Low-lying gamma-strength within microscopic models

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2010

OUTLINE

- Pygmy dipole resonance within relativistic many-body methods

  Microscopic models based on the covariant density functional:
  - Relativistic mean field (RMF) model
  - Self-consistent (parameter-free) many-body methods beyond relativistic quasiparticle random phase approximation (RQRPA)

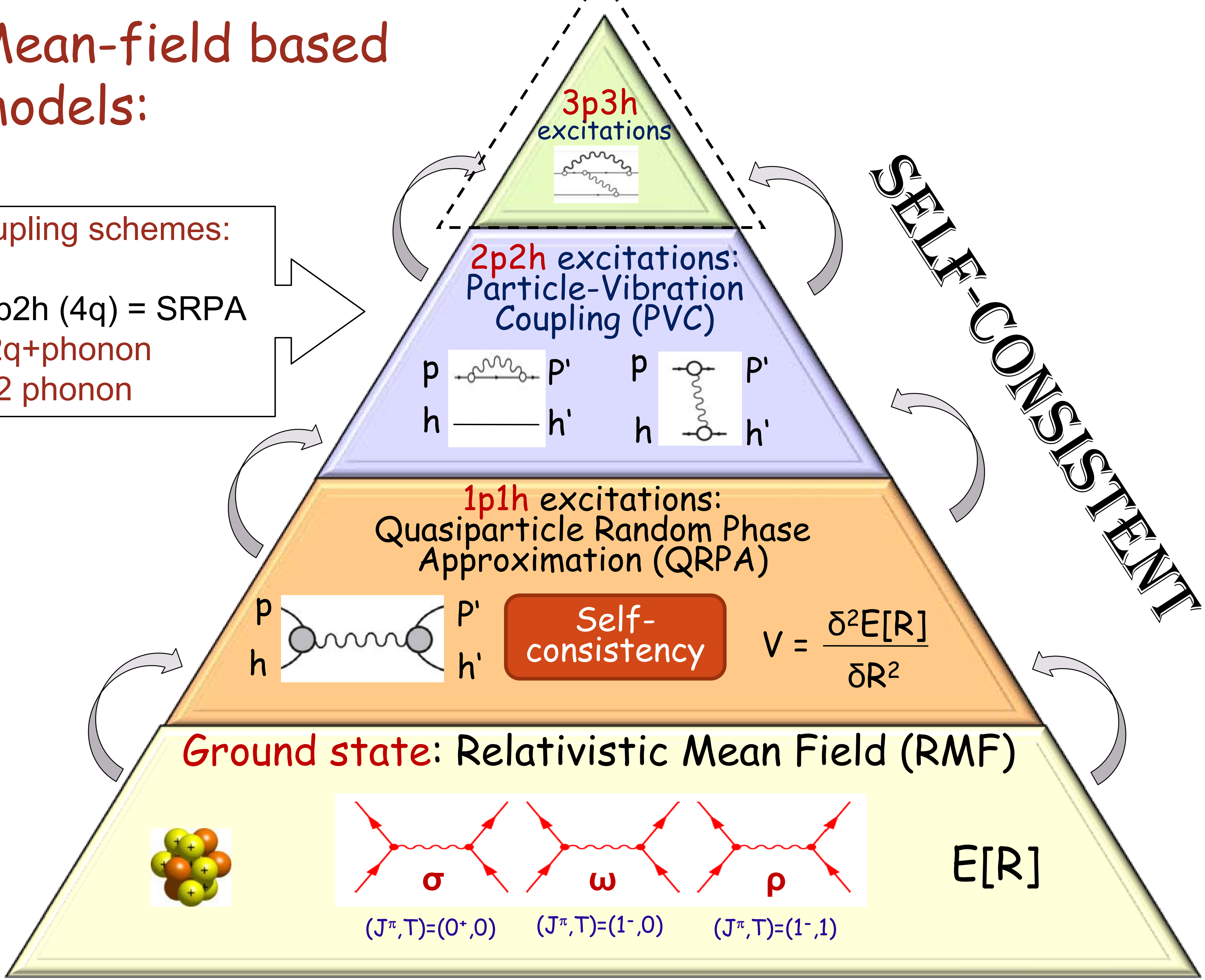
  Applications:
  Nuclear low-energy response, neutron capture cross sections and reaction rates

- Transitions between excited states:
  Finite temperature continuum QRPA: origin of the lowest gamma-strength and Brink hypothesis

Mean-field based models:

Coupling schemes:

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



Relativistic mean field

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

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

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

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

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

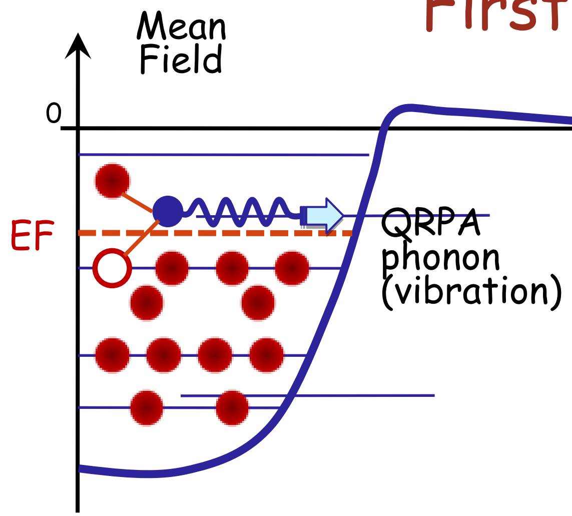
RMF self-energy

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

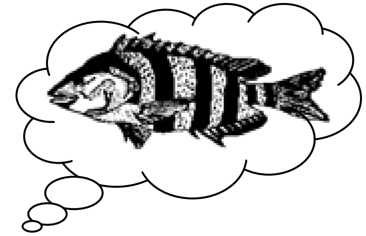
Eigenstates

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

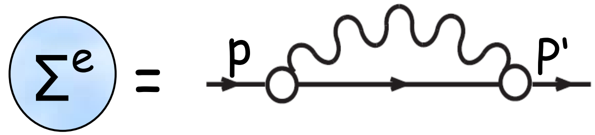
First step beyond relativistic mean field:



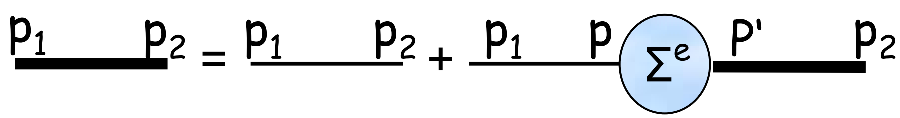
Coupling to vibrations



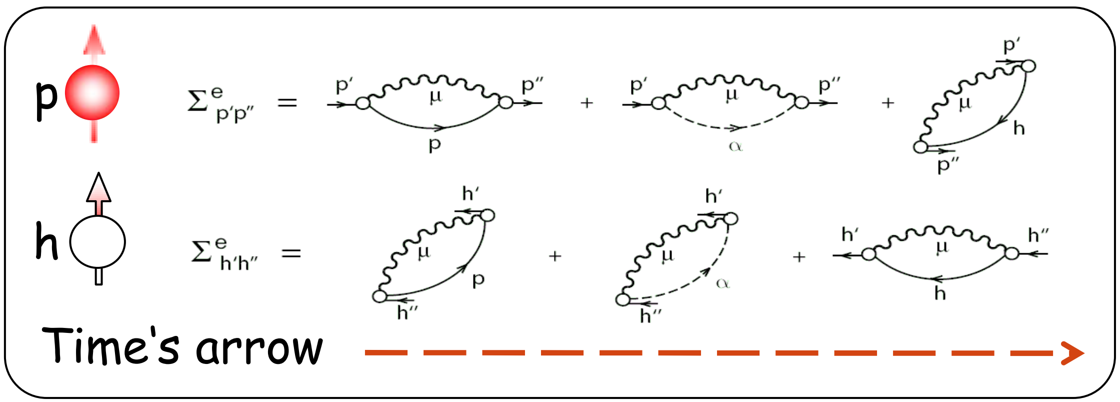
First order coupling:
self-energy diagram "fish"

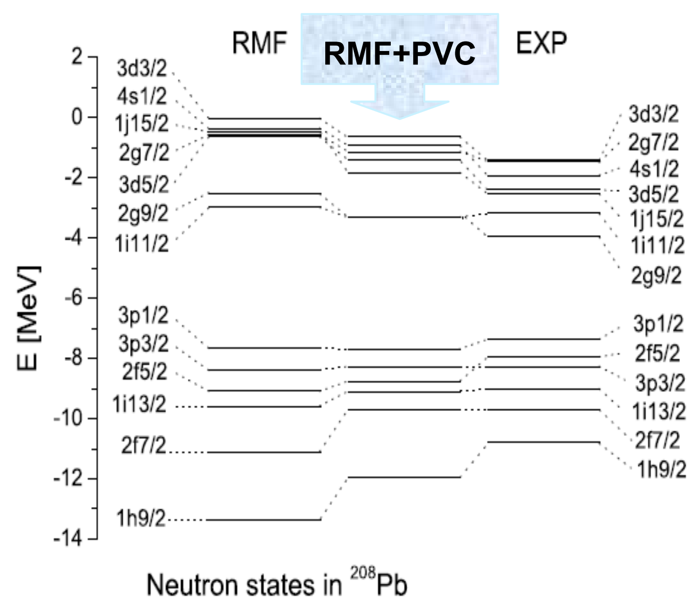


One-body propagation:



(Dyson equation)





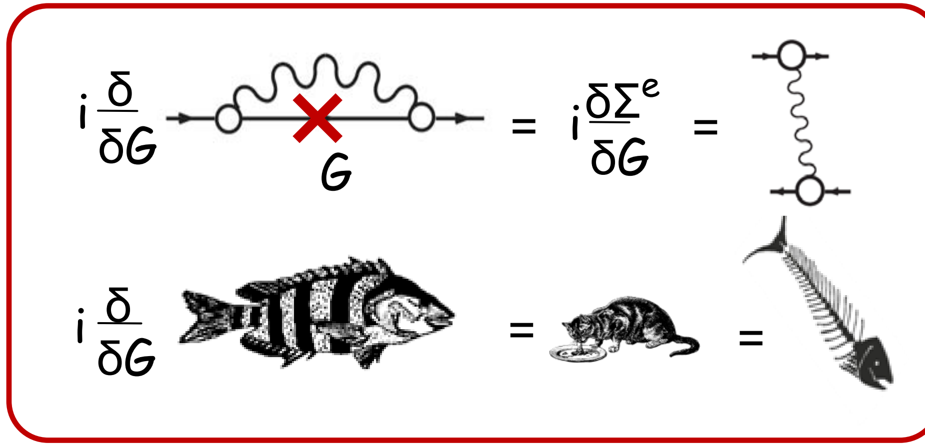
Splitting and shift of single-quasiparticle levels
& distribution of single-particle strength
» spectroscopic factors

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

Not complete: pairing vibrations
have to be studied!

Nuclear response function

Functional derivative of the nucleon self-energy



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

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

2p2h:
Energy-dependent

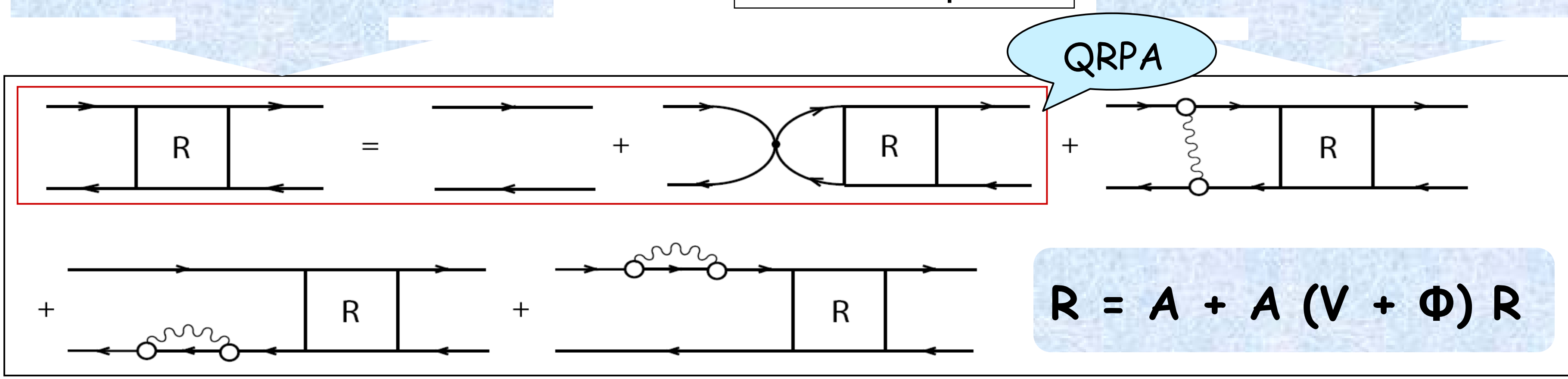
$$U^e = i\,\frac{\delta\Sigma^e}{\delta G}$$

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!



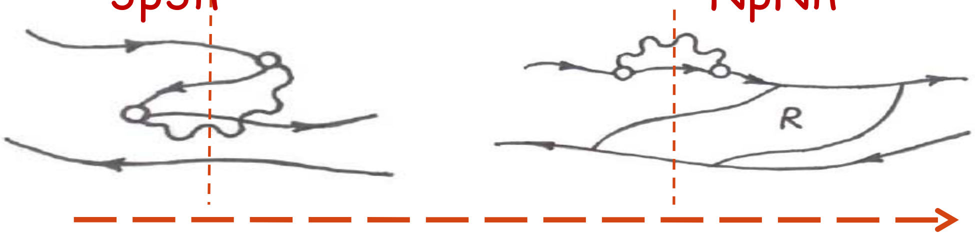
$$\mathbf{R = A + A\,(V + \Phi)\,R}$$

Time blocking*

Problem:

'Melting' diagrams

3p3h NpNh



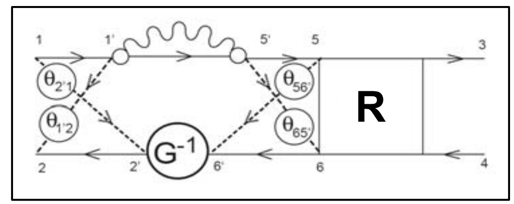
Time's arrow

Unphysical result:
negative
cross sections

Solution:

Time-projection operator:

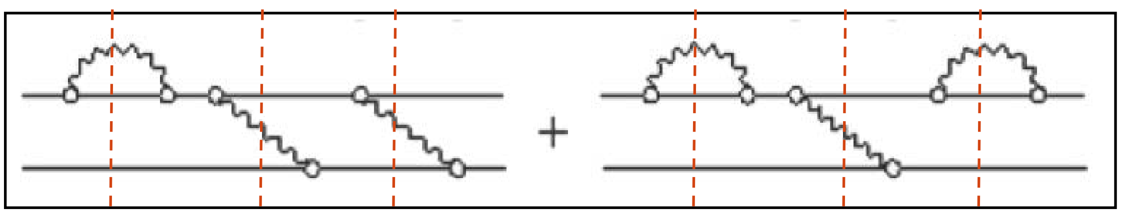
$$\delta_{\sigma_1-\sigma_{2'}}\theta(\sigma_1 t_{2'1}) = 1 \dashrightarrow \theta_{2'1} \dashrightarrow 2'$$
$$\delta_{\sigma_2-\sigma_{1'}}\theta(\sigma_{1'} t_{1'2}) = 2 \dashleftarrow \theta_{1'2} \dashleftarrow 1'$$

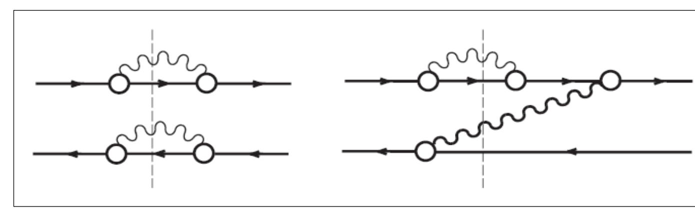


Partially fixed

Allowed terms: 1p1h, 2p2h

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





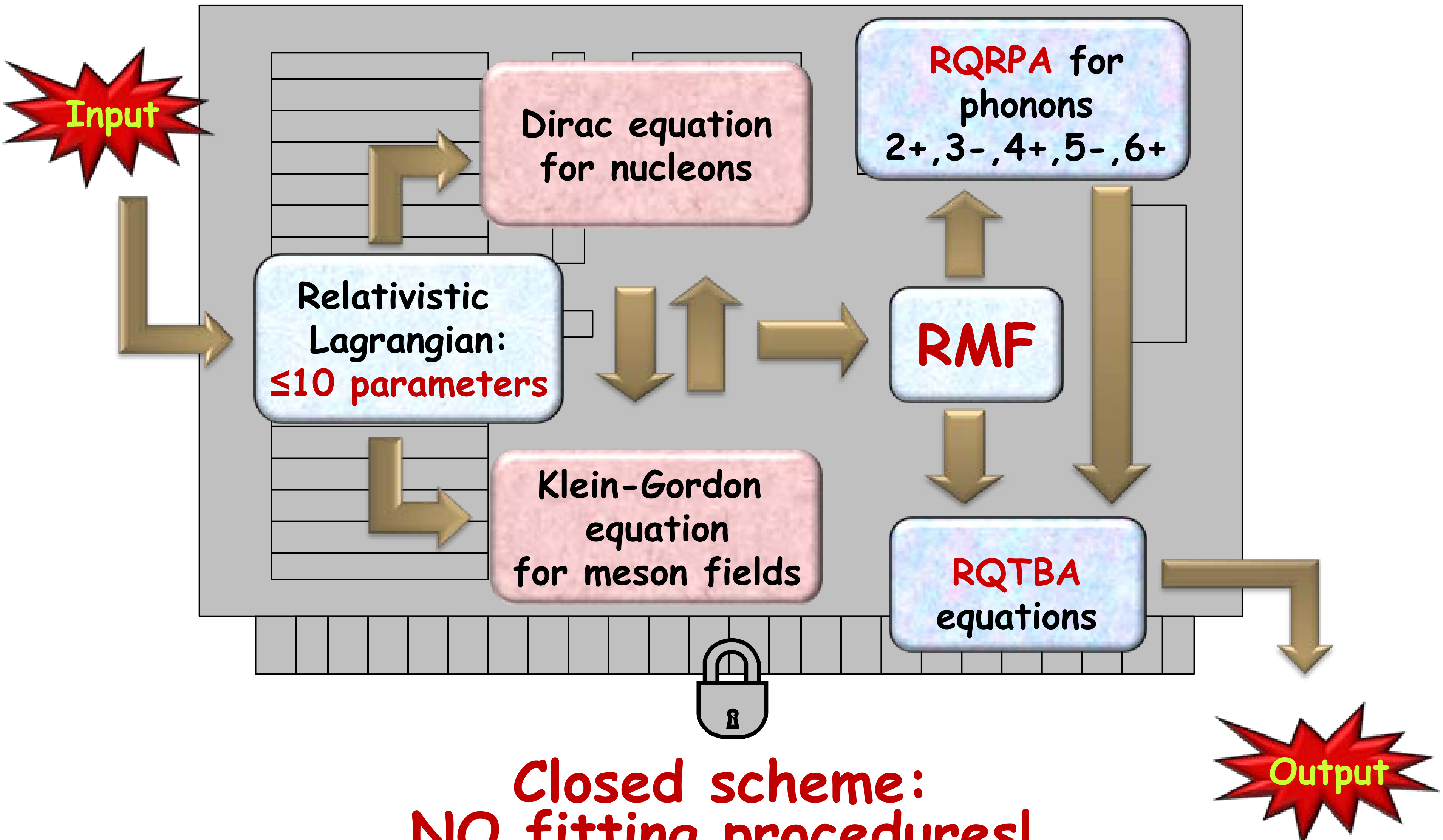
Time's arrow

Time blocking approximation = one-fish approximation!

*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).

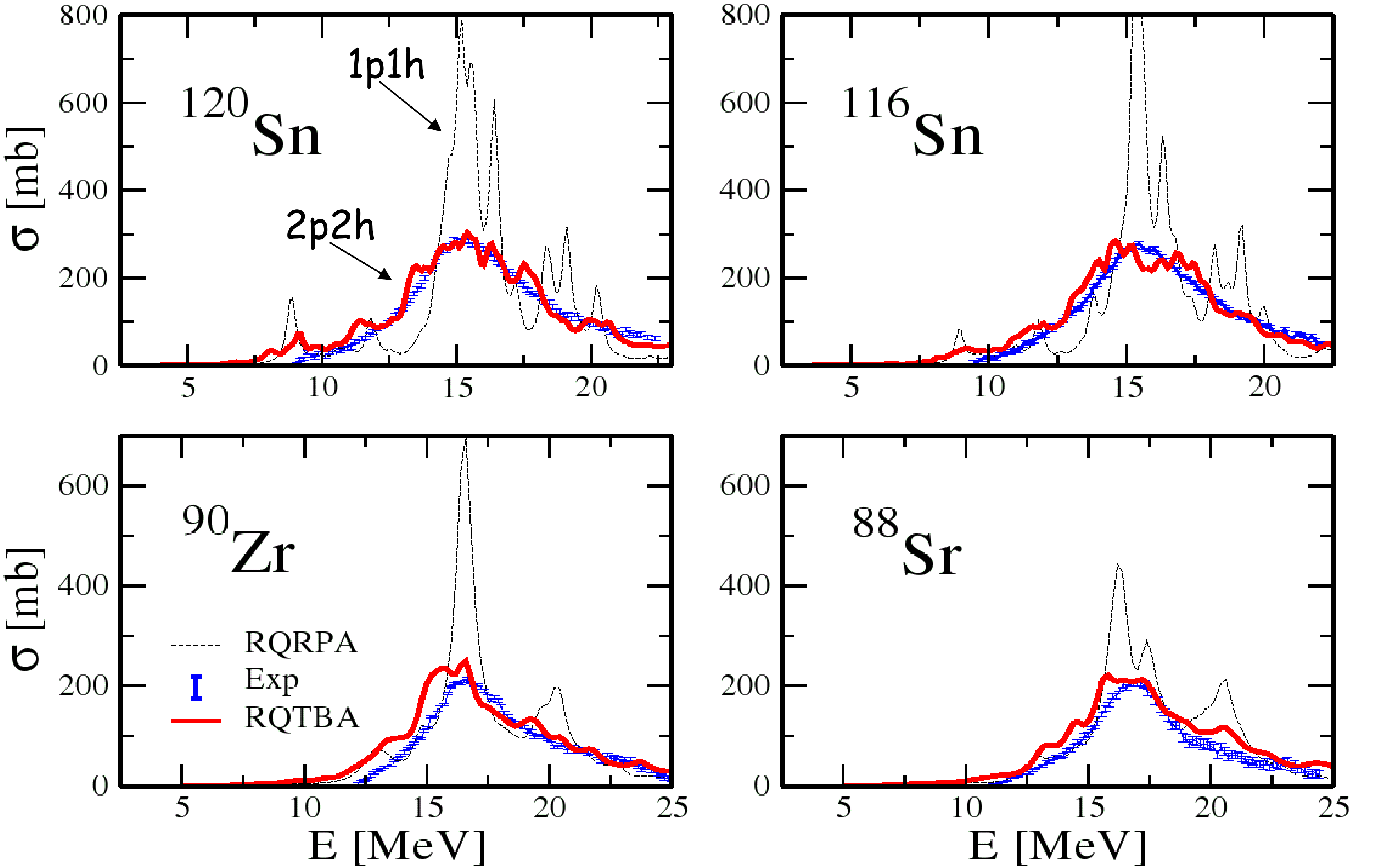
- Separation of the integrations in the BSE kernel
- R has a simple-pole structure (spectral representation)
  »» Strength function is positive definite!

Calculations within the Relativistic Quasiparticle Time Blocking Approximation (RQTBA)

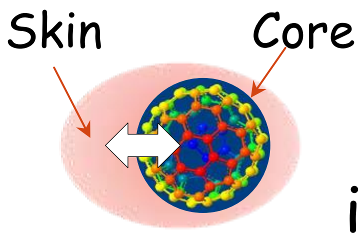


Closed scheme: NO fitting procedures!

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

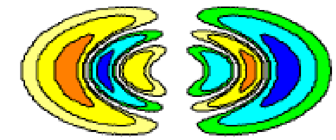


*E. L., P. Ring, and V. Tselyaev,
Phys. Rev. C 78, 014312 (2008)



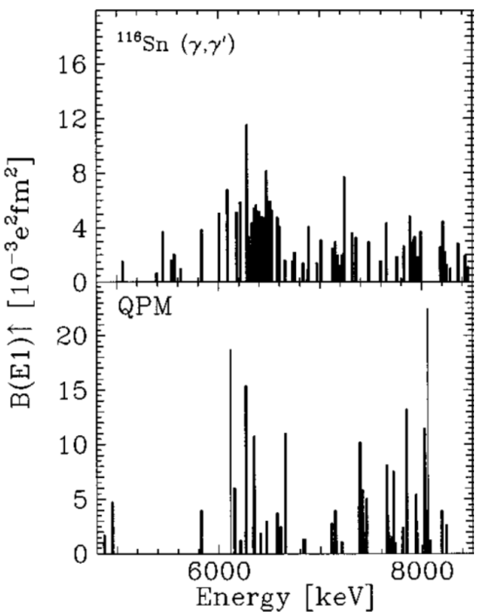
Pygmy dipole resonanse

in the mode coupling interpretation



Low-lying dipole strength in ^{116}Sn

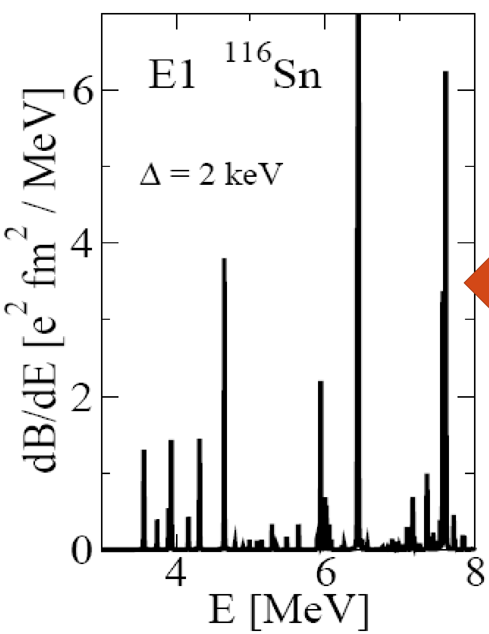
Experiment*



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

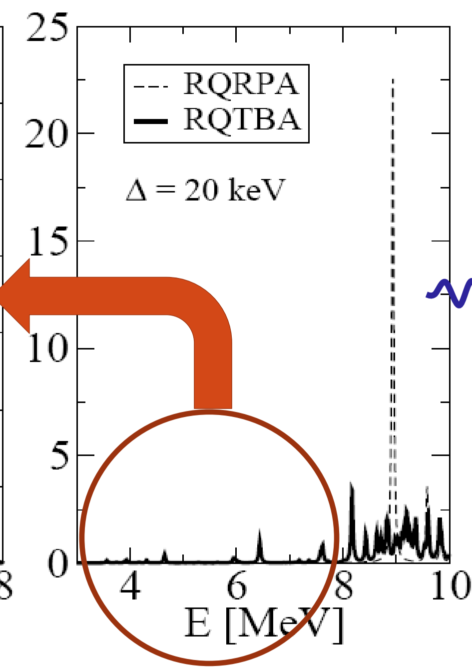
* K. Govaert et al.,
PRC 57, 2229 (1998)

Fine structure

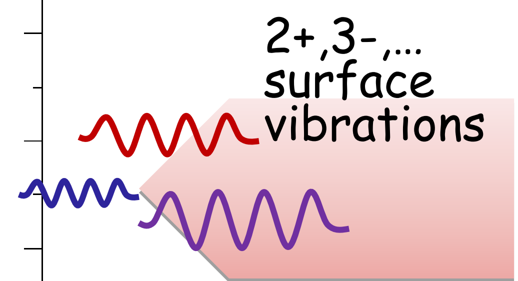


RQTBA 2p2h

Gross structure



RQRPA 1p1h vs
RQTBA 2p2h

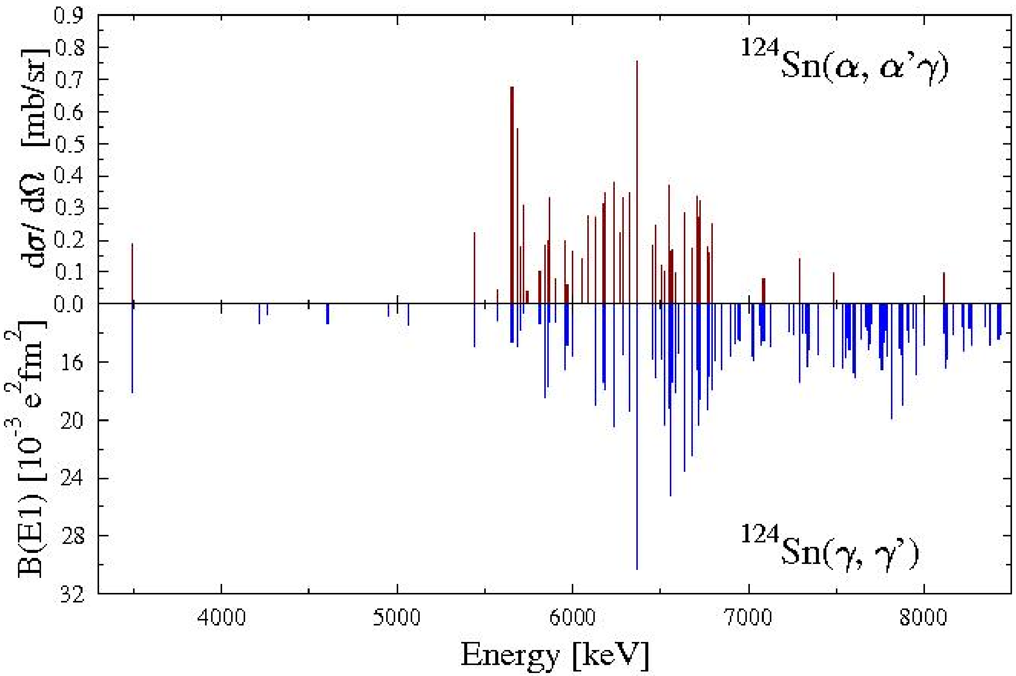


Integral
5-8 MeV:
$\Sigma B(E1)\uparrow$ [e^2 fm^2]

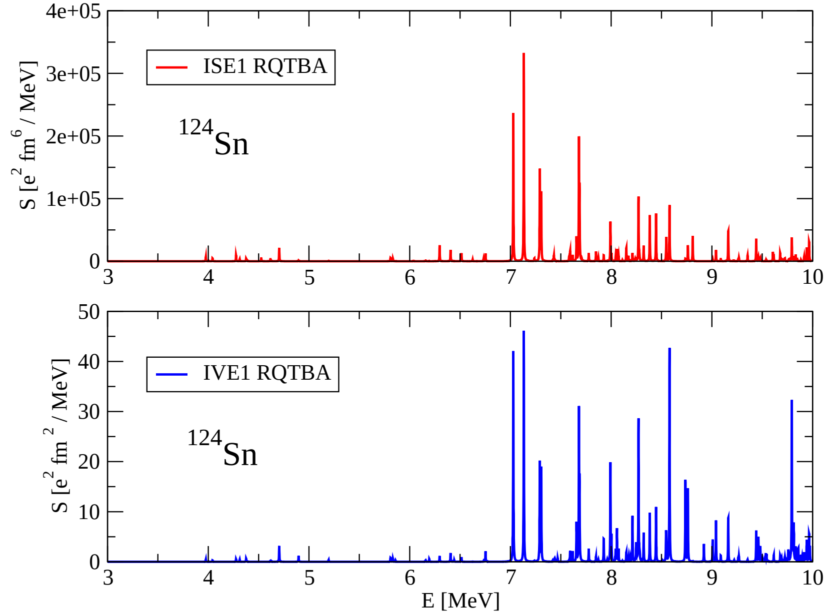
Exp.	0.204(25)
QPM	0.216
RQTBA	0.27

Isospin properties of the pygmy dipole resonance in ^{124}Sn

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

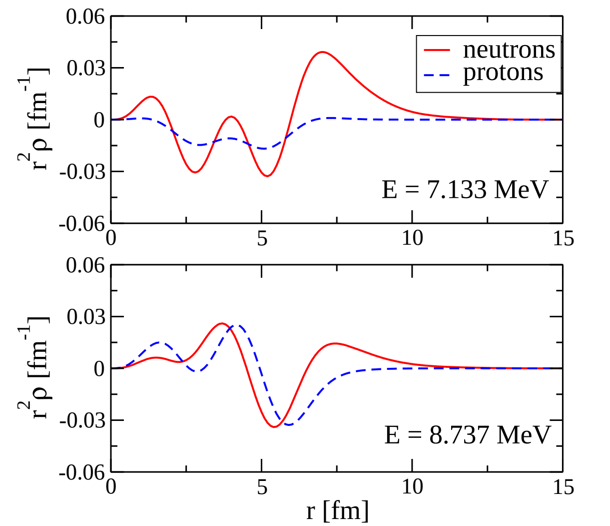


Theory: RQTBA



Hadron vs Coulomb excitation

Transition Densities
$\delta\rho(r)$

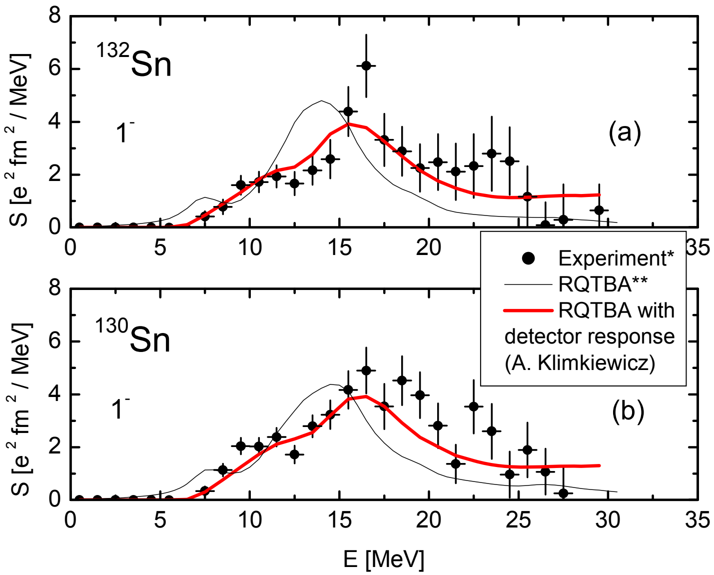


J.Endres et al, subm. to PRL

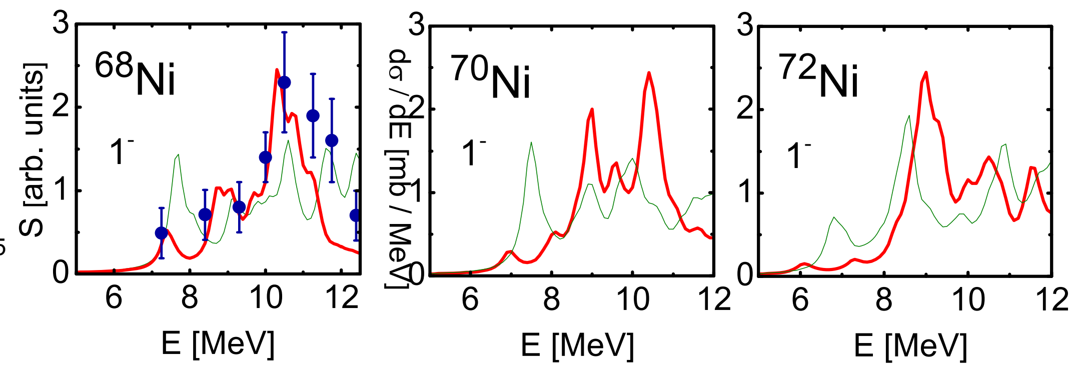
$$\rho(r,t) = \rho_0\,(r) + \delta\rho(r,t)$$

Dipole strength in neutron-rich nuclei

Neutron-rich Sn



Neutron-rich Ni



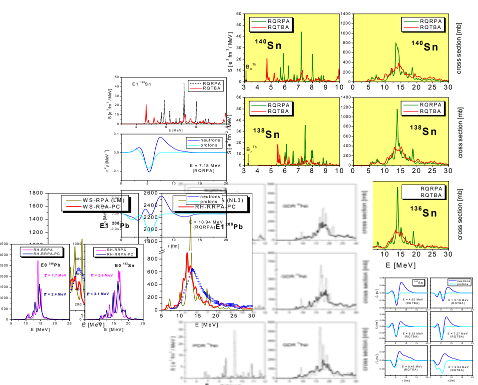
RQTBA

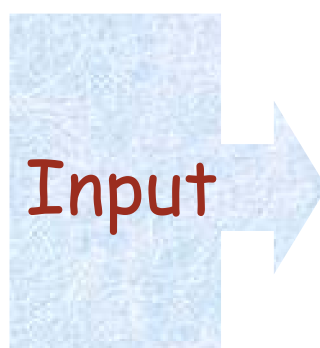
RQTBA-2 E. Litvinova et al., PRL 105, 022502 (2010)

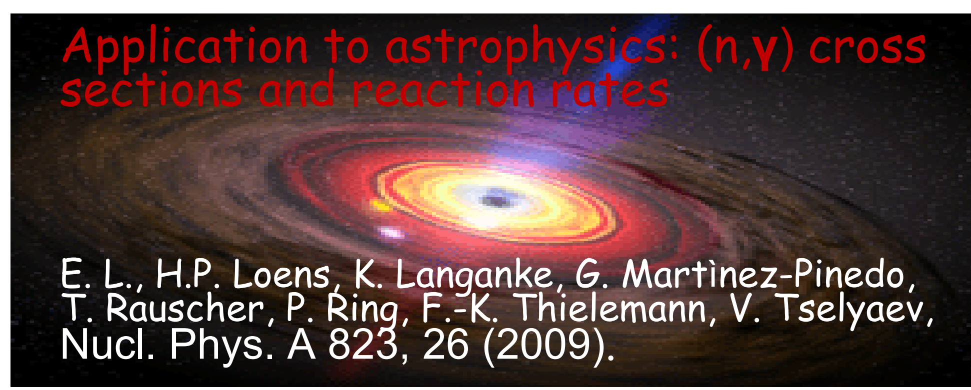
Exp. O.Wieland et al., PRL 102, 092502 (2009)

* P. Adrich, A. Klimkiewicz, M. Fallot et al., PRL 95, 132501 (2005)

**E. L., P. Ring, V. Tselyaev, K. Langanke PRC 79, 054312 (2009)

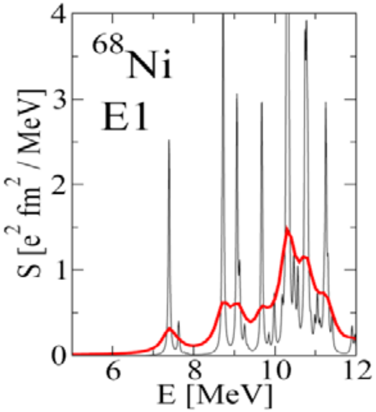


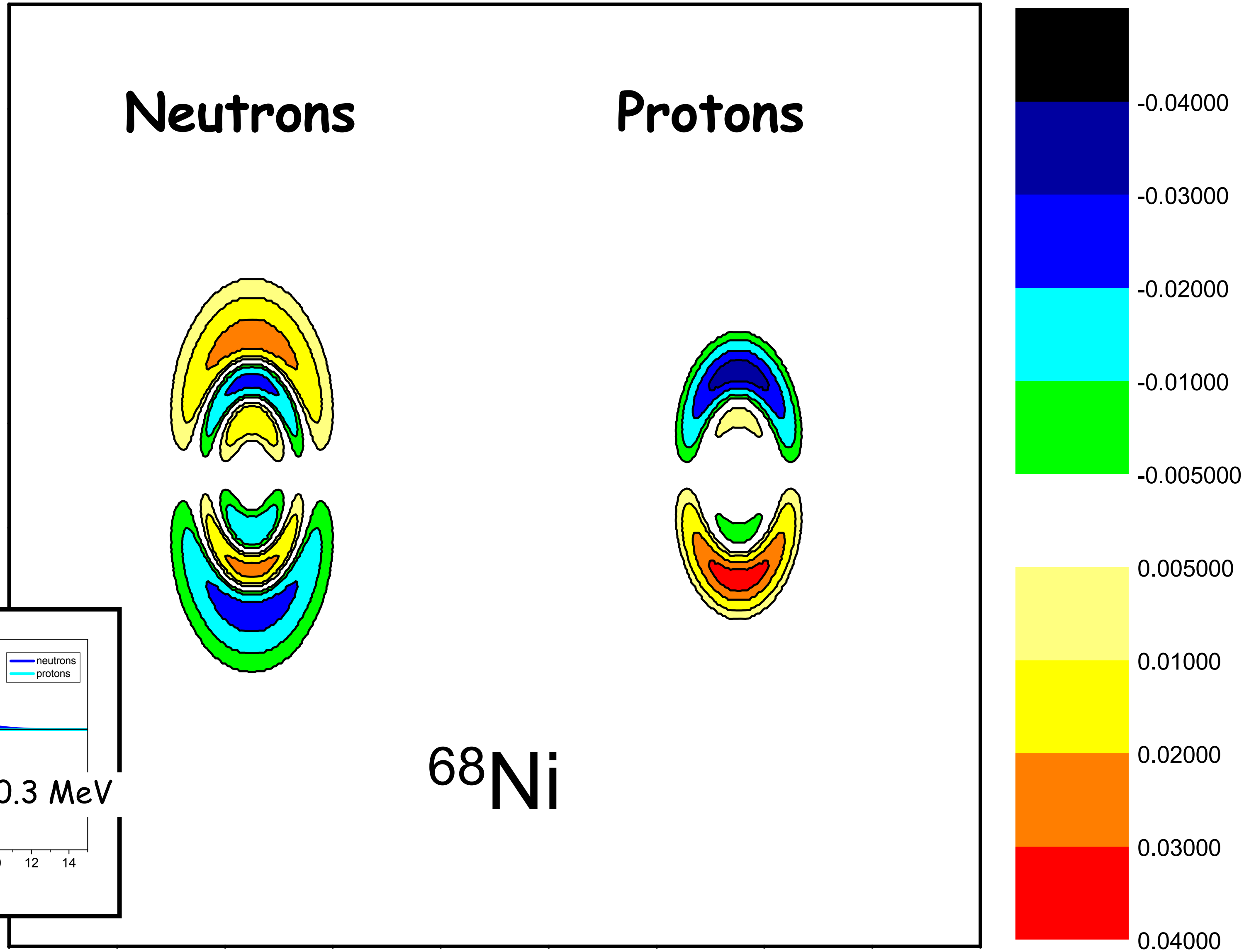


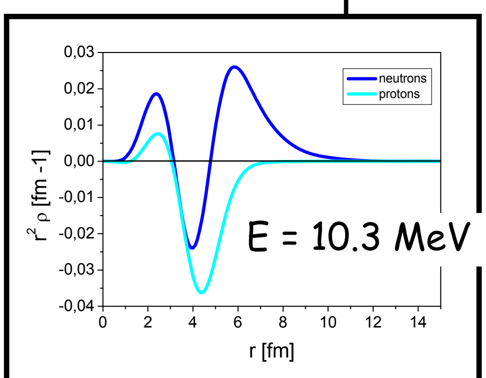


RQTBA dipole transition densities in ^{68}Ni at 10.3 MeV

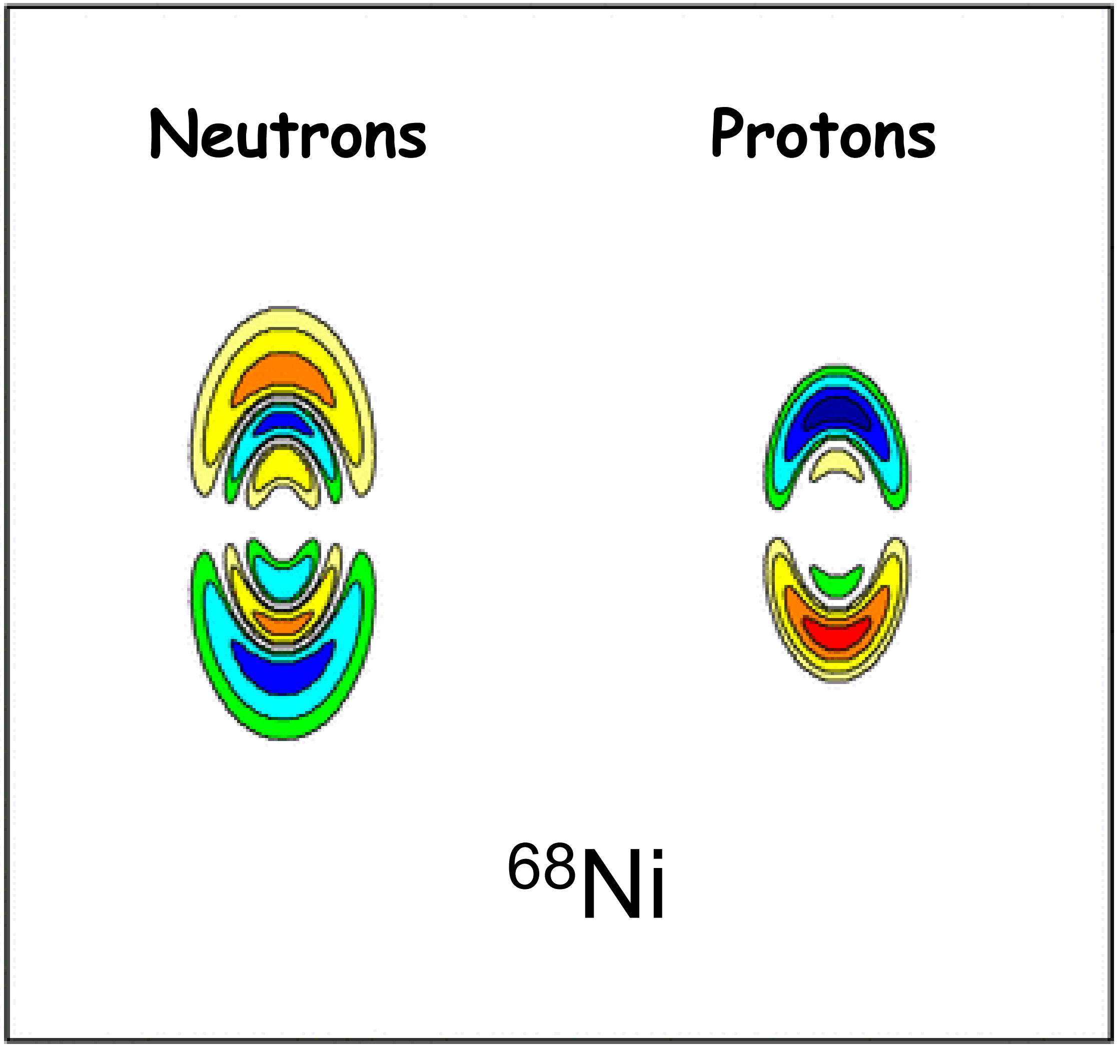
Theory:
RQTBA-2



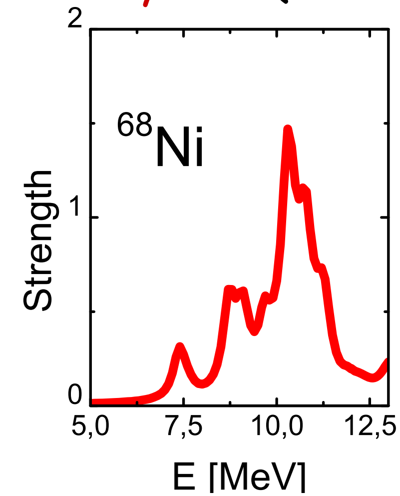




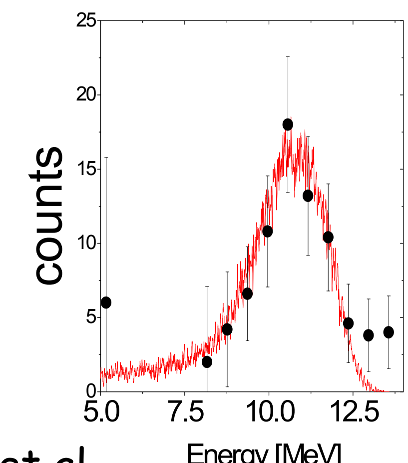
Neutron-rich nuclei: neutron skin oscillations



Theory*: RQTBA-2



Experiment**:
Coulomb excitation
of 68Ni at 600 AMeV

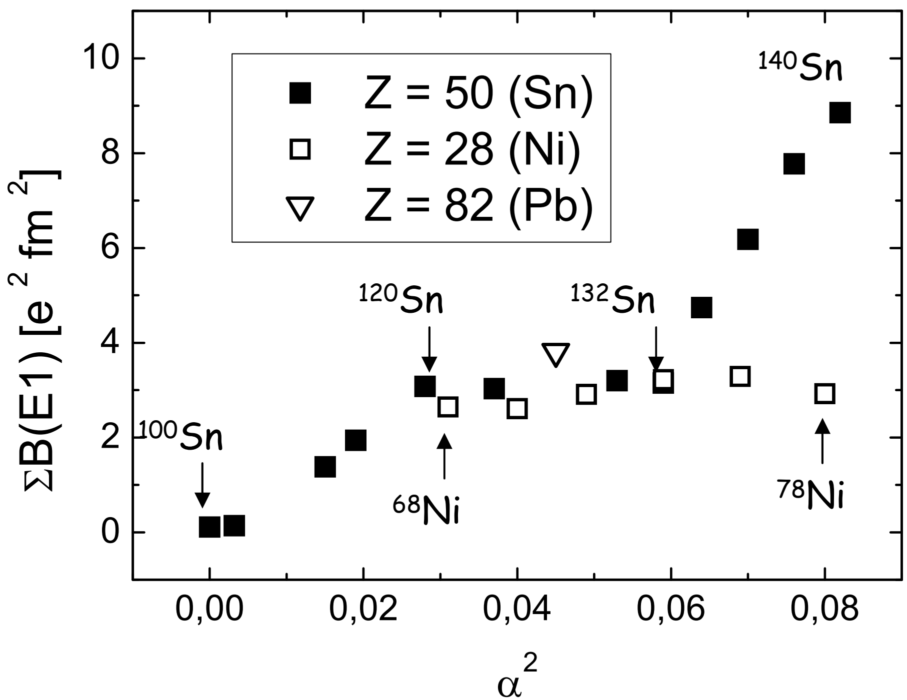


Th: *E. Litvinova et al., PRL 105, 022502 (2010)

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

RQTBA systematics for PDR:

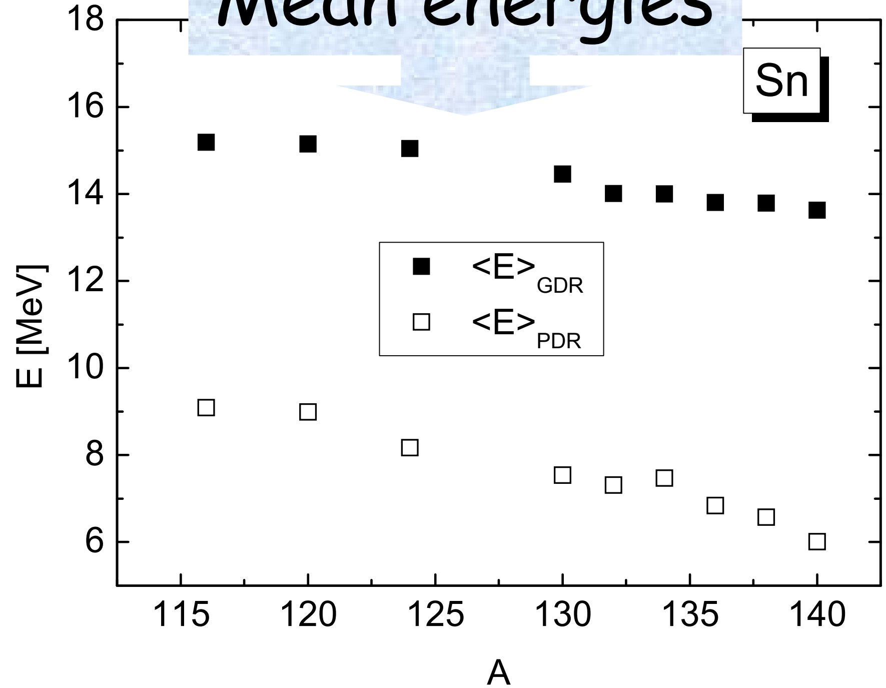
A proper definition of Pygmy Dipole Resonance is highly important!
PDR = all states with the "isoscalar" underlying structure!



Strength vs α^2

$\alpha = (N - Z)/A$
(Asymmetry parameter)

Mean energies

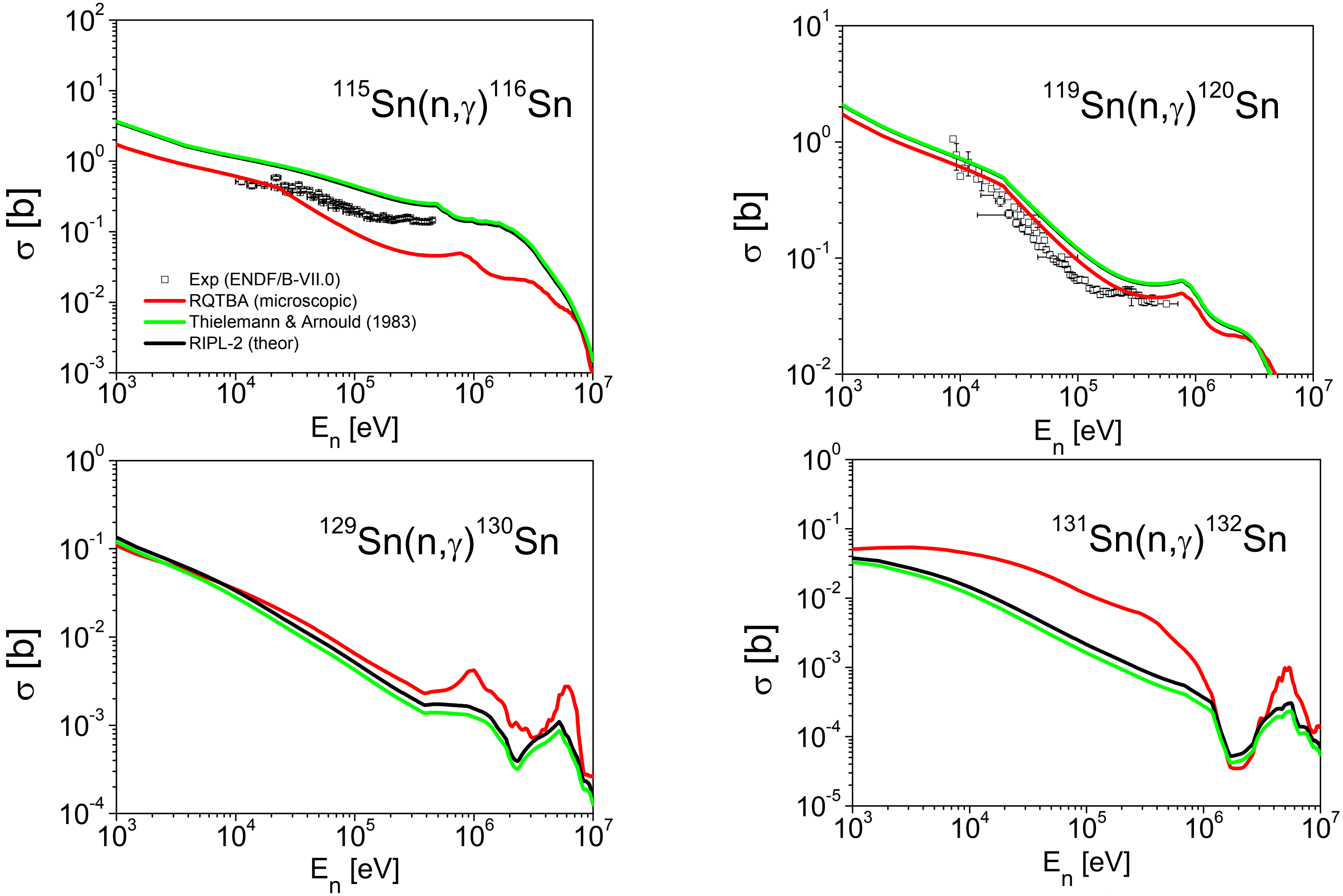


^{120}Sn → ^{132}Sn: 1h11/2 (n)
^{68}Ni → ^{78}Ni: 1g9/2 (n)

Intruder orbits !

E.L. et al. PRC 79, 054312 (2009)

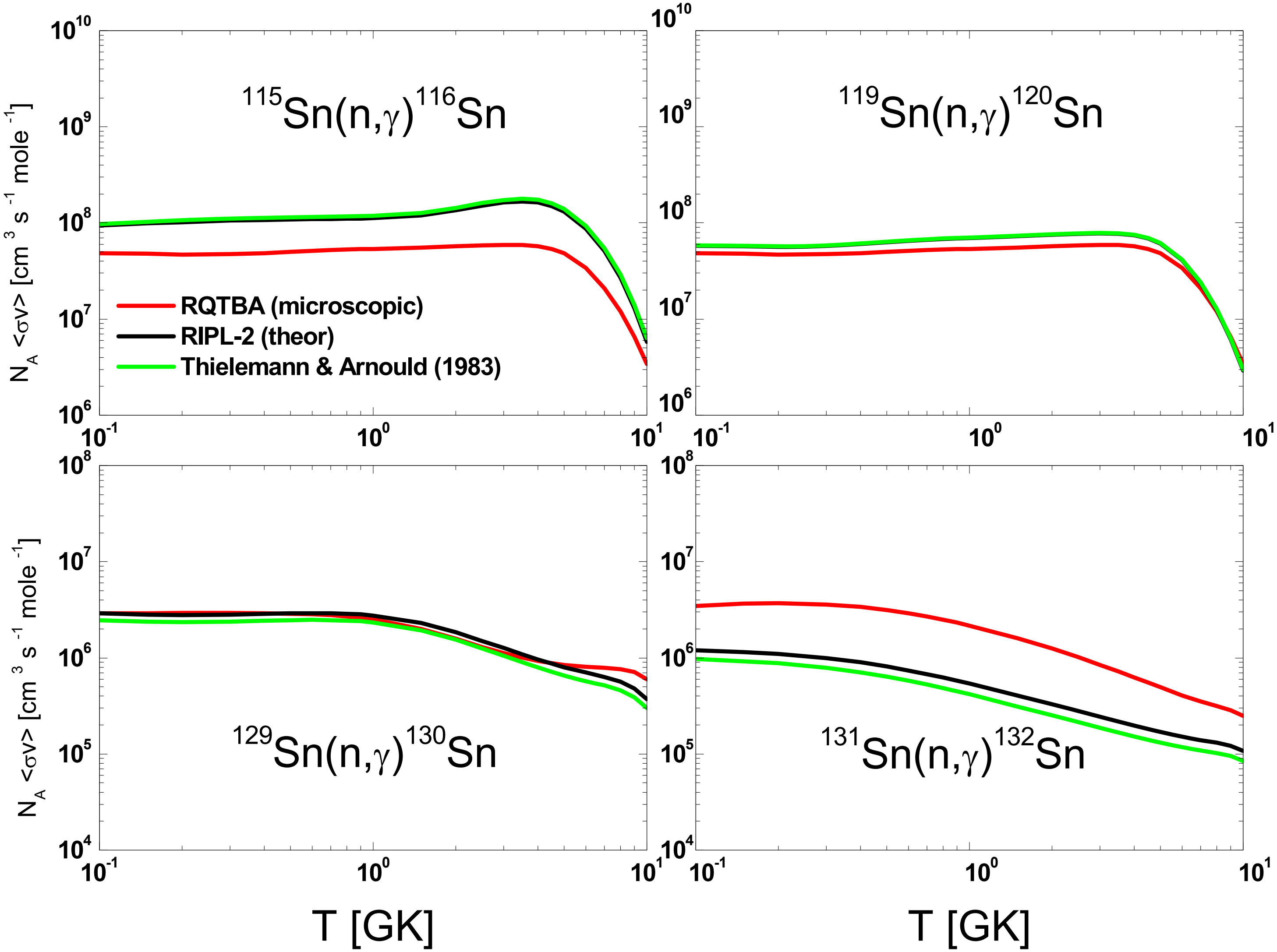
Radiative neutron capture in the Hauser-Feshbach model: standard Lorentzians and microscopic input*



*E. L., H.P. Loens, K. Langanke, G. Martínez-Pinedo, T. Rauscher, P. Ring, F.-K. Thielemann, V. Tselyaev, Nucl. Phys. A 823, 26 (2009).

^{132}Sn:
PDR at the neutron threshold!

(n,γ) stellar reaction rates*

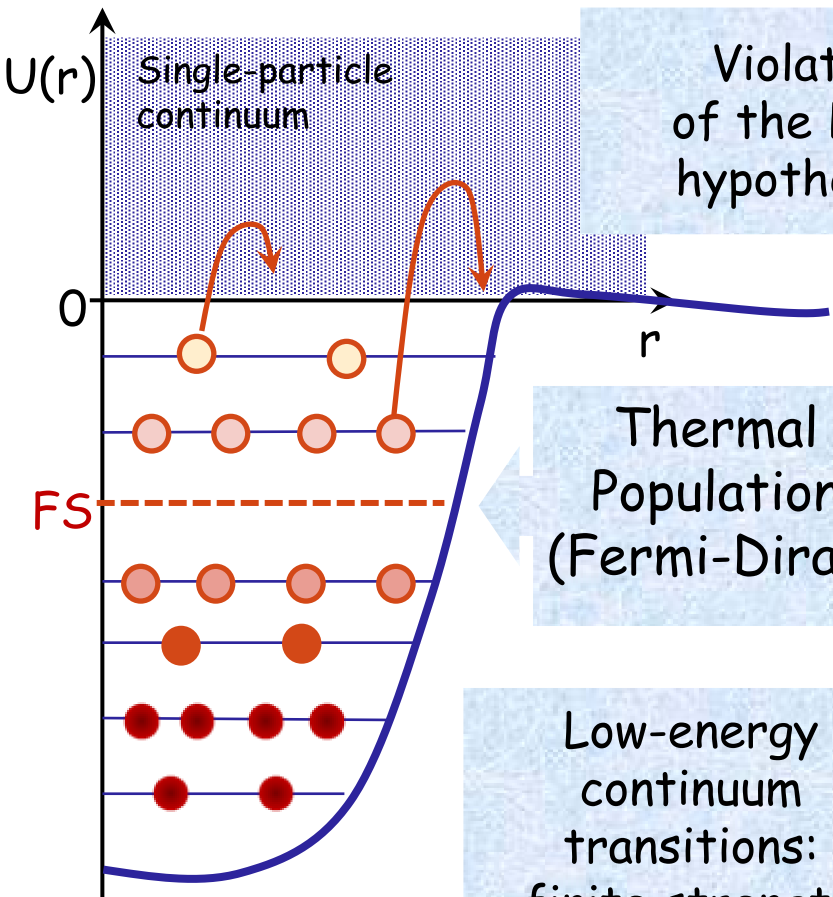


*E. L., H.P. Loens, K. Langanke, G. Martínez-Pinedo, T. Rauscher, P. Ring, F.-K. Thielemann, V. Tselyaev, Nucl. Phys. A 823, 26 (2009).

^{132}Sn:
PDR at the neutron threshold!

Is there a dependence of the gamma-strength on the excitation energy ?

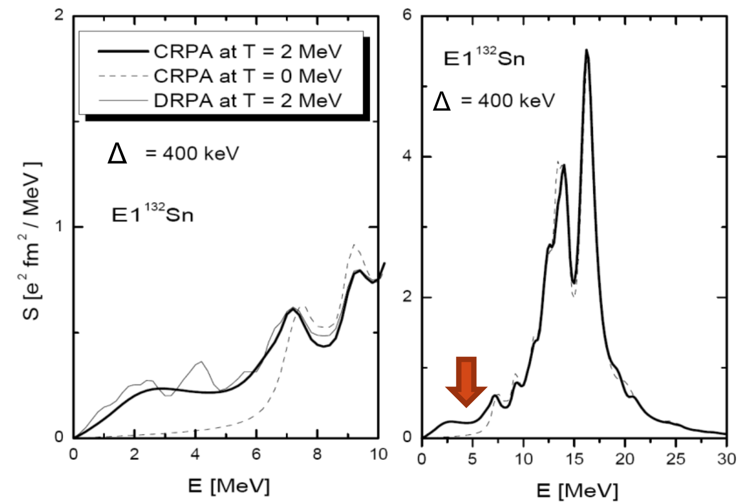
Temperature dependence of low-lying dipole strength: Continuum QRPA at finite temperature revisited*

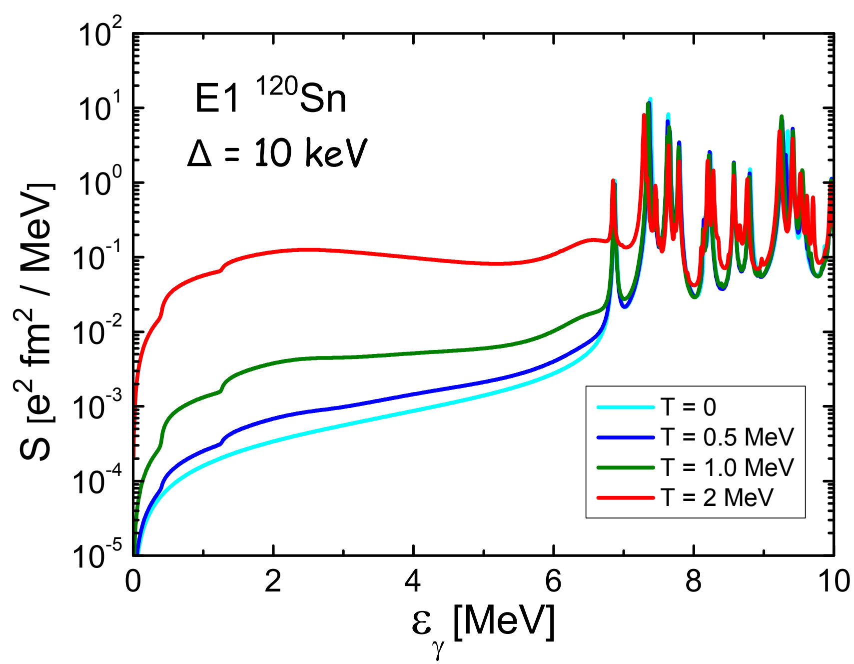


Violation of the Brink hypothesis?

Thermal Population (Fermi-Dirac)

Low-energy continuum transitions: finite strength at $\varepsilon_\gamma \rightarrow 0$

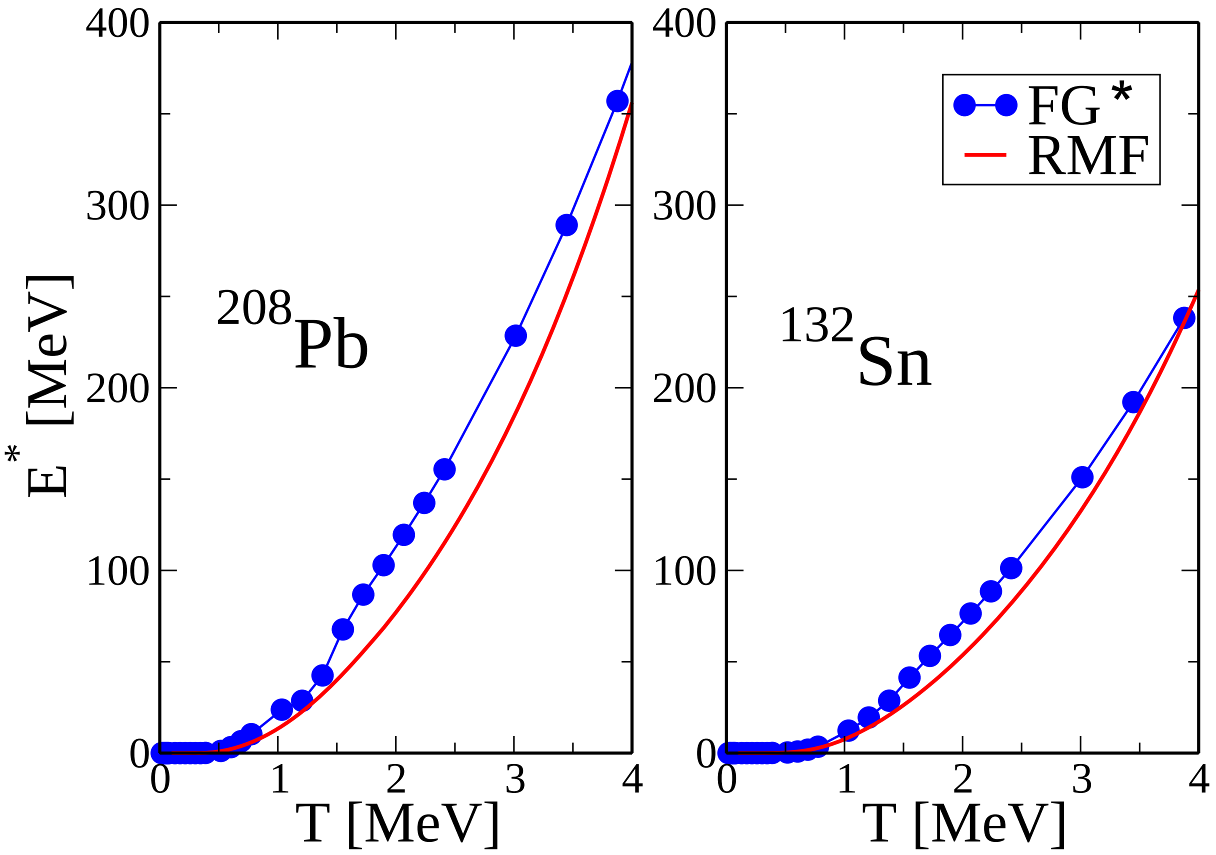




*E.L. et al., in preparation.

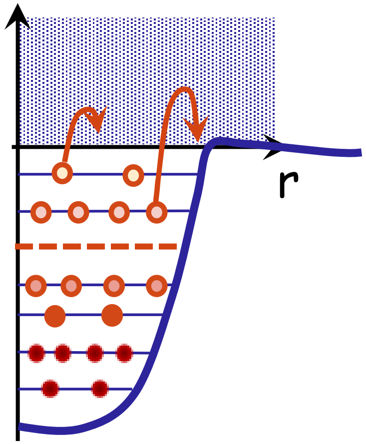
How good the thermal mean field is ?

Temperature dependent covariant energy density functional E[ρ]
= Thermal Relativistic Mean Field (RMF)



*T. Rauscher, Astrophys. J. Suppl. Ser. 147, 403 (2003).

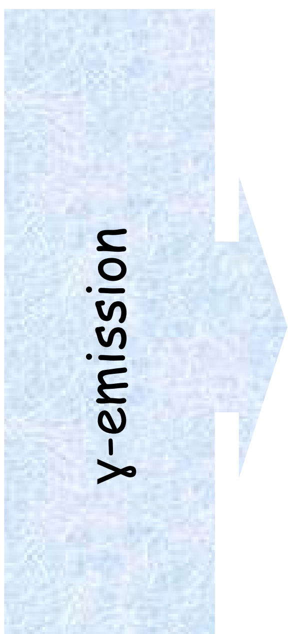
Dipole gamma-strength in ^{132}Sn

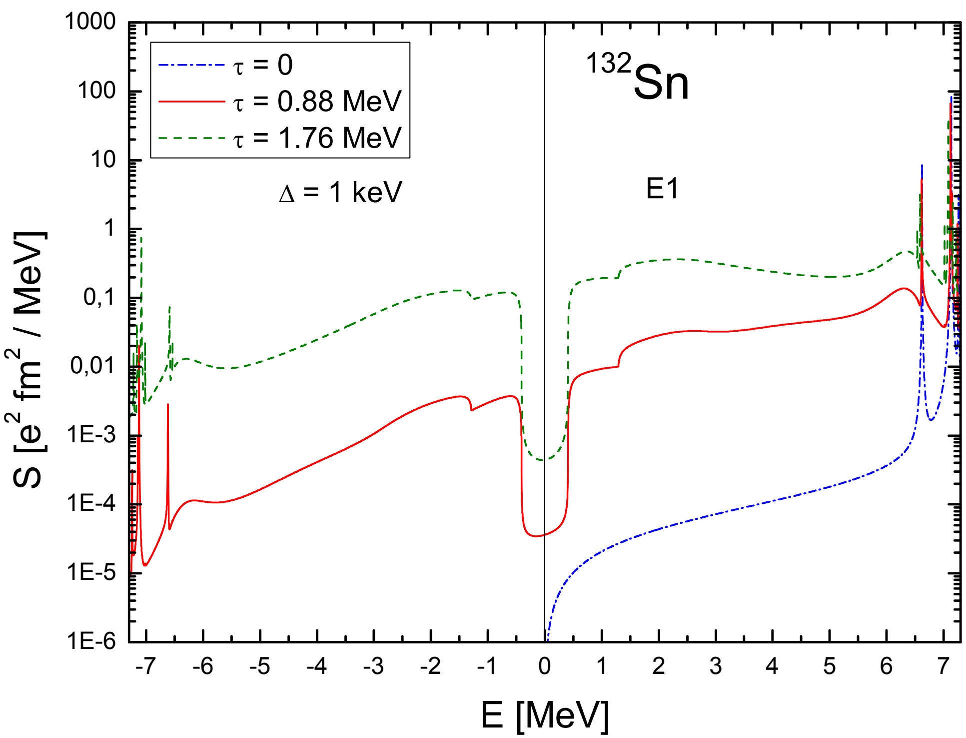


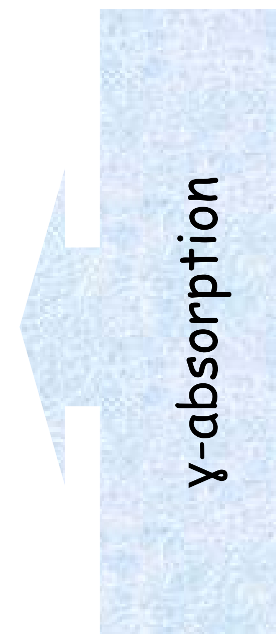
$$S(E_\gamma) = \sum_{if} p_i |\langle f|D|i\rangle|^2 \delta(E_\gamma - E_f + E_i)$$

$$S(E_\gamma, \tau) = -\frac{1}{\pi}\frac{1}{1-e^{-E_\gamma/\tau}} \mathrm{Im}\langle D^\dagger R(E_\gamma + i\Delta, \tau) D\rangle$$

$T \leftarrow\rightarrow E^*[\rho, T] = S_n$





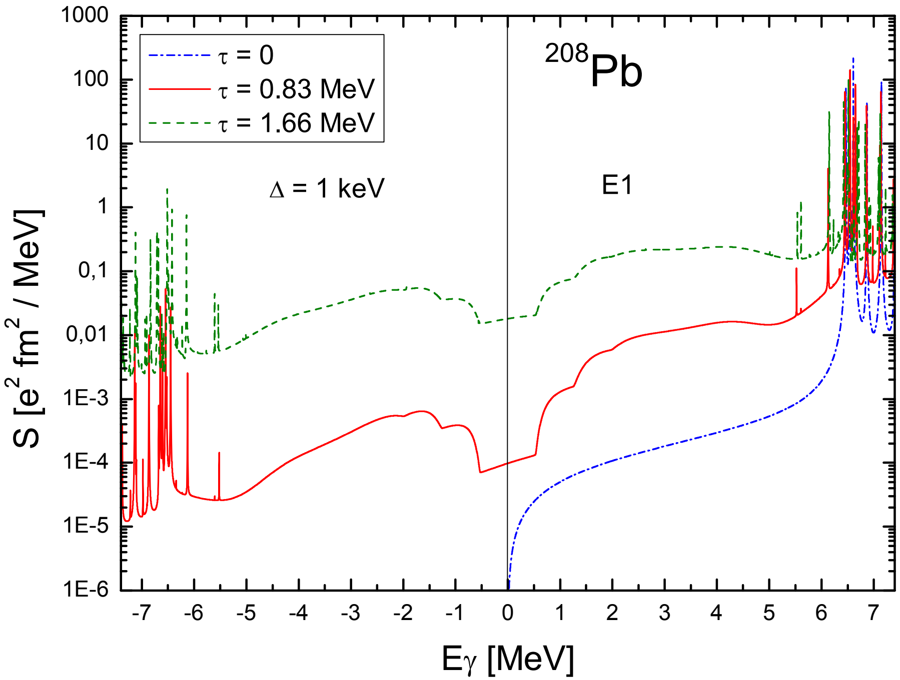


Dipole radiative strength in ^{208}Pb

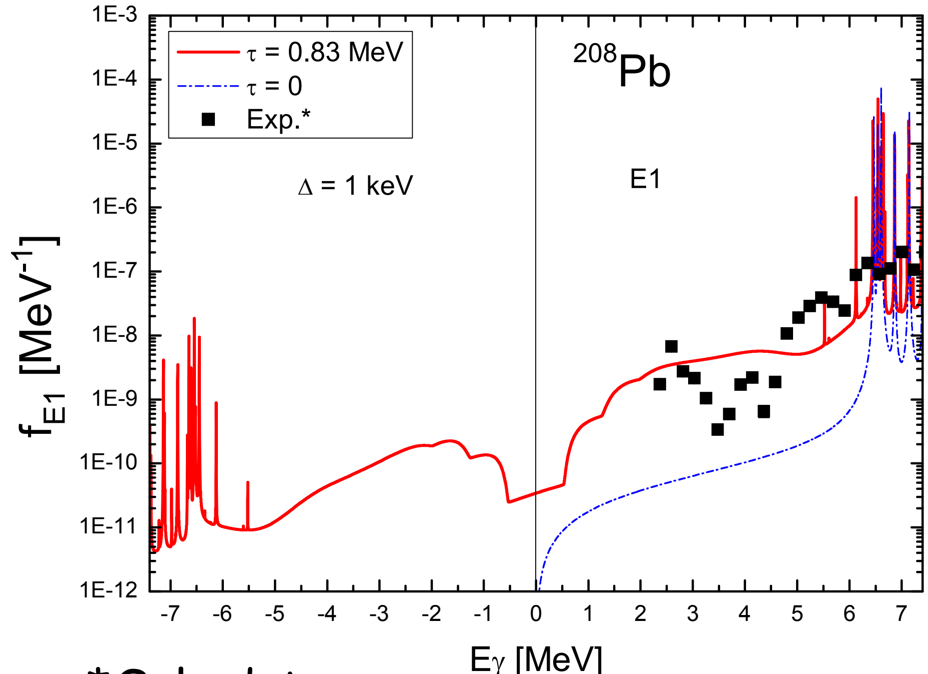
From $S_{E1}(E_\gamma)$ to $f_{E1}(E_\gamma)$

$$\left\{ \begin{aligned} \sigma_{E1}(E_\gamma) &= \frac{16\pi^3 e^2}{9\hbar c} E_\gamma S_{E1}(E_\gamma) \\ \sigma_{\mathrm{E1}}(E_\gamma) &= 3\pi^2(\hbar c)^2 E_\gamma f_{\mathrm{E1}}(E_\gamma) \end{aligned} \right\}$$

$S_{E1}(E_\gamma)$

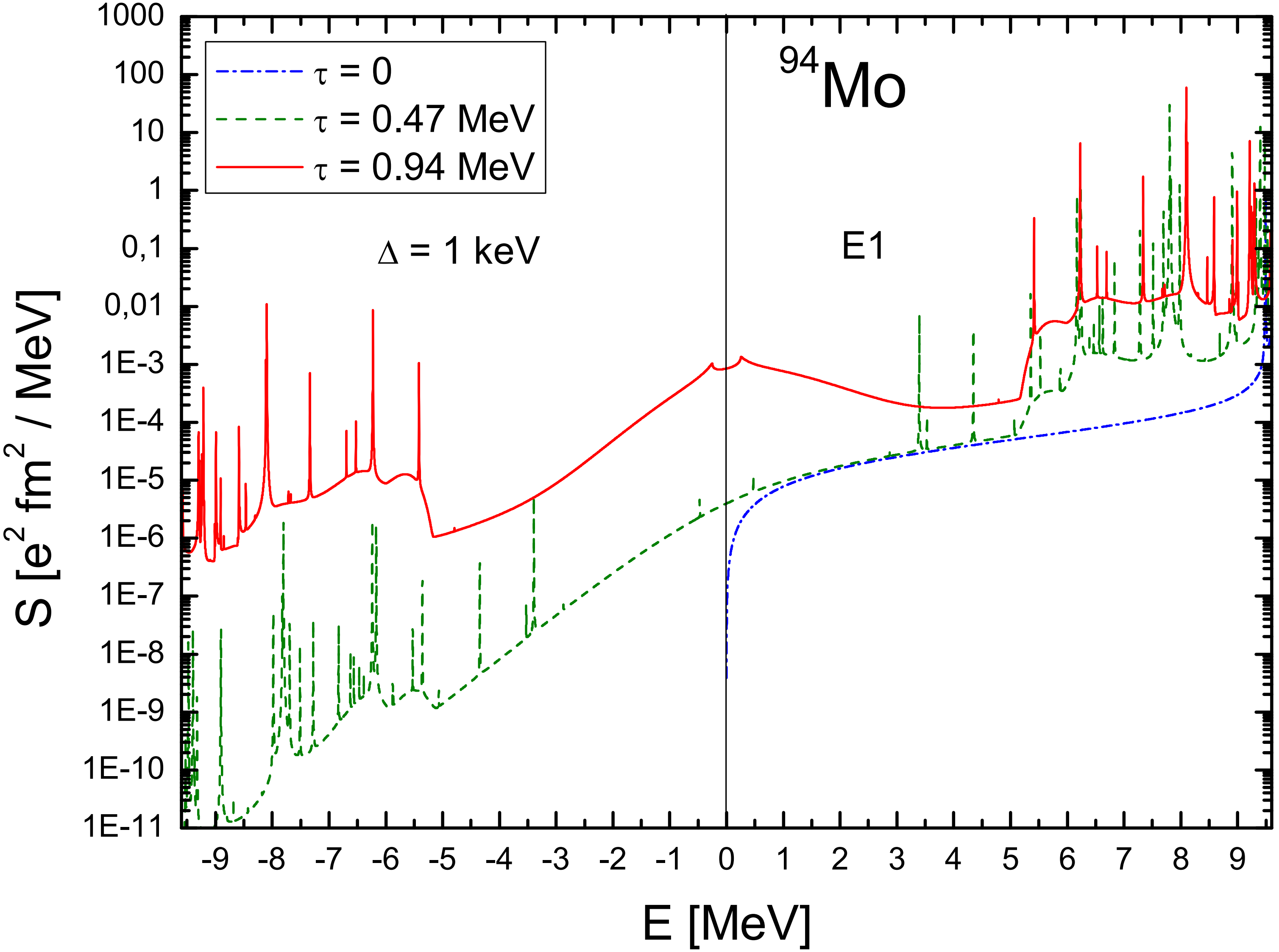


$f_{E1}(E_\gamma)$



*Oslo data:
N.U.H. Syed et al., PRC 79, 024316

Gamma-strength in ^{94}Mo (preliminary)



Summary & Outlook

Present status:

I. Recently developed microscopic approaches based on the covariant DFT with consistent treatment of many-body correlations by the parameter-free Green's function techniques have been applied to description of the nuclear excited states

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

The microscopic strength functions are used as an input for the (n,γ) cross sections and astrophysical reaction rates

II. Thermal continuum QRPA is considered as a possible explanation of the finite radiative dipole strength functions at lowest gamma-energies

Open problems & perspectives:

Improvements of the RMF forces, inclusion of the next orders of many-body correlations

Combined approach: Consistent combination of I & II

Comparison to data for radiative dipole strength

Thanks for collaboration:

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