Nuclear Pygmy Modes as Doorways to Nucleosynthesis

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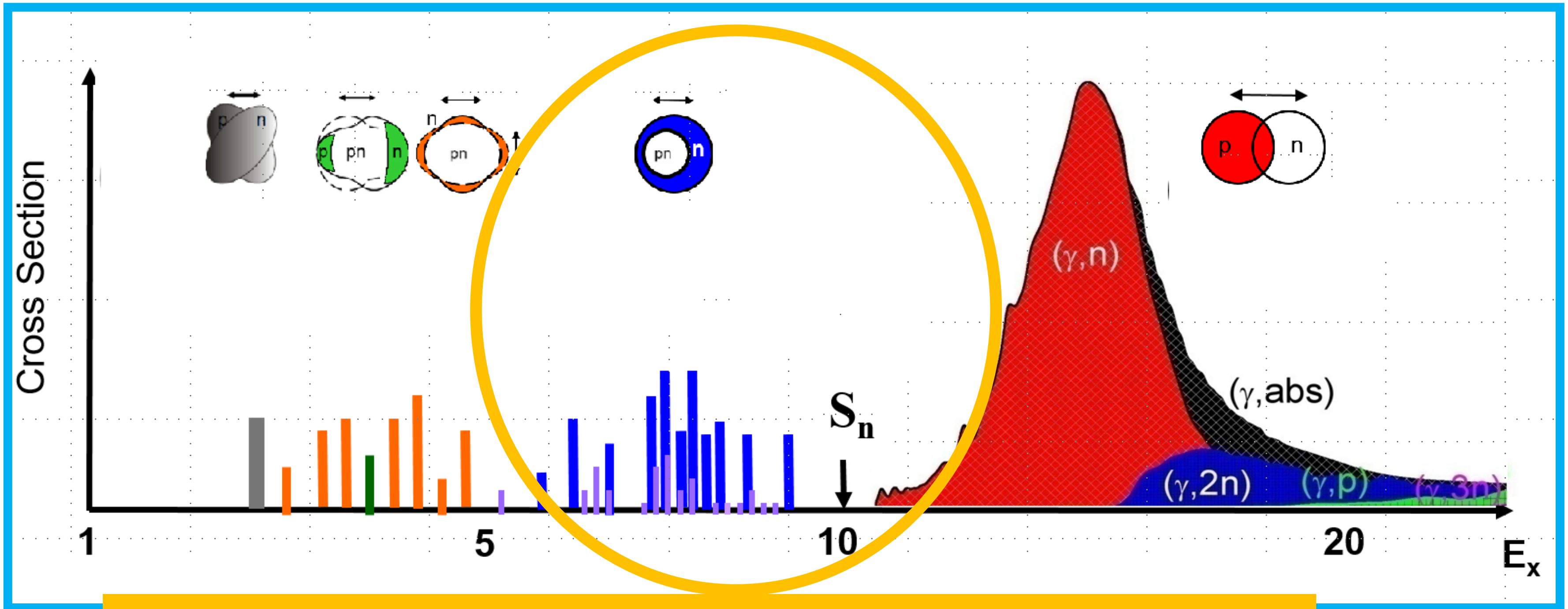
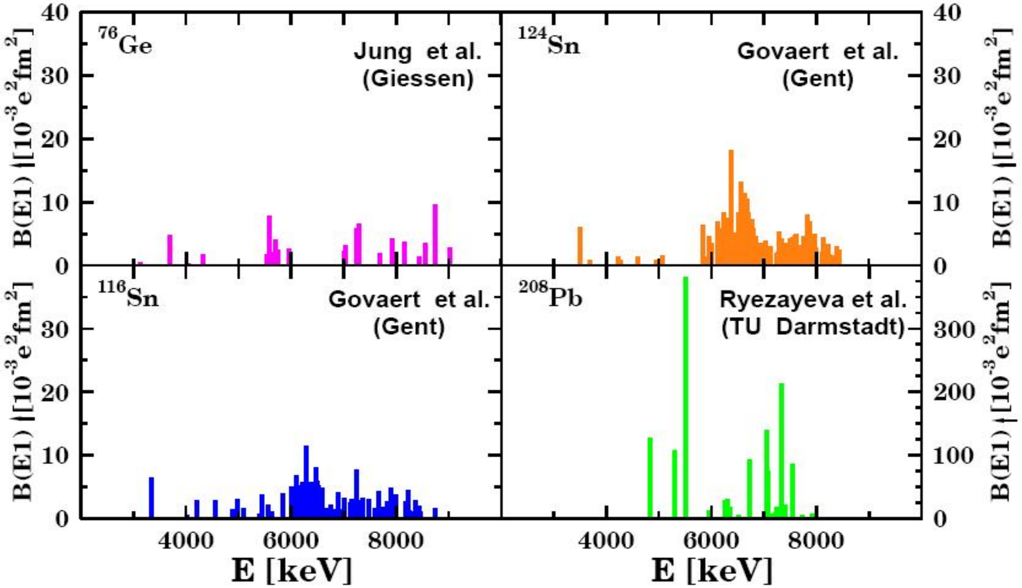
The Richness of Nuclear Spectra…

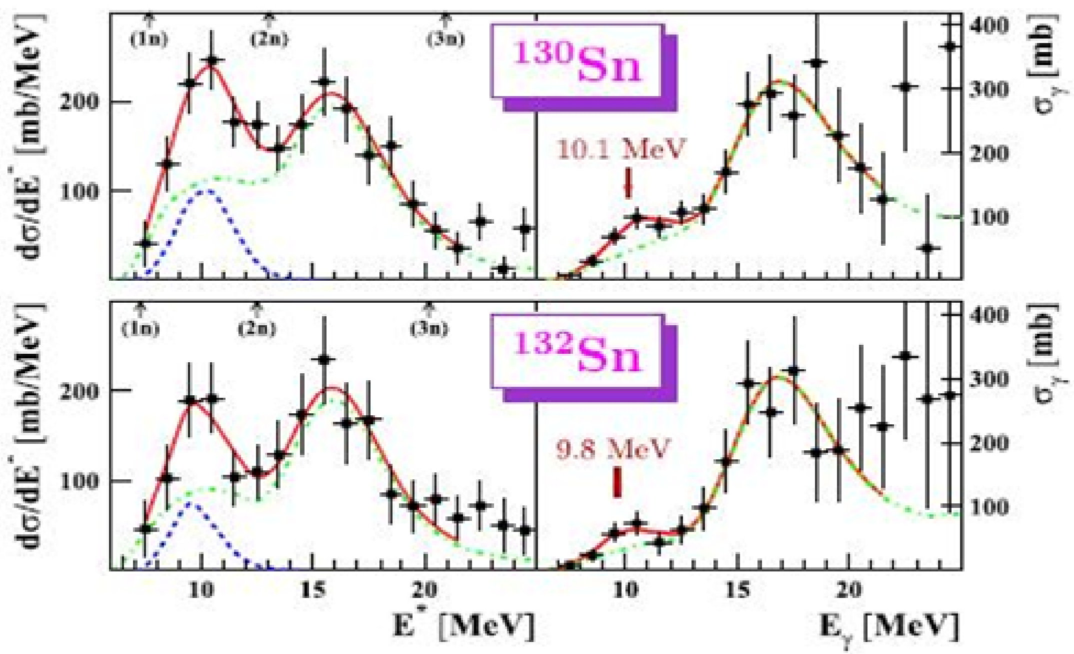


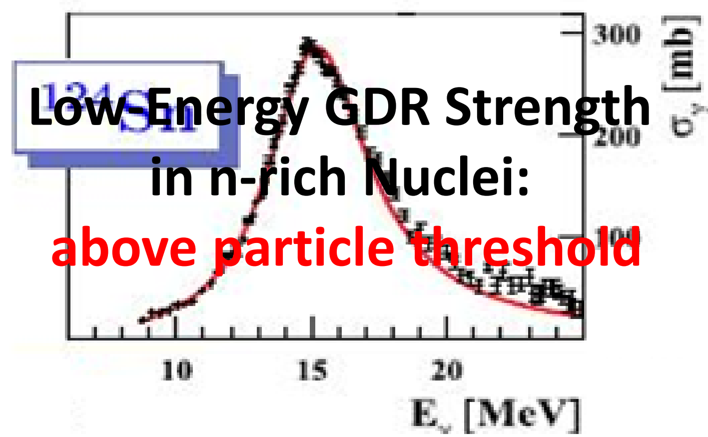
Pygmy Modes of n-rich heavy nuclei:
PDR, PMR, PQR…



Pygmy Dipole Strength in n-rich Nuclei:

below particle threshold





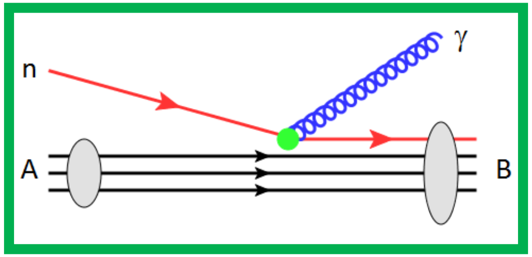
Low-Energy GDR Strength in n-rich Nuclei:

above particle threshold

Astropyhysical (n,γ) Capture Cross Sections and Nuclear Structure

$$d\sigma_{n\gamma} \sim \sum_{J,c} \left| \left\langle \vec{q}_{\gamma B} \left| \left\langle B_{J,c} \left| V \right| A \right\rangle \right| \chi^{(+)}_{nA} \right\rangle \right|^2 d\Omega_\gamma$$

- **Compund Nuclear Capture: statistical approach at high level density → Hauser-Feshbach theory**
- **Direct Capture: population of identifyable nuclear states → microscopic reaction theory**
- **Investigations by Detailed Balance: (n,γ) ↔ (γ,n)**



$$\sigma(E_{\rm c.m.}) = \sum_{LSJ_iJ_f\ell} \frac{8\pi}{2J_f+1} \frac{\alpha}{v_{\rm rel}} \frac{q}{1+q/m_f} \left[\left| E_\ell^{LSJ_iJ_f}(q) \right|^2 + \left| M_\ell^{LSJ_iJ_f}(q) \right|^2 \right]$$

Agenda

- **Pygmy modes: new low-energy modes of nuclear excitation**
- **Theory of low energy modes**
- **Dipole and quadrupole pygmy modes**
- **Pygmy modes, (γ,n) cross sections and nuclear reaction rates**

Our Goals

- **Microscopic approach to infinite matter and finite nuclei**
- **Ground states and nuclear excitations**
- **Astrophysical investigations**

Nuclear Density Functional Theory

The Giessen Meson Exchange EDF Approach:

$$E(\rho,\kappa) \approx E(\rho_0,\kappa_0) + \sum_{q=p,n} \left(\left(T_q + U_q(\rho_0) \right) \delta\rho_q + \Delta_q \delta\kappa_q \right) + \sum_{q,q'=p,n} f_{qq'}(\rho_0) \delta\rho_q \delta\rho_{q'} + \ldots$$

$$\delta\rho_q \sim \varphi_k^\dagger \varphi_n \quad ; \quad \delta\kappa_q \sim \tilde{\varphi}_k \varphi_n \ \ \& \text{ h.c.}$$

Single Particle Self-Energy:

$$U_q = \frac{\delta}{\delta\rho_q} \frac{1}{2} \langle V \rangle = \sum_{q'} V_{qq'}(\rho) \rho_{q'} + \frac{1}{2} \sum_{q'q''} \rho_{q'} \rho_{q''} \frac{\delta}{\delta\rho_q} V_{q'q''}(\rho)$$

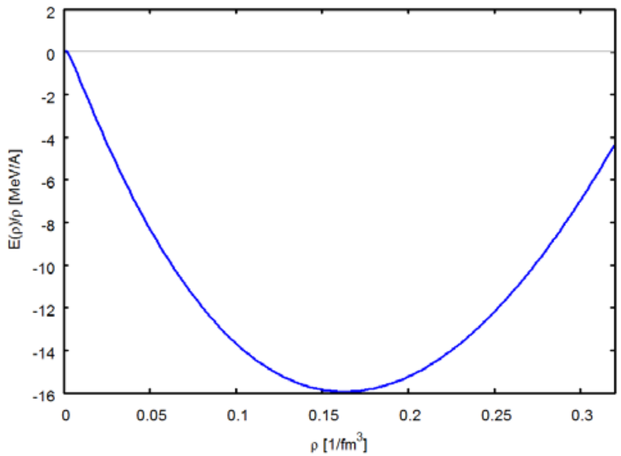
HFB → Gorkov Wave Equation :

$$\left(-\vec{\nabla} \frac{\hbar^2}{2m_q^*} \vec{\nabla} + U_q - \lambda_q - E_q \right) \varphi_q^{(+)} + \Delta_q \varphi_q^{(-)} = 0$$

$$-\Delta_q \varphi_q^{(+)} + \left(-\vec{\nabla} \frac{\hbar^2}{2m_q^*} \vec{\nabla} + U_q - \lambda_q + E_q \right) \varphi_q^{(-)} = 0$$

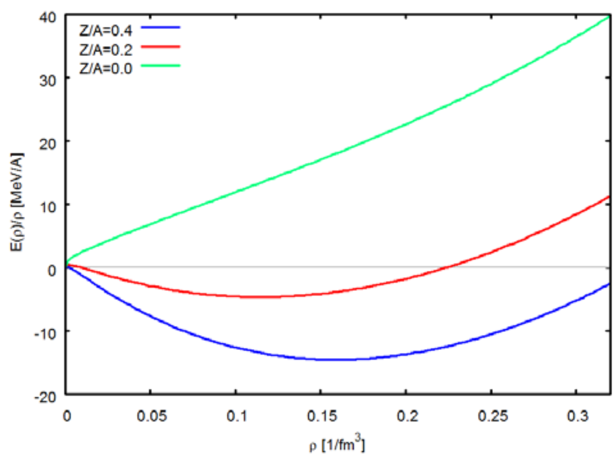
GiEDF: Infinite Matter Properties

Symmetric Infinite Matter



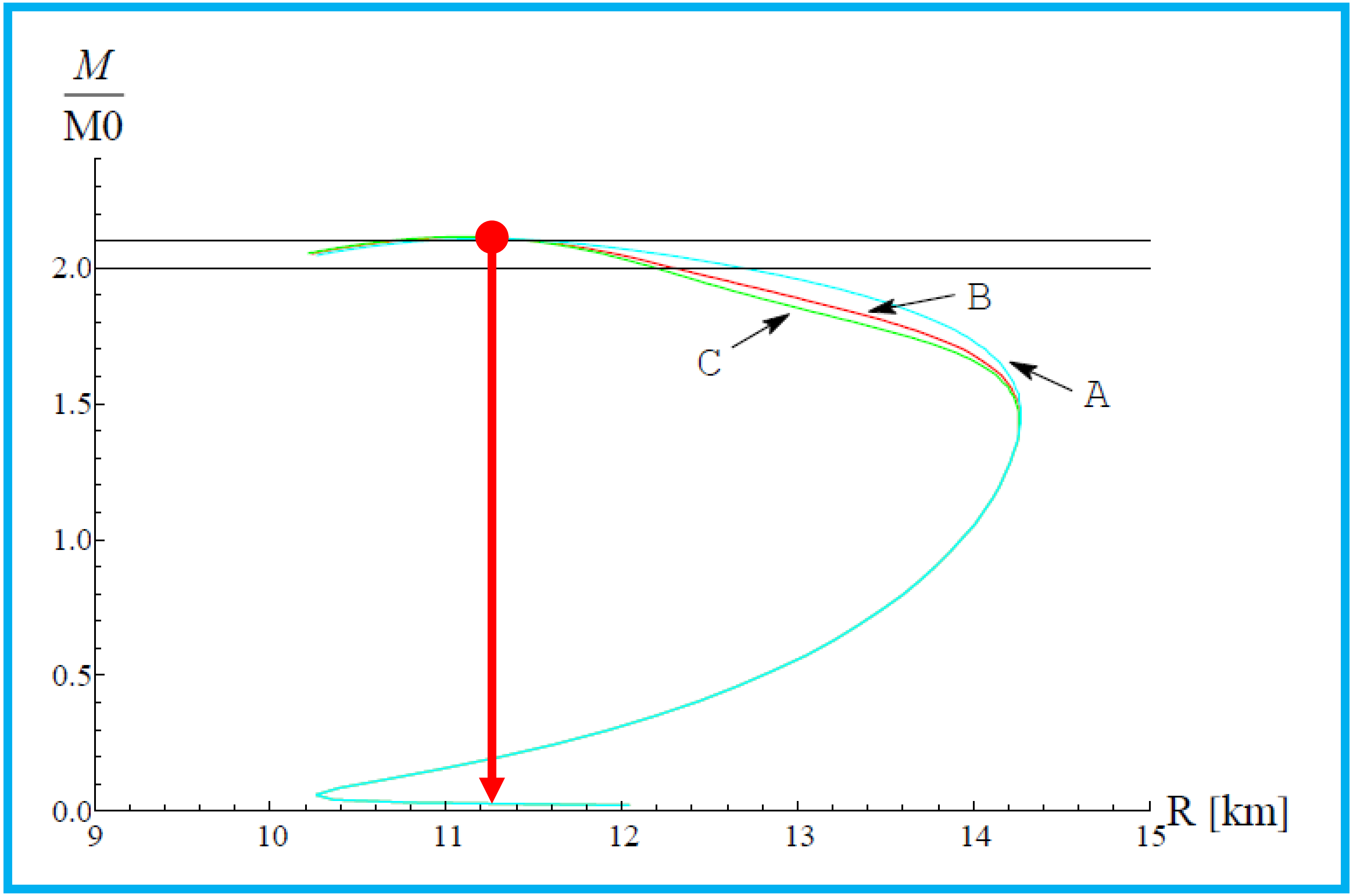
$$\rho_{sat} = 0.162\ [\mathrm{fm}^{-3}]$$
$$E(\rho_{sat})/\rho_{sat} = -15.91\ [\mathrm{MeV}]$$
$$K_\infty(\rho_{sat}) = 247.05\ [\mathrm{MeV}]$$

Asymmetric Infinite Matter

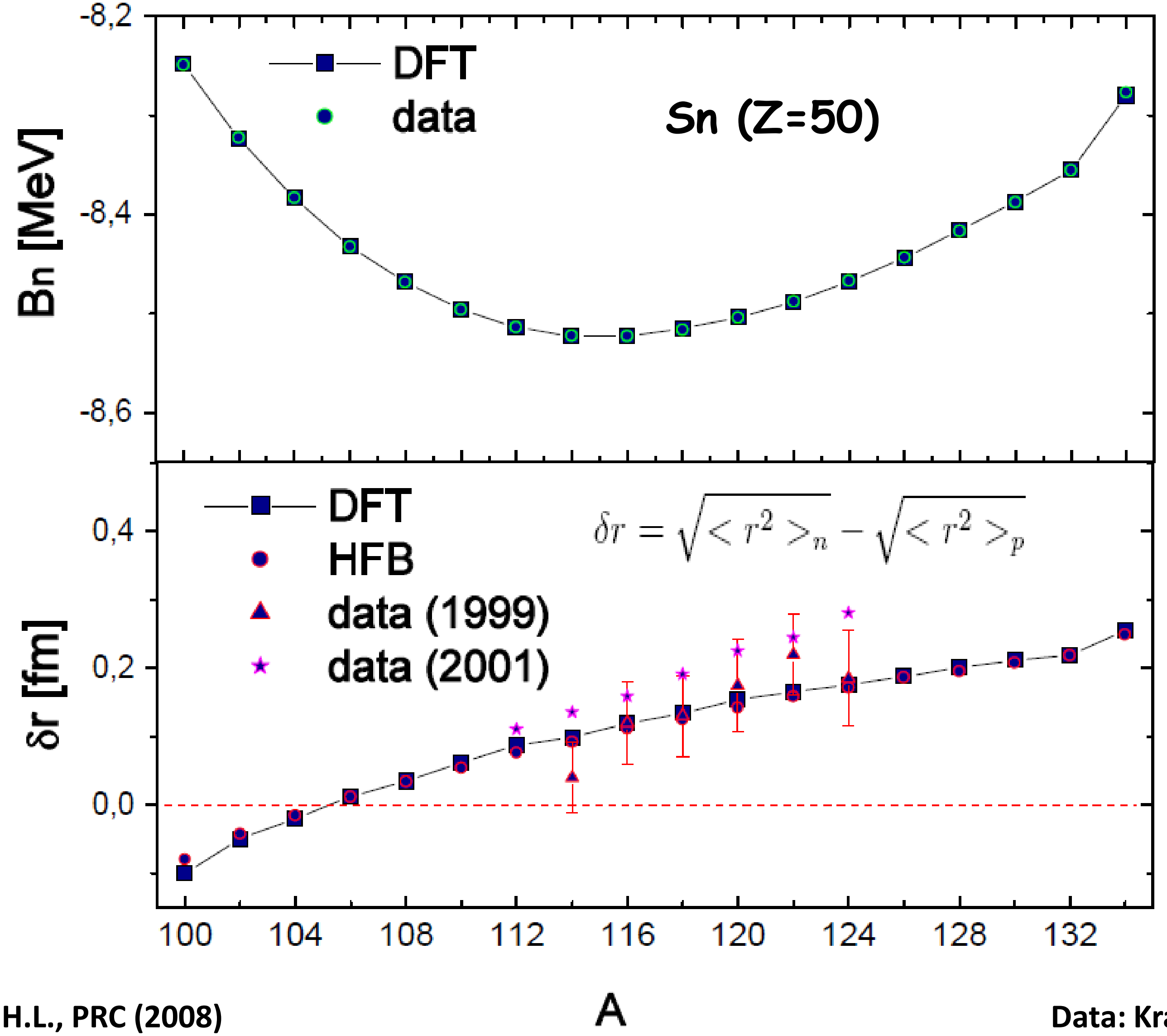


$$\mathrm{E_{sym}}(\rho_{sat}) = 33.41\ [\mathrm{MeV}]$$
$$\mathrm{L_{sym}}(\rho_{sat}) = 53.86\ [\mathrm{MeV}]$$
$$\mathrm{K_{sym}}(\rho_{sat}) = -188.37\ [\mathrm{MeV}]$$

GiEDF and (npΛeμ) Neutron Stars



GiEDF and Nuclei: Binding Energy and Skin Thickness



N. Tsoneva, H.L., PRC (2008)

Data: Krasnahorkay et al.

Nuclear Excitations

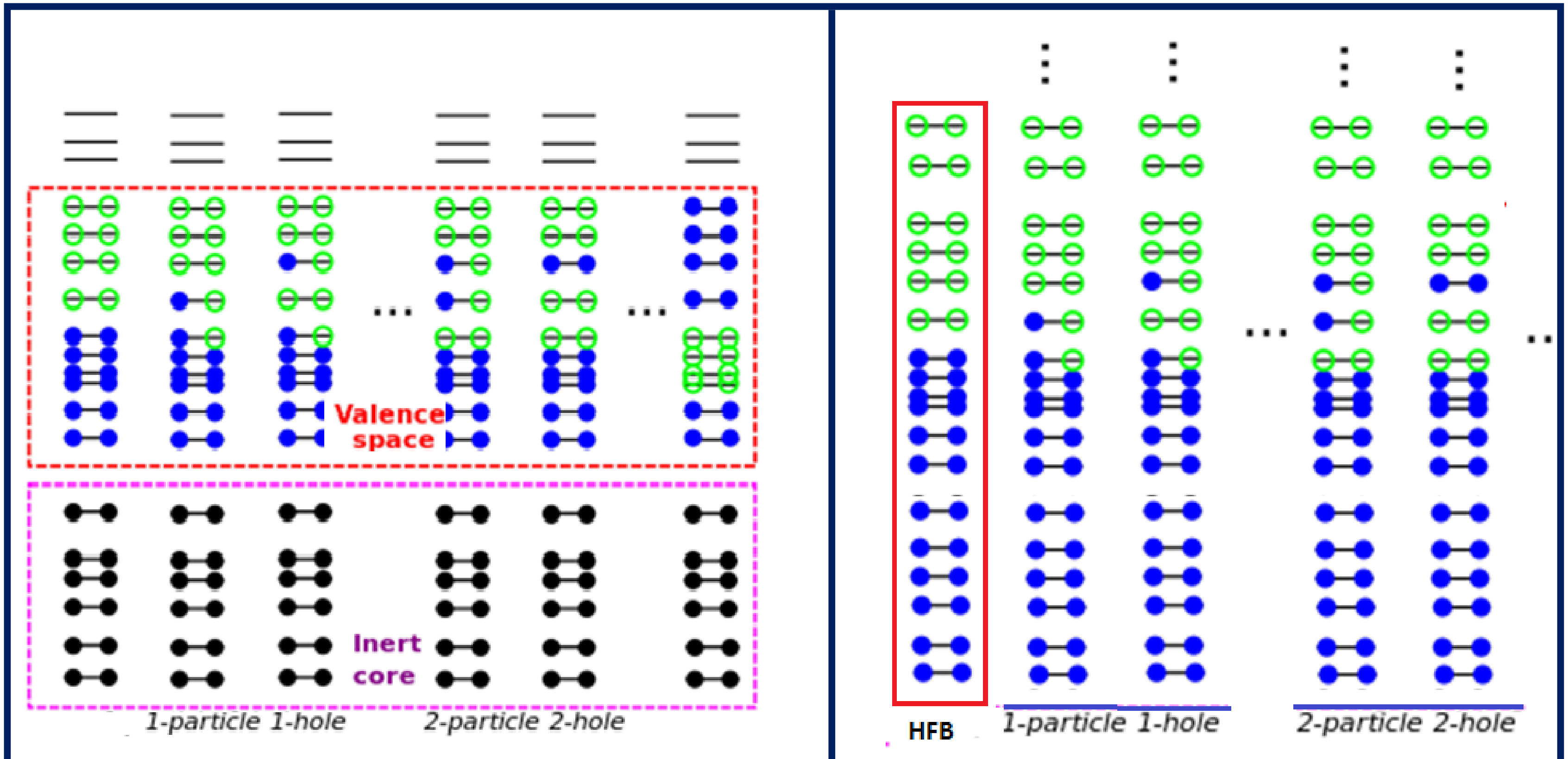
Strategies for Nuclear Spectroscopy

Multi-configuration Shell Model

- Truncation to a few valence shells
- Complete np-nh treatment within the valence space
- Systematic expansion in valence shell number

Multi-configuration Mean-Field Model

- Truncation in ph-number
- Limited, but unrestricted configuration space
- Sytematic expansion in np-nh number



Giessen DFT and Multi-Phonon QRPA (QPM) Theory

$$E(\rho,\kappa) \approx E(\rho_0,\kappa_0) + \sum_{q=p,n}\left(\left(T_q + U_q(\rho_0)\right)\delta\rho_q + \Delta_q\delta\kappa_q\right) + \sum_{q,q'=p,n} f_{qq'}(\rho_0)\delta\rho_q\delta\rho_{q'} + \ldots$$

$$\delta\rho_q \sim \varphi_k^\dagger\varphi_n \quad ; \quad \delta\kappa_q \sim \tilde{\varphi}_k\varphi_n \ \text{\& h.c.}$$

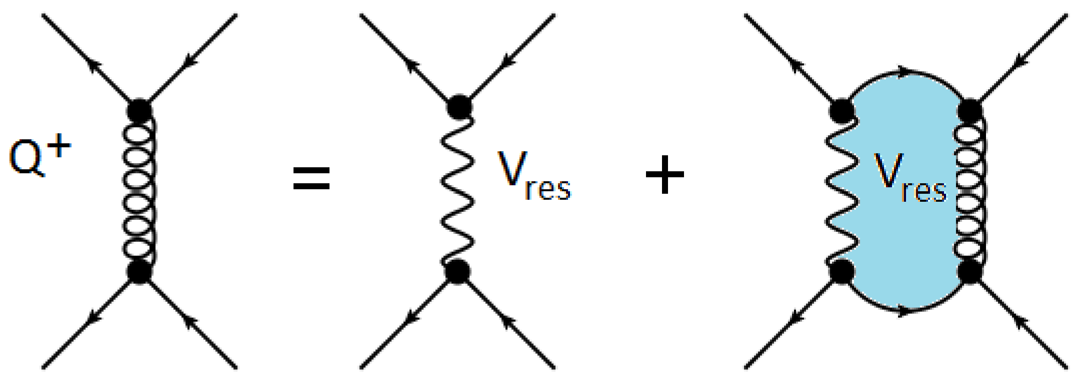
Landau-Migdal Residual Interaction:

$$f_{qq'} = V_{qq'}(\rho) + 2\sum_{q''}\rho_{q''}\frac{\delta}{\delta\rho_q}V_{q'q''}(\rho) + \frac{1}{2}\sum_{k'k''}\rho_{k'}\rho_{k''}\frac{\delta^2}{\delta\rho_q\delta\rho_{q'}}V_{k'k''}(\rho)$$

2-Quasiparticle RPA States

$$Q_\alpha^+ = \sum_{ph} \left(x_{ph}^{\alpha} A_{ph}^{+} - y_{ph}^{*\alpha} \tilde{A}_{ph} \right)$$

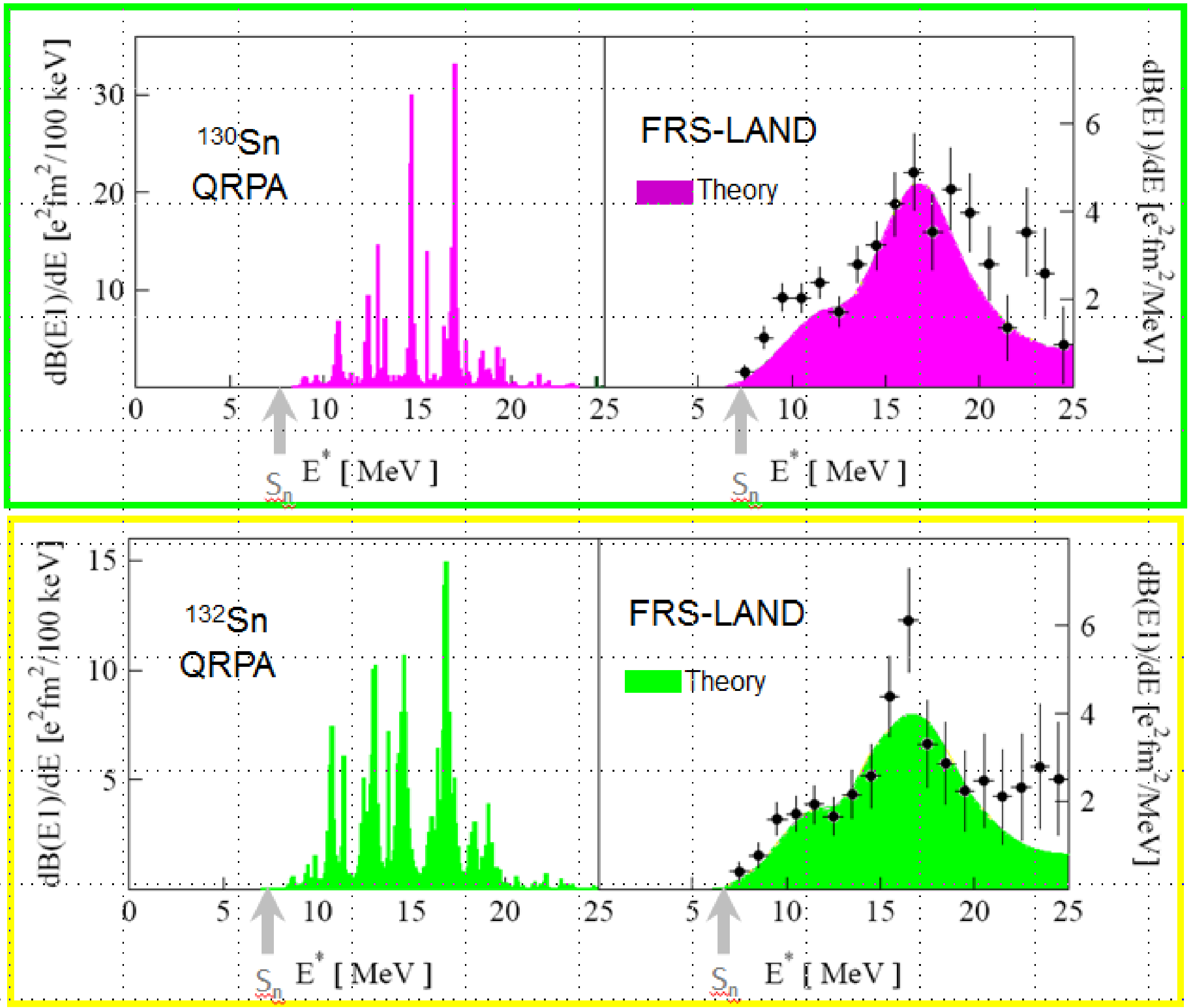
(Q)RPA Dyson Equation:



(Q)RPA Polarization Propagotor:

$$\tilde{\Pi}_{ac}(\omega, q) = \langle 0 | \Gamma_a^{\dagger} \Pi(\omega, q) \Gamma_c | 0 \rangle$$

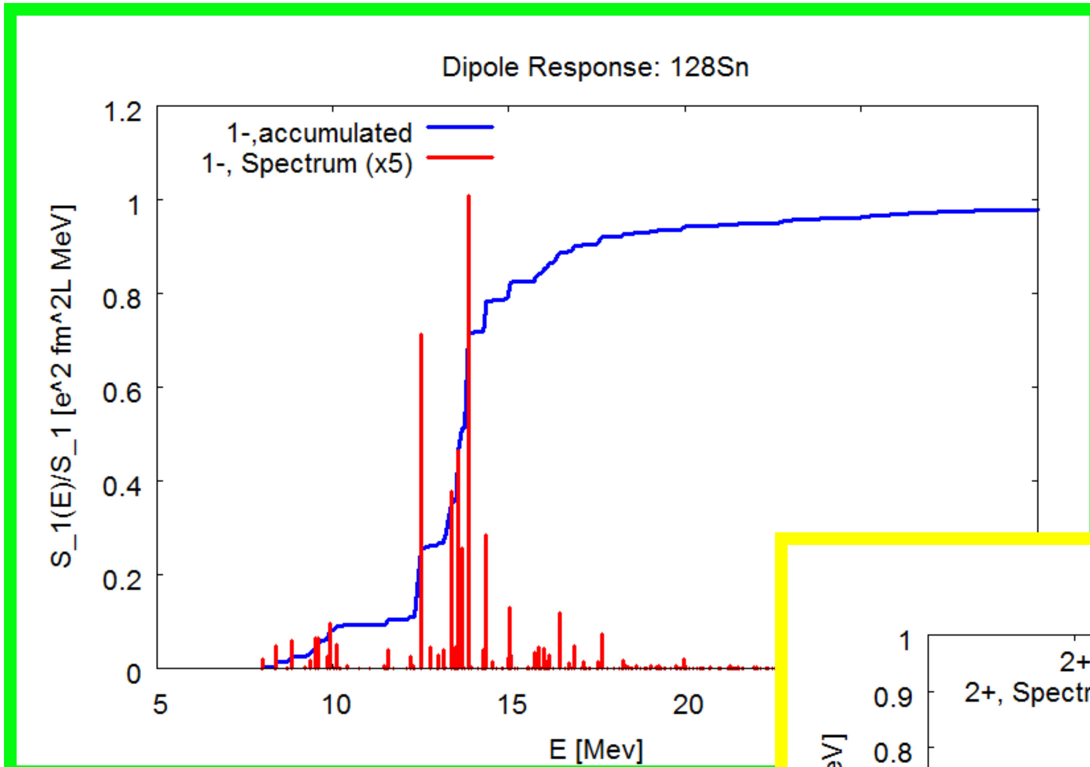
QRPA Dipole Response Functions

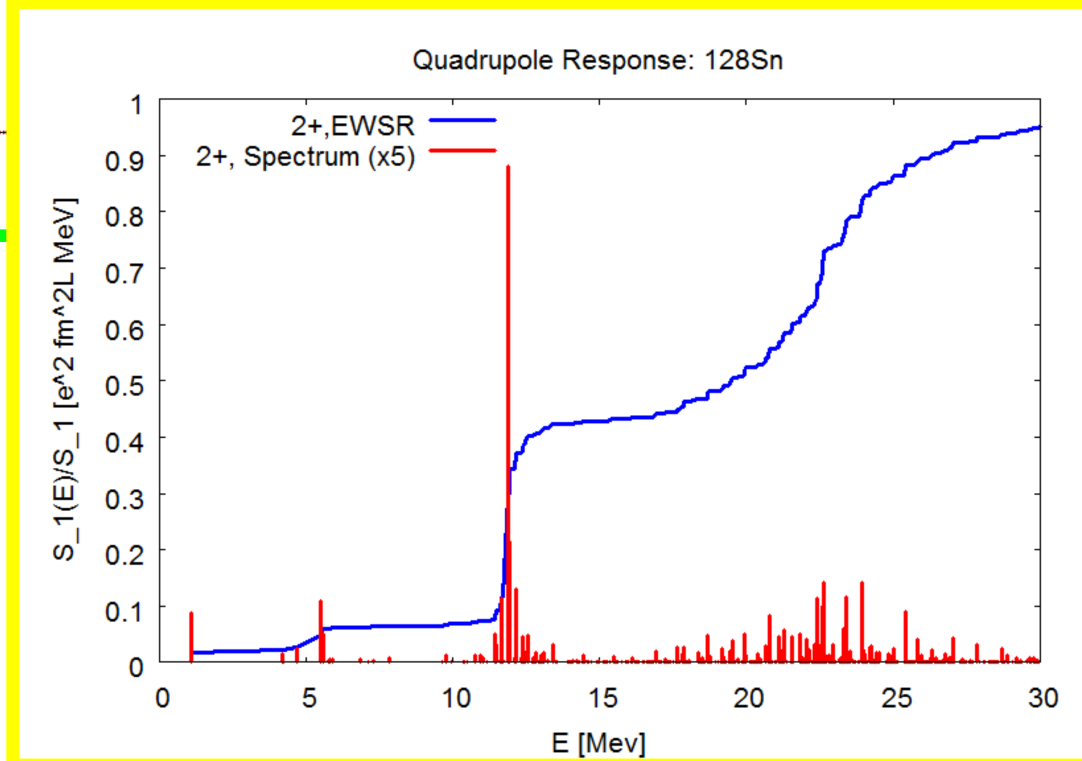


N. Tsonev, H. Lenske, PRC 77:024321 (2008)

P. Adrich et al. PRL95 :132501 (2005)

QRPA-Response ^{128}Sn
Microscopic
DD-QRPA





accumulated, normalized EWSR

$$S_1(E;E\lambda) = \frac{1}{S_1(E\lambda)} \sum_{E_c \leq E} E_c B_c(E\lambda)$$

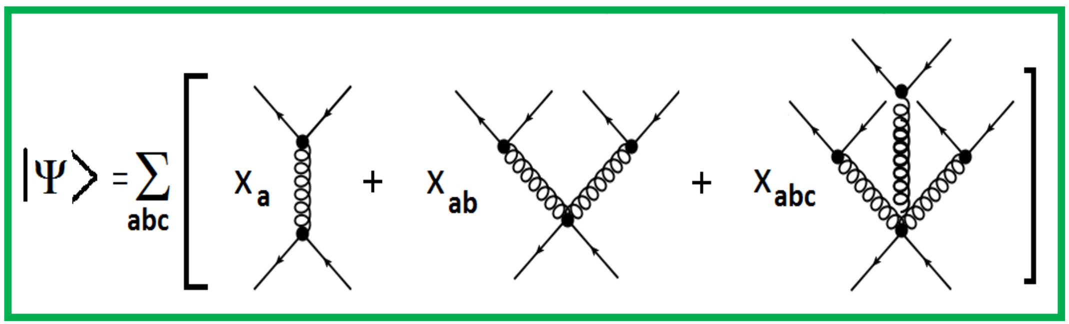
N.Tsoneva, HL,
Phys. Lett. B695 (2011) 174

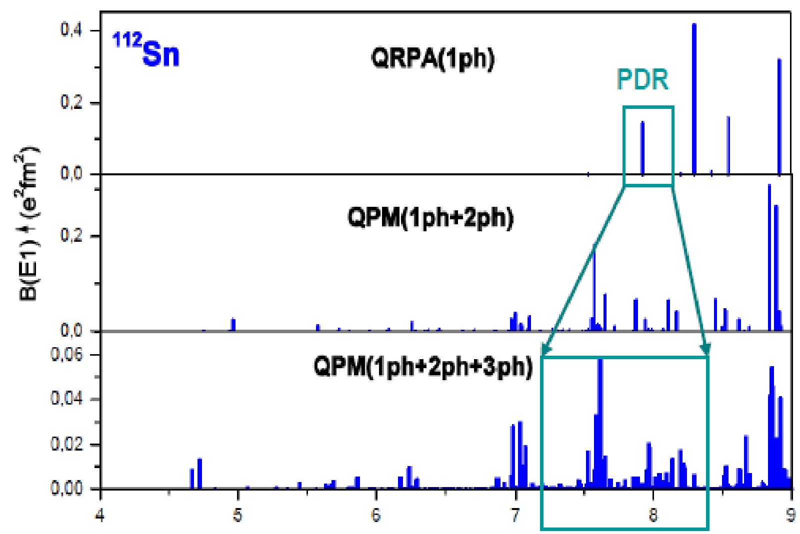
Beyond QRPA – including Anharmonicities: Expansion into up to 6-QP Components

$$\Psi_\nu(JM) = \Big\{ \sum_i R_i(J\nu) Q^+_{JMi} + \sum_{\substack{\lambda_1 i_1 \\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) \left[Q^+_{\lambda_1 \mu_1 i_1} \times Q^+_{\lambda_2 \mu_2 i_2} \right]_{JM}$$

$$+ \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2 \\ \lambda_3 i_3 I}} T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(J\nu) \left[\left[Q^+_{\lambda_1 \mu_1 i_1} \otimes Q^+_{\lambda_2 \mu_2 i_2} \right]_{IK} \otimes Q^+_{\lambda_3 \mu_3 i_3} \right]_{JM} \Big\} \Psi_0$$

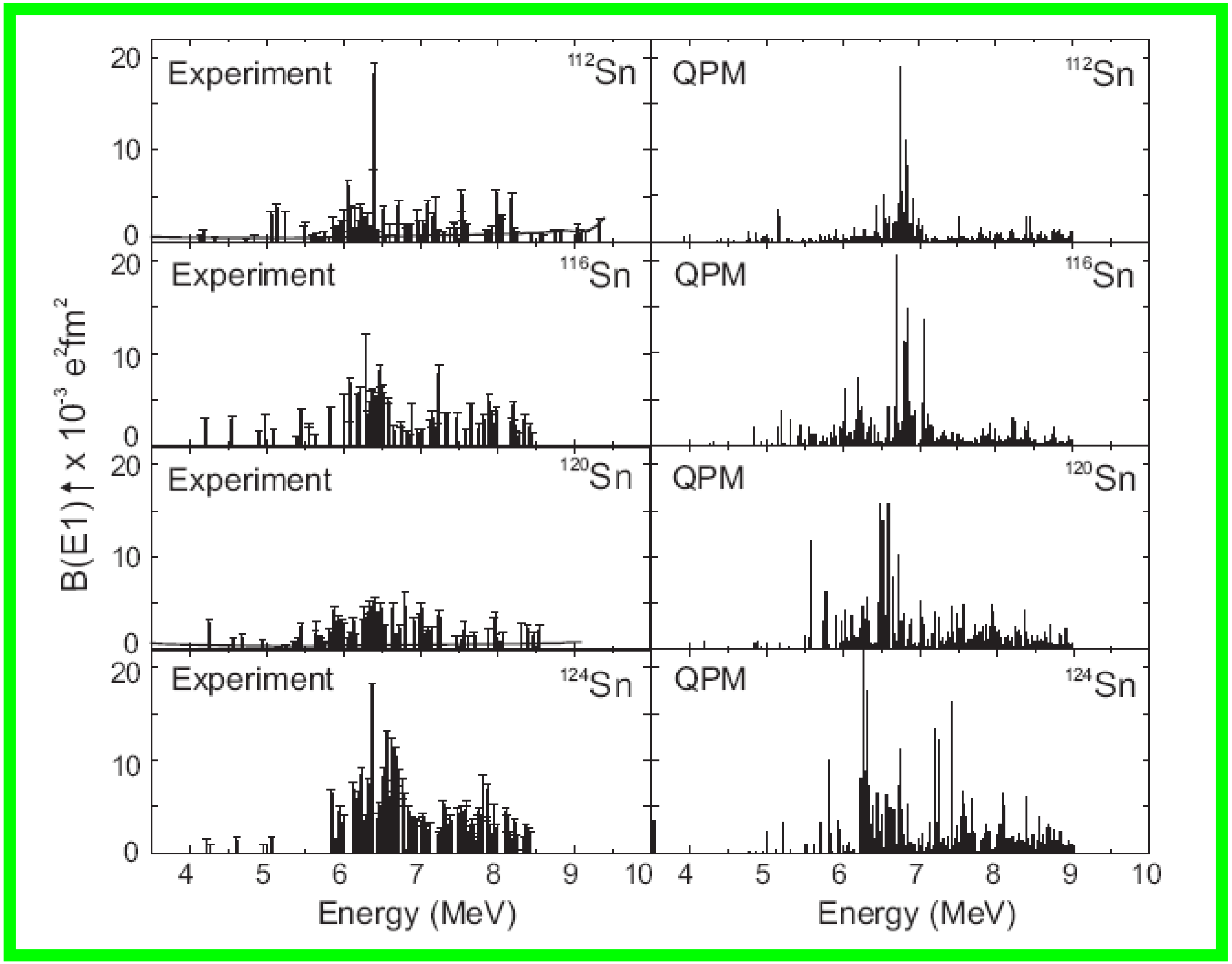
- Basis of QRPA phonons:
- „ph"- and „pp"-type configurations
- Pauli-principle, orthogonality…
- SPECTRAL FRAGMENTATION
- SPECTRAL SHIFTS





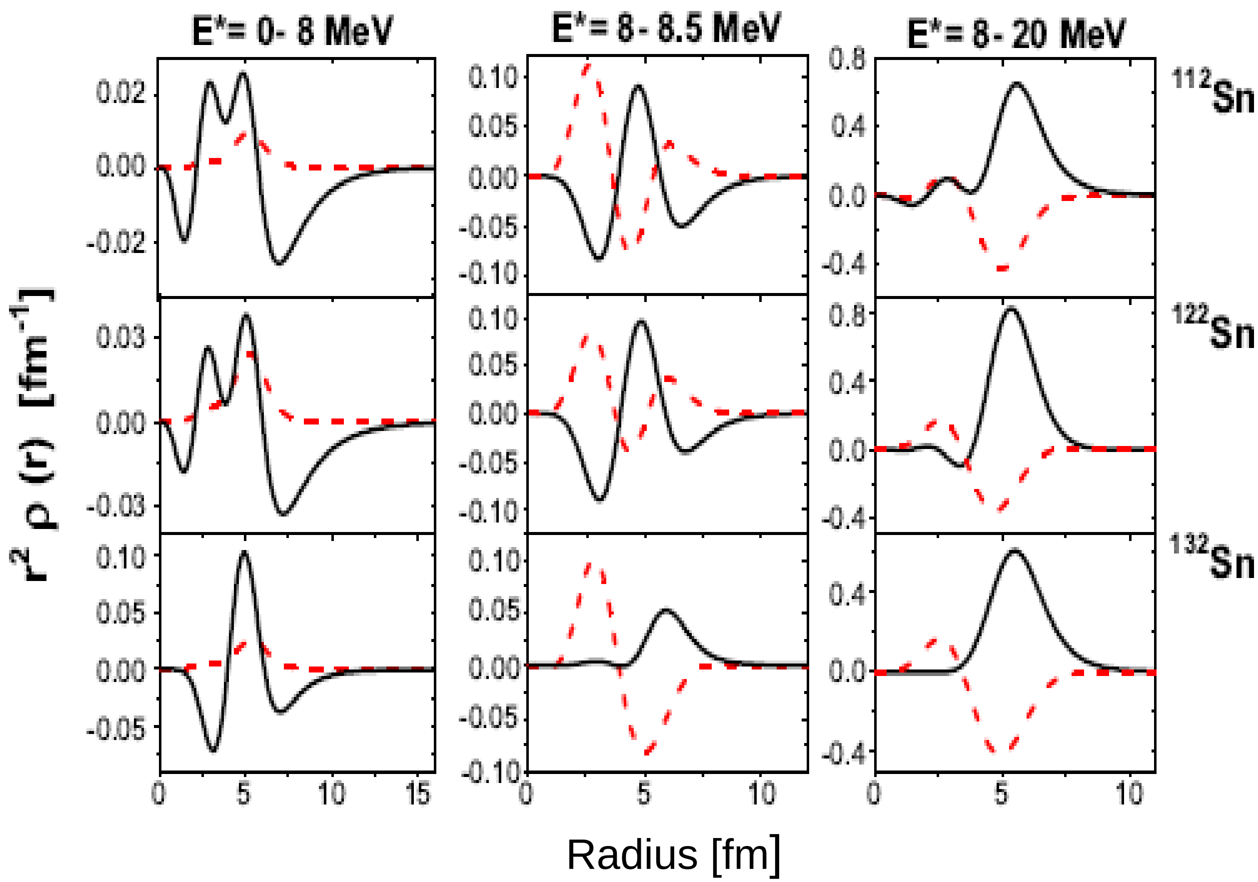
Multi-Configuration Multi-Quasiparticle Wave Function

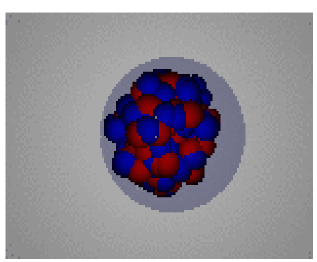
Confronting Theory (GiEDF) with Data (S-DALINAC): Do we understand nuclear Spectra?



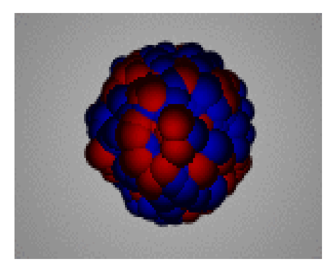
PhysRevC.90.024304(2014)

Identifying the Skin-Mode: Dipole Transition Densities in Sn Isotopes





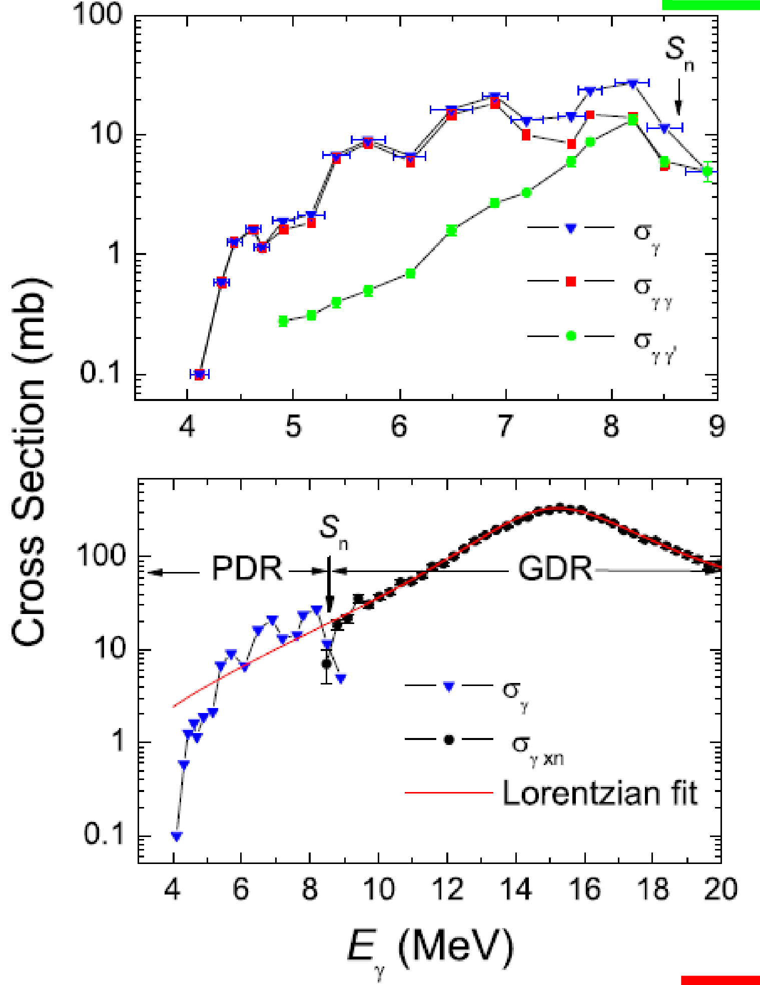
Mixed
transient

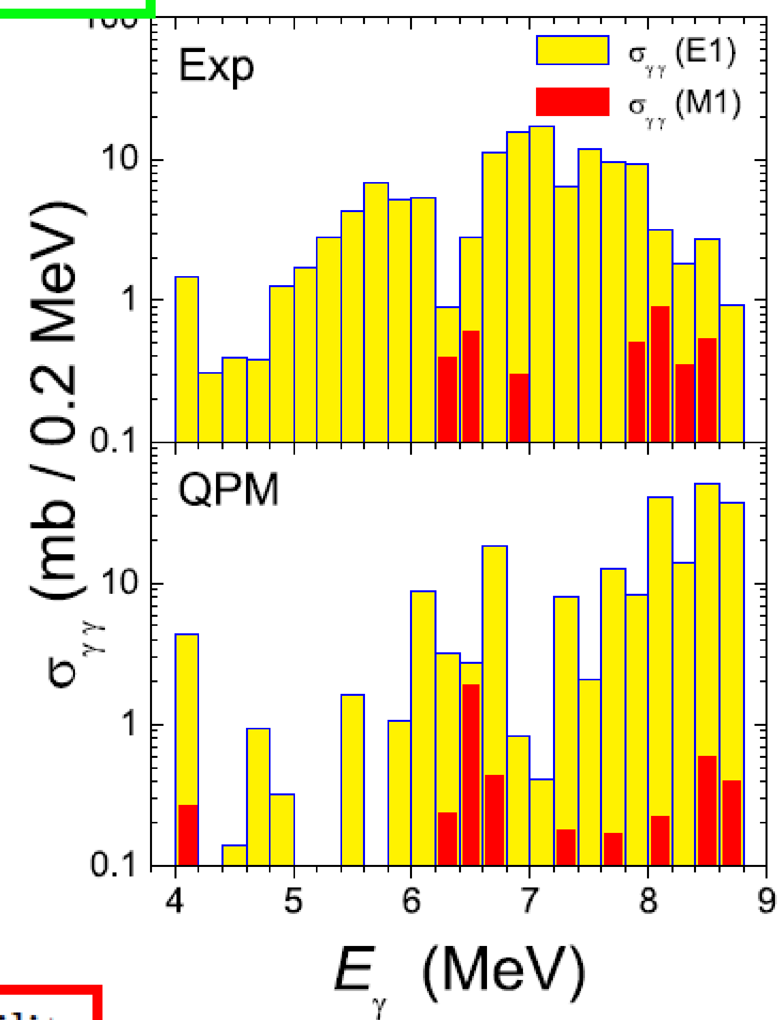


N.Tsoneva, H. Lenske, PRC 77 (2008) 024321

Low Energy Dipole Response: Parity Assignment

$^{138}Ba(\vec{\gamma}, \gamma')$



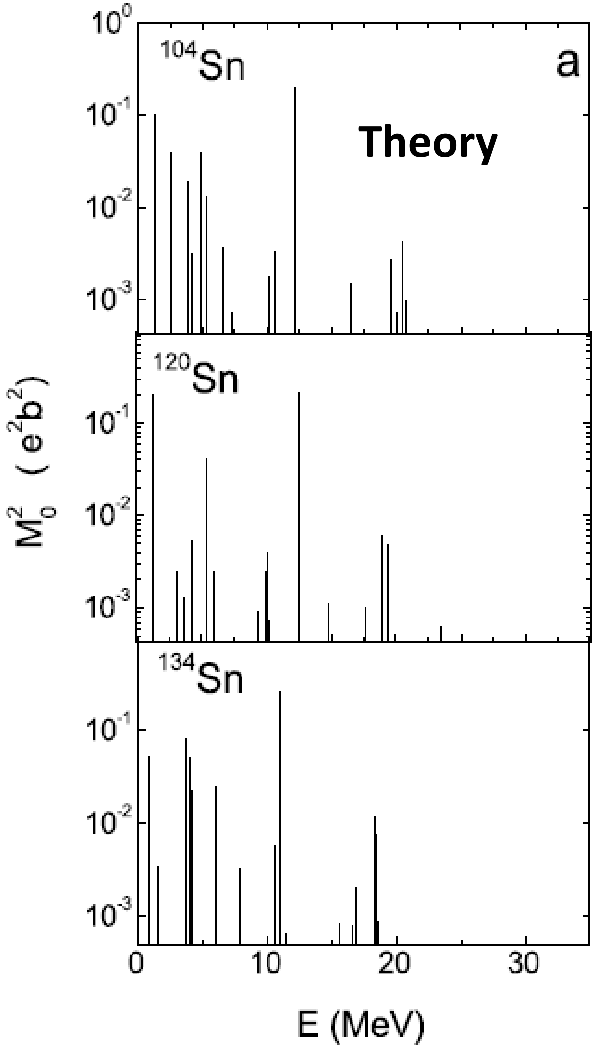


$HI\vec{\gamma}S$ facility

PRL 104, 072501 (2010)

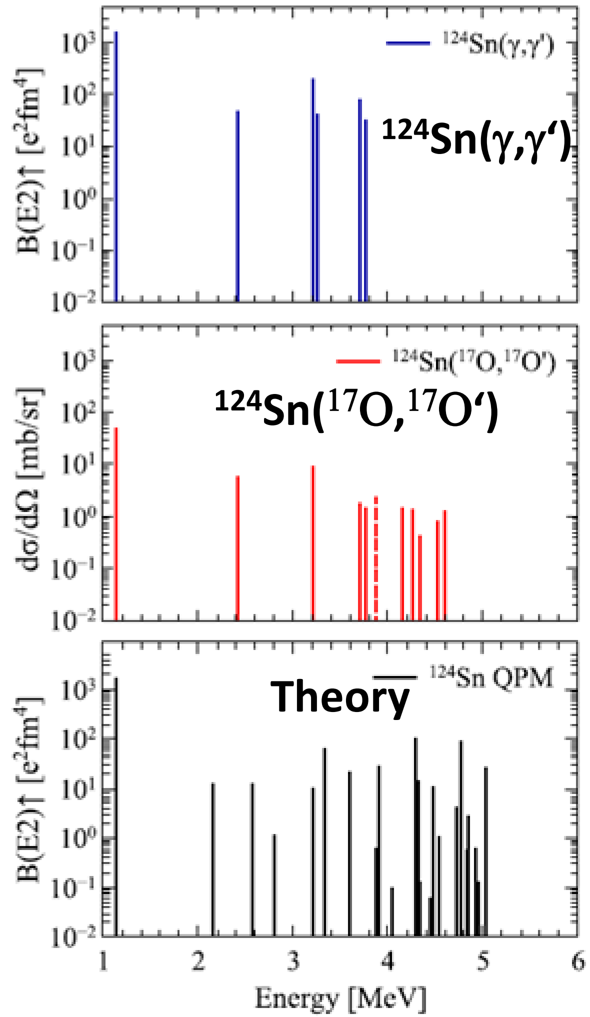
The PQR Mode – Quadrupole Oscillations of the Neutron Skin

…predicted in 2011:

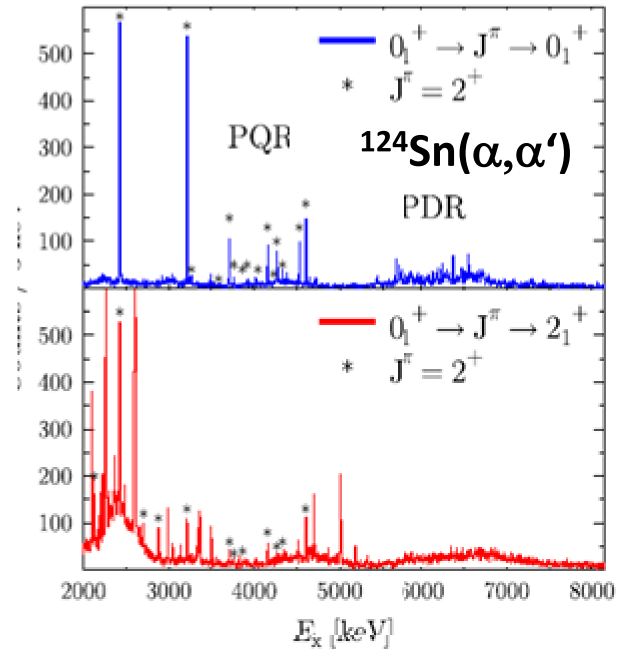


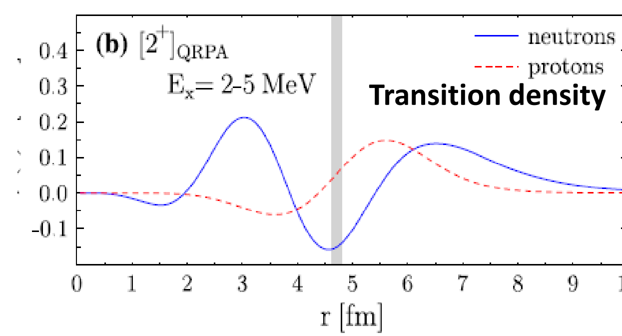
N. Tsoneva, H. Lenske, PLB 695 (2011)

…experimentally confirmed in 2015/2016:



L.Pellegri, N. Tsoneva et al., PRC 92, 014330 (2015)

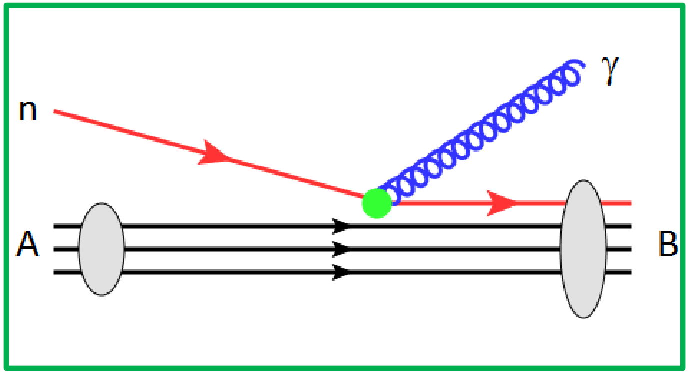




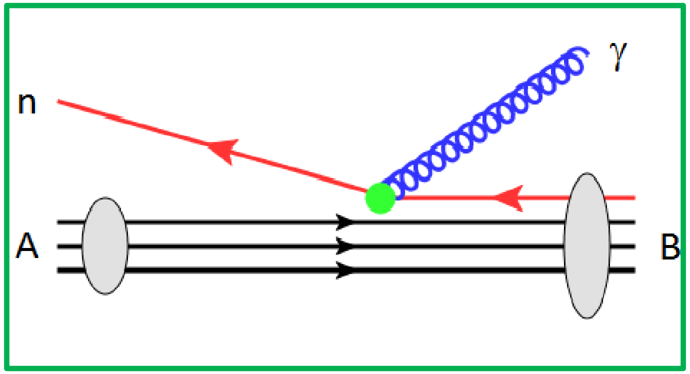
M. Spieker, N. Tsoneva et al., PLB 752 (2016)

Capture Cross Sections

Astropyhysical (n,γ) Capture Cross Sections and Nuclear Structure



Detailed balance

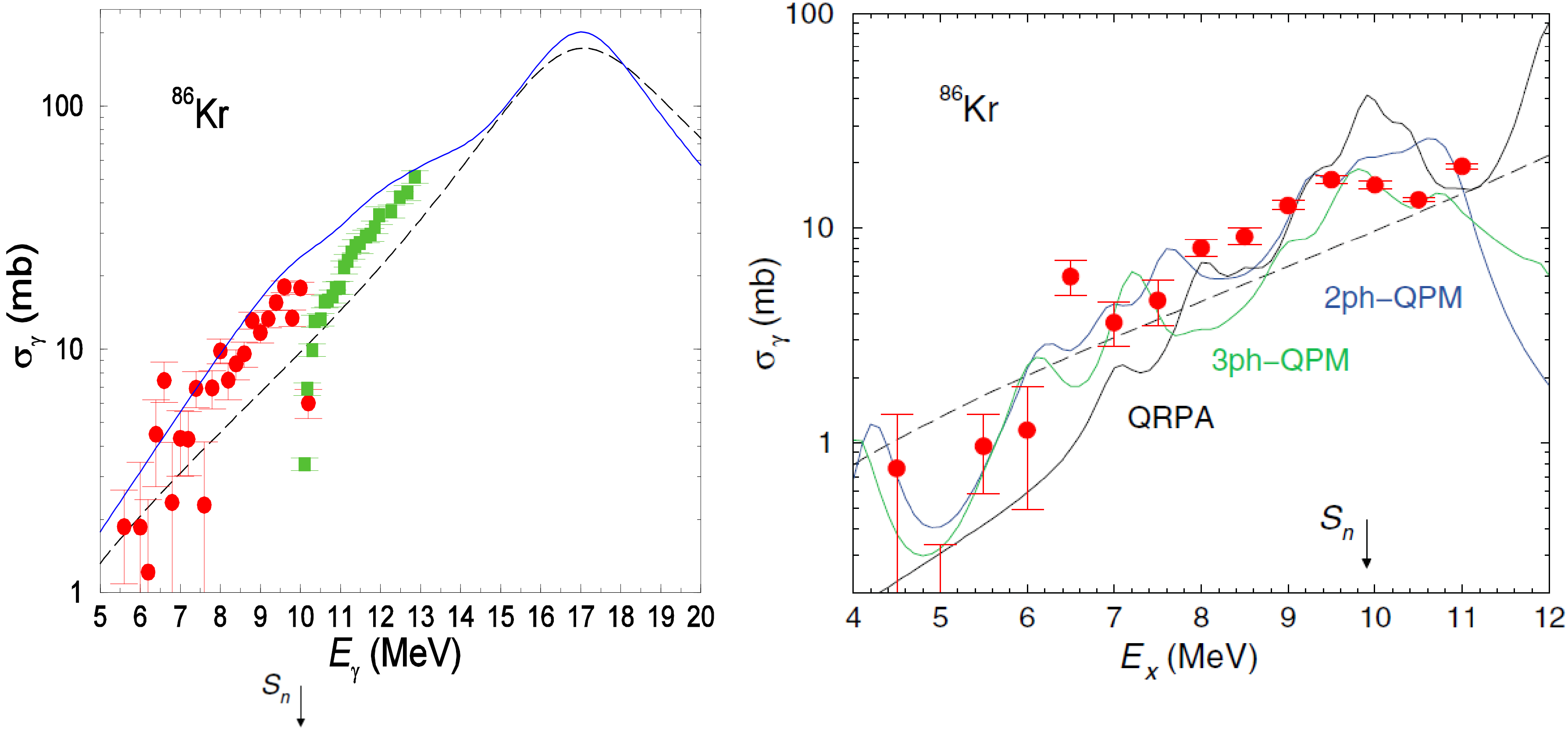


Total capture cross section:
Incoherent superposition of electric (E) and magnetic (M) Multipoles

$$\sigma(E_{\mathrm{c.m.}}) = \sum_{LSJ_iJ_f\ell} \frac{8\pi}{2J_f+1} \frac{\alpha}{v_{\mathrm{rel}}} \frac{q}{1+q/m_f} \left[\left| E_\ell^{LSJ_iJ_f}(q) \right|^2 + \left| M_\ell^{LSJ_iJ_f}(q) \right|^2 \right]$$

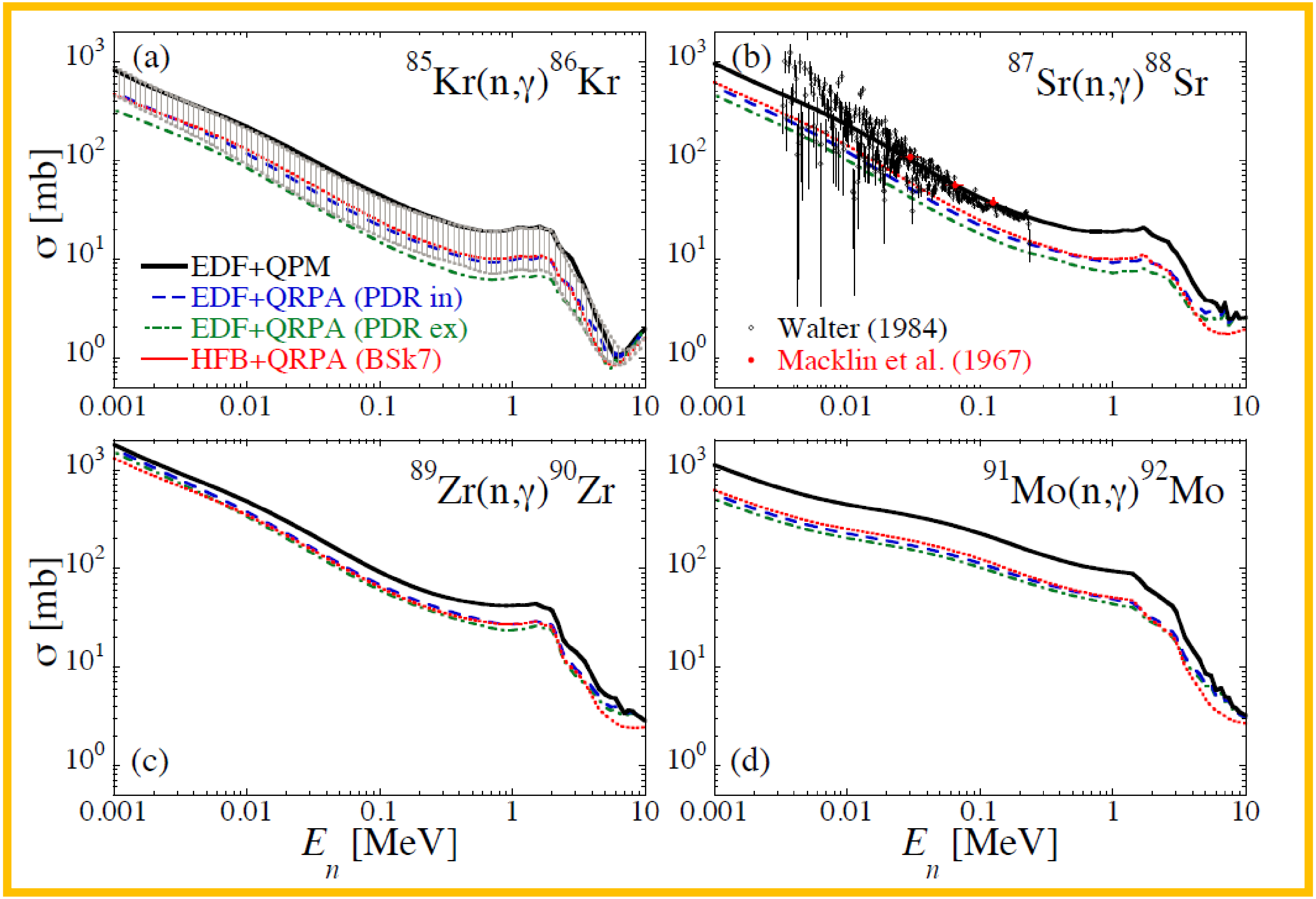
$$E_\ell^{LSJ_iJ_f}(q) \underset{q\to 0}{\to} \frac{q^L}{(2L+1)!!} \sqrt{B_{J_iJ_f}(EL)}\ \delta_{S0} \quad \text{etc.}$$

Cross Section measurements of the $^{86}Kr(\gamma,n)$ Reaction → Probing the s-Process Branch Point at ^{85}Kr



R. Schwengner, N. Tsoneva et al., PhysRevC.87. 024306 (2013)

GiEDF Multiphonon (QPM) Approach to Capture Cross Sections



N.Tsoneva et al., PhysRevC.91.044318 (2015)

Collection of Observables recording the Charge Asymmetry

Skin Thickness

$$\Delta r_{np} = \sqrt{\langle r^2 \rangle_n} - \sqrt{\langle r^2 \rangle_p},$$

Symmetry Energy

$$S(\rho) \equiv \frac{1}{2} \left(\frac{\partial^2 \mathcal{E}(\rho, \alpha)}{\partial \alpha^2} \right)_{\alpha=0} \approx \mathcal{E}(\rho, \alpha = 1) - \mathcal{E}(\rho, \alpha = 0)$$

Density Dependence of the Symmetry Energy

$$S(\rho) = J + Lx + \frac{1}{2} K_{\mathrm{sym}} x^2 + \ldots \quad \text{with } x \equiv \frac{\rho - \rho_0}{3\rho_0}.$$

Nuclear Dipole Polarizability and Photoabsorption

$$\alpha_D = \frac{1}{2\pi^2 \alpha} \int_0^\infty \frac{\sigma_\gamma(E)}{E^2} \, dE = \frac{\sigma_{-2}}{2\pi^2 \alpha}$$

Summary and Outlook

- **New low-energy modes: PDR, PMR. PQR…**
- **GiEDF: extended DFT approach to nuclear spectra**
- **Nuclear ground states by HFB theory**
- **Multi-phonon approach to nuclear excitations**
- **Subthreshold pygmy modes and capture cross sections**
- **Correlations: PDR ↔ skin thickness ↔ polarizability ↔ slope L ↔ …?**
- **Predictions of s- and r-process nucleosynthesis rates**

In collaboration with:

N. Tsoneva, S. Goriely, J. Piekarewicz, R. Schwengner, M. Spieker, A. Tonchev…

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