

# Nuclear matter Equation of State Studied by Polarized Proton Inelastic Scattering

Takashi Hashimoto

Institute for Basic Science (IBS)  
Rare Isotope Science Project (RISP)

For RCNP-E282, E316 Collaborations

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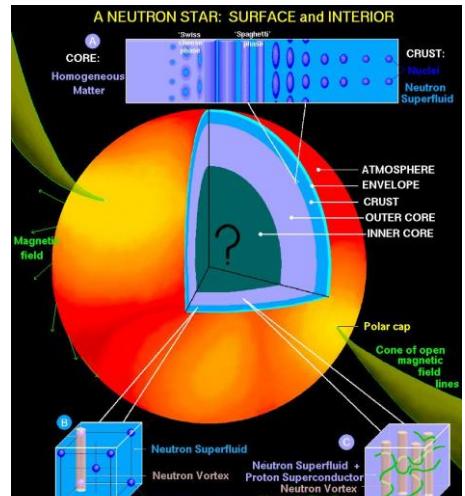
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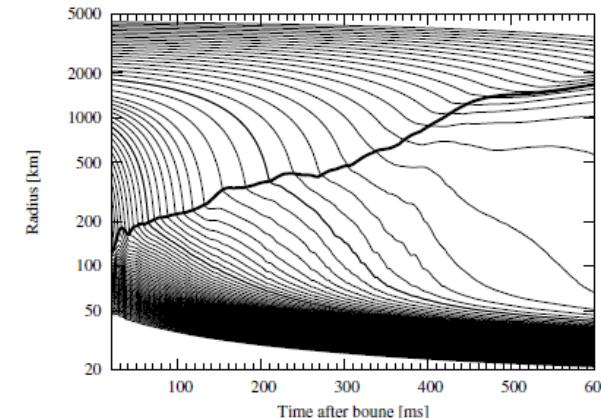
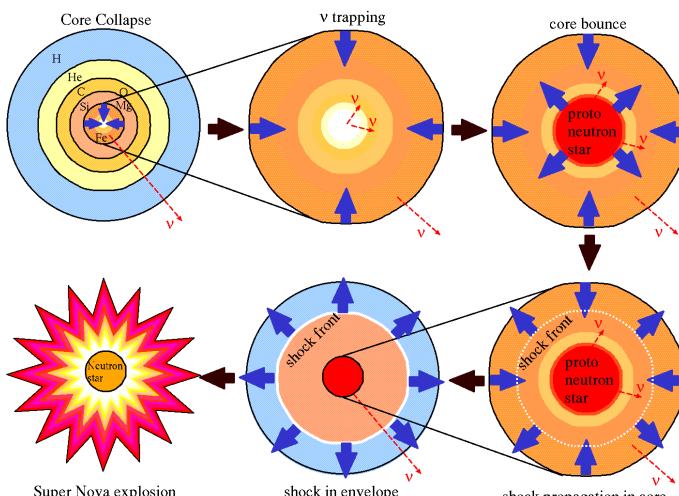
# Physics Motivation and Strategy

Symmetry energy of Nuclear EoS is important in nuclear physics as well as nuclear astrophysics

Structure of neutron star

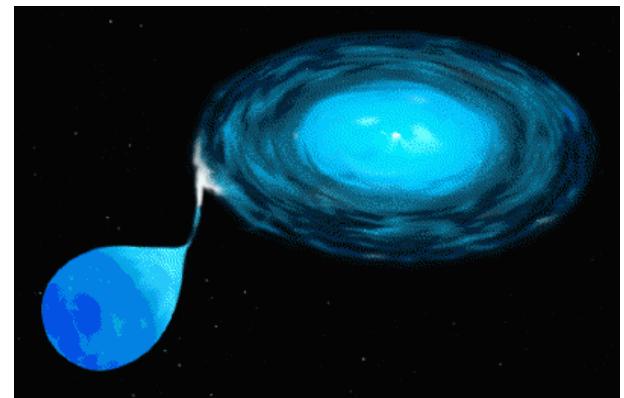


<http://www.astro.umd.edu/~miller/nstar.html>

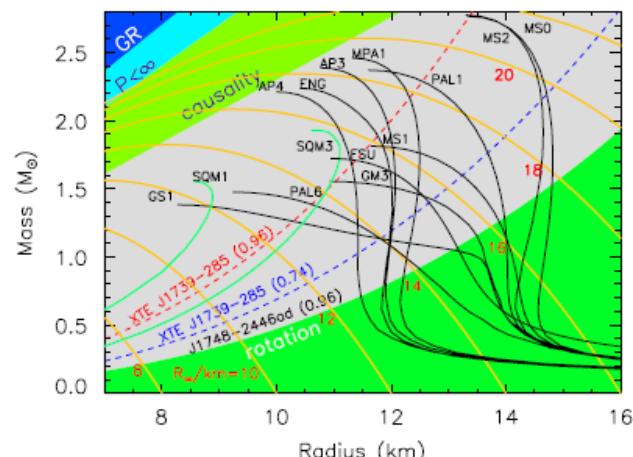


Y. Suwa, et.al. ApJ764(2013)99

Accreting neutron star  
X-ray bursts



Neutron star mass vs  
radius



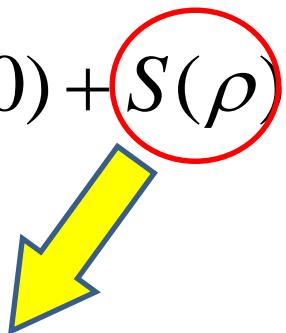
Lattimer et al., Phys. Rep. 442(2007)109

[http://science1.nasa.gov/science-news/science-at-nasa/1997/ast19sep97\\_3/](http://science1.nasa.gov/science-news/science-at-nasa/1997/ast19sep97_3/)

# Physics Motivation and Strategy

EoS for Energy per nucleon at zero temperature

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



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

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

Symmetry energy

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

J: Symmetry energy at the saturation density

L: Slope parameter

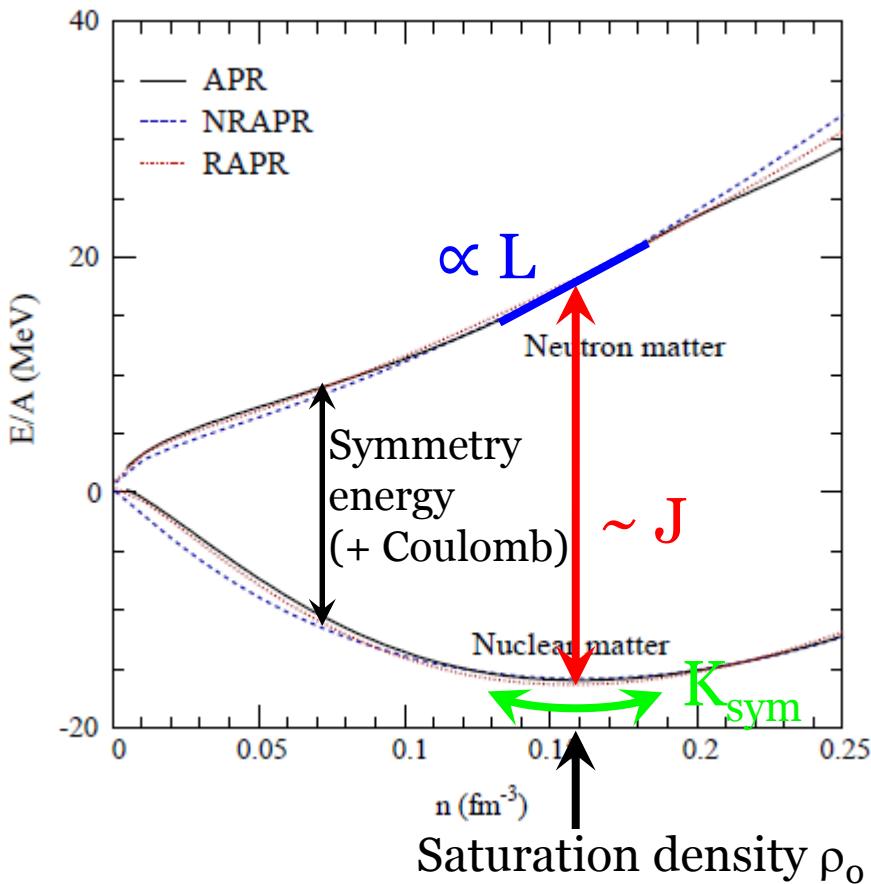
Salutation density  
 $\rho_0 = \sim 0.16 \text{ fm}^{-3}$

$$L \mu P \mu R_{n-star}^4$$

P: baryonic pressure

Determination of J and L is important for nuclear astrophysics related to neutron star

# Physics Motivation and Strategy



A. W. Steiner et al., Phys. Rep. 411(2005)325

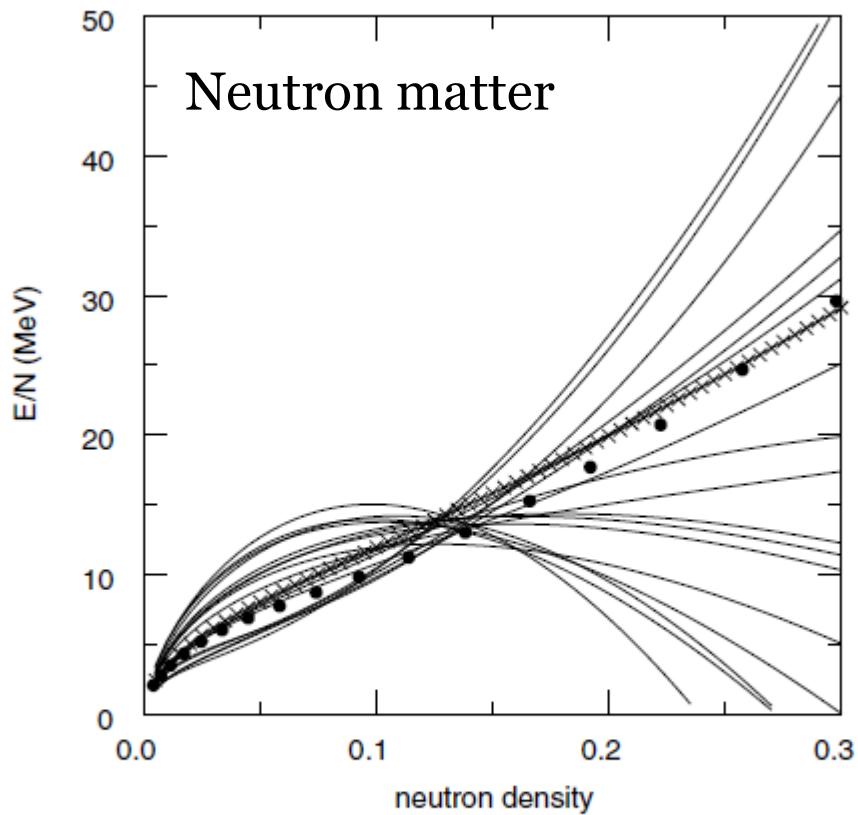


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/ $\text{fm}^3$ .

B. A. Brown, Phys. Rev. Lett, 85(2000)5296

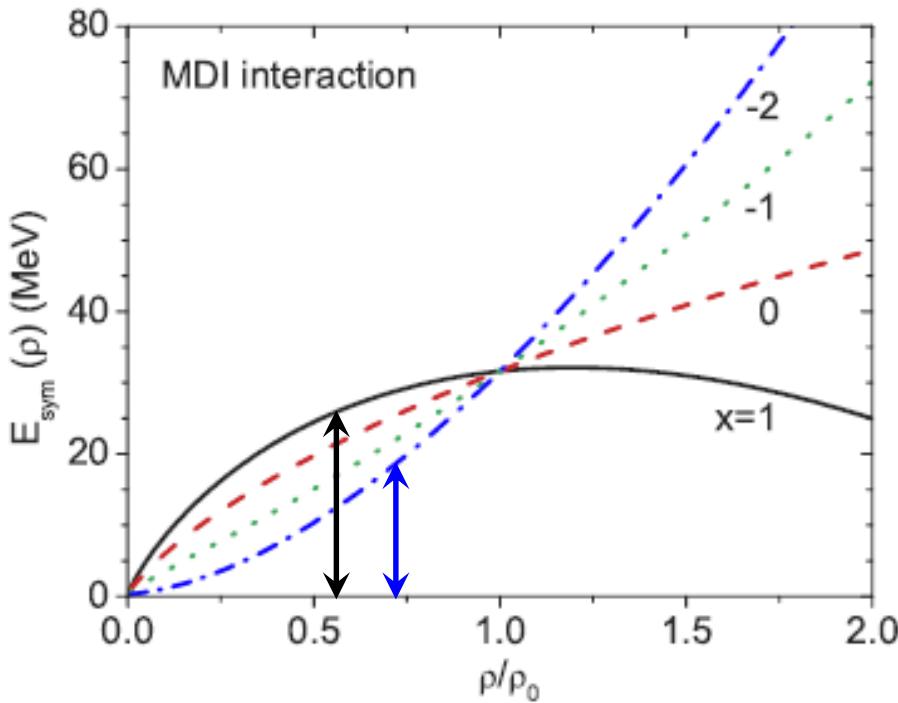
Prediction of the neutron matter EOS is much parameter dependent

# Physics Motivation and Strategy

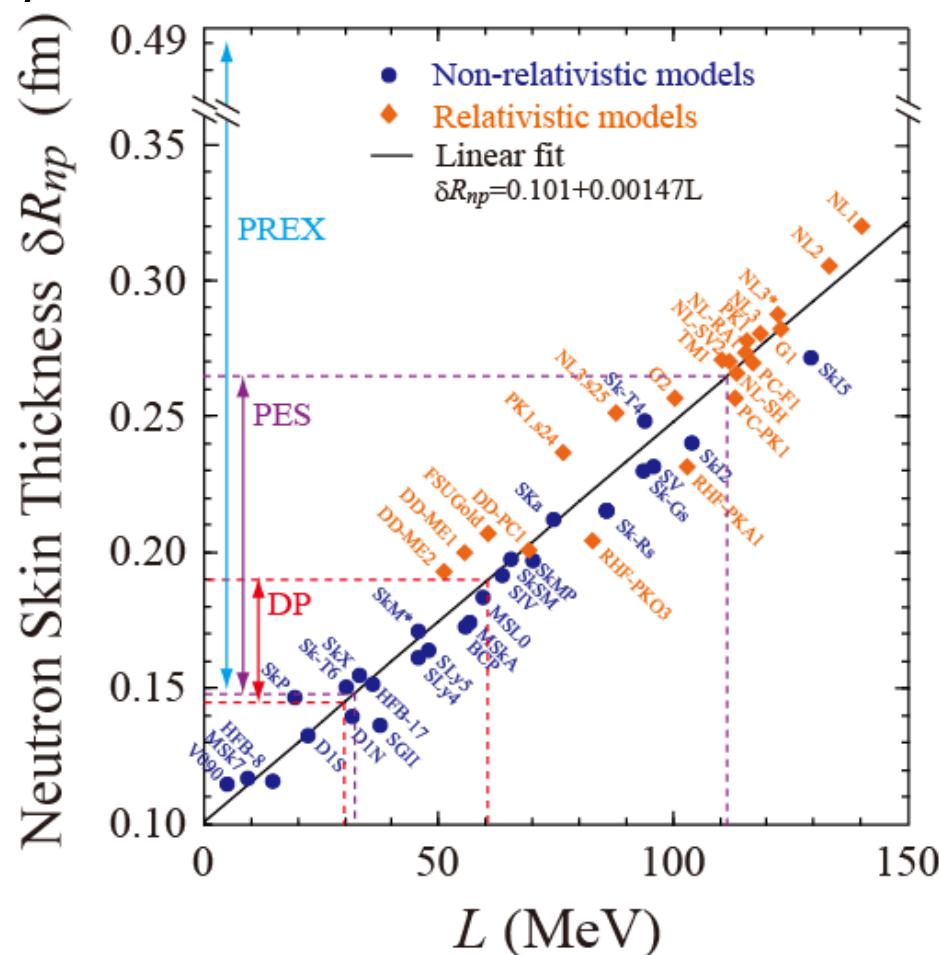
## Slope parameter ( $L$ ) and Neutron Skin thickness

Large L  $\Leftrightarrow$  Small E<sub>sym</sub> in low ρ  $\Leftrightarrow$  Thick neutron skin

Small L  $\Leftrightarrow$  Large E<sub>sym</sub> in low  $\rho$   $\Leftrightarrow$  Thin neutron skin

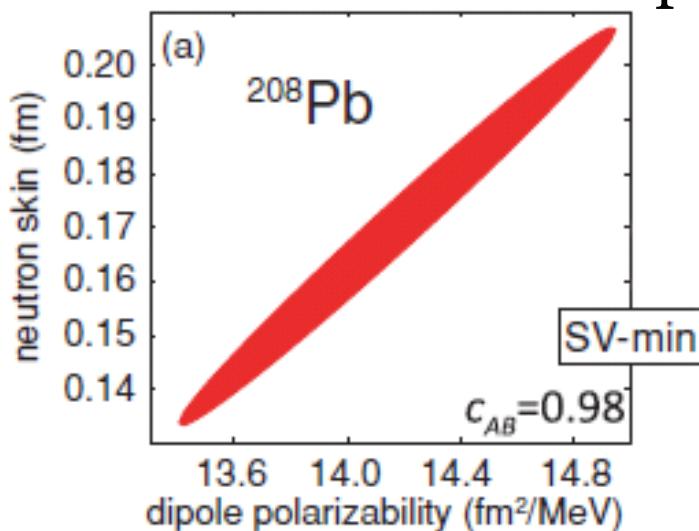


Lie-Wen Chen et al., PRL94(032701)

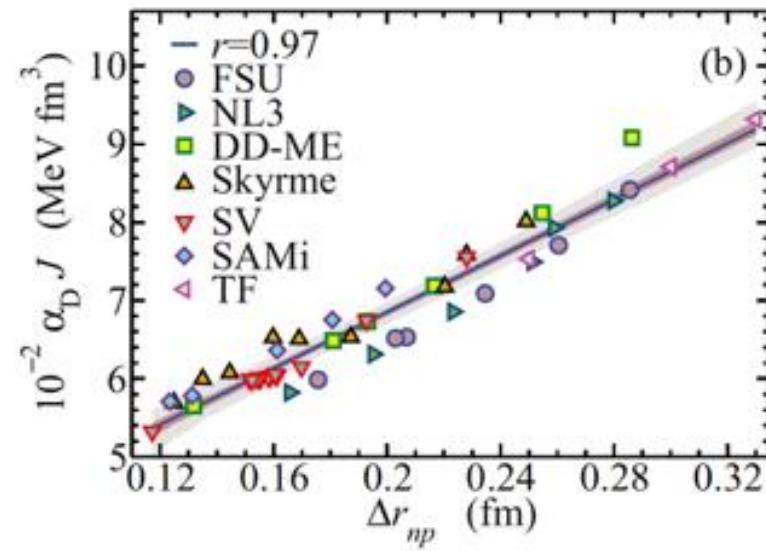


# Physics Motivation and Strategy

## Correlation between Neutron Skin Thickness and Dipole Polarizability ( $\alpha_D$ )

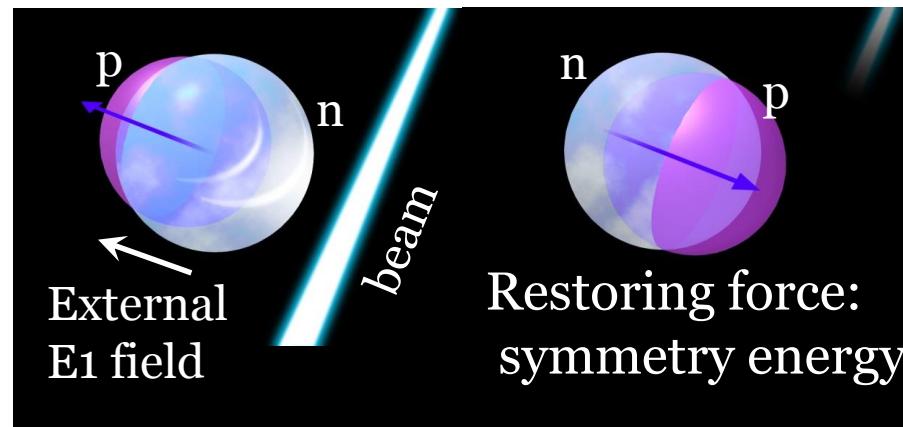


P. -G. Reinhard, W. Nazarewicz, PRC**81**, 051303 (2010)



X. Roca-Maza, et al., PRC**88**, 024316 (2013)

Strong correlation between the dipole polarizability and the neutron skin thickness of  $^{208}\text{Pb}$

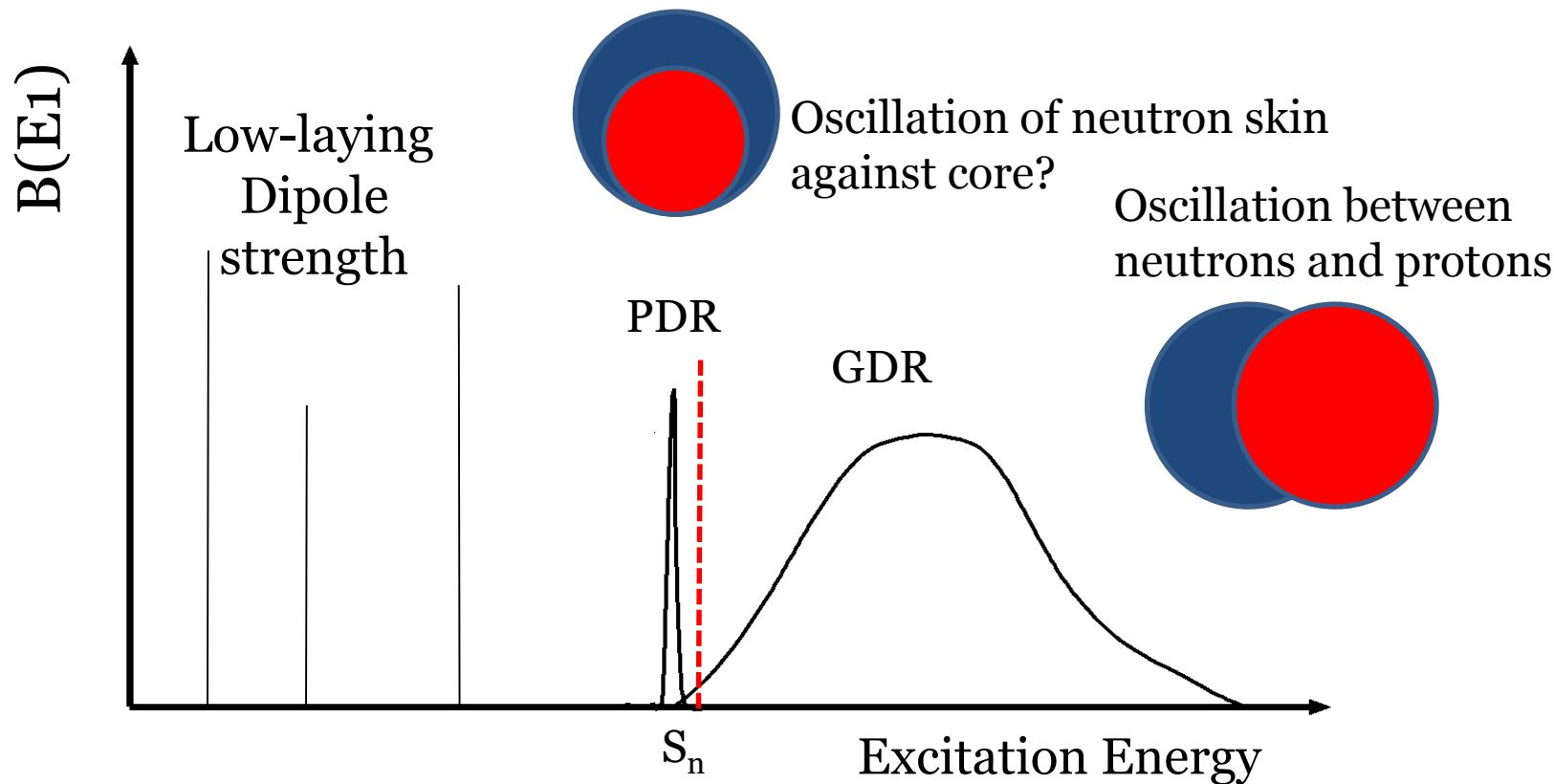


# Physics Motivation and Strategy

## Electric Dipole Polarizability ( $\alpha_D$ )

Inversely energy weighted sum-rule of  $B(E1)$

$$\alpha_D = \frac{8\pi}{9} \int \frac{dB(E1)}{E_x}$$

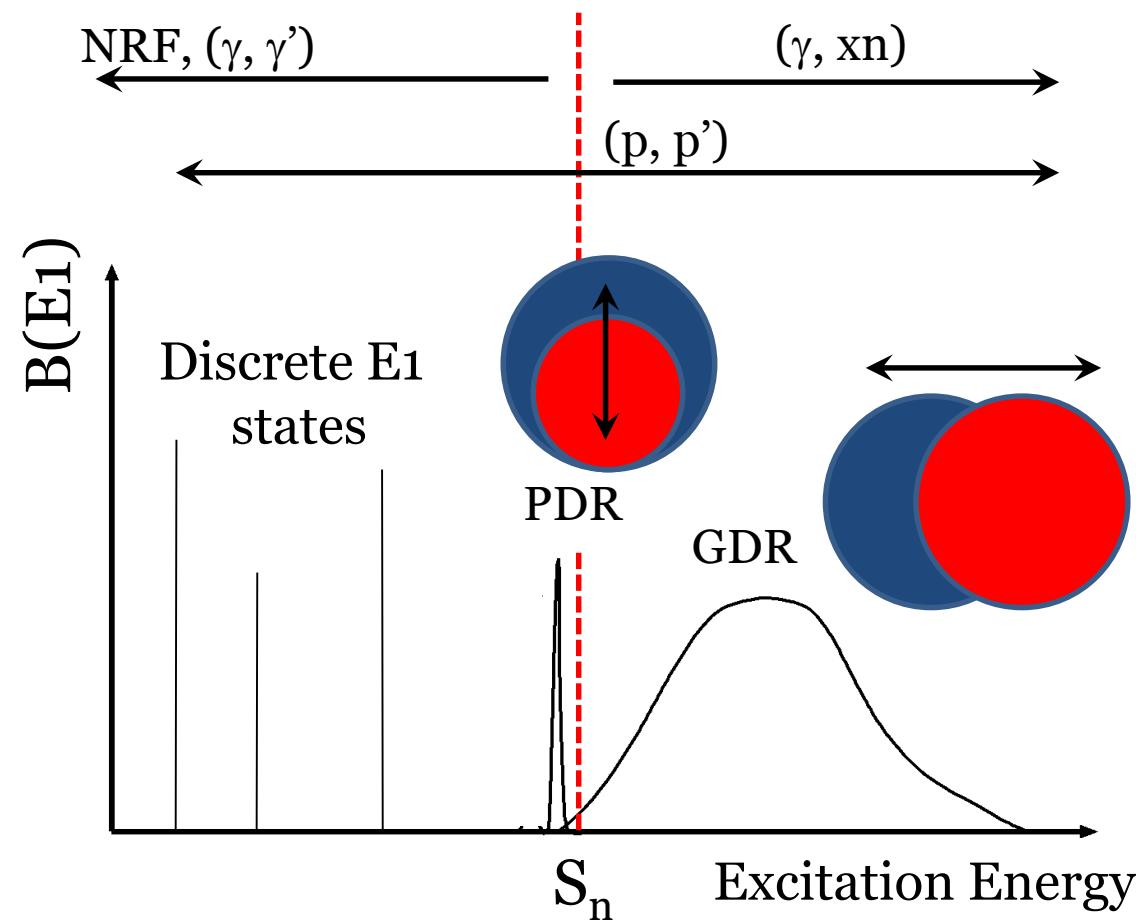


Key of experimental issue:

precise measurement of  $E1$  strength in wide energy region  
including PDR and GDR. (Especially, low excitation energy region is

# Physics Motivation and Strategy

How to measure electric dipole response of nuclei, precisely?



The  $(\gamma, \text{xn})$  reaction has been used to measure the GDR region.

→ There is difficulty to measure at around  $S_n$  due to the threshold problem.

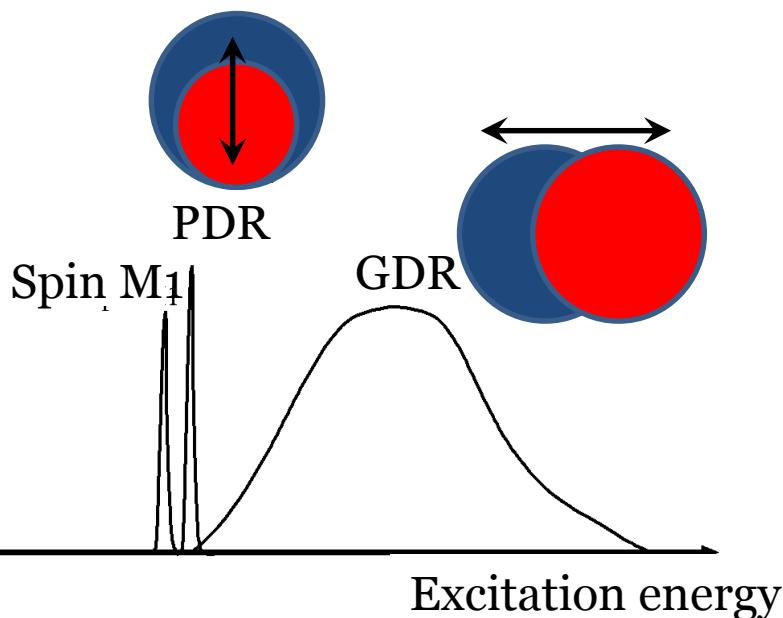
The  $(\gamma, \gamma')$  reaction has been used to measure the PDR region.

→ Extraction of the  $E_1$  strength is quite model-dependent.

Polarized proton inelastic scattering can measure the total strength in wide excitation energy region

# Physics Motivation and Strategy

In the present experimental condition,  
both of E1 and spin-M1 mode are observed.



E1/spin-M1 decomposition  
1. Multipole decomposition  
2. Polarization transfer  
analysis at  $0^\circ$

spin flip/non-flip separation  
Model independent  
T. Suzuki PTP 104(2000)859

Total Spin Transfer ( $\Sigma$ )

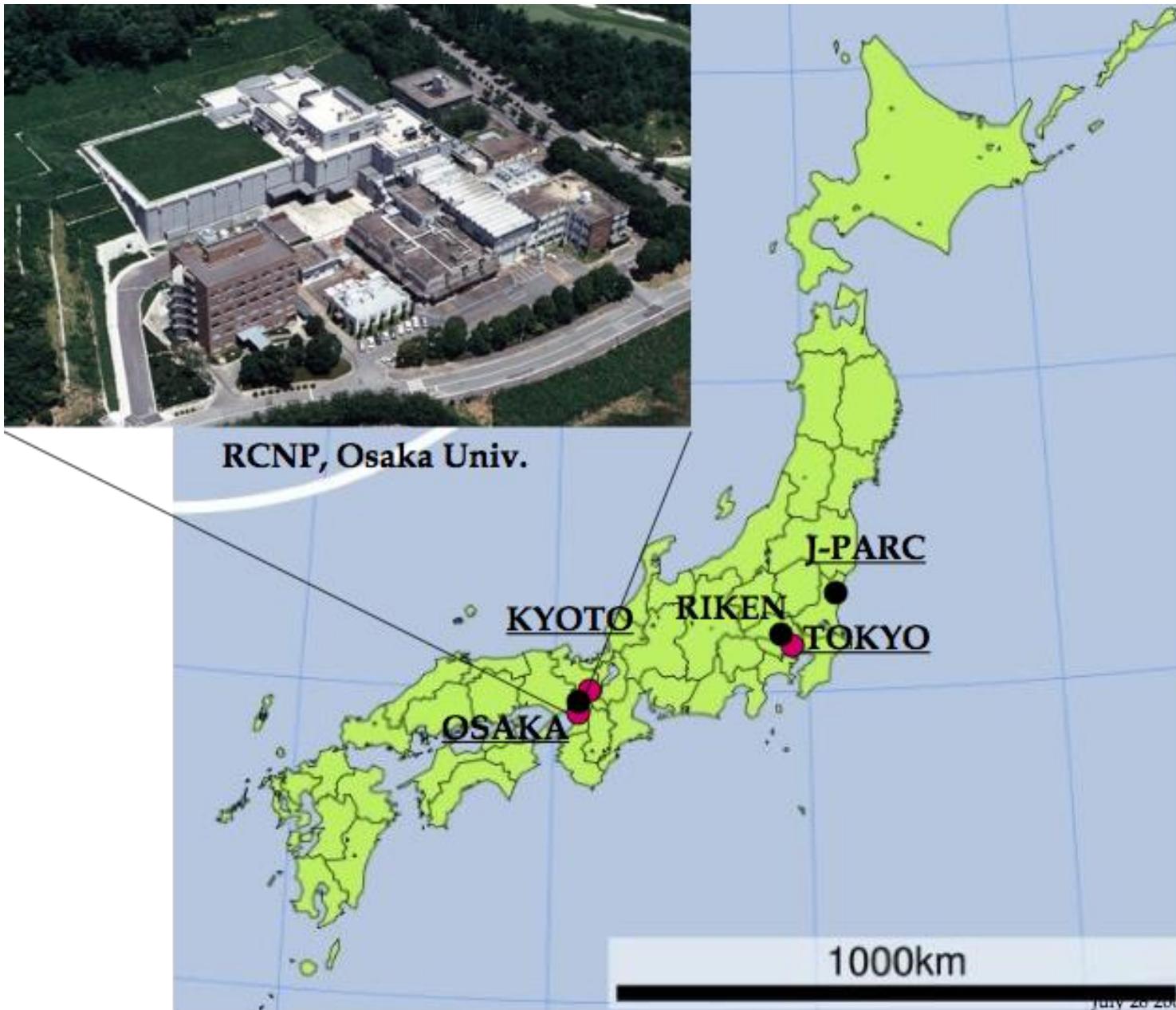
$$S \equiv \frac{3 - (2D_{SS} + D_{LL})}{4} = \begin{cases} 1 & \text{for } \Delta S = 1 \text{ spin-M1} \\ 0 & \text{for } \Delta S = 0 \text{ E1} \end{cases}$$

$D_{SS}$  and  $D_{LL}$ : Spin transfer observable

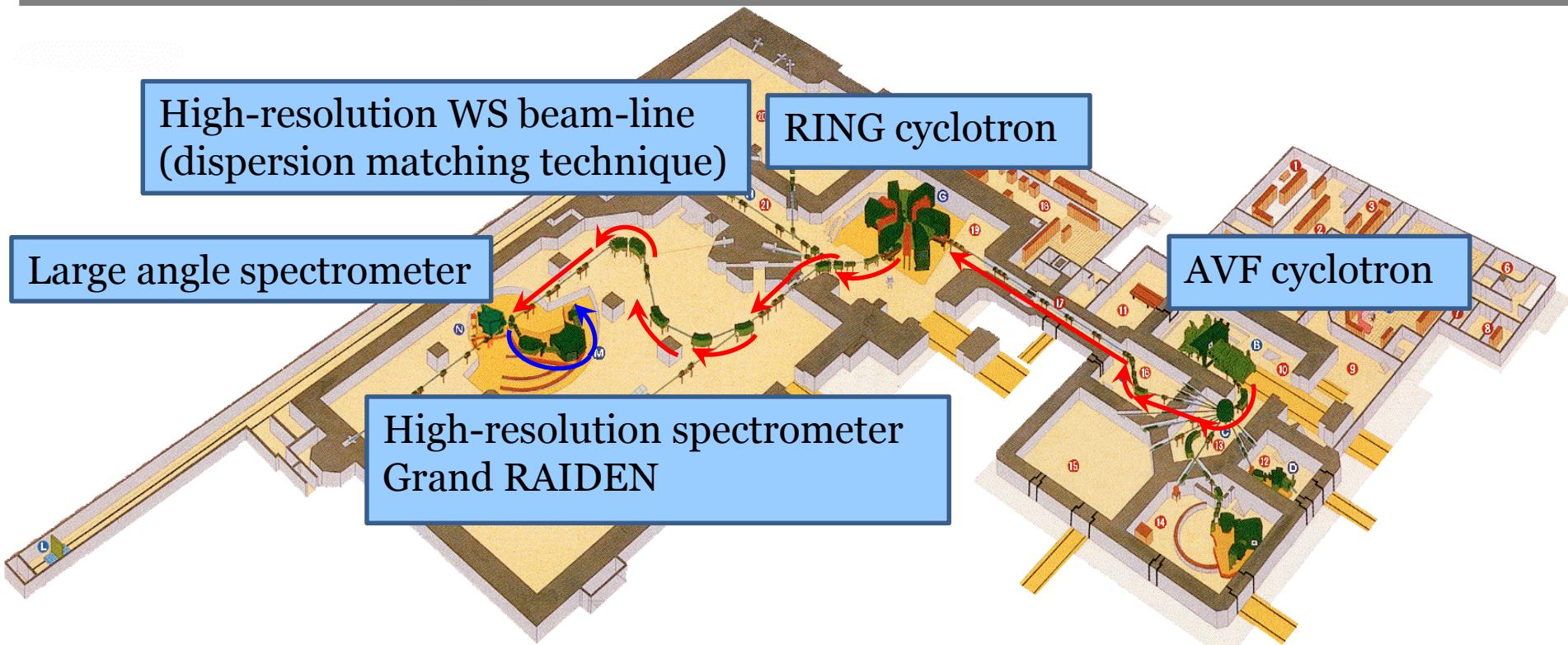
# Experimental Method

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

# Experimental method

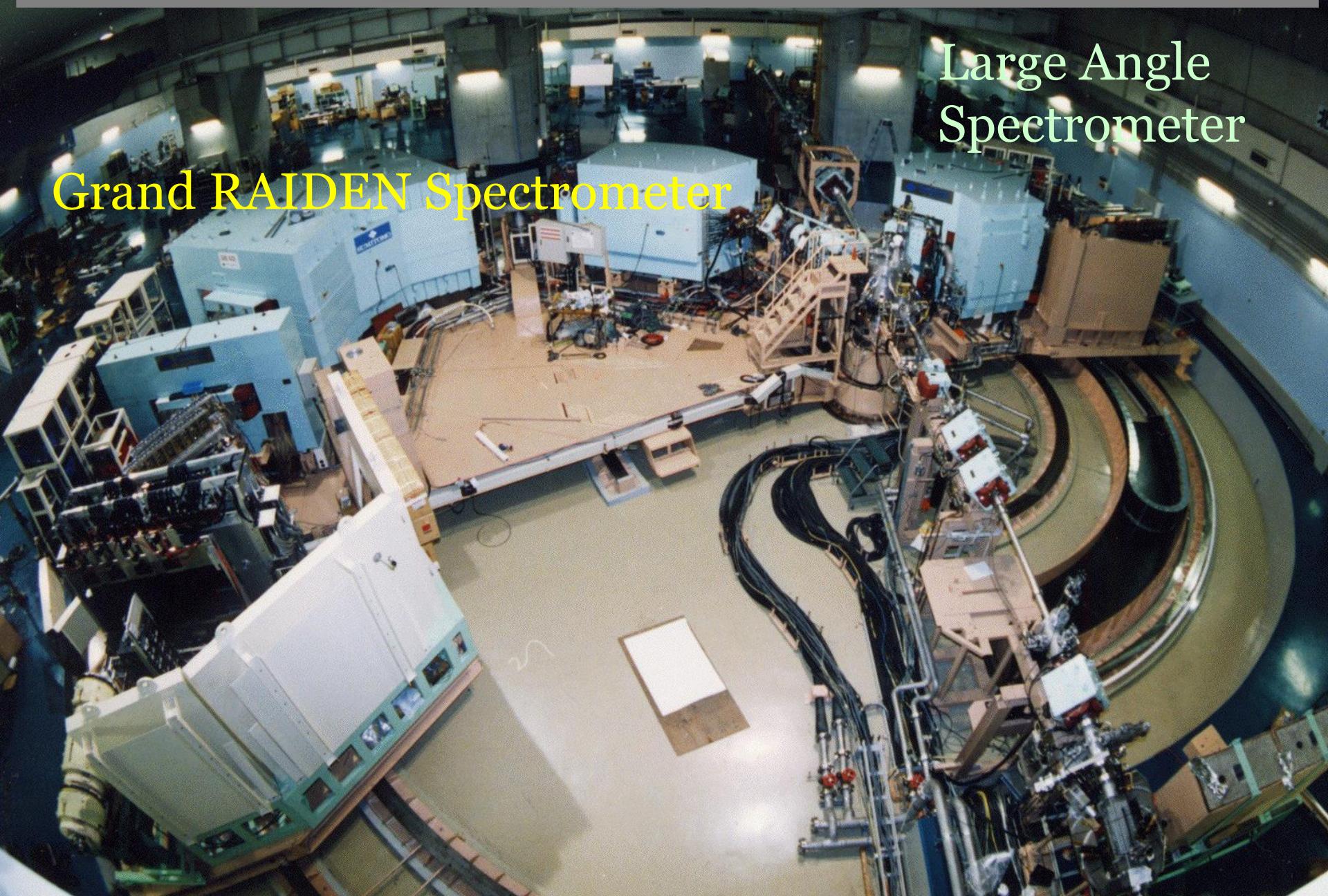


# Experimental method



Polarized proton beam  
Energy: 295 MeV  
Energy resolution:  $\sim 25$  keV  
Intensity: 2 nA  
Averaged polarization:  $\sim 0.7$   
(both of longitudinal and sideway)

# Experimental method

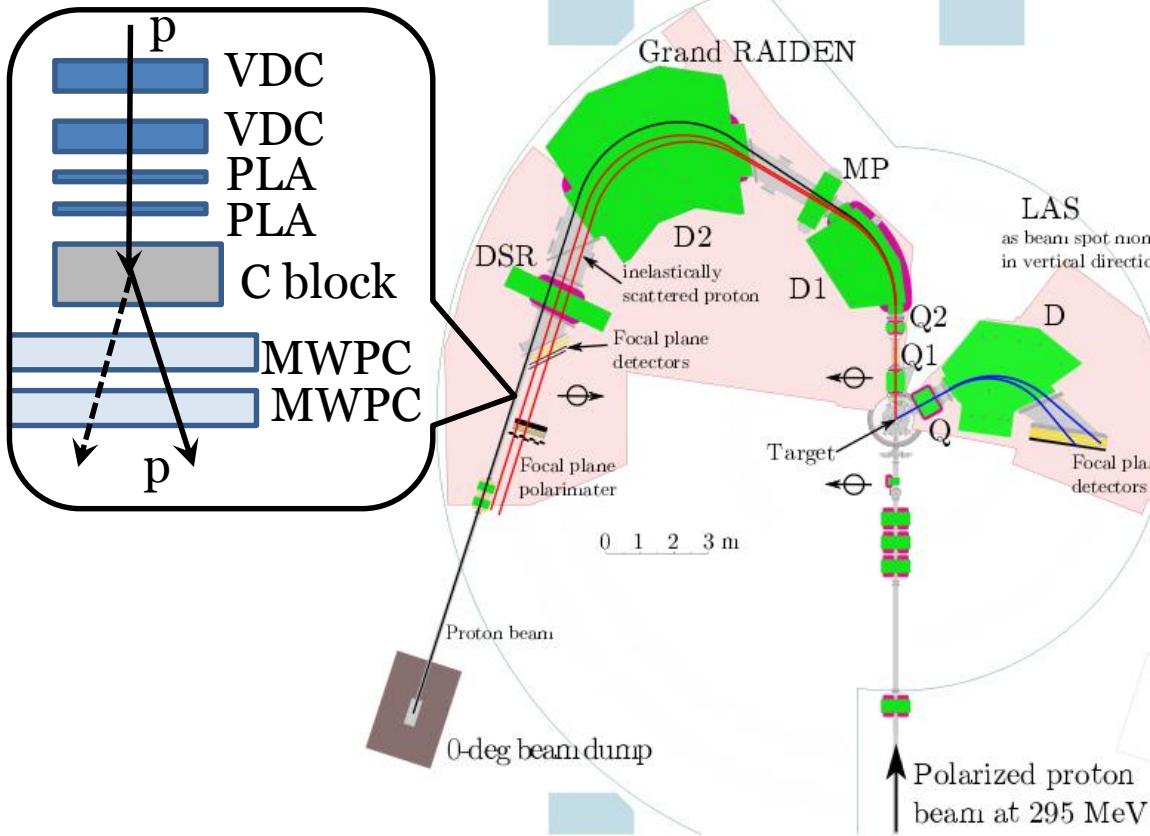


Grand RAIDEN Spectrometer

Large Angle  
Spectrometer

# Experimental method

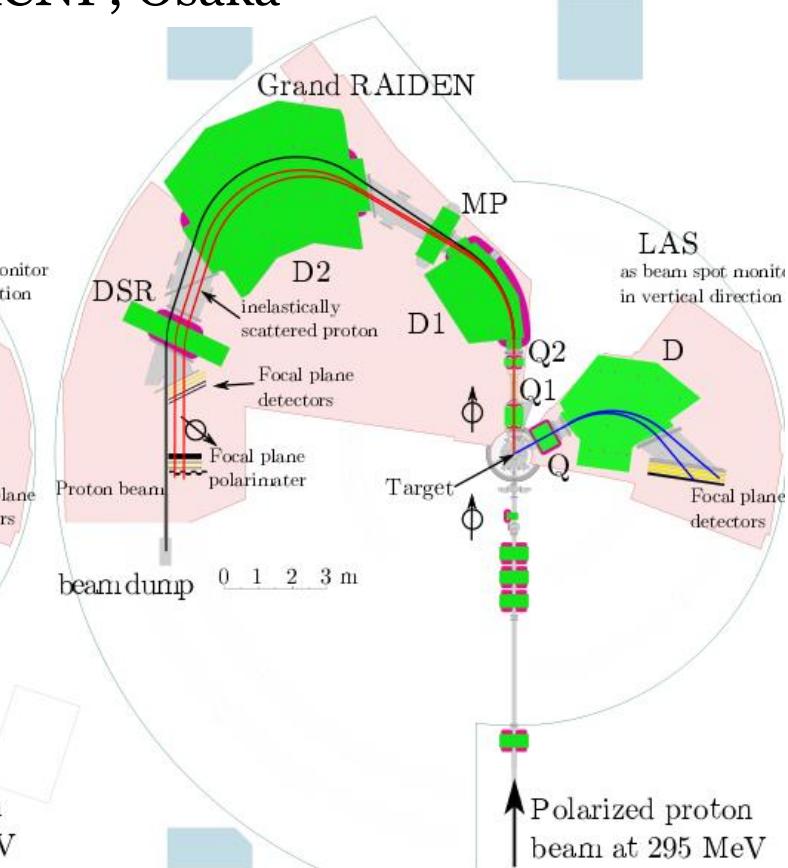
Spectrometers in  $0^\circ$  Experiment setup at RCNP, Osaka



$D_{ss}$  measurement

Total Spin Transfer ( $\Sigma$ )

$$\Sigma \equiv \frac{3 - (2D_{ss} + D_{LL})}{4} \quad D_{ss} \text{ and } D_{LL} : \text{Spin transfer observable}$$



$D_{LL}$  measurement

$^{208}\text{Pb}$  target: 5.2 mg/cm<sup>2</sup>

$^{120}\text{Sn}$  target : 6.5 mg/cm<sup>2</sup>

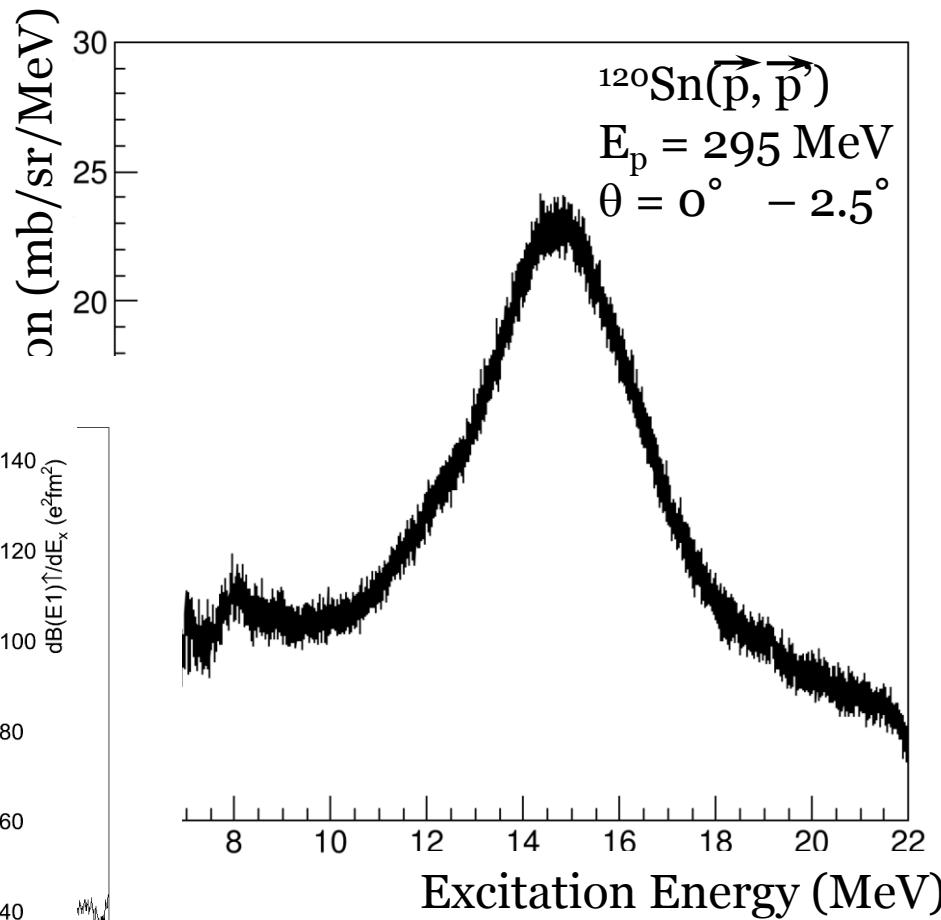
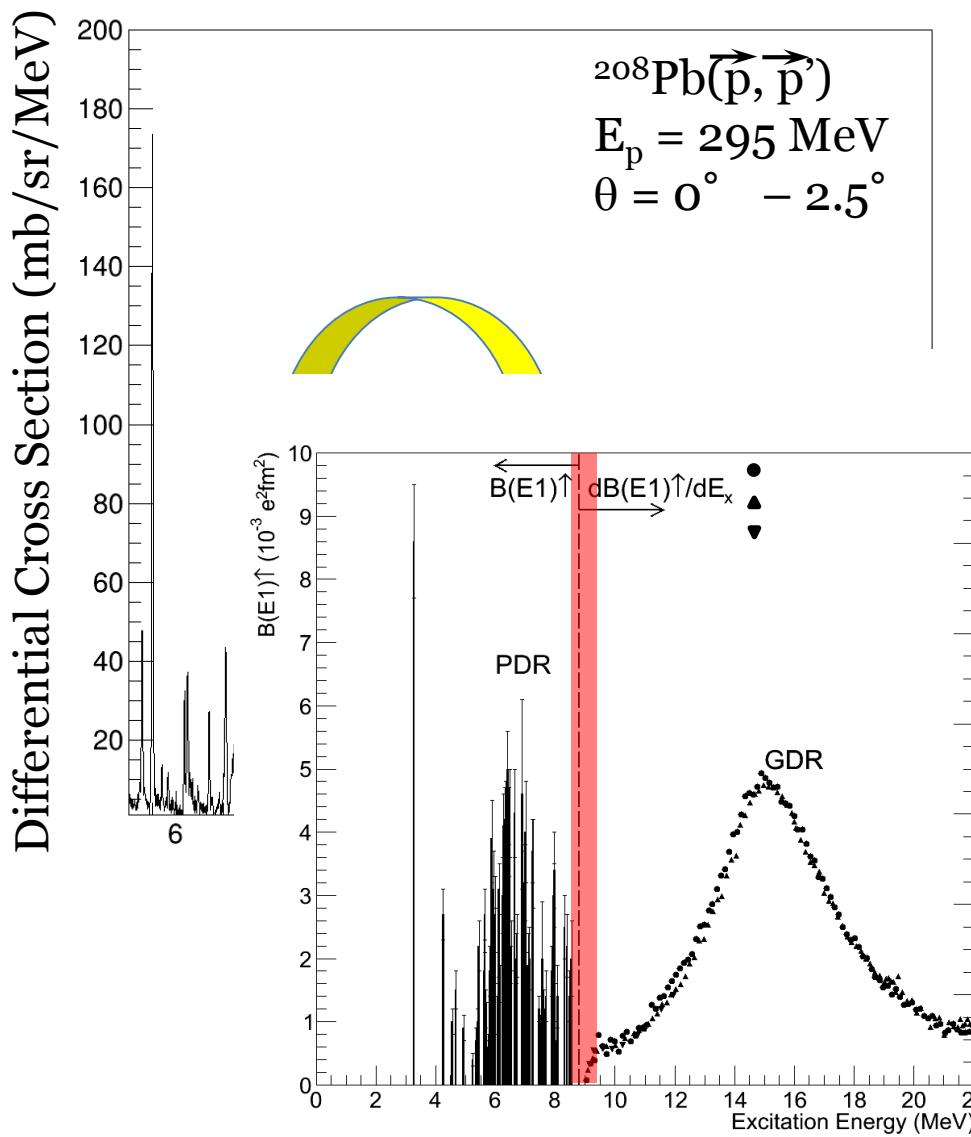
Dispersion matched beam: 1 – 10 nA

Averaged polarization ~ 0.7

# Results

# Results

## Excitation energy spectrum



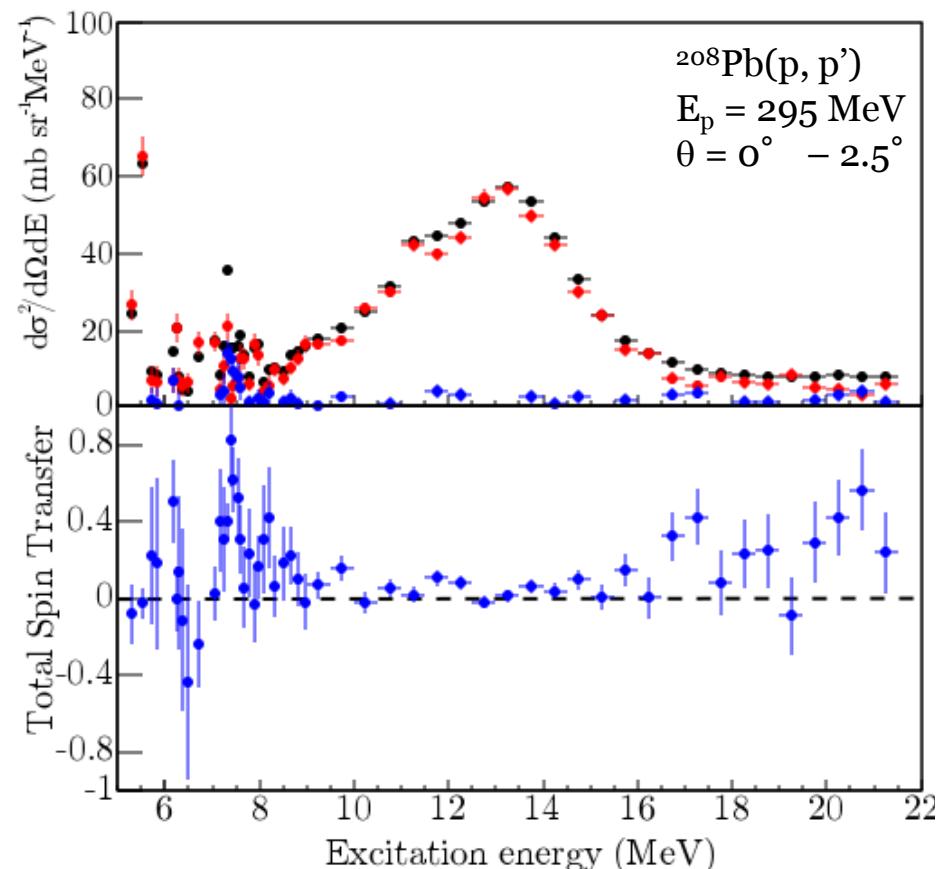
$^{208}\text{Pb}$ : A. Tamii et. al. PRL 107(2011)06250  
 $^{120}\text{Sn}$ : T. Hashimoto et al., PRC92(2015)031305(R)

# Results

E1 and spin-M1 decomposition  
Polarization observable at 0 degs

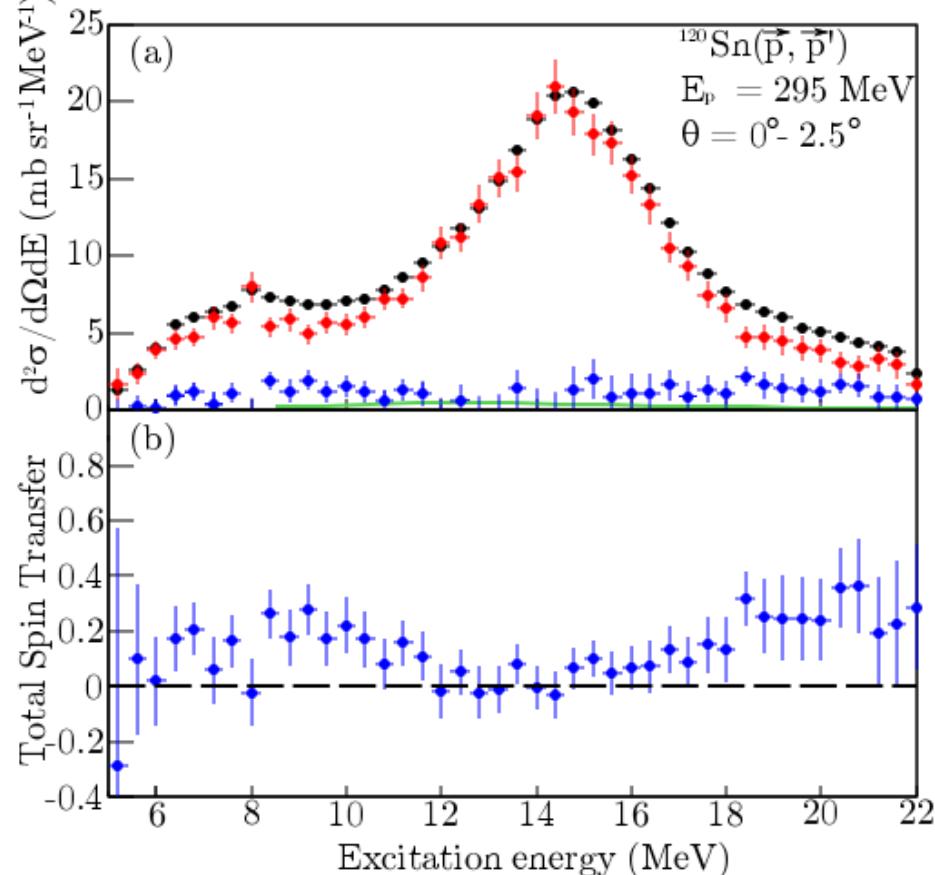
<sup>208</sup>Pb: A. Tamii et. al. PRL 107(2011)06250  
<sup>120</sup>Sn: T. Hashimoto et al., PRC92(2015)031305(R)

Spin flip/non-spin flip separation



Total Spin Transfer

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

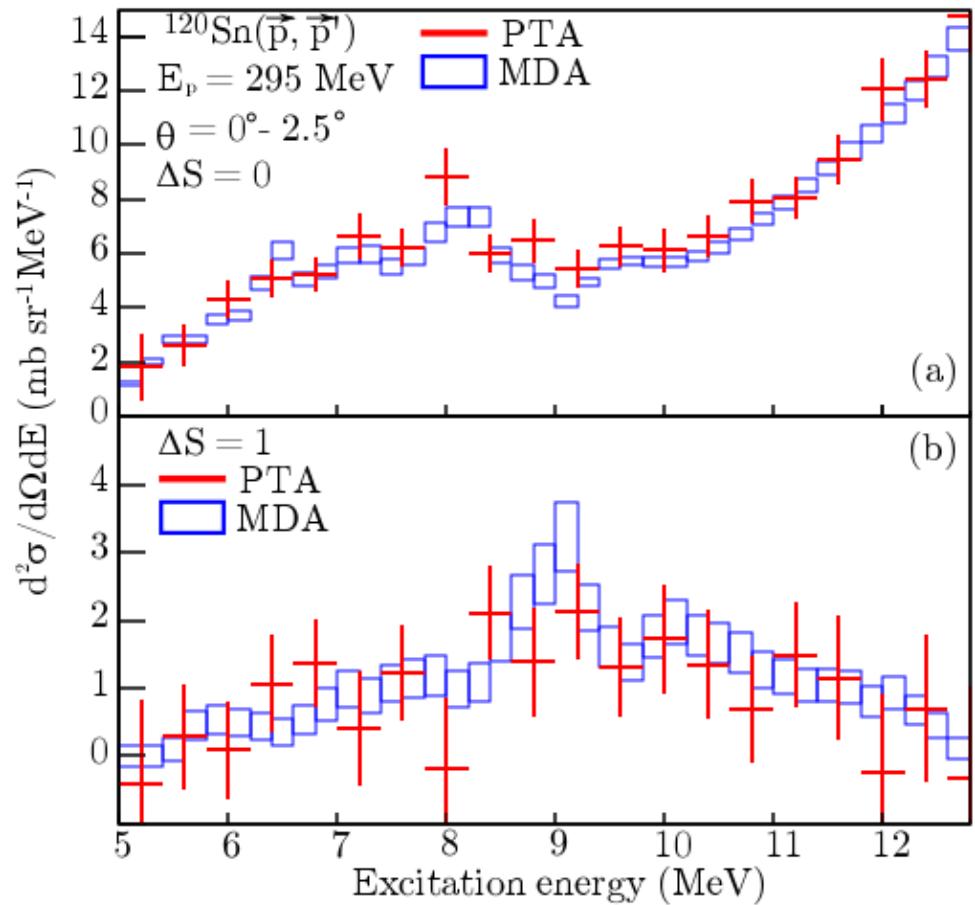
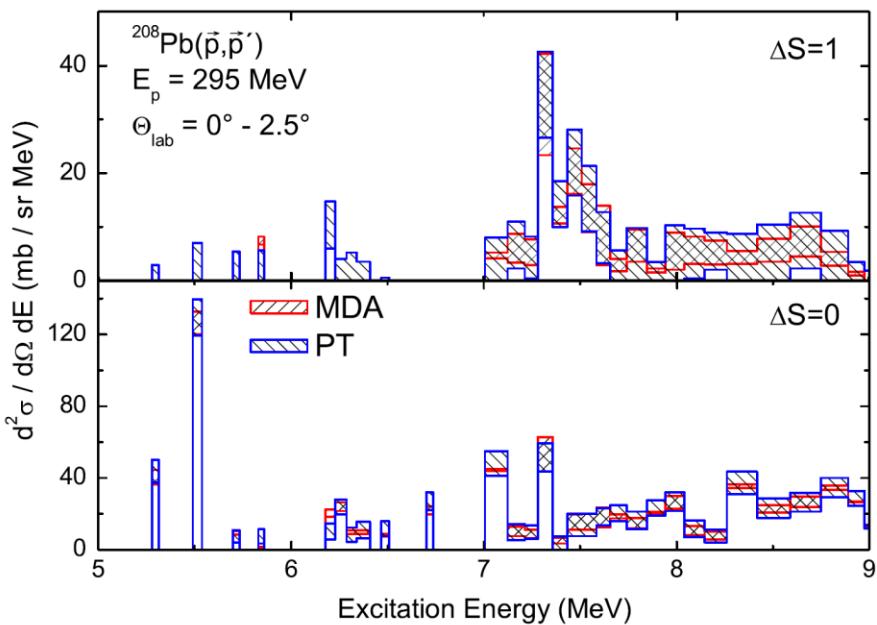


- (p, p') total
- (p, p'), E1
- (p, p'), Spin M1
- (p, p'), E2 (DWBA)

# Results

## E1 and spin-M1 decomposition

### Comparison with Multi-pole Decomposition Analysis

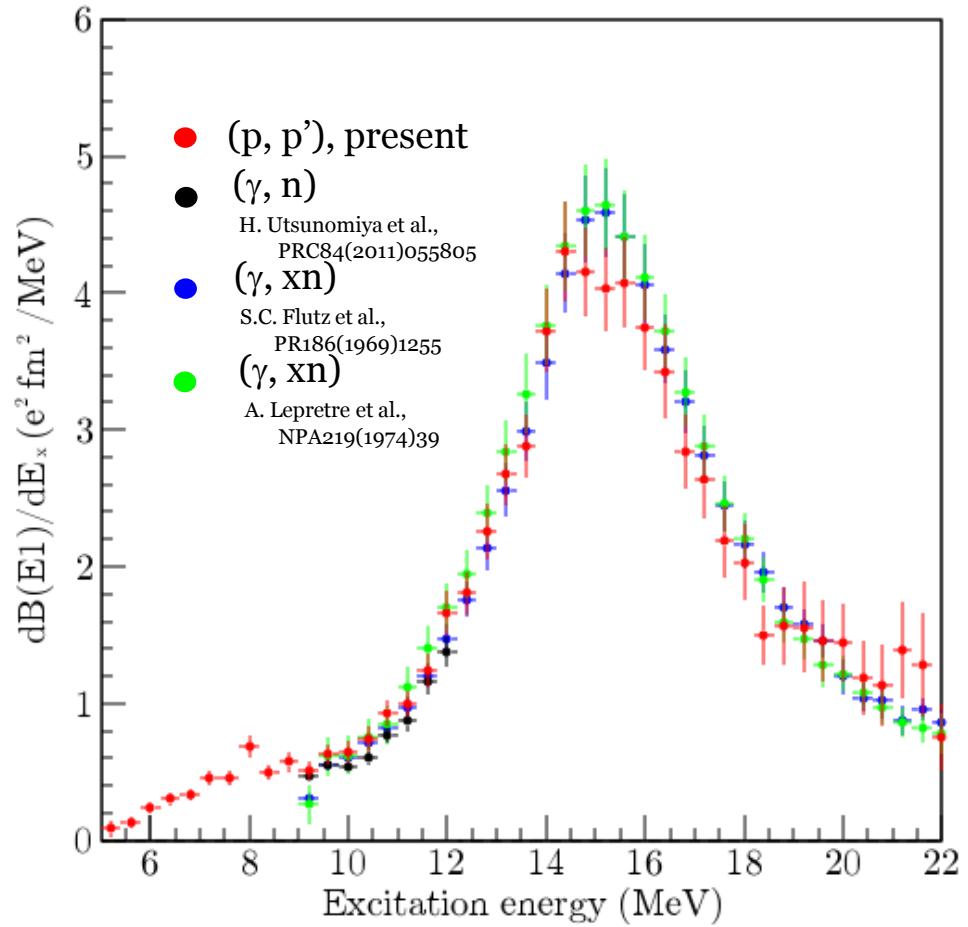
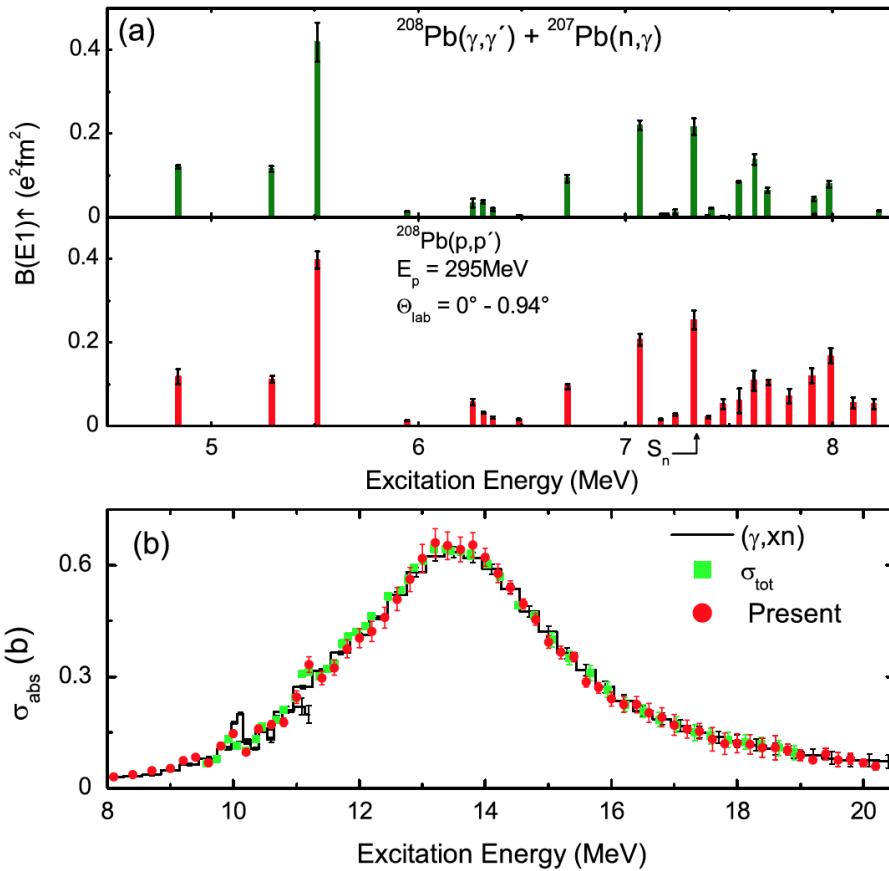


good agreement  
within respective error bars

$^{208}\text{Pb}$ : A. Tamii et. al. PRL 107(2011)06250  
 $^{120}\text{Sn}$ : T. Hashimoto et al., PRC92(2015)031305(R)  
MDA of  $^{120}\text{Sn}$  was performed by A. M. Krumbholtz  
PLB 744(2015)7

# Results

## The $B(E1)$ strength distribution Comparison with $(\gamma, xn)$ results



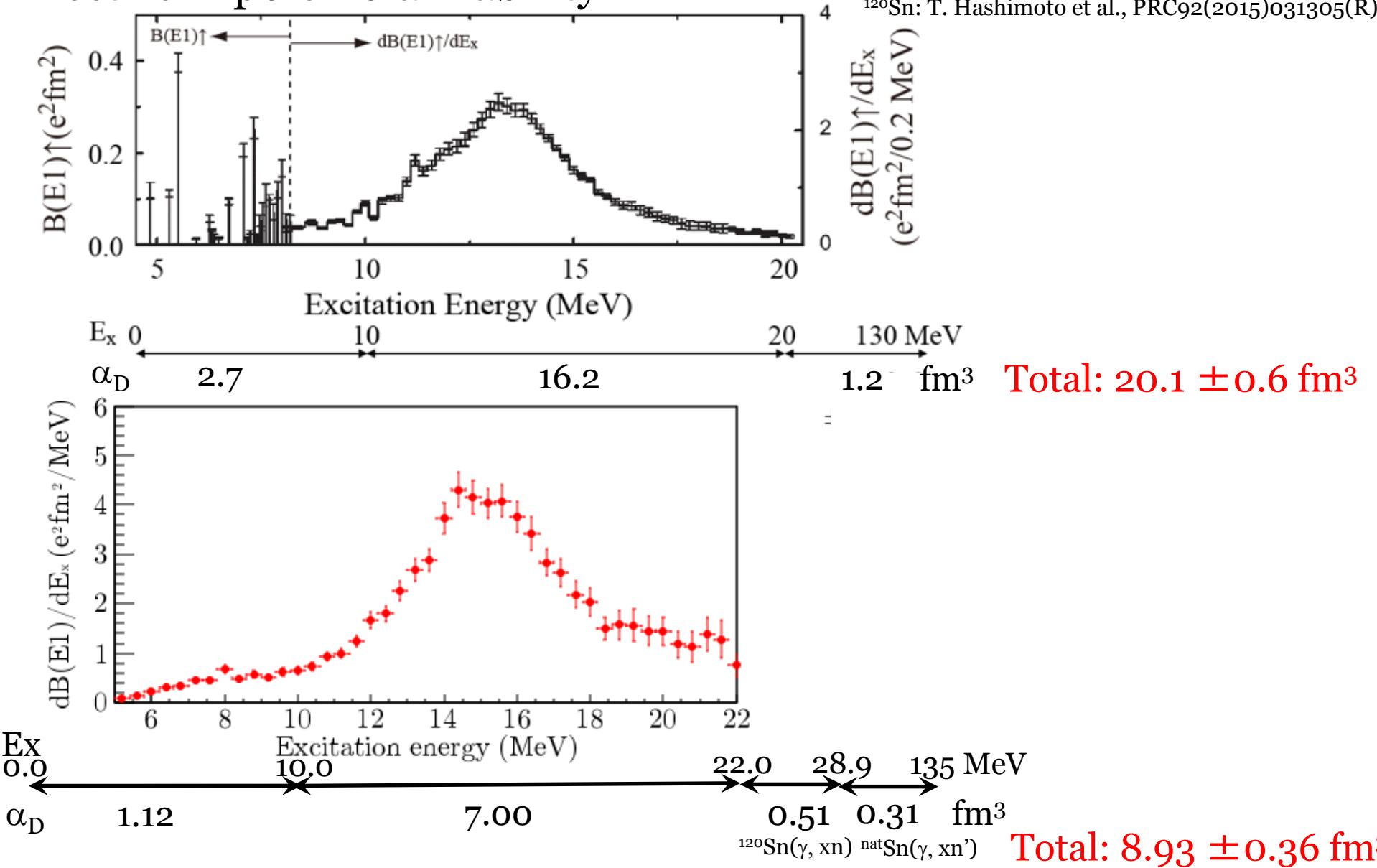
Refs. of  $^{208}\text{Pb}(\gamma, \gamma')$ ,  $^{207}\text{Pb}(n, \gamma)$ ,  $^{208}\text{Pb}(\gamma, xn)$   
N. Ryezayava et. al. PRL 89(2002)272502  
J. Enders et. al. NPA 724(2003)243  
T. Shizuma et. al., PRC 78(2008)061303  
R. Schwengner et. al., PRC81(2010)054315  
A. Veysiire et. al., NPA 159(1970) 561

All data are excellent agree with each other

$^{208}\text{Pb}$ : A. Tamii et. al. PRL 107(2011)06250  
 $^{120}\text{Sn}$ : T. Hashimoto et al., PRC92(2015)031305(R)

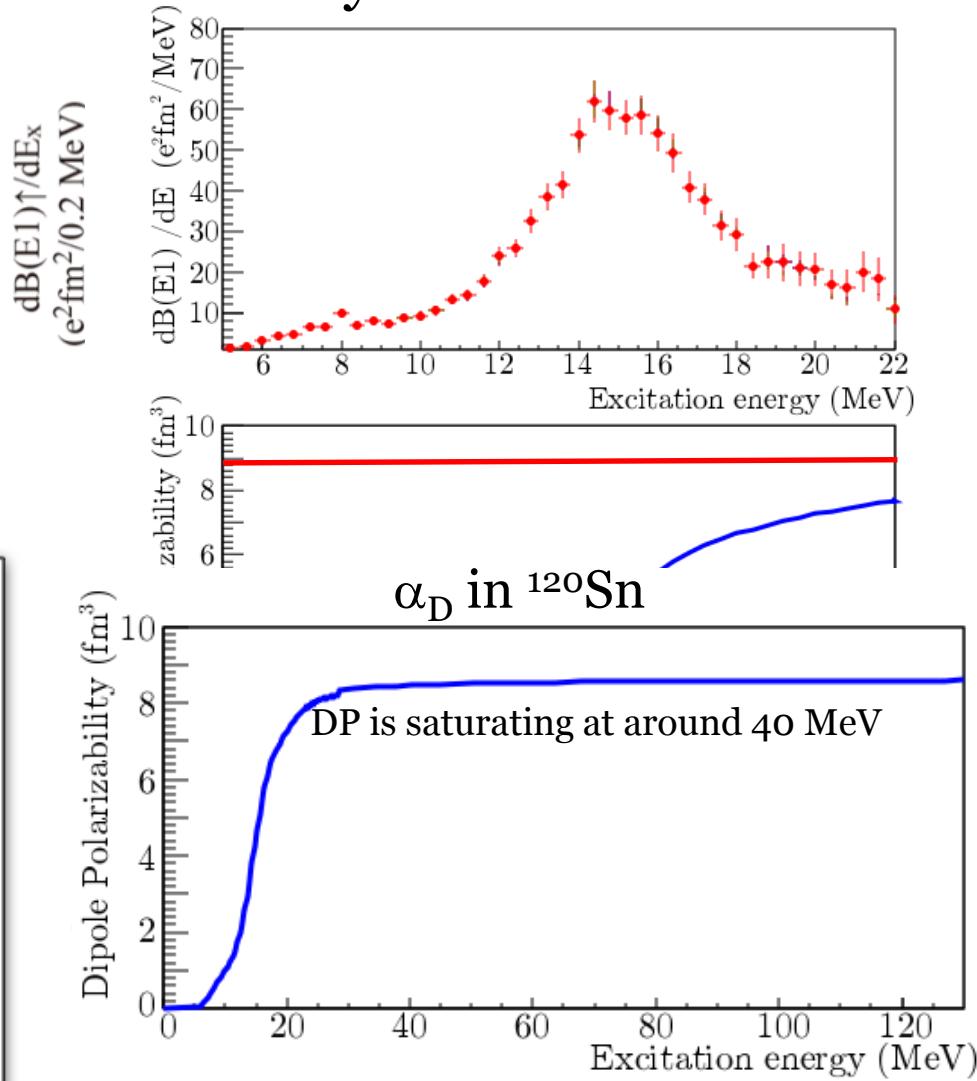
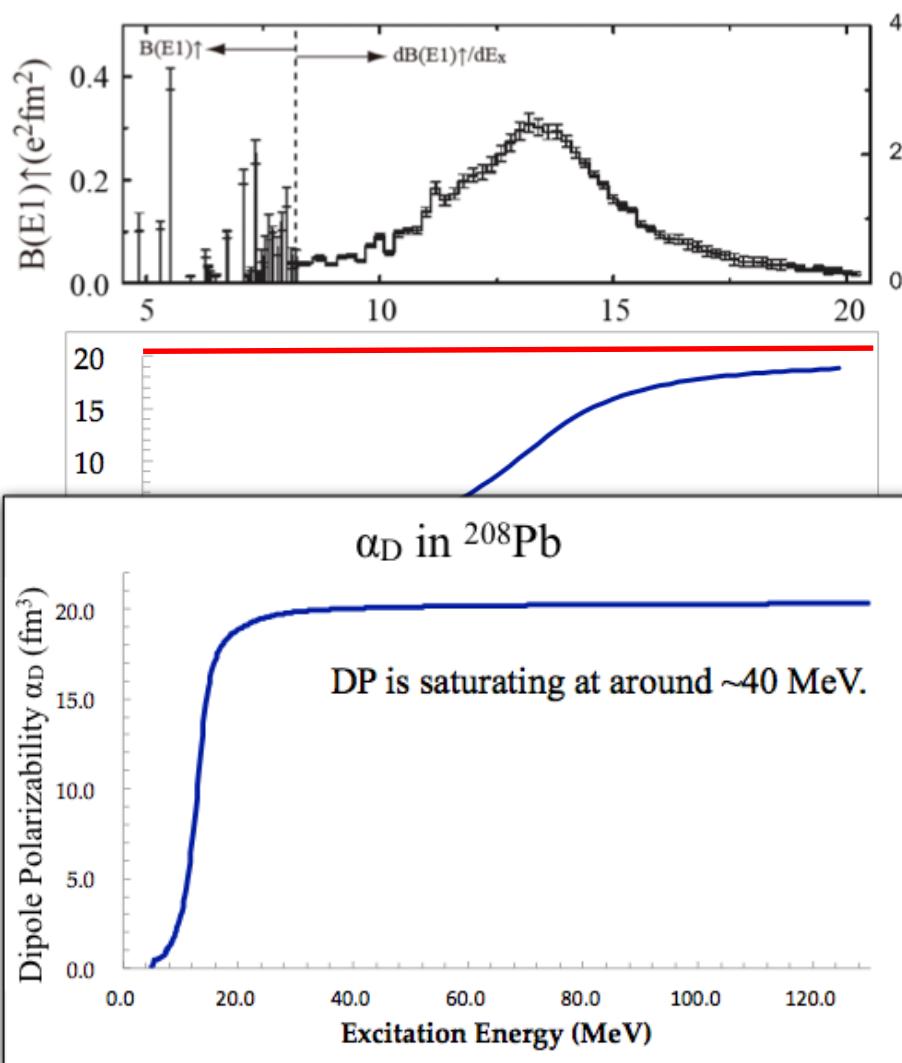
# Results

## Electric Dipole Polarizability



# Results

## Running sum of Electric Dipole Polarizability



# Discussion

Constraints on J-L and neutron-skin thickness from DP data

# Discussion

## Quasi-Deuteron Excitation Contribution

Photon absorption by a virtual deuteron in the nucleus

Needs to be subtracted for comparison with EDF calculations.

$^{208}\text{Pb}$

$$\alpha_D(^{208}\text{Pb}): 20.1 \pm 0.6 \text{ fm}^3$$

$$\text{quasi-}d: 0.51 \pm 0.15 \text{ fm}^3$$

$$\text{w/o quasi-}d: 19.6 \pm 0.6 \text{ fm}^3$$

$\sim 2.5\%$

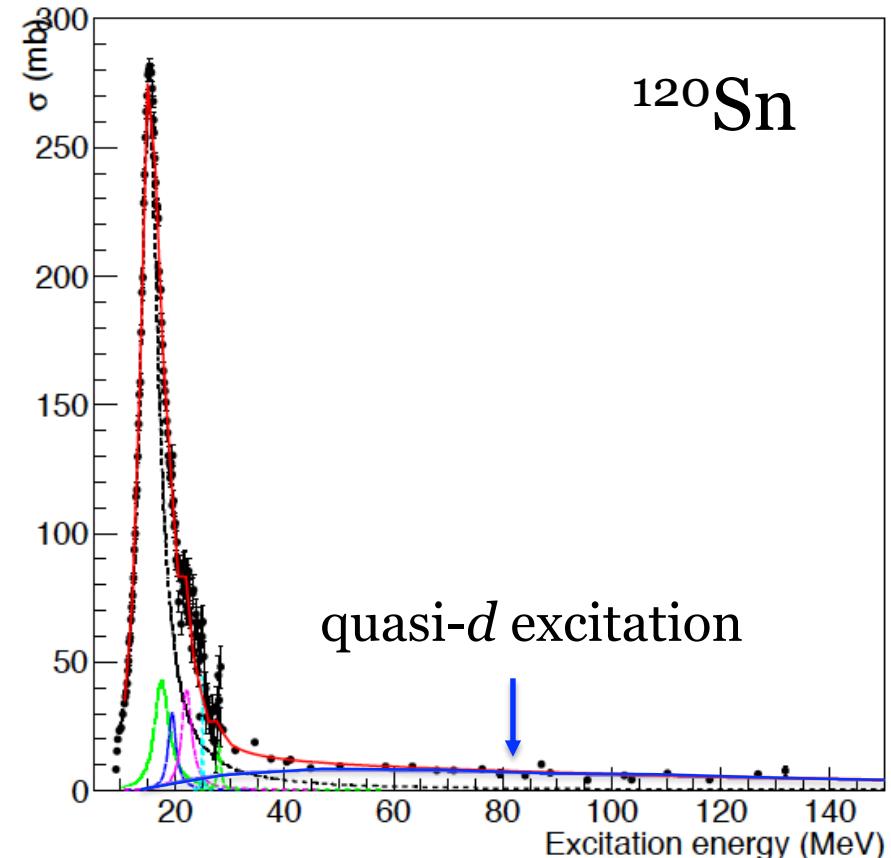
$^{120}\text{Sn}$

$$\alpha_D(^{120}\text{Sn}): 8.93 \pm 0.36 \text{ fm}^3$$

$$\text{quasi-}d: 0.34 \pm 0.08 \text{ fm}^3$$

$$\text{w/o quasi-}d: 8.59 \pm 0.37 \text{ fm}^3$$

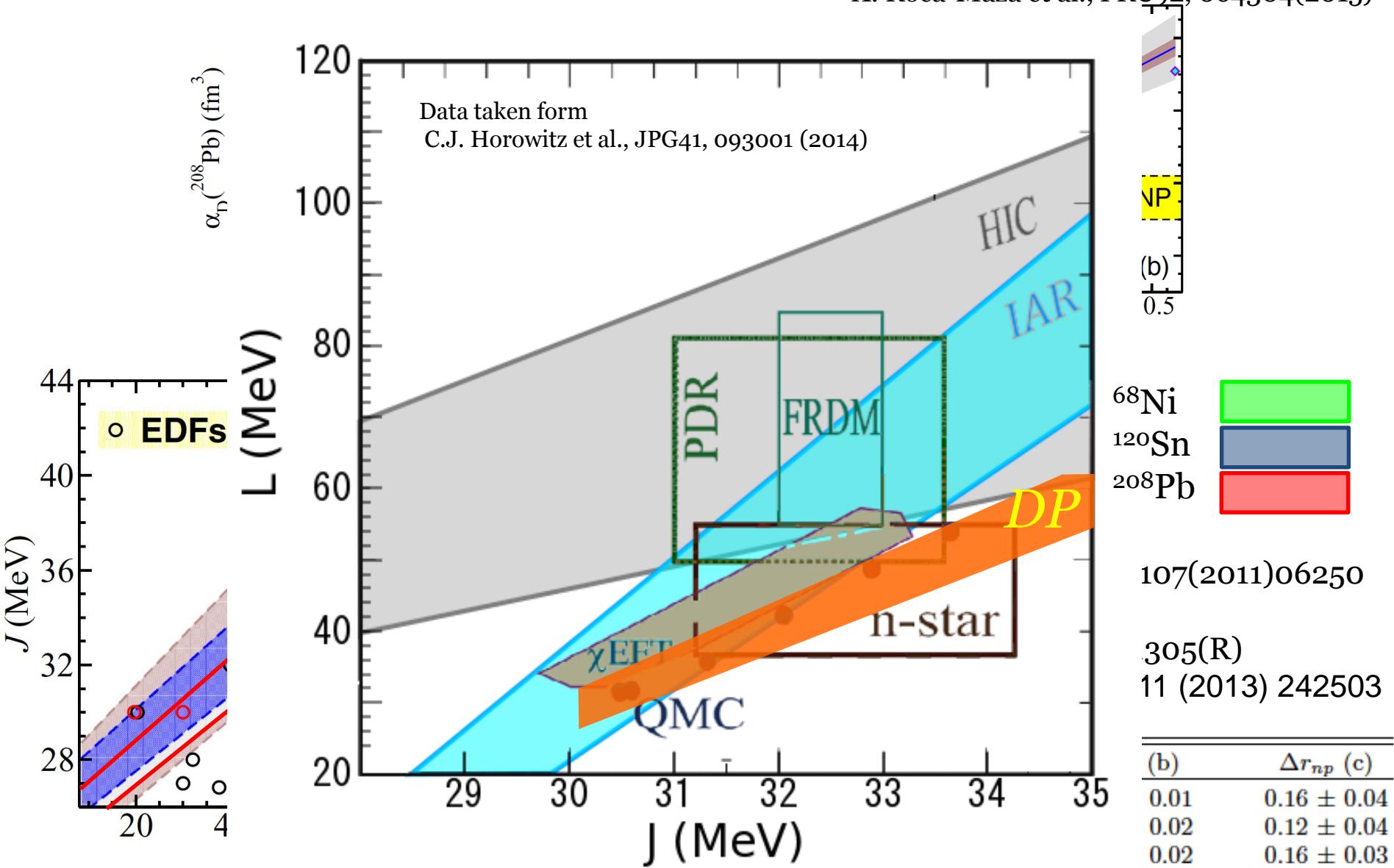
$\sim 4\%$



# Discussion

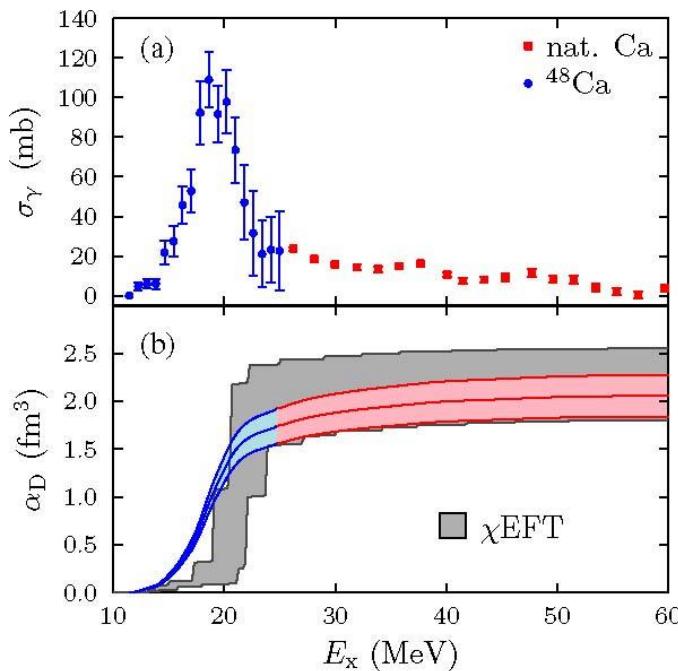
## Constraints on J-L from DP data

X. Roca-Maza et al., PRC92, 064304(2015)

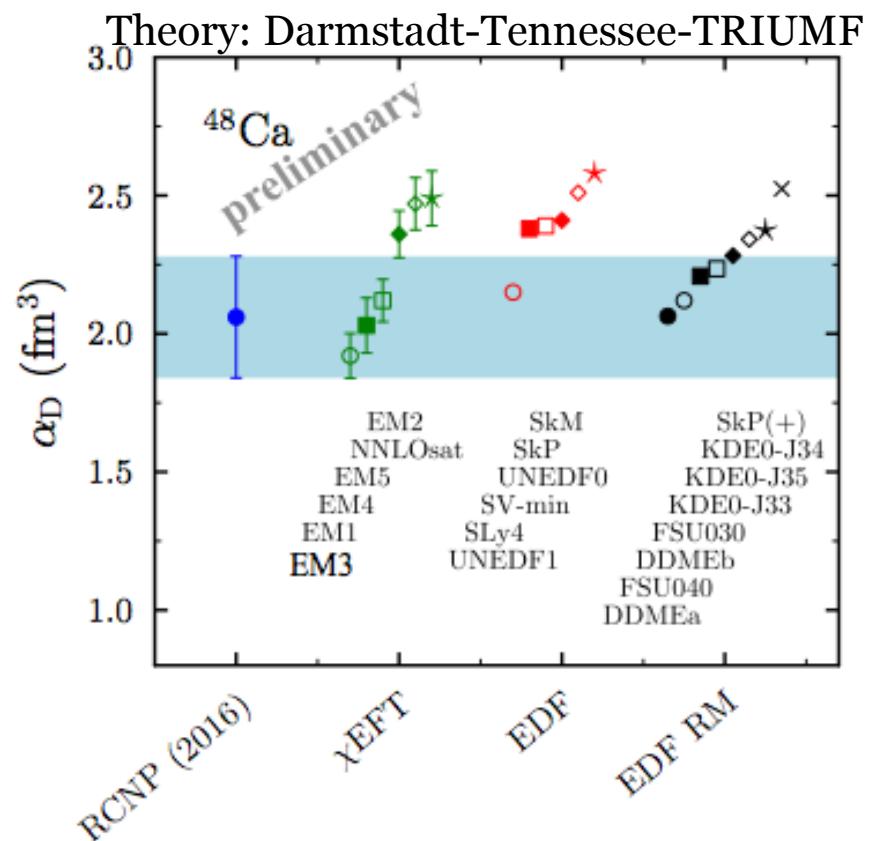


# Work in progress

- Measurements on  $^{112}\text{Sn}$ ,  $^{124}\text{Sn}$  and on  $^{92}\text{Zr}$ ,  $^{94}\text{Zr}$ ,  $^{96}\text{Zr}$  have been measured in 2015.
- Data analysis on  $^{90}\text{Zr}$   $^{96}\text{Mo}$   $^{154}\text{Sm}$  (deformed nucleus)
- The result of  $^{48}\text{Ca}$  experiment is publication in preparation



Uncertainty dominate by parameterization of nuclear background in MDA



New measurements including  $^{40}, 44\text{Ca}$  for a smaller uncertainty are approved at RCNP

# Summary

- The **electric dipole polarizability** is a well-defined observable which is sensitive to the symmetry energy parameters of the nuclear EOS.
- Proton inelastic scattering at very forward angles was employed as an **electromagnetic probe** for extracting the **full electric dipole response** of nuclei.

→ IV properties of the effective interaction:

Electric dipole response of  $^{208}\text{Pb}$ ,  $^{120}\text{Sn}$  and  $^{48}\text{Ca}$  measured precisely by proton inelastic scattering.

Constraints on the symmetry energy and Neutron skin thickness  
Pygmy dipole resonance distribution and Nuclear structure etc..

Isotope dependence on Sn and Zr have been measured  
and on Ca will be measured

***RCNP, Osaka University***

A. Tamii, H. Matsubara, H. Fujita, K. Hatanaka,  
H. Sakaguchi Y. Tameshige, M. Yosoi and J. Zenihiro

***IKP, TU-Darmstadt***

P. von Neumann-Cosel, A-M. Heilmann,  
Y. Kalmykov, I. Poltoratska, V.Yu. Ponomarev,  
A. Richter and J. Wambach

***Dep. of Phys., Osaka University***

Y. Fujita

***Dep. of Phys., Kyoto University***

T. Kawabata

***KVI, Univ. of Groningen***

T. Adachi and L.A. Popescu

***IFIC-CSIC, Univ. of Valencia***

B. Rubio and A.B. Perez-Cerdan

***Sch. of Science Univ. of Witwatersrand***

J. Carter and H. Fujita

***iThemba LABS***

F.D. Smit

***Texas A&M Commerce***

C.A. Bertulani

***GSI***

E. Litvinova

***CNS, Univ. of Tokyo***

K. Nakanishi,  
Y. Shimizu and Y. Sasamoto

***CYRIC, Tohoku University***

M. Itoh and Y. Sakemi

***Dep. of Phys., Kyushu  
University***

M. Dozono

***Dep. of Phys., Niigata  
University***

Y. Shimbara

T. Hashimoto<sup>†</sup>, A. M. Krumbholz<sup>1</sup>, A. Tamii<sup>2</sup>, P. von Neumann-Cosel<sup>1</sup>, N. Aoi<sup>2</sup>,  
O. Burda<sup>2</sup>, J. Carter<sup>3</sup>, M. Chernykh<sup>2</sup>, M. Dozono<sup>4</sup>, H. Fujita<sup>2</sup>, Y. Fujita<sup>2</sup>,  
K. Hatanaka<sup>2</sup>, E. Ideguchi<sup>2</sup>, N. T. Khai<sup>5</sup>, C. Iwamoto<sup>2</sup>, T. Kawabata<sup>6</sup>,  
D. Martin<sup>1</sup>, K. Miki<sup>1</sup>, R. Neveling<sup>7</sup>, H. J. Ong<sup>2</sup>, I. Poltoratska<sup>1</sup>, P.-G. Reinhard<sup>8</sup>,  
A. Richter<sup>1</sup>, F.D. Smit<sup>6</sup>, H. Sakaguchi<sup>2,4</sup>, Y. Shimbara<sup>9</sup>, Y. Shimizu<sup>4</sup>, T. Suzuki<sup>2</sup>,  
M. Yosoi<sup>1</sup>, J. Zenihiro<sup>4</sup>, K. Zimmer<sup>1</sup>

<sup>†</sup>Institute for Basic Science, Korea

<sup>1</sup>IKP, Technische Universität Darmstadt, Germany

<sup>2</sup>RCNP, Osaka University, Japan

<sup>3</sup>Wits University, South Africa

<sup>4</sup>RIKEN, Japan

<sup>5</sup>Institute for Nuclear Science and Technology (INST), Vietnam

<sup>6</sup>Kyoto University, Japan

<sup>7</sup>iThemba LABs, South Africa

<sup>8</sup>Institut Theoretical Physik II, Universität Erlangen-Nürnberg, Germany

<sup>9</sup>CYRIC, Tohoku University, Japan

Thank you  
for your attention

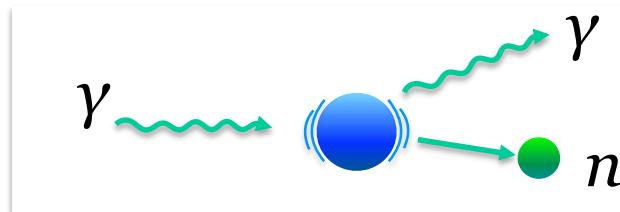
# Backup Slides

# Physics Motivation and Strategy

## Probes of the Electric Dipole Response

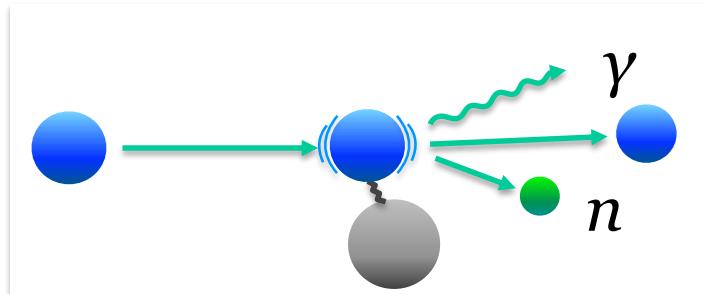
### 1. Real photon absorption

- $(\gamma, \gamma')$  Nuclear Resonance Fluorescence
- $(\gamma, n)$ ,  $(\gamma, 2n)$ , ...

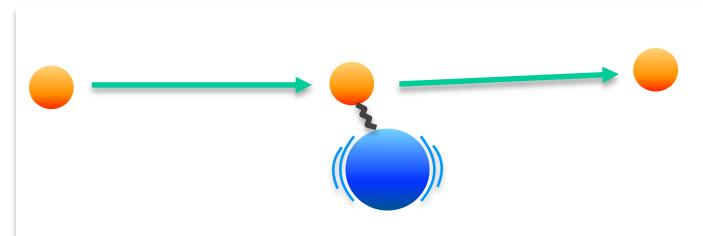


### 2. Virtual photon excitations (Coulomb excitation)

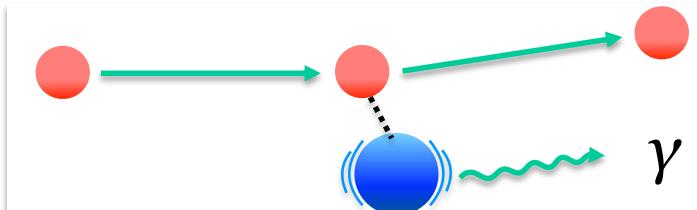
- Invariant mass method  
with an unstable nucleus beam



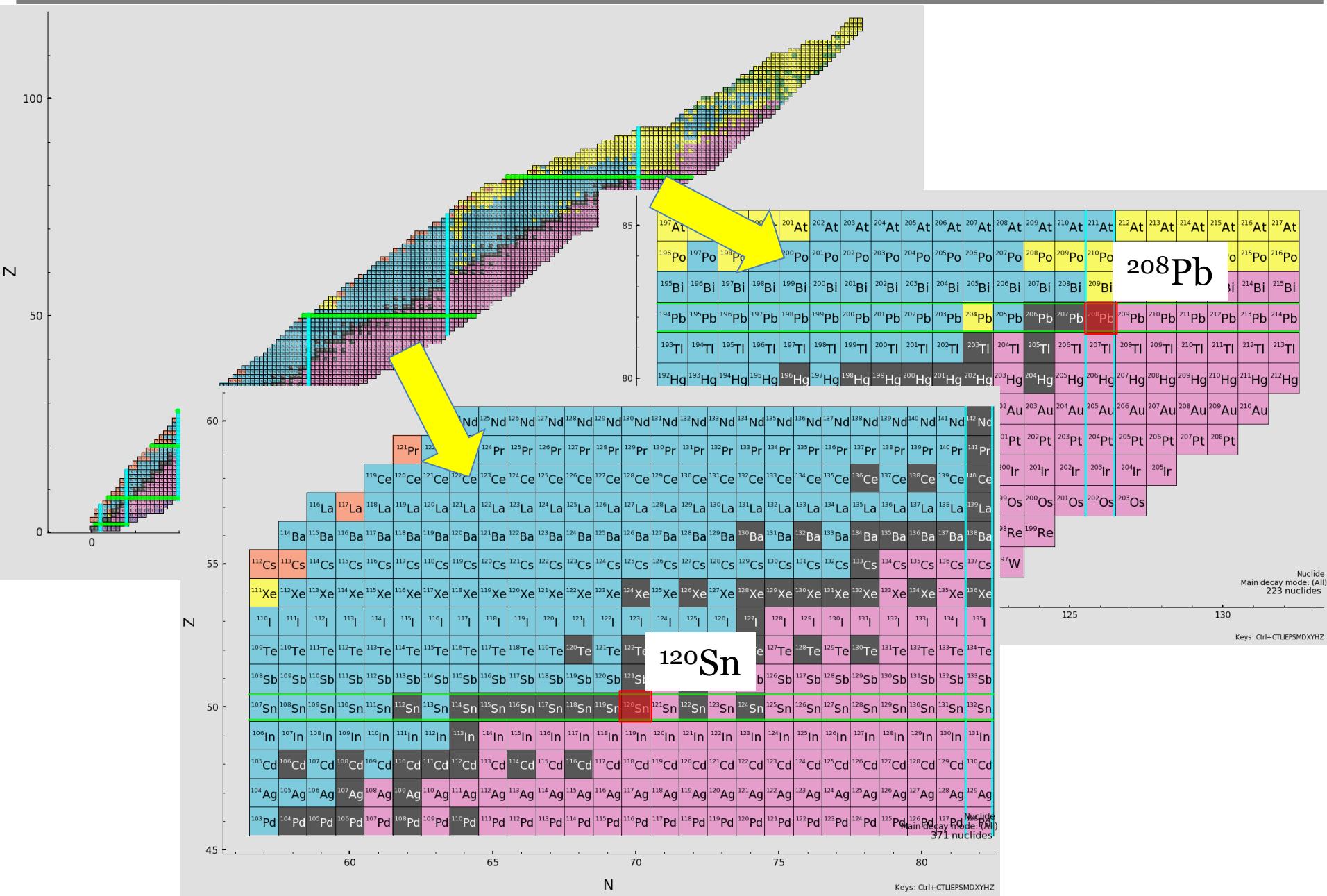
- Missing mass method  
with proton inelastic scattering



### 3. Excitation by nuclear force with $\alpha$ or $^{17}\text{O}$ inelastic scattering



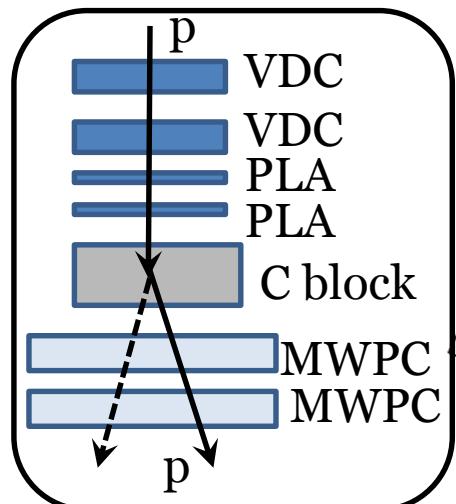
# Physics Motivation and Strategy



# Experimental method

Grand Raiden spectrometer @ RCNP

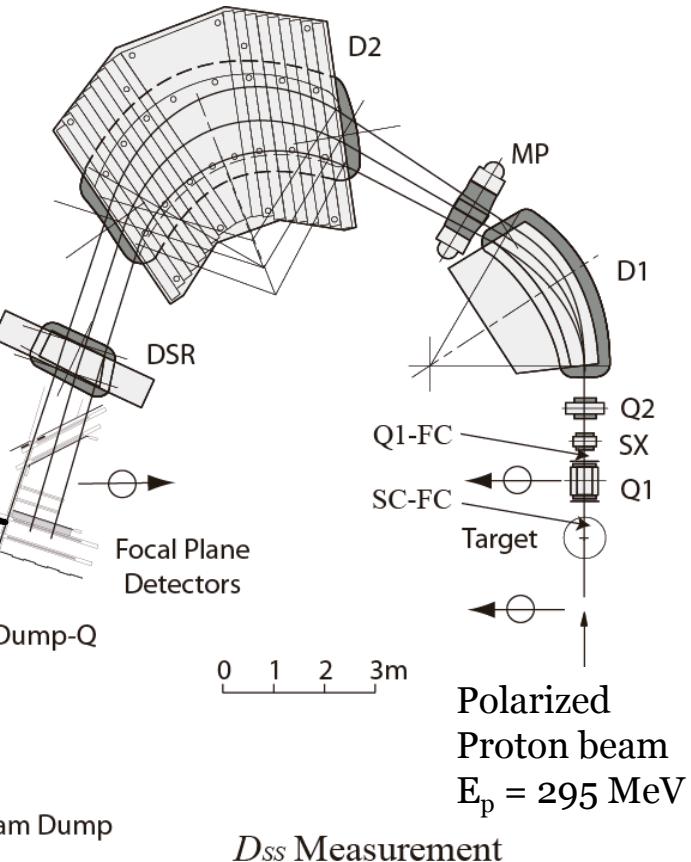
Focal plane detectors



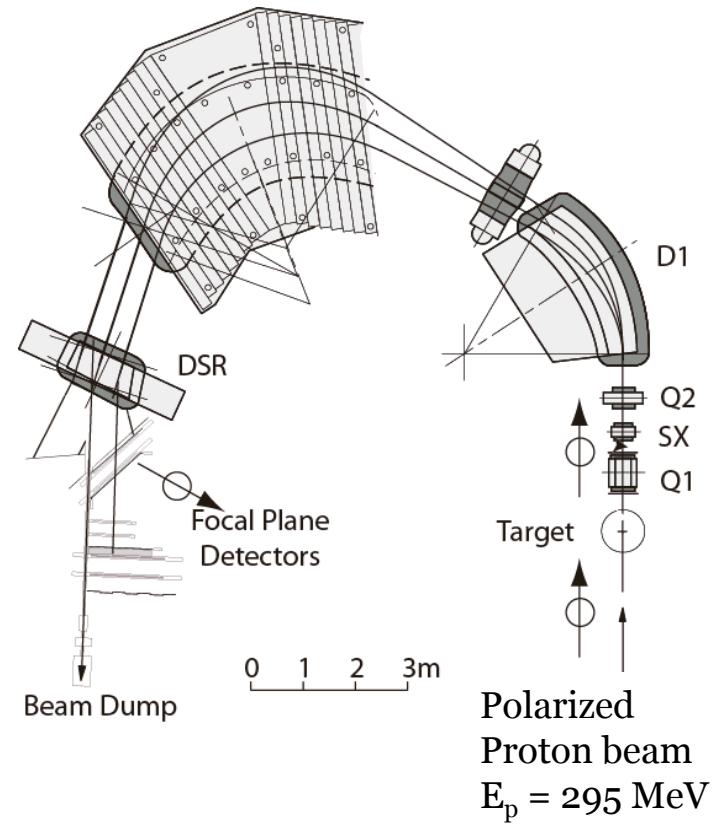
Total Spin Transfer ( $\Sigma$ )

$$\Sigma \equiv \frac{3 - (2D_{ss} + D_{ll})}{4}$$

$D_{ss}$  and  $D_{ll}$ : Spin transfer observable



$D_{ss}$  Measurement

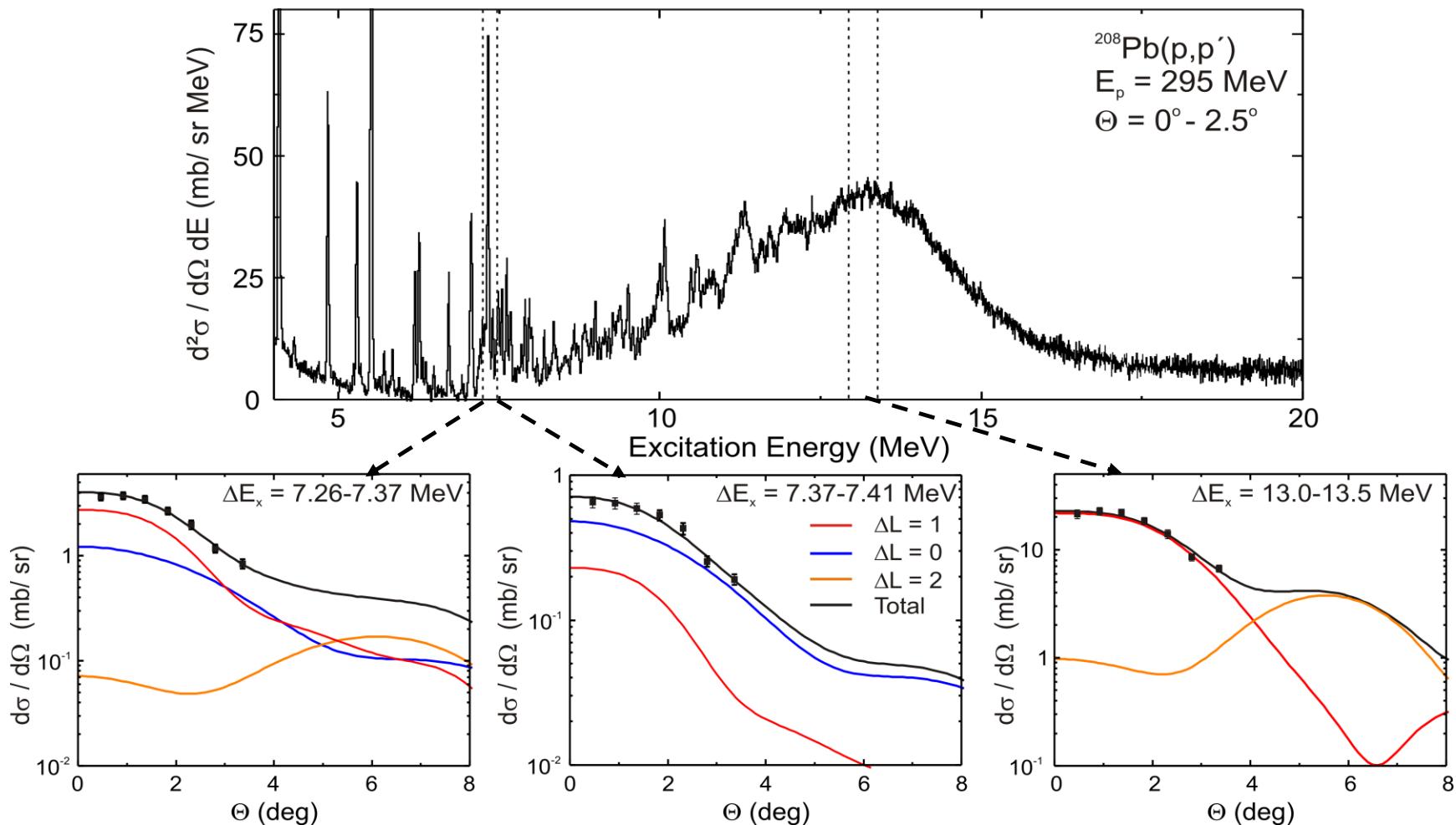


$D_{ll}$  Measurement

$^{120}\text{Sn}$  target  
Thickness:  $6.5 \text{ mg/cm}^2$   
Purity 98.4 %

# B(E1): continuum and GDR region

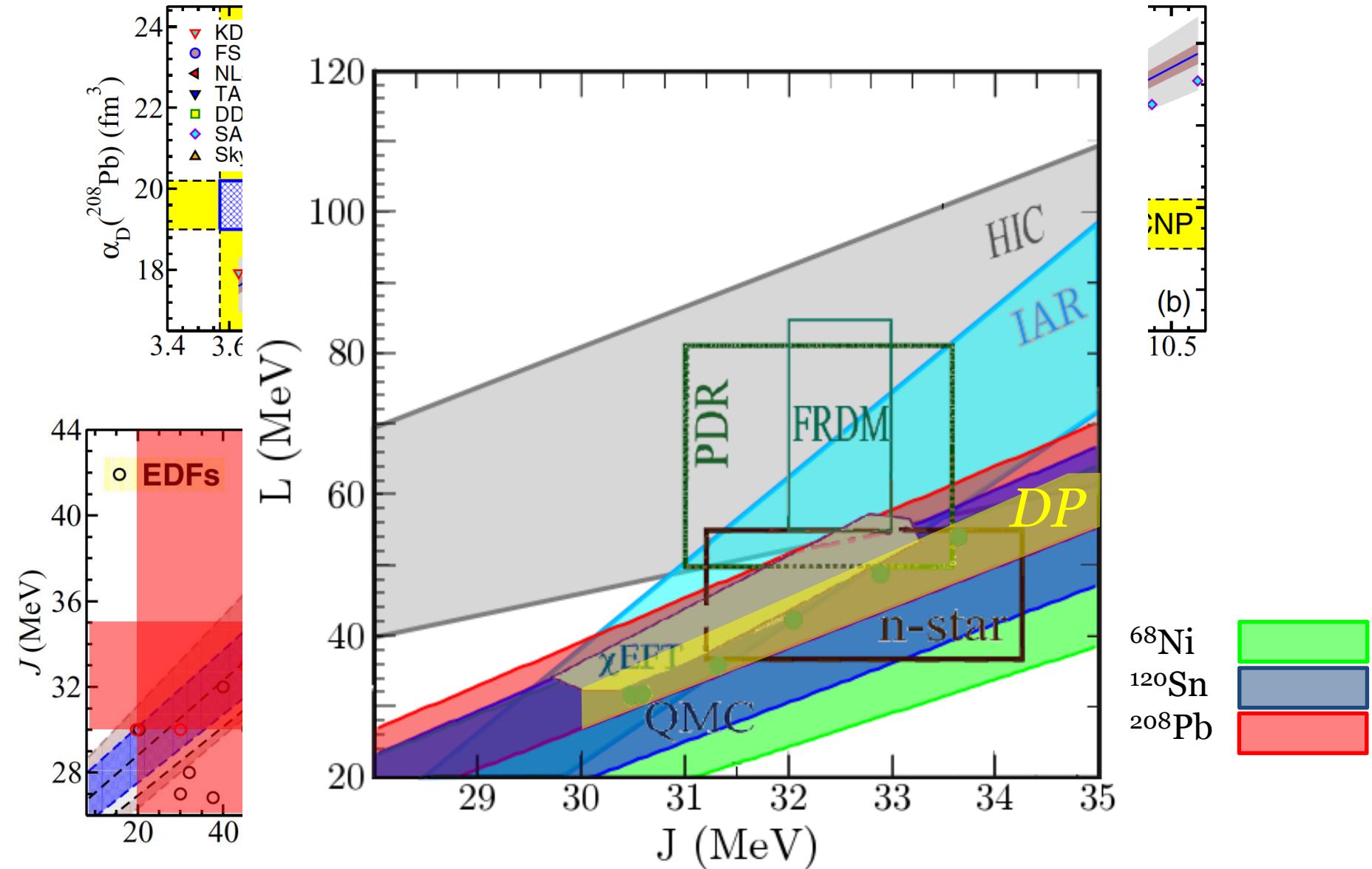
## Method 1: Multipole Decomposition



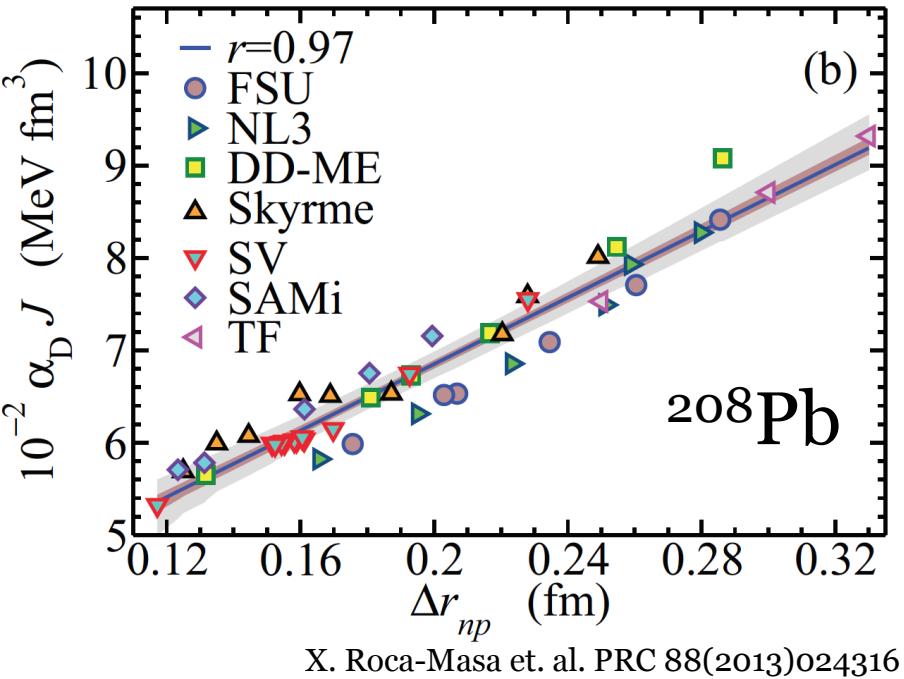
- Neglect of data for  $\Theta > 4^\circ$ : ( $p,p'$ ) response too complex
- Included E1/M1/E2 or E1/M1/E3 (little difference)

# Discussion

## Constraints on J-L from DP data

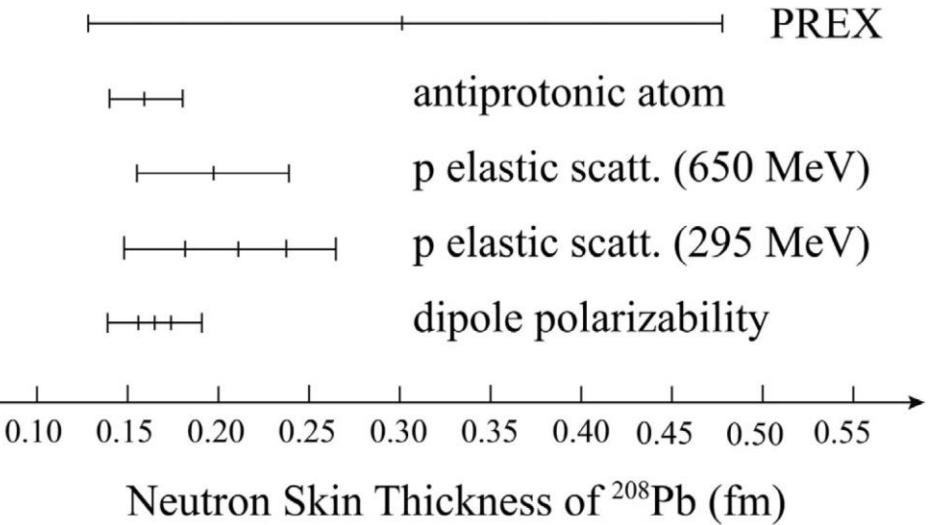


# Discussion



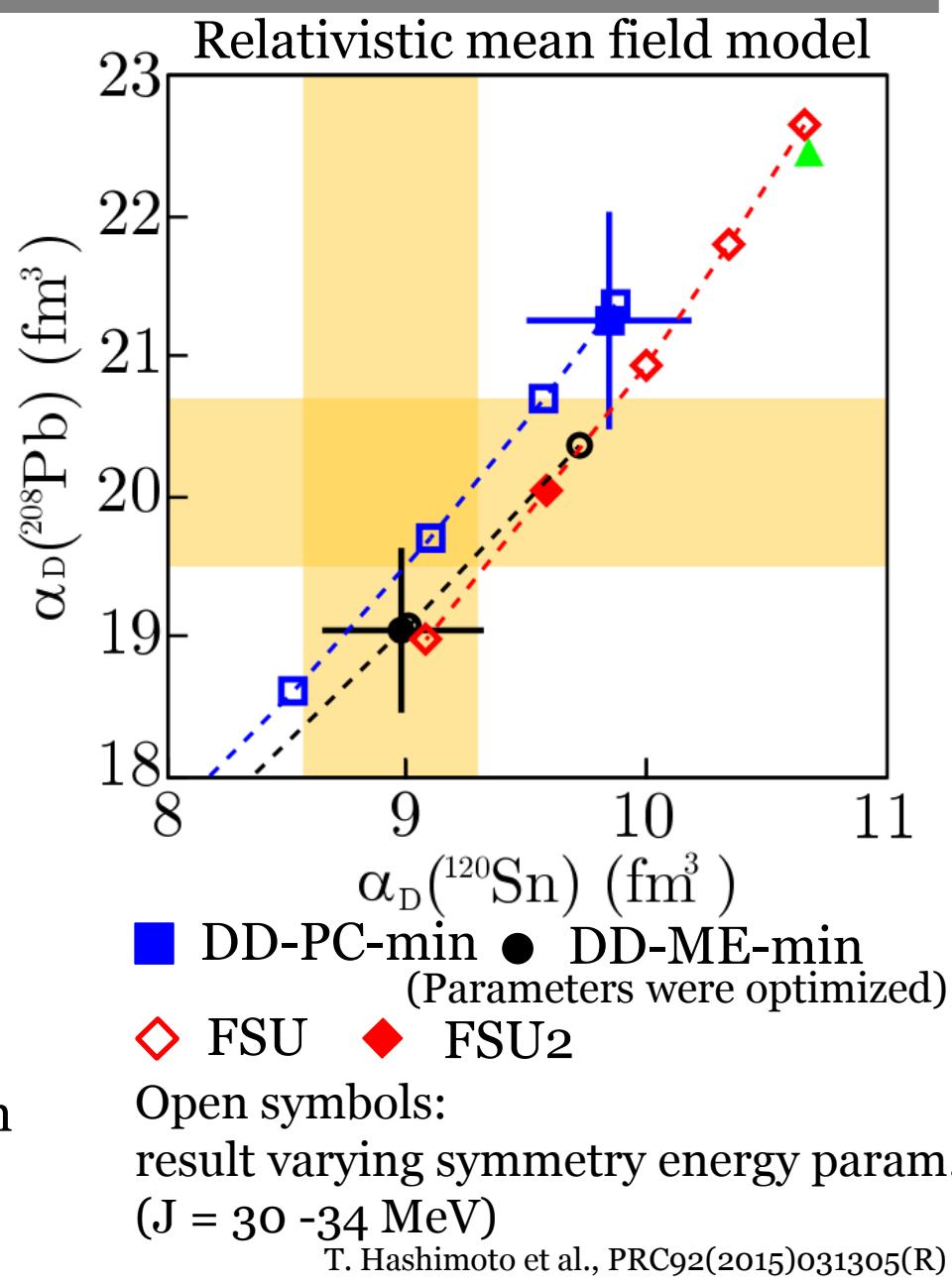
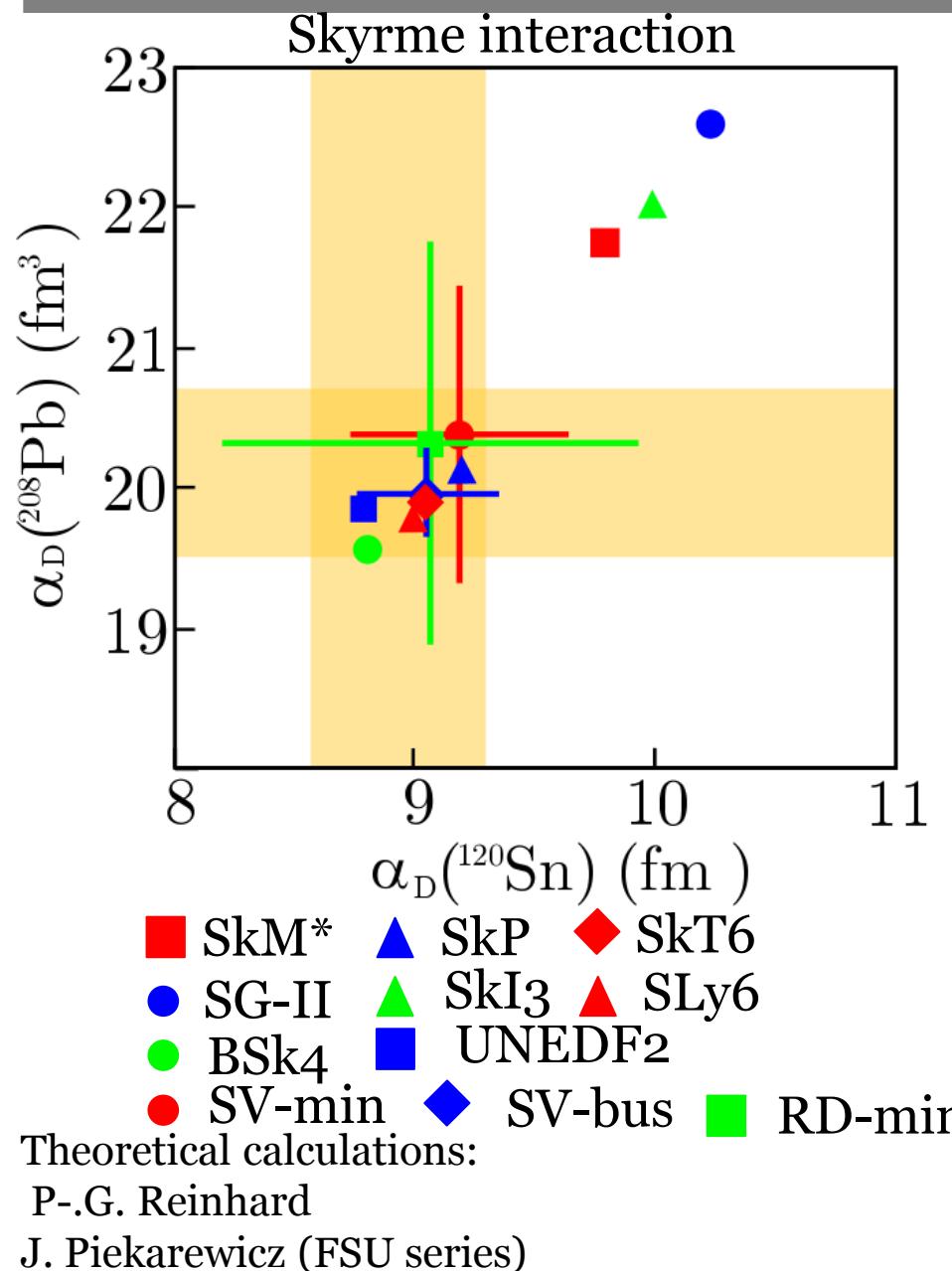
$\Delta r_{np} = 0.165 \pm (0.009)_{\text{expt}} \pm (0.013)_{\text{theor}} \pm (0.021)_{\text{est}}$  fm  
for the estimated  $J = 31 \pm (2)_{\text{est}}$

A. Tamii et. al. EPJ50(2014)28



All results agree with error bars  
and limit the range of neutron skin thickness to 0.15-0.20 fm

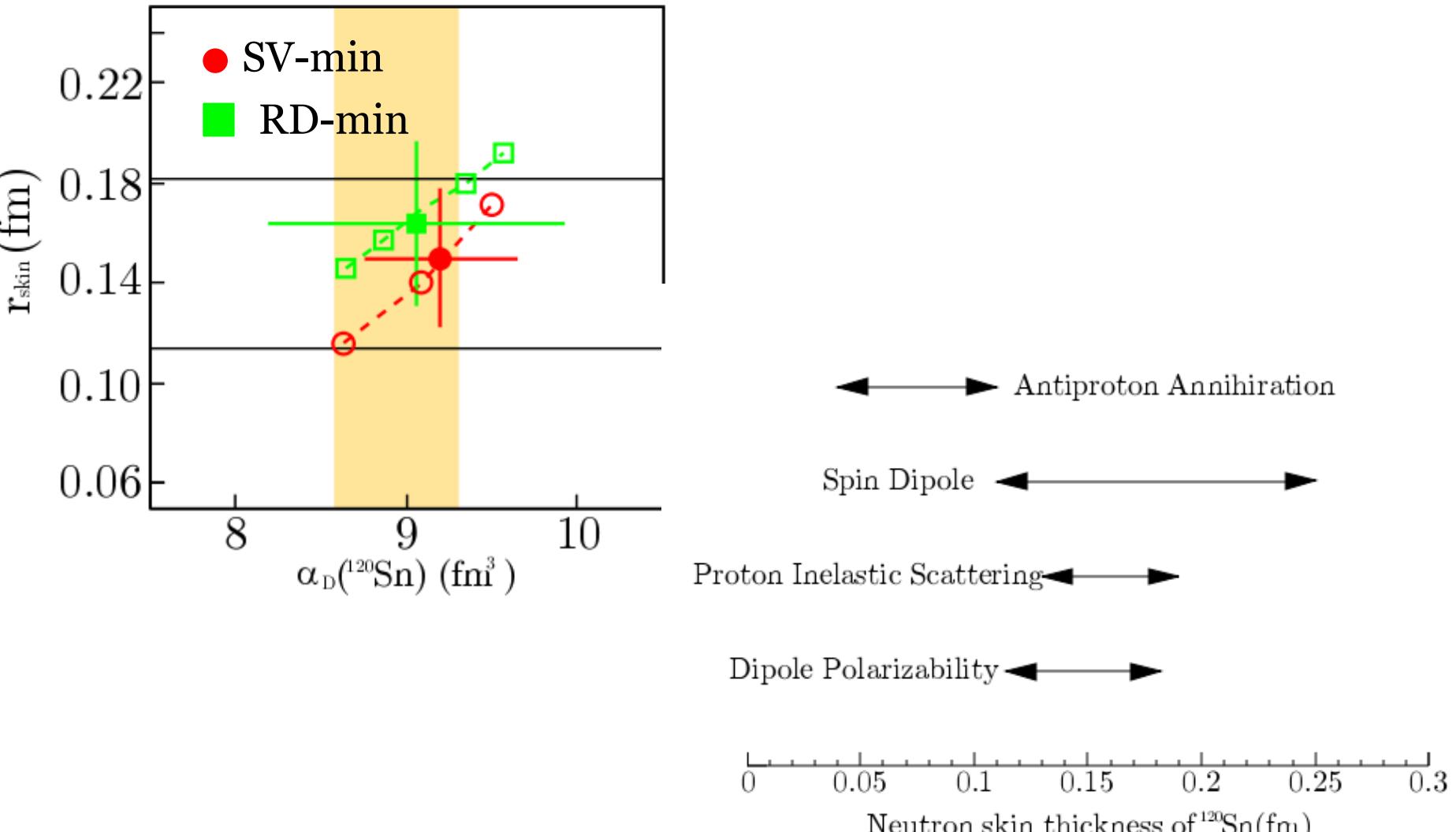
# Discussion



# Discussion

## Neutron Skin Thickness

T. Hashimoto et al., PRC92(2015)031305(R)

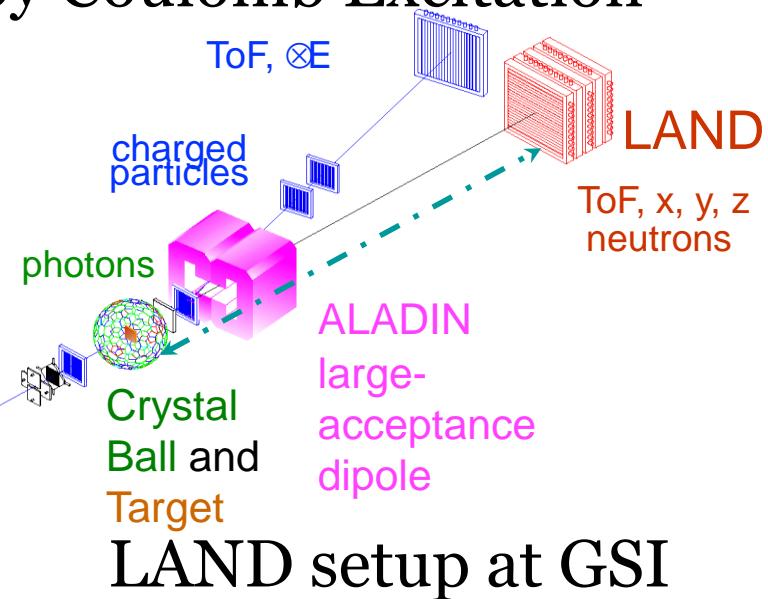
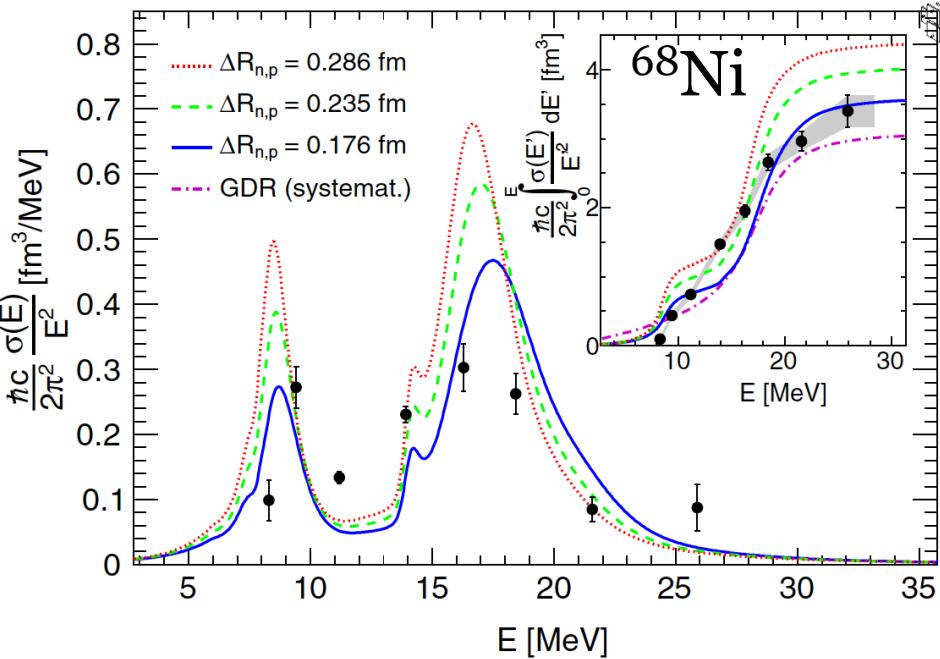


The result is in good agree with error bars  
except for the result of antiproton annihilation

# Discussion

## Electric Dipole Polarizability of $^{68}\text{Ni}$ Invariant mass spectroscopy by Coulomb Excitation

D. Rossi et al., PRL 111 (2013) 242503



LAND setup at GSI

$$\alpha_D = 3.40 \pm 0.23 \text{ fm}^3$$

# CAGRA+GR Campaign Exp. From Oct. 2016

Structure of the PDR via the ( $p, p' \gamma$ ) and ( $\alpha, \alpha' \gamma$ )

\*1&Savran et al 31 days

( ${}^6\text{Li}; {}^6\text{Li}' [\text{o}+]$ ) reaction for inelastic  $\nu$ -nucleus response Noji et al.5

Super-deformed states in  ${}^{28}\text{Si}$  via  $\gamma$ -particle coinc.

Jenkins et al. 6

high-spin states population by light-ion reactions,

Ideguchi et al. 3

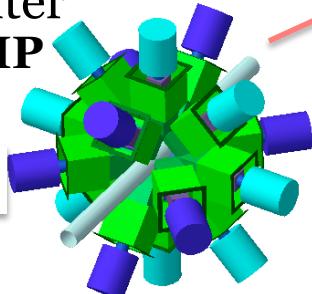
\*1 A. Bracco, F. Crespi, V. Derya, M.N. Harakeh, T. Hashimoto, P. von Neumann-Cosel, N. Pietralla, D. Savran, A. Tamii, V. Werner, and A. Zilges *et al.*



## CAGRA(Clover Ge Array)

E. Ideguchi and M. Carpenter

**Clovers: ANL+Tohoku+IMP**



Preparation in progress



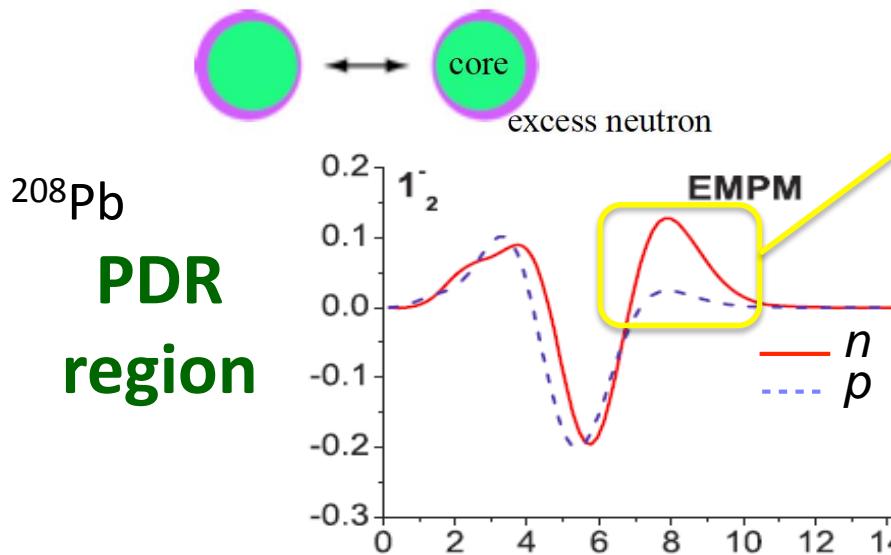
## Collaboration

**RCNP, Tohoku, ANL, LBNL, Milano,  
TU-Darmstadt, GSI, Köln, KVI, IFJ-PAN, IMP, ...**

Aug. 2016

# Excess Neutron Oscillation of the PDR

Predictions of the transition densities.

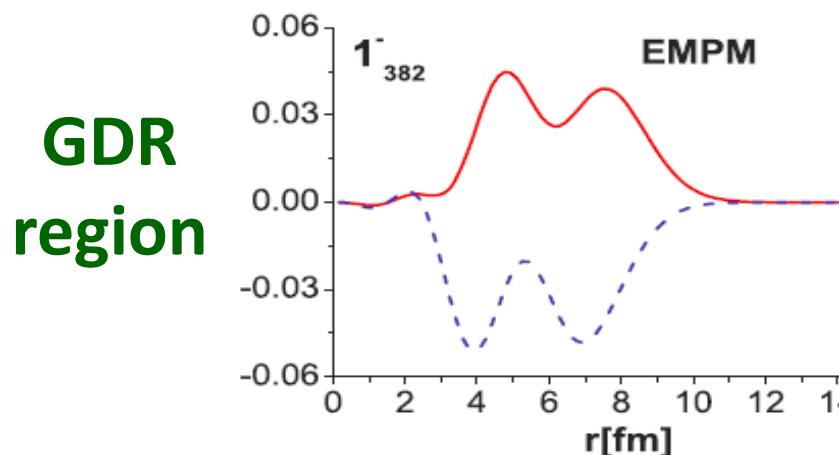


Dipole oscillation of the excess neutron on surface against the isospin saturated core?

In both the IS and IV response

Signature of the neutron excess oscillation

- sensitivity to the surface transition
- IS excitation
- characteristic  $q$ -dependence



Out of phase  $n-p$  oscillation

Only in the IV response

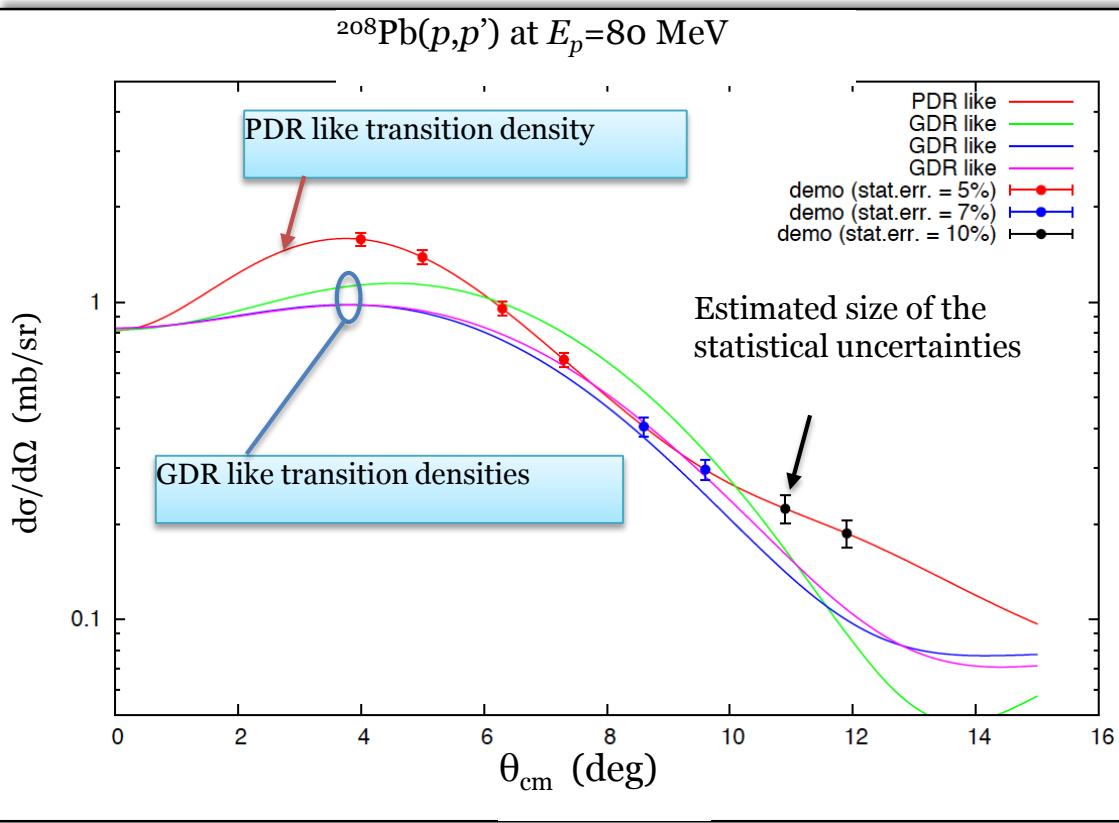
# Structure of the PDR

(p,p'γ) and (α,α'γ) for PDR in  $^{64}\text{Ni}$ ,  $^{90,94}\text{Zr}$ ,  $^{120,124}\text{Sn}$ ,  $^{206,208}\text{Pb}$

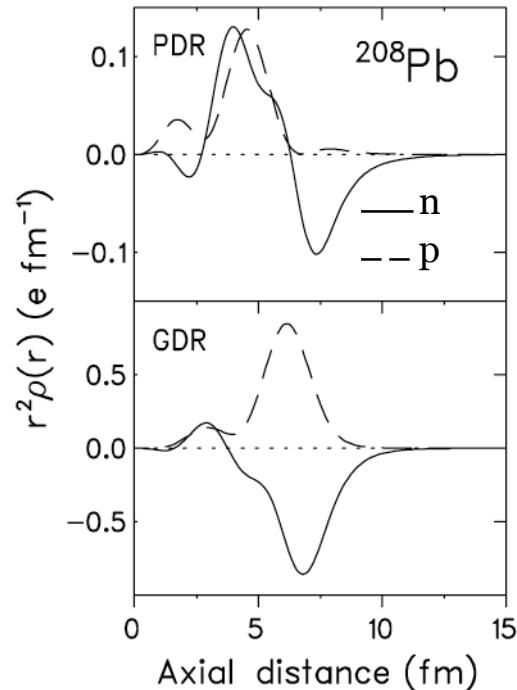
## Collaboration

**RCNP, Tohoku, ANL,  
Berkley, Milano,  
TU-Darmstadt, GSI,  
Köln, KVI, IFJ-PAN**

Transition densities by QPM calc.

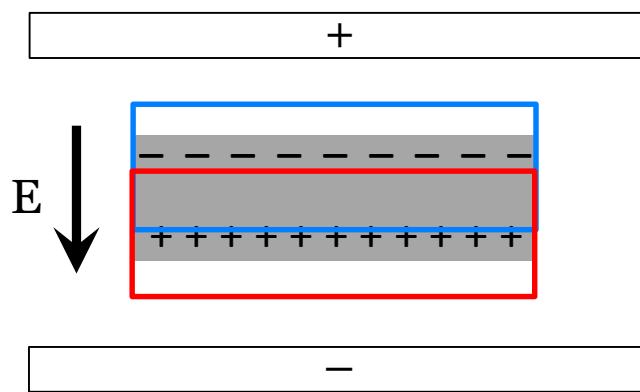


q-dep. of the PDR excitation for  $^{208}\text{Pb}$



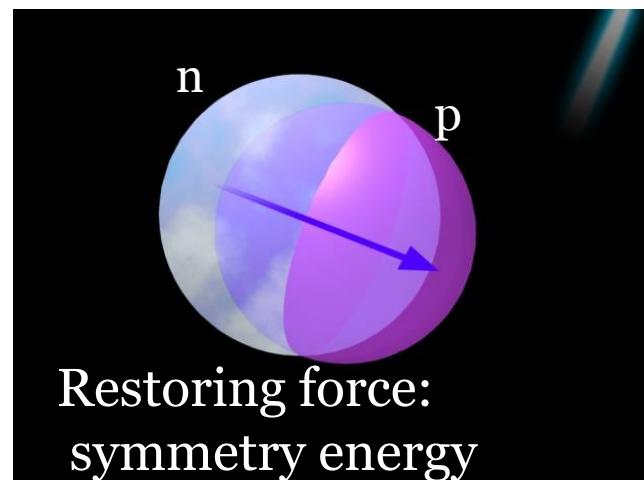
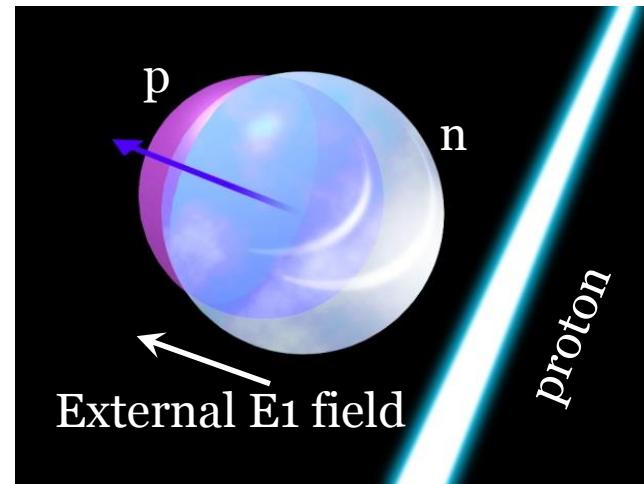
# Physics Motivation and Strategy

## Electric Dipole Polarizability ( $\alpha_D$ )



$$\vec{P} = \alpha N \vec{E}$$

$\alpha$ : dipole polarizability of an atom



# Collaboration $^{48}\text{Ca}$

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TECHNISCHE  
UNIVERSITÄT  
DARMSTADT

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Experiment: Darmstadt-Osaka

Theory: Darmstadt-Tennessee-TRIUMF

S. Bacca (TRIUMF)

S. Bassauer (TUD)

J. Birkhan (Darmstadt)

G. Hagen (ORNL)

H. Matsubara (RCNP)

M. Miorelli (TRIUMF)

P. von Neumann-Cosel (TUD)

T. Papenbrock (U Tennessee)

N. Pietralla (TUD)

A. Richter (TUD)

A. Schwenk (TUD)

A. Tamii (RCNP)