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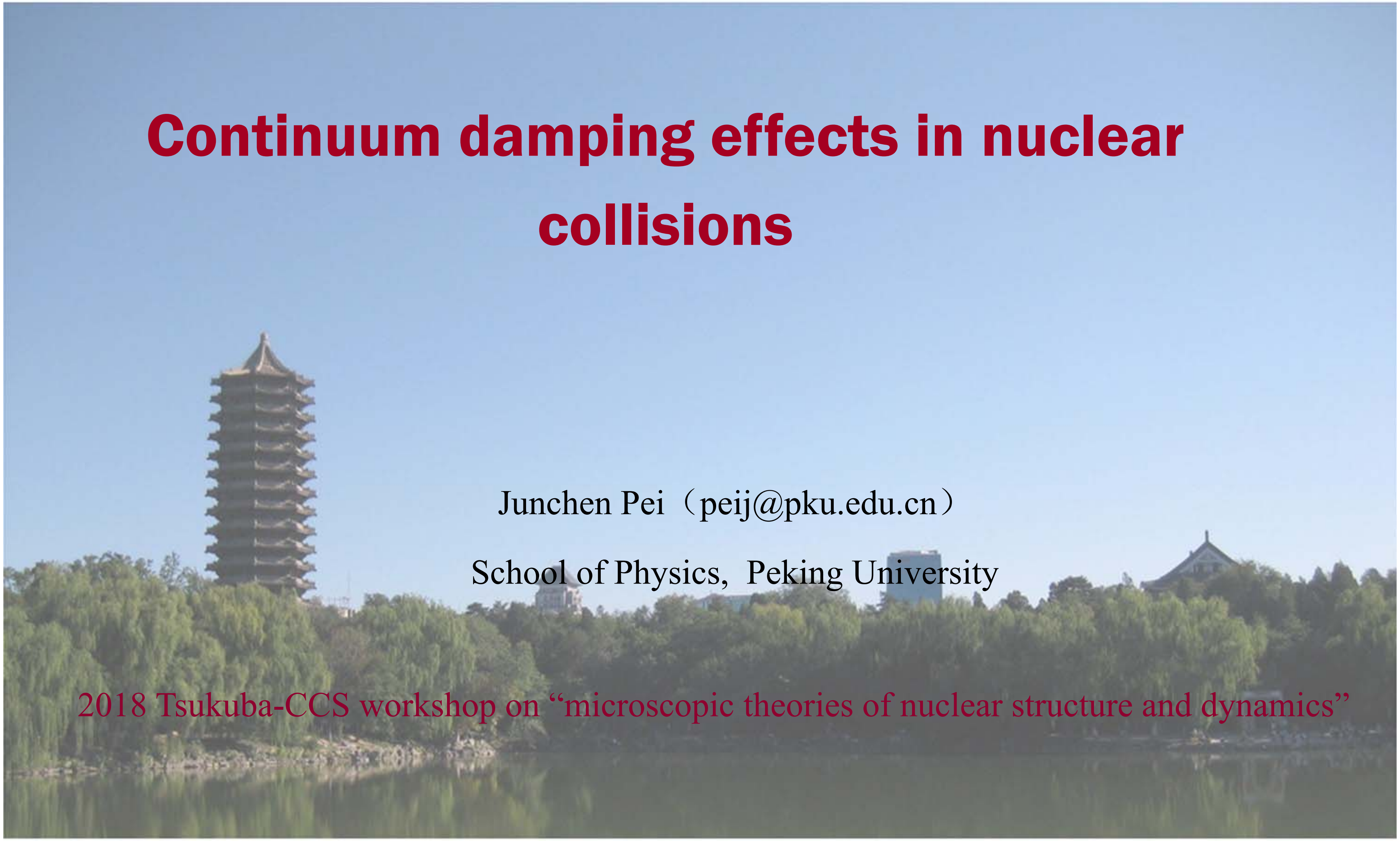
Continuum damping effects in nuclear collisions



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2018 Tsukuba-CCS workshop on “microscopic theories of nuclear structure and dynamics”

Background

- Rich dynamic phenomena of quantum many-body problems

$$i\frac{d|\Psi(t)\rangle}{dt} = \hat{H}|\Psi(t)\rangle,$$

Coupling of collective and single-particle dof;
Can present well organized collective motion;
Can not be solved exactly for complex systems

- Time-dependent Hartree-Fock: large amplitude collective motion, fission, fusion, one-body dissipation, emission to continuum

J.A.Maruhn, et al., CPC 185 (2014) 2195–2216

- Time-dependent HFB: orbital exchanges, pairing with phases $\Delta_1(\boldsymbol{r}) = |\Delta_1(\boldsymbol{r})|e^{i\varphi_1(\boldsymbol{r})}$

A.Bulgac, et al, PRL 116, 122504 (2016) P.Magierski, et al. PRL 119, 042501 (2017)

- Quantum molecular dynamics: two-body dissipation, medium-energy dynamics
- Small amplitude collective motion: QRPA, linear response theory, vibrations and resonances

T.Nakatsukasa, K.Matsuyanagi, M. Matsuo, and K. Yabana
Rev. Mod. Phys. 88, 045004 (2016)

- Related to dynamics in other quantum systems, and effective interactions, while ab initio dynamics is too expensive.

Time dependent Hartree-Fock Calculations

Time-dependent Hartree-Fock equations:

$$i\frac{d\rho_{\beta\alpha}}{dt} = [h[\rho], \rho]_{\beta\alpha} . \qquad h[\rho] = t + U[\rho]$$

$$\hat{h}_q = U_q(\vec{r}) - \nabla \cdot \left[B_q(\vec{r})\nabla\right] + \mathrm{i}\vec{W}_q \cdot (\vec{\sigma} \times \nabla) + \vec{S}_q \cdot \vec{\sigma} - \frac{\mathrm{i}}{2}\left[(\nabla \cdot \vec{A}_q) + 2\vec{A}_q \cdot \nabla\right],$$

$$|\psi_\alpha(t + \Delta t)\rangle = \hat{U}(t, t + \Delta t)|\psi_\alpha(t)\rangle$$

$$\hat{U}(t, t + \Delta t) = \hat{\mathcal{T}} \exp\left(-\frac{\mathrm{i}}{\hbar}\int_t^{t+\Delta t} \hat{h}(t')\,\mathrm{d}t'\right),$$

$$\exp\left(-\tfrac{\mathrm{i}}{\hbar}\hat{h}\,\Delta t\right)\psi \approx \sum_{n=0}^{m} \frac{(-\mathrm{i}\Delta t)^n}{\hbar^n\; n!}\hat{h}^n\psi,$$

J.A.Maruhn, et al., CPC 185 (2014) 2195

- Boundary conditions

- Periodic boundary condition is usually adopted: spurious quantization within a finite box, continuum not well discretized
- Absorbing boundary condition: continuum gas are absorbed by an adjusted imaginary potential
- Twisted boundary condition: efficient as absorbing method, but independent of imaginary potential

B. Schuetrumpf, W. Nazarewicz, and P.-G. Reinhard,PRC **93**, 054304 (2016)

Twisted boundary condition

- Average over twisted angles

$$\psi_{\alpha\theta}(\boldsymbol{r}+\boldsymbol{T}_i) = e^{\mathrm{i}\theta_i}\psi_{\alpha\theta}(\boldsymbol{r}),$$

$$\langle\hat{O}(t)\rangle = \frac{1}{8\pi^3}\iiint_0^{2\pi} d^3\boldsymbol{\theta}\,\langle\Psi_{\boldsymbol{\theta}}(t)|\hat{O}|\Psi_{\boldsymbol{\theta}}(t)\rangle.$$

Θ=0, Periodic Boundary Condition

Also called phase randomization

TD-HF calculations for giant resonances, continuum damping

B. Schuetrumpf, W. Nazarewicz, and P.-G. Reinhard， Phys. Rev. C 93, 054304 (2016)

3D-HF calculations of nuclear pastra in ns, avoid finite size effects

B. Schuetrumpf and W. Nazarewicz Phys. Rev. C **92**, 045806 (2015)

useful for lattice QCD calculations: remove finite volume effects

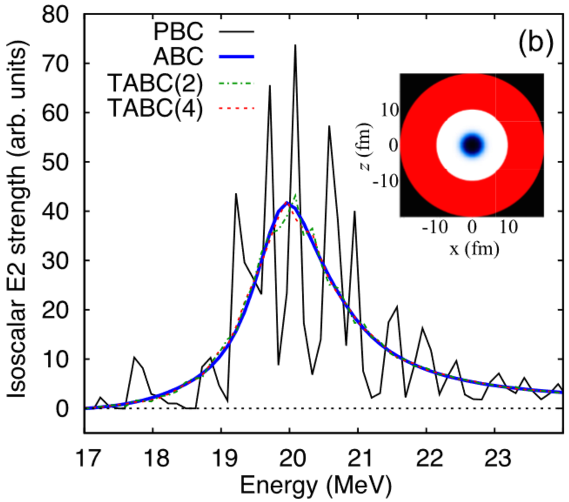
C.T.Sachrajda et al. ,PLB 609, 73(2005)

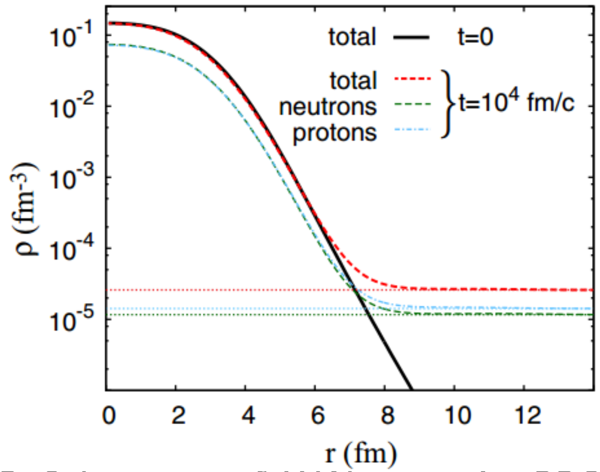
and quantum Monte Carlo: faster convergence to thermodynamic limit

C.Lin, et al, PRE 64, 016702(2001)

Absorbing boundary condition depends on the equation, spectral and grids; TBC is robust

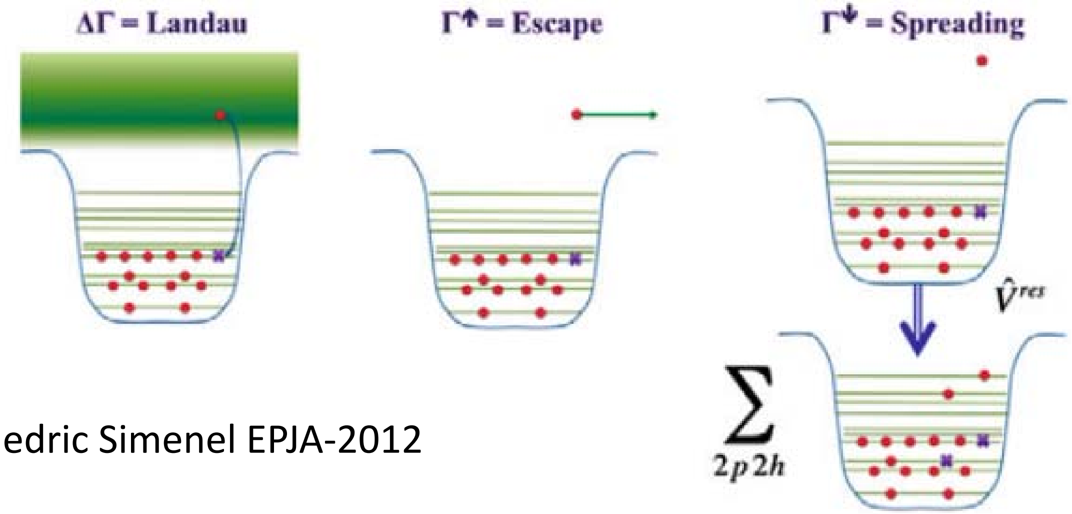
- Smooth of Giant Resonances with twisted boundary condition





B. Schuetrumpf, W.Nazarewicz PRC**93**, 054304 (2016)

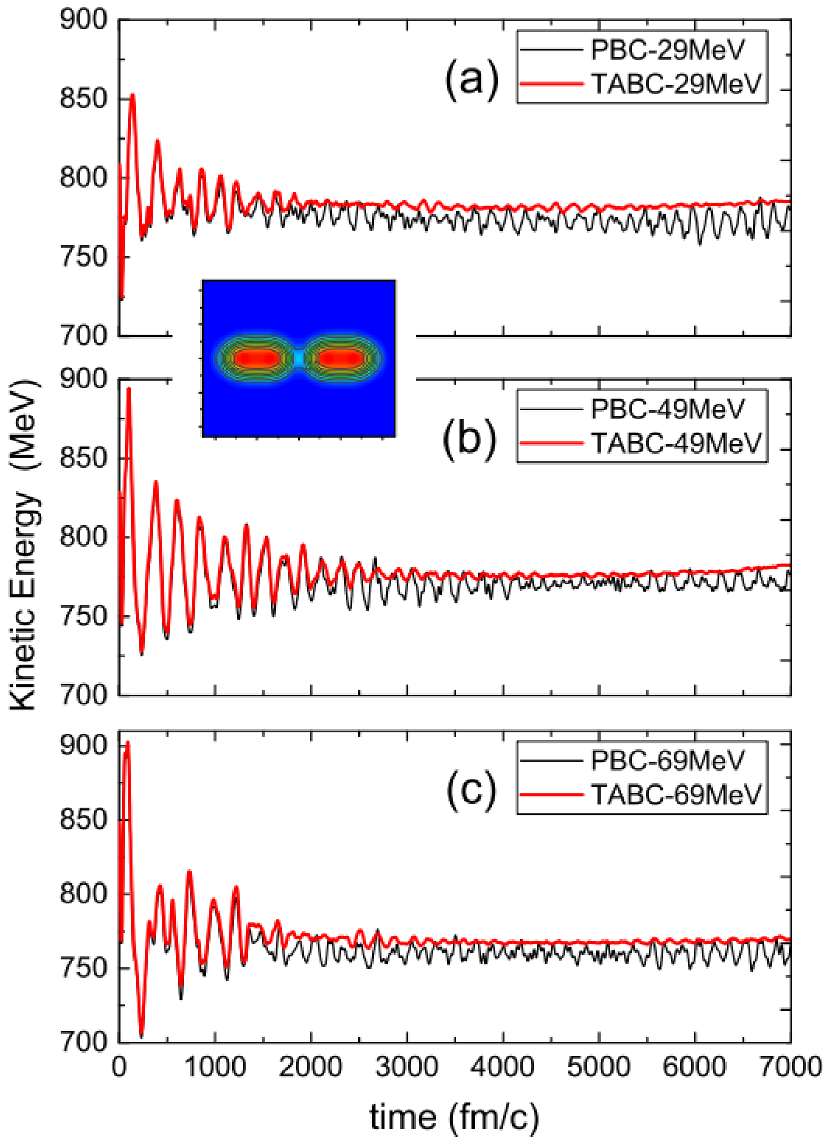
- Various contributions to widths, continuum treatment is important



Escaping damping
Landau damping
Surface collision damping
--"Line-broadening"
G.Bertsch, R.A. Broglia, *Oscillations in finite quantum systems*

C´edric Simenel EPJA-2012

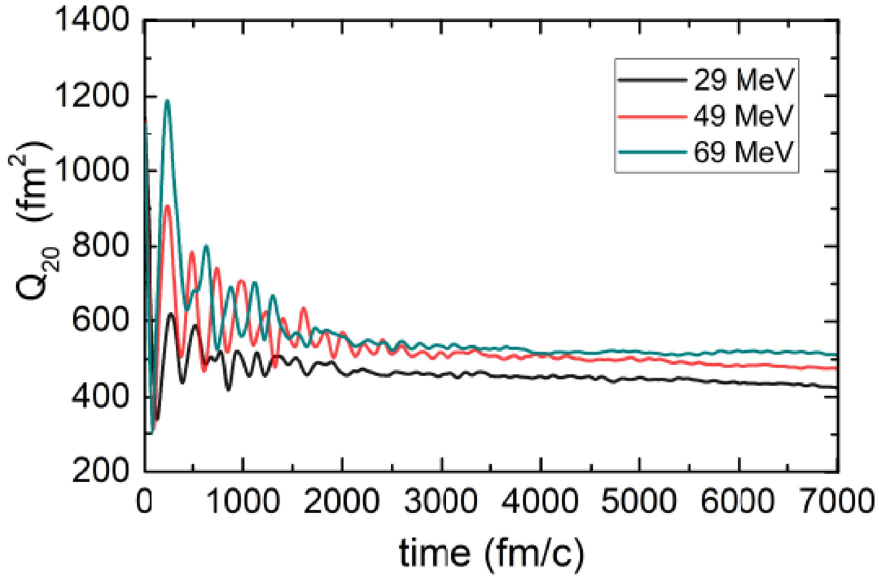
TDHF study of Mg24+Mg24 collisions

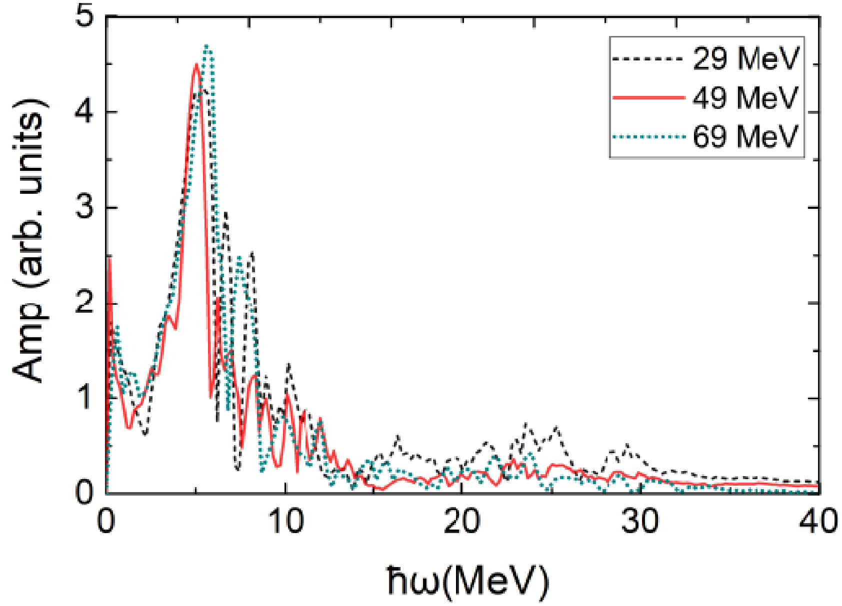


- Evident damping effects with the TBC, faster convergence
- Damping is related to surface continuum gas, similar to Plasmon environment

- *Warning*: PBC calculations with a finite box size can have false molecular vibrations

- Deformation evolution of head-to-head collision with different energies

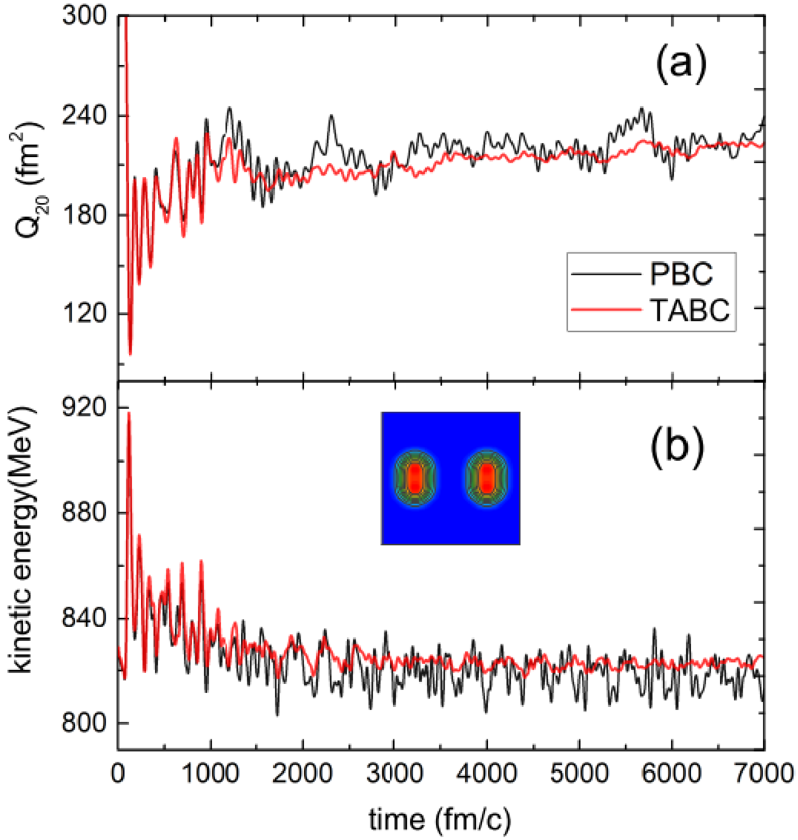




With TBC calculations we now can see:

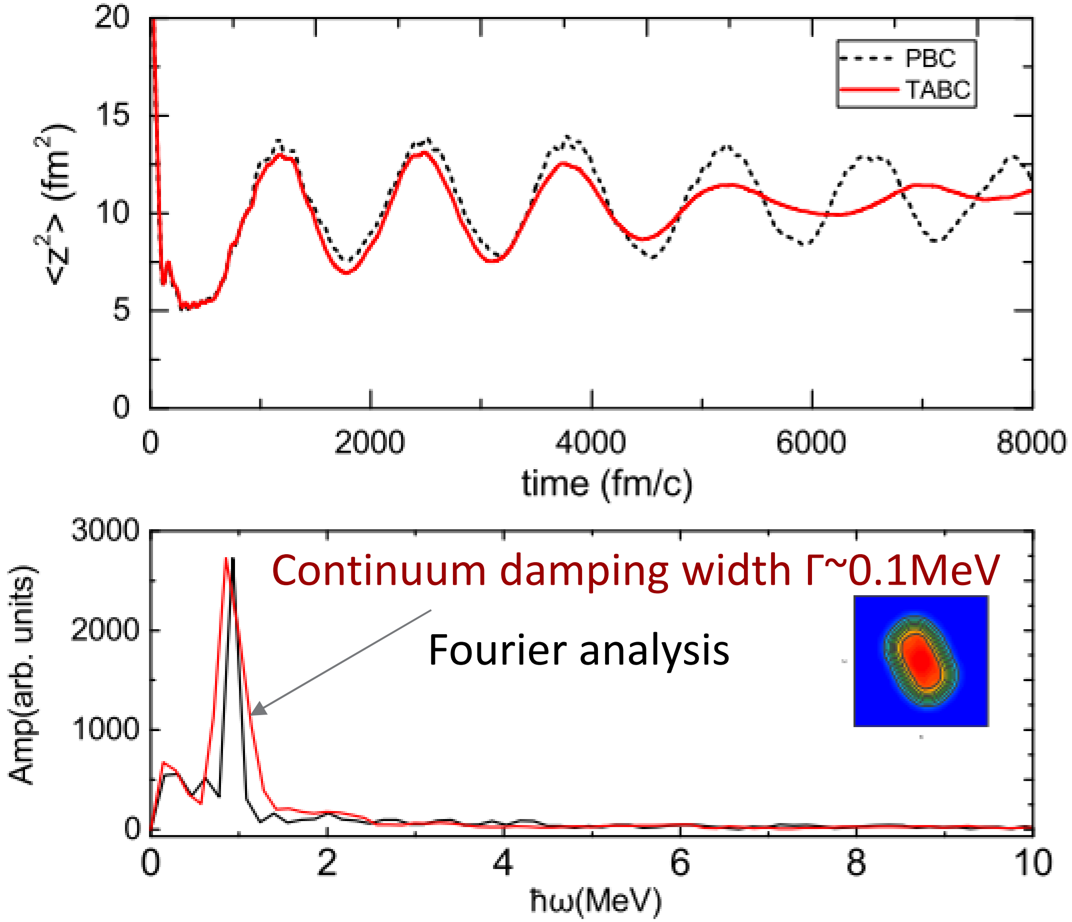
- Higher collision energy leading to larger deformation expansion amplitude
- Final kinetic energies are smaller with larger final deformations

- Waist to waist Collison



Similar: the vibrations with PBC are damped by the surface continuum (TBC)

- Damping effects in rotational case (waist-to-waist)



$$A(t) = Ae^{i(\omega + i\Gamma/2)t} = Ae^{-\frac{\Gamma t}{2}} e^{i\omega t}$$

Surprising phenomena: the rotation in the continuum can also be damped; does the equilibrium compound nuclei rotate?

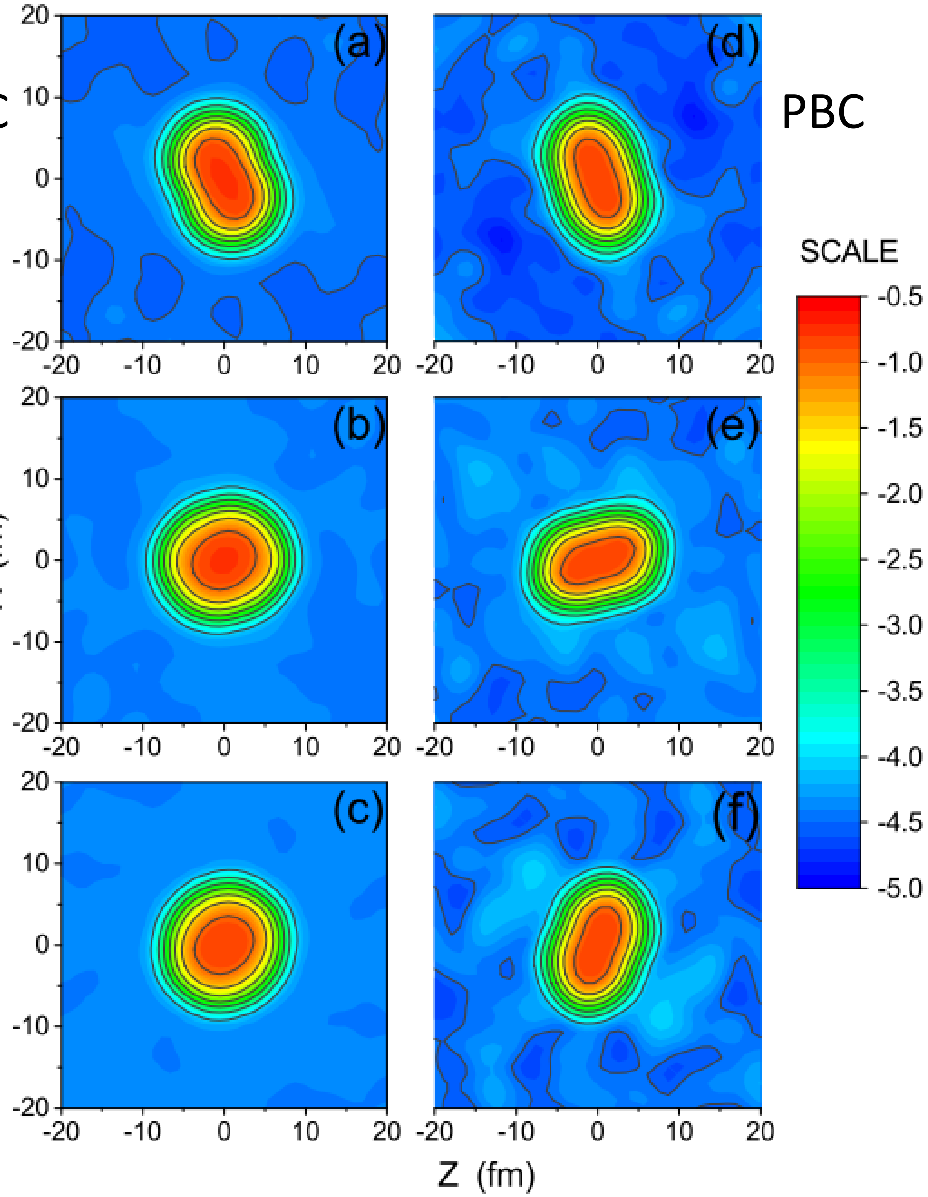
TBC

PBC

t=2000fm/c

t=4000fm/c

t=6000fm/c



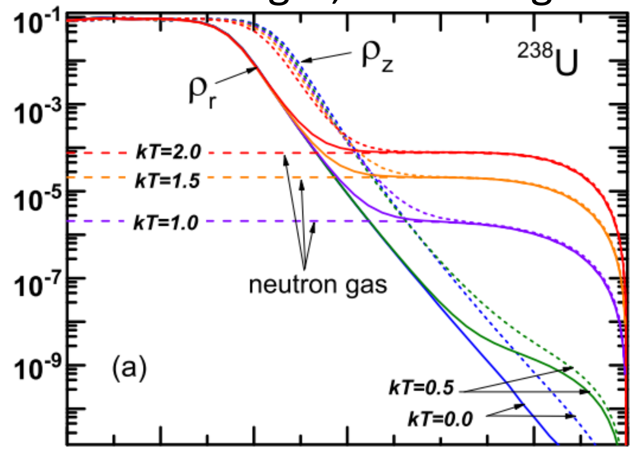
Chuanqi He, Pei, in preparing

Density distributions show:

TBC evolutions to uniform continuum gas; while PBC always produce some *false*-structured surface density distributions due to finite box-sizes and artificial reflections .

Compound nuclei (averaged) becomes spherical

Thermal gas, width ∝ gas



Y. Zhu, Pei, PRC 2014

FAM-QRPA in deformed coordinate space

- An efficient solving method of QRPA equations: particularly useful for deformed nuclei, weakly bound nuclei

$$F(t) = \eta\{F(\omega)e^{-i\omega t} + F^\dagger(\omega)e^{i\omega t}\},$$

Nuclear dynamics under a weak external field

$$F(\omega) = \frac{1}{2}\sum_{\mu\nu}\{F^{20}_{\mu\nu}(\omega)A^\dagger_{\mu\nu} + F^{02}_{\mu\nu}(\omega)A_{\mu\nu}\} + \sum_{\mu\nu} F^{11}_{\mu\nu}(\omega)B_{\mu\nu},$$

FAM-QRPA iterative solution

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

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

$$\delta\rho(\omega) = UXV^T + V^*Y^TU^\dagger.$$

(P. Avogadro and T. Nakatsukasa, PRC 2011)

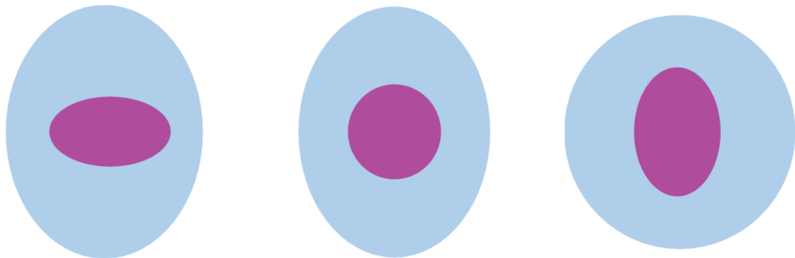
Conventional QRPA matrix form

$$\left[\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix} - \omega \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}\right]\begin{pmatrix} X(\omega) \\ Y(\omega) \end{pmatrix} = \begin{pmatrix} F^{20}(\omega) \\ F^{02}(\omega) \end{pmatrix}$$

A numerical challenge for **deformed continuum QRPA,** based on axial-symmetric coordinate-space HFB solver HFBAX

What's the nature of deformed PDR

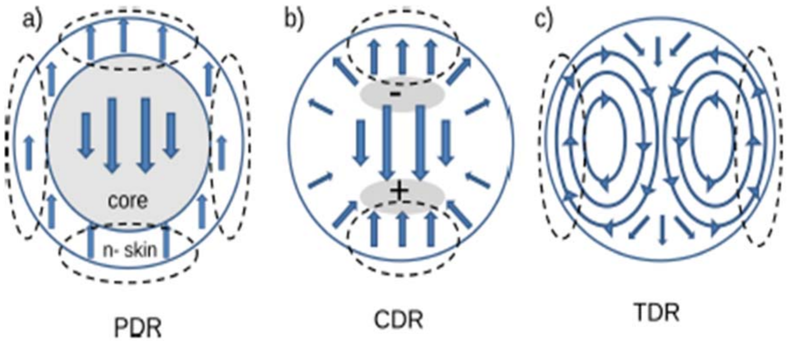
- Various deformed halos---shape decoupling---How to detect?



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

T. Misu, W. Nazarewicz, S. Aberg, NPA 614, 44(1997)
S.-G. Zhou,J. Meng, P. Ring, and E-G. Zhao, PRC 82, 011301(R) (2010)
J.C.Pei, Y.N.Zhang, F.R.Xu., PRC 87, 051302(R) (2013)

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

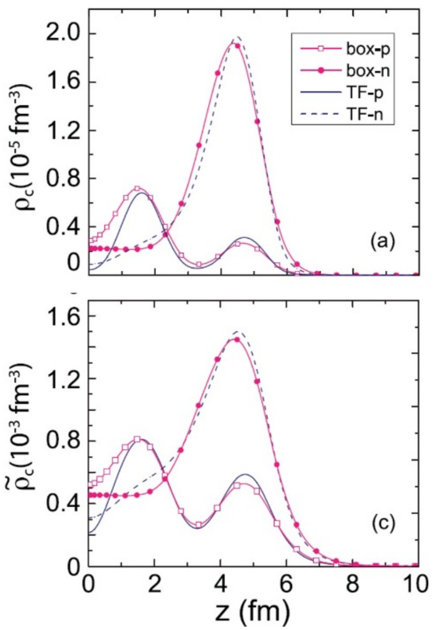


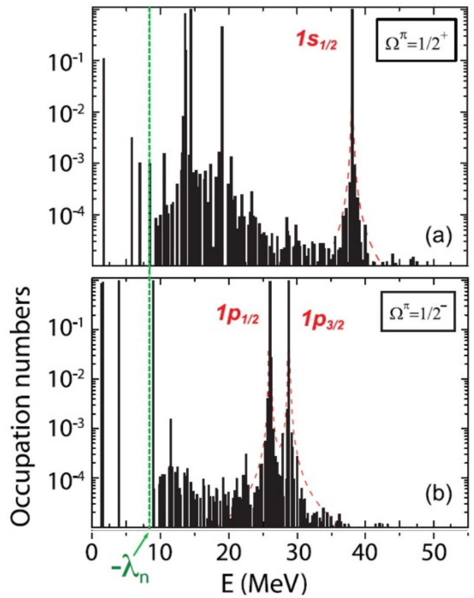
V.O. Nesterenko, J. Kvasil, A. Repko, W. Kleinig, P.-G. Reinhard, Phys. Atom. Nucl. 79-842,2016

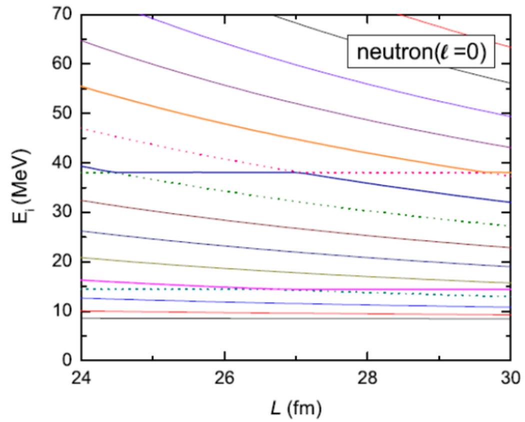
- Can be studied directly by transition currents in deformed QRPA
- Deformed QRPA is needed even for spherical nuclei because internal motions is prohibited due to symmetry

Continuum discretization in lattice

- Non-resonant continuum checked with superfluid Thomas-Fermi







- Estimate HFB resonance widths with box stabilization method

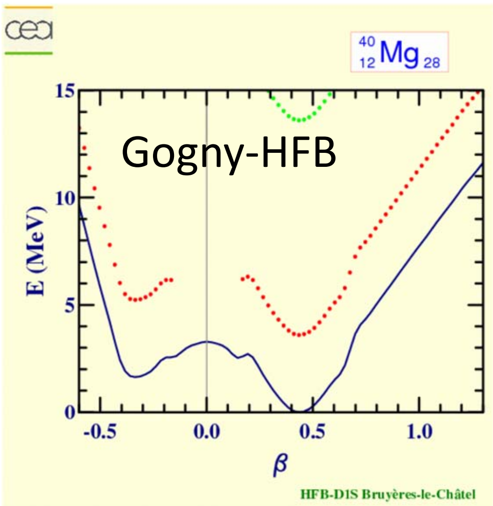
  Pei, Kruppa, Nazarewicz, PRC, 2011

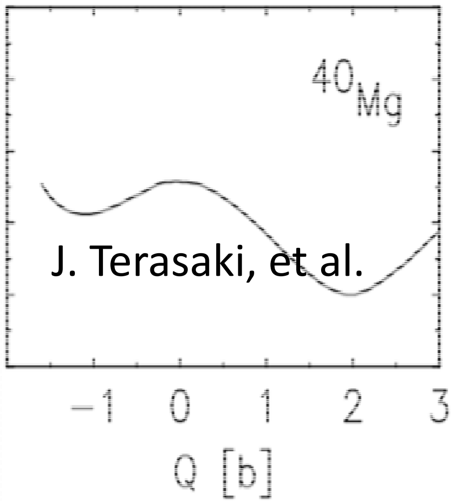
- Large coordinate-spaces result in a vast number of continuum states and provides good resolutions for resonances and continuum (proportional L^3)

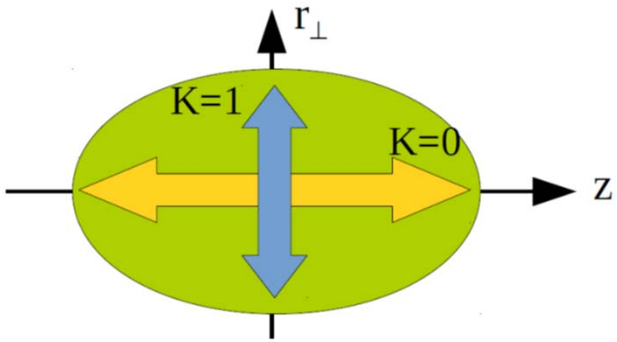
^{40}Mg: Weakly bound and shape coexistence

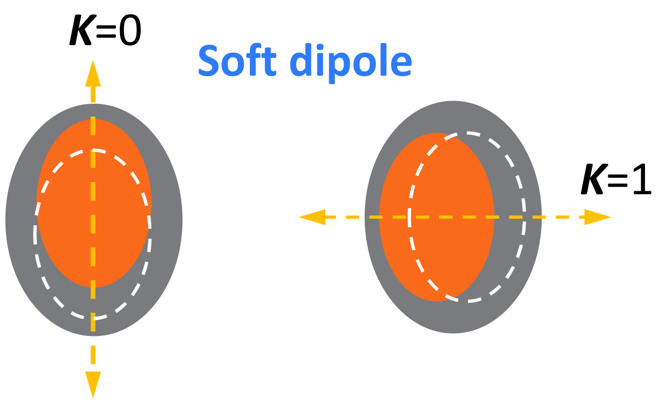
- Last Mg isotope, weakly bound deformed
- Prolate-oblate coexistence in 40Mg (N=28)
- Experimental interests of spectroscopy
  (from H. Crawford talk)

Deformed K-splitting



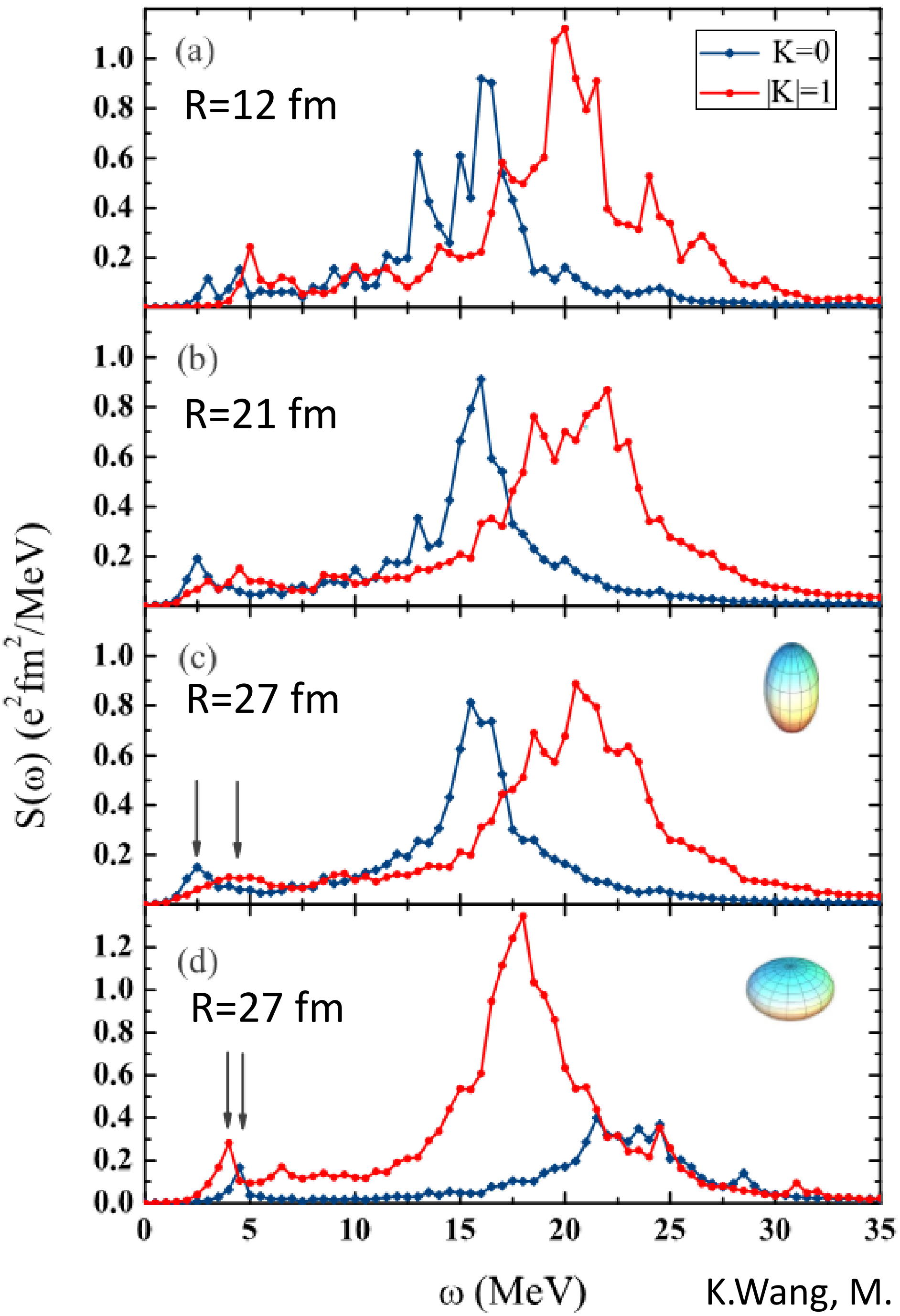






Shape evolution from oblate 42Si to prolate 40Mg

A good case to probe excitations based on different shapes



K.Wang, M. Kortelainen, J.C. Pei, PRC96,031301 (R) 2017

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:**

The splitting is proportional to deformation and centroid energy

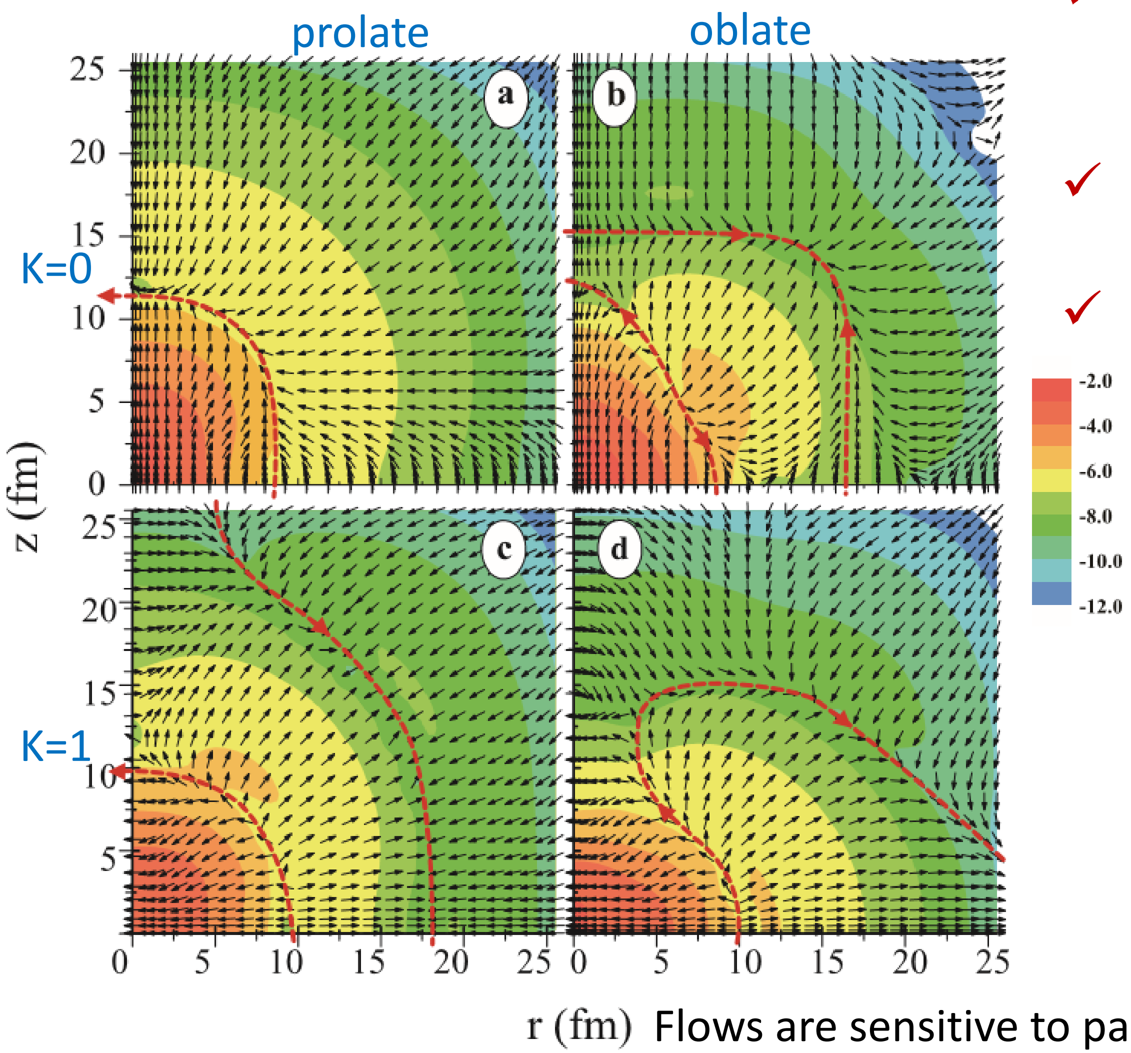
Prolate PDR splitting is 1.4 (0.95) MeV

Oblate PDR splitting is 0.45 (1.05) MeV

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

Compressional PDR

- The quantum flow topology of the PDR



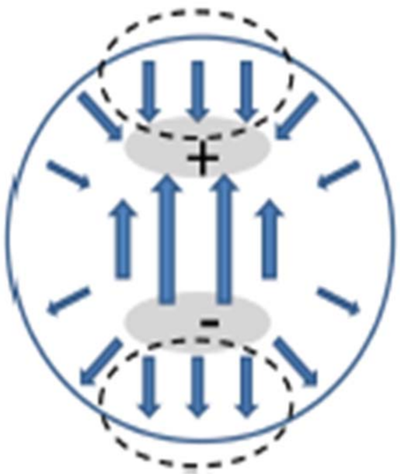
Flows are sensitive to pairing

Kai Wang, M. Kortelainen, J.C. Pei, PRC96,031301 (R) 2017

✓ **A long-sought collective and compressional dipole structures, poles at $\pm$12 fm**

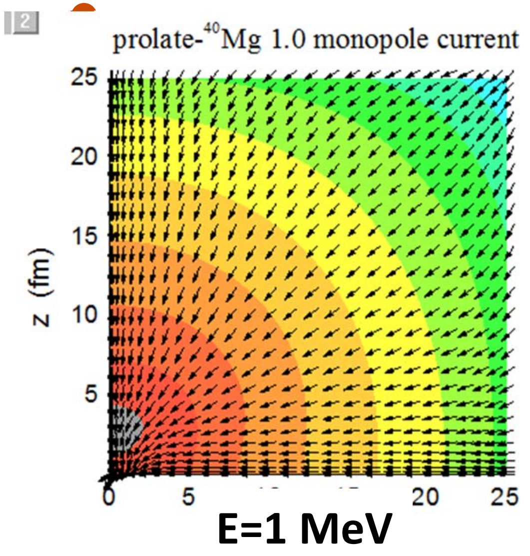
✓ the simplest flow topology with the lowest energy

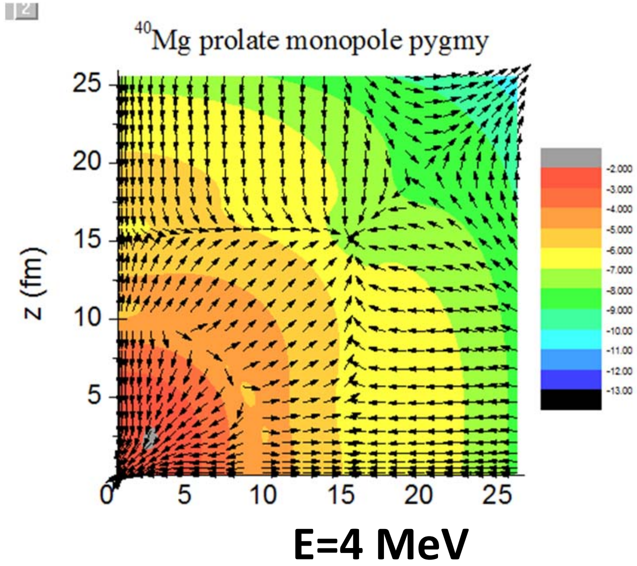
✓ Flow patterns characterized by boundary lines

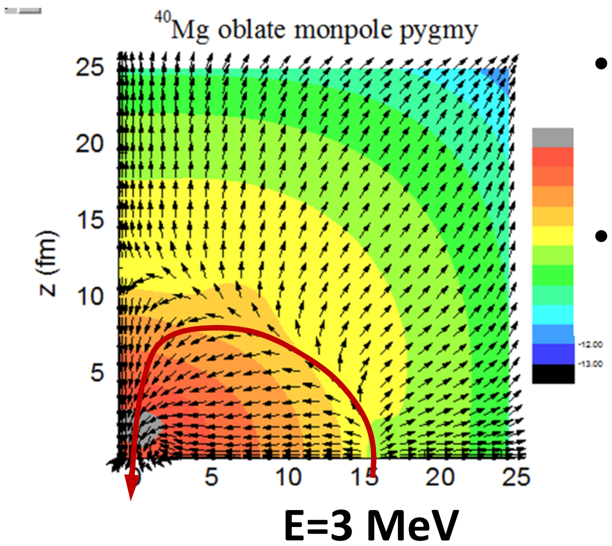


Self-Organization

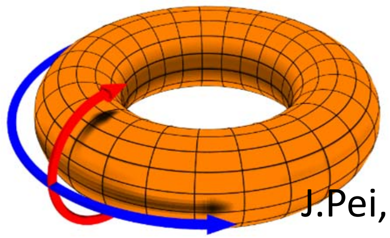
Current flows of isoscalar monopole modes

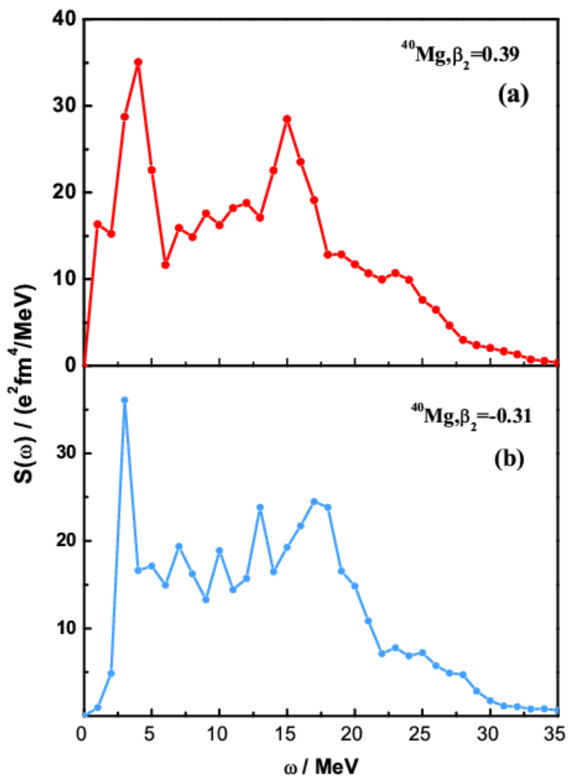






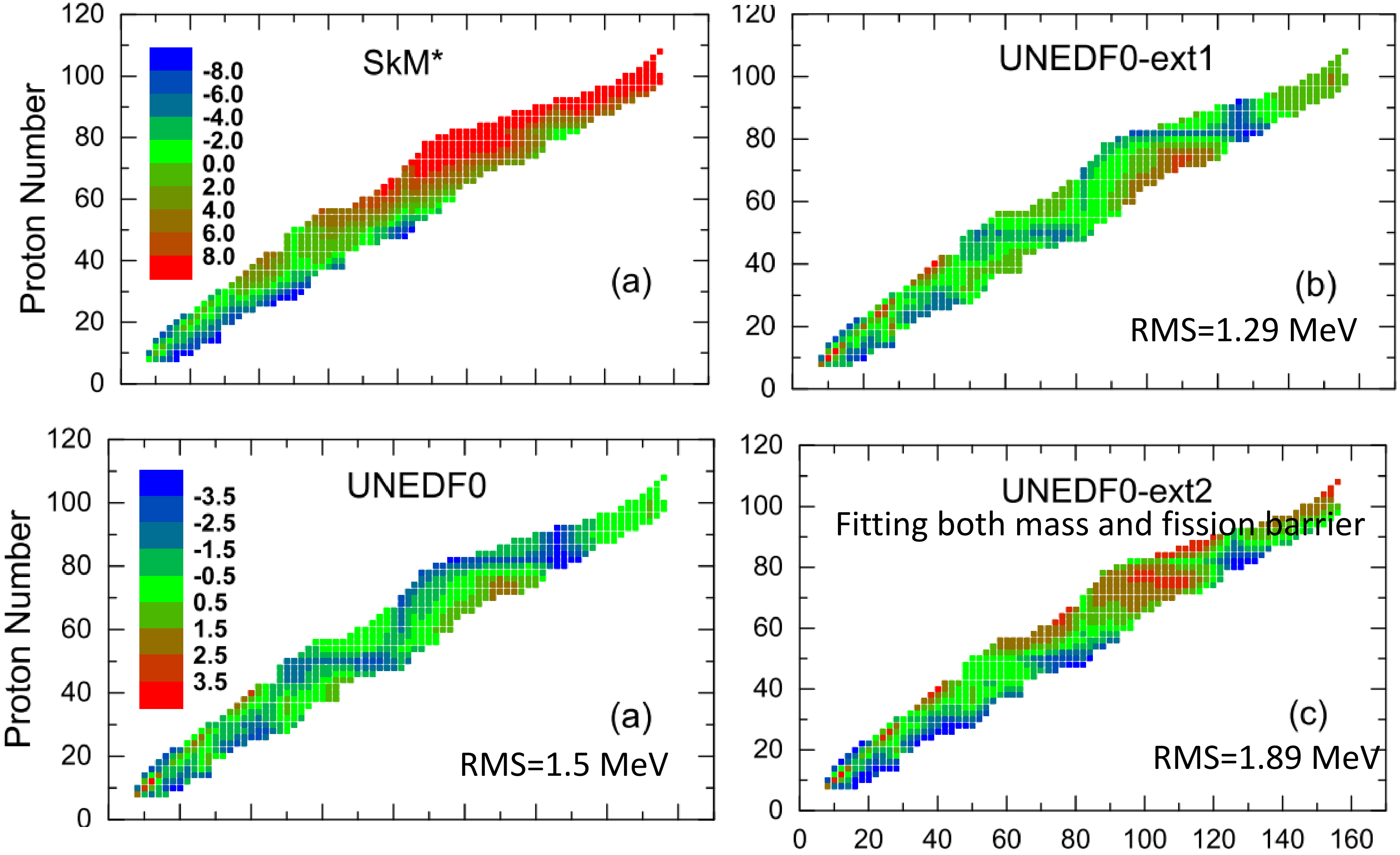
- Monopole flow patterns are non-trivial and becomes complicated as E* increases
- A flow circulation clearly appear in oblate shape



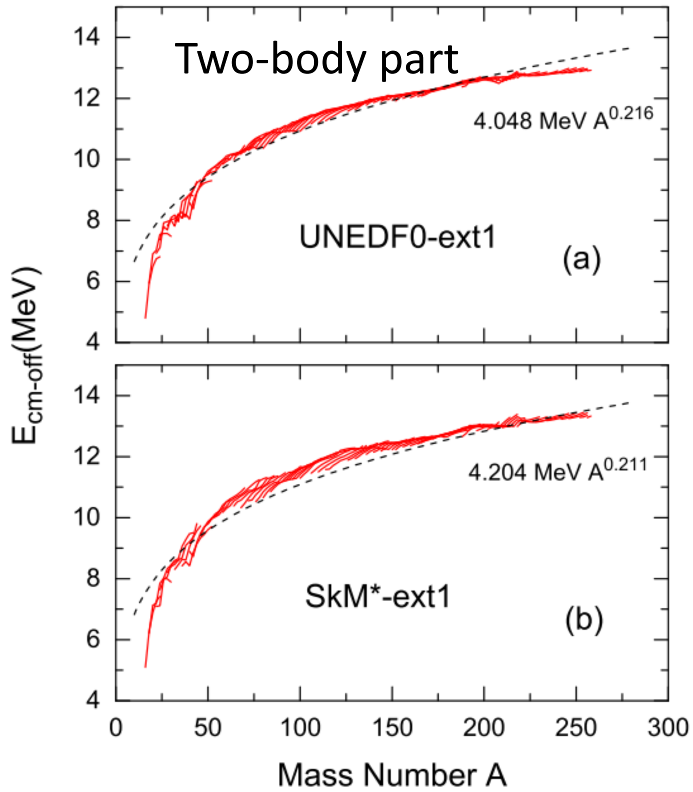


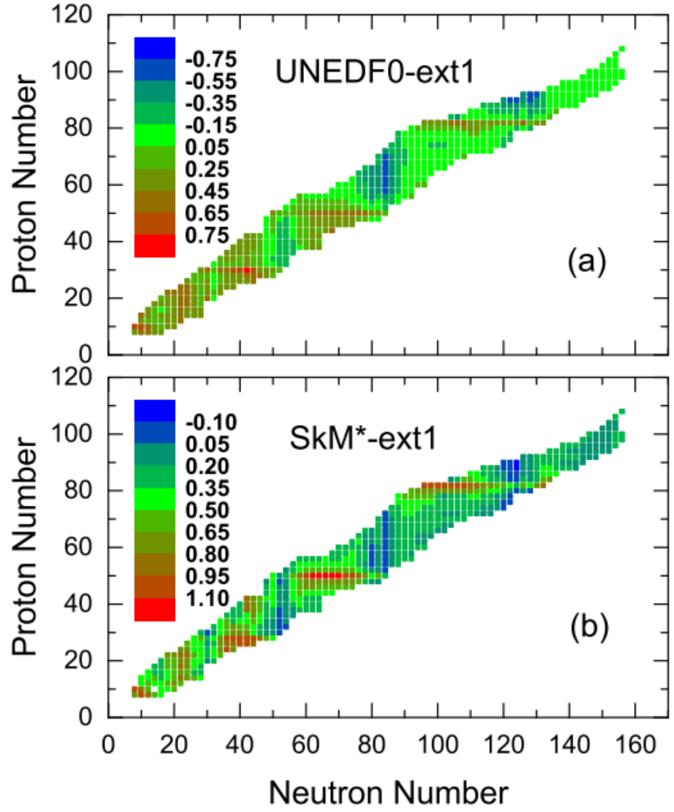
J.Pei,K.Wang,M.Kortelainen, JPCS 966,012051(2018)

Global analysis and optimization of Skyrme forces



Z.W.Zuo, J.C.Pei, X.Y.Xiong, Y.Zhu, CPC-42-064106-2018





$$E_{c.m.} = \frac{1}{2mA}\sum_{i=1}^{A}\mathbf{P}_i^2 + \frac{1}{2mA}\sum_{i>j}\mathbf{P}_i \cdot \mathbf{P}_j$$

$$\Delta E_{LN} = E_{\mathrm{HF-LN}} - E_{\mathrm{HF-BCS}}$$

- Inversion island around N=20 is a big challenge for DFT optimization
- Binding of N=Z nuclei are significantly understand estimated
- Include fission barrier overestimate neutron drip-line and underestimate proton drip-line

Summary

- We demonstrated that Twisted boundary condition can evidently damp collective motions, similar to absorbing boundary condition.
- We developed the fully self-consistent deformed continuum FAM-QRPA in coordinate spaces for multipole excitations of weakly bound nuclei
- The abnormal pygmy deformation splitting, the surface quantum flows, etc, indicating the potential for more interesting phenomena

Summary

- Collaborations:

F.R. Xu, W. Nazarewicz, G. Fann, M. Kortelainen, P. Schuck,
Y. Zhu, Z.W. Zuo, X.Y. Xiong, K. Wang, N. Fei, Z.H. Sun, Q. Wu.....
And many others for discussions

Thank you for your attention !