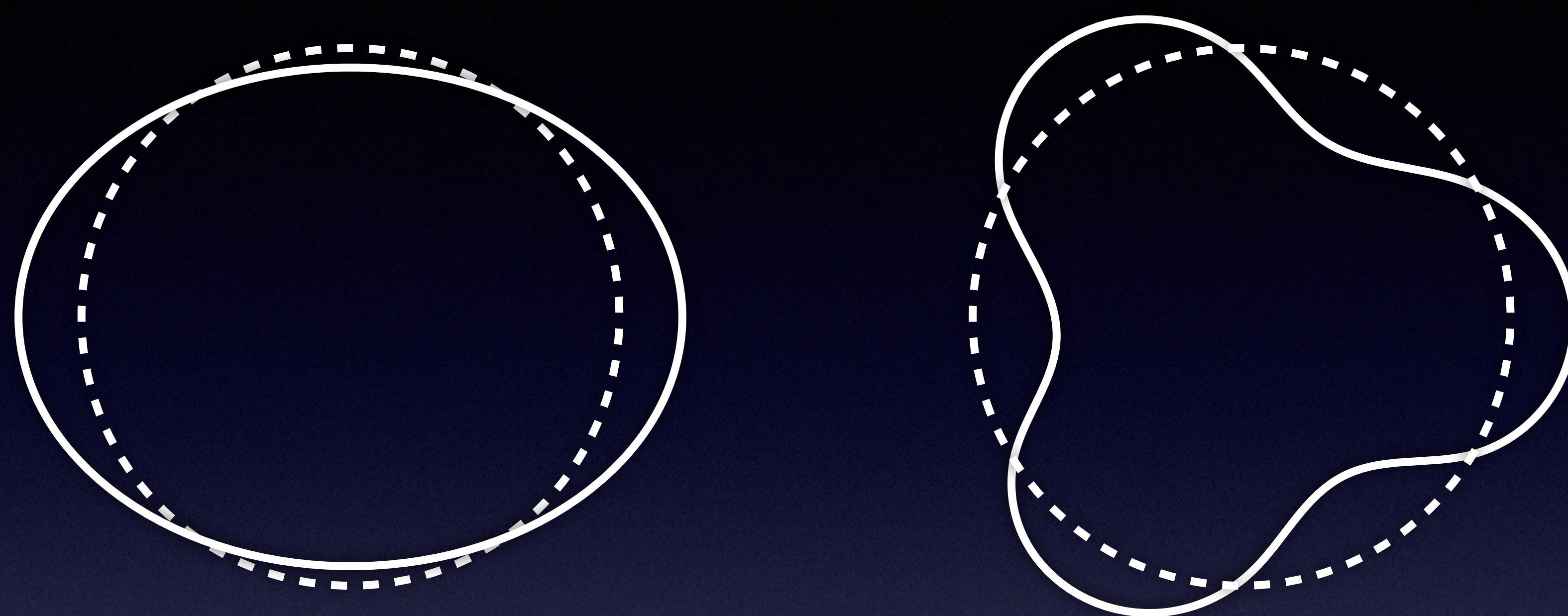
Analog pygmy-dipole resonance and low-lying charge-exchange dipole state in neutron-rich nuclei

京都大学
KYOTO UNIVERSITY

Kenichi Yoshida

Giant resonances: typical collective mode of surface vibration

classical and intuitive picture



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

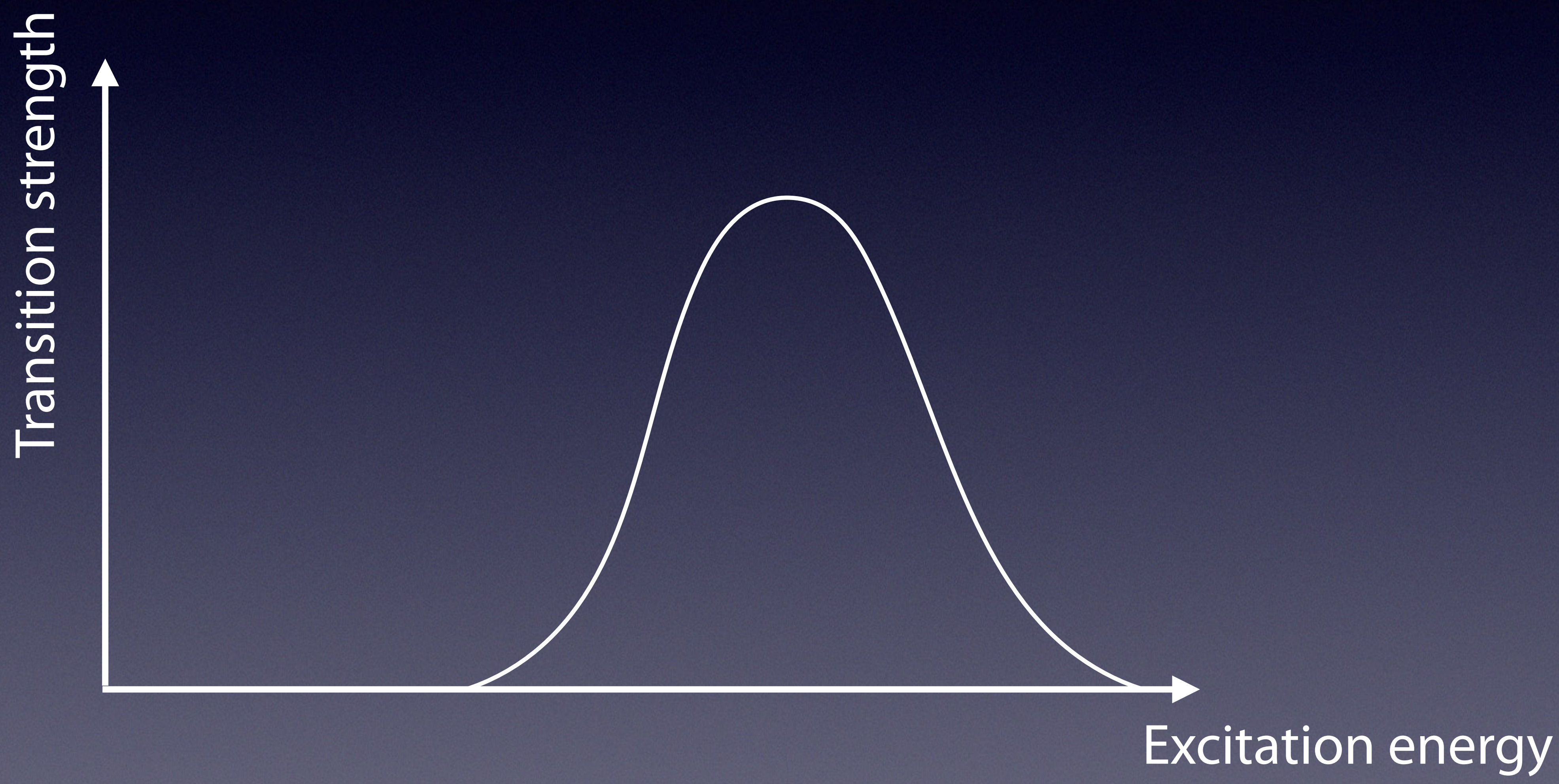
strongly excited by a one-body operator, exhaust a sum-rule value

$$\hat{F} = \sum_{\sigma,\sigma'} \sum_{\tau,\tau'} \int d\boldsymbol{r} r^L Y_L(\hat{r}) \hat{\psi}^\dagger(\boldsymbol{r}\sigma\tau) \langle\sigma| \begin{Bmatrix} 1 \\ \boldsymbol{\sigma} \end{Bmatrix} |\sigma'\rangle \langle\tau| \begin{Bmatrix} 1 \\ \boldsymbol{\tau} \end{Bmatrix} |\tau'\rangle \hat{\psi}(\boldsymbol{r}\sigma'\tau')$$

space spin isospin

Nuclear response: appearance of modes of excitation

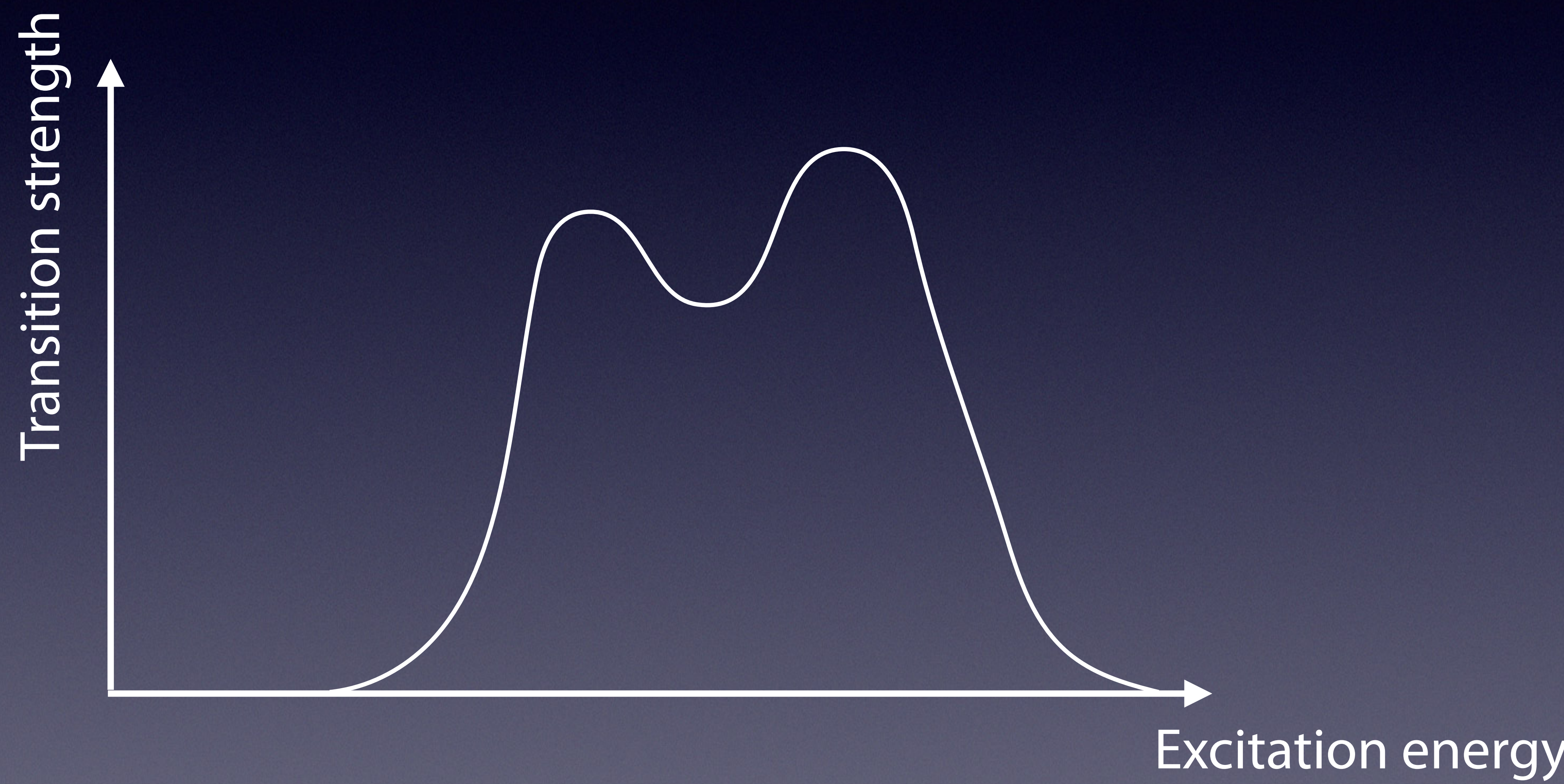
- rich variety of modes: *S* (spin), *T* (isospin), and *L* (angular mom.)
  - vibration in spin-space, isospin-space and real-space, and coupling among them
  - influenced by many-body correlations (deformation and superfluidity)



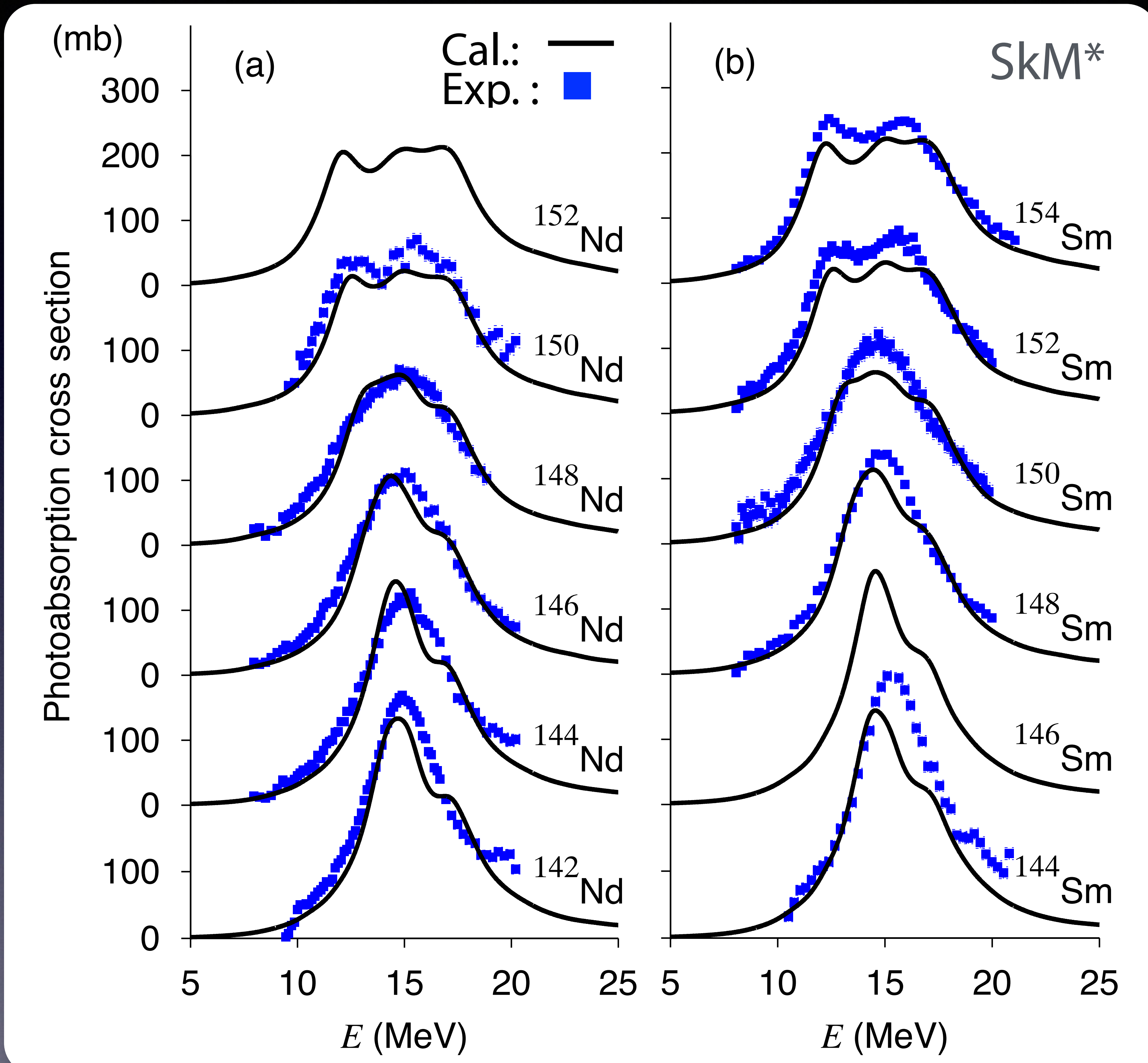
Nuclear response: appearance of modes of excitation

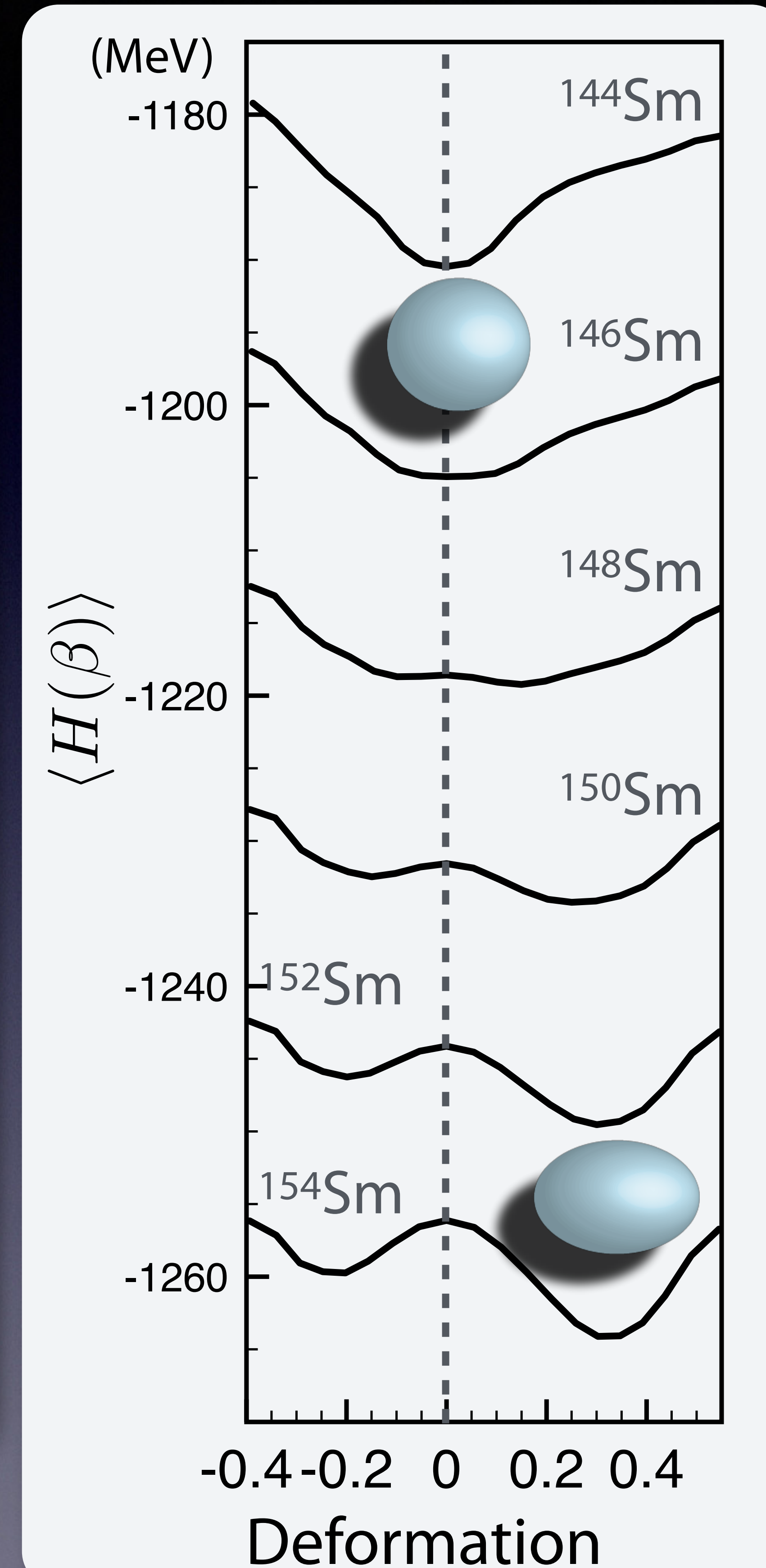
rich variety of modes: *S* (spin), *T* (isospin), and *L* (angular mom.)

- vibration in spin-space, isospin-space and real-space, and coupling among them
- influenced by many-body correlations (deformation and superfluidity)



Nuclear response: appearance of modes of excitation





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

Nuclear response: appearance of modes of excitation

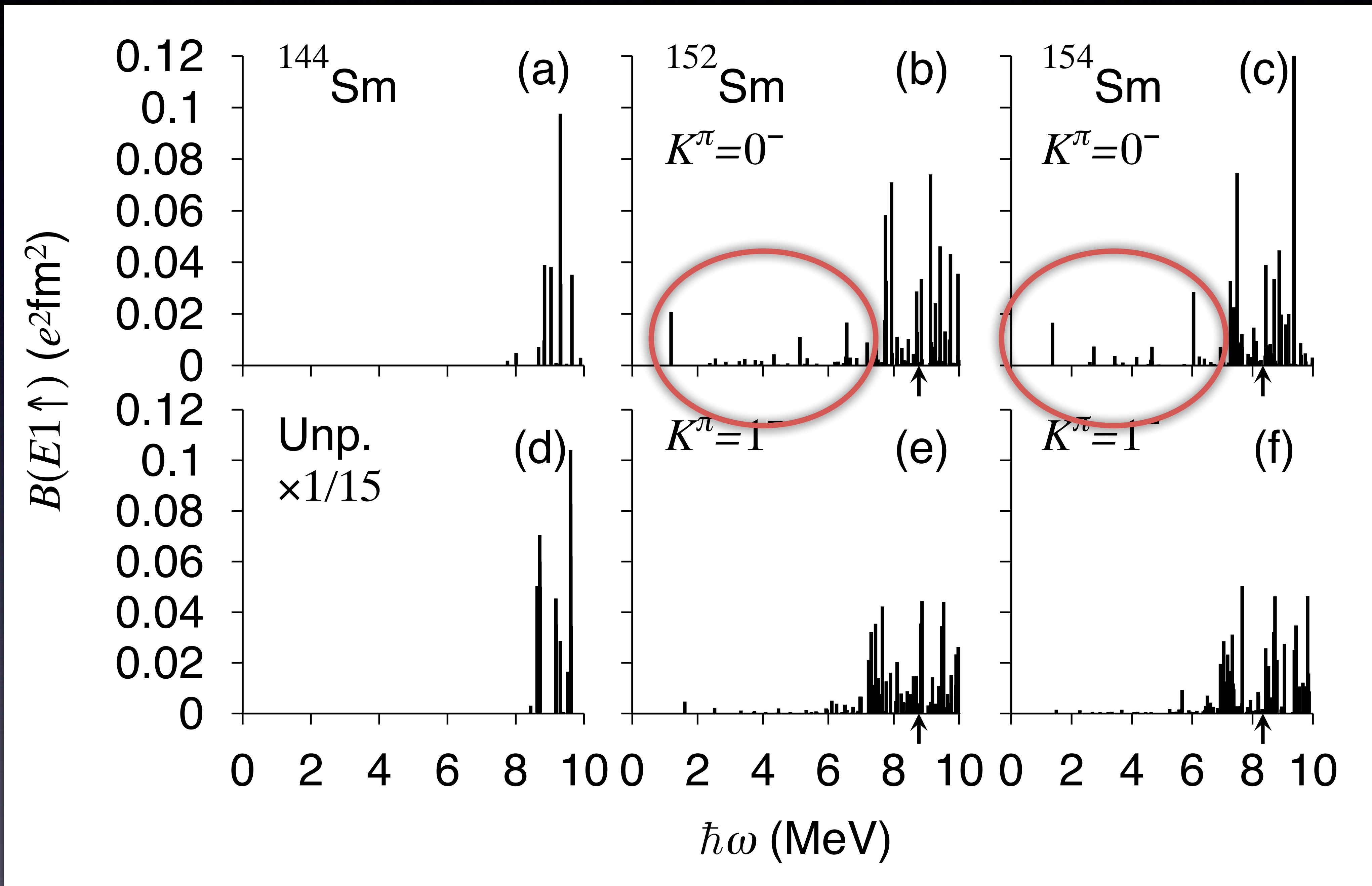
rich variety of modes: *S* (spin), *T* (isospin), and *L* (angular mom.)

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

influenced by many-body correlations (deformation and superfluidity)

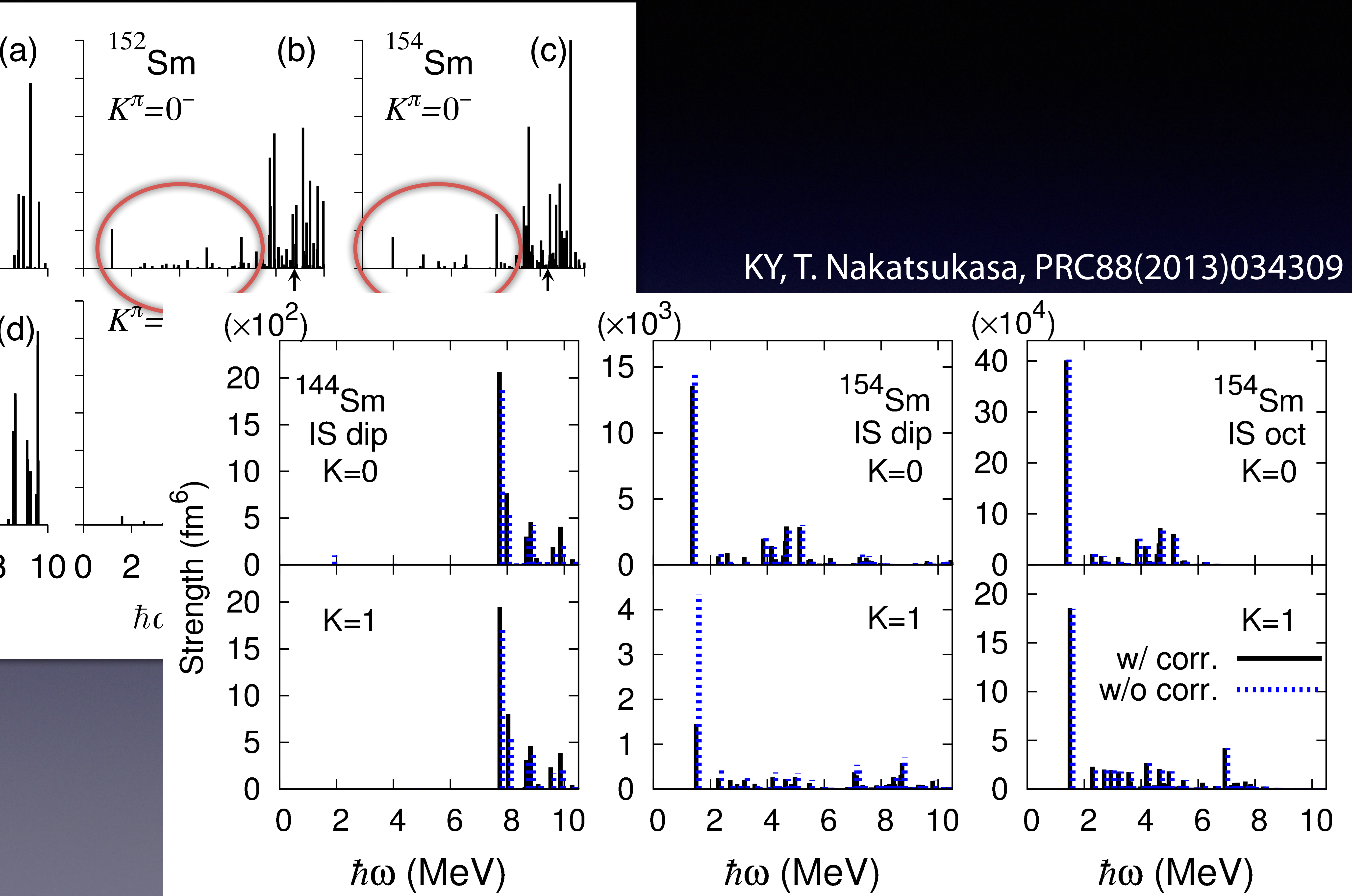
occurrence of low-lying states associated with new physics

Nuclear response: appearance of modes of excitation



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

Nuclear response: appearance of modes of excitation

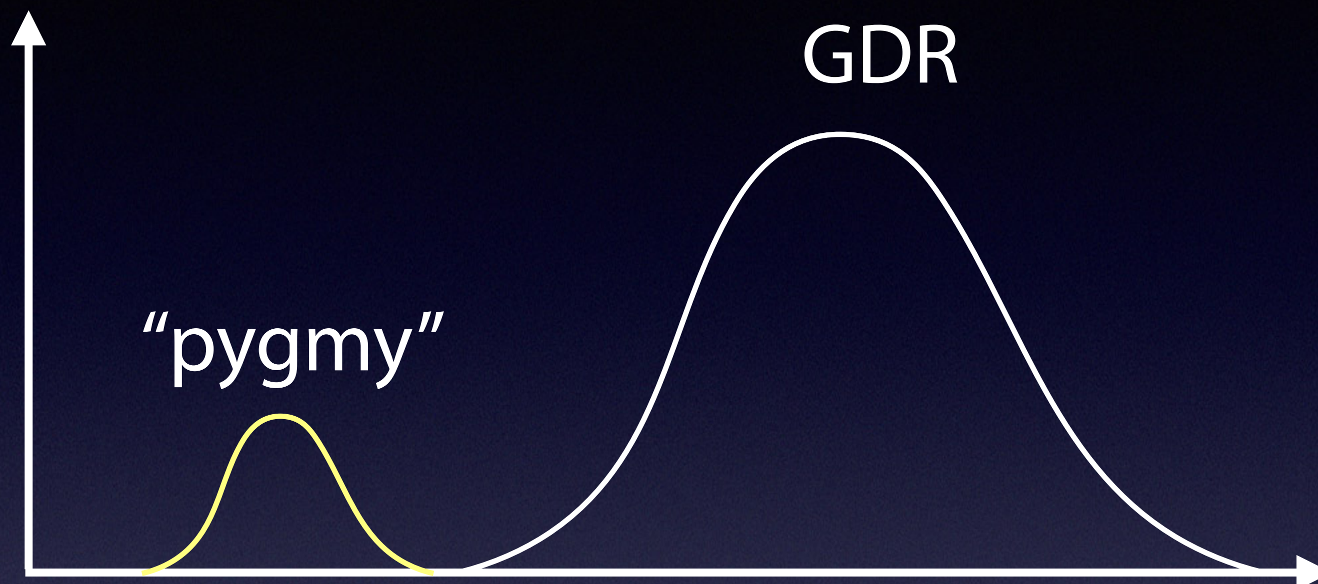


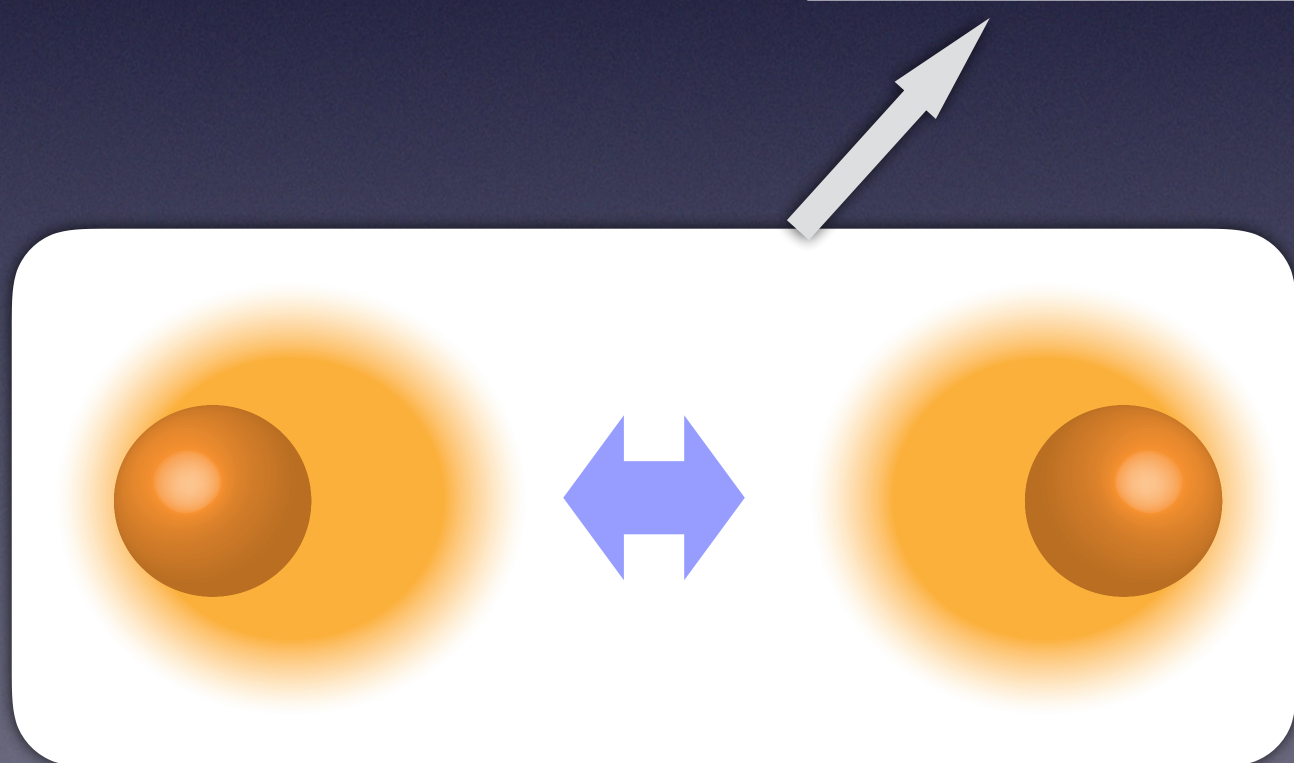
KY, T. Nakatsukasa, PRC88(2013)034309

Unique modes of excitation in neutron-rich nuclei

neutron-skin structure

a new degree of freedom





neutron-skin excitation modes ??

For a review: N. Paar *et al.*, Rep. Prog. Rev. 70 (2007) 691

Mysterious PDR

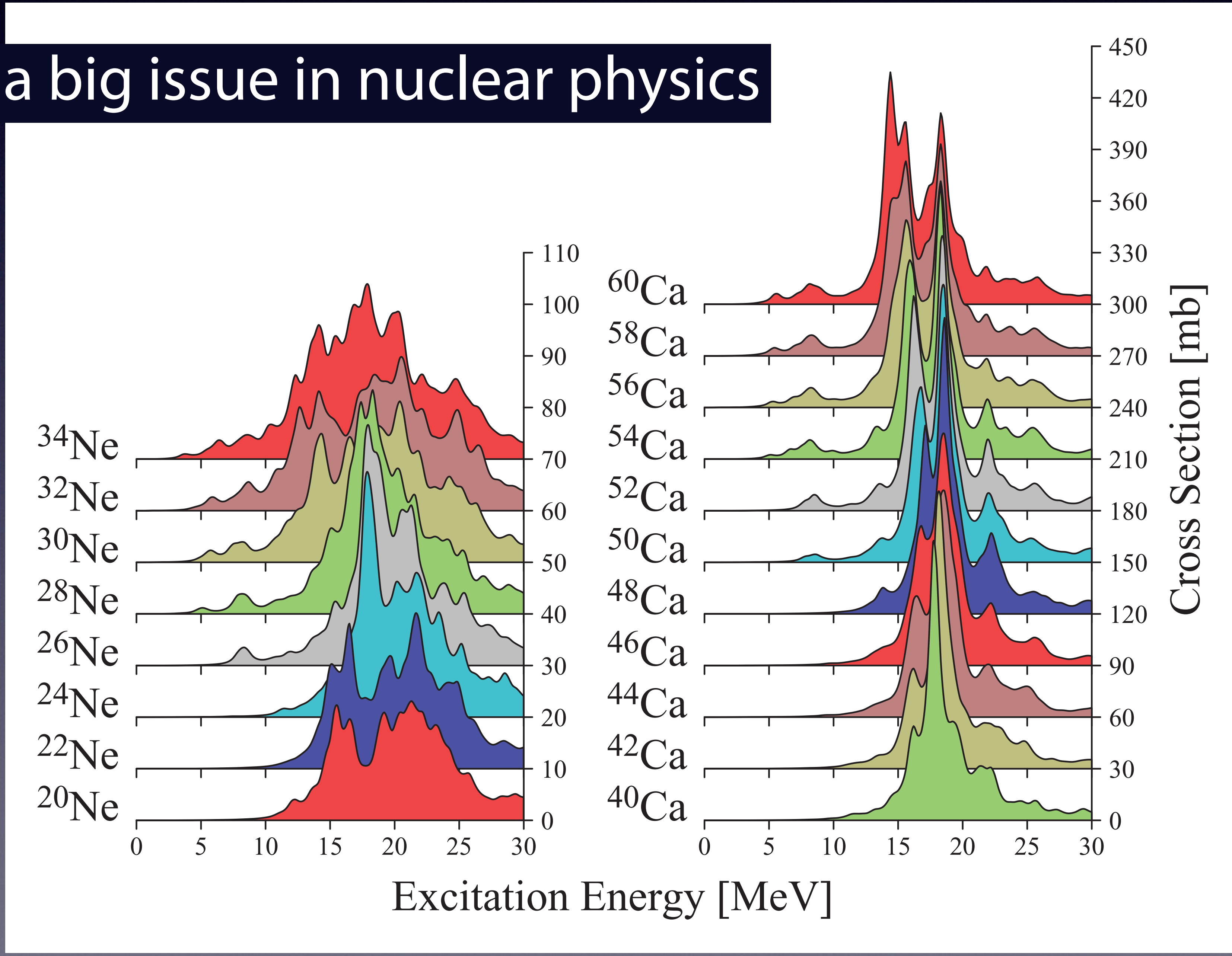
Theoretical calculations predict

- PDR appears in neutron-rich nuclei systematically
- Its collectivity depends on the nucleus, and the model employed

Unravelling the structure is a big issue in nuclear physics

- isospin structure
- vortical nature
- …

Different probes needed



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

IV dipole excitations in neutron-rich nuclei

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

analog of pygmy dipole mode??

- understanding of PDR in terms of iso-triplet states
- isospin character of PDR
- general mechanism for emergence of the PDR

any other types of excitation mode??

IV dipole excitations in neutron-rich nuclei

systematic calculation based on nuclear DFT

fully-selfconsistent calculation

Skyrme-HFB + proton-neutron QRPA

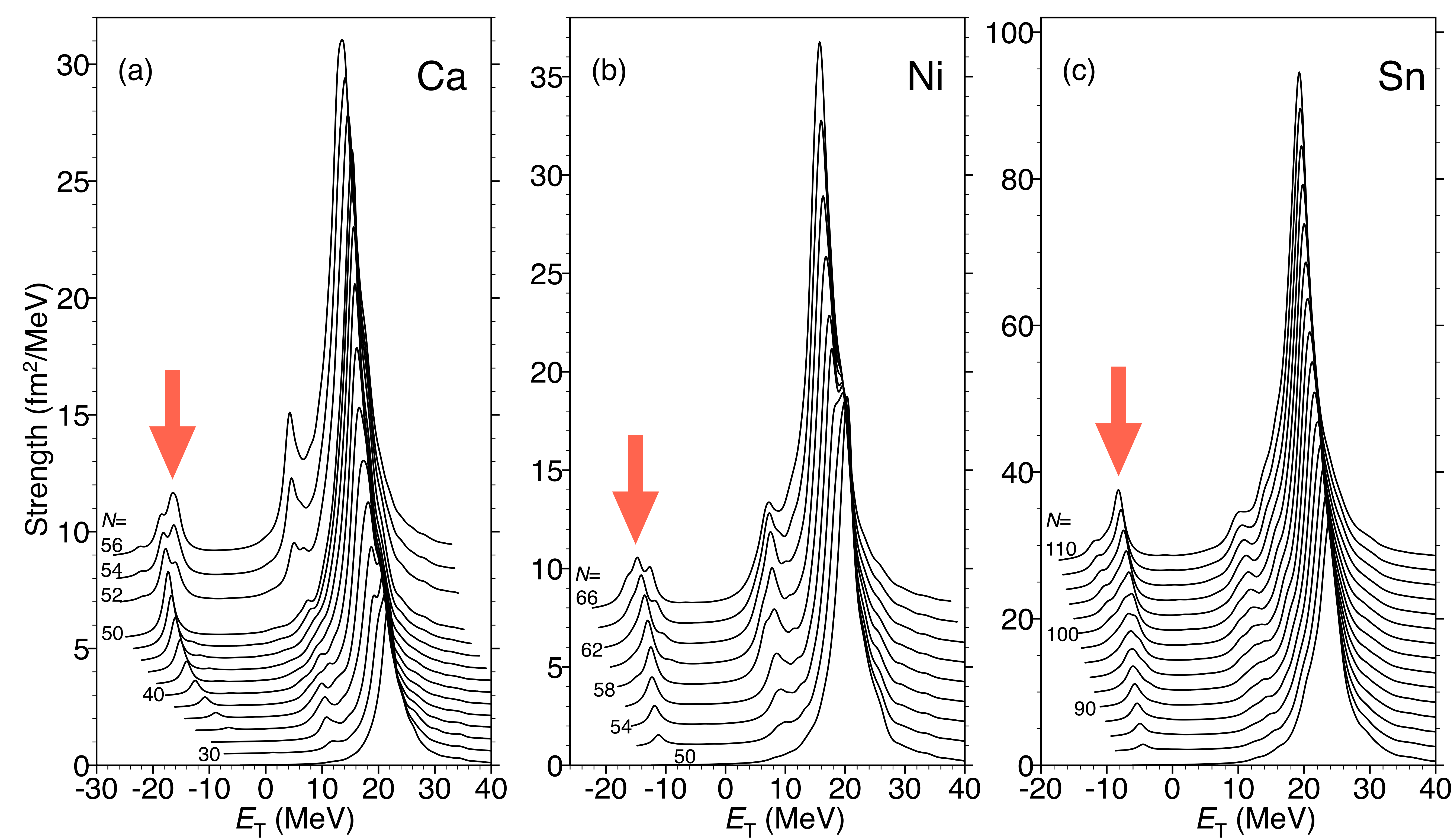
Ca: $N = 28\text{-}56$
Ni: $N = 50\text{-}66$
Sn: $N = 82\text{-}110$

spherical systems for simplicity

cf. T=0 pairing does not affect the following discussions

IV dipole strength distributions ($\tau = -1$)

KY, PRC96(2017)051302R
SkM*, Γ=2.0 MeV



Mechanism for occurrence of the low-lying states

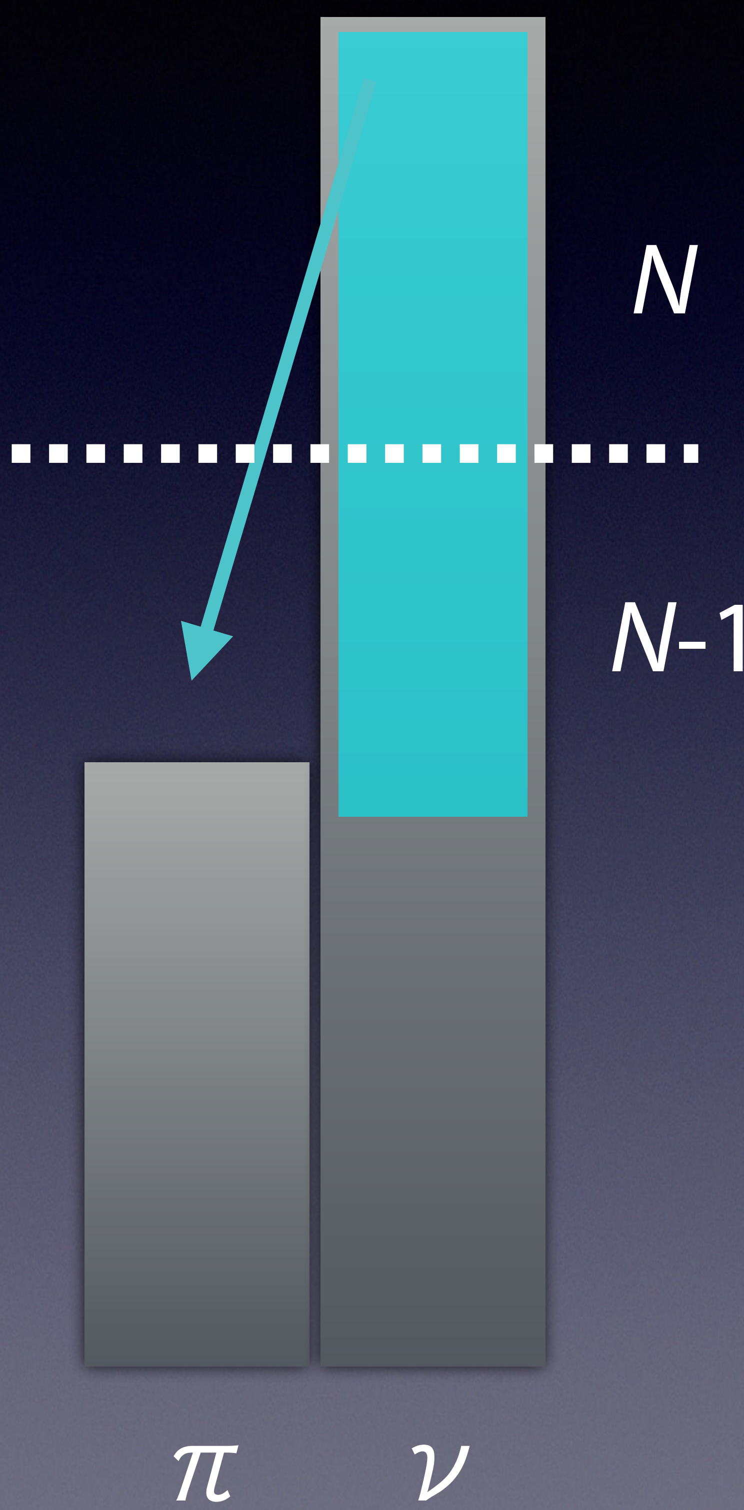
cross-shell ($N \rightarrow N$-1) excitation in low-energy

$-1\hbar\omega$ excitation

neutrons are weakly bound/
(quasi)neutrons are in the continuum when $|\lambda| \simeq 0$

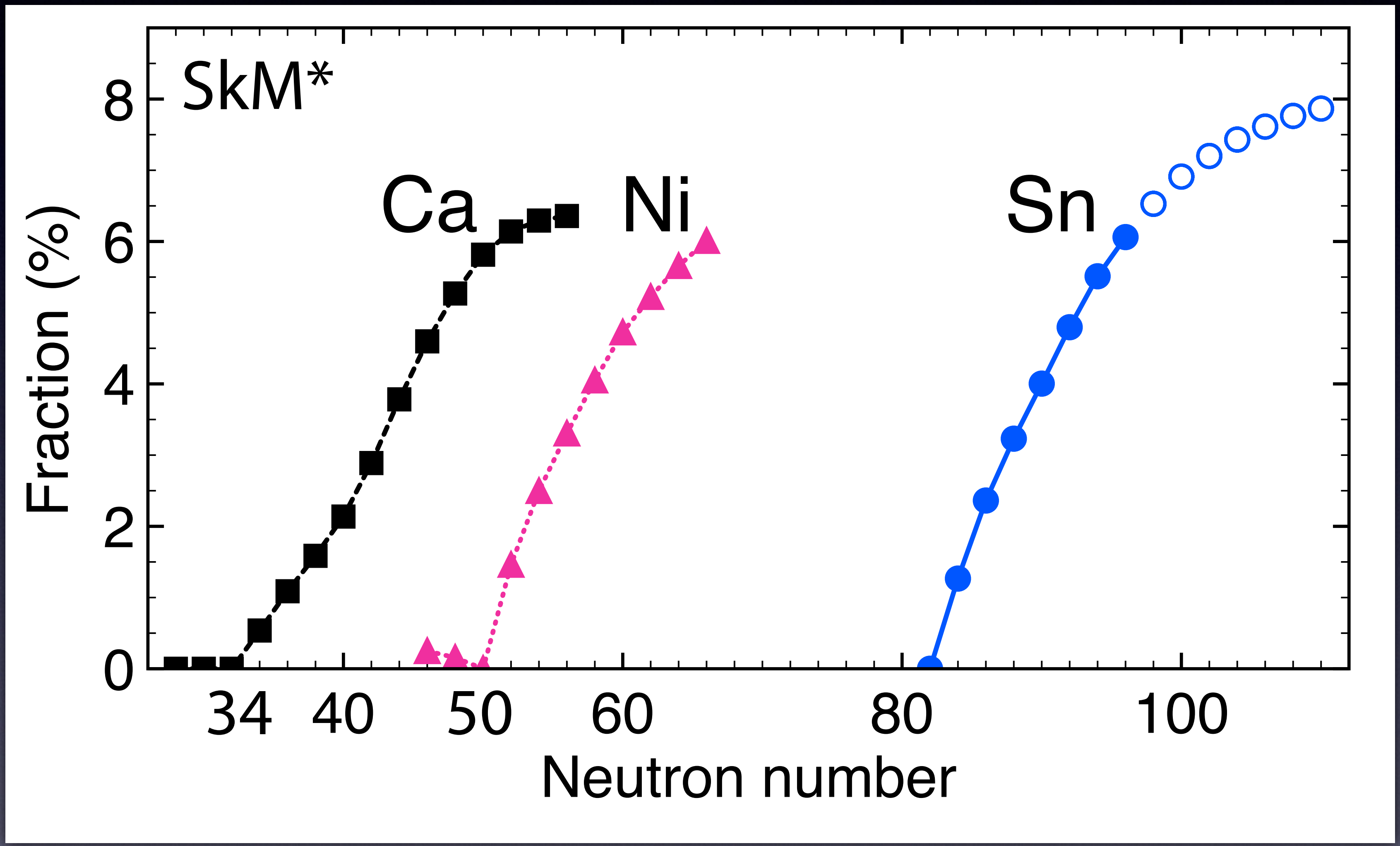
↓

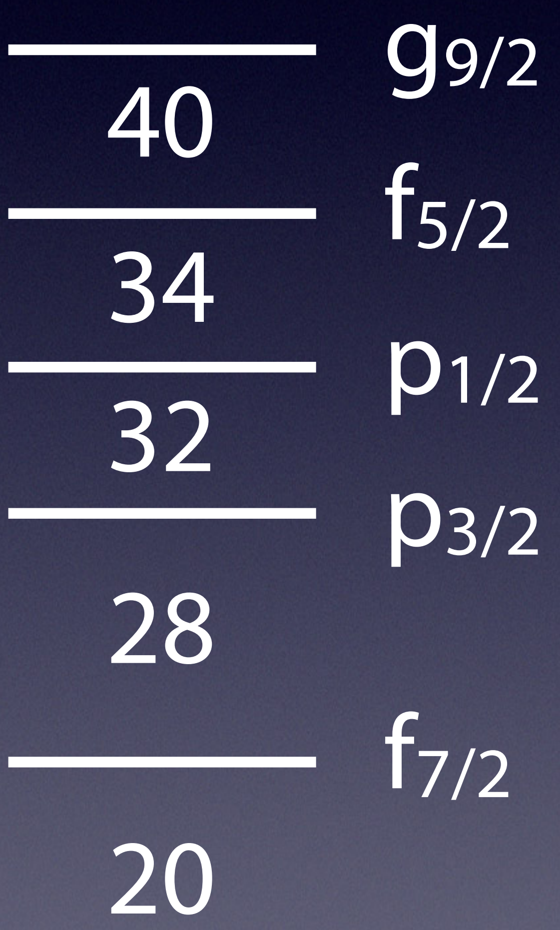
protons are deeply bound



Onset of the low-lying states: strong shell effect

summed strength in low-energy (ω < 15 MeV, E_T<0 MeV)



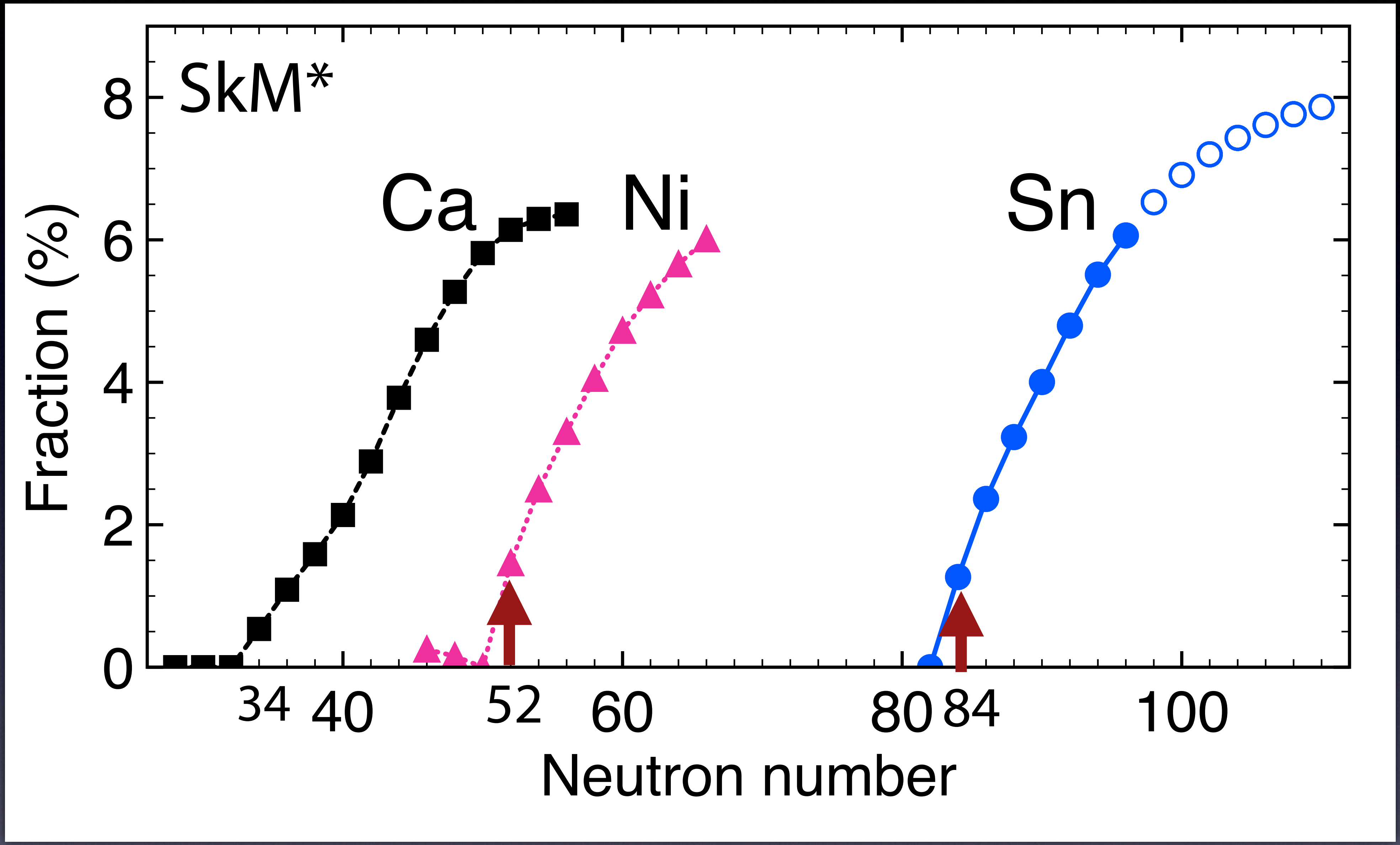


$\nu g_{9/2} \rightarrow \pi f_{7/2}$

due to neutron pairing

gradual development

Onset of the low-lying states: strong shell effect



occupation of $2d_{5/2}$

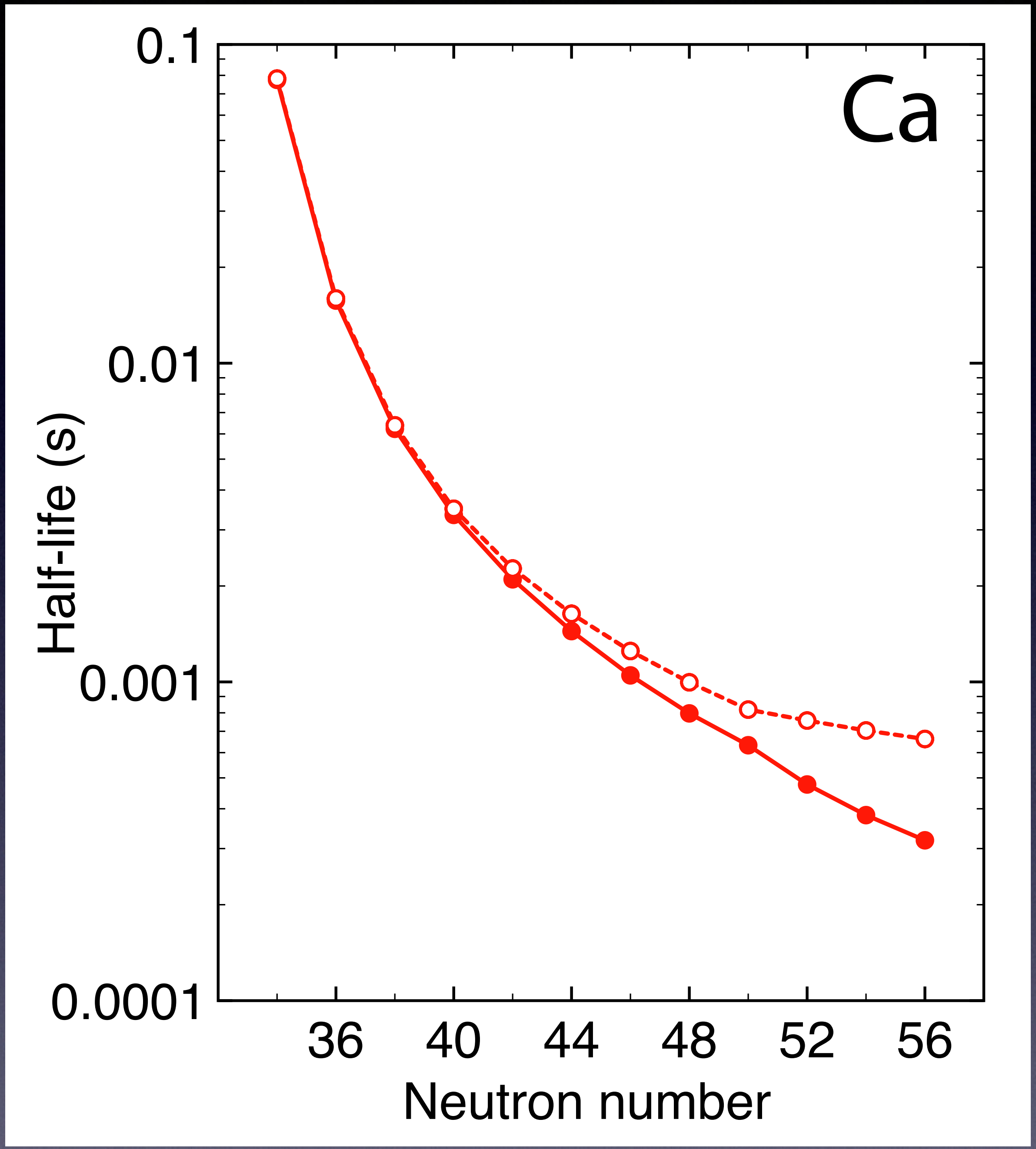
$\nu d_{5/2} \rightarrow \pi p_{3/2}$

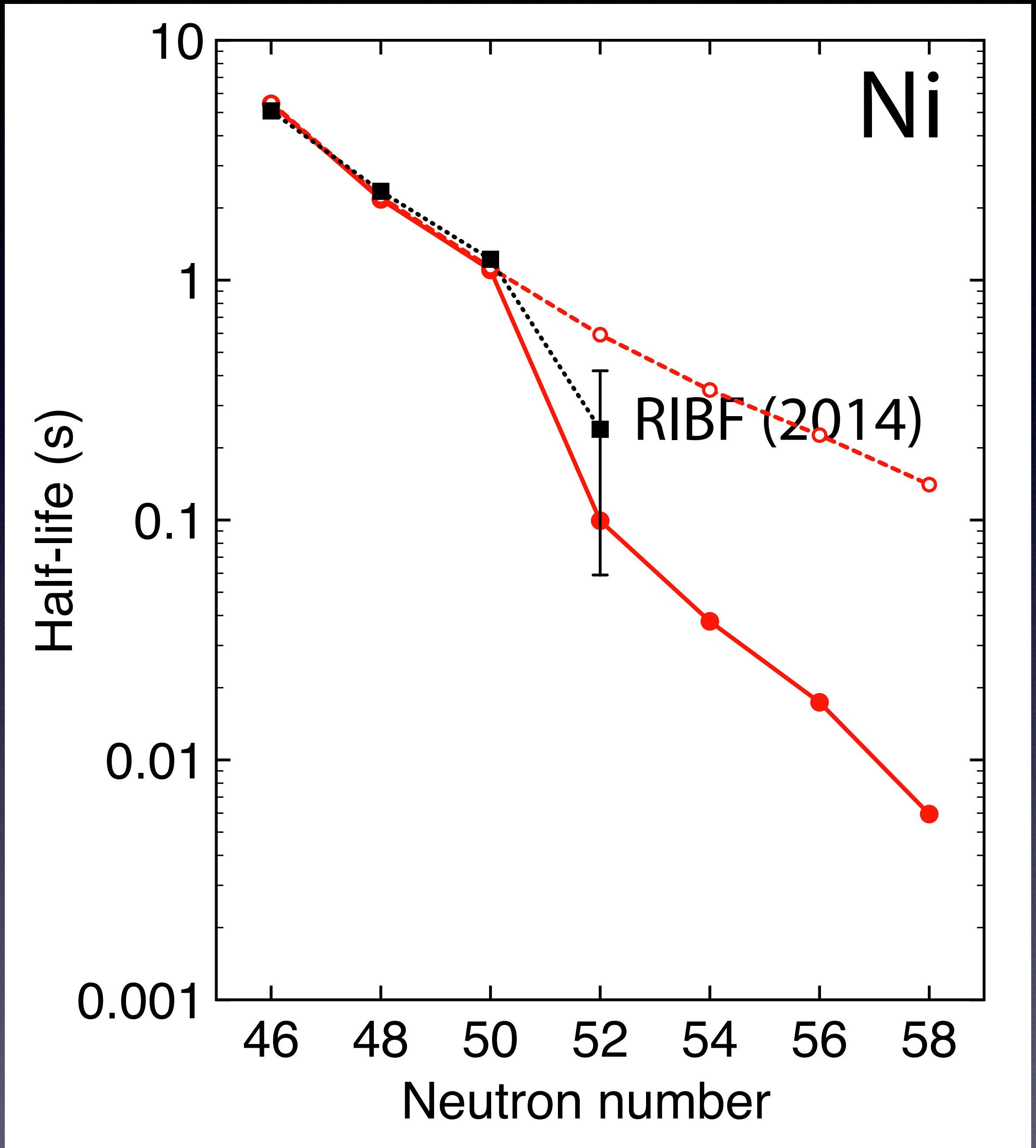
occupation of $2f_{7/2}$

$\nu f_{7/2} \rightarrow \pi d_{5/2}$

Effect of the low-lying dipole states on β-decay rate

Allowed + FF transitions





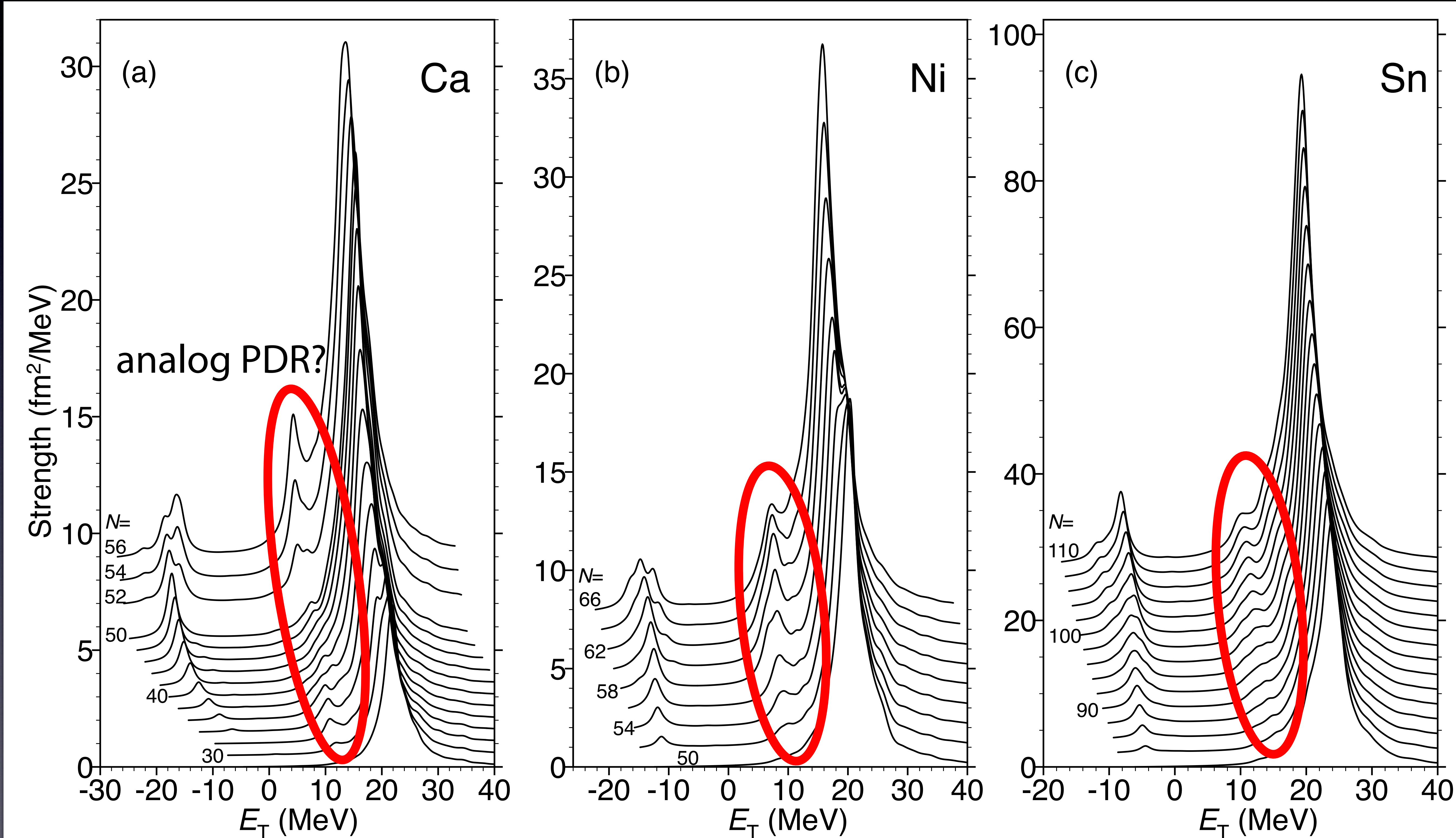
gradually dominating

suddenly dominating

at N>50

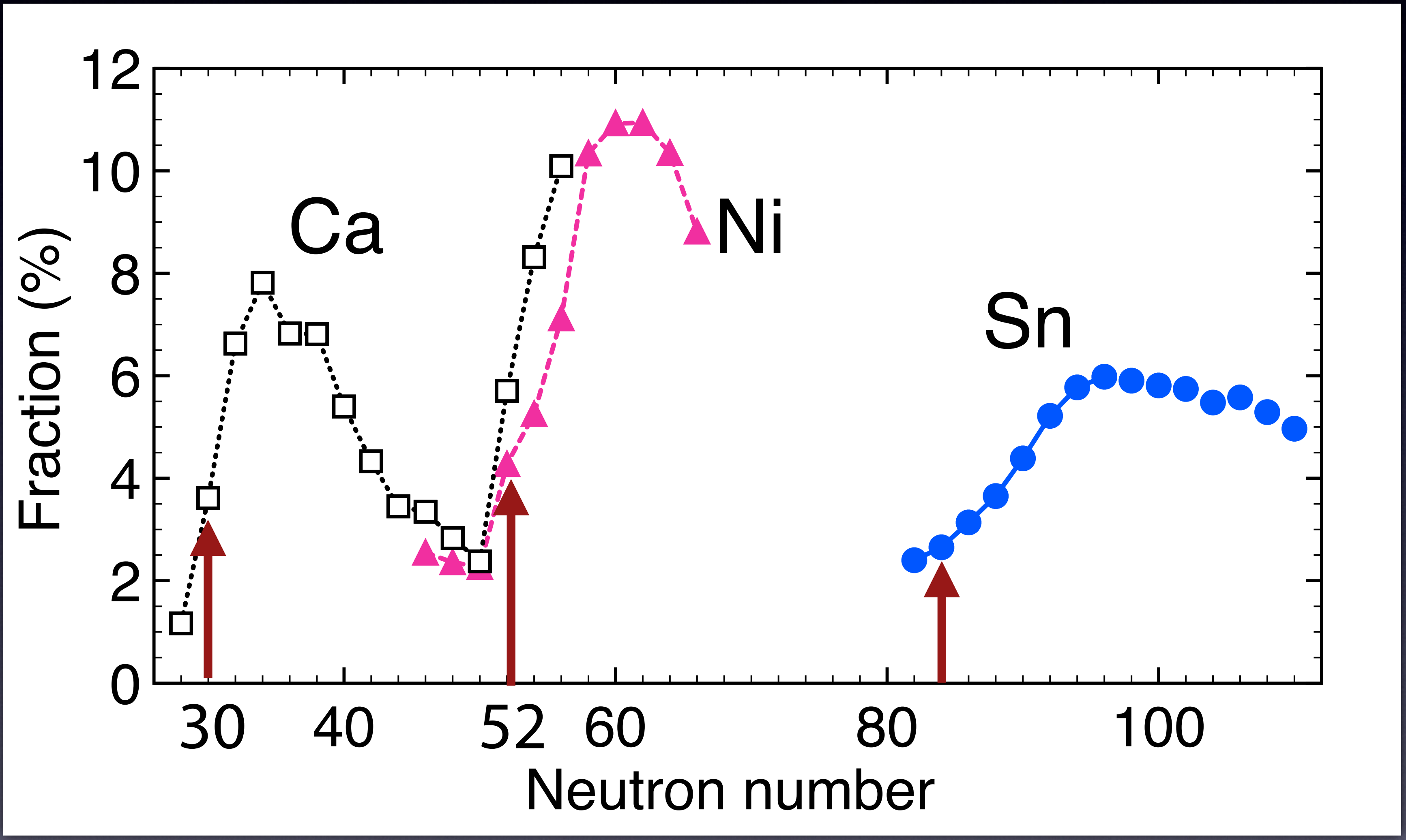
IV dipole strength distributions ($\tau = -1$)

KY, PRC96(2017)051302R
SkM*, Γ=2.0 MeV



Appearance of the analog PDR

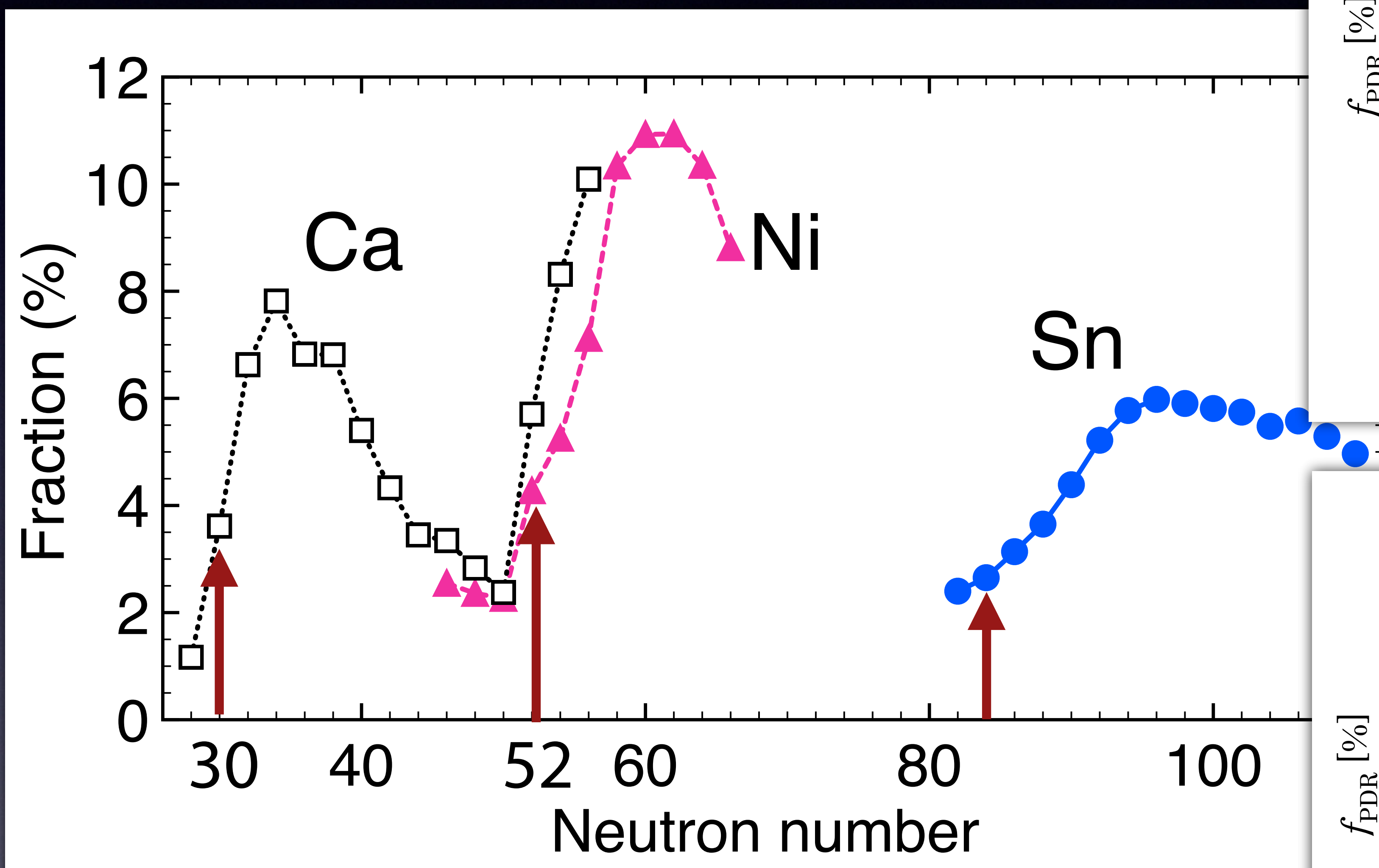
summed strength below the GR
excluding $-1\hbar\omega$ type states

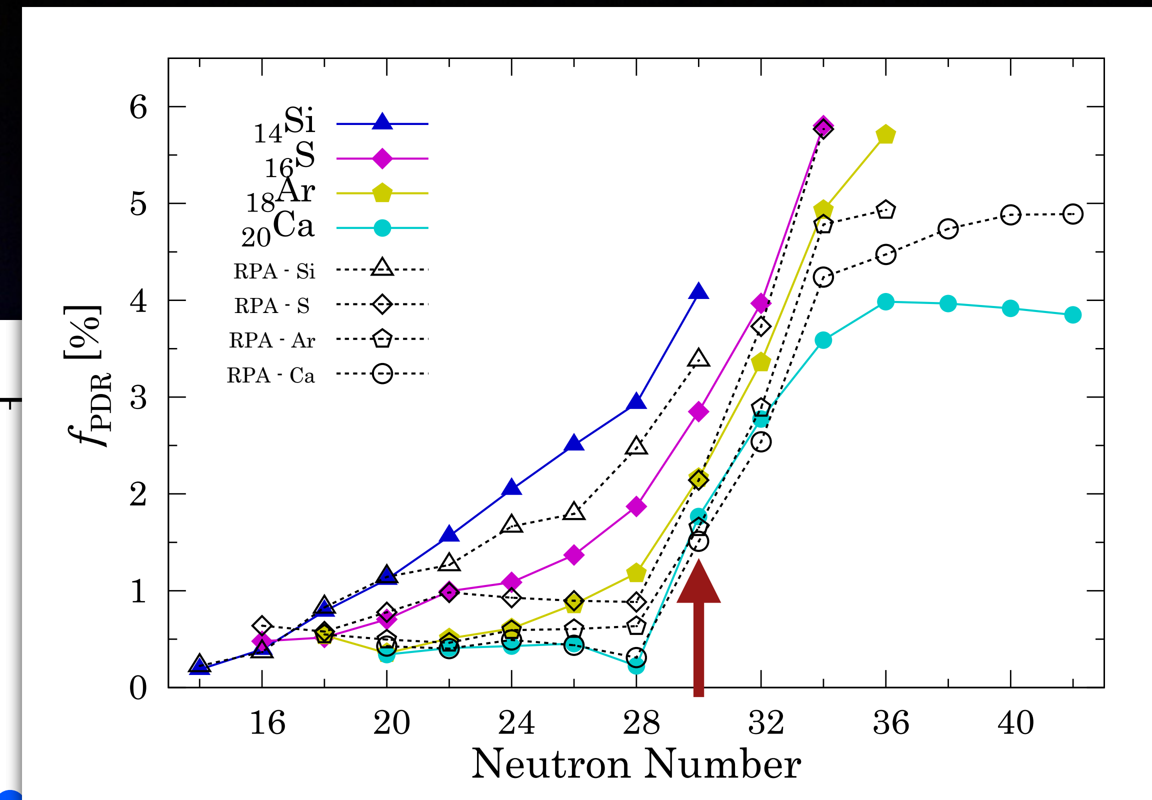


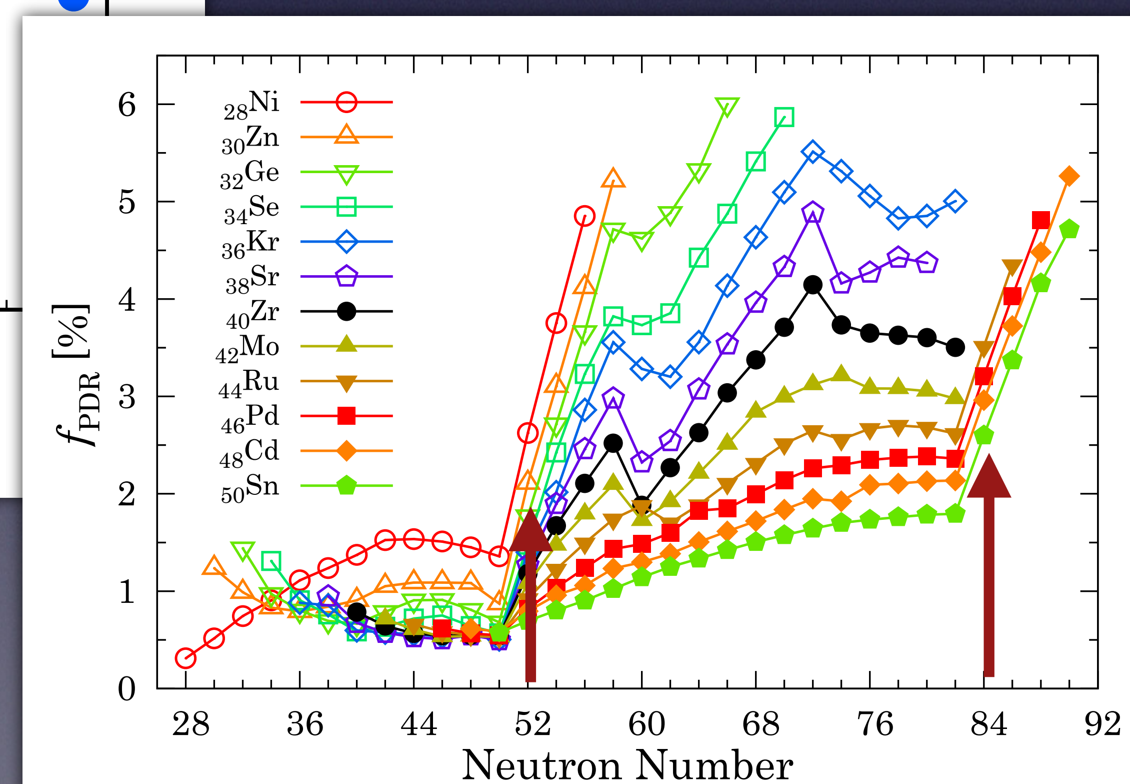
occupation of weakly-bound $p_{3/2}$ (N>28), $d_{5/2}$(N>50), and $f_{7/2}$ and $f_{5/2}$ (N>82)

Appearance of the analog PDR

summed strength below the GR
excluding $-1\hbar\omega$ type states



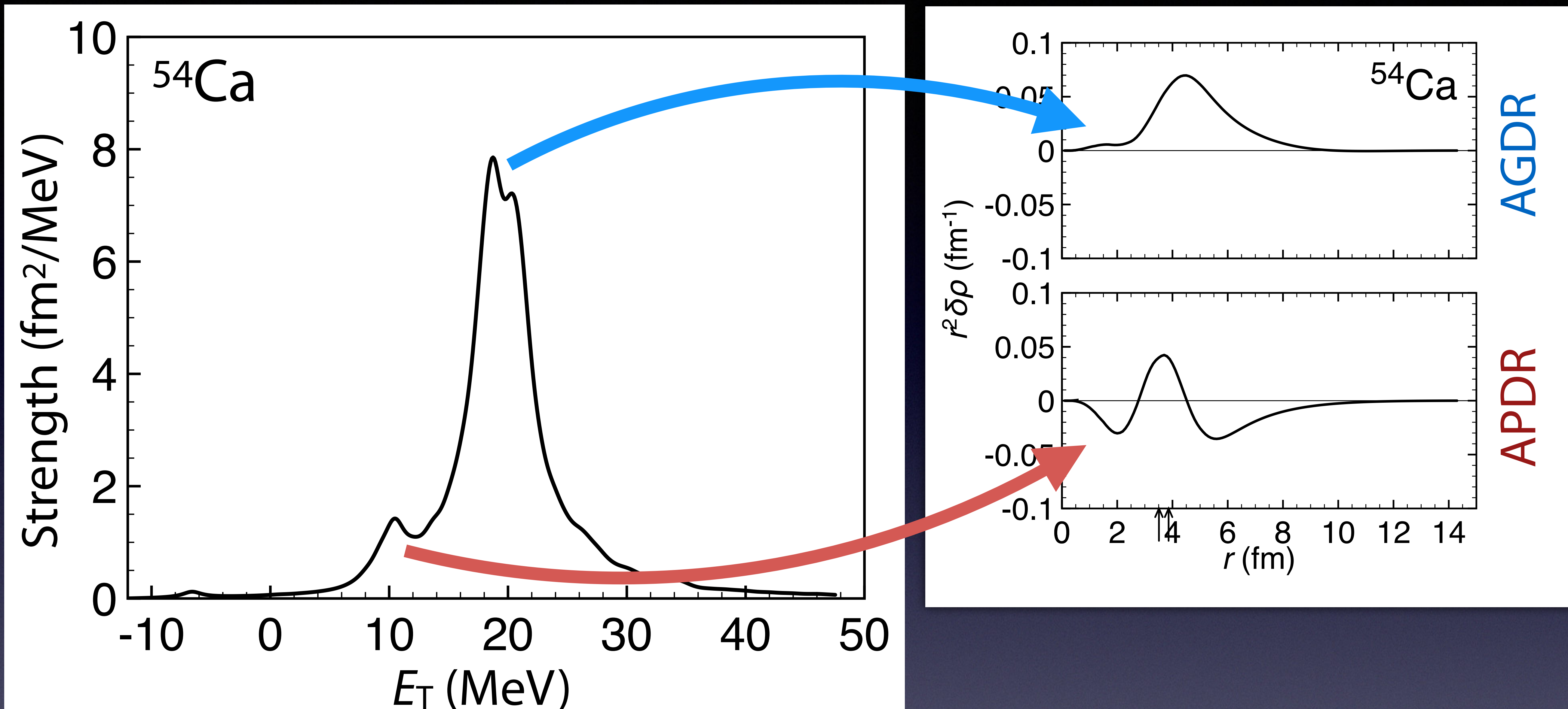




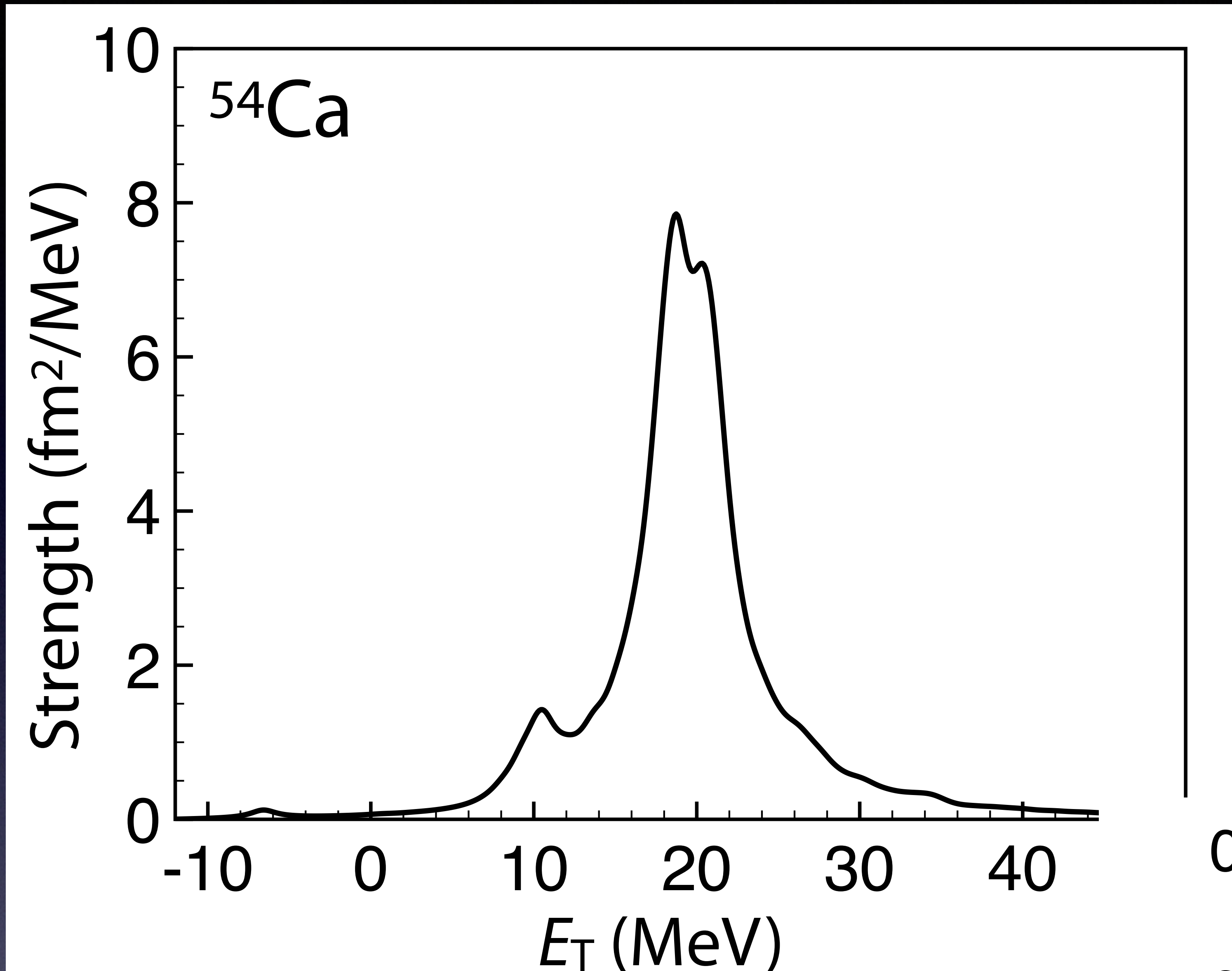
occupation of weakly-bound $p_{3/2}$ (N>28), $d_{5/2}$(N>50), and $f_{7/2}$ and $f_{5/2}$ (N>82)

S. Ebata et al., PRC90(2014)024303

Microscopic structure of the analog PDR

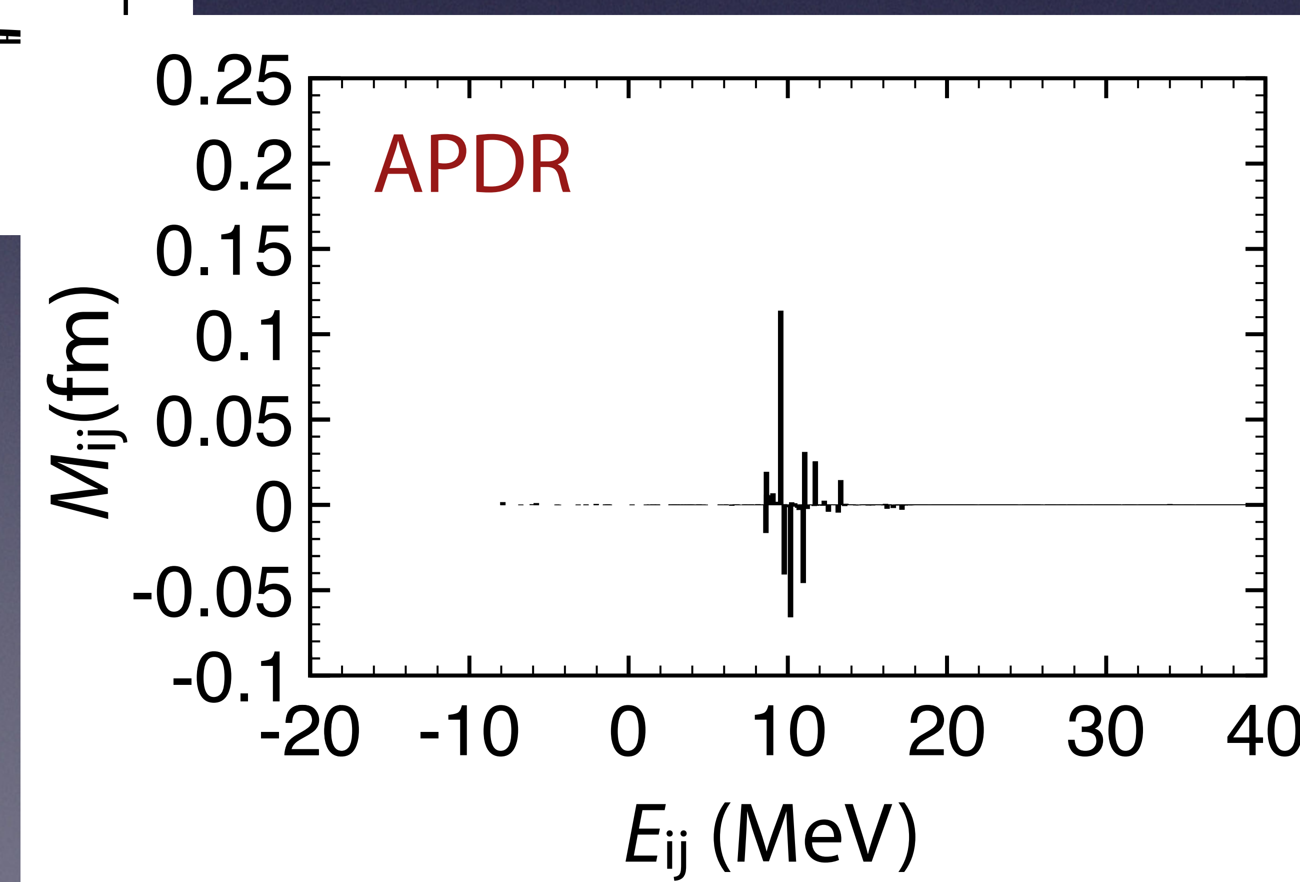


Microscopic structure of the analog PDR



strength= $|\langle\lambda|\hat{F}|0\rangle|^2$

$$\langle\lambda|\hat{F}|0\rangle = \sum_{ij}(X_{ij}+Y_{ij})F_{ij} = \sum_{ij} M_{ij}$$



NOT a single-particle excitation

superposition of 2qp excitations
~10

NOT coherent for a dipole operator

Occurrence of the CE dipole states in n-rich nuclei

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

neutrons are weakly bound

↓

protons are deeply bound:

low-lying $-1\hbar\omega$ excitation

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

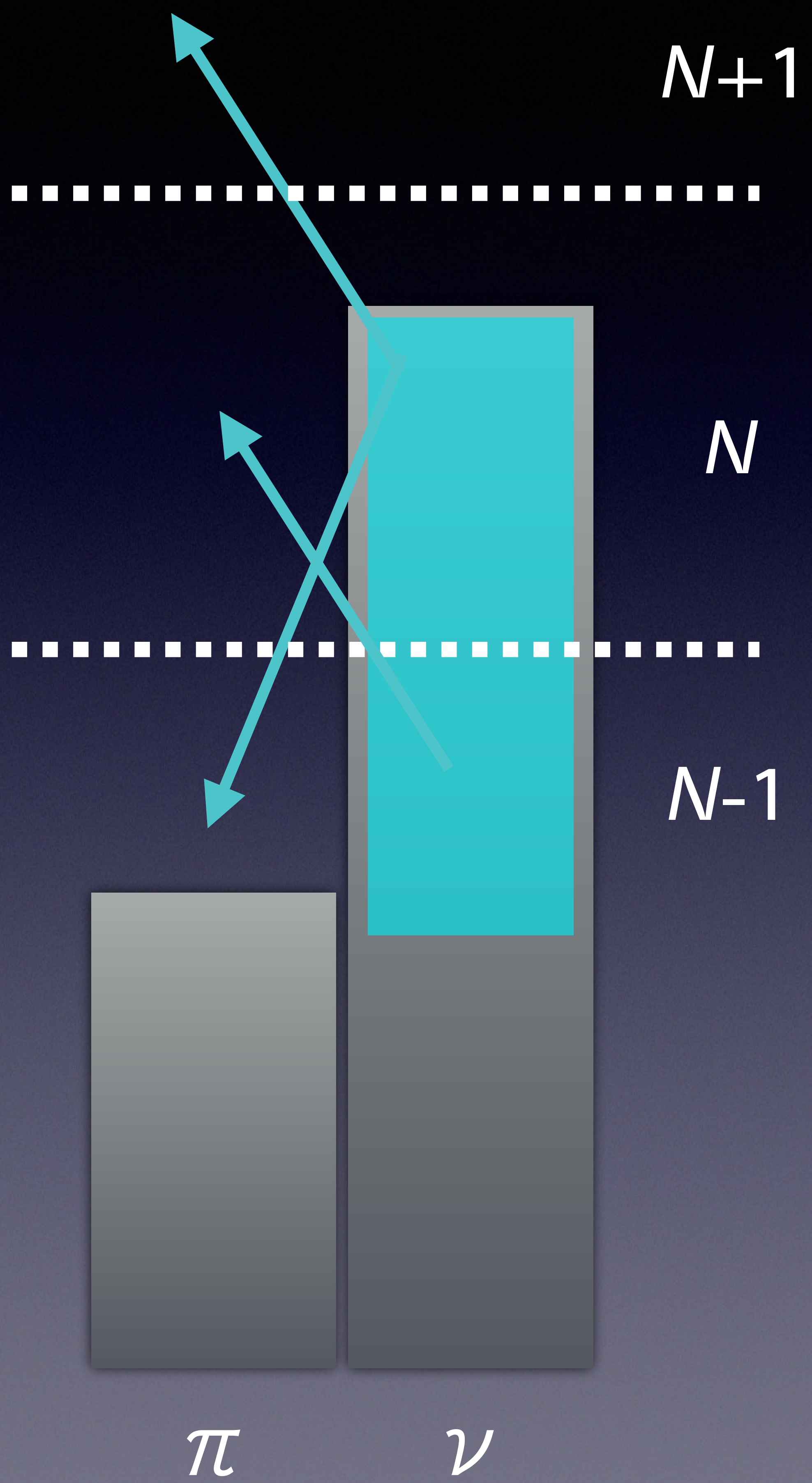
protons are in the continuum:

giant and pygmy resonances

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

deeply-bound neutrons:

giant resonance



Summary

✓low-lying dipole state appears uniquely in very n-rich nuclei

$-1\hbar\omega$ excitation

✓strong shell effect

steady selection rule due to the deeply-bound proton orbitals
single-particle type excitation

# of neutron hole states satisfying the selection rule is limited

✓affects the half-life substantially

together with the axial-vector (spin-flip) dipole excitations

✓emergence of analog PDR below the giant resonance peak

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

✓destructive for a dipole operator, while several 2qp excitations are involved