INSTABILITY OF THE INTERFACE BETWEEN TWO SLIDING SUPERFLUIDS AND VORTEX FORMATION

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OVERVIEW

1. Vortex formation in ^{3}He-A and ^{3}He-B.

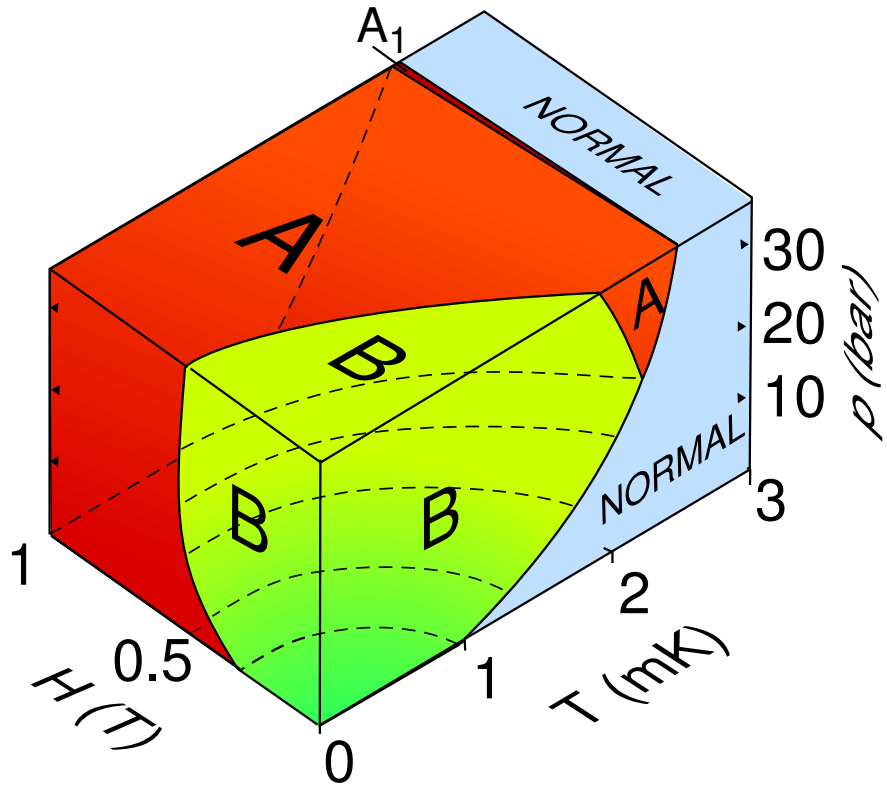
2. Observation of vortex formation triggered by instability of the AB interface.

3. Properties of vortex formation process.

4. Controlling shape of the AB interface with magnetic field.

SUPERFLUID ^{3}He

Fermi system with pairing in $S = 1$ and $L = 1$ state.



Two major superfluid phases, A and B:

- 1st order phase transition, controlled by magnetic field,
- superfluid phase boundary.

Various kinds of unconventional quantized vortices in rotation.

Non–trivial vortex formation mechanisms can be studied.

ROTATION OF SUPERFLUIDS AND CRITICAL VELOCITY

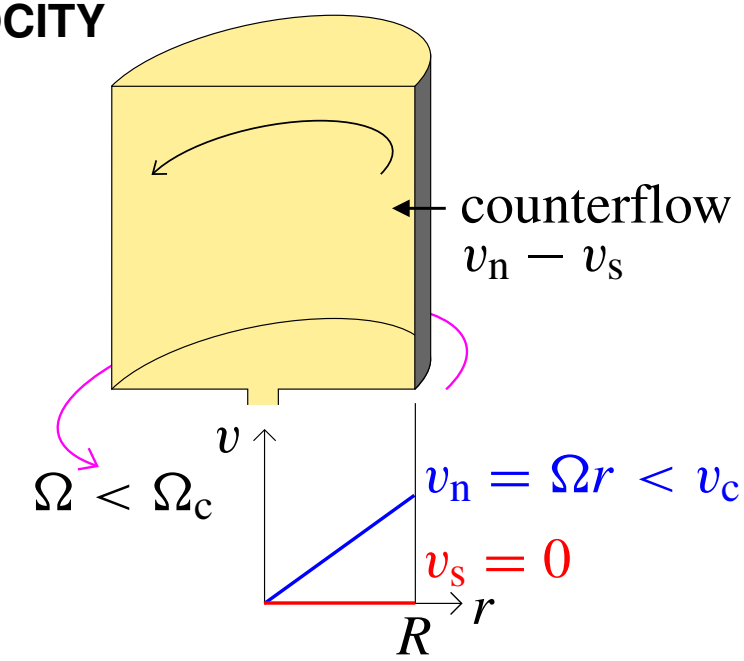
Vortex lines are energetically favourable at

$$\Omega > \Omega_{c1} = \frac{\nu\kappa}{2\pi R^2} \ln \frac{R}{a}$$

κ – quantum of circulation ν – vortex line charge

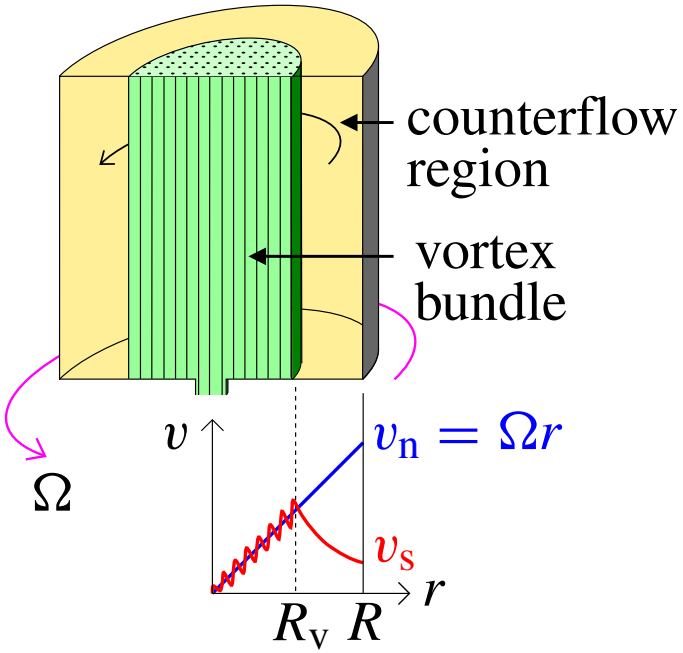
a – vortex line core size R – sample radius

$\Omega_{c1} \sim 10^{-2}$ rad/s in a sample of $R \sim$ few mm.



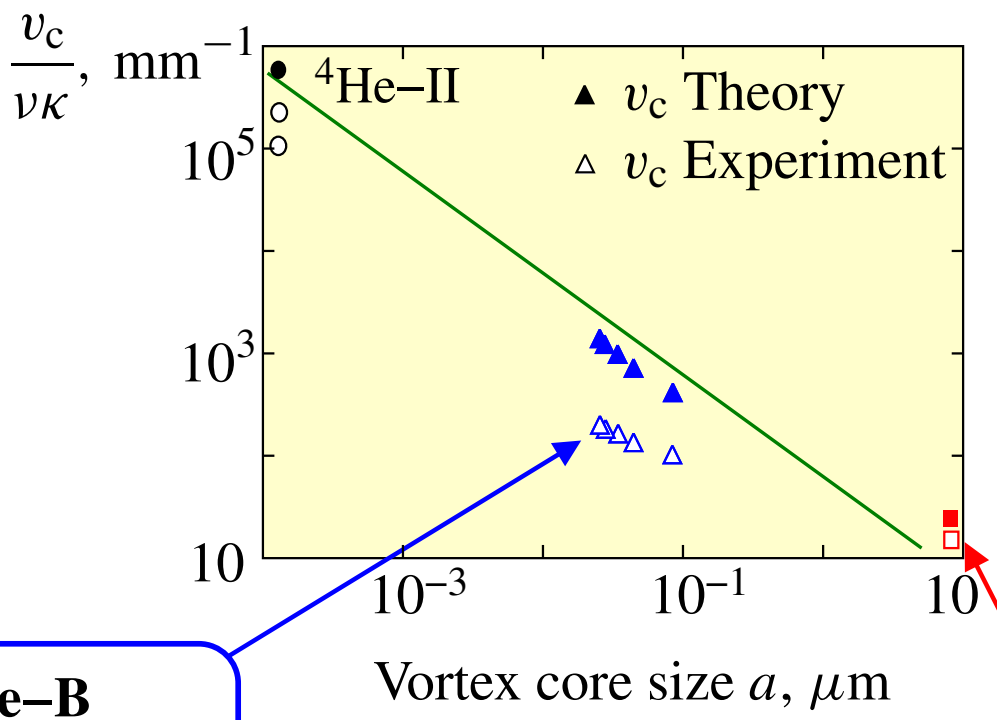
However in superfluid ^{3}He:

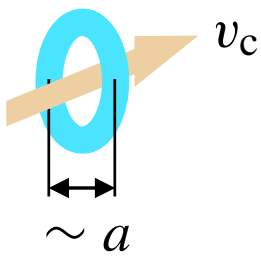
- Vortex-free rotation up to $\Omega_c \sim 1$ rad/s $\gg \Omega_{c1}$.
- Counterflow $v_n - v_s < v_c = \Omega_c R$ in macroscopic volume.
- Vortex formation at Ω_c is non-trivial process which occurs through some **instability**.



VORTEX FORMATION BY FLOW INSTABILITY

$$\text{flow energy} \sim \text{small loop energy} \Rightarrow \rho_s v_c^2 a^3 \sim \rho_s \nu^2 \kappa^2 a \Rightarrow v_c \sim \frac{\nu\kappa}{2\pi a}$$

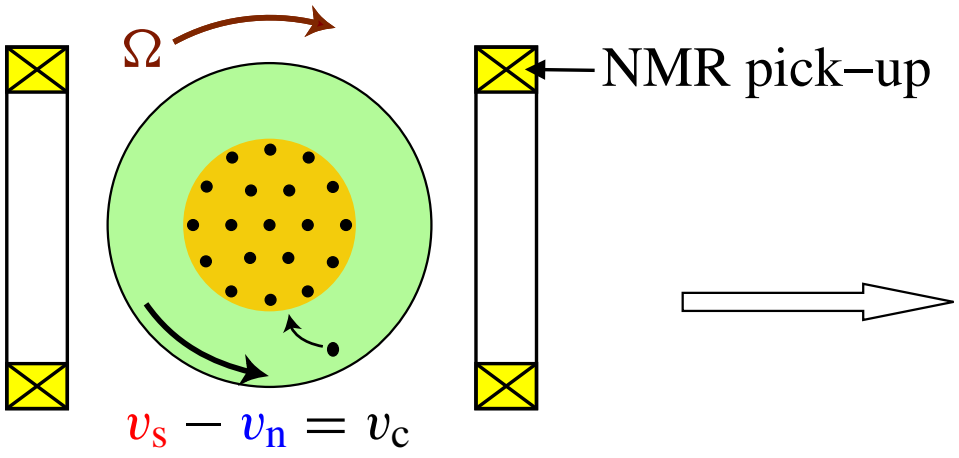




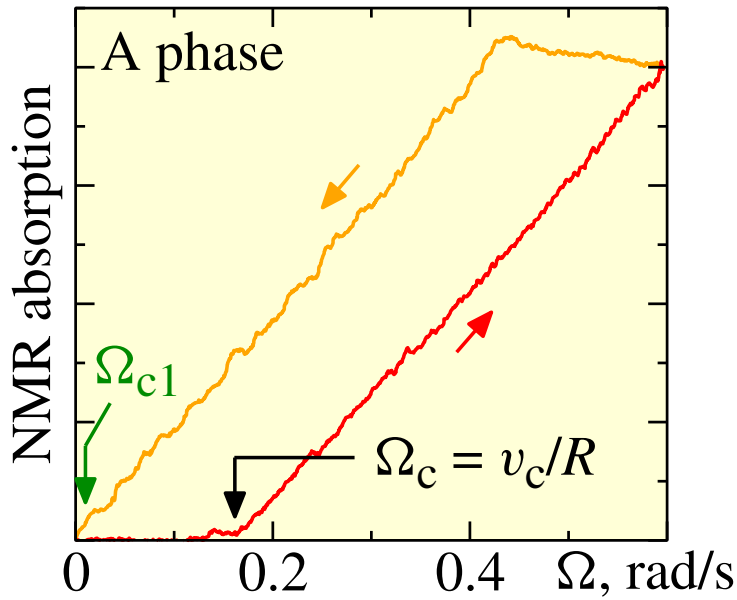
^{3}He–B
hard core
$\nu = 1$
$a \sim \xi \sim 0.01\,\mu$m

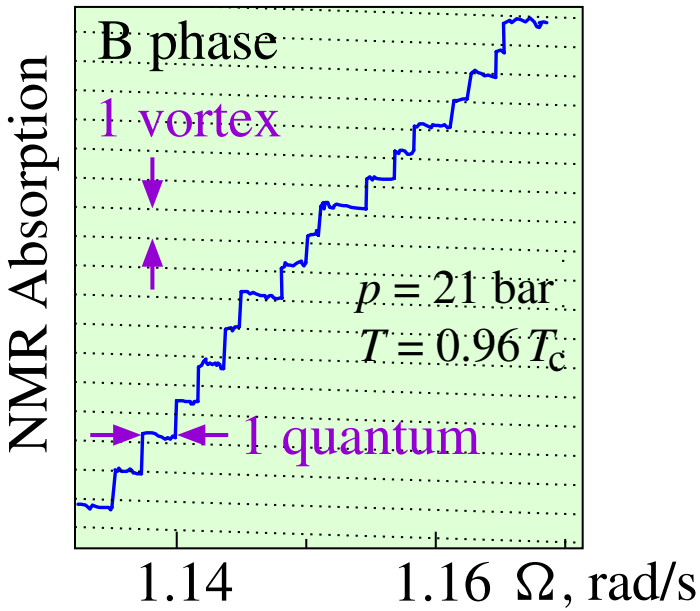
^{3}He–A
continuous vorticity
$\nu = 2$
$a \sim \xi_D \sim 10\,\mu$m

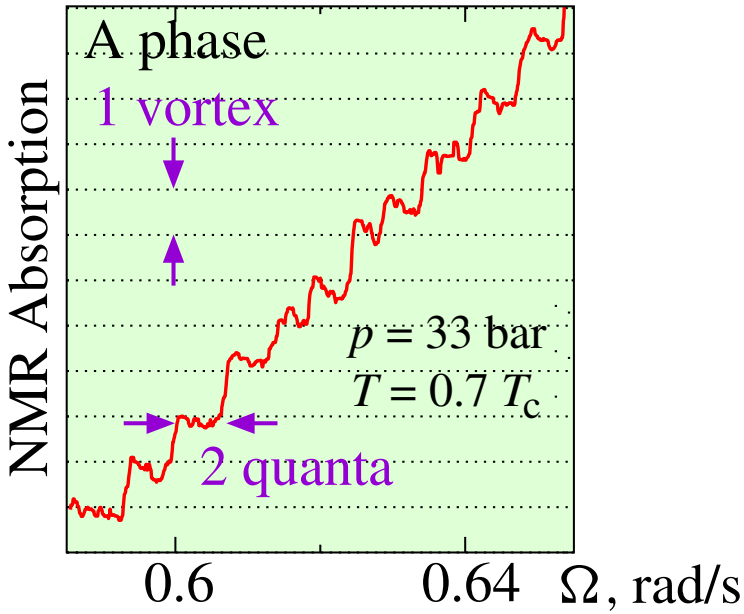
NMR OBSERVATIONS OF VORTEX FORMATION



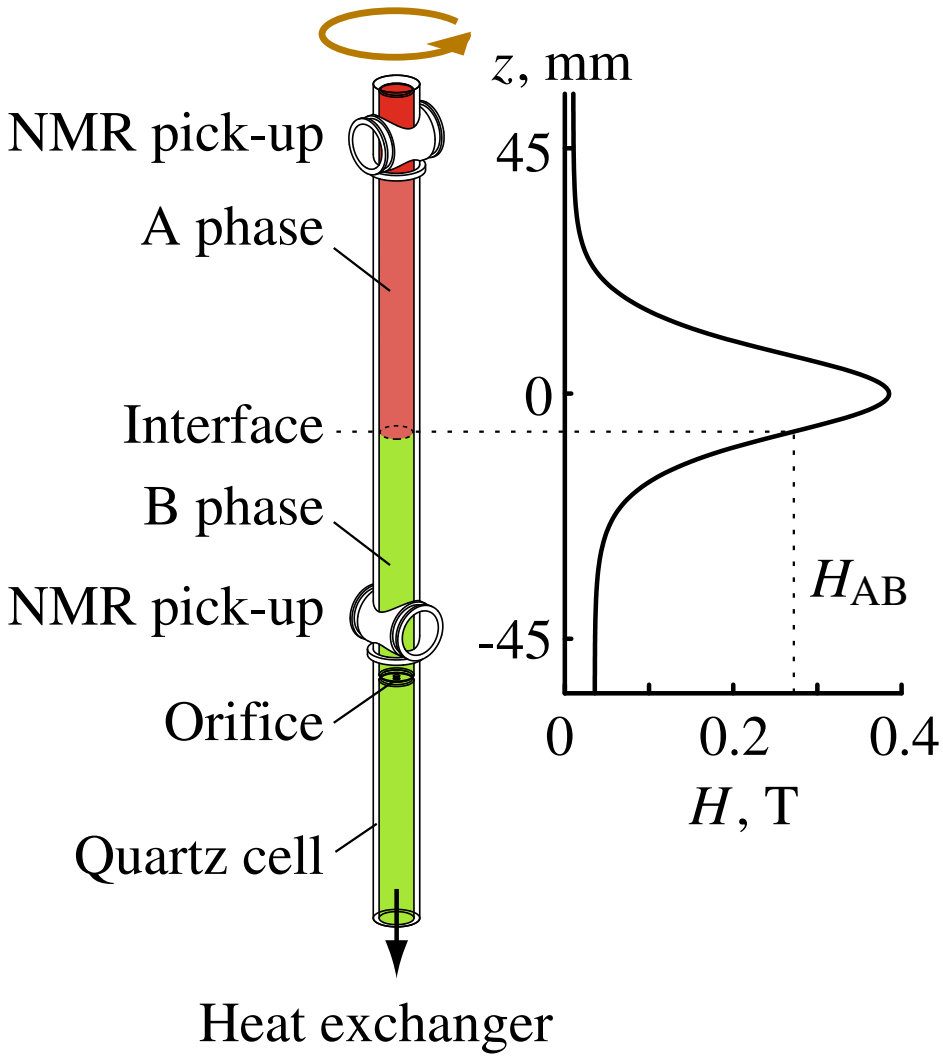
vortex formation
one by one at the outer sample boundary

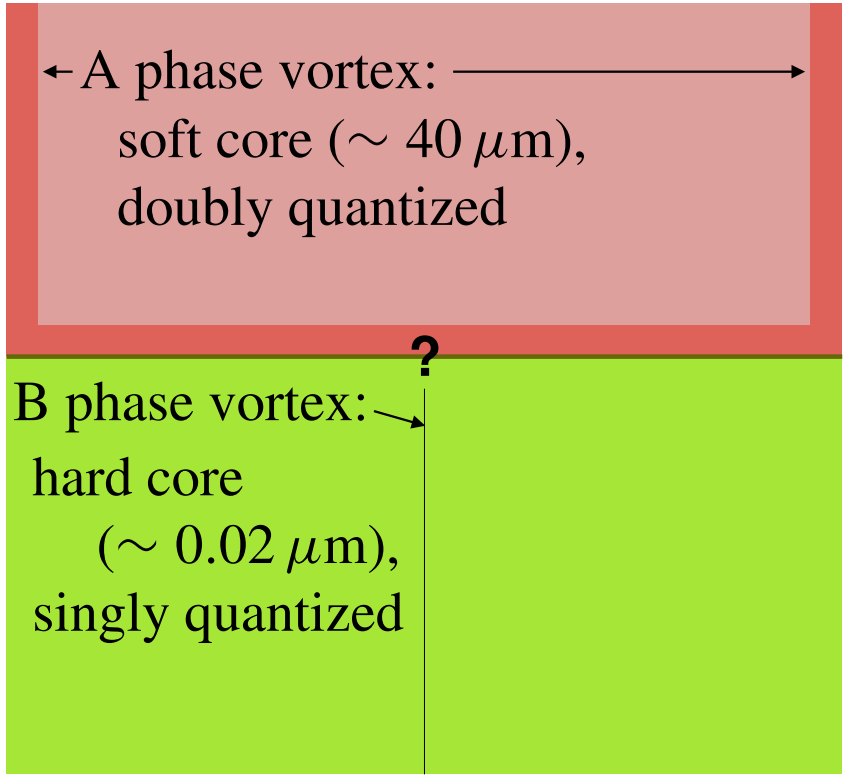




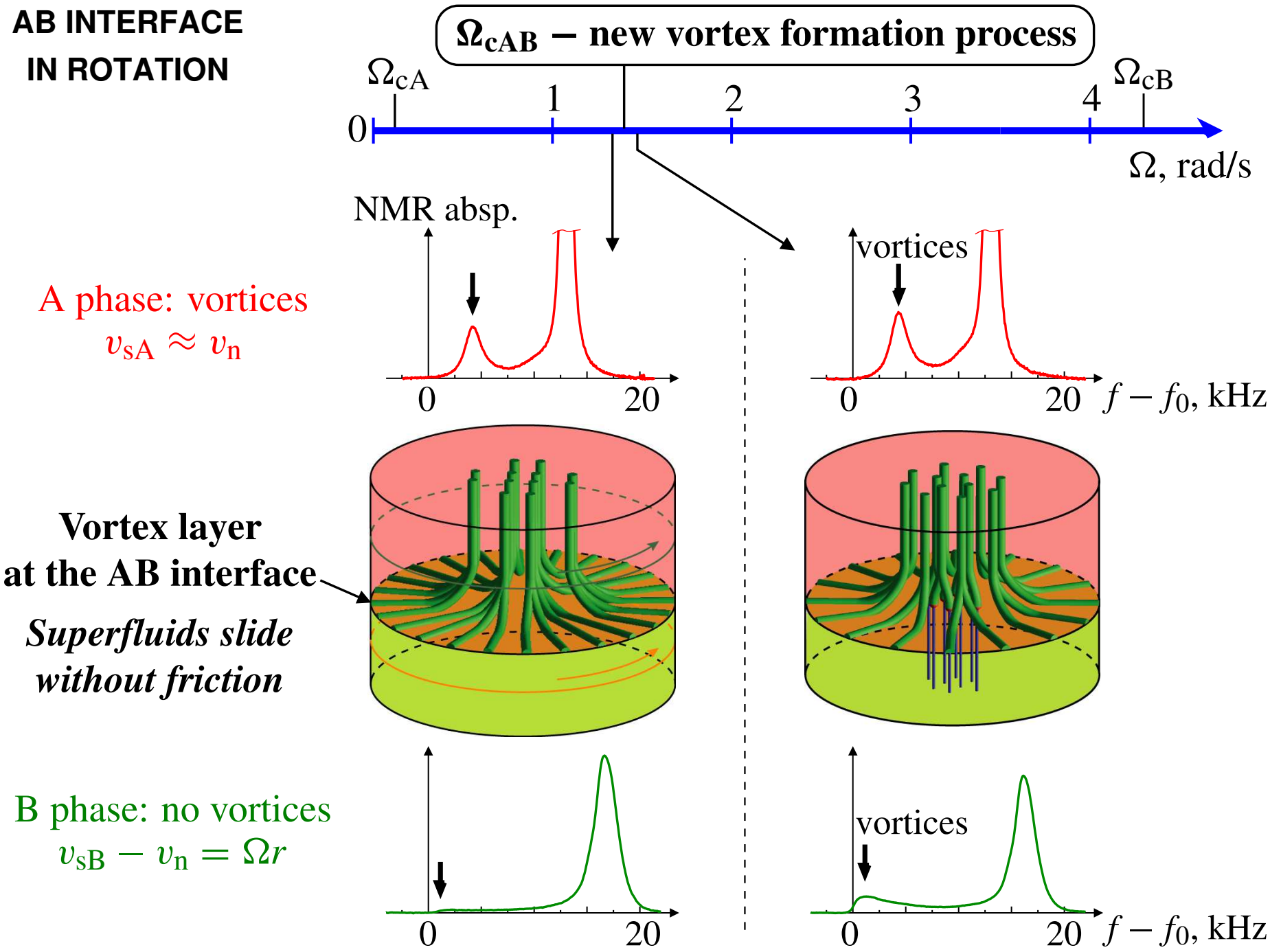


QUESTION: VORTICES AND AB INTERFACE

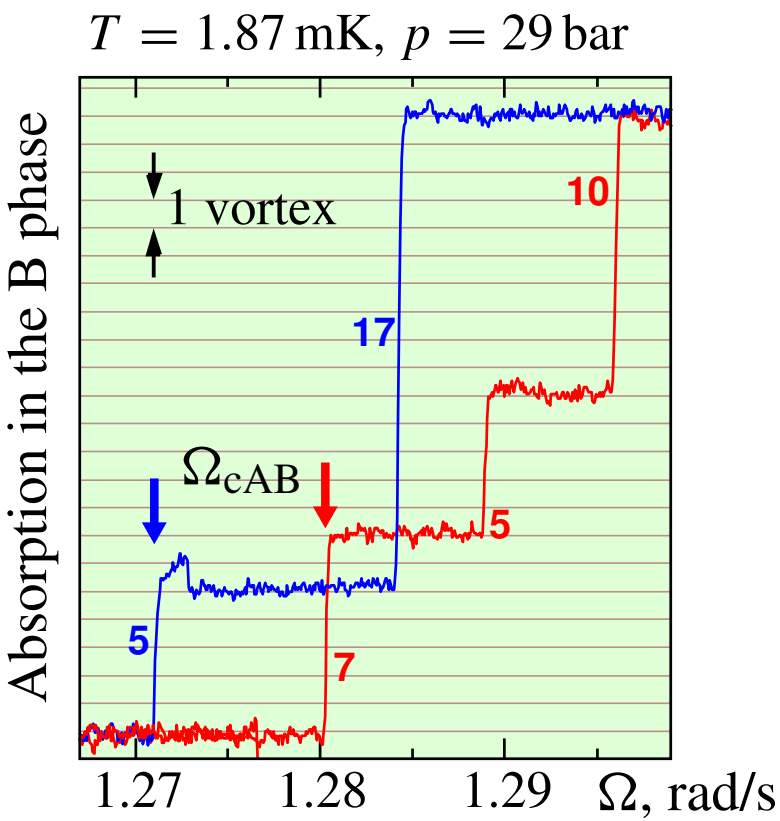


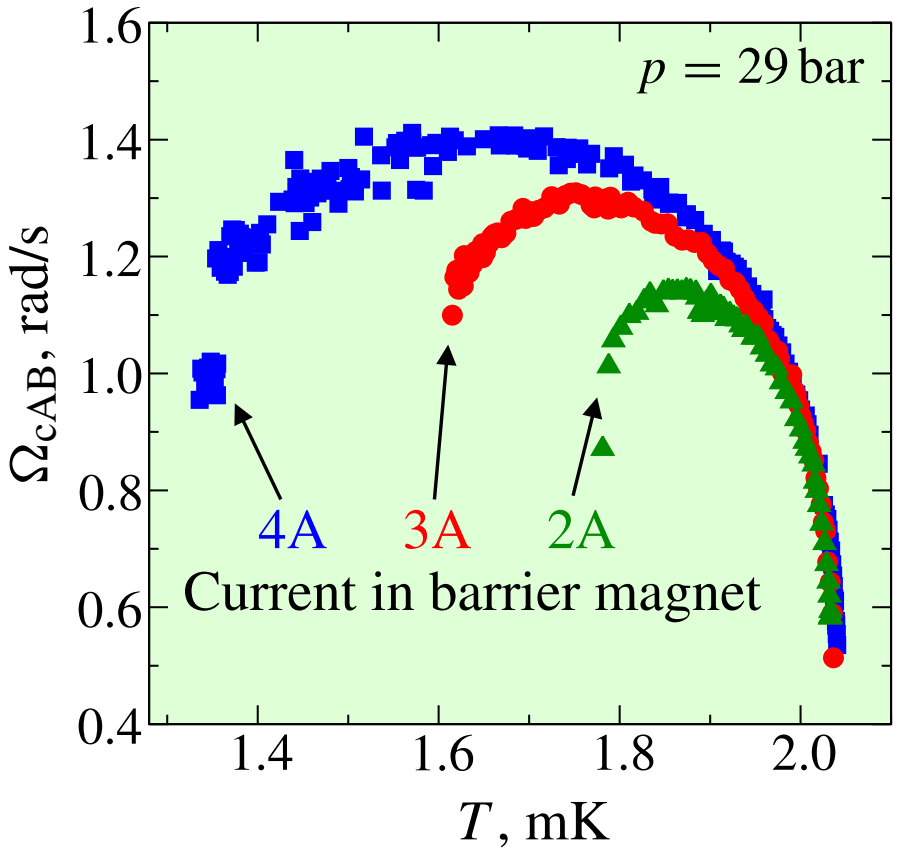


AB INTERFACE IN ROTATION



NEW VORTEX FORMATION PROCESS

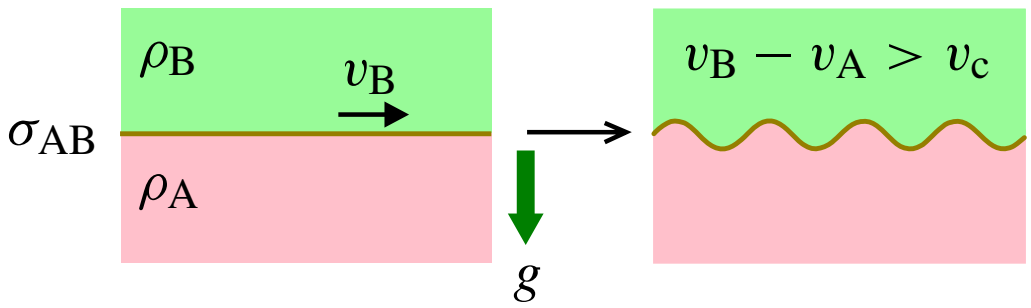




- New critical velocity $\Omega_{cAB} < \Omega_{cB}$.
- Ω_{cAB} depends on pressure, temperature and **barrier field**.
- In one event $\Delta N_B \sim 10$ vortices form.

INSTABILITY OF THE AB INTERFACE

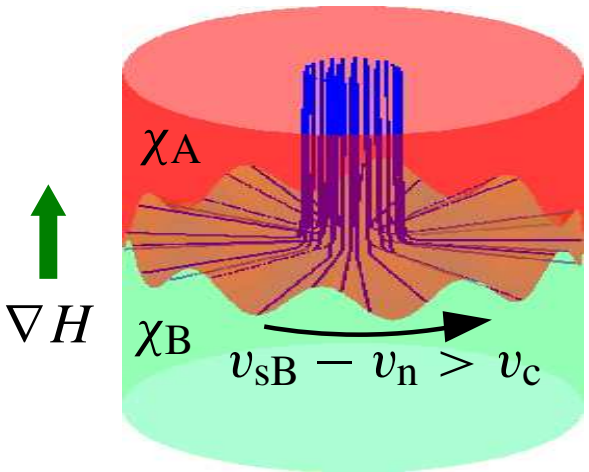
Kelvin–Helmholtz instability in classical liquids (Lord Kelvin, 1871):



$$\frac{1}{2}\frac{\rho_A \rho_B}{\rho_A + \rho_B}(v_B - v_A)^2 = \sqrt{\sigma_{AB} F_R}$$

$$F_R = (\rho_A - \rho_B) g$$

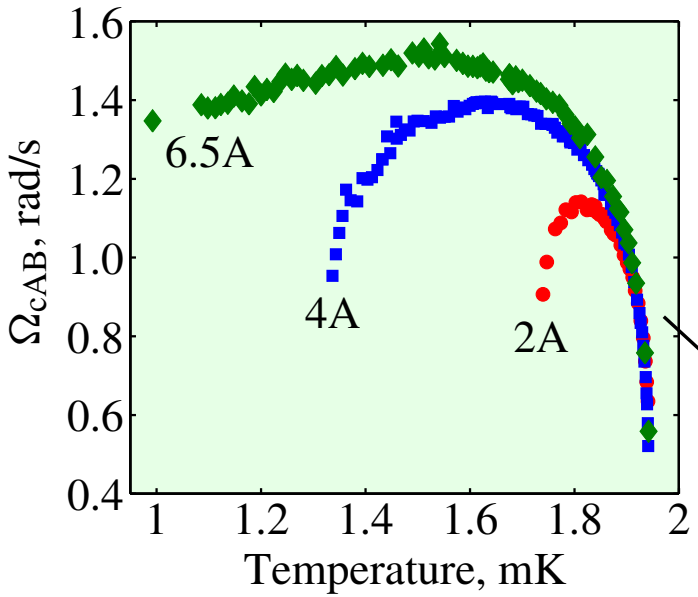
Modified in two–fluid hydrodynamics (G.E. Volovik):



$$\frac{1}{2}\rho_{sA}(v_{sA} - v_n)^2 + \frac{1}{2}\rho_{sB}(v_{sB} - v_n)^2 = \sqrt{\sigma_{AB} F_R}$$

$$F_R = (\chi_A - \chi_B) H_{AB} (\nabla H)_{H = H_{AB}}$$

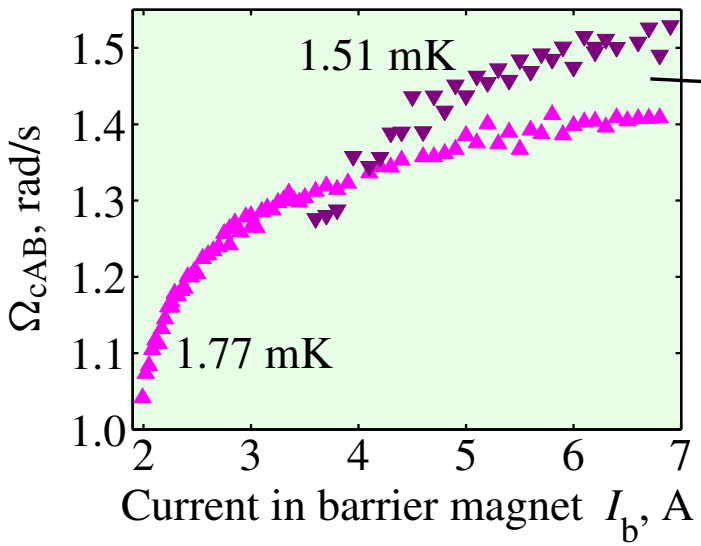
SCALING OF THE CRITICAL VELOCITY

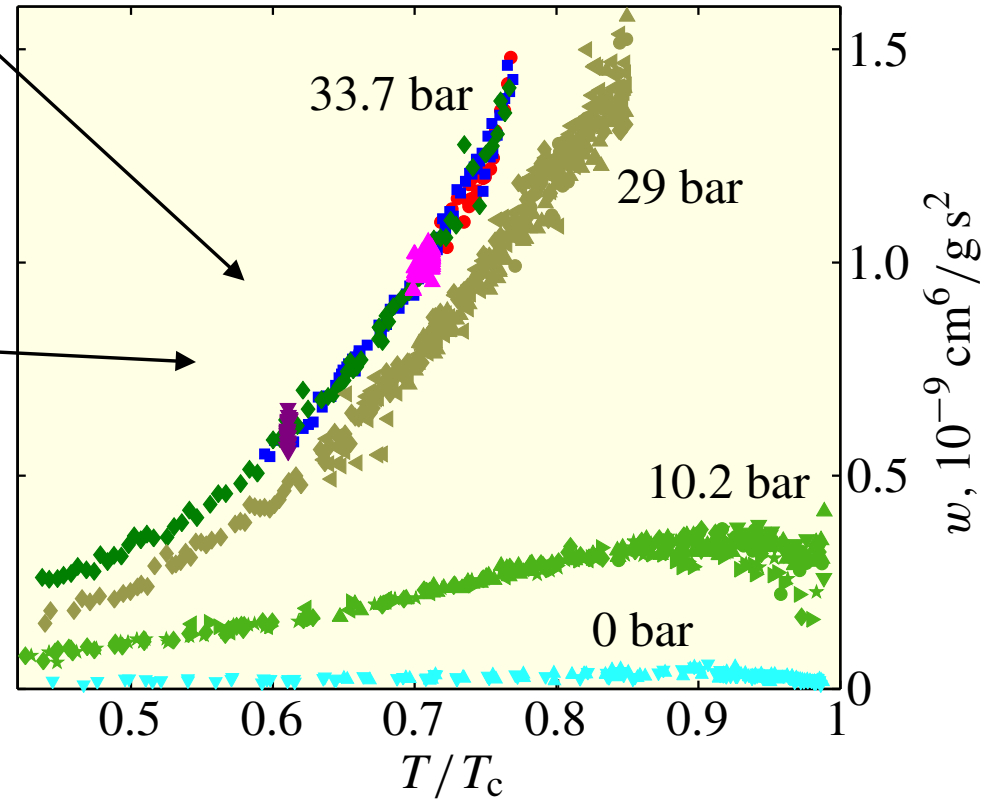


According to the theory

$$w = \frac{(\Omega_{cAB} R)^4}{2\nabla(H^2)} = \frac{\sigma_{AB}(\chi_A - \chi_B)}{\rho_{sB}^2}$$

is function of only T, P.

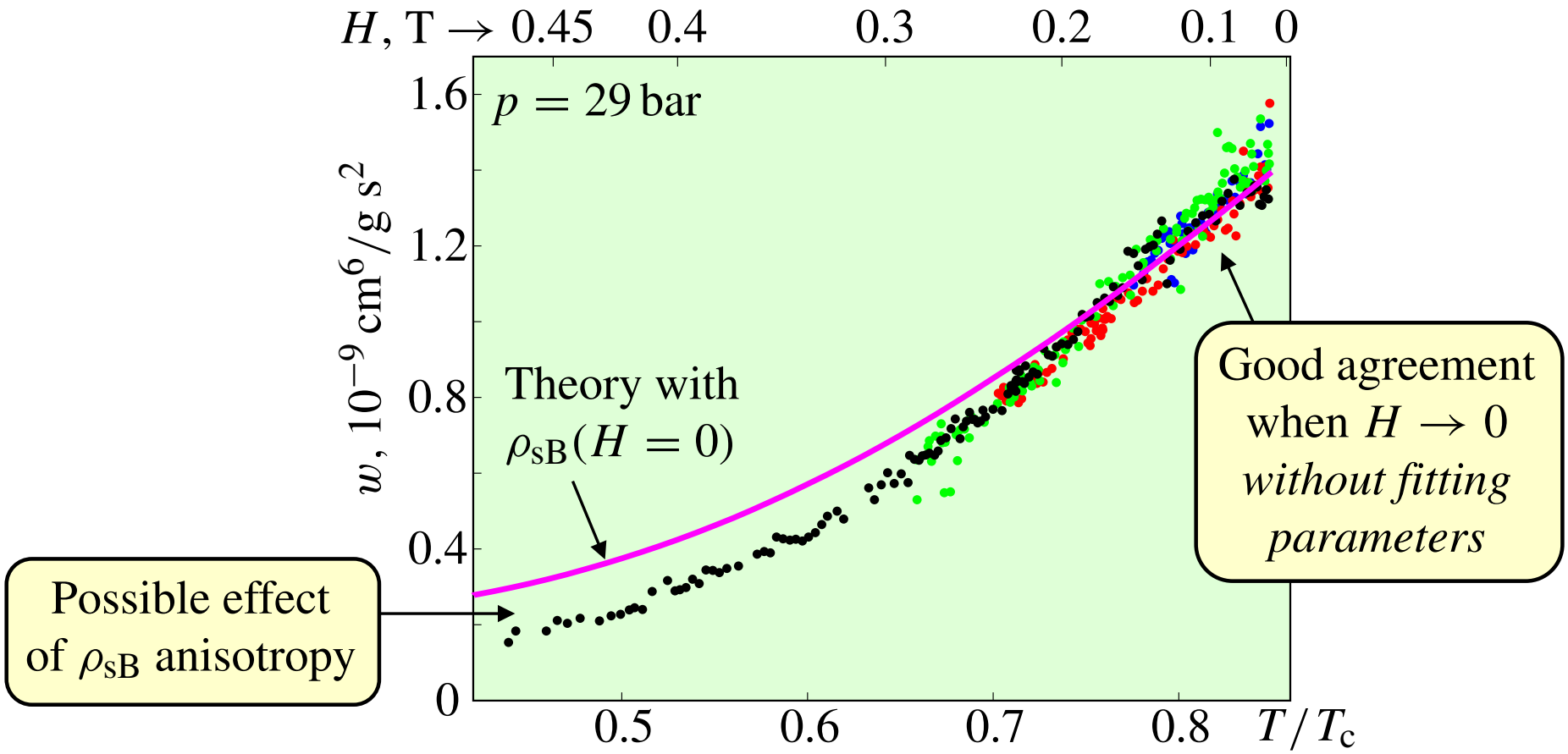




COMPARISON OF THEORY AND EXPERIMENT

$$\text{Experiment} \rightarrow \quad \frac{(\Omega_{\mathrm{cAB}} R)^4}{2\nabla(H^2)|_{H=H_{\mathrm{AB}}}} = w = \frac{\sigma_{\mathrm{AB}}(\chi_{\mathrm{A}} - \chi_{\mathrm{B}})}{\rho_{\mathrm{sB}}^2} \quad \leftarrow \text{Theory}$$

(^{3}He data: Hahn 1993, Osheroff & Cross 1977, Scholz 1993)

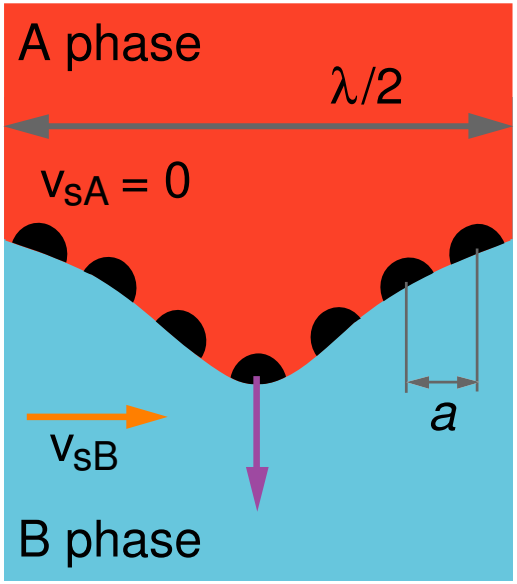


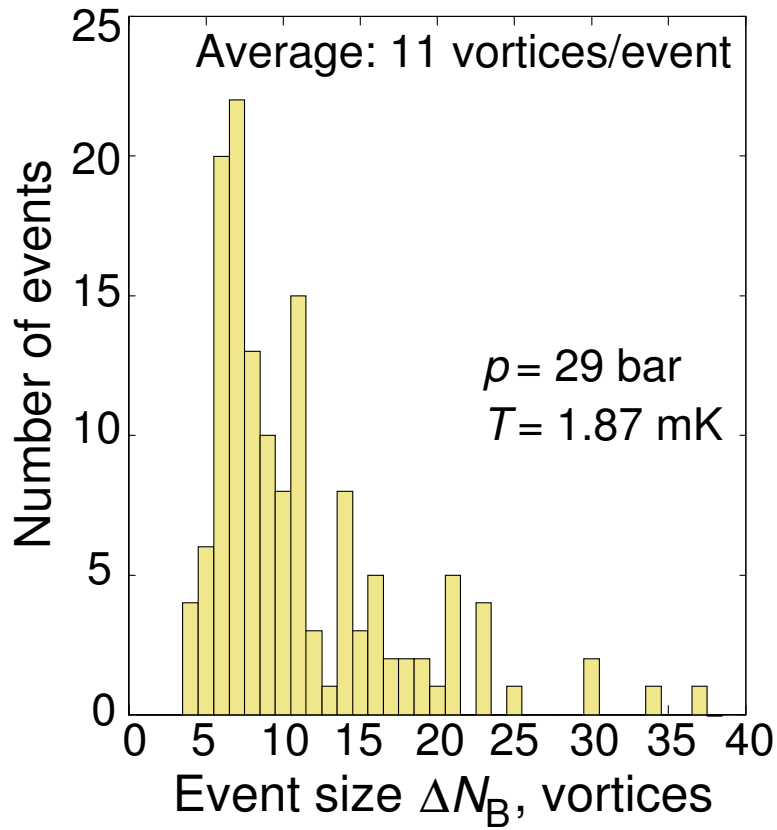
Extension of theory to anisotropic ρ_{s} is work in progress (J. Kopu & T. Ruokola)

HOW THE INTERFACE INSTABILITY EXPLAINS EVENT SIZE

How many vortices are formed simultaneously?

Answer: roughly as many as fit to $\lambda/2$ of the instability.





$$v_{\mathrm{sB}} \approx \Omega_{\mathrm{cAB}} R = 0.4\,\mathrm{cm/s} \text{ at } T = 1.87\,\mathrm{mK}$$

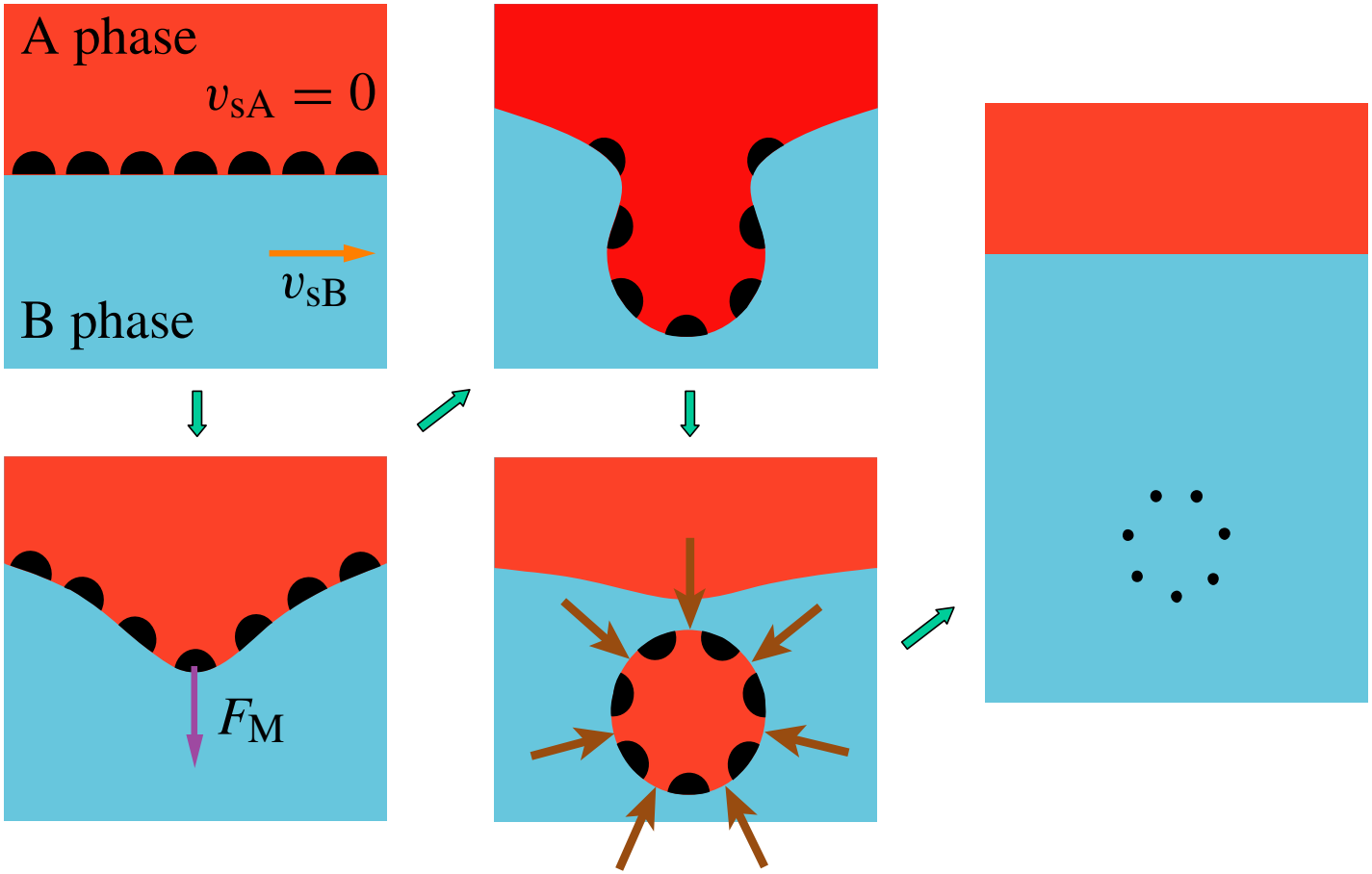
$$\lambda = 2\pi\sqrt{\frac{F_{\mathrm{R}}}{\sigma_{\mathrm{AB}}}} = \frac{4\pi\sigma_{\mathrm{AB}}}{\rho_{\mathrm{sB}} v_{\mathrm{sB}}^2} \approx 280\,\mu\mathrm{m}$$

$$a = \kappa / v_{\mathrm{sB}} \approx 17\,\mu\mathrm{m}$$

$$\Delta N_{\mathrm{B}} \sim \frac{\lambda}{2a} \approx 8$$

VORTEX FORMATION THROUGH THE INTERFACE INSTABILITY

Creation of B-phase vortices with hard cores requires concentration of flow energy from 10 μm to 0.01 μm scale. How does the interface instability with wavelength $\lambda \sim 300\,\mu\mathrm{m}$ assist in this process?



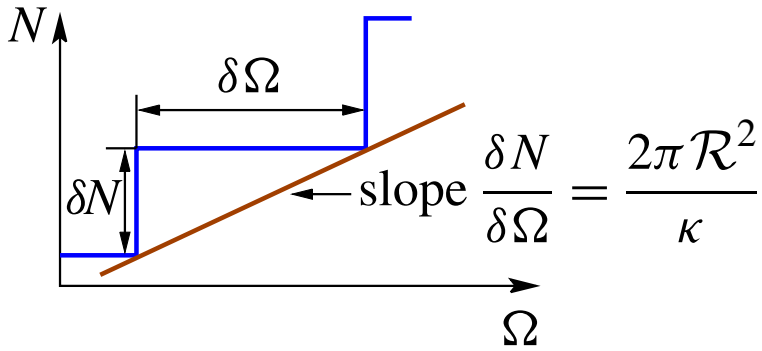
WHERE ARE VORTICES CREATED AT THE INTERFACE?

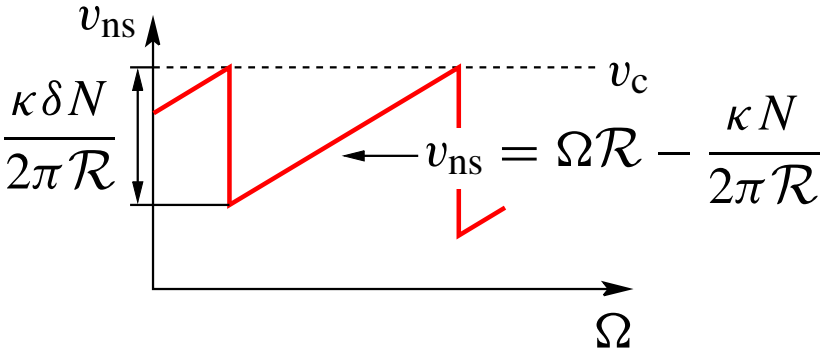
Interface should be first destabilized close to the wall of the sample.

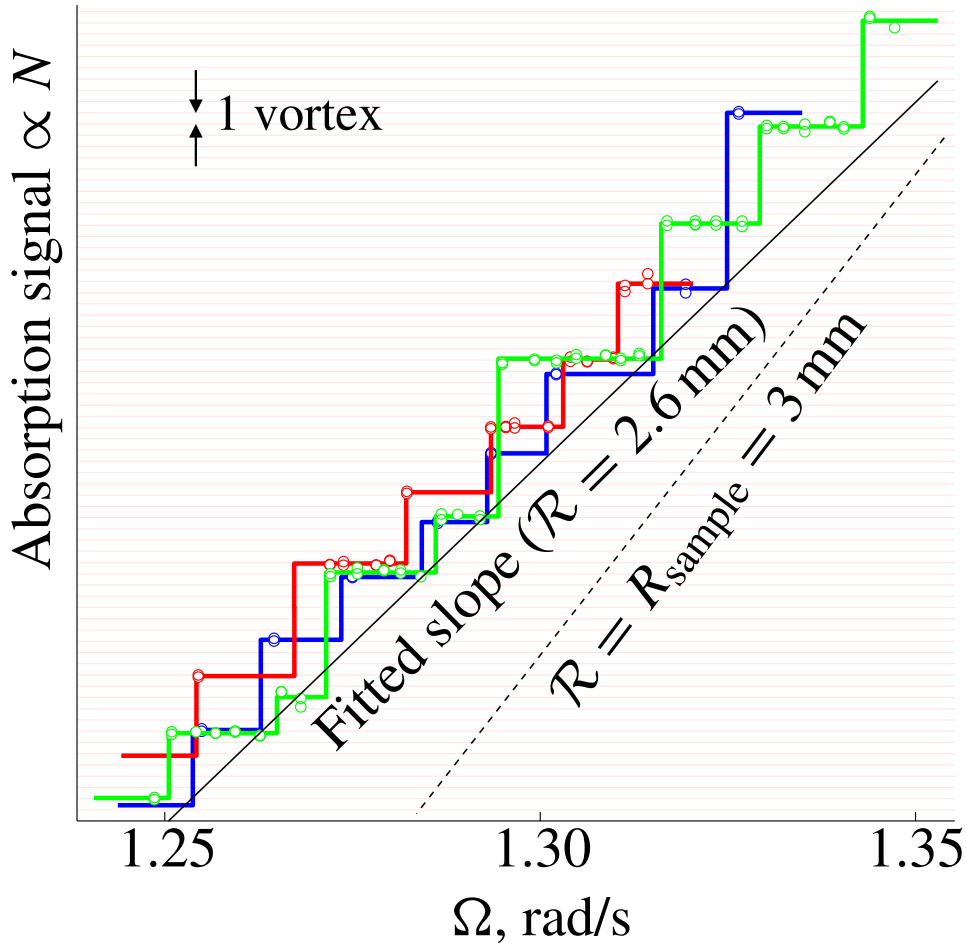
How to see?

Periodic formation with $\dot{\Omega} > 0$:

- effective radius $\mathcal{R} = \text{const}$,
- critical velocity $v_c = \text{const}$.

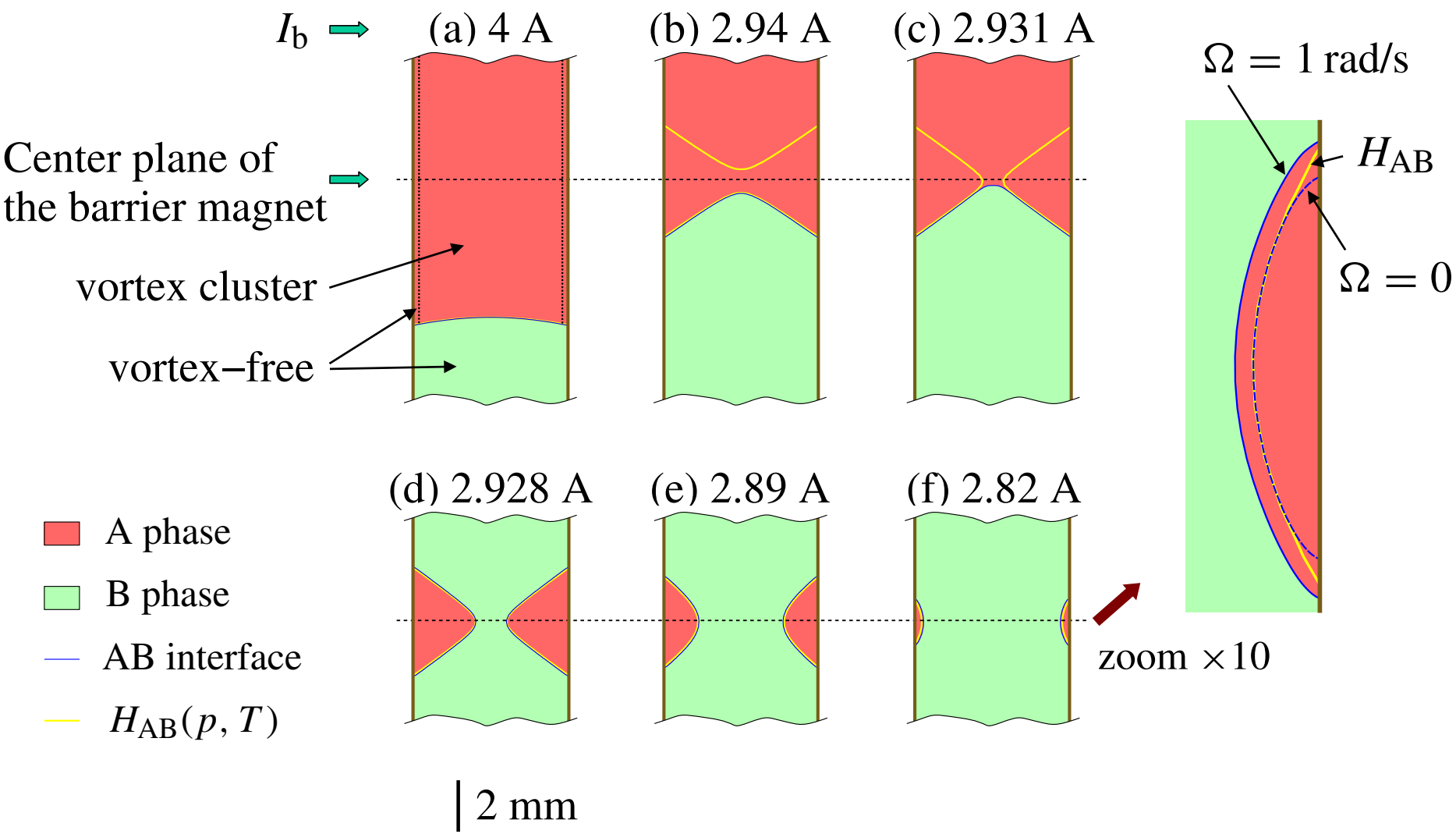






$$\mathcal{R} = 2.64 \pm 0.04\,\text{mm}$$

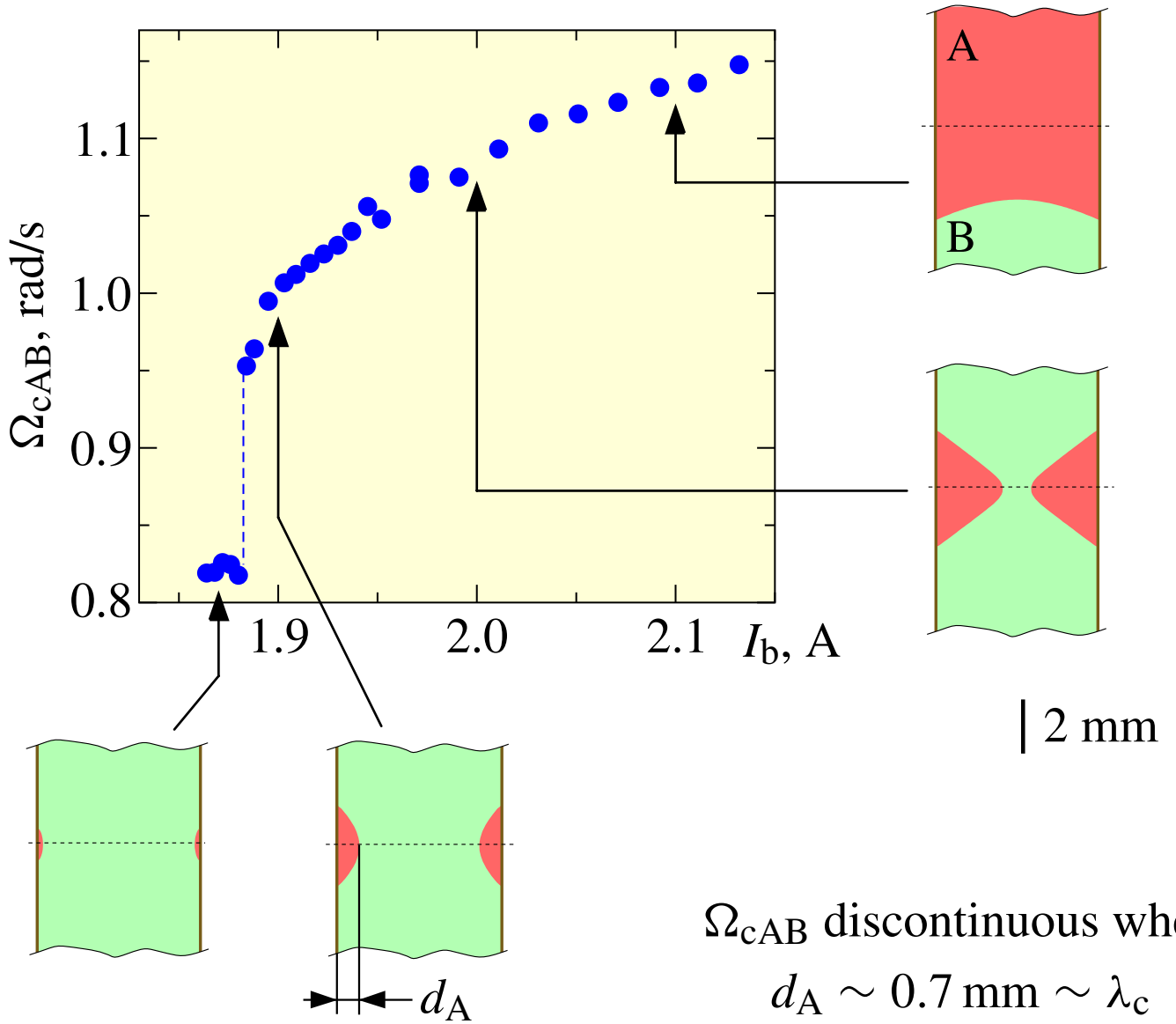
CONTROLLING SHAPE OF THE AB INTERFACE WITH MAGNETIC FIELD



Energy minimization including magnetic, surface and kinetic energy at $p = 29$ bar, $T = 1.616$ mK, $\Omega = 1$ rad/s, $\Omega_{cA} = 0.15$ rad/s.

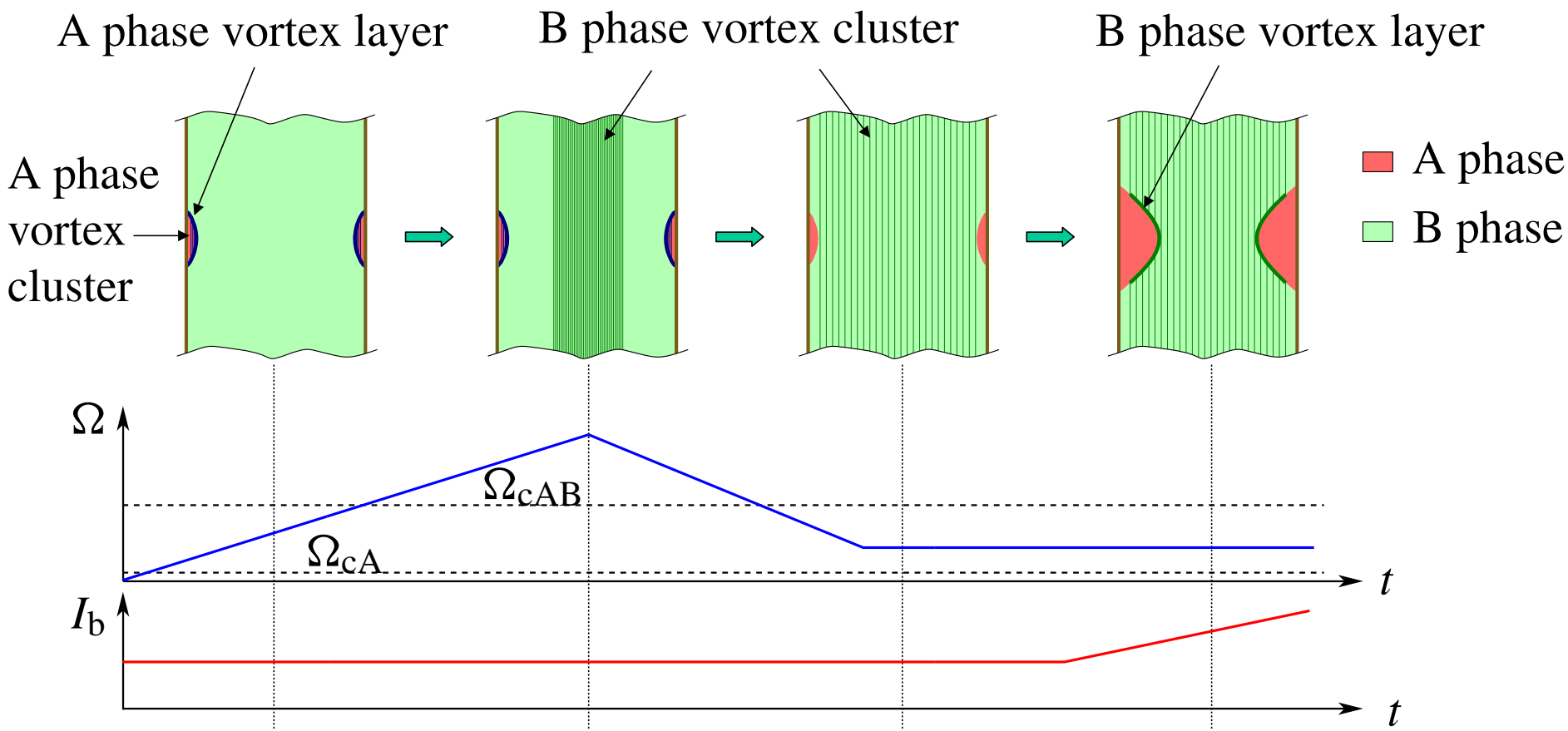
AB INTERFACE INSTABILITY AND RESTRICTED A PHASE GEOMETRY

$p = 29$ bar
$T = 1.81$ mK



Ω_{cAB} discontinuous when
$d_A \sim 0.7\,\text{mm} \sim \lambda_c$

INTERACTION OF B PHASE VORTICES WITH AB INTERFACE

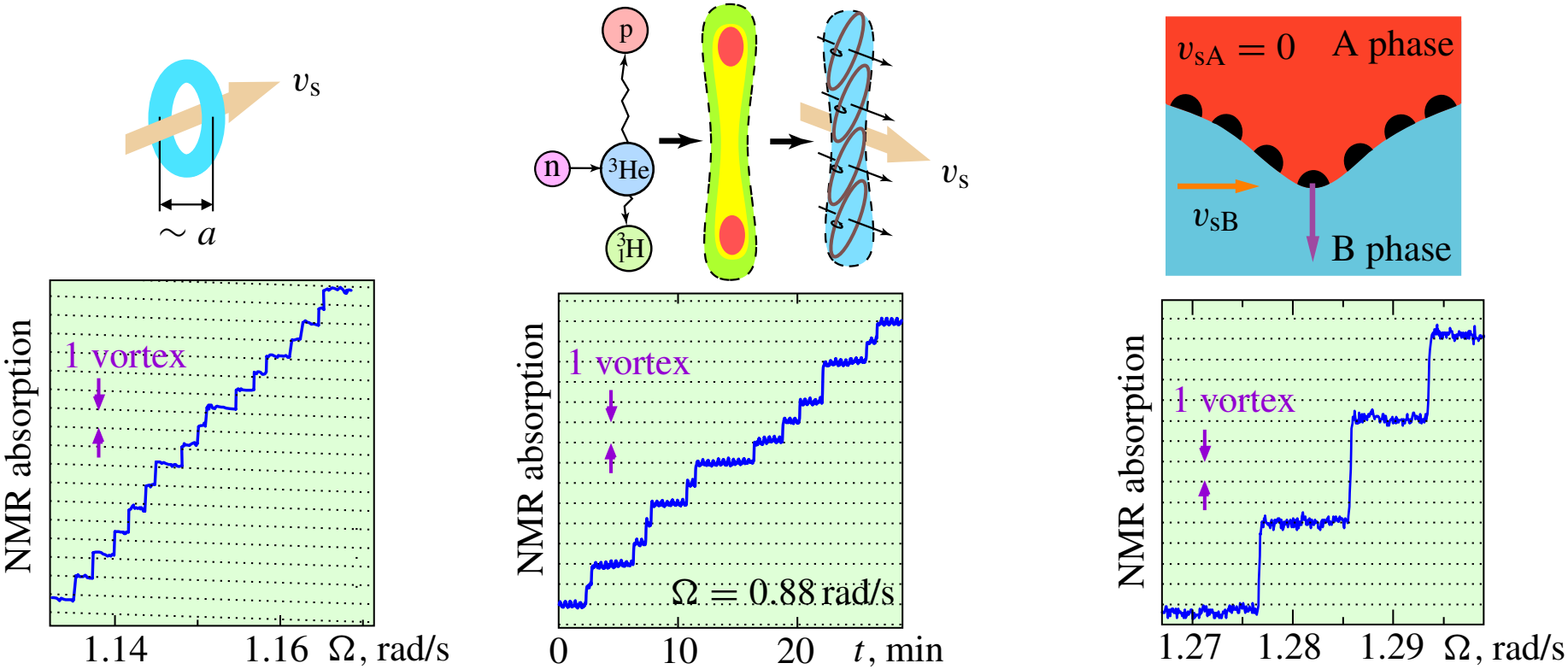


No traces of the hard cores of the B phase vortices are left in the A phase $\Rightarrow$ hard cores are "dissolved" to the continuous A-phase textures by interaction with the AB interface.

CONCLUSION

- AB interface stabilizes vortex layer and shear flow (at low velocities).
- Instability of the AB interface is a new mechanism of vortex formation.

Bulk flow instability *Fast NS transition in superflow* *Shear−flow interface instability*



- May be applicable to other types of interfaces (f.e. normal-superfluid).
- Useful tool for injection of vortices into the B-phase superflow.