Shell-model study of strength function in the *sd-pf* shell region

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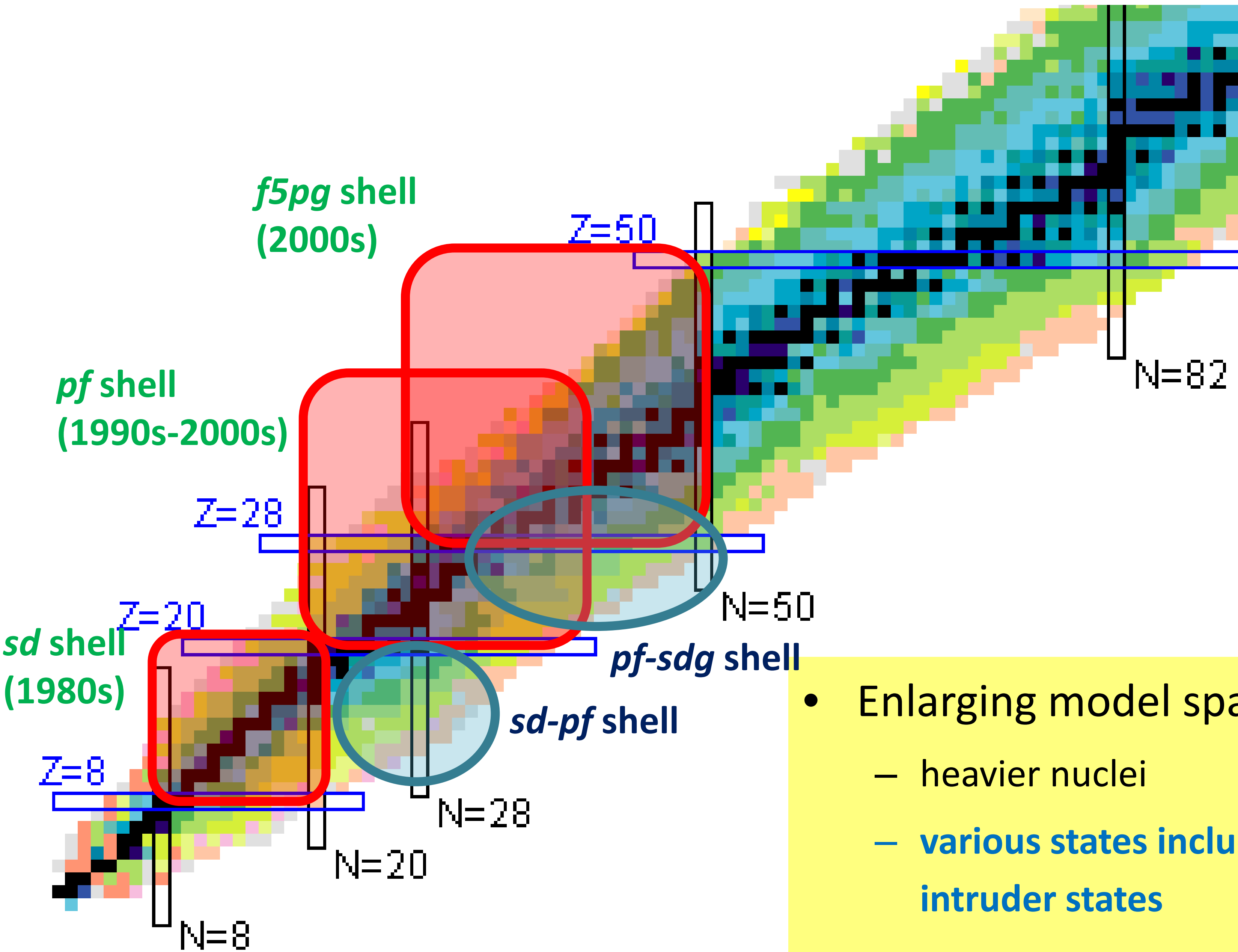
Frontier of large-scale shell-model calculations

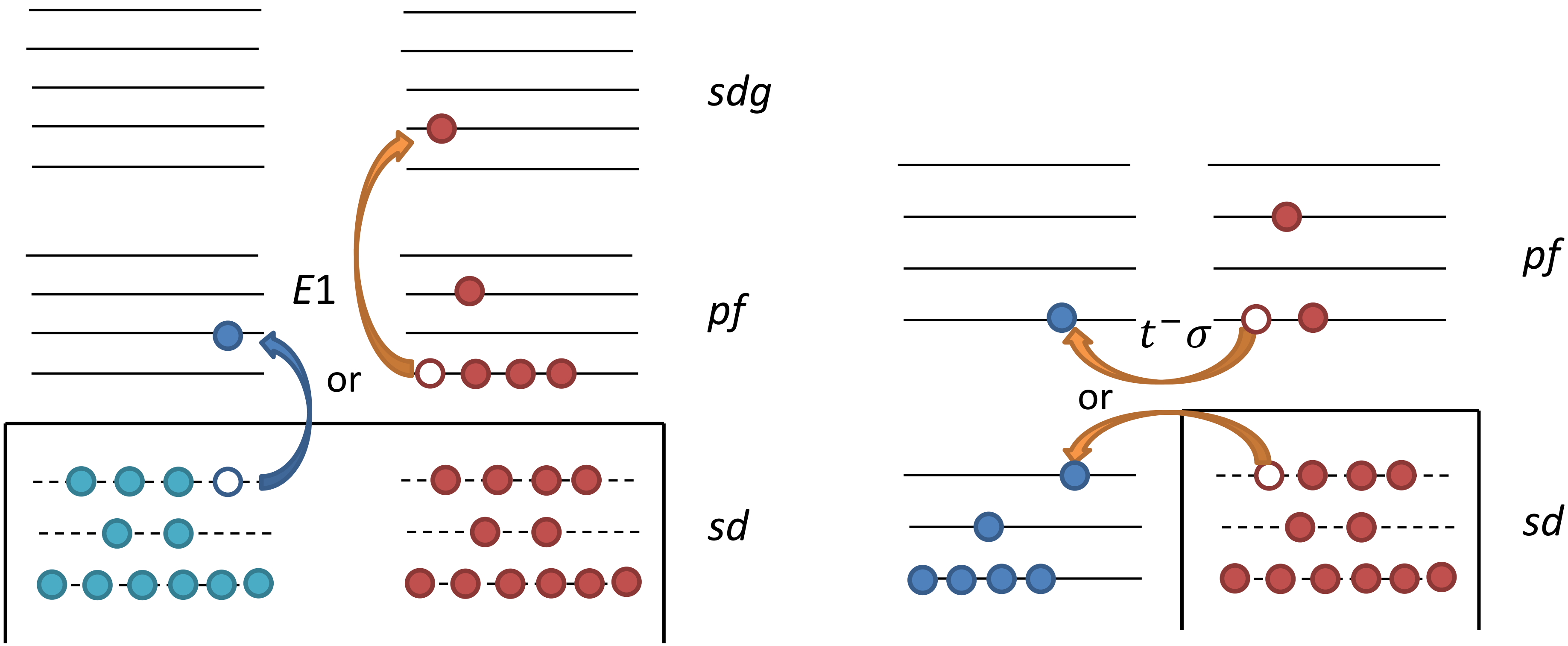


- Enlarging model space
  - heavier nuclei
  - various states including intruder states

Objectives of this study

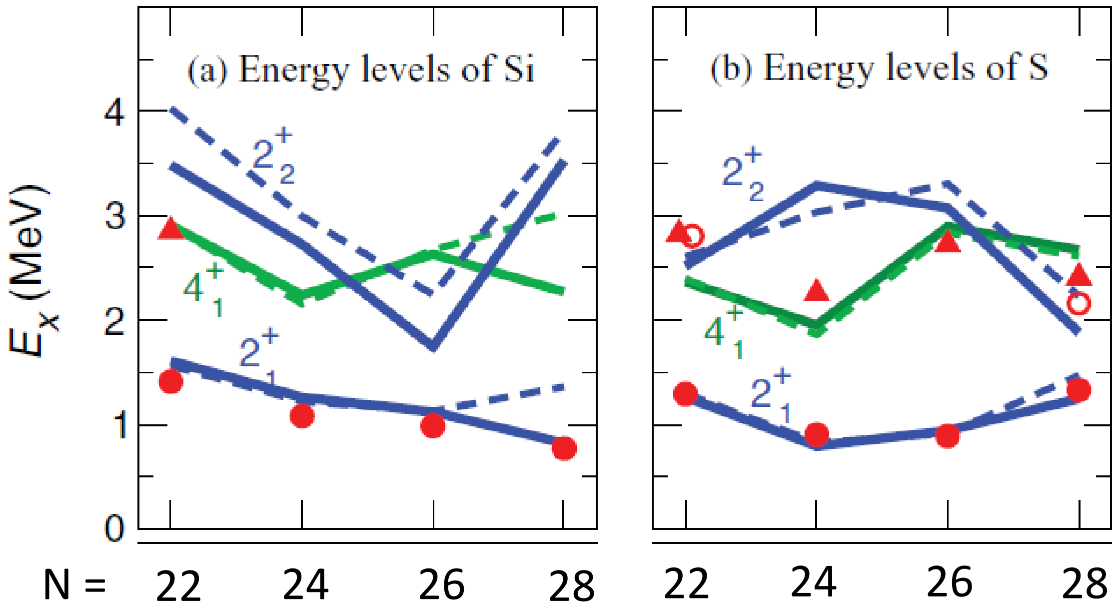
- Unnatural-parity states and strength function in the *sd*-*pf* shell
  - More than one major shell are required.

1. Systematics of unnatural-parity states and *E*1 strength function in Ca isotopes
2. Gamow-Teller strength function of neutron-rich nuclei



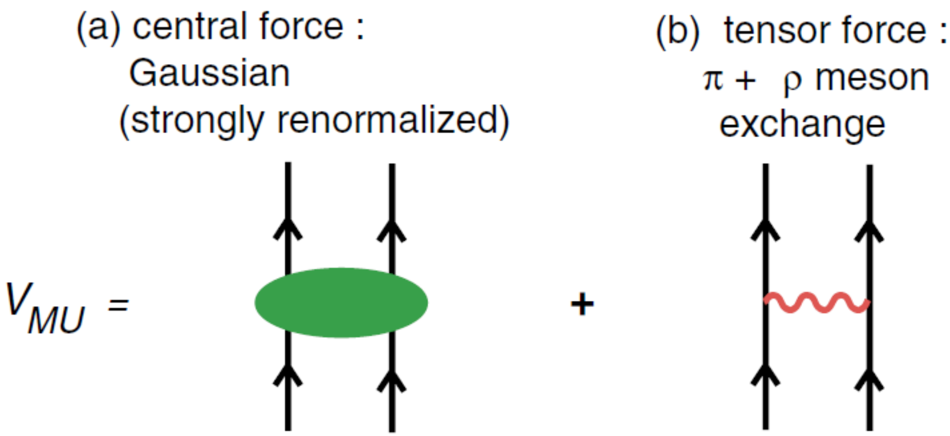
Model space and effective interaction

- Model space
  - Full *sd-pf-sdg* shell for E1 calc. or Full *sd-pf* shell for GT calc.
  - $1\hbar\omega$ [or $(1+3)\hbar\omega$] calculation in the given model space
- Effective interaction
  - SDPF-MU for the *sd-pf* shell or its natural extension to the *sd-pf-sdg* shell:
    - USD (*sd*) + GXPF1B (*pf*) + the refined V_{MU} for the remaining



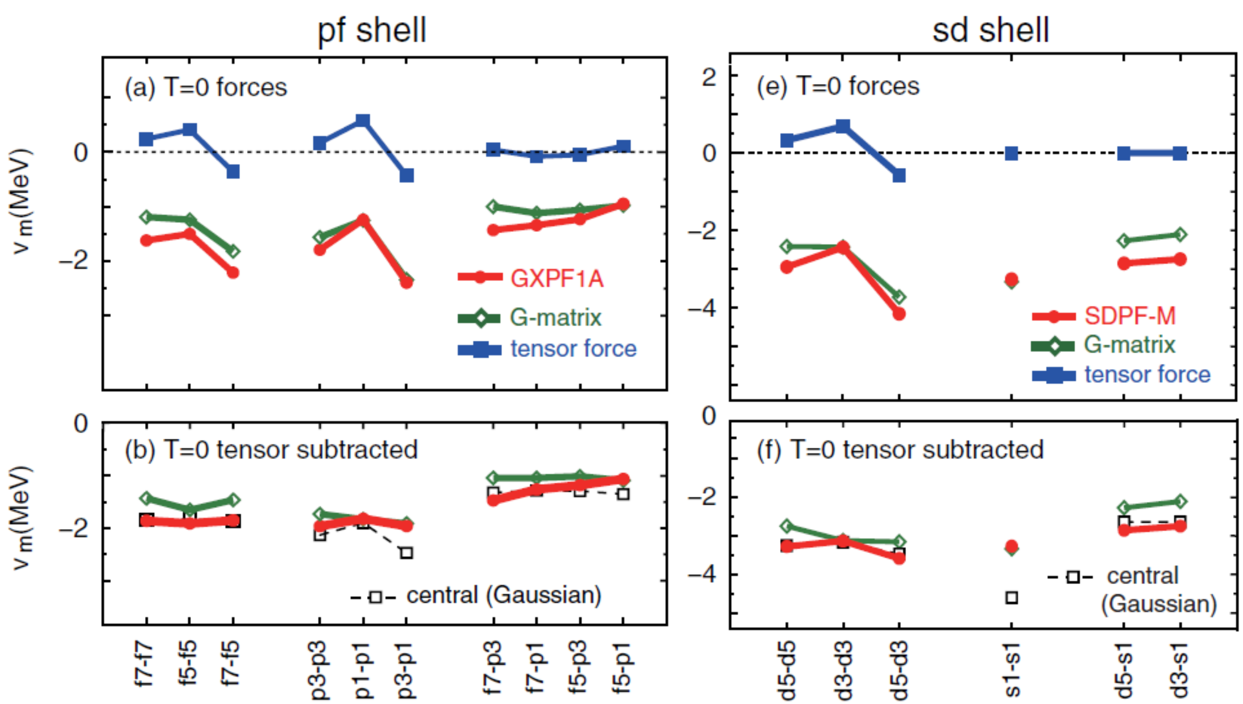
Y. Utsuno et al., Phys. Rev. C 86, 051301(R) (2012).
Y. Utsuno et al., Phys. Rev. Lett. 114, 032501 (2015).

Monopole-based universal interaction V_{MU}



T. Otsuka et al., Phys. Rev. Lett. 104, 012501 (2010).

- Bare tensor
  - Renormalization persistency
- Phenomenological Gaussian central
  - Supported by empirical interactions

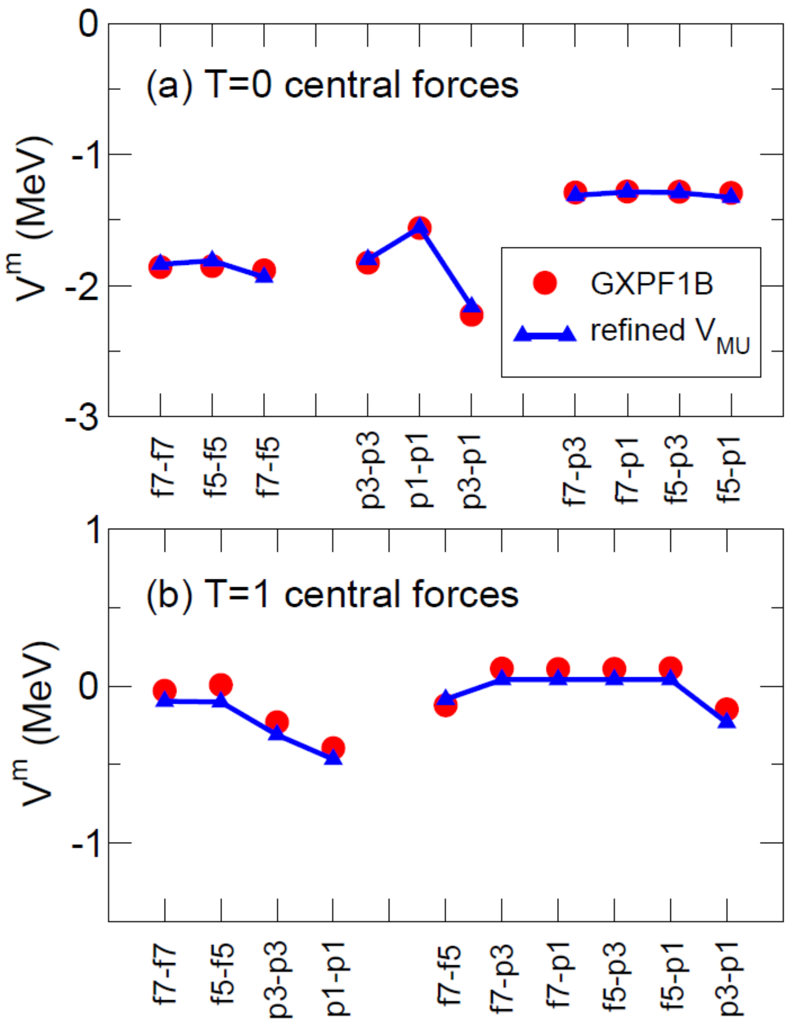


Refined V_{MU} for the shell-model

- tensor: π+ρ
- spin-orbit: M3Y
  - Works in some cases
- central: to be close to GXPF1
  - Including "density dependence" to better fit empirical interactions

a good guide for a shell-model interaction without direct fitting to experiment

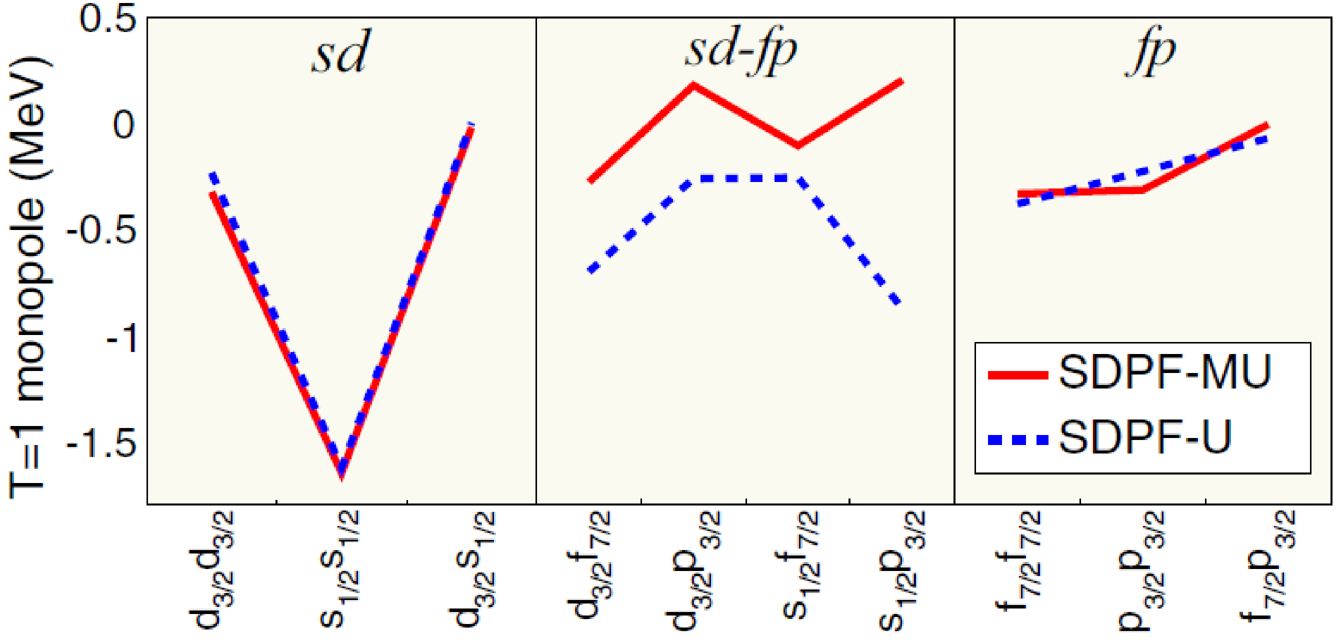
Central force fitted with six parameters



Y. Utsuno et al., EPJ Web of Conferences 66, 02106 (2014).

T=1 monopole: case of *sd-pf* shell

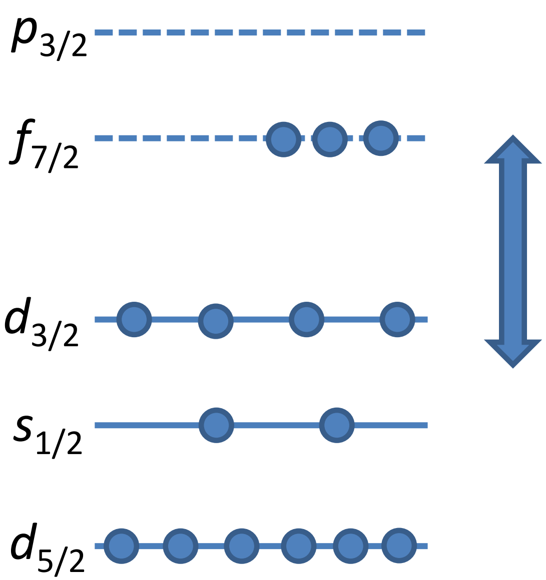
- SDPF-MU interaction based on the refined V_{MU}
  - USD for the *sd* shell and GXPF1B for the *pf* shell
  - Refined V_{MU} for the cross-shell



S. R. Stroberg, A. Gade et al., Phys. Rev. C 91, 041302(R) (2015).

Cross-shell of SDPF-U: two-body G martix

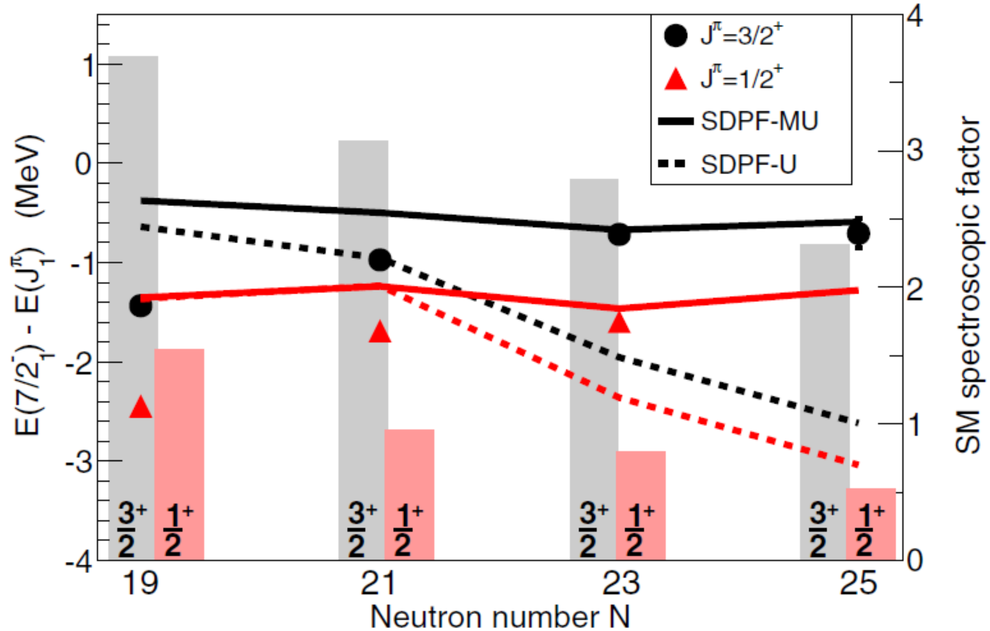
Evolution of unnatural-parity states in Si



The gap changes with increasing neutrons in $f_{7/2}$ depending on the T=1 monopole strength.

Unnatural-parity states are good indicators of the gap.

- A recent experiment at NSCL supports nearly zero value of T=1 cross-shell monopole matrix elements.



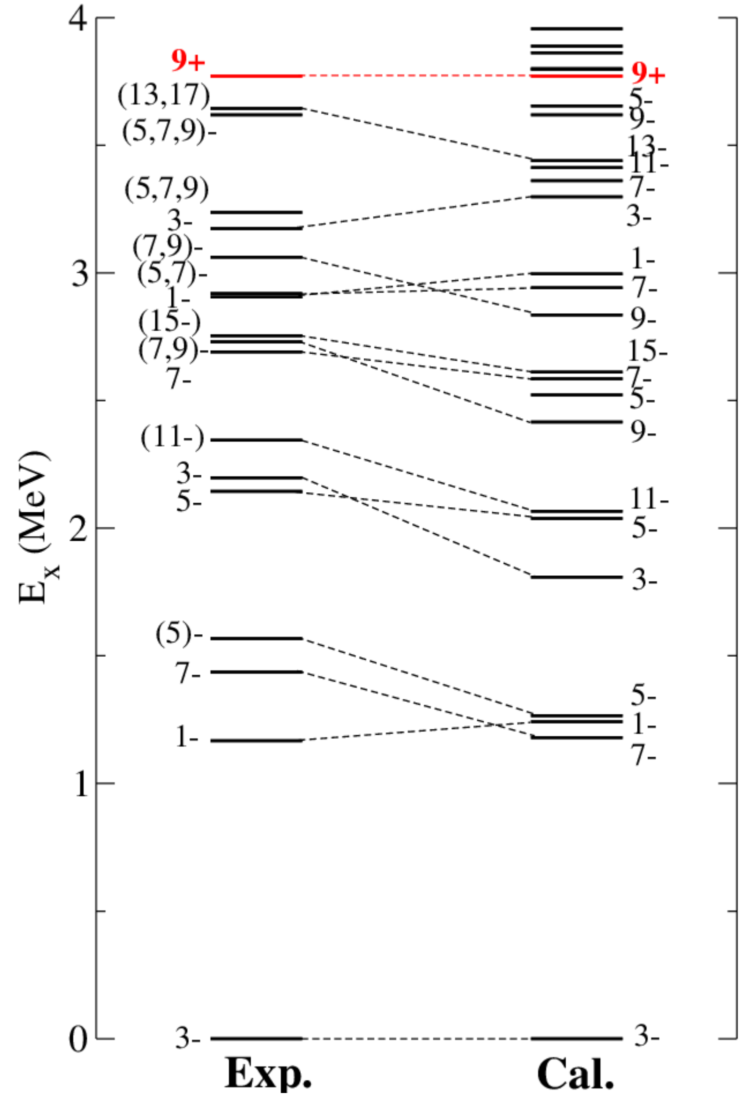
S. R. Stroberg, A. Gade et al., Phys. Rev. C 91, 041302(R) (2015).

Position of $g_{9/2}$ in *n*-rich Ca isotopes

- $g_{9/2}$ orbit in neutron-rich Ca isotopes
  - Plays a crucial role in determining the drip line and the double magicity in ^{60}Ca
  - Unnatural-parity states are examined.
- Determining SPE of *sdg*
  - $g_{9/2}$: to reproduce the $9/2^+_1$ of ^{51}Ti
  - other *sdg*: to follow schematic spin-orbit splitting

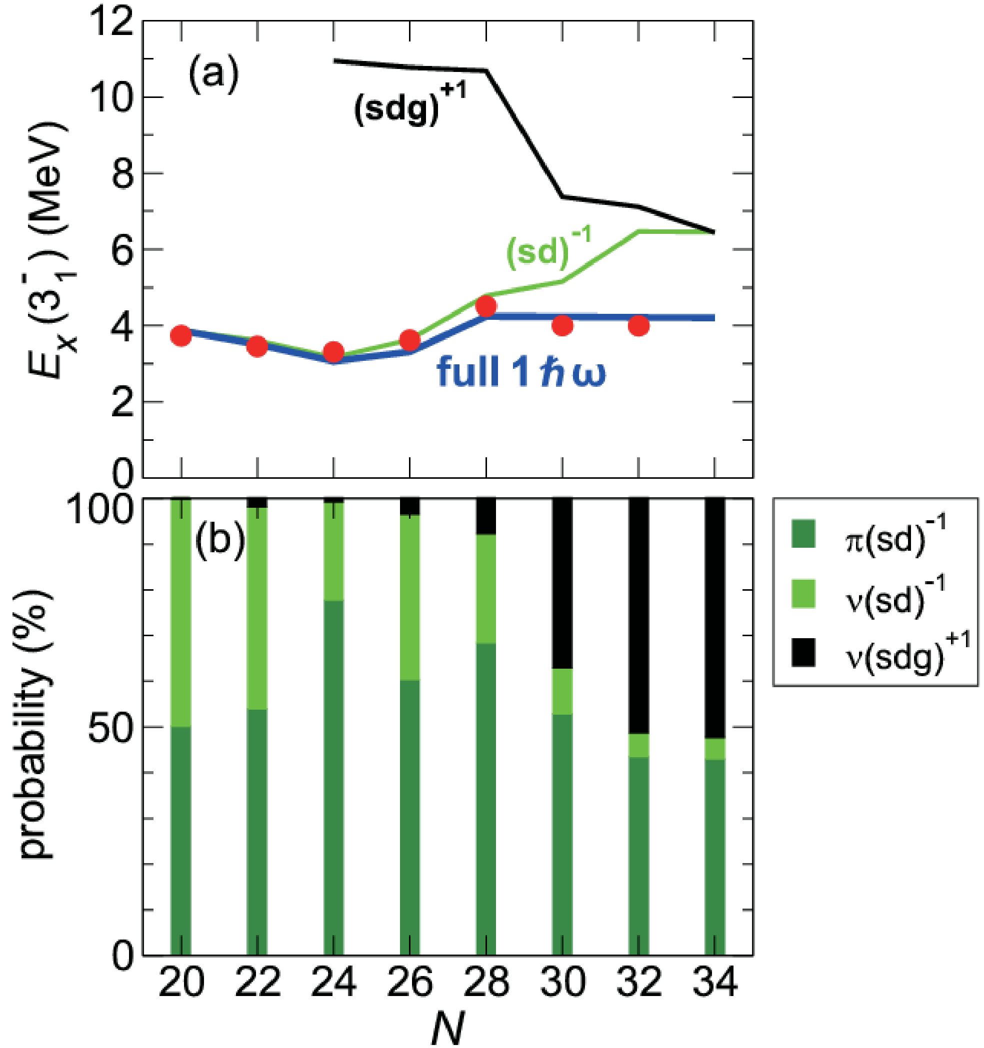
	Expt.		Calc.
Optical pot.	B4	CA	
$C^2S(g_{9/2})$	0.54	0.37	0.47

What happens in Ca levels?



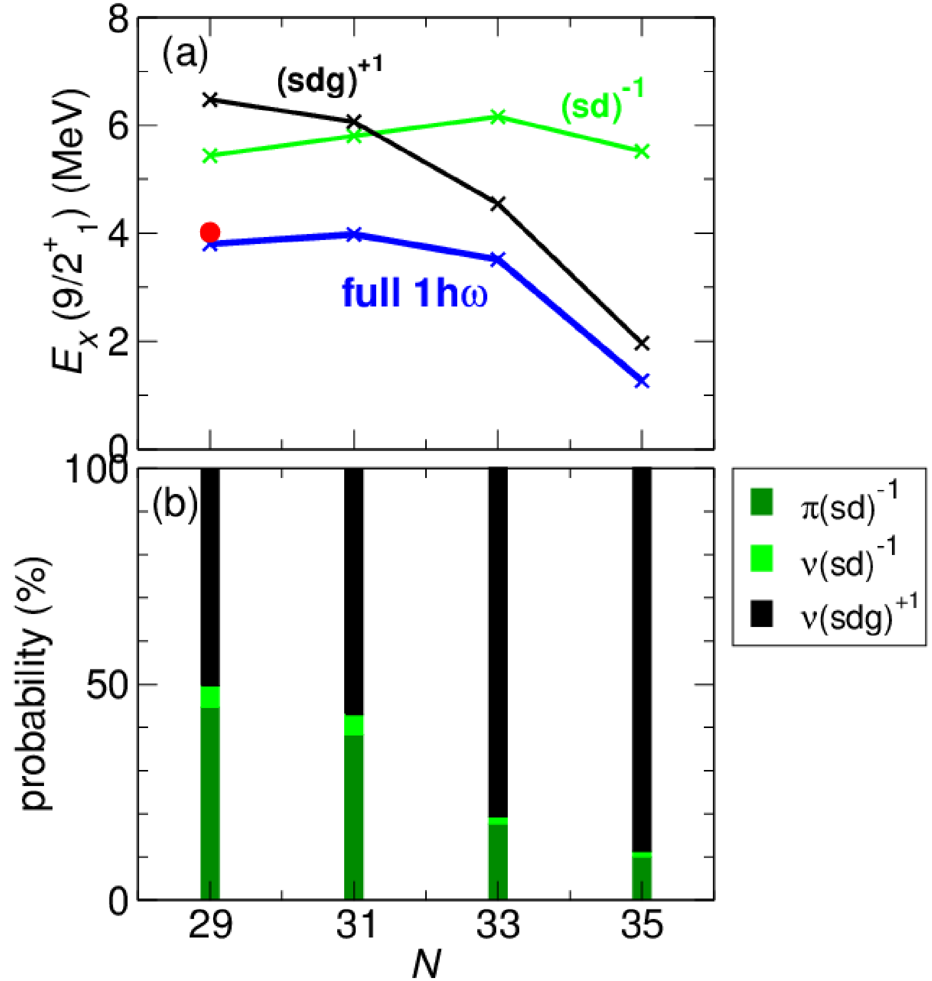
Systematics of the 3^-_1 state in even-*A* Ca

- Three calculations
  - A) excitations from *sd* to *pf* only
  - B) excitations from *pf* to *sdg* only
  - C) full $1\hbar\omega$ configurations
- 3^-_1 levels
  - *sd*-*pf* calc.
    - good agreement for $N \leq 28$
    - large deviation for $N > 28$
  - full $1\hbar\omega$ calc.
    - Strong mixing with the *sdg* configuration accounts for the stable positioning of the 3^- levels.



Systematics of the $9/2^+_1$ state in odd-A Ca

- $9/2^+_1$ in the *sd-pf* calculation
  - Core-coupled state
  - Located stably at 5-6 MeV
- $9/2^+_1$ in the *pf-sdg* calculation
  - Sharply decreasing due to the shift of the Fermi level
- $9/2^+_1$ in the full $1\hbar\omega$ calculation
  - 3-4 MeV up to *N*=33 but drops considerably at *N*=35
  - The state at *N*=55 is nearly a single-particle character.



Application to photonuclear reaction

N. Shimizu et al., in preparation; Y. Utsuno et al., Prog. Nucl. Ener. 82, 102 (2015).

- A good Hamiltonian for the full $1\hbar\omega$ space is constructed.
- It is expected that photonuclear reaction, dominated by $E1$ excitation, is well described with this shell-model calculation:

$$\sigma_{\mathrm{abs}}(E) = \frac{16\pi^3 E}{9\hbar c} S_{E1}(E)$$

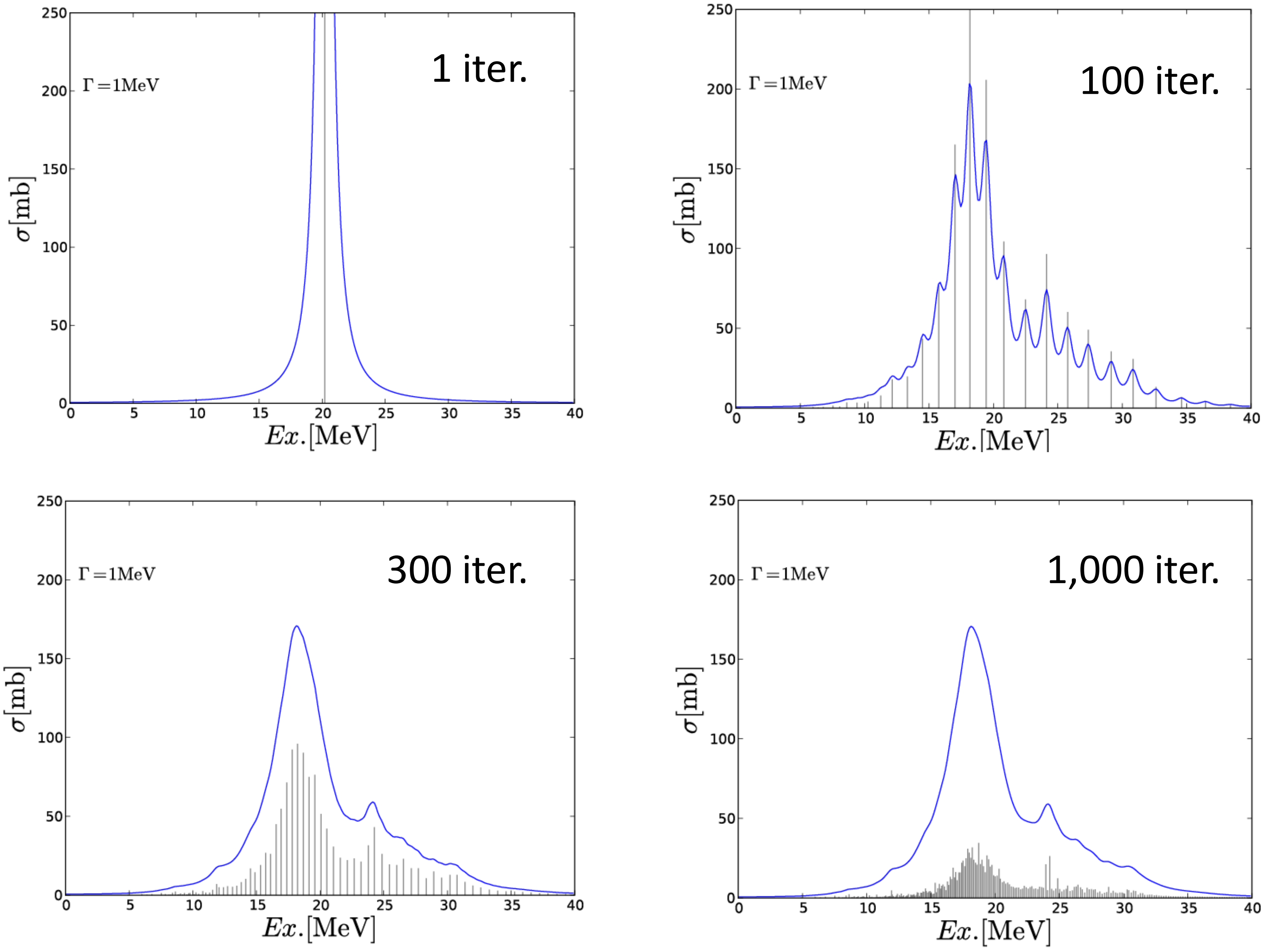
with $S_{E1}(E) = \sum_\nu B(E1; g.s. \to \nu)\delta(E - E_\nu + E_0)$

- Shell-model calculation provides good level density, including non-collective levels, the coupling to which leads to the width of GDR.
- Application of shell model to photonuclear reaction has been very limited due to computational limitation.
  - Sagawa & Suzuki (O isotopes), Brown (^{208}Pb), Ormand & Johnson (ab initio)

Lanczos strength function method

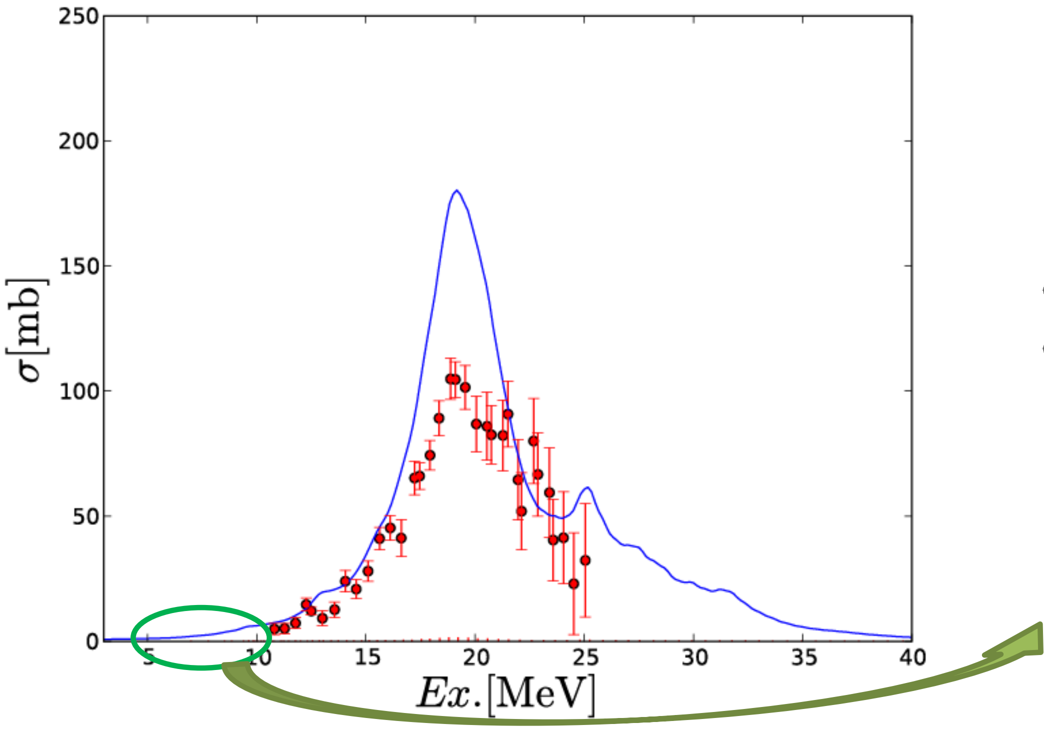
- It is almost impossible to calculate all the eigenstates concerned using the exact diagonalization.
- Moment method of Whitehead [Phys. Lett. B 89, 313 (1980)]
  - The shape of the strength function can be obtained with much less Lanczos iterations.
    1. Take an initial vector: $\overrightarrow{v_1} = T(E1)|\mathrm{g.s.}\rangle$
    2. Follow the usual Lanczos procedure
    3. Calculate the strength function $\sum_\nu B(E1; g.s. \to \nu) \frac{1}{\pi} \frac{\Gamma/2}{(E-E_\nu+E_0)^2+(\Gamma/2)^2}$ by summing up all the eigenstates ν in the Krylov subspace with an appropriate smoothing factor Γ until good convergence is achieved.
  - See Caurier et al., Rev. Mod. Phys. 77, 427 (2005), for application to Gamow-Teller.

Convergence of strength distribution

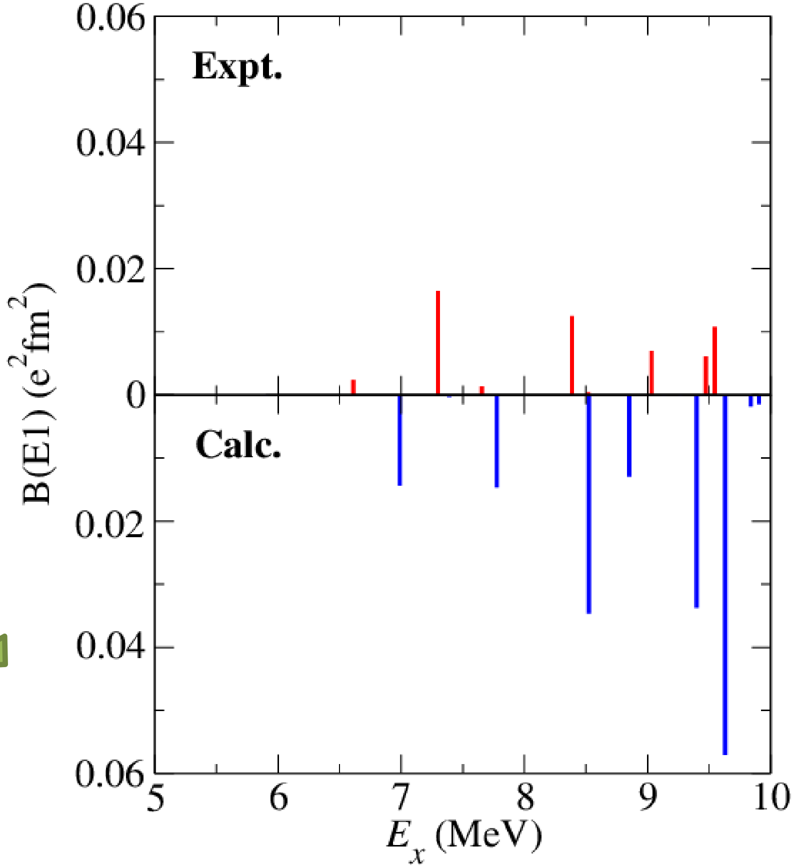


Comparison with experiment for ^{48}Ca

GDR with Γ=1 MeV

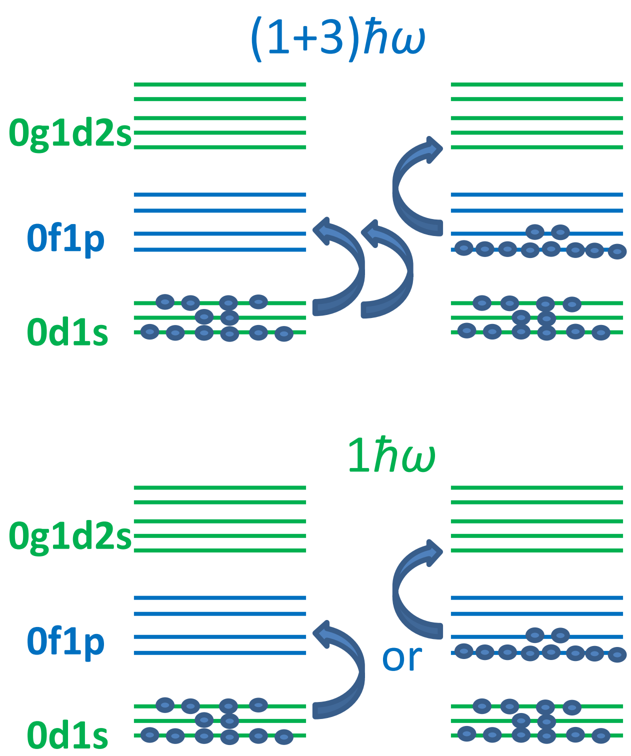


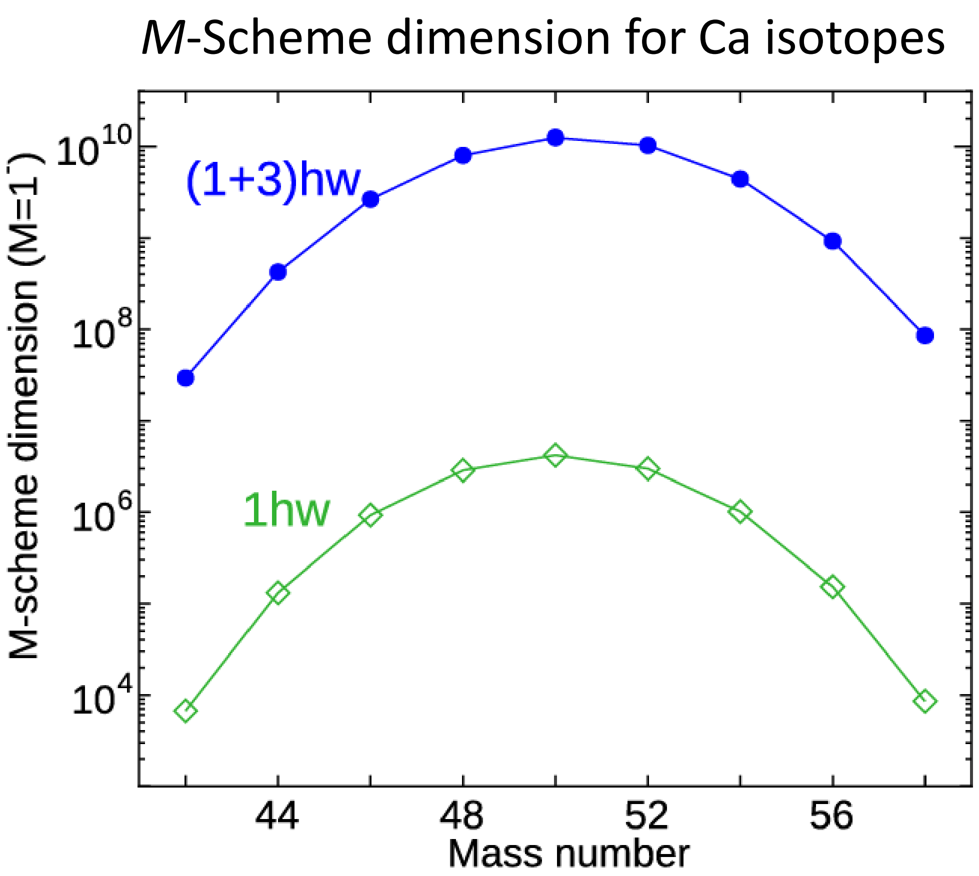
Low-lying 1^- states



- GDR peak position: good
- GDR peak height: overestimated
- Low-lying states: about 0.7 MeV shifted

Beyond 1$\hbar\omega$ calculation



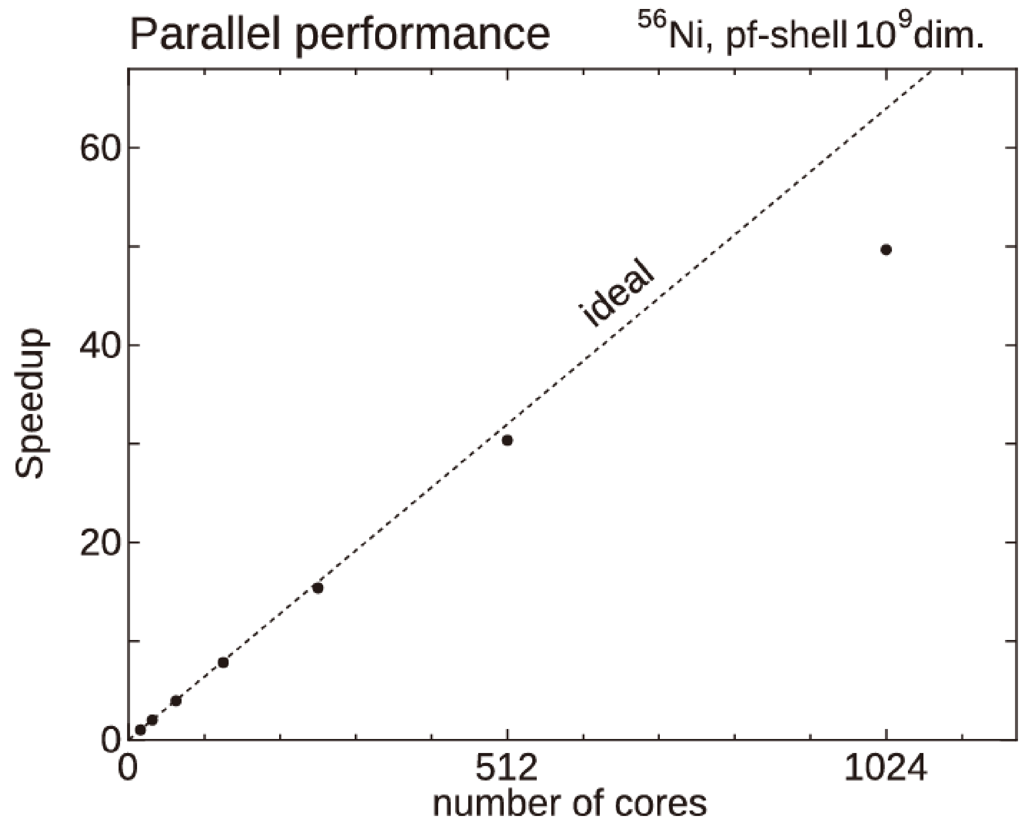


- 3$\hbar\omega$ states in the *sd-pf-sdg* shell are included.
  - No single-nucleon excitation to the 3$\hbar\omega$ above shell
- Dimension becomes terrible!

KSHELL: MPI + OpenMP hybrid code

N. Shimizu, arXiv:1310.5431 [nucl-th]

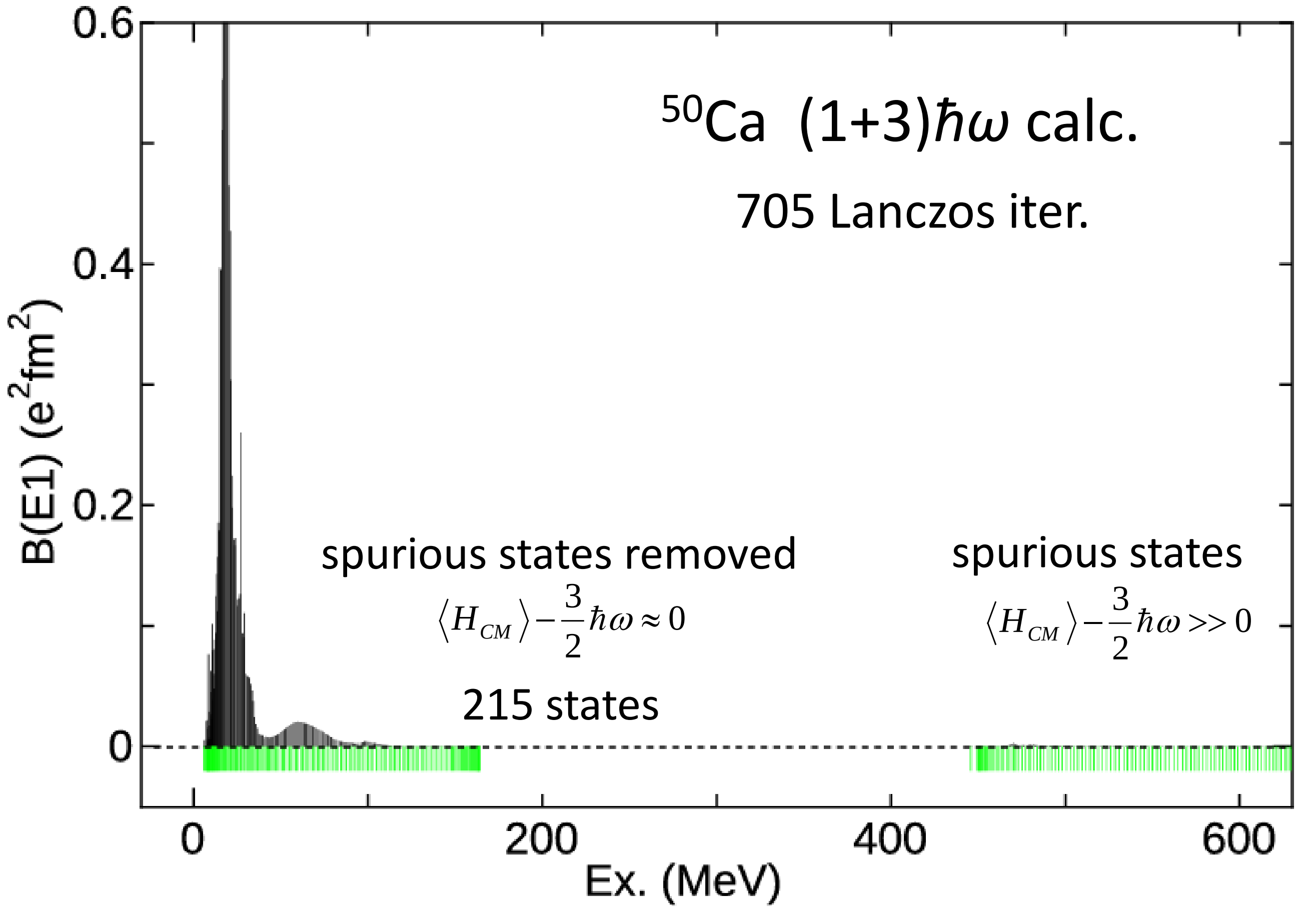
- *M*-scheme code
  - "On the fly": Matrix elements are not stored in memory (analogous to ANTOINE and MSHELL64)
- Good parallel efficiency
  - Owing to categorizing basis states into "partition", which stands for a set of basis states with the same sub-shell occupancies



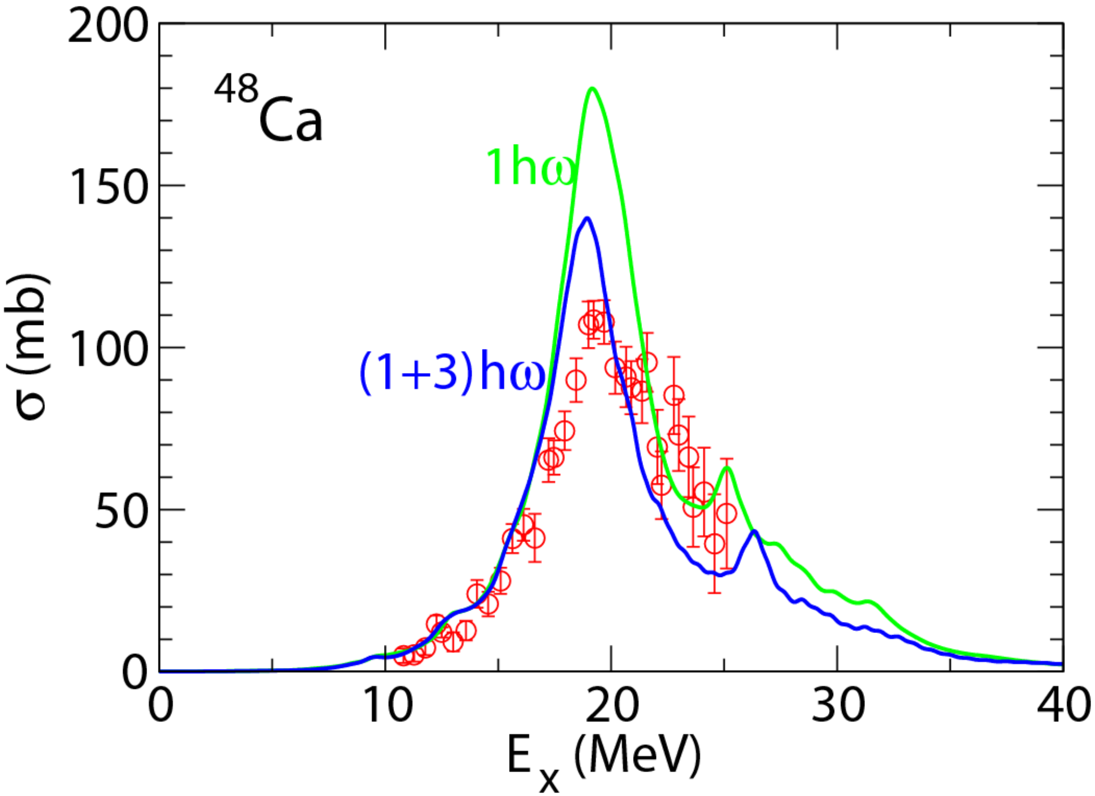
time/iteration : 25 min. (16 cores) ➡ 30 sec. (1024 cores)

Removal of spurious center-of-mass motion

- Usual prescription of Lawson and Gloeckner
  $H' = H + \beta H_{CM}$ with $\beta = 10\hbar\omega/A$ MeV
  - Confirming that eigenstates are well separated

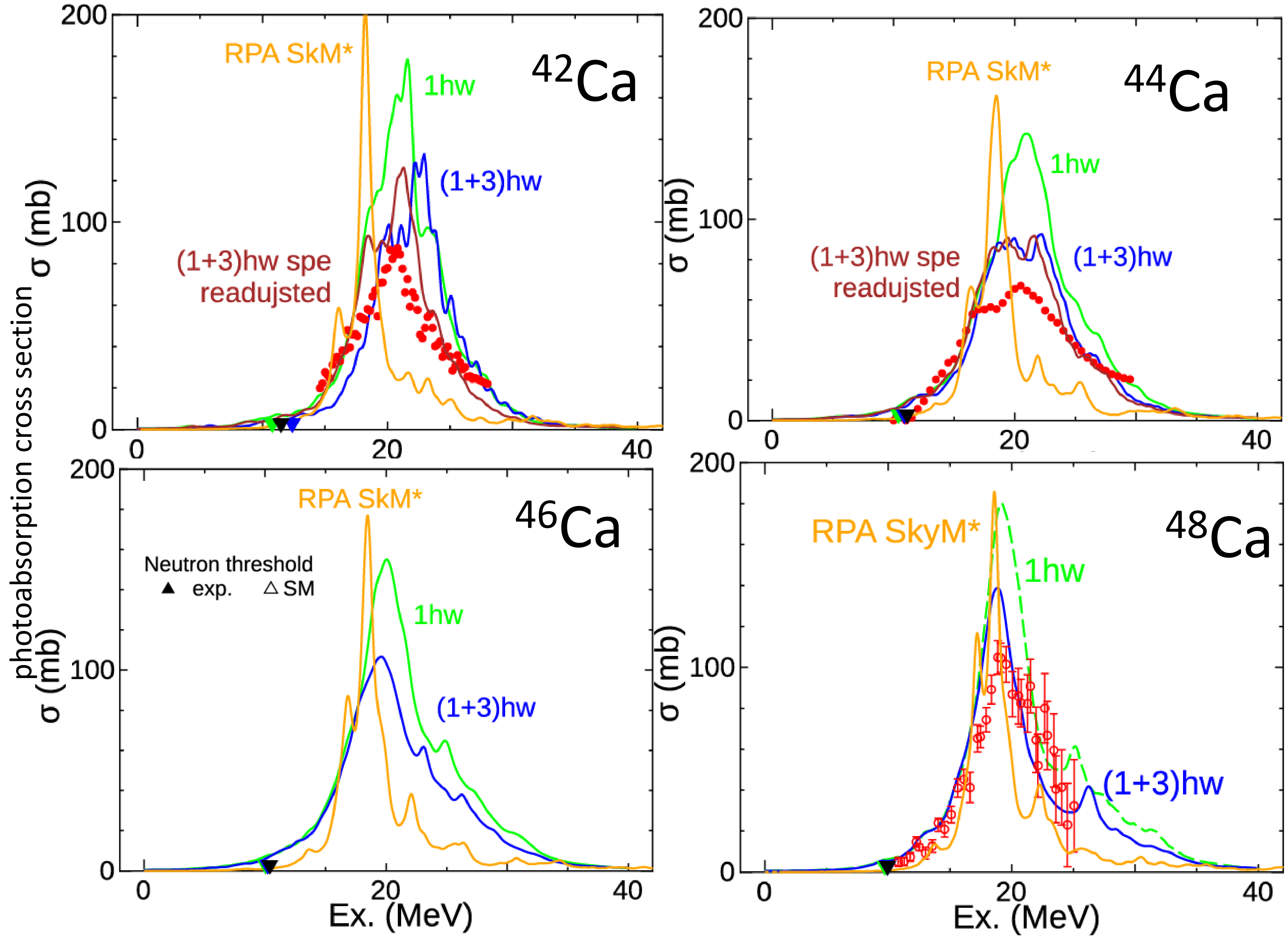


Effect of correlation

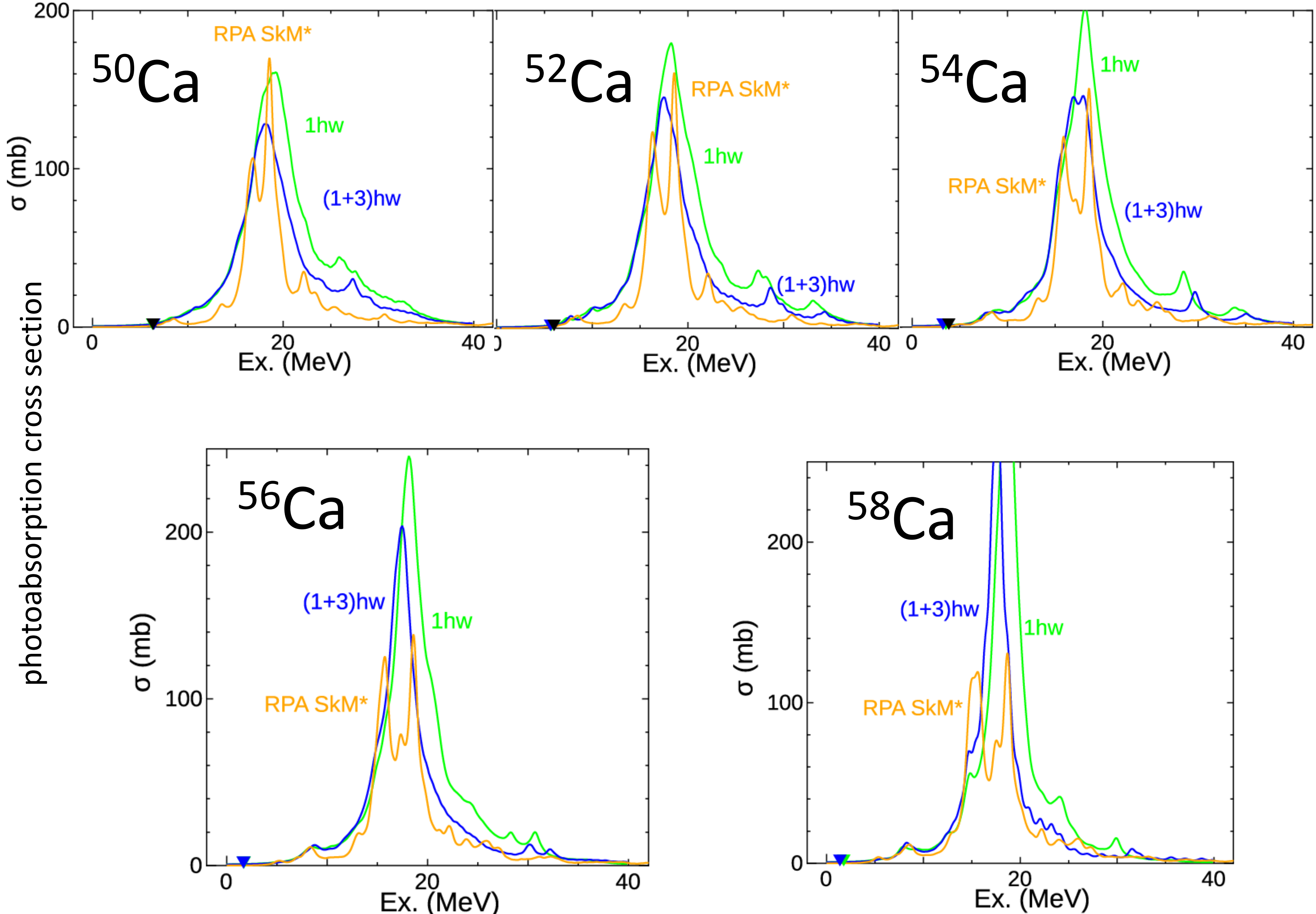


	B(E1) sum
1ħω	16.5
(1+3)ħω	13.6
MCSM 50 dim.	10.1

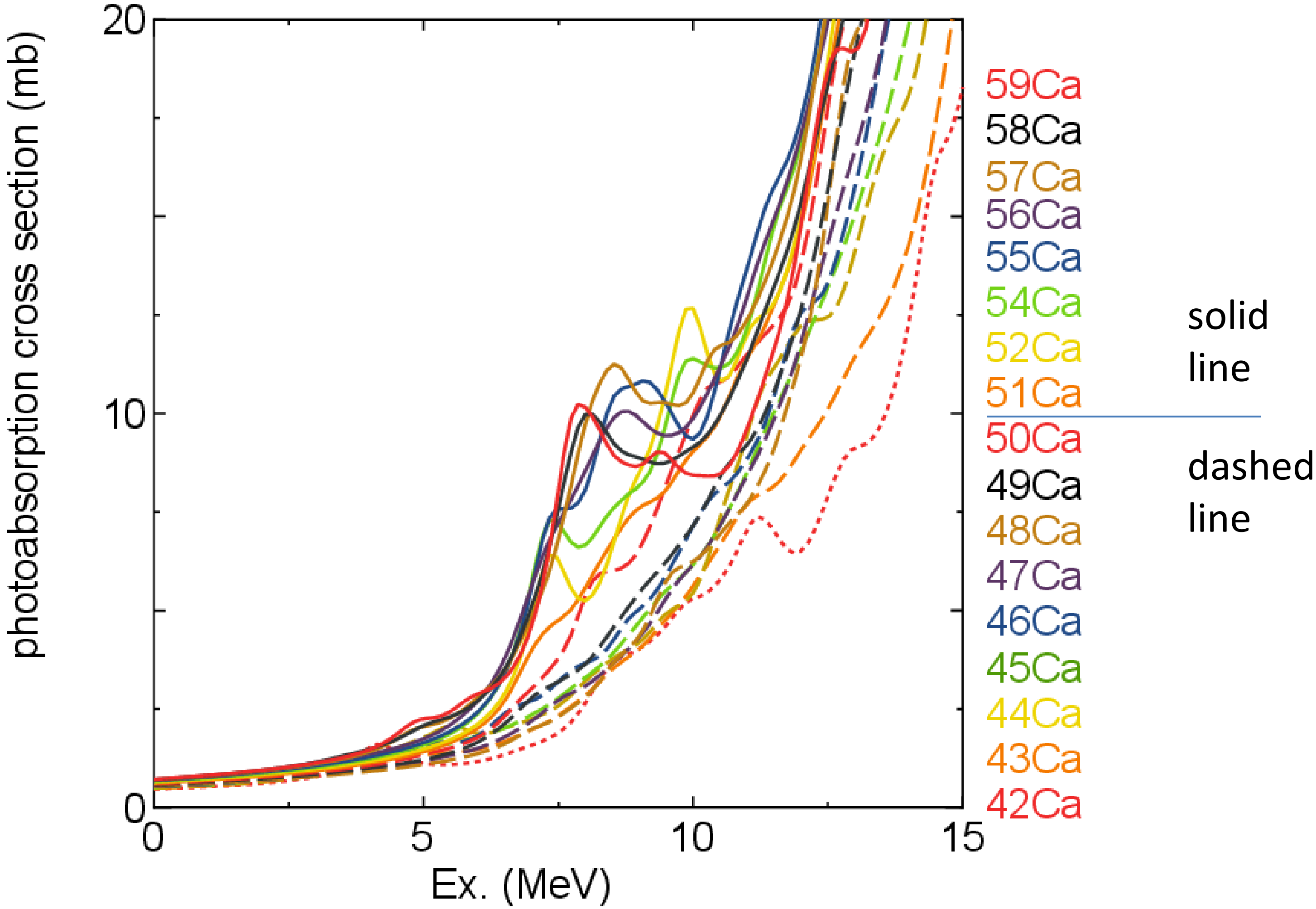
- GDR peak height is suppressed and improved with increasing ground-state correlation.
- Low-energy tail is almost unchanged.



photoabsorption cross section
^{42}Ca
RPA SkM*
1hw
(1+3)hw
(1+3)hw spe
readujsted
σ (mb)
^{44}Ca
RPA SkM*
1hw
(1+3)hw
(1+3)hw spe
readujsted
σ (mb)
^{46}Ca
RPA SkM*
Neutron threshold
▲ exp. △ SM
1hw
(1+3)hw
σ (mb)
Ex. (MeV)
^{48}Ca
RPA SkyM*
1hw
(1+3)hw
σ (mb)
Ex. (MeV)


photoabsorption cross section
σ (mb)
Ex. (MeV)
50Ca
52Ca
54Ca
56Ca
58Ca
RPA SkM*
1hw
(1+3)hw
0
100
200
0
20
40

Development of pygmy dipole resonance

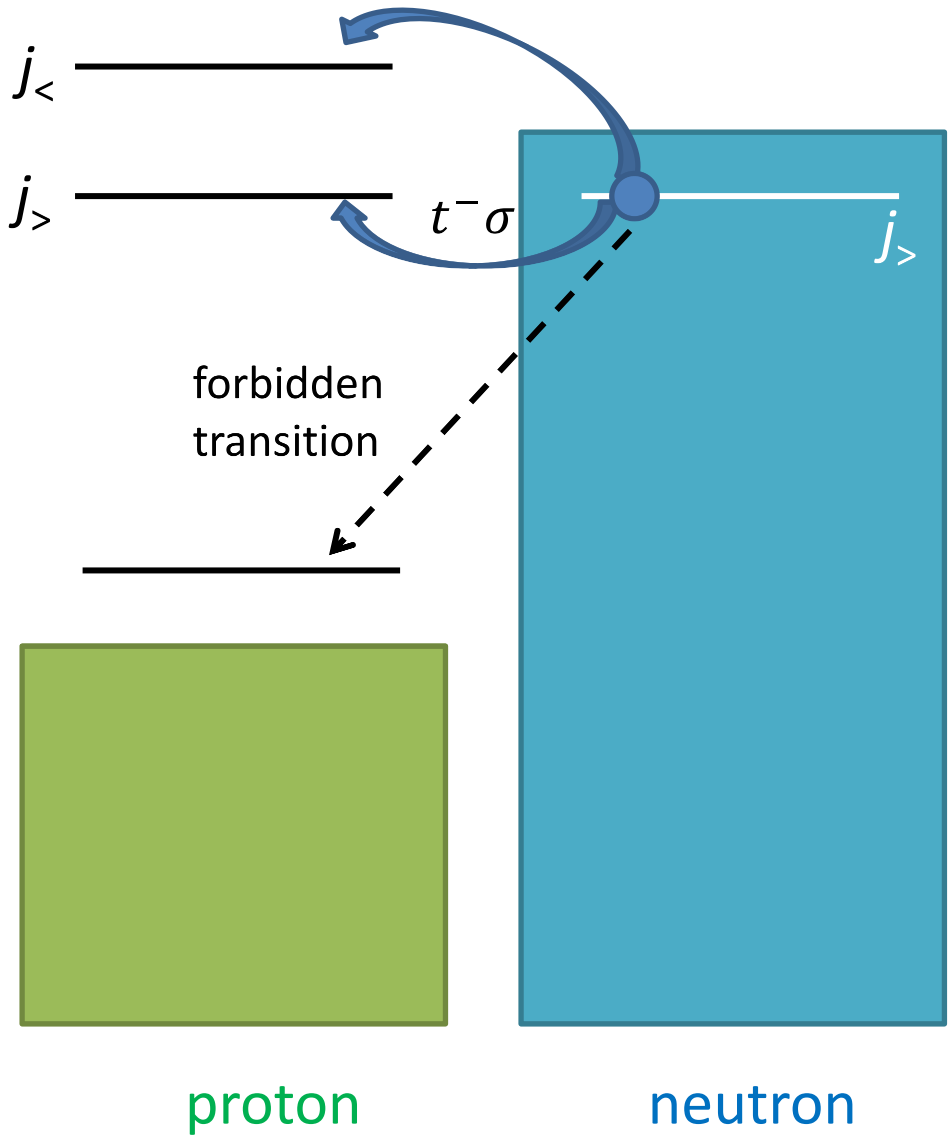


- PDR develops for $A \geq 50$, but the tail of GDR makes the peak less pronounced.

β decay

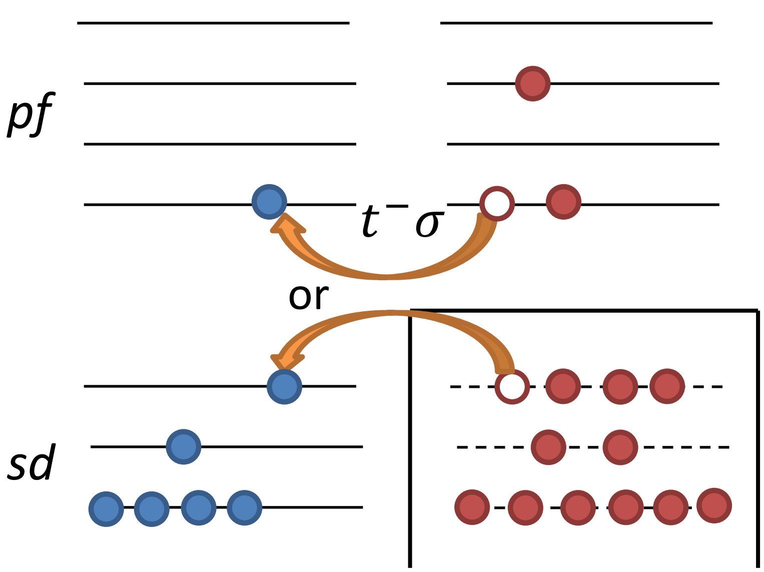
- Describing the Gamow-Teller strength for very neutron-rich nuclei using the shell model is a big challenge because a large model space is required to satisfy the sum rule.

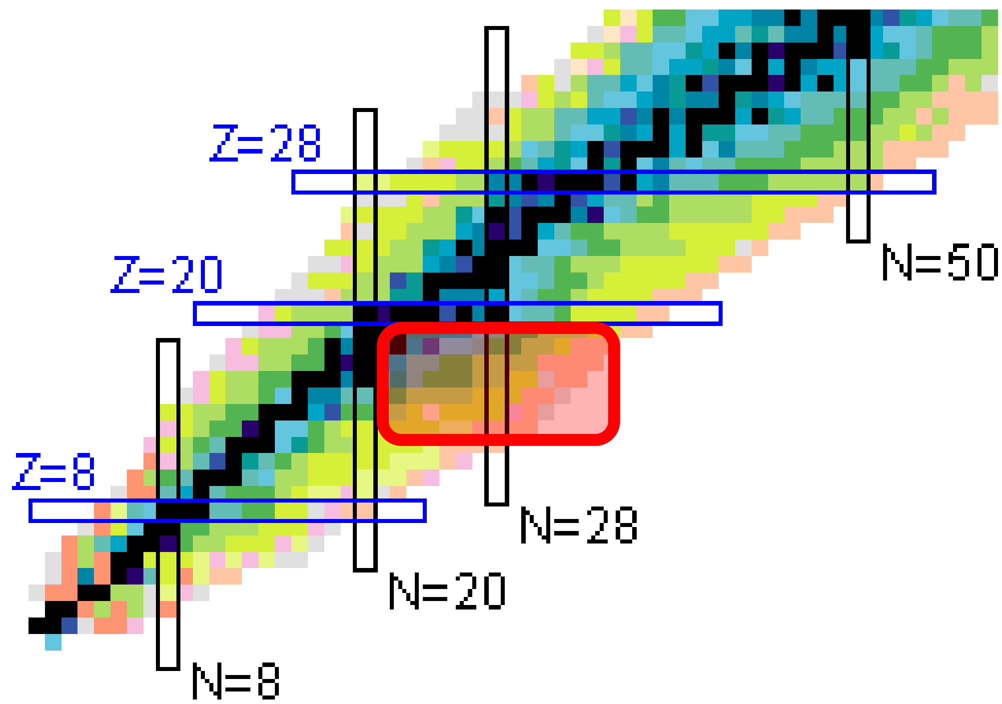
Most of previous shell-model studies were one-major-shell calculations such as the *pf*-shell calc.



sd-pf case: example of multi major shell

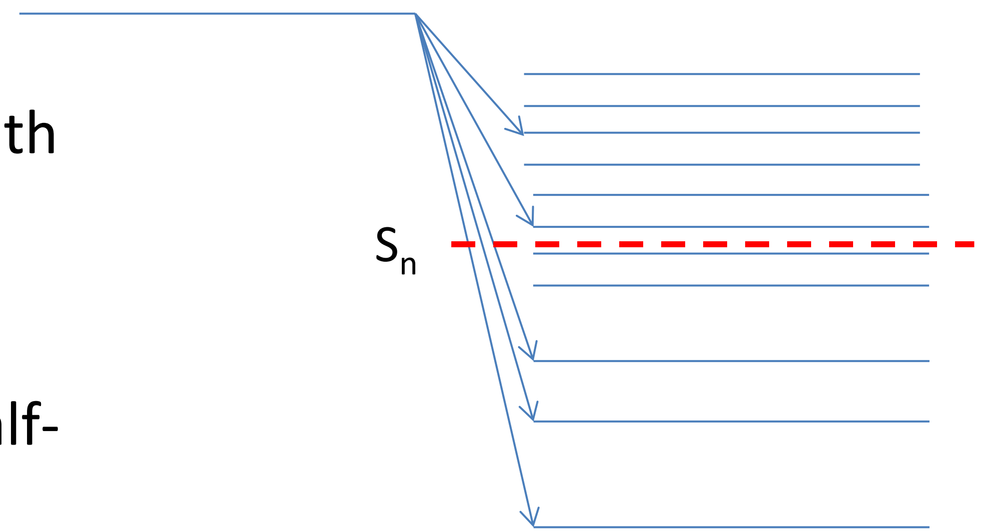
- Calculation for $Z < 20$, $N > 20$ nuclei
  - Model space: $0\hbar\omega$ state for the parent state and $1\hbar\omega$ states in the *sd-pf* shell for the daughter states
    - Satisfying the Ikeda sum rule
    - Applicable to all the nuclei except the "island of inversion"
  - SDPF-MU interaction





Half lives and delayed neutron probabilities

- $\frac{1}{t_{1/2}} = \sum_i \frac{1}{t_{1/2}(i)}$
- Calculate the GT distribution with the Lanczos strength function method until convergence
- P_n is evaluated by the partial half-lives with $E_x > S_n$.



Comparison with recent data

half lives

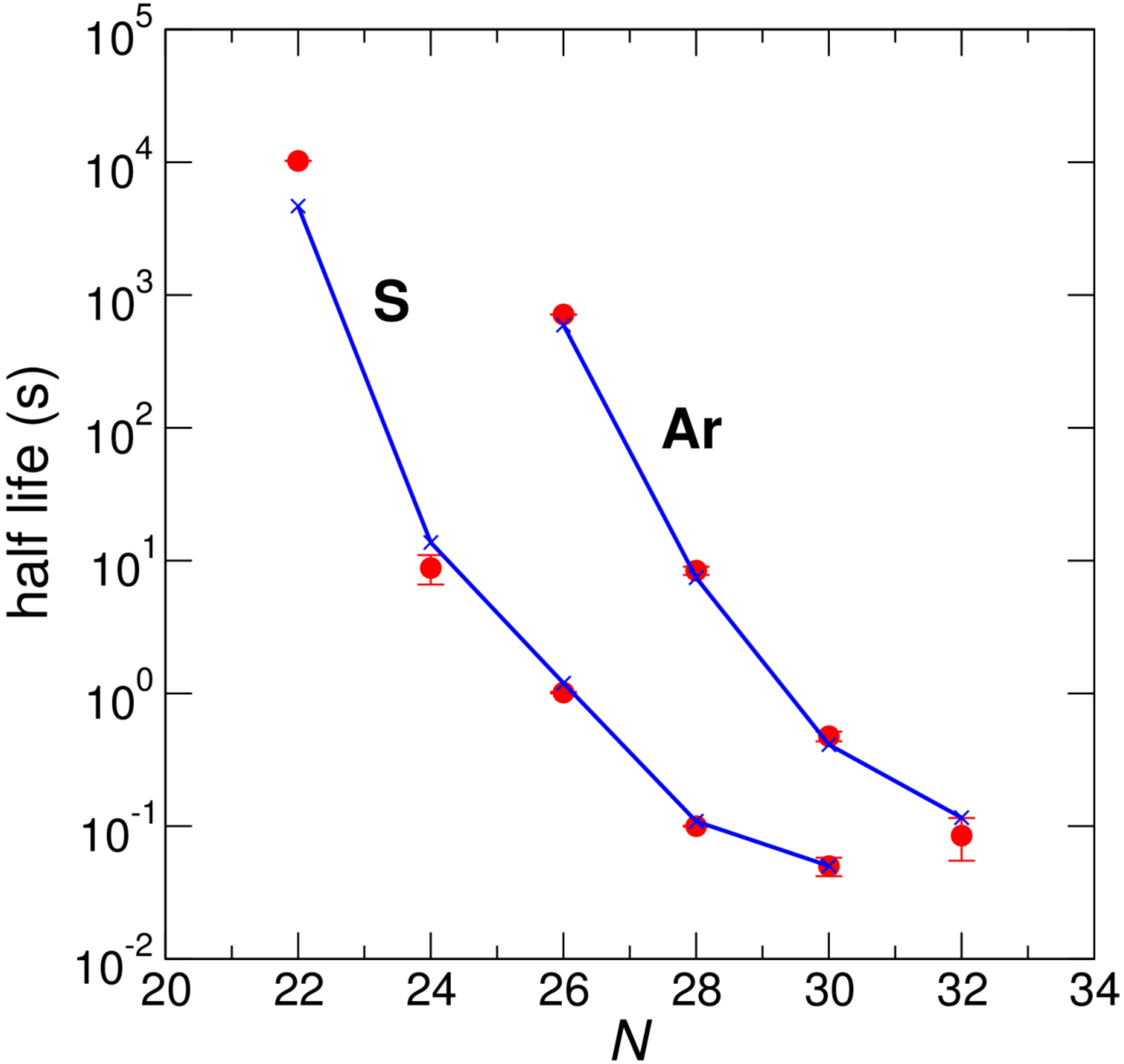
	RIBF Expt.	Calc.
^{37}Al	11.5(4) ms	11.0 ms ($5/2^+$)
^{38}Al	9.0(7) ms	8.3 ms (5^-), 8.8 ms (0^-)

quenching factor: 0.77

K. Steiger, …, Y. Utsuno, N. Shimizu et al., accepted in EPJA.

Systematics of even-*A* S and Ar isotopes

S. Yoshida et al.



Delayed neutron emission probability (P_n)

	Expt.	Calc.
^{44}S	18(3)%	16%
^{50}Ar	35(10)%	48%

quenching factor: 0.77

Q values used: experimental or AME2012 evaluation ($^{48,50}Ar$ and ^{46}S)

Summary

- Recent development in large-scale shell-model calculations (methodology, computing, effective interaction …) allows to extend its frontier for heavier nuclei and higher excited states.
- We focus on unnatural-parity states and their $E1$ and Gamow-Teller strength functions in exotic nuclei in the *sd*-*pf* shell region, which also provide a good testing ground for effective interaction.
- Photonuclear cross sections are well reproduced in stable Ca isotopes, and pygmy dipole resonances are predicted for $N > 28$.
- The ground-state correlation works to reduce the B($E1$) sum.
- Half lives and delayed neutron emission probabilities are excellently reproduced for $N > 20$ exotic nuclei. More systematic calculations will be performed.