Coexistence of Anderson-Bogoliubov phonon and cluster quadrupole vibration in inner crust of neutron star

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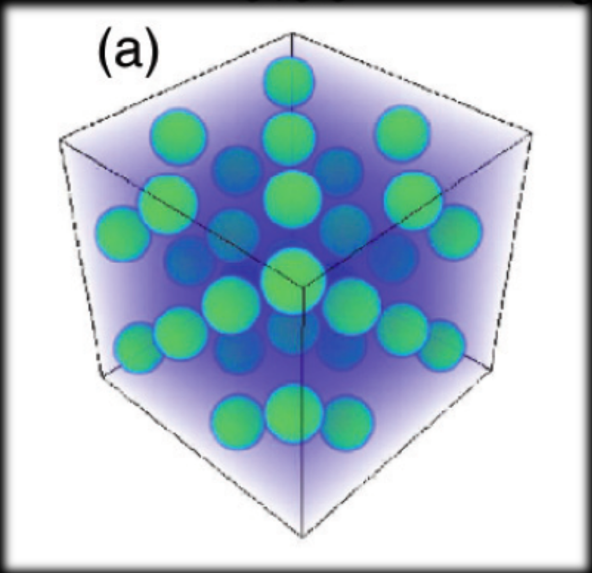
Inner crust of neutron star

= **Lattice of nuclear cluster**

\+ **superfluid neutron sea**



Okamoto+, PRC88, 025801.

Superfluidity plays key roles in

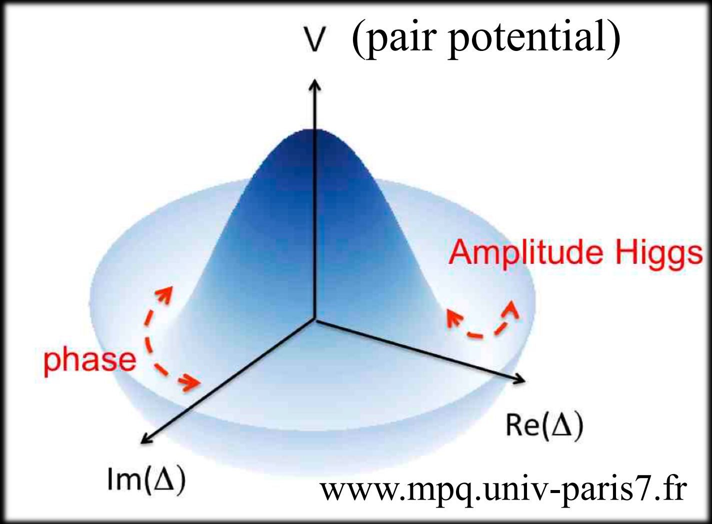
- **Glitch** (pinning/unpinning of superfluid vortex)
- **Cooling of newly born NS, soft X-ray transients** (specific heat via quasiparticle excitation)

Low-lying collectivity attracts attentions.

- **Quasi-periodic oscillation in giant flares** (**lattice phonon**)
- **New cooling mechanism of magnetar** (thermal conductivity via **superfluid phonon**)

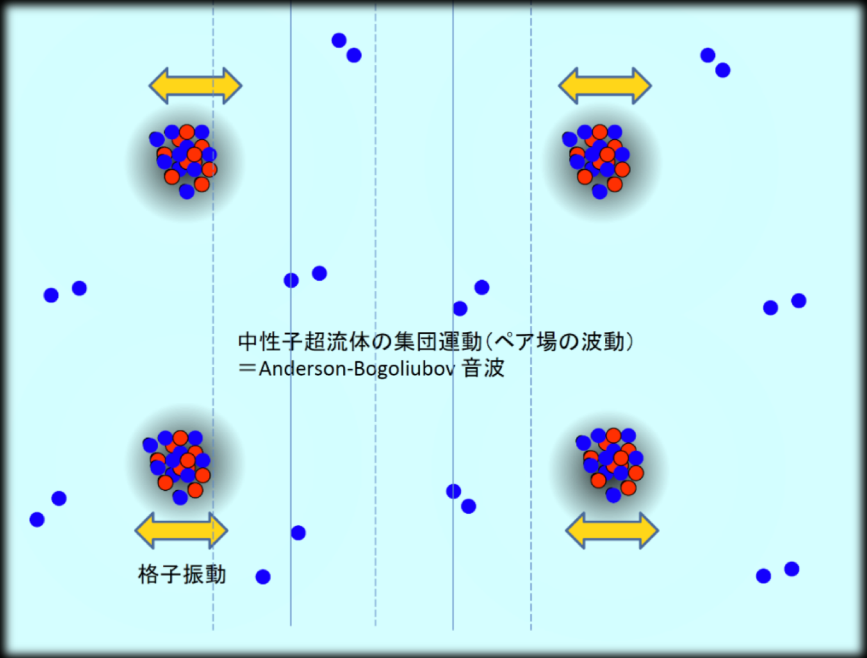
Collective excitation of superfluild: Anderson-Bogoliubov phonon (superfluid phonon)

Anderson, 1958.
Bogoliubov+, 1958.



Nambu-Goldstone mode, related to spontaneously broken U(1) gauge symmetry.

This collective vibration propagates in superfluild as a phonon (density wave).

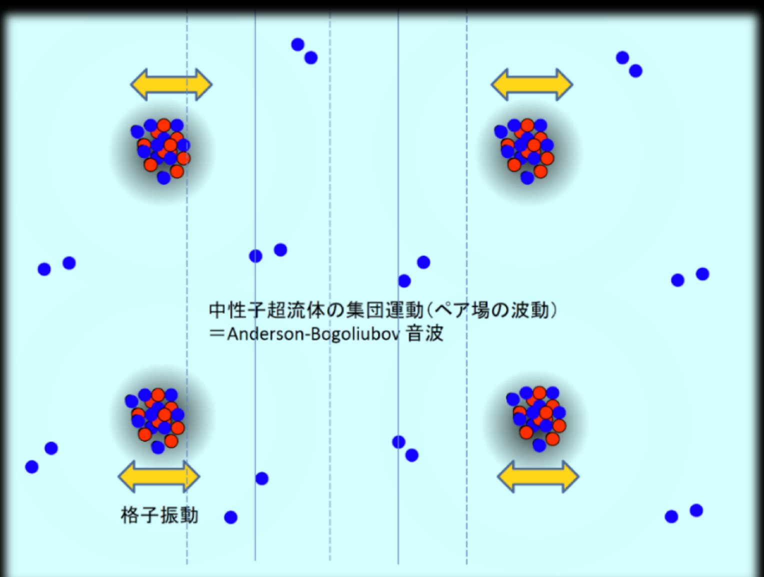


How does superfluid phonon couple to clusters ?

Superfluid phonon as a new mechanism of NS cooling

Aguilera+, PRL102, 091101 (2009)
Cirigliano+, PRC84, 045809 (2011)
Chamel+, PRC87, 035803 (2013) etc.

- **Superfluid phonon (SPH) is a new agent of heat carrier.**
- **Thermal conductivity by SPH can be comparable to that by electrons under strong magnetic field, i.e. in magnetars**



Key physics is the coupling between SPH and lattice phonon (LPH),
which determines the mean-free-path of SPH, and hence the thermal conductivity.

Previous studies

- **The above mentioned previous works adopt macroscopic models.**
- **Little microscopic information from nuclear many-body theories, except**

[1] linear response (QRPA) in uniform neutron superfluid

⇒ SPH in uniform matter, but neglecting clusters. Martin+, PRC90, 065805.

[2] linear response (QRPA) in Wigner-Seitz cell

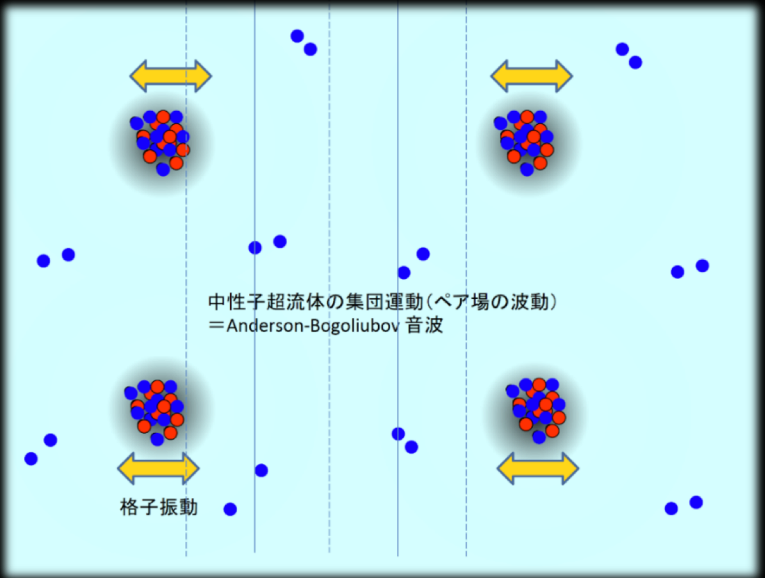
⇒ SPH-like mode is obtained, but no detailed study of SPH-LPH coupling.

Khan+, PRC71, 042801.

Purpose of present study

- We follow the same line as [1,2],
- using the nuclear density functional theory, powerful to describe collective excitations

> **SPH in non-uniform configuration, influence of clusters on SPH**
>
> **Interplay between SPH and cluster excitations responsible for the new cooling**



Linear response (QRPA) for inner crust

- **Skyrme functional: SLy4**
  appropriate both for neutron matter (APR EOS) and isolated nuclei.
- **Hartree-Fock-Bogoliubov (Bogoliubov-de Gennes theory)**
  non-uniform equilibrium configuration at T=0 with superfluidity
  effective pairing int. (density-dep. contact int.) that reproduces BCS gap
- **QRPA (Linear response) to describe collective excitation**
  focus on dipole and quadrupole modes.
- **Wigner-Seitz approximation**
  spherical cell with radius 20fm
  von-Neuman Derichlet boundary condition
- **Systematic studies**
  proton numbers of clusters: $Z=20$, 28, 40, and 50
  varying densities (chemical potential λ_n) of neutron superfluid.

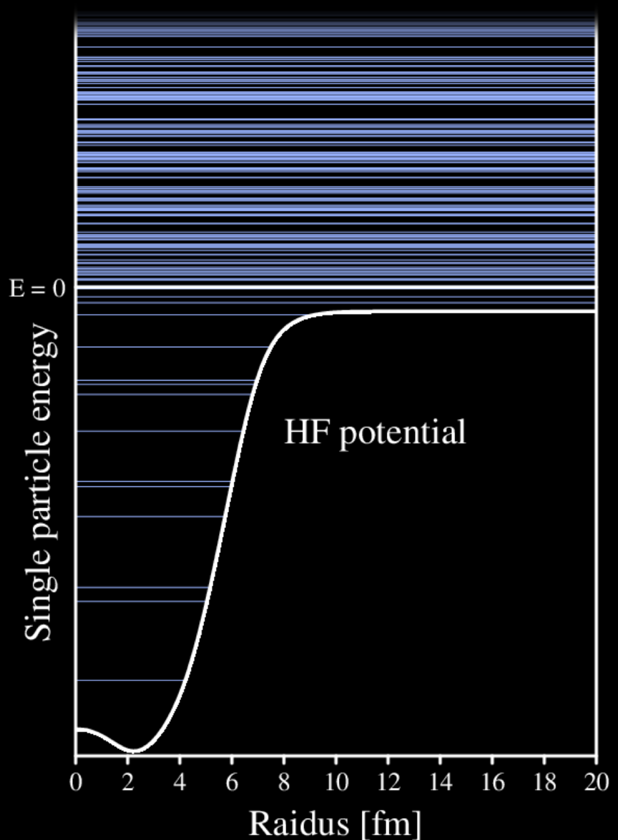
A model inner crust and ground state

Spherical box with $R_{\text{box}} = 20$ fm

von-Neumann-Dirichlet condition:

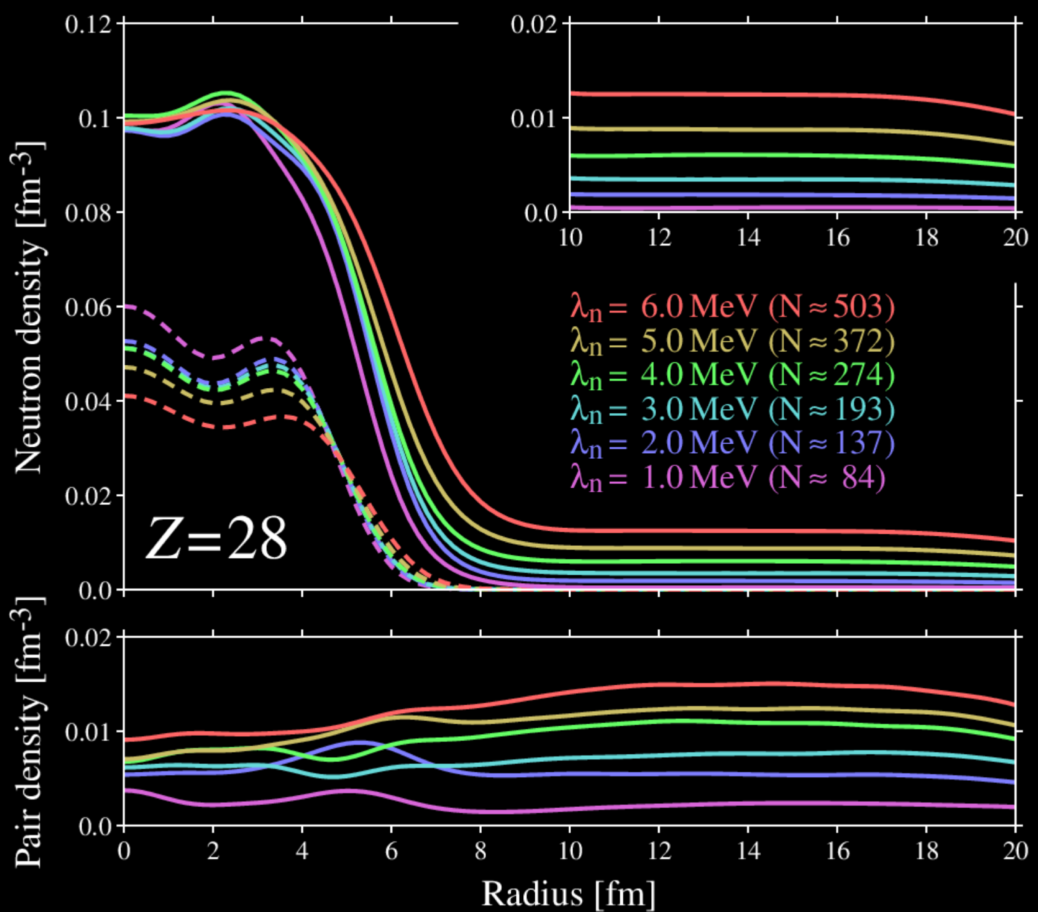
$$\left.\frac{d\phi(r)}{dr}\right|_{r=R_{\text{box}}} = 0 \quad \text{for odd-parity}$$

$$\phi(r=R_{\text{box}}) = 0 \quad \text{for even-parity}$$



Inputs

- Proton number ***Z*** of nuclear cluster
- Neutron chemical potential λ_n (nucleon density)



QRPA (Linear response calc.)

$$\begin{bmatrix} \delta\rho \\ \delta\tilde{\rho} \\ \delta\tilde{\rho}^* \end{bmatrix} = \left[R_0^{\alpha\beta}(\omega) \right] \begin{bmatrix} \delta h + V_{\mathrm{ext}} \\ \delta\Delta \\ \delta\Delta^* \end{bmatrix}$$

Matsuo, NPA 696, 371.
Matsuo+, NPA 788, 307c.

- Continuum state is also discretized with von-Neumann-Direchlet condition.
  $\Longrightarrow$ **Discrete spectrum** representation.
- Landau-Migdal approximation to momentum-dependent term in δh.
  $\Longrightarrow$ **Renormalize δh** to bring displacement motion (center-of-mass motion) to zero energy.

Dipole excitation

PHYSICAL REVIEW C **96**, 025806 (2017)

Anderson-Bogoliubov phonons in the inner crust of neutron stars: Dipole excitation in a spherical Wigner-Seitz cell

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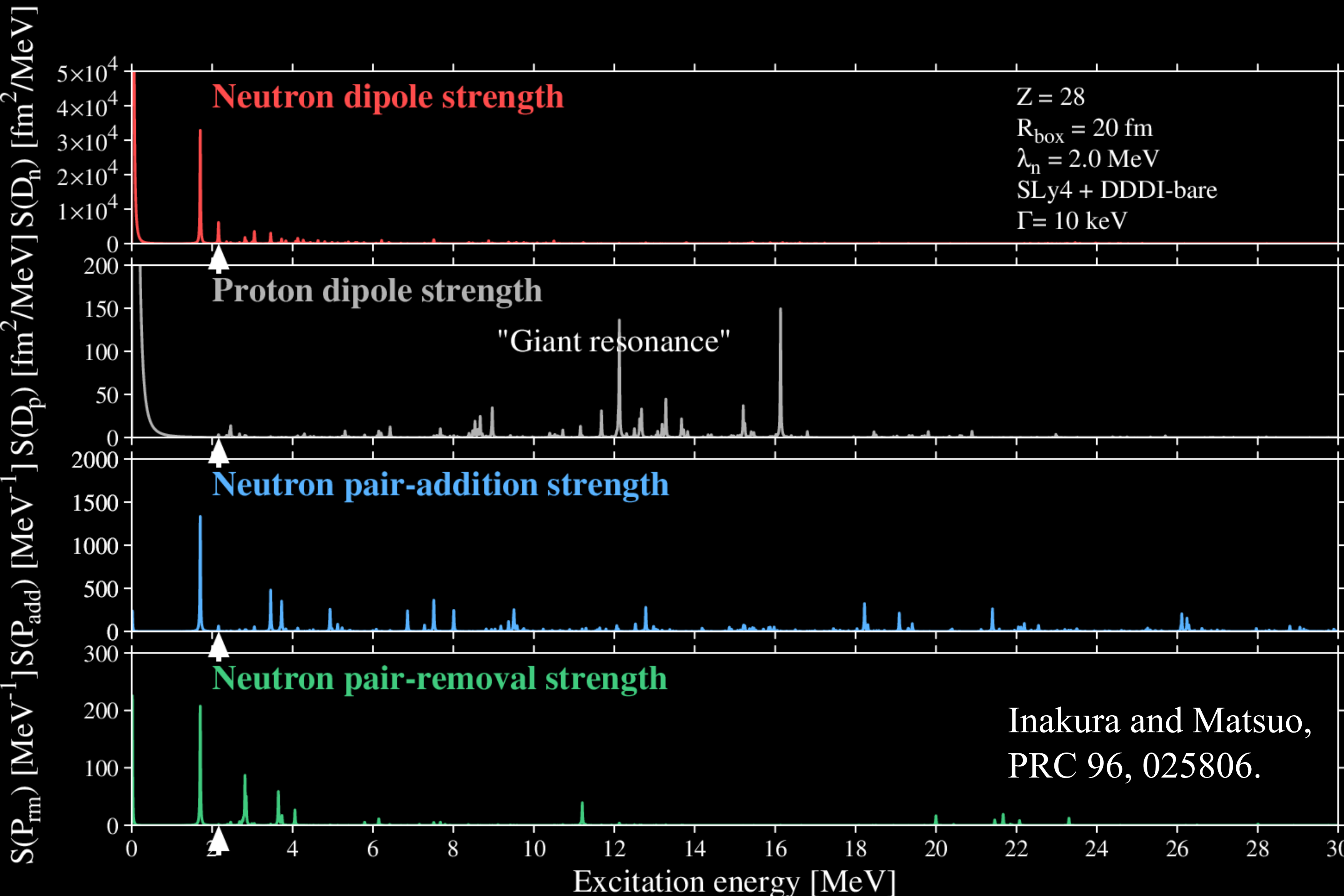
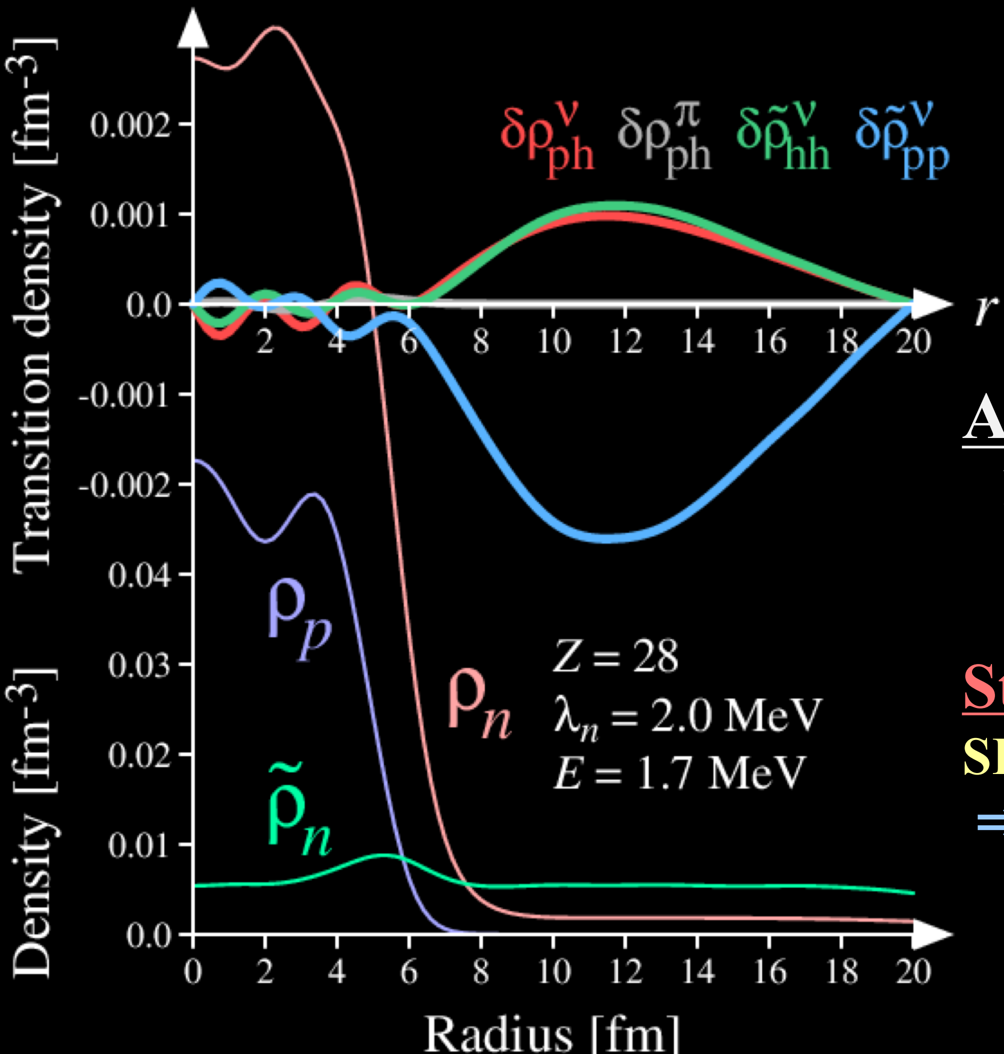
Inakura and Matsuo, PRC 96, 025806.

Excitation spectra of inner crust: Dipole

Distinctive low-energy collective mode in strength functions



Transition density



Anderson-Bogoliubov mode:

large $\delta\tilde{\rho}_{pp}$ & $\delta\tilde{\rho}_{hh}$ with **opposite** signs.

Strong influence of cluster

SPH does not penetrate into cluster

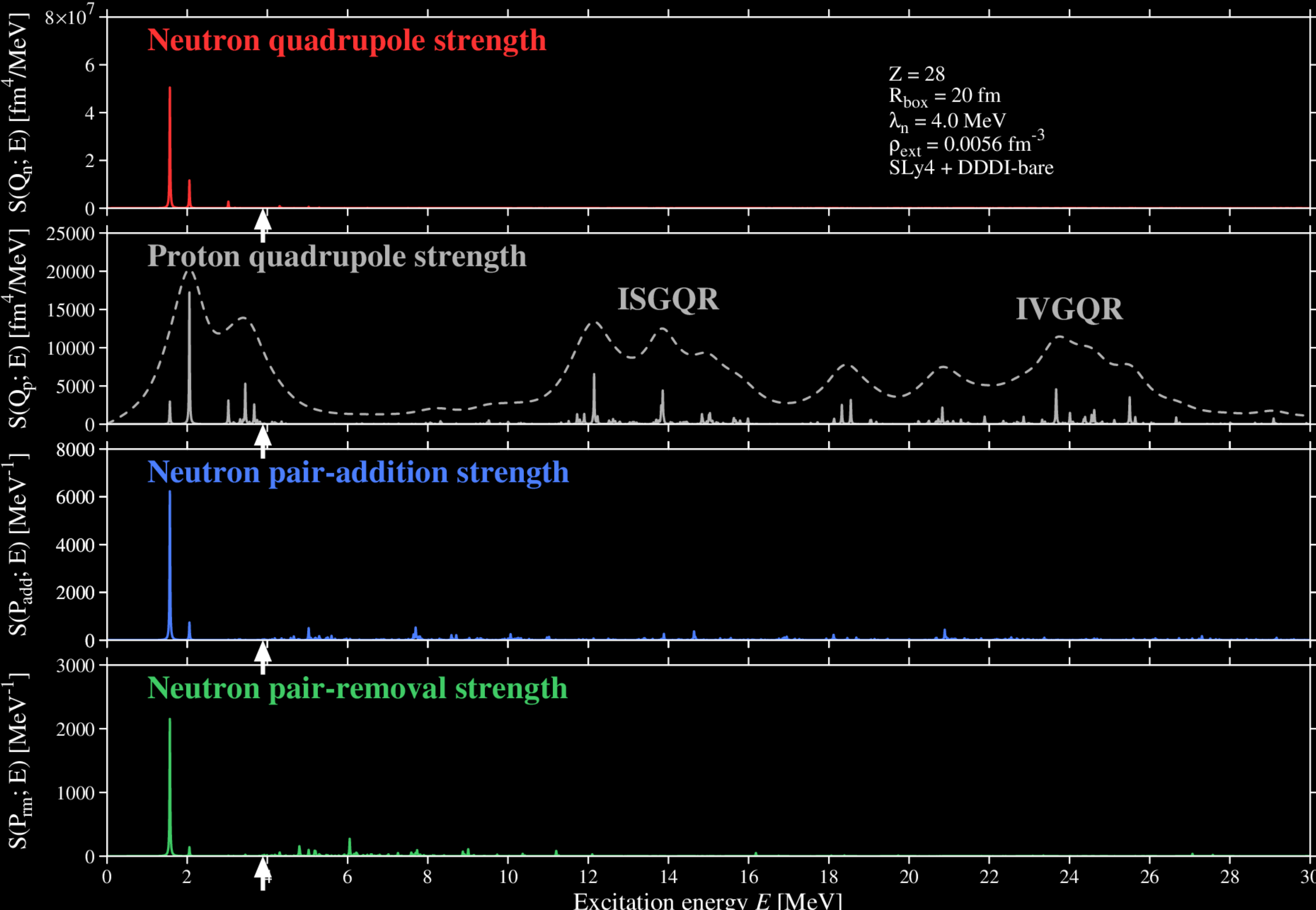
⇒ Weak SPH-LPH coupling.

Inakura and Matsuo, PRC 96, 025806.

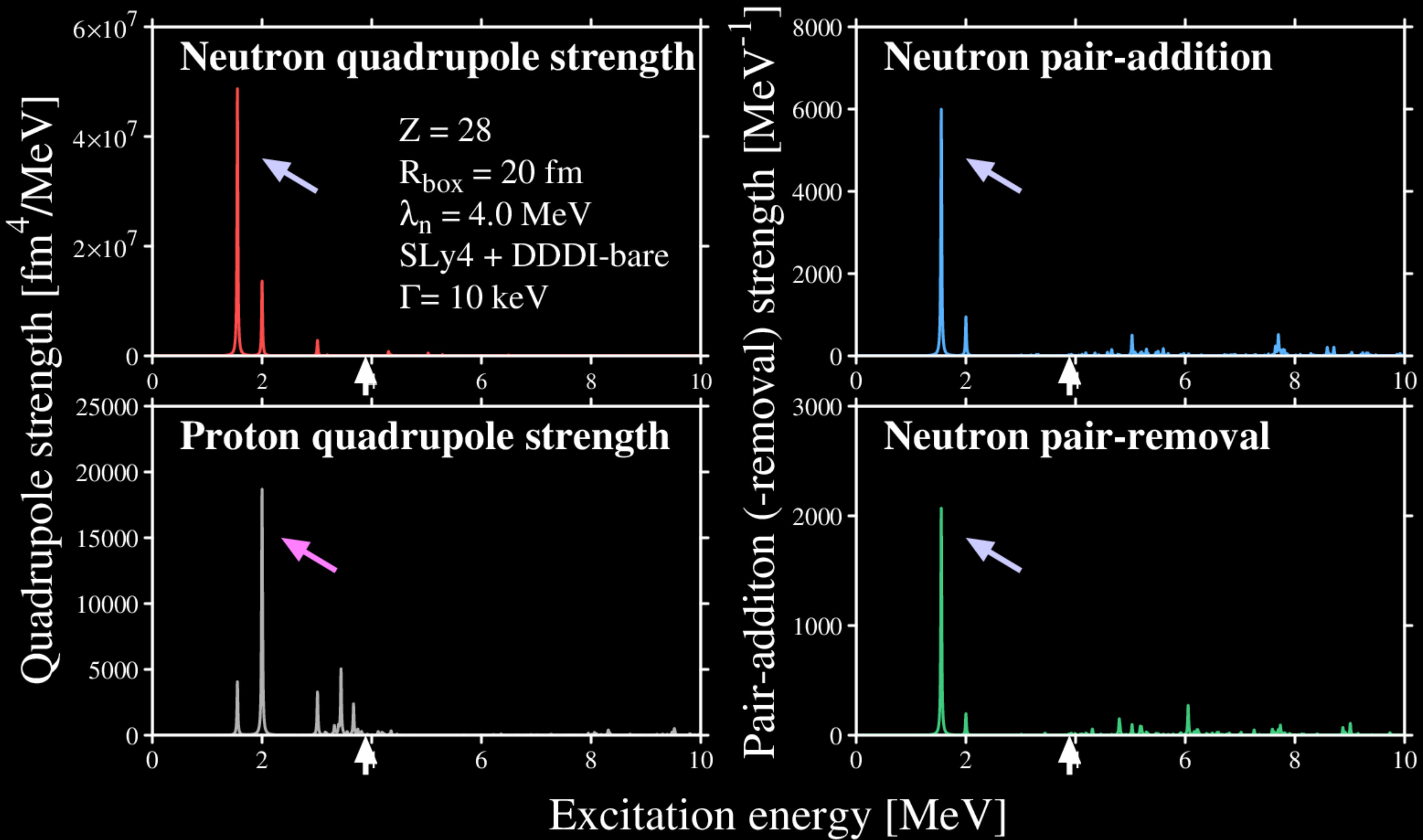
Quadrupole excitation

Excitation spectra of inner crust: Quadrupole

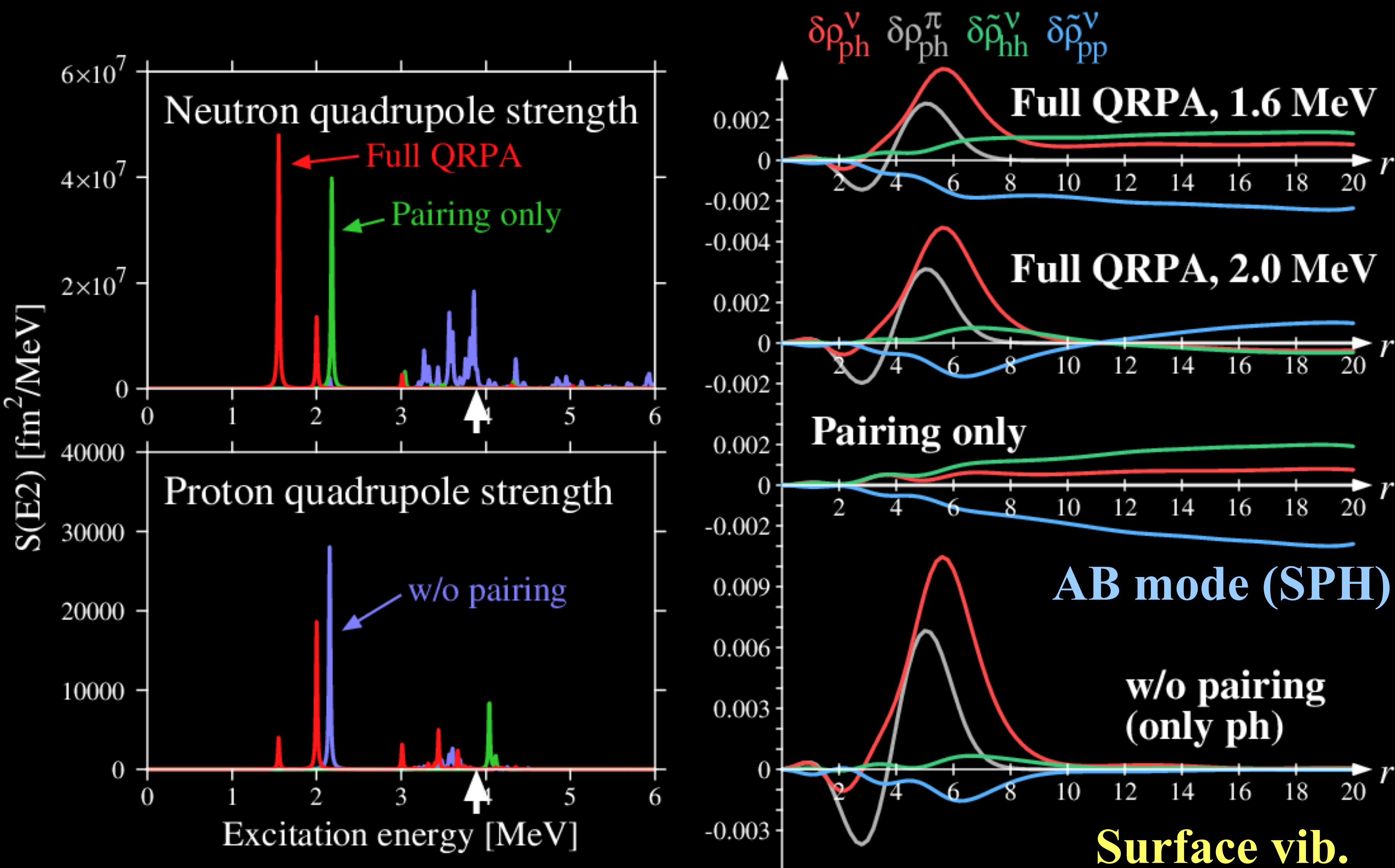
Distinctive low-energy collectives modes in strength functions



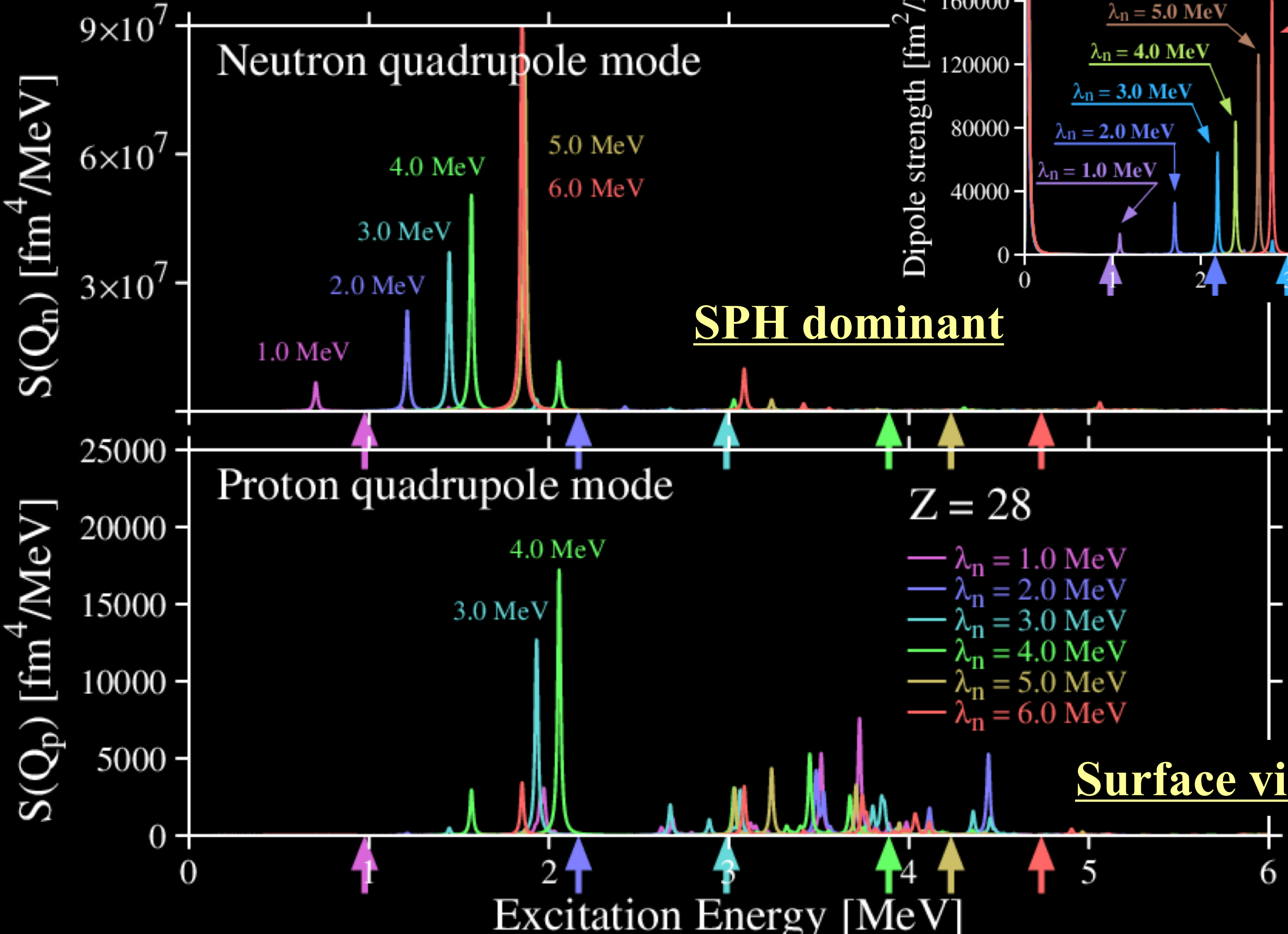
Two types of quadrupole excitation

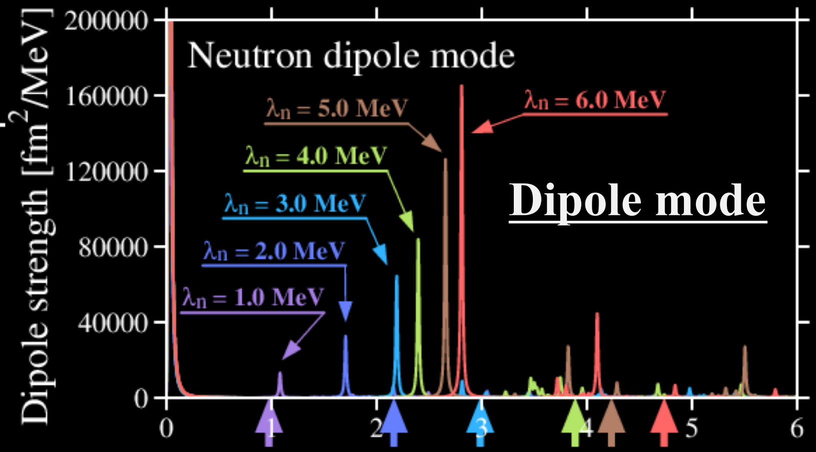


SPH and surface vibration coexist and couples



SPH and surface vib. have different density dependence





Dipole mode

SPH dominant

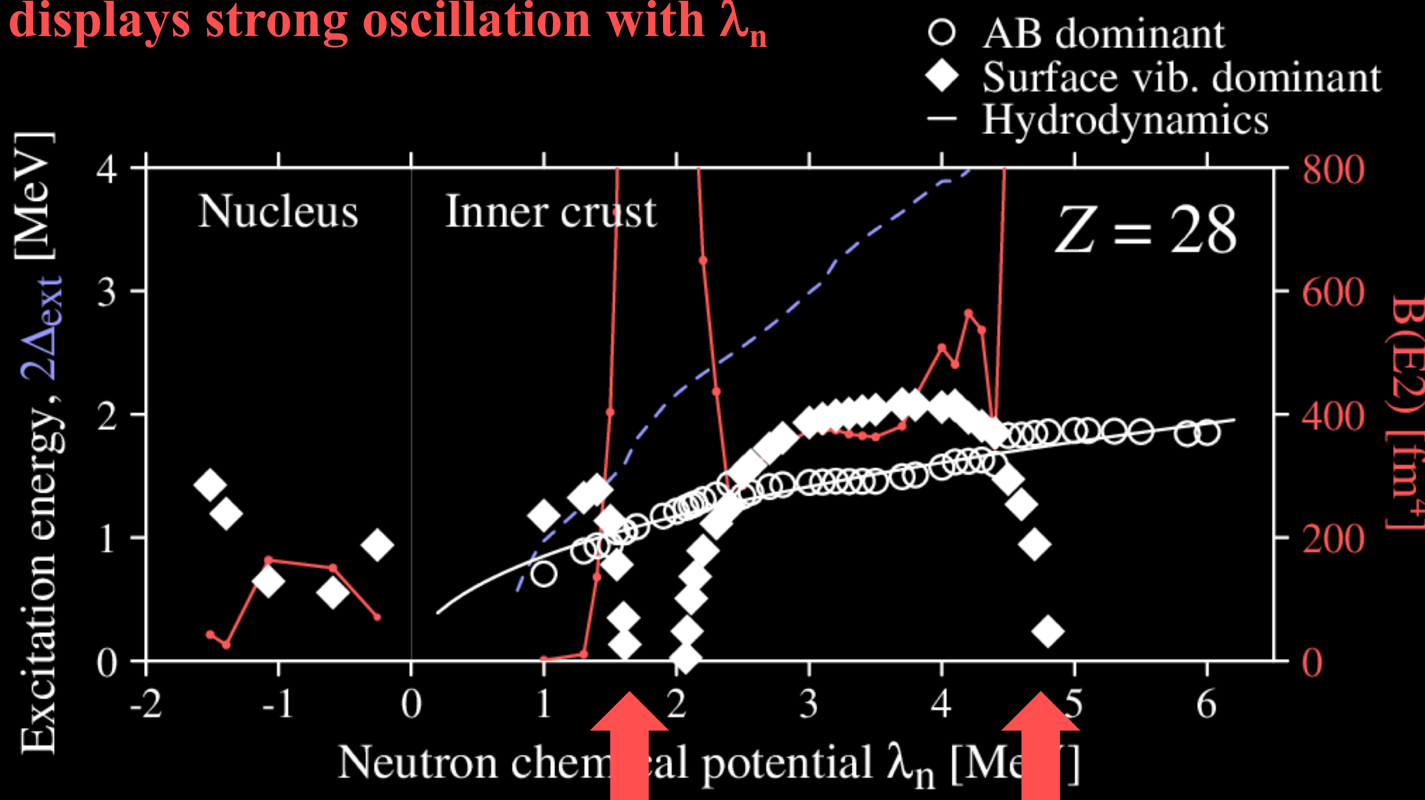
Surface vib. dominant

SPH and surface vib. have different density dependence

SPH (AB dominant mode) has monotonic λ_n dependence.

⇒ Weak coupling between SPH and surface vibration.

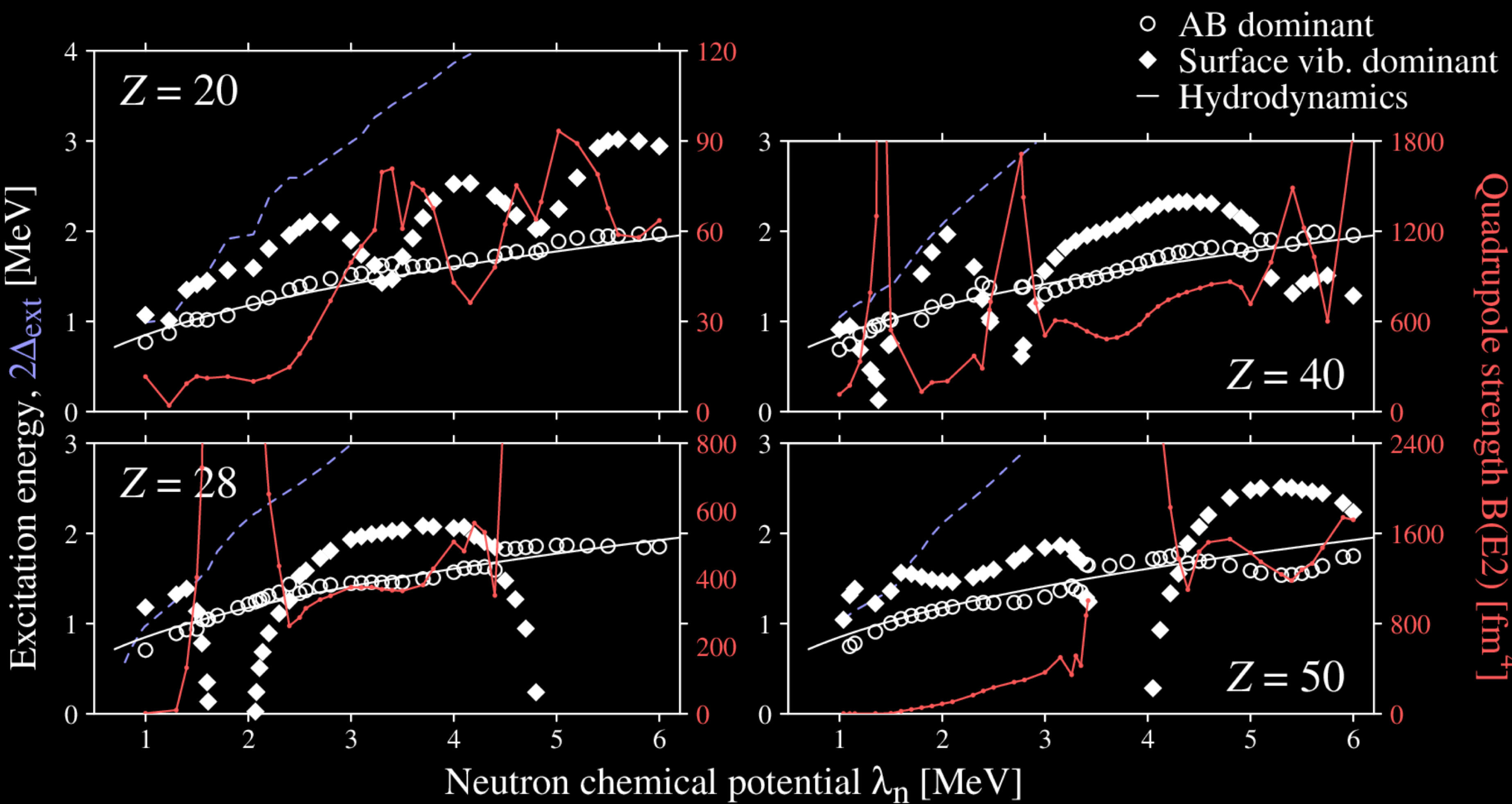
Surface vib. displays strong oscillation with λ_n



Quadrupole instability occurs at specific λ_n
⇒ manifestation of deformed cluster

What mechanism ?

Oscillation and instability in surface vibration



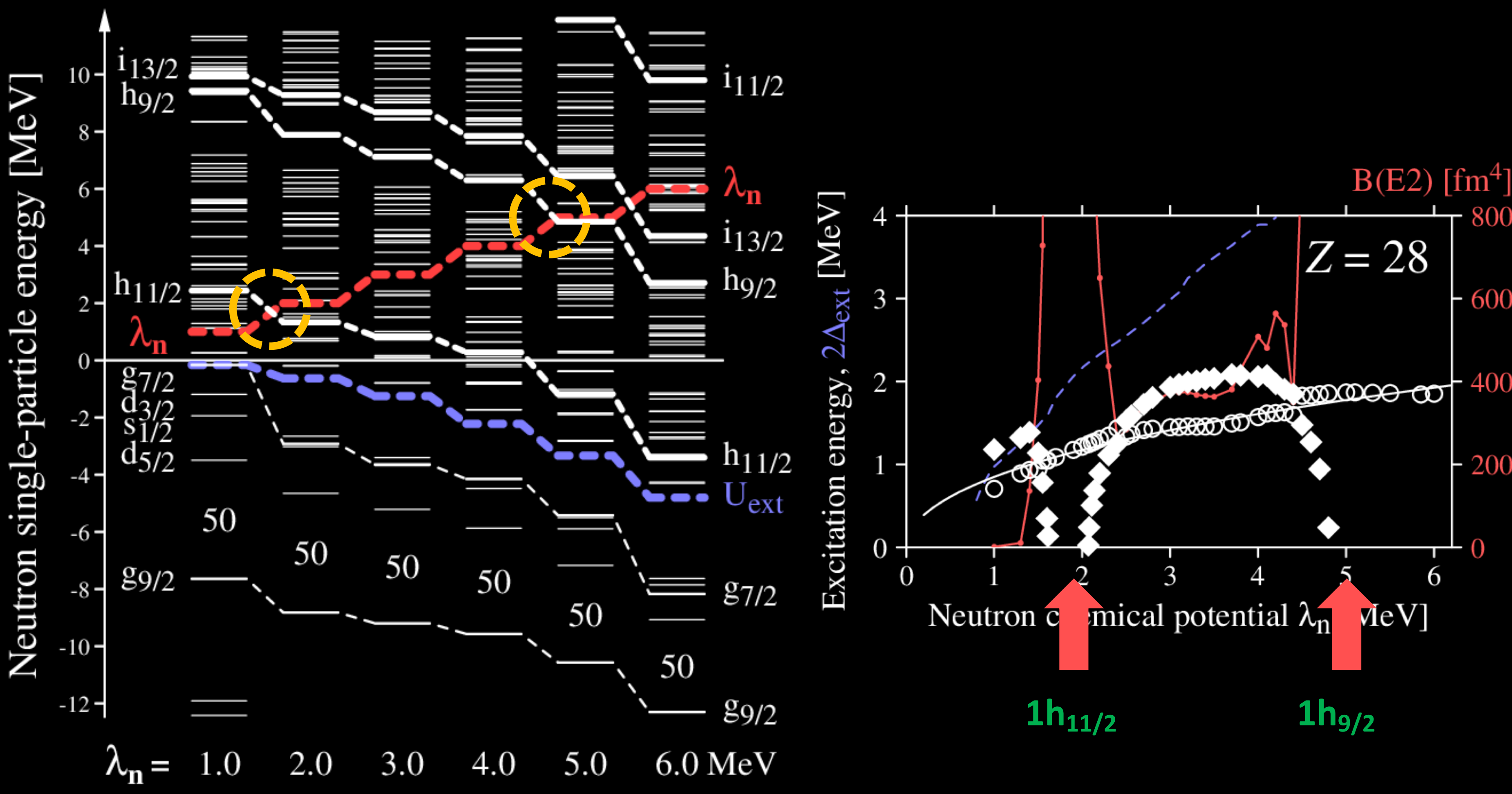
What mechanism ?

Shell effect ?

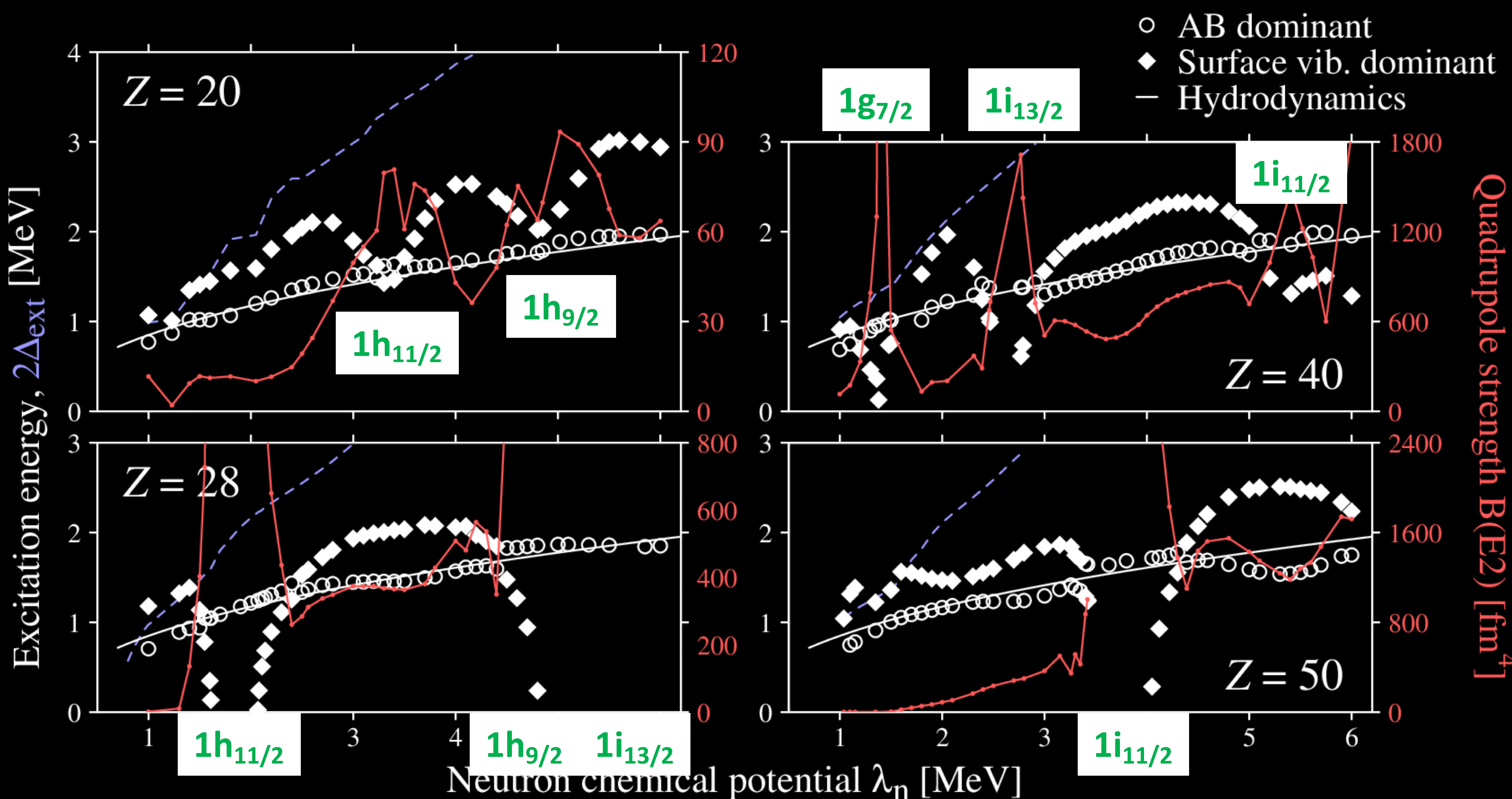
What shell ?

Key is resonant high-j single-particle orbits in the continuum

1. **Enhanced collectivity & instability when a high-j resonant s.p. orbit crosses around Fermi energy.**
2. **Non-resonant s.p. orbits do not play role in the shell effect.**



Oscillation and instability in surface vibration



Shell effect due to resonant high-j orbit in the valence continuum

Conclusions

We have studied quadrupole collectivity in inner crust of neutron stars,
using the nuclear density functional theory,
treating explicitly the presence of nuclear cluster,
under the Wigner-Seitz approx.

- **Coexistence of SPH phonon (neutron superfluid) and surface vibration (cluster)**
- **Weak coupling between SPH and surface vibration.**
- **SPH has monotonic density dependence (λ_n) as in uniform neutron superfluid.**
- **Surface collectivity displays novel shell effect governed by high-j resonant orbits in the valence continuum.**

Submitted to PRC, see also nuclear theory archives arXiv: 1811.10311.