Temperature evolution of the nucleon effective mass and symmetry energy coefficient in the $^{68\text{-}78}$Ni isotopic chain

Herlik Wibowo

Collaborator: Elena Litvinova

7th International Conference on Collective Motion in Nuclei under Extreme Conditions (COMEX7)
June 11-16, 2023

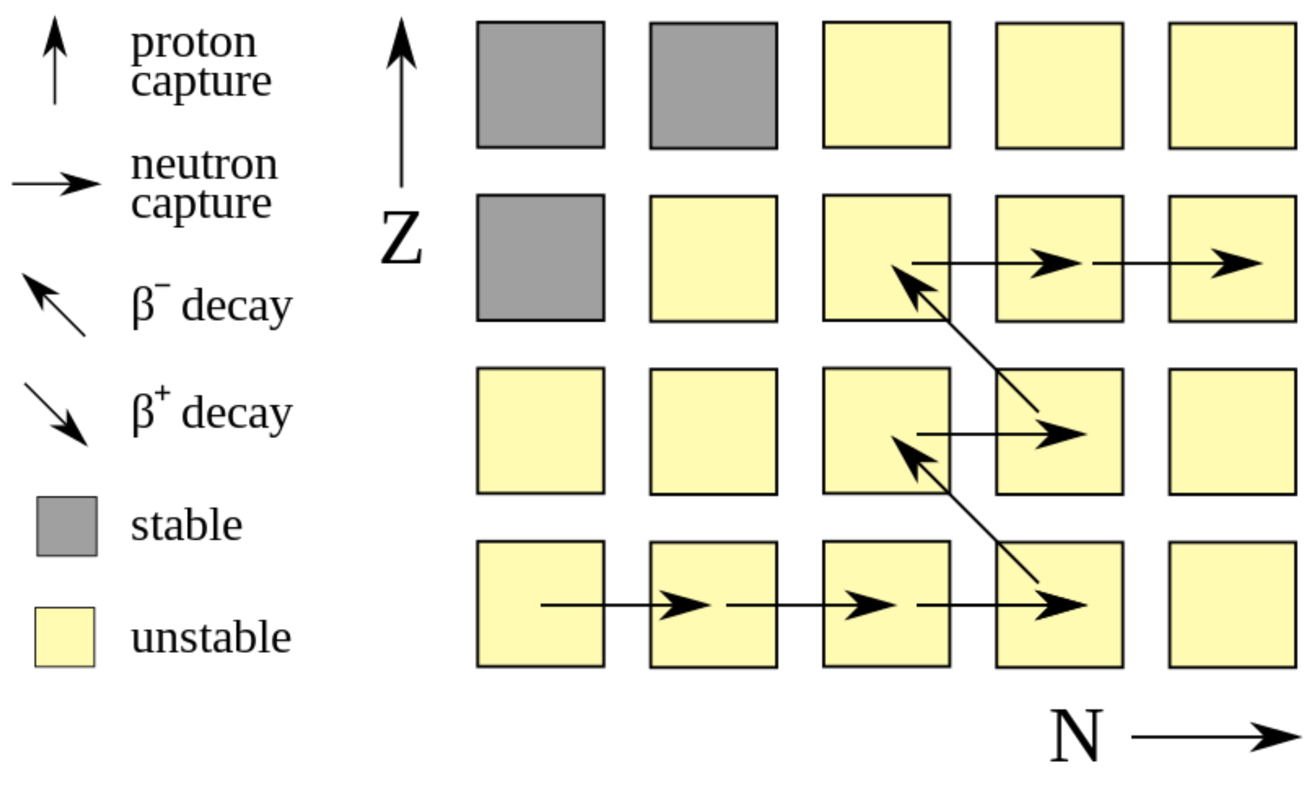
UNIVERSITY of York

WESTERN MICHIGAN UNIVERSITY

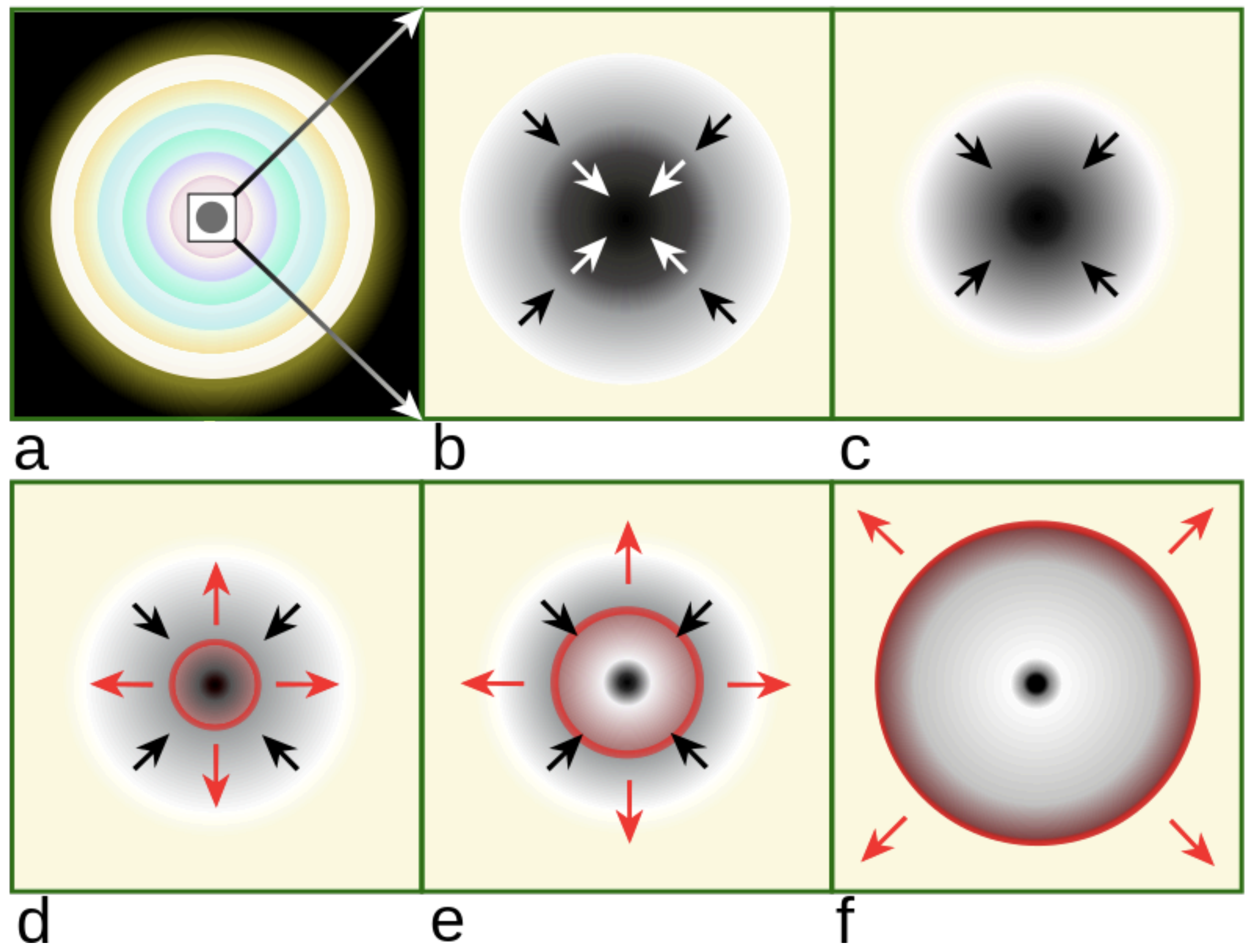
Astrophysical motivation

r-process
rapid neutron captures

X(n,γ)Y



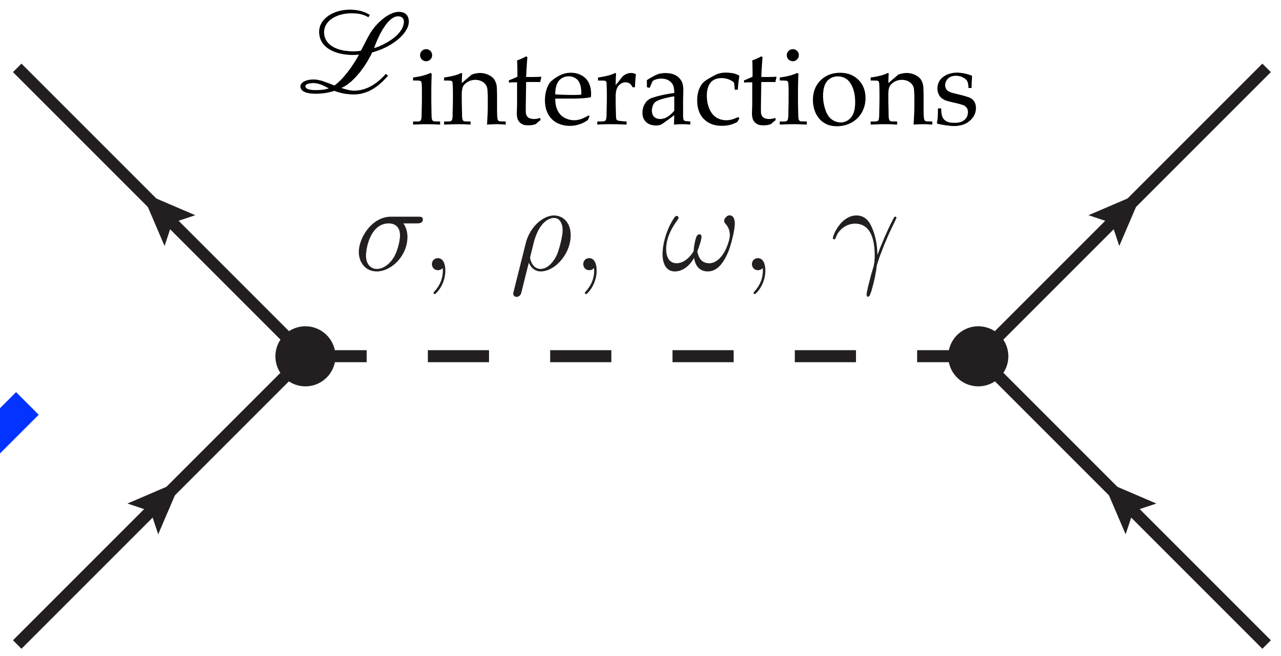
synthesis of neutron-rich nuclei
A > 60



By Illustration by R.J. Hall. Redrawn in Inkscape by Magasjukur2 - File:Core collapse scenario.png, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=12779311

- Nuclear physics input for the r-process modeling: nuclear masses, beta-decay half-lives, and neutron capture rates.
- In the neutron capture rates calculations, the level density of the excited states and gamma-ray strength functions are the critical statistical properties. [Stephane Goriely's talk, S. Nikas et al., arXiv:2010.01698]
- The evolution of the nuclear shell structure with temperature has an impact on the nuclear level density.
- During the core-collapse supernova, the rate of electron capture is affected by the temperature evolution of the nucleon effective mass and the symmetry energy. [P. Donati et al., Phys. Rev. Lett. **72**, 2835 (1994)]

Nuclear mean field at finite temperature

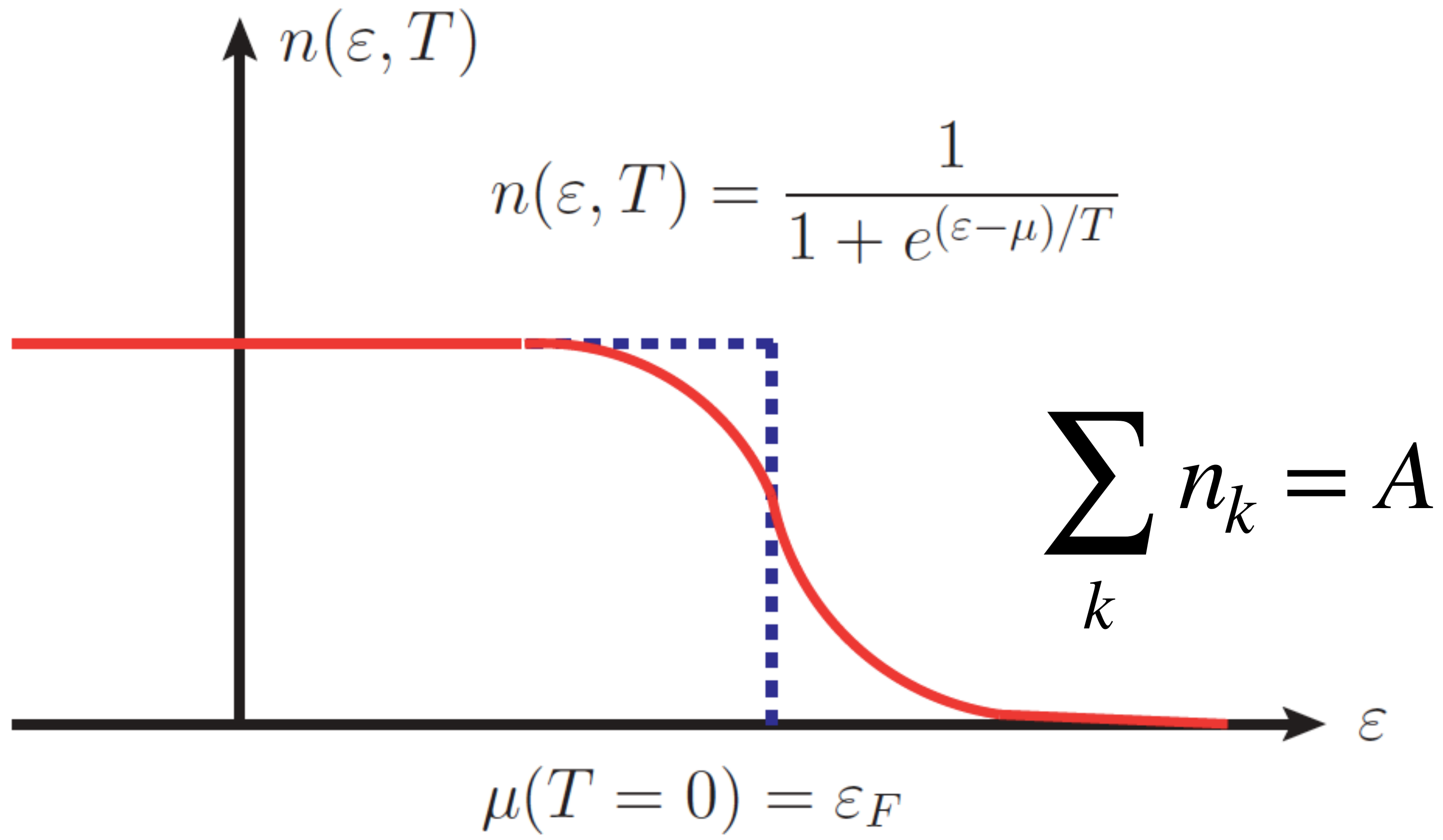


Mean-field approximation

Dirac equation

Klein-Gordon equations

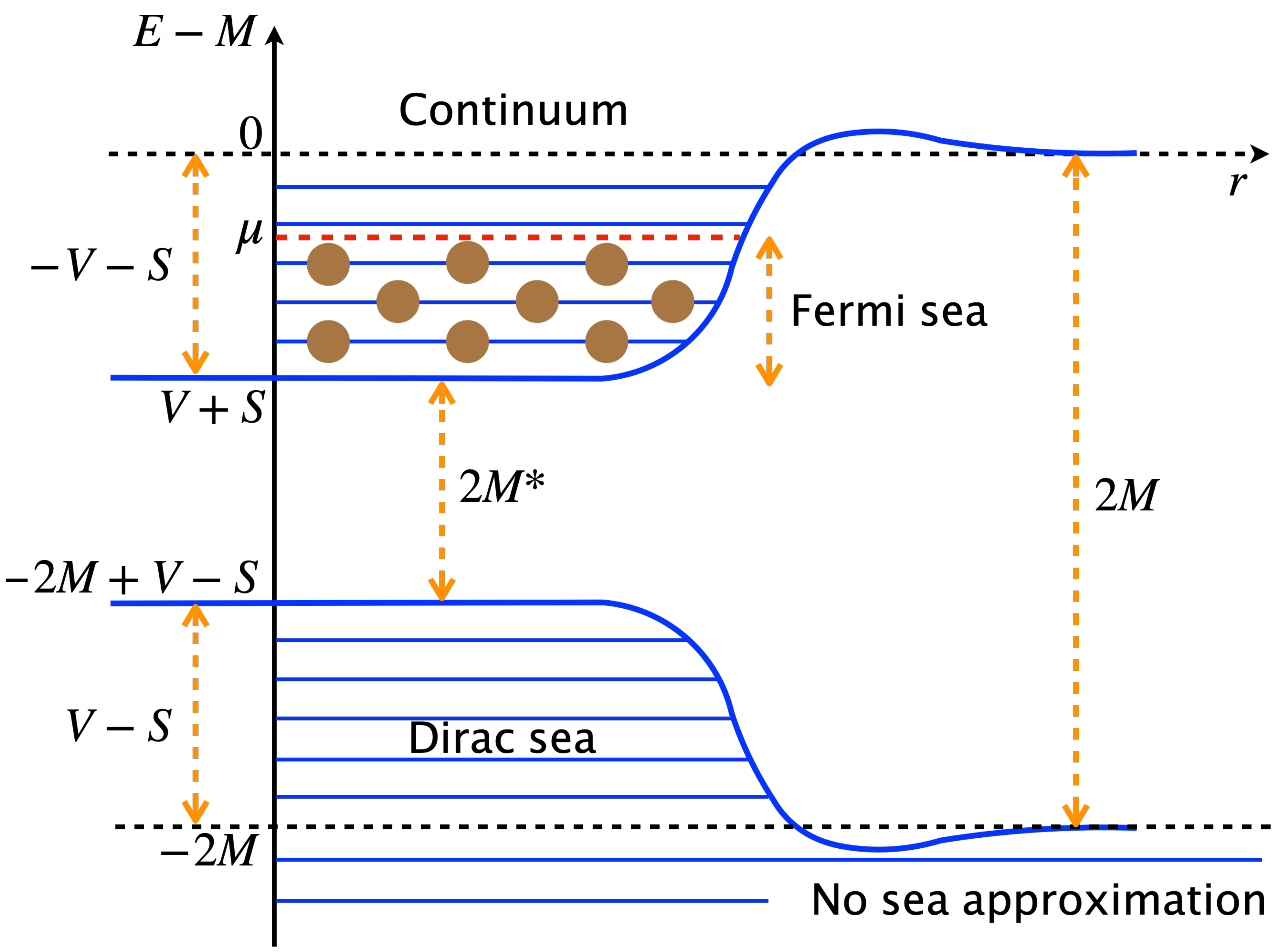
Four baryonic densities



$$\sum_k n_k = A$$

NL3 parametrization

Self-consistent mean field



Serot and Walecka, Advance in Nuclear Physics, Vol. 16 (1986)

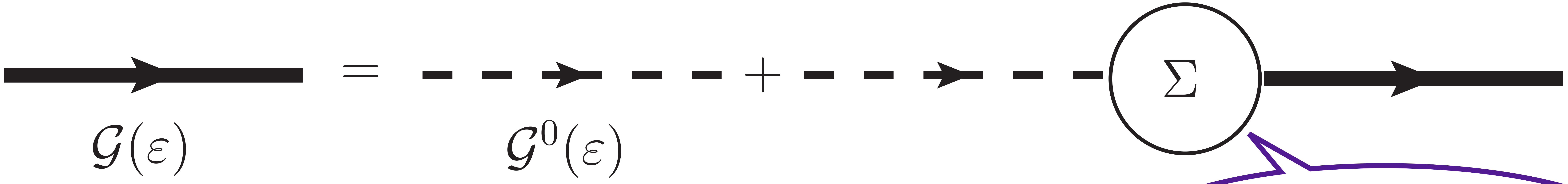
Ring, Prog. Part. Nucl. Phys. **37**, 193 (1996)

G. A. Lalazissis, J. König, and P. Ring, Phys. Rev. C **55**, 540 (1997)

Correlations beyond mean field

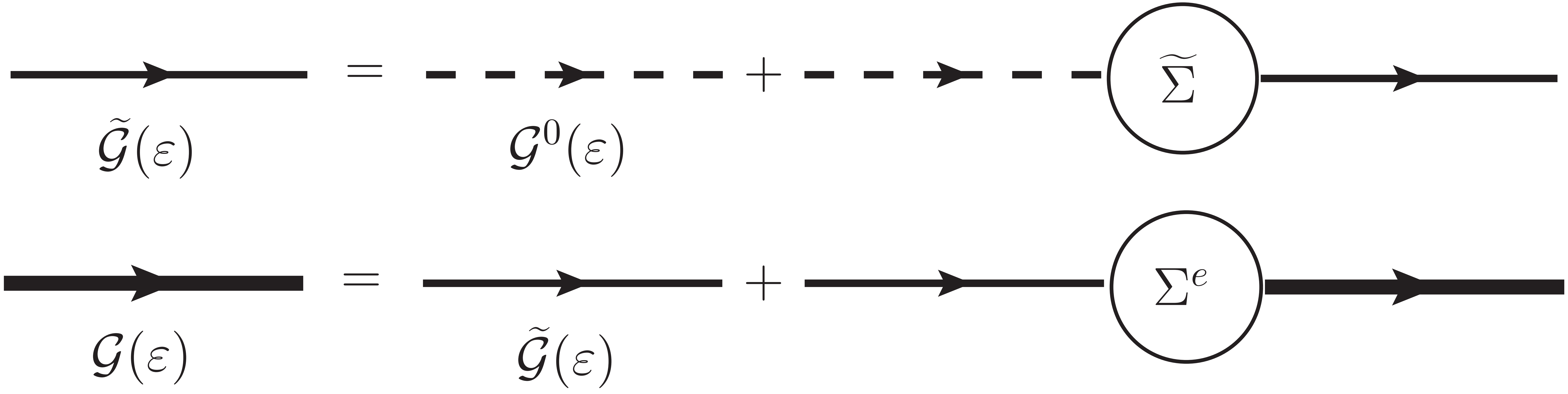
E. Litvinova and P. Schuck, **Nuclear superfluidity at finite temperature**

Full Dyson equation:

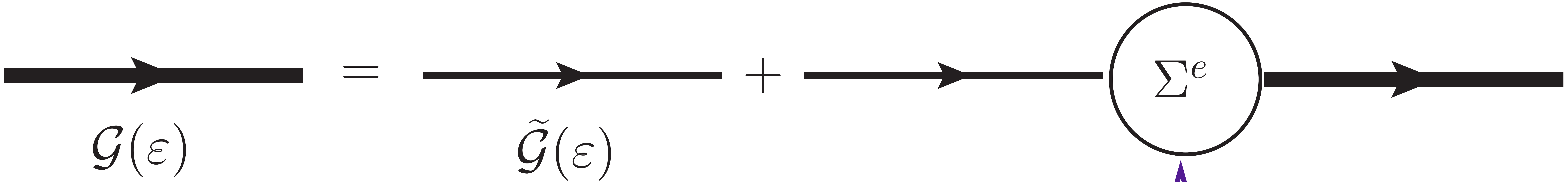


$$\Sigma(\varepsilon) = \widetilde{\Sigma} + \Sigma^e(\varepsilon)$$

is equivalent to two Dyson equations:



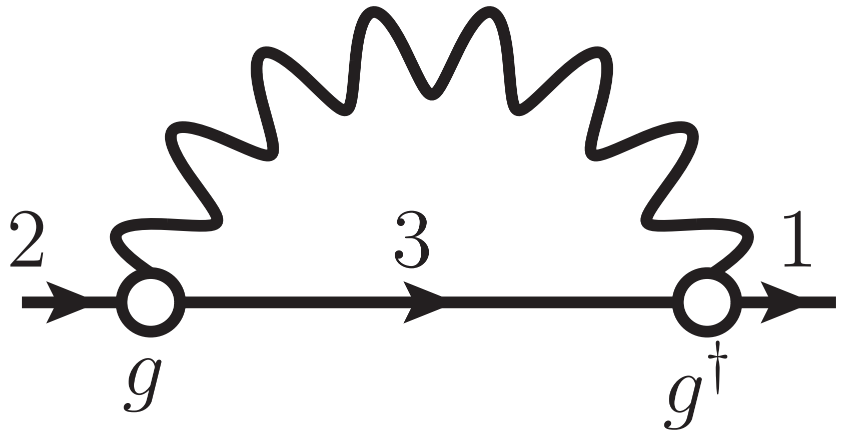
4



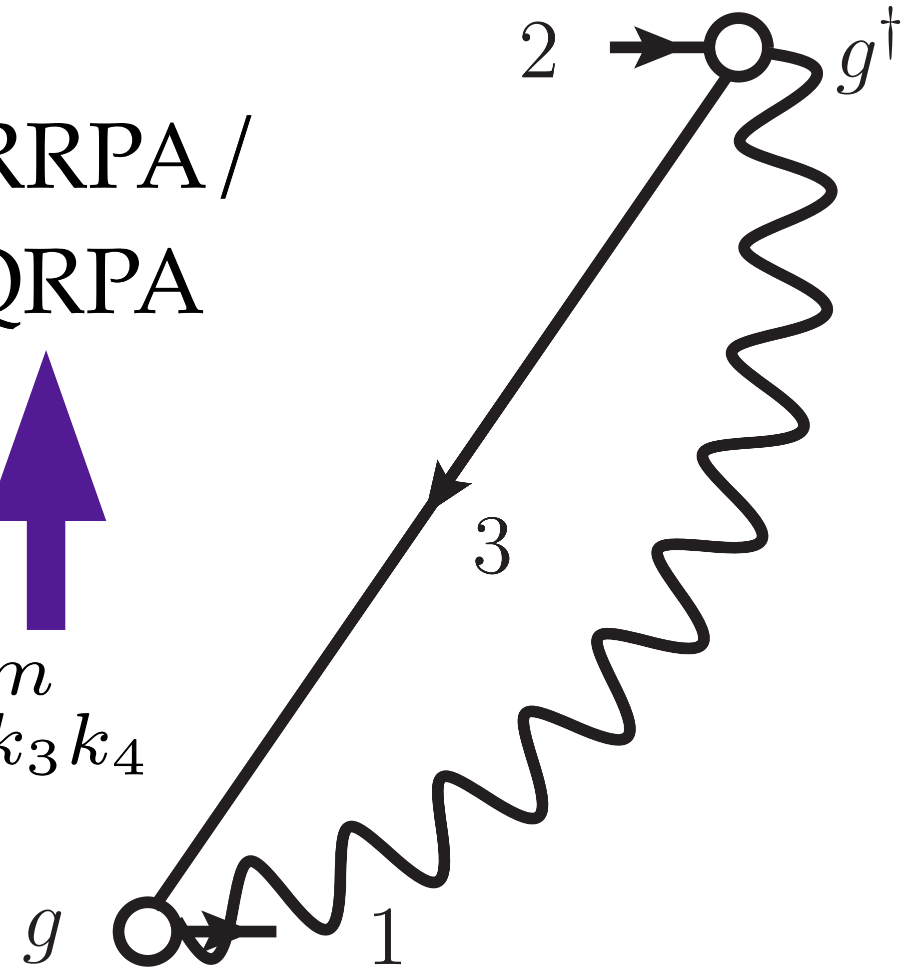
$$\tilde{\mathcal{G}}_{k_2k_1}(\varepsilon_\ell) = \frac{\delta_{k_2k_1}}{i\varepsilon_\ell - \varepsilon_{k_1} + \mu}$$

$$\varepsilon_\ell = (2\ell + 1)\pi T$$

T. Matsubara, Prog. Theor. Phys. **14**, 351 (1995)



FT-RRPA / RQRPA



$$g^m_{k_1k_2} = \sum_{k_3k_4} \tilde{\mathcal{U}}_{k_1k_2,k_3k_4}\rho^m_{k_3k_4}$$

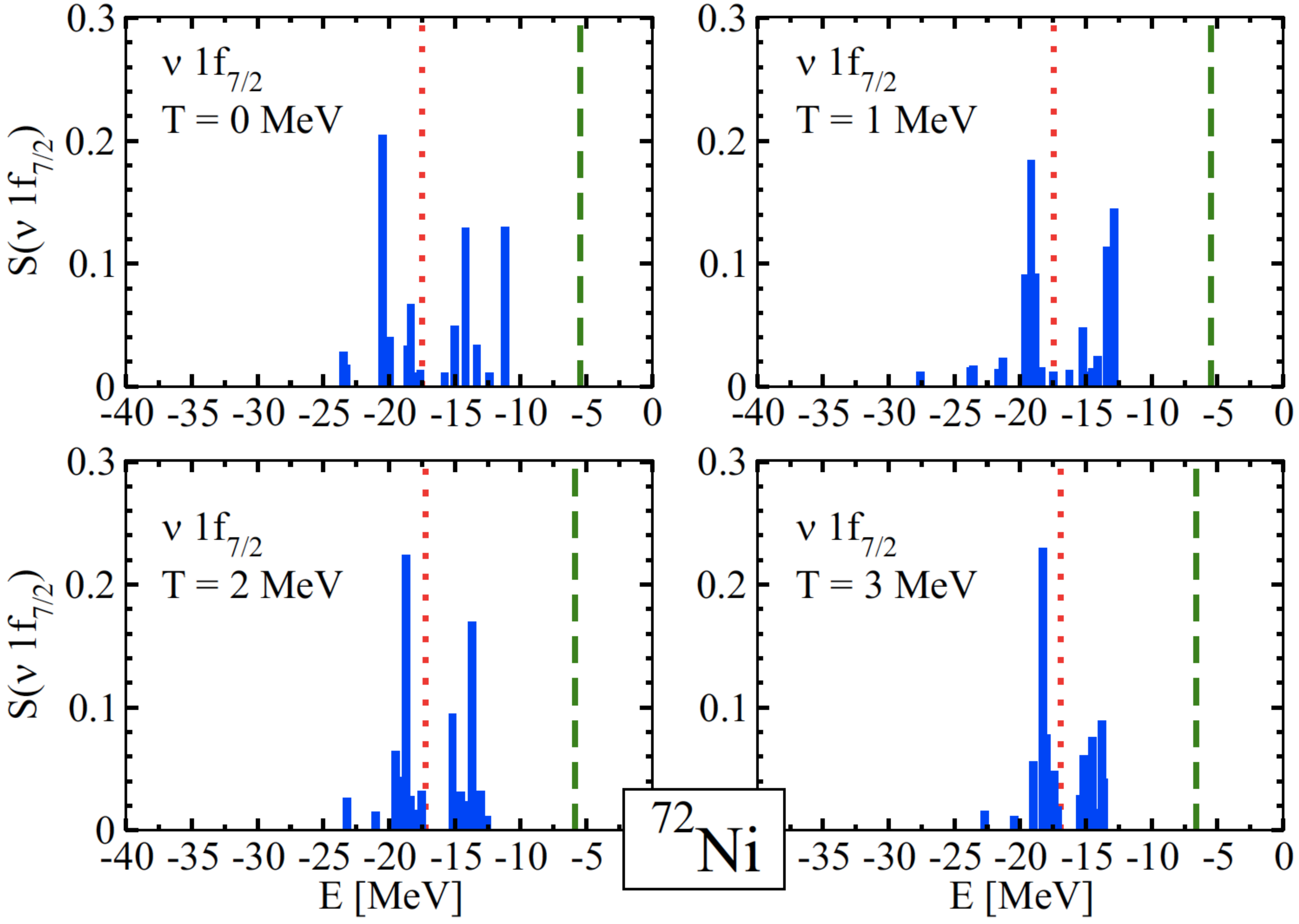
Particle-vibration coupling (PVC) self-energy

FT-Dyson equation: $\left[\varepsilon - \varepsilon_k + \mu - \Sigma^e_k(\varepsilon)\right]\mathcal{G}_k(\varepsilon) = 1 \rightarrow \left\{\varepsilon^{(\lambda)}_k\right\}$

Spectroscopic factor: $S^{(\lambda)}_k = \left(1 - \frac{d\Sigma^e_k(\varepsilon)}{d\varepsilon}\Big|_{\varepsilon=\varepsilon^{(\lambda)}_k}\right)^{-1}; \quad \sum_\lambda S^{(\lambda)}_k = 1$

5

Fragmentation of single-particle states

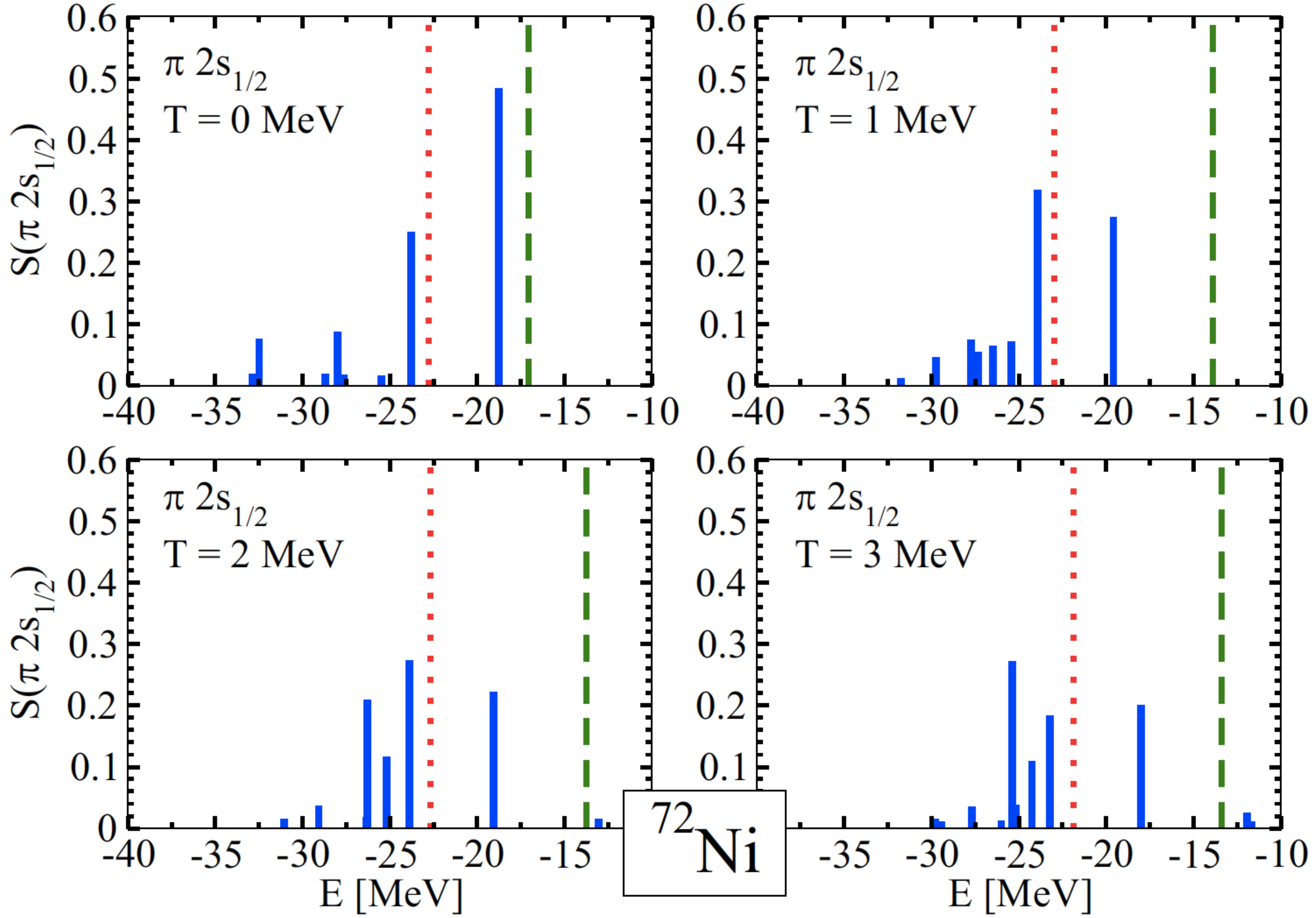


H. Wibowo and E. Litvinova, Phys. Rev. C **106**, 044304 (2022)

: spectroscopic factors of the fragmented states

: spectroscopic factors of the pure mean-field states

: position of chemical potential



6 Role of (q)PVC in nuclear multipole responses

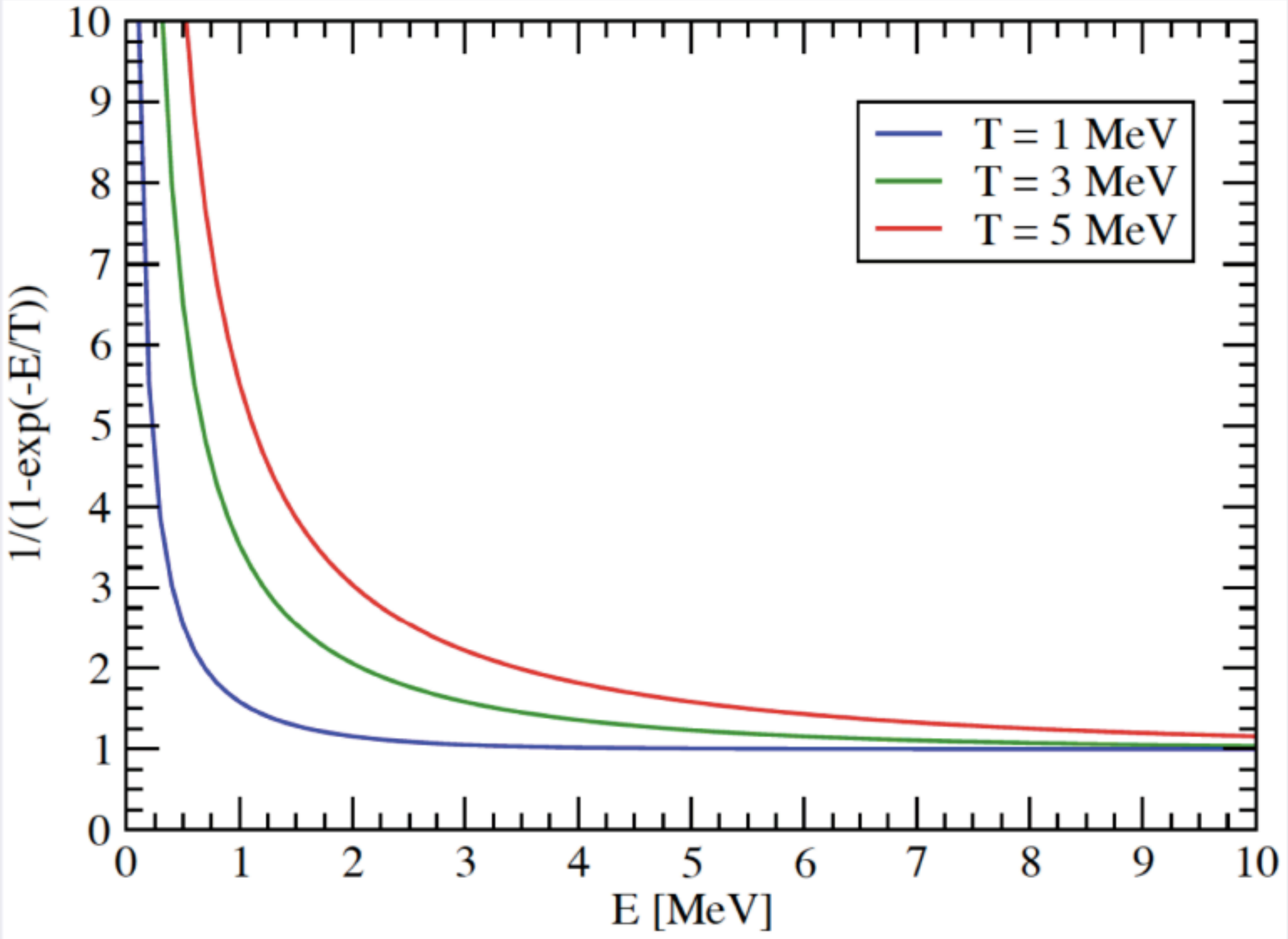
Strength Function at $T > 0$

$$\widetilde{S}(E) = \frac{1}{1 - e^{-E/T}} \lim_{\Delta \to +0} \frac{1}{\pi} \mathrm{Im} \sum_{1234} V^{0*}_{21} \mathscr{R}_{12,34}(E + i\Delta)\, V^{0}_{43}$$

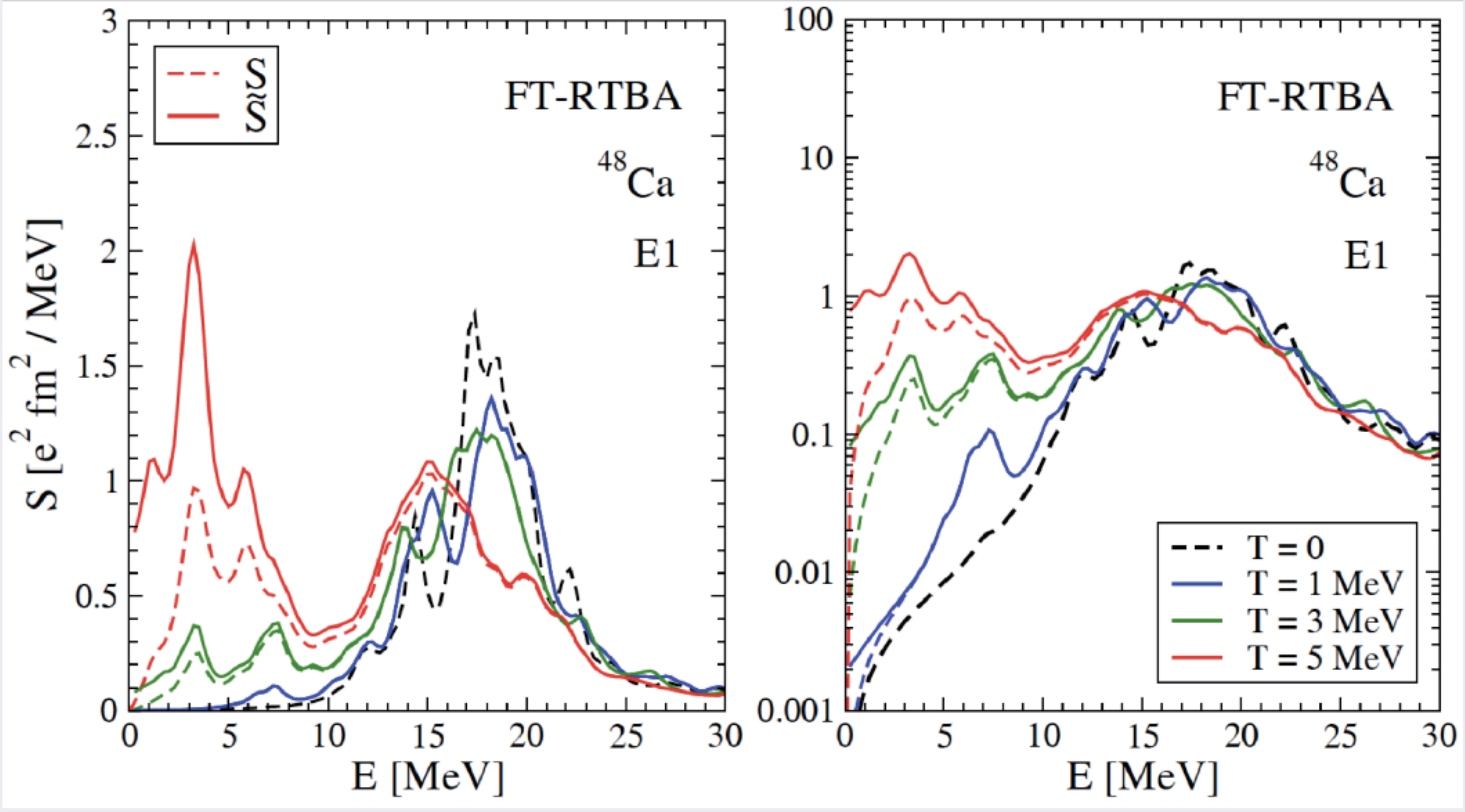
Spectral density $S(E)$

Exponential factor

Exponential Factor



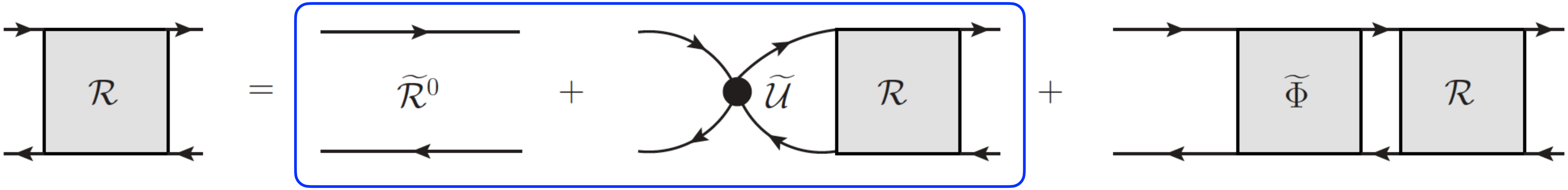
The Role of Exponential Factor



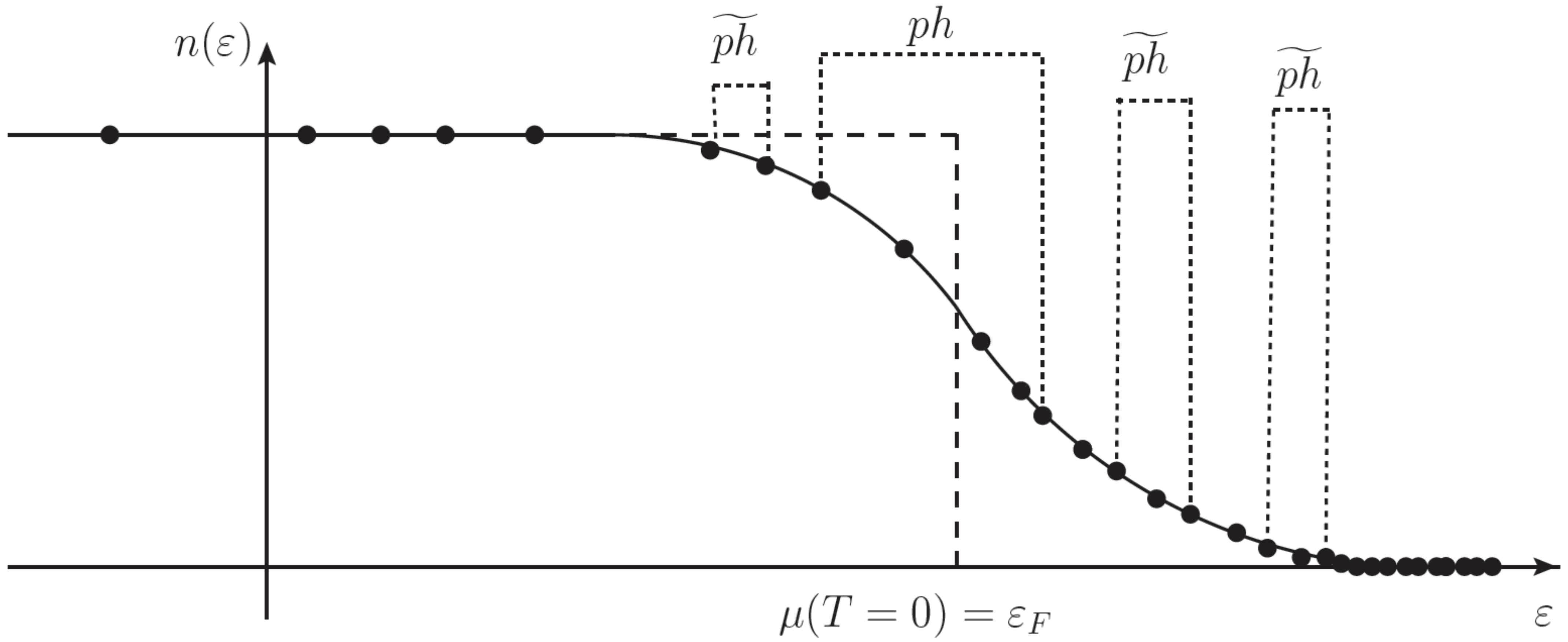
E. Litvinova and **H. Wibowo**, EPJA **55**, 223 (2019)

Bethe-Salpeter equation:

FT-RRPA



Free response: $$\widetilde{\mathscr{R}}^0_{12,34}(\omega) = \delta_{13}\delta_{24}\frac{n_2(T) - n_1(T)}{\omega - \varepsilon_1 + \varepsilon_2}$$

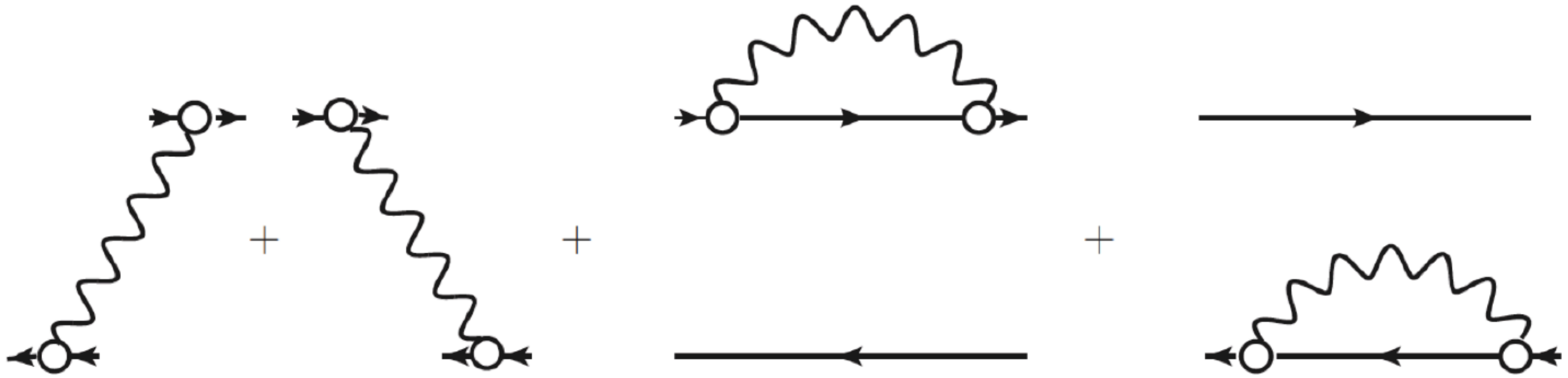


Effective meson-exchange interaction:

$$\widetilde{\mathscr{U}}_{k\ell,k'\ell'} = \frac{\delta\widetilde{\Sigma}_{k'\ell'}}{\delta\rho_{k\ell}}$$

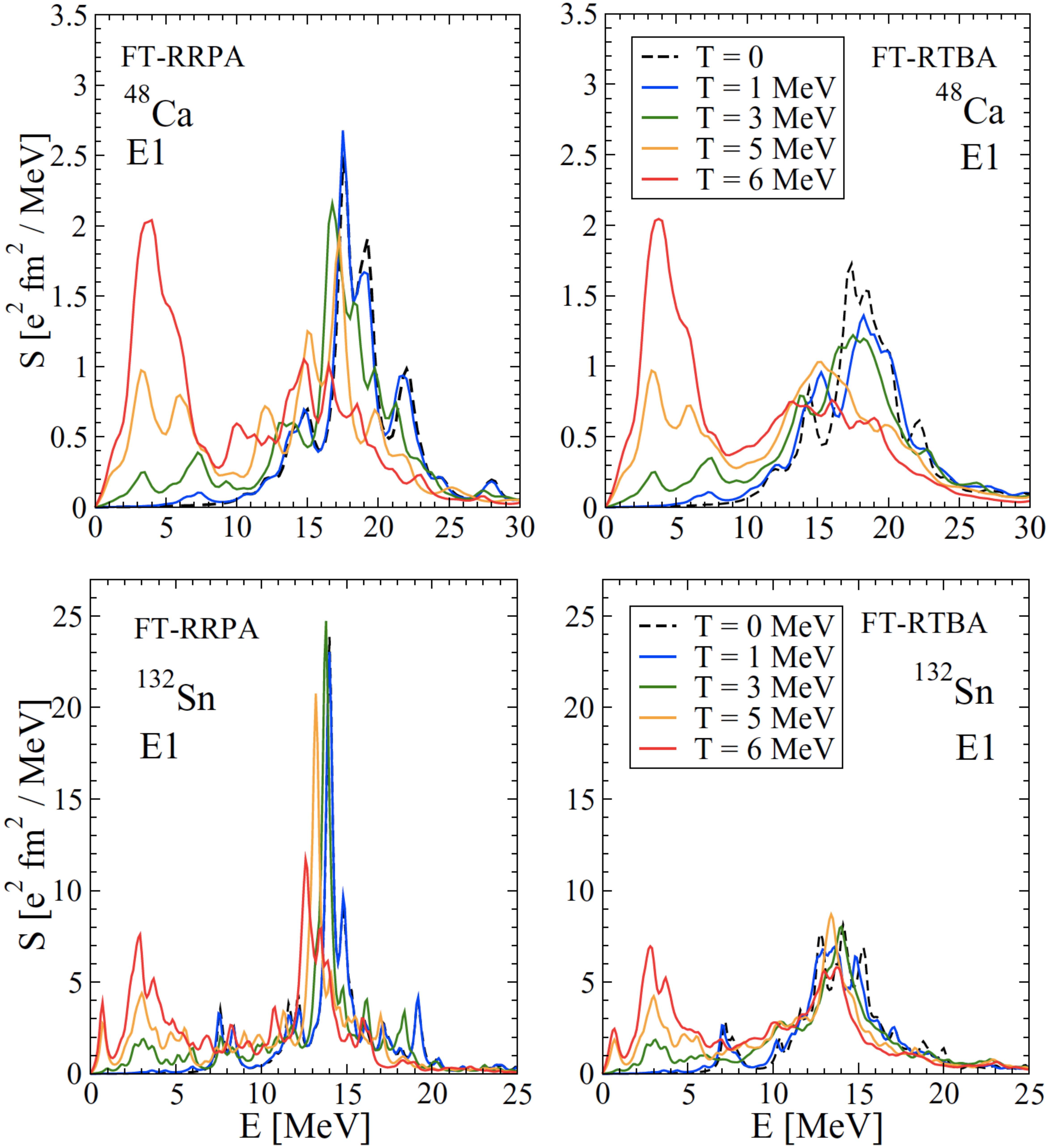
PVC amplitude:
(FT-RTBA)

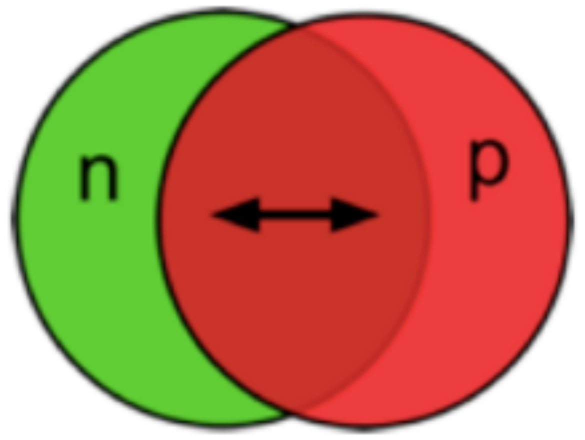
$\widetilde{\Phi}(\omega) =$



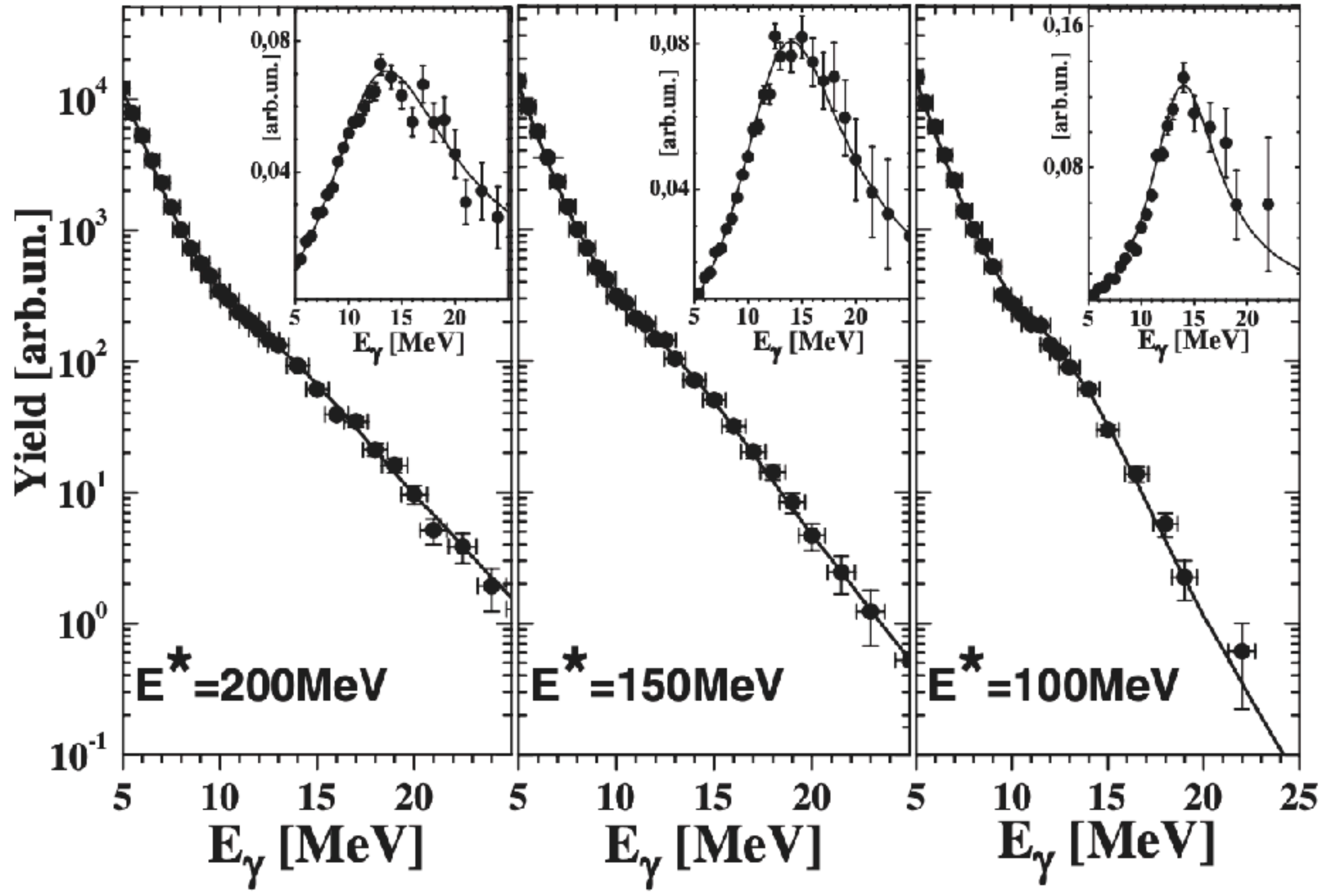
E. Litvinova and H. Wibowo, Phys. Rev. Lett. **121**, 082501 (2018)   H. Wibowo and E. Litvinova, Phys. Rev. C **100**, 024307 (2019)

(FT-RRPA) (FT-RTBA = FT-RRPA + PVC)





*O. Wieland et al., PRL **97,** 012501 (2006):*
GDR in ^{132}Ce



H. Wibowo and E. Litvinova, Phys. Rev. C **100**, 024307 (2019)

7

Temperature evolution of nucleon effective mass

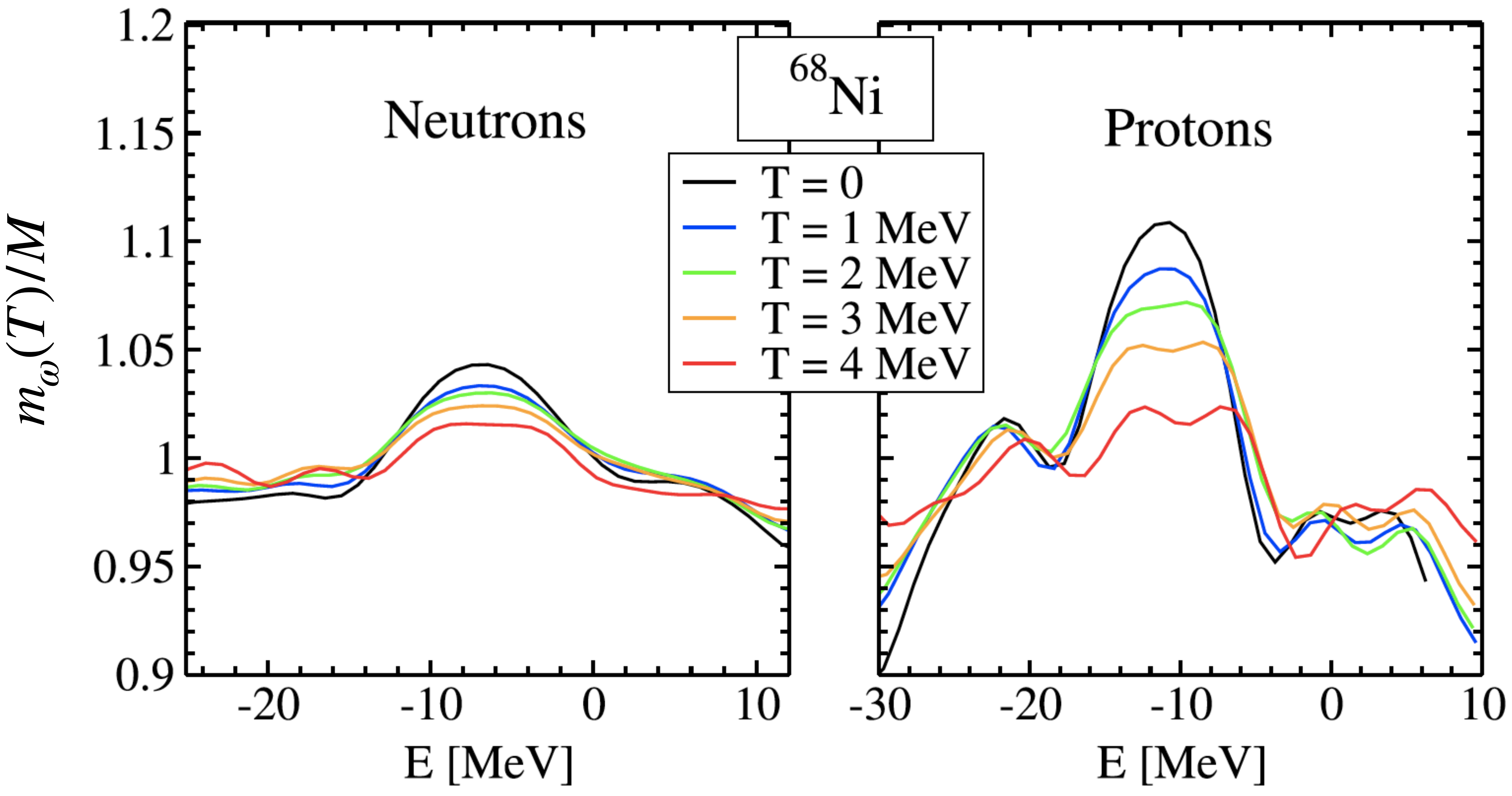
- The T-dependent nucleon effective mass:

$$\frac{m^*(T)}{M} = \frac{\widetilde{m}}{M}\,\frac{m_\omega(T)}{M}$$

P. F. Bortignon, A. Bracco, and R. A. Broglia, *Giant Resonances: Nuclear Structure at Finite Temperature*

- For NL3 parametrization, the value of k mass, $\widetilde{m}$, is $0.6M$.

- The omega mass, $m_\omega(T)$, accounts for (q)PVC and finite temperature effects.



H. Wibowo, E. Litvinova, Y. Zhang, and P. Finelli, Phys. Rev. C **102**, 054321 (2020)

Procedure to determine the omega mass

1. For each T, we determine $\overline{m}_{(k)}(E,T)/M$ as function of E:

$$\frac{\overline{m}_{(k)}(E,T)}{M} = 1 - \frac{\partial}{\partial \varepsilon} \mathrm{Re}\, \Sigma^{e}_{(k)}(\varepsilon)$$

$$\varepsilon = E + i\Delta$$

- Interval of real part E: $\mu - 5 \leq E \leq \mu + 5$ [MeV].
- The imaginary part Δ is the average distance between the energy fragments with the spectroscopic factors larger than 0.5 within the given interval of E values.

H. Wibowo and E. Litvinova, Phys. Rev. C **106**, 044304 (2022)

2. For each T, we determine $m_\omega(T)$ by the average over s.p. states:

$$\frac{m_\omega(T)}{M} = \max_E \left[\frac{\sum_{(k)} (2j_{(k)}+1)\left(\overline{m}_{(k)}(E,T)/M\right)\left(1/v^2_{(k)}\right)}{\sum_{(k)} (2j_{(k)}+1)} \right]$$

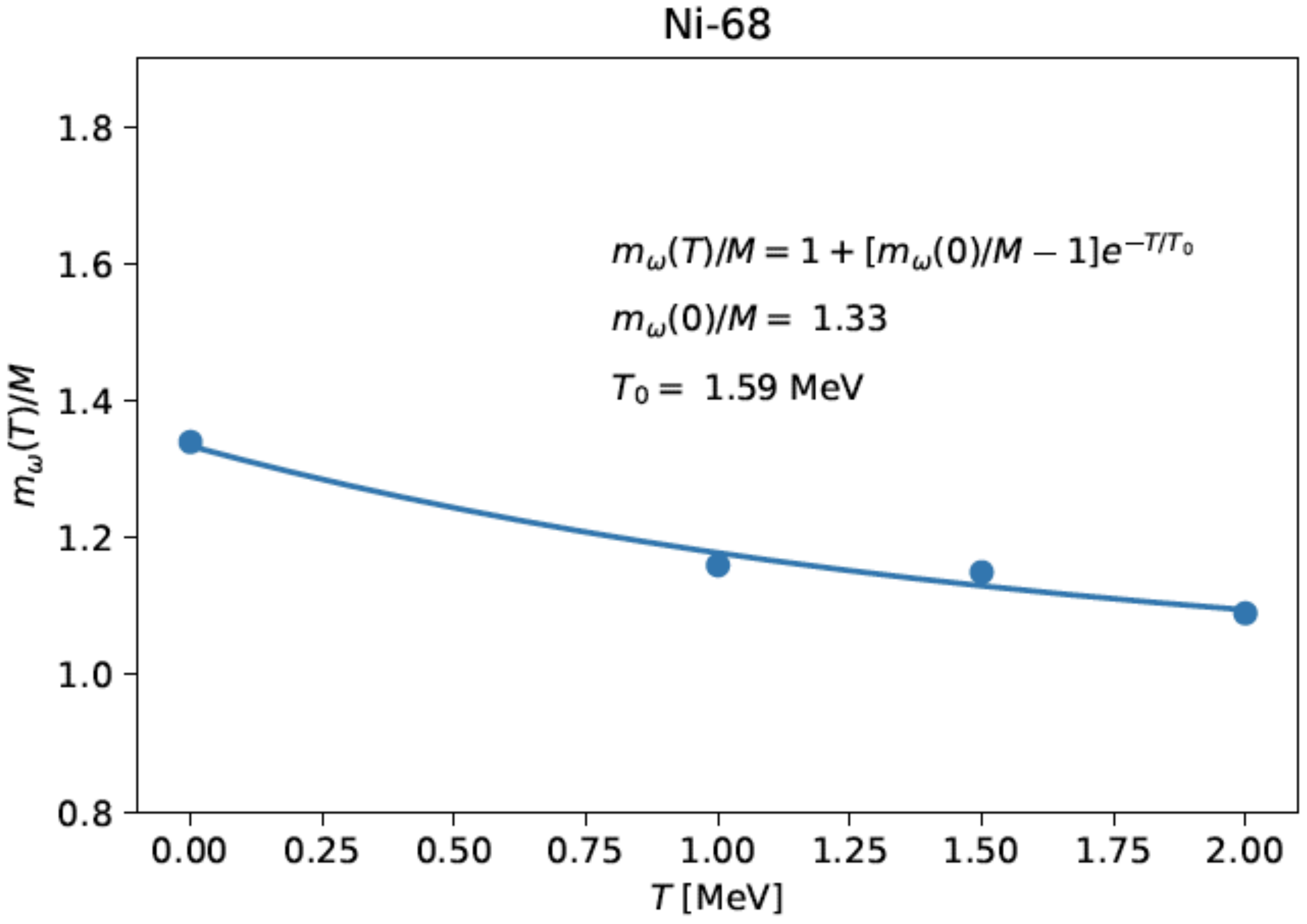
3. Exponential fit:

$$\frac{m_\omega(T)}{M} = 1 + \left[\frac{m_\omega(T=0)}{M} - 1\right] e^{-T/T_0}$$

P. Donati, P. M. Pizzochero, P. F. Bortignon, and R. A. Broglia, Phys. Rev. Lett. **72**, 2835 (1994)

9

Parameters for the exponential fit



	^{68}Ni	^{70}Ni	^{72}Ni	^{74}Ni	^{76}Ni	^{78}Ni
$m_\omega(T=0)/M$	1.33	1.34	1.39	1.54	1.34	1.14
T_0 (MeV)	1.59	1.99	1.61	0.96	1.26	4.80

H. Wibowo and E. Litvinova, Phys. Rev. C **106**, 044304 (2022)

Average values: $m_\omega(T=0)/M = 1.39;\ T_0 = 1.48$ MeV

Temperature evolution of symmetry coefficient

- The symmetry energy term in the nuclear EOS:

$$E_S = S(T=0)\left(1-2\frac{Z}{A}\right)^2$$

P. Donati, P. M. Pizzochero, P. F. Bortignon, and R. A. Broglia, Phys. Rev. Lett. **72**, 2835 (1994)

- The symmetry coefficient $S(T)$ at finite temperature:

$$S(T) = S(T=0) + \frac{\hbar^2 c^2 k_F^2}{6M}\left[\frac{M}{m^*(T)} - \frac{M}{m^*(T=0)}\right] \qquad k_F = \left(\frac{3}{2}\pi^2\rho_0\right)^{1/3}$$

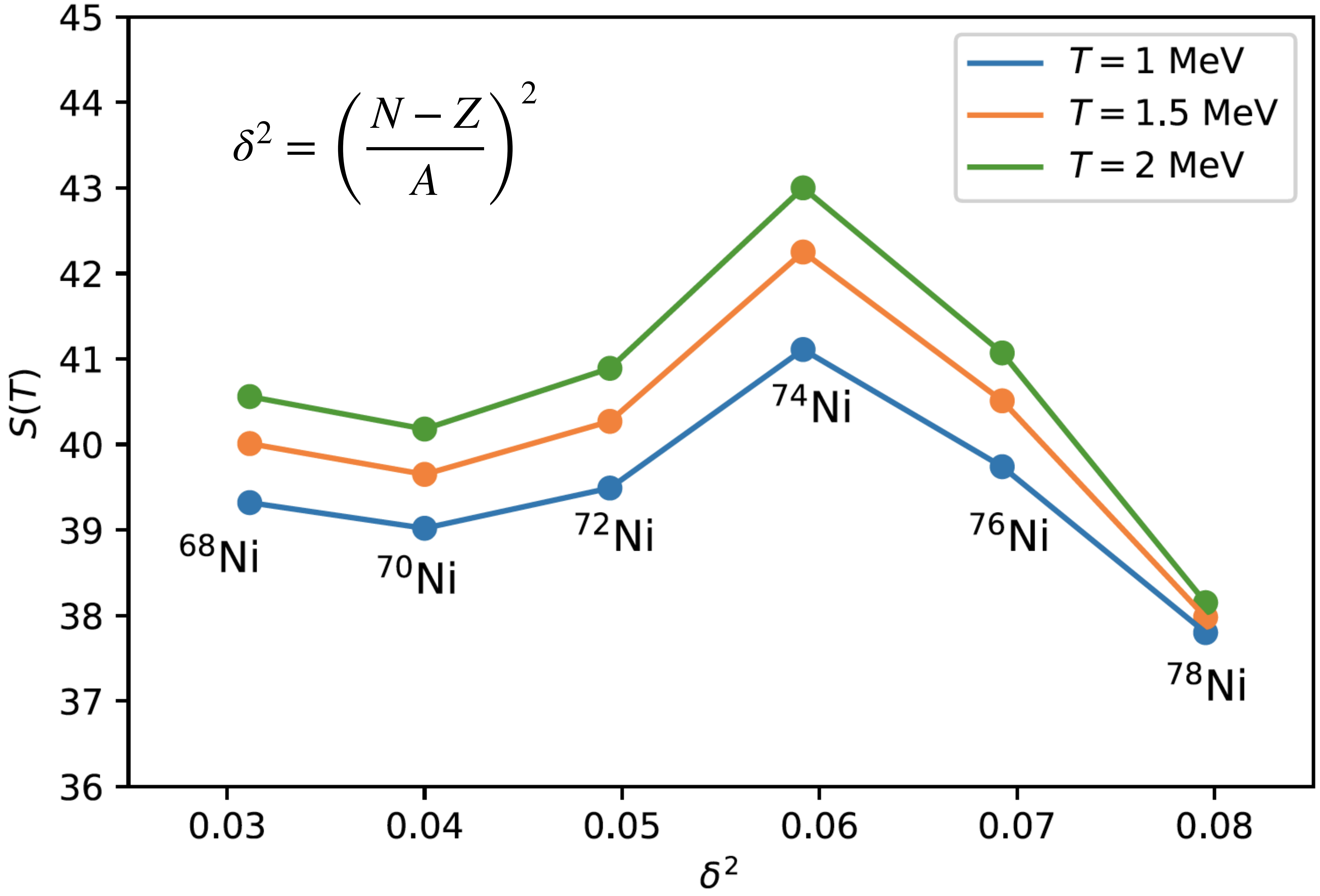
- For the NL3 parametrization:

$$S(T=0) = 37.4 \text{ MeV}; \quad M = 939 \text{ MeV}; \quad \rho_0 = 0.148 \text{ fm}^{-3}$$

	$T=0$	$T=1$ MeV	$T=1.5$ MeV	$T=2.0$ MeV
m^*/M	0.83	0.72	0.68	0.66
S (MeV)	37.4	39.6	40.4	41.1

H. Wibowo and E. Litvinova, Phys. Rev. C **106**, 044304 (2022)

Dependence of $S(T)$ on δ^2



12

$$S(T) = S(T=0) + \frac{\hbar^2 c^2 k_F^2}{6M}\left[\frac{M}{m^*(T)} - \frac{M}{m^*(T=0)}\right]$$

$$\frac{m^*(T)}{M} = \frac{\tilde{m}}{M}\frac{m_\omega(T)}{M}$$

$$\frac{m_\omega(T)}{M} = \max_E \left[\frac{\sum_{(k)}(2j_{(k)}+1)\left(\overline{m}_{(k)}(E,T)/M\right)\left(1/v^2_{(k)}\right)}{\sum_{(k)}(2j_{(k)}+1)}\right]$$

Nucleus	$2d_{5/2}$	$2d_{3/2}$	$3s_{1/2}$	$1g_{9/2}$	$2p_{1/2}$	$2p_{3/2}$	$1f_{5/2}$
^{68}Ni				0.812	0.839	0.765	0.790
^{70}Ni	0.540			0.808	0.824	0.676	0.756
^{72}Ni				0.730	0.733	0.522	0.617
^{74}Ni			0.653	0.752	0.708	0.537	0.580
^{76}Ni		0.597	0.755	0.655	0.752	0.608	0.605
^{78}Ni	0.884		0.892	0.800	0.852	0.709	0.708

Dominant spectroscopic factors

Nucleus	$2d_{5/2}$	$2d_{3/2}$	$3s_{1/2}$	$1g_{9/2}$	$2p_{1/2}$	$2p_{3/2}$	$1f_{5/2}$
^{68}Ni				0.931	0.790	0.918	0.933
^{70}Ni	0.982			0.817	0.930	0.929	0.970
^{72}Ni				0.640	0.962	0.978	0.982
^{74}Ni			0.974	0.537	0.968	0.990	0.984
^{76}Ni		0.982	0.976	0.736	0.980	0.988	0.990

BCS occupation numbers $v^2_{(k)}$

H. Wibowo and E. Litvinova, Phys. Rev. C **106**, 044304 (2022)

Summary

- We model a hot nucleus in the framework of the thermal relativistic mean-field theory.
- Particle-vibration coupling (PVC) significantly modifies the mean-field single-particle states.
- The nucleon effective mass decreases with temperature, whereas the symmetry energy coefficient grows with temperature.
- The pairing correlations below the critical temperature and the PVC effects determine the isotopic dependence of $S(T)$.

GRAZIE PER L'ATTENZIONE!!!

THANK YOU FOR YOUR ATTENTION!!!