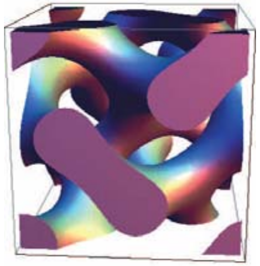
Nuclear shapes at subnuclear densities: analogy with polymer system

Supernova

Gyroid



Dept. of Astronomy, Kyoto Univ.（JSPS Fellow）

Ken’ichiro Nakazato

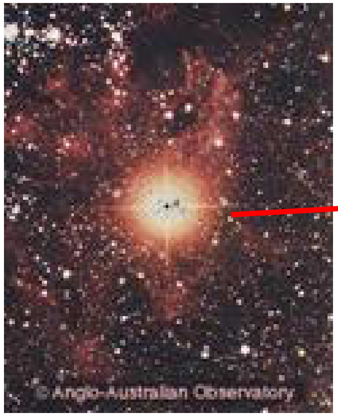
@ GCOE Symposium: Symmetry Breaking and Quantum Phenomena

Ref: Nakazato et al., *Physical Review Letters* **103** (2009), 132501

Core collapse supernova

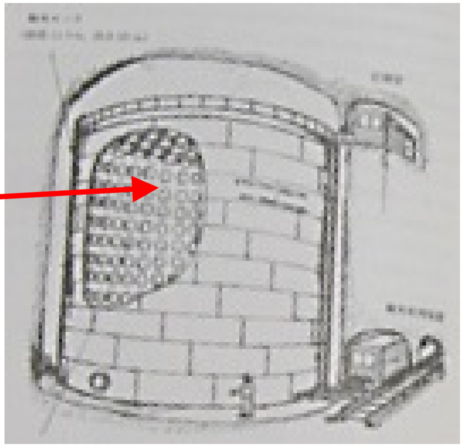
- The central subject in astrophysics.
  - Death of massive stars and birth of neutron stars.
  - One of the most energetic phenomena in the Universe; engine for the evolution of the galaxy.
  - Origin of elements, i.e., lives.
- Emission of enormous neutrinos.

Prof. Koshiba



Supernova 1987A

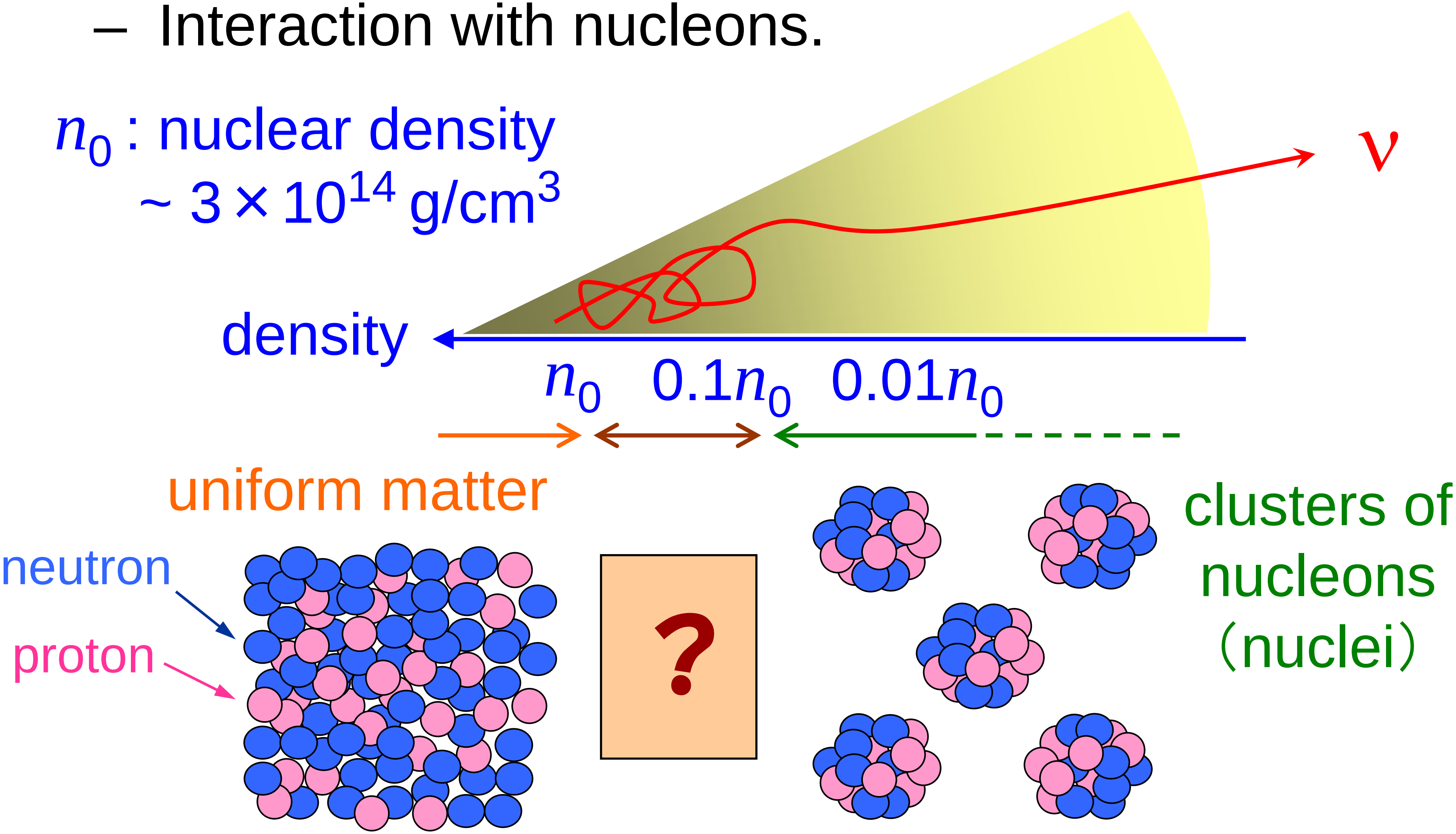
ν



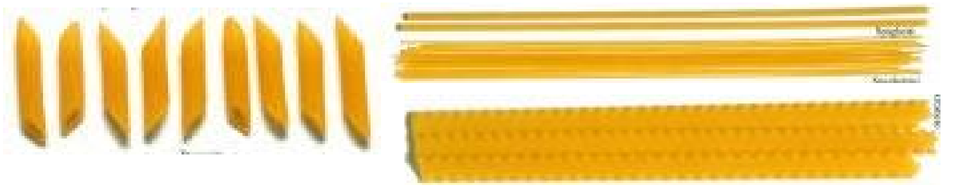
Kamiokande

Supernova neutrino

- Neutrinos come from deep inside supernova.
  - Interaction with nucleons.

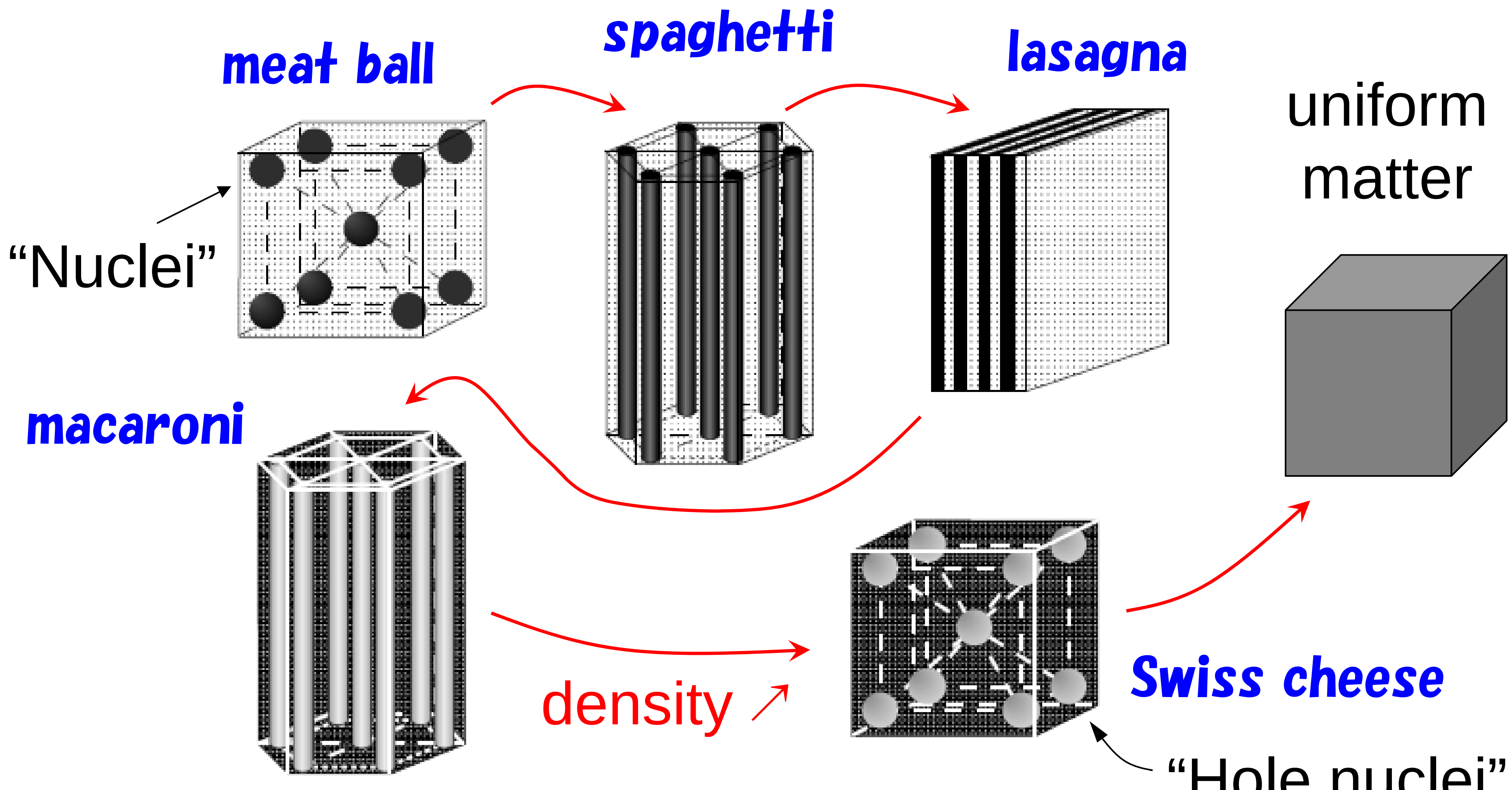


Nuclear pasta

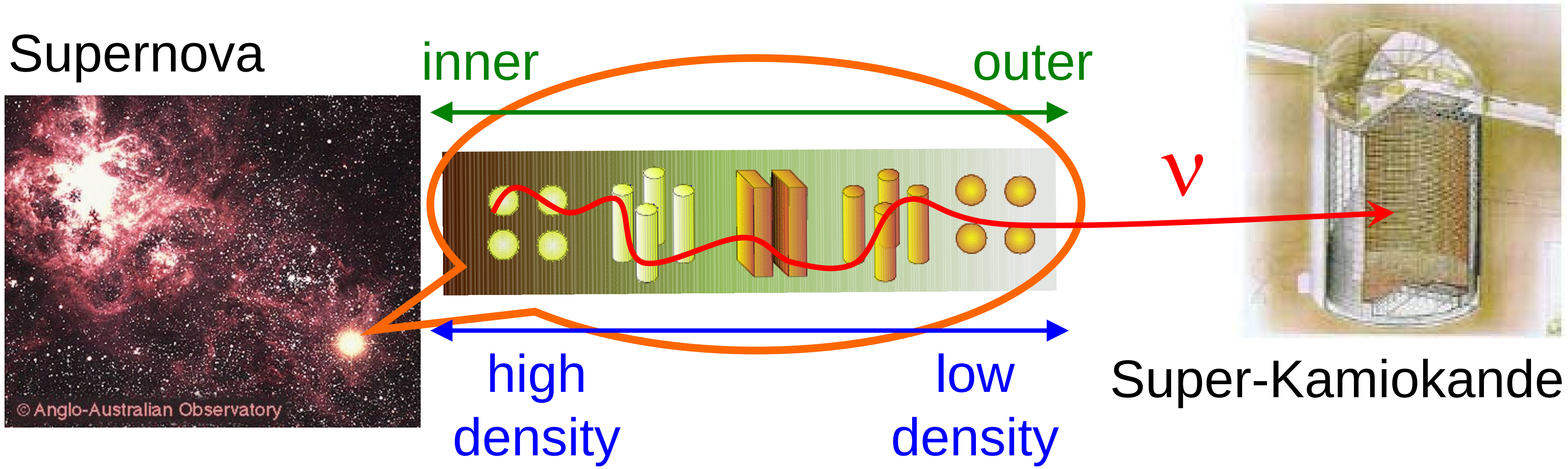


- "Nuclei" deform at subnuclear densities.

Figure by K. Oyamatsu (1993)

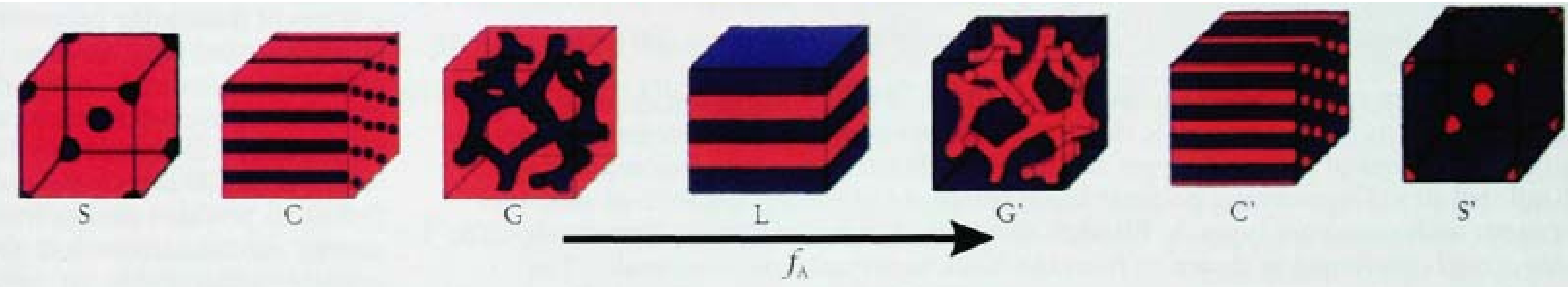


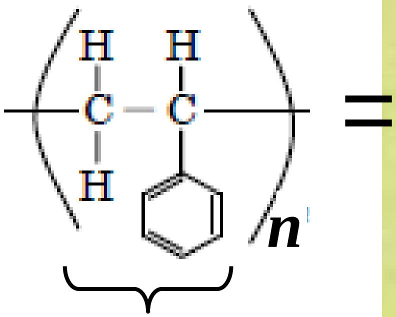
Neutrinos meet pasta



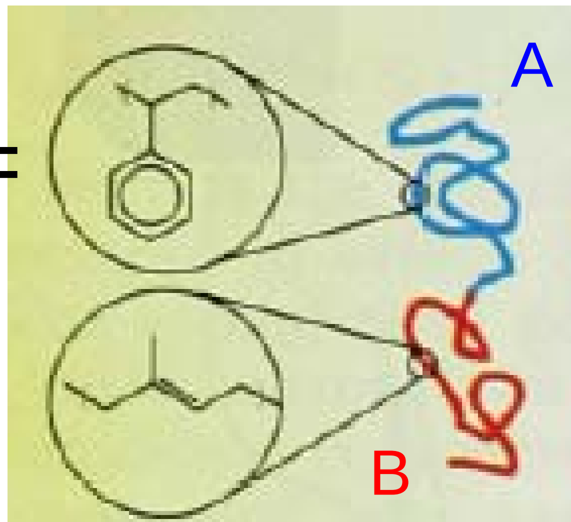
- Inside the supernova, neutrinos interact with nucleons of the pasta nuclei.
- Interaction rate depends on nuclear shape（sphere, cylinder or slab?）.
- Since there are impacts on the neutrino detection, nuclear pasta is impotant!

Shapes of block copolymers

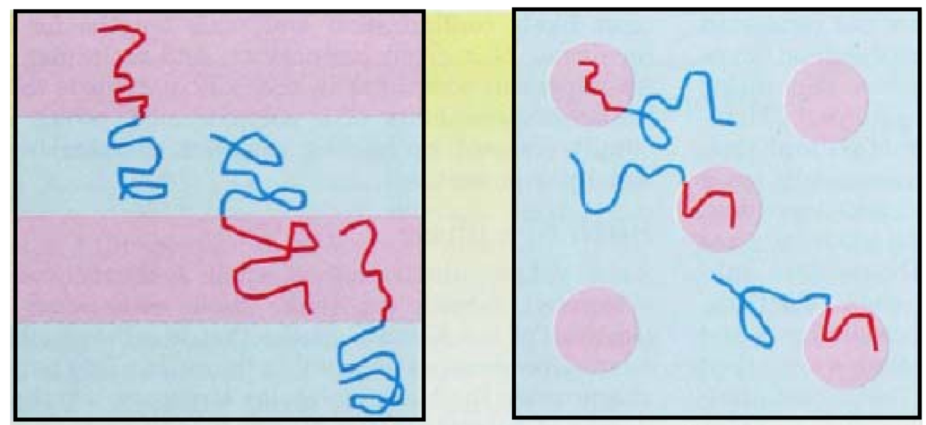




This unit repeats.



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

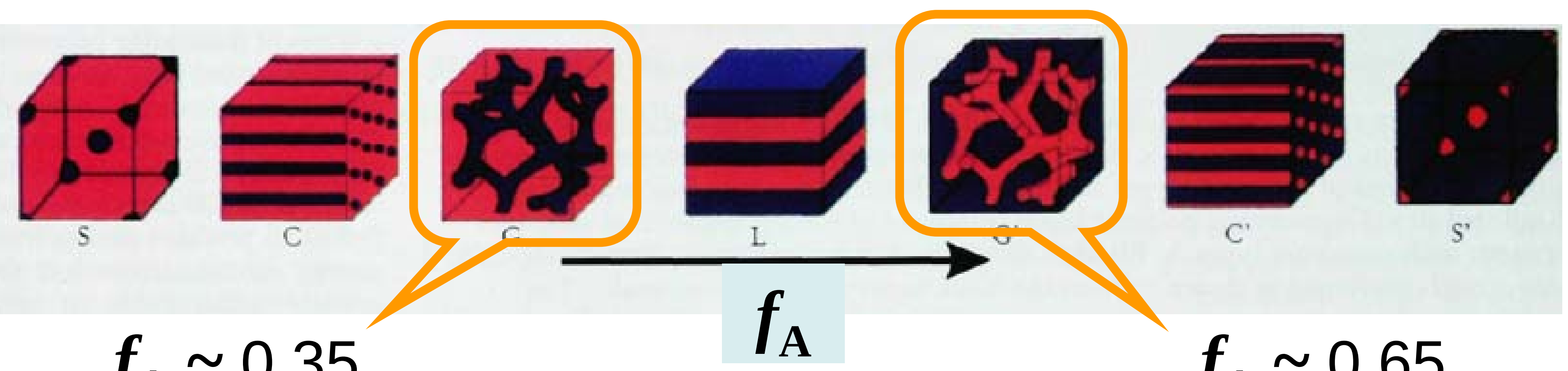


- Two blocks of polymers（A & B）are linked.
- Blocks self-assemble spontaneously.

Gyroid phase in polymer system

- Shapes of block copolymers are determined by the fraction of one polymer (f_A).
- A complex structure（gyroid）is discovered experimentally between cylinder and slab.
- Gyroid appears in the narrow range of f_A.

f_A: fraction of “black” polymer



$f_A \sim 0.35$

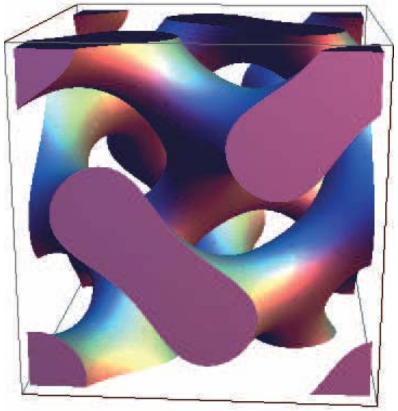
$f_A \sim 0.65$

Gyroid phase in nuclear pasta

Nakazato et al., PRL 103 (2009), 132501

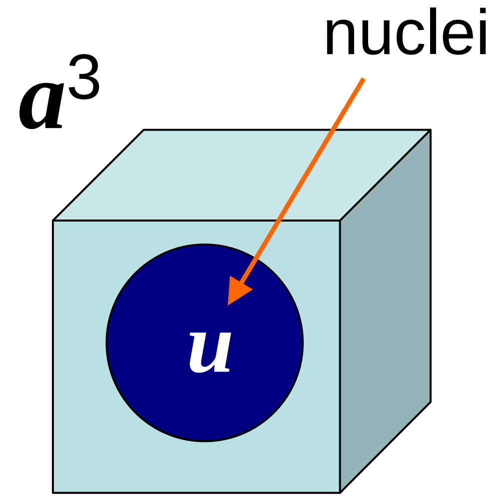
- This is the first study of gyroid (and its hole) structure as a new type of nuclear pasta.
- Liquid drop model is used for the nuclear matter.
- Analytic approximation is used for the gyroid shape.

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



Analyses by liquid drop model

- Simple phenomenological model.
  - Take a cell with a volume, a^3.
  - Set the region called "nuclei" with a volume fraction, u.
  - Neutrons and protons reside in "nuclei" (proton fraction: $x_p = 0.3$).
  - Electrons distribute uniformly.



- Total energy of the cell is given as,

$$W = (\text{bulk}) + (\text{surface}) + (\text{Coulomb})$$

$$\propto a^3 \qquad \propto a^2 \qquad \propto a^5$$

Energy minimization

- For given $\boldsymbol{u}$, shape and size（$\boldsymbol{a}$）which minimize the energy density（$W / \boldsymbol{a}^3$）are realized.

$$\frac{W_{\min}(u)}{a^3} = \min_{a,\text{shape}}\left(\frac{W(u,a,\text{shape})}{a^3}\right) = \min_{\text{shape}}\left(w'(u,\text{shape})\right)$$

eliminating $\boldsymbol{a}$

$$\frac{\partial}{\partial a}\left(\frac{W(u,a,\text{shape})}{a^3}\right) = 0 \quad \Rightarrow \quad a = a(u,\text{shape})$$

c.f. $\frac{W(u,a,\text{shape})}{a^3}$ = (bulk) + (surface) + (Coulomb)

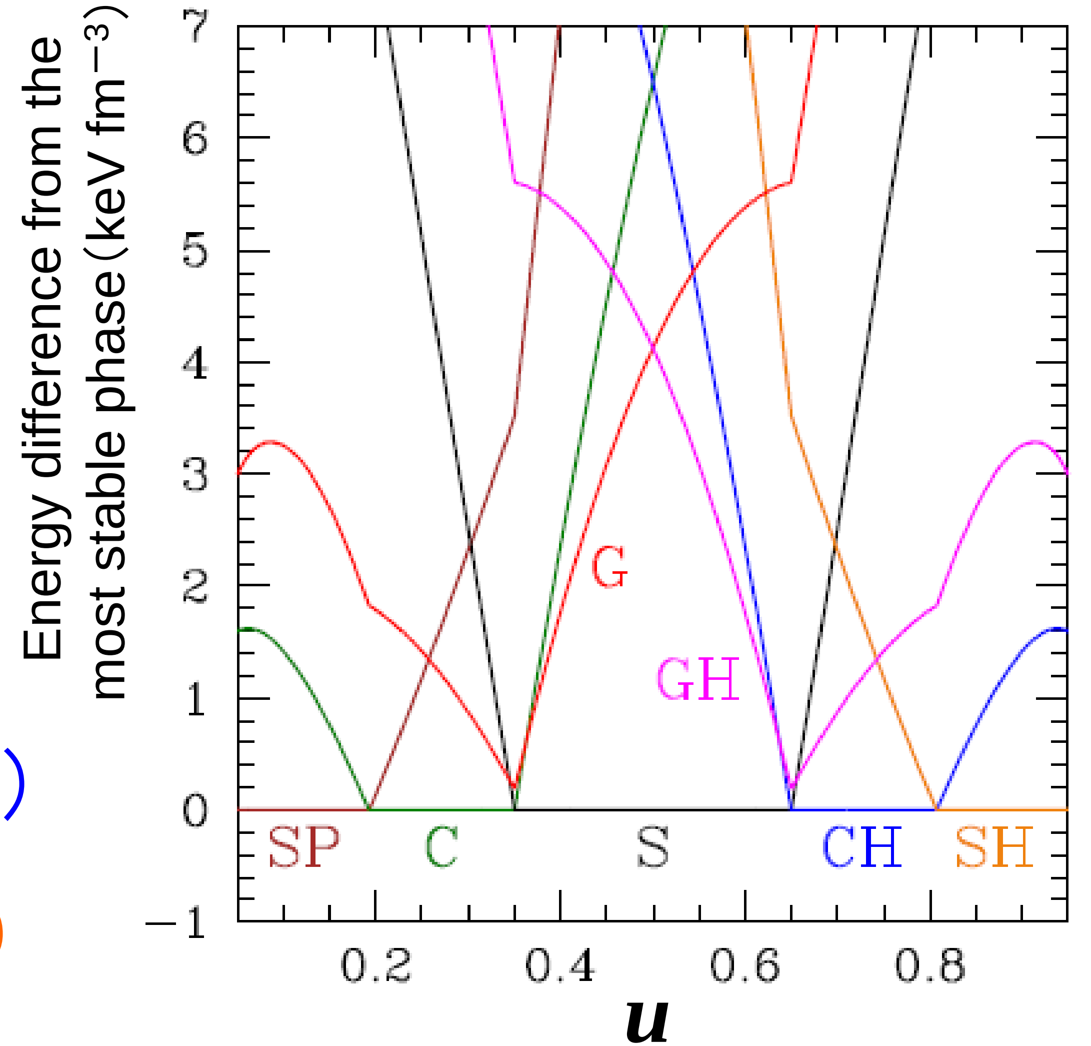
$\propto \boldsymbol{a}^0$ $\propto \boldsymbol{a}^{-1}$ $\propto \boldsymbol{a}^2$

- Let's compare $\boldsymbol{w'}(\boldsymbol{u}$, shape$)$ for each shape.

Energy comparison

- Minimum energy is give by

Sphere (SP)
↓
Cylinder (C)
↓
Slab (S)
↓
Cylindrical hole (CH)
↓
Spherical hole (SH)



- Gyroid (G) does not appear, however,,,

Energy comparison

- Gyroid becomes close to minimum at u = 0.35, 0.65.

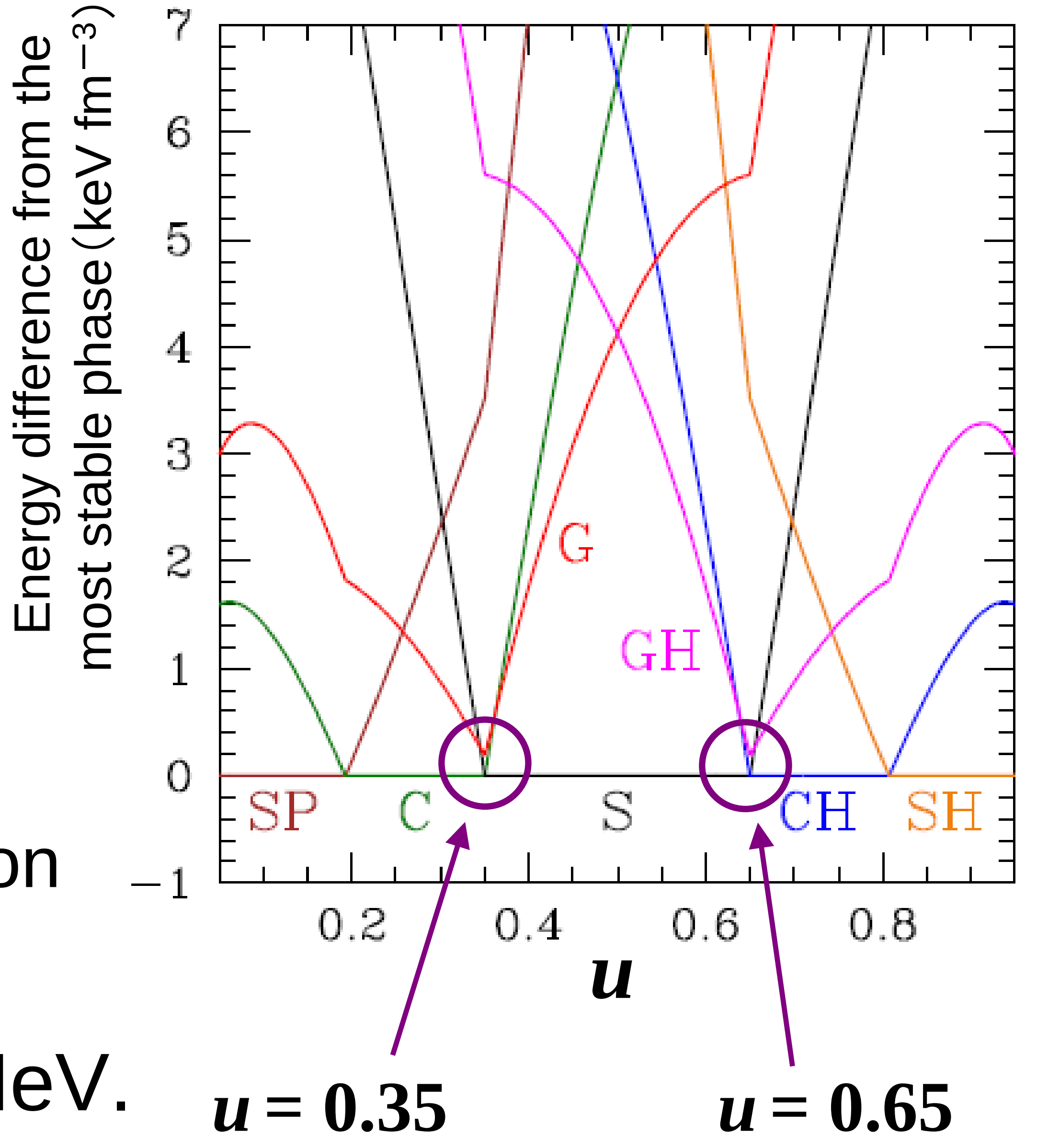
→ Similar with the block copolymers.

- Energy difference

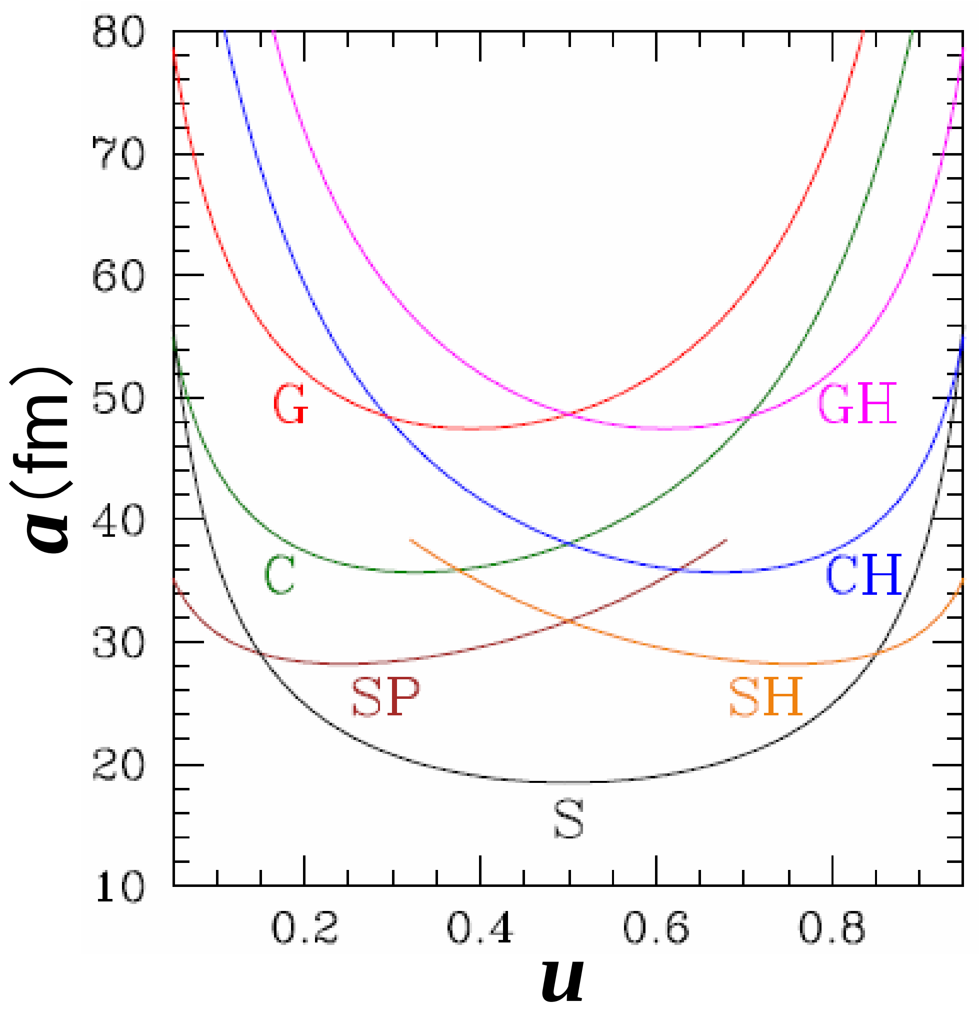
  ~ 0.2 keV fm^{-3}

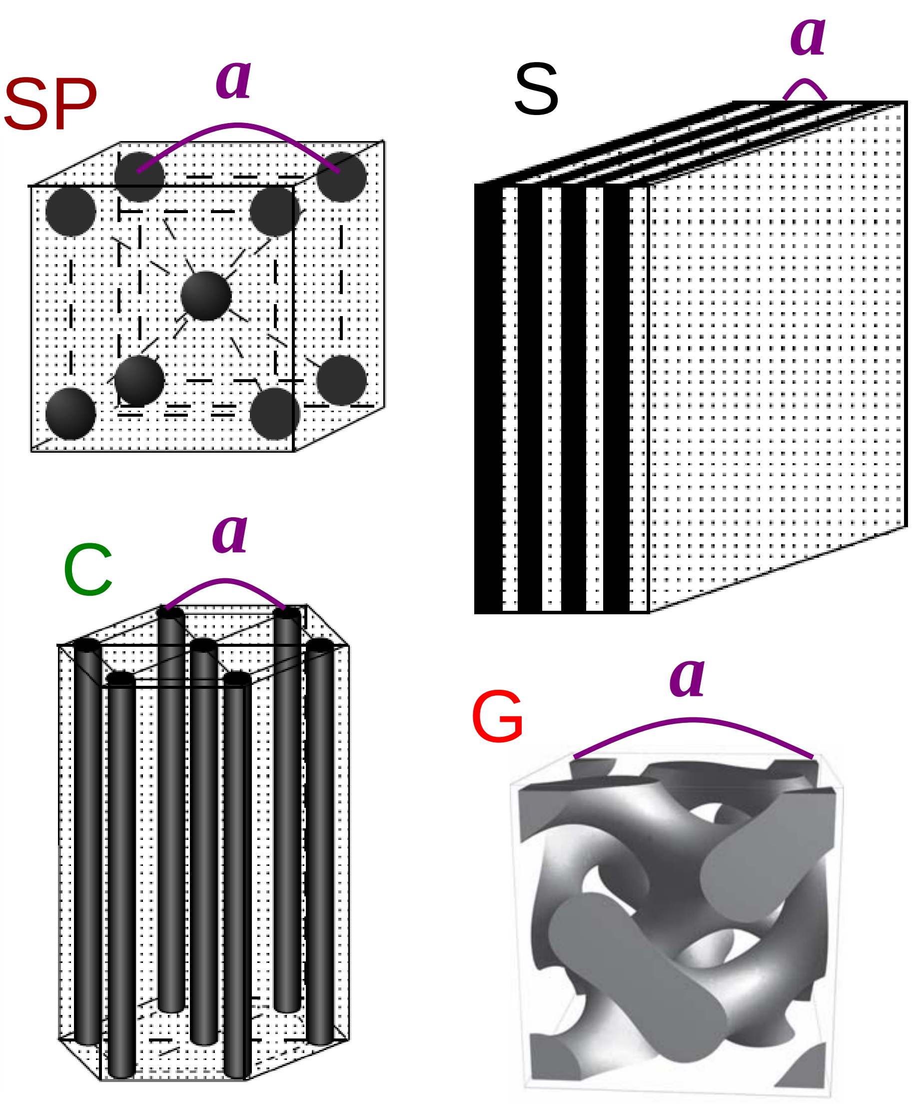
  ~ 3 keV per nucleon

→ << temperature of supernova, ~ MeV.



“Nuclear” size





- Length scale of nuclear pasta is ~ 10 fm
→ 10 nm scale for block copolymers.

Summary

- We have evaluated the energy densities of gyroid phase for nuclear pasta.

- Gyroid phase is not the most stable phase for any $\boldsymbol{u}$. However, the energy differences from the most stable phase become tiny at $\boldsymbol{u} = 0.35, 0.65$.

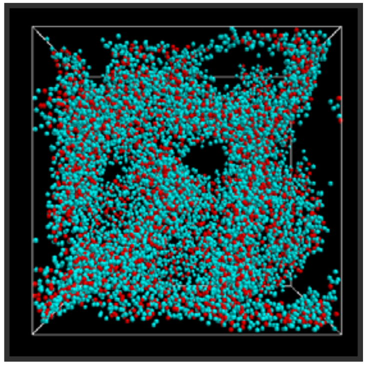
→ Interesting similarity with polymer system.

- Gyroid phase in nuclear pasta is ~ 10 fm.

→ Different from polymer system, ~ 10 nm.

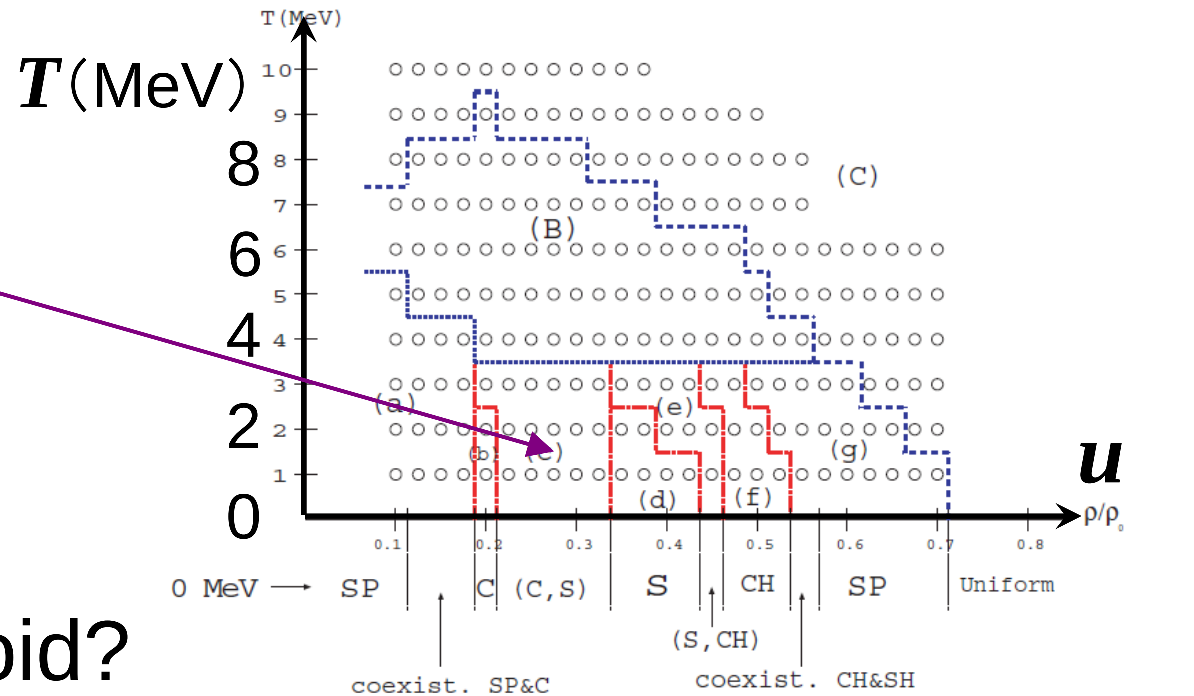
Discussion: Implication from QMD

- Recent study by the quantum molecular dynamics（QMD）showes the existence of "intermediate" phase between cylinder and slab（slab and cylindrical hole）phases.



→ metastable?

→ looks like gyroid?



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