Electric Dipole Response of ^{208}Pb and Constraints on the Symmetry Energy

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and RCNP-E282 Collaboration

NuSym13, July 22-26, 2013, NSCL

Contents

- Electric dipole response of ^{208}Pb has been precisely measured.

  Method: proton inelastic scattering, electro-magnetic probe

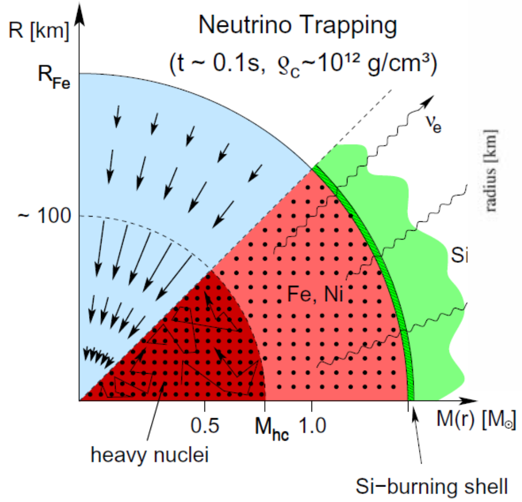
  Extracted data: dipole polarizability, PDR strength

- Constraints on the symmetry energy has been determined.

  with a help of mean-field calculations

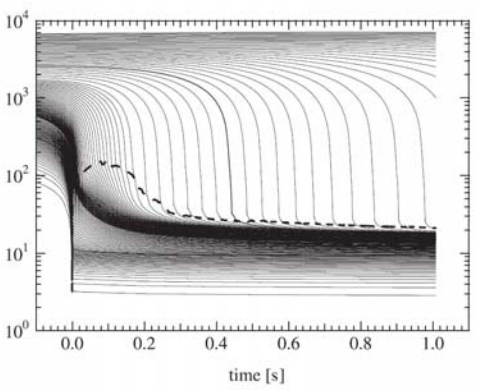
Determination of the Symmetry Energy Term in EOS.

Core-Collapse Supernova



Langanke and Martinez-Pinedo

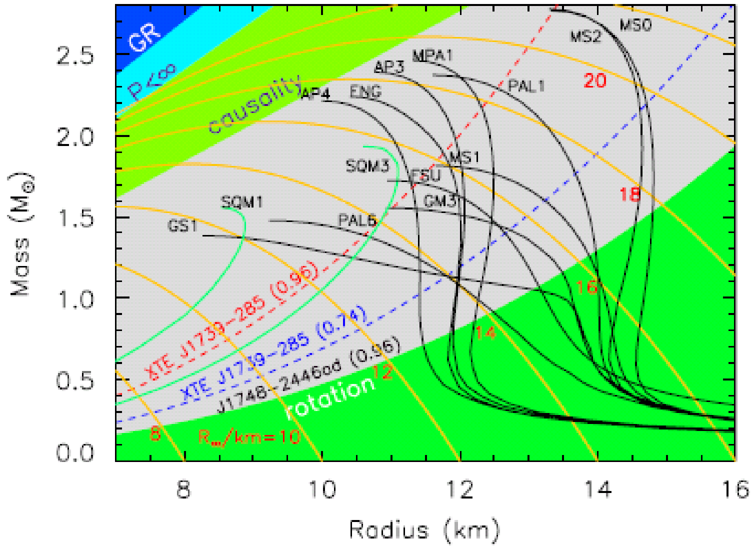
K. Sumiyoshi, Astrophys. J. 629, 922 (2005)



Nucleosynthesis

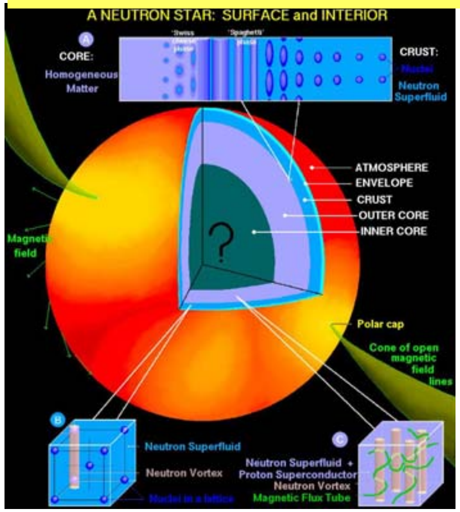
Neutron Star Cooling

Neutron Star Mass and Radius



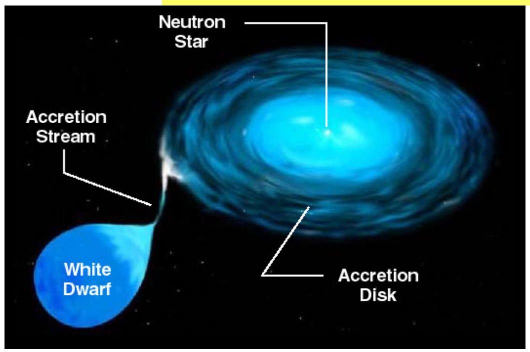
Lattimer et al., Phys. Rep. 442, 109(2007)

Neutron Star Structure



http://www.astro.umd.edu/~miller/nstar.html

Accreting neutron star/white dwarf, X-Ray burst, Superburst



Nuclear Equation of State (EOS)

$$\rho(r) = \rho_n(r) + \rho_p(r)$$

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

EOS for Energy per nucleon

$$\frac{E}{A}(\rho, \delta) = \frac{E}{A}(\rho, 0) + S(\rho)\delta^2 + \ldots$$

Symmetry energy

Saturation Density ~0.16 fm^{-3}

ρ_0 :

$$S(\rho) = J + \frac{L}{3\rho_0}(\rho - \rho_0) + \frac{K_{sym}}{18\rho_0^2}(\rho - \rho_0)^2 + \ldots$$

$$L \propto P \propto R^4_{\mathrm{n-star}}$$

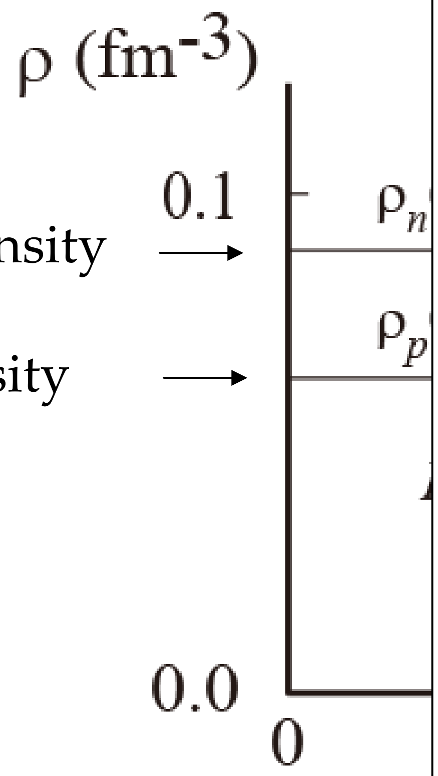
(Baryonic Pressure)

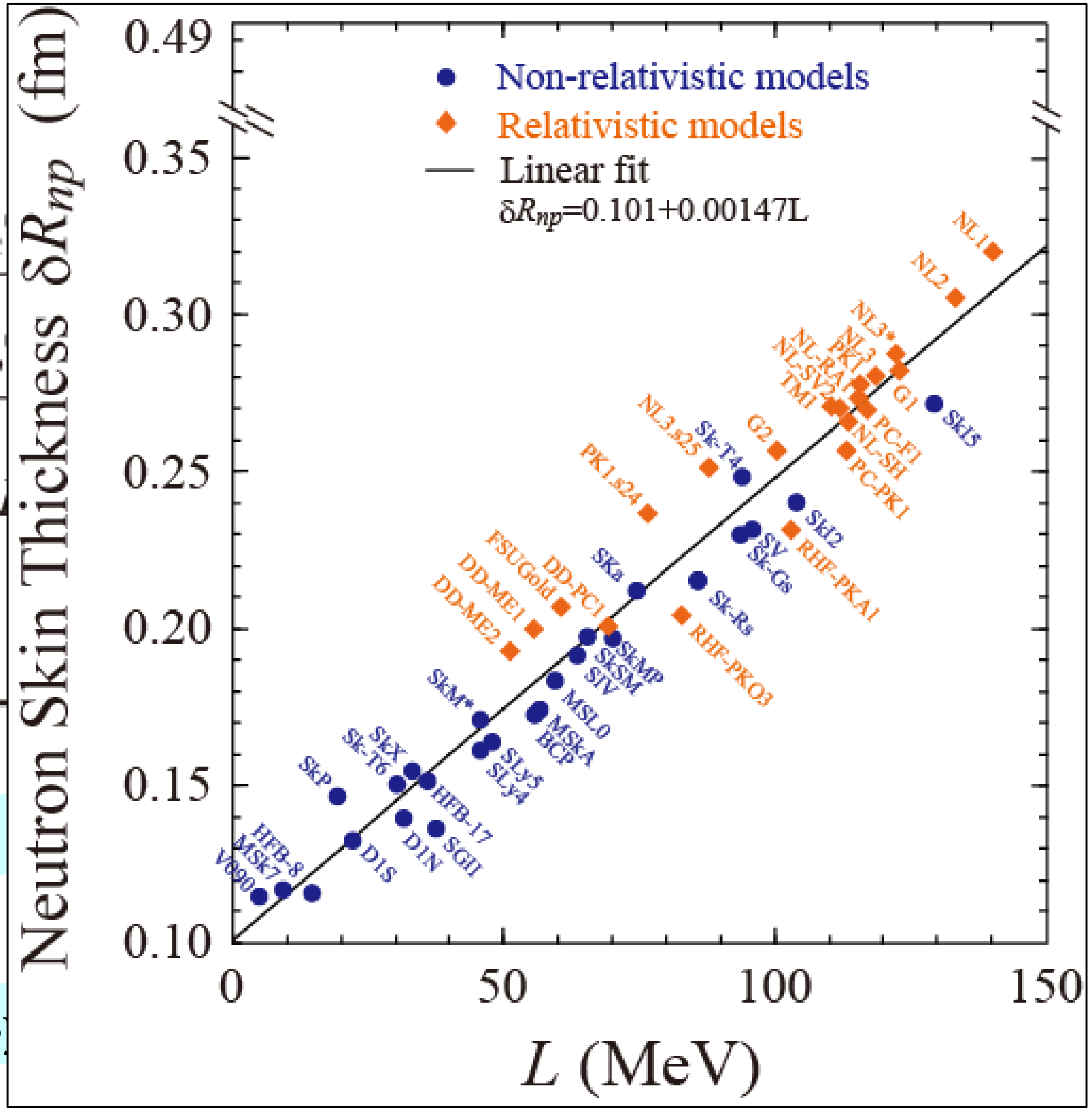
Neutron Skin and the Density Dependence of the Symmetry Energy

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

Neutron density

Proton density





Neutron skin thickness

Density dependence of the sy

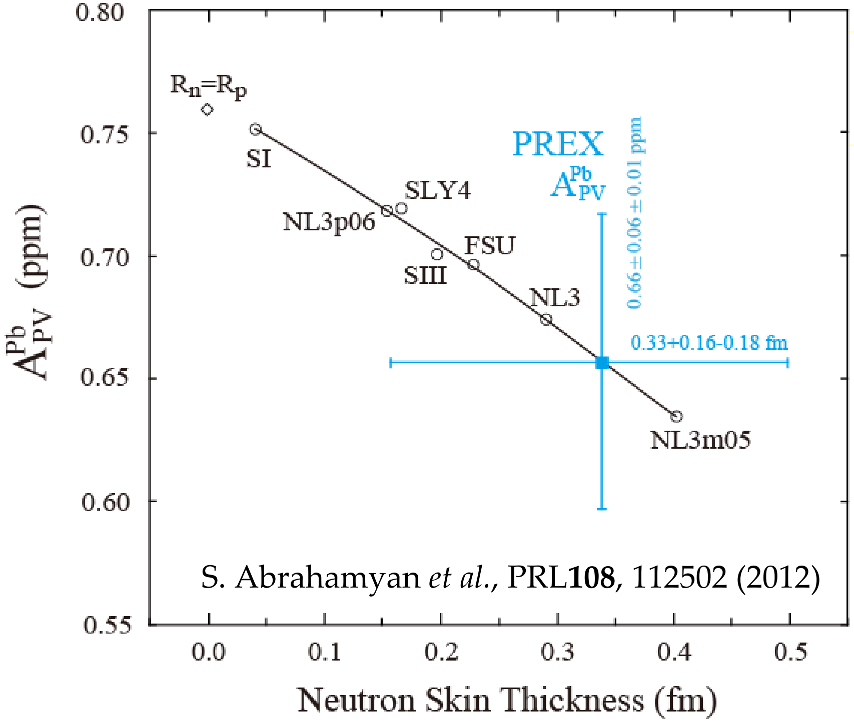
Neutron Skin Thickness Measurement by Electroweak Interaction

PREX at J-Lab: Z^0 of weak interaction : sees the neutrons

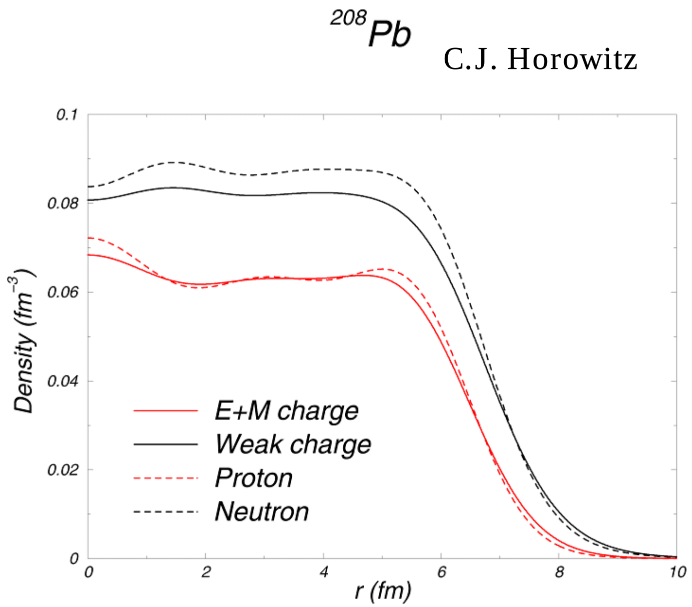
	p	n
Electric charge	1	0
Weak charge	0.08	1

$$A = \frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[1 - 4\sin^2\theta_W - \frac{}{F_P(Q^2)}\right]$$

$$A = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[1 - 4\sin^2\theta_W - \frac{F_N(Q^2)}{F_P(Q^2)}\right]$$



Parity Violating Asymmetry

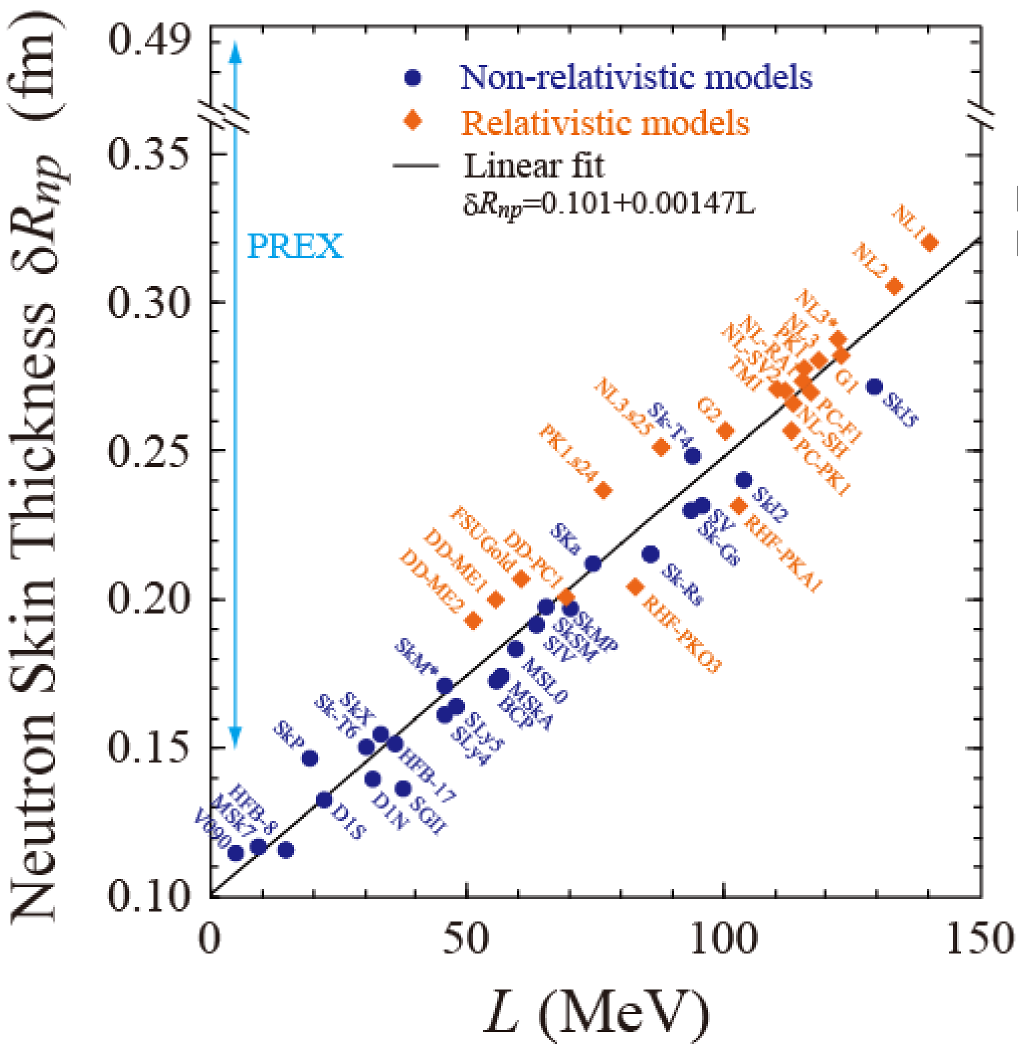


Talk by K. Kumar Thursday

Model independent determination of the neutron skin thickness

Neutron Skin Thickness Measurement by Electroweak Interaction

PREX



REX Result: S. Abrahamyan *et al.*, RL**108**, 112502 (2012)

Theor. Calc.: X. Roca-Maza *et al.*, PRL**106**, 252501 (2011)

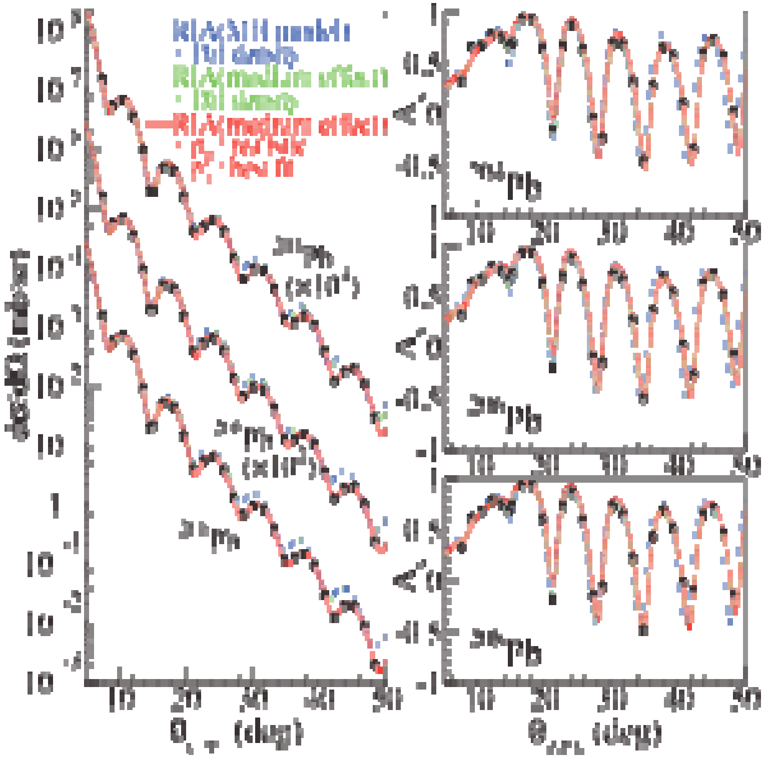
The model independent determination of δR_{np} by PREX is important but the present accuracy is limited.

Determination of Neutron Density Distribution by Strong Interaction

Polarized proton elastic scattering at 295 MeV (RCNP, Osaka University)

Analysis with relativistic impulse approximation (RIA), medium modification fixed with ^{58}Ni data

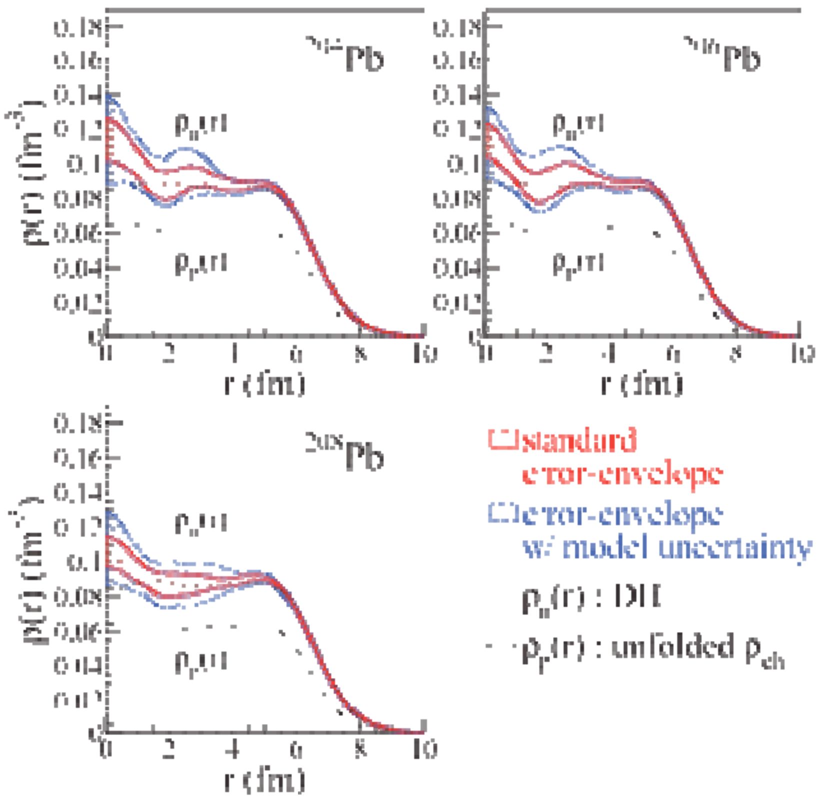
dσ/dΩ, Ay



J.Zenihiro et al., PRC 82, 044611 (2010)

RIA + Medium Effect

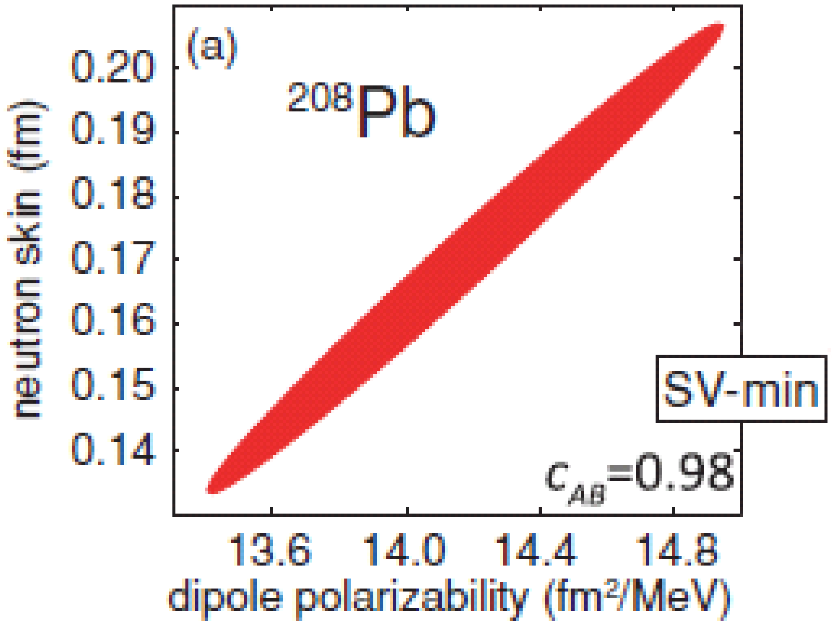
$\rho_n(r)$



Poster presentation by J. Zenihiro

neutron skin thickness of ^{208}Pb: 0.211+0.054-0.063 fm

Neutron Skin Thickness Measurement by Electromagnetic Interaction

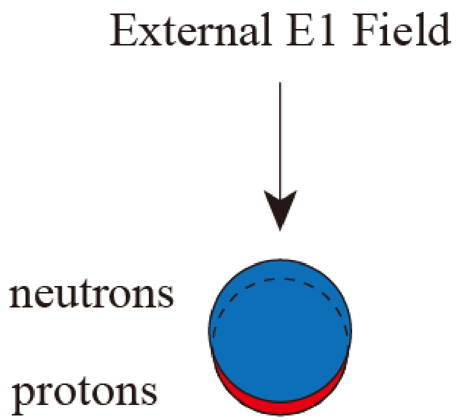


Covariance analysis of energy density functional calculations with Skrym SV-min effective interaction.

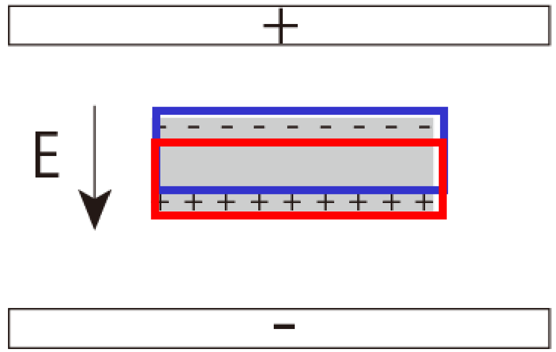
P.-G. Reinhard and W. Nazarewicz, PRC 81, 051303(R) (2010).

Strong correlation between the (electric) dipole polarizability and the neutron skin of ^{208}Pb

(Electric) Dipole Polarizability



Electric Dipole Polarizability



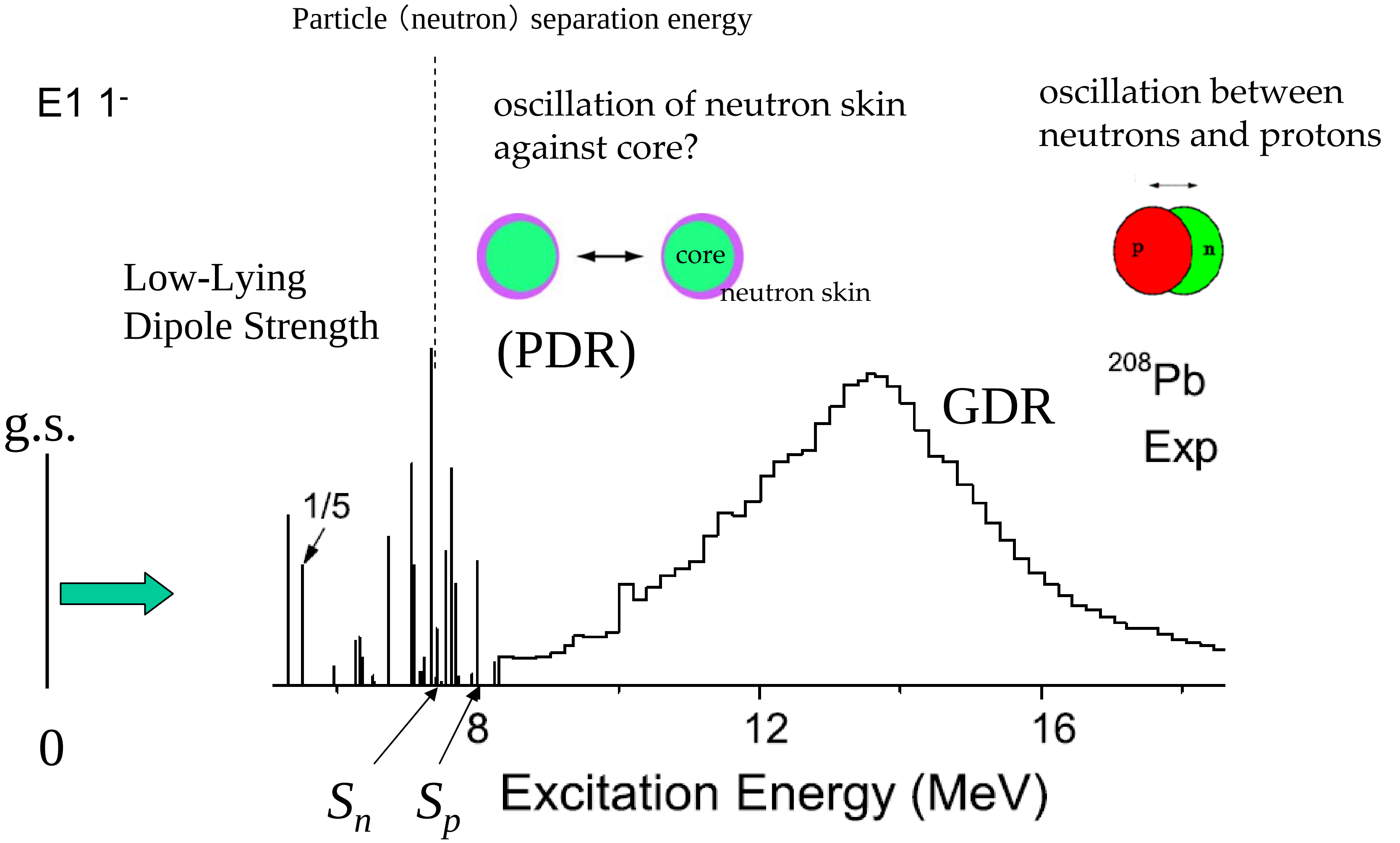
Electric Dipole Polarization

$$\mathbf{P} = \alpha \mathbf{E}$$

Inversely energy weighted sum-rule of B(E1)

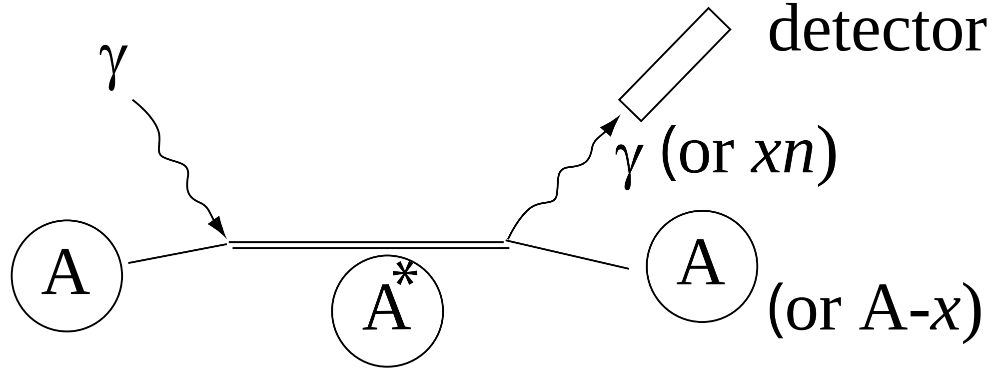
$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{abs}}{\omega^2} d\omega = \frac{8\pi}{9} \int \frac{dB(E1)}{\omega}$$

Electric Dipole (E1) Response



Probing EM response of the target nucleus

○ **Real Photon Measurements, NRF and (γ,xn)**



Target Nucleus

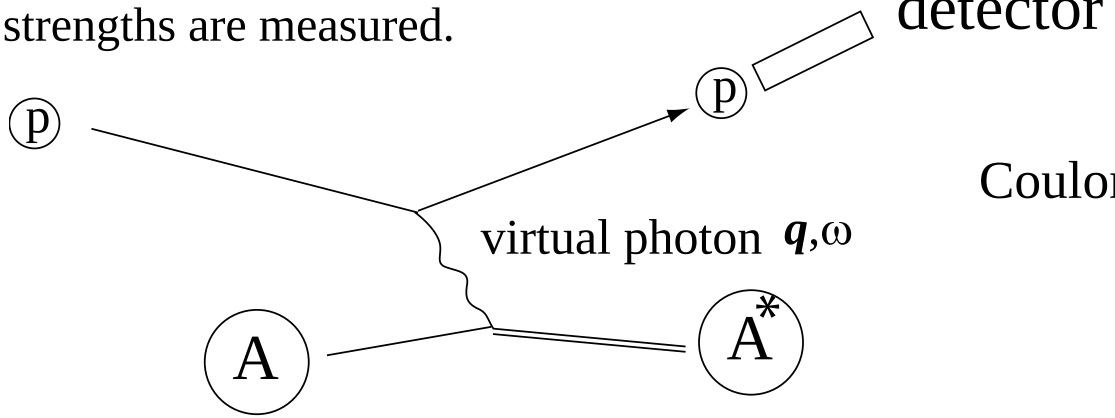
Excited State

Decay γ-rays or neutrons are measured.

○ **Missing Mass Spectroscopy with Virtual Photon**

Only the scattered protons are measured.

Insensitive to the decay channel.
Total strengths are measured.



Target Nucleus

Excited State

Select low momentum transfer (q~0) kinematical condition, i.e. at zero degrees

Coulomb Excitation at 0 deg.

EM Interaction is well known (model independent)

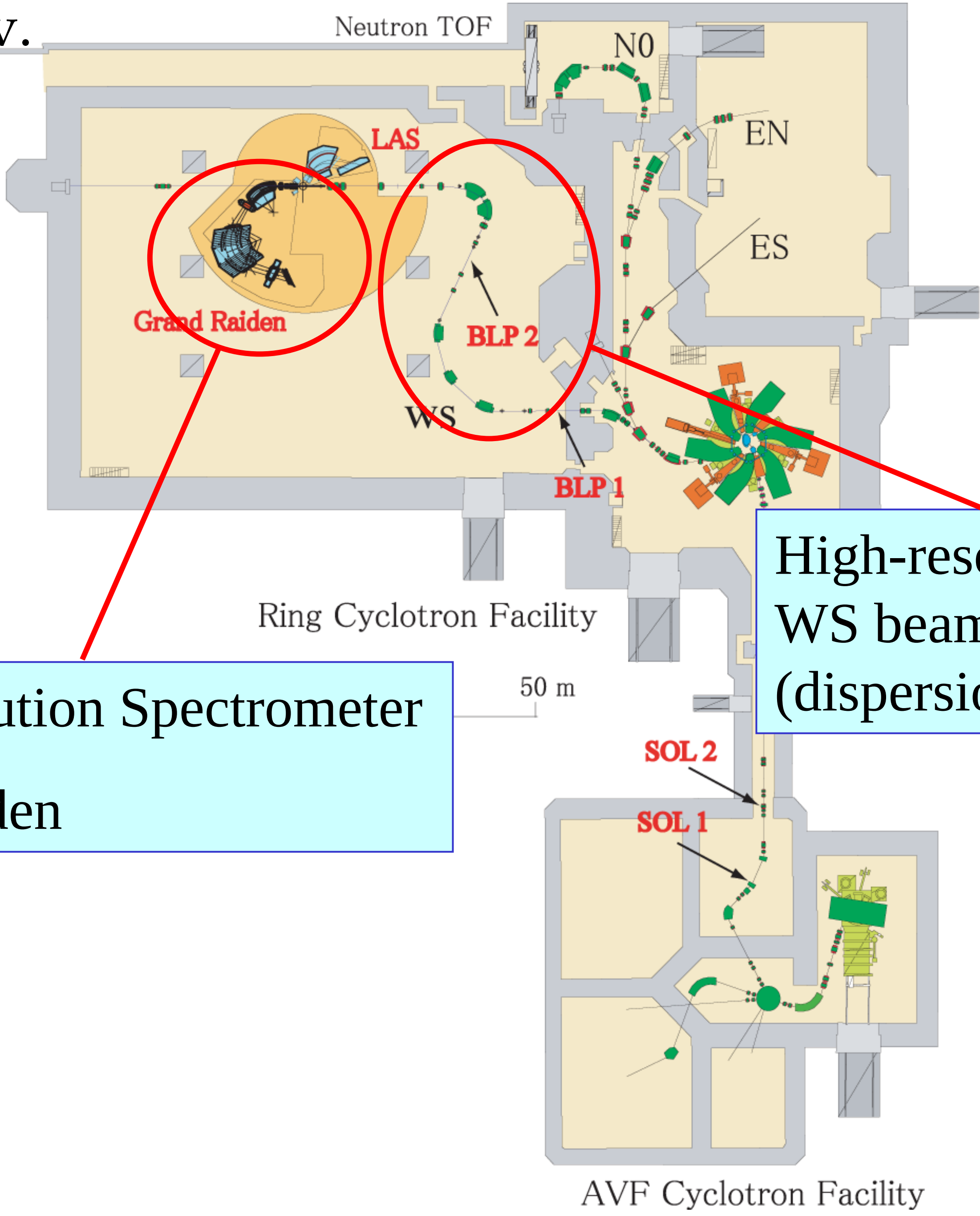
Proton Inelastic Scattering at Forward Angles

- **An electromagnetic** probe (Coulomb excitation)
- **High-resolution** (20-30keV), **high** (~90%)/**uniform efficiency**
- Covers a broad **Ex of 5-25MeV**
- Insensitive to the decay property
- Requires **small amount of target** (several mili-gram) and a few days of beam time
- Applicable to stable nuclei

Experimental Method

High-resolution polarized (p,p') measurement
at zero degrees and forward angles

Research Center for Nuclear Physics, Osaka Univ.



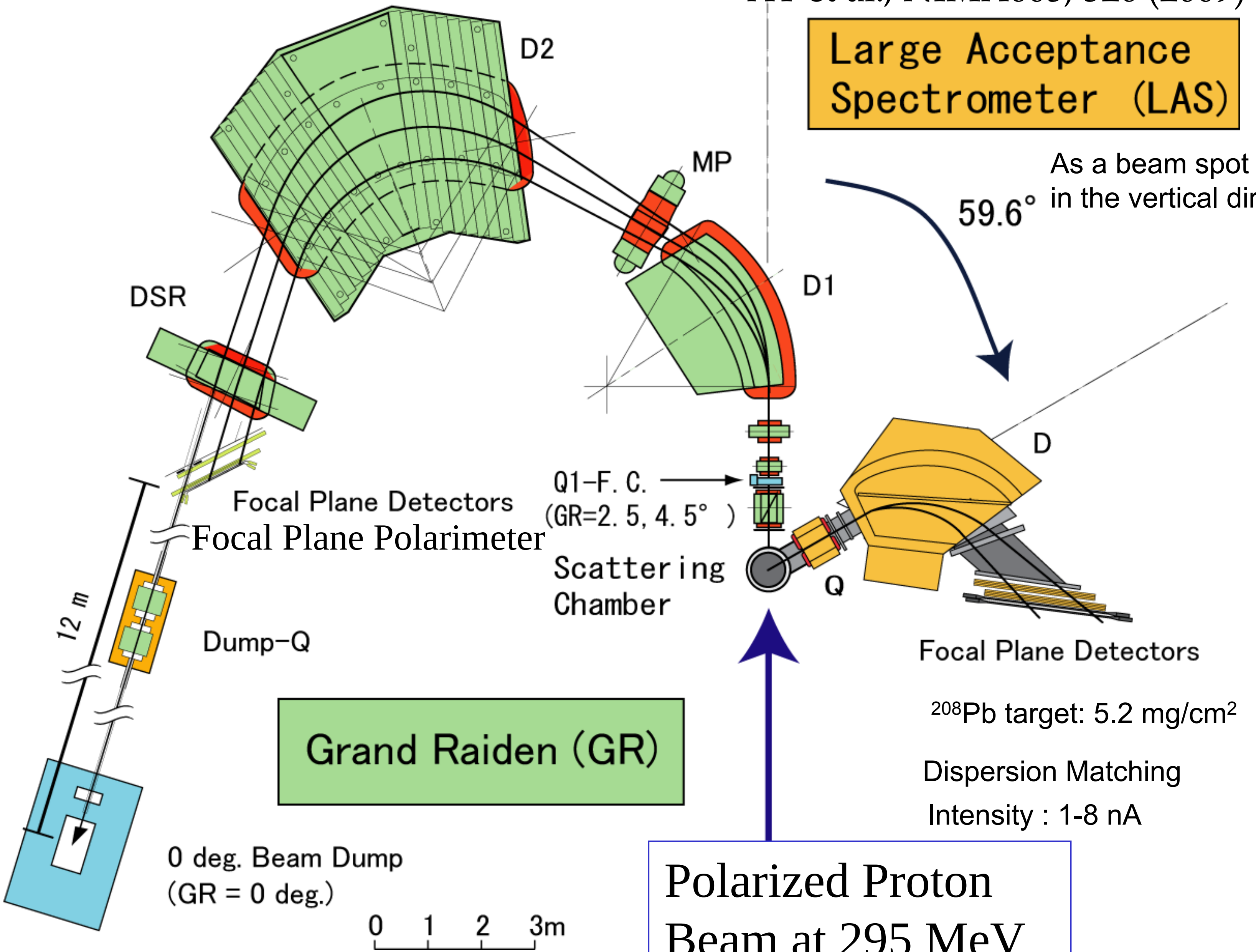
High-resolution Spectrometer

Grand Raiden

High-resolution
WS beam-line
(dispersion matching)

Spectrometers in the 0-deg. experiment setup

AT et al., NIMA605, 326 (2009)



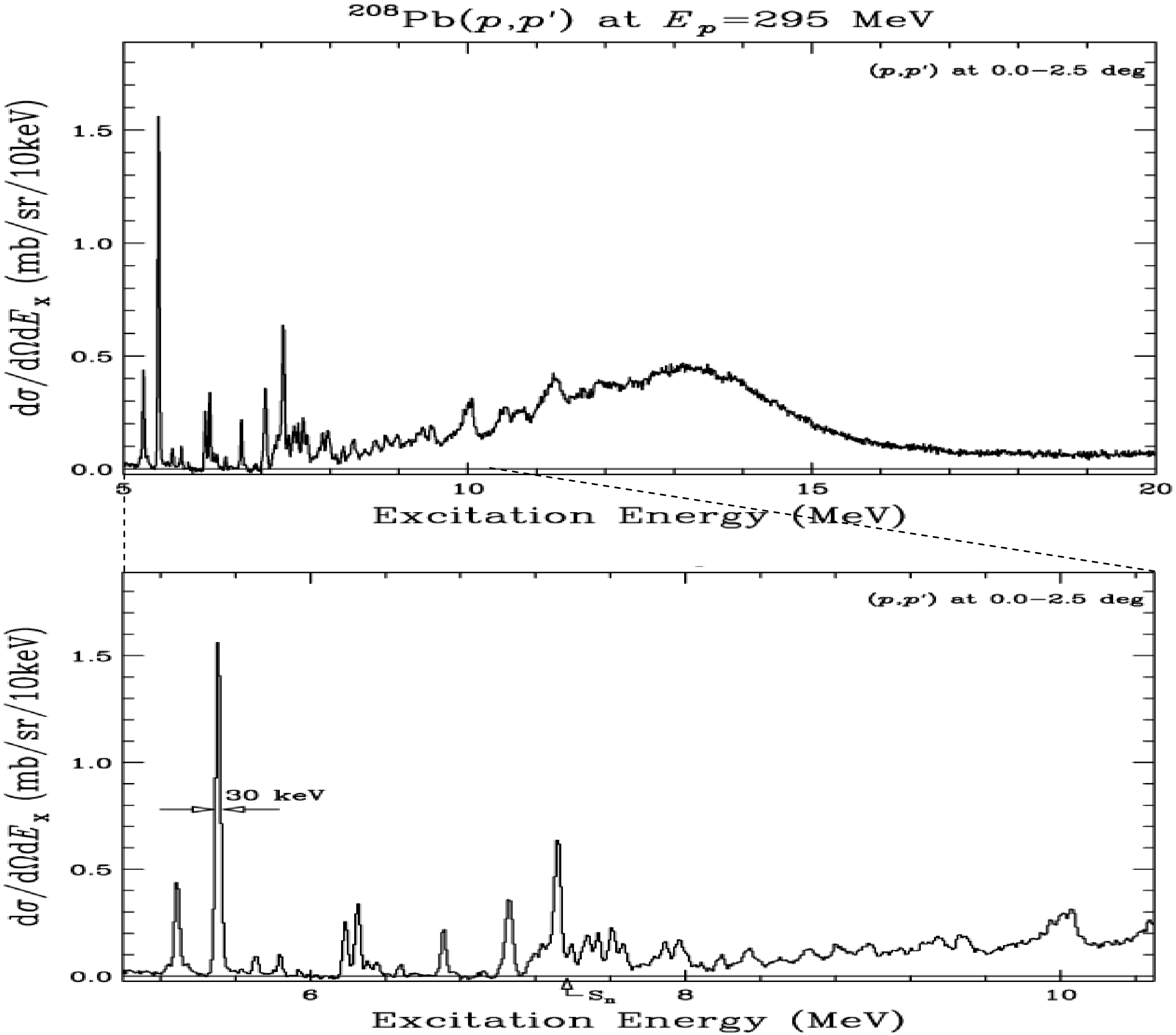
^{208}Pb target: 5.2 mg/cm^2

Dispersion Matching

Intensity : 1-8 nA

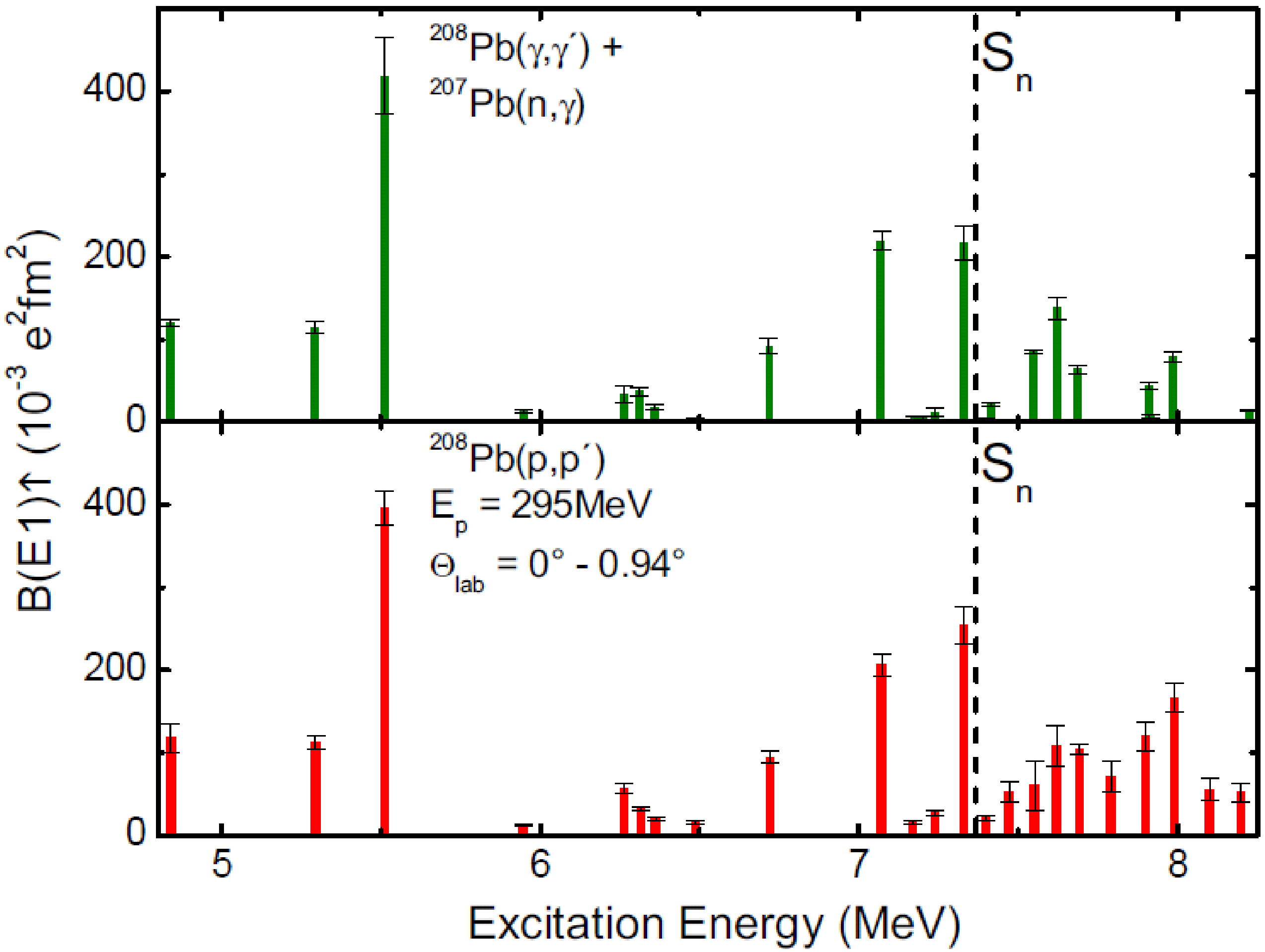
Polarized Proton Beam at 295 MeV

Setup for E282&E316



^{208}Pb(p,p') at E_p=295 MeV
(p,p') at 0.0–2.5 deg
dσ/dΩdE$_x$ (mb/sr/10keV)
0.0
0.5
1.0
1.5
5
10
15
20
Excitation Energy (MeV)
(p,p') at 0.0–2.5 deg
30 keV
S$_n$
6
8
10
Excitation Energy (MeV)

B(E1): low-lying discrete states

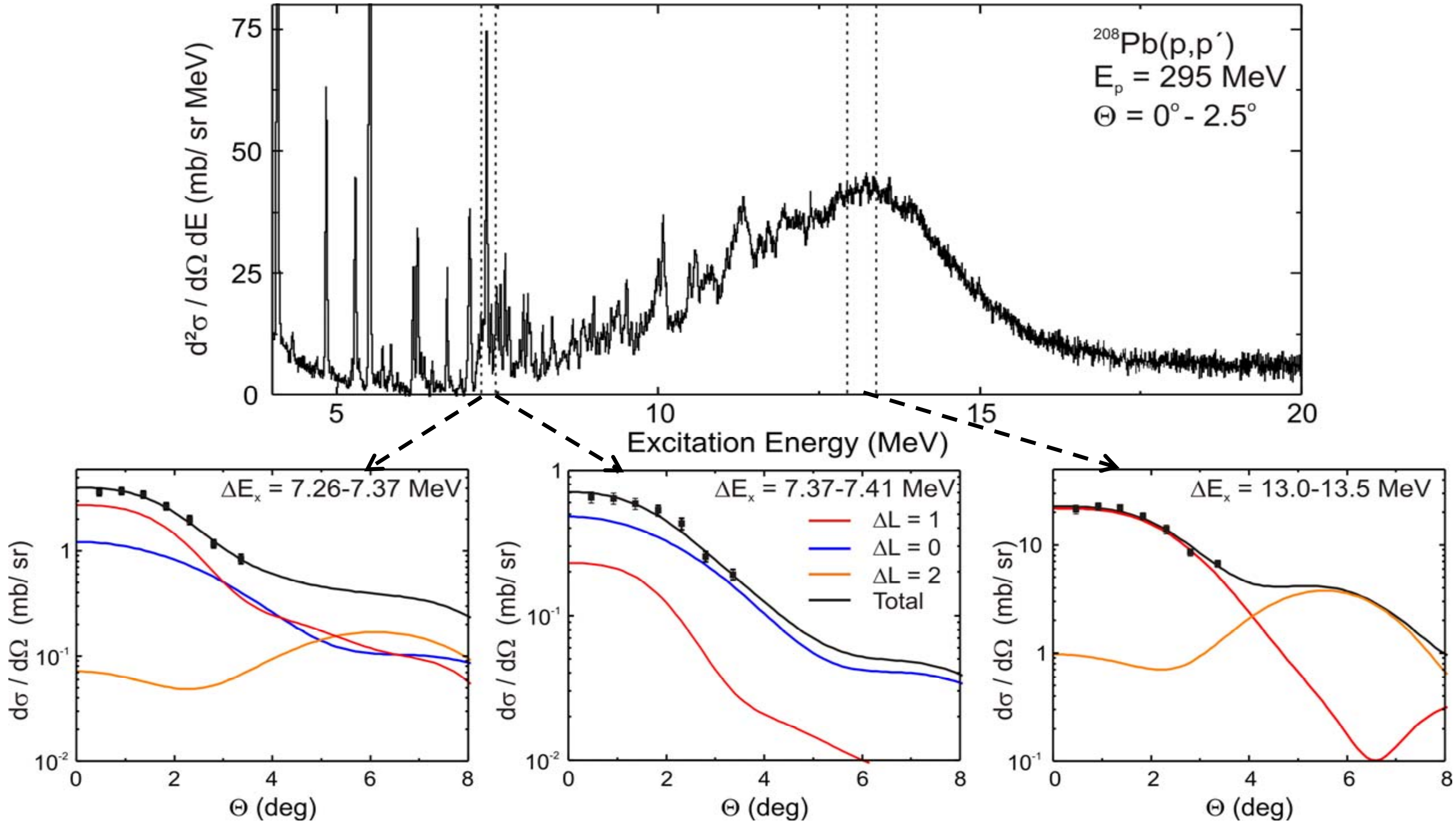


Excellent agreement between (p,p′) and (γ,γ′) below ~S_n

I. Poltoratska, PhD thesis

B(E1): continuum and GDR region

Method 1: Multipole Decomposition



- Neglect of data for Θ>4: (p,p´) response too complex
- Included E1/M1/E2 or E1/M1/E3 (little difference)

B(E1): continuum and GDR region

Method 2: Decomposition by Spin Observables

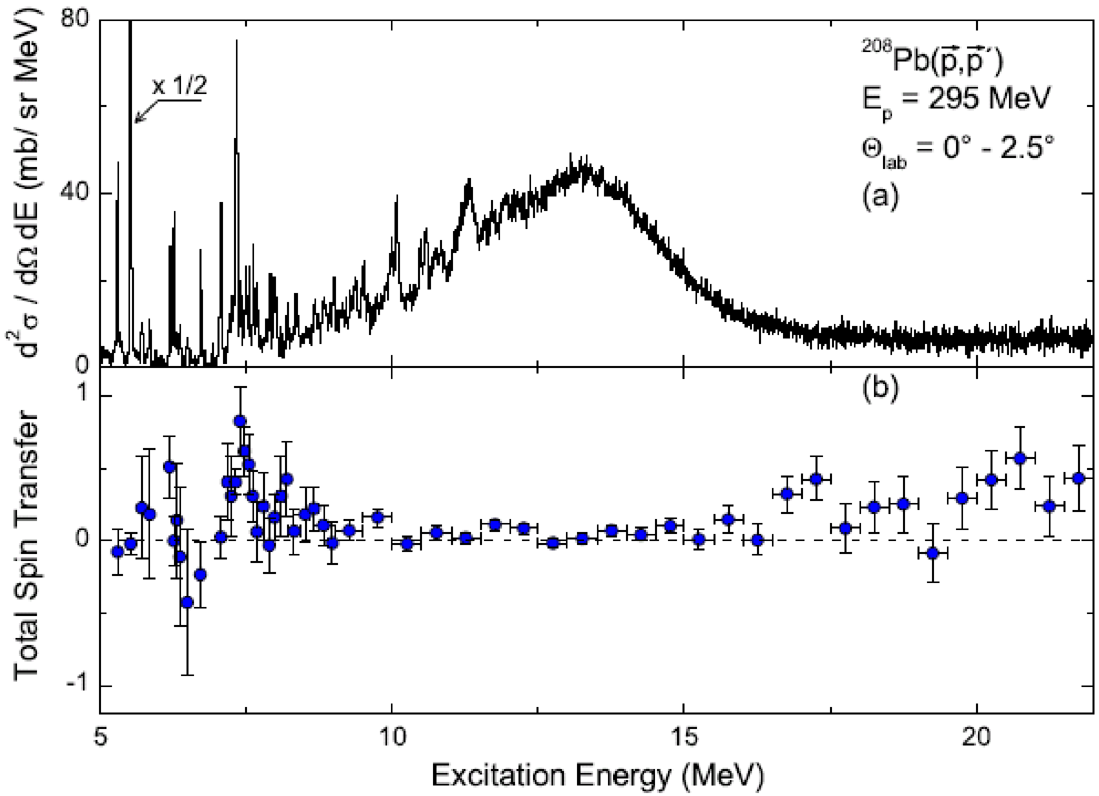
- Polarization observables at 0° → spinflip / non-spinflip separation

model-independent

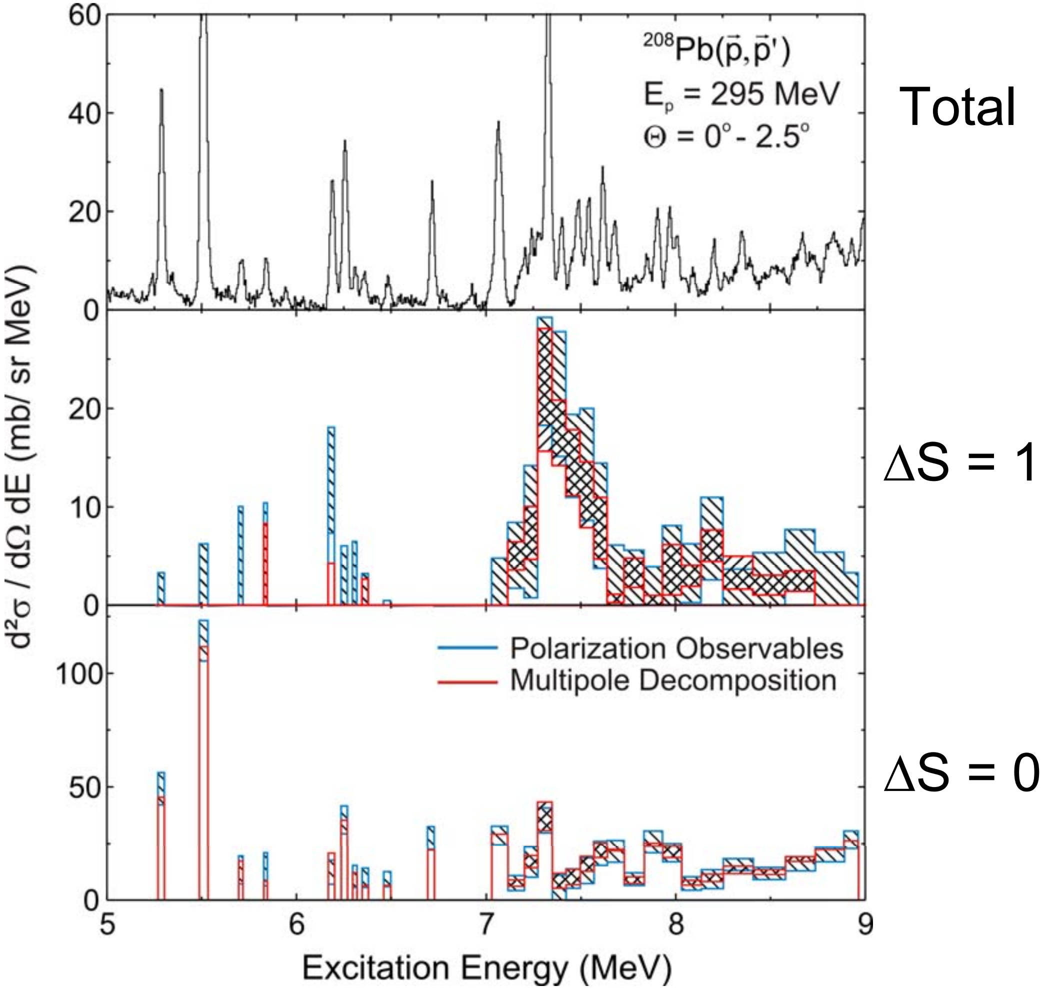
E1 and M1 decomposition

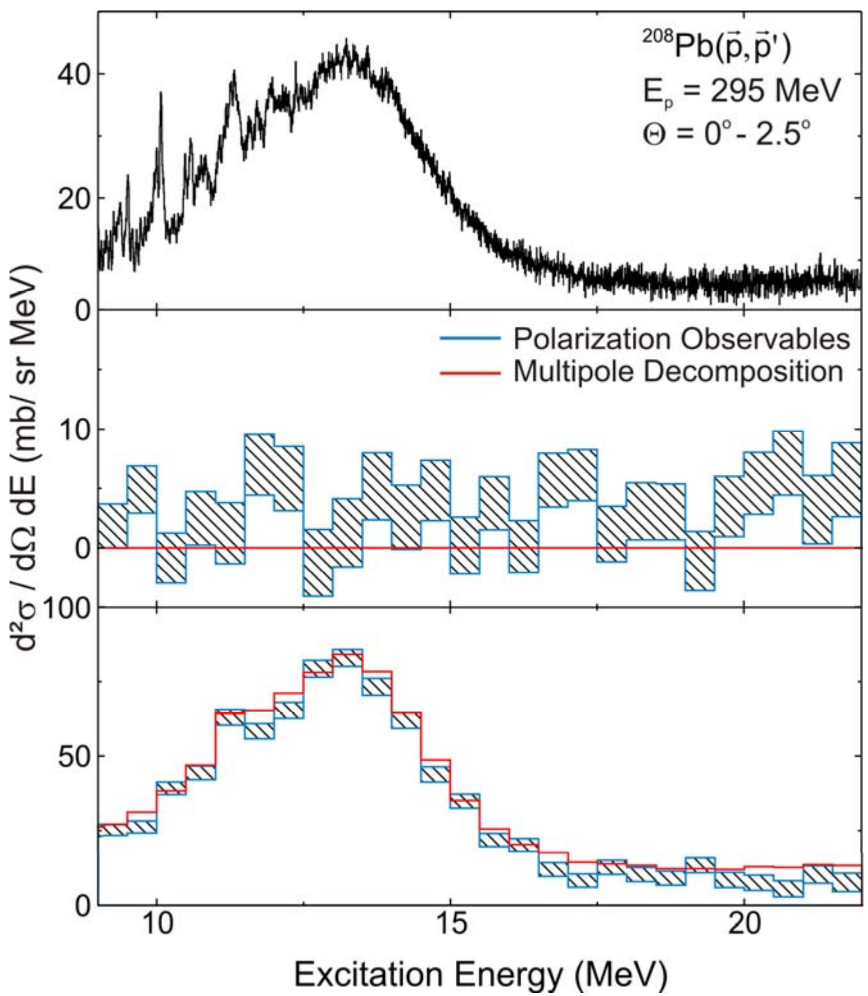
T. Suzuki, PTP 103 (2000) 859

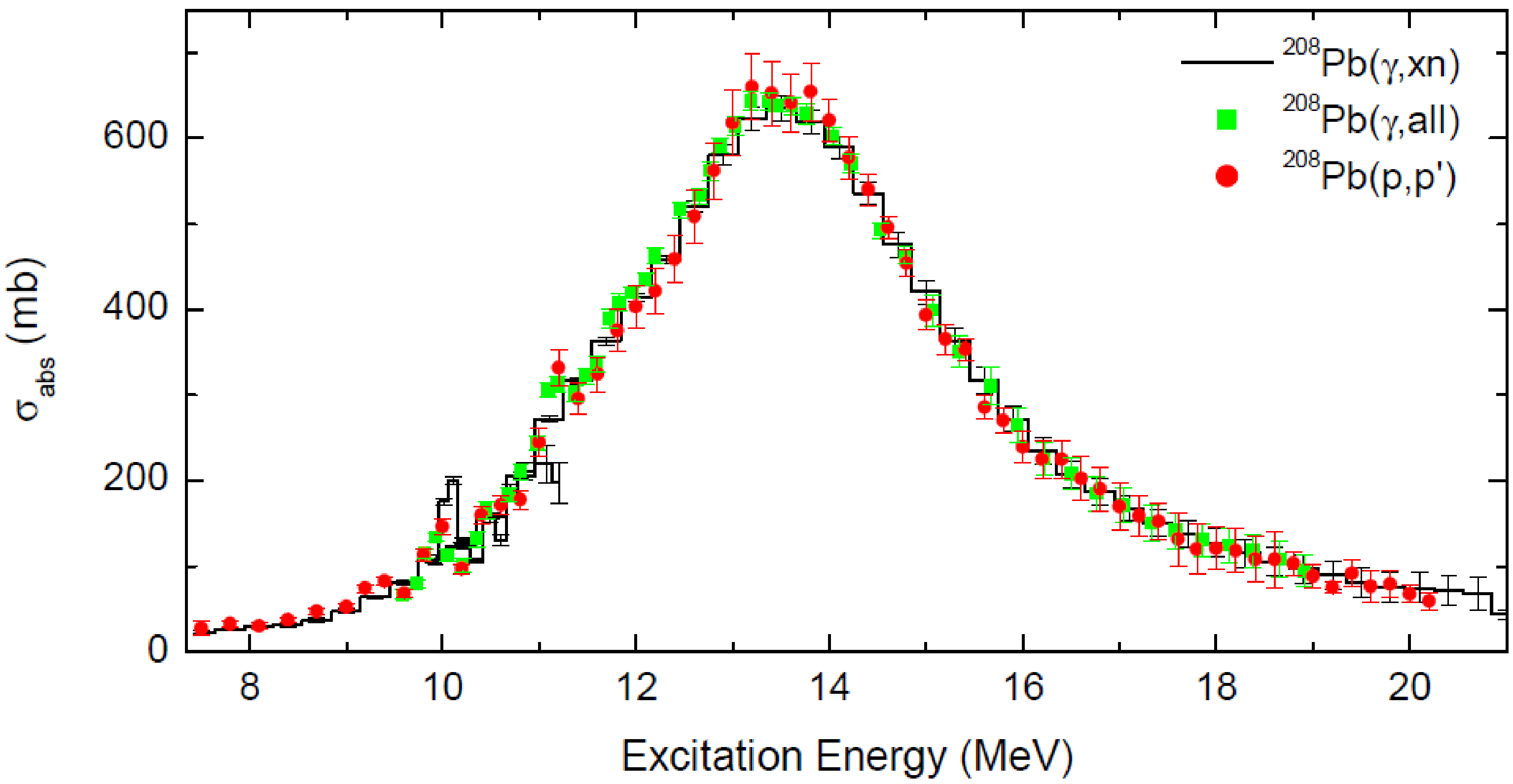
$$\text{Total Spin Transfer} \quad \Sigma \equiv \frac{3-(2D_{SS}+D_{LL})}{4} = \begin{cases} 1 \text{ for } \Delta S = 1 & \text{M1} \\ 0 \text{ for } \Delta S = 0 & \text{E1} \end{cases}$$



Comparison between the two methods



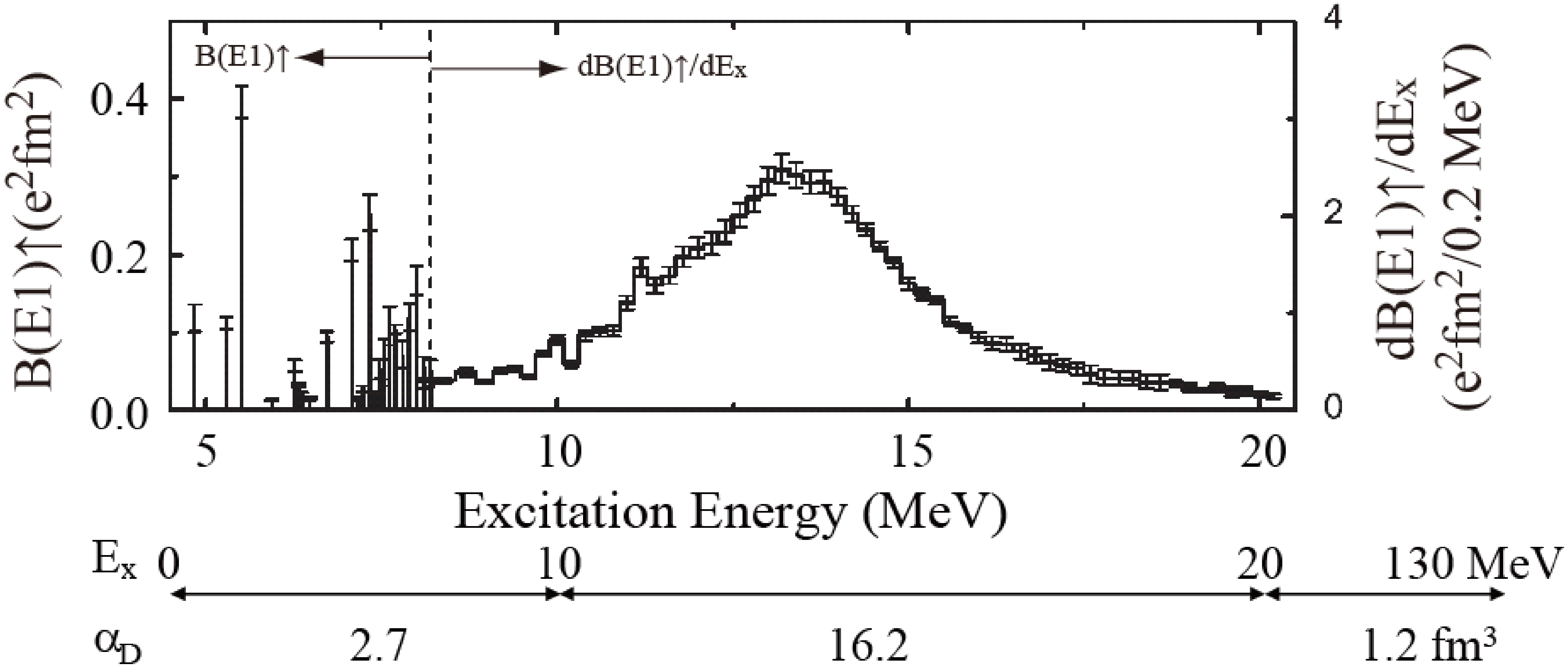




Excellent agreement among three measurements around the GDR bump region

I. Poltoratska, PhD thesis

E1 Response of ^{208}Pb and α_D



total 20.1±0.6 fm³

combined data

The dipole polarizability of ^{208}Pb has been precisely determined.

AT et al., PRL107, 062502(2011)

Abstract

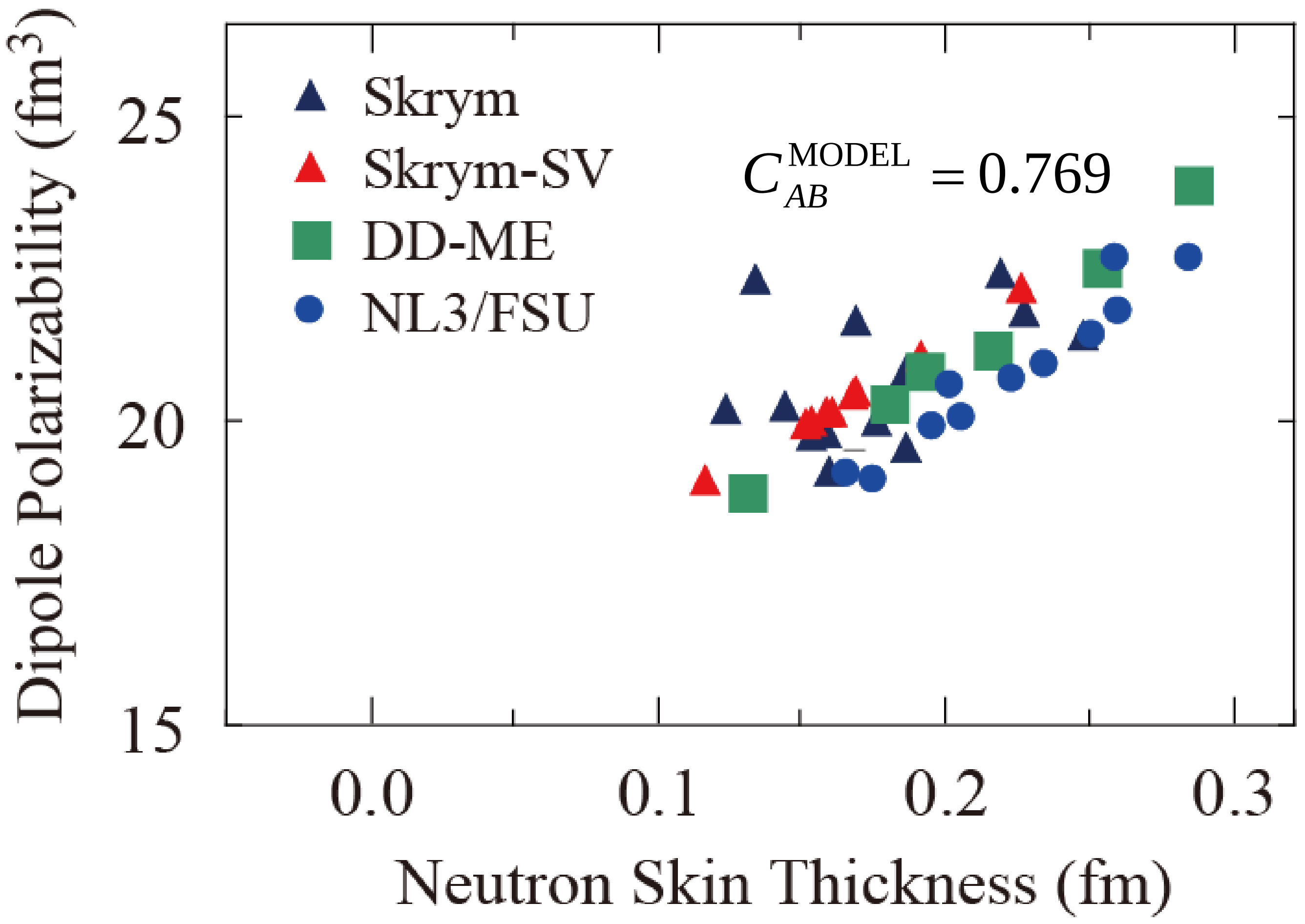
B(E1) distribution of ^{208}Pb has been precisely determined.

Dipole polarizability: $\alpha_D = 20.1 \pm 0.6\,\mathrm{fm}^3$

Constraints on the symmetry energy

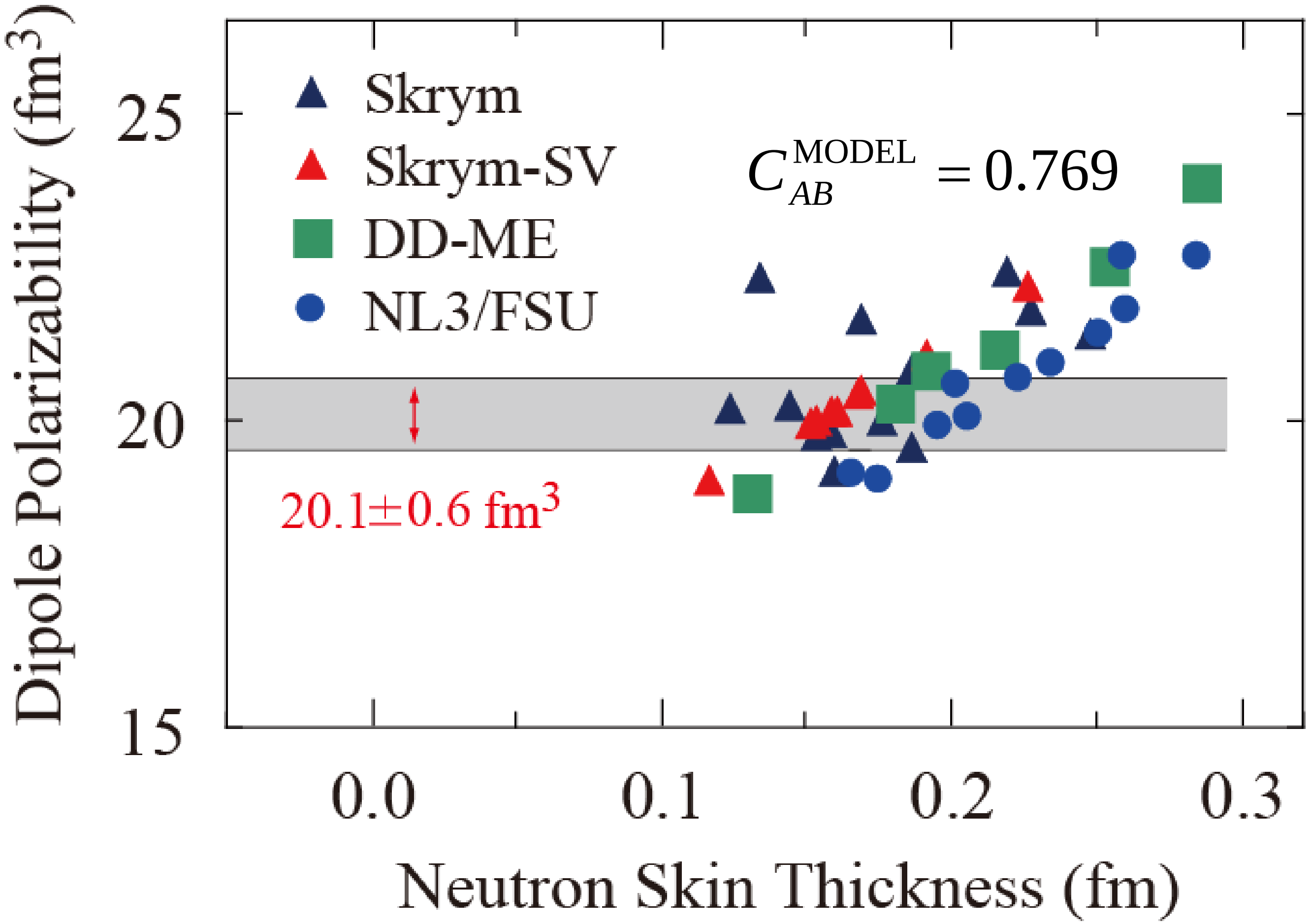
with a help of theoretical models

Correlation Between Dipole Polarizability and Neutron Skin Thickness



J. Piekarewicz et al., PRC85, 041302(2012)

Correlation Between Dipole Polarizability and Neutron Skin Thickness



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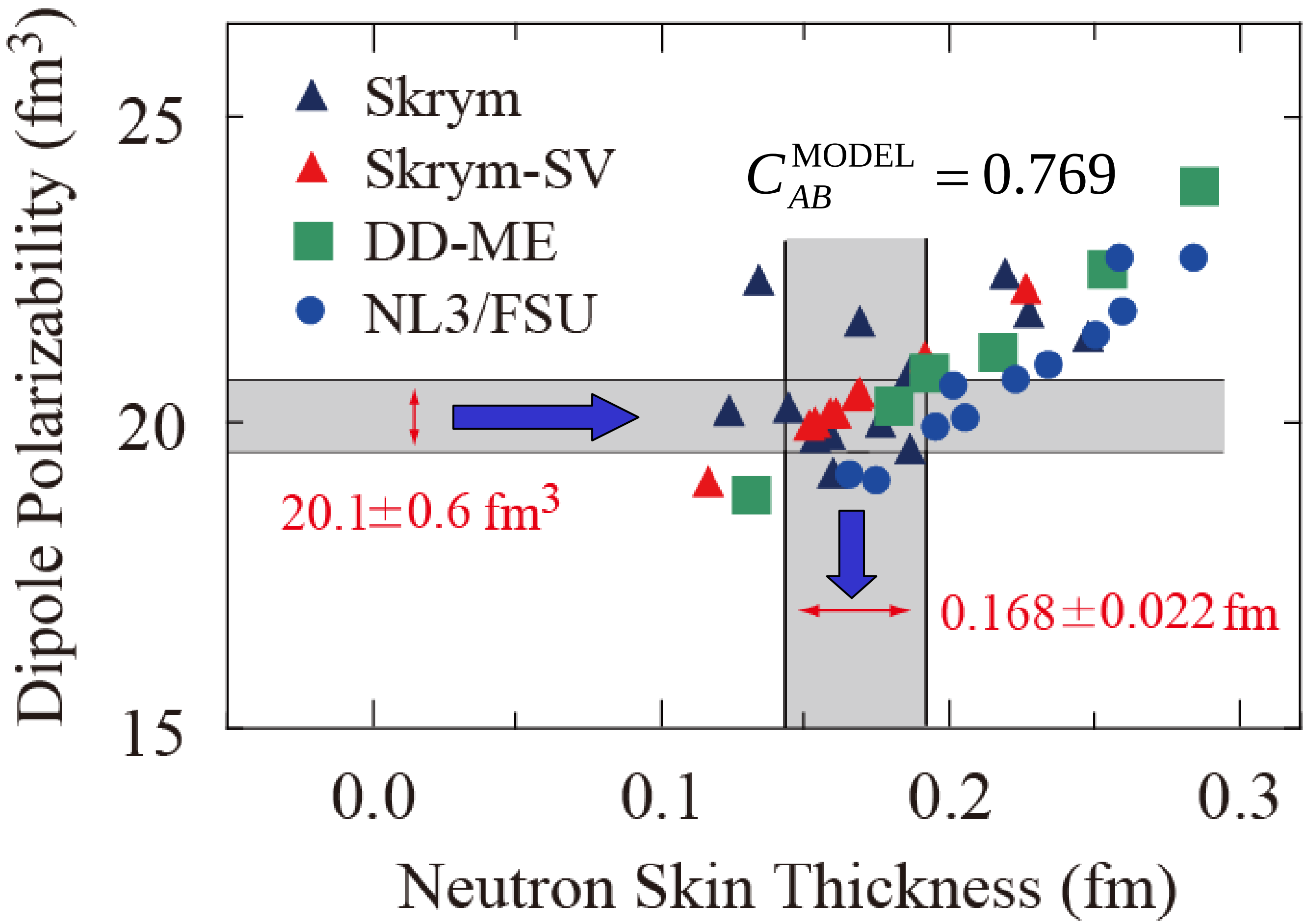
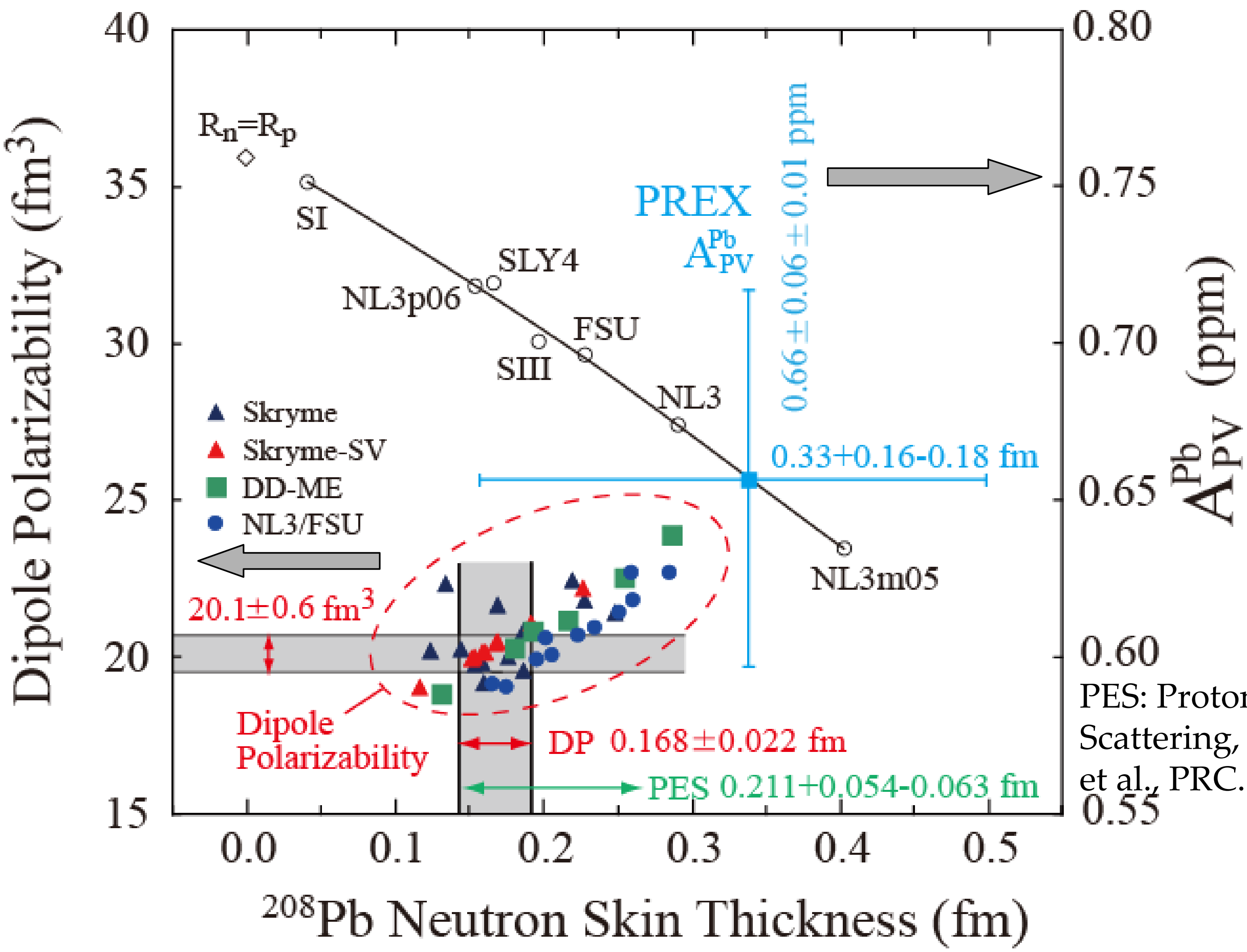


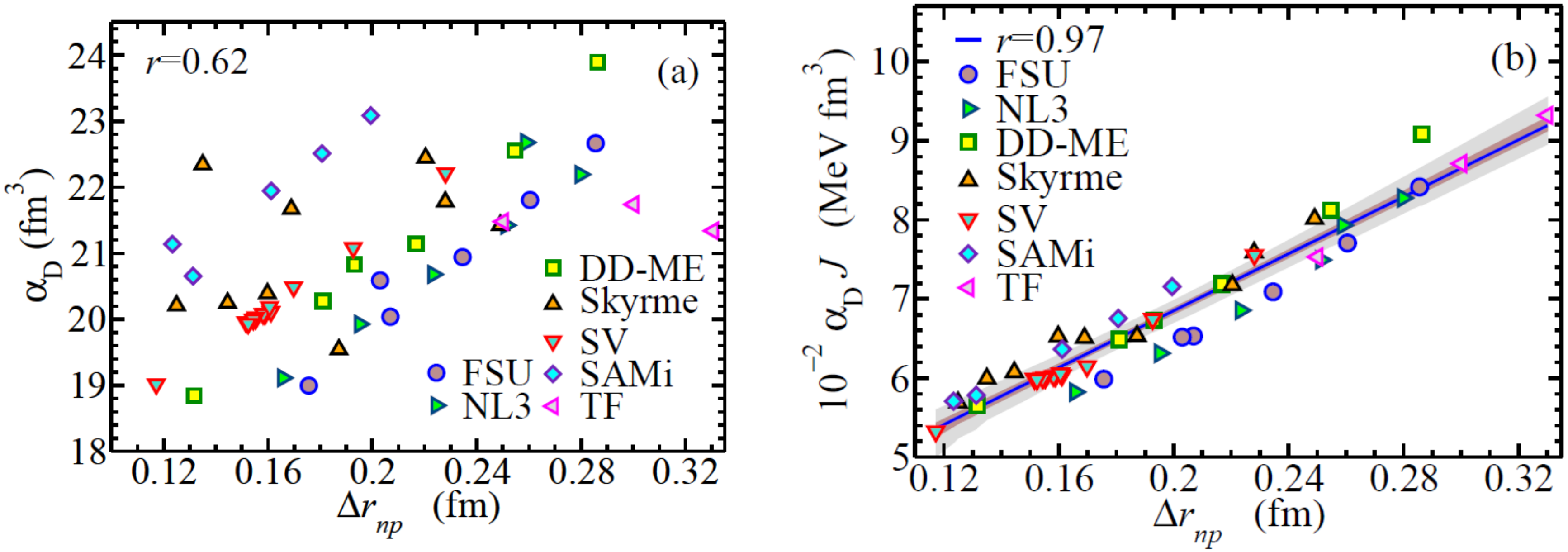
(0.168 ± 0.022) fm in ^{208}Pb

Neutron Skin Thickness Measurement by Electromagnetic Interaction



PES: Proton Elastic Scattering, Zenihiro et al., PRC.

X. Roca-Maza et al., arXiv:1307.4806



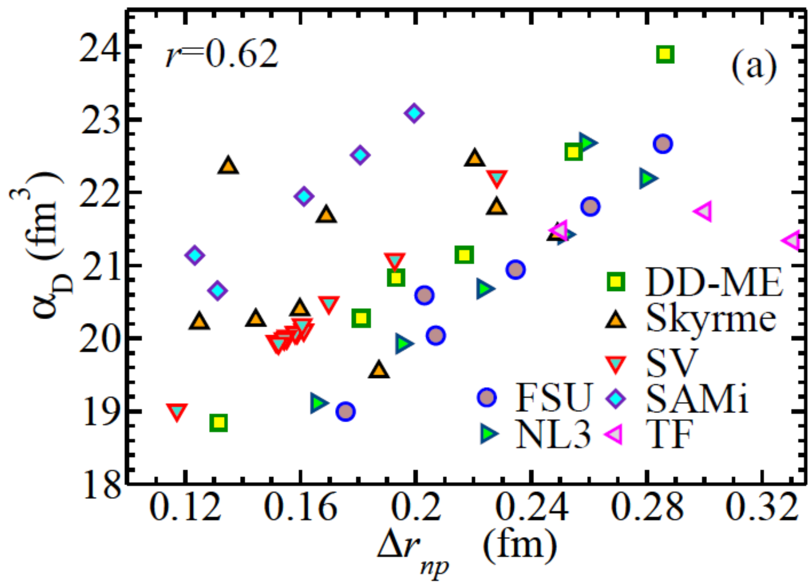
$$10^{-2}\alpha_D J = (3.25 \pm 0.14) + (17.99 \pm 0.70)\Delta r_{np}$$

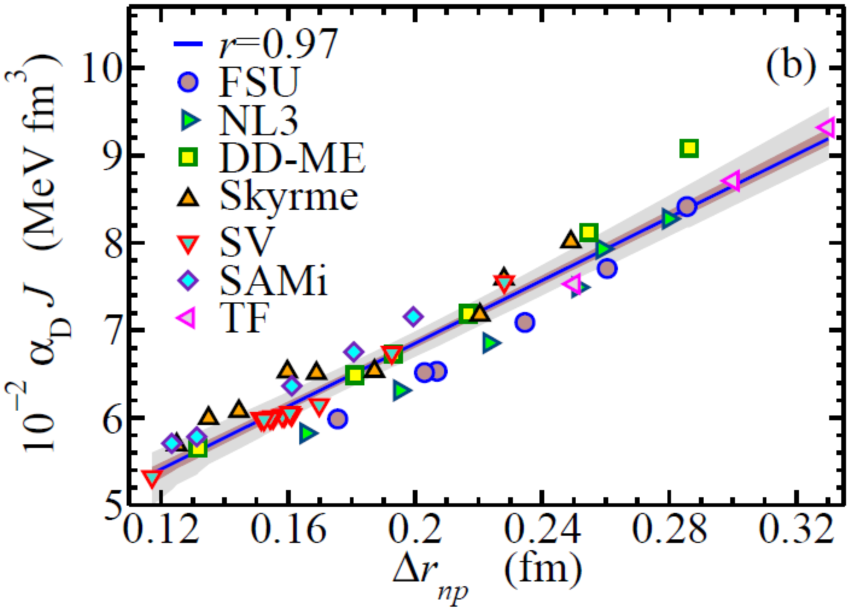
α_D J is a strong isovector indicator.

Insights from the droplet model $\alpha_D^{\rm DM} \approx \frac{\pi e^2}{54}\frac{A\langle r^2\rangle}{J}\left[1+\frac{5}{3}\frac{L}{J}\epsilon_A\right]$

Talk by X. Roca-Maza (next session)

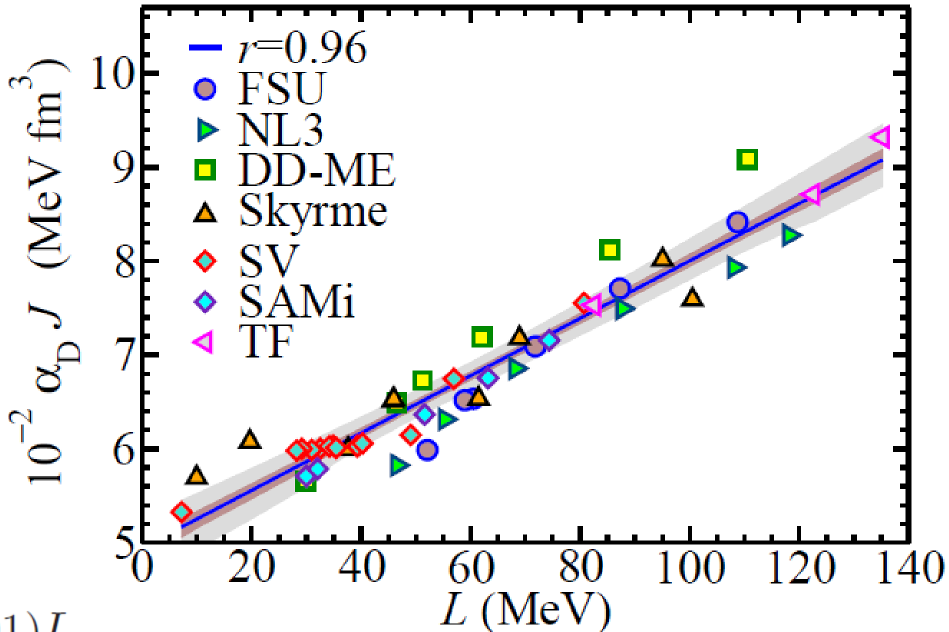
X. Roca-Maza et al., arXiv:1307.4806





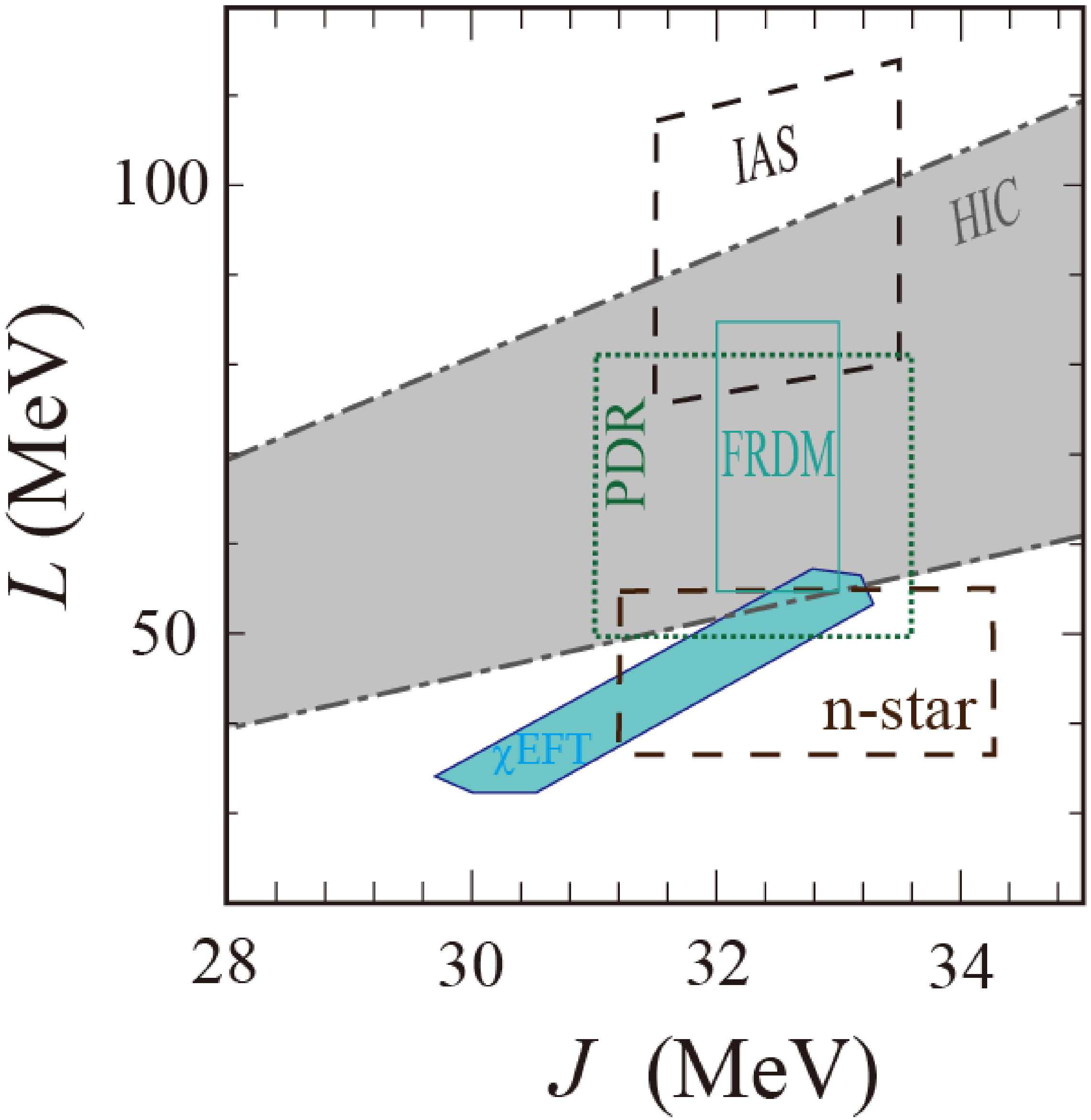
It would be better to use the correlation between α_D J and L (or Δ_{np}) than use the correlation between α_D and L (or Δnp) to extract constraints.

We have used the correlation between α_D J and L (gray band in the right figure) to extract a constraint band in the J-L plane.



$$10^{-2}\alpha_D J = (4.94 \pm 0.09) + (0.031 \pm 0.001)L$$

Constraints on J and L

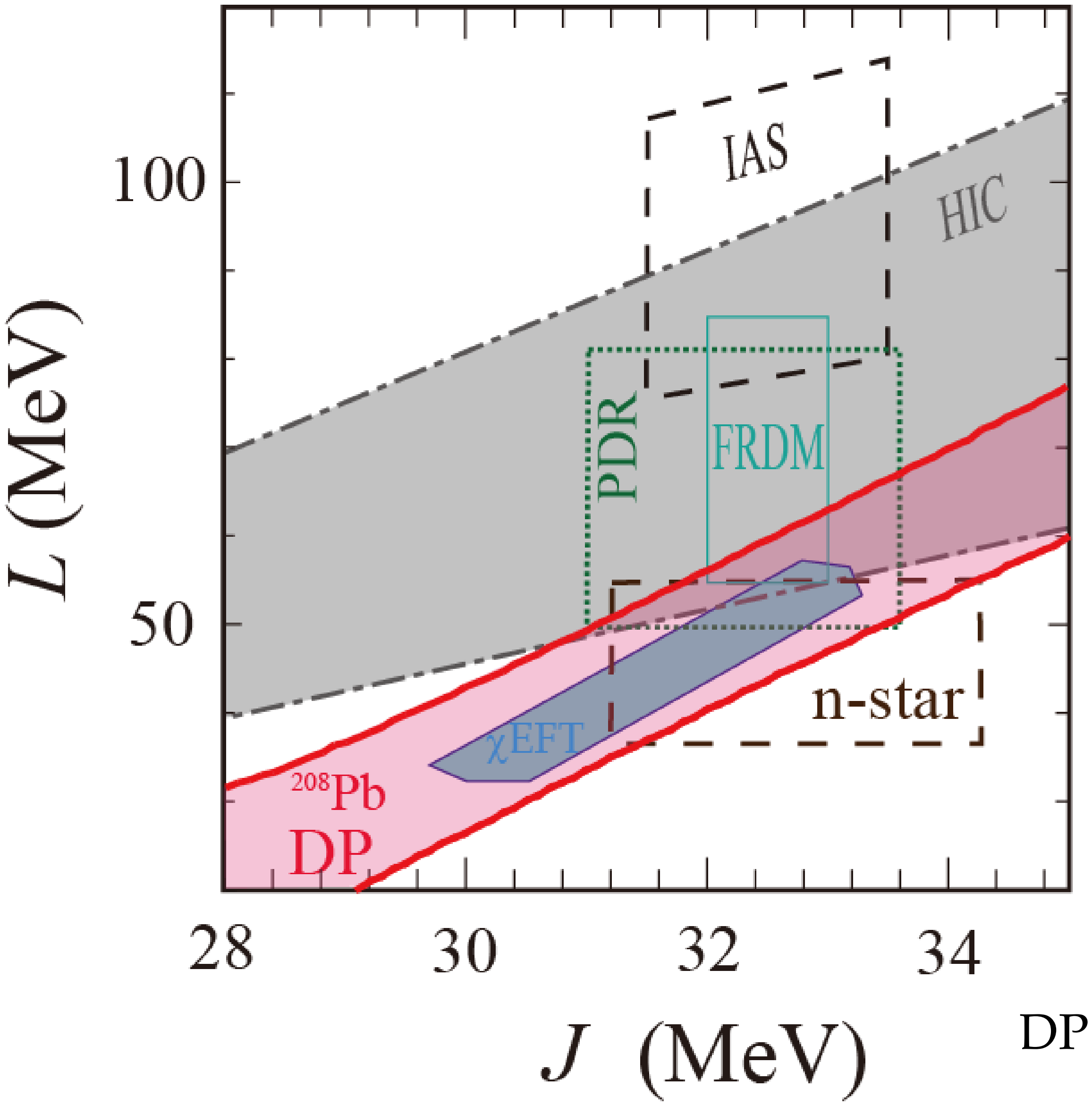


M.B. Tsang *et al.*, PRC**86**, 015803 (2012).

I. Tews et al., PRL110, 032504 (2013)

DP: Dipole Polarizability
HIC: Heavy Ion Collision
PDR: Pygmy Dipole Resonance
IAS: Isobaric Analogue State
FRDM: Finite Range Droplet Model (nuclear mass analysis)
n-star: Neutron Star Observation
χEFT: Chiral Effective Field Theory

Constraints on J and L



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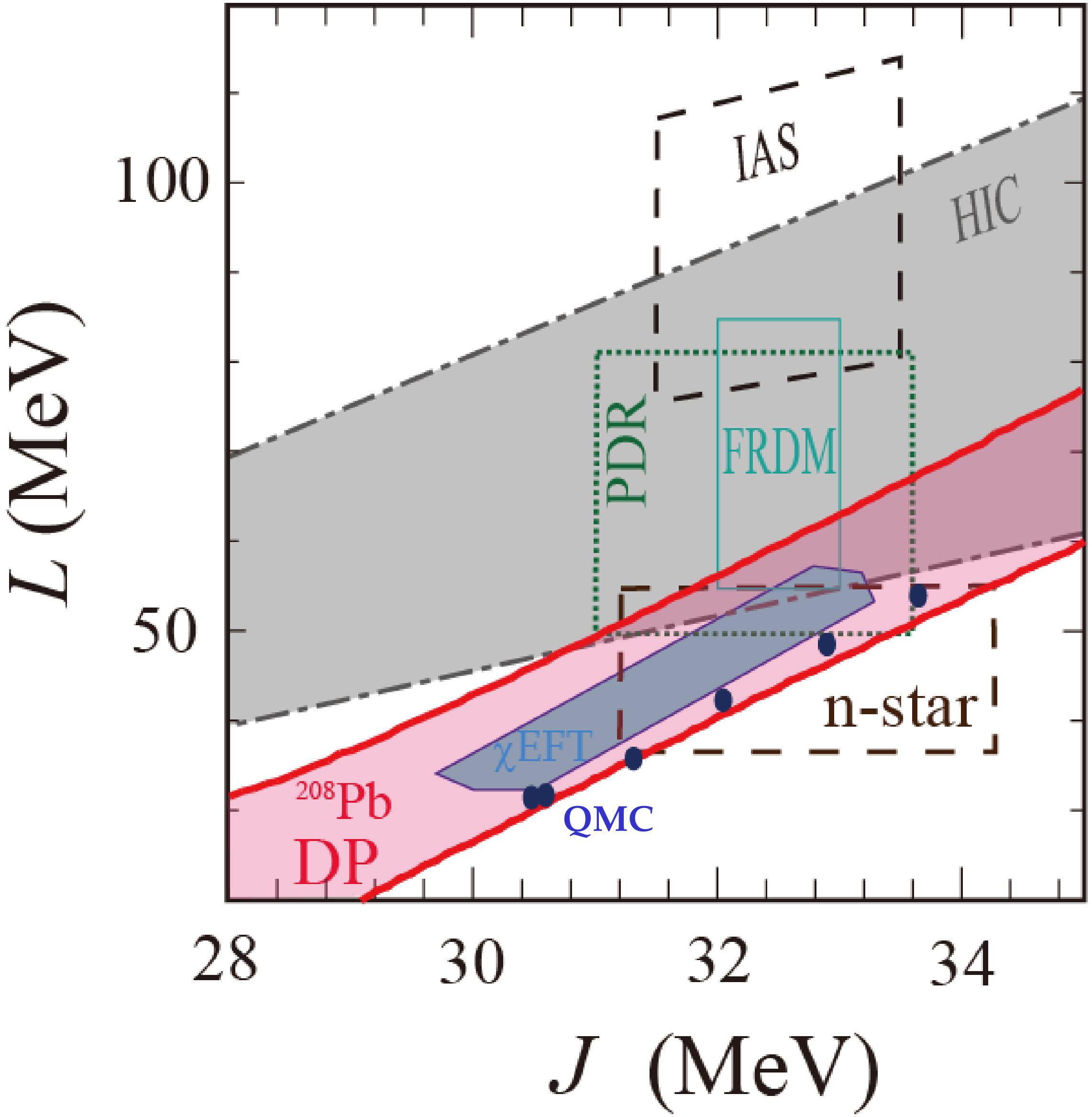
DP: $\alpha_D = 20.1 \pm 0.6\,\mathrm{fm}^3$

+ theoretical uncertainty

Constraints on J and L



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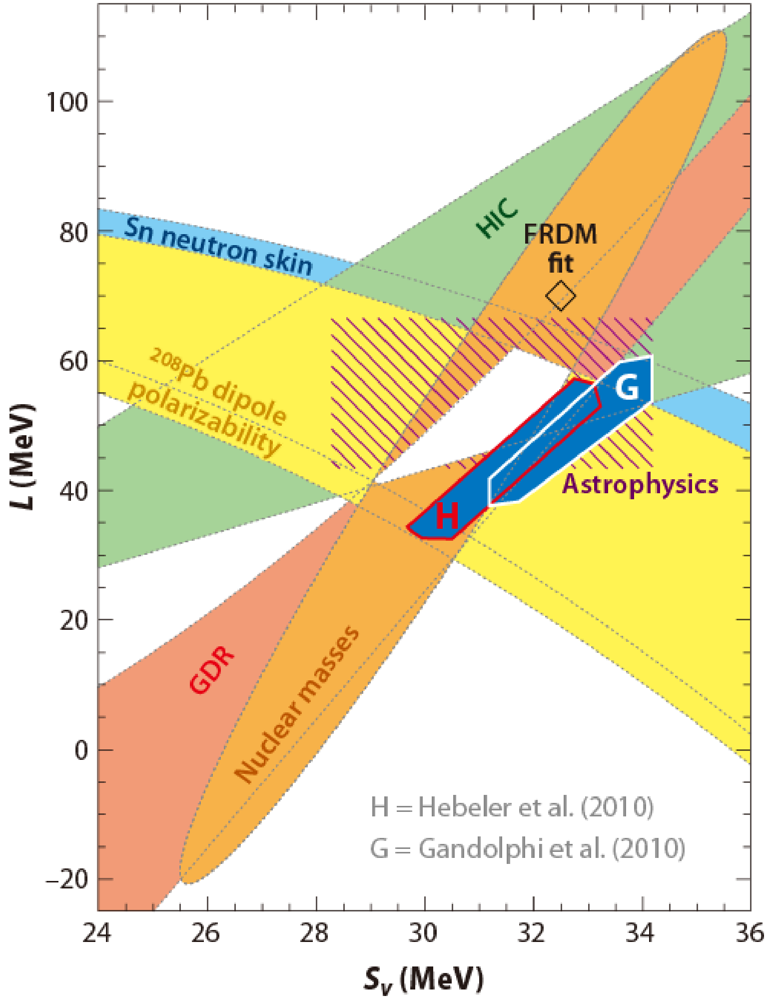
QMC by S. Gandolfi et al., talk on Tuesday

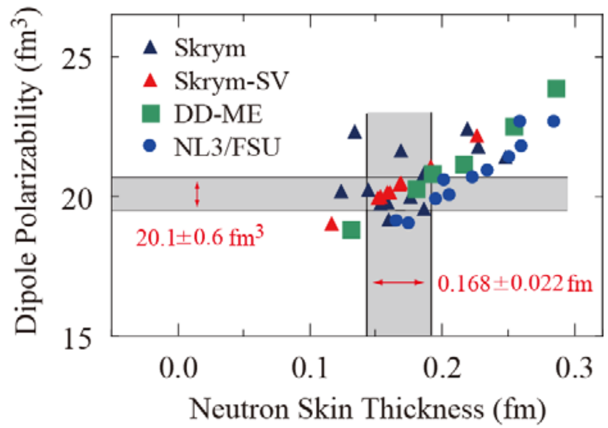
A short note

J. Lattimer Ann. Rev. Nucl. Part. Sci. 62, 485 (2012): talk on Tuesday



J (MeV)

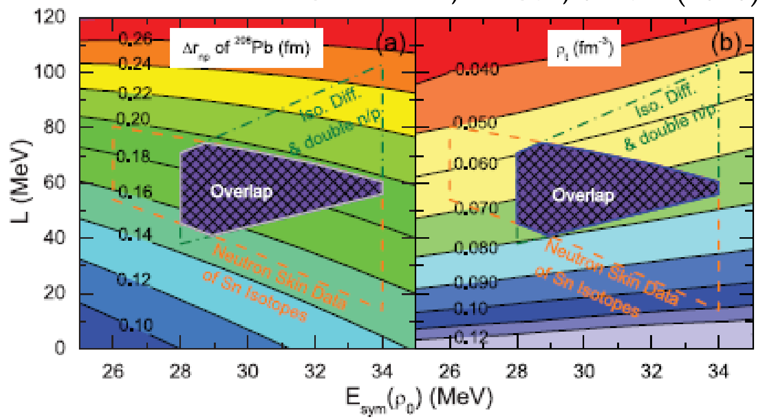
different correlation from the two-step evaluation



^{208}Pb Dipole Polarizability

^{208}Pb neutron skin thickness

L.-W. Chen et al., PRC82, 024321(2010)

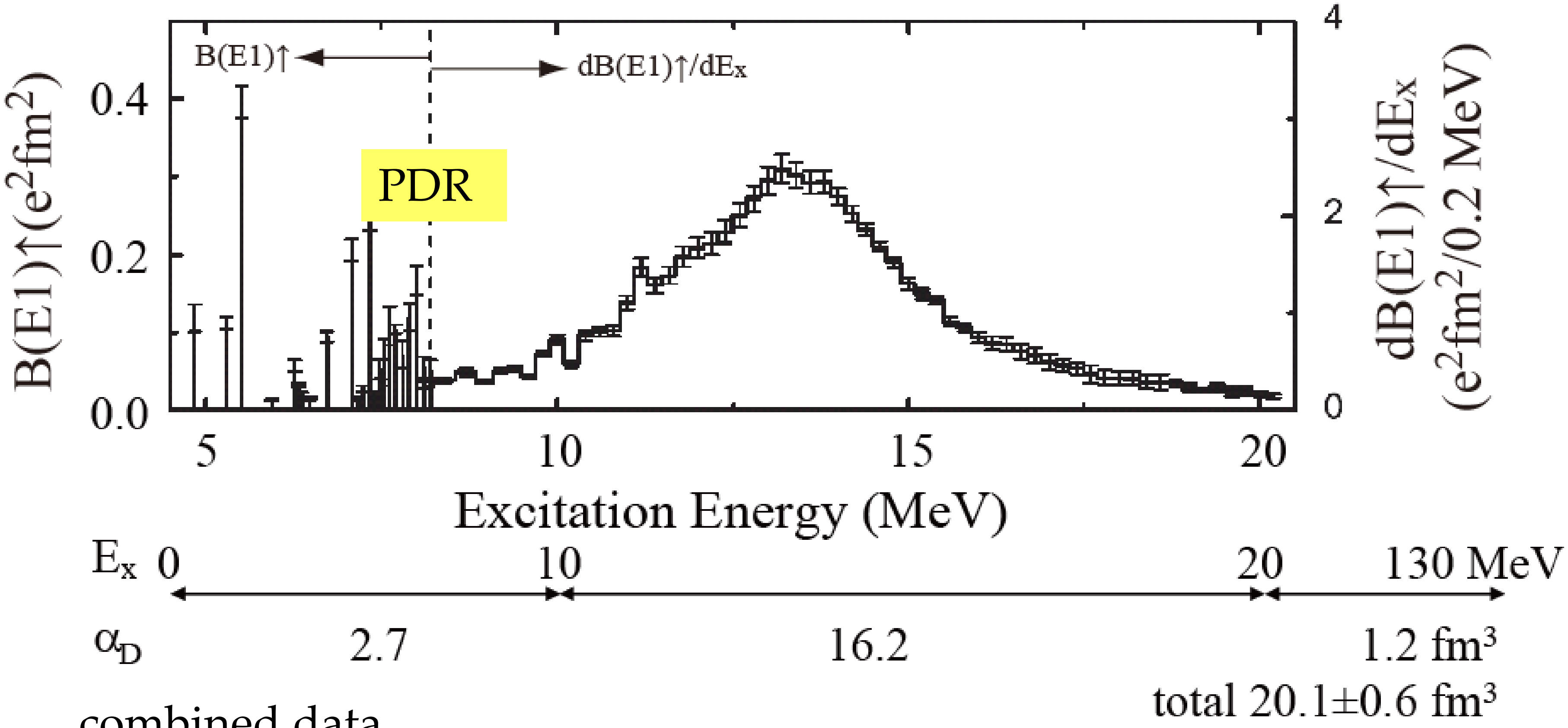


^{208}Pb neutron skin thickness

Constraints on the L-J plane

PDR strength

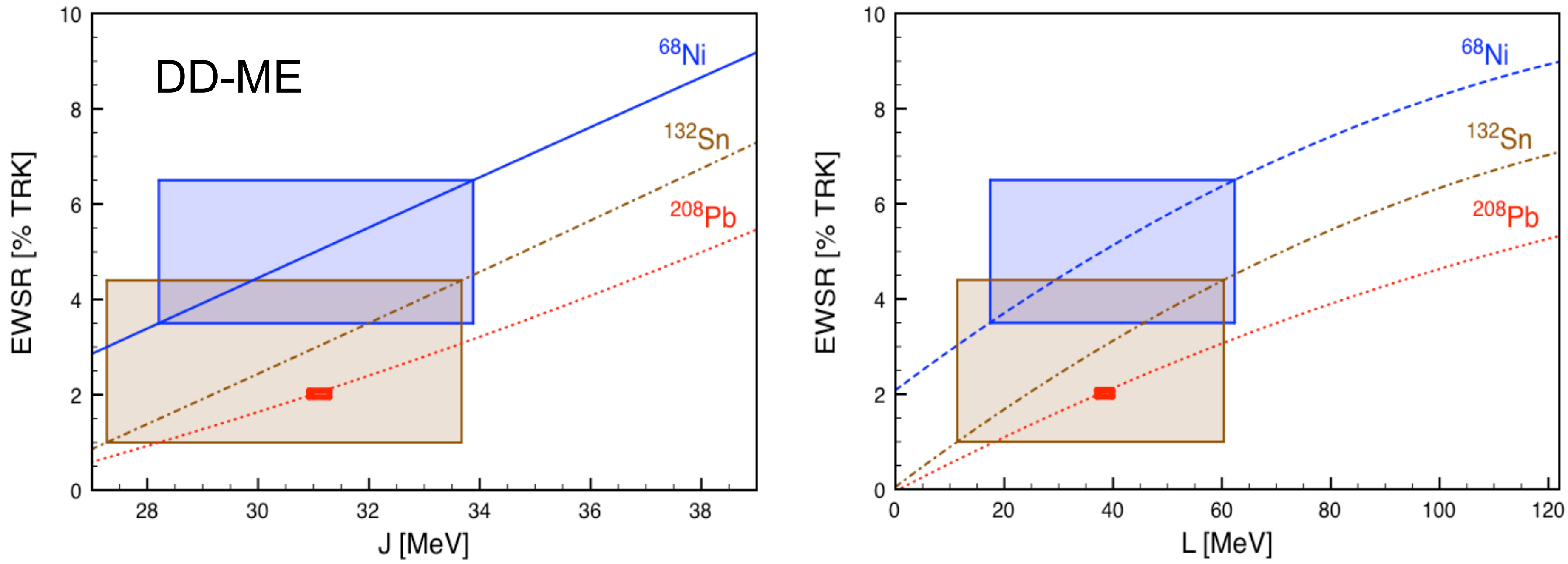
E1 Response of ^{208}Pb and α_D



combined data

AT et al., PRL107, 062502(2011)

• Theoretical dependences of pygmy EWSR on J and L are determined using relativistic energy density functionals spanning the range of J and L values. Available experimental data provide constraints on theoretical models.

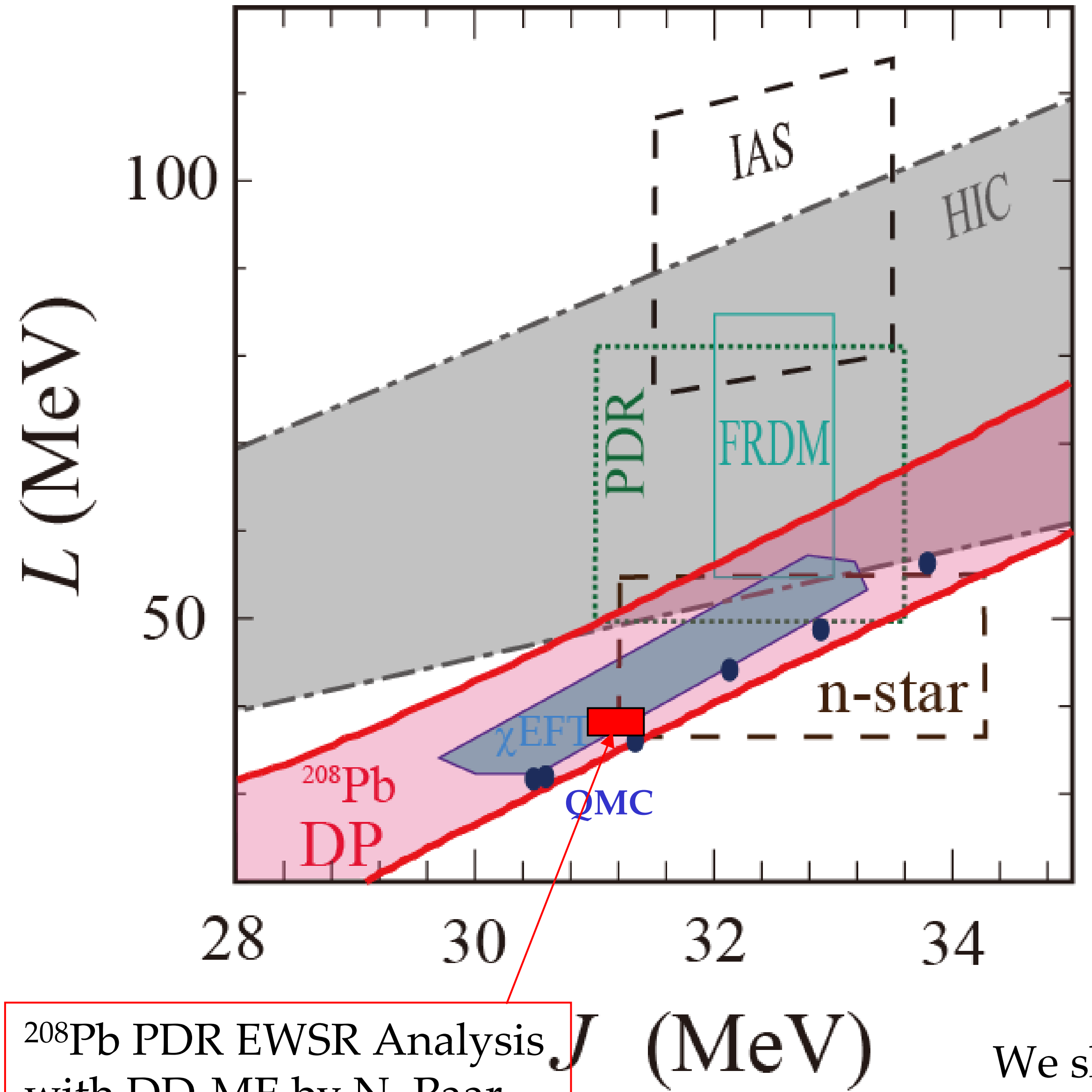


Similar approach but different theory ➔ A. Carbone et al, PRC 81, 041301(R) (2010)

Exp. Data: ^{68}Ni : O. Wieland et al, PRL 102, 092502 (2009)
^{132,130}Sn: A. Klimkiewicz et al., PRC 76, 051603 (R) (2007)
^{208}Pb: I. Poltoratska et al., PRC 85, 041304 (R) (2012)

Courtesy of N. Paar

Determination of Symmetry Energy



208Pb PDR EWSR Analysis with DD-ME by N. Paar

M.B. Tsang *et al.*, PRC**86**, 015803 (2012).

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FRDM: Finite Range Droplet Model (nuclear mass analysis)
n-star: Neutron Star Observation
χEFT: Chiral Effective Field Theory

We should take care of the model uncertainty.

Summary

- The electric dipole response of ^{208}Pb has been precisely measured by using proton inelastic scattering as an electro magnetic probe.

  as α_D=20.1±0.6 fm^3/e^2

- Constraints on the symmetry energy parameters have been extracted with a help of theoretical calculations.

- A lot of data under analysis:

^{96}Mo (DCS and PT): D. Martin
^{48}Ca (DCS): J. Birkhan
^{90}Zr (DCS): C. Iwamoto (PDR-region, published in PRL**108**, 262501 (2012))
^{120}Sn (DCS and PT): A.M. Krumbholtz, T. Hashimoto
^{154}Sm (DCS and PT): A. Krugmann
^{88}Sr, ^{92}Mo (DCS): C. Iwamoto
^{70}Zn (DCS):

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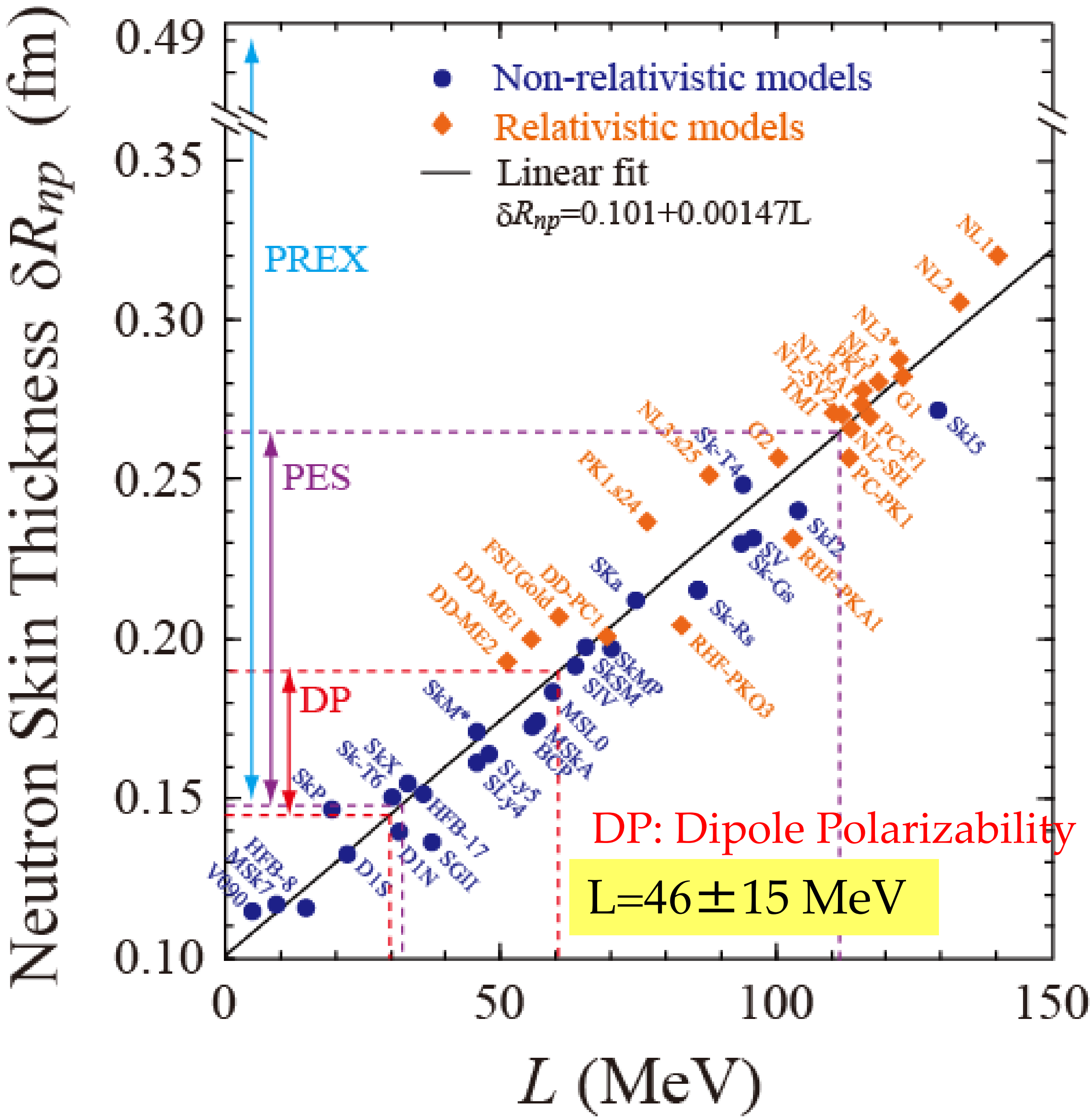


Based on the work by X. Roca-Maza *et al.*, PRL**106**, 252501 (2011)

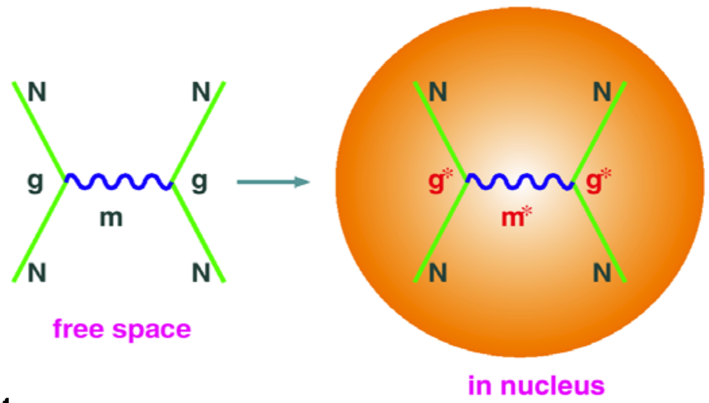
Medium modification of RLF *NN* interaction

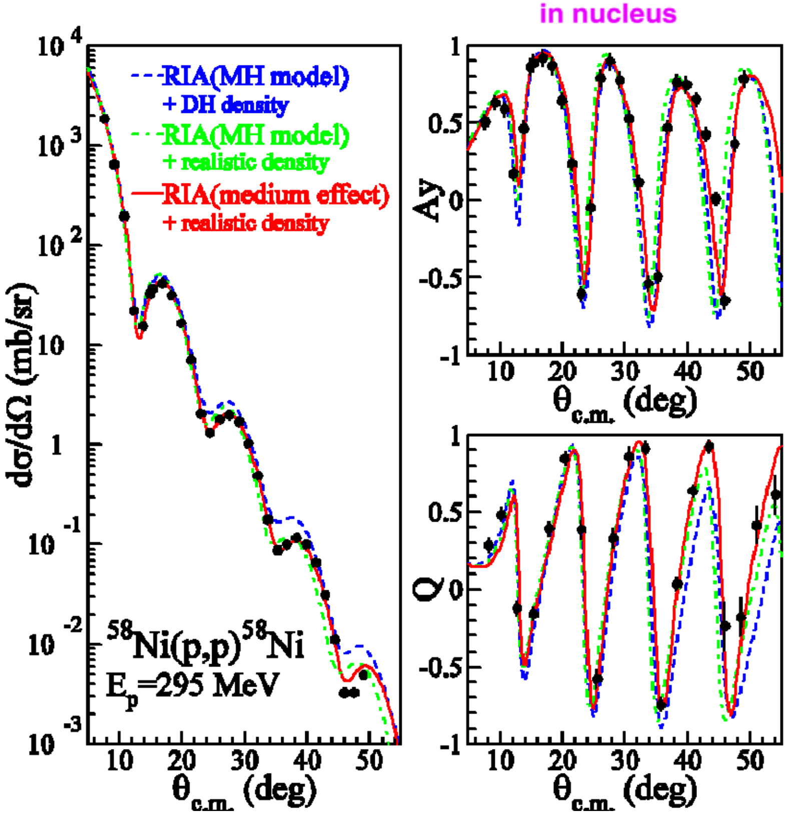
Medium effect

$$g_j^2 \rightarrow g_j^{*2} \equiv \frac{g_j^2}{1 + a_j \rho(r)/\rho_0},$$

$$m_j \rightarrow m_j^* \equiv m_j \left(1 + b_j \rho(r)/\rho_0\right)$$

$$j = \sigma, \omega.$$





→ Phenomenological parameters; a_j, b_j

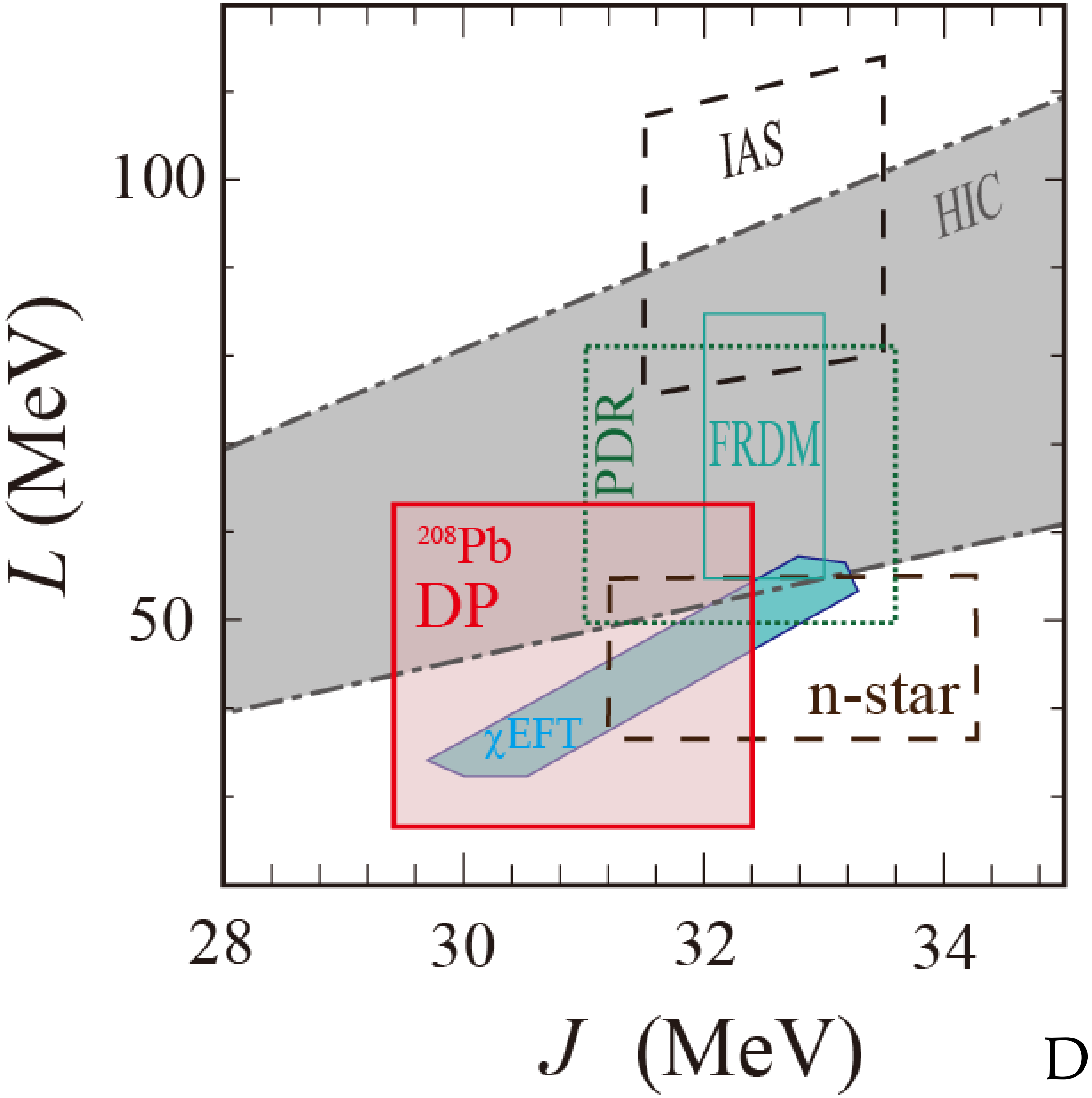
→ Universal form of density-dependent terms

→ At ρ=0, same as free *NN* interaction

Need to calibrate with real data

H. Sakaguchi et al., PRC57, 1749.

Determination of Symmetry Energy



M.B. Tsang *et al.*, PRC**86**, 015803 (2012).

I. Tews et al., PRL110, 032504 (2013)

and this work

DP: Dipole Polarizability
HIC: Heavy Ion Collision
PDR: Pygmy Dipole Resonance
IAS: Isobaric Analogue State
FRDM: Finite Range Droplet Model (nuclear mass analysis)
n-star: Neutron Star Observation
χEFT: Chiral Effective Field Theory

DP: L=45±18 MeV
J=30.9±1.5 MeV

X. Roca-Maza et al., arXiv:1307.4806

$$10^{-2}\alpha_D J = (4.94 \pm 0.09) + (0.031 \pm 0.001)L$$

$$L = -145 \pm (9)_{\text{theo.}} + \left[6.07 \pm (0.18)_{\text{exp.}} \pm (0.26)_{\text{theo.}}\right] J,$$

$$\Delta r_{np} = 0.168 \pm (0.009)_{\text{exp.}} \pm (0.019)_{\text{theo.}} \pm (0.021)_{\text{est.}} \,\text{fm}$$