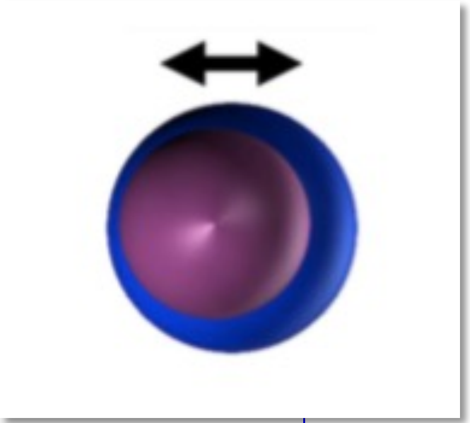
Neutron skins and stars

C.A. Bertulani

TEXAS A&M UNIVERSITY
COMMERCE

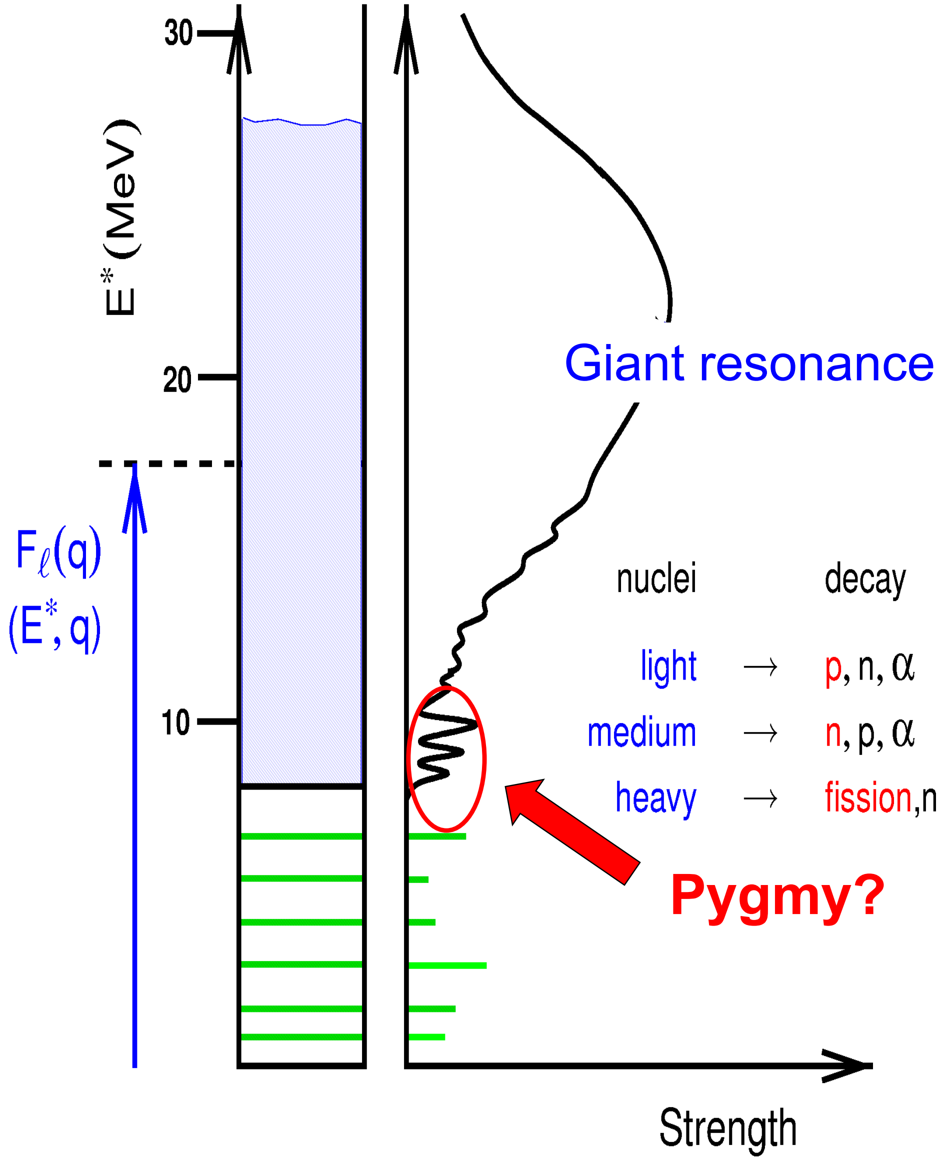
Pygmy Resonances: Origins



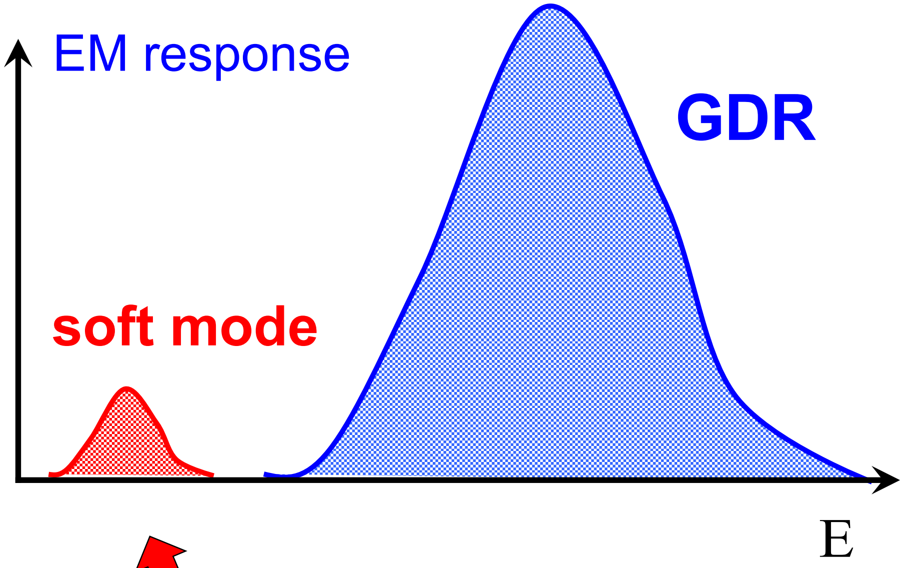
Low-energy dipole strength

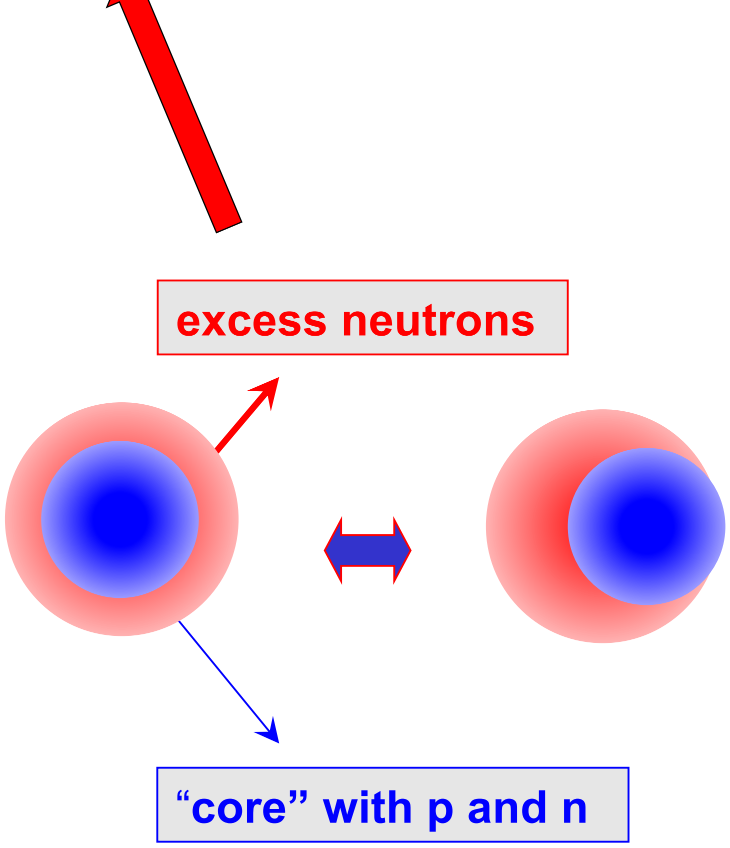
- First observation in 1961
  γ rays from neutron capture
  Bartholomew, Annu. Rev. Nucl. Sci. 11, 259 (1961)
- First use of name “pygmy resonance” (PDR)
  Brzosko et al., Can. J. Phys 47, 2849 (1969)
- Description as a collective excitation
  Mohan et al., Phys. Rev. C 3, 1740 (1971)
  “Three-Fluid 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



nuclei		decay
light	→	p, n, α
medium	→	n, p, α
heavy	→	fission,n



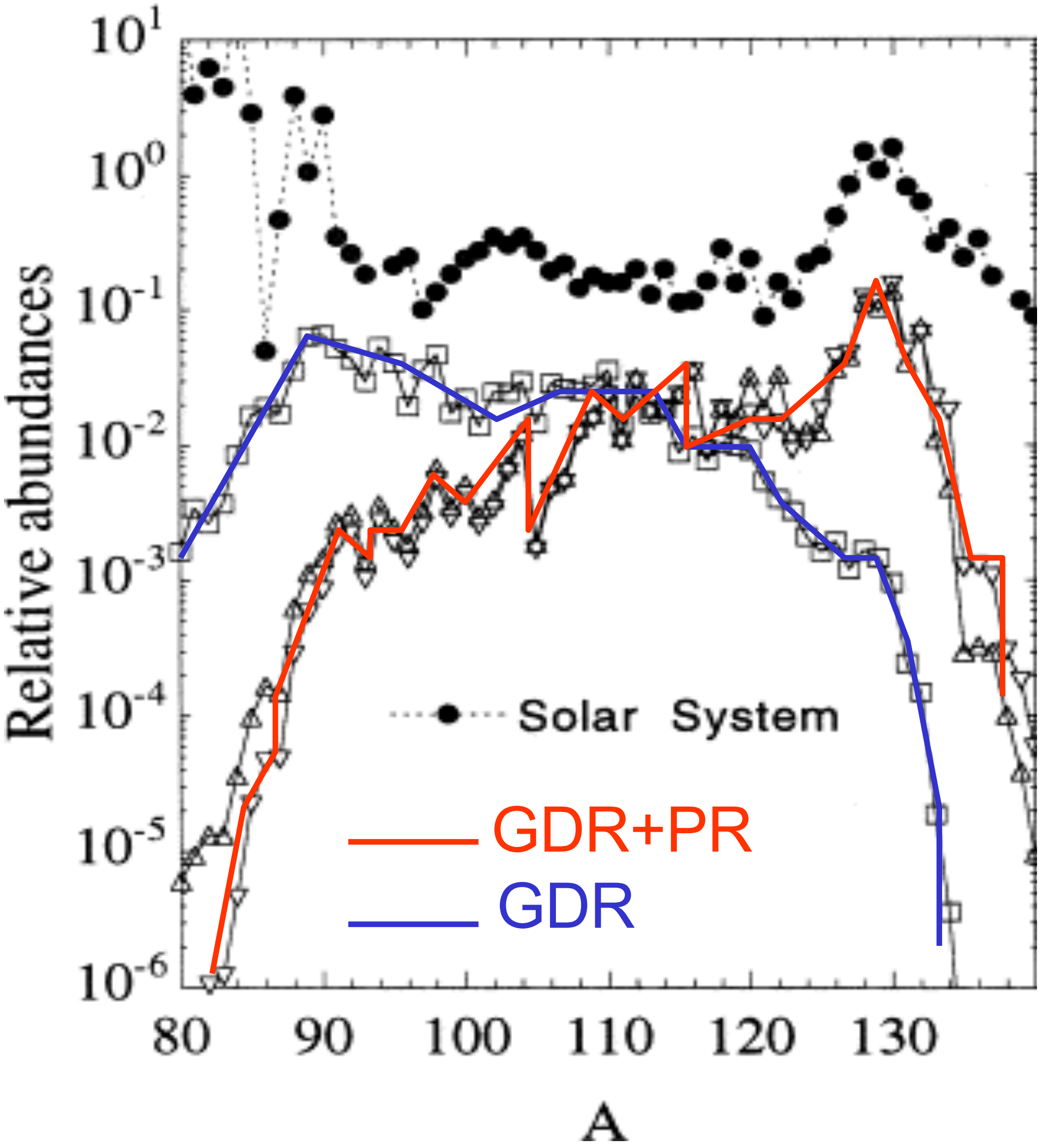


excess neutrons

“core” with p and n

Impact of pygmies on nucleosynthesis (??!)

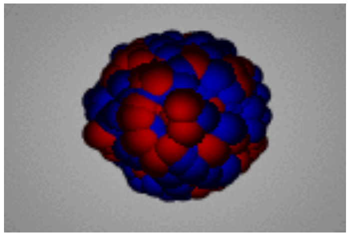
(γ,n) or (n,γ) cross sections in the r-process



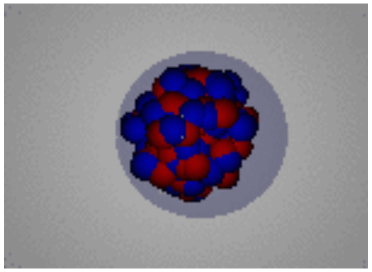
Goriely, PLB 436, 10 (1998)

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

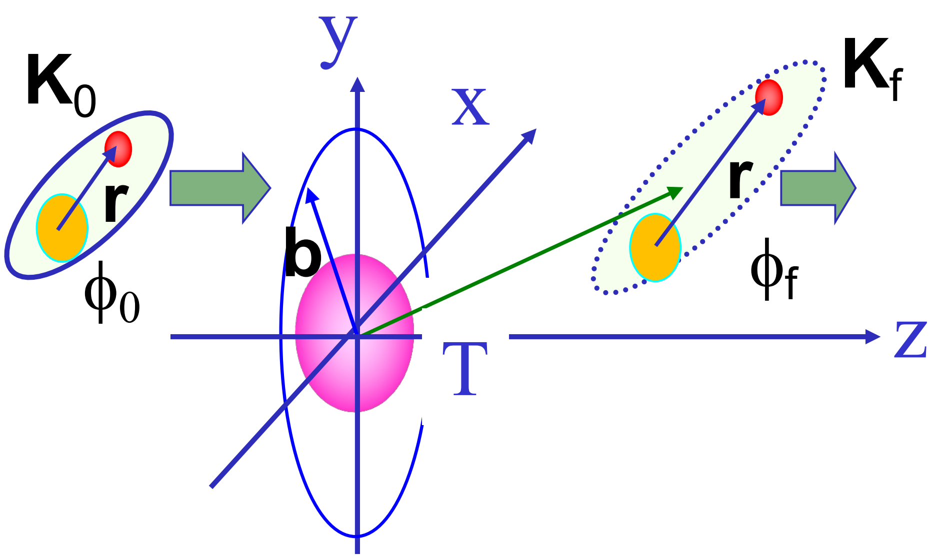


Giant dipole

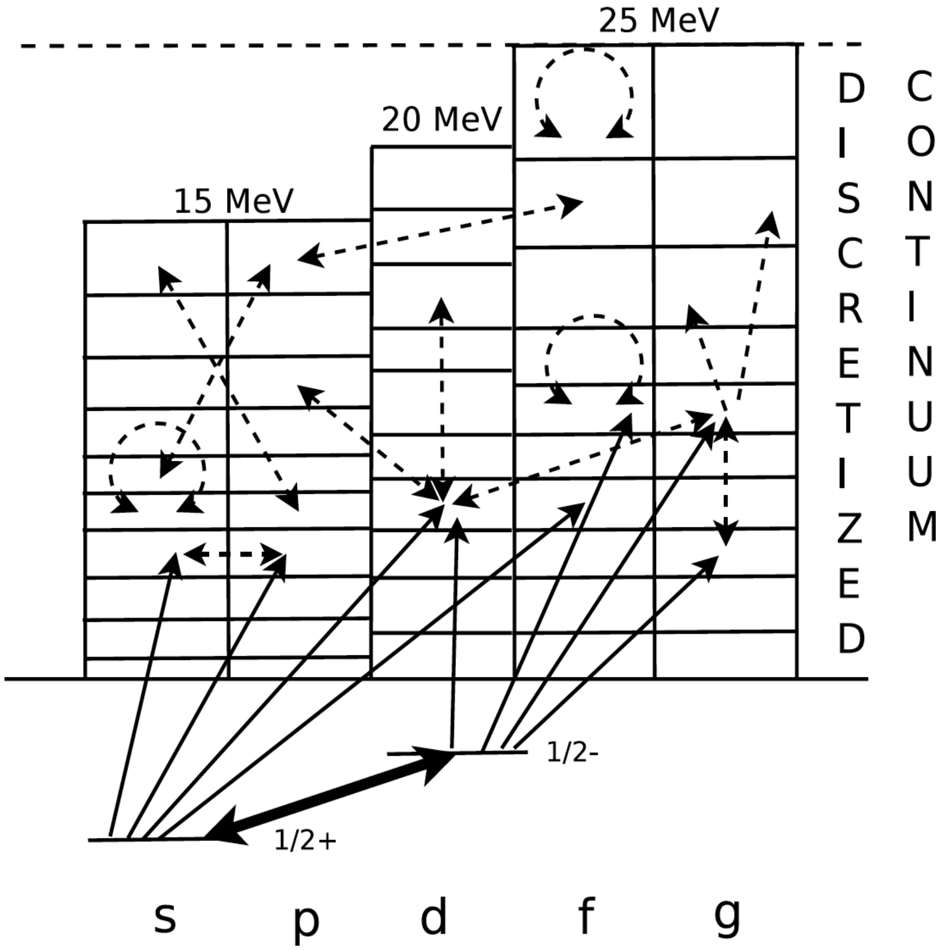


Pygmy dipole

Reactions with light neutron-rich nuclei



- Basis expansion for intrinsic φ
- Eikonal scattering waves
- Nuclear + EM potentials
- Relativity

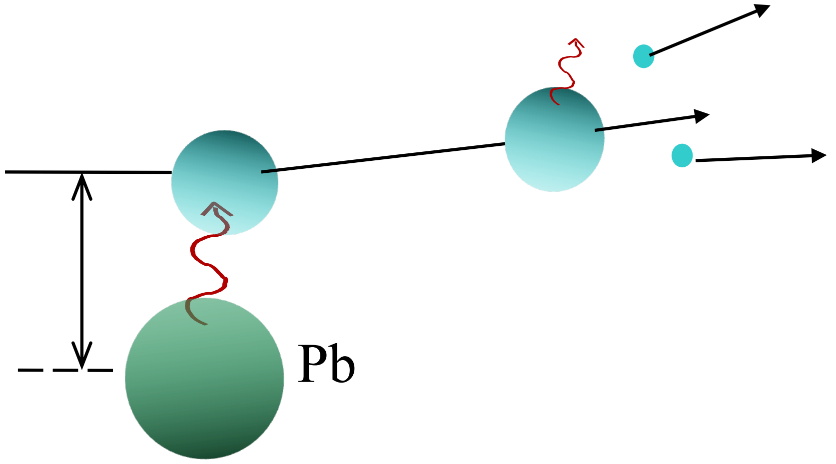


- Continuum discretization
- Coupled-channels (relativistic CDCC)

CB, PRL 94, 072701 (2005)

EM response functions

E & M response in light neutron-rich nuclei



bound

continuum

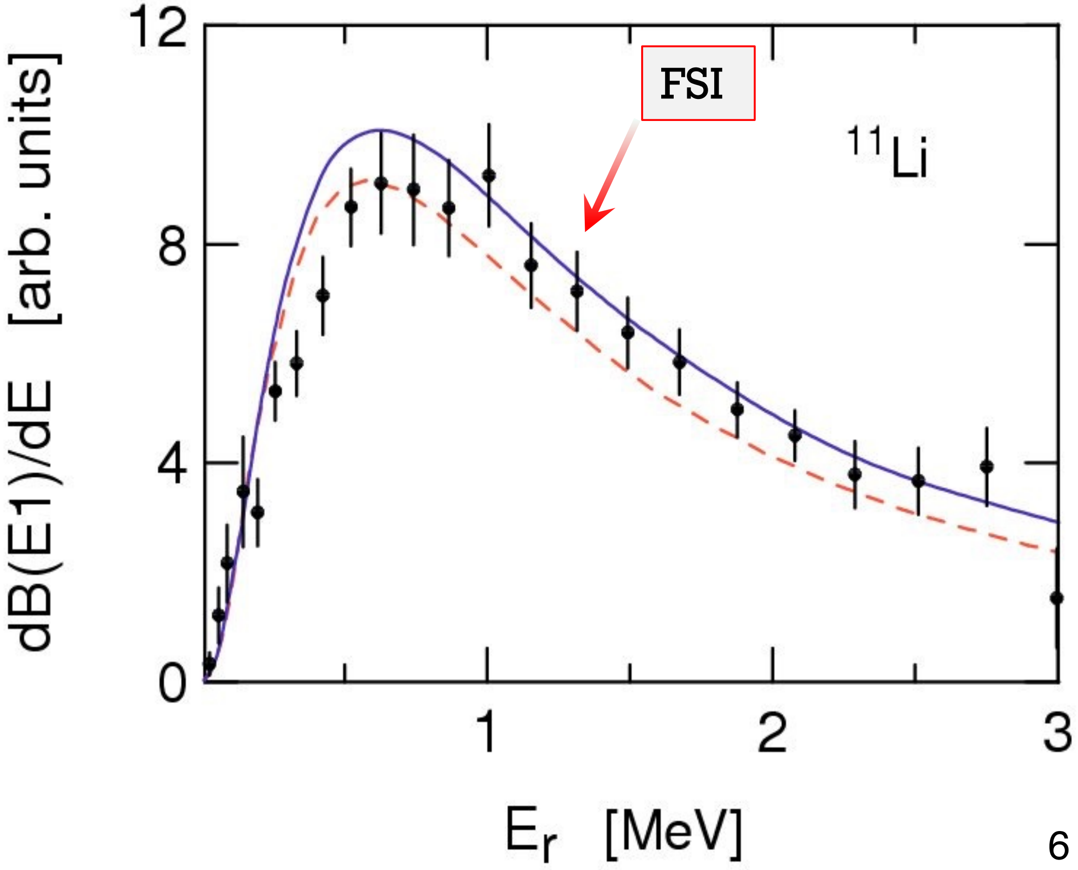
$$\frac{dB(EL)}{dE} \sim \left|\left\langle \Psi_f \middle| r^L Y_L \middle| \Psi_i \right\rangle\right|^2 \sim \frac{\left(E_x - S_n\right)^{L+1/2}}{E_x^{2L+2}}$$

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

Three-body:
CB, PRC 75, 024606 (2007)
NPA 790, 467 (2007)

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

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

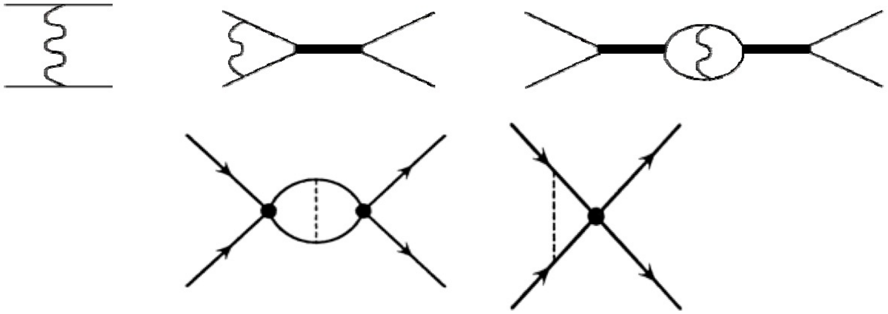


Similarly, is the tetraneutron a phase-space phenomenon?
See Meytal Duer's talk

Halo EFT for light nuclei

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

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



- Most general Lagrangian consistent with assumed symmetries, e.g., spontaneously broken chiral symmetry
- Infinitely many Feynman diagrams
- loop integrals, divergences
- regularization, renormalization
- Find the importance of diagrams (we cannot calculate infinitely many diagrams)

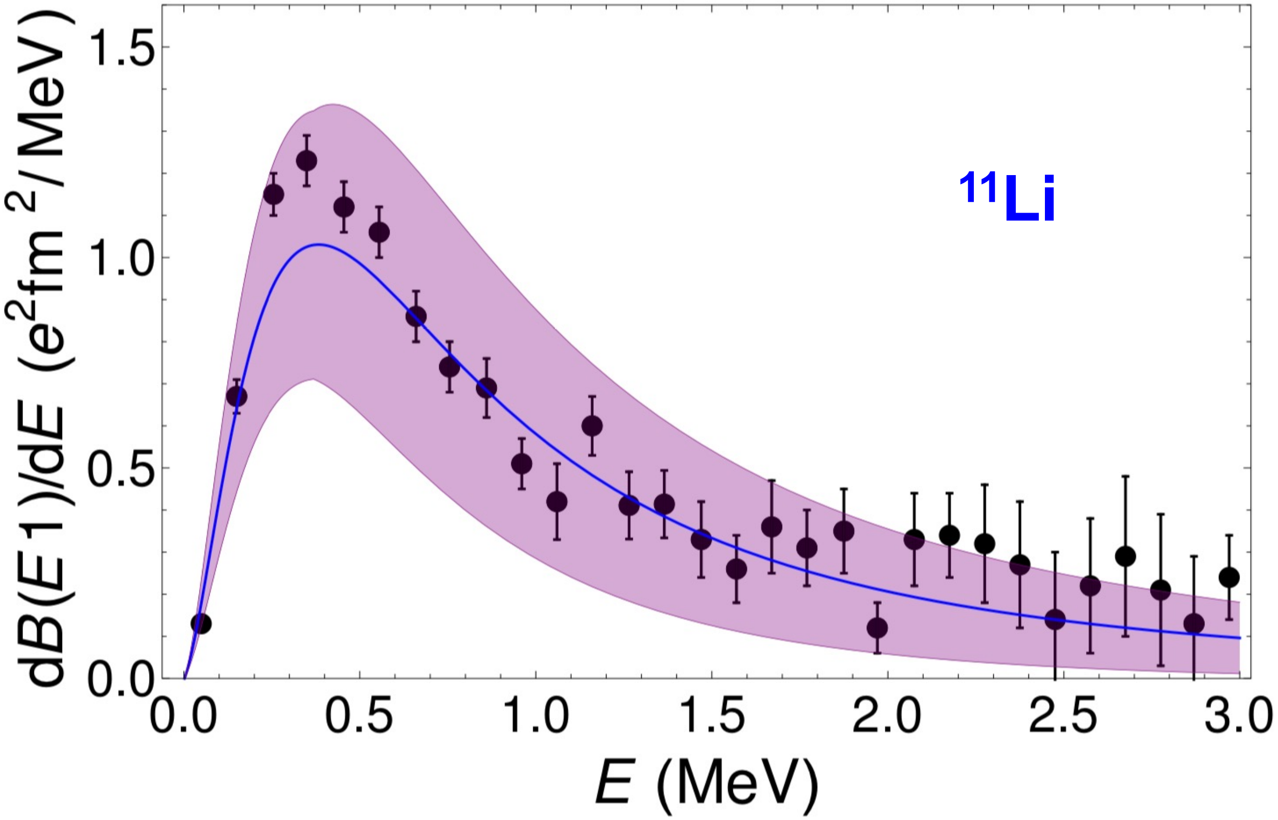
E & M response in halo EFT

Organize contributions in terms of $\left(\frac{Q}{\Lambda}\right)^n$, $n \geq 0$

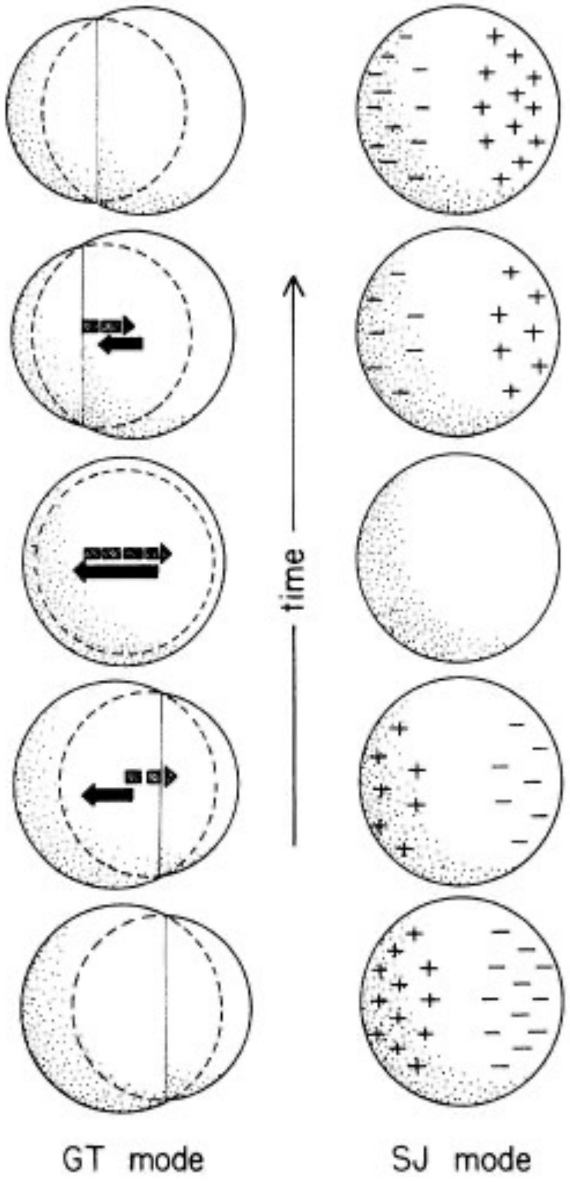
Q = a momentum (derivative) or pion mass (m_π)

Λ = chiral symmetry breaking scale, $\Lambda \approx 1$ GeV

Acharya, Phillips,
EPJ 113, 06013 (2016)



Hydrodynamics



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

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

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

Myers et al, PRC 15, 2032 (1977)

Heavier nuclei: pygmy properties with hydrodynamics

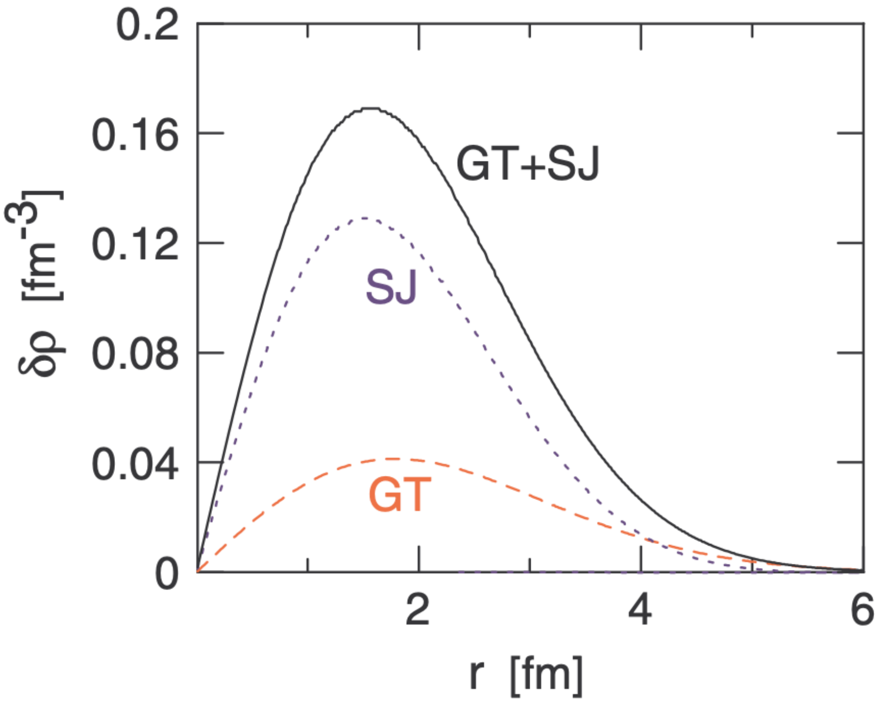
Suzuki, Ikeda, Sato, PTP 83 (1990) 180
Van Isacker, Nagarajan, Warner, PRC 45 (1992) 13

GT

SJ

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

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



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

$$\Gamma_{PR} = \frac{\hbar \sqrt{\bar{v}_{core} \bar{v}_{skin}}}{R} \sim 3\ \mathrm{MeV}$$

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

Pygmy properties: density functional models

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

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

$$\begin{aligned}
V_{ij}^{NN} = {} & t_0(1+x_0P_{ij}^{\sigma})\delta(\mathbf{r}_i-\mathbf{r}_j) + \frac{1}{2}t_1(1+x_1P_{ij}^{\sigma})[\overleftarrow{\mathbf{k}}_{ij}^{2}\delta(\mathbf{r}_i-\mathbf{r}_j) + \delta(\mathbf{r}_i-\mathbf{r}_j)\overrightarrow{\mathbf{k}}_{ij}^{2}] + \\
& t_2(1+x_2P_{ij}^{\sigma})\overleftarrow{\mathbf{k}}_{ij}\delta(\mathbf{r}_i-\mathbf{r}_{jj})\overrightarrow{\mathbf{k}}_{ij} + \frac{1}{6}t_3(1+x_3P_{ij}^{\sigma})\rho^{\alpha}\left(\frac{\mathbf{r}_i+\mathbf{r}_j}{2}\right)\delta(\mathbf{r}_i-\mathbf{r}_j) + \\
& iW_0\overleftarrow{\mathbf{k}}_{ij}\delta(\mathbf{r}_i-\mathbf{r}_j)(\vec{\sigma}_i+\vec{\sigma}_j)\overrightarrow{\mathbf{k}}_{ij},
\end{aligned}$$

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

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

+ pairing

HF + BCS

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

HFB

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

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

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

Neutron stars

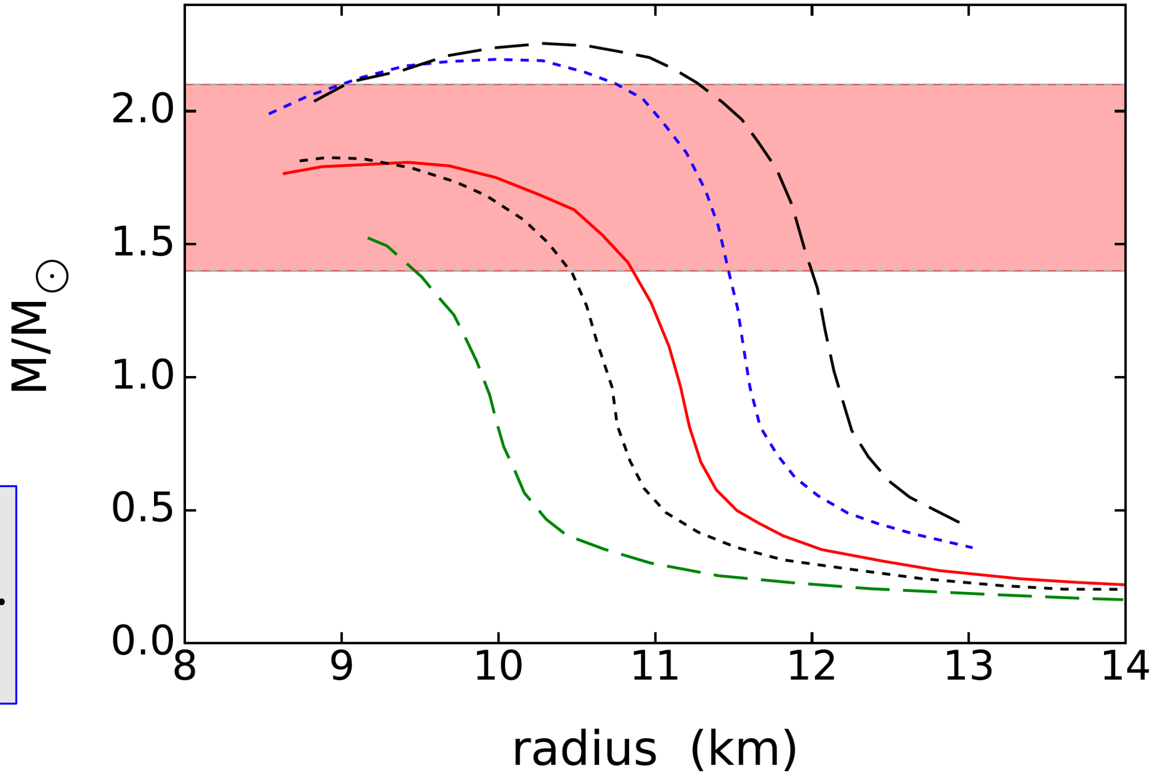
$$\frac{dP}{dr} = -\frac{G\rho(r)M(r)}{r^2}\left[1+\frac{P(r)}{\rho(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

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

Tolman-Oppenheimer-Volkoff

EOS

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



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

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

EOS + symmetry energy

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

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

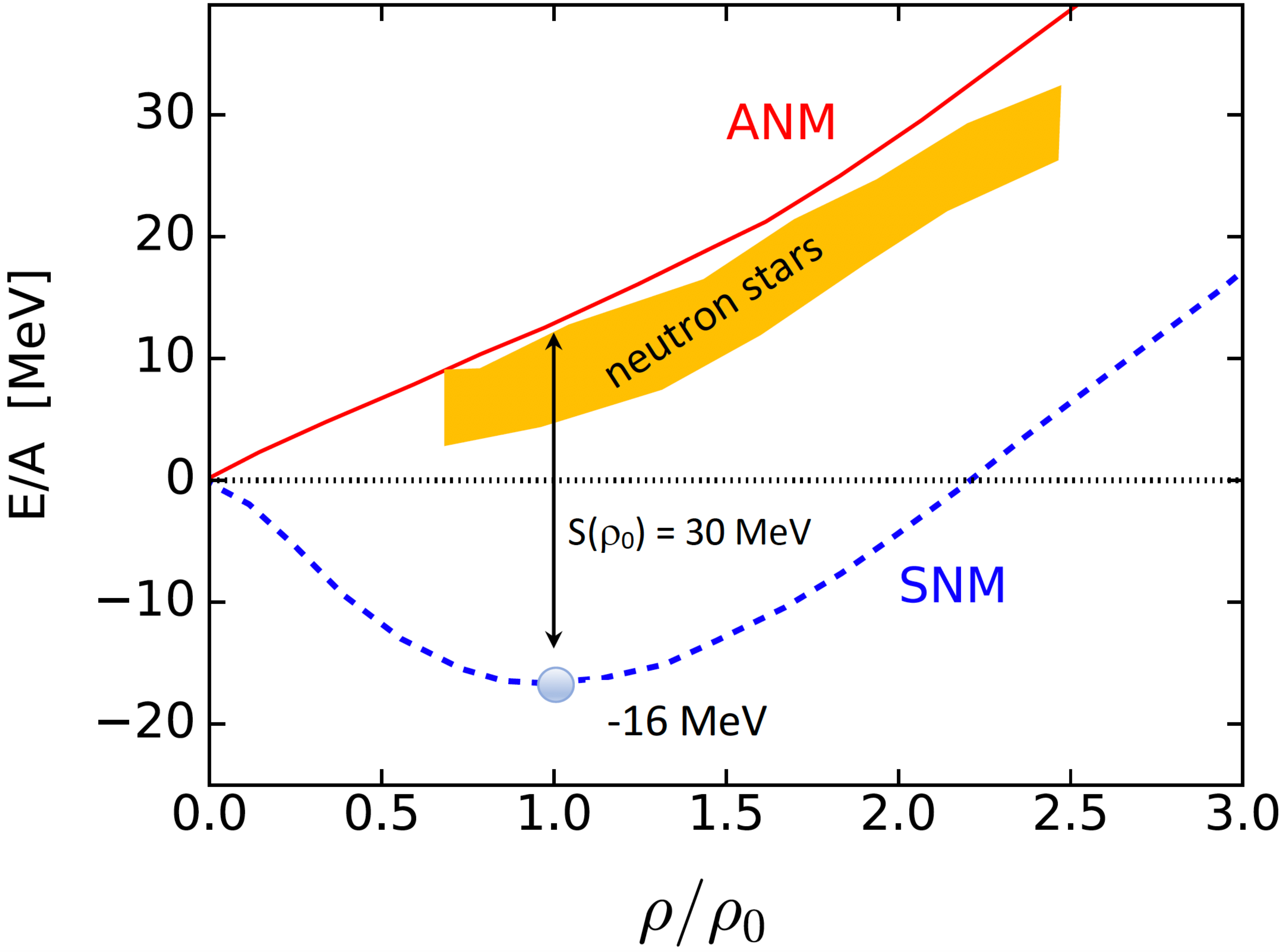
$$L=3\rho_0\frac{dS(\rho)}{d\rho}\bigg|_{\rho_0},\quad \delta=\frac{\rho_n-\rho_p}{\rho},\quad x=\frac{(\rho-\rho_0)}{3\rho_0}$$

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

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

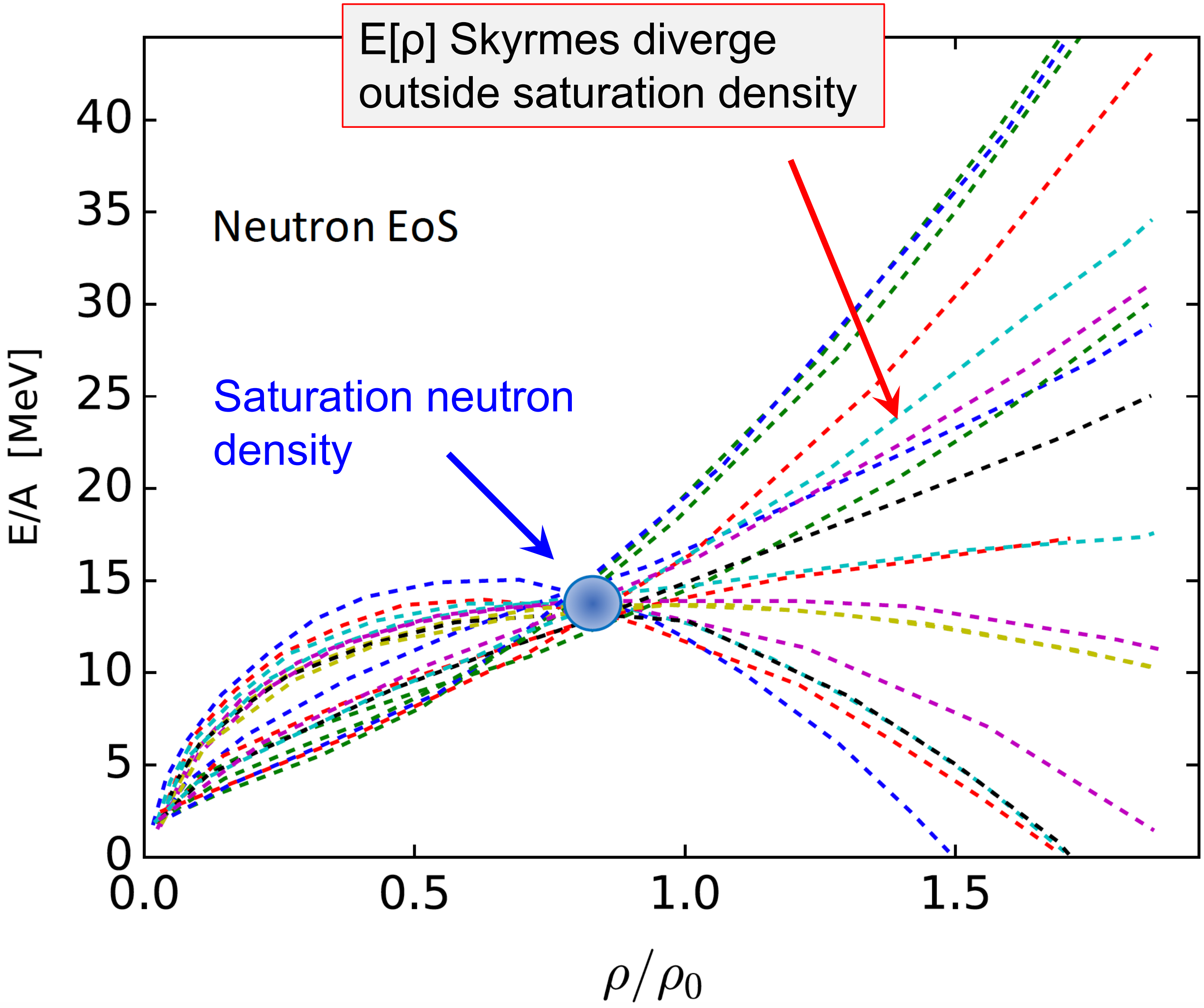
L crucial for neutron matter

EOS of neutron stars



EOS & Neutron stars

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



E[ρ] Skyrmes diverge outside saturation density

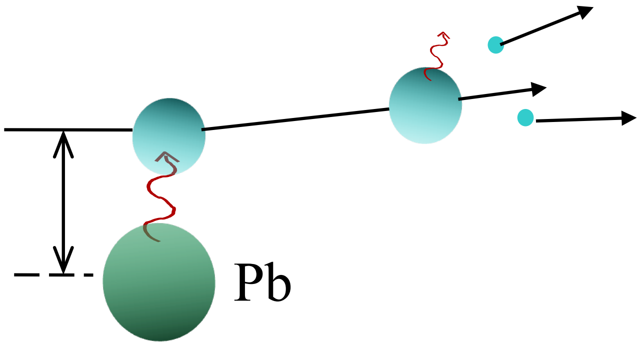
Saturation neutron density

Dipole polarizability

Rossi et al.
PRL 111 (2013) 242503

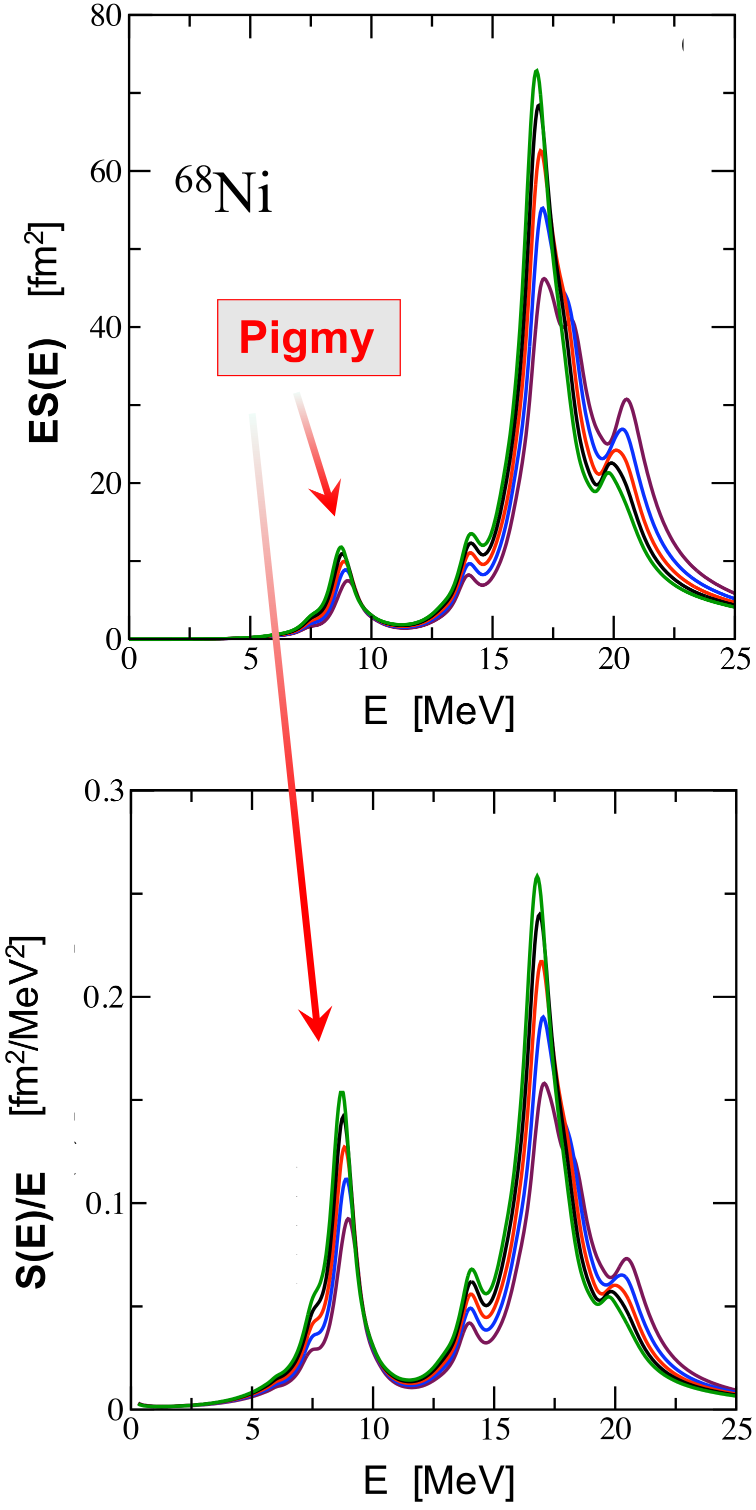
Wieland et al.
PRL 102, 092502 (2009)

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

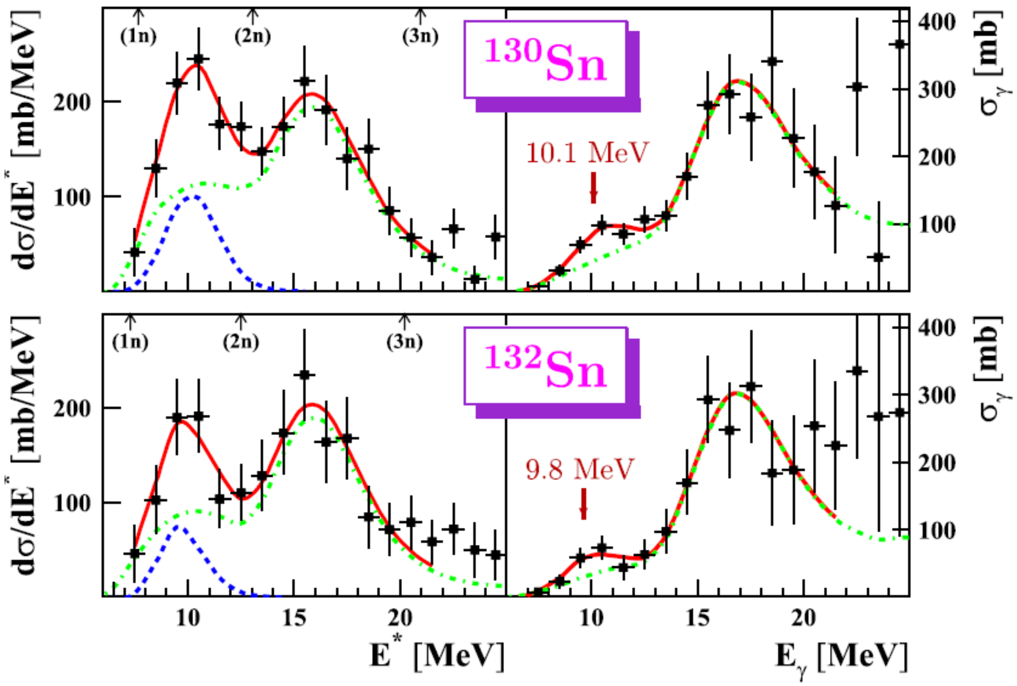


Dipole polarizability

$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma_\gamma(E)}{E^2}dE$$
$$= \frac{8\pi}{9}\int \frac{B(E1,E_x)}{E_x}dE_x$$

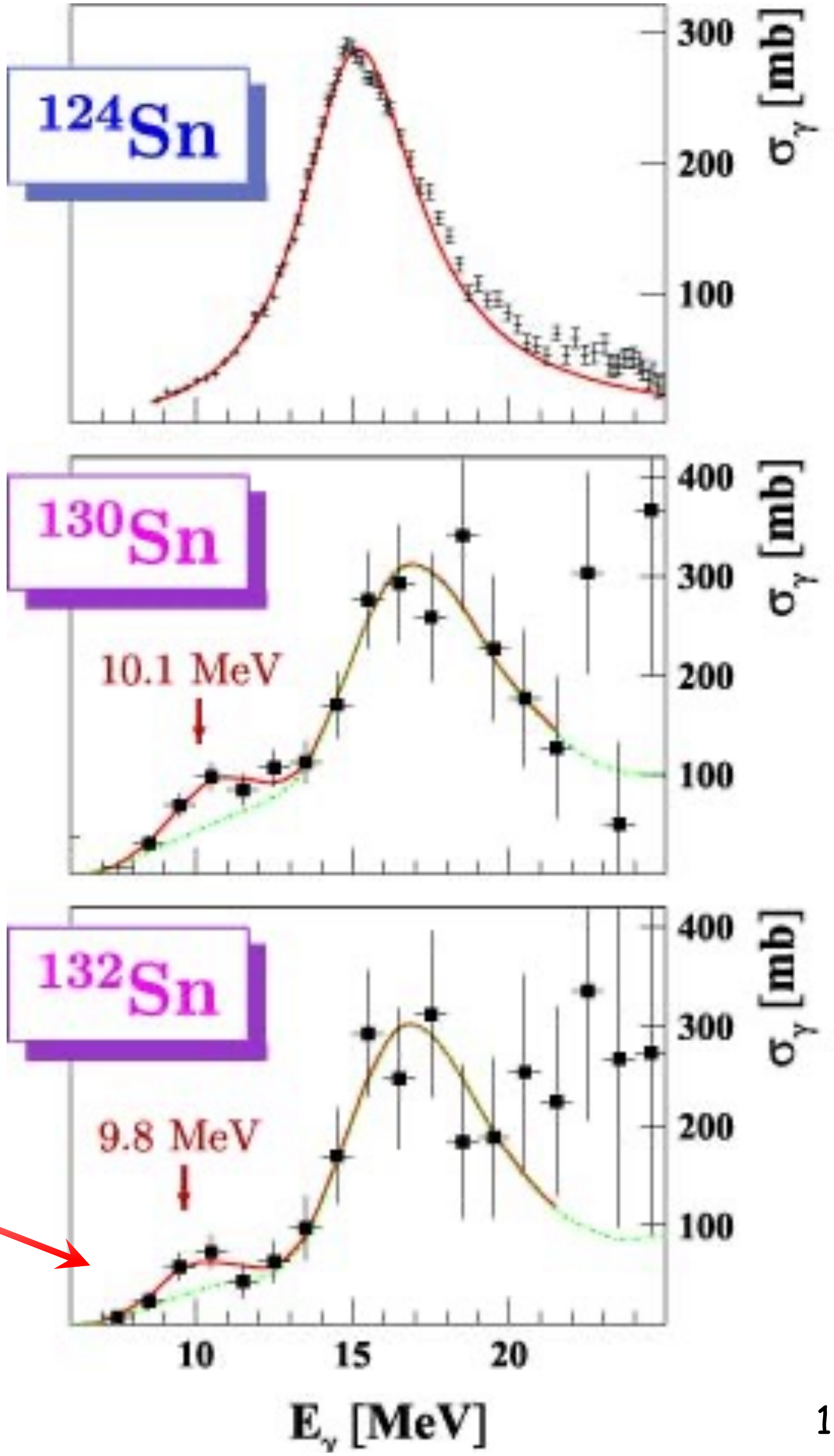


Dipole polarizability

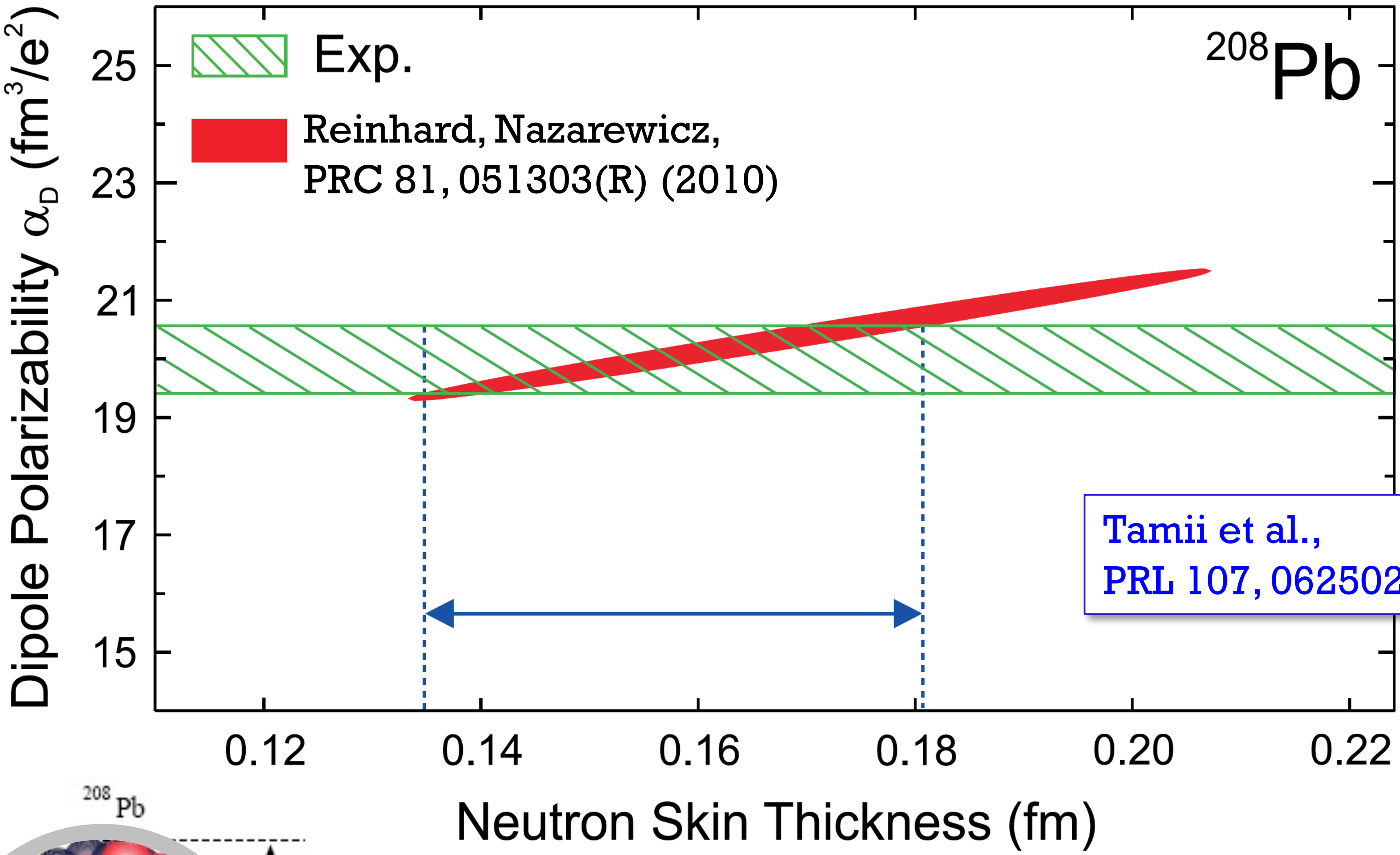


Adrich et al., PRL 95, 132501 (2005)

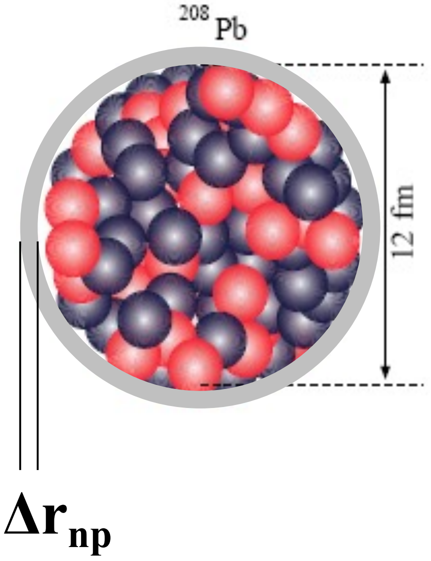
Pigmy



Dipole polarizability & neutron skin



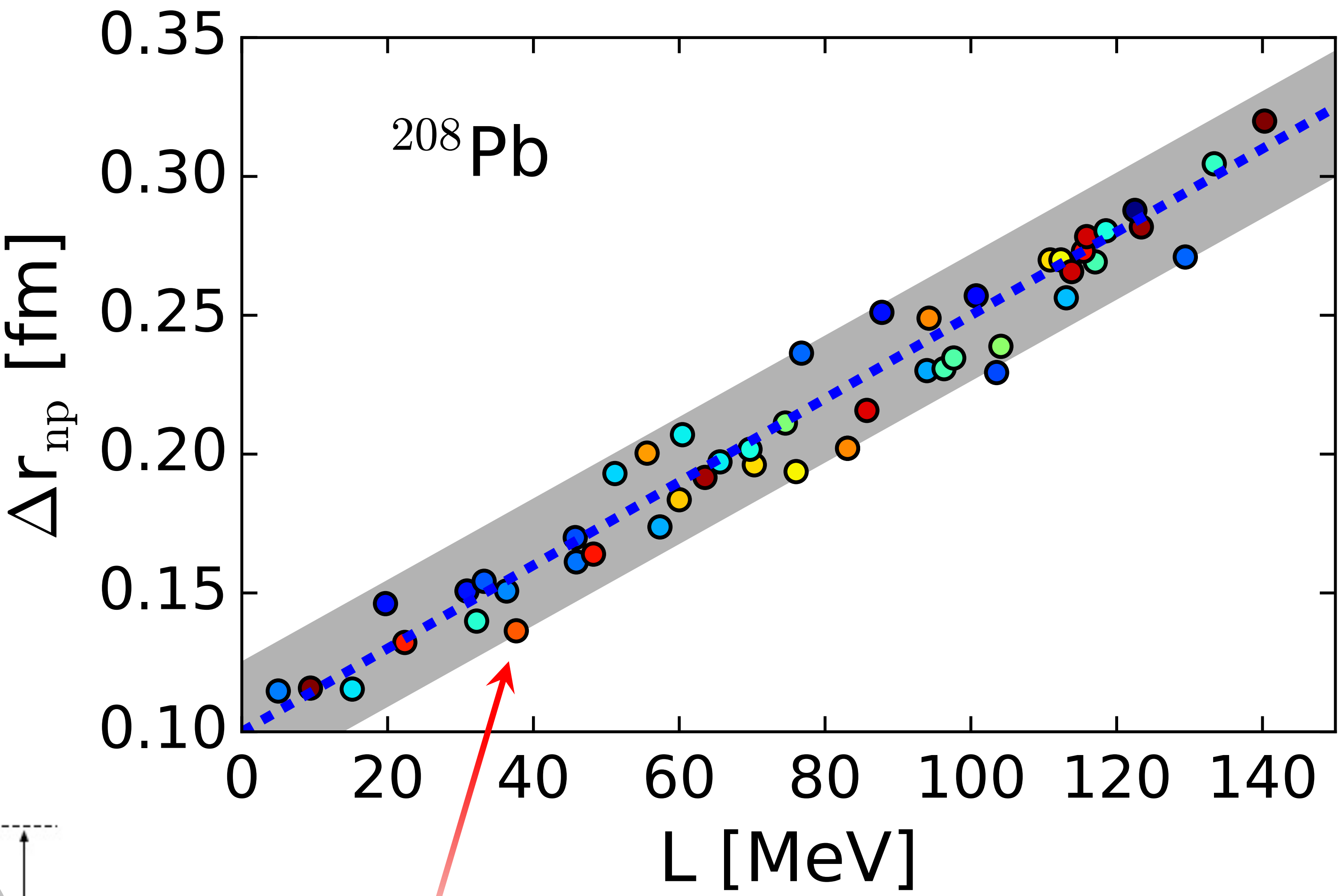
Tamii et al.,
PRL 107, 062502 (2011)



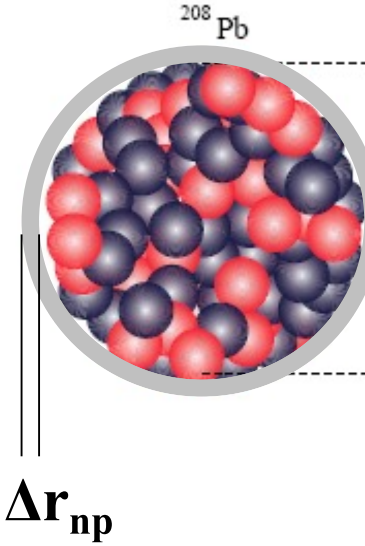
$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma_\gamma(E)}{E^2}dE$$

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

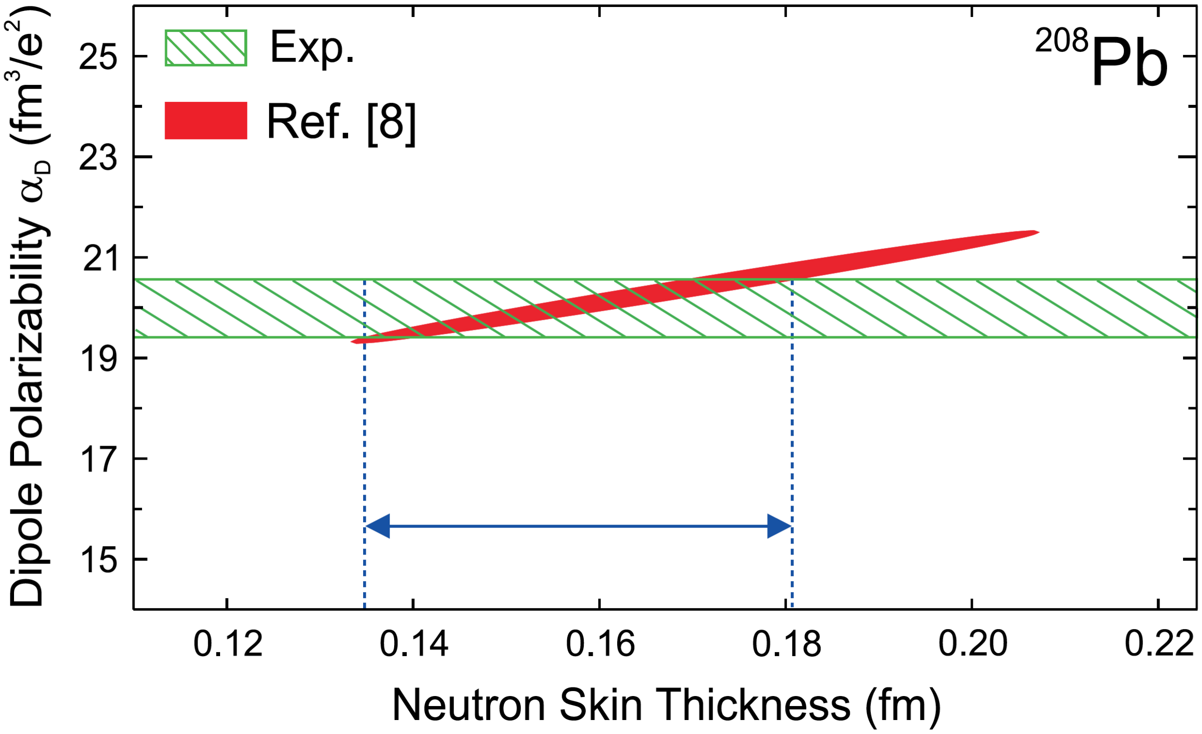
Correlation between symmetry energy & neutron skin



Numerous EDF



Dipole polarizability & neutron skin



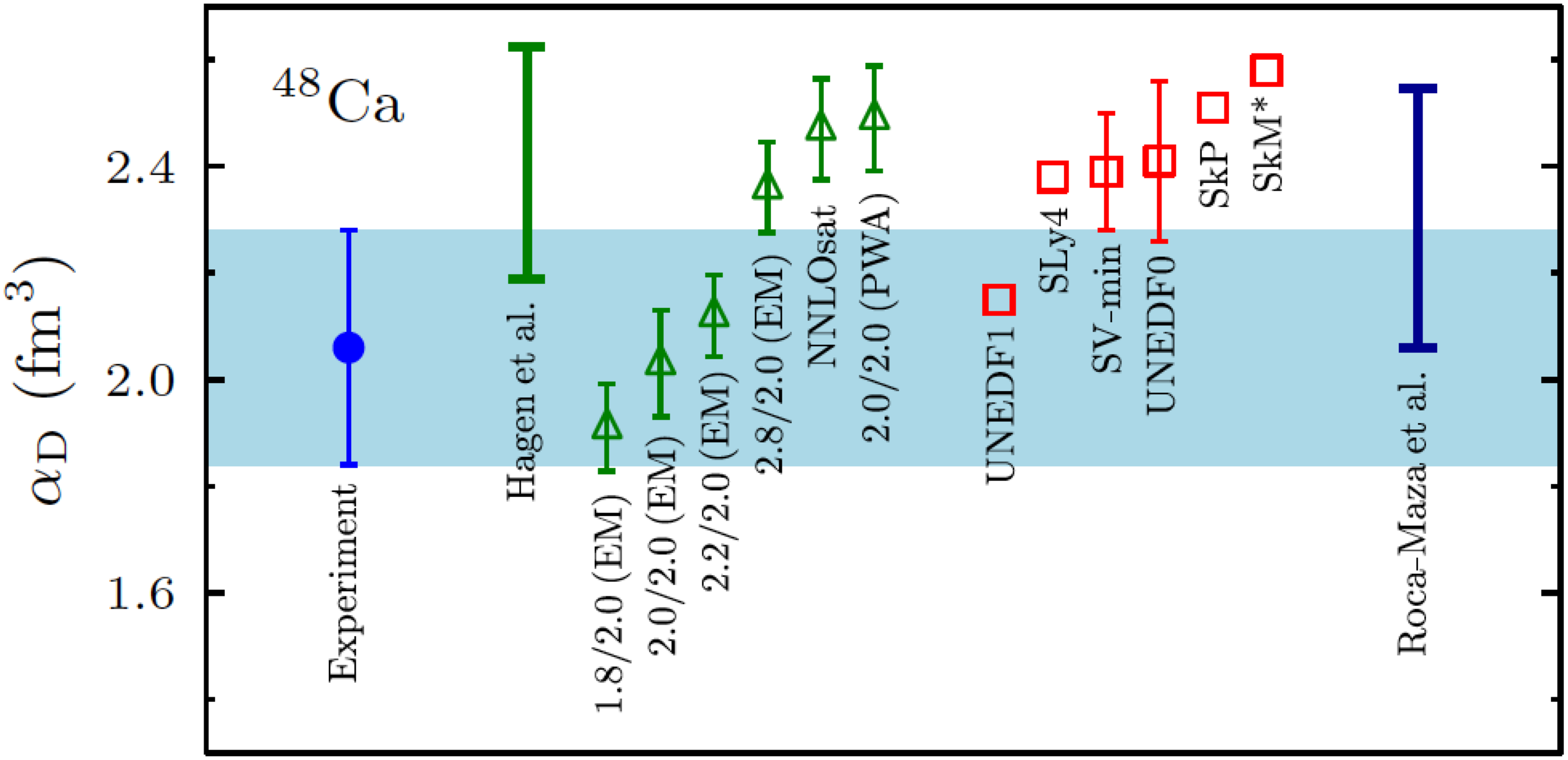
Experiment:
Tamii et al.,
PRL 107, 062502 (2011)

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

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

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

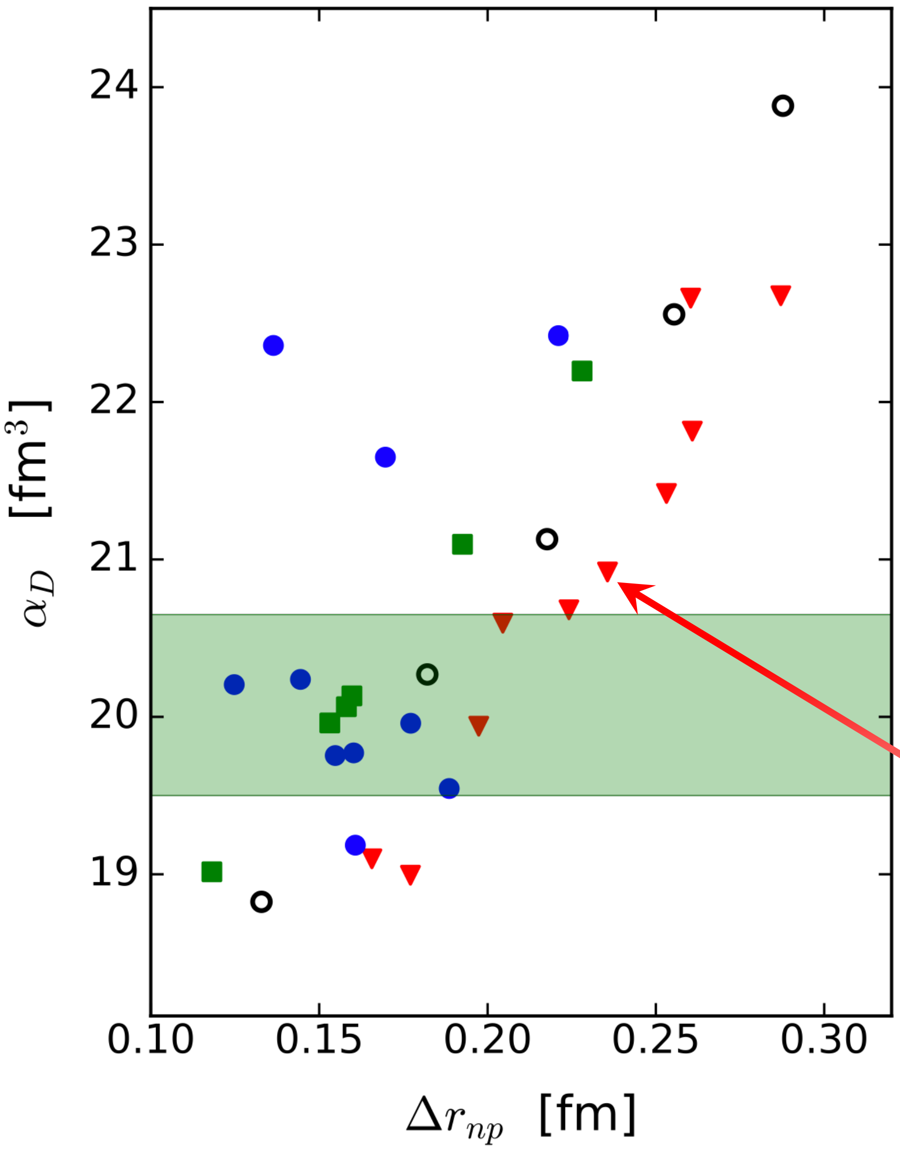
Dipole polarizability ^{48}Ca

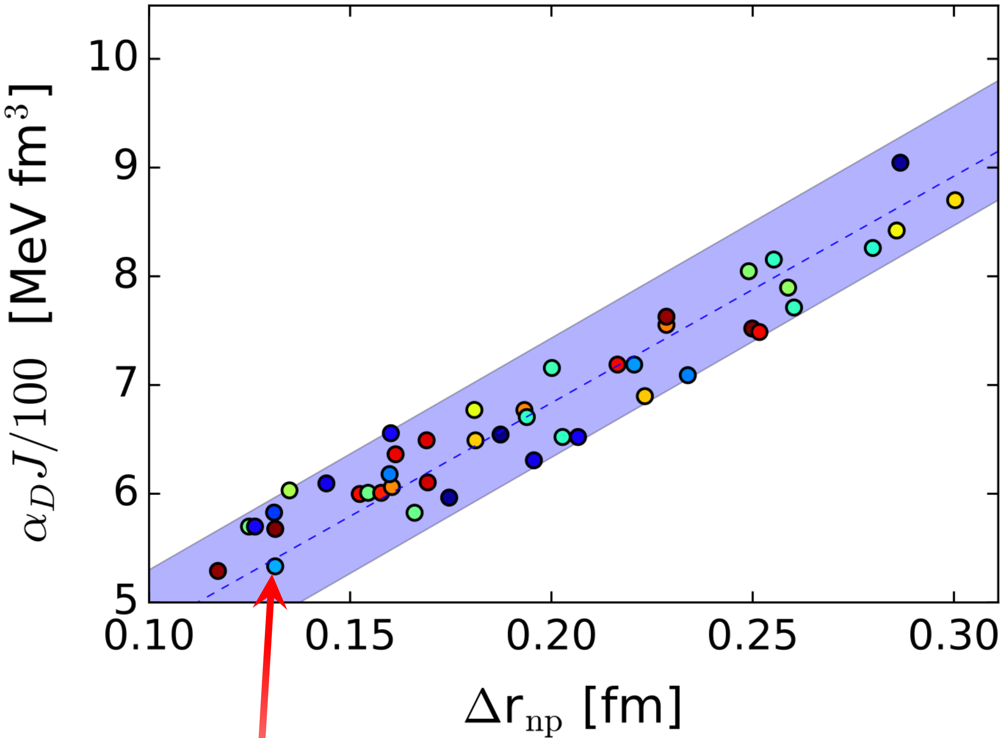


Experimental electric dipole polarizability in 48Ca (blue band) and predictions from EFT (green triangles) and χEDFs (red squares)

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

Dipole polarizability & neutron skin correlation rescaling





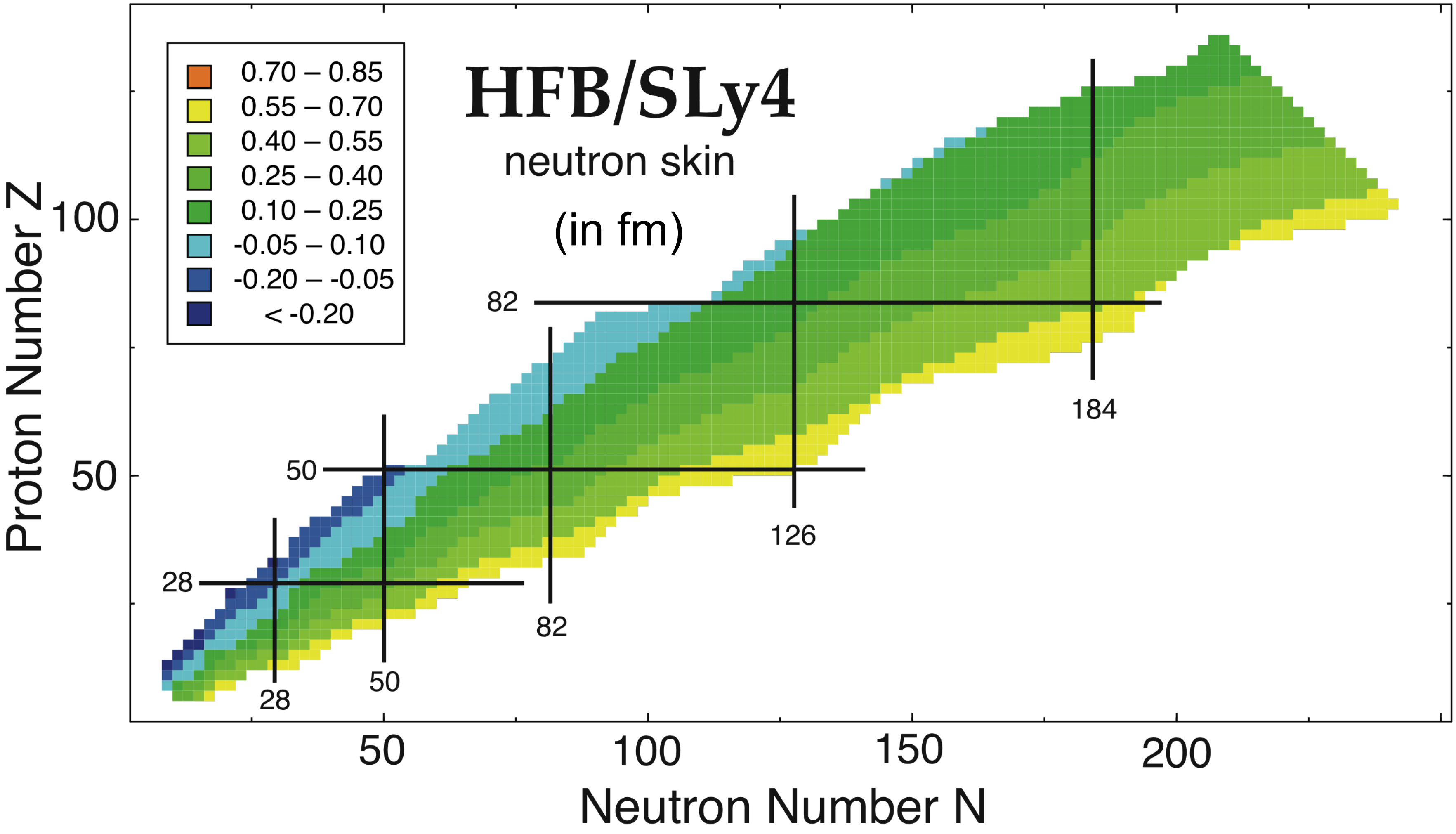
Numerous EDF

Roca-Maza, Paar, PNP 101, 96 (2018)

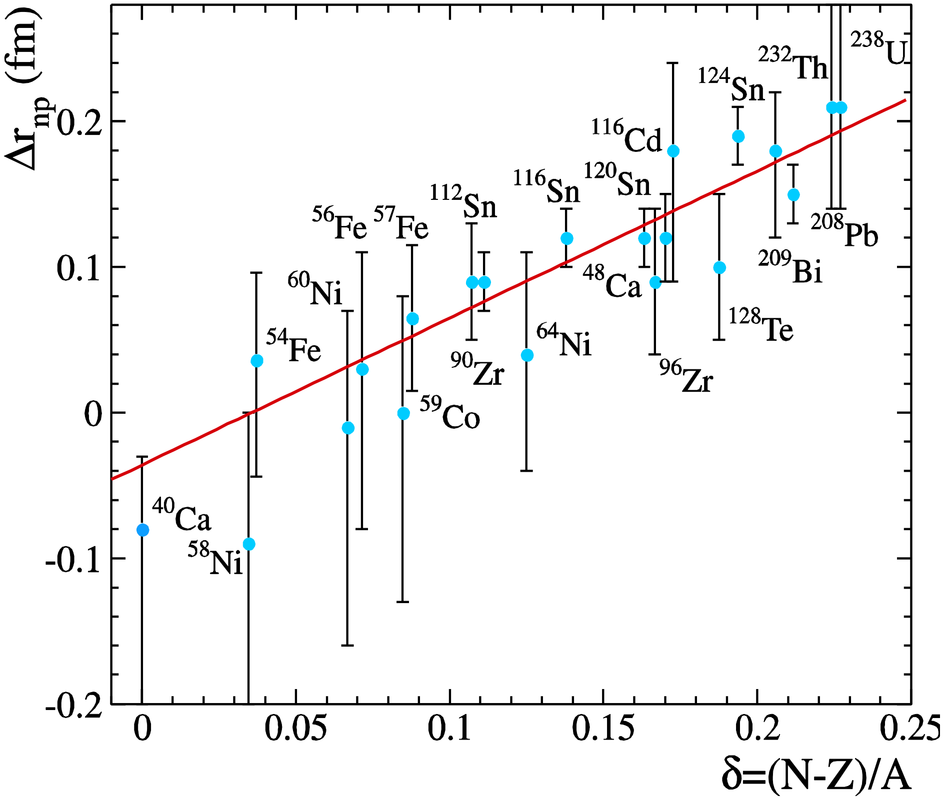
Aumann, CB, PPNP 112, 103753 (2020)

Neutron skin

Mizutori et al, PRC61, 044326 (2000)



Neutron skins measurements



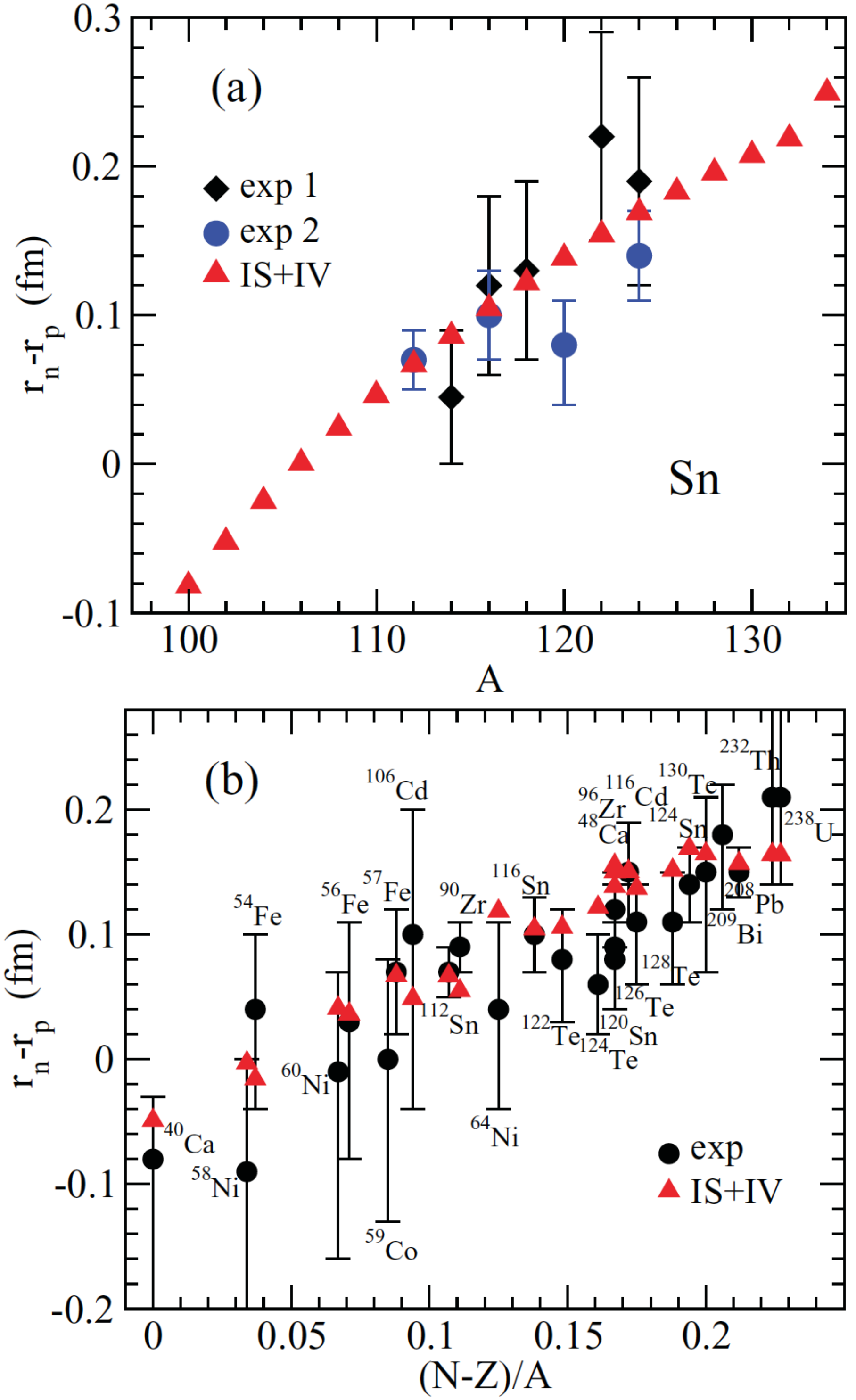
Radii from spin-dipole resonances

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

&

Antiprotonic atoms

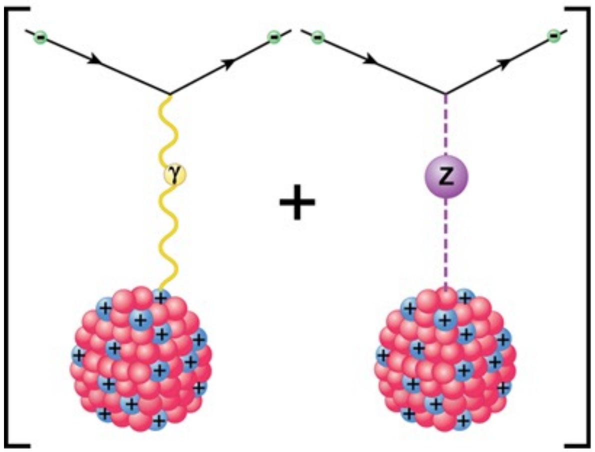
Trzcinskaet al., PRL 87, 082501 (2001)



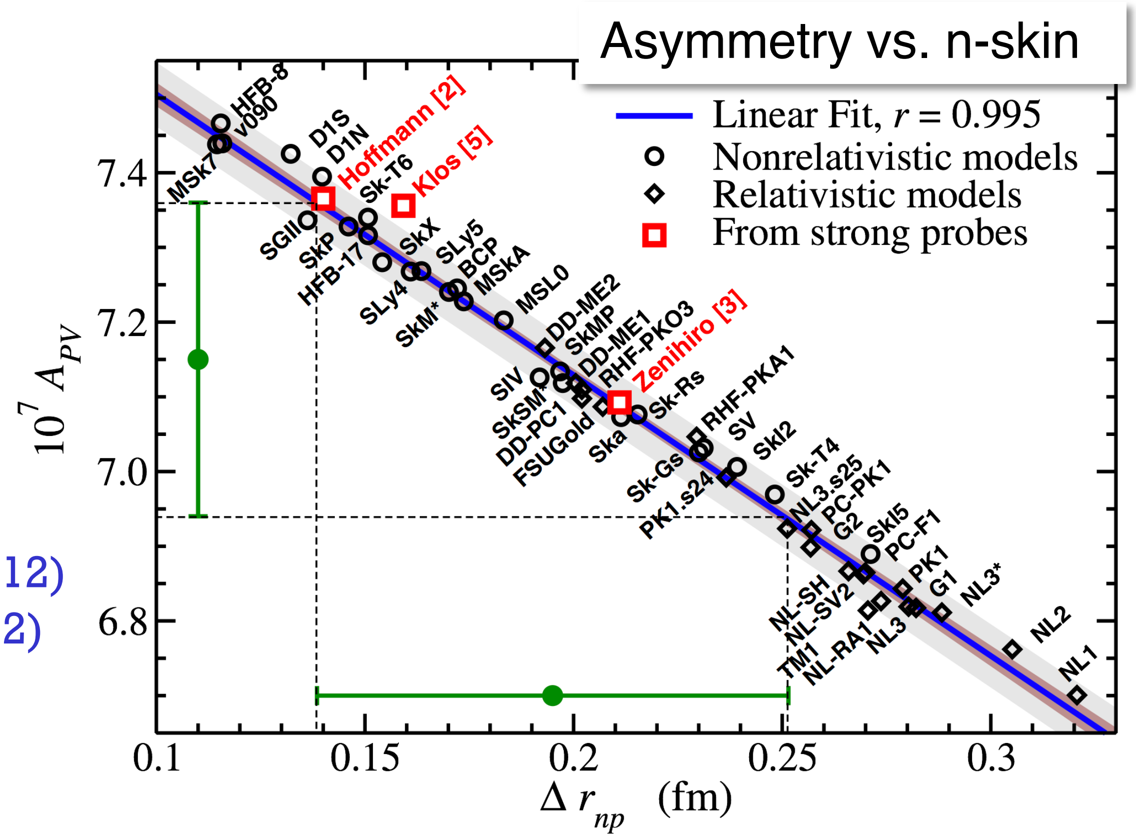
CB, Liu, Sagawa, PRC 85, 014321 (2012)

n-skin from PV e^- scattering

Roca-Maza, PRL (2011)



Abrahamyan et al, PRL 108, 112502 (2012)
Howowitz et al, PRC 85, 032501(R) (2012)



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

$$A_{PV}(Q^2) \sim \frac{G_F Q^2}{4\pi e^2 \sqrt{2}} \frac{F_W(Q)}{F_{ch}(Q)}$$

$$F_W = \frac{1}{Q_W} \int dr \frac{\sin(Qr)}{Qr} \rho_W(r)$$

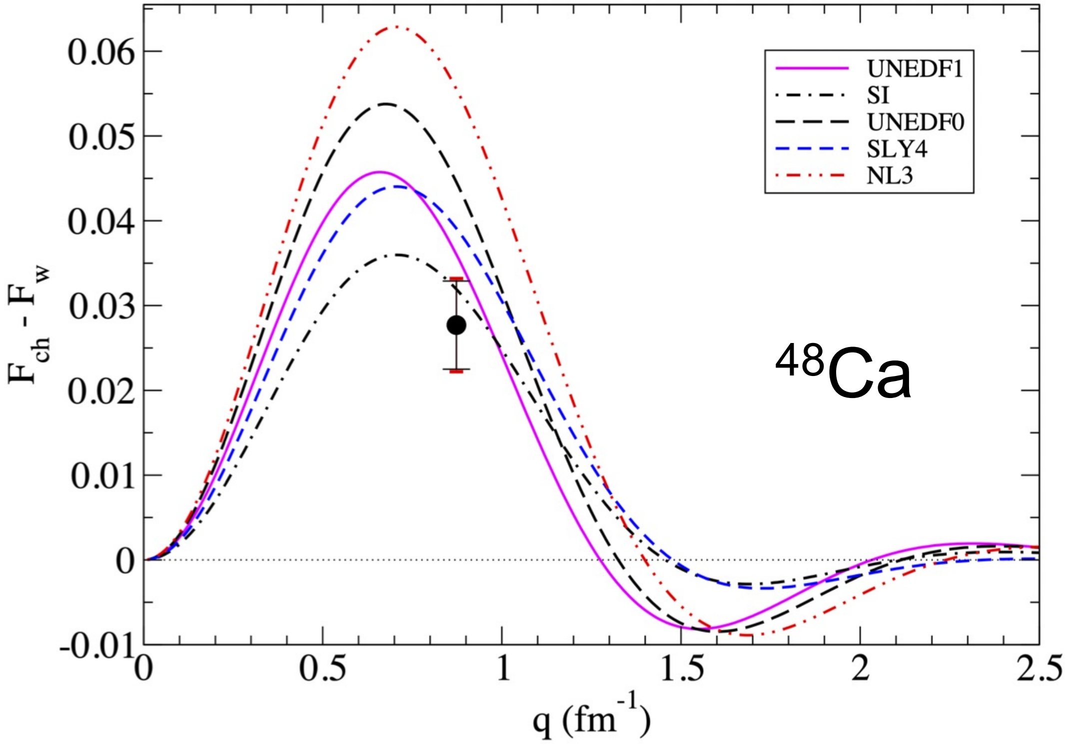
$$\rho_W(r) = q_p\, \rho_{ch}(r) + q_n \int d^3r' \left[G_E^p \rho_n + G_E^n \rho_p \right]$$

$$q_p = 0.0721, \qquad q_n = 0.0721,$$

n-skin from e$^-$ PV scattering ^{48}Ca

$$F(Q^2) \sim 1 - \frac{1}{6} q^2 \langle r^2 \rangle$$

$$\langle r^2 \rangle \cong -6 \frac{dF(Q^2)}{dQ^2}$$

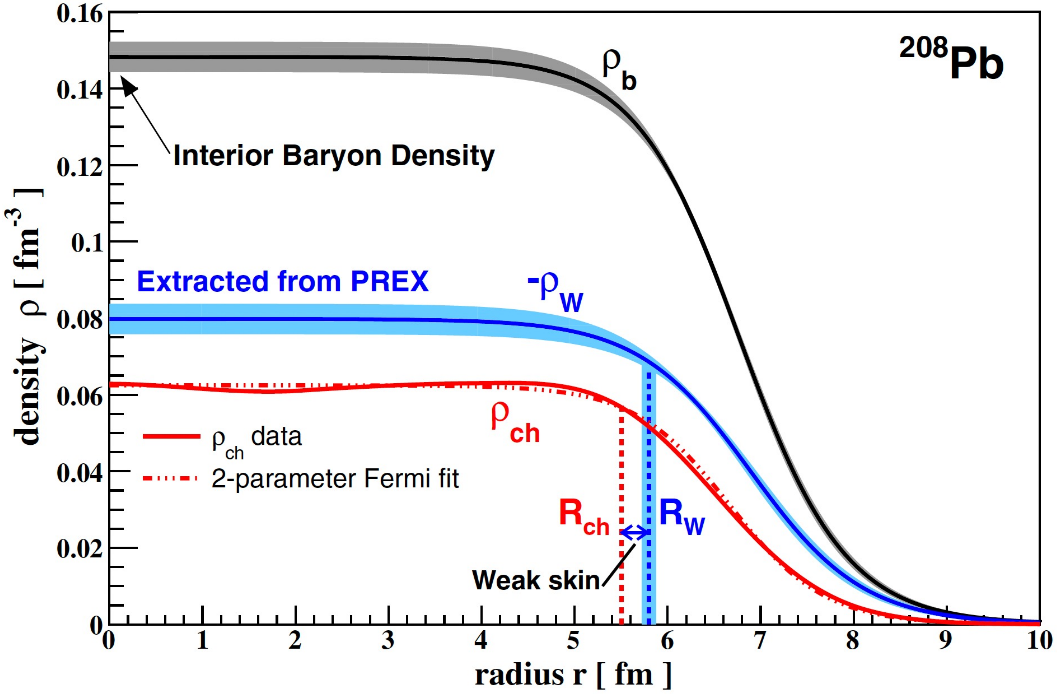


- ○ PREX: measurement of parity violating asymmetry
- ○ Determine n-skin and/or L by comparison to predictions from DFT

$$(R_n - R_p)_{48Ca} = 0.121 \pm 0.025 \text{ fm}$$

Adhikari et al, arXiv:2205.11593 (2022)

n-skin from e$^-$ scattering ^{208}Pb



- PREX: measurement of parity violating asymmetry
- Determine n-skin and/or L by comparison to predictions from DFT

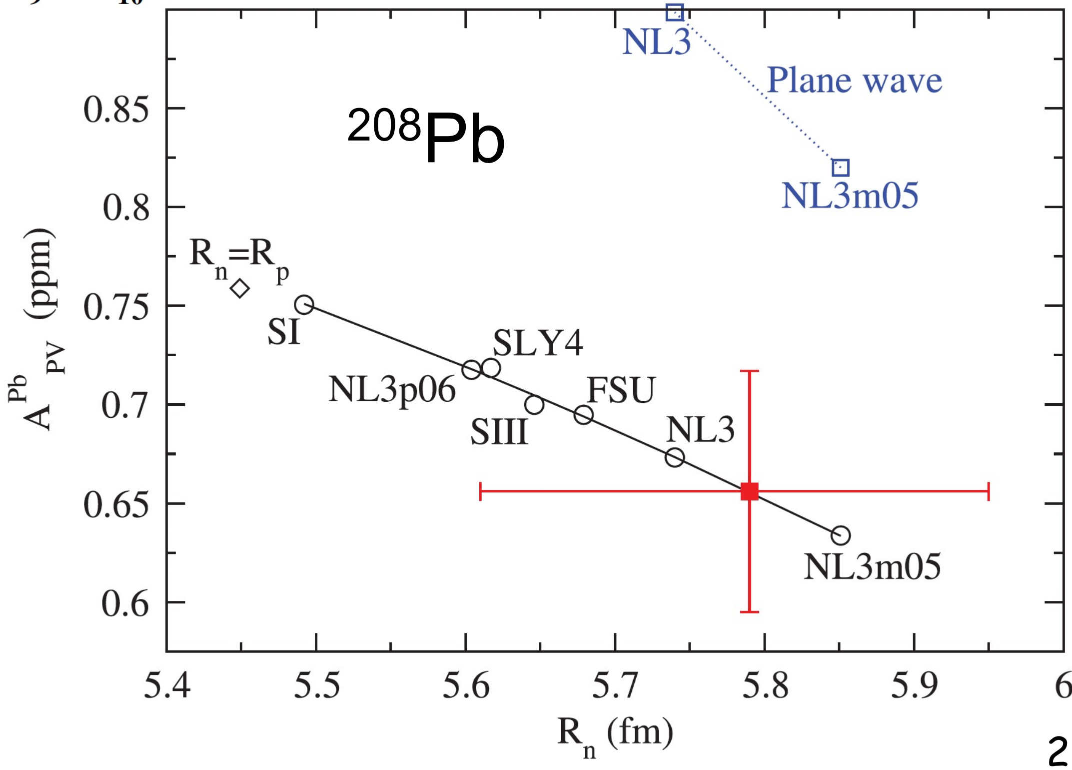
R_n - R_p = 0.33 ± 0.17 fm

Adhikari et al, PRL 126, 172502 (2021)

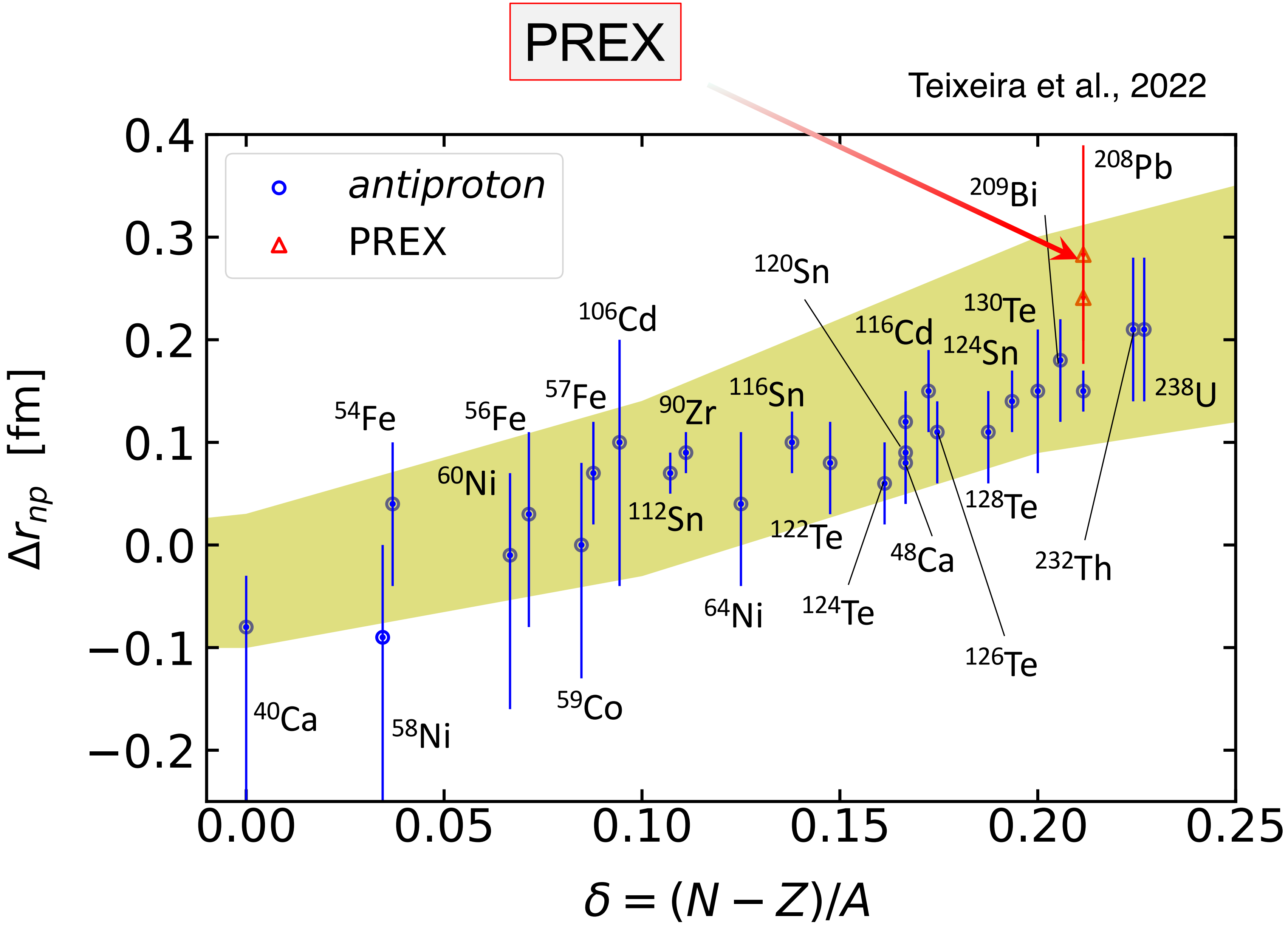
very large value

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

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



Compilation of neutron skins

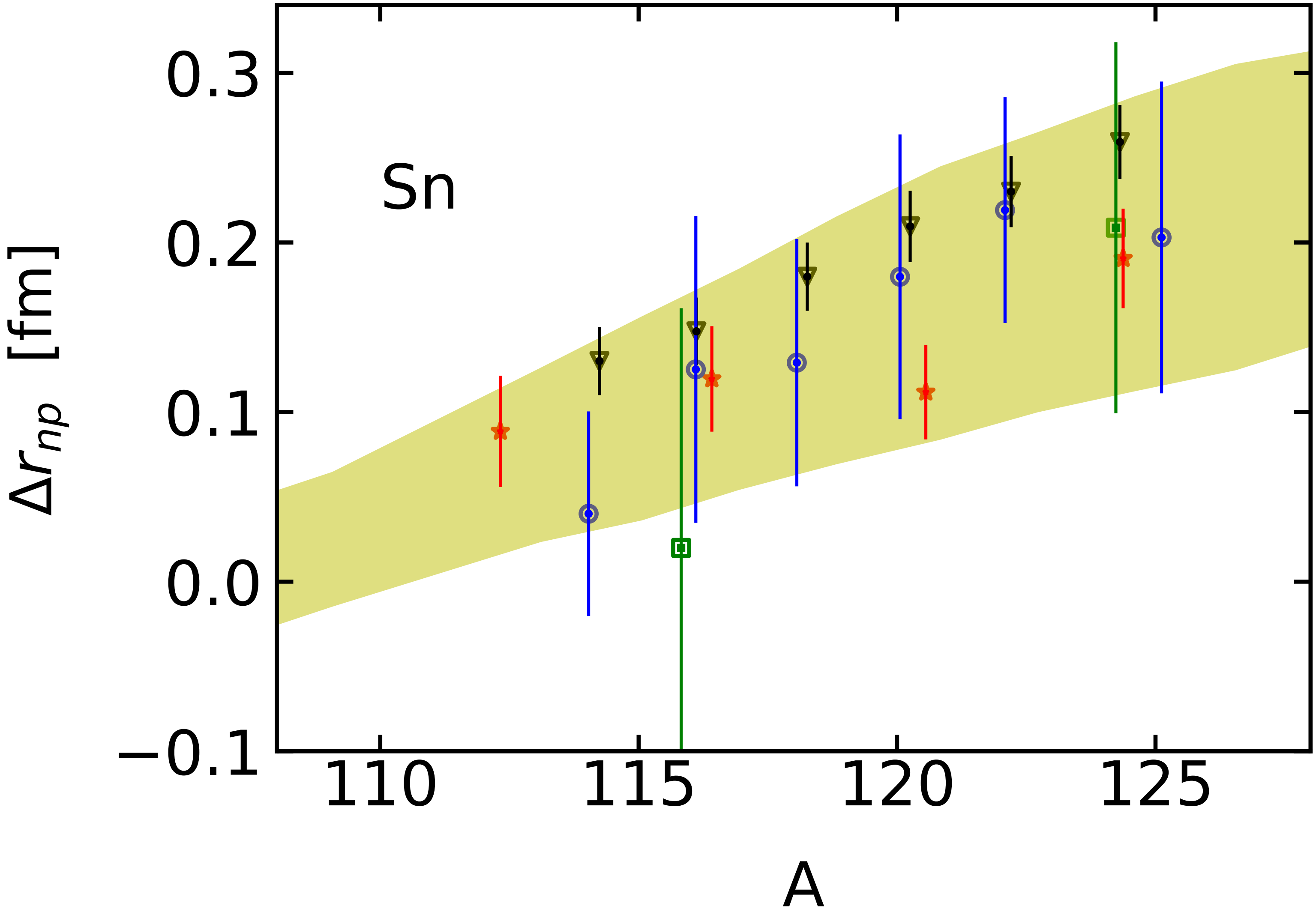


Teixeira et al., 2022

Shaded band: 23 Sky HF + 6 RMF predicitons

Compilation of neutron skins

Teixeira et al., 2022



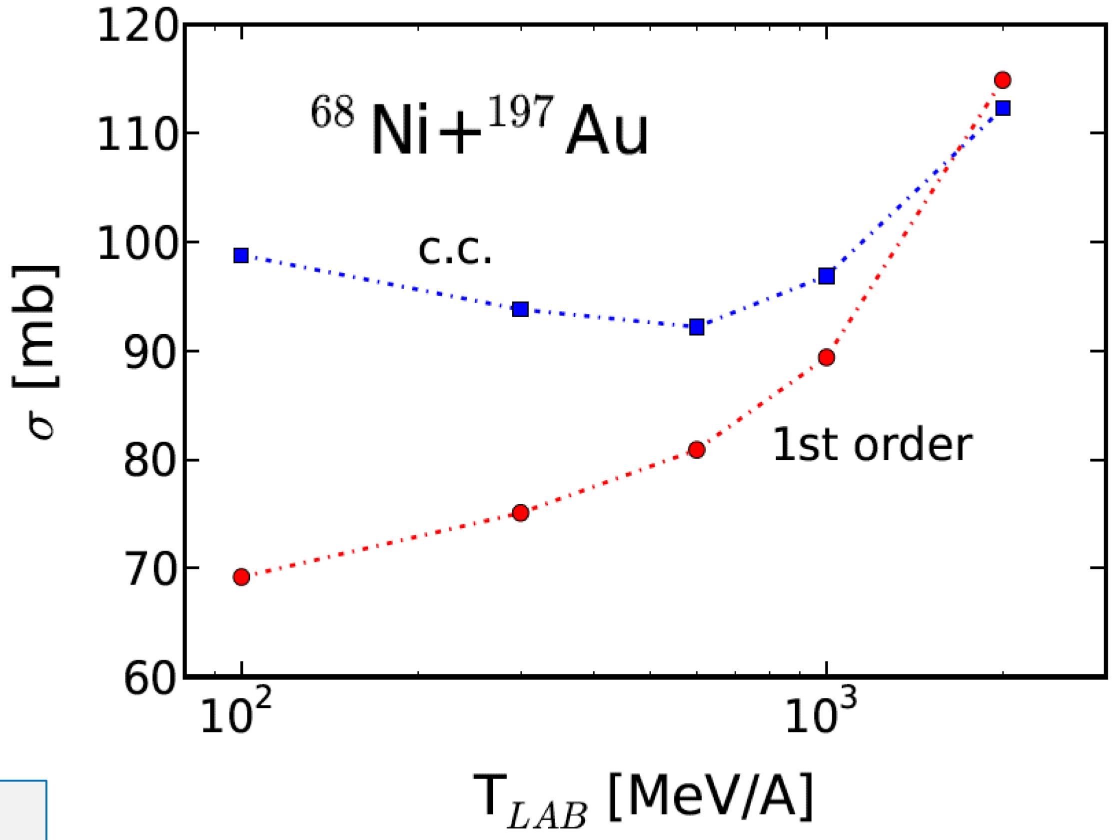
Shaded band: 23 Sky HF + 6 RMF predicitons

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, CB, 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

New proposal: Peeling off neutrons

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

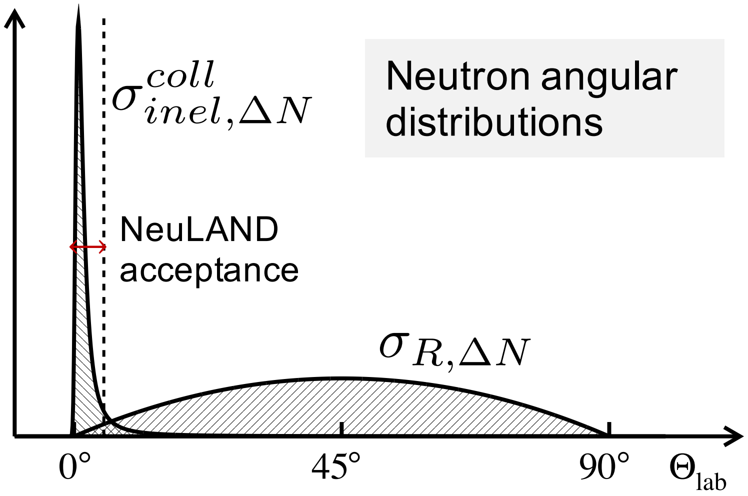
$$P_p(b) = \int dz\, d^2s\, \rho_p^P(\mathbf{s},z) \exp\left[-\sigma_{pp} Z_T \int d^2s \rho_p^T(\mathbf{b}-\mathbf{s},z) - \sigma_{pn} N_T \int d^2s \rho_n^T(\mathbf{b}-\mathbf{s},z)\right]$$

Experiment (4 independent measurements):

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

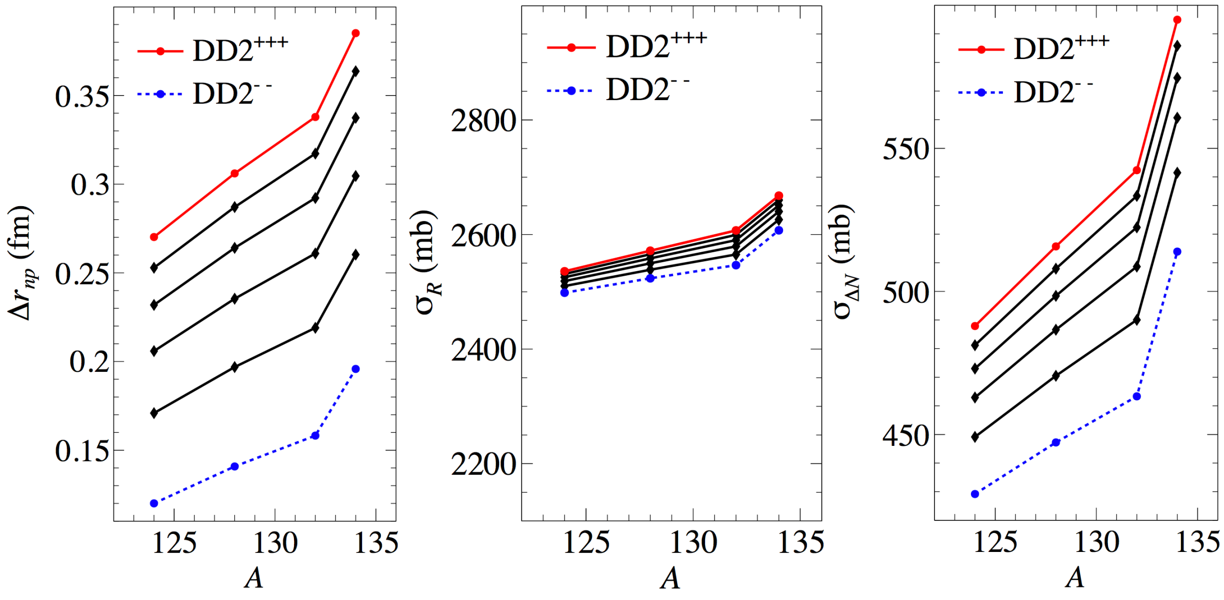
Aumann, Bertulani, Schindler, Typel
PRL 119, 262501 (2017)

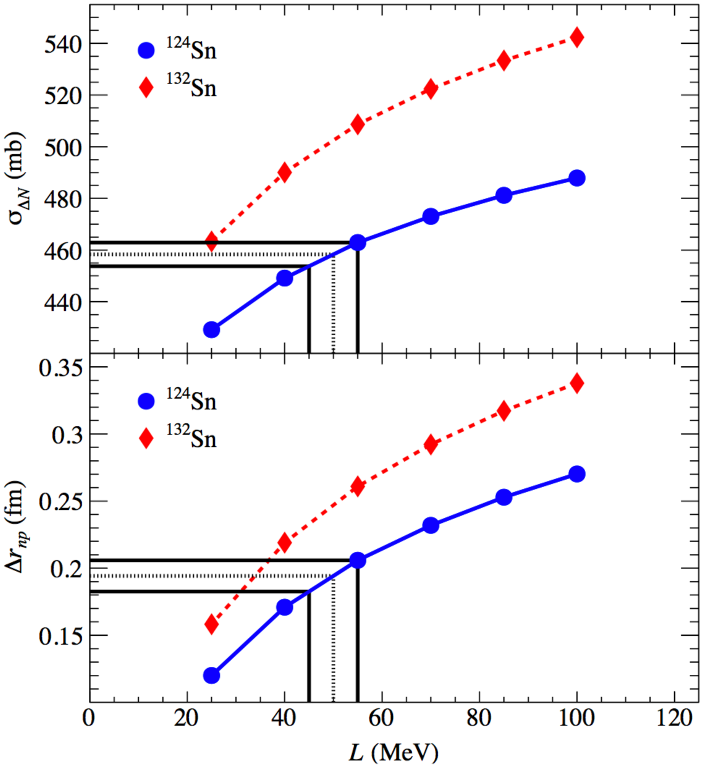
σ_{inel} ⇒ Relation $\sigma_{\Delta N} \leftrightarrow L$


Neutron angular distributions

n-removal cross section: n-skin and L

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



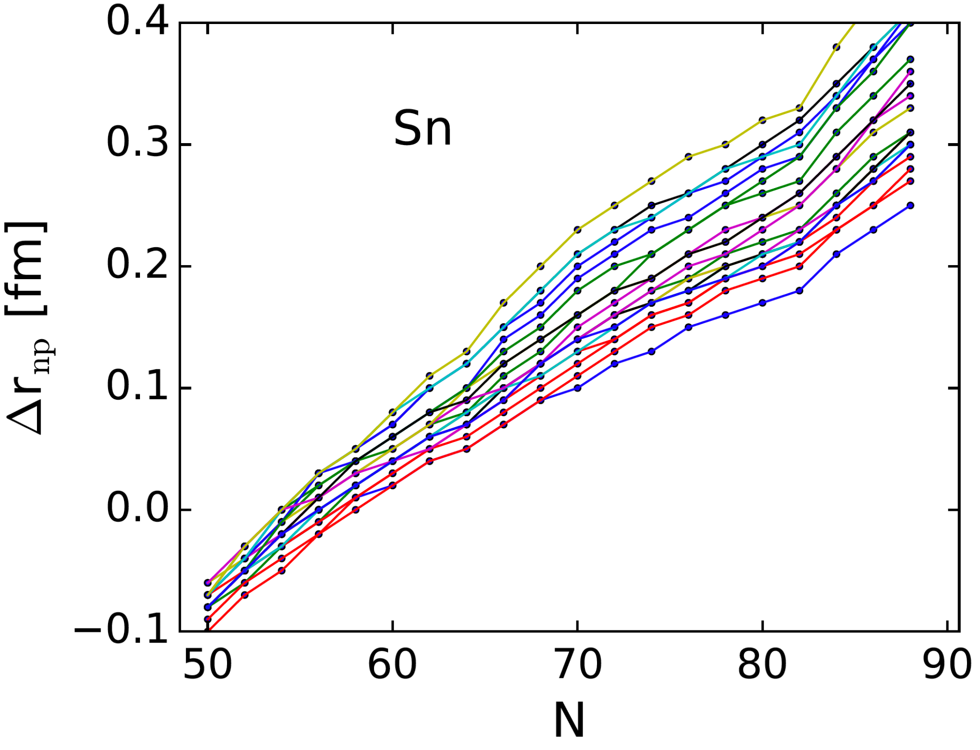


- n-skin changes by 0.19 fm for ^{132}Sn
- Total reaction cross section changes only by 2.5% !
- Total neutron-removal cross section changes by 20% !

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

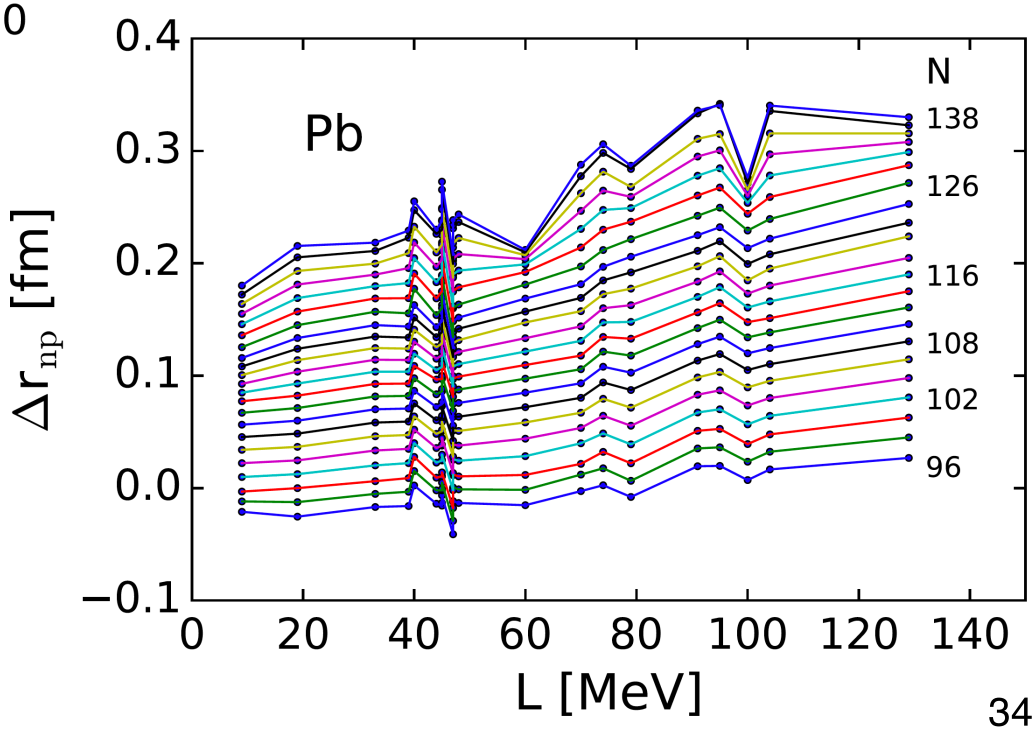
  → σ_{DN} very sensitive, limit given by DFT predictions reached
- Relation of σ_{DN} with L or Δr_{np} needs good reaction theory

Neutron skin and fragmentation reactions



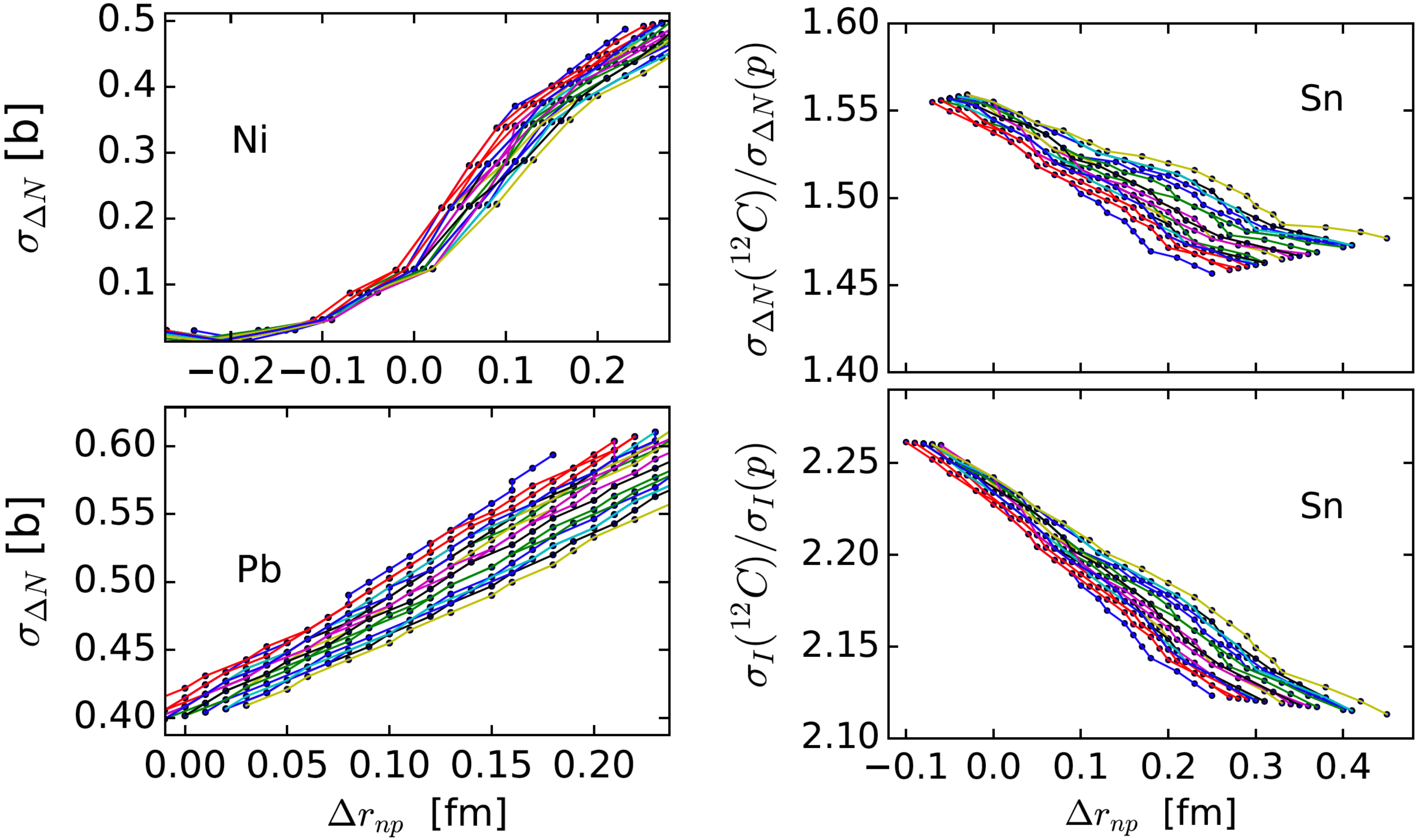
Points = different Skyrme interactions

→ different values of L



CB, Valencia,
PRC 100, 015802 (2019)

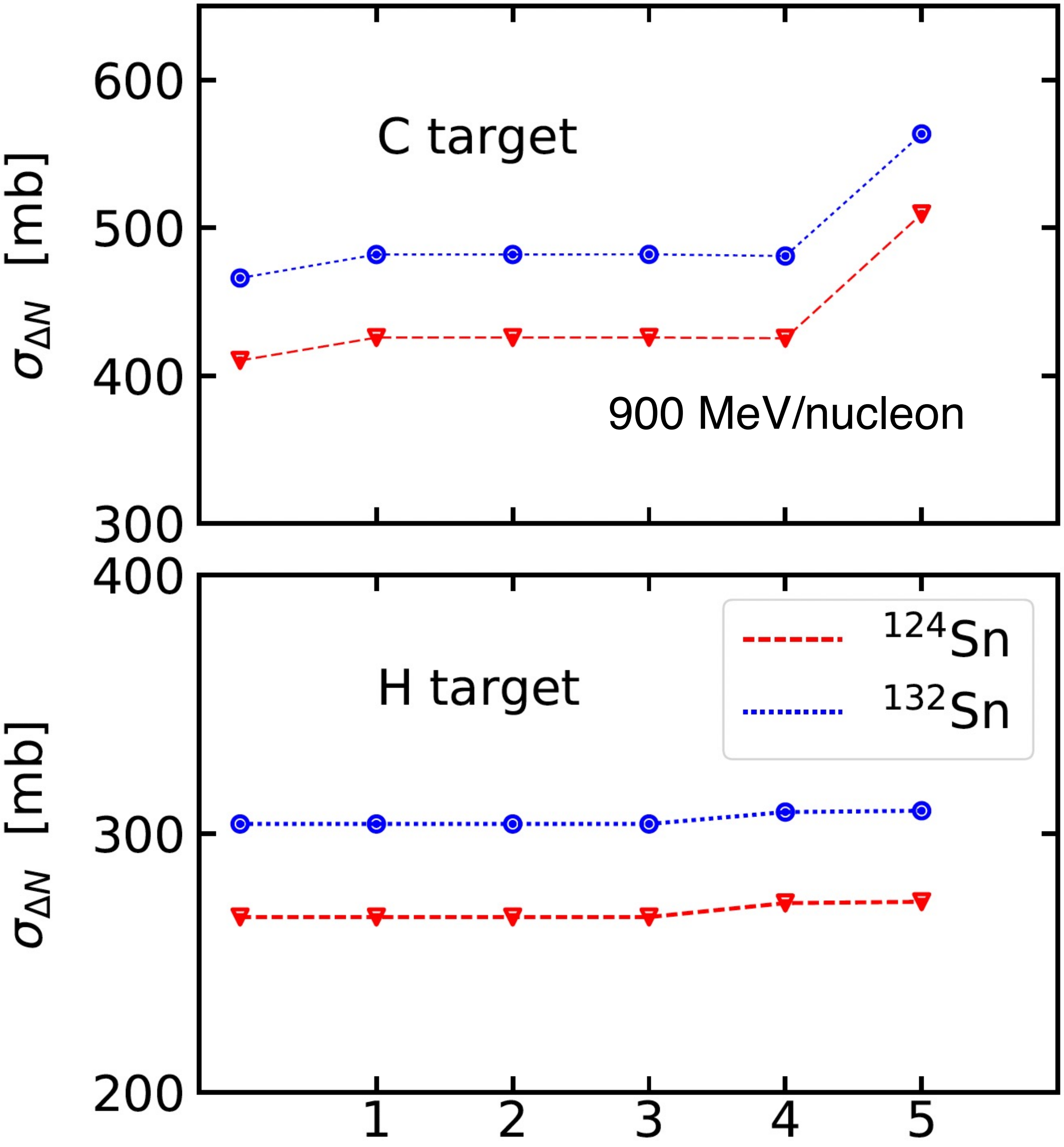
Neutron skin and fragmentation reactions



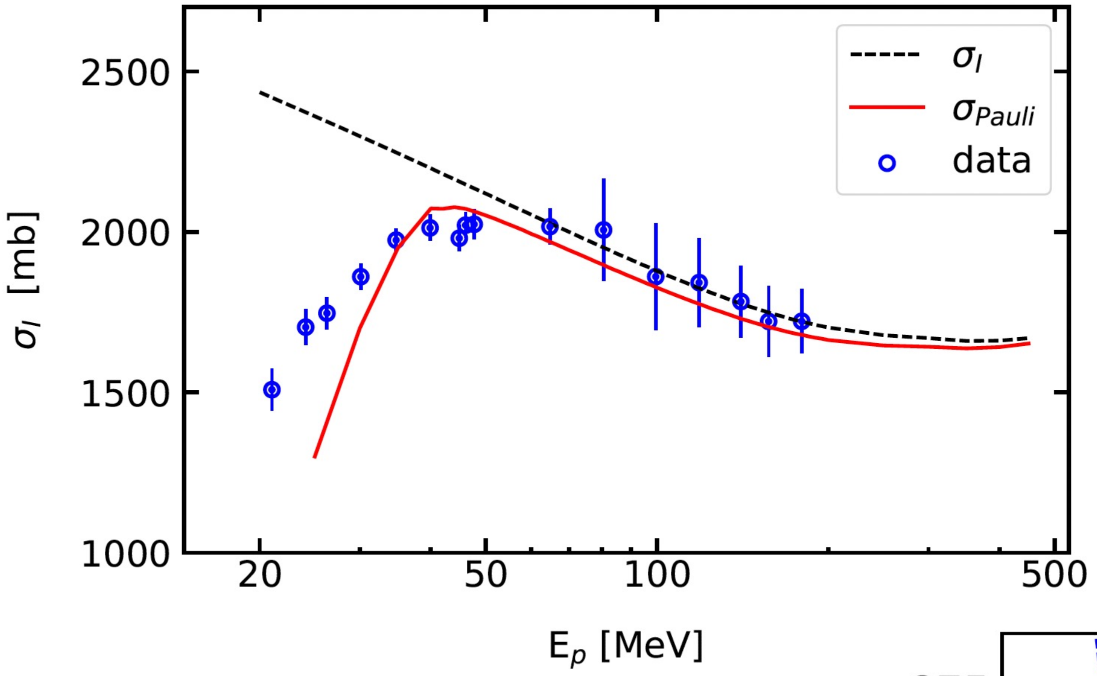
Corrections of Glauber calculations

Texeira, Aumann, CB, Carlson (2012)

- Fermi motion (1)
- Coulomb distortion (2)
- Higher order corrections of eikonal scattering waves (3)
- Medium corrections of NN cross sections (4)
- Excitation of GRs (5)

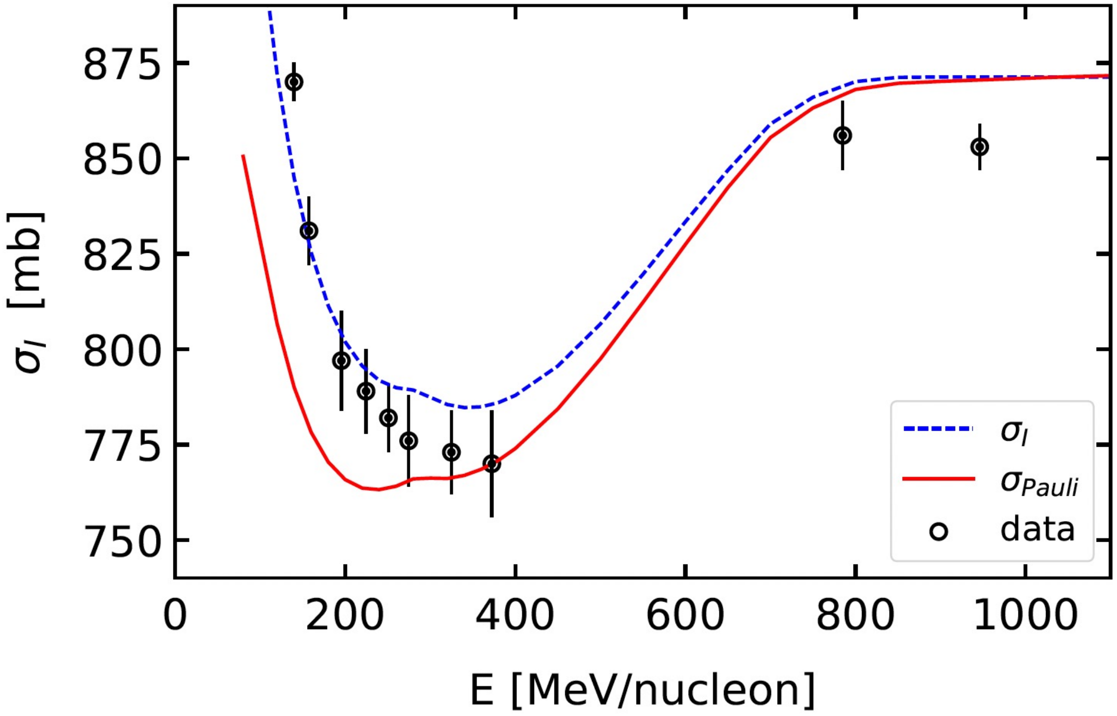


Comparison with existing data

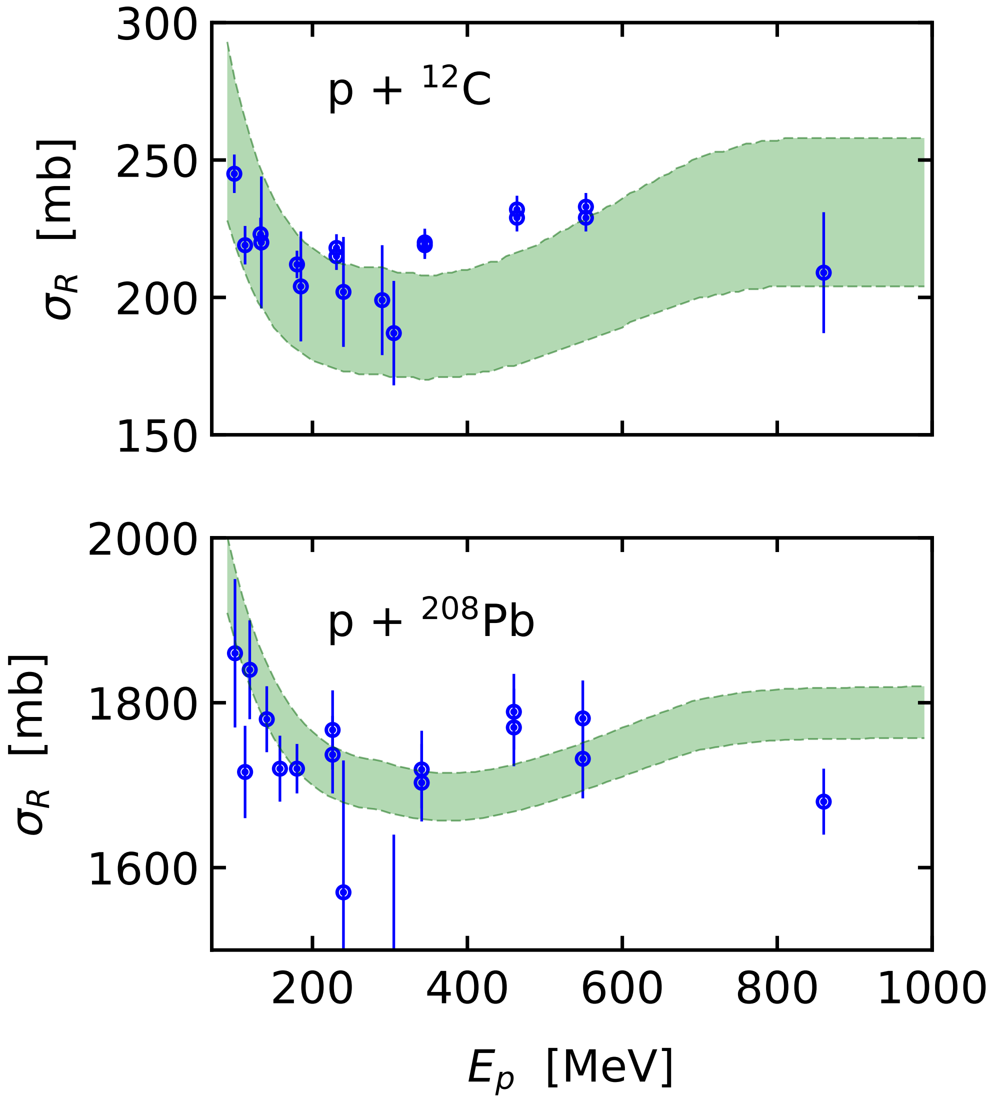


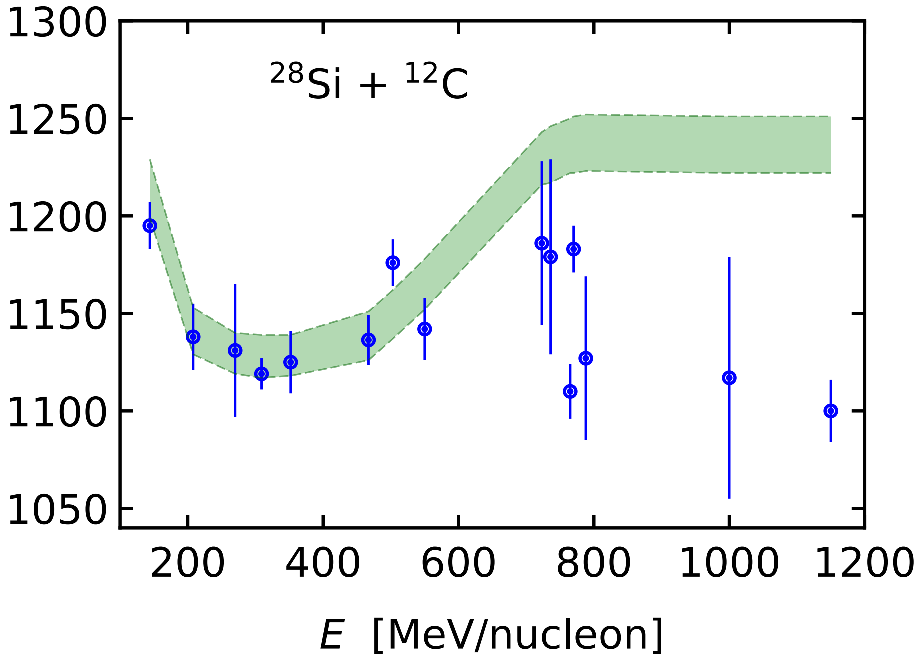
Medium corrections still poorly understood.

Good description of interaction cross sections only possible with introduction of poorly understood parametrizations.

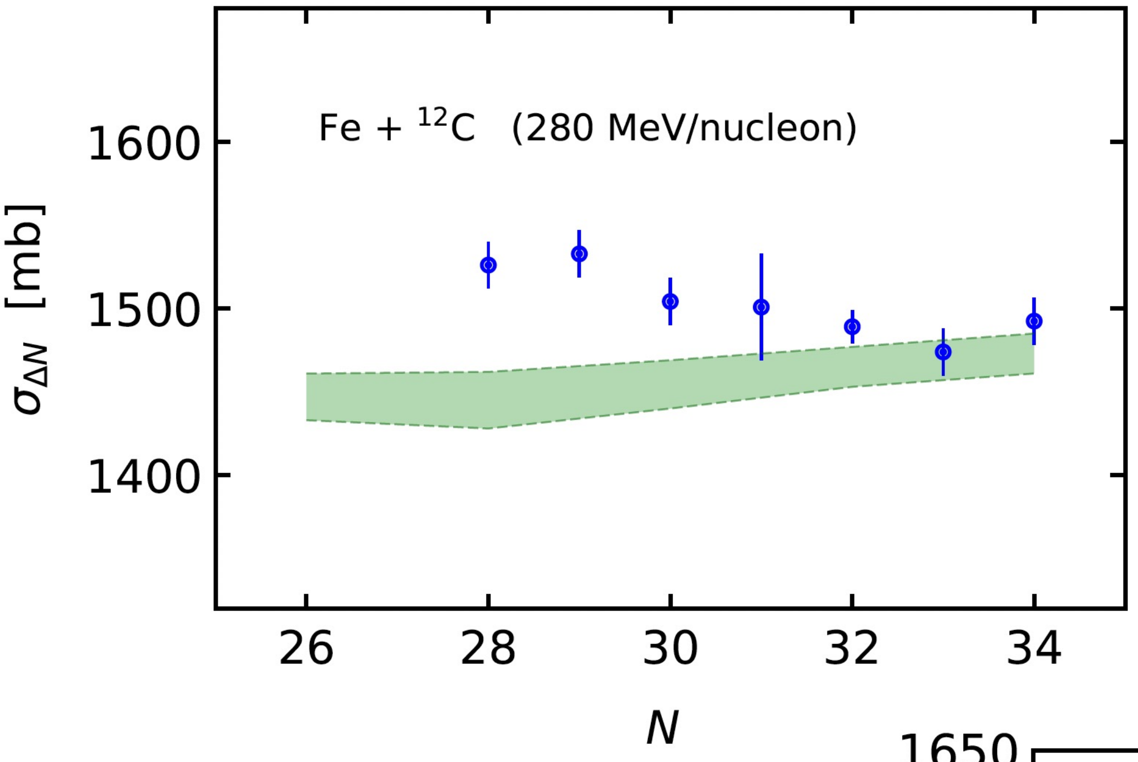


Comparison with existing data





Shaded band:
23 Sky HF + 6 RMF predicitons



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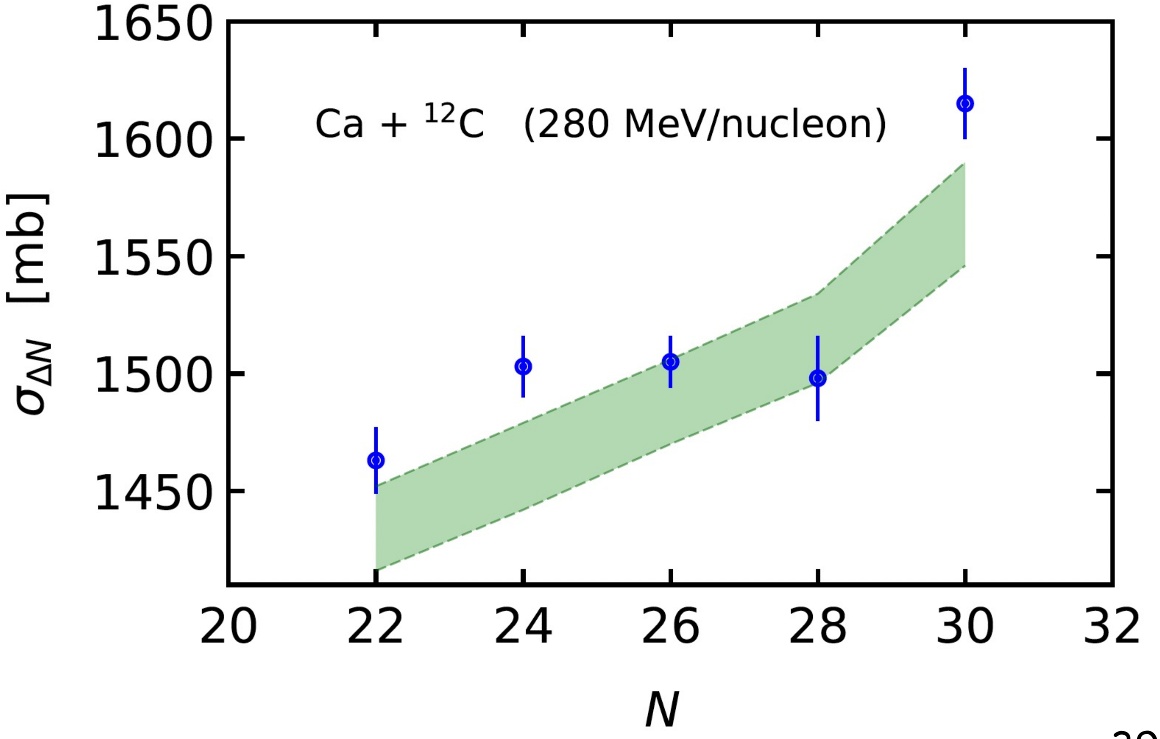
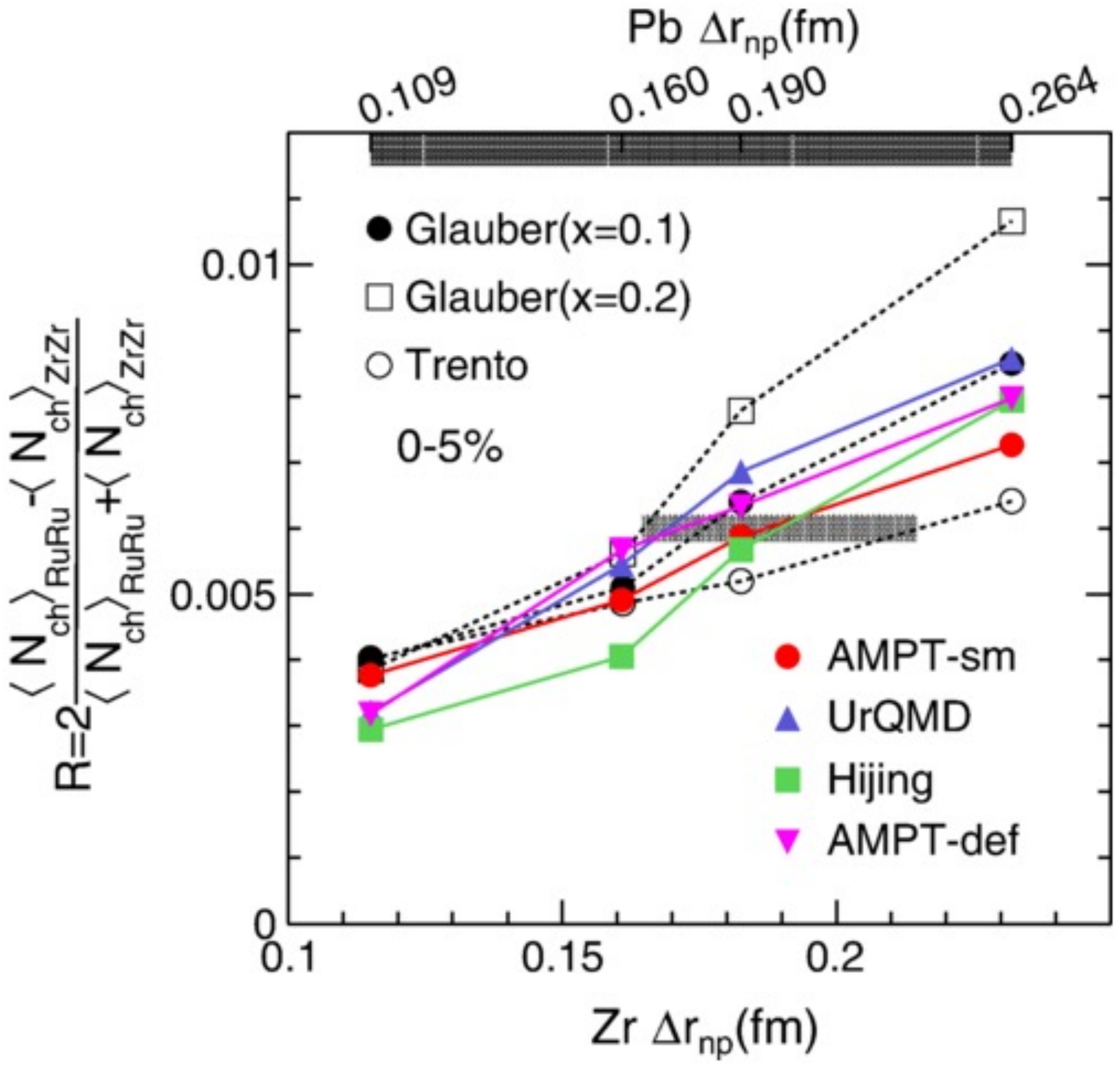


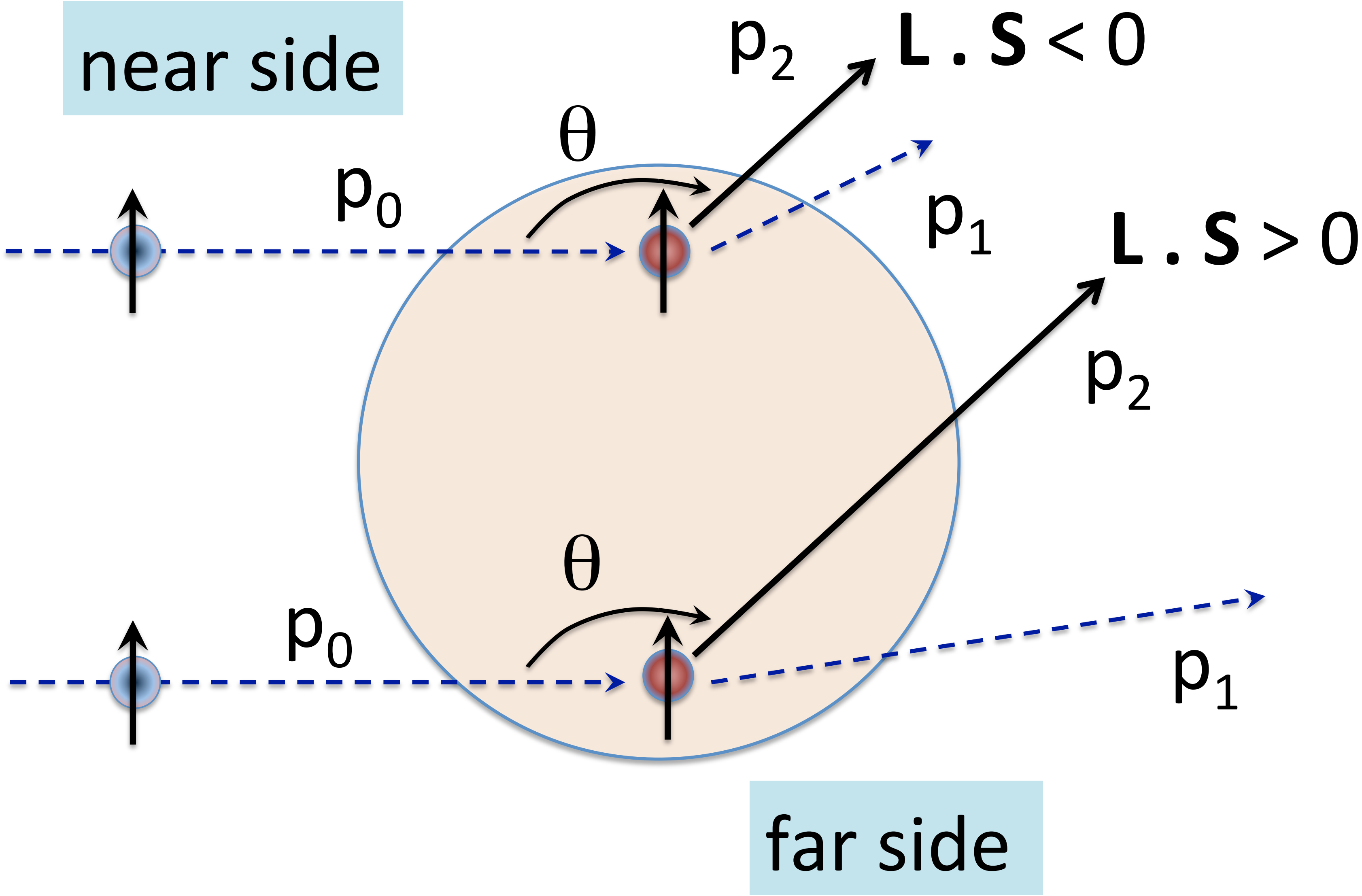
New proposal: charged particle multiplicity



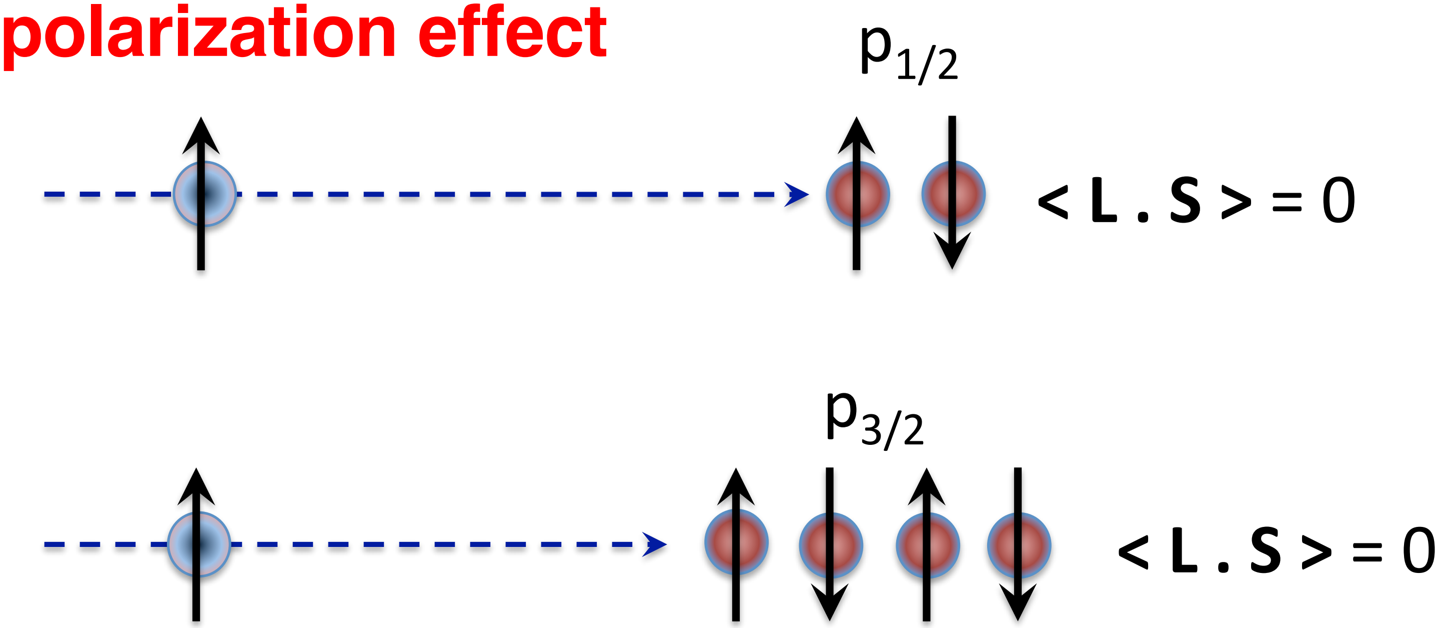
Lc20, SLy4, Lc47, Lc70 densities

Hanlin Li, et al., Phys. Rev. Lett. 125, 222301 (2020)

New proposal: (p,2p) Maris polarization effect



Maris polarization effect



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

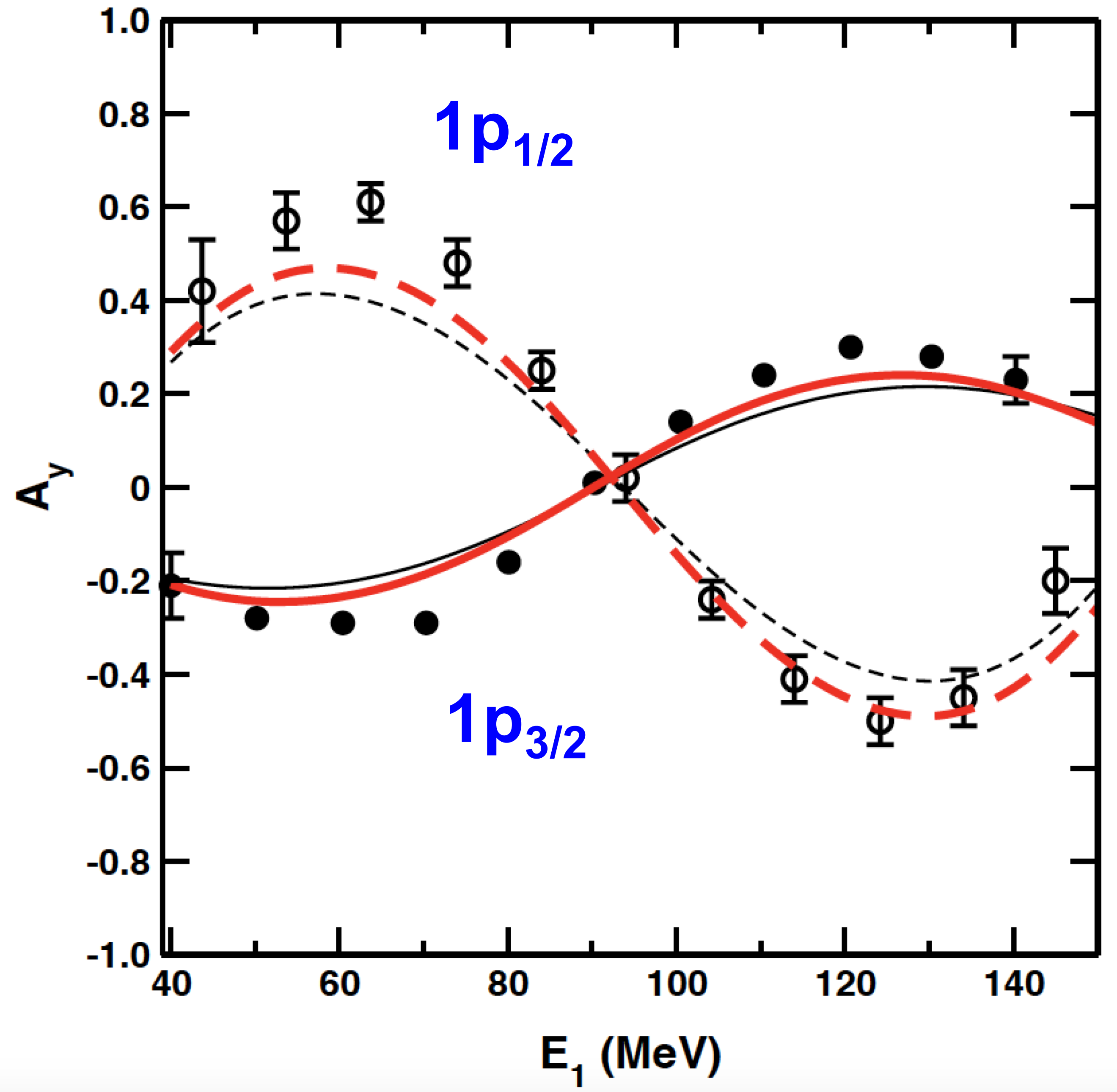
⇨ Scattering asymmetries (twice larger for $p_{3/2}$)

+ **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)

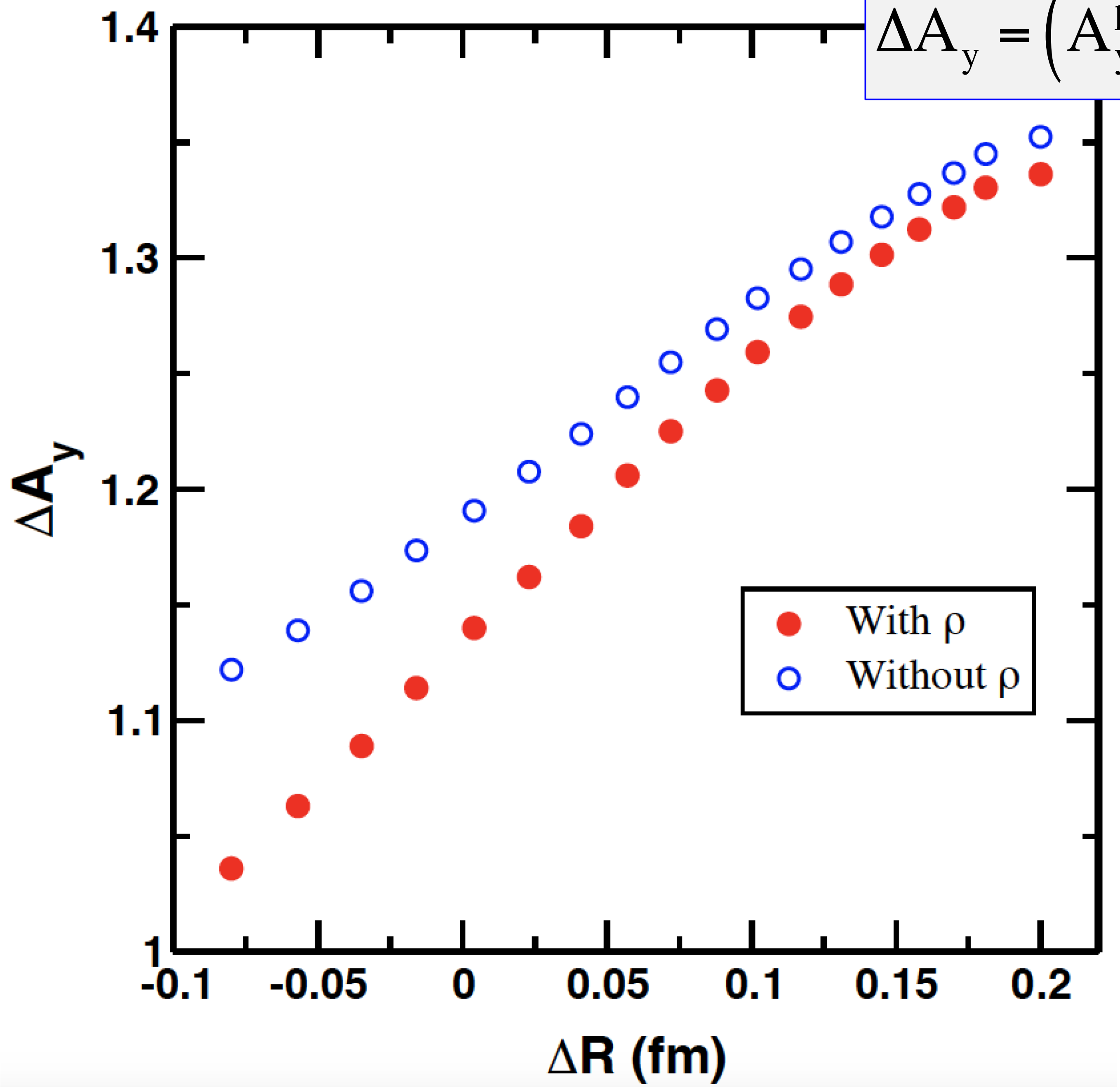
→ $P_{eff} \sim \text{const} \times A_y$

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

thick lines = full
thin lines = no r

Maris polarization and neutron skins

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



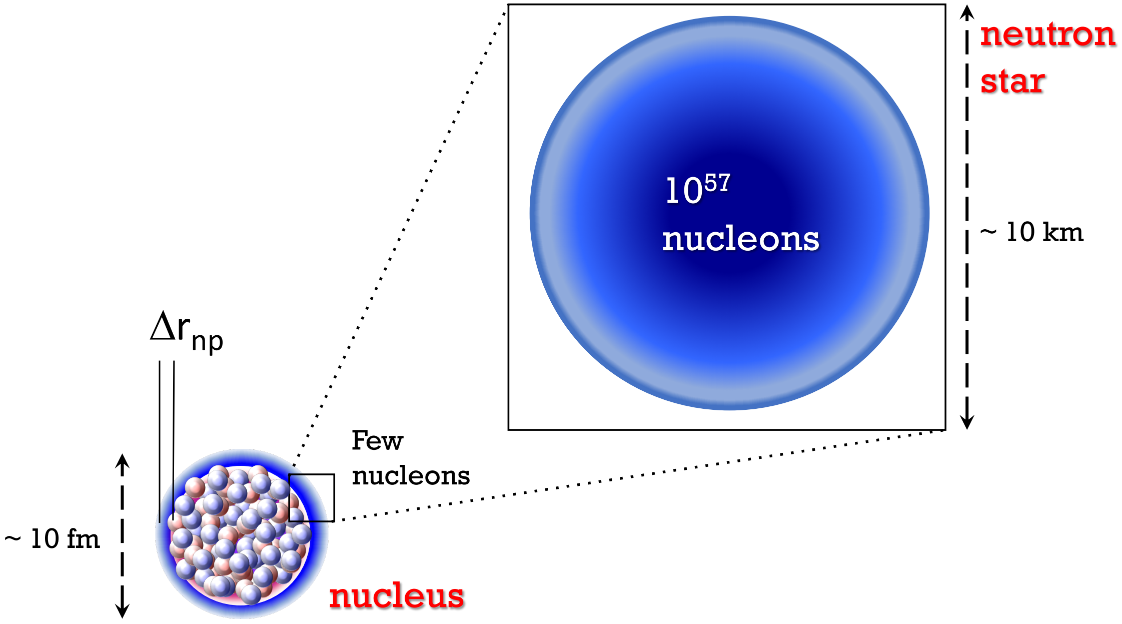
(p,2p) on Sn isotopes at 200 MeV/nucleon

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

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

Summary

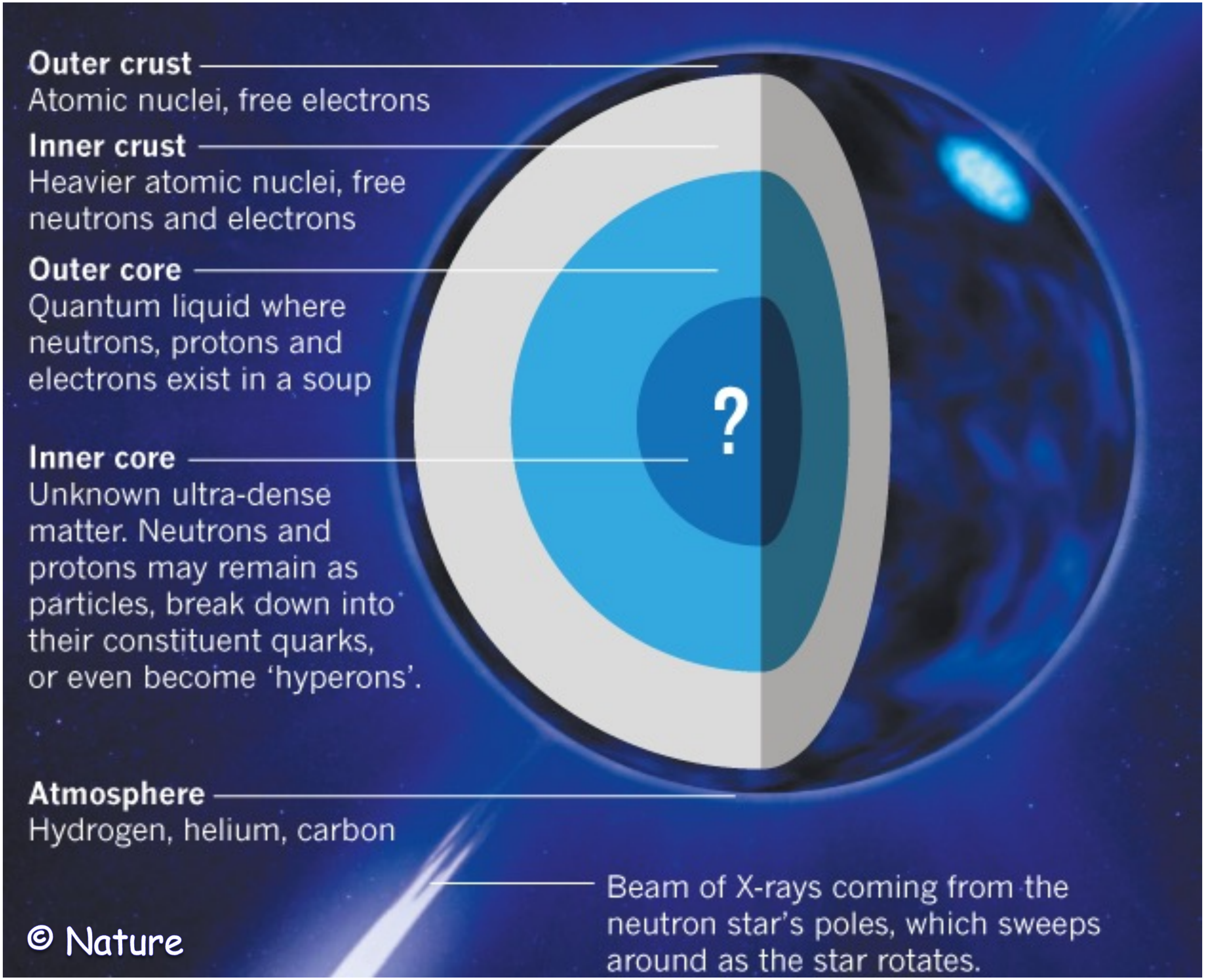
Skins, halos, pygmies,
and neutron stars



- Halos ←→ pygmy
- Heavier nuclei → skins → pygmy → symmetry energy
- PV term in electron scattering → skins → symmetry energy
- Other probes necessary:
  Nuclear fragmentation
  Polarization probes in hadronic scattering

Work in progress

Inside a neutron star



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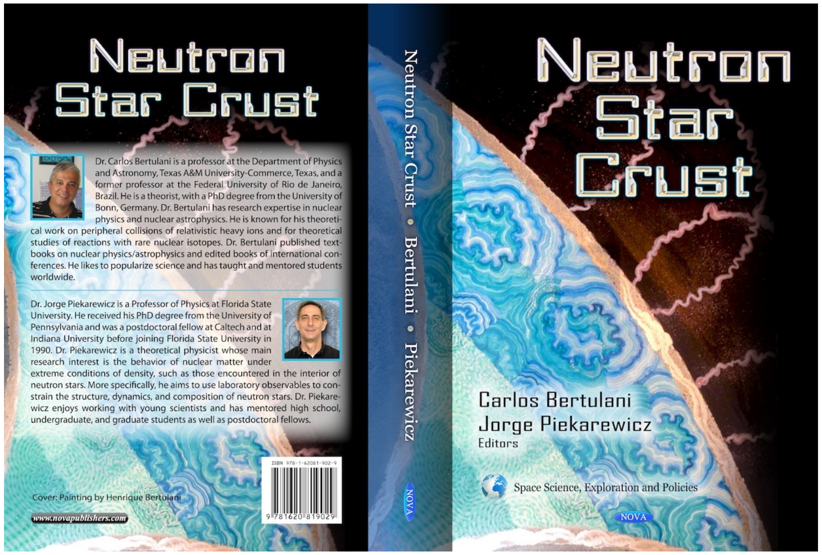
Neutron stars in a nutshell

- 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)

Jocelyn Bell

Jocelyn Bell in Commerce, TX, USA, 2010

Neutron Star Crust: (preface by Jocelyn Bell)



Neutron Star Crust

Dr. Carlos Bertulani is a professor at the Department of Physics and Astronomy, Texas A&M University-Commerce, Texas, and a former professor at the Federal University of Rio de Janeiro, Brazil. He is a theorist, with a PhD degree from the University of Bonn, Germany. Dr. Bertulani has research expertise in nuclear physics and nuclear astrophysics. He is known for his theoretical work on peripheral collisions of relativistic heavy ions and for theoretical studies of reactions with rare nuclear isotopes. Dr. Bertulani published textbooks on nuclear physics/astrophysics and edited books of international conferences. He likes to popularize science and has taught and mentored students worldwide.

Dr. Jorge Piekarewicz is a Professor of Physics at Florida State University. He received his PhD degree from the University of Pennsylvania and was a postdoctoral fellow at Caltech and at Indiana University before joining Florida State University in 1990. Dr. Piekarewicz is a theoretical physicist whose main research interest is the behavior of nuclear matter under extreme conditions of density, such as those encountered in the interior of neutron stars. More specifically, he aims to use laboratory observables to constrain the structure, dynamics, and composition of neutron stars. Dr. Piekarewicz enjoys working with young scientists and has mentored high school, undergraduate, and graduate students as well as postdoctoral fellows.

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Neutron Star Crust

Carlos Bertulani
Jorge Piekarewicz
Editors

Space Science, Exploration and Policies

NOVA

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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

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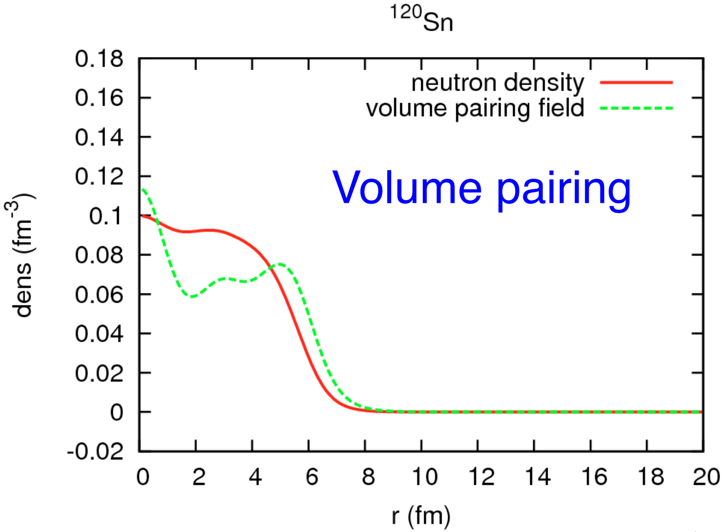
[*] j.bellburnell@physics.ox.ac.uk

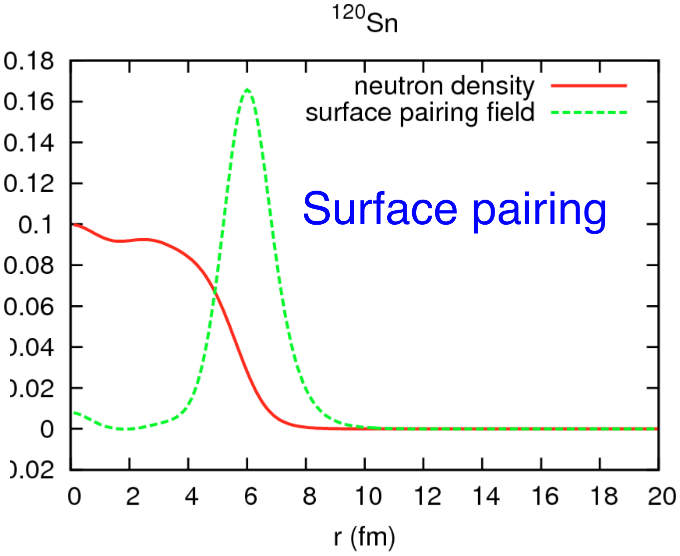
Table of Contents

Bertulani, Piekarewicz, editors

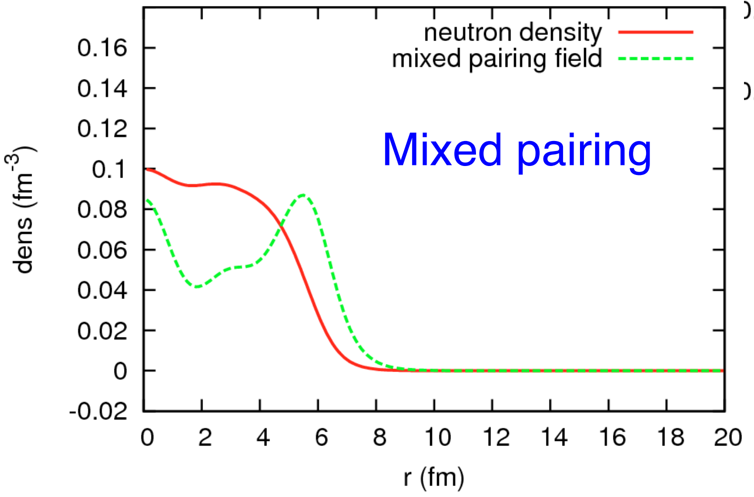
Mean field + Pairing

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

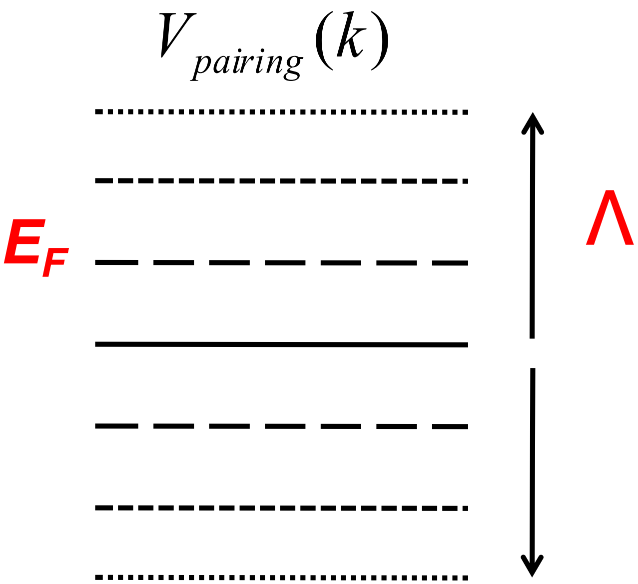


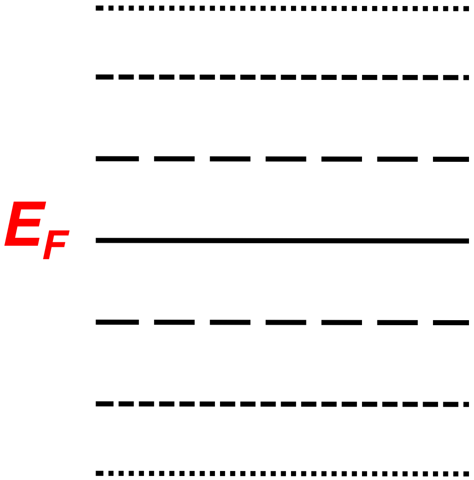


^{120}Sn



Odd nuclei: Blocking procedure

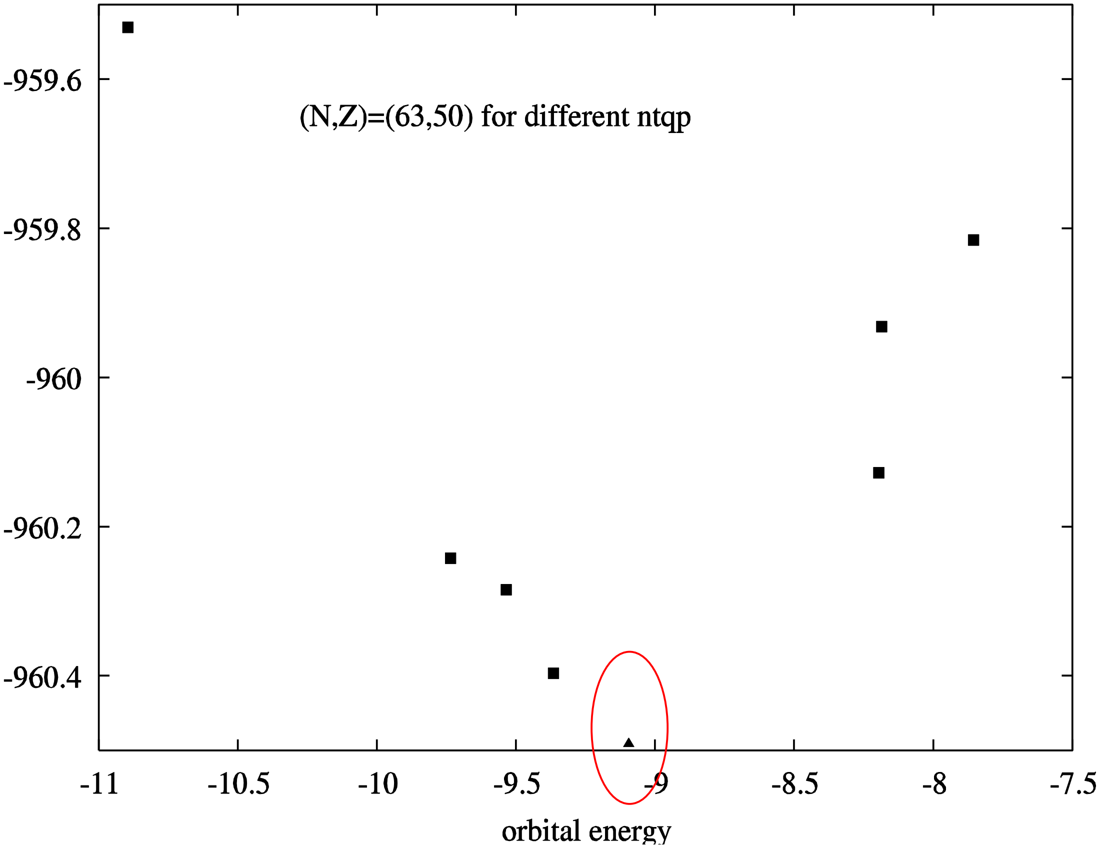




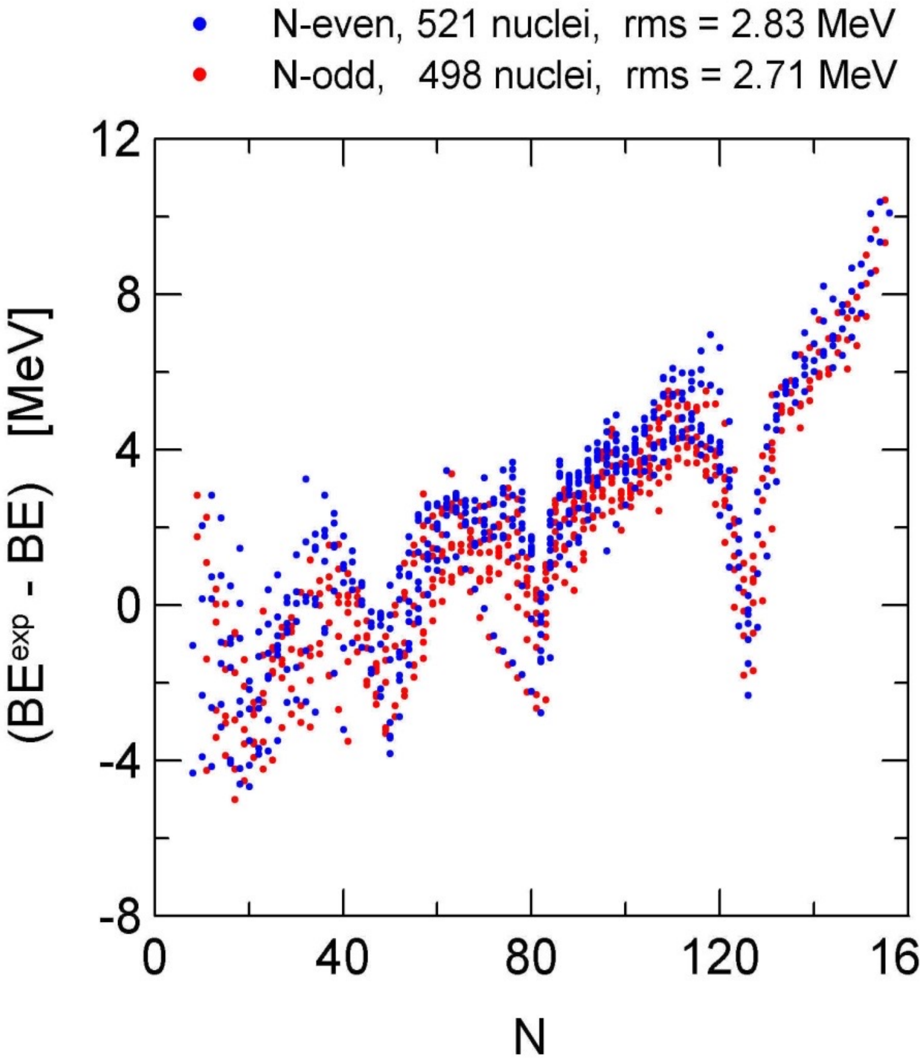
$$\mathrm{v}^2 = \frac{1}{2}, \quad \tilde{\mathrm{v}}^2 = \frac{1}{2}$$

for one orbit and its time-conjugate partner

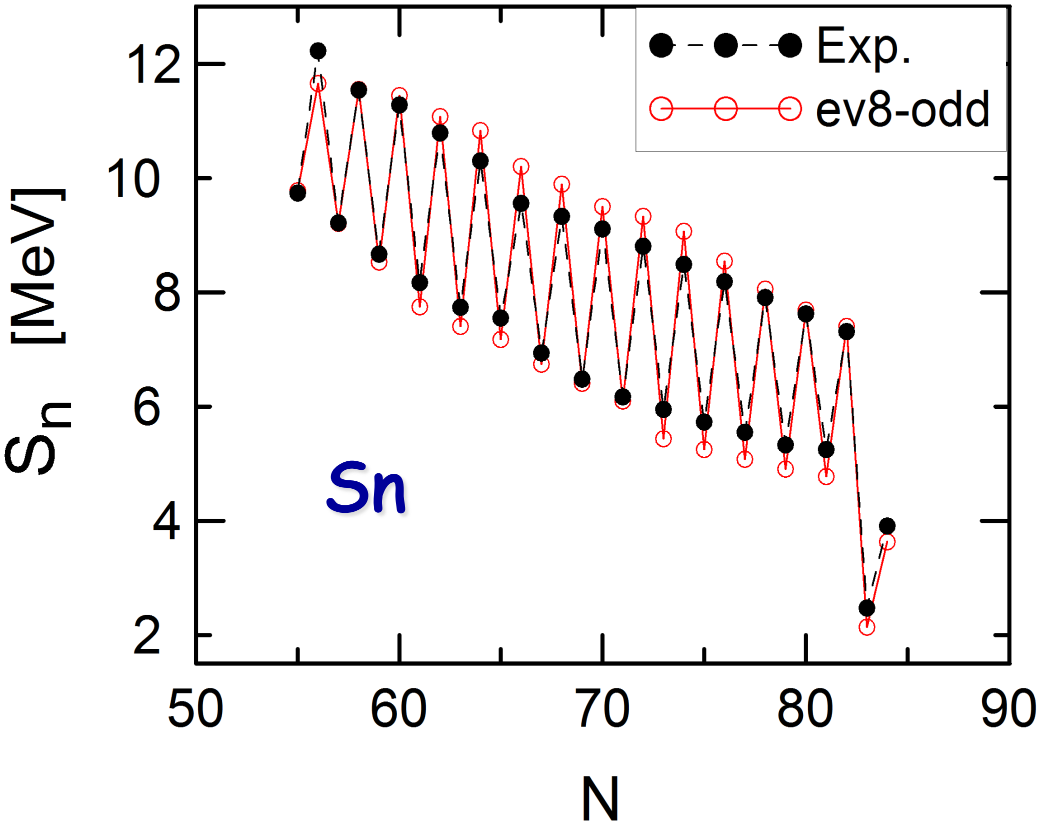
$\Lambda \sim 50$ MeV



Pairing improves nuclear properties



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



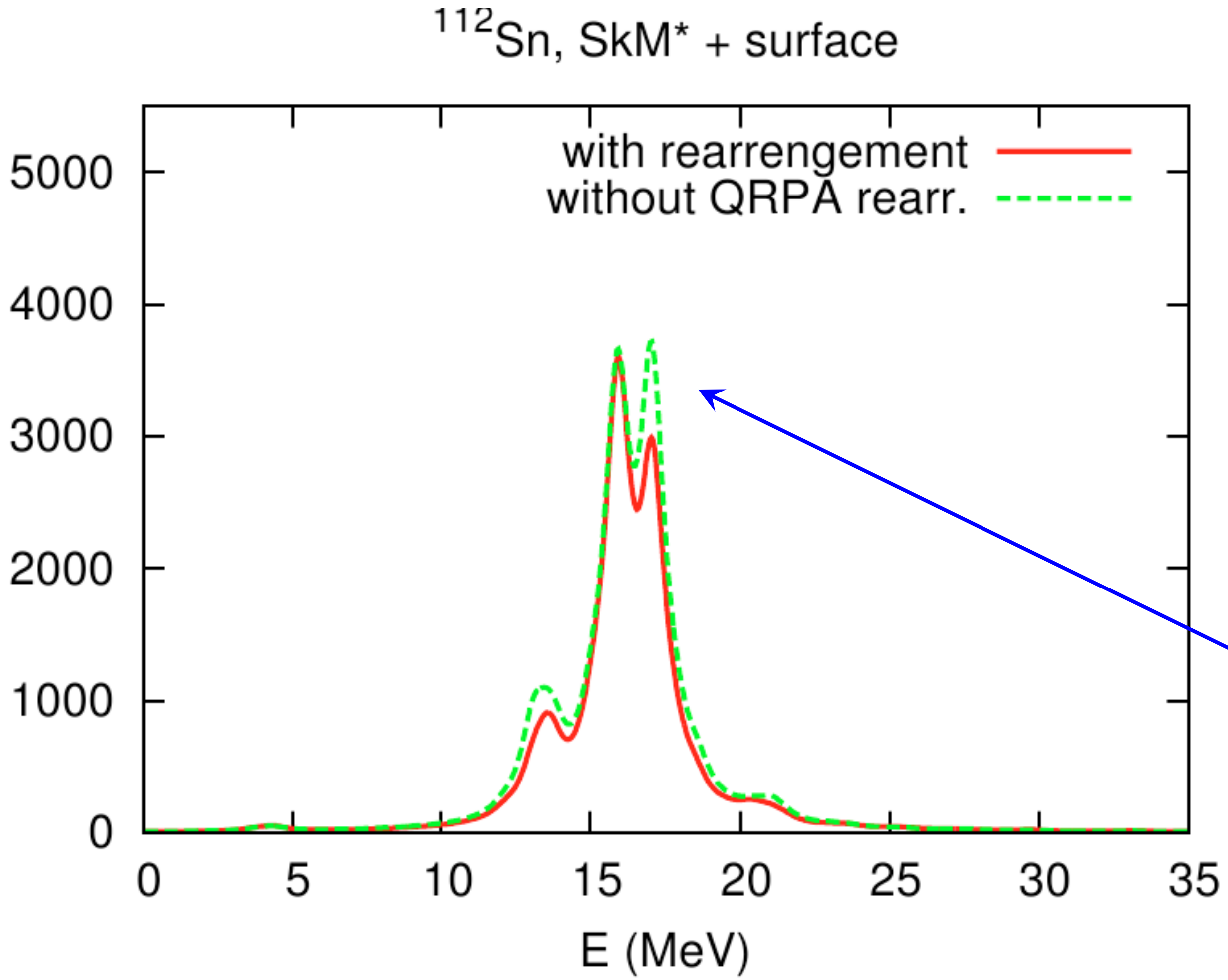
Bertsch, Bertulani, Nazarewicz, Schunck, Stoitsov,
PRC 79, 0343306 (2009)

QRPA: pairing induces rearrangement terms

Avogadro, Bertulani, PRC 88, 044319 (2013)

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

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

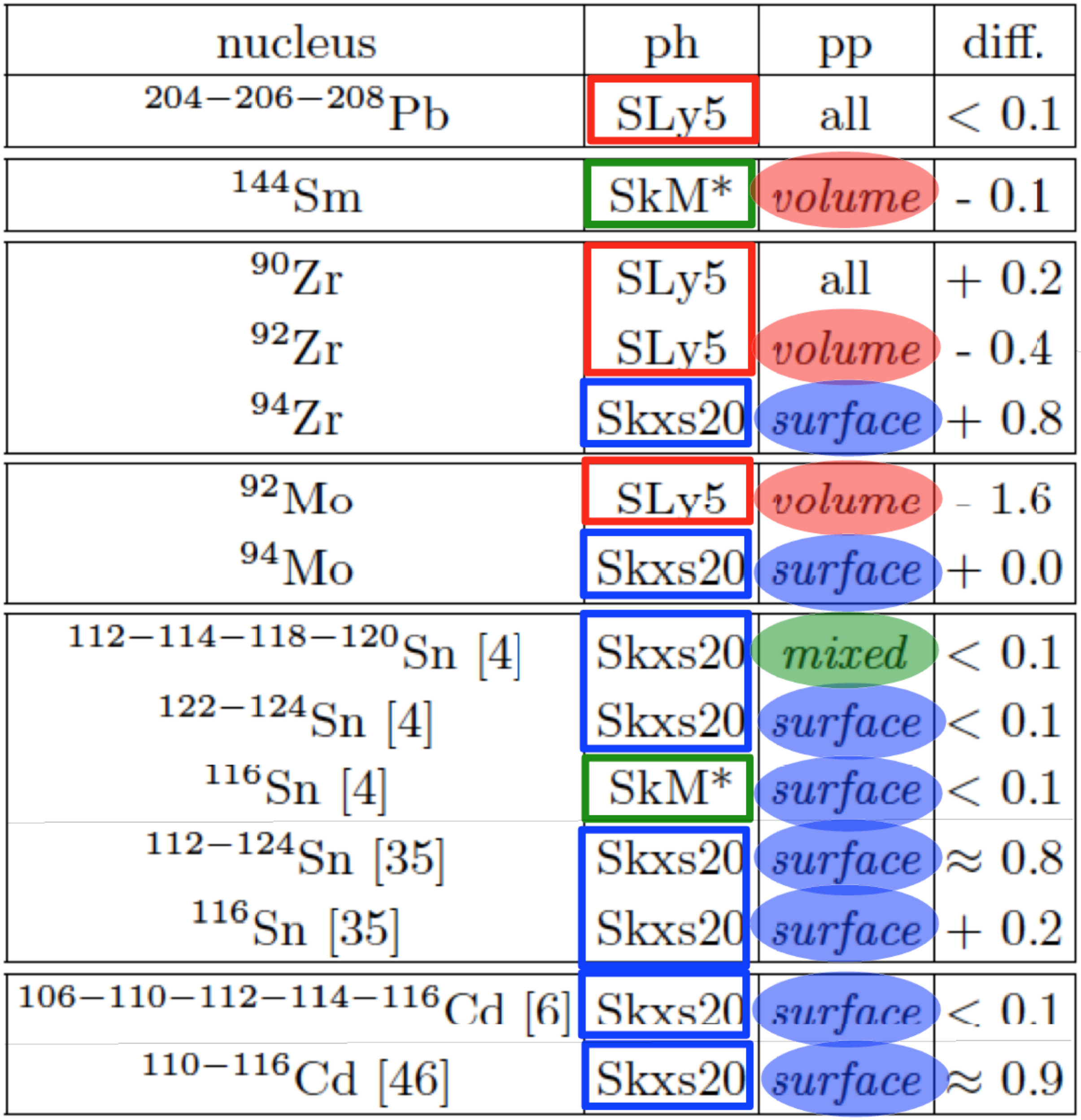


$$\frac{\delta h_{\mathrm{rearr}}}{\delta\rho} = \frac{\delta}{\delta\rho}\left(\frac{\delta E_{\mathrm{pair}}}{\delta\rho}\right)$$

≠ 0 if E_{pair} depends on density

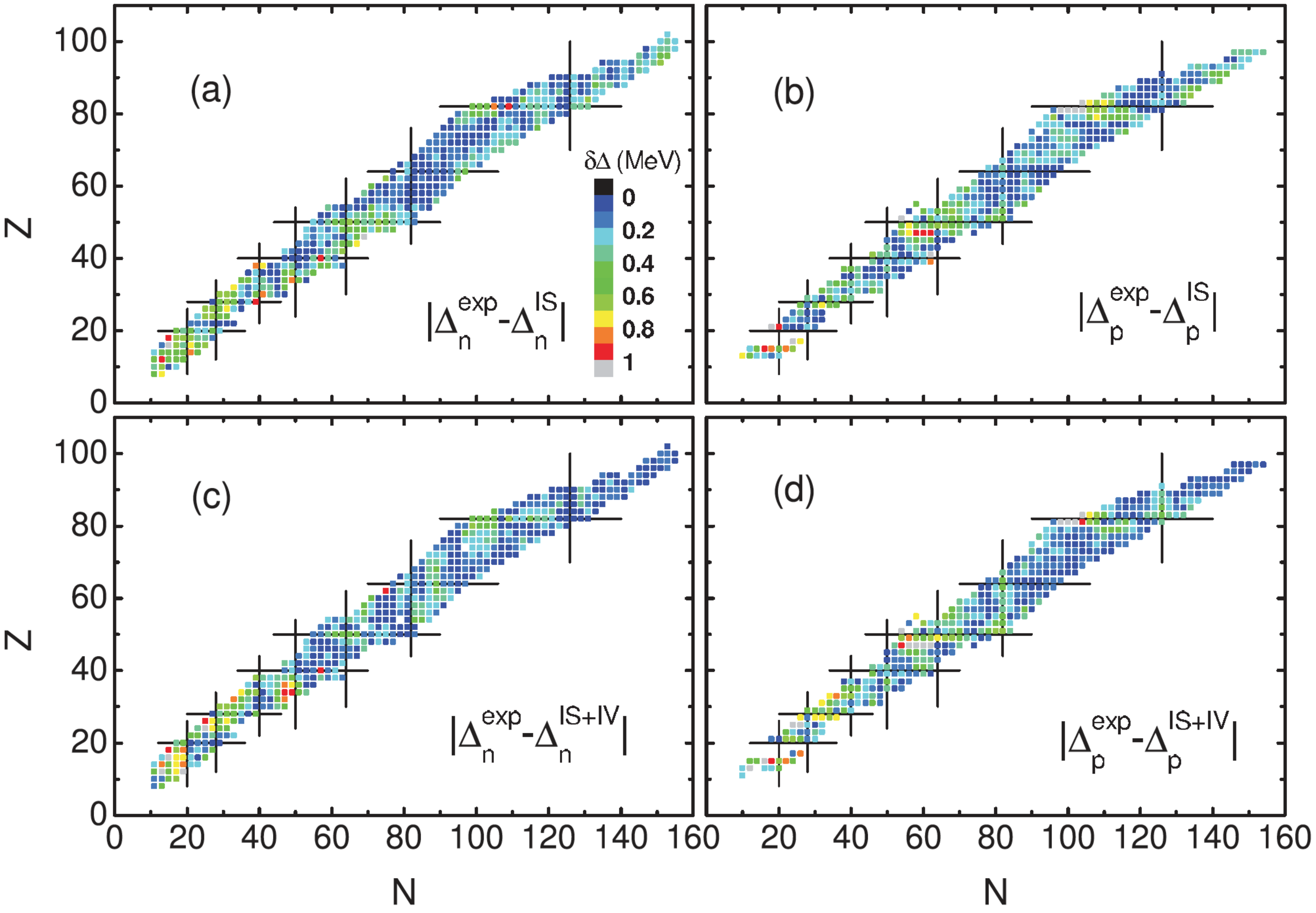
Calculations without rearrangements tend to return higher centroids respect to the fully self-consistent case.

Pairing – ISGMR – Comparison to data



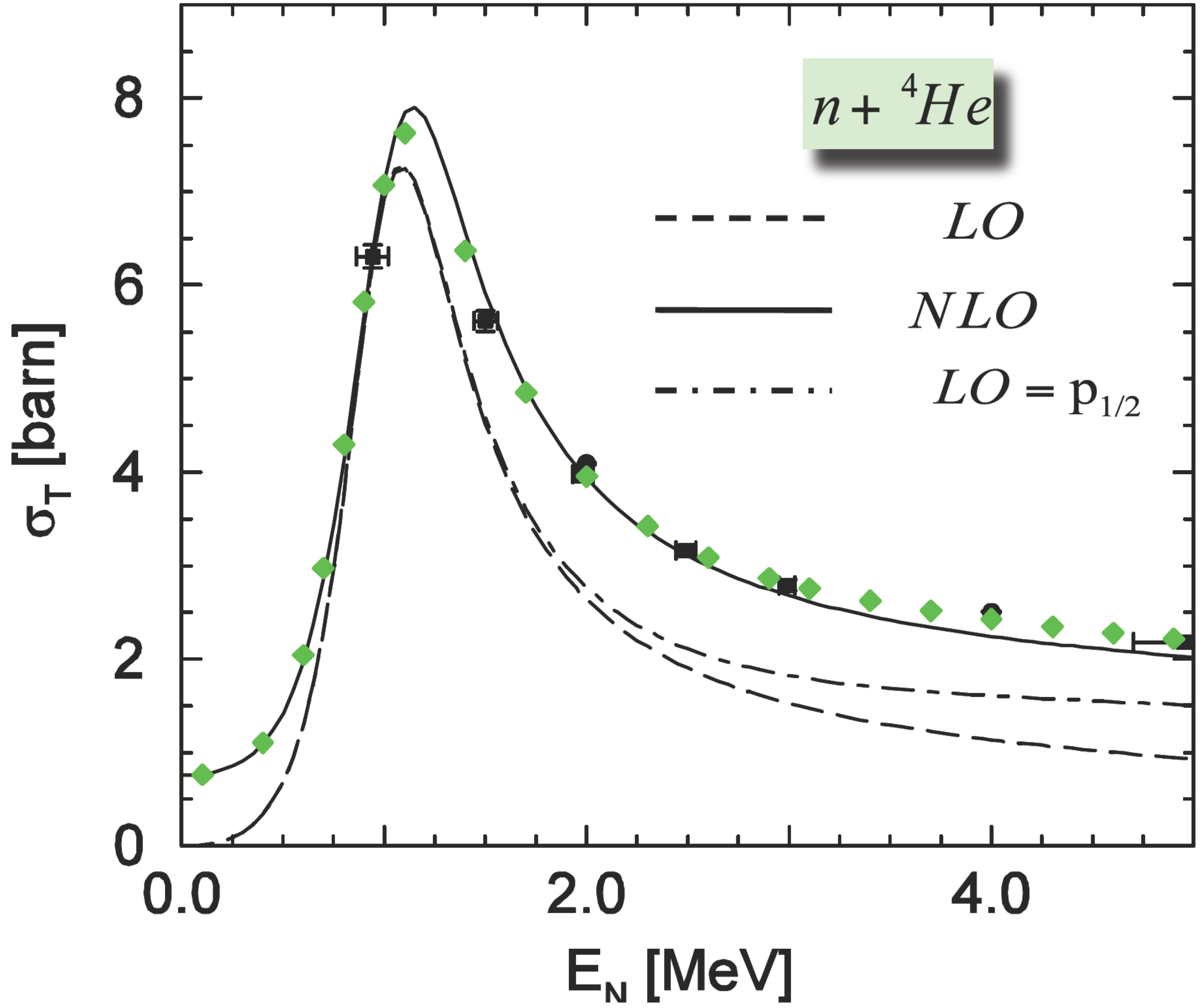
	nucleus	ph	pp	diff.
TAMU/ RCNP	$^{204-206-208}$Pb	SLy5	all	< 0.1
TAMU/ RCNP	^{144}Sm	SkM*	*volume*	- 0.1
TAMU/ RCNP	^{90}Zr	SLy5	all	+ 0.2
TAMU	^{92}Zr	SLy5	*volume*	- 0.4
	^{94}Zr	Skxs20	*surface*	+ 0.8
TAMU	^{92}Mo	SLy5	*volume*	- 1.6
	^{94}Mo	Skxs20	*surface*	+ 0.0
RCNP	$^{112-114-118-120}$Sn [4]	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



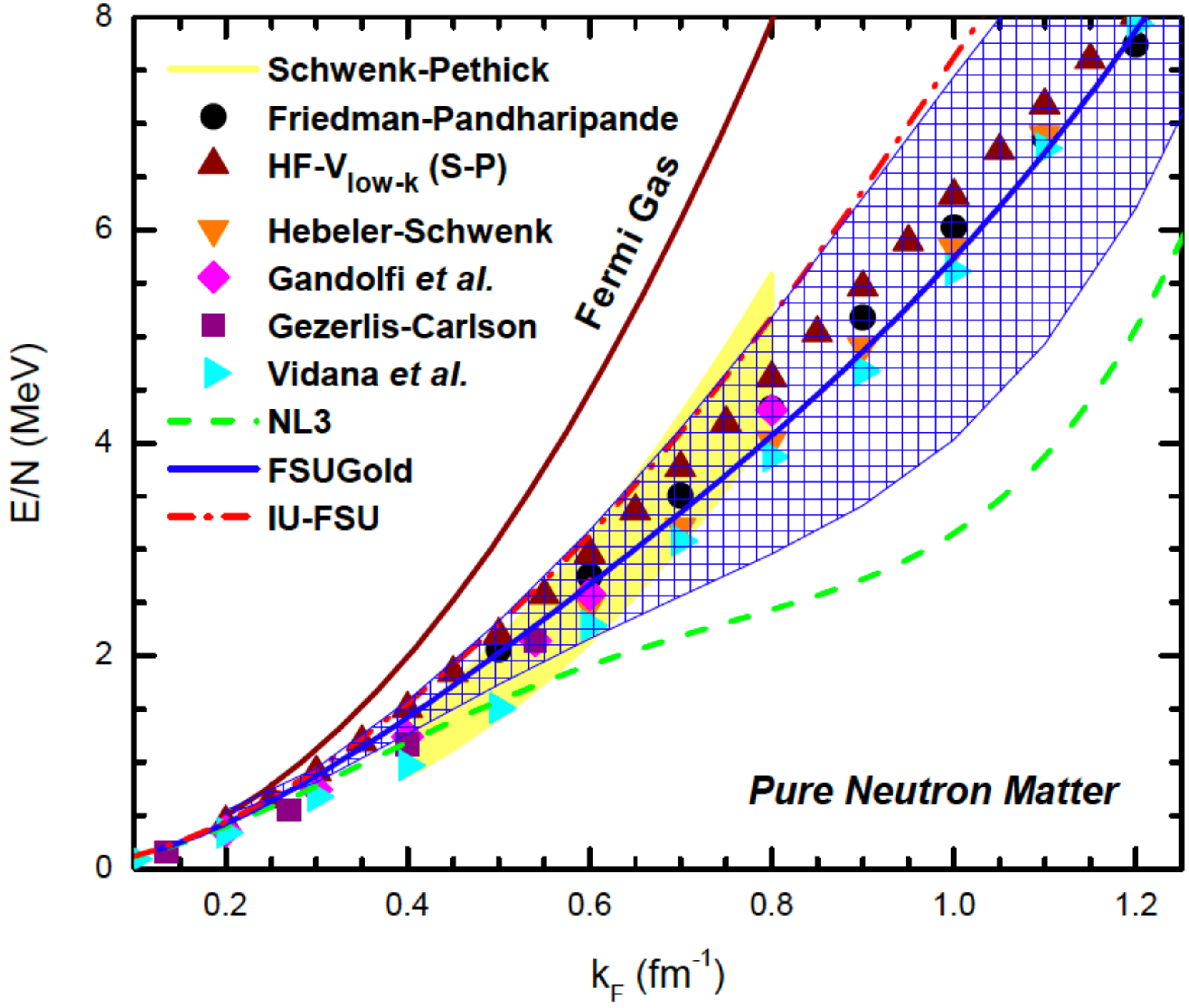
Bertulani, Liu, Sagawa, PRC 85, 014321 (2012)

Halo EFT



EOS & Neutron stars

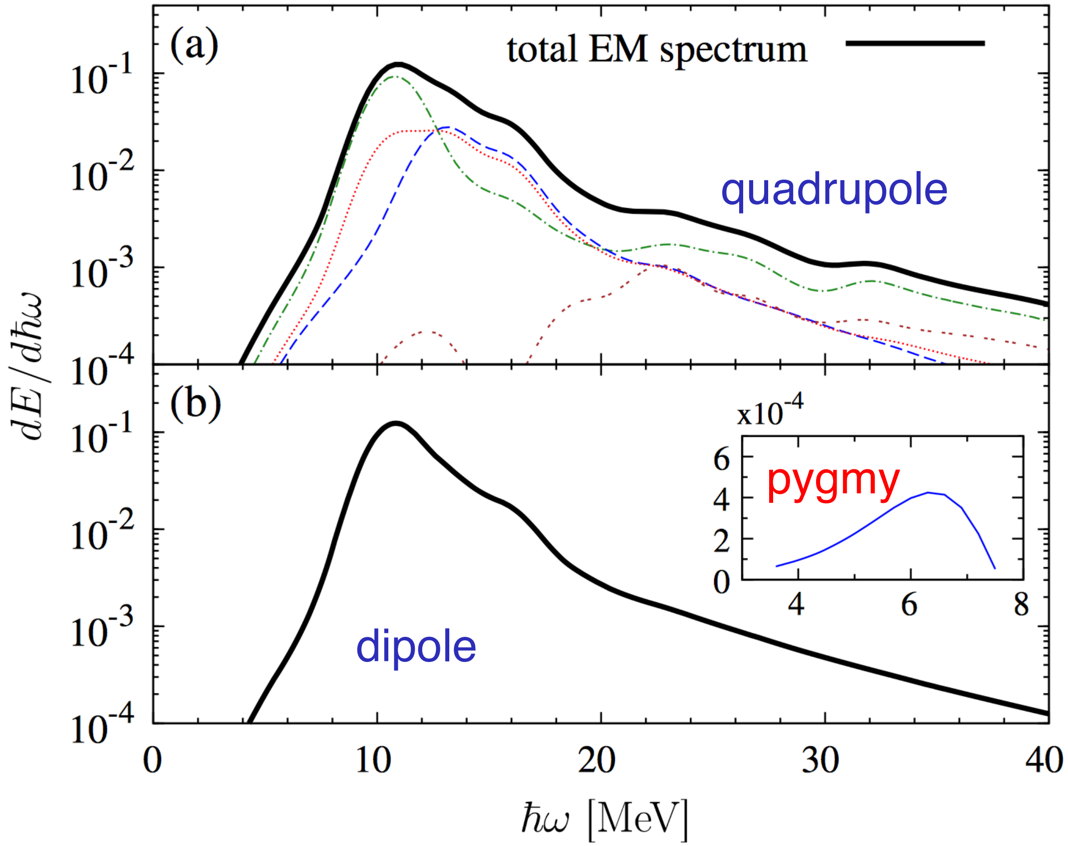
Fattoyev, Piekarewicz, PRC 86, 015802 (2012)



Mean-Field Dynamics with pairing in heavy ion collisions

Time dependent superfluid local density approximation (TDSLDA)

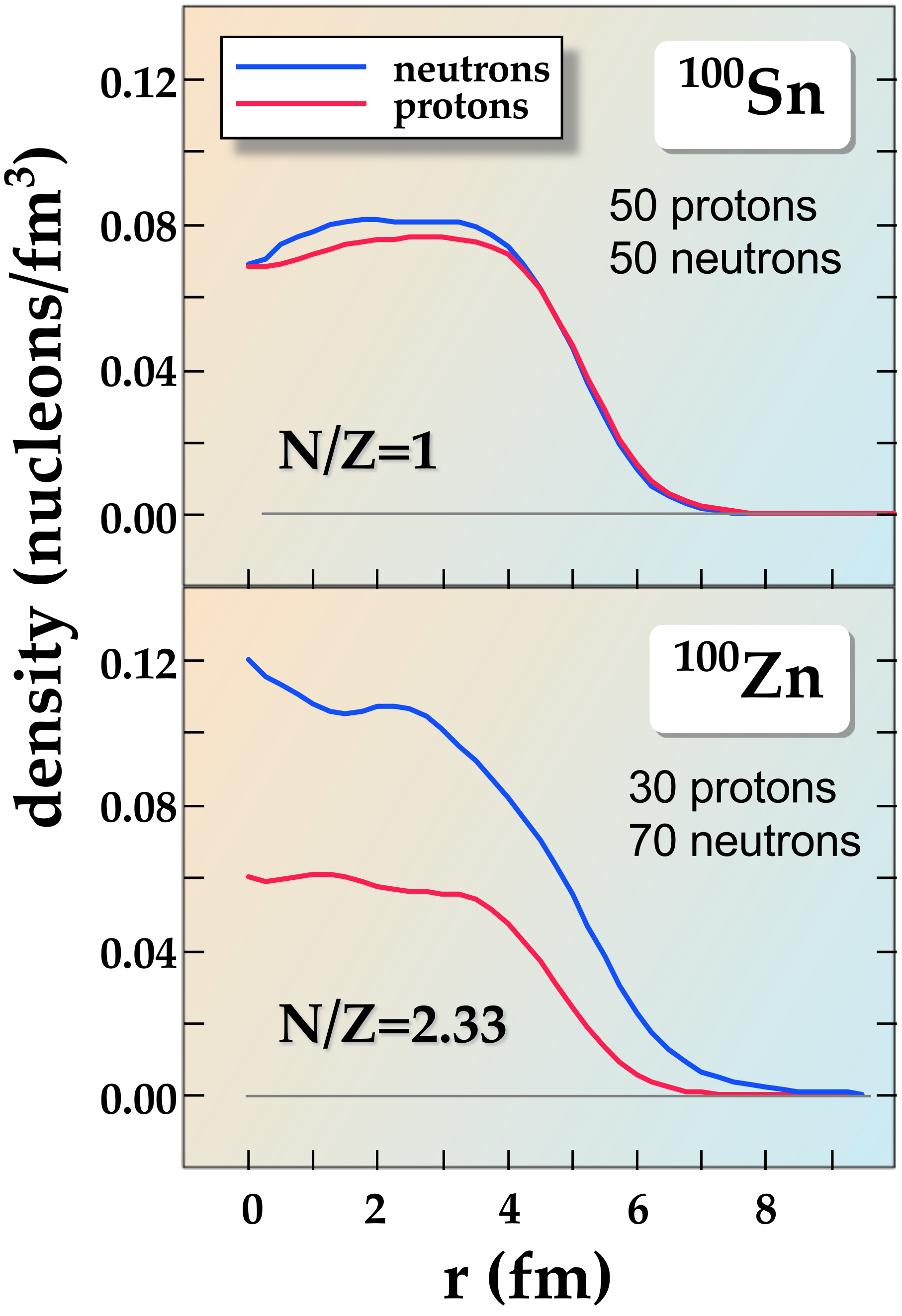
Emitted EM radiation
^{238}U + ^{238}U (1 GeV/nucleon)

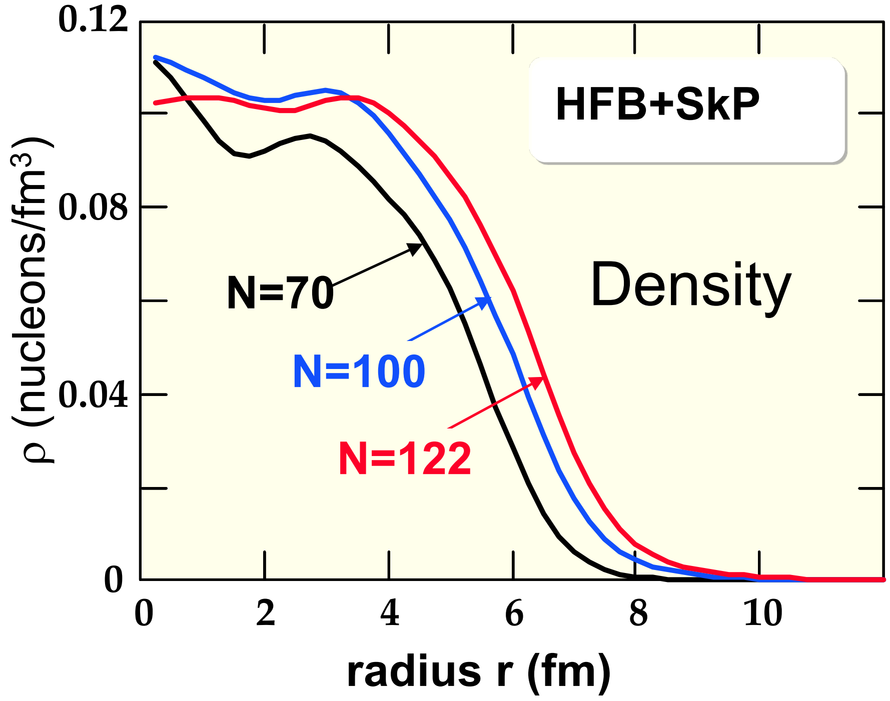


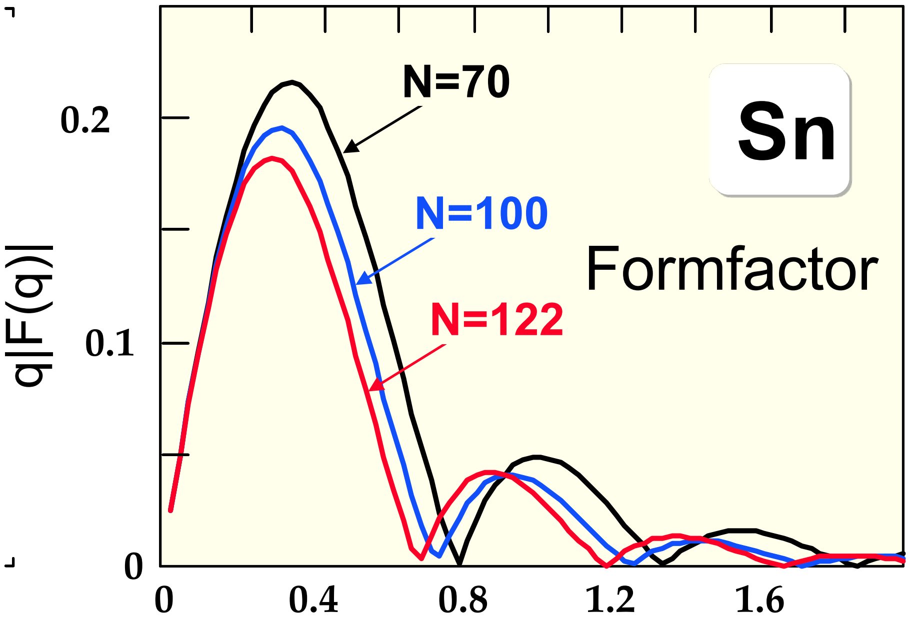
An exact QRPA approach would severely underestimate the amount of internal energy deposited, one reason being the nonlinearity of the response, naturally incorporated in TDSLDA

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

Neutron skins

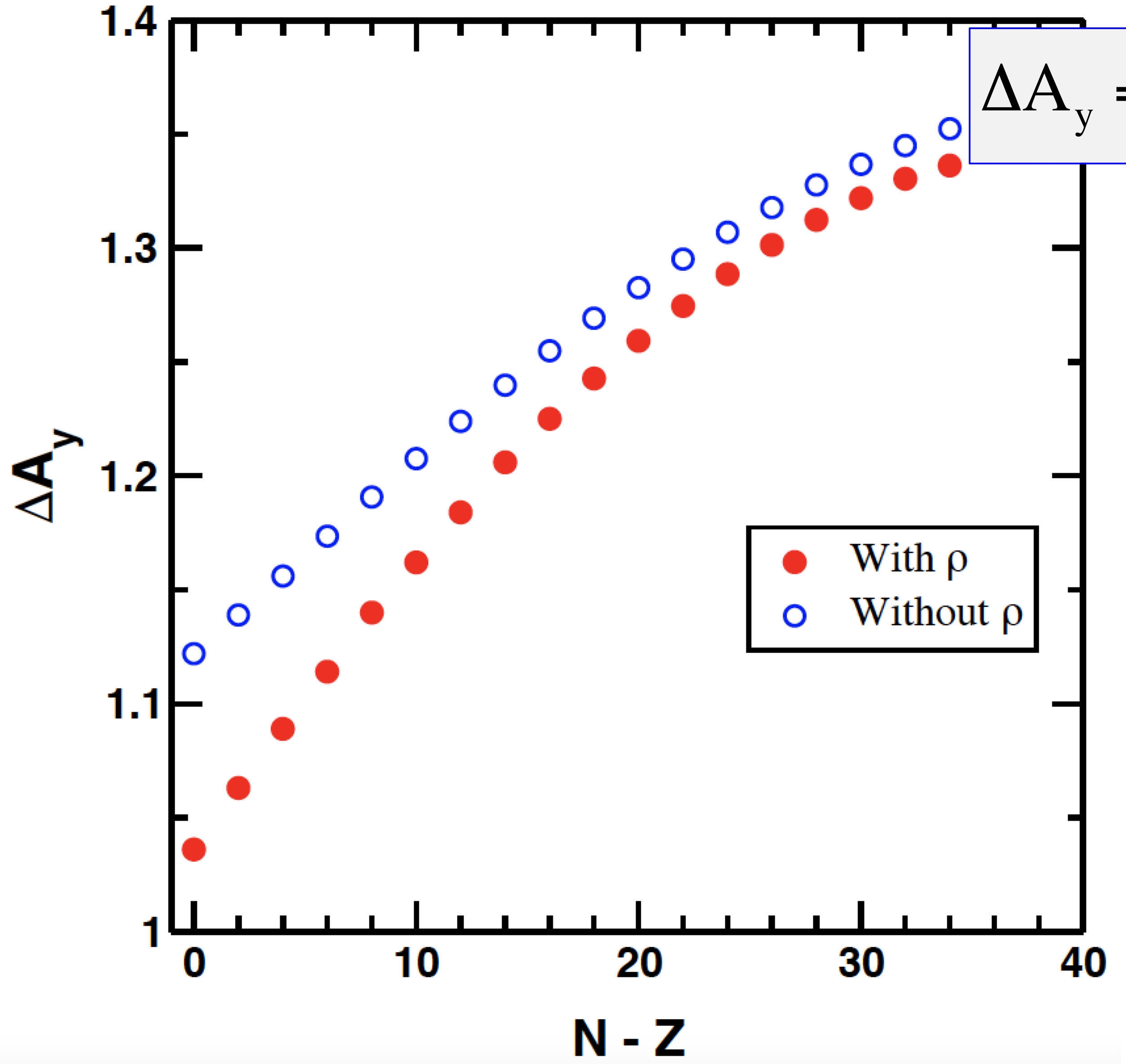






Credit: W. Nazarewicz

Maris polarization in asymmetry systems

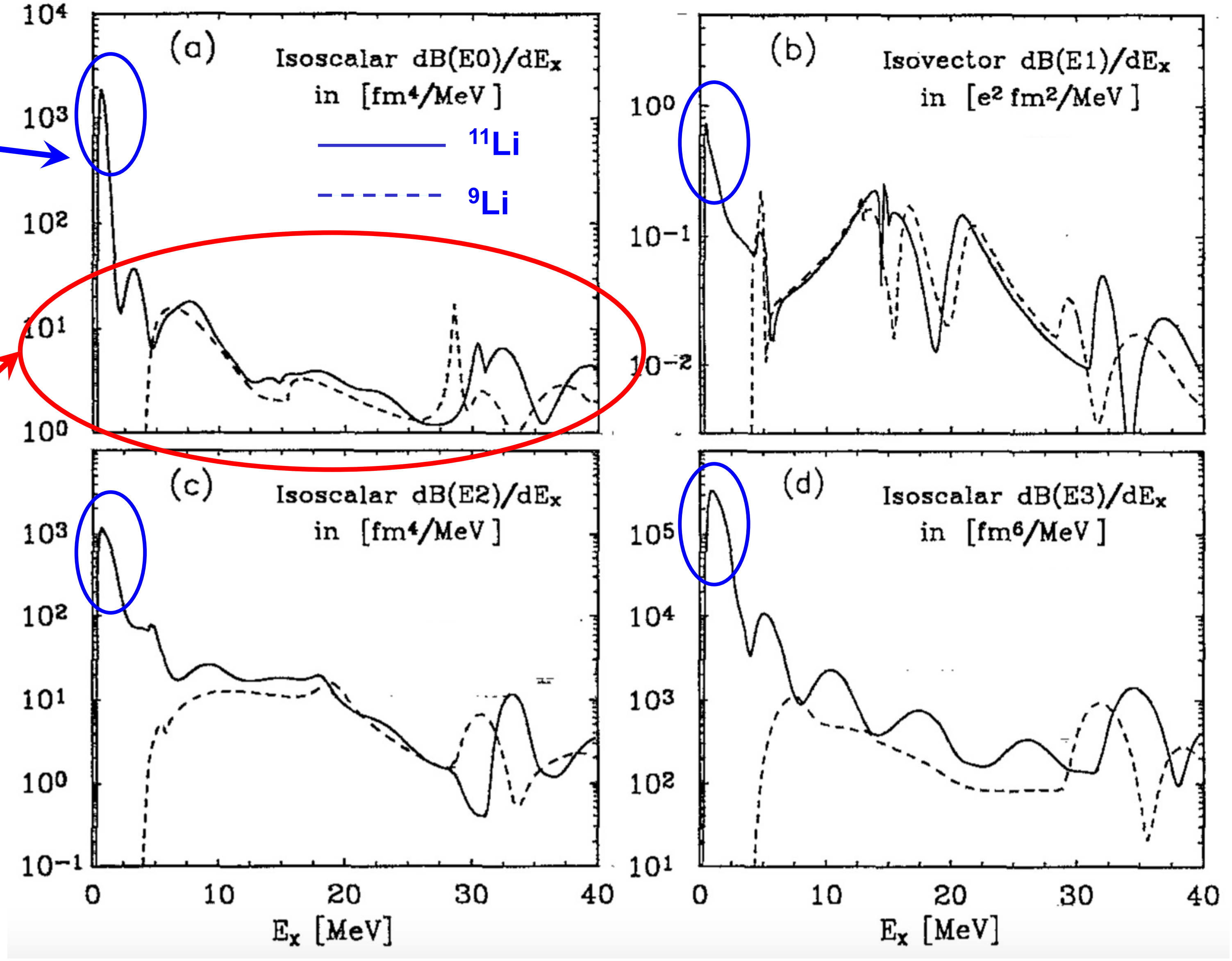


$$\Delta A_y = \left(A_y^{p_{1/2}}\right)_{max} - \left(A_y^{p_{3/2}}\right)_{min}$$

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

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

Many-body models

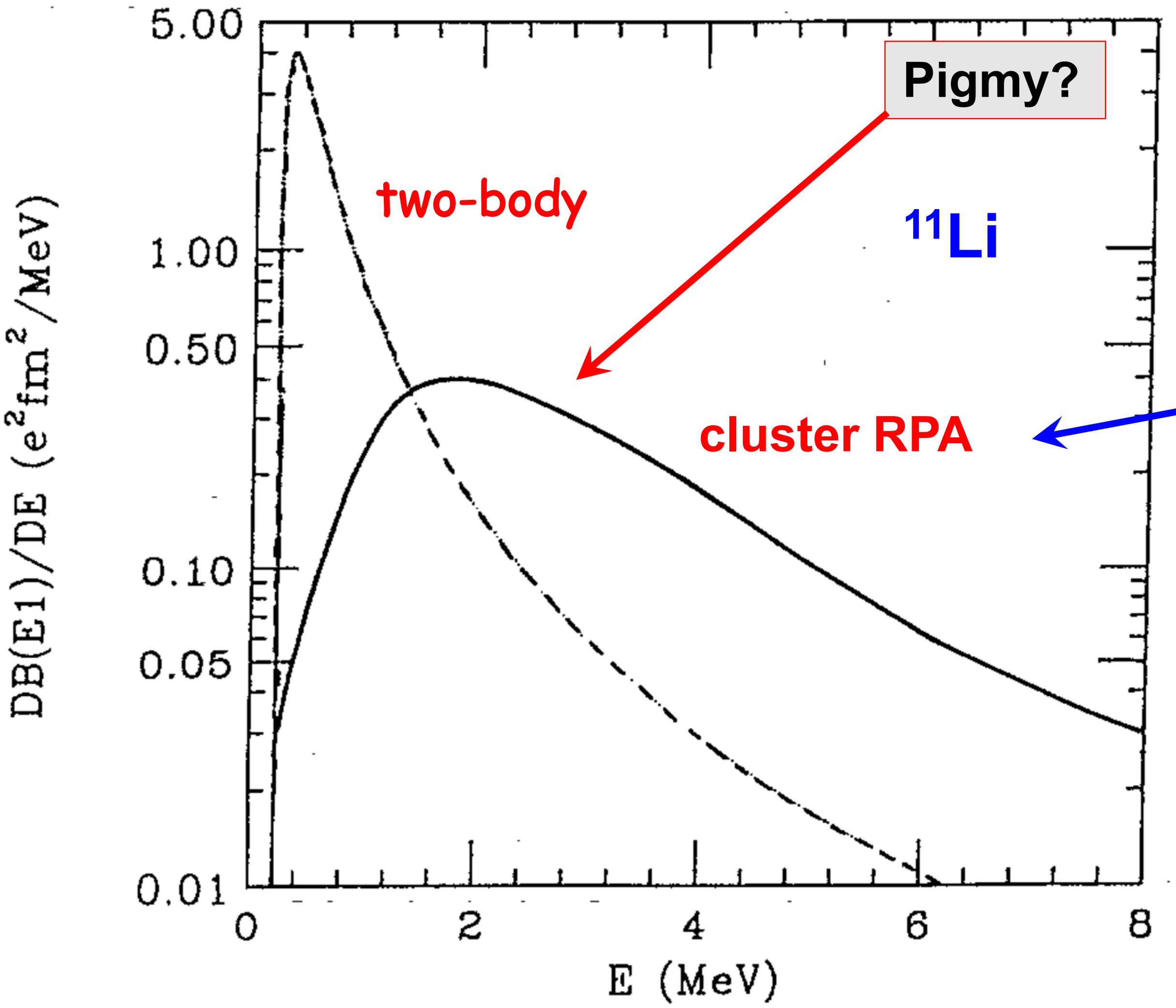


Pygmy?

Core excitations

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

Many-body models

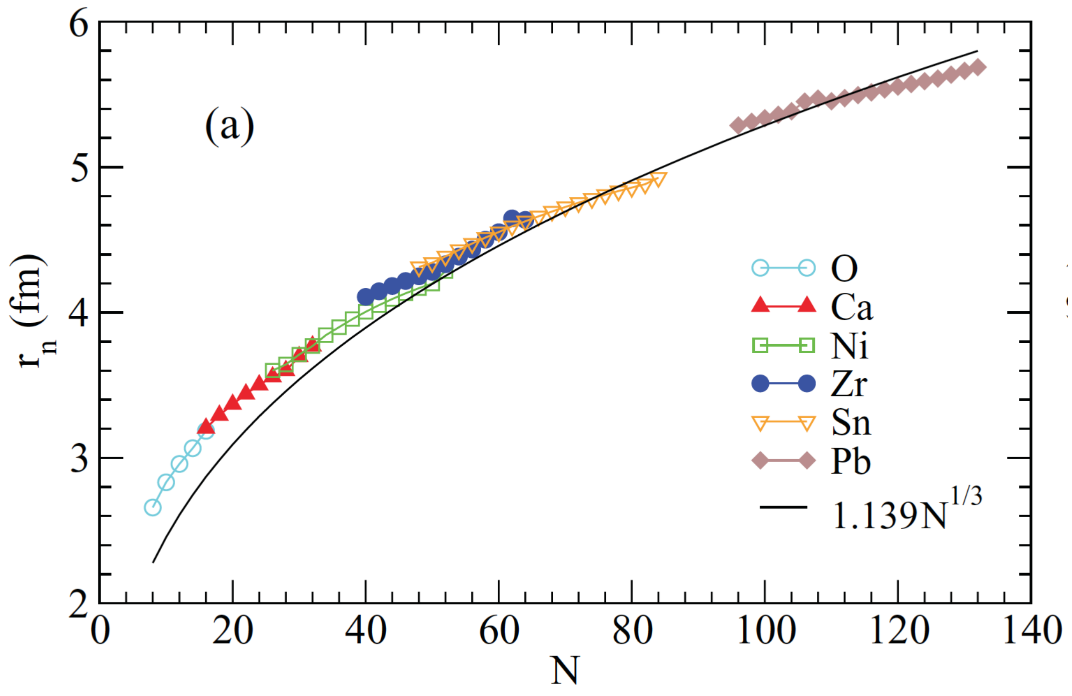


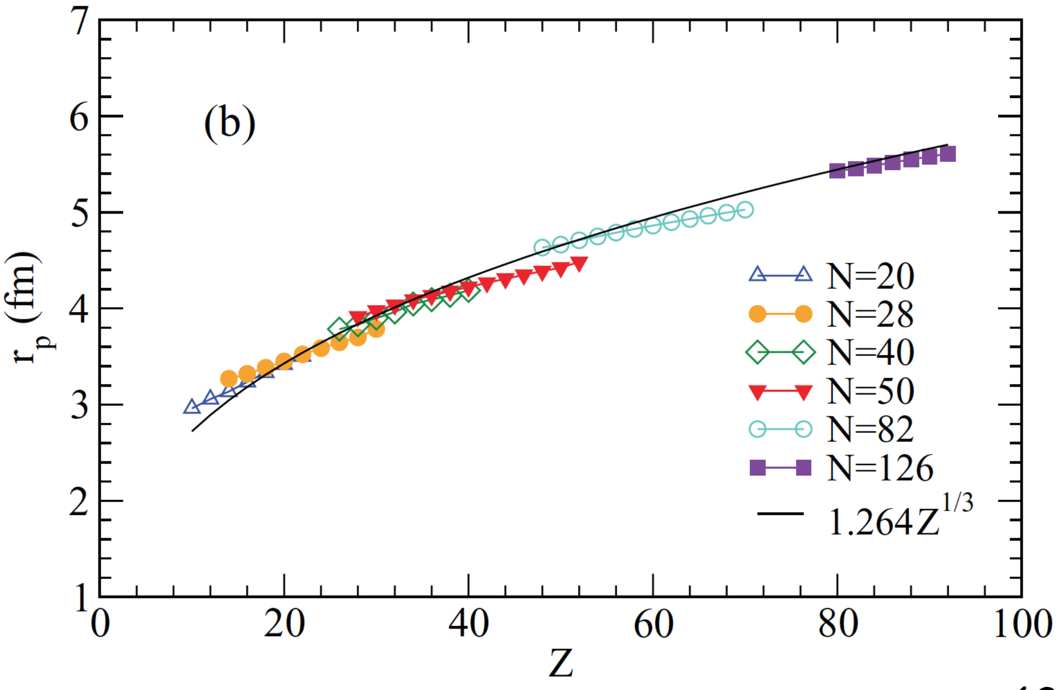
Pigmy?

RPA + $2n_p$-$2n_h$ excitations

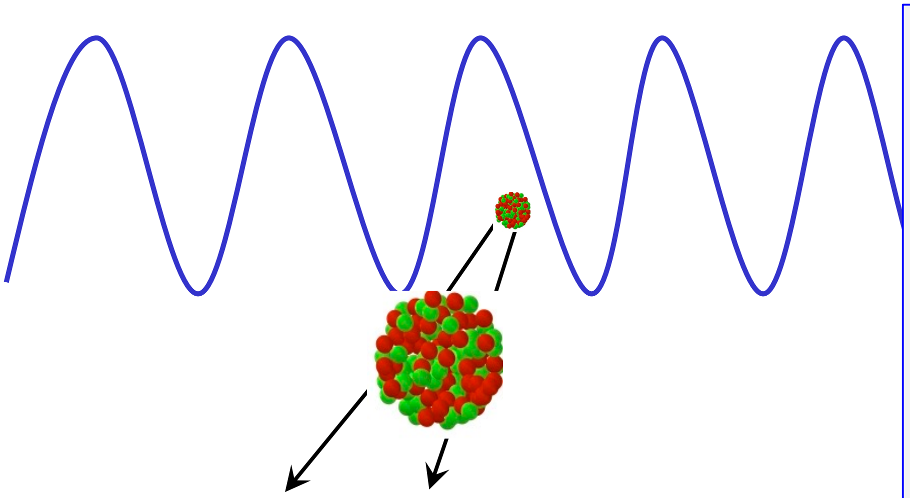
Teruya, CB, Krewald, Dias, Hussein, PRC 43, 2049 (1991)

DFT and nuclear radii





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: ●●

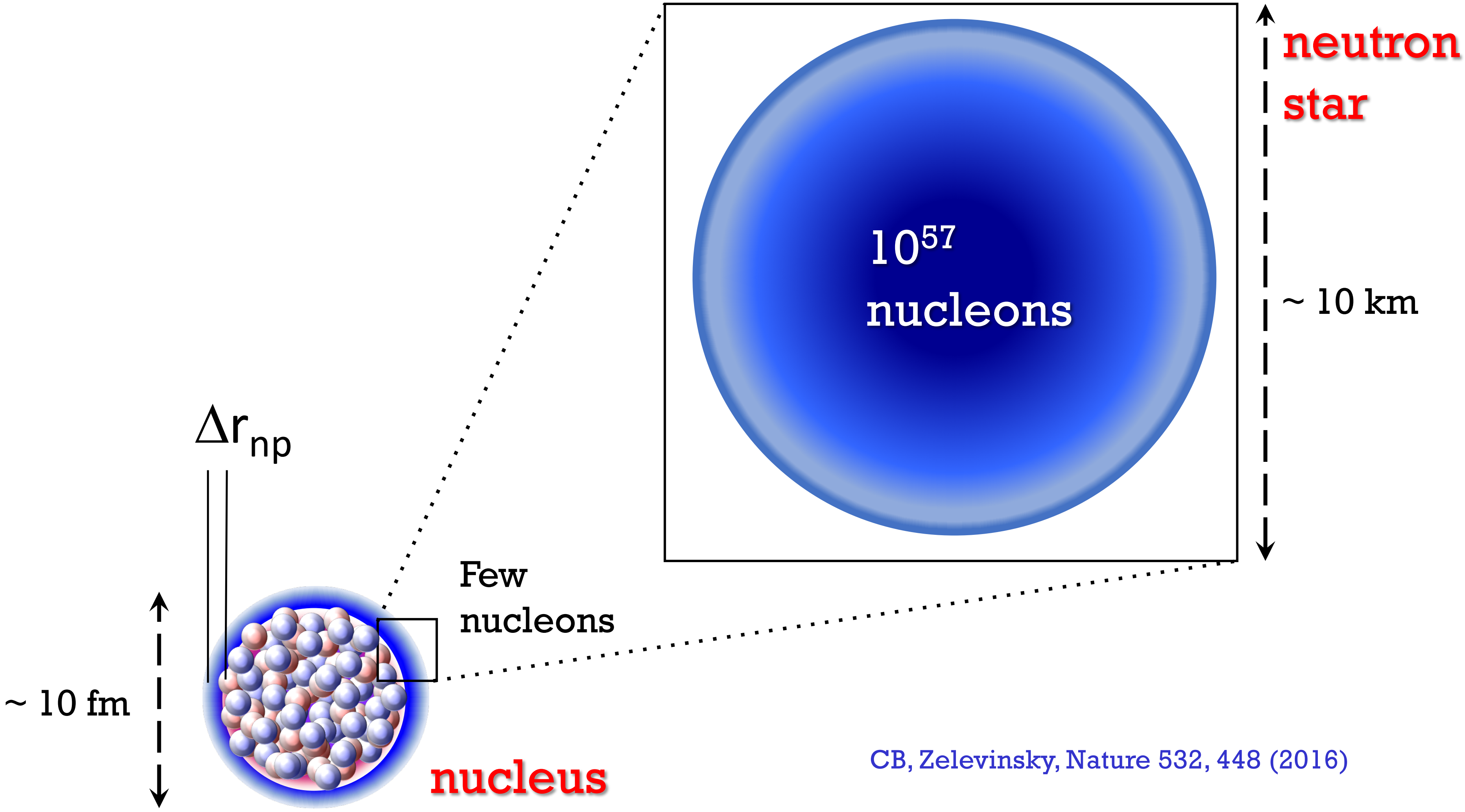
quadrupole: ●●●

controlled
precision

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

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

Neutron skins and neutron stars



neutron star

10^{57} nucleons

~ 10 km

Δr_{np}

Few nucleons

~ 10 fm

nucleus

CB, Zelevinsky, Nature 532, 448 (2016)