Low-energy nuclear response: structure and underlying mechanisms

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Building blocks of nuclear structure models

❖ Degrees of freedom

at ~1-50 MeV excitation energies:
single-particle & collective (vibrational, rotational)
NO complete separation of the scales!
-Coupling between single-particle and collective:
-Coupling to continuum
as nuclei are open quantum systems

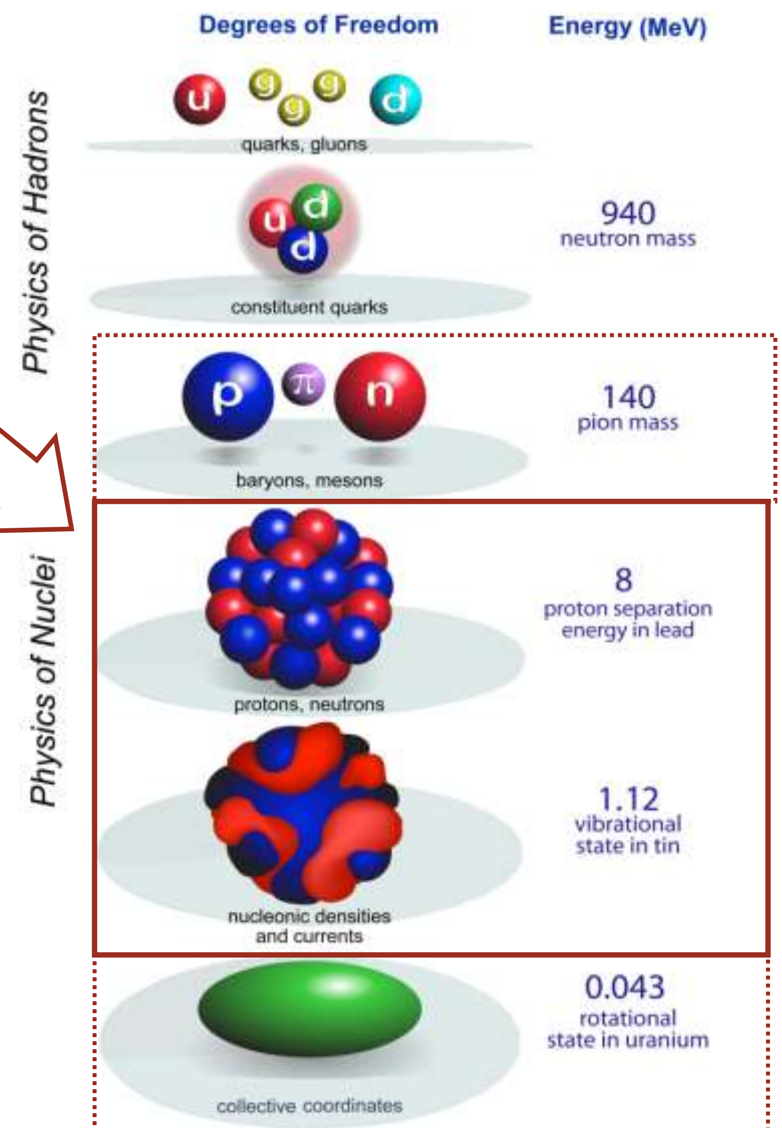
❖ Symmetries -> Eqs. of motion

Galilean inv. -> Schrödinger Eq.
Lorentz inv. -> Dirac Eq.

❖ Interaction V_{NN} : 3 basic concepts

Ab initio: from vacuum V_{NN} -> in-medium V_{NN}
Density functional: an ansatz for in-medium V_{NN}
Configuration interaction: matrix elements for in-medium V_{NN}

Separation of the scales



Nuclear models

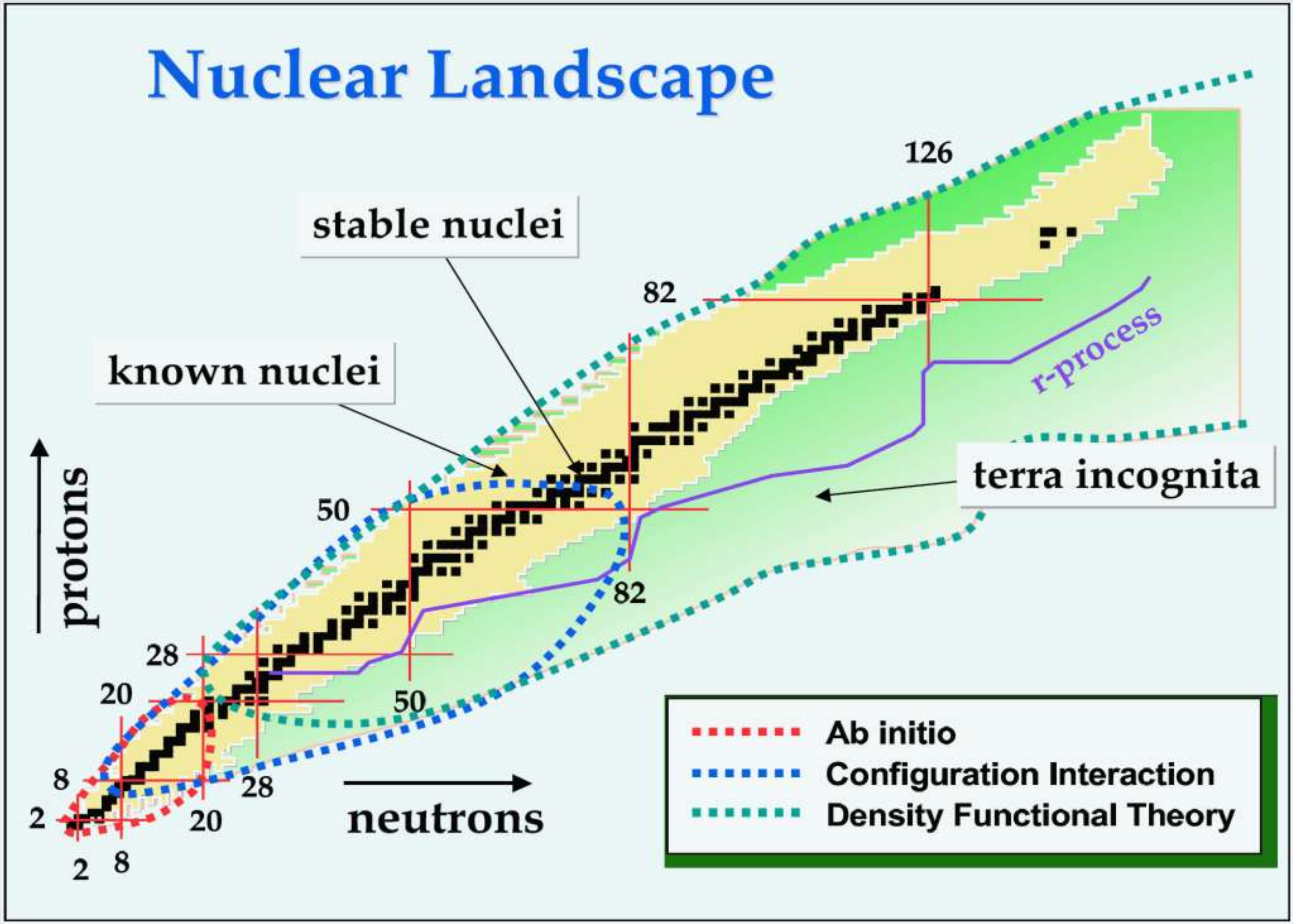


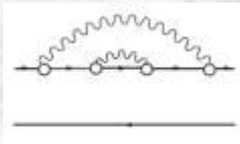
Figure from: G.F. Bertsch, J. Phys.: Conf. Ser. 78, 012005 (2007)

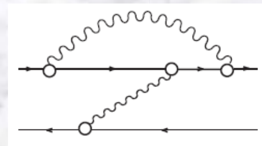
Correlations
in the models based on the density functional:

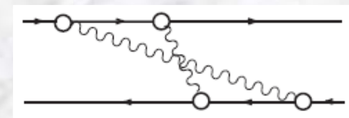
SELF-CONSISTENT

NpNh: ...

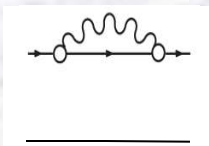
3p3h correlations: iterative scheme

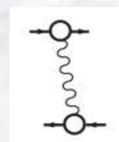


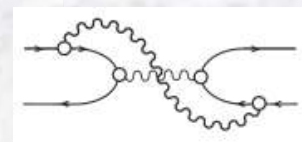




2p2h correlations:





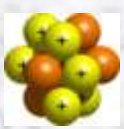


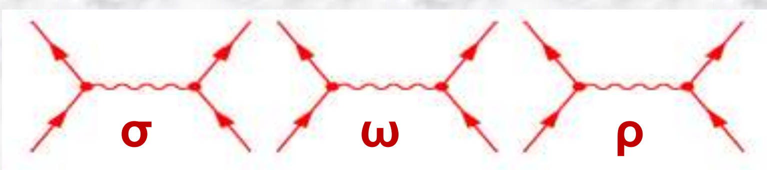
1p1h correlations:

$$V = \frac{\delta^2 E[R]}{\delta R^2}$$

Ground state: Density functional theory

E[R]





$(J^\pi,T)=(0^+,0)$ $(J^\pi,T)=(1^-,0)$ $(J^\pi,T)=(1^-,1)$

(covariant: 7-9 parameters)

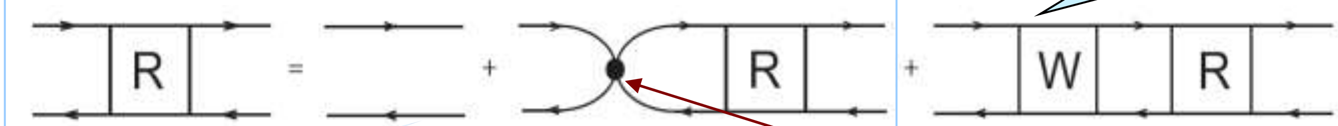
SELF-CONSISTENT

Excited states: nuclear response function

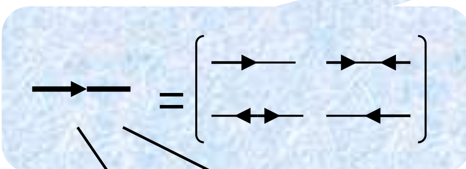
QRPA

Extension

Bethe-Salpeter Equation (BSE):



E.L., V. Tselyaev,
PRC 75, 054318 (2007)

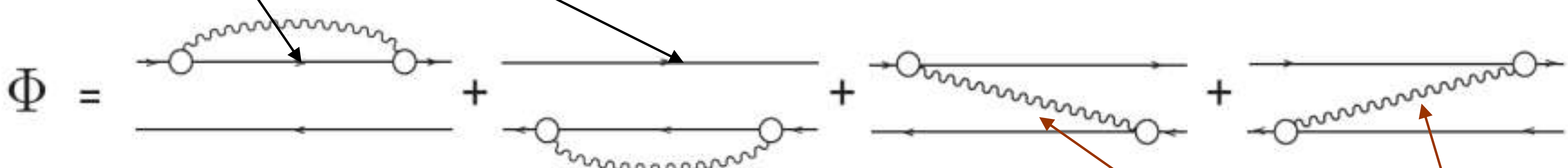


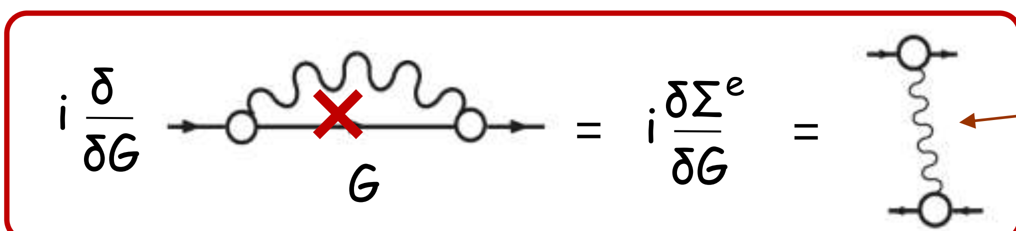
$$R(\omega) = A(\omega) + A(\omega)\,\left[V + W(\omega)\right] R(\omega)$$

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

Self-consistency

$$W(\omega) = \Phi(\omega) - \Phi(0)$$

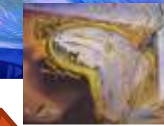




$$U^e = i\,\frac{\delta\Sigma^e}{\delta G}$$

Consistency on 2p2h-level

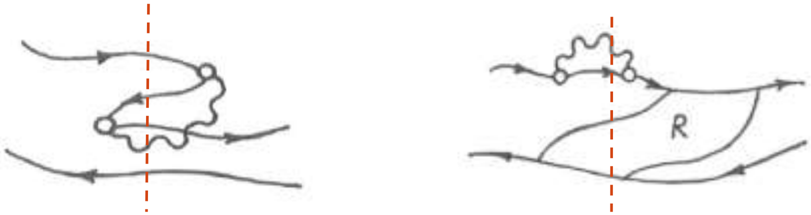
Time blocking



Problem:

'Melting' diagrams

3p3h NpNh



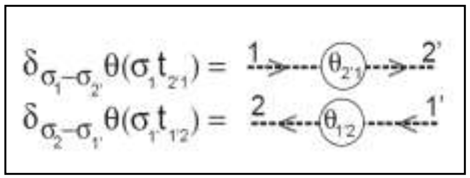
Time

Approx. schemes

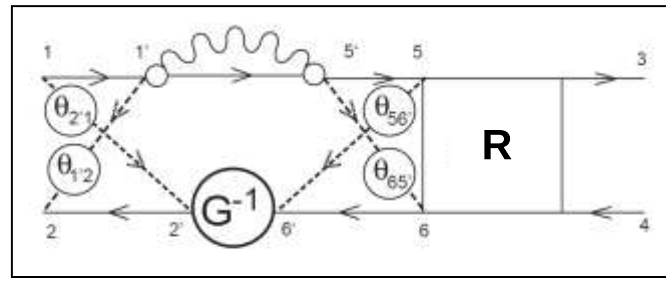
Unphysical result: negative cross sections

Solution:

Time-projection operator:

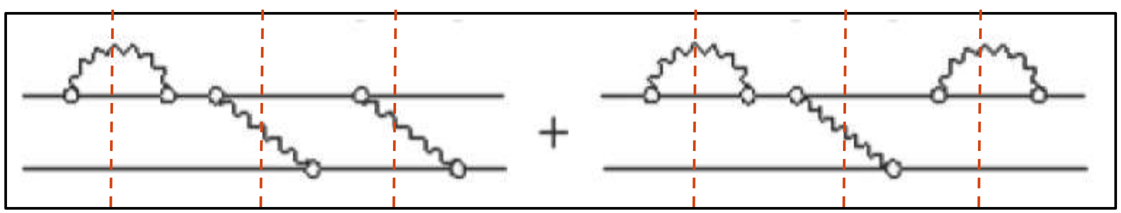


V.I. Tselyaev,
Yad. Fiz. 50,1252 (1989)

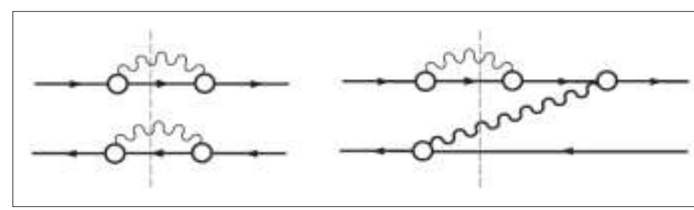


Partially fixed

Allowed terms: 1p1h, 2p2h



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

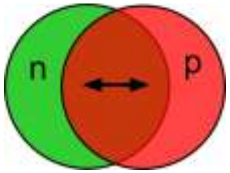


Time blocking approximation =
= „one-fish" approximation!

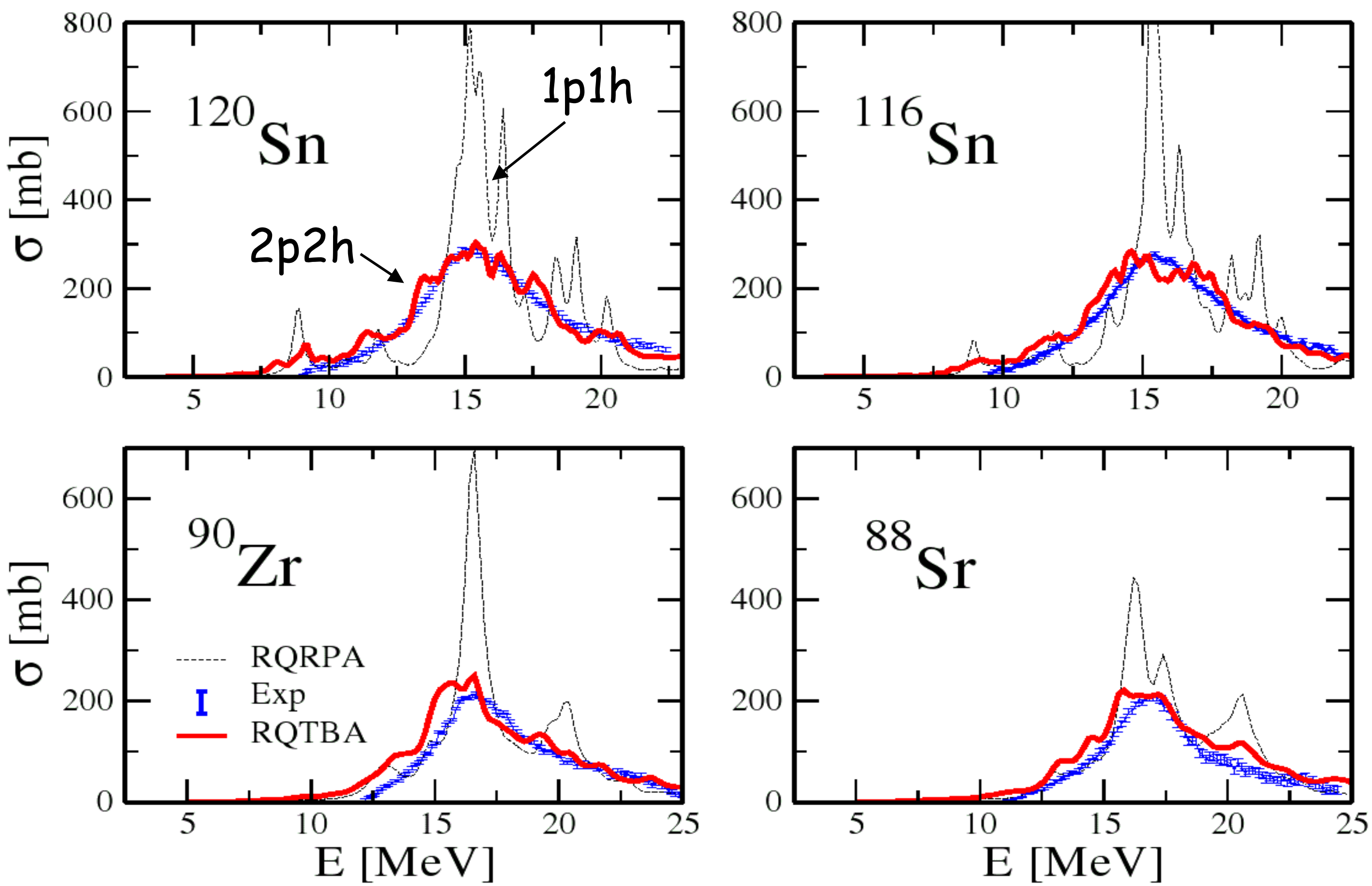
- Separation of the integrations in the BSE kernel
- R has a simple-pole structure (spectral representation)
  »» Strength function is positive definite!

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

$$P = \sum_{i=1}^{A} \left(\tau_z^{(i)} - \frac{N-Z}{2A} \right) r_i Y_{1M}(\hat{\vec{r}}_i)$$



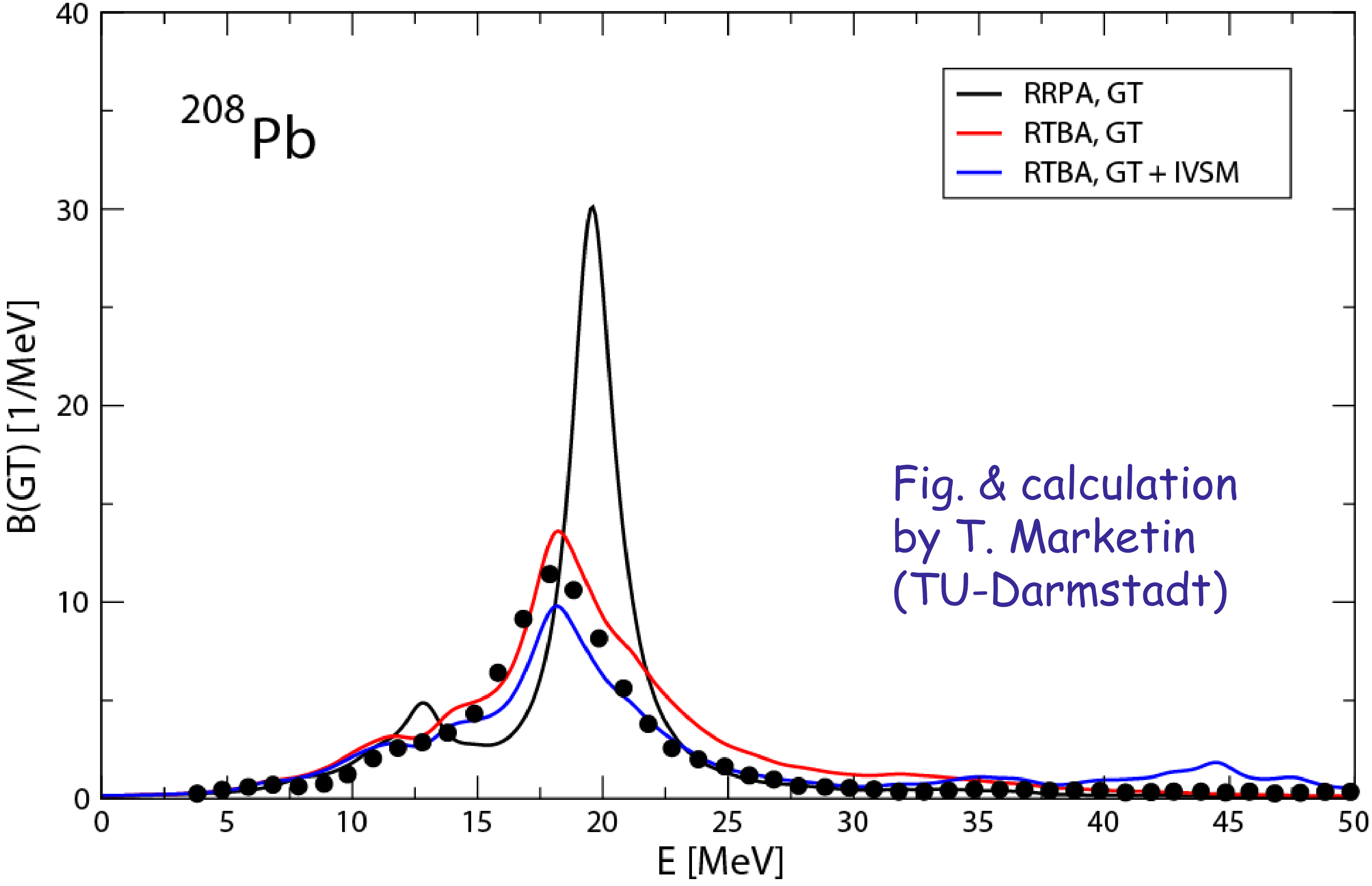
ΔL = 1
ΔT = 1
ΔS = 0



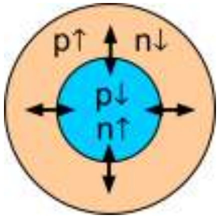
*E. L., P. Ring, and V. Tselyaev,
Phys. Rev. C 78, 014312 (2008)

Gamow-Teller Resonance in 208-Pb

„Proton-Neutron" relativistic time blocking approximation: ρ, π, phonons



$$P = \sum_i \sigma^{(i)} \tau_{\pm}^{(i)}$$

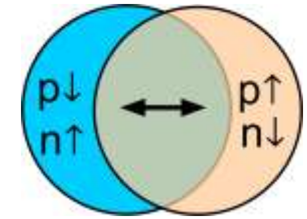


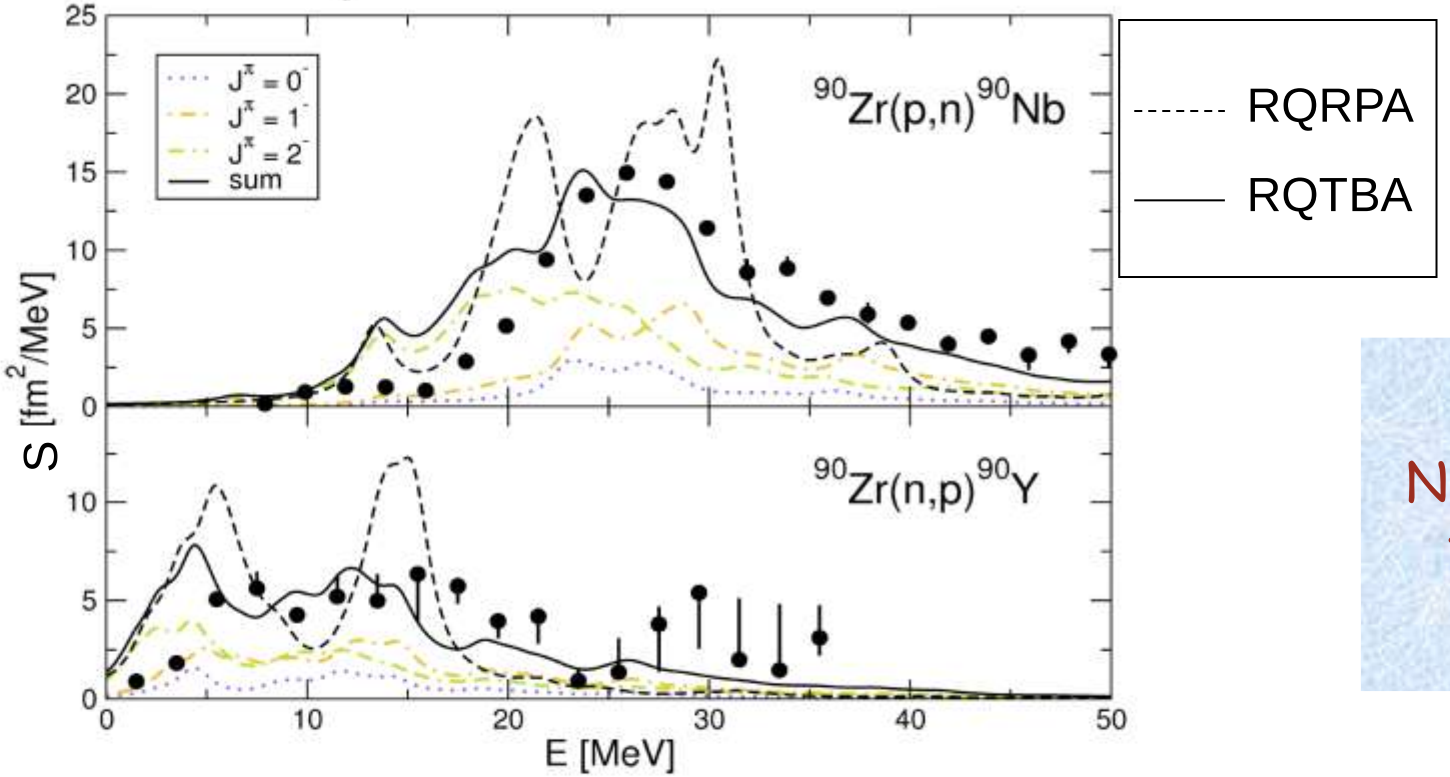
ΔL = 0
ΔT = 1
ΔS = 1

Natural quenching of S^- due to ph+phonon configurations, relativistic effects and finite momentum transfer

Spin-dipole resonance: beta-decay, electron capture

$$P_{\pm}^{\lambda} = \sum_i r_i \left[\boldsymbol{\sigma}^{(i)} \otimes Y_1(\hat{\vec{r}}_i) \right]_{\lambda} \tau_{\pm}^{(i)}$$





ΔL = λ = 0,1,2
ΔT = 1
ΔS = 1

Neutron skin thickness

Sum rule:

$$S_{-}^{\lambda} - S_{+}^{\lambda} = \frac{2\lambda + 1}{4\pi} \left(N \left\langle r^2 \right\rangle_n - Z \left\langle r^2 \right\rangle_p \right)$$

$$\delta_{np} = \sqrt{\left\langle r^2 \right\rangle_n} - \sqrt{\left\langle r^2 \right\rangle_p}$$

T. Marketin, E.L., D. Vretenar, P. Ring, PLB 706, 477 (2012).

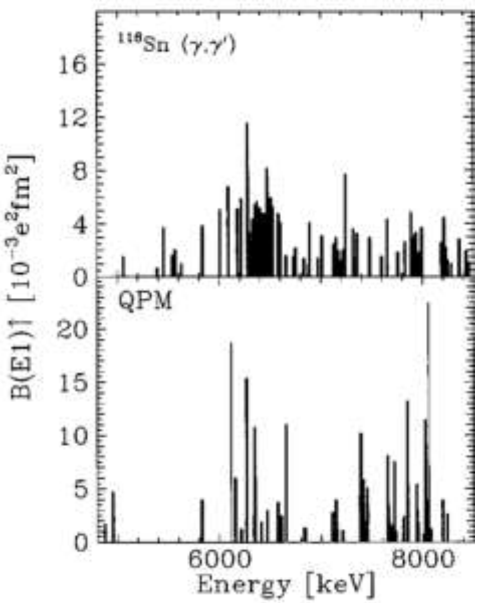
Fragmentation of pygmy dipole resonanse

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

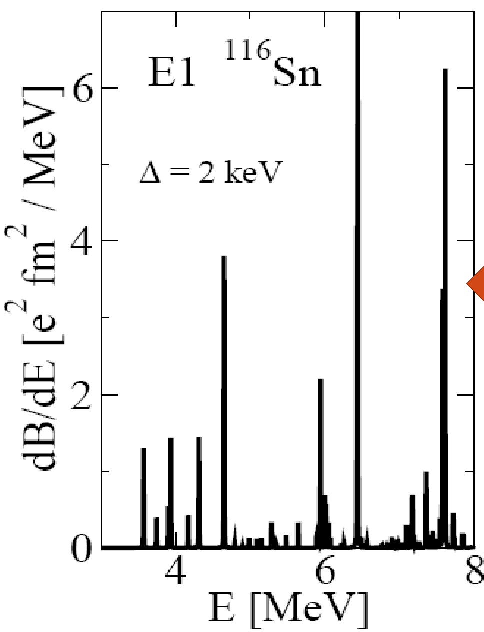
Low-lying dipole strength in ^{116}Sn

Please, do not compare this „PDR" to data!

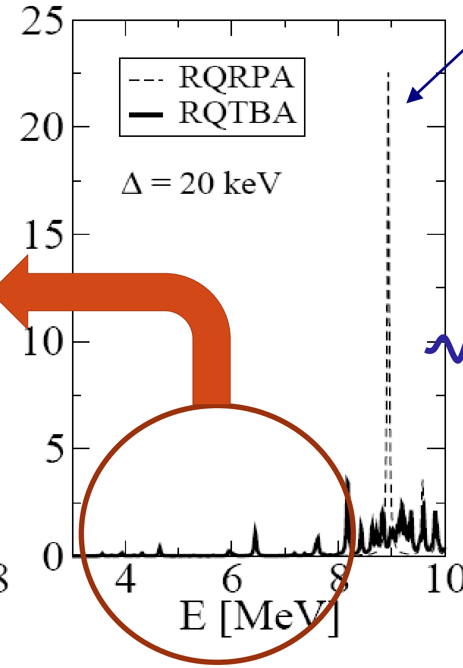
Experiment*



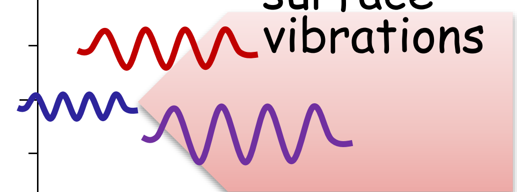
Fine structure



Gross structure



2+,3-,...
surface
vibrations



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

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

RQTBA 2p2h

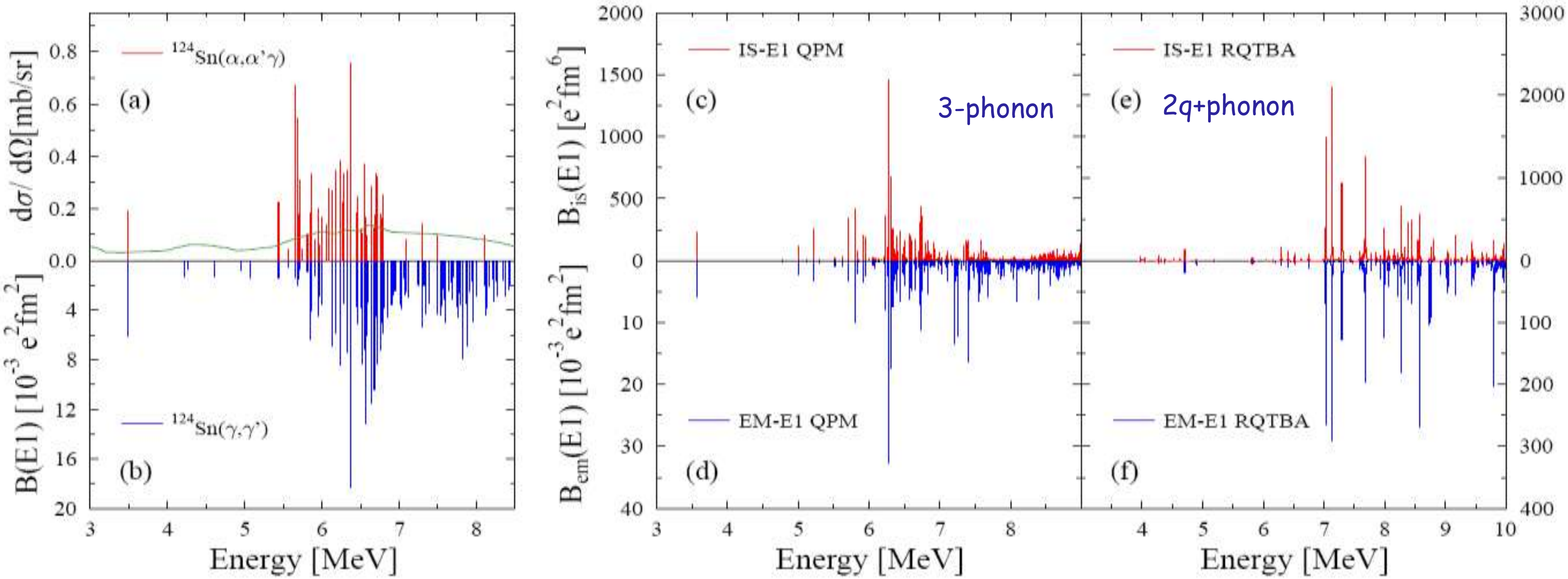
RQRPA 1p1h vs
RQTBA 2p2h

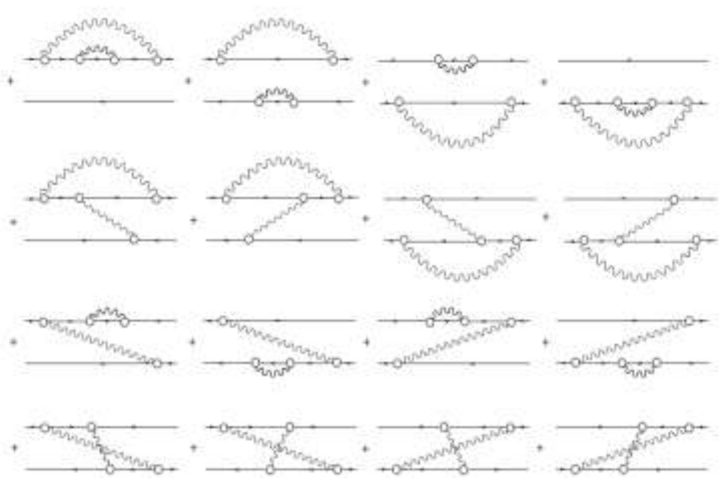
Integral
5-8 MeV:
ΣB(E1)↑ [e^2 fm^2]

Exp.	0.204(25)
QPM	0.216
RQTBA	0.27

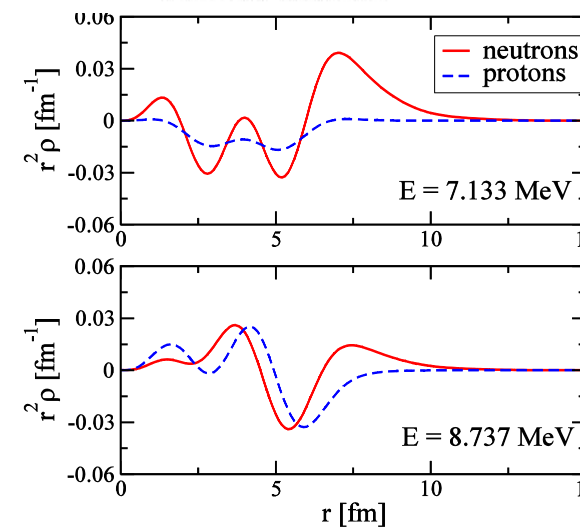
Isospin structure of the pygmy dipole resonance in ^{124}Sn

J. Endres et al., PRL 105, 212503 (2010).





2q+2phonon
to be
included



Fine structure of spectra: next-order correlations from "2q+phonon" to "2 phonons"

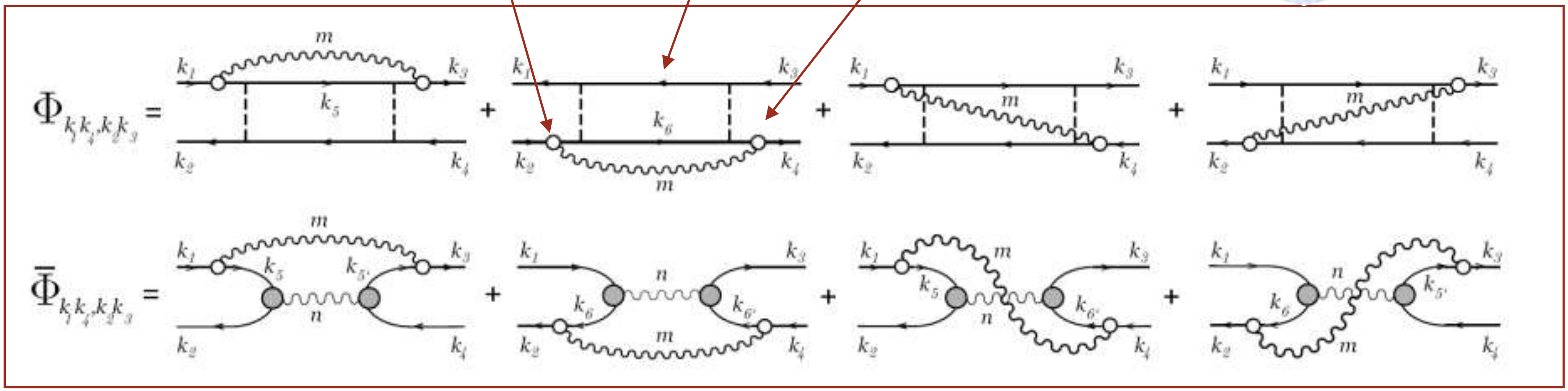
P. Schuck, Z. Phys. A 279, 31 (1976)
V.I. Tselyaev, PRC 75, 024306 (2007)

&

Mode Coupling Theory
Time Blocking

$$\Phi_{12,34}(\omega) = - \sum_{5678,\eta,m} \gamma_{12}^{m56(\eta)} \boxed{A_{56,78}^{(\eta)}(\omega - \eta\,\omega_m)} \gamma_{34}^{m78(\eta)*}$$

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



Nuclear response: $R = A + A\,(V + \bar{\Phi} - \bar{\Phi}_0)\,R$

Poles may appear at lower energies:

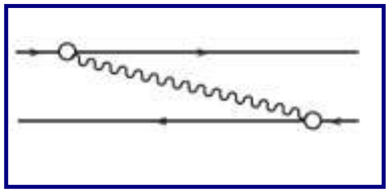
'2q+phonon' response:
$\Phi_{iji'j'}(\omega) \sim \Sigma_{\mu k}\, a_{ijk\mu}/(\omega - E_{i'} - E_k - \Omega_\mu)$

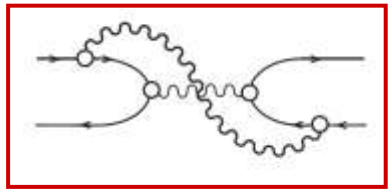
'2 phonon' response:
$\Phi_{iji'j'}(\omega) \sim \Sigma_{\mu\nu}\, a_{iji'j'}/(\omega - \Omega_\nu - \Omega_\mu)$

Fine features of dipole spectra: two-phonon effects

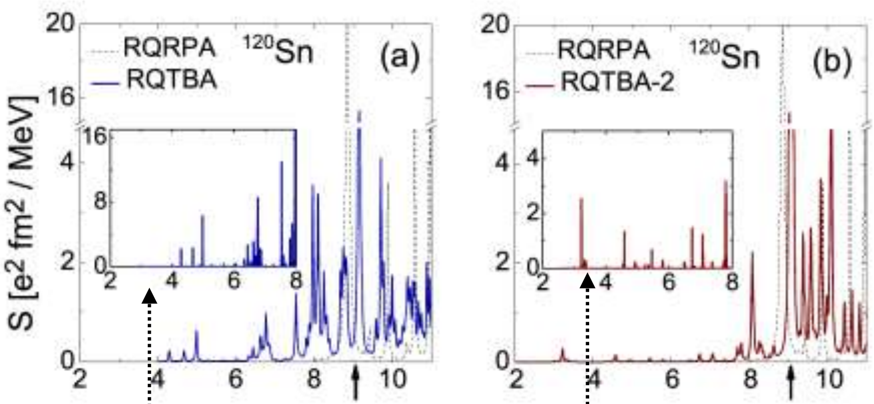
2q+phonon

2 phonon





^{120}Sn



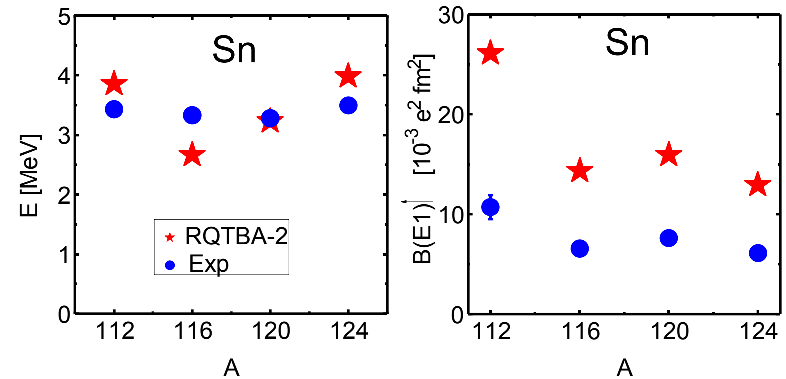
Does not exist

$3^- \otimes 2^+$

E.L., P.Ring, V.Tselyaev, PRL 105, 02252 (2010)

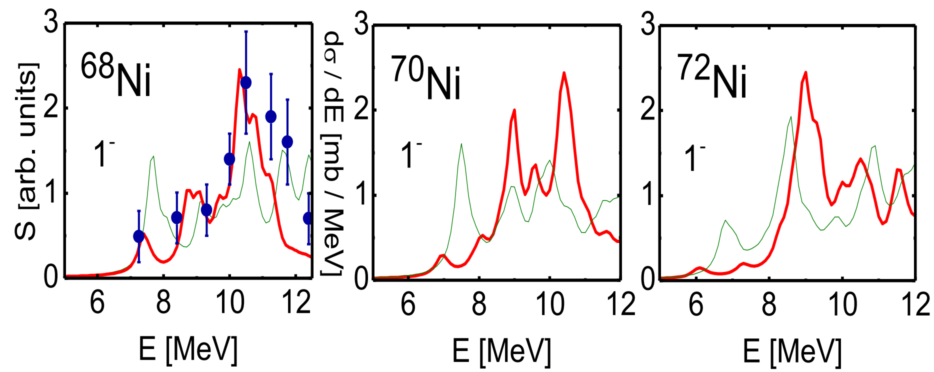
First two-phonon state 1^-_1 : $3^- \otimes 2^+$

E(1^-_1) B(E1) ↑



Data: I.Pysmenetska et al., PRC73 (2006) 017302

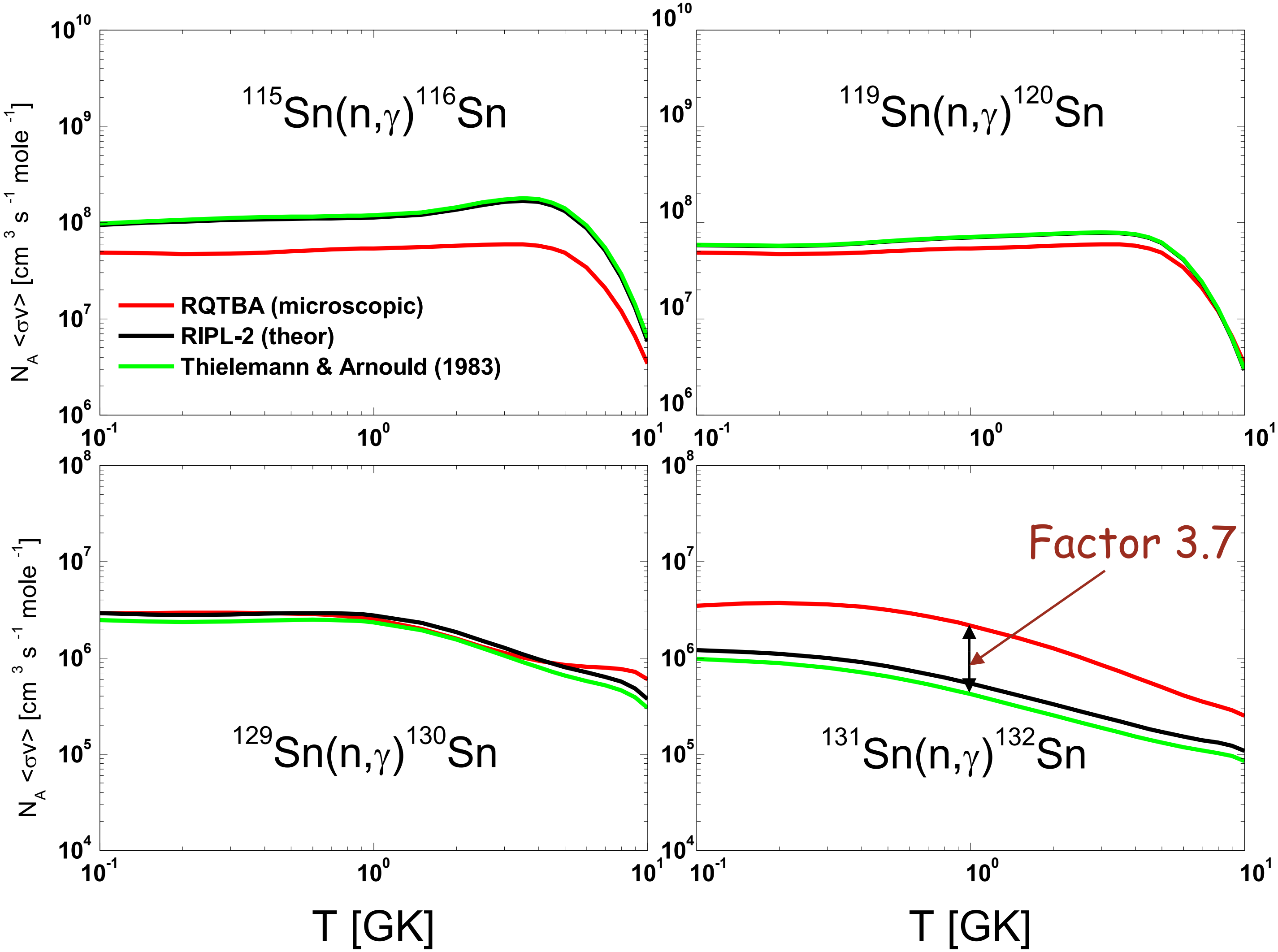
Pygmy dipole resonance in neutron-rich Ni:
2q+phonon vs 2 phonon



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

(n,γ) stellar reaction rates

E. L., H.P. Loens, K. Langanke, et al. Nucl. Phys. A 823, 26 (2009).



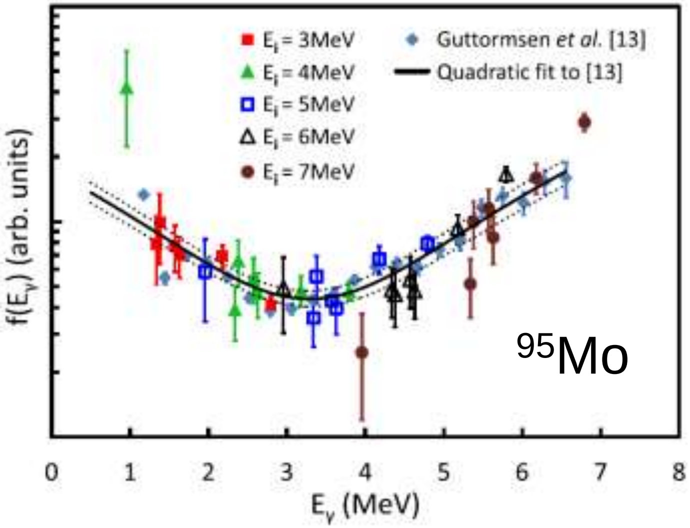
PDR at neutron threshold

(n,γ) via compound nucleus: γ-transitions between excited states in the quasicontinuum

Low-energy enhancement of γ-strength

A. Voinov et al., PRL 93, 142504 (2004)
M. Guttormsen et al., PRC 71, 044307 (2005)
Oslo method

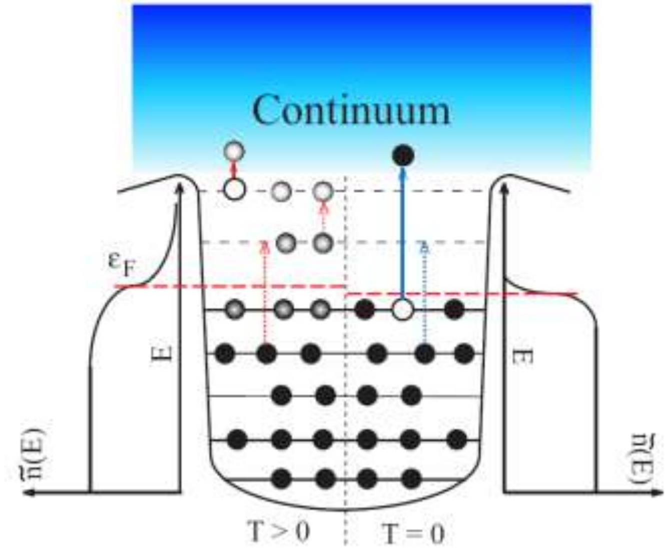
M. Wiedeking et al., PRL 108, 162503 (2012):

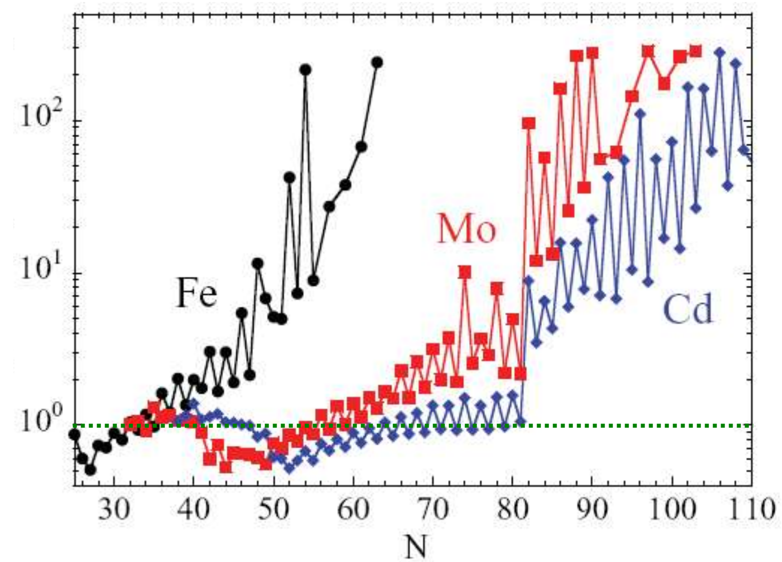


$$\frac{(n,\gamma) \text{ reaction rate (enh.)}}{(n,\gamma) \text{ reaction rate (no enh.)}} = \eta$$

A.C. Larsen, S. Goriely, PRC 014318 (2010)
Oslo data

Correlations due to coupling to single-particle continuum





Nuclear response at finite temperature

Density matrix variation at T > 0:

$$\delta\mathcal{R}(x;\omega,T) = \delta\mathcal{R}^{(0)}(x;\omega,T) +$$
$$+\int dx'dx''\mathcal{A}(x,x';\omega,T)F(x',x'')\delta\mathcal{R}(x'';\omega,T)$$

Thermal continuum quasiparticle random phase approximation

E.L. et al., Phys. Atomic Nuclei 66, 558 (2003) (TCQRPA)

$$\mathcal{A}(x,x';\omega,T) = \sum_{1234}\varphi_1^*(x)\varphi_2(x)\varphi_3(x')\varphi_4^*(x')\int\frac{d\varepsilon}{2\pi i}\underbrace{G_{12}(\varepsilon,T)G_{34}(\varepsilon+\omega,T)}_{\text{Matsubara GF}}$$

Radiative strength function (RSF):

$$f_{E1}(E_\gamma,T) = -\frac{8e^2}{27(\hbar c)^3}\mathrm{Im}\int dx P_{E1}^{\dagger}(x)\delta\mathcal{R}(x;\omega,T)$$

$$\omega = E_\gamma + i\Delta, \Delta\to 0$$ Exp. energy resolution

Structure of the TCQRPA propagator in ph-channel

$$
\begin{aligned}
&\mathcal{A}^{\mathrm{cont}L}_{LS,LS'}(r,r';\omega;T)\\
&= -\sum_{1} \boxed{v_1^2(T)(1-n_1(T))} R_1(r)R_1(r') \sum_{l_2 j_2} T^{LSS'}_{12}\\
&\quad \times \Big[\mathcal{G}_{l_2 j_2}(r,r';\mu(T)-E_1(T)+\omega)\\
&\quad + (-1)^{S+S'}\mathcal{G}_{l_2 j_2}(r,r';\mu(T)-E_1(T)-\omega)\Big]\\
&\quad - \sum_{1} \boxed{u_1^2(T)n_1(T)} R_1(r)R_1(r') \sum_{l_2 j_2} T^{LSS'}_{12}\\
&\quad \times \Big[\mathcal{G}_{l_2 j_2}(r,r';\mu(T)+E_1(T)+\omega)\\
&\quad + (-1)^{S+S'}\mathcal{G}_{l_2 j_2}(r,r';\mu(T)+E_1(T)-\omega)\Big],
\end{aligned}
$$

$$
\begin{aligned}
&\mathcal{A}^{\mathrm{disc}L}_{LS,LS'}(r,r';\omega;T)\\
&= \sum_{12}^{\mathrm{disc}} R_1(r)R_2(r')R_1(r')R_2(r) T^{LSS'}_{21}\\
&\quad \times \Big[\mathcal{L}_{12}(\omega,T) + \frac{v_2^2(T)(1-n_2(T))}{\omega+\mu(T)-\epsilon_1-E_2(T)}\\
&\quad - \frac{v_1^2(T)(1-n_1(T))}{\omega-\mu(T)+\epsilon_2+E_1(T)}\\
&\quad + \frac{u_2^2(T)n_2(T)}{\omega+\mu(T)-\epsilon_1+E_2(T)}\\
&\quad - \frac{u_1^2(T)n_1(T)}{\omega-\mu(T)+\epsilon_2-E_1(T)} + (-1)^S \mathcal{M}_{12}(\omega,T)\Big]
\end{aligned}
$$

$$
n_1(T) = \frac{1}{1+\exp(E_1(T)/T)},
$$

$$
v_1^2(T) = \frac{1}{2}\left(1 - \frac{\epsilon_1-\mu(T)}{E_1(T)}\right),
$$

$$
E_1(T) = \sqrt{(\epsilon_1-\mu(T))^2 + \Delta_1^2(T)}
$$

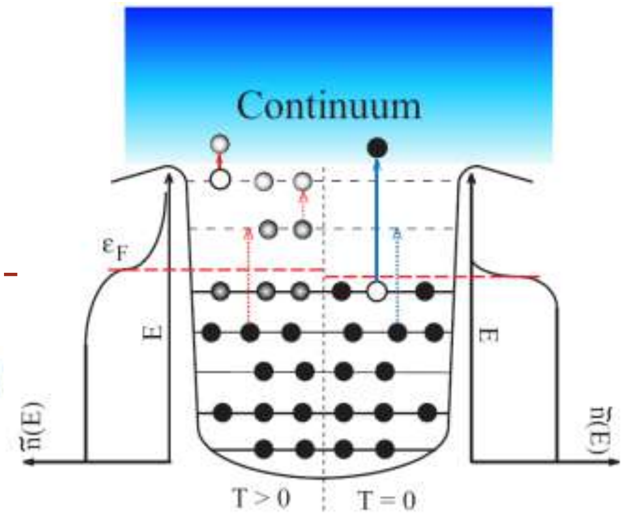
$$
u_1^2(T) = 1 - v_1^2(T)
$$

$$
\begin{aligned}
&\mathcal{L}_{12}(\omega,T) = -A_{ph}(\omega,T)\\
&\times \Big[(u_1^2u_2^2+v_1^2v_2^2)(E_1-E_2) - (u_1^2u_2^2-v_1^2v_2^2)\omega\Big]\\
&\quad - A_{pp}(\omega,T)\Big[-(u_1^2v_2^2+v_1^2u_2^2)(E_1+E_2)\\
&\quad + (u_1^2v_2^2-v_1^2u_2^2)\omega\Big],\\
&\mathcal{M}_{12}(\omega,T) = \frac{\Delta_1\Delta_2}{2E_1E_2}\Big[A_{ph}(\omega,T)(E_1-E_2)\\
&\quad + A_{pp}(\omega,T)(E_1+E_2)\Big],\\
&A_{ph}(\omega,T) = \frac{n_1(T)-n_2(T)}{(E_1-E_2)^2-\omega^2},\\
&A_{pp}(\omega,T) = \frac{1-n_1(T)-n_2(T)}{(E_1+E_2)^2-\omega^2};
\end{aligned}
$$

Mechanism of the RSF formation at low E_γ

$$\tilde{n}_i(E_i,T) = (1-v_i^2(T))n_i(E_i,T)$$

$$\tilde{n}_i(E_i,T) = v_i^2(T)(1-n_i(E_i,T))$$



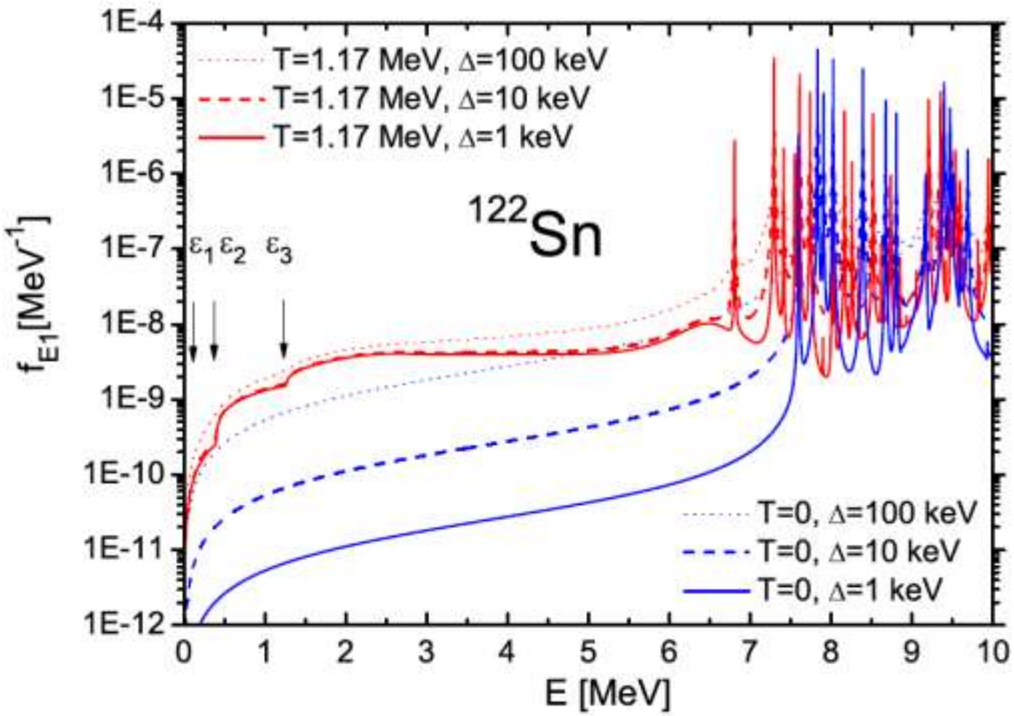
$$v_i^2$$

1. Saturation of RSF with Δ
   at Δ = 10 keV for T>0

2. The low-energy RSF is not
a tail of the GDR and not a part of
PDR!

3. The nature of RSF at E_γ-> 0
is continuum transitions
from the thermally unblocked states

4. Spurious translation mode should be
eliminated exactly.



Elimination of the spurious state

$$\delta\rho(x;\omega,T) = \frac{\zeta(x;T)}{\omega-\omega_0} + \delta\rho^{reg}(x;\omega,T), \qquad \omega_0 \to 0$$

Condition 1

$$F(x,x') = F^{LM}(x,x') + F^{rest}(x,x')$$

$$F^{LM}(x,x') = C_0\Big[f(x) + f'(x)\boldsymbol{\tau\tau}' + (g(x) + g'(x)\boldsymbol{\tau\tau}')\boldsymbol{\sigma\sigma}'\Big]\delta(\mathbf{r}-\mathbf{r}'),$$

$$f(x) = f_{ex} + (f_{in} - f_{ex})\frac{\rho_0(x)}{\rho_0(0)}$$

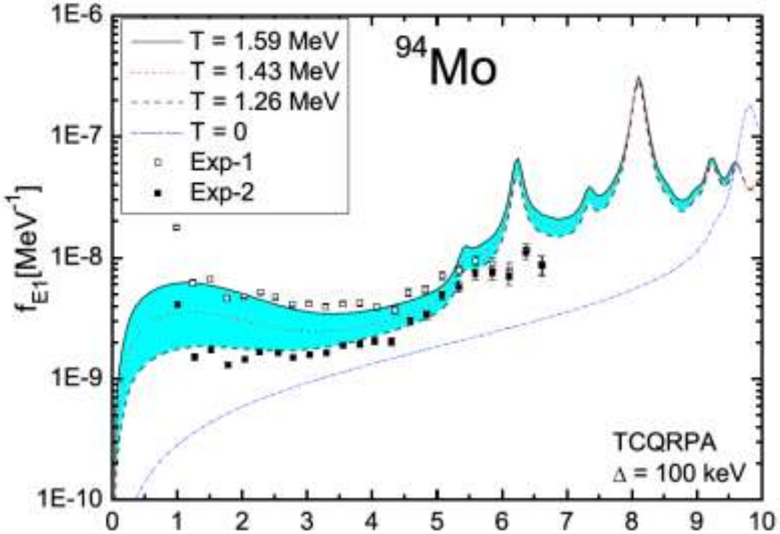
$$F^{rest}(r,r') = \sum_{k=1,2} \kappa_k f_k(x) f_k(x')$$

$$B_{E1}^{(0)} = \int dx \zeta(x,T) P_{E1}(x) = 0$$

Condition 2

V. Tselyaev: S. Kamerdzhiev et al., PRC 58, 172 (1998)
M.I. Baznat et al., Sov. J. Nucl. Phys. 52, 627 (1990)

RSF in even-even Mo isotopes

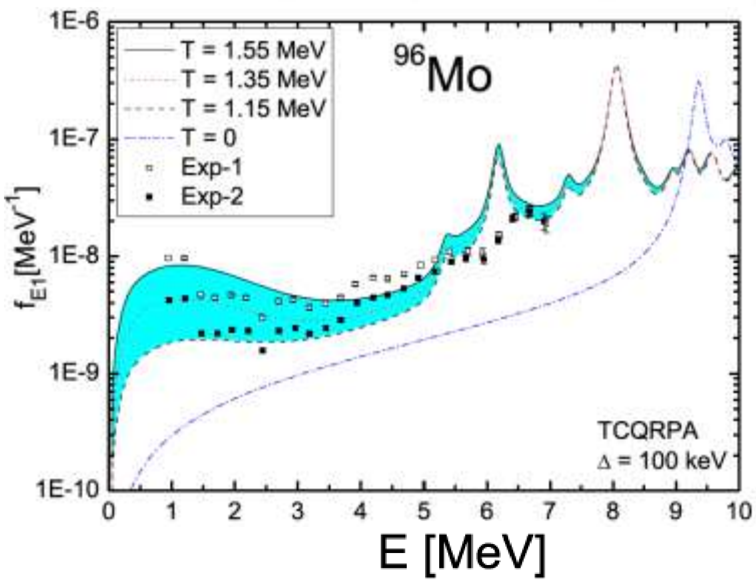


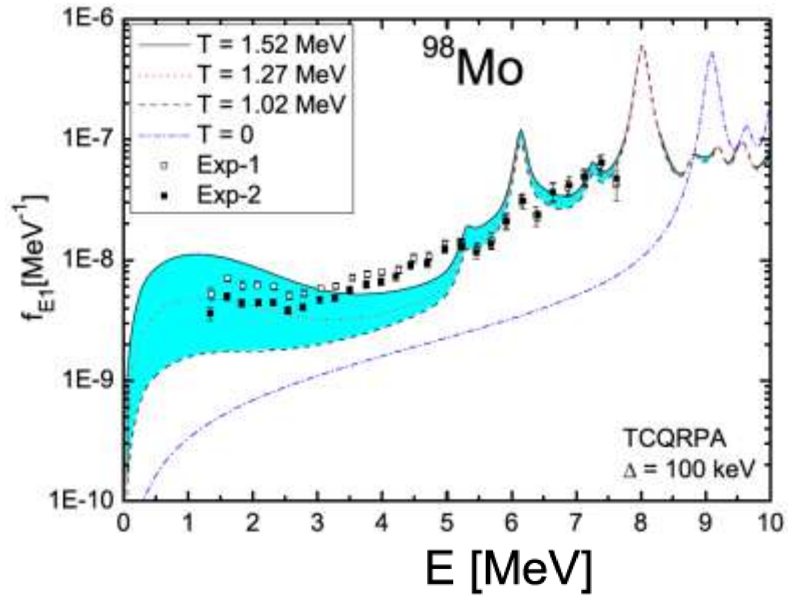
$$T = \sqrt{(E^* - \delta)/a}$$

$$a = a_{EGSF} => T_{min} \quad \text{(RIPL-3)}$$

$$a = \pi^2(g_\nu + g_\pi)/6 \ => T_{max}$$

Exp-1: NLD norm-1,
M. Guttormsen et al., PRC 71, 044307 (2005)
Exp-2: NLD norm-2,
S. Goriely et al., PRC 78, 064307 (2008)

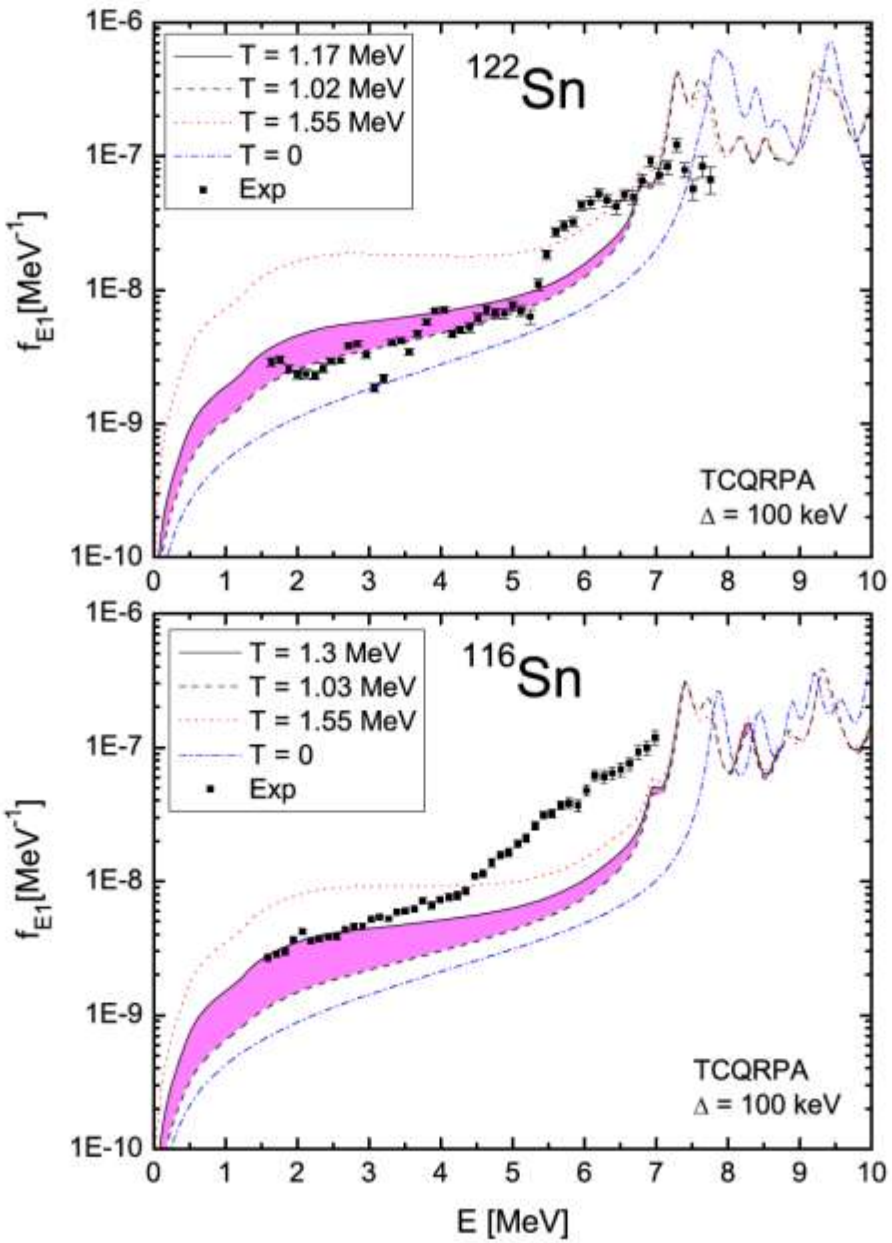




Theory: E. Litvinova, N. Belov, arXiv: 1302.4478, submitted to Phys. Rev.

Data: A.C. Larsen, S. Goriely, PRC 014318 (2010)

RSF in $^{116,122}Sn$



No upbend?

Larger microscopic level density parameter a
=> Lower upper limit for the temperature at S_n

Other effects
(ideally, all to be combined in one approach)

At 3-4 MeV:
- 2-phonon state (as above)

Above 4-5 MeV:
- Coupling to vibrations (as above),
- Thermal fluctuations:
  M. Gallardo et al., NPA443, 415 (1985)

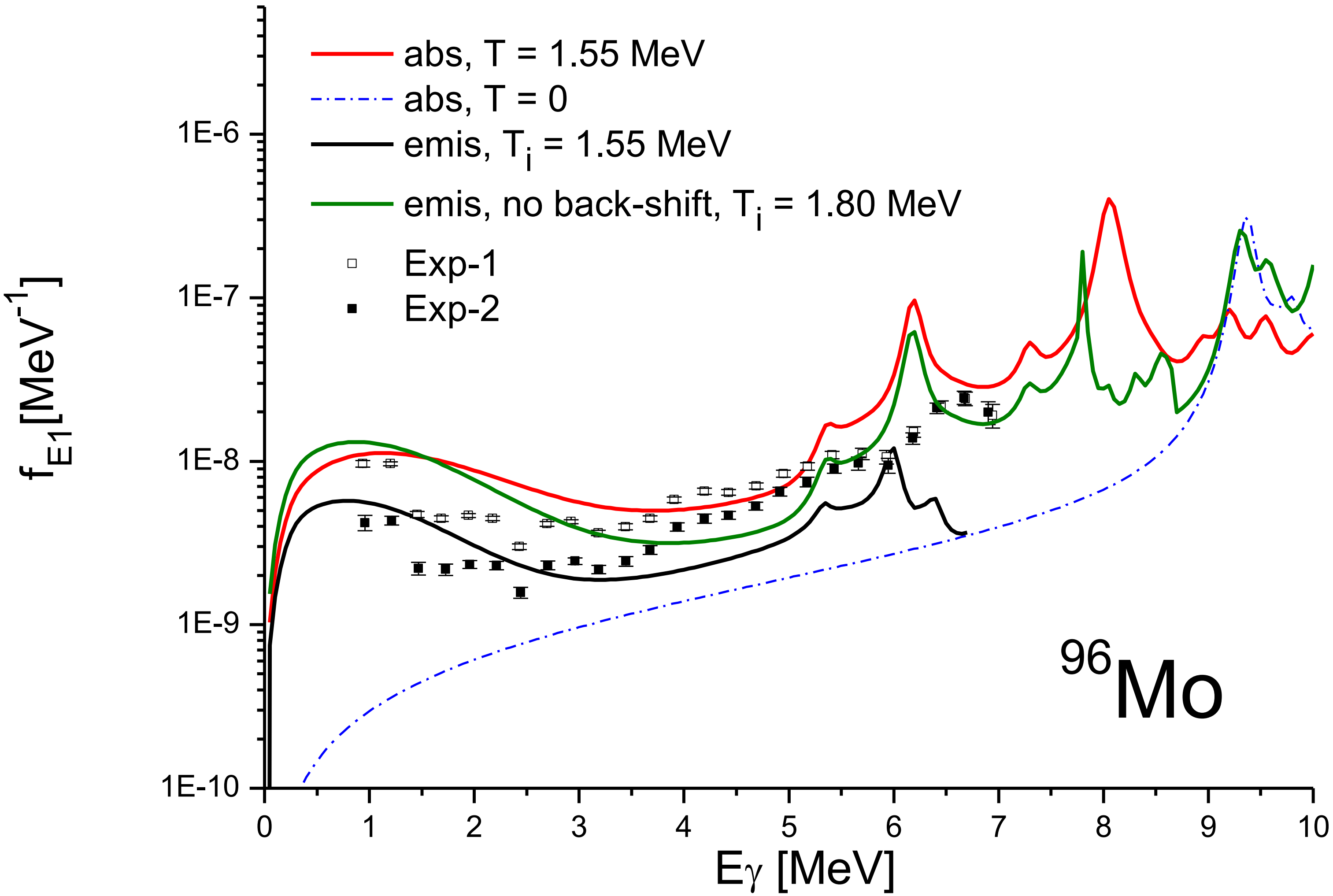
- More correct for γ-emission:
  „final temperature",
  V. Plujko, NPA649, 209c (1999)

$$T_f = \sqrt{(E^* - \delta - E_\gamma)/a}$$

Data: H.K. Toft et al., PRC 81, 064311 (2010),
PRC 83, 044320 (2011)

Absorption vs emission (preliminary)

$$T_f = \sqrt{(E^* - \delta - E_\gamma)/a}$$

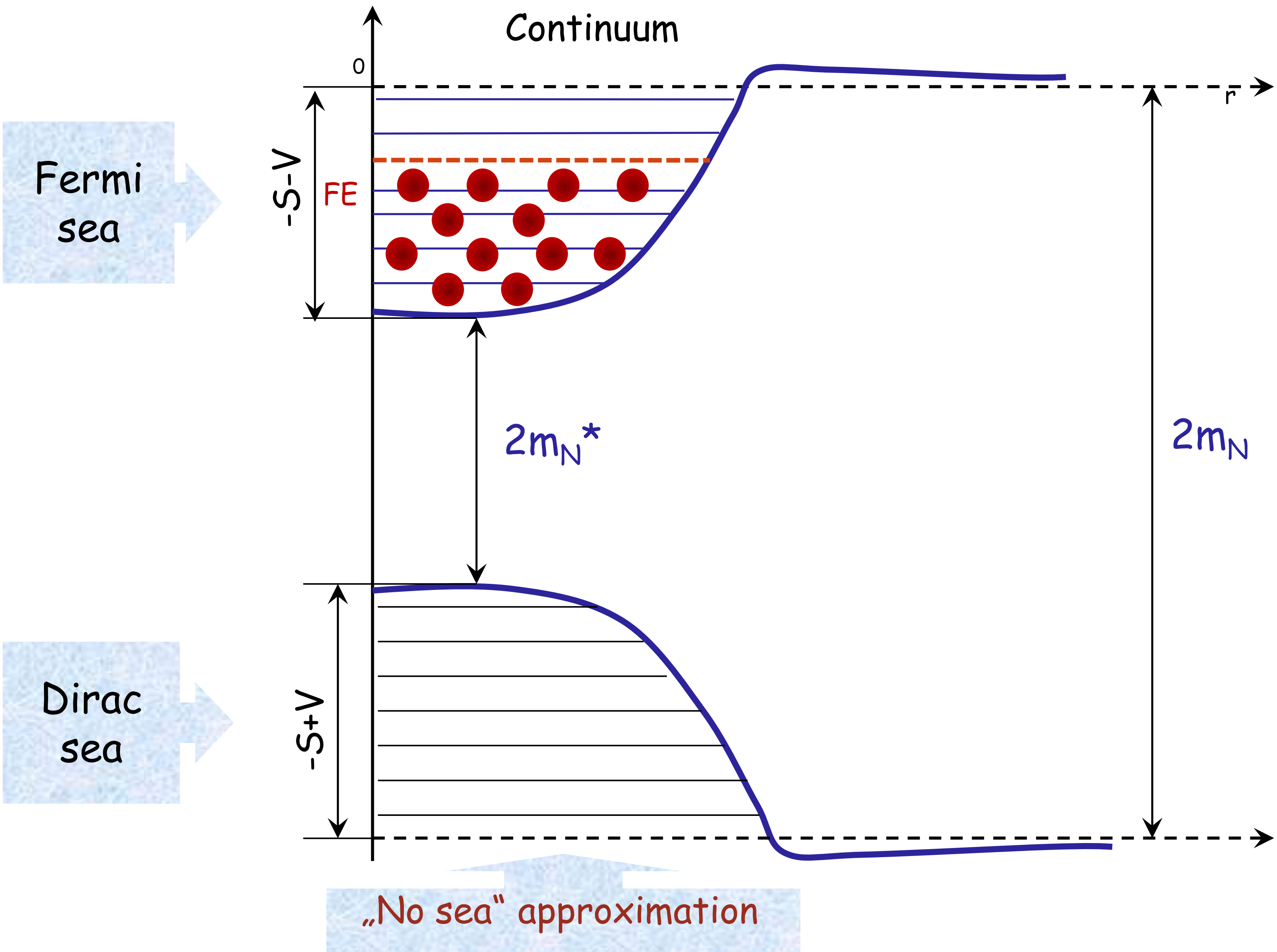


Many thanks for collaboration:

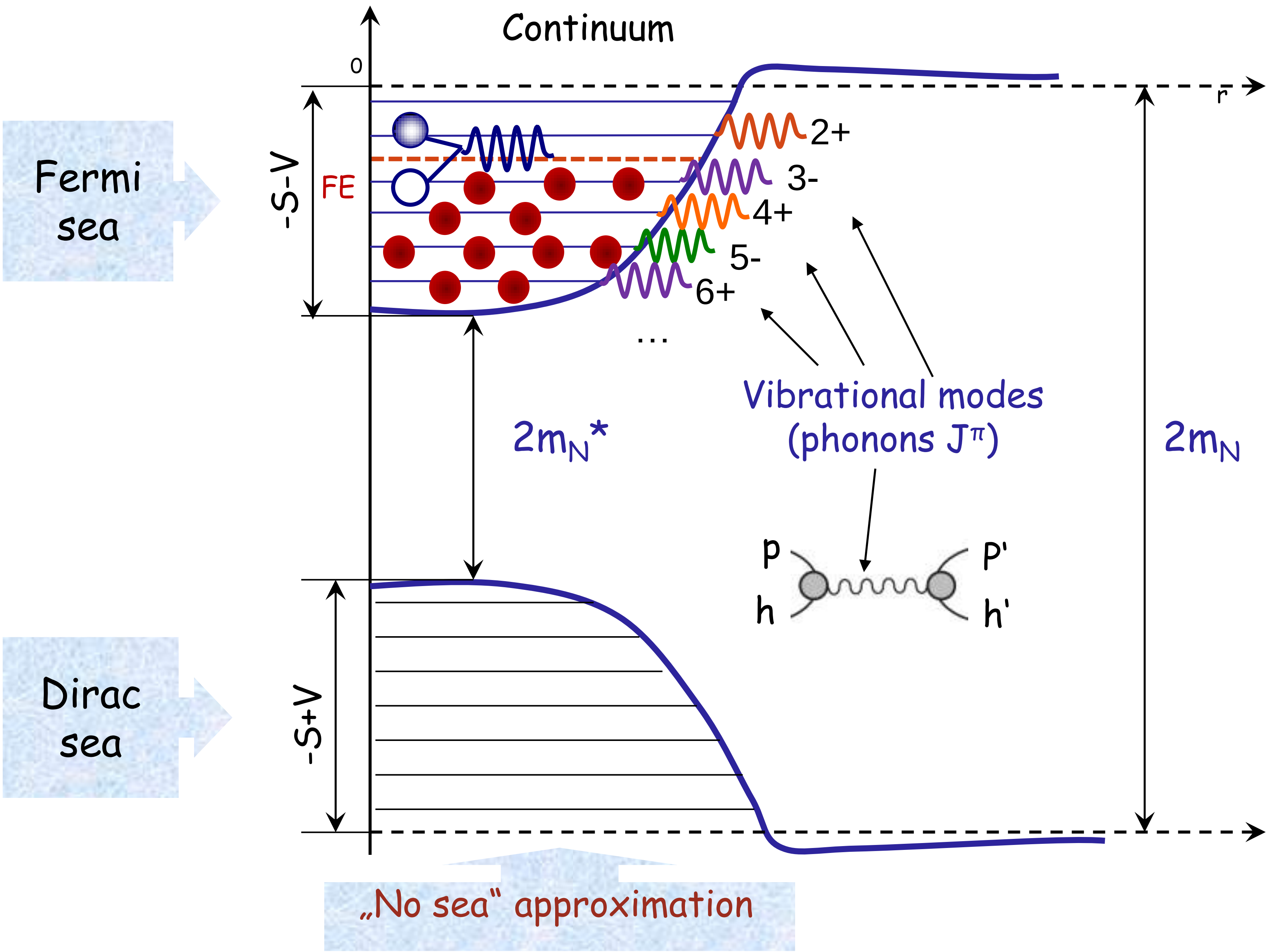
Peter Ring (Technische Universität München)
Victor Tselyaev (St. Petersburg State University)
Tomislav Marketin (TU-Darmstadt)

Anatoli Afanasjev (Mississippi State University)
Nikolay Belov (Heidelberg)
Thomas Aumann (TU-Darmstadt)
Janis Endres (University of Köln)
Hans Feldmeier (GSI)
Hans Peter Loens (GSI)
Karlheinz Langanke (GSI)
Gabriel Martínez-Pinedo (GSI)
Thomas Rauscher (University of Basel)
Deniz Savran (EMMI, Darmstadt)
Friedrich-Karl Thielemann (University of Basel)

Static description as zero approximation: Relativistic Mean Field (RMF)

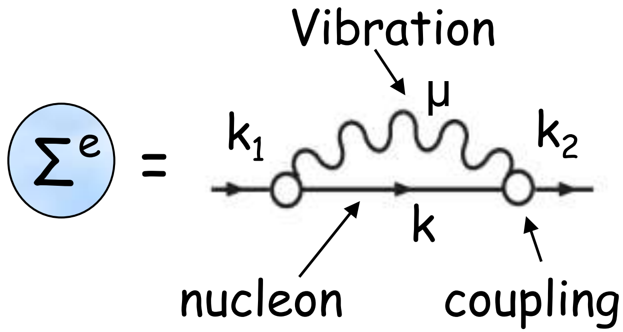


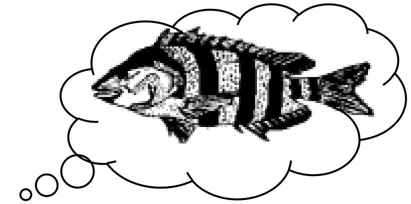
Oscillations of the mean nuclear potential



First step beyond relativistic mean field: quasiparticles coupled to vibrations

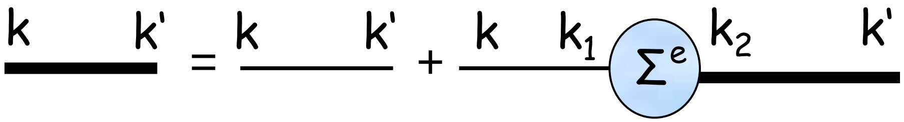
Additional "potential"
= "self-energy" =
= "mass operator"
with energy dependence





"Fish" diagram

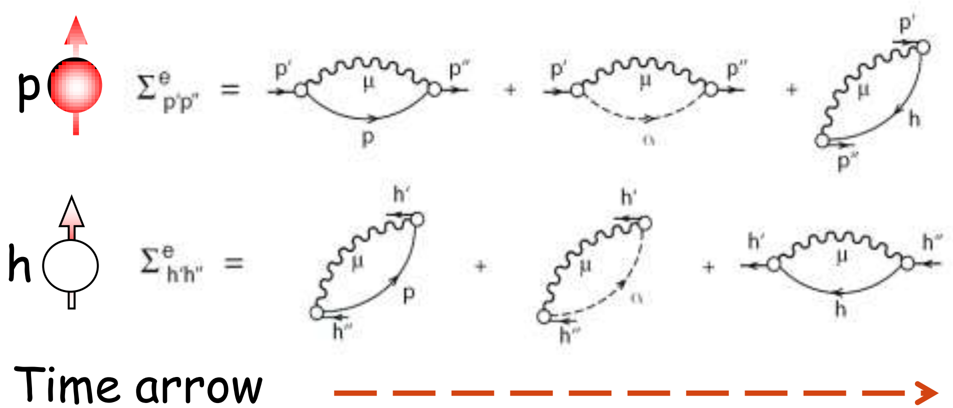
One-body propagator G: Dyson equation



G = G0 + G0 Σ^e G

$$\left(\varepsilon - \mathcal{H}_{RHB} - \Sigma^{(e)}(\varepsilon)\right)G(\varepsilon) = 1$$

Energy dependence



Doubled quasiparticle space:

$$\eta = \pm 1$$

$$\Sigma^{(e)\eta_1\eta_2}_{k_1k_2}(\varepsilon) = \sum_{\eta=\pm1}\sum_{k,\mu}\frac{\gamma^{\eta;\eta_1\eta}_{\mu;k_1k}\,\gamma^{\eta;\eta_2\eta*}_{\mu;k_2k}}{\varepsilon - \eta(E_k + \Omega_\mu - i\delta)}$$

Single-quasiparticle Green's function

Doubled quasiparticle space: $\eta = \pm 1$

$$G_k^{\eta}(\varepsilon) = \sum_{\nu,\eta'} \frac{\tilde{S}_k^{\eta'(\nu)}}{\varepsilon - \eta\eta' E_k^{(\nu)}}$$

Spectroscopic factors

Energies

One-body Green's function in N-body system (Lehmann):

$$G(\xi,\xi';\varepsilon) = \sum_n \frac{(\Psi(\xi))_{0n}(\Psi^\dagger(\xi'))_{n0}}{\varepsilon - (E_n^{(N+1)} - E_0^{(N)}) + i\delta} + \sum_m \frac{(\Psi^\dagger(\xi'))_{0m}(\Psi(\xi))_{m0}}{\varepsilon + (E_m^{(N-1)} - E_0^{(N)}) - i\delta},$$

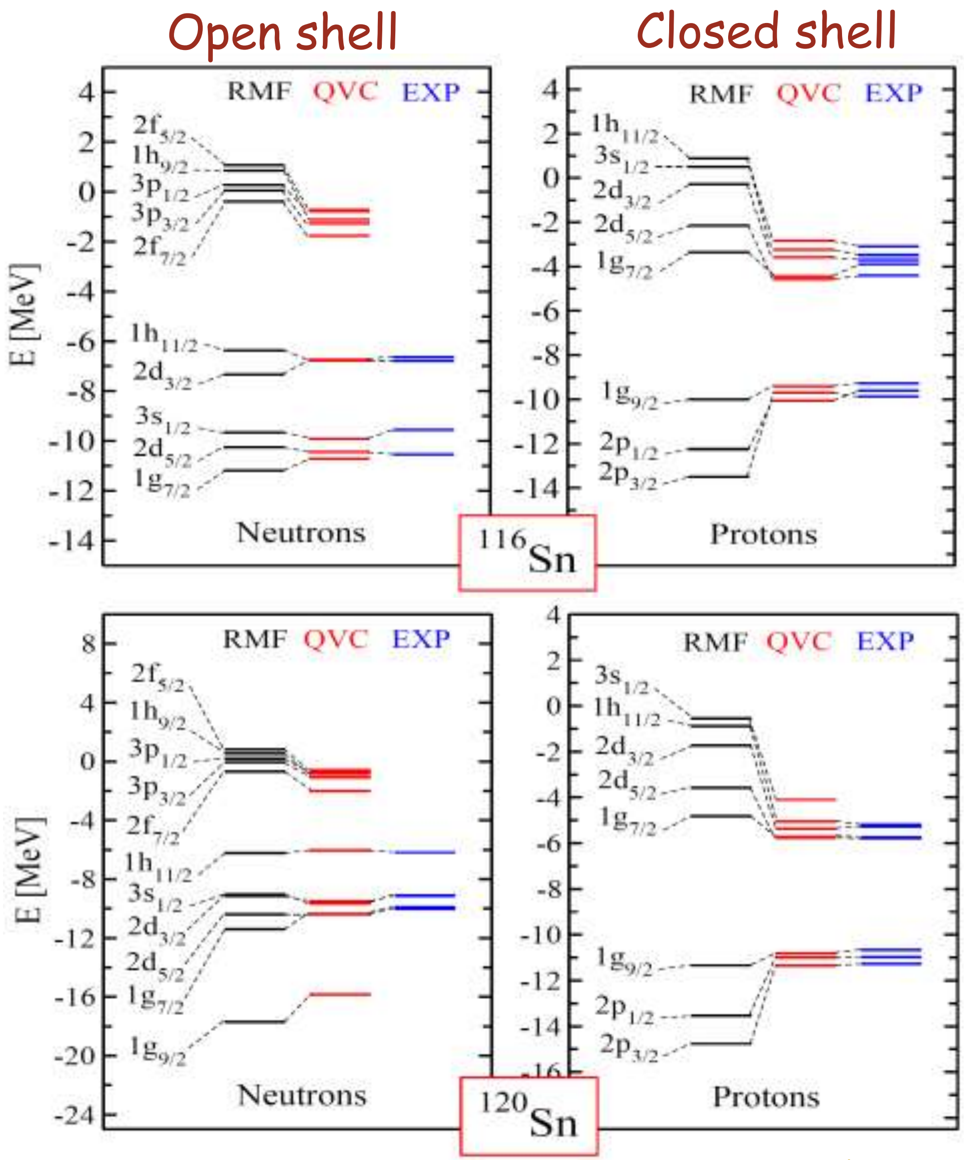
Model dependence of S!

Excited state (N+1)

$$(\Psi^\dagger(\xi))_{n0} = \langle \Phi_n^{(N+1)} | \Psi^\dagger(\xi) | \Phi_0^{(N)} \rangle,$$
$$(\Psi(\xi))_{n0} = \langle \Phi_n^{(N-1)} | \Psi(\xi) | \Phi_0^{(N)} \rangle,$$

Ground state (N)

Quasiparticle-vibration coupling:
Pairing correlations of the superfluid type + coupling to phonons



E.L., PRC 85, 021303(R)(2012)

Spectroscopic factors in ^{119,121}Sn:

(nlj) ν	S^{th}	S^{exp}
$2d_{5/2}$	0.32	0.43
$1g_{7/2}$	0.40	0.60
$2d_{3/2}$	0.53	0.45
$3s_{1/2}$	0.43	0.32
$1h_{11/2}$	0.58	0.49
$2f_{7/2}$	0.31	0.35
$3p_{3/2}$	0.58	0.54

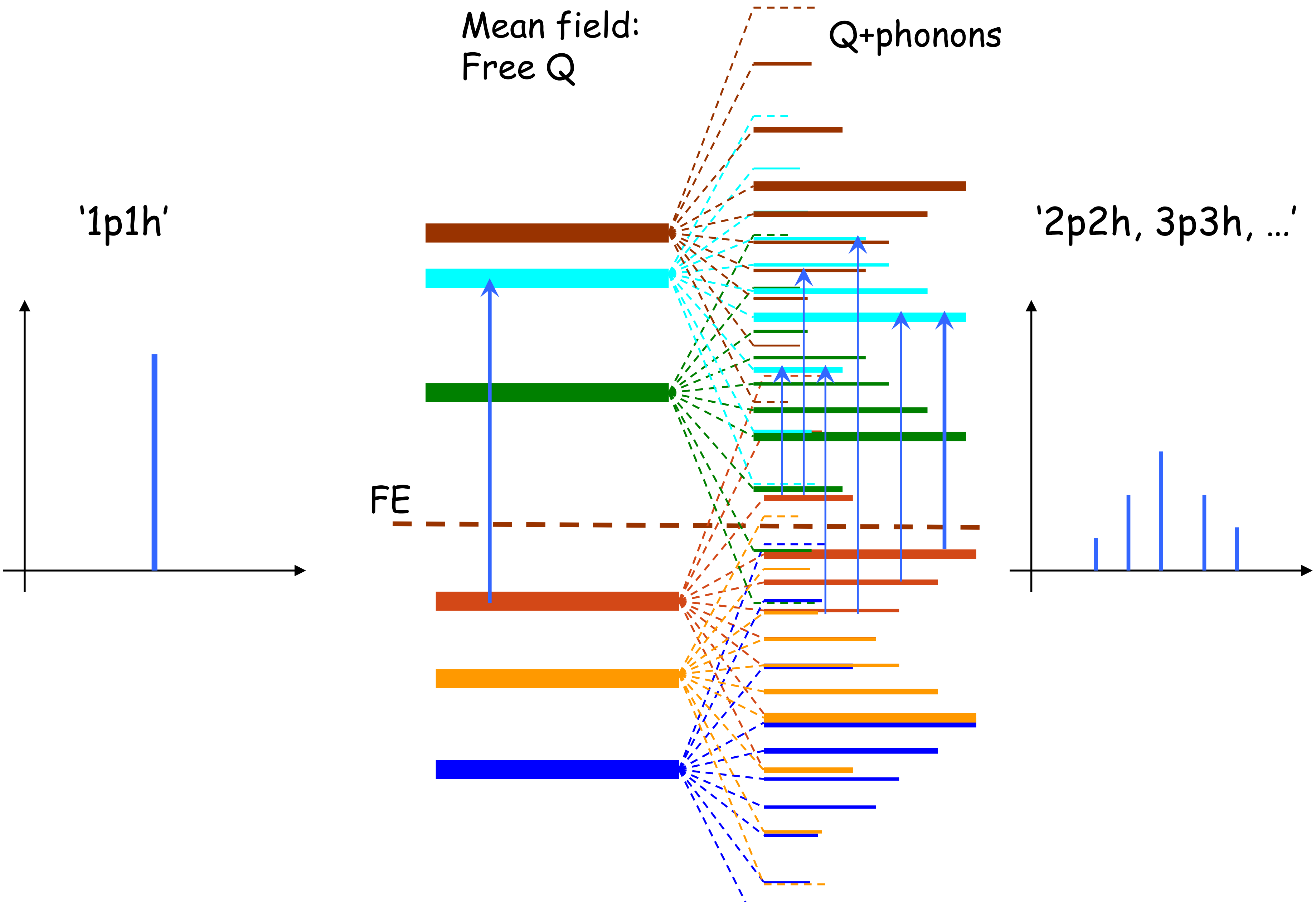
Spectroscopic factors in ^{133}Sn:

(nlj) ν	S^{th} *	S^{exp} **
$2f_{7/2}$	0.89	0.86±0.16
$3p_{3/2}$	0.91	0.92±0.18
$1h_{9/2}$	0.88	
$3p_{1/2}$	0.91	1.1±0.3
$2f_{5/2}$	0.89	1.1±0.2

*E. L., A.V. Afanasjev, PRC 84, 014305 (2011)

**K.L. Jones et al., Nature 465, 454 (2010)

Transitions: fragmentation mechanism (schematic)



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

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

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

RMF self-energy

Eigenstates

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

Response to an external field: strength function

Nuclear Polarizability:

$$\Pi_{PP}(\omega) = P^{\dagger}R(\omega)P := \sum_{k_1k_2k_3k_4} P^*_{k_1k_2}R_{k_1k_4,k_2k_3}(\omega)P_{k_3k_4}$$

External field

Strength function:

$$S(E) = -\frac{1}{\pi}\lim_{\Delta\to+0} Im\,\Pi_{PP}(E+i\Delta)$$

Transition density:

$$\rho^{\nu}_{k_1k_2} = \langle 0|\psi^{\dagger}_{k_2}\psi_{k_1}|\nu\rangle$$

Response function:

$$R^{\nu}_{k_1k_4,k_2k_3}(\omega) \approx \frac{\rho^{\nu}_{k_1k_2}\rho^{\nu*}_{k_3k_4}}{\omega-\Omega^{\nu}} \qquad \omega \longrightarrow \Omega^{\nu}$$

Algebraic equation for the response function

$$R^{\eta\eta'}_{k_1k_4,k_2k_3}(\omega) = \tilde{R}^{(0)\eta}_{k_1k_2}(\omega)\delta_{k_1k_3}\delta_{k_2k_4}\delta_{\eta\eta'} + \tilde{R}^{(0)\eta}_{k_1k_2}(\omega)\sum_{k_5k_6k_7k_8}\sum_{\eta''}\bar{W}^{\eta\eta''}_{k_5k_8,k_6k_7}(\omega)R^{\eta''\eta'}_{k_7k_4,k_8k_3}(\omega)$$

Mean field propagator

Subtraction to avoid double counting

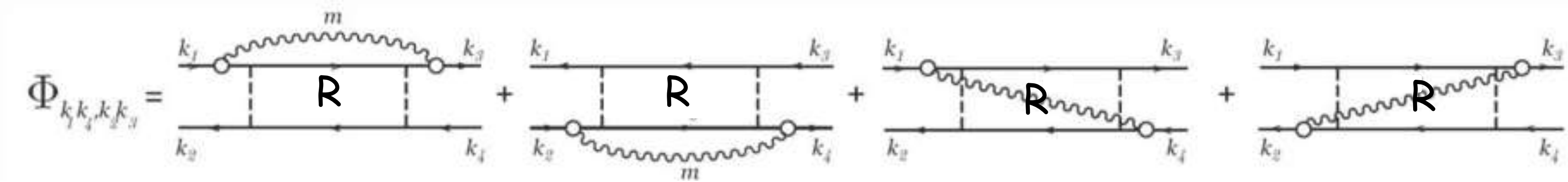
$$\bar{W}^{\eta\eta'}_{k_1k_4,k_2k_3}(\omega) = \tilde{V}^{\eta\eta'}_{k_1k_4,k_2k_3} + \Big(\Phi^{\eta}_{k_1k_4,k_2k_3}(\omega) - \Phi^{\eta}_{k_1k_4,k_2k_3}(0)\Big)\delta_{\eta\eta'}$$

2q-phonon coupling amplitude

$$\Phi^{\eta}_{k_1k_4,k_2k_3}(\omega) = \sum_{\mu,\xi}\delta_{\xi\eta}\Big[\delta_{k_1k_3}\sum_{k_6}\frac{\gamma^{-\xi*}_{\mu;k_2k_6}\gamma^{-\xi}_{\mu;k_4k_6}}{\eta\omega - E_{k_1} - E_{k_6} - \Omega^{\mu}} + \delta_{k_2k_4}\sum_{k_5}\frac{\gamma^{\xi}_{\mu;k_1k_5}\gamma^{\xi*}_{\mu;k_3k_5}}{\eta\omega - E_{k_5} - E_{k_2} - \Omega^{\mu}} - \Big(\frac{\gamma^{\xi}_{\mu;k_1k_3}\gamma^{-\xi}_{\mu;k_4k_2}}{\eta\omega - E_{k_3} - E_{k_2} - \Omega^{\mu}} + \frac{\gamma^{\xi*}_{\mu;k_3k_1}\gamma^{-\xi*}_{\mu;k_2k_4}}{\eta\omega - E_{k_1} - E_{k_4} - \Omega^{\mu}}\Big)\Big],$$

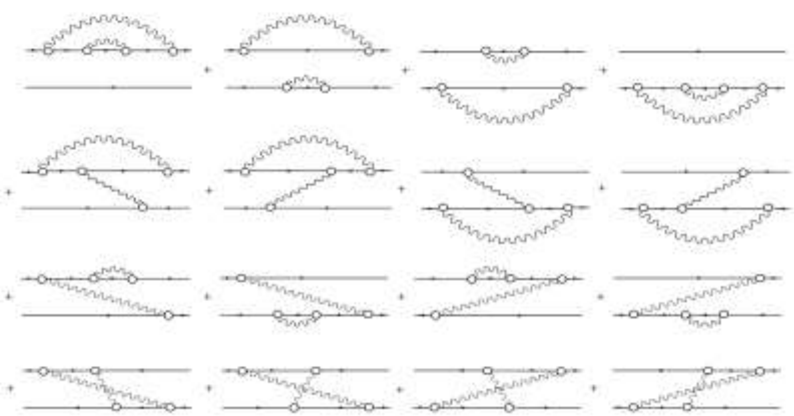
Next-order RQTBA for 3p-3h configurations & iterative procedure for multiphonon response

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



Nested configurations

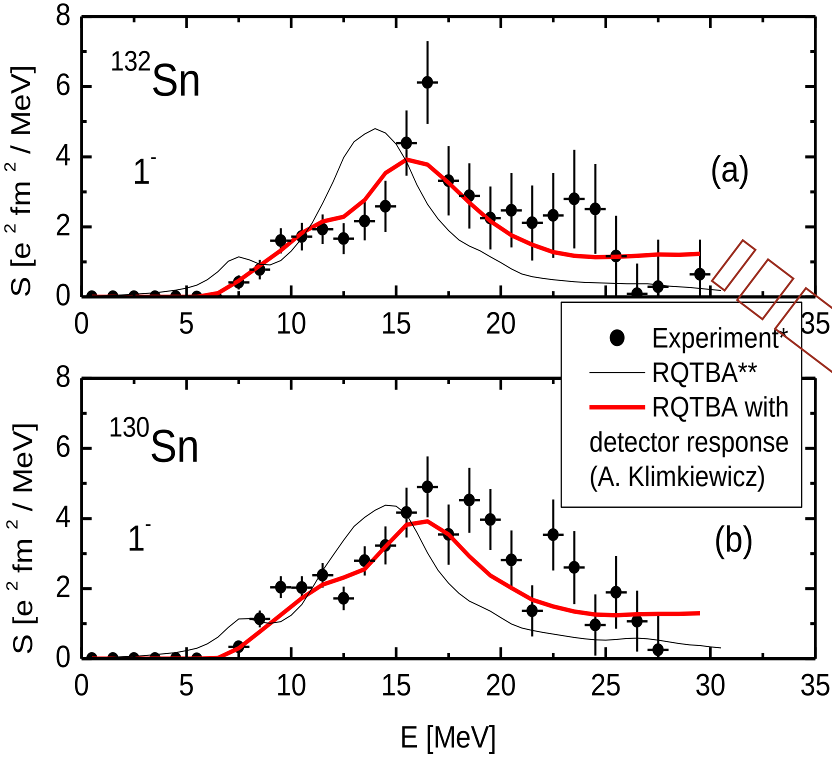
γ^4 terms in Φ-amplitude:

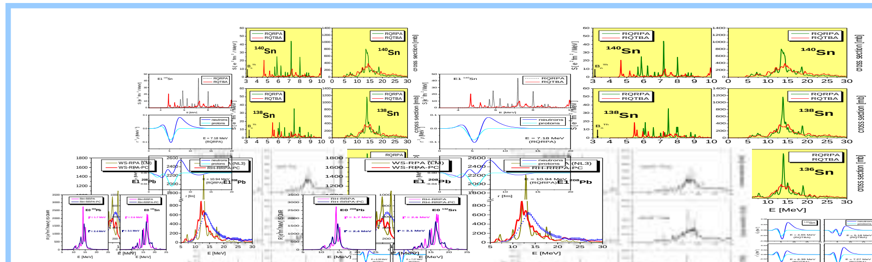


3p3h: two-fish approximation, …

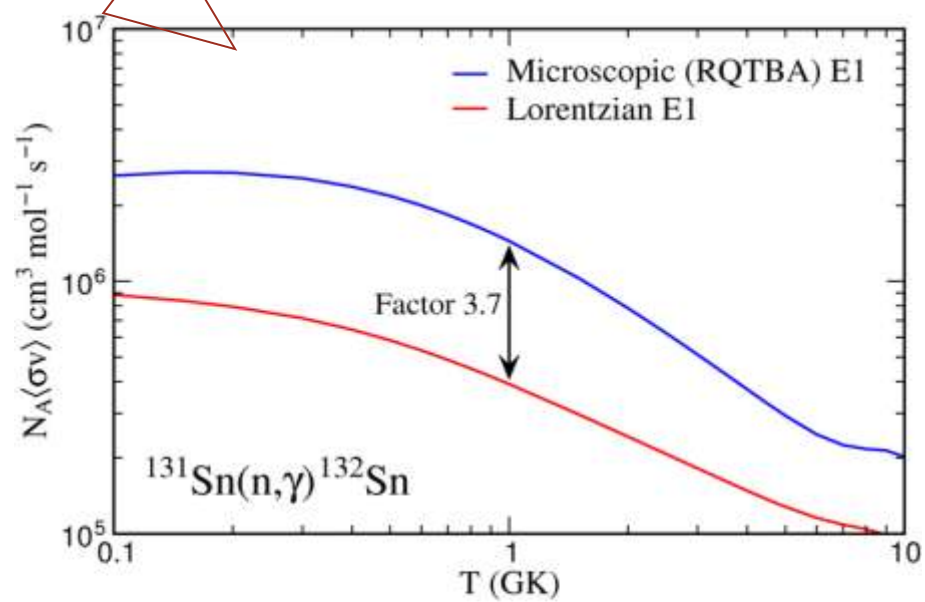
Dipole strength in neutron-rich nuclei: importance for astrophysics

Neutron-rich Sn





Input for astrophysics:
cross sections, reaction rates etc. under astrophysical conditions

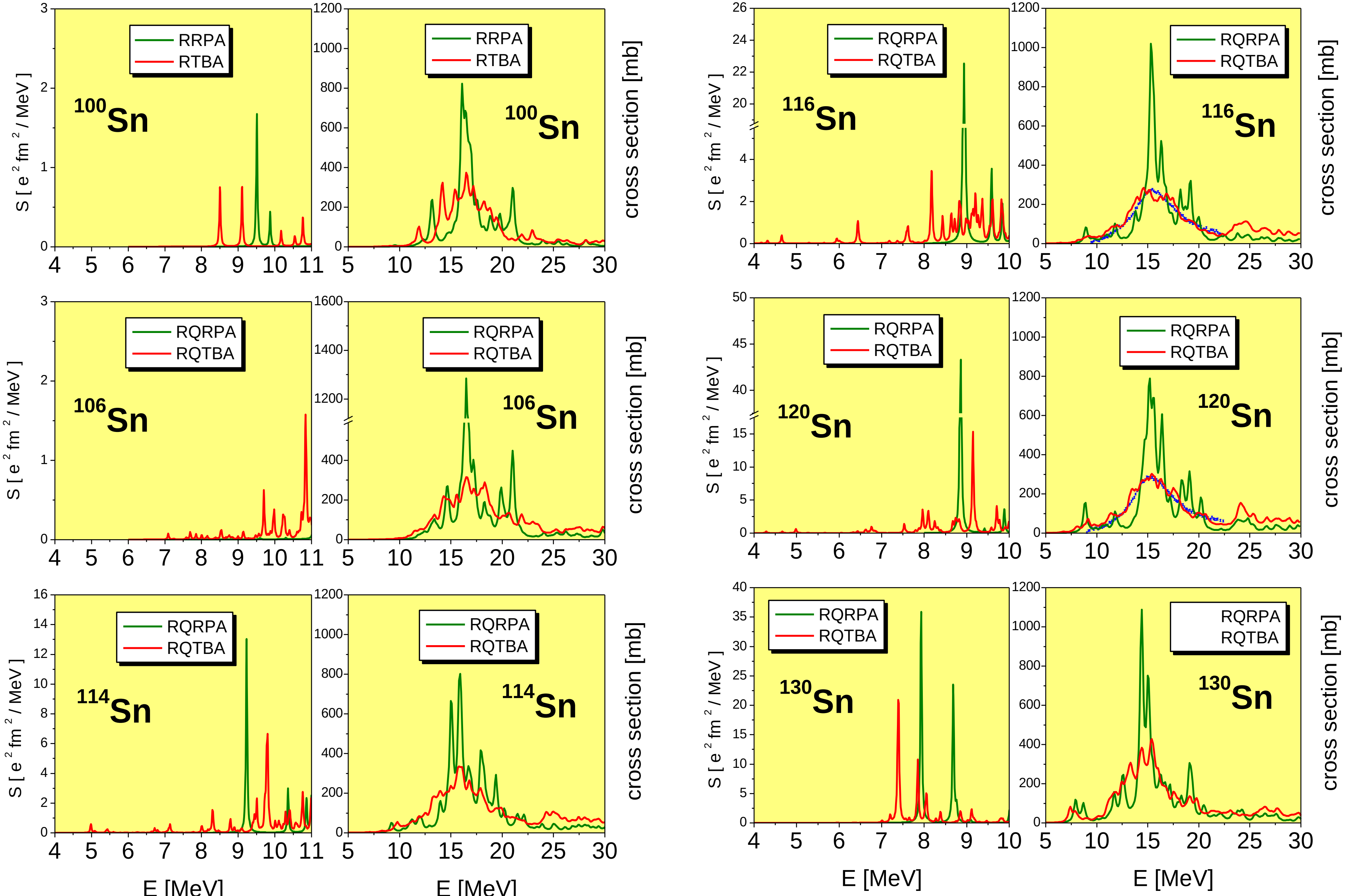


*P. Adrich, et al., PRL 95, 132501 (2005)

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

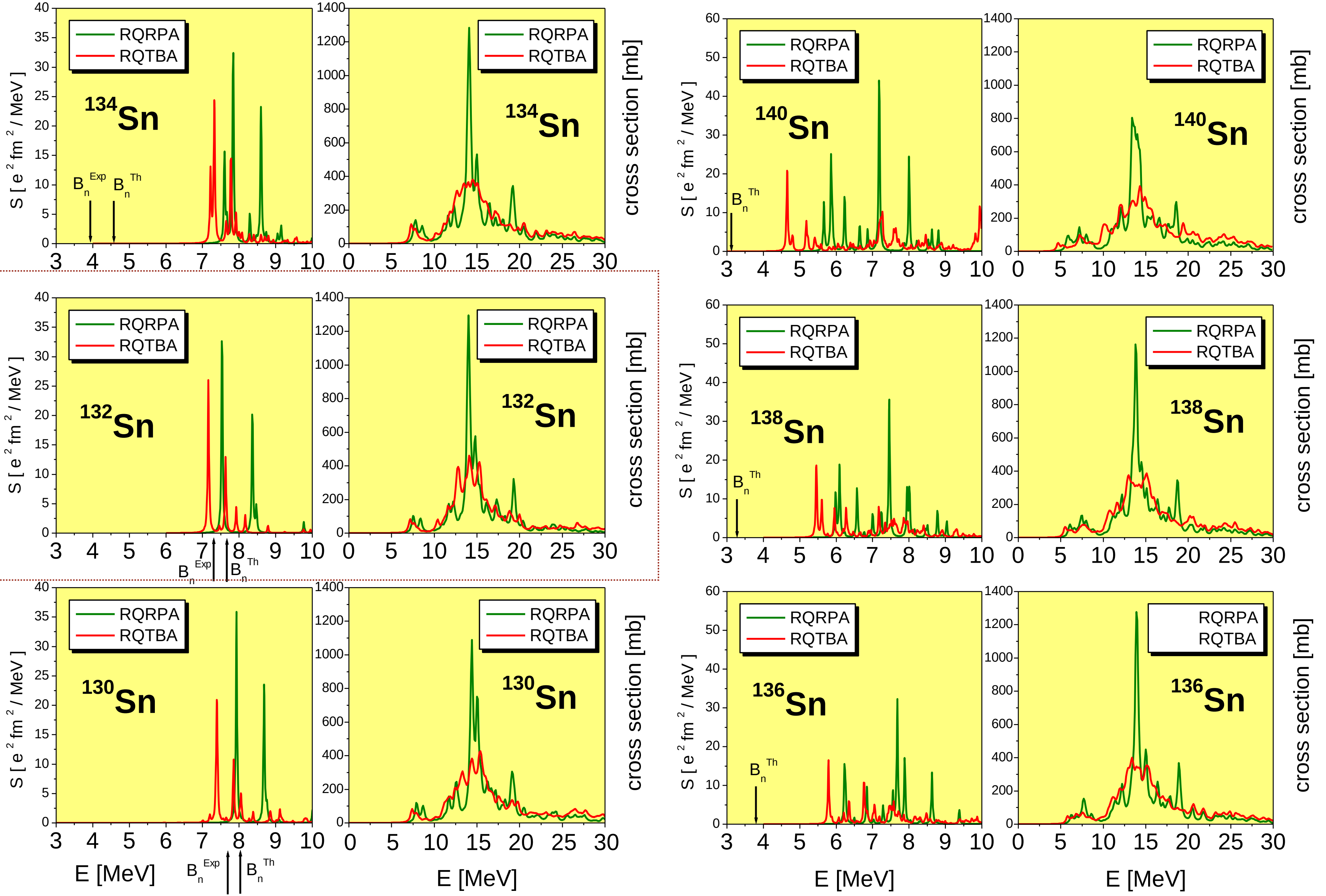
Dipole strength in Sn isotopes

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

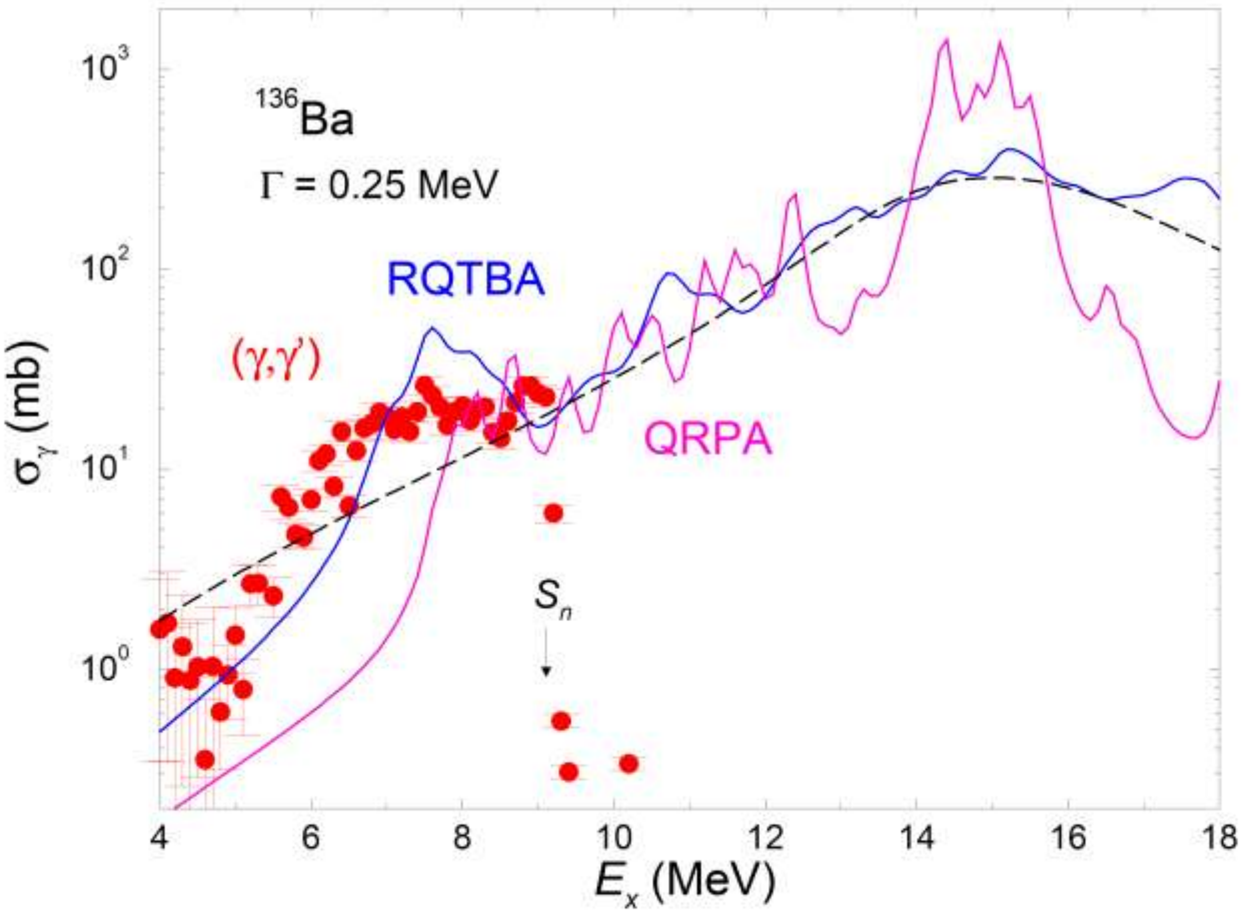


Dipole strength in Sn isotopes

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



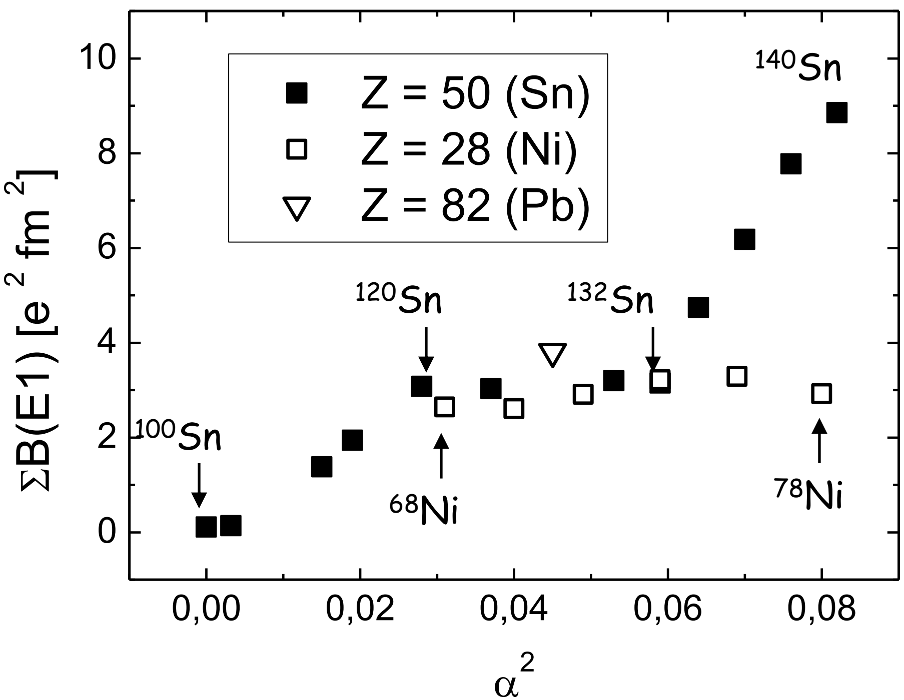
Low-lying dipole strength in 136-Ba



R. Massarczyk, R. Schwengner, F. Doenau, E. Litvinova, G. Rusev et al., Phys. Rev. C 86, 014319 (2012)

RQTBA systematics for PDR:

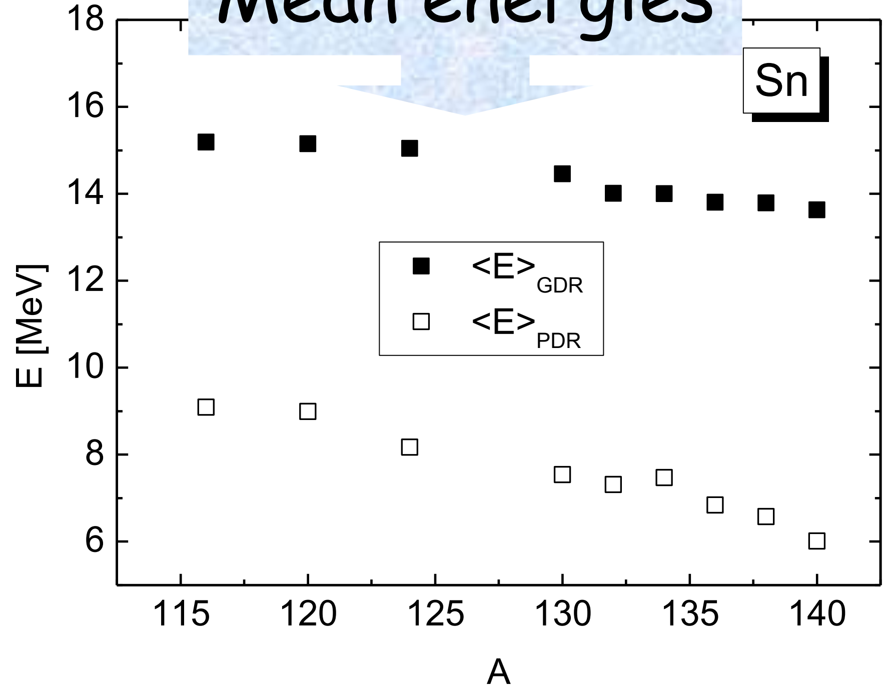
A proper definition of Pygmy Dipole Resonance is important!
PDR = all states with the "isoscalar" underlying structure!



Strength vs α^2

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

Mean energies



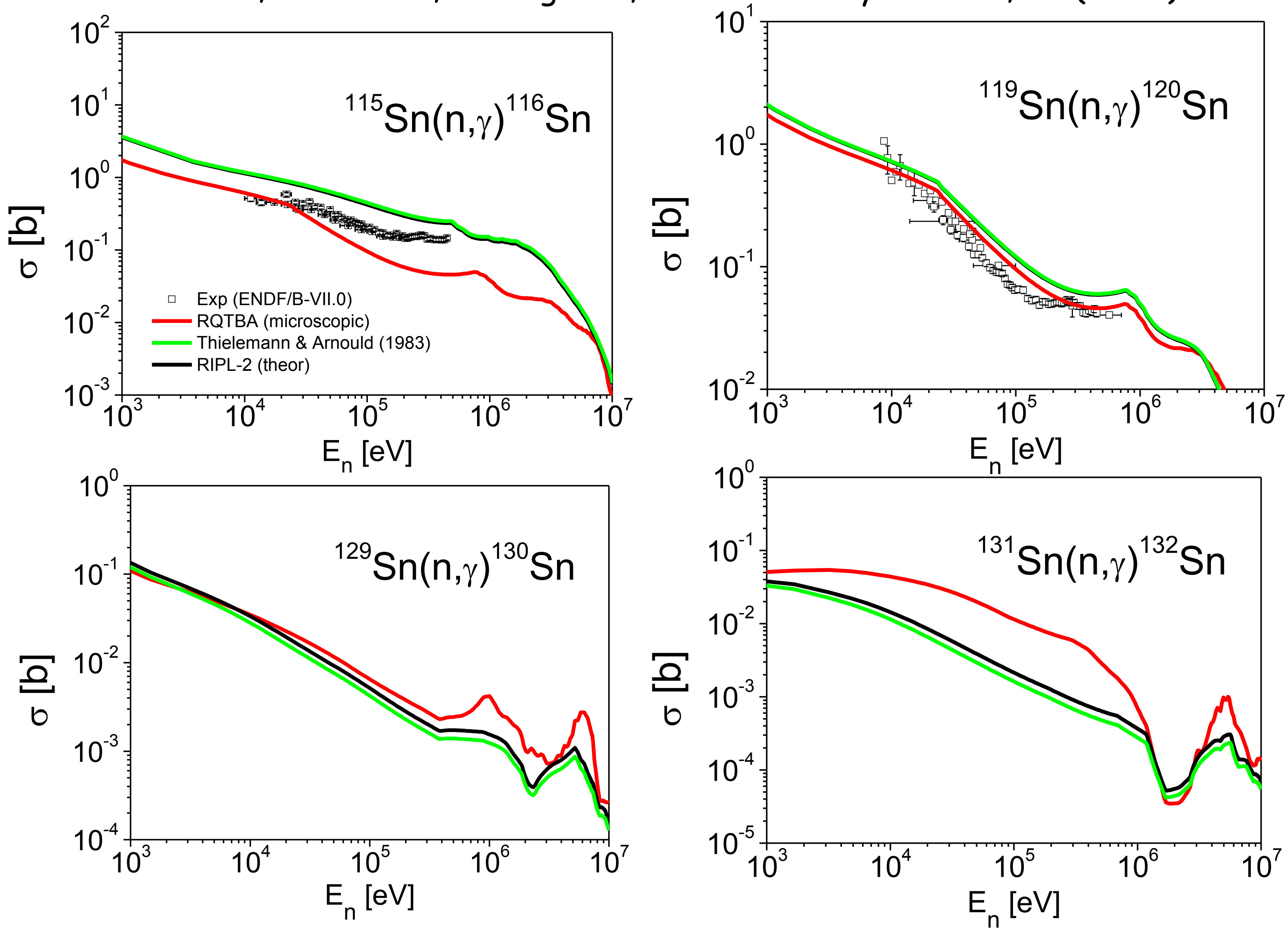
$^{120}Sn \rightarrow {}^{132}Sn$: 1h11/2 (n)
$^{68}Ni \rightarrow {}^{78}Ni$: 1g9/2 (n)

Intruder orbits !

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

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

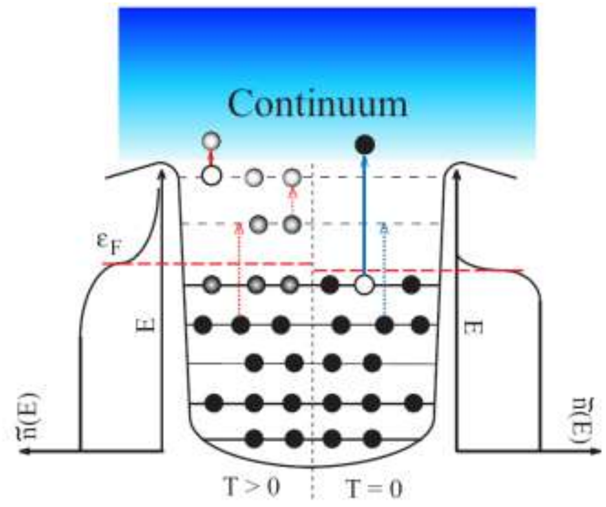
E. L., H.P. Loens, K. Langanke, et al. Nucl. Phys. A 823, 26 (2009).

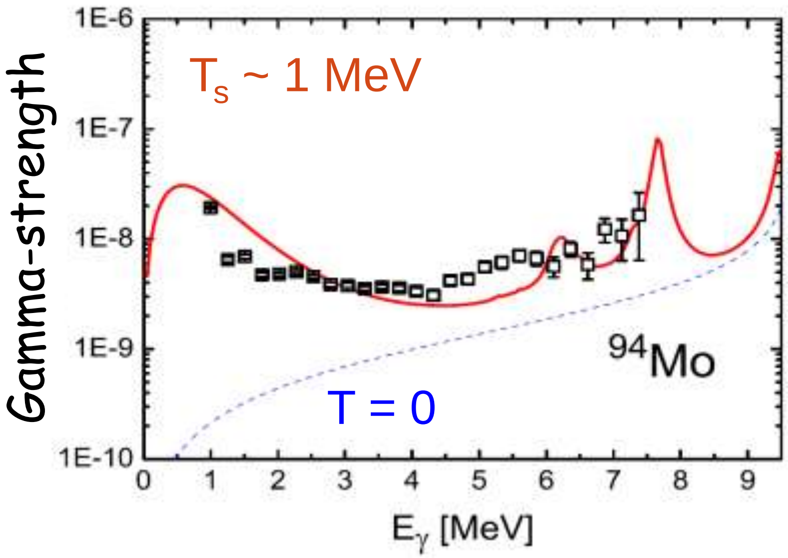


$$
\begin{aligned}
\mathcal{A}^{(\tau)L}_{LS,LS'}(r_1, r_2; \omega; T) = {} & \mathcal{A}^{\mathrm{cont}(\tau)L}_{LS,LS'}(r_1, r_2; \omega; T) \\
& + \mathcal{A}^{\mathrm{disc}(\tau)L}_{LS,LS'}(r_1, r_2; \omega; T),
\end{aligned}
$$

Nuclei are heated in astrophysical environment!

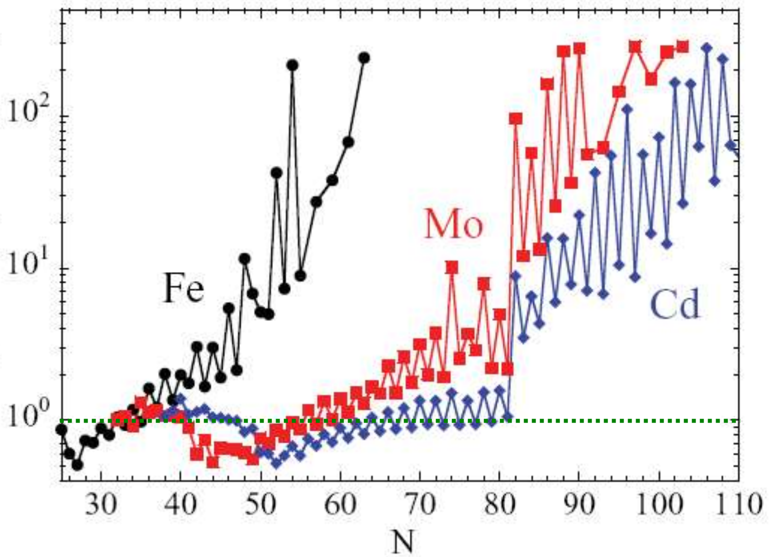
New correlations: transitions to continuum from thermally unblocked states:





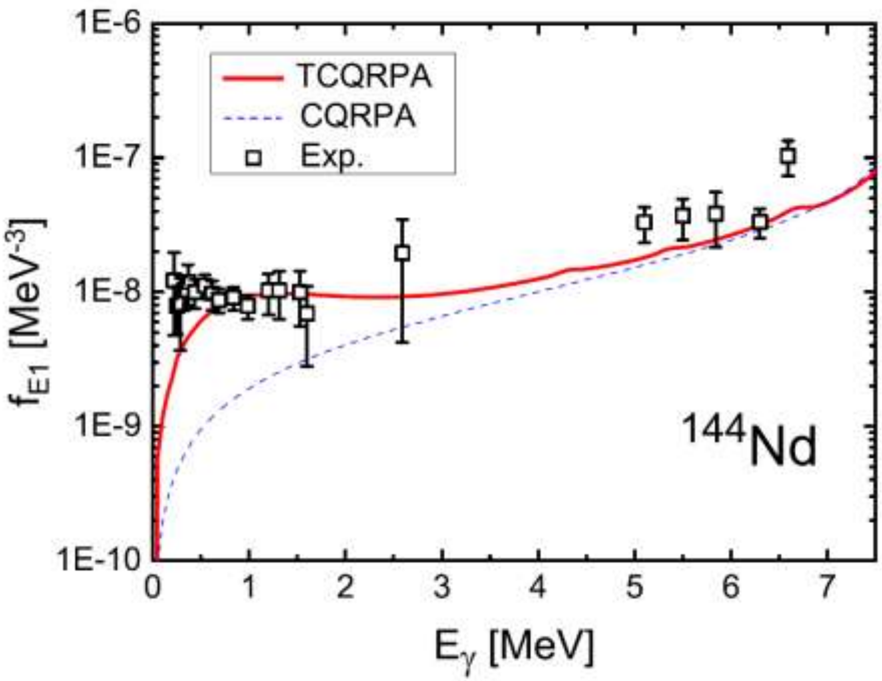
E. Litvinova, N. Belov, arXiv: 1302.4478

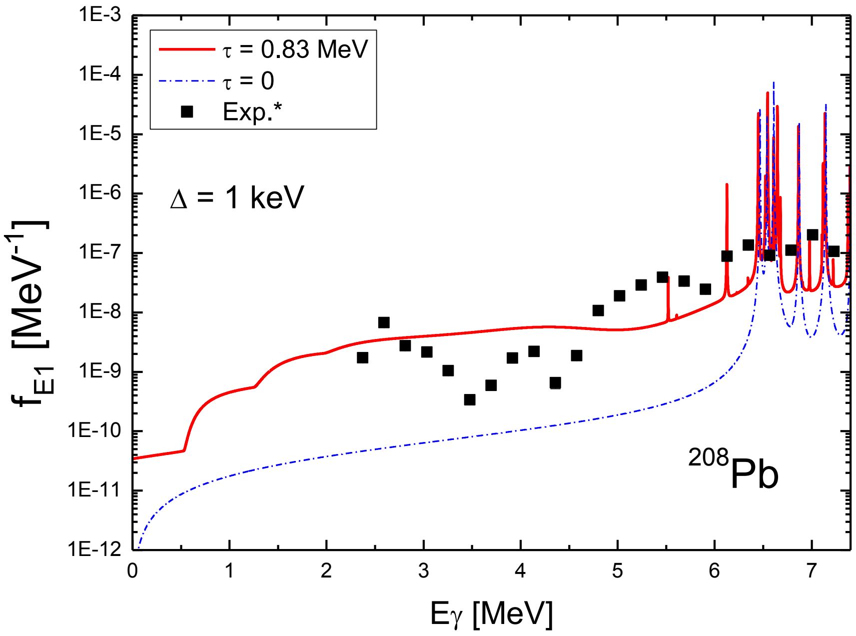
$$\frac{(n,\gamma) \text{ reaction rate } (T=Ts)}{(n,\gamma) \text{ reaction rate } (T=0)} = \eta$$



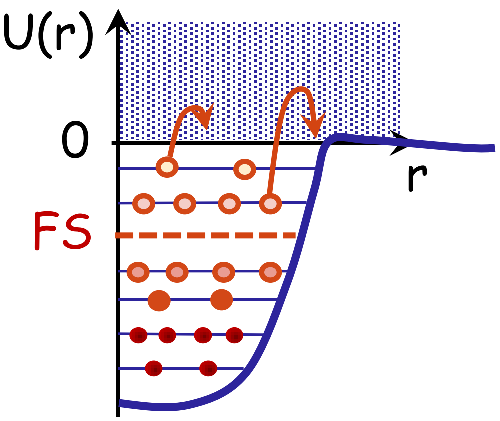
A.C. Larsen, S. Goriely, PRC 014318 (2010)

Dipole gamma-strength function (preliminary)

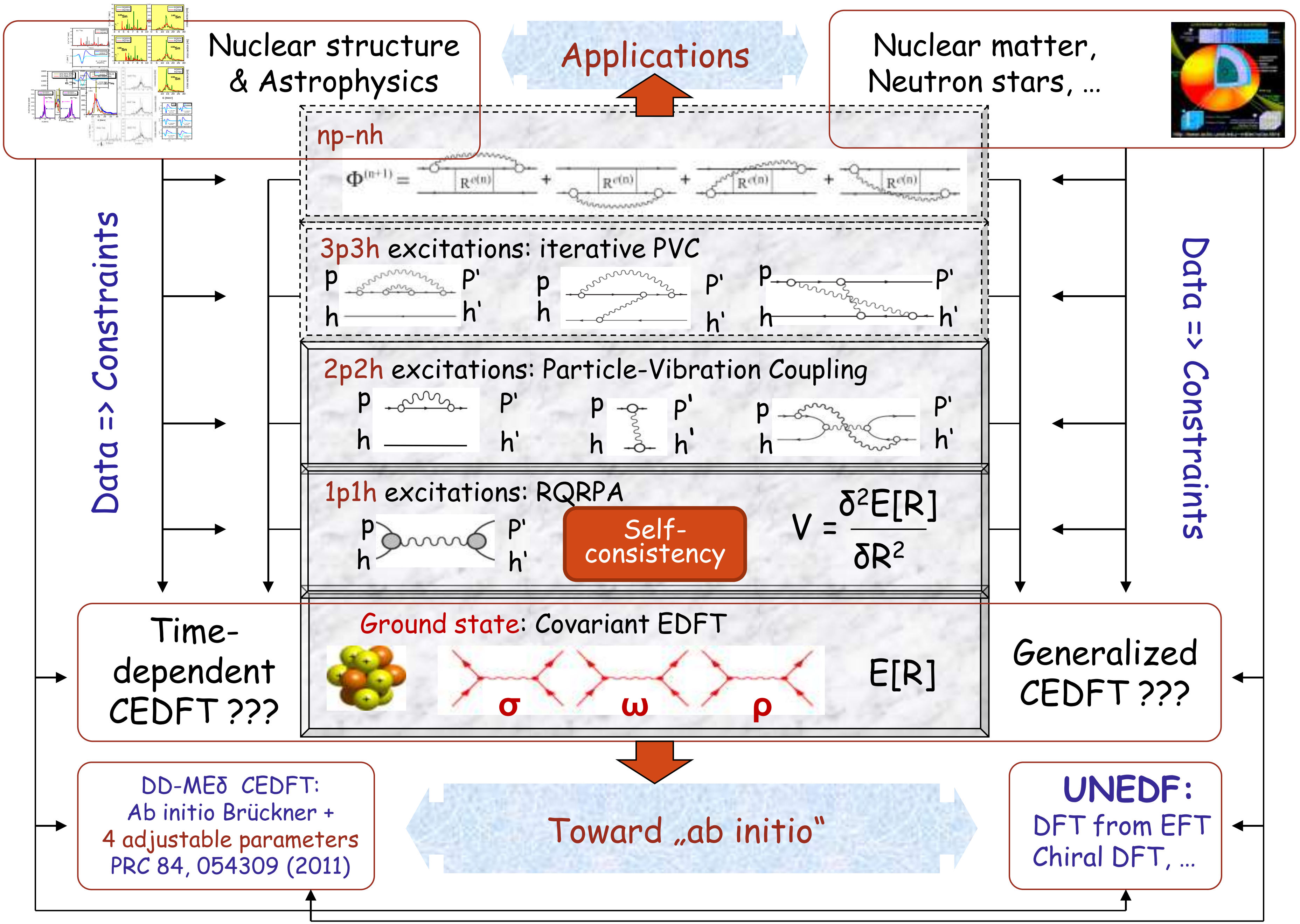




- Consequences for (n,γ) reaction rates - ?
- For electric dipole polarizability (EDP) - ???
- For EDP – neutron skin correlation - ??



Outlook



Nuclear structure & Astrophysics
Applications
Nuclear matter, Neutron stars, ...
np-nh
3p3h excitations: iterative PVC
2p2h excitations: Particle-Vibration Coupling
1p1h excitations: RQRPA
Self-consistency
$V = \frac{\delta^2 E[R]}{\delta R^2}$
Ground state: Covariant EDFT
σ
ω
ρ
E[R]
Data => Constraints
Data => Constraints
Time-dependent CEDFT ???
Generalized CEDFT ???
DD-MEδ CEDFT:
Ab initio Brückner +
4 adjustable parameters
PRC 84, 054309 (2011)
Toward „ab initio"
UNEDF:
DFT from EFT
Chiral DFT, ...