7th International Symposium on Nuclear Symmetry Energy, GANIL (France) 4-7.9.2017

Constraining the symmetry energy based on relativistic point coupling interactions and excitations in finite nuclei

N. Paar

Faculty of Science University of Zagreb, Croatia

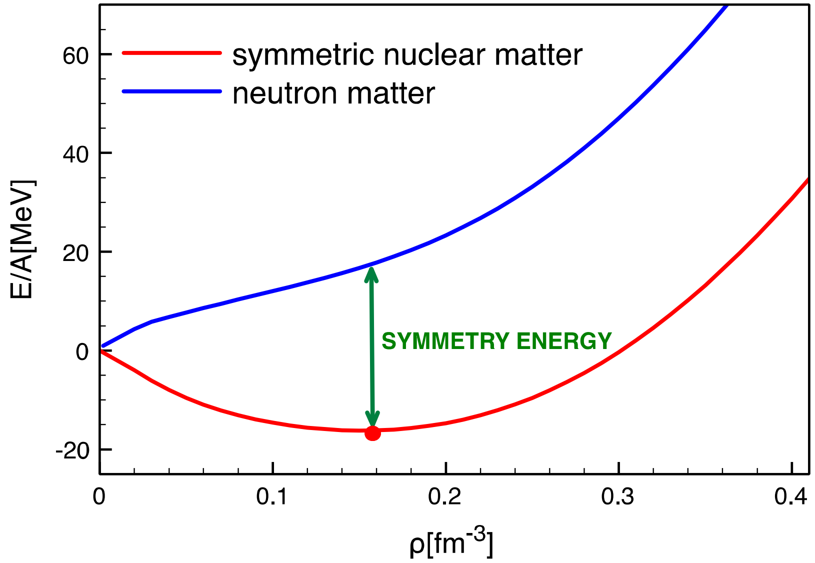
QuantiXLie

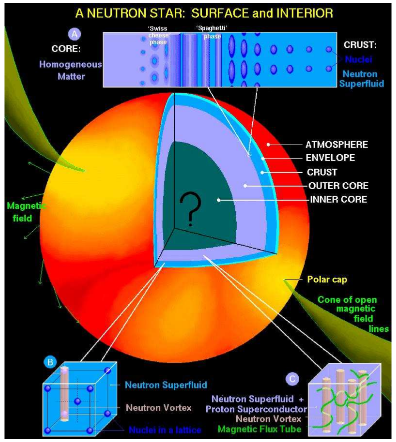
hrzz
Hrvatska zaklada za znanost

CENTER OF EXCELLENCE FOR THE THEORY OF QUANTUM AND COMPLEX SYSTEMS AND LIE ALGEBRA REPRESENTATION

INTRODUCTION

- Nuclear matter equation of state (EOS) plays important role in nuclear physics and astrophysics
- EOS of neutron matter is essential to understand the physics of neutron stars and binary mergers





- Symmetry energy S(ρ) describes the increase in the energy of the N≠Z system as protons are turned into neutrons;
- It is important for understanding the properties of neutron-rich matter and neutron rich nuclei
- Constraining S(ρ) by data on finite nuclei near the saturation density

- Neutron star properties
- Core collapse supernovae
- Nucleosynthesis

SYMMETRY ENERGY

- Nuclear matter equation of state:

$$E(\rho,\delta) = E_{SNM}(\rho) + E_{sym}(\rho)\delta^2 + \ldots$$

$$\rho = \rho_n + \rho_p \qquad \delta = \frac{\rho_n - \rho_p}{\rho}$$

- Symmetry energy term:

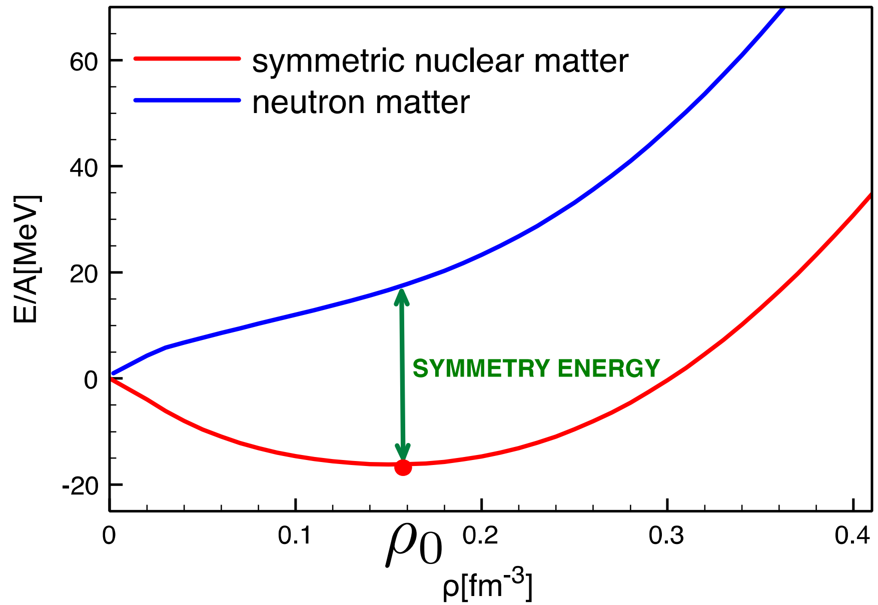
$$E_{sym}(\rho) \equiv S_2(\rho) = J - L\epsilon + \ldots$$

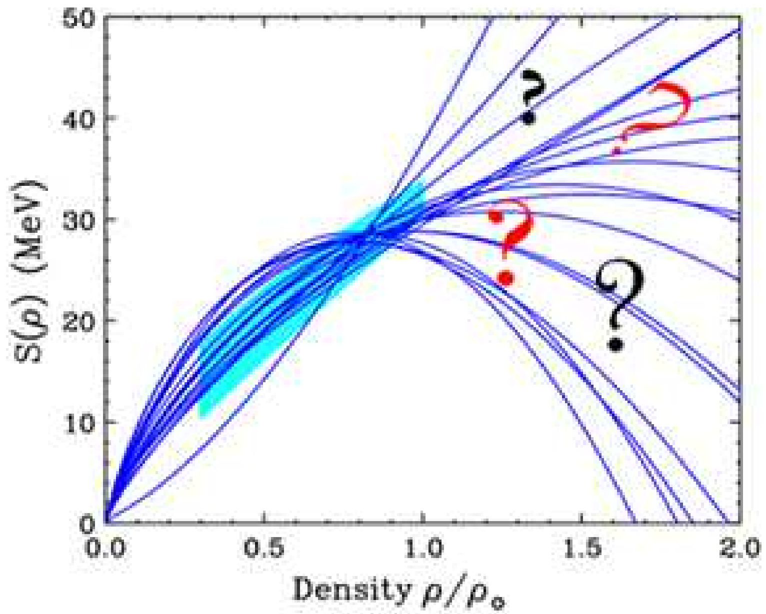
$$\epsilon = (\rho_0 - \rho)/(3\rho_0)$$

$$L = 3\rho_0 \frac{dS_2(\rho)}{d\rho}|_{\rho_0}$$

J – symmetry energy at saturation density

L – slope of the symmetry energy
(related to the pressure of neutron matter)





B. Tsang, NSCL

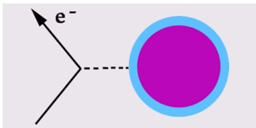
- In nuclei, thickness of the neutron skin $r_{np} = r_n - r_p$ depends on the pressure of neutron matter $P_{PNM} \sim L$

➢ the size of r_{np} increases with pressure as neutrons are pushed out against surface tension

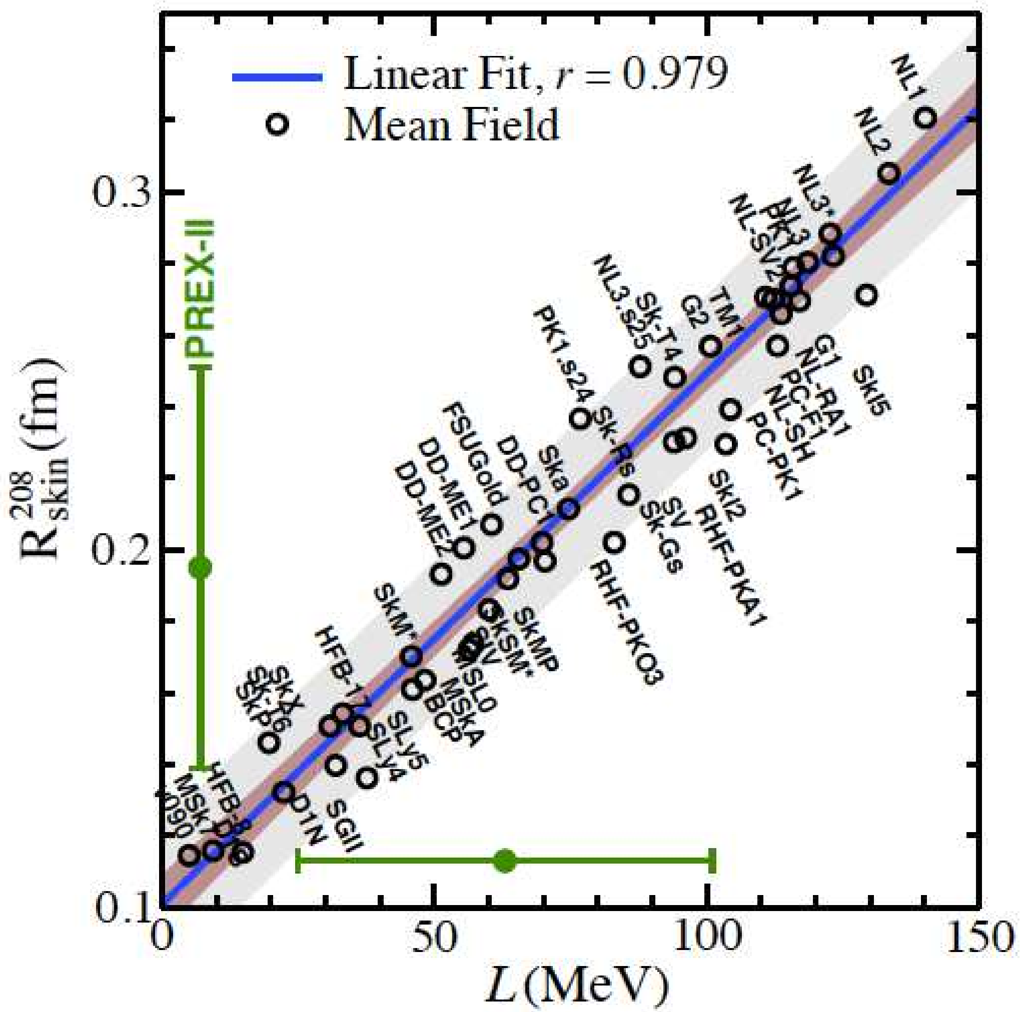
- The pressure of neutron matter $P_{PNM} \sim L$ is poorly constrained

- Parity violating electron scattering - Lead Radius Experiment (PREx) @ JLab:

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



Abrahamyan et al. PRL 108, 112502 (2012)



X. Roca-Maza et al., PRL106, 252501 (2011)
J. Piekarewicz, arXiv:1502.01559 (2015)

- PREx II, CREX

COLLECTIVE EXCITATIONS AND THE SYMMETRY ENERGY

- There are various (isovector) modes of collective excitations in nuclei that provide constraints on the neutron skin thickness, with recent experimental data available

  - Isovector giant dipole resonances

  - Dipole polarizability: A. Tamii et al., PRL 107, 062502 (2011)
    D.M. Rossi et al., PRL 111, 242503 (2013)
    T. Hashimoto et al., Phys. Rev. C 92, 031305(R) (2015)

    $\alpha_D \sim m_{-1}$

  - Pygmy dipole resonances: A. Carbone et al., PRC 81, 041301(R) (2010)
    A. Klimkiewitz et al., PRC 76, 051603(R) (2007)

  - Anti-analog GDR: A. Krasznahorkay et al., PLB 720, 428 (2013)

  - Isovector giant quadrupole resonances: S.S. Henshaw, M.W. Ahmed, et al, PRL 107, 222501 (2011)

  - ...

- The aim: <u>exploit collective excitations to constrain the symmetry energy J & L</u>

SELF-CONSISTENT RELATIVISTIC MEAN FIELD MODEL

- Relativistic point coupling model

- The basis is an effective Lagrangian with four-fermion (contact) interaction terms; isoscalar-scalar, isoscalar-vector, isovector-vector, derivative term

$$
\begin{aligned}
\mathcal{L} &= \bar{\psi}(i\gamma\cdot\partial - m)\psi \\
&- \frac{1}{2}\alpha_S(\hat{\rho})(\bar{\psi}\psi)(\bar{\psi}\psi) - \frac{1}{2}\alpha_V(\hat{\rho})(\bar{\psi}\gamma^{\mu}\psi)(\bar{\psi}\gamma_{\mu}\psi) \\
&- \frac{1}{2}\alpha_{TV}(\hat{\rho})(\bar{\psi}\vec{\tau}\gamma^{\mu}\psi)(\bar{\psi}\vec{\tau}\gamma_{\mu}\psi) \\
&- \frac{1}{2}\delta_S(\partial_{\nu}\bar{\psi}\psi)(\partial^{\nu}\bar{\psi}\psi) - e\bar{\psi}\gamma\cdot A\frac{(1-\tau_3)}{2}\psi
\end{aligned}
$$

- many-body correlations encoded in density-dependent coupling functions that are motivated by microscopic calculations but parameterized in a phenomenological way

- Extensions: pairing correlations in finite nuclei T. Niksic, et al., Comp. Phys. Comm. 185, 1808 (2014).
  - Relativistic Hartree-Bogoliubov model (e.g. with separable form of the pairing interaction Y. Tian et al., PLB 676, 44 (2009).)

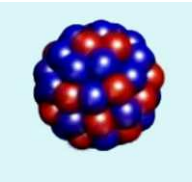
- In the small amplitude limit, self-consistent quasiparticle random phase approximation (QRPA) is used to compute nuclear excitations, etc.

CONSTRAINING THE FUNCTIONAL

- The model parameters $\mathbf{p} = (p_1, ..., p_n)$ are constrained directly by many-body observables using χ^2 minimization

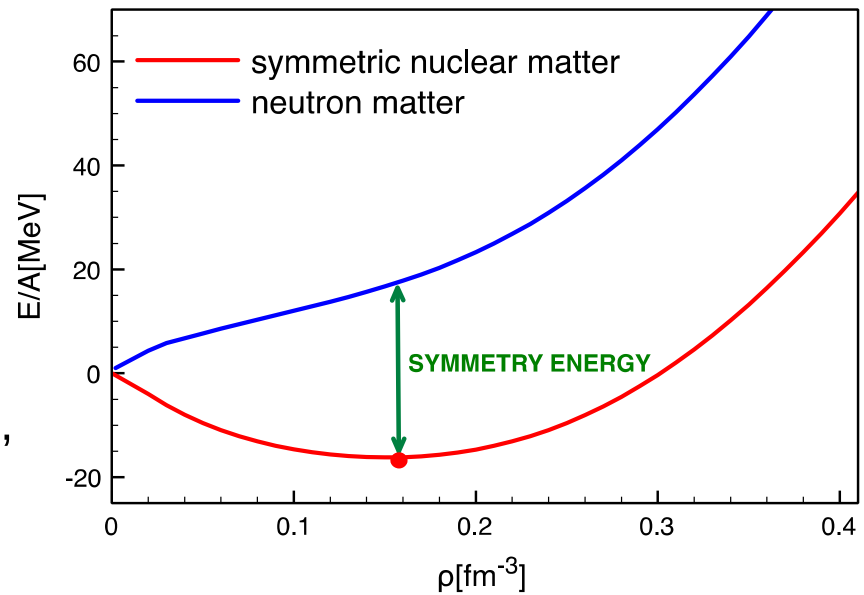
$$\chi^2(\boldsymbol{p}) = \sum_{i=1}^{m} \left(\frac{\mathcal{O}_i^{\text{theo.}}(\boldsymbol{p}) - \mathcal{O}_i^{\text{ref.}}}{\Delta \mathcal{O}_i^{\text{ref.}}} \right)^2$$

- Calculated values can be compared to experimental, observational, and pseudo-data



- properties of finite nuclei – binding energies, charge radii, diffraction radii, surface thicknesses, pairing gaps, etc.,…

- nuclear matter properties – equation of state, binding energy and density at the saturation, symmetry energy J & L, incompressibility…

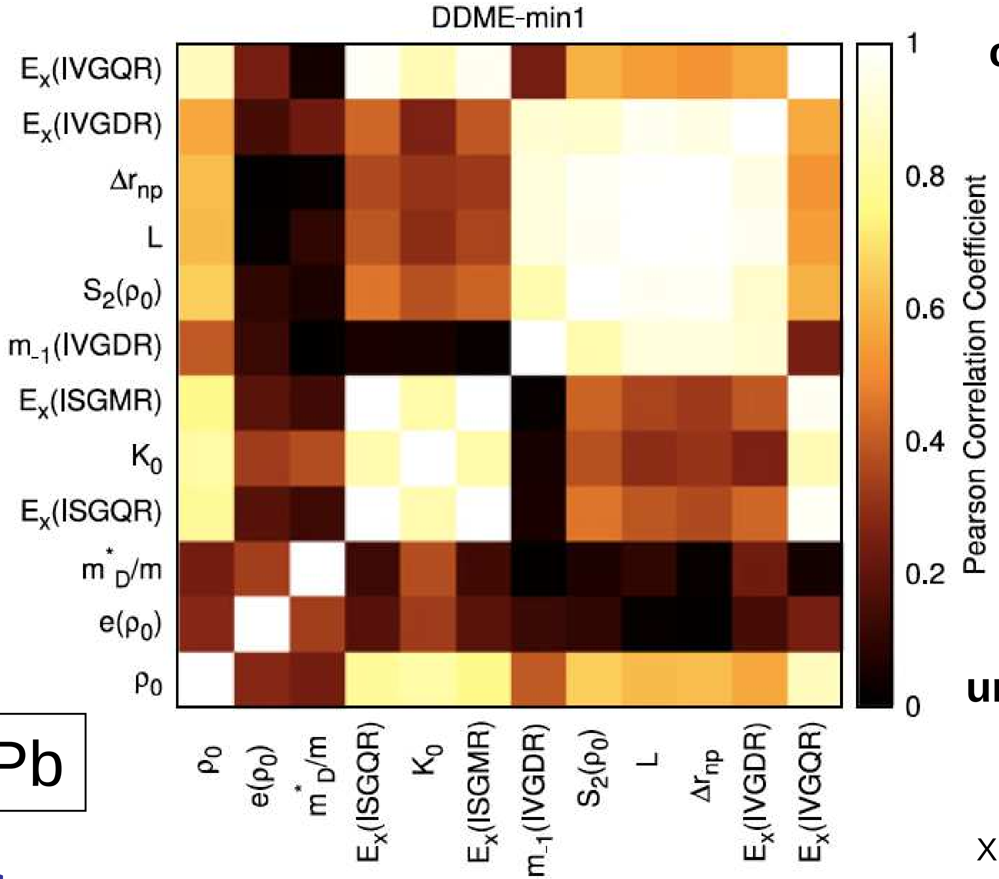


- Isovector channel of the EDF is weakly constrained by exp. data such as binding energies and charge radii. Possible observables for the isovector properties: *neutron radii, neutron skins, dipole polarizability, pygmy dipole strength, neutron star radii*

CORRELATIONS: NUCLEAR MATTER vs. PROPERTIES OF NUCLEI

- **Covariance analysis in the EDF framework**
  information on relevant correlations and statistical uncertainties

- **Pearson product-moment correlation coefficient**
  provides a measure of the correlation (linear dependence) between two variables A and B



correlated

uncorrelated

^{208}Pb

Correlation matrix between nuclear matter properties and properties for ^{208}Pb

- neutron skin thickness, properties of giant resonances,…

X. Roca Maza, N.P., G. Colò, JPG 42, 034033 (2015)

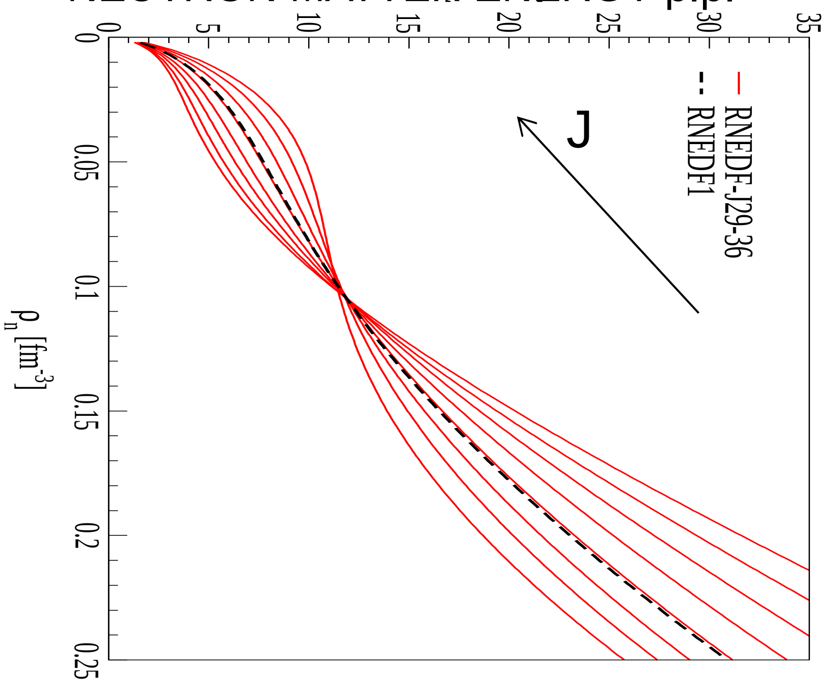
VARIATION OF THE SYMMETRY ENERGY IN CONSTRAINING THE EDF

- Adjust the properties of 72 spherical nuclei to exp. data (binding energies, charge radii, diffraction radii, surface thickness, pairing gaps)

- Establish a set of 8 relativistic point coupling interactions that span the range of values of the symmetry energy at saturation density: J=29,30,…36 MeV

- Each interaction is determined independently using the same dataset supplemented with an additional constraint on J

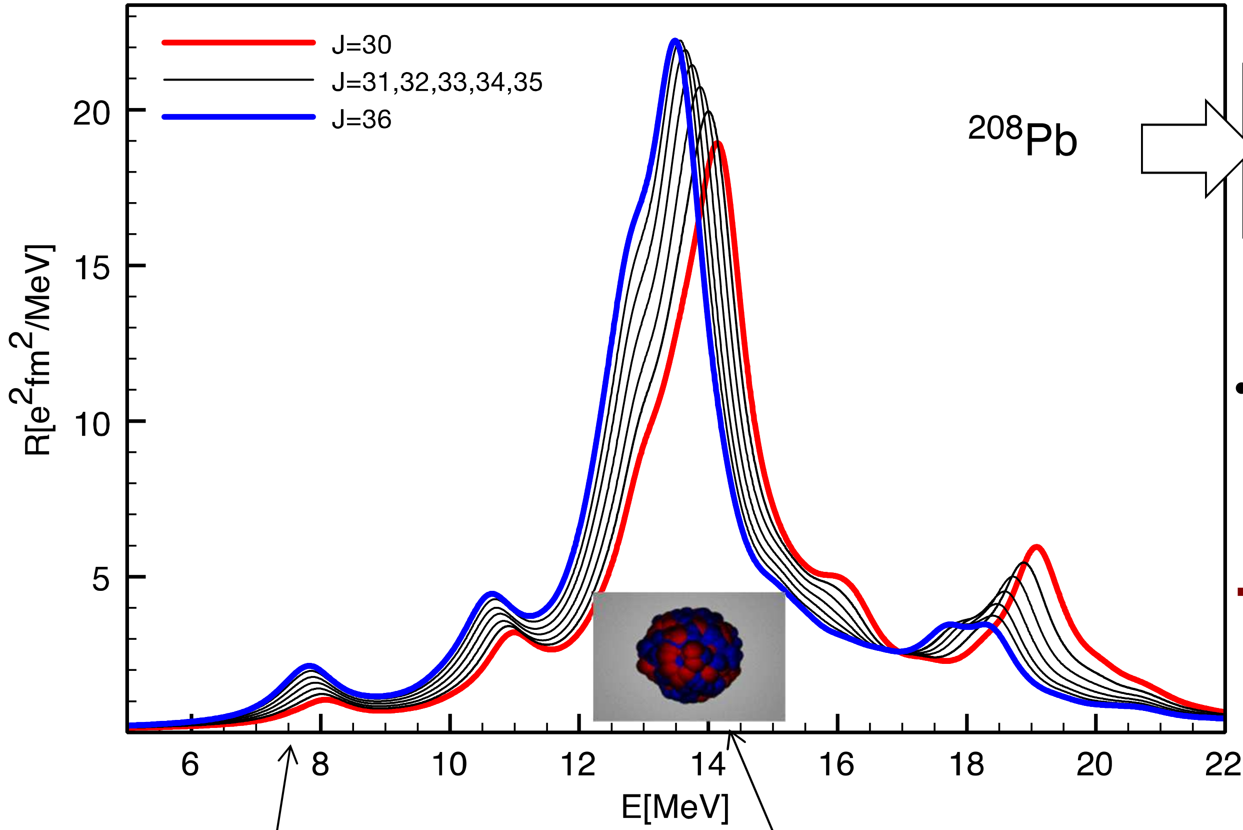
NEUTRON MATTER ENERGY p.p.



J[MeV]	L[MeV]
29	31.9
30	37.0
31	44.1
32	52.5
33	62.2
34	72.3
35	83.4
36	94.3

CONSTRAINING THE SYMMETRY ENERGY

- Isovector dipole transition strength for ^{208}Pb using a set of relativistic point coupling interactions which vary the symmetry energy properties (J=30,31,…,36 MeV)



Pygmy strength

Isovector giant dipole resonance

- Isovector giant dipole resonance
- Pygmy dipole strengths
- Dipole polarizability ($\alpha_D \sim m_{-1}$)

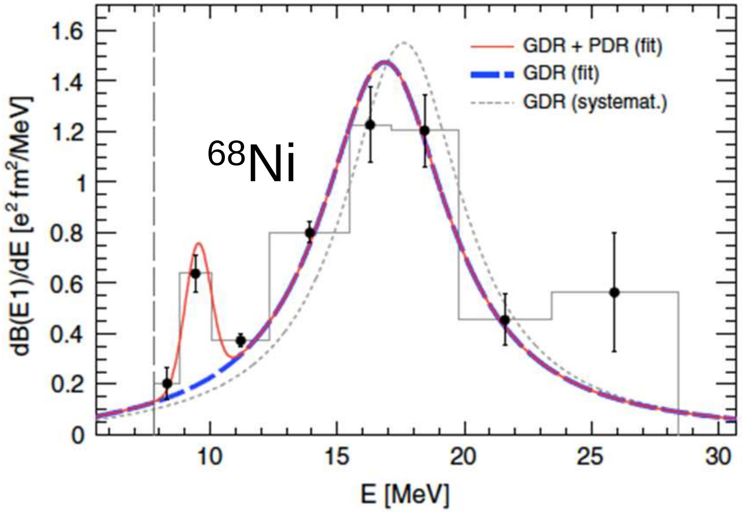
- The transition strength is sensitive on the properties of symmetry energy - (J,L)

➔ Dipole response can be used to constrain effective nuclear interactions (isovector channel)

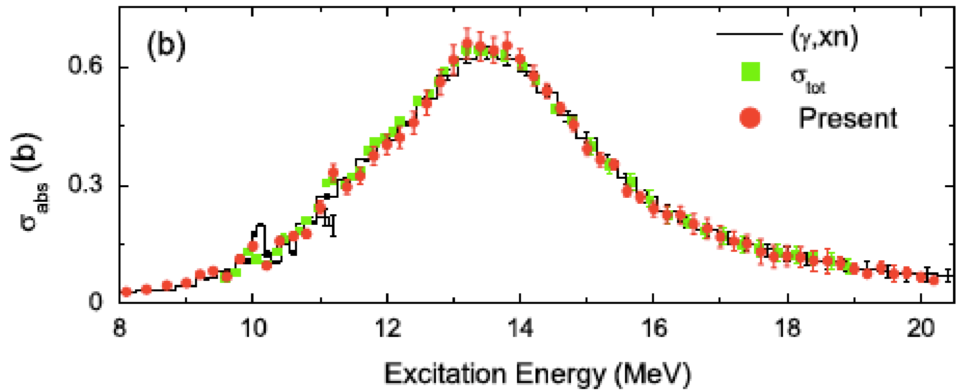
- There are exp. data available on the dipole response in nuclei (α_D, IVGDR, pygmy strength)

DIPOLE POLARIZABILITY AND SYMMETRY ENERGY

- Dipole polarizability from experiment, e.g.,



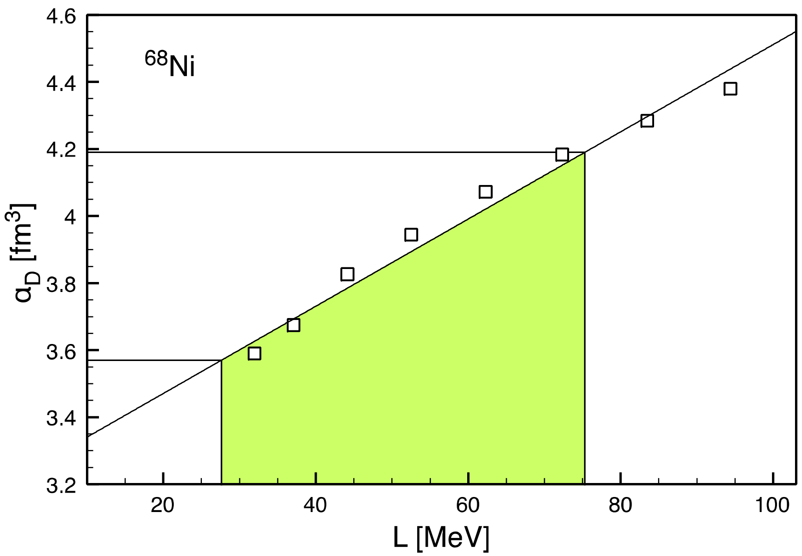
208Pb

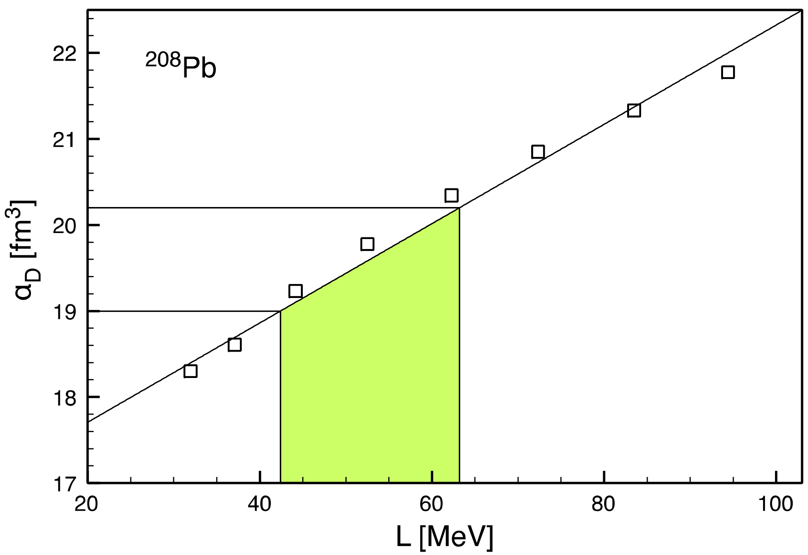


D. Rossi et al, PRL 111, 242503 (2013)

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

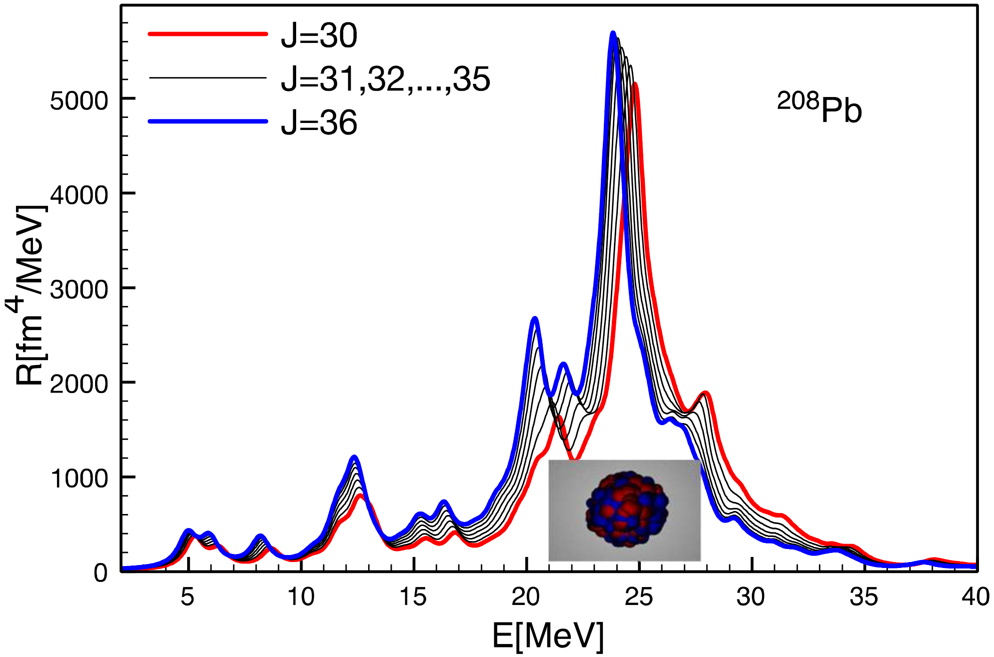
- constraining the slope of the symmetry energy using relativistic point-coupling interactions





GIANT QUADRUPOLE RESONANCES IN ^{208}Pb AND SYMMETRY ENERGY

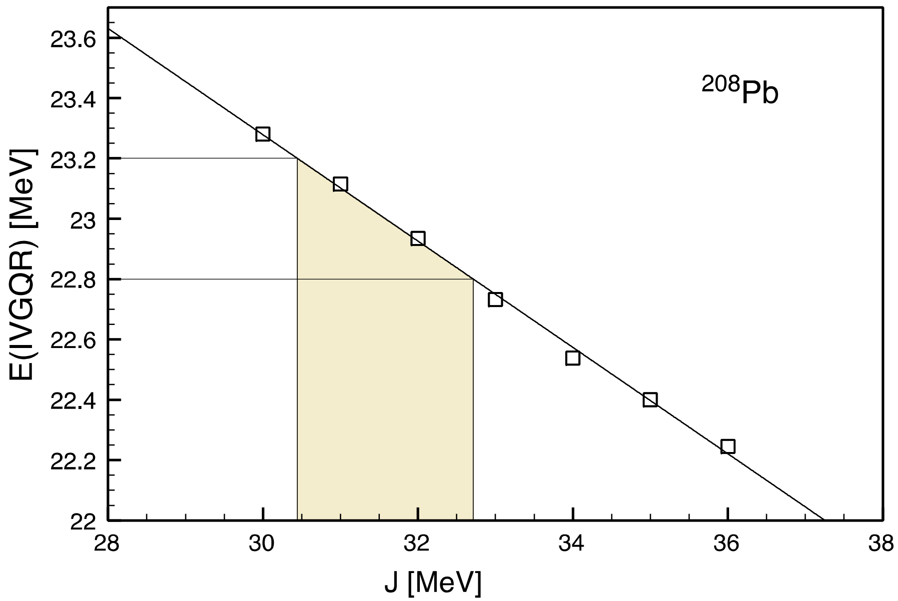
- Isovector quadrupole transition strength for ^{208}Pb using a set of relativistic point coupling interactions which vary the symmetry energy properties (J=30,31,…,36 MeV)



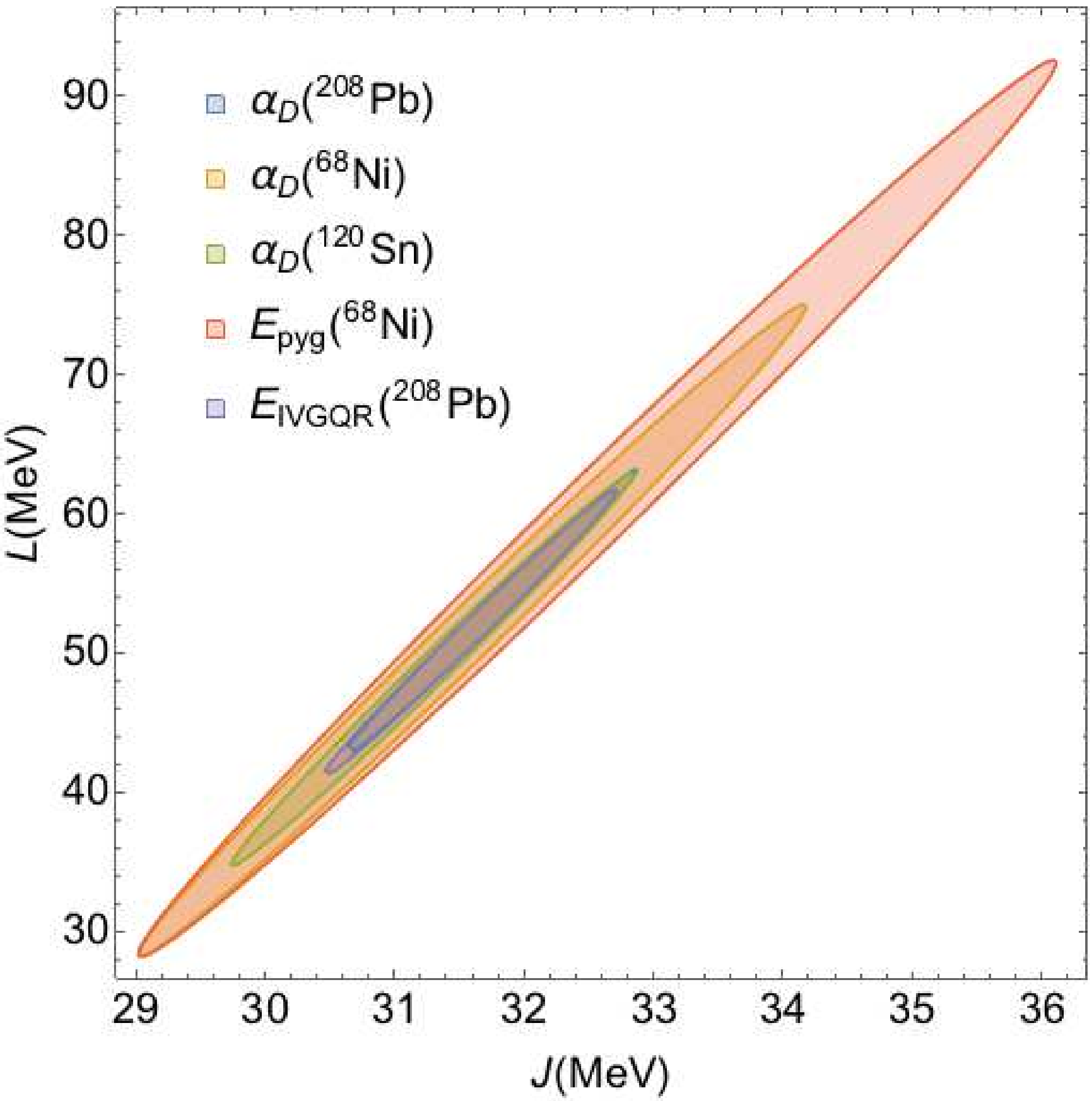
- Precise determination of isovector giant quadrupole resonances available and could be used to constrain the theory

  S.S. Henshaw, M.W. Ahmed, G. Feldman et al, PRL 107, 222501 (2011)

- The IVGQR energy is strongly correlated with the symmetry energy properties

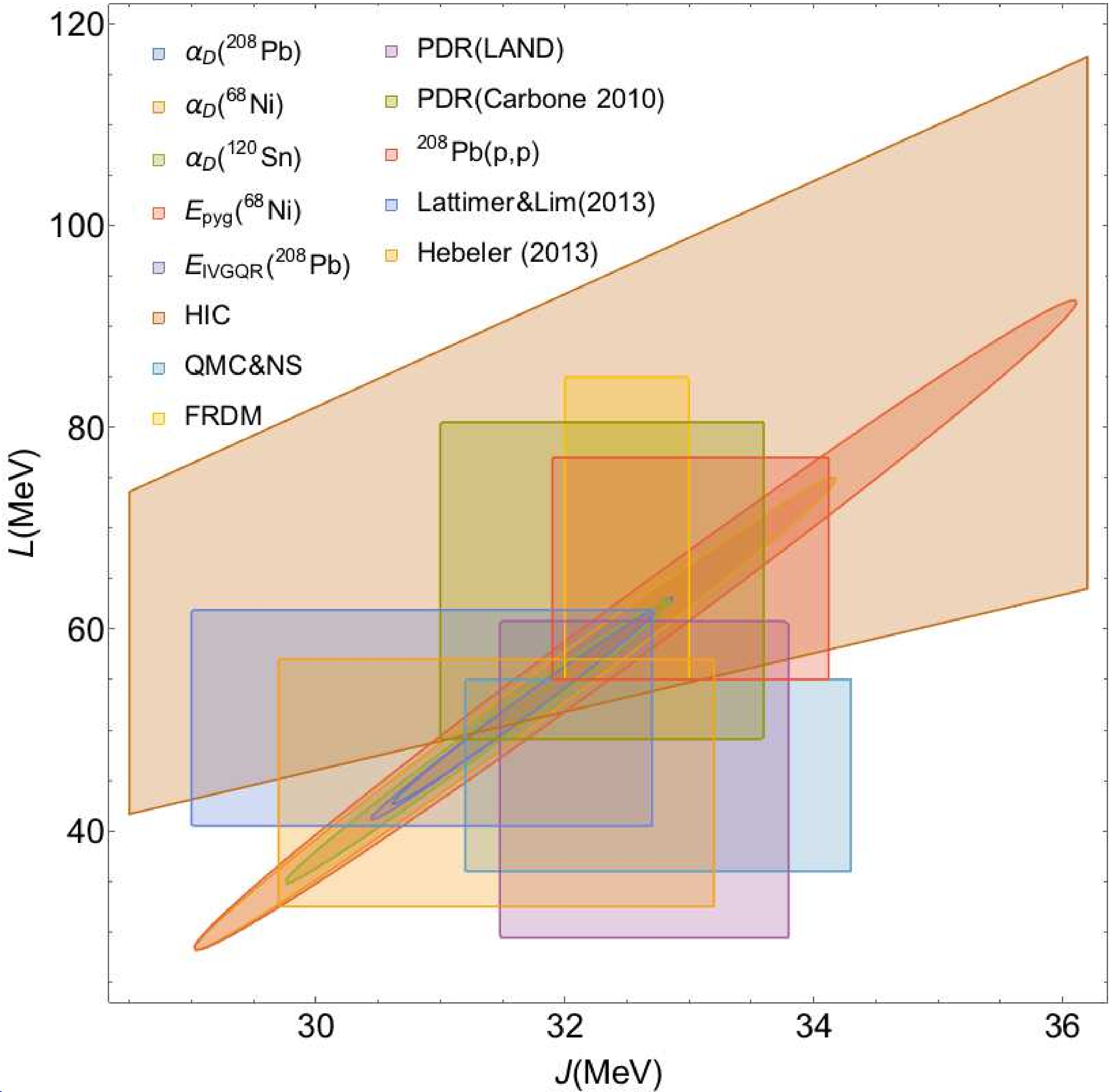


CONSTRAINING THE SYMMETRY ENERGY (J-L)



- Correlaton between J & L taken into account
- The overall result is centered around J=31.6 MeV and L=50.6 MeV

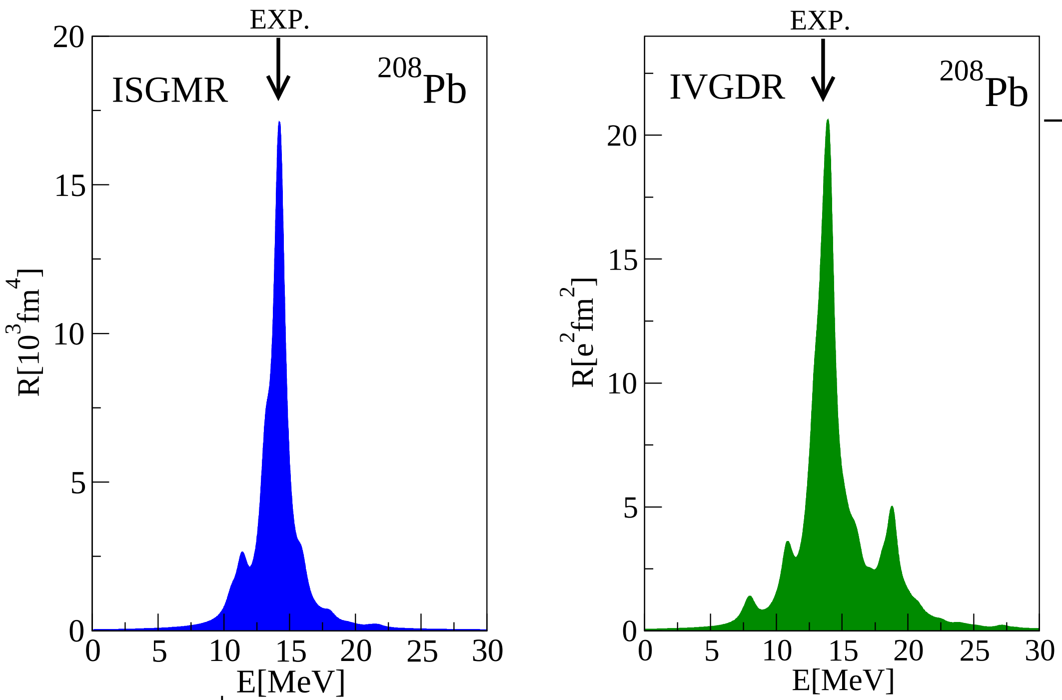
CONSTRAINING THE SYMMETRY ENERGY (J-L)



- Lattimer & Lim, ApJ. 771, 51 (2013) – compilation from various approaches
- K. Hebeler et al., AJ 773, 11 (2013) – nuclear interactions derived from chiral EFT
- ^{208}Pb(p,p) – J. Zenihiro et al., PRC 82, 044611 (2010)
- A. Carbone, G. Colo, A. Bracco, et al., PRC 81, 041301 (2010) – PDR
- A. Klimkiewicz et al. (LAND), PRC 76,051603(R) (2007)
- P. Moller, et al., PRL 108, 052501 (2012).
- A. W. Steiner and S. Gandolfi, PRL 108, 081102 (2012) – QMC (Av8')+ neutron stars
- H. S. Xu et al., PRL 85, 716 (2000)
- Z. Y. Sun et al., PRC 82, 051603(R) (2010)
- M. B. Tsang et al., PRC 86, 015803 (2012)

CONSTRAINING THE SYMMETRY ENERGY: 2nd approach

- use the experimental data on collective excitations to constrain the symmetry energy within the fitting protocol to determine the parameters of the functional



Dipole polarizability:
$\alpha_D = (19.68 \pm 0.21)\ fm^3$

Exp.
$\alpha_D = (19.6 \pm 0.6)\ fm^3$

A.Tamii et al., PRL 107, 062502 (2011). + update (2015).

- IVGDR – α_D determine the symmetry energy for the PC interaction

J = 31.89 MeV
L = 51.48 MeV

- ISGMR energy determines the nuclear matter incompressibility: **K_{nm}=232.4 MeV**

E (Exp.) = (13.91 ± 0.11) MeV (TAMU)
E (Exp.) = (13.7 ± 0.1) MeV (RCNP)

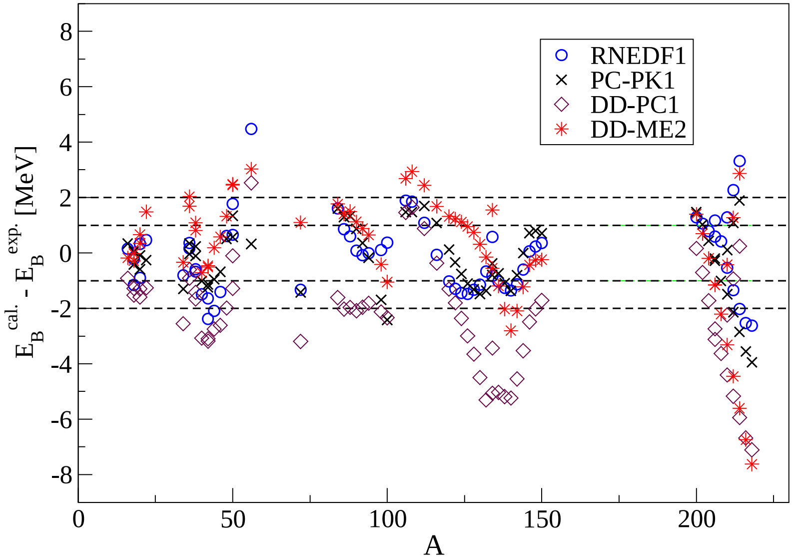
"Correct symmetry energy" is the one obtained for the interaction that reproduces the exp. data on dipole polarizability

CONCLUDING REMARKS

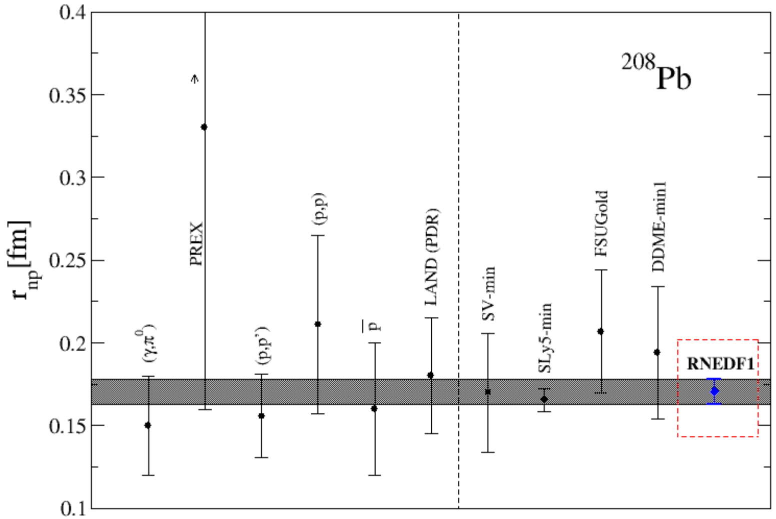
- Dipole excitations in nuclei (PDR, α_D, IVGDR, AGDR) and other modes (IVGQR,…) provide useful constraints for the nuclear matter symmetry energy J & L
- Microscopic theory frameworks are well established and (some) accurate exp. data are available
- Accurate measurements of collective excitations have important implications to reduce uncertainties in the symmetry energy
- On the other side, they allow improved constraining of the EDFs (their isovector channel)
- Prospects to include directly the properties of collective excitations as additional observables in the fitting protocols to determine the parameters of the EDF

SOME OTHER PROPERTIES…

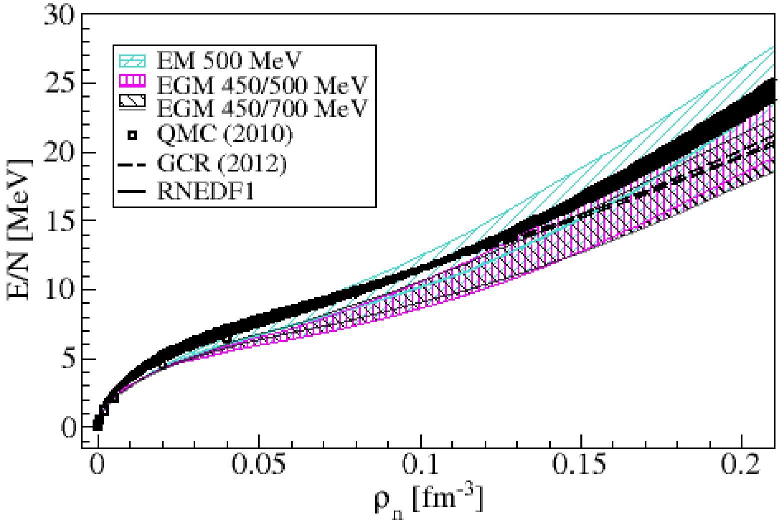
Nuclear binding energies (calc. – exp.)



Neutron skin thickness



Pure neutron matter



Neutron star mass-radius relationship