Nuclear Emergence/Collective Behavior

Overarching question:

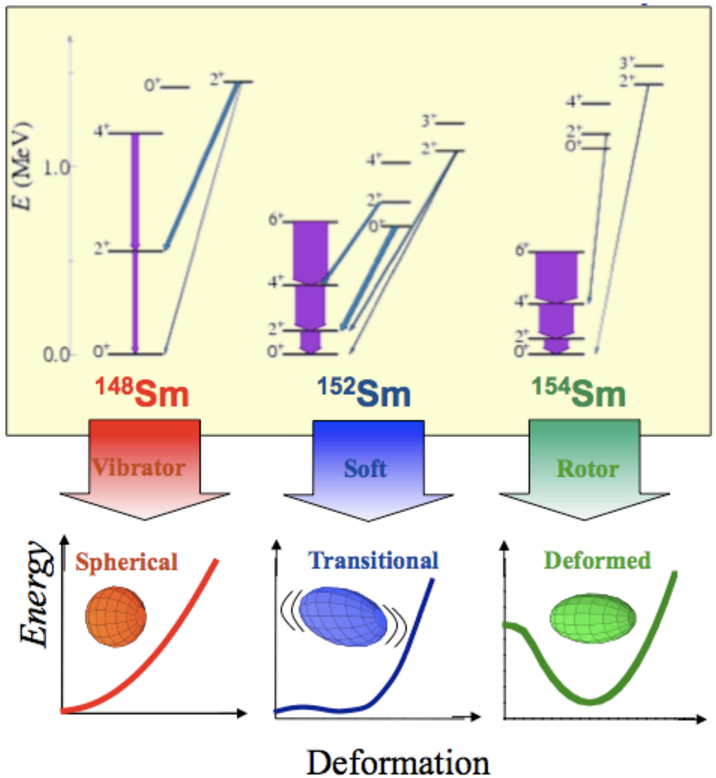
“How does subatomic matter organize itself and what phenomena emerge?”

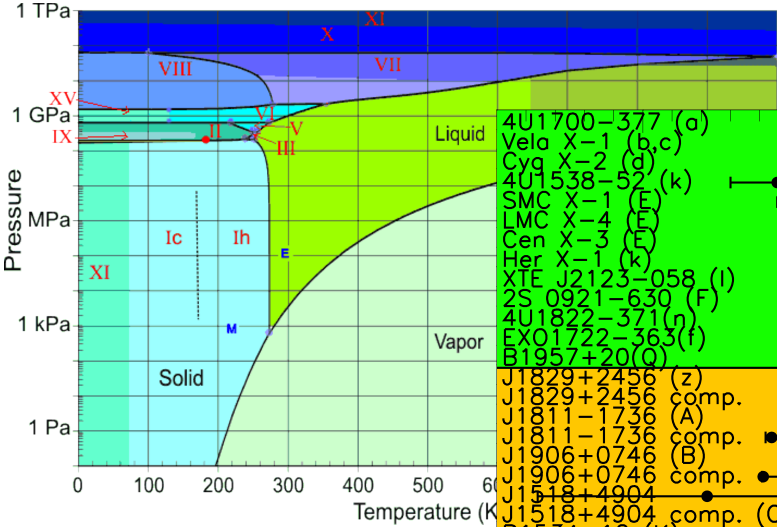
Characterization of phases

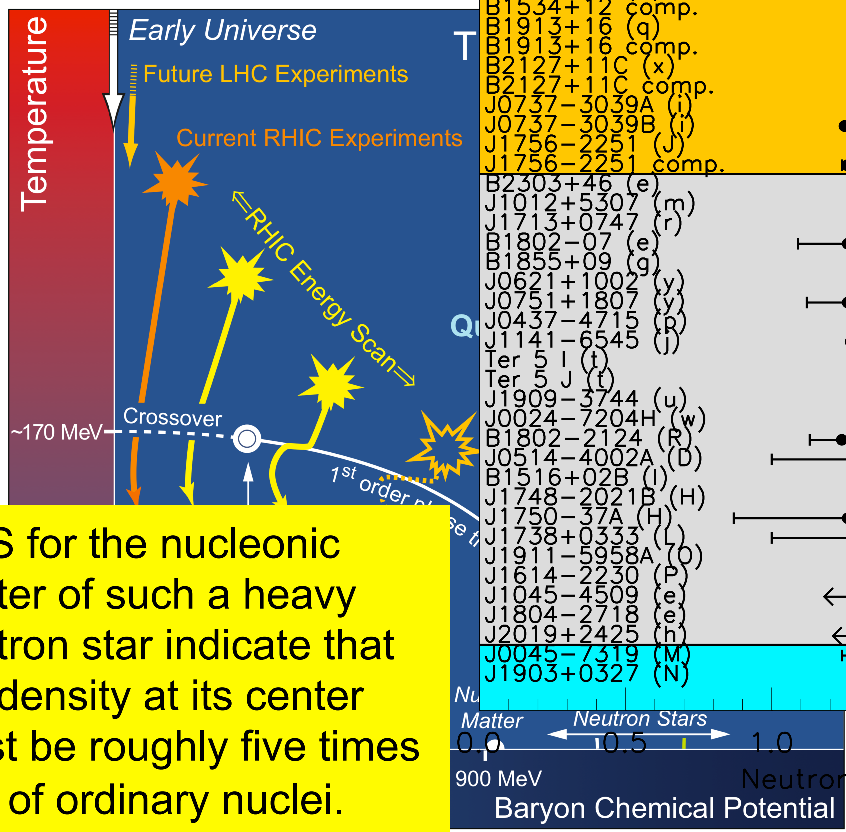
ground state, excitations, collective modes

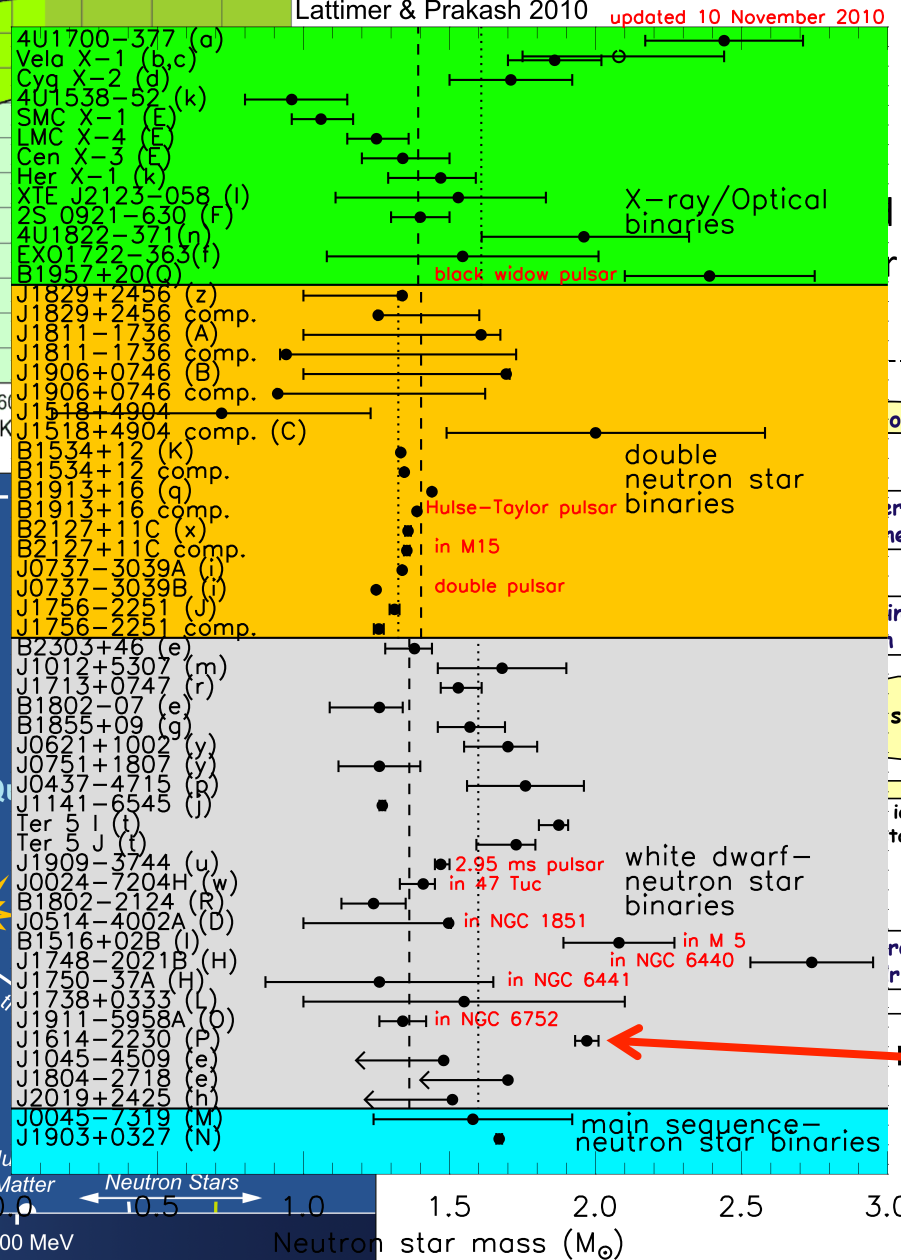
- In bulk matter
- In finite systems (quantum phase transitions)

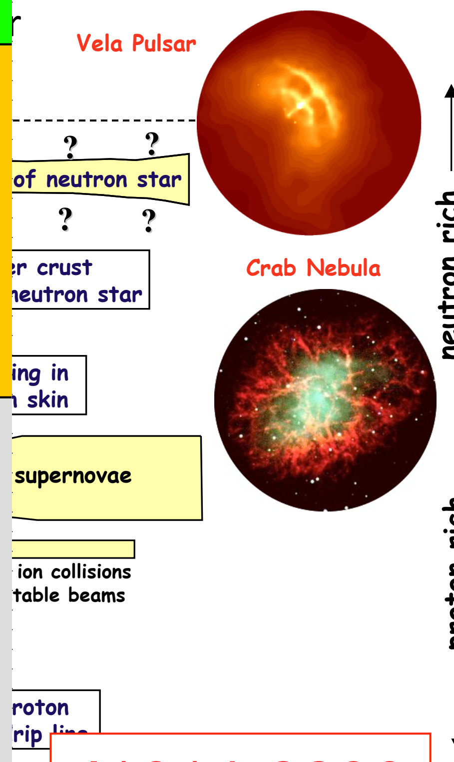
Characterization of individual phases is the first step towards understanding the phase diagram. The characterization of transitions between phases, critical points, triple points… is a true challenge!







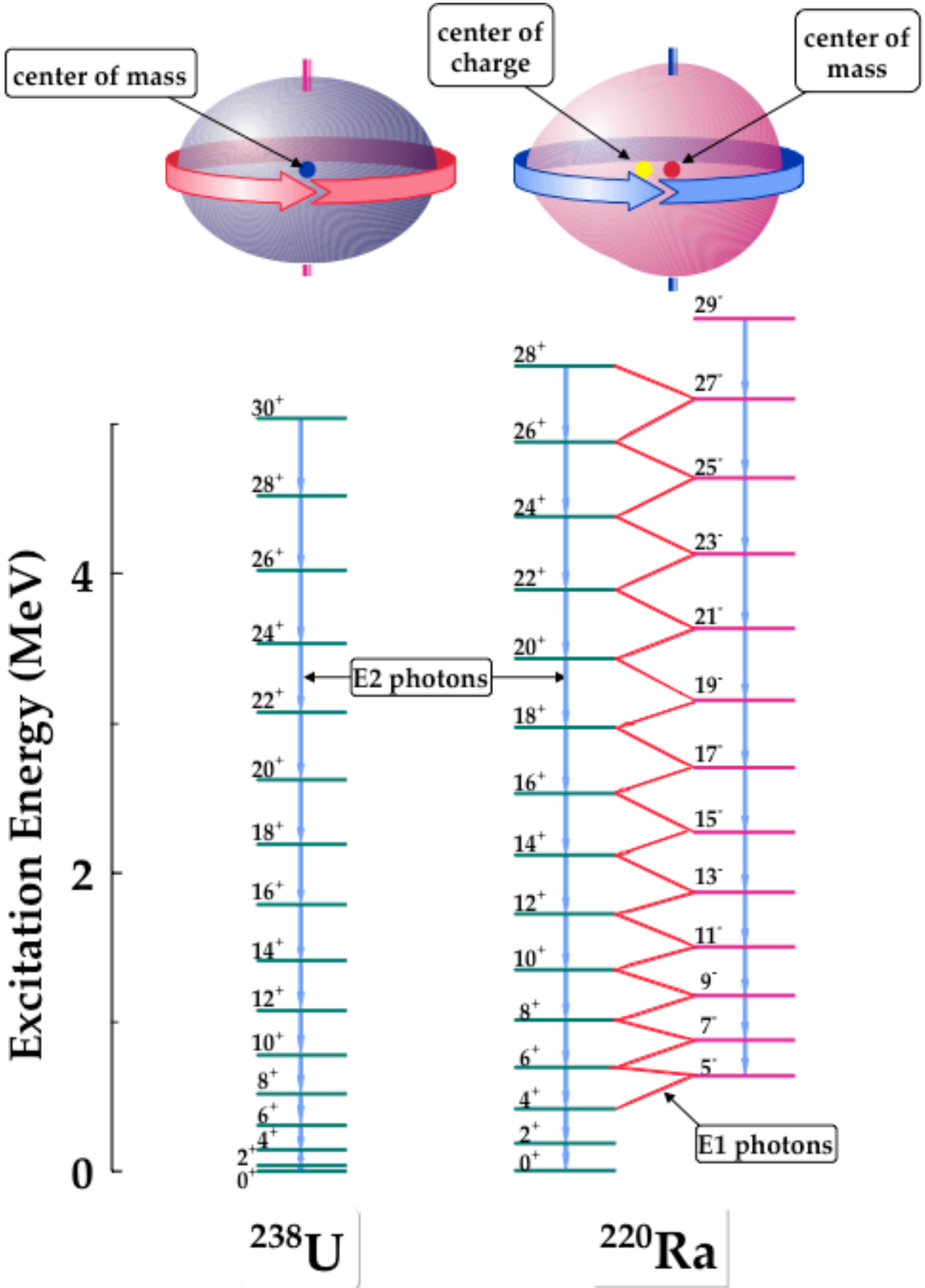




J1614-2230
1.97 ± 0.04

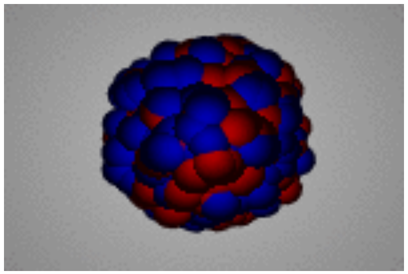
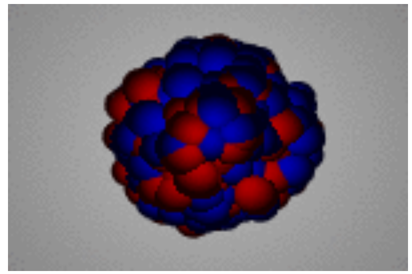
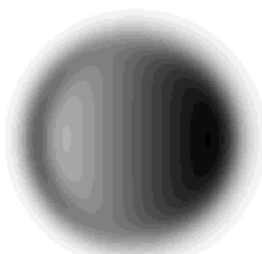
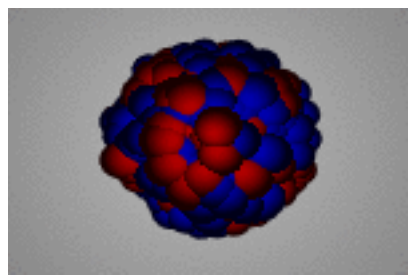
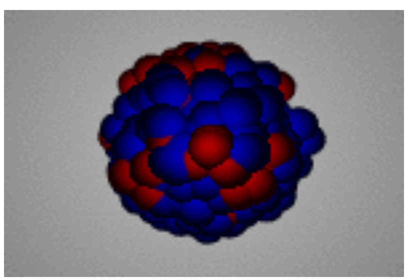
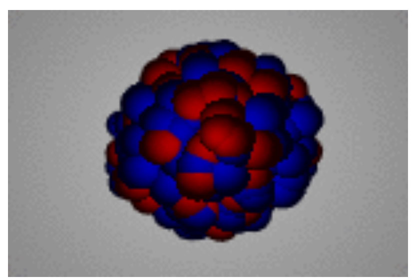
EOS for the nucleonic matter of such a heavy neutron star indicate that the density at its center must be roughly five times that of ordinary nuclei.

Nuclear Rotations



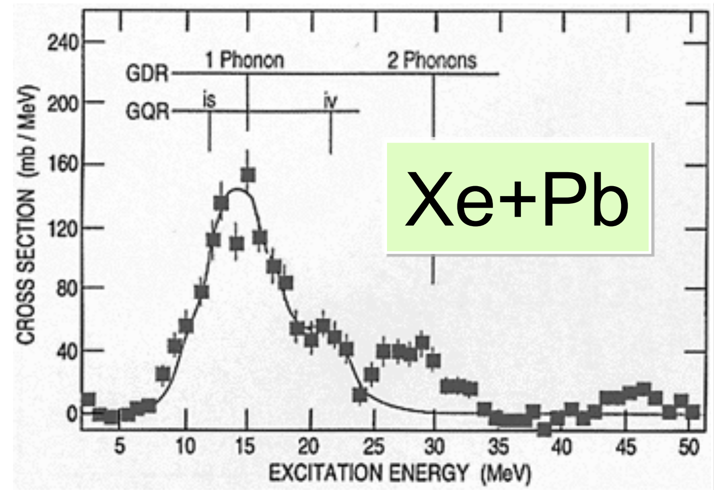
Nuclear collective motion

Giant nuclear vibrations (electric)

	Isoscalar p-n in phase	Isovector p-n out of phase
Monopole (GMR)		
Dipole (GDR)	 squeezing mode	
Quadrupole (GQR)		

by A. Krasznahorkay

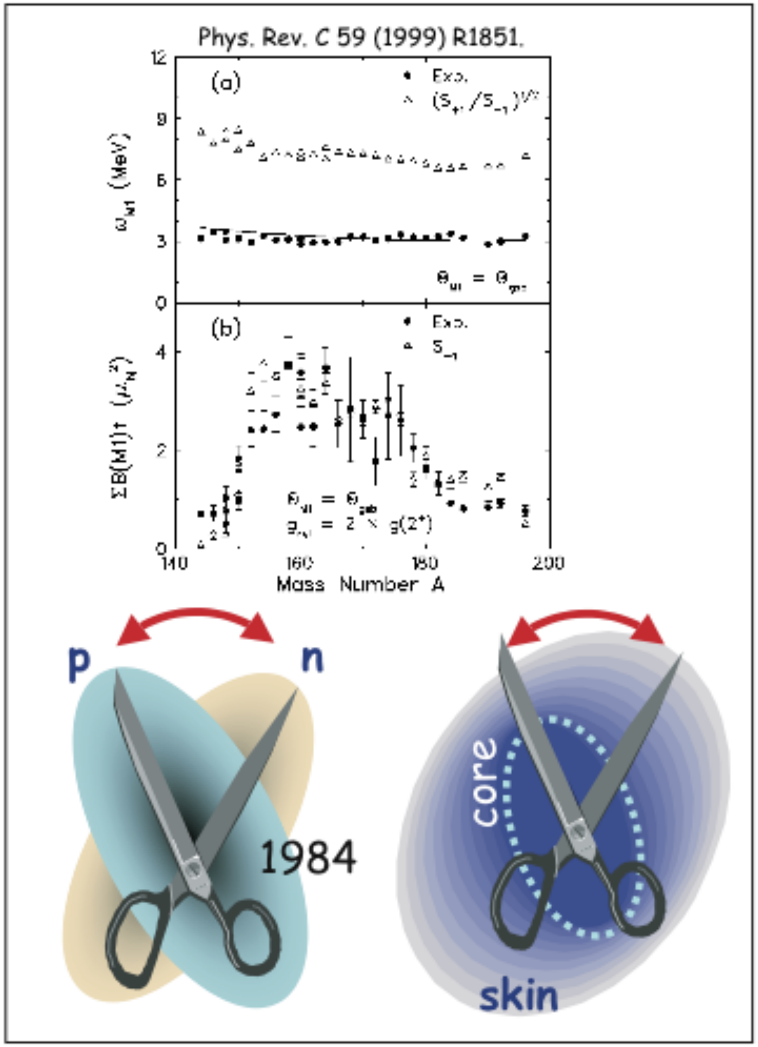
Nuclear response to external force



- Dipole polarizability and skins
- Isoscalar dipole and EDM
- Monopole modes, radii and beta decay
- Multipole modes and fission
- Scissors (magnetic) modes

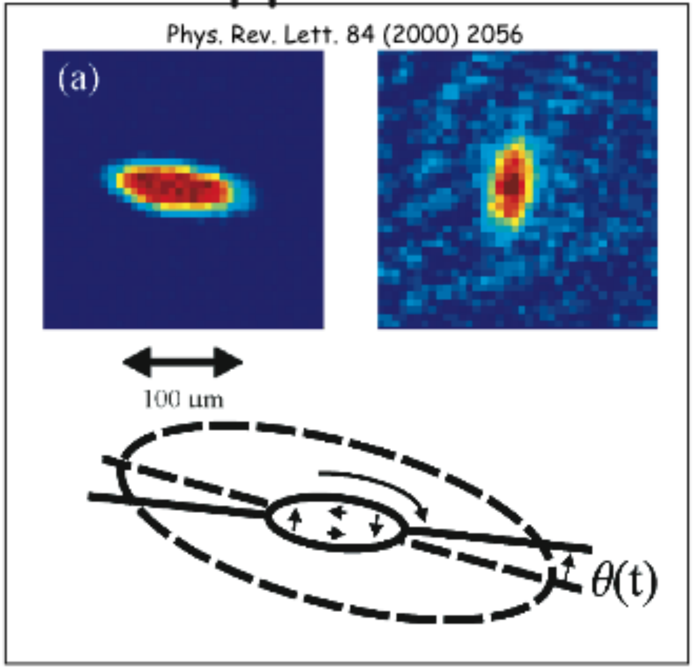
Giant nuclear resonances (magnetic)

Nuclei



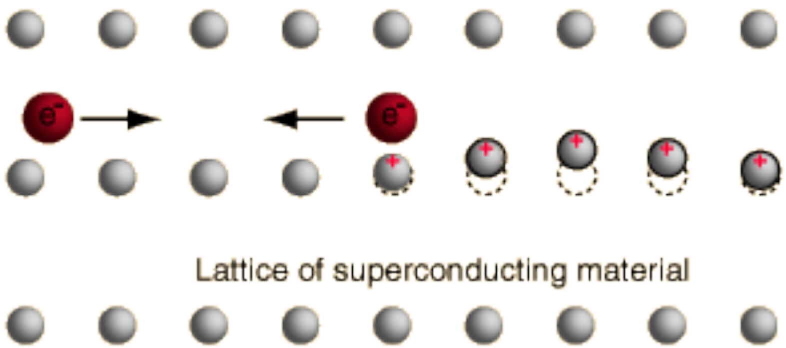
Scissors Vibrations

Trapped BEC

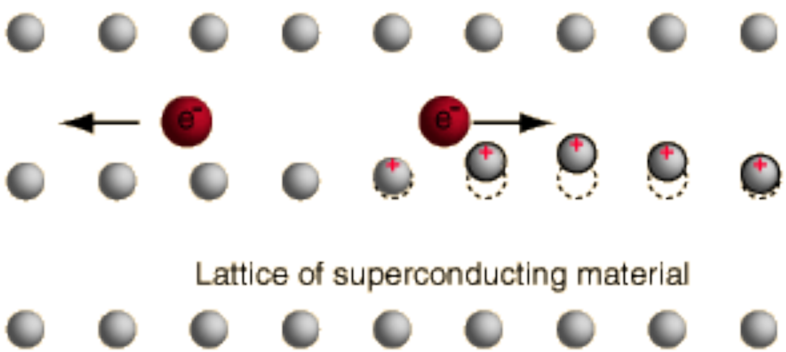


BCS Pairing

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



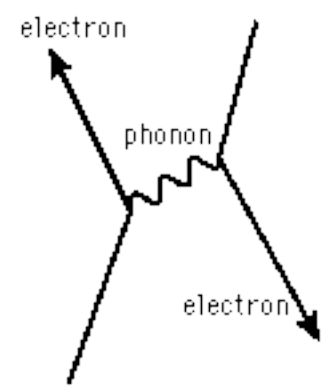
A passing electron attracts the lattice, causing a slight ripple toward its path



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

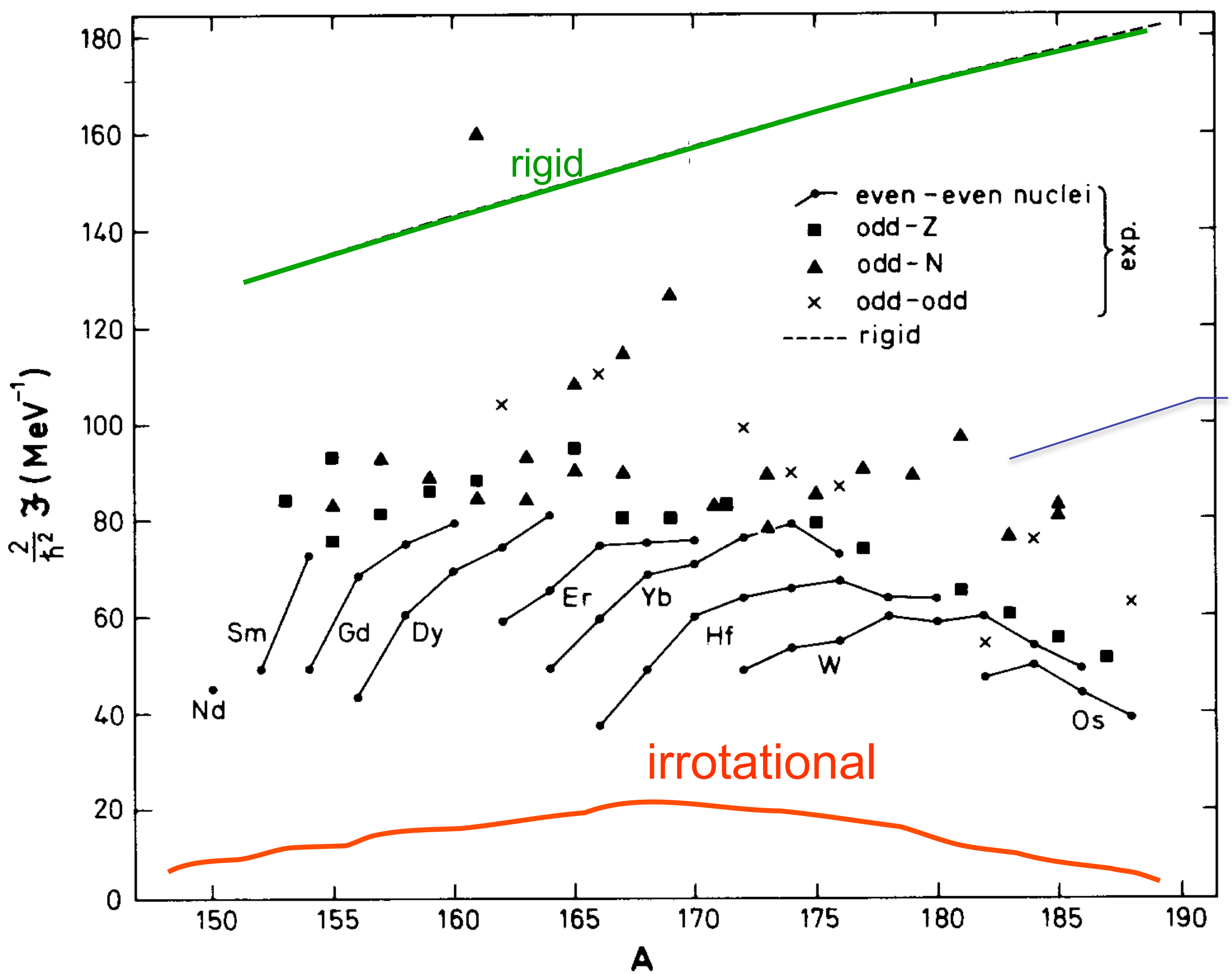
http://hyperphysics.phy-astr.gsu.edu/hbase/solids/coop.html

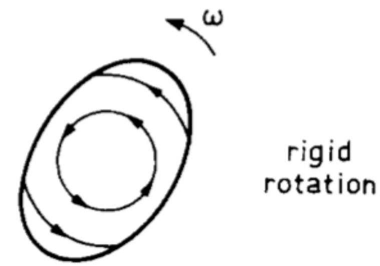
Cooper pair



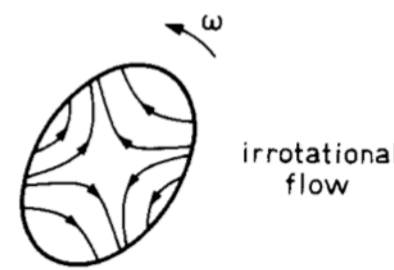
Ground-state nuclear moments of inertia

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





well reproduced by cranked HFB calculations



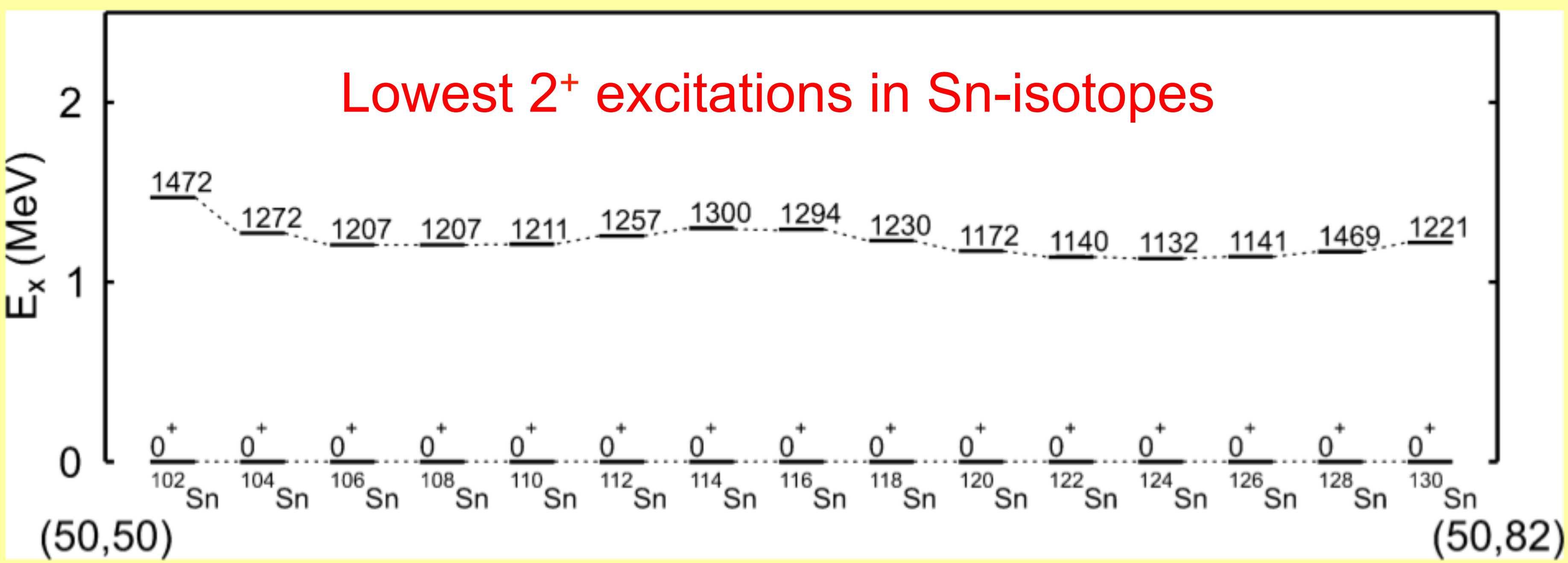
Nuclear moments of inertia at T=0 lie between the superfluid and normal limits

Seniority excitations

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

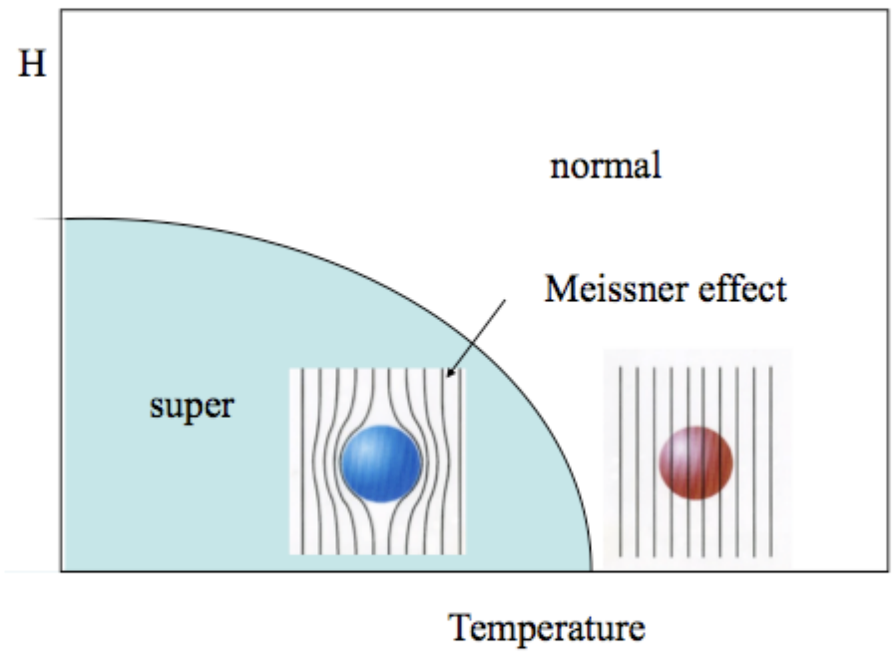
$$|\nu = 2; JM\rangle = (P_j^+)^{(n-2)/2} A^+(j^2 JM)|\Phi_0\rangle$$

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



Polarization → Angular momentum
Vortices → Broken pairs

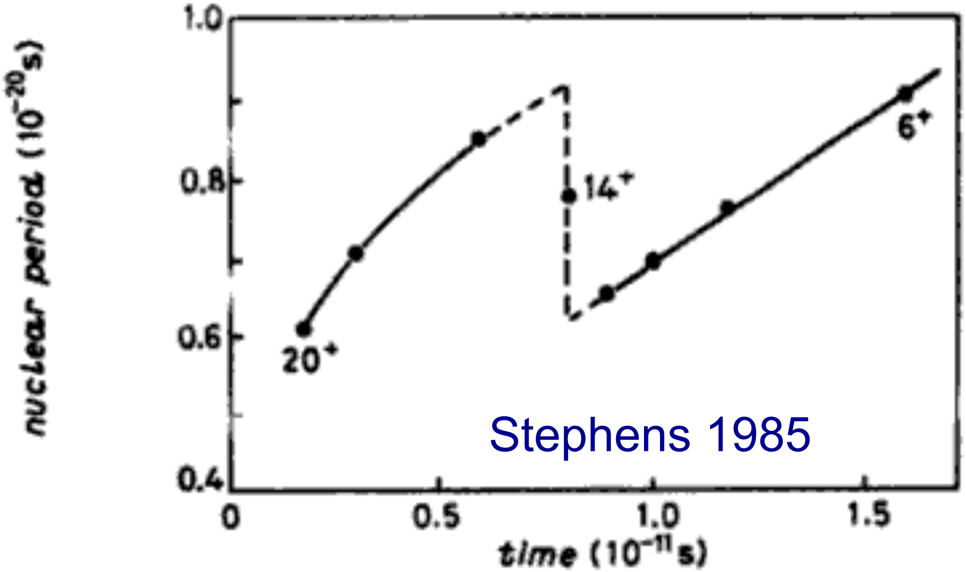
- Nuclear Meissner effect (Mottelson-Valatin 1960)
- Nuclei are Type-II superconductors (Birbrair 1971)
- Backbending and pair decoupling (Stephens 1972)

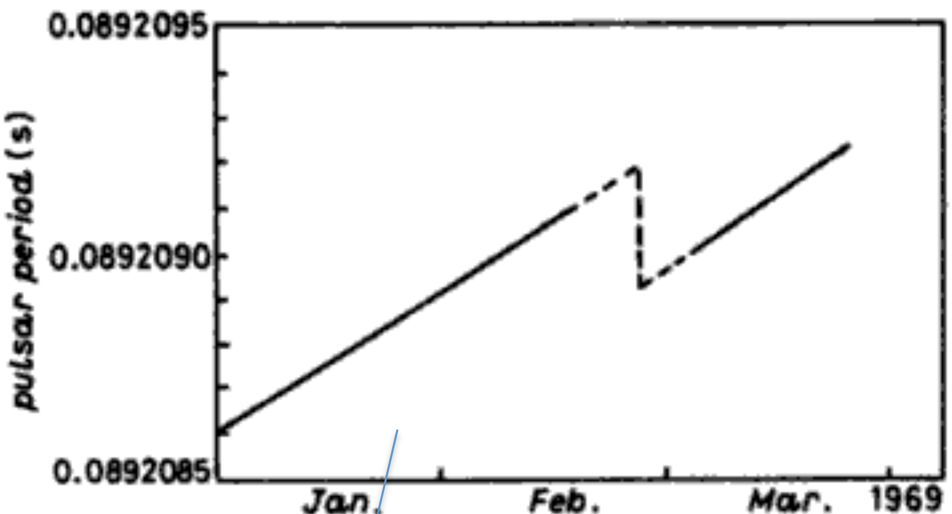


$$H \longrightarrow \omega$$

$$M \longrightarrow J$$

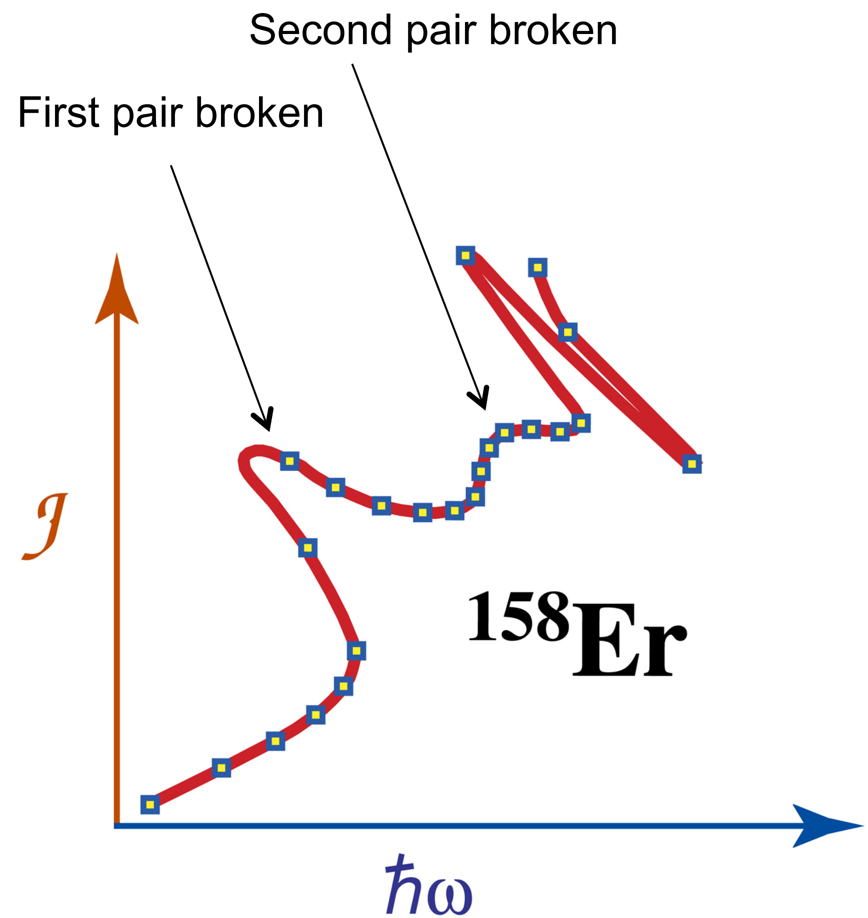
$$\hat{H}^{\omega} = \hat{H} - \boldsymbol{\omega} \hat{\boldsymbol{J}}$$

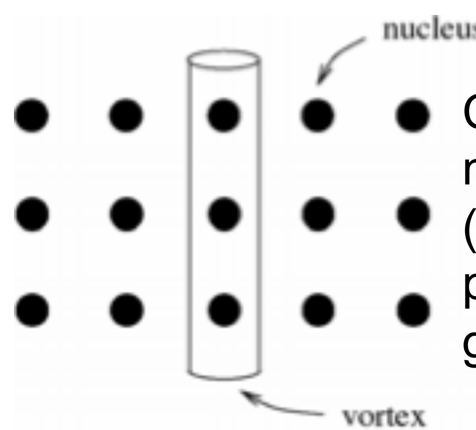




Pulsar glitches
vortices in the flow pattern?

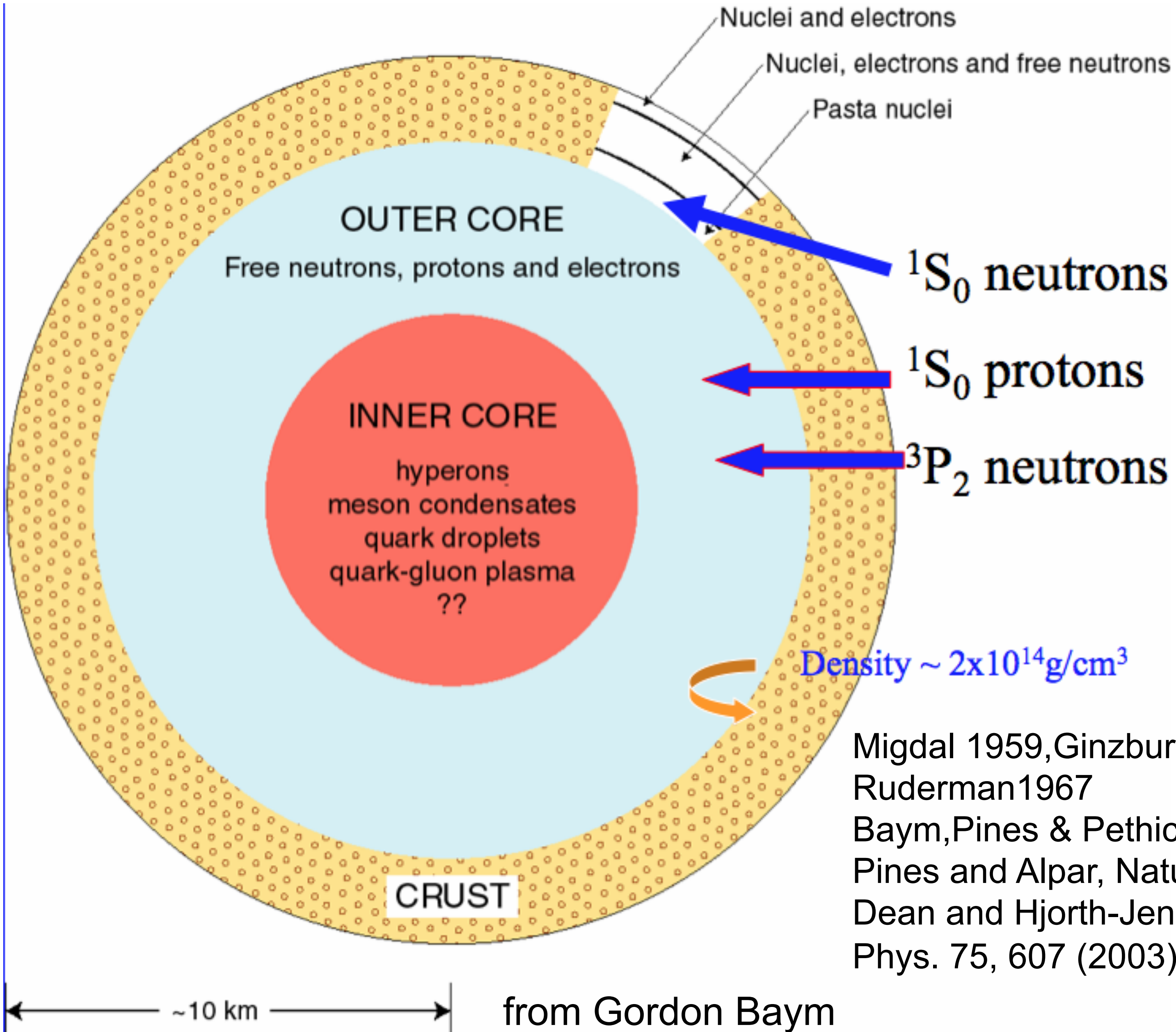
Anderson and Itoh, 1975





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

Superfluidity in neutron stars



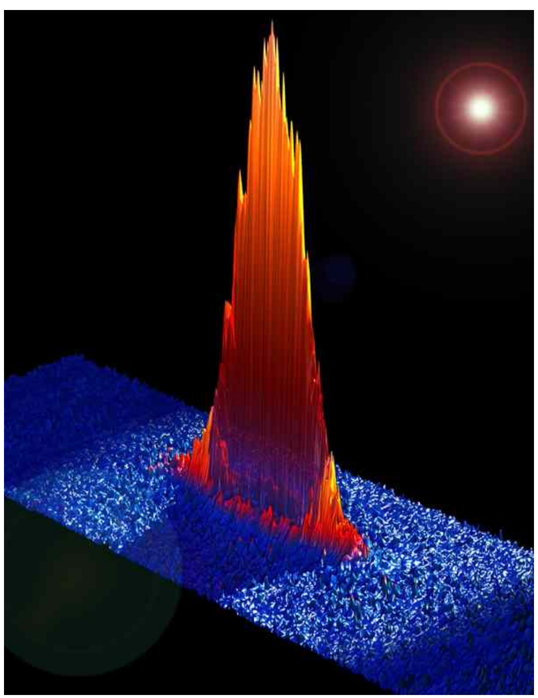
from Gordon Baym

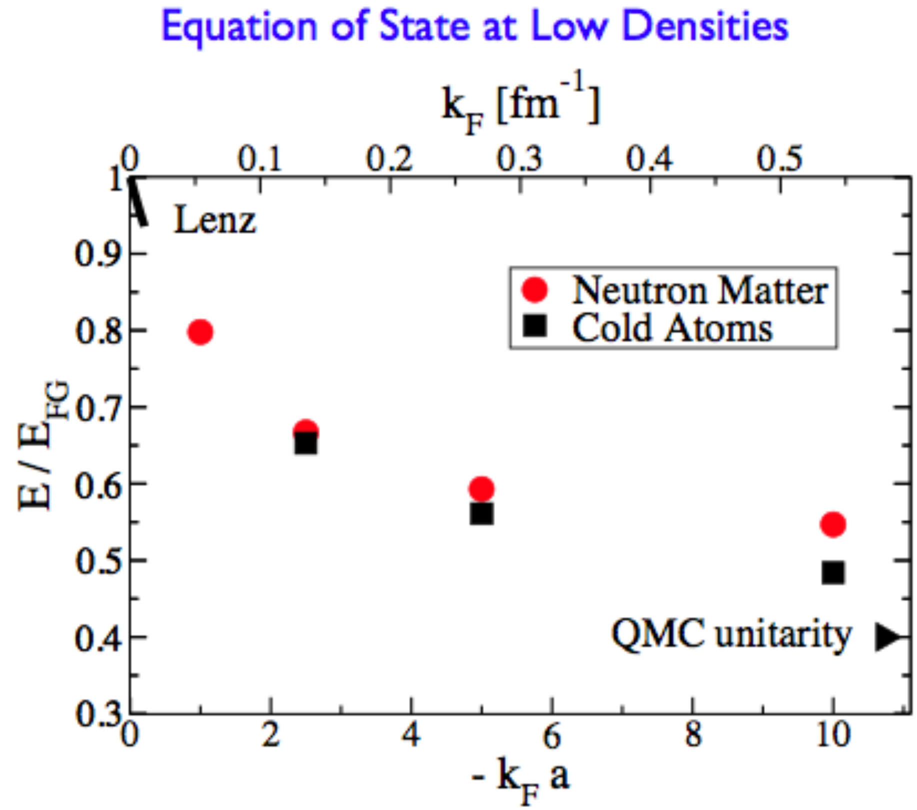
Migdal 1959,Ginzburg&Kirshnits1964
Ruderman1967
Baym,Pines & Pethick,1969
Pines and Alpar, Nature 316, 27 (1985)
Dean and Hjorth-Jensen,, Rev. Mod. Phys. 75, 607 (2003)

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