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The ^{132}Sn isovector giant dipole resonance as a constraint on nuclear matter properties

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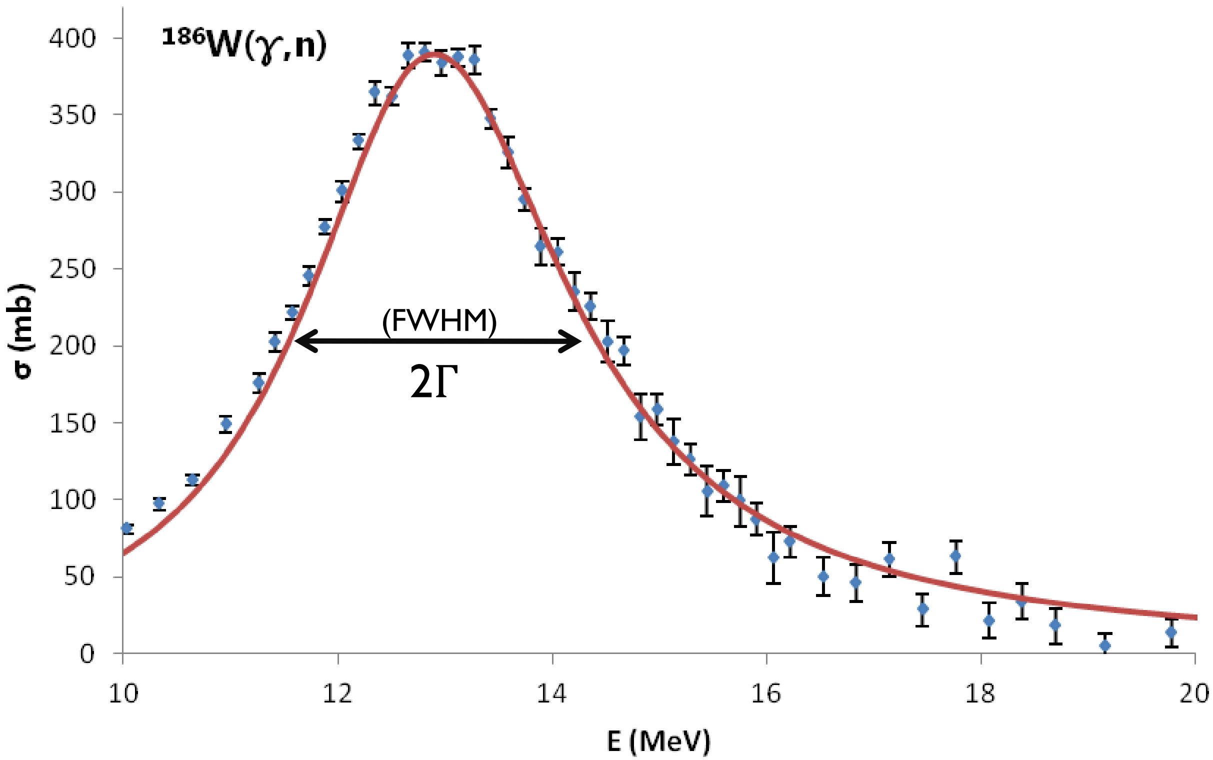
Plan

- Introduction
- Hartree-Fock – RPA
- Connection to nuclear matter
- Our work: ^{132}Sn IVGDR

Giant resonances

- Broad peaks in the γ-absorption cross-section σ at specific energies
  - Correspond to specific vibrational modes



Lorentzian:

$$\sigma(E) = \frac{E^2\Gamma^2\sigma_R}{(E^2 - E_R^2)^2 + E^2\Gamma^2}$$

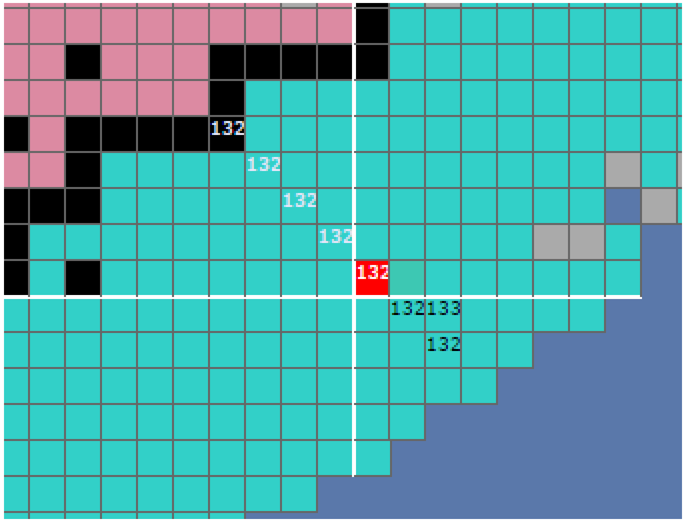
- B. L. Berman *et al.* Phys. Rev. **185**, 1576 (1969).

Motivation

- Why study giant resonances?
  - Refine the nuclear equation of state (EOS)
  - Provide insight for the nature of the nuclear interaction
  - Accurately describe astrophysical processes
    - Neutron star formation & structure (nsEOS)
    - Supernovae & nucleosynthesis

^{132}Sn

- Very neutron rich
- Doubly-magic (Z = 50, N = 82)
- Half-life ~40 sec



- Can be produced in current accelerators with sufficient beam intensity for experiments

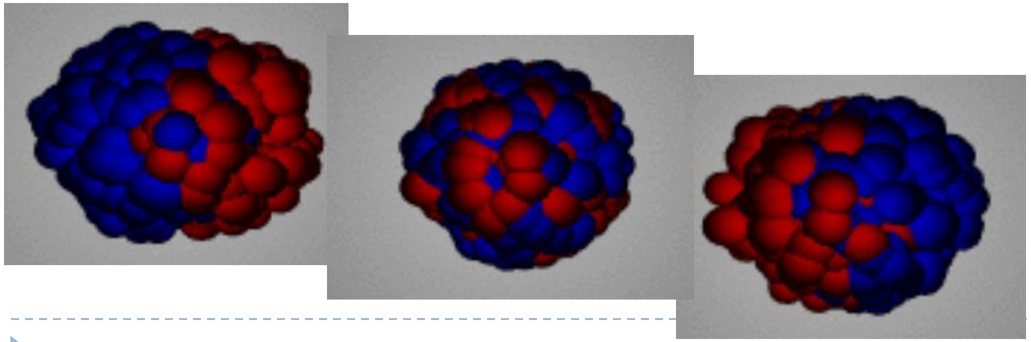
Image credit: IAEA NDS, https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

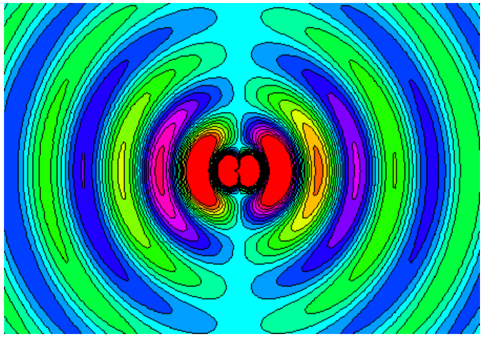
Giant resonances – theory

- Giant resonances are classified by their multipolarity *L* (shape oscillation) and isospin T (phase)

- We consider the IVGDR (L = 1, T = 1)

- Goldhaber and Teller [1] explained the IVGDR as collective oscillations of neutrons against protons
  - Microscopically, GR are described as coherent sum of particle-hole excitations





https://web-docs.gsi.de/~wolle/TELEKOLLEG/KERN/index-s.html

https://upload.wikimedia.org/wikipedia/commons/3/3d/Dipole.gif

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Hartree-Fock

- Determine the ground-state wavefunction of a nucleus by using a mean-field Hamiltonian [2]:

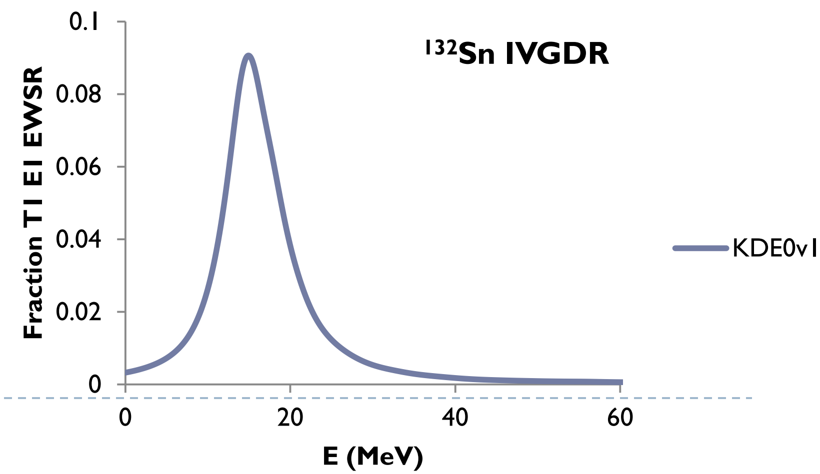
$$H = \left[T + \sum_{i=1}^{A} v(\vec{r}_i) \right] + \left[V - \sum_{i=1}^{A} v(\vec{r}_i) \right] = H_{mf} + V_{res}$$

- Give the (antisymmetric) nuclear wavefunction as a Slater determinant of single-particle (s.p.) wavefunctions
  - Nucleons = fermions

- Introduce a perturbation to the s.p. wavefunctions and use a variational approach to minimize $E = \langle \Phi | H | \Phi \rangle$

RPA

- "Random-phase approximation"
- Giant resonance → coherent sum of p-h excitations
- Key results [3]:
  - Strength function $S(E) = \sum_n |\langle 0|F|n\rangle|^2 \delta(E - E_n)$
  - Scattering operator (IV) $\hat{F}_L = \frac{Z}{A}\sum_n f(r_n)Y_{L0}(n) - \frac{N}{A}\sum_p f(r_p)Y_{L0}(p)$
  - Energy moments $m_k = \int E^k S(E)dE$
    - $E_{cen} = m_1/m_0$
    - $\alpha_D = (e^2/27\pi)m_{-1}$



Skyrme interaction

- Skyrme interaction is a means of parameterizing the nucleon-nucleon potential [4,5]:

$$V_{ij}^{NN} = t_0(1 + x_0 P_{ij}^{\sigma})\delta(\vec{r}_i - \vec{r}_j) + \tfrac{1}{2}t_1(1 + x_1 P_{ij}^{\sigma})\left[\overleftarrow{k}_{ij}^{2}\delta(\vec{r}_i - \vec{r}_j) + \delta(\vec{r}_i - \vec{r}_j)\vec{k}_{ij}^{2}\right] +$$
$$t_2(1 + x_2 P_{ij}^{\sigma})\overleftarrow{k}_{ij}^{2}\delta(\vec{r}_i - \vec{r}_j)\vec{k}_{ij} + \tfrac{1}{6}t_3(1 + x_3 P_{ij}^{\sigma})\rho^{\alpha}\left(\frac{\vec{r}_i+\vec{r}_j}{2}\right)\delta(\vec{r}_i - \vec{r}_j) +$$
$$iW_0\overleftarrow{k}_{ij}\delta(\vec{r}_i - \vec{r}_j)(\sigma_i + \sigma_j)\vec{k}_{ij}$$

- Key attributes:
  - Contact interaction (δ)
  - 3-body interaction approximated by $t_3(\ldots)\rho^{\alpha}$ term
  - 10 parameters – x, t, W_0 and α
  - Several hundred in literature (fitted differently) [6,7]

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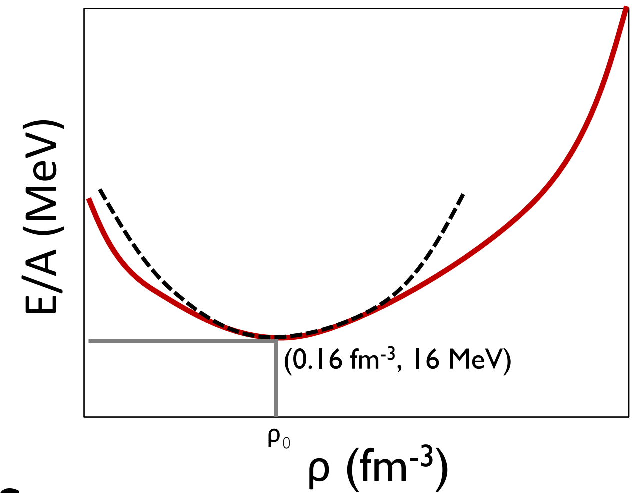
Infinite symmetric nuclear matter (N = Z)

- No Coulomb interactions

- E/A ~ 16 MeV

- ρ_0 ~ 0.16 fm^{-3}

- Skyrme parameters ↔ NM properties



Infinite nuclear matter (general)

- EOS gives binding energy per nucleon as a function of density [2]:

$$E[\rho_p, \rho_n] = E_0[\rho] + E_{sym}[\rho]\left(\frac{\rho_n - \rho_p}{\rho}\right)$$

- E_{sym} determines favorability of neutron-proton interaction
  - Isospin dependence of the nuclear force

- We focus on the symmetry energy E_{sym} :

$$E_{sym}[\rho] = J + L\left(\frac{\rho - \rho_0}{\rho_0}\right) + \frac{1}{18}K_{sym}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 \quad \begin{cases} J = E_{sym}[\rho_0] \\ L = 3\rho_0 \left.\frac{\partial E_{sym}}{\partial \rho}\right|_{\rho_0} \\ K_{sym} = 9\rho_0^2 \left.\frac{\partial^2 E_{sym}}{\partial \rho^2}\right|_{\rho_0} \end{cases}$$

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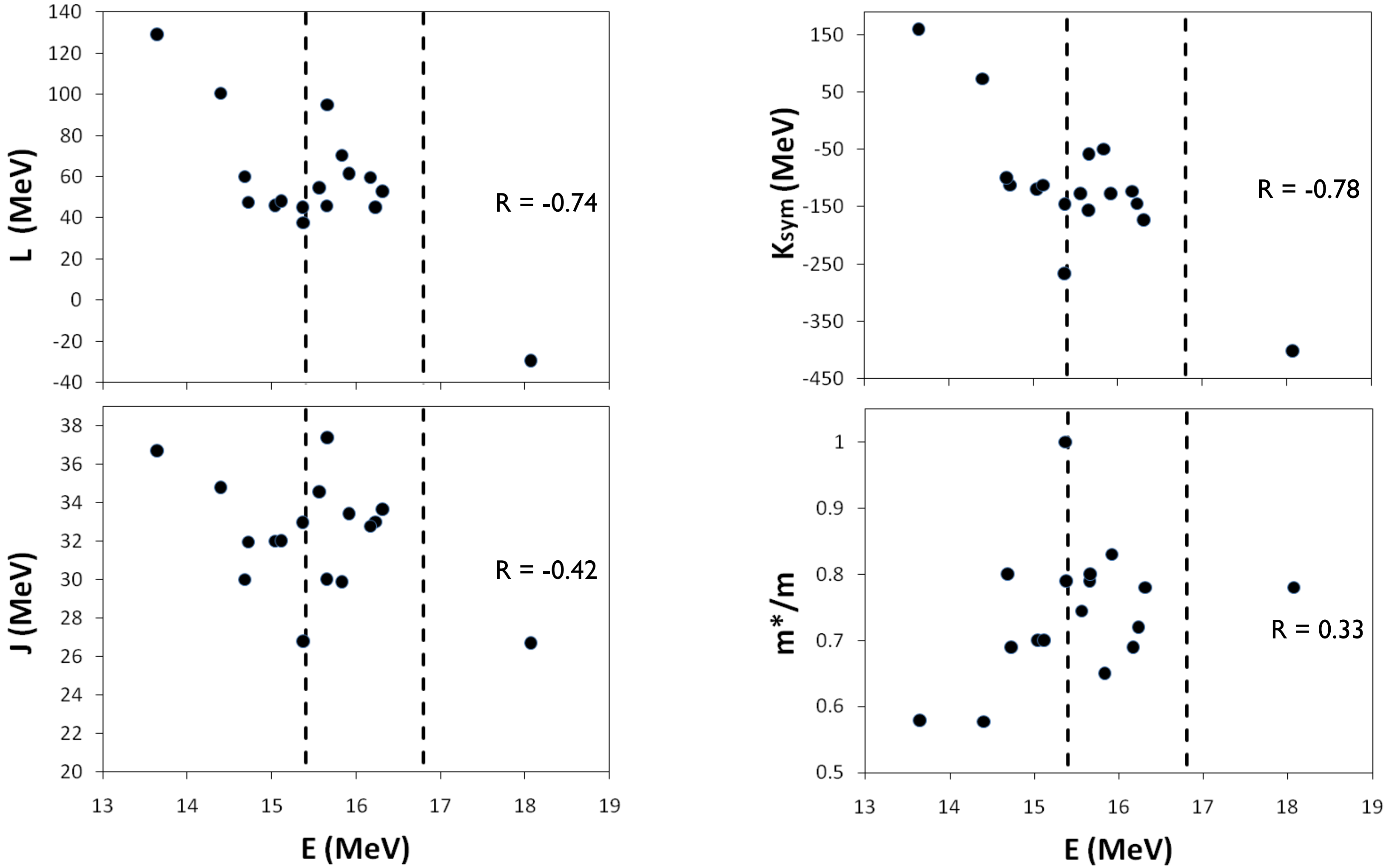
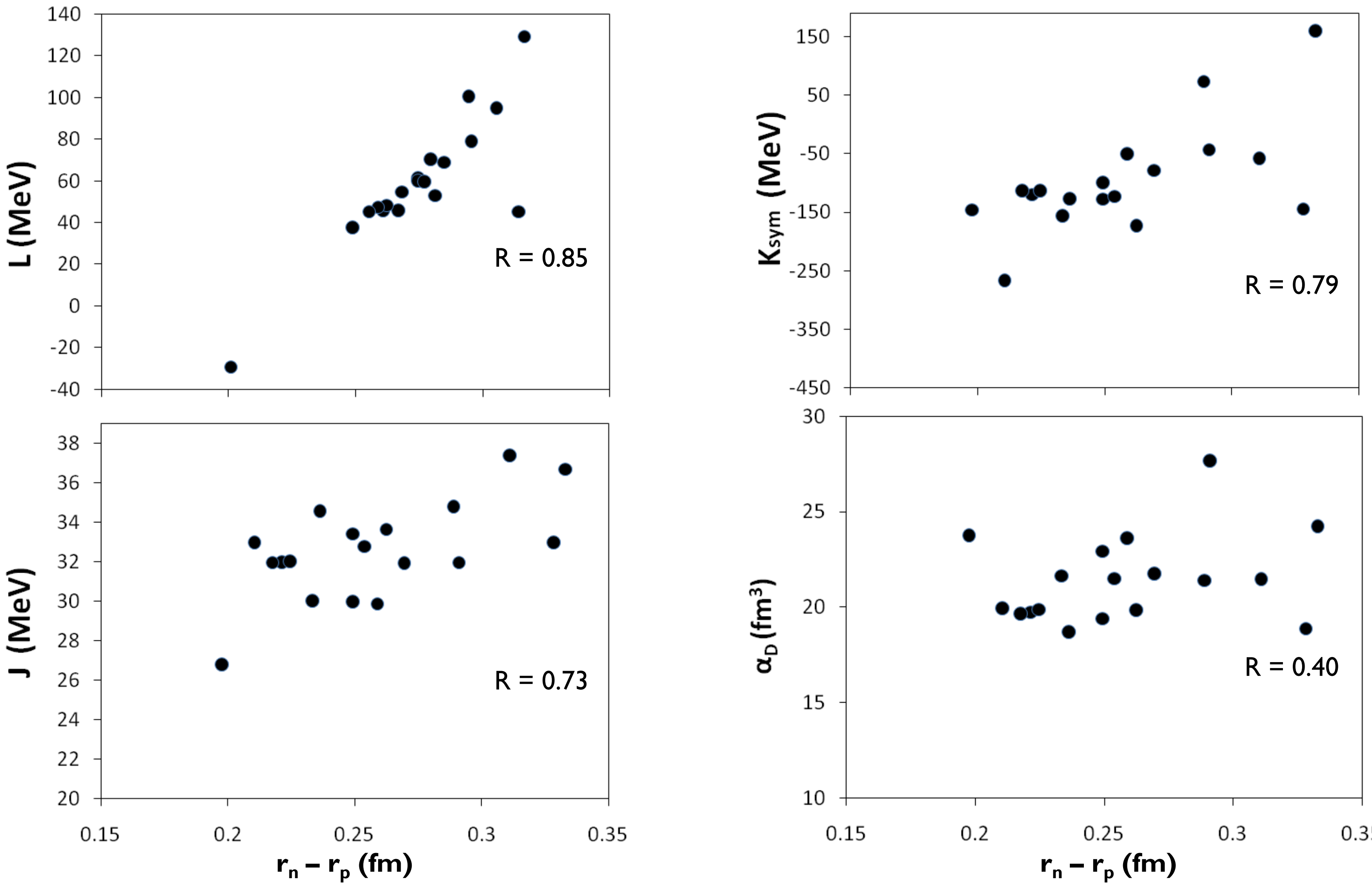
Approach

- Calculate E_{cen} of ^{132}Sn IVGDR using HF-RPA [2,8] for 17 Skyrme interactions
- Calculate NM properties J, L, K_{sym} , ρ_0 , E/A, κ ... , for these interactions
- Search for correlations among these properties
- Attempt to use correlations between *Ecen* and NM properties to constrain symmetry energy quantities J, L, and K_{sym}, and effective mass m^*/m
  - Also considered ^{132}Sn neutron skin thickness $r_n - r_p$
  - Compared with experimental value of IVGDR E_{cen} from [9]

Results - E_{cen}



Results – neutron skin

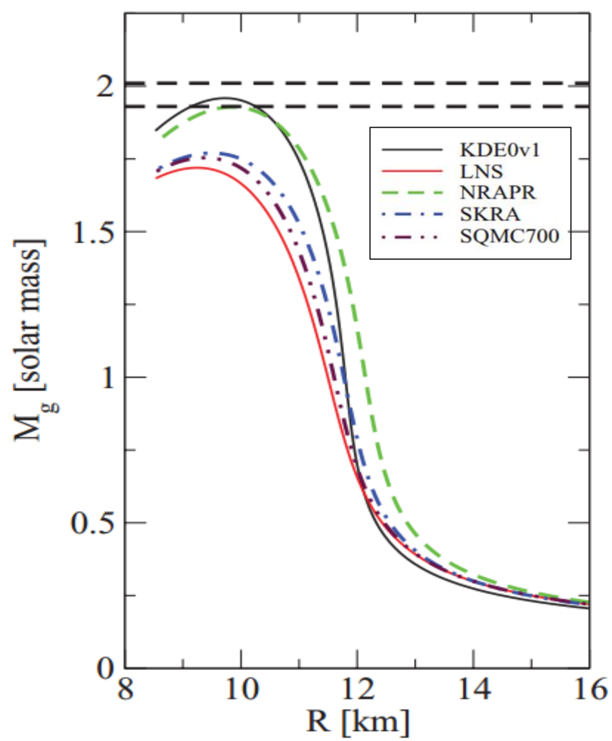


Summary

- Correlations?
  - Yes
- Constraints?
  - Yes, but not more stringent than previous work
- Dipole electric polarizability α_D *vs.* neutron skin
  - X. Roca-Maza *et al.* [10], ^{208}Pb, $R = 0.77$
  - M. R. Anders [11], ^{208}Pb, $R = 0.67$
  - Present work, ^{132}Sn, $R = 0.40$
  - Neutron asymmetry (N-Z)/A ~ 0.2 for both nuclides

Implications – neutron star EOS

- Neutron star equation of state [6]
  - Mass-radius relationship determined by symmetry energy?
  - KDE0v1 interaction



- Plot from [6]

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Acknowledgements

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