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Nuclear structure from β-decay lifetimes: N=50 magic number and shell structure around ^{78}Ni

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arXiv: 1903.03310, PRC(in press.)

Magic number

shell structure and shell gap

emergence of the simple pattern

understanding of the mechanism

fundamental problem in nuclear structure physics

eg. shell evolution in exotic nuclei

link to physical observable

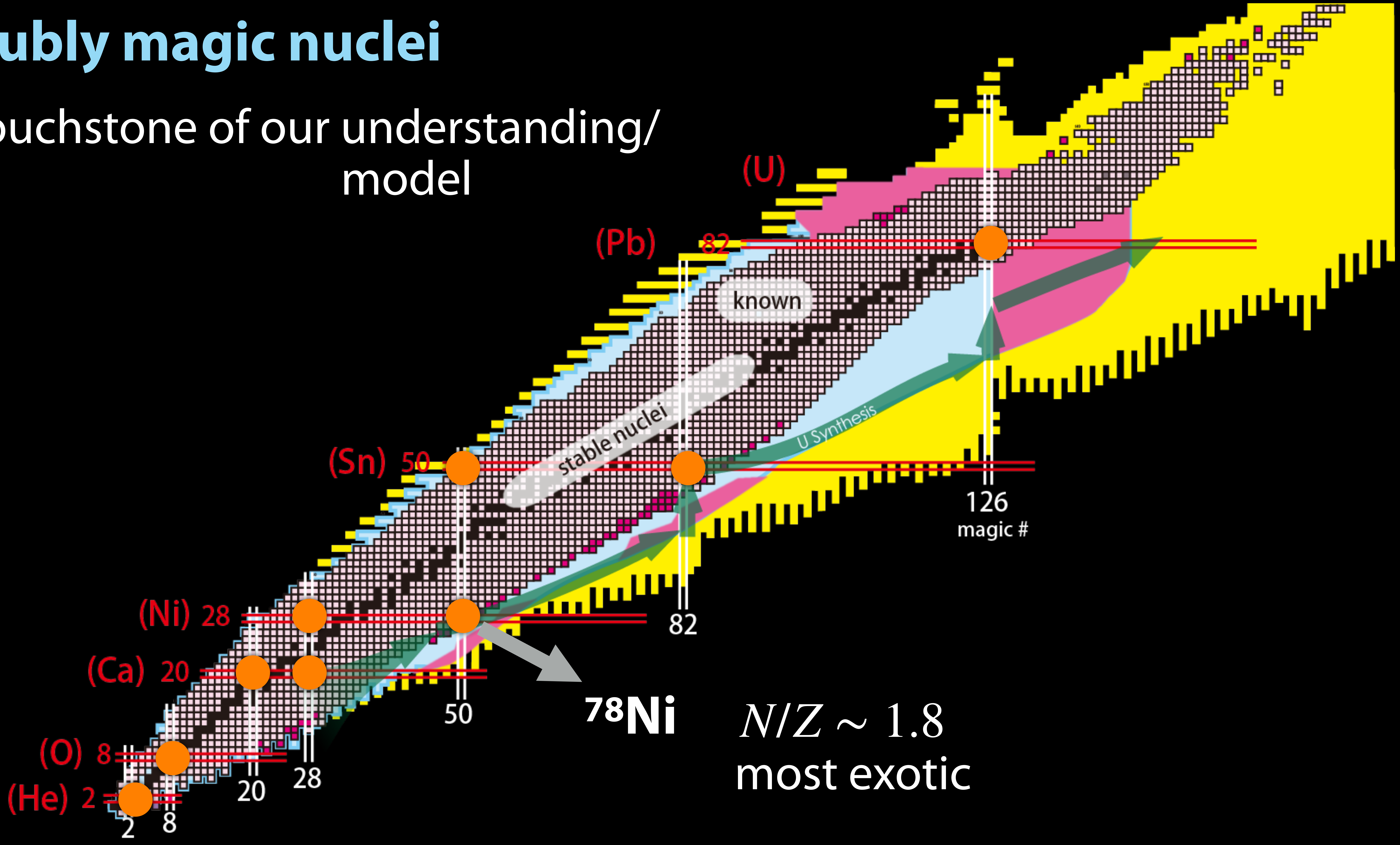
mass/separation energy

excitation energy and transition prob.

β-decay

Doubly magic nuclei

touchstone of our understanding/
model



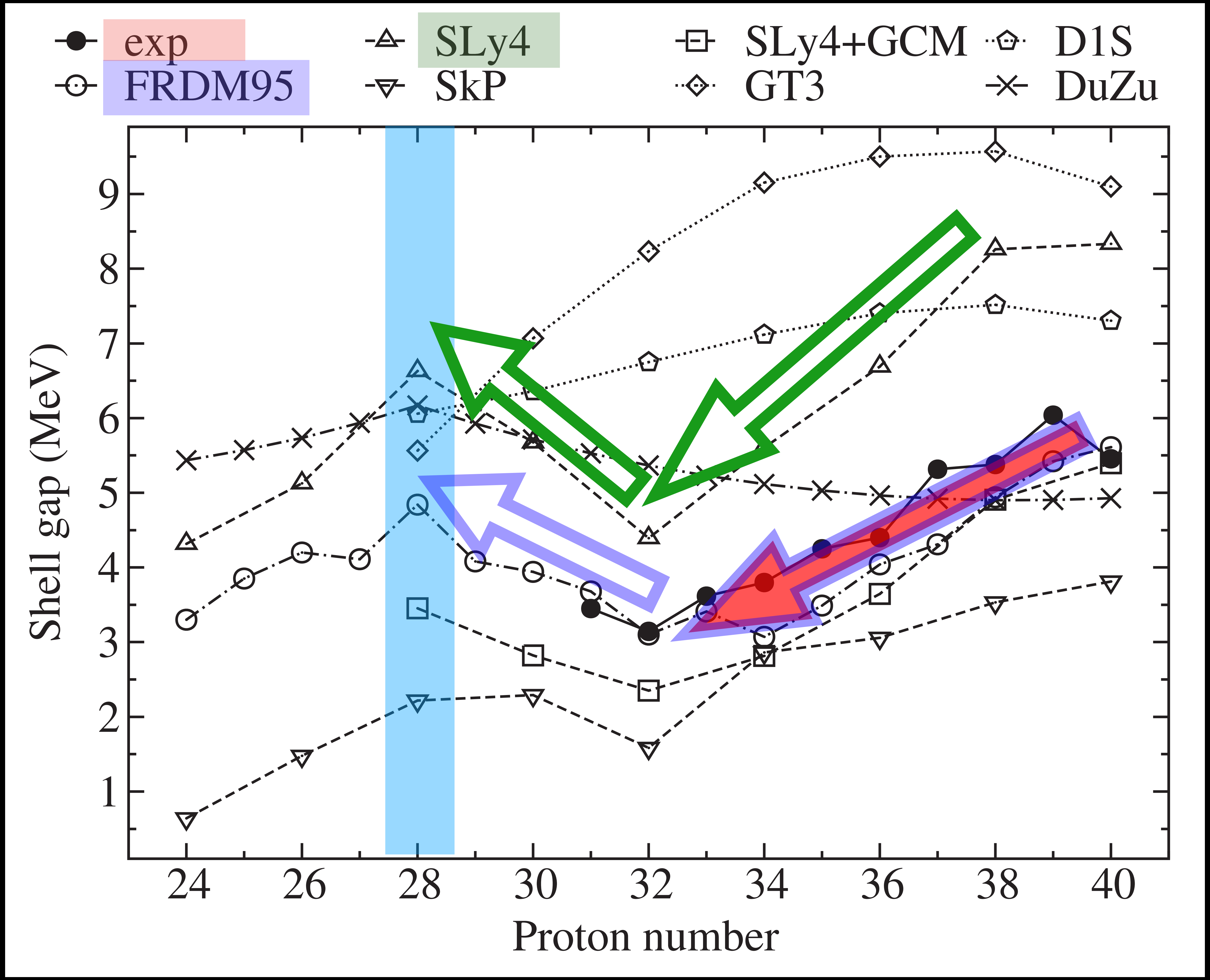
^{78}Ni

$N/Z \sim 1.8$
most exotic

N=50 magic number in ^{78}Ni

(i) mass/separation energy

gap energy: $\Delta = S_{2n}(N=50) - S_{2n}(N=52)$



J. Hakala *et al.*, PRL101(2008)052502

FRDM produces well the exp.

EDF's produce the trend of the exp.

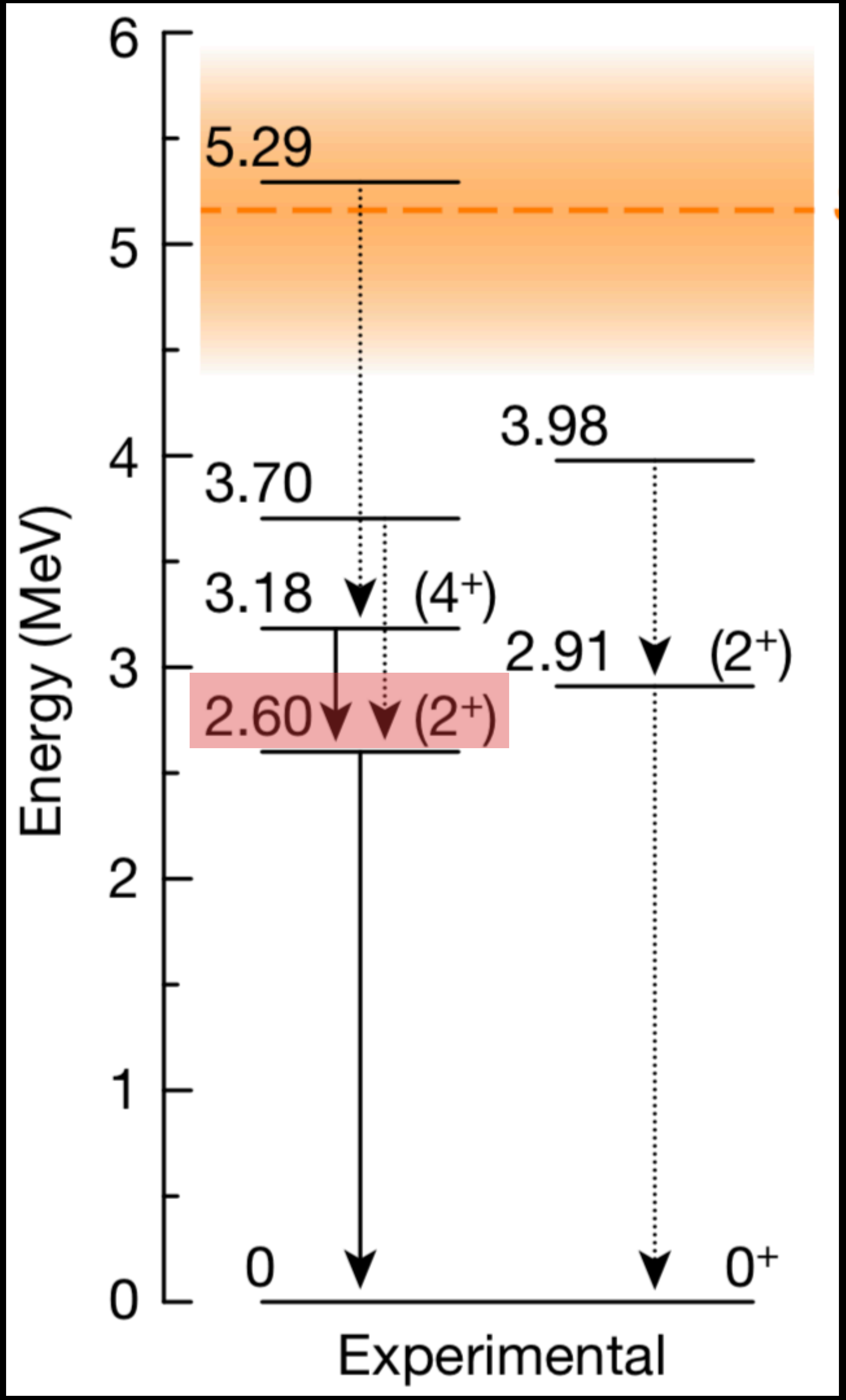
high shell gap energy at ^{78}Ni expected

direct measurement has yet to exist

N=50 magic number in ^{78}Ni

(ii) qudrupole state

R. Taniuchi *et al.*, Nature 569(2019)53

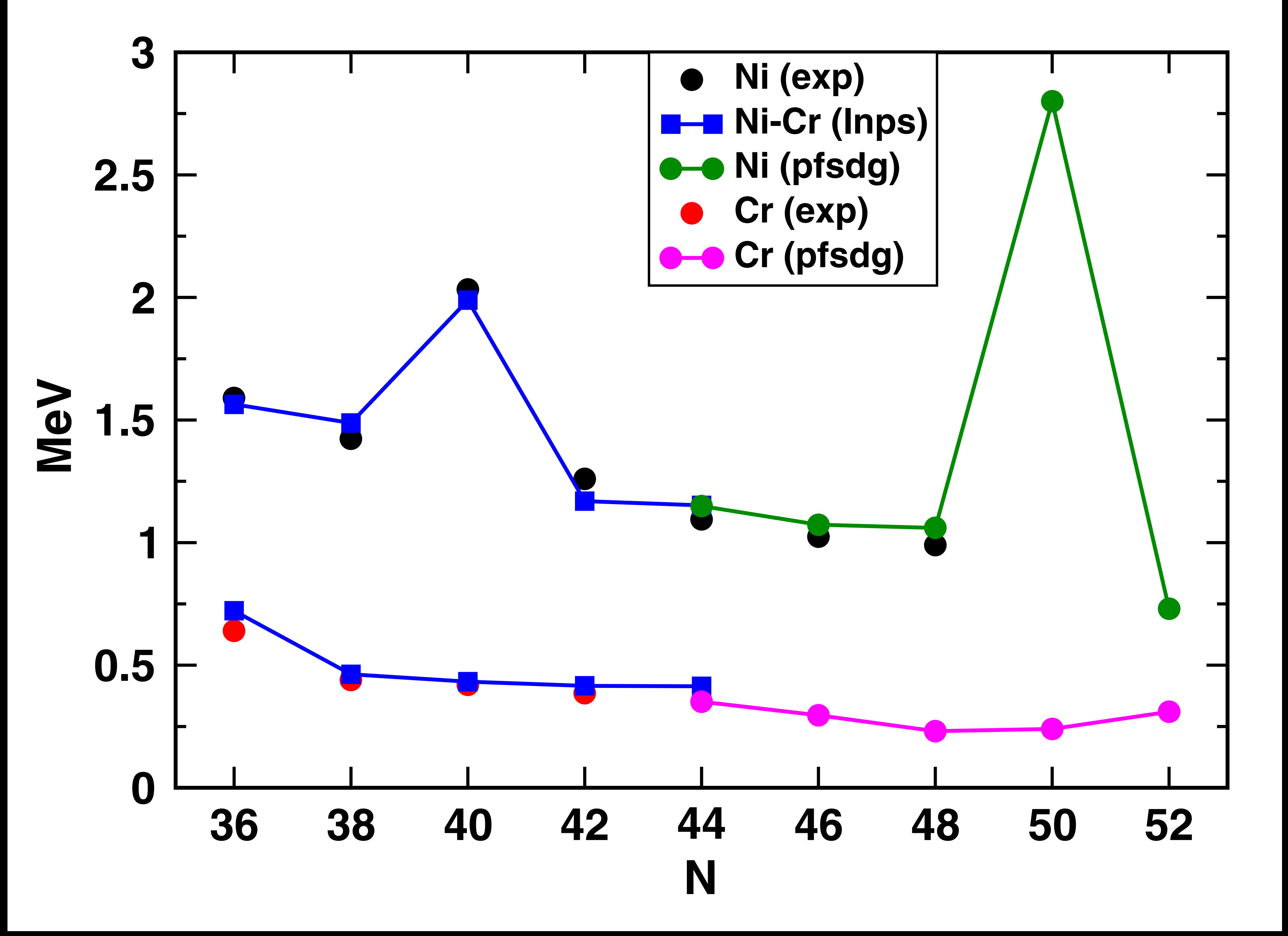


high 2$^+$ energy

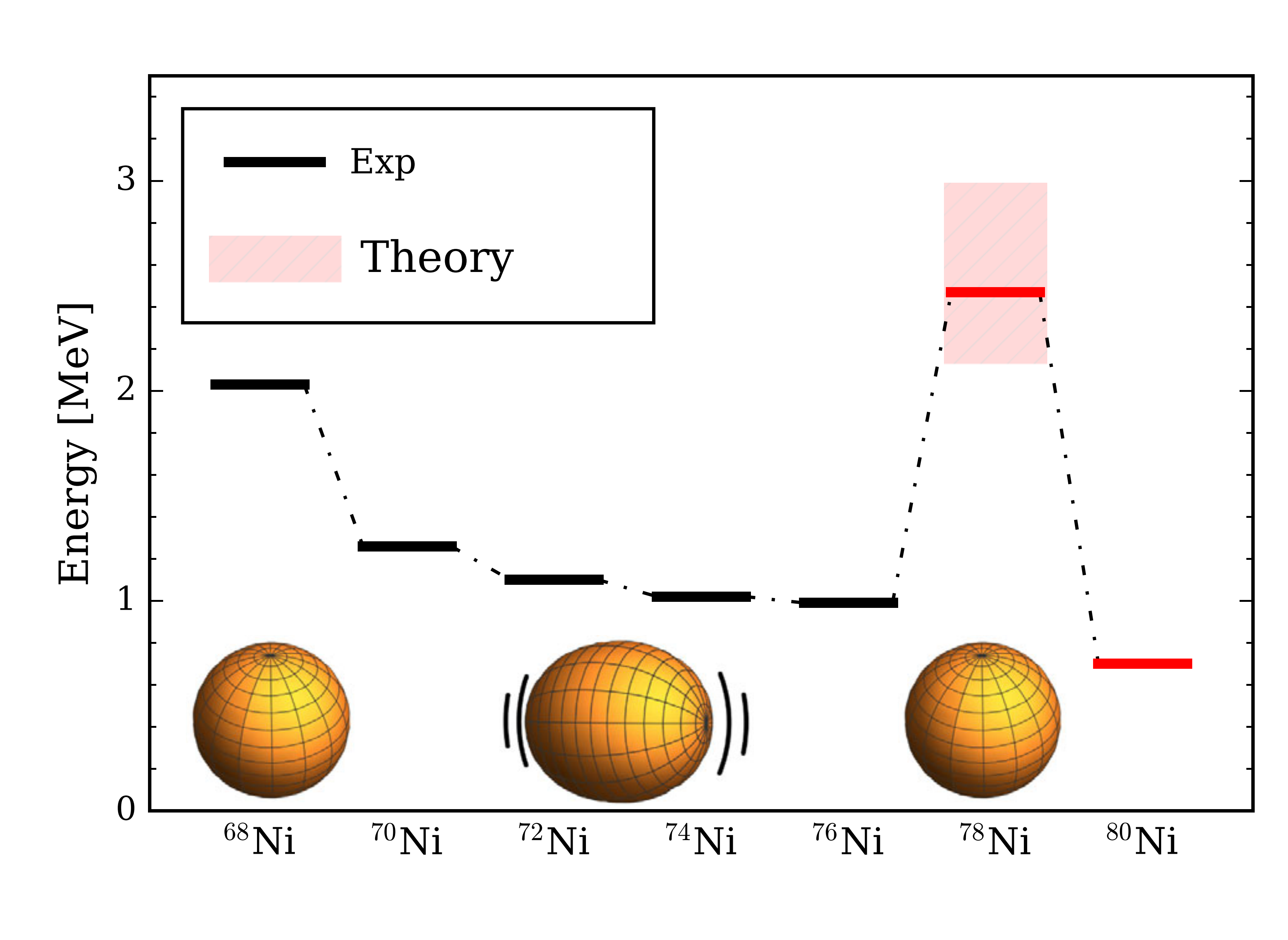
$$R_{42} = \frac{E(4^+)}{E(2^+)} = 1.22$$

single-particle-like excitation

F. Nowacki *et al.*, PRL117(2016)272501



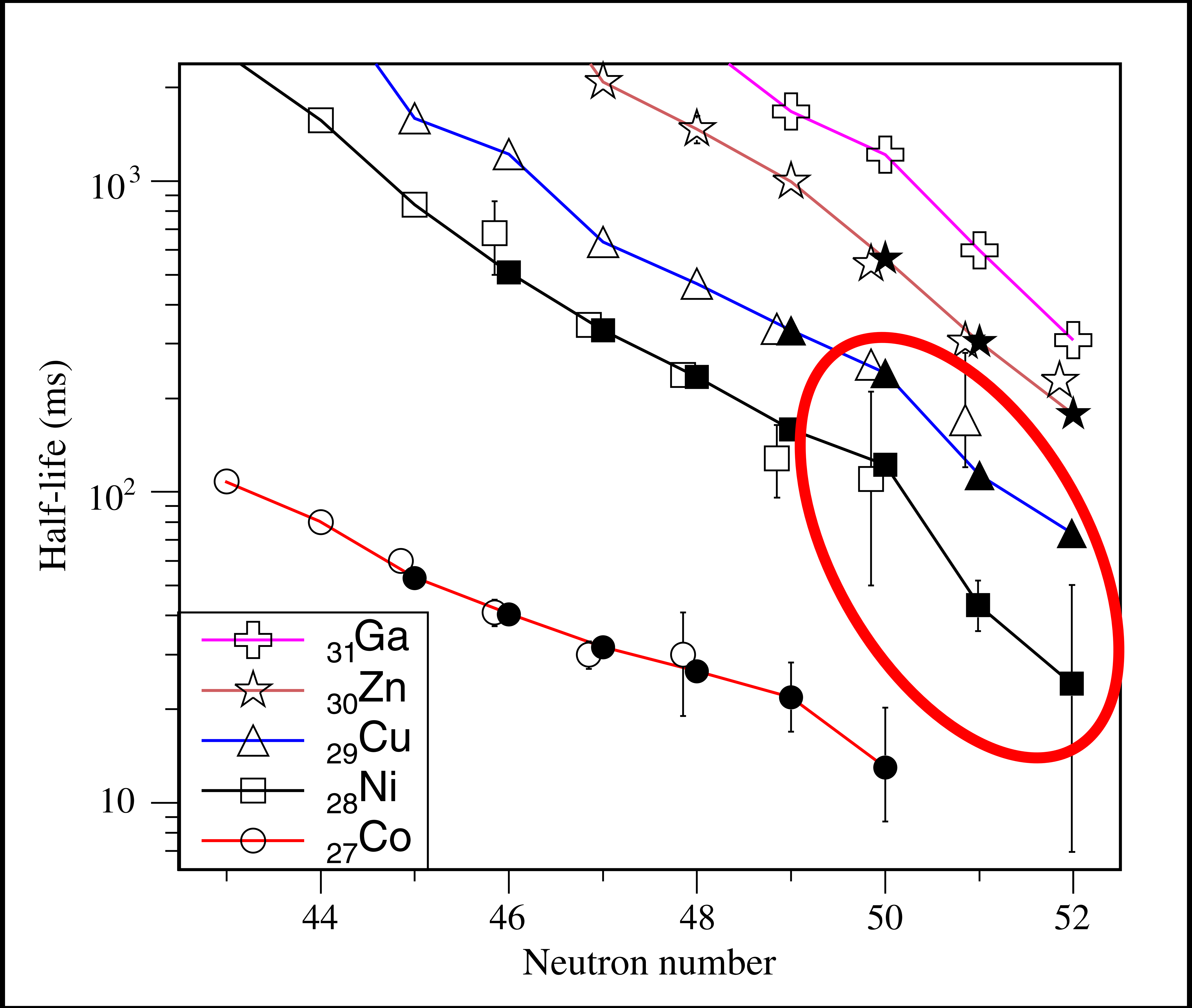
G. Hagen *et al.*, PRL117(2016)172501



N=50 magic number in ^{78}Ni

(iii) β-decay

Z. Y. Xu *et al.*, PRL113(2014)032505



sudden shortening beyond *N*=50

due to the gap at *N*=50 ?

theory is needed to understand what is happening

Microscopic mode employed

KY, PTEP2013, 113D02

Nuclear density-functional theory (DFT)

Kohn-Sham(Hartree-Fock)-Bogoliubov

Linear-response time-dependent DFT: Quasiparticle-RPA

external field: $e^{-i\omega t}\hat{F}_{\pm}$ $\quad$ $\hat{F}_{\pm} = \sum_{\tau,\tau'} f(\mathbf{r})\hat{\psi}^{\dagger}(\mathbf{r}\tau)\hat{\psi}(\mathbf{r}\tau')\langle\tau|\tau_{\pm}|\tau'\rangle$

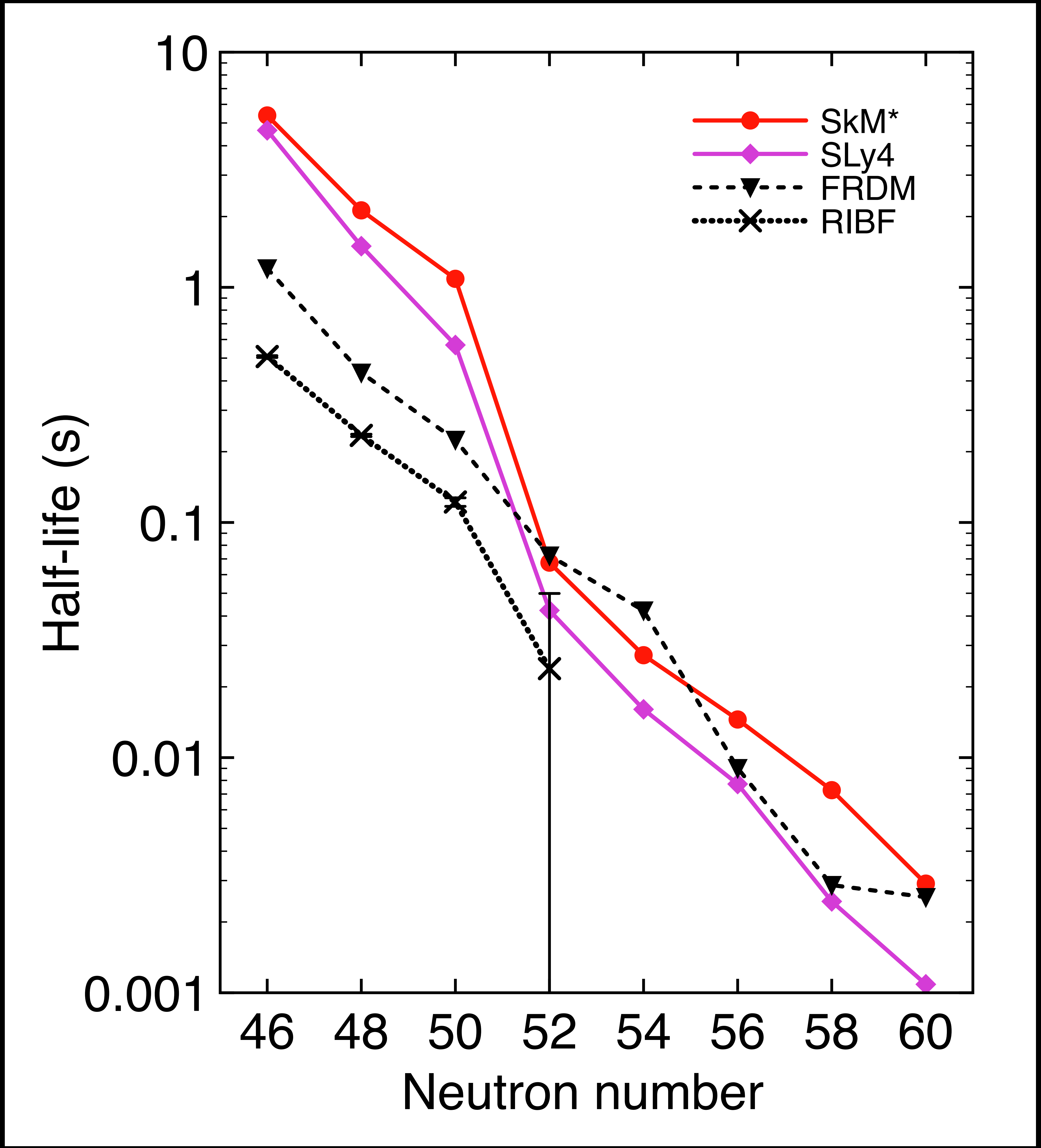
density vibration:

$$\delta\rho_{\pm}(\mathrm{r},t) \sim \delta\rho_{\pm}(\mathrm{r})e^{-i\omega t} \qquad \delta\rho_{\pm}(\mathbf{r}) = \int d\mathbf{r}'\chi_0(\mathbf{r},\mathbf{r}')\left[\frac{\delta^2 \boxed{E[\rho]}}{\delta^2\rho}\delta\rho_{\pm}(\mathbf{r}') + f(\mathbf{r}')\right]$$

Skyrme energy-density functional (EDF)

transition matrix element : $\langle\Psi_{\lambda}|\hat{F}_{\pm}|\Psi_0\rangle = \int d\mathbf{r}\delta\rho_{\pm}(\mathbf{r};\omega_{\lambda})f(\mathbf{r})$

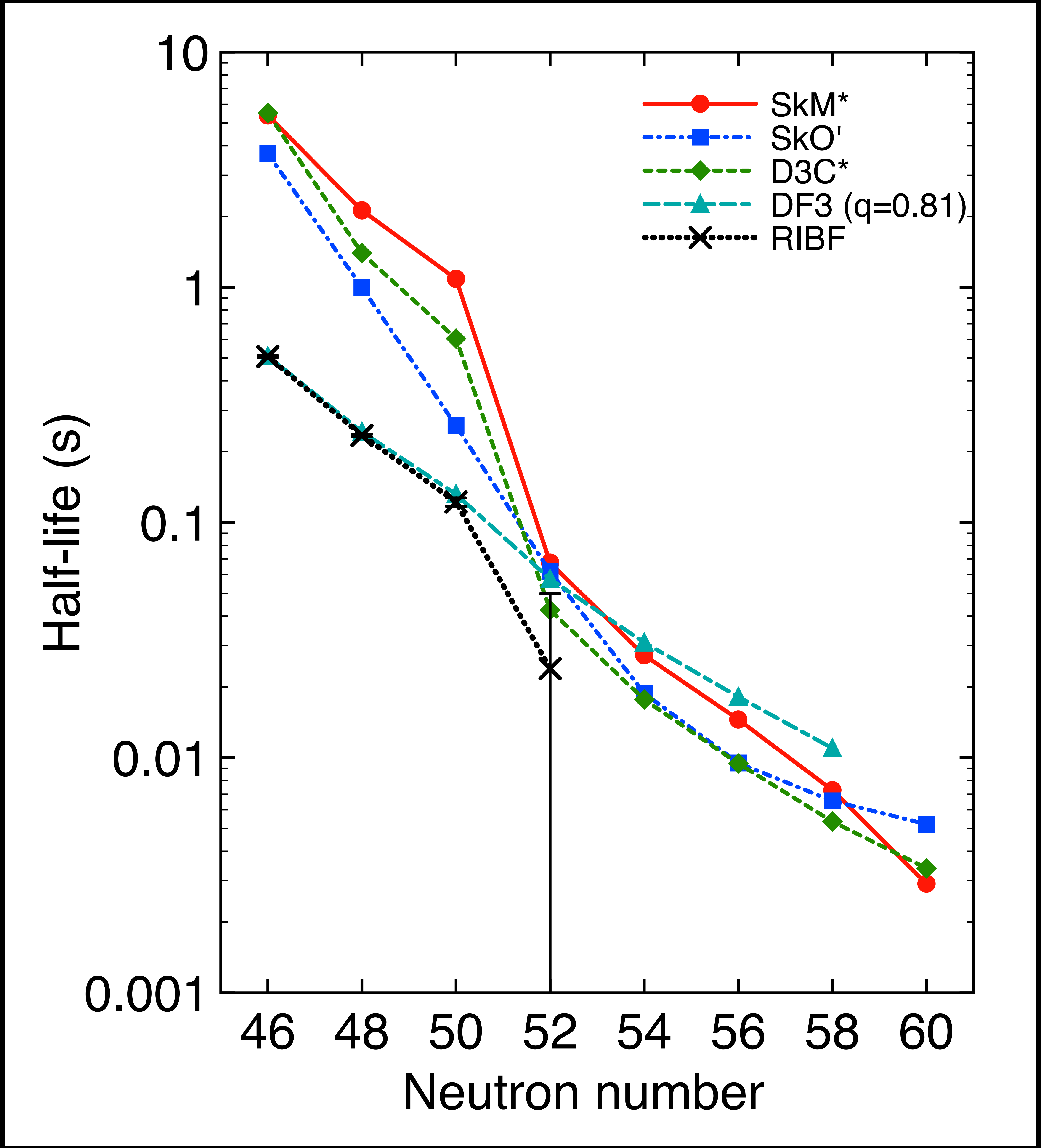
β-decay half-lives of Ni isotopes



- ✓ sudden drop beyond N=50
- ✓ monotonic shortening below 50, and above 52
- ✓ something occurs in between
- ✓ FRDM predicts a drop beyond 54

P. Möller *et al.*, PRC67(2003)055802

β-decay half-lives of Ni isotopes



SkO′: M. T. Mustonen *et al.*, PRC93(2016)014304

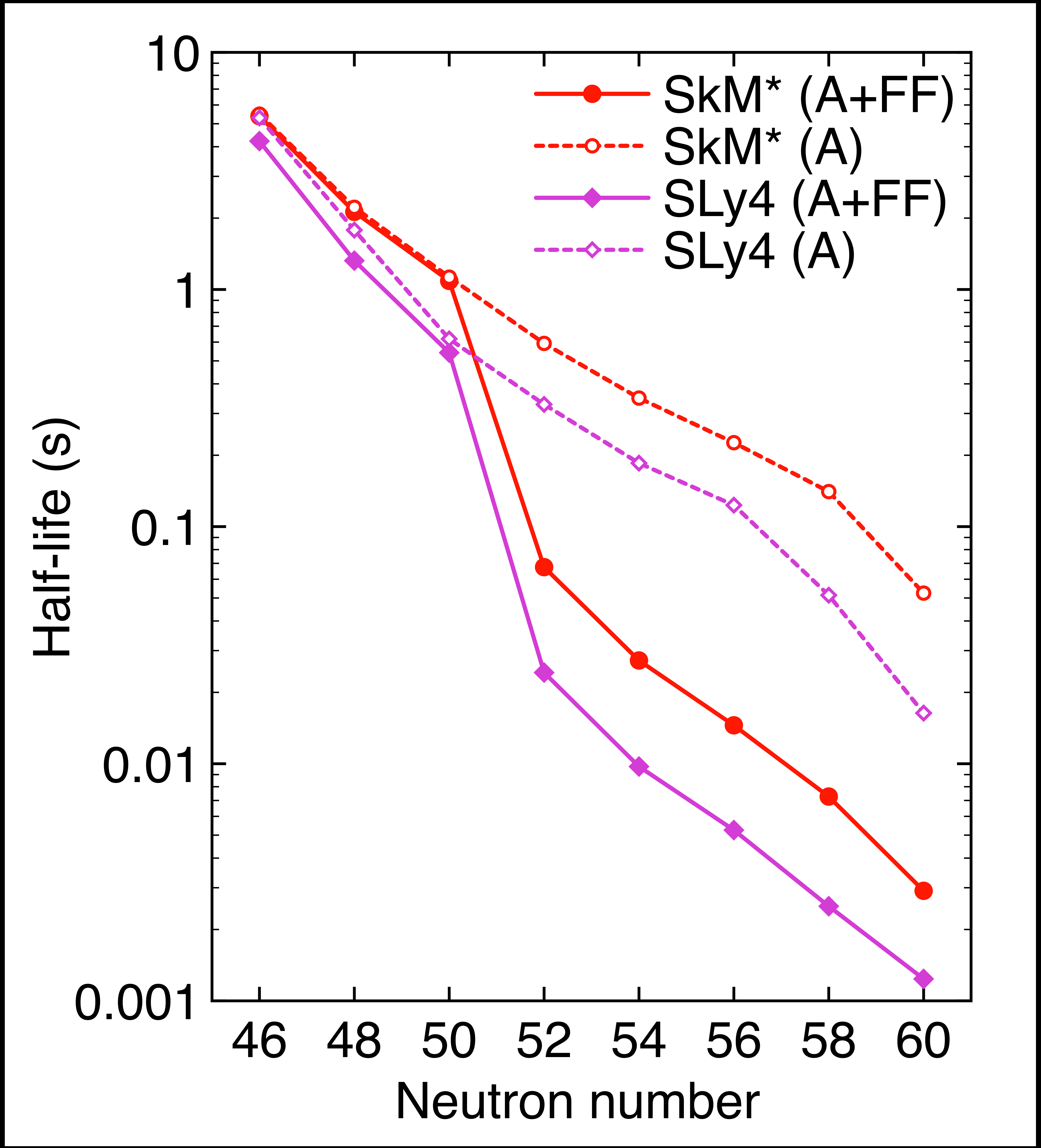
D3C*: T. Marketin *et al.*, PRC93(2016)025805

DF3: I. N. Borzov, PRC71(2005)065801

✓ Not all the DFT calculations can describe the drop beyond N=50

What is a key to understanding a sudden shortening of $T_{1/2}$?

Role of the first-forbidden transitions



✓ allowed transitions give only a monotonic shortening

✓ sudden drop is due to the FF transitions

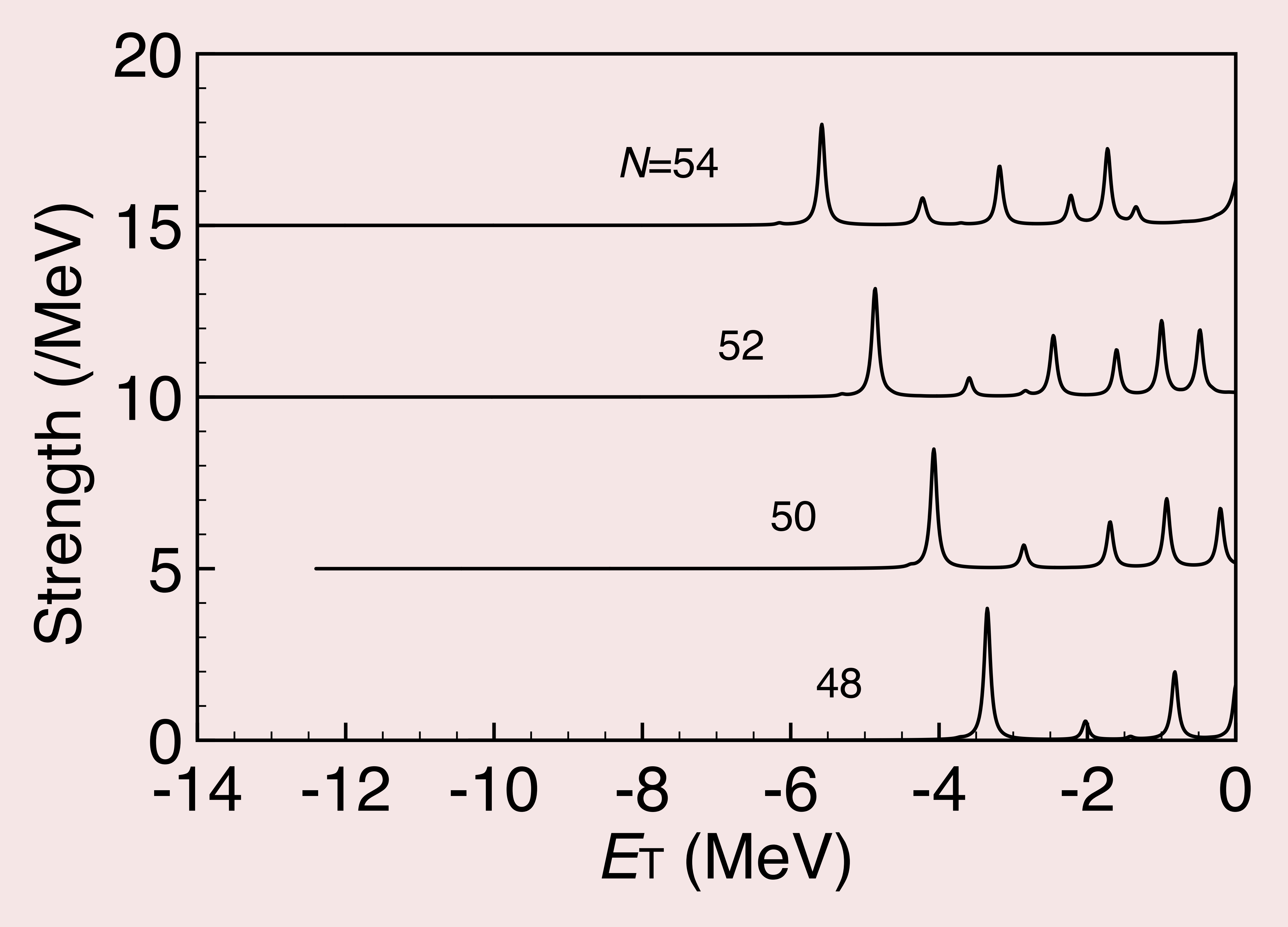
appearance of the low-lying negative-parity states

Shape factors of Ni isotopes

$$f = \int_1^{W_0} C_0 F_0(Z, W)(W^2 - 1)^{1/2} W (W_0 - W)^2 \mathrm{d}W$$

$$C_0 = |\langle \tau_- \rangle|^2 + \left(\frac{g_A}{g_V}\right)^2 |\langle \boldsymbol{\sigma} \tau_- \rangle|^2$$

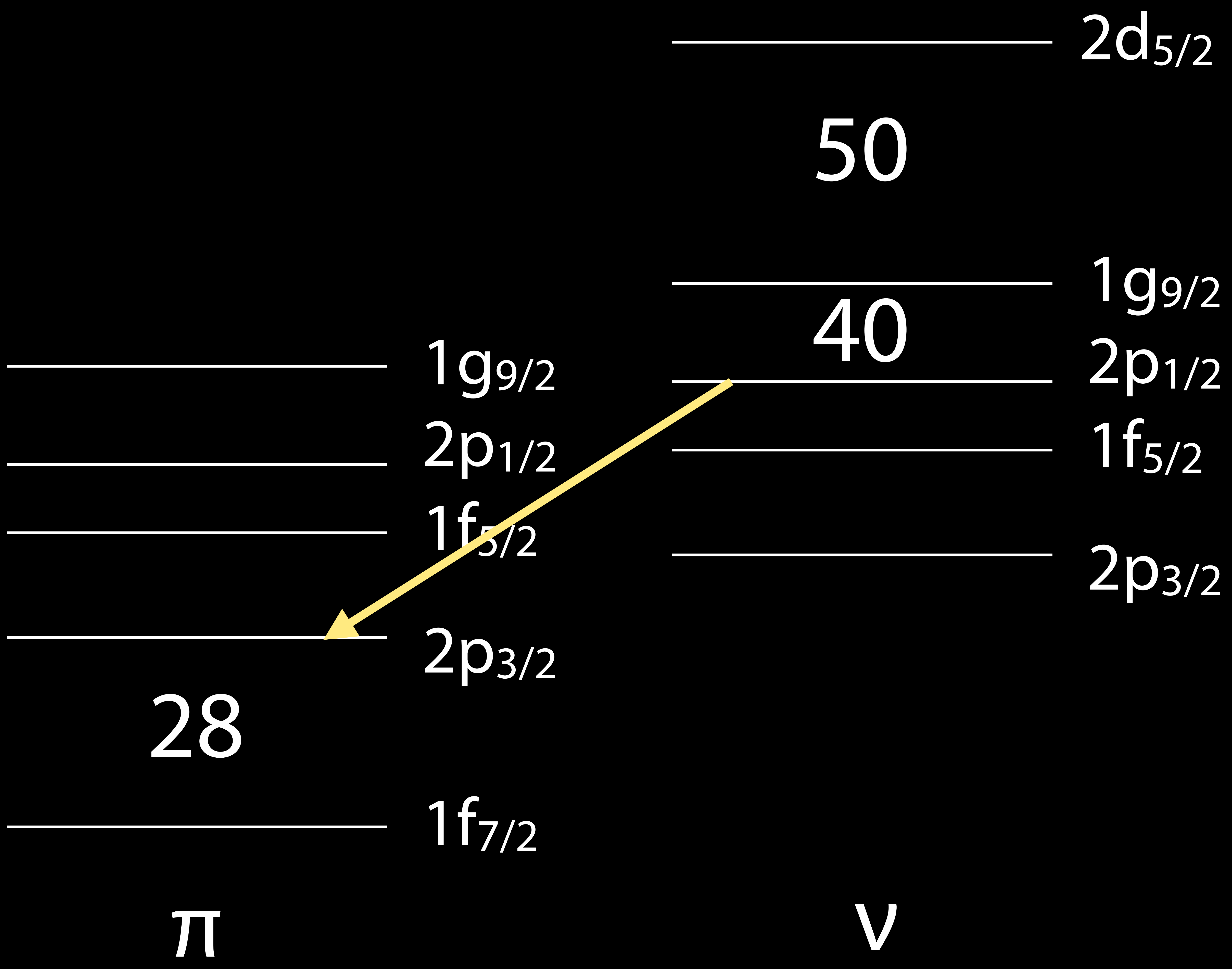
Allowed transitions



SkM*

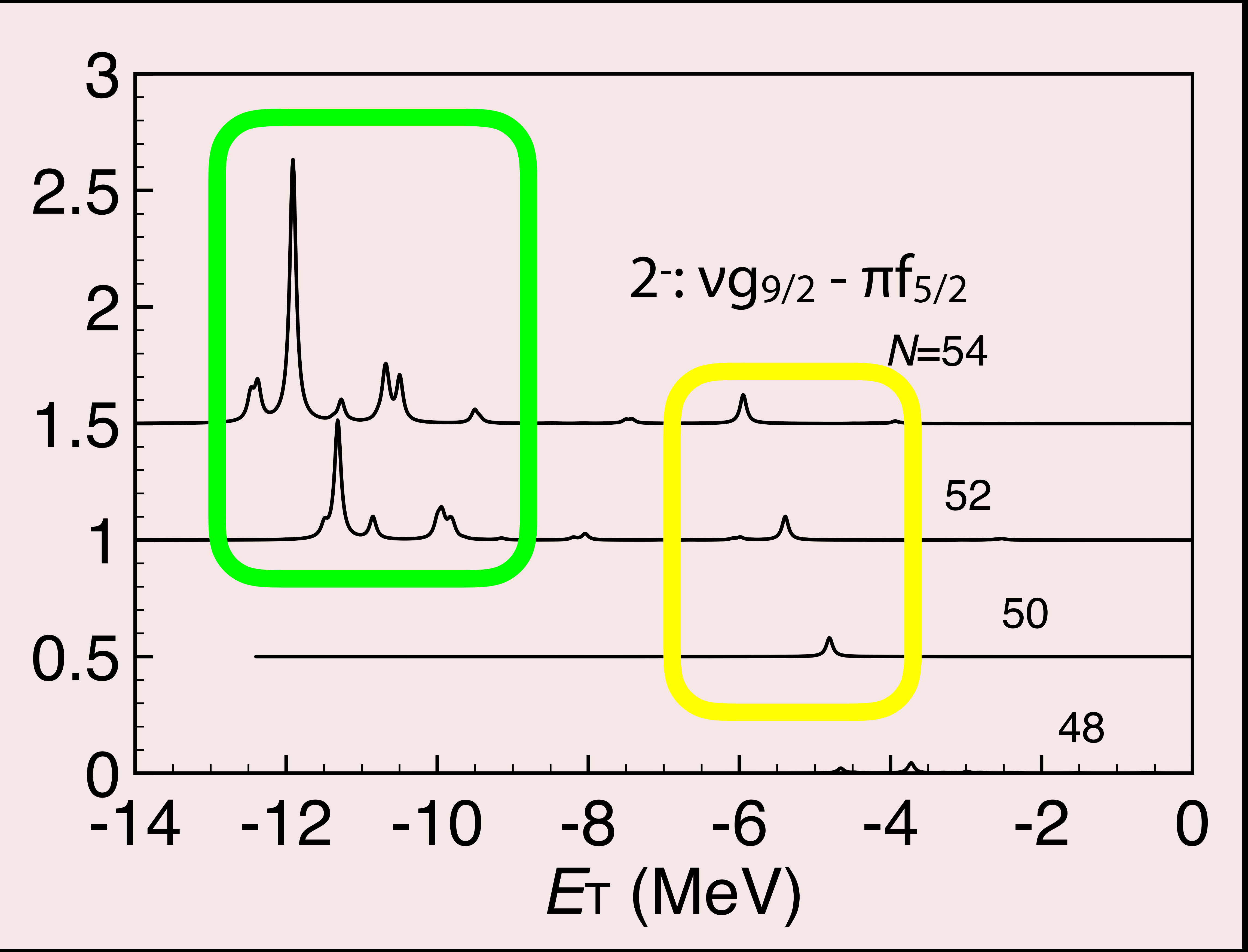
$$Q = -E_\mathrm{T} - \Delta M_{\mathrm{n-H}}$$

$$\Delta M_{\mathrm{n-H}} = 0.78\mathrm{MeV}$$



Shape factors of Ni isotopes

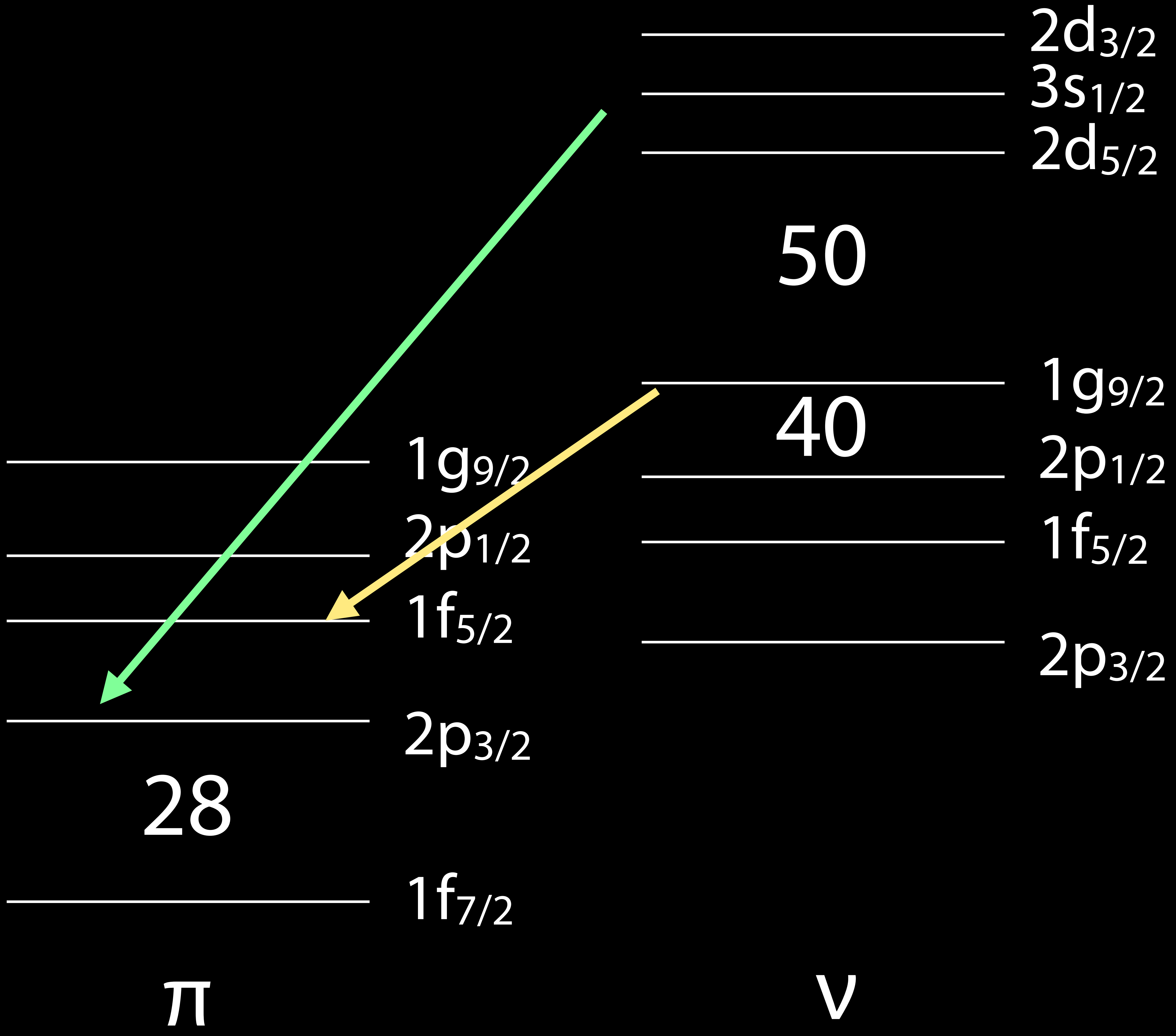
First-forbidden transitions



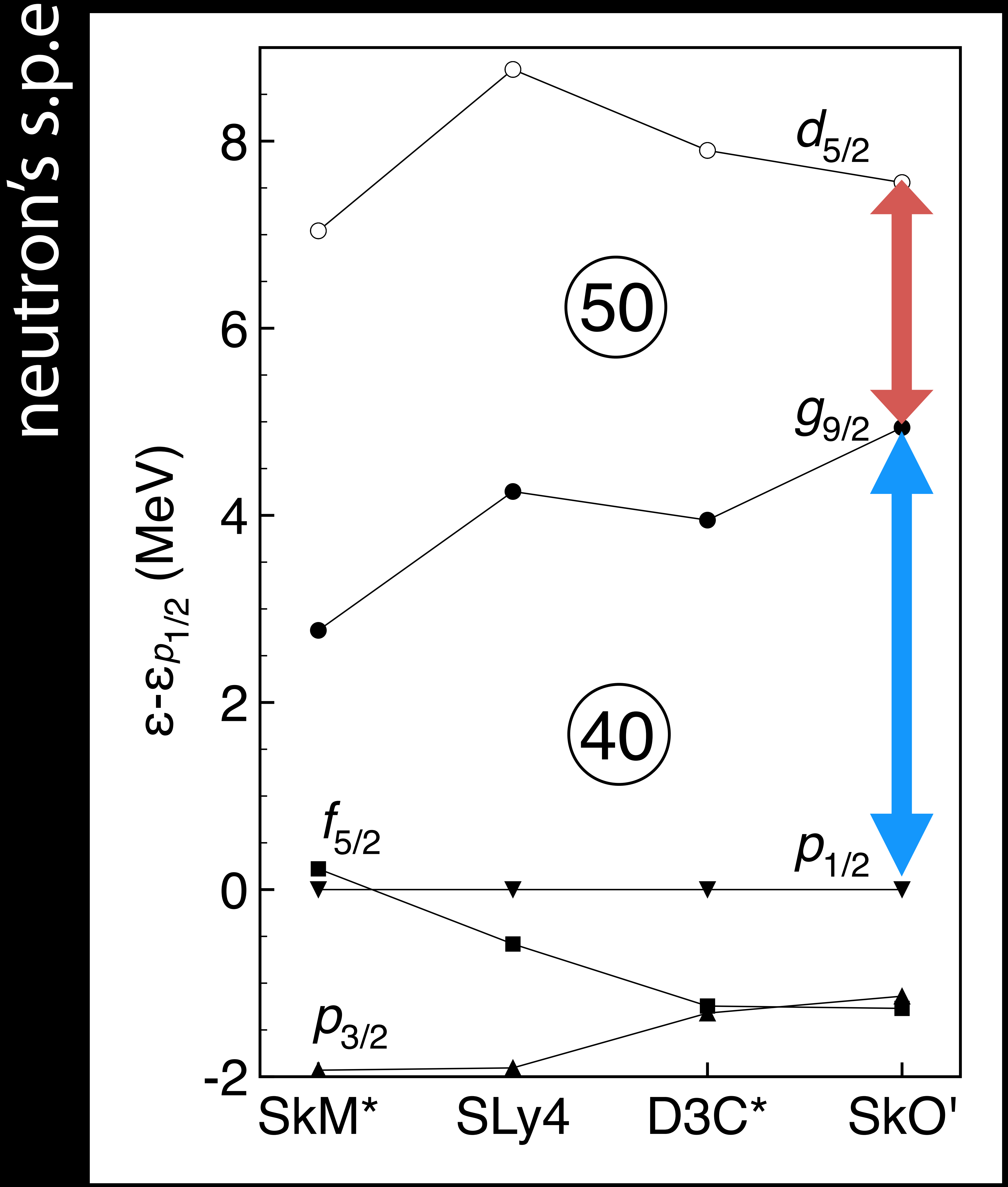
SkM*

"$-1\hbar\omega_0$ excitation" KY, PRC96(2017)051302(R)

low-lying negative parity states in a daughter



Shell gaps at N=40 and 50 for the decay rate



Calculated $T_{1/2}$:

SkM*, SLy4, D3C*

drop beyond N=50

SkO'

monotonic decrease

✓ gap energy of 40+50 ↗

FF contribution ↗

✓ gap energy of 40 ↗

higher energy 2^- ($\nu g_{9/2}$ - $\pi f_{5/2}$)

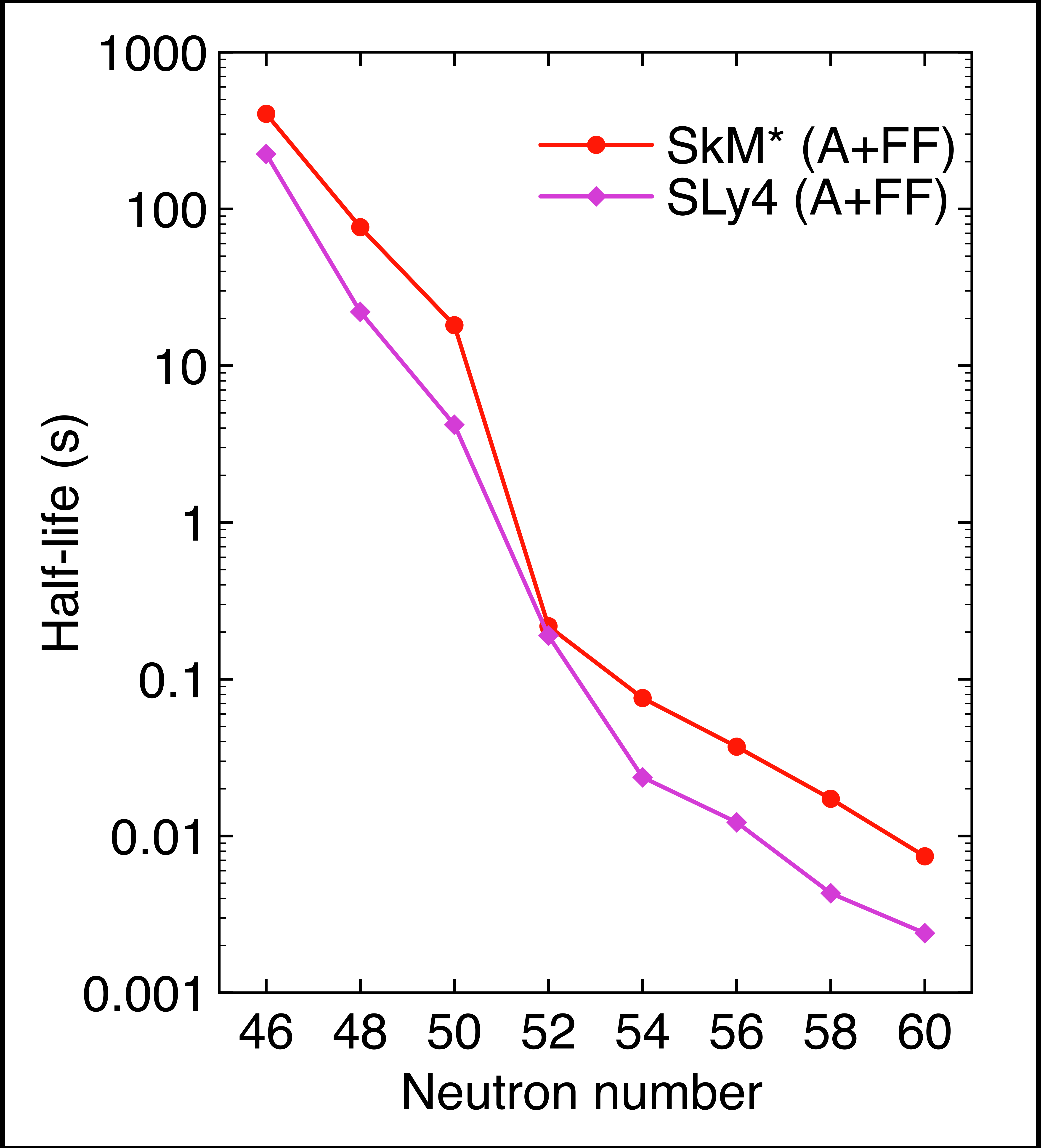
monotonic decrease in $T_{1/2}$

✓ gap energy of 40 ↘

lower energy 2^- ($\nu g_{9/2}$ - $\pi f_{5/2}$)

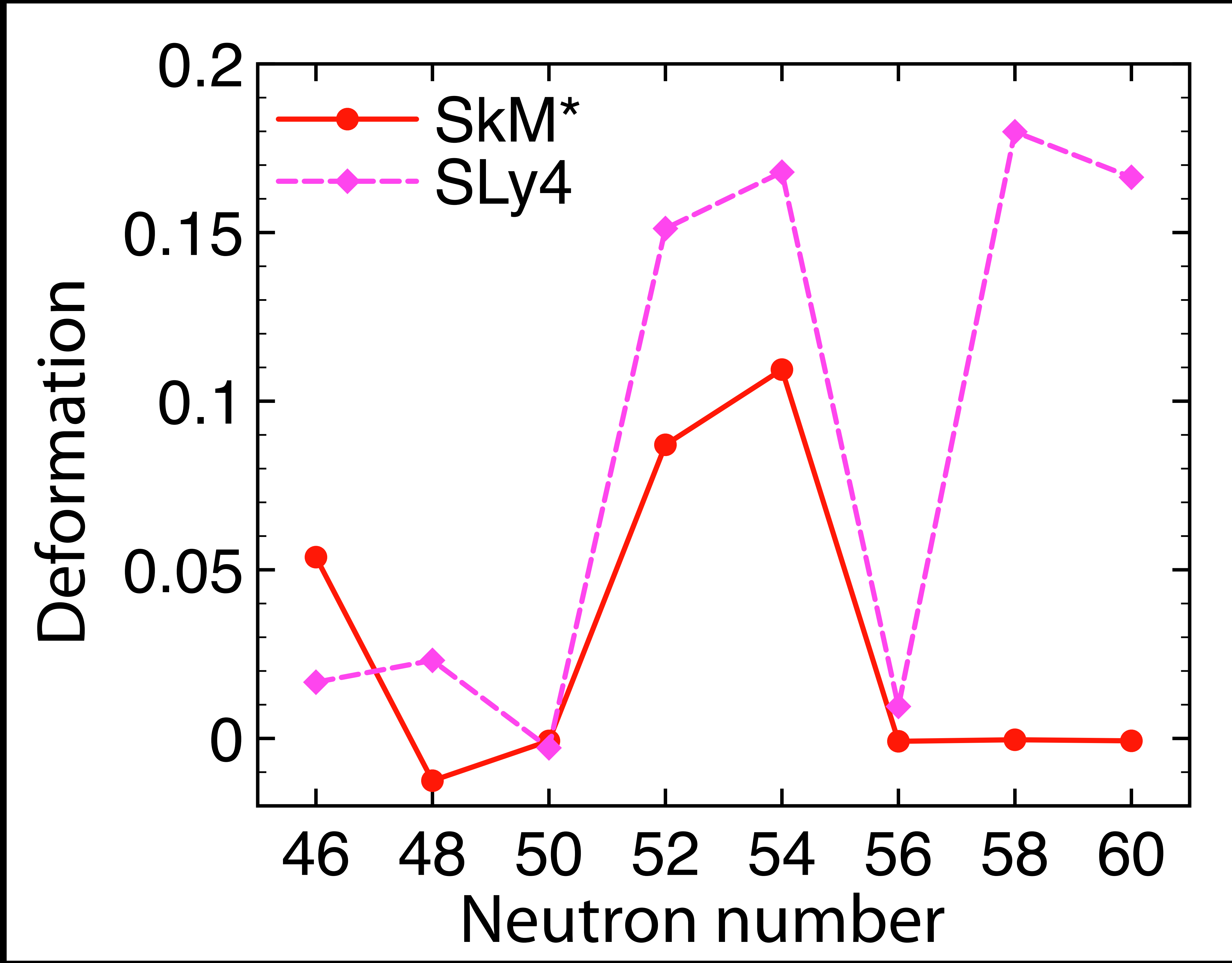
sudden decrease in $T_{1/2}$

β-decay half-lives of Zn isotopes



SLy4 gives monotonic shortening up to N=54

SLy4 produces larger deformation
additional high-energy allowed transitions



Summary

- Global (systematic) and microscopic calculation of the weak-interaction rates is strongly desirable
  - DFT-based calculation is promising
- Systematic calculation of β-decay rates of neutron-rich Ni isotopes around ^{78}Ni
  - Observed sudden shortening of the half-lives beyond N=50 was well described
  - Decisive role by the high-energy non-unique first-forbidden transitions
  - Smooth trend due to high-energy allowed transitions in the Zn isotopes associated with deformation