Recent Results from Proton Scattering Experiments at RCNP

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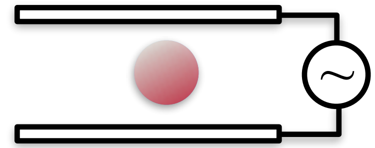
6th Int. Conf. on Collective Motion in Nuclei under Extreme Conditions (COMEX6)
29 October - 2 November, 2019, Cape Town

Sep-2007

Dec-2012

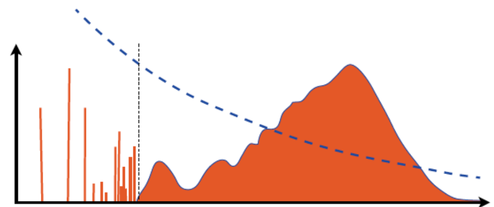
Oct-2009

Outline

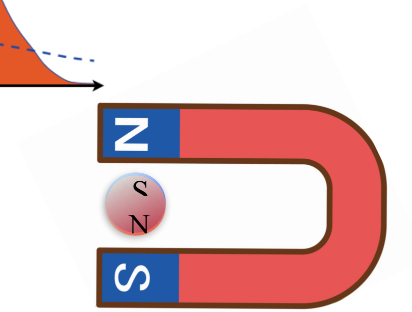


<u>Experimental methods</u>

proton scattering at forward angles

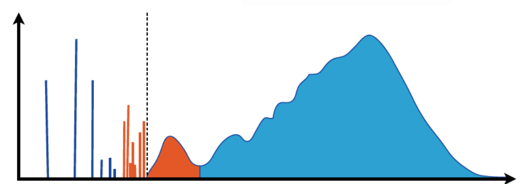


<u>Research highlights</u>

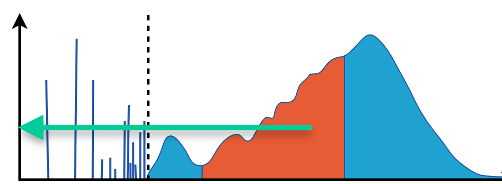


I. Electric Dipole Polarizability
and Nuclear Symmetry Energy

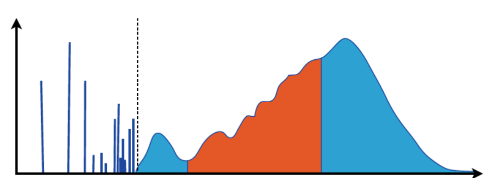
II. Spin Magnetic Excitations



III. Gamma-Decay of GRs and ED excitations
PDR and GDR

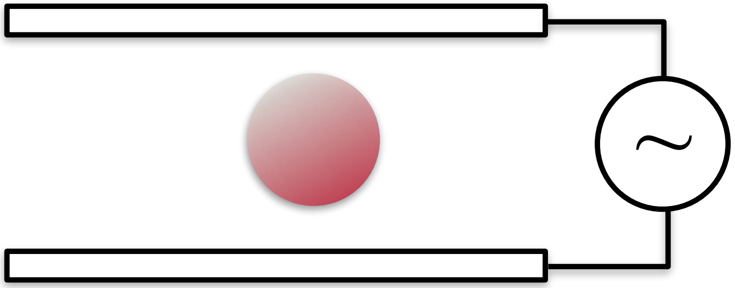


IV. Fine Structure and Nuclear Level Density



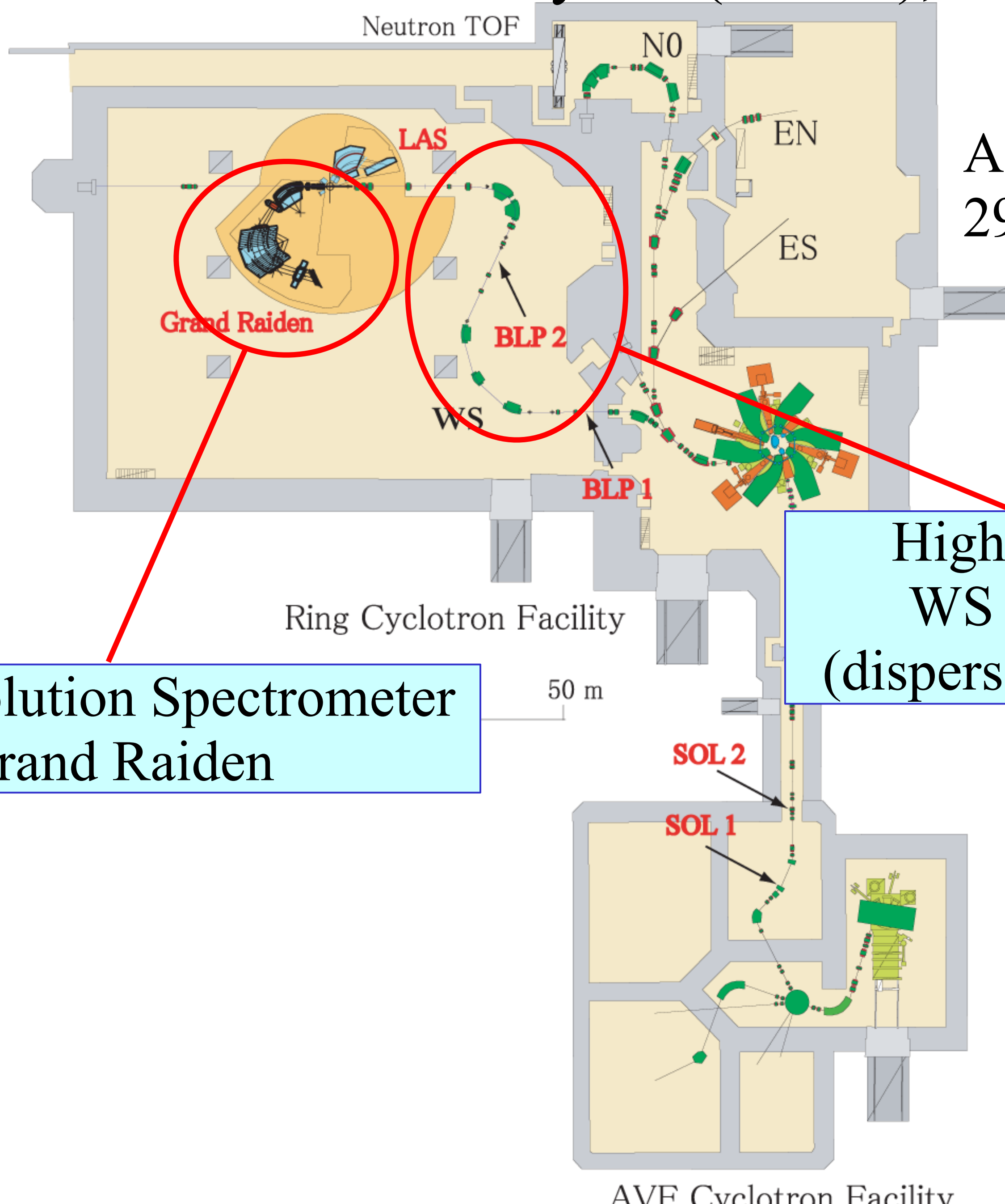
Experimental Methods

Proton Scattering Experiments at Forward Angles



RCNP, Osaka Univ.

Research Center for Nuclear Physics (RCNP), Osaka University



A proton beam at 295/392 MeV

High-resolution WS beam-line (dispersion matching)

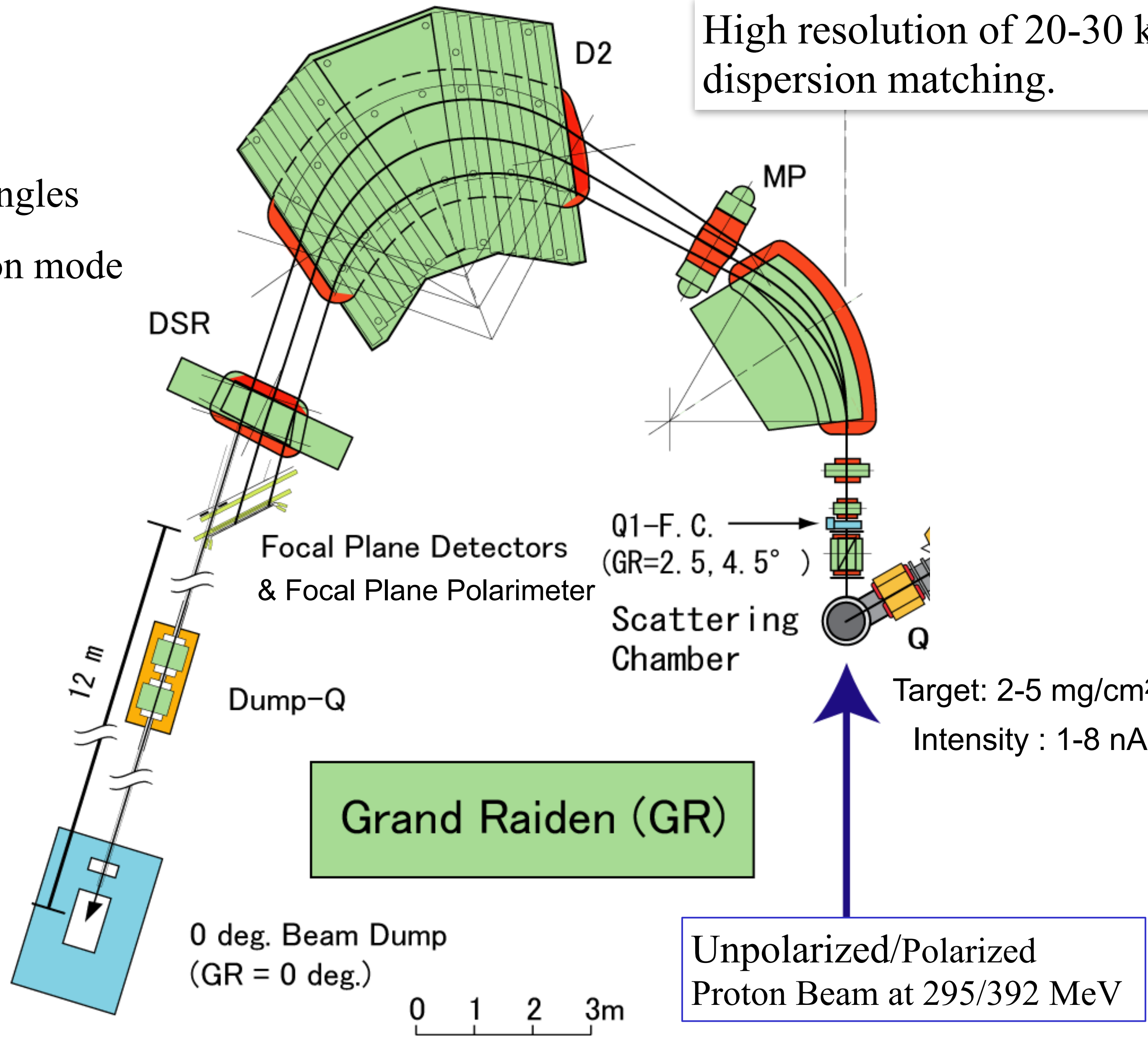
High-resolution Spectrometer Grand Raiden

High-Resolution Spectrometer "Grand Raiden"

High resolution of 20-30 keV:
dispersion matching.

Proton scattering
at very forward angles

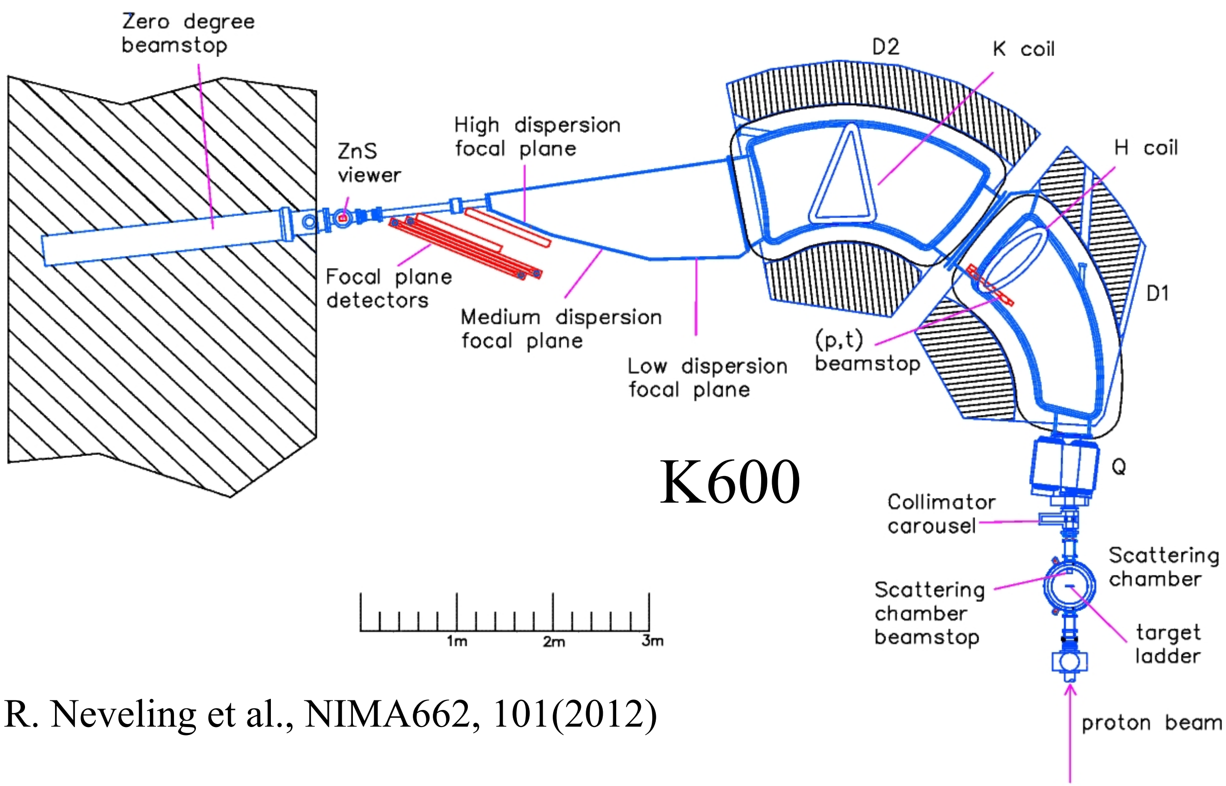
0-deg transmission mode



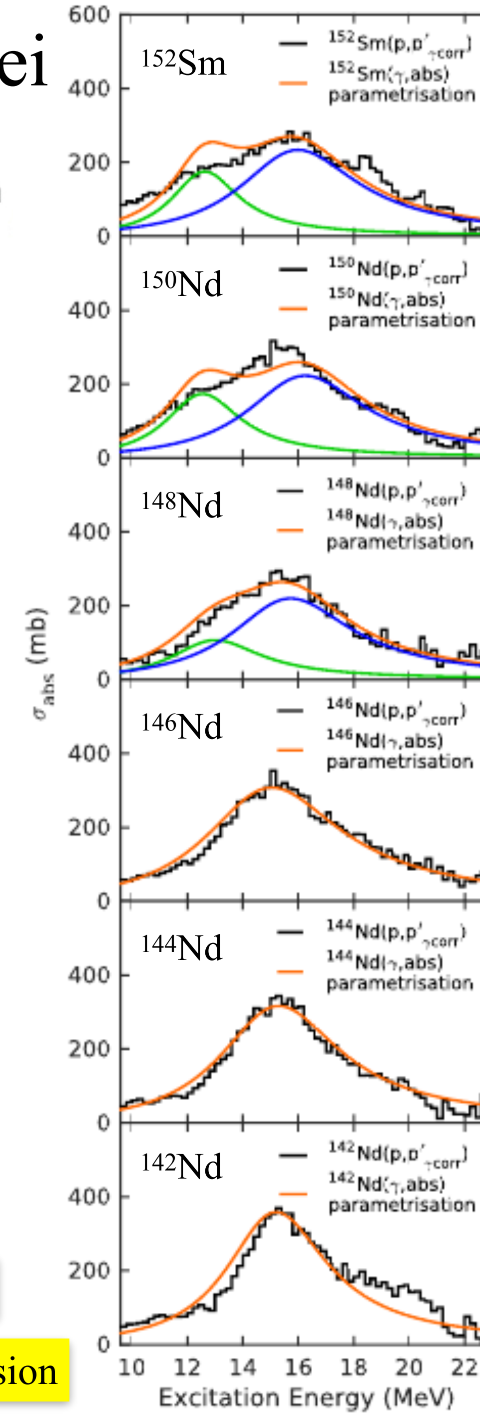
Unpolarized/Polarized
Proton Beam at 295/392 MeV

AT et al., NIMA605, 326 (2009)

Electric Dipole Response of Deformed Nuclei Measurement at iThemba LABS



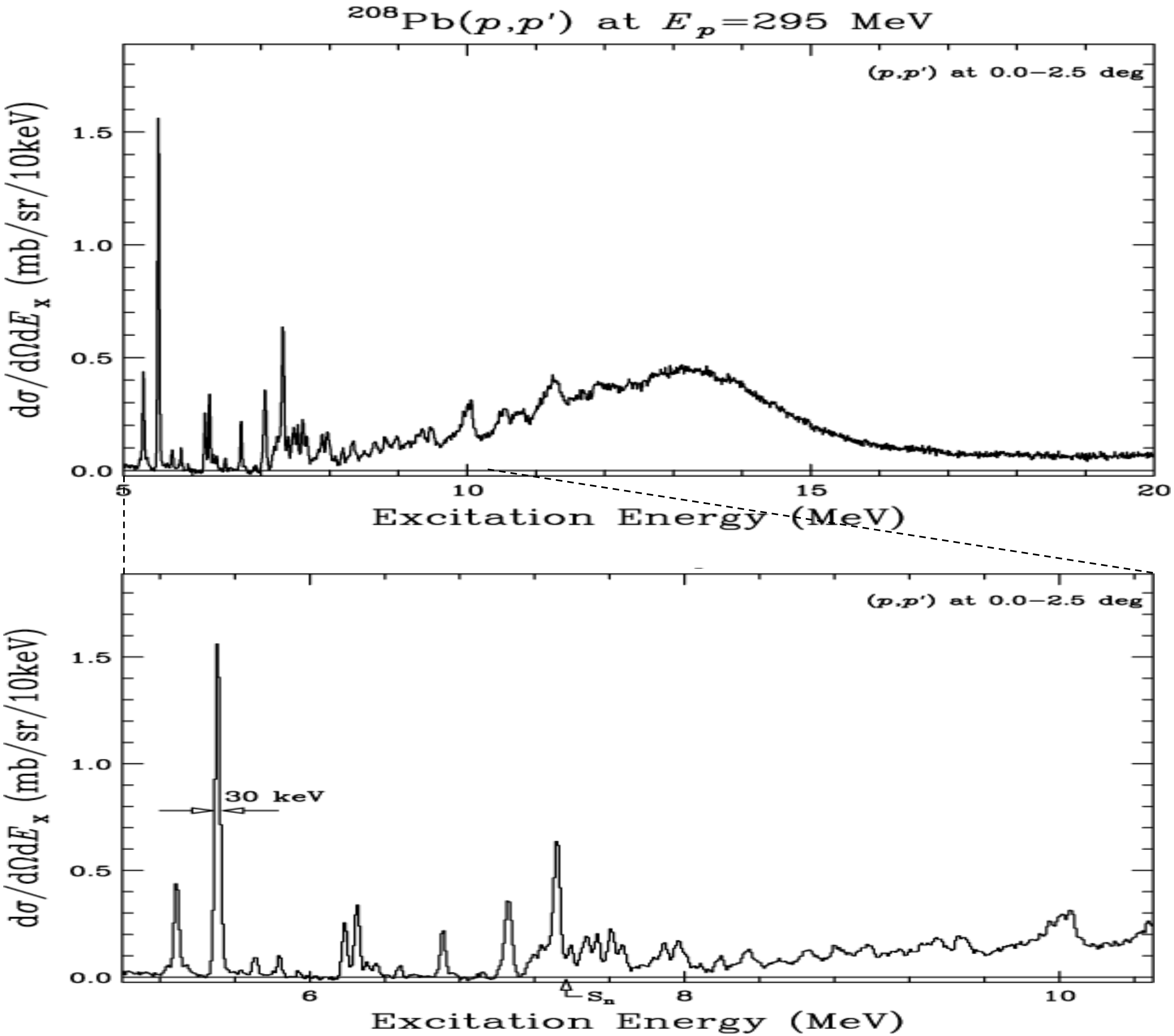
R. Neveling et al., NIMA662, 101(2012)



Talk by L. Pellegri, this morning

Talk by L. Donaldson, in this session

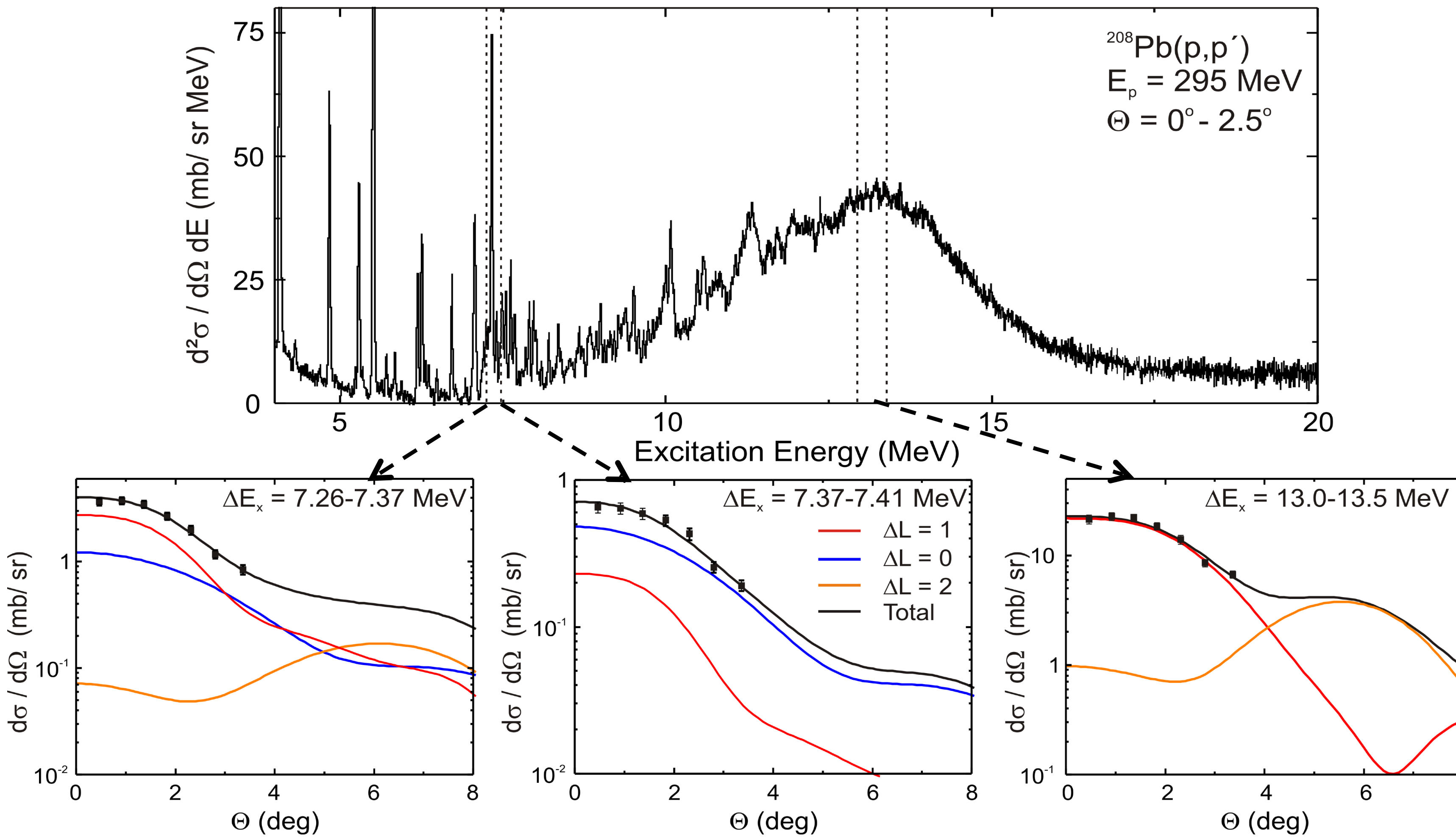
Courtesy of R. Neveling



208Pb(p,p') at Ep=295 MeV
(p,p') at 0.0–2.5 deg
dσ/dΩdEx (mb/sr/10keV)
1.5
1.0
0.5
0.0
5
10
15
20
Excitation Energy (MeV)
(p,p') at 0.0–2.5 deg
dσ/dΩdEx (mb/sr/10keV)
1.5
1.0
0.5
0.0
30 keV
6
8
10
Sn
Excitation Energy (MeV)

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)

Grazing Angle = 3.0 deg

B(E1): continuum and GDR region

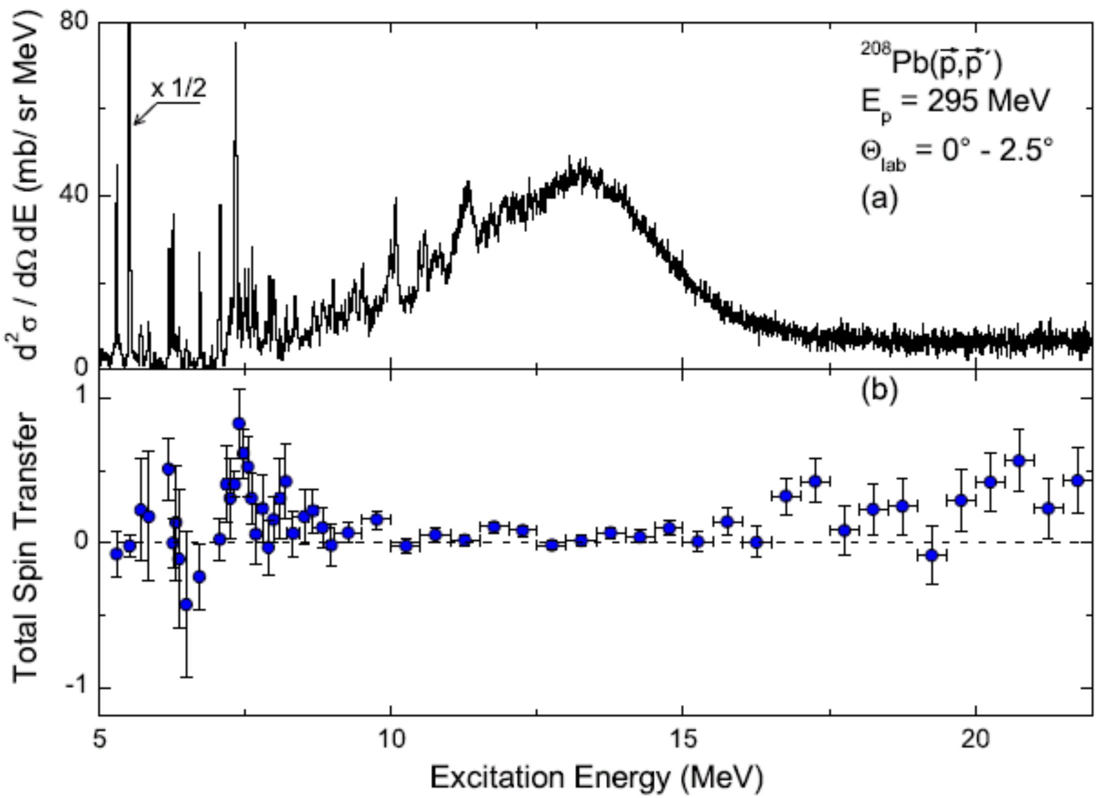
Method 2: Decomposition by Spin Observables

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

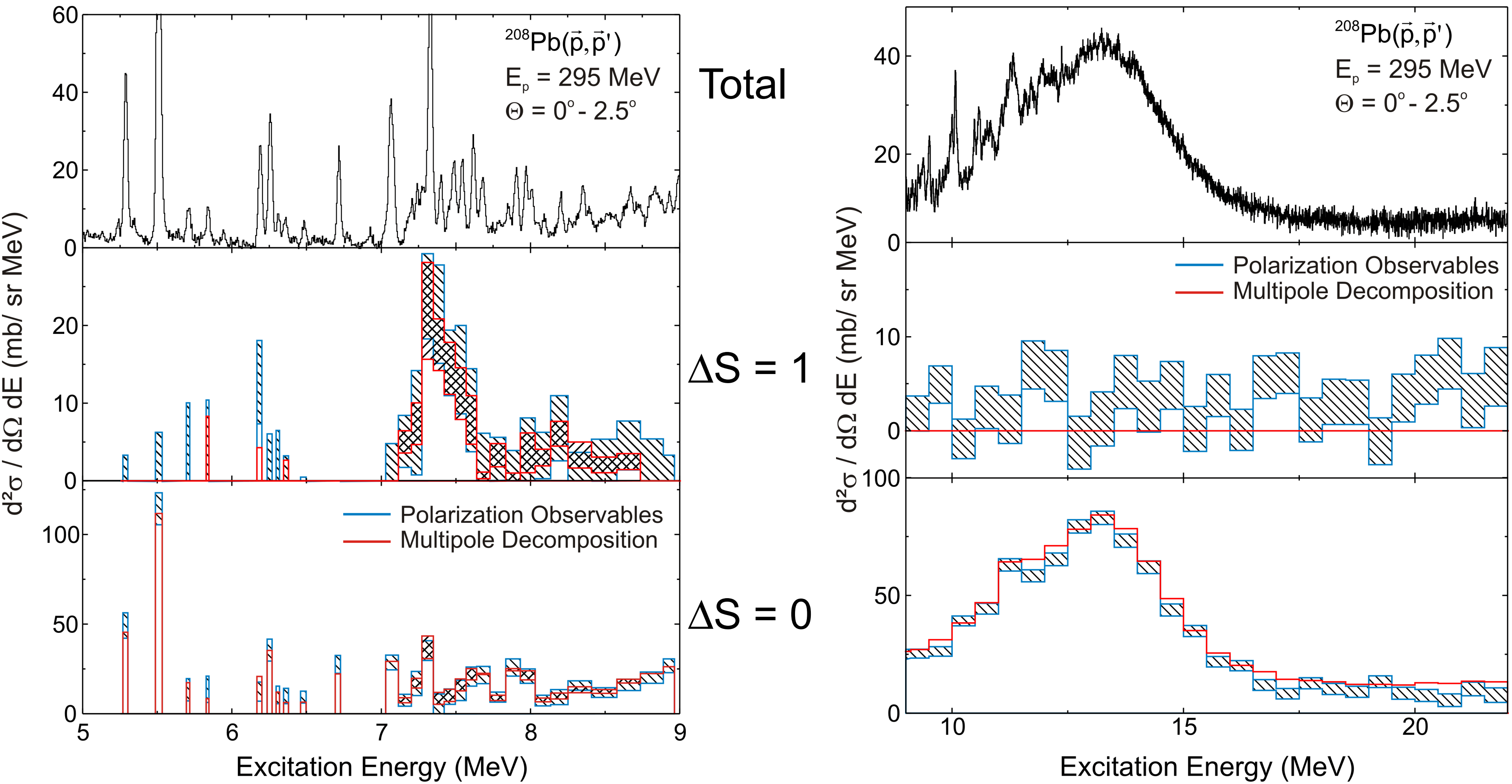
  model-independent

  E1 / spin-M1 decomposition — T. Suzuki, PTP 103 (2000) 859

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

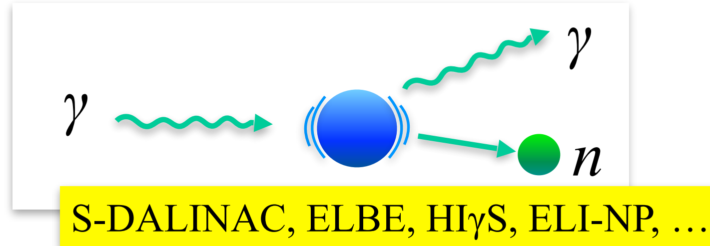


Comparison between the two methods

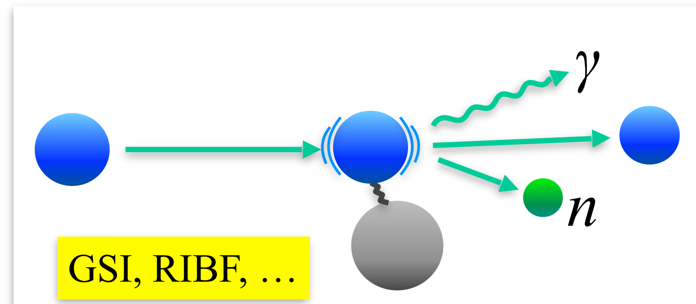


Probes of the Electric Dipole Response

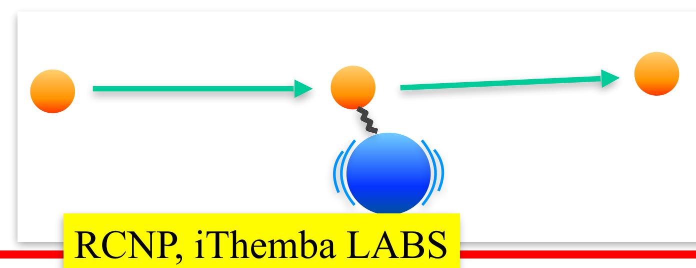
1. Real photon absorption
    - (γ,γ') Nuclear Resonance Fluorescence
    - (γ,n), (γ,2n), …



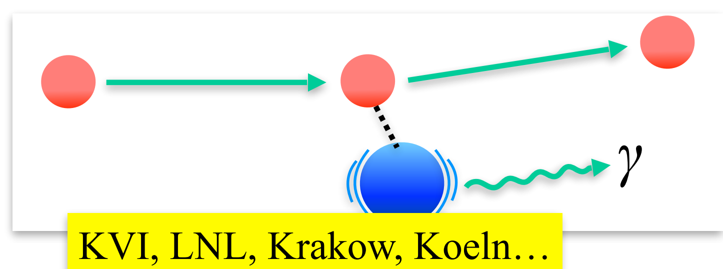
2. Virtual photon excitations (Coulomb excitation)
    - Invariant mass method with an unstable nucleus beam



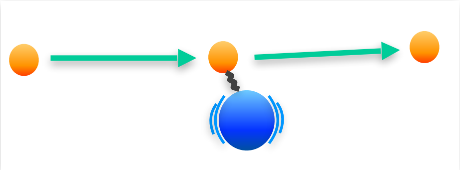
- Missing mass method with proton inelastic scattering

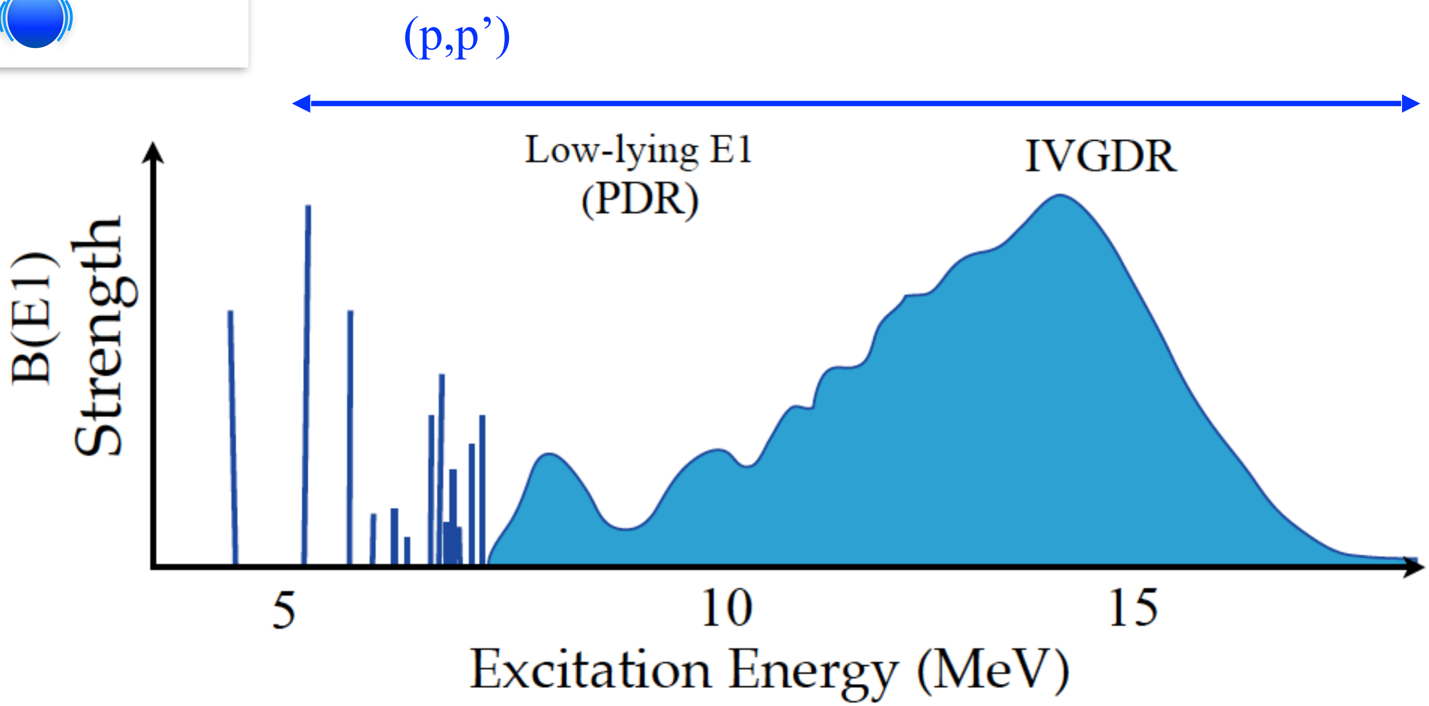


3. Excitation by nuclear force with p, α or ^{17}O inelastic scattering



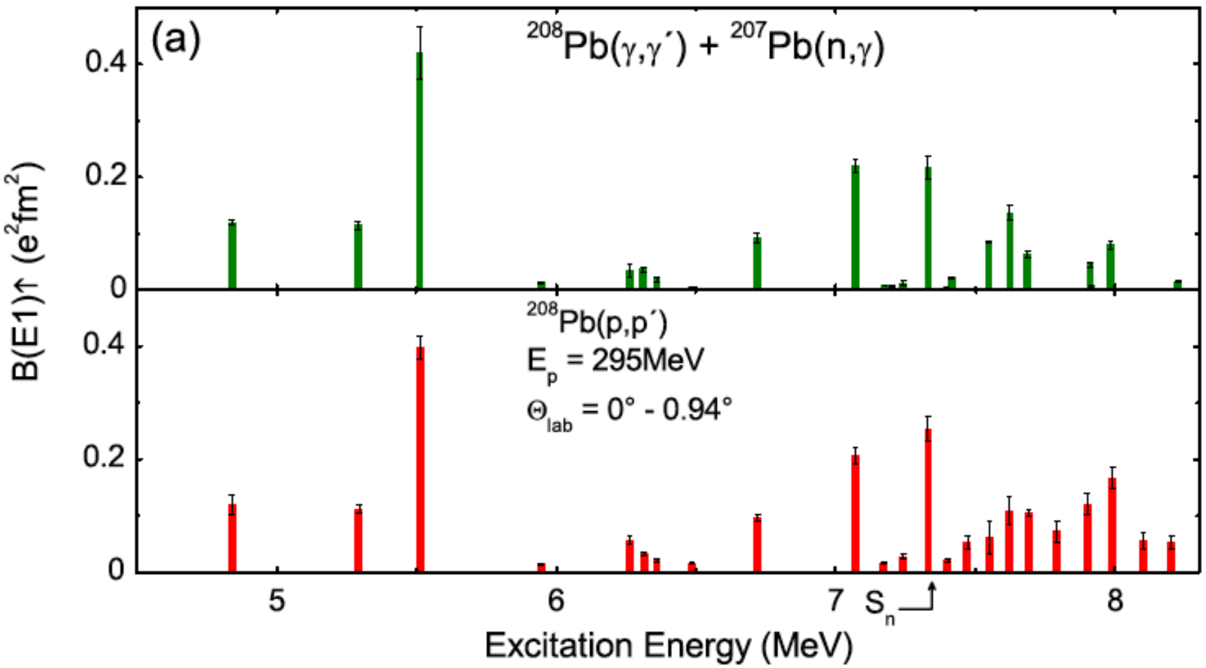
Coulomb Excitation by Proton Scattering



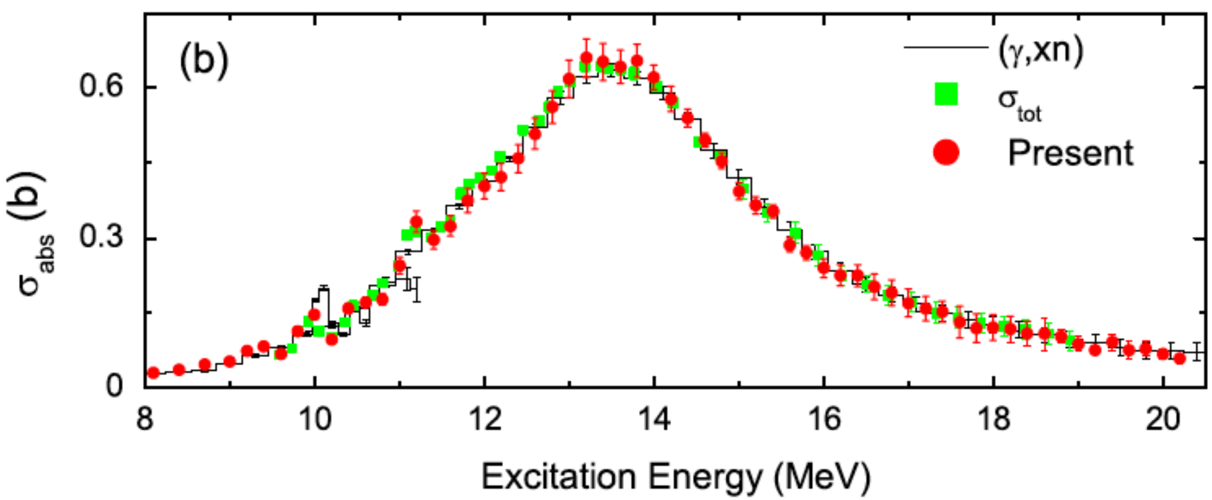


- **Total excitation strengths** for all the decay channels (inclusive)
- Single shot measurement across S_n in $E_x = 5(7)\text{-}22(32)$ MeV.
- High energy resolution (20-30 keV)
- MDA or Polarization Transfer → extraction of E1

Comparison with (γ,γ') and (γ,xn)

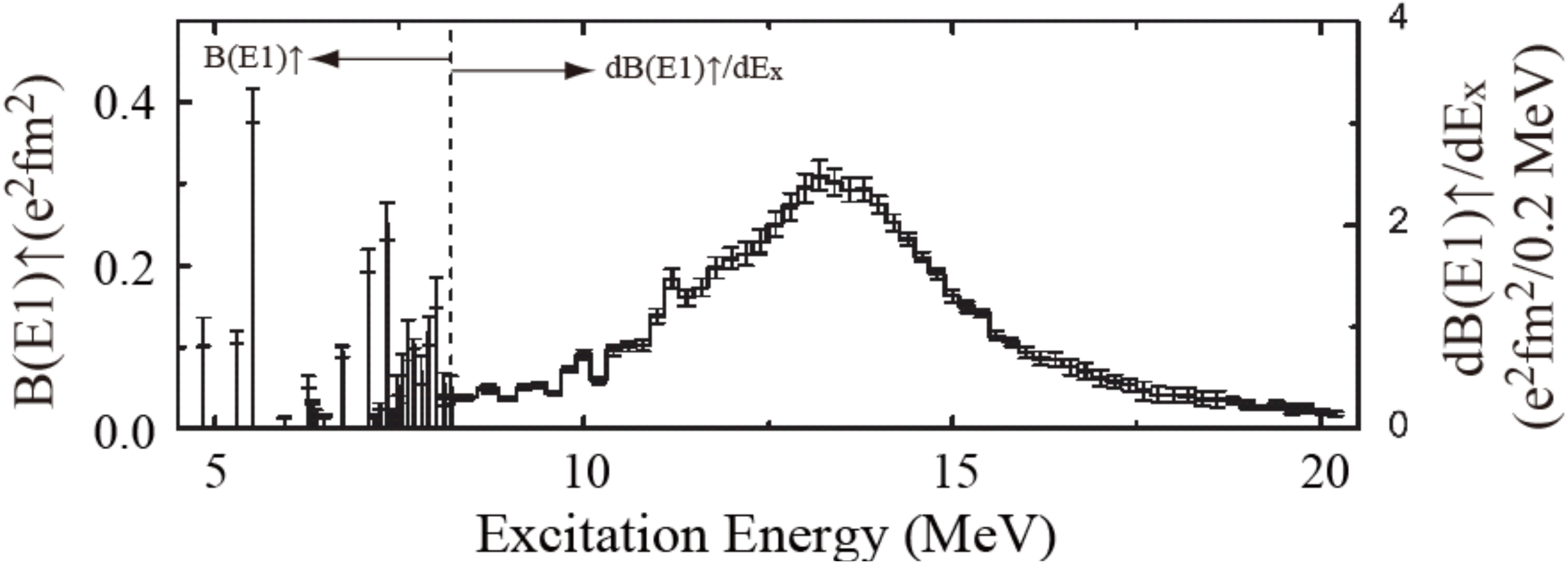


low-lying discrete states



GDR region

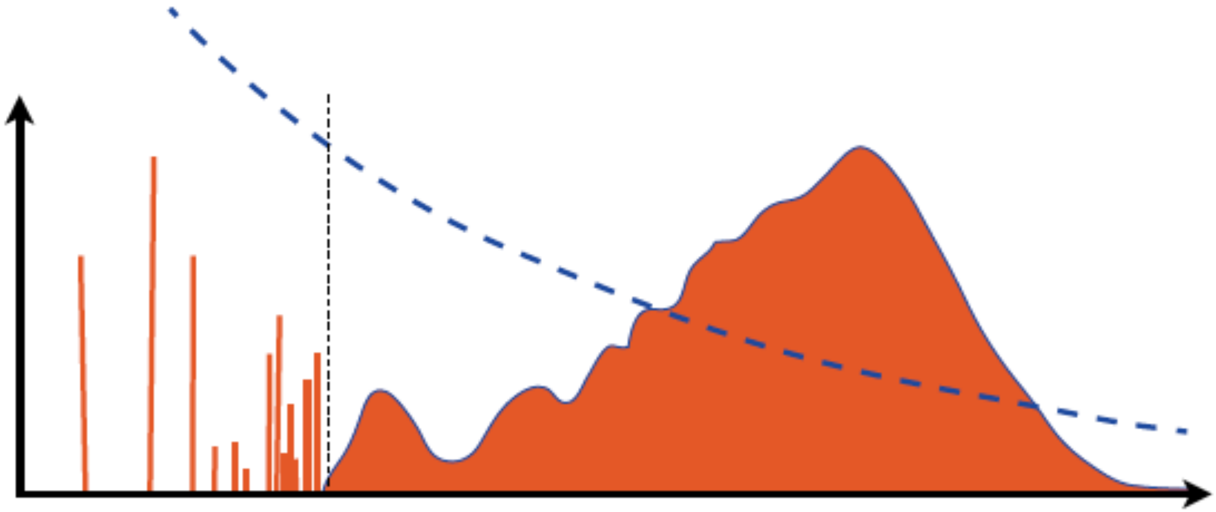
E1 Response of ^{208}Pb



The electric dipole transition strength in ^{208}Pb has been determined.

AT et al., PRL107, 062502(2011)

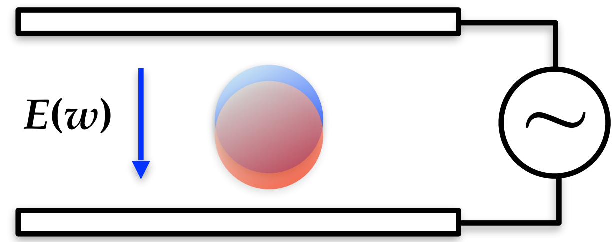
II
Electric Dipole Polarizability and Symmetry Energy



Electric Dipole Polarizability (α_D)

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

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

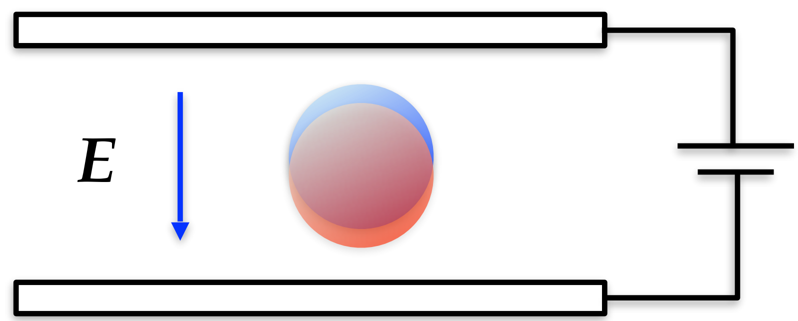


first order perturbation calc. A.B. Migdal: 1944

Electric dipole moment

$$p = \alpha_D \times E$$

α_D: electric dipole polarizability



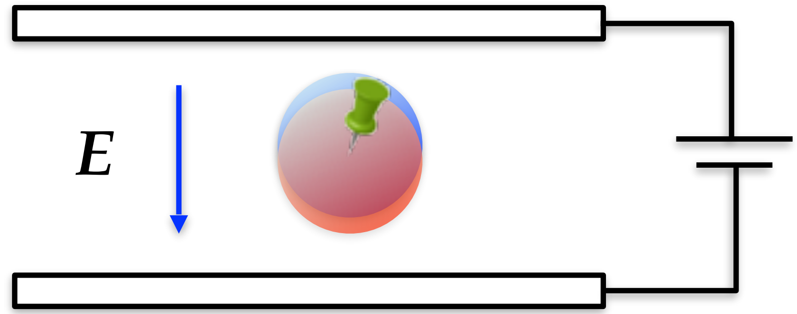
nucleus
in a static electric field
with fixing the c.m. position

Electric Dipole Polarizability (α_D)

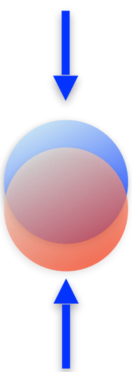
Electric dipole moment

$$p = \alpha_D \times E$$

α_D: electric dipole polarizability

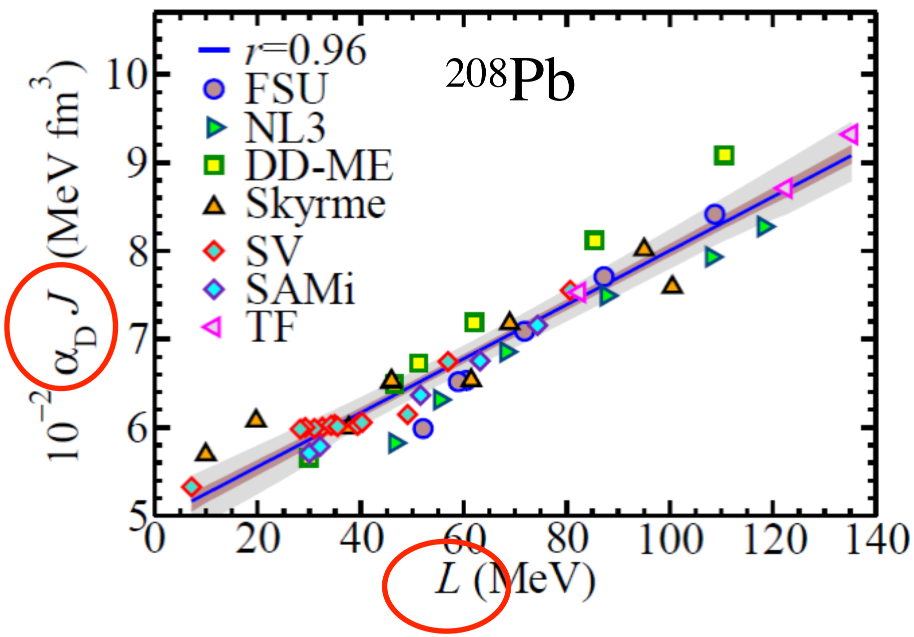


nucleus



The **restoring force** originates from the **symmetry energy** due to the difference of ρ_n and ρ_p on the surface.

Electric Dipole Polarizability (α_D) in the correlation of J and L



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

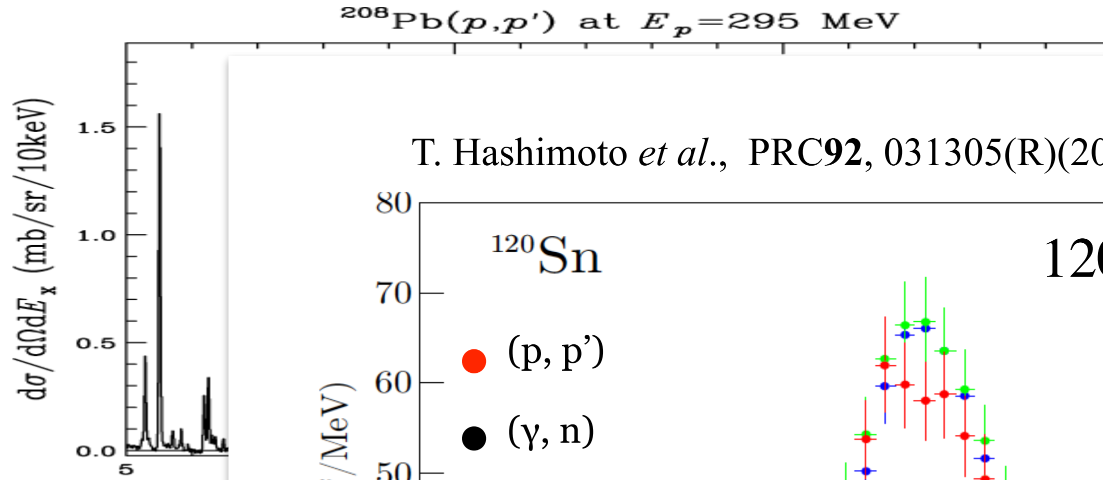
Correlations observed in various interaction sets in the framework of EDF.

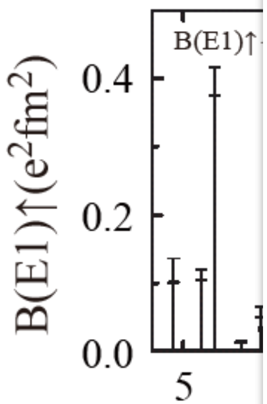
$$\alpha_D^{\mathrm{DM}} \approx \frac{\pi e^2}{54}\frac{A\langle r^2\rangle}{J}\left[1+\frac{5}{3}\frac{L}{J}\epsilon_A\right]$$

insights from the droplet model

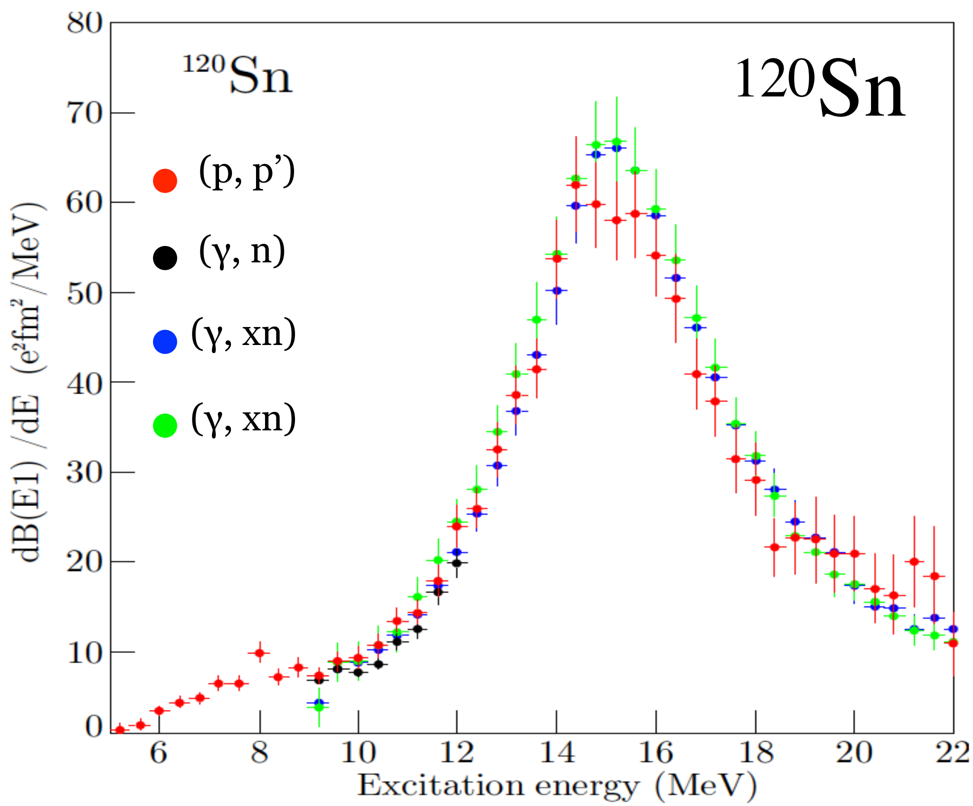
Precise determination of α_D of ^{208}Pb gives a constraint band in the *J*-*L* plane.

Electric Dipole Polarizability: ^{208}Pb, ^{120}Sn





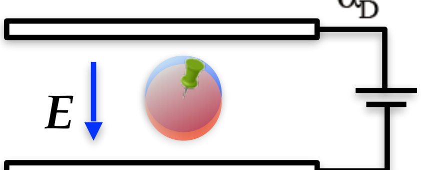
T. Hashimoto *et al.*, PRC**92**, 031305(R)(2015).



E_x 0 — 135 MeV

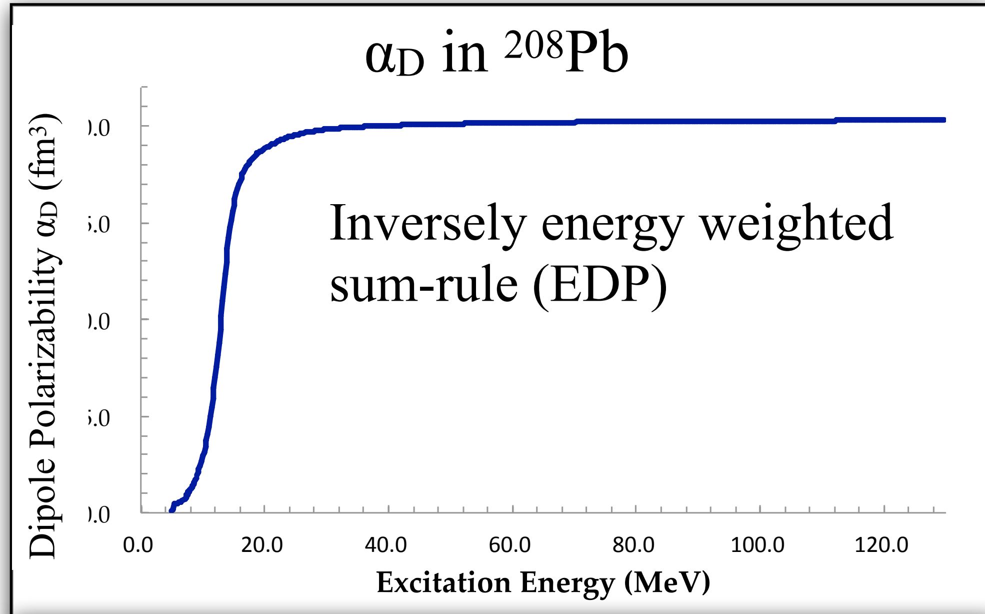
α_D

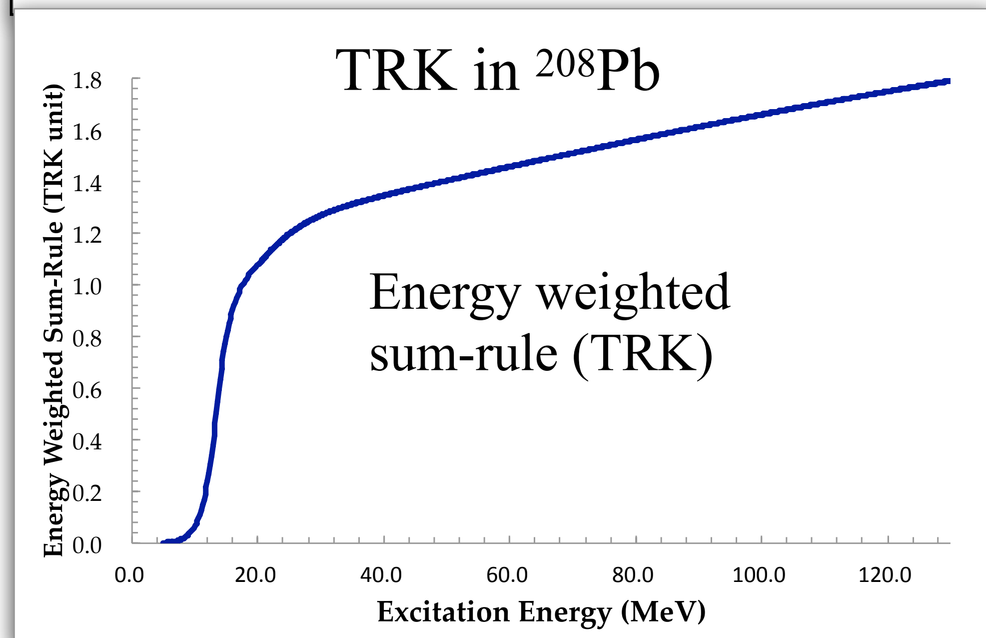
1.12 ± 0.07 | 7.00 ± 0.29 | 0.82 ± 0.12



Total: $\alpha_D = 8.93 \pm 0.36$ fm^3

Convergence: EDP vs TRK

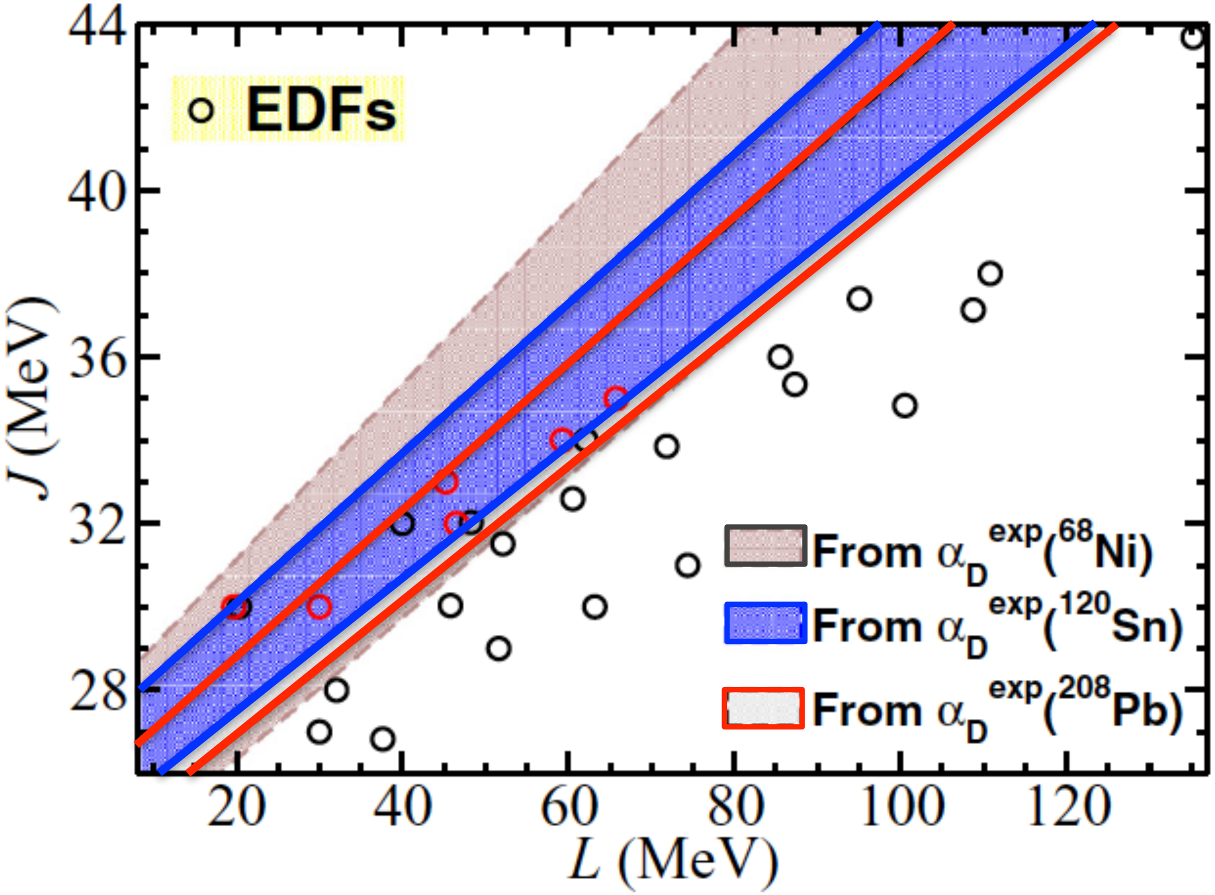




Good Convergence!

Constraints on J-L and the n-skin thickness

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



^{208}Pb

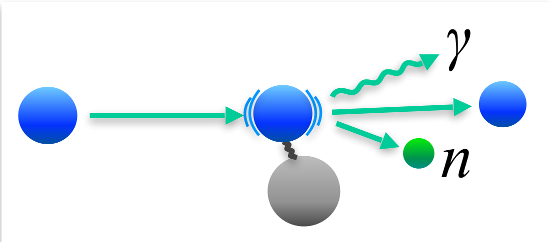
^{120}Sn

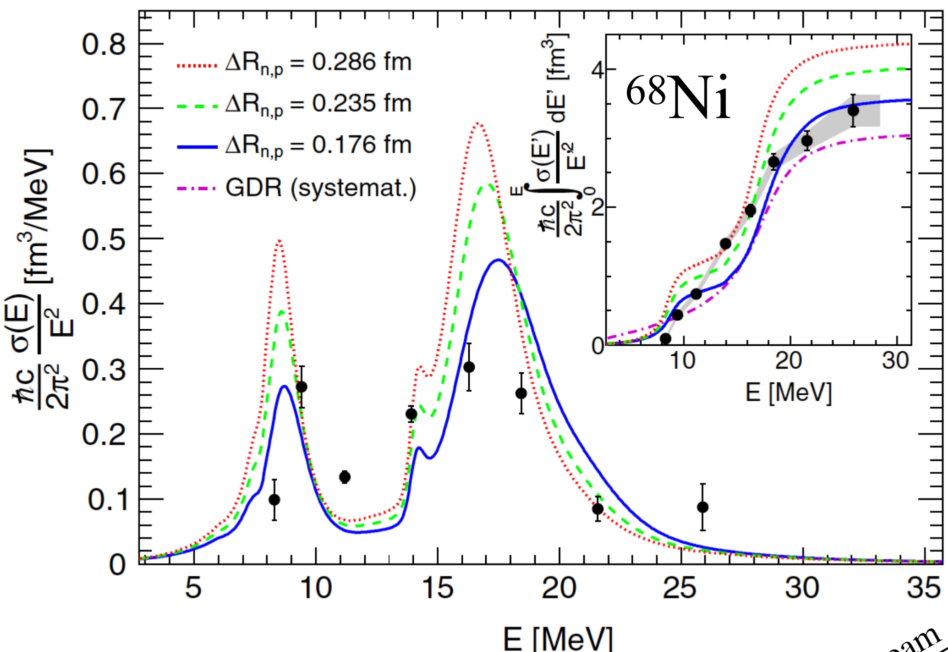
RCNP ^{208}Pb: AT *et al.*, PRL**107**, 062502 (2011).

RCNP ^{120}Sn: T. Hashimoto *et al.*, PRC**92**, 031305(R)(2015).

Electric Dipole Polarizability of ^{68}Ni

Invariant mass spectroscopy by Coulomb Excitation

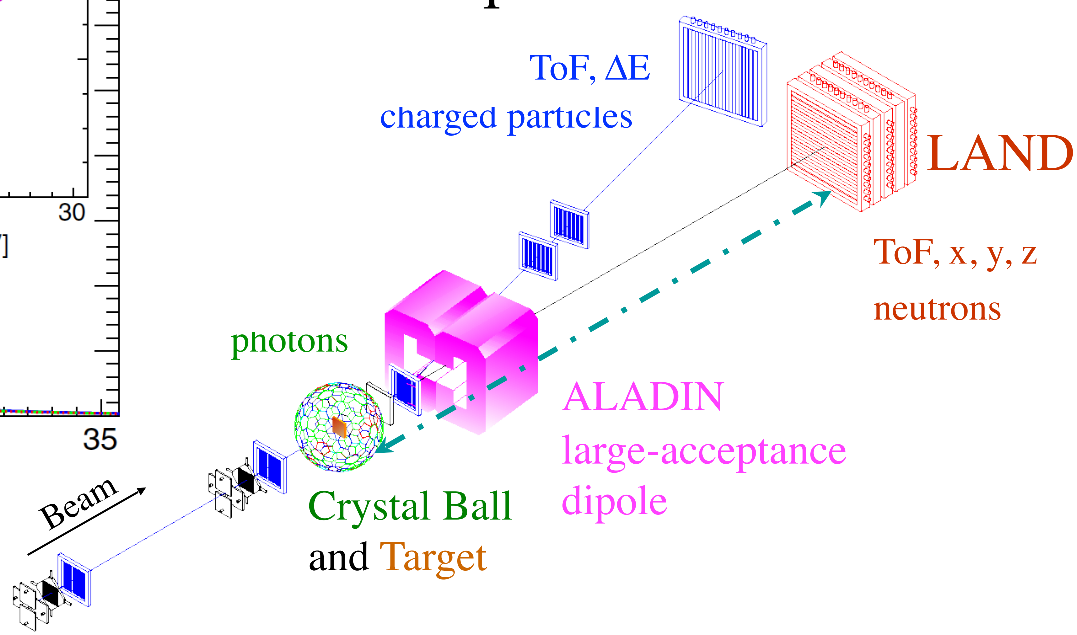




$\alpha_D = 3.40 \pm 0.23$ fm^3

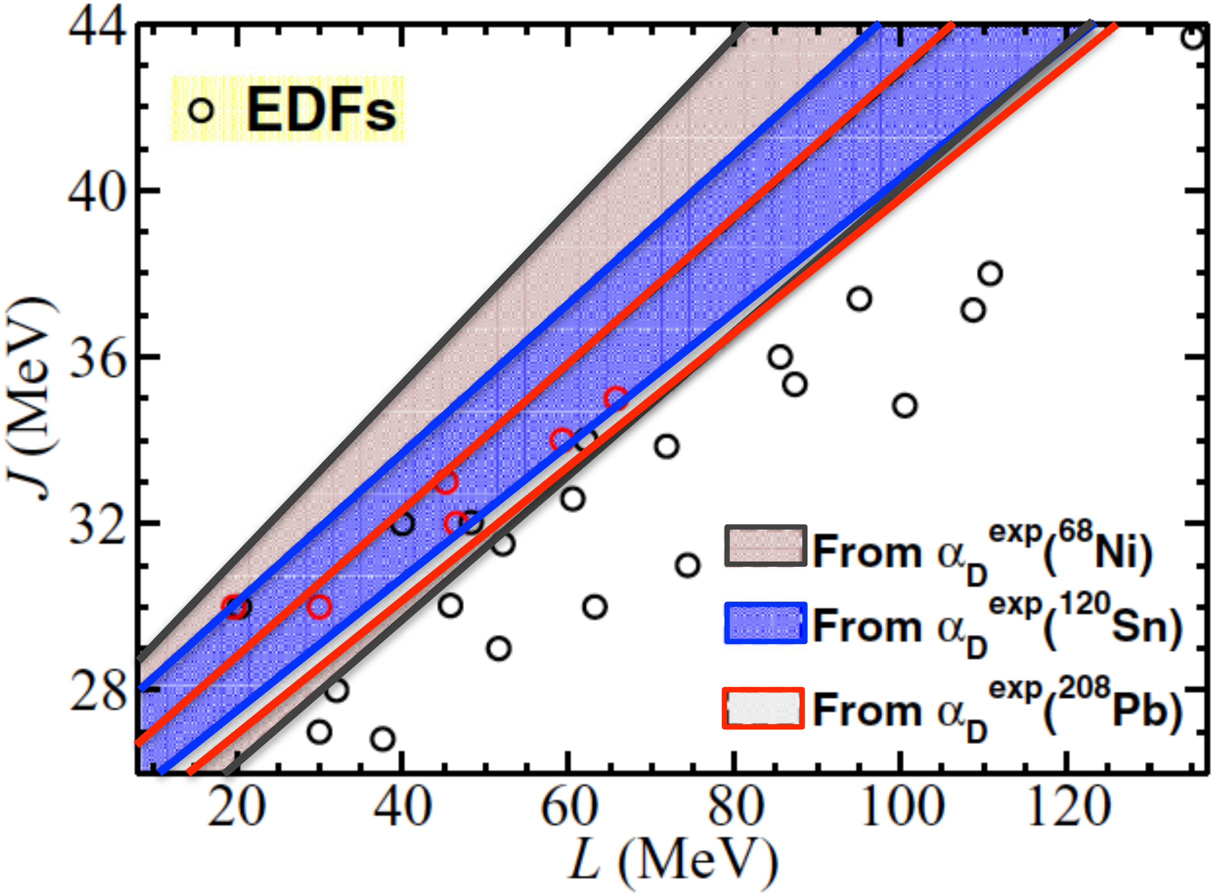
^{68}Ni: D. Rossi et al., PRL 111 (2013) 242503

LAND setup at GSI



Constraints on J-L and the n-skin thickness

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



^{208}Pb

^{120}Sn

^{68}Ni

These α_D data give essentially one constraint on the symmetry energy in the *J*-*L* plane.

RCNP ^{208}Pb: AT *et al.*, PRL**107**, 062502 (2011).

RCNP ^{120}Sn: T. Hashimoto *et al.*, PRC**92**, 031305(R)(2015).

GSI ^{68}Ni: D.M. Rossi *et al.*, PRL**111**, 242503 (2013).

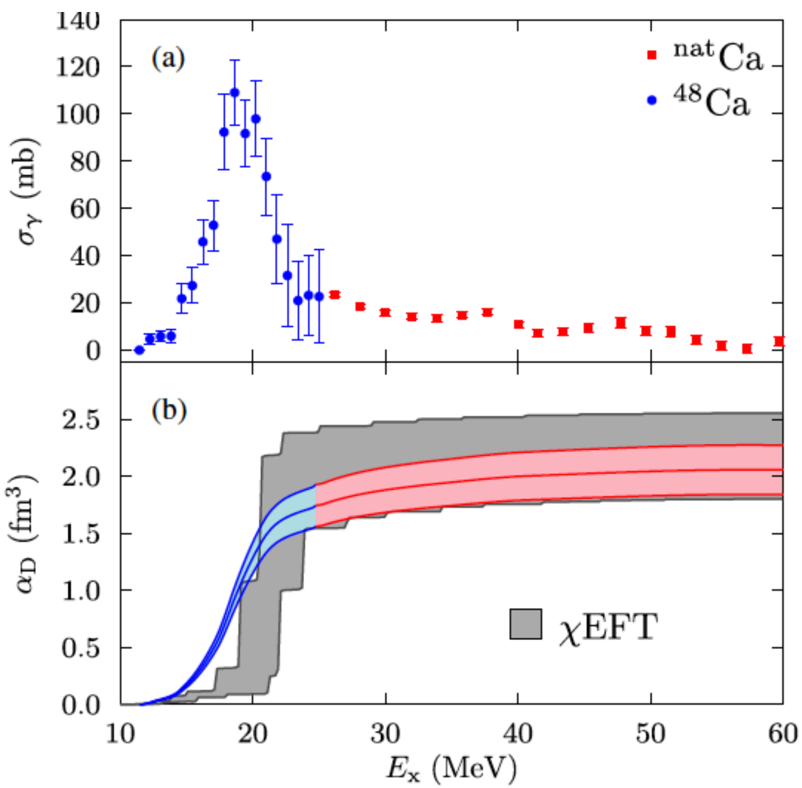
Dipole Polarizability of ^{48}Ca

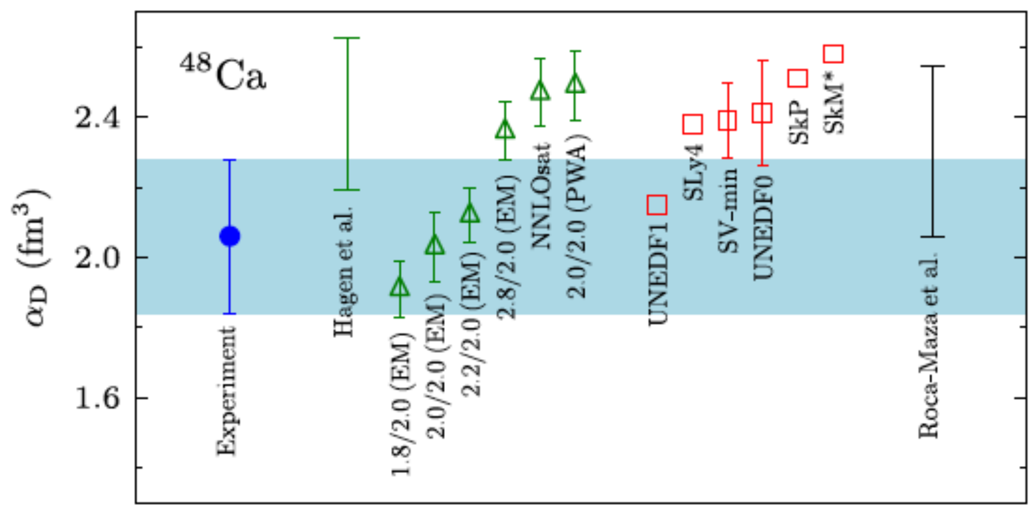
RCNP

TECHNISCHE UNIVERSITÄT DARMSTADT

where the EDF and ab-initio calculations meet

Theory: Darmstadt-Tennessee-TRIUMF

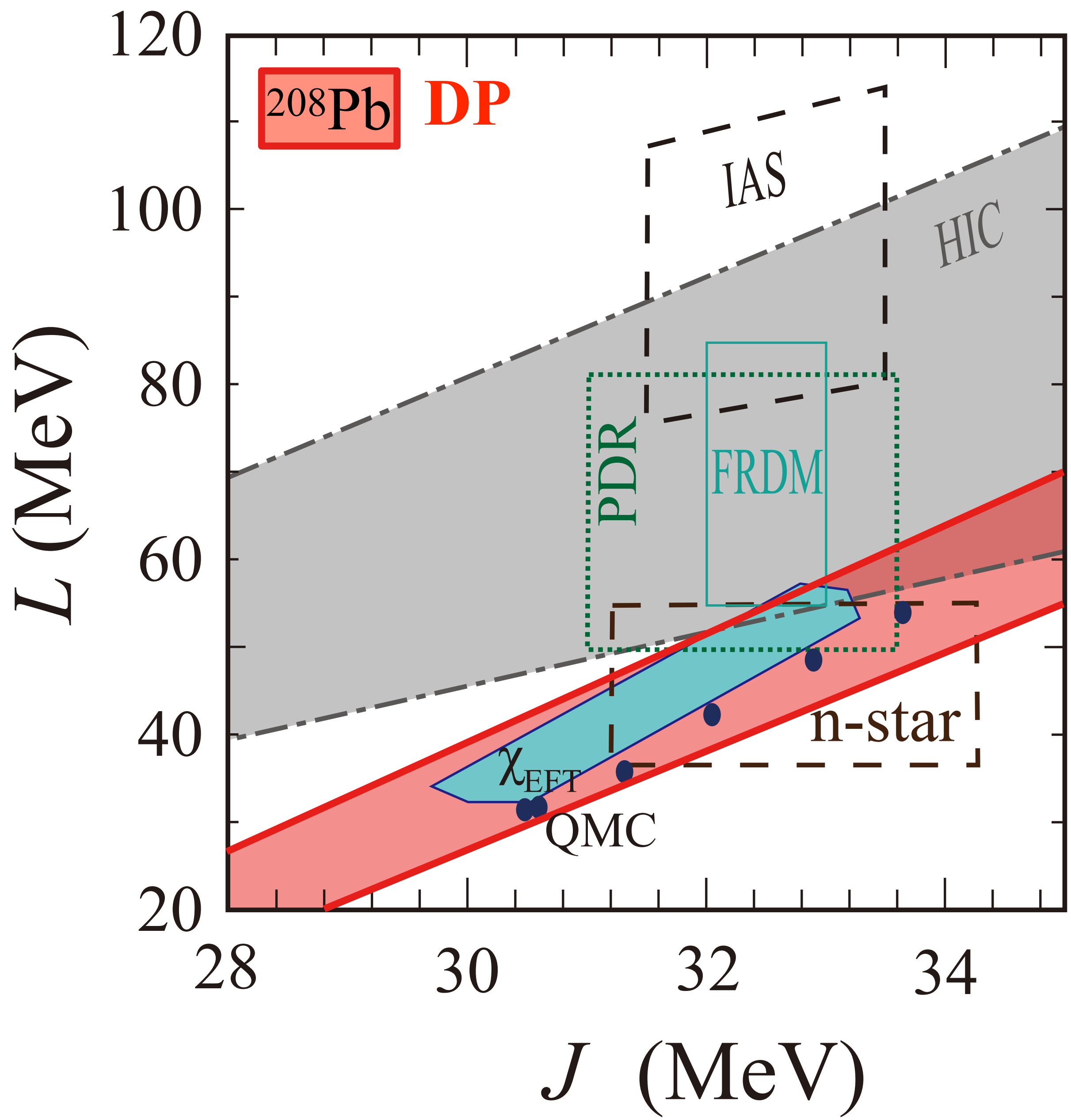




J. Birkhan et al., PRL 118, 252501 (2017)

Sn isotope Chain: P. von Neumann-Cosel, in this session

Constraints on J and L



Tsang PRC2012

HIC: Heavy Ion Collision Analysis
Tsang PRL2009

IAS: Isobaric Analog State Energy
Danielewicz&Lee NPA2009

PDR: Pygmy Dipole Resonance in
^{132}Sn, ^{68}Ni, Carbone PRC2010

FRDM: Finite Range Droplet Model
Moller PRL2012

n-star: Quiescent Low-Mass X-ray
Binaries, Stainer PRL2012

χEFT: Chiral Effective Field Theory,
Tews PRL2013

QMC: Quantum Monte-Carlo Calc.
Gandolfi, EPJA50, 10(2014).

DP: Dipole Polarizability
^{208}Pb AT PRL2011

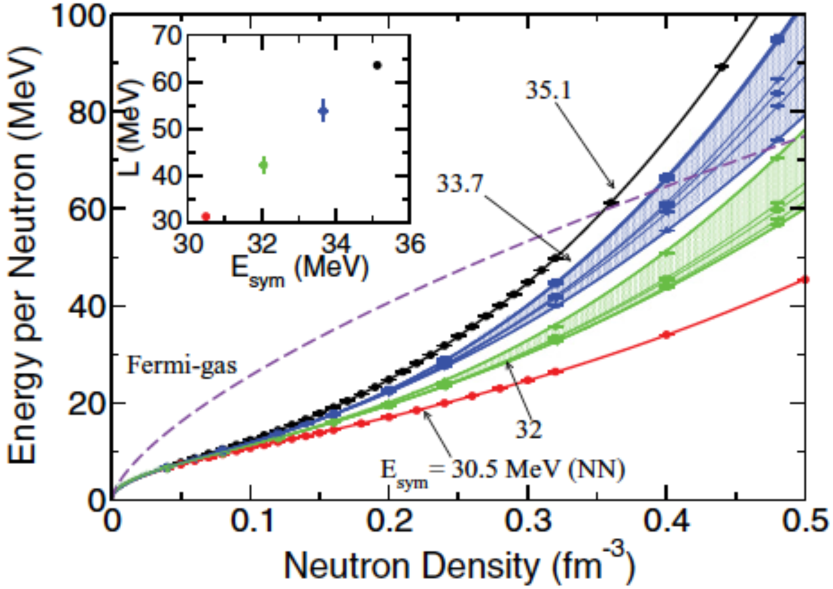
QMC

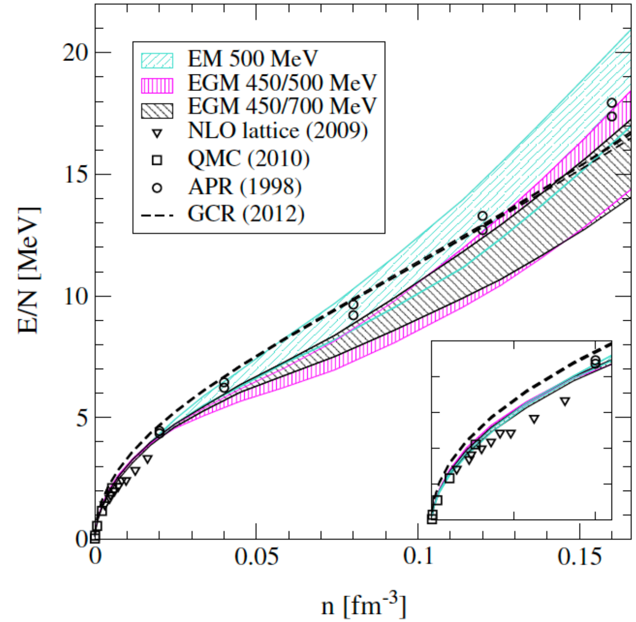
S. Gandolfi, J. Carlson et al., EPJA50, 10 (2014)

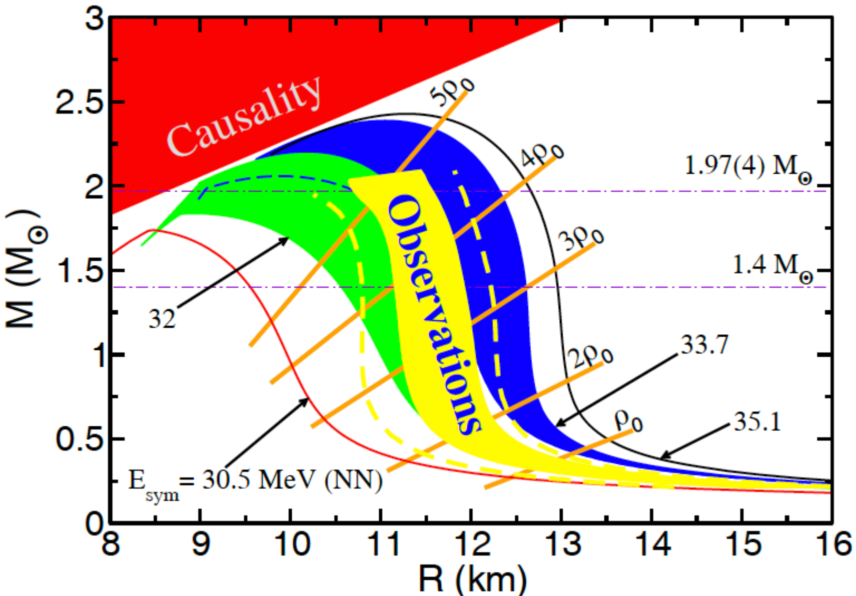
χEFT

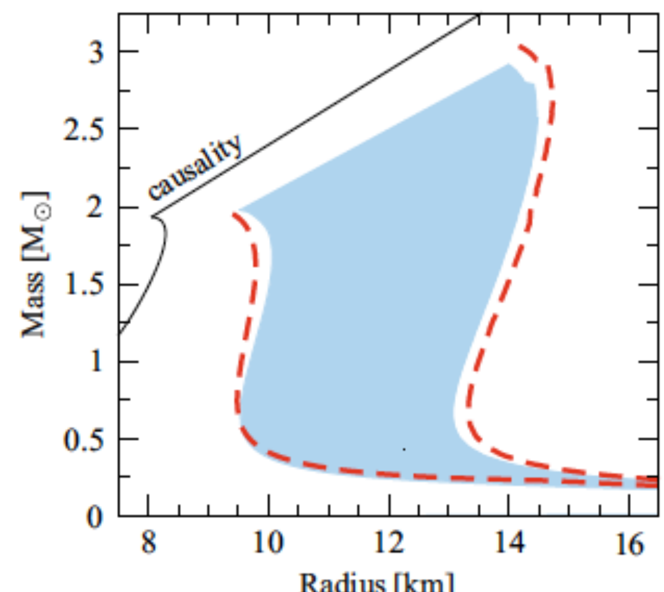
I. Tews, K. Hebeler et al., PRL110, 032504(2013)

K. Hebeler et al., et al., EPJA50, 11 (2014)



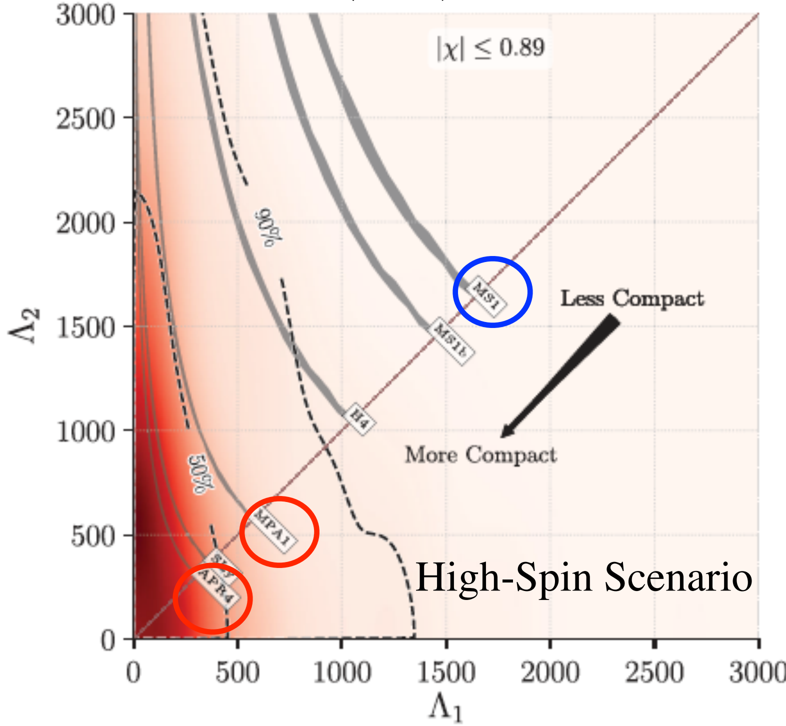




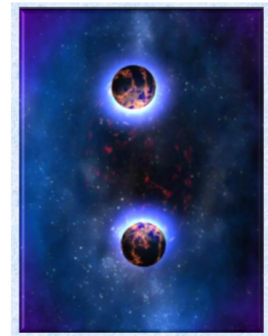


Constraints from the N-Star Merger GW170817

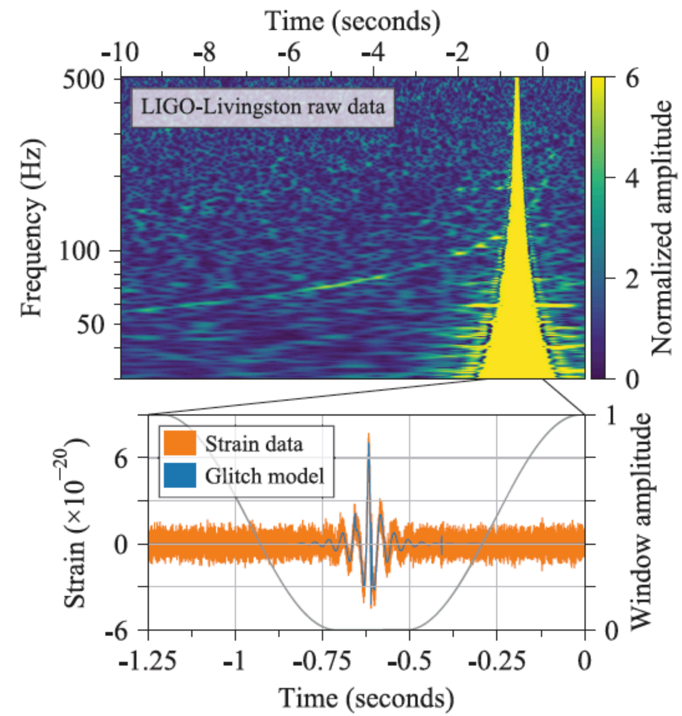
PRL119, 161101(2017)



Tidal Deformation Parameters



Tidal Deformation



N-Star Radius (1.4M$_\odot$)

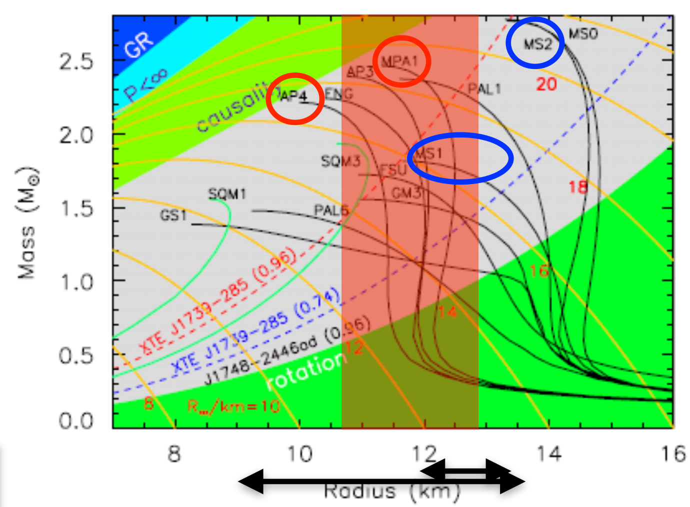
$R^{1.4}$ < 13.76 km F.J. Fattoyev et al., PRL120, 172702(2018)

12.00 < $R^{1.4}$ < 13.45 km E.R. Most et al., PRL120, 261103(2018)

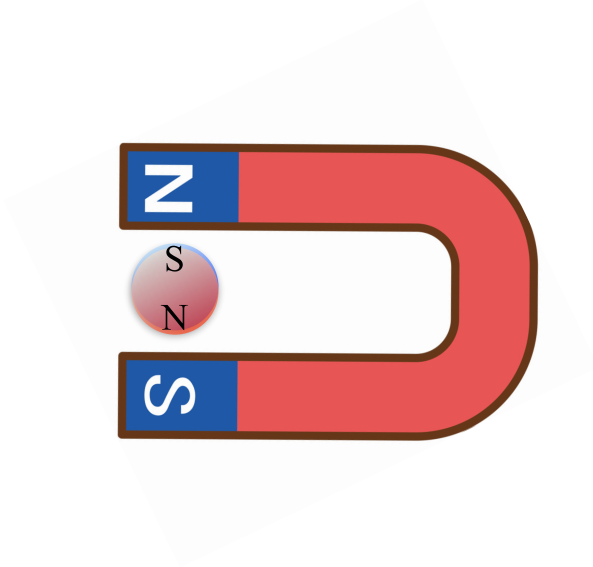
9.0 < $R^{1.4}$ < 13.6 km I. Tews et al., talk in the next session

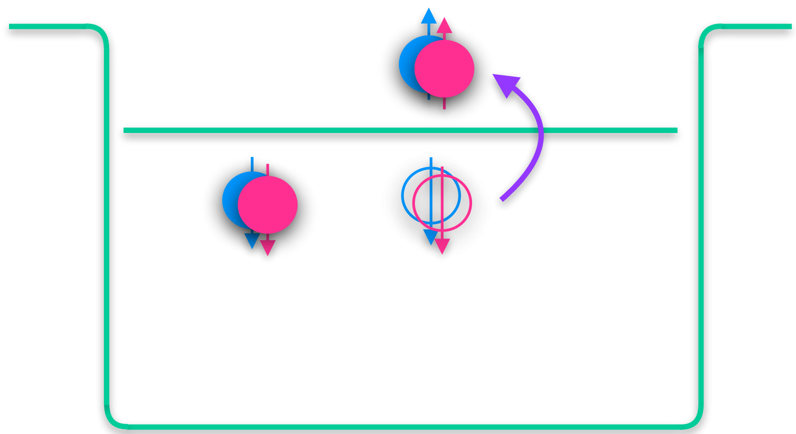
N-star merger GW analysis is giving constraints on the nuclear EOS that are consistent with the study of atomic nuclei.

Further observations!

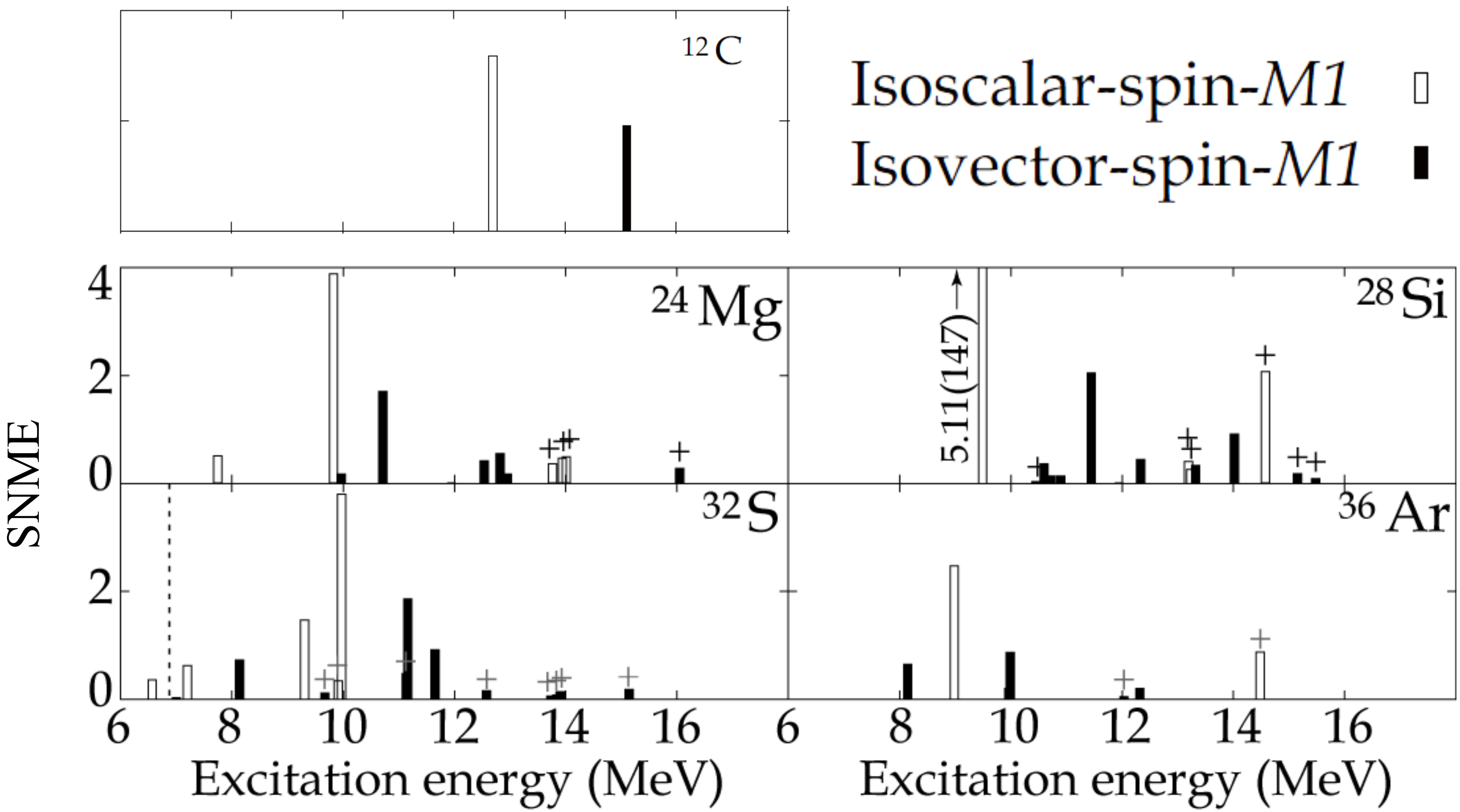


II
Spin-M1 Excitations





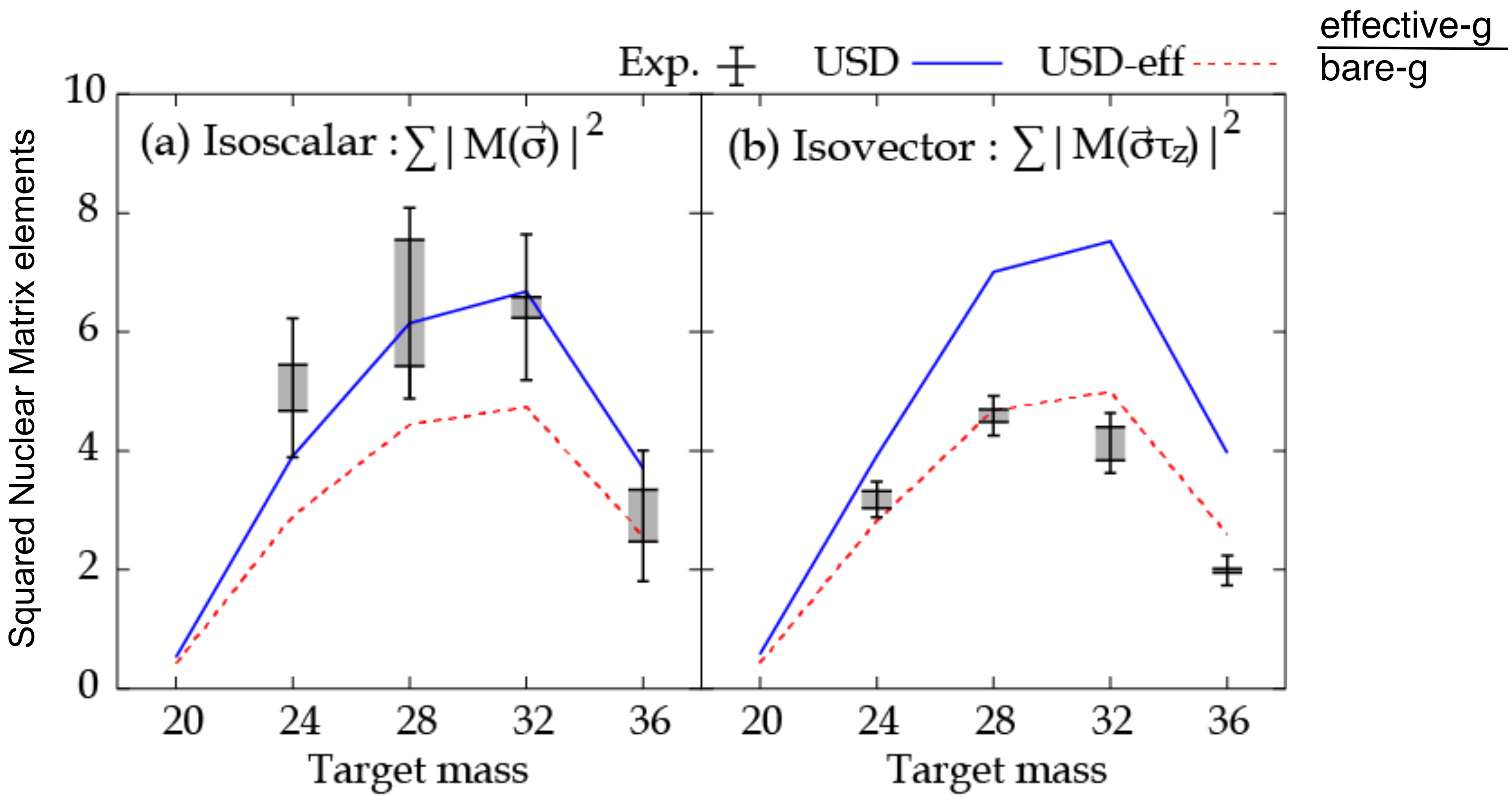
IS/IV-spin-M1 Squared Nuclear Matrix Elements (SNMEs)



IS/IV-spin-M1 Squared Nuclear Matrix Elements (SNMEs)

H. Matsubara et al., PRL**115**, 102501 (2015)

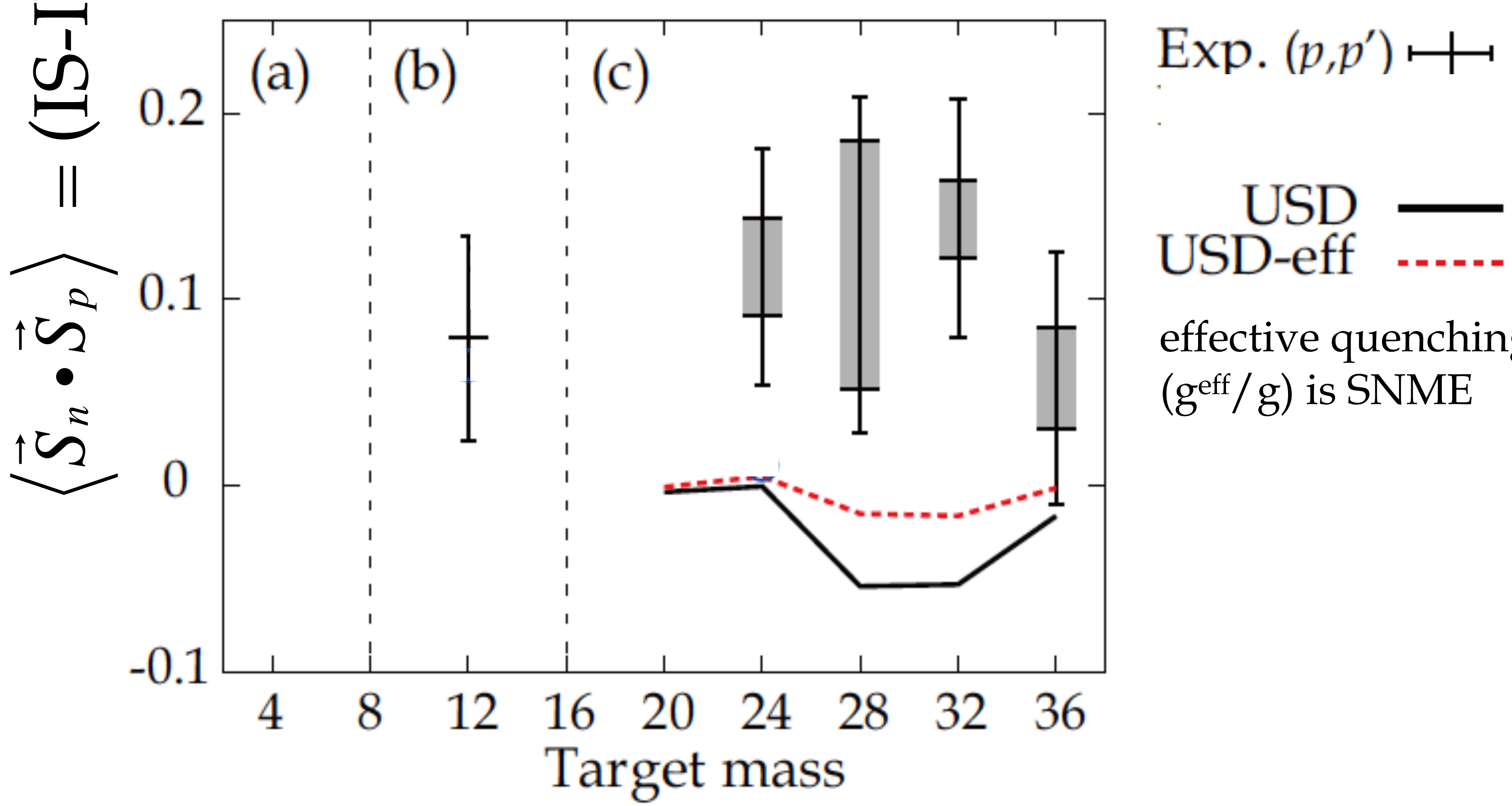
- Summed <u>up to **16 MeV**</u>.
- Compared with shell-model predictions using the USD interaction



Isoscalar spin-M1 SNME does not quench.

np Spin Correlation Function

Shell-Model: USD interaction



effective quenching (g^{eff}/g) is SNME

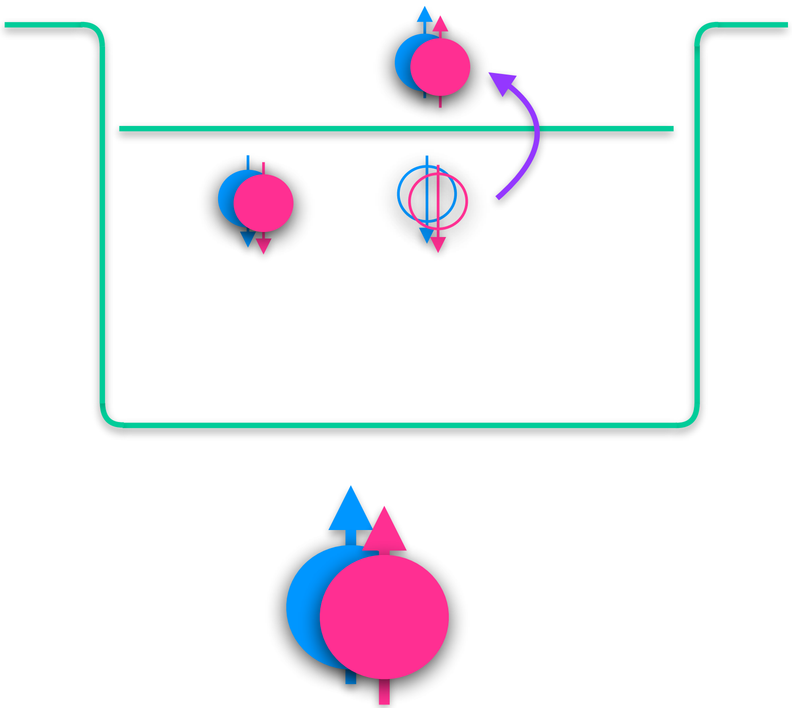
np spin correlation function in the g.s.

$$\vec{S}_n \equiv \sum_i^N \vec{s}_{n,i} \qquad \vec{S}_p \equiv \sum_i^Z \vec{s}_{p,i}$$

$$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle = \frac{1}{4}\left\langle \left(\vec{S}_n + \vec{S}_p\right)^2 - \left(\vec{S}_n - \vec{S}_p\right)^2 \right\rangle$$
$$= \frac{1}{16}\left(\sum \left|M\left(\vec{\sigma}\right)\right|^2 - \sum \left|M\left(\vec{\sigma}\tau_z\right)\right|^2\right)$$

: *np* spin correlation function of the nuclear ground state

→ probes isoscalar *np*-pairing in the ground state



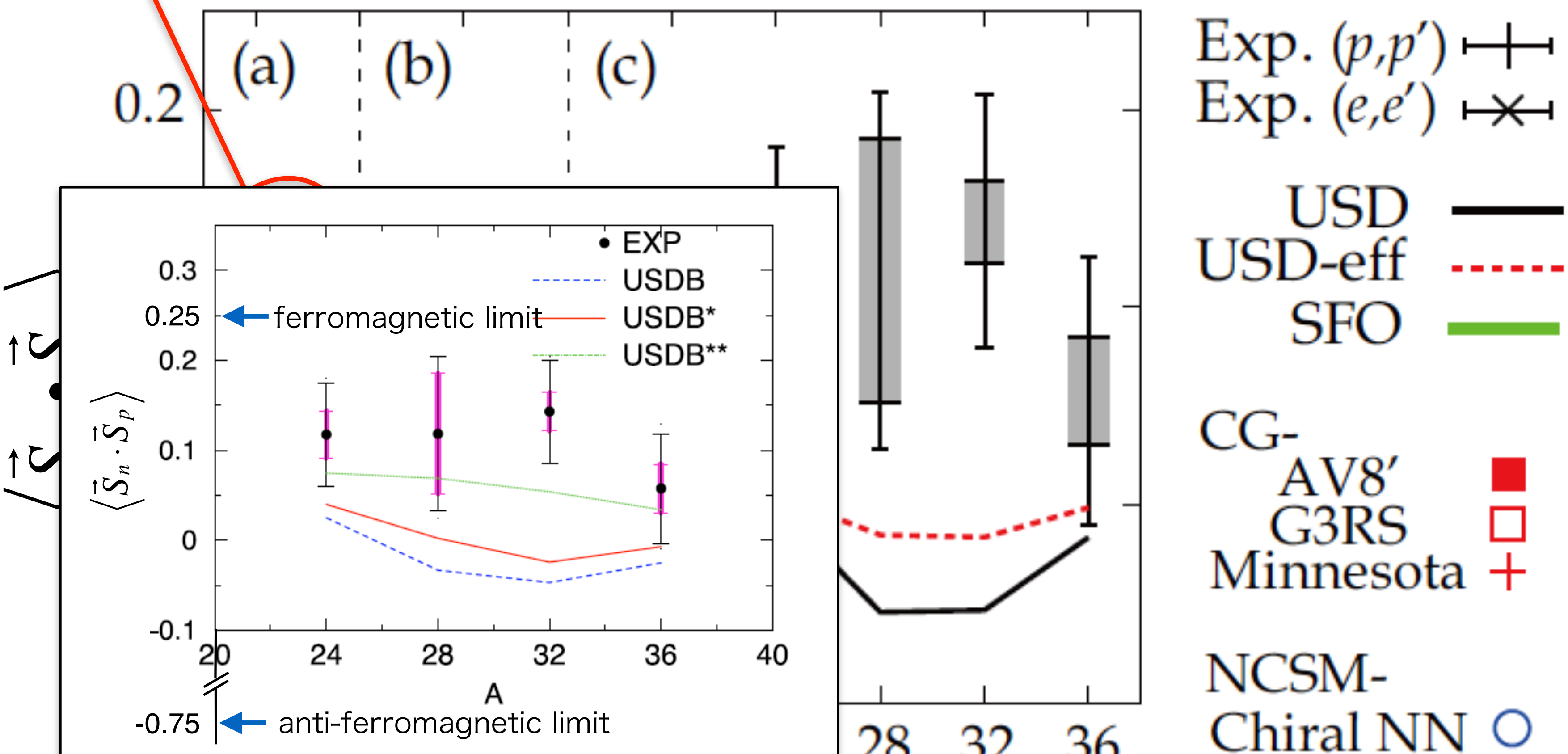
spin aligned *np*-pair

$$\left\langle \vec{s}_n \cdot \vec{s}_p \right\rangle > 0$$

np Spin Correlation Function

ab-initio type calc.
with realistic NN int.

Shell-Model: USD interaction
Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil

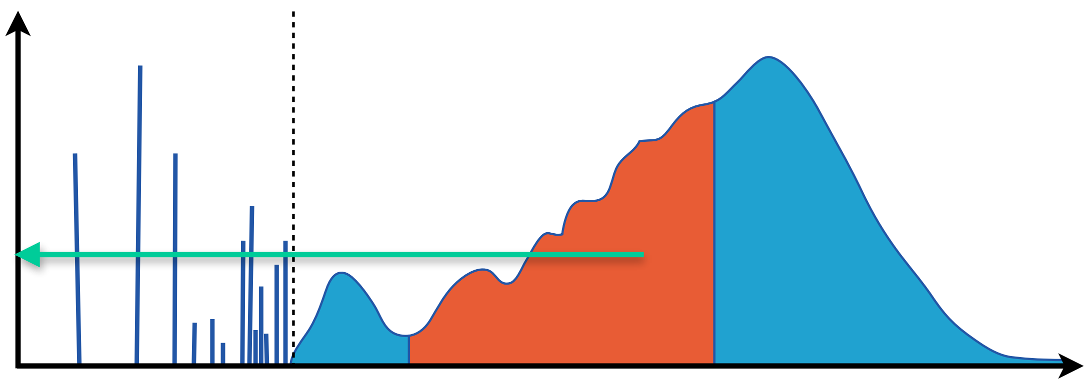


Explainable by stronger IS np interaction and the Delta-hole excitations?

H. Sagawa et al., PRC94, 041303(2016)

H. Matsubara et al., PRL**115**, 102501 (2015)

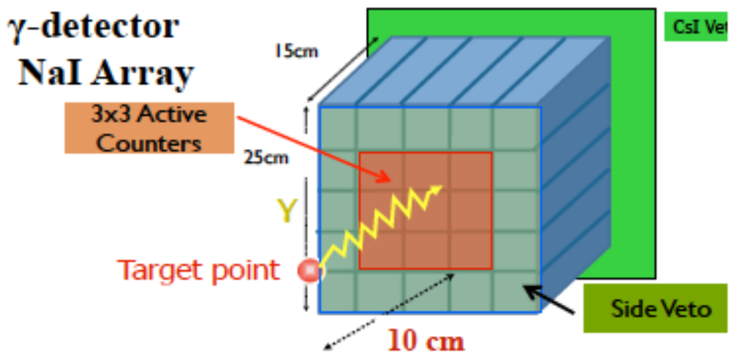
III
Gamma-Decay of
GRs and Electric Dipole Excitations

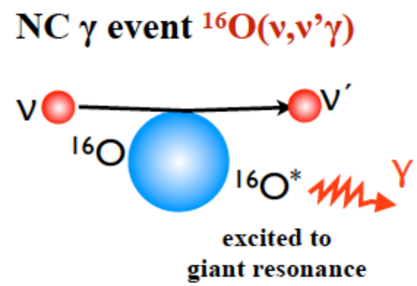


Gamma Emission from Giant Resonances

for NC ν-detection with water Čerenkov and Liquied scintillation detectors

Mandeep, Sudo, Sakuda et al., publication in preparation

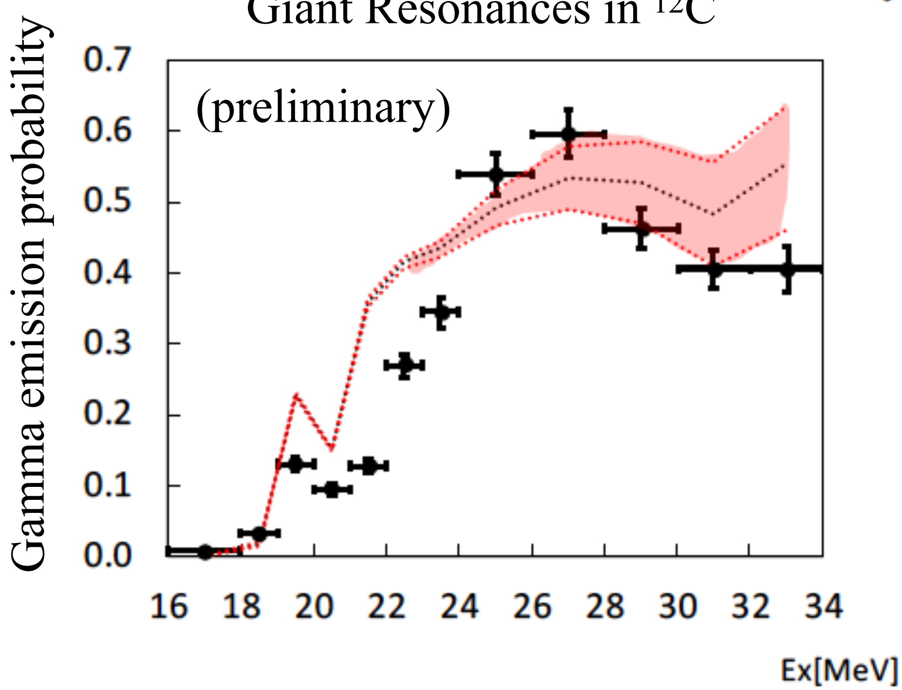




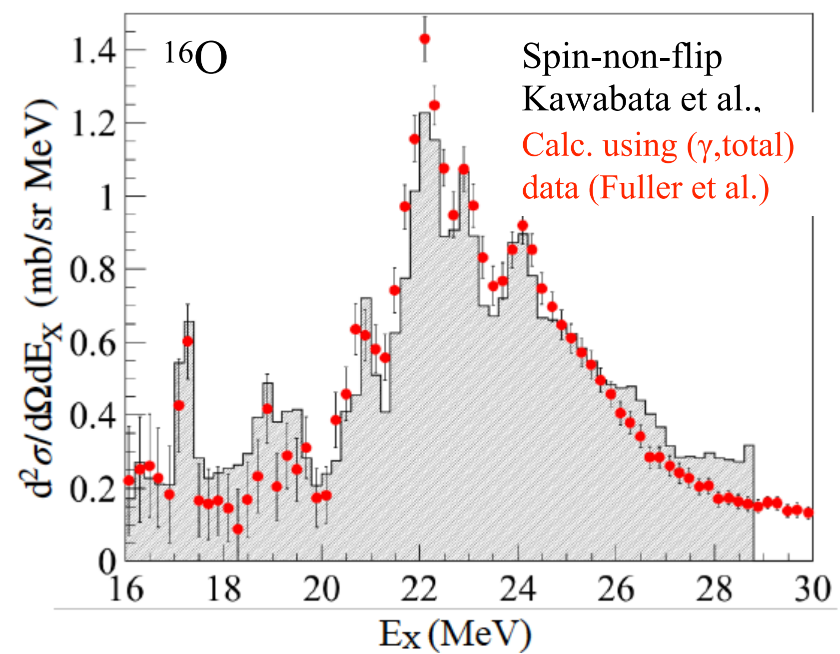
c.f. Langanke et at., PRL76(1996),NPA540(1992)

γ-emission after particle decays

Gamma emission probability from Giant Resonances in ^{12}C

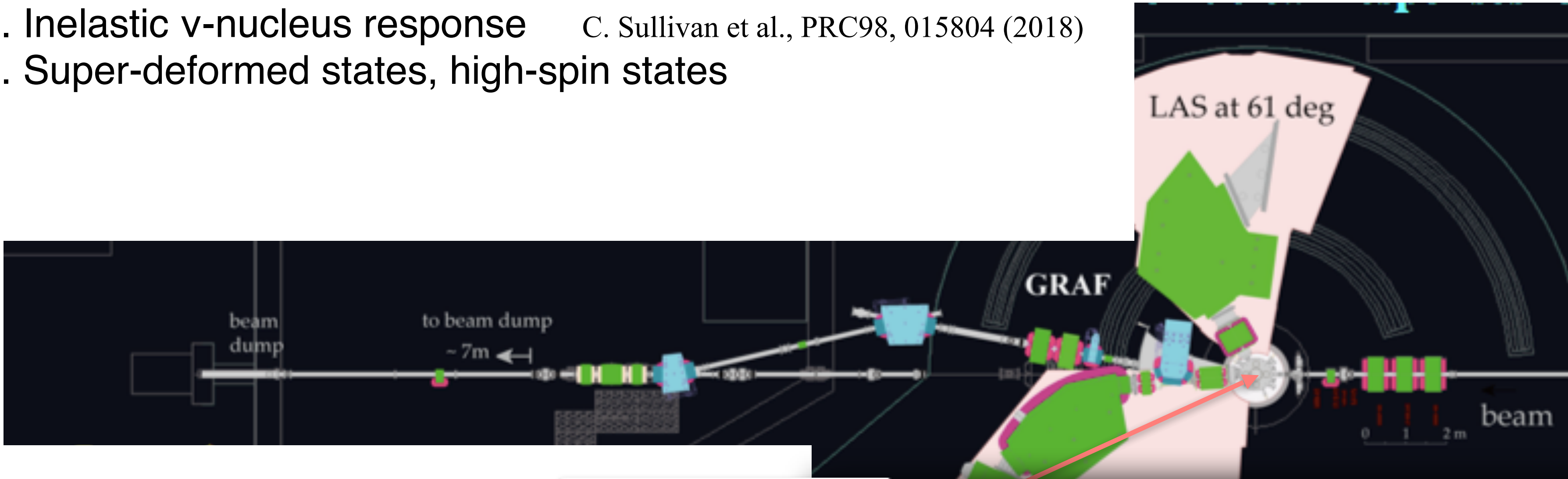


Spin-non-flip cross sections are quite compatible the c.s. calc. by Coulomb excitation with Eikonal approx. using the B(E1) data from (γ,total) for both of ^{12}C and ^{16}O.



CAGRA+GR Campaign Exp. Oct-Dec 2016

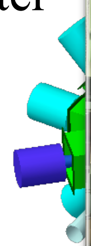
1. **Structure of the PDR** (α,α'γ) and (p,p'γ) on ^{64}Ni, ^{90,94}Zr, ^{120,124}Sn, ^{206,208}Pb
2. Inelastic ν-nucleus response C. Sullivan et al., PRC98, 015804 (2018)
3. Super-deformed states, high-spin states



CAGRA(Clover Ge Arra

E. Ideguchi and M. Carpenter

Clovers: ANL+Tohoku+IMP



Collaboration

RCNP, Tohoku, ANL, LBNL, Mila
Darmstadt, GSI, Köln, KVI, IFJ-PAN,
MSU, Yoke, IMP, ELI-NP, ARL, …

Talks by F. Crespi and N. Kobayashi on Friday

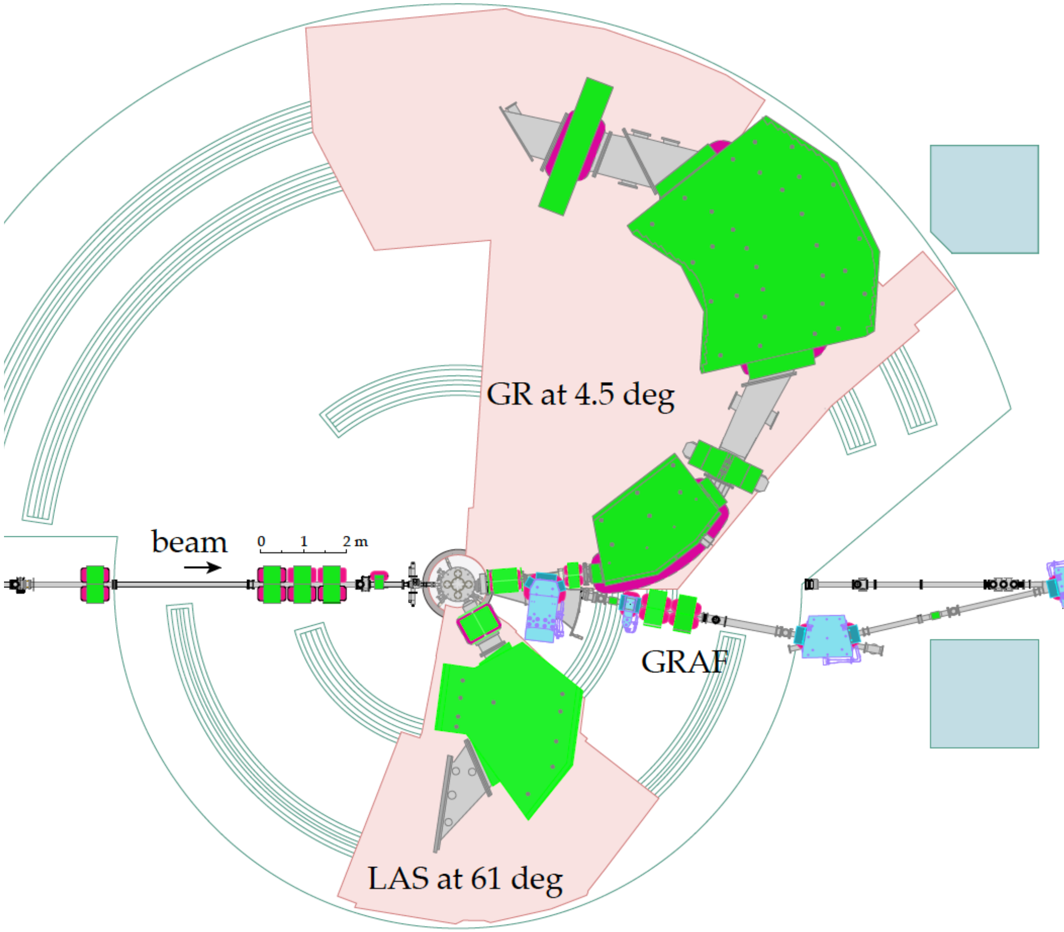
Construction of GRAF

Grand RAiden Forward mode beam line

Miki, Hashimoto, Nagayama, Morinobu, Matsuda, Fujita, Iwamoto, Yoshida, Ideguchi, Aoi, Hatanaka, Tamii

2012.12-2013.1	Proposal
FY2013	GRAF Design/Construction
2014.7	Physics Runs


GRAF under construction, March 17, 2014



Construction of GRAF

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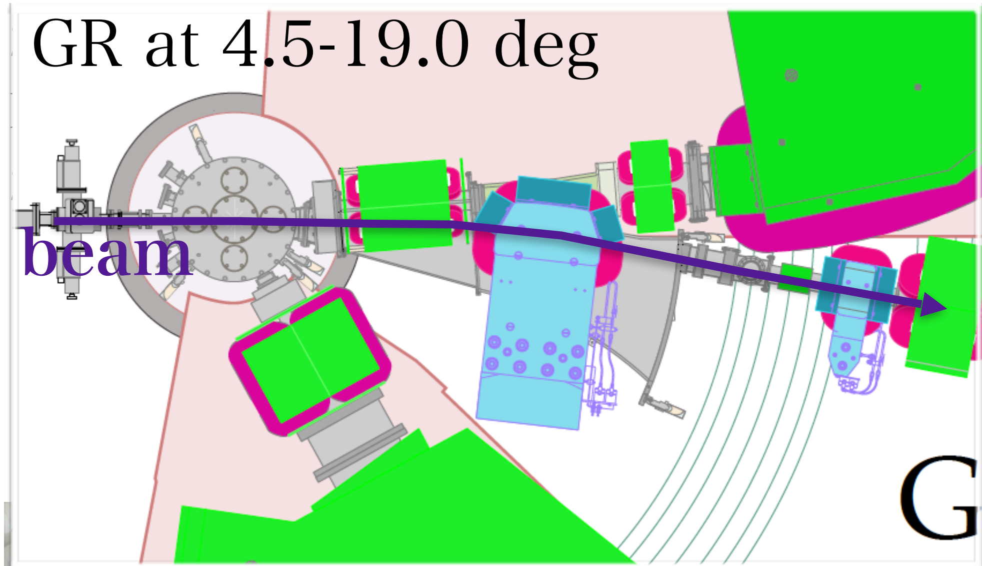
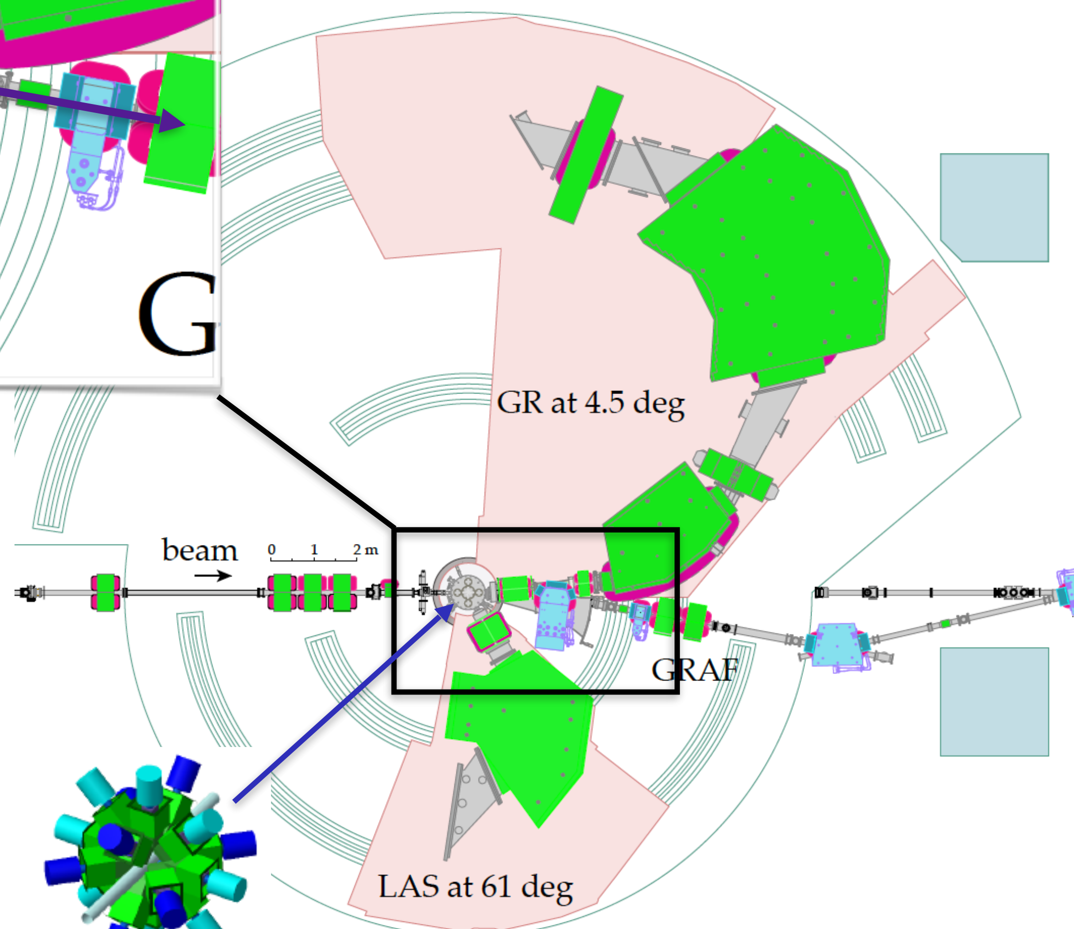
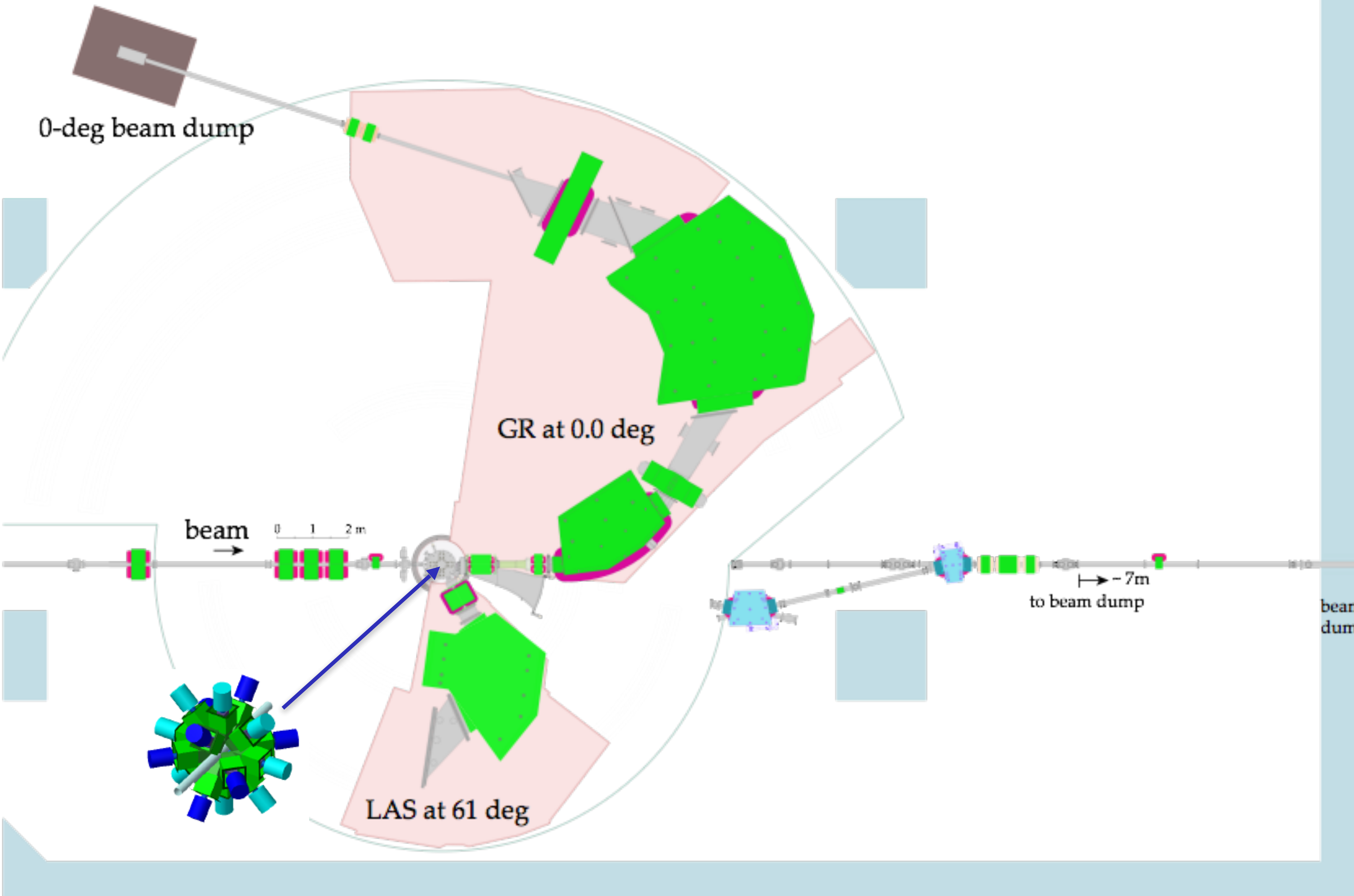



GRAF under construction, March 17, 2014



Zero degree Transmission Mode



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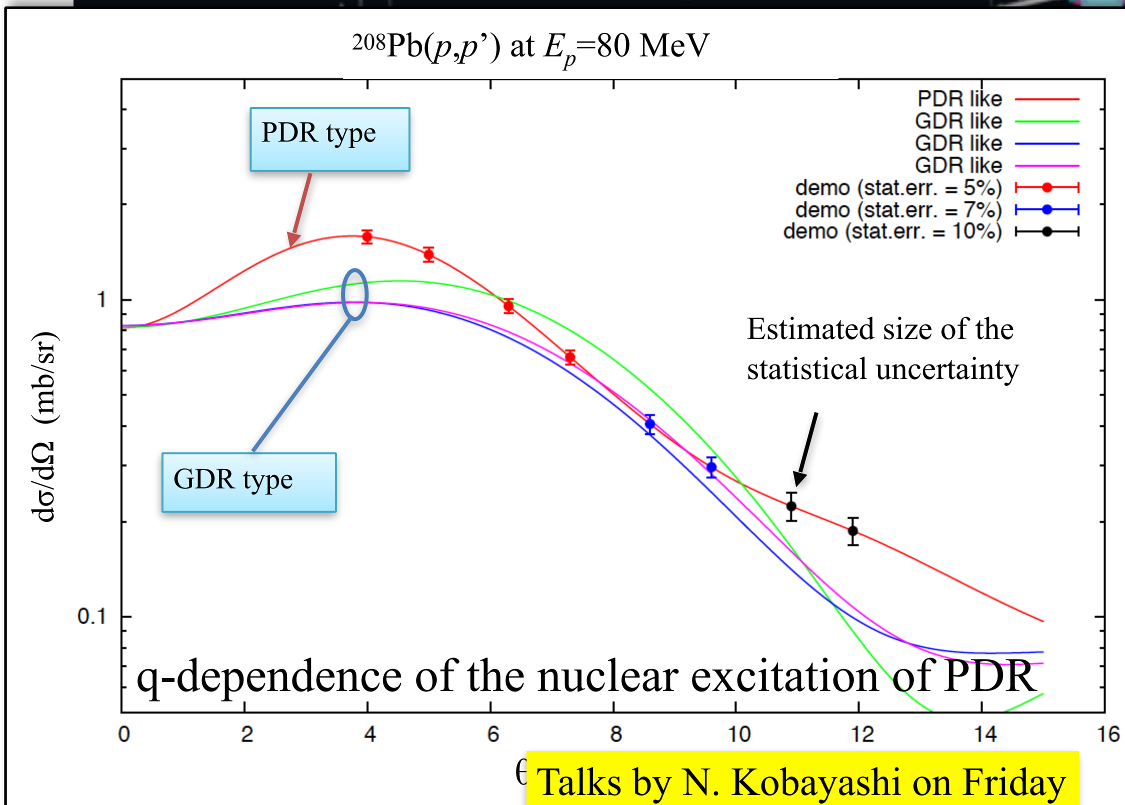
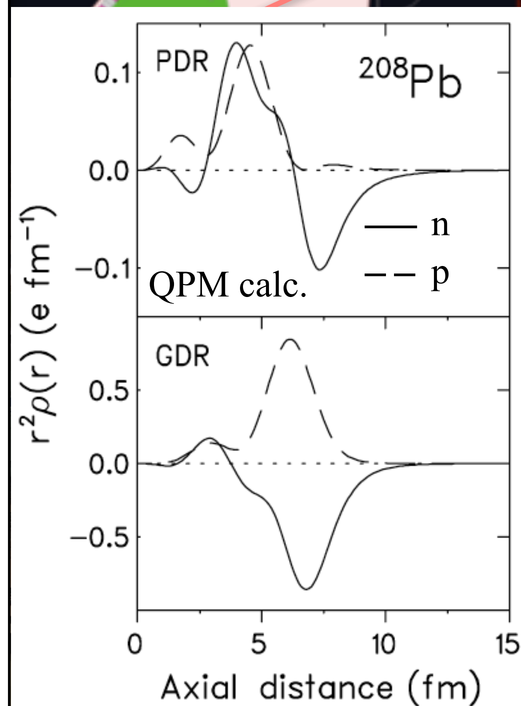
2. Inelastic ν-nucleus response
3. Super-deformed states, high-spin states

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





Talks by N. Kobayashi on Friday

Gamma-Decay of GDR: Damping Mechanism

RCNP, TUD, Milano, KVI, iThemba LABS/Wits, ELI-NP, IFJ-PAN, ..

γ_0: gamma-decay to the ground state

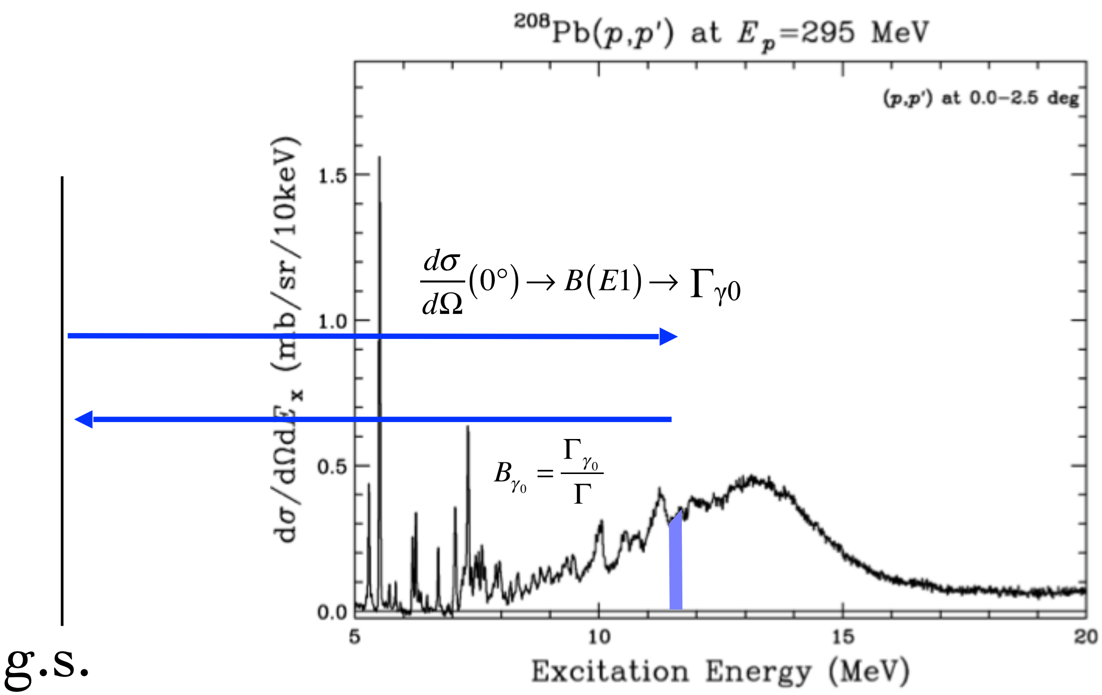
viscosity between the *n/p* fluids

$$B_{\gamma_0} = \frac{\Gamma_{\gamma_0}}{\Gamma} \qquad \Gamma_{\gamma_0} \propto \frac{2J_0+1}{2J+1} E_x^3 B(E1)\uparrow$$

measured by γ-decay

measured by Coulomb excitation

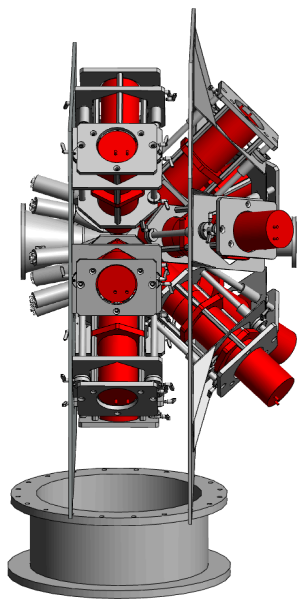
Characteristic width Γ across the IVGDR



An experimental campaign is planned in ~2020.
Proposal submission July-2019, contact A. Tamii

A pilot experiment for ^{90}Zr
RCNP-E498 in July 2018

LaBr3 scintillator array (Scylla)



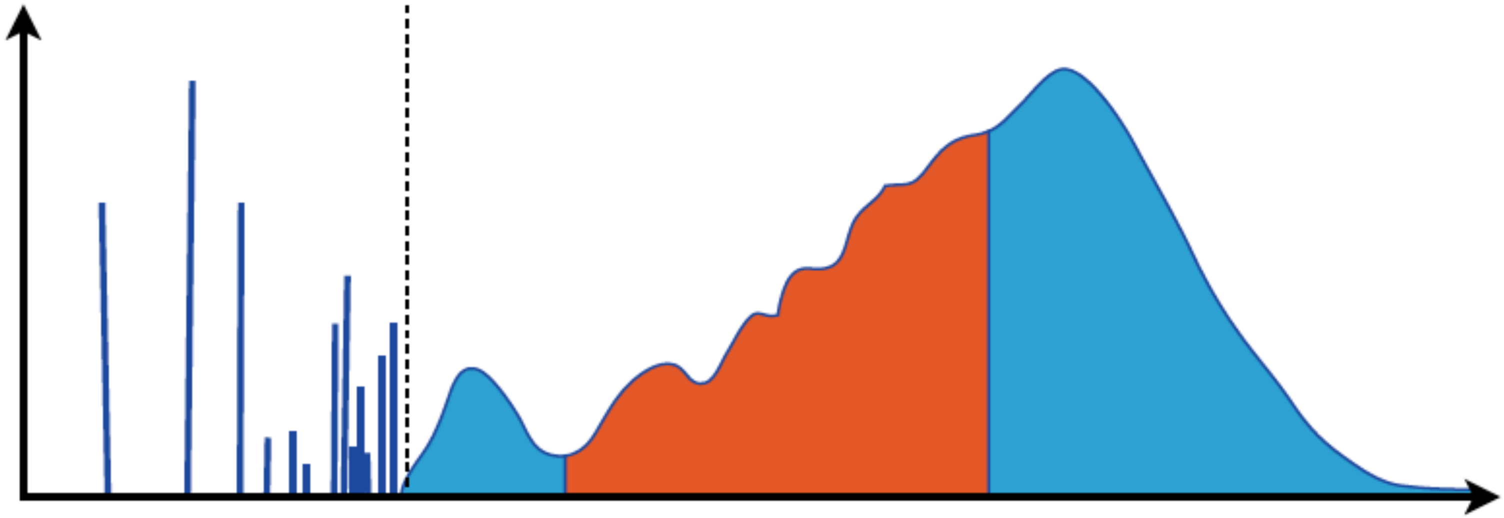
Talk by S. Nakamura,
in this session

IFJ-PAN: talks by Kmiecik, Wasilewska

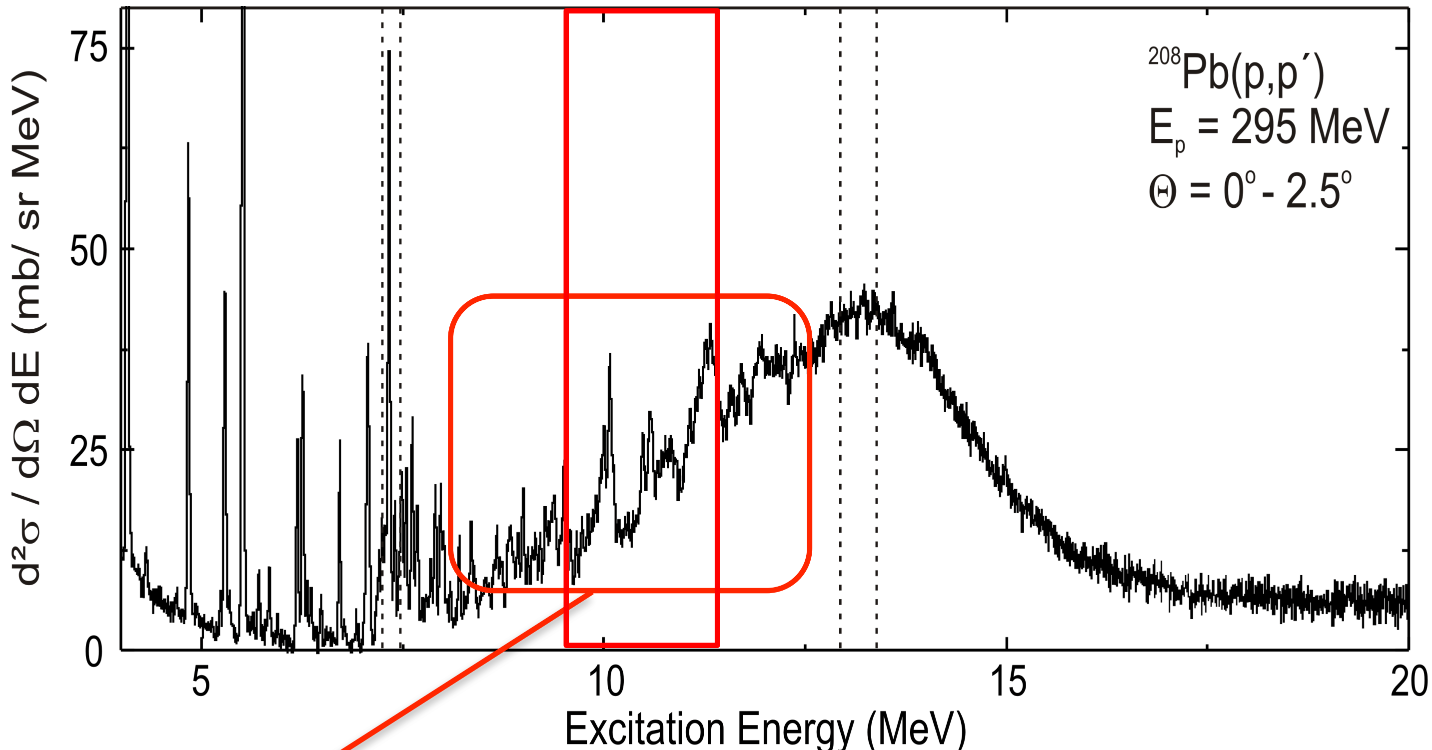
iThemba LABS: talk by L. Pellegri

Exp. planned at ELI-NP

IV
Fine Structure
and
Nuclear Level Density

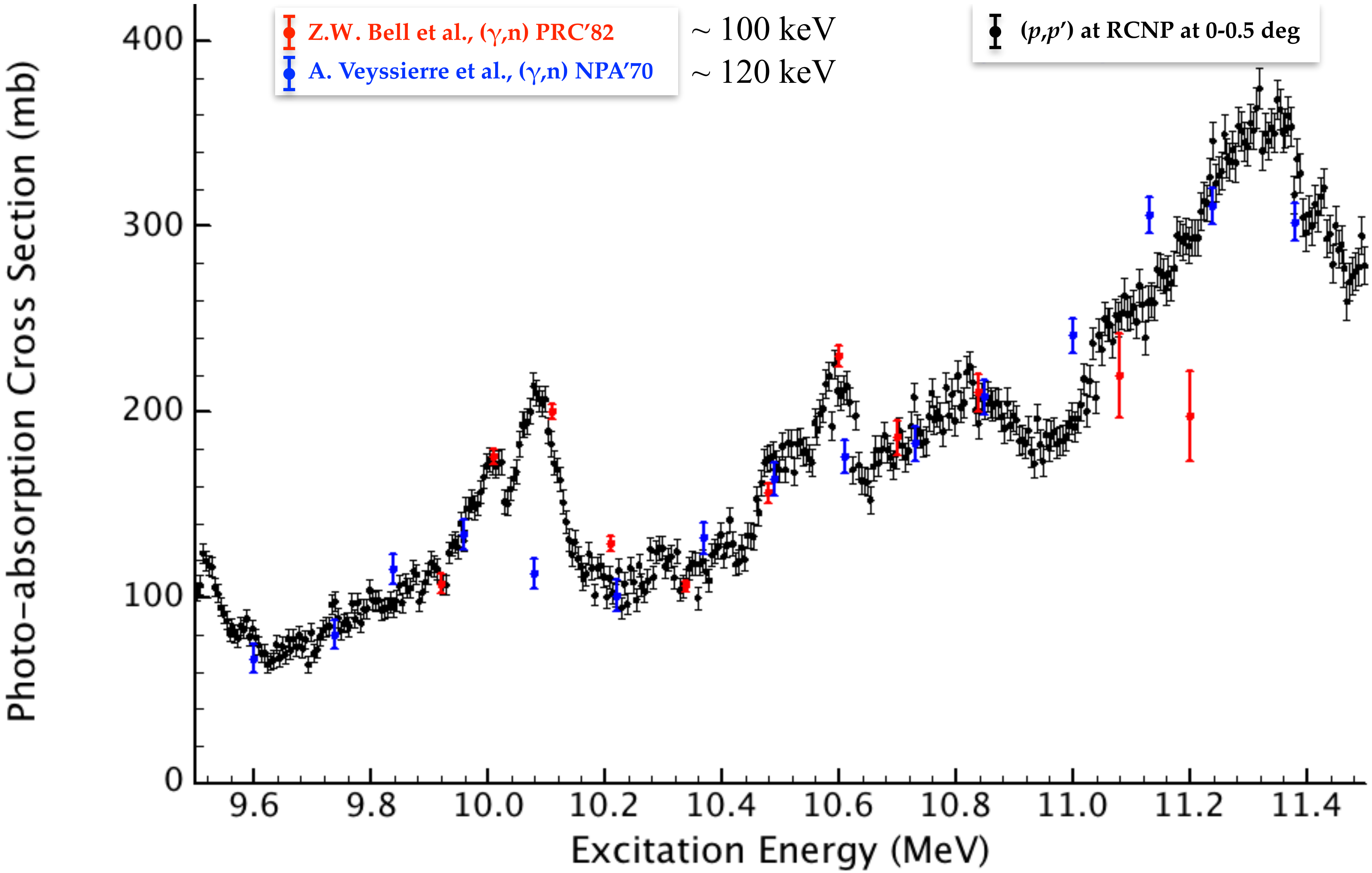


Fine Structure of the GDR



Fine structure of the GDR is clearly observed.

Fine Structure of the GDR

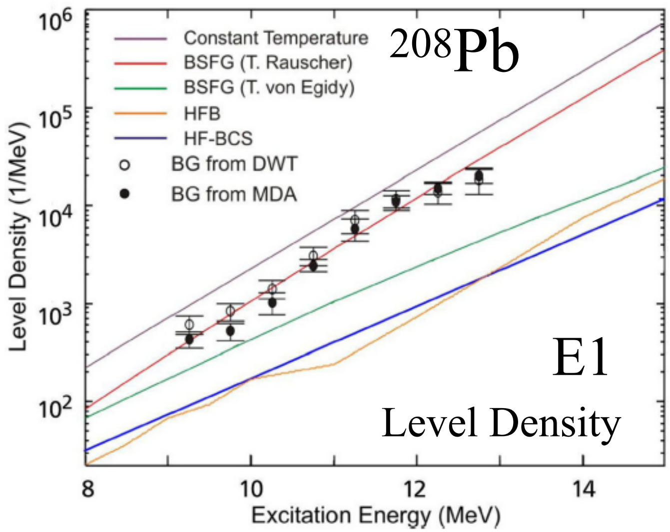


20-30 keV resolution is required.

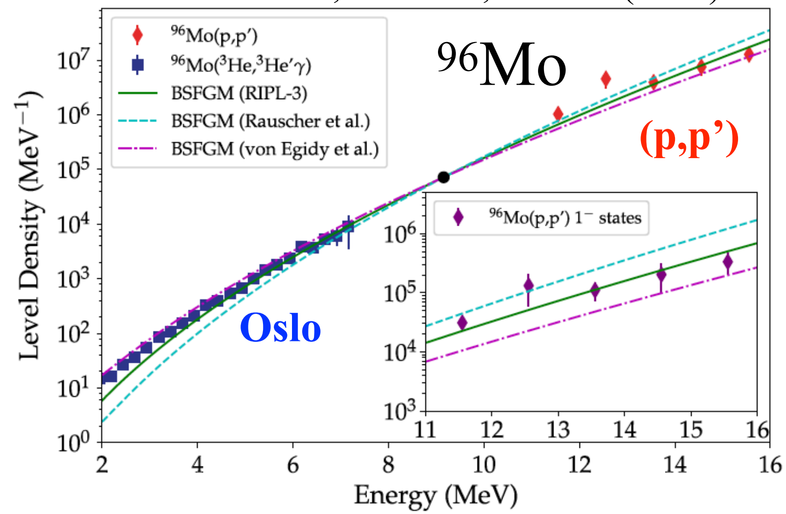
Nuclear Level Densities

extracted by fluctuation analysis using auto-correlation function

I. Poltoratska et al., PRC89, 054322 (2014)

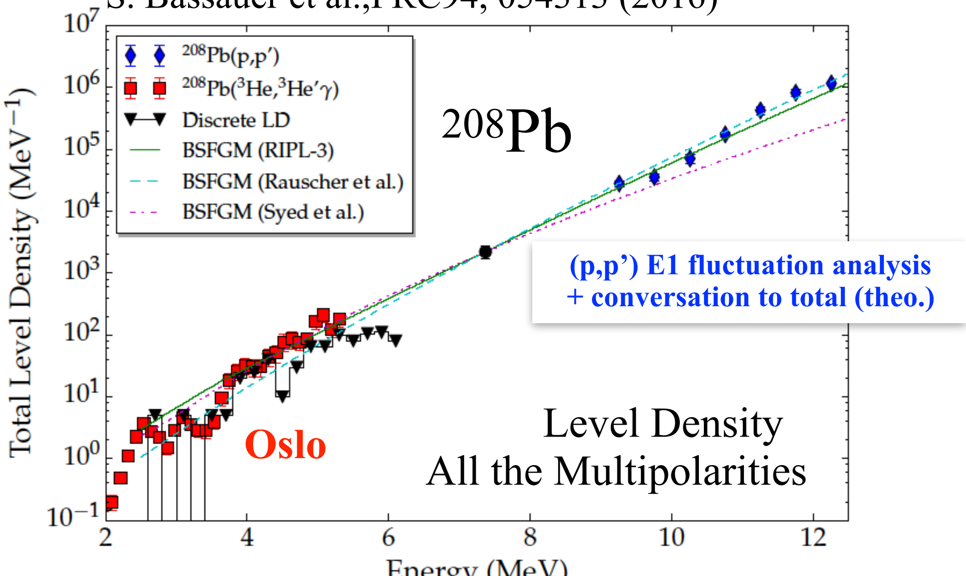


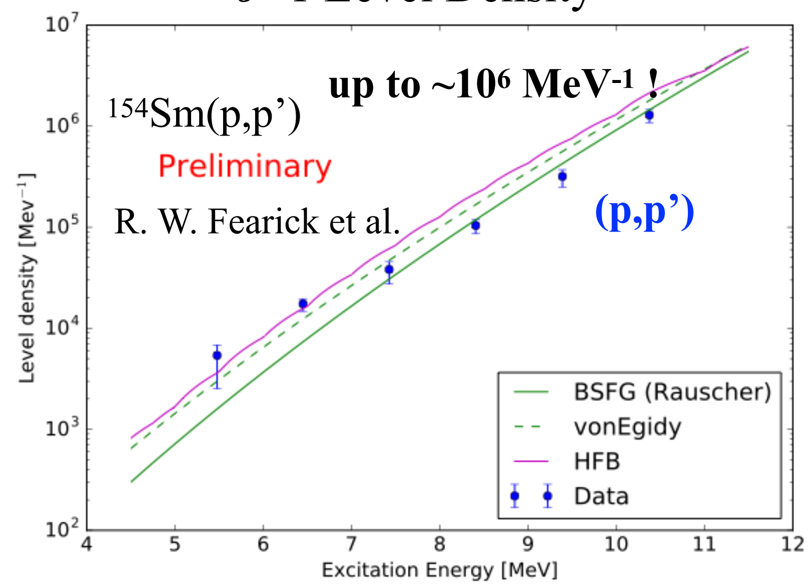
D. Martin et al., PRL 119, 182503 (2017)



J=1 Level Density

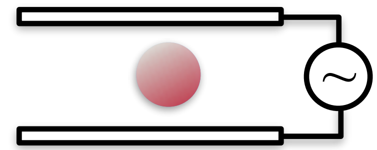
S. Bassauer et al.,PRC94, 054313 (2016)





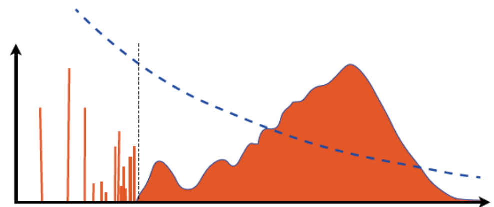
See also R. W. Fearick et al ., PRC97, 044325 (2018)
origin of the fine structures of GDR in ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca

Summary

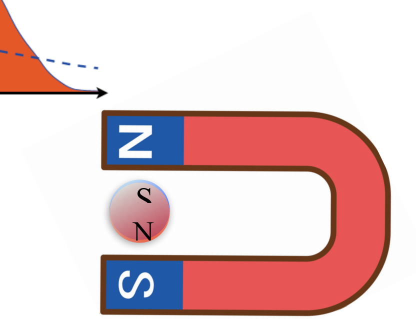


Experimental methods

proton scattering at forward angles

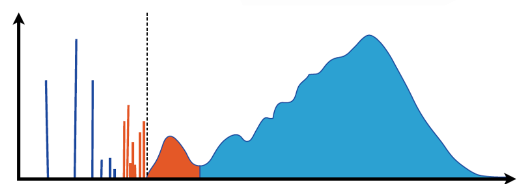


Research highlights

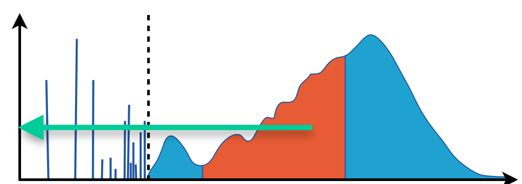


I. Electric Dipole Polarizability
and Nuclear Symmetry Energy

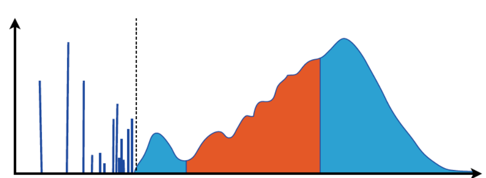
II. Spin Magnetic Excitations



III. Gamma-Decay of GRs and ED excitations
PDR and GDR



IV. Fine Structure and Nuclear Level Density



Thank you for your attention

COMEX6
Oct-2018