NEWS Colloquium: 25 Sep.

Charge-exchange dipole modes of excitation in neutron-rich nuclei

Kenichi Yoshida
Kyoto Univ.

based on

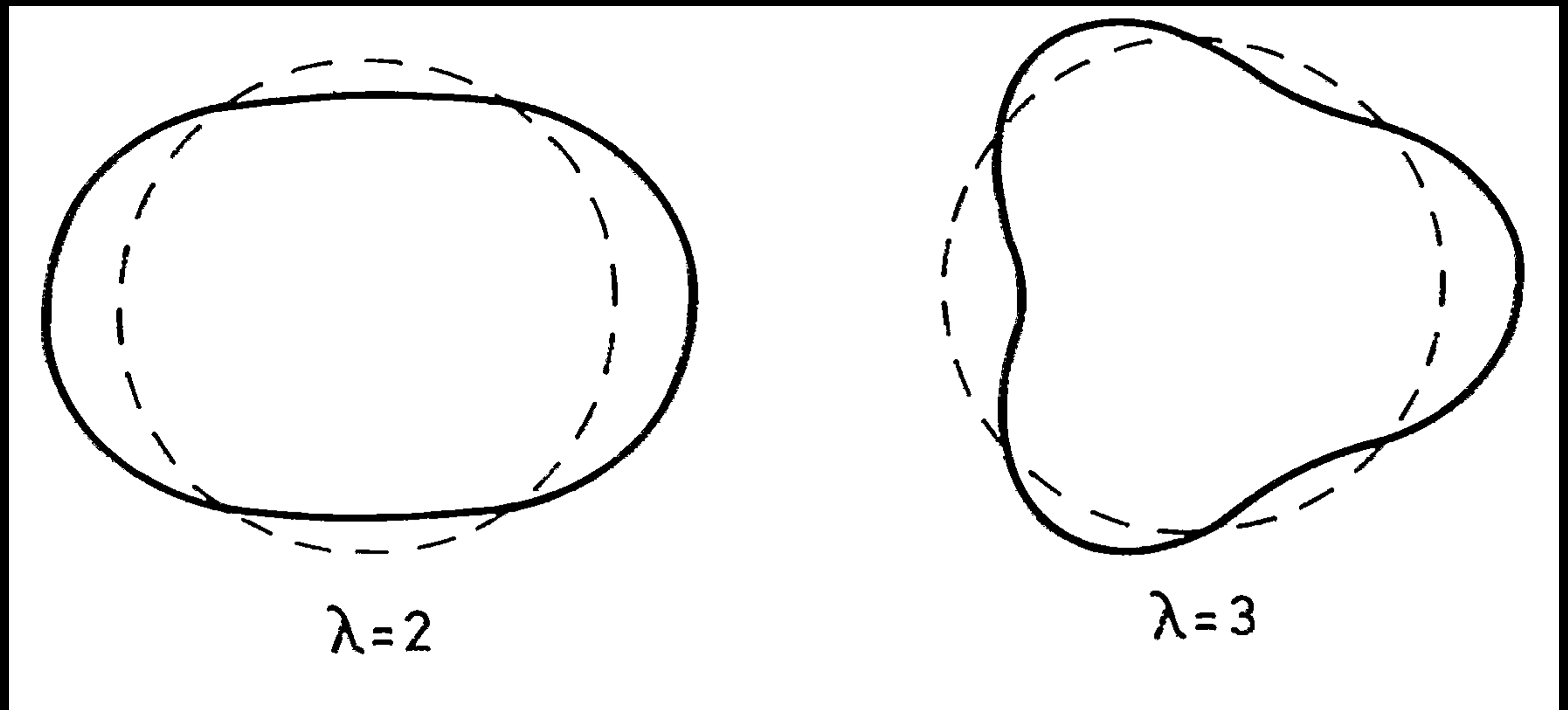
KY, Phys. Rev. C96, 051302R (2017)

KY, arXiv: 2008.03947

Contents

Giant resonance: typical collective mode of surface vibration

classical and intuitive picture (Bohr's liquid drop)



λ=2: Giant Quadrupole Resonance (GQR)
λ=3: High Energy Octupole Resonance (HEOR)

strongly excited by a one-body operator, exhausts a sum-rule

$$\hat{H} \to \hat{H} + f(t)\hat{F}_\lambda$$

$$\hat{F}_\lambda = \sum_{\sigma,\sigma'} \sum_{\tau,\tau'} \int d\vec{r} r^\lambda Y_\lambda(\hat{r}) \hat{\psi}^\dagger(\vec{r}\sigma\tau)\hat{\psi}(\vec{r}\sigma'\tau')\delta_{\sigma,\sigma'}\delta_{\tau,\tau'}$$

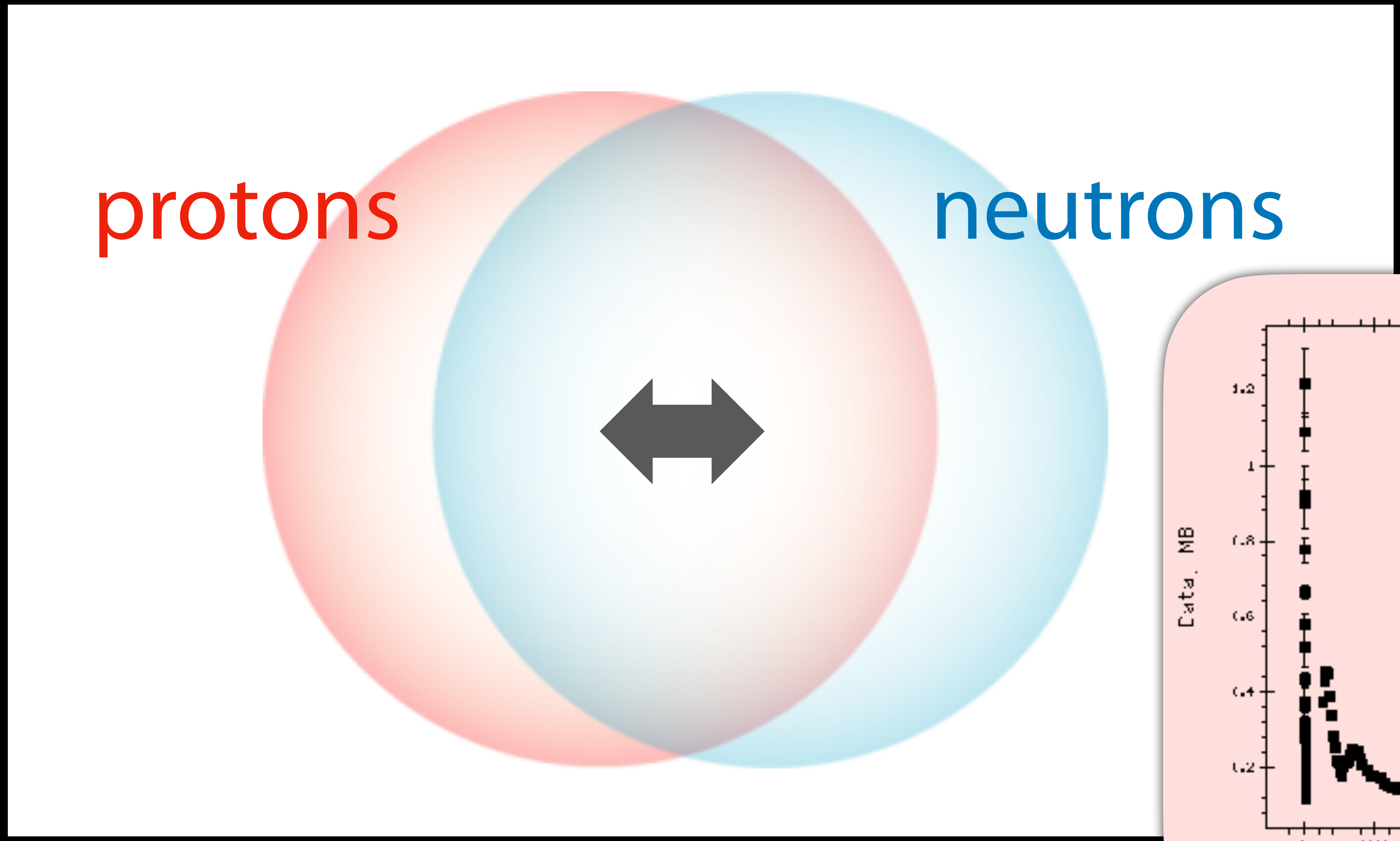
scalar, isoscalar
nucleus as a whole

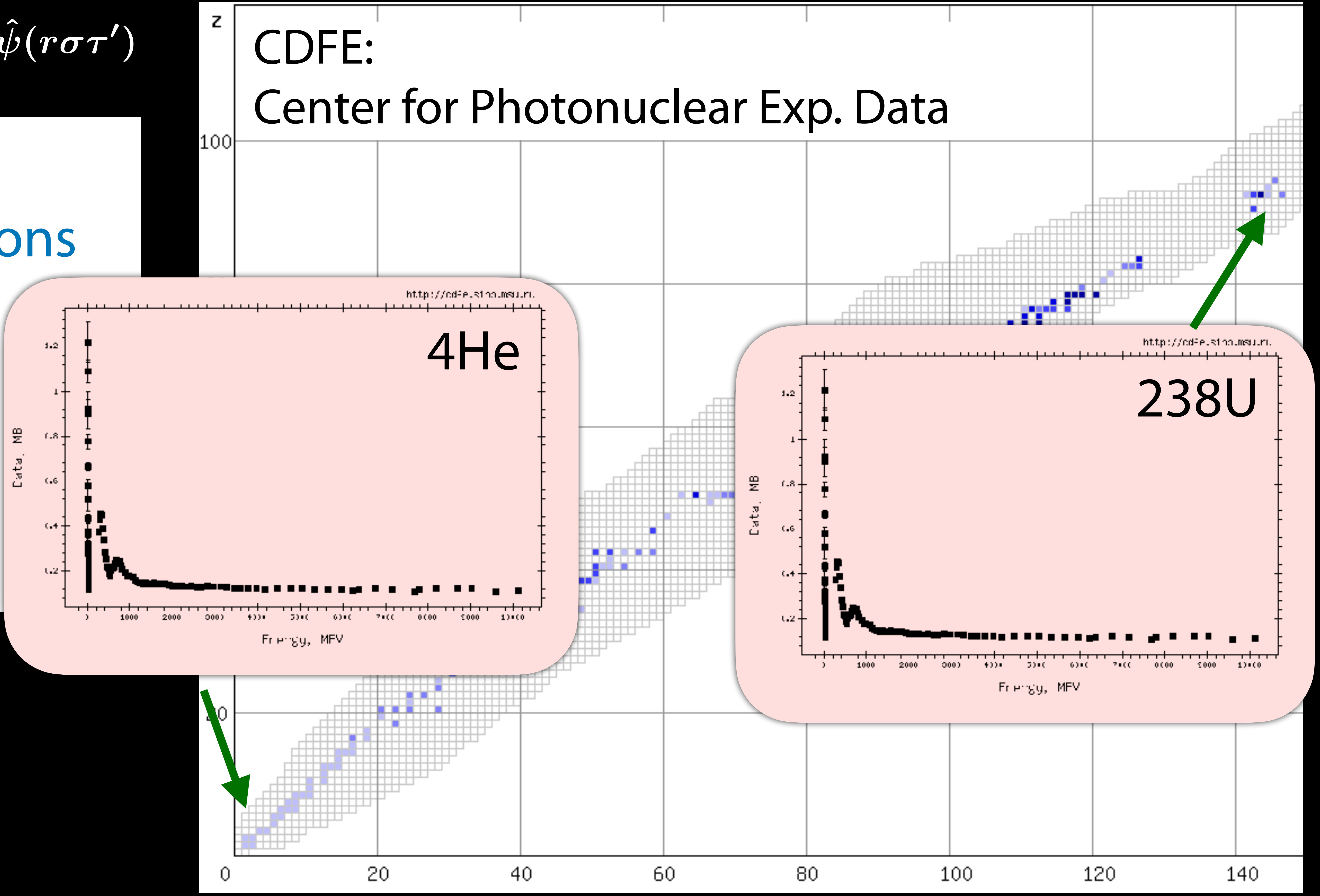
Photo-nuclear responses (γ,γ’), (γ,n), (γ,2n), (γ,p)…

the most famous collective vibration: the **Isovector** Giant Dipole Resonance (GDR)

the first vibrational mode observed in nuclei: (p,γ) 1939, (γ,f) 1947, G–T picture 1948

$$\hat{F}_1^0 = \sum_{\sigma} \sum_{\tau\tau'} \int drr Y_1(r) \hat{\psi}^\dagger(r\sigma\tau) \langle\tau|\tau_0|\tau'\rangle \hat{\psi}(r\sigma\tau')$$





Nuclear structure information in GDR

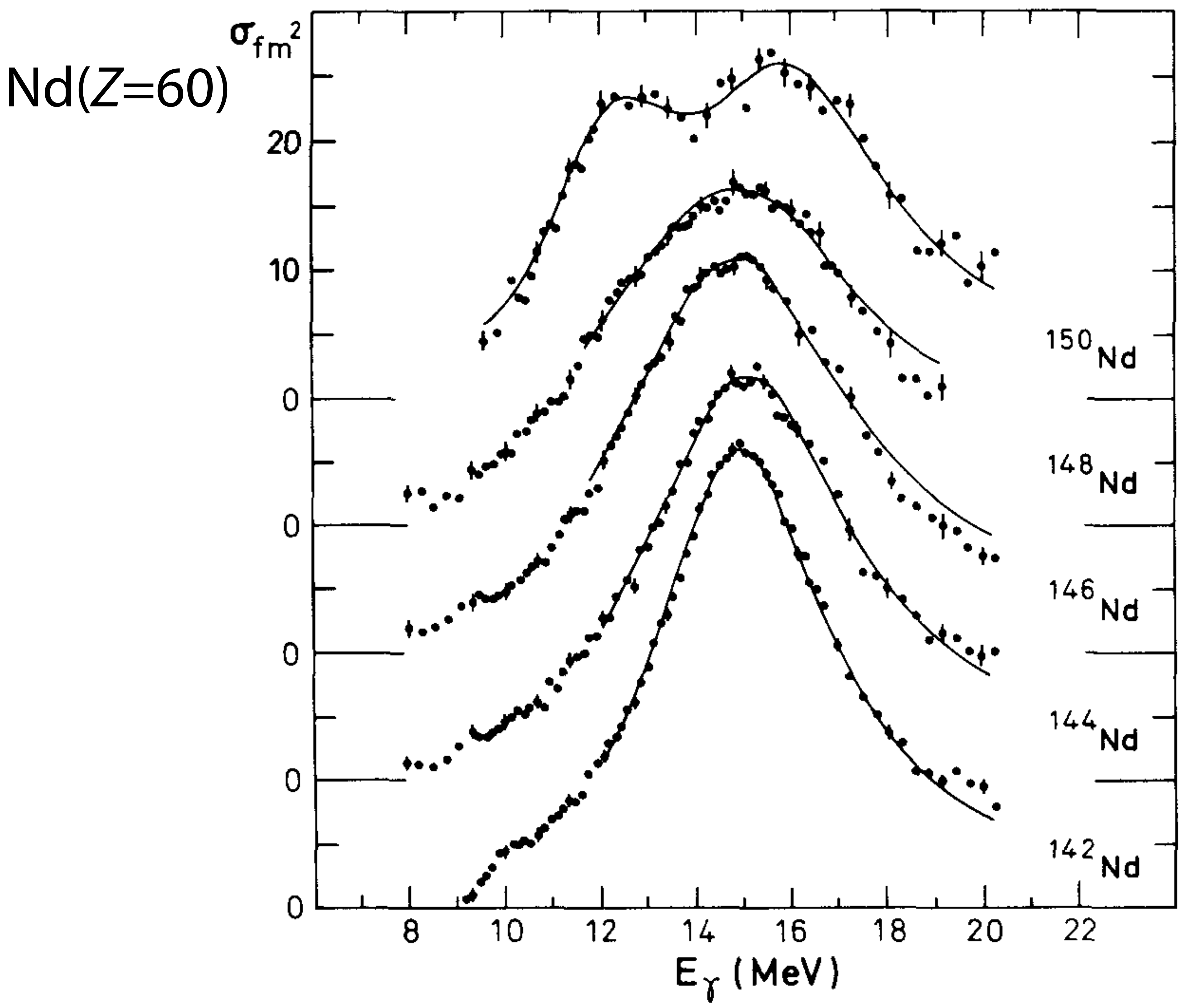


Figure 6-21 Photoabsorption cross section for even isotopes of neodymium. The experimental data are from P. Carlos, H. Beil, R. Bergère, A. Lepretre, and A. Veyssière, *Nuclear Phys.* **A172**, 437 (1971). The solid curves represent Lorentzian fits with the parameters given in Table 6-6.

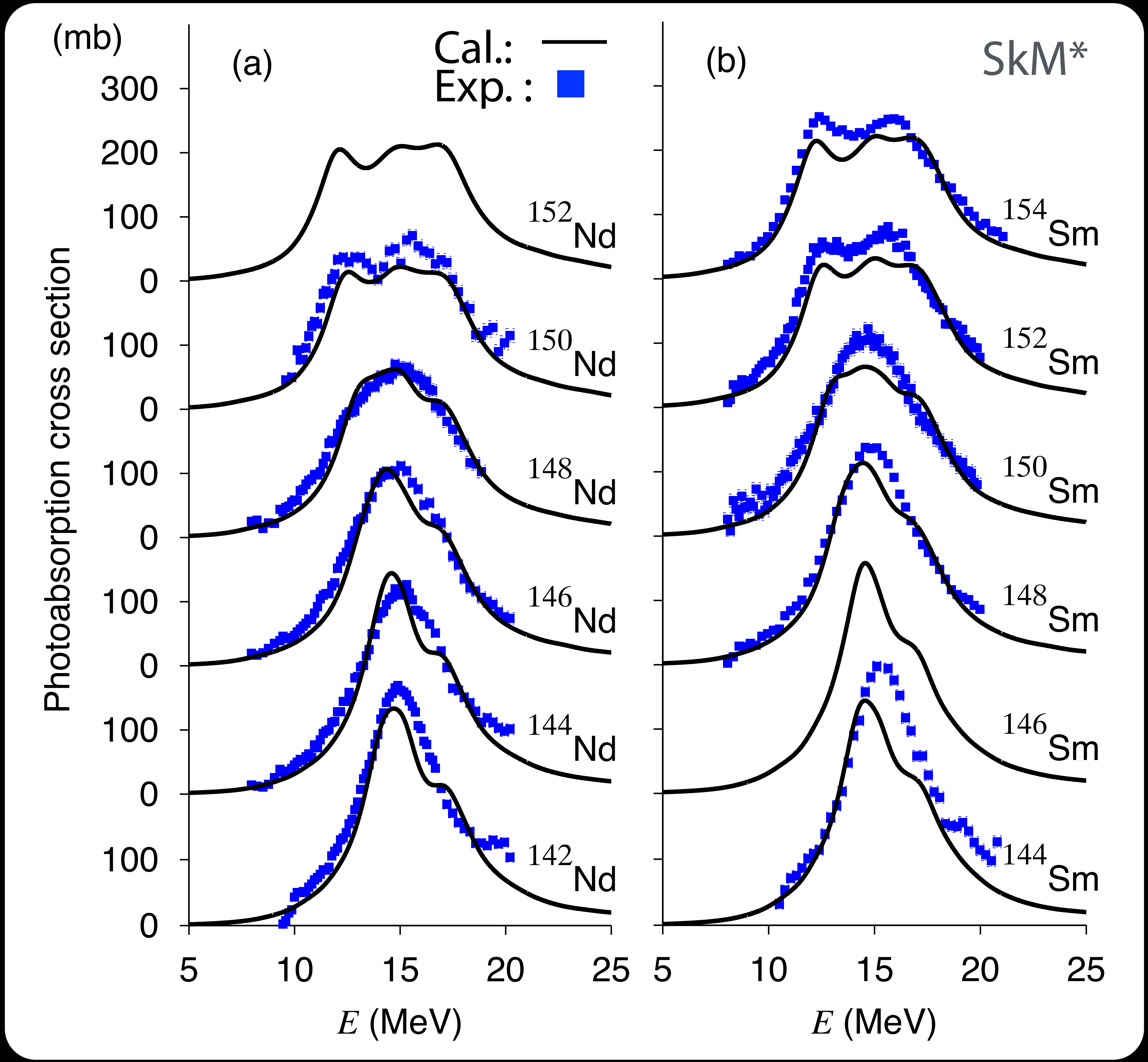
two-hump structure

N=90

N=82

Bohr and Mottelson, *Nuclear Structure, Vol 2* (1975)

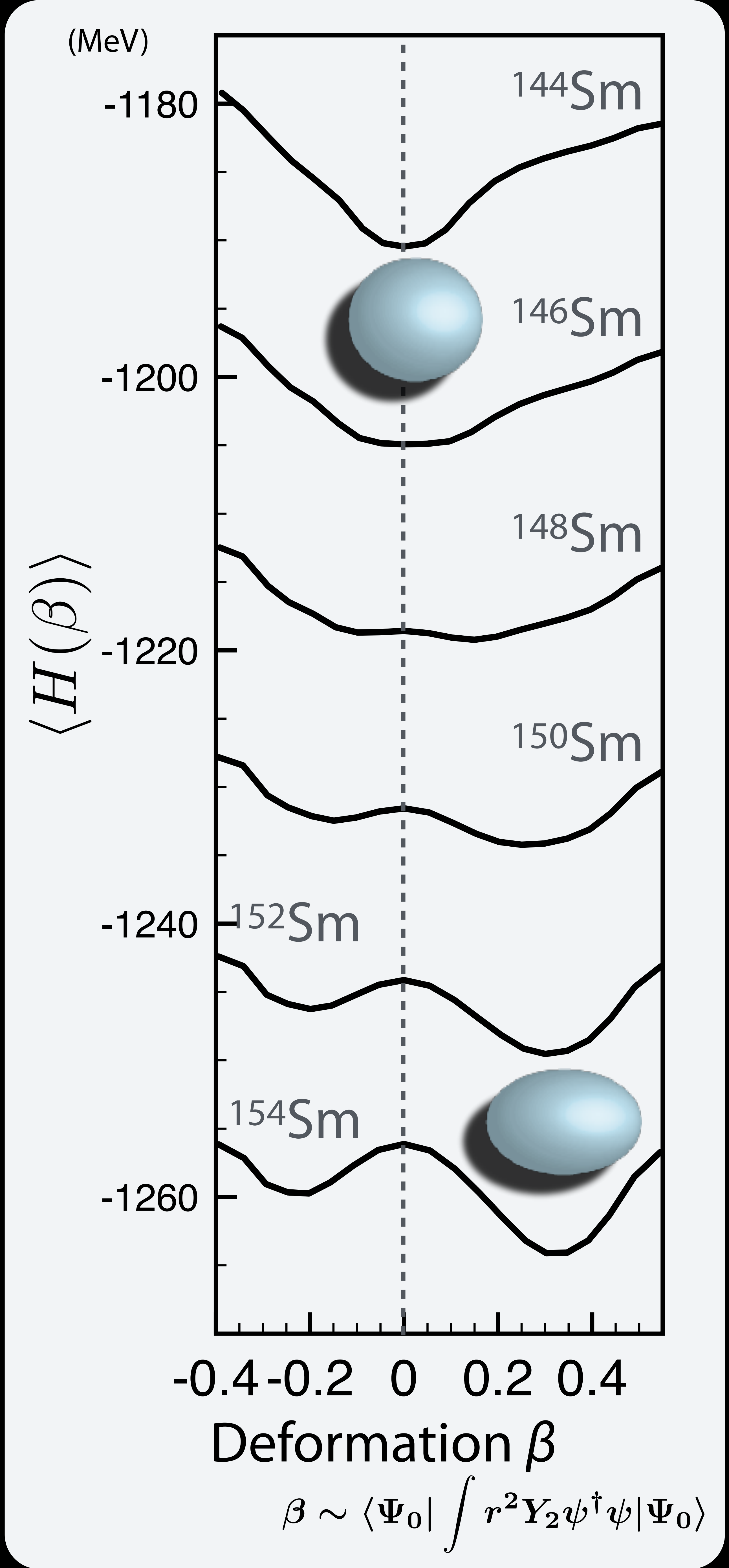
Microscopic description of GDR



N=92

N=82

KY, T. Nakatsukasa, PRC83(2011)021304R

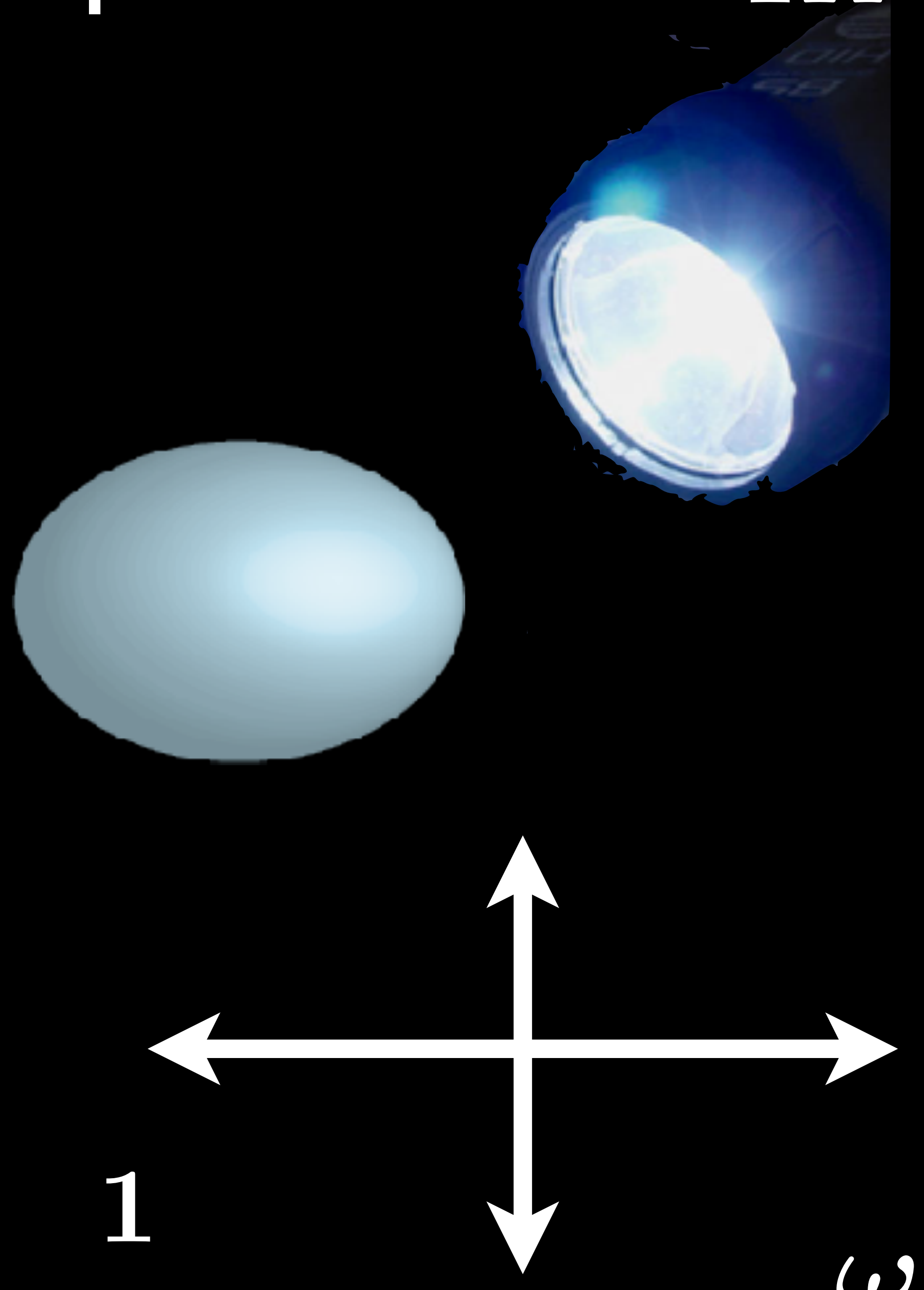


N=82

N=92

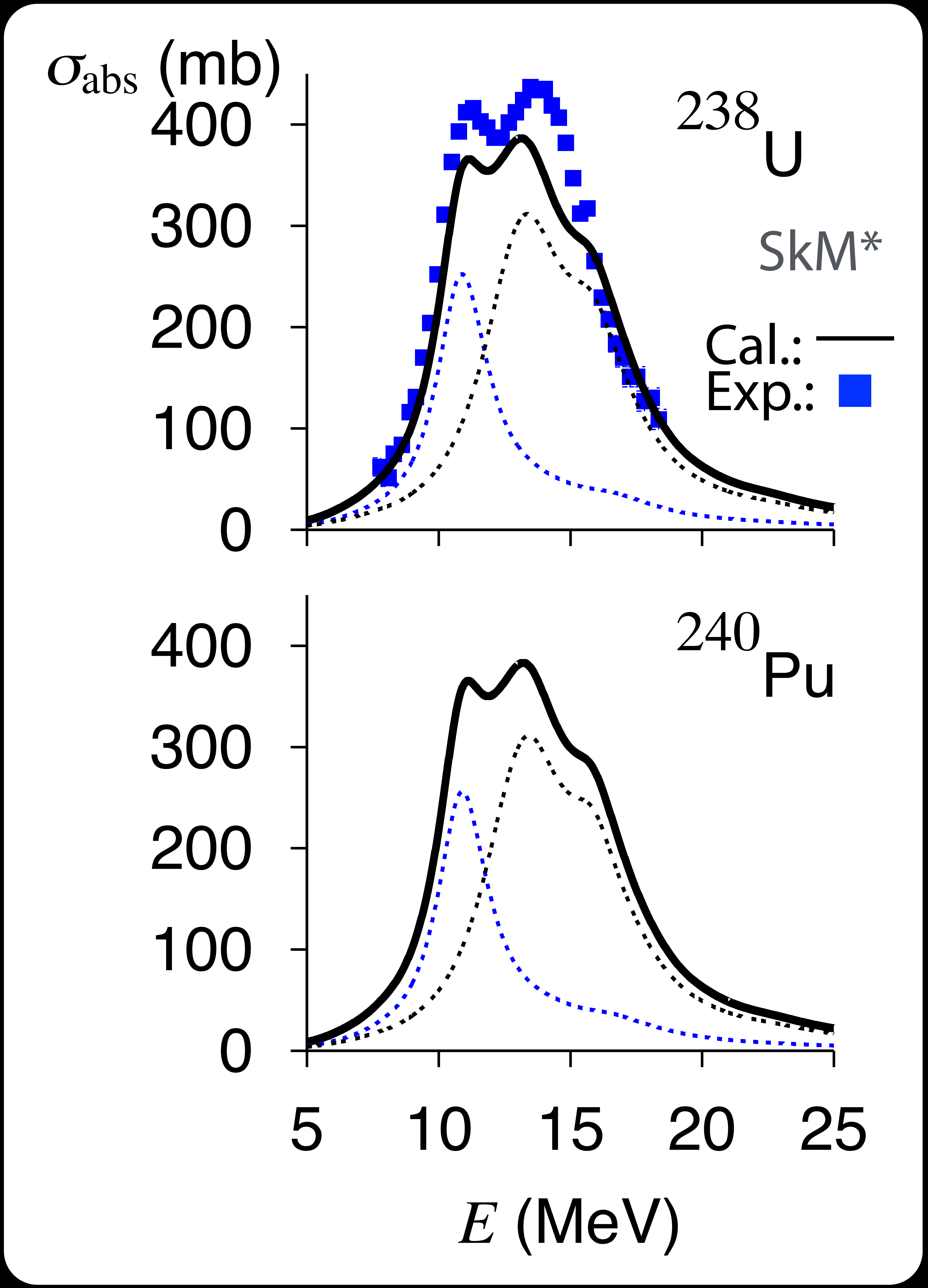
Nuclear deformation in GDR

IV dipole operator: $rY_{1K}(\hat{r})\tau_z$



$\omega_{\perp} \propto \frac{1}{R_{\perp}}$ $\omega_{\parallel} \propto \frac{1}{R_{\parallel}}$

K=1 K=0



arbitrary heavy nuclei now calculable thanks to HPC

Collective modes revealed by nuclear responses

rich variety of excitation modes associated with *S*, *T*, *L*, and *N*

vibration in spin-space, isospin-space, real-space, and gauge-space
and coupling/mixing among them

$$\hat{F}_L = \sum_{\sigma\sigma'} \sum_{\tau\tau'} \int dr r^L Y_L(\hat{r}) \hat{\psi}^\dagger(r\sigma\tau) \left\{ \begin{array}{c} \langle\sigma|1|\sigma'\rangle \\ \langle\sigma|\sigma|\sigma'\rangle \end{array} \right\} \left\{ \begin{array}{c} \langle\tau|1|\tau'\rangle \\ \langle\tau|\tau|\tau'\rangle \end{array} \right\} \hat{\psi}(r'\sigma'\tau')$$

scalar isoscalar
vector isovector

and $\hat{\psi}^\dagger\hat{\psi}^\dagger$, $\hat{\psi}\hat{\psi}$ types

influenced by many-body correlations: magnetism, deformation, superfluidity

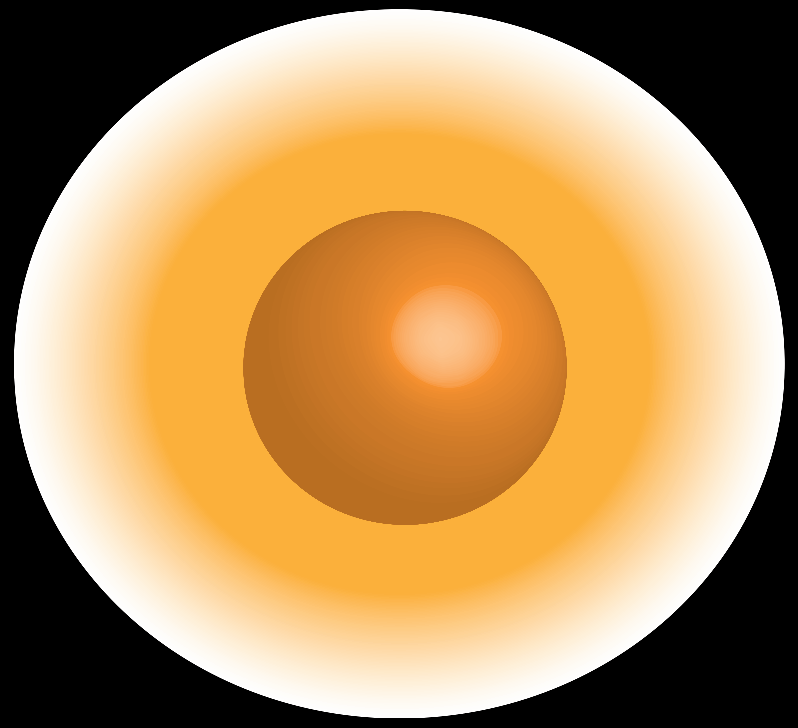
deformation in spin-space/real-space/gauge-space

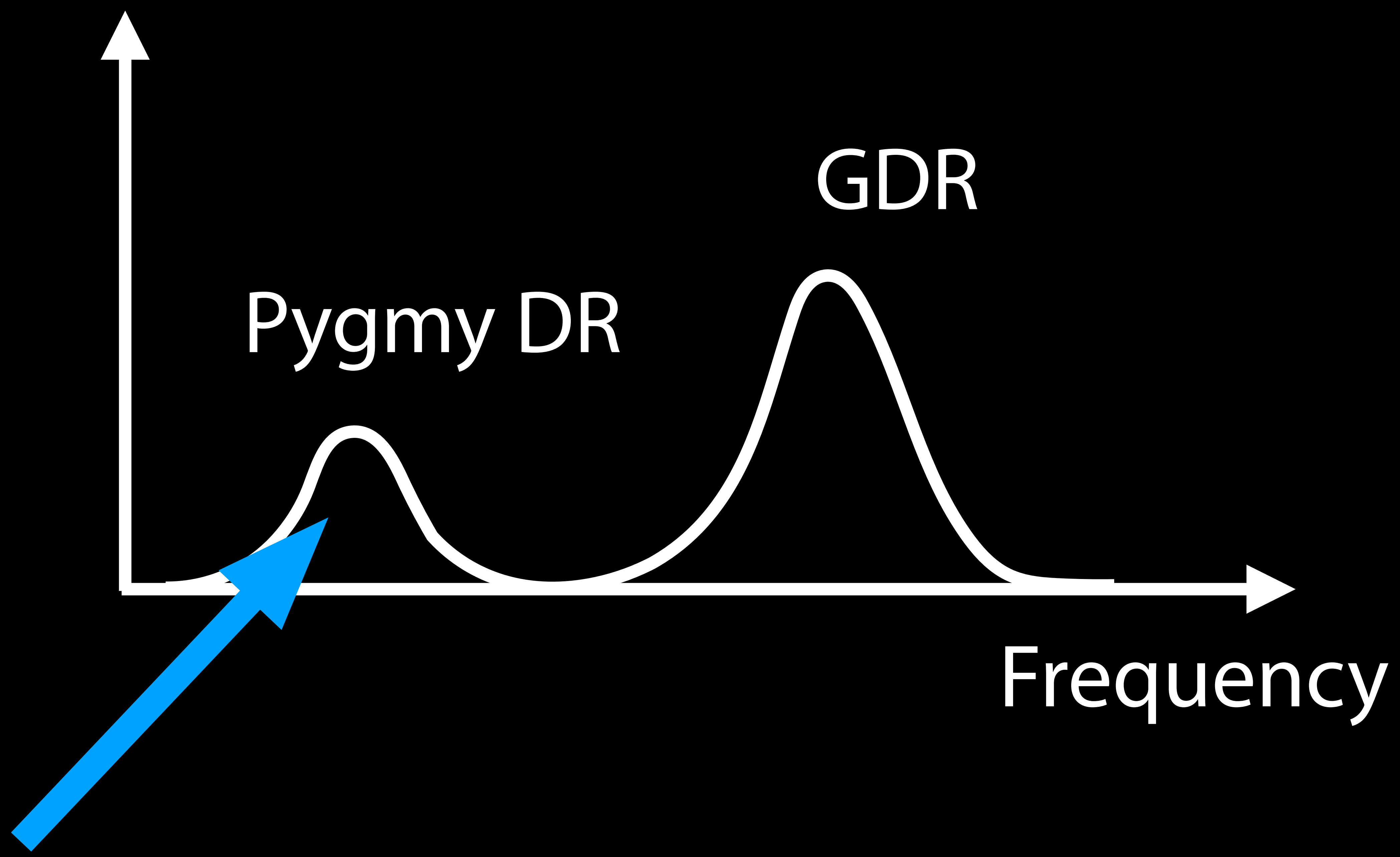
in neutron-rich nuclei

imbalanced Fermi levels: deformation in isospin-space (“isomagnetism”)

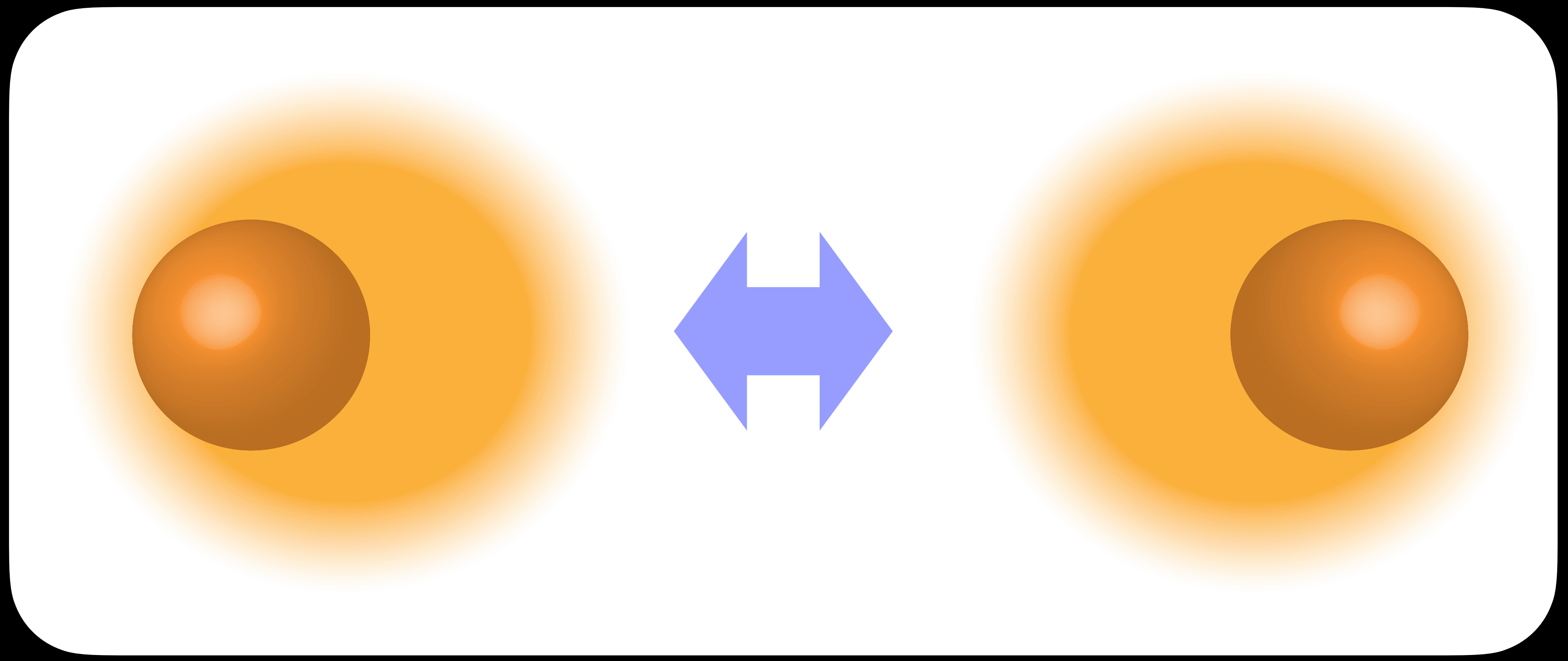
Quest for collective modes unique in neutron-rich nuclei

neutron-skin structure





neutron-skin excitation modes



K. Ikeda, in INS Report (1988)

S. Goriery, PLB436(1998)10

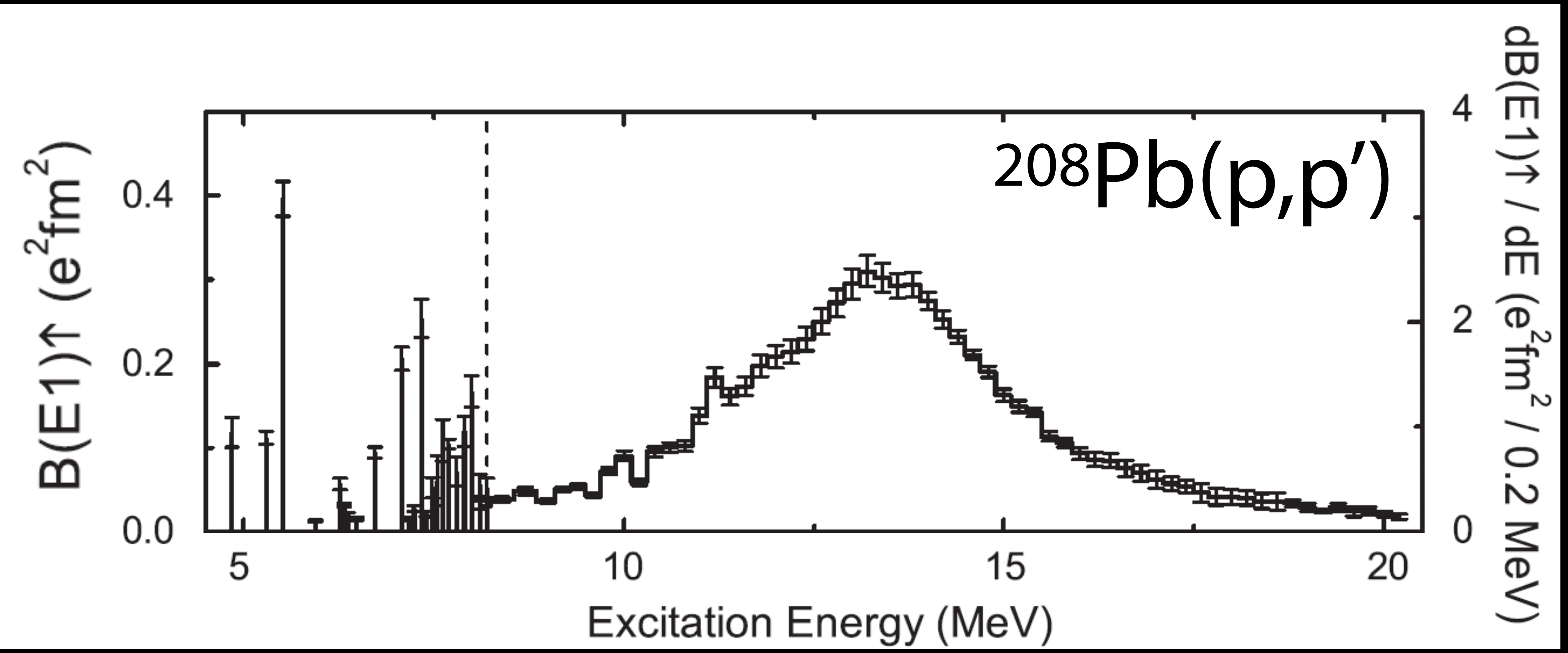
impact on the neutron-capture rate during the r-process nucleosynthesis

Mysterious PDR

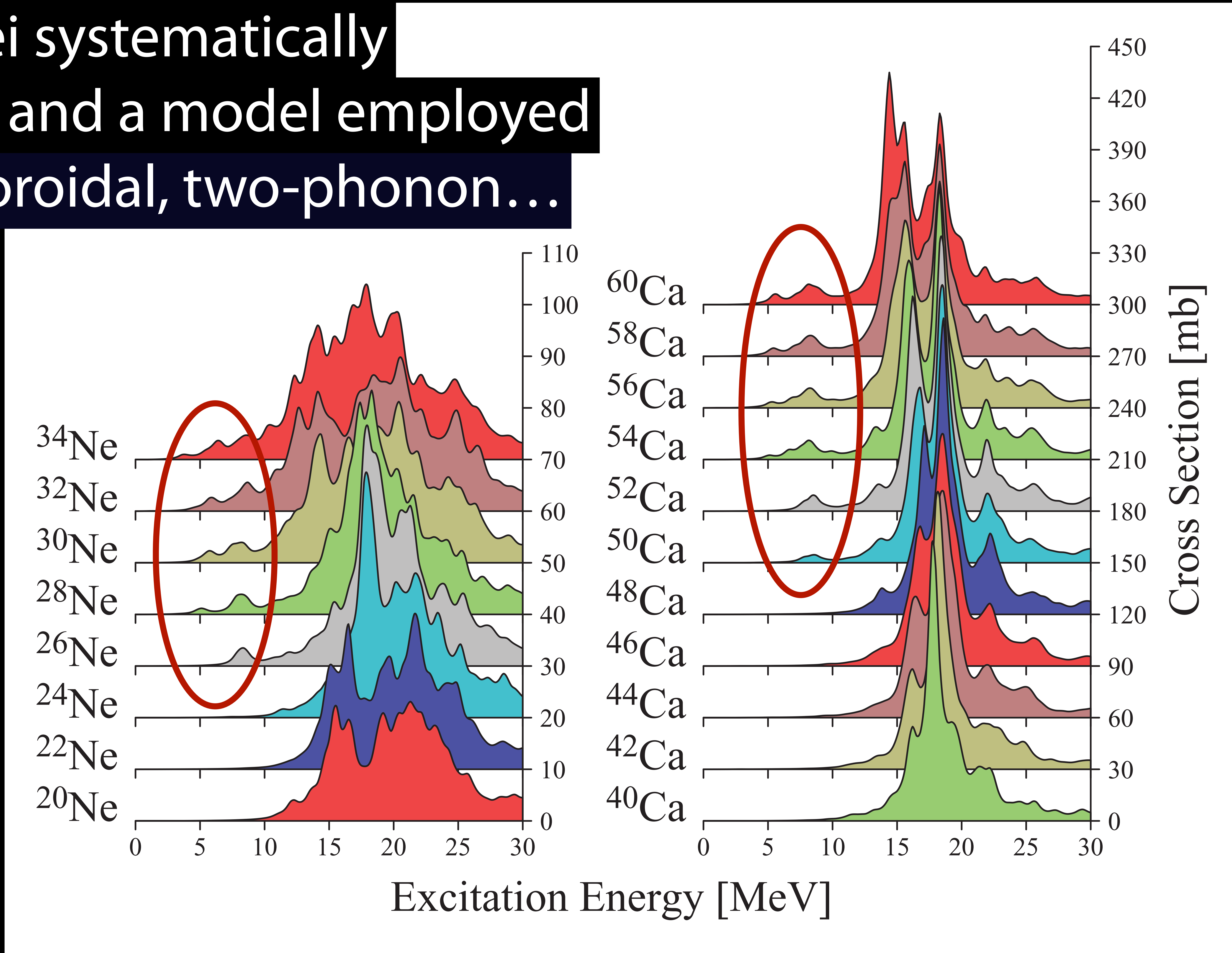
A. Bracco *et al.*, PPNP106 (2019) 360

theoretical cals. tell us:

PDR appears in neutron-rich nuclei systematically
collectivity depends on a nucleus, and a model employed
structure has the nature of IS/IV, toroidal, two-phonon…



A. Tamii *et al.*, PRL107(2011)062502



T. Inakura *et al.*, PRC84(2011)021302R

Collective modes revealed by nuclear responses

rich variety of excitation modes associated with *S*, *T*, *L*, and *N*

vibration in spin-space, isospin-space, real-space, and gauge-space
and coupling/mixing among them

influenced by many-body correlations: magnetism, deformation, superfluidity

deformation in spin-space/real-space/gauge-space

charge-exchange modes have a strong impact on the nuclear weak processes:

β-decay, $\beta\beta$-decay, lepton capture, charged-current ν-scattering…

application to astrophysics and fundamental physics

ex., β-decay rates of hundreds/thousands of exotic nuclei for r-process

Quest for collective modes unique in neutron-rich nuclei in charge-exchange channel

✓ Low-frequency negative parity modes

analog of pygmy dipole resonance?
neutron-skin excitation modes?

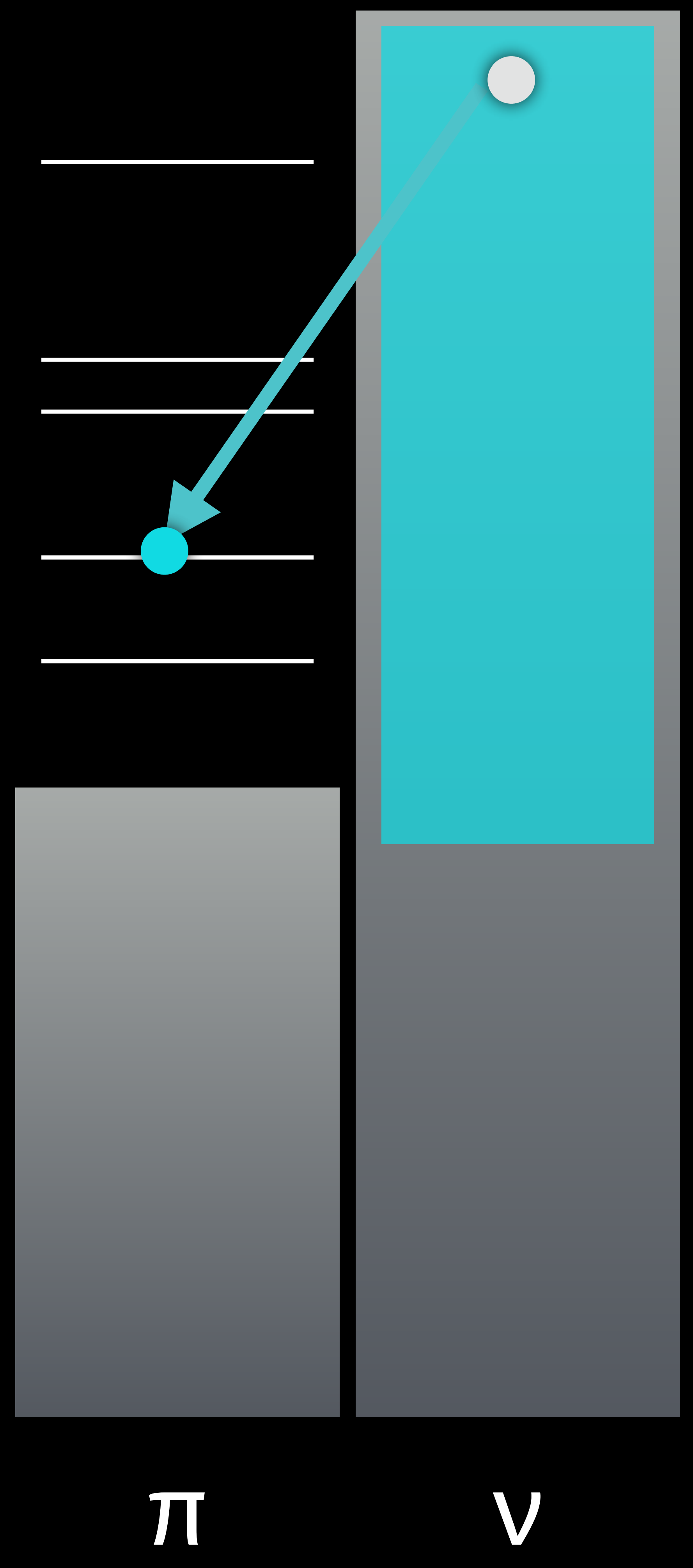
✓ Strongly collective Gamow-Teller GR?

carrying large strength

$$S_- - \cancel{S_+} = 3(N - Z)$$

✓ “Super allowed” GTGR in heavier nuclei?

H. Sagawa *et al.*, PLB303(1993)215
in light nuclei close to the neutron drip line



many p-h excitations possible

Density-functional theory (DFT)

practical and versatile method for many-body problems

Hohenberg–Kohn (1964) >33,500 citations

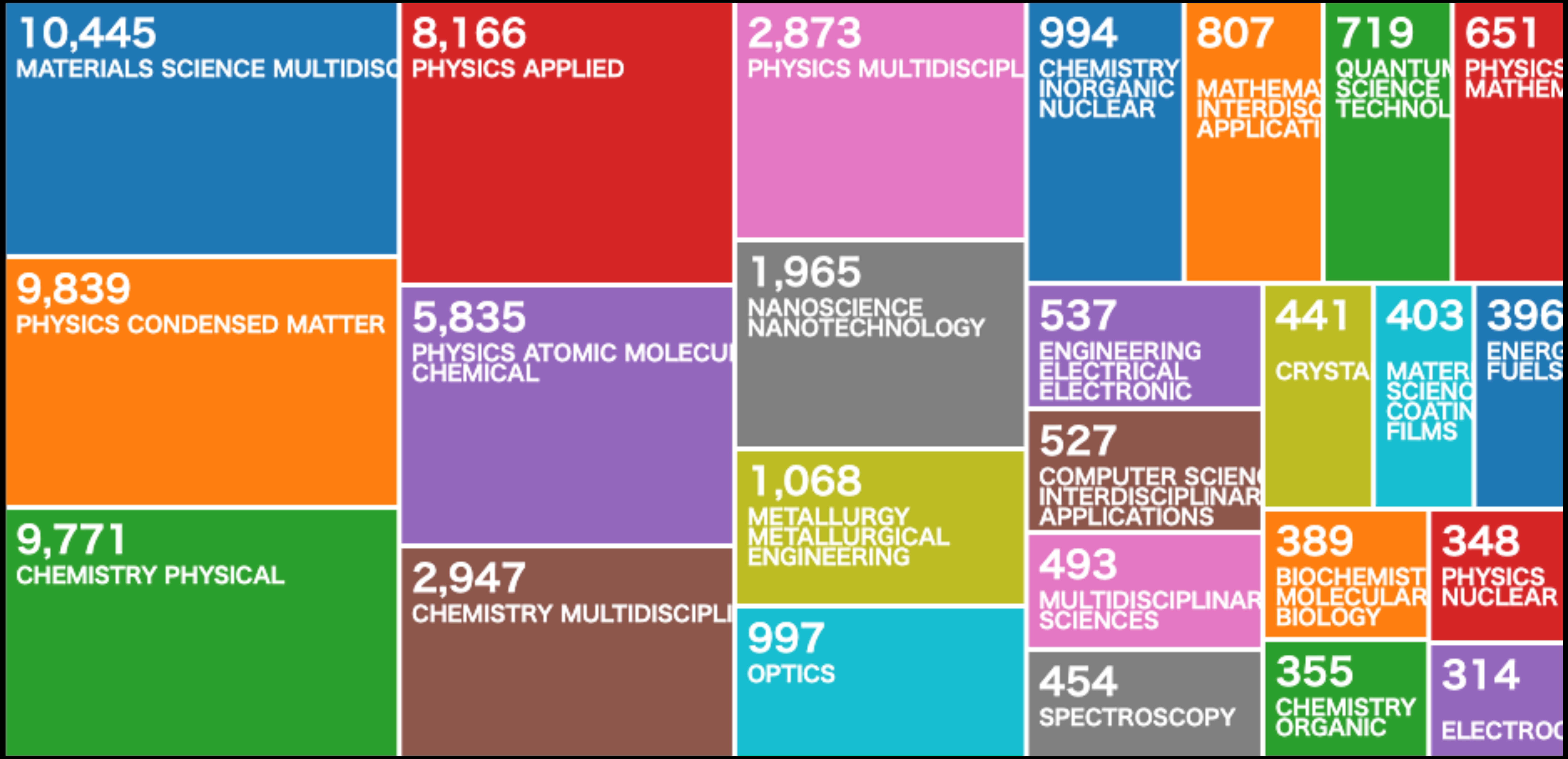
energy-density functional

$$E[\rho] = \langle \Psi \,|\, \hat{H} \,|\, \Psi \rangle$$

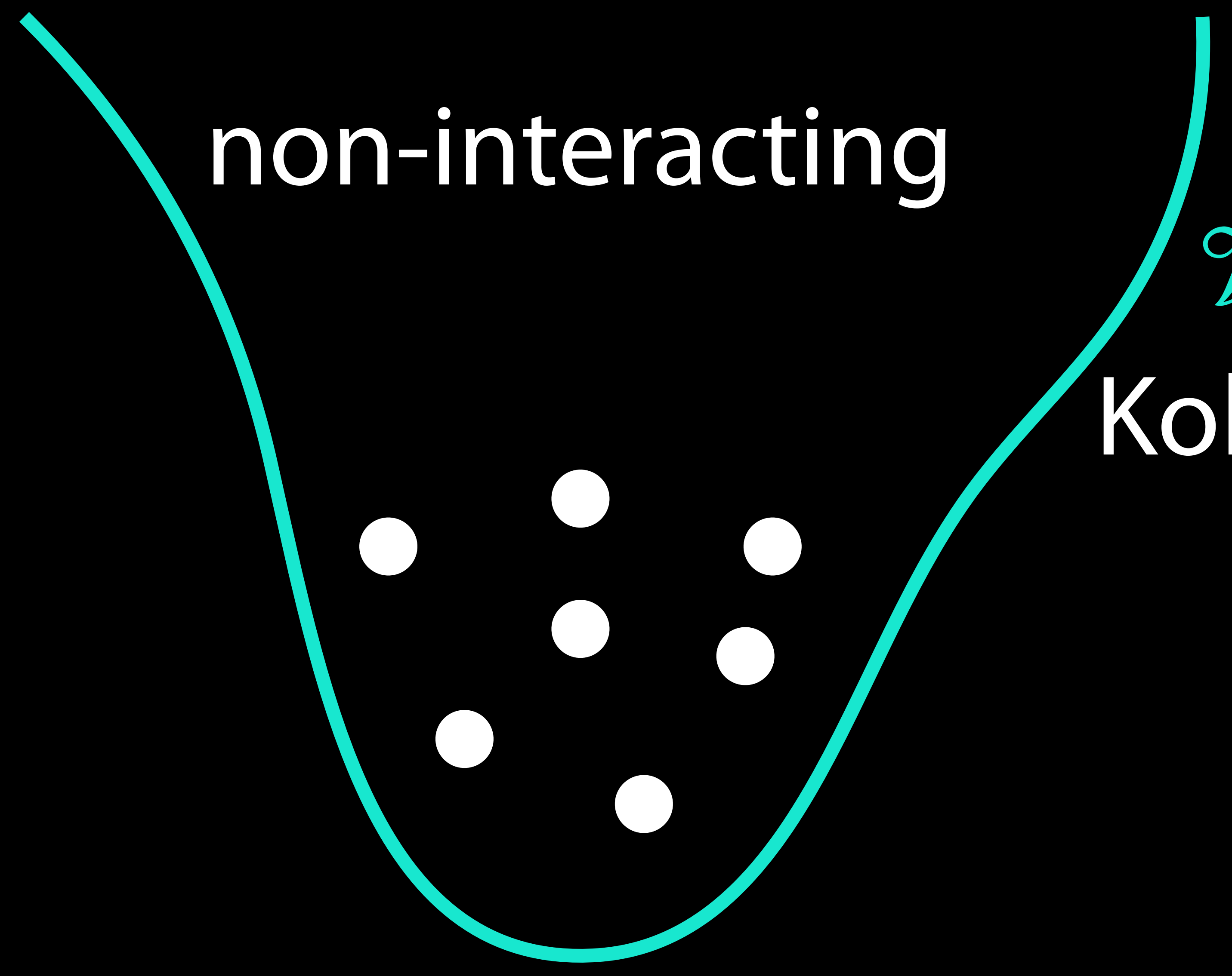
ground state

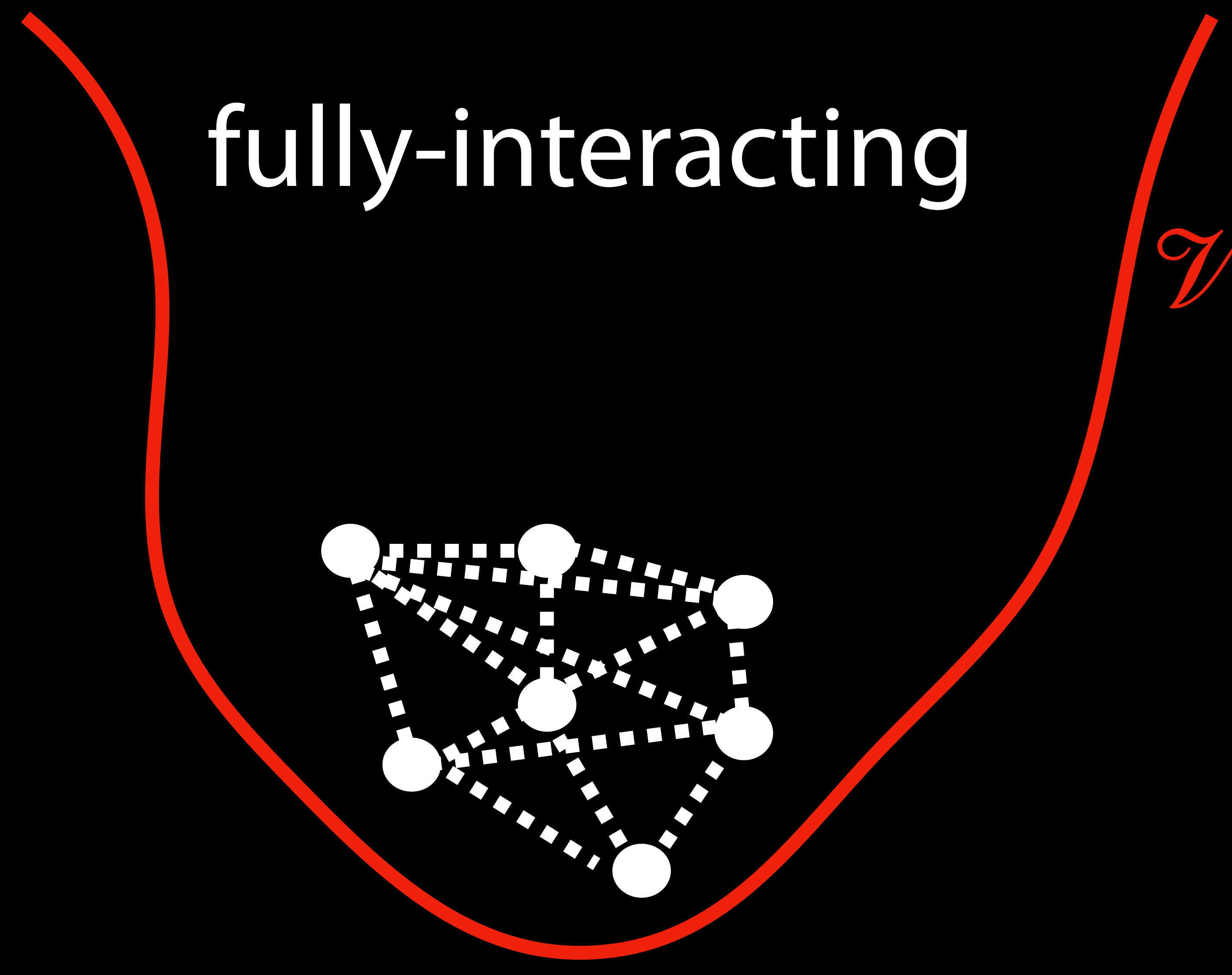
$$E_{\mathrm{gs}} = \inf_{\rho} E[\rho]$$

$$= E[\rho_{\mathrm{gs}}]$$



Kohn–Sham DFT





gs density

$$\rho_0(\vec{r}) = \langle \phi_{\mathrm{KS}} | \psi^\dagger(\vec{r})\psi(\vec{r}) | \phi_{\mathrm{KS}} \rangle$$

gs density

$$\rho_0(\vec{r}) = \langle \Psi_0 | \psi^\dagger(\vec{r})\psi(\vec{r}) | \Psi_0 \rangle$$

$$\Updownarrow$$

both systems give the same density

Kohn–Sham DFT

W. Kohn and L. J. Sham, PR140(1965)A1133

correlation

$$E[\rho] = T_s[\rho] + E_{\mathrm{ext}}[\rho] + E_{\mathrm{H}}[\rho] + E_{\mathrm{x}}[\rho] + E_{\mathrm{c}}[\rho]$$
$$= T_s[\rho] + F[\rho]$$

non-interacting system w/one-body potential $H = T + \int d\vec{r} v_s(\vec{r})\psi^\dagger(\vec{r})\psi(\vec{r})$

one-body problem

$$\left\{ -\frac{\hbar^2}{2m}\nabla^2 + v_s[\rho] \right\} \phi_i = \epsilon_i \phi_i \quad \Rightarrow \quad \rho_0(\vec{r}) = \sum_i |\phi_i(\vec{r})|^2$$

$$T_s[\rho] = \sum_i \langle \phi_i | -\frac{\hbar^2 \nabla^2}{2m} | \phi_i \rangle = \sum_i \epsilon_i - \int d\vec{r} \rho(\vec{r}) v_s[\rho] \qquad v_s[\rho] = -\frac{\delta T_s[\rho]}{\delta \rho}$$

fully-interacting system

Hohenberg–Kohn variation principle

$$v_s[\rho] = \frac{\delta F[\rho]}{\delta \rho}$$

KS potential

$$\frac{\delta E}{\delta \rho} = 0 \quad \Rightarrow \quad \frac{\delta T_s[\rho]}{\delta \rho} + \frac{F[\rho]}{\delta \rho} = 0 \quad \Rightarrow \quad \rho_0(\vec{r})$$

Kohn–Sham DFT

W. Kohn and L. J. Sham, PR140(1965)A1133

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$$E[\rho] = T_s[\rho] + E_{ext}[\rho] + E_H[\rho] + E_x[\rho] + E_c[\rho]$$
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non-interacting system w/one-body potential $\quad H = T + \int d\vec{r} v_s(\vec{r})\psi^\dagger(\vec{r})\psi(\vec{r})$

one-body problem

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$$E[\rho] = T_s[\rho] + E_{ext}[\rho] + E_H[\rho] + E_x[\rho] + E_c[\rho]$$
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$$T_s[\rho] = \sum_i \langle\phi_i| -\frac{\hbar^2\nabla^2}{2m}|\phi_i\rangle = \sum_i \epsilon_i - \int d\vec{r}\rho(\vec{r})v_s[\rho] \qquad v_s[\rho] = -\frac{\delta T_s[\rho]}{\delta\rho}$$

KS potential

Hartree–Fock potential

$$v_s[\rho] = \frac{\delta F[\rho]}{\delta\rho} \quad \longrightarrow \quad v_{HF}[\rho]$$

without correlation $\frac{\delta E_c[\rho]}{\delta\rho}$

DFT for dynamics and excitations: TDDFT

E. Runge and E. K. U. Gross, PRL52(1984)997

$$\rho(\vec{r},t) \Leftrightarrow v_{\rm ext}(\vec{r},t) \Leftrightarrow \Psi(\vec{r},t)$$

$$A[\rho] = \int_{t_0}^{t_1} dt \langle \Psi[\rho] \,|\, i\partial_t - H(t) \,|\, \Psi[\rho] \rangle \quad \Rightarrow \quad \frac{\delta A}{\delta \rho} = 0$$

for practical calculation

time-dependent Kohn–Sham $\Longleftrightarrow$ time-dependent Hartree–Fock

linear-response $\hat{H} \rightarrow \hat{H} + f(t)\hat{F}_\lambda$

$$\rho(\vec{r},t) = \rho_0(\vec{r}) + \delta\rho(\vec{r}) e^{-i\omega t} + \mathrm{cc}$$

$$\delta\rho(\mathbf{r}) = \int d\mathbf{r}' \chi_0(\mathbf{r},\mathbf{r}') \left[\frac{\delta^2 E[\rho]}{\delta^2 \rho} \delta\rho(\mathbf{r}') + f(\mathbf{r}') \right]$$

RPA-like equation

$$\delta\rho = \frac{\chi_0}{1 - \chi_0 v_{\rm res}} f = \chi_{\rm RPA} f$$

$$v_{\rm res} = \frac{\delta^2 E[\rho]}{\delta^2 \rho}$$

Skyrme-energy-density functional

Kohn–Sham(–Bogoliubov-de Gennes)+proton-neutron LR-TD(S)DFT w/Skyrme EDF

"Skyrme–Hartree–Fock(–Bogoliubov)+proton-neutron (Q)RPA"

EDF $E = \int d\mathbf{r} \mathscr{H}(\mathbf{r})$

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

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

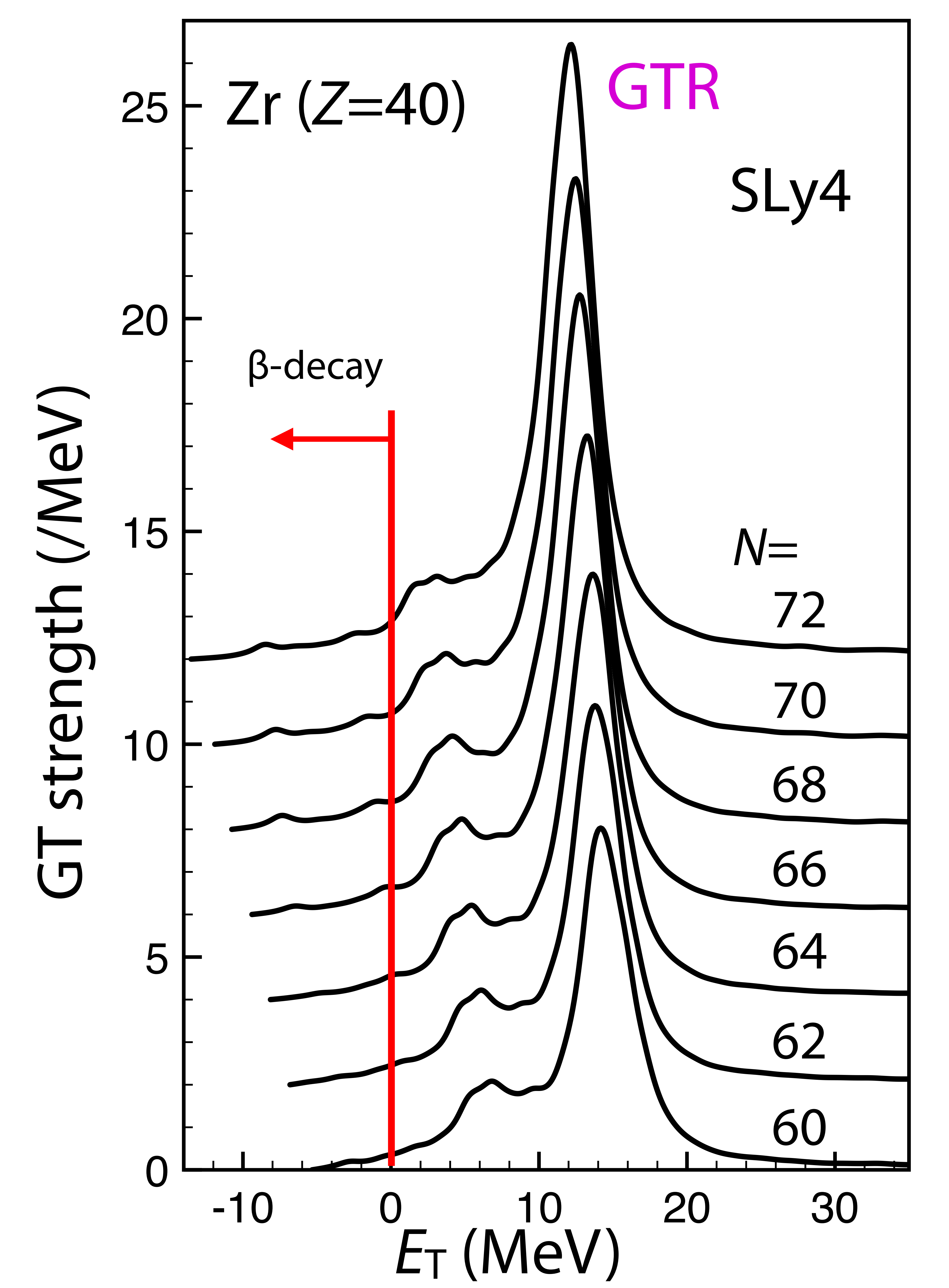
$$\mathcal{H}_{tt_3}^{\mathrm{even}} = C_t^{\rho}\,\rho_{tt_3}^2 + C_t^{\Delta\rho}\,\rho_{tt_3}\Delta\rho_{tt_3} + C_t^{\tau}\,\rho_{tt_3}\tau_{tt_3} + C_t^{\nabla J}\rho_{tt_3}\,\nabla\cdot\mathbf{J}_{tt_3} + C_t^{J}\overleftrightarrow{J}_{tt_3}^2$$

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

residual interaction for charge-changing channel:

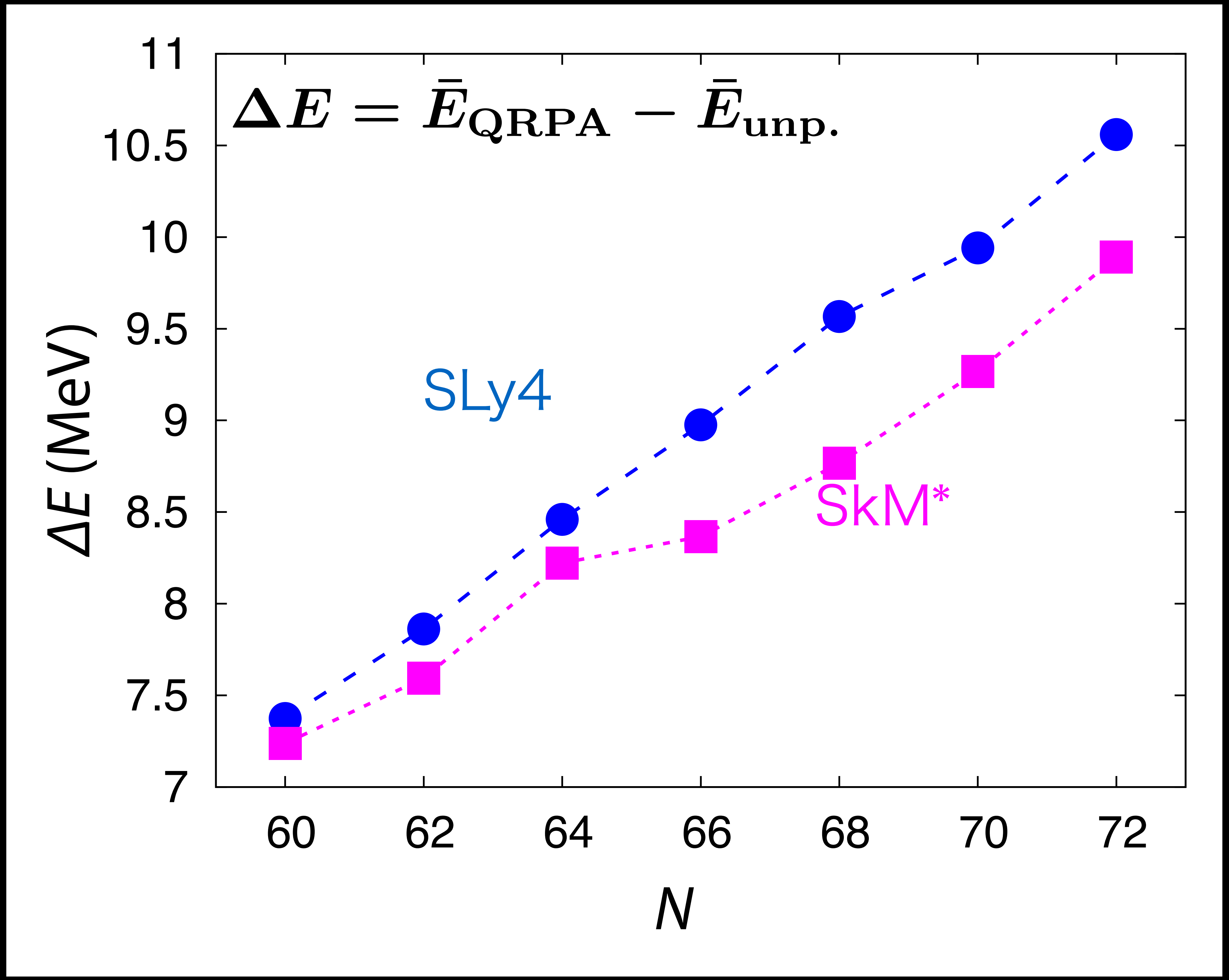
$$v_{\mathrm{res}}(\mathbf{r}_1,\mathbf{r}_2) = \frac{\delta^2 E}{\delta\rho_1(\mathbf{r}_1)\delta\rho_1(\mathbf{r}_2)}\vec{\tau}_1\cdot\vec{\tau}_2 + \frac{\delta^2 E}{\delta\vec{s}_1(\mathbf{r}_1)\delta\vec{s}_1(\mathbf{r}_2)}\vec{\sigma}_1\cdot\vec{\sigma}_2\vec{\tau}_1\cdot\vec{\tau}_2$$

Strongly collective GTR in n-rich nuclei



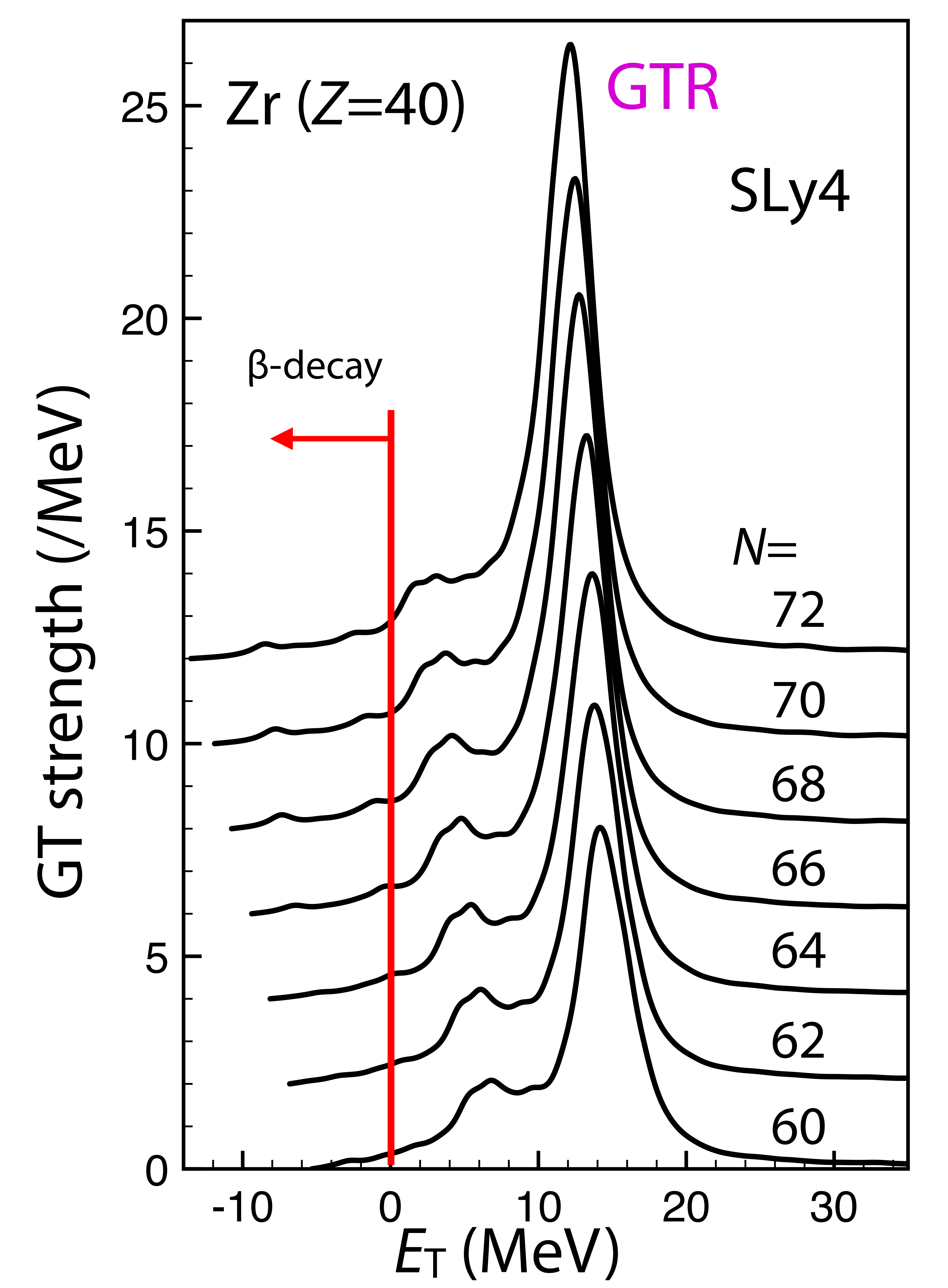
KY, PTEP2013, 113D02

energy shift due to RPA correlations



$$\bar{E} = \frac{\int_0^\infty \omega S(\omega) d\omega}{\int_0^\infty S(\omega) d\omega}$$

Strongly collective GTR in n-rich nuclei



KY, PTEP2013, 113D02

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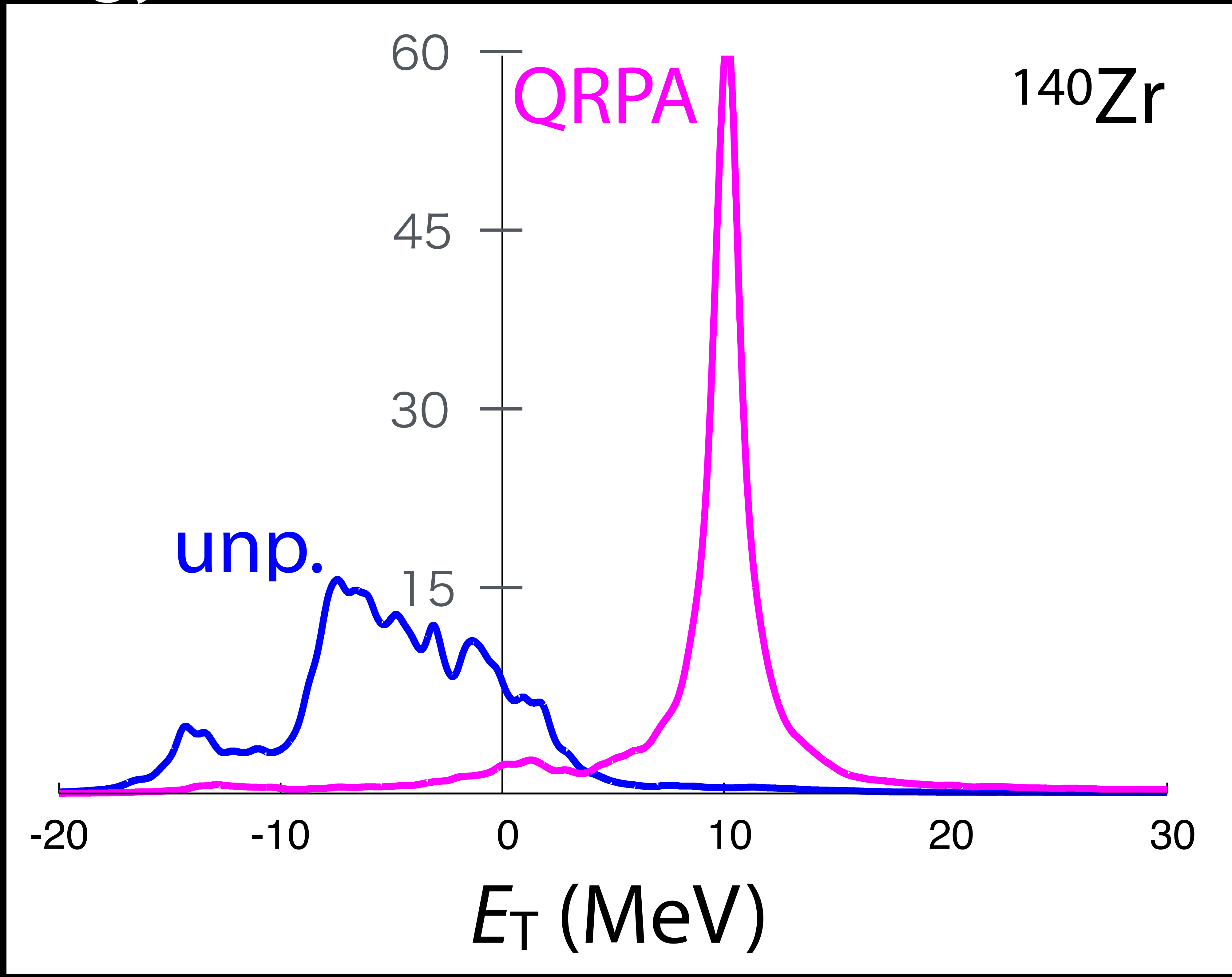
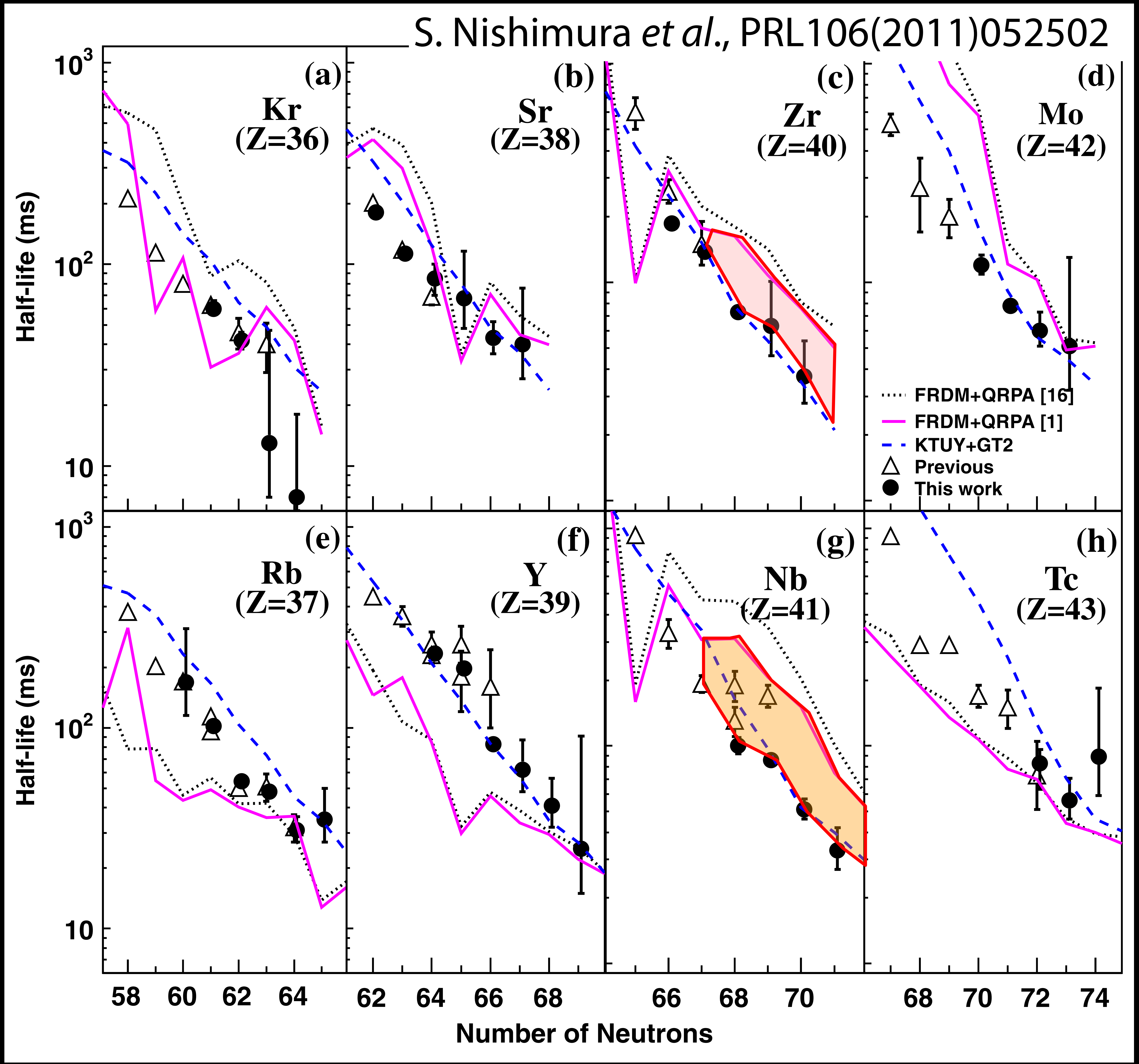


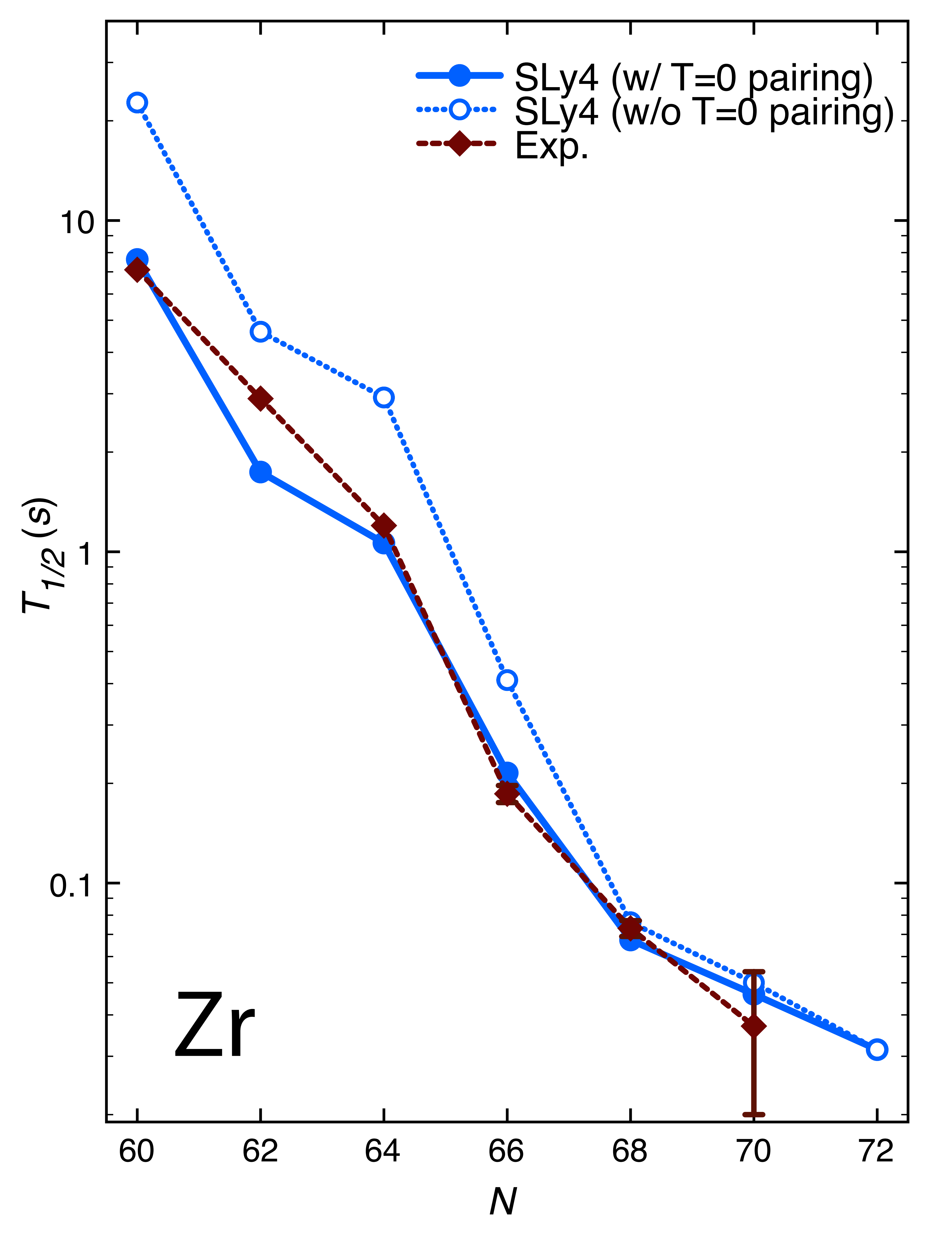
superallowed GT resonance is unlikely to appear

Impact of low-lying GT states on beta-decay rates

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



KY, PTEP2013, 113D02



Isovector dipole excitations

electric (spin non-flip) dipole

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

spin dipole $(\lambda = 0,1,2)$

$$\hat{F}^{\lambda}_{1K} = \sum_{\sigma,\sigma'} \sum_{\tau,\tau'} \int d\vec{r} r [Y_1 \otimes \sigma]^{\lambda}_{K} \hat{\psi}^{\dagger}(\vec{r}\sigma\tau) \hat{\psi}(\vec{r}\sigma'\tau') \langle \tau | \tau_{\mu} | \tau' \rangle$$

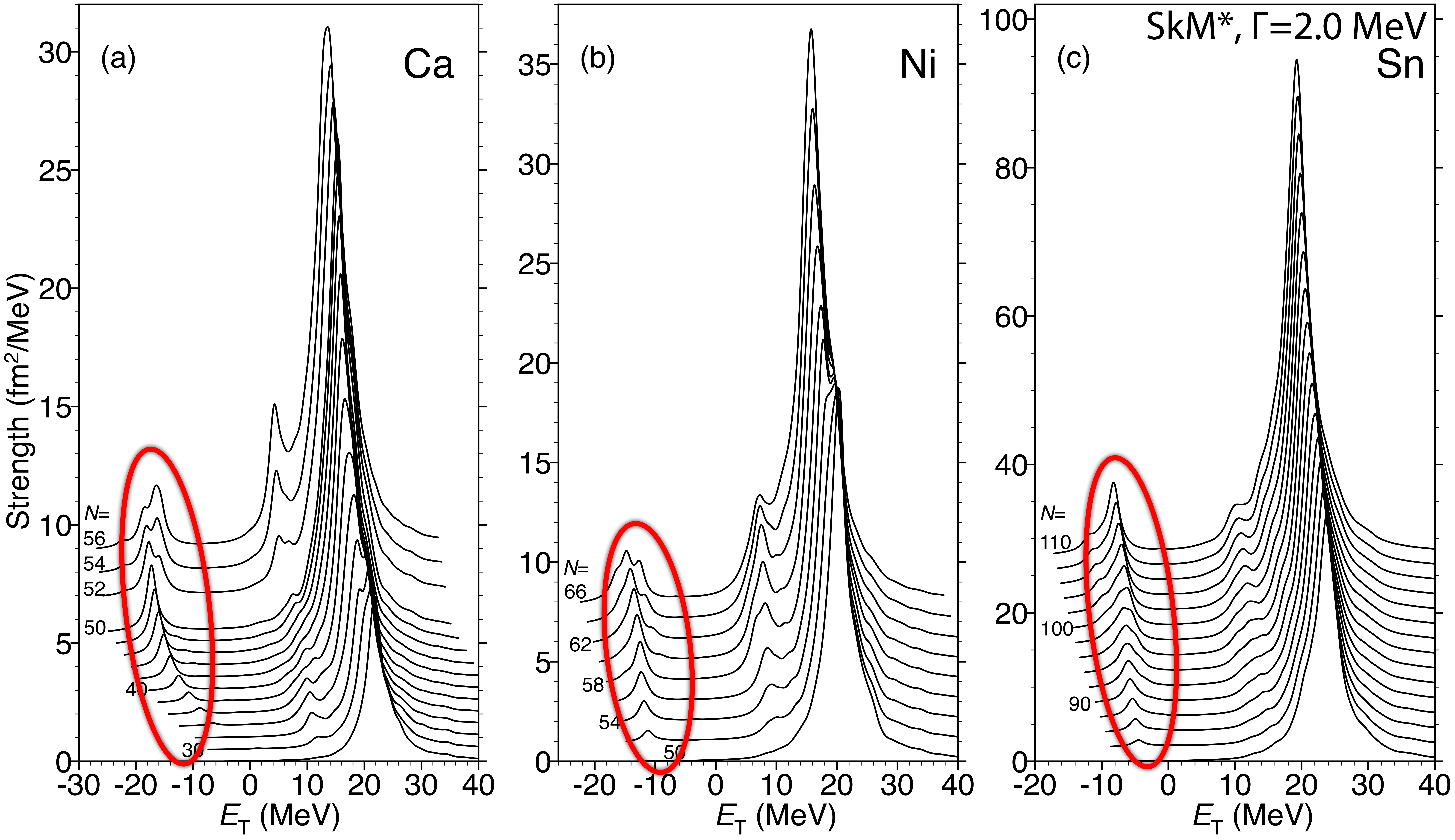
charge-exchange channel:

$\mu = +1$	$\psi^{\dagger}_{\nu}\psi_{\pi}$	(n,p) type, β+ decay
$\mu = -1$	$\psi^{\dagger}_{\pi}\psi_{\nu}$	(p,n) type, β- decay

Electric dipole excitations
in neutron-rich Ca, Ni, and Sn isotopes

Ca: $N = 28\text{-}56$
Ni: $N = 50\text{-}66$
Sn: $N = 82\text{-}110$

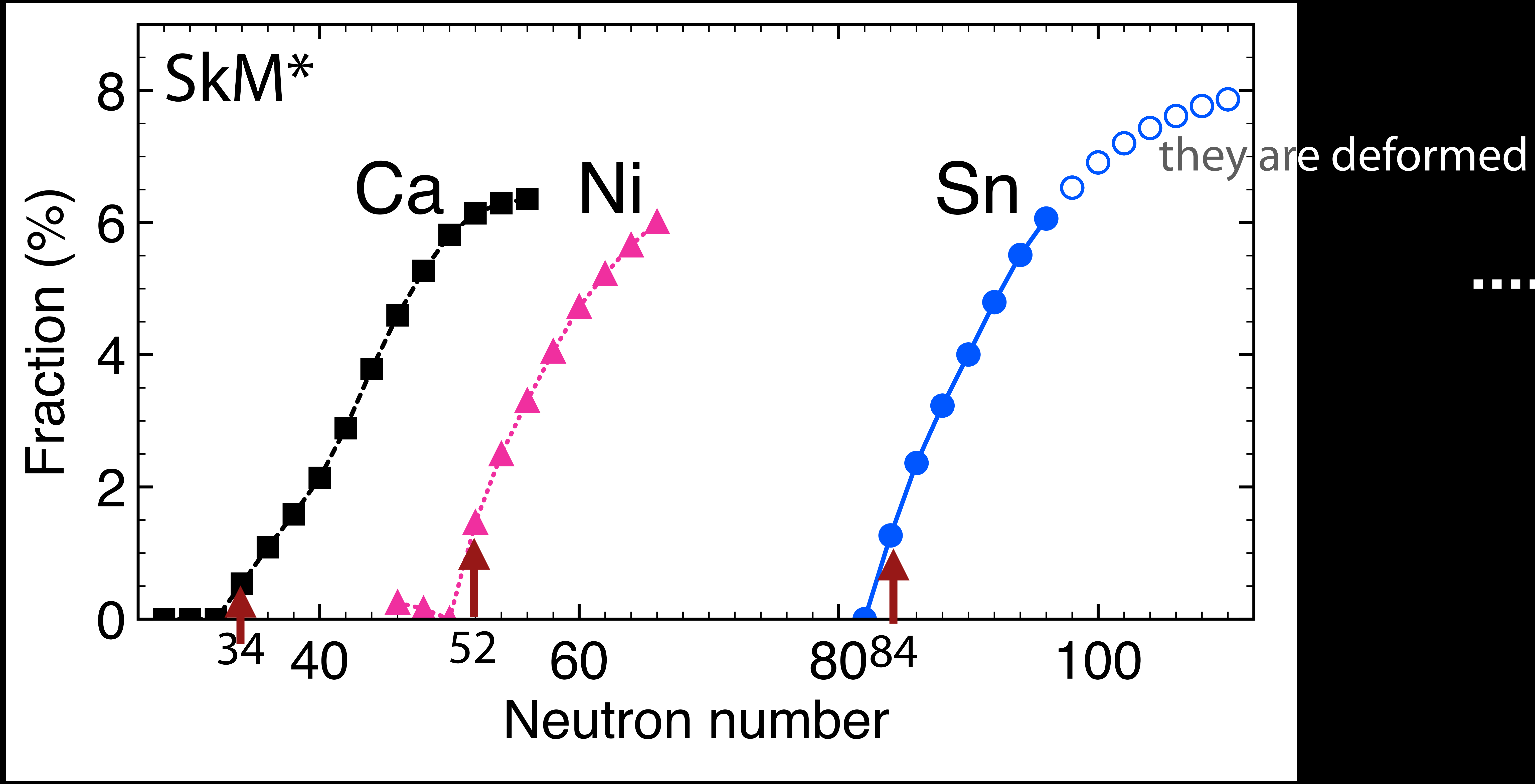
KY, Phys. Rev. C96, 051302R (2017)



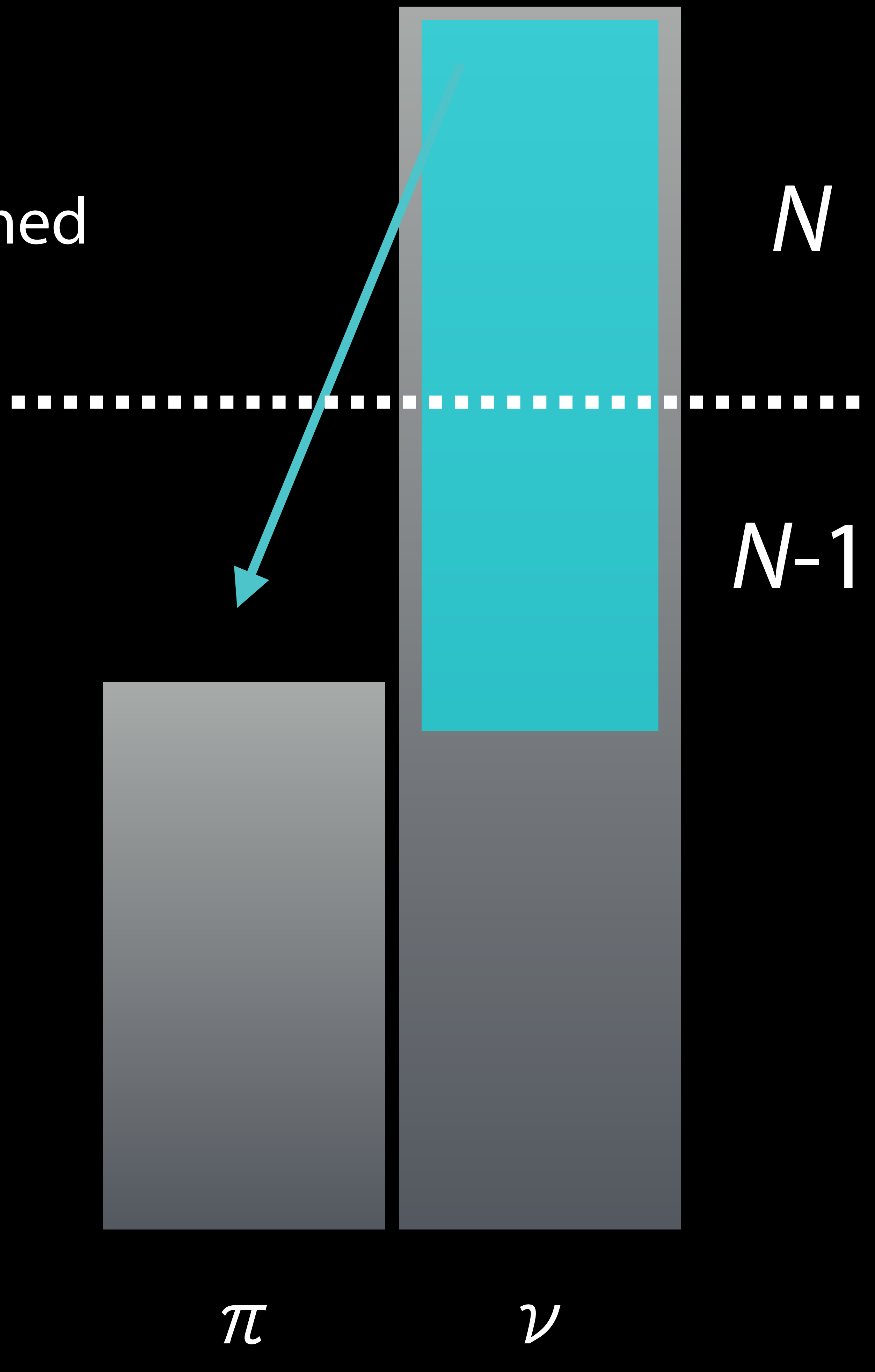
SkM*, Γ=2.0 MeV
(a)
Ca
(b)
Ni
(c)
Sn
Strength (fm²/MeV)
E_T (MeV)
N=
56
54
52
50
40
30
N=
66
62
58
54
50
N=
110
100
90

Low-lying dipole excitation: shell effect

summed strength in low-energy

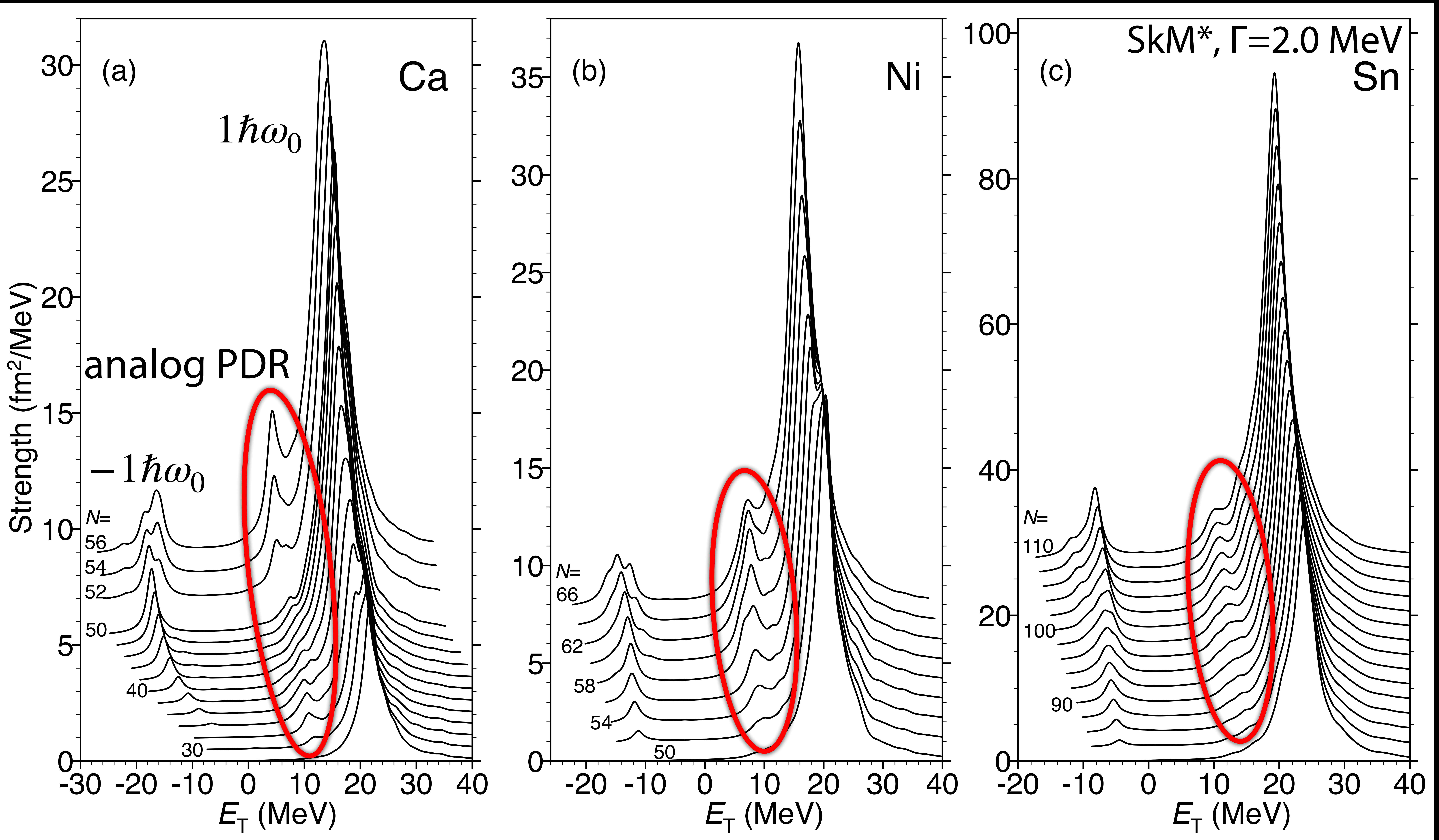


$-1\hbar\omega_0$ excitation



partial occupation of $g_{9/2}$ — occupation of $2d_{5/2}$ — occupation of $2f_{7/2}$

$\nu g_{9/2} \rightarrow \pi f_{7/2}$ — $\nu d_{5/2} \rightarrow \pi p_{3/2}$ — $\nu f_{7/2} \rightarrow \pi d_{5/2}$



(a)
Ca
$1\hbar\omega_0$
analog PDR
$-1\hbar\omega_0$
N=
56
54
52
50
40
30
Strength (fm²/MeV)
E_T (MeV)
(b)
Ni
N=
66
62
58
54
50
E_T (MeV)
(c)
SkM*, Γ=2.0 MeV
Sn
N=
110
100
90
E_T (MeV)

Charge-exchange dipole excitations in n-rich nuclei

✓ cross-shell ($N \rightarrow N\pm1$) excitation for negative-parity excitation

neutrons are weakly bound

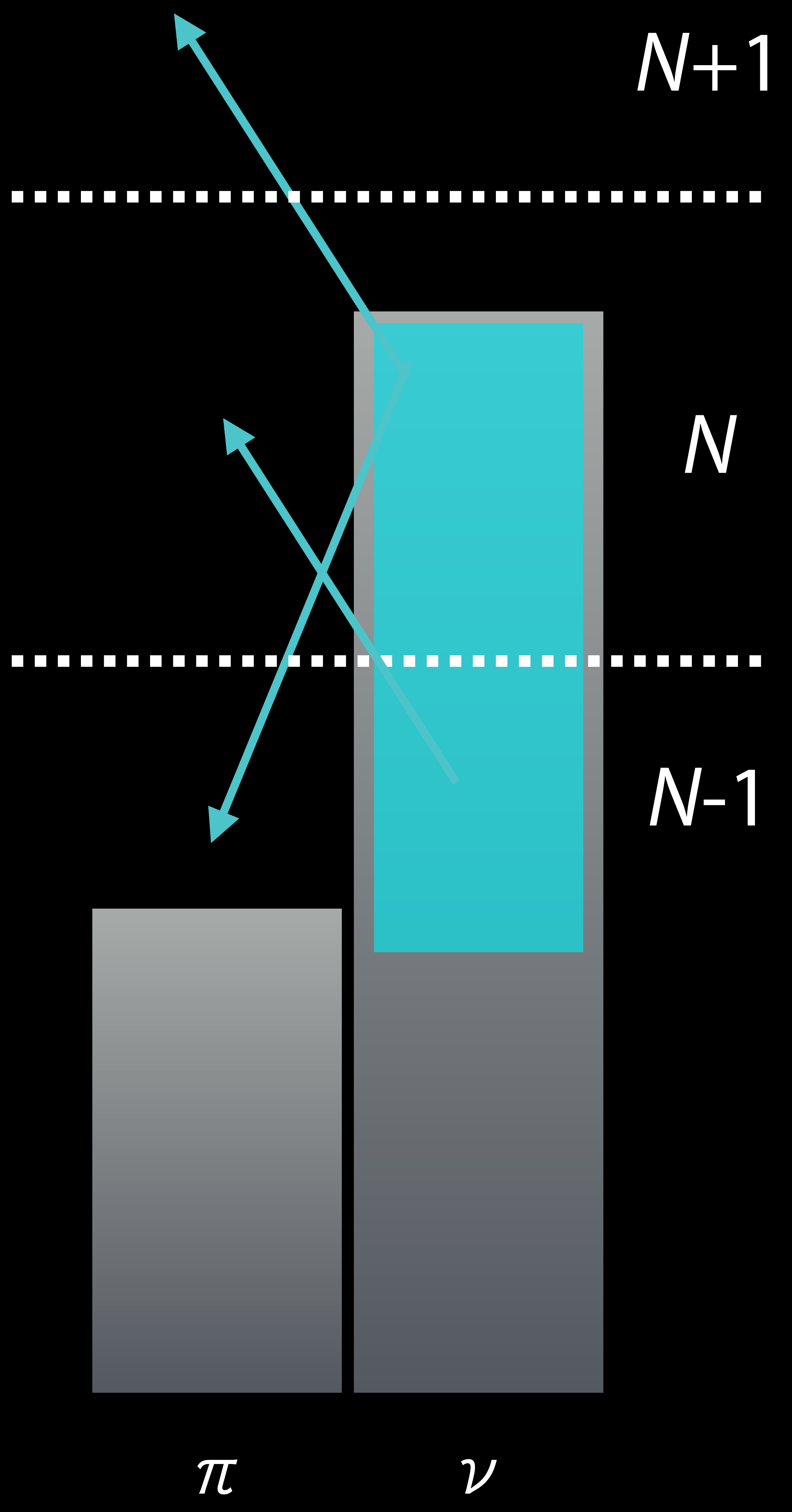
↓

protons are deeply bound: low-lying $(-1\hbar\omega_0)$ mode

protons are in the continuum: pygmy

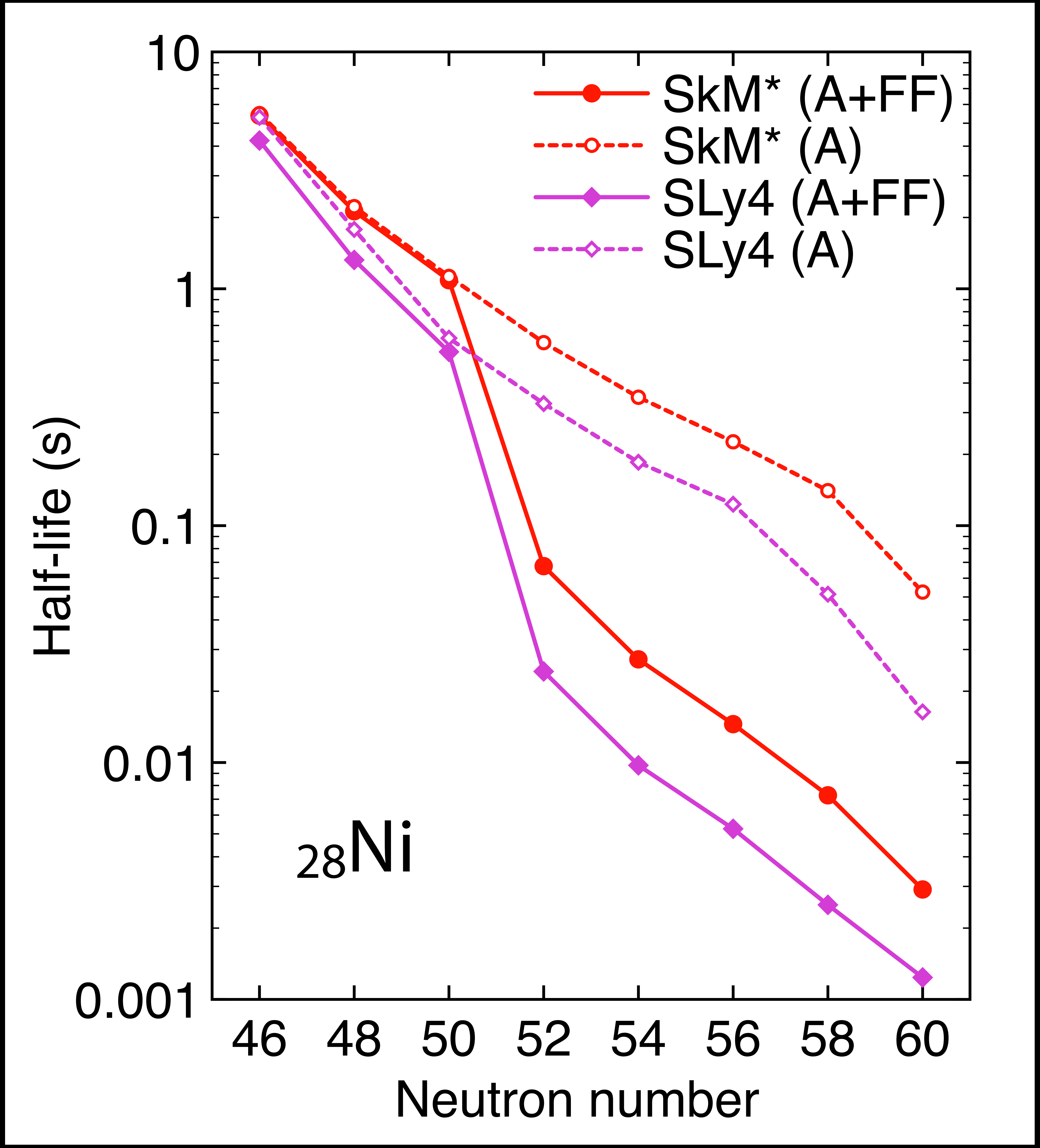
✓ cross-shell (N-1 $\rightarrow N$) excitation

deeply-bound neutrons: giant resonance

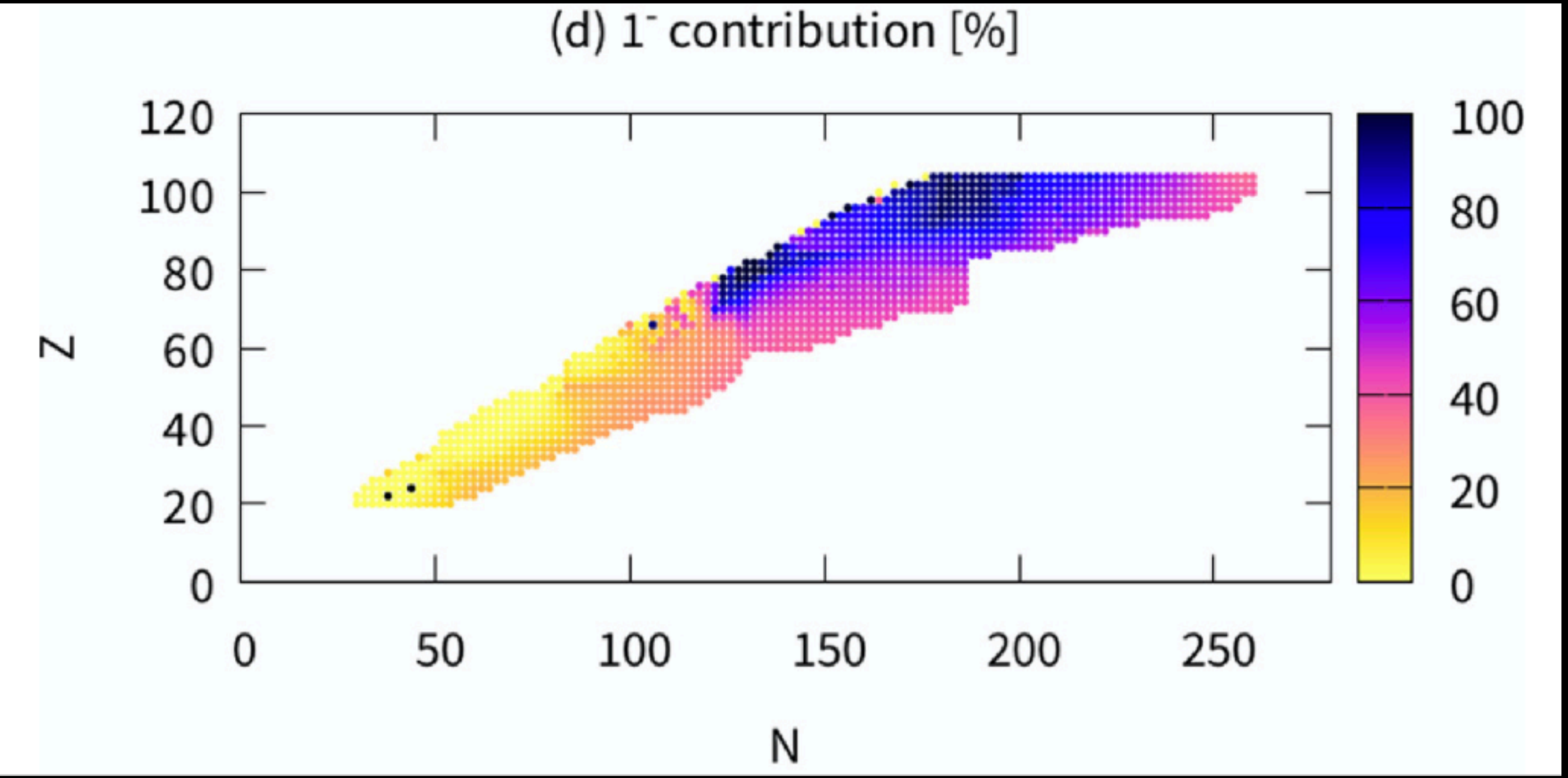


Impact of low-lying dipole states on beta-decay rates

KY, PRC100(2019)024316



M. T. Mustonen, J. Engel, PRC93(2016)014304



Shell effect (purely quantal)
determines the β-decay half-life.

Microscopic approach is necessary.

Dipole excitations in deformed nuclei

^{24}Mg, ^{40}Mg

Nd and Sm isotopes with shape changes

KY, arXiv: 2008.03947

Isovector dipole excitations in deformed nuclei

Isospin symmetry

degeneracy for μ for N=Z nuclei w/o the Coulomb int.

broken by the Coulomb int.

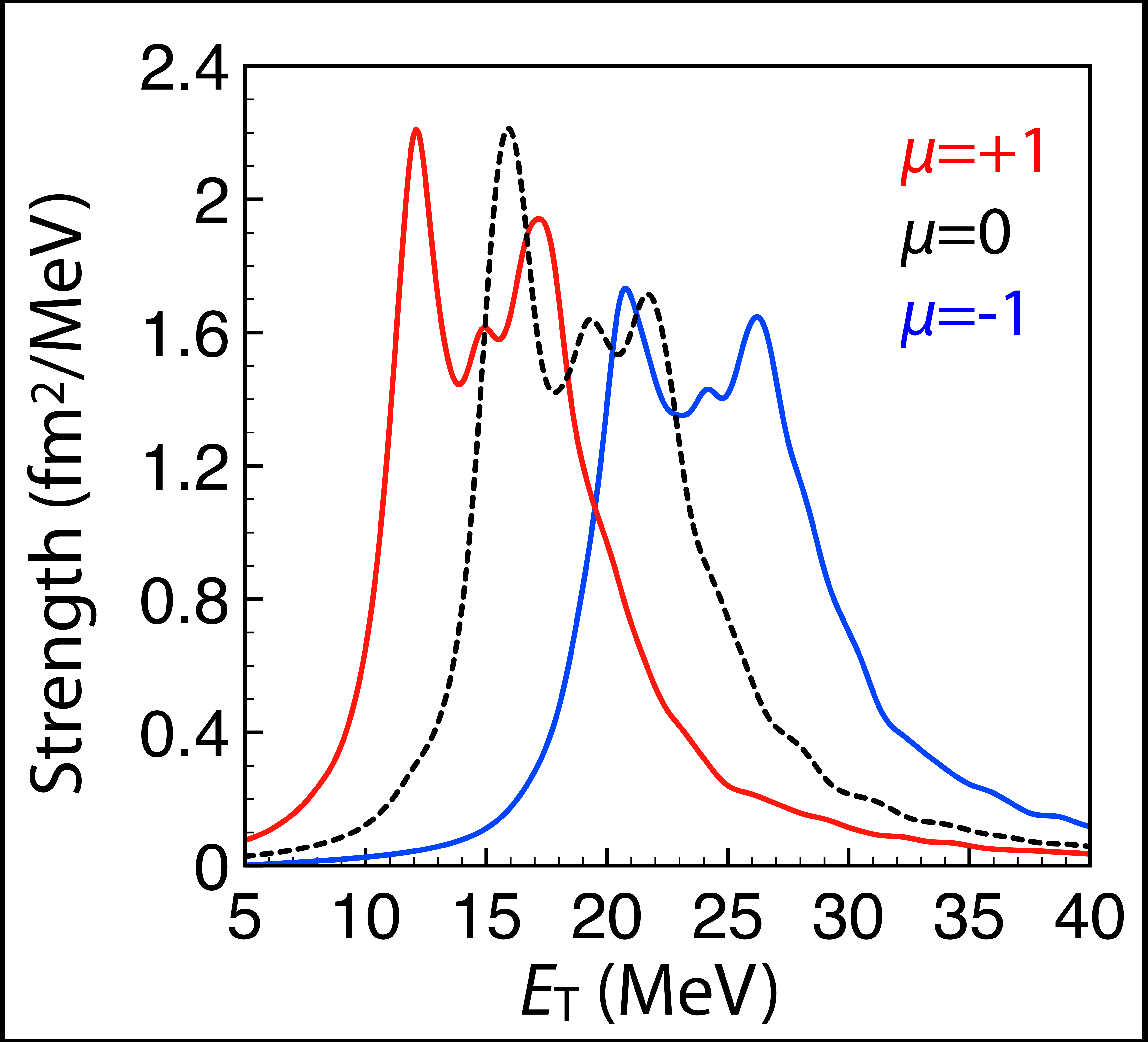
$\langle r^2 \rangle_\nu = 9.0$ fm^2
$\langle r^2 \rangle_\pi = 9.2$ fm^2

$$S_- - S_+ \propto N\langle r^2\rangle_\nu - Z\langle r^2\rangle_\pi$$

Shape deformation effect

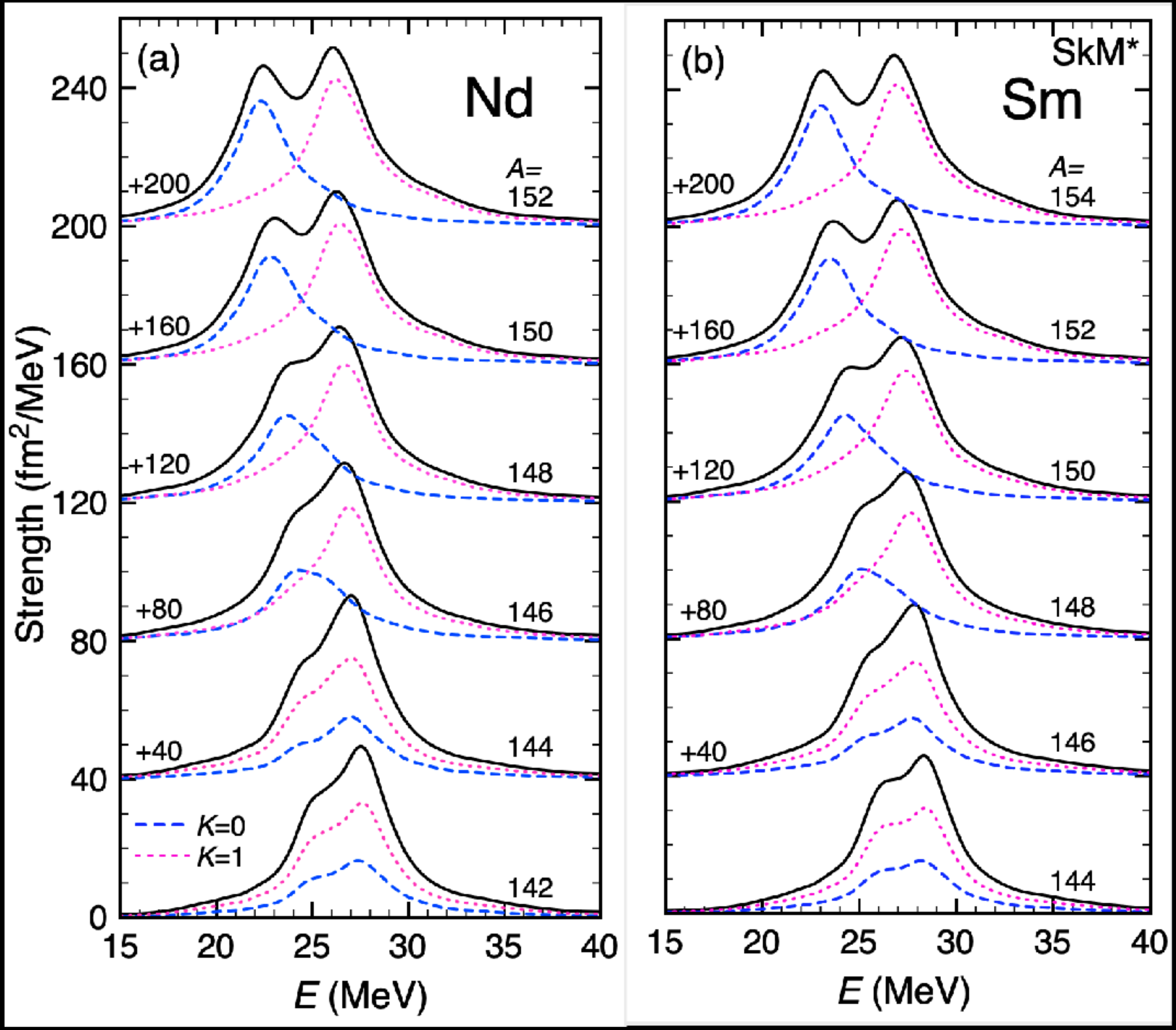
K-splitting

^{24}Mg SkM*



excitation energy w.r.t. the g.s of target (mother)

Evolution of deformation in charge-exchange dipole resonance



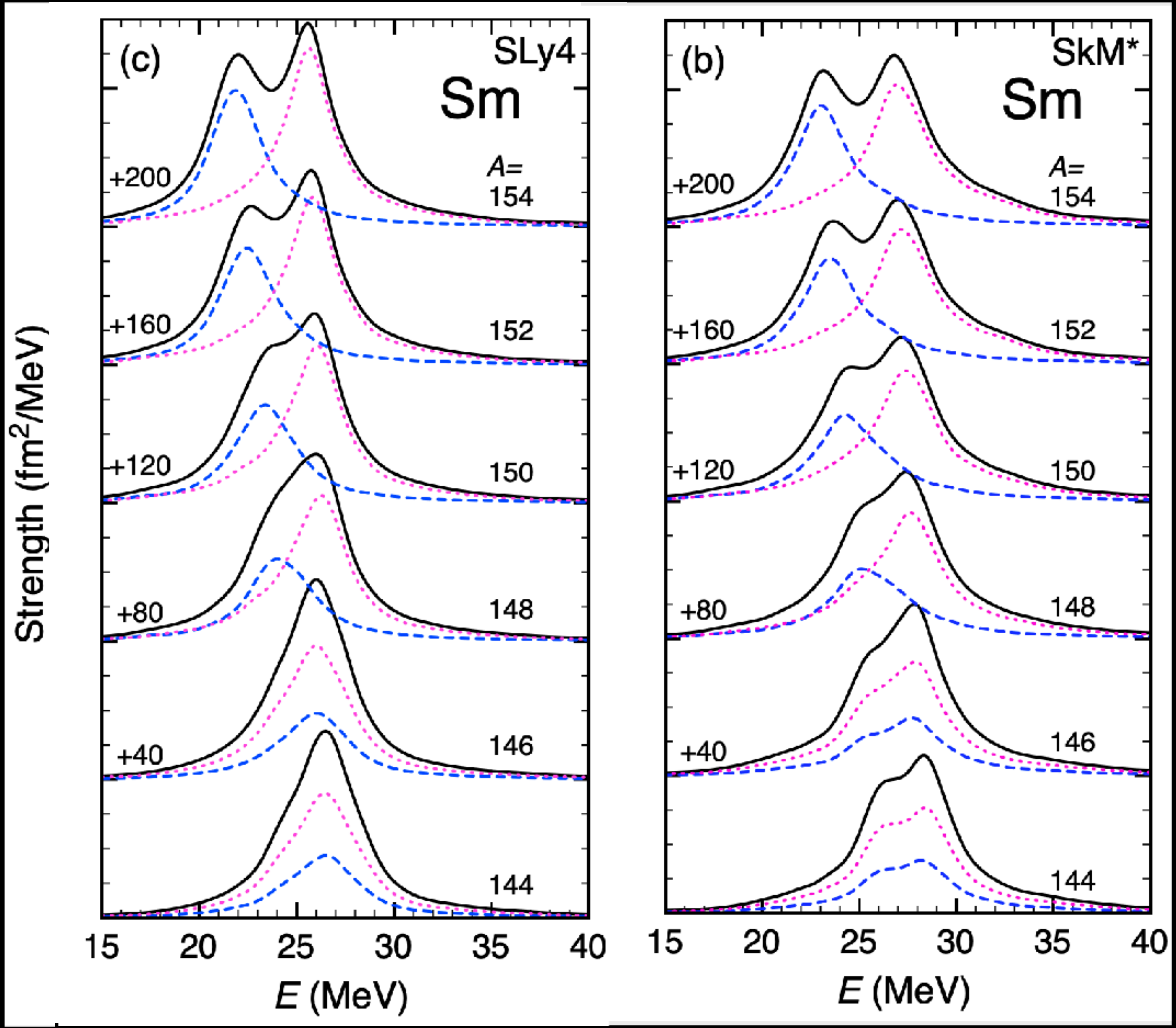
μ=-1

K-splitting appears $N \geq 86$

shoulder structure seen in spherical sys.

K-splitting is distinguishable from the shoulder ??

Evolution of deformation in charge-exchange dipole resonance

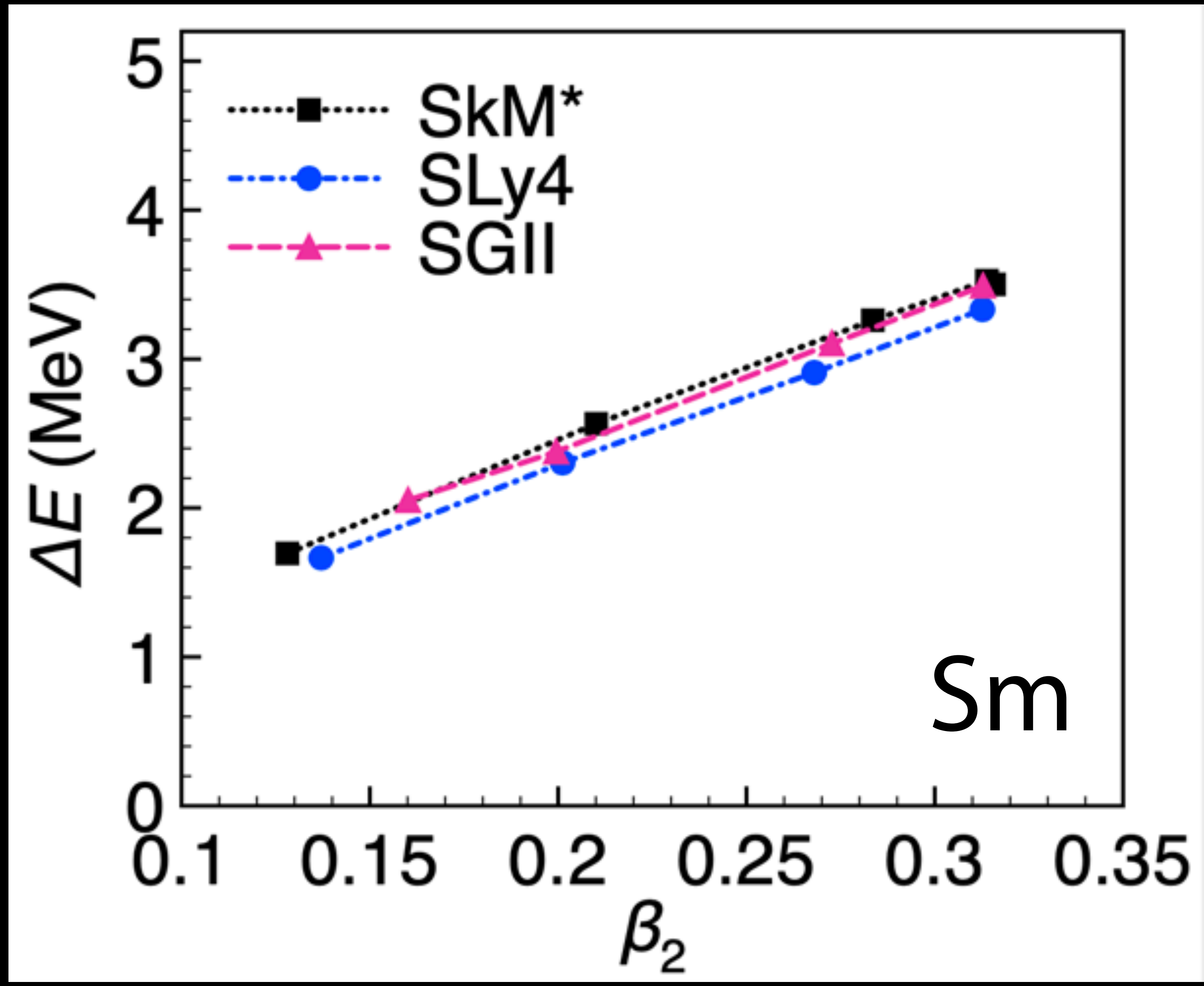


μ=-1

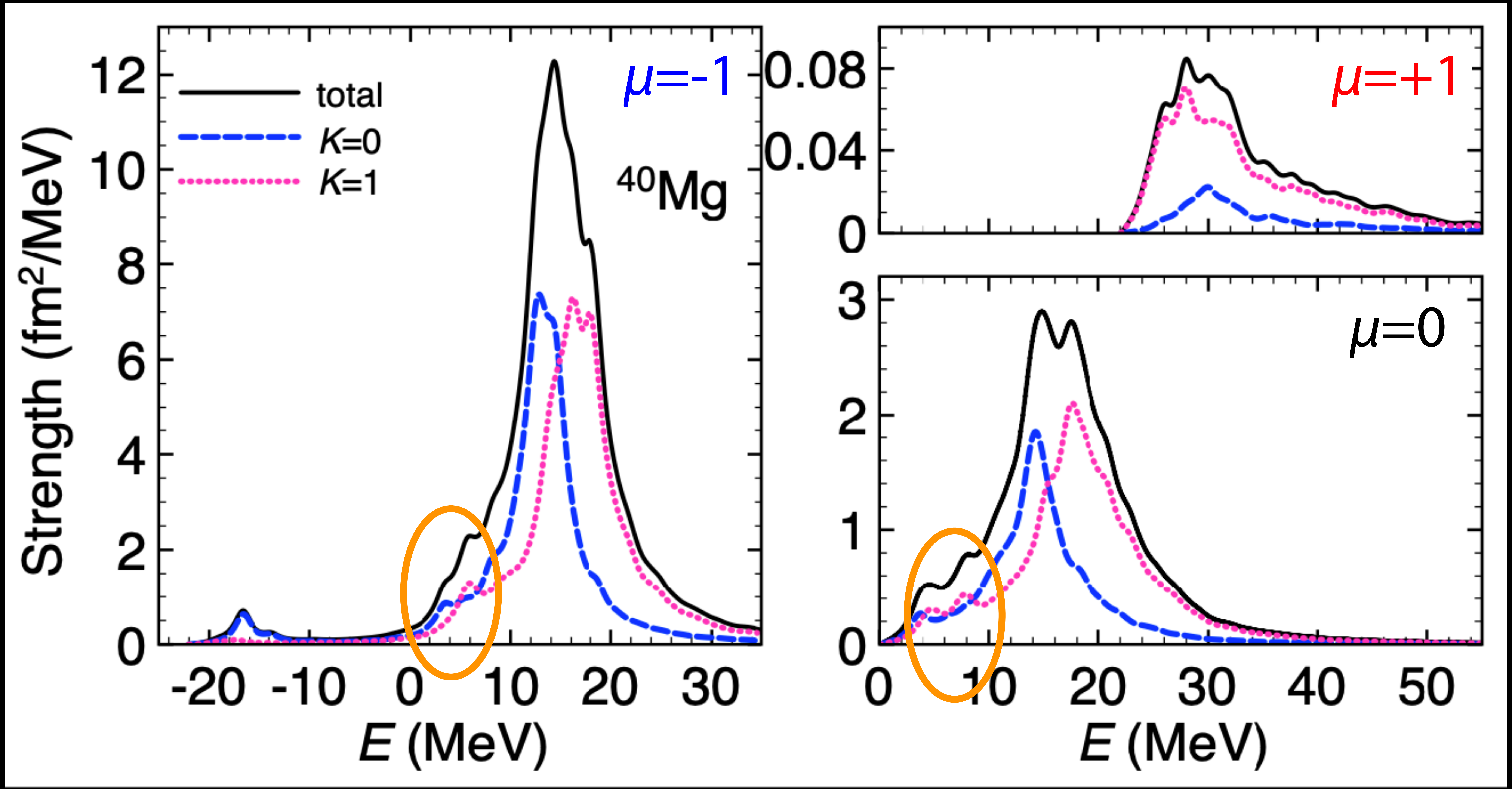
K-splitting appears $N \geq 86$

shoulder structure depends on the EDF

splitting is proportional to deformation



Charge-exchange dipole resonance at neutron-drip line



K-splitting

$-1\hbar\omega_0$ excitation

analog-pygmy resonance

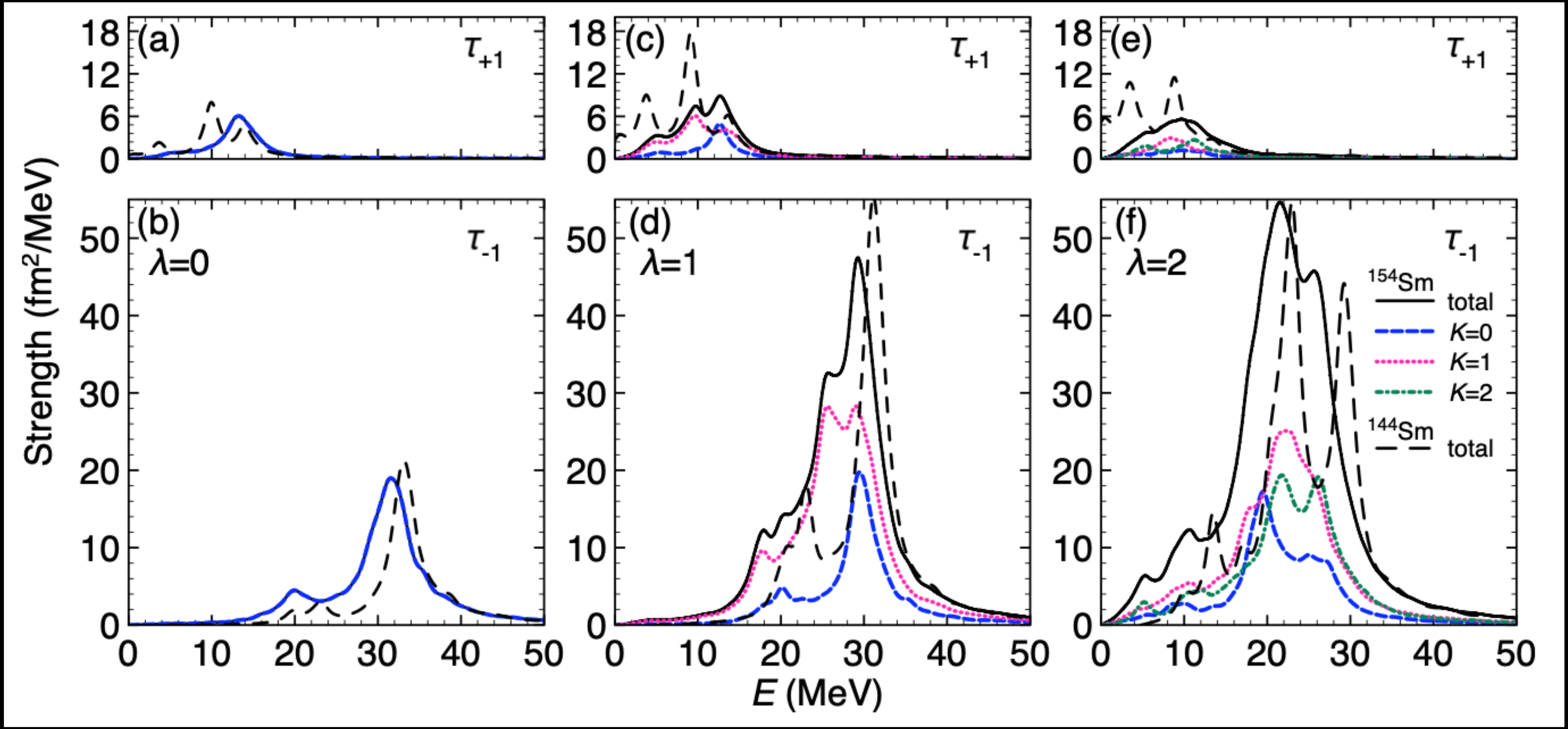
pygmy resonance

KY, PRC80(2009)044324

K. Wang *et al*, PRC96(2017)031301

Spin-dipole resonance in deformed nuclei

deformation effect in ^{154}Sm is not clear
strengths are fragmented even in ^{144}Sm

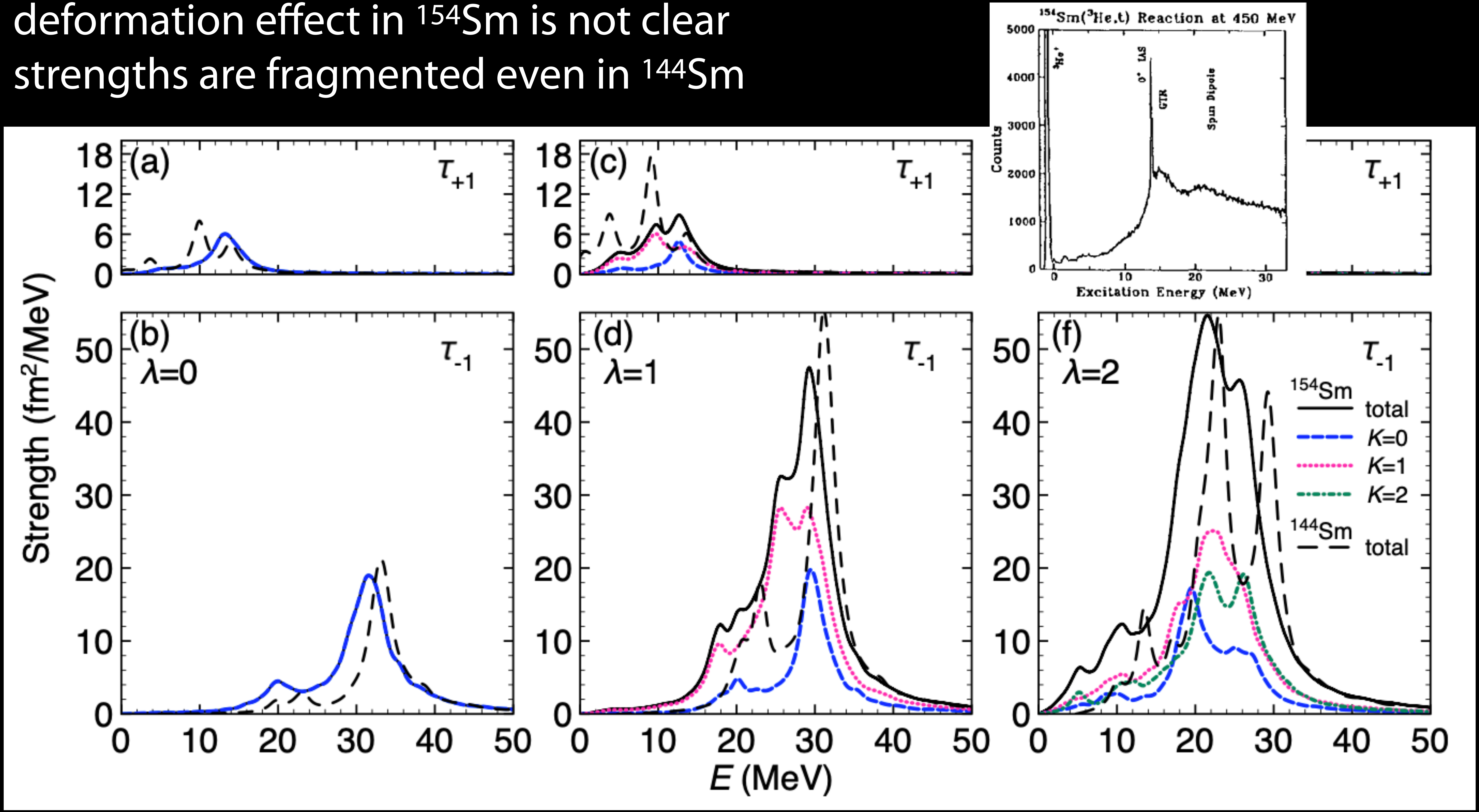


Spin-dipole resonance in deformed nuclei

H. Akimune et al., NPA569(1994)245c

deformation effect in ^{154}Sm is not clear

strengths are fragmented even in ^{144}Sm



Summary

✓ Low-lying dipole state appears uniquely in very neutron-rich nuclei

$-1\hbar\omega_0$ excitation

✓ strong shell effect

✓ high impact on the beta-decay rate

✓ emergence of analog-PDR below giant resonance

loosely-bound neutrons with low-angular momentum play an important role

✓ *K*-splitting is generic in IV dipole resonance in deformed nuclei

A further application of nuclear DFT for nuclear weak processes is in progress

Roles of the first-forbidden transitions

KY, PRC100, 024316 (2019)