ICNT workshop@RIKEN

Skyrme-EDF for charge-changing excitation modes

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Outline

- ✓ Self-consistent Skyrme-pnQRPA approach
- ✓ GT strengths in neutron-rich deformed Zr isotopes

  deformation

  T=0 pairing
- ✓ pn-pair transfer strengths in N=Z nuclei in fp-shell

  collectivity of the pn-pairing vibration

Skyrme energy-density functional (EDF) approach

Energy functional: $\mathcal{E} = \int d\boldsymbol{r}\mathcal{H}(\boldsymbol{r})$

Energy density: $\mathcal{H} = \mathcal{H}_{\rm kin} + \mathcal{H}_{\rm Skyrme} + \mathcal{H}_{\rm em}$

Skyrme energy density: $\mathcal{H}_{\rm Skyrme} = \sum_{t=0,1} \sum_{t_3=-t}^{t} \left(\mathcal{H}^{\rm even}_{tt_3} + \mathcal{H}^{\rm odd}_{tt_3} \right)$

$$\mathcal{H}^{\rm even}_{tt_3} = C^{\rho}_t \, \rho^2_{tt_3} + C^{\Delta\rho}_t \, \rho_{tt_3} \Delta\rho_{tt_3} + C^{\tau}_t \, \rho_{tt_3} \tau_{tt_3} + C^{\nabla J}_t \rho_{tt_3} \, \nabla \cdot \mathbf{J}_{tt_3} + C^{J}_t \overleftrightarrow{J}^2_{tt_3}$$

$$\mathcal{H}^{\rm odd}_{tt_3} = C^{s}_t \, \mathbf{s}^2_{tt_3} + C^{\Delta s}_t \, \mathbf{s}_{tt_3} \cdot \Delta \mathbf{s}_{tt_3} + C^{T}_t \, \mathbf{s}_{tt_3} \cdot \mathbf{T}_{tt_3} + C^{\nabla s}_t \, (\nabla \cdot \mathbf{s}_{tt_3})^2 + C^{j}_t \, \mathbf{j}^2_{tt_3} + C^{\nabla j}_t \, \mathbf{s}_{tt_3} \cdot \nabla \times \mathbf{j}_{tt_3}$$

T-odd densities vanish in g.s of e-e nuclei

T-odd Skyrme energy density is not well constrained,
but plays a role in studying compact star

EoS of polarized neutron matter:

T-odd components

$$\frac{\mathcal{H}}{\rho_0} = 2^{4/3} \left(\frac{3\pi^2}{2} \right)^{2/3} \left[\frac{\hbar^2}{2m} + (C^{\tau}_0 + C^{\tau}_1 + C^{T}_0 + C^{T}_1) \rho_0 \right] \rho_0^{2/3} + (C^{\rho}_0 + C^{\rho}_1 + C^{s}_0 + C^{s}_1) \rho_0$$

isovector components

T-odd energy density seen in nuclear responses

Collective motion is generated by the residual interaction

$$v_{\rm res}(\boldsymbol{r}_1, \boldsymbol{r}_2) \equiv \frac{\delta^2 \mathcal{E}}{\delta\rho(\boldsymbol{r}_1)\delta\rho(\boldsymbol{r}_2)}$$: self-consistency

spin density → spin excitation modes

Nuclear response to the IV external field: $\int d\boldsymbol{r} r^L Y_L \hat{\boldsymbol{s}}_{1t}$

IV spin density: $\hat{\boldsymbol{s}}_{1t} = \psi^\dagger(\boldsymbol{r}\sigma\tau)\langle\sigma|\boldsymbol{\sigma}|\sigma'\rangle\langle\tau|\boldsymbol{\tau}_t|\tau'\rangle\psi(\boldsymbol{r}\sigma'\tau')$

→ Gamow-Teller, Spin dipole,...

Self-consistent Skyrme-EDF approach for spin-isospin excitations in superfluid systems

North Carolina + Oak Ridge group

PHYSICAL REVIEW C, VOLUME 60, 014302

β decay rates of *r*-process waiting-point nuclei in a self-consistent approach

J. Engel,[1] M. Bender,[1,2] J. Dobaczewski,[2,3,4] W. Nazarewicz,[2,3,5] and R. Surman[1]

Skyrme-pnQRPA (1999)

coordinate-space 1D-HFB + QRPA in canonical basis

Application to fixing the coupling constants

PHYSICAL REVIEW C, VOLUME 65, 054322

Gamow-Teller strength and the spin-isospin coupling constants of the Skyrme energy functional

M. Bender,[1,2,3,4] J. Dobaczewski,[5,6] J. Engel,[3] and W. Nazarewicz[1,2,5]

PHYSICAL REVIEW C **87**, 064302 (2013)

Large-scale calculations of the double-β decay of ^{76}Ge, ^{130}Te, ^{136}Xe, and ^{150}Nd in the deformed self-consistent Skyrme quasiparticle random-phase approximation

M. T. Mustonen[1,2,*] and J. Engel[1,†]

The first deformed Skyrme-pnQRPA

coordinate-space 2D-HFB + QRPA in canonical basis

Milano group

PHYSICAL REVIEW C **76**, 044307 (2007)

Spin-isospin nuclear response using the existing microscopic Skyrme functionals

S. Fracasso and G. Colò

1D-HFBCS + QRPA

Sichuan + Wako group

Physics Letters B 719 (2013) 116–120

Role of $T = 0$ pairing in Gamow–Teller states in $N = Z$ nuclei

C.L. Bai[a], H. Sagawa[b,c,*], M. Sasano[c], T. Uesaka[c], K. Hagino[d], H.Q. Zhang[e], X.Z. Zhang[e], F.R. Xu[f]

coordinate-space 1D-HFB+ QRPA

Intermezzo -constrained by *ab-initio* calculations-

Skyrme-EDF for matter

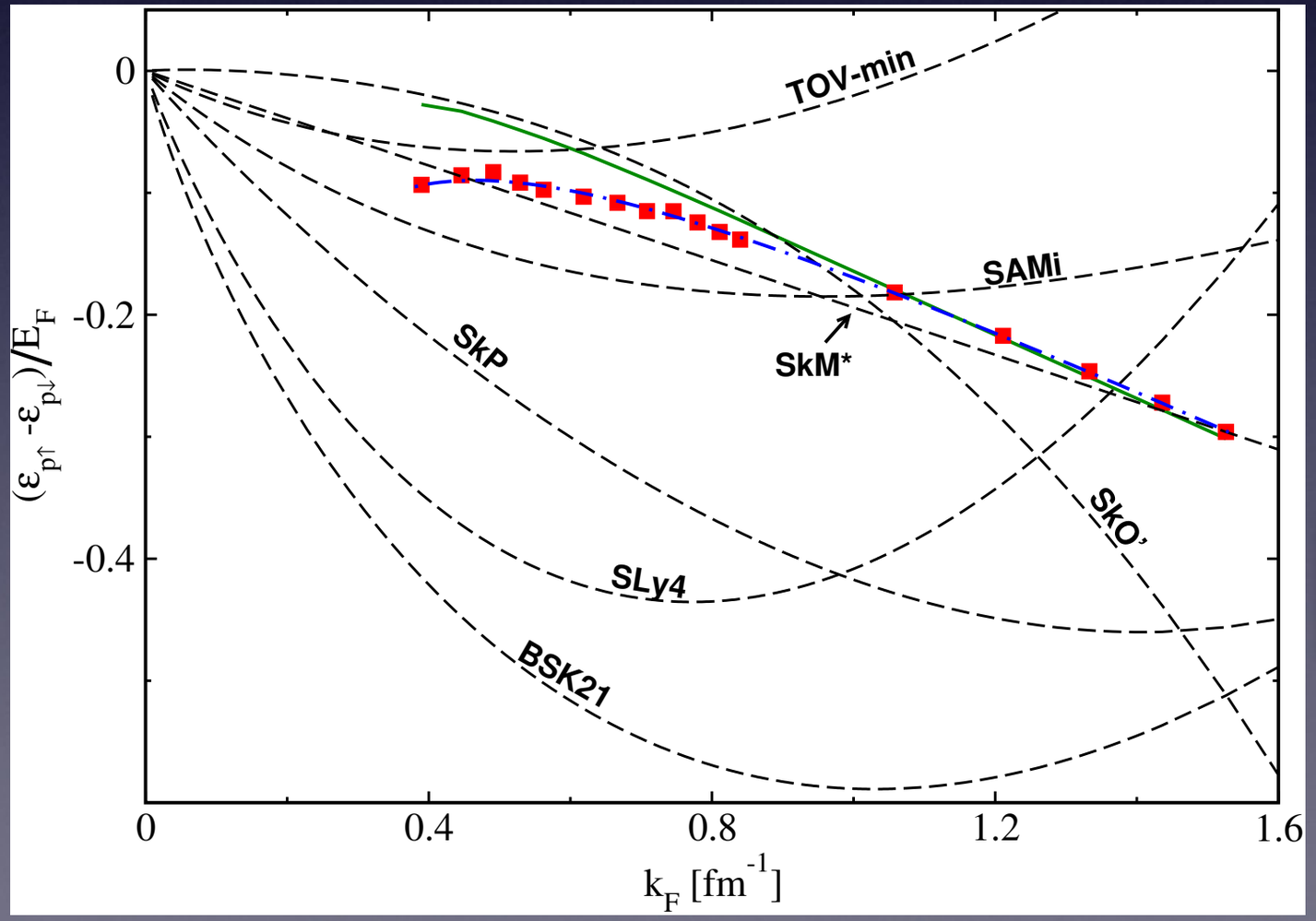
$$\mathcal{H} = \mathcal{H}_{\rm kin} + \sum_{t=0,1} (C_t^\rho \rho_t^2 + C_t^\tau \rho_t \tau_t + C_t^s \boldsymbol{s}_t^2 + C_t^T \boldsymbol{s}_t \cdot \boldsymbol{T}_t)$$

w/ density dependence

$$C_t^\rho = A_t^\rho + B_t^\rho \rho_0^\alpha$$
$$C_s^\rho = A_s^\rho + B_s^\rho \rho_0^\alpha$$

Configuration Interaction QMC cal. by Trento group

A. Roggero et al., arXiv:1406.1631



Polarized neutron matter w/ impurity

"impurity energy"

spin-up *N* neutrons, and a spin-up (-down) proton

$$\frac{\varepsilon_{p\uparrow} - \varepsilon_{p\downarrow}}{E_F} = \frac{4m(C_0^s - C_1^s)}{3\pi^2\hbar^2} k_F - \frac{2m(C_0^T - C_1^T)}{5\pi^2\hbar^2} k_F^3$$

purely T-odd

KY, PTEP2013,113D02

Self-consistent pnQRPA for spin-isospin excitations in deformed nuclei

starting point: Skyrme EDF $\mathcal{E}[\rho(\boldsymbol{r}), \tilde{\rho}(\boldsymbol{r})]$

variation w.r.t densities

The coordinate-space Hartree-Fock-Bogoliubov eq. for ground states

J. Dobaczewski et al., NPA422(1984)103

$$\begin{pmatrix} h^q(\boldsymbol{r},\sigma) - \lambda^q & \tilde{h}^q(\boldsymbol{r},\sigma) \\ \tilde{h}^q(\boldsymbol{r},\sigma) & -(h^q(\boldsymbol{r},\sigma) - \lambda^q) \end{pmatrix} \begin{pmatrix} \varphi^q_{1,\alpha}(\boldsymbol{r},\sigma) \\ \varphi^q_{2,\alpha}(\boldsymbol{r},\sigma) \end{pmatrix} = E_\alpha \begin{pmatrix} \varphi^q_{1,\alpha}(\boldsymbol{r},\sigma) \\ \varphi^q_{2,\alpha}(\boldsymbol{r},\sigma) \end{pmatrix}$$

$q = \nu,\ \pi$

"s.p." hamiltonian and pair potential: $h^q = \dfrac{\delta\mathcal{E}}{\delta\rho^q}, \qquad \tilde{h}^q = \dfrac{\delta\mathcal{E}}{\delta\tilde{\rho}^q}$

quasiparticle basis $\alpha, \beta \cdots$

The proton-neutron quasiparticle RPA eq. for excited states $[\hat{H}, \hat{O}^\dagger_\lambda]|\Psi_\lambda\rangle = \omega_\lambda \hat{O}^\dagger_\lambda |\Psi_\lambda\rangle$

Collective excitation = coherent superposition of 2qp excitations:

$$\hat{O}^\dagger_\lambda = \sum_{\alpha\beta} X^\lambda_{\alpha\beta} \hat{a}^\dagger_{\alpha,\nu} \hat{a}^\dagger_{\beta,\pi} - Y^\lambda_{\alpha\beta} \hat{a}_{\bar{\beta},\pi} \hat{a}_{\bar{\alpha},\nu}$$

residual interactions derived self-consistently :

$$v_{\rm res}(\boldsymbol{r}_1, \boldsymbol{r}_2) = \frac{\delta^2\mathcal{E}}{\delta\rho_{1t_3}(\boldsymbol{r}_1)\delta\rho_{1t_3}(\boldsymbol{r}_2)} \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 + \frac{\delta^2\mathcal{E}}{\delta\boldsymbol{s}_{1t_3}(\boldsymbol{r}_1)\delta\boldsymbol{s}_{1t_3}(\boldsymbol{r}_2)} \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$$

Canonical basis and quasiparticle basis

J. Engel et al., PRC60 (1999) 014302

$$A_{pn,p'n'} = E_{p,p'}\delta_{n,n'} + E_{n,n'}\delta_{p,p'} + \tilde{V}_{pn,p'n'}(u_p v_n u_{p'} v_{n'} + v_p u_n v_{p'} u_{n'}) + V_{pn,p'n'}(u_p u_n u_{p'} u_{n'} + v_p v_n v_{p'} v_{n'}) \quad (16)$$

$$B_{pn,p'n'} = \tilde{V}_{pn,p'n'}(v_p u_n u_{p'} v_{n'} + u_p v_n v_{p'} u_{n'}) - V_{pn,p'n'}(u_p u_n v_{p'} v_{n'} + v_p v_n u_{p'} u_{n'}). \quad (17)$$

calculation cost ~ BCS-QRPA

introduction of cutoff
occupation probability

KY, PTEP (2013)113D02

calculation cost ~
4*BCS-QRPA

introduction of cutoff
simply by the 2qp energy

↓

pp(hh) and ph excitations are
treated on the same footing

$$\begin{aligned} A_{\alpha\beta\alpha'\beta'} = {} & (E_\alpha + E_\beta)\delta_{\alpha\alpha'}\delta_{\beta\beta'} \\ & + \int d1d2d1'd2' \{ \varphi^{\nu}_{1,\alpha}(\boldsymbol{r}_1\bar{\sigma}_1)\varphi^{\pi}_{1,\beta}(\boldsymbol{r}_2\bar{\sigma}_2)\bar{v}_{\rm pp}(12;1'2')\varphi^{\nu *}_{1,\alpha'}(\boldsymbol{r}'_1\bar{\sigma}'_1)\varphi^{\pi *}_{1,\beta'}(\boldsymbol{r}'_2\bar{\sigma}'_2) \\ & + \varphi^{\nu}_{2,\alpha}(\boldsymbol{r}_1\sigma_1)\varphi^{\pi}_{2,\beta}(\boldsymbol{r}_2\sigma_2)\bar{v}_{\rm pp}(12;1'2')\varphi^{\nu *}_{2,\alpha'}(\boldsymbol{r}'_1\sigma'_1)\varphi^{\pi *}_{2,\beta'}(\boldsymbol{r}'_2\sigma'_2) \\ & + \varphi^{\nu}_{1,\alpha}(\boldsymbol{r}_1\bar{\sigma}_1)\varphi^{\pi *}_{2,\beta'}(\boldsymbol{r}_2\sigma_2)\bar{v}_{\rm ph}(12;1'2')\varphi^{\pi}_{2,\beta}(\boldsymbol{r}'_1\sigma'_1)\varphi^{\nu *}_{1,\alpha'}(\boldsymbol{r}'_2\bar{\sigma}'_2) \\ & + \varphi^{\pi}_{1,\beta}(\boldsymbol{r}_1\bar{\sigma}_1)\varphi^{\nu *}_{2,\alpha'}(\boldsymbol{r}_2\sigma_2)\bar{v}_{\rm ph}(12;1'2')\varphi^{\nu}_{2,\alpha}(\boldsymbol{r}'_1\sigma'_1)\varphi^{\pi *}_{1,\beta'}(\boldsymbol{r}'_2\bar{\sigma}'_2)\}, \end{aligned} \quad (7)$$

$$\begin{aligned} B_{\alpha\beta\alpha'\beta'} = {} & \int d1d2d1'd2' \{ -\varphi^{\nu}_{1,\alpha}(\boldsymbol{r}_1\bar{\sigma}_1)\varphi^{\pi}_{1,\beta}(\boldsymbol{r}_2\bar{\sigma}_2)\bar{v}_{\rm pp}(12;1'2')\varphi^{\nu}_{2,\bar{\alpha}'}(\boldsymbol{r}'_1\sigma'_1)\varphi^{\pi}_{2,\bar{\beta}'}(\boldsymbol{r}'_2\sigma'_2) \\ & - \varphi^{\nu}_{2,\alpha}(\boldsymbol{r}_1\sigma_1)\varphi^{\pi}_{2,\beta}(\boldsymbol{r}_2\sigma_2)\bar{v}_{\rm pp}(12;1'2')\varphi^{\nu}_{1,\bar{\alpha}'}(\boldsymbol{r}'_1\bar{\sigma}'_1)\varphi^{\pi}_{1,\bar{\beta}'}(\boldsymbol{r}'_2\bar{\sigma}'_2) \\ & - \varphi^{\nu}_{1,\alpha}(\boldsymbol{r}_1\bar{\sigma}_1)\varphi^{\pi}_{1,\bar{\beta}'}(\boldsymbol{r}_2\bar{\sigma}_2)\bar{v}_{\rm ph}(12;1'2')\varphi^{\pi}_{2,\beta}(\boldsymbol{r}'_1\sigma'_1)\varphi^{\nu}_{2,\bar{\alpha}'}(\boldsymbol{r}'_2\sigma'_2) \\ & - \varphi^{\pi}_{1,\beta}(\boldsymbol{r}_1\bar{\sigma}_1)\varphi^{\nu}_{1,\bar{\alpha}'}(\boldsymbol{r}_2\bar{\sigma}_2)\bar{v}_{\rm ph}(12;1'2')\varphi^{\nu}_{2,\alpha}(\boldsymbol{r}'_1\sigma'_1)\varphi^{\pi}_{2,\bar{\beta}'}(\boldsymbol{r}'_2\sigma'_2)\}. \end{aligned} \quad (8)$$

QRPA for heavy axially-deformed nuclei with HPC

HFB cal. (64 CPUs)

Box size: 14.7 fm × 14.4 fm

Cut-off: $\Omega \leqq \frac{31}{2}$, $E_\alpha \leqq 60$ MeV

HFB Hamiltonian:
block diagonal in Ω^π

distributed to cores

QRPA cal. (512 CPUs)

Cut-off: $E_\alpha + E_\beta \leqq 60$ MeV

Matrix elements of A and B:

2D-numerical integration

independent of each 2qp configuration

For each K^π

# of 2qp excitation: ~50,000

matrix elements: 590 core hours

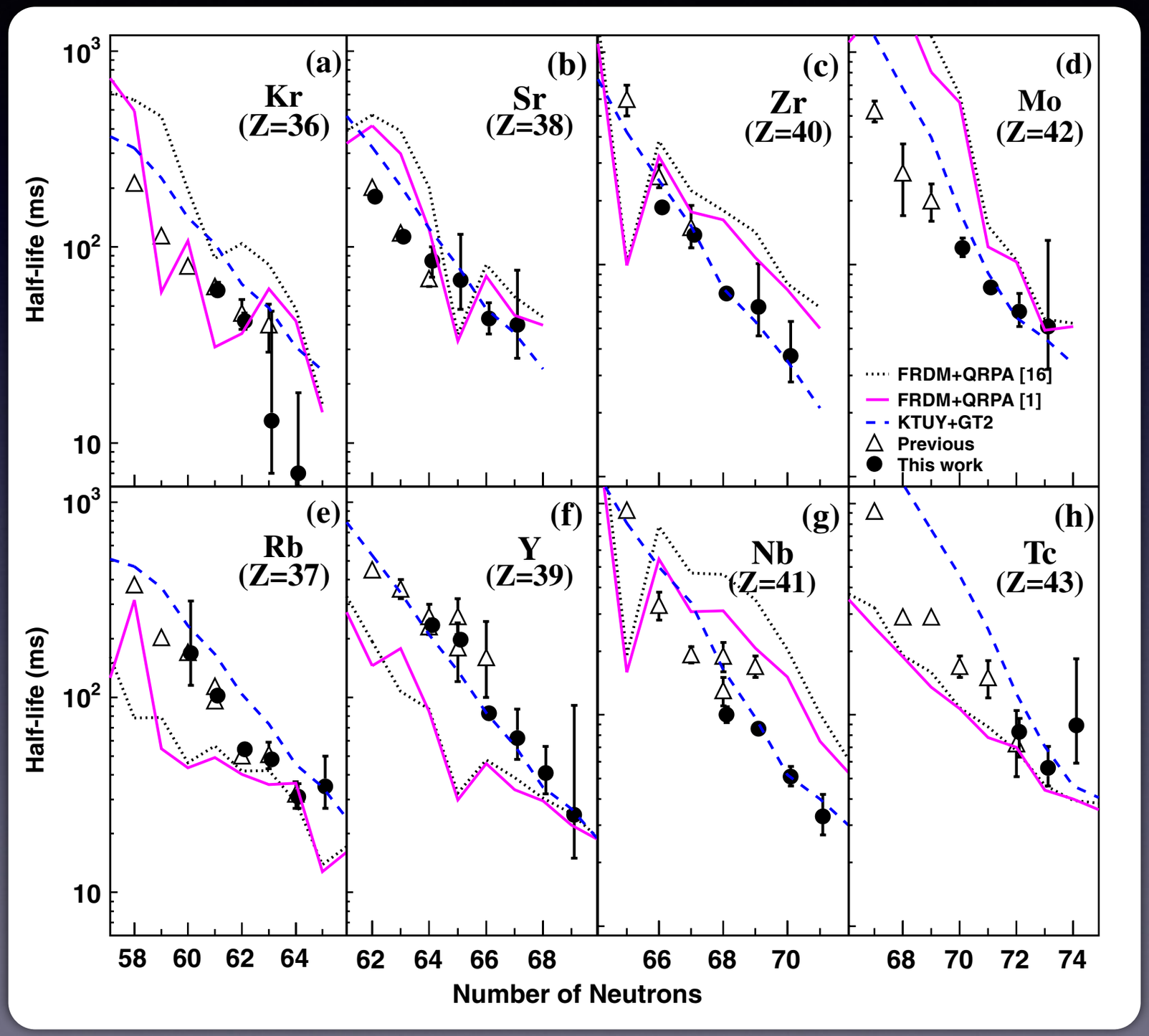
diagonalization: 330 core hours

with the help of ScaLapack

✓ GT strengths and beta-decay properties of neutron-rich Zr isotopes

β-decay half-lives in neutron-rich Zr isotopes

S. Nishimura et al., PRL106(2011)052502



β-decay half-lives in neutron-rich Zr isotopes

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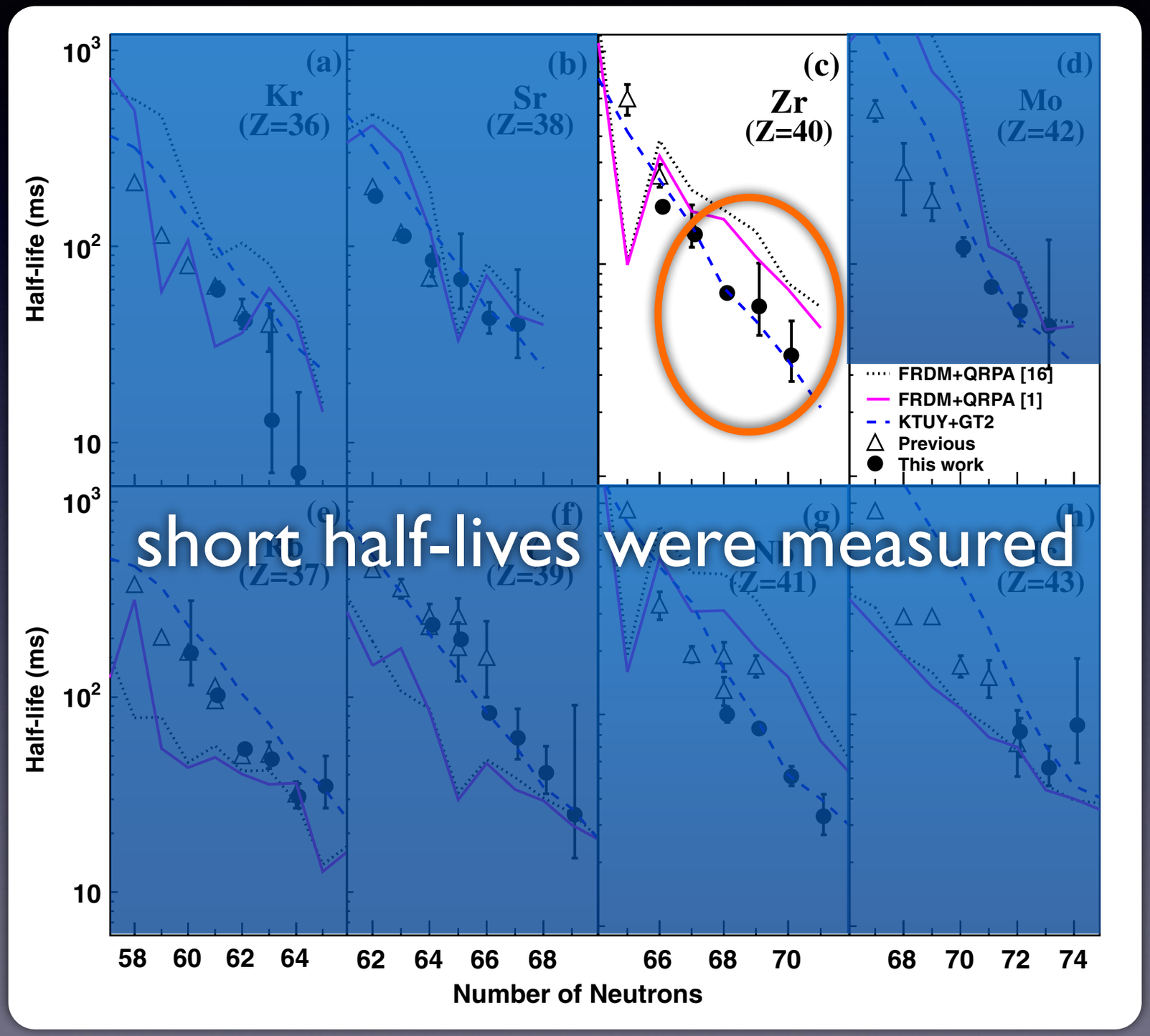
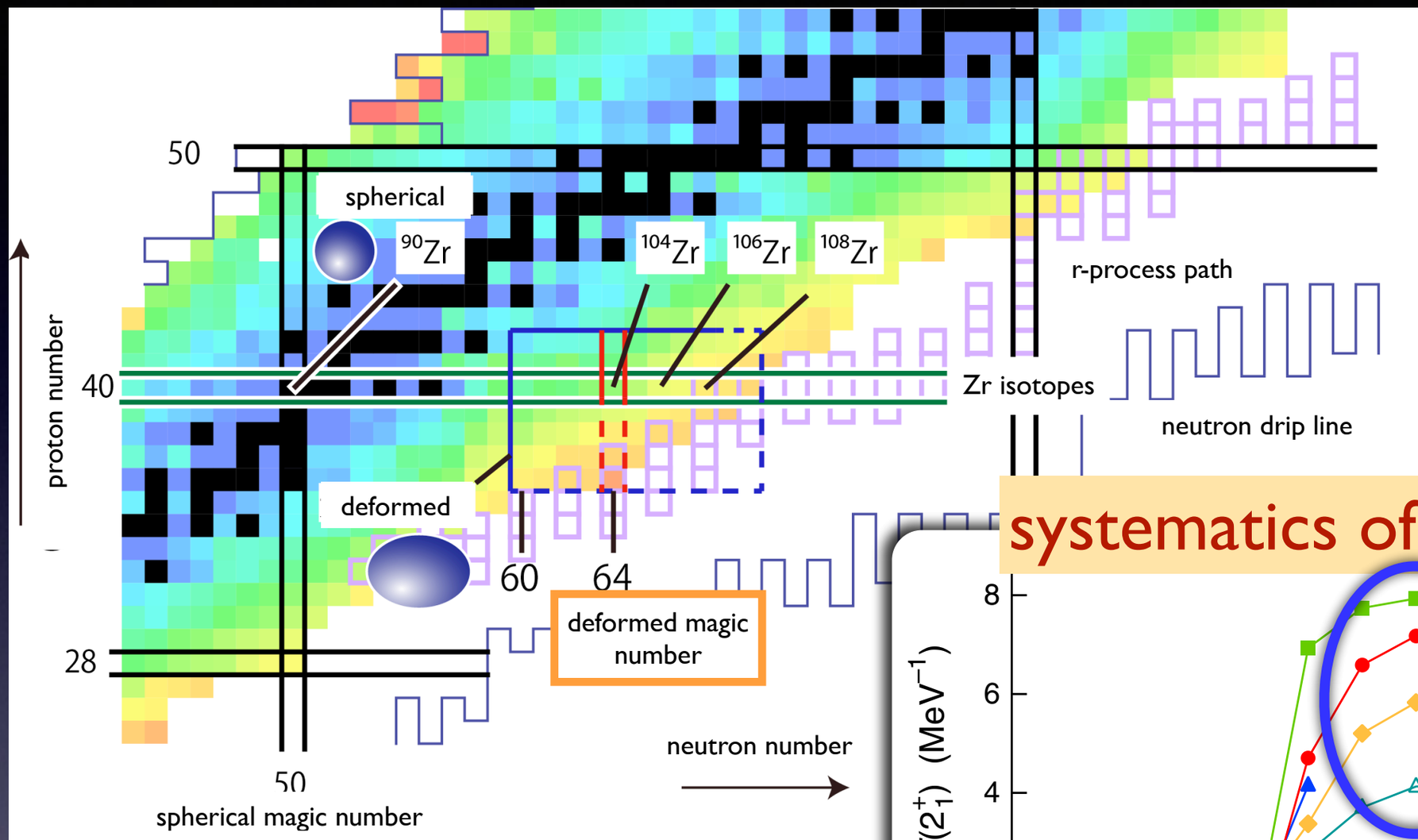
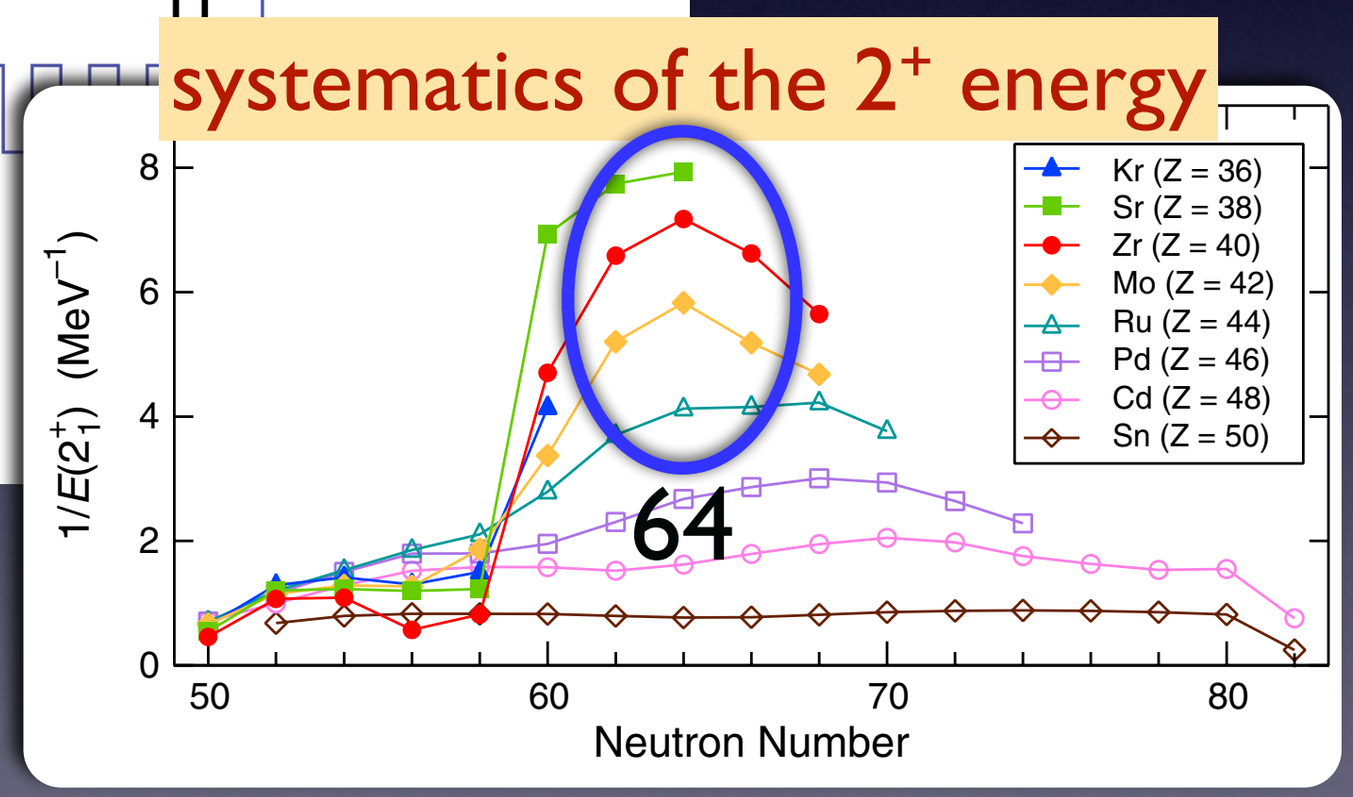


Deformed Zr isotopes on the r-process path

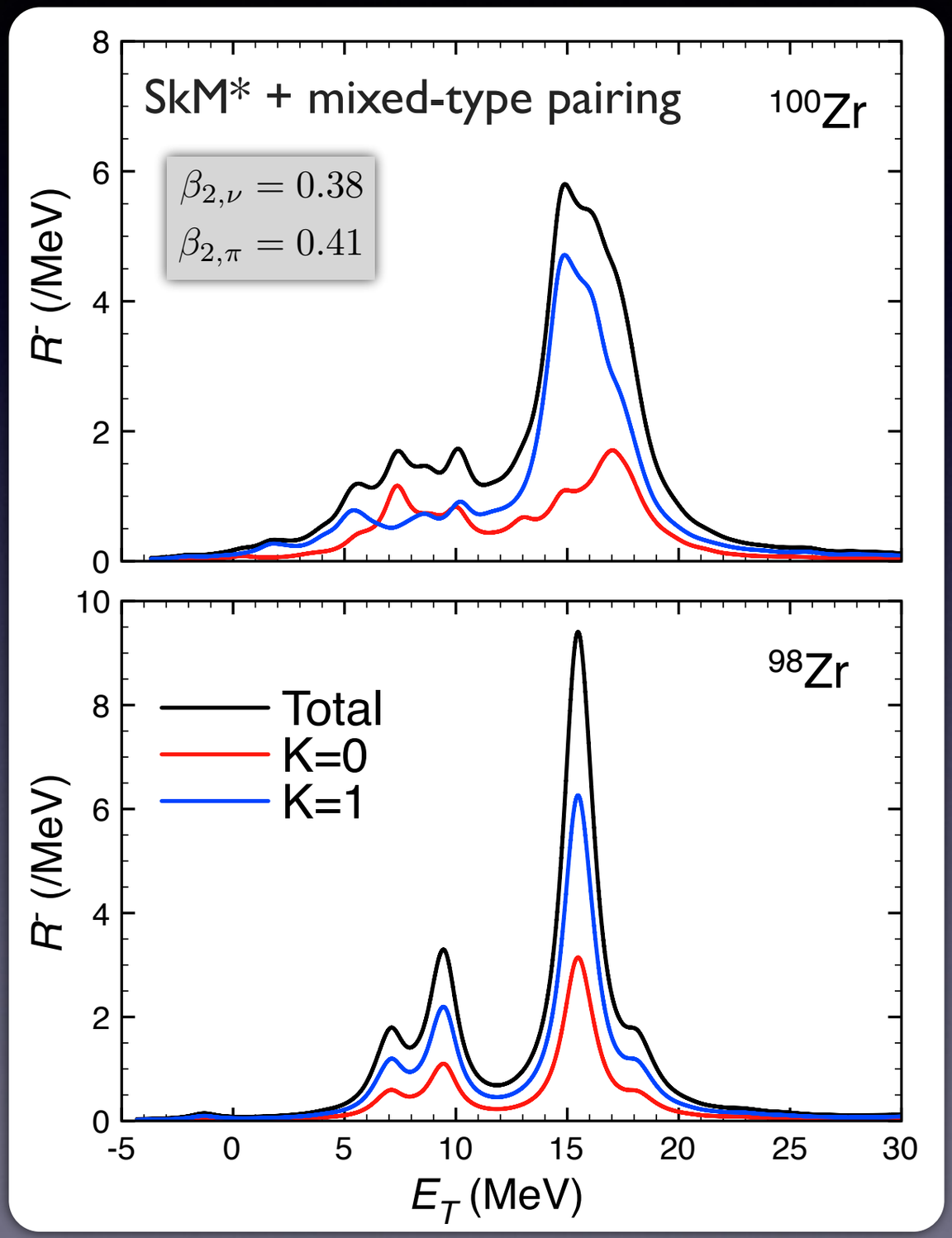




T. Sumikama et al., PRL106(2011)202501

GT giant resonance

$$\hat{F}_K^{t_3} = \sum_{\sigma,\sigma'}\sum_{\tau,\tau'}\int d\boldsymbol{r}\hat{\psi}^\dagger(\boldsymbol{r}\sigma\tau)\langle\sigma|\boldsymbol{\sigma}_K|\sigma'\rangle\langle\tau|\boldsymbol{\tau}_{t_3}|\tau'\rangle\hat{\psi}(\boldsymbol{r}\sigma'\tau')$$



1 MeV smearing width

✓sudden onset of deformation at N=60

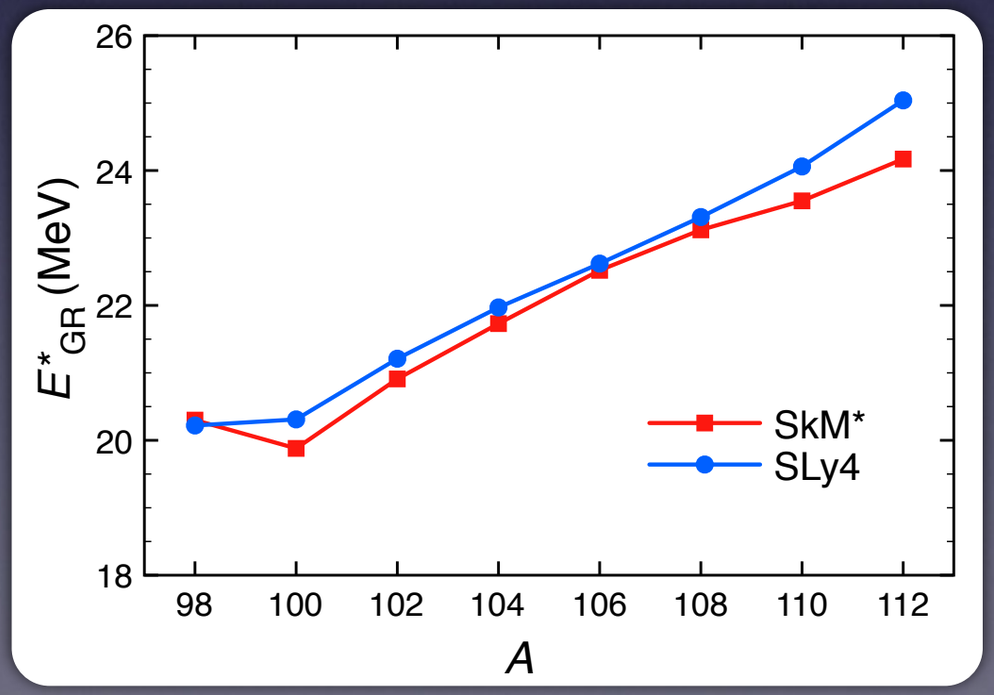
SLy4: A. Blazkiewicz et al., PRC71(2005)054321

✓fragmentation of strength distribution due to deformation

separable pnRPA:
P. Urkedal et al., PRC64(2001)054304

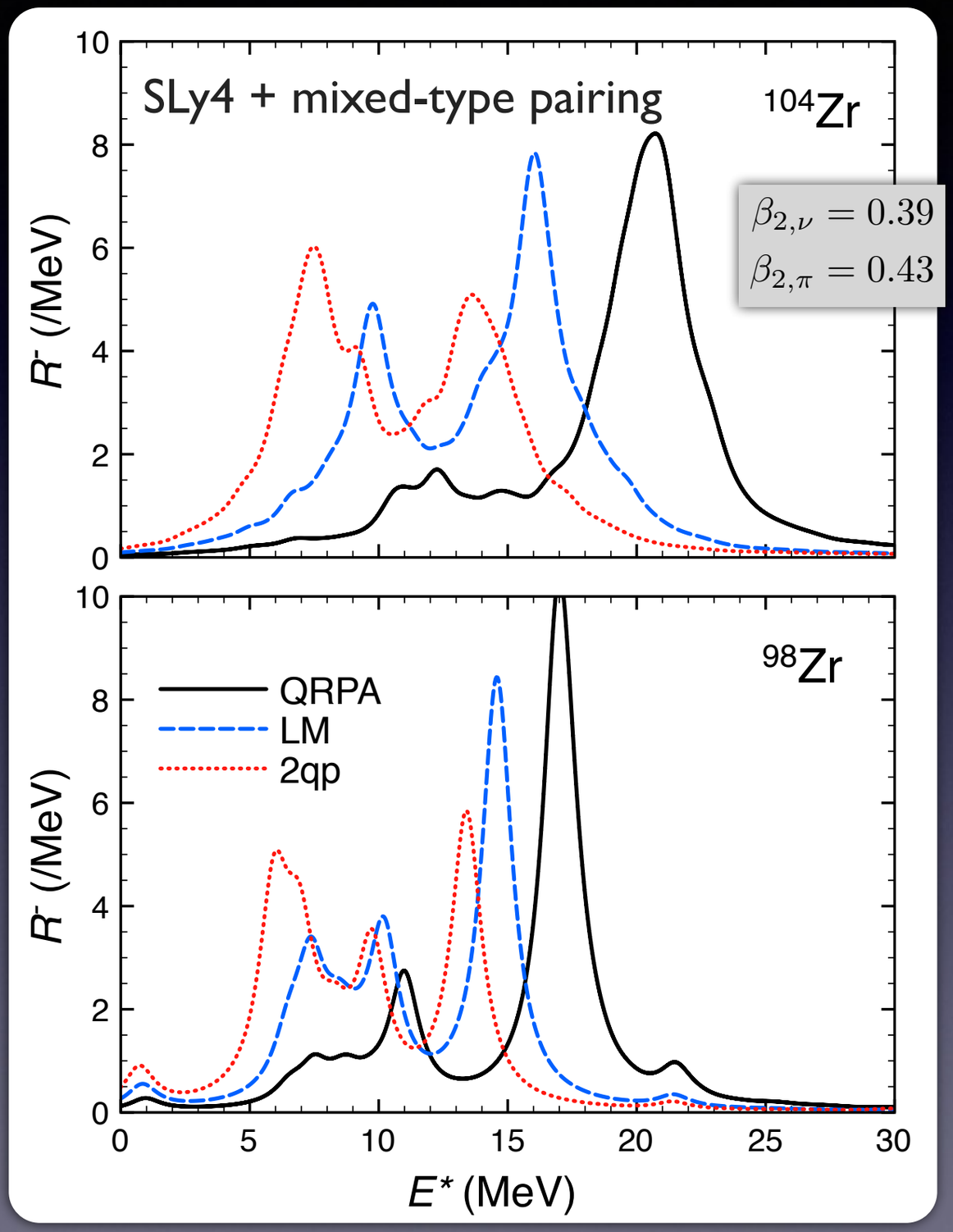
✓SkM* and SLy4 give almost the same (ΔE<1 MeV) excitation energies of GTGR

g_0'=0.94 (SkM*), 0.90 (SLy4)



excitation energy w.r.t. the g.s of daughter

GTGR: the need of self-consistency



✓a repulsive character of the residual interaction raises the peak energy

✓low-lying strengths are absorbed to the high-energy peak

strong collectivity of the GTGR

✓the collectivity generated by the Landau-Migdal approximation is weak

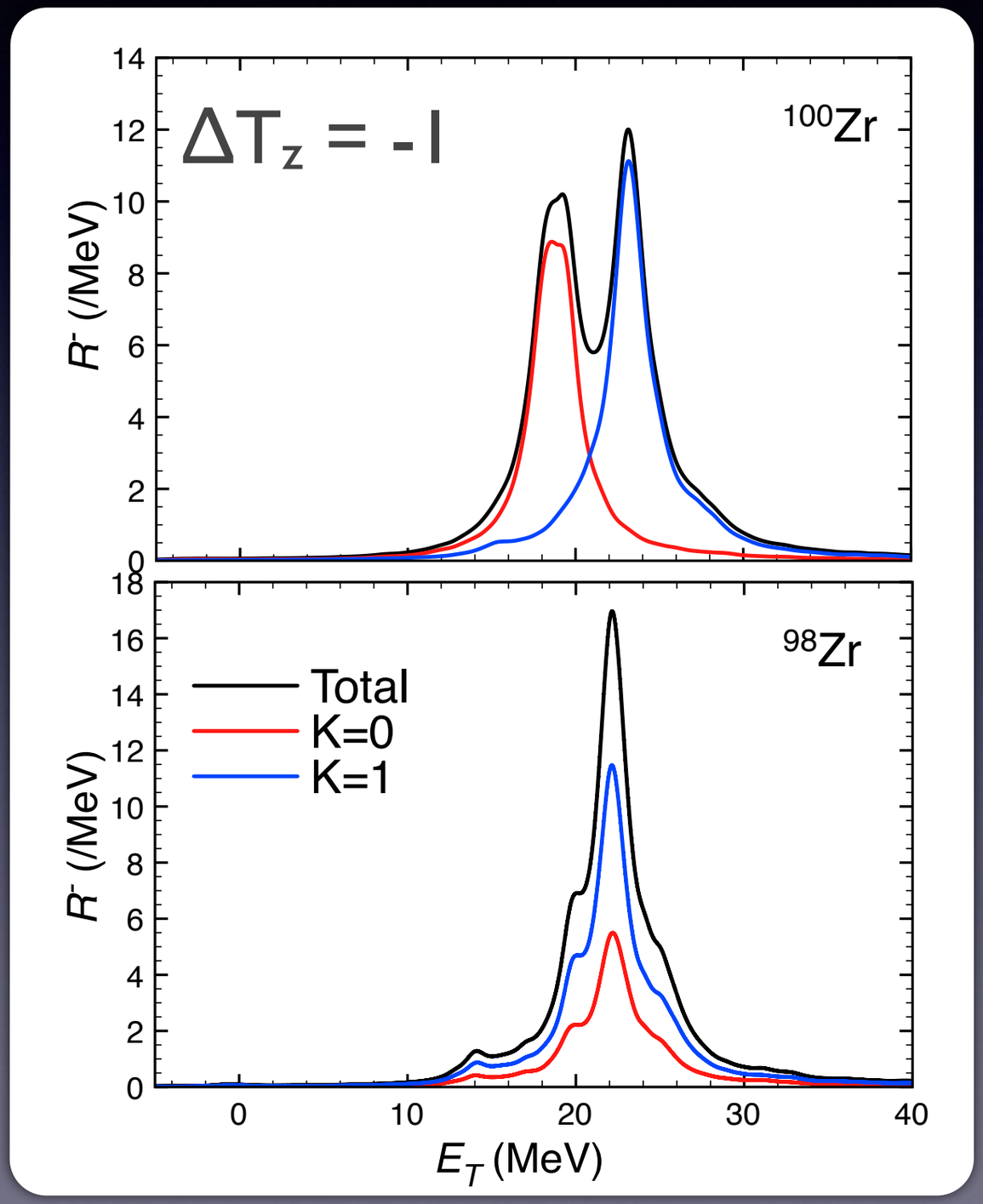
$$v_{\rm ph}(\boldsymbol{r}_1\,\boldsymbol{r}_2) = N_0^{-1}\left[f_0'\tau_1\cdot\tau_2 + g_0'\sigma_1\cdot\sigma_2\tau_1\cdot\tau_2\right]\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)$$

LM parameter:
M. Bender et al., PRC65(2002)054322

self-consistency is required for a quantitative description of the GTGR

IV giant dipole resonance: Anti-analog GDR

$$\hat{F}^{t_3}_{1K} = \sum_{\sigma} \sum_{\tau,\tau'} \int d\boldsymbol{r} r Y_{1K} \hat{\psi}^{\dagger}(\boldsymbol{r}\sigma\tau) \langle \tau | \boldsymbol{\tau}_{t_3} | \tau' \rangle \hat{\psi}(\boldsymbol{r}\sigma\tau')$$

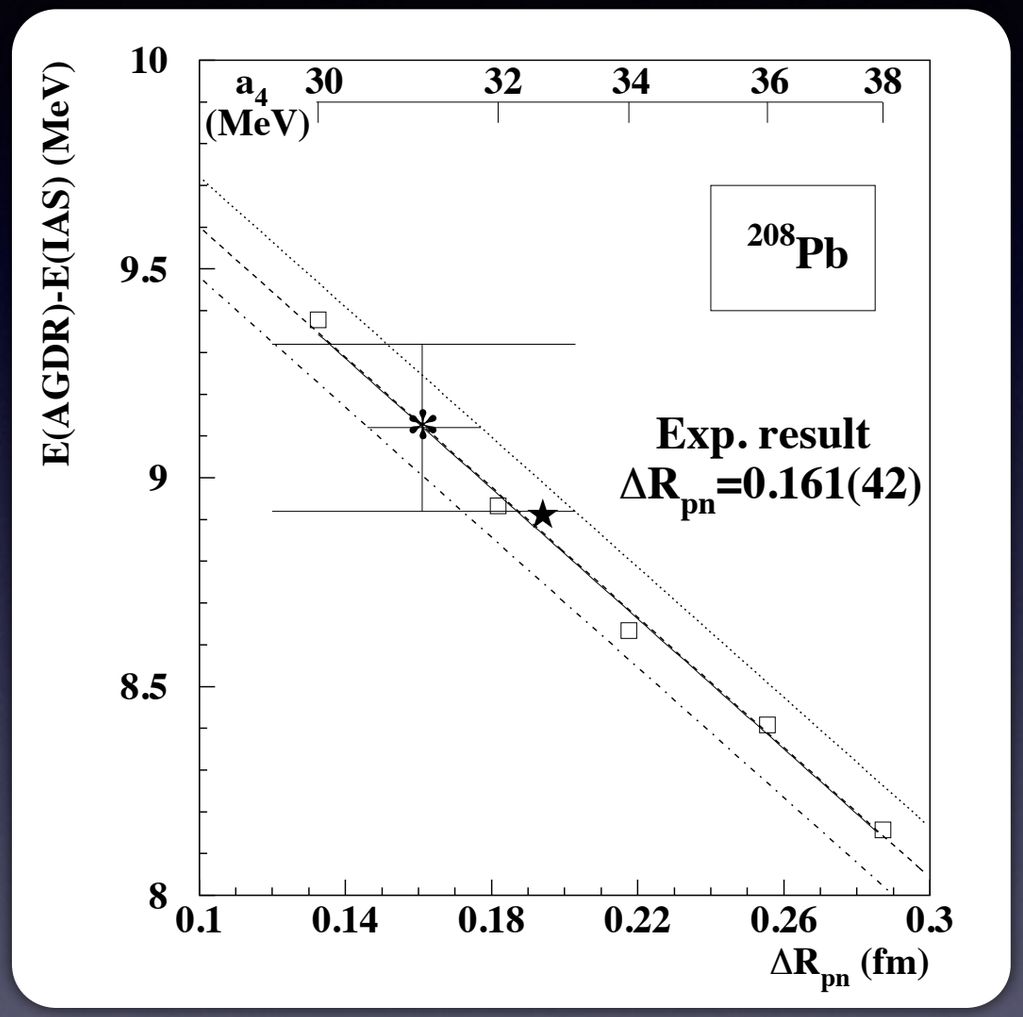


SLy4 + mixed-type pairing

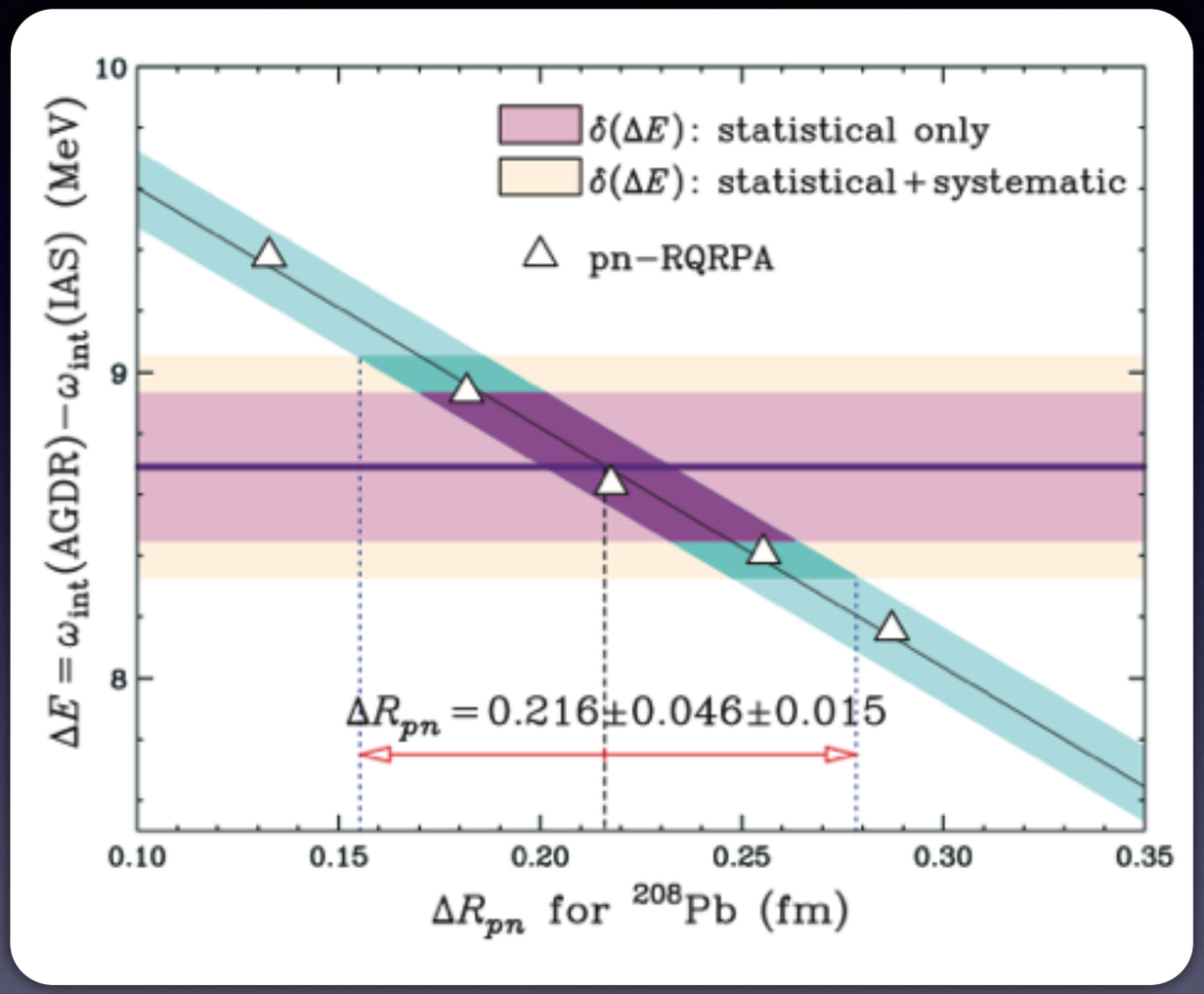
✓deformation splitting (K-splitting) is clearly seen as in GDR

AGDR and neutron skin thickness

linear relationship between the neutron-skin thickness and the AGDR energy



A. Krasznahorkay, N. Paar, D. Vretenar, M.N.Harakeh, Phys. Scr. T154(2013)4018



J.Yasuda, T.Wakasa et al., PTEP2013, 063D02

T=0 (S=1) pairing

✓affects the GT response

if we have (a) T=1 pairing condensate(s)

due to the coupling between the p-h and p-p excitations

→ we may see the effect in the low-lying states that are generated by 2qp excitations around the Fermi levels

✓does not affect the gs properties in N>Z nuclei

→ a form of the interaction or an np-pairing EDF is seldom known

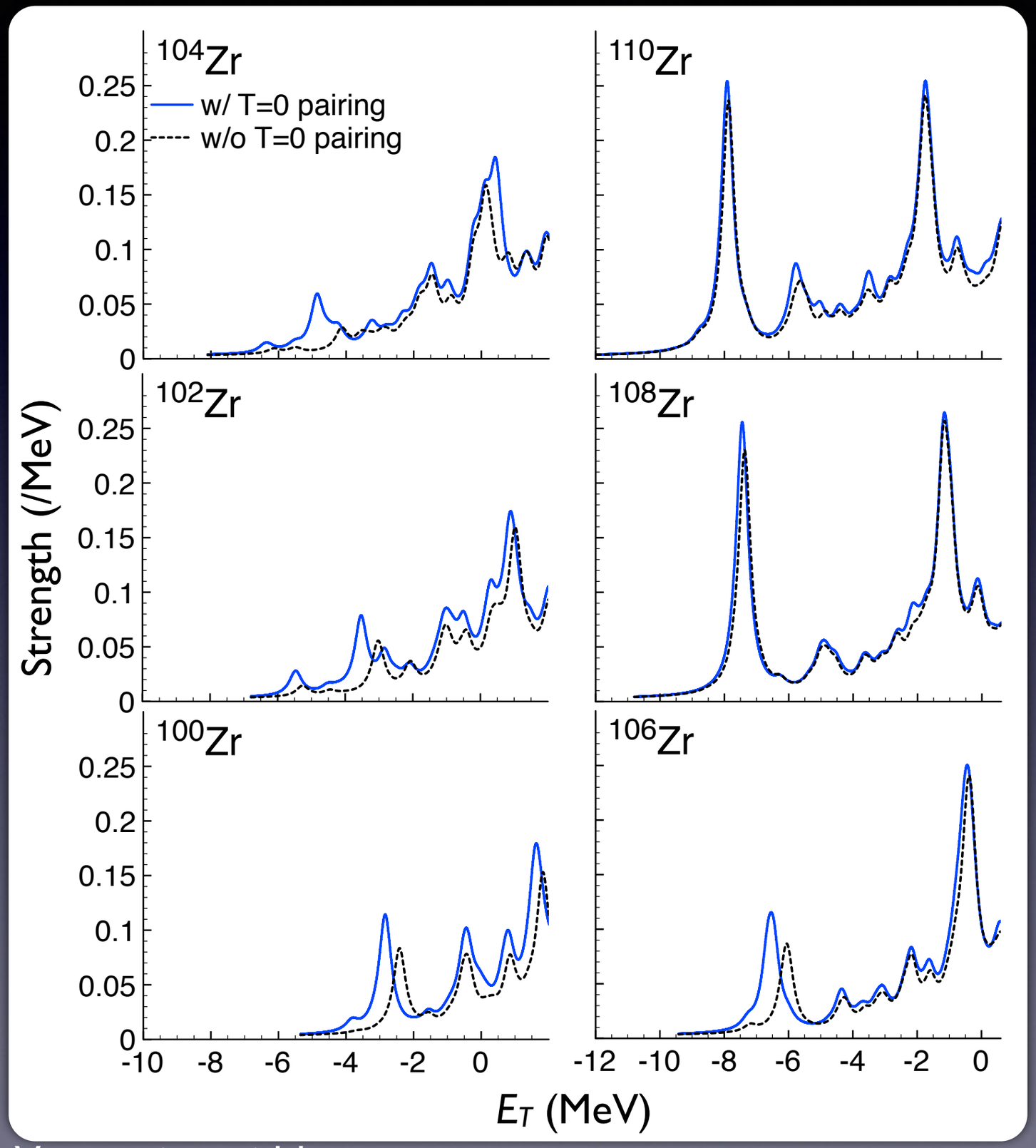
Take the simplest one;

$$v_{\rm pp}^{T=0}(\boldsymbol{r},\boldsymbol{r}') = \frac{1+P_\sigma}{2}\frac{1-P_\tau}{2}V_0\delta(\boldsymbol{r}-\boldsymbol{r}')$$

the pairing strength determined to reproduce the β-decay half-life of ^{100}Zr (7.1 s)

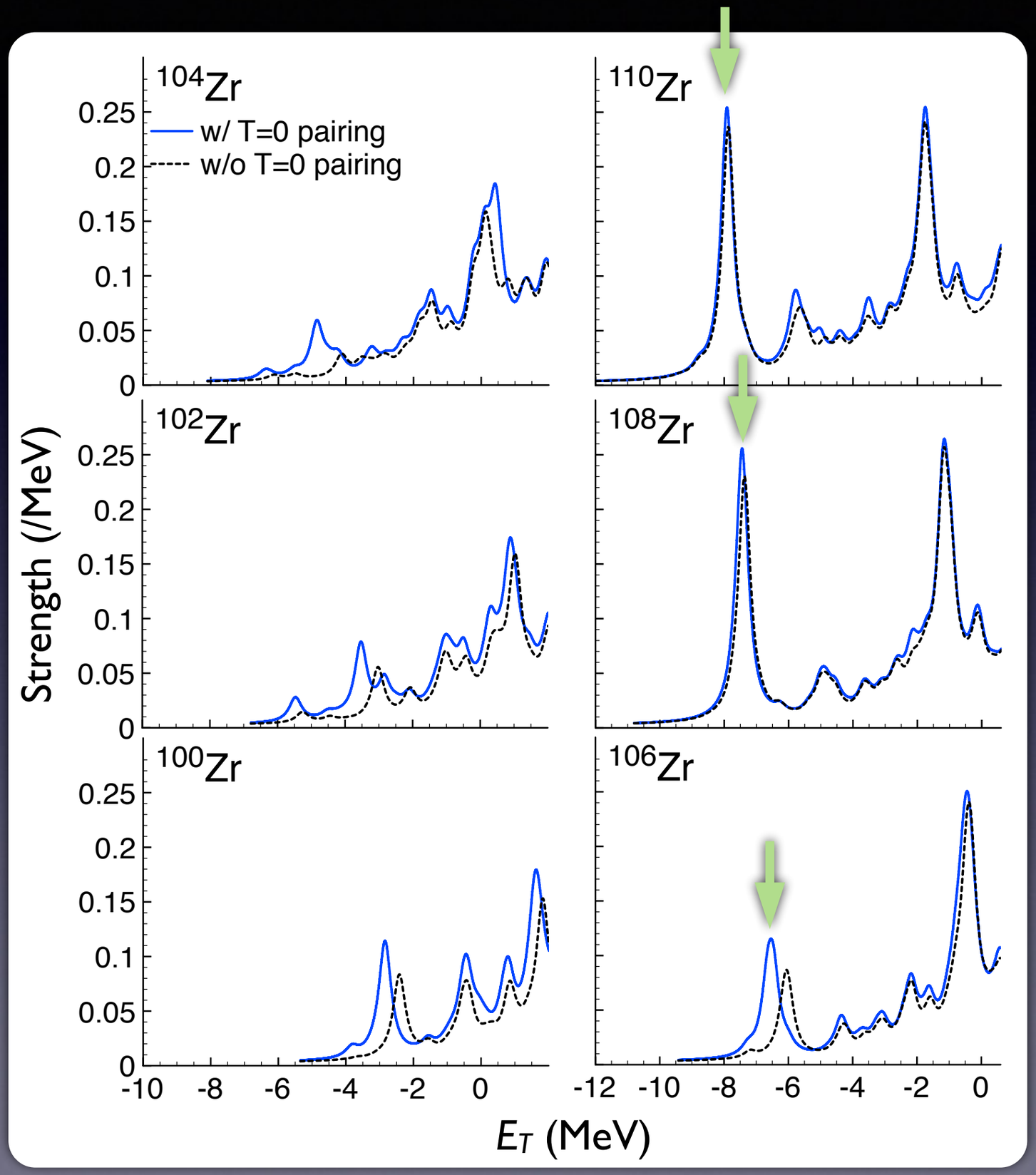
Low-lying GT states

SLy4+Mixed-type pairing
0.1 MeV smearing width



0.1 MeV smearing width

Low-lying GT states



selection rule for GT-

$$|\langle\pi[Nn_3\Lambda]\Omega=\Lambda+1/2|t_-\sigma_{+1}|\nu[Nn_3\Lambda]\Omega=\Lambda-1/2\rangle|=\sqrt{2}$$

^{106}Zr

constructed dominantly by

$\pi[413]7/2 \otimes \nu[413]5/2$

particle-like particle-like

✓T=0 pairing effective

neutrons added

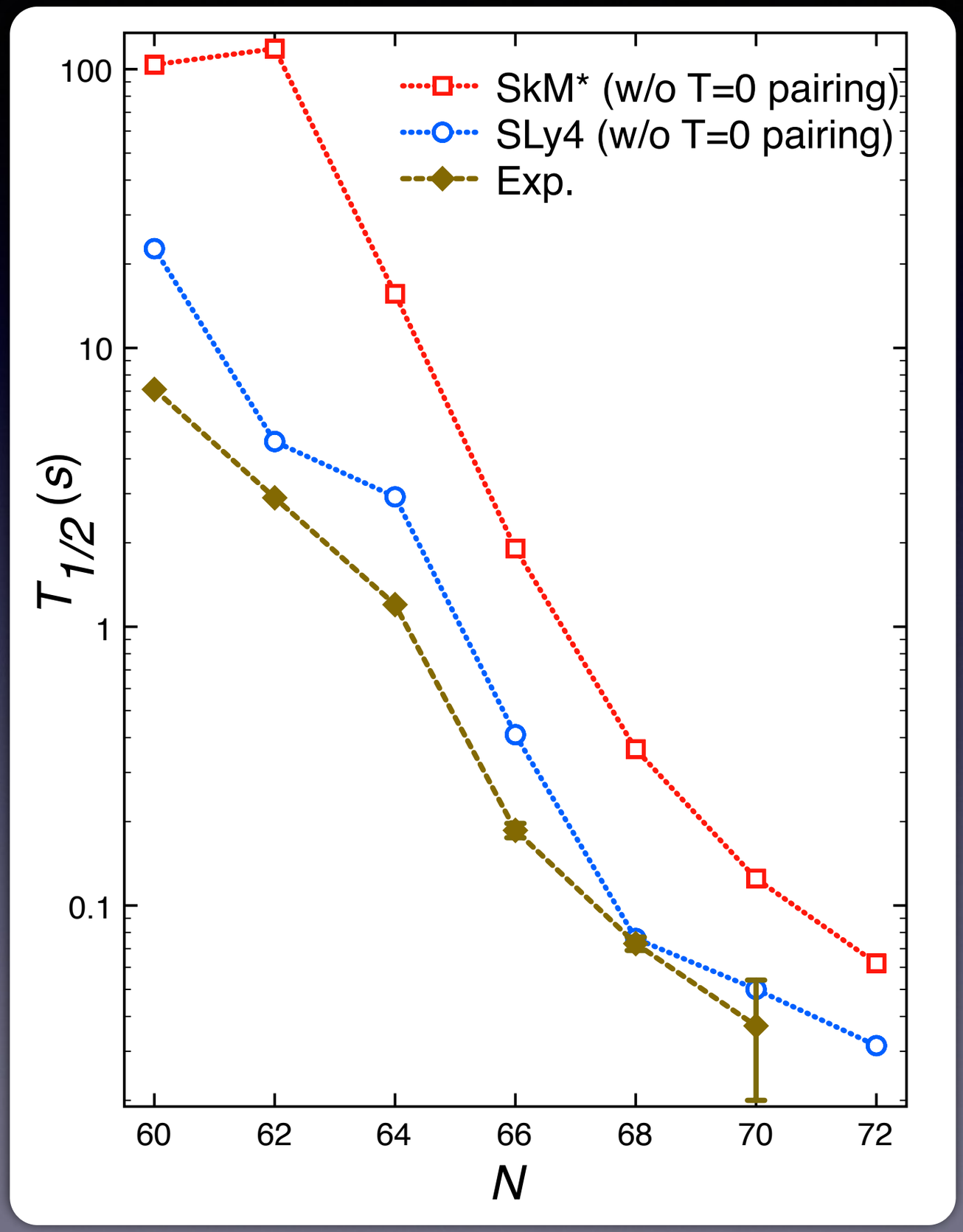
108, ^{110}Zr

$\pi[413]7/2 \otimes \nu[413]5/2$

particle-like hole-like

✓T=0 pairing ineffective

Beta-decay half-lives



✓Fermi's golden rule

N. B. Gove, M. J. Martin,
At. Data Nucl. Data Tables 10(1971)205

✓Fermi and Gamow-Teller strengths included

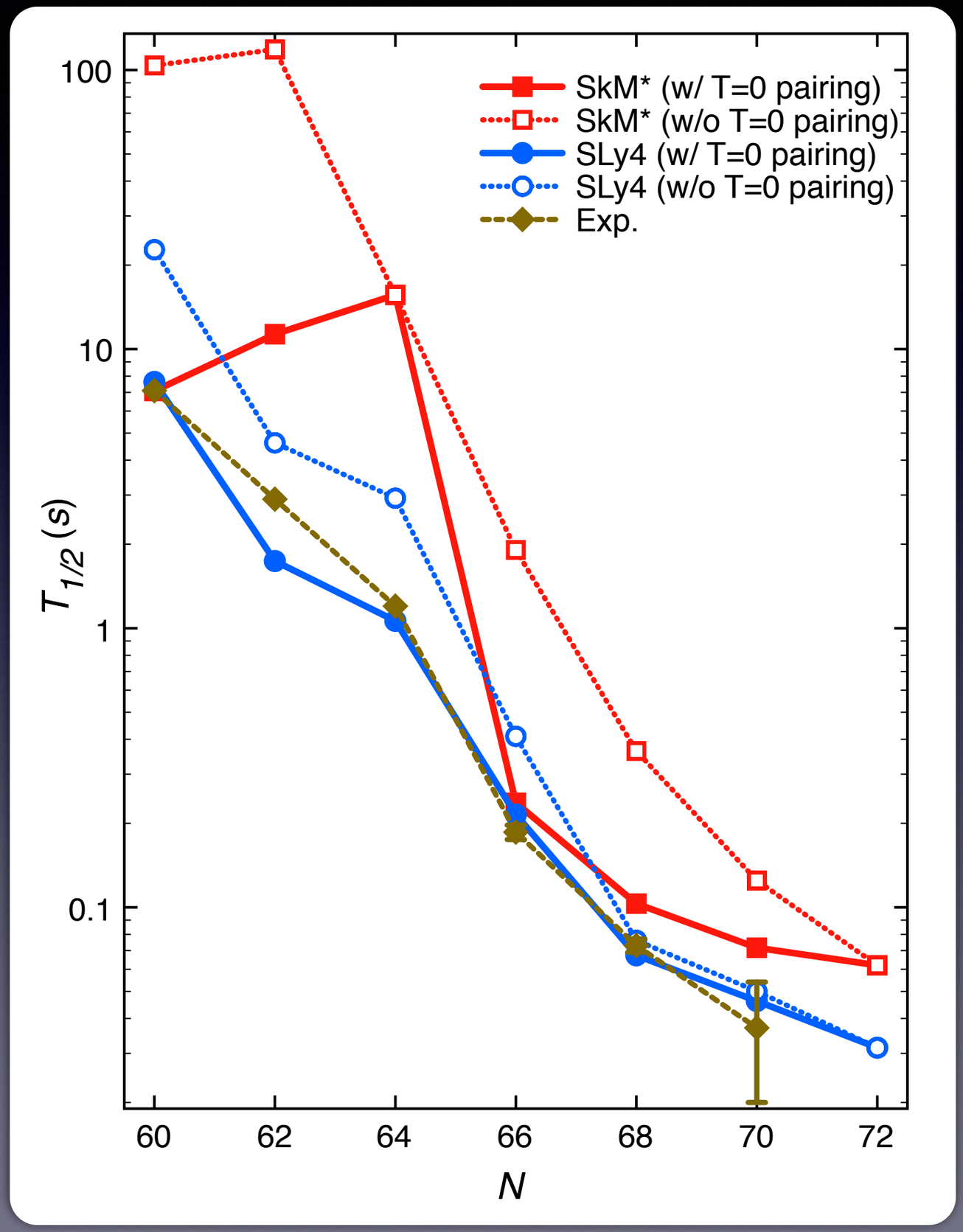
✓SkM* produces longer half-lives primarily due to a large Q-value

approximate Q-value

$$Q_{\beta^-} = \Delta M_{\mathrm{n-H}} + B(A, Z+1) - B(A, Z)$$
$$\simeq \Delta M_{\mathrm{n-H}} + \lambda_\nu - \lambda_\pi - E_0$$
$$E_0 = \min[E_\nu + E_\pi]$$

cf. J. Engel et al., PRC60(1999)014302

Beta-decay half-lives with T=0 pairing



✓Strength of T=0 pairing determined at N=60

SLy4

✓reproduces well the observed isotopic dependence with T=0 pairing

✓Effect of the T=0 pairing is small beyond N=68

SkM*

✓gives a strong deformed gap at N=64

✓ pn-pair transfer strengths in N=Z nuclei in fp-shell

Proton-neutron pair excitations

IS
spin triplet

$$\hat{P}^\dagger_{T=0,S=1,S_z=0} = \frac{1}{2}\sum_{\sigma,\sigma'}\sum_{\tau}\int d\boldsymbol{r}\hat{\psi}^\dagger(\boldsymbol{r}\sigma\tau)\langle\sigma|\boldsymbol{\sigma}_0|\sigma'\rangle\hat{\psi}^\dagger(\boldsymbol{r}\tilde{\sigma}'\tilde{\tau})$$

$$\hat{P}^\dagger_{T=0,S=1,S_z=\pm1} = \frac{1}{2}\sum_{\sigma,\sigma'}\sum_{\tau}\int d\boldsymbol{r}\hat{\psi}^\dagger(\boldsymbol{r}\sigma\tau)\langle\sigma|\boldsymbol{\sigma}_{\pm1}|\sigma'\rangle\hat{\psi}^\dagger(\boldsymbol{r}\tilde{\sigma}'\tilde{\tau})$$

IV
spin singlet

$$\hat{P}^\dagger_{T=1,T_z=0,S=0} = \frac{1}{2}\sum_{\sigma}\sum_{\tau,\tau'}\int d\boldsymbol{r}\hat{\psi}^\dagger(\boldsymbol{r}\sigma\tau)\langle\tau|\boldsymbol{\tau}_0|\tau'\rangle\hat{\psi}^\dagger(\boldsymbol{r}\tilde{\sigma}\tilde{\tau}')$$

Interactions employed for pn-pairing vibration in fp-shell nuclei

HFB eq:

SGII + surface pairing

V_0 = -520 MeV fm^3

^{44}Ti

Δ_n = 1.82 MeV

Δ_p = 1.87 MeV

pnQRPA eq:

p-h channel: SGII

p-p channel:

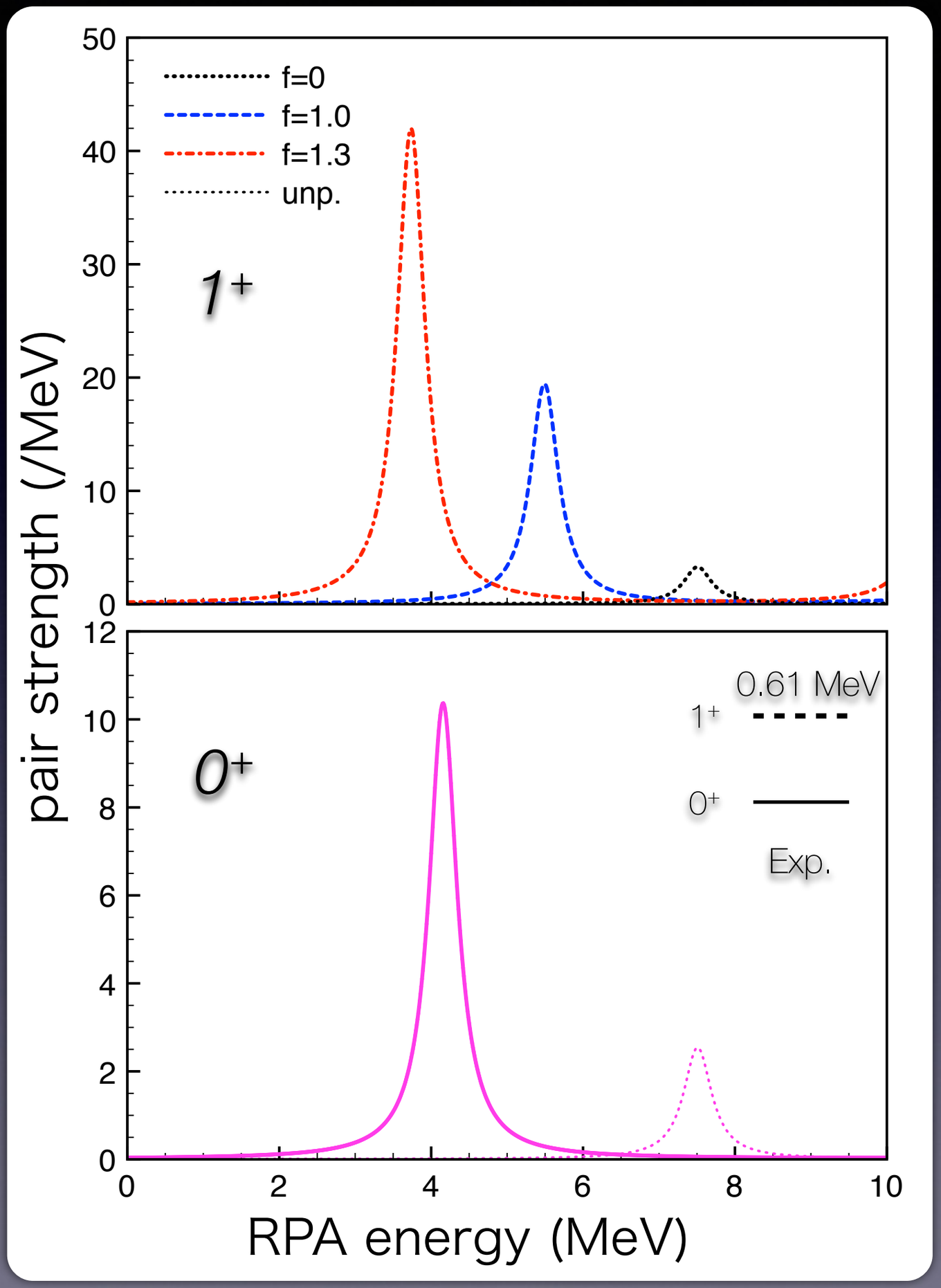
$$v_{\rm pp}^{T=0}(\boldsymbol{r}\sigma\tau,\boldsymbol{r}'\sigma'\tau') = f \times V_0 \frac{1+P_\sigma}{2}\frac{1-P_\tau}{2}\left[1-\frac{\rho(\boldsymbol{r})}{\rho_0}\right]\delta(\boldsymbol{r}-\boldsymbol{r}')$$

$$v_{\rm pp}^{T=1}(\boldsymbol{r}\sigma\tau,\boldsymbol{r}'\sigma'\tau') = V_0 \frac{1-P_\sigma}{2}\frac{1+P_\tau}{2}\left[1-\frac{\rho(\boldsymbol{r})}{\rho_0}\right]\delta(\boldsymbol{r}-\boldsymbol{r}')$$

cf. C. Bai et al., PLB719(2013)116

^{40}Ca

^{42}Sc



f=1.3

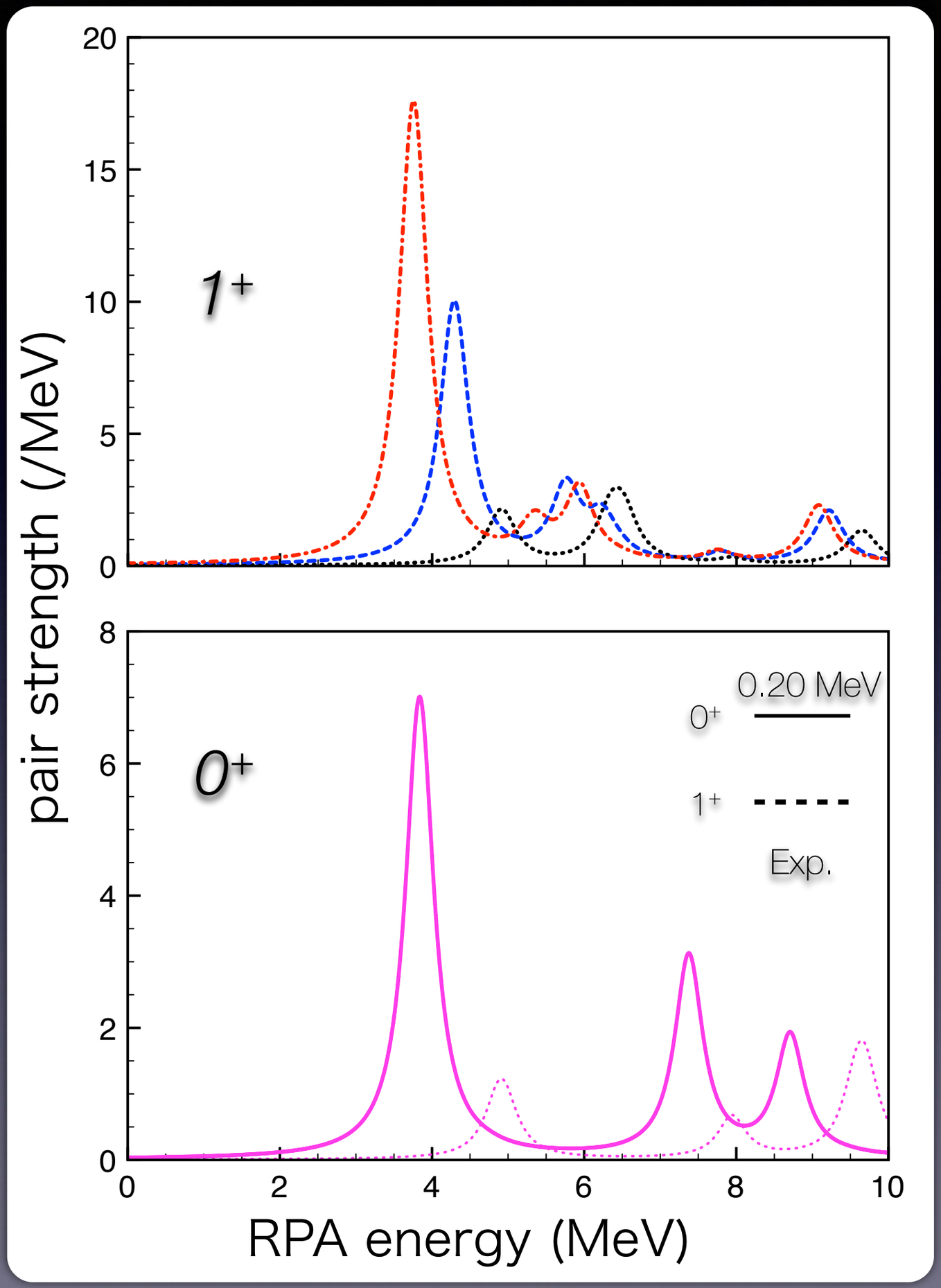
^{42}Sc		$J^\pi = 1^+$	$J^\pi = 0^+$
configuration	$E_\alpha + E_\beta$	$M_{\alpha\beta}^{S=1,S_z=0}$	$M_{\alpha\beta}^{S=0}$
$\pi 1f_{7/2} \otimes \nu 1f_{7/2}$	7.5	1.70	2.85
$\pi 1f_{7/2} \otimes \nu 1f_{5/2}$	15.2	0.62	
$\pi 1f_{5/2} \otimes \nu 1f_{7/2}$	14.7	0.51	
$\pi 2p_{3/2} \otimes \nu 2p_{3/2}$	16.1	0.17	0.22
$\pi 1d_{3/2} \otimes \nu 1d_{3/2}$	4.2	0.25	0.48
$\pi 2s_{1/2} \otimes \nu 2s_{1/2}$	6.6	0.25	
$\pi 1d_{3/2} \otimes \nu 1d_{5/2}$	10.1	0.32	
$\pi 1d_{5/2} \otimes \nu 1d_{3/2}$	10.2	0.32	
$\pi 1d_{5/2} \otimes \nu 1d_{5/2}$	16.1	0.16	0.31

Transition matrix element

$$\langle \lambda | \hat{P}^\dagger_{T,S} | 0 \rangle = \sum_{\alpha\beta} M^{T,S}_{\alpha\beta}$$

^{56}Ni

^{58}Cu

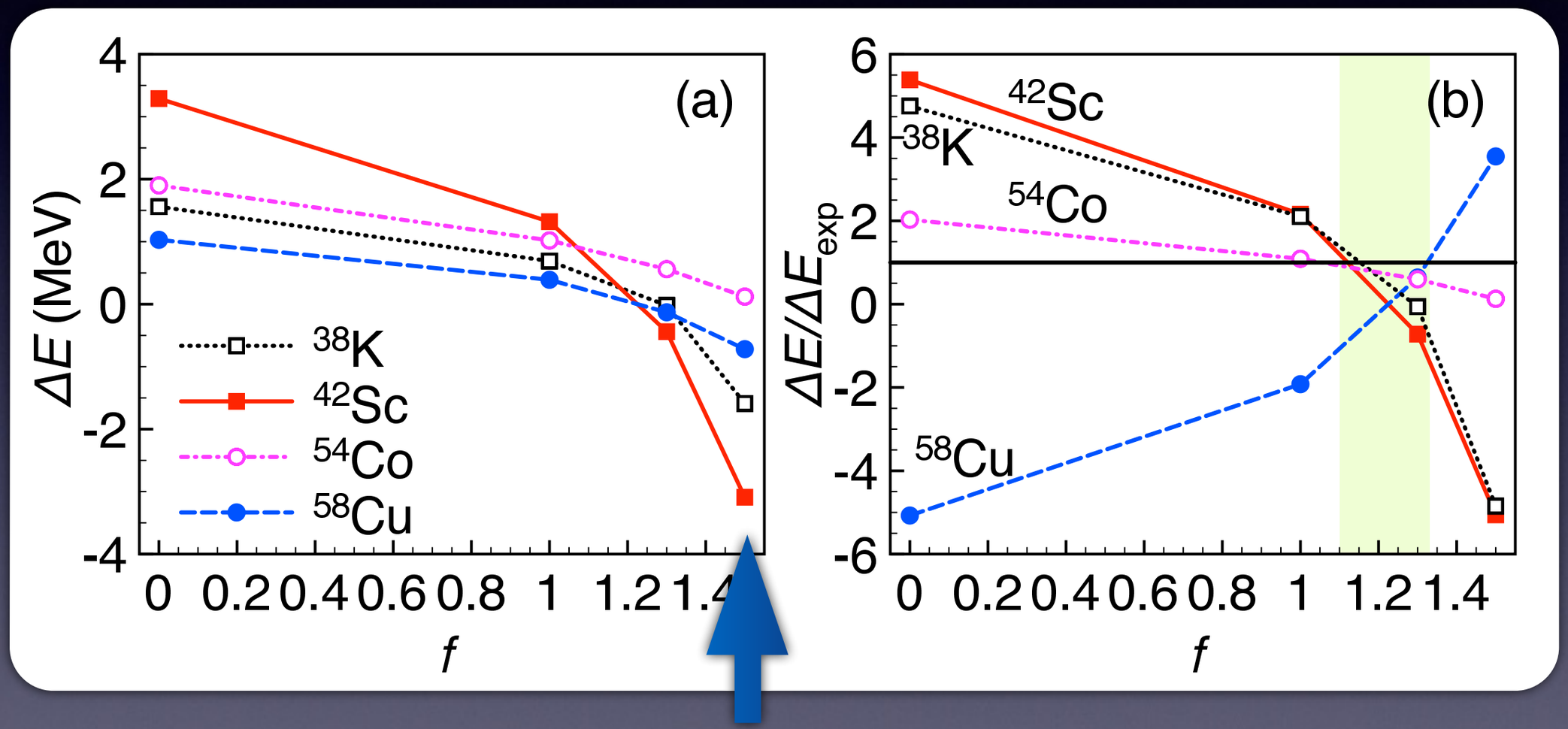


f=1.3

^{58}Cu		$J^\pi = 1^+$	$J^\pi = 0^+$
configuration	$E_\alpha + E_\beta$	$M_{\alpha\beta}^{S=1,S_z=0}$	$M_{\alpha\beta}^{S=0}$
$\pi 2p_{3/2} \otimes \nu 2p_{3/2}$	4.5	1.28	1.90
$\pi 2p_{1/2} \otimes \nu 2p_{3/2}$	6.4	0.39	
$\pi 2p_{3/2} \otimes \nu 2p_{1/2}$	6.5	0.37	
$\pi 2p_{1/2} \otimes \nu 2p_{1/2}$	7.9		0.26
$\pi 1f_{5/2} \otimes \nu 1f_{5/2}$	9.7	0.15	0.55
$\pi 1f_{7/2} \otimes \nu 1f_{7/2}$	5.1	0.17	0.50

Collective pn-pairing vibration mode precursory to the T=0 pairing condensation

$\Delta E = \omega_{1+} - \omega_{0+}$

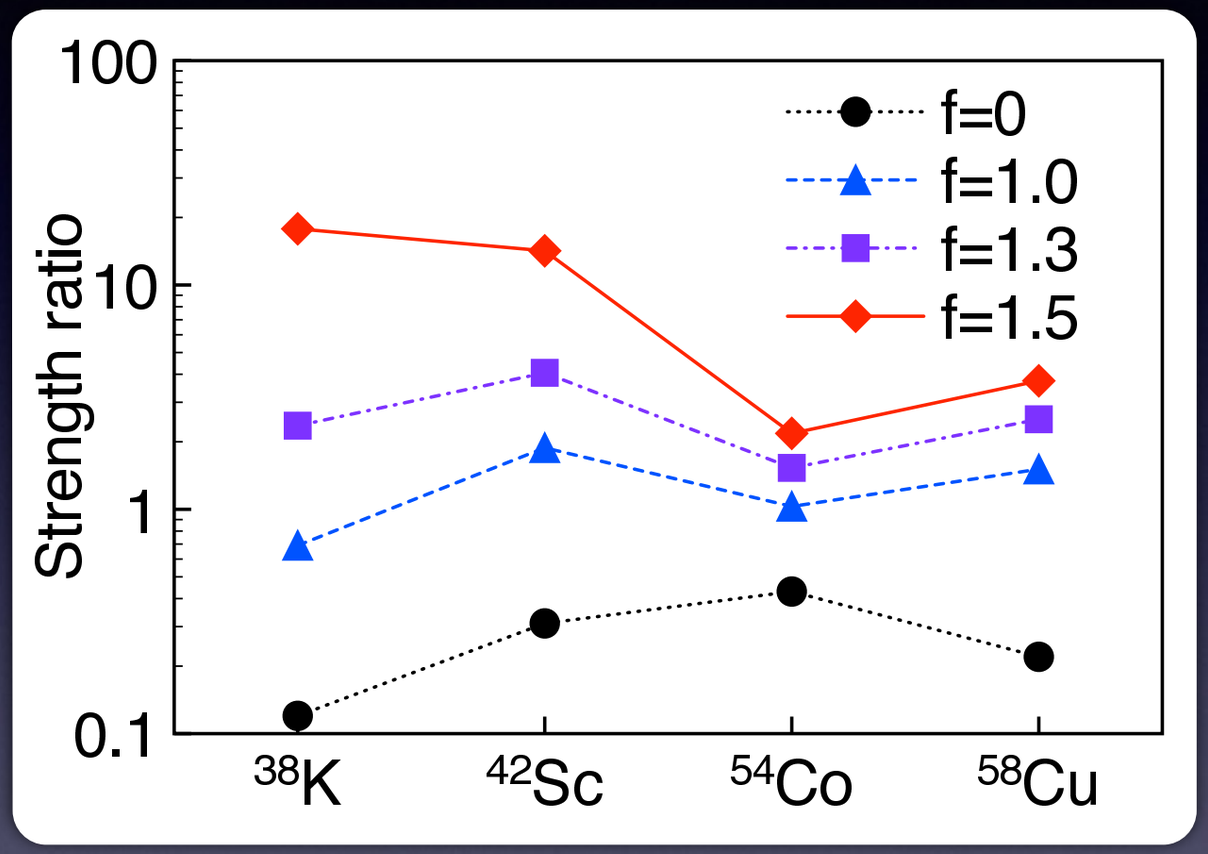


approaching the critical point to the T=0 pairing condensation

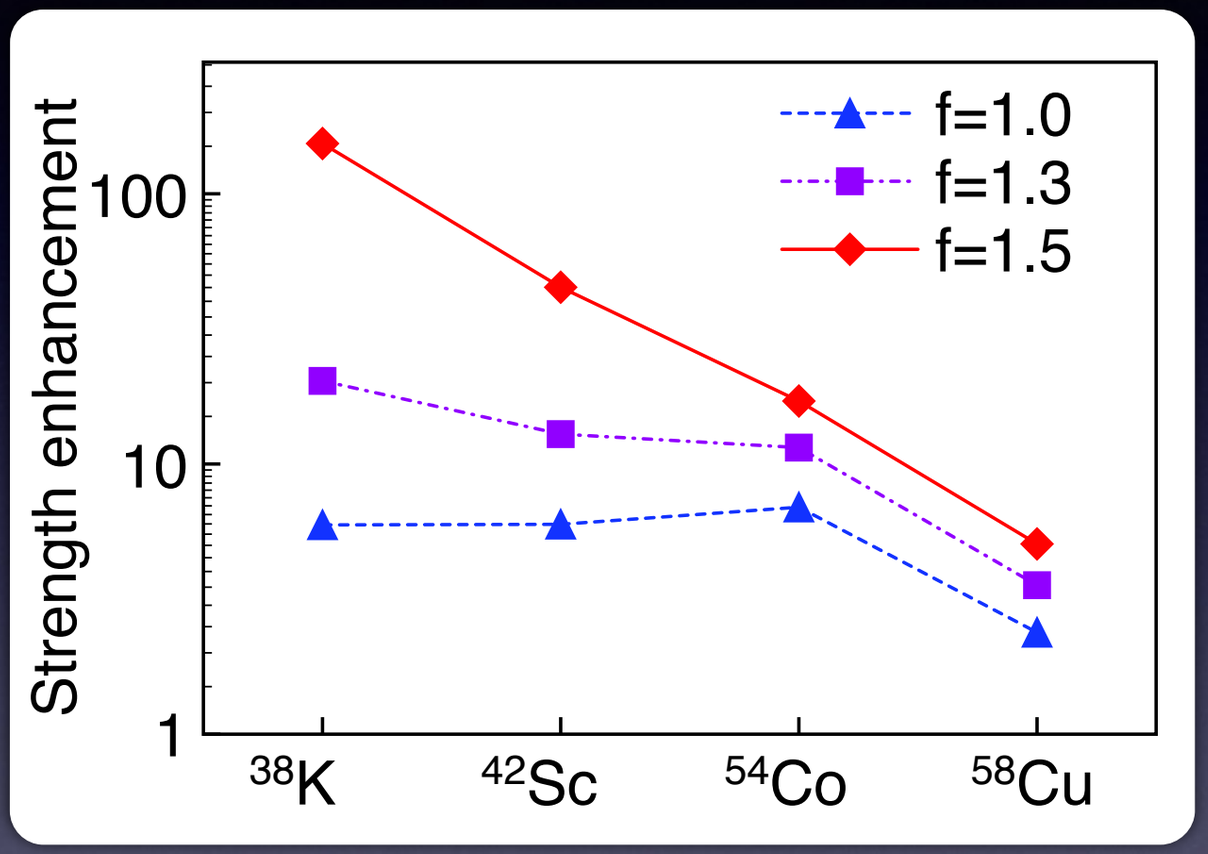
$f_c = 1.53$

Enhancement of the transfer strengths

$$\frac{|\langle\lambda|\hat{P}^\dagger_{T=0}|0\rangle|^2}{|\langle\lambda|\hat{P}^\dagger_{T=1}|0\rangle|^2}$$



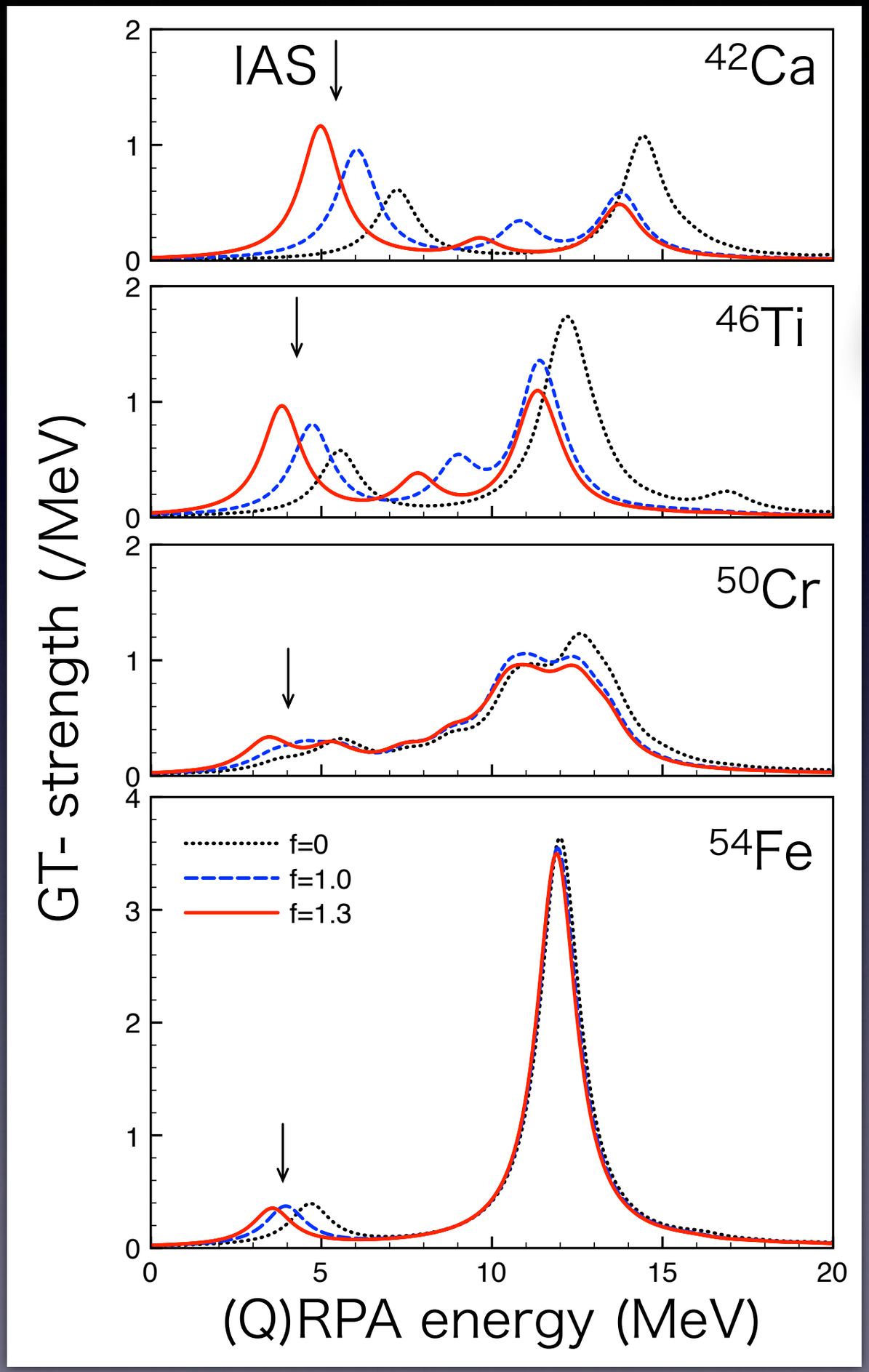
$$\frac{|\langle\lambda|\hat{P}^\dagger_{T=0}|0\rangle|^2}{|\langle\mathrm{unp.}|\hat{P}^\dagger_{T=0}|0\rangle|^2}$$



d-tranfer: ^{40}Ca(^{3}He,p)^{42}Sc

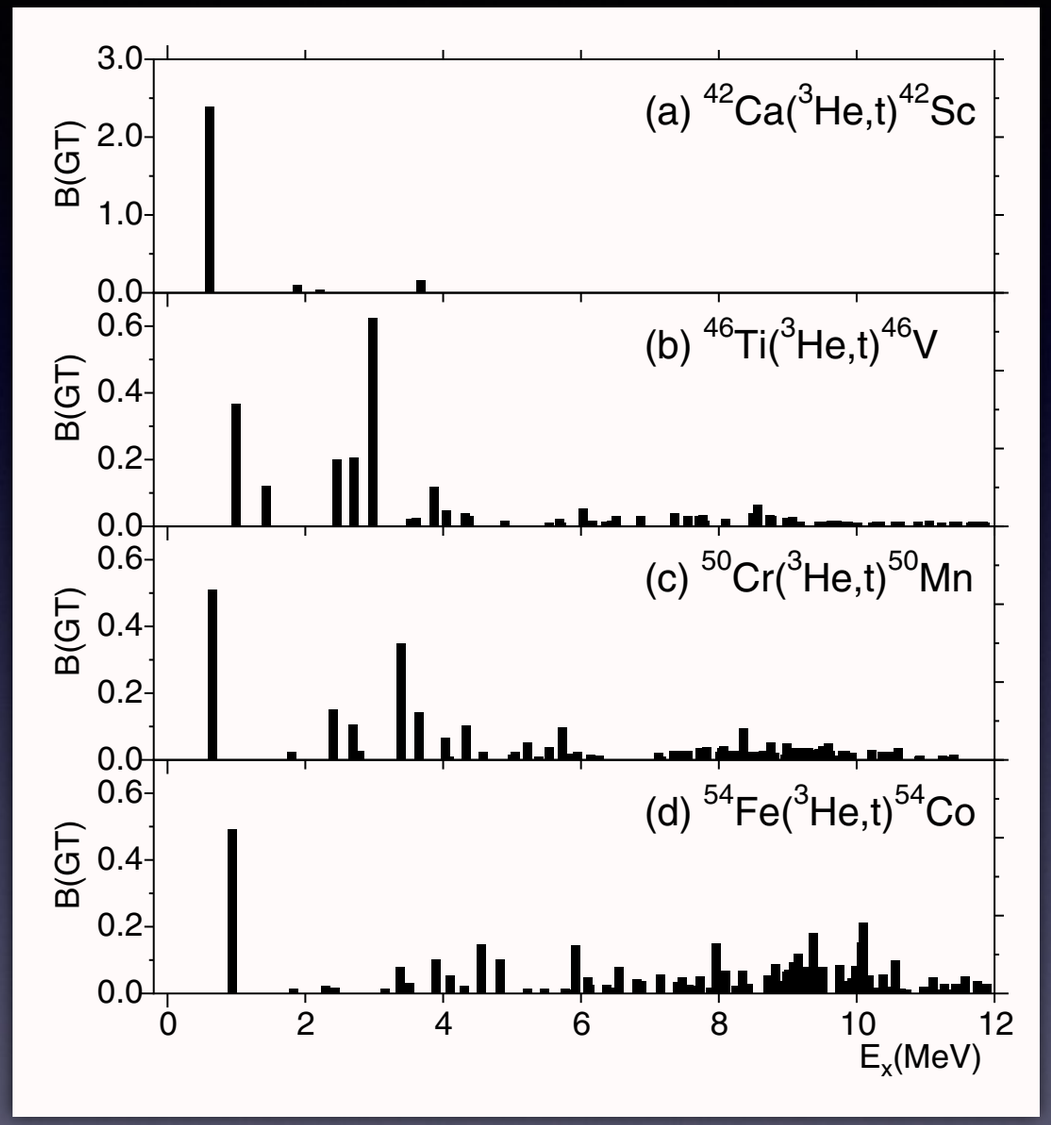
$$\frac{\sigma(1^+)_{\mathrm{exp}}}{\sigma(1^+)_{\mathrm{unp}}} = 23.9$$

F. Pühlhofer, NPA116 (1968) 516



pn-pairing more effective

RCNP



Y. Fujita et al.,PRL112 (2014) 112502

T. Adachi, Y. Fujita et al., NPA788 (2007) 70c

Summary

Fully-selfconsistent deformed pnQRPA is developed in a Skyrme EDF framework

Microscopic and quantitative description of spin-isospin excitations in nuclei with arbitrary mass number whichever they are spherical or deformed, located around the stability line or close to the drip line

→ provide a microscopic input to the astrophysical simulation

Deformation effects on spin-isospin responses

Tiny deformation splitting in Gamow-Teller excitation → Fragmentation of GTGR

Clear deformation splitting in Anti-analog GDR as seen in IVGDR

Effects of T=0 pairing

Low-lying GT states are sensitive to the location of the Fermi levels, and the beta-decay half-lives are shortened

Proton-neutron pair-transfer strengths

Strong collectivity due to the T=0 pairing suggests emergence of a soft mode toward the T=0 pairing condensation

Restoration of the isospin symmetry breaking (ISB)

Even w/o the Coulomb int., the ISB occurs in N>Z nuclei in a MFA

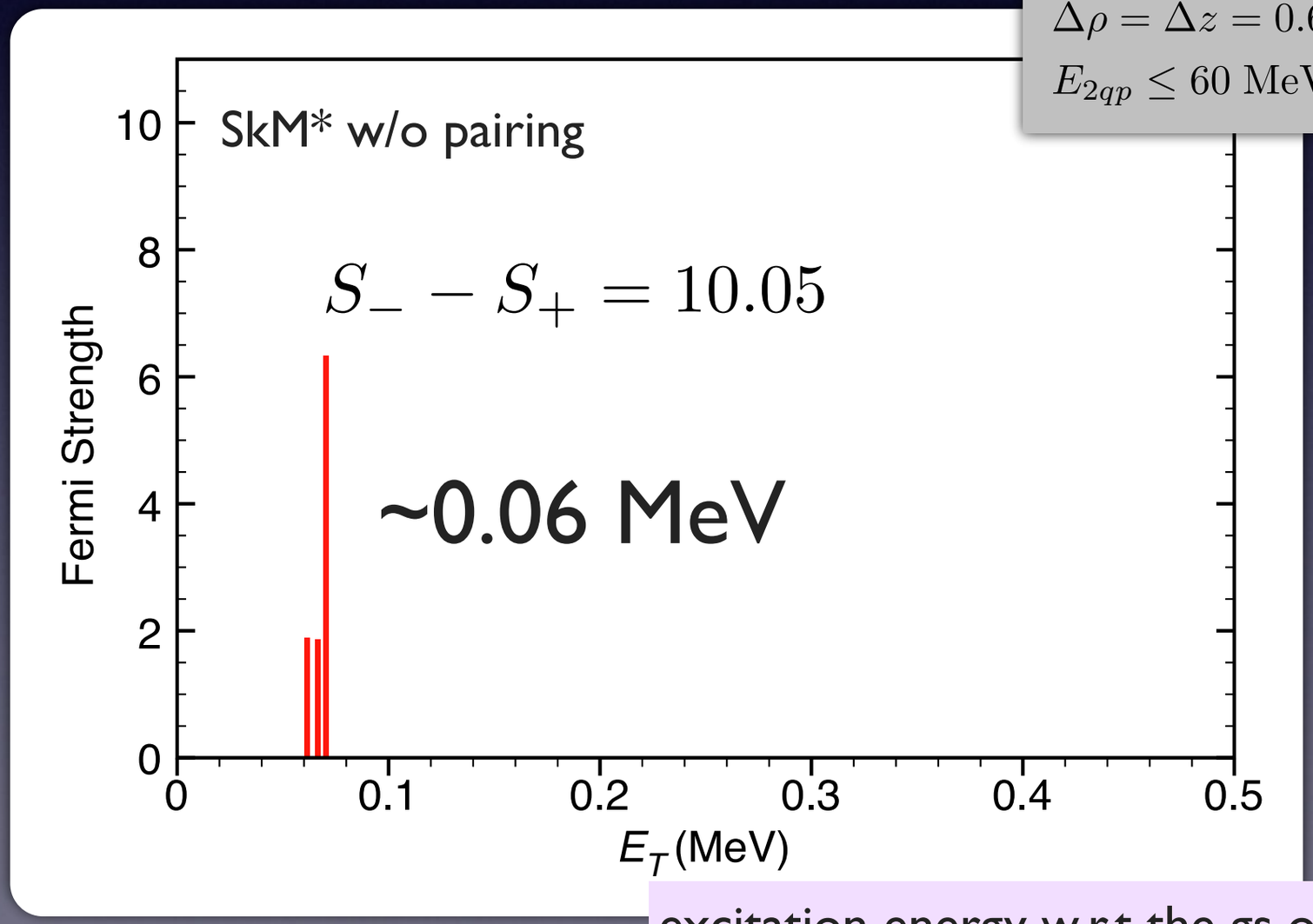
$$[H_{\mathrm{MF}}, T_-] \neq 0$$

C. A. Engelbrecht and R. H. Lemmer, PRL24(1970)607

→ IAS appears as a NG mode in the pnRPA

Ex. ^{90}Zr (N-Z=10) w/o Coulomb

$\rho_{\max} \times z_{\max} = 14.7\ \mathrm{fm} \times 14.4\ \mathrm{fm}$
$\Delta\rho = \Delta z = 0.6\ \mathrm{fm}$
$E_{2qp} \leq 60\ \mathrm{MeV}$

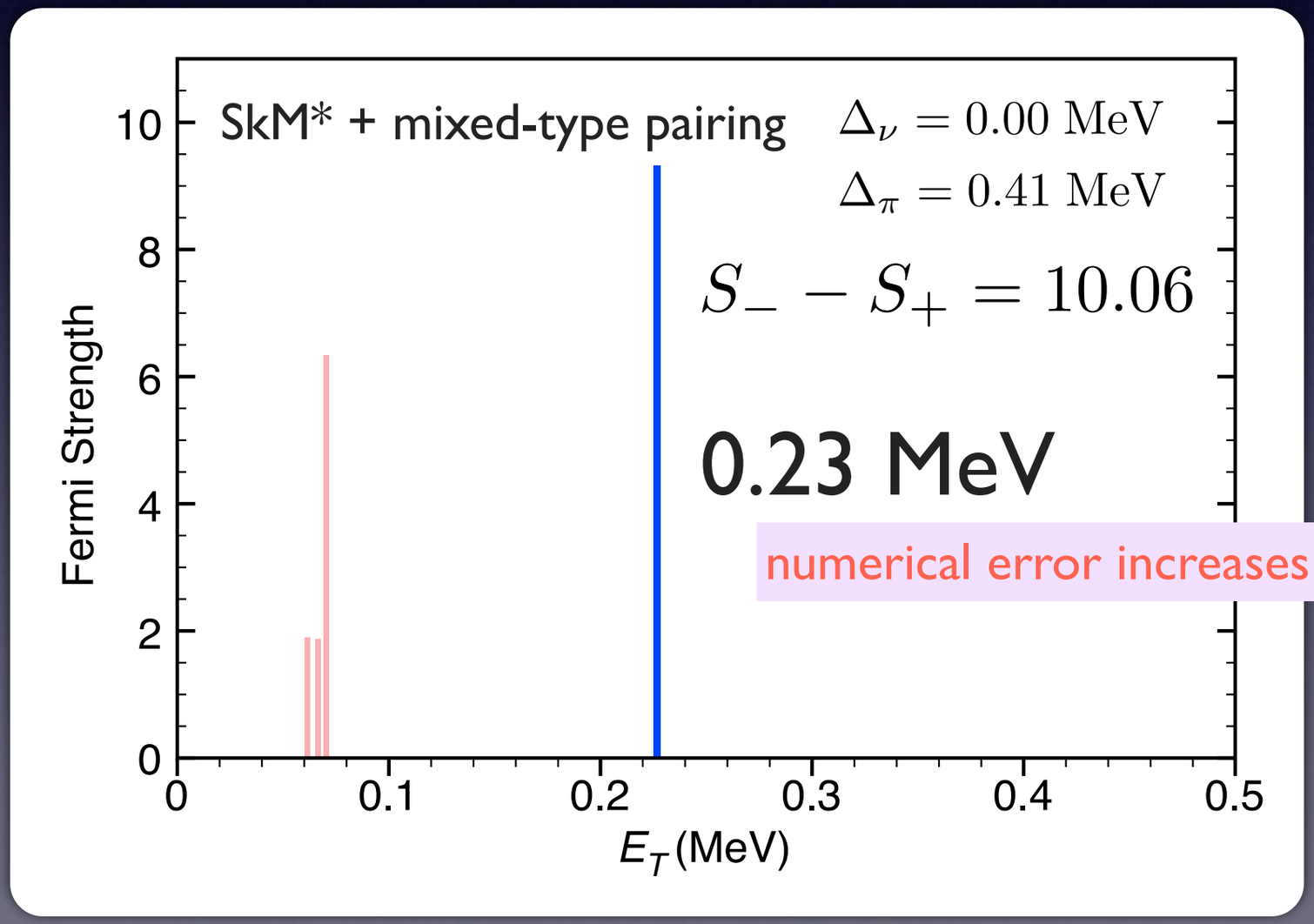


excitation energy w.r.t the gs of ^{90}Zr

Restoration of the isospin symmetry breaking (ISB)

Ex. ^{90}Zr (N-Z=10) w/o Coulomb

protons are paired



Restoration of the isospin symmetry breaking (ISB)

Ex. ^{90}Zr (N-Z=10) w/o Coulomb

inclusion of the T=1 (S=0) pairing interaction in the pnQRPA

$$v_{\rm pp}^{T=1}(\boldsymbol{r},\boldsymbol{r}') = \frac{1-P_\sigma}{2}\frac{1+P_\tau}{2}V_0\left[1-\frac{1}{2}\frac{\rho_{00}(\boldsymbol{r})}{\rho_0}\right]\delta(\boldsymbol{r}-\boldsymbol{r}')$$