Electric Dipole Response of Nuclei: Symmetry Energy and Neutron Skin

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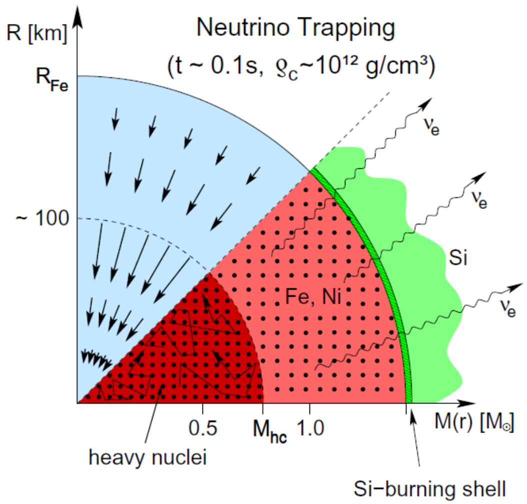
On behalf of the RCNP Proton Inelastic Scattering Project Collaborators

Neutrinos, Electro-Weak interactions, and Symmetries
(NEWS) Colloquium, June 20, 2019 at RCNP

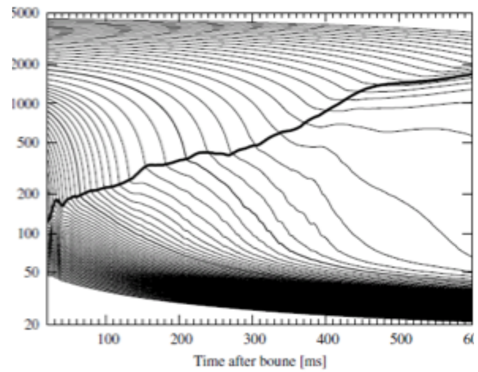
Symmetry Energy of the Nuclear EOS

is important for nuclear physics and nuclear-astrophysics

Core-collapse supernova

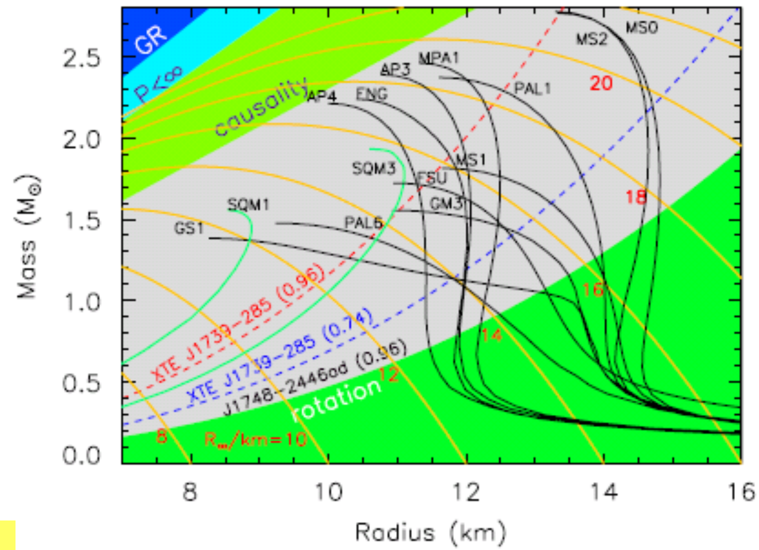


Langanke and Martinez-Pinedo



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

Neutron star mass vs radius



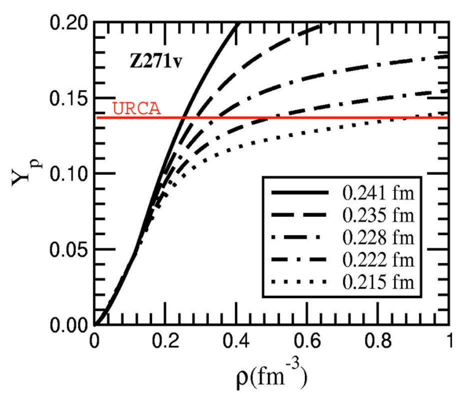
Lattimer et al., Phys. Rep. 442, 109(2007)

Nucleosynthesis

Neutron Star Merger Gravitational Wave

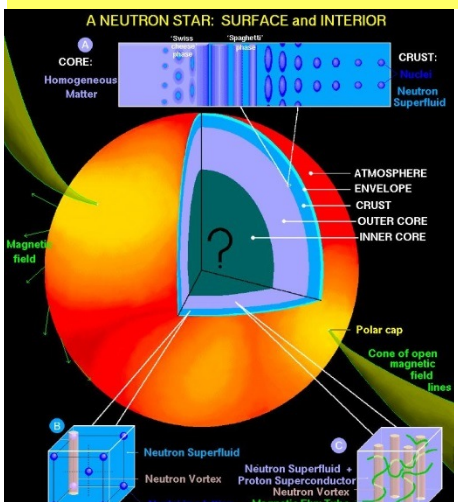
https://www.youtube.com/watch?v=IZhNWh_lFuI

Neutron star cooling



Lattimer and Prakash, Science 304, 536 (2004).

Neutron star structure



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

Nuclear Equation of State (EOS)
at zero temperature

Nuclear EOS neglecting Coulomb

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

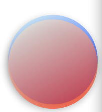
$$\delta\equiv\frac{\rho_n-\rho_p}{\rho_n+\rho_p}$$ Asymmetry parameter

Symmetry energy

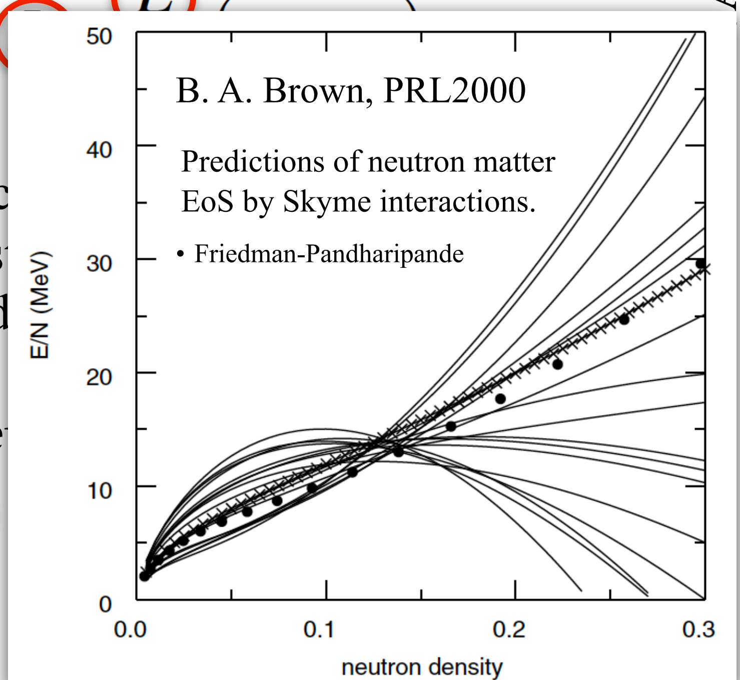
$S(\rho)=$ … L …

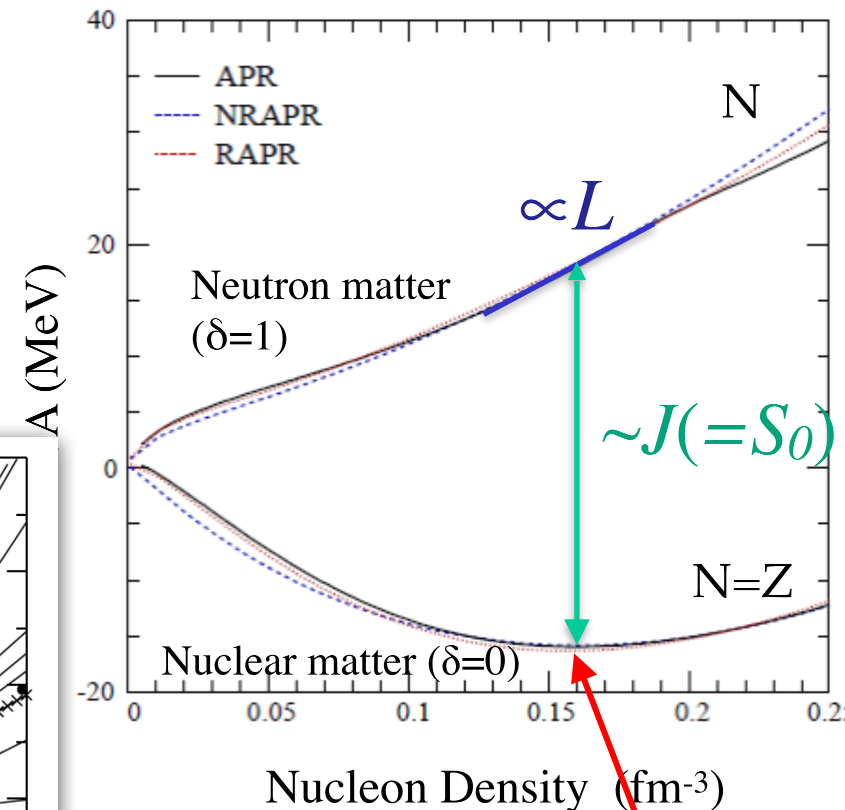
⇔ differenc
how the sys
are replaced

Nucle



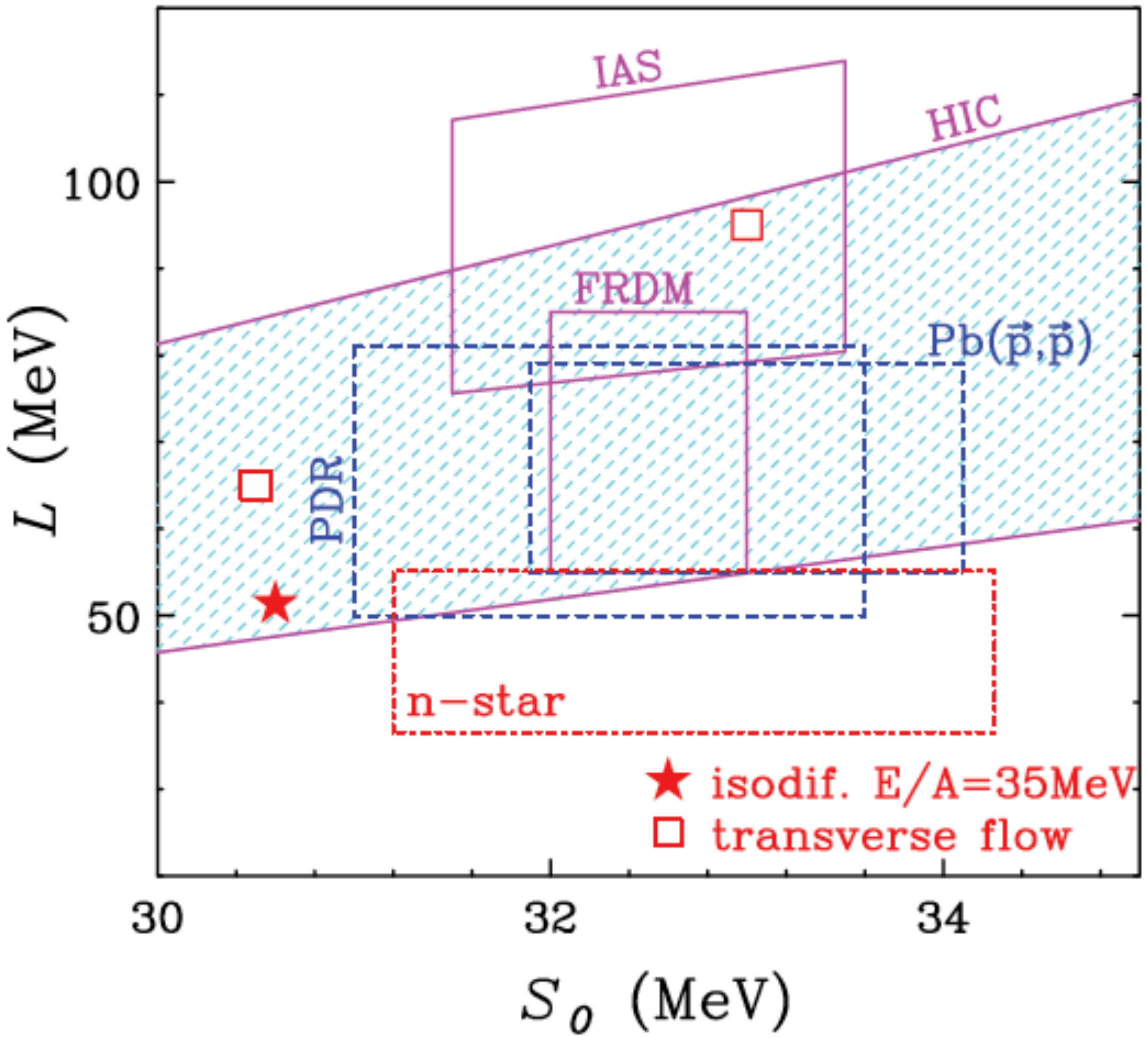
Z≤N





~0.16 fm^{-3}

Constraints on *J* and *L*



M.B. Tsang et al., PRC2012

HIC: Heavy Ion Collision Analysis
Tsang PRL2009

IAS: Isobaric Analog State Energy
Danielewicz&Lee NPA2009

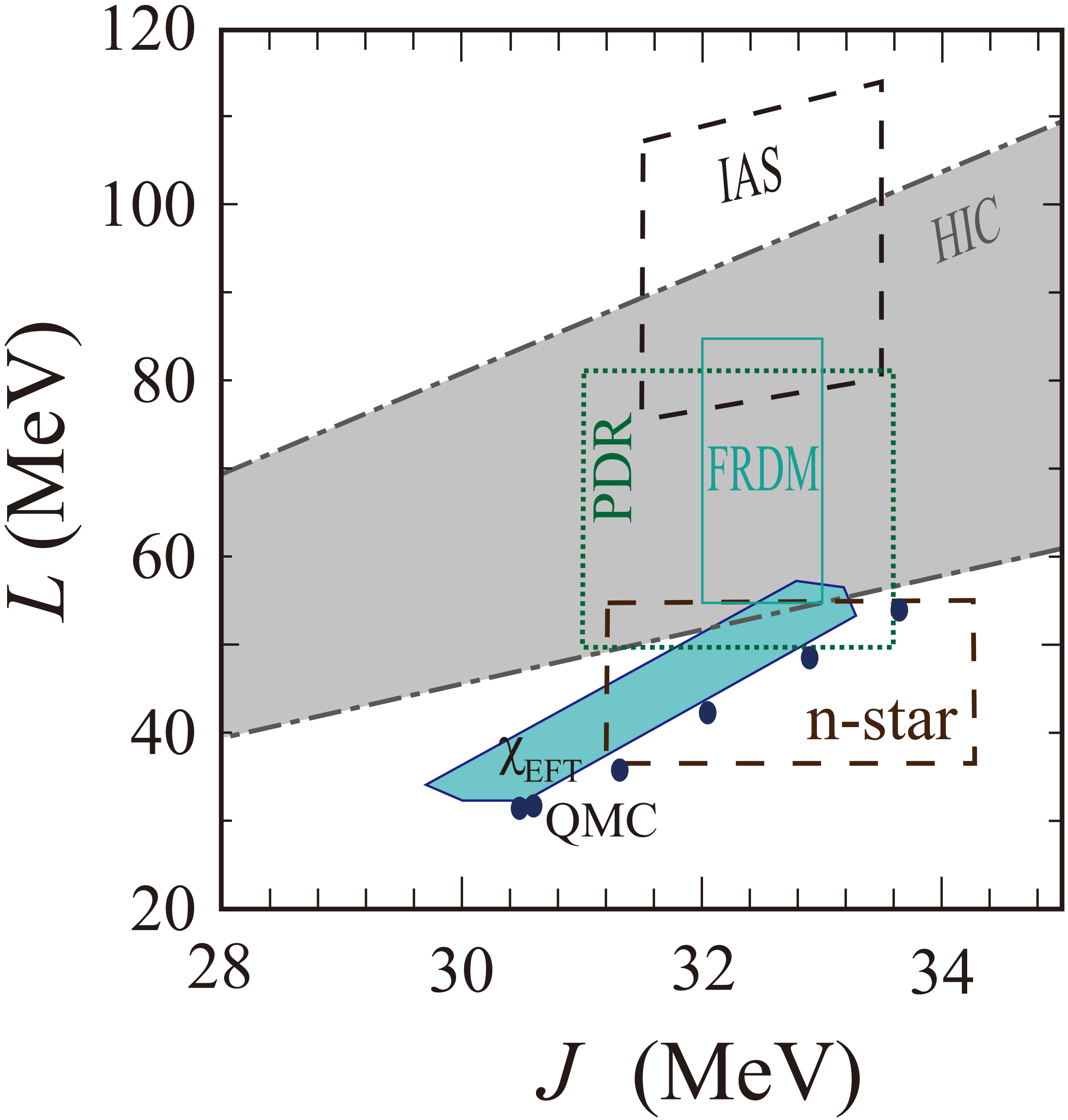
PDR: Pygmy Dipole Resonance in
^{132}Sn, ^{68}Ni, Carbone PRC2010

FRDM: Finite Range Droplet Model
Moeller PRL2012

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

Pb(p,p): proton elastic scattering
J. Zenihiro et al., PRC2010

Constraints on J and L



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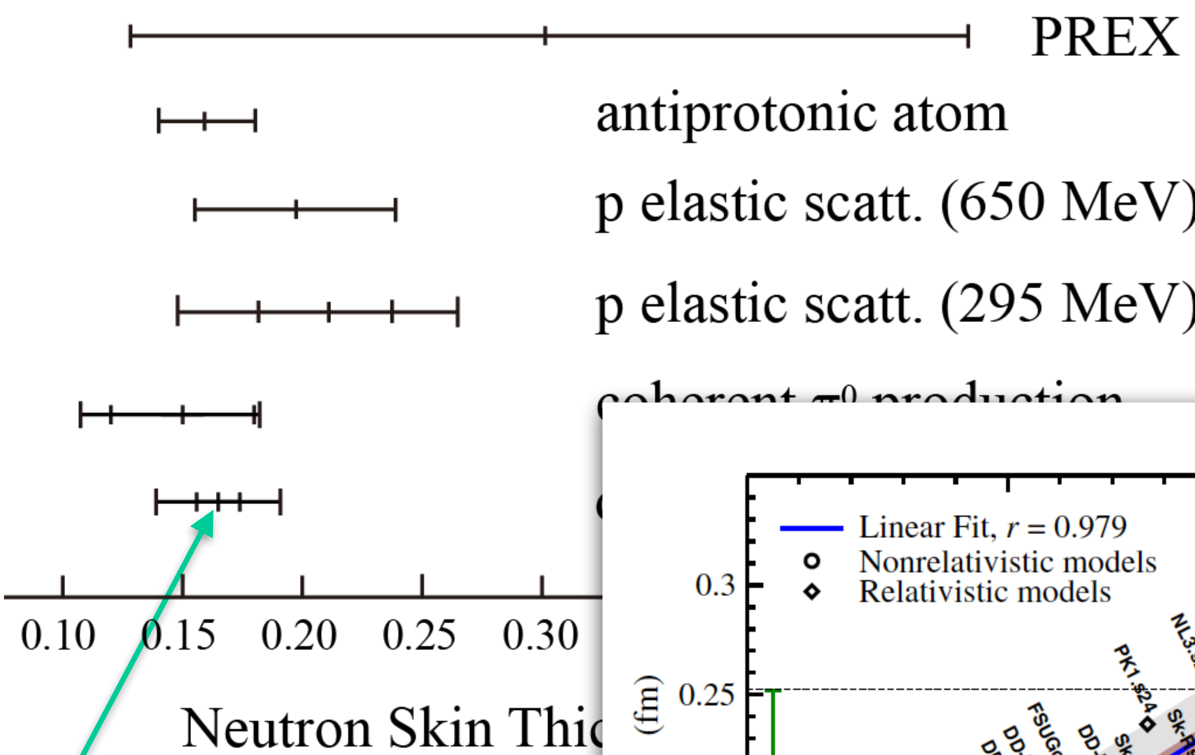
n-star: Quiescent Low-Mass X-ray
Binaries, Stainer PRL2012

χ_{EFT}: Chiral Effective Field Theory,
Tews PRL2013

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

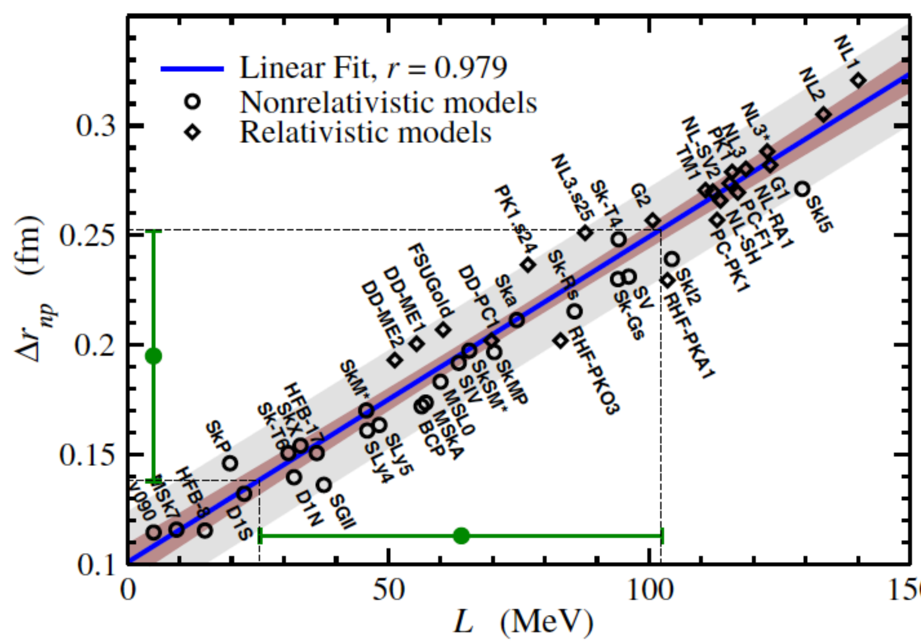
Neutron Skin Thickness of ^{208}Pb



$\Delta R_{np} = R_n - R_p = 0.165 \pm (0.009)_{exp}$

for the estimated J=31 ± (2)$_{est}$

X. Roca-Maza *et al.*, PRC**88**, 02431



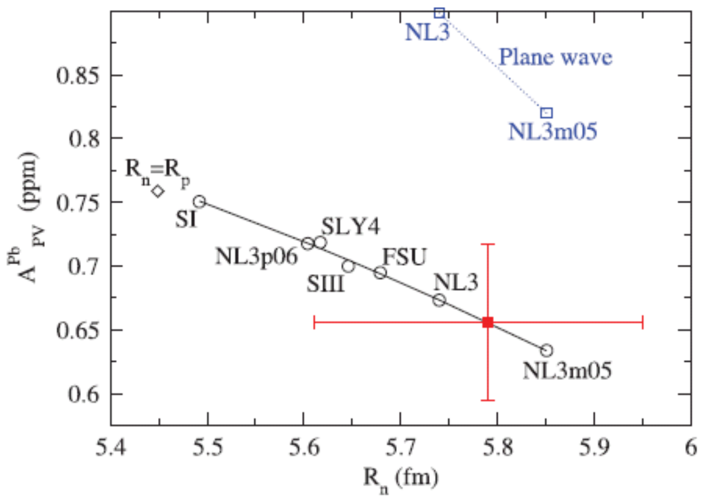
X. Roca-Maza *et al.*, PRL**106**, 252501 (2011)

see also Furnstahl **NPA706**, 85(2002)

Parity Violating Electron Weak-Scattering from ^{208}Pb (PREX@J-Lab) for Neutron-Skin Thickness and L

Lead (^{208}Pb) Radius Experiment: PREX

S. Abrahamyan et al., PRL108, 112502 (2012)

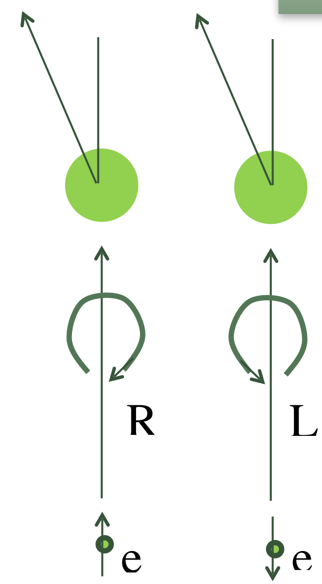


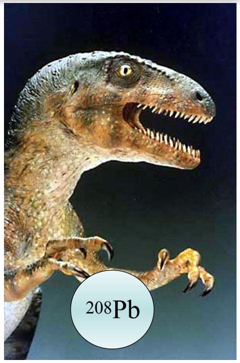
$$R_n = 5.78^{+0.16}_{-0.18}$$

$$R_n - R_p = 0.33^{+0.16}_{-0.18}\ \text{fm}$$

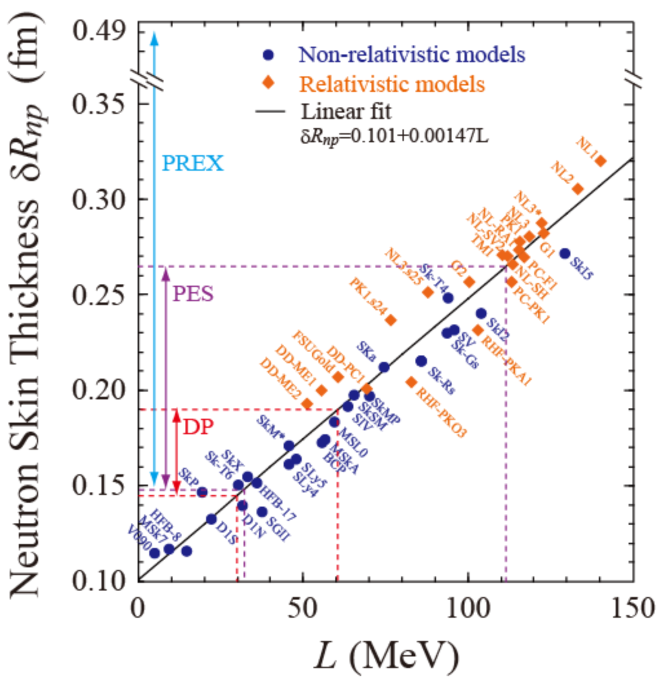
$$R_n - R_p = 0.302 \pm 0.175\ (\text{exp}) \pm 0.026\ (\text{mod}) \pm 0.005\ (\text{str})\ \text{fm}.$$

C.J. Horowitz et al., PRC85,032501(R)(2012)





"Model independent" determination of the neutron radius of ^{208}Pb.



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

PREX-II and C-REX in ~2019

Jefferson Laboratory Hall-A

Science

Physicists Measure the Skin of a Nucleus

by Adrian Cho on 2 March 2012

Science Now

...

Nailing down such parameters would have equally big implications for the theory of neutron stars, says James Lattimer, a theoretical astrophysicist at Stony Brook University in New York state. "That directly tells you the radius of a neutron star [of a given mass] and a lot of other things like the thickness of its crust, the response of its surface to explosions, et cetera," Lattimer says.

Alas, the uncertainty on the PREX measurement is still too large to pin down the parameters, Lattimer says. "It's a very important experiment and has the potential to constrain theory very nicely, but it's not there yet," he says. JLab's Michaels says the PREX team will run the experiment next year and aims to reduce the uncertainty to one-third its current value. "Then it becomes a very interesting result," he says.

Something else physicists will be watching for: The PREX measurement suggests that the neutron skin of lead-208 is twice as thick as more-precise but model-dependent methods indicate. Right now, the PREX result has too much uncertainty to pose a direct challenge to earlier estimates. But if the new value holds up as the uncertainty shrinks, things could get really interesting, Nazarewicz says: "Then, there is something wrong with all theoretical models." There's a possibility to set your skin a-tingling.

Outline of Our Work

<u>Purpose</u>

Symmetry energy of nuclear EOS at $\leqq \rho_0$

<u>Method</u>

An observable that is sensitive to the density difference between *p* and *n* in heavy nuclei

<u>Experiment</u>

Measured electric dipole response of Nu

<u>Results</u>

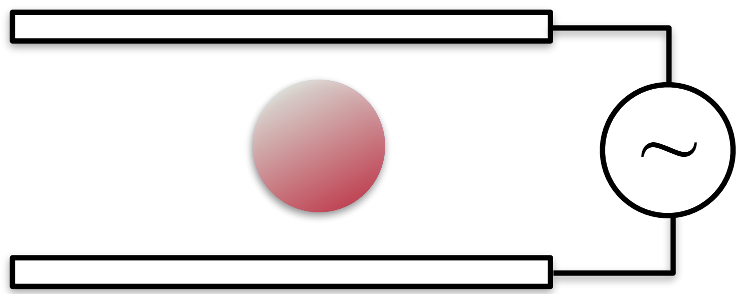
Constraints on symmetry energy

$N \gtrsim Z$
$\rho \lesssim \rho_0$
$T=0$
p and n

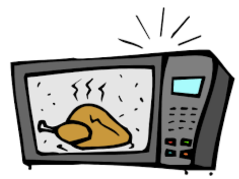
Ordinary nuclear matter

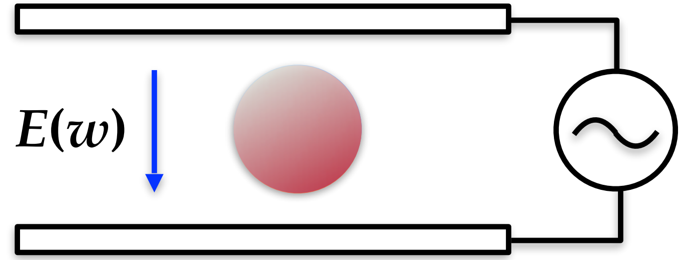
Starting point to further exotic conditions

Electric Dipole Response of Nuclei and the Nuclear Symmetry Energy



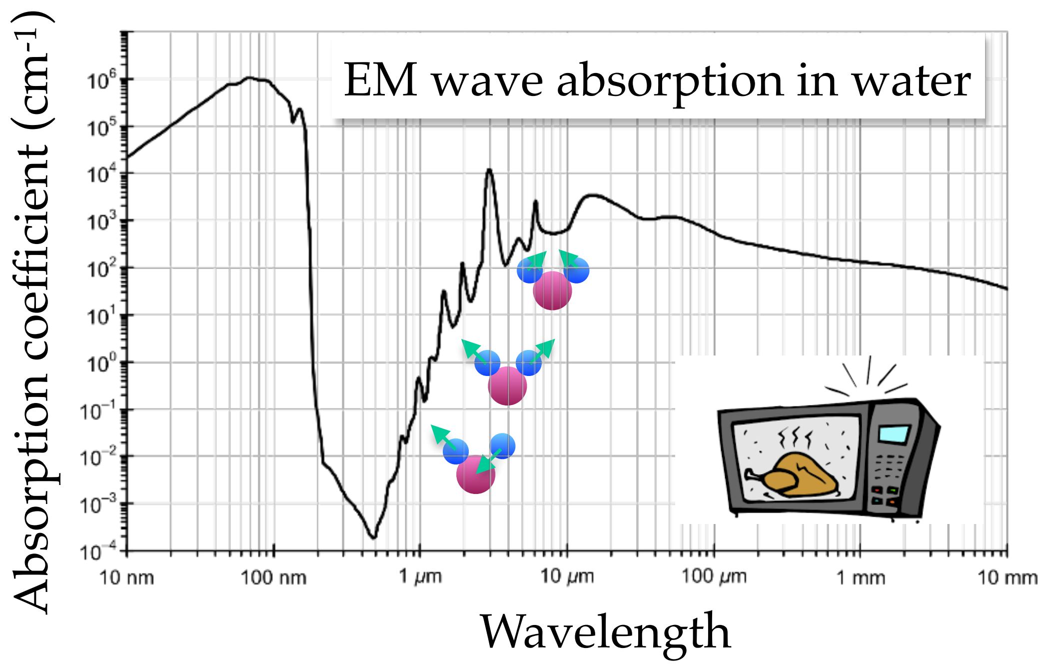
Electric Dipole Response of Nuclei

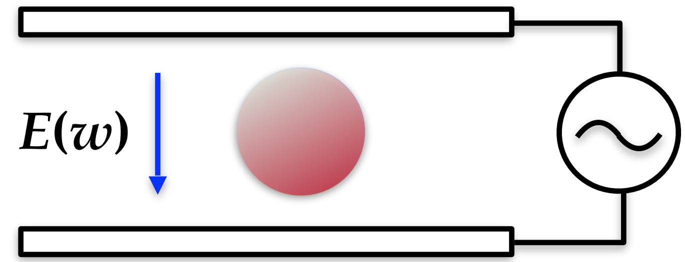




dielectric material
in an oscillating electric field

Electric Dipole Response of Nuclei





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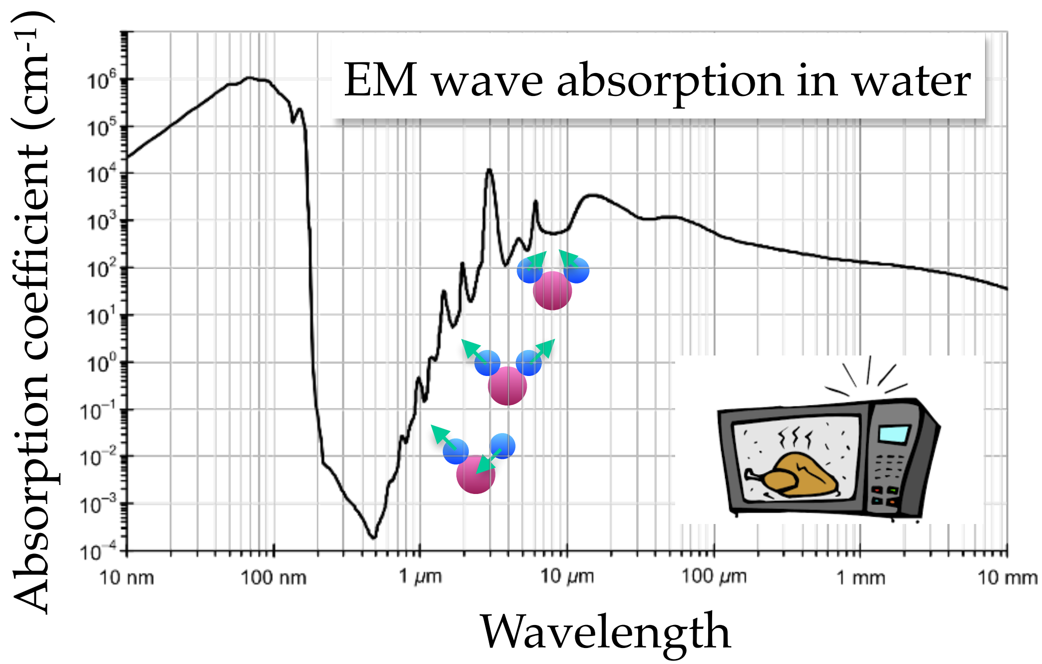
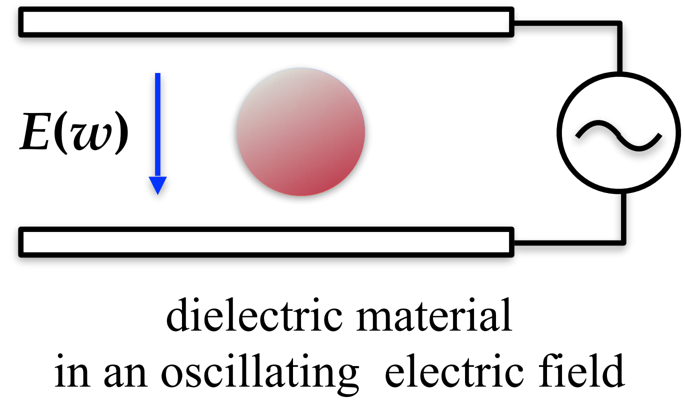
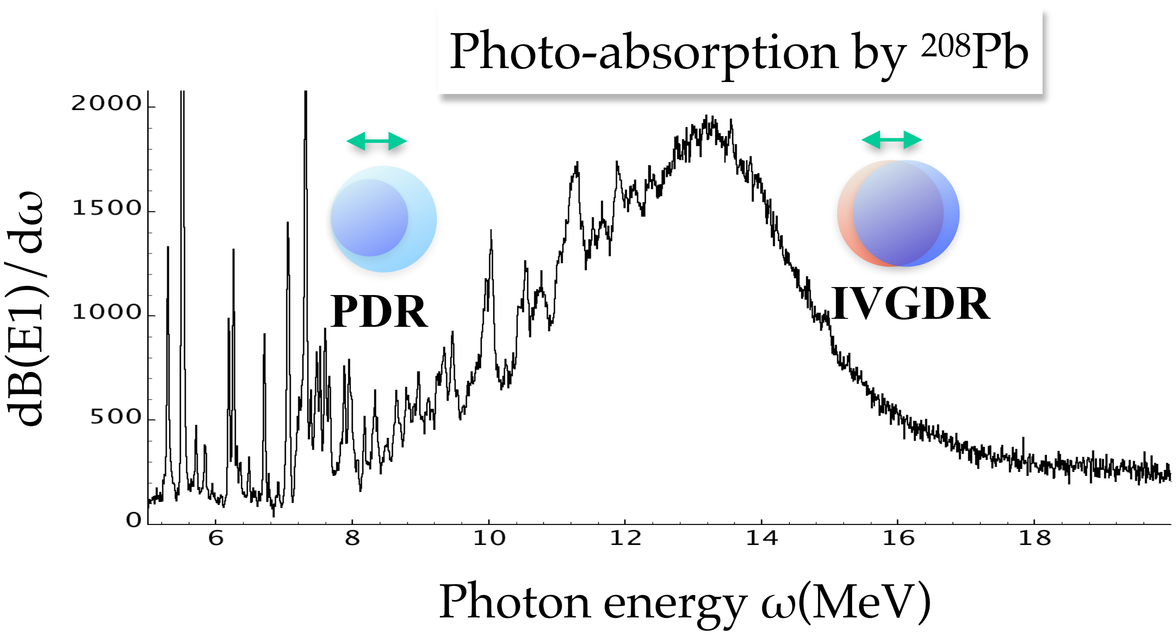
Electric Dipole Response of Nuclei





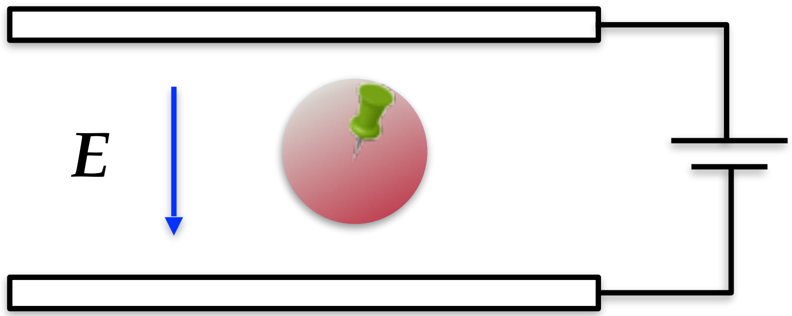


Static Electric Dipole Polarizability (α_D)

Electric dipole moment

$$p = \alpha_D \times E$$

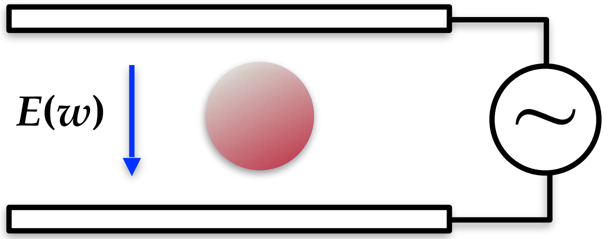
α_D: electric dipole polarizability



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

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

$$\alpha_D = \frac{8\pi e^2}{9} \int \frac{dB(E1)}{E_x}$$



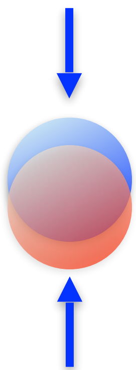
first order perturbation calc. A.B. Migdal: 1944

Static Electric Dipole Polarizability (α_D)

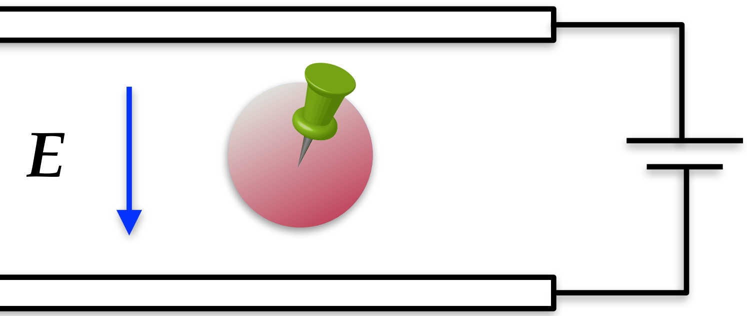
Electric dipole moment

$$p = \alpha_D \times E$$

α_D: electric dipole polarizability



The **restoring force** originates from the **symmetry energy.**



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

Electric dipole polarizability (EDP) is sensitive to the symmetry energy below the nuclear saturation density and to the neutron skin thickness.

Nuclear Equation of State (EOS)
at zero temperature

Nuclear EOS neglecting Coulomb

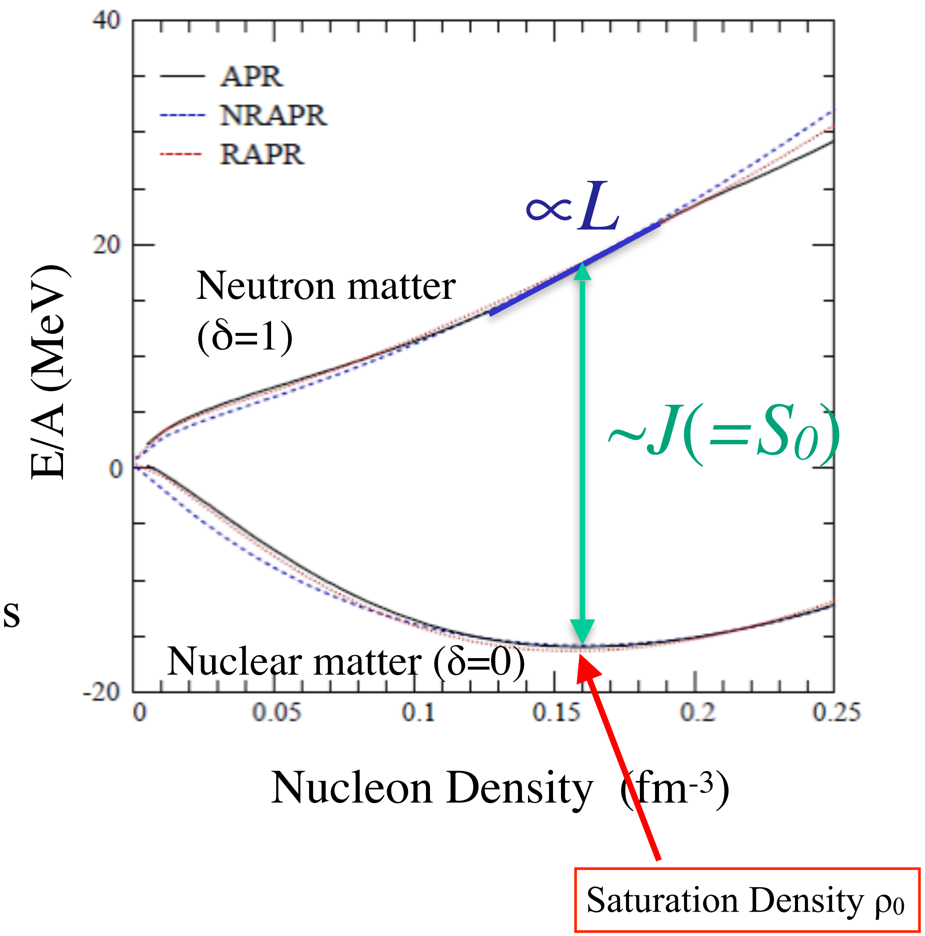
$$\frac{E}{A}(\rho,\delta)=\frac{E}{A}(\rho,0)+S(\rho)\delta^2+\cdots$$

$$\delta\equiv\frac{\rho_n-\rho_p}{\rho_n+\rho_p}$$ Asymmetry parameter

Symmetry energy

$$S(\rho)=J+\frac{L}{3\rho_0}(\rho-\rho_0)+\dots$$

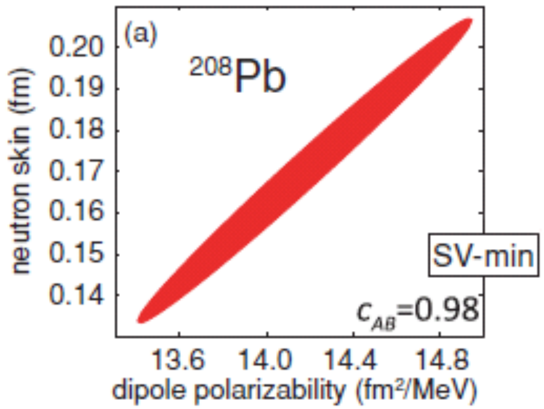
Density difference between *n* and *p* increases the system energy by the symmetry energy.

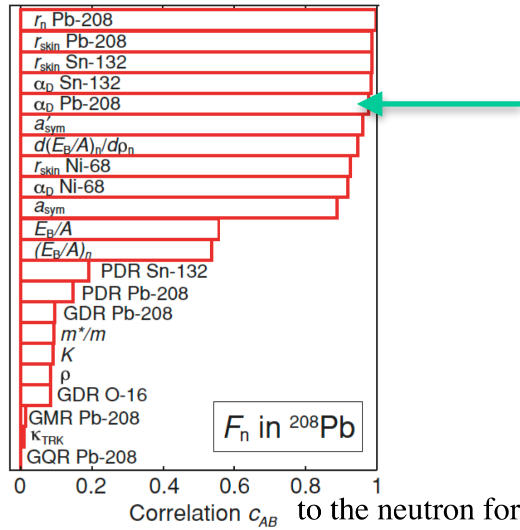


~0.16 fm^{-3}

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

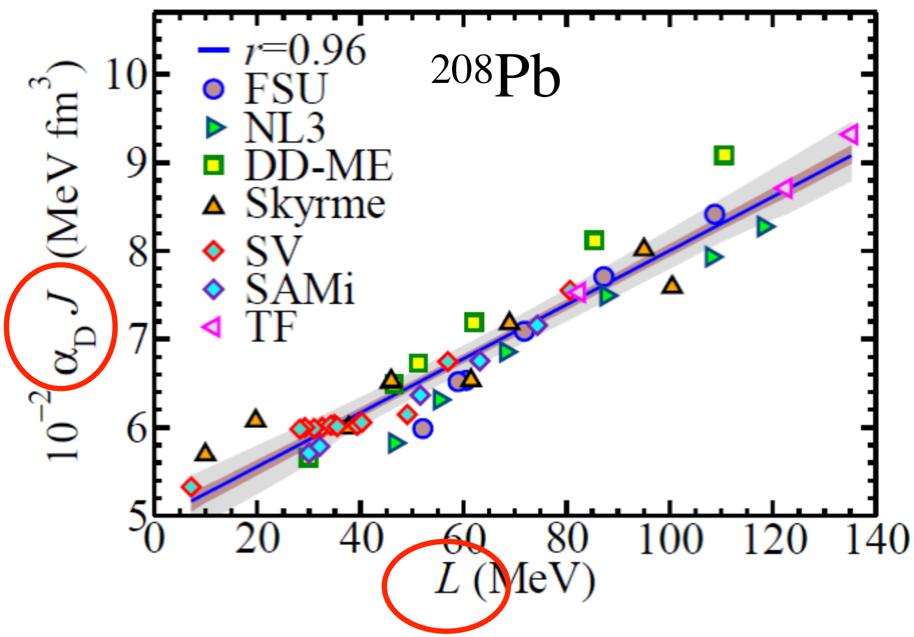
$\sim L$





to the neutron form factor in ^{208}Pb

Reinhard and Nazarewicz, PRC81, 051303(R) (2010)



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

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

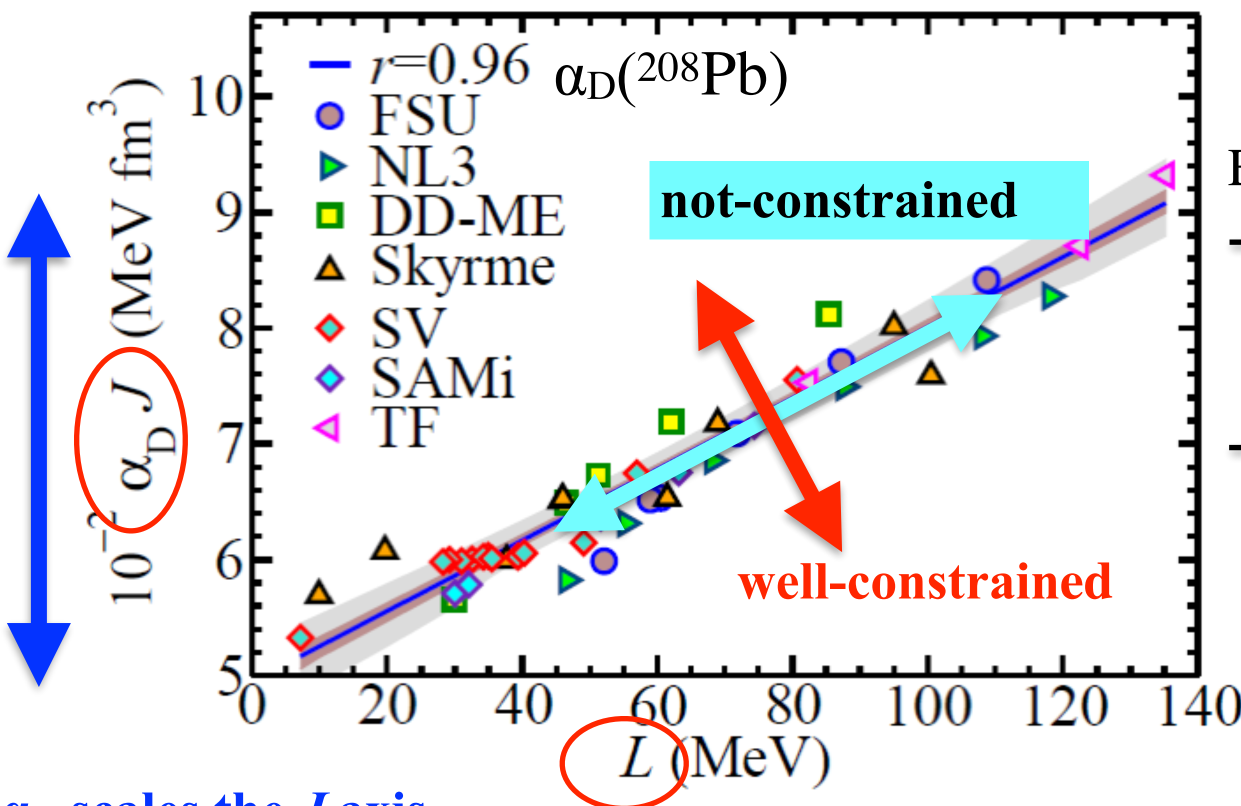
$$\alpha_D^{\mathrm{DM}} \approx \frac{\pi e^2}{54}\frac{A\langle r^2\rangle}{J}\left[1+\frac{5}{3}\frac{L}{J}\epsilon_A\right]$$

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 (α_D) in the correlation of *J* and *L*

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



α_D scales the *J* axis

α_D scales the J axis.

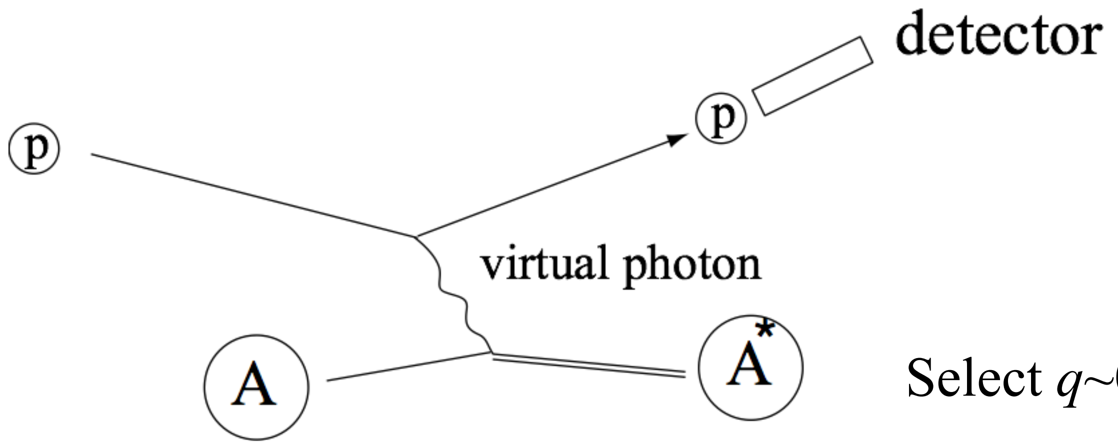
Effective Interactions

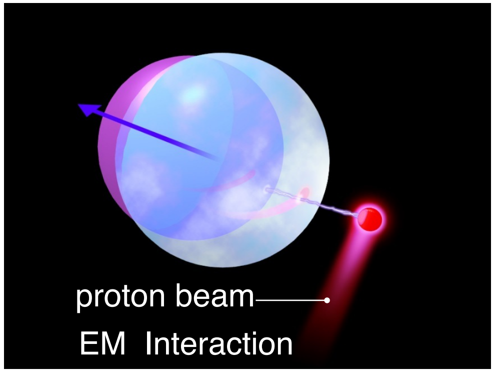
- → reproduce e.g. nuclear masses and charge radii of representative nuclei
- → constrained in one direction but not in the other

One of the unknowns, a_D, has been determined experimentally to extract the constraint band in the *J*-*L* plane.

Probing the E1 Response by Proton Scattering

Missing Mass Spectroscopy by Virtual Photon Excitation

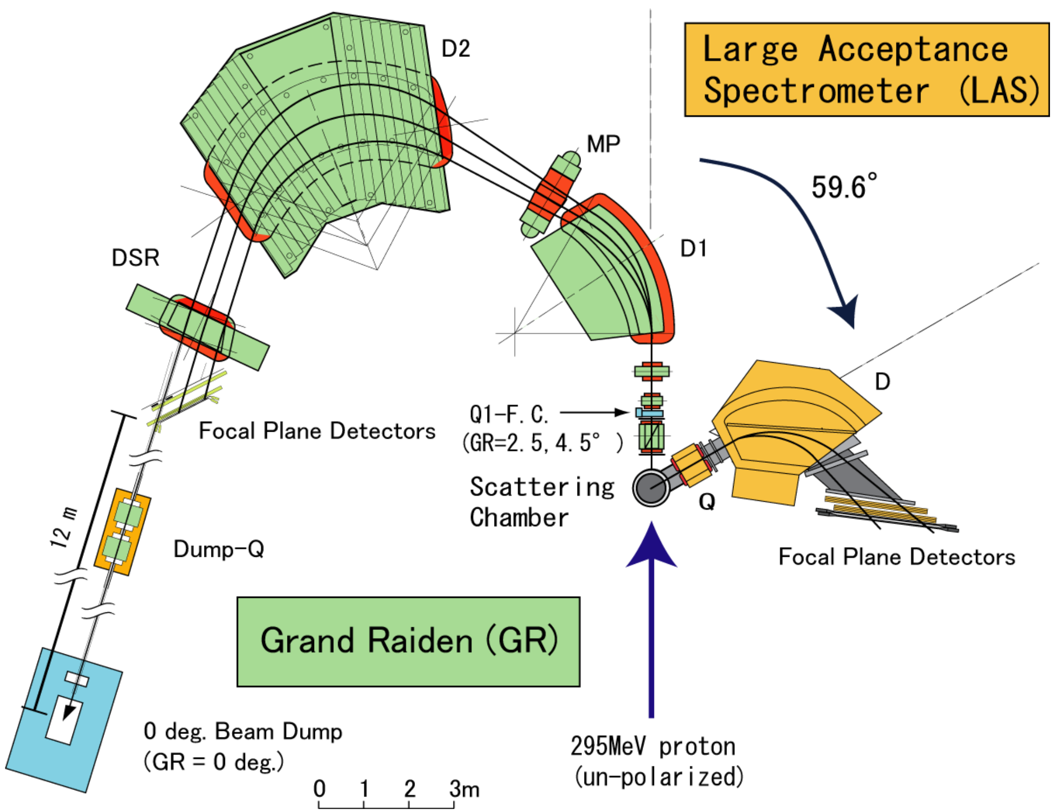


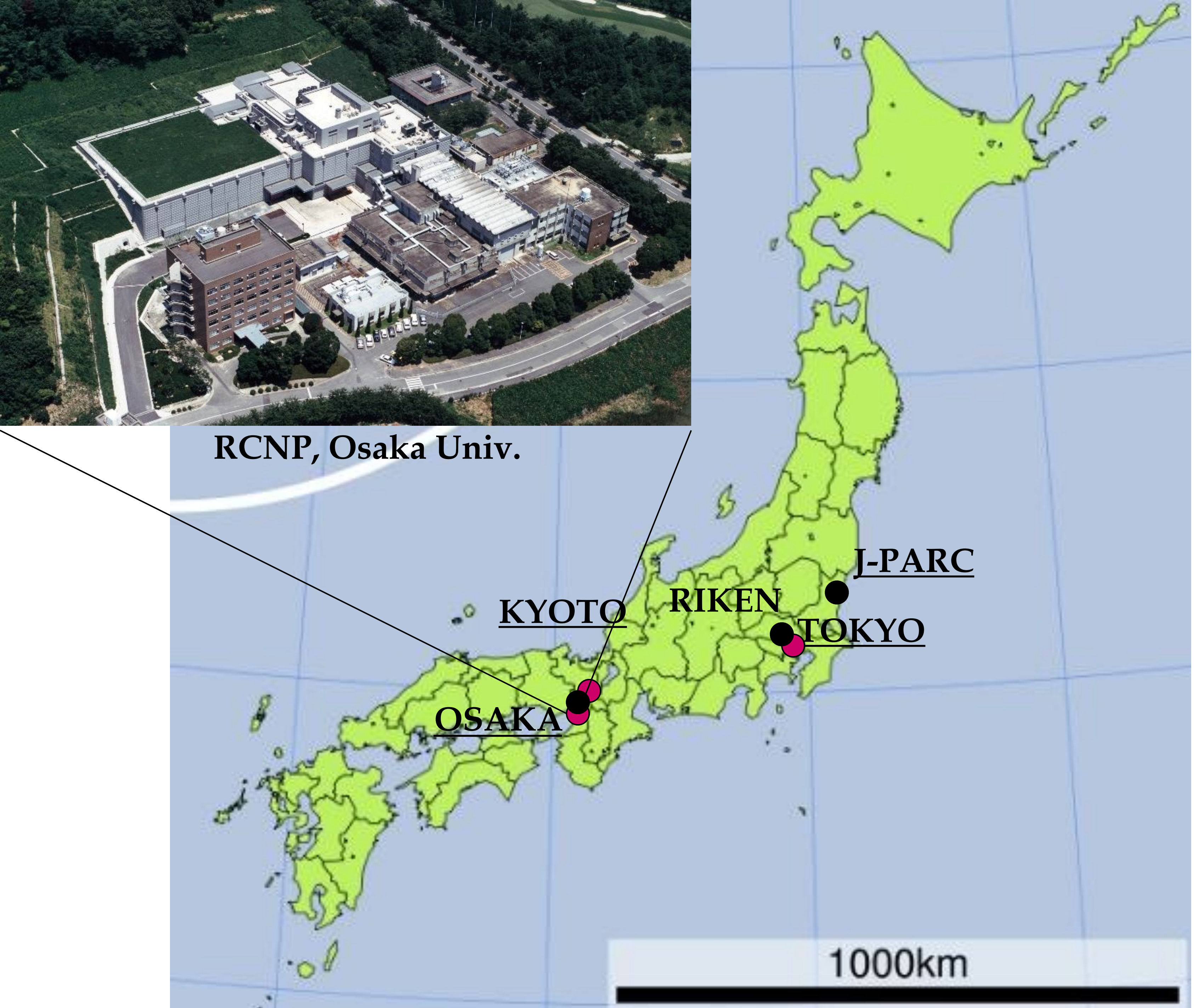


Select q~0 (~0 deg.)

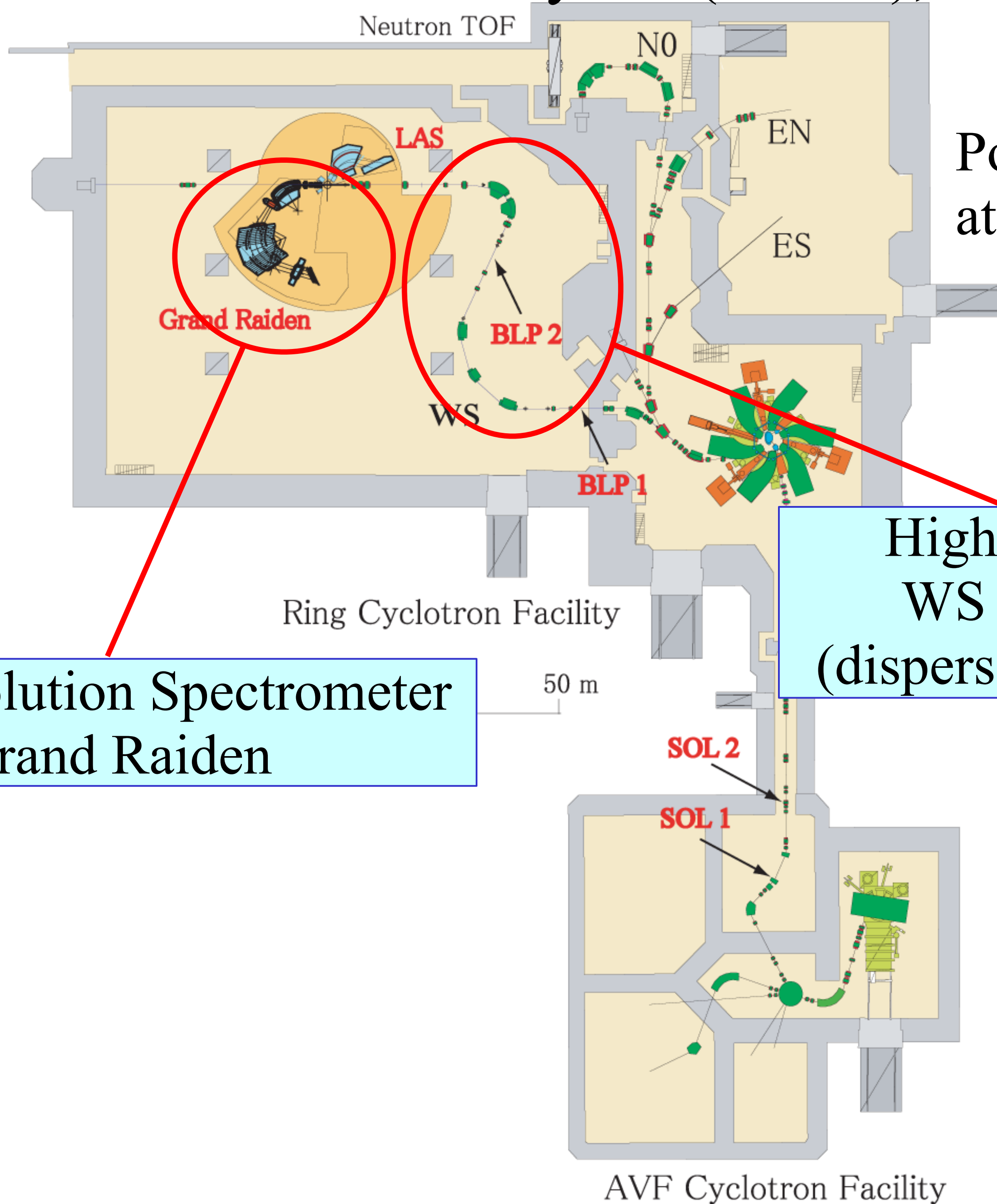
- **Missing mass spectroscopy**:
  Total strength is measured independently from the decaying channels.
- **Multipole decomposition** of the strength in the continuum:
  Includes the contribution of unresolved small states
- **Coulomb excitation**: EM Interaction
  Absolute determination of the transition strength.

Experimental Methods




RCNP, Osaka Univ.
J-PARC
RIKEN
KYOTO
TOKYO
OSAKA
1000km

Research Center for Nuclear Physics (RCNP), Osaka University



Polarized p beam at 295 MeV

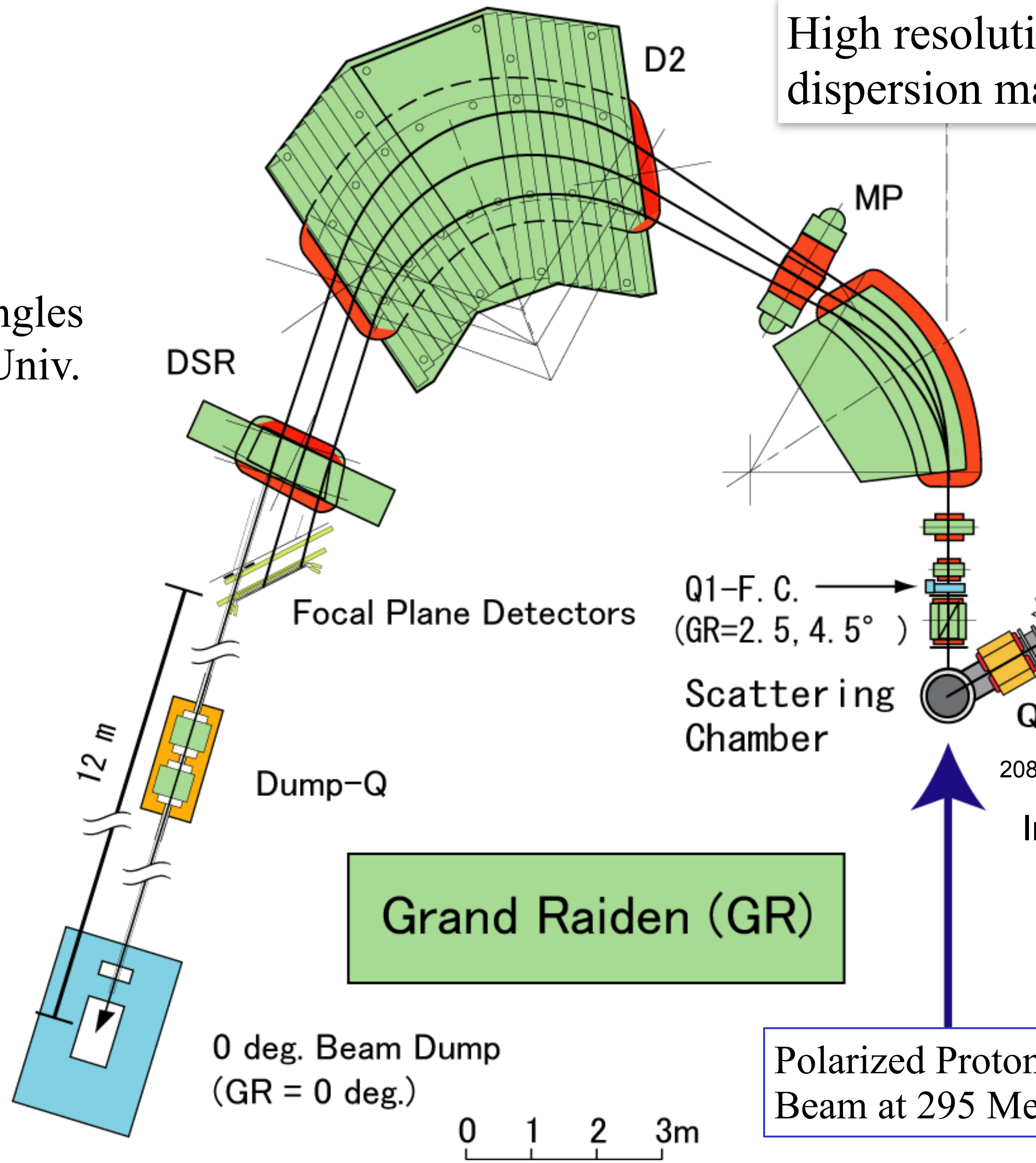
High-resolution Spectrometer
Grand Raiden

High-resolution
WS beam-line
(dispersion matching)

High-Resolution Spectrometer "Grand Raiden"

High resolution of 20-30 keV: dispersion matching.

Proton scattering
at very forward angles
at RCNP, Osaka Univ.



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

Intensity : 1-8 nA

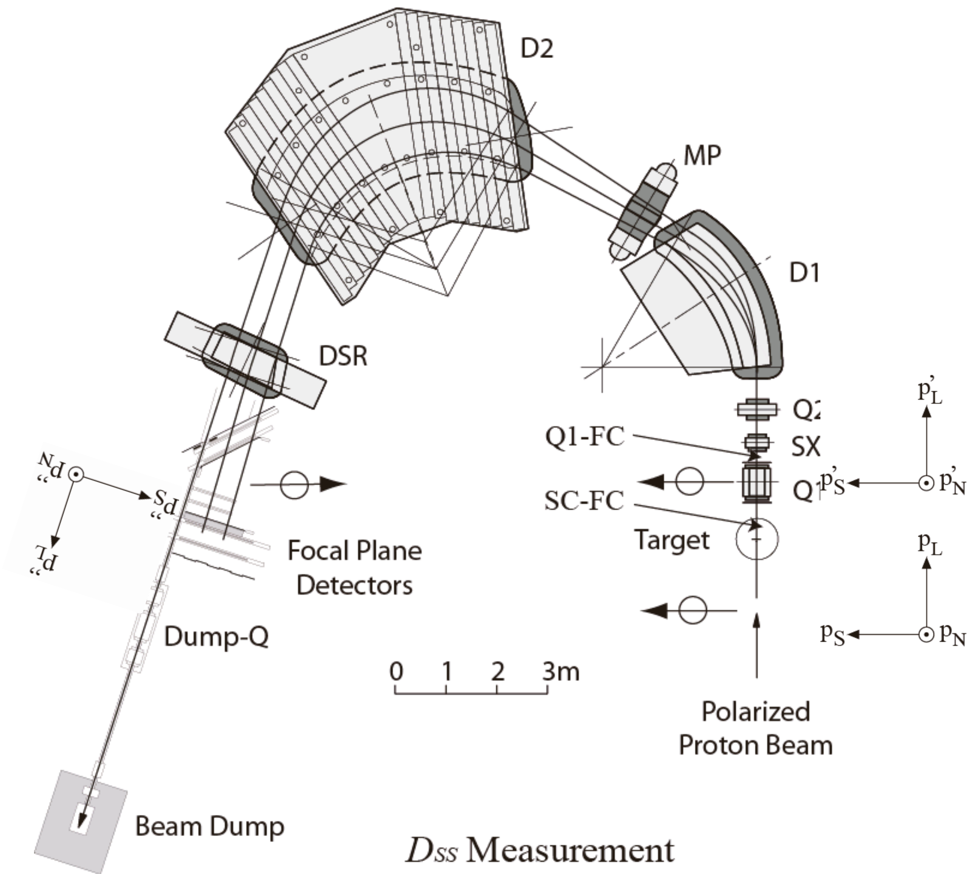
Polarized Proton
Beam at 295 MeV

AT et al., NIMA605, 326 (2009)

Spin Precession in the Spectrometer

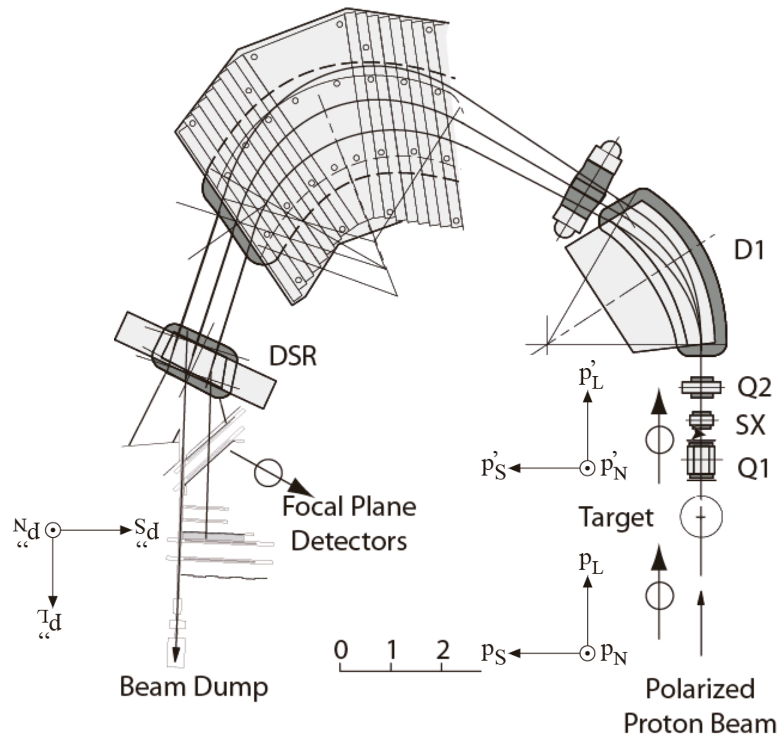
$$\theta_p = \gamma\,(\frac{g}{2} - 1)\theta_b$$

q_p: precession angle with respect to the beam direction
q_b: bending angle of the beam
g: Lande's g-factor
g: gamma in special relativity



D_{SS} Measurement

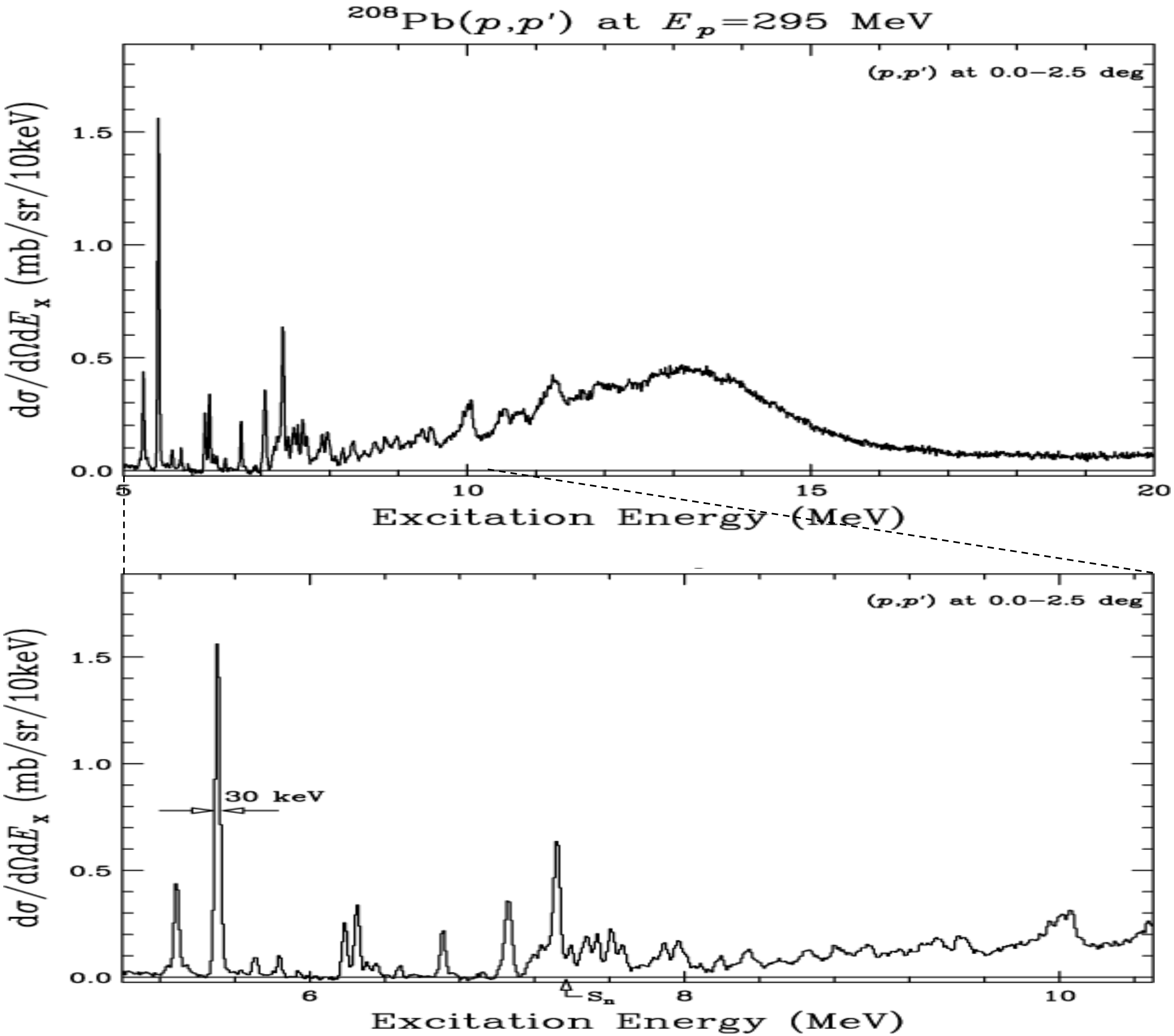
$\theta_b \cong 162°$



D_{LL} Measurement

$\theta_b \cong 180°$

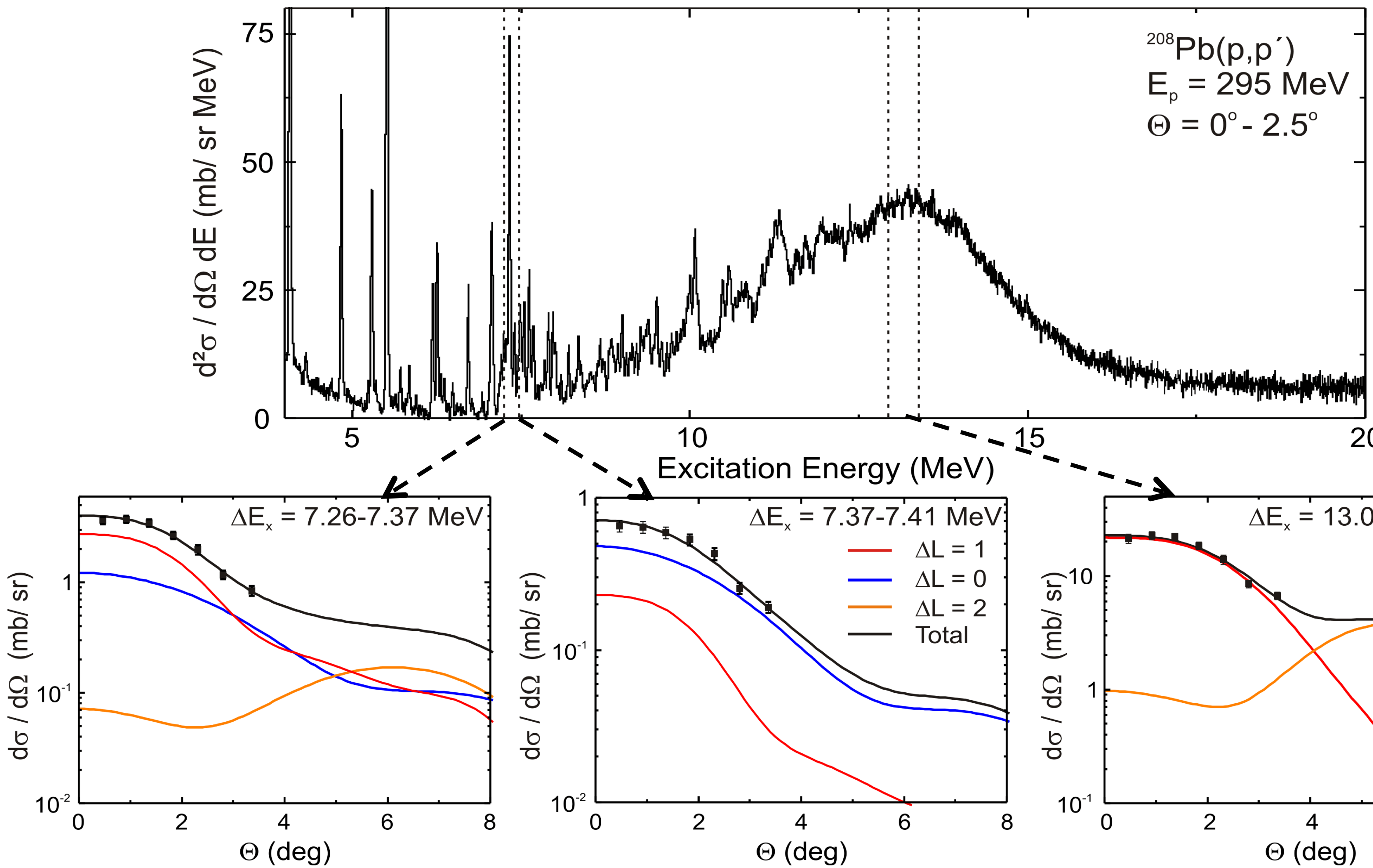
Setup for E282&E316



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

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

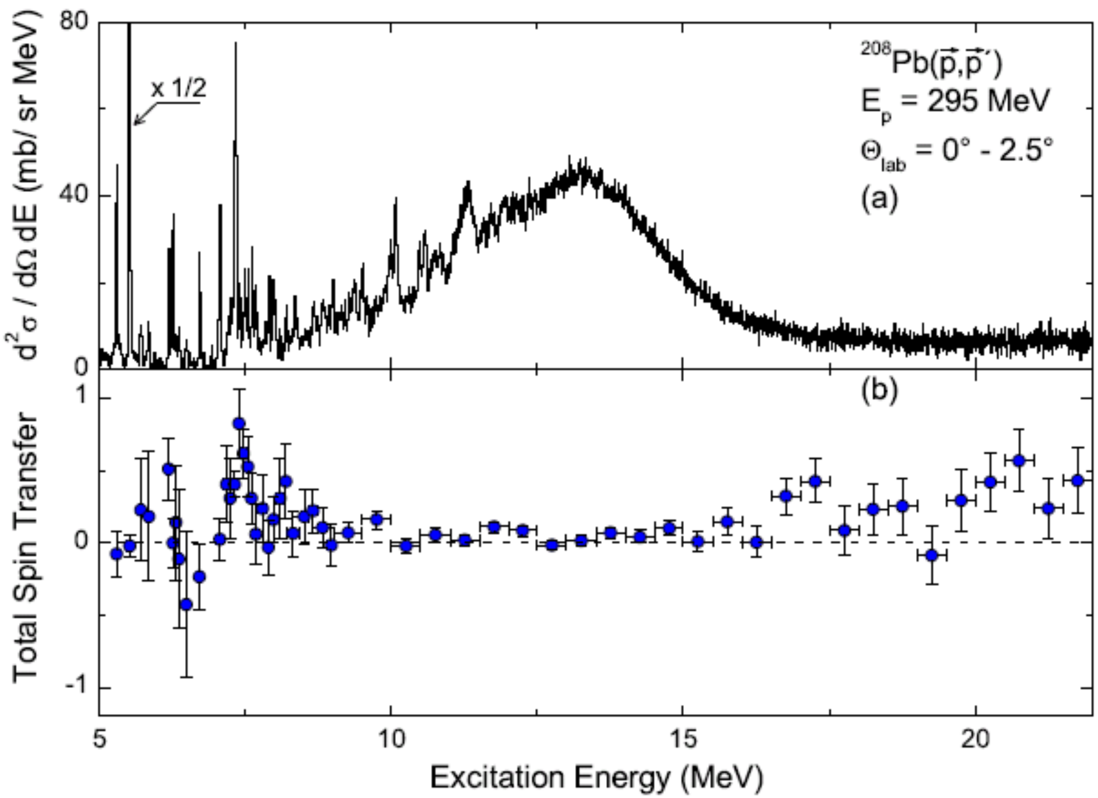
- Polarization observables at 0° ➡ spinflip / non-spinflip separation

model-independent

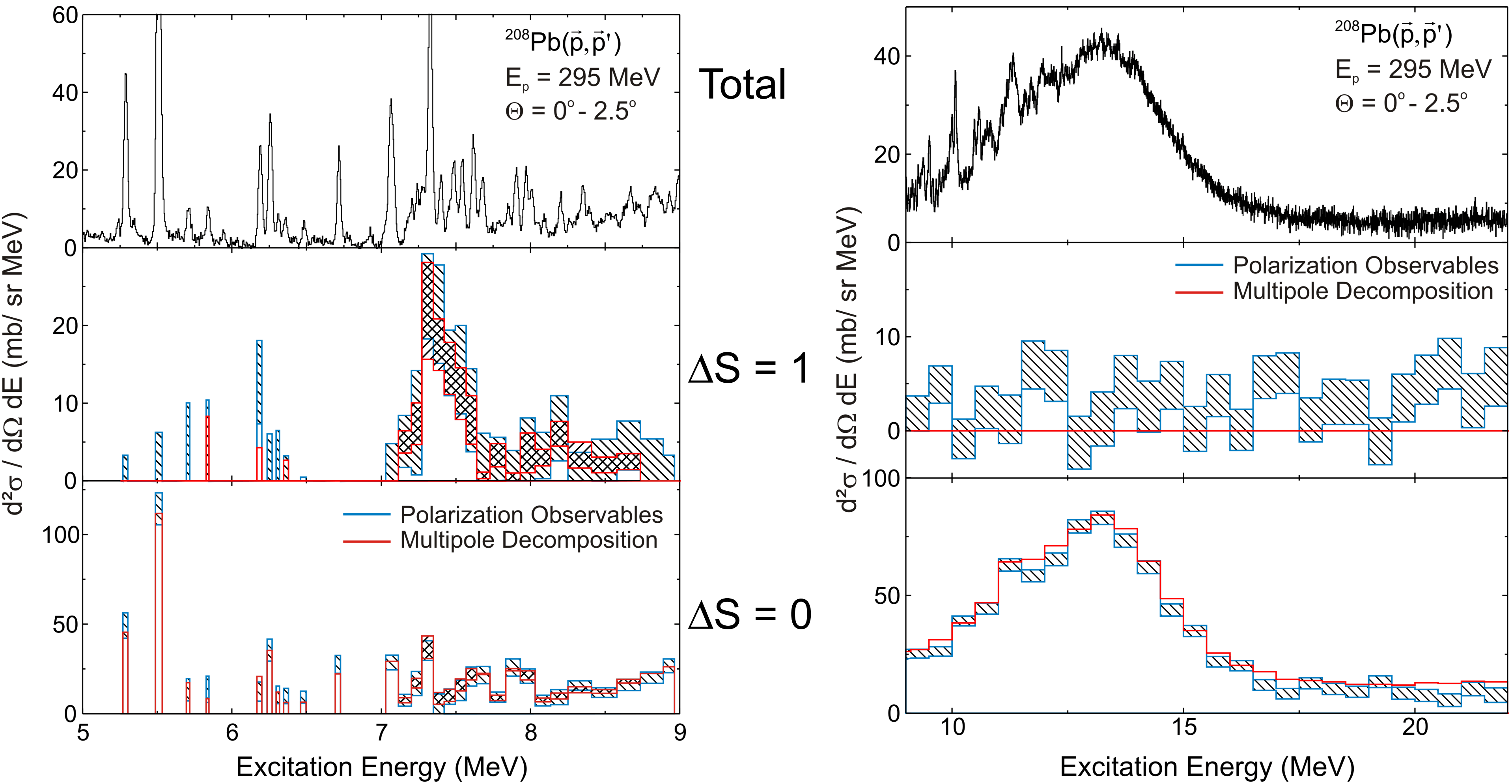
T. Suzuki, PTP 103 (2000) 859

E1 / spin-M1 decomposition

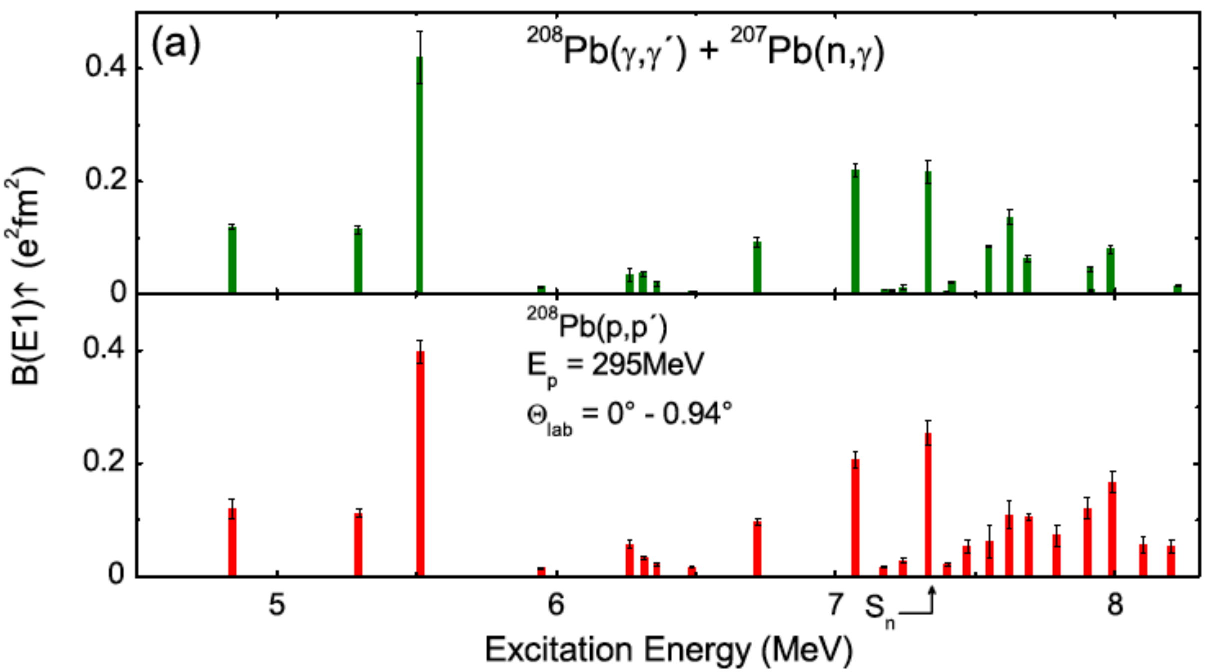
$$\text{Total Spin Transfer } \Sigma \equiv \frac{3-(2D_{SS}+D_{LL})}{4} = \begin{cases} 1 \text{ for } \Delta S = 1 & \text{spin-M1} \\ 0 \text{ for } \Delta S = 0 & \text{E1} \end{cases}$$



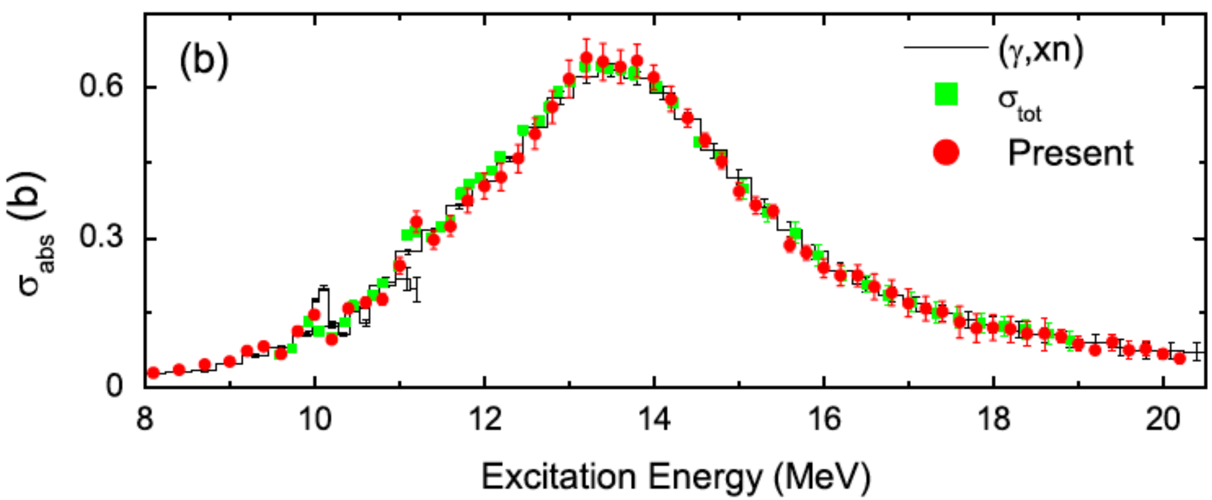
Comparison between the two methods



Comparison with (γ,γ’) and (γ,xn)

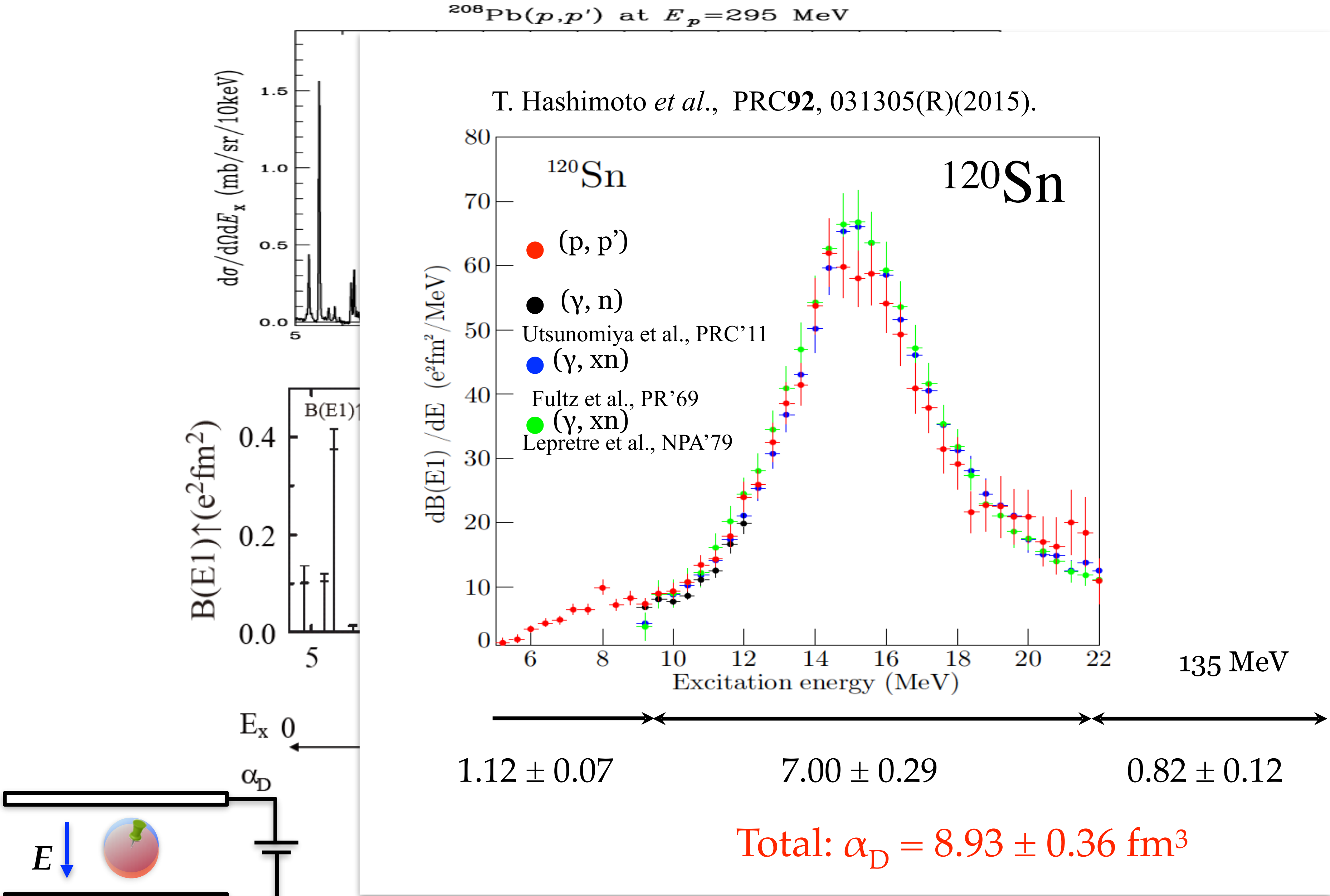


low-lying discrete states



GDR region

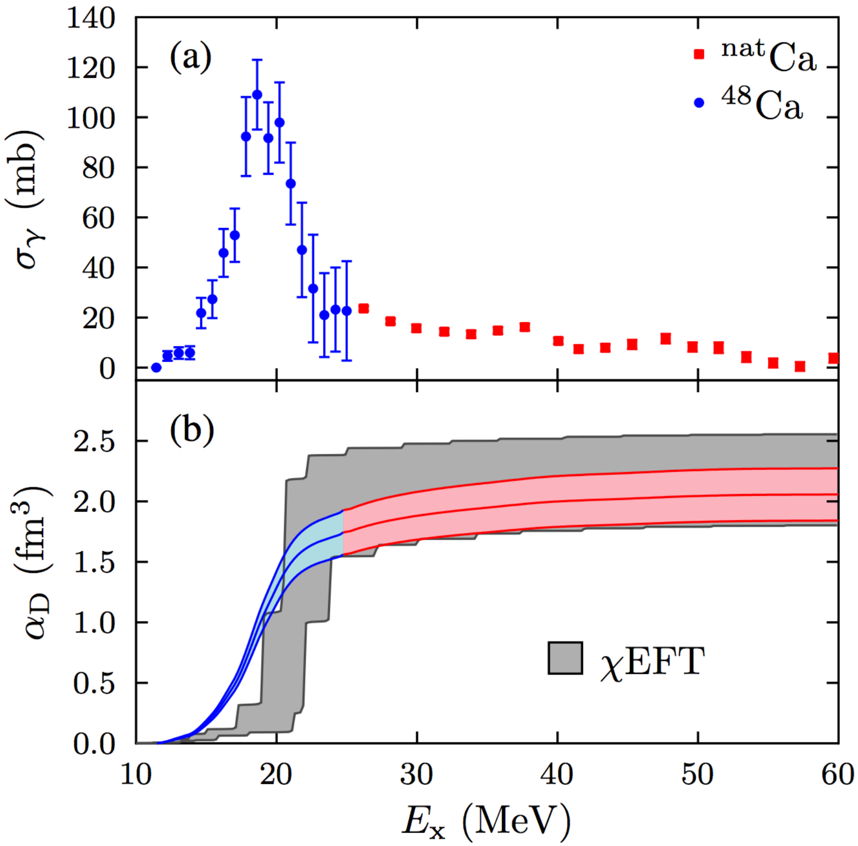
Electric Dipole Polarizability: ^{208}Pb, ^{120}Sn



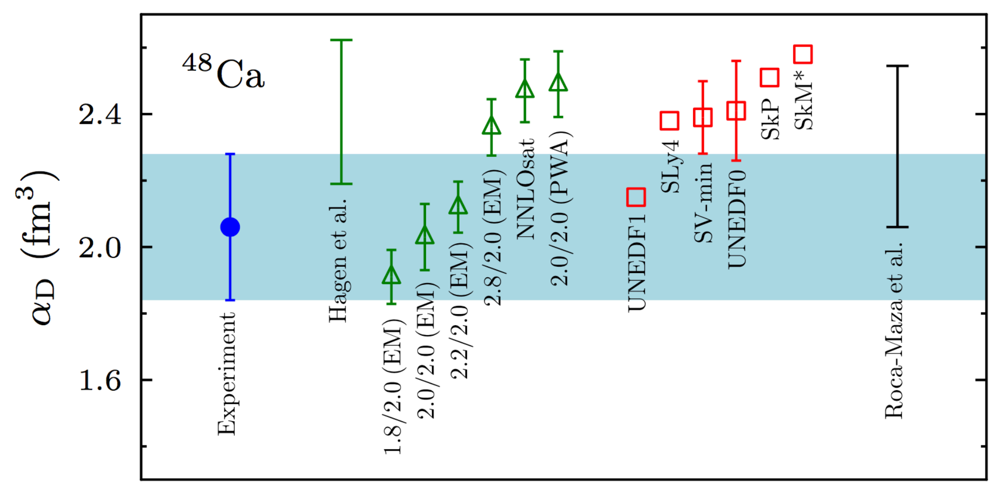
Total: $\alpha_D = 8.93 \pm 0.36$ fm³

Electric Dipole Polarizability of ^{48}Ca

where the EDF and ab-initio calculations meet each other



Theory: Darmstadt-Tennessee-TRIUMF



J. Birkhan et al., PRL118, 252501(2017)

Electric Dipole Polarizability

Clear definition

Unambiguous in the integration ra

↔ Pygmy Dipole Strength

Inversely energy weighted sum-rule

More sensitive to the low-energy st

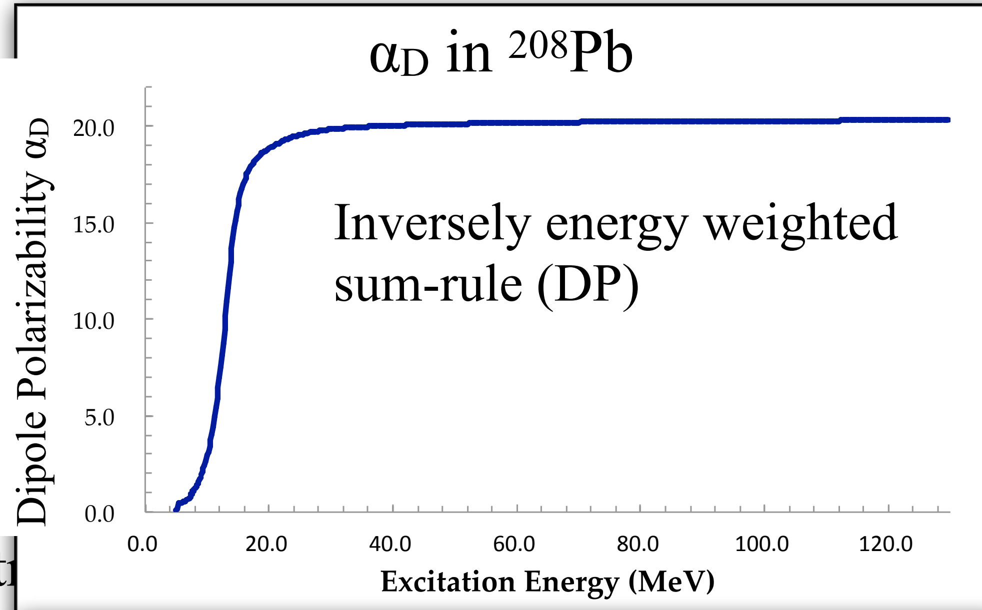
Good convergence in the excitation

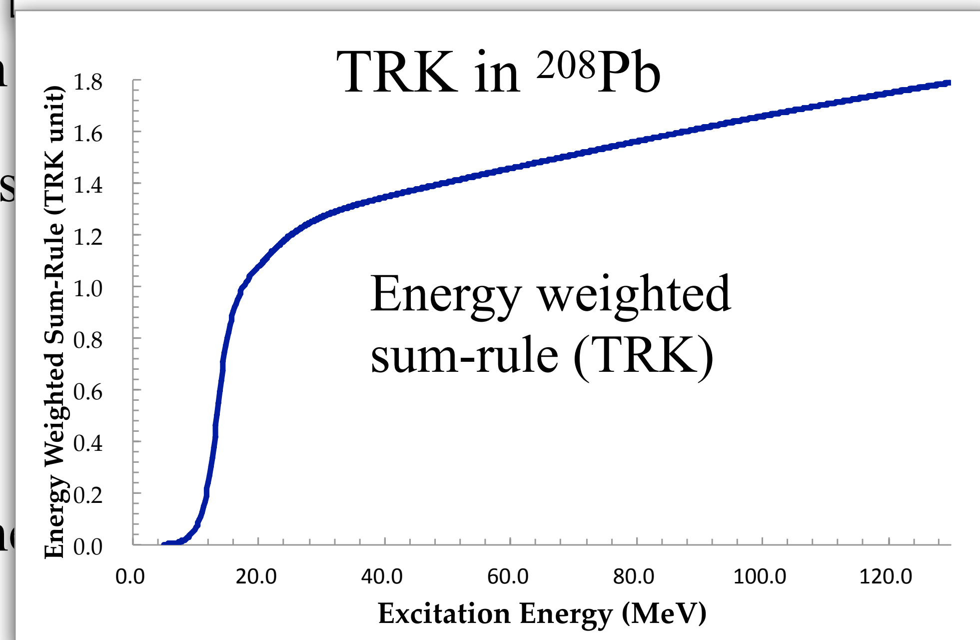
↔ energy-weighted (TRK) s

Sum-rule for all the transitions

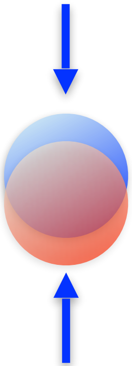
= Ground state property

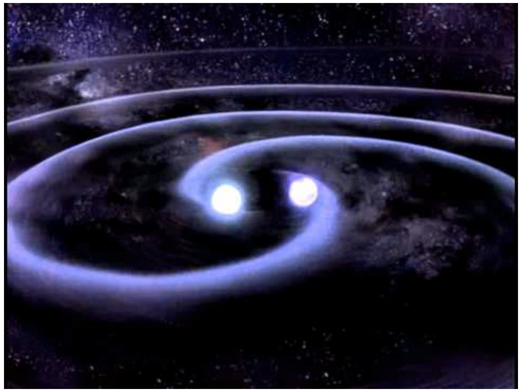
↔ easier comparison with th





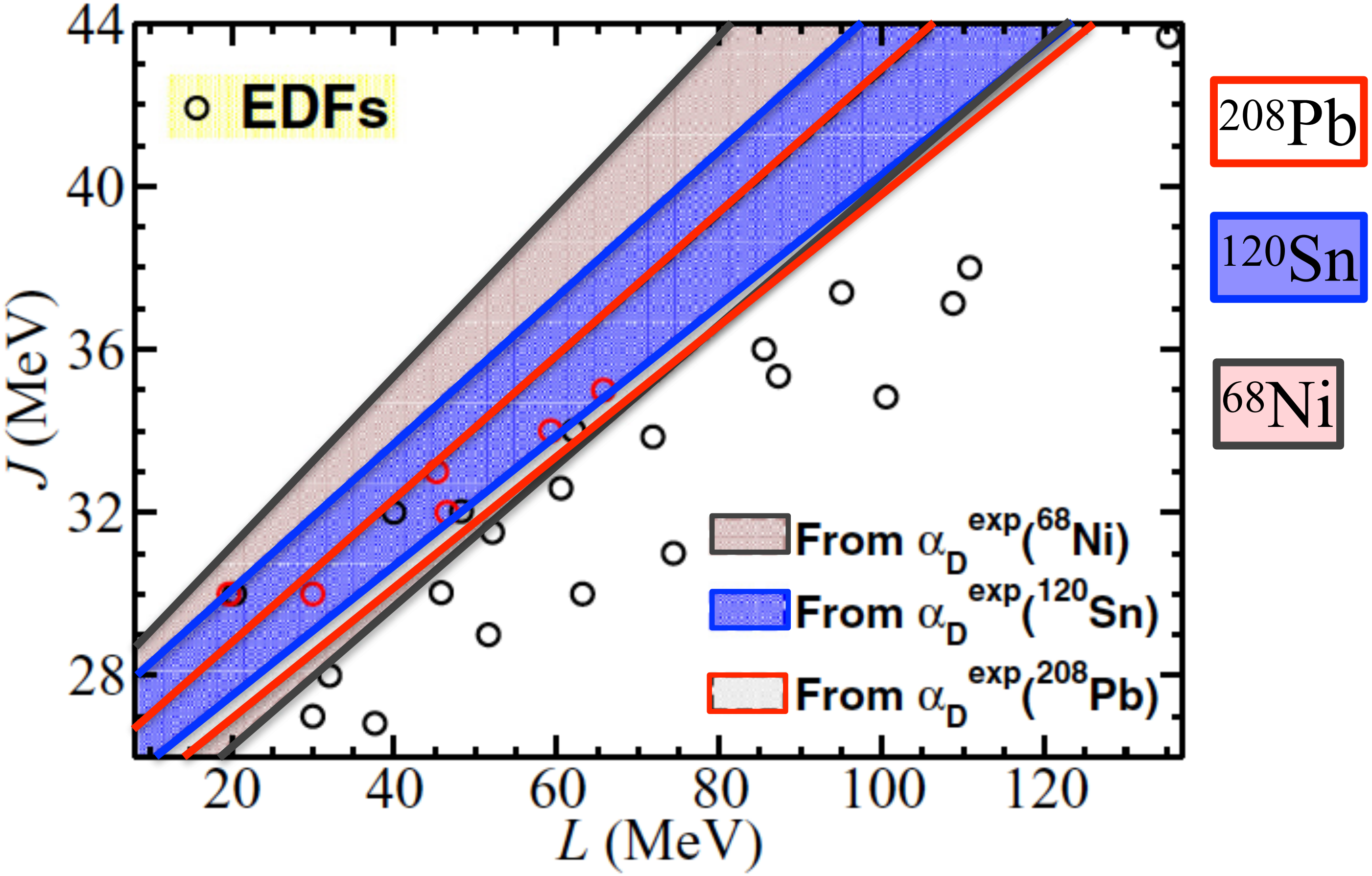
Constraints on the Symmetry Energy





Constraints on *J*-*L* from the EDP data

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

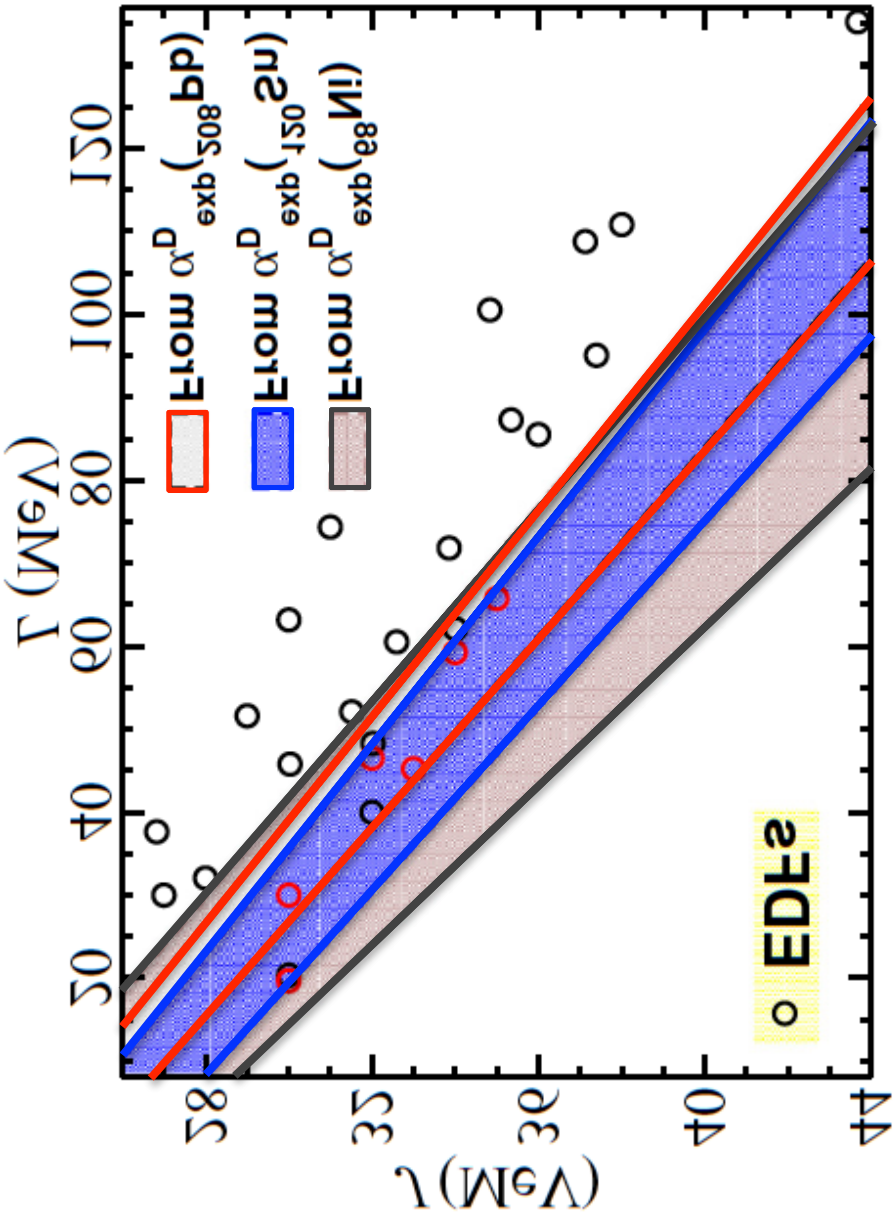


RCNP ^{208}Pb: AT *et al*., PRL**107**, 062502 (2011).

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

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

Constraints on *J*-*L* from the EDP data



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

^{208}Pb

^{120}Sn

^{68}Ni

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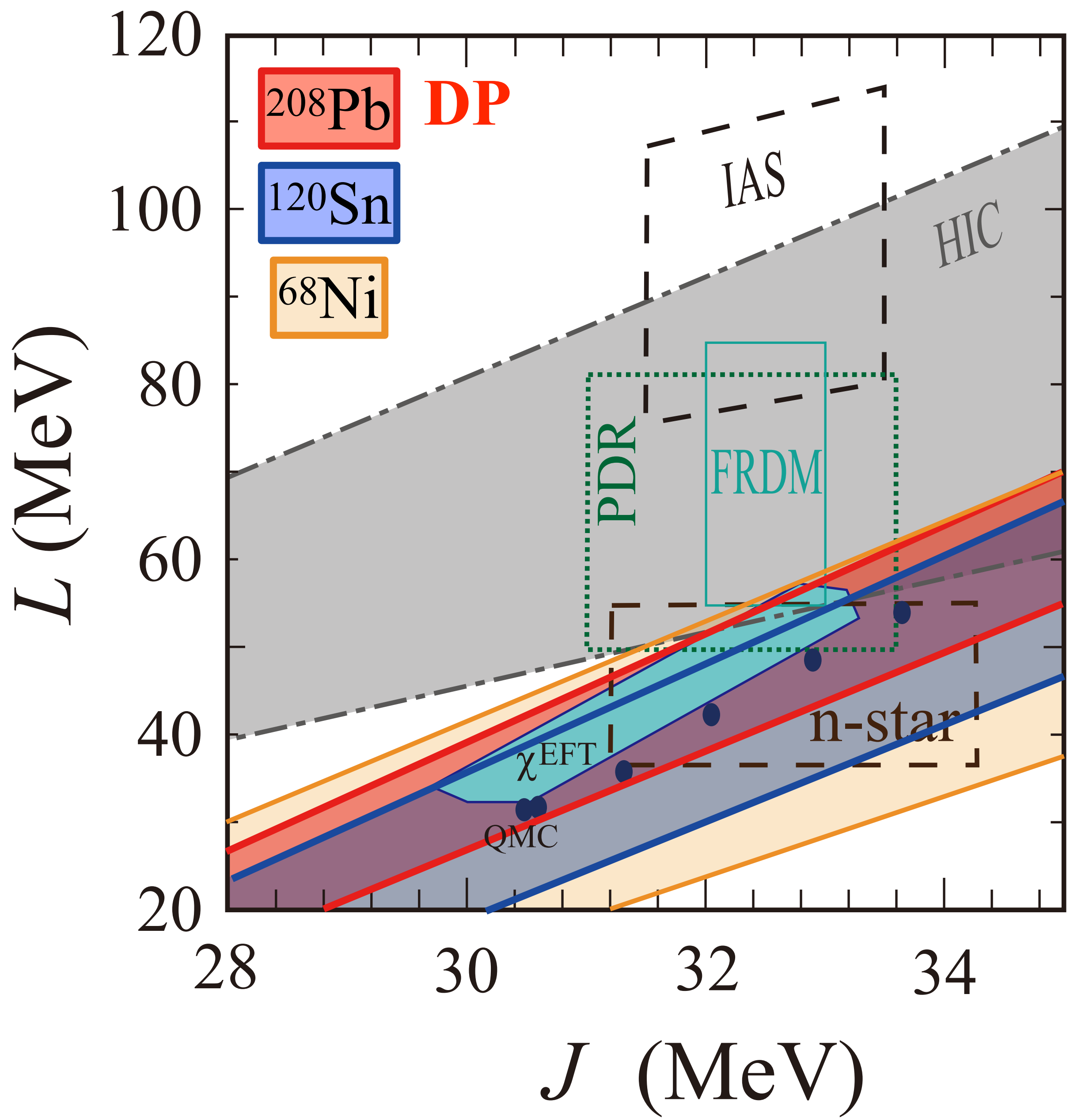
RCNP ^{120}Sn: T. Hashimoto *et al.*, PRC**92**, 031305(R)(2015).

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

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

Constraints on J and L



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Tsang PRL2009

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Gandolfi, EPJA50, 10(2014).

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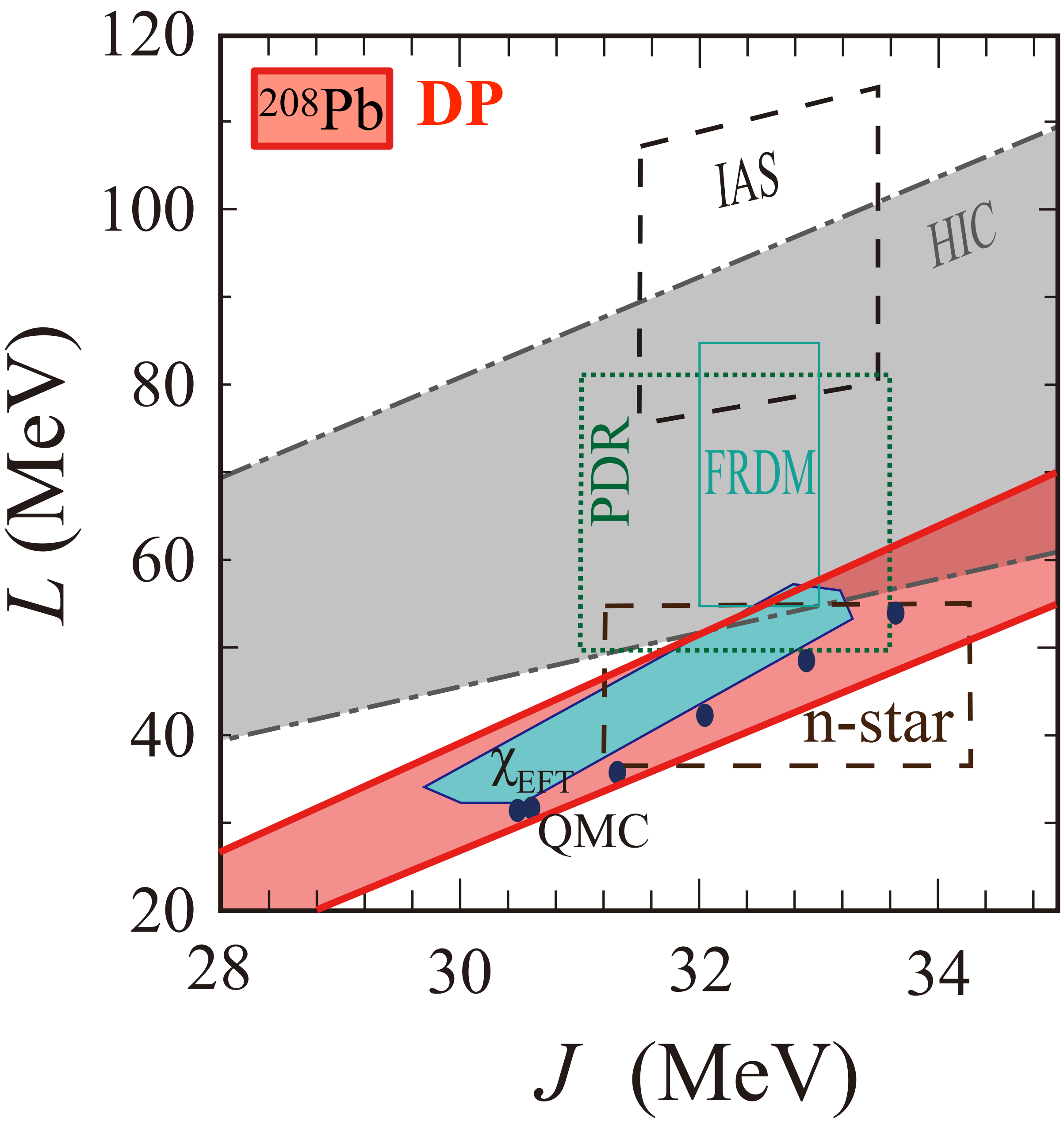
^{208}Pb AT PRL2011
^{120}Sn Hashimoto PRC2015
^{68}Ni Rossi PRL2013

Constraints on *J* and *L*



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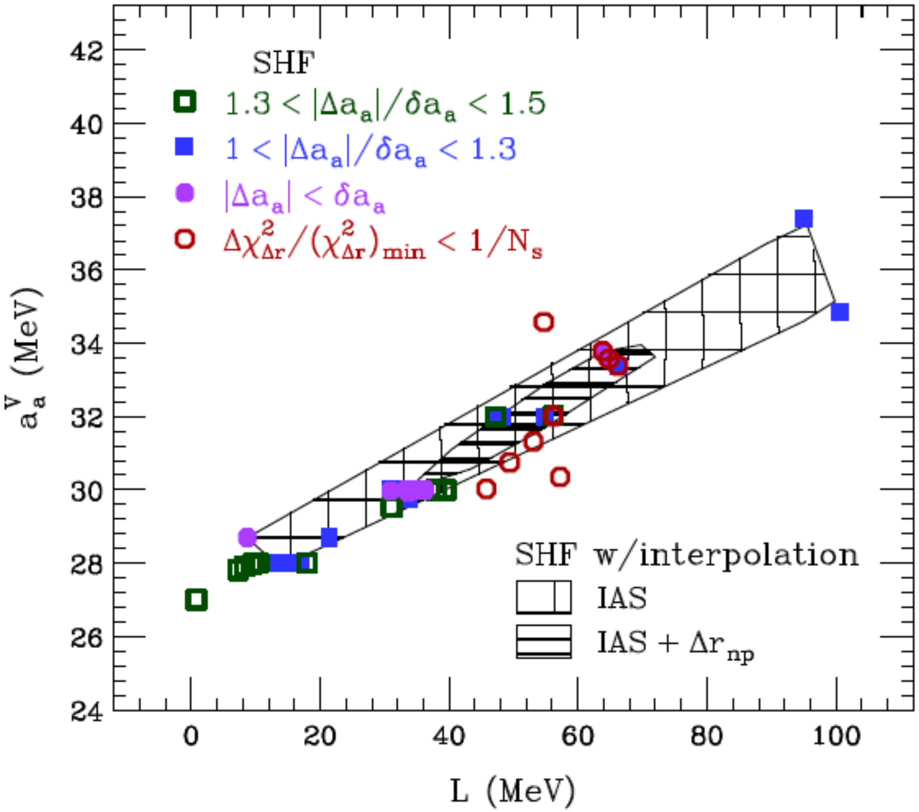
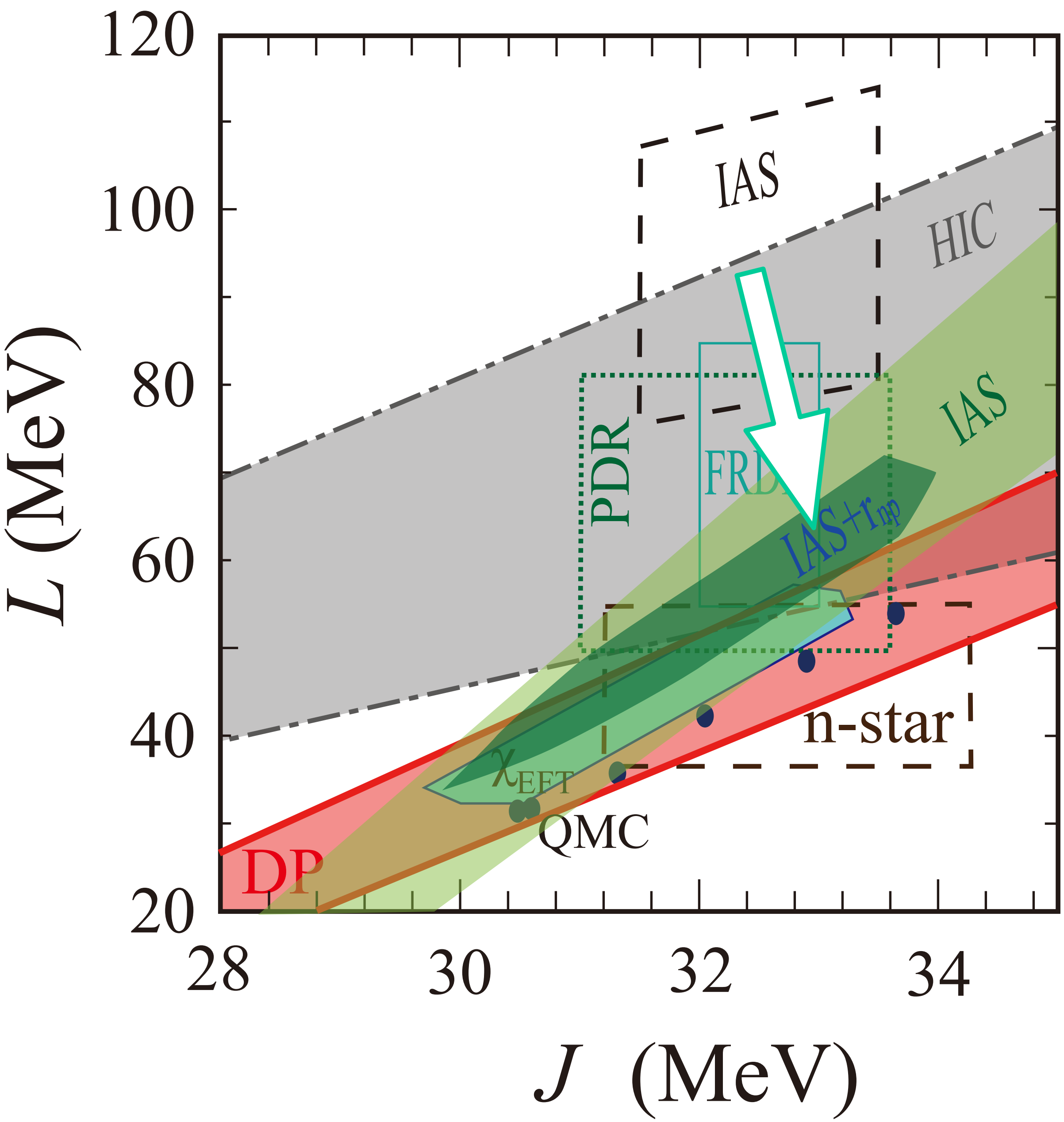


quoted neutron-skin studies

Nucleus	Reference	Data source	Δr_{np} [fm]	Δr_{np}^{GF} [fm]
^{48}Ca	Friedman [93]	pionic atoms	0.13 ± 0.06	
	Gils et al. [94]	elastic α scattering	0.175 ± 0.050	
	Ray [95]	elastic $\vec{p}$ scattering	0.229 ± 0.050	
	Clark et al. [96]	elastic p scattering	0.103 ± 0.040	
	Shlomo et al. [97]	elastic p scattering	0.10 ± 0.03	
	Gibbs et al. [98]	elastic π scattering	0.11 ± 0.04	
		combined results	0.129 ± 0.053*	0.218 ± 0.015
^{50}Ti	Gils et al. [94]	elastic α scattering	0.031 ± 0.040	0.133 ± 0.011
^{64}Ni	Ray [95]	elastic $\vec{p}$ scattering	0.167 ± 0.050	0.102 ± 0.015
^{116}Sn	Ray [95]	elastic $\vec{p}$ scattering	0.146 ± 0.050	0.103 ± 0.015
^{124}Sn	Ray [95]	elastic $\vec{p}$ scattering	0.252 ± 0.050	0.184 ± 0.021
^{204}Pb	Zenihiro et al. [99]	elastic p scattering	0.178 ± 0.059	0.161 ± 0.024
^{206}Pb	Zenihiro et al. [99]	elastic p scattering	0.180 ± 0.064	
	Starodubsky et al. [100]	elastic p scattering	0.181 ± 0.045	
		combined results	0.181 ± 0.037	0.172 ± 0.024
^{207}Pb	Starodubsky et al. [100]	elastic p scattering	0.186 ± 0.041	0.178 ± 0.024
^{208}Pb	Starodubsky et al. [100]	elastic p scattering	0.197 ± 0.042	
	Ray [95]	elastic $\vec{p}$ scattering	0.16 ± 0.05	
	Clark et al. [96]	elastic p scattering	0.119 ± 0.045	
	Zenihiro et al. [99]	elastic p scattering	0.211 ± 0.063	
	Friedman [93]	elastic π^+ scattering	0.11 ± 0.06	
	Friedman [93]	pionic atoms	0.15 ± 0.08	
		combined results	0.159 ± 0.041*	0.179 ± 0.023

any average effects of asymmetry on the reactions competing with a variety of physical effects subject to modeling uncertainties. In this paper we attempt to learn about the average effects of neutron–proton asymmetry on nuclear energies, exploiting excitation energies to isobaric analog states and to reach the conclusions in as model-independent manner as possible. Our early efforts in this direction have been reported in [1–3]. As we progress, we find that we need to reassess our strategy.

Constraints on *J* and *L*



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^{208}Pb AT PRL2011

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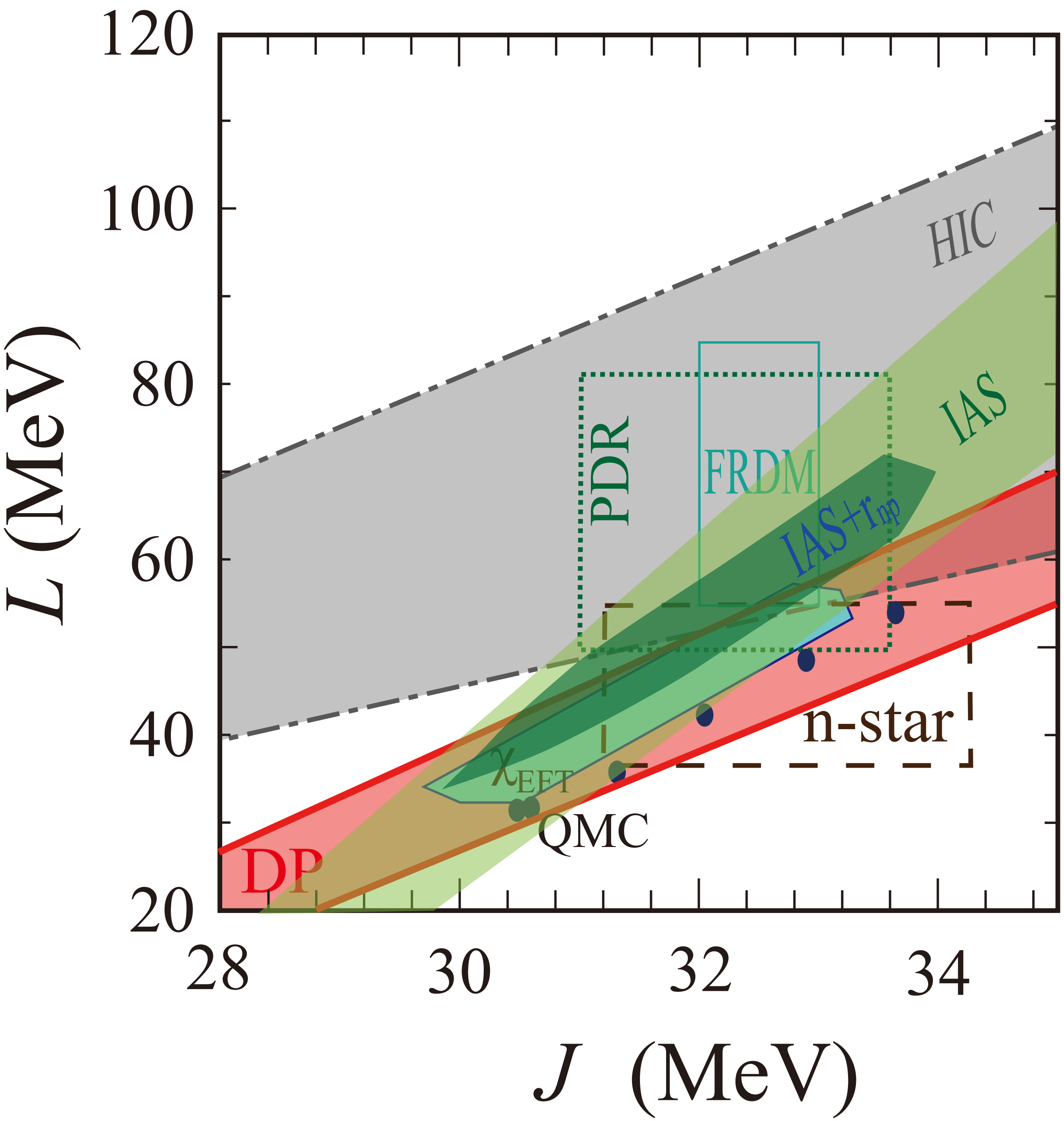

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LA-UR-16-26401 Sagawa and Moller

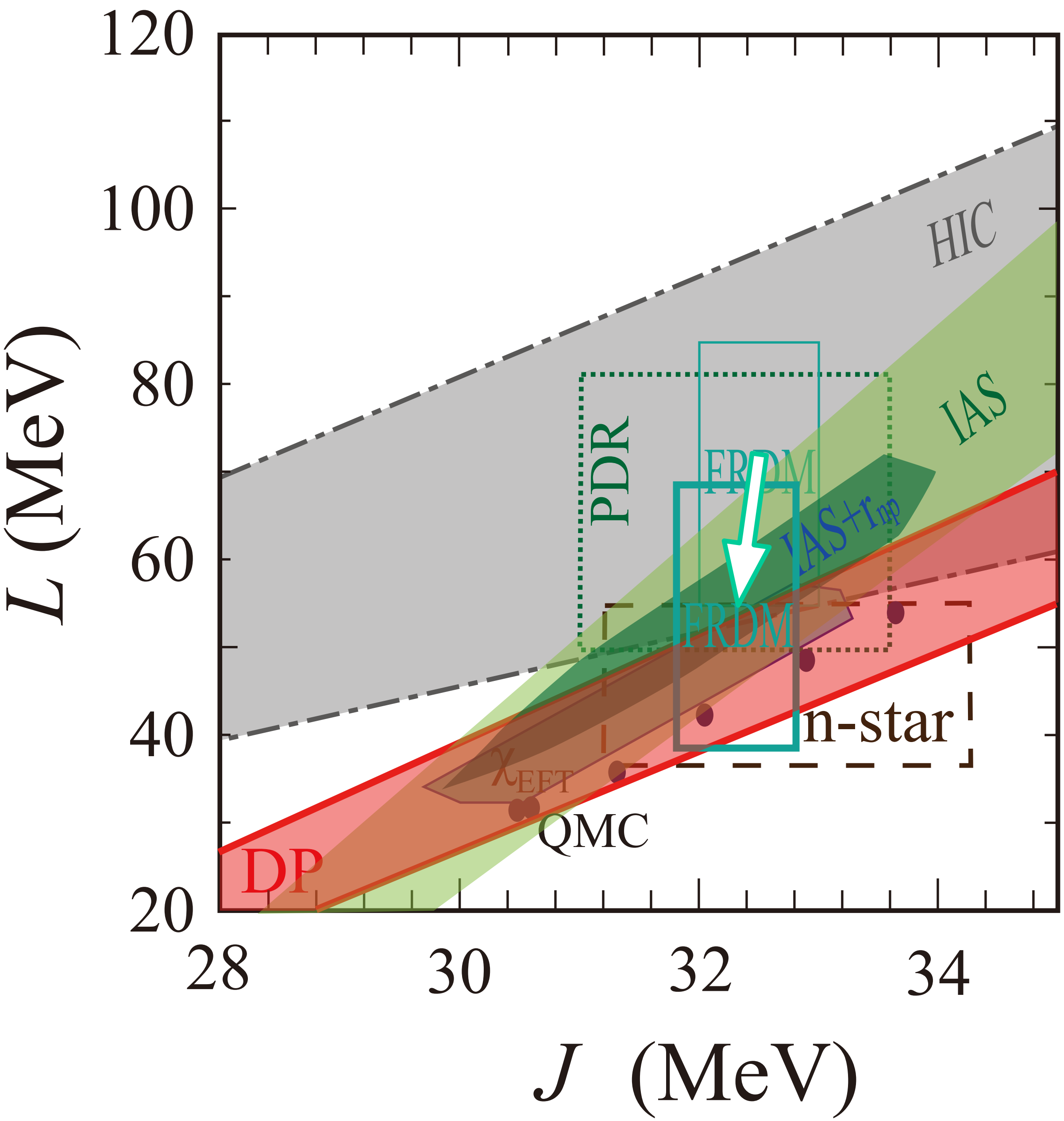
The optimal values of the asymmetry variables J and L that we obtained from the mass model FRDM (2012) study are

$$J = 32.3 \pm 0.5 \text{ MeV}$$
$$L = 53.5 \pm 15 \text{ MeV}$$

with the minimum rms deviation of σ <560 keV as shown in Fig. 2. The above optimal L value is somewhat smaller than the value in Ref. [3], because we have implemented a more accurate calculation of the zero-point fluctuation effect, see [2] for more details.

FRDM: Finite Range Droplet Model
Moeller ADNTD2016

Constraints on *J* and *L*



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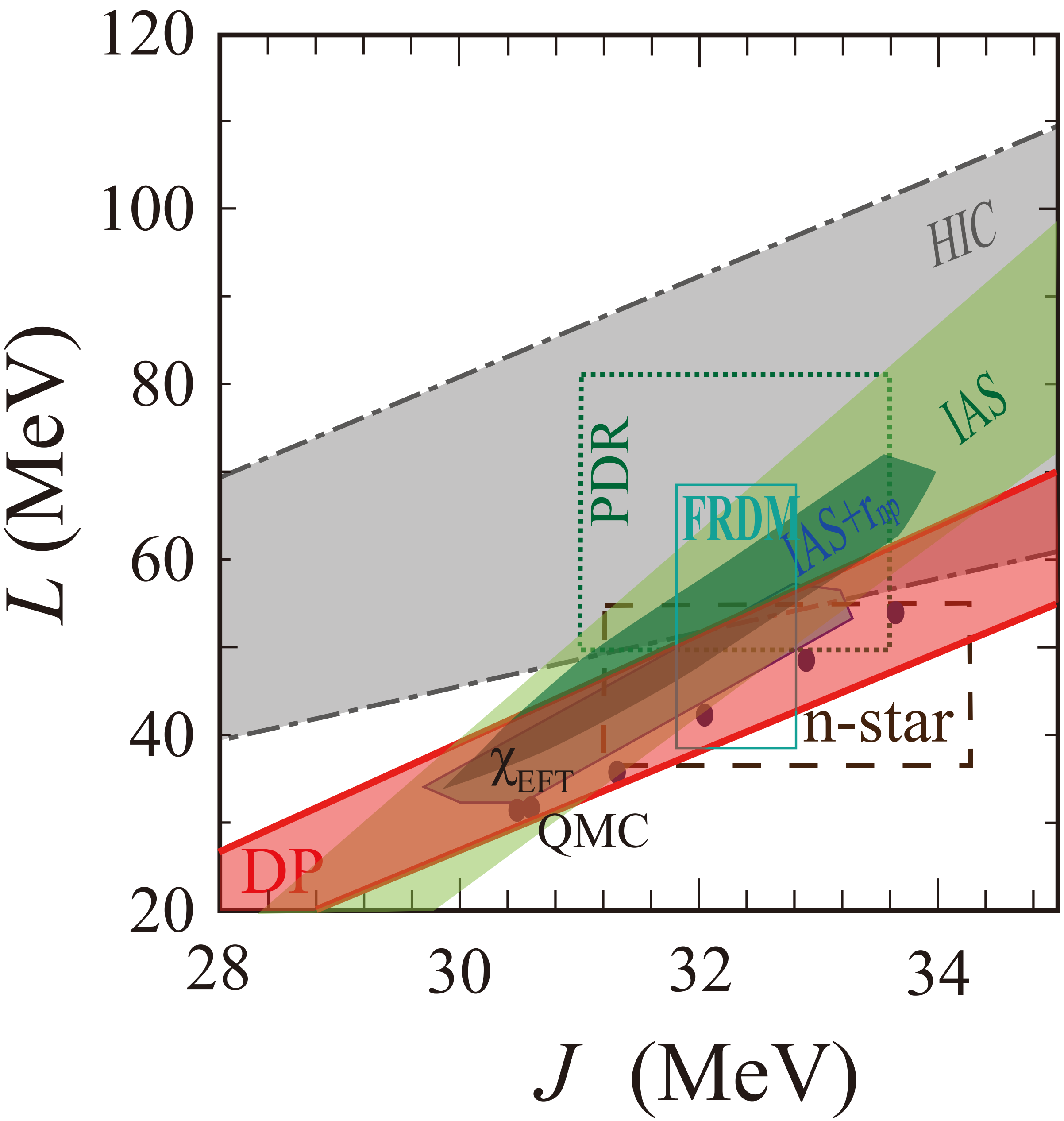
Constraints on J and L



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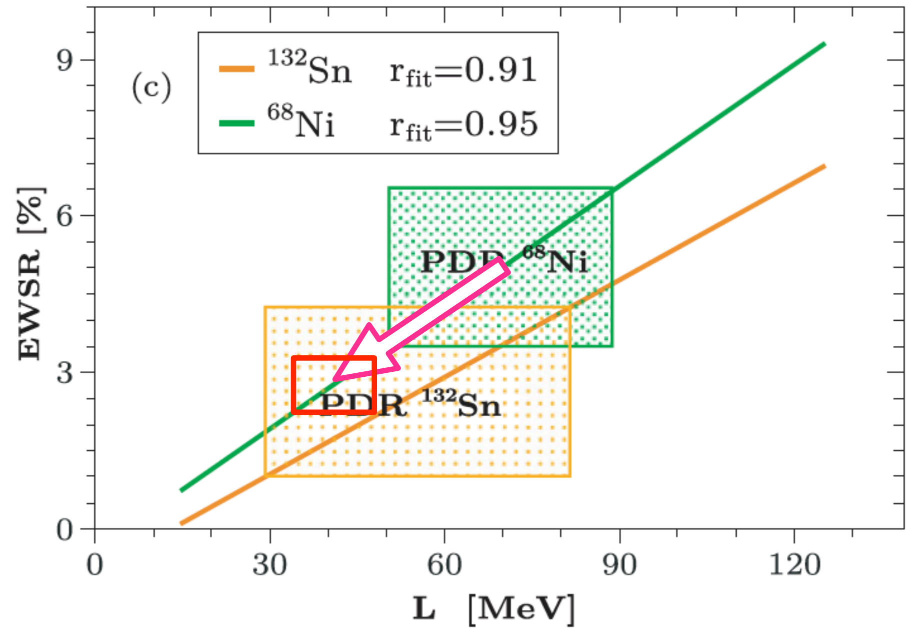
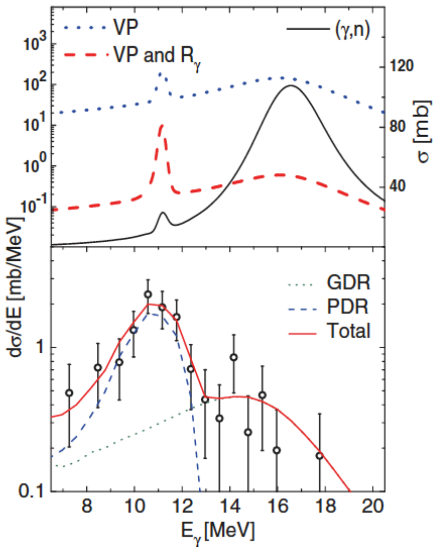


Wieland: PRL2009

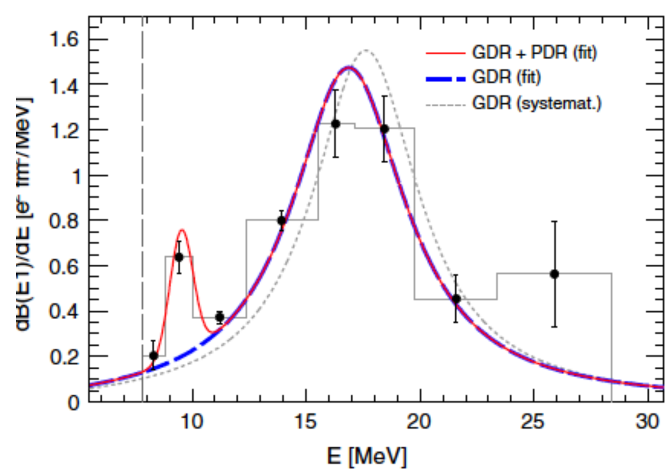
In summary, we have here presented the first experimental search of a pygmy resonance in the neutron-rich ^{68}Ni nucleus using the virtual photon scattering technique. Evidence is found for the presence of sizeable strength energetically located below the GDR and centered at ≈11 MeV with approximately 5% of the EWSR strength.



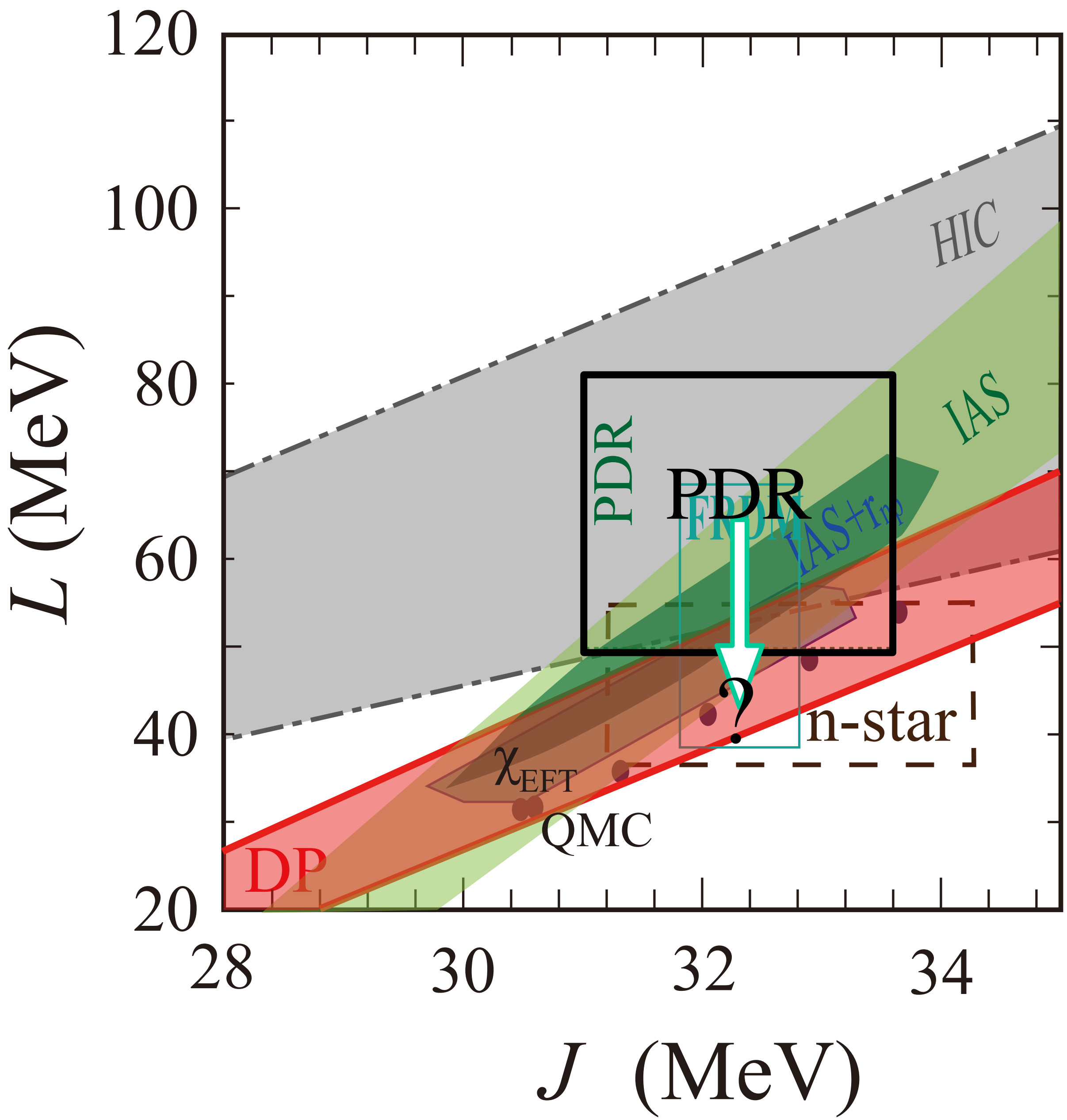
Rossi: PRL2013

TABLE I. GDR and PDR parameters for ^{68}Ni from fit to $E1$ strength, as shown in Fig. 3. Included as well are the GDR and PDR parameters from the literature.

			This work	Literature	Reference
GDR	E_m	[MeV]	17.1(2)	17.84	[30]
	Γ	[MeV]	6.1(5)	5.69	[30]
	S_{EWSR}	[%]	98(7)	100	
PDR	E_m	[MeV]	9.55(17)	11.0(5)	[25,31]
	σ	[MeV]	0.51(13)	<1	[25]
	S_{EWSR}	[%]	2.8(5)	5.0(1.5)	[13,25]



Constraints on J and L



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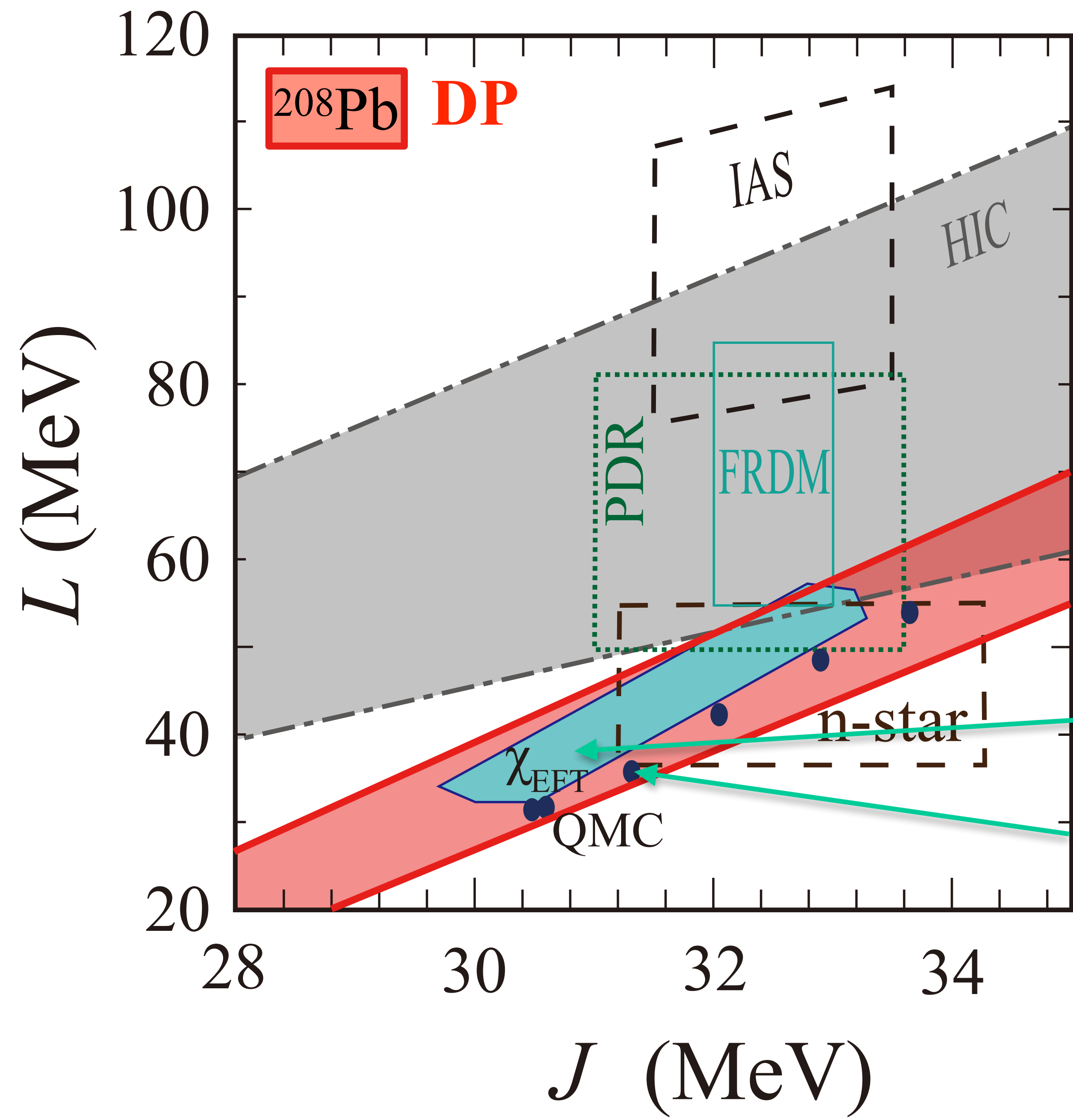

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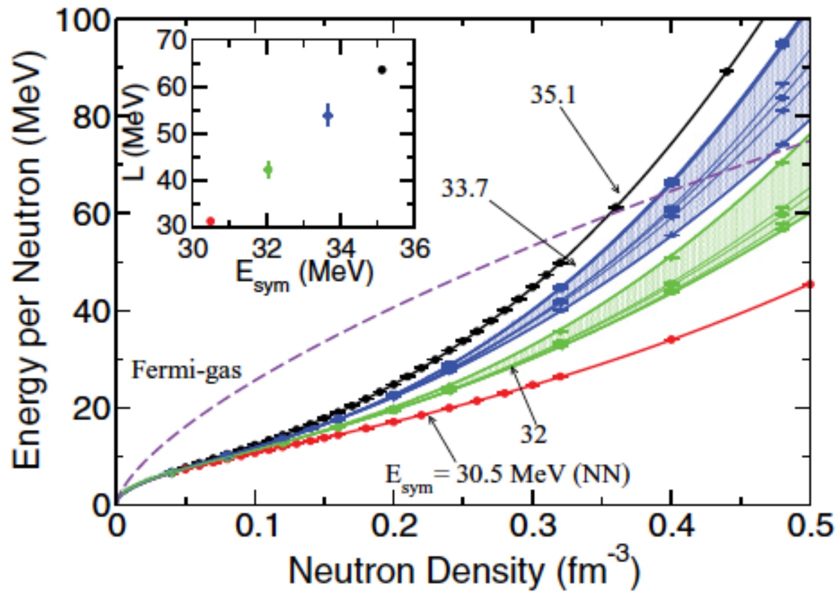
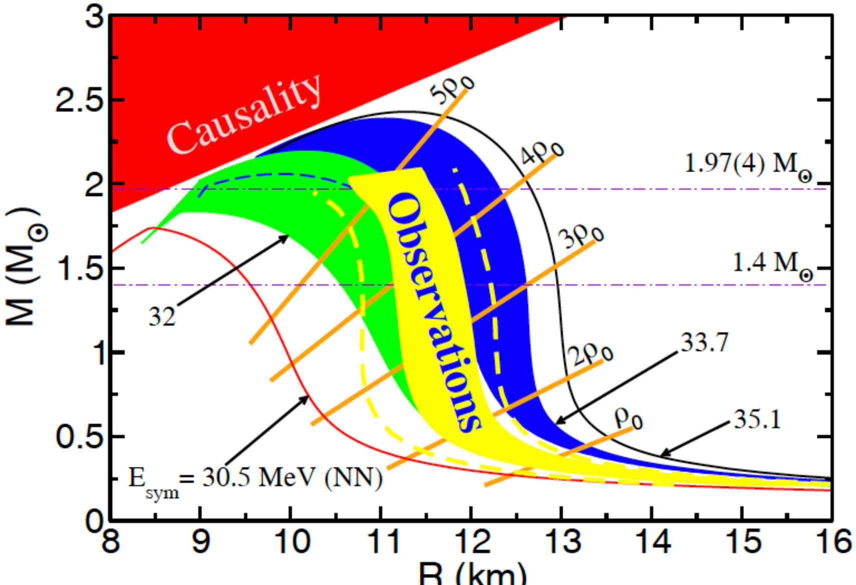
QMC

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

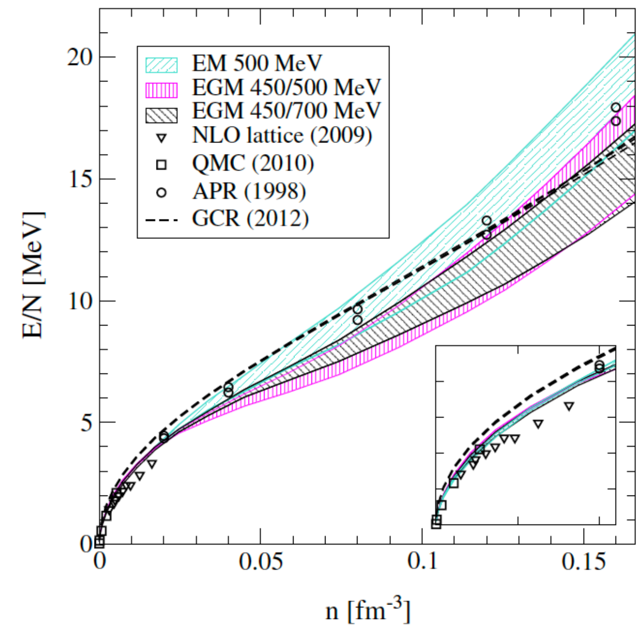


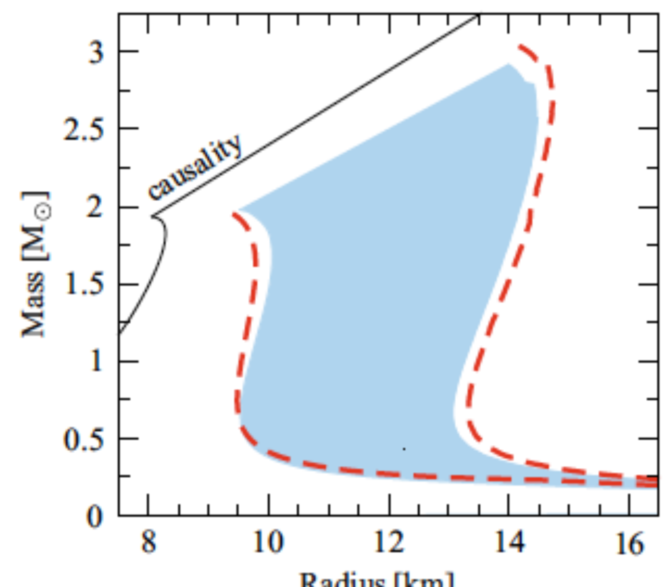


χEFT

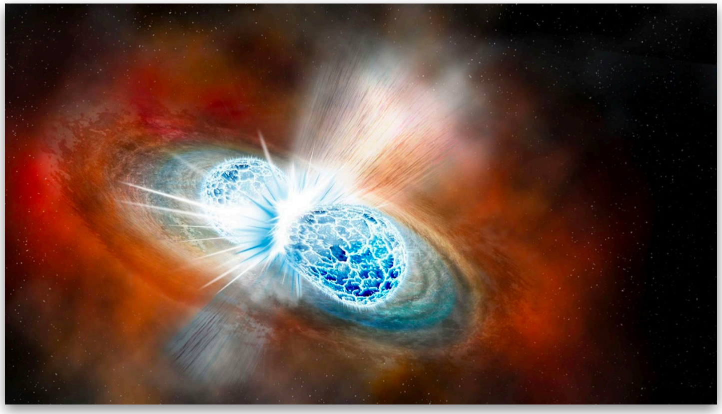
I. Tews, K. Hebeler et al., PRL110, 032504(2013)

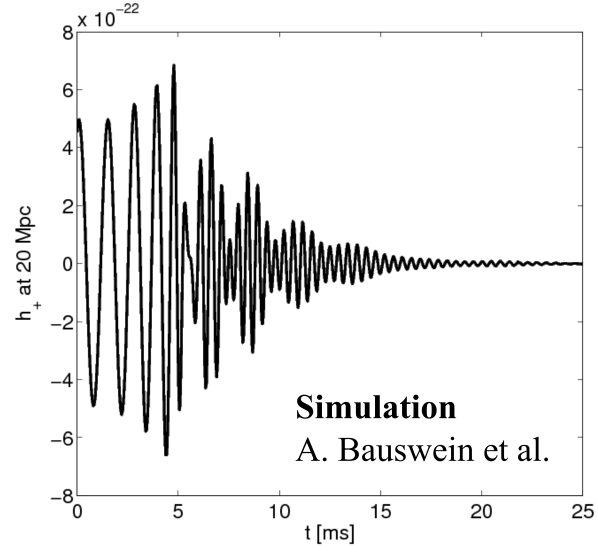
K. Hebeler et al., et al., EPJA50, 11 (2014)





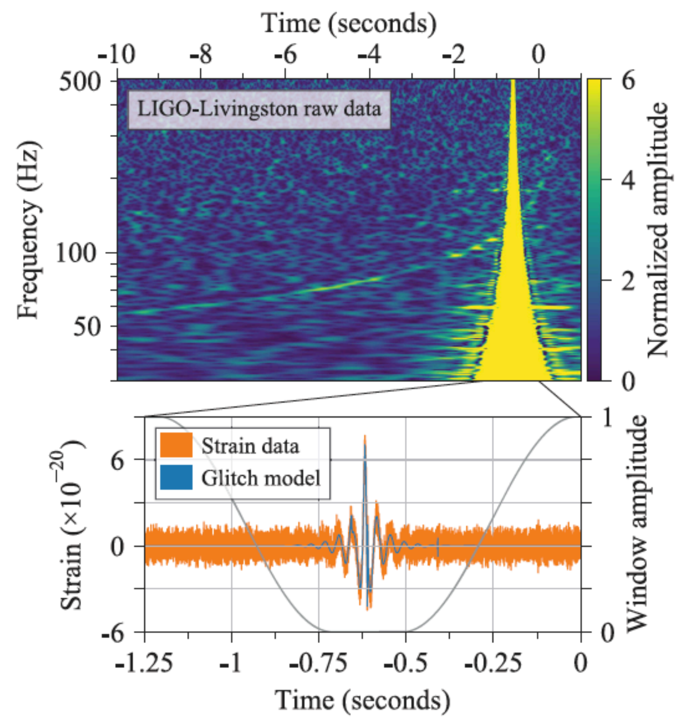
Neutron Star Merger GW170817





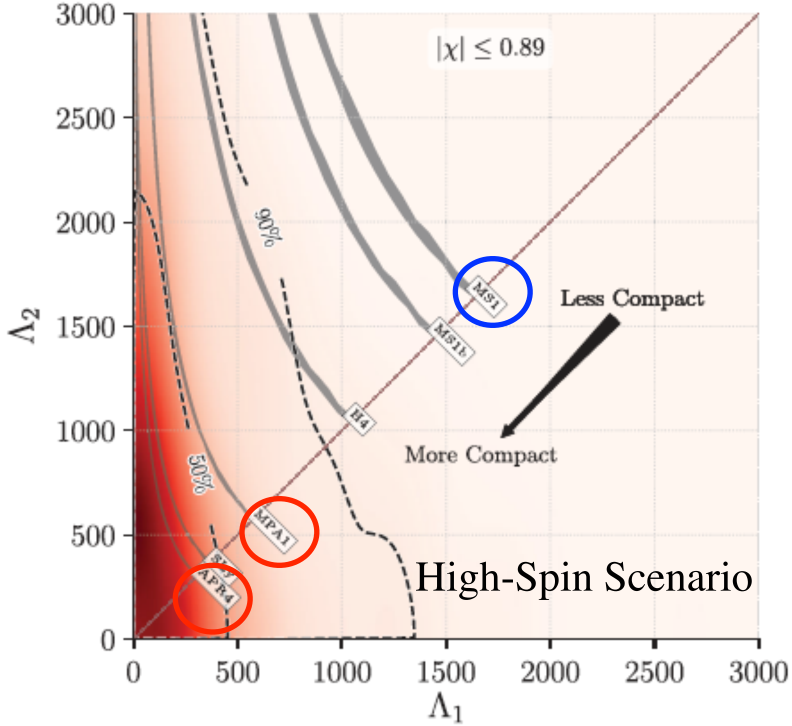
GW170817
PRL119, 161101(2017)

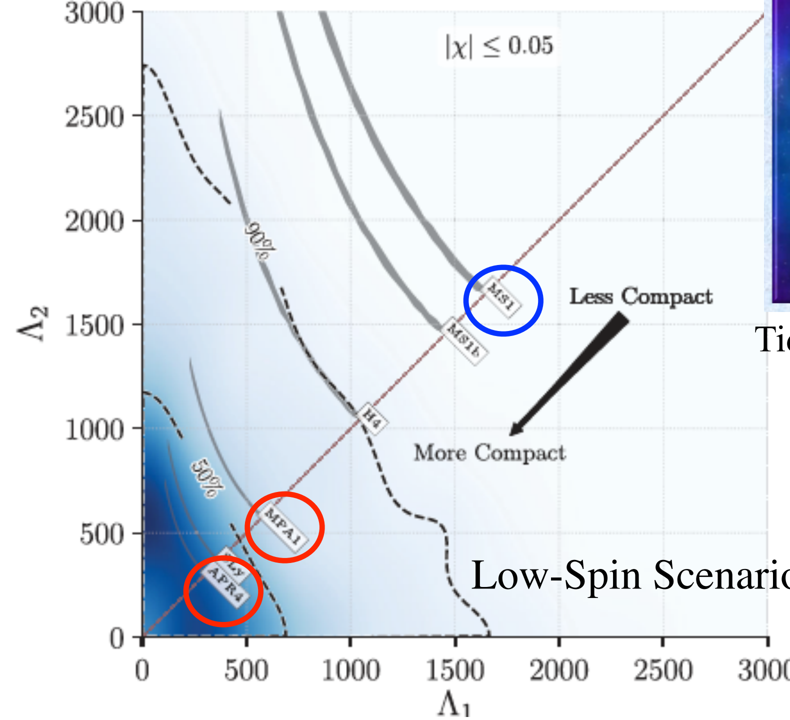
LIGO



Constraints from the N-Star Merger GW

PRL119, 161101(2017)





Tidal Deformatio

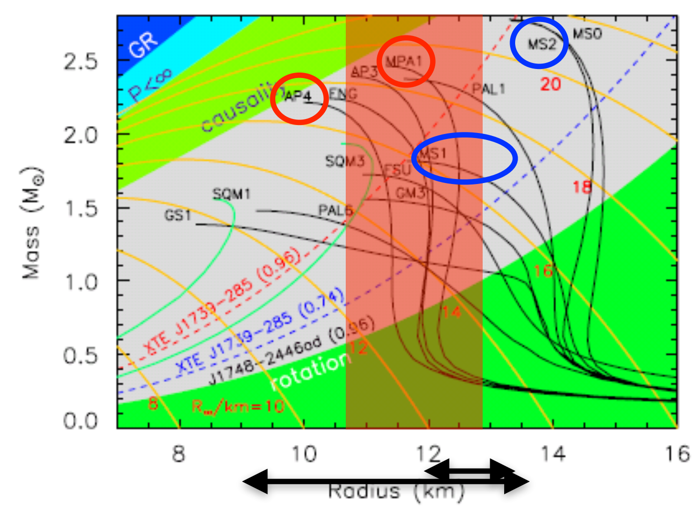
Tidal Deformation Parameters

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

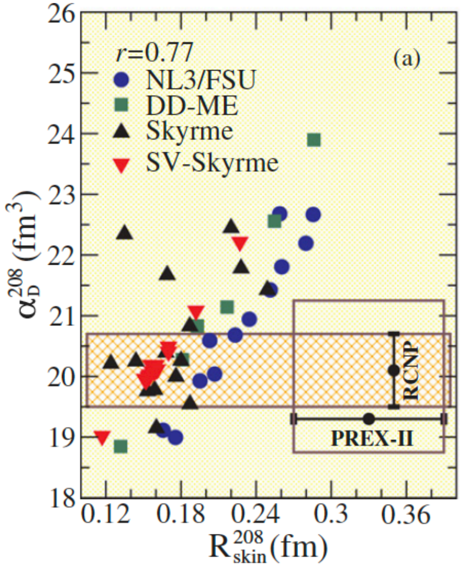
$R^{1.4} < 13.76$ km F.J. Fattoyev et al., PRL120, 172702(2018)

$12.00 < R^{1.4} < 13.45$ 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

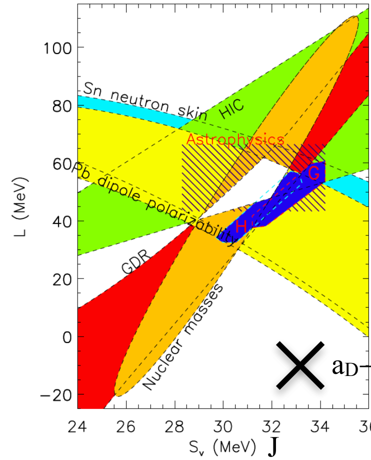


N-star merger GW analysis is giving constraints on the nuclear EOS that are consistent with the study of atomic nuclei.



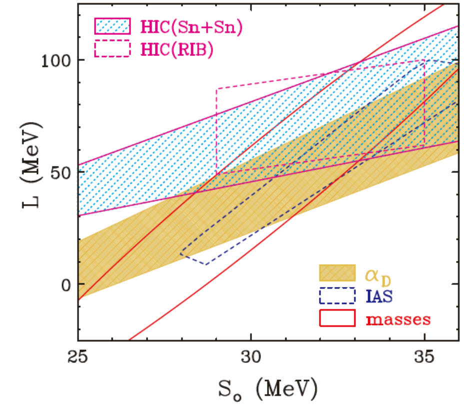
C.J. Horowitz et al., JPG41, 093001(2014)

※PREX-II
in preparation for exp.



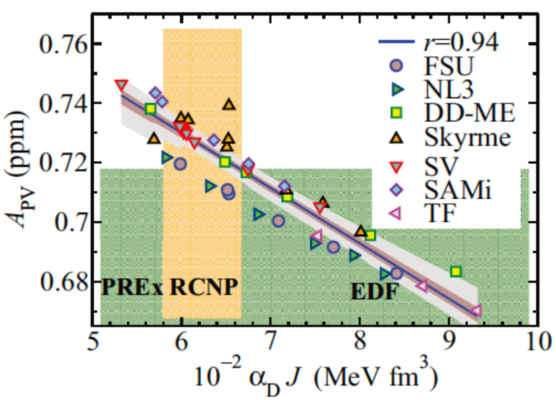
× $a_D \rightarrow \delta R_{np} \rightarrow$ J-L

Lattimer and Lim, AJ771, 51(2013)



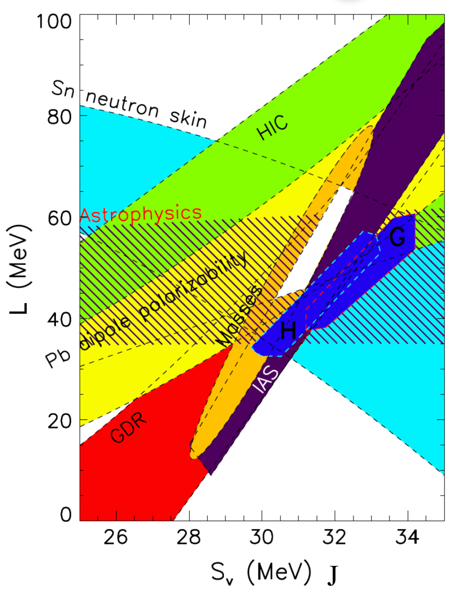
C.J. Horowitz et al., JPG41, 093001(2014)

○ $a_D \rightarrow$ J-L

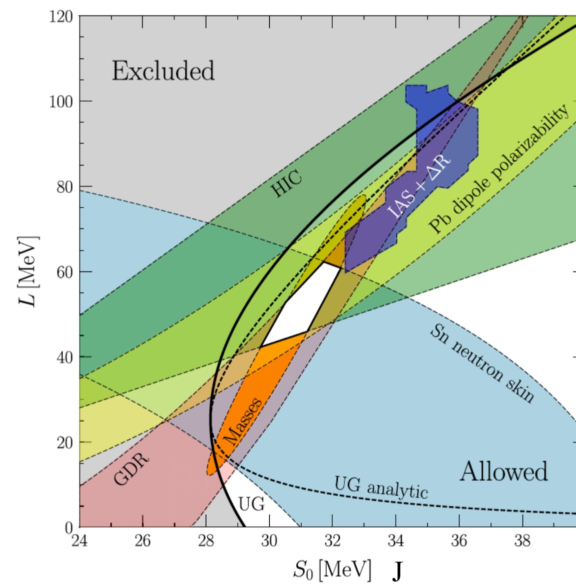


Roca-Maza et al, PRC88, 024316(2013)

PREX: $A_{PV} = 0.656 \pm (0.060)_{stat} \pm (0.014)_{syst}$ ppm.



Lattimer and Steiner, EPJA50, 40(2014)
Lattimer, GenRelativGravit 46, 1713(2014)
Roca-Maza and Paar, PPNP101, 96(2018)



Tew, Lattimer, Ohnishi,
Kolomeitsev, ApJ848, 105(2017)

Publications from Proton Inelastic Scattering Project

- **Electric Dipole Polarizability and the Symmetry Energy**
  J. Birkhan et al., Physical Review Letters **118**, 252501 (2017).
  T. Hashimoto et al., Physical Review C **92**, 031305 (2015).
  A. Tamii et al., Butsuri **69**, 6 (2014).
  A. Tamii et al., European Physical Journal A **50**, 28 (2014).
  A. Tamii et al., Physical Review Letters **107**, 062502 (2011).

- Pygmy Dipole Resonance
  A. M. Krumbholz et al., Physics Letters B **744**, 7 (2015).
  C. Iwamoto et al., Physical Review Letters **108**, 262501 (2012).
  I. Poltoratska et al., Physical Review C **85**, 041304 (2012).

- Spin-M1 Strengths
  M. Mathy et al., Physical Review C **95**, 044616 (2017)
  J. Birkhan et al., Physical Review C **93**, 041302 (2016).
  H. Matsubara et al., Physical Review Letters **115**, 102501 (2015).

- Gamma Strength Function and Nuclear Level Densities
  D. Martin et al., Physical Review Letters **119**, 182503 (2017).
  R. W. Fearick et al., Physical Review C **97**, 044325 (2018).
  S. Bassauer et al., Physical Review C **94**, 054313 (2016).
  I. Poltoratska et al., Physical Review C **89**, 054322 (2014).

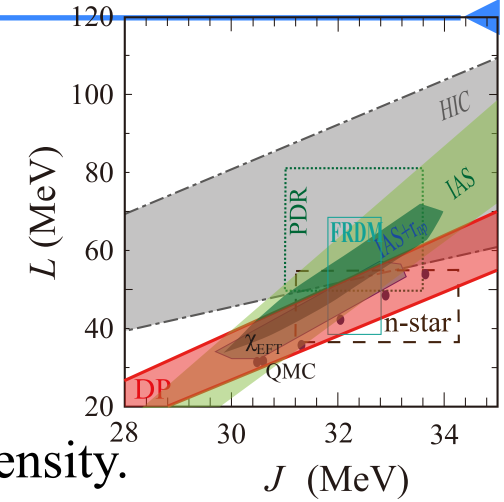
- Technical Development
  H. Matsubara et al., Nucl. Inst. Meth. A **678**, 122 (2012).
  H. Matsubara et al., Nucl. Inst. Meth. B **267**, 3682 (2009).
  A. Tamii et al., Nucl. Inst. Meth. A **605**, 326 (2009).

- Gamma Decay Coincidence
  M.S. Reen et al., submitted to PRC
  N. Kobayashi et al. submitted to EPJA
  C. Sullivan et al, Physical Review C **98**, 015804 (2018)

- Review Papers
  - A. Bracco, E. G. Lanza and A. Tamii,
    Prog. in Part. Nucl. Phys., **106**, 360 (2019).
    (E1 response of nuclei)
  - P. von Neumann-Cosel and A. Tamii,
    to be published in EJPA (2019);
    arXiv:1903.11159 [nucl-ex]
    (proton inelastic scattering)

updated on 2019.5.28

Summary



- The **electric dipole polarizability** (EDP) of ^{208}Pb, ^{120}Sn, and ^{48}Ca were measured precisely with Coulomb excitation by proton scattering.
- Constraint bands in the *J*-*L* plane has been determined that describes the **symmetry energy** at and below the saturation density.
- The result from the laboratory nuclear experiments is consistent with the information from GW170817. Further observation of N-Star merger GW's are anticipated.

<u>Works in near future</u>

- More experimental data are still in the analysis:
  Sn isotopes, Zn isotopes, ^{154}Sm
- Gamma-decay of Giant Resonances: damping mechanism and fine structure
- Systematic measurement on E1 with γ,p,α-decays for nuclei A≦~60.

^{208}Pb

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Thank you

for your attention