Nuclear response at finite temperature

Elena Litvinova

Western Michigan University

MICHIGAN STATE UNIVERSITY

In collaboration with C. Robin, P. Schuck, and H. Wibowo

Tsukuba-CCS workshop on "microscopic theories of nuclear structure and dynamics" December 10-12, 2018

Introduction

- *Motivation: to build a consistent and predictive approach to describe the entire nuclear chart (ideally, an arbitrary strongly-correlated many-body system), numerically executable and useful for applications (Not only astrophysics :)*

- *Challenges: the nuclear hierarchy problem, complexity of NN-interaction.*

- *Accurate non-perturbative solutions: Relativistic Nuclear Field Theory (RNFT). Emerged as a synthesis of Landau-Migdal Fermi-liquid theory, Copenhagen-Milano NFT and Quantum Hadrodynamics (QHD); now put in the context of a systematic equation of motion (EOM) formalism and linked to ab-initio interactions.*

- ***n-body correlation functions:** complete characteristics of strongly-coupled many-body systems. Define all dynamical and geometrical properties of nuclear and condensed matter systems, in quantum chemistry, quantum gravity & dualities.*

- *Nuclear 2-body correlation functions = observable nuclear response to major neutral and charge-exchange probes: giant EM resonances, Gamow-Teller, spin dipole etc. (neutron capture, gamma and beta decays, pair transfer, …).*

- *Nuclear response at finite temperature: thermal RNFT for transitions between nuclear excited states.*

- *Conclusions and perspectives.*

Equation of motion (EOM) for particle-hole response

Many-body Hamiltonian:
$$H = \sum_{12} t_{12}\psi^\dagger{}_1\psi_2 + \frac{1}{4}\sum_{1234}\bar{v}_{1234}\psi^\dagger{}_1\psi^\dagger{}_2\psi_4\psi_3$$
(or relativistic)

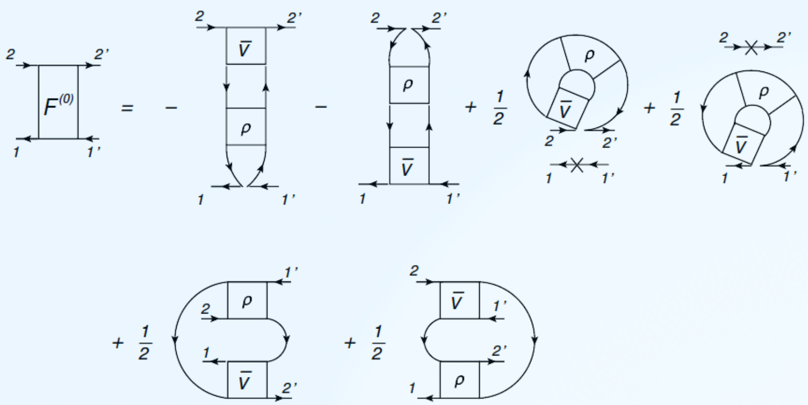
Particle-hole response (correlation function):
$$R^{(ph)}_{12,1'2'}(t-t') = -i\langle T(\psi_1^\dagger\psi_2)(t)(\psi_{2'}^\dagger\psi_{1'})(t')\rangle$$
spectra of excitations, masses, decays, …

EOM:
$$R(\omega) = R^{(0)}(\omega) + R^{(0)}(\omega)F(\omega)R(\omega) \qquad (*) \qquad F(t-t') = F^{(0)}\delta(t-t') + F^{(r)}(t-t')$$

Free propagator

Irreducible kernel:

instantaneous term ("bosonic" mean field):

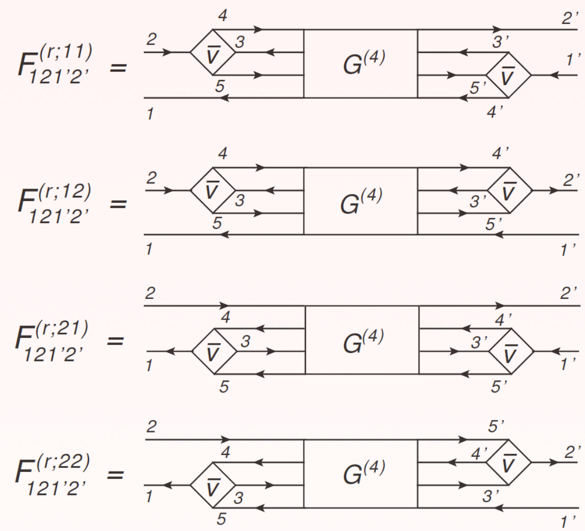


Mean field $F^{(0)}$, where $\rho_{12,1'2'} = \lim_{t\to t'-0} R(12,1'2')$

*contains the full solution of (*) **including the dynamical term!***

t-dependent (dynamical) term:

$$F^{(r)}_{12,1'2'}(t-t') = F^{(r;11)}_{12,1'2'}(t-t') + F^{(r;12)}_{12,1'2'}(t-t') + F^{(r;21)}_{12,1'2'}(t-t') + F^{(r;22)}_{12,1'2'}(t-t')$$



EOM:

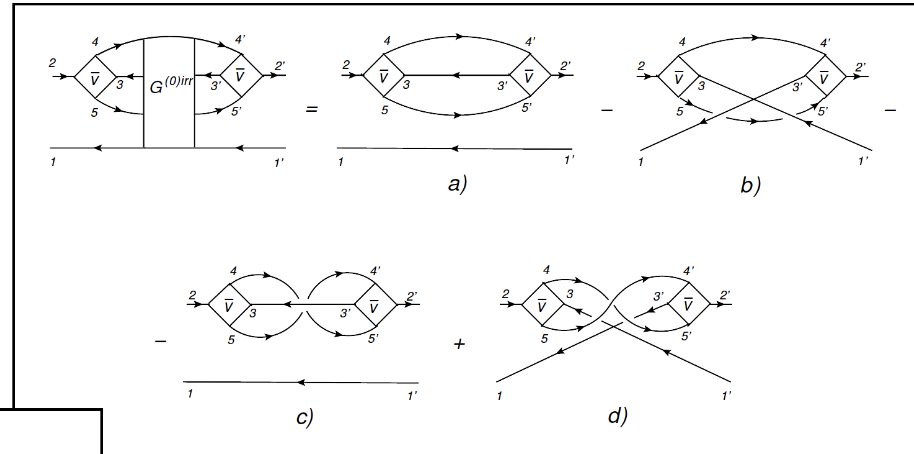
S. Adachi and P. Schuck, NPA496, 485 (1989).
J. Dukelsky, G. Roepke, and P. Schuck, NPA 625, 14 (1995).
P. Schuck and M. Tohyama, PRB 93, 165117 (2016). Etc.

Expansion of the dynamics kernel $F^{(r;12)irr}$: truncation on the 2-body level

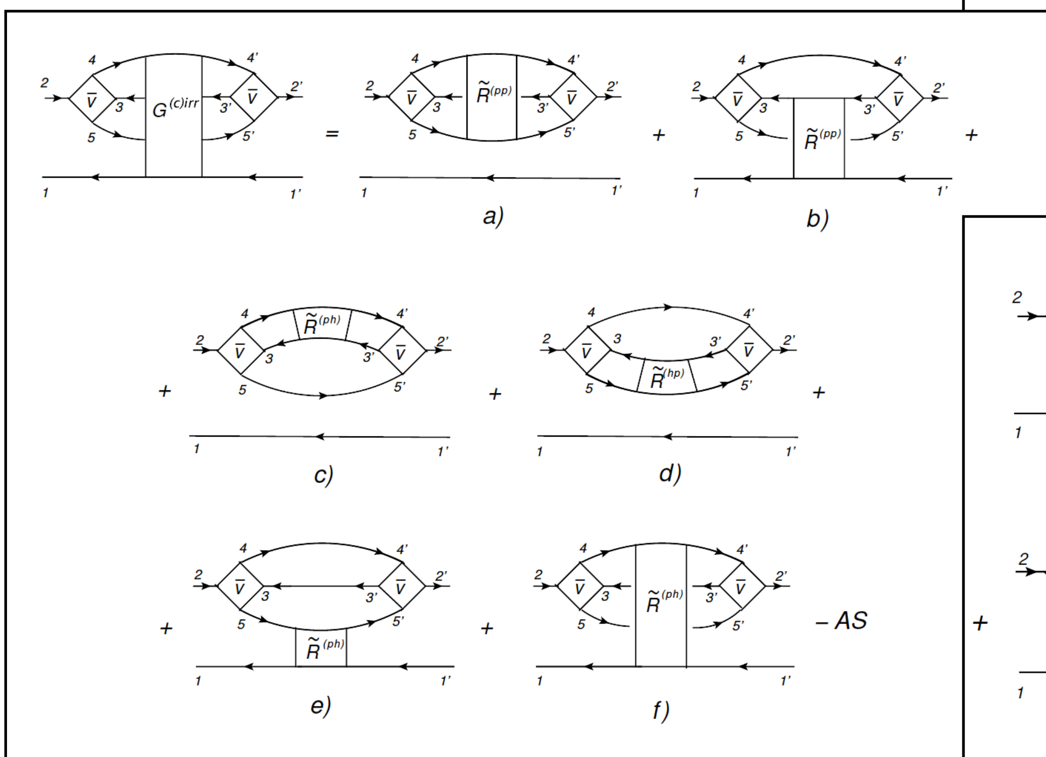
Irreducible part of $G^{(4)}$ is decomposed into uncorrelated, singly-correlated and doubly-correlated terms (approximation, but very accurate):

$$\boxed{G^{irr}(543'1',5'4'31) = G^{(0)irr}(543'1',5'4'31) + + G^{(c)irr}(543'1',5'4'31) + G^{(cc)irr}(543'1',5'4'31)}$$

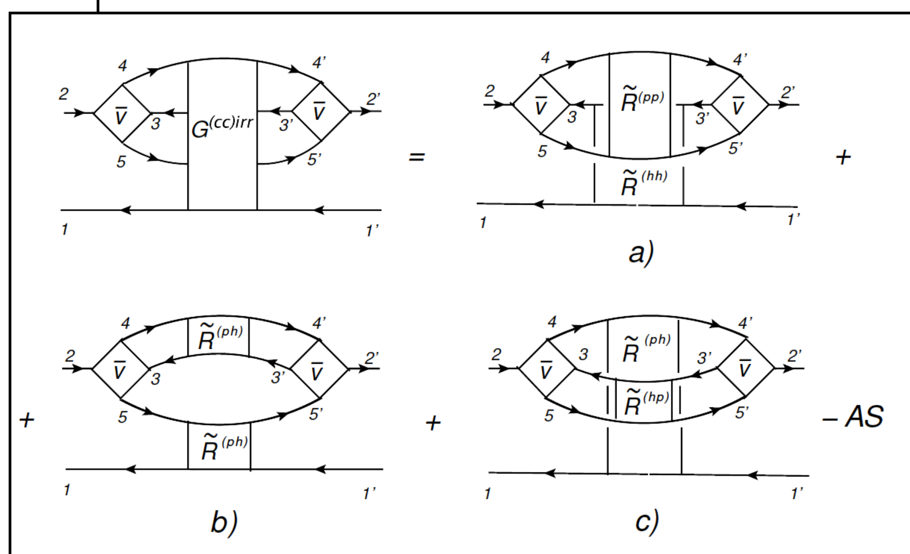
(i) Uncorrelated terms ("Second RPA"):



(ii) Singly-correlated terms, up to phases (PVC, QVC, …):



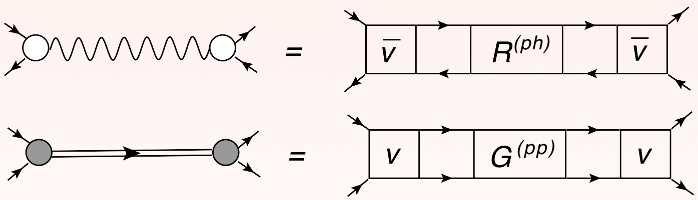
(iii) Doubly-correlated terms, up to phases (generalized QVC):



Mapping to the (Quasi)particle-Vibration Coupling (QVC, PVC)

Model-independent mapping to the QVC-TBA:

$$\sum_{343'4'} \tilde{V}^{*}_{12,34} R_{34,3'4'}(\omega) \tilde{V}_{3'4'1'2'} = \sum_{m} g^{m*}_{12} D_m(\omega) g^{m}_{1'2'}$$

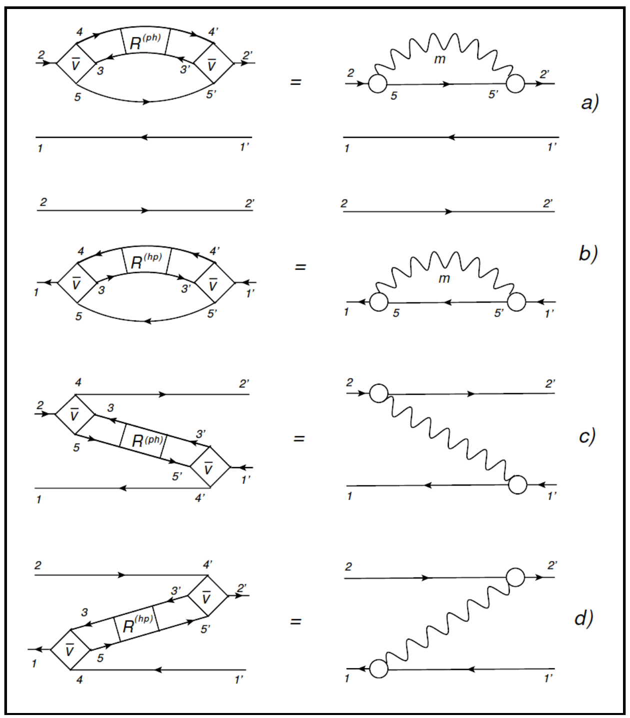


$$R_{12,1'2'}(\omega) = \sum_m \Big(\frac{\rho^{m*}_{12}\rho^{m}_{1'2'}}{\omega - \Omega_m + i\delta} - \frac{\rho^{m}_{21}\rho^{m*}_{2'1'}}{\omega + \Omega_m - i\delta} \Big)$$

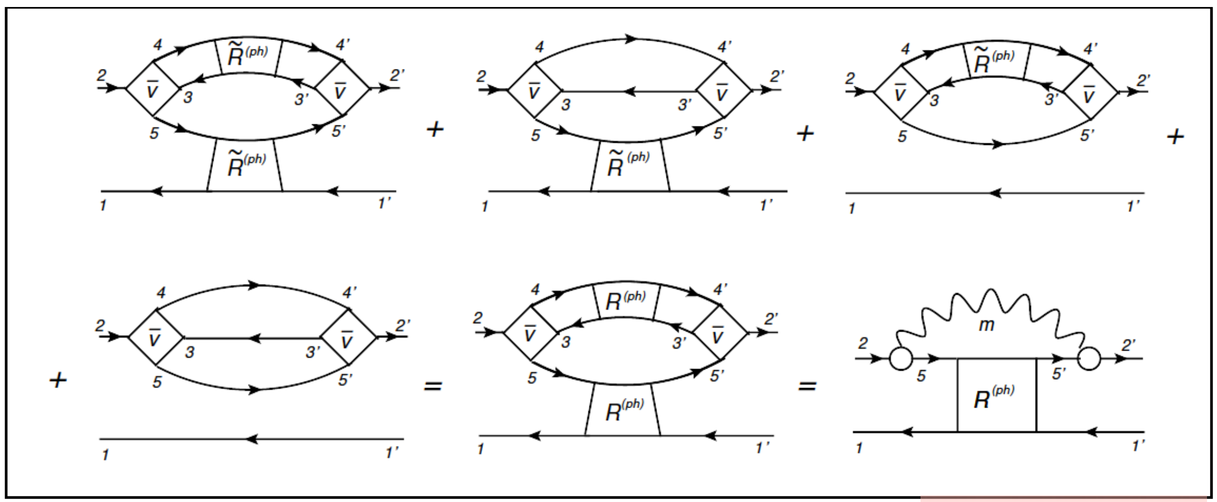
$$g^{m}_{12} = \sum_{34} \tilde{V}_{12,34}\rho^{m}_{34}$$ *"phonon" vertex*

$$D_m(\omega) = \frac{1}{\omega - \Omega_m + i\delta} - \frac{1}{\omega + \Omega_m - i\delta}$$ *"phonon" propagator*

Original QVC (NFT, R(Q)TBA): non-correlated and main singly-correlated terms:



Generalized R(Q)TBA (E.L. PRC91, 034332 (2015): meets EOM: ALL correlated terms



Self-consistent closed system of equations

$$\boxed{\hat{R}(\omega) = \hat{R}^{(0)}(\omega) + \hat{R}^{(0)}(\omega) W[\hat{R}(\omega)] \hat{R}(\omega)}$$

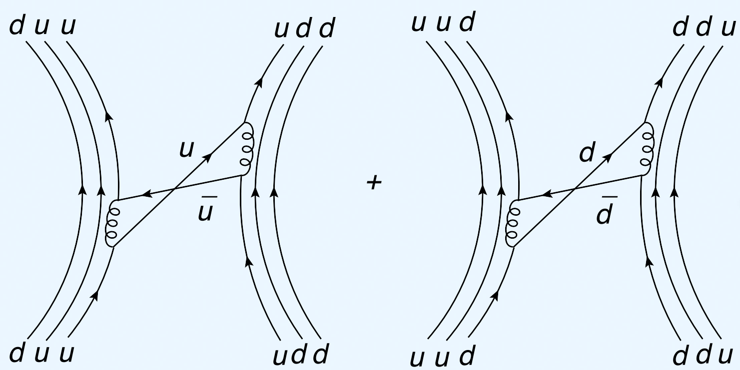
All channels are coupled in W[R(ω)]

E.L., P. Schuck, in progress

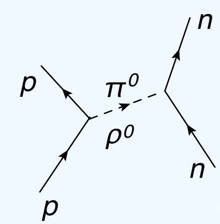
The underlying NN-interaction: meson exchange (ME)

Neutral mesons σ, ω, π, ρ…:

QCD



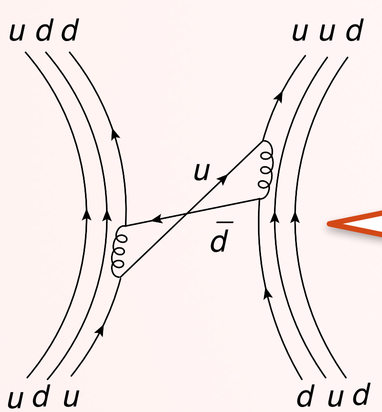
QHD



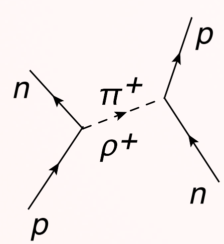
- *The full many-body scheme has not been (yet) executed neither for the bare meson-exchange (ME) interaction nor for any other bare interaction.*
- *A good starting point - the use of effective ME interactions adjusted to nuclear bulk properties on the mean-field level (J. Walecka, M. Serot, …, P. Ring) and to supplement the many-body correlation theory with proper subtraction techniques (V. Tselyaev), in the covariant framework.*

Charged mesons: π, ρ,…

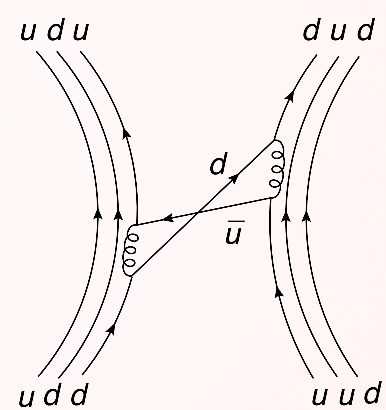
QCD



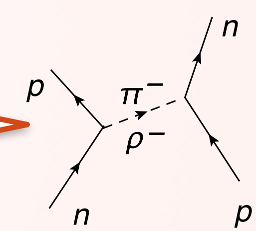
QHD



QCD

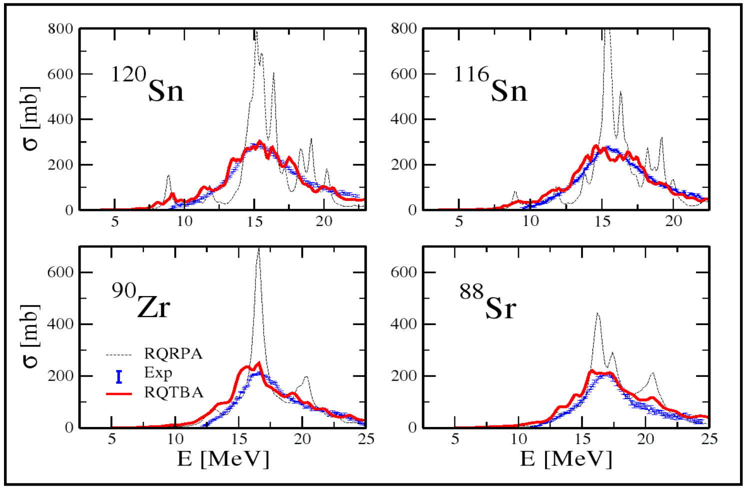


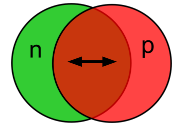
QHD



Response of medium-mass and heavy nuclei within Relativistic (Quasiparticle) Time Blocking Approximation (R(Q)TBA)

Giant dipole resonance (GDR) in stable nuclei



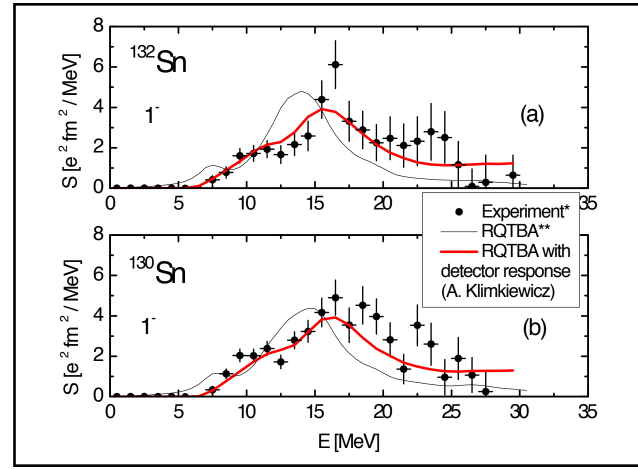


**E. L., P. Ring, and V. Tselyaev et al.,
Phys. Rev. C 78, 014312 (2008).
Phys. Rev. C 79, 054312 (2009).
Phys. Rev. Lett. 105, 022502 (2010).
Phys. Rev. C 88, 044320 (2013).

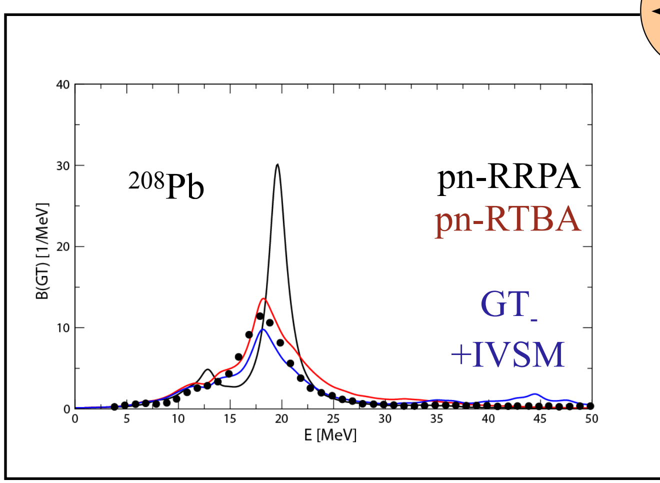
J. Endres, E. Litvinova, D. Savran et al., Phys. Rev. Lett. 105, 212503 (2010).

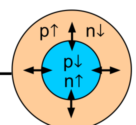
…

GDR in neutron-rich Sn



Gamow-Teller resonance





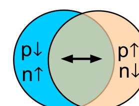
E.L., B.A. Brown, D.-L. Fang, T. Marketin, R.G.T. Zegers,
Phys. Lett. B 730, 307 (2014).

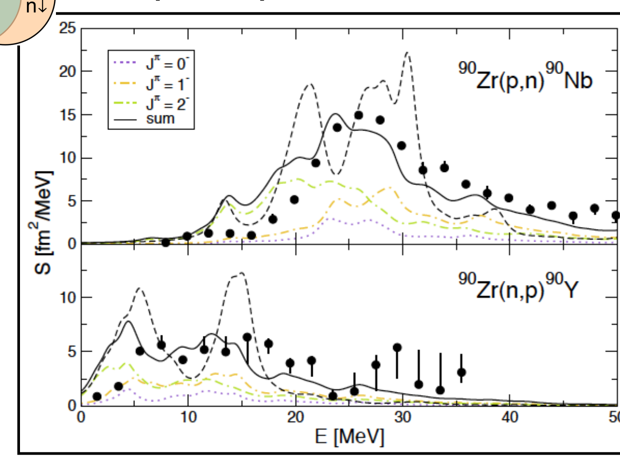
T. Marketin, E.L., D. Vretenar, P. Ring,
Phys. Lett. B 706, 477 (2012).

C. Robin and E. Litvinova,
Eur. Phys. J. A 52, 205 (2016).

E. Litvinova, C, Robin, and I.A. Egorova,
Phys. Lett. B 776, 72 (2018).

Spin-dipole resonance



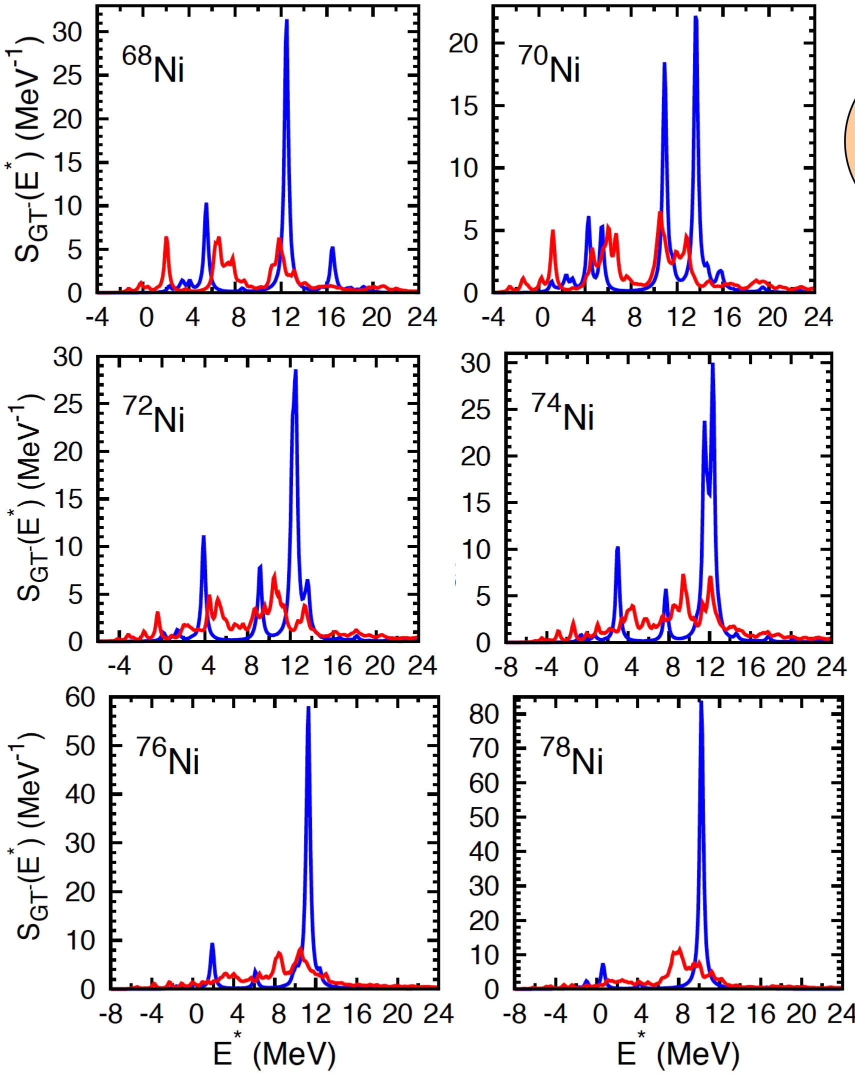


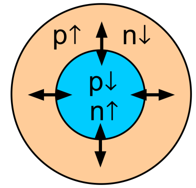
The dynamical part of the interaction kernel (quasiparticle-vibration coupling) brings a significant overall improvement to the description of both high-frequency and low-lying strengths.

Gamow-Teller resonance in open-shell nuclei: spectra of odd-odd systems. Interplay of superfluid pairing and phonon coupling (pn-RQTBA)

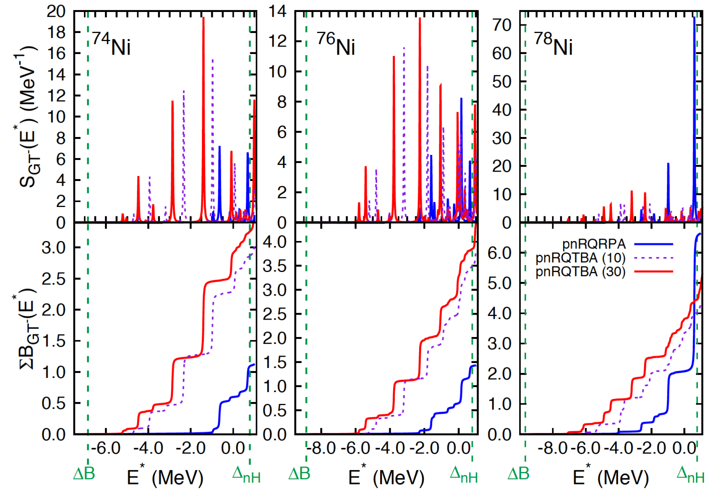
Overall strength

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

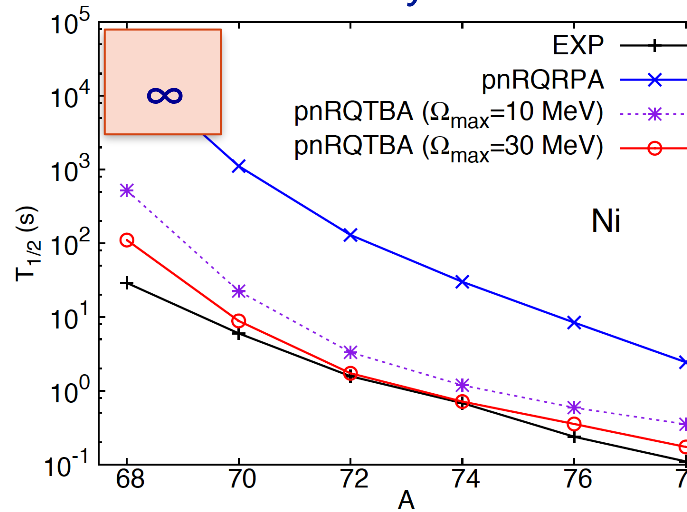




Low-energy part



Beta decay half-lives

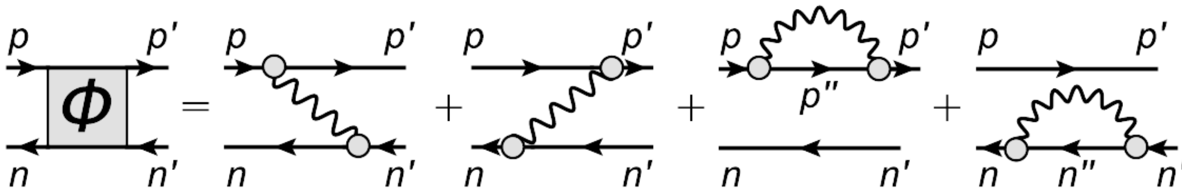


pn-RQRPA
pn-RQTBA

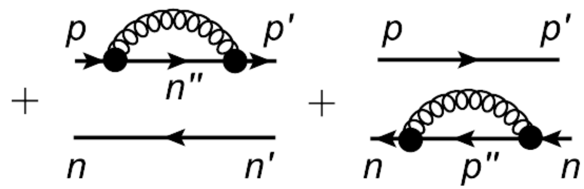
***C. Robin**, E.L., Eur. Phys. J. A 52, 205 (2016)*

No fits, no artificial quenching, no adjustable proton-neutron pairing

The role of coupling to charge-exchange (CE) vibrations

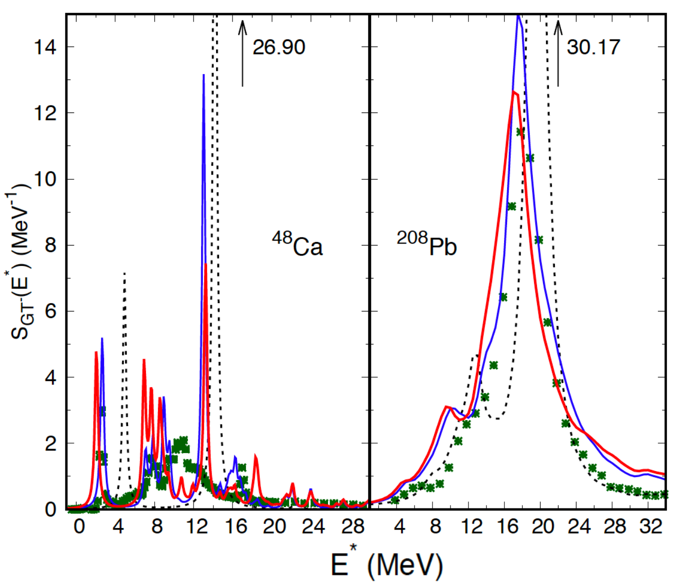


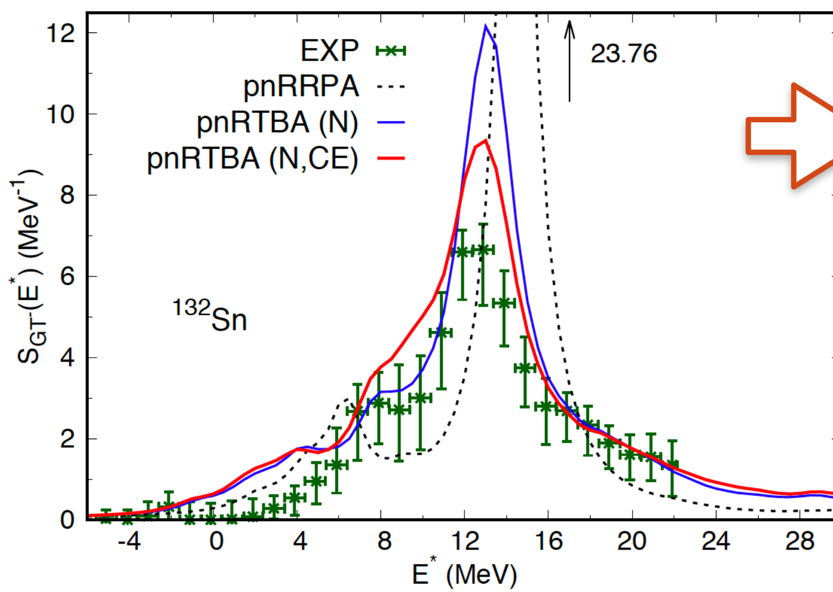
Neutral phonons:
Both phonon-exchange
and self-energy
contributions



Charge-exchange phonons:
no phonon-exchange counterparts
=> larger than expected contribution!

Gamow-Teller response





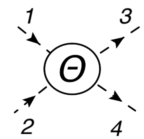
3p3h-configurations are needed for a consistent description without applying quenching factors (in progress)

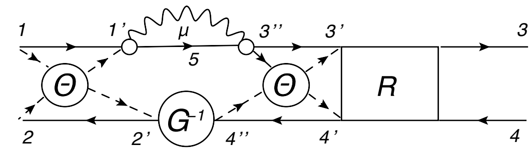
C. Robin, E.L. PRC 98, 051301(R) (2018)

Data: J. Yasuda et al., Phys. Rev. Lett. 121, 132501 (2018)

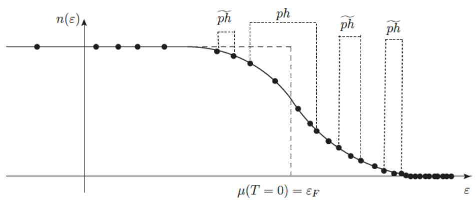
Time blocking (diagram ordering) at T>0

$$\Theta(14,23;T) = \delta_{\sigma_1,-\sigma_2}\theta(\sigma_1 t_{14})\theta(\sigma_1 t_{23})$$
$$\times\left[n(\sigma_1\varepsilon_2,T)\theta(\sigma_1 t_{12}) + n(-\sigma_1\varepsilon_1,T)\theta(-\sigma_1 t_{12})\right]$$





$$\sigma_1 = sign(\varepsilon_1 - \varepsilon_2)$$



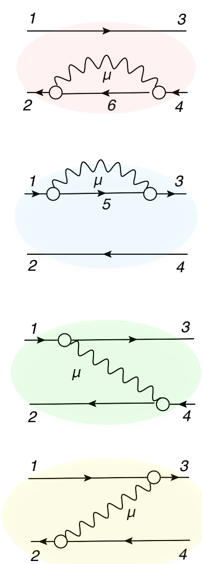
"Soft" time blocking at T>0 leads to a single-frequency variable equation for the response function

$$\mathcal{R}_{14,23}(\omega,T) = \tilde{\mathcal{R}}^0_{14,23}(\omega,T) +$$
$$+\sum_{1'2'3'4'}\tilde{\mathcal{R}}^0_{12',21'}(\omega,T)\left[\tilde{V}_{1'4',2'3'}(T) + \delta\Phi_{1'4',2'3'}(\omega,T)\right]\mathcal{R}_{3'4,4'3}(\omega,T)$$
$$\delta\Phi_{1'4',2'3'}(\omega,T) = \Phi_{1'4',2'3'}(\omega,T) - \Phi_{1'4',2'3'}(0,T)$$

T > 0:

$$\Phi^{(ph)}_{14,23}(\omega,T) = \frac{1}{n_{43}(T)}\sum_{\mu,\eta_\mu=\pm1}\eta_\mu\Big[\delta_{13}\sum_6 \gamma^{\eta_\mu}_{\mu;62}\gamma^{\eta_\mu *}_{\mu;64}\times$$
$$\times\frac{\big(N(\eta_\mu\Omega_\mu)+n_6(T)\big)\big(n(\varepsilon_6-\eta_\mu\Omega_\mu,T)-n_1(T)\big)}{\omega-\varepsilon_1+\varepsilon_6-\eta_\mu\Omega_\mu} +$$
$$+\,\delta_{24}\sum_5 \gamma^{\eta_\mu}_{\mu;15}\gamma^{\eta_\mu *}_{\mu;35}\times$$
$$\times\frac{\big(N(\eta_\mu\Omega_\mu)+n_2(T)\big)\big(n(\varepsilon_2-\eta_\mu\Omega_\mu,T)-n_5(T)\big)}{\omega-\varepsilon_5+\varepsilon_2-\eta_\mu\Omega_\mu} -$$
$$-\,\gamma^{\eta_\mu}_{\mu;13}\gamma^{\eta_\mu *}_{\mu;24}\times$$
$$\times\frac{\big(N(\eta_\mu\Omega_\mu)+n_2(T)\big)\big(n(\varepsilon_2-\eta_\mu\Omega_\mu,T)-n_3(T)\big)}{\omega-\varepsilon_3+\varepsilon_2-\eta_\mu\Omega_\mu} -$$
$$-\,\gamma^{\eta_\mu *}_{\mu;31}\gamma^{\eta_\mu}_{\mu;42}\times$$
$$\times\frac{\big(N(\eta_\mu\Omega_\mu)+n_4(T)\big)\big(n(\varepsilon_4-\eta_\mu\Omega_\mu,T)-n_1(T)\big)}{\omega-\varepsilon_1+\varepsilon_4-\eta_\mu\Omega_\mu}\Big],$$

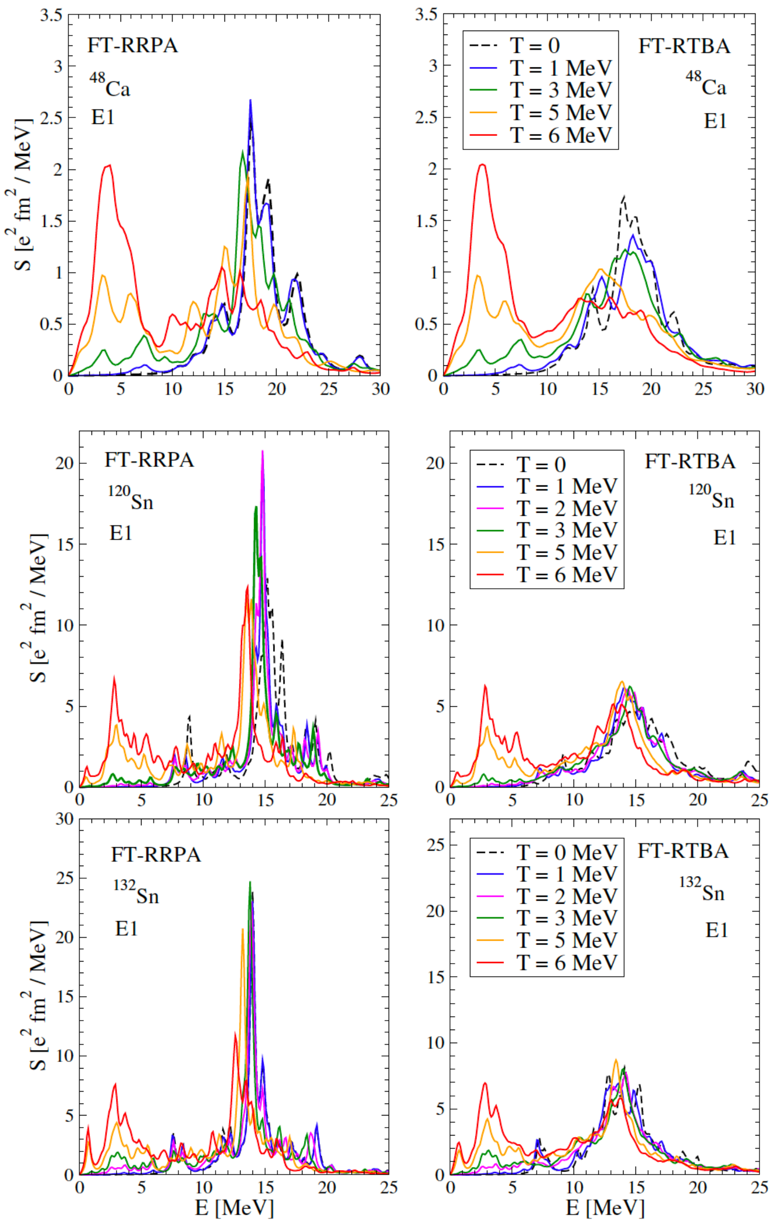
Dynamical kernel:



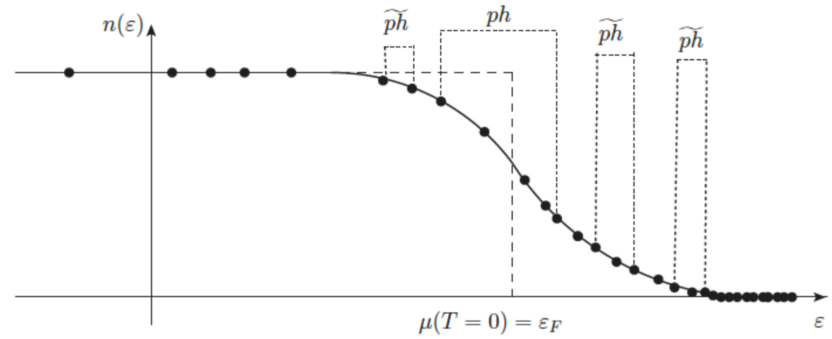
T = 0:

$$\Phi^{(ph,ph)}_{14,23}(\omega) = \sum_\mu \times$$
$$\times\Big[\delta_{13}\sum_6\frac{\gamma^\mu_{62}\gamma^{\mu *}_{64}}{\omega-\varepsilon_1+\varepsilon_6-\Omega_\mu} +$$
$$+\delta_{24}\sum_5\frac{\gamma^\mu_{15}\gamma^{\mu *}_{35}}{\omega-\varepsilon_5+\varepsilon_2-\Omega_\mu} -$$
$$-\frac{\gamma^\mu_{13}\gamma^{\mu *}_{24}}{\omega-\varepsilon_3+\varepsilon_2-\Omega_\mu} -$$
$$-\frac{\gamma^{\mu *}_{31}\gamma^\mu_{42}}{\omega-\varepsilon_1+\varepsilon_4-\Omega_\mu}\Big]$$

Giant Dipole Resonance in ^{48}Ca and ^{120,132}Sn at T>0



Thermal unblocking:



Uncorrelated propagator:

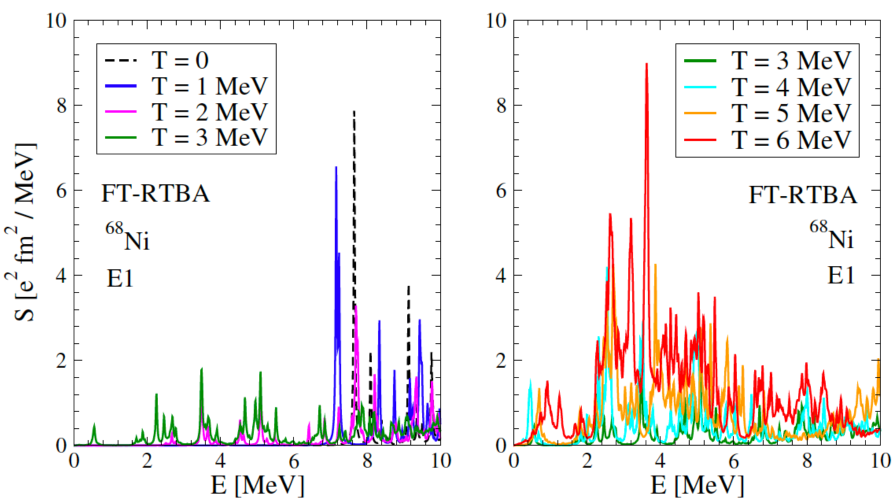
$$\tilde{R}^0_{14,23}(\omega) = \delta_{13}\delta_{24}\frac{n_2 - n_1}{\omega - \varepsilon_1 + \varepsilon_2}$$

- *New transitions due to the thermal unblocking effects*
- *More collective and non-collective modes contribute in the PVC self-energy (~400 modes at T=5-6 MeV)*
- *Broadening of the resulting GDR spectrum*
- *Development of the low-energy part => a feedback to GDR*

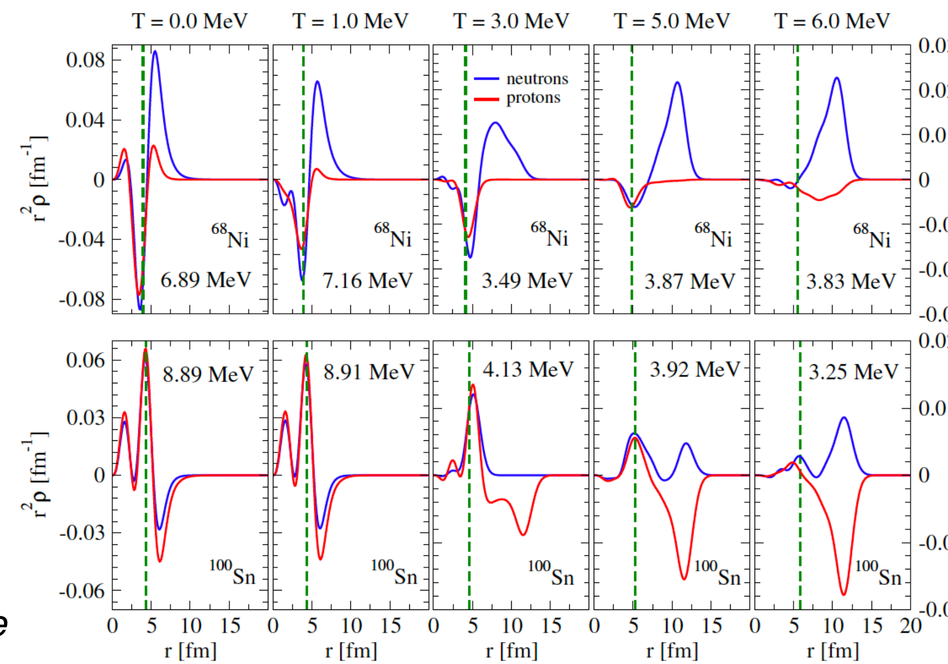
- *The spurious translation mode is properly decoupled as the mean field is modified consistently*
- *The role of the new terms in the Φ amplitude increases with temperature*
- *A very little fragmentation of the low-energy peak (possibly due to the absence of GSC/PVC)*

Evolution of the pygmy dipole resonance (PDR) at T>0

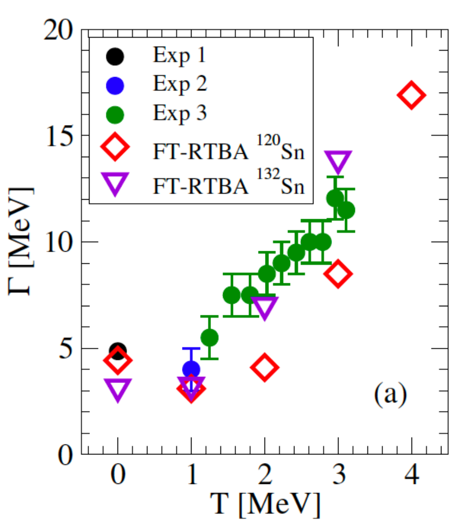
Low-energy strength distribution in ^{68}Ni



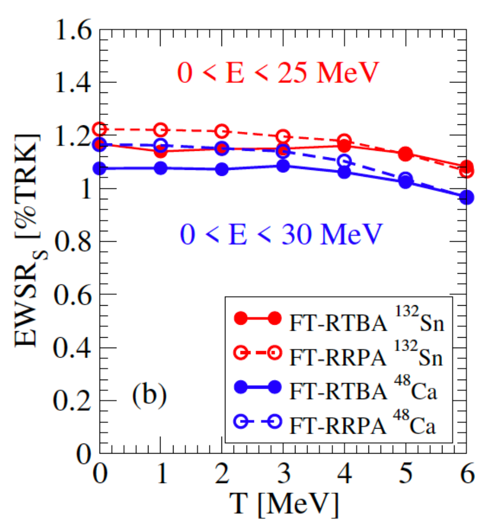
Transition density for the low-energy peak in ^{68}Ni, ^{100}Sn



GDR's width



Energy-weighted sum rule



- *The low-energy peak (PDR) gains the strength from the GDR with the temperature growth: EWSR ~ const*
- *The total width $\Gamma \sim T^2$ (as in the Landau theory)*
- *The PDR develops a new type of collectivity originated from the thermal unblocking*
- *The same happens with other low-lying modes (2+, 3-, …) => strong PVC => "destruction" of the GDR at high temperatures*

E.L., H. Wibowo, Phys. Rev. Lett. 121, 082501 (2018).

H. Wibowo, E.L., arXiv:1810.01456.

The role of the exponential factor: low-energy strength

$$S(E,T) = -\frac{1}{\pi}\lim_{\Delta\to+0} Im\, \langle V^{0\dagger}\mathcal{R}(E+i\Delta,T)V^{0}\rangle$$

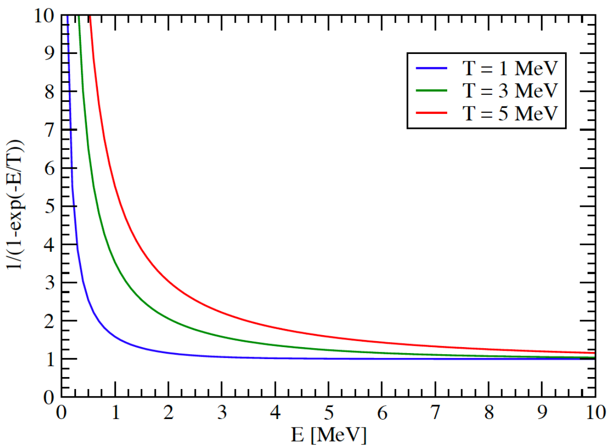
The final strength function at T>0:

$$\tilde{S}(E) = \frac{1}{1-e^{-E/T}}S(E)$$

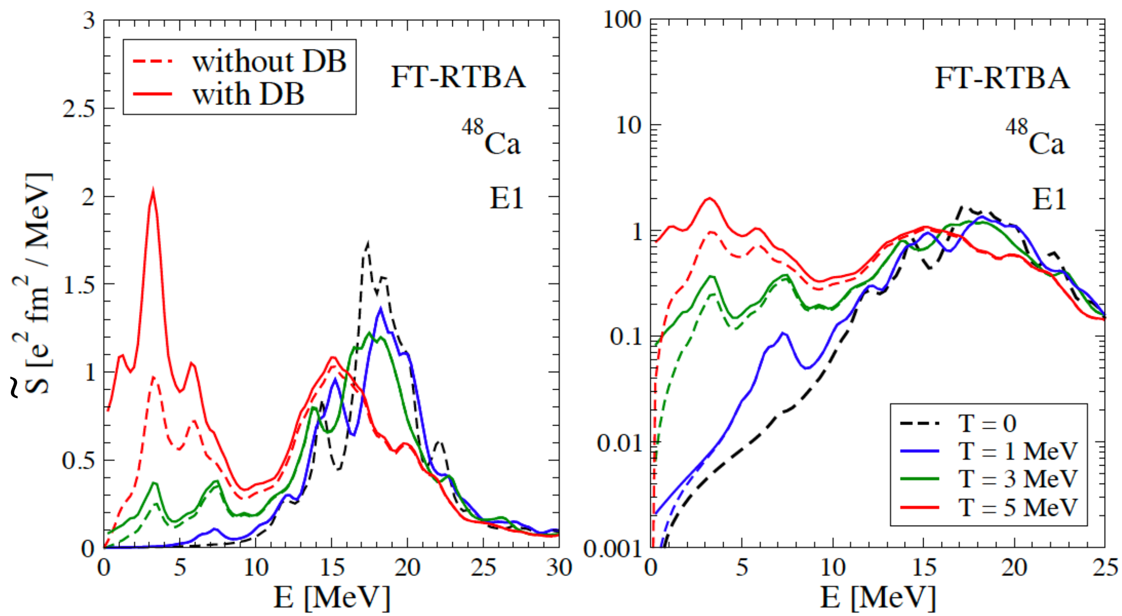
Averaging over the initial state energies, Detailed balance at T>0

$$\lim_{E\to 0} S(E,T) = 0$$

The exponential factor:



Dipole strength: absorption at T>0:



- *The exponential factor brings an additional enhancement in E<T energy region and provides the finite zero-energy limit of the strength (regardless its spin-parity)*

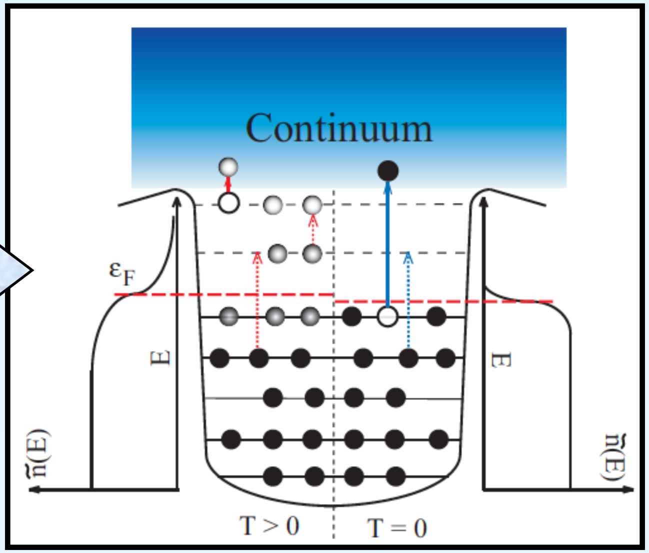
Continuum effects

- Theory including the continuum, QVC and superfluid pairing at T=0:
E.L., V.I. Tselyaev, PRC 75, 054318 (2007):

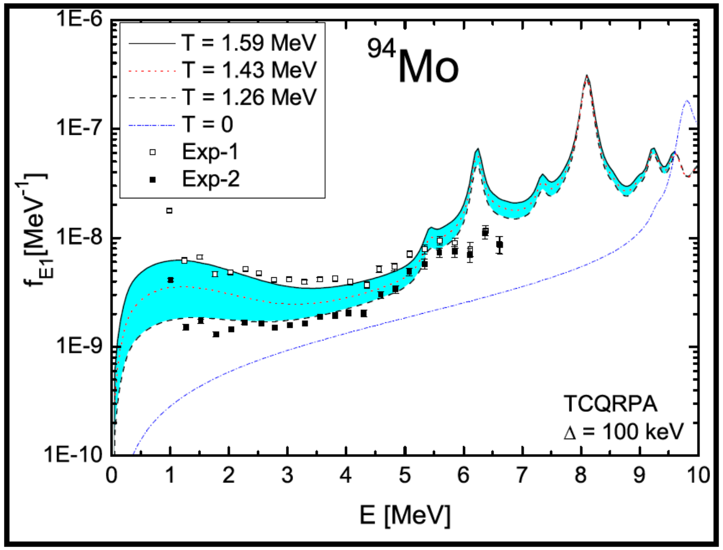
Continuum is mostly important for light nuclei

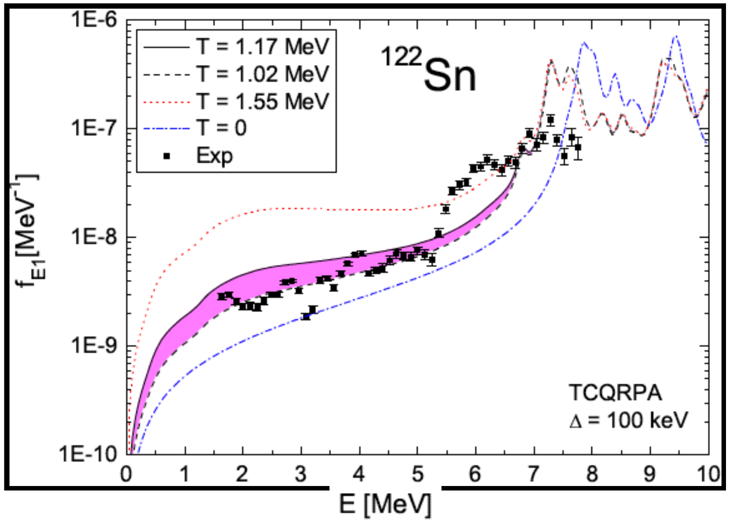
- However, the continuum effects become important also in heavy systems at finite temperatures: excited compound nuclei (CN), for instance, after the thermal neutron capture

Thermal unblocking



Low-energy limit of the radiative dipole strength functions



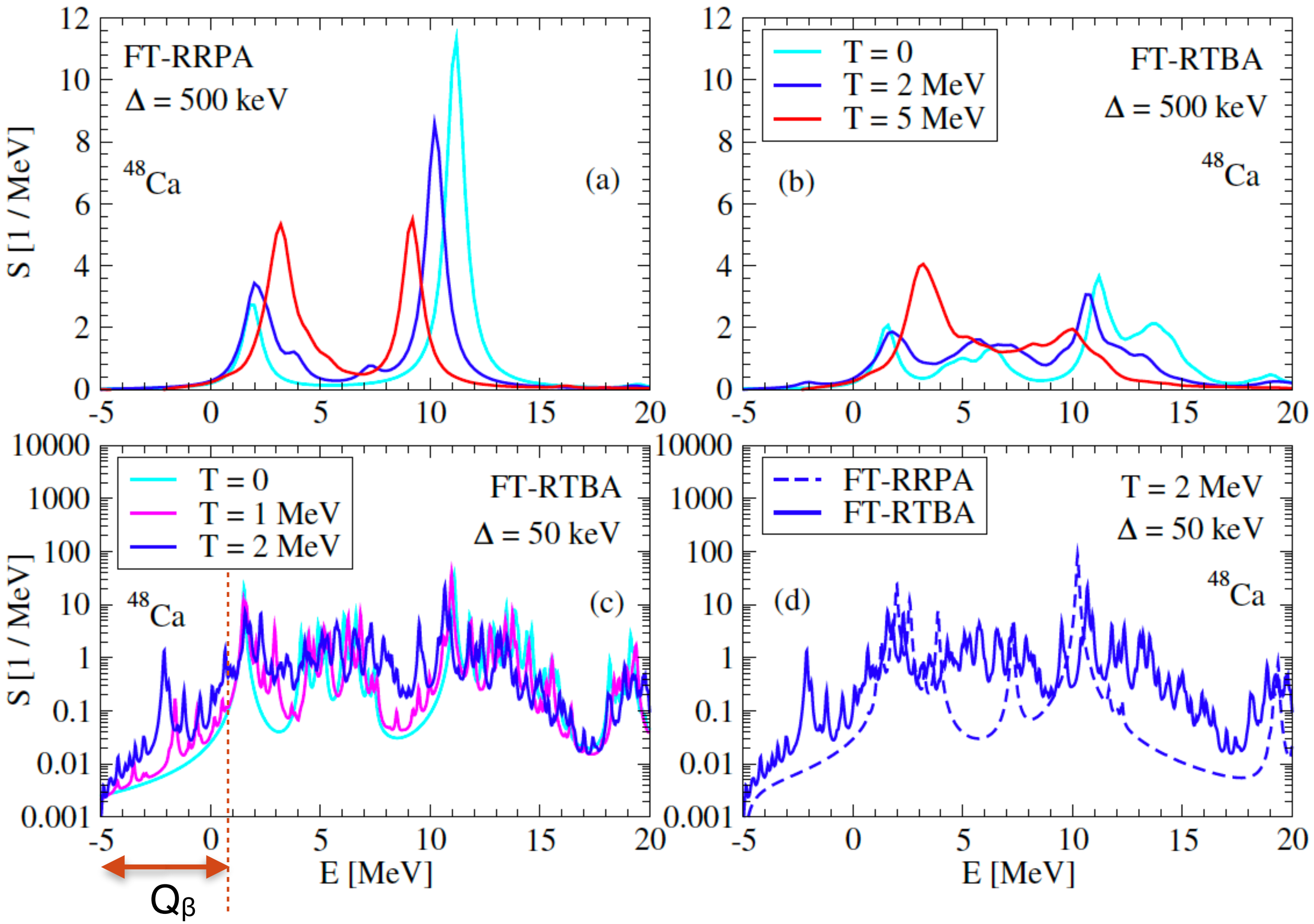


Theory: E. Litvinova, N. Belov, PRC 88, 031302(R)(2013)

Exp.: Oslo data M. Guttormsen et al., PRC 71, 044307 (2005), S. Goriely et al., PRC 78, 064307 (2008)

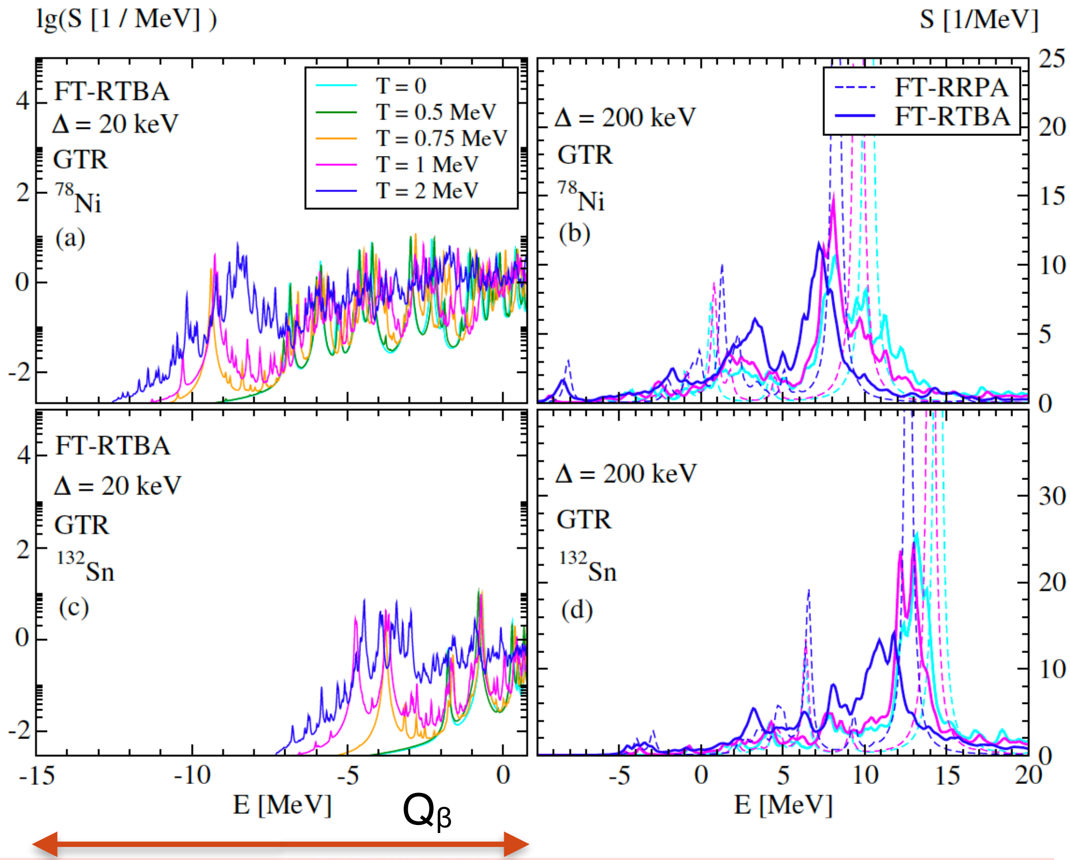
Exponential factor not included; QVC not included; **work in progress**

Temperature dependence of the Gamow-Teller Resonance (GTR): the case of ^{48}Ca



- The GTR shows a stronger sensitivity to temperature than the non-charge-exchange GDR.
- The strength gets "pumped" into the low-energy peak with the temperature increase.
- New states appear in the lowest-energy sector due to the thermal unblocking => beta instability enhancement
- PVC fragmentation effects remain strong at T>0.

Gamow-Teller Resonance: ^{78}Ni and ^{132}Sn

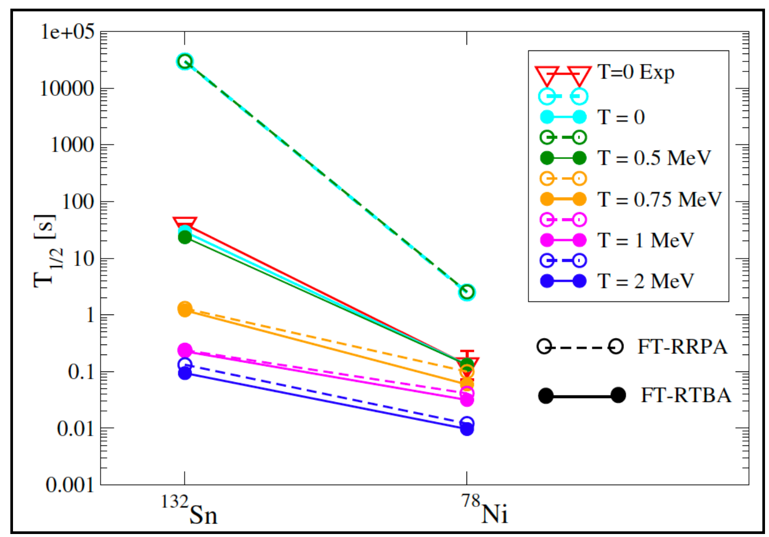


Beta decay half-life $T_{1/2}$

$$T_{1/2}^{-1} = \frac{g_A^2}{D}\int_{\Delta B}^{\Delta_{nH}} f(Z,\Delta_{np}-E)S_{GT^-}(E)dE$$

$\Delta_{nH} = 0.78$ MeV; $g_A = 1.27$ (unquenched)

E.L., C. Robin, H. Wibowo, arXiv:1808.07223

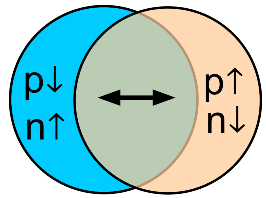


- *The thermally unblocked transitions enhance the GTR strength within the Q_β window. This causes the decrease of the $T_{1/2}$ with temperature.*
- *At the typical r-process temperatures T~0.2-0.3 MeV the thermal unblocking is still suppressed by the large shell gaps, however, the situation should change in the open-shell nuclei.*

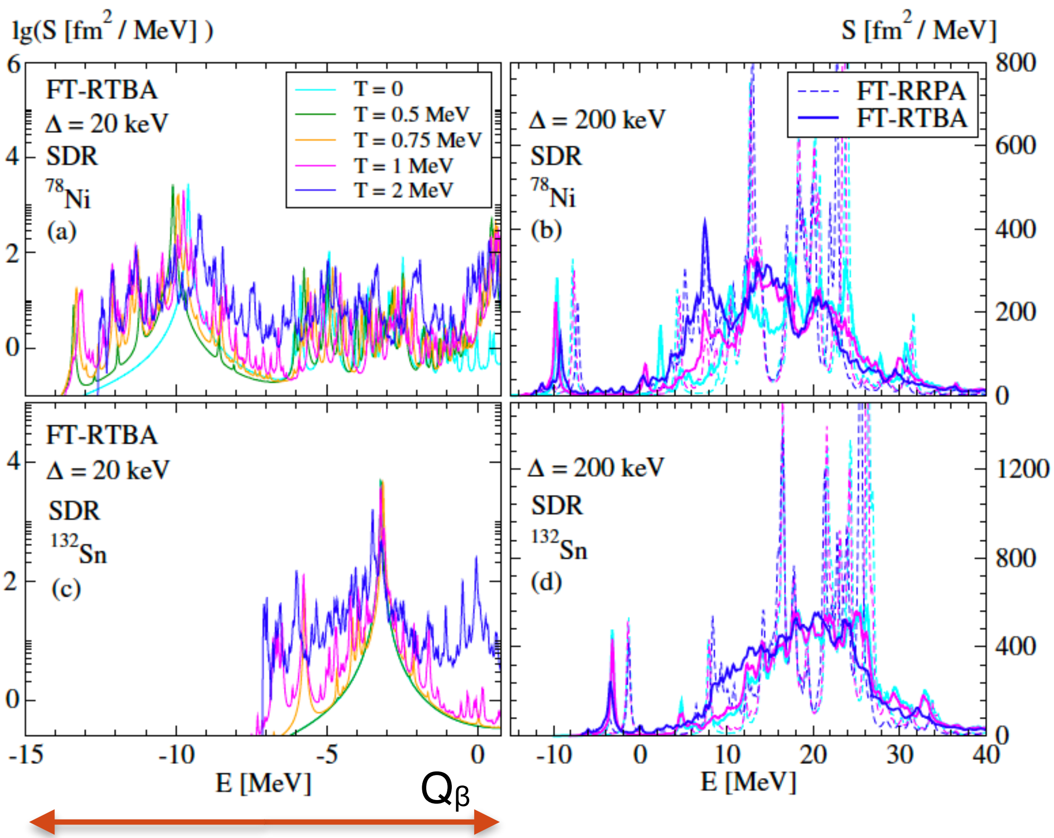
Temperature dependence of the Spin Dipole (SD) Resonance: First forbidden transitions in ^{78}Ni

Response to the operator:

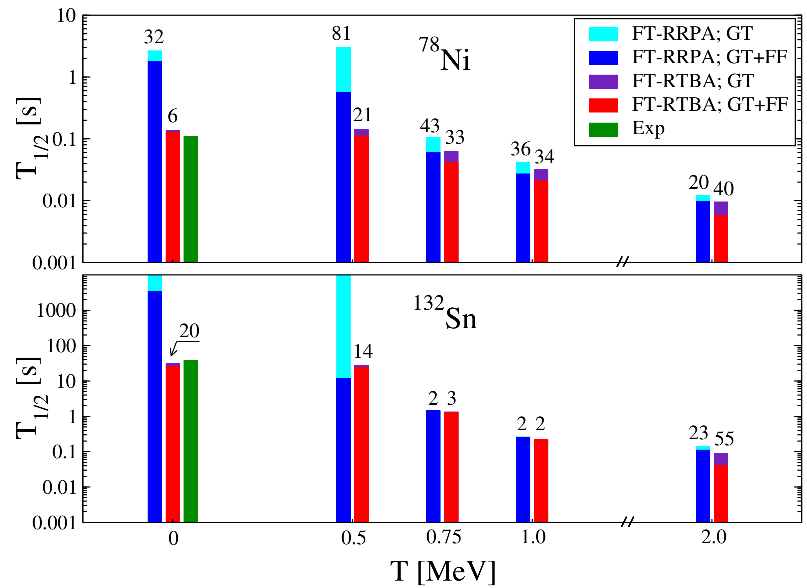
$$P_{\pm}^{\lambda} = \sum_i r(i)\,[\boldsymbol{\sigma}(i) \otimes Y_1(i)]_{\lambda}\, t_{\pm}(i)$$



Angular momentum: $\Delta L = 1$
Isospin: $\Delta T = 1$
Spin: $\Delta S = 1$
3 components: $\lambda = 0,1,2$



Beta decay half-lives in a hot stellar environment, $lg(\rho Y_e) = 7$:



- *The SD strength changes noticeably already at temperatures T< 0.5 MeV*

  => a non-negligible impact on $T_{1/2}$ and beta decay rates which increases with temperature

- *Further consequences for astrophysics: electron capture, neutrino transport*

Outlook

Summary:

- Relativistic NFT offers a powerful framework for a high-precision solution of the nuclear many-body problem.

- The non-perturbative response theory based on QHD and including high-order correlations is available now for a large class of nuclear excited states in even-even and odd-odd nuclei.

- The time blocking approximation to the nuclear response beyond RPA is generalized to finite temperature snd applied to GDR, GTR and SDR.

Current and future developments:

- An approach to nuclear response including both continuum and PVC at finite temperature, for both neutral and charge-exchange excitations;

- Inclusion of the superfluid pairing at T>0 to extend the application range (r-process);

- Inclusion of 3p3h-configurations (ongoing for T=0);

- Applications to neutron stars and other QFT cases;

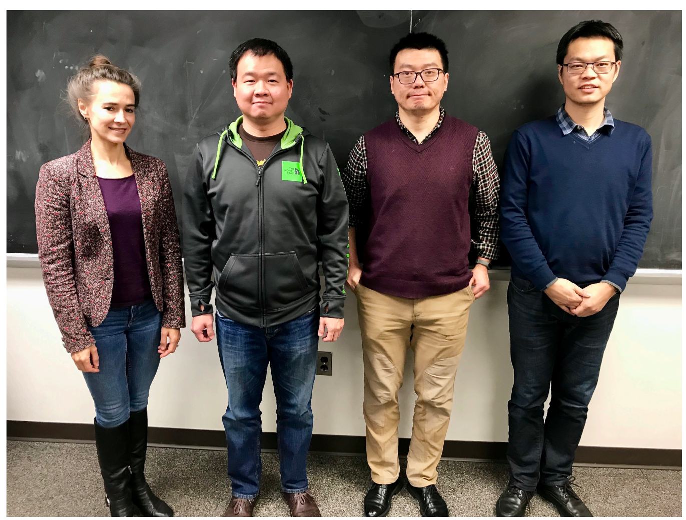
- Toward an "ab initio" description: realization of the approach based on the bare relativistic meson-exchange potential (CD-Bonn etc.).

Many thanks for collaboration and support:

Herlik Wibowo (WMU)
Caroline Robin (INT Seattle)
Peter Schuck (IPN Orsay)
Peter Ring (TU München)
Irina Egorova (WMU, JINR Dubna)
Tomislav Marketin (U Zagreb)
Dario Vretenar (U Zagreb)
Remco Zegers (NSCL MSU)
Vladimir Zelevinsky (NSCL MSU)
And others…

WMU Nuclear Theory group in 2017

…in 2018



Funding:

US-NSF Award PHY-1404343 (2014-2017)

NSF CAREER Award PHY-1654379 (2017-2022)