Pygmy resonances, neutron skins and neutron stars

C.A. Bertulani

TEXAS A&M UNIVERSITY COMMERCE

UNIVERSITY of the WESTERN CAPE

X TASTES OF NUCLEAR PHYSICS

University of the Western Cape, South Africa, December 4, 2020

In collaboration with

Gerhard Baur

Andrew Sustich

Hiroyuki Sagawa

Thomas Aumann

Mahir Hussein

Stefan Typel

Peter von Neumann-Cosel

Aurel Bulgac

In collaboration with

TEXAS A&M UNIVERSITY COMMERCE

Postdocs

Paolo Avogadro

Shubhchintak

Hongliang Liu

Ronaldo Lobato

Students

Josilyn Valencia

Michael Hartos

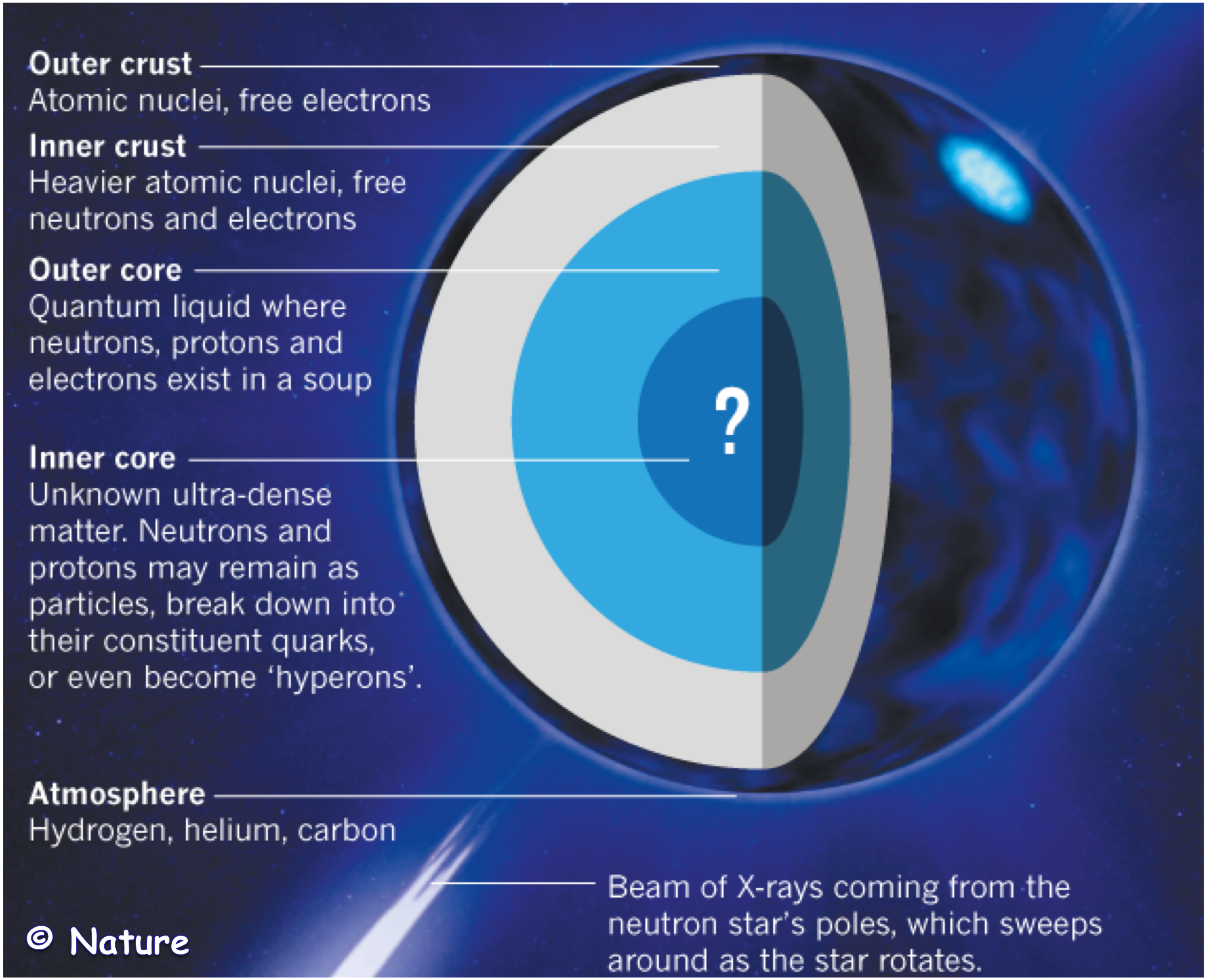
James Thomas

Nathan Brady

Neutron stars in a nutshell

- Existence proposed by Baade and Zwicky (1934) – Landau (1932)
- Remnants of supernovae, $M = 8 - 30\ M_{\odot}$ & 100 million in galaxy
- $M_{NS} = 1.4 - 3\ M_{\odot}$ & $> 3\ M_{\odot}$ collapse to BH & Largest observed = $2\ M_{\odot}$
- L-conservation in collapse → NS rotate with period = 1.4 ms – 30 s
- $\rho = 4 - 6 \times 10^{17}\ kg/m^3 \sim 10^{14} \rho_{\odot}$ & matchbox = 10000 Empire States bl
- $R = 10$ km & $T_{surf} = 10^6$ K (X-ray emiss.) & $P_C = 10^{34}$ Pa (unimaginable)
- Magnetic field = $10^4 - 10^{11}$ T → vac. pol. & crust fracture → SGRs?
- $g_{NS} = 2 \times 10^{12}\ m/s^2$ → *spaghettification* & grav. bind. = 100 MeV/A
- $R_{NS} \times M_{NS}$ depends on EOS $P(\rho)$: $1.5\ M_{\odot}$ → 10 – 15 km uncertainty
- Pulsars = spinning NS radiating from poles – Jocelyn Bell (1967)

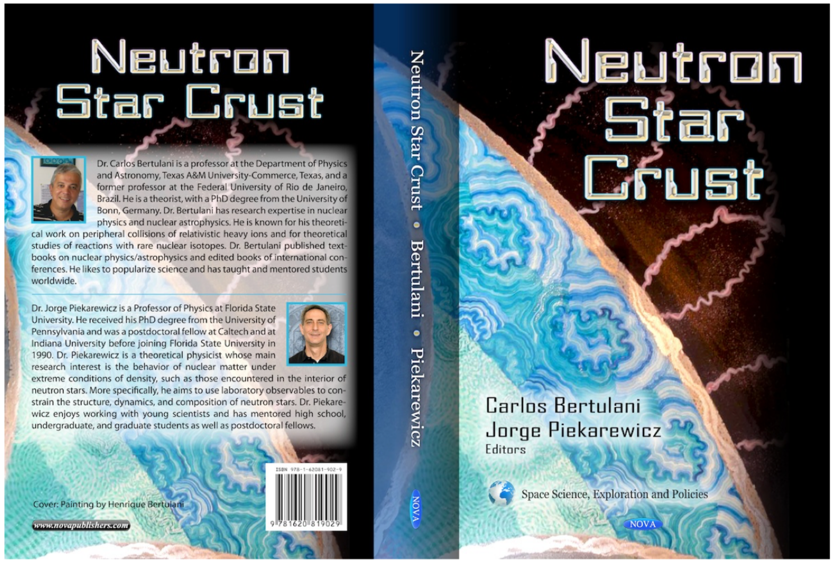
Inside a neutron star



Jocelyn Bell

Jocelyn Bell in Commerce, TX, USA, 2010

Neutron Star Crust: (preface by Jocelyn Bell)



Jocelyn Bell Burnell *
University of Oxford, Denys Wilkinson Building
Keble Road, Oxford OX1 3RH, UK

I judge myself fortunate to be working in an exciting and fast moving area of science and at a time when the public has become fascinated by questions regarding the birth and evolution of stars, the nature of dark matter and dark energy, the formation of black holes and the origin and evolution of the universe.

The physics of neutron stars is one of these fascinating subjects. Neutron stars are formed in supernova explosions of massive stars or by accretion-induced collapse of smaller white dwarf stars. Their existence was confirmed through the discovery of radio pulsars during my thesis work in 1967. Since then this field has evolved enormously. Today we know of accretion-powered pulsars which are predominantly bright X-ray sources, rotation-powered pulsars observed throughout the electromagnetic spectrum, radio-quiet neutron stars, and highly magnetized neutron stars or magnetars. No wonder there has been an explosion in the research activity related to neutron stars!

It is now hard to collect in a single book what we already know about neutron stars along with some of the exciting new developments. In this volume experts have been asked to articulate what they believe are the critical, open questions in the field. In order for the book to be useful to a more general audience, the presentations also aim to be as pedagogical as possible.

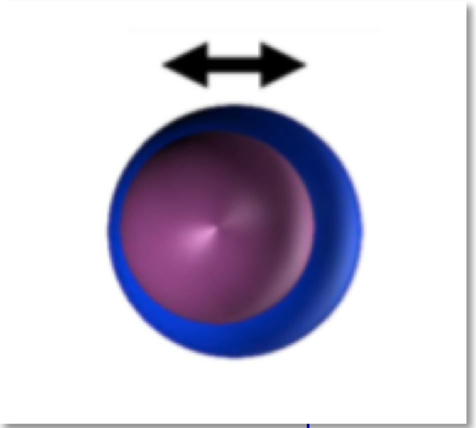
This book is a collection of articles on the neutron stars themselves, written by well-known physicists. It is written with young researchers as the target audience, to help this new generation move the field forward. The invited authors summarize the current status of

*j.bellburnell@physics.ox.ac.uk

Table of Contents

Bertulani, Piekarewicz, editors

Pygmy Resonances: Origins



Low-energy dipole strength

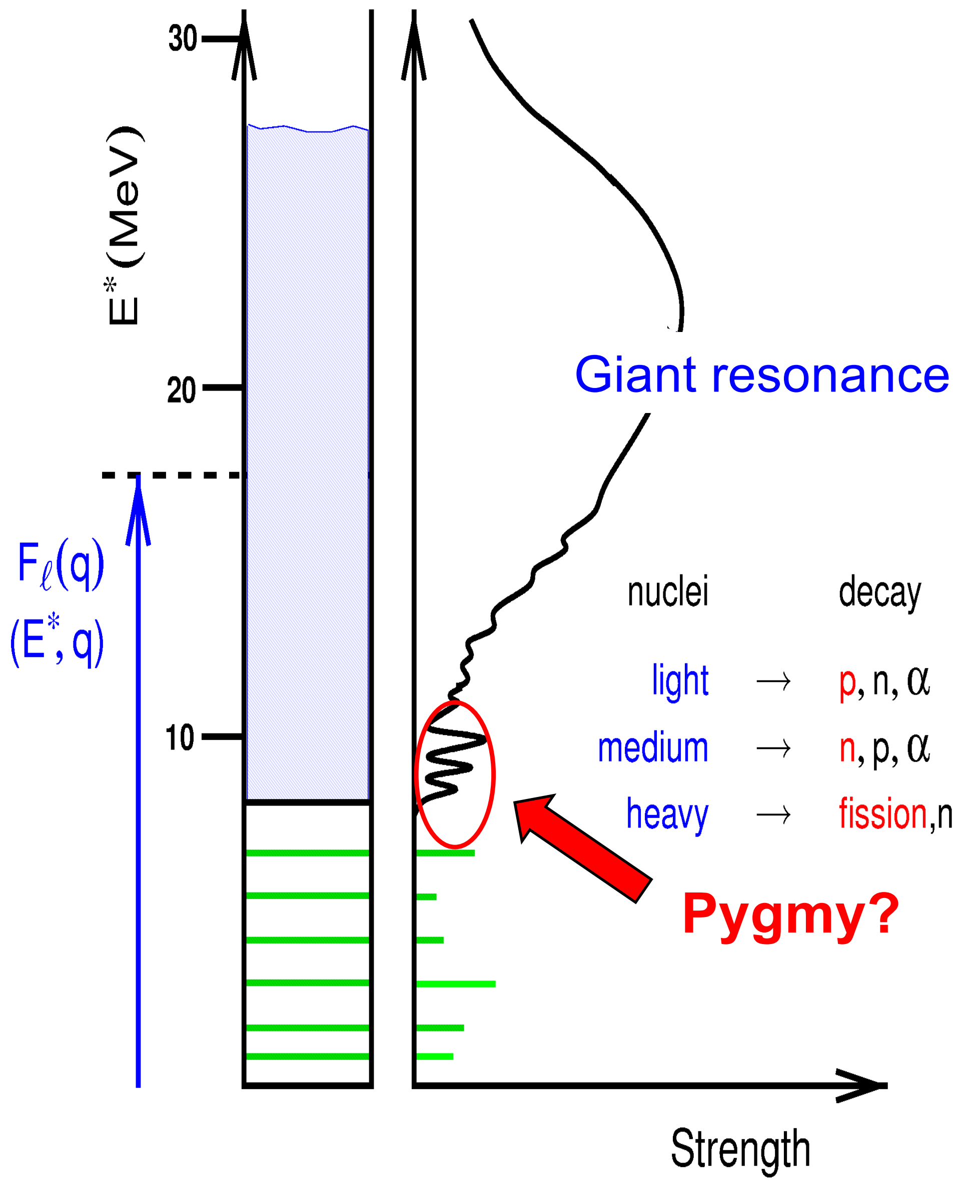
- First observation in 1961
  γ rays from neutron capture
  Bartholomew, Annu. Rev. Nucl. Sci. 11, 259 (1961)

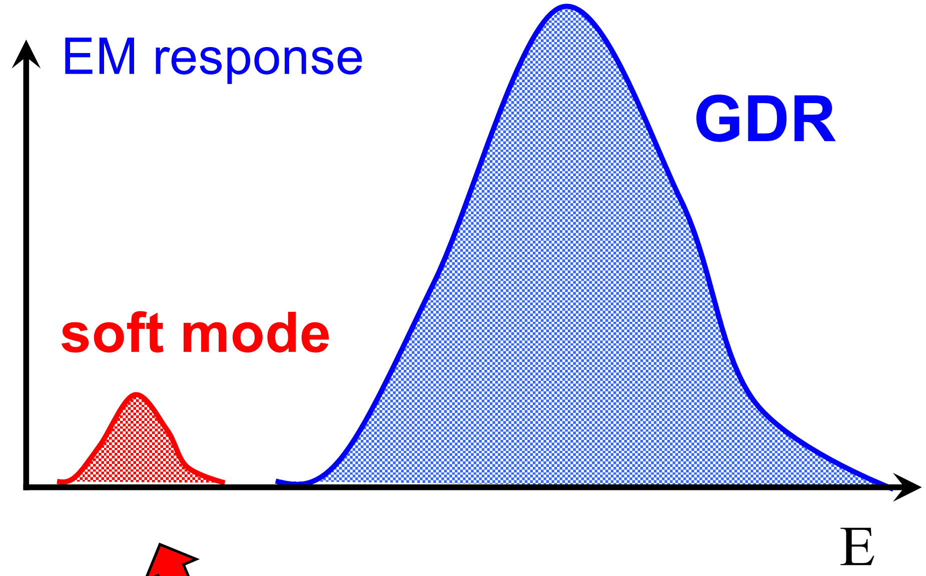
- First use of name “pygmy resonance” (PDR)
  Brzosko et al., Can. J. Phys 47, 2849 (1969)

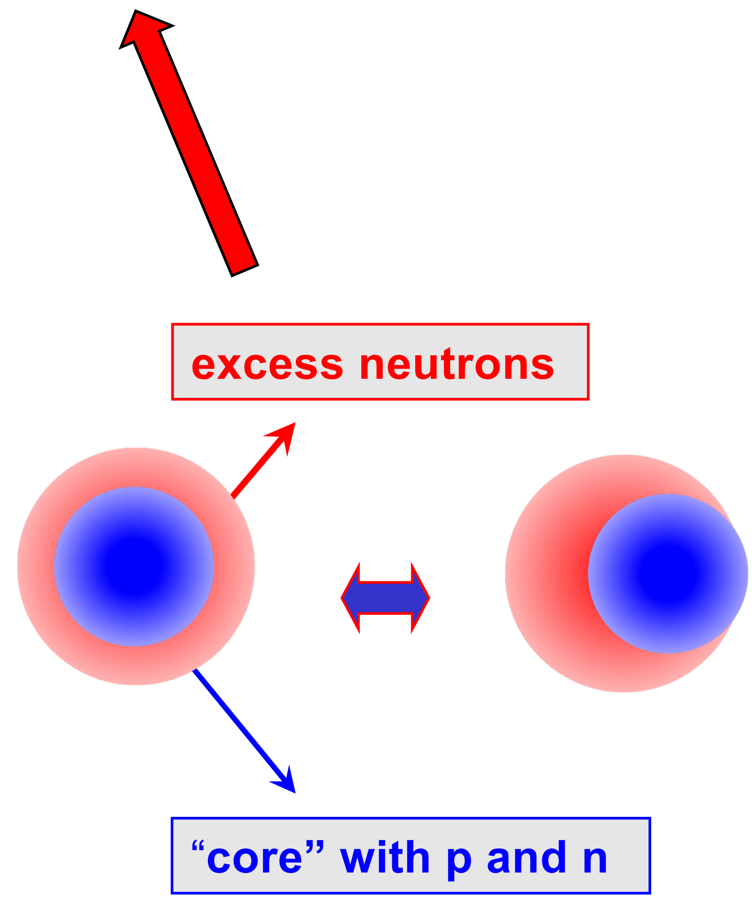
- Description as a collective excitation
  Mohan et al., Phys. Rev. C 3, 1740 (1971)
  “Three-Fluid Hydrodynamical Model of Nuclei”:
  Neutron excess oscillates against the N = Z core

- First experimental proposal:
  Nomura, Kubono, et al., June 1987
  Experiment proposal (J-PARC)

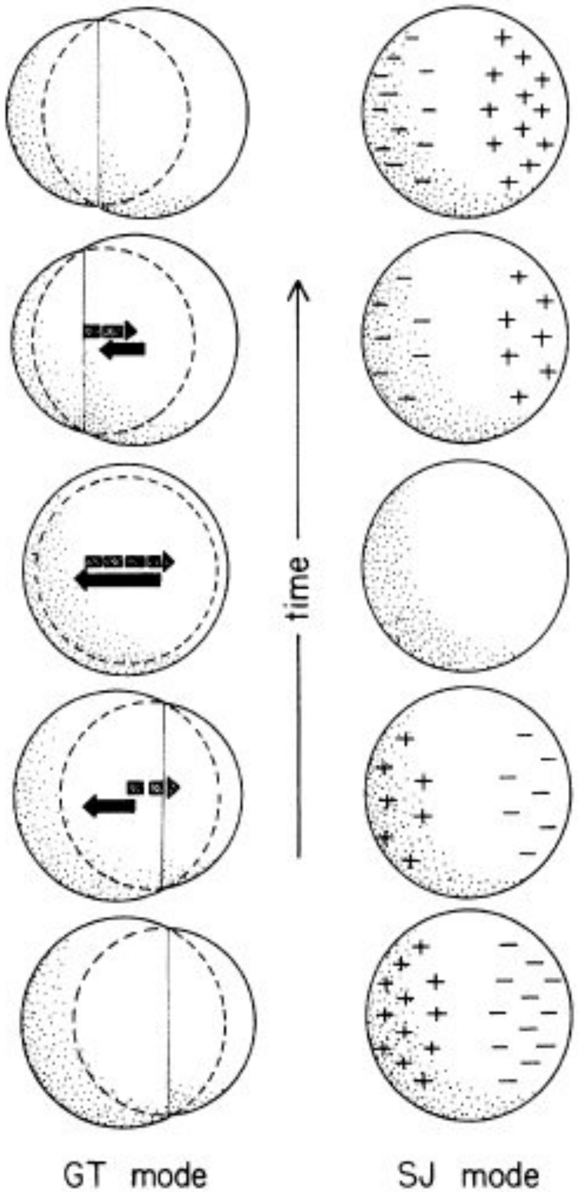
Collective vibrations







Hydrodynamics



$$T = \frac{1}{2} m^* \int \rho_p \left(\mathbf{v}_{SJ}^{(p)} + \mathbf{v}_{GT}^{(p)} \right)^2 + \rho_n \left(\mathbf{v}_{SJ}^{(n)} + \mathbf{v}_{GT}^{(n)} \right)^2$$

$$V = -\kappa \int d^3r \frac{(\rho_n - \rho_p)^2}{\rho_n - \rho_p} + \text{surf.}\, terms$$

$$\kappa \sim 30 - 40 \text{ MeV}$$

Myers et al, PRC 15, 2032 (1977)

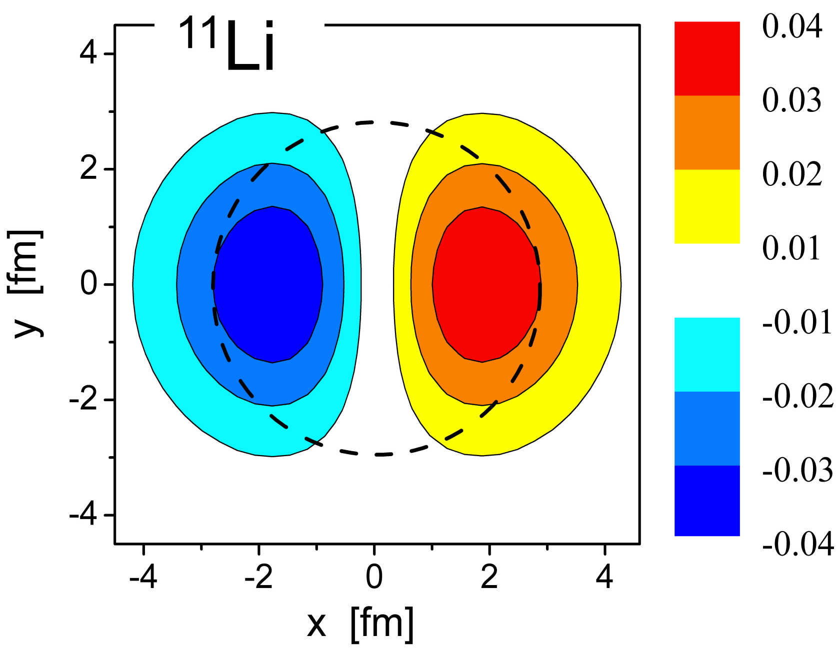
Pygmy transition densities

Suzuki, Ikeda, Sato, PTP 83 (1990) 180
Van Isacker, Nagarajan, Warner, PRC 45 (1992) 13

GT **SJ**

$$\delta\rho = \sqrt{\frac{4\pi}{3}} R \left[Z_{eff}^{(GT)} \alpha_{GT} \frac{d}{dr} + Z_{eff}^{(SJ)} \alpha_{SJ} \frac{K}{R} j_1(kr) \right] \rho_0(r)$$

$$kR = 2.081, \qquad K = 9.93$$



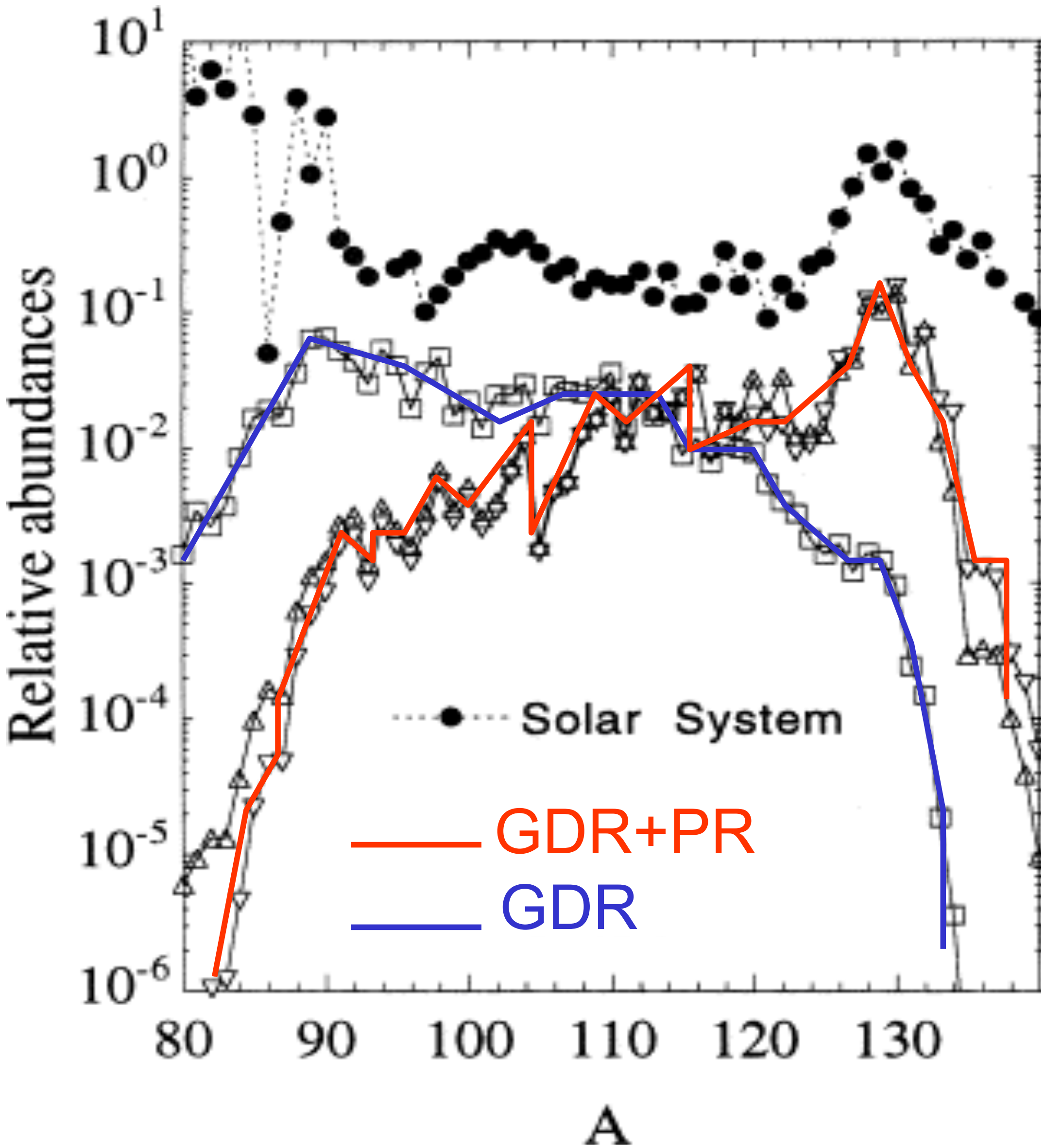
$$E_{PR} = \left[\frac{3 S_n A \hbar^2}{2 a R m_N A_c (A - A_c)} \right]^{1/2} \sim 1\text{–}3 \text{ MeV}$$

$$\Gamma_{PR} = \frac{\hbar \sqrt{\overline{V}_{core} \overline{V}_{skin}}}{R} \sim 3 \text{ MeV}$$

Bertulani, PRC 75, 024606 (2007)
NPA 790, 467 (2007)

Impact of pygmies on nucleosynthesis (??!)

(γ,n) or (n,γ) cross sections in the r-process

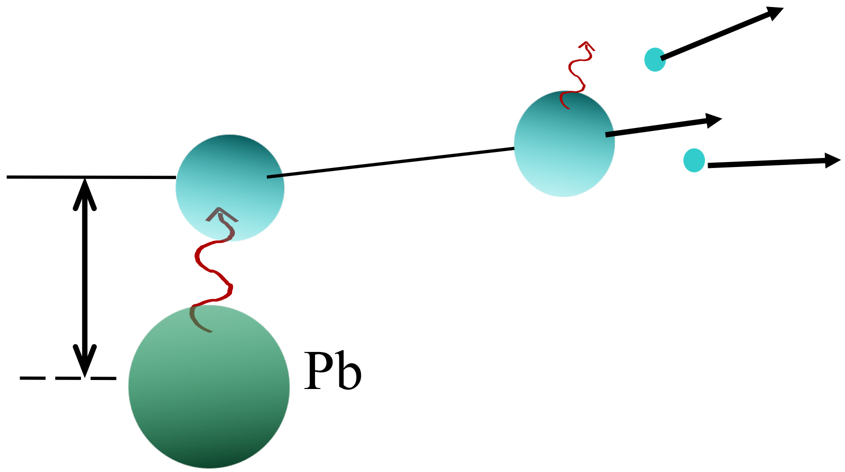


Impact: r-process abundances

- Calculation for $T = 10^9$ K, $N_n = 10^{20}$ cm^{-3}, $\tau = 2.3$ s
- Under some conditions, PDR can enhance production in some regions

Goriely, PLB 436, 10 (1998)

E & M response in neutron-rich nuclei



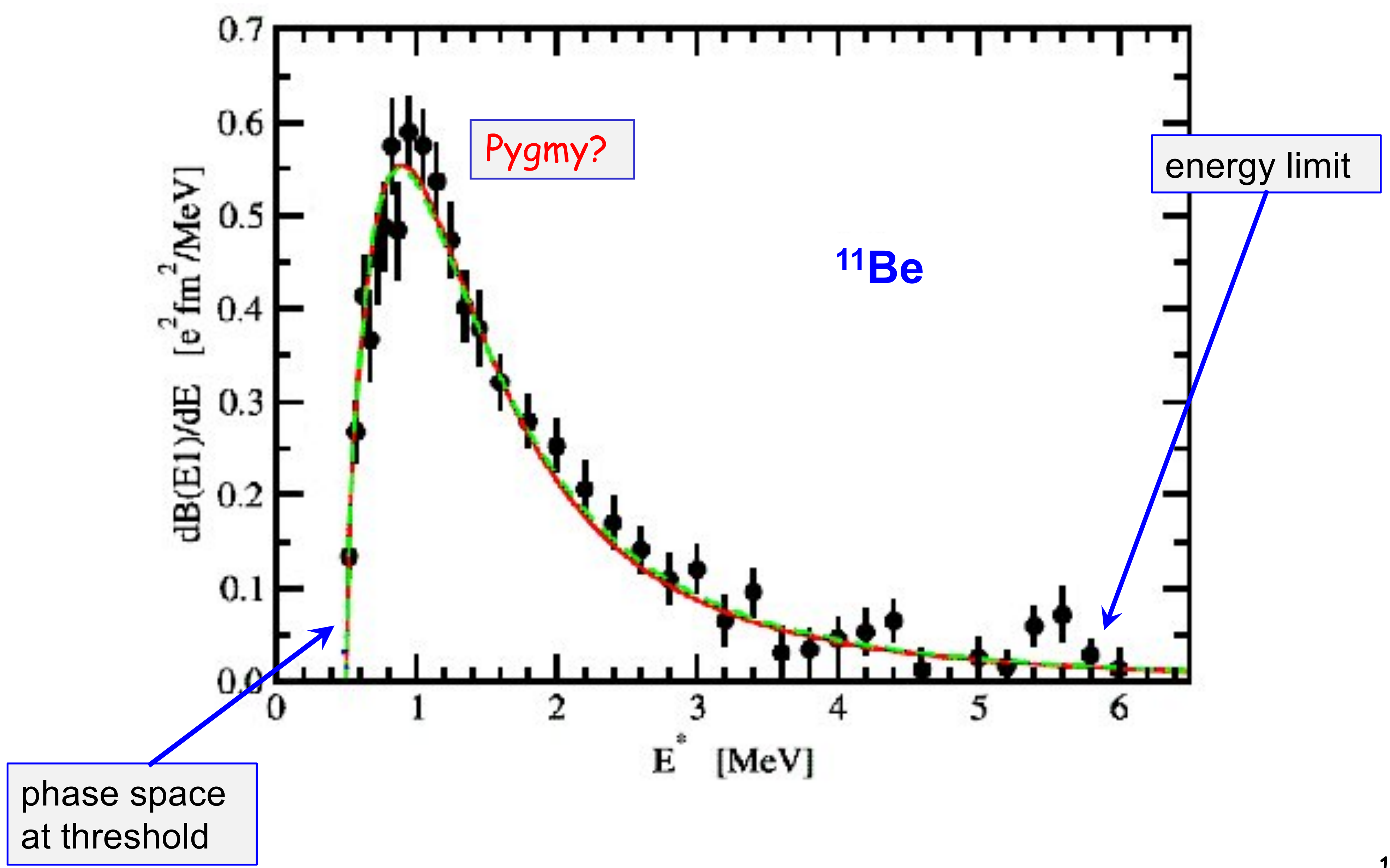
bound $\sim e^{-\kappa r}$ continuum $\sim e^{-i\mathbf{k}.\mathbf{r}}$

$$\frac{dB(EL)}{dE} \sim \left| \left\langle \Psi_f \left| r^L Y_L \right| \Psi_i \right\rangle \right|^2 \sim \frac{\left(E_x - S_n\right)^{L+1/2}}{E_x^{2L+2}}$$

$$E_r^{(EL)peak} \sim \frac{L+1/2}{L+3/2} S_n$$

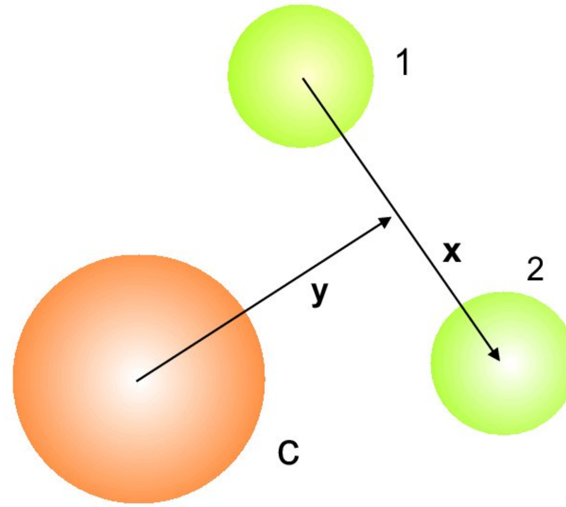
Two-body cluster: Bertulani, Sustich, PRC 46, 2340 (1993)

E & M response in neutron-rich nuclei



3-body models & FSI

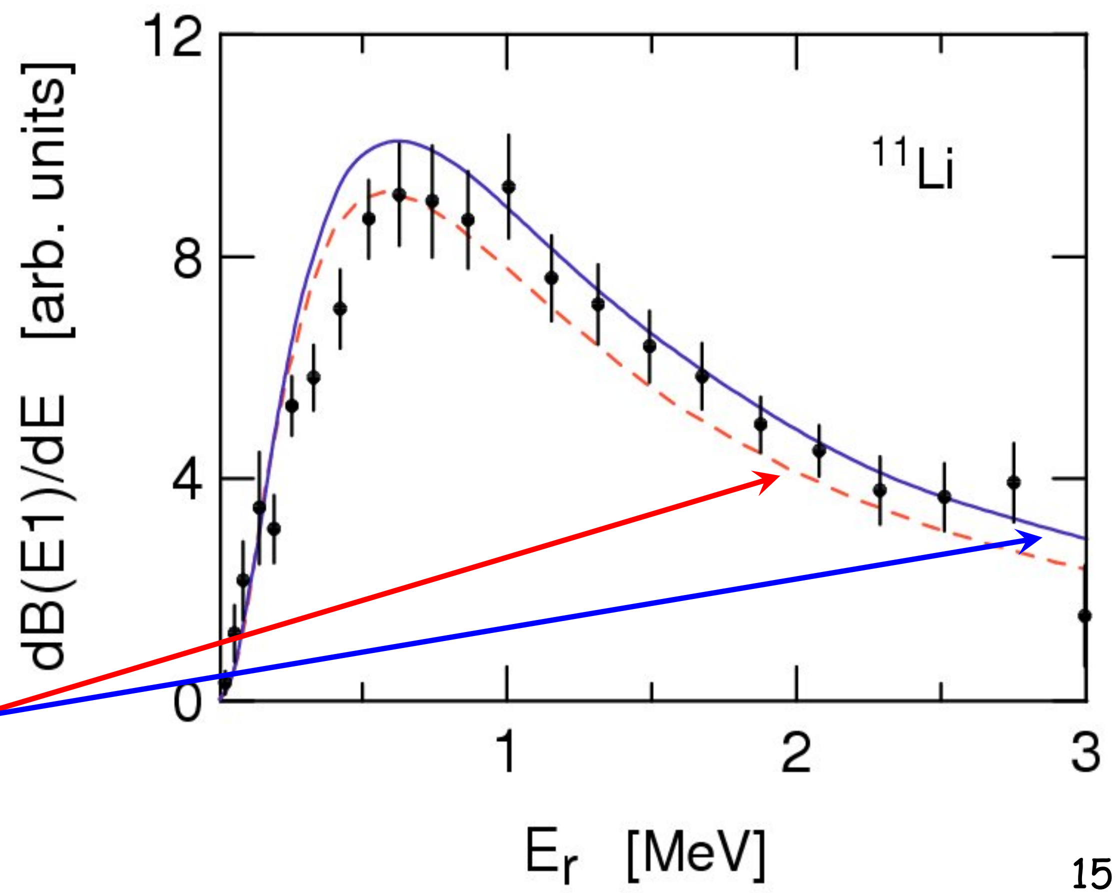
$$\langle \Psi_f | r Y_1 | \Psi_i \rangle \propto \int dx\, dy \frac{\Phi_\alpha(\rho)}{\rho^{5/2}} y^3 x\, u_p(x) u_q(y)$$



$$\frac{dB(E1)}{dE_r} \propto \frac{E_r^3}{\left(S_{2n}^{eff} + E_r\right)^{11/2}} \left(1 + FSI\right)^2$$

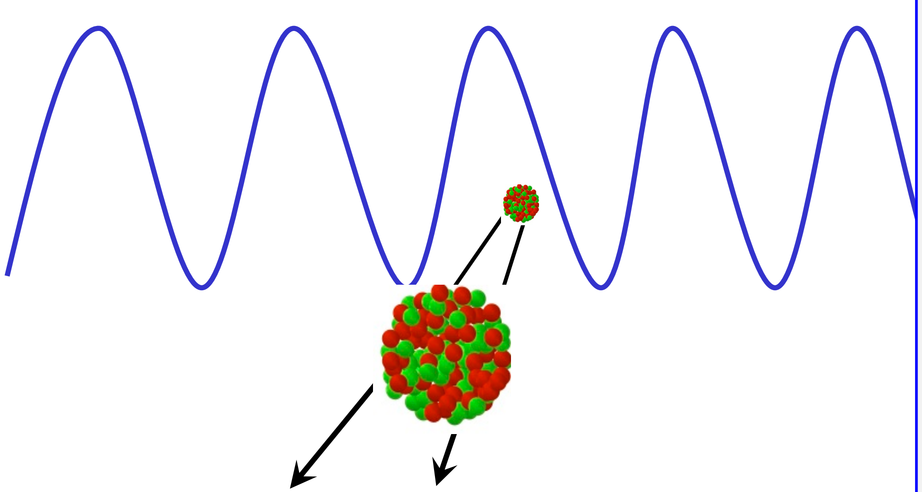
$$S_{2n}^{eff} \sim 1.8\, S_{2n}$$

Bertulani, PRC 75, 024606 (2007)
NPA 790, 467 (2007)



FSI: Different scattering lengths, effective ranges

Halo EFT



$$L_{EFT} = N^{+}\left(i\partial_0 + \frac{\nabla^2}{2m_N}\right)N + C_0\, N^{+}N\, N^{+}N + N^{+}\frac{\nabla^4}{8m_N^3}N + C_2\, N^{+}N\, N^{+}\nabla^2 N + C_2'\, N^{+}\vec{\nabla}N \cdot N^{+}\vec{\nabla}N + \ldots$$

$$f(x) = f(0) + \mathbf{p}\cdot\left(\nabla f\right)\Big|_0 + \mathbf{Q}\cdot\left(\nabla^2 f\right)\Big|_0 + \cdots$$

monopole:

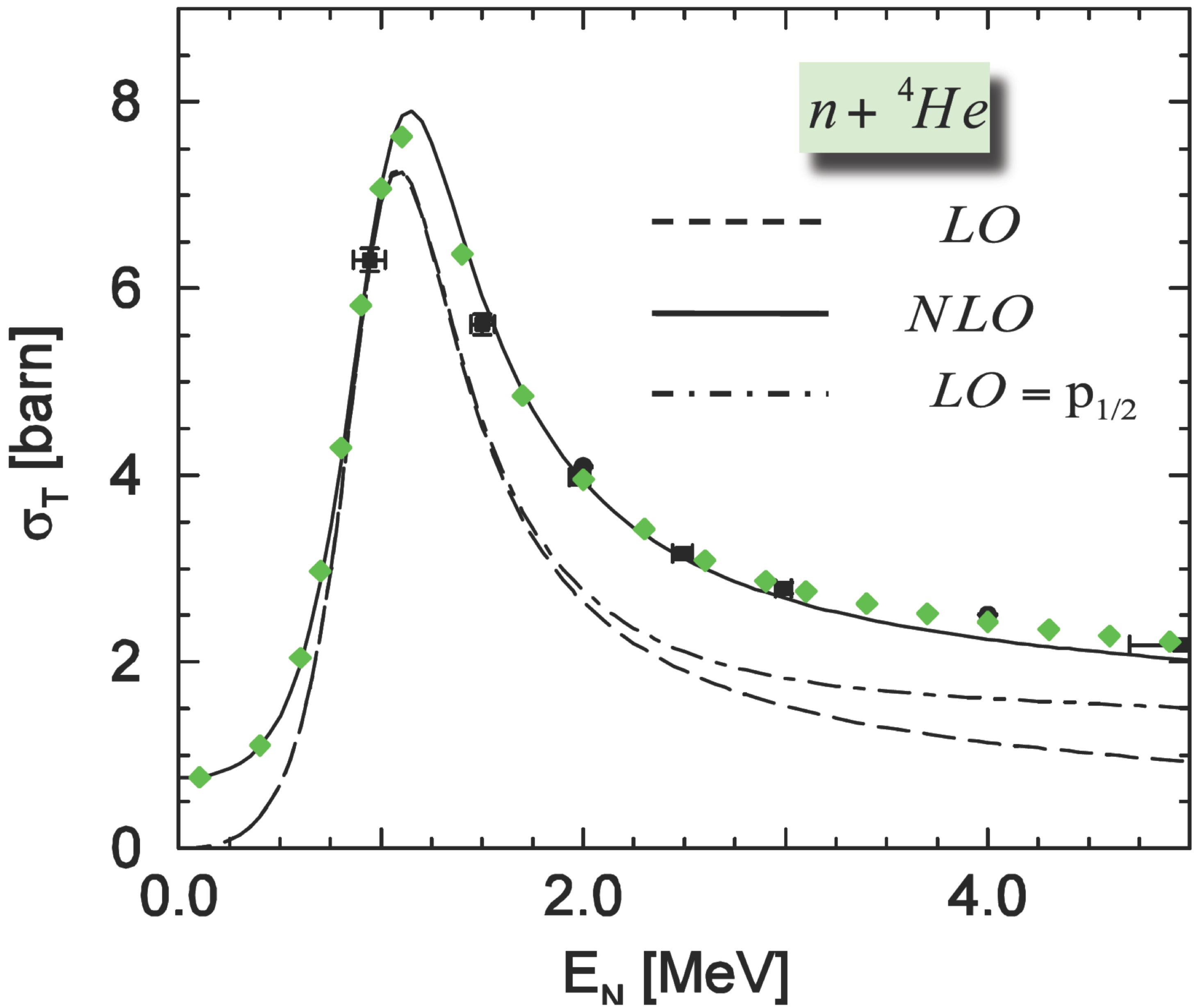
dipole:

quadrupole:

controlled precision

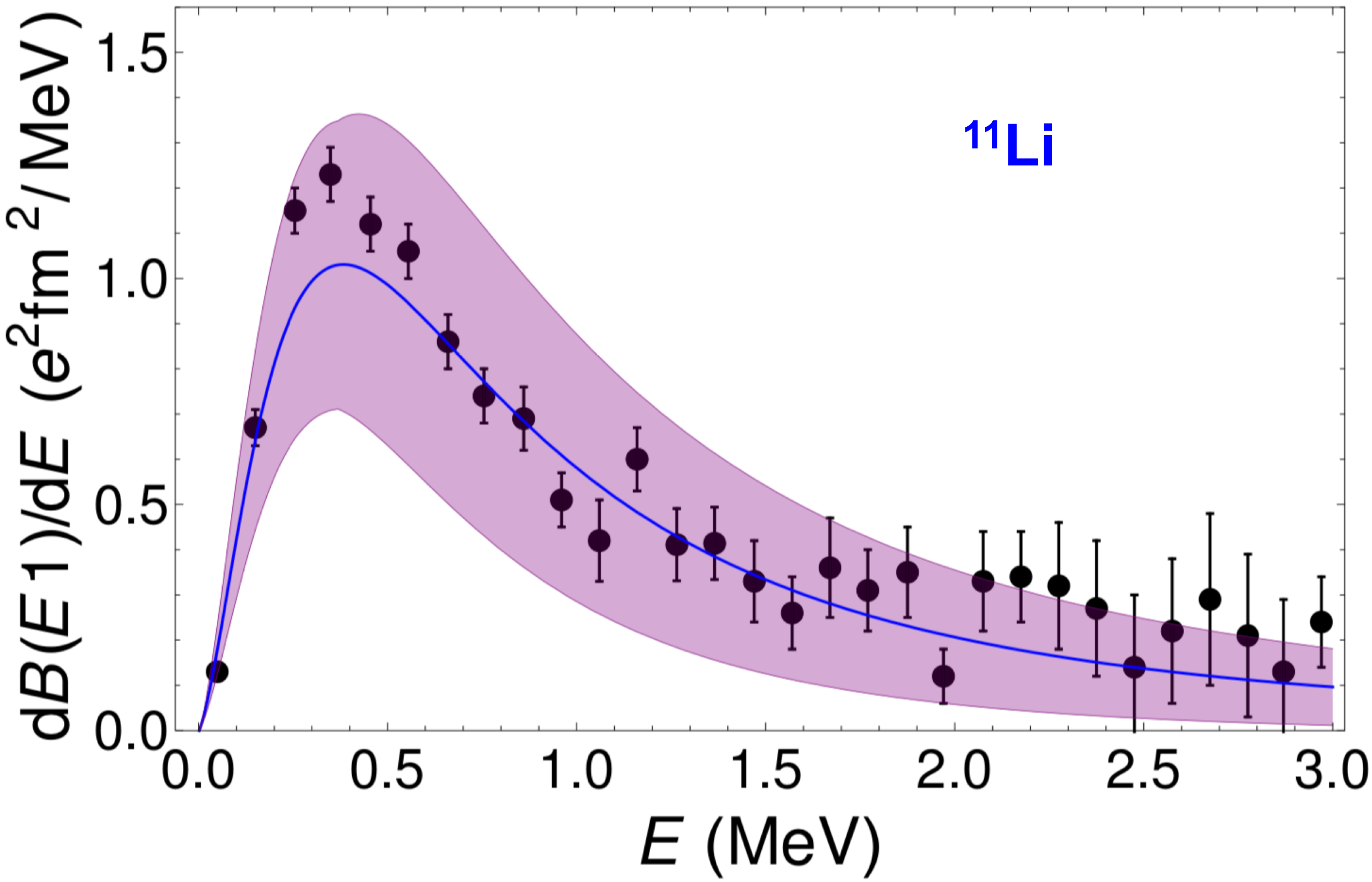
- Feynman diagrams
- particle exchange
- vacuum polarization
- loop integrals, divergences
- regularization, renormalization

Halo EFT



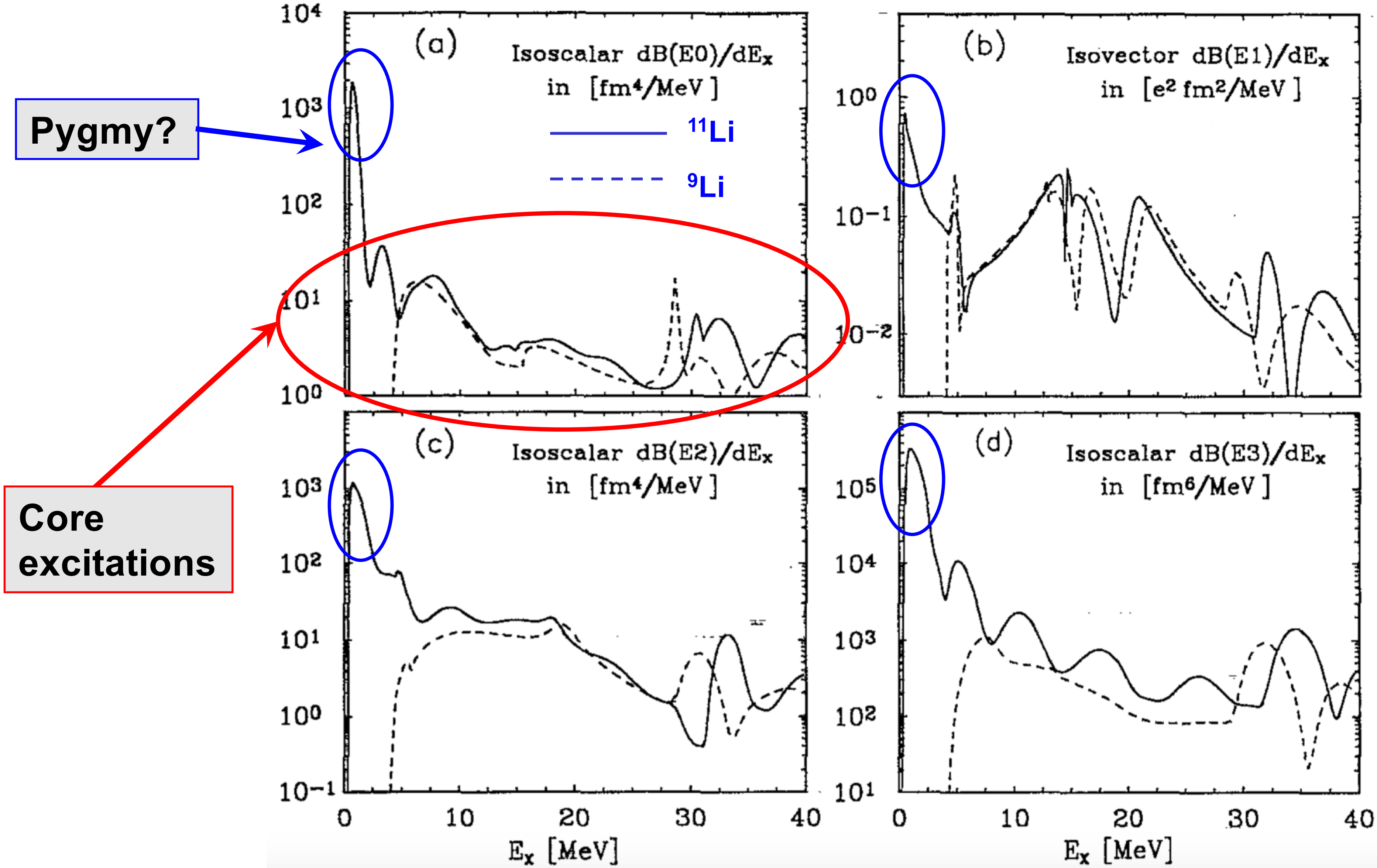
Bertulani, Hammer, van Kolck, NPA 712, 37 (2002)

Halo EFT



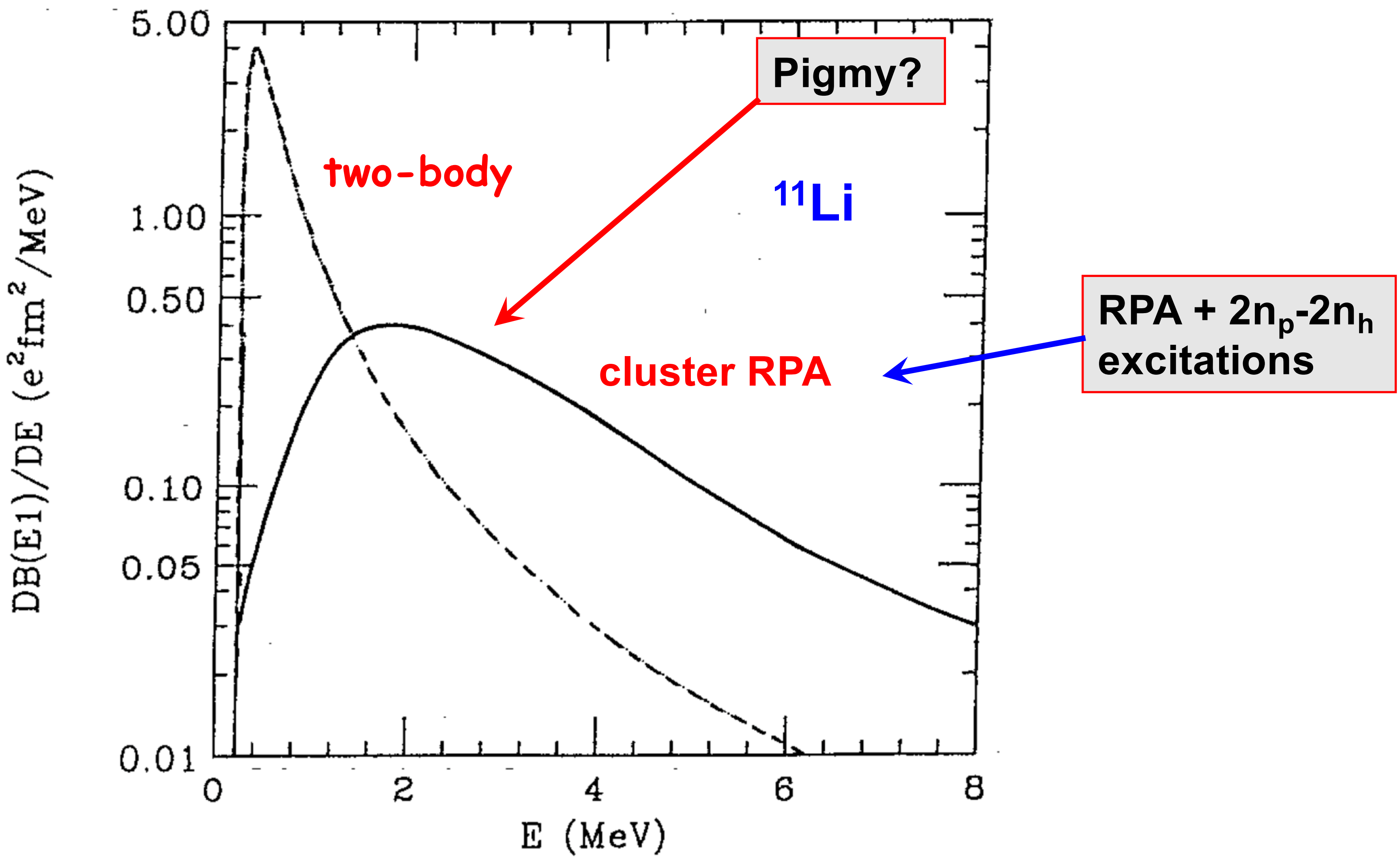
Acharya, Phillips, EPJ 113, 06013 (2016)

Many-body models



Continuum RPA: Bertulani, Sustich, PRC 46 , 2340 (1992)

Many-body models



Teruya, Bertulani, Krewald, Dias, Hussein, PRC 43, 2049 (1991)

Density functional models

For the nucleon-nucleon interaction $V(\mathbf{r}_i,\mathbf{r}_j) = V_{ij}^{NN} + V_{ij}^{Coul}$

$$V_{ij}^{Coul} = -\frac{e^2}{4}\sum_{i,j=1}^{A}\frac{\tau_{ij}^2+\tau_{ij}}{|\mathbf{r}_i-\mathbf{r}_j|}, \qquad \tau_{ij} = \tau_i + \tau_j$$

$$V_{ij}^{NN} = t_0(1+x_0P_{ij}^{\sigma})\delta(\mathbf{r}_i-\mathbf{r}_j) + \frac{1}{2}t_1(1+x_1P_{ij}^{\sigma})[\overleftarrow{\mathbf{k}}_{ij}^2\delta(\mathbf{r}_i-\mathbf{r}_j)+\delta(\mathbf{r}_i-\mathbf{r}_j)\overrightarrow{\mathbf{k}}_{ij}^2] +$$

$$t_2(1+x_2P_{ij}^{\sigma})\overleftarrow{\mathbf{k}}_{ij}\delta(\mathbf{r}_i-\mathbf{r}_{jj})\overrightarrow{\mathbf{k}}_{ij} + \frac{1}{6}t_3(1+x_3P_{ij}^{\sigma})\rho^{\alpha}\left(\frac{\mathbf{r}_i+\mathbf{r}_j}{2}\right)\delta(\mathbf{r}_i-\mathbf{r}_j) +$$

$$iW_0\overleftarrow{\mathbf{k}}_{ij}\delta(\mathbf{r}_i-\mathbf{r}_j)(\vec{\sigma}_i+\vec{\sigma}_j)\overrightarrow{\mathbf{k}}_{ij},$$

$t_i,\ x_i,\ \alpha,\ W_0$ are 10 **Skyrme** parameters

$$\Rightarrow \quad E[\rho] = \left\langle \Phi \middle| T + V_{ij}^{Coul} + V_{ij}^{NN} \middle| \Phi \right\rangle$$

+ pairing

HF + BCS

$$\Delta_i = \frac{1}{2} \sum_j \frac{G_{ij} \Delta_j}{\sqrt{(\varepsilon_j - \lambda)^2 + \Delta_j^2}}$$

HFB

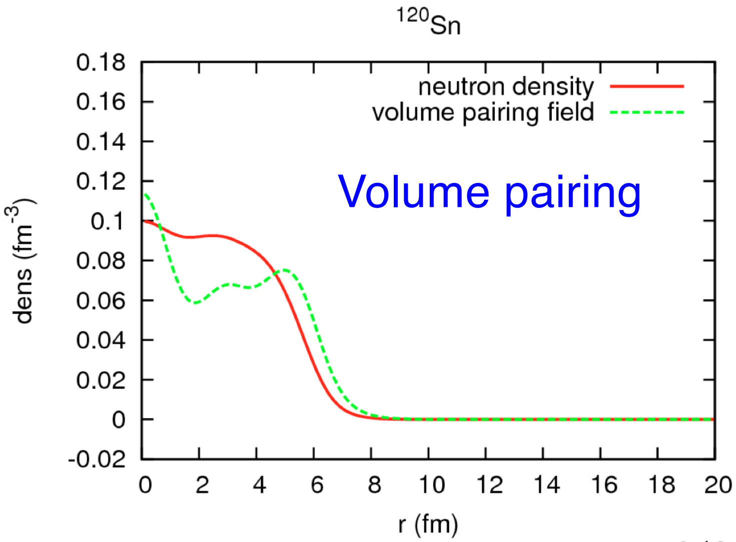
$$\begin{pmatrix} h_{HF} - \lambda & \Delta \\ -\Delta & -h_{HF} + \lambda \end{pmatrix} \begin{pmatrix} u_k \\ v_k \end{pmatrix} = E_k \begin{pmatrix} u_k \\ v_k \end{pmatrix}$$

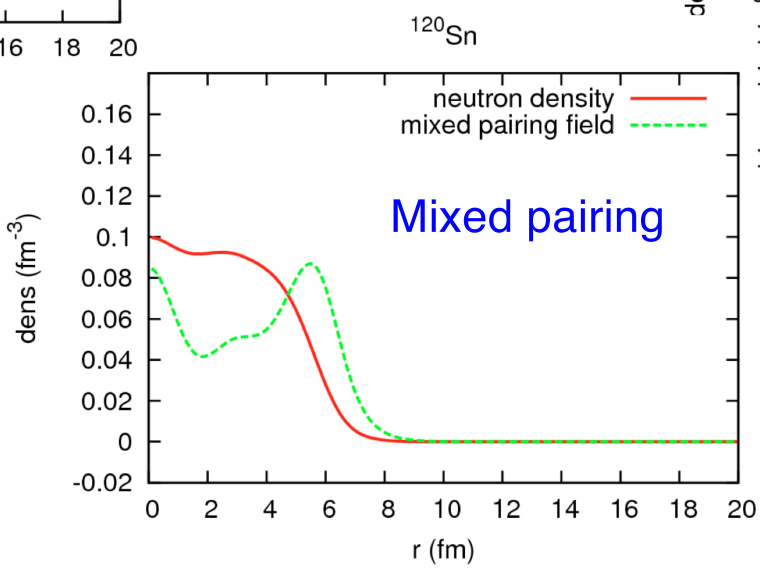
$$V = V_0 \left[1 - \eta \left(\frac{\rho(\mathbf{r})}{\rho_0} \right)^\alpha \right] \delta(\mathbf{r}_1 - \mathbf{r}_2), \qquad \rho_0 = 0.16 \text{ fm}, \quad \alpha = 1$$

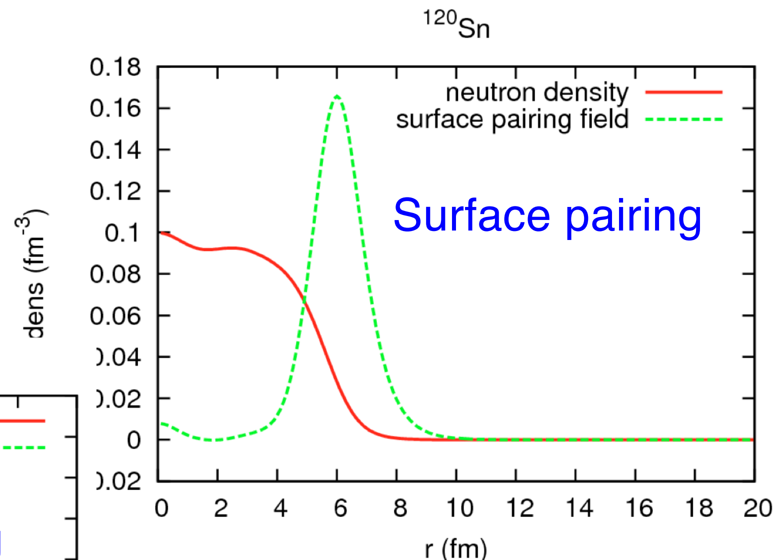
$$\eta = \begin{cases} 0, & \text{"volume" pairing} \\ 1, & \text{"surface" pairing} \\ 1/2, & \text{"mixed" pairing} \end{cases}$$

Mean field + Pairing

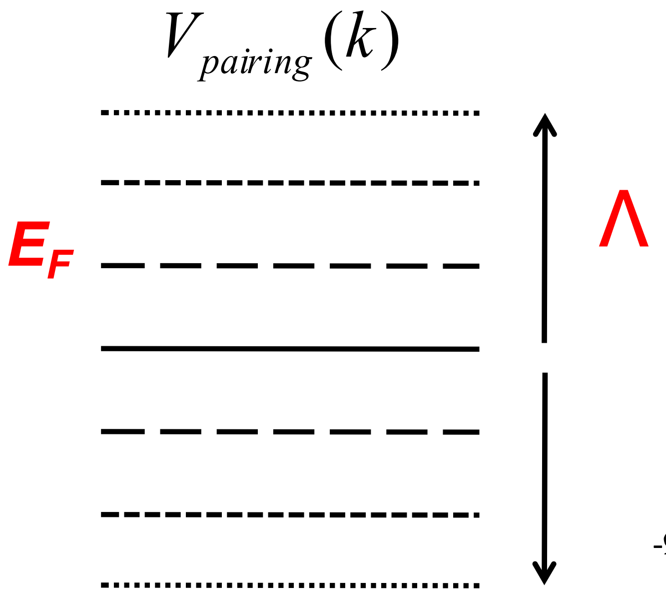
$$v(\mathbf{r},\mathbf{r}') = v_0 \left[1 - \eta \left(\frac{\rho}{\rho_0} \right)^{\gamma} \right] \delta(\mathbf{r}-\mathbf{r}')$$

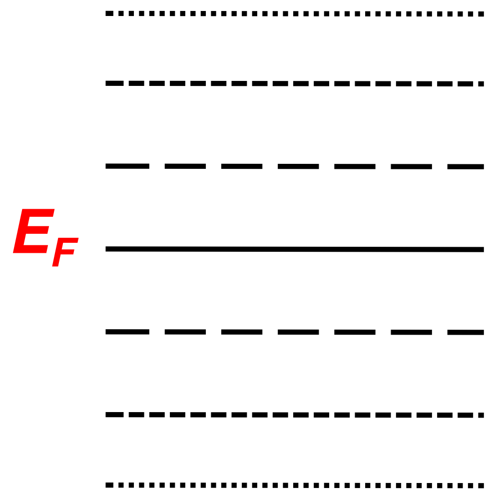






Odd nuclei: Blocking procedure

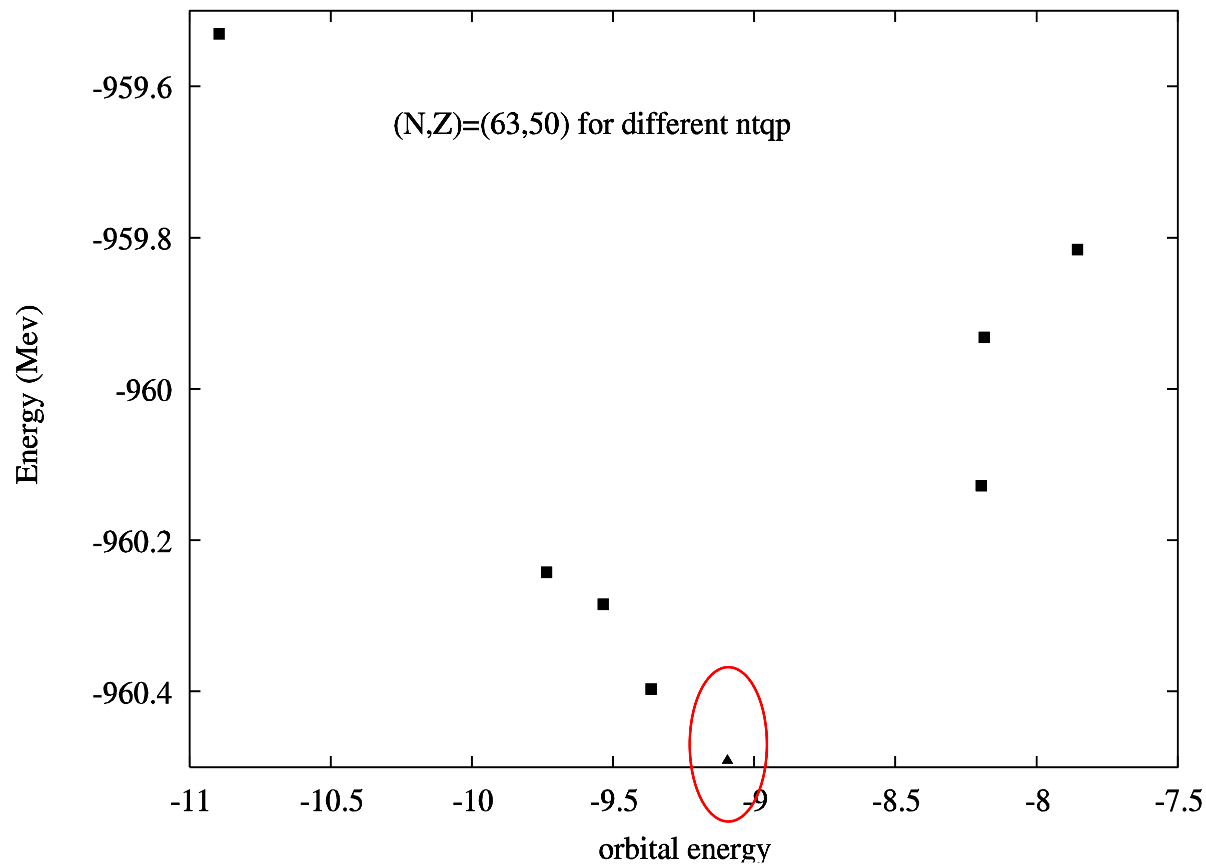




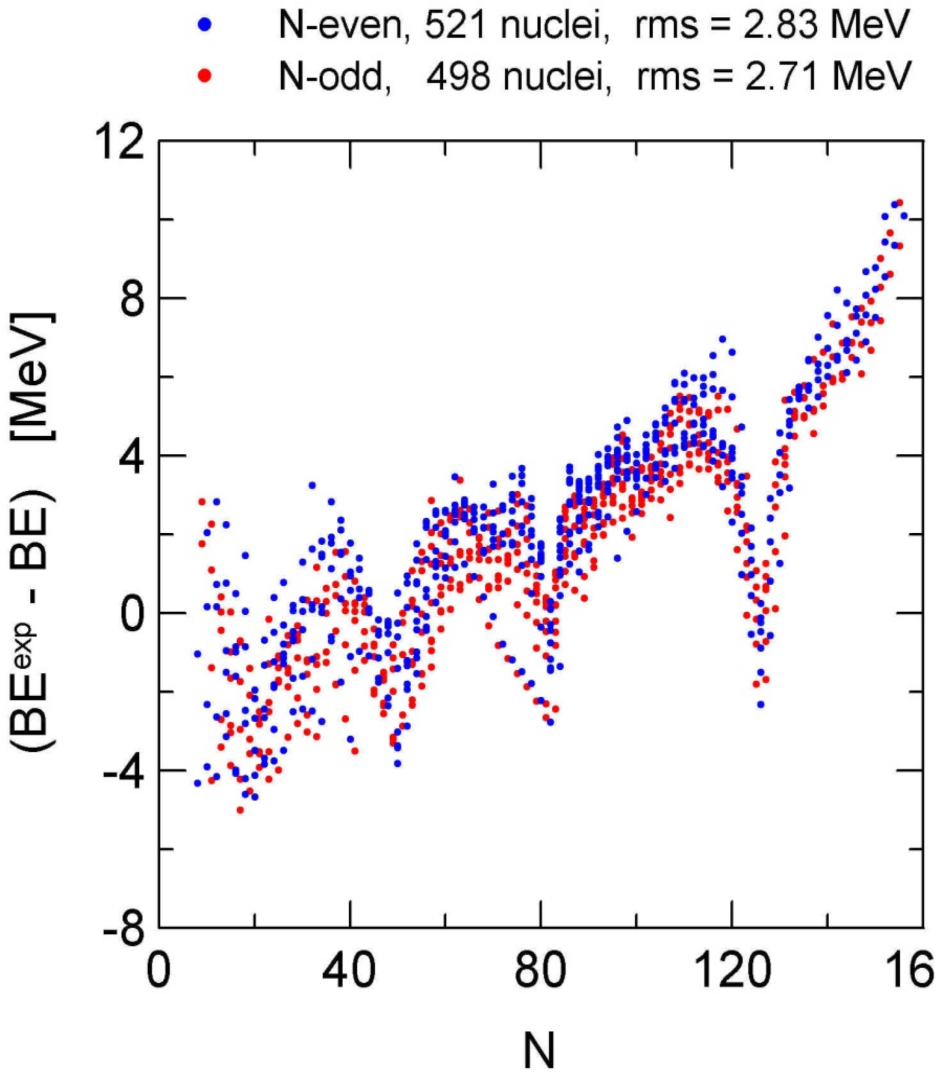
$$v^2 = \frac{1}{2}, \quad \tilde{v}^2 = \frac{1}{2}$$

for one orbit and its time-conjugate partner

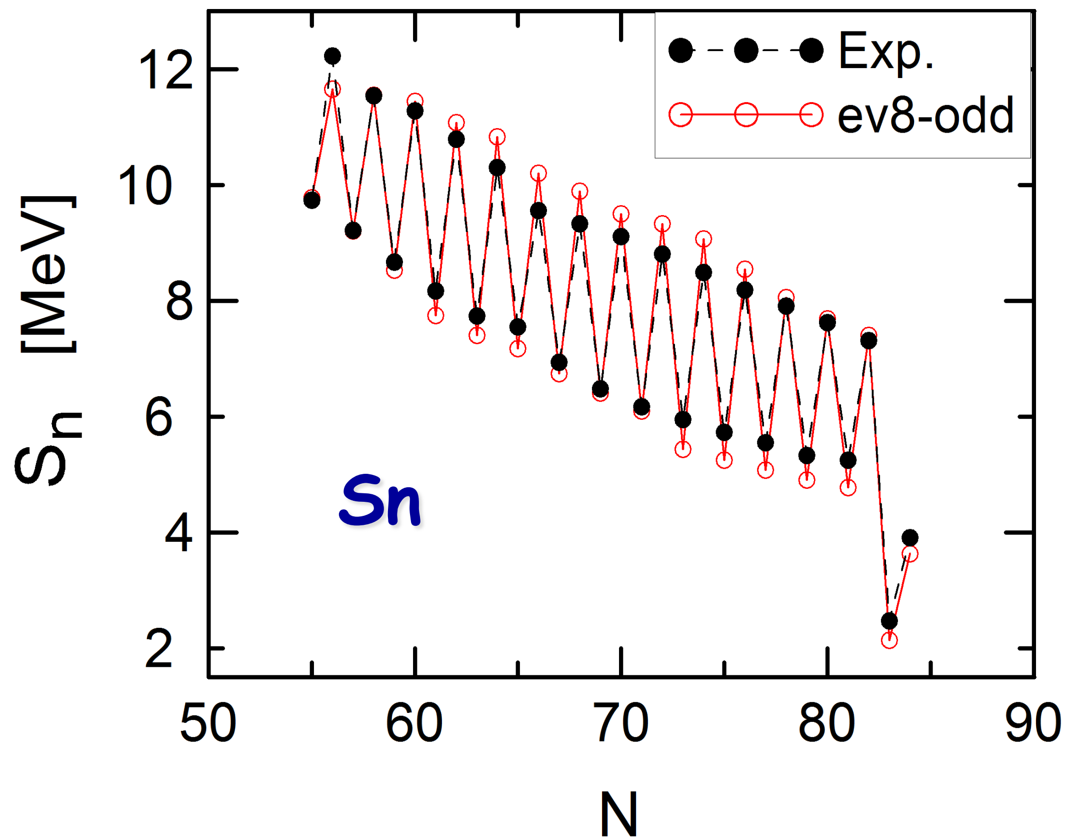
$\Lambda \sim 50$ MeV



Pairing improves nuclear properties



$$\Delta^{(3)} = \frac{1}{2}(-1)^N \left[B(N-1) + B(N+1) - 2B(N)\right]$$



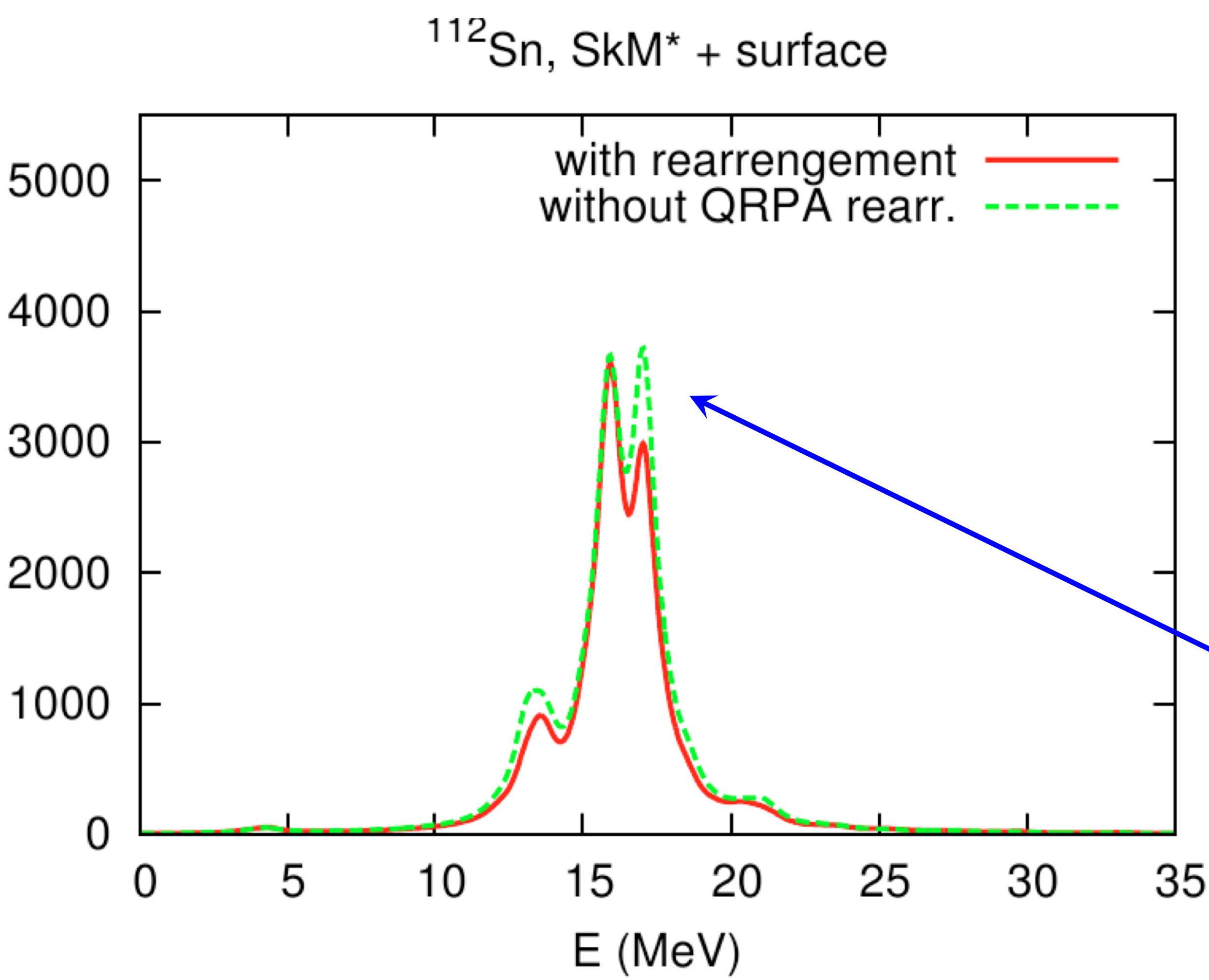
Bertsch, Bertulani, Nazarewicz, Schunck, Stoitsov,
PRC 79, 0343306 (2009)

QRPA: pairing induces rearrangement terms

Avogadro, Bertulani, PRC 88, 044319 (2013)

$$h = \frac{\delta E_{kin}}{\delta \rho} + \frac{\delta E_{skyrme}}{\delta \rho} + \frac{\delta E_{pair}}{\delta \rho} + \frac{\delta E_{Coul}}{\delta \rho}$$

- **Fully self consistent EWSR = 99.2%**
- **Without rearrangement in EWSR =116%**



$$\frac{\delta h_{rearr}}{\delta \rho} = \frac{\delta}{\delta \rho}\left(\frac{\delta E_{pair}}{\delta \rho}\right)$$

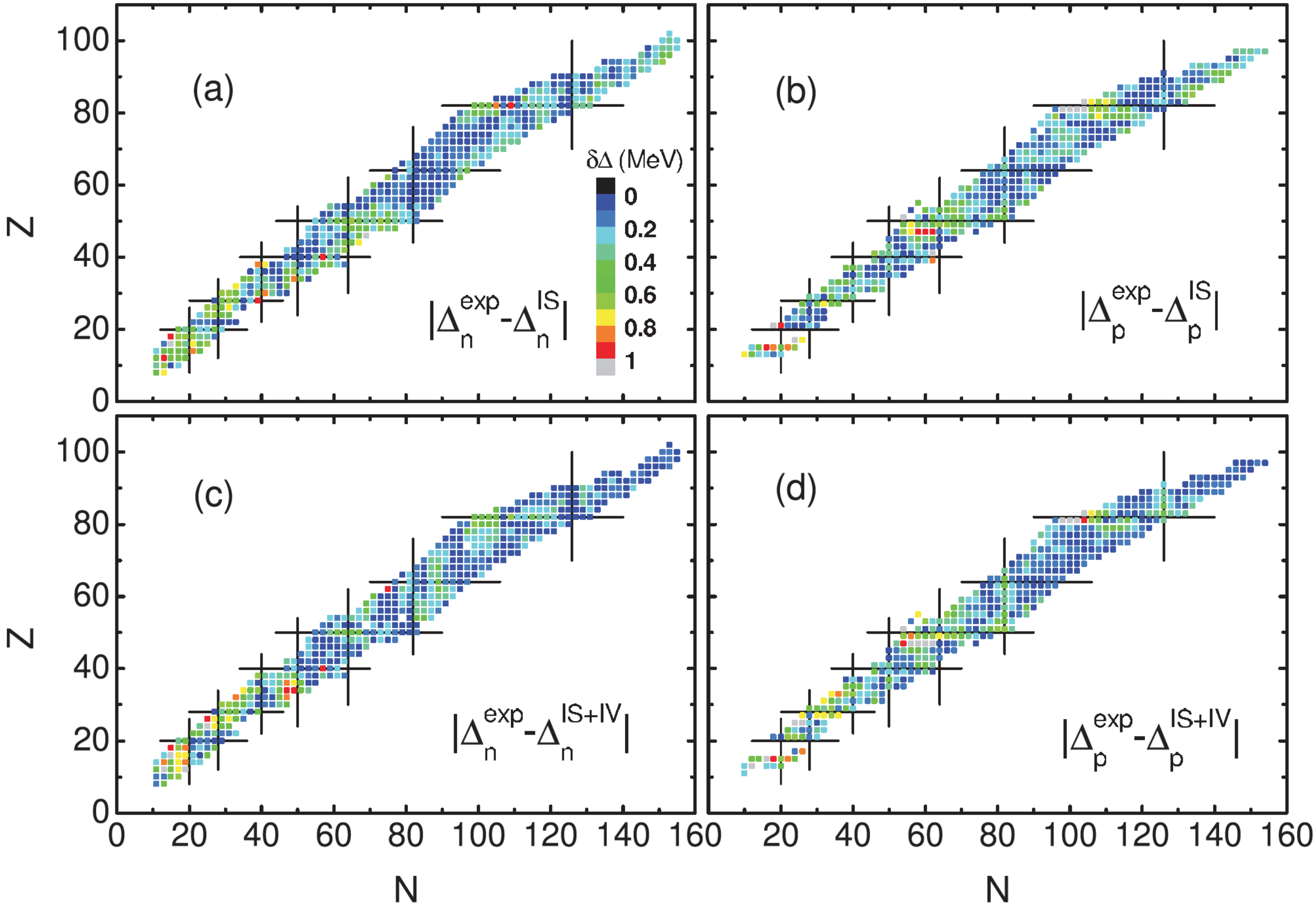
$\neq 0$ if E_{pair} depends on density

Calculations without rearrangements tend to return higher centroids respect to the fully self-consistent case.

Pairing – ISGMR – Comparison to data

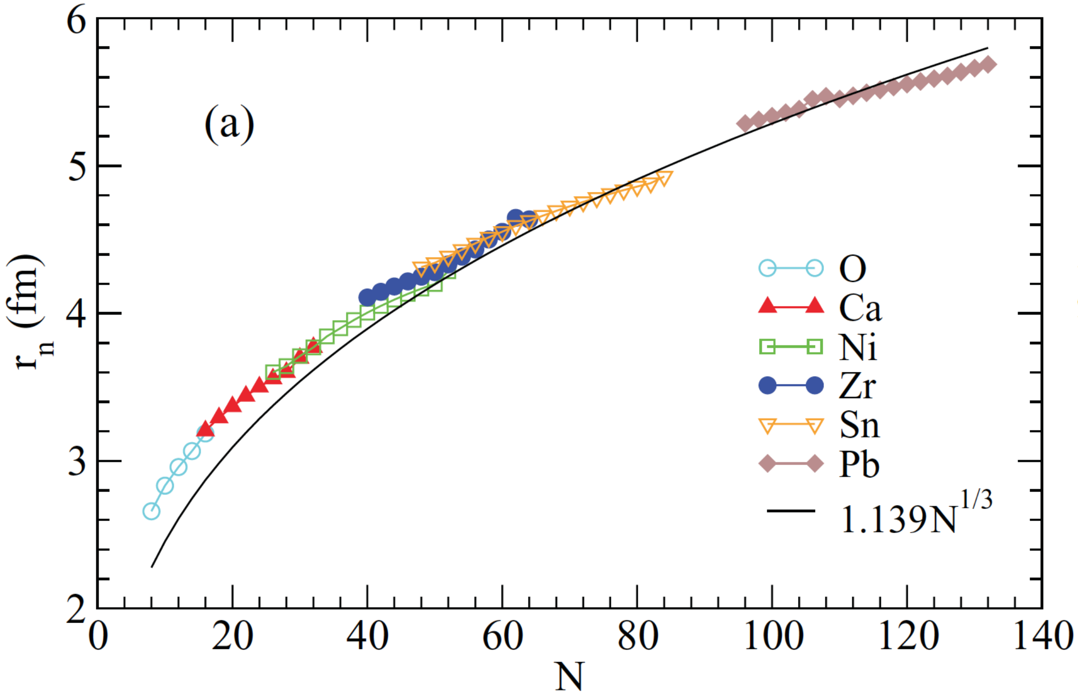
	nucleus	ph	pp	diff.
TAMU/ RCNP	$^{204-206-208}$Pb	SLy5	all	< 0.1
TAMU/ RCNP	^{144}Sm	SkM*	*volume*	- 0.1
TAMU/ RCNP	^{90}Zr	SLy5	all	+ 0.2
TAMU	^{92}Zr	SLy5	*volume*	- 0.4
	^{94}Zr	Skxs20	*surface*	+ 0.8
TAMU	^{92}Mo	SLy5	*volume*	- 1.6
	^{94}Mo	Skxs20	*surface*	+ 0.0
RCNP	$^{112-114-118-120}$Sn [4]	Skxs20	*mixed*	< 0.1
	$^{122-124}$Sn [4]	Skxs20	*surface*	< 0.1
	^{116}Sn [4]	SkM*	*surface*	< 0.1
TAMU	$^{112-124}$Sn [35]	Skxs20	*surface*	≈ 0.8
	^{116}Sn [35]	Skxs20	*surface*	+ 0.2
RCNP	$^{106-110-112-114-116}$Cd [6]	Skxs20	*surface*	< 0.1
TAMU	$^{110-116}$Cd [46]	Skxs20	*surface*	≈ 0.9

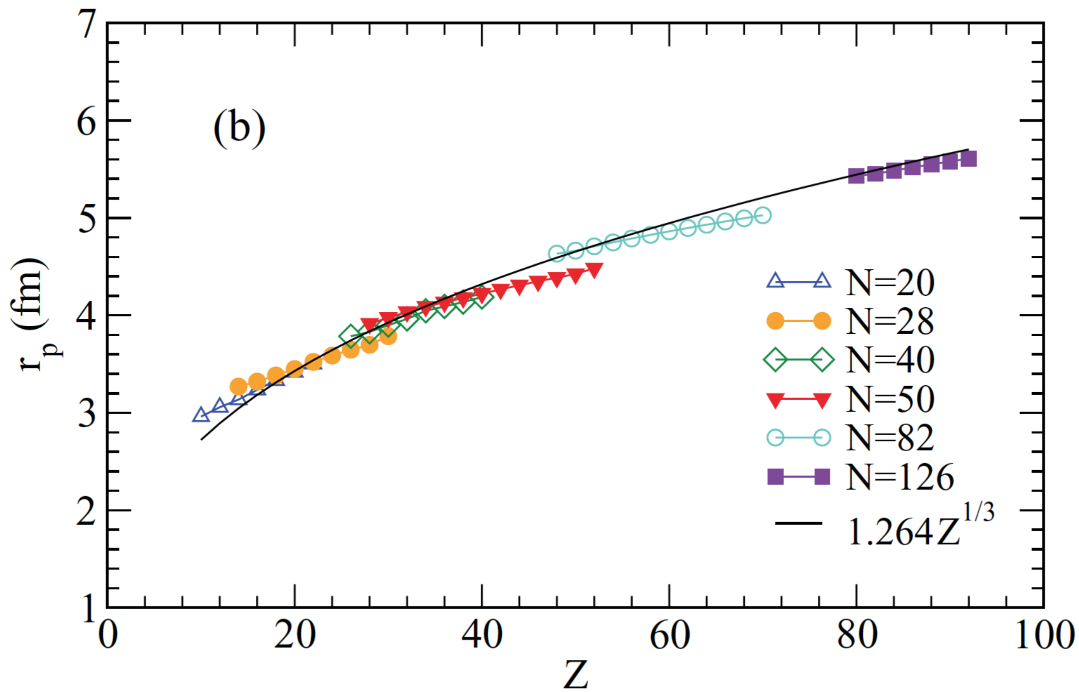
Isovector pairing – Good global fits to pairing gaps



Bertulani, Liu, Sagawa, PRC 85, 014321 (2012)

DFT and nuclear radii





Neutron stars

$$\frac{dP}{dr} = -\frac{G\rho(r)M(r)}{r^2}\left[1+\frac{P(r)}{\rho(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

$$\frac{dM}{dr} = 4\pi r^2 \rho(r)$$

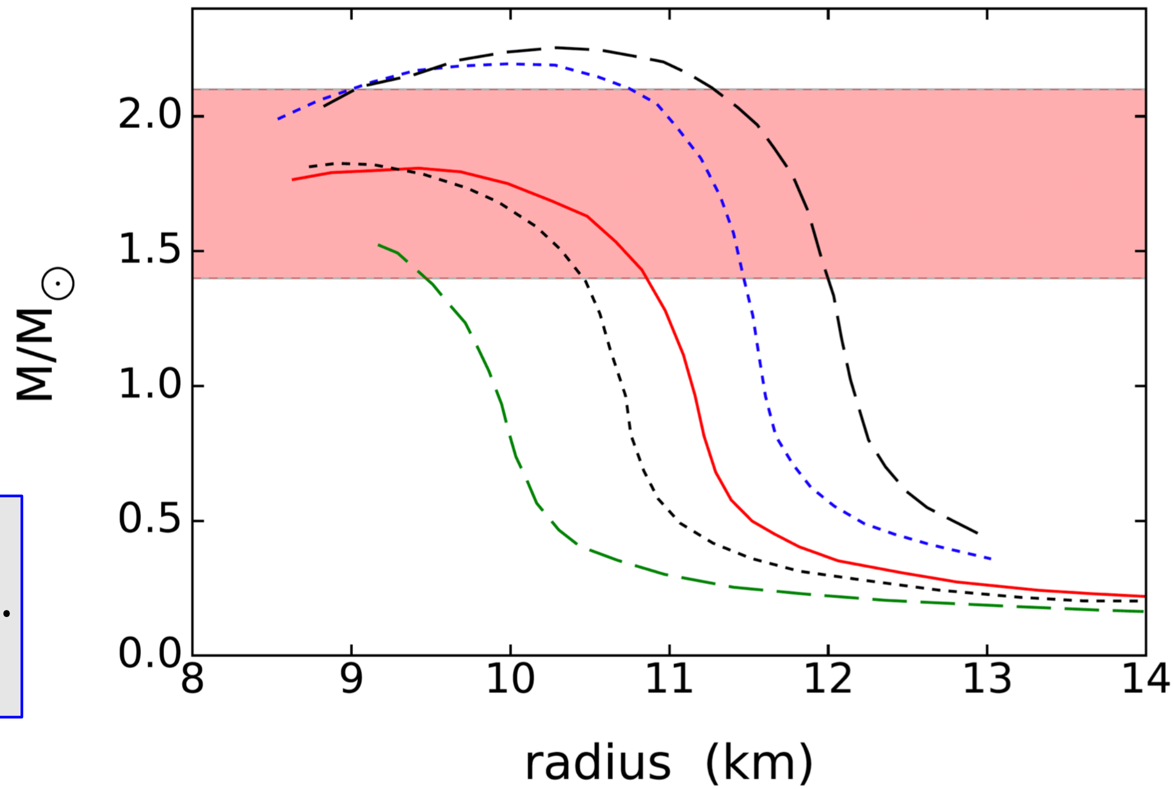
Tolman-Oppenheimer-Volkoff

EOS

$$p[\rho] = \rho^2 \frac{d}{d\rho}\left(\frac{E}{A}[\rho]\right)$$

$$\frac{E}{A}[\rho] = \frac{E}{A}[\rho_0] + \frac{1}{18}K_\infty\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \cdots$$

$$K_\infty = 9\rho^2 \frac{d^2[E/A]}{d\rho^2}\bigg|_{\rho_0}$$



EOS + symmetry energy

$$\frac{E}{A}[\rho] = \frac{E}{A}[\rho_0] + \frac{1}{18}K_\infty\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + S\left(\frac{\rho_n-\rho_p}{\rho}\right)^2 + \cdots$$

$$S = \frac{1}{2}\frac{\partial^2(E/A)}{\partial\delta^2}\bigg|_{\delta=0} = J + Lx + \frac{1}{2}K_{sym}x^2 + O(x^3),$$

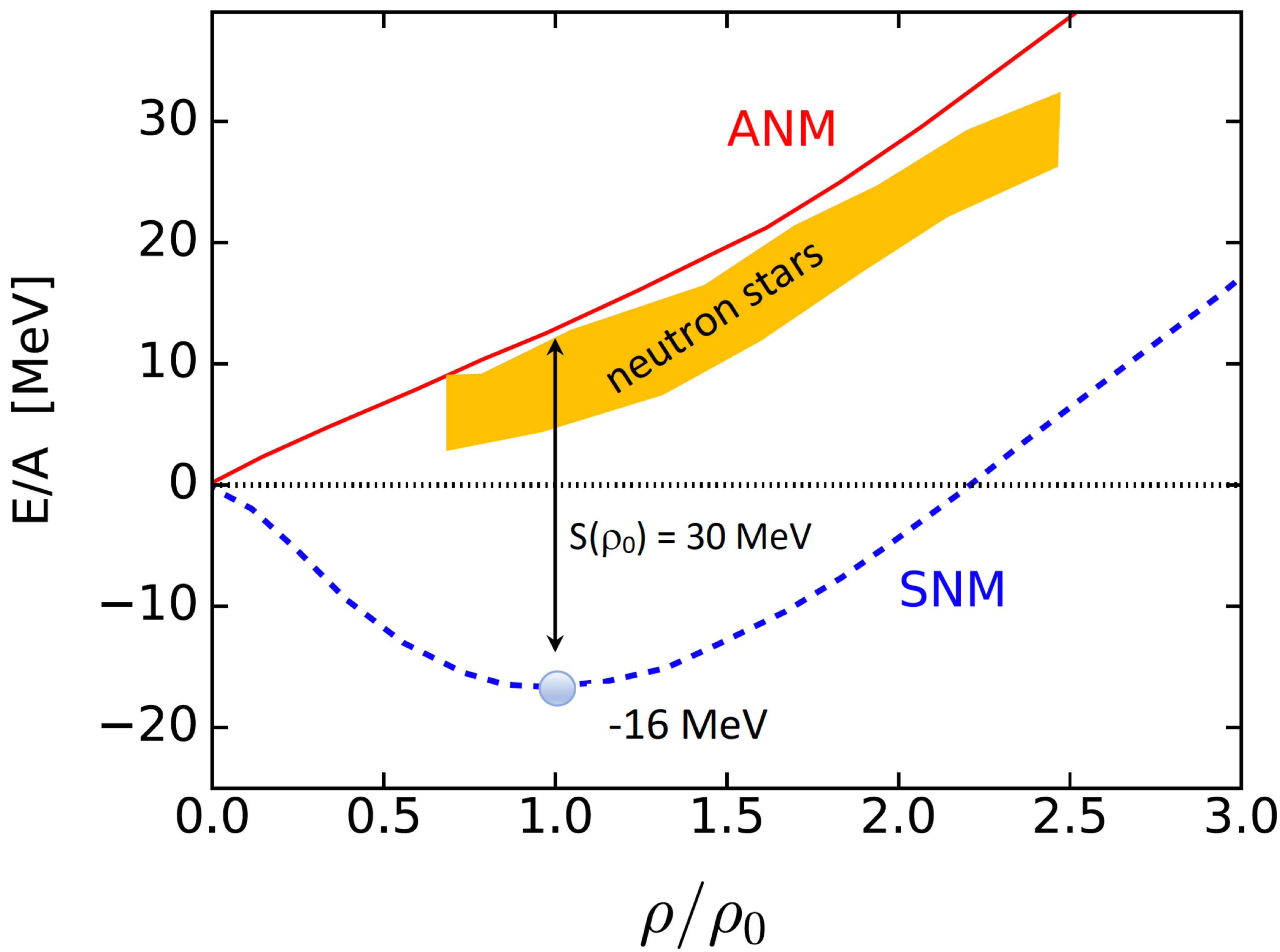
$$L = 3\rho_0\frac{dS(\rho)}{d\rho}\bigg|_{\rho_0}, \quad \delta = \frac{\rho_n-\rho_p}{\rho}, \quad x = \frac{(\rho-\rho_0)}{3\rho_0}$$

Skyrme	ρ_0	E0	K_∞	J	L	K_{sym}
SLy5	0.161	-15.99	229.92	32.01	48.15	-112.76
SkM*	0.160	-15.77	216.61	30.03	45.78	-155.94
Skxs20	0.162	-15.81	201.95	35.50	67.06	-122.31

For $\rho \sim \rho_0$ and $\delta \sim 1 \Rightarrow p = \frac{L\rho_0}{3}$

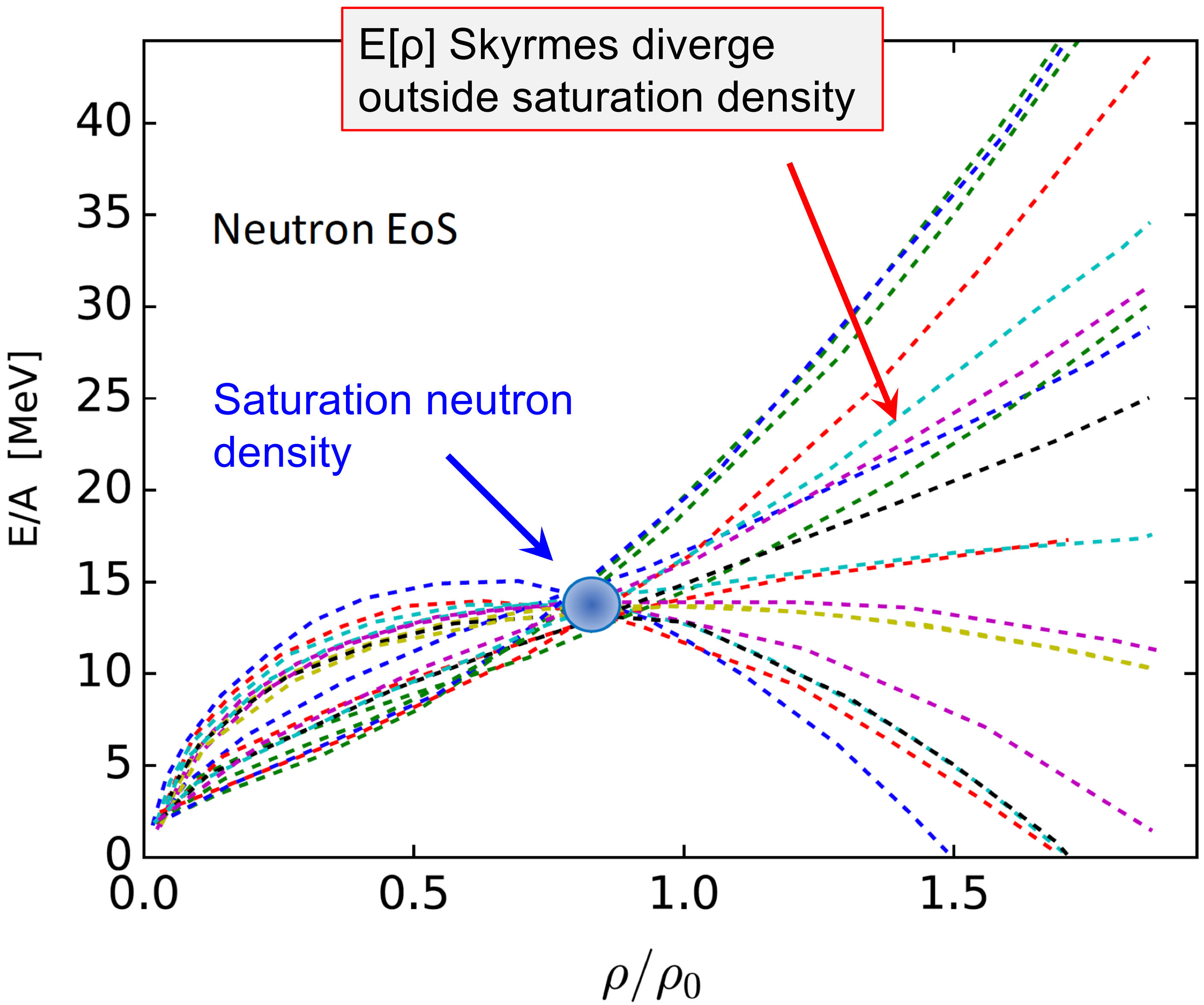
L crucial for neutron matter

EOS & Neutron stars



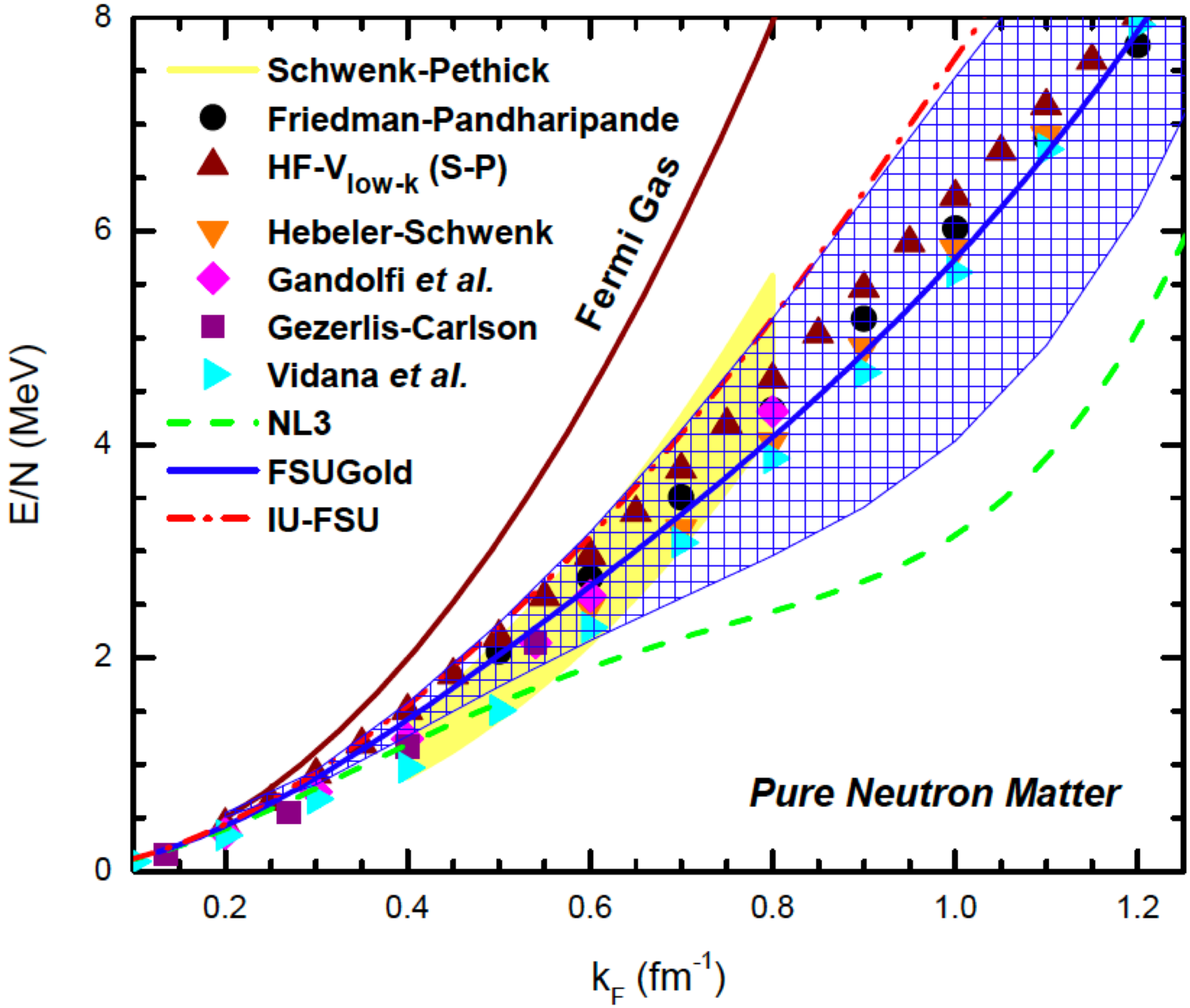
EOS & Neutron stars

Pethick, Ravenhall, ARNPS 45 (1995) 429
Brown, PRL 85 (2000) 5296

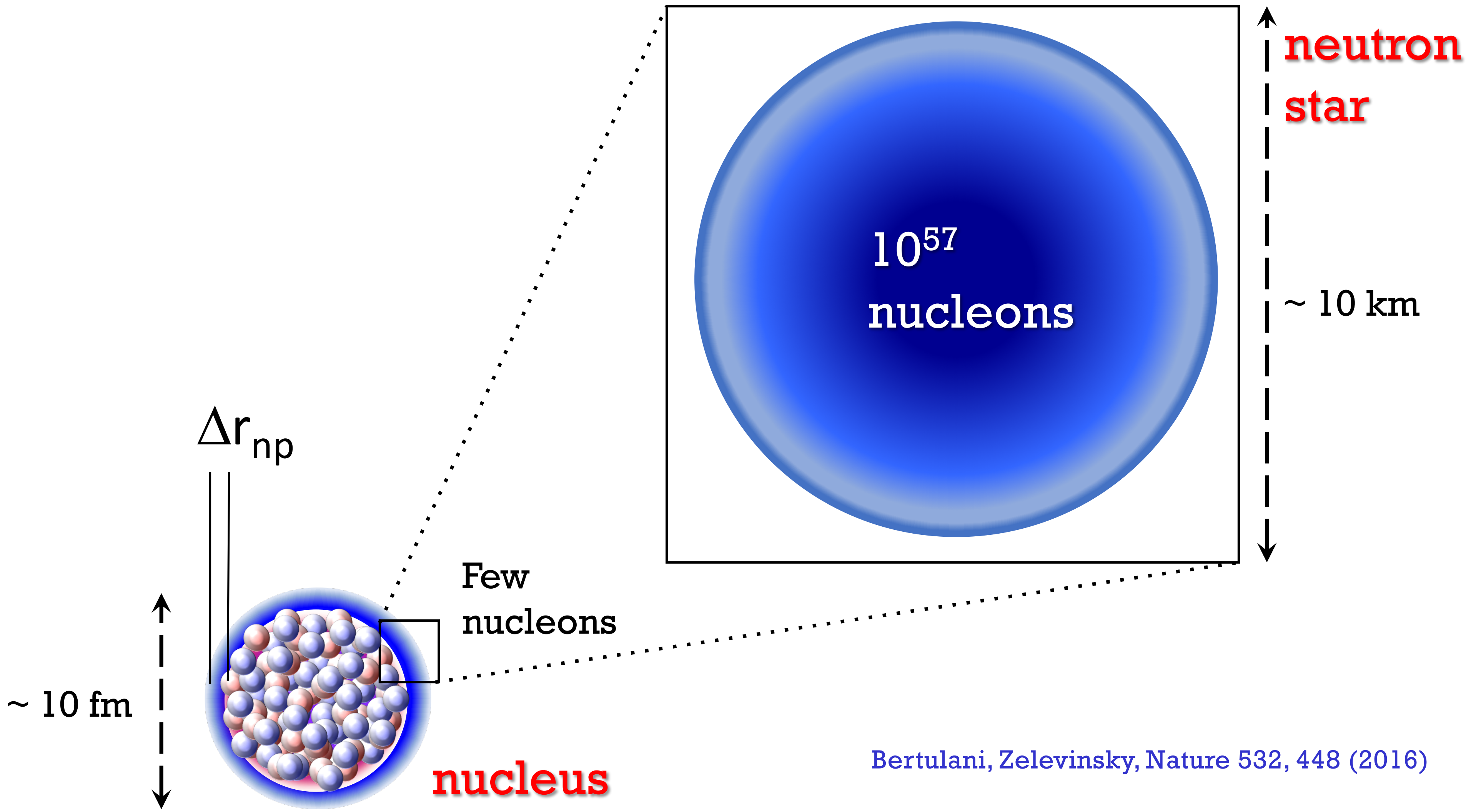


EOS & Neutron stars

Fattoyev, Piekarewicz, PRC 86, 015802 (2012)



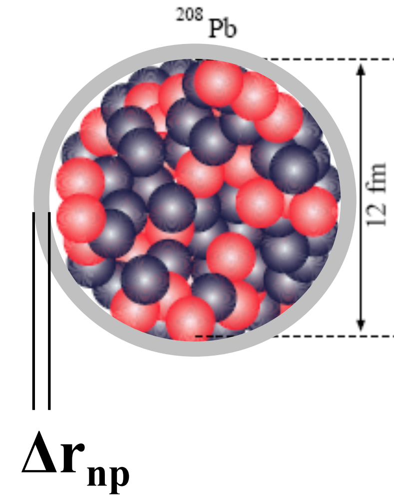
Neutron skins and neutron stars

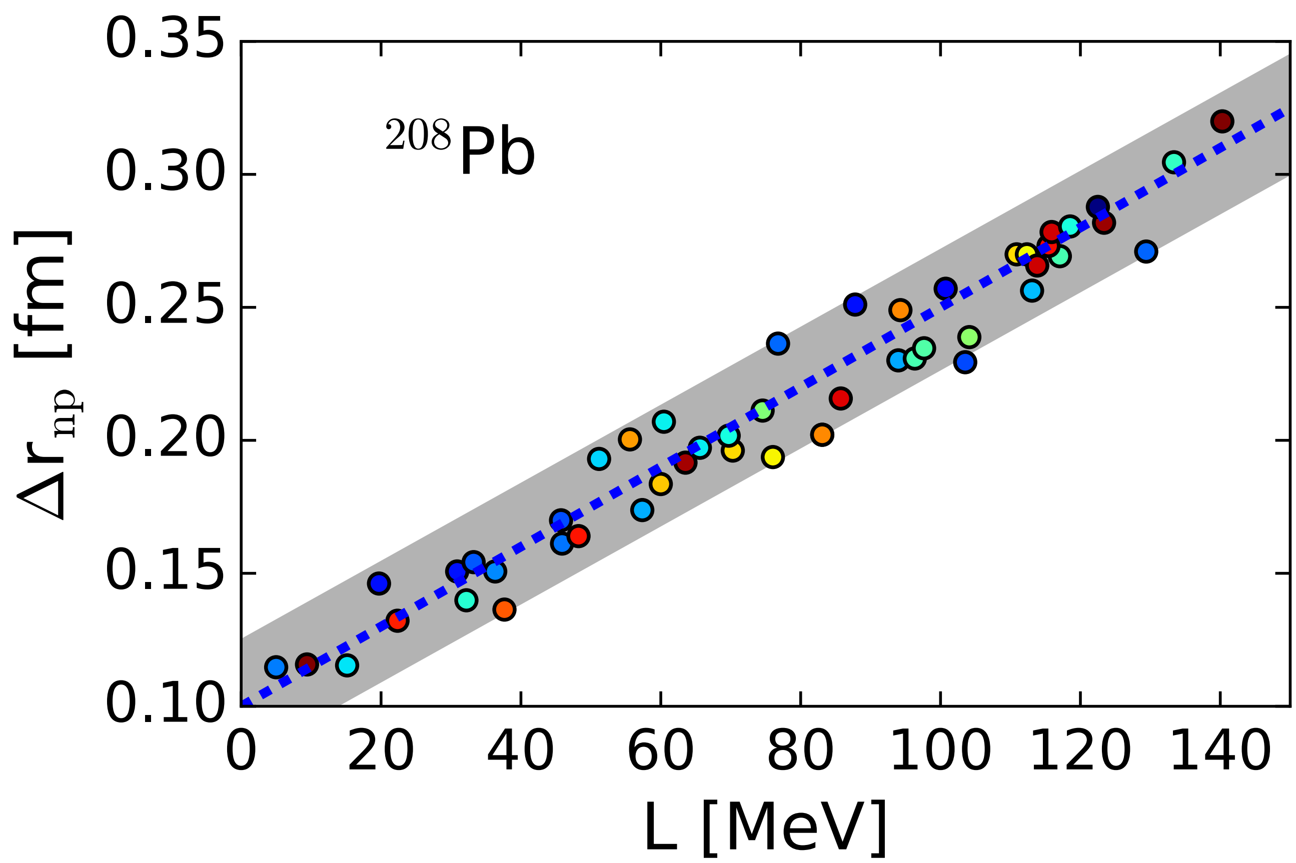


Bertulani, Zelevinsky, Nature 532, 448 (2016)

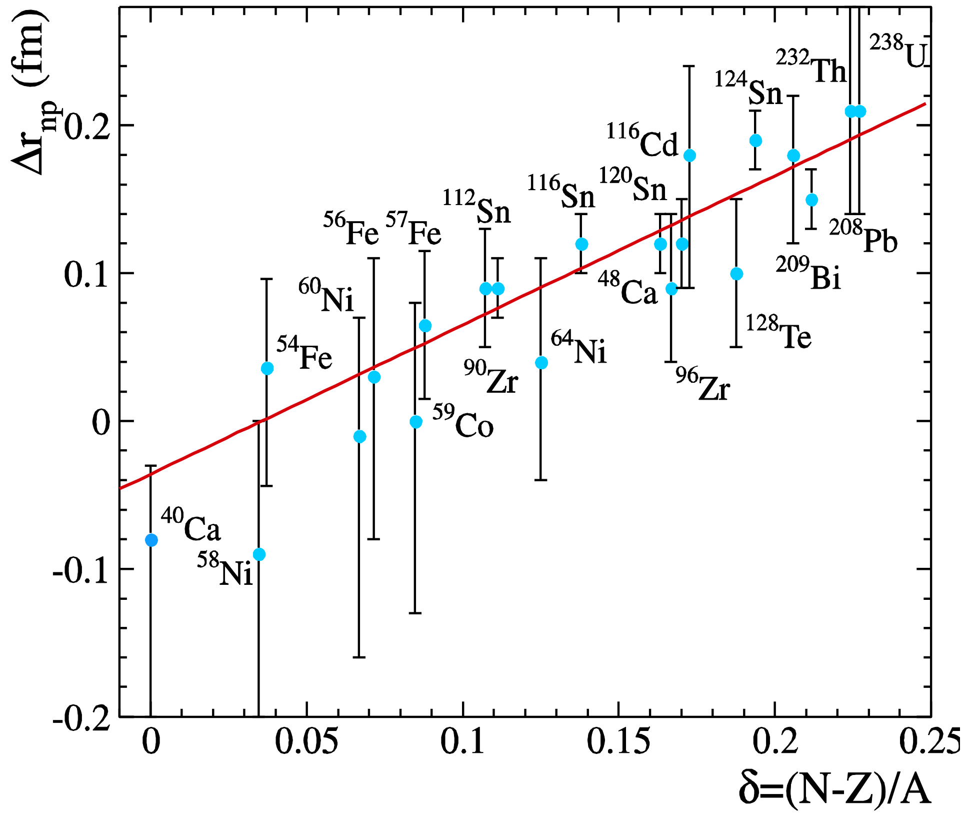
Correlation between symmetry energy & neutron skin

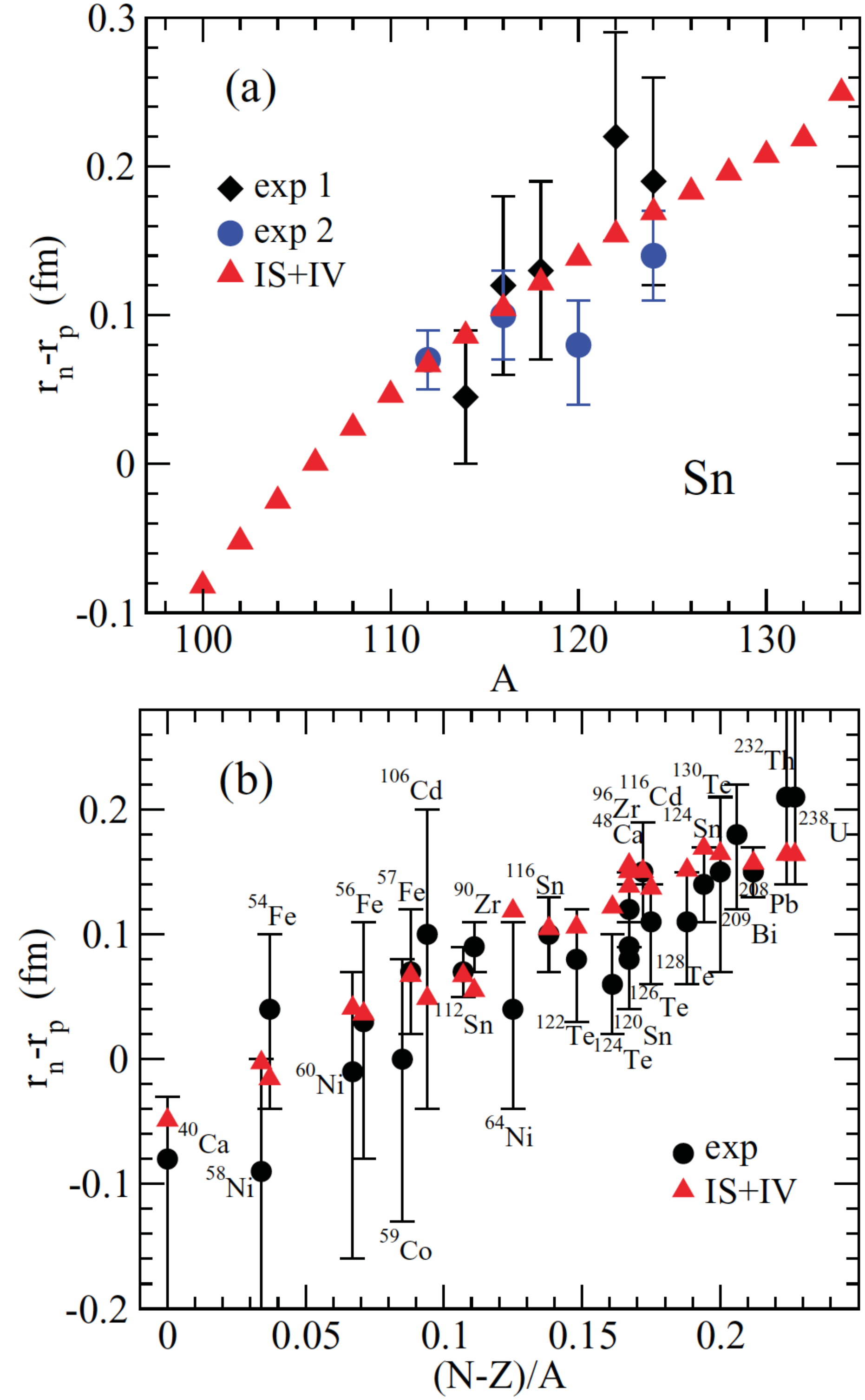
$$S = J + Lx + \frac{1}{2}K_{sym}x^2 + \cdots, \qquad x = \frac{(\rho - \rho_0)}{3\rho_0}$$





Neutron skins measurements





Radii from spin-dipole resonances

Krasznahorkay et al., PRL 82, 3216 (1999)

&

Antiprotonic atoms

Trzcinskaet al., PRL 87, 082501 (2001)

Bertulani, Liu, Sagawa, PRC 85, 014321 (2012)

n-skin from e⁻ scattering (PREX)

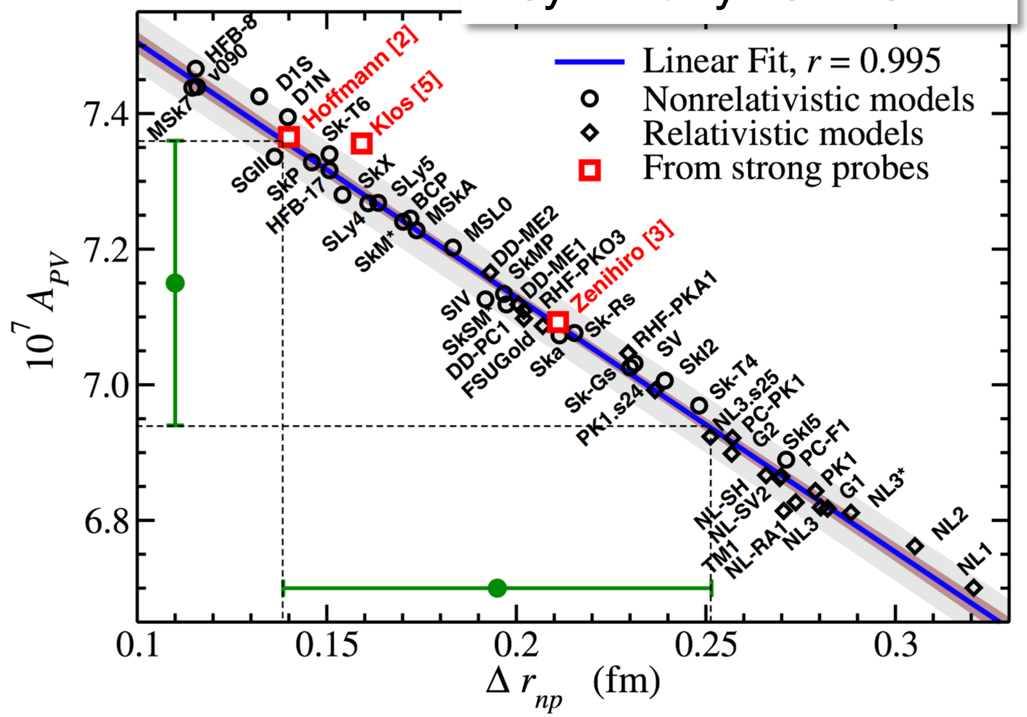
$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}$$

$$A_{PV}(Q^2) = \frac{G_F Q^2}{4\pi e^2 \sqrt{2}}$$

$$\text{x} \left[4 \sin^2 \theta_W - 1 + \frac{F_n(Q)}{F_p(Q)} \right]$$

Horowitz, Pollock, Soulder, Michaels
PRC 63 (2001) 025501

Asymmetry vs. n-skin



Roca-Maza *et al.*, PRL 106, 252501 (2011)

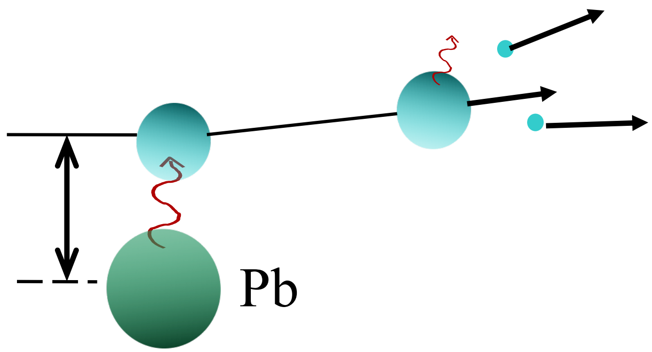
- PREX: measurement of parity violating asymmetry (goal: ±3%)
- Determine n-skin and/or L by comparison to predictions from DFT
- Scatter of theory points provides estimate for uncertainty of this method
- Constraining L to ± 5 MeV (one sigma) possible if measurement would be accurate

Dipole polarizability

Rossi et al.
PRL 111 (2013) 242503

Wieland et al.
PRL 102, 092502 (2009)

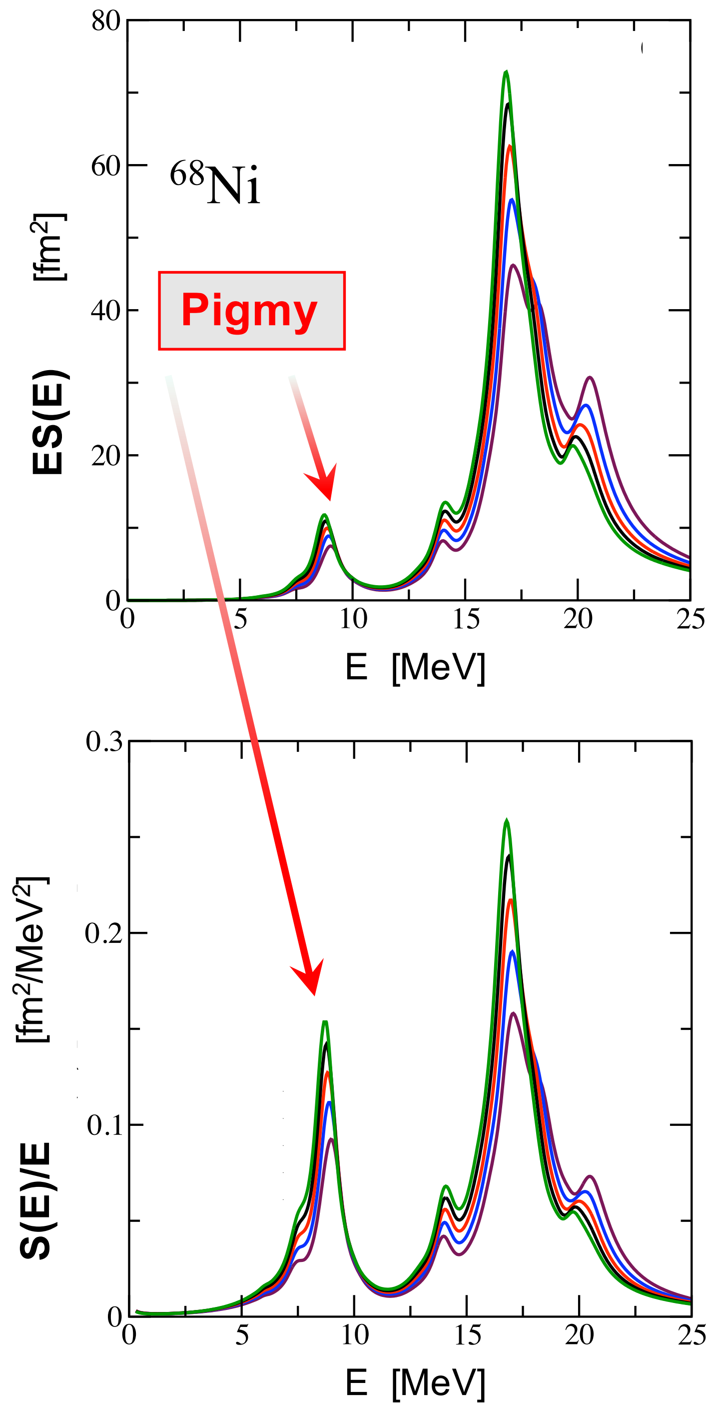
$$\sigma_C \sim (\cdots) \int_0^\infty \frac{\sigma_\gamma(E)}{E^2} dE$$



Dipole polarizability

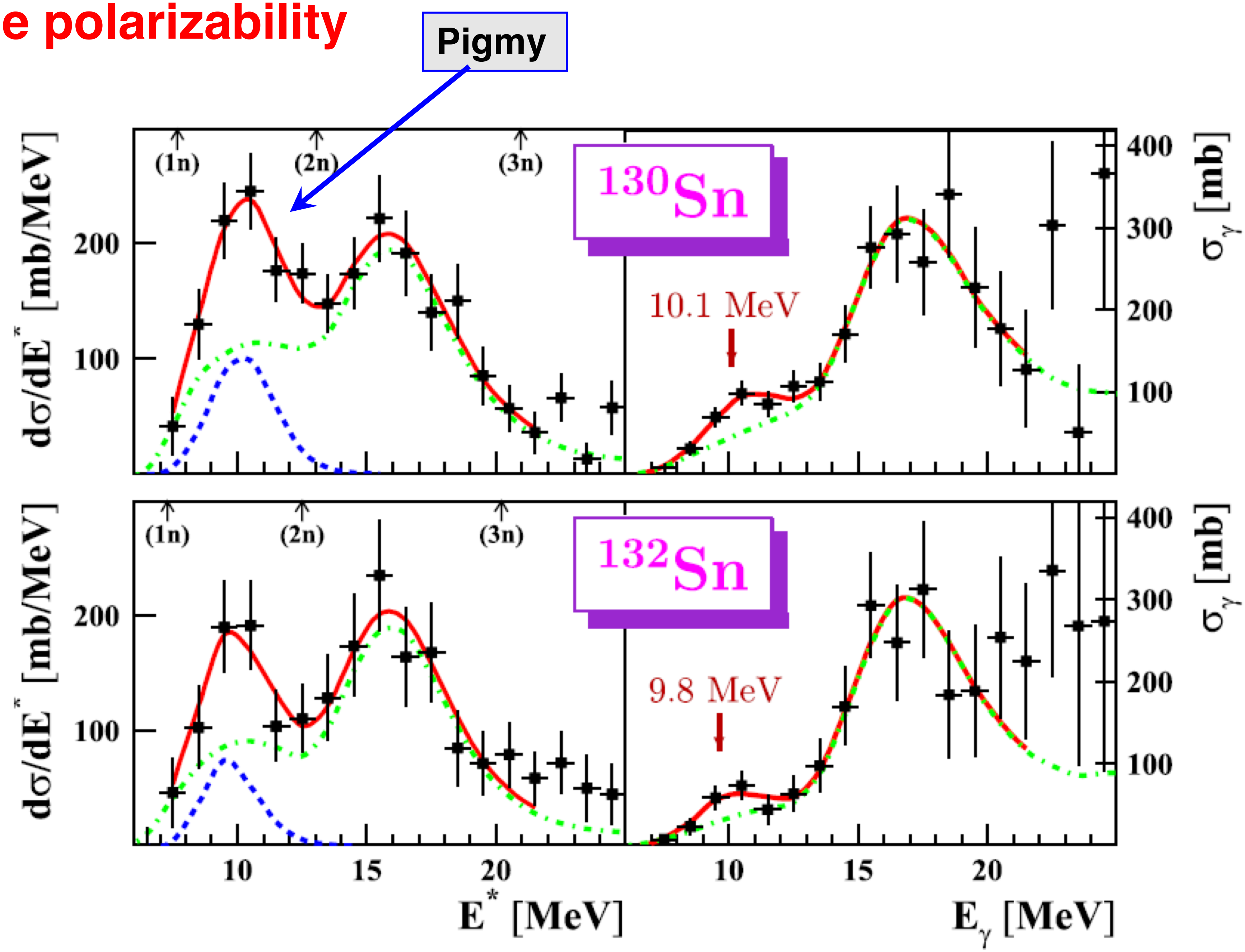
$$\alpha_D = \frac{\hbar c}{2\pi^2} \int_0^\infty \frac{\sigma_\gamma(E)}{E^2} dE$$

$$= \frac{8\pi}{9} \int \frac{B(E1, E_x)}{E_x} dE_x$$



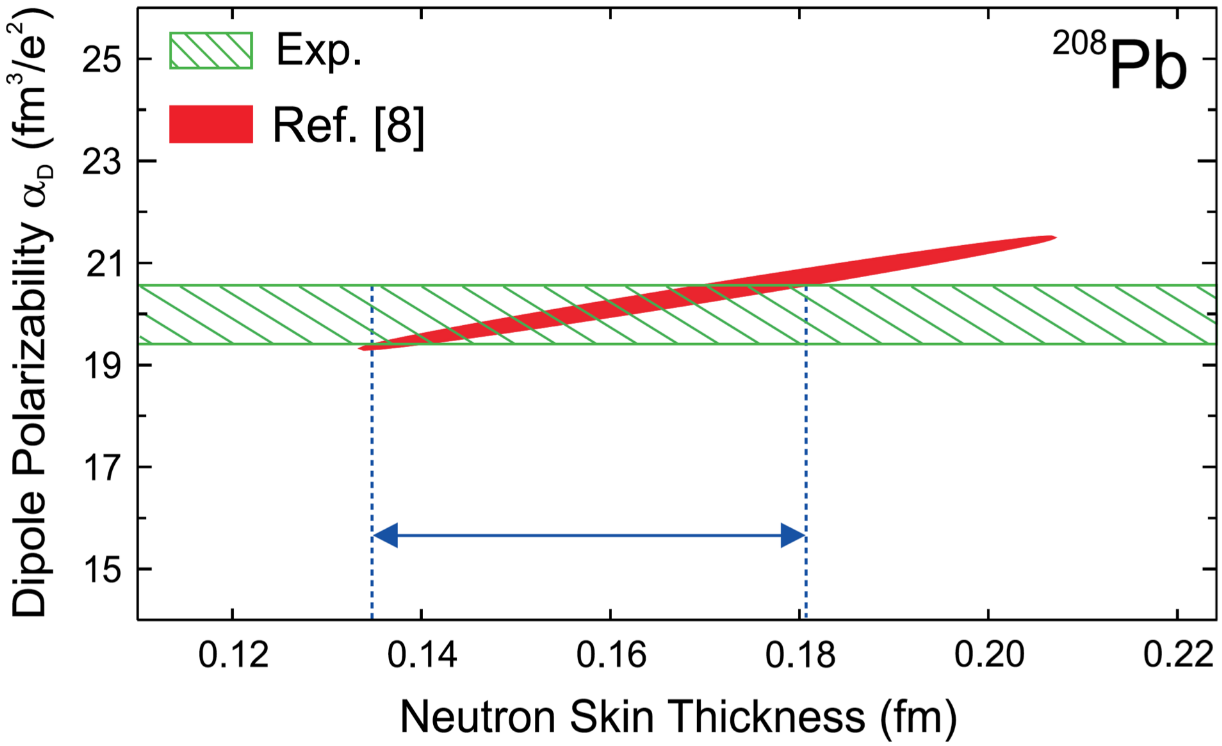
Piekarewicz,PRC 83, 034319 (2011)

Dipole polarizability



Adrich et al., PRL 95, 132501 (2005)

Dipole polarizability & neutron skin



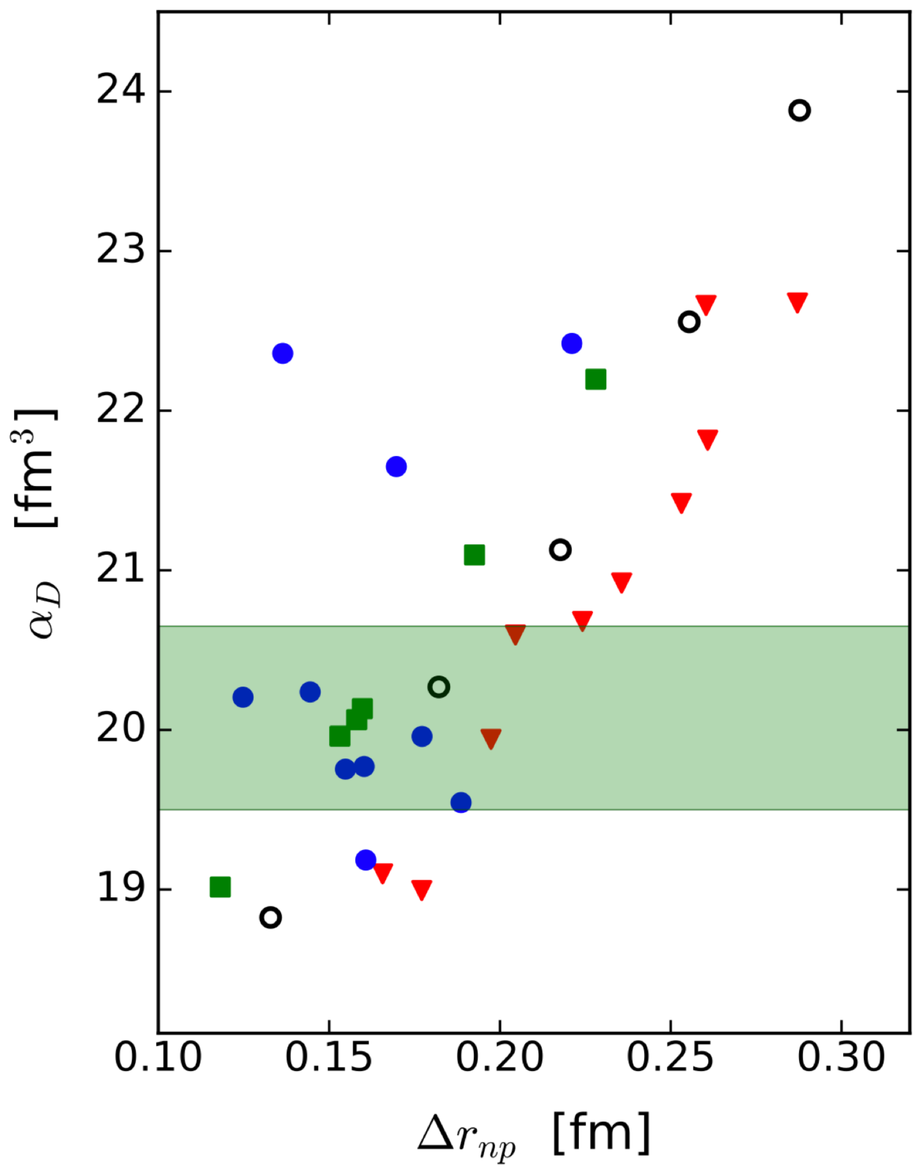
Experiment:
Tamii et al.,
PRL 107, 062502 (2011)

$\Delta r_{np} \sim 0.156$ fm

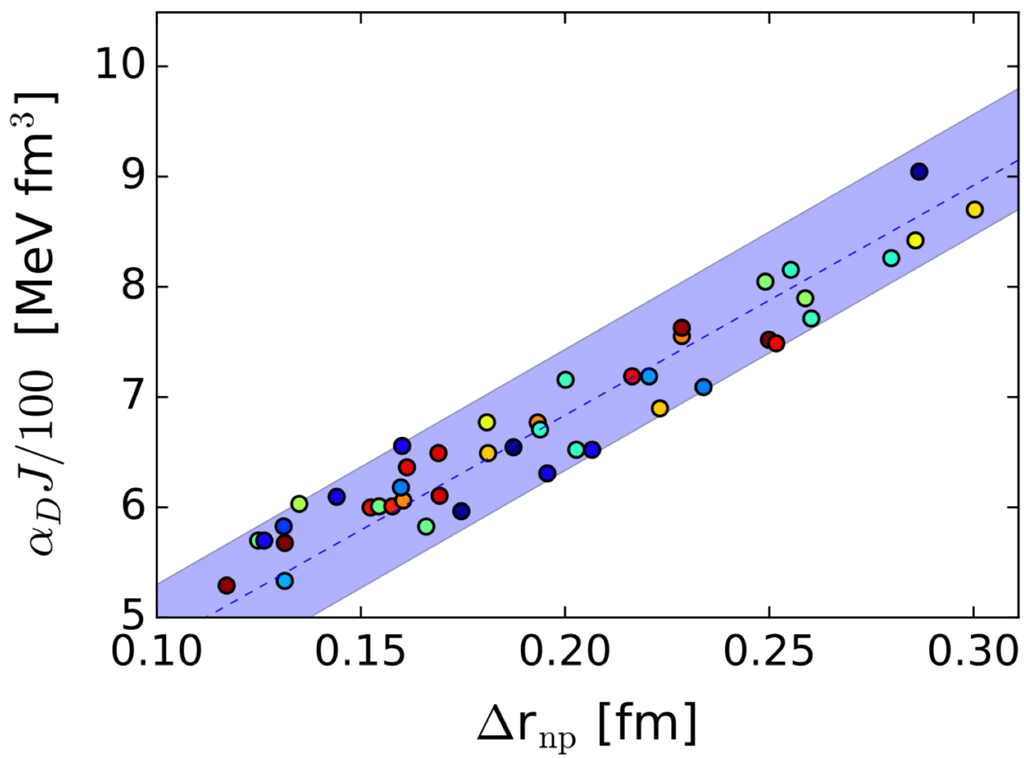
EFT:
Hebeler et al.,
PRL 105, 161102 (2010)

$\Delta r_{np} \sim 0.17$ fm

Dipole polarizability & neutron skin correlation??

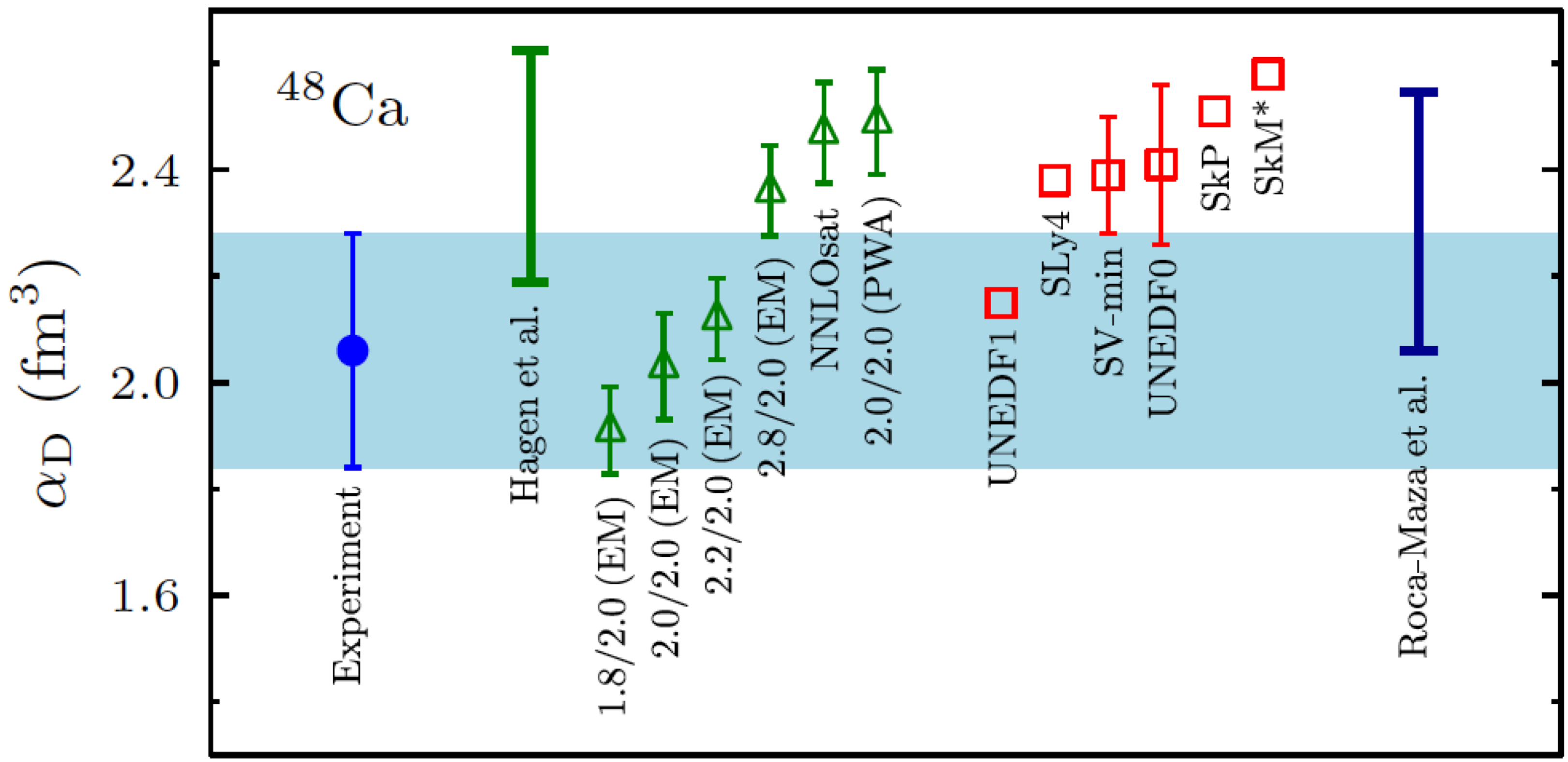


Reinhard, Nazarewicz, PRC 81 (2010) 051303



Roca-Maza, Paar, PPNP 101 (2018) 96
Aumann, Bertulani, PPNP 112, 103753 (2020)

Dipole polarizability



Experimental electric dipole polarizability in 48Ca (blue band) and predictions from EFT (green triangles) and χEDFs (red squares)

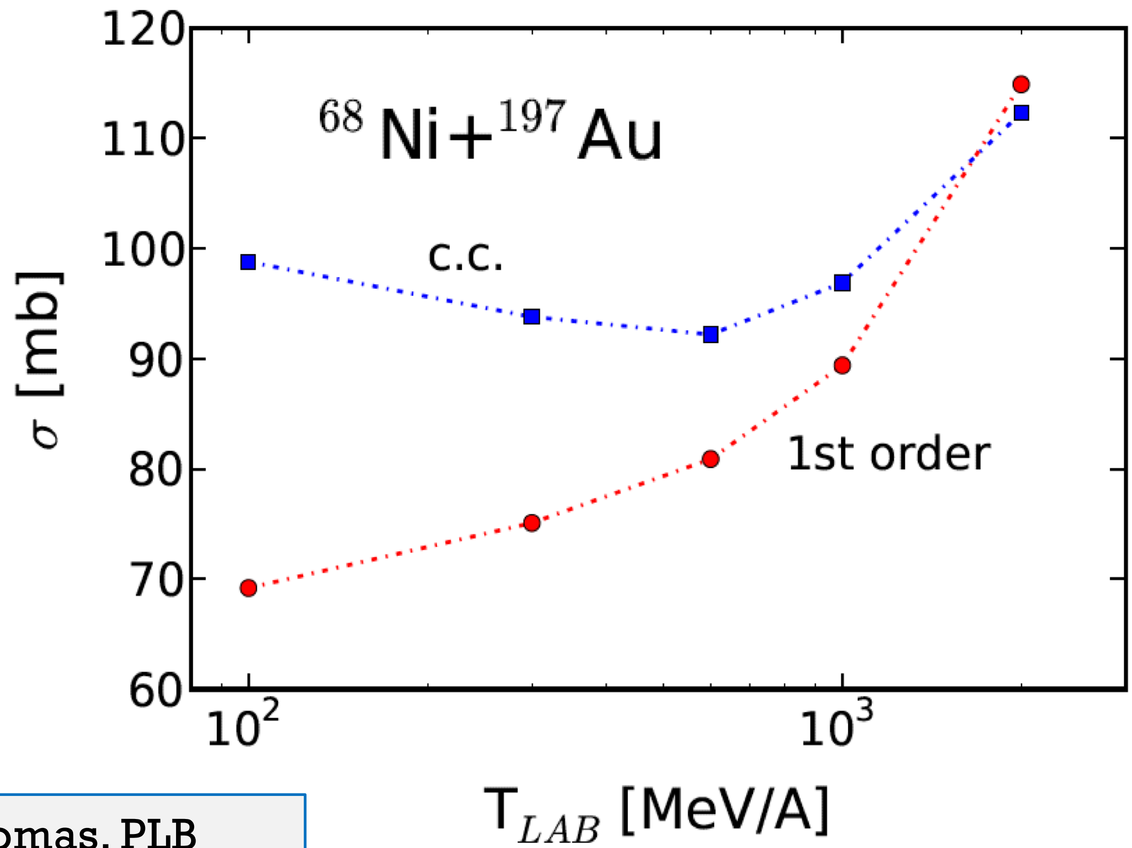
Birkhan et al., PRL 118, 252501 (2017)

Reaction dynamics: coupling of PDR, GDR and GQR

Rossi at al.,
PRL 111, 242503 (2013)

→ $\alpha_D = 3.40\ fm^3$

Our new analysis
→ $\alpha_D = 3.16\ fm^3$



Brady, Aumann, Bertulani, Thomas, PLB 757, 553 (2016)

Neutron skin
→ $\Delta r_n = 0.17$ fm

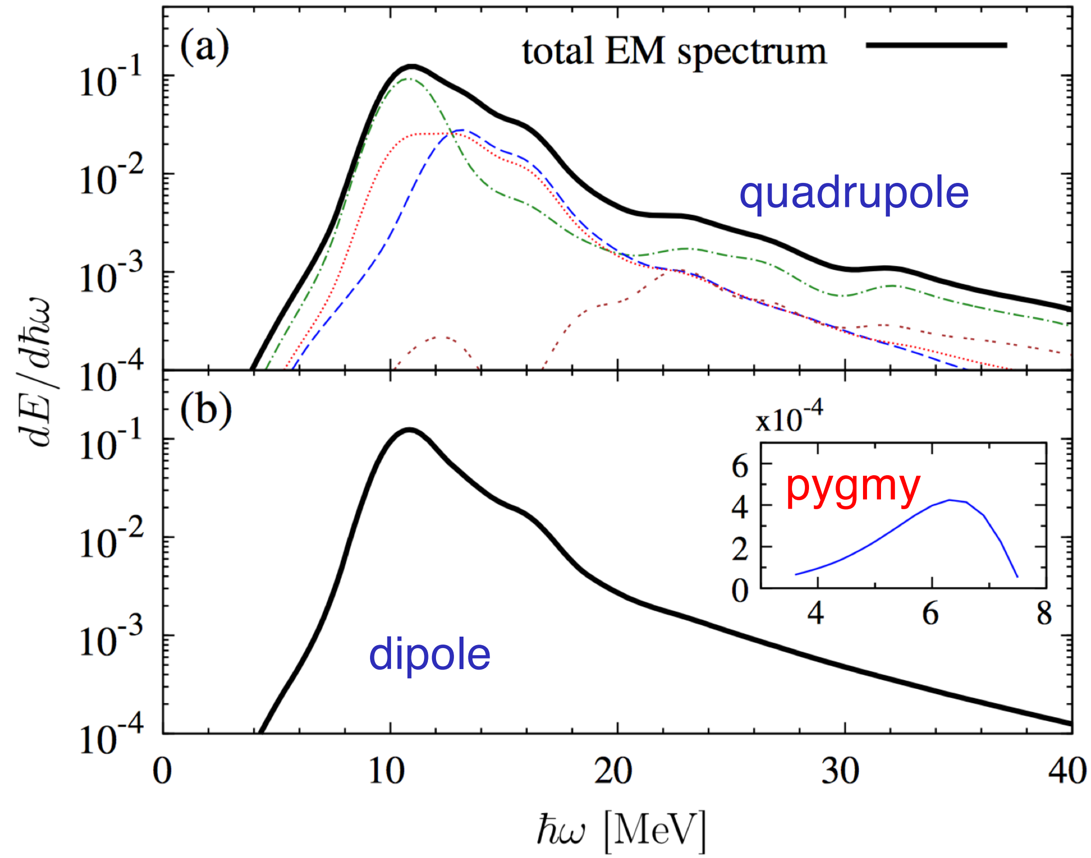
Our new analysis
→ $\Delta r_n = 0.16$ fm

But experimental error
= 7% for a_D and
= 0.2 for Δr_n

Mean-Field Dynamics with pairing in heavy ion collisions

Time dependent superfluid local density approximation (TDSLDA)

Emitted EM radiation
$^{238}U + ^{238}U$ (1 GeV/nucleon)



An exact QRPA approach would severely underestimate the amount of internal energy deposited, one reason being the nonlinearity of the response, naturally incorporated in TDSLDA

Stetcu, Bertulani, Bulgac, Magierski, Roche, PRL 114, 012701 (2015)

Peeling off neutrons

$$\sigma_R = \binom{Z_P}{Z}\binom{N_P}{N}\int d^2b\left[1-P_p(b)\right]^{Z_p-Z} P_p^Z(b)\left[1-P_n(b)\right]^{N_p-N} P_n^N(b)$$

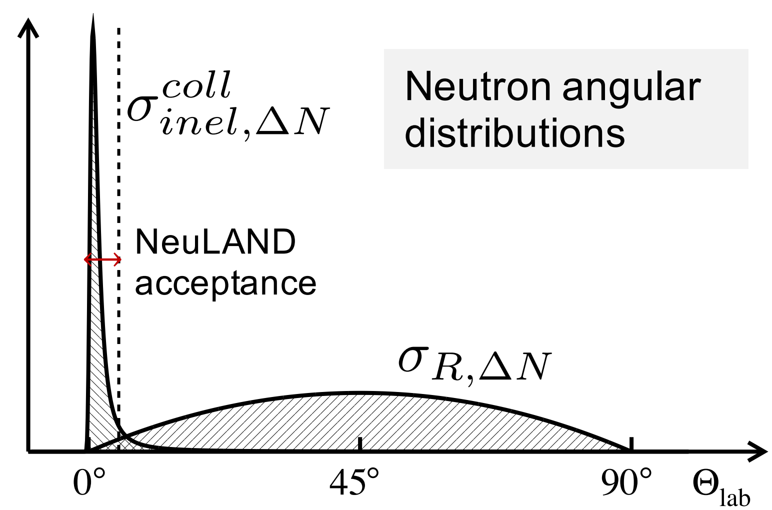
$$P_p(b) = \int dz\, d^2s\, \rho_p^P(\mathbf{s},z)\exp\left[-\sigma_{pp}Z_T\int d^2s\rho_p^T(\mathbf{b}-\mathbf{s},z)-\sigma_{pn}N_T\int d^2s\rho_n^T(\mathbf{b}-\mathbf{s},z)\right]$$

Experiment (4 independent measurements):

$$\sigma_I = \sigma_{R,\Delta Z} + \sigma_{R,\Delta N} + \sigma_{inel,\Delta N}$$

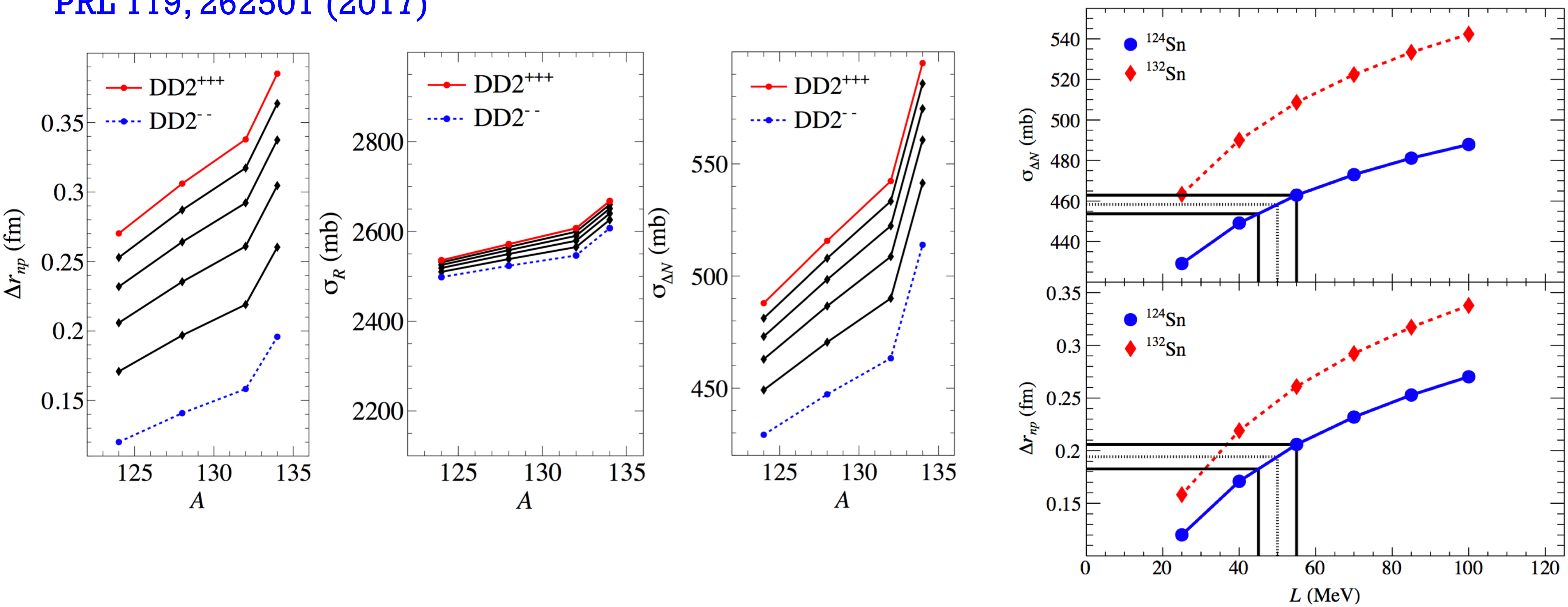
Aumann, Bertulani, Schindler, Typel
PRL 119, 262501 (2017)

σ_{inel} ⇒ Relation $\sigma_{\Delta N}$ ←→ L



n-removal cross section: n-skin and L

Aumann, Bertulani, Schindler, Typel
PRL 119, 262501 (2017)

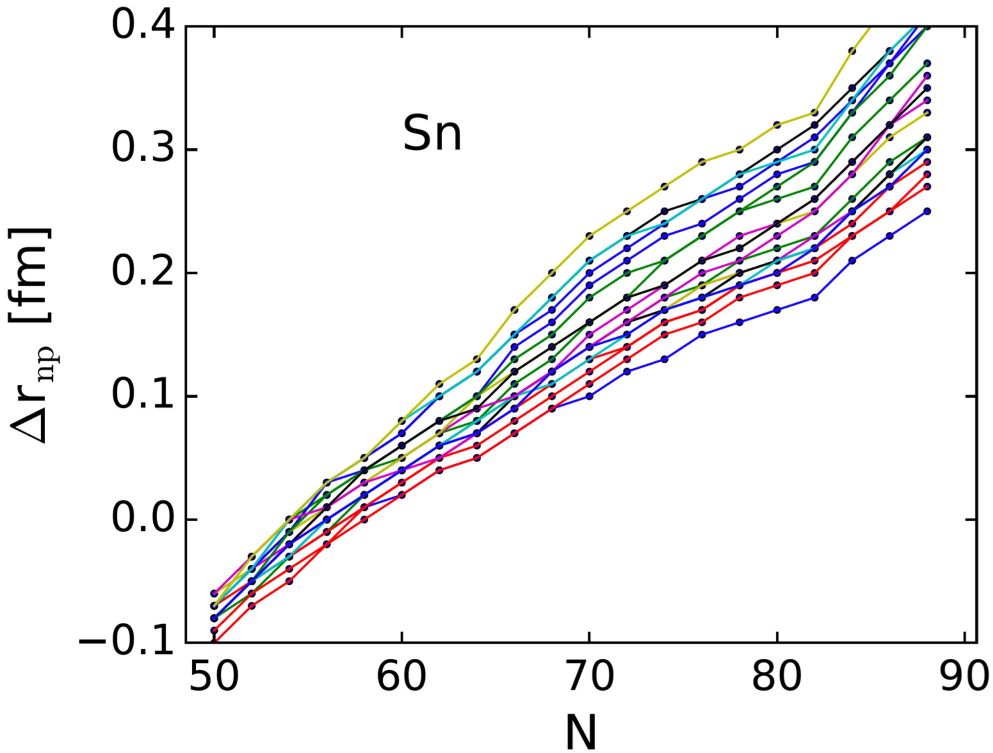


- n-skin changes by 0.19 fm for ^{132}Sn
- Total reaction cross section changes only by 2.5% !
- Total neutron-removal cross section changes by 20% !

  Variation δL = ± 5 MeV → $\delta\Delta r_{np} \approx \pm 0.01$ fm and $\delta\sigma_{DN} \approx \pm 1\%$

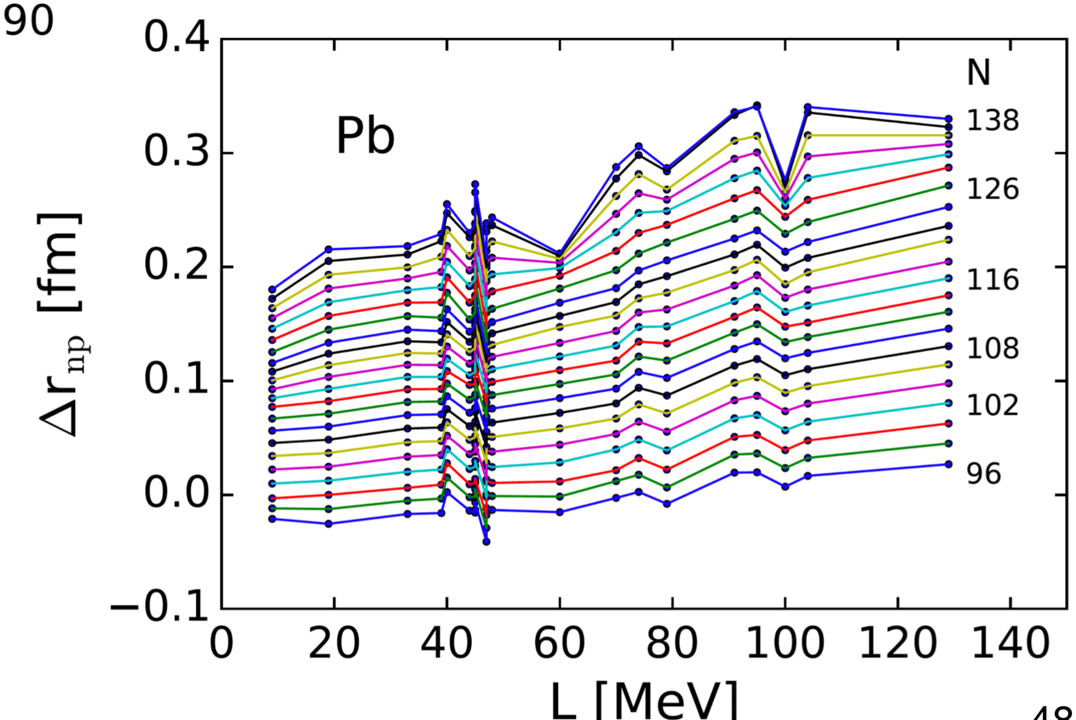
  → σ_{DN} very sensitive, limit given by DFT predictions reached
- Relation of σ_{DN} with L or Δr_{np} needs good reaction theory

Neutron skin and fragmentation reactions



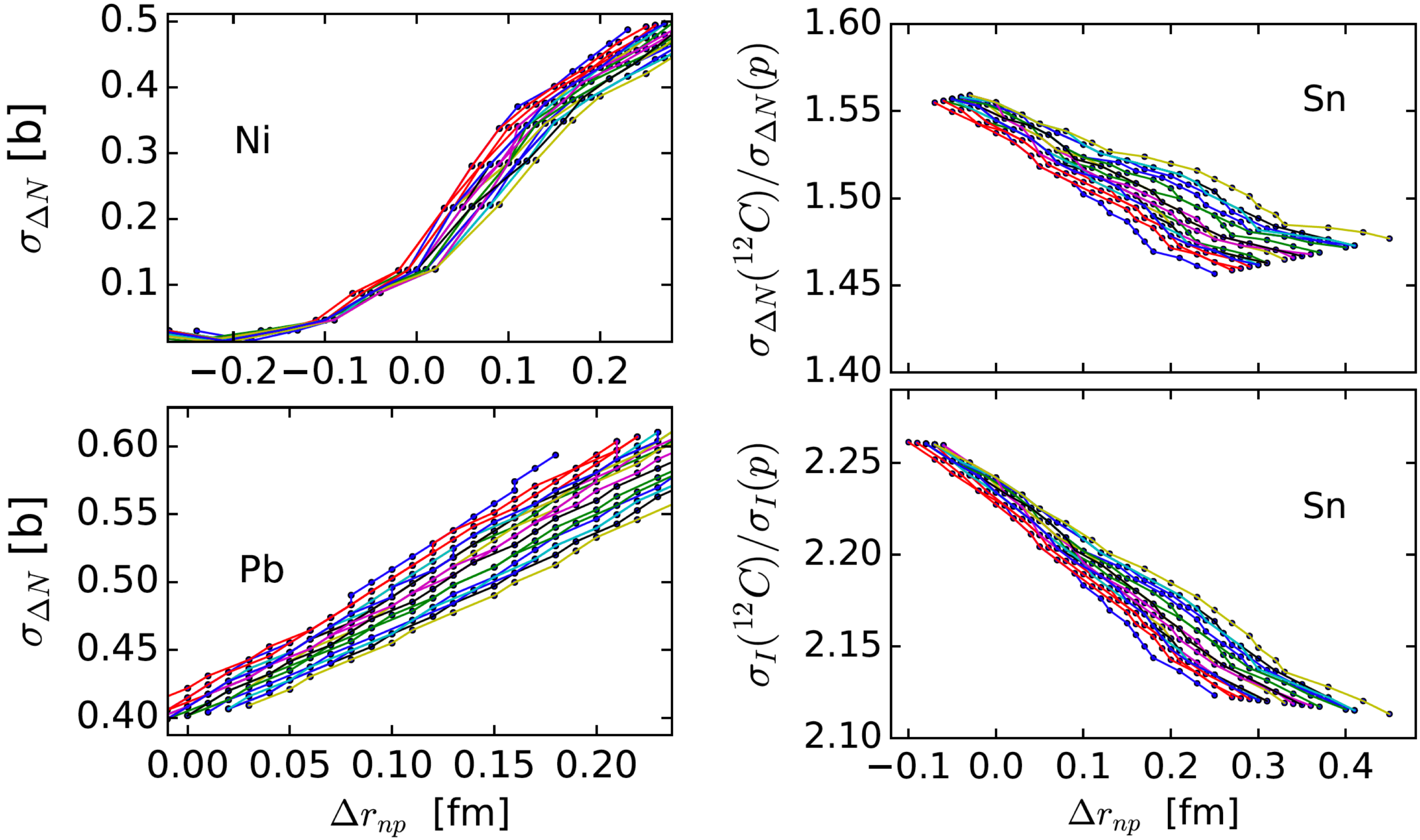
Points = different Skyrme interactions

→ different values of L

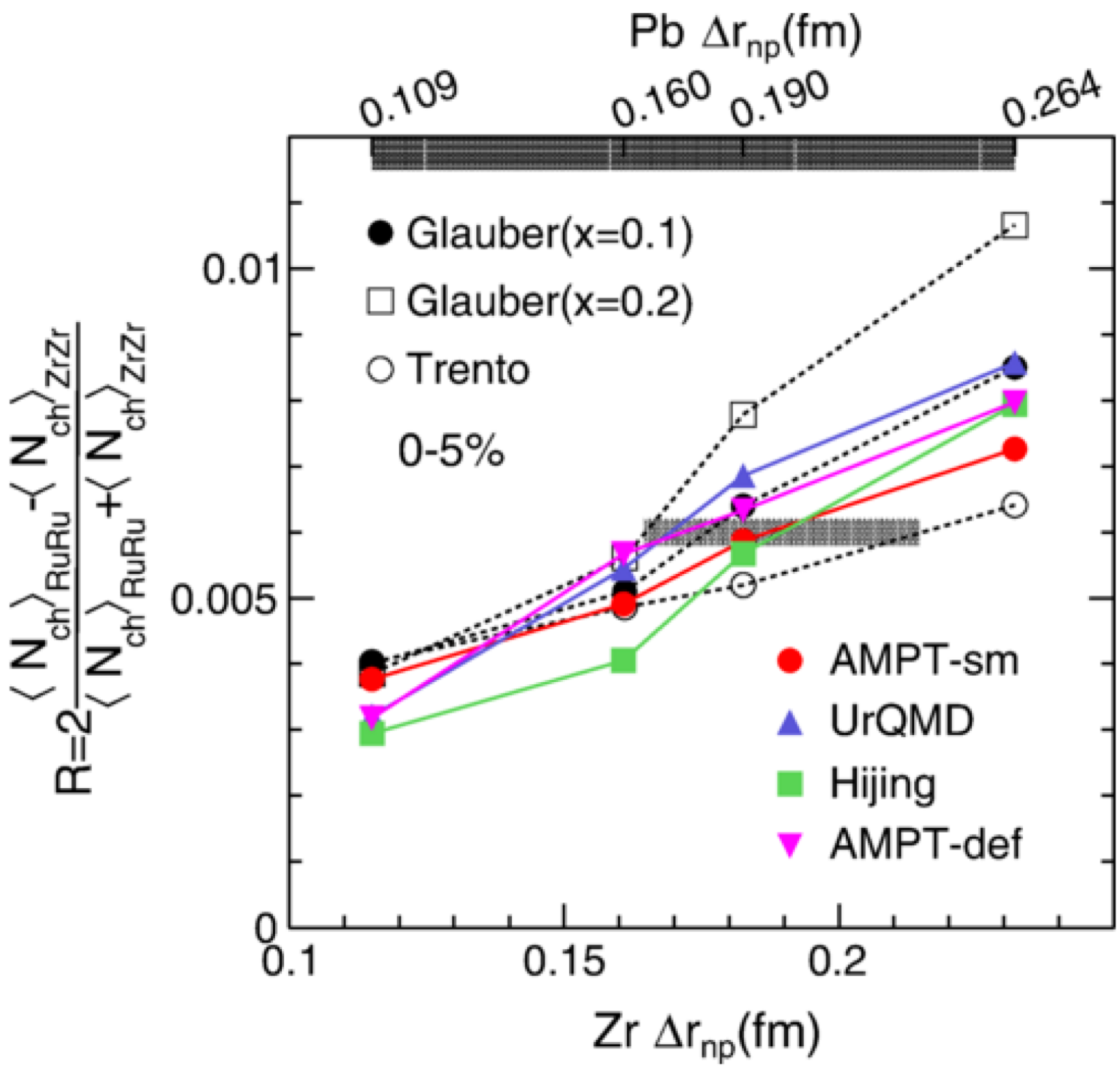


Bertulani, Valencia,
PRC 100, 015802 (2019)

Neutron skin and fragmentation reactions

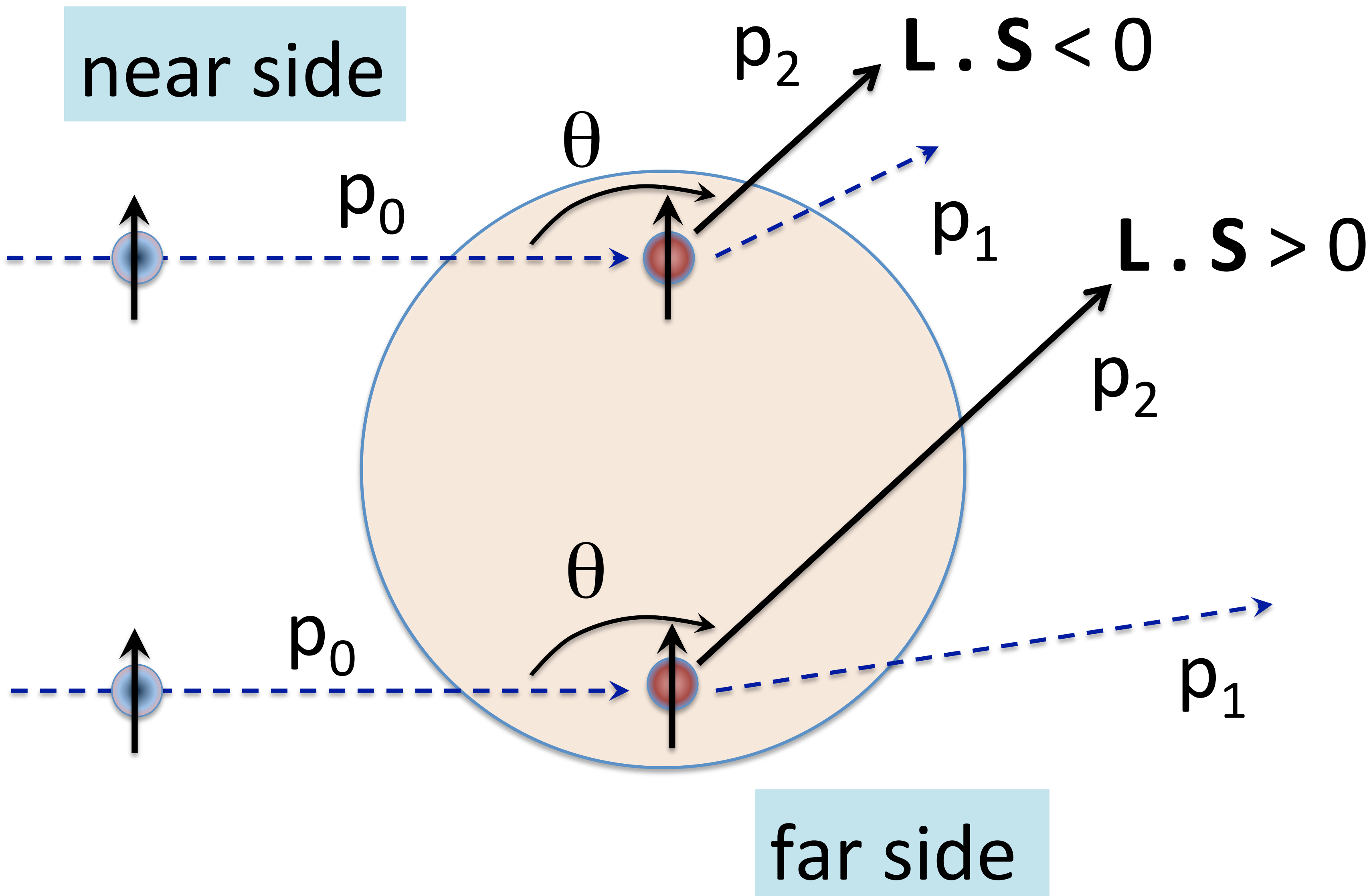


Neutron skin and fragmentation reactions

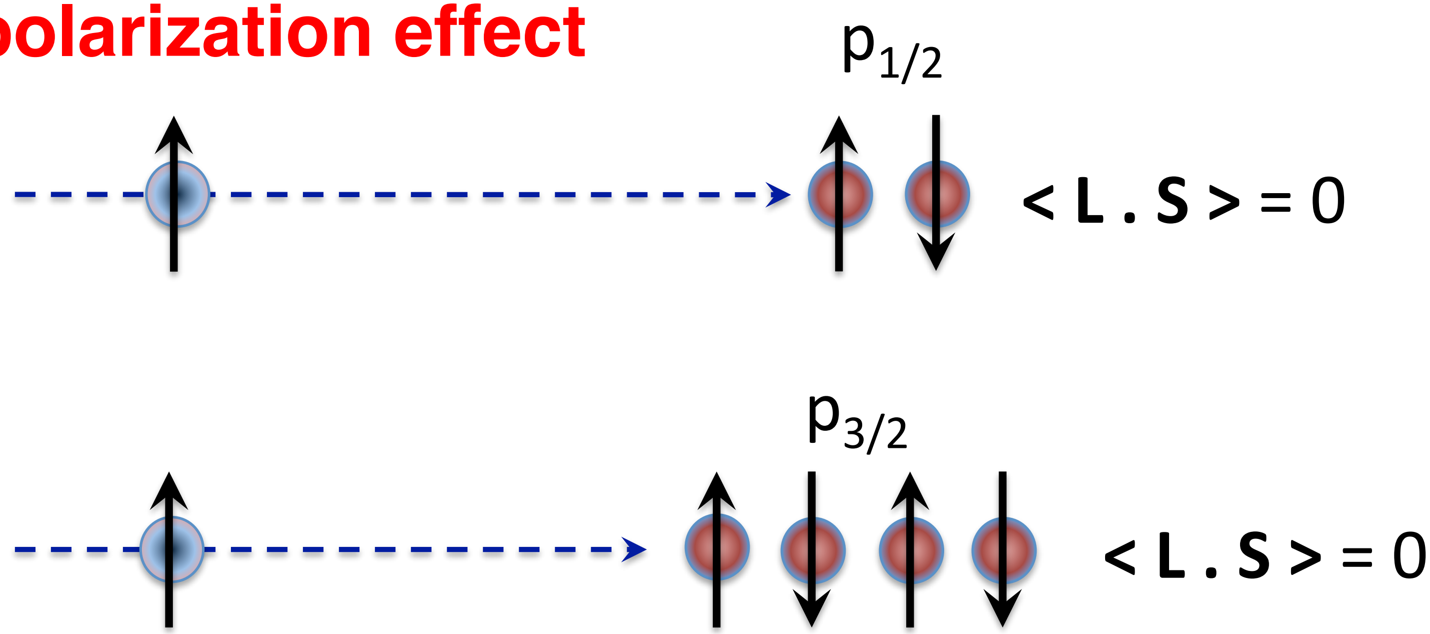


Hanlin Li, et al., Phys. Rev. Lett. 125, 222301

(p,2p) reactions: Maris polarization effect



Maris polarization effect



But NN interaction different for singlet (↑↓) and triplet (↑↑) scattering

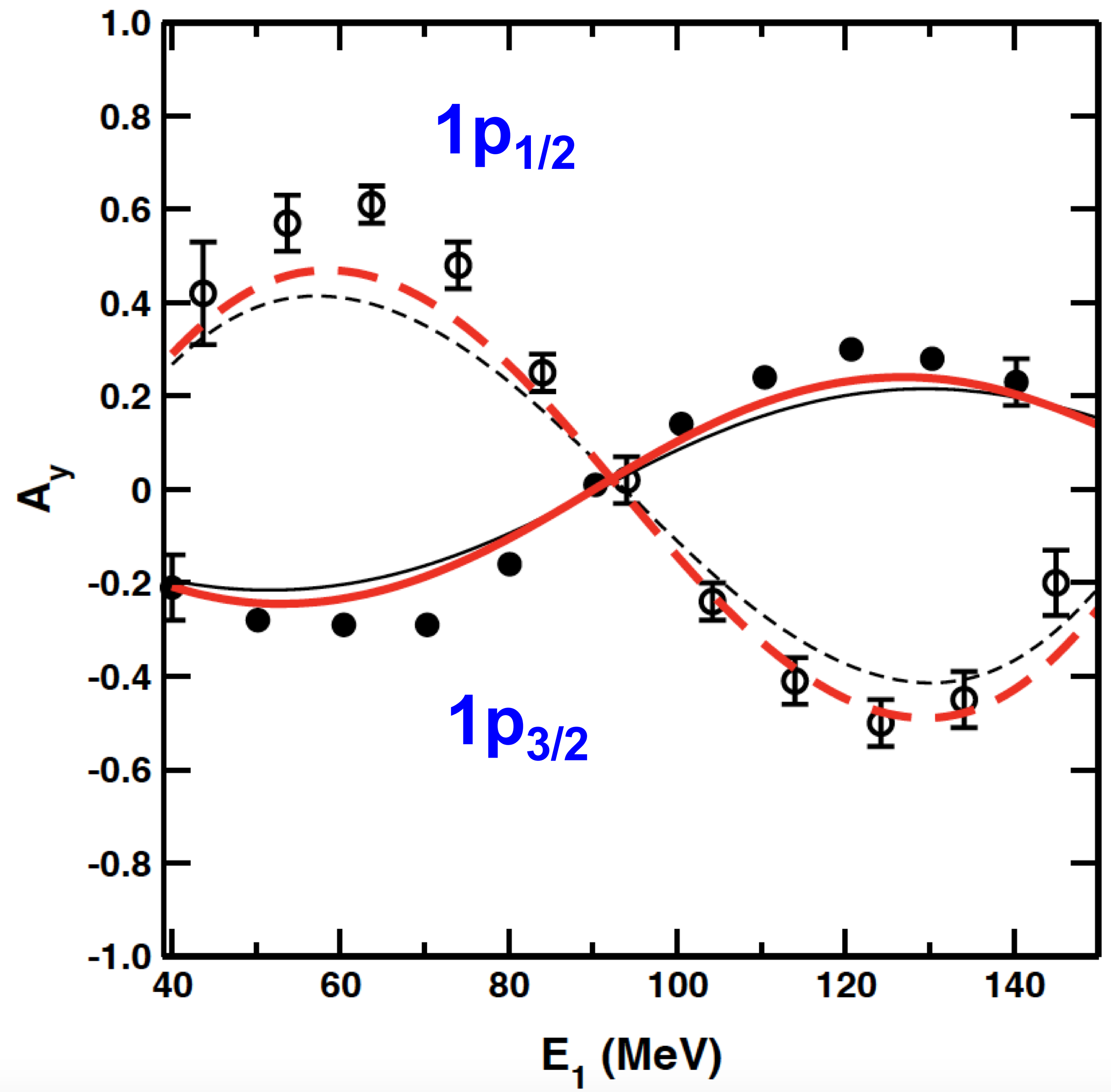
➡ Scattering asymmetries (twice larger for $p_{3/2}$)

+ **L.S** flips, changes optical potential and absorption in near (shorter path) and far (longer path) side

➡ Effective polarization (Maris polarization), P_{eff}

Maris, et al. NPA 322, 461 (1979)

Maris polarization effect



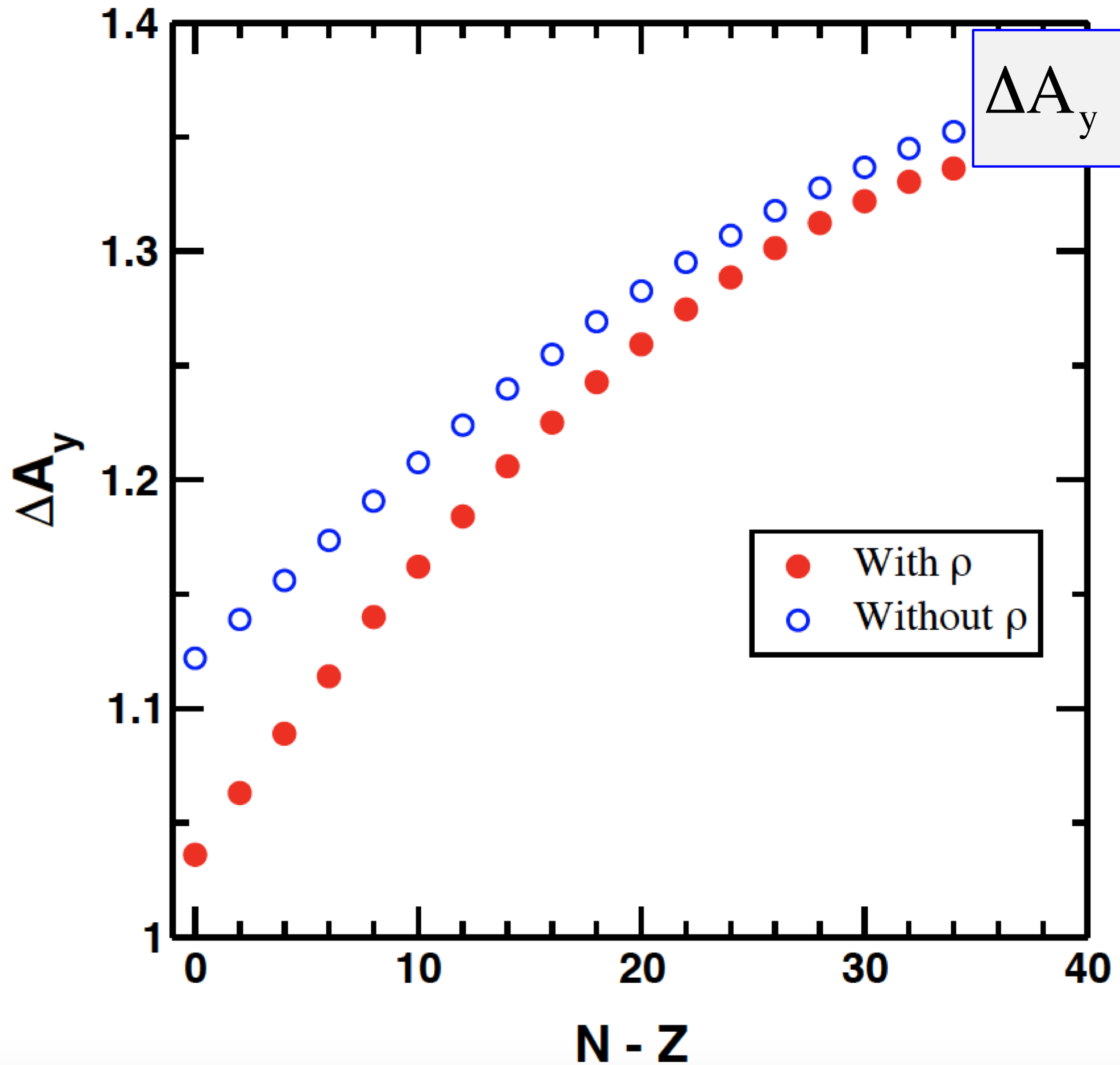
Maris, et al.
NPA 322, 461 (1979)

→ P_{eff} ~ const x A_y

$^{16}O(p,2p)$
at 200 MeV

thick lines = full
thin lines = no r

Maris polarization in asymmetry systems



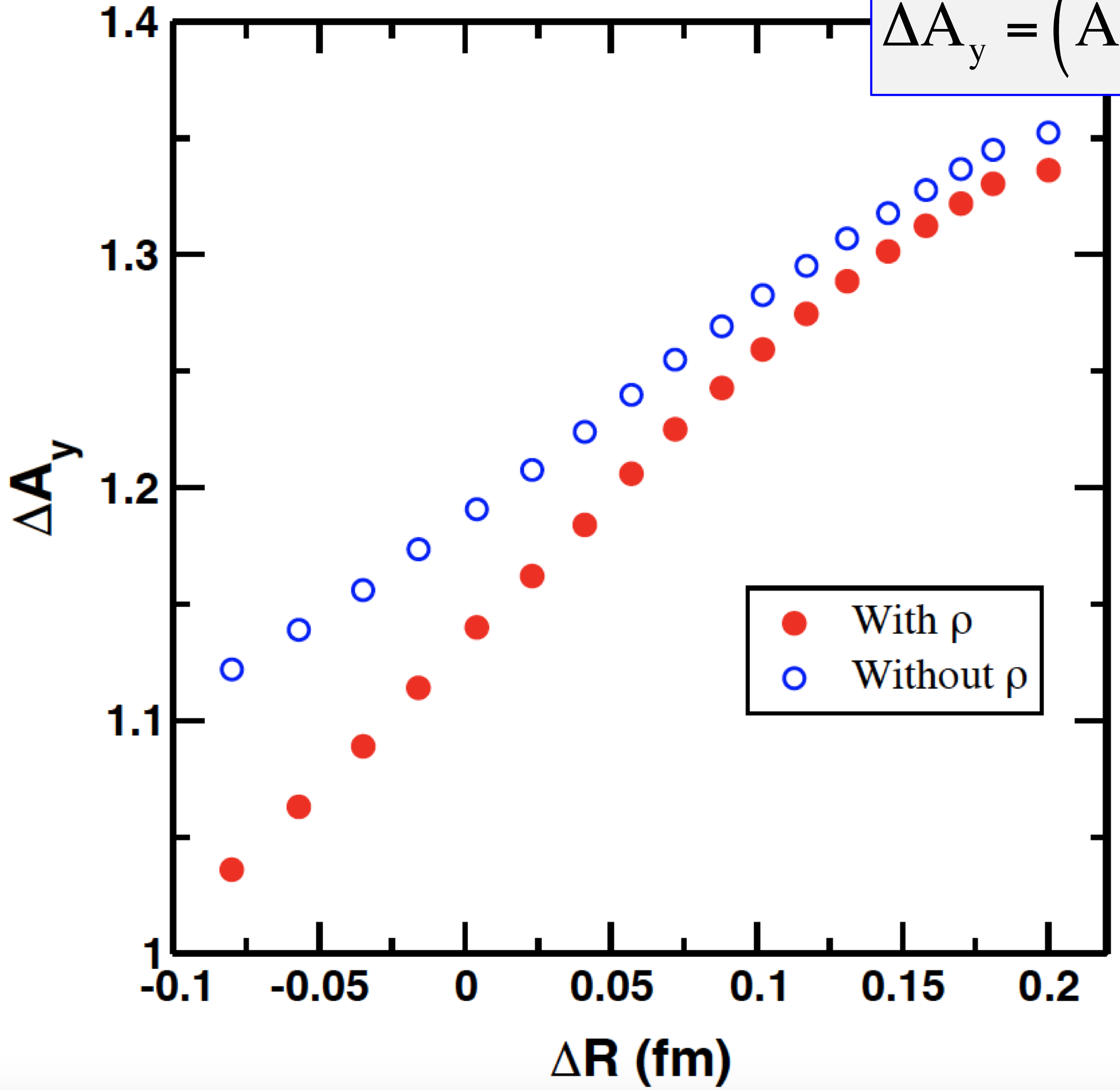
$$\Delta A_y = \left(A_y^{p_{1/2}}\right)_{max} - \left(A_y^{p_{3/2}}\right)_{min}$$

(p,2p) on Sn isotopes at 200 MeV

Shubhchintak, Bertulani, Aumann PLB 778, 30 (2018)

Maris polarization and neutron skins

$$\Delta A_y = \left(A_y^{p_{1/2}}\right)_{max} - \left(A_y^{p_{3/2}}\right)_{min}$$

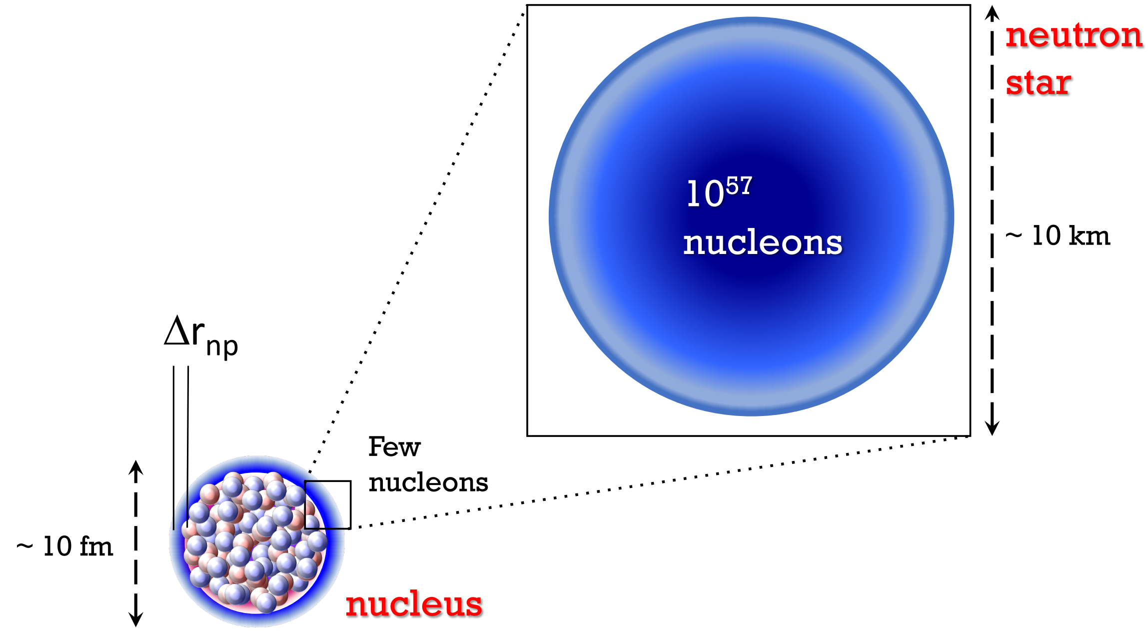


(p,2p) on Sn isotopes at 200 MeV/nucleon

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

Summary

Skins, halos, pygmies, and neutron stars



- Halos ←→ pygmy?
- Skins → pygmy (nearly linear correlation)
- Dipole polarization → magnify pygmy properties (Coulex)
- Fragmentation reactions – total neutron removal cross sections
- Pygmy + skin + other ideas → symmetry energy
- Long way to go from nuclear matter to neutron matter