# Collective excitations in spherical Mo isotopes

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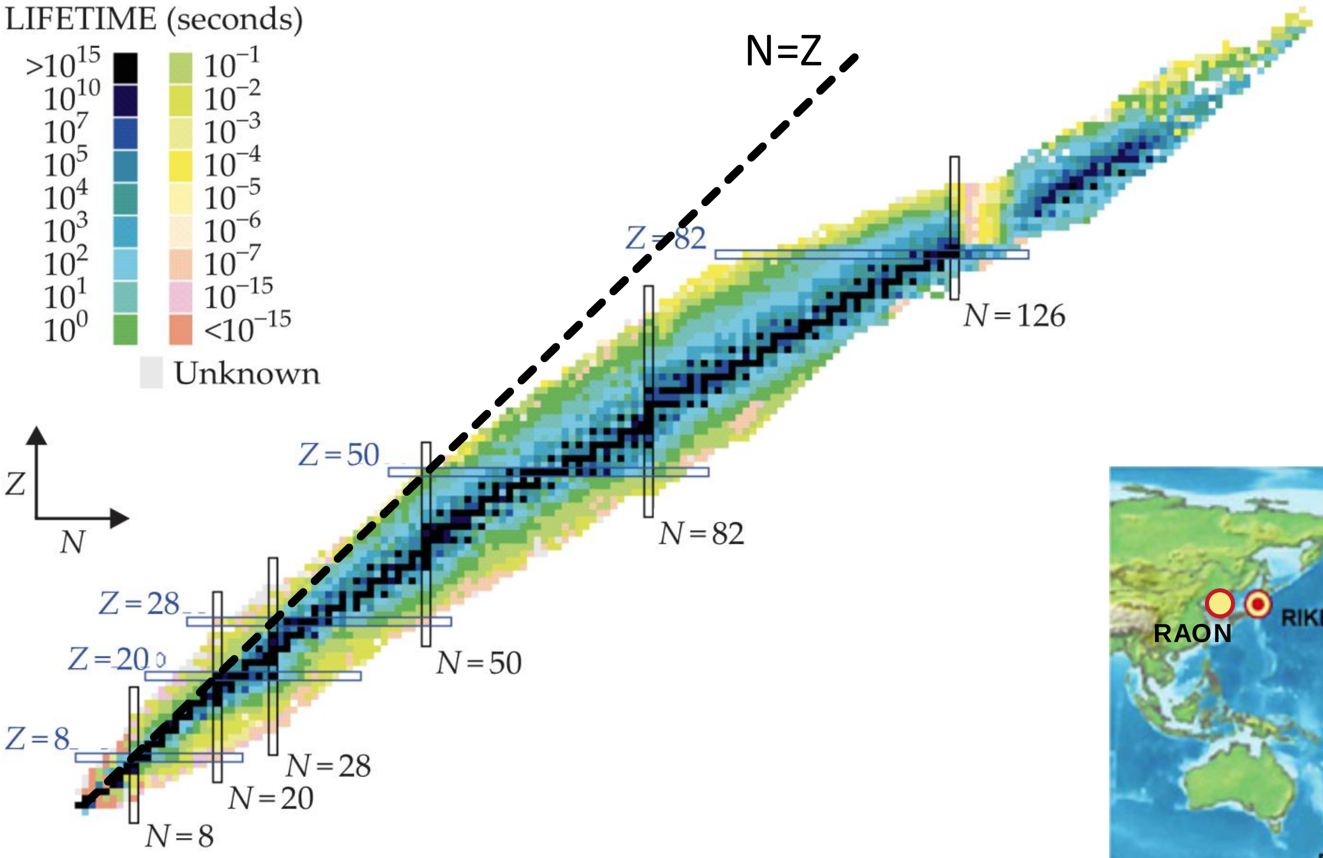
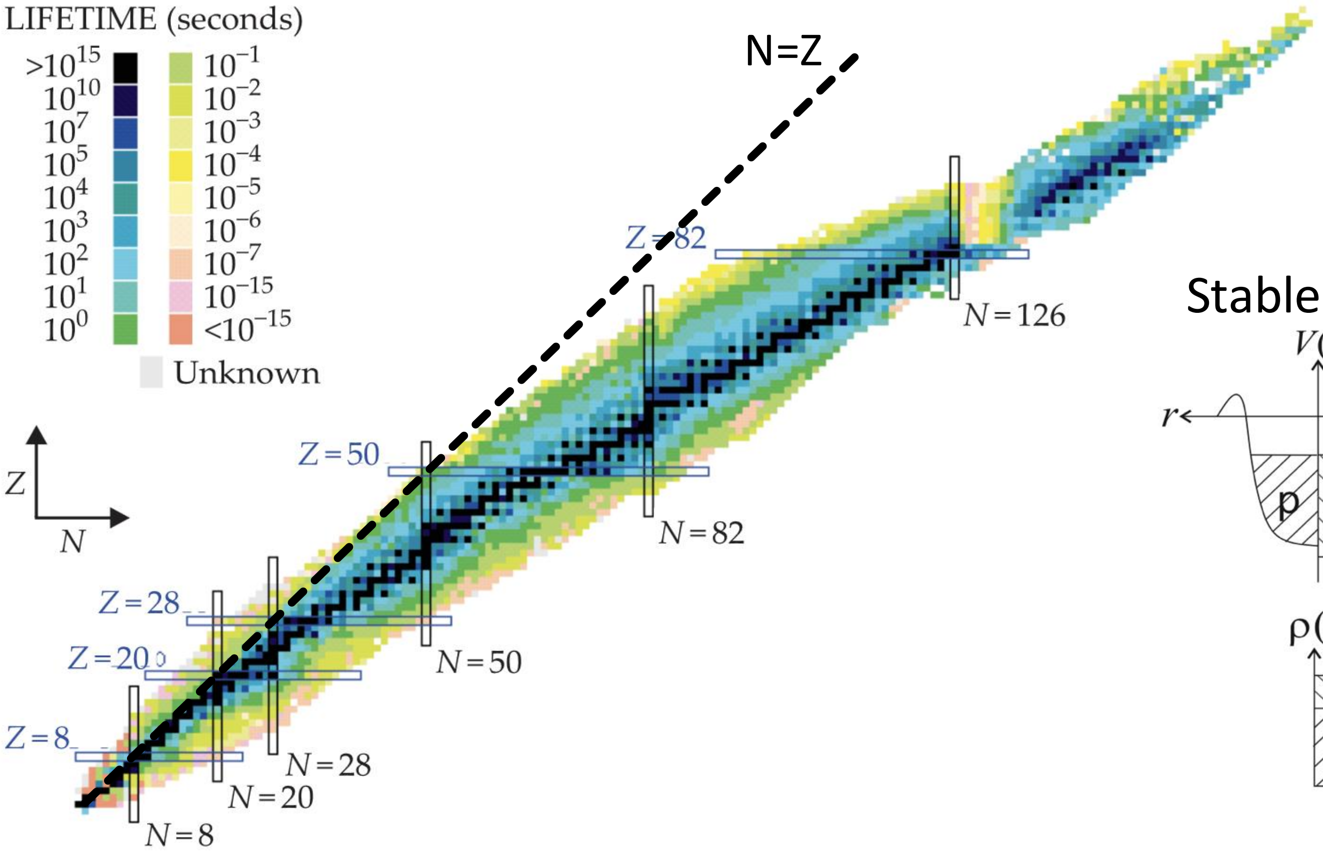
# We journey to a new era of discoveries – far beyond the valley of stability

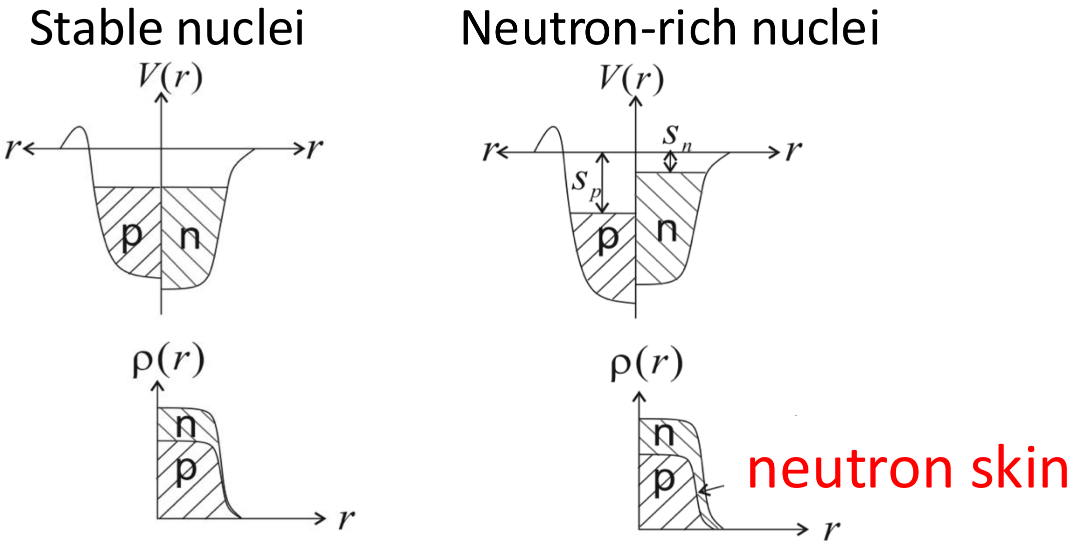



*F. Nunes, Physics Today 74,* ***5*** *(2021)*

# Proton-neutron asymmetry in nuclei leads to the formation of a neutron skin

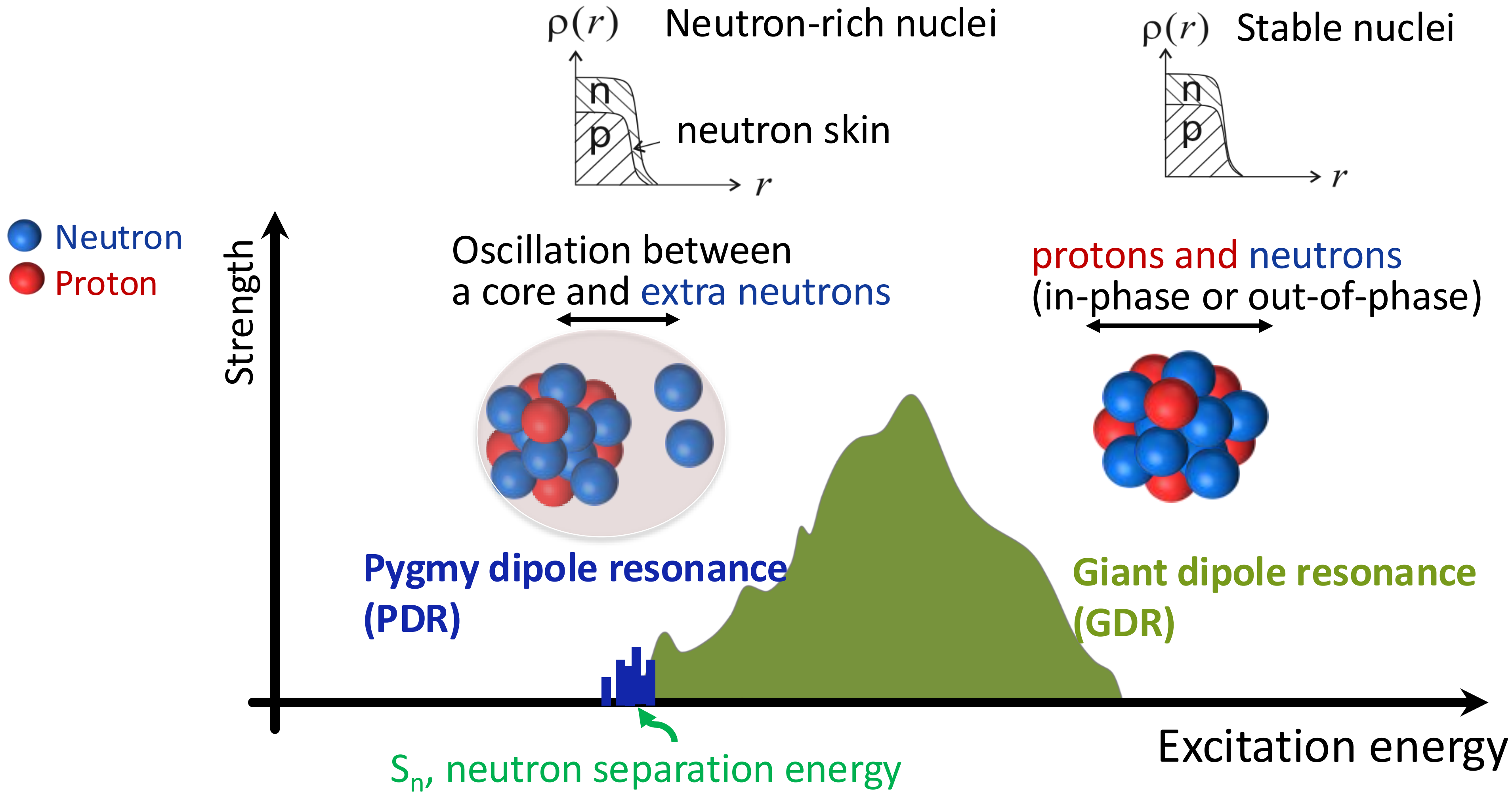



F. Nunes, Physics Today ***74***, 5 (2021)

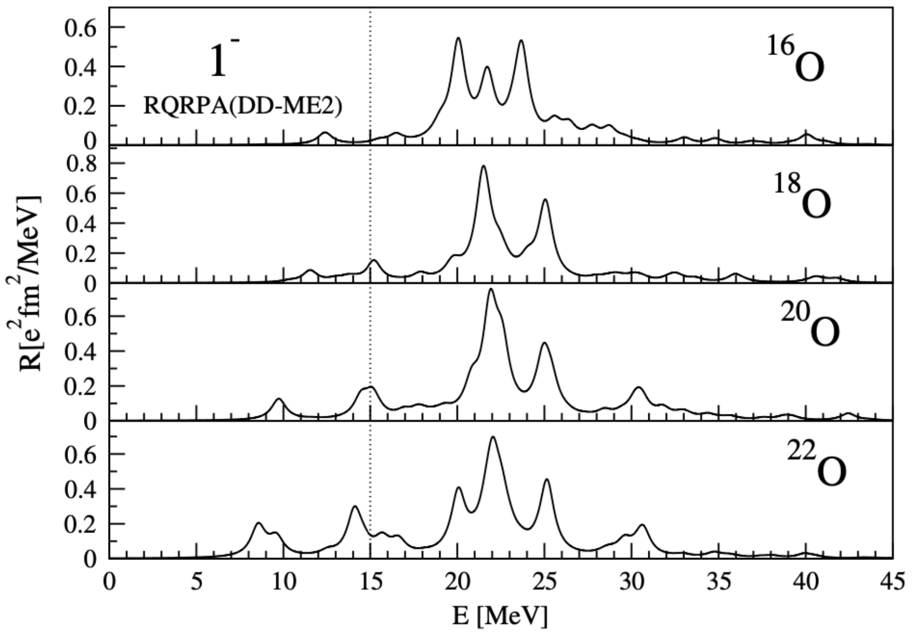



*Phys. Scr. T* ***152*** *(2013) 014012*

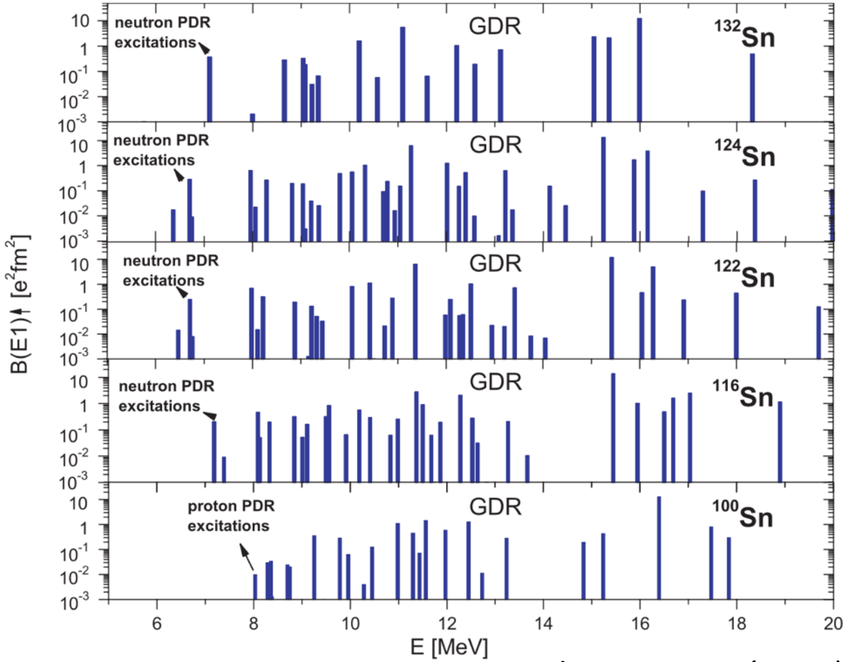
# Neutron skin is linked to exotic dipole excitations, pygmy dipole resonances



# Dipole mode evolution reveals a link to neutron skin thickness and PDRs




*N. Paar, Rep. Prog. Phys. 70, 691 (2007)*




*N. Paar, Rep. Prog. Phys. 70, 691 (2007)*

- PDR strength below 15 MeV varies from close to 0 % for the $^{16}$O to about 16 % for $^{22}$O
- PDR strength below 10 MeV smoothly increases from $^{100}$Sn to $^{132}$Sn

**We need more systematic studies of dipole mode evolution across various nuclei**

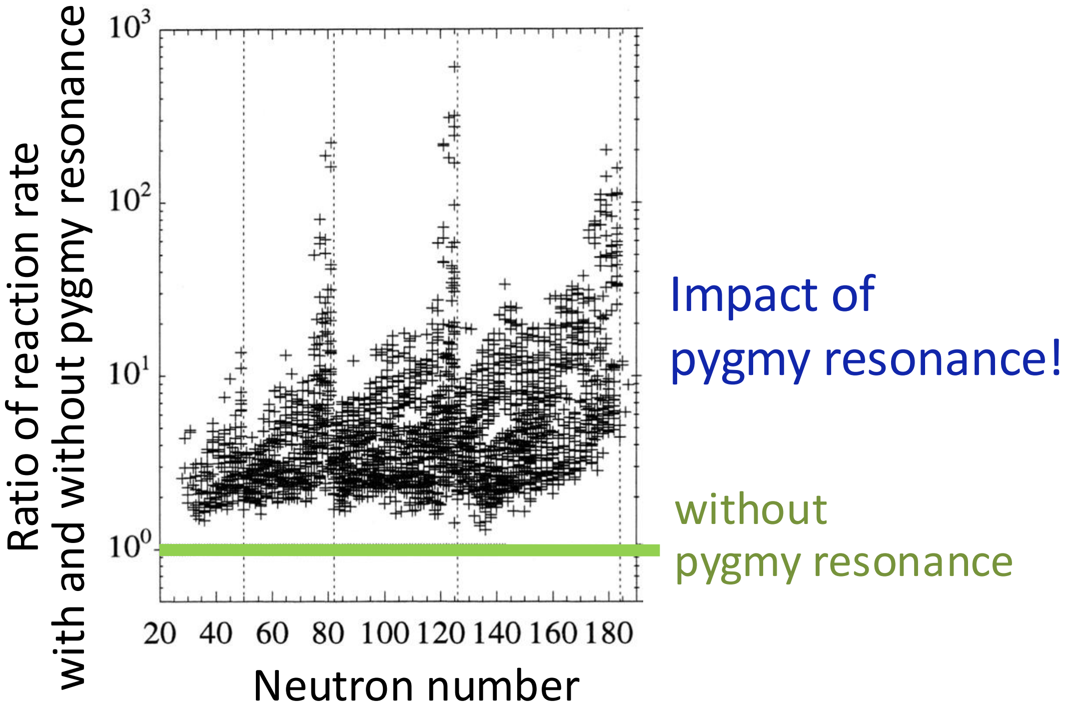
# Questions

Where is the exact location of the PDR excitation energy?
What gives us clues to predict its position?

Is the PDR a collective excitation or resonance structure/oscillation?
And how does its degree of collectivity evolve as neutron numbers increases?

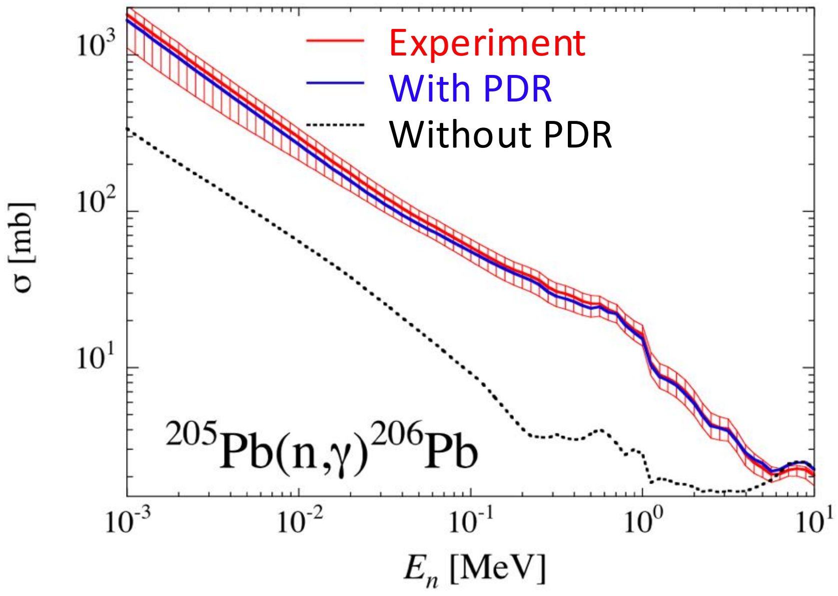
# Nuclear pygmy modes serve as doorways to nucleosynthesis

Neutron capture rates of nuclei involved in the astrophysical *r*-process




*Nucl. Phys. A* ***739***, *331 (2004)*

Neutron capture cross sections for $^{205}$Pb(n,$\gamma$)$^{206}$Pb




*A. P. Tonchev, Phys. Lett. B* ***773*** *(2017)*

# Mo isotopes are ideal for studying single-particle and collective excitations

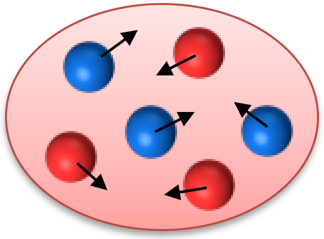
| Nuclei with excess proton | N=Z nuclei | Nuclei with excess neutron | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $^{82}$Mo | $^{84}$Mo | $^{86}$Mo | $^{88}$Mo | $^{90}$Mo | $^{92}$Mo | $^{94}$Mo | $^{96}$Mo | $^{98}$Mo |

*$^{90}$Mo with nearly zero skin thickness

- ❑ We investigate Mo isotopes, which exhibit diverse behaviors with excess protons and neutrons
- ❑ With 42 protons, Mo isotopes are close to the semi-magic number 40, making them ideal for studying both single-particle or collective excitations
- ❑ Mo isotopes participate in multipole astrophysical processes, including *s*-, *r*-, and *p*-processes

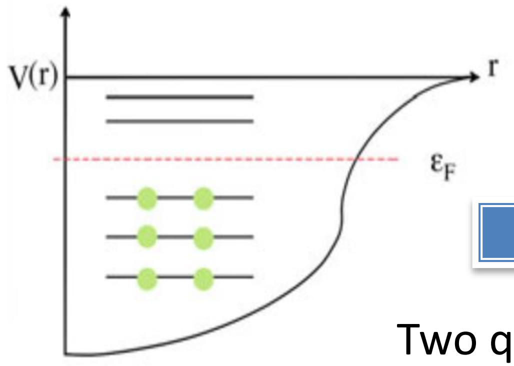
# Collectivity is analyzed in terms of two quasiparticle configurations within HFB+QRPA

**Nucleon-nucleon interaction**:
Gogny D1M force



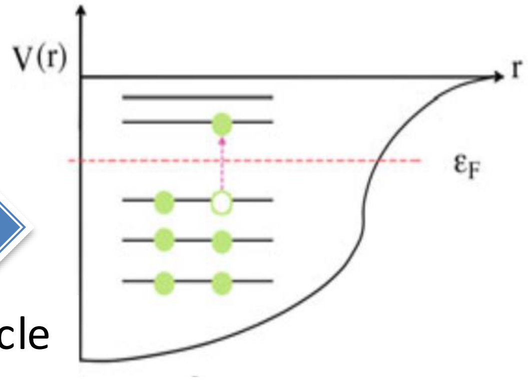
Mean field +
pairing correlations

**Many-body method for ground state:**
Hartree-Fock-Bogoliubov (HFB)

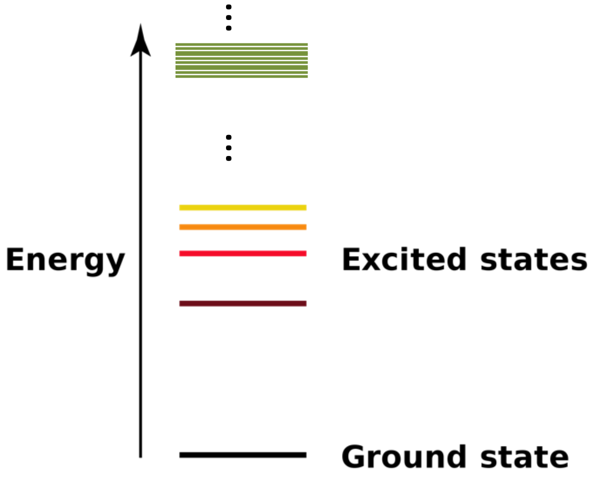



Two quasiparticle
(2qp) excitations

**Many-body method for vibrational excited states:**
Quasiparticle Random Phase Approximation (QRPA)



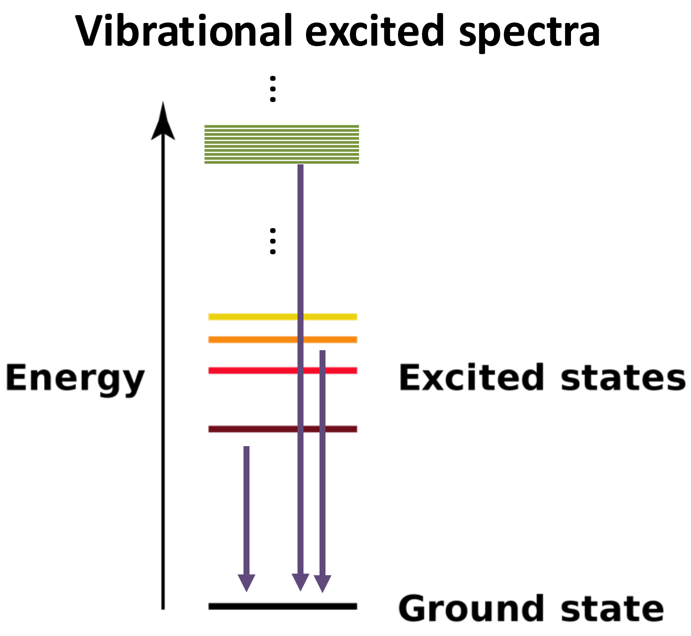

**Vibrational excited spectra**




$$\theta_n^+ = \sum_{ij} \left( X_{ij}^n \eta_i^+ \eta_j^+ - Y_{ij}^n \eta_j \eta_i \right)$$

- ✓ The degree of collectivity depends on how many 2qp configurations actively participate in an excitation
- ✓ $\left(X_{ij}^n\right)^2 - \left(Y_{ij}^n\right)^2$ tell us the contributions of each 2qp configuration to the excitation

# Transition densities describe dynamics of each excitation

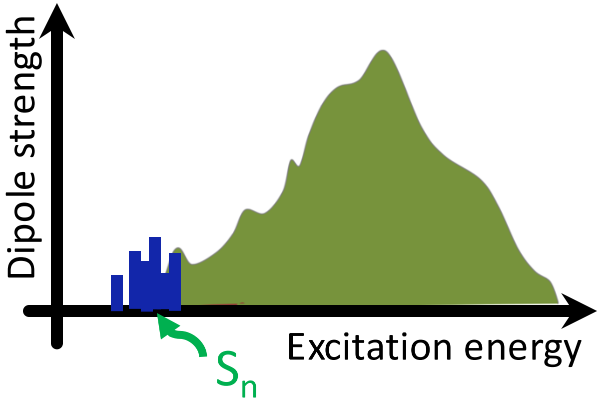



To treat collective excitations like GDRs and PDRs, we compute transition matrix elements from the ground state to excited states

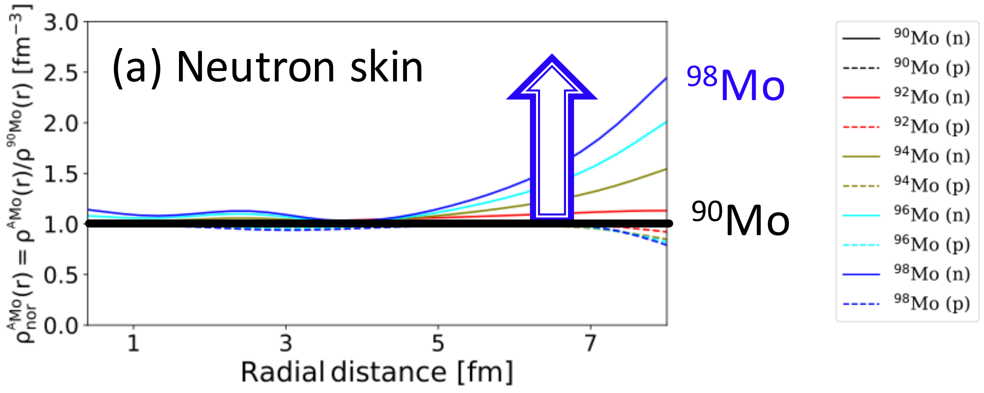
$$\langle \psi_{e.s.} | \hat{O}_{E1} | \psi_{g.s.} \rangle \quad \text{where} \quad \hat{O}_{E1} = \frac{eZ}{A} \sum_{n=1}^{N} r_n Y_{1m}(\hat{r}_n) - \frac{eN}{A} \sum_{p=1}^{Z} r_p Y_{1m}(\hat{r}_p),$$

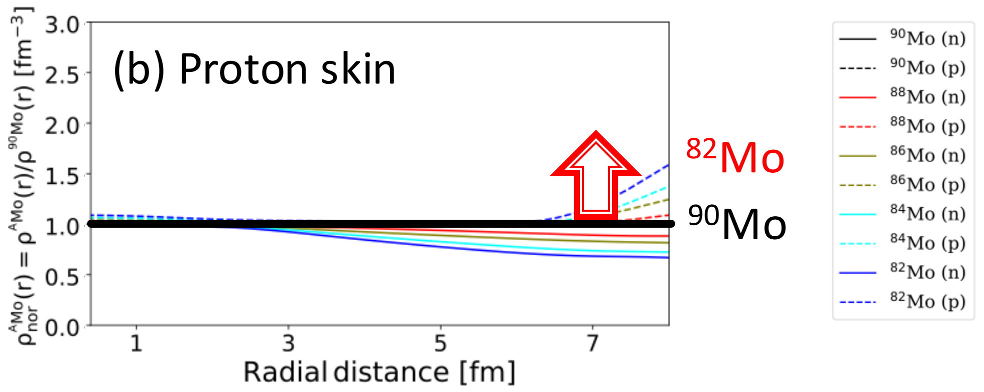
Then, main results:

1) Dipole response functions
2) Transition densities of each excited state



# Skin evolution: neutron skins for $^{90-98}$Mo and proton skins for $^{82-90}$Mo



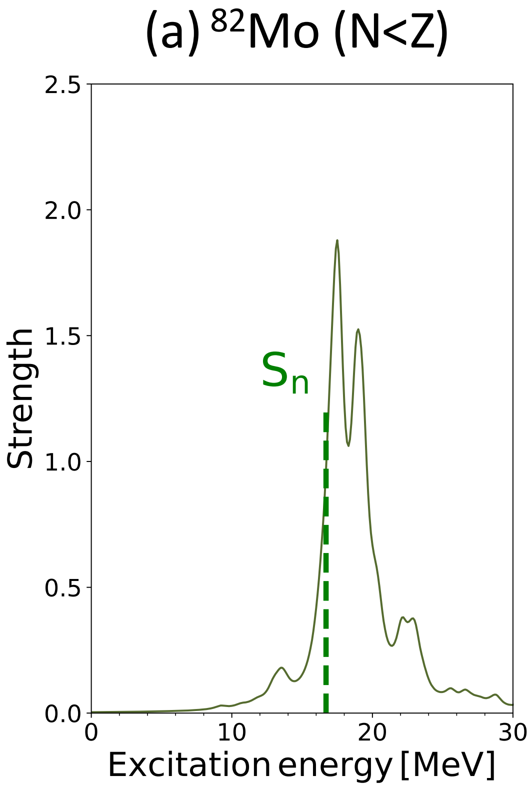



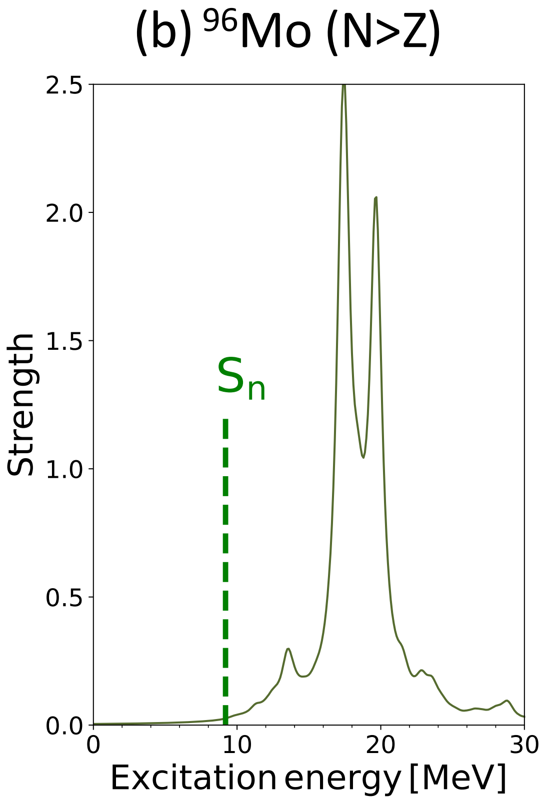

- Skin thickness is quantified as $\delta r = \sqrt{\langle R_n^2 \rangle} - \sqrt{\langle R_p^2 \rangle}$
- $^{90}$Mo serve as a reference due to its nearly zero skin thickness
- We normalize the ground state spatial densities of each isotope by $1/\rho_{^{90}\mathrm{Mo}}(r)$
- The figures illustrate:

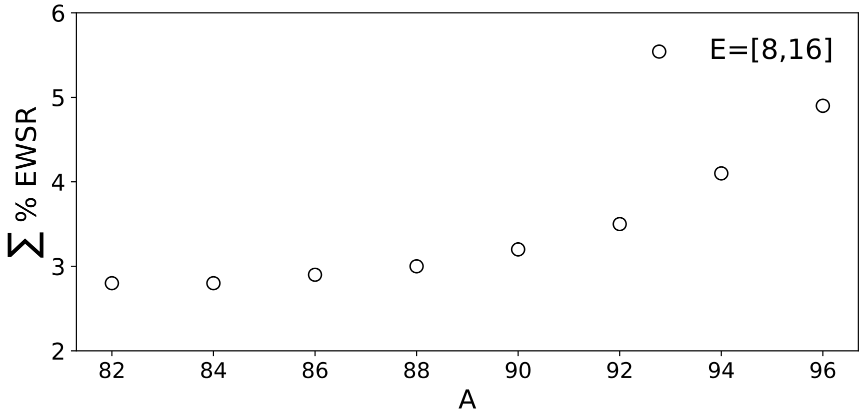
  (a) A gradual increase in neutron skins from $^{90}$Mo to $^{98}$Mo

  (b) A gradual increase in proton skins from $^{90}$Mo to $^{82}$Mo from 5 to 8 fm relative to $^{90}$Mo

# Small enhancements of dipole strengths appear in the lower tail of GDR



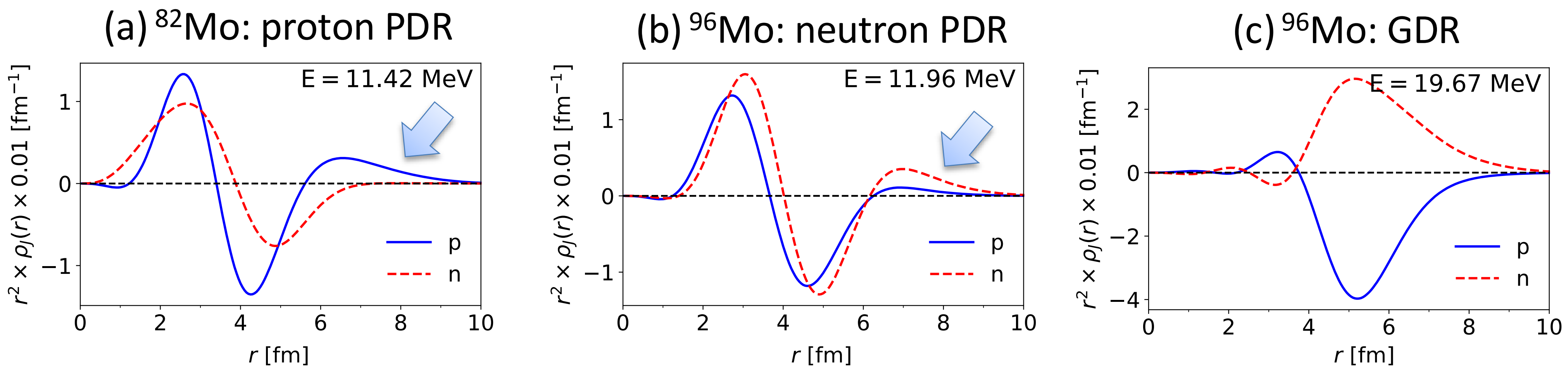




✓ As the neutron number increases, the potential PDR strengths increase from about 3% to about 6%.

Excitation spectrum alone does not provide information on the nature of the each excitation

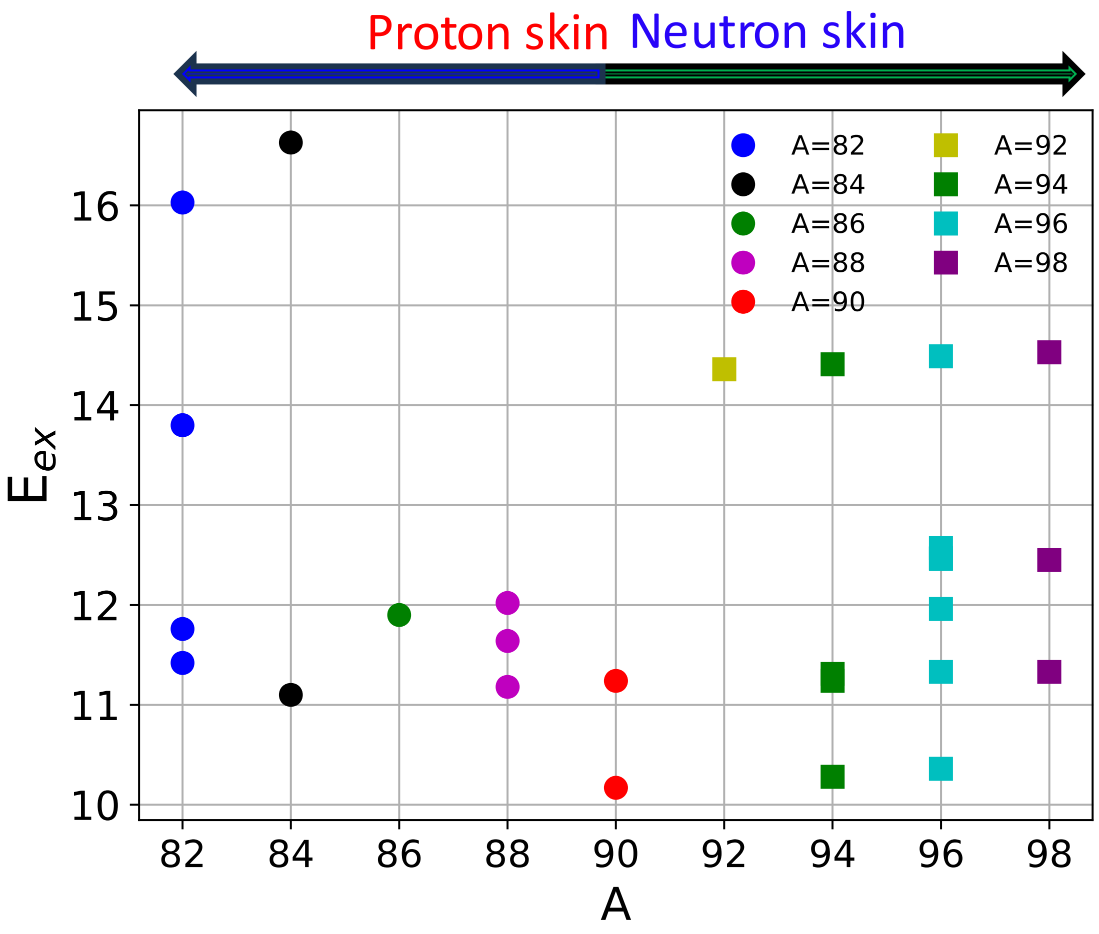
# Transition densities reveal exotic pygmy character of states




The dynamics of the PDR completely differ from those of the GDR !

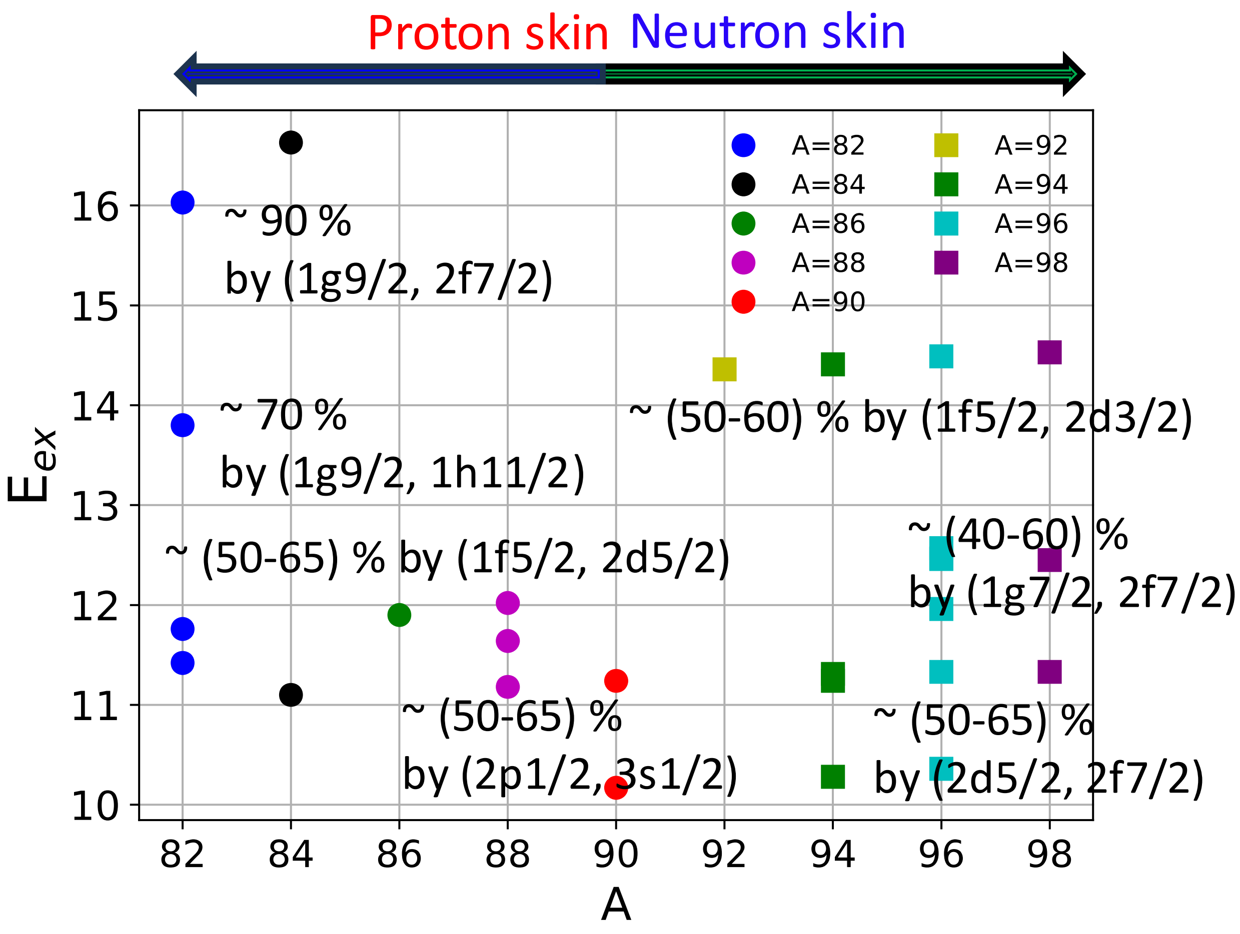
- ❑ GDR: protons and neutrons out of phase
- ❑ PDR: neutrons and protons in phase inside and at the surface only neutrons survive

# We identify pygmy candidates linked to different types of skins



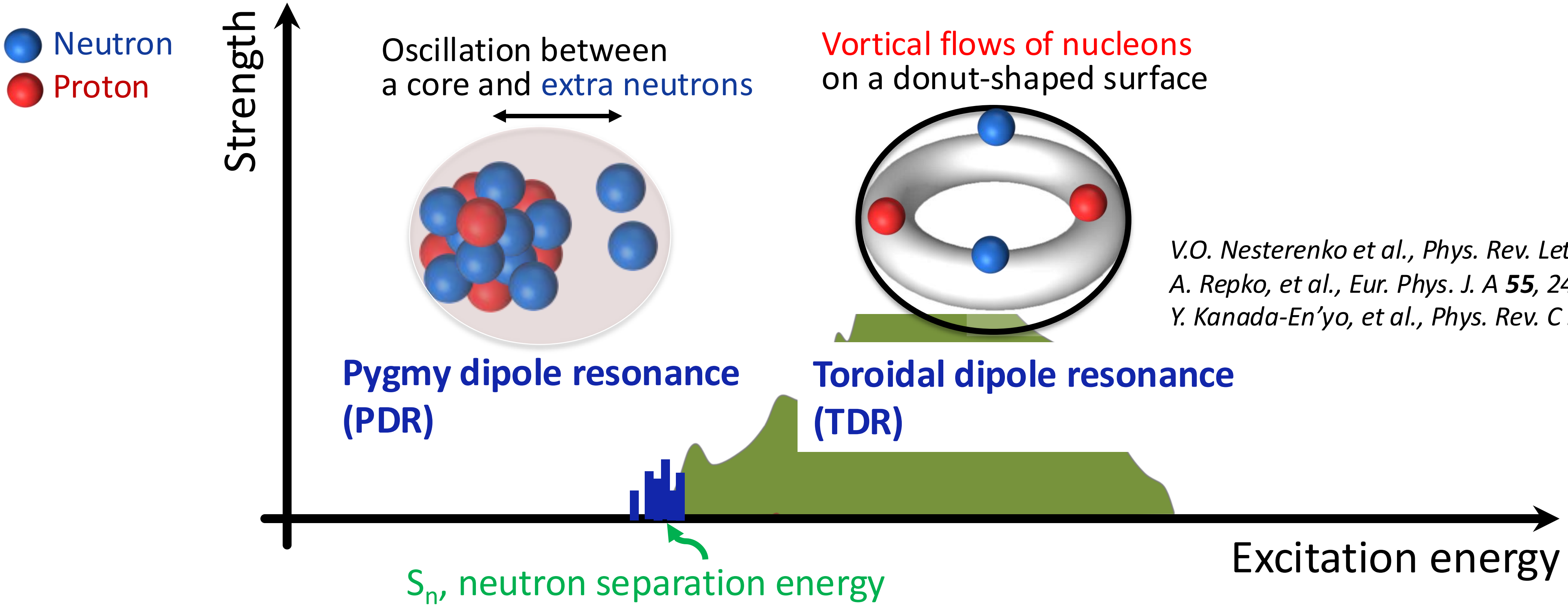

- We observe proton pygmy candidates in isotopes with a proton skin, and neutron pygmy candidates in isotopes with a neutron skin

# Microscopic structure of the pygmy states differs from the GDR




- The percentages indicate contributions of major 2qp configurations
- The structure of the pygmy states is dominated by specific 2qp transitions, whereas the giant states correspond to excitations from many different transitions
- For example, the structure of a giant dipole state in $^{94}$Mo shows a mixing of **many distributed 2qp configurations**:
  25% of (1f7/2, 2d5/2), 19% of (1f5/2, 1g7/2),
  11% of (1f9/2, 1h11/2), 10% of (1f7/2, 1g9/2), etc
- In contrast, the structure of a pygmy dipole state in $^{94}$Mo shows **a few major 2qp configurations**:
  66 % of (2d5/2,2f7/2), 11% of (2d5/2,3p3/2), etc
- The states near 16 MeV in $^{82,84}$Mo show single particle behavior

# We plan another exotic dipole excitations, toroidal dipole resonances




*V.O. Nesterenko et al., Phys. Rev. Lett.* ***120****, 182501 (2018)*
*A. Repko, et al., Eur. Phys. J. A* ***55****, 242 (2019)*
*Y. Kanada-En'yo, et al., Phys. Rev. C* ***95****, 064319 (2017)*

# Summary and Outlook

- Exploring neutron- or proton-rich nuclei far from stability presents many interesting phenomena, e.g. neutron skins

- We have investigated the electric dipole response of Mo isotopes within Gogny HFB+QRPA framework to explore the existence and characters of pygmy dipole states
  - Identified candidates of the PDR states and their microscopic structure through transition densities
  - Studied the relationship between pygmy dipole states and neutron and proton skins
  - Examined collective behaviors associated with proton and neutron skins

- We plan to:
  - Investigate PDR states in deformed nuclei
  - Study additional excitation mode, toroidal dipole resonances

- Studying collective excitations in astrophysically relevant nuclei, such as Mo isotopes, will deepen our understanding of the origin of heavy elements in the cosmos.

# Thank you

Lawrence Livermore
National Laboratory