β-decay half-life as an indicator of shap-phase transition in neutron-rich Zr isotopes

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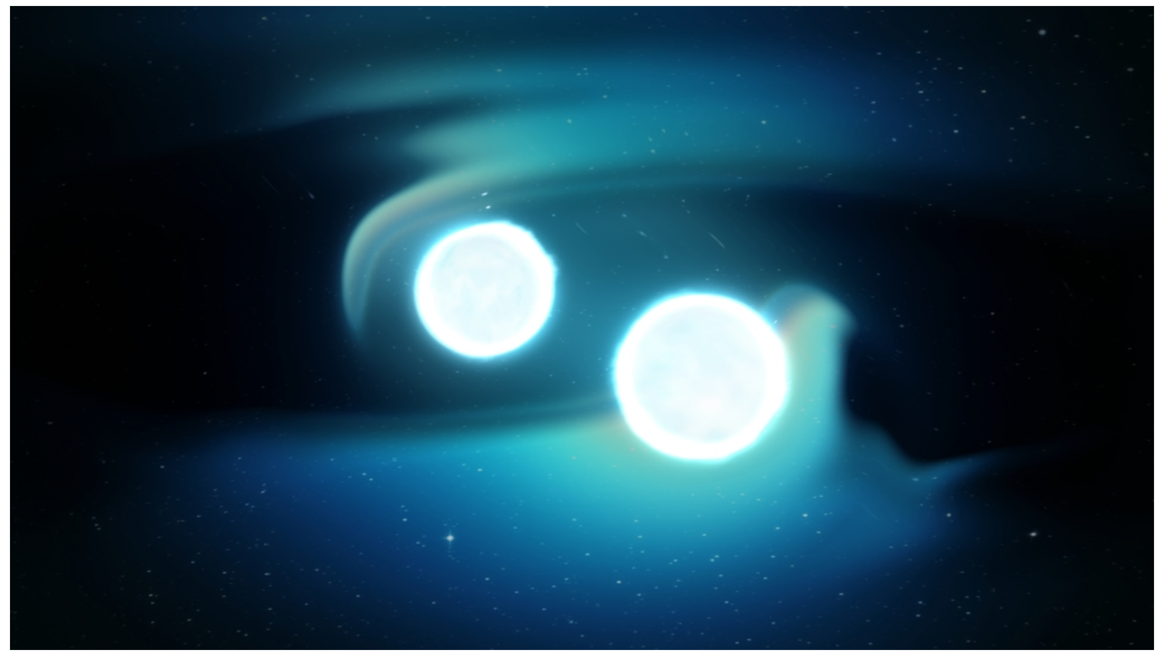
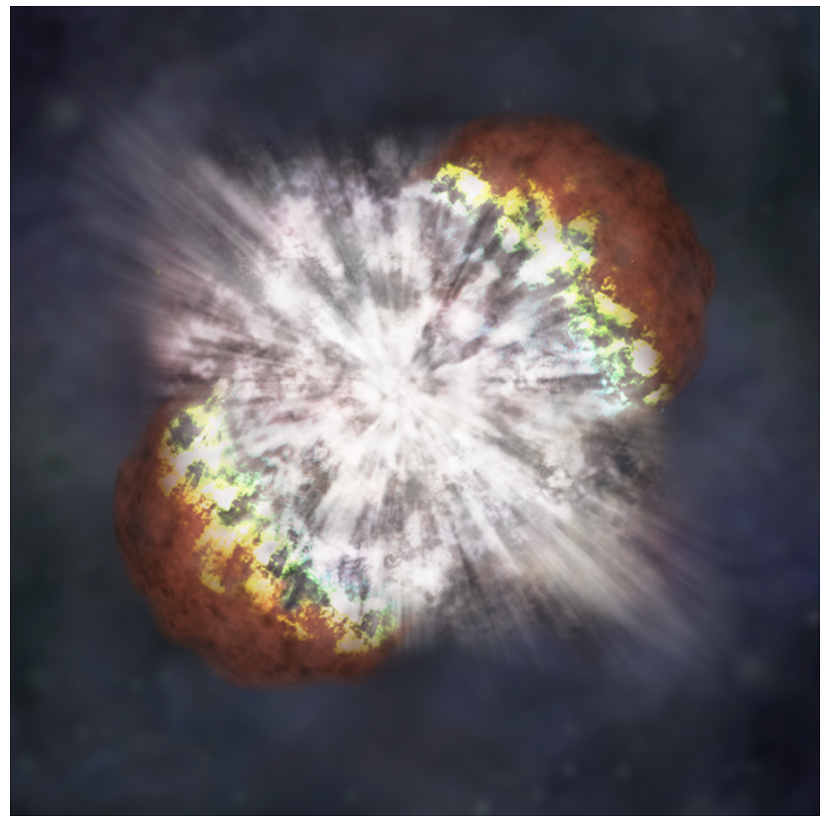
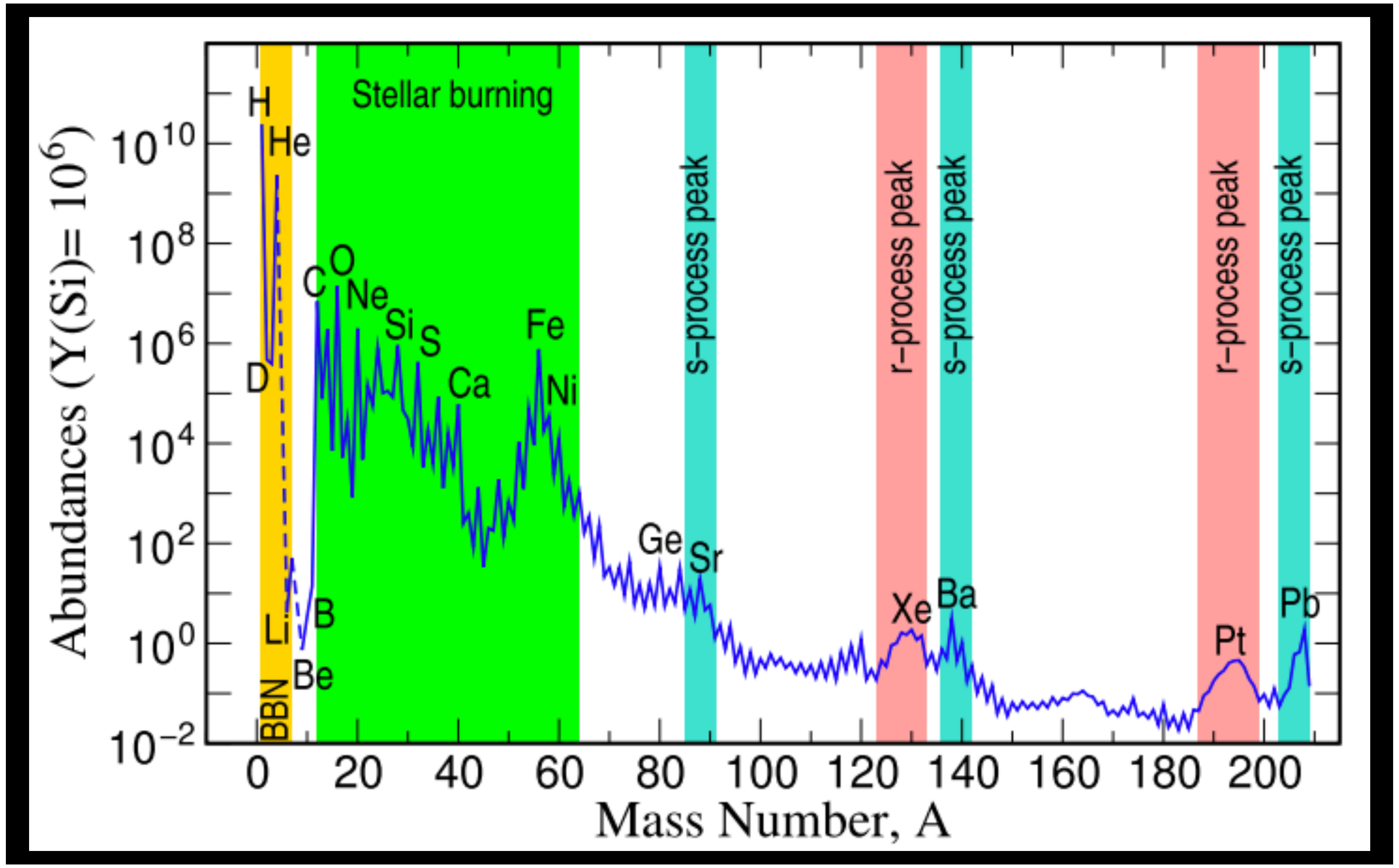
Thourough understanding of the r-process nucleosynthesis

- nuclear physics inputs
- nucleosynthesis modeling
- astrophysical conditions
- observations





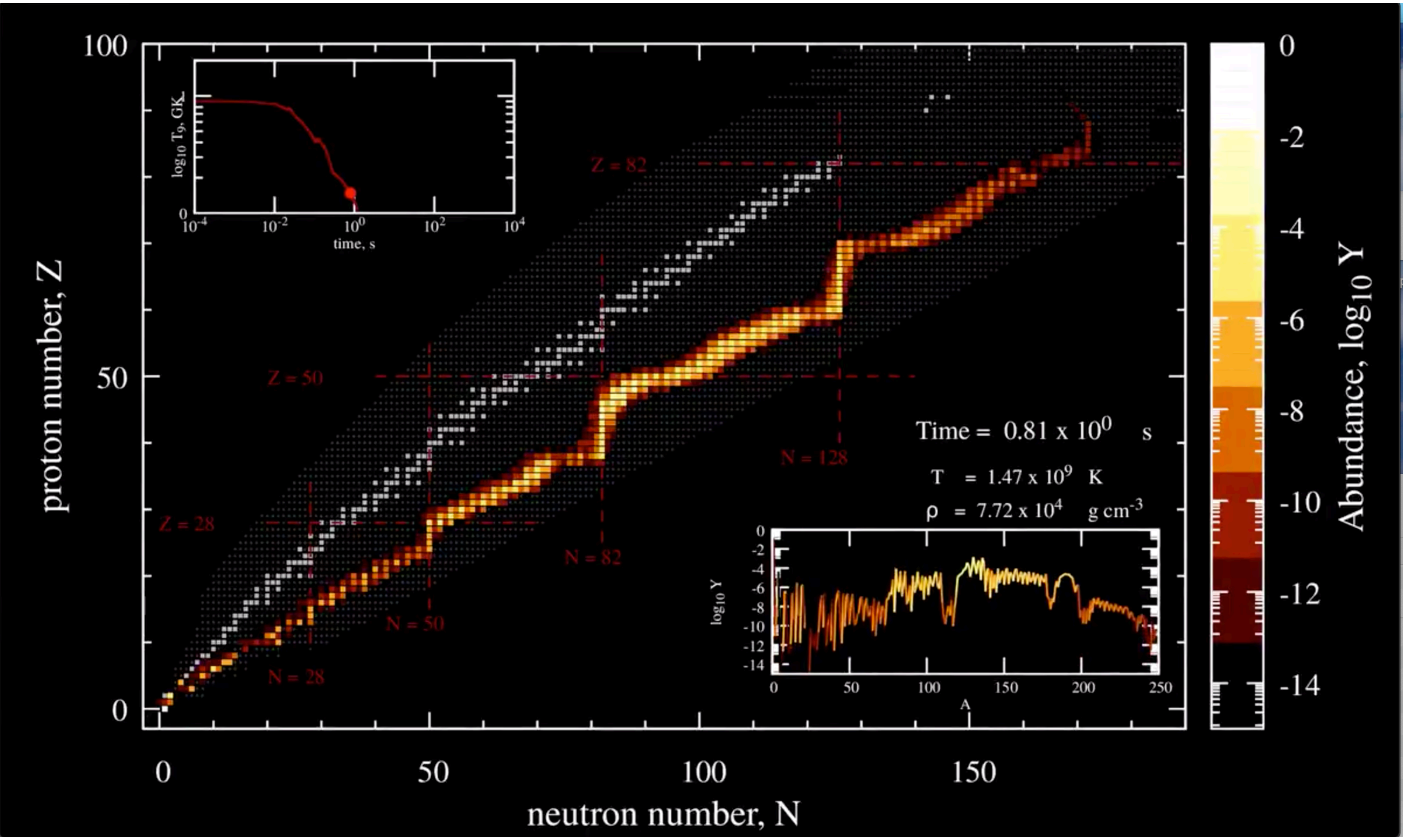


Cowan+, RMP(2021)

uncertainties both in nuclear physics and astophysics

→ enhance the reliabity of nuclear physics inputs

β-decay: a key in the r-process



simulation by N. Nishimura (CNS, Tokyo)

seed nuclei

neutron capture
***β* decay**

neutron-rich nuclei

reaching heavy nuclei

fission

neutron-induced fission

β-delayed fission

fission after *β*-delayed n-emission

late phase:

abandance pattern formed by ***β* decay**

Nuclear beta decay: looks simple

A semileptonic process governed by
an effective Hamiltonian for a low-energy ($\ll m_W$) charged current reaction:

$$H_{\text{eff}} = \frac{G_F V_{ud}}{\sqrt{2}} \int d\boldsymbol{x} \left[\bar{e}(\boldsymbol{x}) \gamma^\mu (1-\gamma_5) \nu_e(\boldsymbol{x}) J_\mu(\boldsymbol{x}) + \mathrm{H.c.} \right]$$

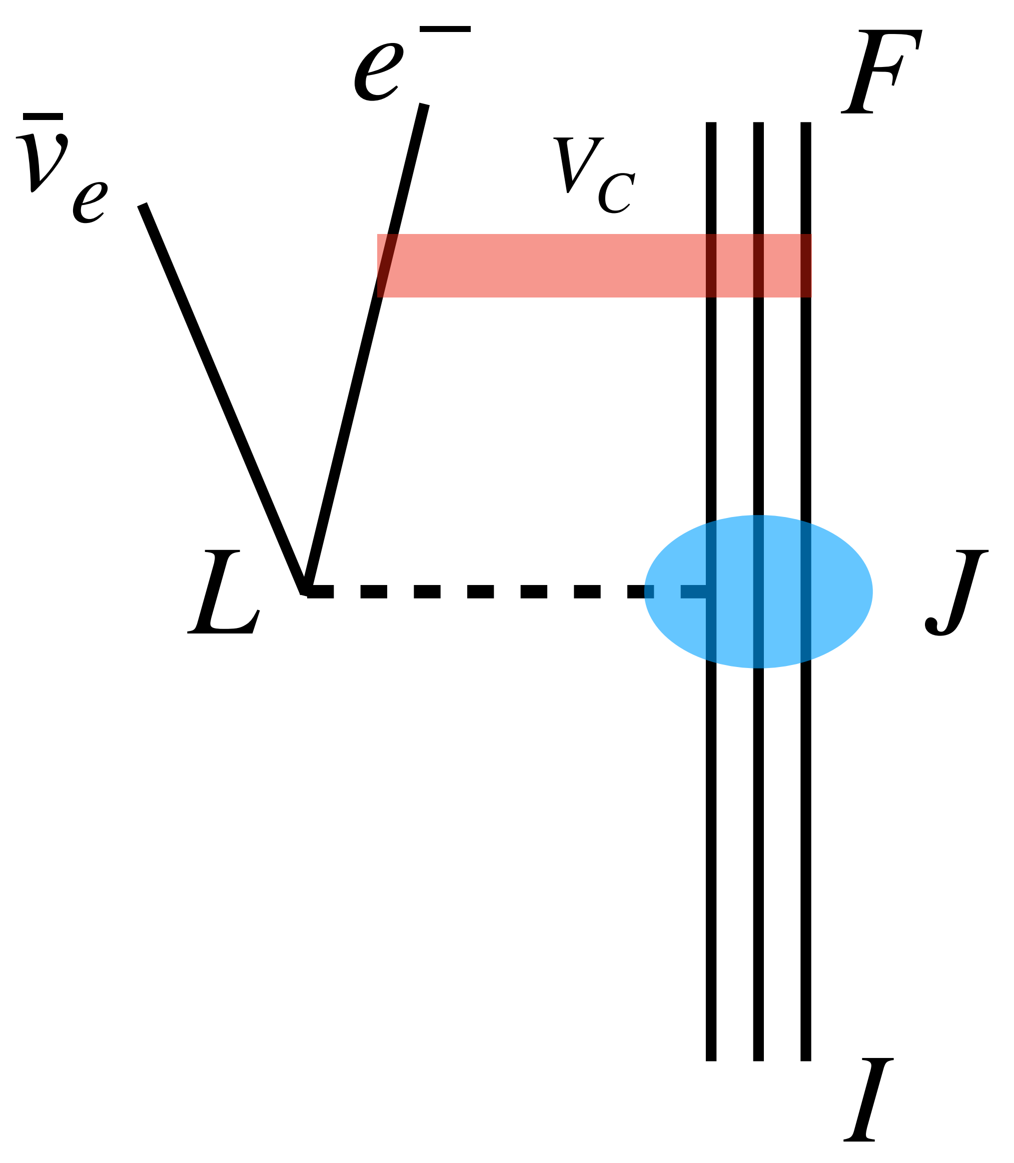
$G_F = 1.166 \times 10^{-5}\,\mathrm{GeV}^{-2}$

$V_{ud} = 0.9737$

Nuclear beta decay: really simple?

transition matrix element:

$$T_{fi} = \frac{G_F V_{ud}}{\sqrt{2}} \int d\boldsymbol{x} \overline{\psi}_{e^-}(\boldsymbol{x}) \gamma^\mu (1-\gamma_5) \psi_\nu(\boldsymbol{x}) \underline{\langle F | J_\mu(\boldsymbol{x}) | I \rangle}$$



Nuclear currents involving not only the nuclear many-body wave functions but the form factors and momentum tranfer

$$J^\mu(\boldsymbol{x}) = \mathscr{V}^\mu(\boldsymbol{x}) - \mathscr{A}^\mu(\boldsymbol{x})$$

vector currents $\mathscr{V}^\mu = (V^0, \boldsymbol{V})$ axial-vector currents $\mathscr{A}^\mu = (A^0, \boldsymbol{A})$

decay rate: $$\Gamma = \frac{(G_F V_{ud})^2}{\pi^2} \int_{m_e}^{E_0} dE_e\, p_e E_e \left(E_0 - E_e\right)^2 \sum_{J,\kappa_e,\kappa_\nu} \frac{1}{2J_i+1} \left| \sum_L \langle f || \underline{\Xi_{JL}(\kappa_e,\kappa_\nu)} || i \rangle \right|^2$$

multipole operator

Nuclear transition density

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

$$\hat{F}^\pm = \sum_{\tau,\tau'} f(\mathbf{r}) \hat{\psi}^\dagger(\mathbf{r}\tau) \hat{\psi}(\mathbf{r}\tau') \langle \tau | \tau_\pm | \tau' \rangle$$

- Ab-inito and CI methods for light nuclei and heavy nuclei near the magic number
- Linear-response TDDFT for all the nuclei

cf. talk by Miyagi

$$\delta\rho(\mathbf{r}, t) \sim \delta\rho(\mathbf{r}) e^{-i\omega t} \qquad e^{-i\omega t} \hat{F} = e^{-i\omega t} \int d\mathbf{r} f(\mathbf{r}) \hat{\psi}^\dagger(\mathbf{r}) \hat{\psi}(\mathbf{r})$$

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

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

equivalent to (Q)RPA ⟷

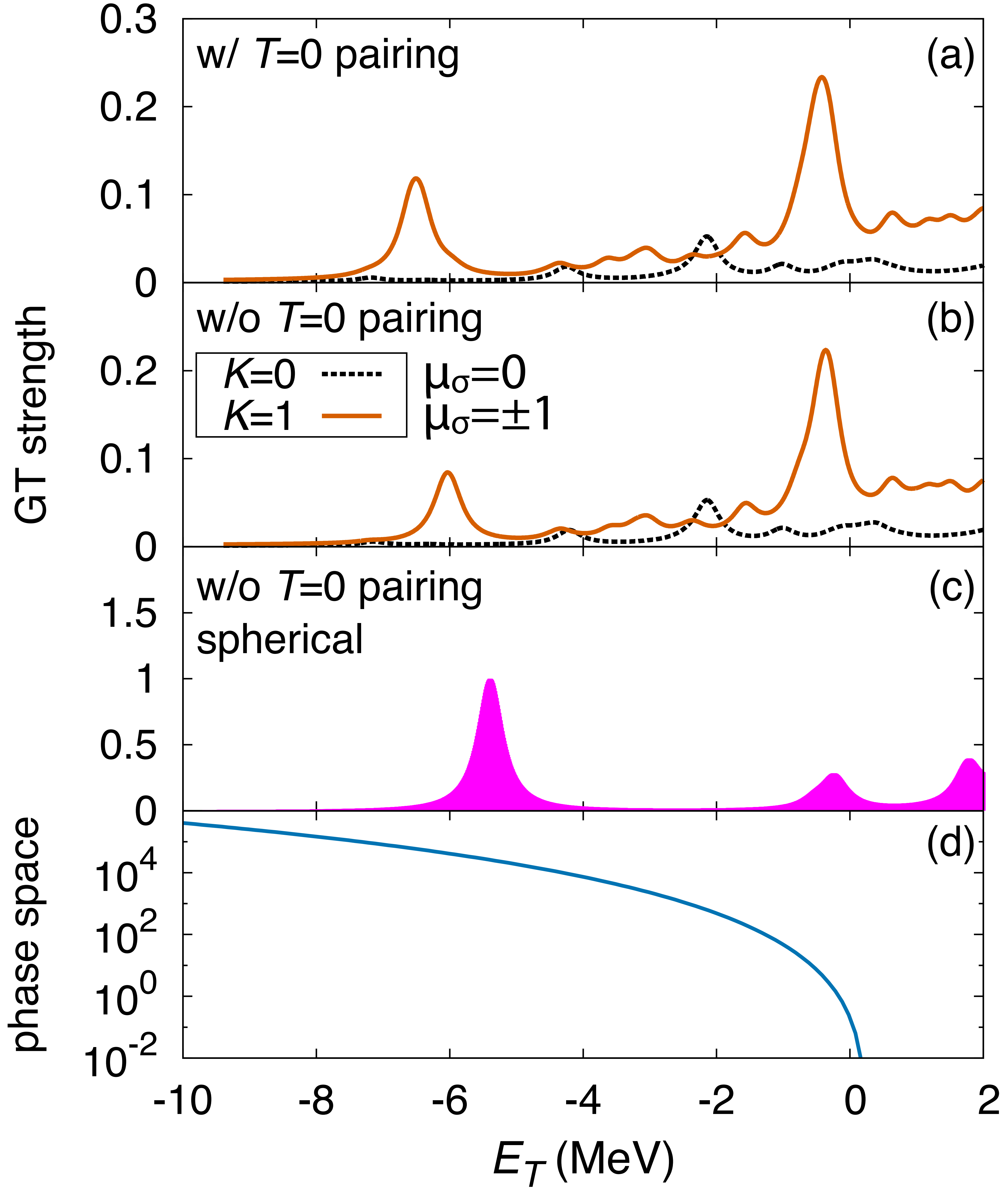
$$\delta\rho = \frac{\chi_0}{1 - \chi_0 v_{\rm res}} f = \chi_{\rm RPA} f$$

proton-neutron (Q)RPA: linear response to the charge-exchange operator

β-decay as a probe of nuclear structure: many-body correlations

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

^{106}Zr



KY, JPS Conf. Proc. 6(2015)020017

SLy4

$T_{1/2} = 0.21$ s

$T_{1/2} = 0.41$ s

deformation
superfluidity

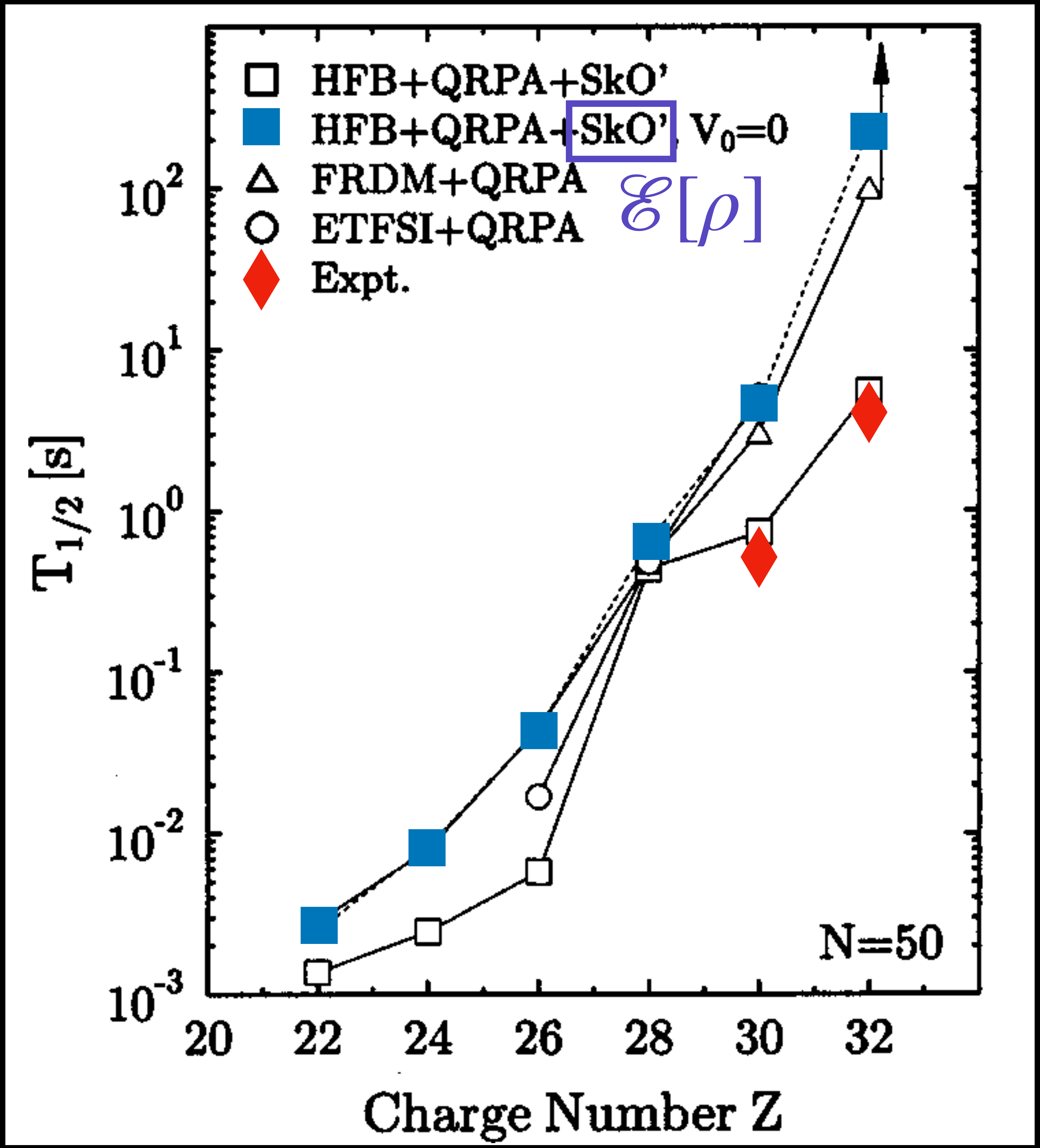
$T_{1/2} = 0.07$ s

Exp.
$T_{1/2} = 0.186(11)$ s

β-decay rate is sensitive to the details of nuclear structure

Pioneering microscopic cal. for β-decay based on DFT

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



Hadronic current

$$J_\mu(x) = \bar{\psi}_{\rm p}(x)[V_\mu - A_\mu]\psi_{\rm n}(x)$$

$$V_\mu = g_{\rm V}(q^2=0)\gamma_\mu \cancel{+ i g_{\rm M}(q^2)\frac{\sigma_{\mu\nu}}{2m_{\rm n}}q^\nu}$$

$$A_\mu = g_{\rm A}(q^2=0)\gamma_\mu\gamma_5 \cancel{+ i g_{\rm P}(q^2)q_\mu\gamma_5}$$

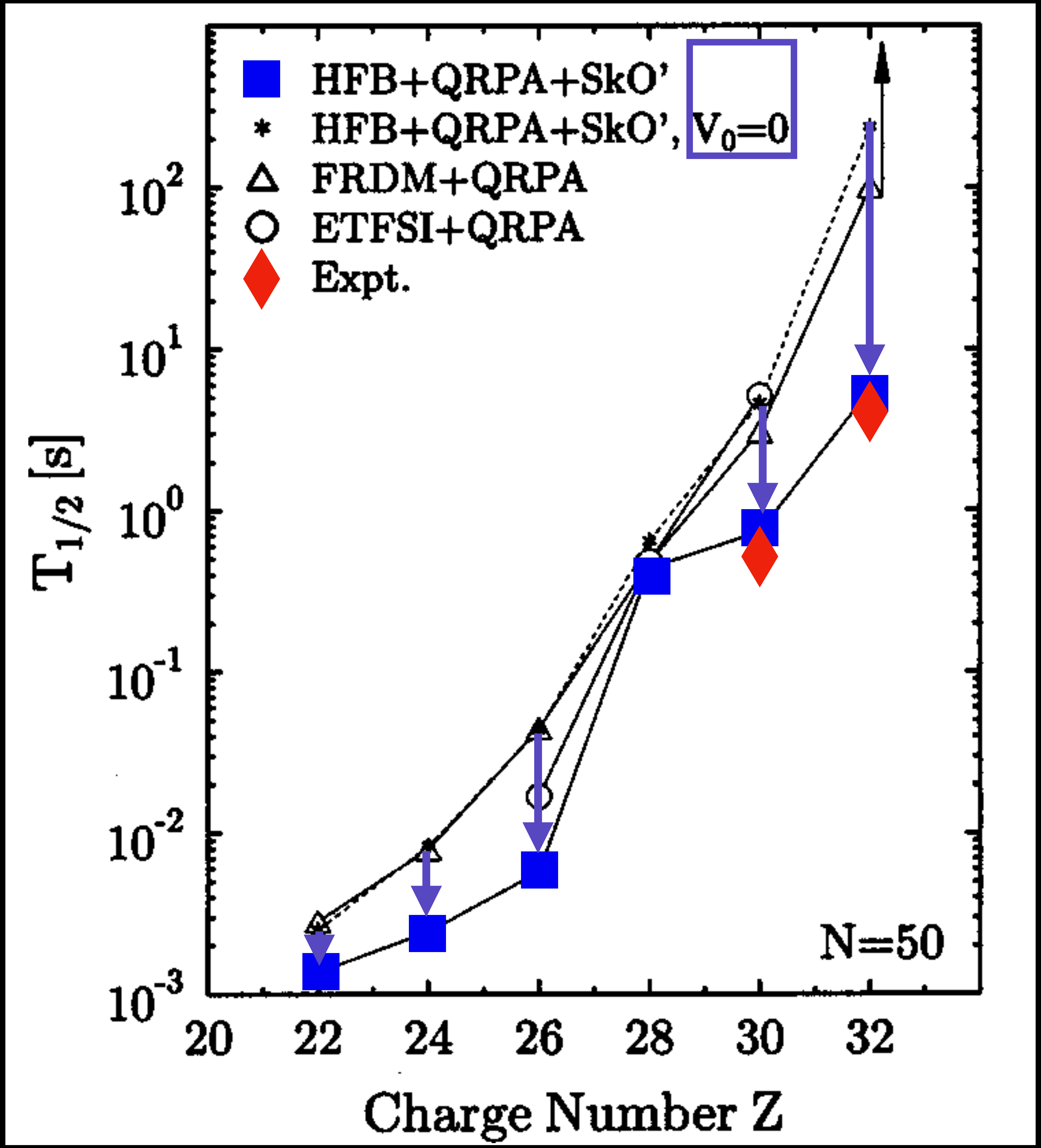
quenching

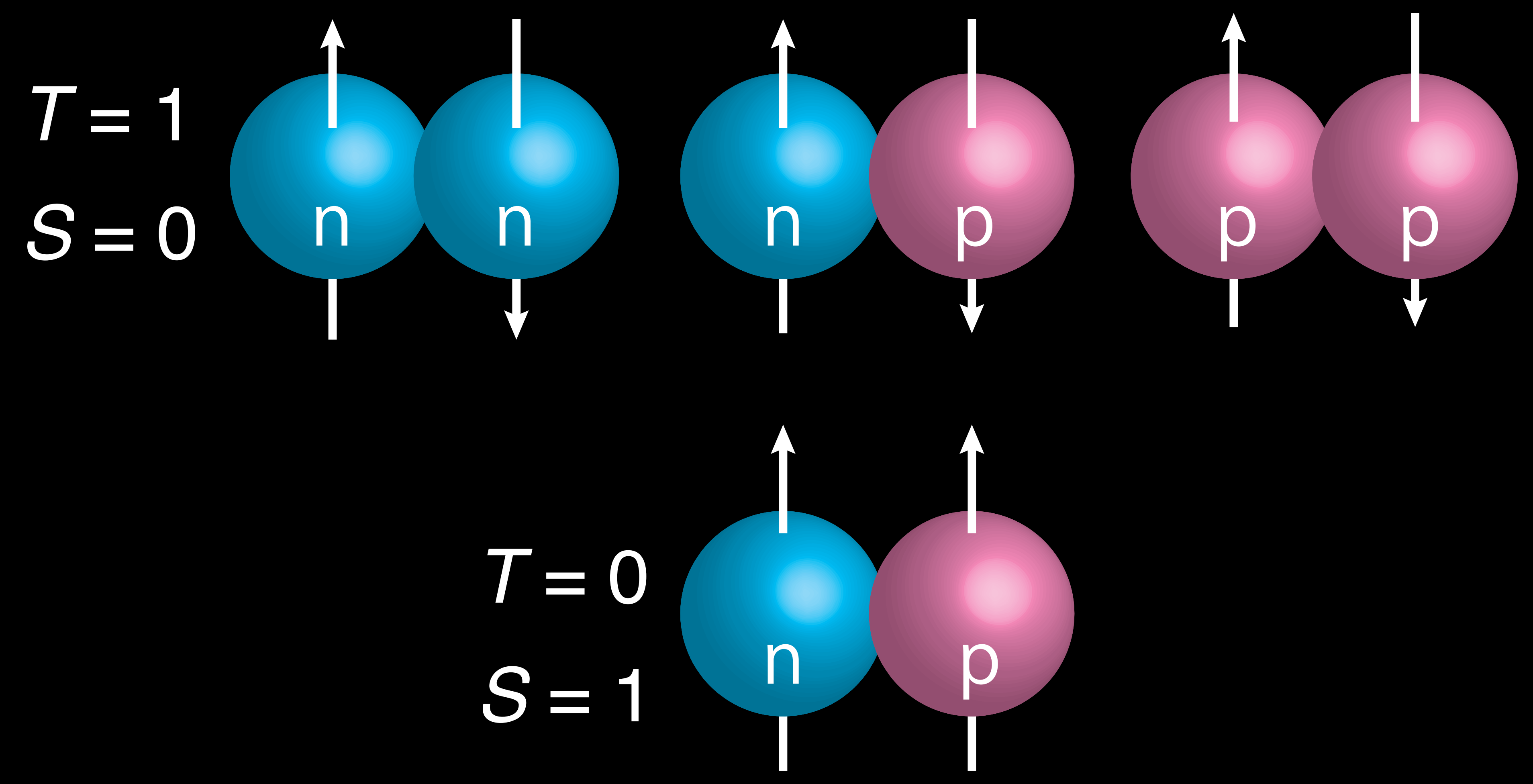
$$g_{\rm A}^{\rm eff} = q g_{\rm A}$$
$$q \sim 0.78$$

non-nucleonic d.o.f.
two-body currents
short-range correlation
truncation of many-body space

Important role of the spin-triplet pairing revealed by the microscopic cal.

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



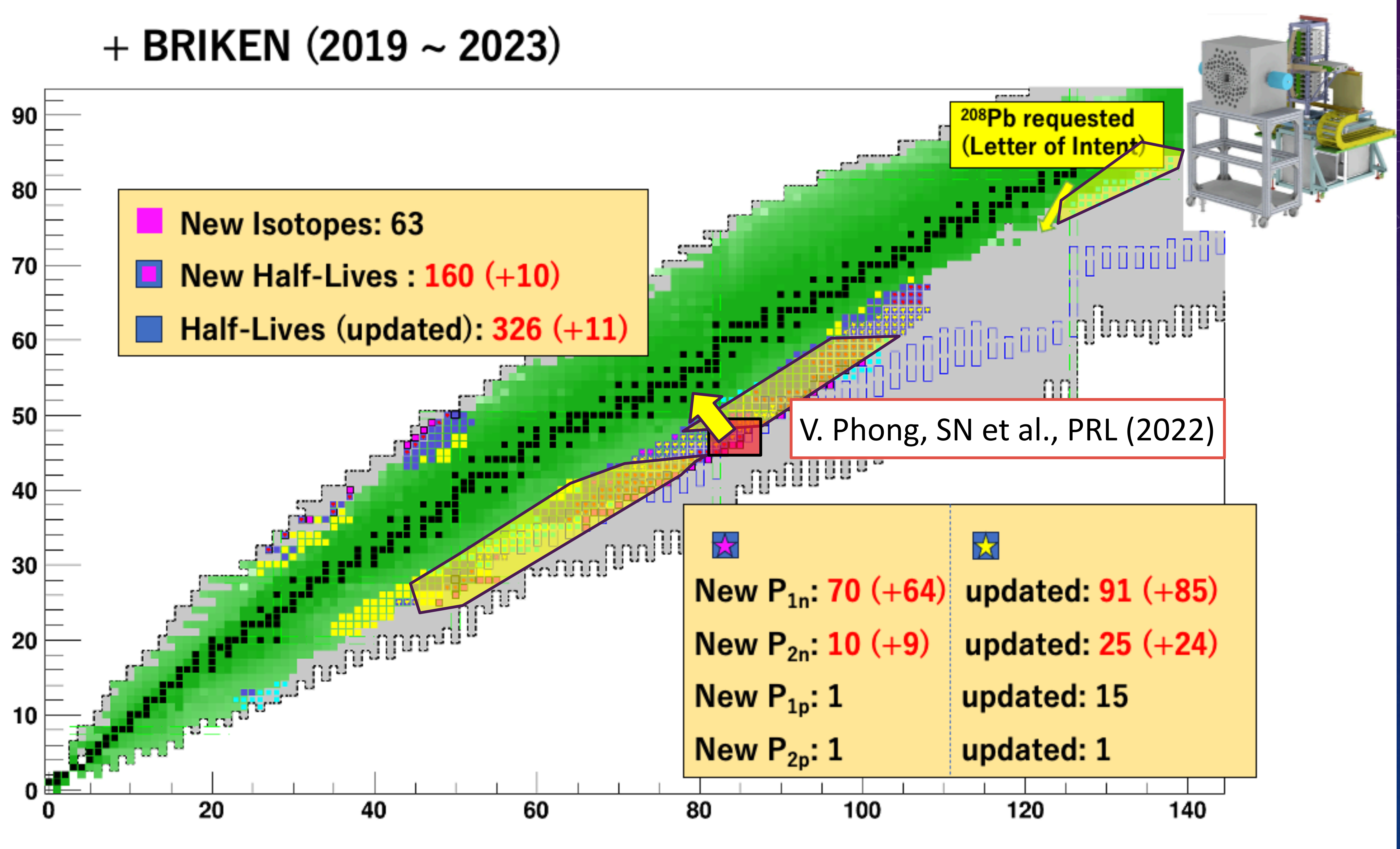


- ✓ being not included in FRDM
- ✓ shortens the half-lives
- ✓ sensitive to the shell structure

Decay Properties Surveyed

courtesy of S. Nishimura (RIKEN)

EURICA

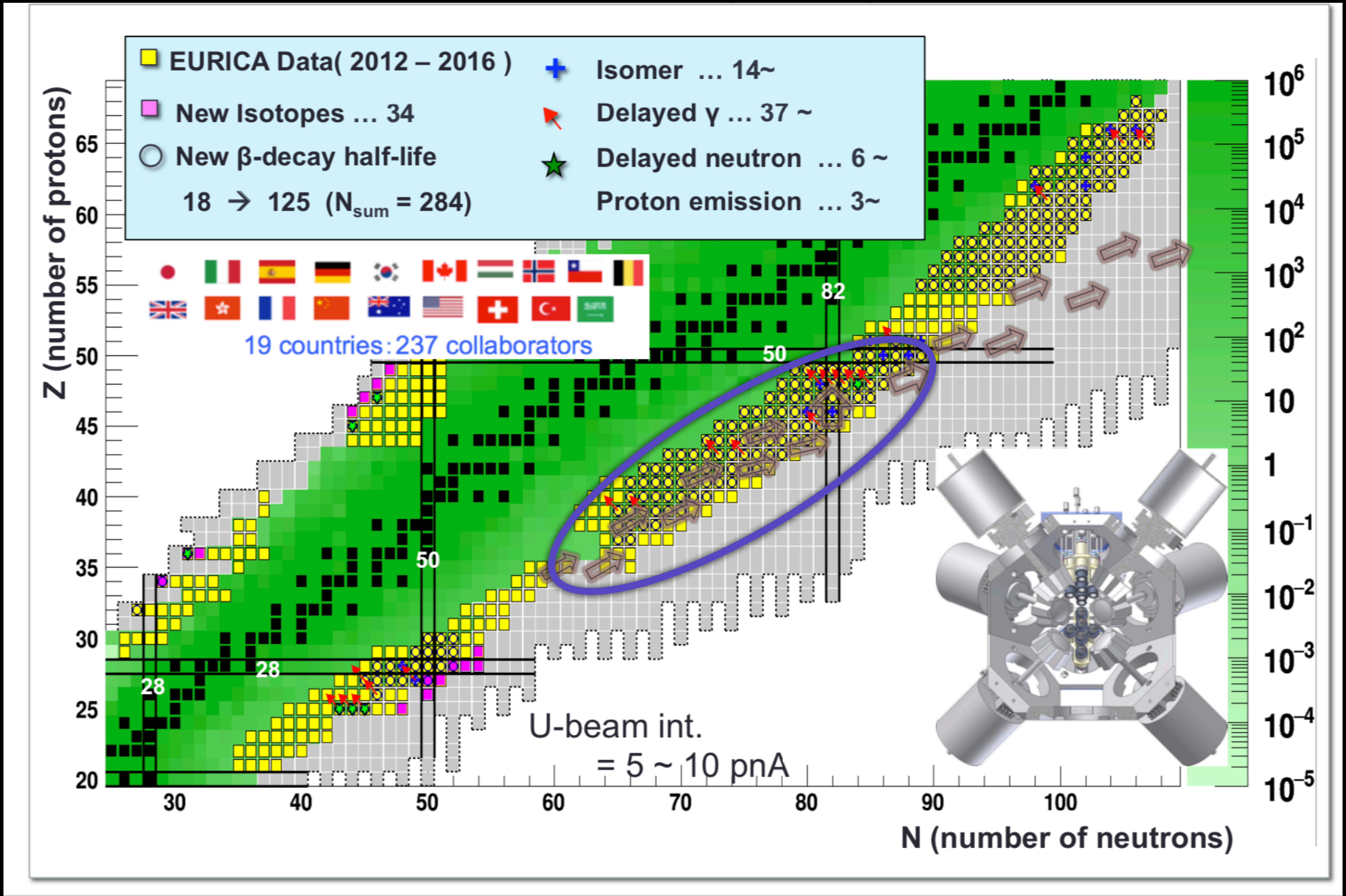


More Decay Data ($T_{1/2}$, P_{xn}) … + ~ 200 Isotopes expected from BRIKEN

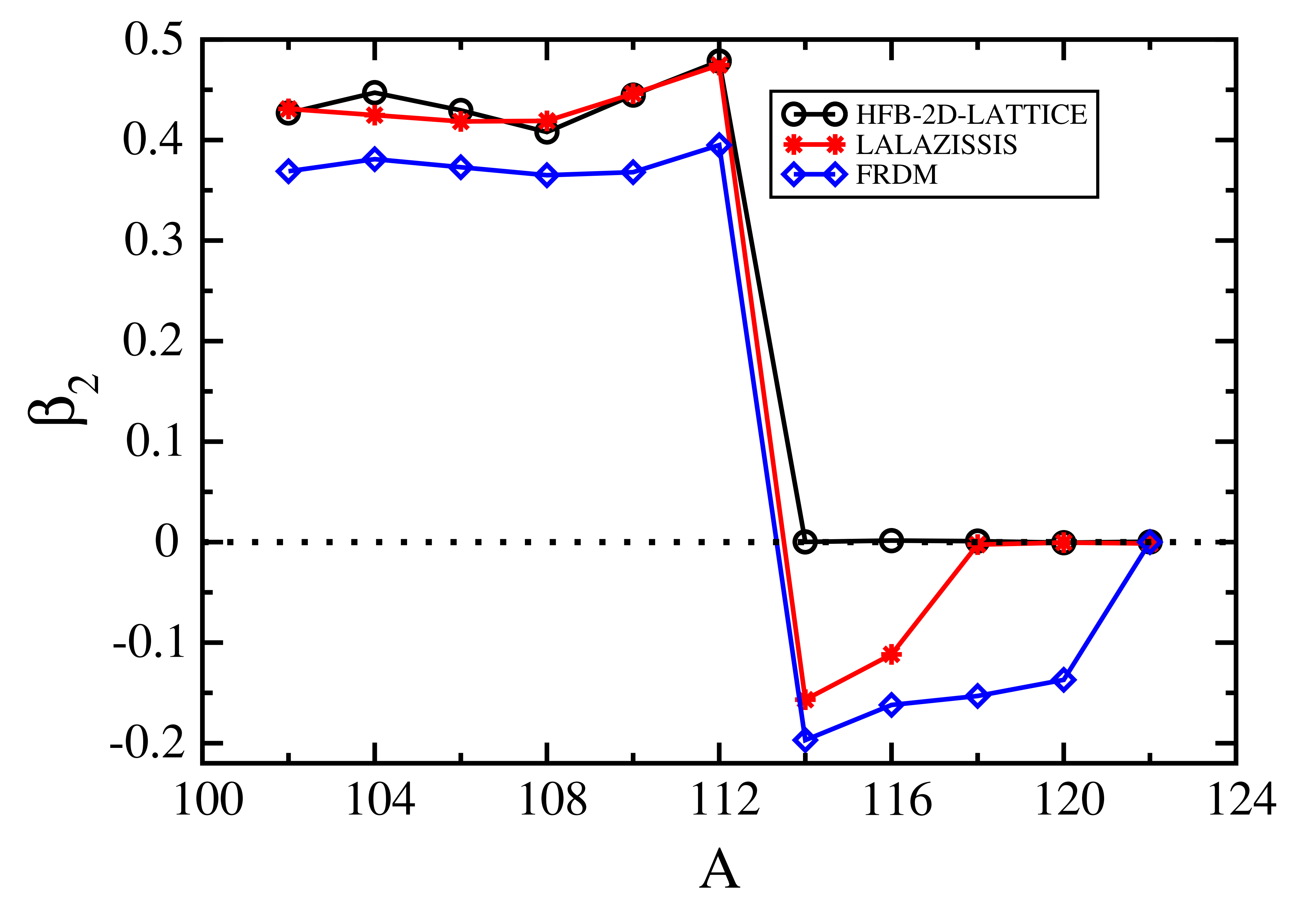
Systematic measurement of β-decay@RIBF

S. Nishimura *et al.*

β-decay half-lives of r-process nuclei



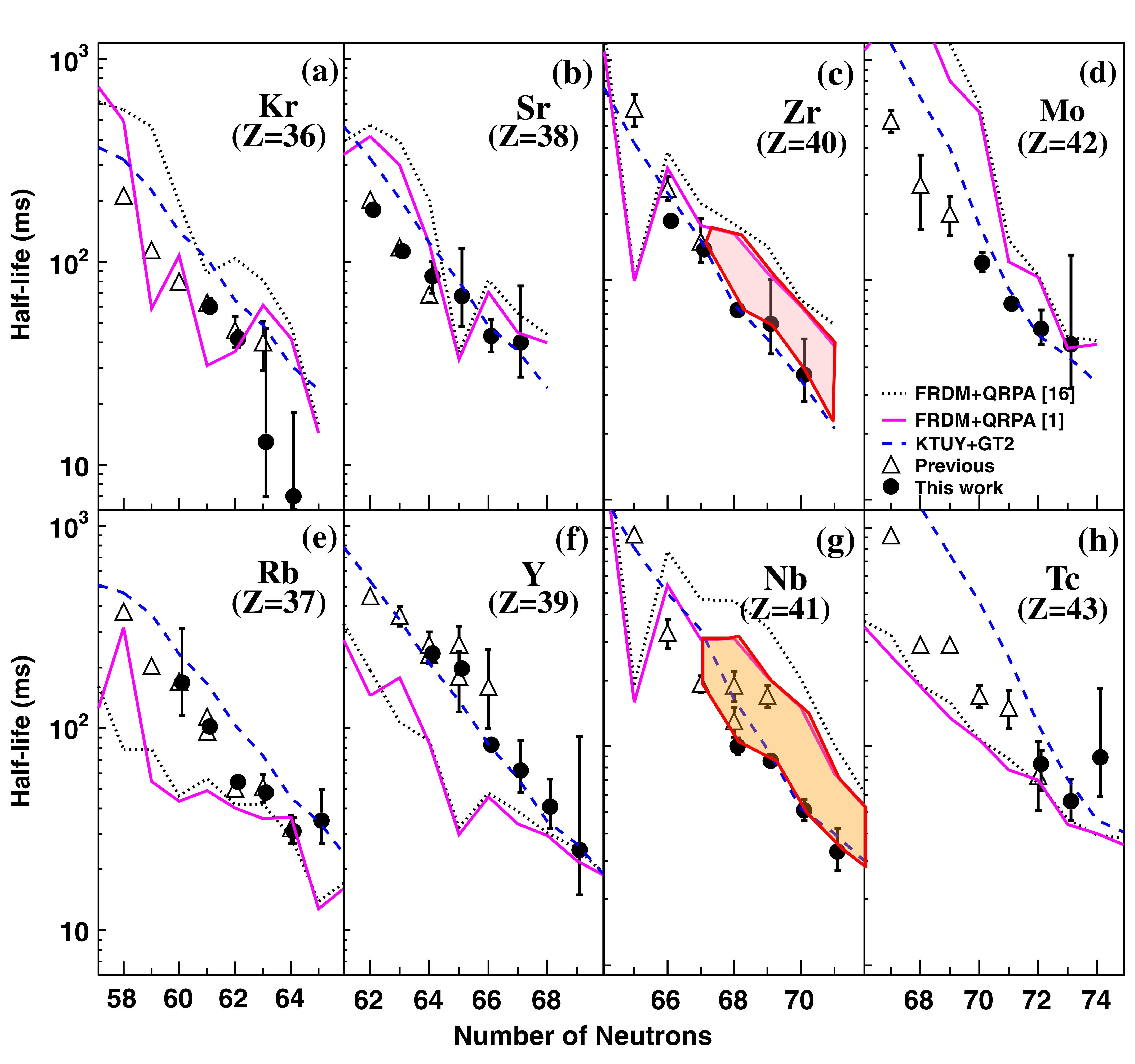
neutron-rich Zr isotopes:
predicted to be well deformed
by DFT cal.

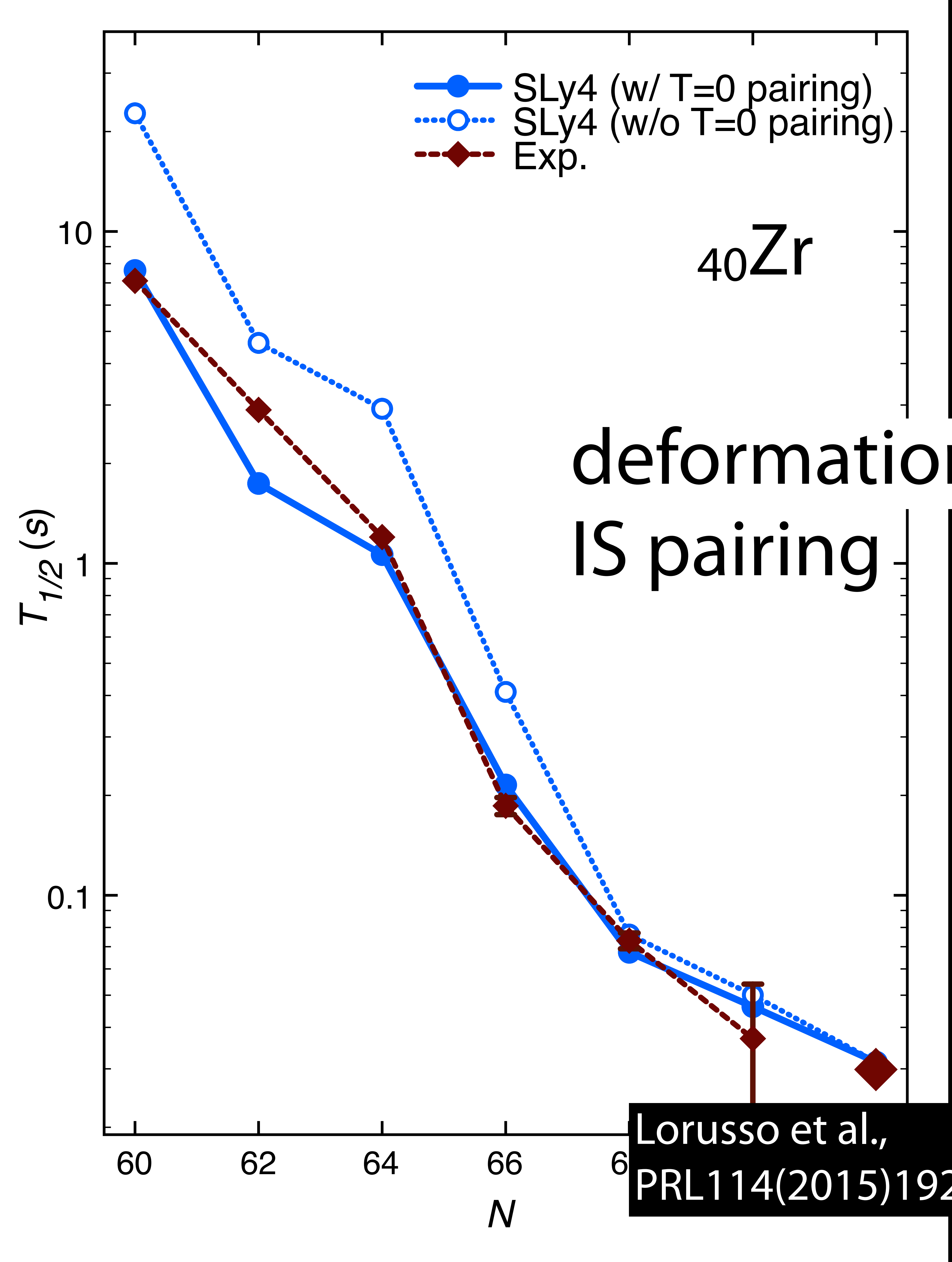


A. Blazkiewicz+, PRC71(2005)054321

Short half-lives in the Zr region

KY, PTEP(2013)113D02

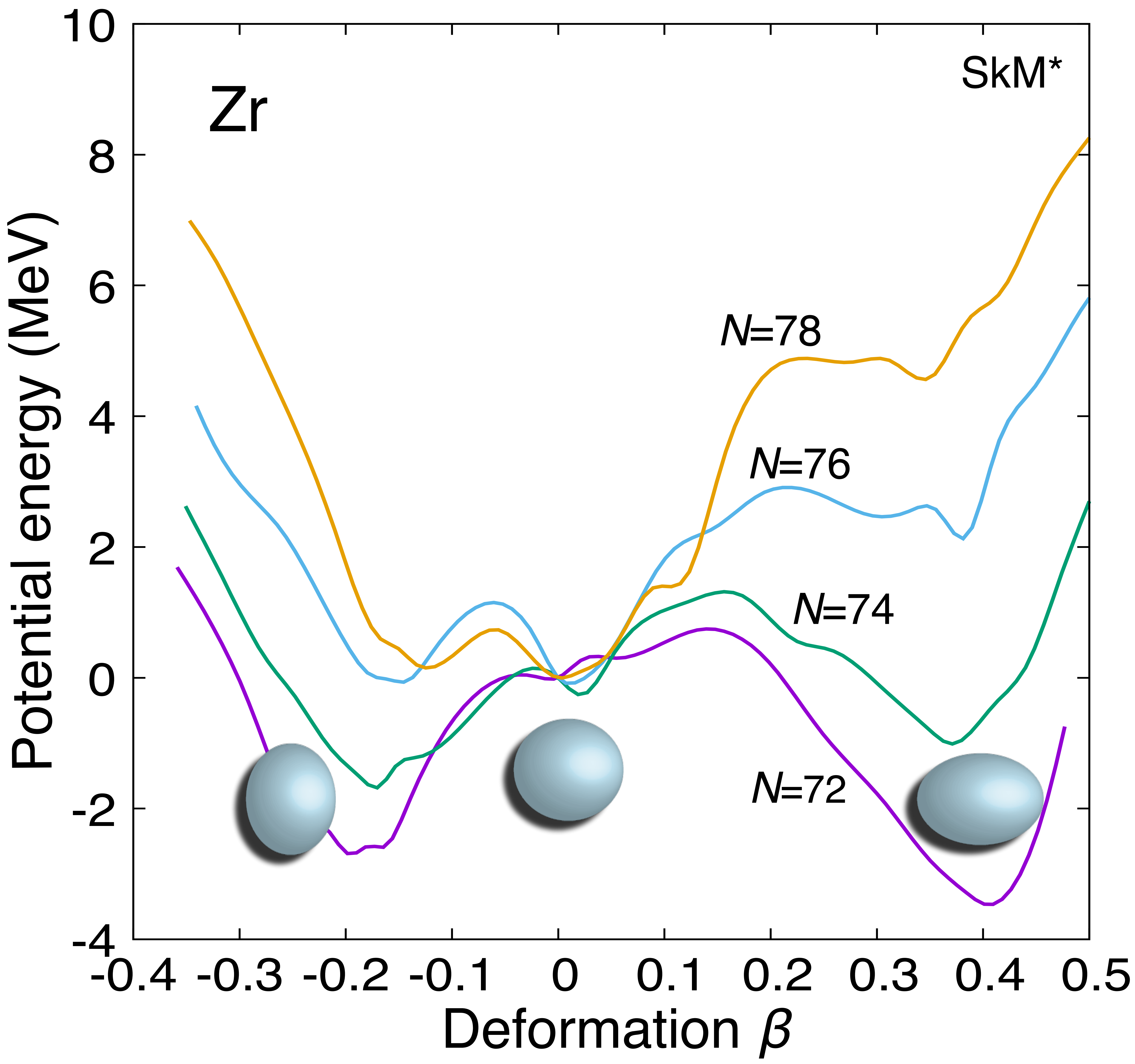




deformation
IS pairing

Lorusso et al.,
PRL114(2015)192501

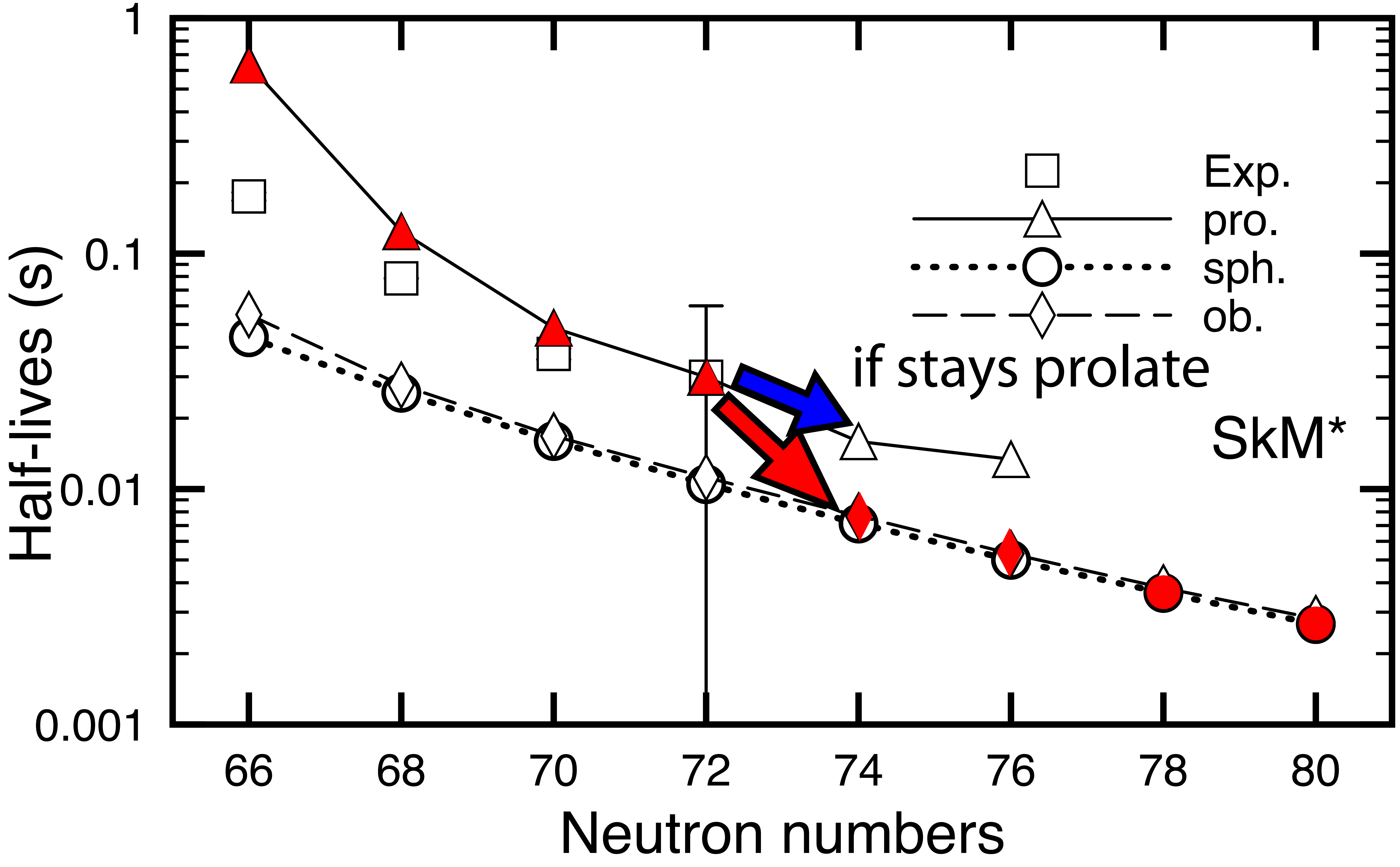
Neutron-rich Zr isotopes: shape phase transition



shape changes can be seen in β-decay?

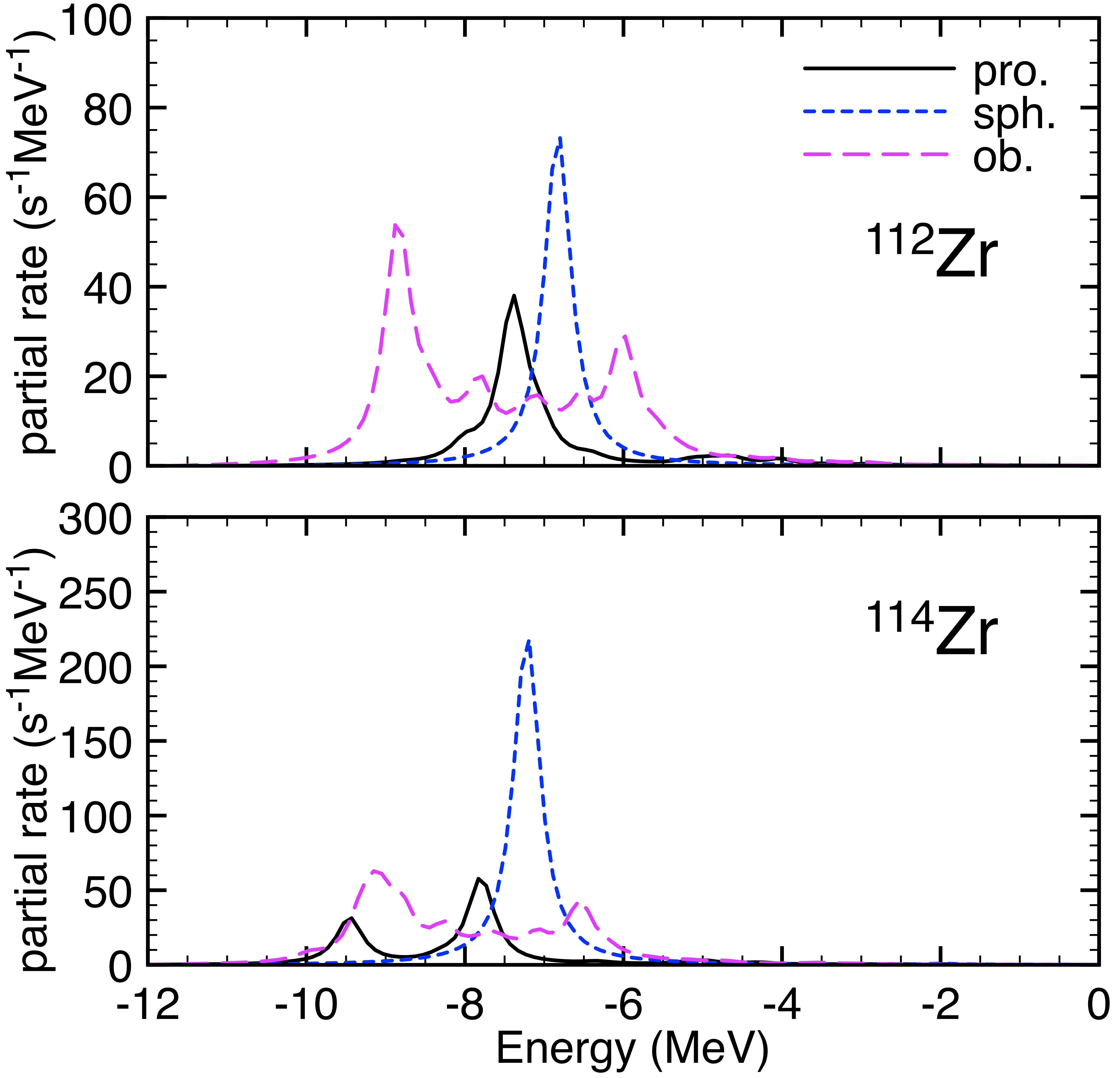
A drop with the shape-phase transition at *N*=74

KY, Y. Niu, F. Minato, PRC(2023)



$(-E)^5$

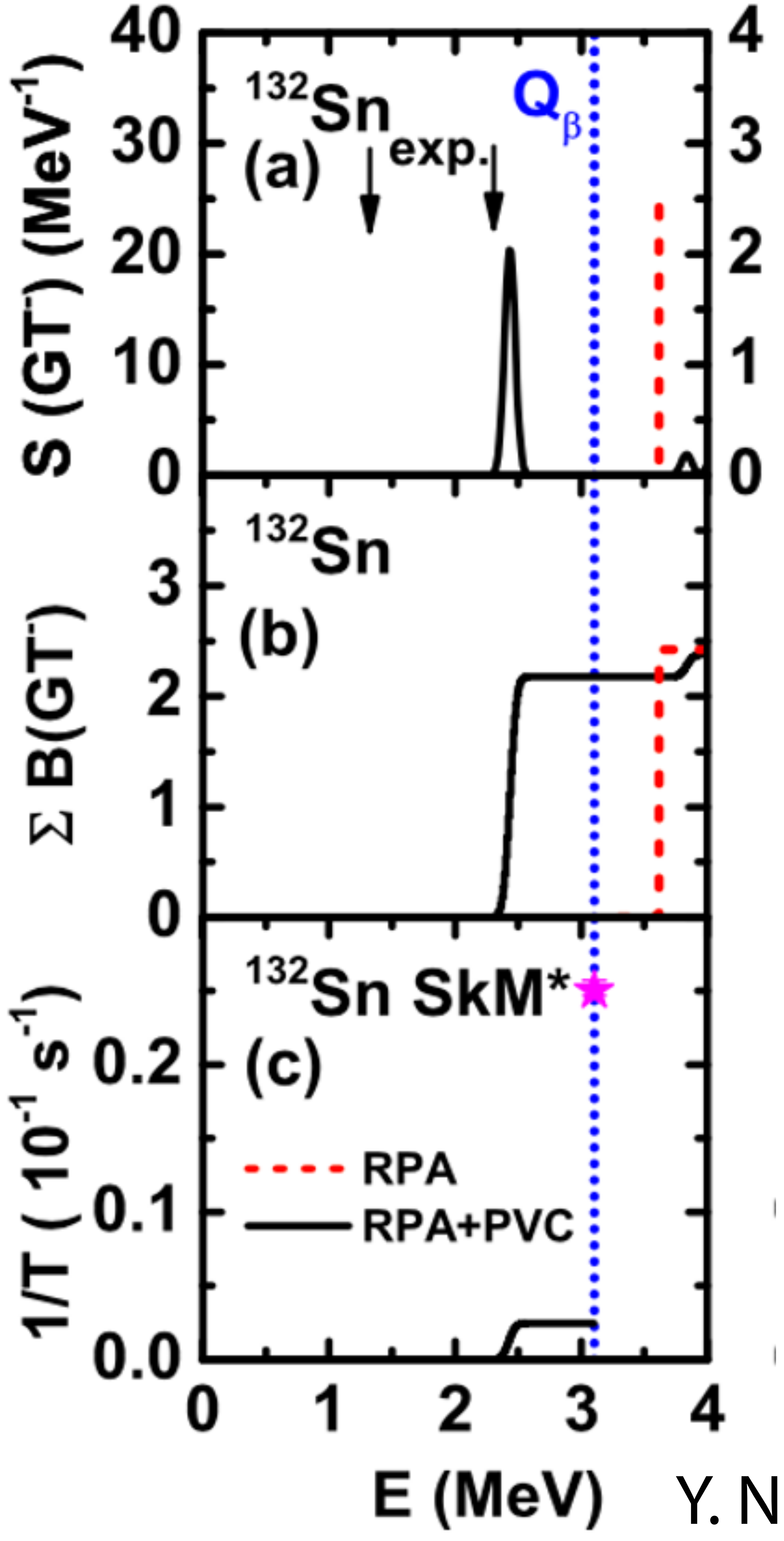
~strength×phase space



wrt mother nucleus

Consideration going beyond the RPA

fragmentation of the strengths



Y. Niu+, PRL(2015)

RPA

single peak above Q_β

$$T_{1/2} = \infty$$

beyond RPA (1p1h)

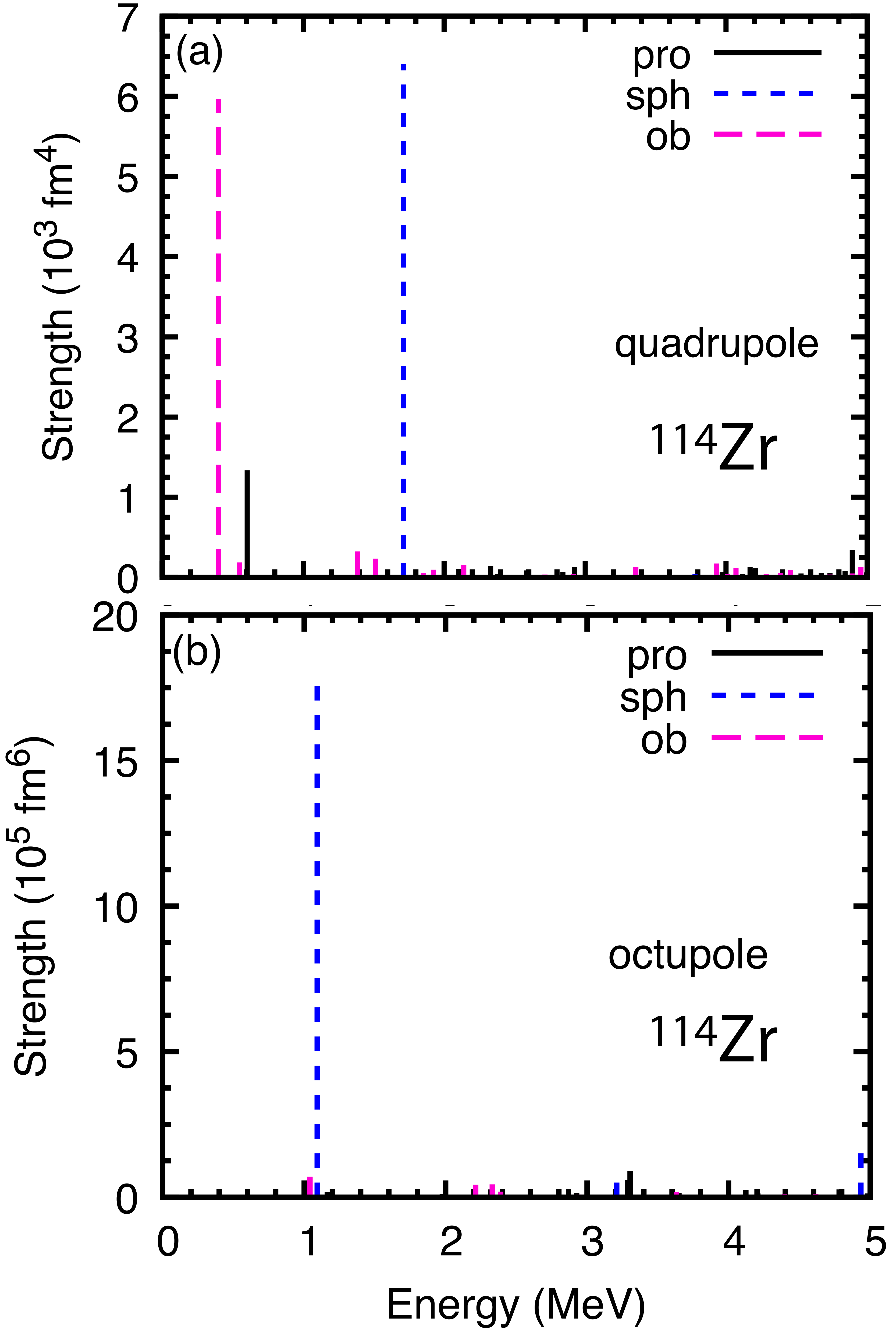
particle-vibration coupling (PVC)

spreading

lowering

low-energy collective states strongly affect the PVC effect

Consideration going beyond the RPA



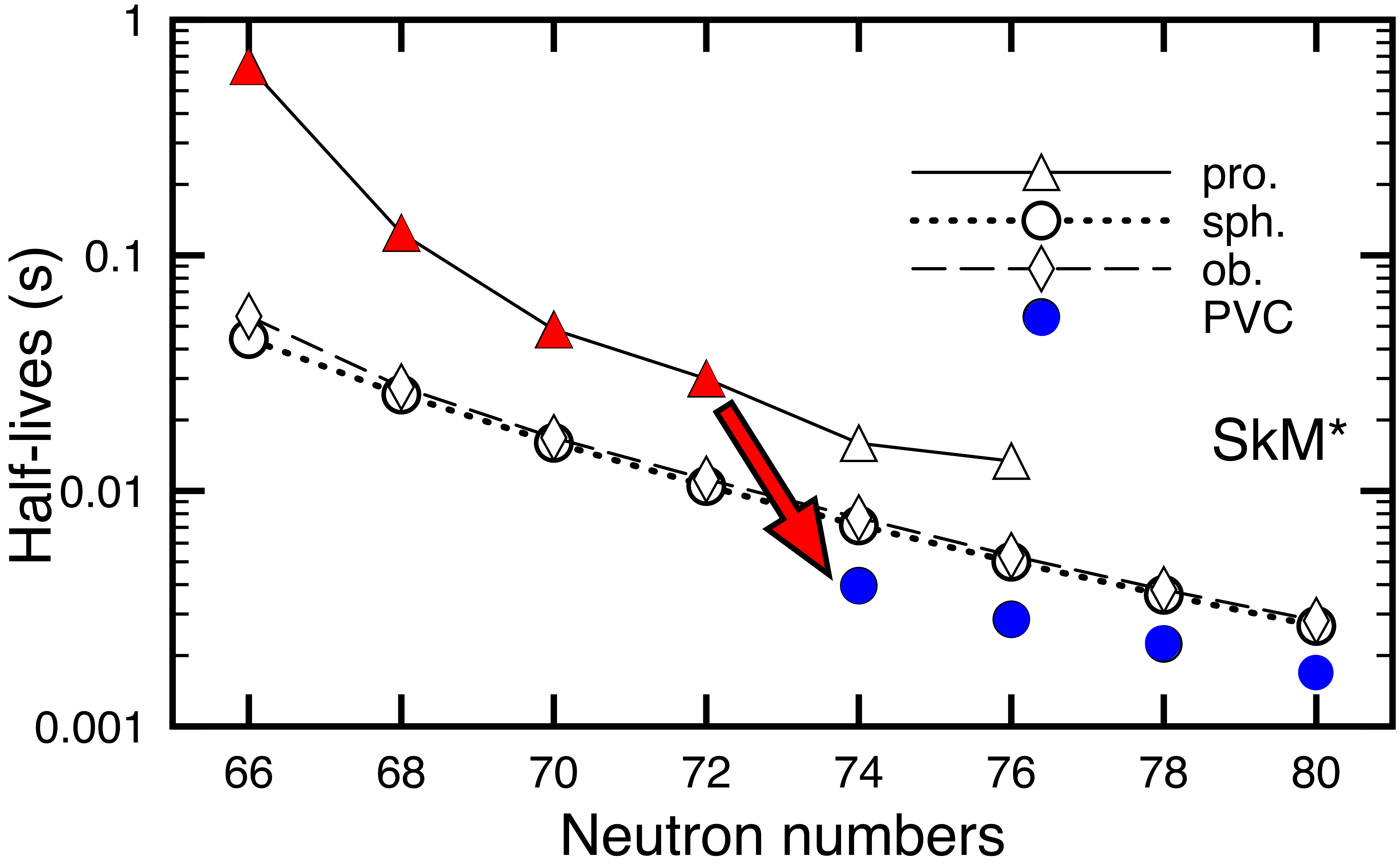
appearance of the collective states

quadrupole state in the oblate config.

octupole state in the spherical config.

		$T_{1/2}$ (ms)		$T_{1/2}$ (ms)
RPA	sph	6.4		
PVC(q)	sph	3.9	obl	2.6
PVC(o)	sph	1.1	obl	5.4
PVC(q+o)	sph	0.9	obl	2.4

Further shortening in the shape transition to spherical



Summary

We need a theoretical framework to provide nuclear data involved in the r-process.

DFT for entire region of nuclear chart in a single framework

reliability and accuracy

development of EDF (input of cal.) and many-body techniques

We need experimental data in n-rich nuclei to verify the framework.

beta-decay half-life in the Zr region undergoing the shape phase transition

first order

One-body charged-current operators: Impulse Approx.

Gamow–Teller type

spatial component

$$\boldsymbol{A}(\boldsymbol{r}) = \sum_{j=1}^{A} \delta(\boldsymbol{r} - \boldsymbol{r}_j) g_A \boldsymbol{\sigma}_j \tau_j^{\pm}$$

momentum transfer:

$$\boldsymbol{q} = \boldsymbol{p}_j' - \boldsymbol{p}_j$$

$$g_A(q^2 = 0) = g_A$$

$$g_V(q^2 = 0) = g_V$$

$$\langle f || \sum_L \Xi_{JL}(\kappa_e, \kappa_\nu) || i \rangle = \mathrm{sign}(\kappa_e) \int_0^\infty dr\, r^2 \left[\rho^{\sigma}_{J-1J}(r) \phi_a(r) + \rho^{\sigma}_{J+1J}(r) \phi_b(r) \right]$$

leptons wfs

nuclear transion density: $\rho^{\sigma}_{LJ}(r) = \langle f || \sum_{j=1}^{A} \int d\Omega_r \delta(\boldsymbol{r} - \boldsymbol{r}_j) \tau_j^{\pm} [Y_L(\hat{r}) \otimes \boldsymbol{\sigma}_j]_J || i \rangle$

usually $J = 1, L = 0$ is only considered

"allowed"

Fermi type

time component

$$V^0(\boldsymbol{r}) = \sum_{j=1}^{A} \delta(\boldsymbol{r} - \boldsymbol{r}_j) g_V \tau_j^{\pm}$$

$$\langle f || \sum_L \Xi_{JL}(\kappa_e, \kappa_\nu) || i \rangle = \mathrm{sign}(\kappa_e) \int_0^\infty dr\, r^2 \rho_J(r) \phi_A(r)$$

$$\rho_J(r) = \langle f || \sum_{j=1}^{A} \int d\Omega_r \delta(\boldsymbol{r} - \boldsymbol{r}_j) \tau_j^{\pm} Y_J(\hat{r}) || i \rangle$$

usually $J = L = 0$ is only considered