Exotic halos and collective excitations in weakly-bound deformed nuclei

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- Physics and motivations
- Coordinate-space HFB developments
- Ground state studies of weakly-bound nuclei
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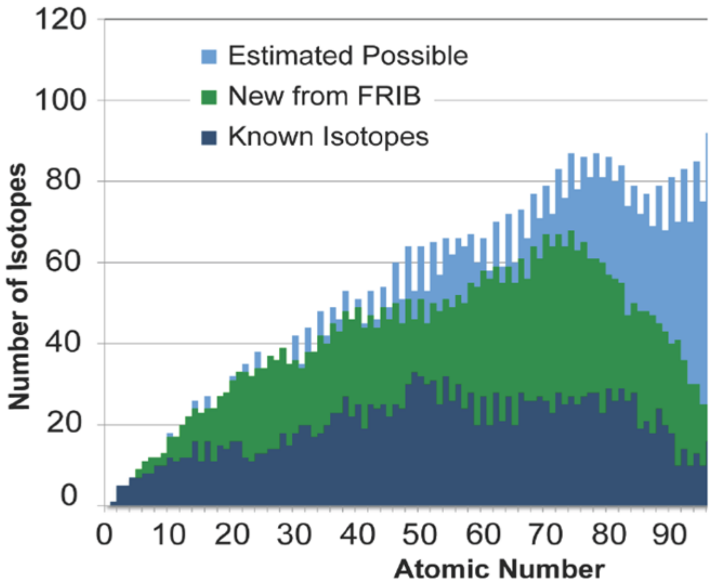
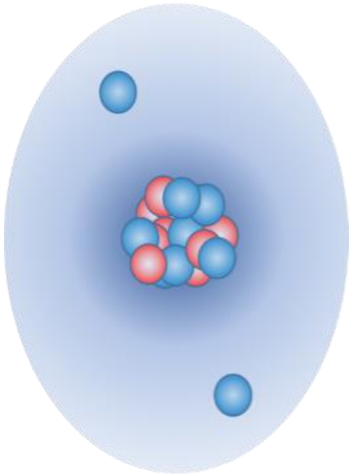
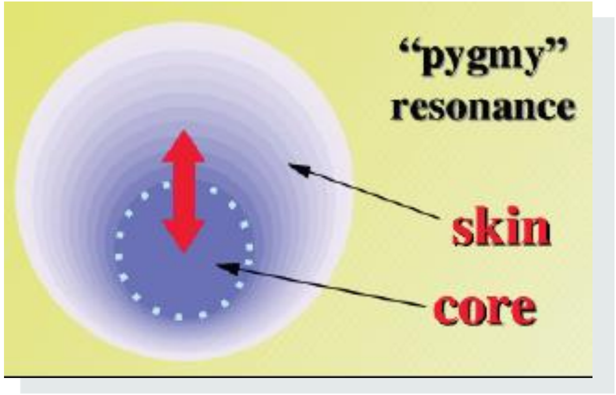
- Summary

Physics and motivations

- Radioactive Beam Facilities can provide great opportunities and challenges for study of extremely unstable nuclei
- FRIB(U.S), HIAF(China recently approved); supercomputing
- Exotics: threshold effects, continuum coupling vs pairing anti-halo, exotic surfaces (dilute halos/deformed halos, vibrations/new modes, few-body vs many-body, BEC-BCS---low density superfluity, decoupling, clustering)

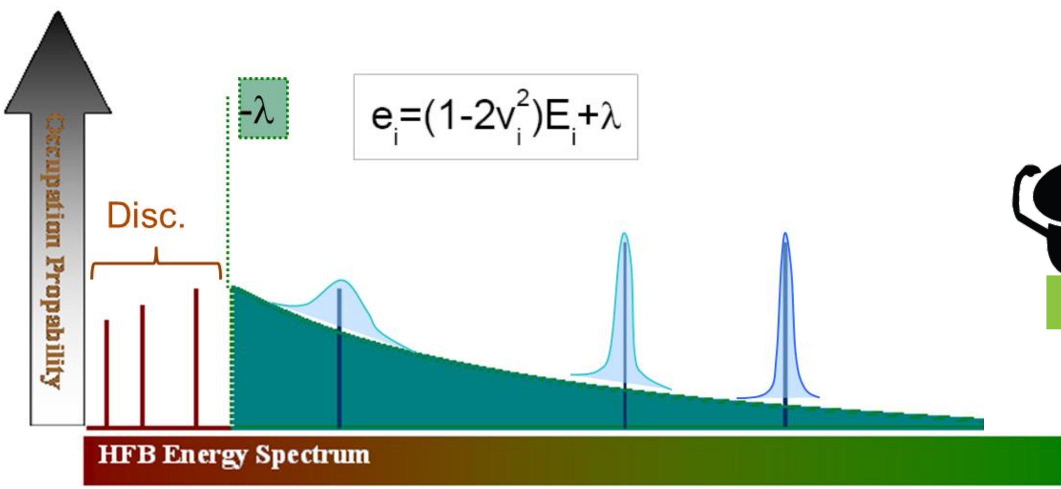




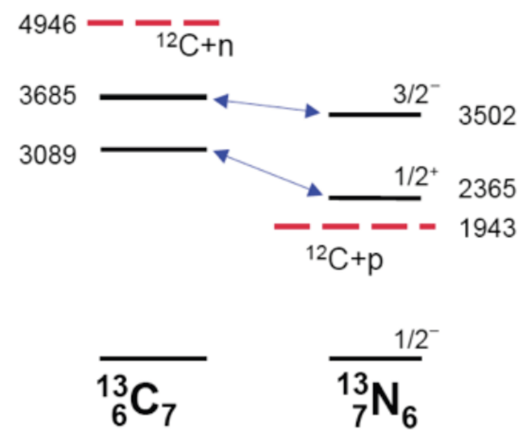


Continuum effects

- Continuum coupling: pairing induced; angular-momentum dependence
- Weakly-bound s.p. states coupled with continuum: resonances
- Near-threshold non-resonant continuum is important for halos (Pei 2013)
- High energy continuum: Thomas-Fermi approximation (Pei 2011)
- Enhance stability; enhance halo features; enhance collectivity?

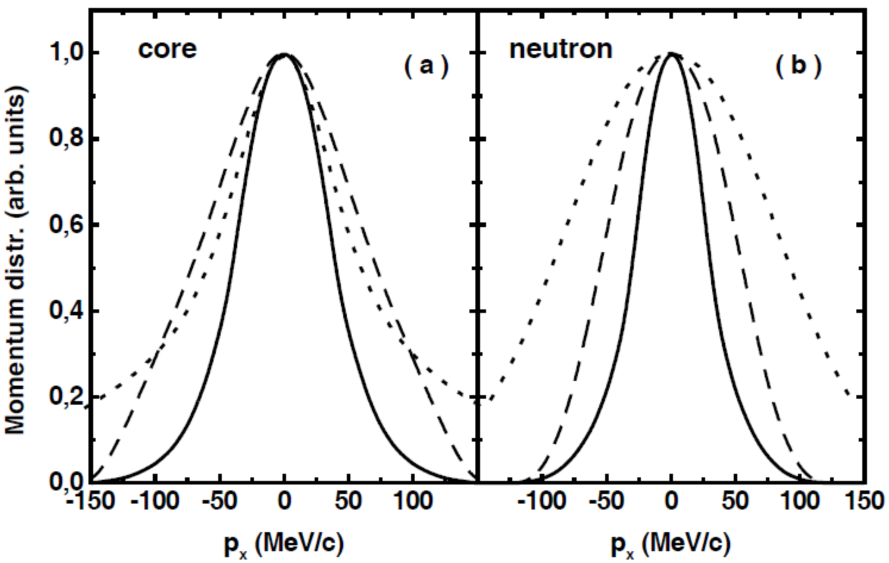


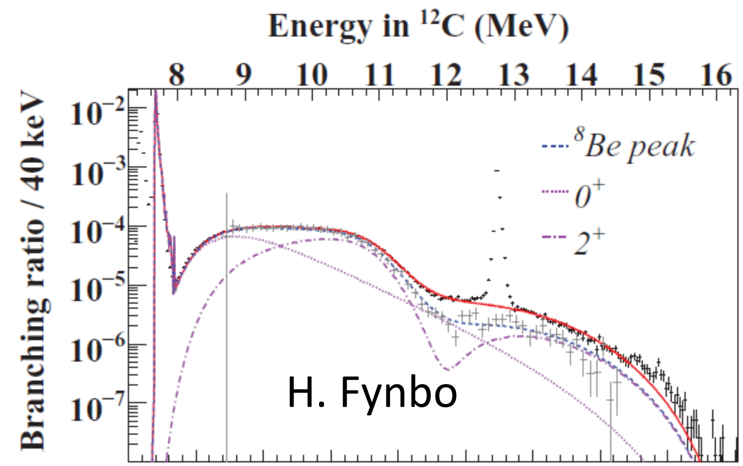
Thomas-Ehrmann shift (1951)

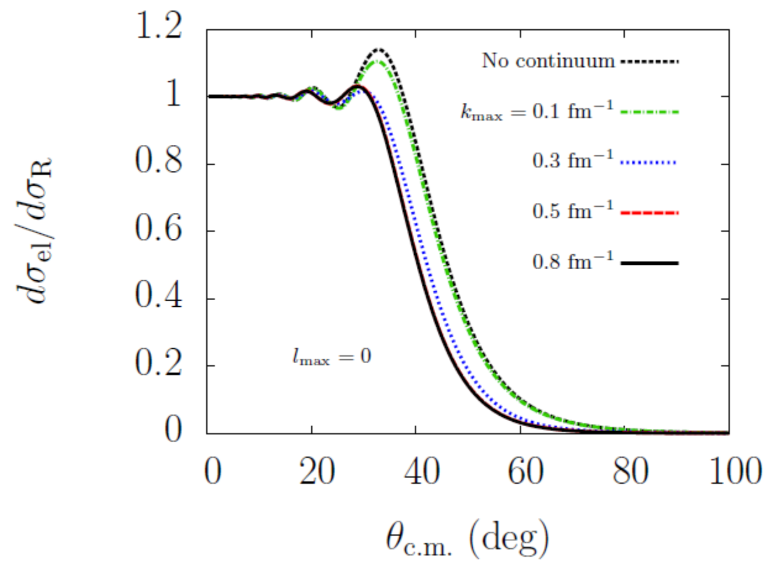


Continuum effects

- 6He: momentum distribution with conti
- Breakup, elastic scattering, transfer…
- Continuum effect (ghost) in 12C







S.N. Ershov, et al, PRL 1998
J. Al-Khalili & F. Nunes, JPG 2003
T.Druet, P. Descouvemont, EPJA,2012

Continuum coupling in HFB theory

- Current progress: particularly difficult for deformed nuclei

□ Diagonalization on single-particle basis :HO, woods-saxon, PTG, Gamow…

□ Direct diagonalization on coordinate-space lattice

□ Outgoing boundary condition: ***difficult for deformed cases***

※*H. Oba, M. Matsuo, PRC, 2009,* self-consistent calculations are still missing

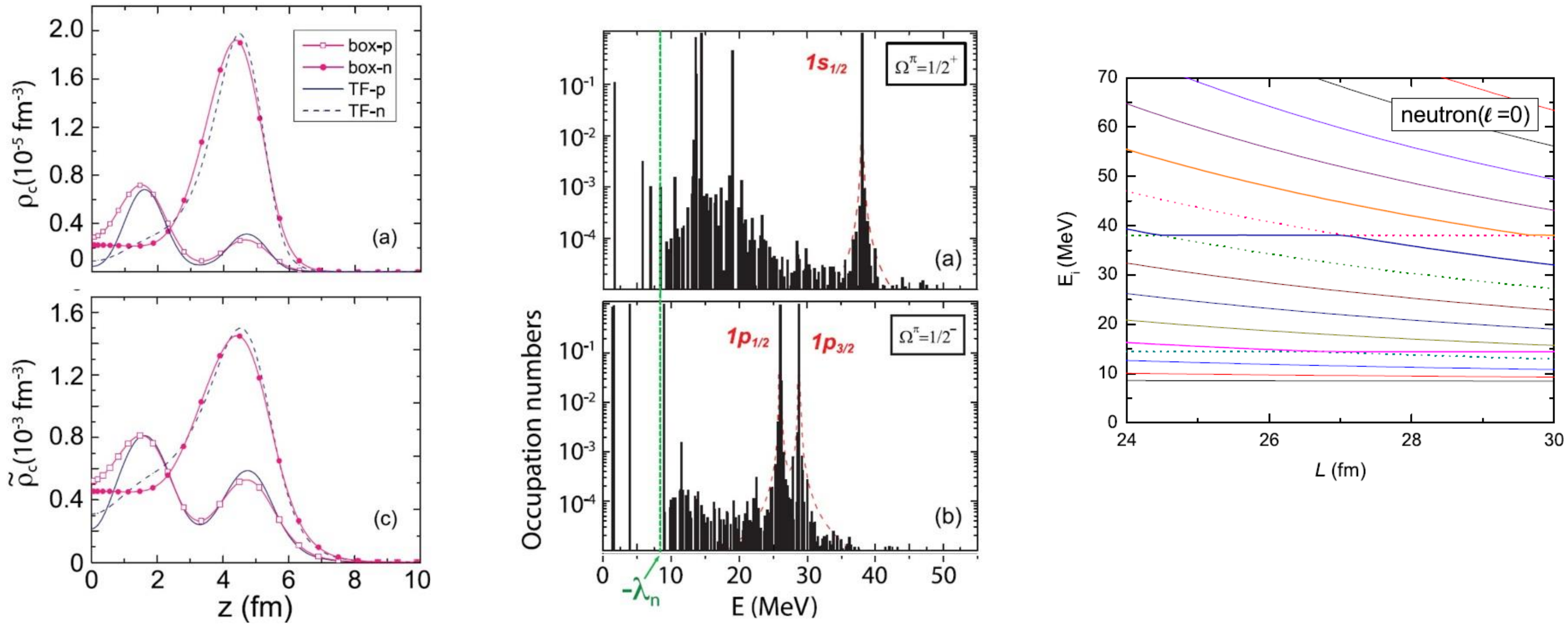
- Coordinate-space HFB has advantages for describing weakly-bound systems and large deformations

□ *Bound states, continuum and embedded resonances are treated on an equal footing; L^2 discretization leads to a very large configuration space*

□ Computing resources and capabilities are increasing exponentially

Does continuum discretization work?

- Non-resonant continuum check with Thomas-Fermi approximation



- 2. Calculate the HFB resonance widths with box stabilization

  Pei, Kruppa, Nazarewicz, PRC, 2011

- Problem: broad resonance is expensive (CDCC also surfers)

Large coordinate-space HFB calculations

- Conventionally, HFB solvers were benchmarked by energies, this is not sufficient for detailed properties of soft weakly-bound nuclei.
- Subtle interplay among surface deformations, surface diffuseness, and continuum needs precise HFB solutions.
- Large coordinate-space resulted in a vast number of continuum states and provides good resolutions for resonances and continuum (proportional L^3)
- Small box may not be sufficient for describing pairing properties.

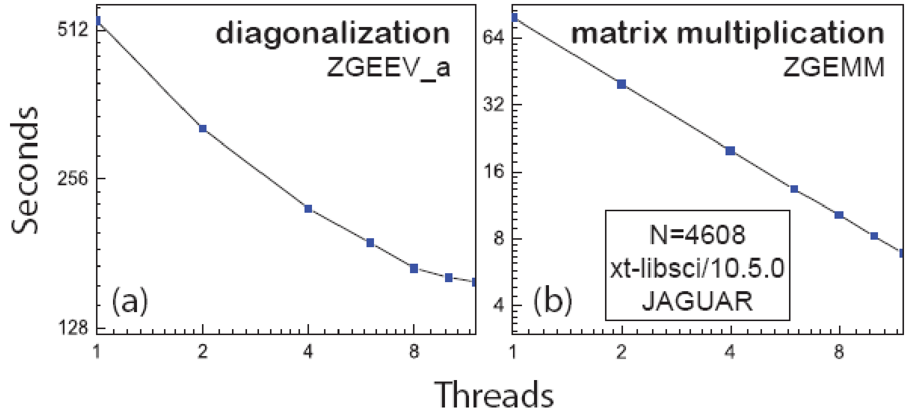
M. Grasso, N. Sandulescu, Nguyen Van Giai, R. Liotta, PRC, 2001.

H. Oba and M. Matsuo, PRC, (2009)

- Small box may be not good for broad resonances.
- Small box may cause false peaks in QRPA

Hybrid parallel HFB calculations

- MPI+OpenMP hybrid parallel calculations



Large boxes calculations are crucial for describing halo densities, large deformation and discretized continuum

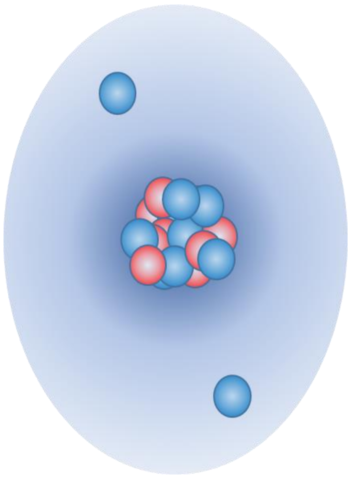
From 20 fm to 40 fm, the estimated computing cost increased by 40 times.

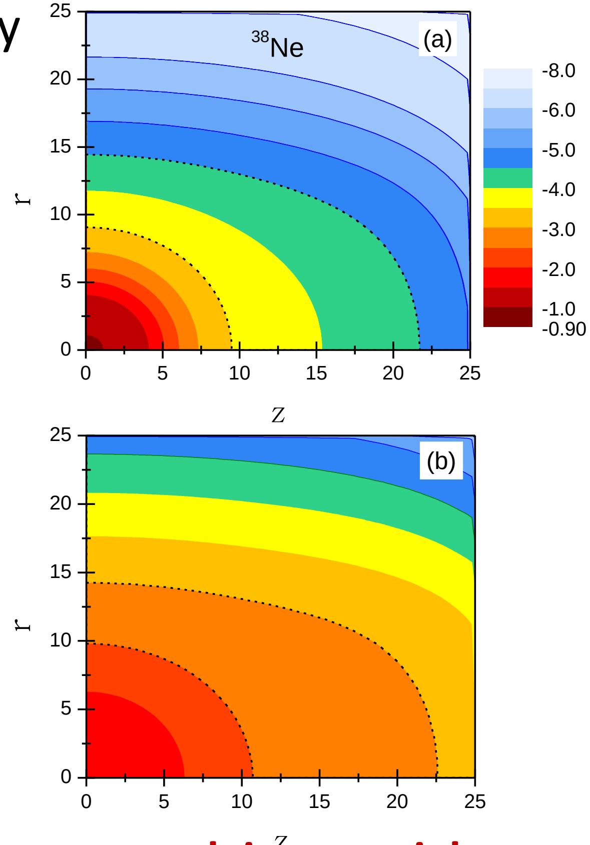
- Calculations performed in Tianhe-1A; Tianhe-2 (TOP 1)

advantage: take into account deformation, pairing, and weak-binding effects simultaneously.

Exotic egg-like halo structure

- Self-consistent calculations: SLy4 force + density dependent pairing
- 38Ne, (a) neutron density; (b) n pairing density
- About 2 neutrons in the halo
- Deformations: beta2 = 0.24, beta2_pair=0.48
- Mainly contributed by near-threshold continuum





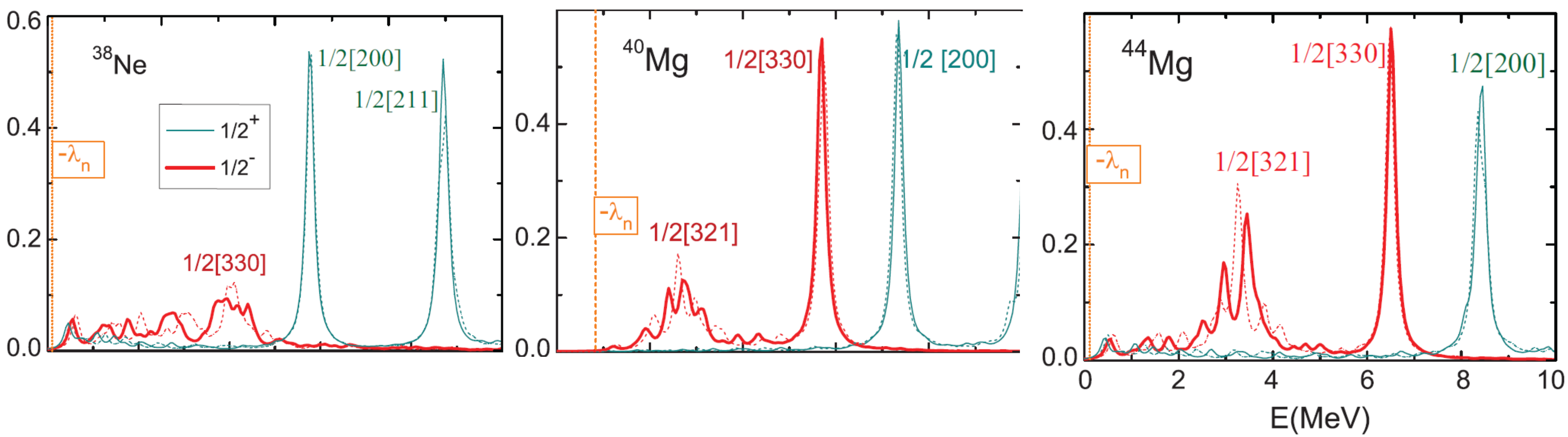
Isovector deformation: pygmy quadrupole resonances

New exotic "egg"-like halo structure obtained; accurate approach is essential

J.P., Y.N. Zhang, F.R. Xu, PRC (R) 87, 051302(2013)

Near-Threshold Continuum

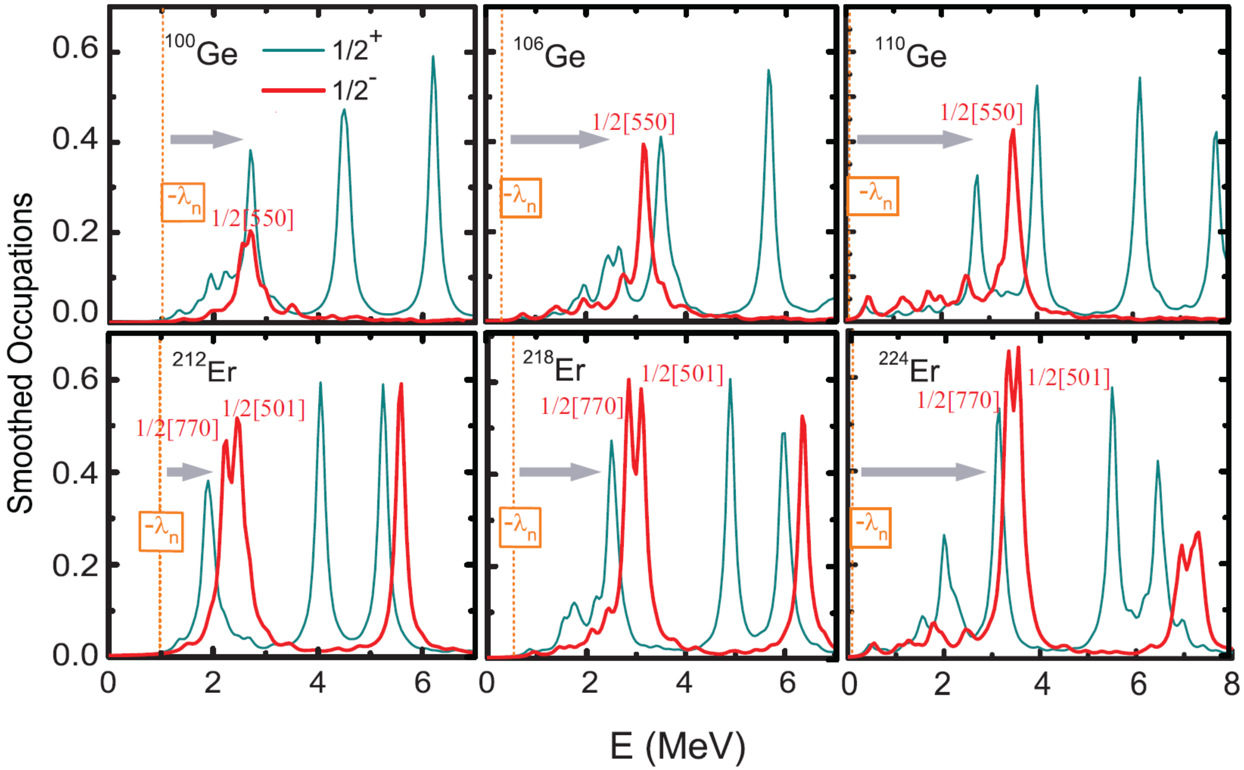
- Different box calculations to distinguish resonances and continuum states
- Near threshold non-resonant continuum is responsible for halo and surface deformations
- No halo in ^{40}Mg since no near-threshold continuum contributions (N=28)



Smoothed neutron quasiparticle spectrum of Ω^{π}=1/2$^{\pm}$

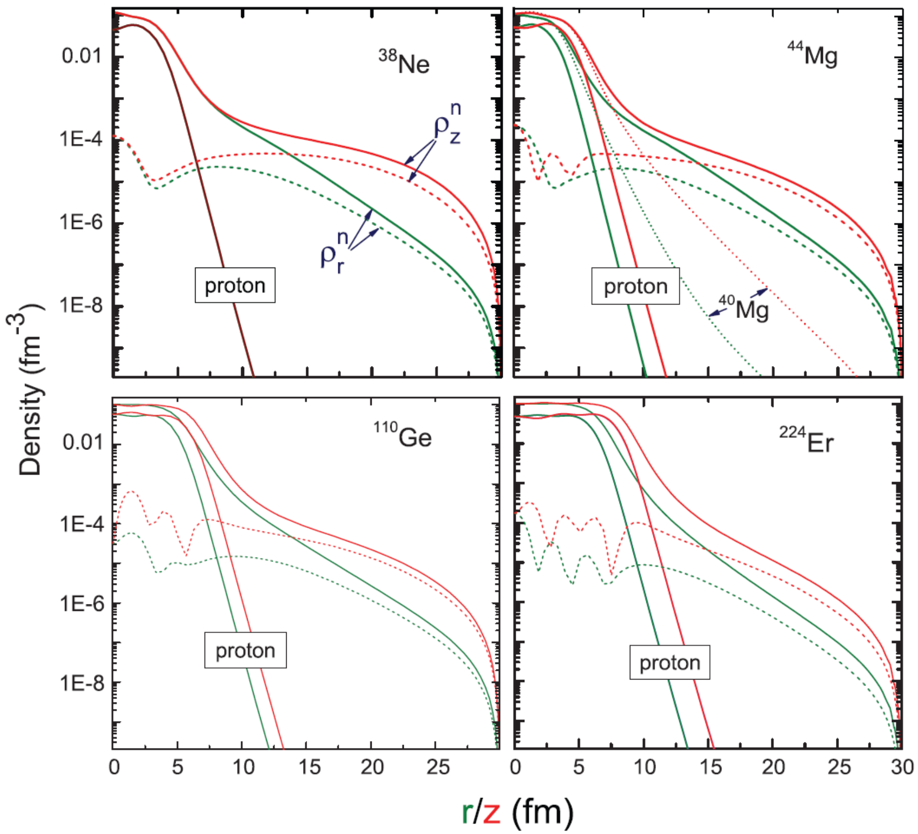
Phase-space decoupling

- Non-resonant continuum states gradually grows and decouples in heavy nuclei
- sparse negative-parity level density is crucial; deformed halos in medium-mass nuclei is possible, e.g. in ^{110}Ge. Heavy halos are hindered due to denser levels.
- Core-halo decoupling is related to the phase space decoupling in quasiptaricle spectrum



Systematics of deformed halos

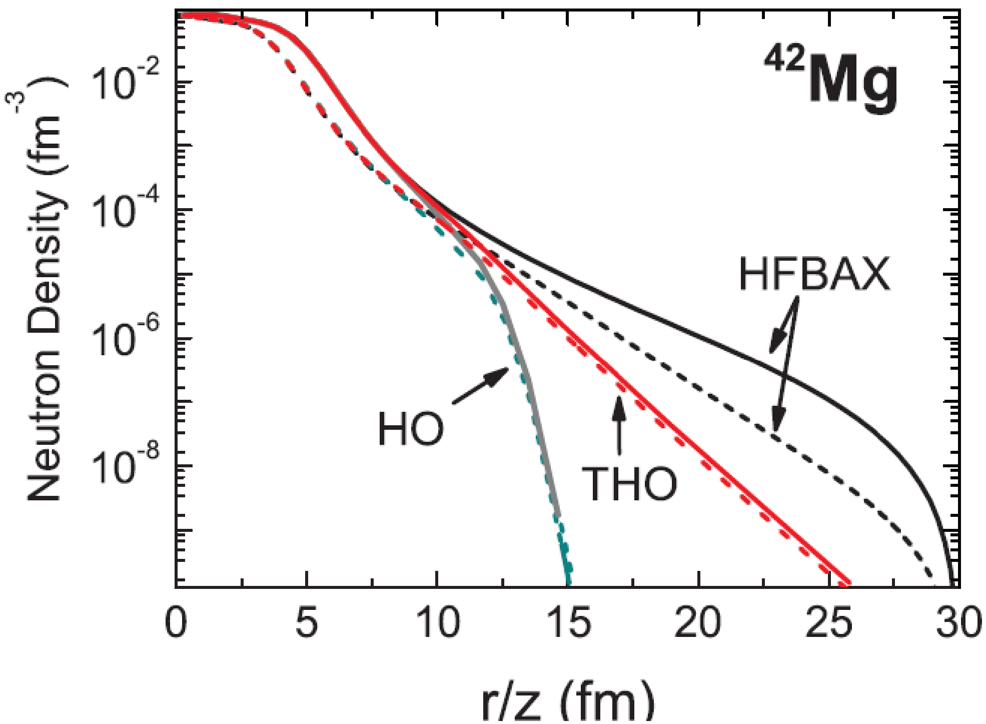
- Halo hindered by deformed cores? (seems correct) *F. Nunes, NPA, 2005(3-body model)*
- *Halo and surface deformations are mainly contributed by near-threshold continuum*
- *Heavy halos not likely existed; decoupling effect decreased*

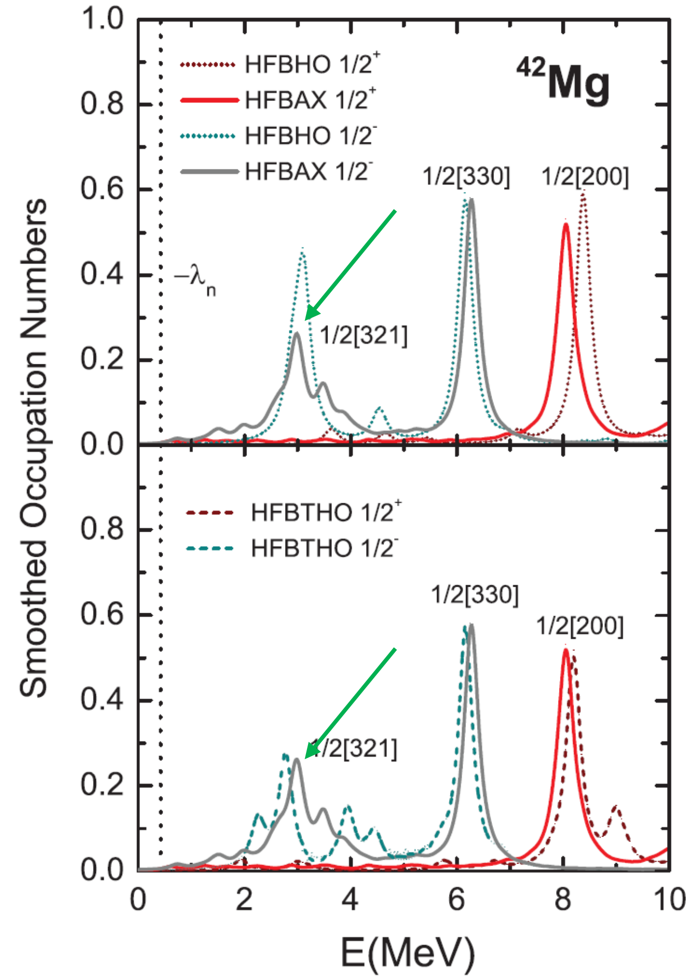


Coordinate-space vs Basis expansion

Basis expansion HFB fails in describing weakly-bound nuclei!

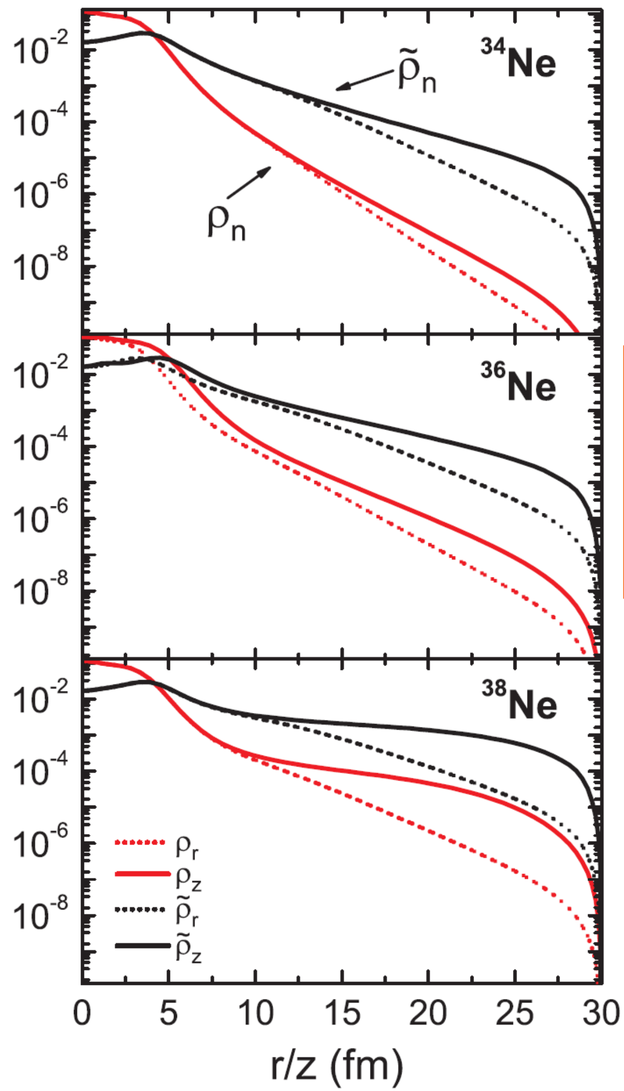
- Different surface asympotics;
- Broad quasiparticle resonances



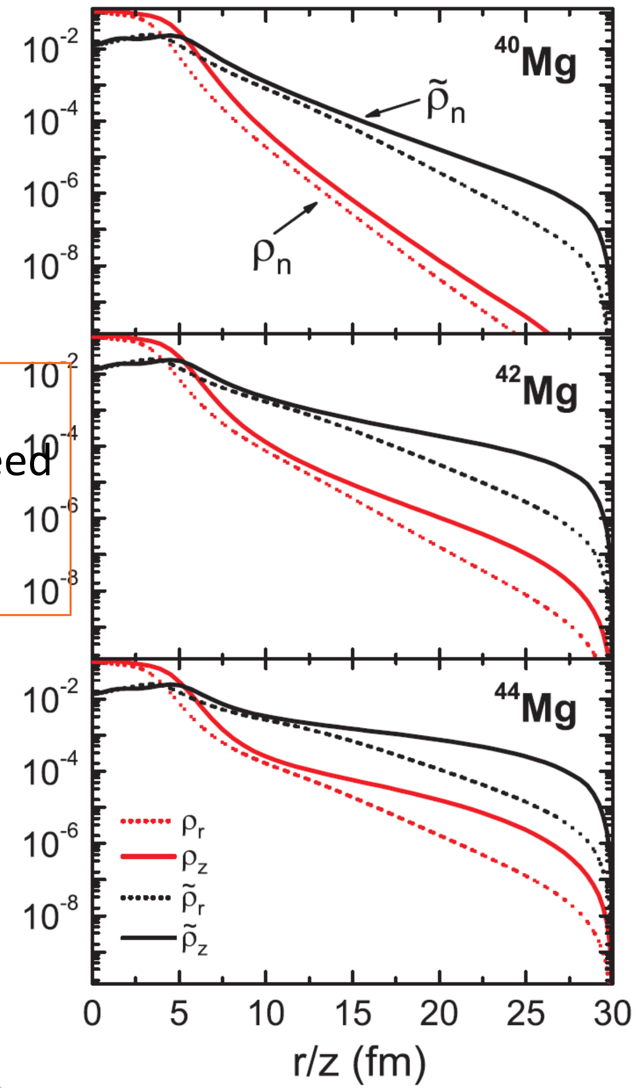


Y.N. Zhang, J.P., F.R. Xu, PRC **88**, 054305, 2013

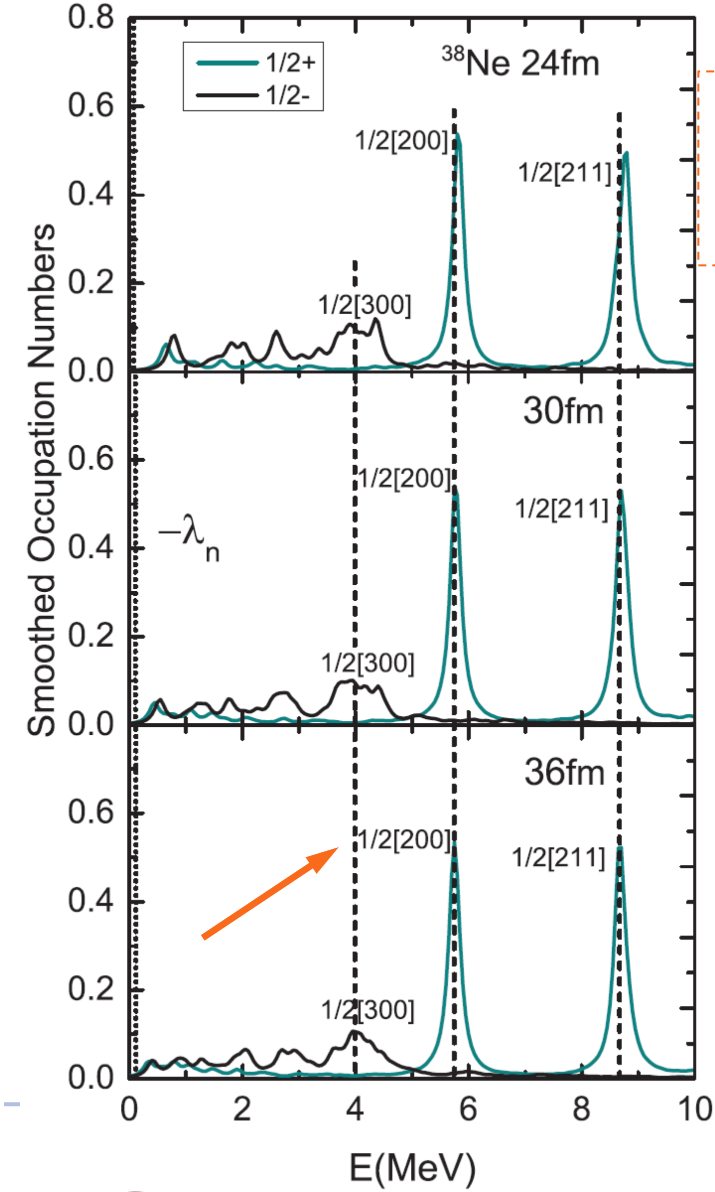
Density and pairing density at surfaces



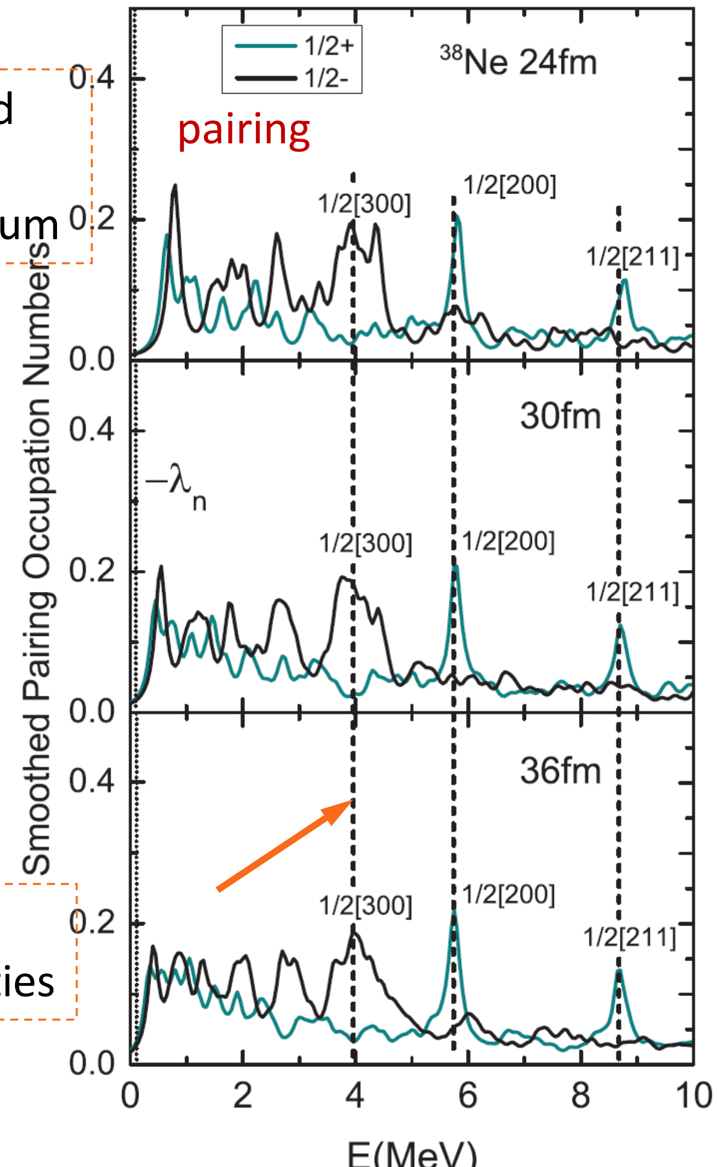
Huge deformed pairing halos, need large coordinate space HFB



Quasiparticle spectrum near thershold



describing broad resonances and non-res continuum



Problems in pairing properties

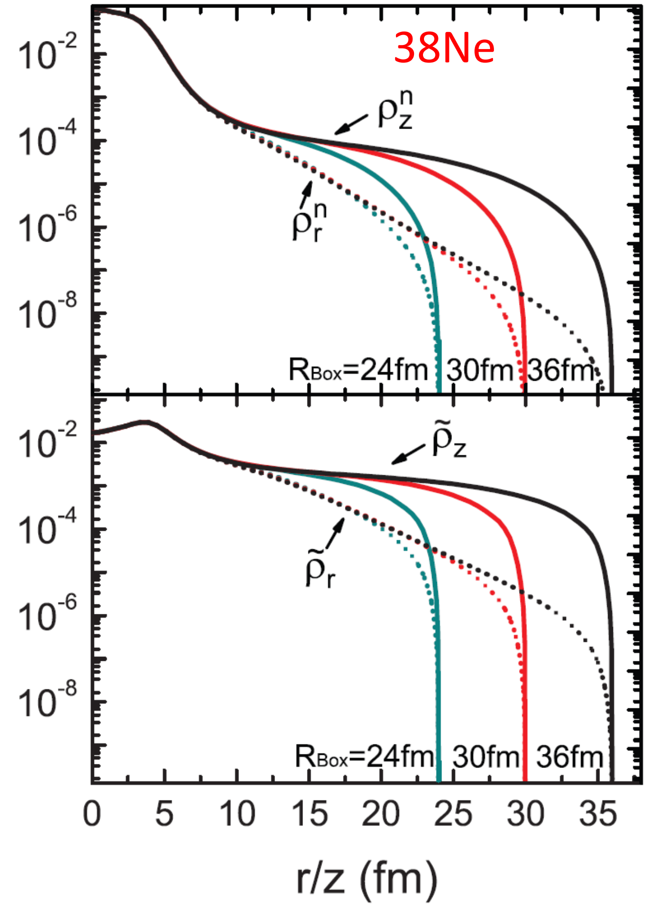
nd Continuum effects--

Box size dependence of energies

- Total energy is not sensitive to box size,

however (pairing, deformation, stability)….

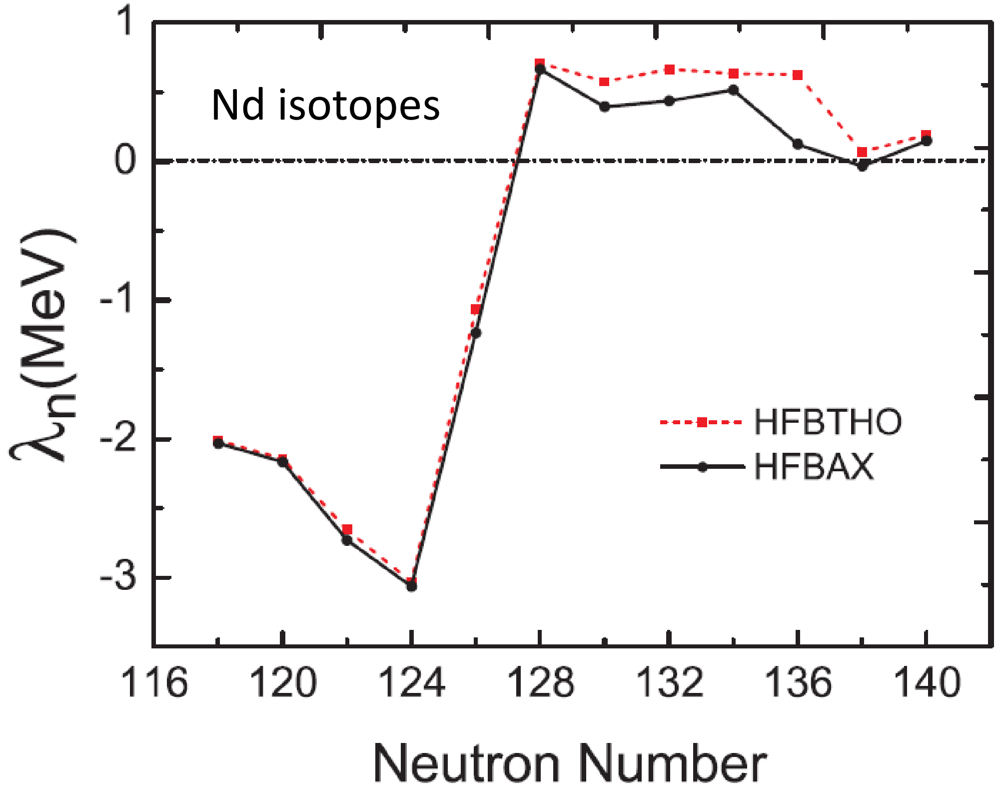
^{38}Ne	24fm	27fm	30fm	36fm
E_{tot}	−220.29	−220.29	−220.35	−220.33
E_c	18.94	18.95	18.95	18.96
E_{pair}	−68.10	−67.77	−67.41	−67.43
E^p_{kin}	138.34	138.46	138.51	138.56
E^n_{kin}	444.84	443.48	442.85	442.10
β_{2p}	0.00	0.00	0.00	0.00
β_{2n}	0.13	0.19	0.24	0.34
R_{rms}	9.39	9.38	9.38	9.37
Δ_p	1.46	1.47	1.47	1.46
Δ_n	2.97	2.95	2.93	2.92
λ_p	−23.853	−23.802	−23.784	−23.747
λ_n	−0.079	−0.096	−0.103	−0.116



Y.N. Zhang, J.C. Pei, F.R. Xu, PRC **88**, 054305, 2013

Peninsula of stability

- Enhanced stability due to deformations and continuum effects



Fermi surfaces
THO(30 shells): 68 keV
HFBAX: -35 KeV

$$S_{2n}(Z,N) \approx -2\lambda_n$$

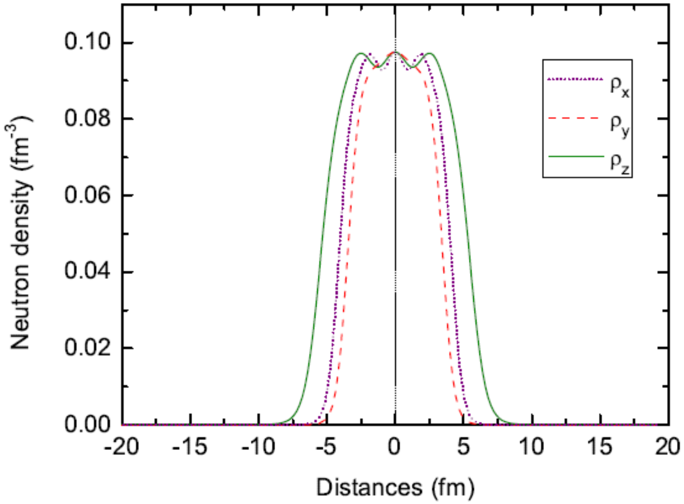
There could be other possible islands or peninsulas of stability by accurate HFB solutions

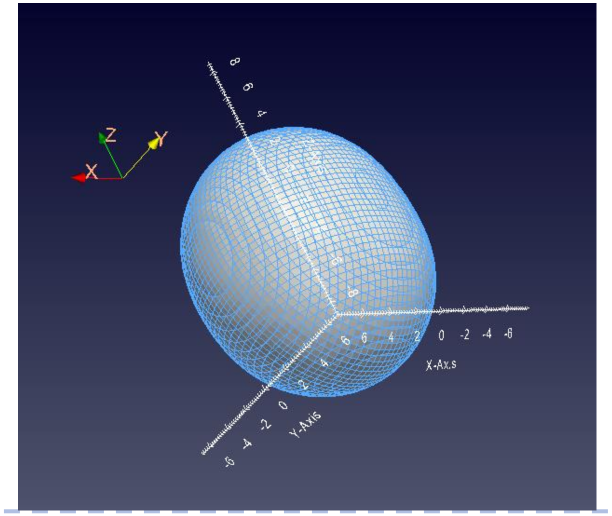
Y.N. Zhang, J. P., F.R. Xu, PRC **88**, 054305, 2013

MADNESS-SHF+BCS solver

- Benchmark for the triaxial deformed nucleus Mo110:

	MADNESS-HF	HFODD(1)	HFODD(2)
E_t	924.77	923.86	924.05
λ_p	-12.743	-12.651	-12.713
λ_n	-5.432	-5.457	-5.459
E_k	2005.89	2005.22	2003.33
E_p	-16.01	-17.27	-16.93
E_c	251.55	251.29	251.43
R_{rms}	4.656	4.66	4.664
Q_{20}	816.36	864.82	834.3
$\|Q_{21}\|$	0.56	0	0.0
$\|Q_{22}\|$	321.46	314.15	314.78
Q_2	1144.54	1178.97	1149.08





- Next step: full 3D HFB calculations are very expensive.

Pei et al, JPCS, 2012
Bonger et al., CPC, 2013
Pei, G. Fann, W. Nazarewicz, et al. in preparation, 2014

Deformed continuum-QRPA study excited states

- Continuum effects in excited states would be very important: cross threshold
- Exotic collective modes: collectivity, weakly binding increase collectivity?
  different modes mixing, astrophysical interests, how to detect
- Study effective interactions: tensor force?
- Sensitive to pairing interactions
- A basic work for further studies: 0v-beta-decay; di-neutron; cold atoms; 3D-QRPA……
- Progress in 2013 year: developed code and benchmark
  (succeed recently for monopole excitations, including time-odd terms)

FAM-QRPA

- Motivation

Standard QRPA in the matrix form is extremely expensive for deformed nuclei, even more to include continuum configuration

FAM-QRPA provides alternative way solving QRPA equation iteratively rather than diagonalization (it is popular in other quantum systems: Chemistry)

First application in nuclear physics: T. Nakatsukasa, PRC, 2007

- Current status of FAM-QRPA

Based on HFBRAD (spherical coordinate-space HFB),

(PRC, T. Nakatsukasa, 2011)

Based on deformed relativistic HB (T. Nikšić, Phys. Rev. C 88, 044327, 2013)

Based on HFBTHO(deformed HO/THO basis),

(M. Stoitsov, PRC 84, 041305(R),2011)

Relativistic FAM-RPA (Liang HZ, PRC, 2013)

Discrete states: N. Hinohara, PRC, 2013

Implementation

- HFB-AX output: 2D wavefunctions and energies, quasiparticle basis
  B-spline lattice transformed to Gauss-Legendre lattice
- FAM-QRPA procedure:

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

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

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

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

Implementation

- 2. Calculate H20, H02(including time-odd terms), F20, etc

$$\delta H^{20}_{\mu\nu}(\omega) = U^{\dagger}\delta h V^{*} - V^{\dagger}\delta\Delta^{(-)*}V^{*} + U^{\dagger}\delta\Delta^{(+)}U^{*} - V^{\dagger}\delta h^{T}U^{*},$$

$$\delta H^{02}_{\mu\nu}(\omega) = -V^{T}\delta h U + U^{T}\delta\Delta^{(-)*}U - V^{T}\delta\Delta^{(+)}V + U^{T}\delta h^{T}V.$$

$$\delta h(\omega) = \frac{h[\rho_\eta, \kappa_\eta^{(+)}, \kappa_\eta^{(-)*}] - h[\rho, \kappa, \kappa^{*}]}{\eta},$$

$$\delta\Delta^{(+)}(\omega) = \frac{\Delta[\rho_\eta, \kappa_\eta^{(+)}, \kappa_\eta^{(-)*}] - \Delta[\rho, \kappa, \kappa^{*}]}{\eta},$$

$$\delta\Delta^{(-)}(\omega) = \frac{\Delta[\rho_\eta^{\dagger}, \kappa_\eta^{(-)}, \kappa_\eta^{(+)*}] - \Delta[\rho, \kappa, \kappa^{*}]}{\eta},$$

- 3. Calculate X, Y; and Broyden iteration on X, Y. (30 iterations kept)
- 4. Finally calculate the strength

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

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

Implementation

- Combined parallel calculations in Tianhe-1A

  for different excitation frequency : MPI distributed parallel

  for each point in a node: OpenMP multi-thread parallel (12 threads)

- Time-consuming: read wavefunctions (10-20 G) and calculate transiton densities and H20

  cutoff at 65 MeV: 6 hours

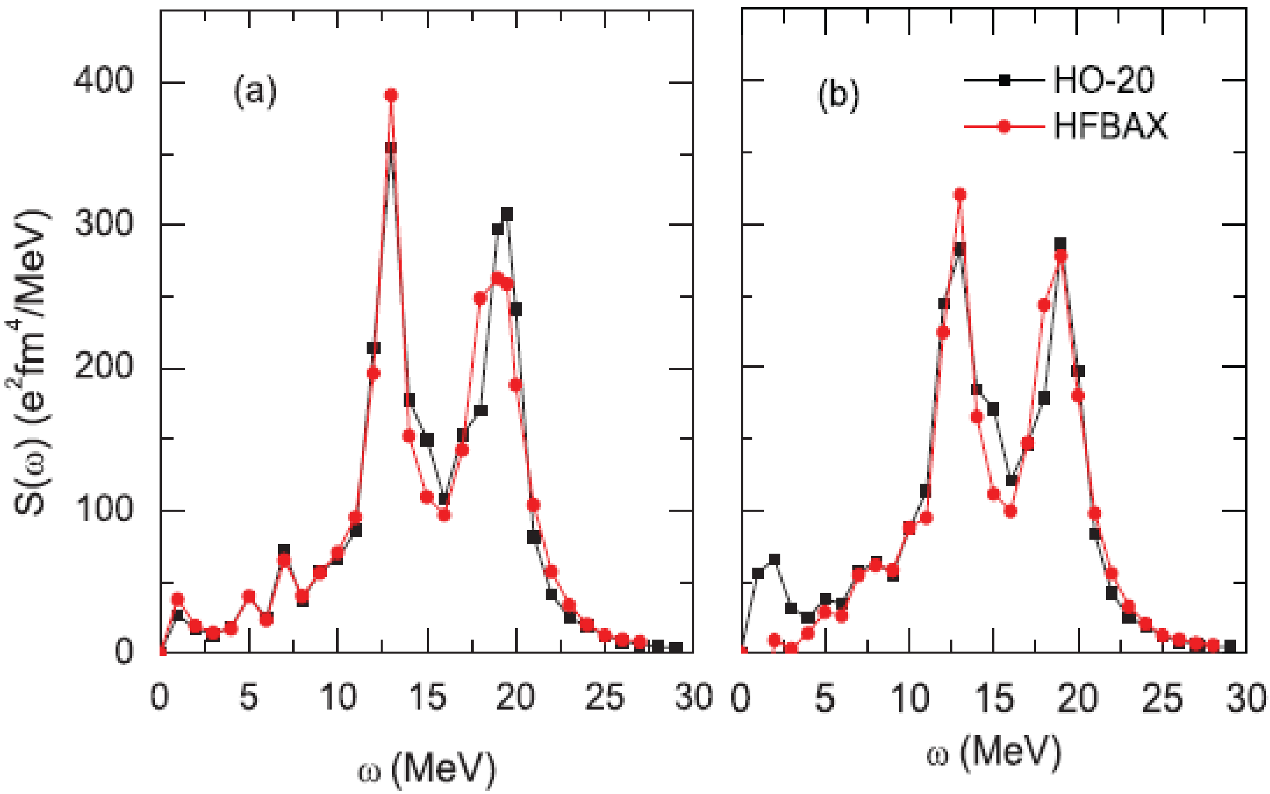
  cutoff at 85 MeV: 12 hours

  cutoff at 95 MeV: 20 hours

- Devoted to the monopole modes due to soft incompressibility

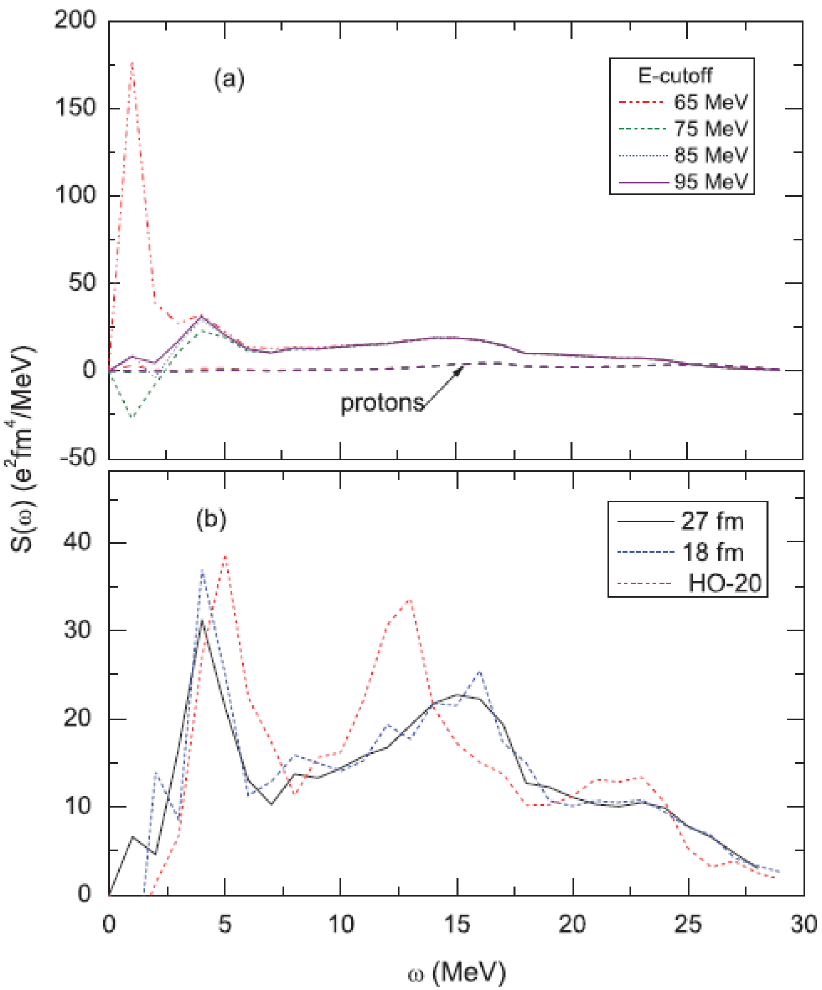
Benchmark

- SLy4+volume pairing and surface pairing (100Zr)



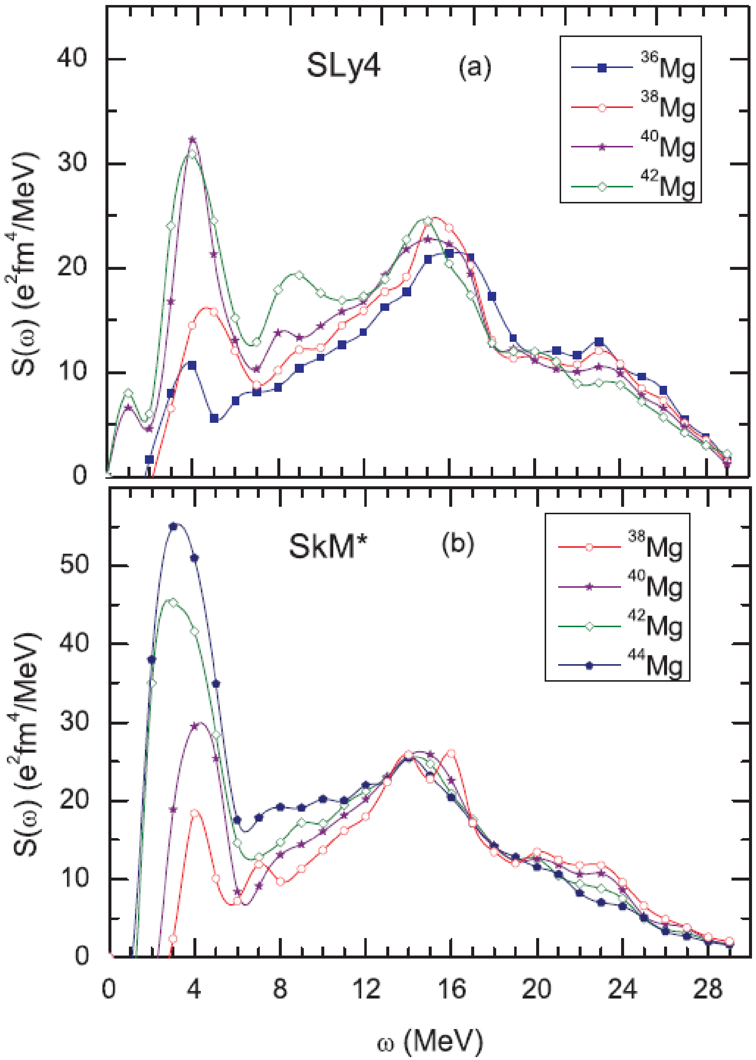
Benchmark

- Tests on Cutoff and box sizes
- Spurious modes <= 2 MeV
- Large box is essential



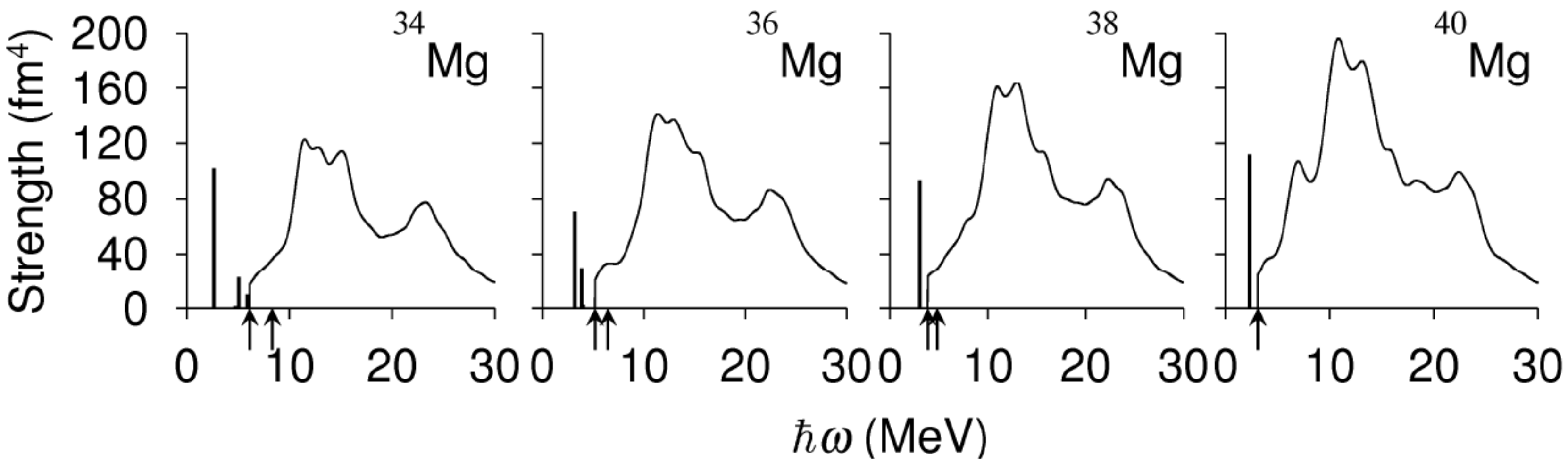
Mg isotopes and soft modes

- Soft mode 4 MeV
  close to threshold
  enhanced due to surface pair
- Novel mode 9 MeV
  novel according to systematics
  weak in SkM* calculations



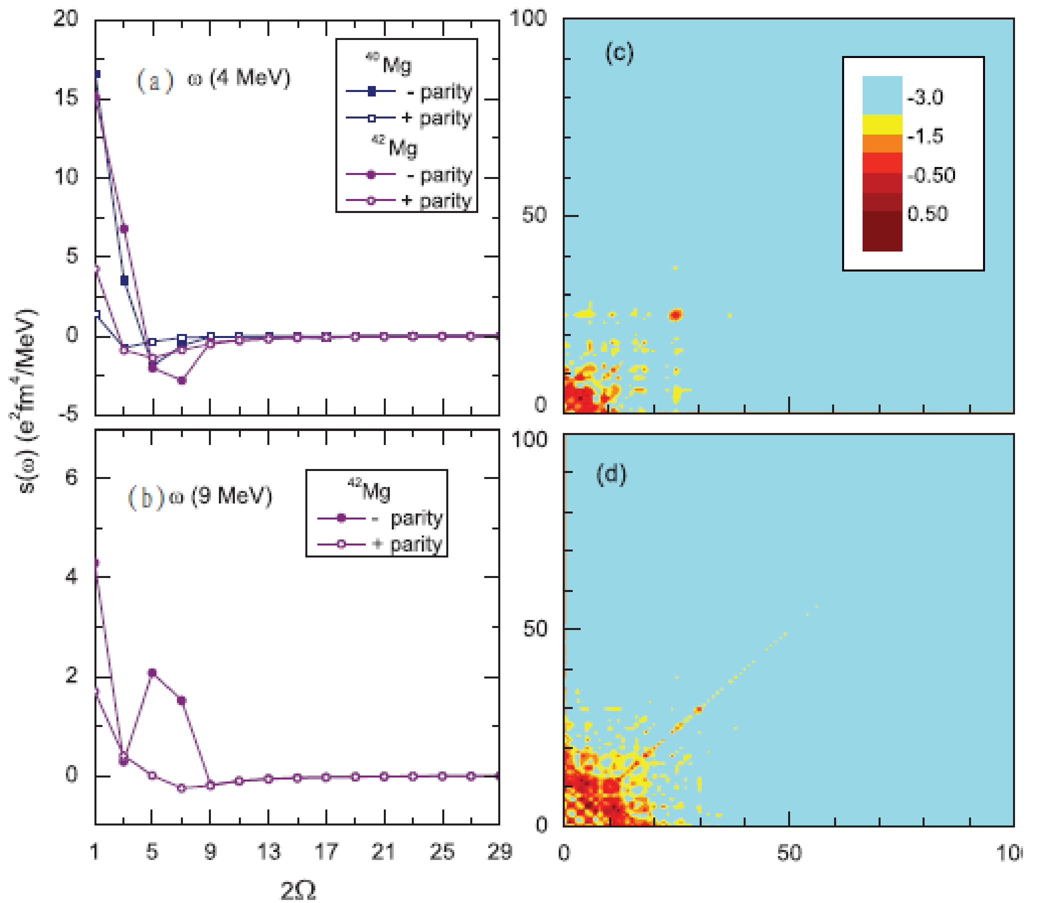
Mg isotopes and soft modes

- Earlier calculations by K. Yoshida: SkM*+mixed pairing, 2009



Collectivity and mechanism

- 4 MeV res. collectivity increase
- 1/2⁻ states most important
  (also for halo)
- Non-resonant continuum
  (around 2 MeV)
  pairing halo vibrations



- 9 MeV res. is collective
  no direct relation to cont.
  Most likely pygmy monopole

◆ For experimental detection: around zero degrees (Z.H.Yang, et al., PRL, 2014)

Summary

- Coordinate-space HFB has a very good opportunity to explore new exotic structures and excitations, with the development of supercomputing facilities
- Soft mode due to pairing halo vibrations and threshold continuum
- Collective mode around 8-9 MeV appears

To be done:

- 3D Continuum FAM-QRPA for multipole excitations

Thanks for your attention!