Anderson-Bogoliubov phonon in inner crust of neutron stars

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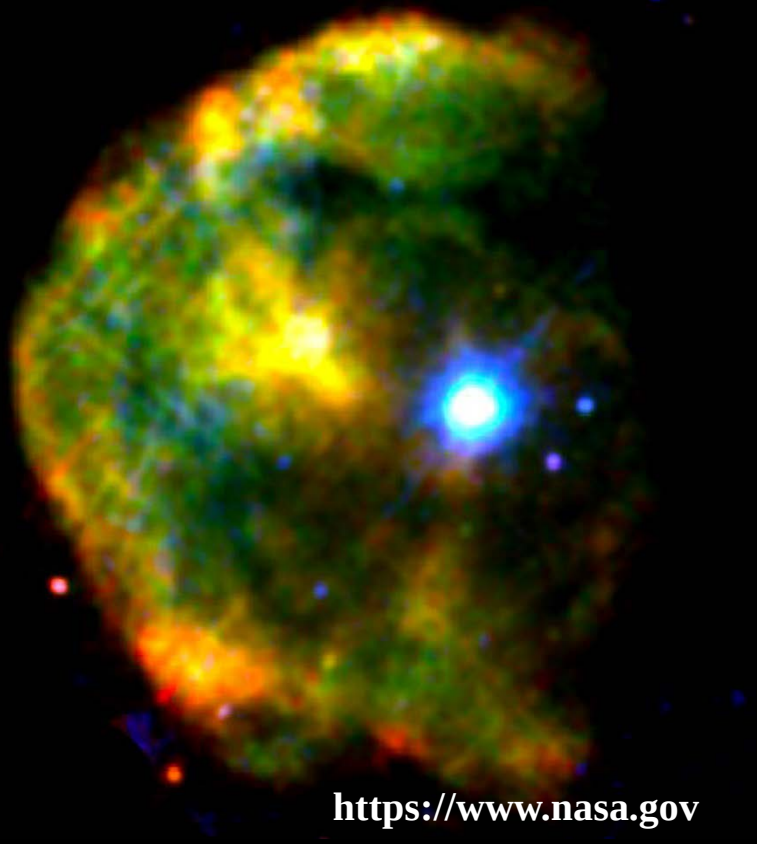
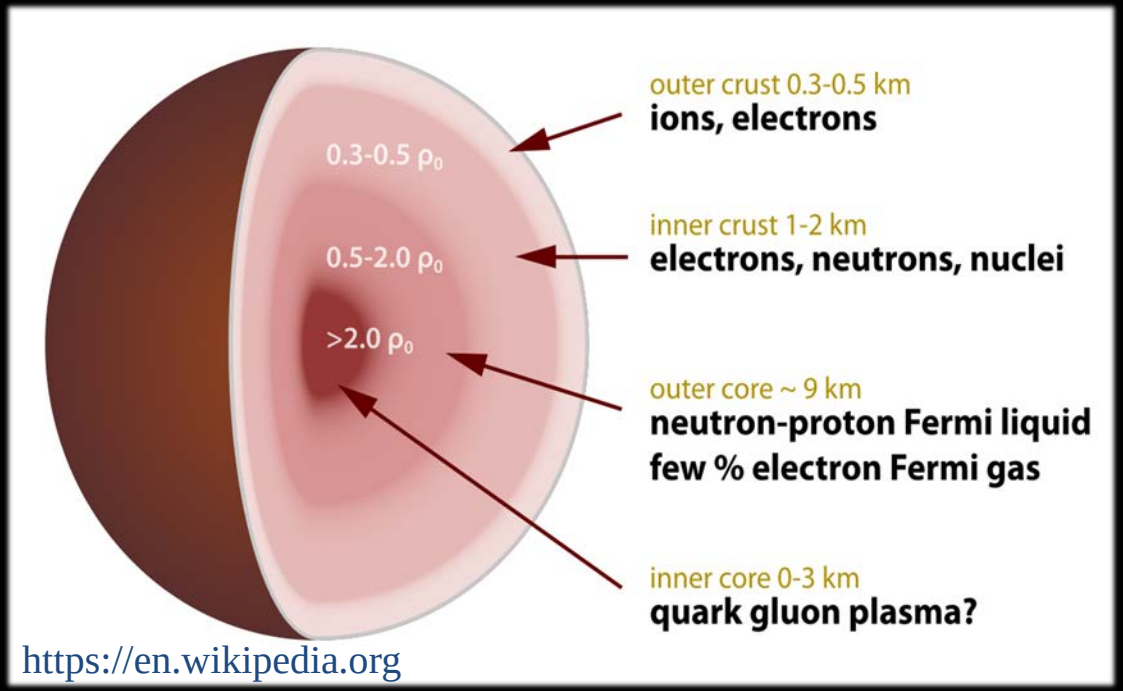
Neutron stars

the smallest and densest stars known to exist.



https://www.nasa.gov



https://en.wikipedia.org

Neutron star:

Radius ~ 10-12 km

Mass ~ 1-2 $M_\odot$

Inner crust:

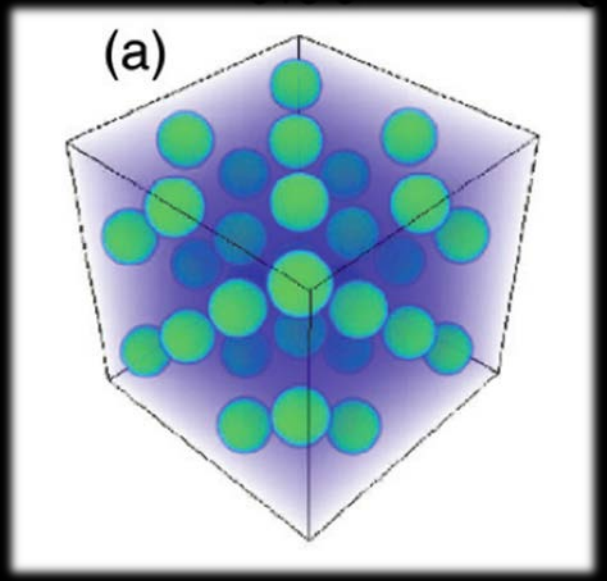
Thickness ~ 1 km

Mass ~ 1 % of NS

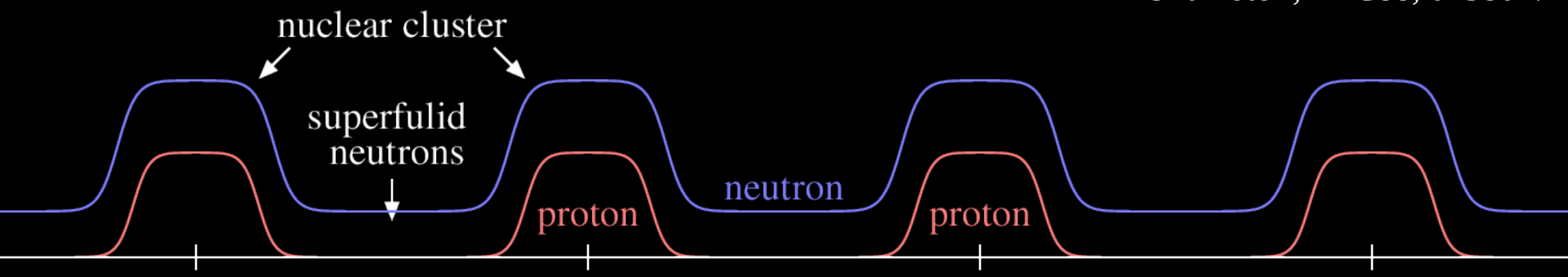
Inner crust of neutron star:

Lattice of nuclear cluster surrounded by superfluid neutron sea

- Two components: neutron and proton
- Self-assembling system
- Inhomogeneous nuclear matter
- Nuclear cluster can excite.



Okamoto+, PRC88, 025801.

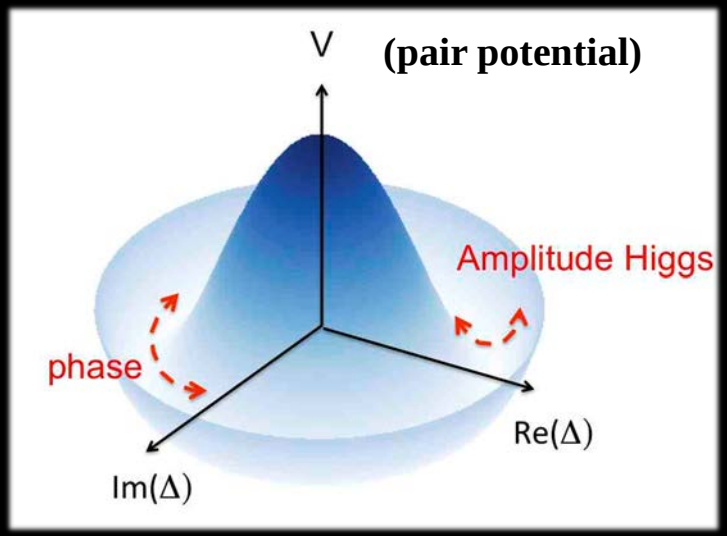


Its properties impact many phenomena, such as

- Cooling process (connected with specific heat, heat conductivity),
- Glitch (sudden change of rotational speed),
- Quasi-periodic oscillation (starquake).

Anderson-Bogoliubov phonon as a new heat carrier.

- **Superfluid phonon (Anderson-Bogoliubov mode) coupled with nuclear excitation (lattice phonon) is a new agent of heat carrier.**
- **Thermal conductivity by AB mode can be comparable to that by electrons under strong magnetic field, i.e. in magnetars.**



www.mpq.univ-paris7.fr

Aguilera+, PRL102, 091191
Cirigliano+, PRC84, 045809
Chamel+, PRC87, 035803, etc.

Anderson-Bogoliubov mode:
Collective excitation mode.
Nambu-Goldstone mode associated with the gauge symmetry broken spontaneously by the pair condensate.

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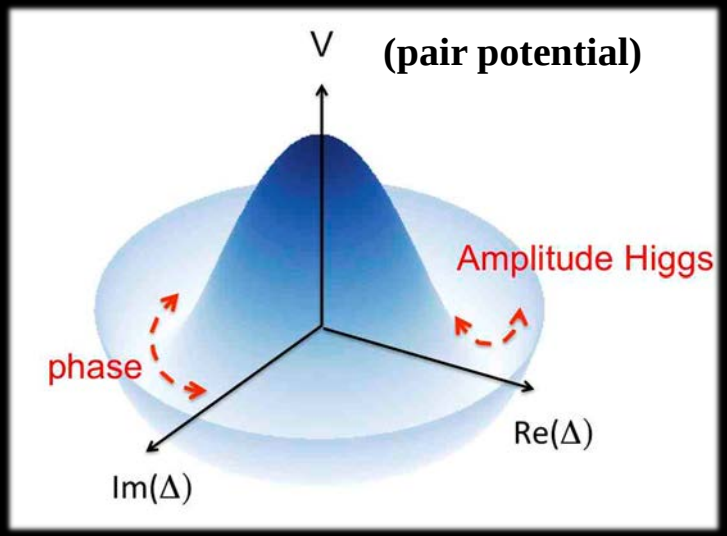

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Anderson-Bogoliubov mode:
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A limited number of microscopic calculations.

Dynamics of inner crust is not well understood.

Motivation:

- Clarify dynamical properties of inner crust by microscopic calculation.
- (in near future, calculate thermal conductivity and so on.)

Method:

1D real-space HFB + QRPA.

- Spherical **Wigner-Seitz cell** with Neumann-Derichlet boundary condition.
- Temperature $T = 0$.
- **Hartree-Fock-Bogoliubov** (Bogoliubov-de Gennes) with Skyrme EDF.
- **Quasiparticle RPA** (linear response TDHFB) for **dipole mode** which is responsible for coupling of displacement motion and AB mode.
- Systematic studies with varying inner crust configurations.

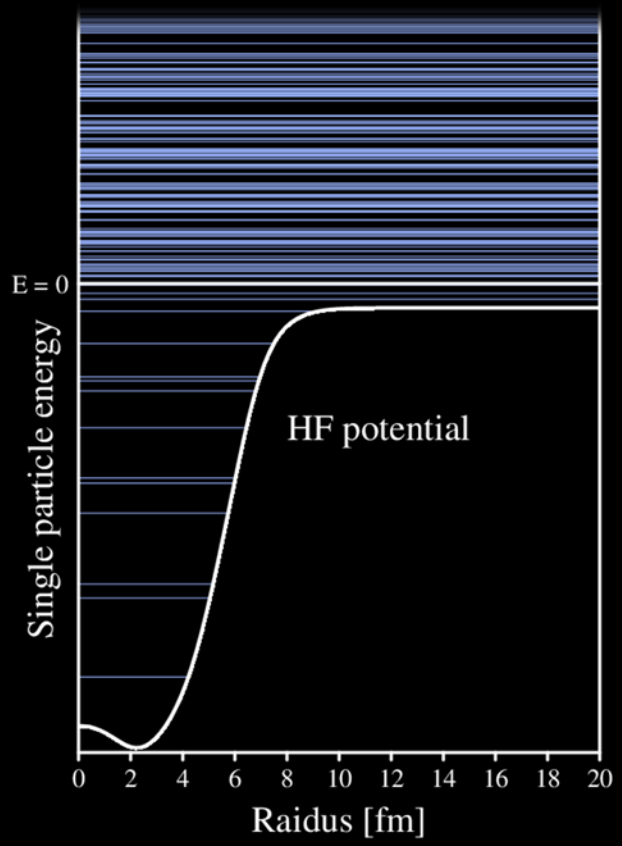
A model inner crust and ground state

Spherical box with R_{box} = 20 fm

Dirichlet-Neumann condition:

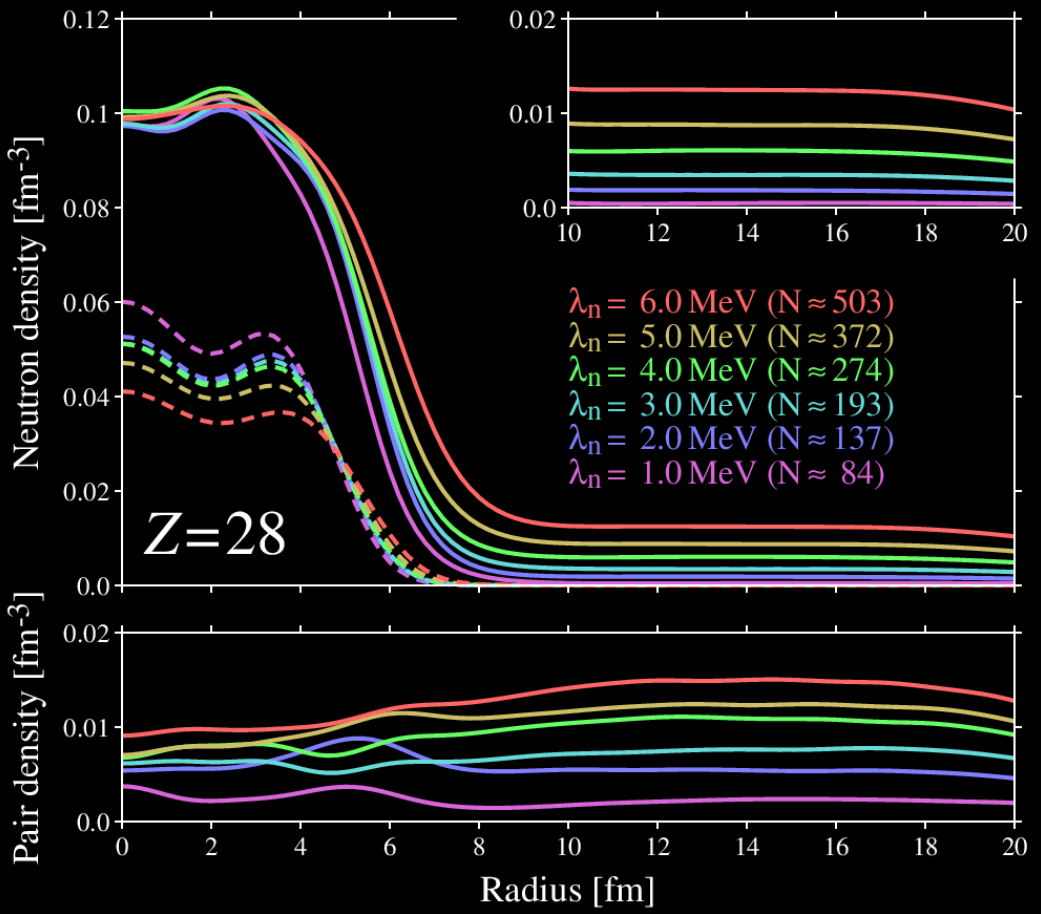
$$\left.\frac{d\phi(r)}{dr}\right|_{r=R_{box}} = 0 \quad \text{for odd-parity}$$

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

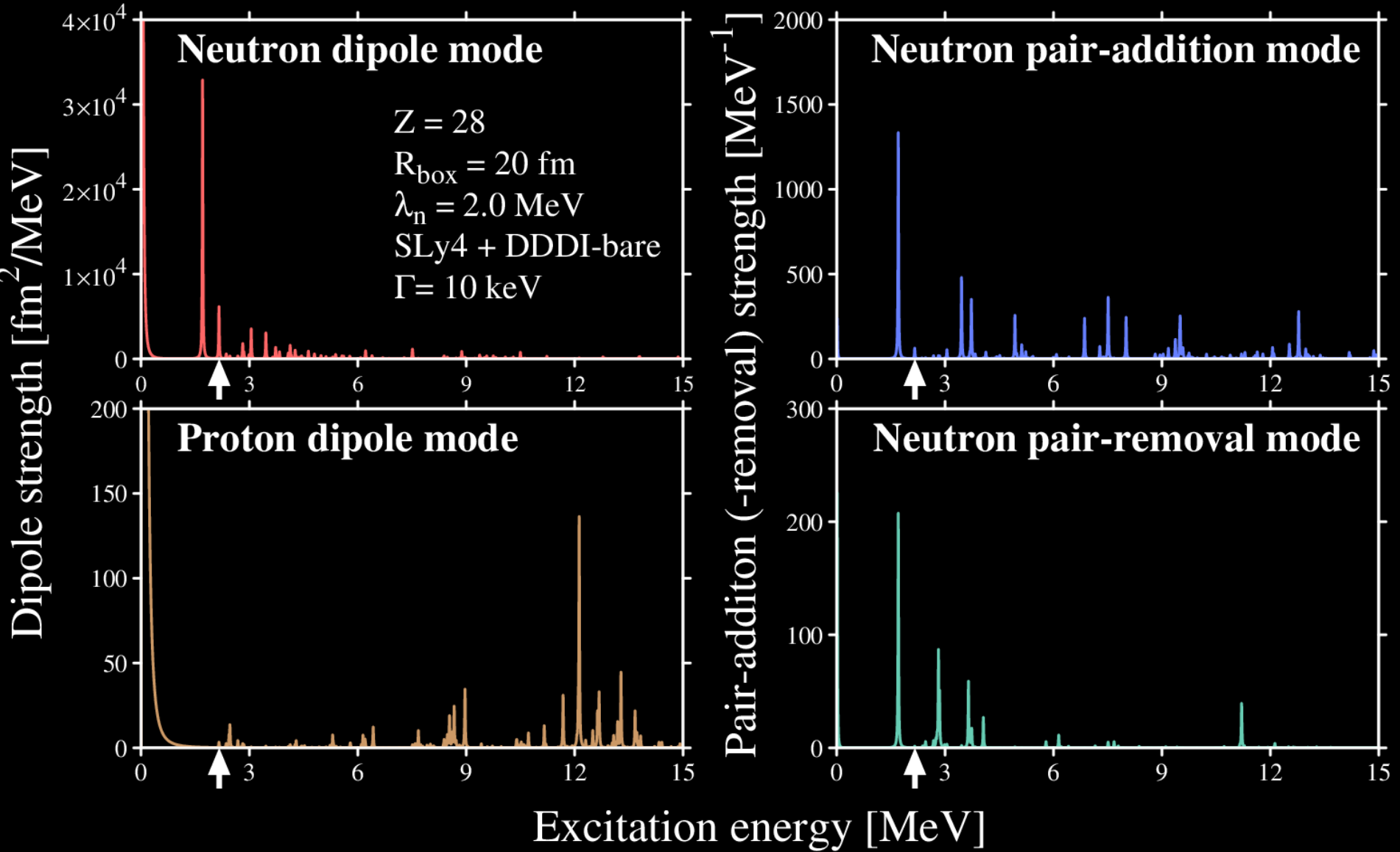


Inputs

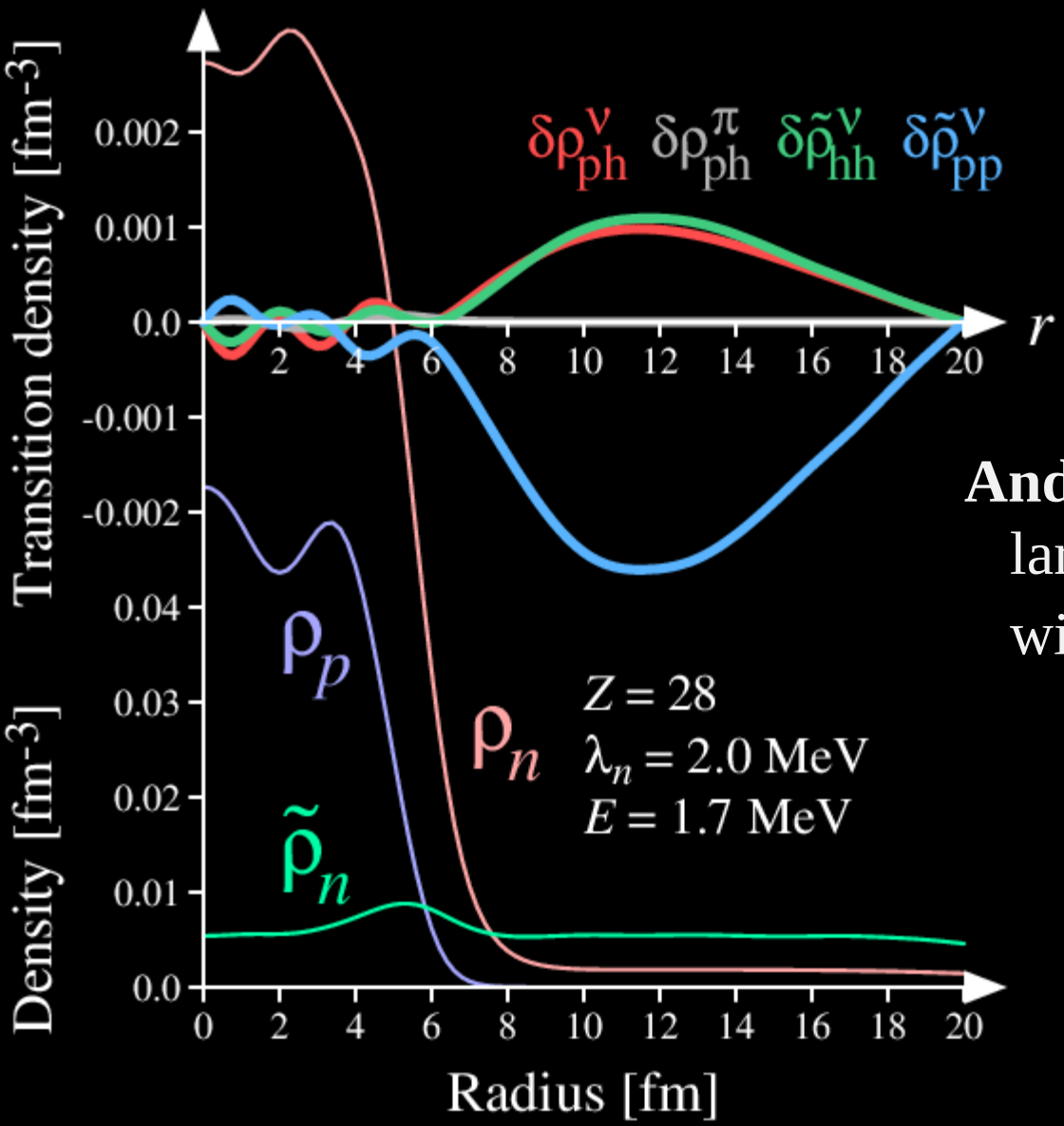
- Proton number **Z**
- Neutron chemical potential λ_n (neutron density)



Excitation of inner crust

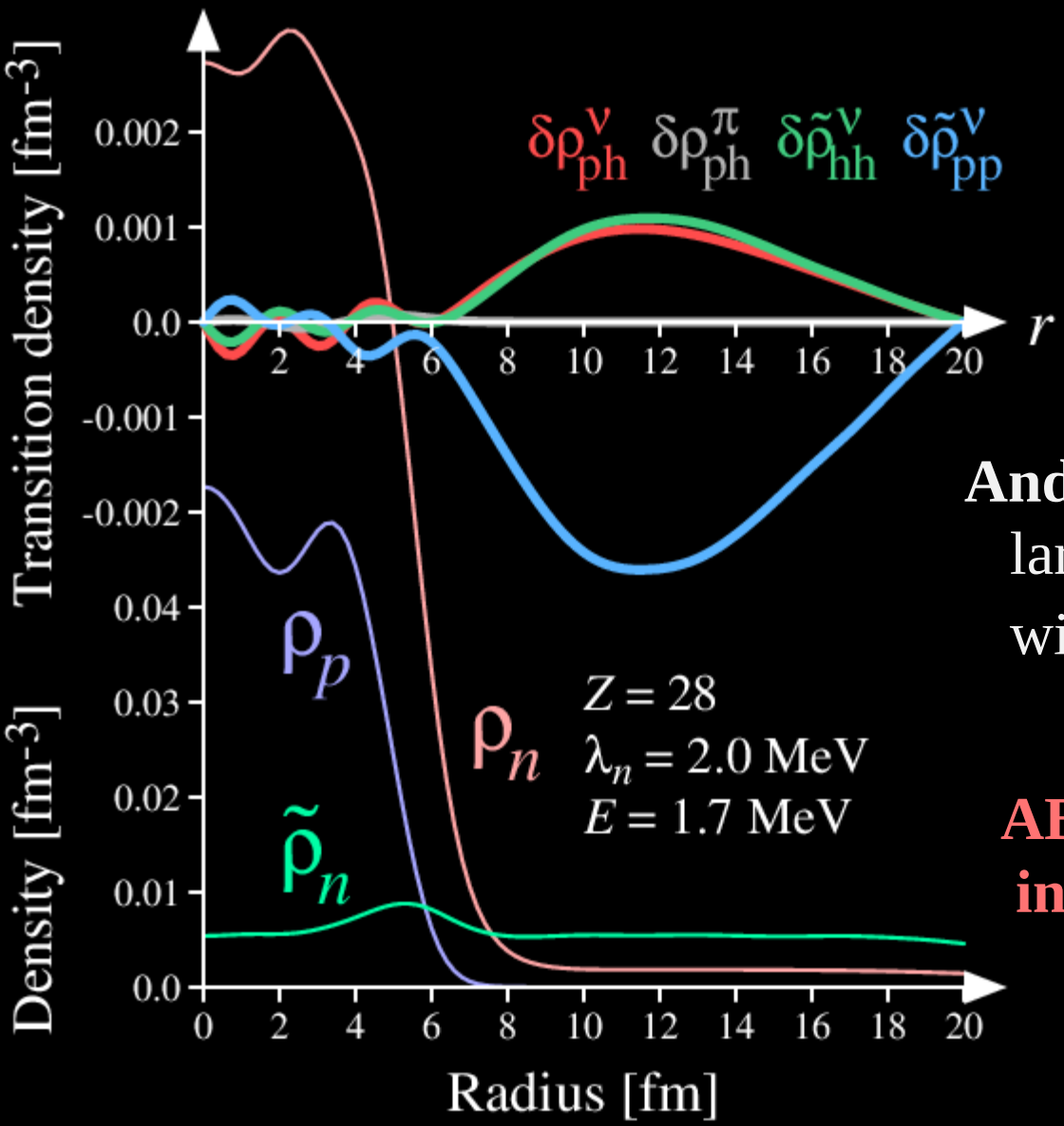


Transition density



Anderson-Bogoliubov mode:
large $\delta\tilde{\rho}_{pp}$ & $\delta\tilde{\rho}_{hh}$
with **opposite** signs.

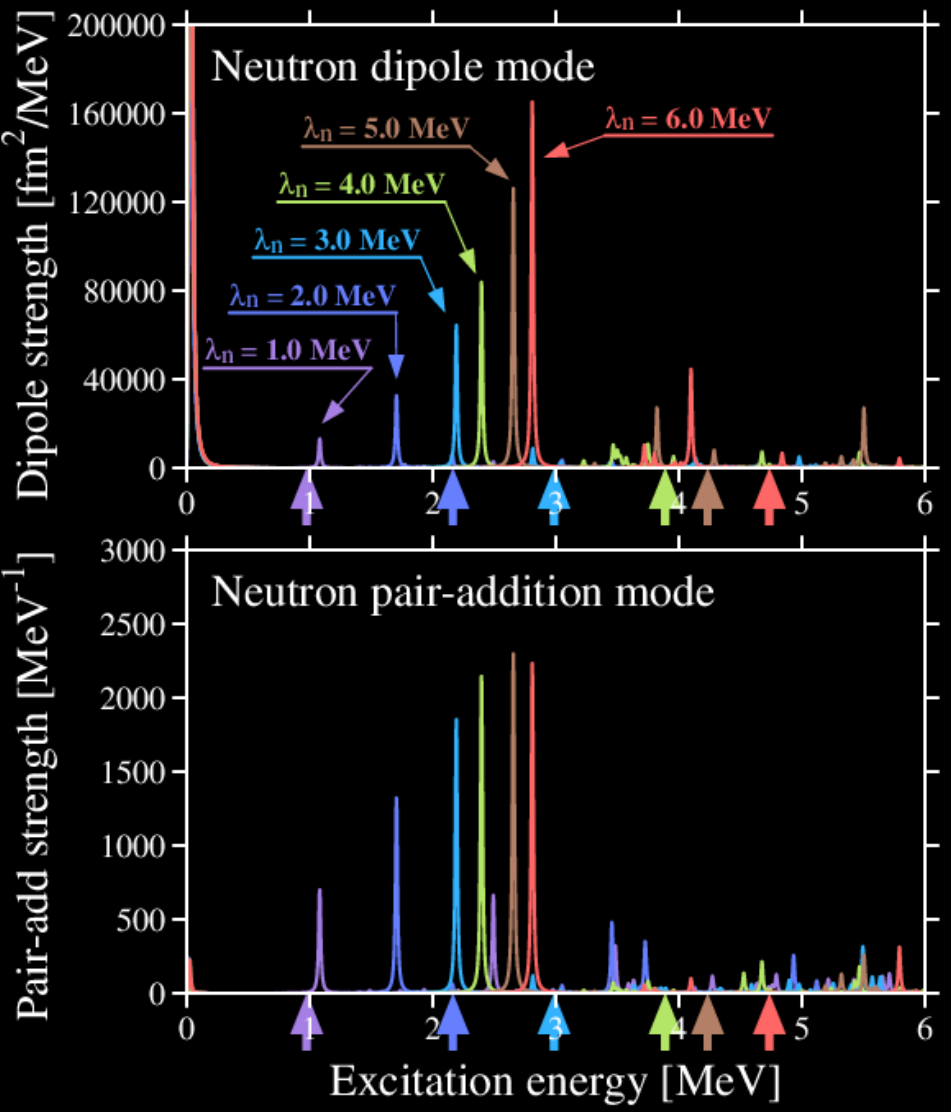
Transition density

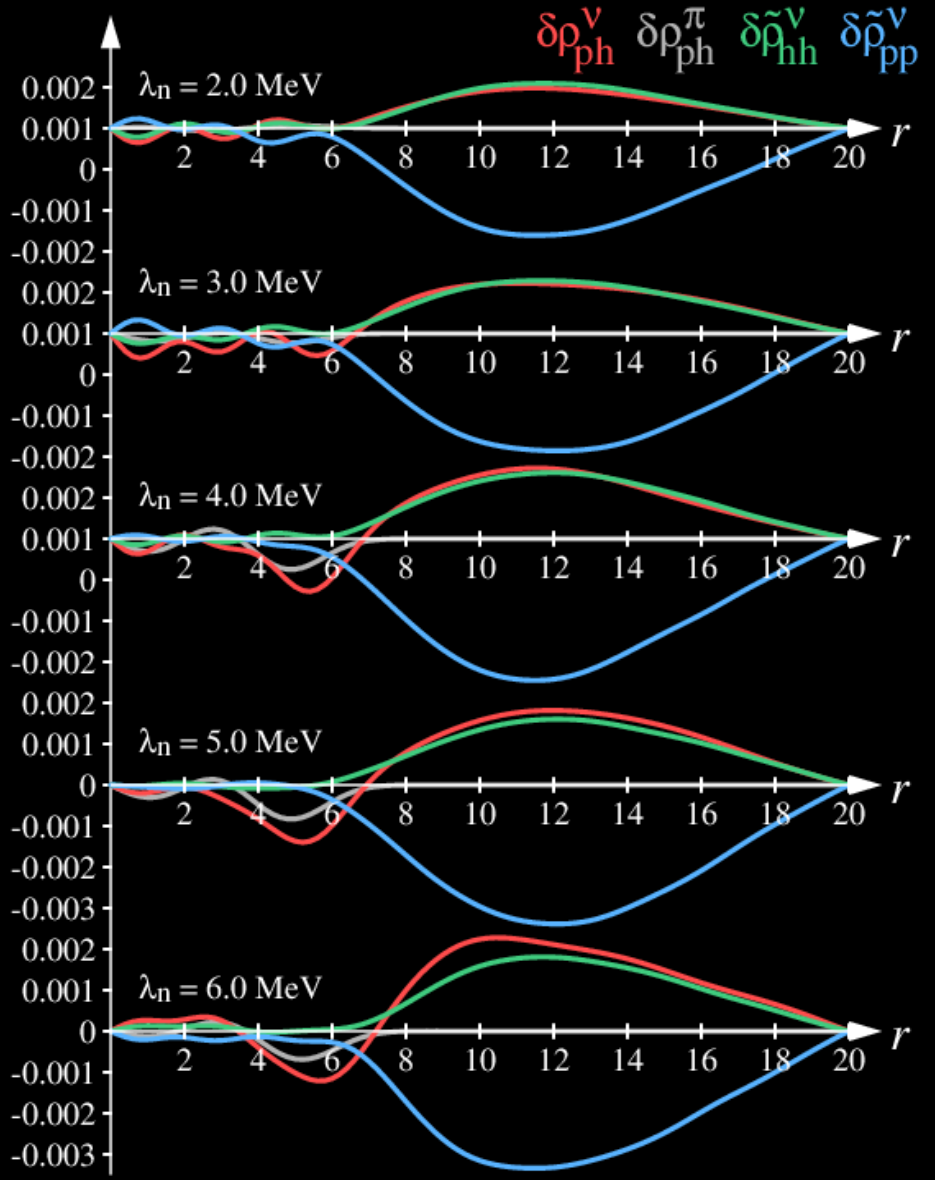


Anderson-Bogoliubov mode:
large $\delta\tilde{\rho}_{pp}$ & $\delta\tilde{\rho}_{hh}$
with **opposite** signs.

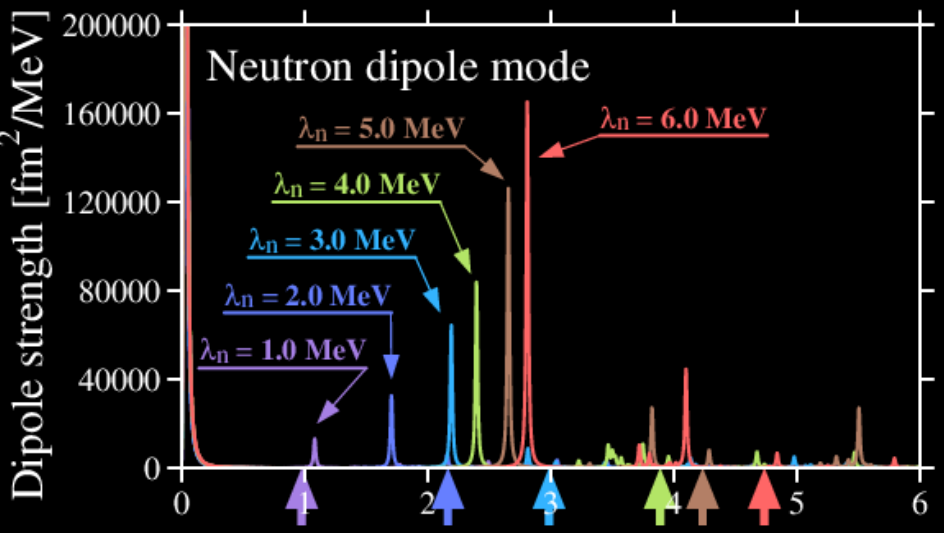
AB mode does not penetrate into nuclear cluster.

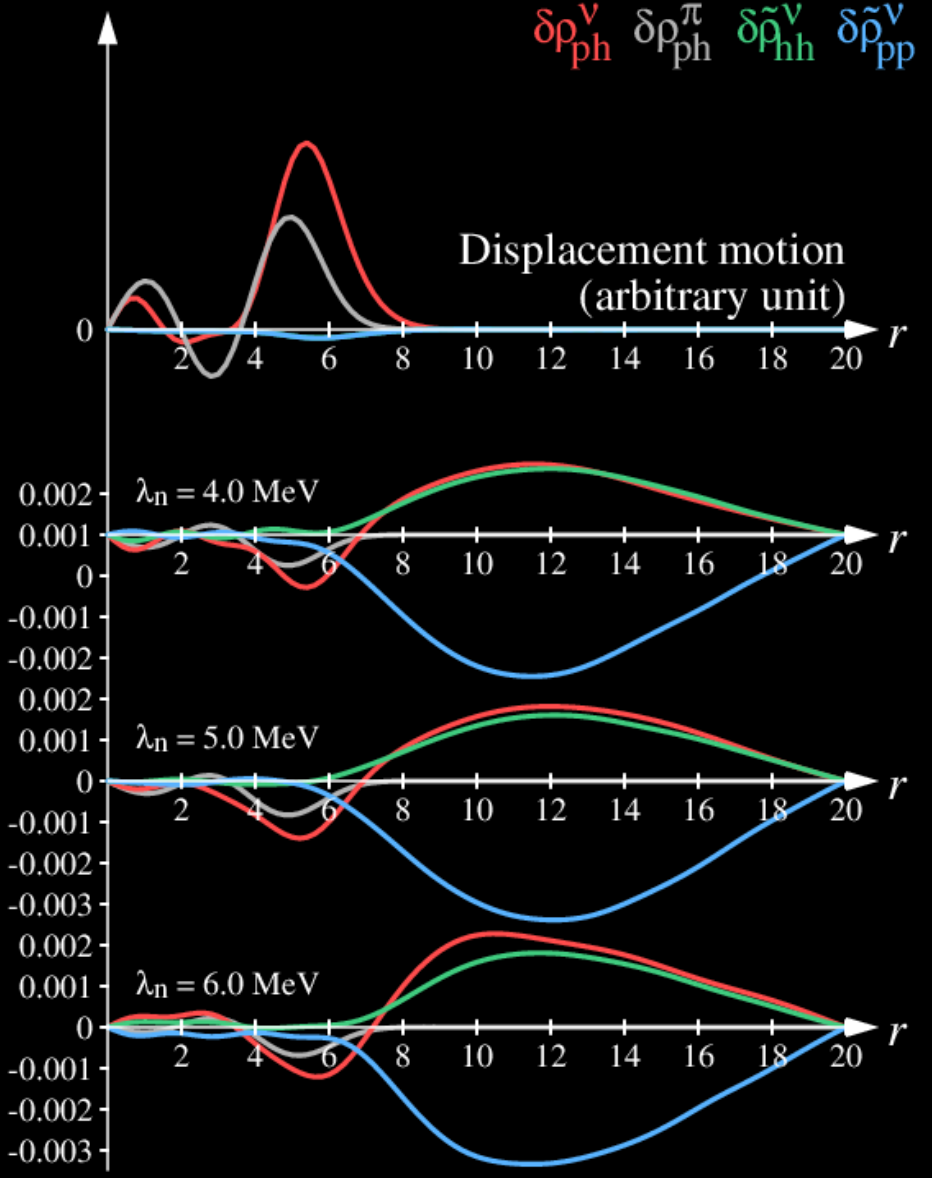
λ_n-dependence of AB mode





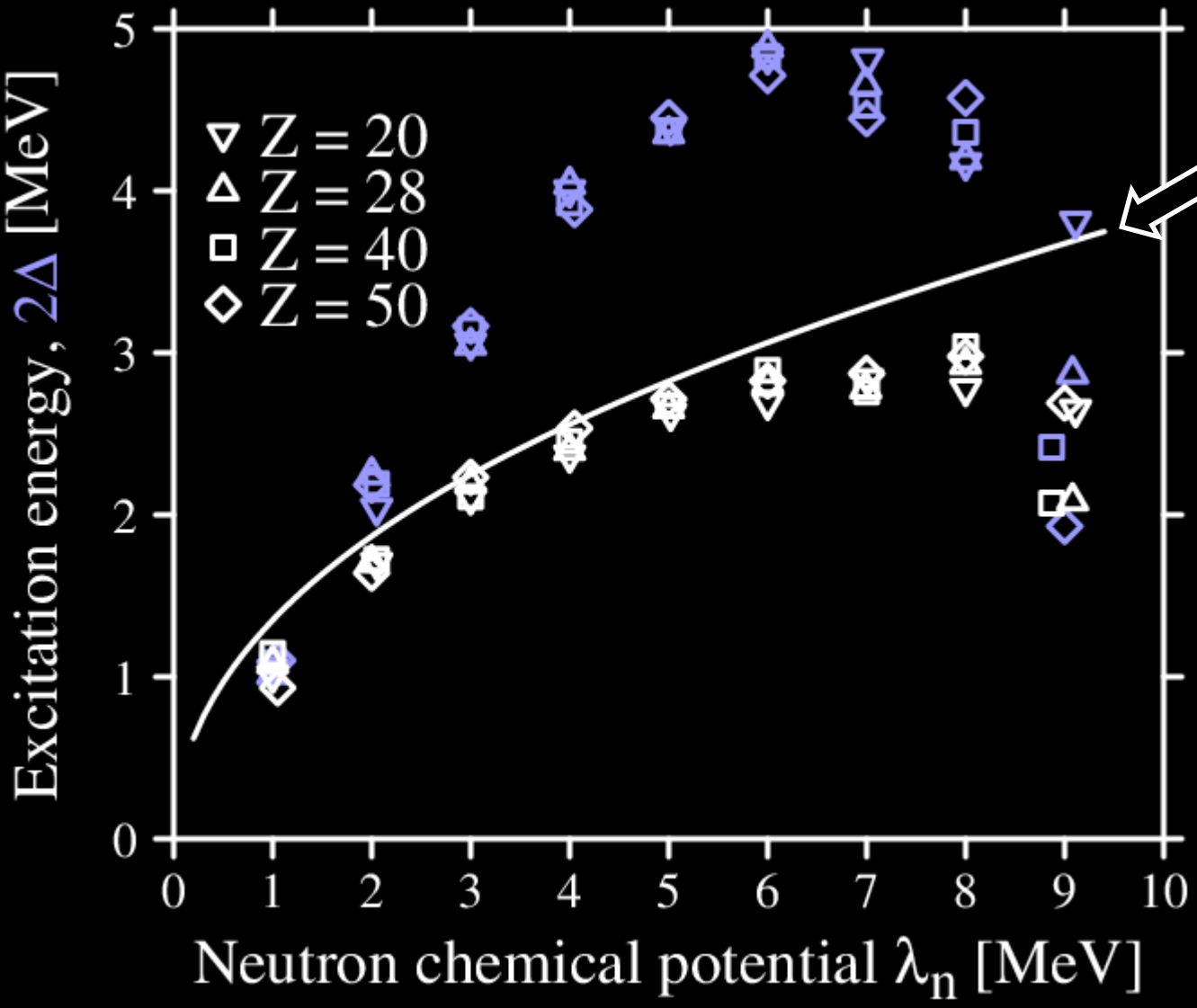
Coupling of AB mode & lattice phonon





At high λ_n, AB mode looks to couple displacement mode.

λ_n-, Z-dependence of AB mode



Hydrodynamics calc.

Summary

Anderson-Bogoliubov mode (superfluid phonon) in inner crust of neutron stars,
using the nuclear density functional theory,
treating explicitly the presence of nuclear cluster,
under the Wigner-Seitz approximation.

- AB mode appears in inner crust in low energy region below 2Δ.
- AB mode does not penetrate nuclear cluster.
- At high λ_n, AB mode looks to couple displacement motion.
- Z do not effect energy of AB mode.

Perspective

- Quantitative evaluation of AB mode - lattice phonon coupling.
- Monopole mode, quadrupole mode.
- Impact on observables in neutron star cooling process.