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The 7th International Conference on Collective Motion in Nuclei under Extreme Conditions (COMEX7)

Finite temperature effects on nuclear excitations and weak interaction processes

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Nuclear Landscape

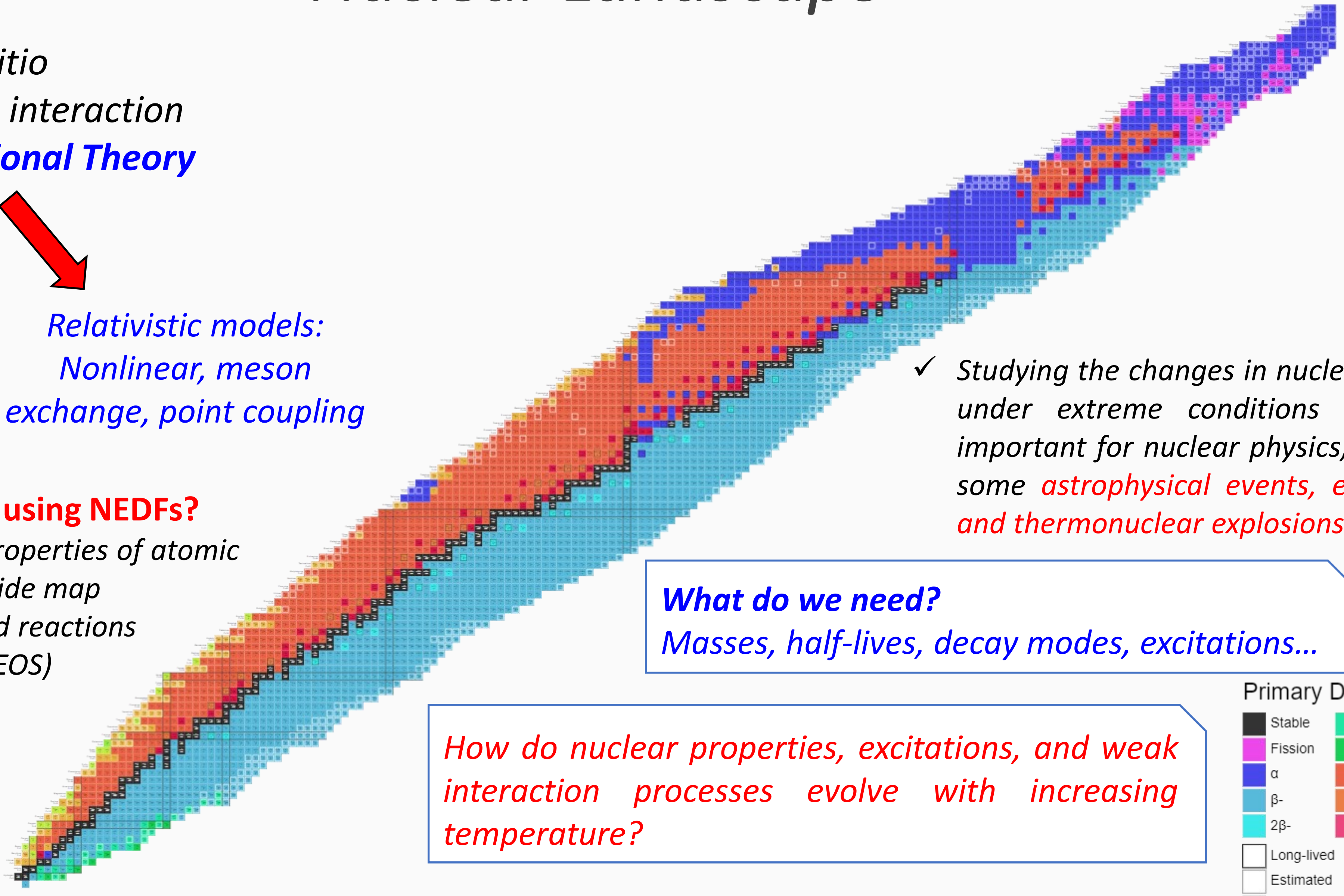
Ab initio
Configuration interaction
Density Functional Theory

Non-relativistic models:
Skyrme, Gogny

Relativistic models:
Nonlinear, meson exchange, point coupling

What can we learn using NEDFs?

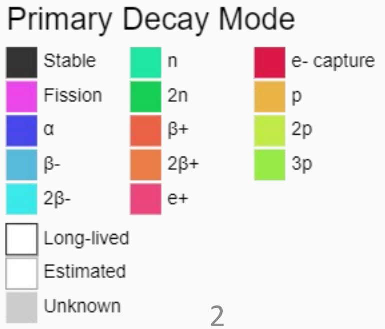
- ✓ *Static and dynamic properties of atomic nuclei across the nuclide map*
- ✓ *Nuclear processes and reactions*
- ✓ *Equation of state of (EOS)*



- ✓ *Studying the changes in nuclear properties under extreme conditions is not only important for nuclear physics, but also for some astrophysical events, e.g, r-process and thermonuclear explosions of stars.*

What do we need?
Masses, half-lives, decay modes, excitations…

How do nuclear properties, excitations, and weak interaction processes evolve with increasing temperature?



Credit for the figure: Colourful Nuclide Chart (anu.edu.au)

Nuclear energy density functionals (NEDF)

- *Nuclear Energy Density Functionals are successful in the description of static and dynamic properties of nuclei.*
- *Interaction between nucleons is represented by a functional which depends on the densities and currents.*

Relativistic models: *a nucleus is described as a system of Dirac nucleons coupled to exchange mesons through an effective Lagrangian.*

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_m + \mathcal{L}_{int}.$$

Free nucleon — *Free meson fields* — *Interaction terms*

$$\mathcal{L}=\bar{\psi}(i\gamma\cdot\partial-m)\psi+\frac{1}{2}(\partial\sigma)^2-\frac{1}{2}m_\sigma^2\sigma^2-\frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu}+\frac{1}{2}m_\omega^2\omega^2-\frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu}+\frac{1}{2}m_\rho^2\vec{\rho}^{\,2}-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-g_\sigma\bar{\psi}\sigma\psi-g_\omega\bar{\psi}\gamma\cdot\omega\psi-g_\rho\bar{\psi}\gamma\cdot\vec{\rho}\vec{\tau}\psi-e\bar{\psi}\gamma\cdot A\frac{(1-\tau_3)}{2}\psi.$$

$$g_i(\rho) = g_i(\rho_{sat})f_i(x) \quad \text{for } i=\sigma,\omega,$$

where

$$f_i(x) = a_i\frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2},$$

$$g_\rho(\rho) = g_\rho(\rho_{sat})e^{-a_\rho(x-1)}$$

Non-Relativistic models: *Based on Hamiltonians with effective interactions of nucleons.*

$$\hat{v}_{\mathrm{Sk}}(\mathbf{r}_{12}) = t_0\,(1+x_0\hat{P}_\sigma)\,\delta(\mathbf{r}_{12})$$ → *Central term*

$$+\frac{1}{2}t_1\,(1+x_1\hat{P}_\sigma)\left(\hat{\mathbf{k}}^{\dagger 2}\,\delta(\mathbf{r}_{12})+\delta(\mathbf{r}_{12})\,\hat{\mathbf{k}}^2\right)$$

$$+\,t_2\,(1+x_2\hat{P}_\sigma)\,\hat{\mathbf{k}}^\dagger\cdot\delta(\mathbf{r}_{12})\,\hat{\mathbf{k}}$$ → *Non-local term*

$$+\frac{1}{6}t_3\,(1+x_3\hat{P}_\sigma)\,\delta(\mathbf{r}_{12})\,\rho^\alpha\left(\frac{\mathbf{r}_1+\mathbf{r}_2}{2}\right)$$ → *Density dependent term*

$$+\,\mathrm{i}W_0\,(\hat{\sigma}_1+\hat{\sigma}_2)\cdot\hat{\mathbf{k}}^\dagger\times\delta(\mathbf{r}_{12})\hat{\mathbf{k}}\,.$$ → *Spin-orbit term*

The constants $t_0, t_1, t_2, t_3, x_0, x_1, x_2, x_3, \alpha, W_0$ are Skyrme parameters.

Total energy $E = \int \mathcal{H}(r)d^3r$

T. H. R. Skyrme, Nuclear Physics 9, 615–634 (1958), P. Ring and P. Schuck, the nuclear many-body problem (1984).
T. Nikšic, N. Paar, D. Vretenar, and P. Ring, Comput. Phys. Commun. 185, 1808 (2014).

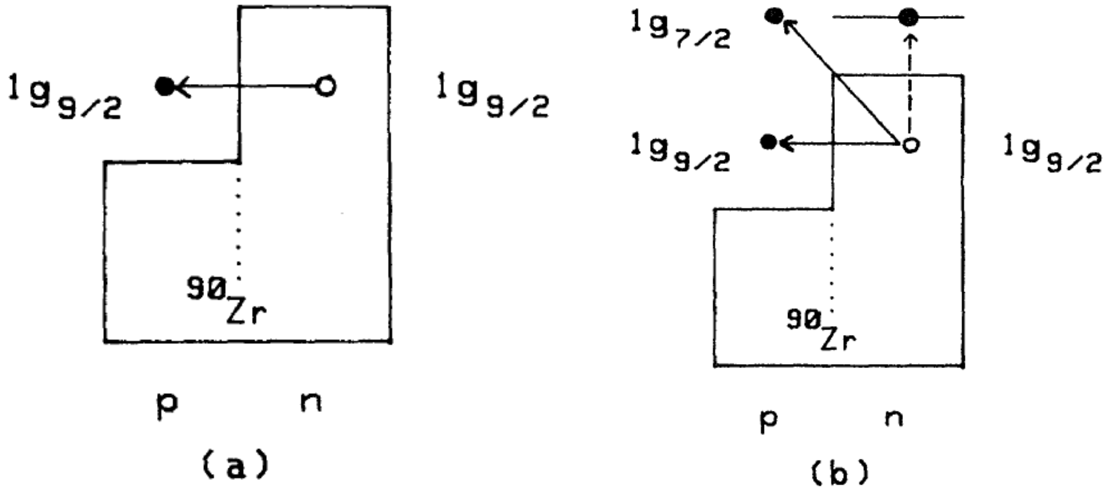
Spin-isospin excitations

✓ *The spin-isospin resonances can be induced by isospin lowering (τ_-) or raising (τ_+) operators.*

- *Isobaric analog states (IAS):*
  $\Delta L = \Delta J = \Delta S = 0;$
- *Gamow-Teller resonance (GTR):*
  $\Delta L = 0;\ \Delta J = \Delta S = 1;$
- *Spin monopole ($J = 0^-$), dipole ($J = 1^-$) and quadrupole ($J = 2^-$) states.*

✓ *Their properties are important to understand the nuclear structure:*

- *Spin and isospin properties of the effective nuclear interaction*
  M. Bender et.al., PRC 65, 054322 (2002), H. Liang et.al., PRL 101 (2008) 122502.,
- *They can be used to predict neutron skin thickness of nuclei*
  D. Vretenar et.al., Phys.Rev.Lett. 91, 262502 (2003).



(a) Fermi (b) Gamow-Teller transitions.
F. Osterfeld, Rev. Mod. Phys., 64, 491557 (1992).

Spin-isospin excitations

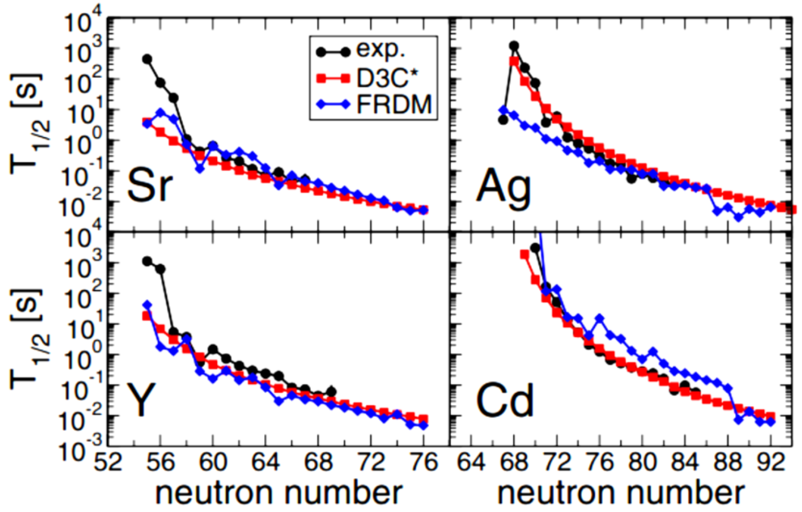
✓ *... and nuclear weak interaction processes in stellar environments:*

- *Calculation of the β-decay rates of r-process nuclei*
  J.Engel et.al., Phys. Rev. C 60, 014302 (1999);
  T. Marketin et.al., Phys. Rev. C 93, 025805 (2015),
- *Electron capture cross sections and rates*
  K. Langanke et.al., Phys. Rev. Lett. 90, 241102 (2003);
  A. L. Cole et.al., Phys. Rev. C86, 015809 (2012).
- *and charged-current neutrino-nucleus reactions*
  N. Paar et.al., Phys. Rev. C 77, 024608 (2008);
  N. Paar et. al., Phys. Rev. C 87, 025801 (2013).

... which take place at finite temperatures.

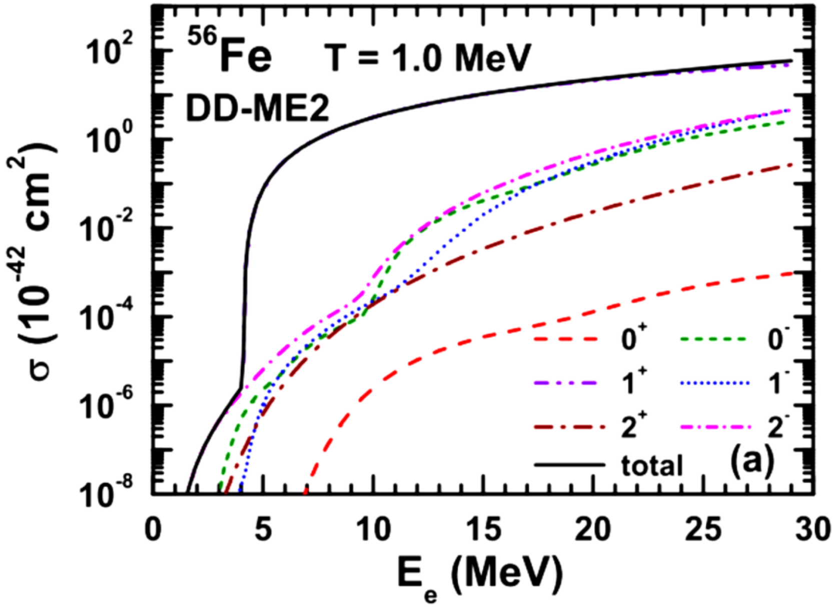
✓ *Therefore, accurate calculations are quite important for the astrophysical calculations.*

HFB(BCS) + Q(RPA) are standing as the prominent tools for calculations.
Finite temperature calculations needs extra work!



Beta decay half lifes.

T. Marketin, et.al., PRC 93, 025805 (2016).



Electron capture cross sections are calculated using FT-PNRPA.
Y.F. Niu et.al., PRC 83, 045807 (2011).

Finite temperature QRPA

The starting point in the Equation of Motion (EOM) method is the definition of a suitable excitation operator

$$\Gamma_\nu^\dagger = \sum_{a\geq b} X_{ab}^\nu a_a^\dagger a_b^\dagger - Y_{ab}^\nu a_b a_a + P_{ab}^\nu a_a^\dagger a_b - Q_{ab}^\nu a_b^\dagger a_a \quad (1)$$

two-quasiparticle creation/destruction operators and one-quasiparticle creation/ destruction operators. With $|BCS\rangle$ as the approximate thermal vacuum the equation of motion can be written as:

$$\langle BCS| \left[\delta\Gamma, H, \Gamma_\nu^\dagger\right] |BCS\rangle = E_\nu \langle BCS| \left[\delta\Gamma, \Gamma_\nu^\dagger\right] |BCS\rangle \quad (2)$$

The FT-QRPA equations are derived as:

$$\begin{aligned}
\widetilde{A}_{abcd} &= \sqrt{1-f_a-f_b}\,A'_{abcd}\sqrt{1-f_c-f_d} + (E_a+E_b)\delta_{ac}\delta_{bd},\\
\widetilde{B}_{abcd} &= \sqrt{1-f_a-f_b}\,B_{abcd}\sqrt{1-f_c-f_d},\\
\widetilde{C}_{abcd} &= \sqrt{f_b-f_a}\,C'_{abcd}\sqrt{f_d-f_c} + (E_a-E_b)\delta_{ac}\delta_{bd},\\
\widetilde{D}_{abcd} &= \sqrt{f_b-f_a}\,D_{abcd}\sqrt{f_d-f_c},\\
\widetilde{a}_{abcd} &= \sqrt{f_b-f_a}\,a_{abcd}\sqrt{1-f_c-f_d},\\
\widetilde{b}_{abcd} &= \sqrt{f_b-f_a}\,b_{abcd}\sqrt{1-f_c-f_d},
\end{aligned}$$

$$f_{a(b)} = \frac{1}{1+exp^{E_{a(b)}/k_B T}}$$

$$\begin{aligned}
A'_{abcd} &= (u_a u_b u_c u_d + v_a v_b v_c v_d)V_{abcd}\\
&+ (u_a v_b u_c v_d + v_a u_b v_c u_d)V_{a\bar{d}\bar{b}c}\\
&- (-1)^{j_c+j_d+J}(u_a v_b v_c u_d + v_a u_b u_c v_d)V_{a\bar{c}\bar{b}d}
\end{aligned}$$

$$\begin{aligned}
C'_{abcd} &= (u_a v_b u_c v_d + v_a u_b v_c u_d)V_{a\bar{b}c\bar{d}}\\
&+ (u_a u_b u_c u_d + v_a v_b v_c v_d)V_{adbc}\\
&+ (-1)^{j_c+j_d+J}(u_a u_b v_c v_d + v_a v_b u_c u_d)V_{a\bar{c}b\bar{d}}
\end{aligned}$$

$$V_{acbd}^{\rm ph} = \delta^2 E(\rho,\kappa,\kappa^*)/\delta\rho_{ba}\delta\rho_{dc}$$

$$V_{abcd}^{\rm pp} = \delta^2 E(\rho,\kappa,\kappa^*)/\delta\kappa_{ab}^*\delta\kappa_{cd},$$

H. M. Sommermann, Ann. Phys. (NY) 151, 163 (1983).

E. Yüksel, G. Colò, E. Khan, Y.F. Niu, K. Bozkurt Phys. Rev. C. 96, 024303 (2017).

Finite temperature QRPA

The finite temperature QRPA equations can be combined into a single matrix as

$$\begin{pmatrix} \tilde{C} & \tilde{a} & \tilde{b} & \tilde{D} \\ \tilde{a}^{+} & \tilde{A} & \tilde{B} & \tilde{b}^{T} \\ -\tilde{b}^{+} & -\tilde{B}^{*} & -\tilde{A}^{*} & -\tilde{a}^{T} \\ -\tilde{D}^{*} & -\tilde{b}^{*} & -\tilde{a}^{*} & -\tilde{C}^{*} \end{pmatrix} \begin{pmatrix} \tilde{P} \\ \tilde{X} \\ \tilde{Y} \\ \tilde{Q} \end{pmatrix} = \hbar\omega \begin{pmatrix} \tilde{P} \\ \tilde{X} \\ \tilde{Y} \\ \tilde{Q} \end{pmatrix}$$

In the limit $T \rightarrow 0$

FT-QRPA → QRPA

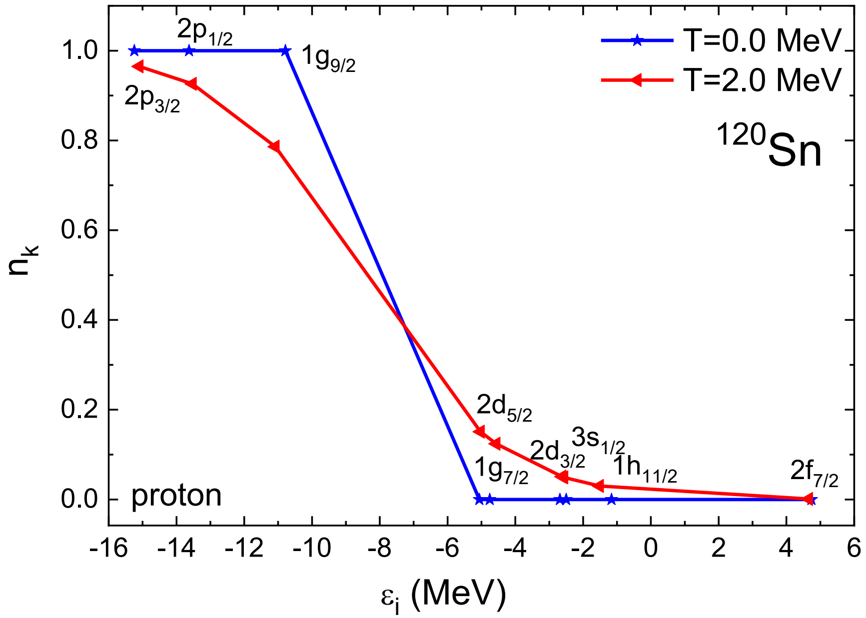
- $\tilde{A}$ and $\tilde{B}$ (and their complex conjugates) describe the effects of two-quasiparticle excitations ($a^{\dagger}a^{\dagger}$ and aa).

$$\sum_{a \geq b} \left\{ \left|\widetilde{X}^{\nu}_{ab}\right|^2 - \left|\widetilde{Y}^{\nu}_{ab}\right|^2 + \left|\widetilde{P}^{\nu}_{ab}\right|^2 - \left|\widetilde{Q}^{\nu}_{ab}\right|^2 \right\} = 1, \tag{18}$$

The reduced transition probability is given as

$$\begin{aligned} B(EJ, \widetilde{0} \to \nu) &= \left|\langle \nu || \hat{F}_J || \widetilde{0} \rangle\right|^2 \\ &= \left| \sum_{c \geq d} \left\{ (\widetilde{X}^{\nu}_{cd} + \widetilde{Y}^{\nu}_{cd})(v_c u_d + u_c v_d)\sqrt{1 - f_c - f_d} + (\widetilde{P}^{\nu}_{cd} + \widetilde{Q}^{\nu}_{cd})(u_c u_d - v_c v_d)\sqrt{f_d - f_c} \right\} \langle c || \hat{F}_J || d \rangle \right|^2 . \end{aligned} \tag{19}$$

How do nuclei behave at finite temperature?

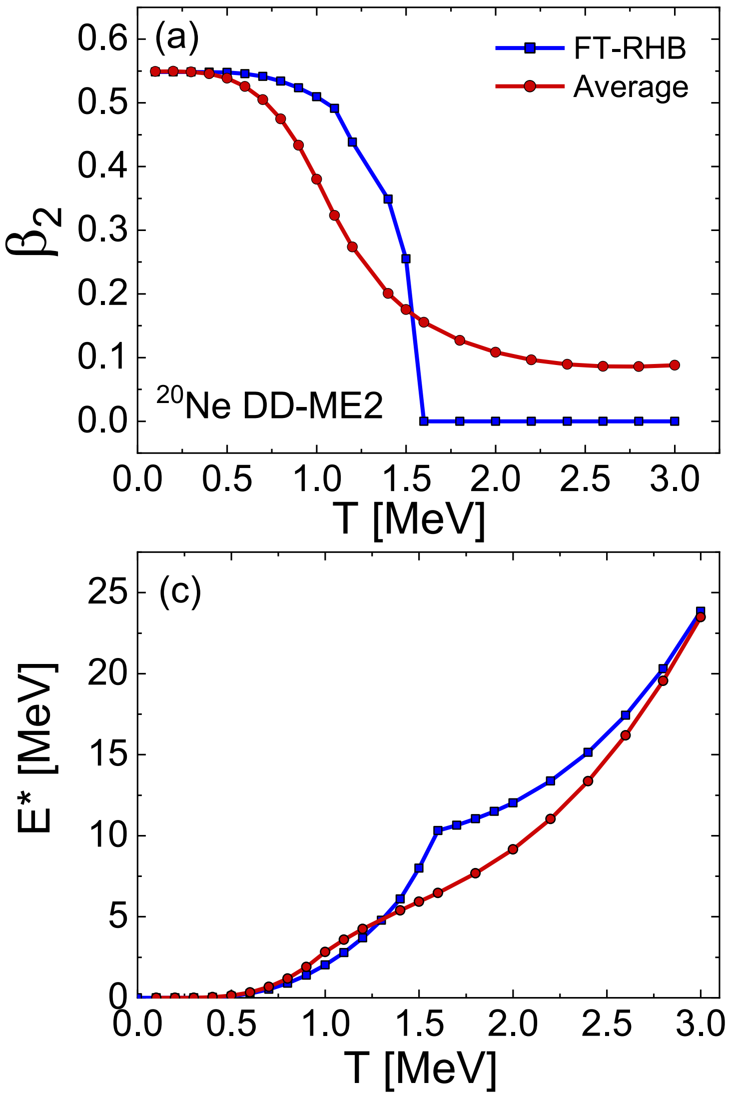


Occupation probabilities of single-particle states are given by

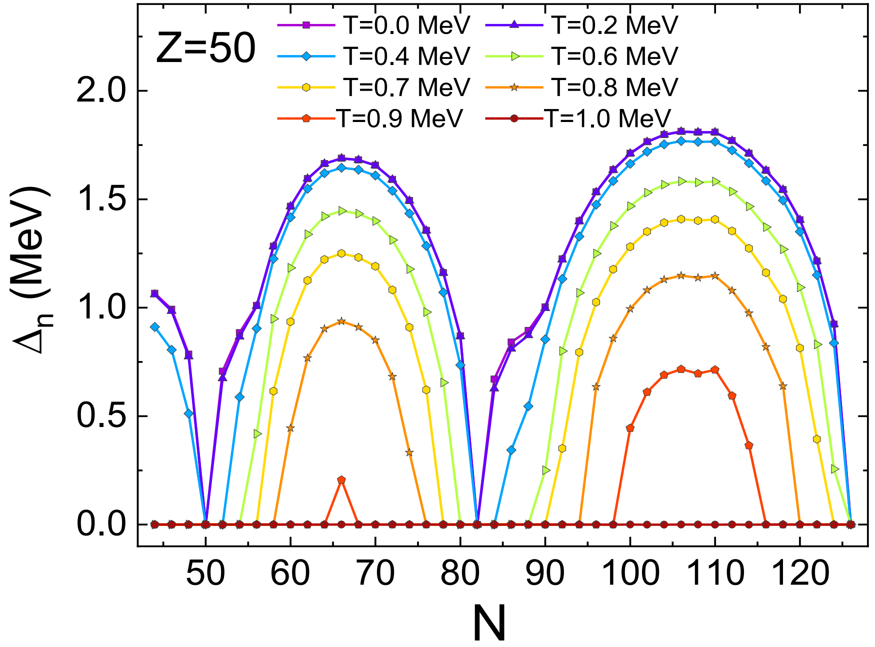
$$n_k = v_k^2(1 - f_k) + u_k^2 f_k$$

$$f_k = \frac{1}{1 + exp^{E_k/k_B T}}$$

E. Yüksel, E. Khan, K. Bozkurt, and G. Colò, Eur. Phys. J. A 50, 160 (2014).



E. Yüksel, F. Mercier, J.-P. Ebran, and E. Khan, Phys. Rev. C 106, 054309 (2022).

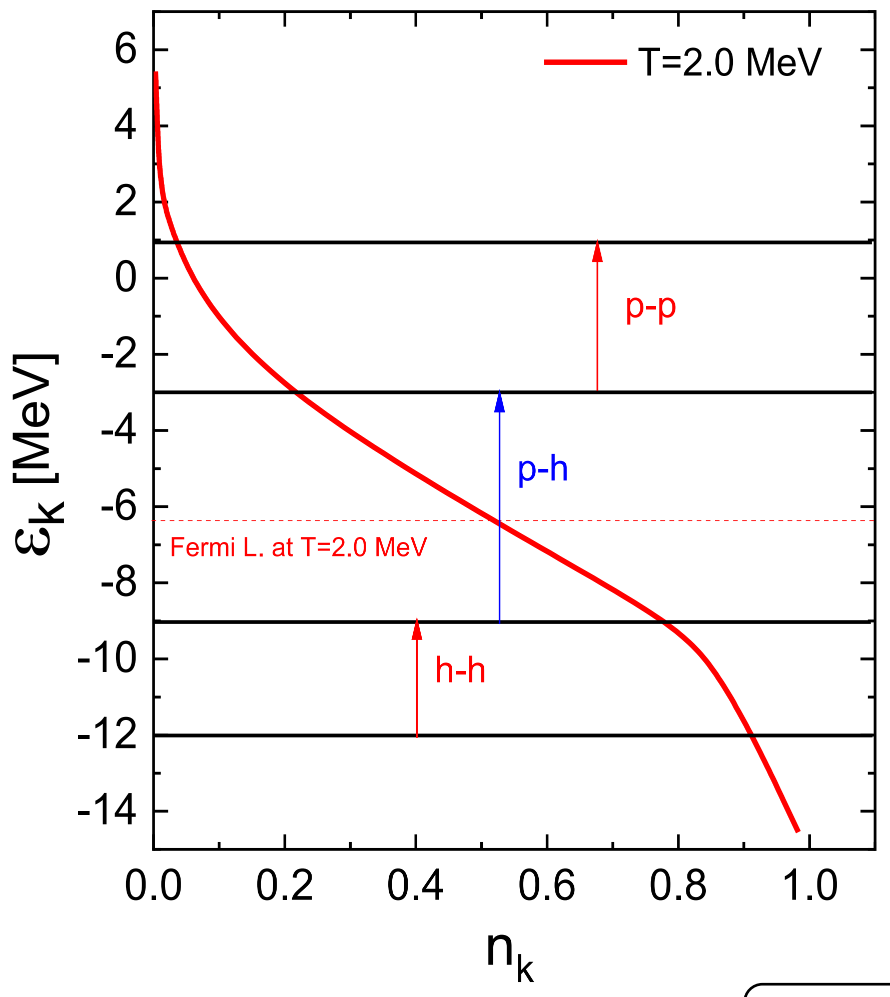


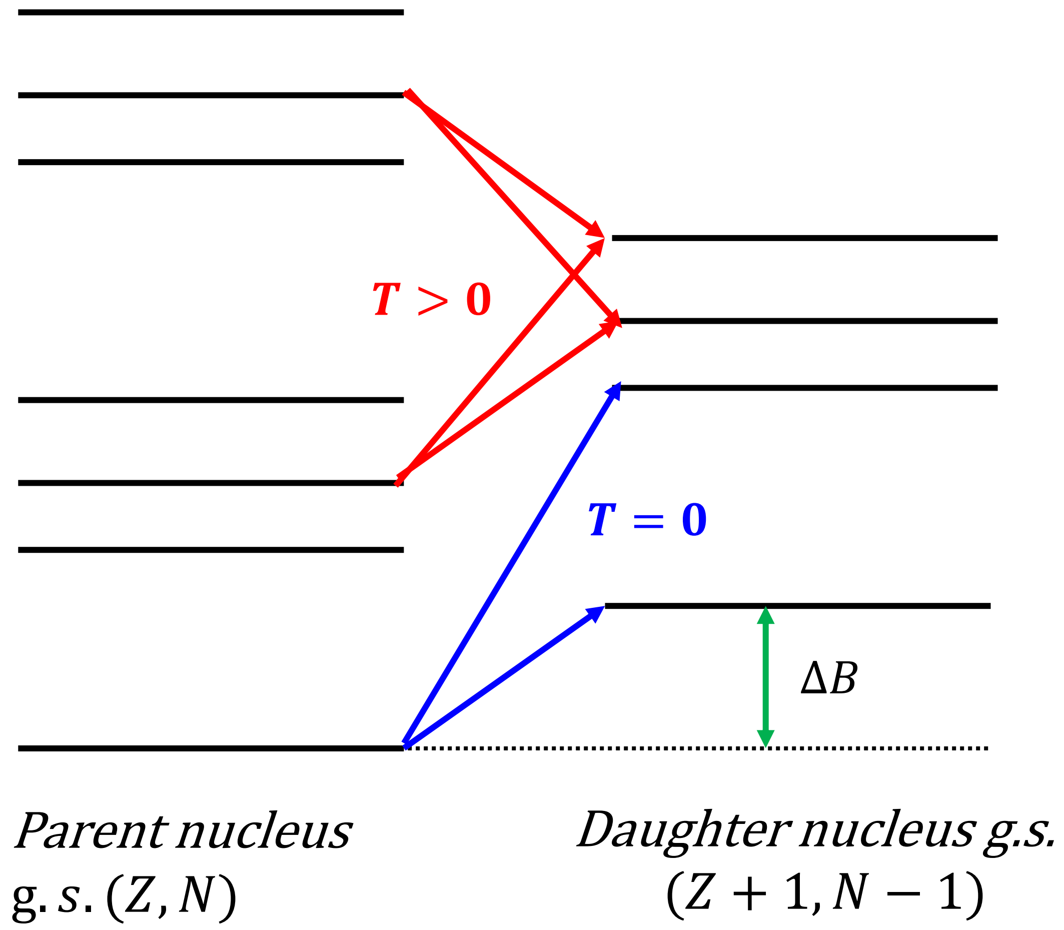
At higher temperatures, the nucleus goes under a pairing phase transition

Pairing properties completely vanish at critical temperatures!

E. Yüksel, Nucl. Phys. A 1014, 122238 (2021).

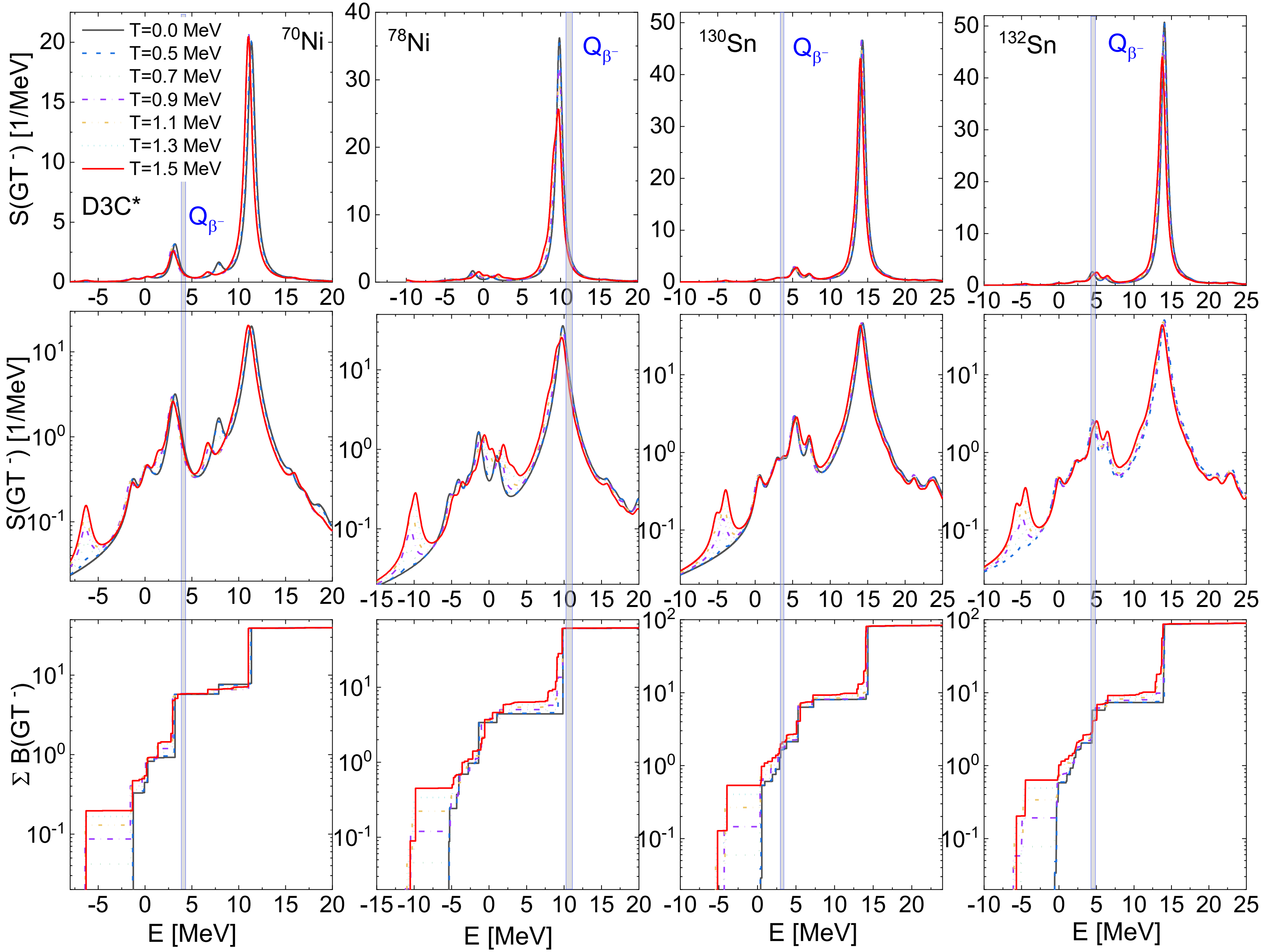
How do nuclei behave at finite temperature?



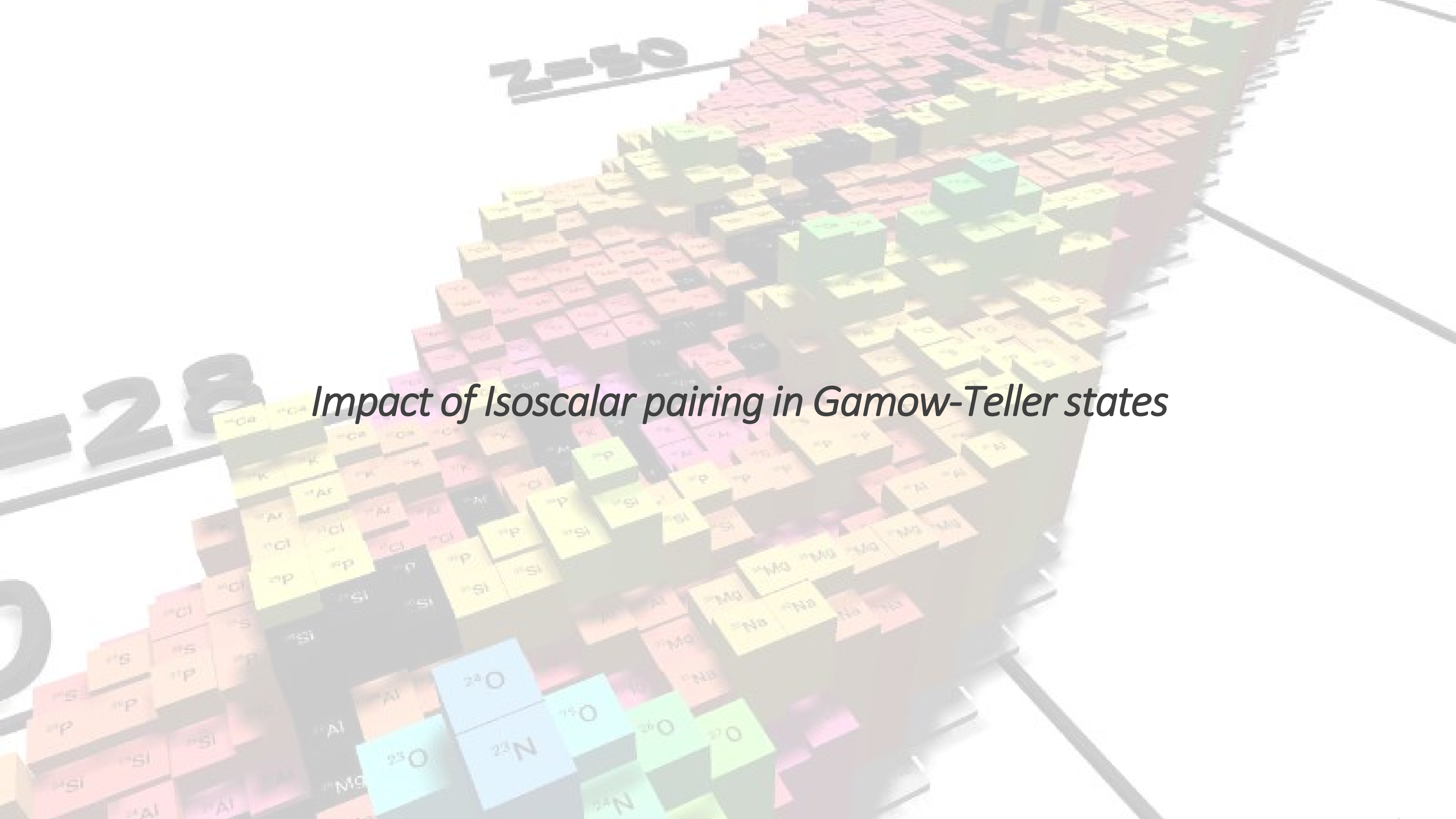


Thermal unblocking of states!

Gamow-Teller response at finite temperature

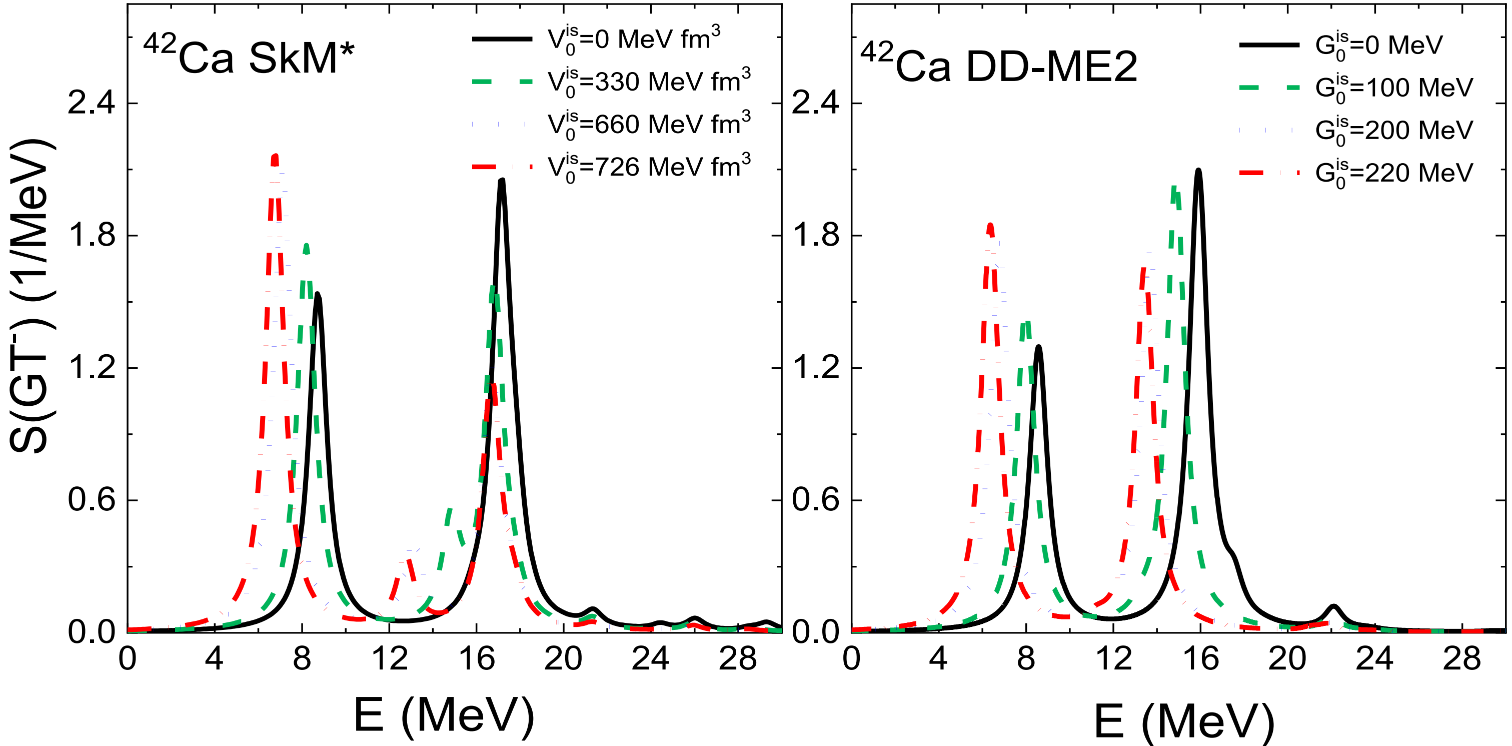


- ✓ *The new excitation channels become possible due to the smearing of the Fermi surface.*
- ✓ *The changes occur due to the temperature induced effects on the nuclear properties of nuclei and the residual particle-hole interaction.*
- ✓ Continuum plays an important role → transitions from thermally unblocked states give rise to an increase in the very low-energy region of the GT strength at finite temperatures.



Impact of Isoscalar pairing in Gamow-Teller states

Gamow-Teller response and isoscalar pairing



Gamow-Teller response at zero temperatures for various IS pairing strength values.

- *The isoscalar pairing has an attractive nature…*

By increasing the isoscalar pairing strength

- *Excitation energies and transition strengths decrease in the GT region*
- *The excited states start to shift downward, and strength increases in the low-energy region.*

w/(wo/) IS pairing (wrt daughter nucleus)
SkM = 0.6 (1.52) MeV; B(GT-)=2.96 (2.41)*
DD-ME2 = 0.6 (1.36) MeV; B(GT-)=2.36 (2.02)
^{42}Ca Exp: E=0.61 MeV and B(GT−) = 2.7(4) *for E < 12 MeV*
Y. Fujita, et.al, Phys. Rev. C 91, 064316 (2015)

Non-relativistic framework

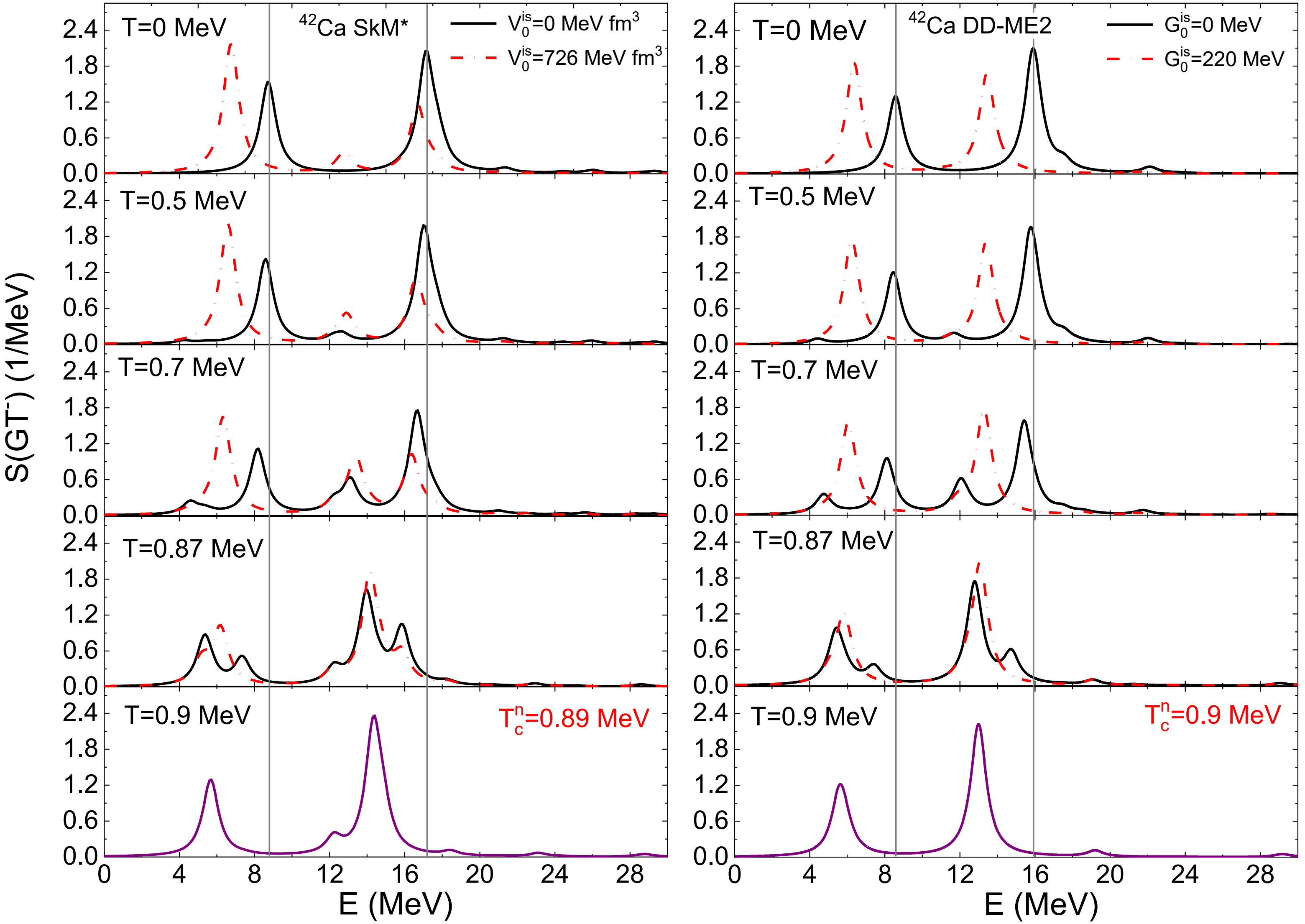
$$V_{\mathrm{is}}(\mathbf{r_1},\mathbf{r_2}) = -V_0^{\mathrm{is}}\frac{1+P_\sigma}{2}\left(1-\frac{\rho(\mathbf{r})}{\rho_o}\right)\delta(\mathbf{r_1}-\mathbf{r_2})$$

Relativistic framework

$$V_{12} = -G_0^{is}\sum_{j=1}^{2} g_j e^{-r_{12}^2/\mu_j^2} \prod_{S=1,T=0},$$

E. Yüksel, N. Paar, G. Colò, E. Khan, and Y. F. Niu, Phys. Rev. C 101, 044305, (2020).

Competition between pairing and temperature effects



Gamow-Teller response for ^{42}Ca with increasing temperature.

- *Without the isoscalar pairing, the changes in the GT states are caused by the decrease of the isovector pairing effects and the softening of the repulsive ph interaction due to the temperature factors with increasing temperature.*

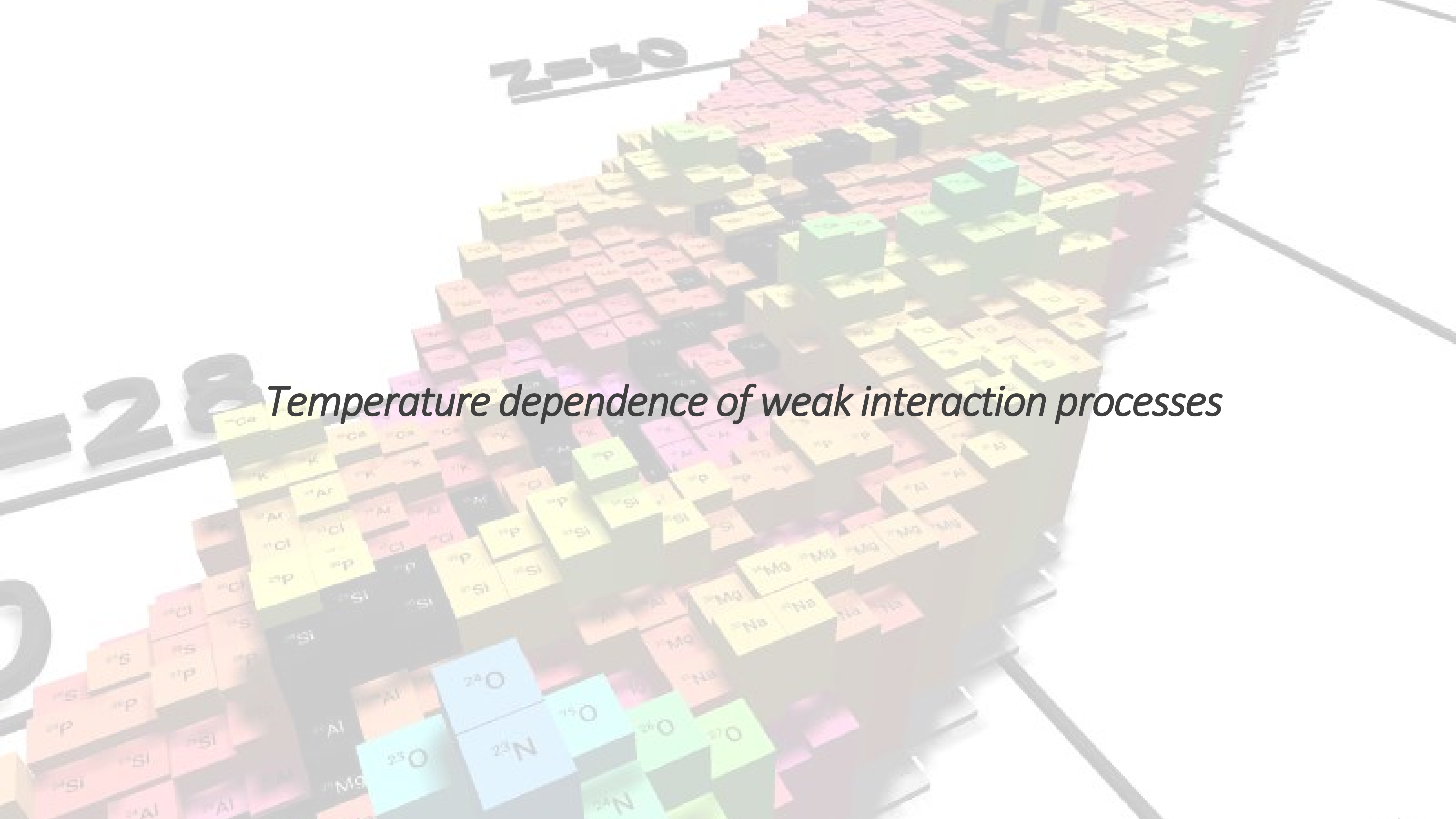
1) $T \uparrow \Longrightarrow$ IV pairing $\downarrow \Longrightarrow E_{conf} \downarrow$
2) $T \uparrow \Longrightarrow V_{res} \downarrow \Longrightarrow E_x \downarrow$

- *With the inclusion of the isoscalar pairing, the decrease in the excitation energies depends on the competition between the temperature and isoscalar pairing effects.*

- *The temperature reduces the impact of the both isoscalar and the isovector pairing.*

E. Yüksel, N. Paar, G. Colò, E. Khan, and Y. F. Niu, Phys. Rev. C 101, 044305, (2020).

Temperature dependence of weak interaction processes

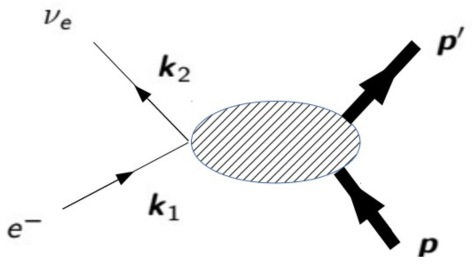


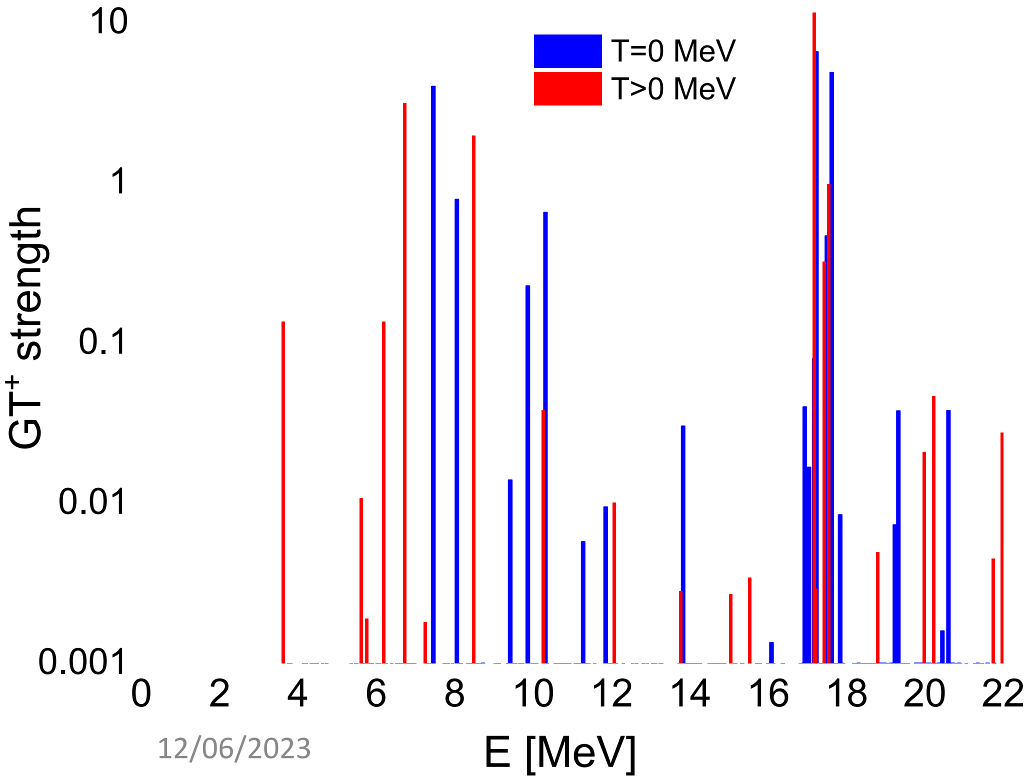
Electron capture in stellar environments

- ✓ *Dynamics of core-collapse supernovae are determined by electron-to-baryon ratio Y_e and the core entropy.*
- ✓ *These two parameters are mainly determined by the weak interaction processes in nuclei, in particular electron capture and β-decay.*

The electron capture on nuclei is a weak interaction process

$$(Z,N) + e^- \rightarrow (Z-1, N+1) + \nu_e$$





e⁻ capture (EC) → decreases Y_e and core entropy

- ✓ *In the presupernova collapse, electron capture on **pf-shell** nuclei occurs at higher densities and temperatures between 300 and 800 keV.*
- ✓ *Sensitive to the details of the GT^+ strength*
- ✓ *Forbidden transitions also play a role!.*
- ✓ *Shell model, Q(RPA) …*

H. T. Janka, Physics Reports, 442, 38-74 (2007),
K. Langanke et. al., Rep. Prog. Phys. 84 066301 (2021)

Electron capture in stellar environments

- In order to derive the electron-capture cross section, we start from the Fermi golden rule

$$\frac{d\sigma}{d\Omega} = \frac{1}{(2\pi)^2}\Omega^2 E_\nu^2 \frac{1}{2}\sum_{lept.spin}\frac{1}{2J_i+1}\sum_{M_i,M_f}|\langle f|\hat{H}_W|i\rangle|^2,$$

Neutrino energy

Matrix element of the weak Hamiltonian

- Final expression written in terms of charge $\widehat{M}_J$, longitudinal $\hat{\mathcal{L}}_J$, transverse electric $\hat{T}_J^{el}$ and transverse magnetic $\hat{T}_J^{mag}$ operators for multipole J^π.
- Electron capture rates are calculated with $\lambda_{ec} = \frac{1}{\pi^2\hbar^3}\int_{E_e^0}^{\infty} p_e E_e \sigma_{ec}(E_e) f(E_e, \mu_e, T) dE_e$

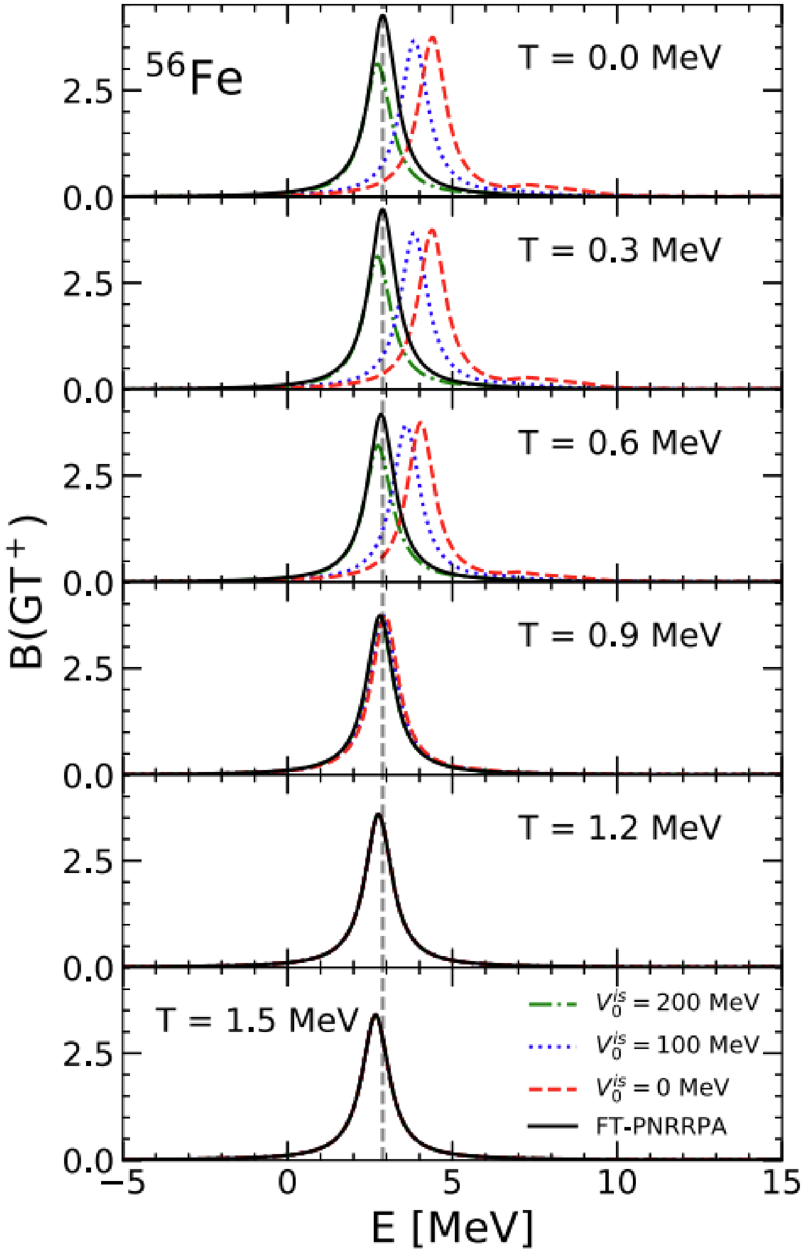
- The energy of the outgoing neutrino

$$E_\nu = E_e - E_{QRPA} - \Delta_{np} - (\lambda_n - \lambda_p)$$

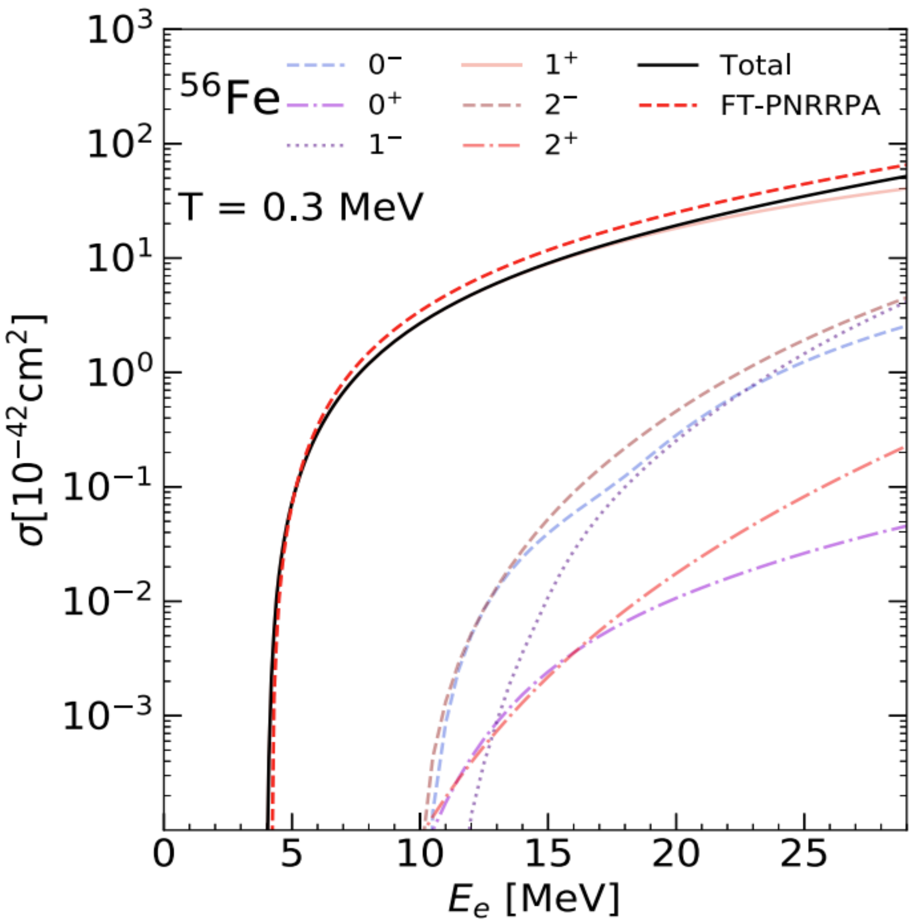
- E_e^0 - threshold energy
- μ_e - electron chemical potential
- T - temperature

$$p_e = \sqrt{E_e^2 - m_e^2}$$

Evolution of electron capture in stellar environments?



Electron-capture cross sections

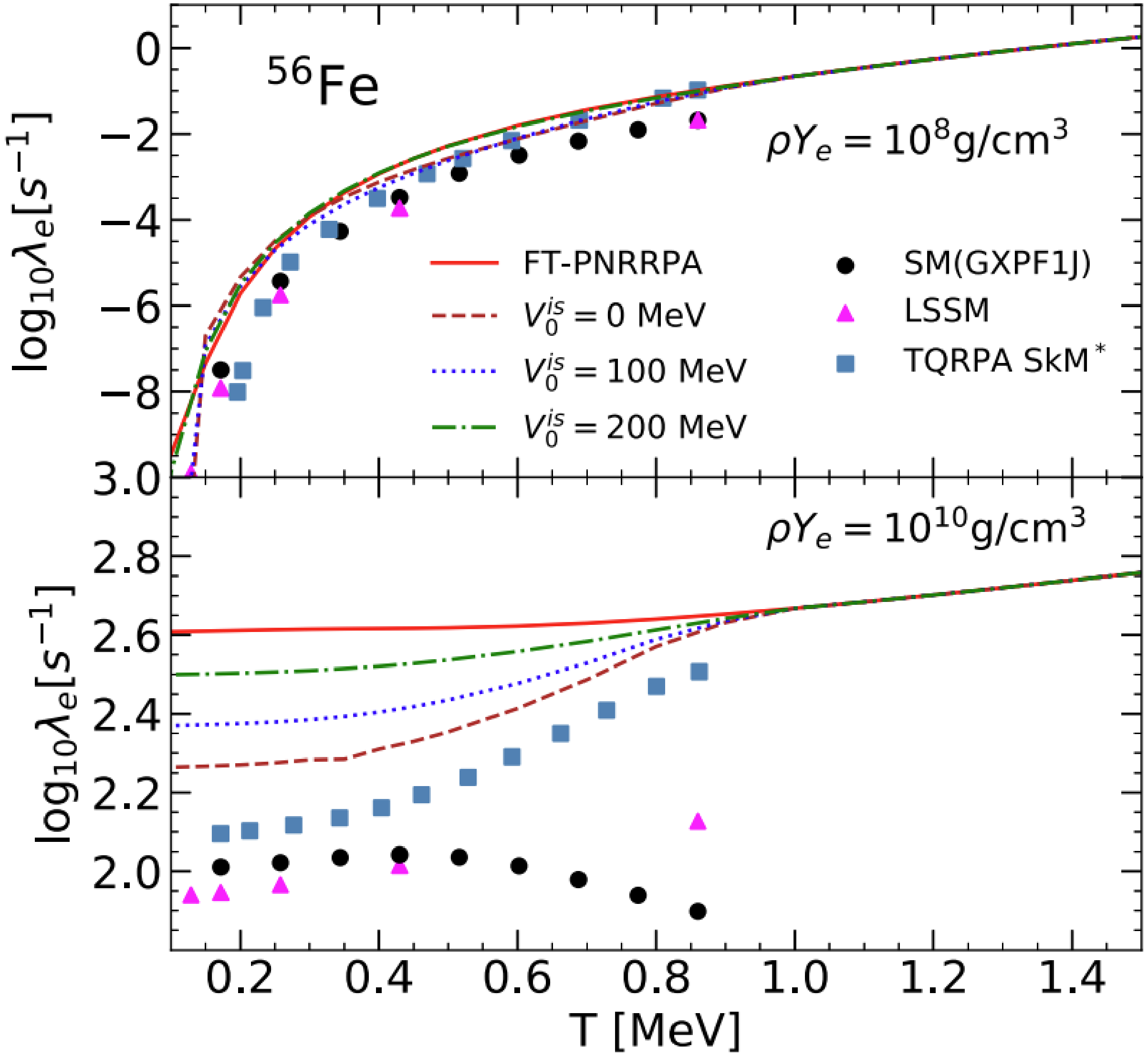


FT-pnQRPA with DD-ME2
$V_0^{is} = 200\ MeV$

- ✓ *EC cross-section σ_{EC} on ^{56}Fe for $J^\pi = 0^\pm$, $1^\pm$, $2^\pm$ multipoles at T = 0.3 MeV using FT-PNRQRPA (black full line + multipoles) and FT-PNRRPA.*
- ✓ *At higher energies of incident electron, the FT-PNRRPA predicts larger total cross section.*
- ✓ 1^+ *excitation dominates the EC cross sections up to high electron energies where contributions from the forbidden multipoles (0^-, 1^-, 2^-) become also non-negligible.*

➢ *A. Ravlić, E. Yüksel, Y. F. Niu, G. Colò, E. Khan, and N. Paar, Phys. Rev. C 102, 065804 (2020).*

Stellar electron-capture rates



- ✓ *Electron capture rates λ_e for $^{56}\boldsymbol{Fe}$ with respect to temperature $\boldsymbol{T}$ for densities $\boldsymbol{\rho Ye} = \mathbf{10^8}$ and $\mathbf{10^{10}}$ $\boldsymbol{g/cm^3}$.*

FT-pnQRPA with DD-ME2

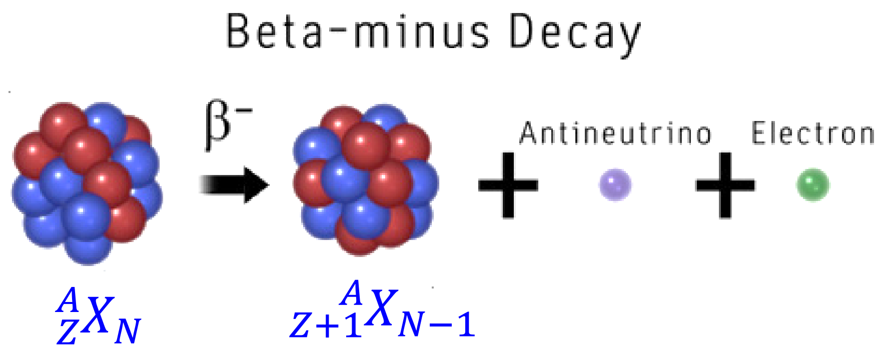
$\boldsymbol{\rho Ye} = \mathbf{10^8}$ → Low λ_e ($\approx 2\ MeV$) → low EC rates

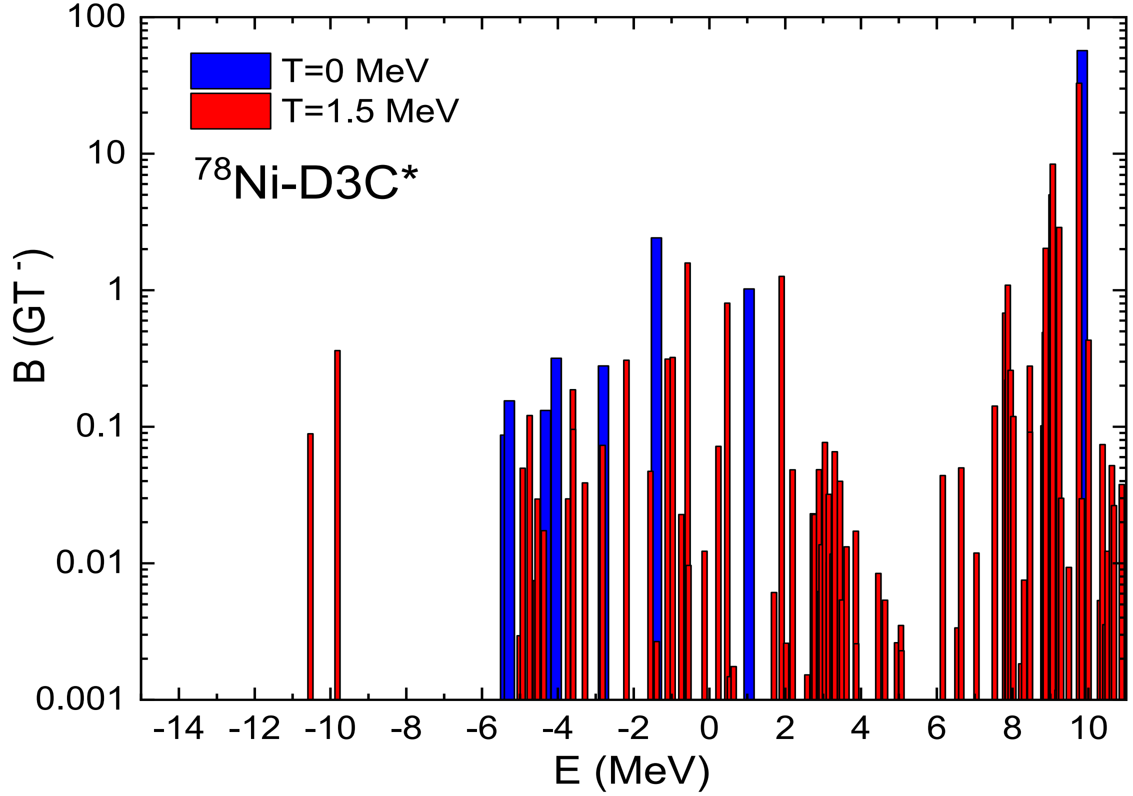
$\boldsymbol{\rho Ye} = \mathbf{10^{10}}$ → high λ_e ($\approx 10\ MeV$) → high EC rates

- ✓ *Very good agreement with the LSSM calculations and the shell-model calculations with GXPF1J interaction in the whole temperature range.*
- ✓ *The EC rates calculated with the FT-PNRQRPA display weak dependence on temperature for high stellar densities.*

➢ *A. Ravlić, E. Yüksel, Y. F. Niu, G. Colò, E. Khan, and N. Paar, Phys. Rev. C 102, 065804 (2020).*

Beta-decay half-lives at finite temperatures





- ✓ *Allowed Gamow-Teller transitions mainly determine the β-decay half-lives.*
- ✓ *Transitions below the Q–value play a major role.*

- ✓ *The general form of β-decay rate in stellar conditions is*

$$\lambda = \frac{\ln 2}{K}\int_0^{p_0} p_e^2 (W_0 - W)^2 F(Z,W) C(W)[1 - f(W)]dp_e$$

- ✓ *For the allowed GT transitions, C(W) is equal to the reduced matrix element of the GT− transition*

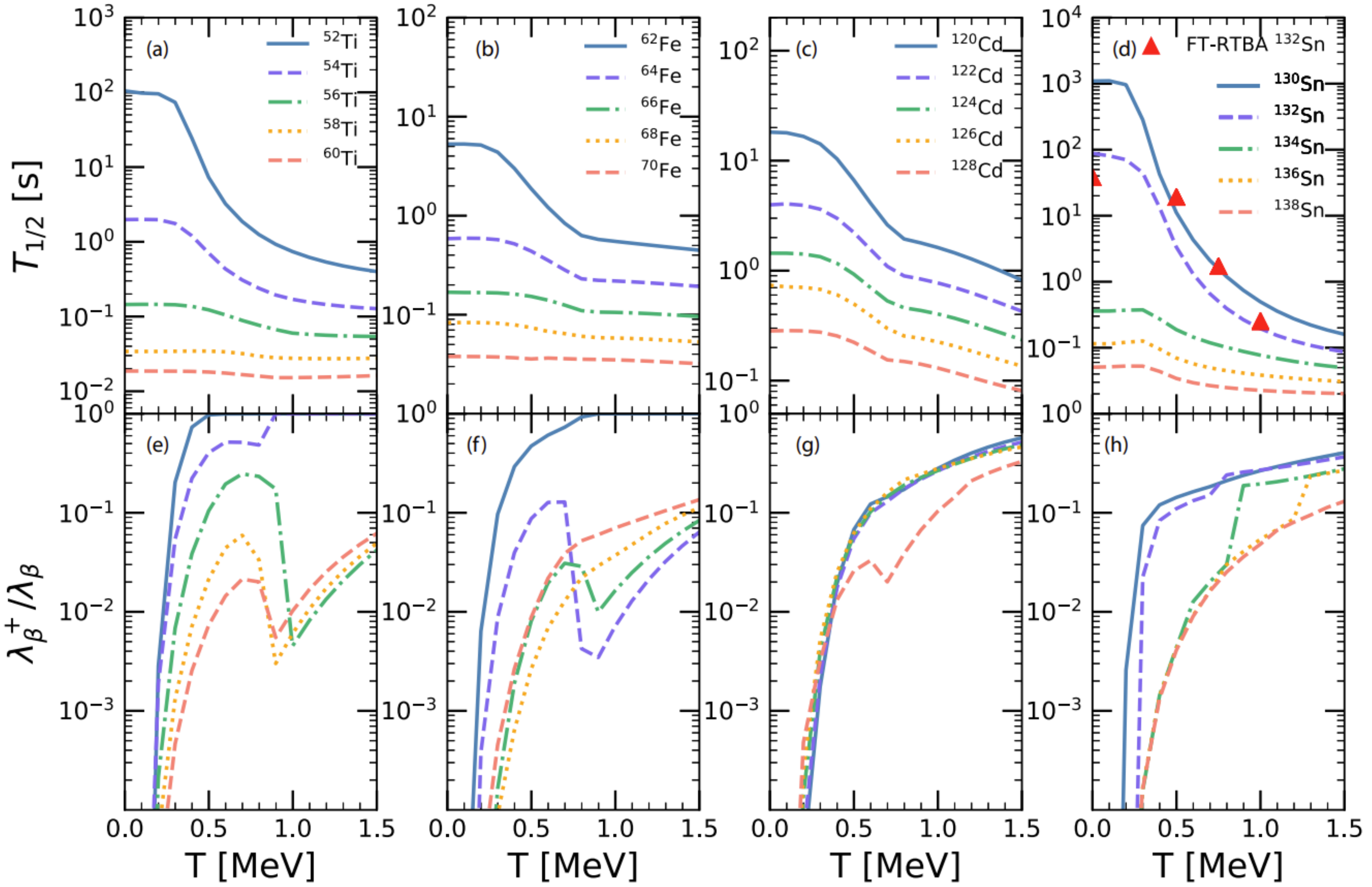
$$B(\mathrm{GT}^-) = g_A^2 \frac{|\langle f \| \boldsymbol{\sigma\tau}_- \| i\rangle|^2}{(2J_i+1)}$$

axial coupling
g_A = −1.26 → −1.0
”quenching”

- ✓ *The excited states shifts downwards*
- ✓ *New excited states are obtained due to the unblocking mechanism of temperature.*
- ✓ *β-decay phase space increases → half-lives decrease.*

For the general form of reaction rate: T. Marketin et al., Phys. Rev. C, 93, 025805, (2016)

β-decay half-lives in stellar environments

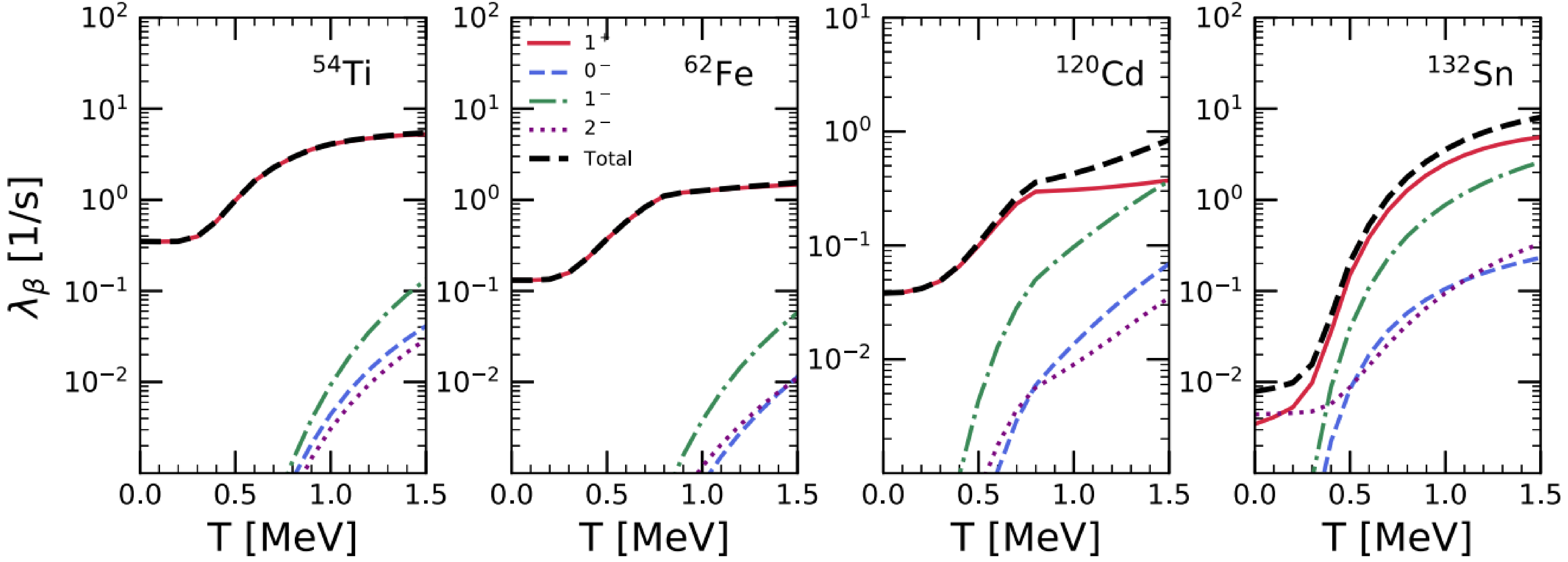


- ✓ *T = 0–1.5 MeV and stellar density is fixed to ρYe = 10^7 g/cm^3.*
- ✓ *Nuclei with long β-decay half-lives at zero temperature are impacted more*
- ✓ *Transitions from highly excited initial states with negative transition energy (de-excitations) start to play a role already at T ≈ 0.3 MeV*
- ✓ *Its contribution increases for all considered nuclei with increasing temperature.*

Total β-decay half-lives $T_{1/2}$ for Ti, Fe, Cd, and Sn isotopes as a function of temperature, including negative-energy transitions (de-excitations).

A. Ravlić, E. Yüksel, Y. F. Niu, and N. Paar, Phys. Rev. C 104, 054318 (2021).

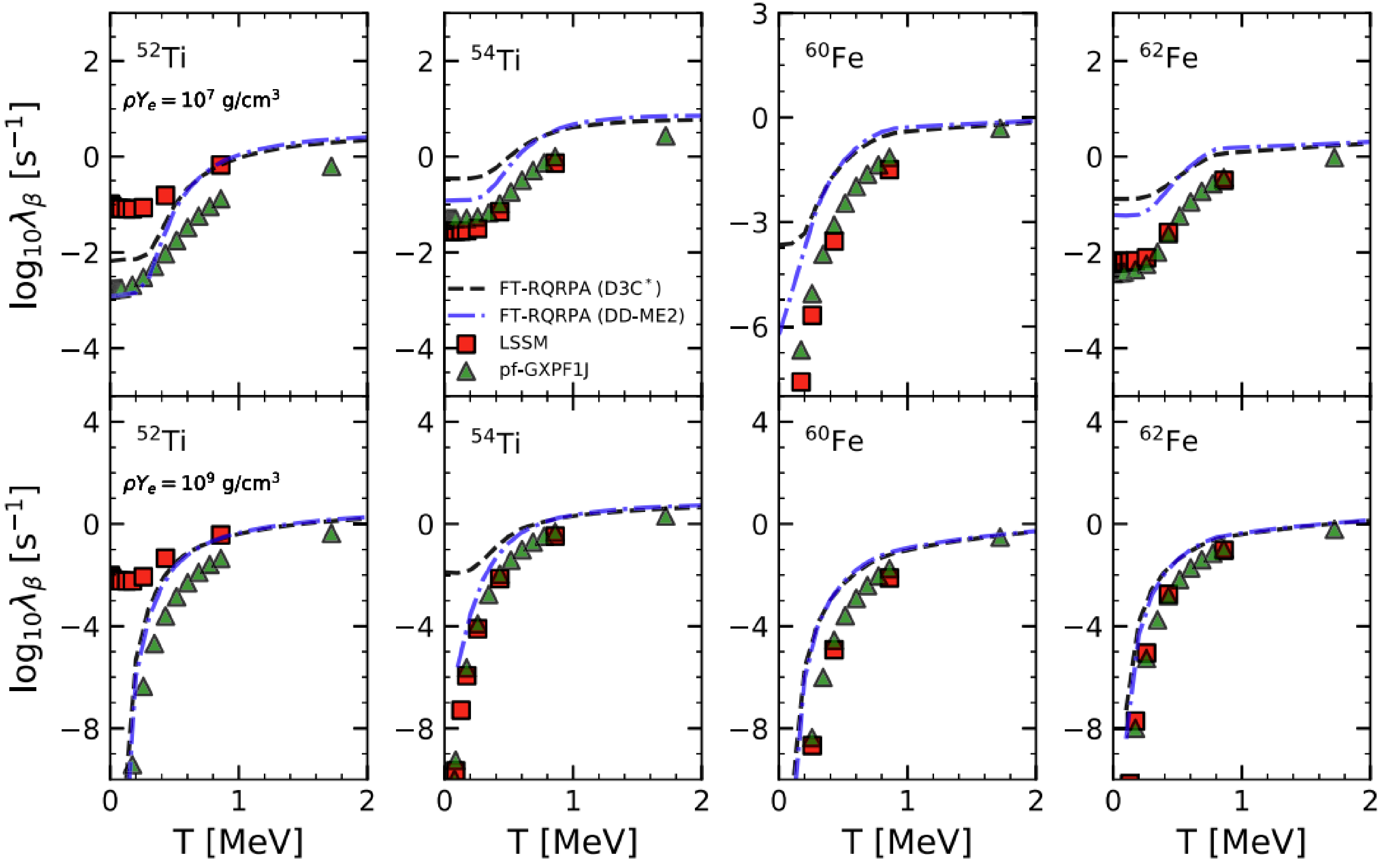
β-decay half-lives in stellar environments



Temperature dependence of β-decay rates λ_β for both allowed (1^+) and first-forbidden transitions ($0^-, 1^-, 2^-$) together with their total sum (Total) for ^{54}Ti, ^{62}Fe, ^{120}Cd, and ^{132}Sn. Calculations are performed at stellar density $\rho Ye = 10^7\ g/cm^3$

A. Ravlić, E. Yüksel, Y. F. Niu, and N. Paar, Phys. Rev. C 104, 054318 (2021).

Comparison of β-decay half-lives with different models

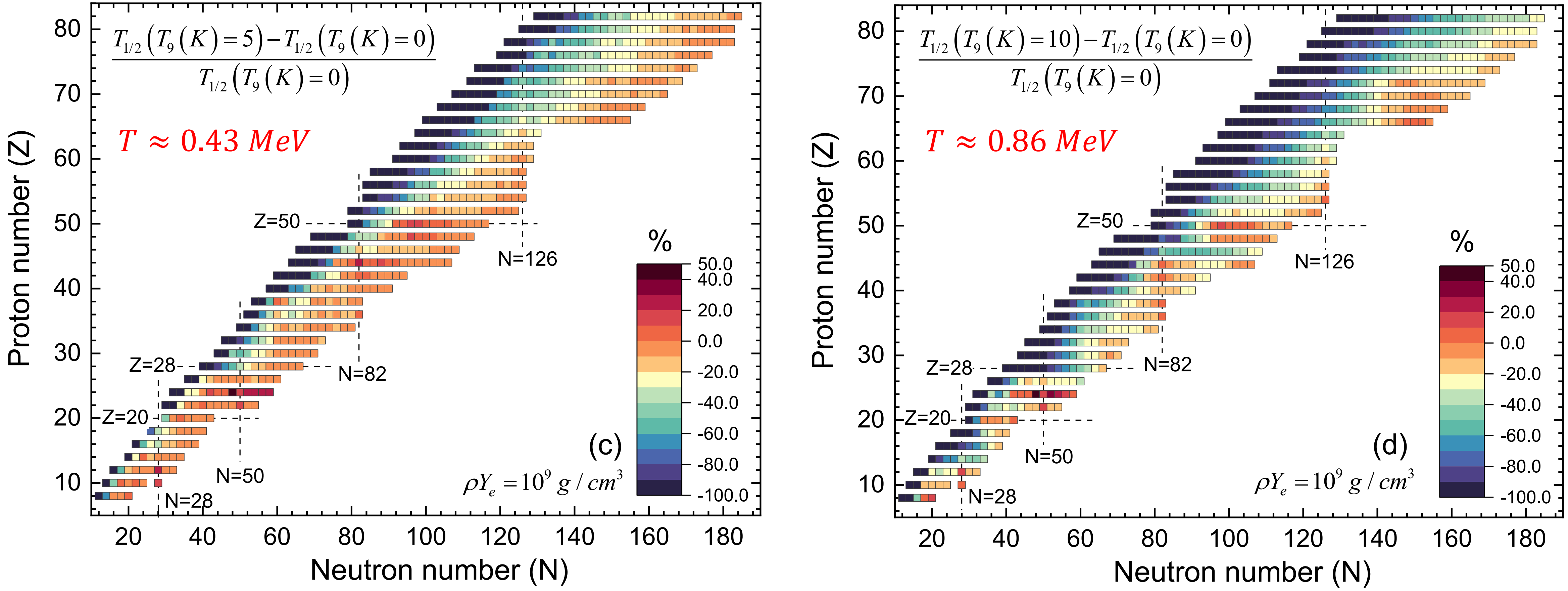


- ✓ *β-decay rates significantly decrease with increasing density.*
- ✓ *Using both D3C∗ and DD-ME2 interactions are in good agreement with both shell-model results*
- ✓ *Trends of increasing rates with increasing temperature are well reproduced.*
- ✓ *The agreement is better at higher temperatures*

A. Ravlić, E. Yüksel, Y. F. Niu, and N. Paar, Phys. Rev. C 104, 054318 (2021).

- LSSM (red squares): K. Langanke and G. Martínez-Pinedo, At. Data Nucl. Data Tables 79, 1 (2001).
- Shell-model calculations based on the pf-GXPF1J interaction (green triangles): K. Mori, M. A.et.al., Astrophys. J. 833, 179 (2016), T. Suzuki (private communication).

Large scale calculations for even-even nuclei



- *In the majority of the nuclide map, a decrease in the β-decay half-lives is obtained with increasing temperature.*
- *Nuclei showing the most change are those with initially long half-lives (magic, semi-magic, and close to the valley of stability).*

A. Ravlić, E. Yüksel, Y. F. Niu, and N. Paar, Phys. Rev. C 104, 054318 (2021).

Conclusions

We developed self-consistent Finite temperature (pn)QRPA: includes both pairing and temperature
Using both relativistic (DD-ME2, D3C) and nonrelativistic Skyrme-type EDFs.*

Spin-isospin excitations at finite temperature

As T increases → Unbloc ... es in the low-energy region

A proper description of nuclei and weak nuclear weak interaction processes in stellar environments requires self-consistent calculations that include both pairing and finite temperature effects….

Impact of the attracti ... nd pairing correlations is decisive on the locatior

β-decay half-lives in st

- *In the majority of th ... ing temperature.*
- *Nuclei showing the ... and close to the valley of stability).*
- *Forbidden transitions starts to play a role with increasing temperature.*
- *Negative energy transitions (de-excitations) are essential for proper description, and they already start to play a role at T ≈ 0.3 MeV.*

Perspectives on the future of work

- *M1 excitations at FT?*
- *Proper treatment of nuclei at finite temperatures: exact canonical treatment of pairing problem.*
- *Inclusion of beyond-mean field effects?*
- *Odd-nuclei?*
- *Large-scale calculations at Finite Temperature (A. Ravlic, E. Yüksel, T. Niksic, N. Paar)*

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