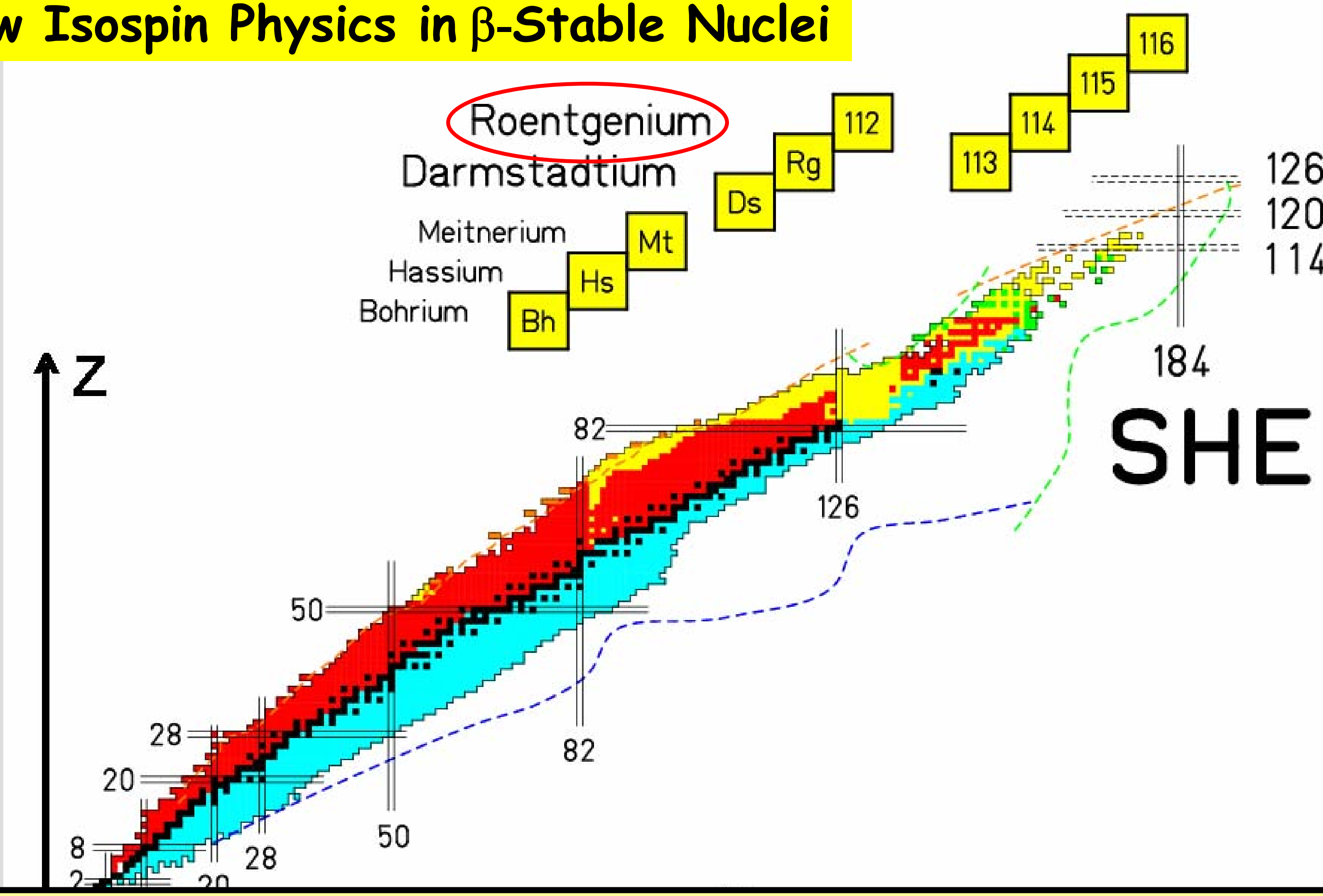
The first Century of Nuclear Physics: Low Isospin Physics in β-Stable Nuclei



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

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

The second Century:
Physics of Asymmetric Nuclear Matter

H. Lenske
Institut für Theoretische Physik, U. Giessen

EuroGK

SFB/TR 16

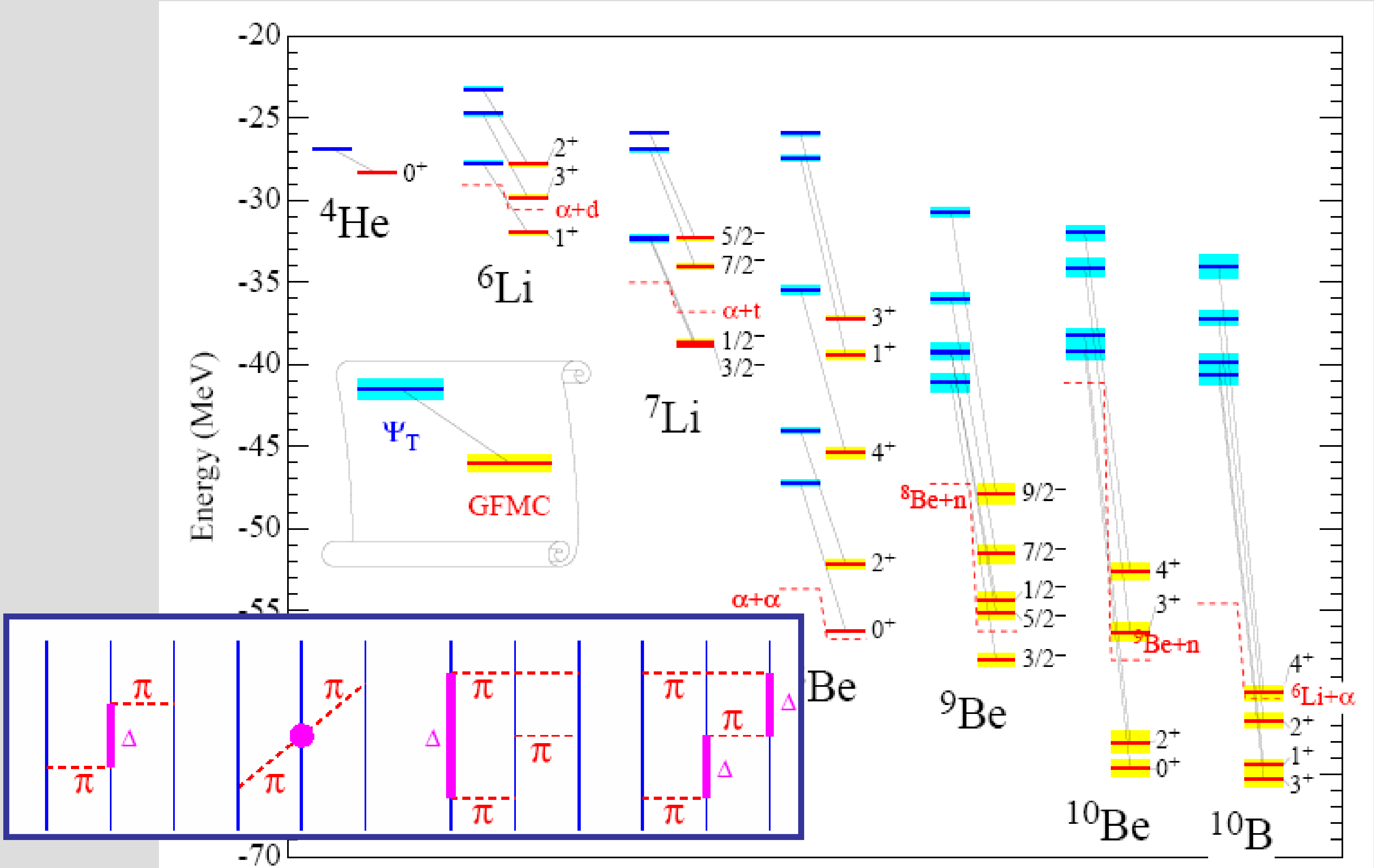
The Agenda:

- Our position : Competing with LHC physics!
- Our goal : Define intellectually demanding Tasks
- Our business : The Physics of Nuclear Matter
- Our wish : Nucleo-Engineering on the Femto-scale

The Topics

- The Fate of Mean-Field Dynamics and Shell Structures?
- Scanning the Isospin Degree of Freedom
- *ab initio* Approaches to Nuclear Structure and Reactions
- Pairing and other correlations in Exotic Nuclei
- New features: Continuum Coupling and Open Quantum Systems
- The End: Summary and Outlook

Modern Nuclear Theory: *ab initio* Calculations



A=4-10 GFMC results: AV18 NN potential + IL2 Urbana 3-Body Interactions

Kohn-Sham-Theorem & Density Functional for Nuclei:

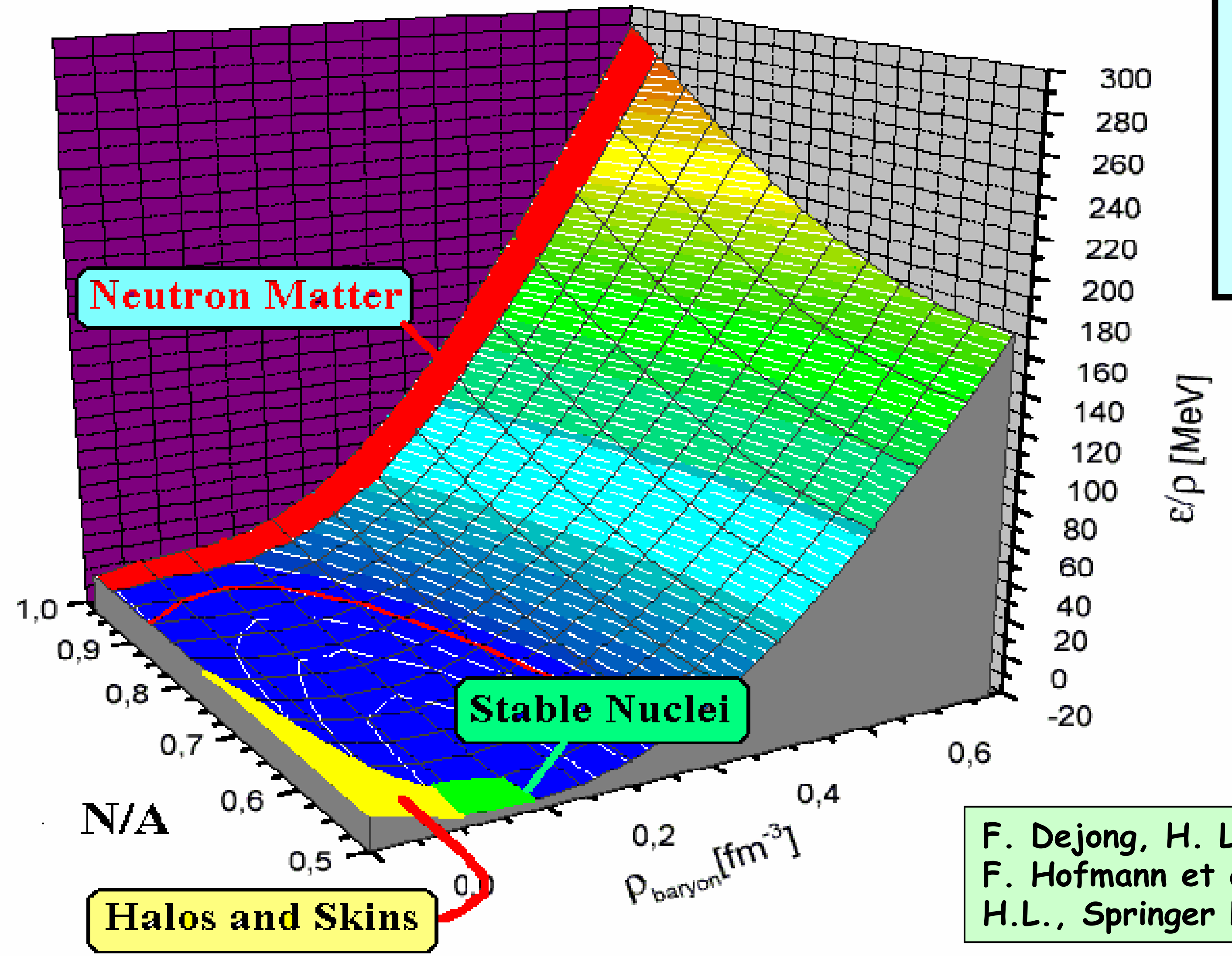
- Hohenberg-Kohn: DFT ~ $E[\rho]$
- Kohn-Sham : DFT ~ $E[\rho,\tau]$
- Nuclei : DFT~ $E[\rho_p,\rho_n,\tau_p,\tau_n\ldots]$

$$E[\rho,\tau] = \rho\tau + \frac{1}{2}\rho^2 \frac{3}{16}\left(a_{SE}(\rho) + a_{TE}(\rho)\right)\frac{4\pi\hbar^2}{M^*(\rho)} + \ldots$$

At $\rho=0$: $a_{SE}(S=0,I=1)= -23.8$fm; $a_{TE}(S=1,I=0)= +5.42$fm

$$\tau = \tau_p + \tau_n \; ; \; \rho = \rho_p + \rho_n$$

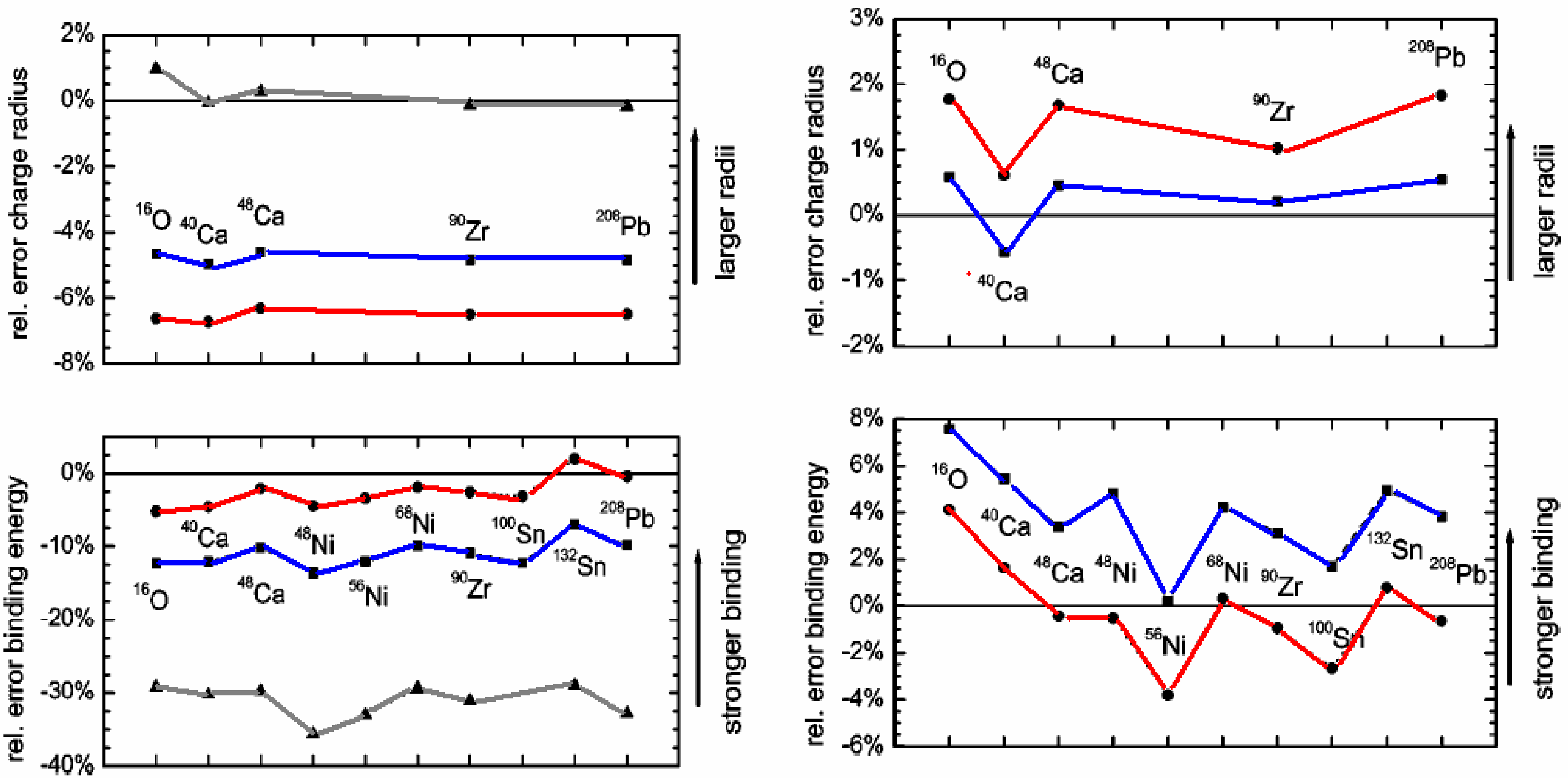
EoS of Asymmetric Nuclear Matter



DDRH Relativistic DFT
(Groningen NN-Potential)

F. Dejong, H. L. PRC58 (1998),
F. Hofmann et al. PRC64 (2001)
H.L., Springer Lecture Notes 2004

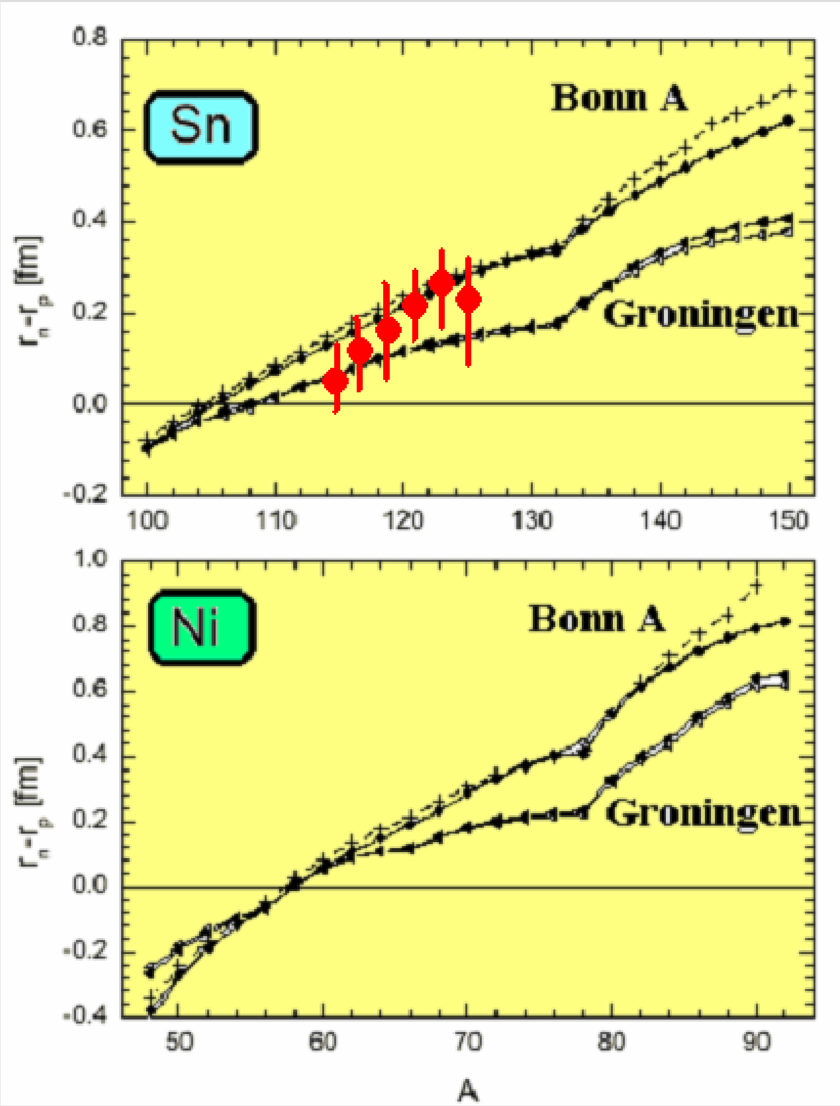
DDRH Results for Binding Energies and Charge Radii



Groningen NN Potential

Bonn A NN Potential

Neutron Skins in Ni and Sn Isotopes



DDRH RMF-Calculations
Dirac-Brueckner In-Medium Vertices
Bonn-A and Groningen NN-Potentials

Neutron Skin and Symmetry Energy:

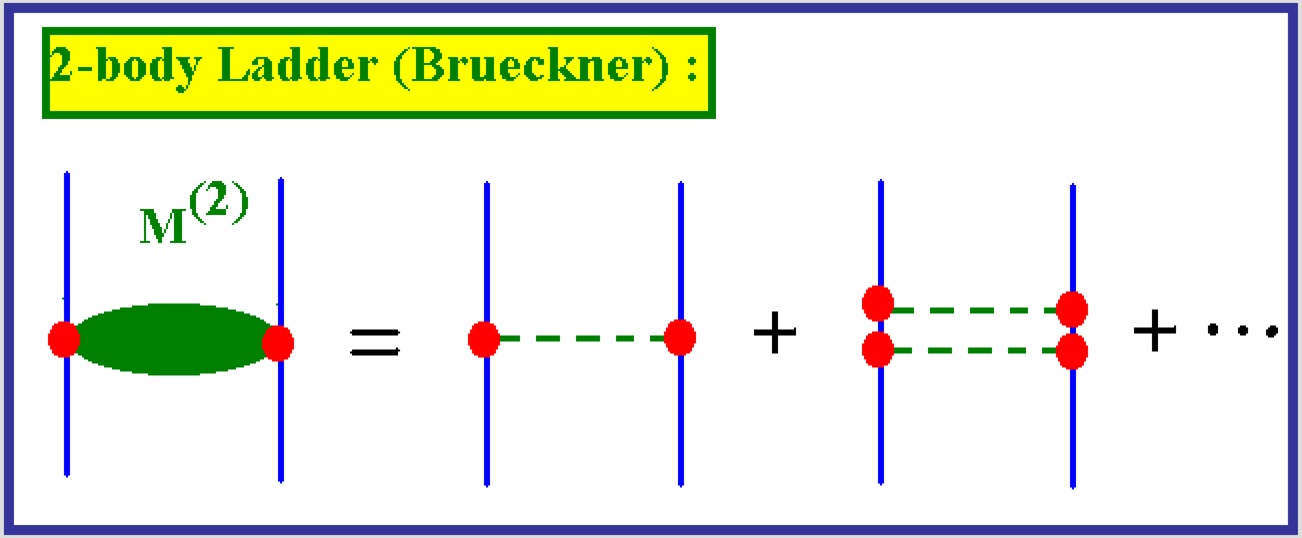
Bonn A : a_4 = 32 MeV

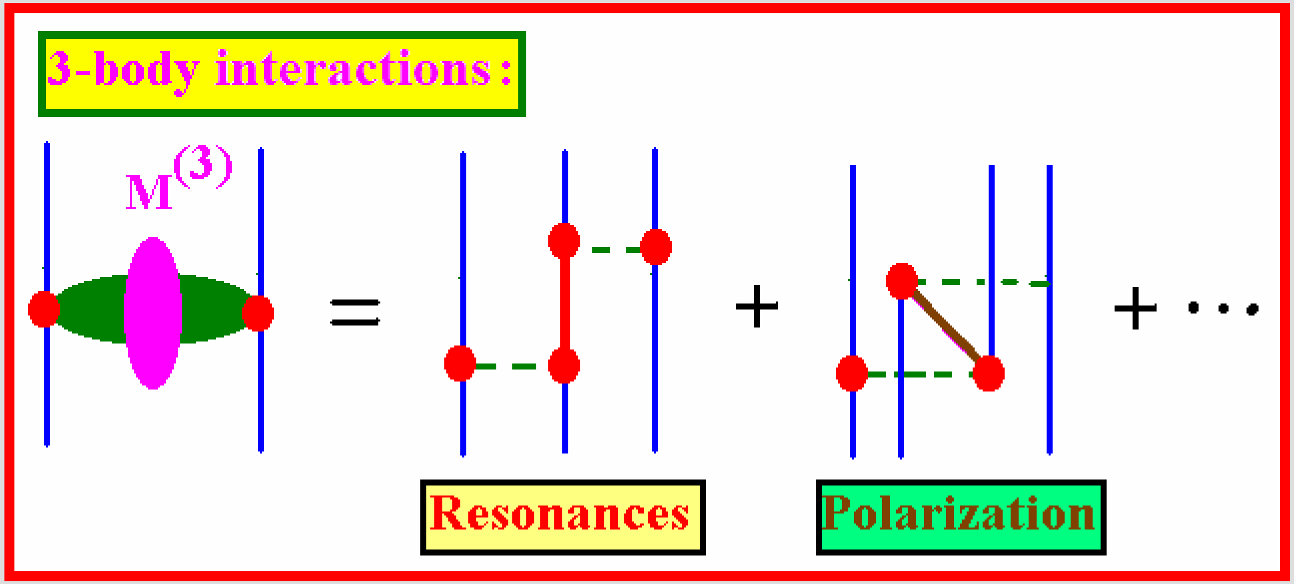
Groningen : a_4 = 26 MeV

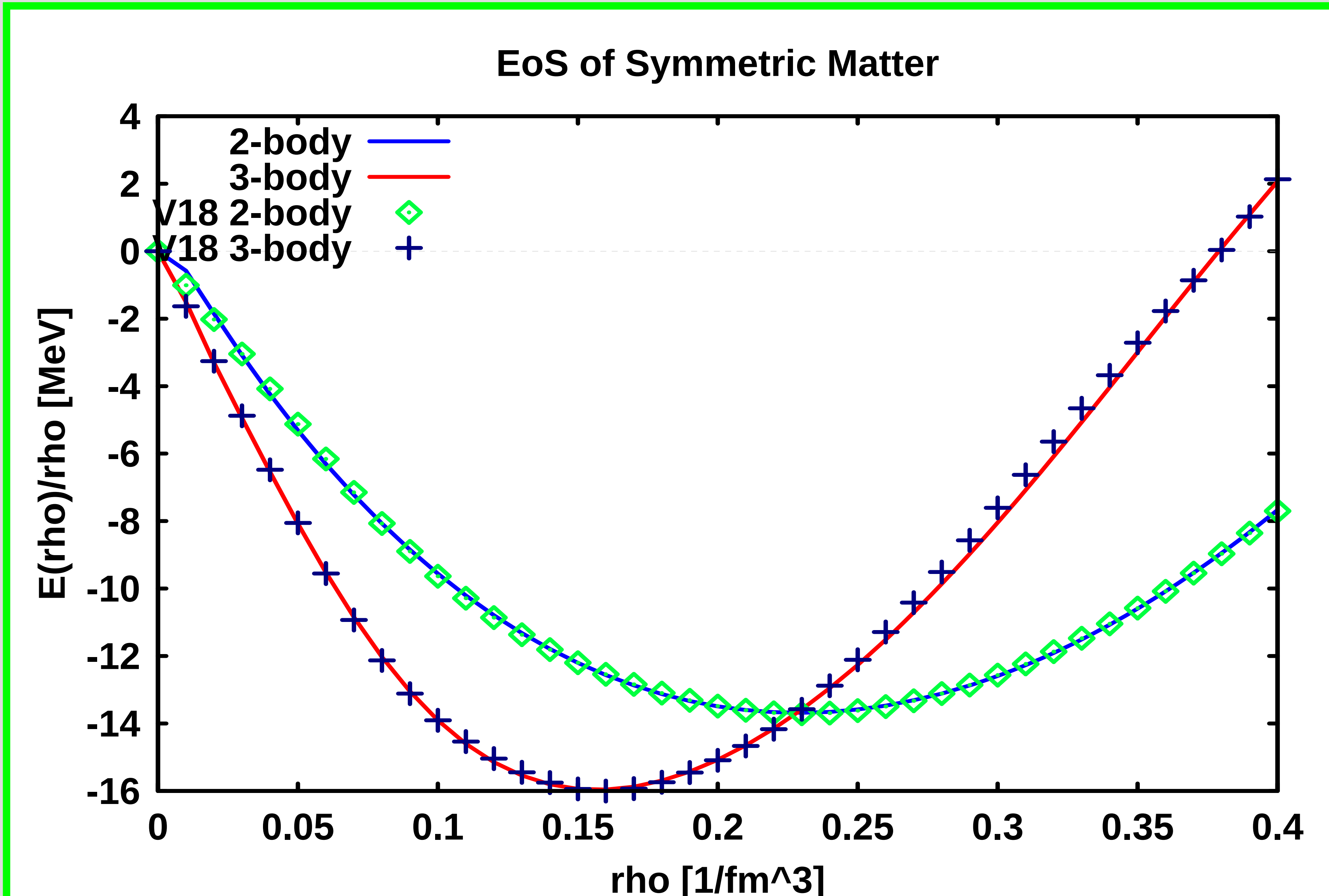
Sn Data: Krasnahorkay et al. PRL 82 (1999) 3216
(from Charge Exchange Spin-Dipole sum rules)

F. Hofmann et al., PR C64 (2001)
N. Tsoneva. H.L., PLB586 (2004)
N. Tsoneva. H.L., PRC (2008) in print

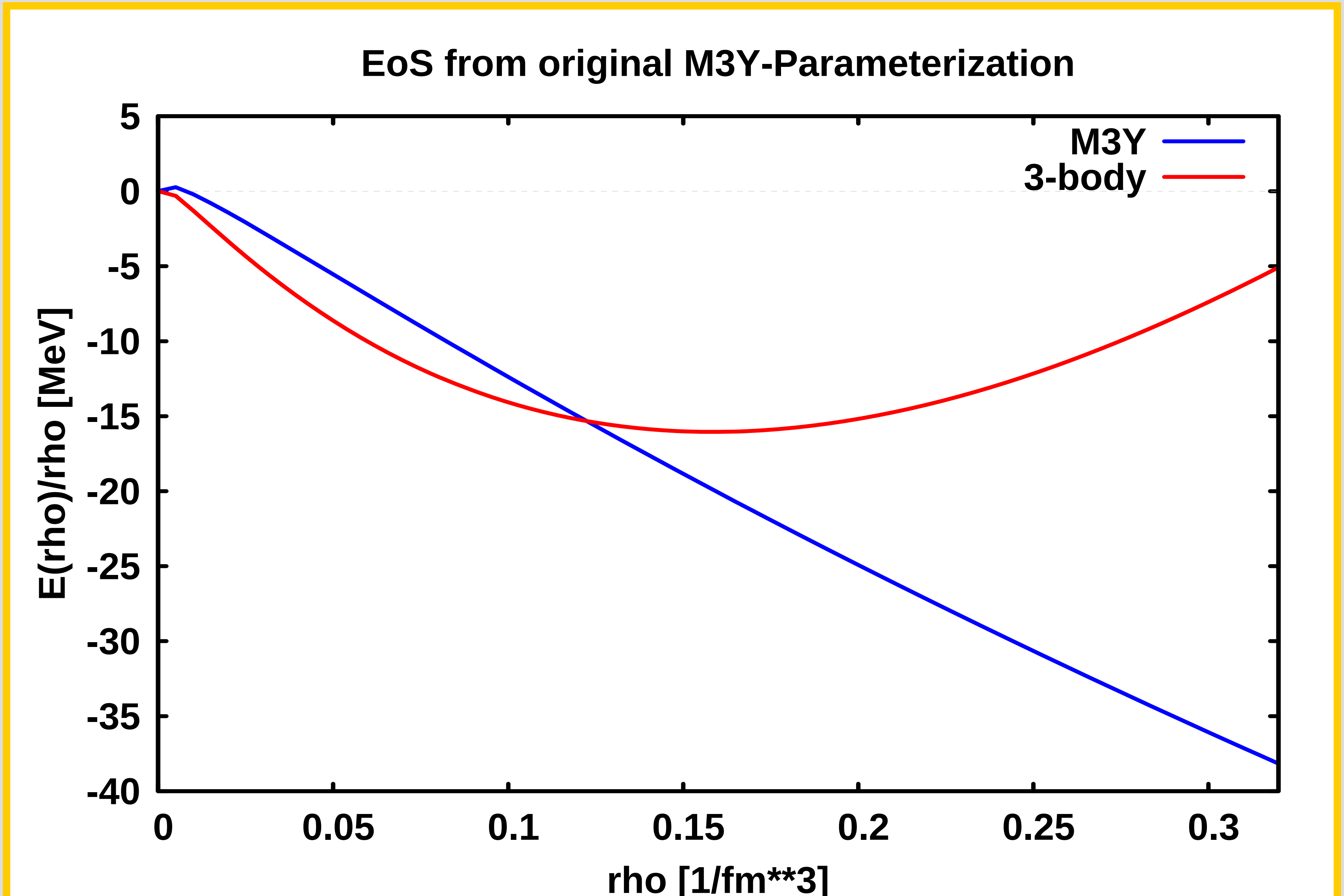
In-Medium Interactions



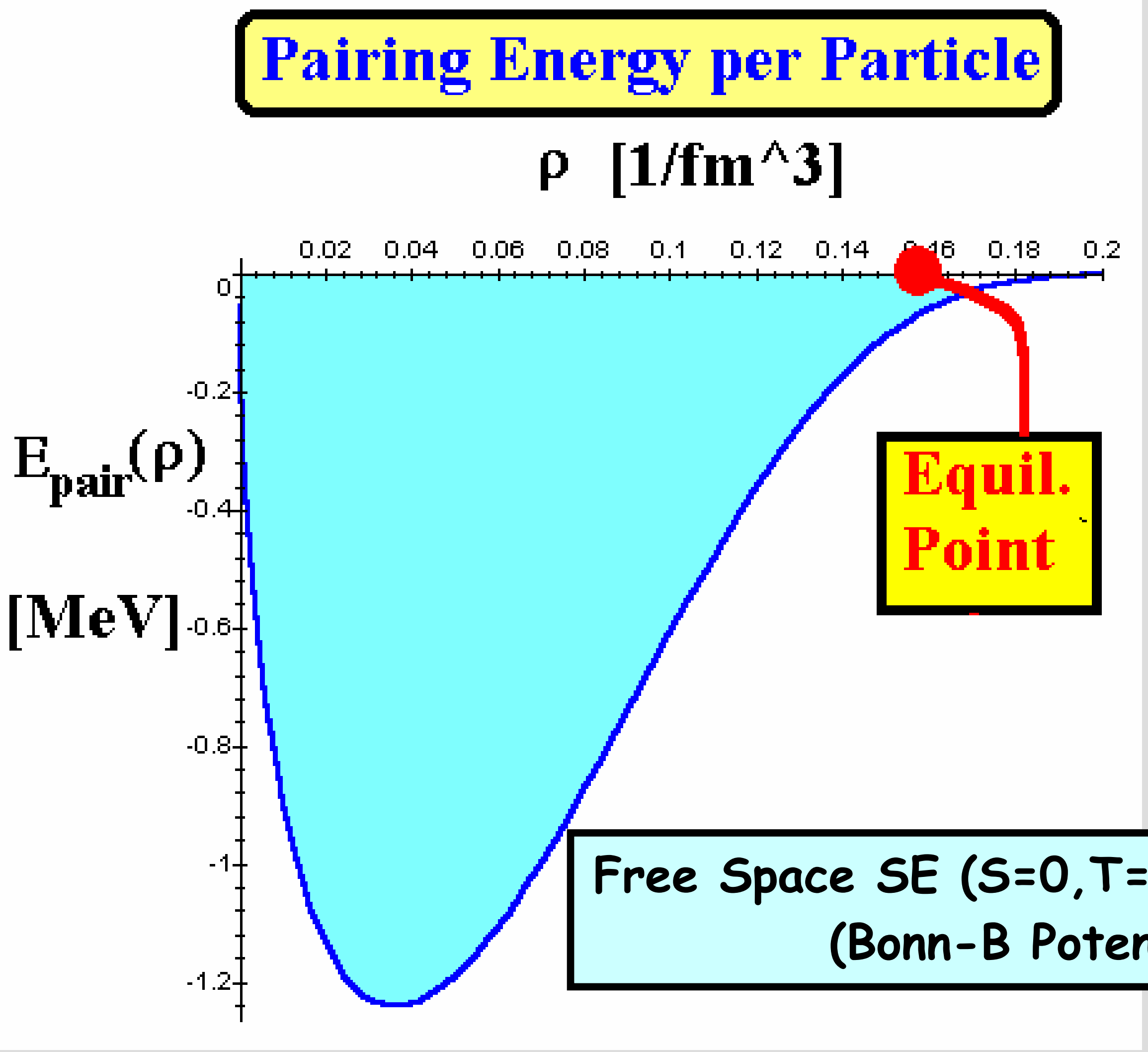




A. Ataie, H.L., in preparation


EoS from original M3Y-Parameterization
M3Y
3-body
5
0
-5
-10
-15
-20
-25
-30
-35
-40
0
0.05
0.1
0.15
0.2
0.25
0.3
E(rho)/rho [MeV]
rho [1/fm**3]

Pairing in Infinite Nuclear Matter



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

Pairing is a LOW DENSITY Phenomenon

Extended HFB 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):

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

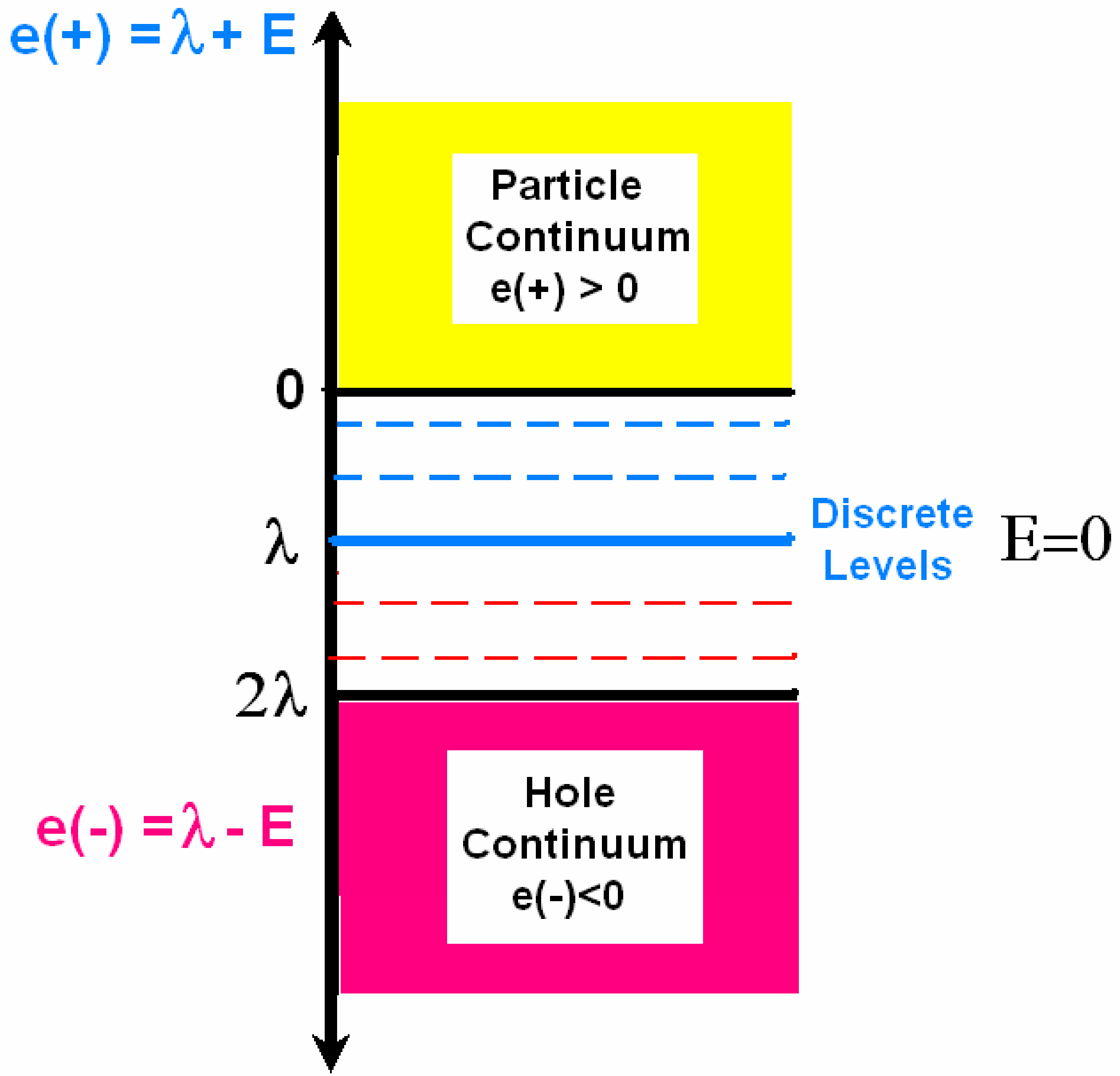
$$\rho_q(r) = \sum_{n\ell j}\frac{2j+1}{4\pi}\,|v^{(q)}_{n\ell j}(r)|^2$$

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

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

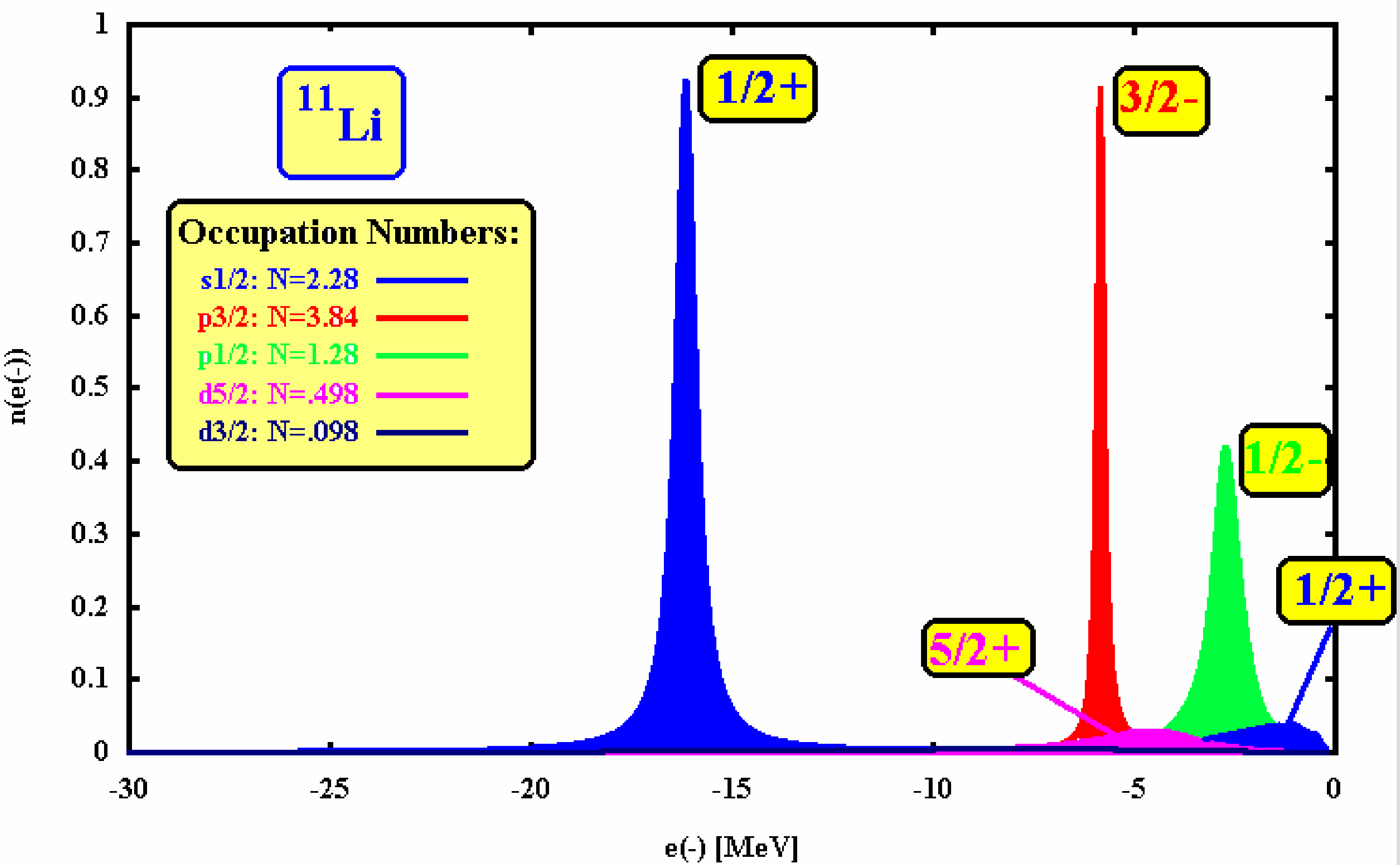
$$\kappa_q(r) = \sum_{n\ell j}\frac{2j+1}{4\pi}u^{(q)}_{n\ell j}(r)v^{(q)*}_{n\ell j}(r)$$

Spectrum of the Gorkov Equation:

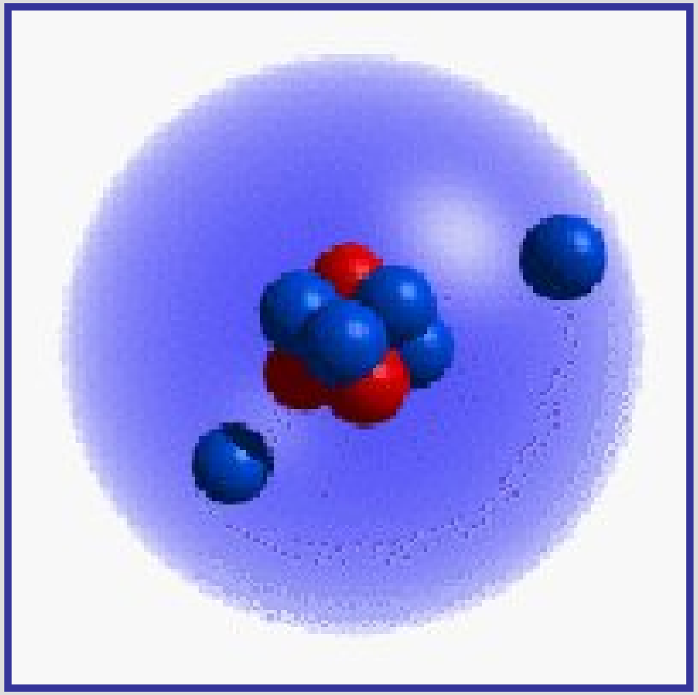


^{11}Li : Continuum HFB Spectral Functions

Neutron Spectrum :

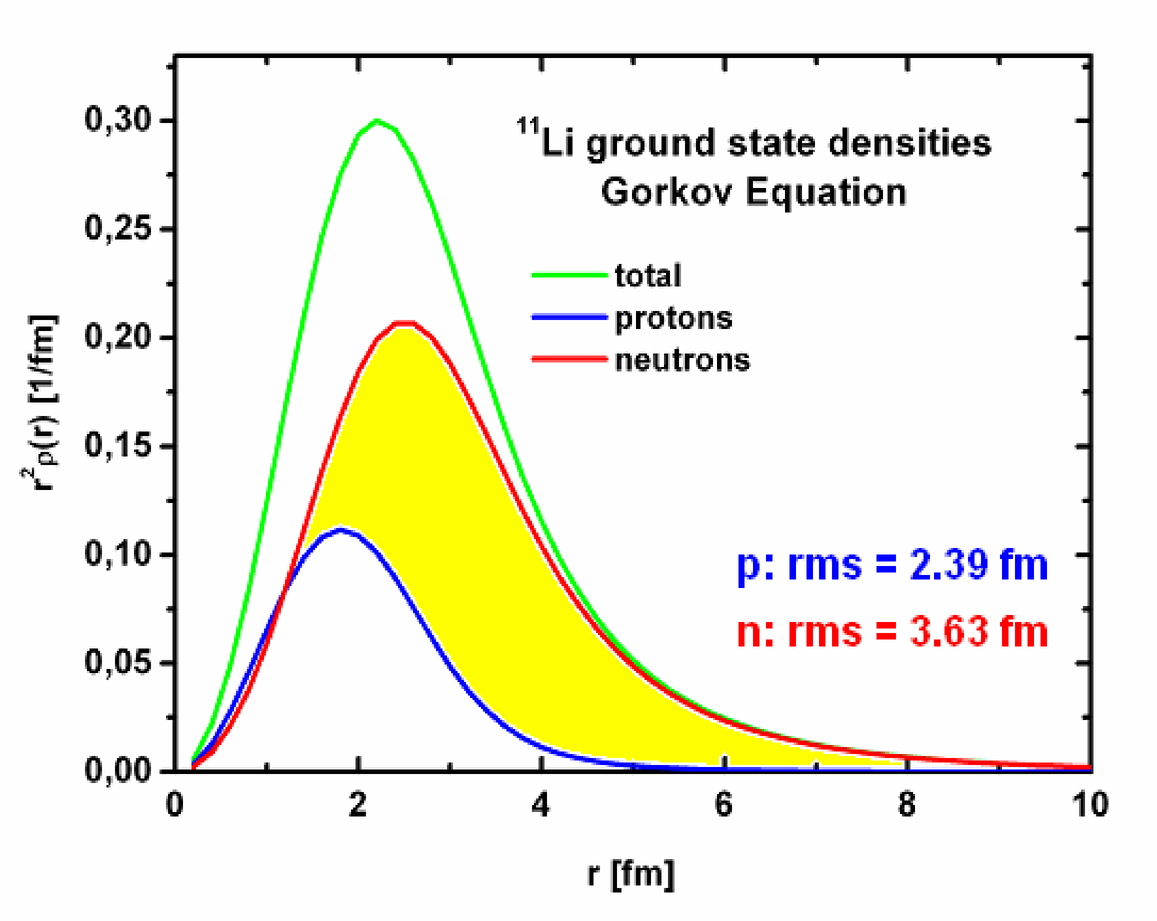


Nuclear Structure far off Stability: 2n-Halo in ^{11}Li



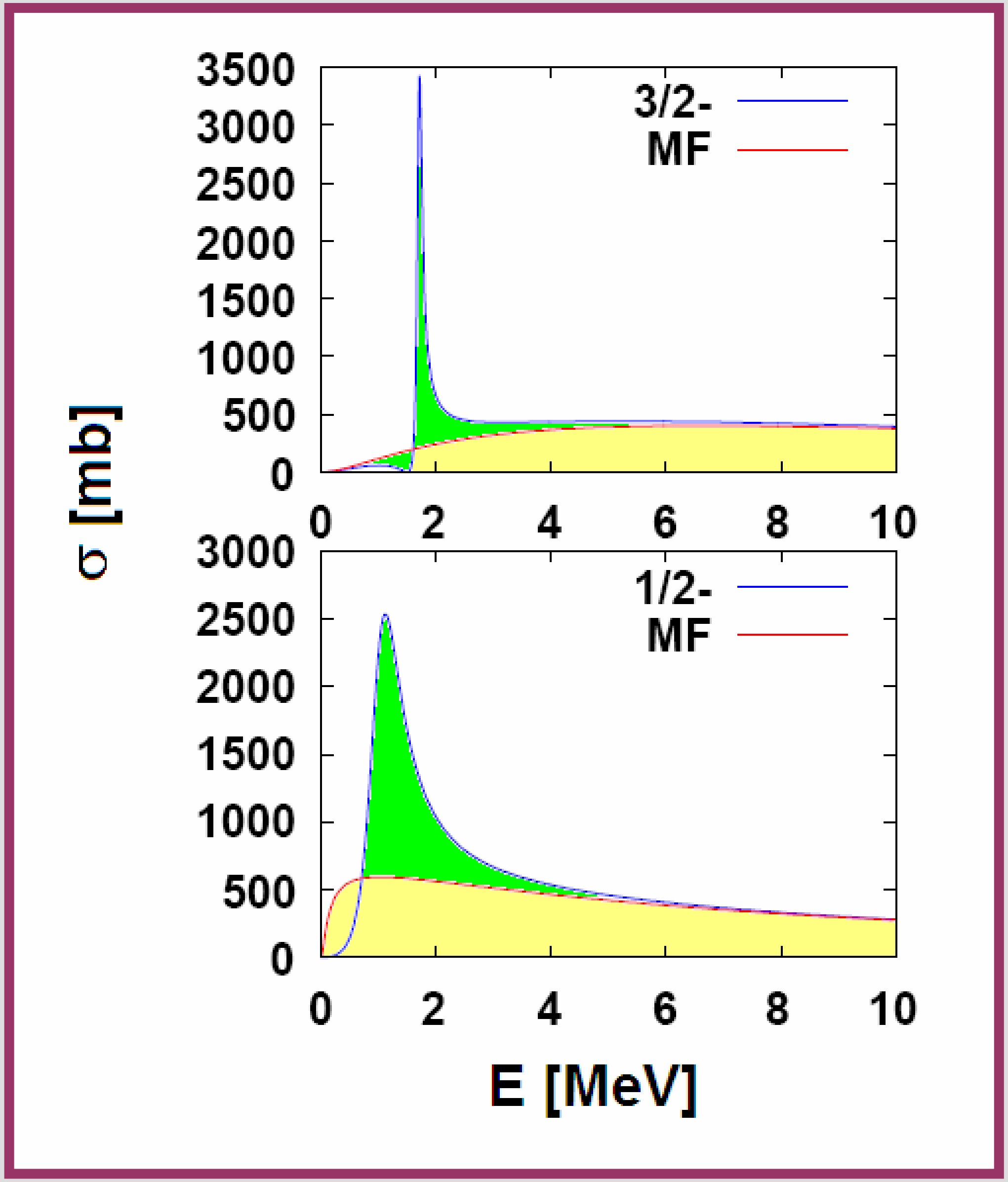
A popular but misleading classical point of view

Halos: pure Quantum Mechanics



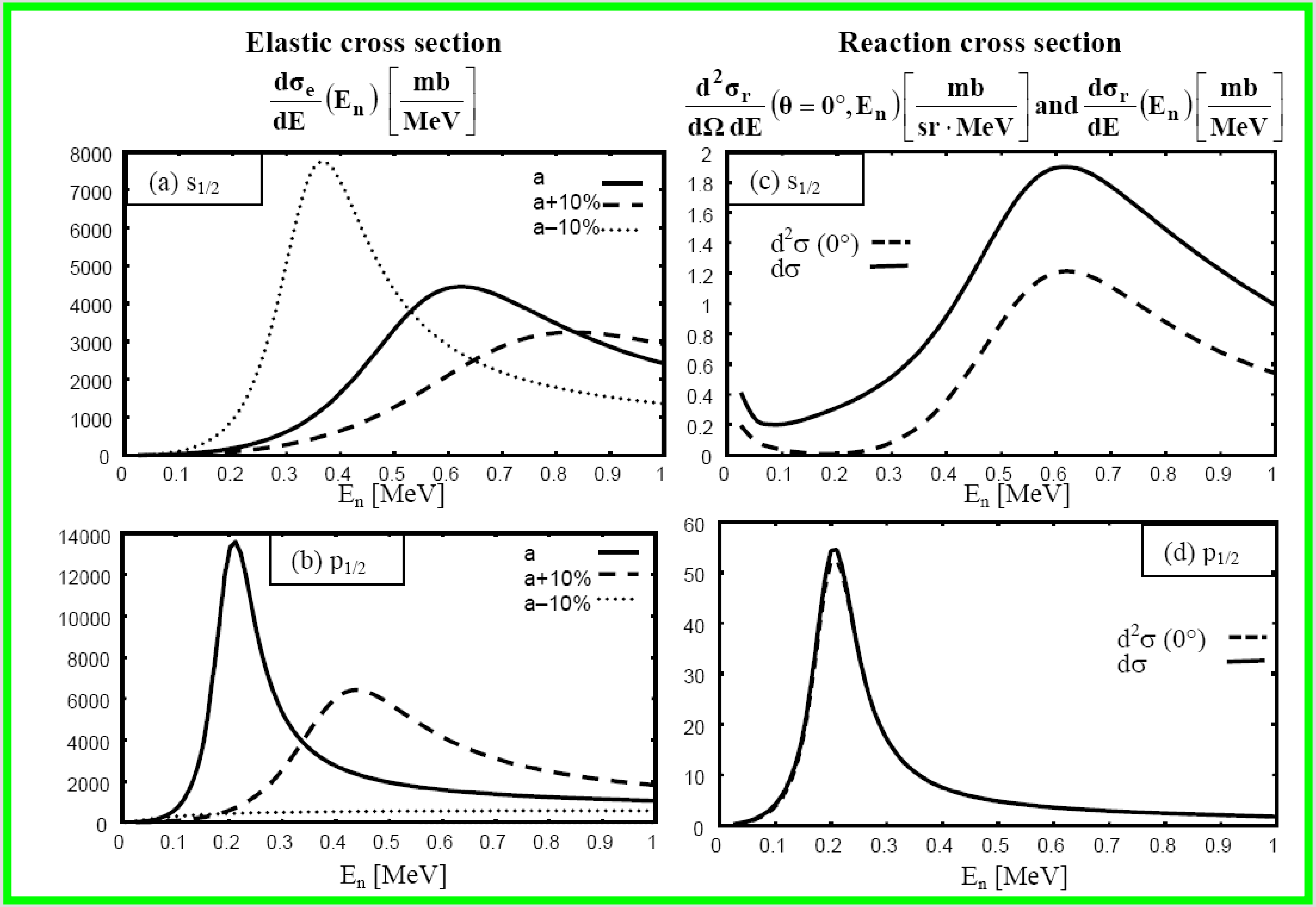
Pairing in the Continuum:

- CC Effects → Interference
- Sharp resonances close to threshold
- Interaction of closed and open channels
- Admixtures of continuum strength into the ground state



Sonja Orrigo, H.L., in preparation

Transfer to the Continuum: $^{9}Li+d \rightarrow {}^{10}Li + p$



Sonja Orrigo, H.L. et al., Phys.Lett. (2008)

Beyond the Ground State:

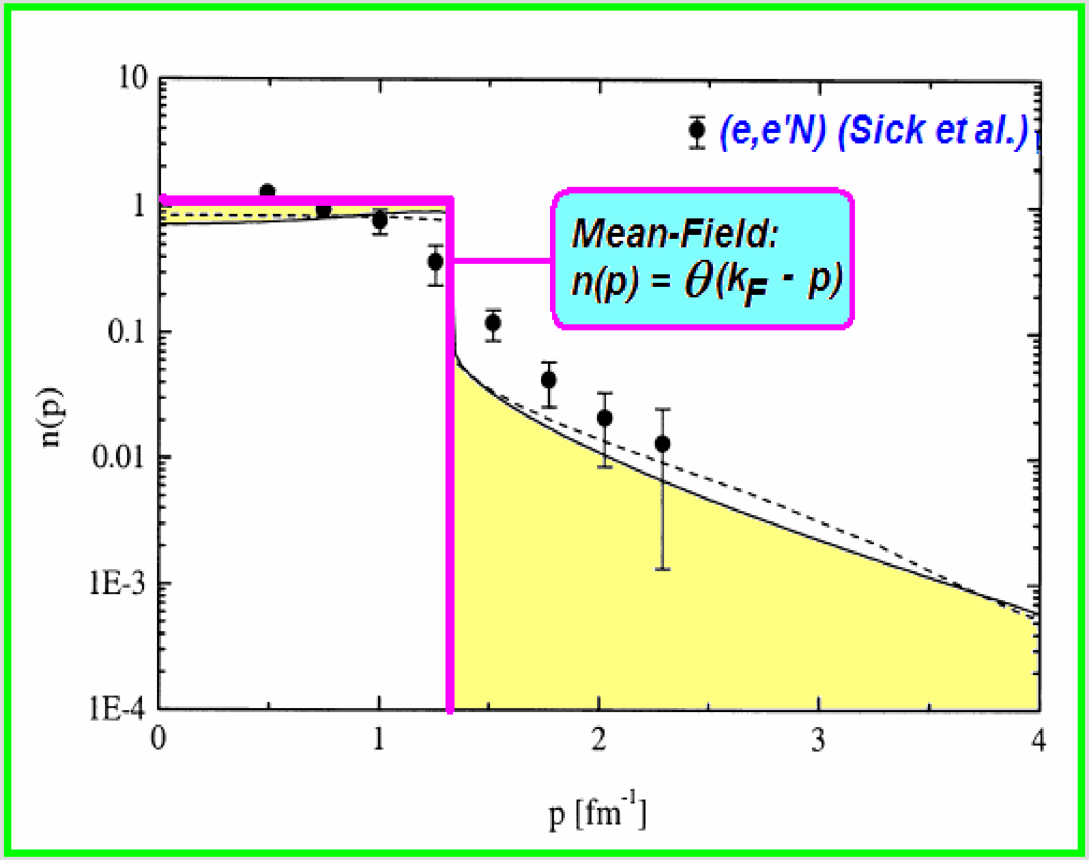
Adding Dynamics, Testing the Restoring Forces

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

$$E(\rho) \approx E(\rho_0) + \sum_{q=p,n} U_q(\rho_0)\delta\rho_q + \sum_{q,q'=p,n} F_{qq'}(\rho_0)\delta\rho_q\delta\rho_{q'} + \ldots$$

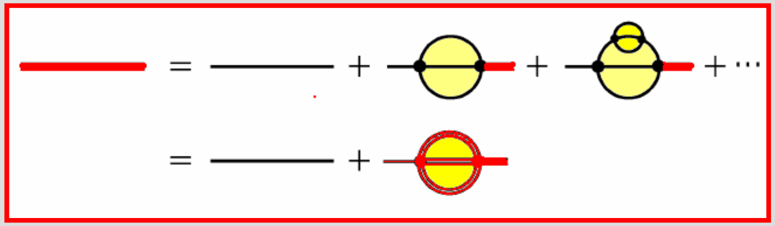
Fermi-Liquid Theory

Beyond the Mean-Field: Short-range Correlations in Nuclear Matter



Momentum Distribution

$$n(p) = N(k_F) \int a(p,\omega)\, d\omega$$



Dynamical Self - Energies :

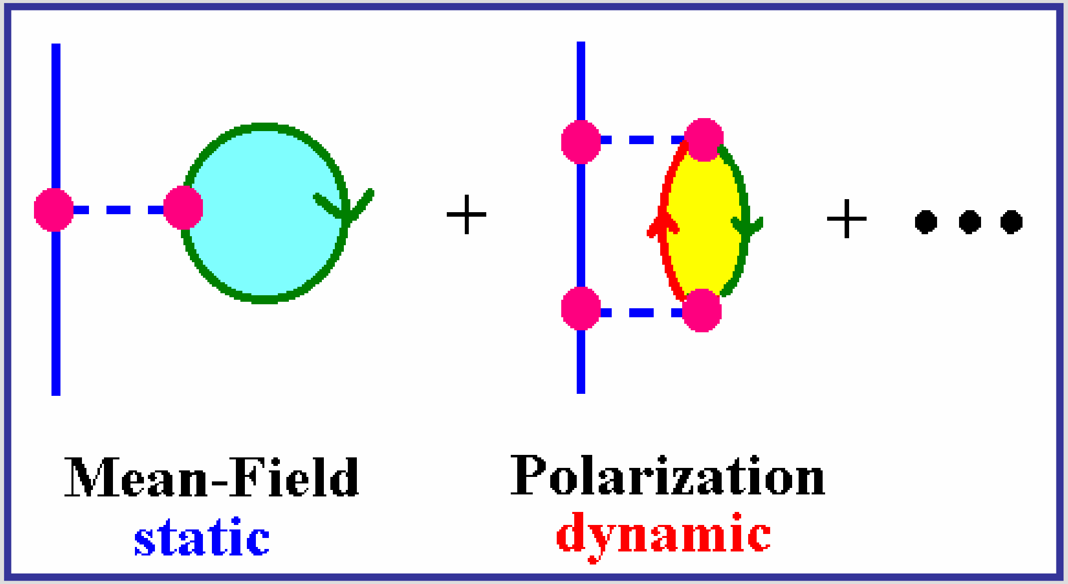
$$g(\omega,q) = \frac{1}{\varepsilon_{MF}(q) + \Sigma^{ret}(\omega,q) - \omega \pm i\eta}$$

$$\Sigma^{ret}(\omega,q) = U(\omega,q) - i\frac{1}{2}\Gamma(\omega,q)$$

$$\Gamma(\omega,q) \to 0 \quad \text{for } \omega \to \omega_F$$

PLB483 (2000) 324 NPA723 (2003) 544 NPA756 (2005) 192

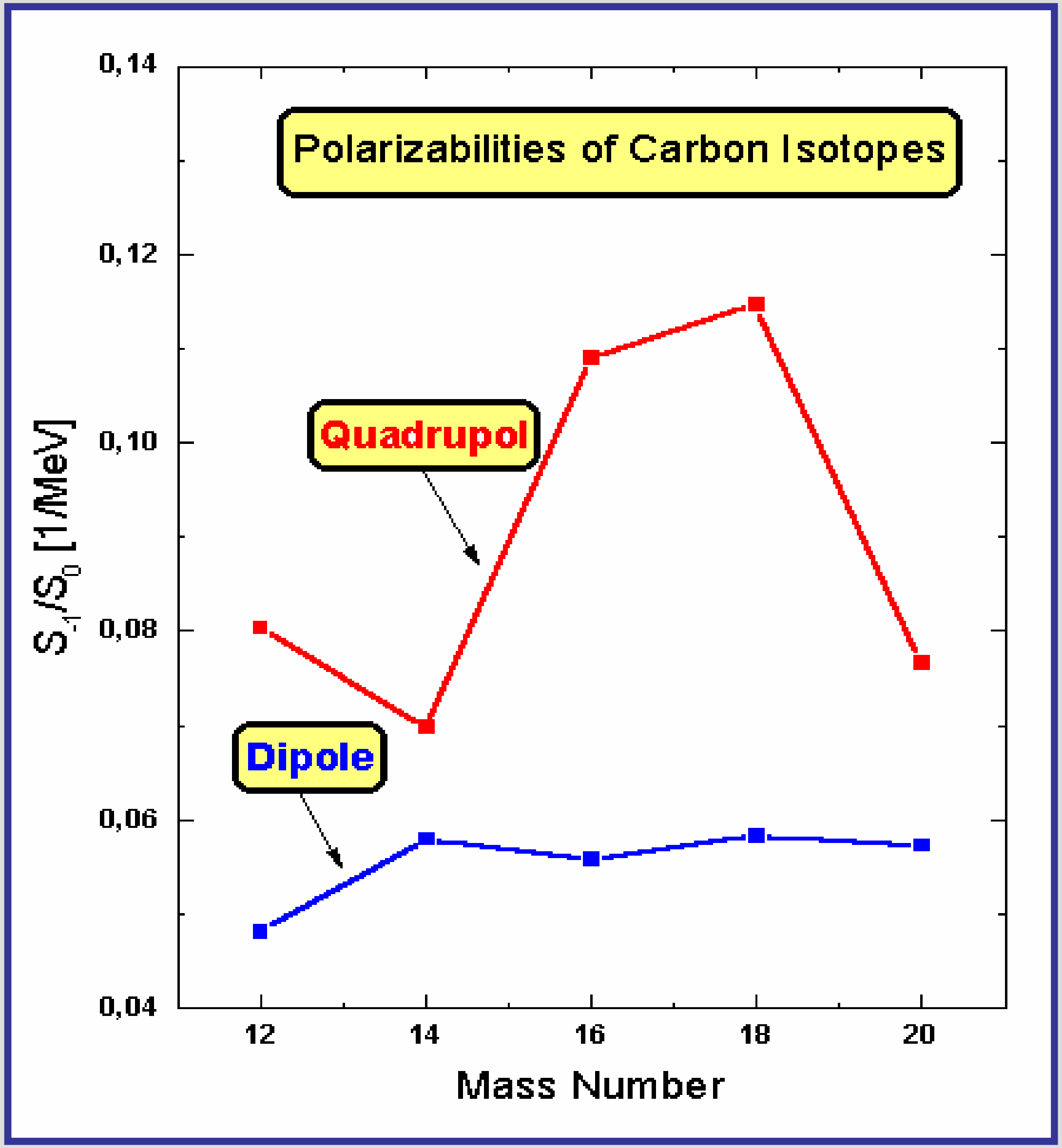
Beyond Mean-Field Dynamics: Dynamical Correlations



$$|\,\beta j_\beta\rangle = \sum_n z_n^\beta \,|\, n j_\beta\rangle + \sum_{kc} z_{kc}^\beta \,|\,(kc)\, j_\beta\rangle$$

- Dynamical Breaking of Symmetries
- Mixing of Mean-Field s.p. States

The Softness of Exotic Nuclei



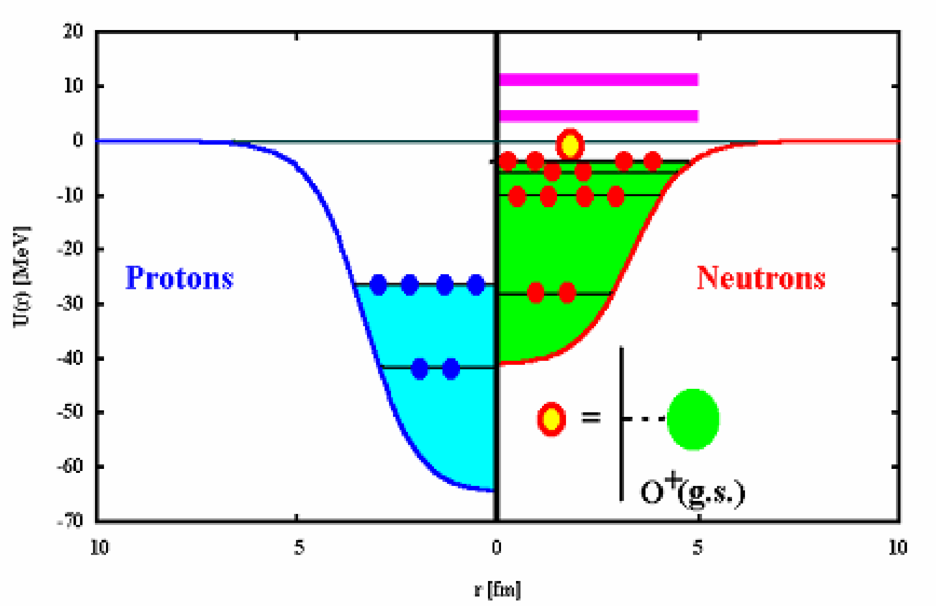
HFB & QRPA Calculations

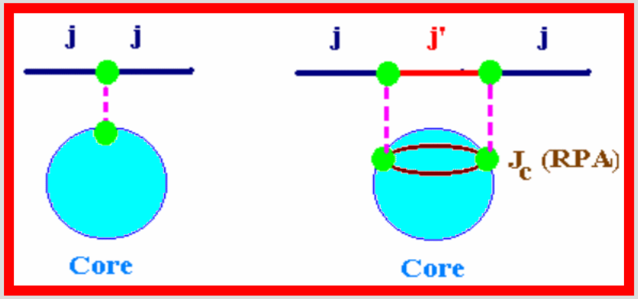
Polarizabilities from Sum Rules:

$$P_\lambda = S_{-1}(\lambda)/S_0(\lambda)$$

$$S_n(\lambda) = \Sigma_c\, |M_c(\lambda)|^2\, E^n{}_c$$

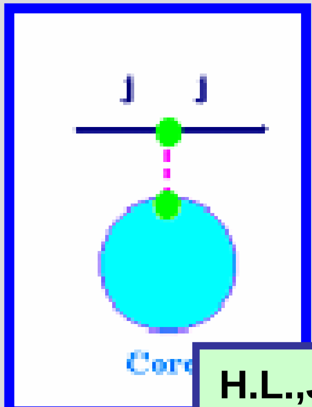
The Neutron Halo in ^{19}C: Transition from Mean-Field to Correlation Dynamics

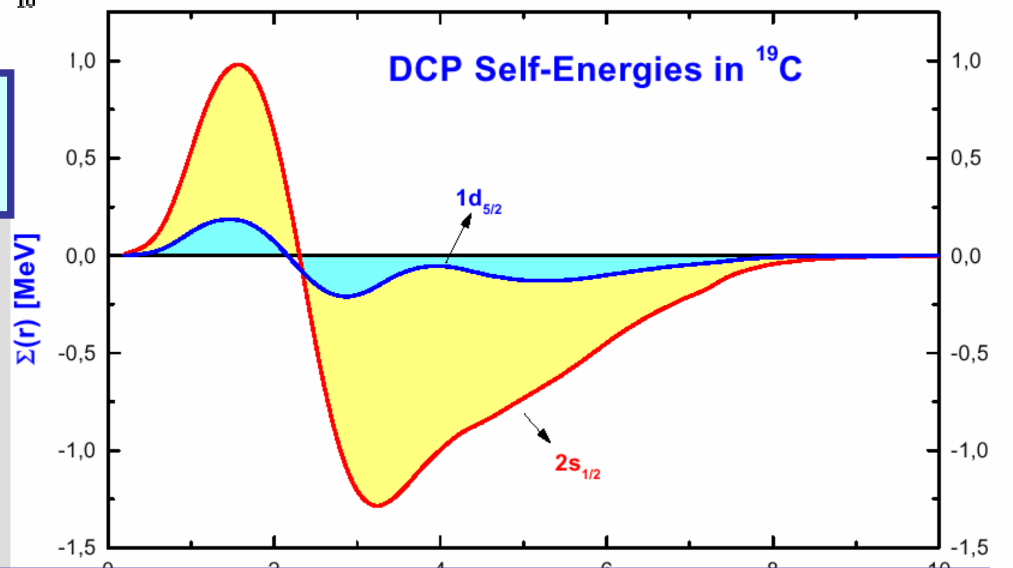




The DCP picture: Binding by Polarization Potential

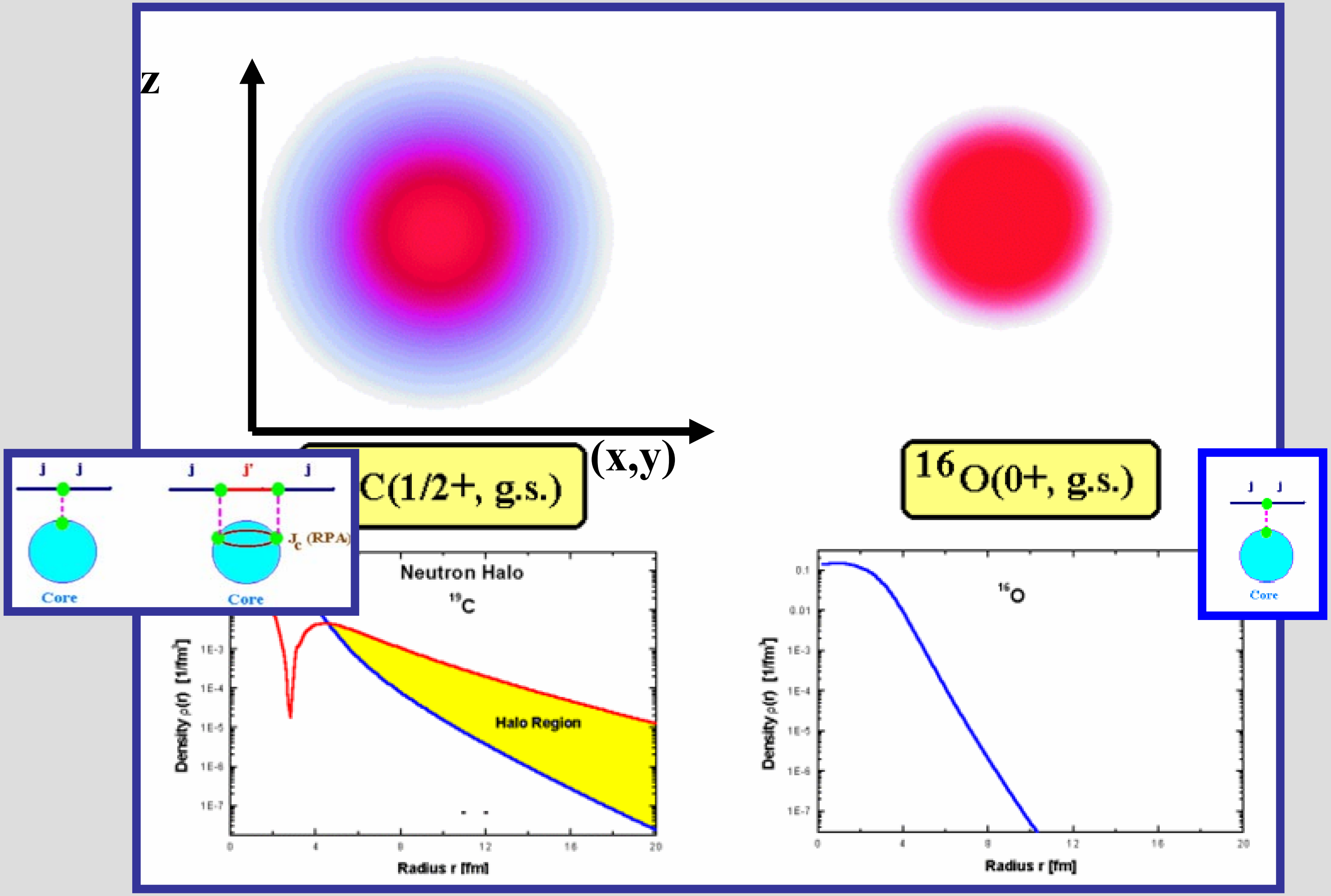
The s.p. shell model picture: Static Potential





H.L.,J. Prog.Part.Nucl. 561 (2003);C. Nociforo, H.L., Nucl.Phys (2006)

Size of ^{19}C and ^{16}O

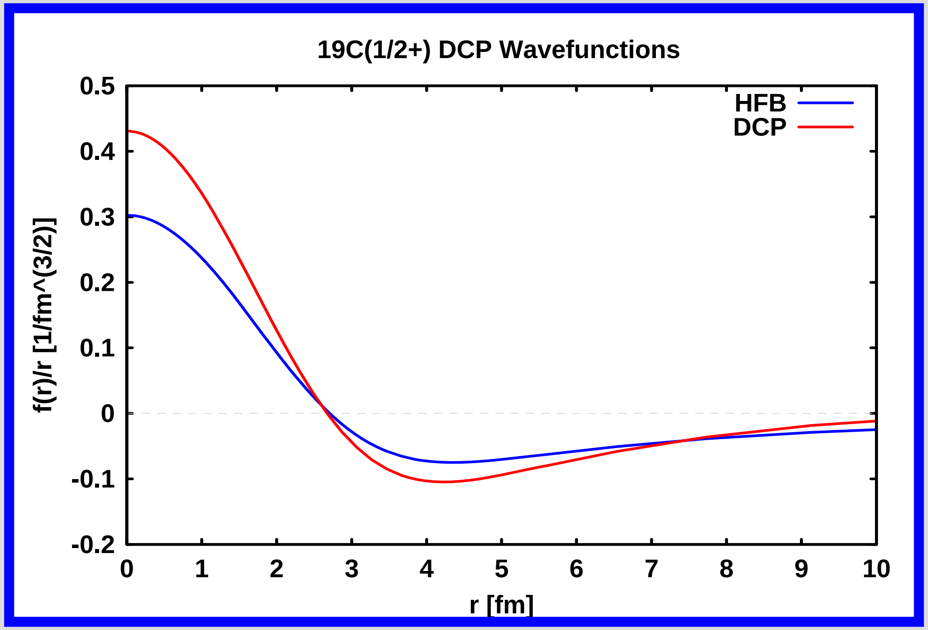


$\sqrt{<r^2>}(1/2+) = 5.34$ fm

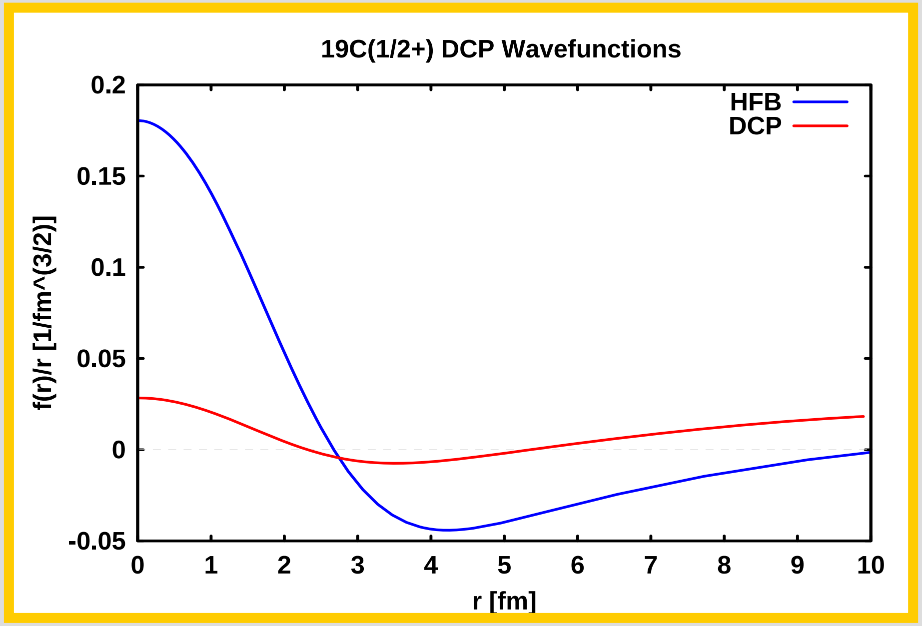
S = 0.40

$\sqrt{<r^2>}(1/2-) = 2.96$ fm

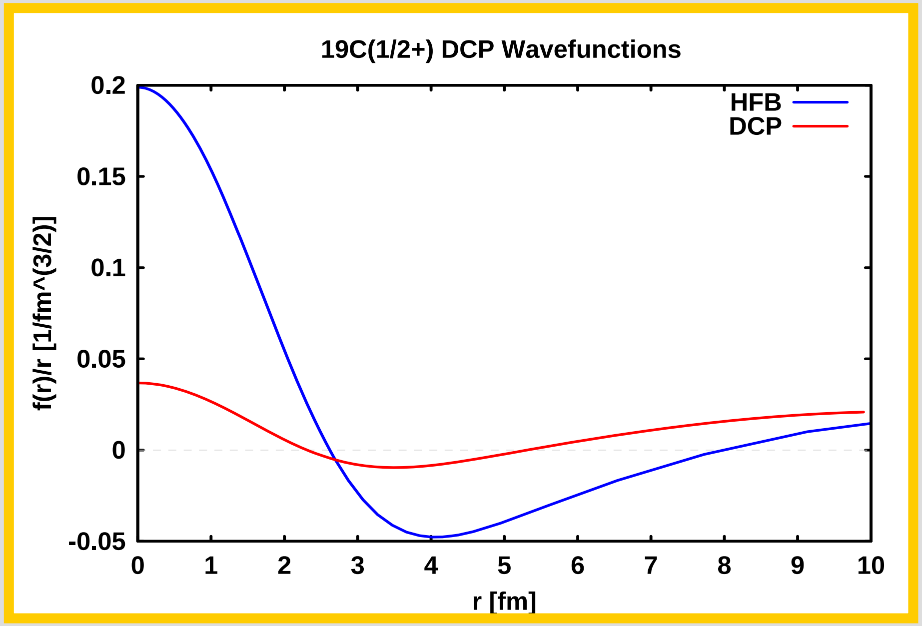
S = 0.97



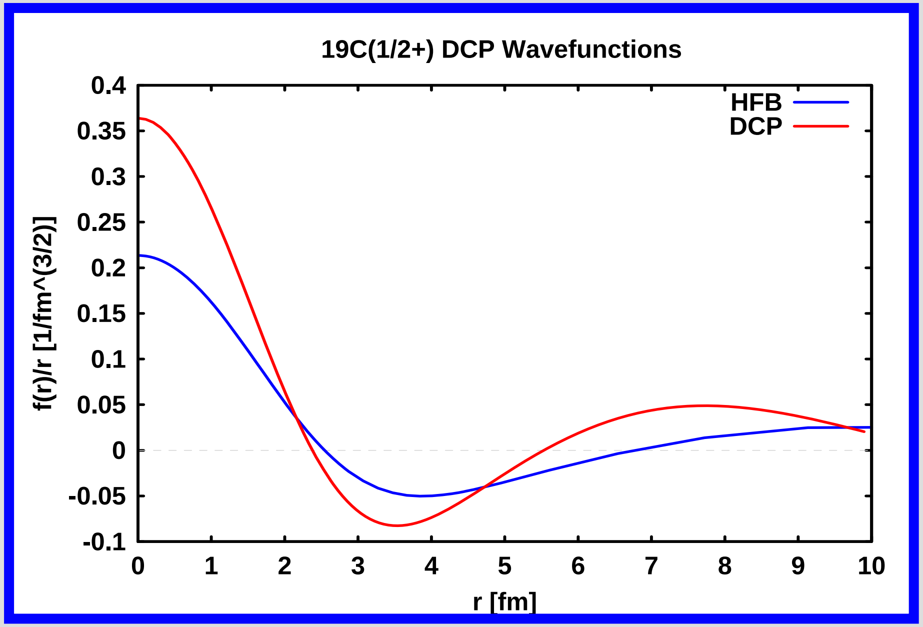
19C(1/2+) DCP Wavefunctions
HFB
DCP
f(r)/r [1/fm^(3/2)]
r [fm]



19C(1/2+) DCP Wavefunctions
HFB
DCP
f(r)/r [1/fm^(3/2)]
r [fm]

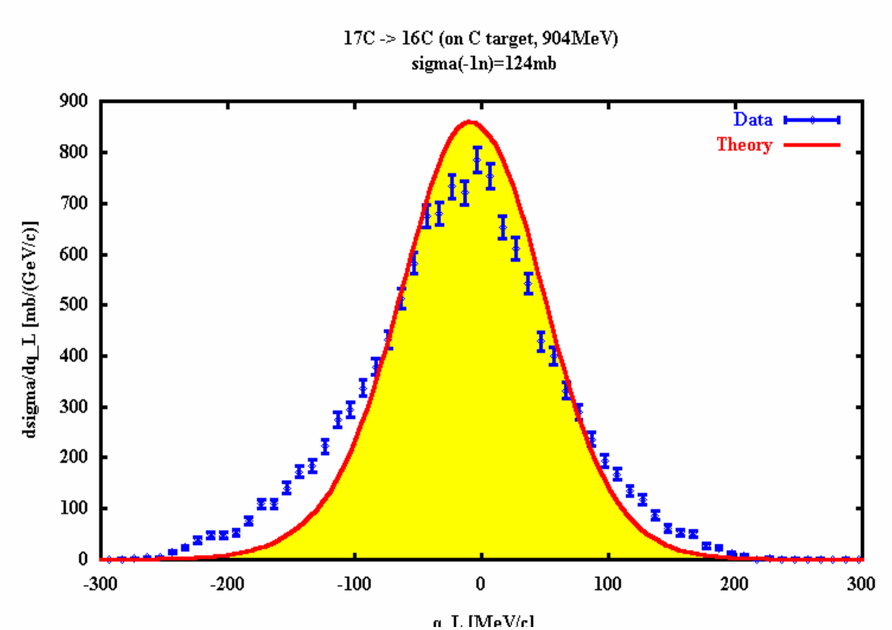


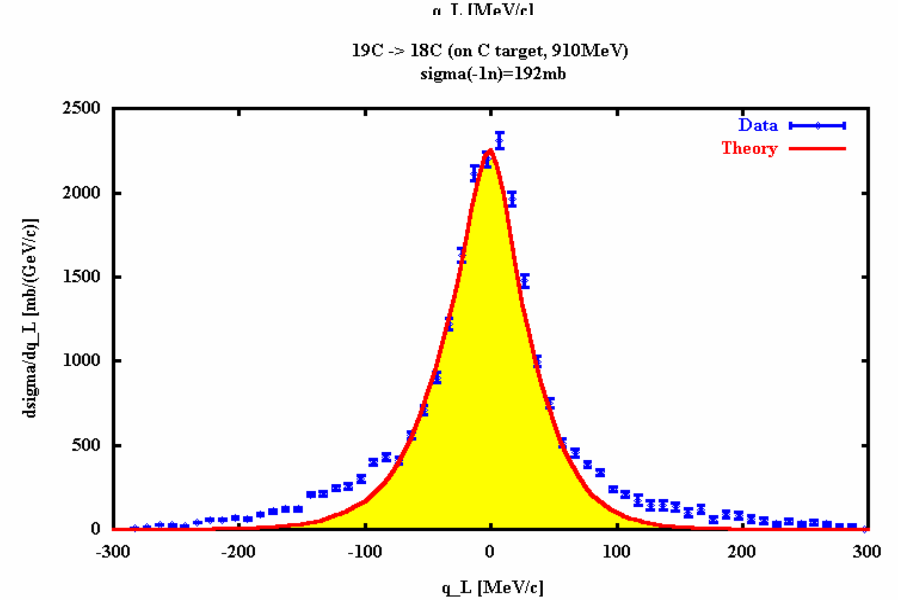
19C(1/2+) DCP Wavefunctions
HFB
DCP
f(r)/r [1/fm^(3/2)]
r [fm]



19C(1/2+) DCP Wavefunctions
HFB
DCP
f(r)/r [1/fm^(3/2)]
r [fm]

Momentum Distributions for $^{17,19}C \rightarrow {}^{16,18}C + n$
Carbon Target, $E_{lab} \approx$ 900 AMeV





- **Binding: Correlation Dynamics**
- **^{17}C(5/2+,g.s.)**
- **S_n(the.)=715keV**
- **C^2S(g.s.) = 0.41**

Γ_{theory} : 132 MeV/c

$\Gamma_{experim.}$: 143 ± 5 MeV/c

σ(-1p,the.): 124 mb

σ(-1p,exp.): 129± 22 mb

- **Binding: Correlation Dynamics**
- **^{19}C(1/2+,g.s.)**
- **S_n(the.)=263keV**
- **C^2S(g.s.) = 0.40**

Γ(the.): 69 MeV/c

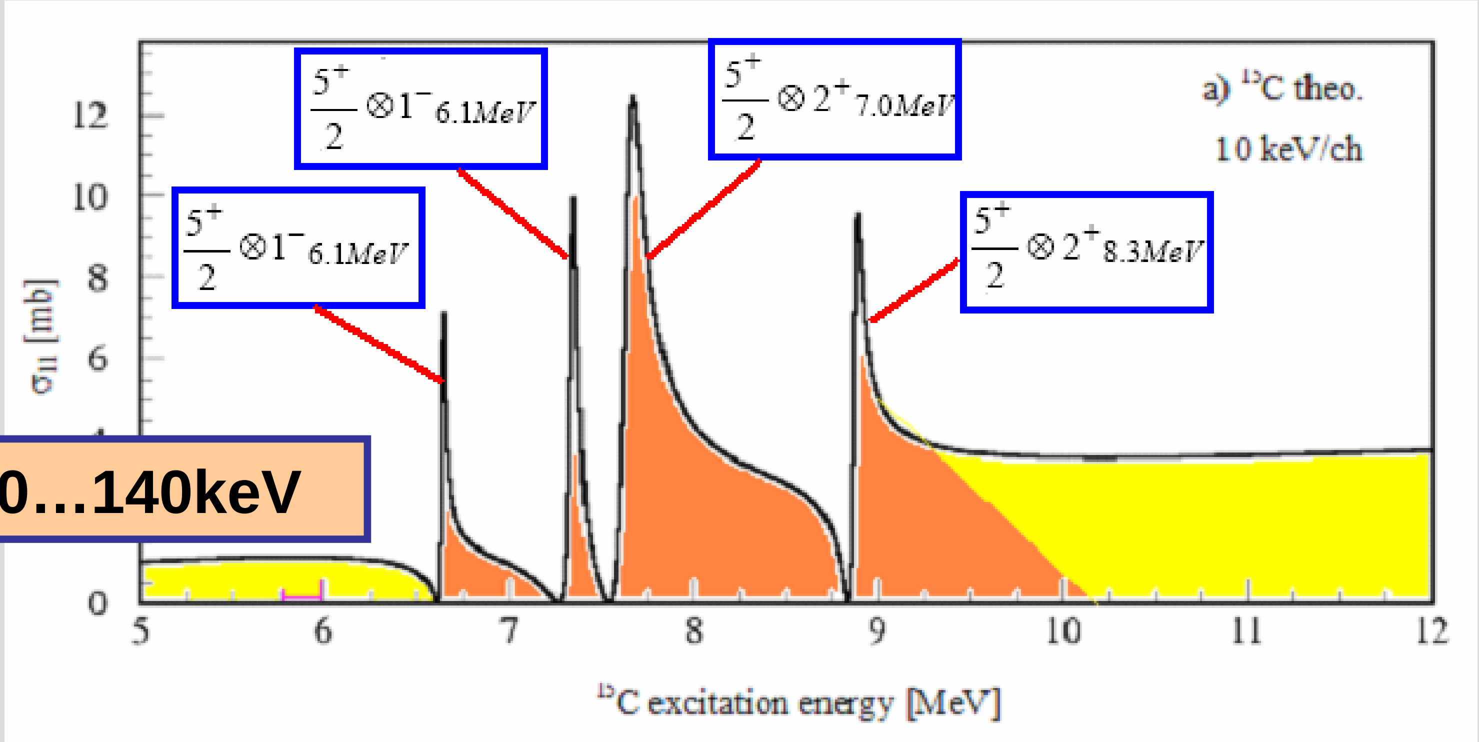
Γ(exp.): 68 ± 3 MeV/c

σ(-1p,the.): 192 mb

σ(-1p,exp.): 233± 51 mb

Core-excited Fano-Resonances in ^{15}C

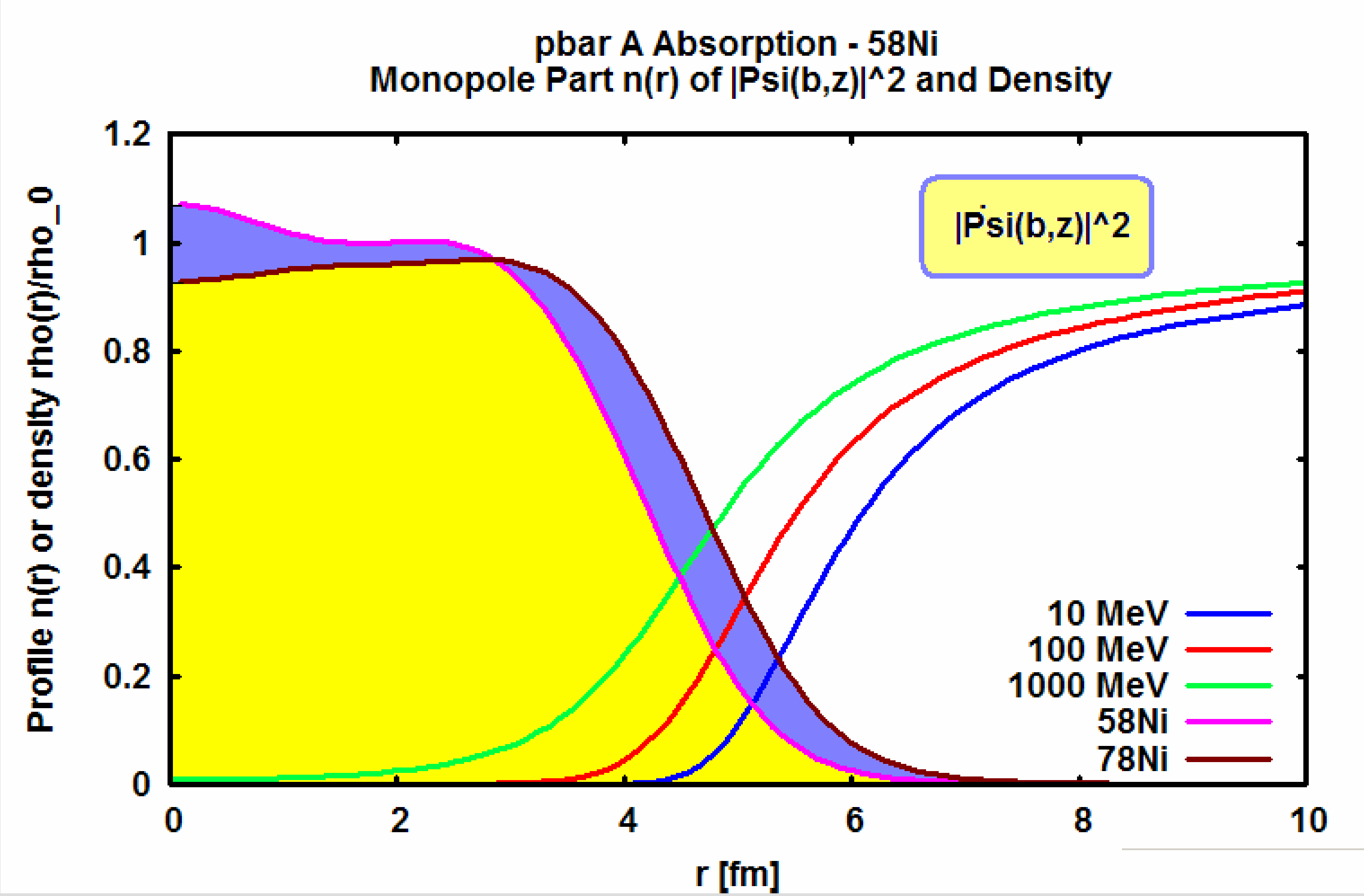
Core excitations in Continuum States:
Open Quantum System



Γ~60…140keV

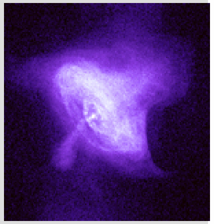
Sonja Orrigo, H.L. et al., Phys.Lett. B633 (2006)

Antiproton+A Absorption: Overlap of the Reaction Kernel and the Nuclear Density



H. **Lenske**, P. **Kienle**, Phys. Lett. B 647 (2007) 82

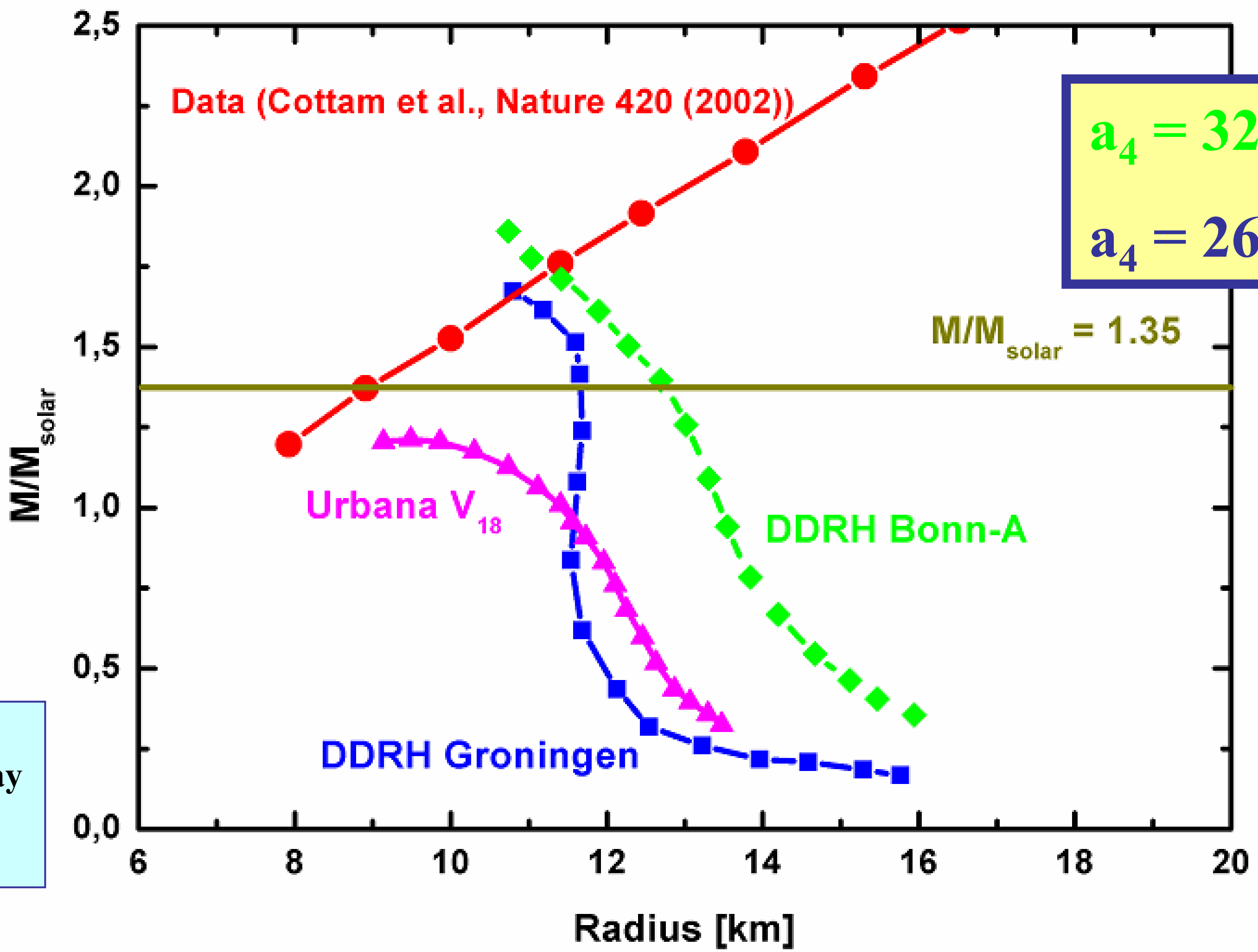
DDRH Neutron Star Mass-Radius Relation (TOV Eq.):



X-ray

Optical

Crab Nebula
Chandra X-Ray
Observatory
and HST



$a_4 = 32$ MeV

$a_4 = 26$ MeV

PRC 64 (2001) 025804; H.L. Springer Lect. Notes (2004)

Data from the XMM-Newton X-ray space observatory:

Gravitational Red-Shift z ~ M/R

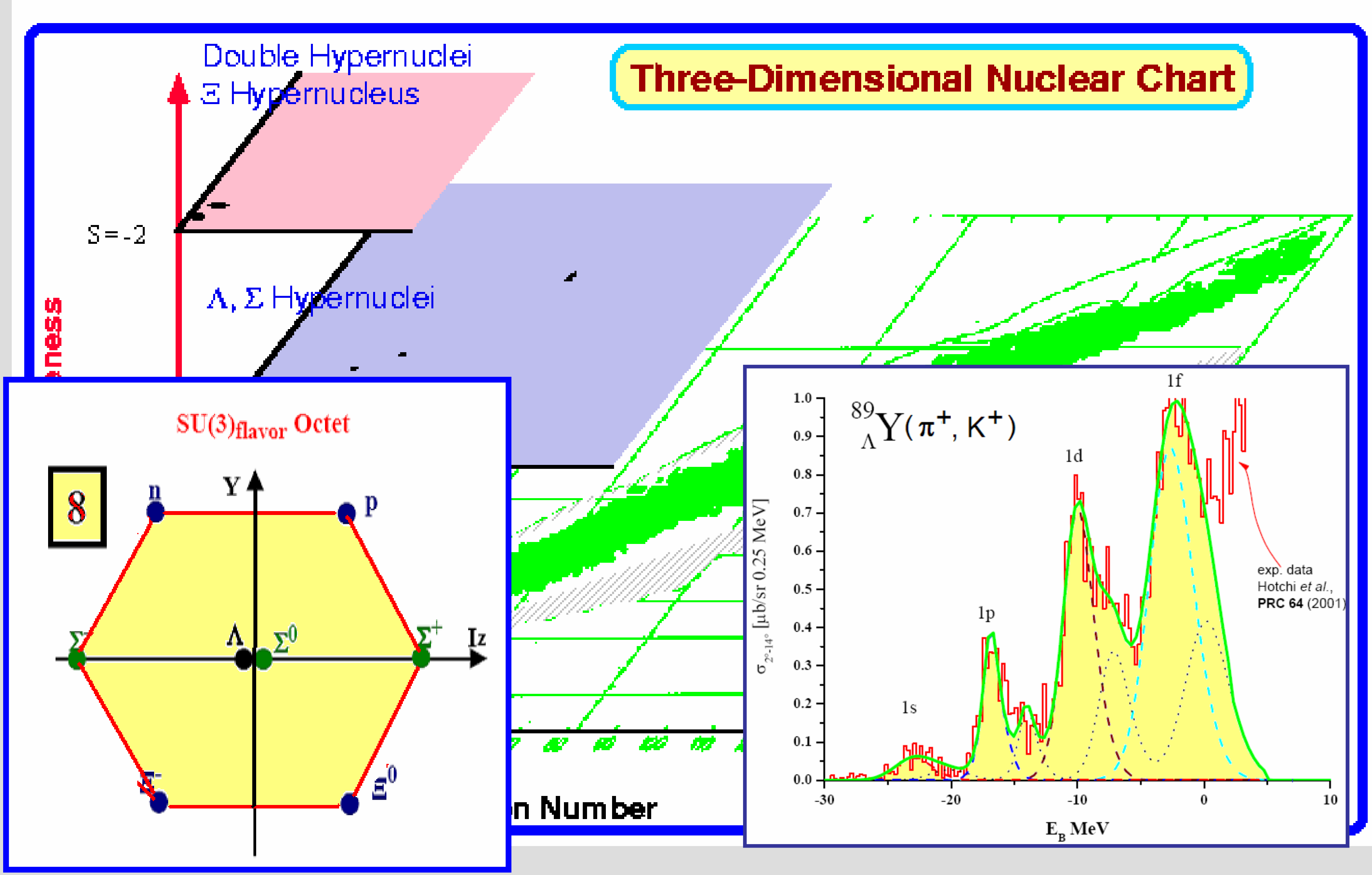
(Fe-Lines from a series of 28 X-ray bursts from EXO07481676)

Summary and Outlook:

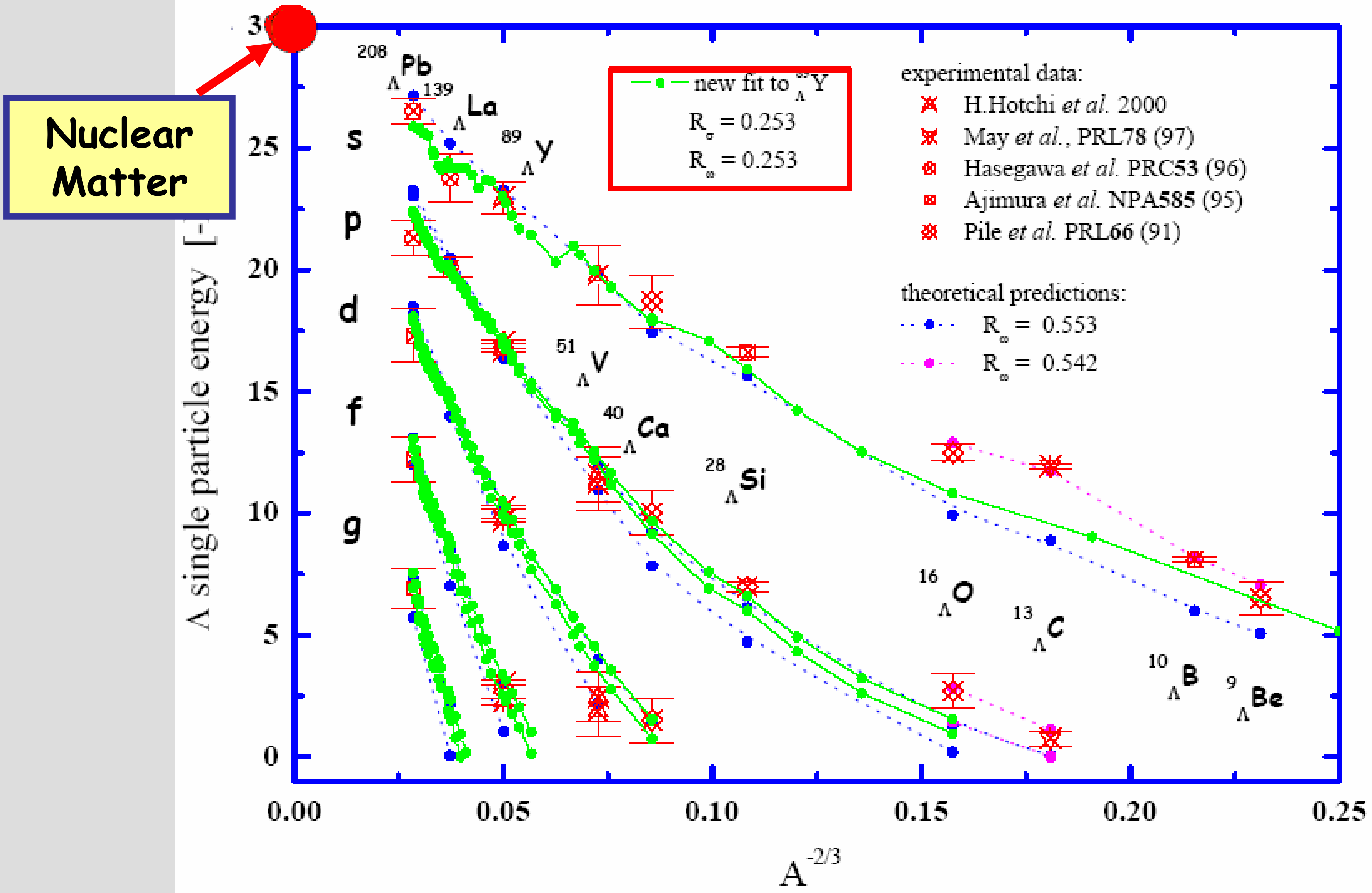
- *ab initio* Description of Stable and Unstable Nuclei
- Interactions in Asymmetric Nuclear Matter
- Contiunuum Effects: Open Quantum Systems
- Softness, Polarizability of Exotic Nuclei and LRC
- Mean-field Cynamics or Correlation Dynamics?
- Relation to Astrophysics: Neutron Stars
- Unique: Nucleo-Engineering on the Femto-scale!

Thanks to all participants from the organizers Tom, Roy, H., and Jeff for the lively discussions and the productive engagement

Strangeness and Hypernuclear Physics: From SU(2) Isospin to SU(3) Flavour Dynamics

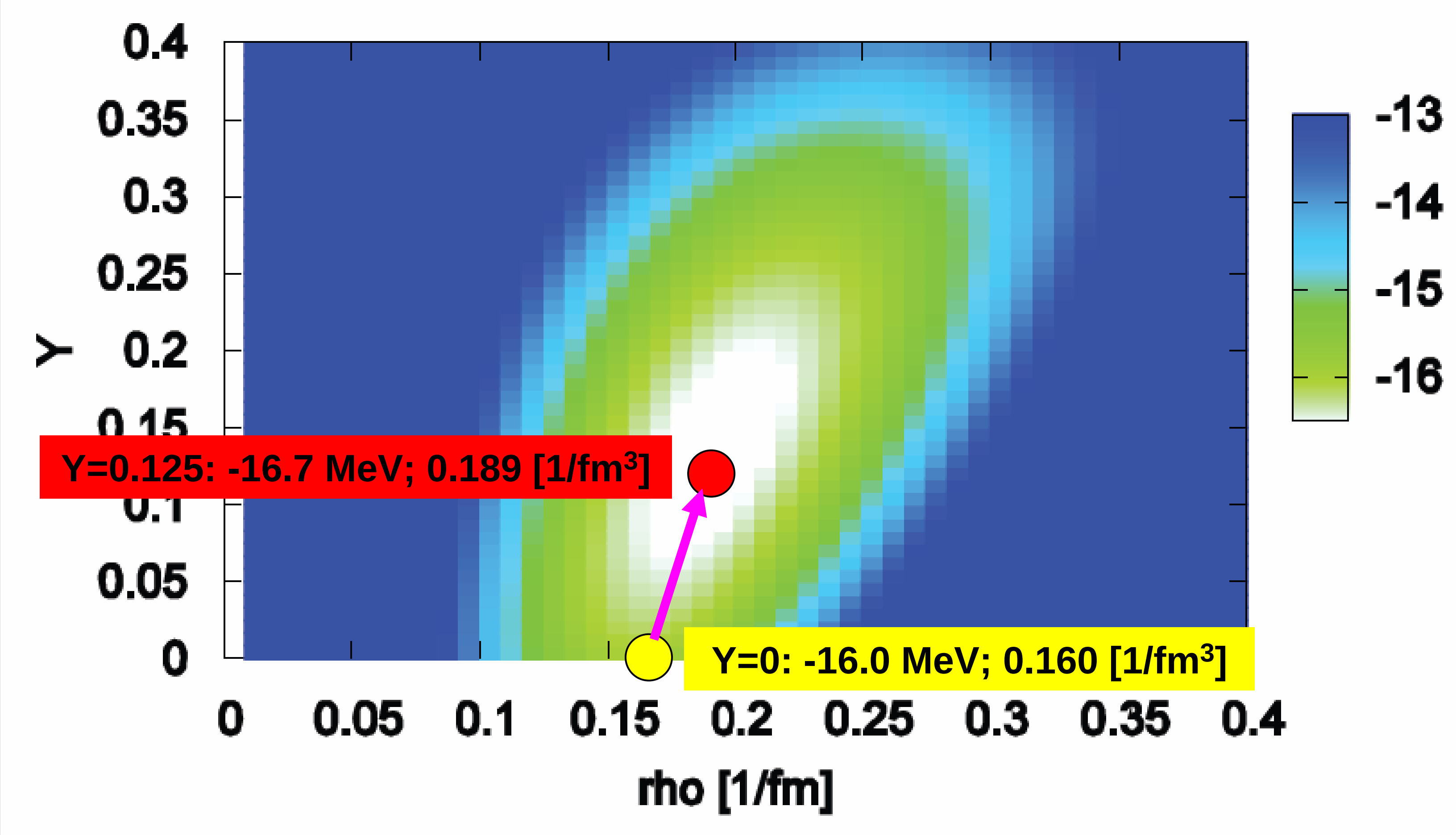


DDRH Flavour Dynamics: Λ Single Particle Energies



DDRH Theory: Density Dependent NN and NΛ Dirac-Brueckner Vertices

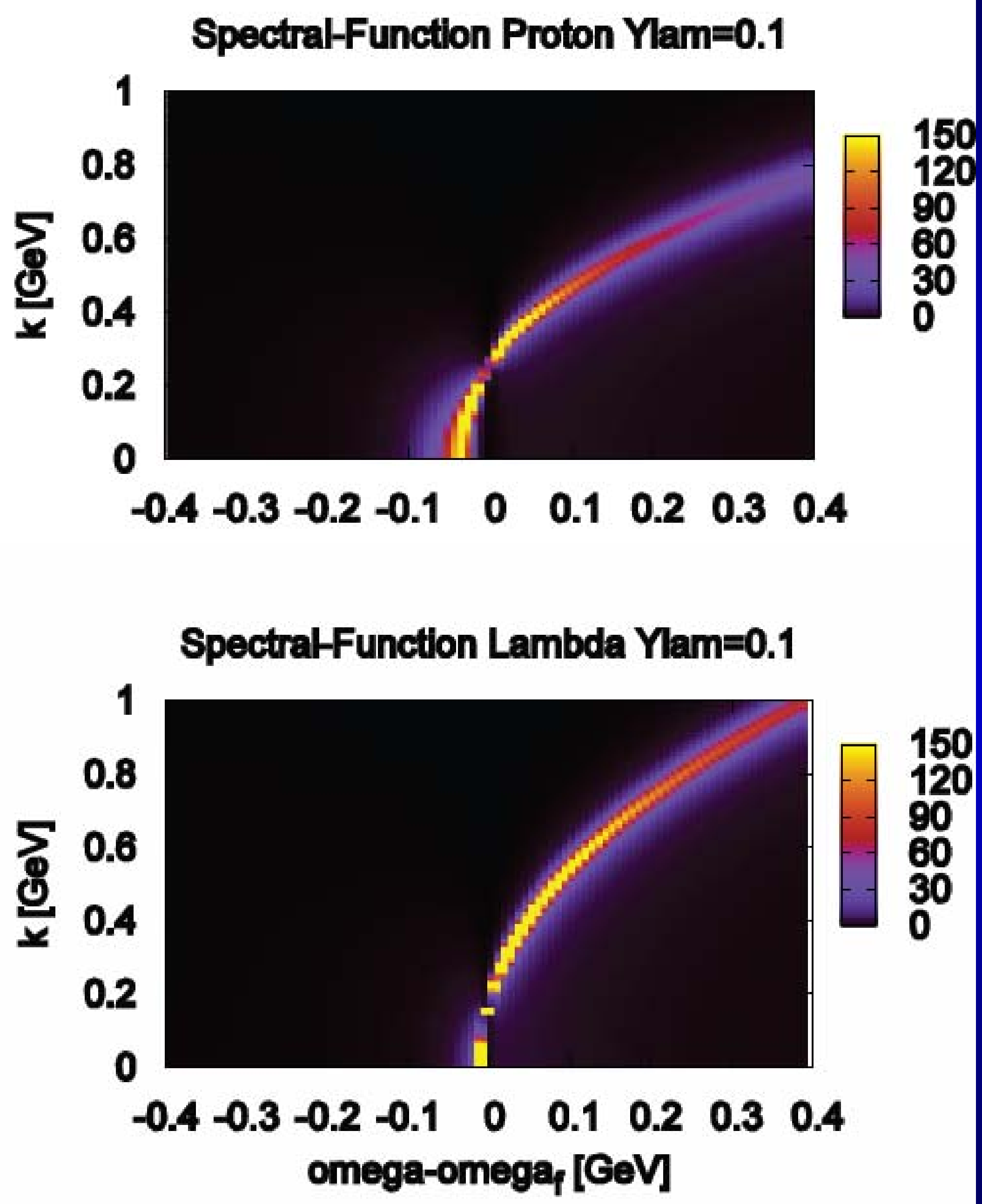
Binding Energy of Infinite Hypermatter



$$B(\rho,Y) = E(\rho,Y)/\rho - YM_{\Lambda} - (1-Y)M_{N}$$

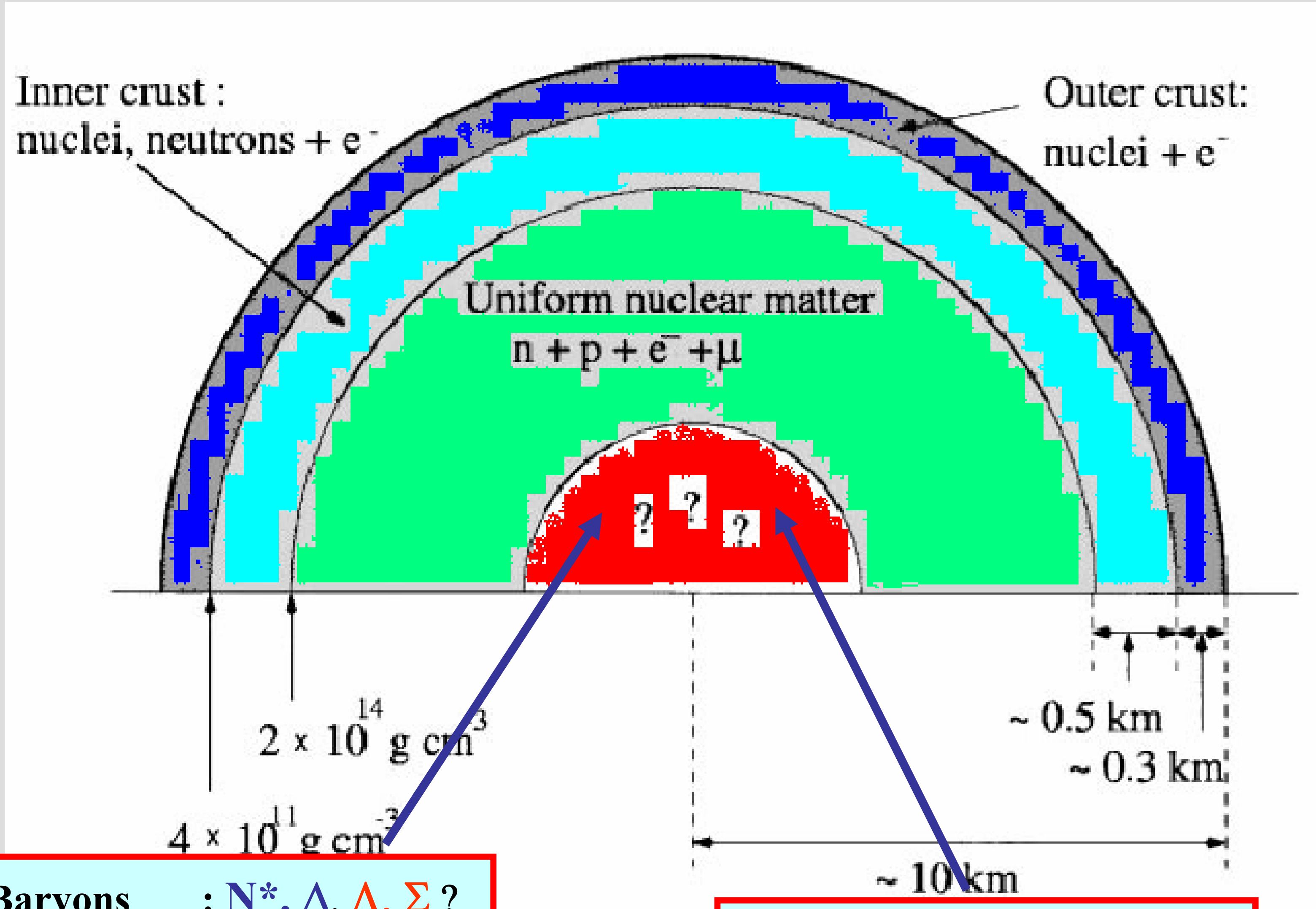
$S_p(k,\omega)$

$S_\Lambda(k,\omega)$



Beyond Mean-Field Dynamics: Spectral Functions in Infinite Hypermatter

Expected Structure of a Neutron Star



Baryons : N*, Δ, Λ, Σ ?
Condensates: π, K ... ?

Quark Matter, QGP, CFL?

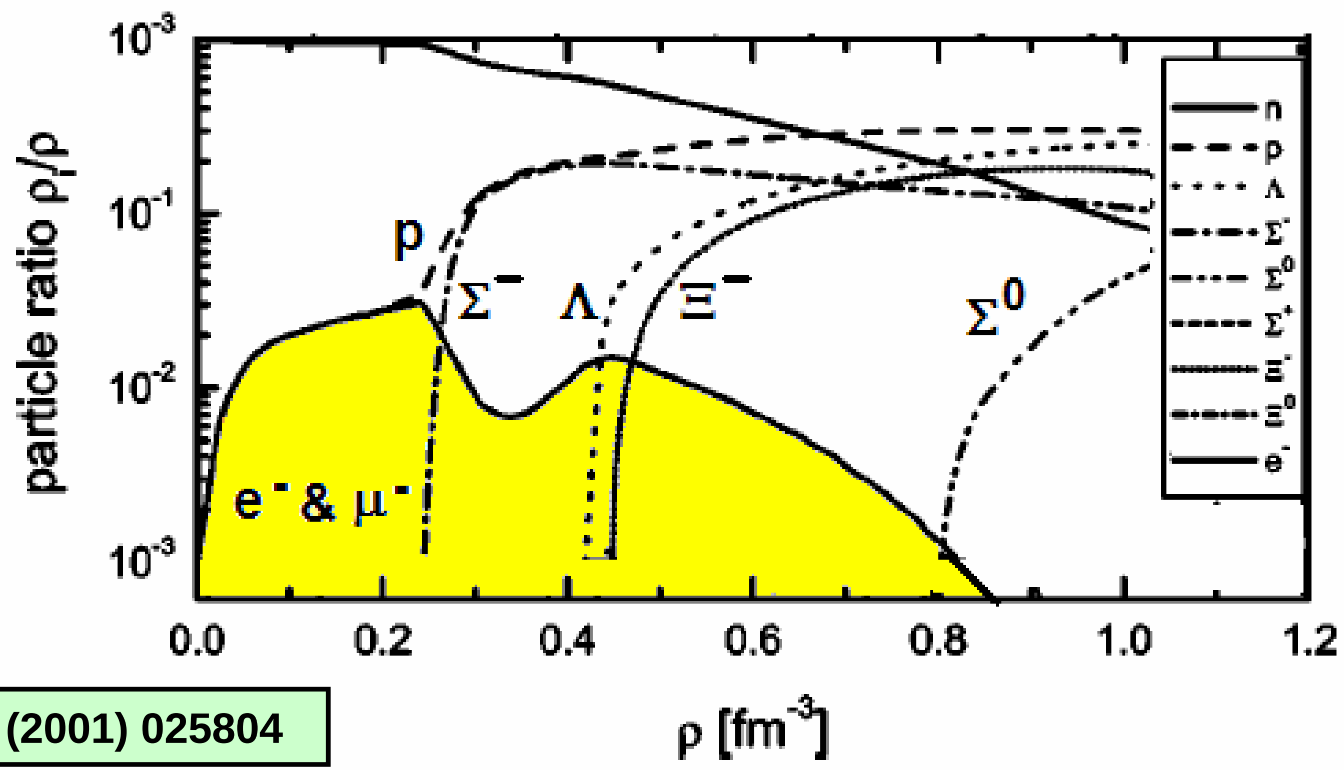
Charge-Neutral Neutron Star Matter in β-Equilibrium

$$n + n \rightarrow \Lambda + n \; ; \; p + n \rightarrow n + n + e^- \; ;$$
$$\Lambda + \Lambda \rightarrow \Xi^- + p$$

$$\mu_i = b_i \mu_n - q_i \mu_e$$

Creation of Strangeness:

$\rho \sim 2\rho_0$: **hyperon threshold (Σ^-, Λ),** $\rho > 5\rho_0$: **hypermatter dominates**



PRC 64 (2001) 025804

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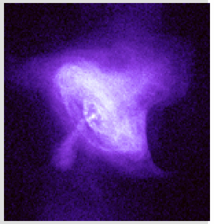
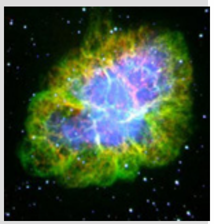


X-ray



Optical

Crab Nebula
Chandra X-Ray
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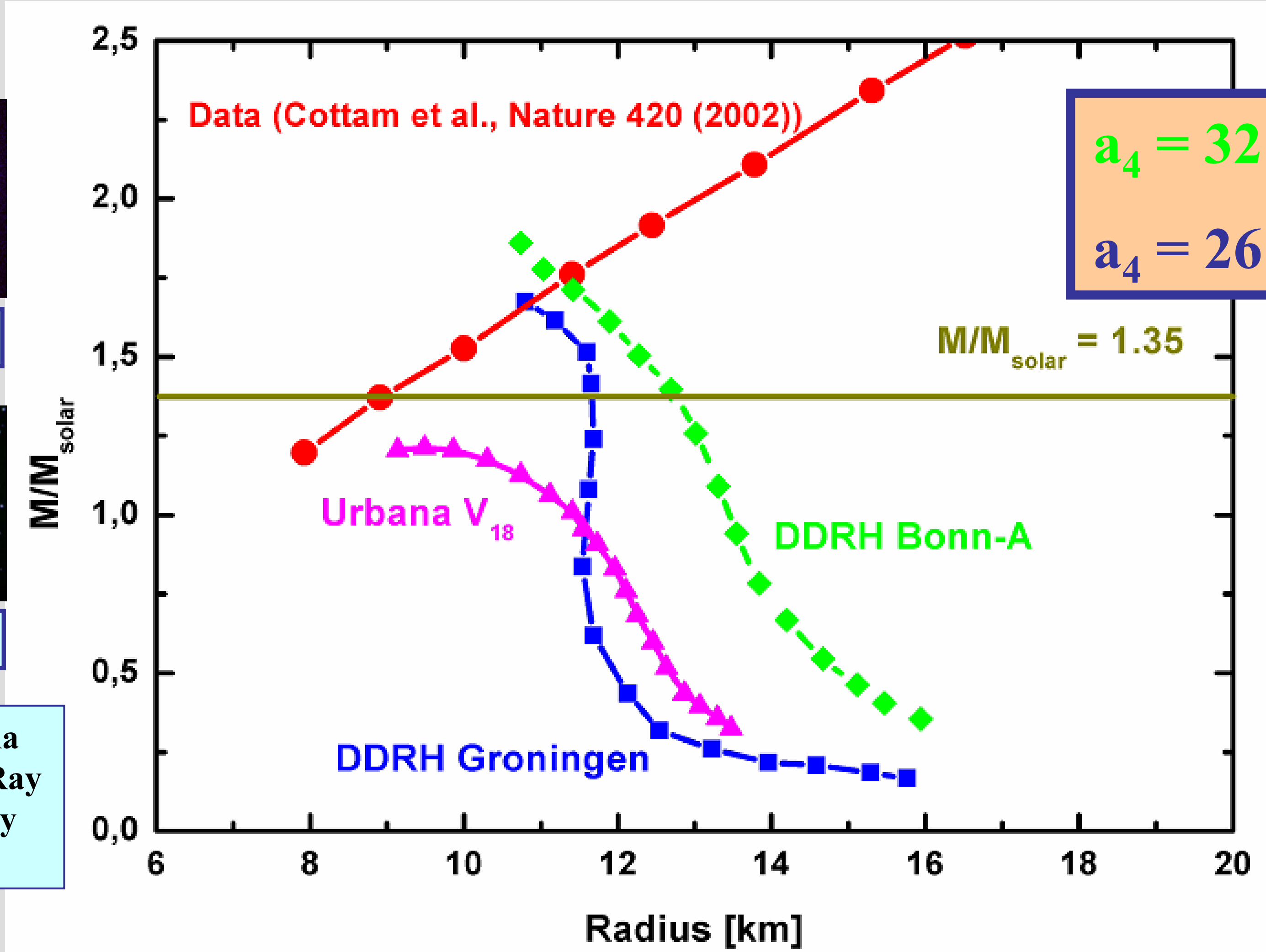

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PRC 64
(2001)
025804;
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