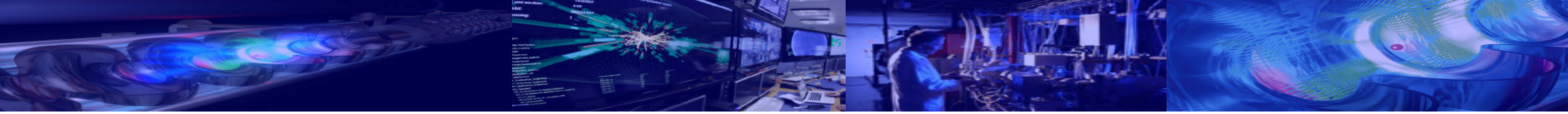


Peter Schuck
(1940-2022)

Solving nuclear structure puzzles with the relativistic nuclear field theory

"Ab-initio" Equation of Motion (EOM) framework

Nuclear Field Theory (NFT)

Ricardo Broglia
(1939-2022)

Elena Litvinova

Western Michigan University

MICHIGAN STATE UNIVERSITY

NSCL

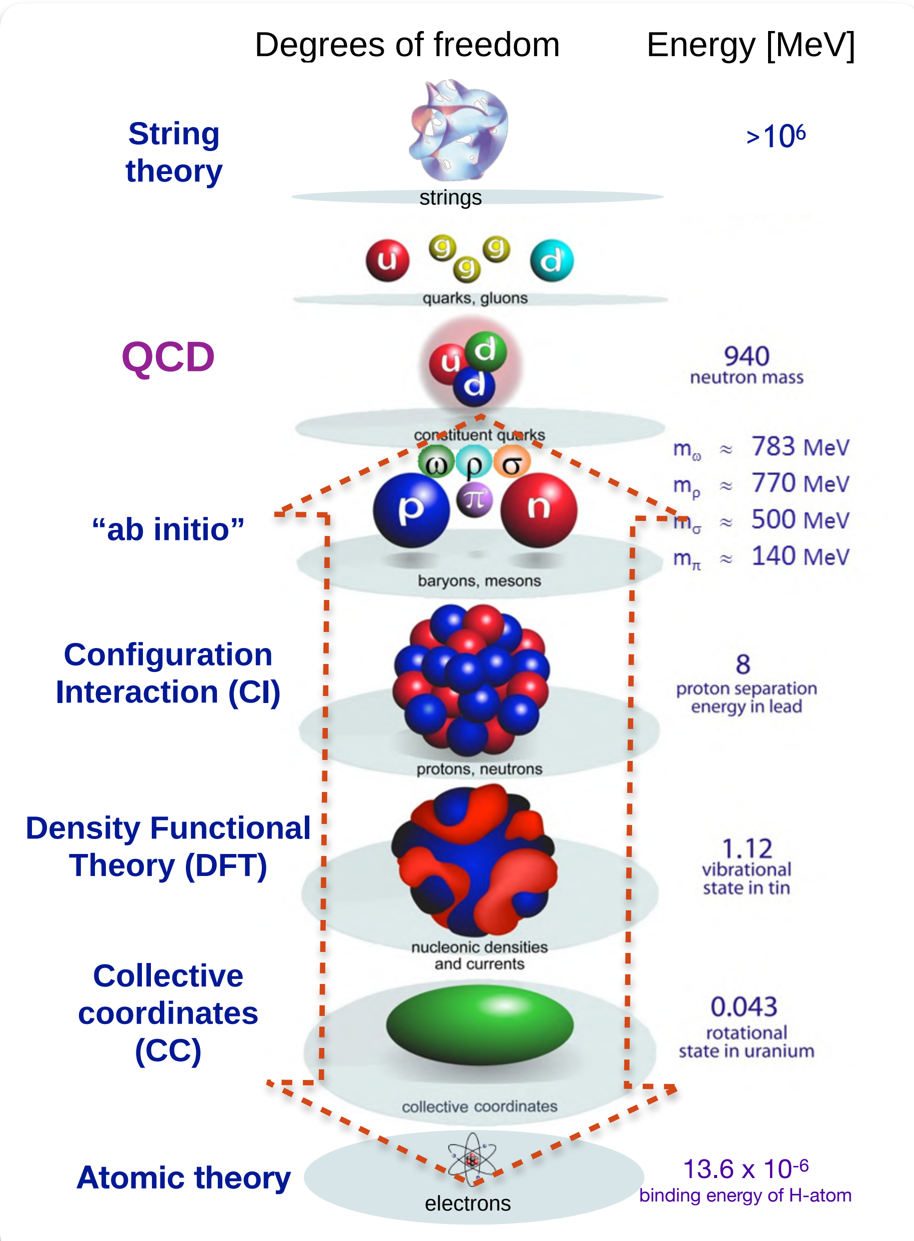
NSF CAREER Award

Collaborators: *Peter Schuck, Peter Ring, Yinu Zhang, Caroline Robin, Herlik Wibowo*

Outline: *(i) Theory (ii) Results (iii) Outlook*

COMEX7 Conference, Catania, Italy, June 12-16, 2023

Hierarchy of energy scales and nuclear many-body problem



- ***The major conflict:***

Separation of energy scales => effective field theories

vs

The physics on a certain scale is governed by the next higher-energy scale

Hamiltonian:

$$H = K + V$$

center of mass

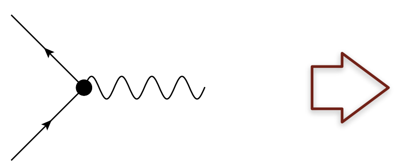
internal degrees of freedom: next energy scale

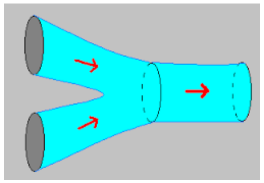
Standard Model:

free propagation and interaction, singularities & renormalizations

String theory:

merging strings
NO "Interaction"



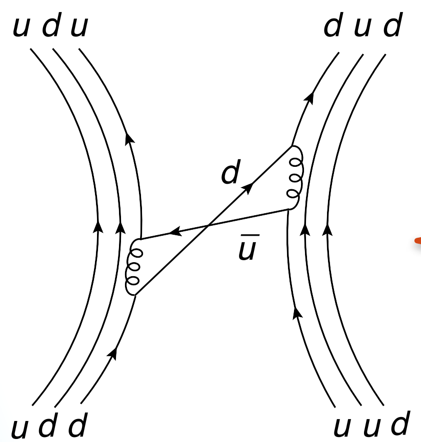


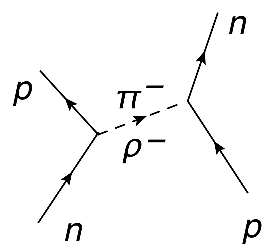
- ***Possible solution:***

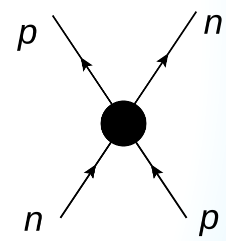
  - *Keep/establish connections between the scales via emergent phenomena*
  - *A universal approach to the strongly-coupled QMBP?*

The underlying mechanism of NN-interaction:

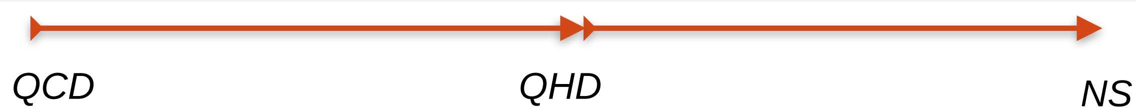
Quantum Chromodynamics (QCD, high energy)	Quantum Hadrodynamics (QHD, intermediate energy)	Nuclear Structure (NS, low energy)





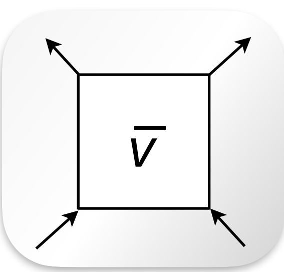


Relay of EFTs:



Formalism:

- Generic bare "interaction": model-independent, all channels included
- Higher-orders are treated via ***in-medium propagators***
- No perturbation theory



In implementations:

- Meson-exchange (ME) at leading order
- Effective coupling constants/ masses (adjusted on the mean-field (MF) level, NL3(*)) + subtraction of qPVC
- Bare ME + subtraction of MF artifacts (in progress)

A strongly-correlated many body system: single-fermion propagator, particle-hole propagator and related observables

$$H = \sum_{12} \bar{\psi}_1(-i\gamma\cdot\nabla + M)_{12}\psi_2 + \frac{1}{4}\sum_{1234} \bar{\psi}_1\bar{\psi}_2\bar{v}_{1234}\psi_4\psi_3 = T + V^{(2)}$$

Hamiltonian, *extendable to 3B forces (3BFs are minimized in covariant theories)*

$$G_{11'}(t-t') = -i\langle T\psi(1)\bar{\psi}(1')\rangle \qquad 1 = \{\xi_1, t\}$$

$$G_{11'}(\varepsilon) = \sum_n \frac{\eta_1^n \bar{\eta}_{1'}^{n*}}{\varepsilon - \varepsilon_n^+ + i\delta} + \sum_m \frac{\chi_1^m \bar{\chi}_{1'}^{m*}}{\varepsilon + \varepsilon_m^- - i\delta}$$

$$\eta_1^n = \langle 0^{(N)}|\psi_1|n^{(N+1)}\rangle \qquad \chi_1^m = \langle m^{(N-1)}|\psi_1|0^{(N)}\rangle$$

Ground state of N particles

(Excited) state of (N+1) particles

Single-particle propagator

Fourier transform: Spectral expansion

Residues *- spectroscopic (occupation) factors*

Poles *- single-particle energies*

$$R_{12,1'2'}(t-t') = -i\langle T(\bar{\psi}_1\psi_2)(t)(\bar{\psi}_{2'}\psi_{1'})(t')\rangle$$

$$R_{12,1'2'}(\omega) = \sum_{\nu>0}\Big[\frac{\rho^{\nu}_{21}\bar{\rho}^{\nu*}_{2'1'}}{\omega - \omega_\nu + i\delta} - \frac{\bar{\rho}^{\nu*}_{12}\rho^{\nu}_{1'2'}}{\omega + \omega_\nu - i\delta}\Big]$$

Excitation energies

$$\rho^{\nu}_{12} = \langle 0|\bar{\psi}_2\psi_1|\nu\rangle$$

Particle-hole response function

Fourier transform: Spectral expansion

Residues *- transition densities*

Poles *- excitation energies*

Exact equations of motion (EOM) for binary interactions: one-body problem

One-fermion propagator

$$G_{11'}(t-t') = -i\langle T\psi(1)\bar{\psi}(1')\rangle$$

***EOM**: Dyson Eq.*

$$G(\omega) = G^{(0)}(\omega) + G^{(0)}(\omega)\Sigma(\omega)G(\omega) \qquad (*)$$

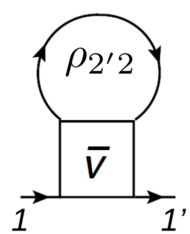
$$\Sigma(\omega) = \Sigma^{(0)} + \Sigma^{(r)}(\omega)$$

Irreducible kernel (Self-energy, exact):

Instantaneous term (Hartree-Fock incl. "tadpole")
Short-range correlations

$$\Sigma^{(0)}_{11'} = -\langle\gamma^0\left\{[V,\psi_1],\bar{\psi}_{1'}\right\}\gamma^0\rangle$$

$$= \sum_{22'}\bar{v}_{121'2'}\langle\bar{\psi}_2\psi_{2'}\rangle =$$

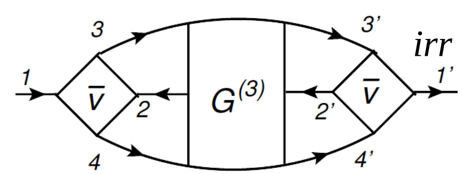


t-dependent (dynamical) term (symmetric version): ***Long-range correlations***

$$\Sigma^{(r)}_{11'} = i\langle T\gamma^0[V,\psi_1](t)[V,\bar{\psi}_{1'}](t')\gamma^0\rangle^{irr}$$

$$= -\frac{1}{4}\sum_{234}\sum_{2'3'4'}\bar{v}_{1234}G^{(3)irr}_{432',23'4'}(t-t')\bar{v}_{4'3'2'1'}$$

$$= -\frac{1}{4}$$



$$\rho_{11'} = -i\lim_{t=t'-0}G_{11'}(t-t')$$

is the full solution of (*):
includes the dynamical term!

Koltun-Migdal-Galitsky sum rule: ***the binding energy***

"Ab-initio DFT":

$$E_0 = \frac{1}{2\pi}\int_{-\infty}^{\varepsilon_F^-}d\varepsilon\sum_{12}(T_{12}+\varepsilon\delta_{12})\mathrm{Im}G_{21}(\varepsilon)$$

Equation of motion (EOM) for the particle-hole response

Particle-hole propagator (response function):

$$R_{12,1'2'}(t-t') = -i\langle T(\bar{\psi}_1\psi_2)(t)(\bar{\psi}_{2'}\psi_{1'})(t')\rangle$$

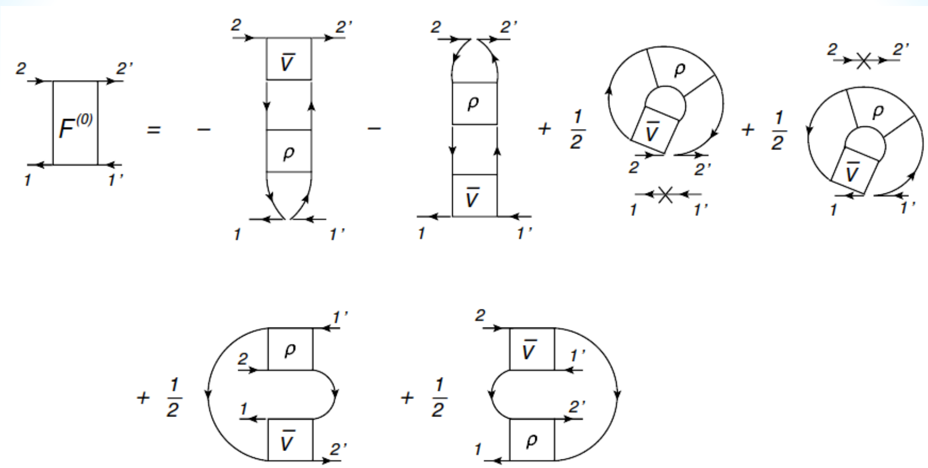
spectra of excitations, masses, decays, …

***EOM**: Bethe-Salpeter-Dyson Eq.*

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

Irreducible kernel (exact):

Instantaneous term ("bosonic" mean field):
Short-range correlations

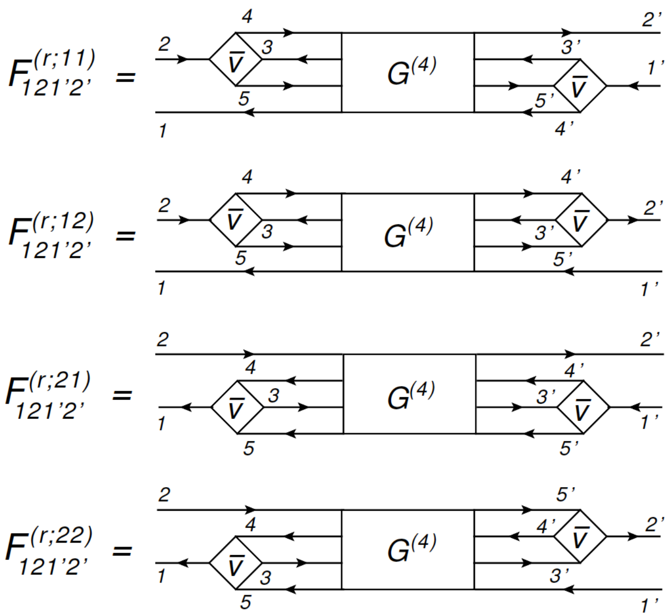


Self-consistent mean field $F^{(0)}$, where

$$\rho_{12,1'2'} = \delta_{22'}\rho_{11'} - i\lim_{t'\to t+0} R_{2'1,21'}(t-t')$$

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

t-dependent (dynamical) term:
Long-range correlations



$$F^{(r)}_{12,1'2'}(t-t') = \sum_{ij} F^{(r;ij)}_{12,1'2'}(t-t')$$

Non-perturbative treatment of two-point $G^{(n)}$ in the dynamical kernels

- ***Quantum many-body problem in a nutshell:*** *Direct EOM for $G^{(n)}$ generates $G^{(n+2)}$ in the (symmetric) dynamical kernels and further high-rank correlation functions (CFs); an equivalent of the BBGKY hierarchy. $N_{Equations} = N_{Particles}$ & Coupled !!!*

Truncation on two-body level

- ***Non-perturbative solutions:***

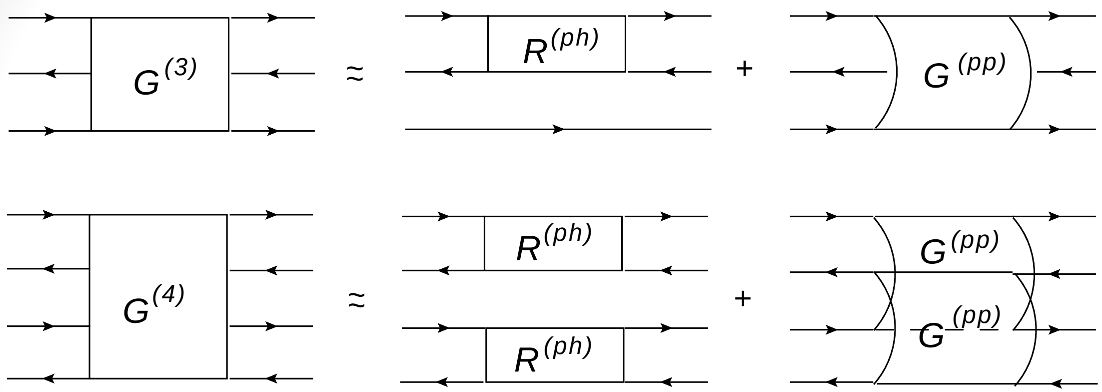
Cluster decomposition

"Self-consistent GFs" *This work*

$$✦\ G^{(3)} = G^{(1)}G^{(1)}G^{(1)} + G^{(2)}G^{(1)} + \Xi^{(3)}$$

"Second RPA" *This work*

$$✦\ G^{(4)} = G^{(1)}G^{(1)}G^{(1)}G^{(1)} + G^{(2)}G^{(2)} + G^{(3)}G^{(1)} + \Xi^{(4)}$$

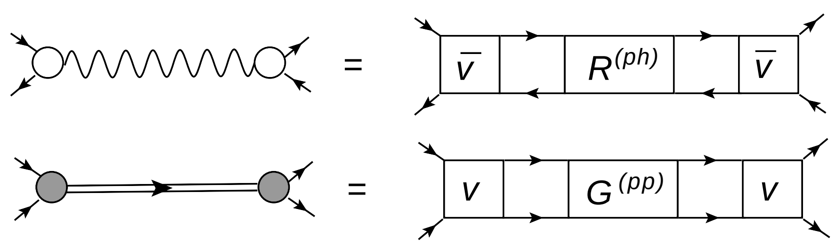


- *P. C. Martin and J. S. Schwinger, Phys. Rev.115, 1342 (1959).*
- *N. Vinh Mau, Trieste Lectures 1069, 931 (1970)*
- *P. Danielewicz and P. Schuck, Nucl. Phys. A567, 78 (1994)*
- *…*

Exact mapping: particle-hole (2q) quasibound states

Emergence of effective "particles" (phonons, vibrations):

Emergence of superfluidity:



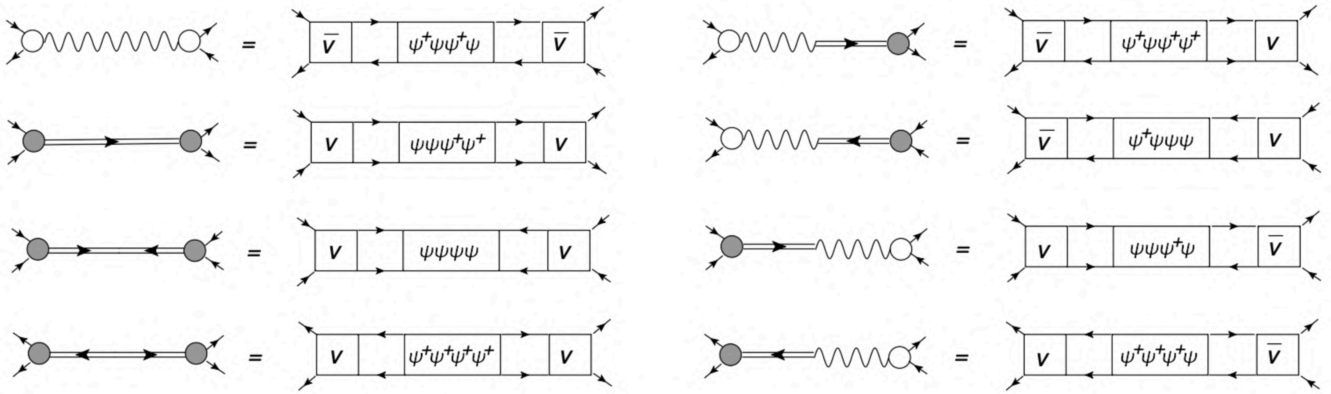
The genesis

of the quasiparticle-vibration coupling (qPVC) in nuclei

"Ab-initio" qPVC in superfluid systems

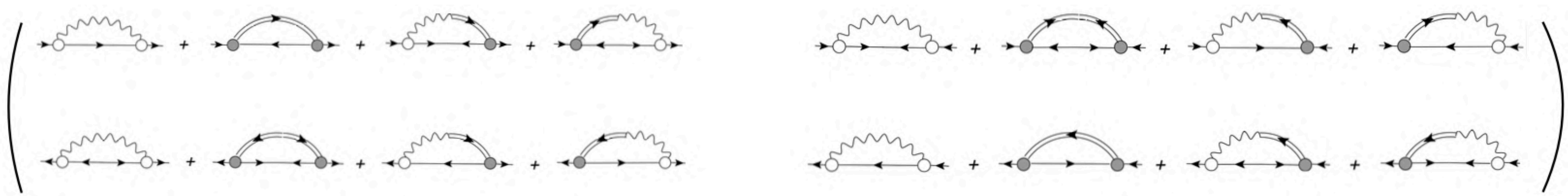
Superfluid dynamical kernel: adding particle-number violating contributions

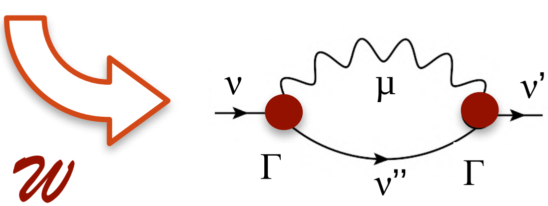
Mapping on the qPVC in the canonical basis



Quasiparticle dynamical self-energy (matrix):
normal and pairing phonons are unified

$\hat{\Sigma}^r =$





Bogoliubov transformation

Cf.: Quasiparticle static self-energy (matrix) in HFB

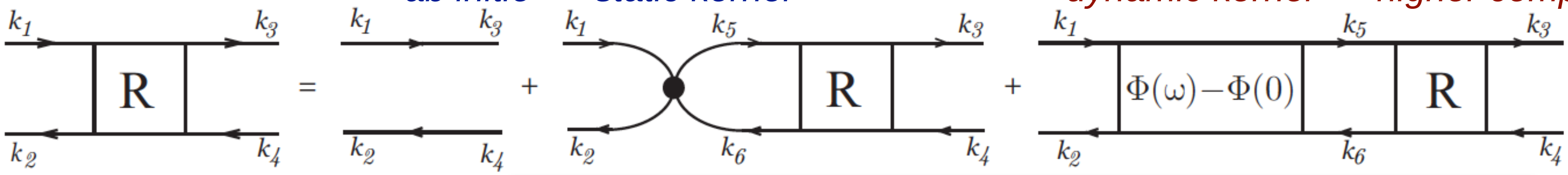
$$\hat{\Sigma}^0 = \begin{pmatrix} \tilde{\Sigma}_{11'} & \Delta_{11'} \\ -\Delta^*_{11'} & -\tilde{\Sigma}^T_{11'} \end{pmatrix}$$

E.L., Y. Zhang, PRC 104, 044303 (2021)
Y. Zhang et al., PRC 105, 044326 (2022)

Nuclear response: toward a complete theory

ab initio <= static kernel

dynamic kernel => higher complexity

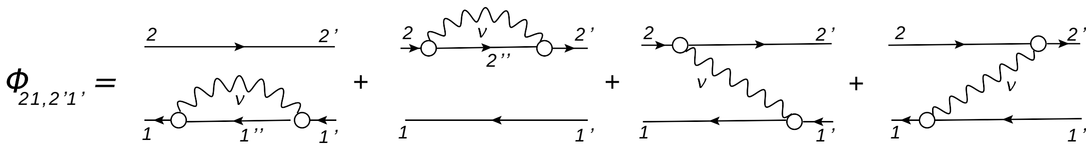


Dyson-Bethe-Salpeter Equation:

$$R(\omega) = R^0(\omega) + R^0(\omega)\,[V+\Phi(\omega)-\Phi(0)\,]\,R(\omega)$$

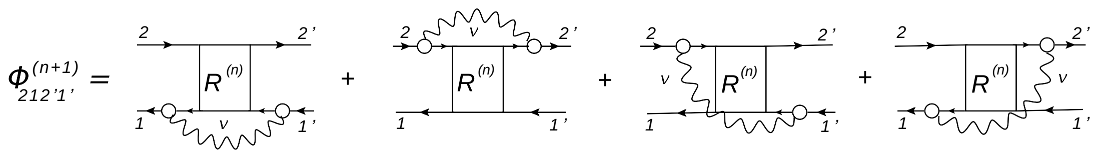
Conventional NFT

Cf. P.-F. Bortignon,
G. Colò, E. Vigezzi,
G. Potel, F. Barranco
&
V. Tselyaev (t-blocking)



Subtraction for effective interactions (Tselyaev 2013)

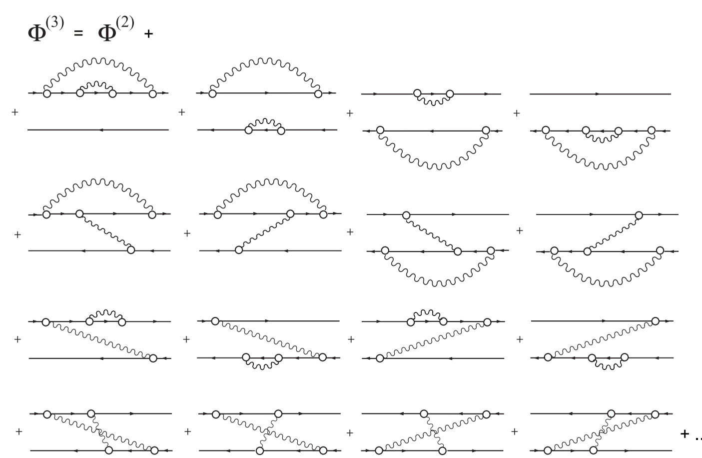
Extended NFT:



Generalized approach for the correlated propagators

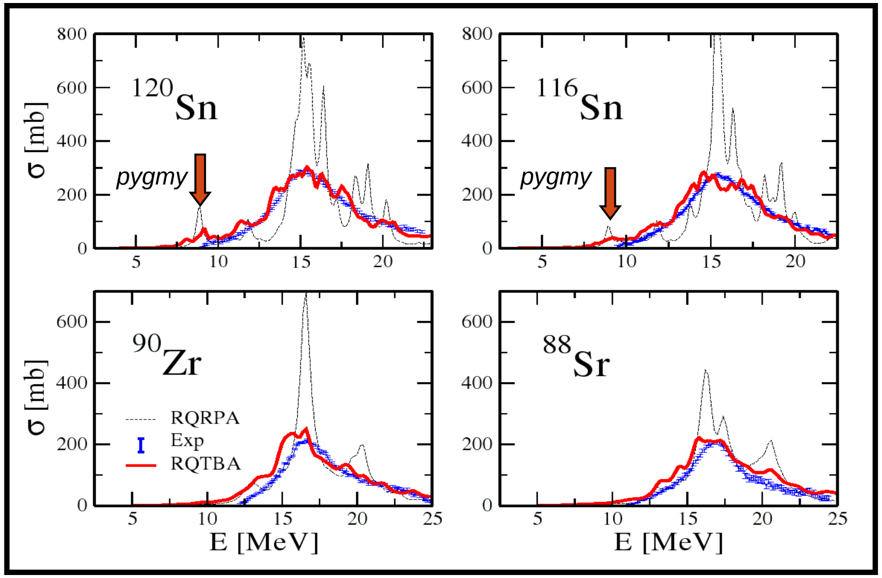
n-th order: E.L. PRC 91, 034332 (2015)

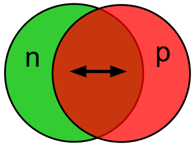
Ab-initio formulation,
$\Phi^{(3)}$ implementation; 2q+2phonon correlations:
E.L., P. Schuck, PRC 100, 064320 (2019)



The giant resonance width puzzle: Relativistic Quasiparticle Time Blocking Approximation (RQTBA)

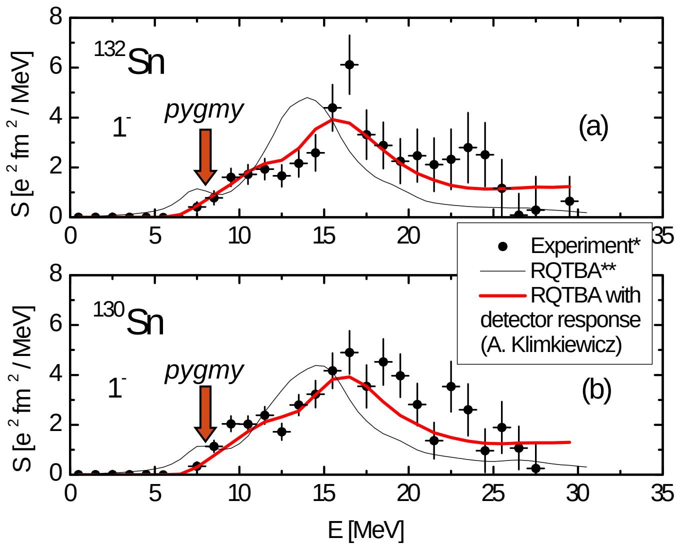
Giant dipole resonance (GDR) in stable nuclei





Giant & pygmy dipole resonances

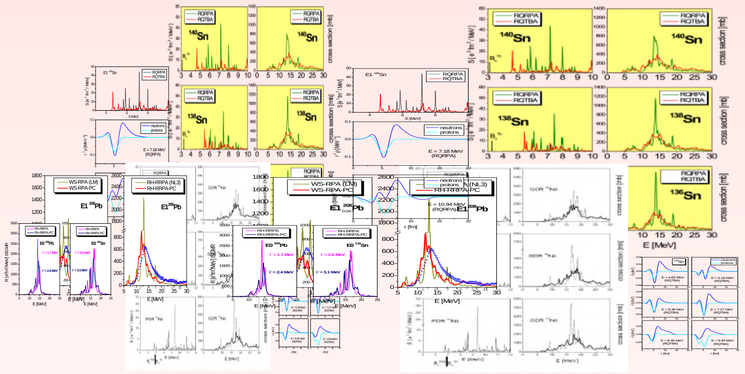
Neutron-rich Sn



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

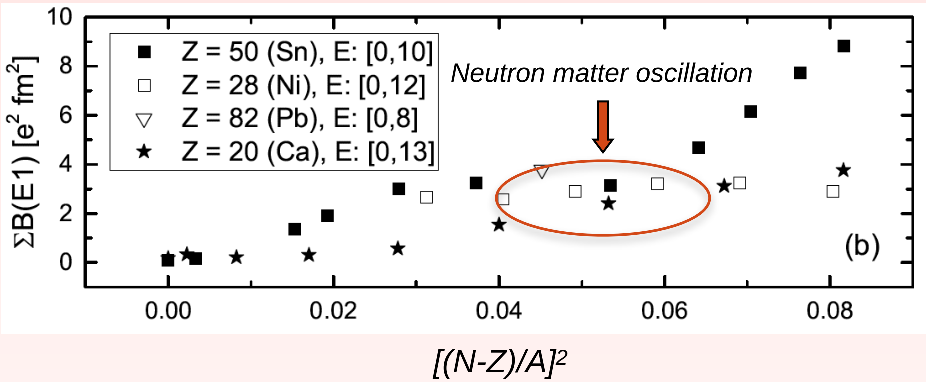
**E. L., P. Ring, and V. Tselyaev, Phys. Rev. C 78, 014312 (2008)

Systematic GMR calculations (various multipoles)



~50+ works on various GMRs

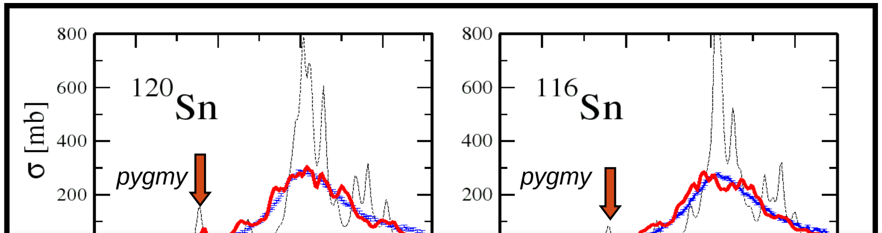
Pygmy dipole strength systematics (important for EOS)

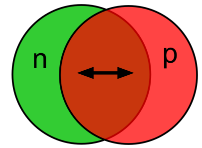


I.A. Egorova, E. Litvinova, Phys. Rev. C 94, 034322 (2016)

Dipole response in medium-mass and heavy nuclei within Relativistic Quasiparticle Time Blocking Approximation (RQTBA)

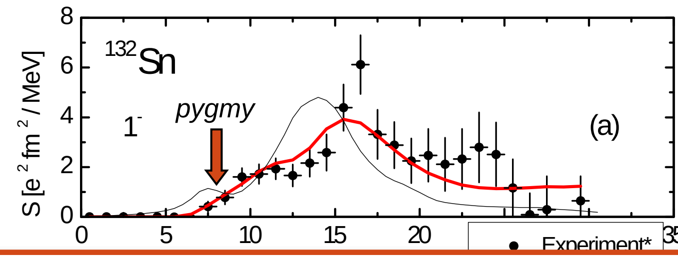
Giant dipole resonance (GDR) in stable nuclei





Giant
&

Neutron-rich Sn



Thanks for the collaboration, discussions and references:

Victor Tselyaev
Marcello Baldo
Gianluca Colò
Armand Bahini
Luna Pellegri
Retief Neveling
Marine Vandebrouck
Francisco Barranco
Enrico Vigezzi
Yifei Niu
Achim Richter
Thomas Aumann

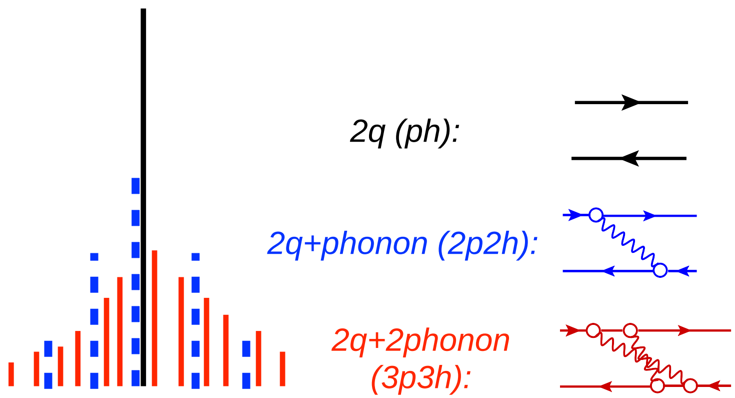
Deniz Savran
Andreas Zilges
Michael Weinert
Maria Markova
Hiroyuki Sagawa
Remco Zegers
Danilo Gambacurta
Masaki Sasano
Nils Paar
Peter von Neumann-Cosel

Gregory Potel
František Knapp
Javier Roca-Maza
Oliver Wieland
Angela Bracco
Edoardo Lanza
Mark Spieker
Adam Maj
Esra Yüksel
Atsushi Tamii
Iolanda Matea

and Others!

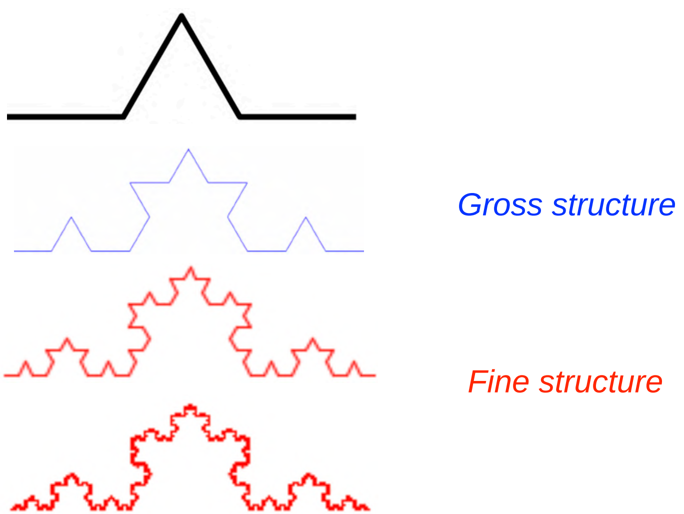
Leading NFT (q)PVC is insufficient: the "3p3h" configurations

Fragmentation mechanism

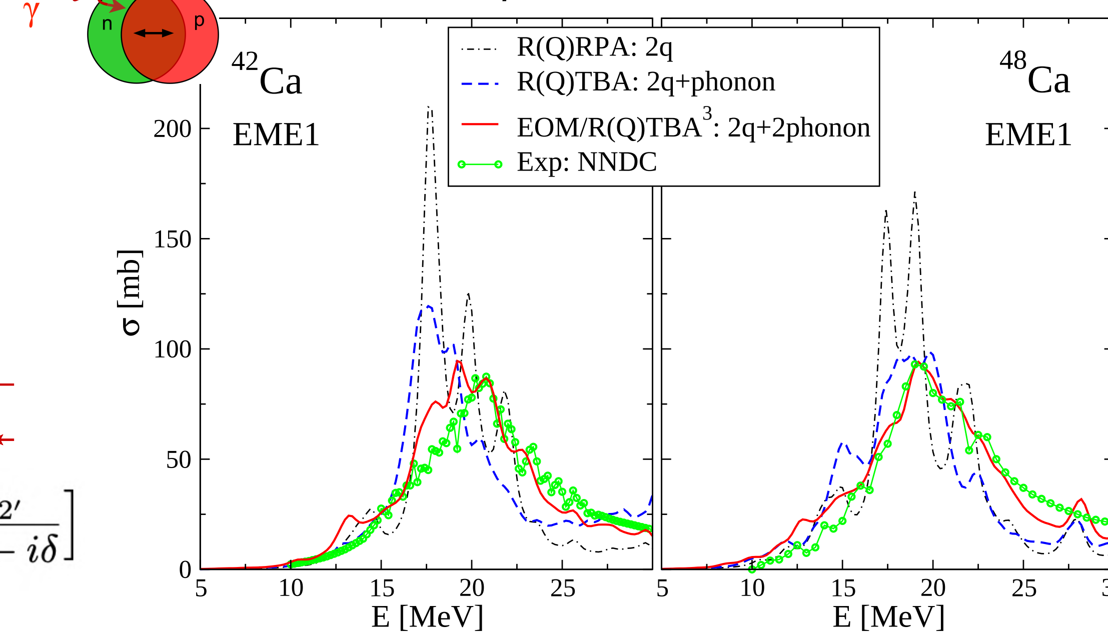


$$R_{12,1'2'}(\omega) = \sum_{\nu>0}\left[\frac{\rho^{\nu}_{21}\bar{\rho}^{\nu *}_{2'1'}}{\omega - \omega_\nu + i\delta} - \frac{\bar{\rho}^{\nu *}_{12}\rho^{\nu}_{1'2'}}{\omega + \omega_\nu - i\delta}\right]$$

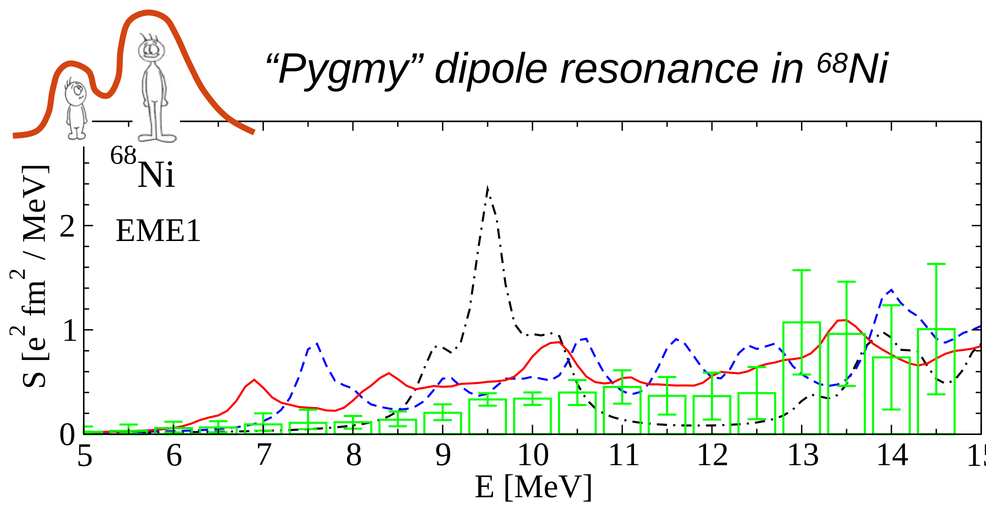
Fractals: Koch curve



Giant dipole resonance in ^{42,48}Ca

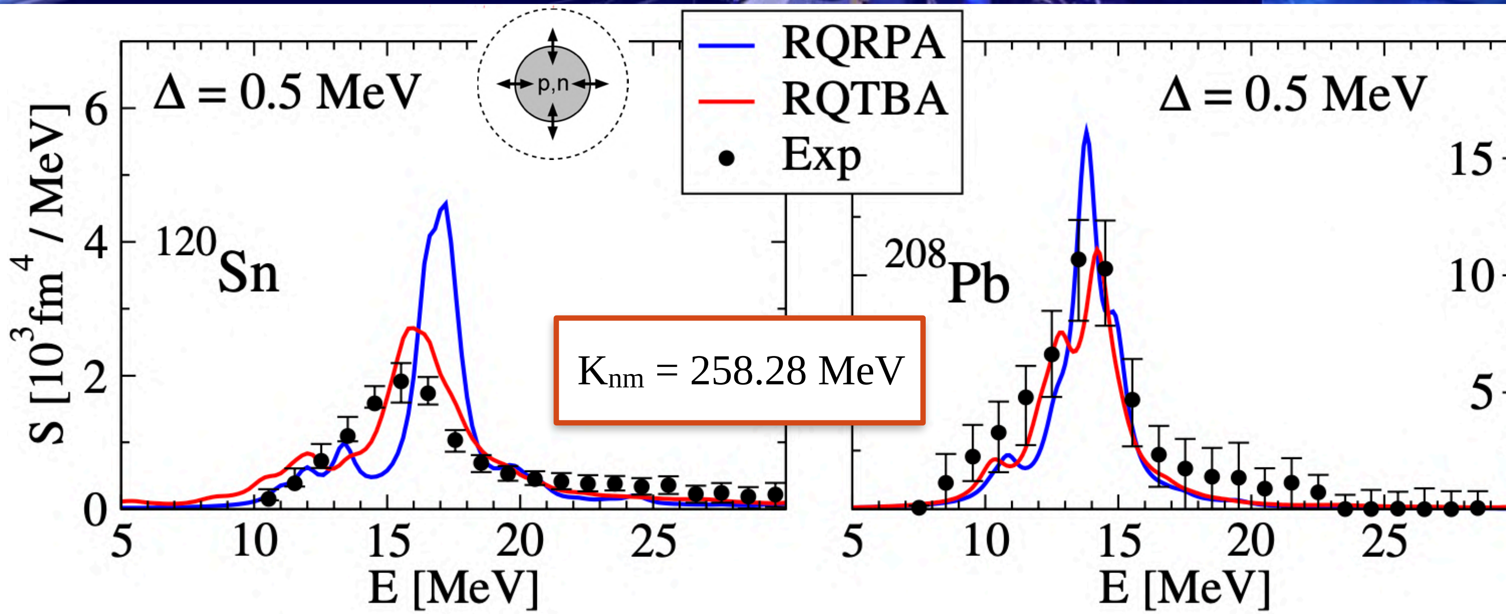


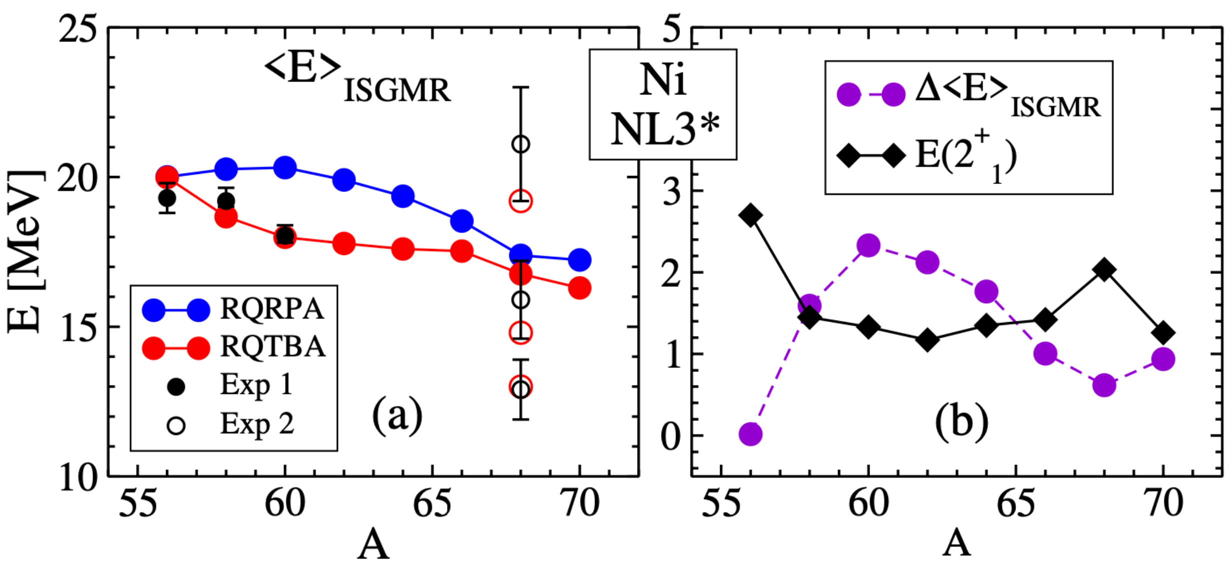
"Pygmy" dipole resonance in ^{68}Ni



Data: O. Wieland et al., Phys. Rev. C 98, 064313 (2018)

Isoscalar giant monopole resonance (ISGMR): The “fluffiness” puzzle





“Softness” increases:

- *with the neutron number*
- *with superfluidity*
- *with correlations beyond QRPA (q)PVC*

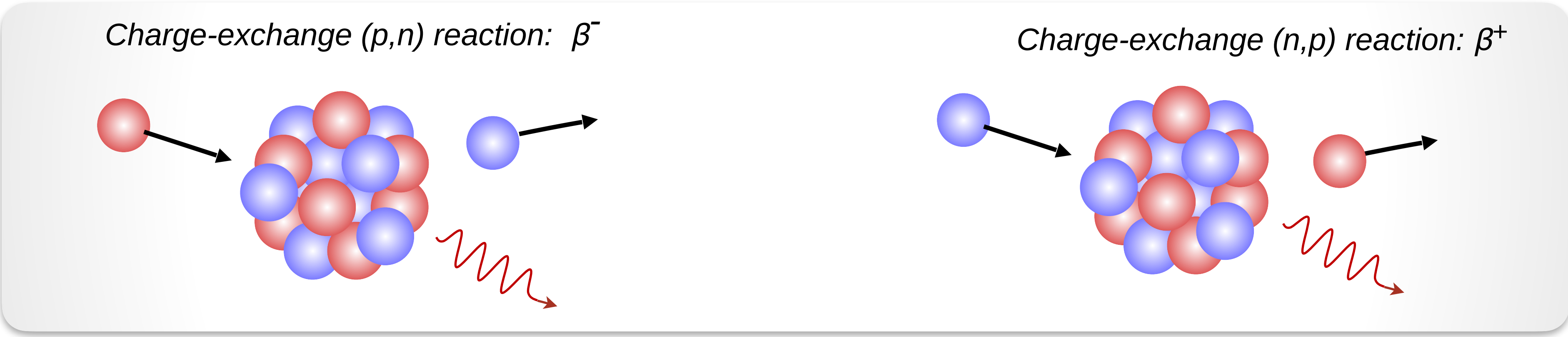
Stiffer EOS can be used

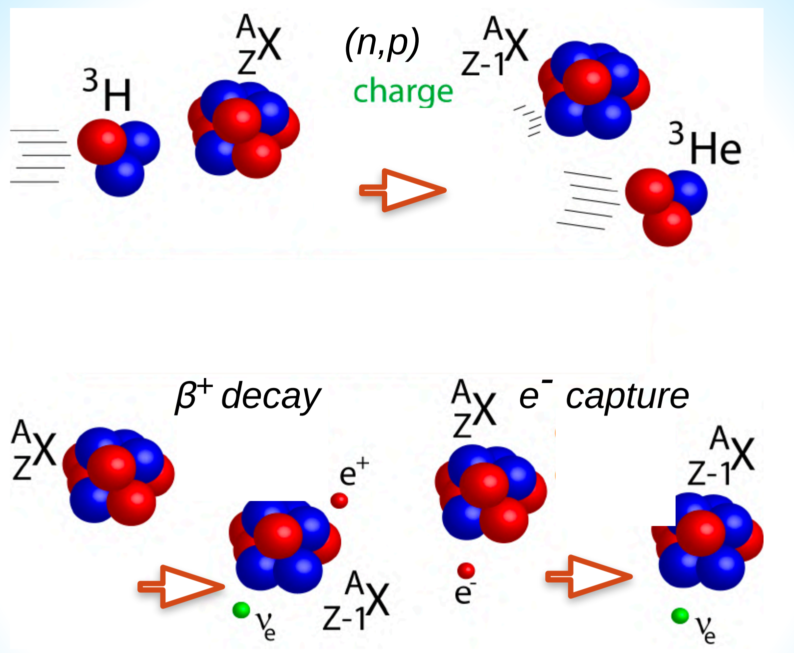
*E.L., Phys. Rev. C **107**, L041302 (2023)*

Cf.: Skyrme HFB+qPVC

G. Colò & Y. Niu

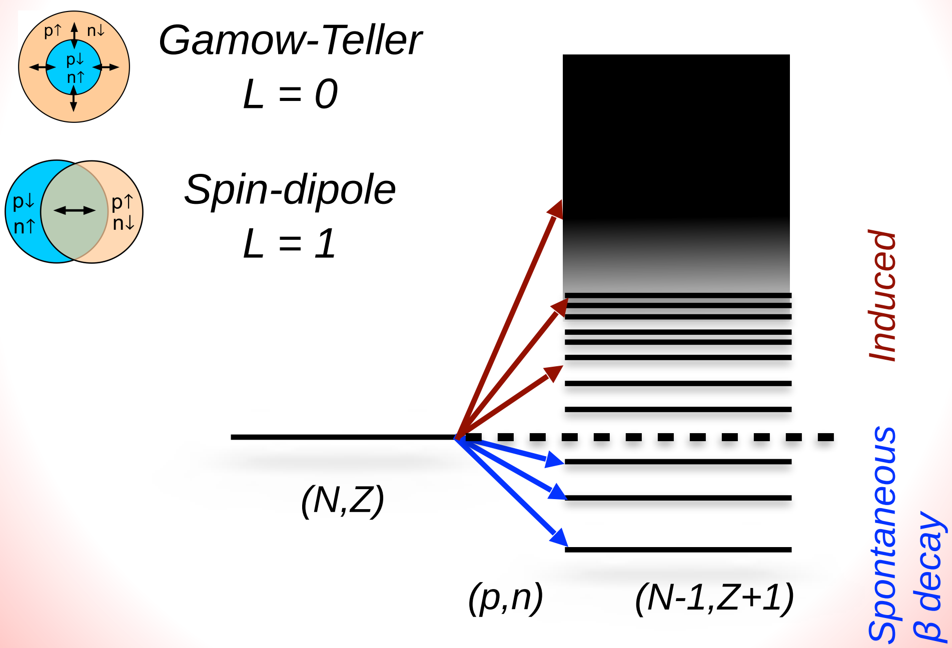
Spin-isospin excitations





R. Zegers et al.

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

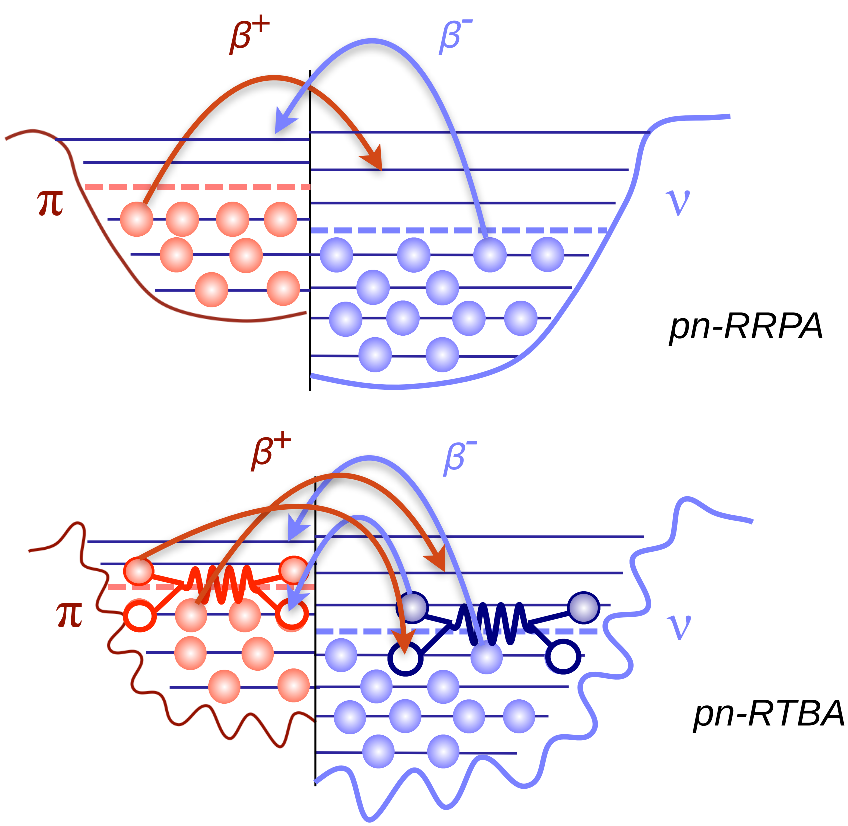


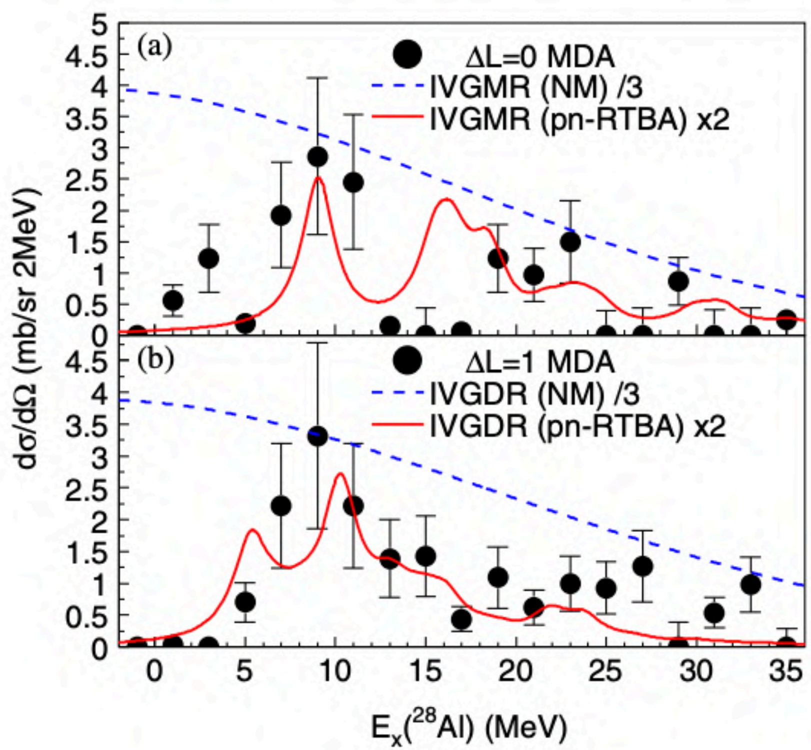
Exotic modes: the Isovector Giant Monopole Resonance

PRL **118,** 172501 (2017) PHYSICAL REVIEW LETTERS week ending 28 APRIL 2017

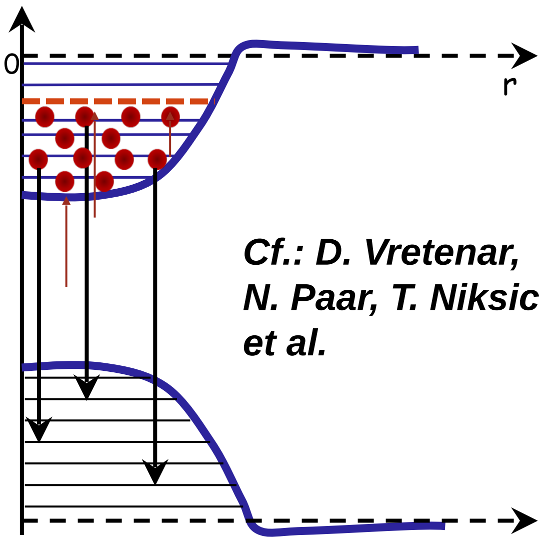
Observation of the Isovector Giant Monopole Resonance via the ^{28}Si(^{10}Be,^{10}B*[1.74 MeV]) Reaction at 100 AMeV

M. Scott,[1,2,3] R. G. T. Zegers,[1,2,3,*] R. Almus,[4] Sam M. Austin,[1,2,3] D. Bazin,[1] B. A. Brown,[1,2,3] C. Campbell,[5] A. Gade,[1,3] M. Bowry,[1] S. Galès,[6,7] U. Garg,[8] M. N. Harakeh,[9] E. Kwan,[1] C. Langer,[1,2] C. Loelius,[1,2,3] S. Lipschutz,[1,2,3] E. Litvinova,[10,1,2] E. Lunderberg,[1,3] C. Morse,[1,3] S. Noji,[1,2] G. Perdikakis,[4,1,2] T. Redpath,[4] C. Robin,[10,2] H. Sakai,[11] Y. Sasamoto,[12,11] M. Sasano,[11] C. Sullivan,[1,2,3] J. A. Tostevin,[13,1] T. Uesaka,[11] and D. Weisshaar[1]

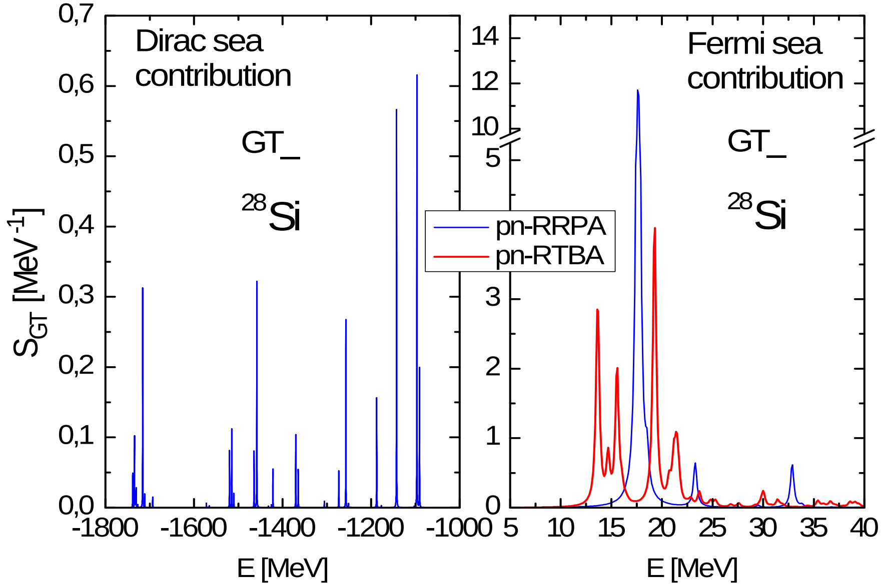




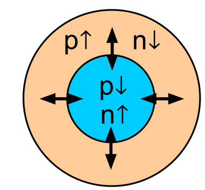
The Gamow-Teller resonance quenching puzzle: 28-Si



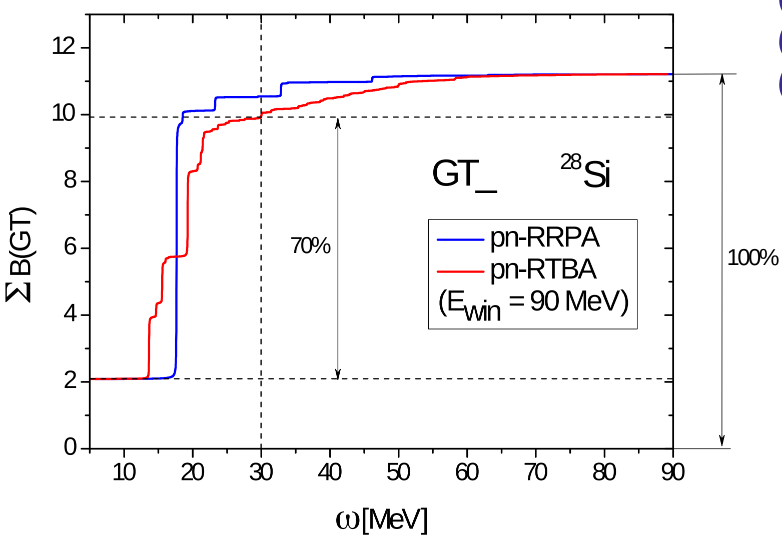
Cf.: D. Vretenar, N. Paar, T. Niksic et al.



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



ΔL = 0
ΔT = 1
ΔS = 1

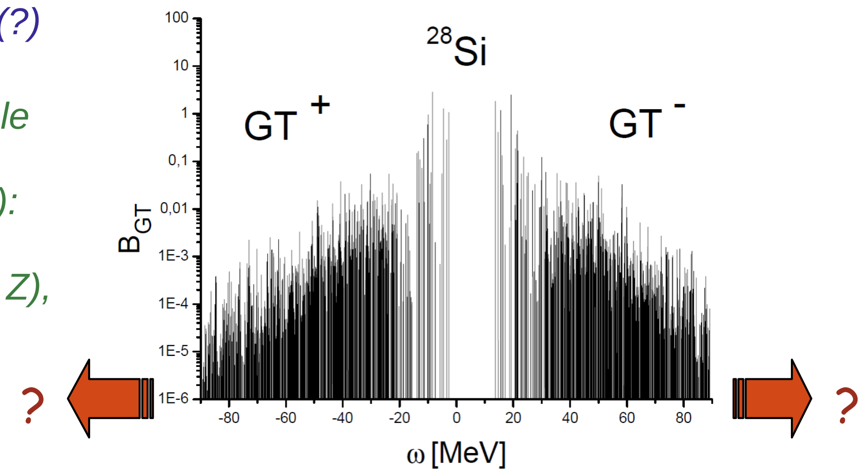


„Microscopic" quenching of B(GT):
(i) relativistic effects,
(ii) ph+phonon and higher configurations
(iii) 2b currents (?)

Cf.: H. Sagawa, Y. Niu, D. Gambacurta

Ikeda Sum rule (model independent):

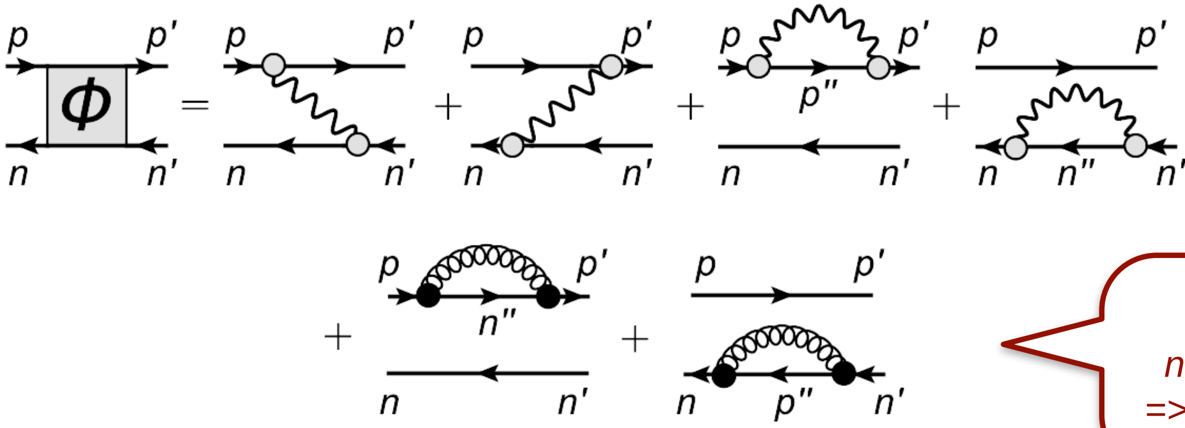
$$S_- - S_+ = 3(N - Z),$$



Problem: finite basis

More on quenching: Coupling to charge-exchange (CE) phonons

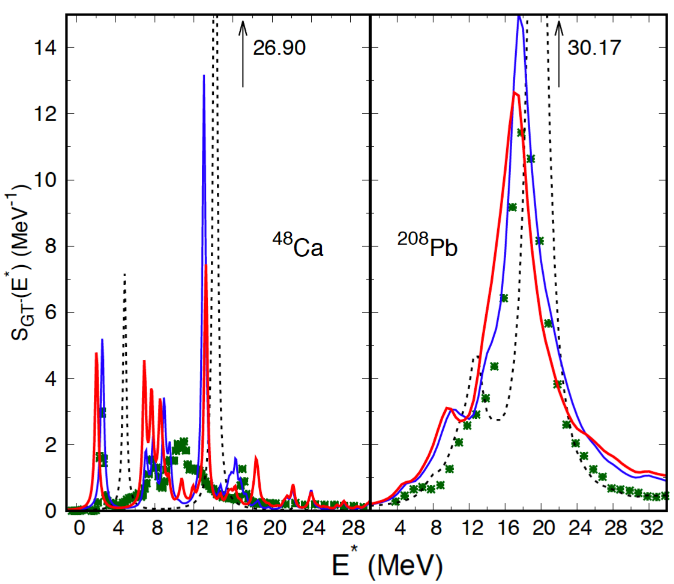
The role of coupling to charge-exchange (CE) vibrations

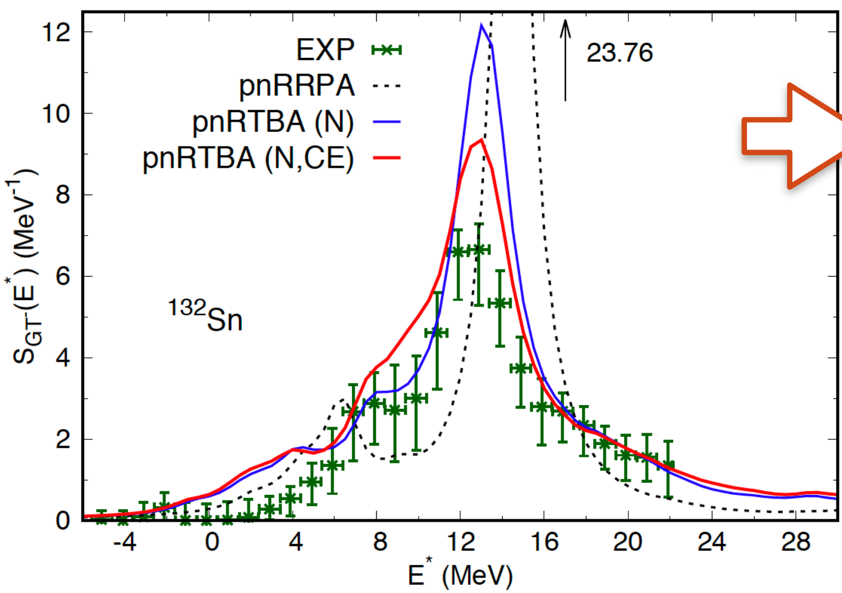


Neutral phonons:
Both phonon-exchange and self-energy contributions

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

Gamow-Teller response





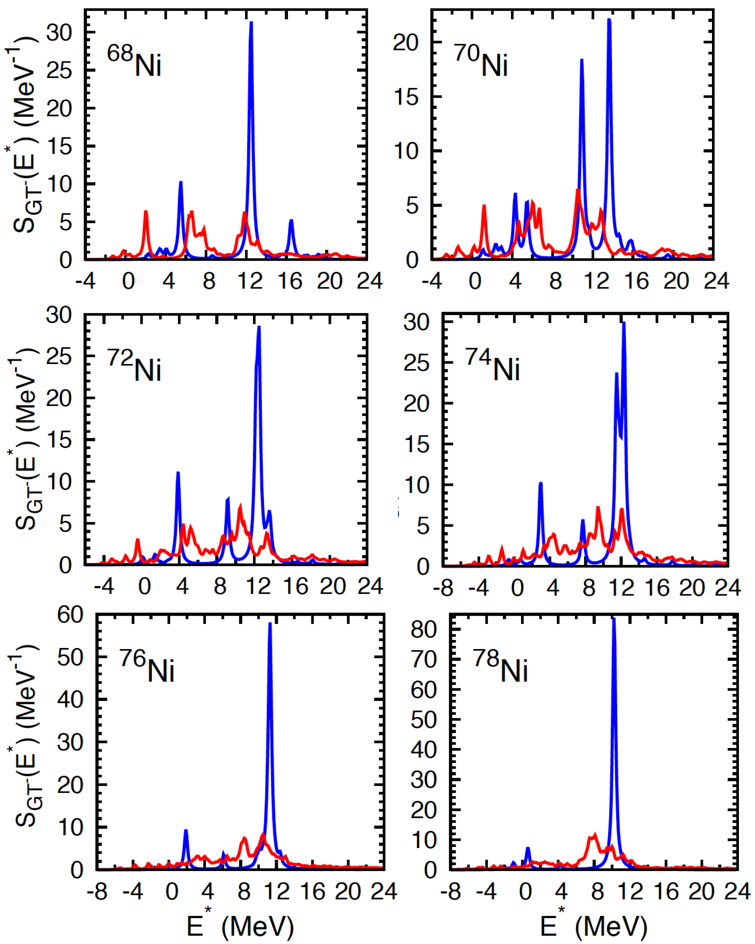
3p3h-configurations are needed for a consistent description without applying quenching factors (in progress)

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

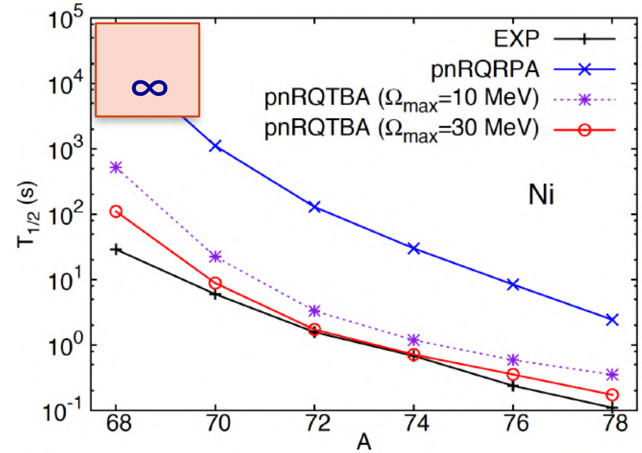
Data: J. Yasuda et al., Phys. Rev. Lett. 121, 132501 (2018)

The beta decay puzzle: Gamow-Teller resonance and $T_{1/2}$

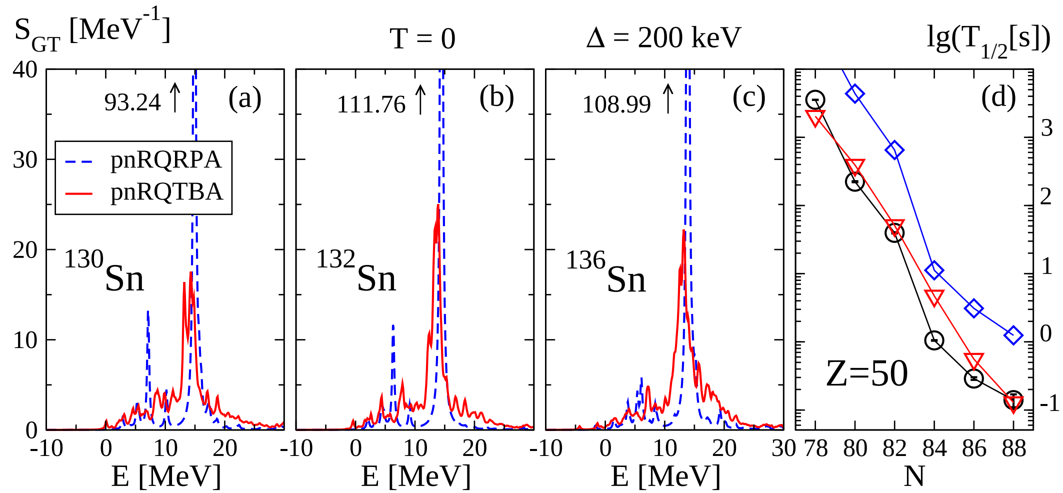
Overall strength
$^{68-78}$Ni isotopes:



Beta decay $T_{1/2}$



$^{128-138}$Sn isotopes:



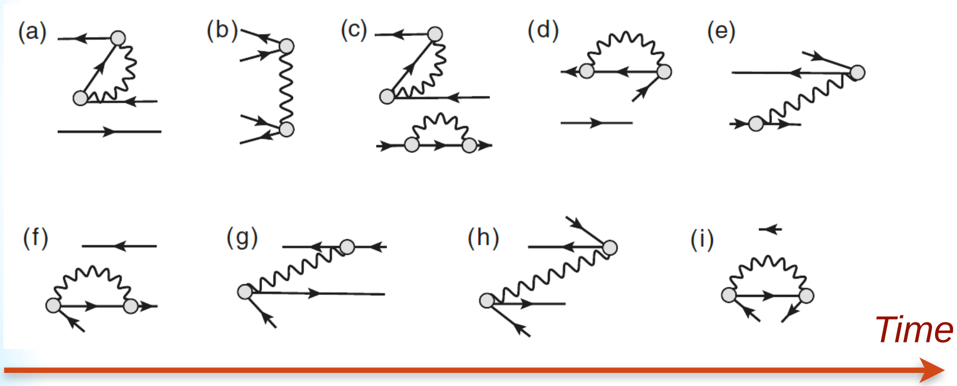
pn-RQRPA — *C. Robin, E.L., Eur. Phys. J. A 52, 205 (2016)*

pn-RQTBA — *E.L., C. Robin, H. Wibowo, PLB 800, 135134 (2020)*

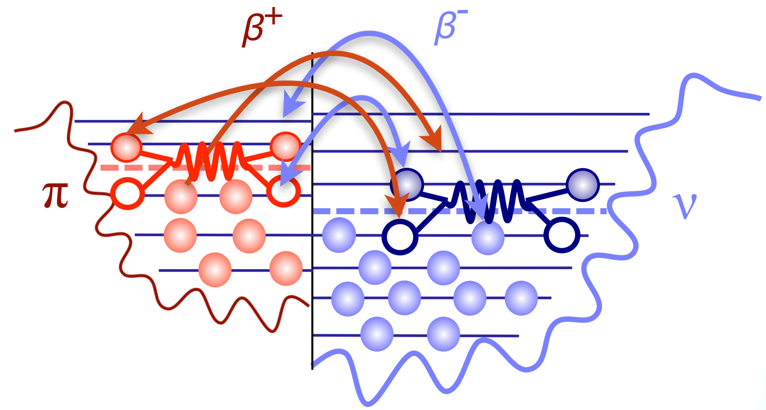
No fits, no artificial quenching,
no adjustable proton-neutron pairing

β+ strength in neutron-rich nuclei: absent in the leading qPVC approach

Ground state correlations induced by qPVC:
backward-going diagrams

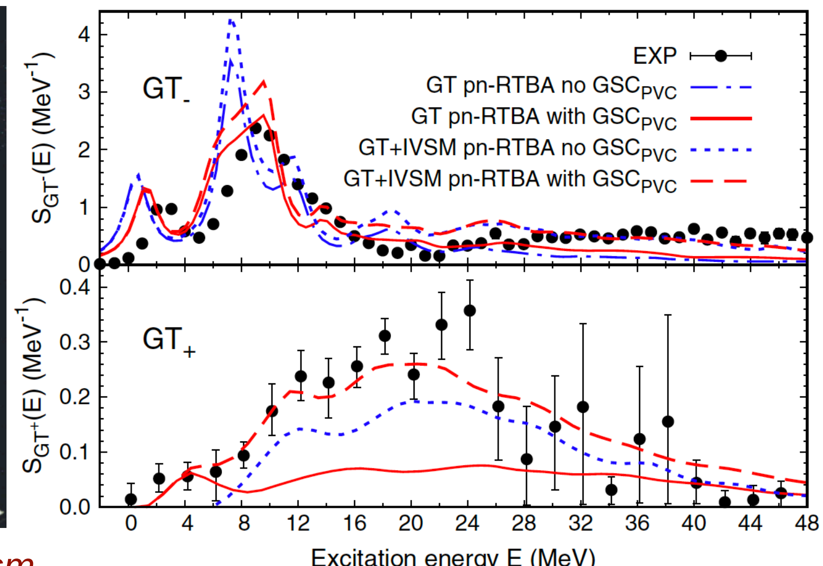


New unblocking mechanism:



Emergent "time machine"

Gamow-Teller +IVSM strength in 90-Zr:



The backward-going diagrams are the leading mechanism of the β+ strength formation in neutron-rich nuclei

C. Robin, E.L., Phys. Rev. Lett. 123, 202501 (2019)

The “Astro” puzzle: Finite-temperature response with the ph+phonon dynamical kernel

$$R_{12,1'2'}(t-t') = -i\langle \mathcal{T}(\bar\psi_1\psi_2)(t)(\bar\psi_{2'}\psi_{1'})(t')\rangle \rightarrow -i\langle \mathcal{T}(\bar\psi_1\psi_2)(t)(\bar\psi_{2'}\psi_{1'})(t')\rangle_T$$

$$< ... > \equiv < 0|...|0 > \;\; \rightarrow \;\; < ... >_T \equiv \sum_n exp\Big(\frac{\Omega - E_n - \mu N}{T}\Big) < n|...|n >$$

averages → *thermal averages*

Method: EOM for Matsubara Green’s functions

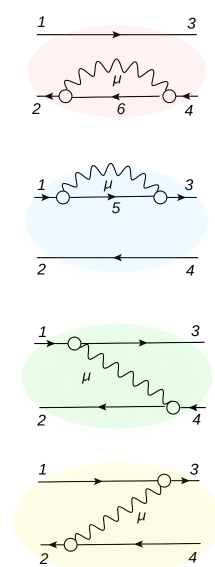
$$\mathcal{R}_{14,23}(\omega,T) = \tilde{\mathcal{R}}^0_{14,23}(\omega,T) + \\ + \sum_{1'2'3'4'} \tilde{\mathcal{R}}^0_{12',21'}(\omega,T)\big[\tilde{V}_{1'4',2'3'}(T) + \delta\Phi_{1'4',2'3'}(\omega,T)\big]\mathcal{R}_{3'4,4'3}(\omega,T)$$

$$\delta\Phi_{1'4',2'3'}(\omega,T) = \Phi_{1'4',2'3'}(\omega,T) - \Phi_{1'4',2'3'}(0,T)$$

See talk of H. Wibowo

T > 0: *1p1h+phonon dynamical kernel:* *T = 0:*

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



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

The "upbend" puzzle: understanding the Oslo data

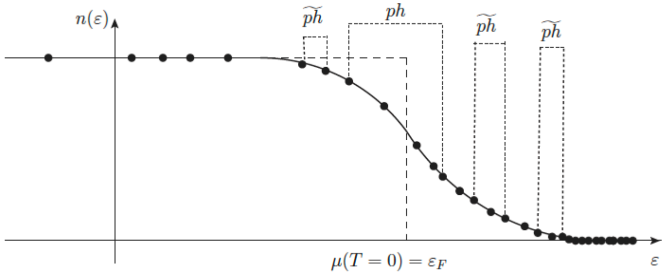
$$S(E,T) = -\frac{1}{\pi}\lim_{\Delta\to+0} Im\,\langle V^{0\dagger}\mathcal{R}(E+i\Delta,T)V^{0}\rangle$$

The final strength function at T>0:

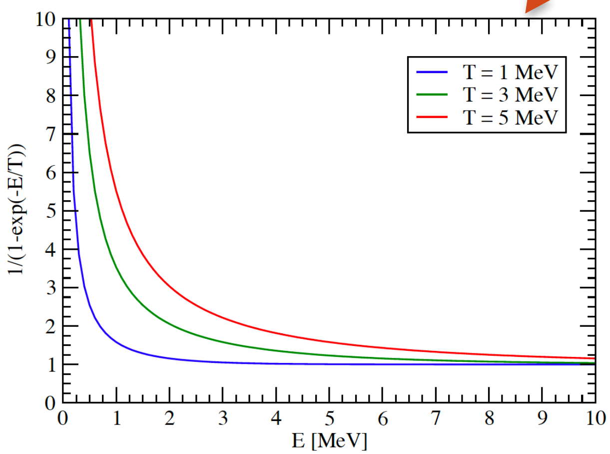
$$\tilde{S}(E) = \frac{1}{1-e^{-E/T}}S(E)$$

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

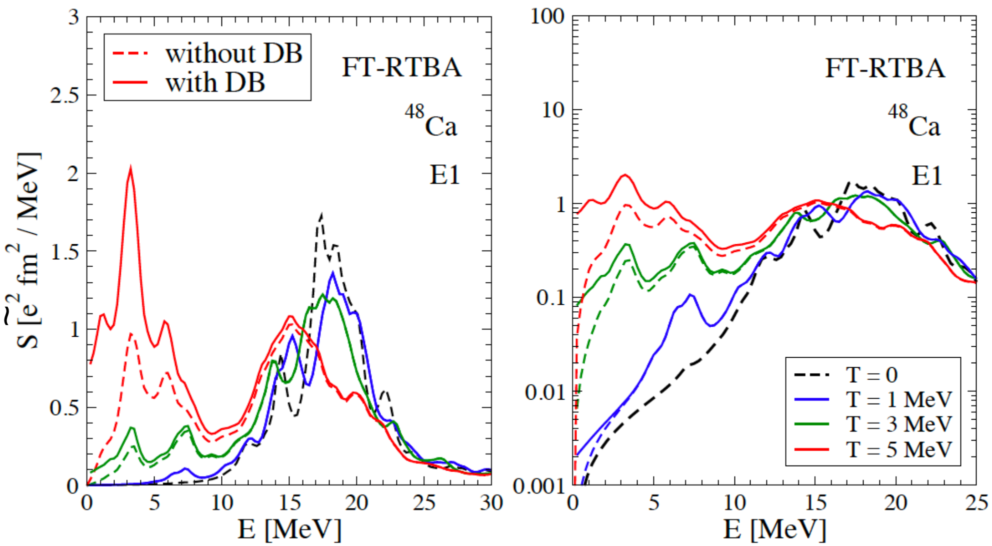
Thermal unblocking:



*The **generic** exponential factor:*



Dipole strength: absorption at T>0:



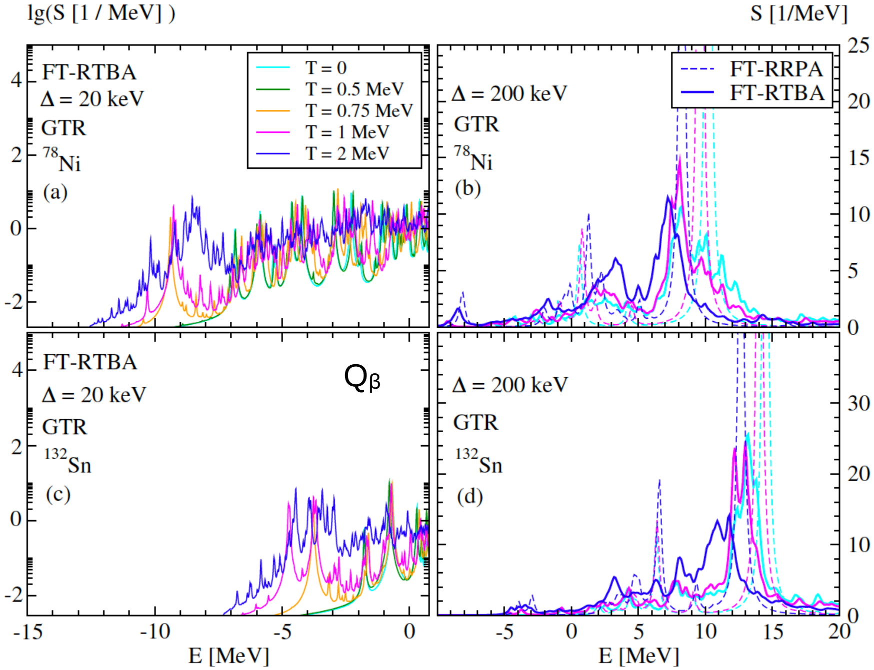
- *The exponential factor brings an additional enhancement in E<T energy region and provides the finite zero-energy limit of the strength (regardless its spin-parity)*

See talk of H. Wibowo

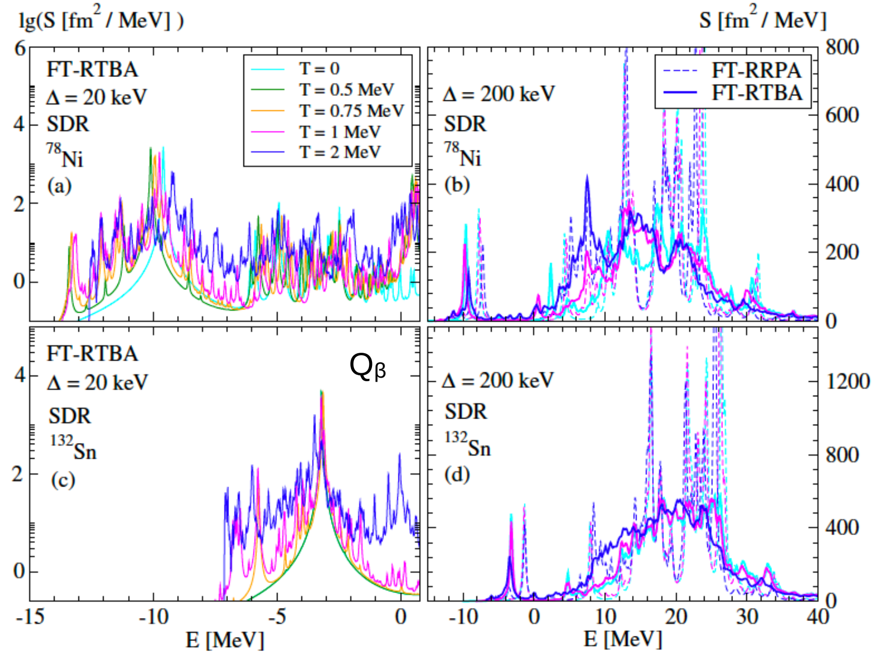
E.L., H. Wibowo, Phys. Rev. Lett. 121, 082501 (2018)
H. Wibowo, E.L., Phys. Rev. C 100, 024307 (2019)

Spin-Isospin response and beta decay in hot stellar environments

Gamow-Teller GT_ response of ^{78}Ni and ^{132}Sn

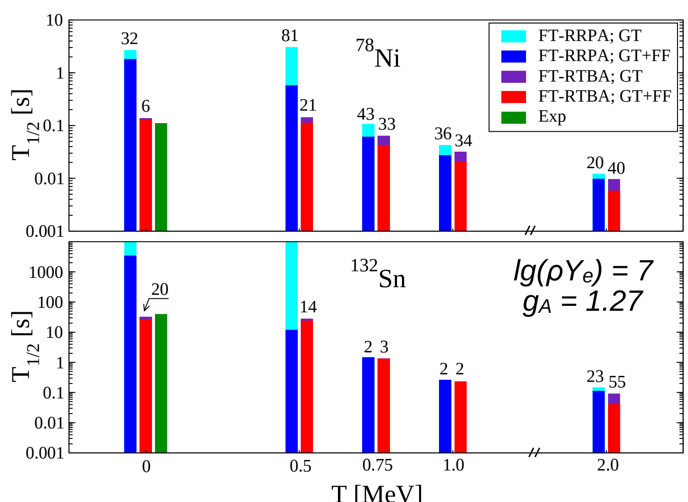


Spin Dipole response of ^{78}Ni and ^{132}Sn



An advanced microscopic description of the beta decay beyond (Q)RPA is available for the r-process modeling

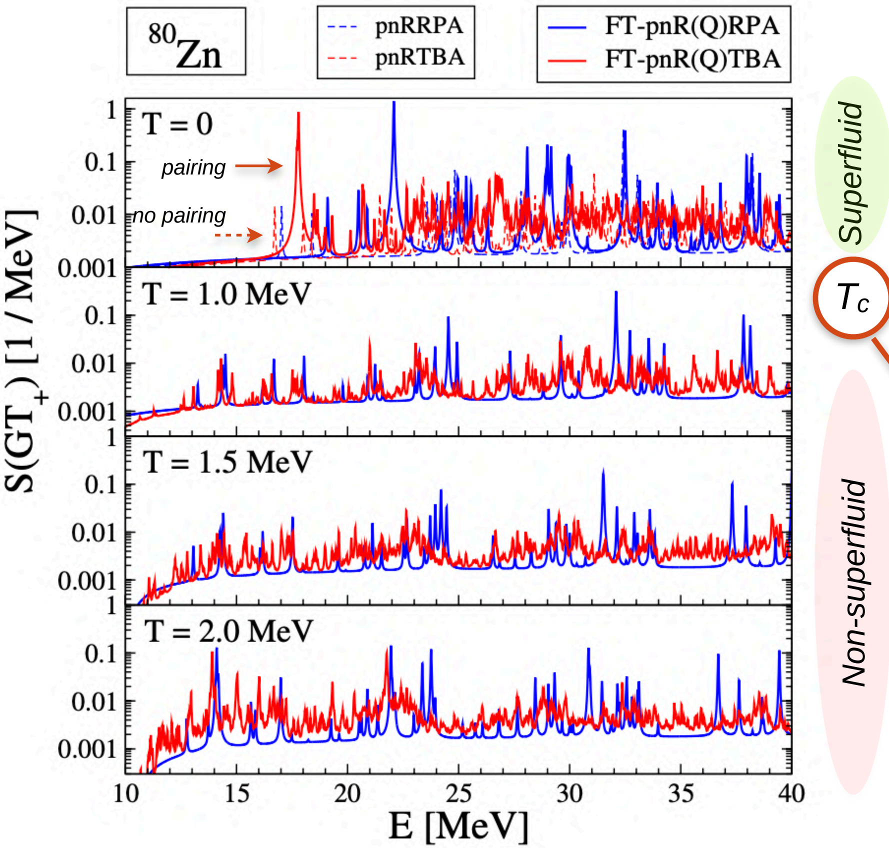
Beta decay half-lives in a hot stellar environment



E. Litvinova, H. Wibowo, Phys. Rev. Lett. 121, 082501 (2018)
H. Wibowo, E. Litvinova, Phys. Rev. C 100, 024307 (2019)
E. Litvinova, C. Robin, H. Wibowo, Phys. Lett. B 800, 135134 (2020)

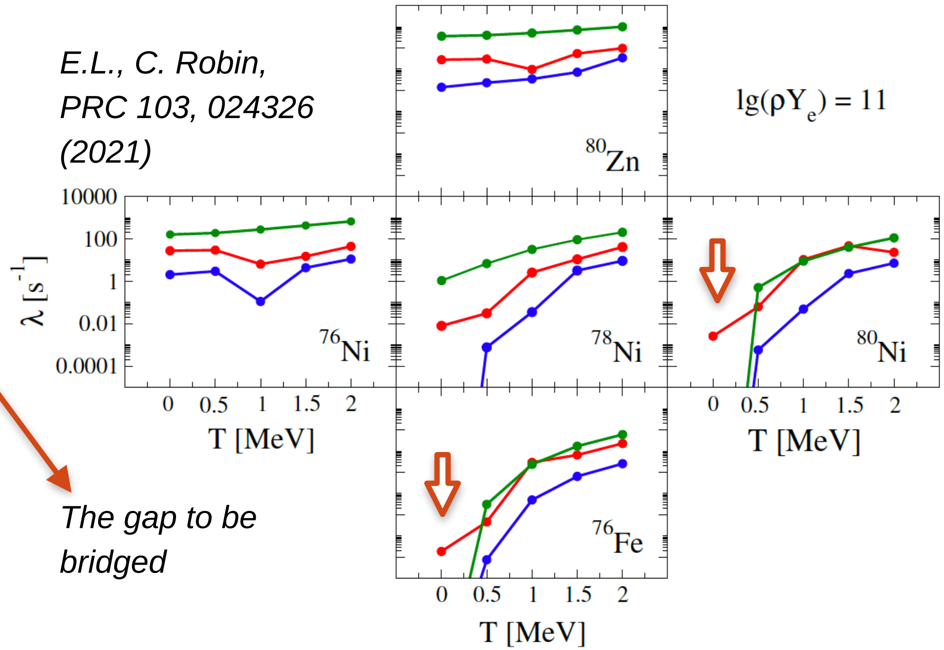
GT+ response and electron capture (EC) rates at T>0: the neighborhood of ^{78}Ni

GT+ response

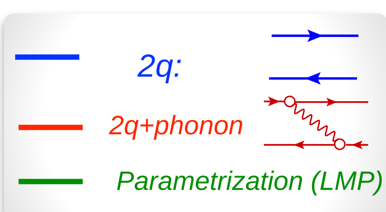


Electron capture rates around ^{78}Ni

E.L., C. Robin, PRC 103, 024326 (2021)



The gap to be bridged



An advanced microscopic description of the EC in the supernova is available

beyond (R)QRPA [E. Yüksel, N. Paar, Y. Niu, R. Zegers et al.]

Interplay *of superfluidity and collective effects in the core-collapse supernovae:*

- *Amplifies the EC rates and, consequently,*
- *Reduces the electron-to-baryon ratio leading to lower pressure*
- *Promotes the gravitational collapse*
- *Increases the neutrino flux and effective cooling*
- *Allows heavy nuclei to survive the collapse*

Towards complete formalism at T>0: the pairing channel

Averages redefined:

$$G_{12,1'2'}(t-t') = -i\langle \mathcal{T}(\psi_1\psi_2)(t)(\bar\psi_{2'}\bar\psi_{1'})(t')\rangle \to -i\langle \mathcal{T}(\psi_1\psi_2)(t)(\bar\psi_{2'}\bar\psi_{1'})(t')\rangle_T$$

Grand Canonical average: $< ... > \equiv < 0|...|0 > \;\;\to\;\; < ... >_T \equiv \sum_n exp\Big(\frac{\Omega - E_n - \mu N}{T}\Big) < n|...|n >$

Matsubara imaginary-time formalism: temperature-dependent dynamical kernel

Direct:

$$\mathcal{K}^{(r;11)}_{121'2'}(\omega_n) = -\sum_{\nu'\nu''} w_{\nu'}w_{\nu''}$$
$$\times\Big[\sum_{\nu\mu}\frac{\Theta^{\mu\nu;\nu'\nu''(+)}_{121'2'}}{i\omega_n - \omega_{\nu\nu'} - \omega^{(++)}_{\mu\nu''}}\big(e^{-(\omega_{\nu\nu'}+\omega^{(++)}_{\mu\nu''})/T} - 1\big)$$
$$-\sum_{\nu\varkappa}\frac{\Theta^{\varkappa\nu;\nu'\nu''(-)}_{121'2'}}{i\omega_n + \omega_{\nu\nu'} + \omega^{(--)}_{\varkappa\nu''}}\big(e^{-(\omega_{\nu\nu'}+\omega^{(--)}_{\varkappa\nu''})/T} - 1\big)\Big]$$

Exchange:

$$\mathcal{K}^{(r;12)}_{121'2'}(\omega_n) = \sum_{\nu'\nu''} w_{\nu'}w_{\nu''}$$
$$\times\Big[\sum_{\nu\mu}\frac{\Sigma^{\mu\nu;\nu'\nu''(+)}_{121'2'}}{i\omega_n - \omega_{\nu\nu'} - \omega^{(++)}_{\mu\nu''}}\big(e^{-(\omega_{\nu\nu'}+\omega^{(++)}_{\mu\nu''})/T} - 1\big)$$
$$-\sum_{\nu\varkappa}\frac{\Sigma^{\varkappa\nu;\nu'\nu''(-)}_{121'2'}}{i\omega_n + \omega_{\nu\nu'} + \omega^{(--)}_{\varkappa\nu''}}\big(e^{-(\omega_{\nu\nu'}+\omega^{(--)}_{\varkappa\nu''})/T} - 1\big)\Big],$$

E.L., P.Schuck, Phys. Rev. C 104, 044330 (2021)

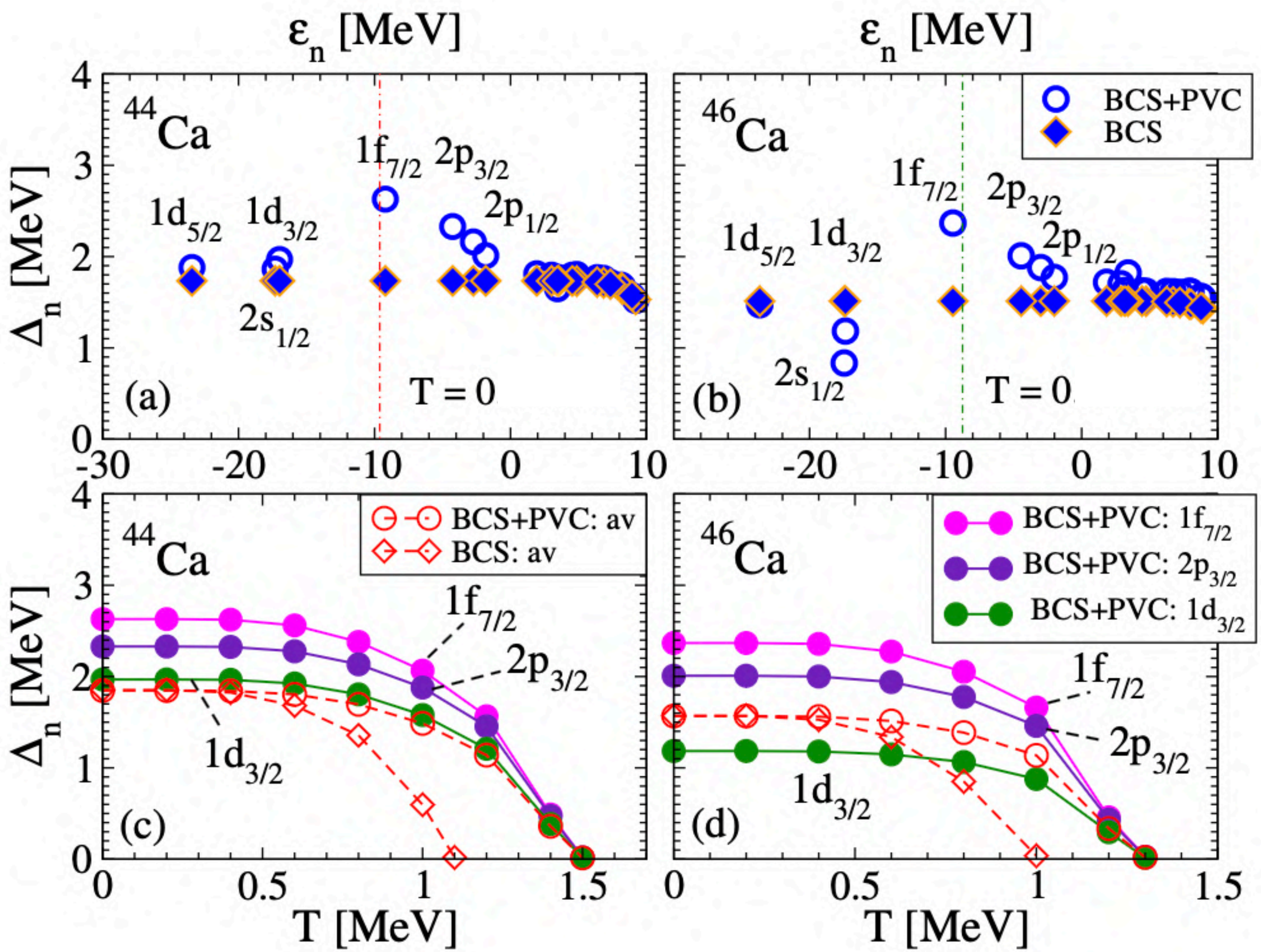
BCS-like gap Eq., but with non-trivial T-dependence in $K^{(r)}$:

$$f_1(T) = \frac{1}{\exp(E_1/T) + 1}$$

$$\Delta_1(T) = -\sum_2 \mathcal{V}_{1\bar1 2\bar2}\frac{\Delta_2(T)(1-2f_2(T))}{2E_2}$$

$$\mathcal{V}_{121'2'} = \frac{1}{2}\Big(K^{(0)}_{121'2'} + K^{(r)}_{121'2'}(2\lambda)\Big)$$

Pairing gap at T = 0, T>0 and critical temperature



E.L., P.Schuck, Phys. Rev. C 104, 044330 (2021)

Outlook

Summary:

- The relativistic nuclear field theory (RNFT) is formulated and advanced in the Equation of Motion (EOM) framework, with the emphasis on emergent collectivity, solving burning nuclear structure issues
- The emergent collective effects renormalize interactions in correlated media, underly the spectral fragmentation mechanisms, affect superfluidity and weak decay rates.
- Relativistic NFT is generalized to finite temperature and applied to nuclear superfluidity.
- Weak rates at astrophysical conditions are extracted: the correlations beyond QRPA are found significant.

Current and future developments:

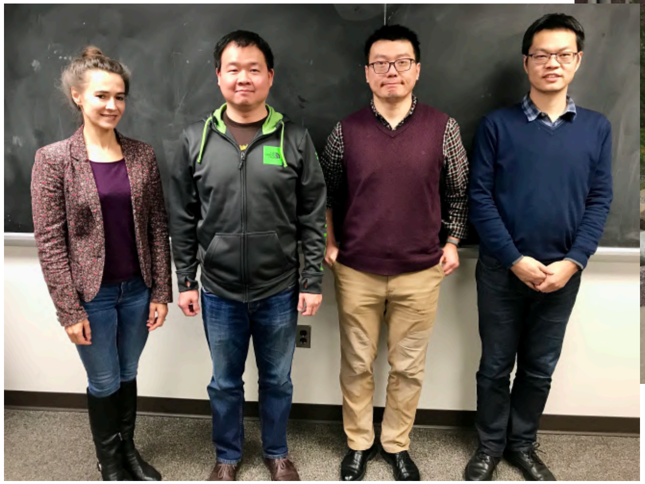
- Deformed nuclei: correlations vs shapes; first results just released (Yinu Zhang et al.);
- Efficient algorithms; quantum computing (Manqoba Hlatshwayo et al.);
- Implementation of the EC rates into the core-collapse supernovae simulations;
- Toward an “ab initio” description: implementations with bare NN-interactions;
- Superfluid pairing at T>0 to extend the application range (r-process);
- Relativistic EOM’s, bosonic EOM’s, beyond Standard Model, …

Many thanks for collaboration and support:

Yinu Zhang (WMU)
Manqoba Hlatshwayo (WMU)
Herlik Wibowo (AS Taipei)
Caroline Robin (U. Bielefeld & GSI)
Peter Schuck (IPN Orsay)
Peter Ring (TU München)
Tamara Niksic (U Zagreb)

2017:

2018:



US-NSF CAREER PHY-1654379 (2017-2023)

US-NSF PHY-2209376 (2022-2025)

2019-2020:

2020-2022:

Thank you!