Nuclear radii, Neutron skins, and Halo orbits

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Introduction

Thomas-Ehrman Shift (TES)

Proton $1s_{1/2}$ orbit in ^{13}N depressed by ~750 keV compared to the neutron one in ^{13}C

Ehrman, *Phys. Rev.* 81, 412 (1951)
Thomas, *Phys. Rev.* 88 , 1109 (1952)

➡ ***Overbinding of orbits with respect to naive expectations***

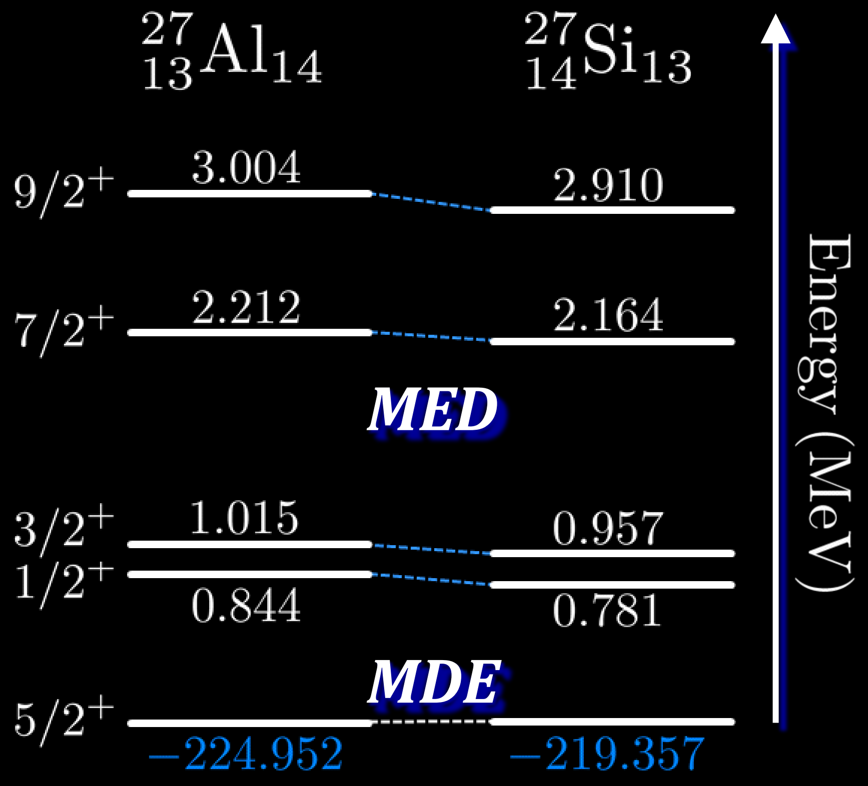
Nolen-Schiffer Anomaly (NSA)

Closed-shell core unperturbed by the the addition of a particle

➡ ***Severe underestimate of MDE***

Nolen & Schiffer, *PLB.* 29, 396 (1968)
Ann. Rev. Nucl. Sci. 19, 471 (1969)

MDE($A = 41$) (MeV)			
exp	IBI	Coul	sch-Coul
7.278	6.683	6.679	6.675



Objective

The strong dependence of MDE and MED on radii allows to study the latter from the calculations of the formers

Duflo-Zuker formula

$$\sqrt{\langle r_\pi^2 \rangle} = \rho_\pi = A^{1/3}\left[\rho_0 - \frac{\zeta}{2}\frac{t}{A^{4/3}} - \frac{\upsilon}{2}\left(\frac{t}{A}\right)^2\right] \mathrm{e}^{g/A} + \lambda\left[\frac{z(D_\pi - z)}{D_\pi^2} \times \frac{n(D_\nu - n)}{D_\nu^2}\right] A^{-1/3}$$

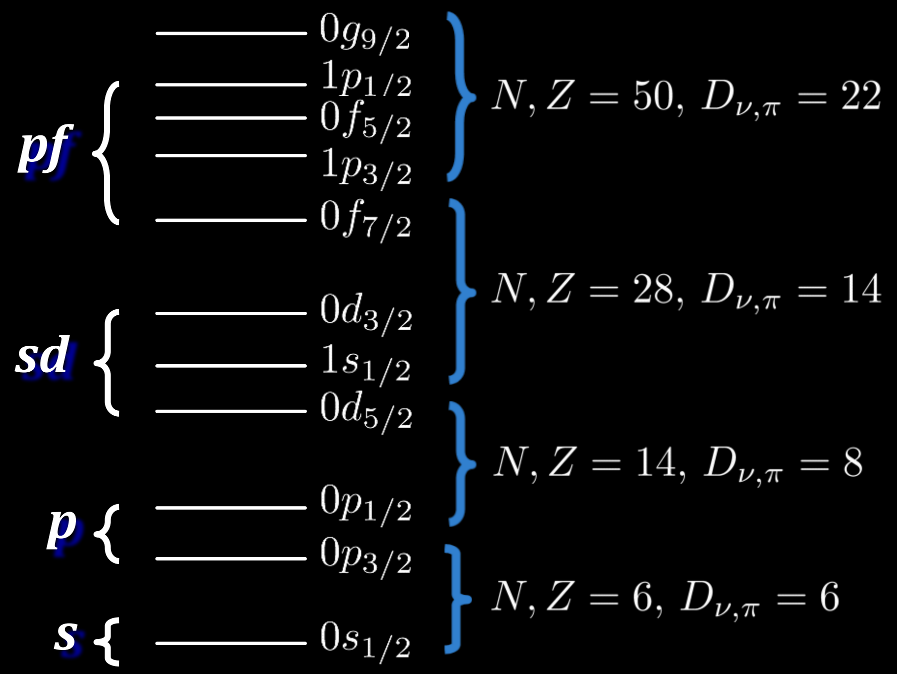
Duflo & Zuker, *PRC* 66, 051304 (2002)

"Naive" term

- $t = N - Z$ *isospin*
- $\rho_0 > 0$ *standard (scalar)*
- $\zeta > 0$ *neutron skin (vector)*
  ⇨ fixed
- $\upsilon > 0$ *uniform contraction (tensor)*
- $\mathrm{e}^{g/A}$ *overall correction (phenomenological)*

"Correlated" term

z, n ***proton, neutron occupations of the valence*** ***Extruder-Intruder*** ***shells***



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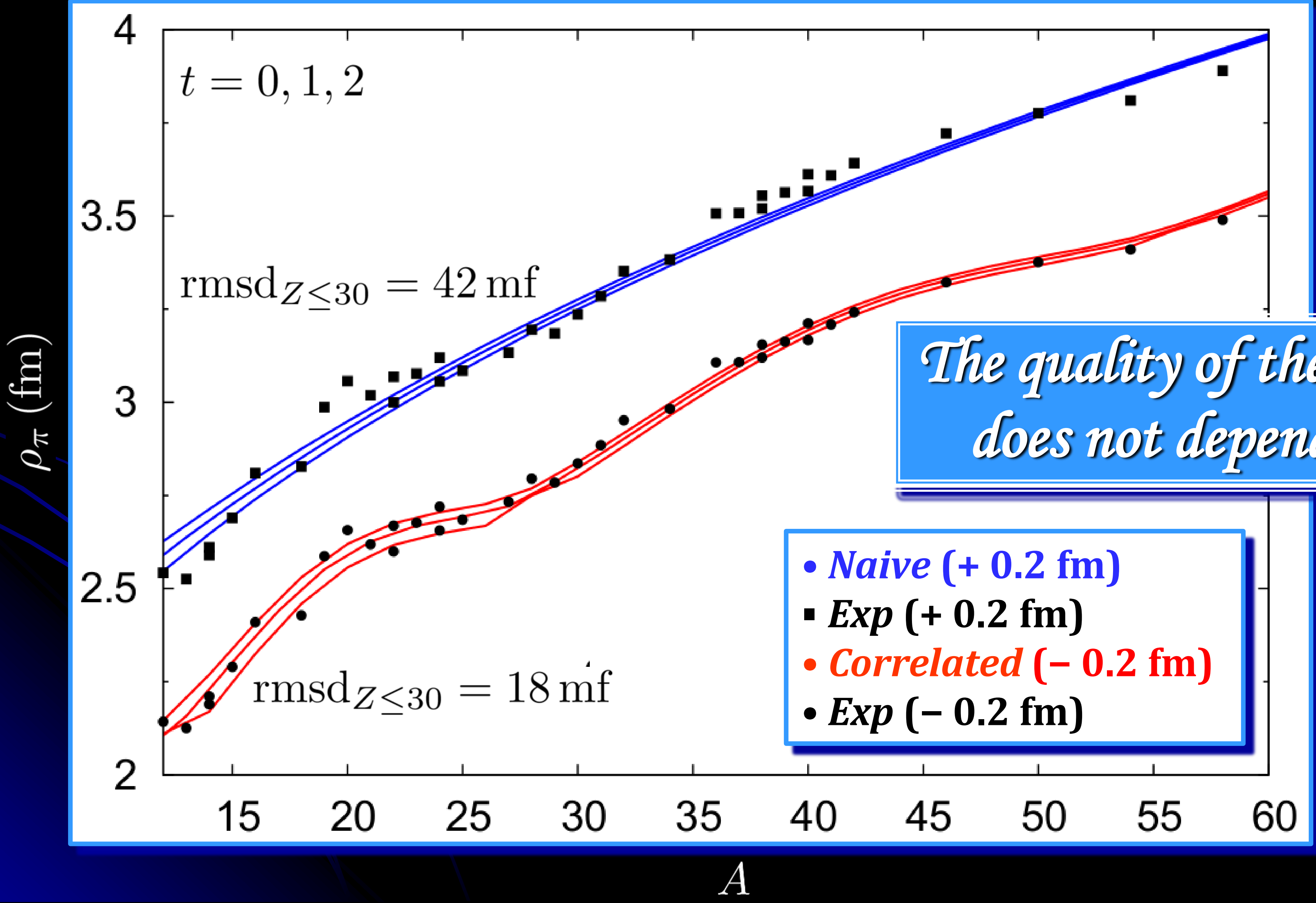

The quality of the DZ fit does not depend on ζ

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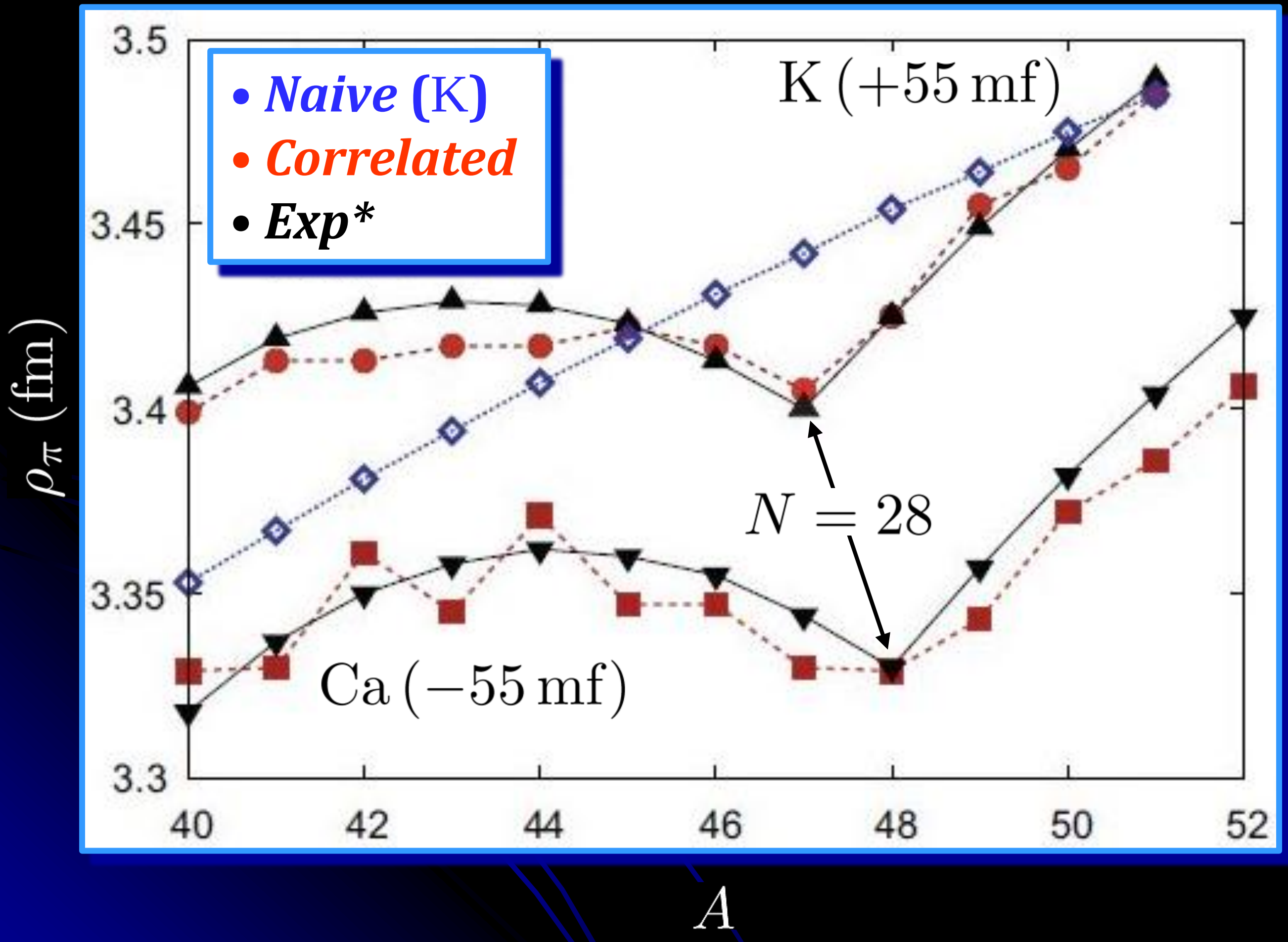

Open problem:

Abrupt raise at $N = 28$?

No existing calculation explains the observed radii

*Kreim *et al.*, *PLB* 731, 97 (2014)
Garcìa Ruiz *et al.*, *Nature Physics* (2016)
† Heylen *et al.*, *in preparation*

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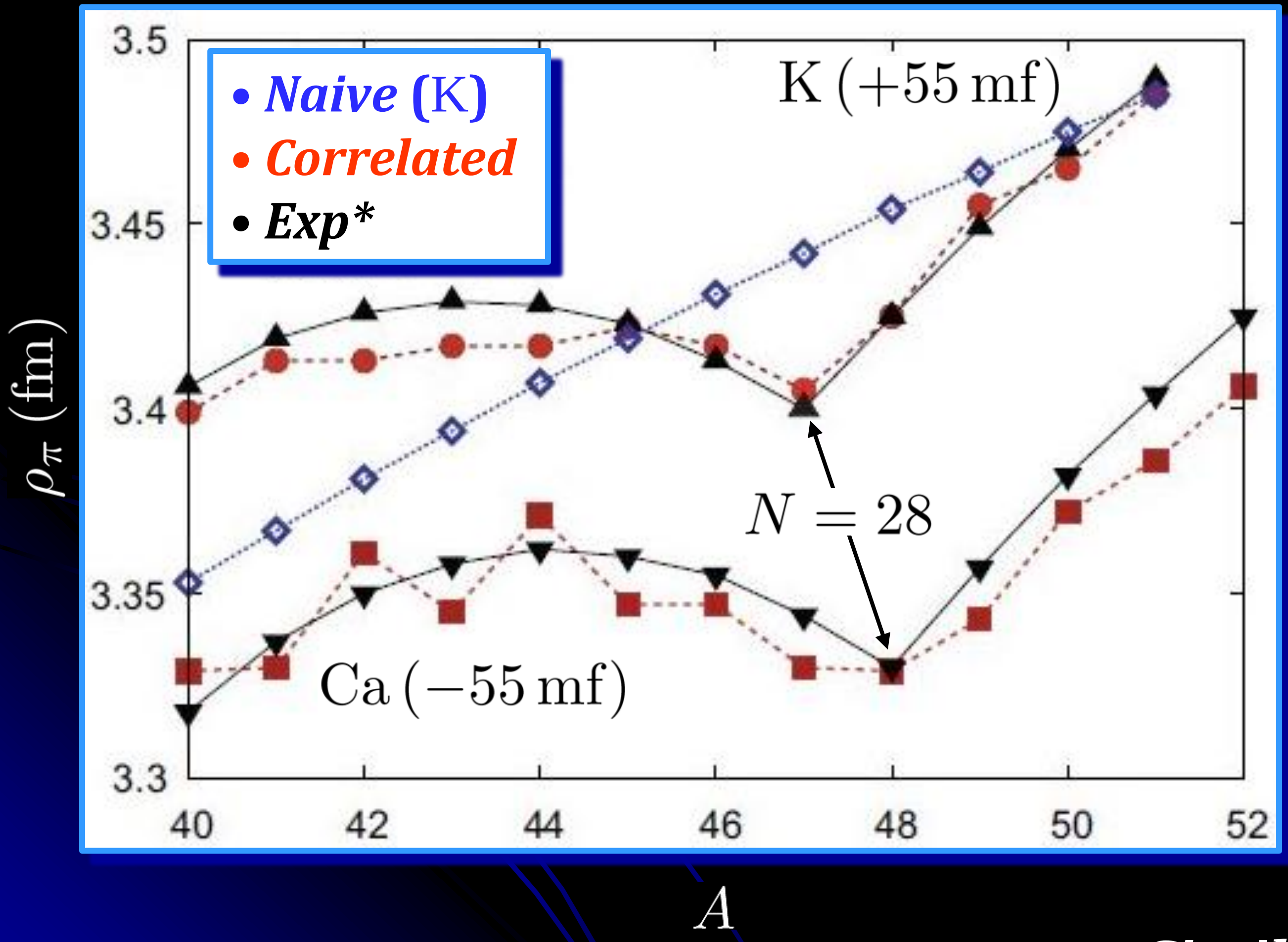

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Filling of huge $p_{3/2}$ orbits

Bonnard, Lenzi, Zuker, *PRL* 113, 212501 (2016)

Similar results obtained for the Mn isotopic chain recently measured†

*Kreim et *al.*, *PLB* 731, 97 (2014)
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Neutron skin

Isospin conservation implies:
Proton rms radius of a $Z > N$ nucleus equals the neutron rms radius of its $N > Z$ mirror

$$\Delta r_{\nu\pi} = \rho_\nu - \rho_\pi = \frac{\zeta t}{A}\, \mathrm{e}^{g/A}$$

	^{48}Ca	^{68}Ni	^{120}Sn	^{208}Pb	^{128}Pb
DZ(ζ = 0.8 fm)	0.14	0.14	0.13	0.17	0.17
Estimates	0.135(15)	0.17(2)	0.14(2)	0.16(3)	0.15(3)
	ab initio	α_D	α_D	α_D	exp
	Hagen *et al.*, *Nat. Phys.* 12 186 (2016)		Roc-Maza *et al.*, *PRC* 92 064304 (2015)		Tarbet *et al.*, *PRL* 112, 242502 (2014)

DZ skins also squares well with Gogny D1S* and Skyrme Sly4† results

*Berger, Girod, Cogny, *Comp. Phys. Comm.* 63, 365 (1991)
† Chabanat *et al., NPA* 365, 231 (2010)

Isovector monopole polarizability

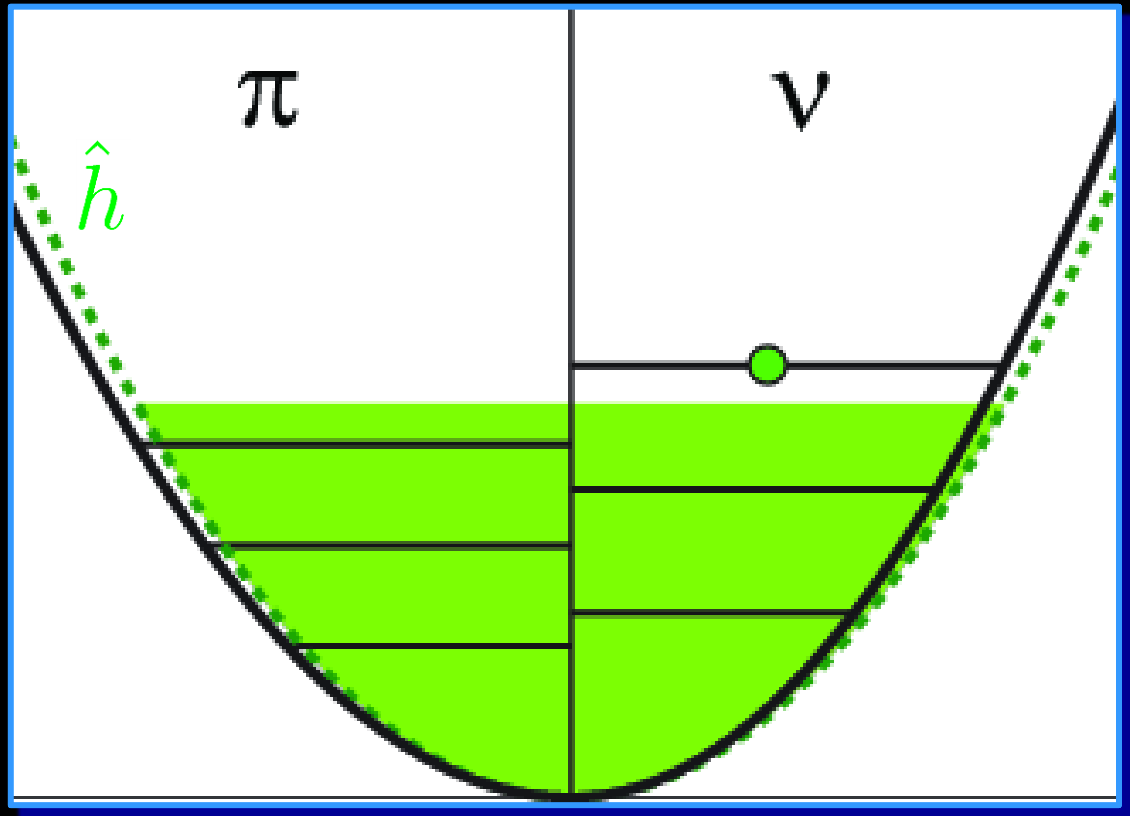
Toy model

Zuker, *Czech. J. Phys. B* 25, 311 (1975)

The extra particle polarizes the system by inducing particle-hole jumps from the core

$$\hat{H} = \hat{h} + \hat{H}_0 + \hat{H}_1$$

- $\hat{h}$ *unperturbed system*
- $\hat{H}_0$ *isoscalar: overall increase*
- $\hat{H}_1$ *isovector: differential contraction-dilation of the fluids*



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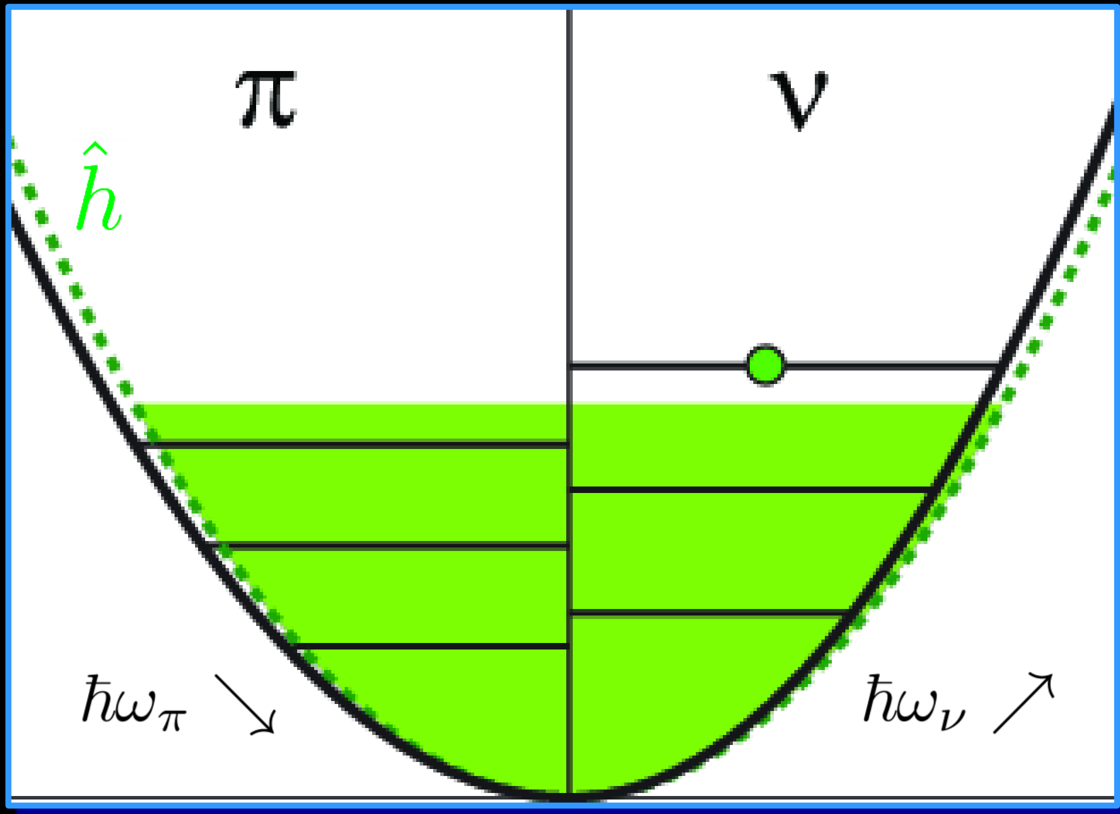


Approximate solution:

The NSA disappears as the proton and neutron radii tends to equalize

$$\hbar\omega_\nu > \hbar\omega_\pi$$

Strategy

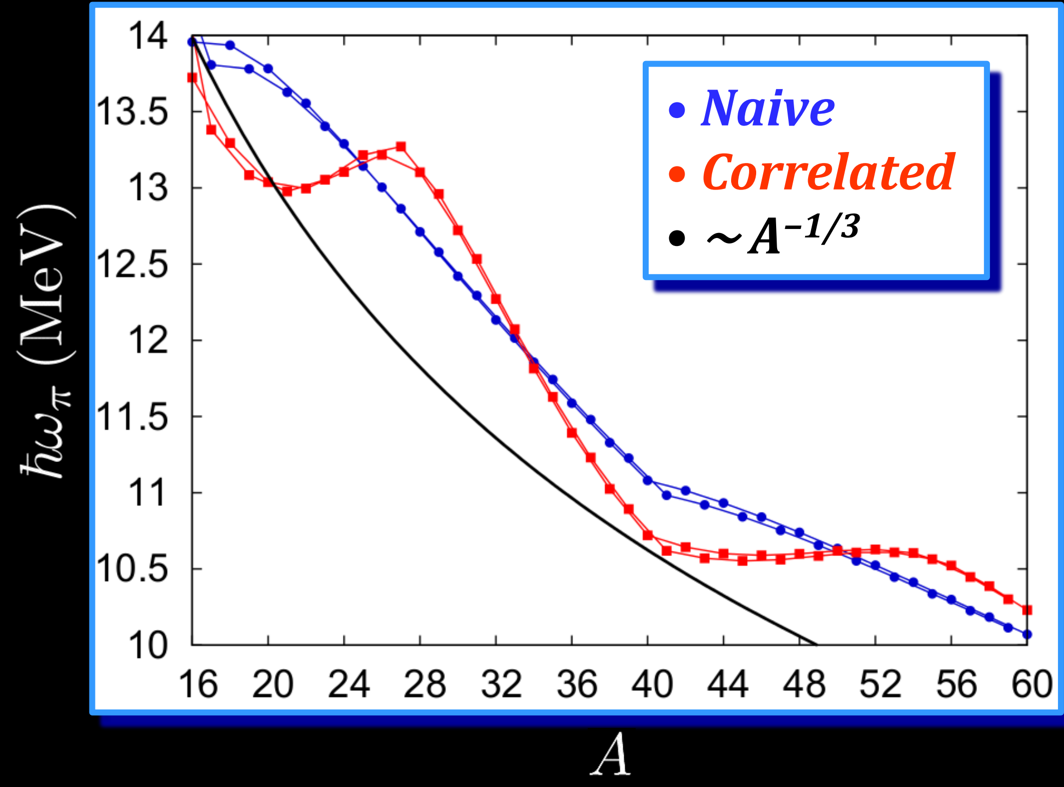
$0\hbar\omega$ ***no-core shell model with*** $V_{\mathrm{low}-k}$ ***potentials from chiral N3LO interaction that incorporates all isospin-breaking effects***

Isovector monopole polarizability: Calculations with different $\hbar\omega$ ***for protons and neutrons***

$$\hbar\omega_\pi = \frac{41.47}{\langle r_\pi^2 \rangle} \sum_i z_i (p_i + 3/2)/Z$$

$$\hbar\omega_\nu = \frac{41.47}{\langle r_\nu^2 \rangle} \sum_i n_i (p_i + 3/2)/N$$

Values interchanged for the mirror

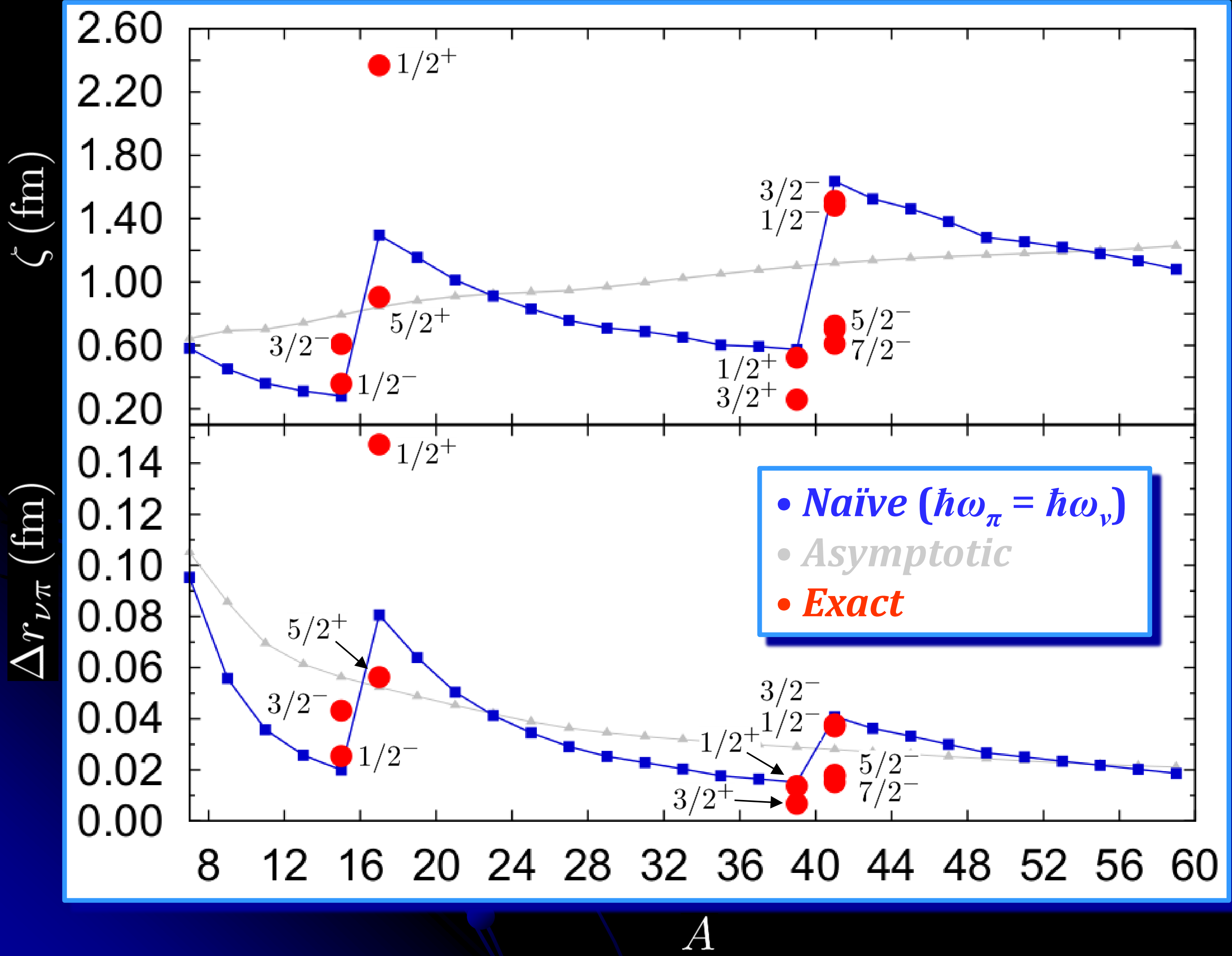


The DZ fit does not depend on ζ

Skin parameters ζ ***adjusted to reproduce the experimental energy differences***

Results

Single-particle/hole states built on ^{16}O and ^{40}Ca



Bonnard, Lenzi, Zuker, *PRL* 113, 212501 (2016)

$A = 15$

$\hbar\omega_\pi > \hbar\omega_\nu$ rules out an isovector polarization mechanism

$A = 17$

- A reasonable ζ solves the NSA for $d_{5/2}$
- $s_{1/2}$ very large: <u>at least</u> 1.2 fm larger than $d_{5/2}$

$A = 39$

No longer huge but keep memory of halo status

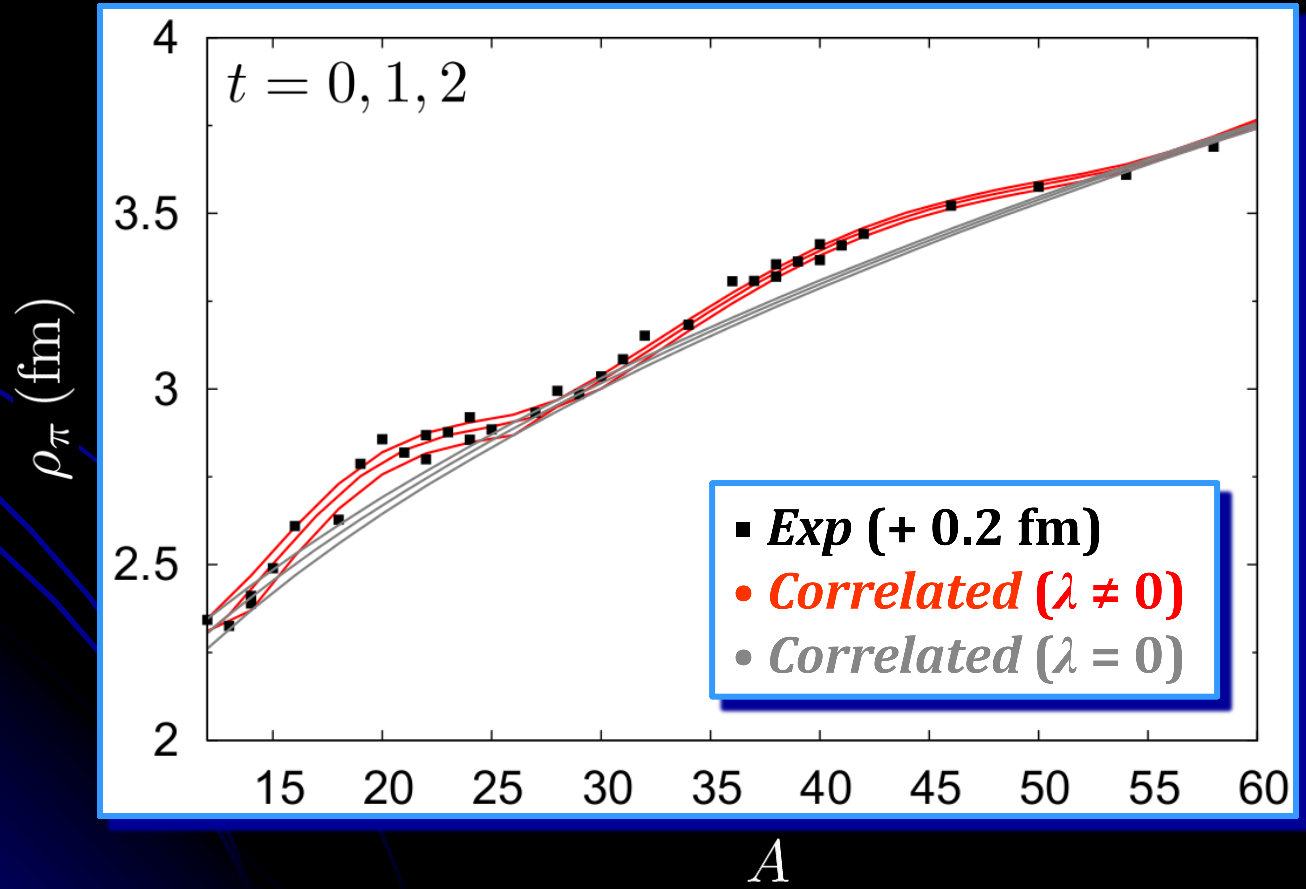
$A = 41$

- A reasonable ζ solves the NSA for $f_{7/2}$
- Same ζ for $f_{5/2}$
- Same ζ for p: at least 0.7 fm larger than f
- Orbits of same l have the same behavior

Radii in the sd shell: Microscopic model

$$\rho_\pi = \frac{41.47}{\hbar\omega}\sum_i m_i(p_i + 3/2 + \delta_i)/A$$

- ***Isospin representation*** ⇨ ***sum over protons and neutrons,*** t ***dependence through*** $\hbar\omega$
- $\hbar\omega$ ***from correlated DZ with*** $\lambda = 0$ ⇨ ***definite positive fluctuations***



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- *Isospin representation* ⇒ *sum over protons and neutrons,* t *dependence through* $\hbar\omega$
- $\hbar\omega$ *from correlated DZ with* $\lambda = 0$ ⇒ *definite positive fluctuations*
- $\delta_{d_{5/2}} = \delta_{d_{3/2}} = 0$ ⇒ $s_{1/2}$ *orbit solely responsible for the fluctuations*
- *Total occupations* m_i *from shell model calculations*
- *Two effective interactions:* - USDa (*scale as* $A^{-1/3}$) Brown & Richter *PRC* 74, 034315 (2014)

  - Monopole corrected interaction (MCI)

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Optimal solution

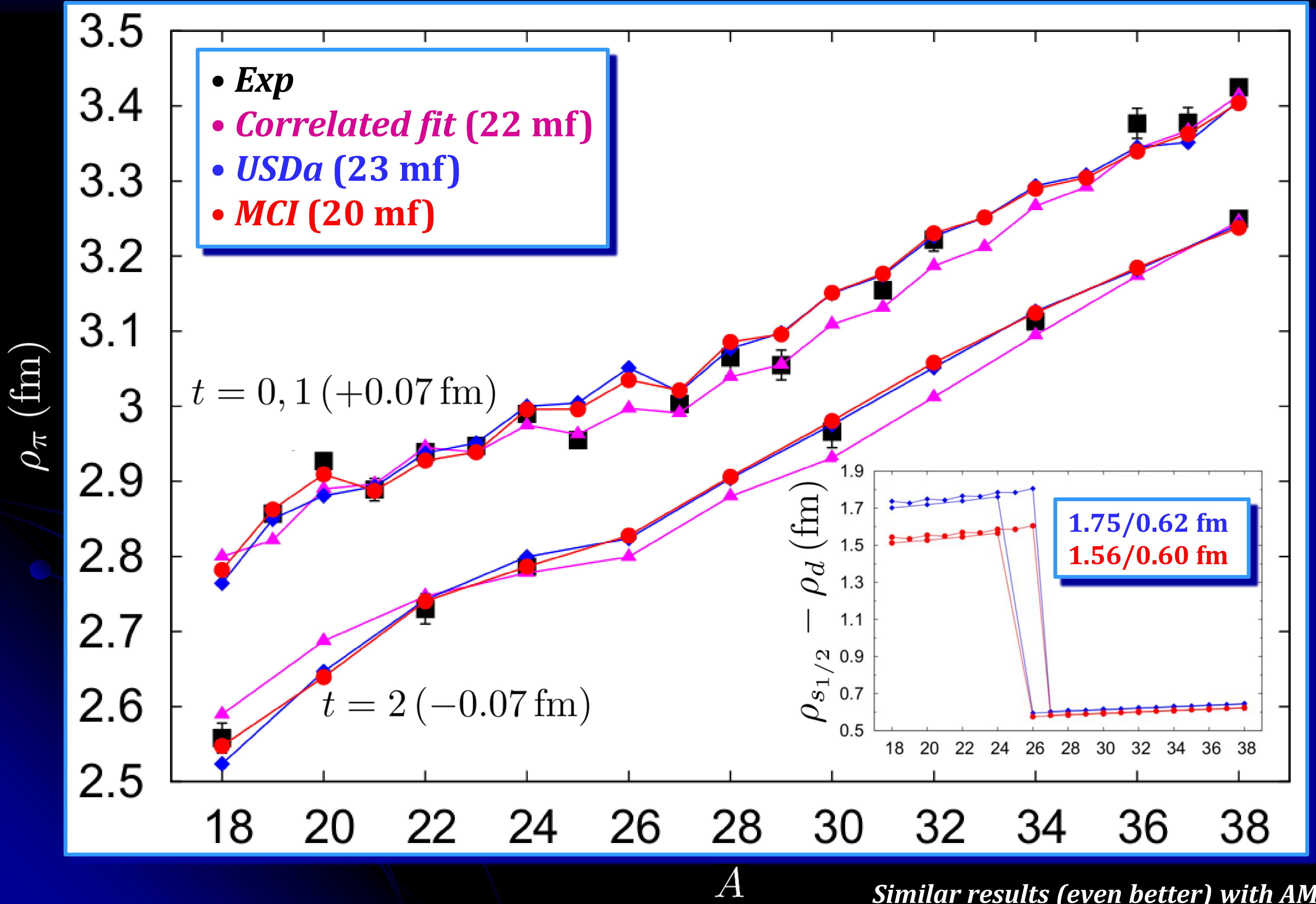
$$\delta_{s_{1/2}} = \begin{cases} \delta_< & \text{if } N \text{ and } Z < 14 \\ \delta_> & \text{if } N \text{ or } Z \geq 14 \end{cases}$$

14 is an EI magic number

	USDa	*MCI*
$\delta_<$(fm)	4.90	4.25
$\delta_>$(fm)	1.40	1.35

Results

Bonnard & Zuker, *nucl-th*/1606.03345



Similar results (even better) with AM radii

Conclusions

Summary

- *First reproduction of the observed isotope shifts in* K *and* Ca via *DZ*
- *Old problems under new guises: NSA as neutron skins, TES as halo orbits*
- $s_{1/2}$ *and* $p_{3/2,1/2}$ *orbits in the* ^{17}O *and* ^{41}Ca *respectively are huge*
- *Microscopic model reproduce well radii throughout the sd shell*
- *Unexpected behavior: The size of* $s_{1/2}$ *drops abruptly at the EI closure* (*N, Z* = 14), *but remains large* (*~1.6 to ~0.6 fm bigger than its d counterparts*)

Open problems

- *Can this surprising behavior be derived from* ab initio *calculations?*
- *Could it not be that the unexplained EI magic numbers are not associated to selfbinding of the orbits with largest j within a major HO shell* (*due to 3B forces*) *but instead to unbinding of halo orbits above?*

Perspectives

- *Calculations of MDE and MED in the sd shell*
- *Applications to the pf shell*

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Thank you for your attention

Assemblée Générale des Théoriciens de Physique Nucléaire

23 juin 2016, IPN d'Orsay