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「超流動ヘリウム3の異方的秩序変数とその制御」

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Anisotropic Superfluid ^{3}He in Some Circumstances

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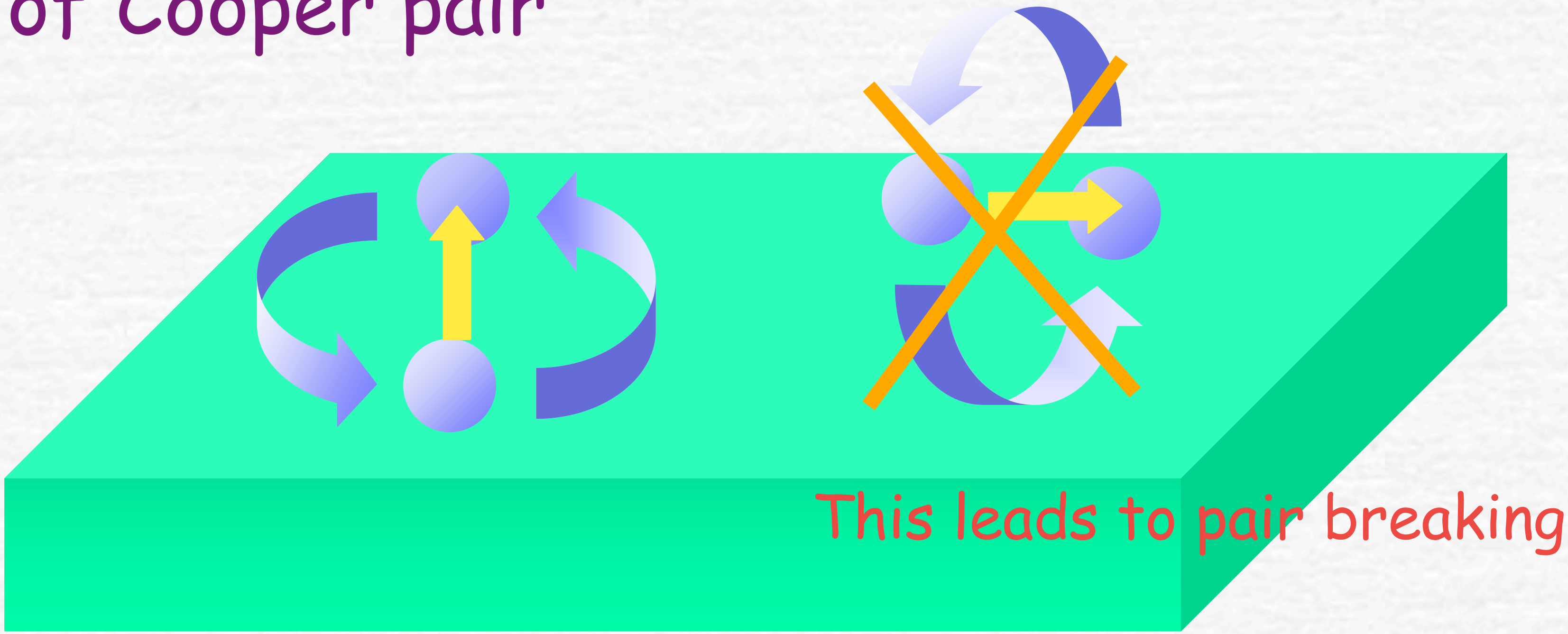
general feature

Superfluid ^3He (anisotropic order parameter)
in narrow space or in complicated structure
and/or
under rotation

- narrow space → thin cylinder
  slab space
- complicated structure → aerogel
- under rotation → rotating cryostat at ISSP

Boundary constraint for angular momentum of Cooper pair



We can control order parameter vector
by using boundary constraint

narrow space with length scale of D

Characteristic length in superfluid ^{3}He

coherence length ξ_0 ~ a few tenth nm

order parameter healing length $\xi_s \sim \xi_0$

textural healing length $\xi_x \geqq 10\ \mu m \gg \xi_0$

(phase dependent)

Sphere diameter;D $\xi_0 < D \leqq \xi_x$ or $\xi_x < D$

Cylinder diameter;D $D \leqq \xi_0$ or $\xi_0 < D \leqq \xi_x$ or $\xi_x < D$

Thin cylinder

Film thickness;D $D \leqq \xi_0$ or $\xi_0 < D \leqq \xi_x$ or $\xi_x < D$

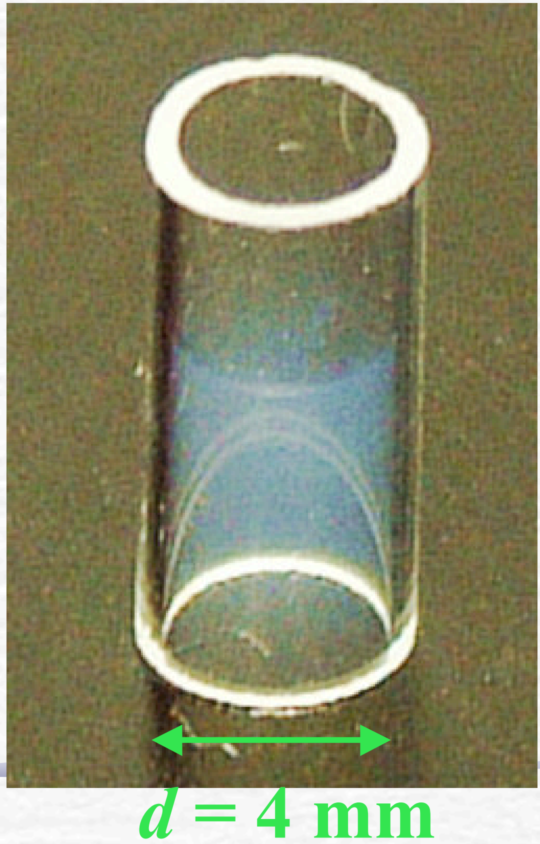
Slab space

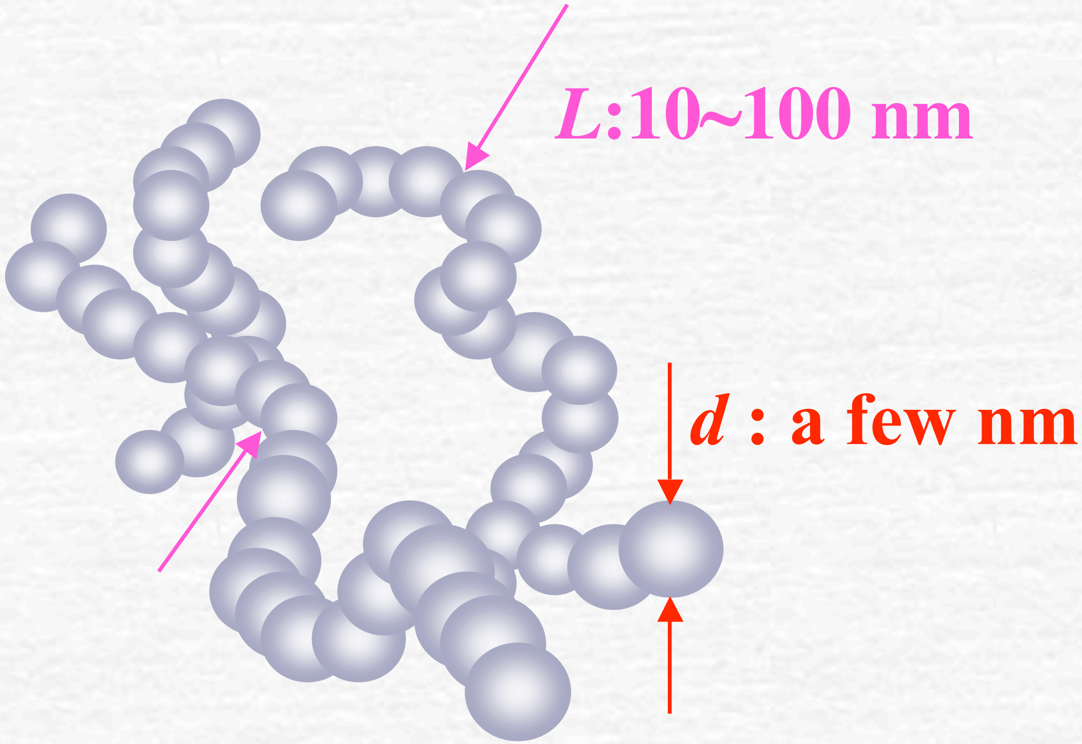
Constraints by boundary cause

(new phase)/ new phase diagram

complicated structure

Aerogel : composed of silica(SiO_2) strands with large porosity (larger than ~ 97%)





Length in aerogel and in superfluid ^{3}He

Fermi wave length $\lambda \approx$ nm

Silica beads diameter d ~ a few nm

Coherence length ξ_0 ~ a few tenth nm

Mean distance L between silica strands

L; a few tenth nm ~ ξ_0

$$\lambda < d \ll \xi_0 \sim L$$

Aerogel partly destroys superfluidity in liquid ^{3}He

/ suppression of T_c etc.

Aerogel behaves as impurity

Possibility of new phase

Superfluidity under rotation

Superconductivity in magnetic field

Coherence length ξ < Penetration depth λ

→ type Ⅱ superconductor
upper/lower critical field Hc_1, Hc_2
vortex state

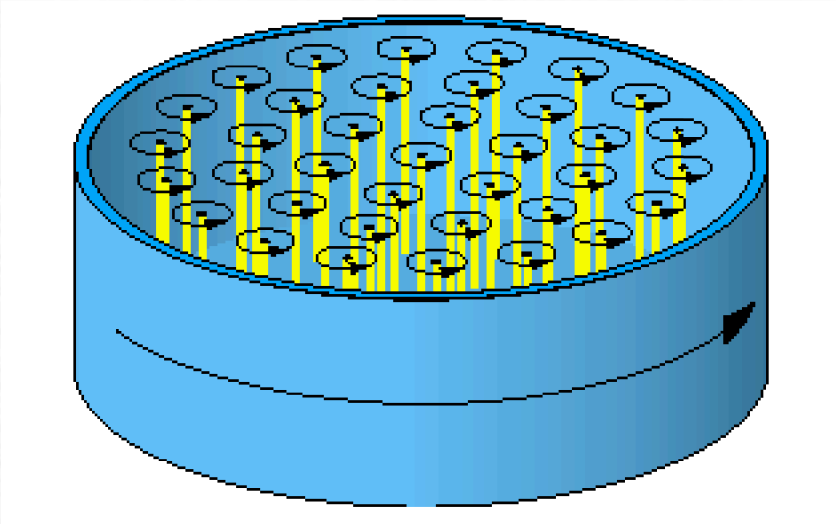
cell size

Type Ⅱ superfluid

→ upper/lower critical angular velocity Ωc_1, Ωc_2
vortex state
vortex line in ^4He
vortices with a few core structures in ^3He

configuration of order parameter vector

Vortex state in ^{3}He under rotation



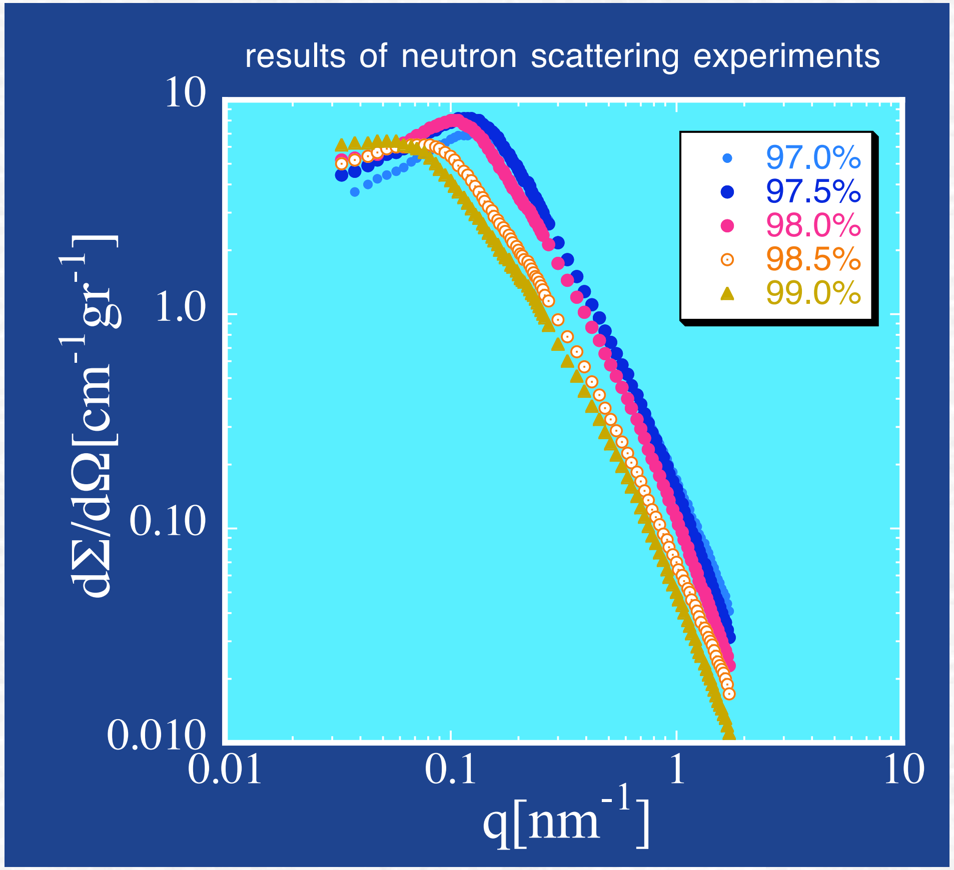
$$vortex\ density\quad n = \frac{2\Omega}{\kappa_0}$$

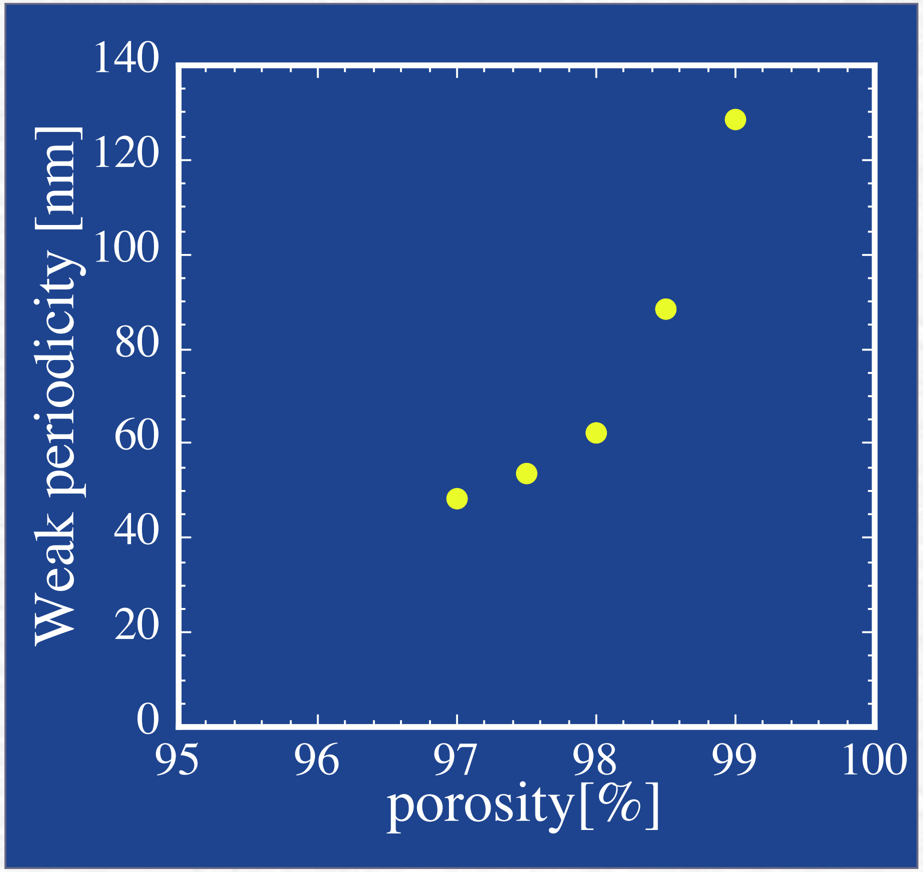
$$\kappa_0 = \frac{h}{m_4}, \quad = \frac{h}{2m_3}$$

Rotating cryostat can create vortex state (vortices) and can control order parameter vector

Also it can be used to detect vortex state or one vortex by combination with another method

◆ Superfluid ^{3}He in aerogel





silica beads diameter D=8.4 nm

Periodic Distance

L_p~52 nm in 97.5 % porosity

Suppression of T_c (by sound and NMR experiments)

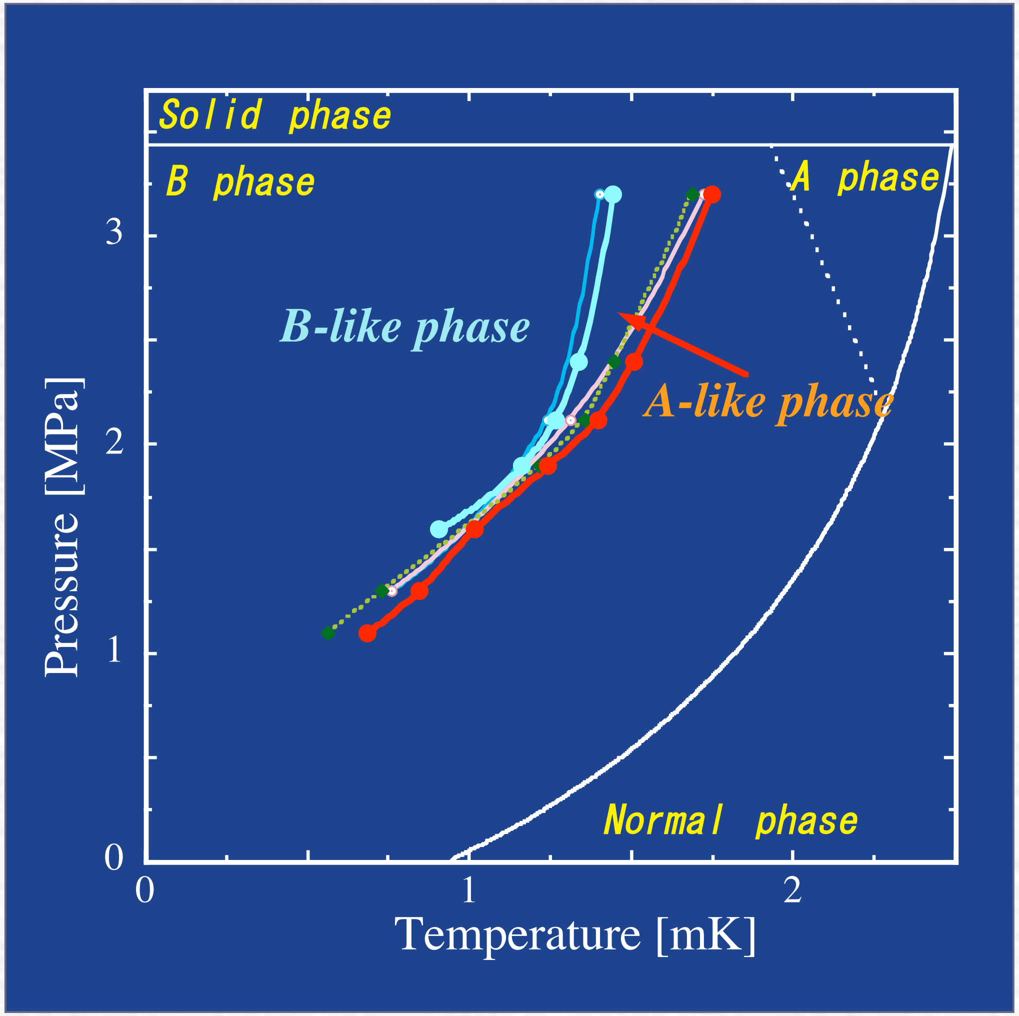
Isotropic Inhomogeneous Scattering Model (IISM)

E.V. Thuneberg et al., *Phys. Rev. Lett*. **80**, 2861 (1998)

We can explain Tc suppression with radius **R** in IISM model as fitting parameter on two porosity of aerogel (97.5% 98.5%)

Obtained radius R depends on porosity as weak periodic length L_p by neutron scattering measurement do.

New Phase/ New Phase Diagram



Phase diagram on cooling in 97.5% aerogel by NMR

A-like phase is an equal spin paring state

↑↑ ↓↓

B-like phase is a non equal spin paring state

↑↑ ↓↓ ↑↓+↓↑

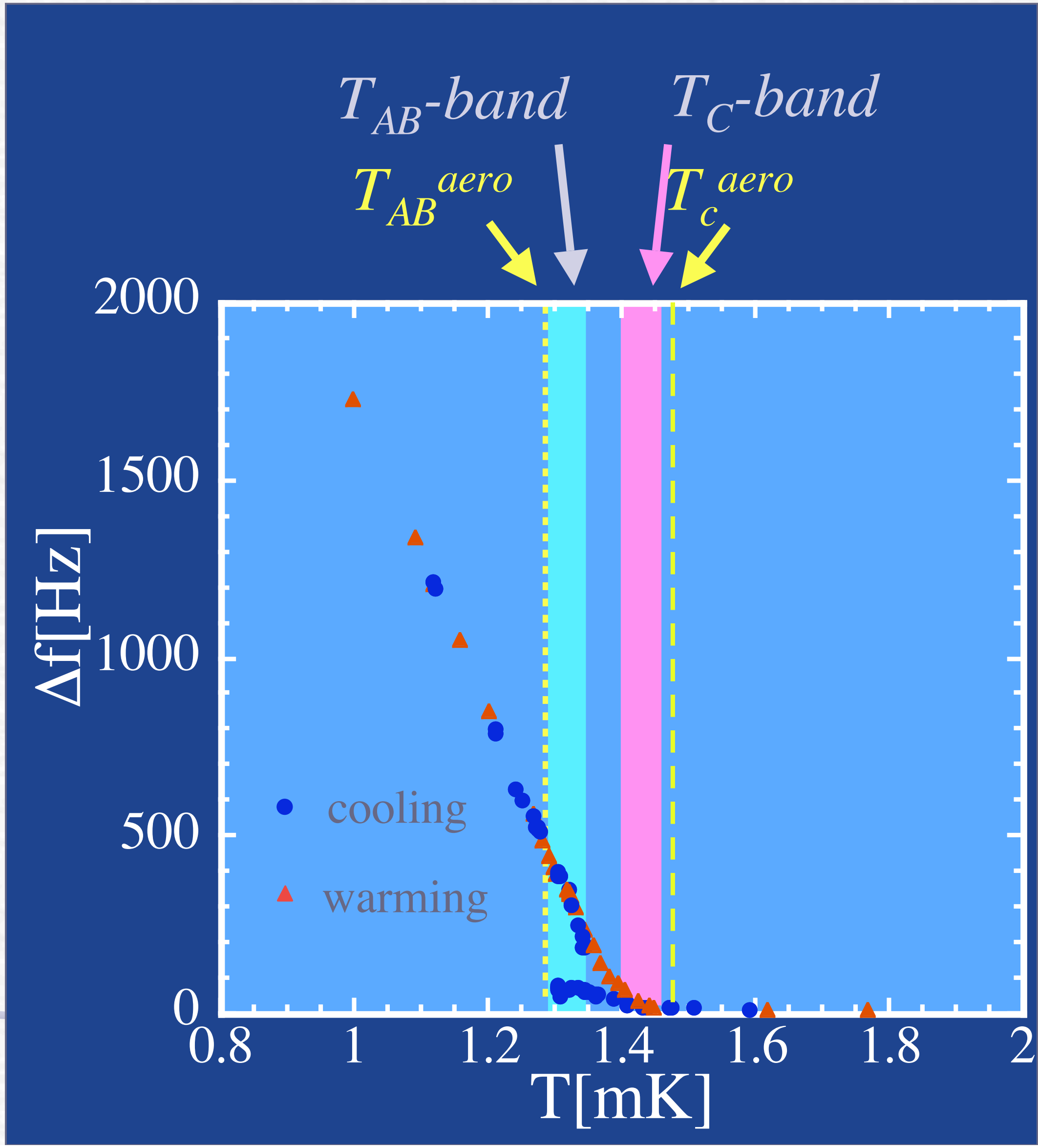
Phase conversion process in superfluid state

2.4 MPa

- Two temperature bands are revealed, only where thefirst order phase conversion develops with changing temperatures.

- T_{AB}*-band* where *A-like phase* to *B-like* phase occurs

- T_C*-band* where *B-like phase* to *A-like* phase occurs



Strange phase conversion

In each temperature band, there is
a phase conversion curve
in the graph of the fraction of *A-like phase.*

Each phase conversion occurs along this curve in one direction.

No phase conversion occurs between two temperature bands

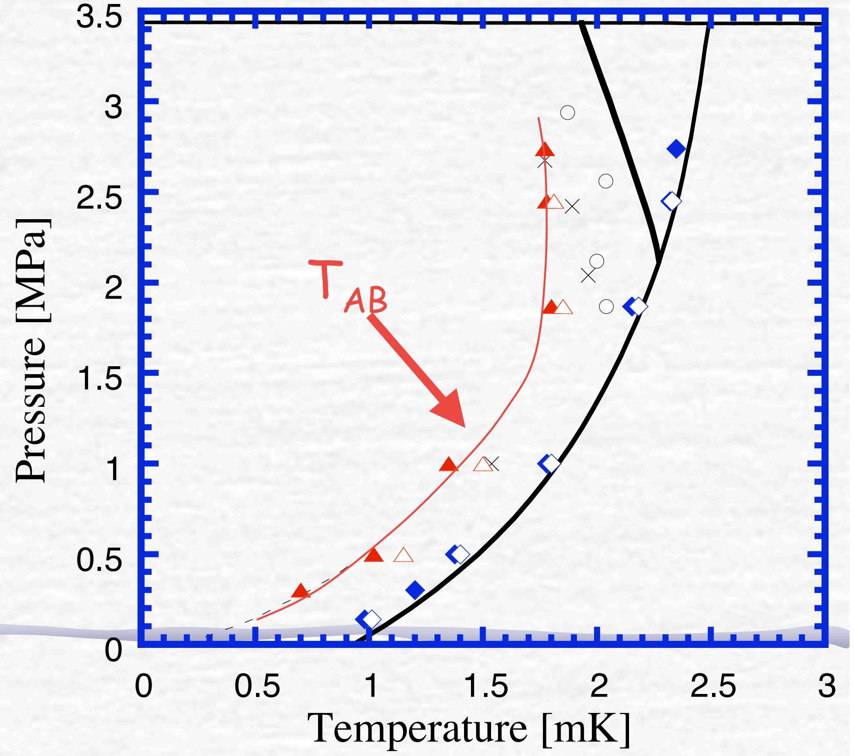
Pinning of phase boundary by aerogel ??

Suppression of A-like phase in 97.5% aerogel

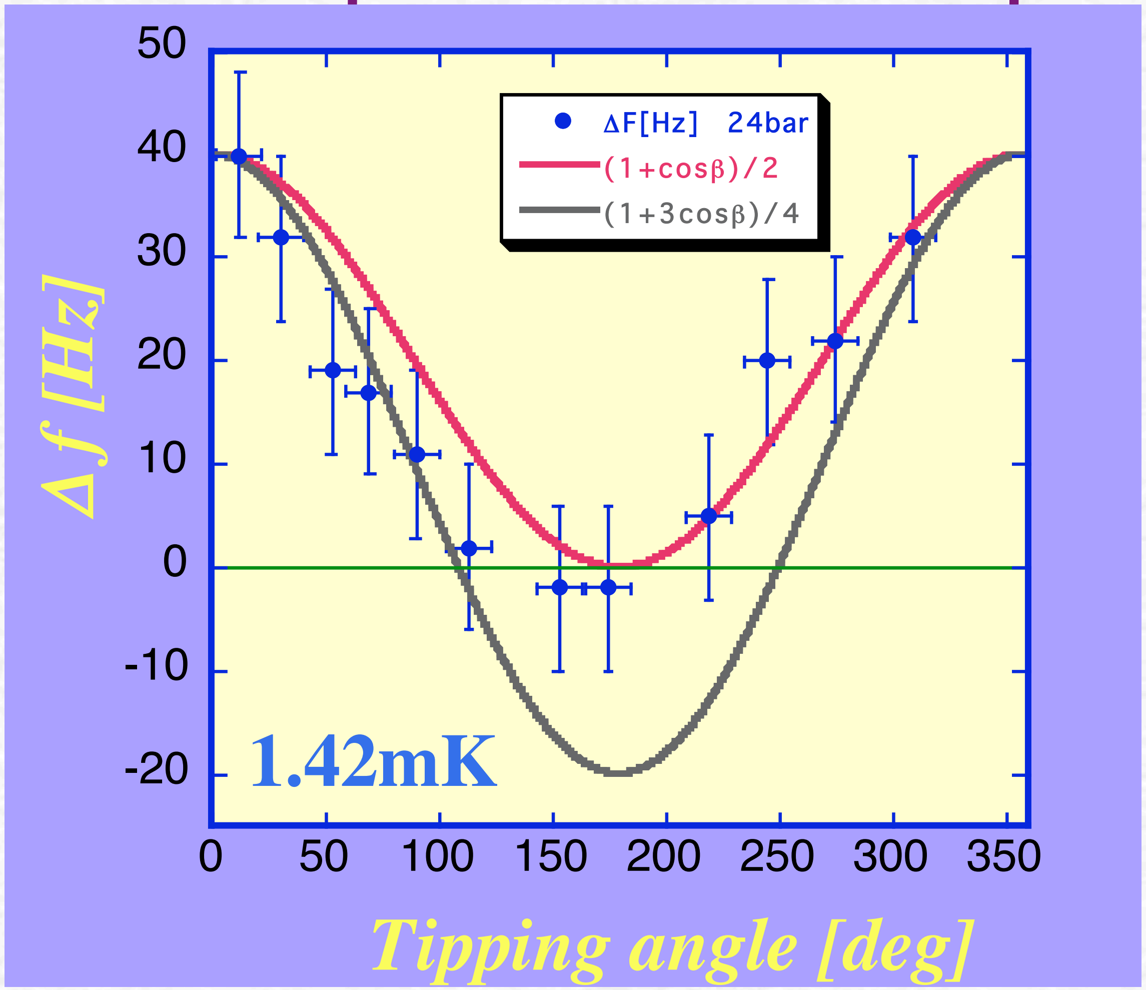
Not only suppression of Tc but also suppression of A-like phase in aerogel on warming process is observed.
This is very different from behavior in A phase in another type of confinement in 0.8 μm thickness film confines between parallel plates.

A-like phase is not A phase ?

Expansion of A phase in 0.8 μm thickness film



A like phase is a new phase ?



Tipping angle dependent frequency shift in FID signal after an rf pulse

Proposed new phase "robust phase"

A *robust phase* proposed by I.A. Fomin explains FID frequencies well

$$d_{\mu j} = \frac{\Delta}{\sqrt{3}}\left[\hat{d}_{\mu}\left(\hat{m}_j + i\hat{n}_j\right) + \hat{e}_{\mu}\left(\hat{l}_j + i\hat{p}_j\right)\right]$$

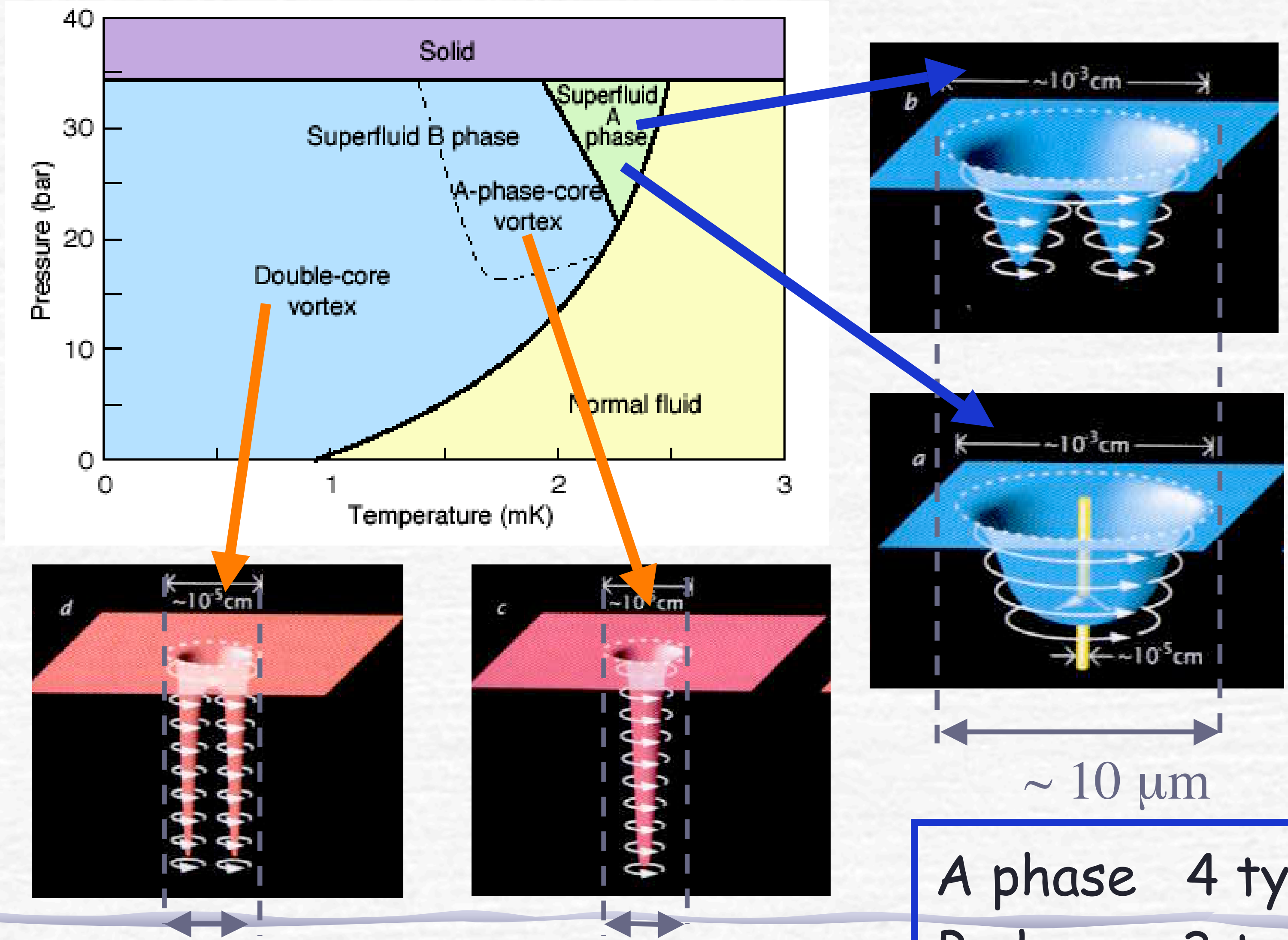
M.Miura, · · ,K.Nagai *JLTP* 138, 153(2005)

$$f^2 = f_L^2 + \frac{1}{2} f_{rbst}^2 \qquad cw\ NMR$$

$$\Delta f(\beta) = \frac{f_{rbst}^2}{f_L} \frac{1+\cos\beta}{8} \qquad pulsed\ NMR$$

$$= \Delta f(0) \frac{1+\cos\beta}{2}$$

◆ Vortex state in bulk liquid



Continuous vortex

~ 10 μm

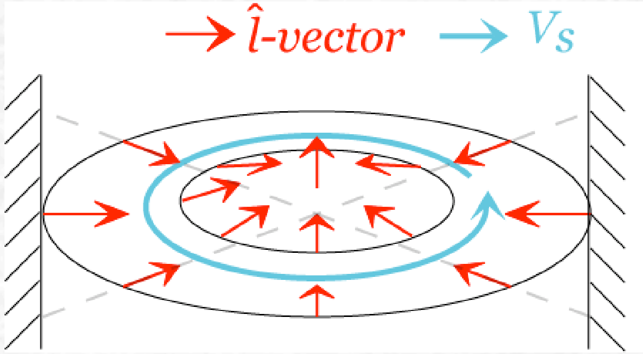
Coherence length

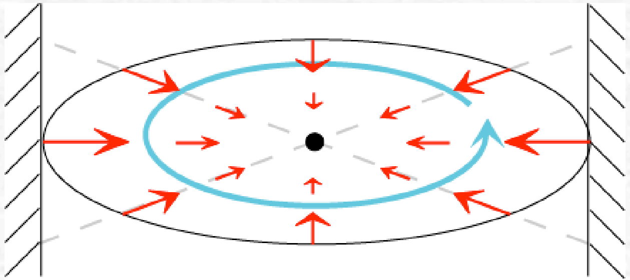
A phase	4 types
B phase	3 types

Vortex state in narrow space or complicated structure

- In thin cylinder (D=100, 200 μm) **A phase**
  - # diameter D ≈ ten times of dipolar healing length
  - ➡ { observed signal from new type of vortex core directly
  - a few interesting phenomena
- In slab between parallel plates (D=12 μm) **A phase**
  - # thickness D ≈ dipolar healing length
  - ➡ { observed a textural transition and vortices indirectly
  - but no signal from core
- In aerogel (98% porosity) **B-like phase**
  - ➡ { observed a textural transition and vortices indirectly
  - vortices pinned by aerogel

In thin cylinder of 200 μm radius



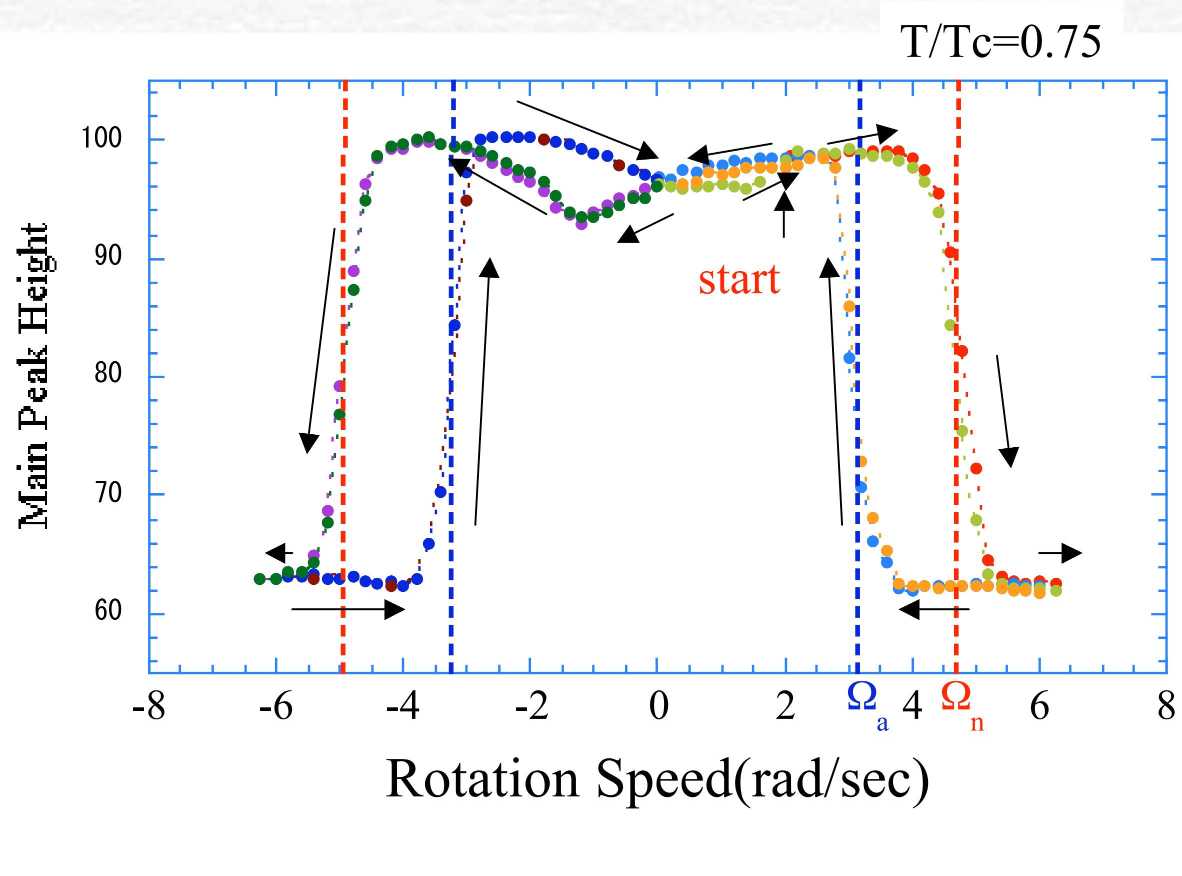


Mermin-Ho vortex Radial disgyration

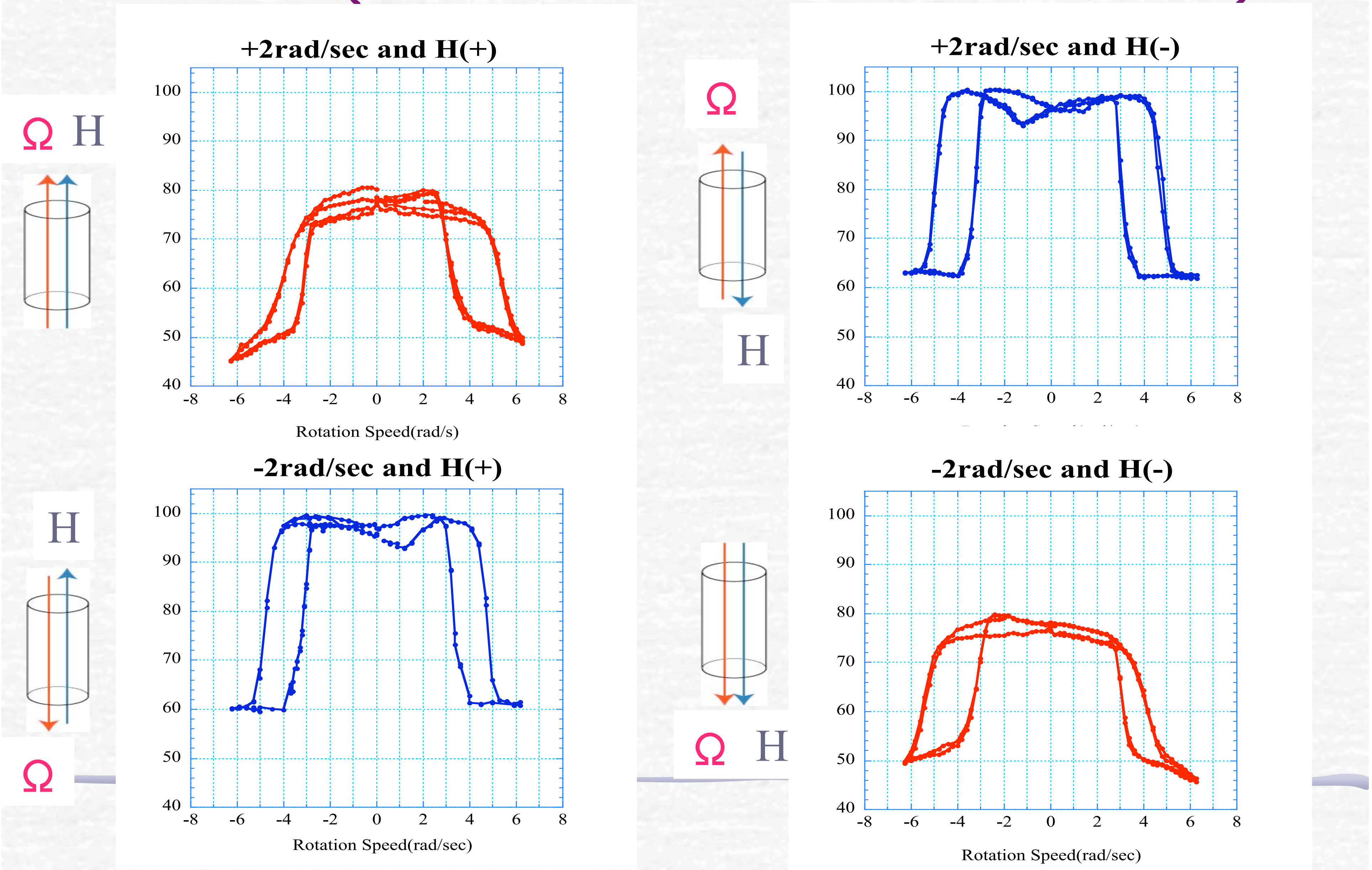
R. Ishiguro, *et. al.*, *Phys. Rev. Lett.* **93**, 125301 (2004)

Vortex is formed in cylinder by boundary and does not disappear by itself

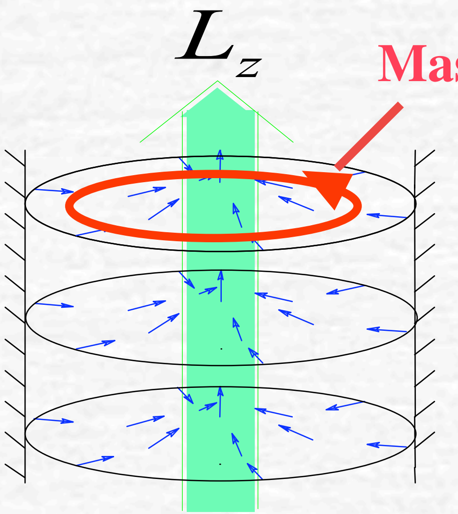
Creation and annihilation of vortex in thin cylinder



Gyromagnetic effect + Memory effect (Einstein de Hass or Barnett effect)



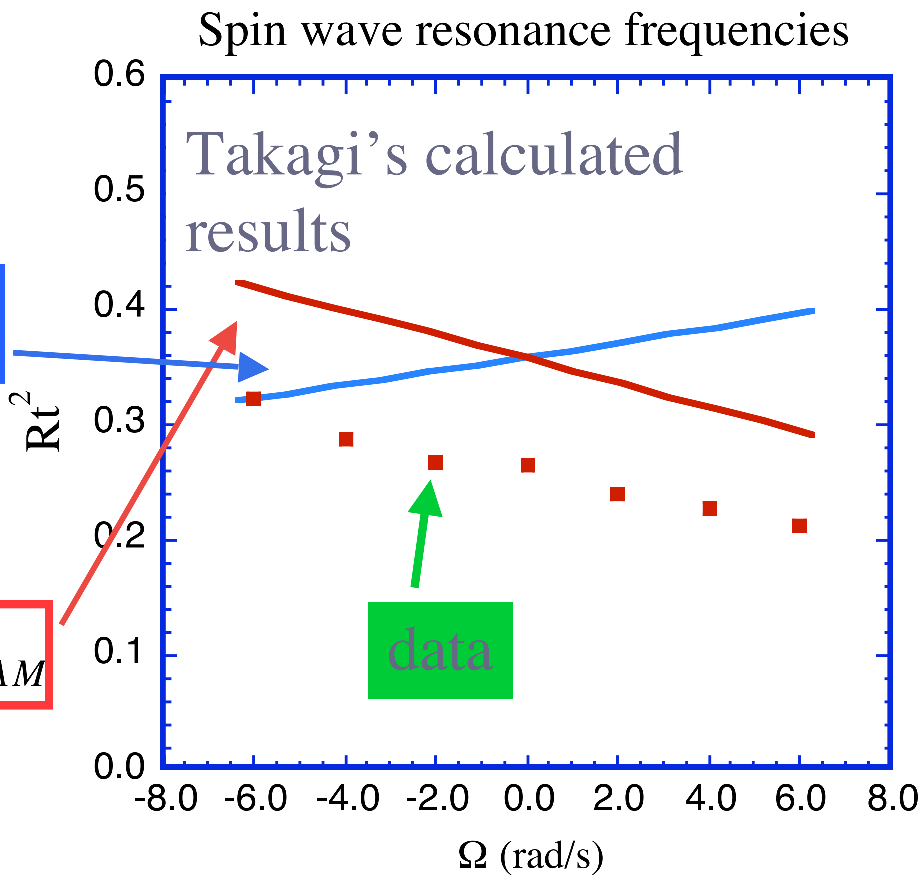
Change of satellite frequency in Mermin-Ho texture in 100 μm diameter



Mermin-Ho texture

$\vec{L} = \vec{L}_{massflow}$

$\vec{L} = \vec{L}_{massflow} + \vec{L}_{IAM}$



Intrinsic angular momentum of Cooper pair
(Angular momentum without mass current)

Problems of the Intrinsic Angular Momentum (IAM) in A phase

All pairs have the same angular momentum in A phase

(1) all pairs contribute to angular momentum

$$L_{\text{int}} = \frac{1}{2} N\hbar$$

(2) Cooper parings occur among particles near the Fermi energy

$$L_{\text{int}} = \frac{1}{2} N\hbar \times \frac{T_c}{T_F} \approx \frac{1}{2} N\hbar \times \frac{\Delta}{\varepsilon_F}$$

(3) cancellation occurs because coherence length ξ is much larger than inter atomic distance La

$$L_{\text{int}} \cong \frac{1}{2} N\hbar \left(\frac{\Delta}{\varepsilon_F}\right) \cdot \frac{L_a}{\xi} \approx \frac{1}{2} N\hbar \left(\frac{\Delta}{\varepsilon_F}\right) \cdot \frac{T_c}{T_F} \approx \frac{1}{2} N\hbar \left(\frac{\Delta}{\varepsilon_F}\right)^2$$

$$L_{\text{int}} \cong \frac{1}{2} N\hbar \left(\frac{\Delta}{\varepsilon_F}\right)^n$$

$$n = 0, or\ 1, or\ 2$$

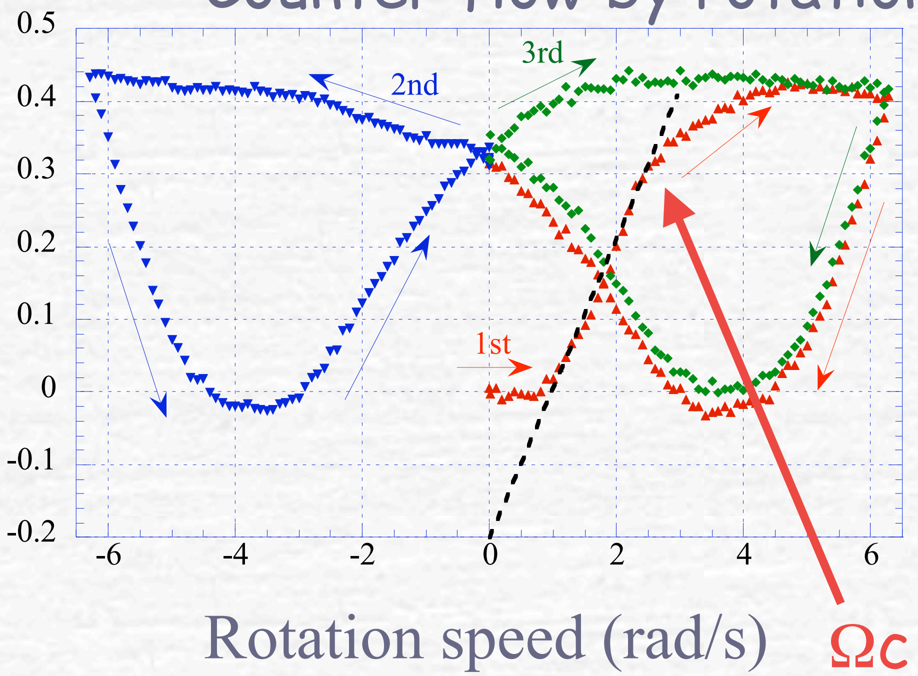
If n=0,

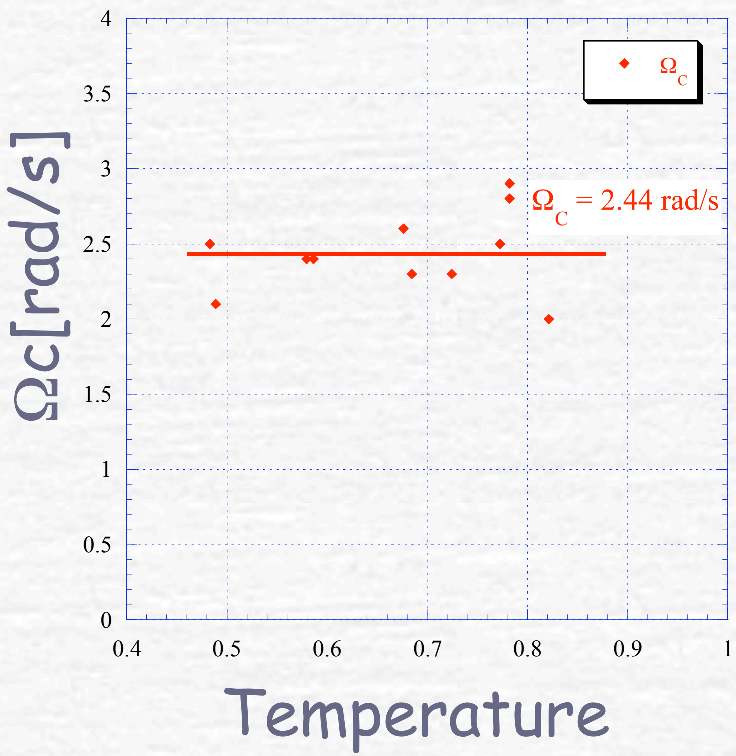
$$\vec{L}_{\text{int}} \approx \vec{L}_{flow}$$

Observable ?

Vortex pinning by aerogel and unpinning by Glaberson-Donnelly instability

Counter flow by rotation

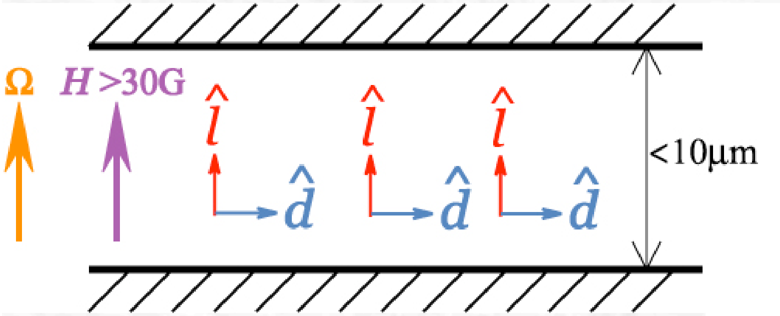




M.Yamashita, et al. *Phys. Rev. Lett.* **94**, 07530 (2005)

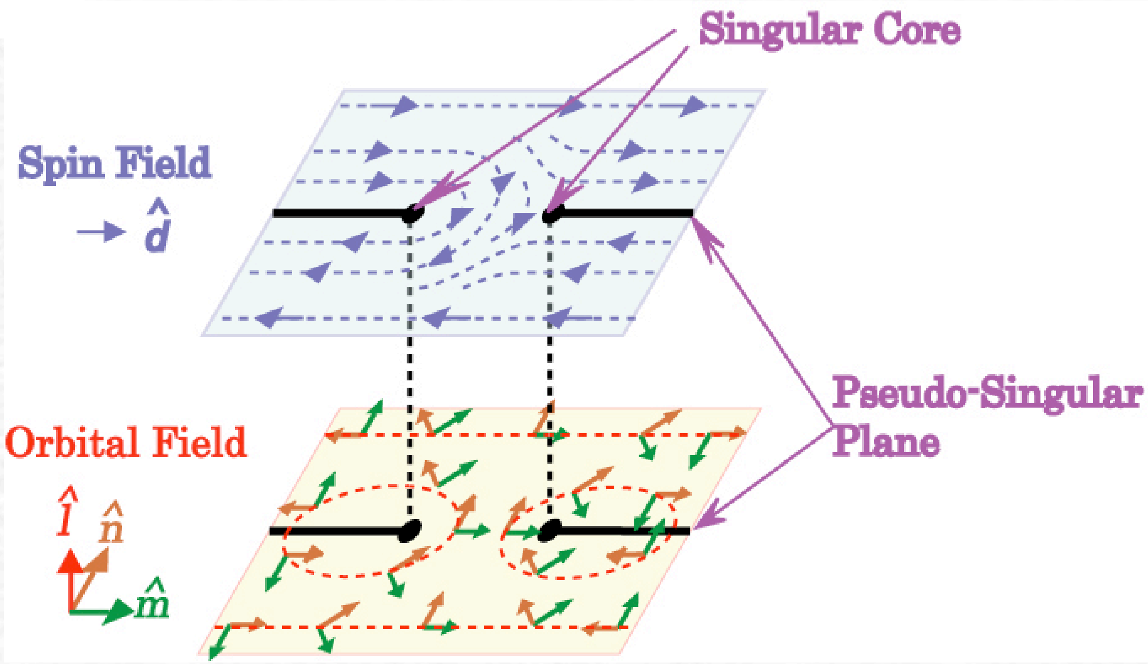
Half quantum vortex in A phase

- Parallel Plate



Half Quantum Vortex

$n = 1/2$, Phase π + Spin π



◆ Future research plans

- in aerogel at rest

  # phase transition mechanism between A-like and B-like phases
  # texture in aerogel in A-like and B-like phases
  # detection of A-like and B-like phases and loss mechanism in 4th sound

- in cylinder under rotation

  # mechanism of gyromagnetic effect in A phase

- in slab under rotation

  # Half quantum vortex in A phase ?

- in aerogel under rotation

  # investigate vortex core structure using homogeneous spin precession