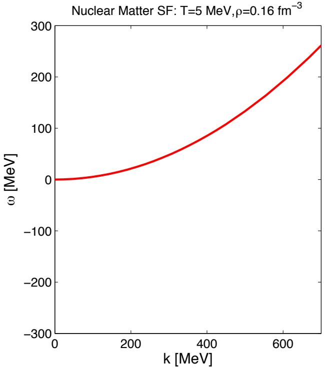
Transport?

- Self-consistency, pp+hh & full off-shell effects

Correlations & spectral functions

$$\varepsilon_k = \frac{k^2}{2m}$$

$$n_k = \frac{1}{1 + e^{\beta(\varepsilon_k - \mu)}}$$

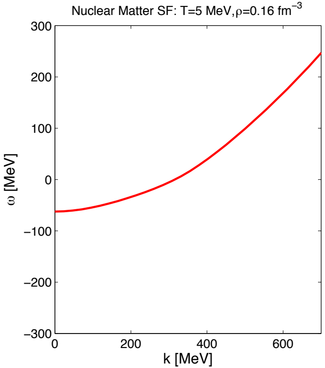


- Free fermions
- Mean-field approximation: sp spectrum
- Correlations do not allow simple ε_k relation!
- A very general approach

Correlations & spectral functions

$$\varepsilon_k = \frac{k^2}{2m} + U(k)$$

$$n_k = \frac{1}{1 + e^{\beta(\varepsilon_k - \mu)}}$$



- Free fermions
- Mean-field approximation: sp spectrum
- Correlations do not allow simple ε_k relation!
- A very general approach

Correlations & spectral functions

Spectral function

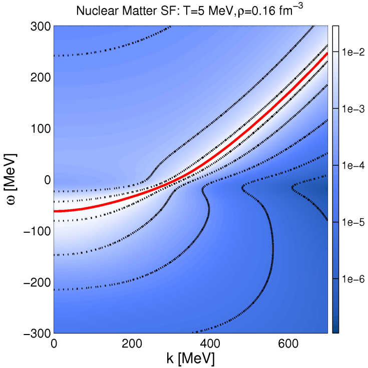
$$\mathcal{A}^{<}(k,\omega) = \sum_{n,m} \frac{e^{-\beta(E_n - \mu A)}}{Z} \left| \langle m | a_{\boldsymbol{k}} | n \rangle \right|^2 \delta \left[\omega - (E_n^A - E_m^{A-} \right.$$

Momentum distribution

$$n_k = \int \frac{\mathrm{d}\omega}{2\pi} f(\omega) \mathcal{A}(k,\omega)$$

Probability

$$\int \frac{\mathrm{d}\omega}{2\pi} \mathcal{A}(k,\omega) = 1$$



- Free fermions
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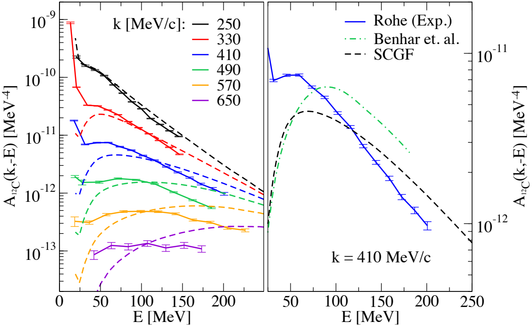
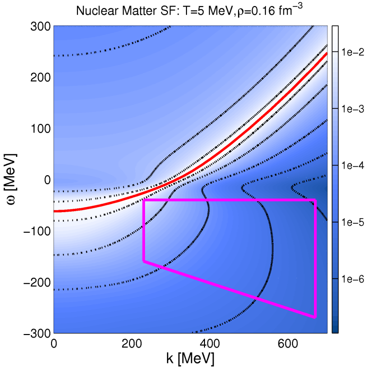
Correlations & spectral functions

^{12}C spectral function from $(e, e'p)$



Rohe *et al.*, PRL **93** 182501 (2004)



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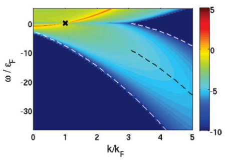
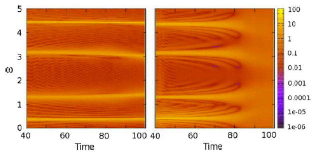
Correlations & spectral functions

Ultracold gases



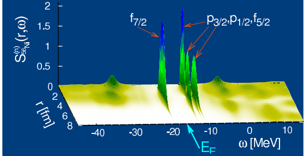
PRA **81**, 021601R (2010)

Nonequilibrium nanostructures



PRB **80**, 115107 (2009)

Nuclei



PRC **79**, 064313 (2009)

- Free fermions
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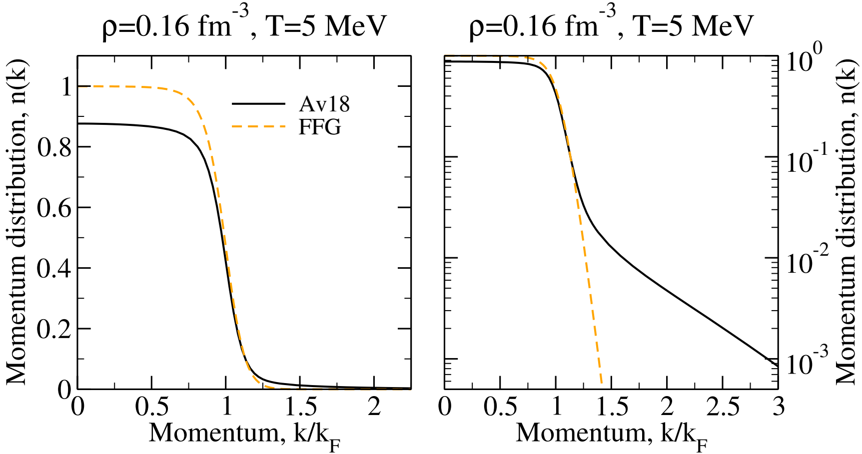
- Correlations do not allow simple ε_k relation!
- A very general approach

Momentum distribution

Single-particle occupation

$$n(k) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \mathcal{A}(k,\omega) f(\omega) \Rightarrow \nu \int \frac{d^3 k}{(2\pi)^3} n(k) = \rho$$



- $11-13\%$ depletion at low k, population at high k
- Dependence on NN interaction under control

Momentum distribution

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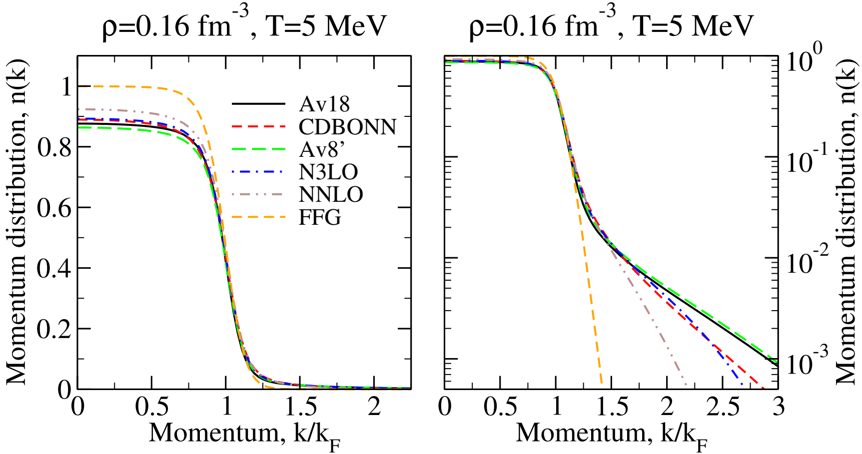
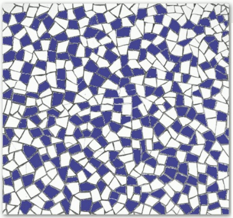


- $11-13\%$ depletion at low k, population at high k
- Dependence on NN interaction under control

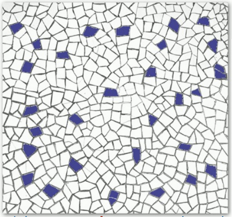
Nuclear "trencadís"

β=0
Symmetric matter



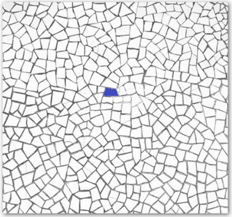
SR+Tensor correlations

β≠0
Asymmetric matter



*Neutrons **less** correlated*
*Protons **more** correlated*

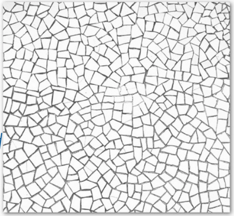
β≈1
Polaron



*Protons **maximally** correlated*
***Hyper**-impurities?*

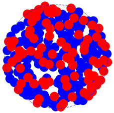
Neutron stars

β=1
Neutron matter



SR correlations

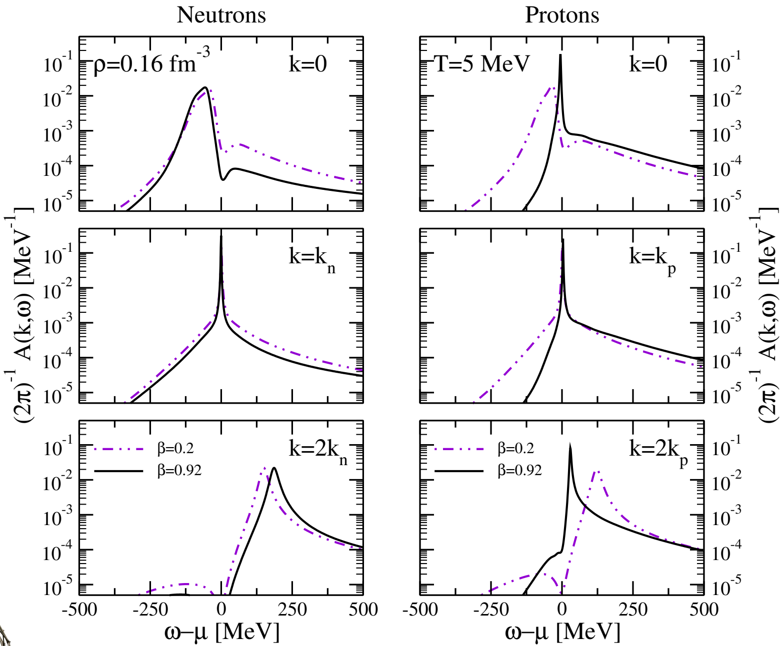
Nuclei



$$\beta = \frac{N-Z}{N+Z}$$

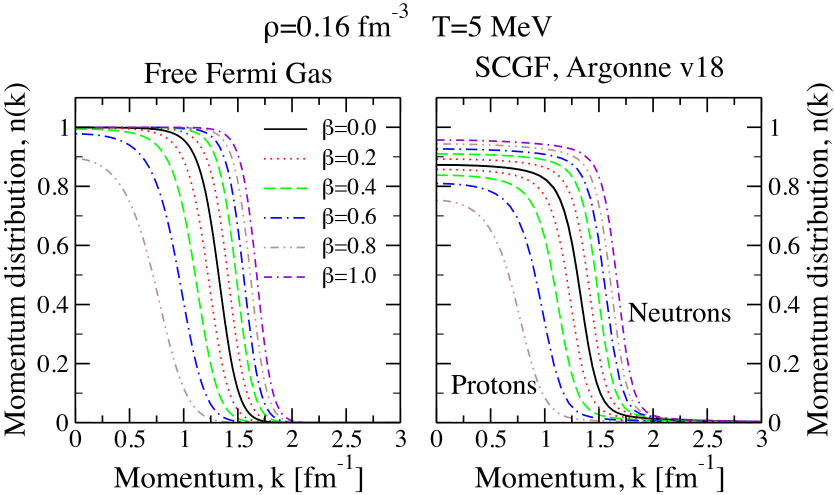
Frick, Rios et al. PRC **71**, 014313 (2005)
Rios et al. PRC **79**, 064308 (2009)
Carbone et al. EPL **97** 22001 (2012)

Asymmetric nuclear matter
Spectral functions



Asymmetric nuclear matter

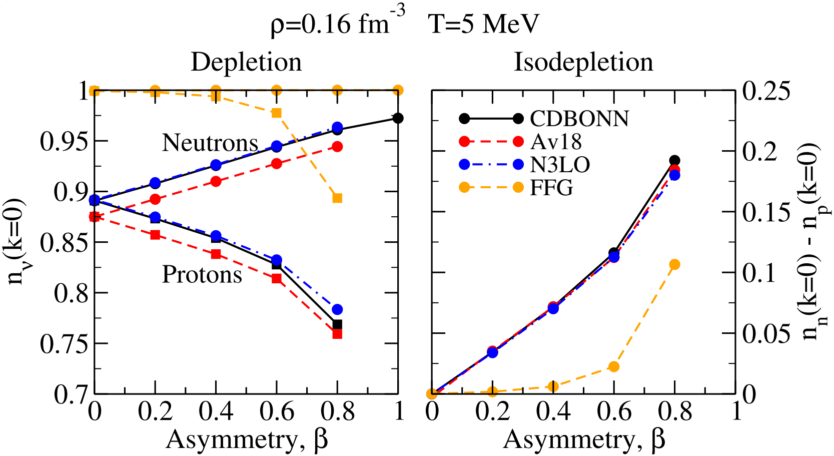
Momentum distribution



- Correlations affect depletion ⇒ non-perturbative effect
- Neutrons become less correlated
- Protons are more correlated

A. Rios *et al.*, PRC 79, 064308 (2009)

Depletion vs. asymmetry
Isodepletion



A. Rios *et al.*, PRC 79, 064308 (2009)

- Realistic potentials lie in a narrow iso-depletion band
- Proton depletion has a thermal component

Depletion vs. asymmetry

Isodepletion

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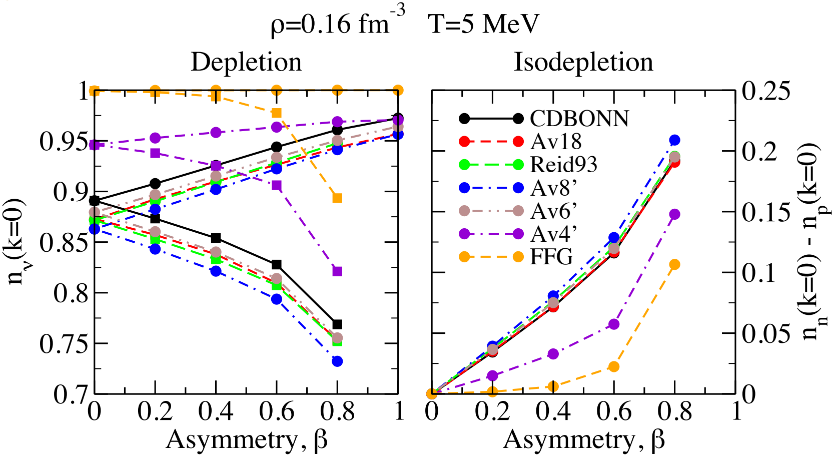


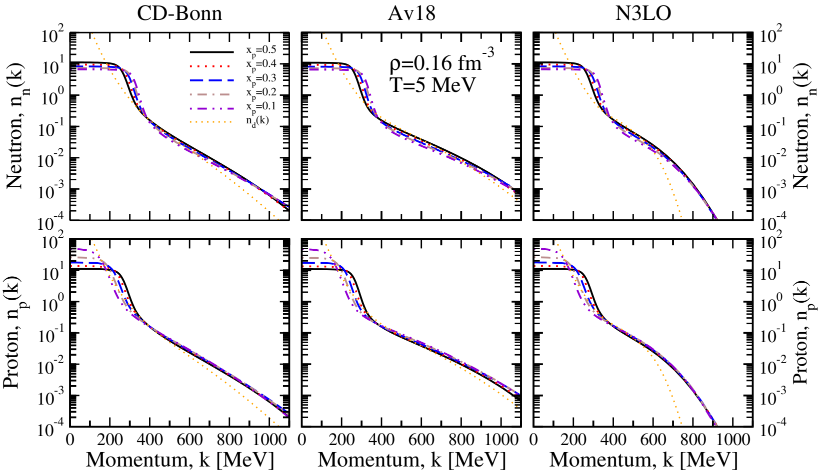
A. Rios *et al.*, PRC 79, 064308 (2009)

- Realistic potentials lie in a narrow iso-depletion band
- Proton depletion has a thermal component

Asymmetric nuclear matter

High momenta

$$\nu \int \frac{d^3k}{(2\pi)^3} n_\tau(k) = 1$$



- High momentum proportional to species density
- Proportional to deuteron

A. Rios, A. Polls & W. H. Dickhoff, in preparation

EoS of neutron matter

Proof of principle

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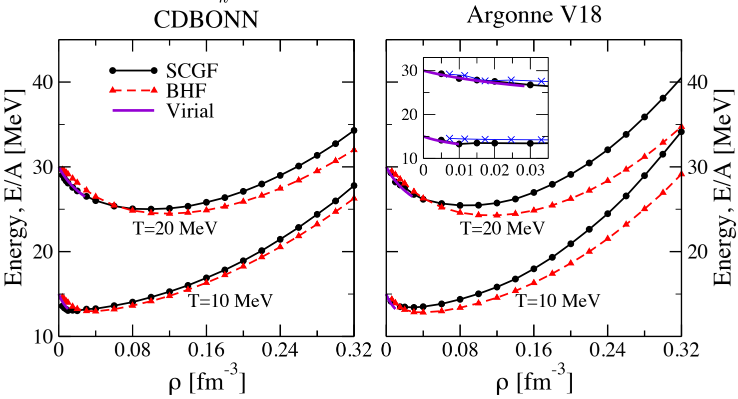
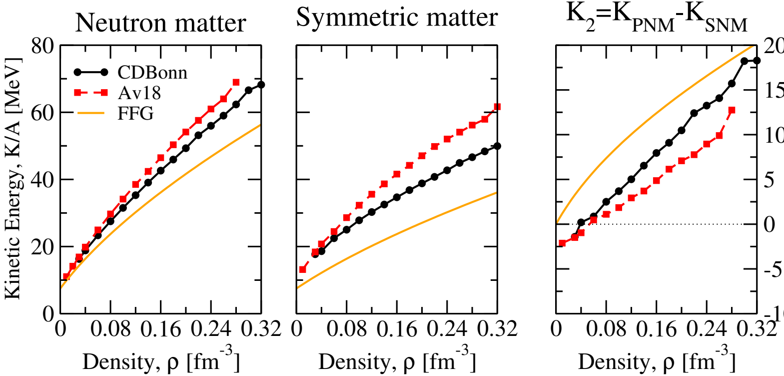
$$E^{GMK} = \sum_k \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{1}{2} \left[\frac{k^2}{2m} + \omega \right] \mathcal{A}(k,\omega) f(\omega)$$



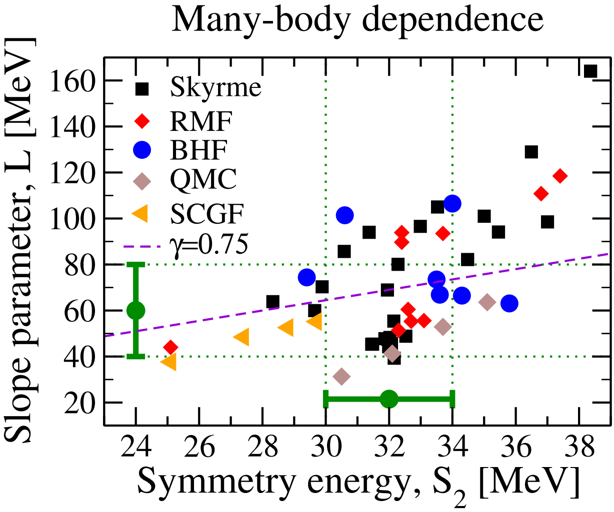
Rios, Polls & Vidaña, PRC **79**, 025802 (2009)

- Potential dependence for $\rho > \rho_0$
- Agrees with virial expansion at low ρ's
- Systematically more repulsive than BHF
- 3BF still needed

Kinetic symmetry energy



	S_{tot} (MeV)	S_{kin} (MeV)	S_{pot} (MeV)	L (MeV)
Av18	25.1	4.9	20.2	37.7
Nij1	27.4	4.6	22.8	48.5
CDBonn	28.8	7.9	20.9	52.6
N3LO	29.7	7.2	22.5	55.2
FFG	12.3	12.3	0	24.6

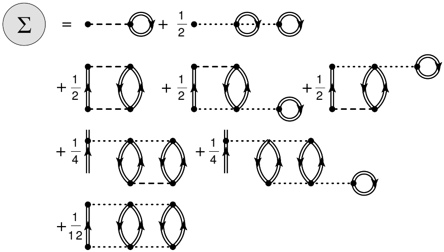


Carbone *et al.*, EPL **97**, 22001 (2012).

3BFs in Green's functions theory

Diagrammatic expansion with 3BF

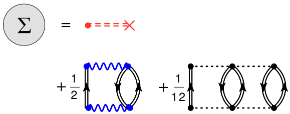
Self-energy expansion to 2nd order



- Only skeleton 1PI diagrams needed
- Anti-symmetrized interactions
- Proper symmetry factors included

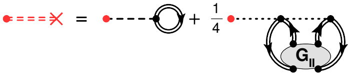
Effective interaction expansion

Rewrite self-energy expansion

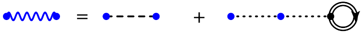


Definition of effective 1B and 2B forces

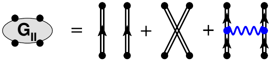
Effective one-body force



Effective two-body force



Two-body propagator



A. Carbone, A. Cipollone, C. Barbieri, A. Rios & A. Polls

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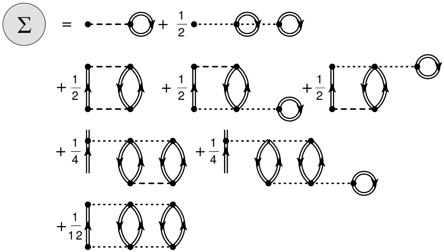

- Only skeleton 1PI diagrams needed
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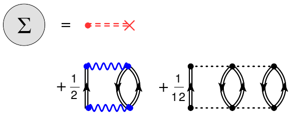
- Number of diagrams substantially reduced
- Usable in higher order resummations
- Implementation in progress

Effective interaction expansion

Rewrite self-energy expansion



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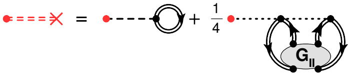
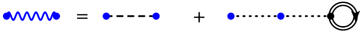
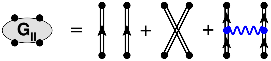


Effective two-body force



Two-body propagator



A. Carbone, A. Cipollone, C. Barbieri, A. Rios & A. Polls

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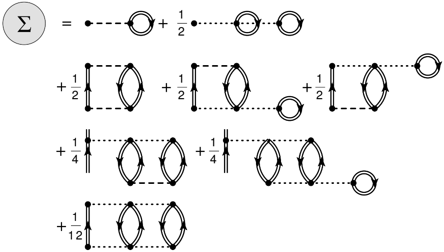

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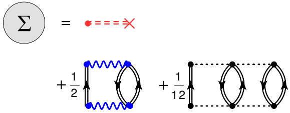

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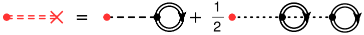
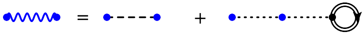
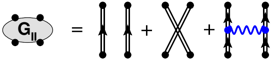


Effective two-body force



Two-body propagator



A. Carbone, A. Cipollone, C. Barbieri, A. Rios & A. Polls

3BFs in Green's functions theory

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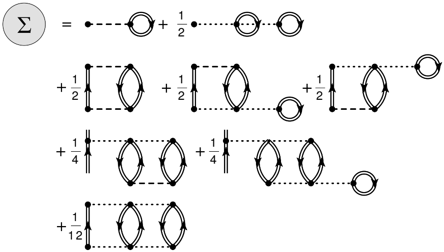

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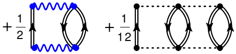
Effective interaction expansion

Rewrite self-energy expansion



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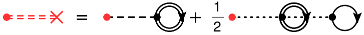

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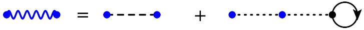
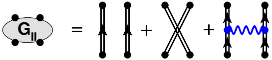
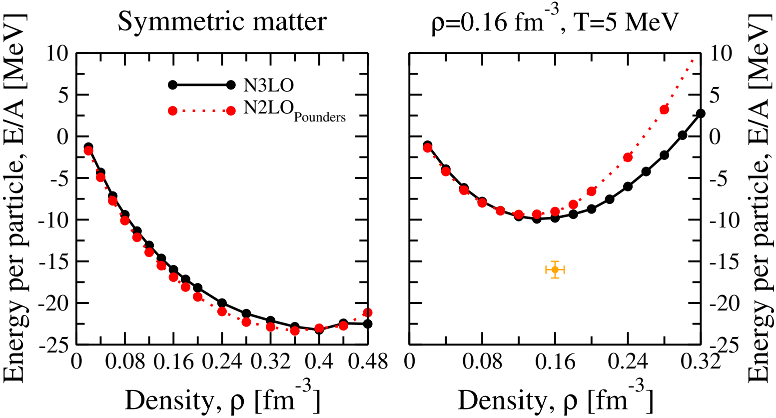


Two-body propagator



A. Carbone, A. Cipollone, C. Barbieri, A. Rios & A. Polls

Chiral EoS



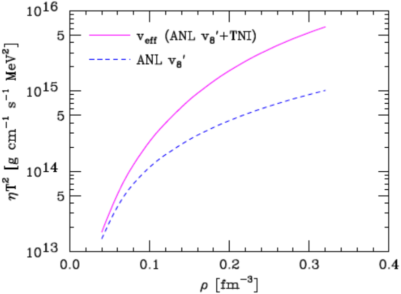
PRELIMINARY, A. Carbone, A. Rios & A. Polls

- 3BF can be added ⇒ modified Koltun sum-rule[1]
- NNLO ⇒ 2B & 3B same order in χ expansion
- Saturation properties of N3LO and NNLO similar
- $S \sim 30$ MeV & $L \sim 56$ MeV

[1] A. Carbone's talk

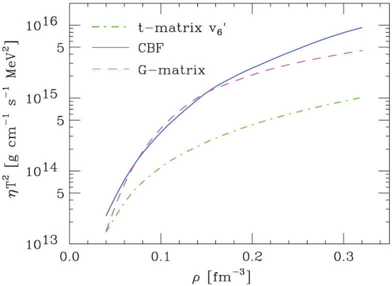
Towards quantum transport

Shear viscosity of neutron matter in CBF



Wambach, Ainsworth & Pines, NPA **555**, 128 (1993)
Benhar & Valli, PRL **99**, 232501 (2007)

Shear viscosity: CBF vs BHF

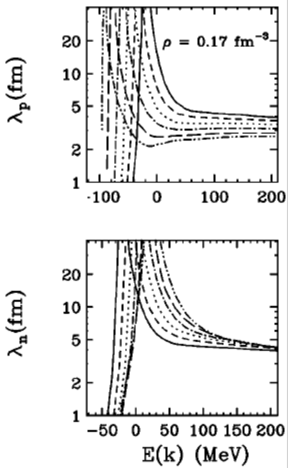


Benhar, Polls, Valli & Vidaña, PRC **81**, 024305 (2010)
Benhar & Carbone, arxiv:0912.0129

- Don't stick to EoS only, aim at complete NS models!
- Better if experimentally testable
  1. Mean-free path ⇒ Optical potentials & scattering
  2. Viscosities ⇒ Resonances
  3. Neutrino responses ⇒ ν-A experiments
  4. Specific heat ⇒ cooling

Ab initio quantum transport?

EBHF calculation of mean-free path



Zuo *et al.*, PRC **60** 024605 (1999)

- Often hybrid models are used:
  - Viscosity: CBF / BHF + Landau-Abrikosov-Khalatnikov
  - MFP: EBHF + quasi-particle pole expansion

- Uncontrolled or inconsistent approximations
- Need of fully quantal, many-body calculations
- Beyond Boltzmann

- Green's functions advantages:
  time-dependence is natural & consistency

- Simplest transport coefficient: mean free path
- Key coefficient, underlying in transport
- Closely related to imaginary optical potential

Negele & Yazaki, PRL **47**, 71 (1981)
Fantoni, Friman & Pandharipande, PLB **104**, 89 (1981)
Mahaux, PRC **28**, 1848 (1983)

Damping and mean-free path

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Naive optical potential model

$$\left[-\frac{\nabla^2}{2m} + \mathrm{Re}\,\Sigma(\varepsilon_k) + i\mathrm{Im}\,\Sigma(\varepsilon_k)\right]\psi(r) = \varepsilon_k \psi(r)$$

$$\psi(r) = N e^{-i\left\{k - \frac{i}{2\lambda_k}\right\}r} \quad \Rightarrow \quad p(r) = |\psi(r)|^2 \sim e^{-\frac{r}{\lambda_k}}$$

$$\lambda_k = -\frac{k}{2m}\frac{1}{\mathrm{Im}\,\Sigma(E_k)} = \frac{k}{m}\frac{1}{\Gamma_k} = \frac{\partial_k \varepsilon_k}{\Gamma_k}$$

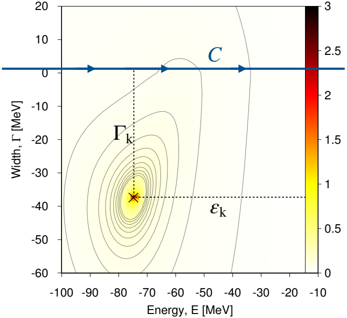
- Mean-free path from quasi-particle properties

$$\lambda_k = \frac{v_k}{\Gamma_k}$$

- Fundamental asymptotic behavior for propagator in real time

$$\mathcal{G}_R(k,t) \to -i\eta_k e^{-i\varepsilon_k t} e^{-|\Gamma_k| t}$$

Quasi-particle "pole"



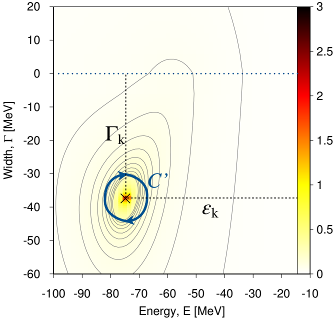
- Fundamental asymptotic behavior for propagator in real time

$$\mathcal{G}_R(k,t) \to -i\eta_k e^{-i\varepsilon_k t} e^{-|\Gamma_k| t} \Rightarrow \lambda_k = \frac{\partial_k \varepsilon_k}{\Gamma_k}$$

- Time-energy Fourier transform using retarded contour + Cauchy

$$\mathcal{G}_R(k,t) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} e^{-i\omega t} \mathcal{G}_R(k,\omega) \sim \int_{C'} \frac{dz}{2\pi} e^{-izt} \frac{\eta(z)}{z-(\varepsilon_k - i|\Gamma_k|)} = -i\eta_k e^{-i\varepsilon_k t} e^{-|\Gamma_k| t}$$

Quasi-particle "pole"



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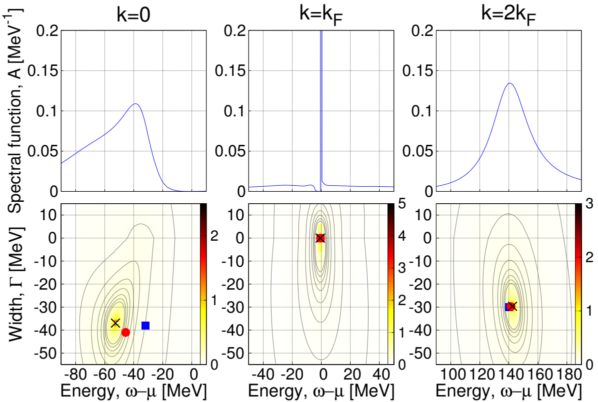
Hunting the pole

CDBonn, $T = 0$, $\rho = 0.16 \text{ fm}^{-3}$



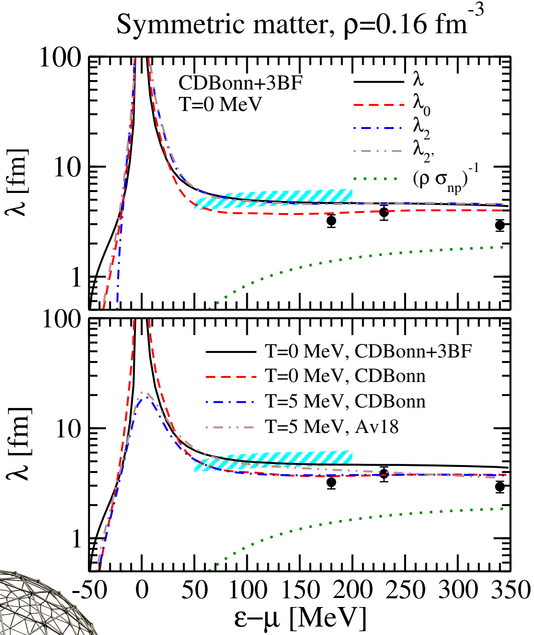
- Circle: first renormalization (expansion on $\text{Im}\, z$ to 1^{st} order)

$$\varepsilon_k = \frac{k^2}{2m} + \text{Re}\Sigma_k(\varepsilon_k) \qquad \Gamma_k = \text{Im}\Sigma_k(\varepsilon_k)$$

- Square: second renormalization (expansion on $\text{Im}\, z$ to 2^{nd} order)

$$\varepsilon_k = \frac{k^2}{2m} + \text{Re}\Sigma_k(\varepsilon_k) \qquad \Gamma_k = \frac{m_k}{m}\text{Im}\Sigma_k(\varepsilon_k)$$

Model dependence



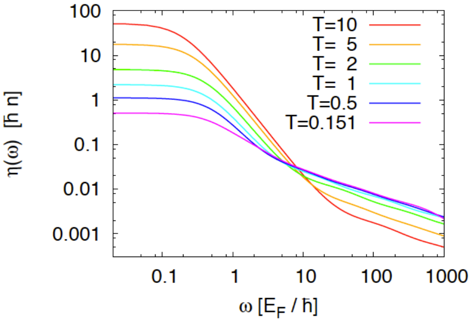
$$\lambda_k = \frac{1}{\Gamma_k} \frac{\partial \varepsilon_k}{\partial k}$$

- $\lambda \sim 4-5$ fm above 50 MeV
- Compatible with pA experiments
- Small model dependence
  - $\lambda_0 \Rightarrow$ no non-locality
  - $\lambda_2 \Rightarrow$ full non-locality
  - $\lambda_2' \Rightarrow m_k^*$ non-locality
- Classical approximation is incorrect!
- Little effect of 3BFs

A. Rios & V. Somà, PRL **108**, 012501 (2012)

Extension to other transport properties

Viscosity spectral function in unitary gas



Enss, Haussman, Zwerger, Ann. Phys. **326**, 770 (2011)

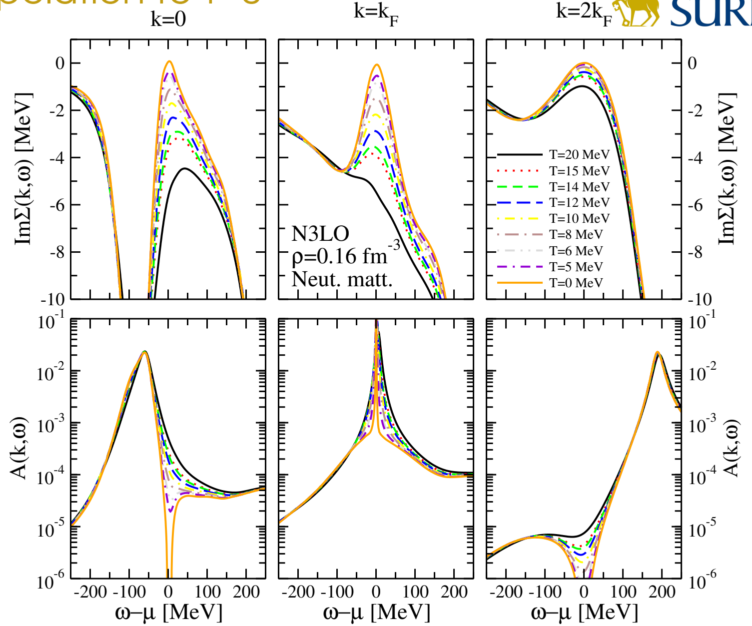
- Viscosity over entropy ratio in ultracold gases

Kadanoff & Martin, Ann. Phys. **24**, 419 (1963)
Taylor & Randeria, PRA **81**, 053610 (2010)

- Specific heat in quantum liquids

Pethick & Carneiro, PRA **7**, 304 (1973)
Carneiro & Pethick, PRA **11**, 1106 (1976)

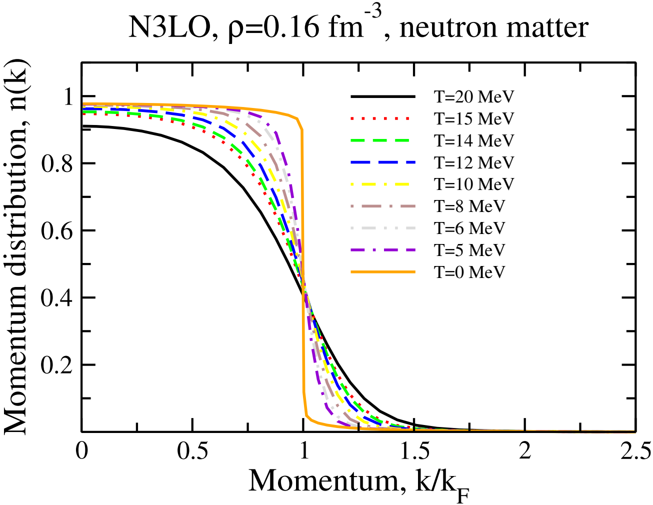
Extrapolation to T=0



A. Rios, in preparation

Extrapolation to T=0

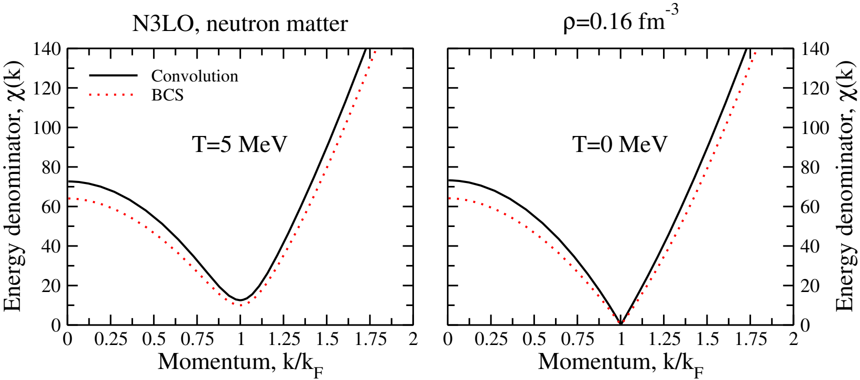
$$n(k) = \int_{-\infty}^{\varepsilon_F} \frac{d\omega}{2\pi} \mathcal{A}(k,\omega) \Rightarrow \nu \int \frac{d^3k}{(2\pi)^3} n(k) = \rho$$



A. Rios, in preparation

Pairing properties

Pairing energy denominator



$$\Delta_{lk}^{JST} = -\sum_{l'} \int_0^\infty \mathrm{d}k' k'^2 \langle kl|V^{JST}|k'l'\rangle \frac{\Delta_{l'k'}^{JST}}{2\chi_{k'}}$$

BCS / quasi-particle

$$\frac{1}{2\chi_k} = \frac{1-2f(\varepsilon_k)}{2\varepsilon_k}$$

Beyond quasi-particle

$$\frac{1}{2\chi_k} = \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega}{2\pi} \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega'}{2\pi} \frac{1-f(\omega)-f(\omega')}{\omega+\omega'} A_k(\omega) A_k^s(\omega')$$

Pairing properties

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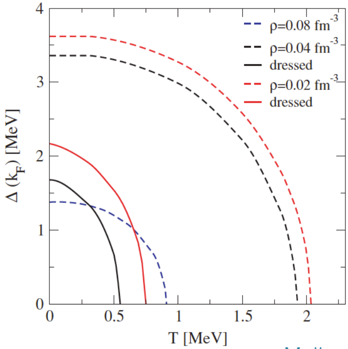
CDBonn neutron matter $^1S_0$ pairing gap



Muther & Dickhoff, PRC **72** 054313 (2005)

$$\Delta_{lk}^{JST} = -\sum_{l'} \int_0^\infty \mathrm{d}k' k'^2 \langle kl | V^{JST} | k'l' \rangle \frac{\Delta_{l'k'}^{JST}}{2\chi_{k'}}$$

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Beyond quasi-particle

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Conclusions

- Ab initio description of nuclear & neutron matter
- Fully self-consistent & quantum mechanical calculation

- One-body microscopic properties ✔
- Thermodynamic properties ✔
- Mean-free path in correlated matter ✔

- Adding three-body forces consistently
- Other transport properties are coming
- Zero-temperature extrapolation
- Pairing: $^1S_0$, $^3PF_2$
- Two-body properties: relative momentum distribution

V. Somà

T. U. Darmstadt

TECHNISCHE UNIVERSITÄT DARMSTADT

W. H. Dickhoff

Wash. U. St. Louis

A. Polls, *A. Carbone*

University of Barcelona

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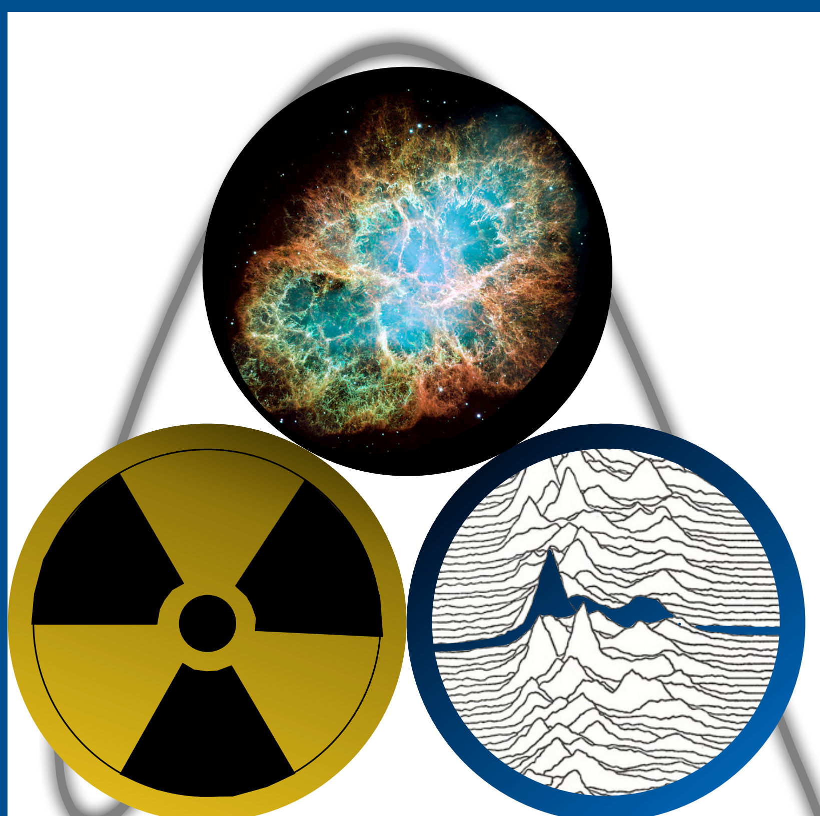
Thank you!



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