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Towards a unified description of giant monopole resonances

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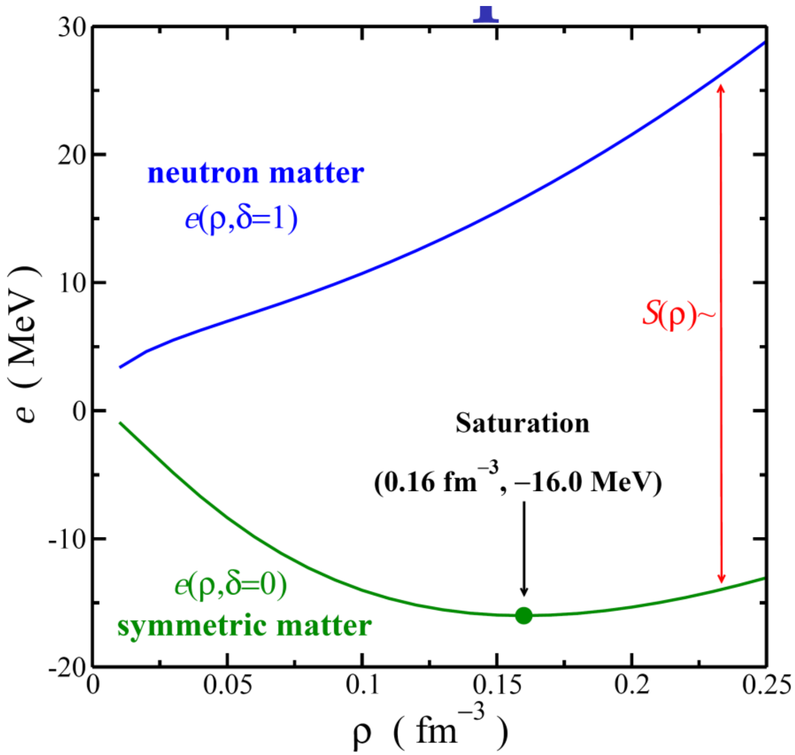
Nuclear Equation of State (EoS)

- **Nuclear equation of state**



Nuclear matter (NM) — **Symmetric NM** — **symmetry energy**

$$\boxed{\frac{E}{A}(\rho,\delta)} = \boxed{\frac{E}{A}(\rho,\delta=0)} + \boxed{S(\rho)}\delta^2$$

$$\delta \equiv (\rho_n - \rho_p)/\rho \qquad \xi = \frac{\rho-\rho_0}{3\rho_0}$$

$$\frac{E}{A}(\rho,\delta=0) = \epsilon_0 + \frac{1}{2}\boxed{K}\xi^2 + o(\xi^3)$$

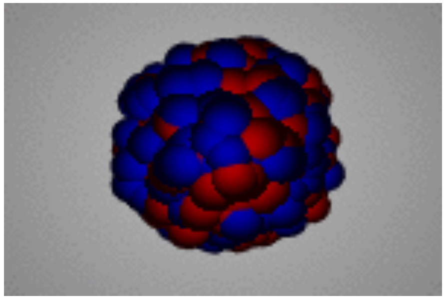
Nuclear incompressibility

- **EoS: dynamics of heavy-ion collisions, the structure of neutron stars, and the simulation of core-collapse supernova, neutron star mergers**

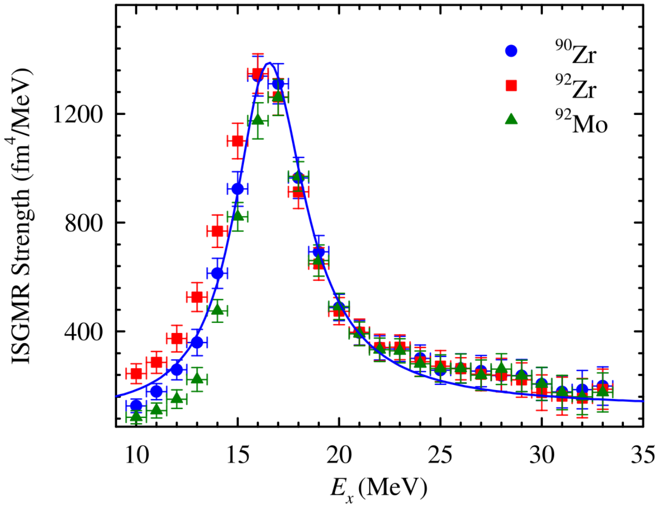
How to constrain EoS of nuclear matter?

Giant Monople Resonances (GMR)

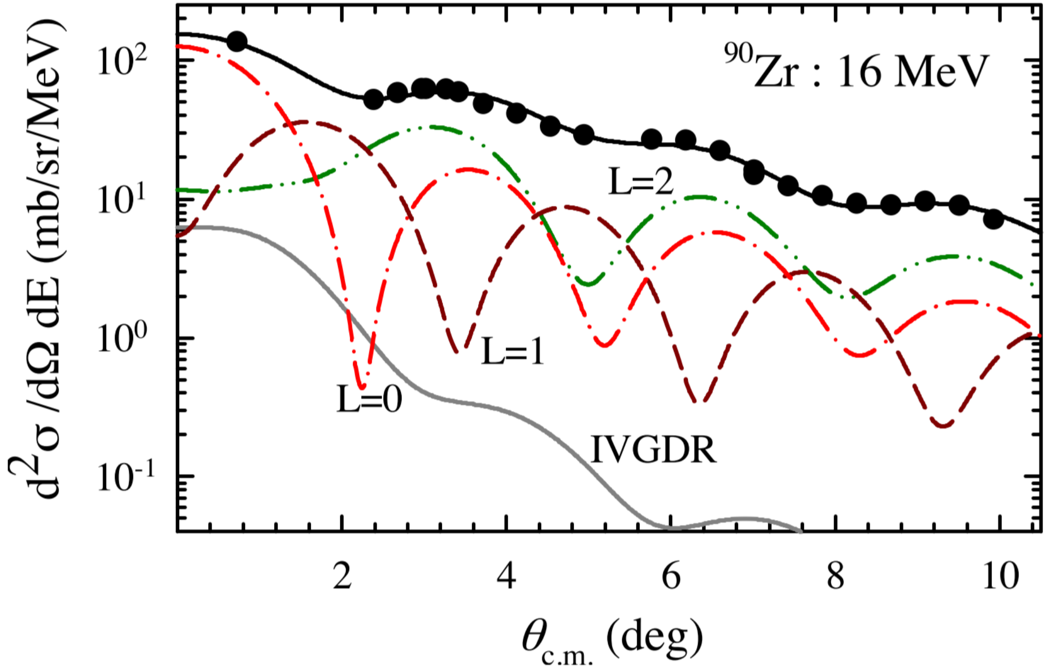
- **Isoscalar giant monople resonance (breathing mode)**



- ISGMR strength distribution



- inelastic α scattering at small angles



- multipole-decomposition analysis (MDA)

$$\frac{d^2\sigma^{\exp}(\theta_{\mathrm{c.m.}}, E_x)}{d\Omega dE} = \sum_{L=0}^{6} a_L(E_x) \frac{d^2\sigma_L^{\mathrm{DWBA}}(\theta_{\mathrm{c.m.}}, E_x)}{d\Omega dE}$$

Gupta et al., PLB 760, 482 (2016)

GMR and nuclear incompressibility

- GMR opens a window into the incompressibility of nuclear matter

✓ K_A can be obtained from centroid energy of GMR

$$E_{ISGMR} = \hbar\sqrt{\frac{K_A}{m\langle r^2\rangle}}$$

K_A: the compression modulus of the nucleus with mass number A

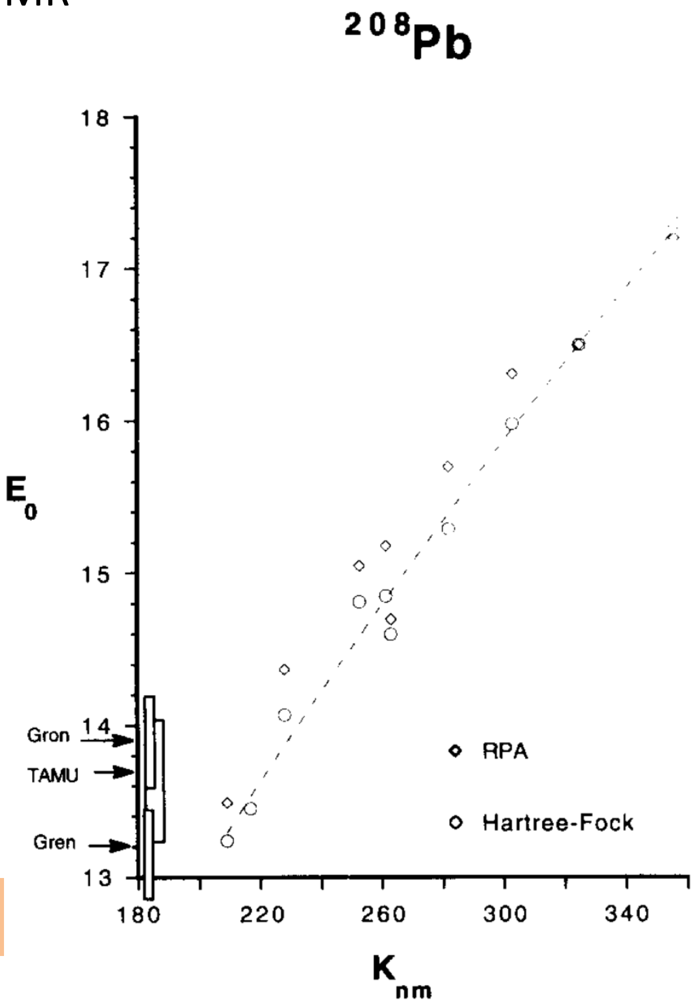
✓ From K_A to K_∞

$$K_A = aK_\infty + b\,.$$

$$E_{\text{ISGMR}} = a'\sqrt{K_\infty} + b'$$

K_∞ : incompressibility of nuclear matter

From ^{208}Pb and ^{90}Zr: $K_\infty = 240 \pm 20\ \text{MeV}$



Garg and Colo, PPNP 101, 55 (2018)

Blaizot et al., NPA 591, 435 (1995)

Puzzle: Why are tins so soft?

IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **37** (2010) 064038 (10pp) doi:10.1088/0954-3899/37/6/064038

Focus issue on open problems in nuclear structure theory

Do we understand the incompressibility of neutron-rich matter?

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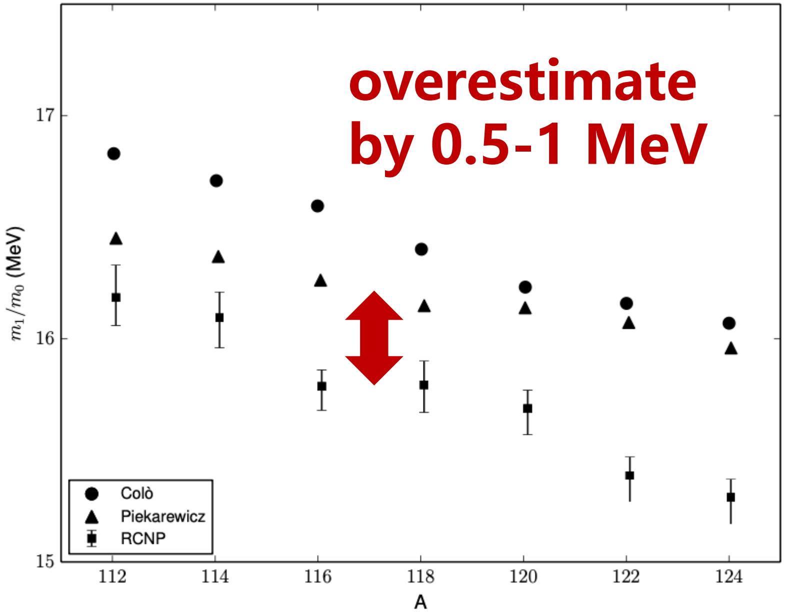
Department of Physics, Florida State University, Tallahassee, FL 32306, USA



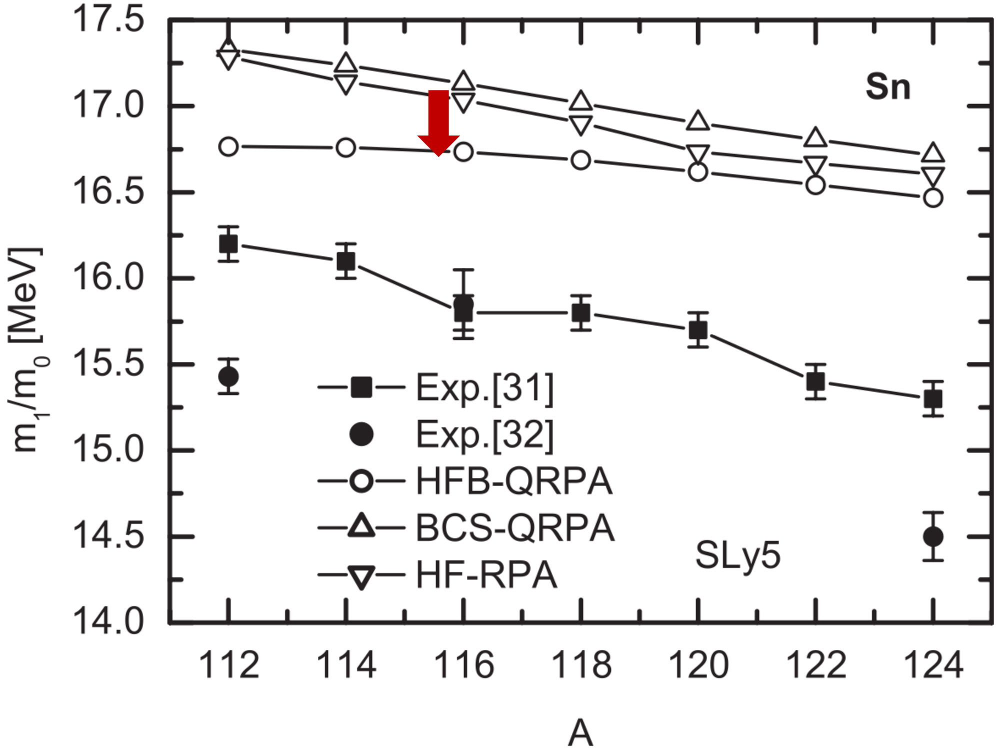
In even-even $^{112-124}$Sn, the ISGMR centroid energy is overestimated by about 1 MeV by the same models which reproduce the ISGMR energy well in ^{208}Pb.

From Sn isotopes: $K_\infty \sim 205$ MeV

Li et al., PRL 99, 162503 (2007) Garg and Colo, PPNP 101, 55 (2018)

Attempts to solve the puzzle

- Effects of pairing correlations



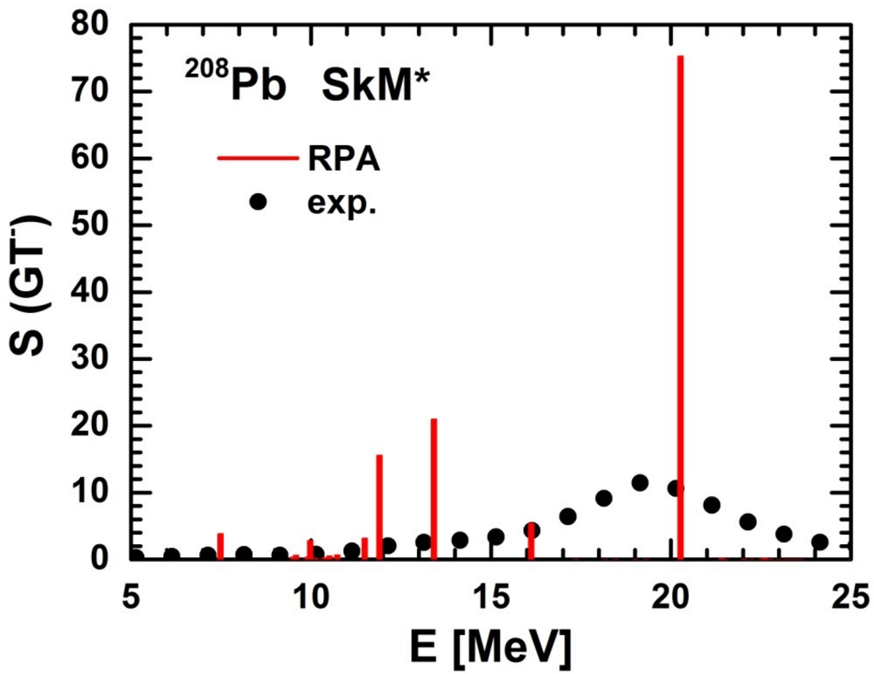
Li et al., PRC 78, 064304 (2008)

✓ Pairing shifts the centroid energy of the ISGMR downwards by several hundreds of keV.

does not seem to solve the issue completely …

Limitations of (Q)RPA Description

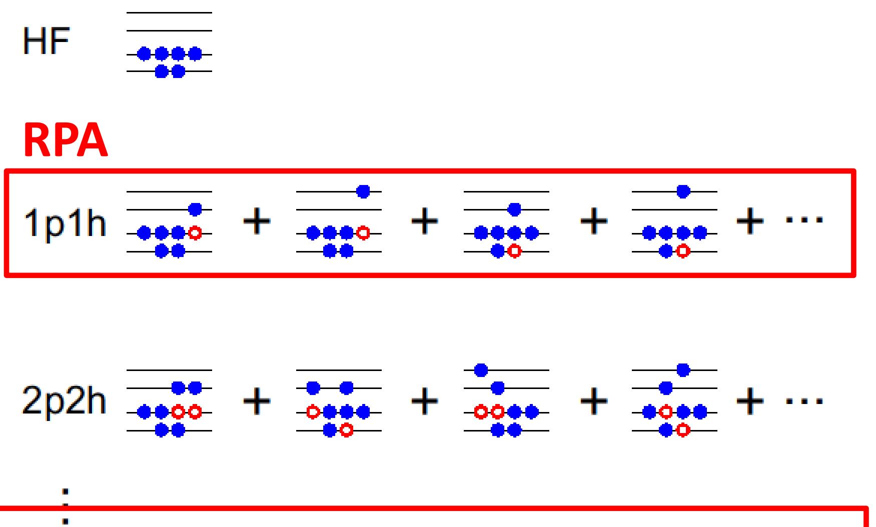
- **(Q)RPA cannot describe the spreading width**

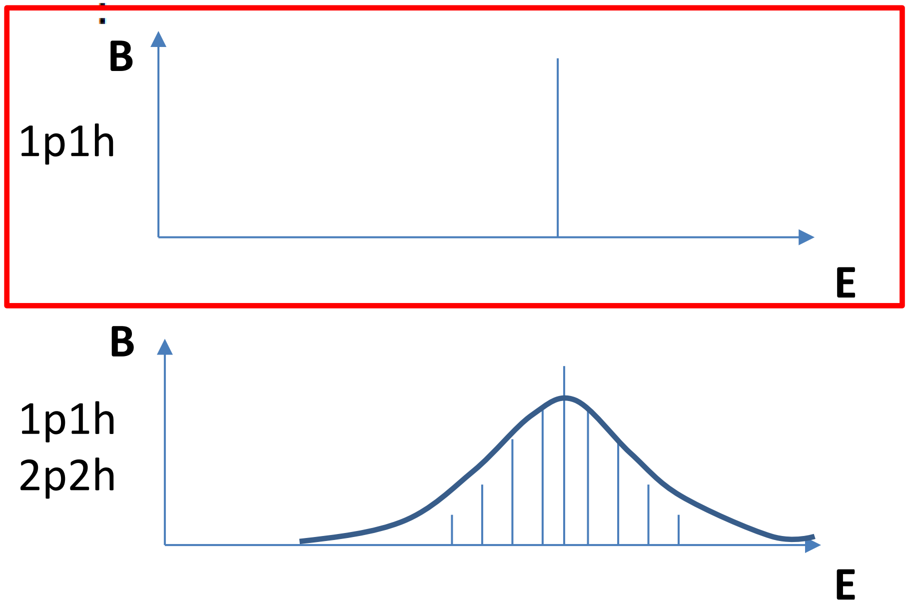


- **Spreading Width (Damping Width)**

  energy and angular momentum of coherent vibrations
  → more complicated states of 2p-2h, 3p-3h, … character

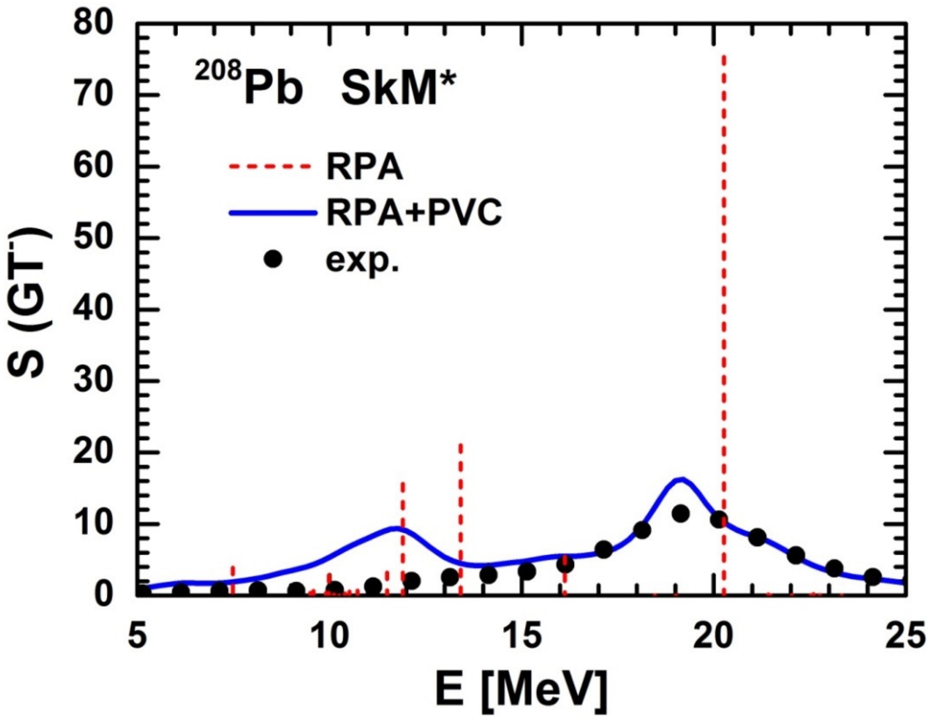
- **Correlations beyond RPA**





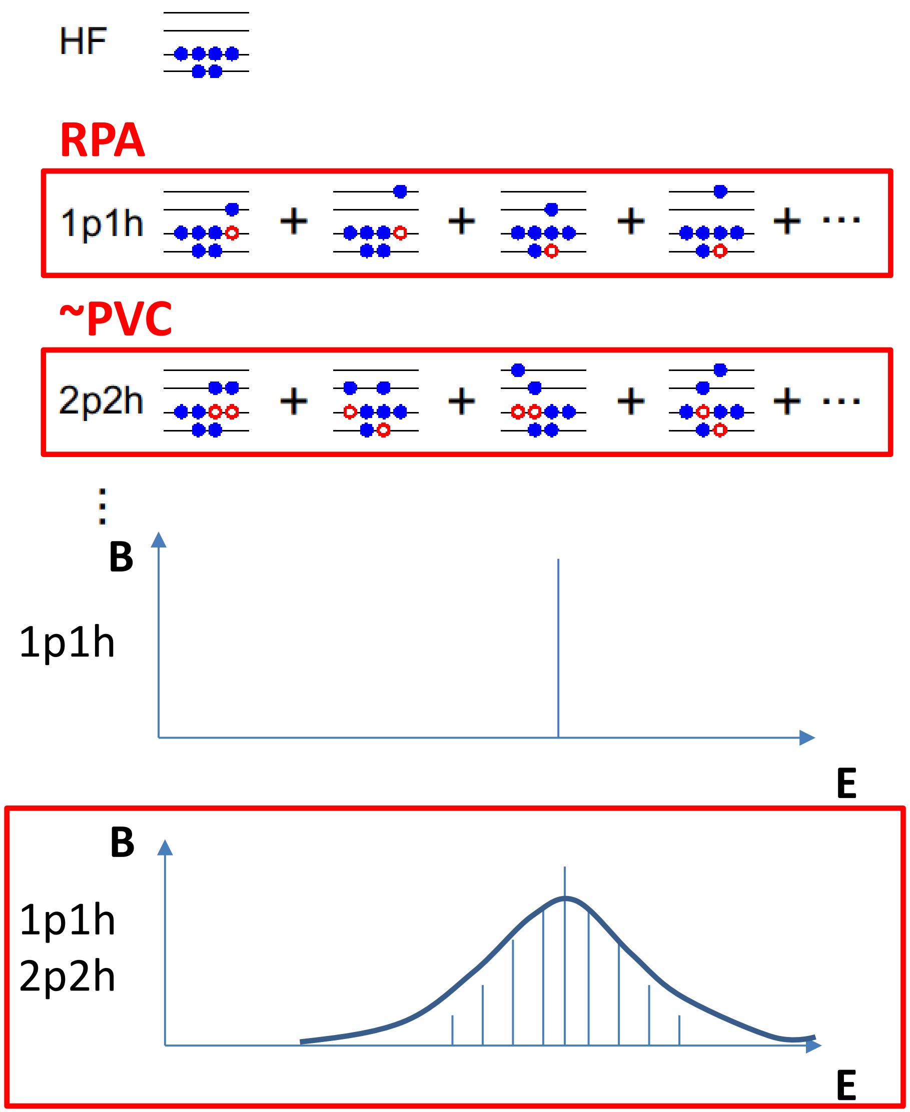
Solution: RPA + PVC

- **Particle Vibration Coupling (PVC) effect**



✓ **Develop a spreading width**
✓ **Reproduce resonance lineshape**

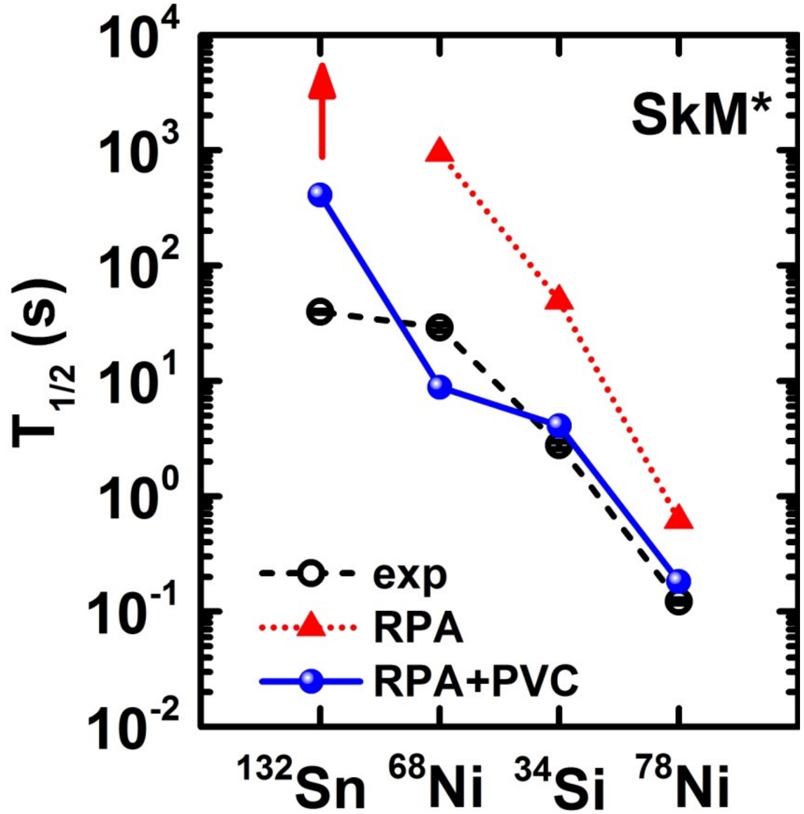
- **Correlations beyond RPA**



Y. F. Niu, G. Colo, and E. Vigezzi, **PRC** 90, 054328 (2014)

β-Decay Half-Lives in Magic Nuclei

- **Improved description of β-decay half-lives**

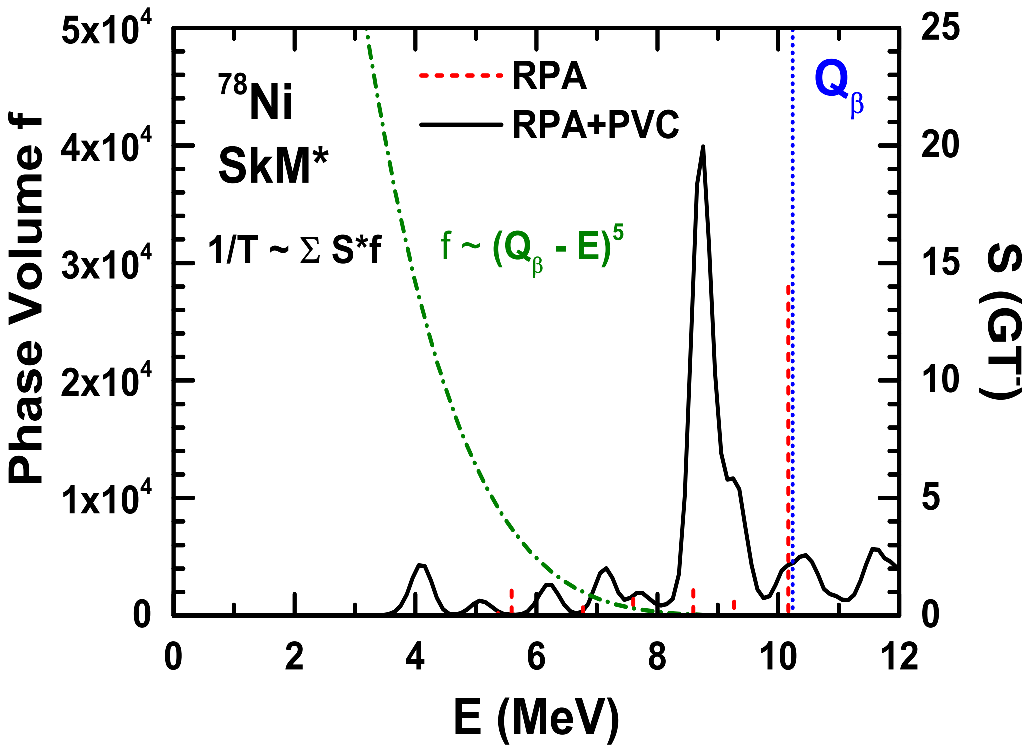


✓ **Reduce half-lives systematically** ✓ **Reproduce β-decay half-lives**

Y.F. Niu, Z. M. Niu, G. Colo, and E. Vigezzi, **PRL** 114, 142501 (2015)

Exp: G. Audi, F. G. Kondev, M. Wang, W. J. Huang, and S. Naimi, CPC 41, 030001 (2017)

How PVC reduces half-lives?



Exp.: Xu, et al., PRL 113, 032505, 2014

- Half-life

$$T_{1/2} = \frac{D}{g_A^2 \int^{Q_\beta} S(E) f(Z,\omega) dE},$$

- Phase Volume

$$f(Z,\omega_0) = \frac{1}{(m_e c^2)^5} \int_{m_e c^2}^{\omega_0} p_e E_e (\omega_0 - E_e)^2 F_0(Z+1, E_e) dE_e$$

✓ **PVC effect:**

energy is shifted downwards -> phase space is increased

-> half-life is decreased

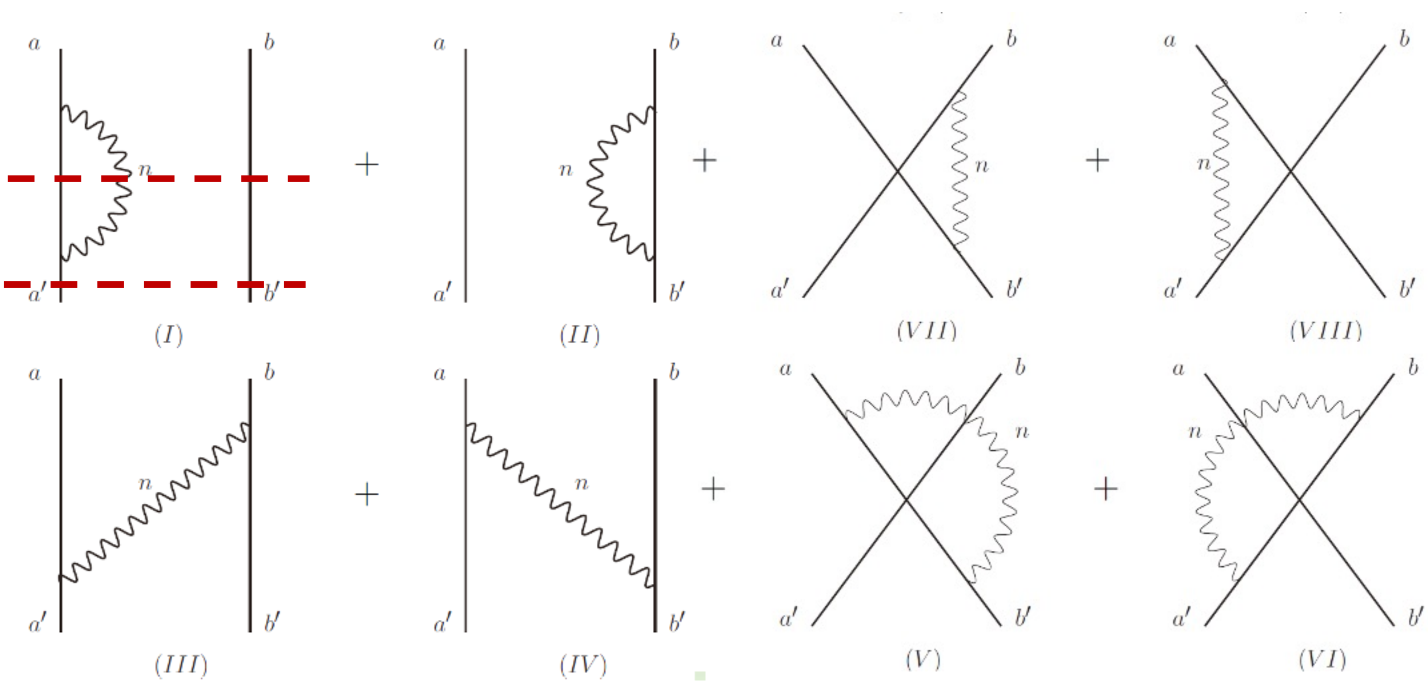
Our attempt to solve the puzzle

- Quasiparticle RPA + quasiparticle vibration coupling
  (**QRPA**) + (**QPVC**)
  fully self-consistent based on Skyrme density functional

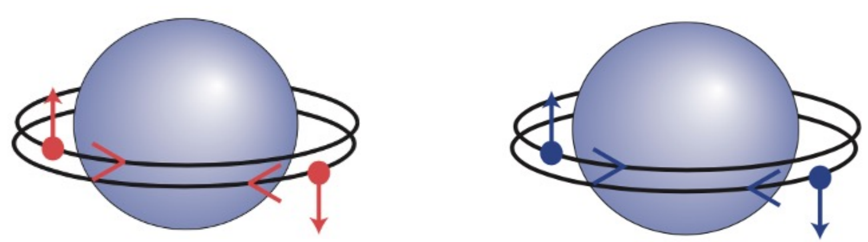
✓ QPVC effect

2 qp ⊗ phonons

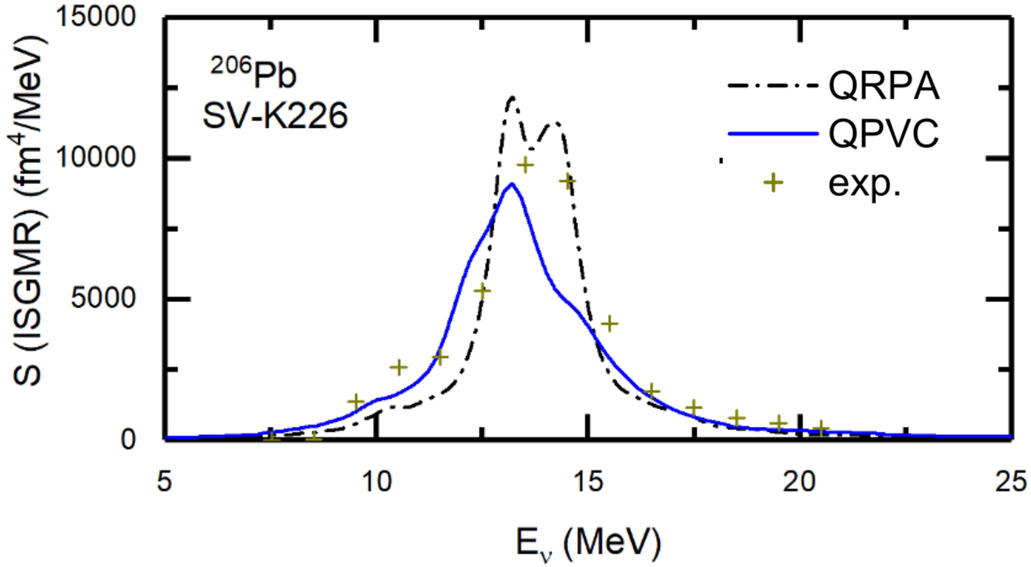
2 quasiparticles(qp)



✓ Pairing effect



GMR of Pb isotopes studied by QRPA+QPVC



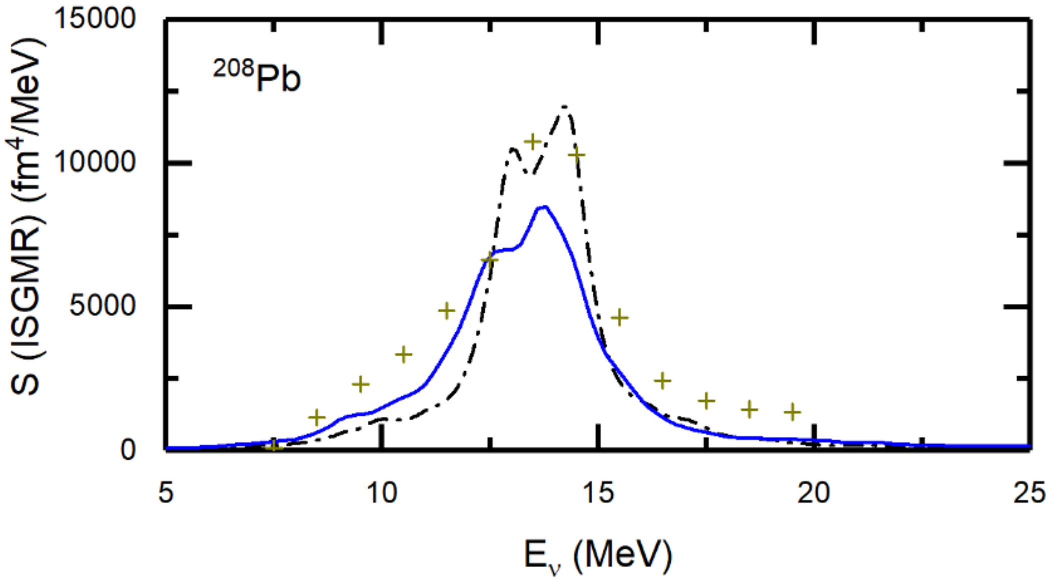
SV-K226:

$$K_\infty = 226\,\mathrm{MeV}$$

Klupfel, Reinhard, et al., PRC 79, 034310 (2009)

QRPA:

- ✓ reproduce exp. GMR energy well
- ✓ Width is small

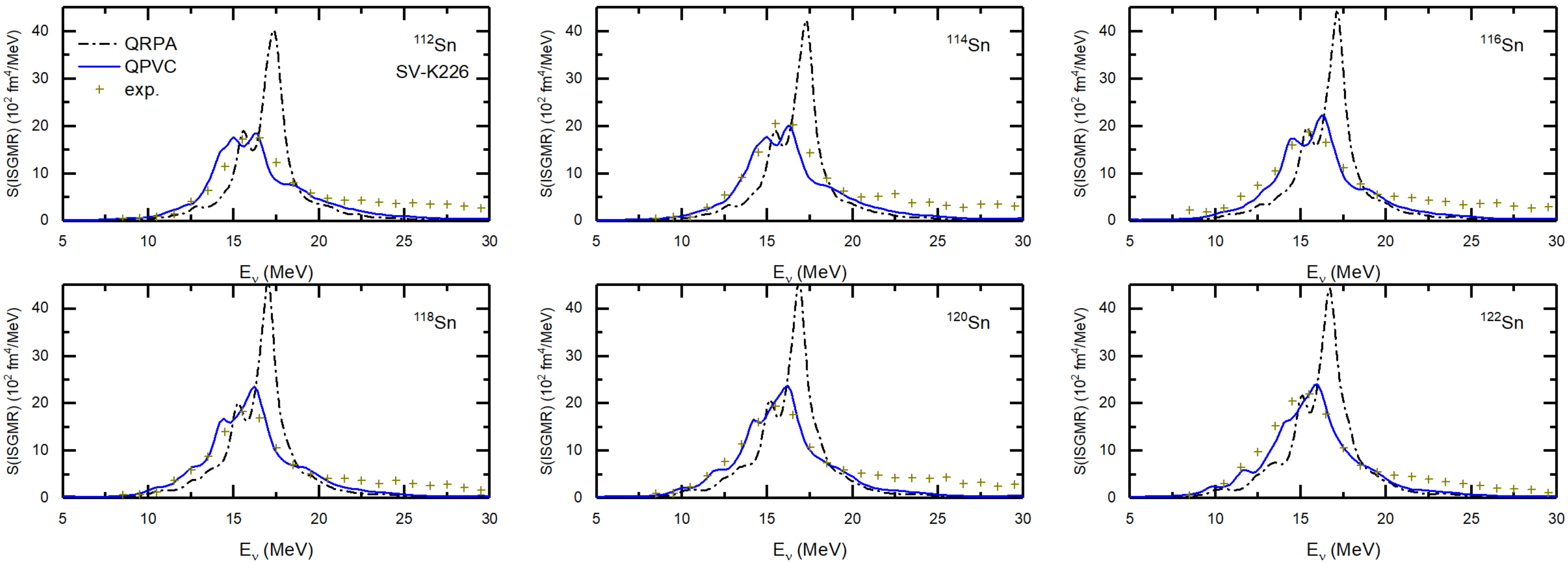


QPVC:

- ✓ GMR energy is moved downwards slightly
- ✓ Width is reproduced

Exp.: *Patel et al., PLB 726, 178 (2013)*

GMR of Sn isotopes studied by QRPA+QPVC



SV-K226: $K_\infty = 226$ MeV

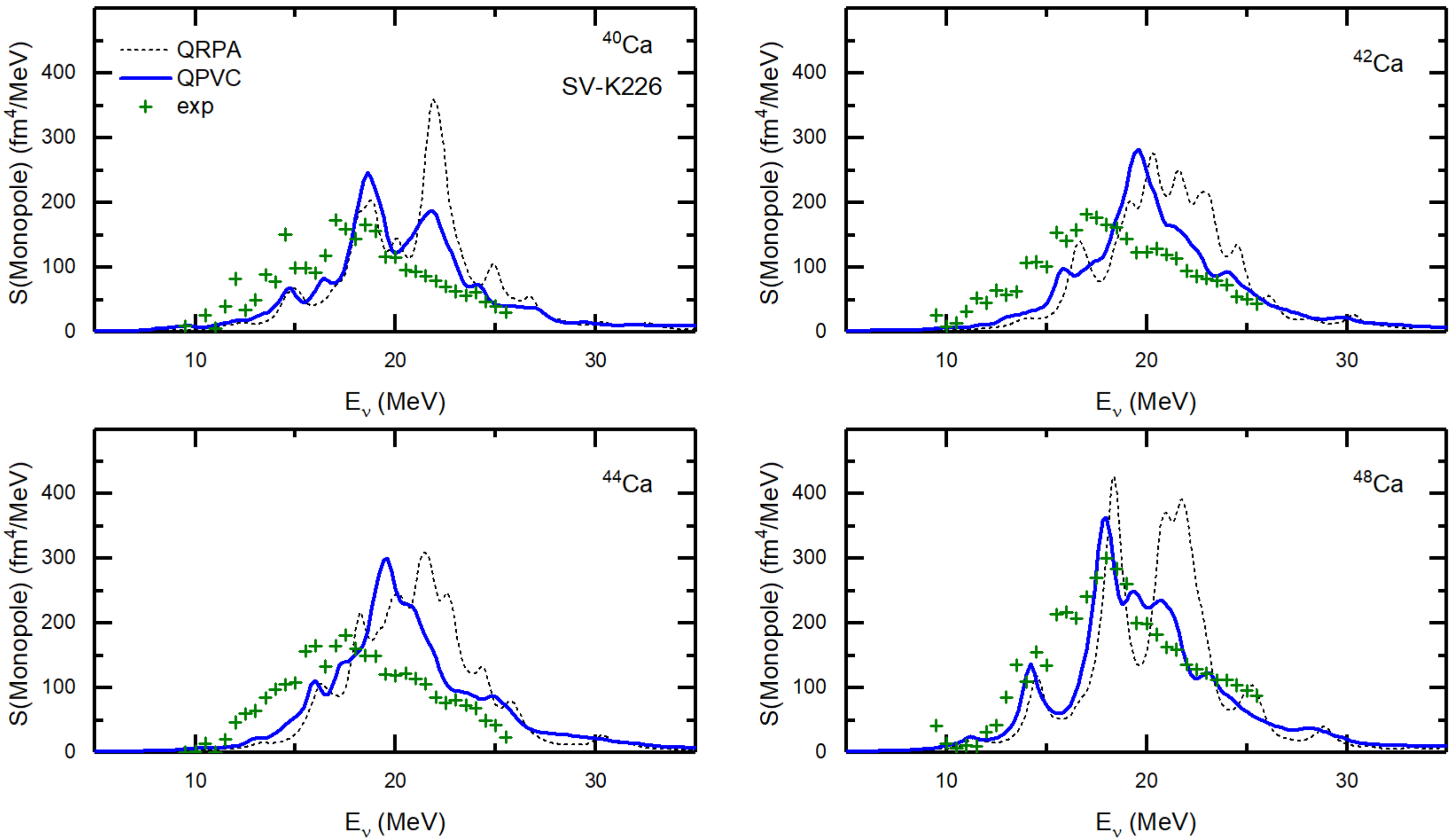
Exp.: *Li et al., PRL 99, 162503 (2007)*

- QRPA:
- ✓ Overestimate exp. GMR energies
  ---> Sn are soft!
- ✓ Width is small

- QPVC:
- ✓ Reproduce exp. GMR energies
  ---> consistent with Pb !
- ✓ Width is reproduced

The puzzle is solved!

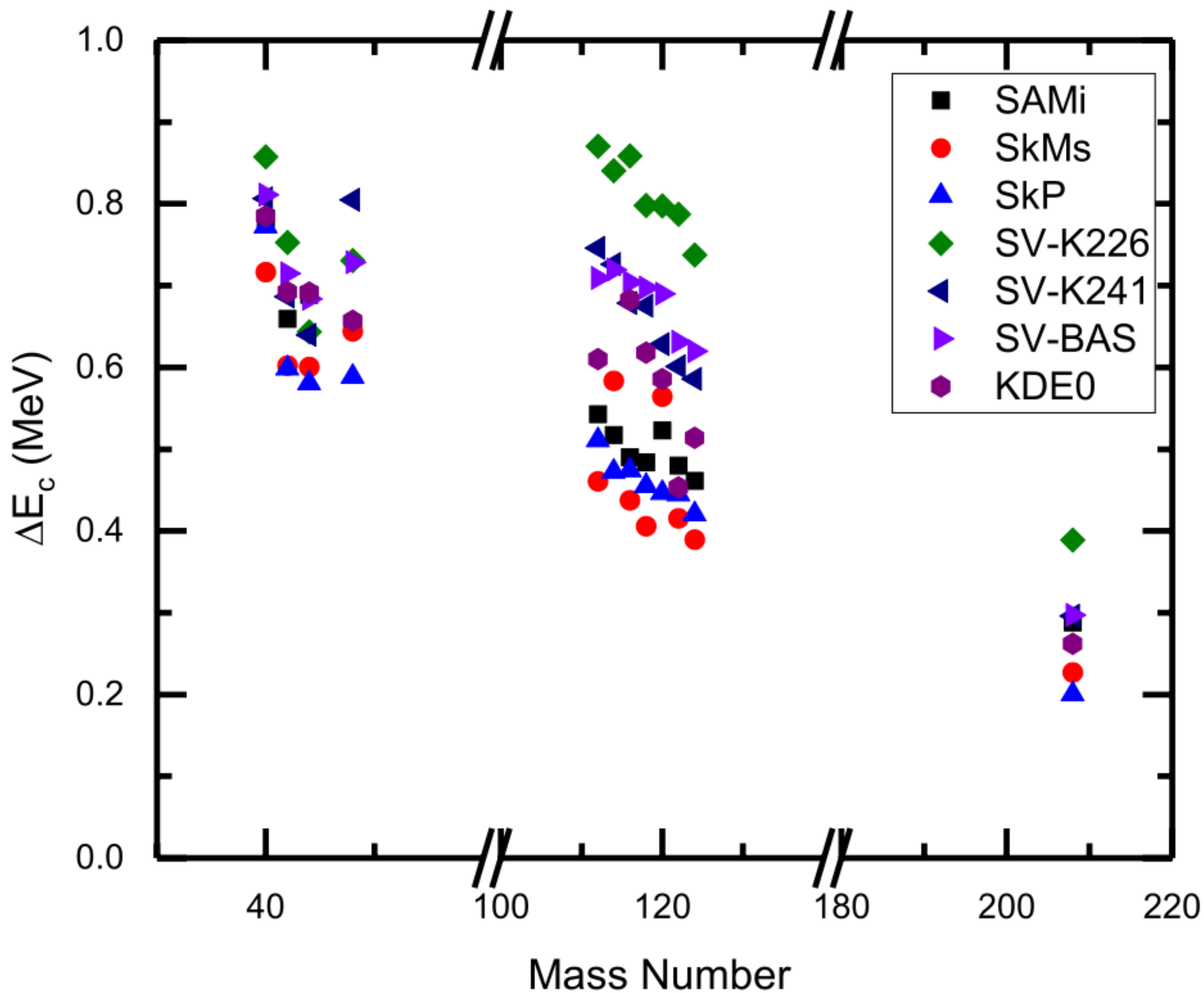
GMR of Ca isotopes studied by QRPA+QPVC



- QRPA:
  - ✓ Much overestimate GMR energies
- QPVC:
  - ✓ Much improve the strength function

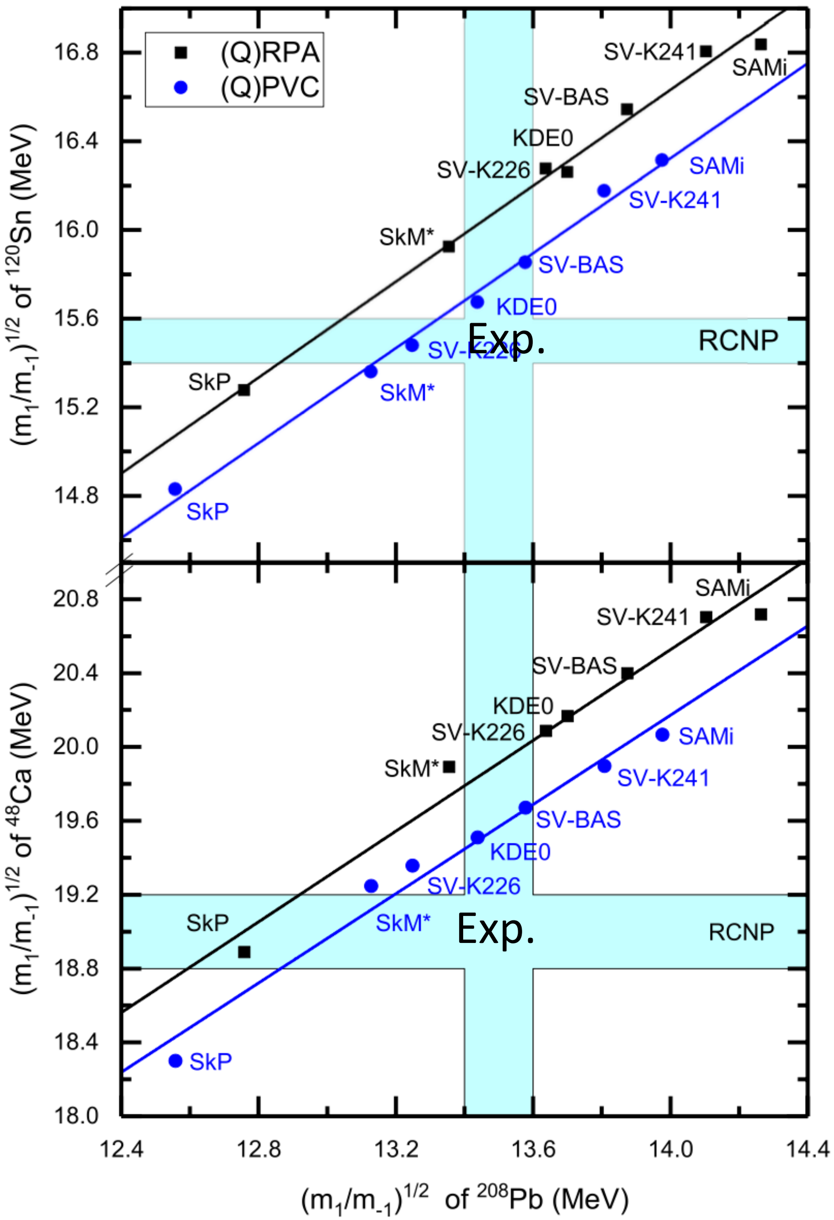
Exp.: *Olorunfunmi et al., PRC 105, 054319 (2022)*

QPVC effect on GMR energies



$$\Delta E_c = E_c(\mathrm{QRPA}) - E_c(\mathrm{QPVC}) \qquad E_c = \sqrt{m_1/m_{-1}}$$

Towards unified description of GMRs



$$E_{\mathrm{ISGMR}} = a'\sqrt{K_\infty} + b'$$

Linear correlation of GMR energies between different nuclei

- QRPA => QPVC

Simultaneous description of Sn (or Ca) and Pb is much improved!

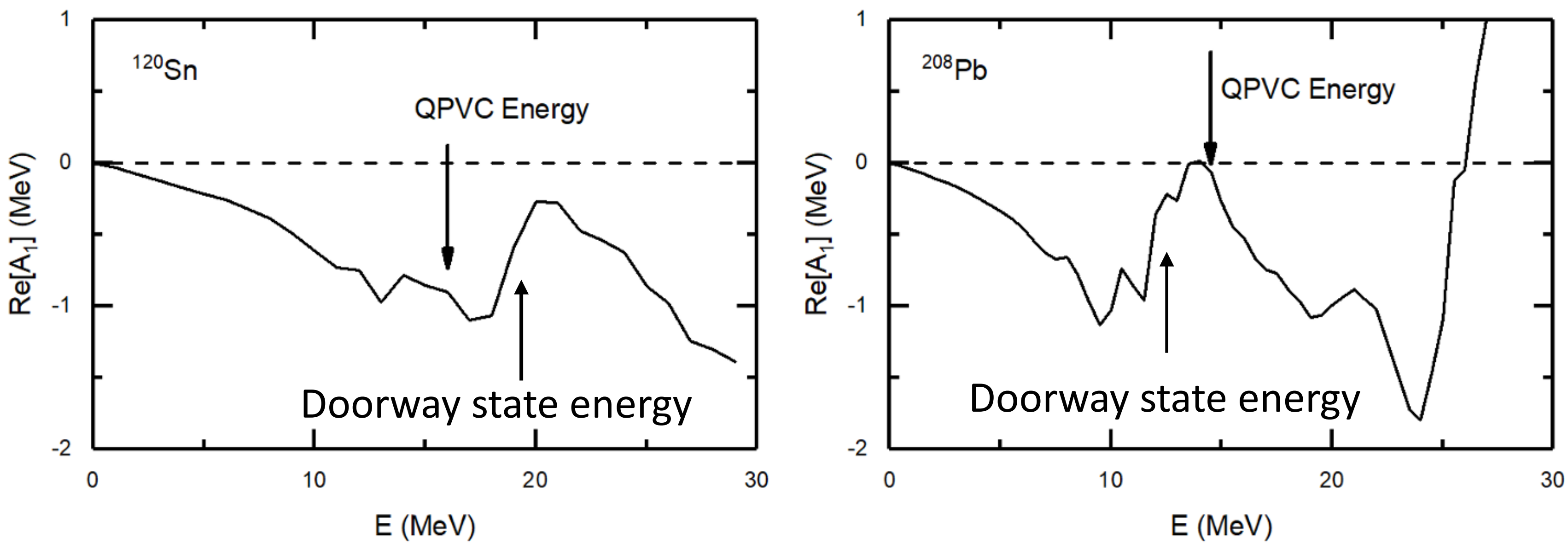
- Best descriptions:

SV-K226 $K_\infty = 226$ MeV
KDE0 $K_\infty = 229$ MeV
consistent with $K_\infty = 240 \pm 20$ MeV

Z.Z.Li, Y.F.Niu, G.Colo, arXiv:2211.01264 (02 Nov, 2022) PRL accepted

Mechanism: Self-energy

- Real part of self-energy for ^{120}Sn and ^{208}Pb: determines the energy shift

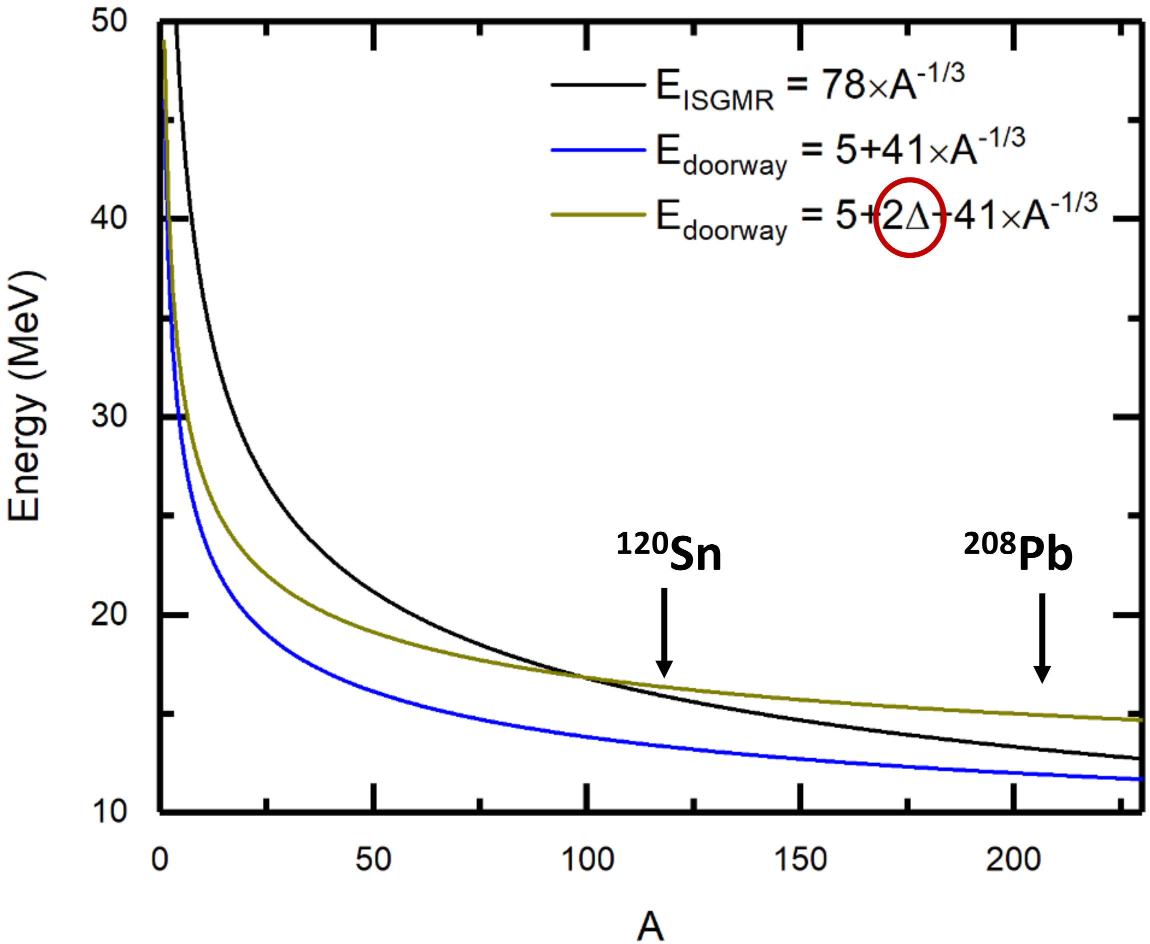


Self-energy: $$\Sigma(E) \approx \int dE' \frac{V^2}{E - E' + i\epsilon}$$

- E: QPVC energy of GMR peak
- E': Doorway-state energy (the energy of important doorway state 2qp$\otimes$phonon)

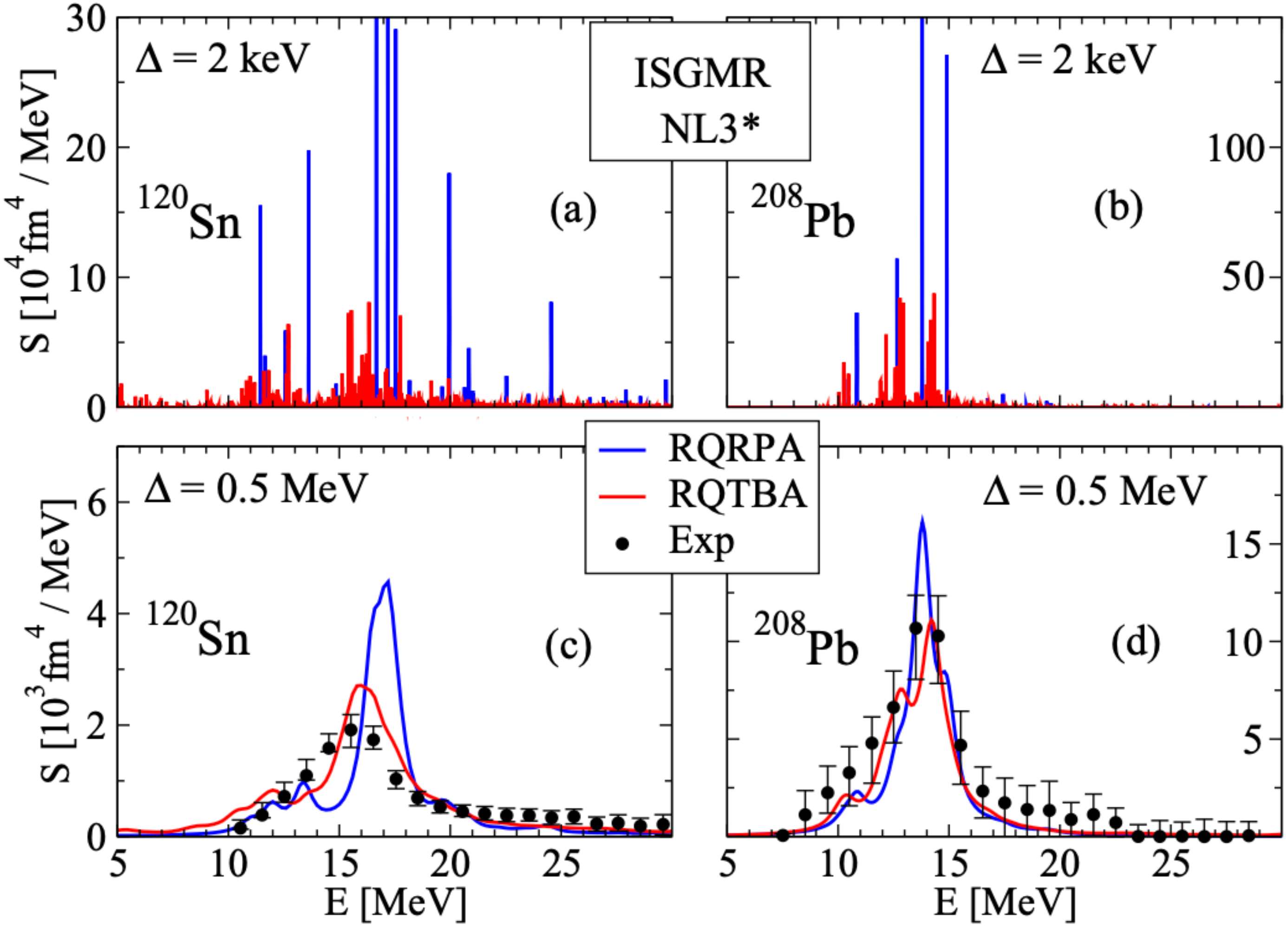
^{120}Sn: QPVC energy < doorway state energy → larger self-energy
^{208}Pb: QPVC energy > doorway state energy → smaller self-energy

Mechanism: Role of pairing gap



The pairing gap makes the relative energy position of GMR and doorway state different!

Relativistic QPVC approach



E. Litvinova, arXiv:2212.14766 (30 Dec. 2022)
PRC 107, L041302 (2023) Editor's suggestion

Summary and Perspectives

Summary

- Fully self-consistent QRPA+QPVC based on Skyrme density functional for non-charge-exchange channel is developed
- ✓ Achieve unified description of GMR in Sn and Pb, which solves a long-standing puzzle “Why is Sn so soft?”

Perspective

- Nuclear dipole excitations
- neutron capture cross sections
- …

Acknowledgement

Collaborators:

- Lanzhou University: Zhengzheng Li
- University of Milan: G. Colo, E. Vigezzi
- University of Aizu & RIKEN: Hiroyuki Sagawa
- Peking University: Jie Meng
- Anhui University: Zhongming Niu

Thank you!