Recent progress in many-body models based on the covariant DFT

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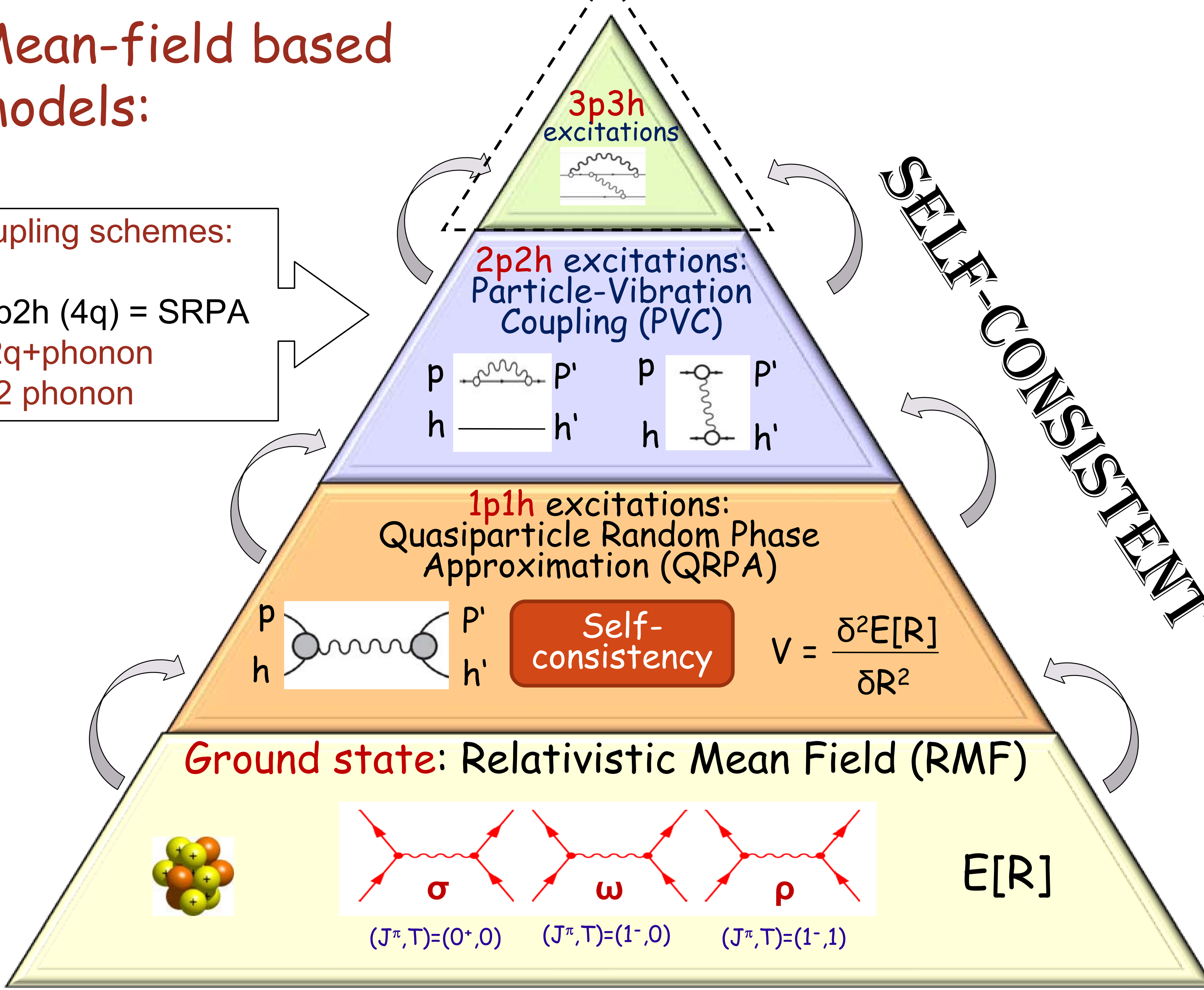
OUTLINE

- Introduction
- Theory:
  - Relativistic mean field (RMF) model
  - Relativistic quasiparticle random phase approximation (RQRPA)
  - Quasiparticle time blocking approximation (QTBA)
  - Particle-vibration coupling (PVC) model
  - Mode-coupling model
- Applications:
  - Nuclear single-particle structure
  - Nuclear low-energy response
- Conclusions and outlook

Mean-field based models:

Coupling schemes:

I. 2p2h (4q) = SRPA
II. 2q+phonon
III. 2 phonon



Relativistic mean field

$$E_{RMF}[\hat{\rho},\phi] = Tr[(\boldsymbol{\alpha}\mathbf{p}+\beta m)\hat{\rho}] + \sum_m \left\{ Tr[(\beta\Gamma_m\phi_m)\hat{\rho}] \mp \int \left[\frac{1}{2}(\boldsymbol{\nabla}\phi_m)^2 + U(\phi_m)\right] d^3r \right\}$$

$$\begin{cases} \mathcal{H}_{RHB}|\psi_k^\eta\rangle = \eta E_k|\psi_k^\eta\rangle, \qquad \eta = \pm 1 \\ -\Delta\phi_m(\boldsymbol{r}) + U'(\phi_m(\boldsymbol{r})) = \mp \sum_k V_k^{\mathsf{T}}(\boldsymbol{r})\beta\Gamma_m V_k^*(\boldsymbol{r}) \end{cases}$$

Nucleons

Mesons

no sea

RHB Hamiltonian

$$\hat{\mathcal{H}}_{RHB} = \frac{\delta E_{RHB}}{\delta\mathcal{R}} = \begin{pmatrix} h^{\mathcal{D}} - m - \lambda & \Delta \\ -\Delta^* & -h^{\mathcal{D}*} + m + \lambda \end{pmatrix}$$

Dirac Hamiltonian

$$h^{\mathcal{D}} = \boldsymbol{\alpha}\mathbf{p} + \beta\Big(m + \underline{\sum_m \Gamma_m\phi_m(\mathbf{r})}\Big)$$

$$\tilde{\Sigma}(\mathbf{r})$$

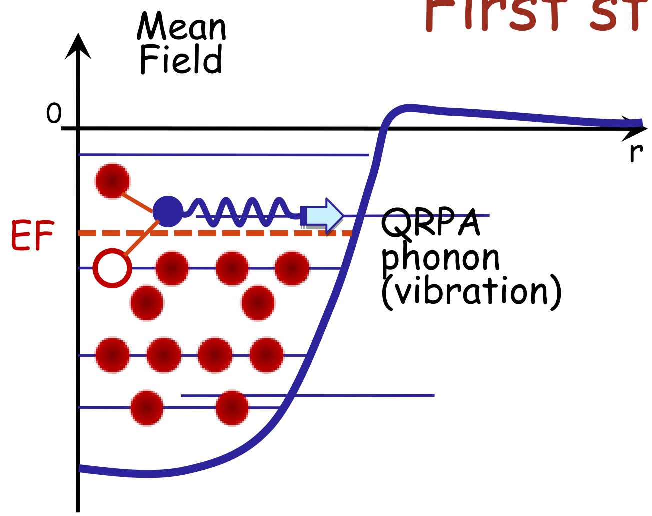
RMF self-energy

$$|\psi_k^+(\boldsymbol{r})\rangle = \begin{pmatrix} U_k(\boldsymbol{r}) \\ V_k(\boldsymbol{r}) \end{pmatrix}$$

Eigenstates

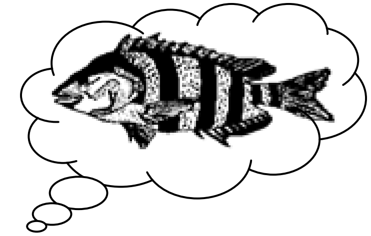
$$|\psi_k^-(\boldsymbol{r})\rangle = \begin{pmatrix} V_k^*(\boldsymbol{r}) \\ U_k^*(\boldsymbol{r}) \end{pmatrix}$$

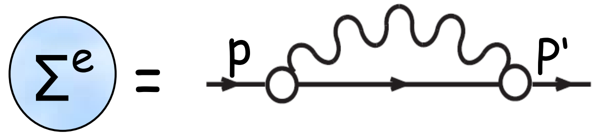
First step beyond relativistic mean field:



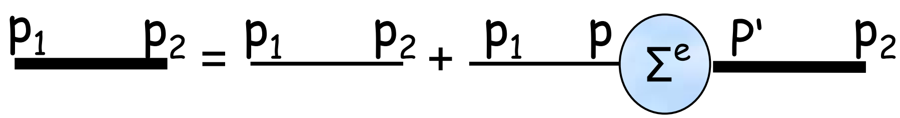
Coupling to vibrations

First order coupling:
self-energy diagram "fish"

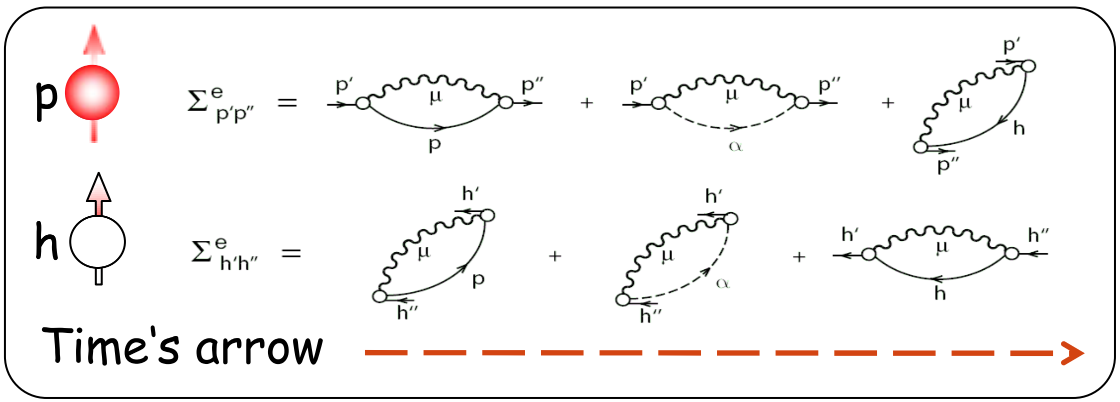


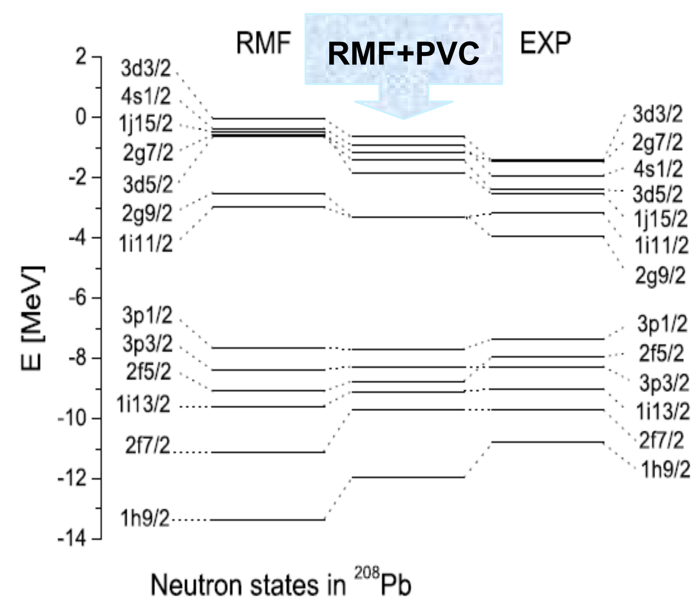


One-body propagation:



(Dyson equation)



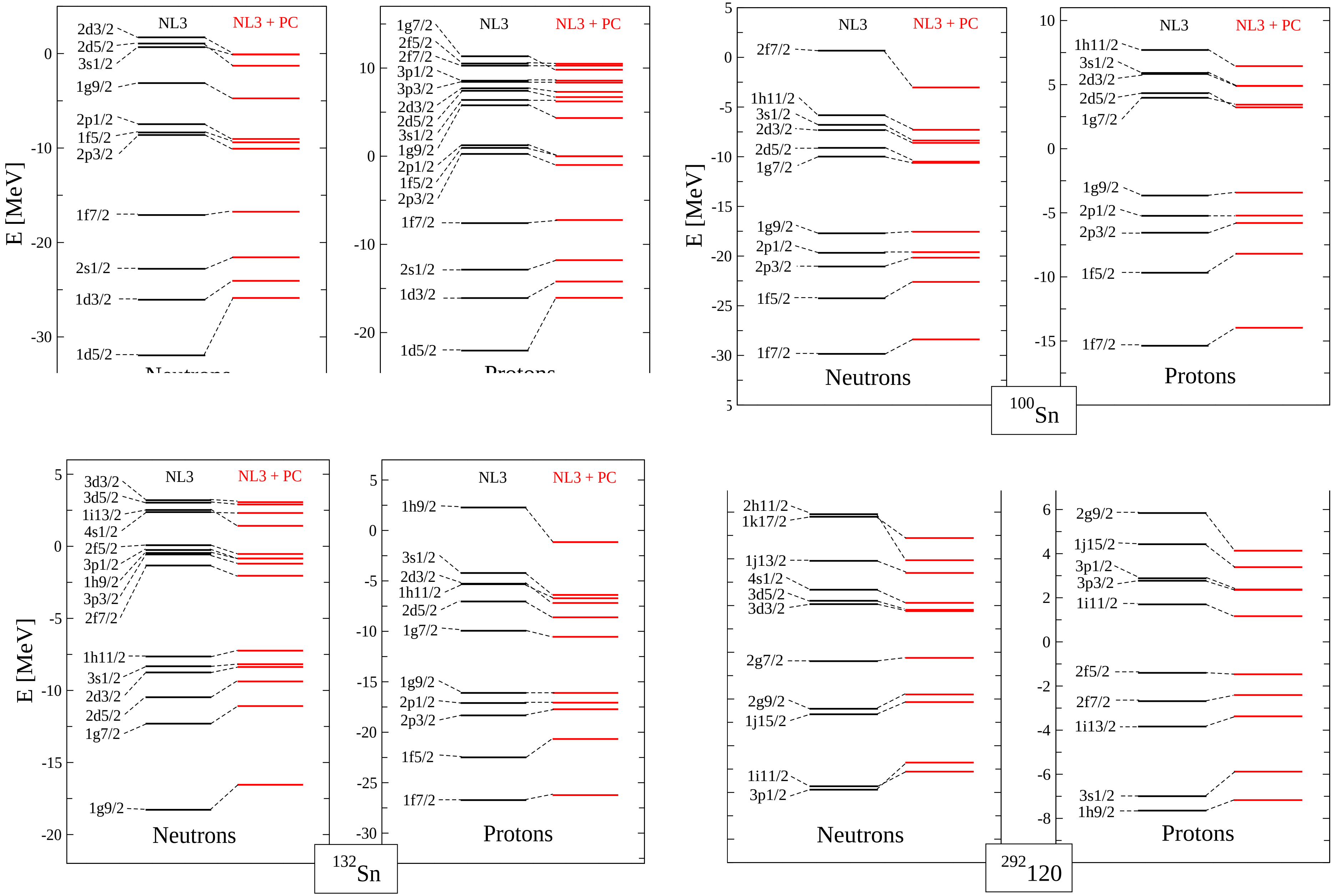


Splitting and shift of single-quasiparticle levels
& distribution of single-particle strength
» spectroscopic factors

E. L., P. Ring,
PRC 73, 044328 (2006)

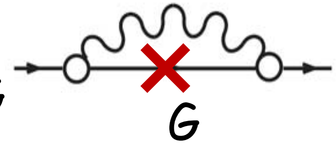
Not complete: pairing vibrations
have to be studied!

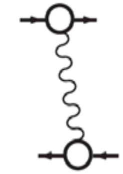
Single-particle spectra of doubly-magic nuclei

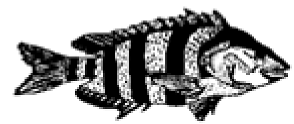
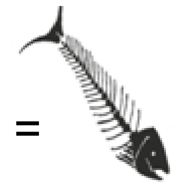


Nuclear response function

Functional derivative of the nucleon self-energy

$i\frac{\delta}{\delta G}$ 

$= i\frac{\delta\Sigma^e}{\delta G} =$ 

$i\frac{\delta}{\delta G}$  $=$  $=$ 

Nuclear response function R:
two-body propagation in the nuclear medium

Bethe-Salpeter equation (BSE) in the p-h channel

2p2h: Energy-dependent

$$U^e = i\,\frac{\delta\Sigma^e}{\delta G}$$

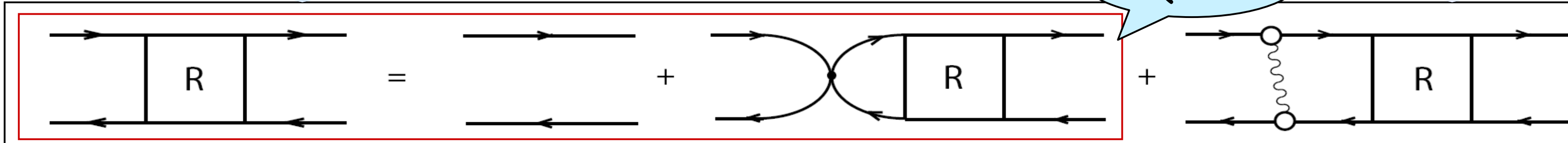
1p1h: static

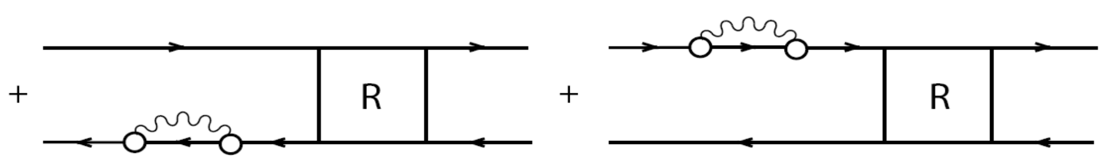
$$V = \frac{\delta\Sigma}{\delta\rho}$$

Bethe-Salpeter equation is solved in the particle-hole (1p1h) basis: all the job on complex configurations is done by intermediate summations.

NO huge matrices!

QRPA



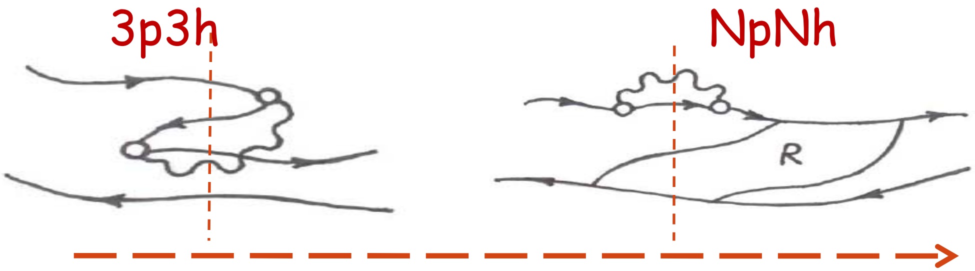


$$\mathbf{R = A + A\,(V + \Phi)\,R}$$

Time blocking*

Problem:

'Melting' diagrams



Time's arrow

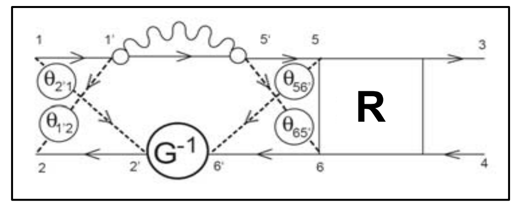
Unphysical result:
negative
cross sections

Solution:

Time-projection operator:

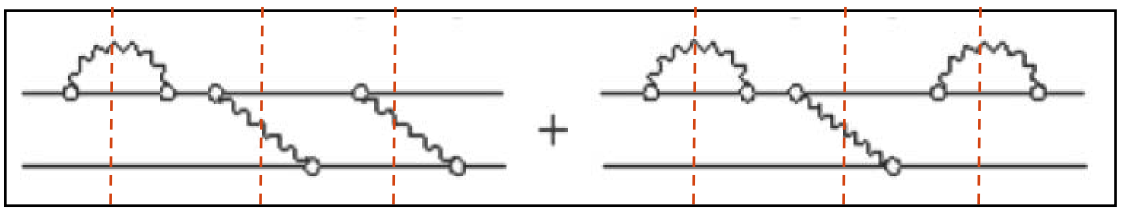
$$\delta_{\sigma_1 - \sigma_{2'}} \theta(\sigma_1 t_{2'1}) = \; 1 \dashrightarrow (\theta_{2'1}) \dashrightarrow 2'$$

$$\delta_{\sigma_2 - \sigma_{1'}} \theta(\sigma_{1'} t_{1'2}) = \; 2 \dashleftarrow (\theta_{1'2}) \dashleftarrow 1'$$

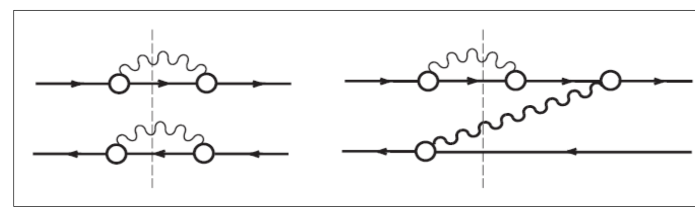


Partially fixed

Allowed terms: 1p1h, 2p2h



Blocked terms: 3p3h, 4p4h,...



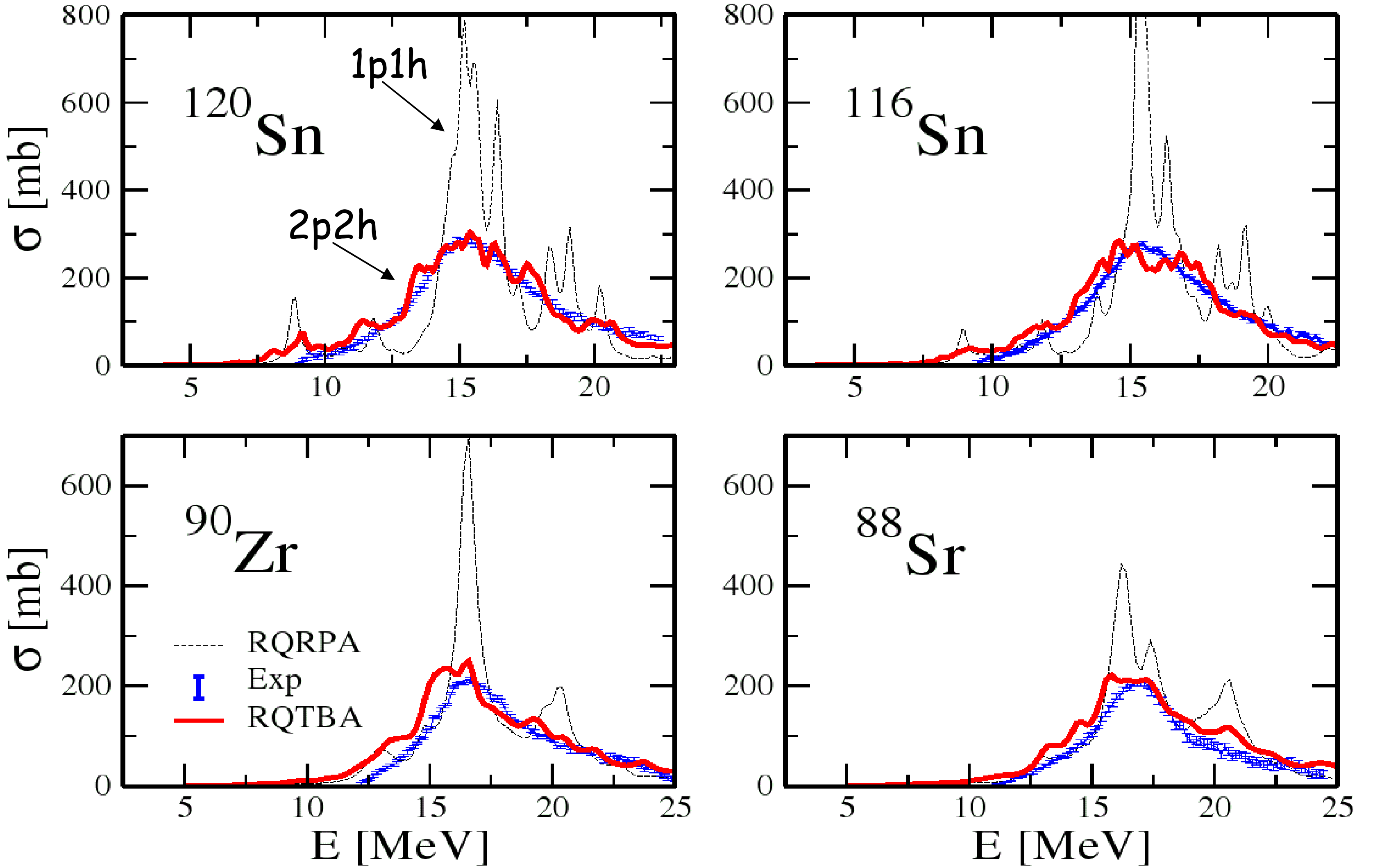
Time's arrow

Time blocking approximation = one-fish approximation!

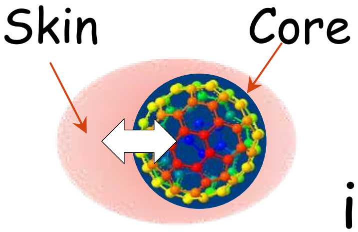
- Separation of the integrations in the BSE kernel
- R has a simple-pole structure (spectral representation)
  »» Strength function is positive definite!

*V.I. Tselyaev, Yad. Fiz. 50,1252 (1989).
S.S. Wu, Scientia Sinica 16, 347 (1973).
F.J.W. Hahne and W.D. Heiss,
Z. Phys. A 273, 269 (1975).

Giant Dipole Resonance within Relativistic Quasiparticle Time Blocking Approximation (RQTBA)*

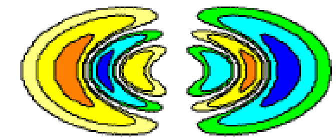


*E. L., P. Ring, and V. Tselyaev, Phys. Rev. C 78, 014312 (2008)



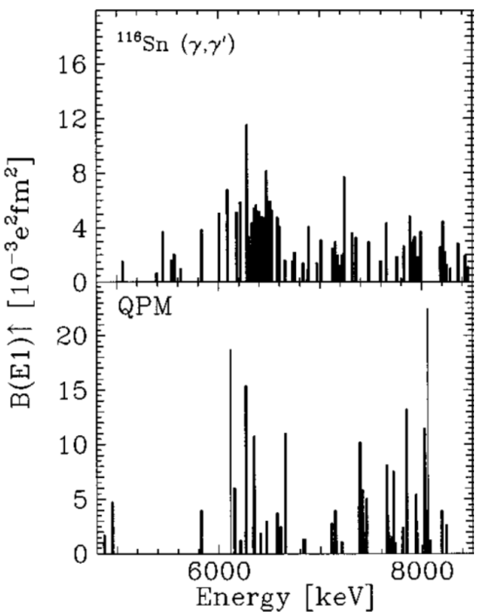
Pygmy dipole resonanse

in the mode coupling interpretation



Low-lying dipole strength in ^{116}Sn

Experiment*

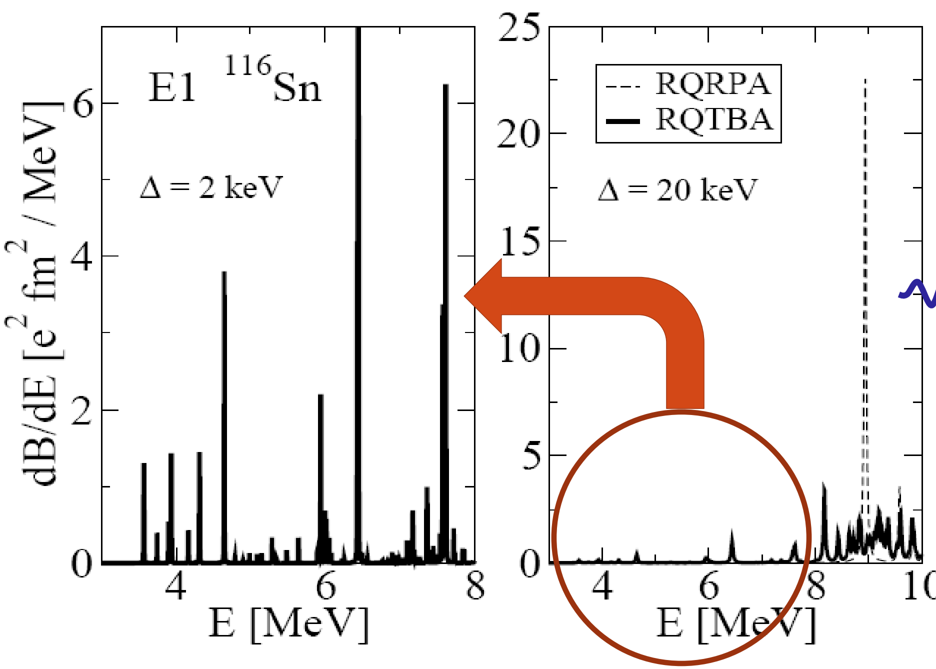


QPM up to 3p3h
(V.Yu. Ponomarev)

* K. Govaert et al.,
PRC 57, 2229 (1998)

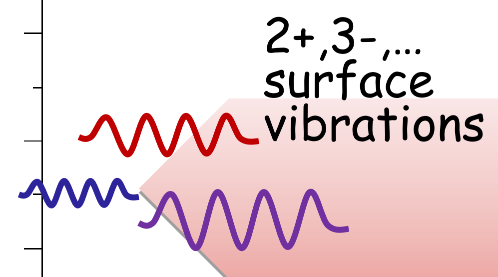
Fine structure

Gross structure



RQTBA 2p2h

RQRPA 1p1h vs
RQTBA 2p2h



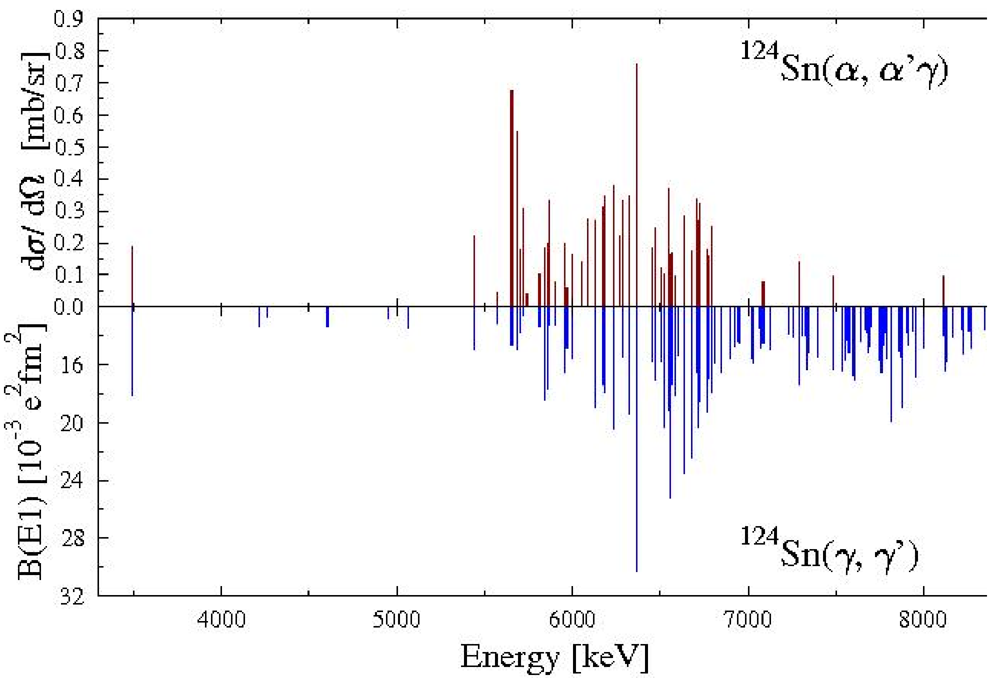
Integral
5-8 MeV:
ΣB(E1)↑ [e^2 fm^2]

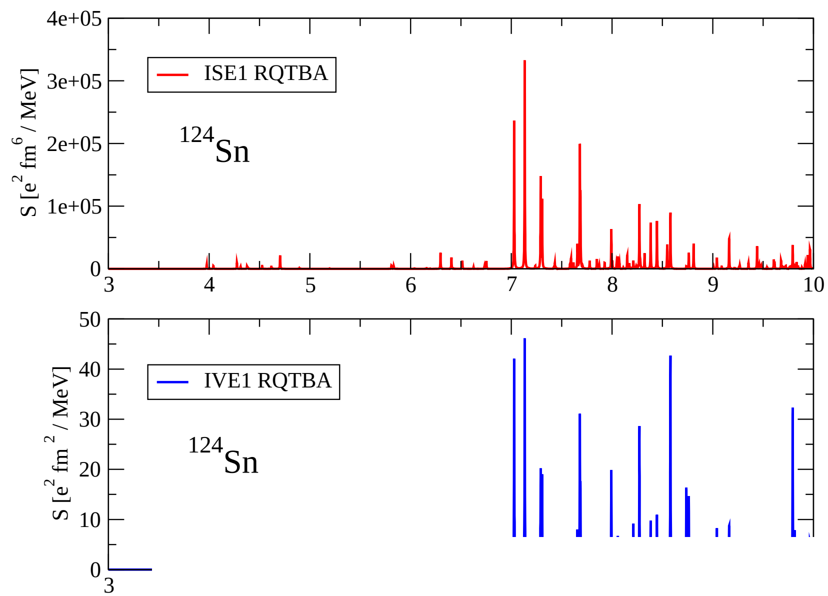
Exp.	0.204(25)
QPM	0.216
RQTBA	0.27

Structure of the pygmy dipole resonance in ^{124}Sn (preliminary)

Experiment (J. Enders, D. Savran et al.)

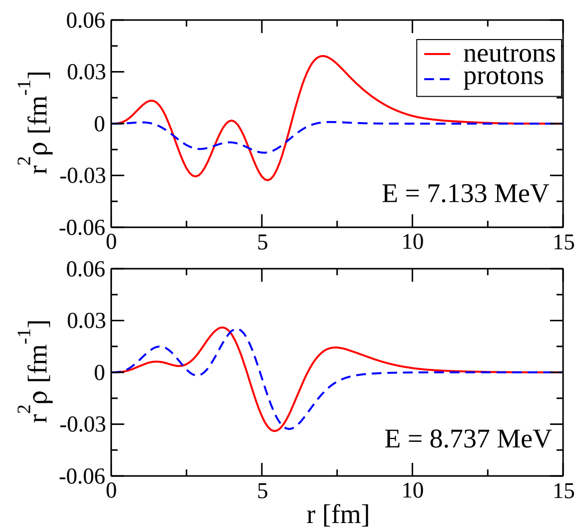
Theory: RQTBA





Hadron vs Coulomb excitation

Transition densities

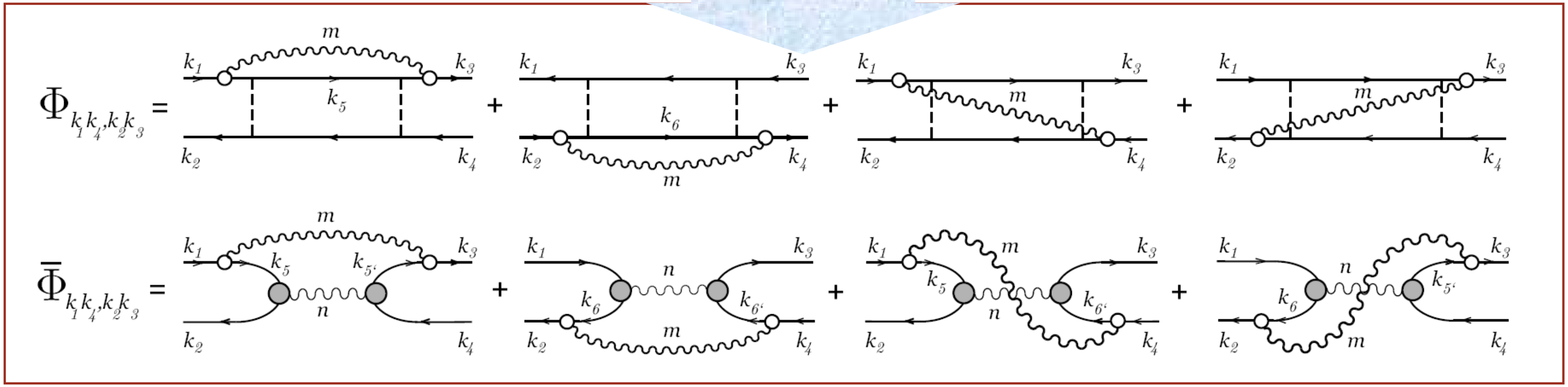


From "2q+phonon" to "2 phonons"

P. Schuck, Z. Phys. A 279, 31 (1976)
V.I. Tselyaev, PRC 75, 024306 (2007)

& Mode Coupling Theory
Time Blocking Approximation

Replacement of the uncorrelated propagator inside the Φ amplitude by QRPA response



Nuclear response: $R = A + A\,(V + \bar{\Phi})\,R$

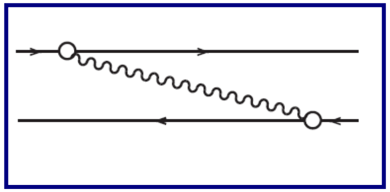
Poles may appear at lower energies:

'2q+phonon' response:
$\Phi_{iji'j'}(\omega) \sim \Sigma_{\mu k}\, \alpha_{ijk\mu}/(\omega - E_{i'} - E_k - \Omega_\mu)$

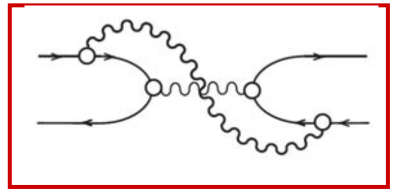
'2 phonon' response:
$\Phi_{iji'j'}(\omega) \sim \Sigma_{\mu\nu}\, \alpha_{iji'j'}/(\omega - \Omega_\nu - \Omega_\mu)$

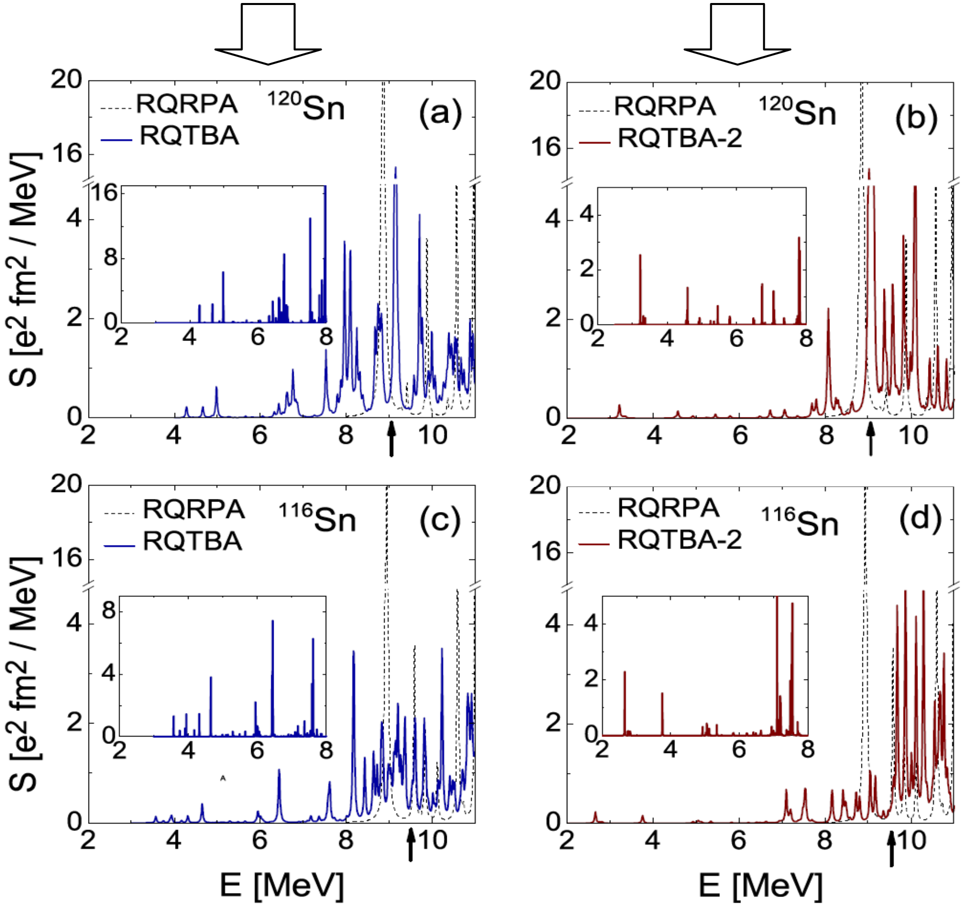
Two-phonon effects in dipole spectra

2q+phonon



2 phonon



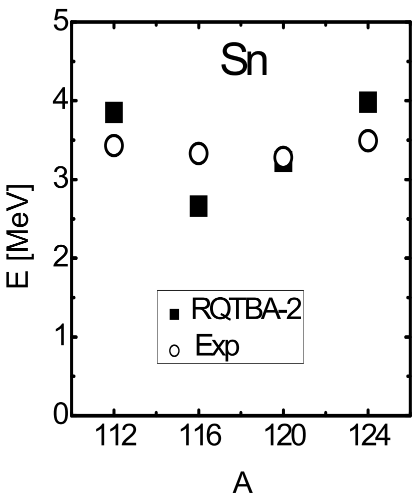


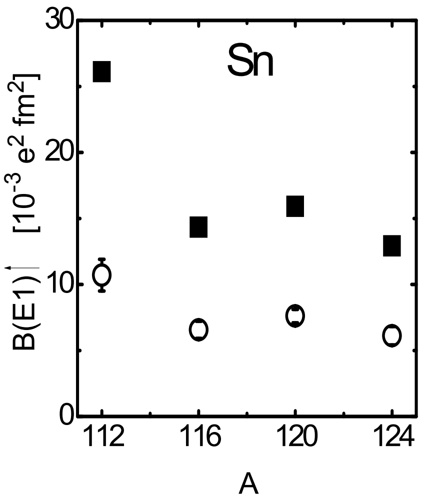
First two-phonon state 1^-_1

$$3^- \otimes 2^+$$

$$E(1^-_1) \approx E(2^+_1) + E(3^-_1)$$

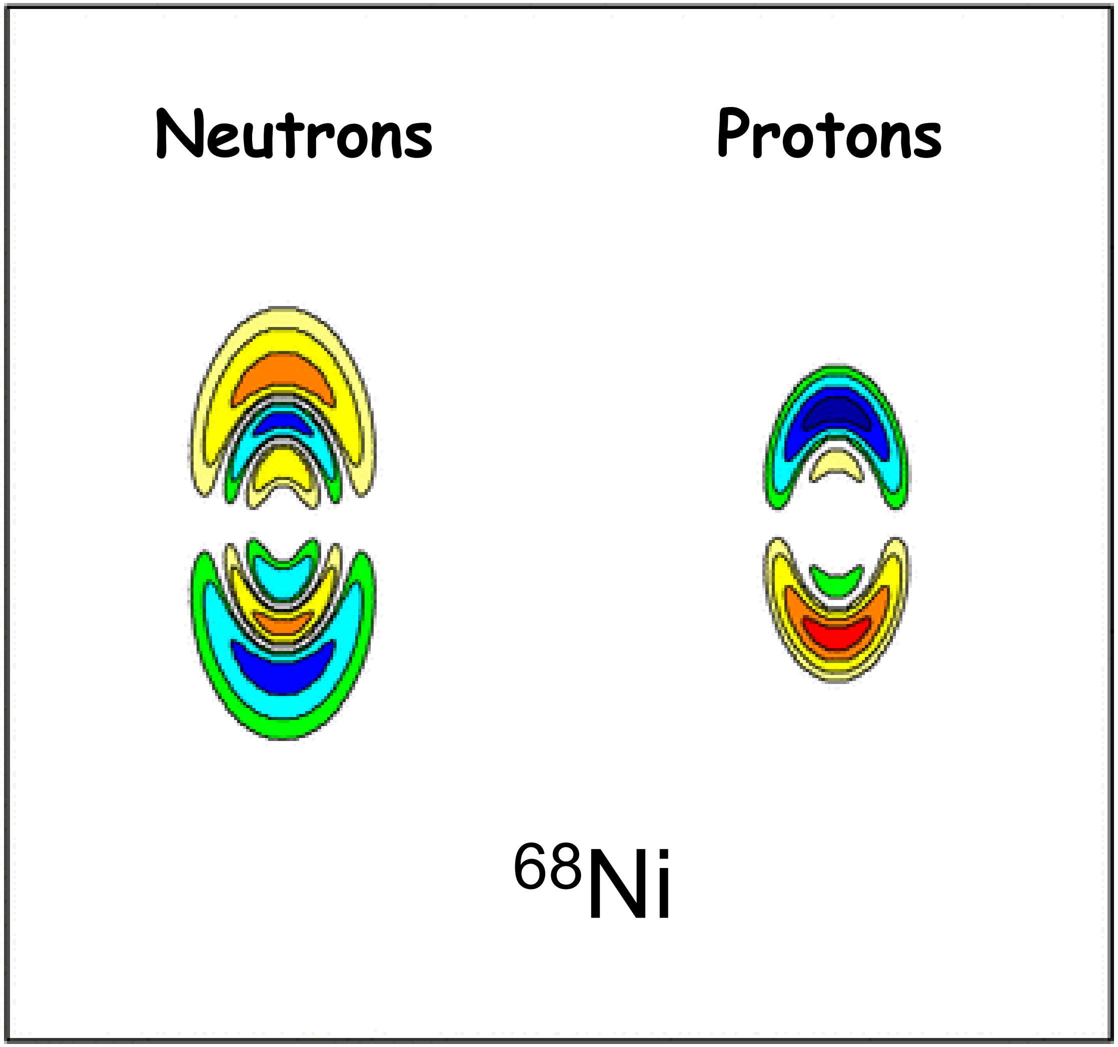
$E(1^-_1)$ $B(E1)\uparrow$



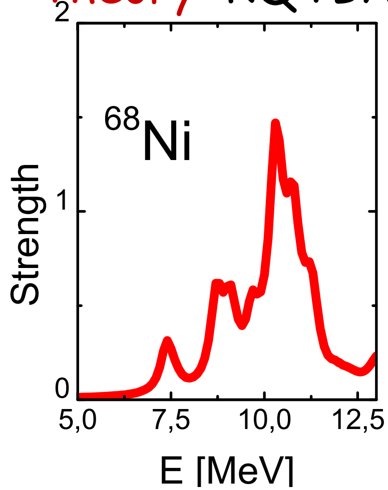


*E.L., P.Ring, V.Tselyaev, arXiv:0910.4343, PRL (2010).
**I.Pysmenetska et al., PRC73 (2006) 017302.

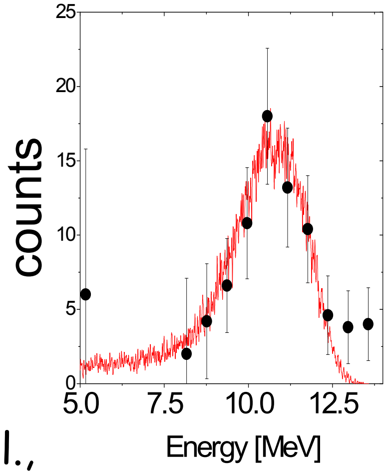
Neutron-rich nuclei: neutron skin oscillations



Theory: RQTBA-2



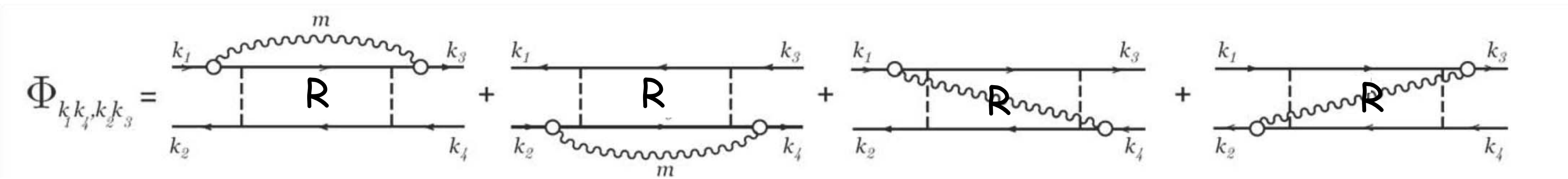
Experiment*:
Coulomb excitation
of 68Ni at 600 AMeV



*O.Wieland et al., PRL 102, 092502 (2009)

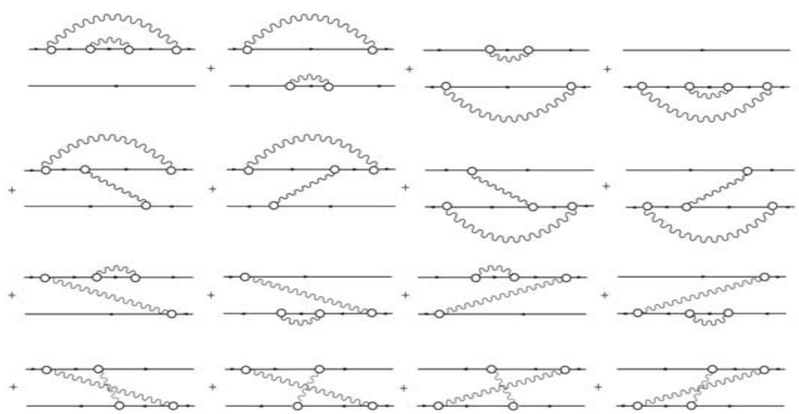
Next-order RQTBA for 3p-3h configurations: iterative procedure for multiphonon response

$$R^{(n+1)} = GG + GG\,[V + \Phi(R^{(n)})]\,R^{(n+1)}$$



Nested configurations

γ^4 terms in Φ-amplitude:



3p3h: two-fish approximation, …

Summary & Outlook

Present status:

Microscopic approaches based on the covariant DFT with consistent treatment of many-body correlations by the parameter-free Green's function techniques have been developed

2q+phonon and 2phonon coupling schemes have been studied within the same framework

Giant resonances' shapes, low-energy fraction of the pygmy dipole resonance and two-phonon states in medium-mass and heavy spherical nuclei including neutron-rich ones are reproduced well within the fully consistent scheme

Open problems & perspectives:

Static part: improvements in the RMF functional in both ph- and pp-channels

Dynamic part: inclusion of the next orders of many-body correlations, explicit single-particle continuum

Spatial symmetry: deformation

Thanks for collaboration:

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Tomislav Marketin (University of Zagreb)

Gabriel Martínez-Pinedo (GSI)

Thomas Rauscher (Basel University)

Peter Ring (Technische Universität München)

Friedrich-Karl Thielemann (Basel University)

Victor Tselyaev (St. Petersburg State University)

Dario Vretenar (University of Zagreb)