北京大學
PEKING UNIVERSITY

2nd China-US-RIB Meeting on Physics of Nuclei and Hadrons
CUSTIPEN-Beijing Workshop
Oct 16-18,2017

Soft Multipole Collective Modes in ^{40}Mg

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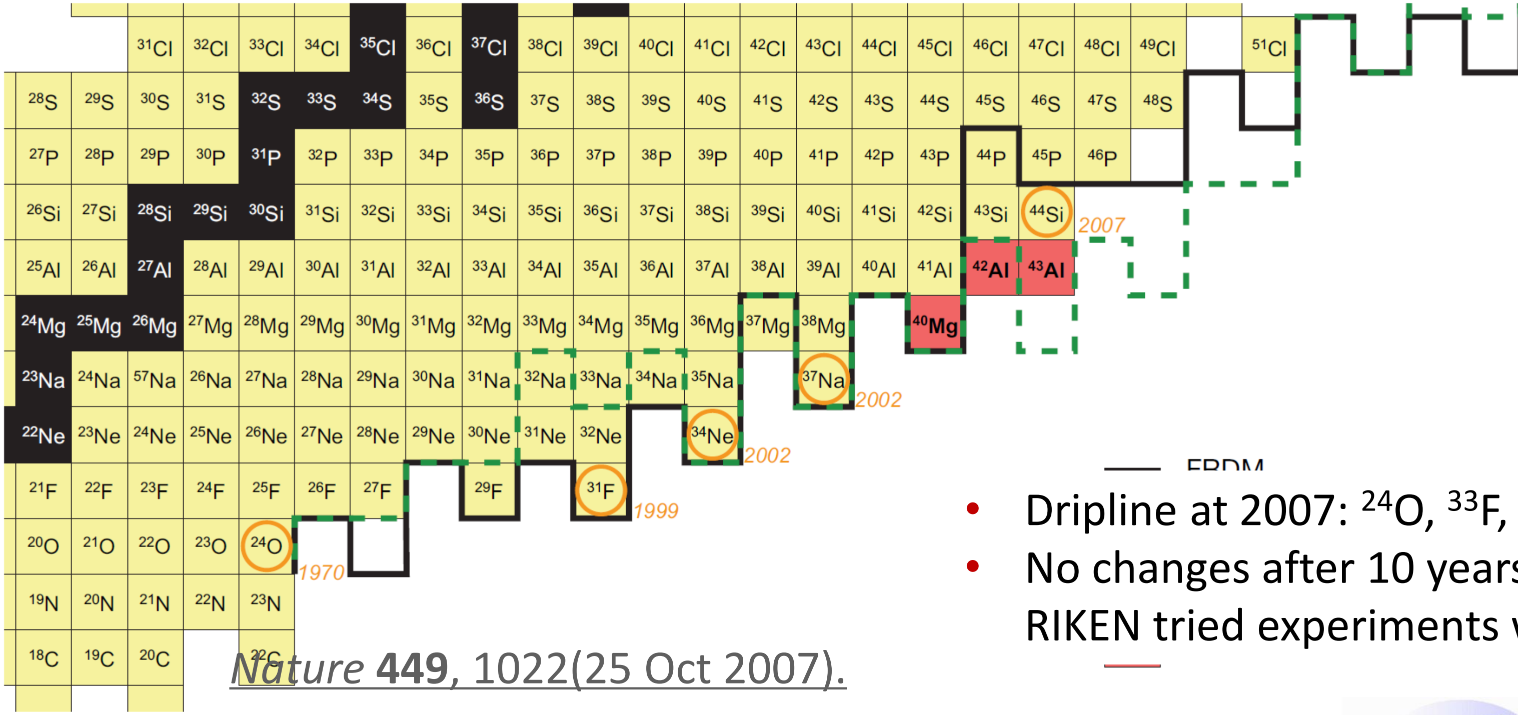
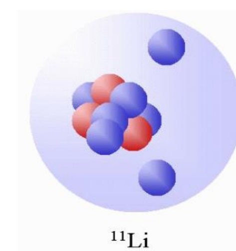
The drip-line physics



Nature **449**, 1022(25 Oct 2007).

- Dripline at 2007: ^{24}O, ^{33}F, ^{34}Ne, ^{40}Mg
- No changes after 10 years, although RIKEN tried experiments with ^{48}Ca



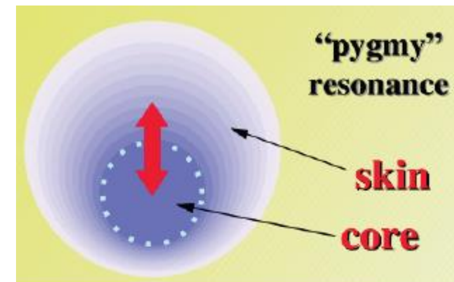
- Halo--extended dilute surface, soft modes…
- Nuclear astrophysical interests
- Explain few-body physics by many-body methods
- Extrapolate, verify and improve theoretical modes

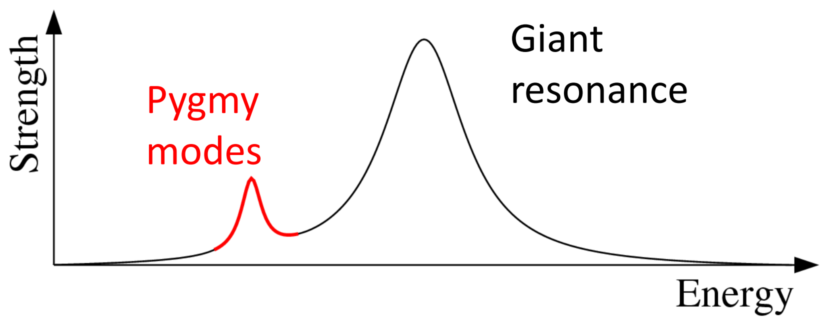
Collective excitations of weakly bound nuclei

- Novel relative motion between halo/skin and core: collective or non-collective?
- Enhance astrophysical neutron capture rates
- Related to continuum, neutron halo, deformation, EOS, symmetry energy, incompressibility…

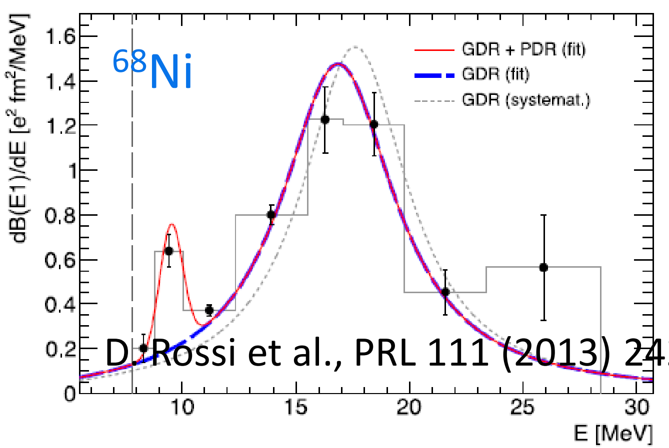
Three-Fluid Hydrodynamical Model of Nuclei*

Radhe Mohan PRC， 1971

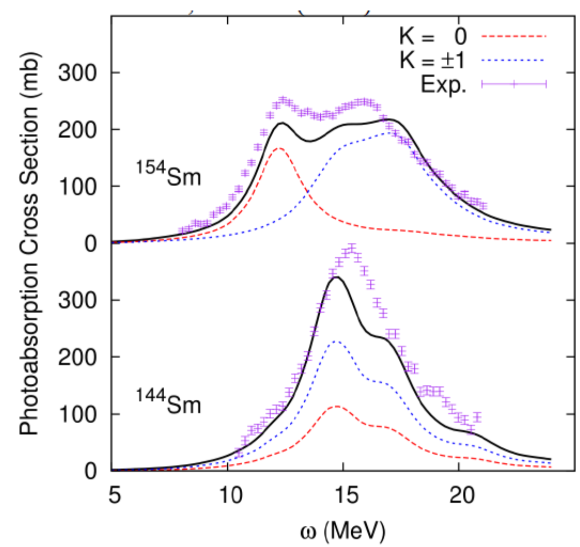




Extensive experiments in less exotic nuclei



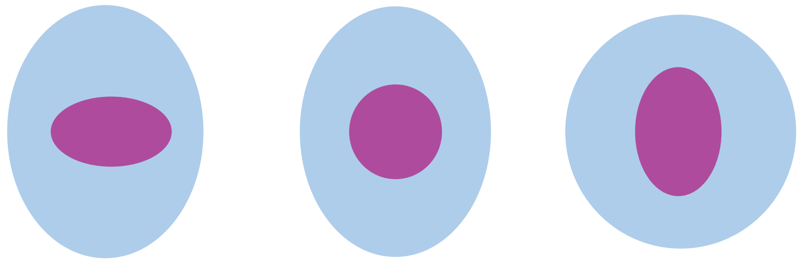
D. Rossi et al., PRL 111 (2013) 242503



(T. Oishi, et.al, Phys.Rev. C 93, 034329 (2016))

What's the nature of deformed PDR

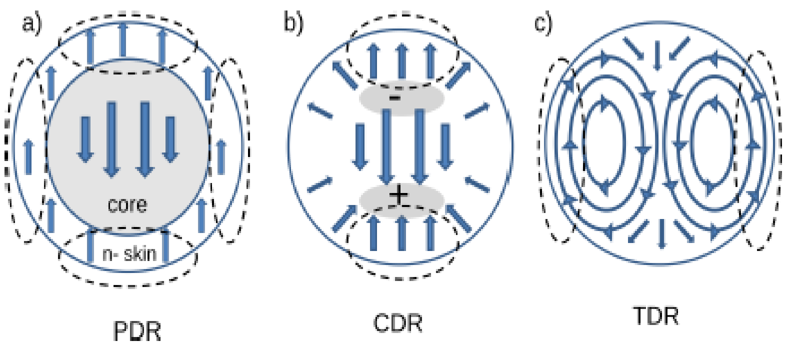
- Various deformed halos---shape decoupling---How to detect?



Comparative experimental study of splittings in K=0 and K=1 modes in GDR and PDR

T. Misu, W. Nazarewicz, S. Aberg, Nucl. Phys. A 614, 44(1997)
S.G. Zhou et al., PRC 2010; J.C.Pei et al., PRC 2013

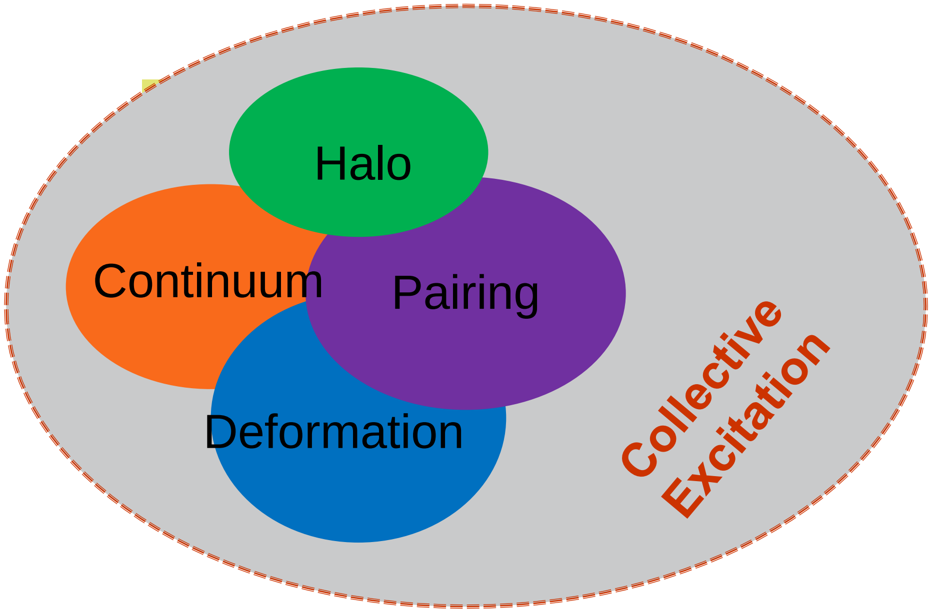
- The flow pattern of PDR in weakly bound nuclei (a long-standing question)



V.O. Nesterenko, J. Kvasil, A. Repko, W. Kleinig, P.-G. Reinhard, arXiv:1602.03326

- Can be studied directly by transition currents in deformed QRPA
- Deformed QRPA is needed even for spherical nuclei because internal motions is prohibited due to symmetry

Methods: Deformed continuum FAM-QRPA



Several spherical continuum QRPA:

- M. Matsuo, Nucl. Phys. A 696, 371 (2001).
- E. Khan, N. Sandulescu, M. Grasso, and N. V. Giai, Phys. Rev. C 66, 024309(2002).

- A numerical challenge for **deformed continuum QRPA**
- Standard QRPA in the matrix form is extremely expensive for deformed nuclei, even more to include continuum configuration (a huge matrix)

Finite-Amplitude-Methods-QRPA provides alternative way solving QRPA equation iteratively rather than diagonalization

(FAM-RPA, T. Nakatsukasa, PRC, 2007)

FAM-QRPA developments

Time(year)	Implement	Authors(Group)
2007	3D FAM-RPA	T.Nakatsukasa, et al.
2011	Spherical FAM-QRPA (based on HFBRAD code)	P.Avogadro, T.Nakatsukasa
2011	Deformed Monopole modes (base on HFBTHO code)	M.Stoitsov, M.Kortelainen *et al*
2013	Monopoles modes in relativistic RPA/QRPA	T. Niksic *et al* Haozhao Liang, *et al*
2013	Discrete states and strengths(based on HFB-THO)	N.Hinohara, M.Kortelainen, W. Nazarewicz, E.Olsen
2014	Beta decay （based on HFB-THO）	M. T. Mustonen and J. Engel
2014	Soft monopole modes (based on HFB-AX code)	J.C.Pei, M.Kortelainen, Y.N.Zhang F.R.Xu
2015	Multipole modes (based on HFB-THO)	M.Kortelainen, N.Hinohara, W.Nazarewicz
2017	Soft Multipole modes (based on HFB-AX code)	K.Wang, M.Kortelainen, J.C.Pei

Implement FAM-QRPA in coordinate-space

- HFB-AX output: axial-deformed wavefunctions (17 GB) and energies
- B-spline lattice transformed to Gauss-Legendre lattice
- FAM-QRPA procedure:

1. Construct full transition densities (including time-odd terms):

$$
\begin{aligned}
\delta\rho(\omega) &= UXV^T + V^*Y^TU^\dagger. \\
\delta\kappa^{(+)}(\omega) &= UXU^T + V^*Y^TV^\dagger, \\
\delta\kappa^{(-)}(\omega) &= V^*X^\dagger V^\dagger + UY^*U^T,
\end{aligned}
$$

$$\left\{s_\phi,\, j_r,\, j_z,\, (\nabla\times\mathbf{j})_\phi\,,\, (\nabla\times\mathbf{s})_r\,,\, (\nabla\times\mathbf{s})_z\,,\, (\Delta\mathbf{s})_\phi\,,\, T_\phi\right\}$$

$$
\begin{aligned}
\mathcal{E}_t^{\text{even}} &= C_t^\rho[\rho]\,\rho_t^2 + C_t^\tau\rho_t\tau_t + C_t^{\Delta\rho}\rho_t\Delta\rho_t + C_t^{\nabla J}\rho_t\nabla\mathbf{J} + C^J\mathbf{J}_t^2\,, \\
\mathcal{E}_t^{\text{odd}} &= C_t^s[\rho]\,\mathbf{s}_t^2 + C_t^{\Delta s}\mathbf{s}_t\cdot\Delta\mathbf{s}_t + C_t^T\mathbf{s}_t\cdot\mathbf{T}_t + C_t^j\mathbf{j}_t^2 + C_t^{\nabla j}\mathbf{s}_t\cdot\nabla\times\mathbf{j}_t \\
&\quad + C_t^{\nabla s}\left(\nabla\mathbf{s}_t\right)\,,
\end{aligned}
$$

Implement FAM-QRPA in coordinate-space

- 2. Calculate H^{20}, H^{02} (including time-odd terms), F^{20}, etc

$$\begin{aligned}
\delta H^{20}_{\mu\nu}(\omega) &= U^\dagger \delta h V^* - V^\dagger \delta\Delta^{(-)*} V^* + U^\dagger \delta\Delta^{(+)} U^* \\
&\quad - V^\dagger \delta h^T U^*, \\
\delta H^{02}_{\mu\nu}(\omega) &= -V^T \delta h U + U^T \delta\Delta^{(-)*} U - V^T \delta\Delta^{(+)} V \\
&\quad + U^T \delta h^T V.
\end{aligned}$$

- 3. Calculate *X, Y*; and do Broyden non-linear iterations on *X, Y*.
- 4. Finally calculate the strength

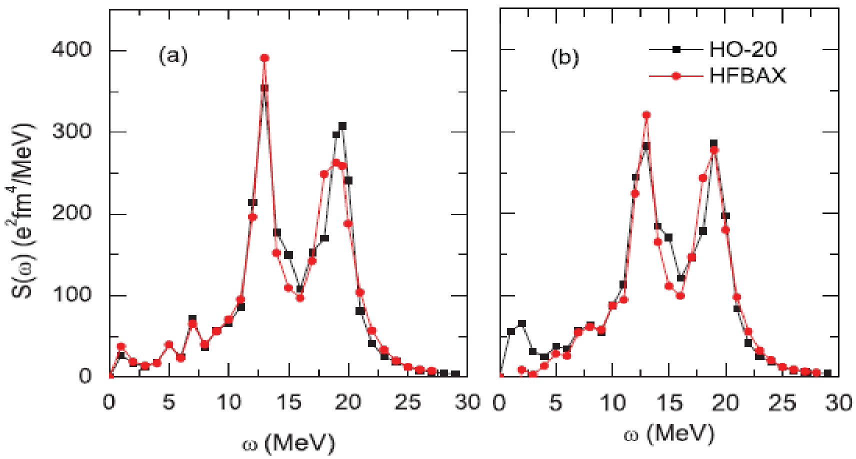
$$X_{\mu\nu} = -\frac{\delta H^{20}_{\mu\nu}(\omega) - F^{20}_{\mu\nu}}{E_\mu + E_\nu - \omega}, \quad Y_{\mu\nu} = -\frac{\delta H^{02}_{\mu\nu}(\omega) - F^{02}_{\mu\nu}}{E_\mu + E_\nu + \omega}.$$

$$S(F,\omega) = \frac{1}{2}\sum_{\mu\nu}\left\{F^{20*}_{\mu\nu} X_{\mu\nu}(\omega) + F^{02*}_{\mu\nu} Y_{\mu\nu}(\omega)\right\},$$

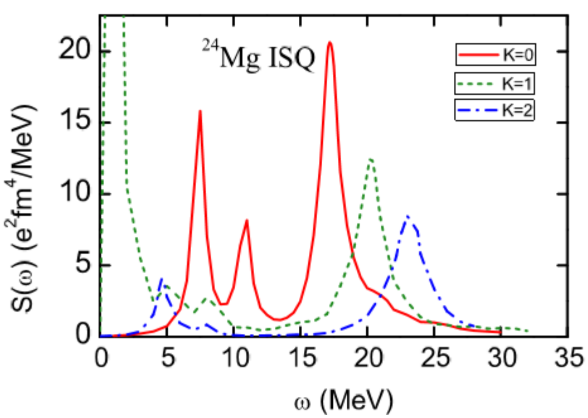
- Combined MPI+OpenMP parallel calculations in TH-1A,TH-2 supercomputers

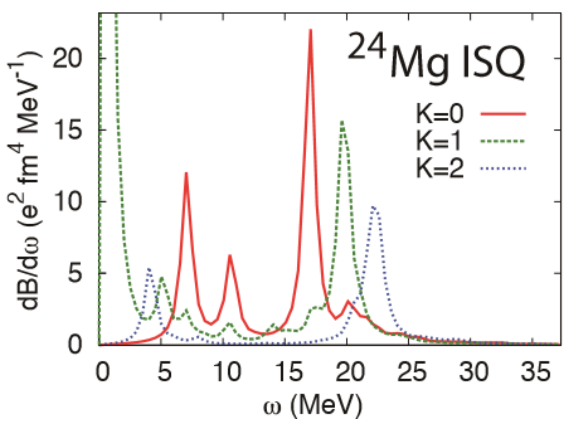
Benchmark with HO basis

- SLy4+volume pairing and surface pairing (100Zr, 24Mg)



Monopole





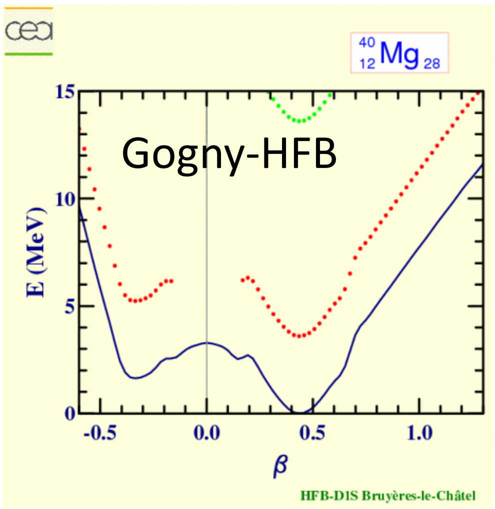
Quadrupole

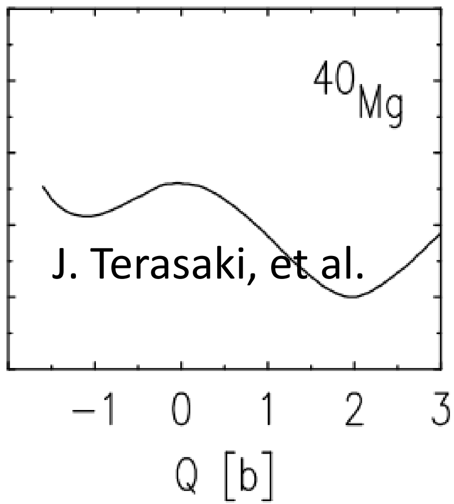
^{40}Mg: shape coexistence

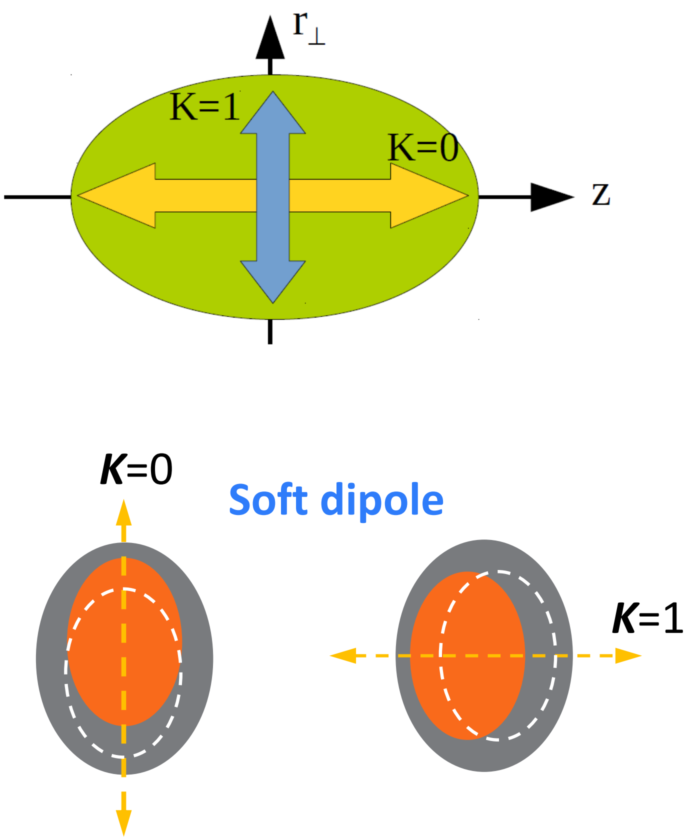
- Last Mg isotope, weakly bound deformed
- Prolate-oblate coexistence in ^{40}Mg (N=28)
- Experimental interests of spectroscopy

  (H. Crawford)

Deformed K-splitting



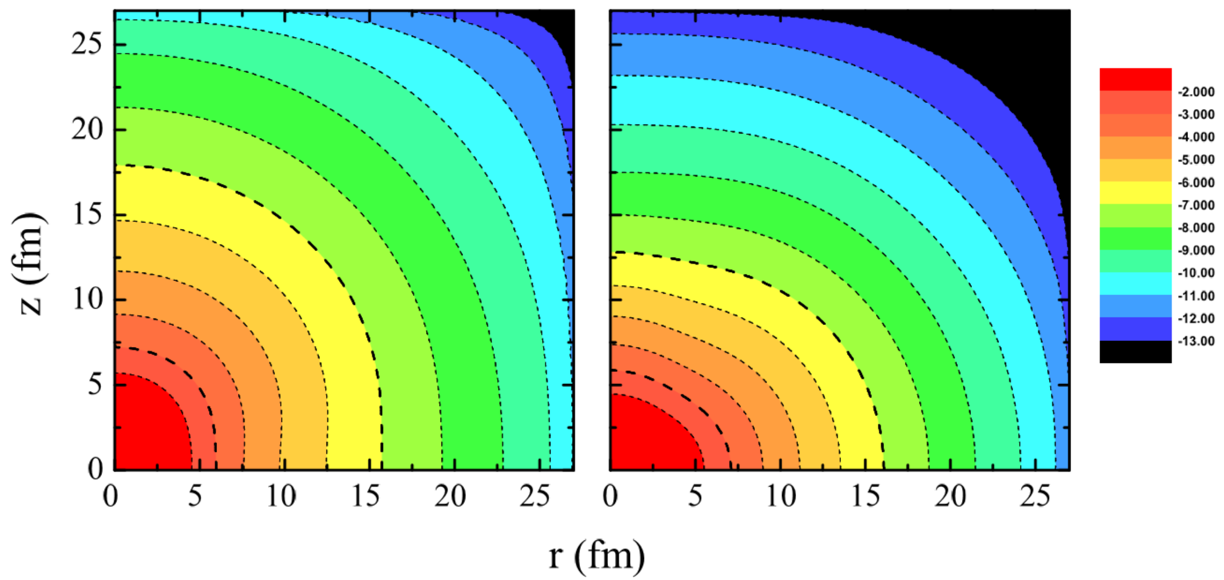




Shape evolution from oblate ^{42}Si to prolate ^{40}Mg

A good case to probe excitations based on different shapes

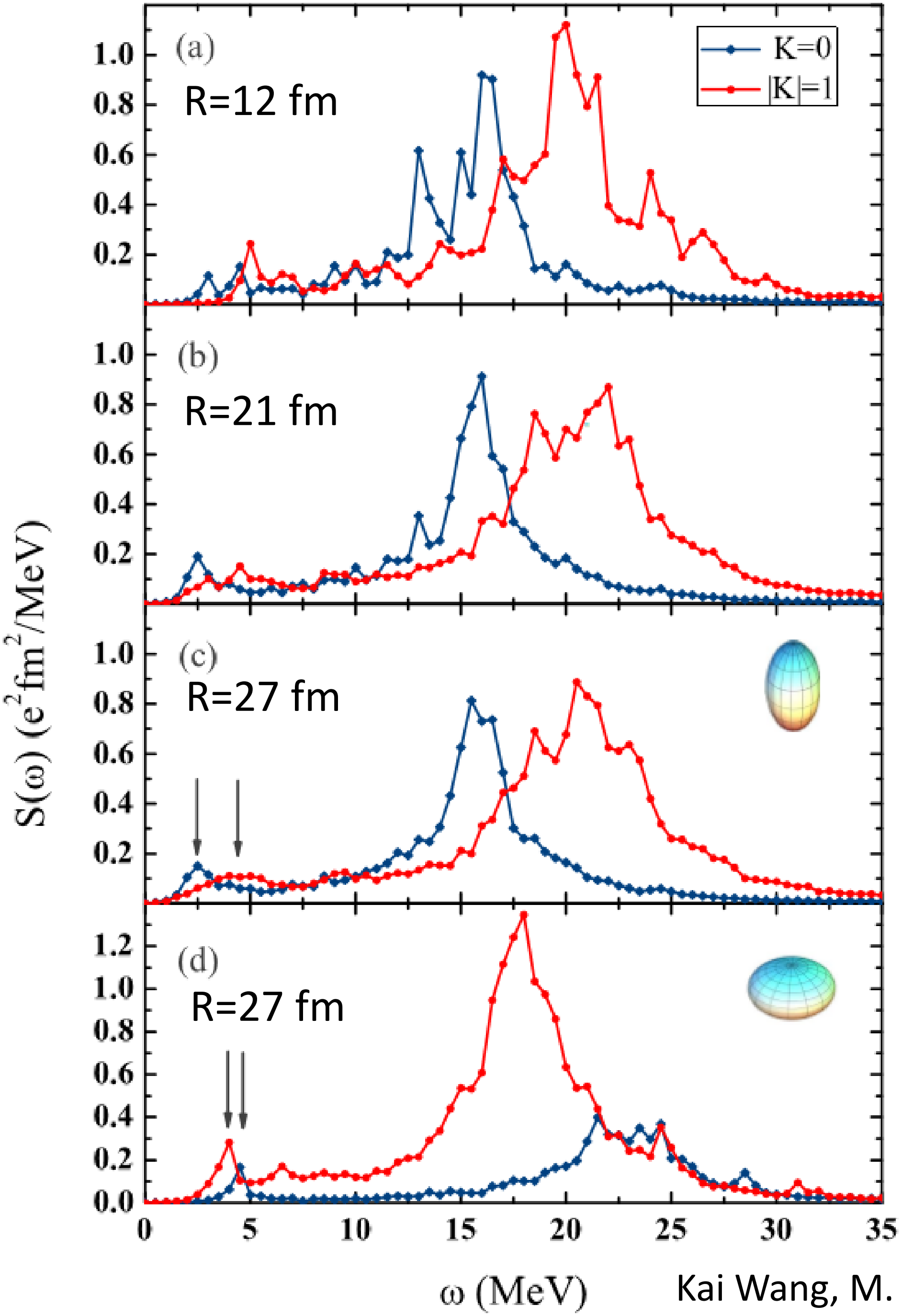
core-halo density—contour lines



$$\frac{z}{r}\Big|_{\rho=10^{-3}}=1.183 \qquad \frac{z}{r}\Big|_{\rho=10^{-3}}=0.841$$

$$\frac{z}{r}\Big|_{\rho=10^{-7}}=1.147 \qquad \frac{z}{r}\Big|_{\rho=10^{-7}}=0.811$$

There is no evident core-halo decoupling, however…..



Isovector dipole Strength

- **Box size dependence:**

Large box is needed for smooth the resonances, otherwise, PDR is fragmented.

- **Self-consistency:**

Very clear low-energy PDR without spurious states

- **Disproportionate splitting:**

<u>The splitting is proportional to deformation and centroid energy</u>

Prolate PDR splitting is 1.4 (0.95) MeV

Oblate PDR splitting is 0.45 (1.05) MeV

Disproportionate splitting is not due to static core-halo shape decoupling

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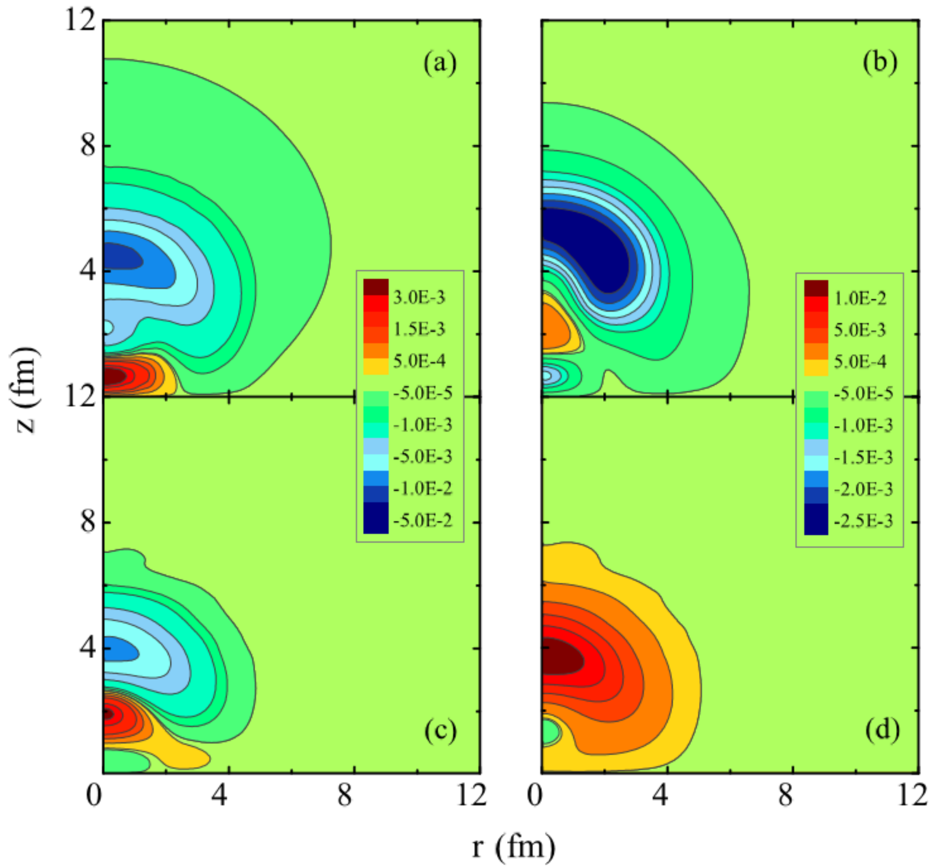
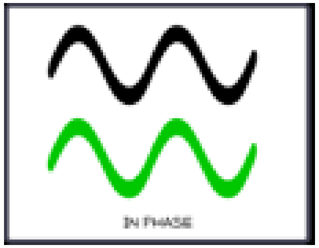
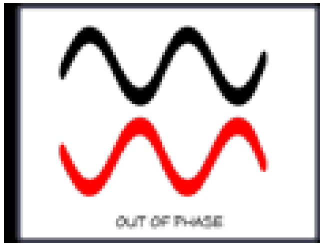
Transition density of IVD

Pygmy IVD (in phase) Giant IVD (out phase)



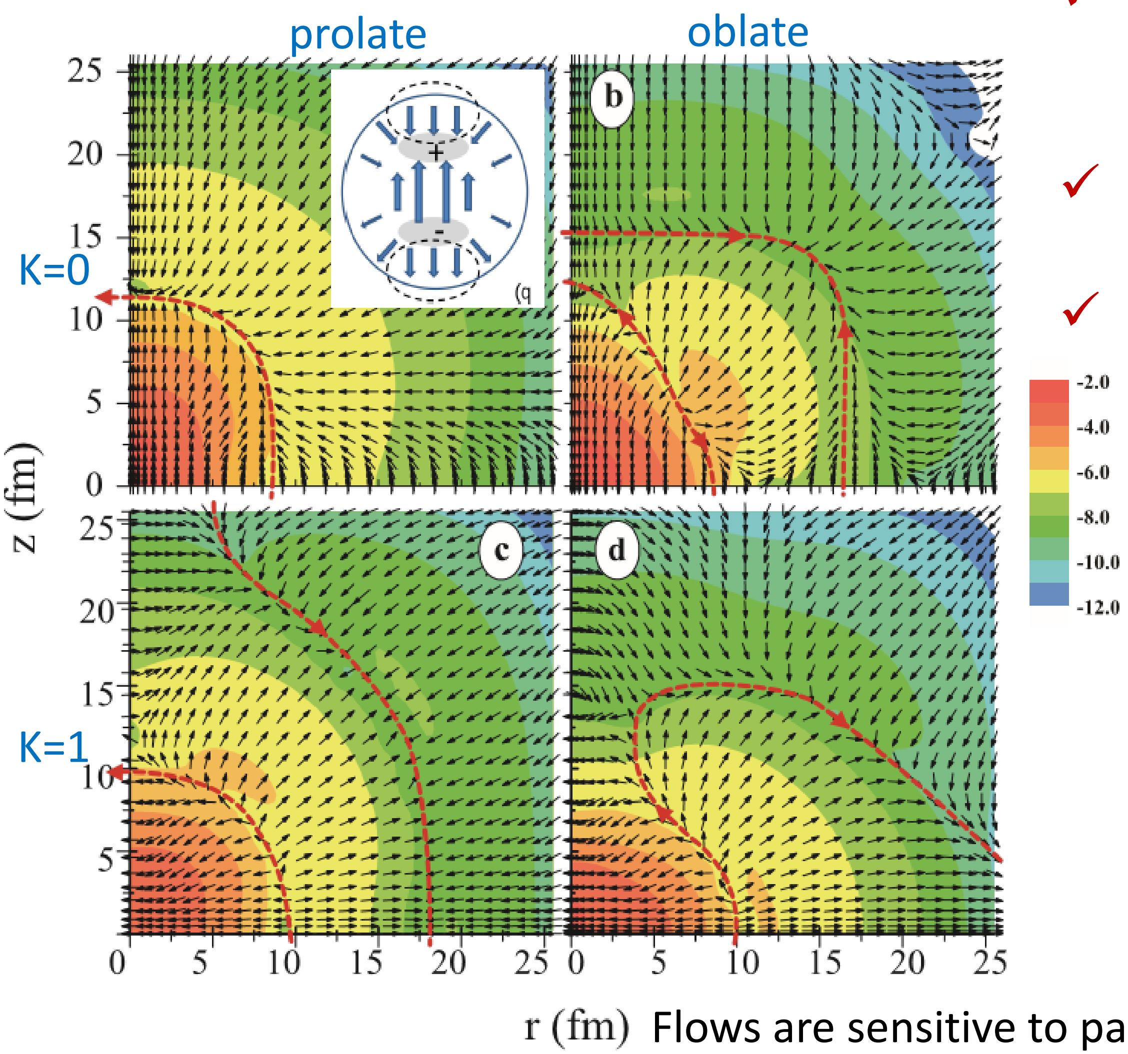




Related to the excessive neutrons at surfaces and isoscalar dipole modes

Compressional PDR

- The quantum flow topology of the PDR



Flows are sensitive to pairing

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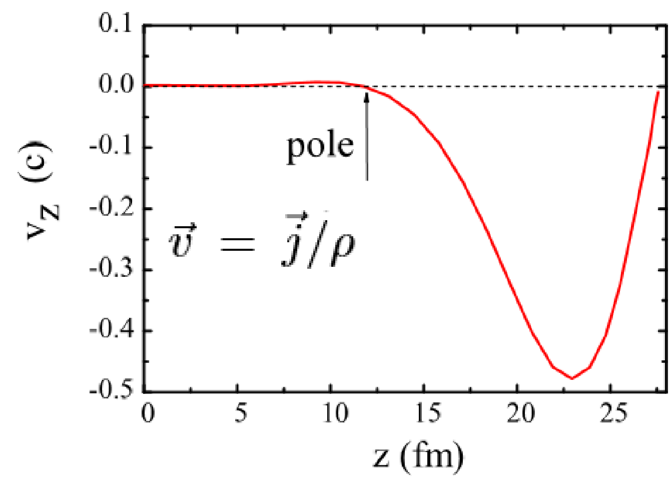
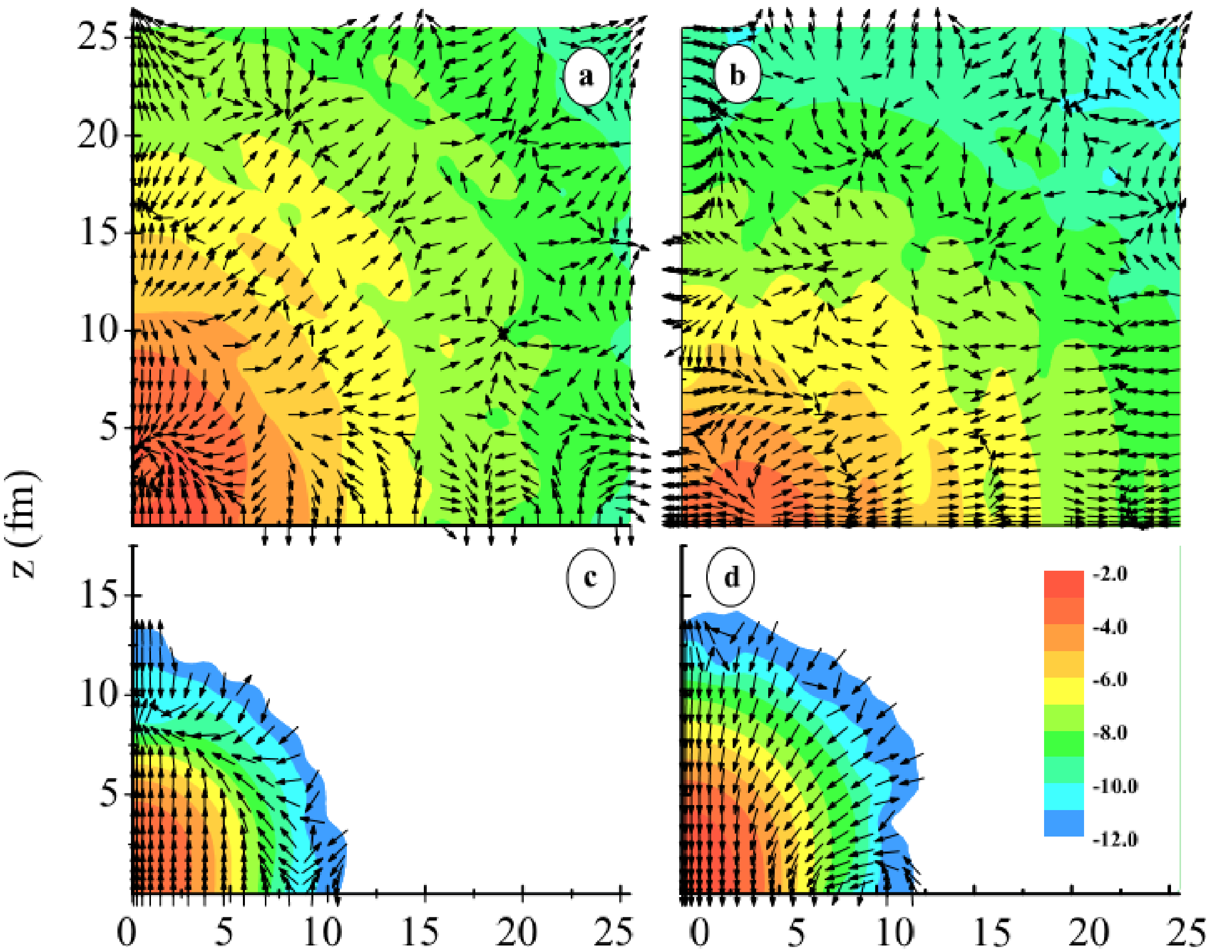
- ✓ **A long-sought collective and compressional dipole structures, poles at ±12 fm**
- ✓ the simplest flow topology with the lowest energy
- ✓ Flow patterns characterized by boundary lines



Large velocity field

Flow pattern in GDR

- More complicated as energies increase



Proton flows are simple

Warm water

Boiling water

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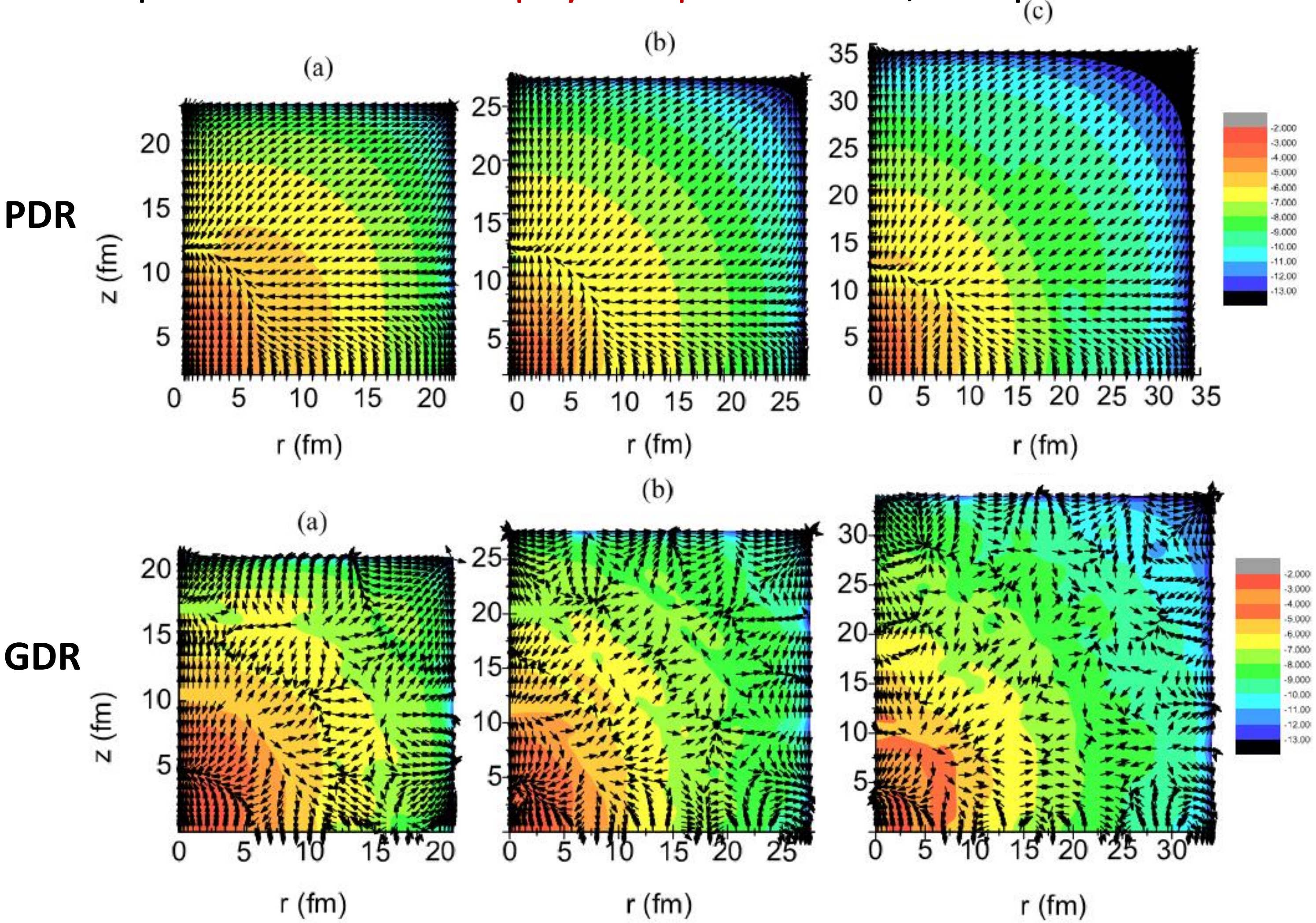
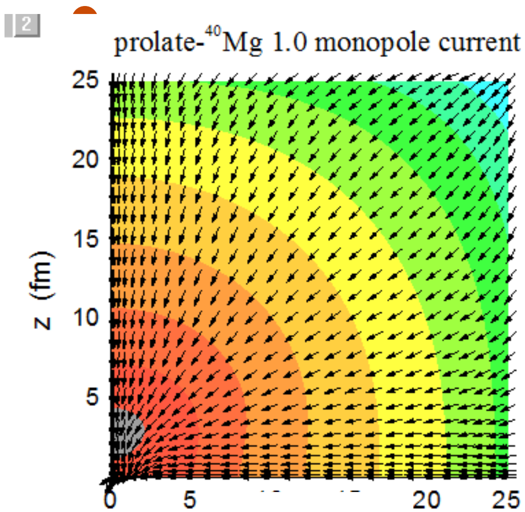
box size dependence of flow pattern

Flow patterns are robust physical phenomena, independent of box sizes

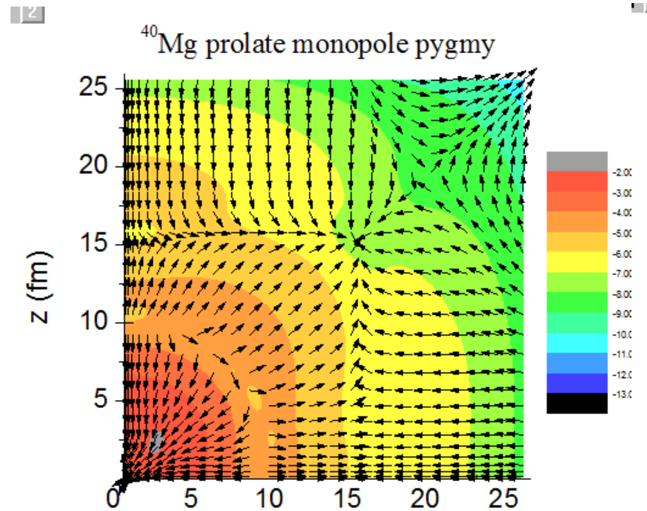


- Isovector dipole is compressional PDR, not a toridal mode
- Isoscalar dipole can have pollutions of spurious states

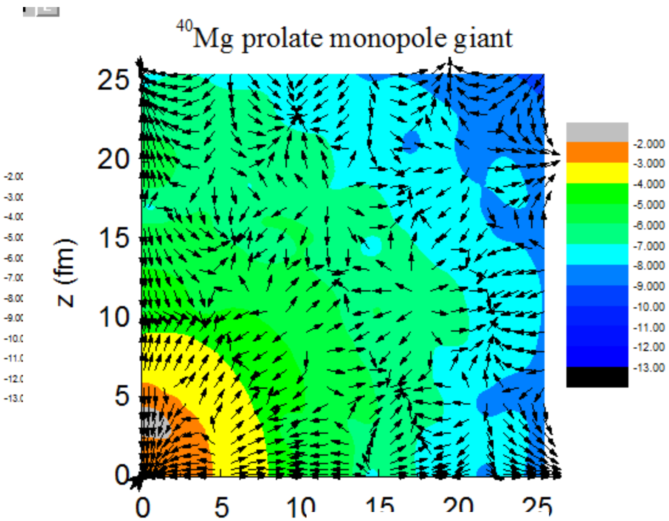
Current flows of isoscalar monopole modes



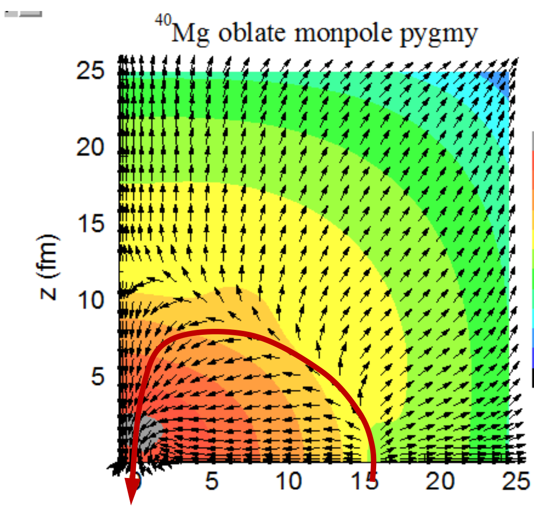
E=1 MeV



E=4 MeV

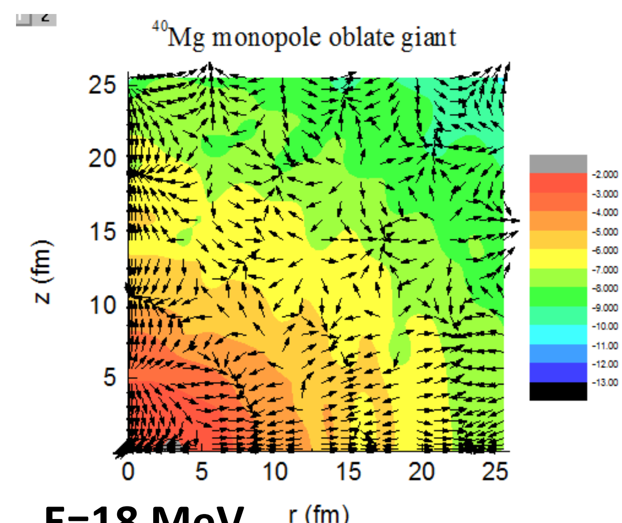


E=15 MeV



E=3 MeV

- Monopole flow patterns are non-trivial and becomes complicated as E* increases
- Toroidal mode is favorable in oblate shape

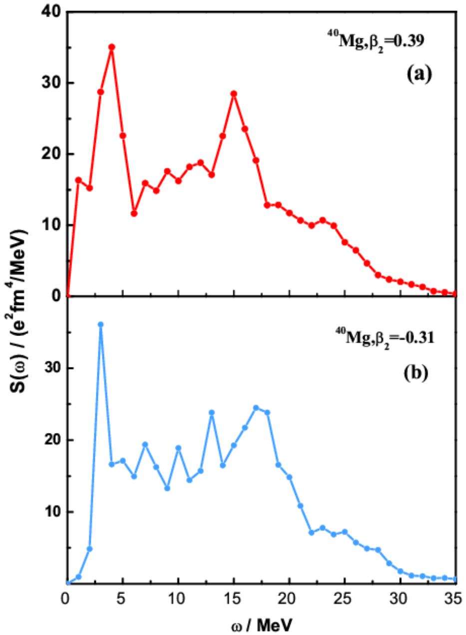


E=18 MeV

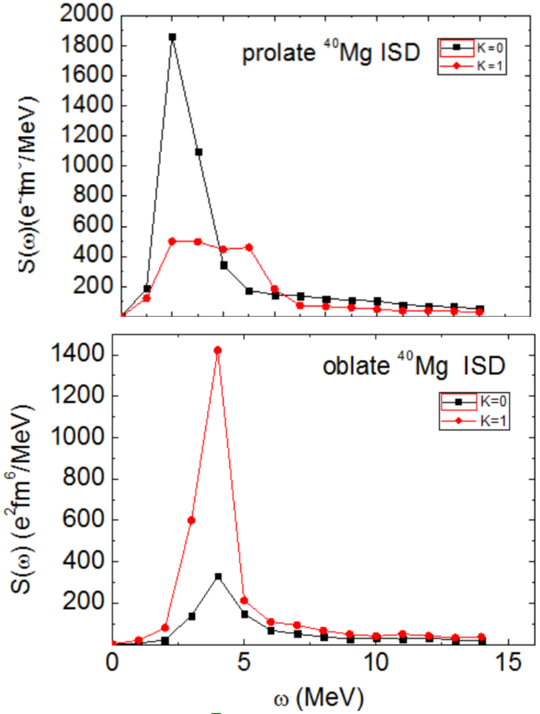
J.C.Pei, K.Wang, M.Kortelained, J. Phys .Conf. Ser.

Summary

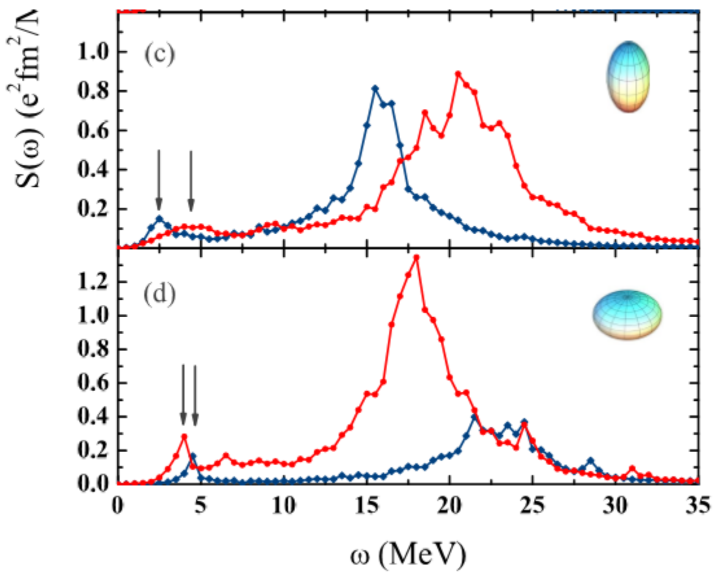
ISM



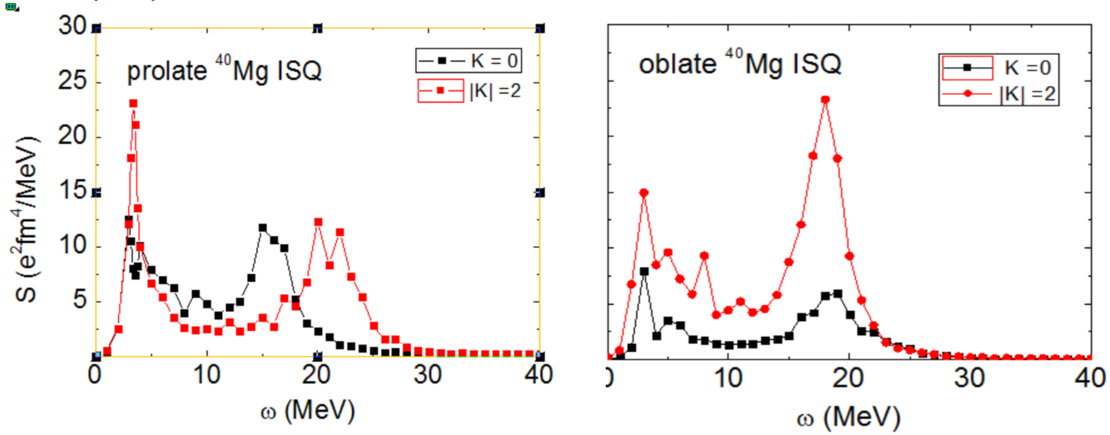
ISD



IVD



ISQ



Summary

- Developed the fully self-consistent deformed continuum FAM-QRPA for multipole excitations in shape-coexisting ^{40}Mg
- Monopole mode is dominated, with lowest excitation energy
- Disproportionate pygmy deformation splitting not due to static shape decoupling
- Amazing flow topologies related to energies has been revealed in a large spatial mesh; the long-sought PDR is collective and compressional.
- Toroidal mode is favorable in oblate shape

Thanks for your attention!