Nuclear Emergence/Collective Behavior

Overarching question:

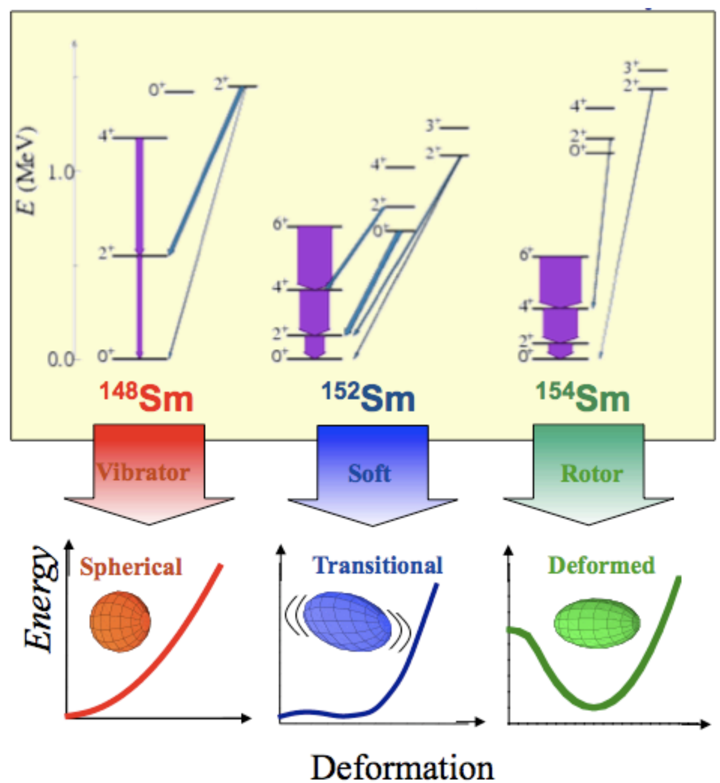
“How does subatomic matter organize itself and what phenomena emerge?”

Characterization of phases

ground state, excitations, collective modes

- In bulk matter
- In finite systems (quantum phase transitions)

Characterization of individual phases is the first step towards understanding the phase diagram. The characterization of transitions between phases, critical points, triple points… is a true challenge!



Nuclear deformation: spontaneous symmetry breaking

Molecular physics: Jahn-Teller effect 1937

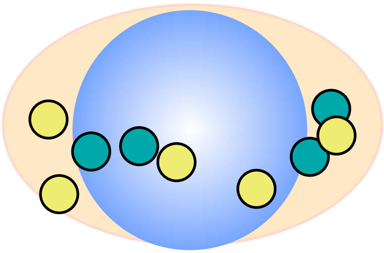
Any configuration of atoms or ions (except for a linear chain) can develop a stable symmetry-breaking deformation provided the coupling between degenerate electronic excitations and collective molecular vibrations is strong.

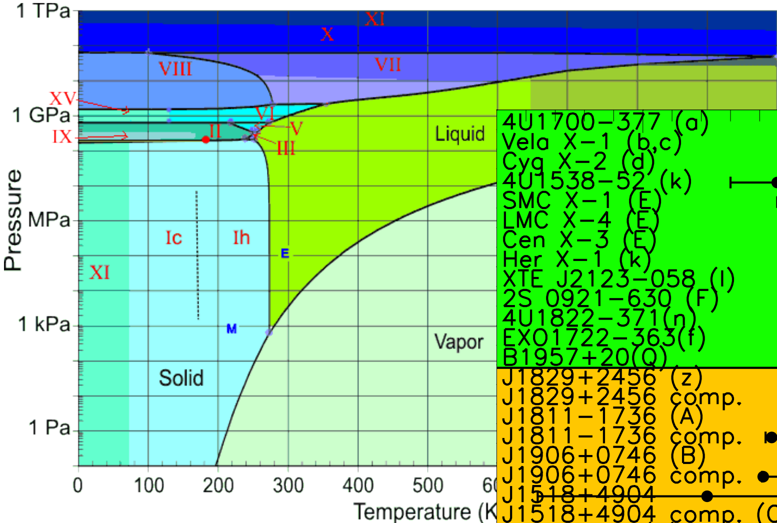
Nuclear physics: Bohr-Mottelson 1952-53

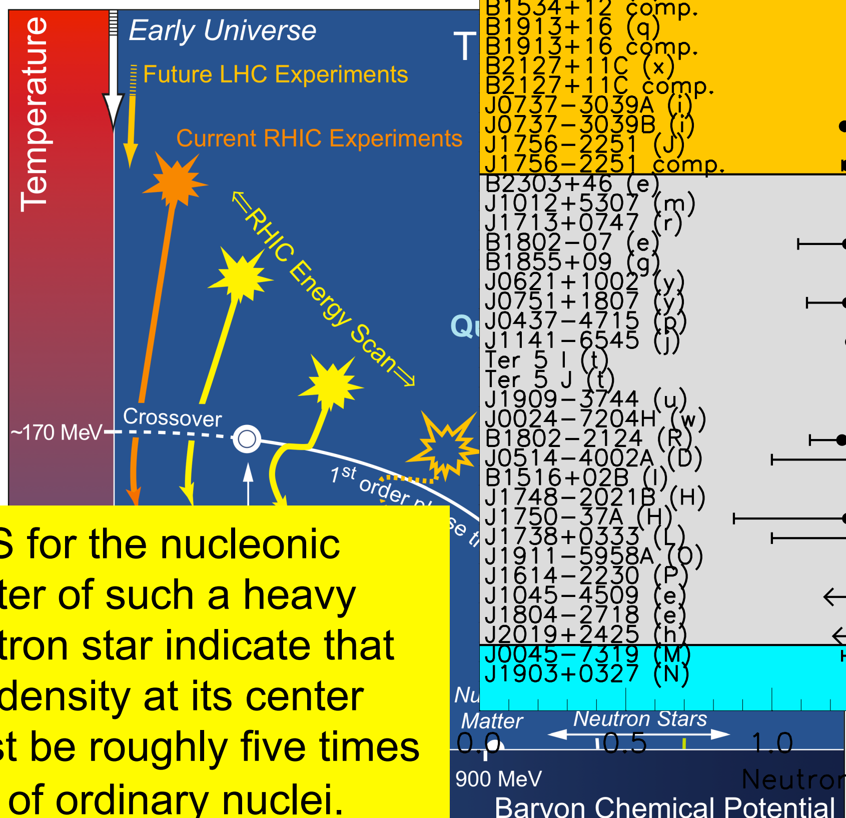
Any nuclear configuration can develop a stable symmetry-breaking deformation provided the coupling between degenerate single-nucleonic excitations and collective nuclear modes is strong.

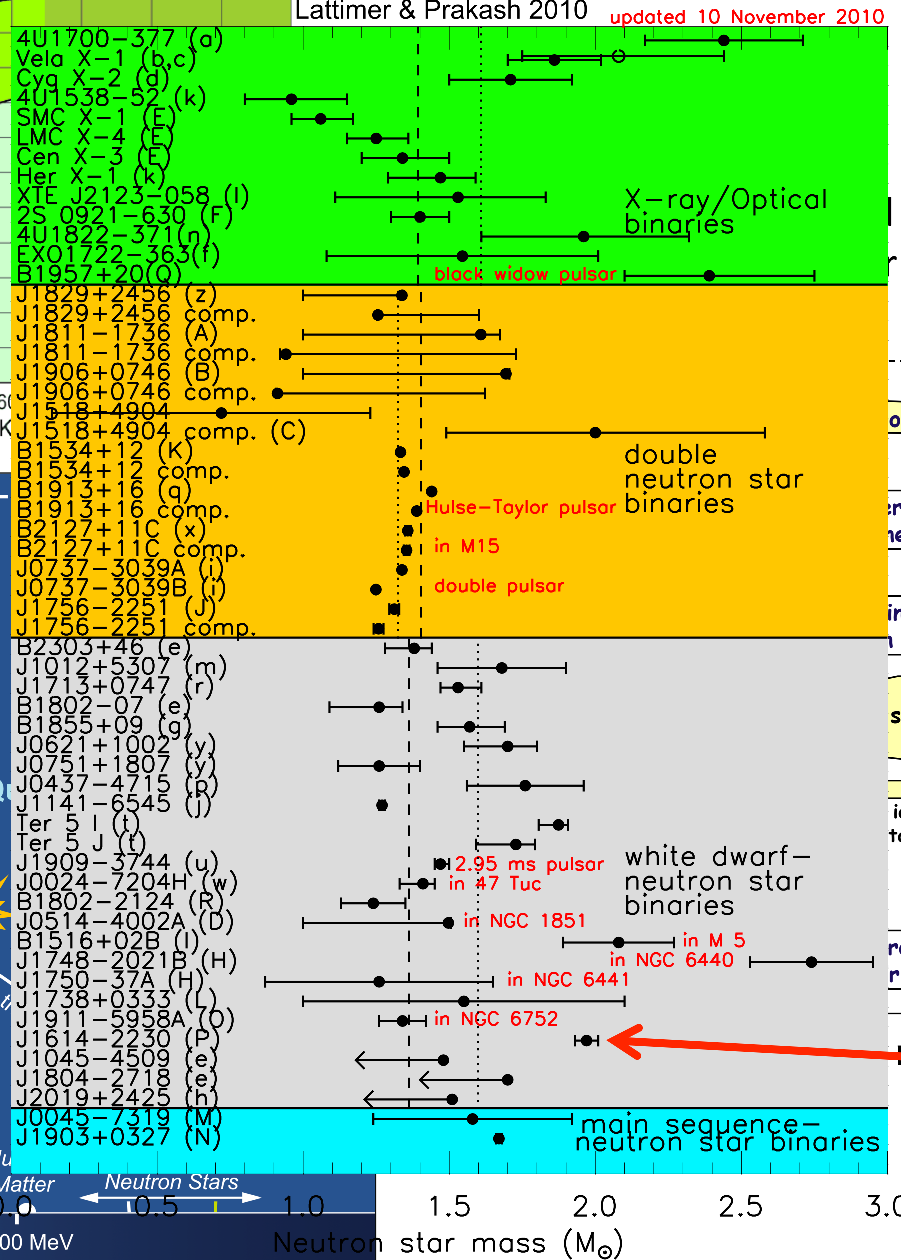
The unified model.
Particle vibration coupling

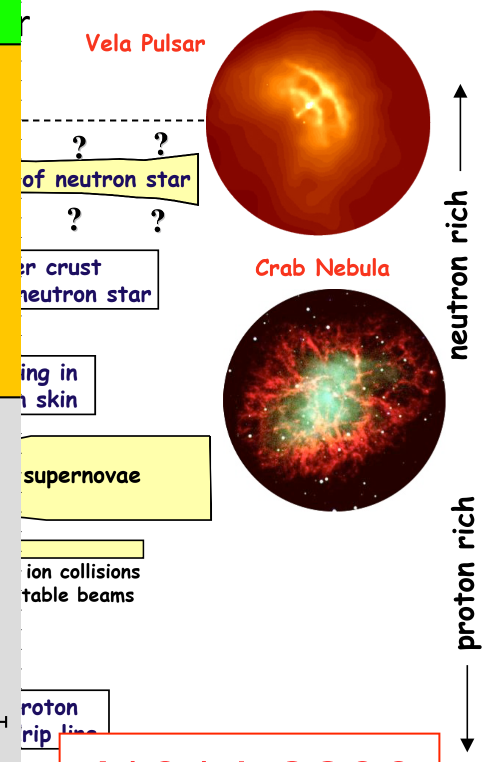
$$V_{\text{int}} = -\kappa(r)\sum_{\lambda\mu}\alpha_{\lambda\mu}Y_{\lambda\mu}(\Omega)$$







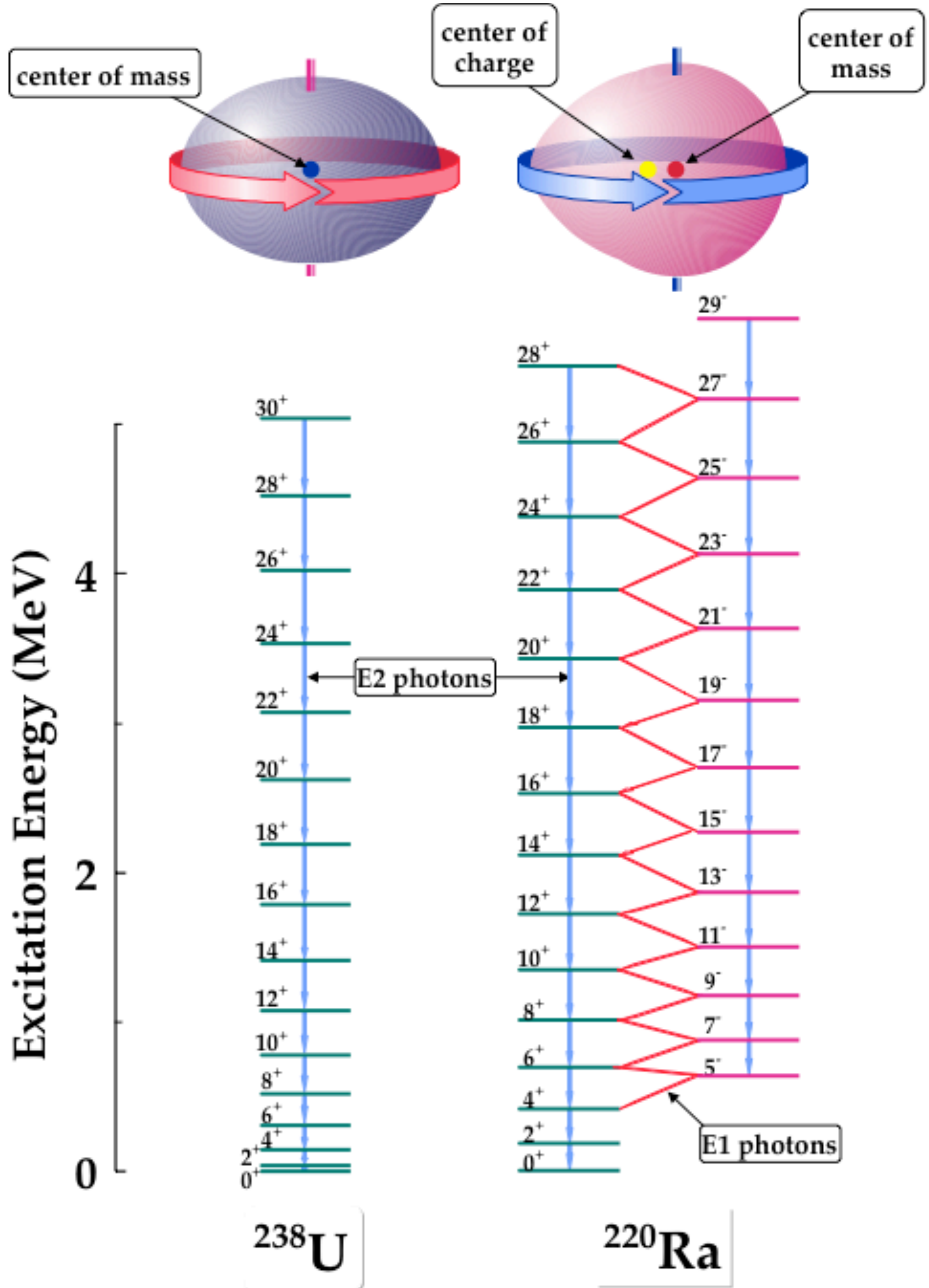


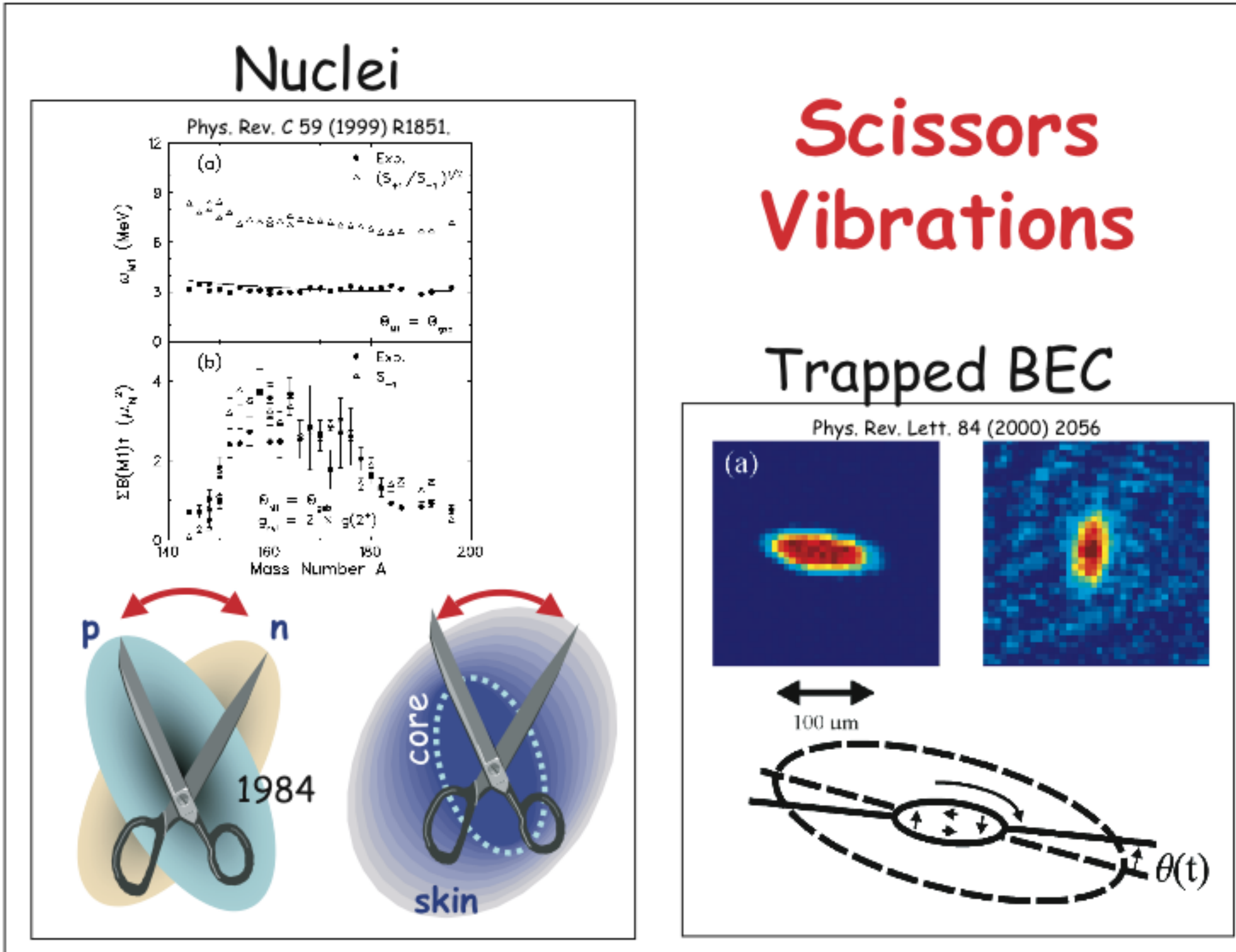


J1614-2230
1.97 ± 0.04

EOS for the nucleonic matter of such a heavy neutron star indicate that the density at its center must be roughly five times that of ordinary nuclei.

Nuclear Rotations

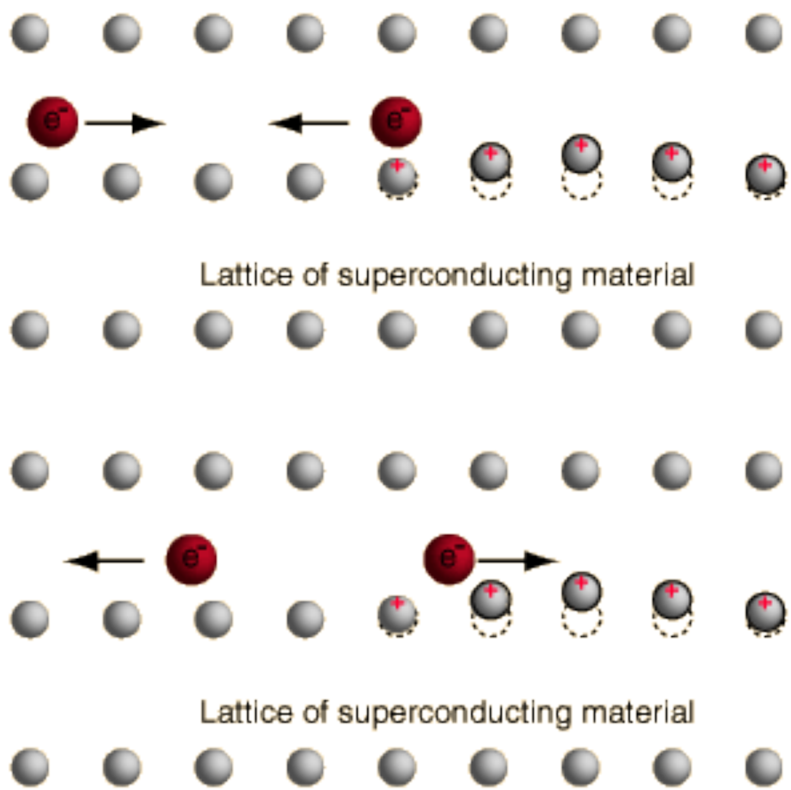




Nuclei
Scissors
Vibrations
Phys. Rev. C 59 (1999) R1851.
(a)
Exp.
Mass Number A
(b)
Exp.
p
n
1984
core
skin
Trapped BEC
Phys. Rev. Lett. 84 (2000) 2056
(a)
100 um
θ(t)

BCS Pairing

BCS theory of superconductivity was proposed by Bardeen, Cooper, and Schrieffer ("BCS") in 1957 (Nobel Prize in 1972).

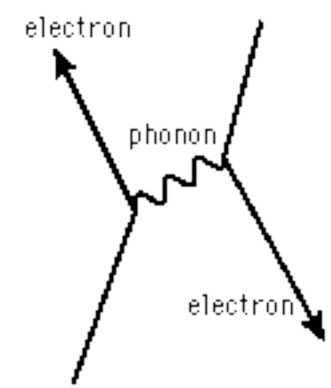


A passing electron attracts the lattice, causing a slight ripple toward its path

Another electron passing in the opposite direction is attracted to that displacement

http://hyperphysics.phy-astr.gsu.edu/hbase/solids/coop.html

Cooper pair

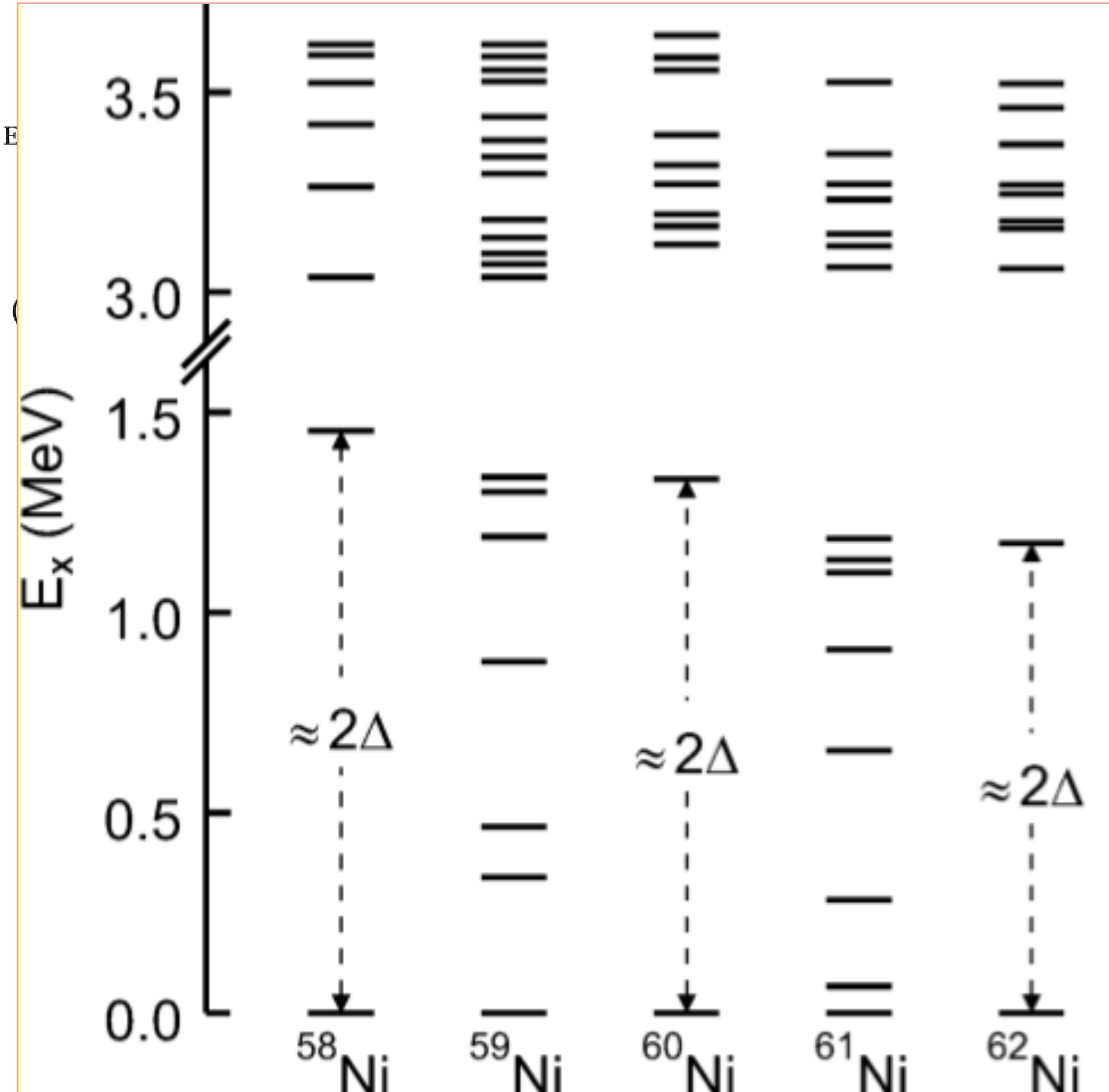


Energies of first excited states: even-even vs. odd-A nuclei

FIG. 1. Energies of first excited intrinsic states in deformed nuclei, as a function of the mass number. The experimental data may be found in *Nuclear Data Cards* [National Research Council, Washington, D. C.] and detailed references will be contained in reference 1 above. The solid line gives the energy $\delta/2$ given by Eq. (1), and represents the average distance between intrinsic levels in the odd-A nuclei (see reference 1).

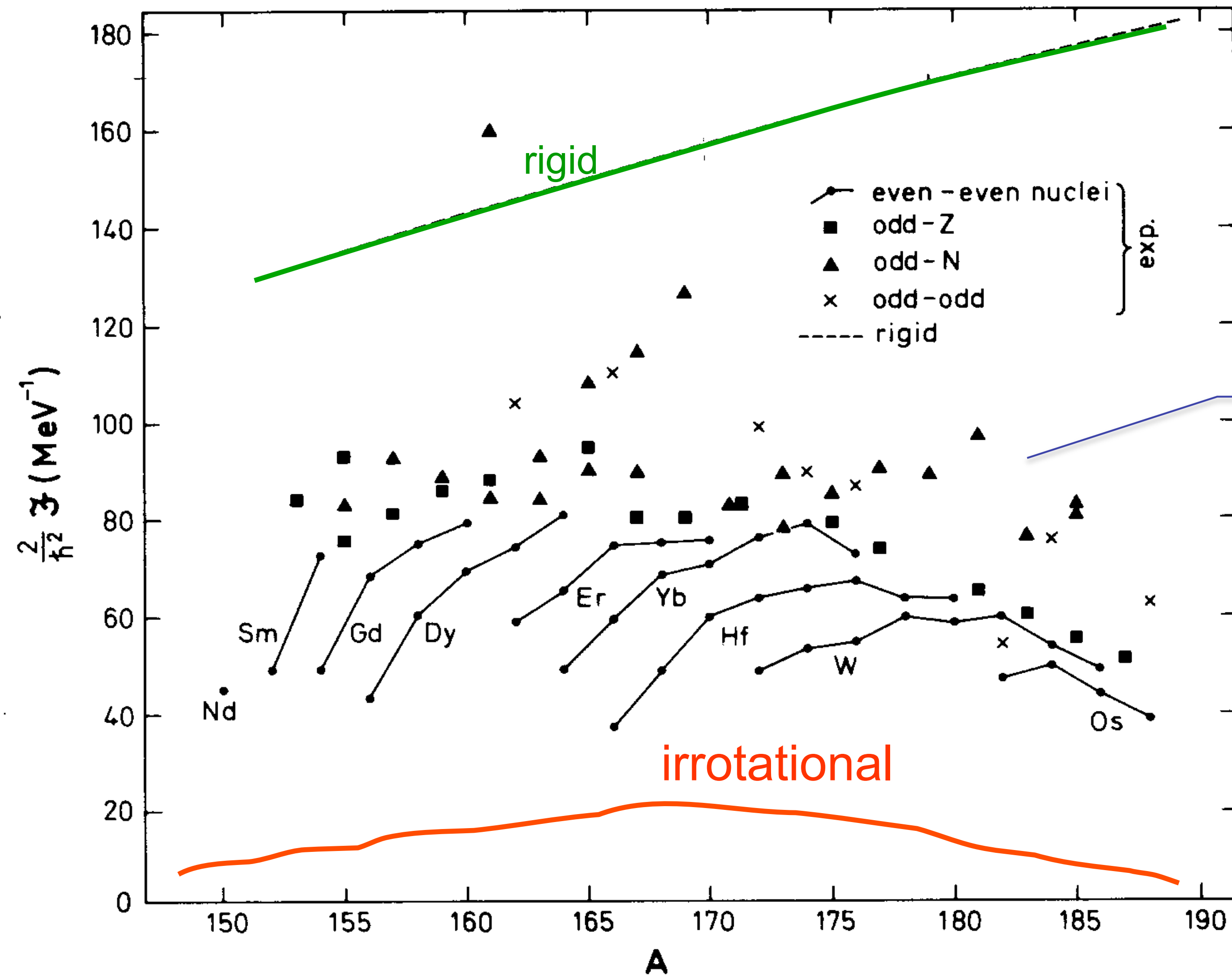
The figure contains all the available data for nuclei with $150<A<190$ and $228<A$. In these regions the nuclei are known to possess nonspherical equilibrium shapes, as evidenced especially by the occurrence of rotational spectra (see, e.g., reference 2). One other such region has also been identified around $A=25$; in this latter region the available data on odd-A nuclei is still represented by Eq. (1), while the intrinsic excitations in the even-even nuclei in this region do not occur below 4 Mev.

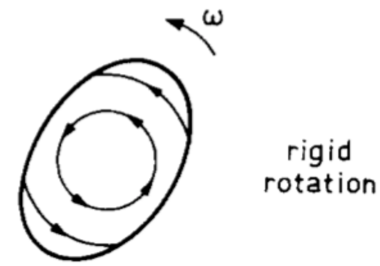
We have not included in the figure the low lying $K=0$ states found in even-even nuclei around Ra and Th. These states appear to represent a collective odd-parity oscillation.



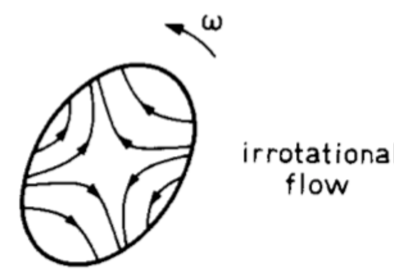
Ground-state nuclear moments of inertia

Reduction of moment of inertia due to BCS pairing. Migdal (59)





well reproduced by cranked HFB calculations



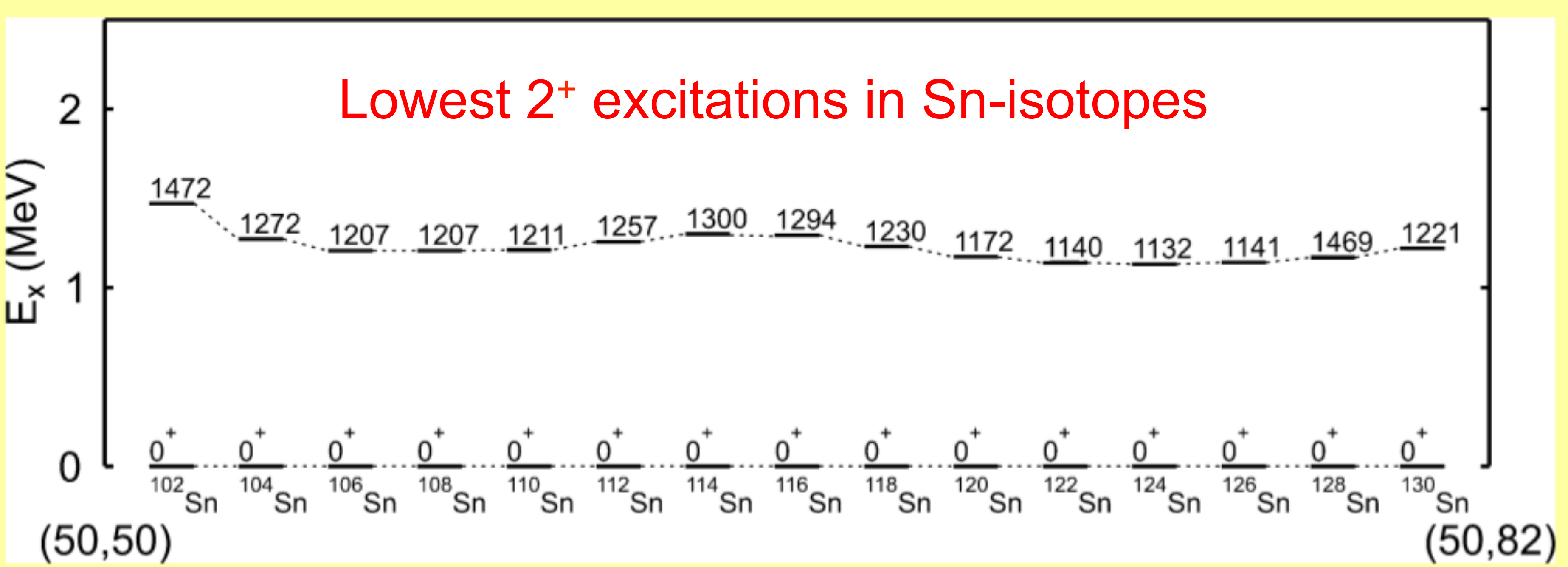
Nuclear moments of inertia at *T*=0 lie between the superfluid and normal limits

Seniority excitations

$$|\text{g.s.}\rangle = |\nu = 0; J = 0\rangle = (P_j^+)^{n/2}|\Phi_0\rangle$$

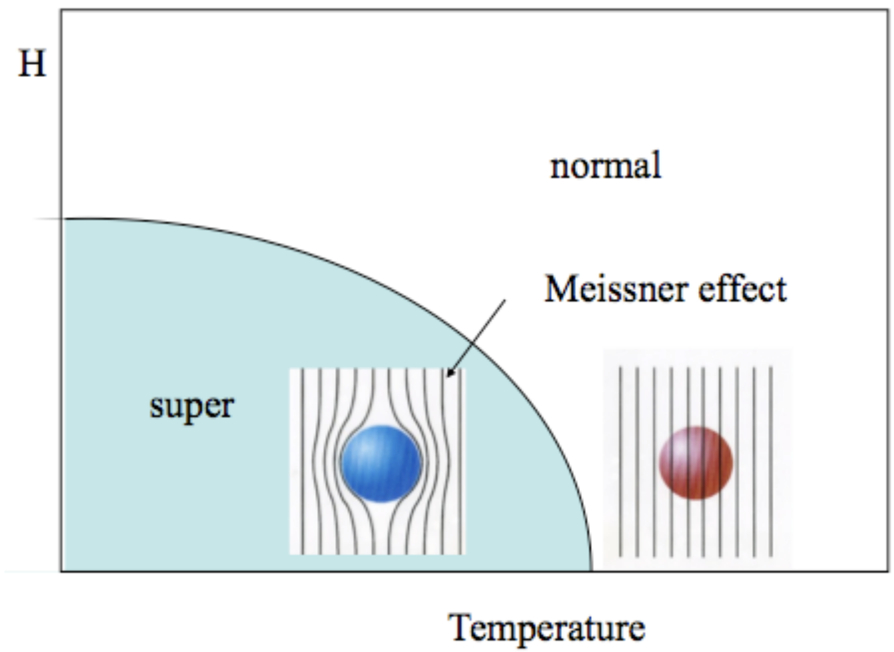
$$|\nu = 2; JM\rangle = (P_j^+)^{(n-2)/2}A^+(j^2JM)|\Phi_0\rangle$$

$$E(n,\nu = 2) - E(n,\nu = 0) = G\Omega$$



Polarization → Angular momentum
Vortices → Broken pairs

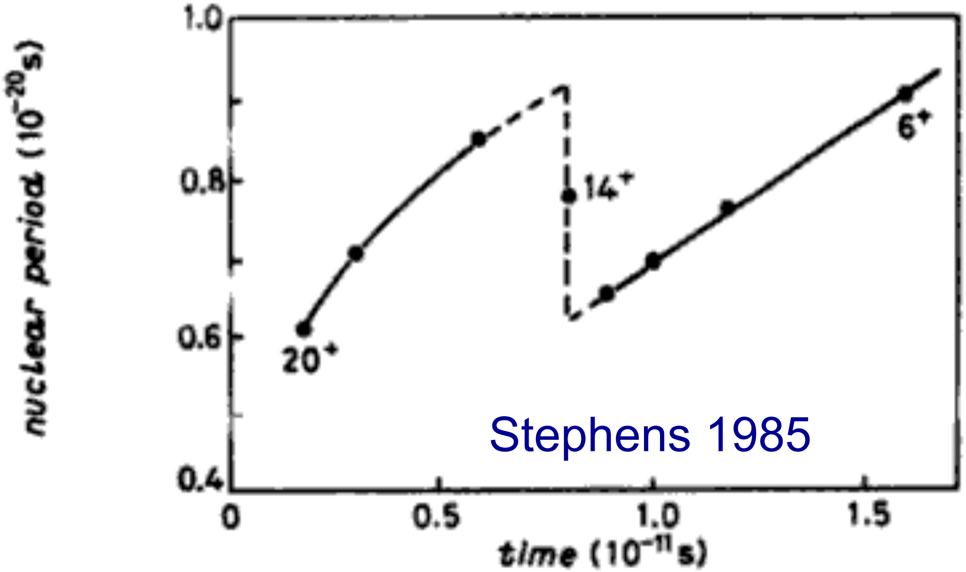
- Nuclear Meissner effect (Mottelson-Valatin 1960)
- Nuclei are Type-II superconductors (Birbrair 1971)
- Backbending and pair decoupling (Stephens 1972)

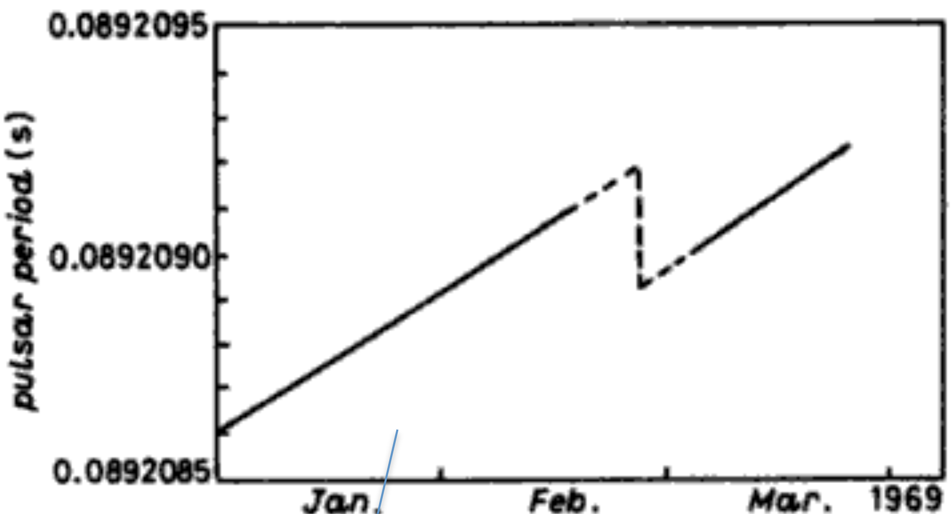


$$H \longrightarrow \omega$$

$$M \longrightarrow J$$

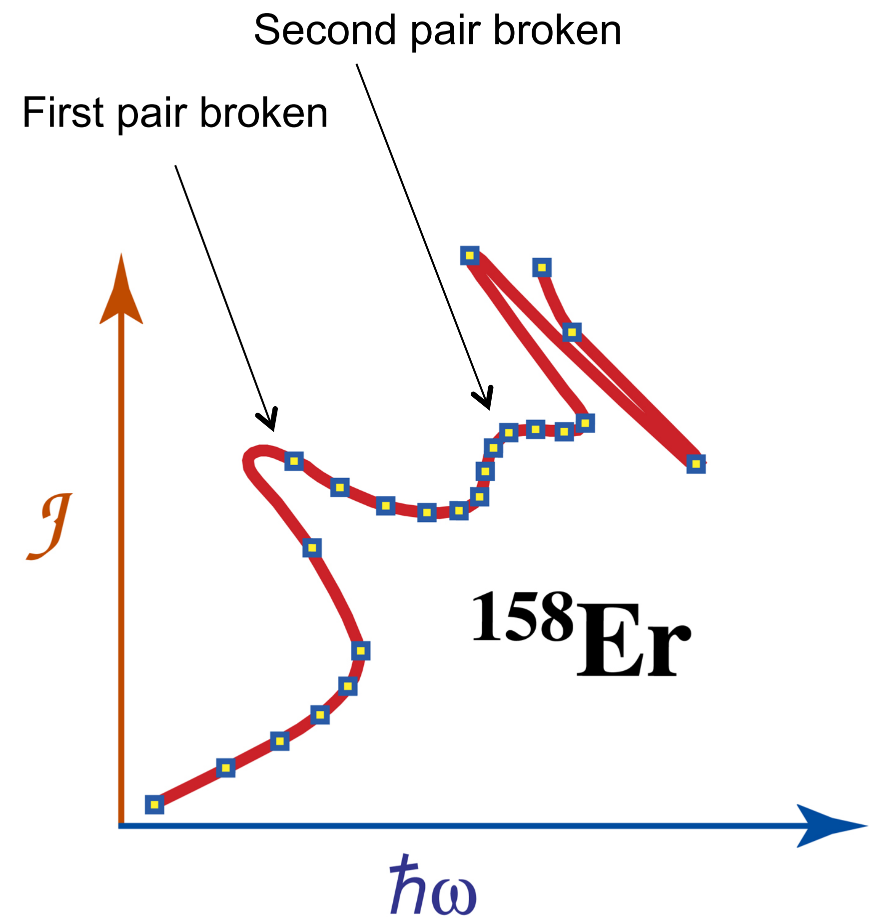
$$\hat{H}^{\omega} = \hat{H} - \boldsymbol{\omega}\hat{\boldsymbol{J}}$$

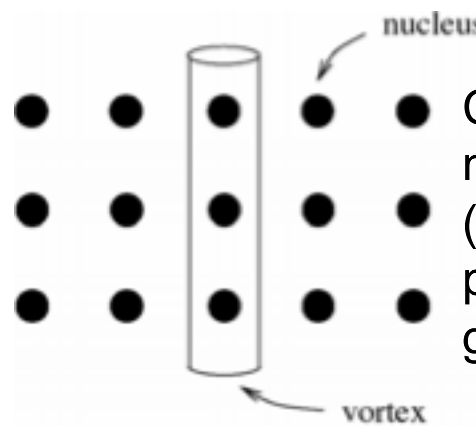




Pulsar glitches
vortices in the flow pattern?

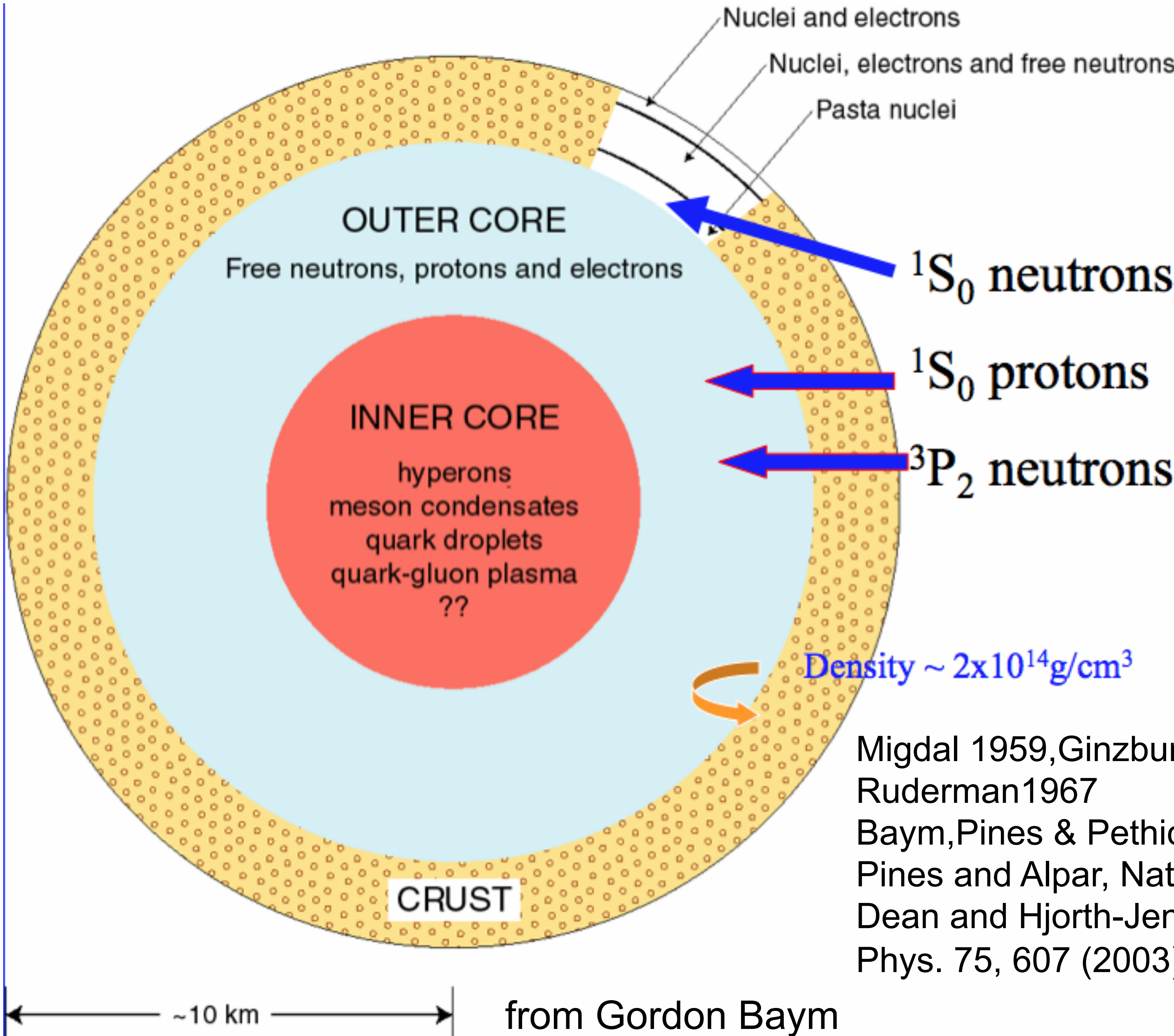
Anderson and Itoh, 1975





Collective outward motion of many (~10^{14}) vortices produces large glitch

Superfluidity in neutron stars



Migdal 1959,Ginzburg&Kirshnits1964
Ruderman1967
Baym,Pines & Pethick,1969
Pines and Alpar, Nature 316, 27 (1985)
Dean and Hjorth-Jensen,, Rev. Mod. Phys. 75, 607 (2003)

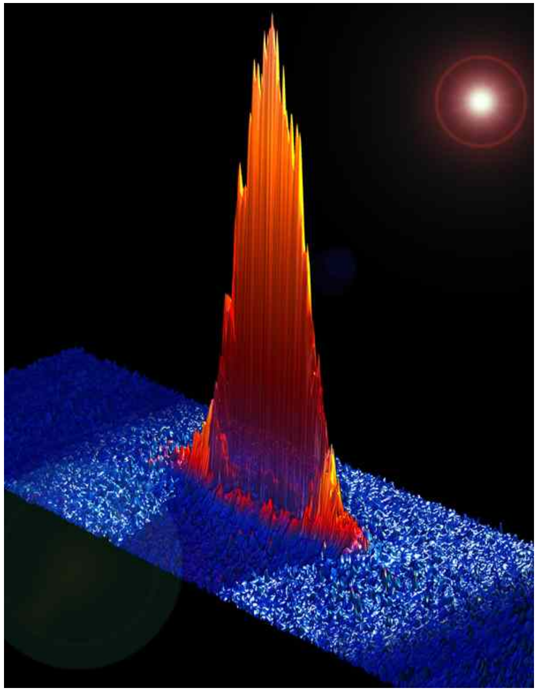
from Gordon Baym

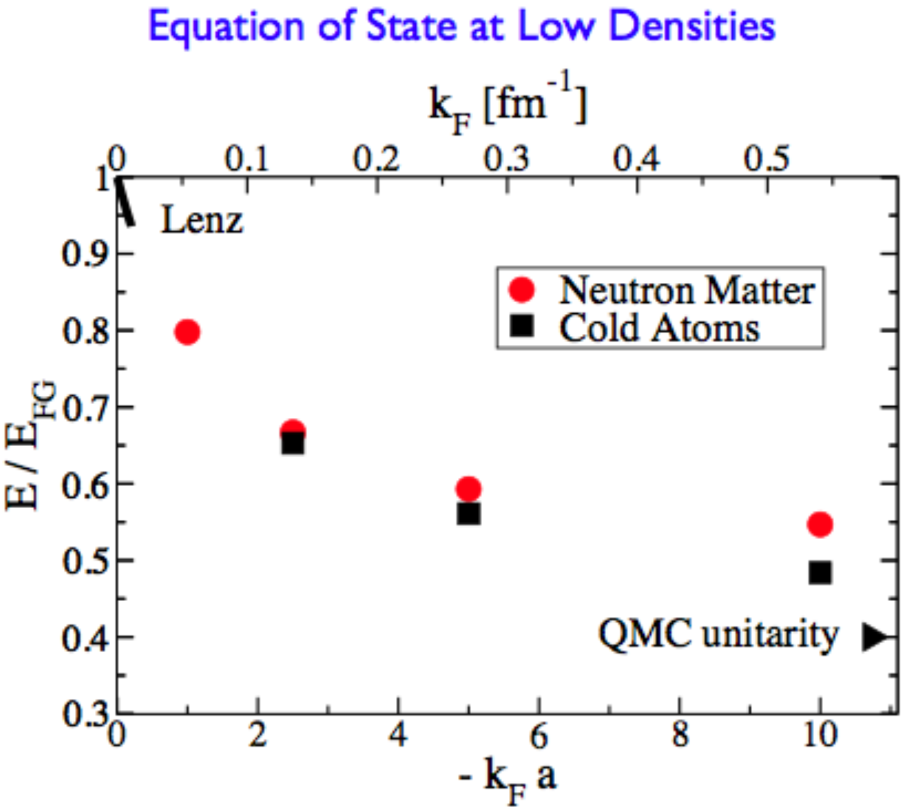
Low-density regime of neutron EOS

Dilute fermion matter:

- **strongly correlated (pairing)**
- **very large scattering length (unitary limit)**

- Low-density neutron matter
- Cold fermions in traps





Gezerlis and Carlson, Phys. Rev. C 77, 032801(R) (2008)

- Connections to nucleonic pairing in nuclei and neutron stars
- Connections to color superconductivity in quark matter