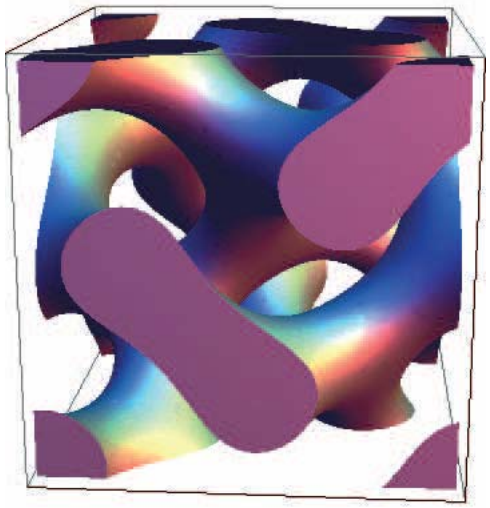
Gyroid Phase in Nuclear Pasta



New type of nuclear shape

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Shoichi Yamada（Waseda U）

Ref: Nakazato et al., arXiv:0905.2016

August 24 - 28, 2009, MICRA 2009

What is “Nuclear Pasta” ?

- “Nuclei” deform at subnuclear densities.

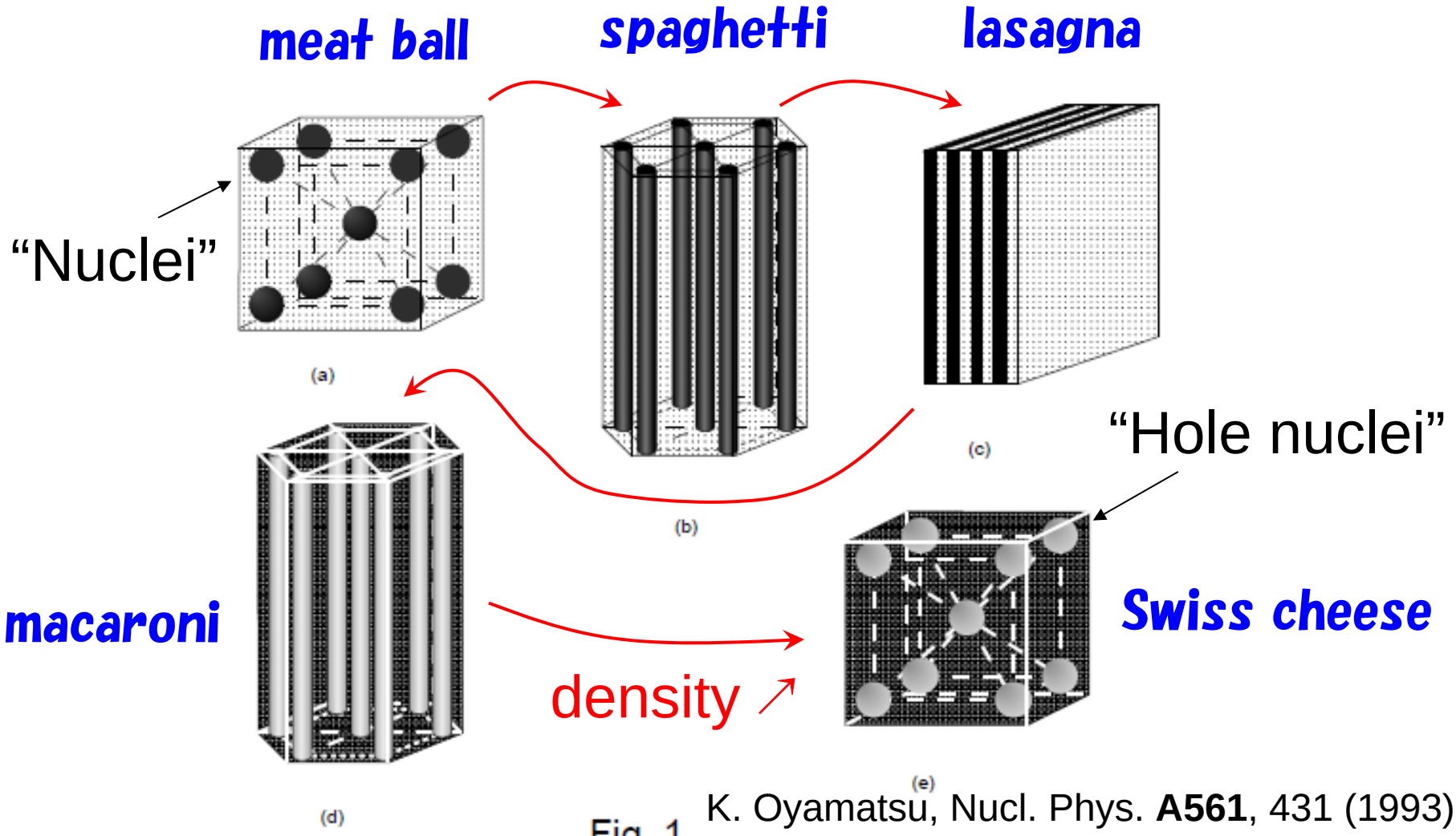


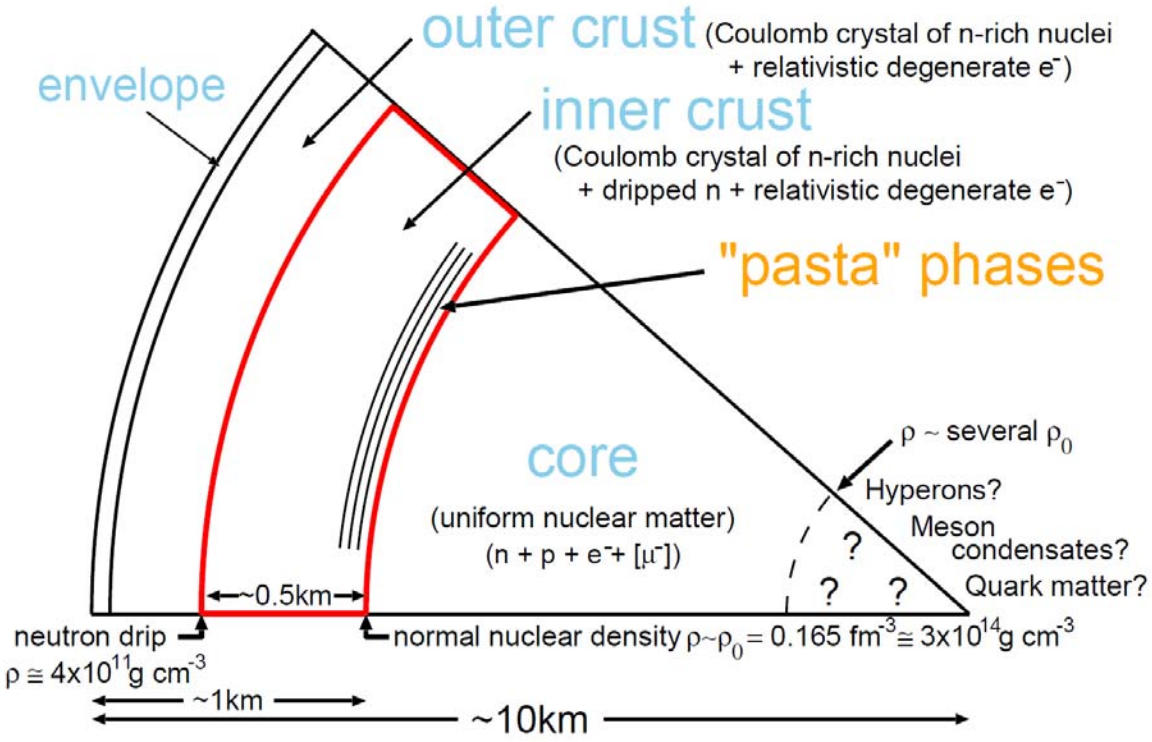
Fig. 1 K. Oyamatsu, Nucl. Phys. **A561**, 431 (1993)

Astrophysical implications

- EOS of supernova matter
- ν reaction rate
  - PNS cooling
  - ν critical opalescence
- Vortex pinning rate
  - pulsar glitch

Supernova explosion

Neutron stars

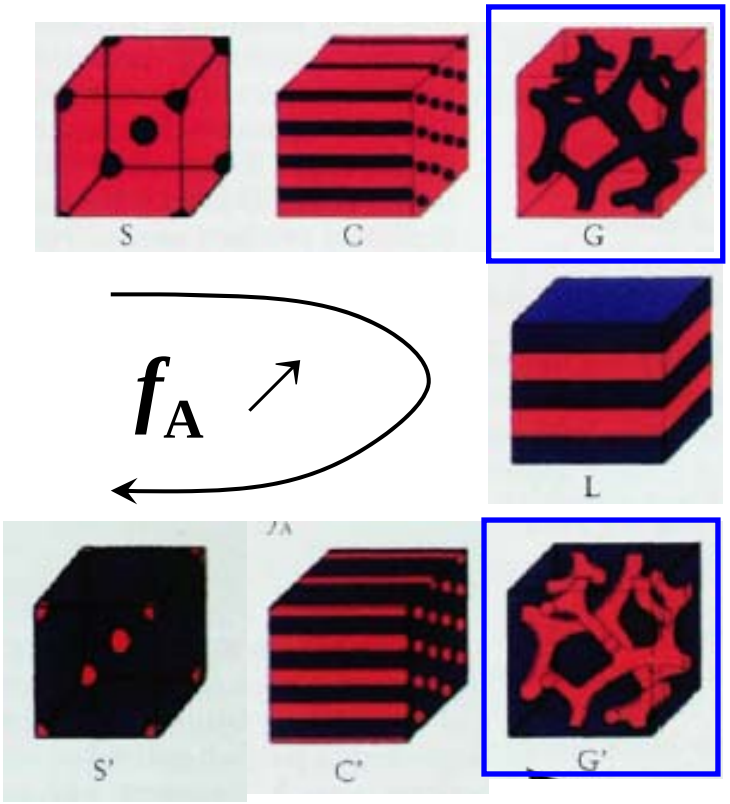


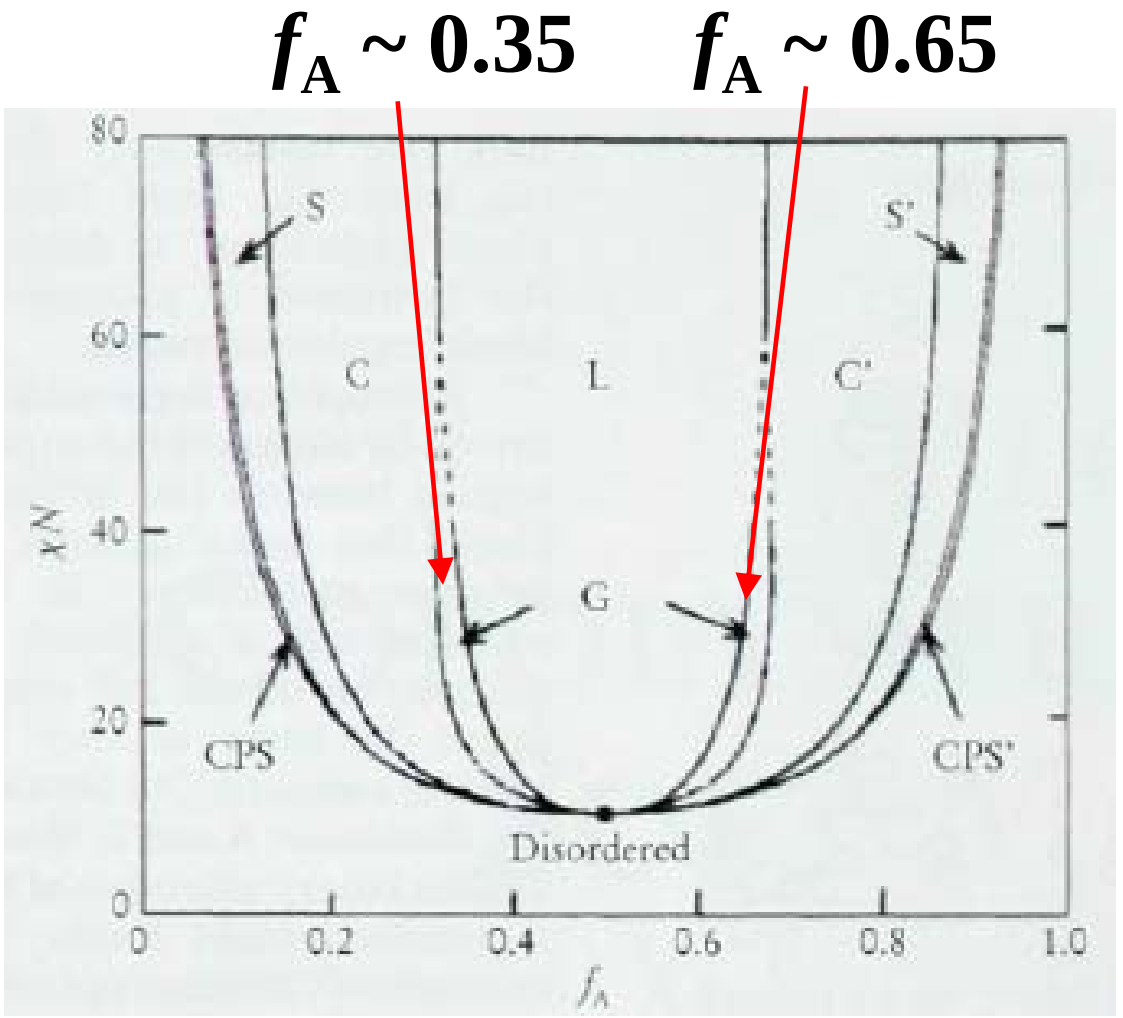
Watanabe and Sonoda, cond-mat/0502515

Analogy with polymer shapes

- Phase diagram of block copolymers.

f_A: fraction of "black" polymer



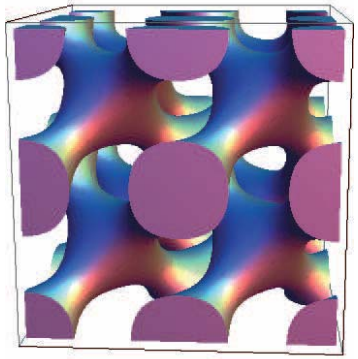


Phys. Today **52**, No.2, 32 (1999)

Bicontinuous structures of polymer

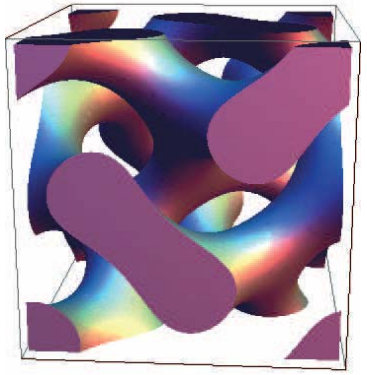
- Discovered late 1980's.
- Initially considered as double-diamond（D）.

$$f(x,y,z) = \cos\frac{2\pi(x-y)}{a}\cos\frac{2\pi z}{a} + \sin\frac{2\pi(x+y)}{a}\sin\frac{2\pi z}{a} = \pm k,$$



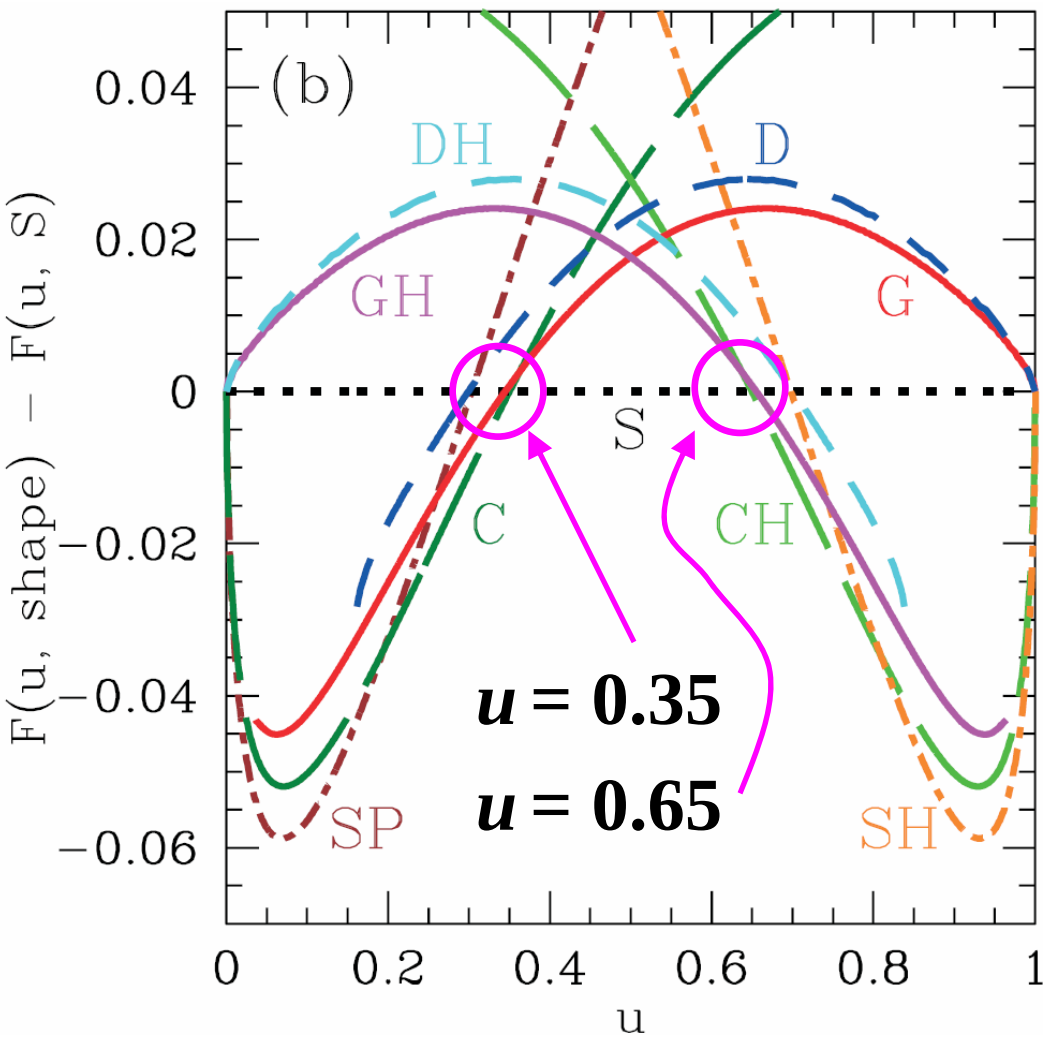
- Now gyroid（G）is thought more probable.

$$f(x,y,z) = \sin\frac{2\pi x}{a}\cos\frac{2\pi y}{a} + \sin\frac{2\pi y}{a}\cos\frac{2\pi z}{a} + \sin\frac{2\pi z}{a}\cos\frac{2\pi x}{a} = \pm k,$$



Comparison of $F(u,$ shape$)$

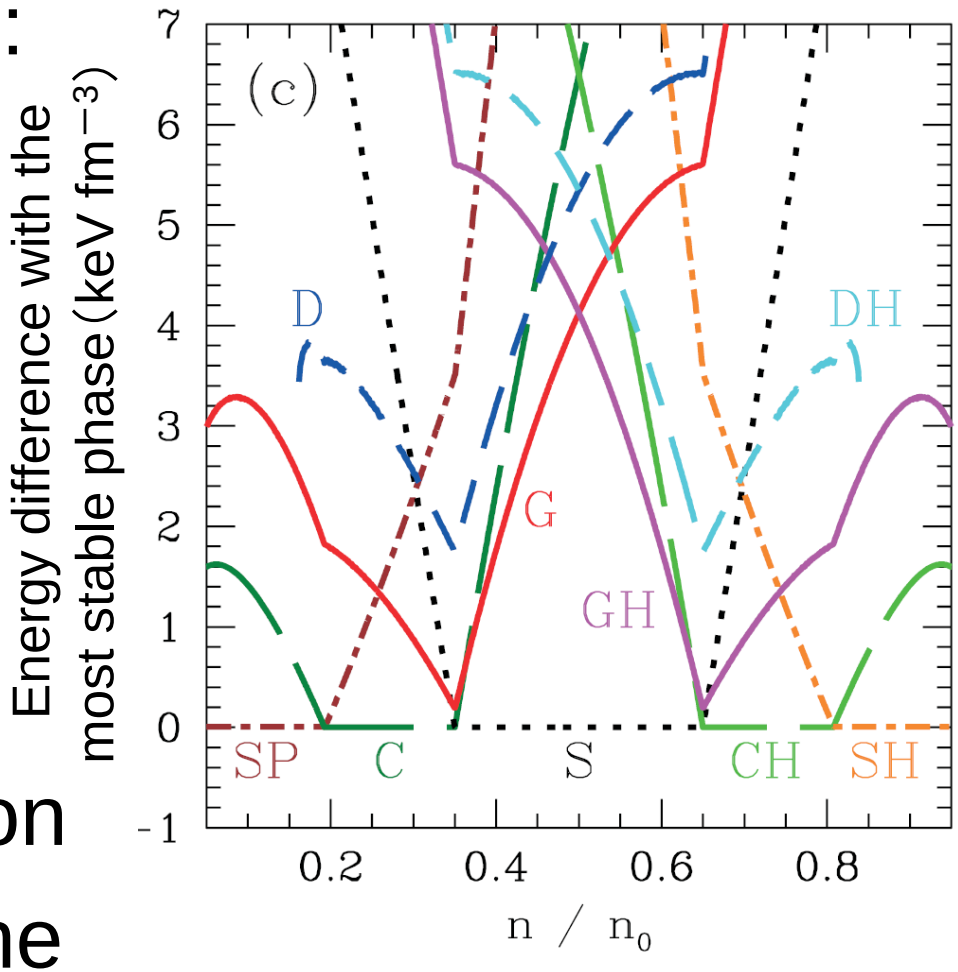
- Minimum: sphere
  → cylinder → slab
  → cylindrical hole
  → spherical hole
  （G and D do not appear.）
- G phase becomes close to minimum at u = 0.35, 0.65.
  → similar to the polymer system.



Numerical estimations

- For supernova matter:
  - $x^{in} = 0.3$
  - $n^{in} = n_0$、$n^{out} = 0$
  - σ = 0.73 MeV fm^{-2}
- Energy difference
  - ~ 0.2 keV fm^{-3}
  - ~ 3 keV per nucleon

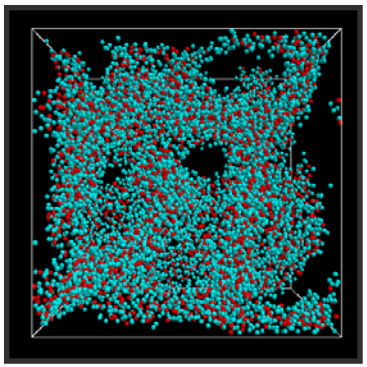
→ much lower than the temperature of supernova core.

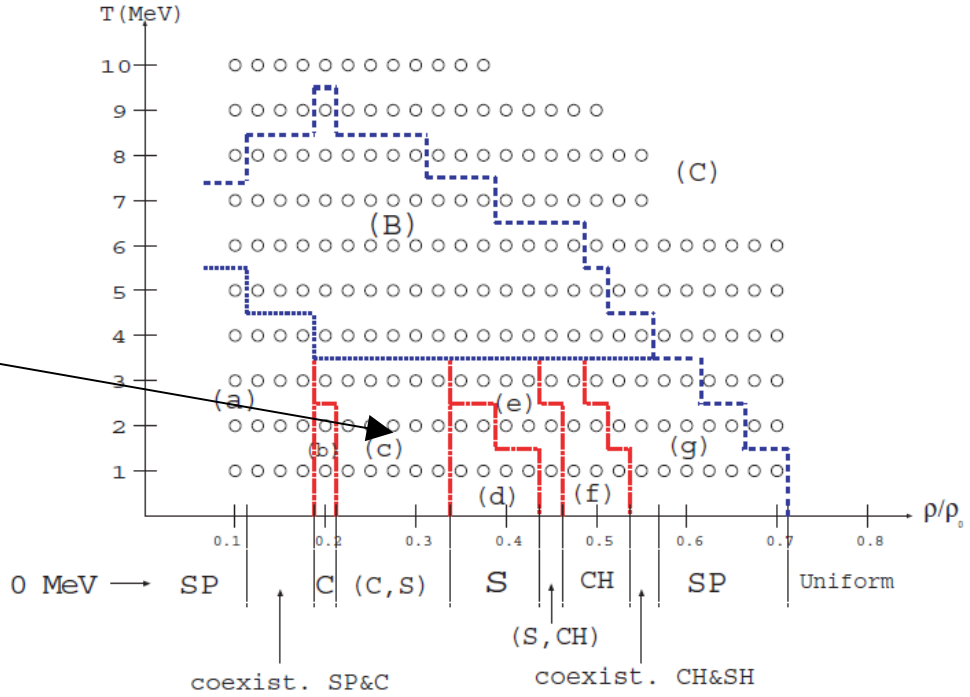


New type pasta in QMD

- In the recent study by quantum molecular dynamics（QMD）show the existence of “intermediate” phase between cylinder and slab（slab and cylindrical hole）phases.

→ metastable?





→ like G phase??

Sonoda et al., Phys. Rev. C **77**, 035806 (2008)

Summary

- We have evaluated the energy densities of G and D phases for nuclear pasta by CLDM.
- G and D phases are not the most stable phase for any $\boldsymbol{u}$. However, the energy differences from the most stable phase become tiny at $\boldsymbol{u}$ = 0.35, 0.65.

→ Interesting similarity with polymer system.

- G phase may appear as metastable state especially for finite temperatures.

→ More detailed studies will be needed.