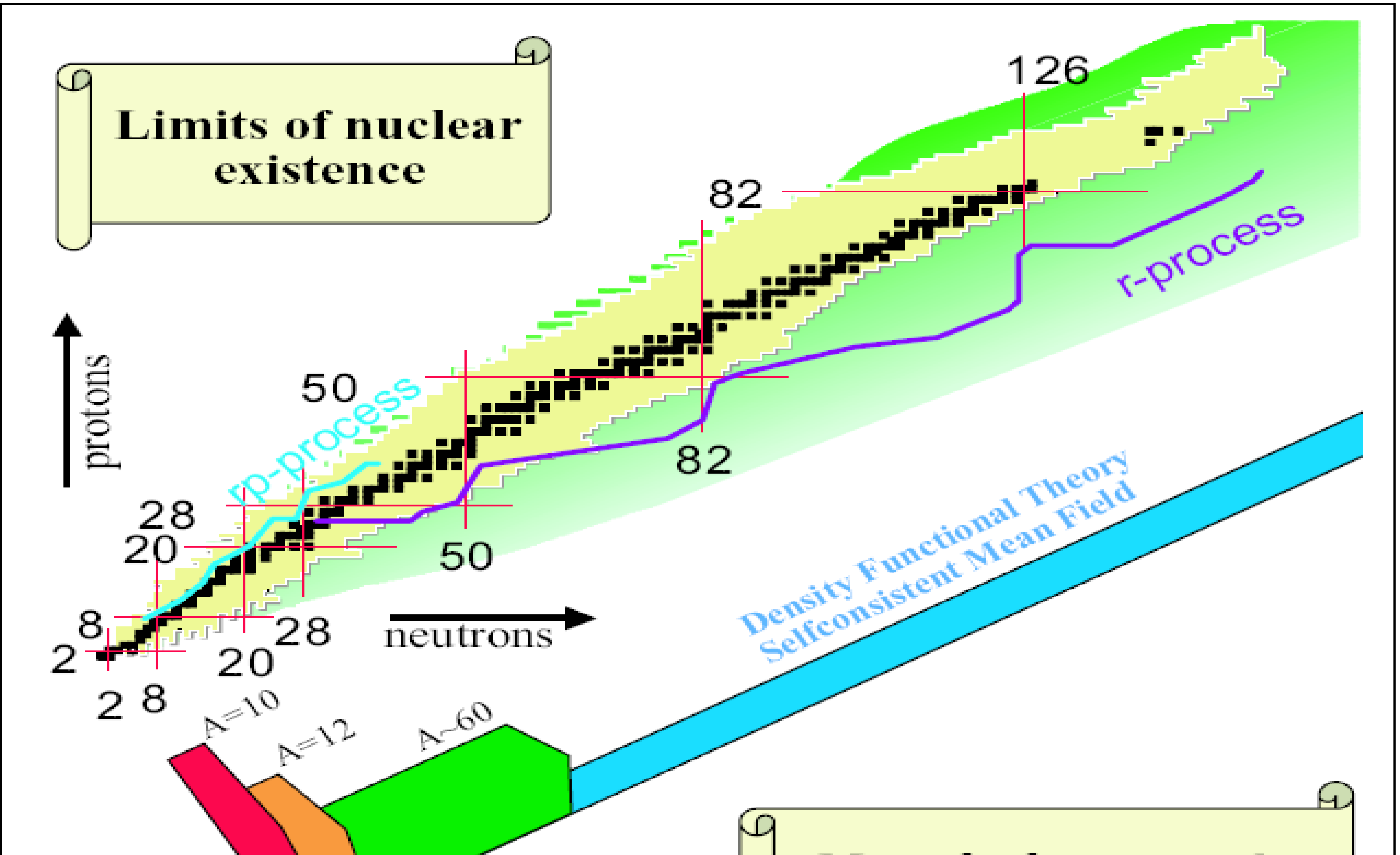
Density Functional Theory for Processes of Astrophysical Interest

H. Lenske

Institut für Theoretische Physik, U. Giessen



$$E(A)/A = -16\,\mathrm{MeV} + E_{surf}/A^{1/3} + E_{pair} + E_{shell} + E_{coul}$$

$$+ [(N-Z)/A]^2(a_4 + C_{sym}/A^{1/3})$$

Agenda:

- Sketch of Density Functional Theory
- Pairing in the Continuum
- Dynamical Correlations and Fano-Resonances
- New Modes of Excitation: Pygmy Dipole States

…the Mass Formula:
a functional of neutron number N and proton number Z

$$E(N,Z)/A = -16\text{MeV} + E_{surf}/A^{1/3} + E_{pair} + E_{shell} + E_{coul}$$

$$+ [(N-Z)/A]^2(a_4 + C_{sym}/A^{1/3})$$

The Nuclear Energy Density Functional

$$E(\rho,\kappa) \approx E(\rho_0,\kappa_0) + \sum_{q=p,n,\Lambda\ldots} \frac{\partial E(\rho,\kappa)}{\partial \rho_q}\Big|_{\rho_0} \delta\rho_q + \sum_{q,q'=p,n,\Lambda\ldots} \frac{\partial^2 E(\rho,\kappa)}{\partial \rho_q \partial \rho_{q'}}\Big|_{\rho_0} \delta\rho_q \delta\rho_{q'} + \ldots$$

$$+ \sum_{q=p,n,\Lambda\ldots} \frac{\partial E(\rho,\kappa)}{\partial \kappa_q}\Big|_{\kappa_0} \delta\kappa_q + \sum_{q,q'=p,n,\Lambda\ldots} \frac{\partial^2 E(\rho,\kappa)}{\partial \kappa_q \partial \kappa_{q'}}\Big|_{\kappa_0} \delta\kappa_q \delta\kappa_{q'} + \ldots$$

$$E(\rho,\kappa) \approx E(\rho_0,\kappa_0) + \sum_{q=p,n} \Big(\big(T_q + U_q(\rho_0) \big) \delta\rho_q + \Delta_q \delta\kappa_q \Big)$$

$$+ \sum_{q,q'=p,n} f_{qq'}(\rho_0) \delta\rho_q \delta\rho_{q'} + \ldots$$

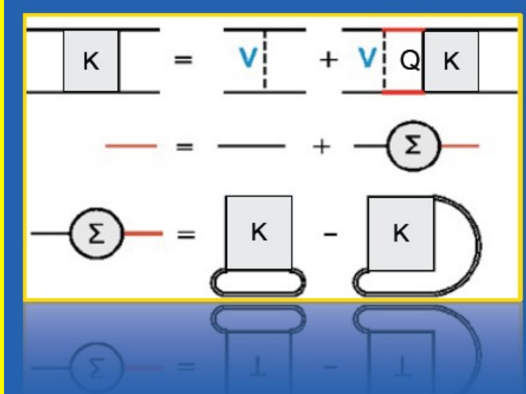
Fermi-Liquid Theory

(A. Ataie, A. Fedoseew, Nadia Tsoneva H.L.)

The Giessen Program: *ab initio* Nuclear DFT:

- NN-Interaction in free space
- in-medium interactions by Dirac-Brueckner Theory
- adding 3-body interactions
- density dependent meson-nucleon vertex functionals
- equation of state, nuclear binding energies, single particle spectra, excitations, reactions…

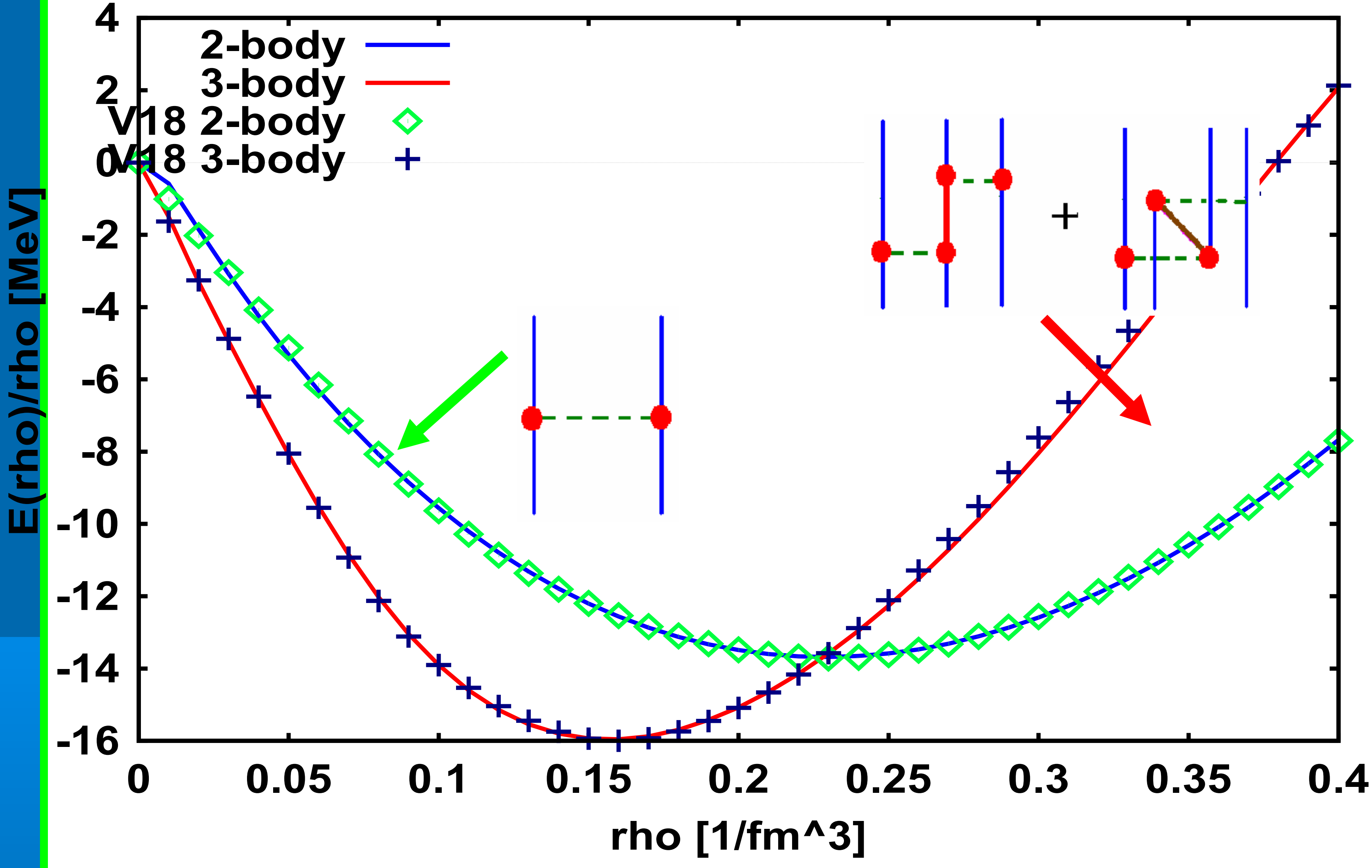
$$K = V + \int V Q_F K$$



- Ladder Kernel
- Map the ab-initio calculations on an effective Lagrangian
- Medium dependent renormalization

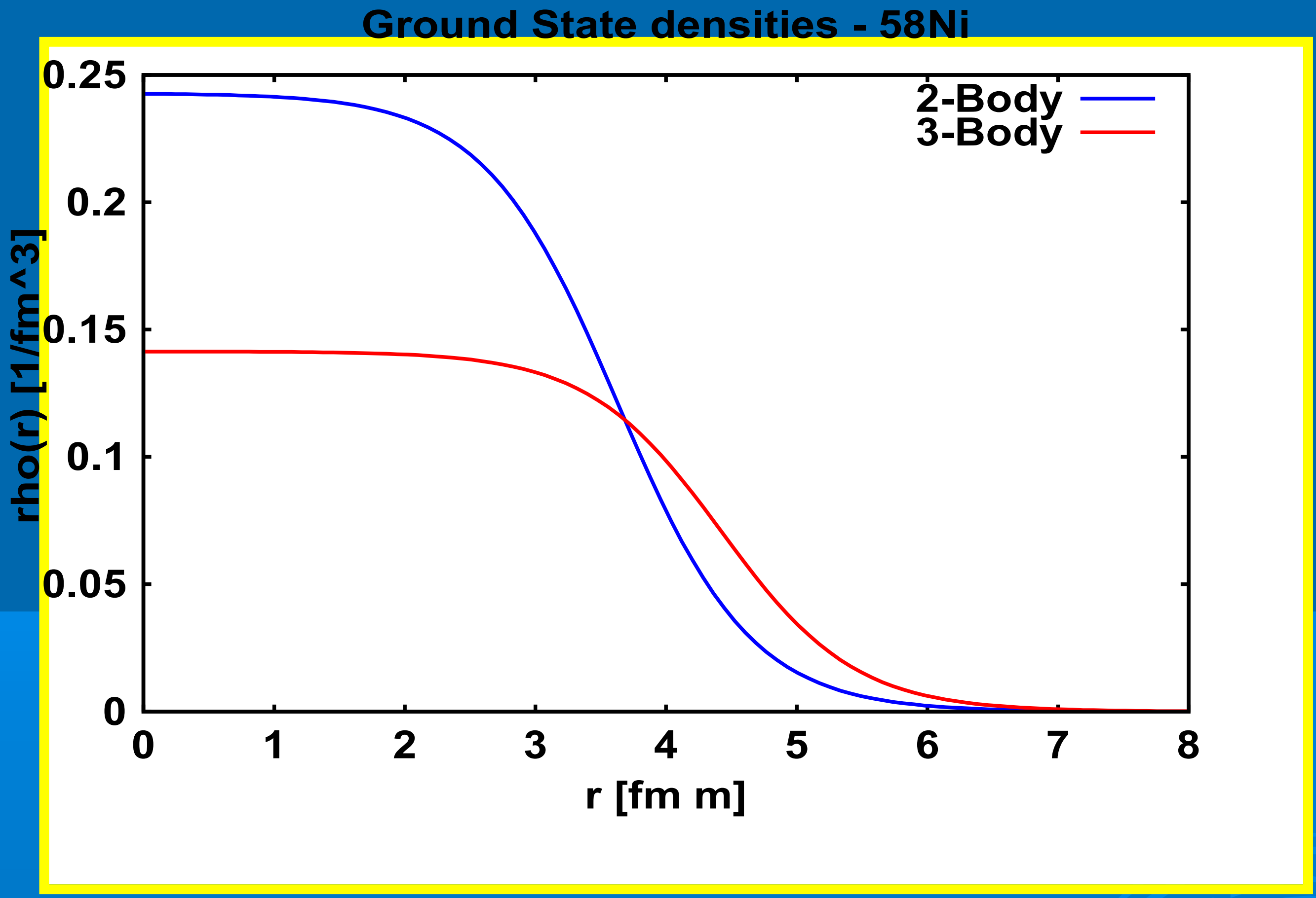
$$V_{OBE} = \sum_\alpha g_\alpha^2 D_\alpha(t) \langle \overline{u}_1 \hat{O}_\alpha u_3 \rangle \langle \overline{u}_2 \hat{O}_\alpha u_4 \rangle$$

EoS of Symmetric Matter



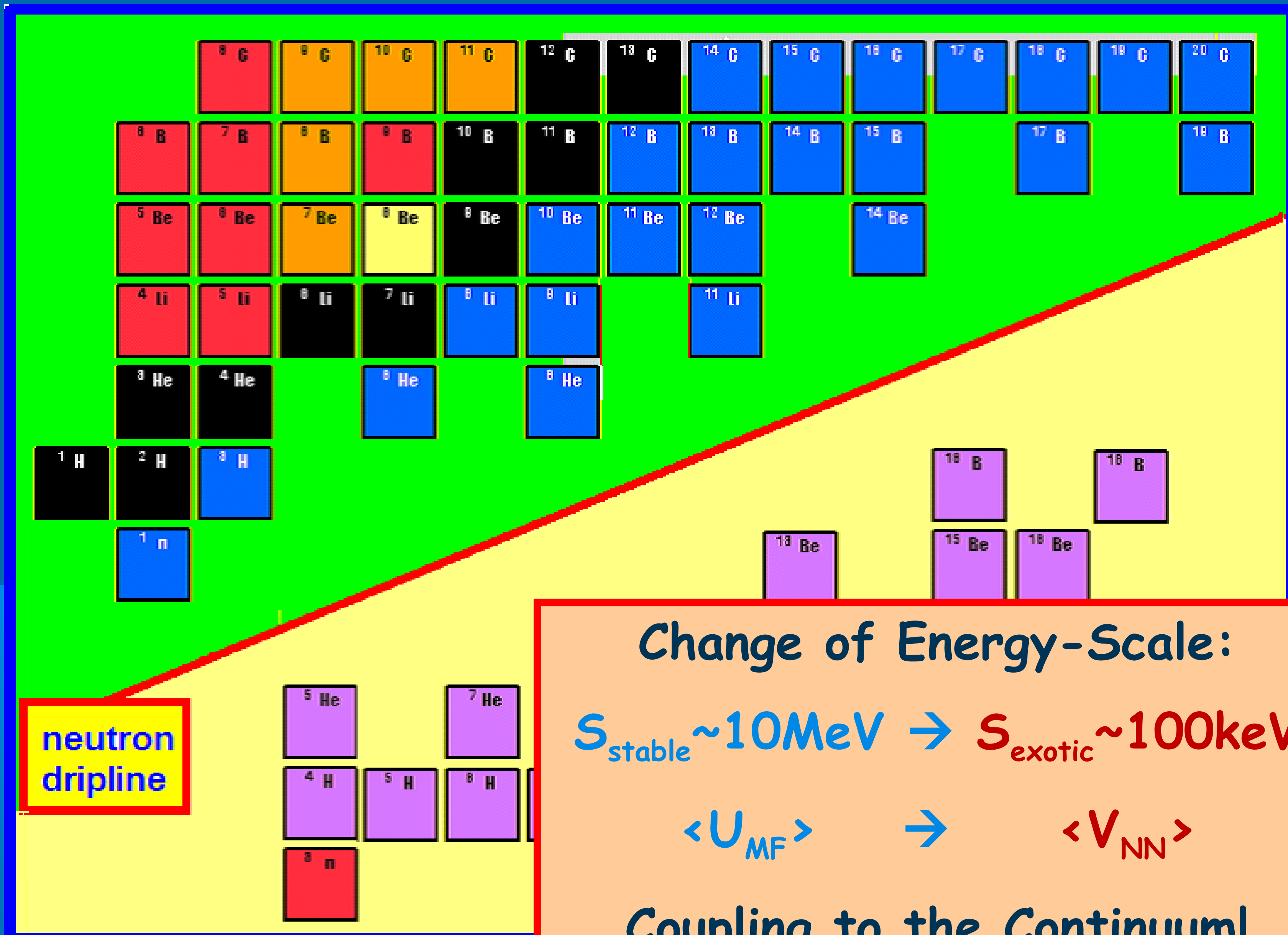
A. Ataie, H.L.

2-body and 3-body Interactions in Nuclei



...two different worlds!

Fluctuating (Fractal?) Structure of the Neutron Dripline



Change of Energy-Scale:

S_{stable}~10MeV → S_{exotic}~100keV

$\langle U_{MF} \rangle$ → $\langle V_{NN} \rangle$

Coupling to the Continuum!

Pairing Theory as Coupled Channels Problem: The Gorkov-Equations

$$\begin{pmatrix} H-\lambda & -\Delta \\ -\Delta^{+} & -(H-\lambda) \end{pmatrix}\begin{pmatrix} \phi_{+} \\ \phi_{-} \end{pmatrix} = E\begin{pmatrix} \phi_{+} \\ \phi_{-} \end{pmatrix}$$

$$\phi_{+} \sim u^{(q)}_{\ell j}(r)\,|(\ell s)jm\rangle;\ \phi_{-} \sim v^{(q)}_{\ell j}(r)\,|(\ell s)jm\rangle$$

Mean-Field Hamiltonian (q = p,n):

$$H = -\frac{\hbar^2}{2m}\vec{\nabla}^2 + U(\rho)$$

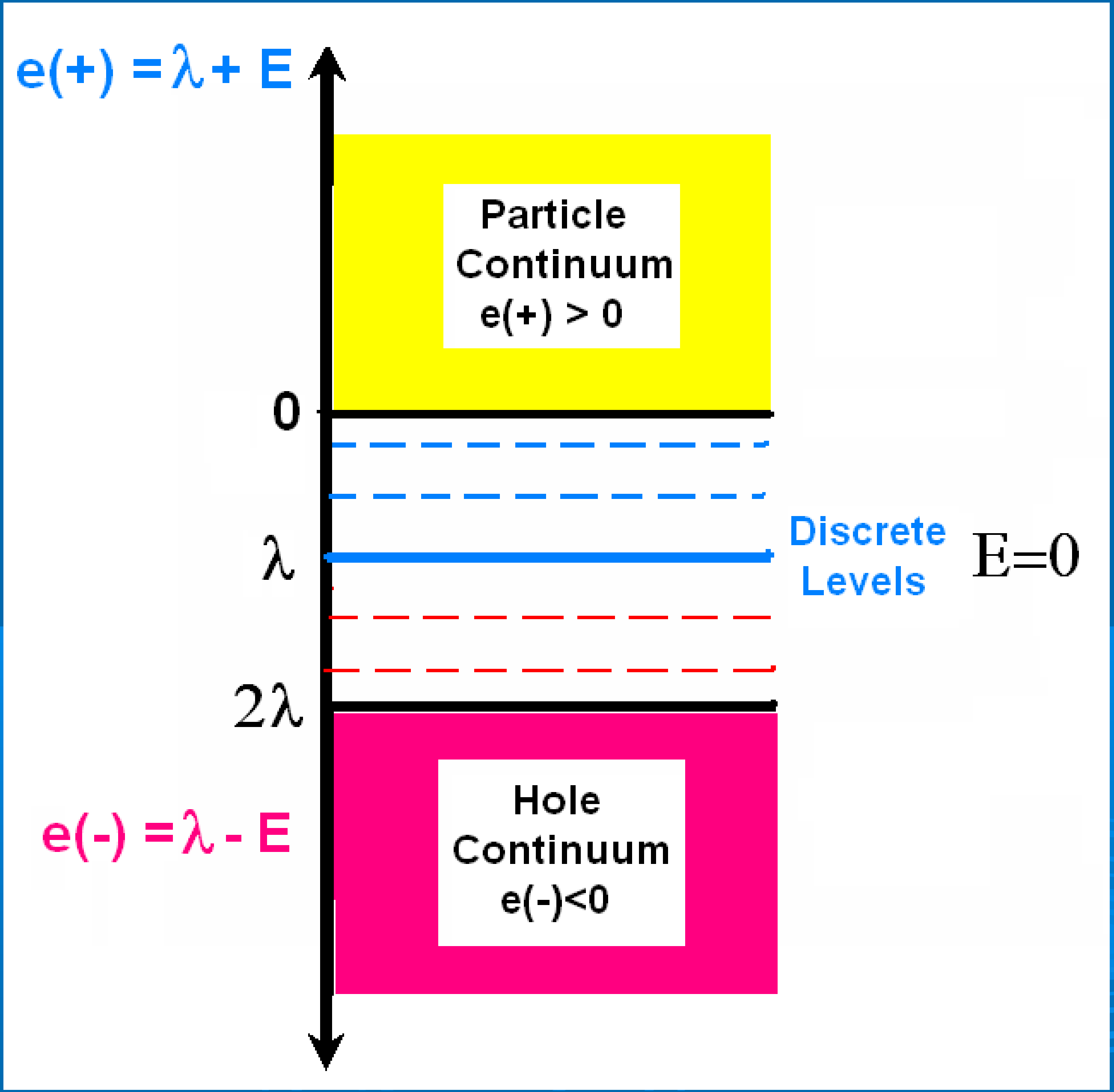
$$\rho_q(r) = \sum_{n\ell j} \frac{2j+1}{4\pi}\,|v^{(q)}_{n\ell j}(r)|^2$$

Pairing-Field & Density (q = p,n):

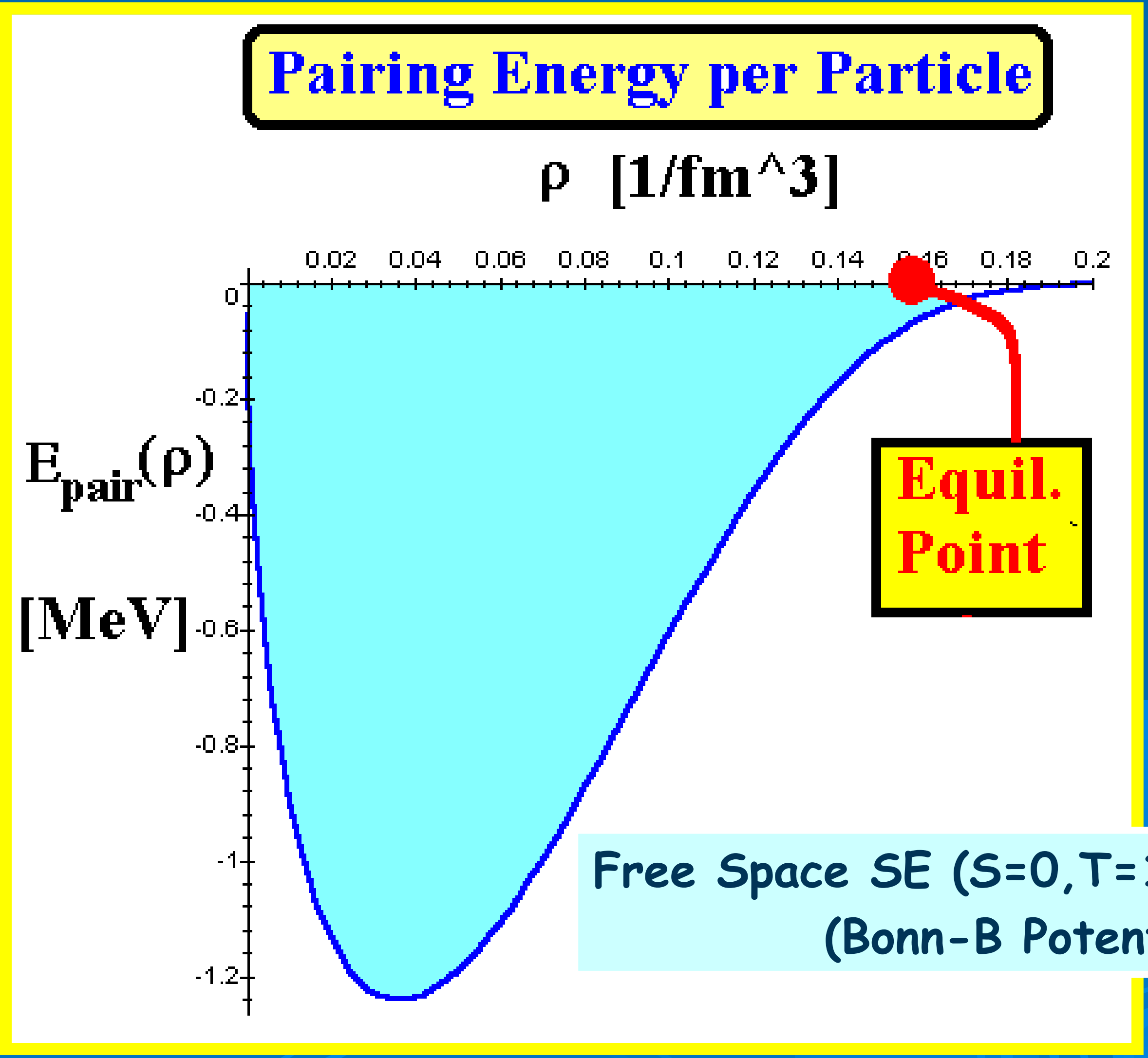
$$\Delta_q = \frac{1}{2} V_{SE}\kappa_q$$

$$\kappa_q(r) = \sum_{n\ell j} \frac{2j+1}{4\pi}\, u^{(q)}_{n\ell j}(r)\, v^{(q)*}_{n\ell j}(r)$$

Spectrum of the Gorkov Equation:



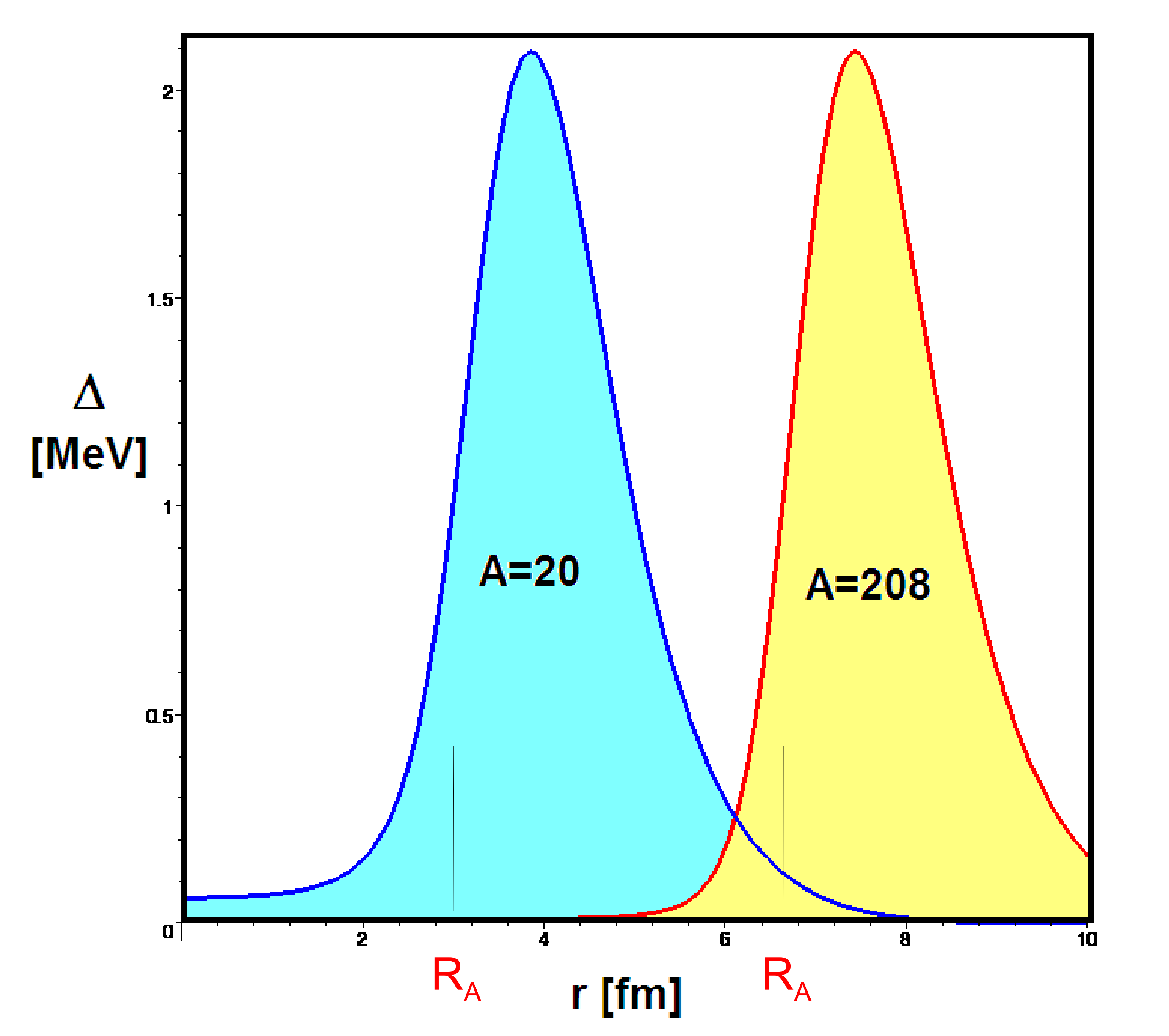
Pairing in Infinite Nuclear Matter



Free Space SE (S=0,T=1) Interaction:
(Bonn-B Potential)

Pairing is a LOW DENSITY Phenomenon

The Pairing-Field in Finite Nuclei



Pairing in the Continuum

$$\Sigma_q^{(c)} = \Delta_q^\dagger \frac{1}{2\lambda_q - e - T_q - U_q} \Delta_q$$

$$u_\alpha(r) \to \cos\left(\delta_\alpha^{(c)}\right) f_\alpha(r) + \sin\left(\delta_\alpha^{(c)}\right) g_\alpha(r),$$

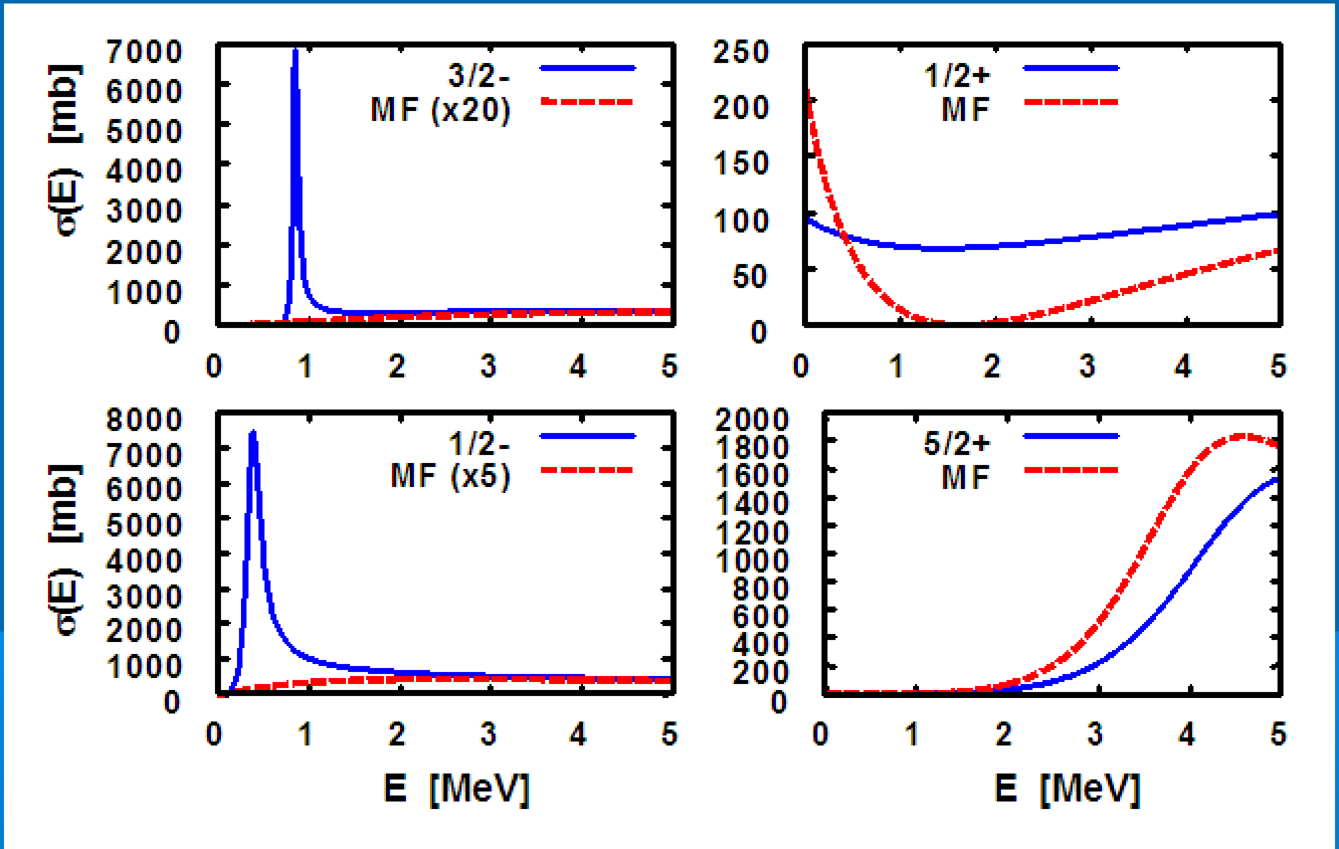
$$\tan\left(\delta_\alpha^{(c)}\right) = -\frac{2\,\tilde{m} k_\alpha}{4\pi\hbar^2} \langle f_\alpha | \Sigma_q^{(c)} | u_\alpha \rangle \sim -\frac{2\,\tilde{m} k_\alpha}{4\pi\hbar^2} \langle f_\alpha | \Sigma_q^{(c)} | f_\alpha \rangle$$

$$\Gamma_\alpha^{(c)} \sim N(k_\alpha) |\langle f_\alpha | \Delta_\alpha | v_b \rangle|^2$$

S. Orrigo, H.L., PLB 677 (2009)

Pairing Resonances in Dripline Nuclei

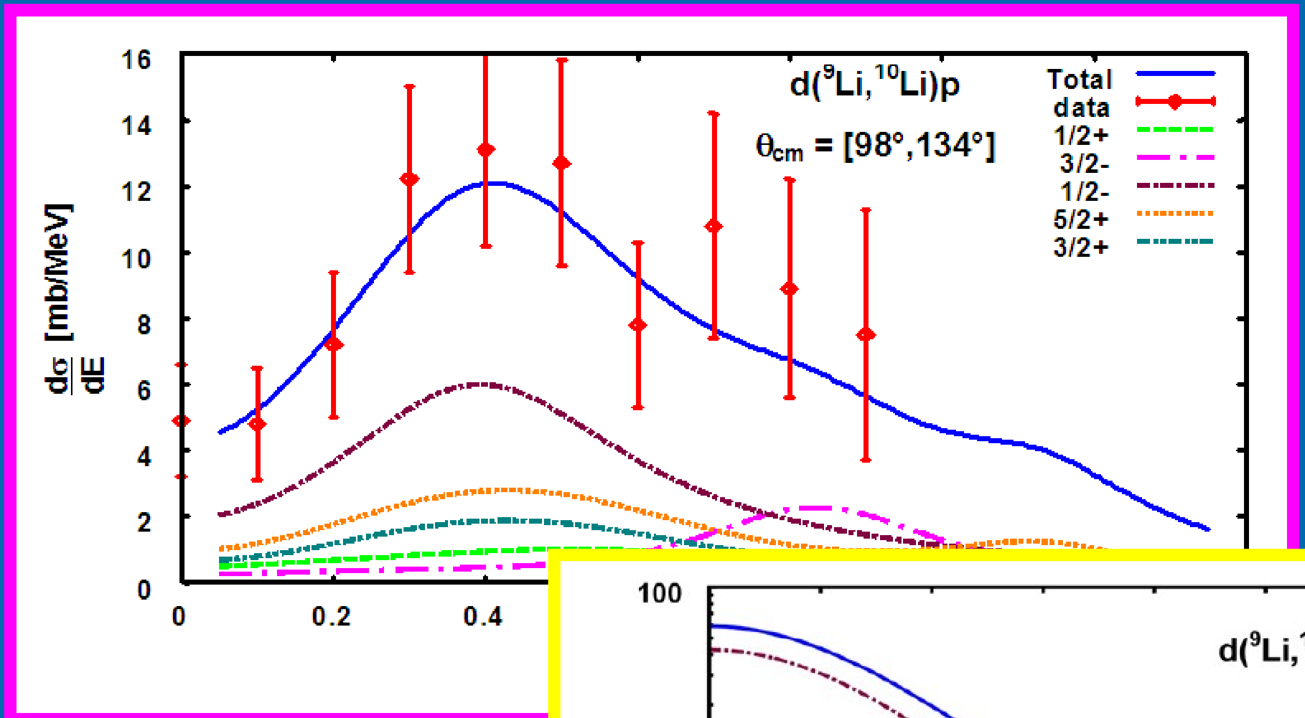
$^{9}Li+n$ —— ^{10}Li

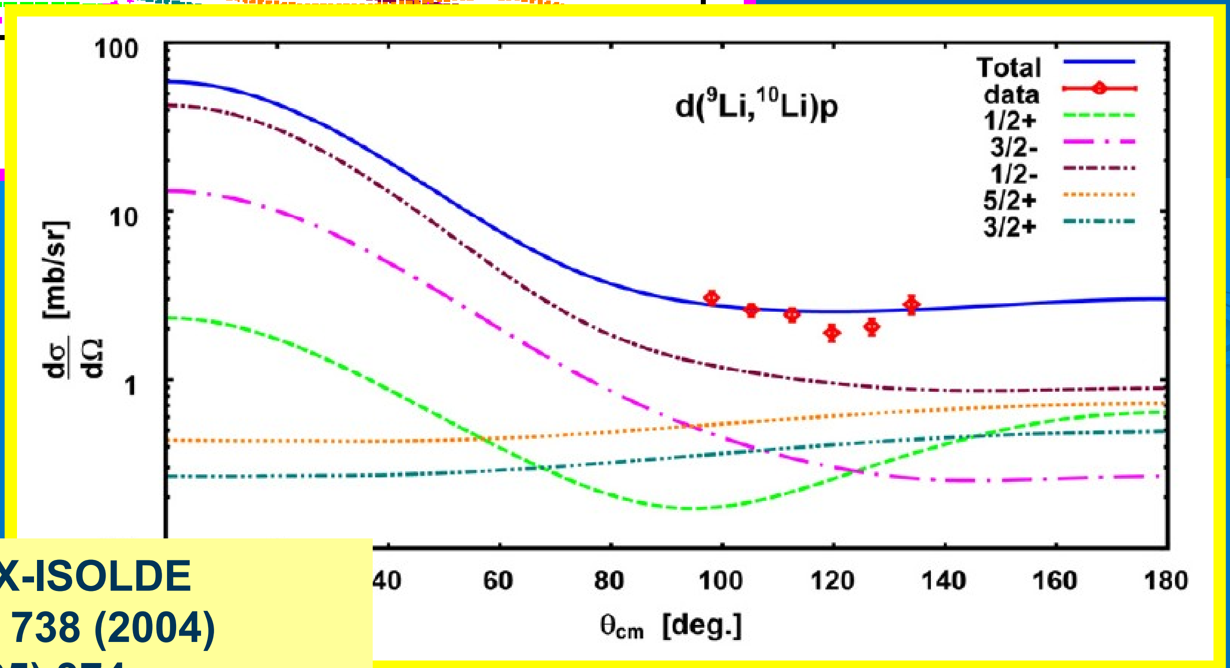


$$\begin{pmatrix} T_q + U_q - 2\lambda_{q\alpha} + e & \Delta_q(\vec{r}) \\ -\Delta_q^{\dagger}(\vec{r}) & -\left(T_q + U_{q\alpha} - e\right) \end{pmatrix} \begin{pmatrix} u_{\alpha q}(\vec{r}) \\ v_{\alpha q}(\vec{r}) \end{pmatrix} = 0$$

S. Orrigo, H.L., PLB 677 (2009), ISOLDE newsletter Spring 2010, p.5

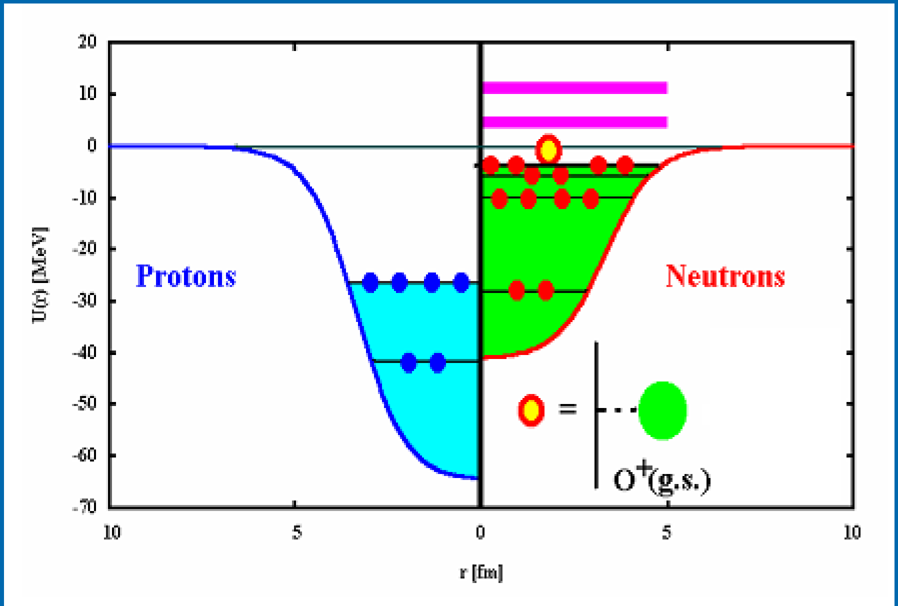
Continuum Spectroscopy: $^{10}Li = {}^{9}Li + n$ @ 2.36AMeV



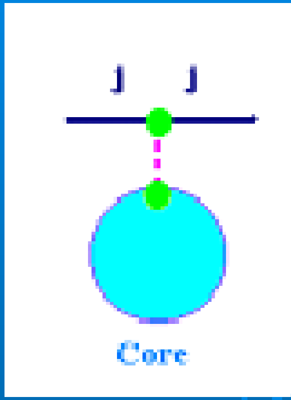


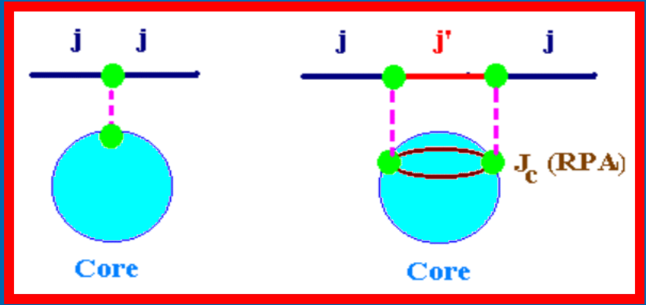
Data: H. Jeppesen et al., REX-ISOLDE Collaboration, Nucl. Phys. A 738 (2004) 511 & Nucl. Phys. A 748 (2005) 374.

1n-Neutron Halo States: Transition from Mean-Field to Correlation Dynamics

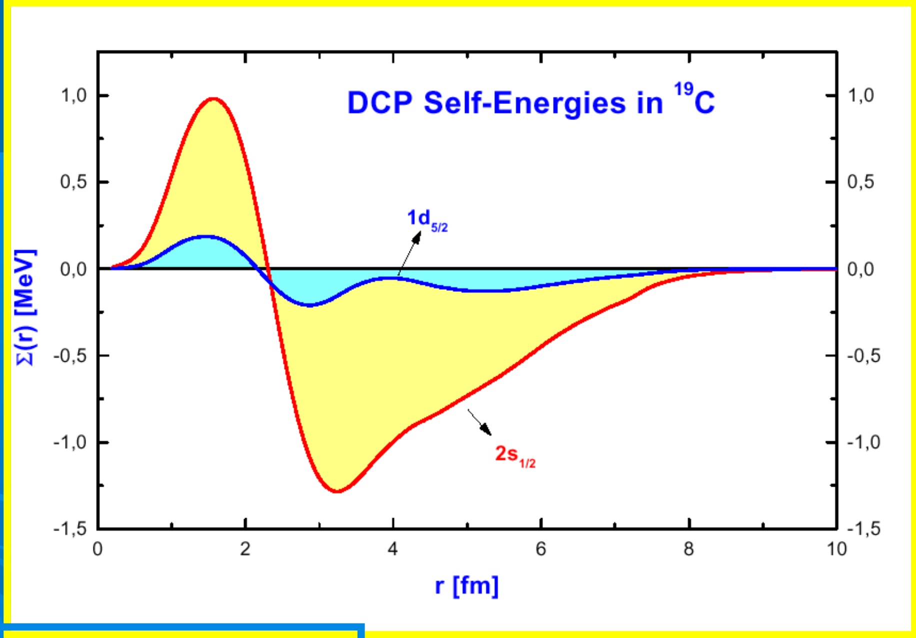


The s.p. shell model picture



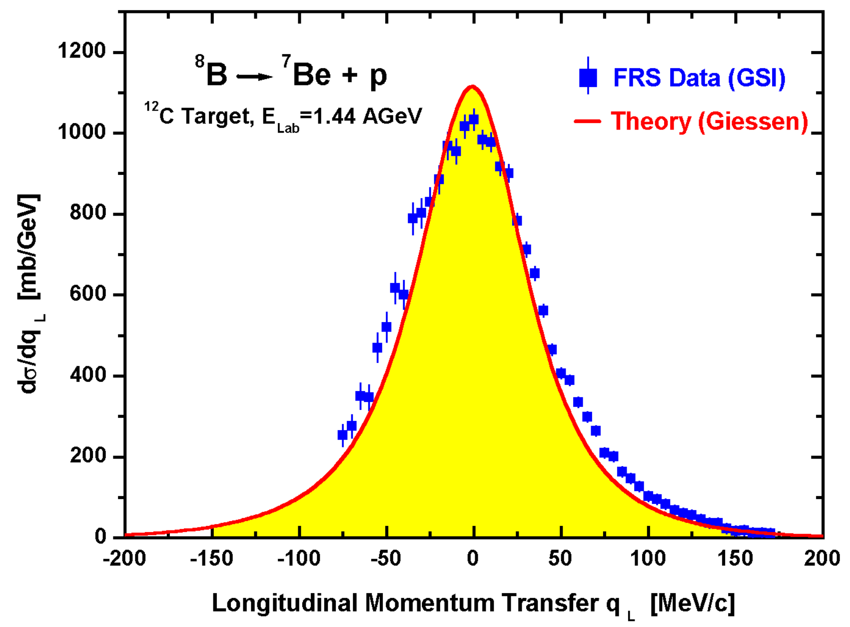


The DCP picture: Binding by Virtual Continuum Coupling



H.L.,J. Prog.Part.Nucl. 561 (2004)

Investigating the Structure of ^8B by breakup reactions

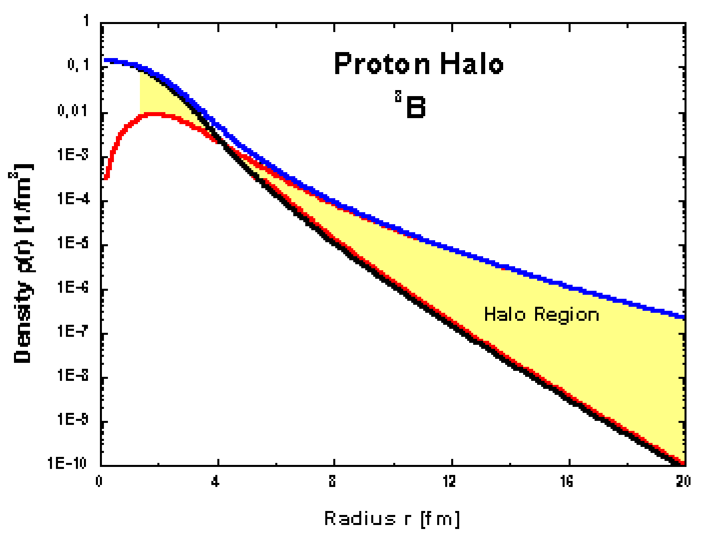


- Relativistic eikonal theory
- NN T-Matrix
- 3-body kinematics
- dynamical Correlations

Γ(the.): 75 MeV/c
Γ(exp.): 91 ± 5 MeV/c

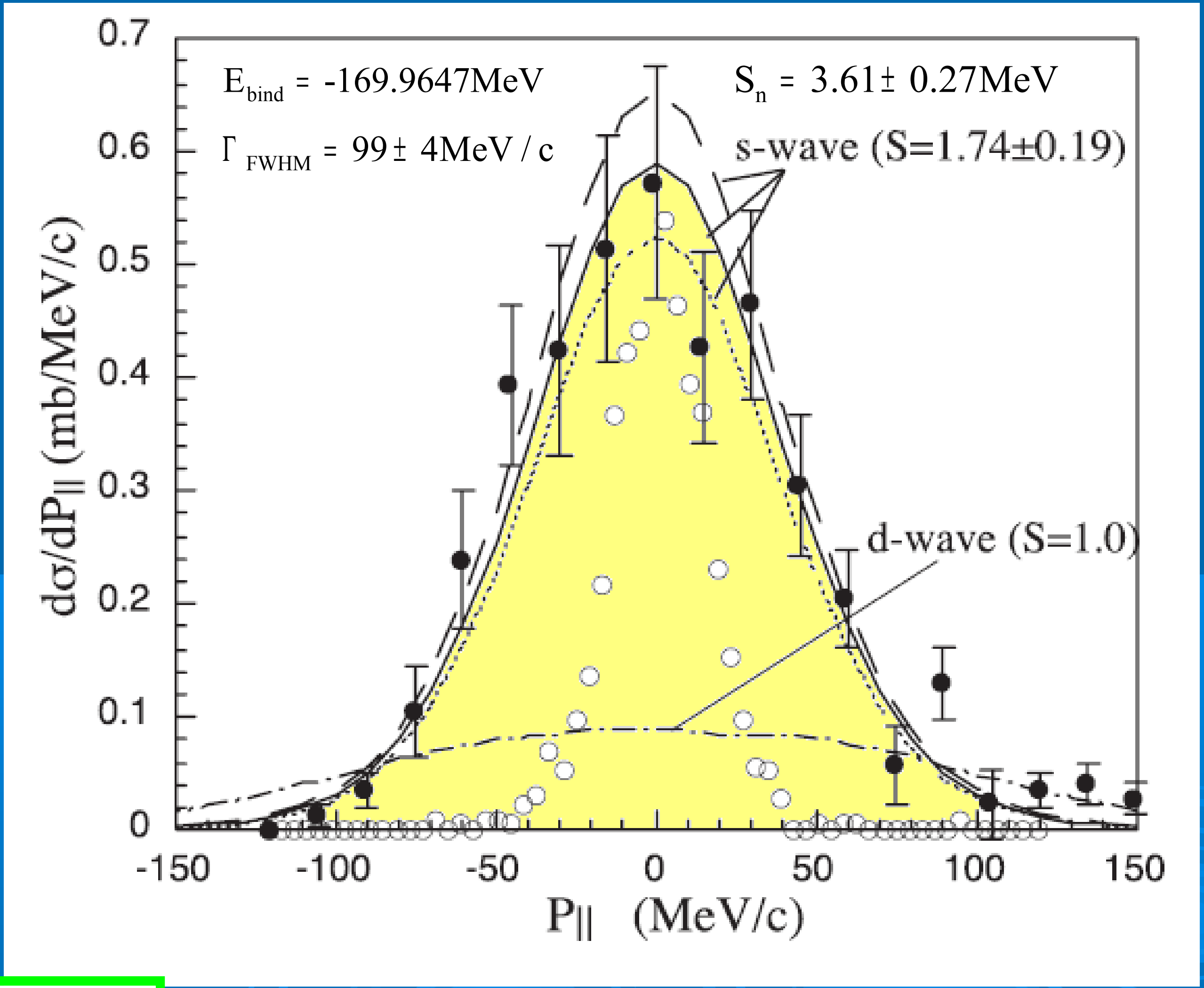
σ(-1p,the.): 104 mb
σ(-1p,exp.): 98 ± 6 mb

^7Be(3/2-,0.0) p3/2: 71%
^7Be(3/2-,0.0) p1/2: 13%
^7Be(3/2-,0.0) f 7/2: 11%
^7Be(3/2-,0.0) f 5/2: 5%
^7Be(1/2-,0.420) : 15%



FRS@GSI: ^{24}O Breakup at 920AMeV:

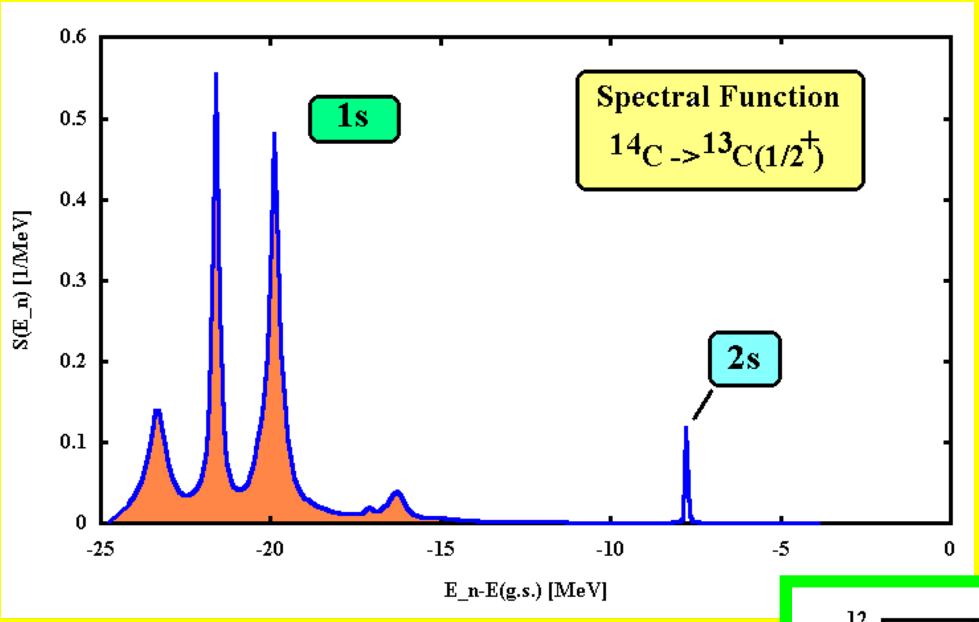
^{24}O a new doubly magic Nucleus (Z=8,N=16)



PRL **102**, 152501 (2009)

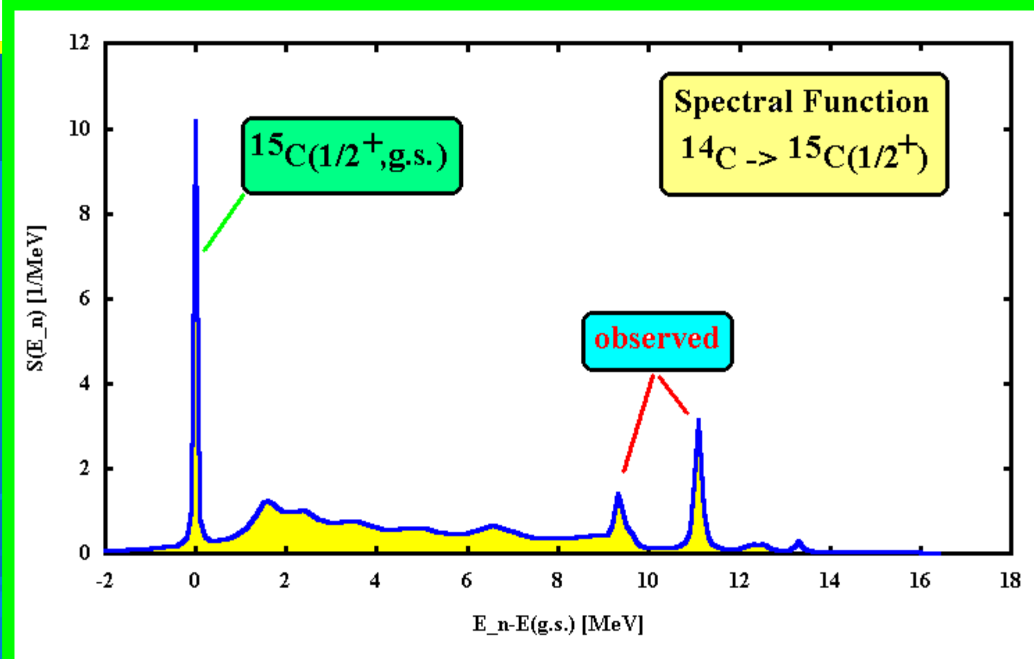
open circles: exp. resolution

1/2$^+$ Particle and Hole Strength Functions in ^{14}C

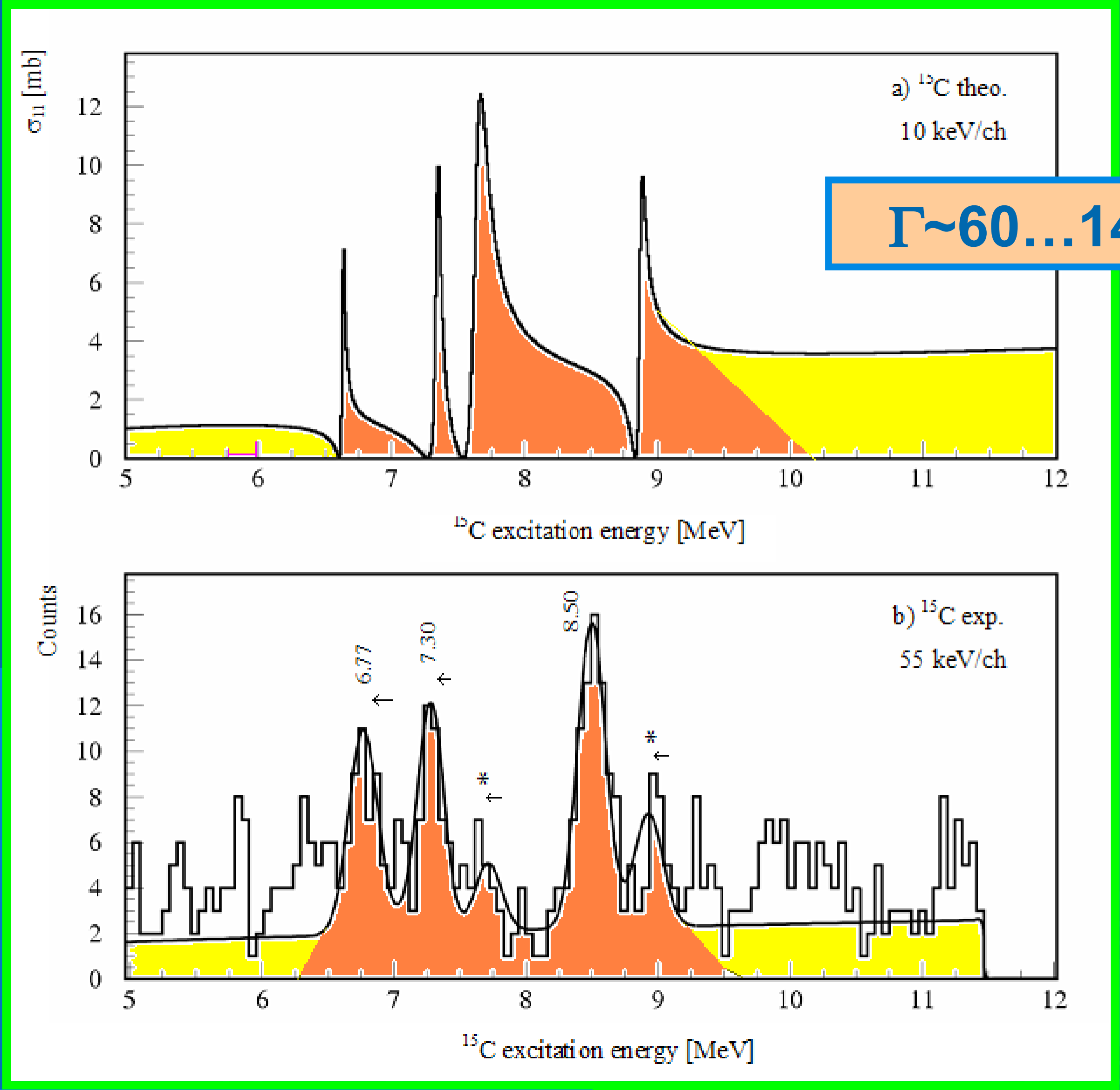


Hole strength function

Particle strength function



Correlation Dynamics in an Open Quantum System: Fano-Resonances in ^{15}C

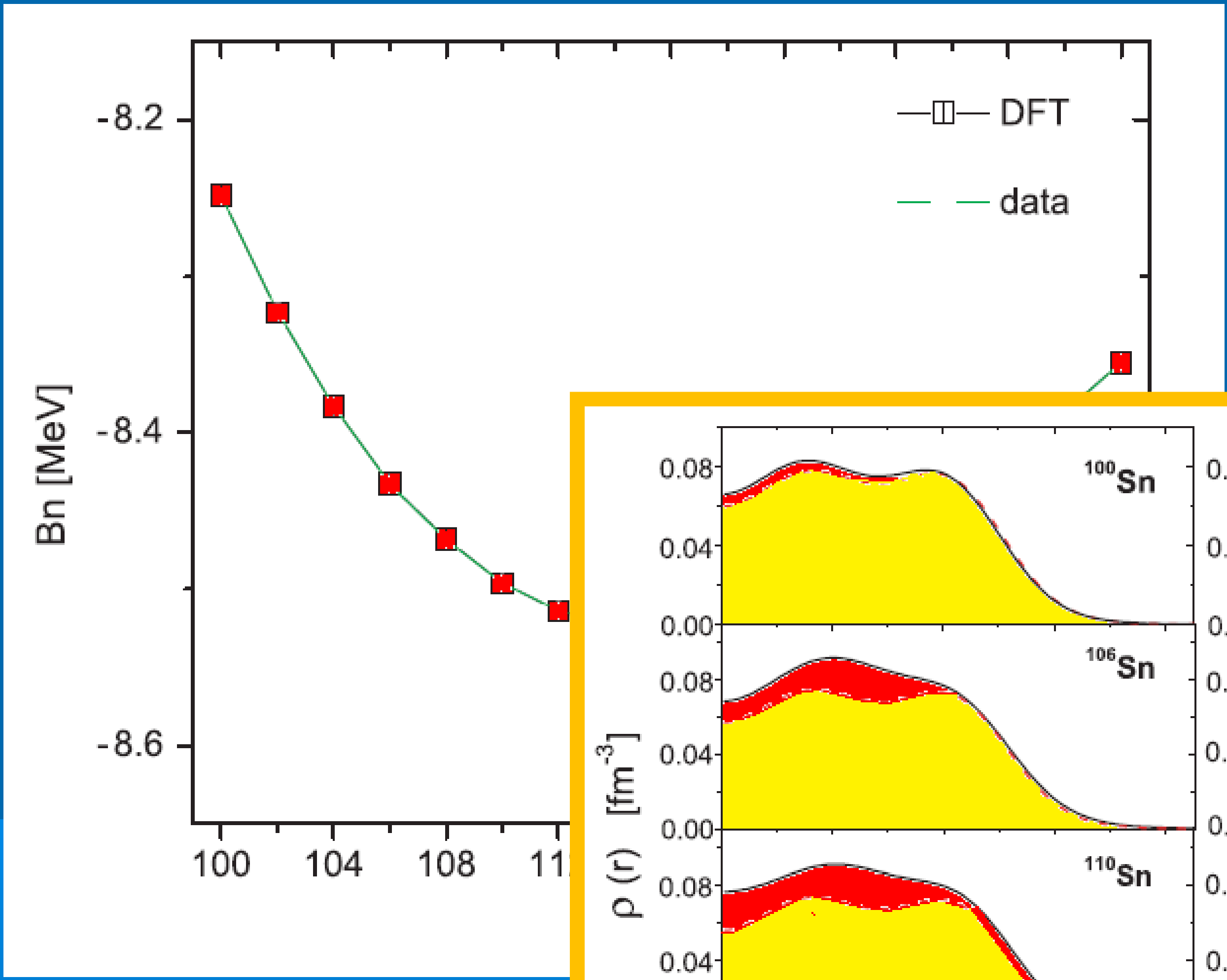


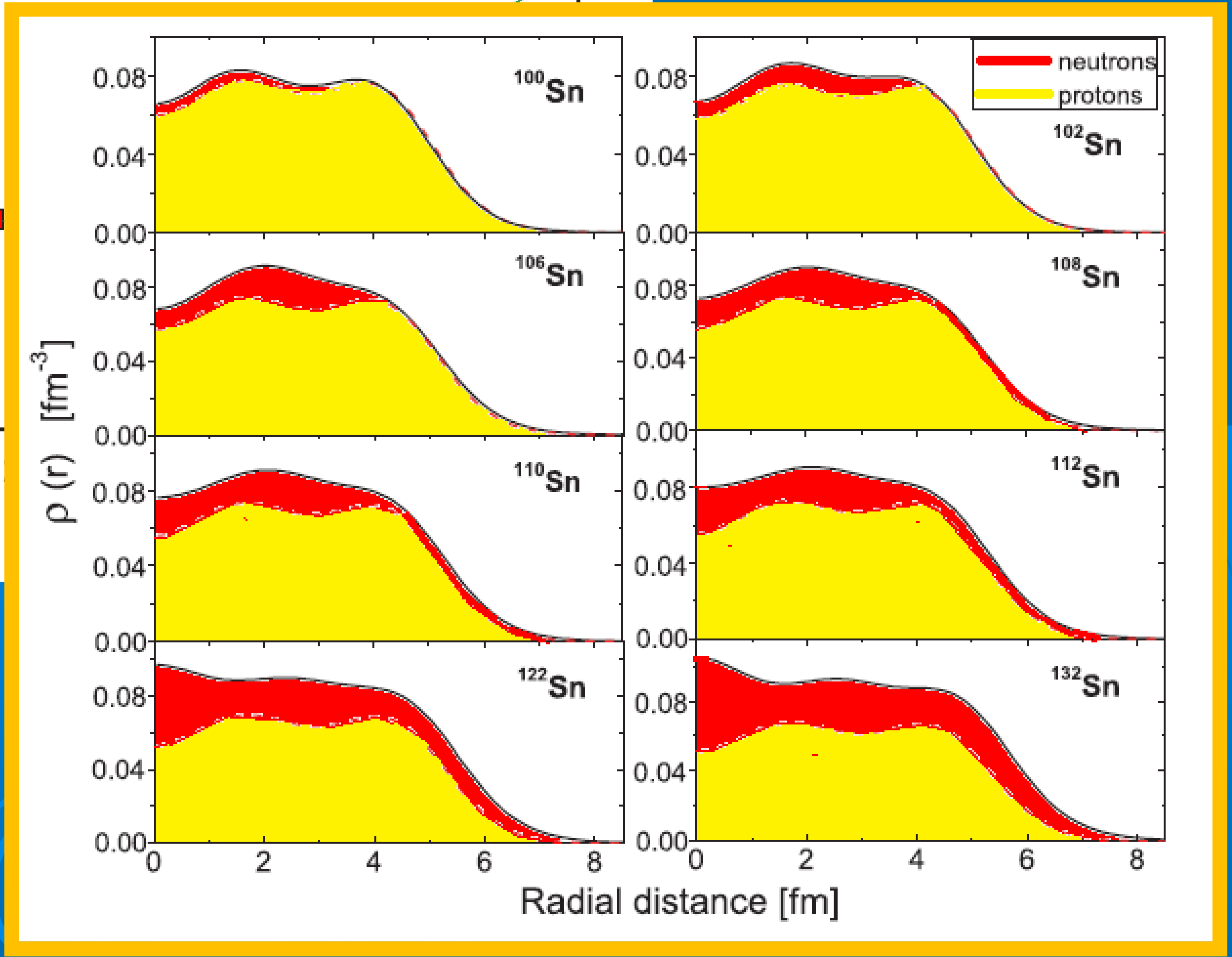
Γ~60…140keV

Sonja Orrigo, H.L., Phys.Lett. B633 (2006)

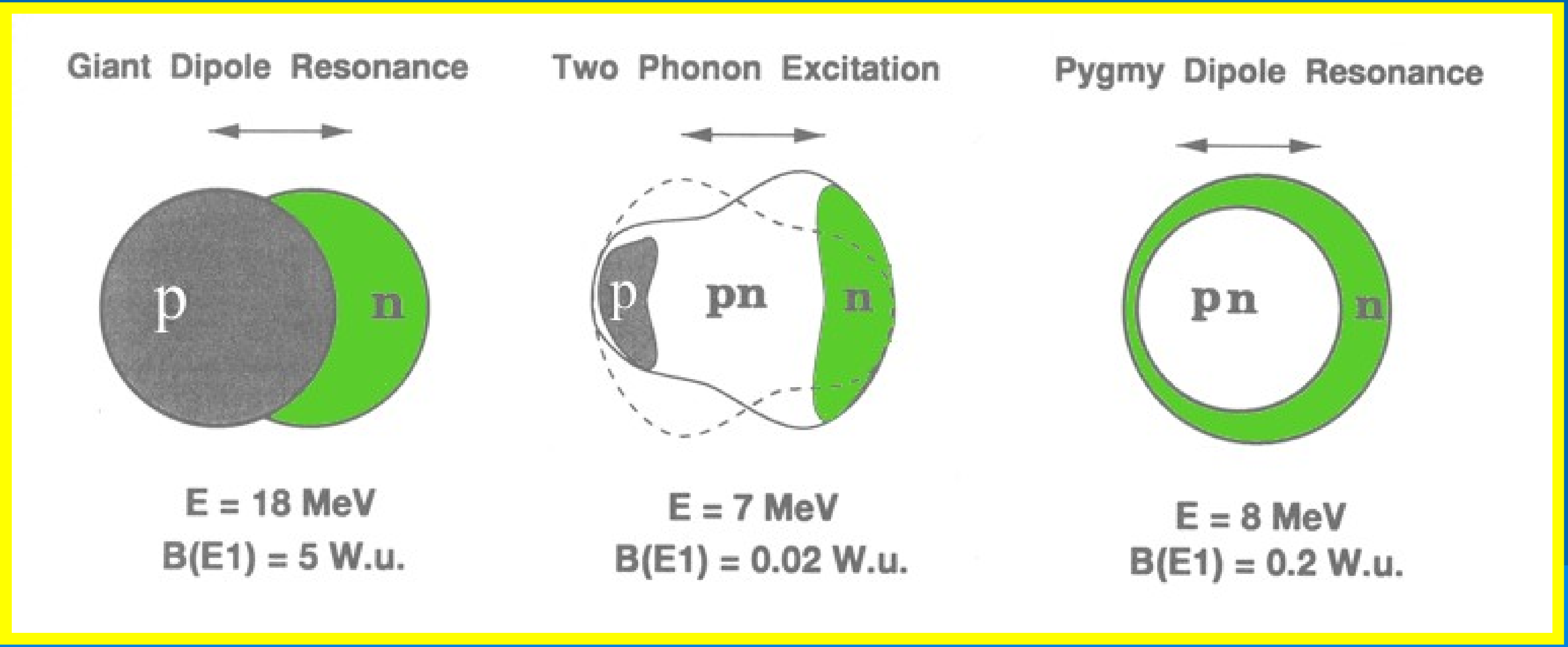
Sn Isotopes: DFT-HFB Results

(N. Tsoneva, HL, PRC77 (2008))





Electric Dipole Response of Exotic Nuclei



$$\vec{D} = \frac{1}{2}\sum_i \vec{\xi}_i(1-\tau_{3i}) = -\frac{1}{2}\sum_i \vec{\xi}_i\,\tau_{3i}\,.$$

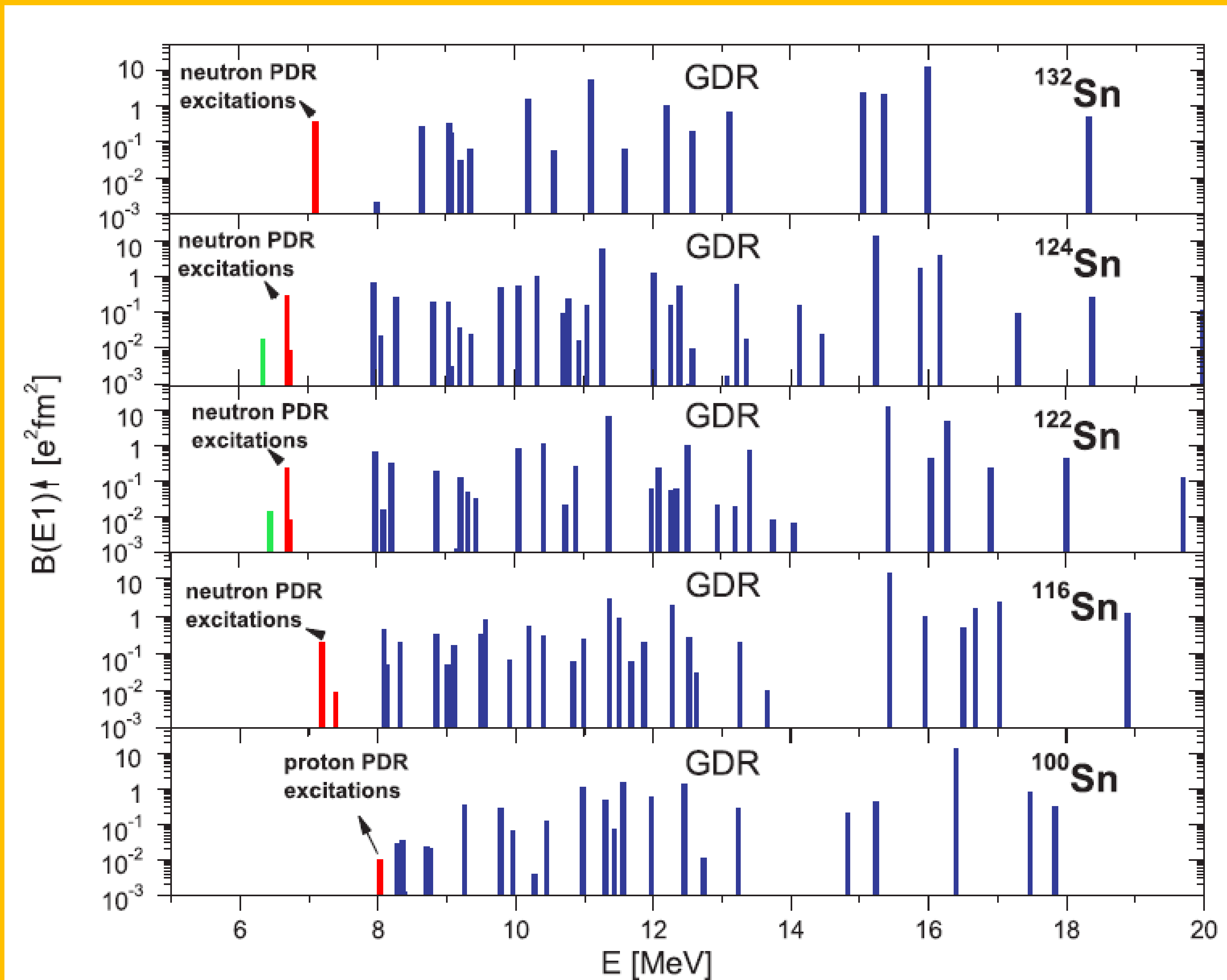
N. Tsoneva, H.L.

HFB g.s. and Multi-Phonon QRPA Theory:

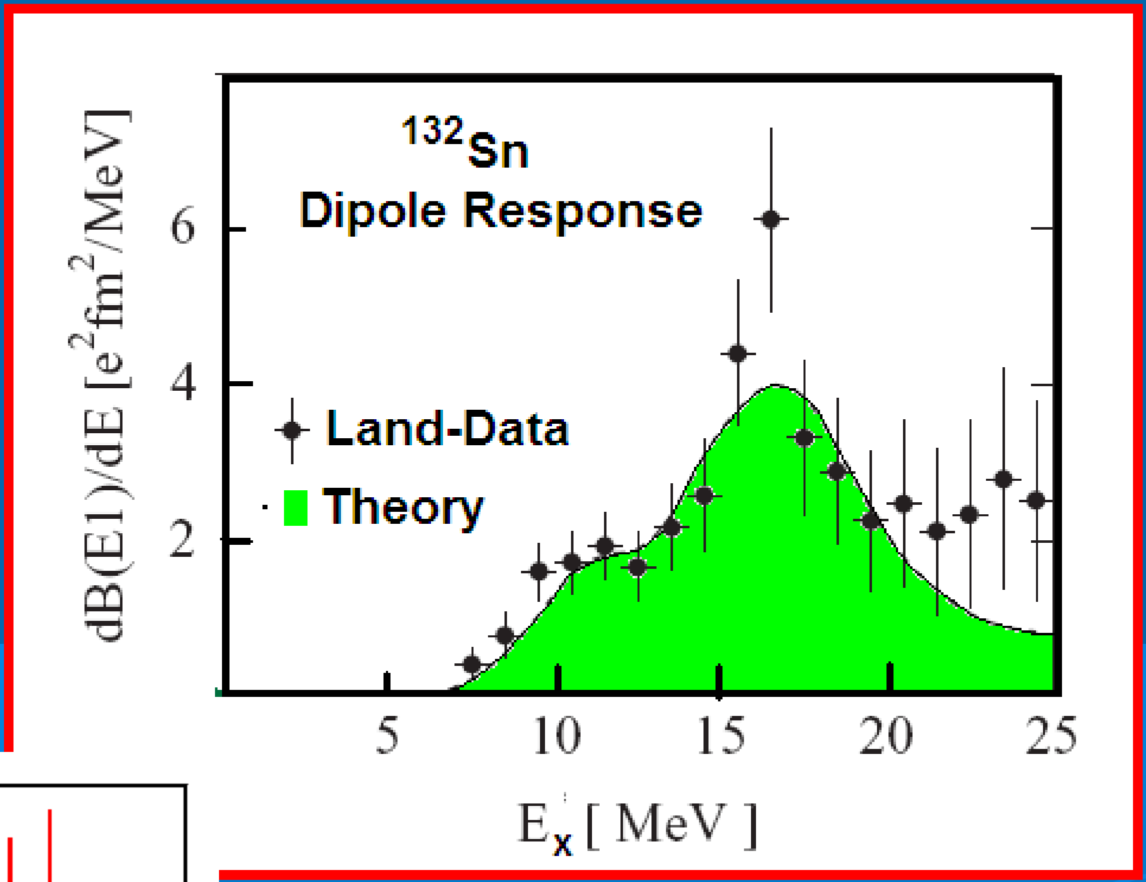
The Multi-Configuration (multi-phonon) Wave Function

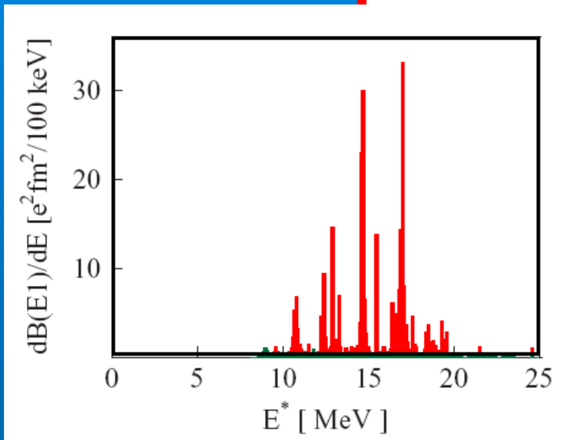
$$\Psi_\nu(JM) = \Bigg\{ \sum_i R_i(J\nu) Q^+_{JMi} + \sum_{\substack{\lambda_1 i_1 \\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) \times [Q^+_{\lambda_1\mu_1 i_1} \times Q^+_{\lambda_2\mu_2 i_2}]_{JM} + \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2 \\ \lambda_3 i_3 I}} T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(J\nu) \times [[Q^+_{\lambda_1\mu_1 i_1} \otimes Q^+_{\lambda_2\mu_2 i_2}]_{IK} \otimes Q^+_{\lambda_3\mu_3 i_3}]_{JM} \Bigg\} \Psi_0$$

Electric Dipole Response in Sn-Isotopes



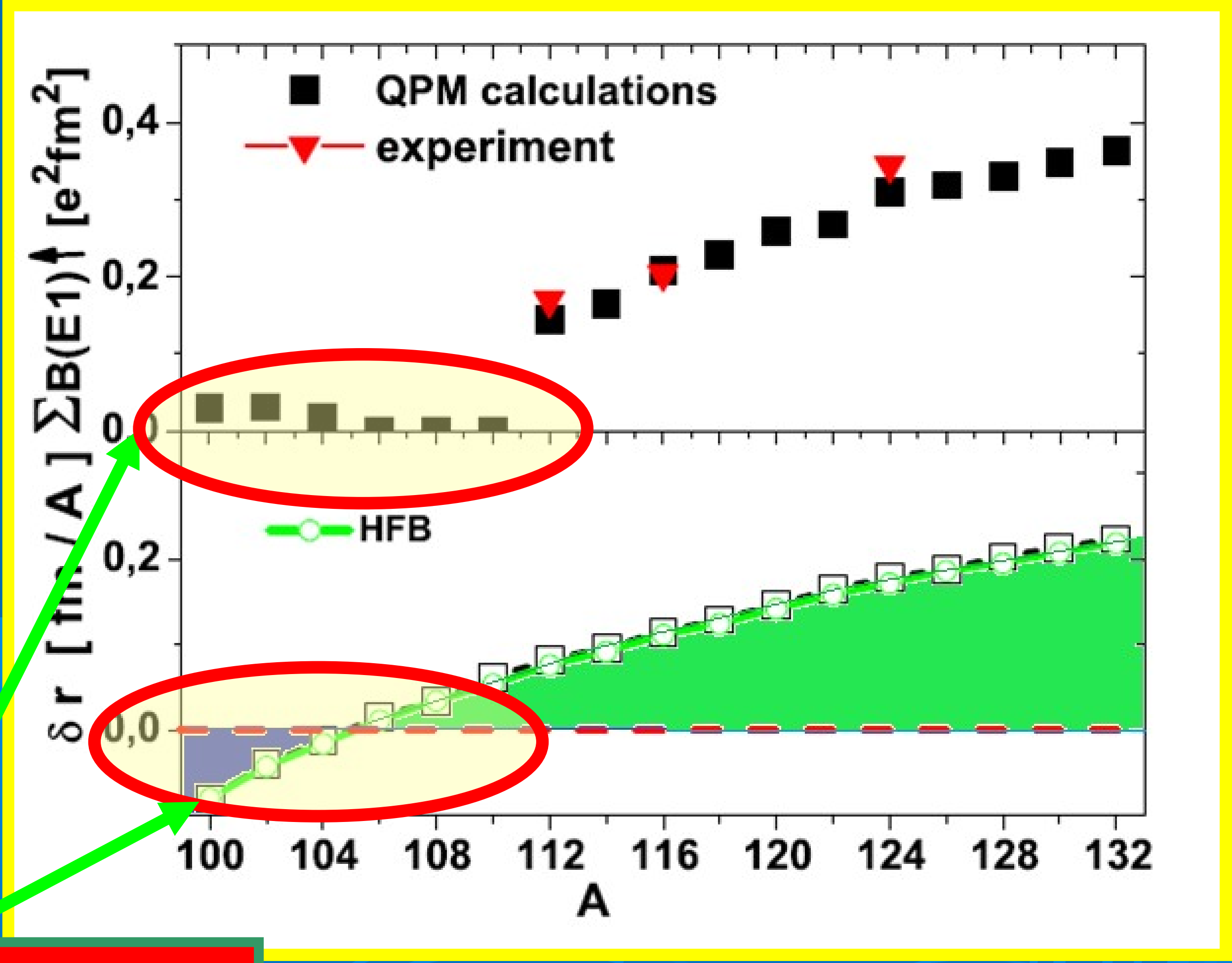
Relativistic Coulex@LAND





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

PDR Response and Nuclear Skins in the Sn Isotopes: HFB g.s. and Multi-Phonon QRPA Theory

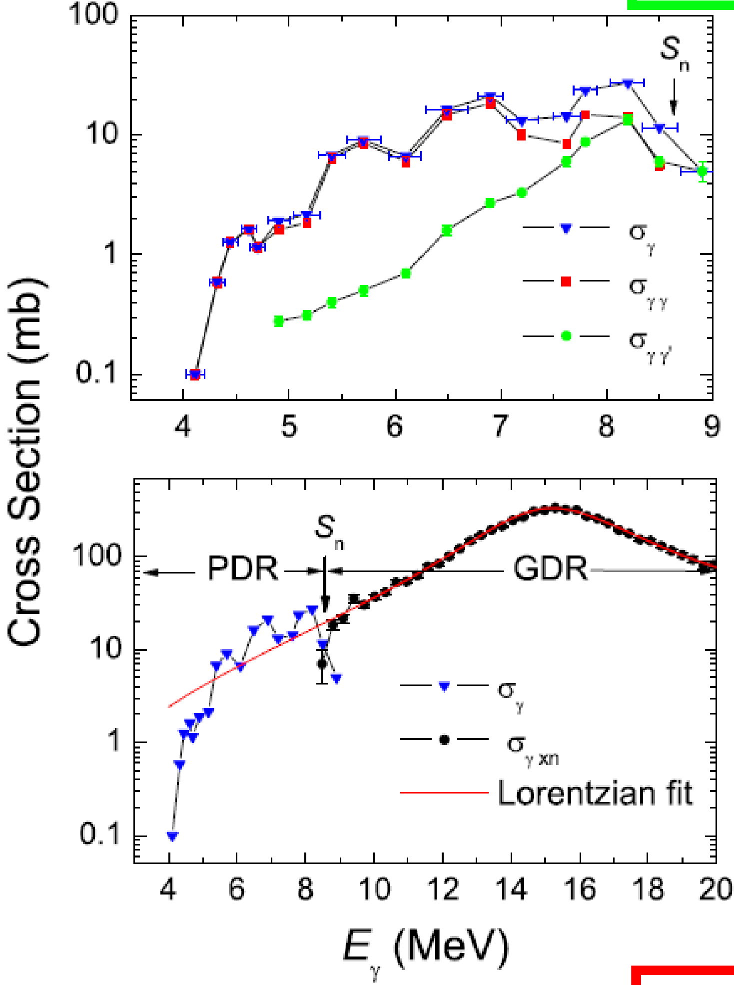


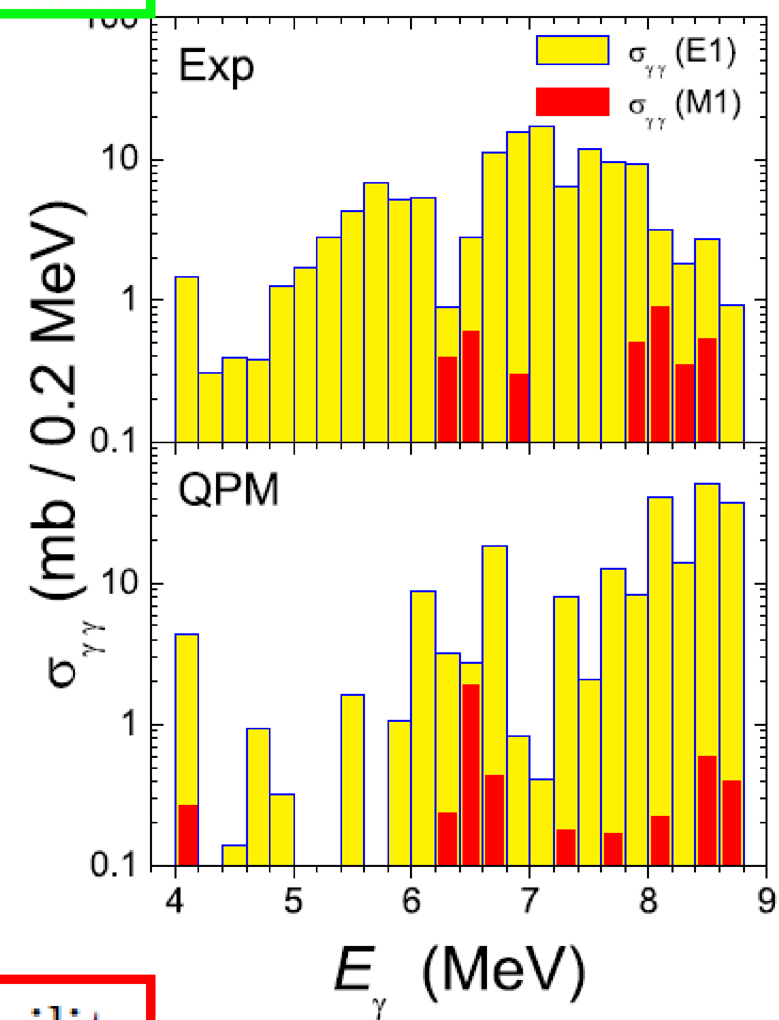
Coulomb-driven proton skins & PDR!

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

Low Energy Dipole Response: Parity Assignment

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





$\mathrm{HI}\vec{\gamma}\mathrm{S}$ facility

PRL 104, 072501 (2010)

Summary and Outlook

- Exotic Nuclei as Open Quantum Systems
- Continuum Spectroscopy and Dynamical Correlations
- New Generic Modes of Exotic Nuclei – PDR, PQR…
- Challenges:
  - Many-body Dynamics at extreme Isospin
  - Nuclear Structure at weak Binding
  - Reaction Theory for weakly Bound Systems

Credits to: Nadia Tsoneva, Urnaa Badarch, A. Ataie, A. Fedoseew, P. Konrad, Anika Obermann, M. Strecker