

可視化技術を使った
狭隘2次元流路内における
超流動ヘリウム中の膜沸騰現象の解明

高田 卓, (筑波大学)

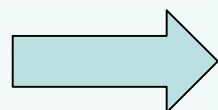
研究背景

実応用上での狭小な冷却流路

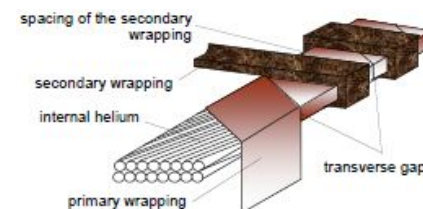
⇒ 狭小流路内における
He II沸騰現象

開放空間→2次元狭隘流路

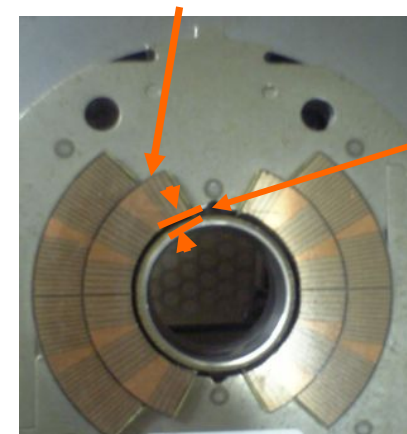
可視化実験(高田)



なぜ始めたか？



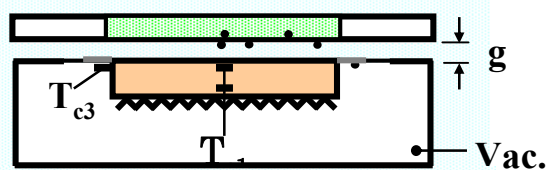
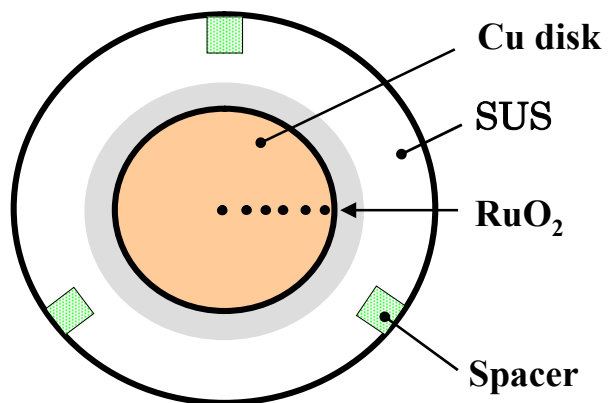
Confined He II (1 atm)
In Narrow channel ($<100 \mu\text{m}$)



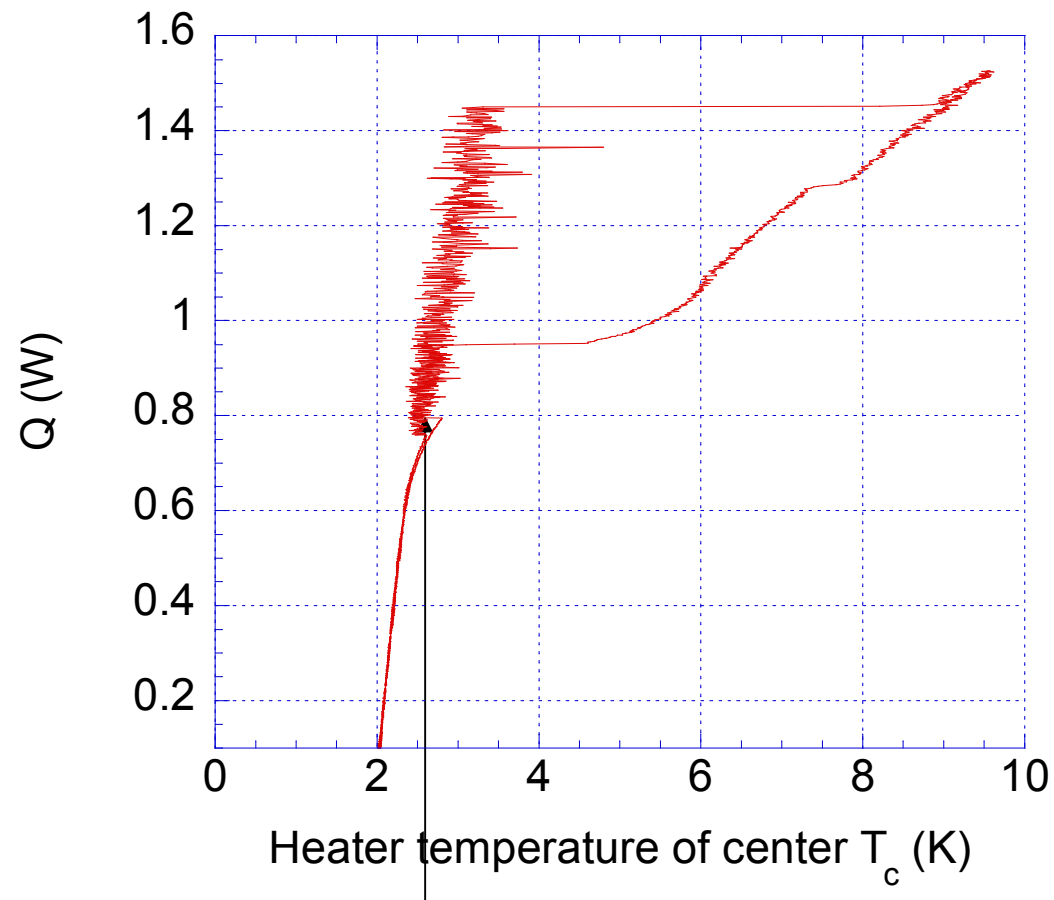
~10mm

Superconducting Magnet
for LHC

小林先生の温度測定実験



2

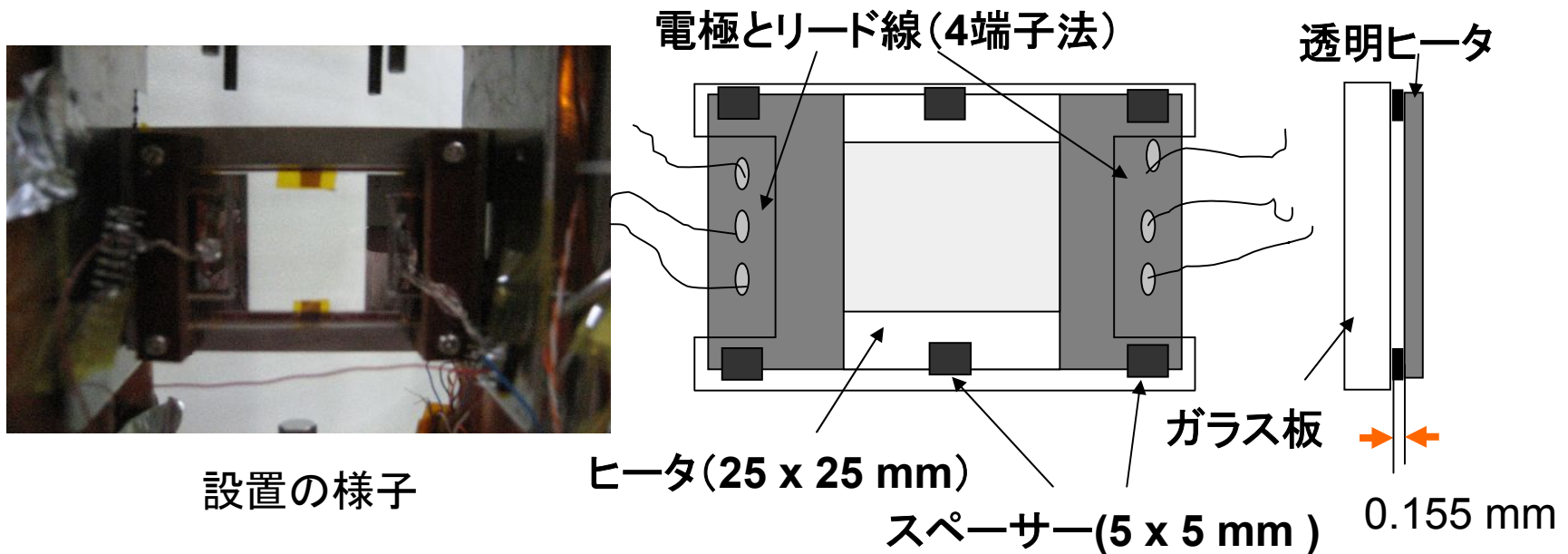


飽和蒸気圧近傍のHe II中における沸騰曲線にも関わらず飽和温度をはるかに超えた温度まで沸騰を起こさない

不思議な温度の振る舞い、正体を知りたい！！

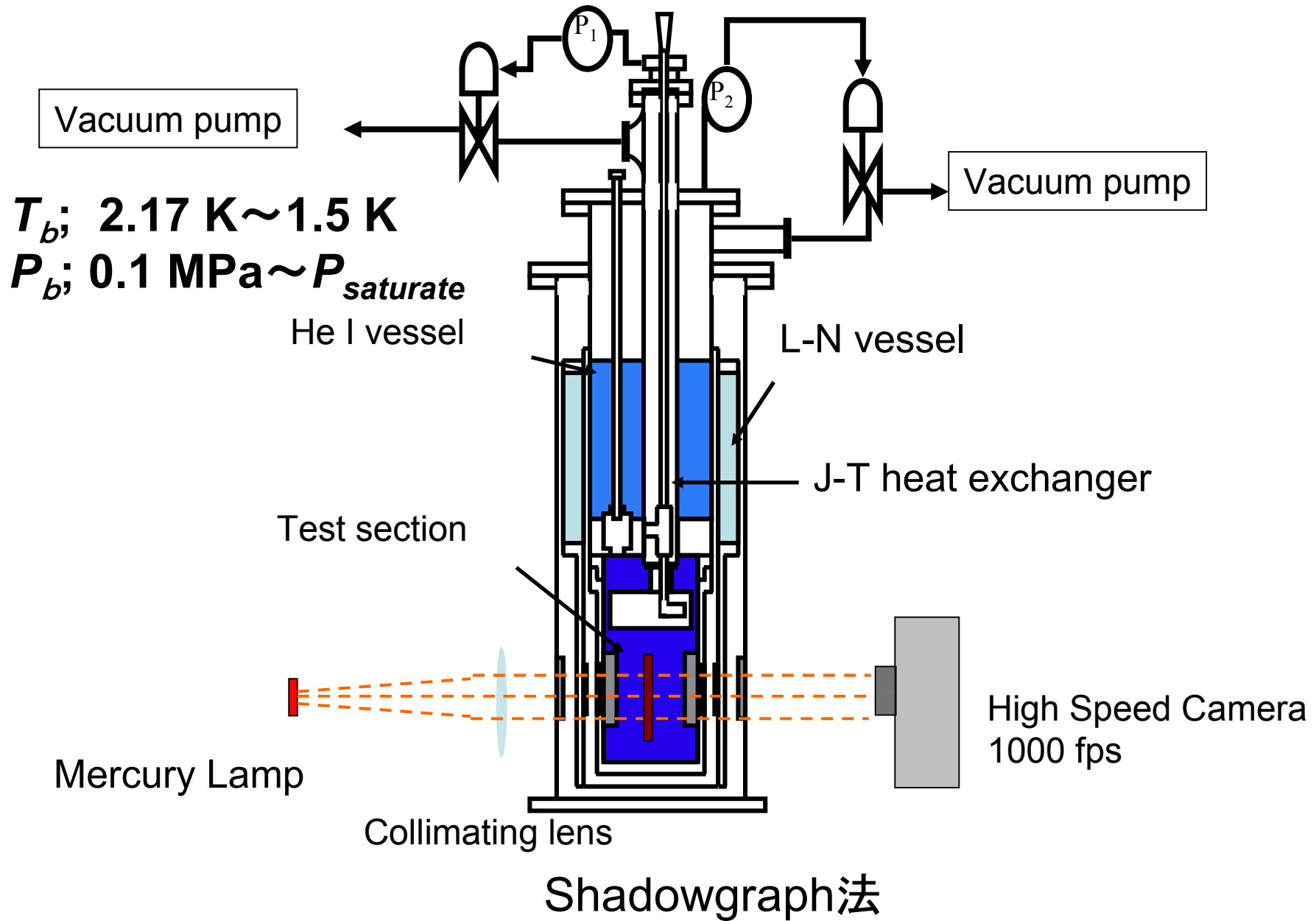
可視化実験

透明ヒータ (酸化インジウム薄膜) & パイレックスガラス

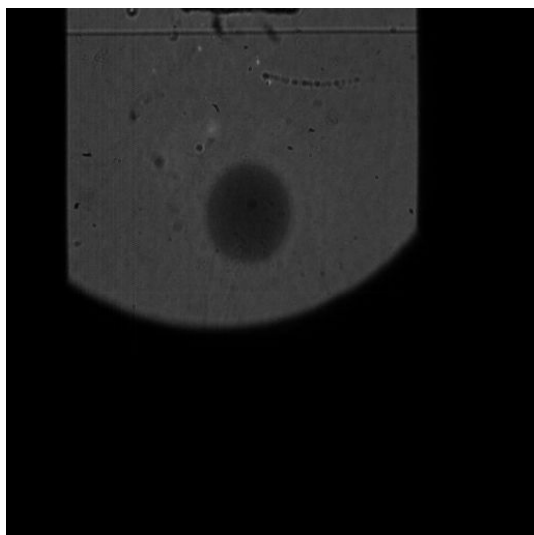


シャドウグラフ可視化法

Claudet type cryostat;



バックグラウンドノイズの除去

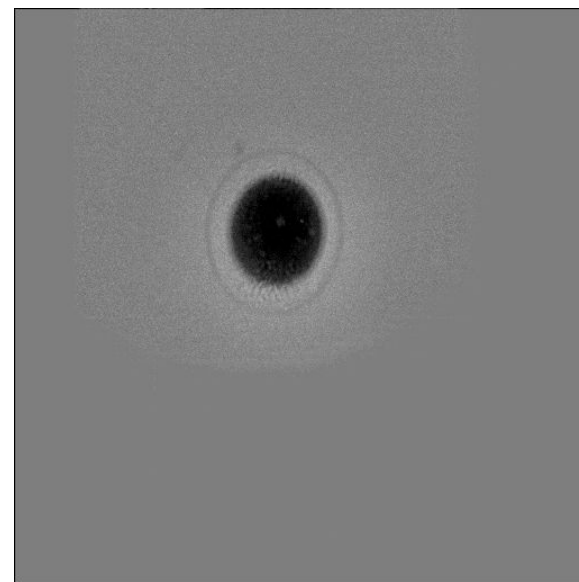


(a) 可視化画像



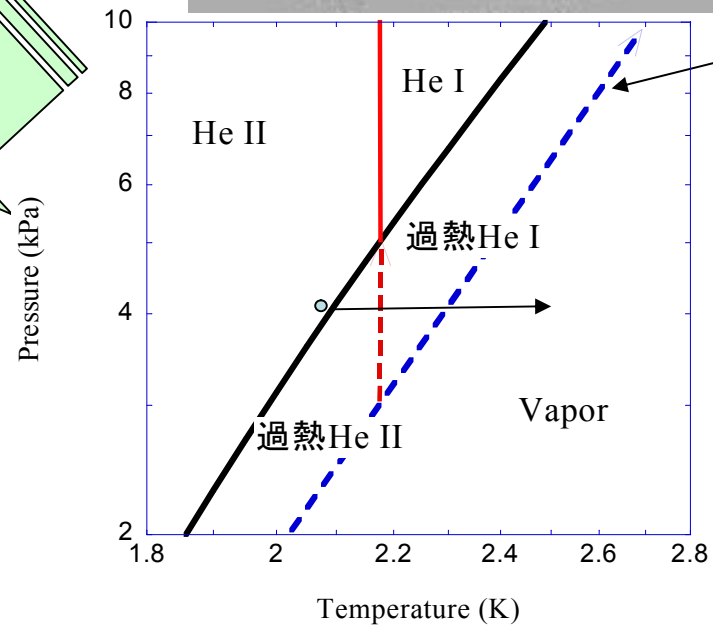
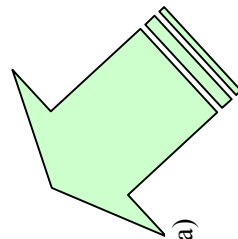
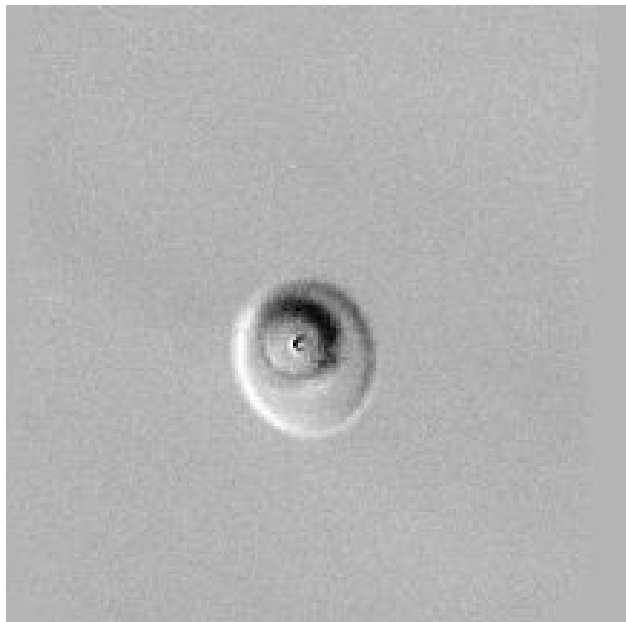
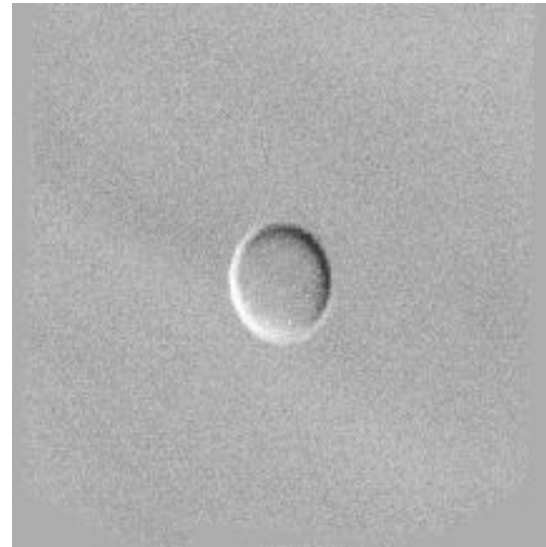
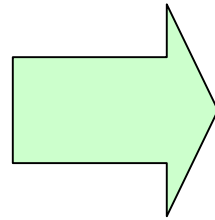
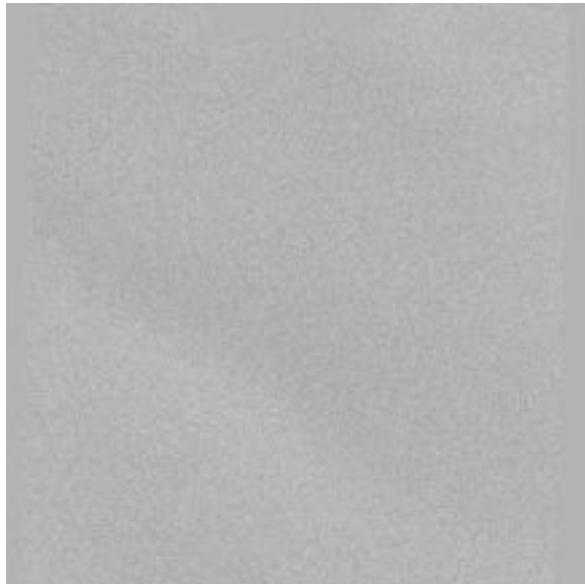
(b) ノイズ成分 (反転画像)

$$((a)+(b)) \div 2 = (c)$$



(c) ノイズ除去後

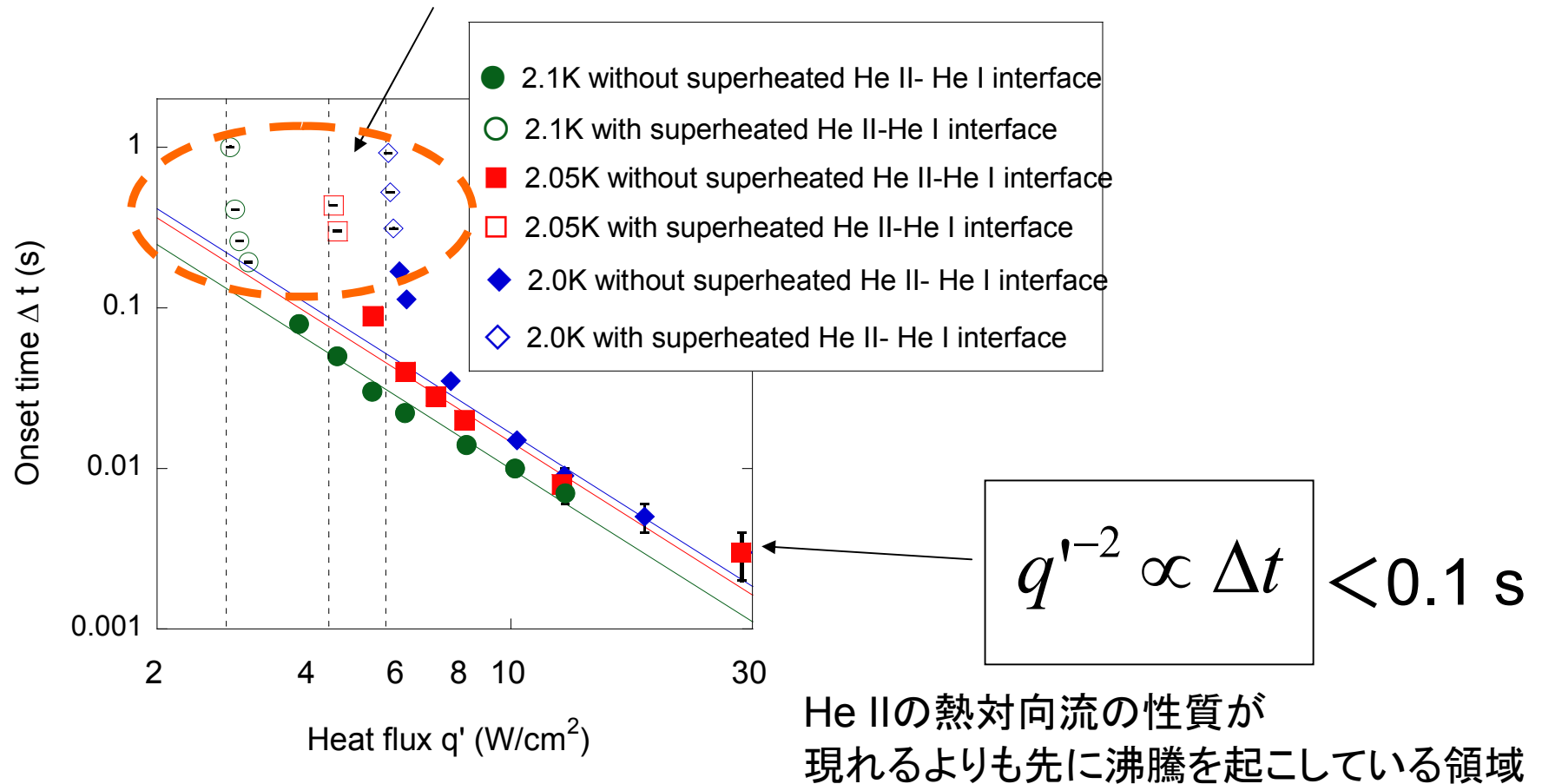
沸騰開始期



2.1 K saturated vapor pressure

Gap thickness $d = 0.155$ mm

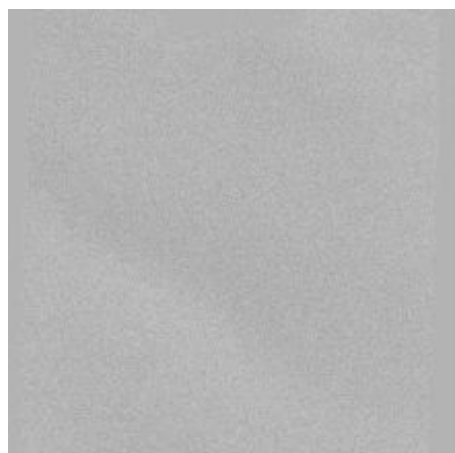
低熱流束のみで過熱He II-過熱He I界面出現



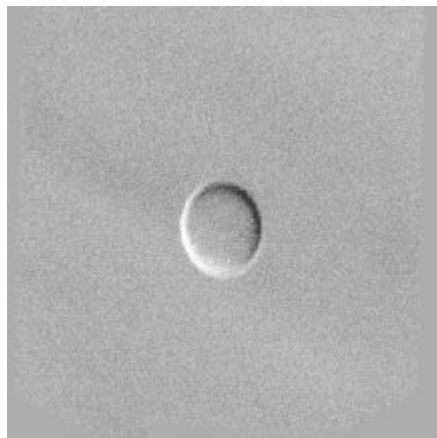
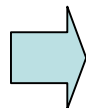
The onset time Δt of boiling depending on heat flux q'

特徴的サイクル

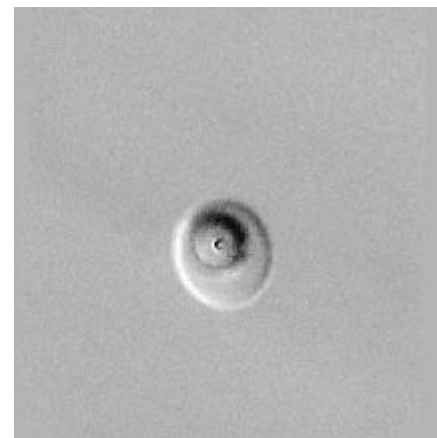
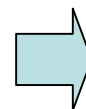
saturated He II, 2.1 K, $q' = 2.64 \text{ W/cm}^2$



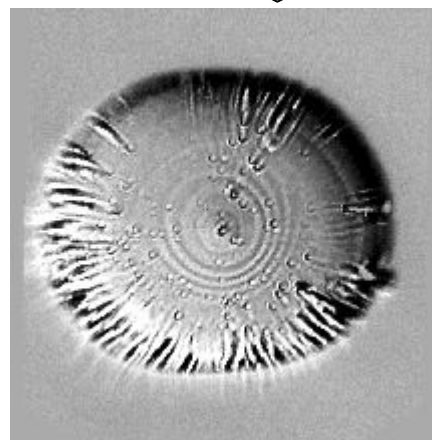
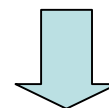
①初期状態



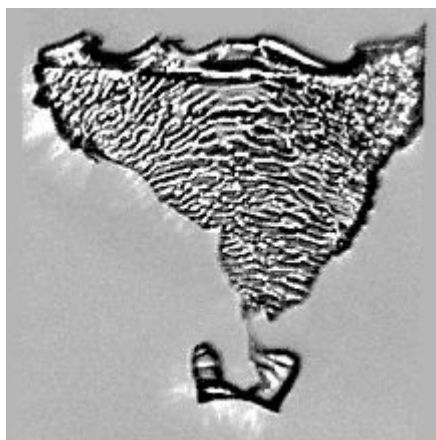
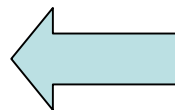
②過熱He II-過熱He I



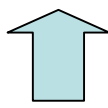
③過熱He II-過熱He + Vapor



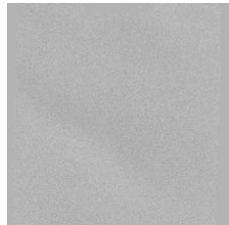
④気泡成長



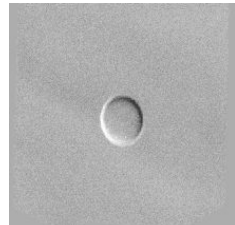
⑤気泡崩壊



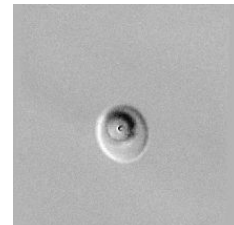
サイクルの定性的理解



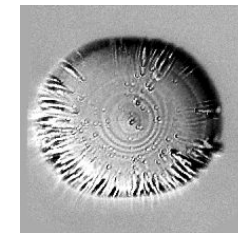
①初期状態



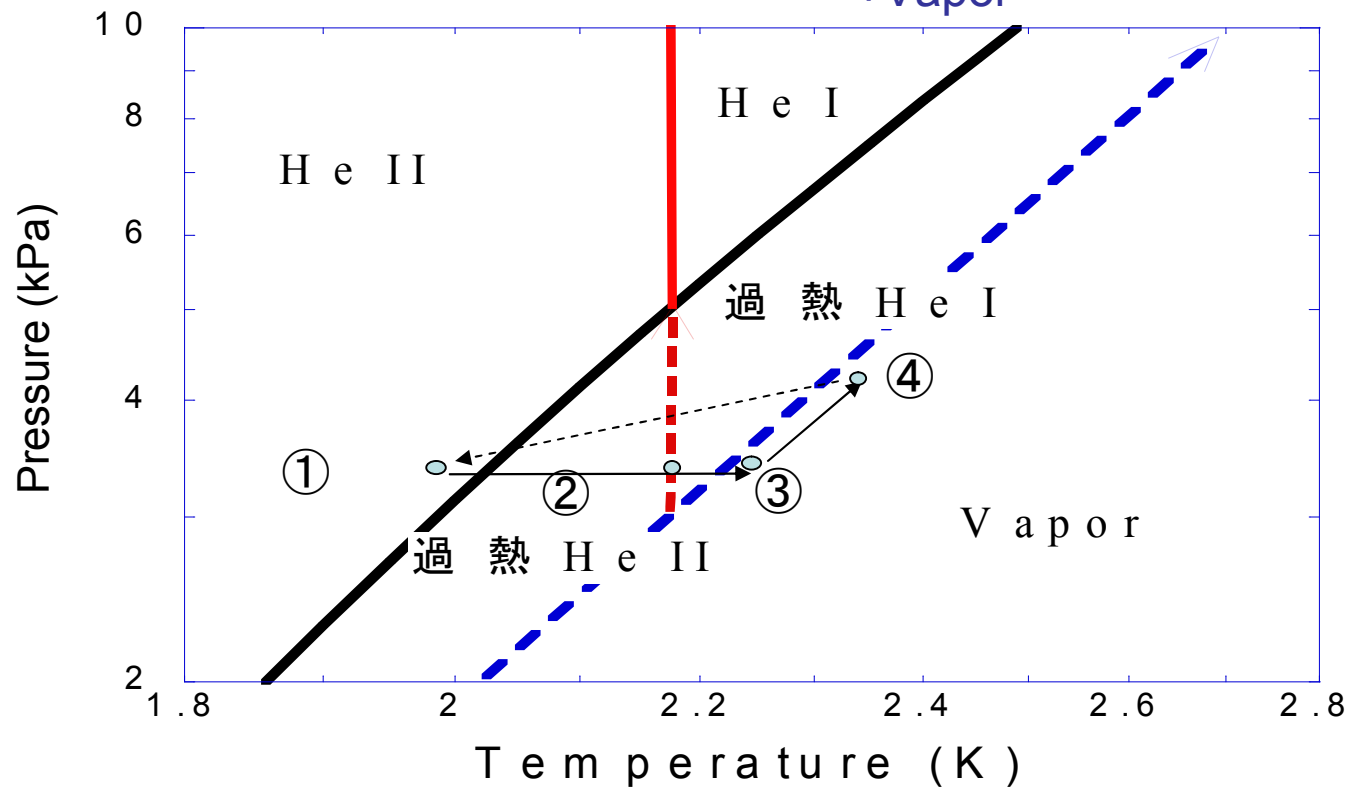
②過熱He II-過熱He I



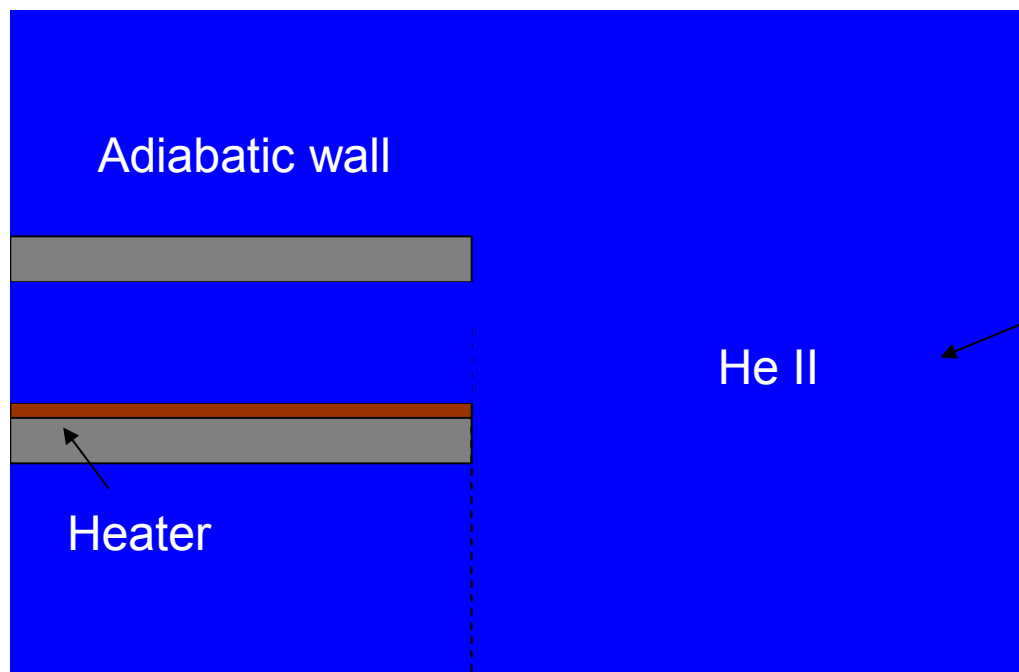
③過熱He II-過熱He I + Vapor



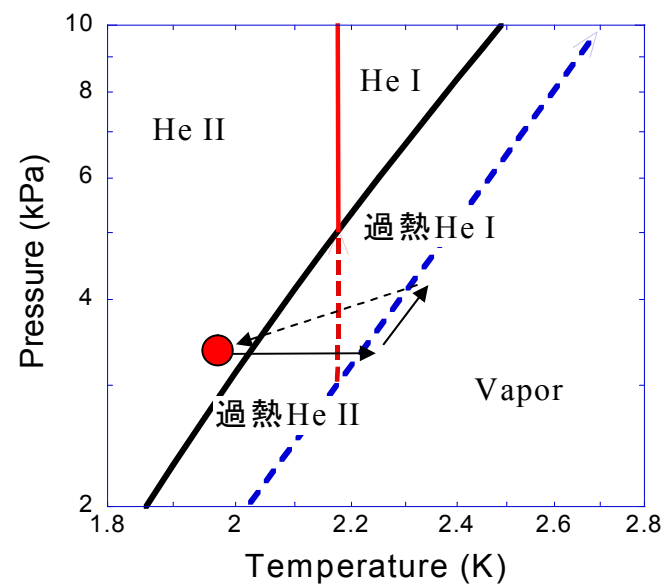
④気泡成長



流路中心部の状態変化

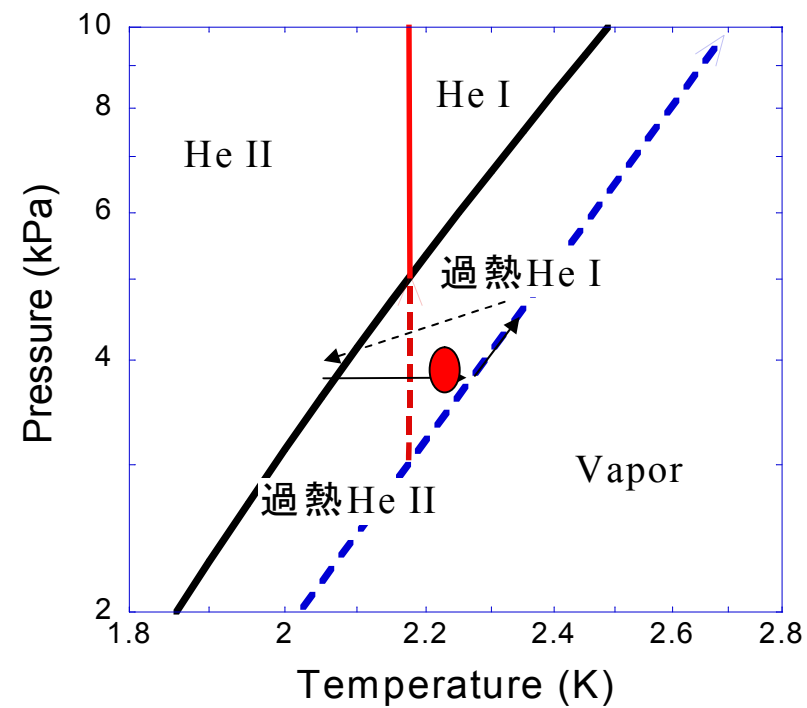
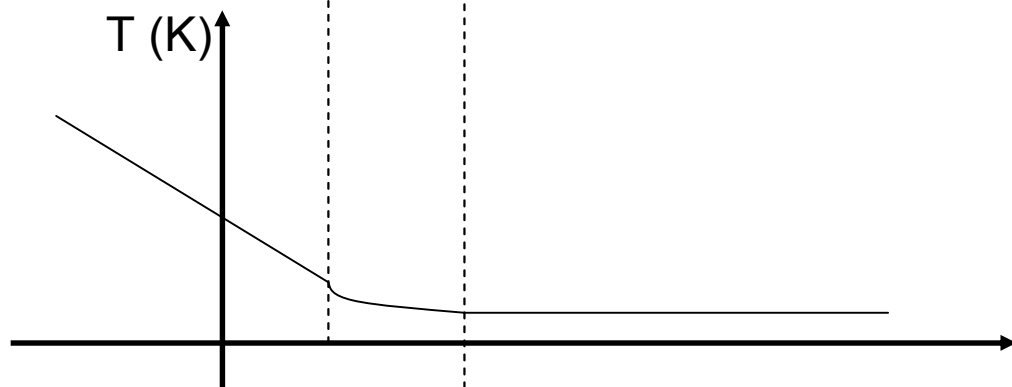
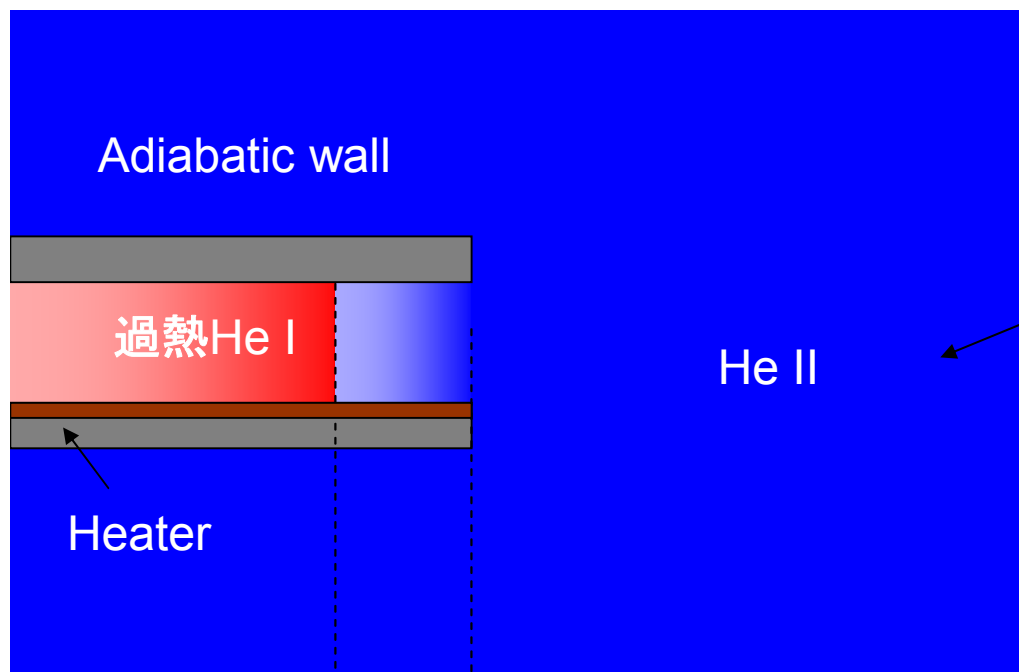


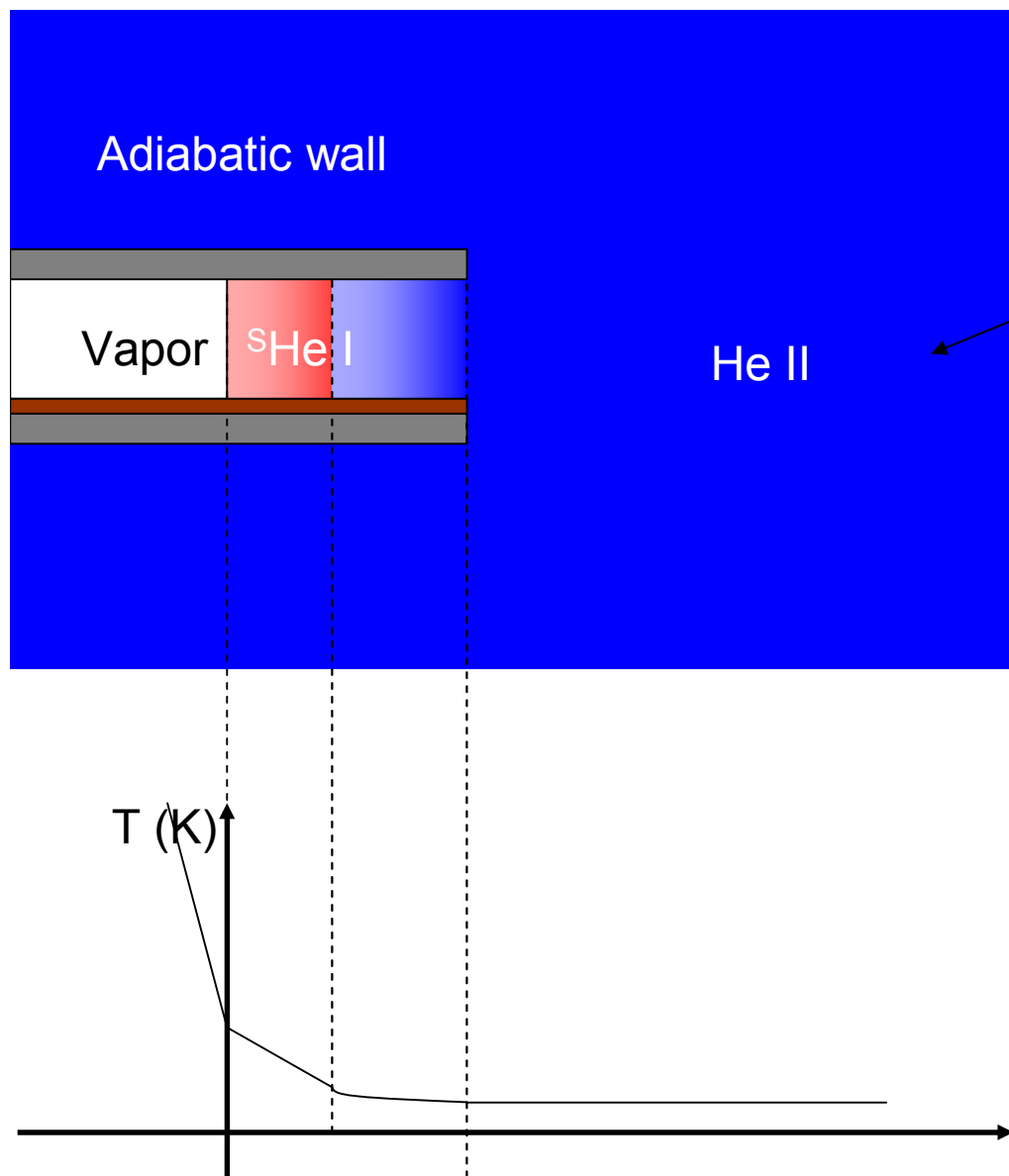
非常に広い流路幅を持ったHe II



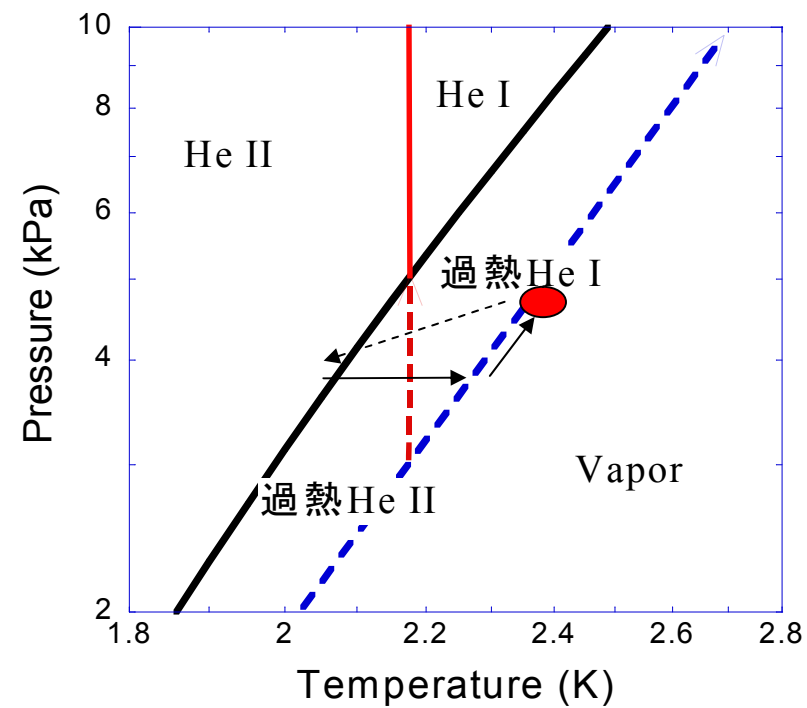
T (K)

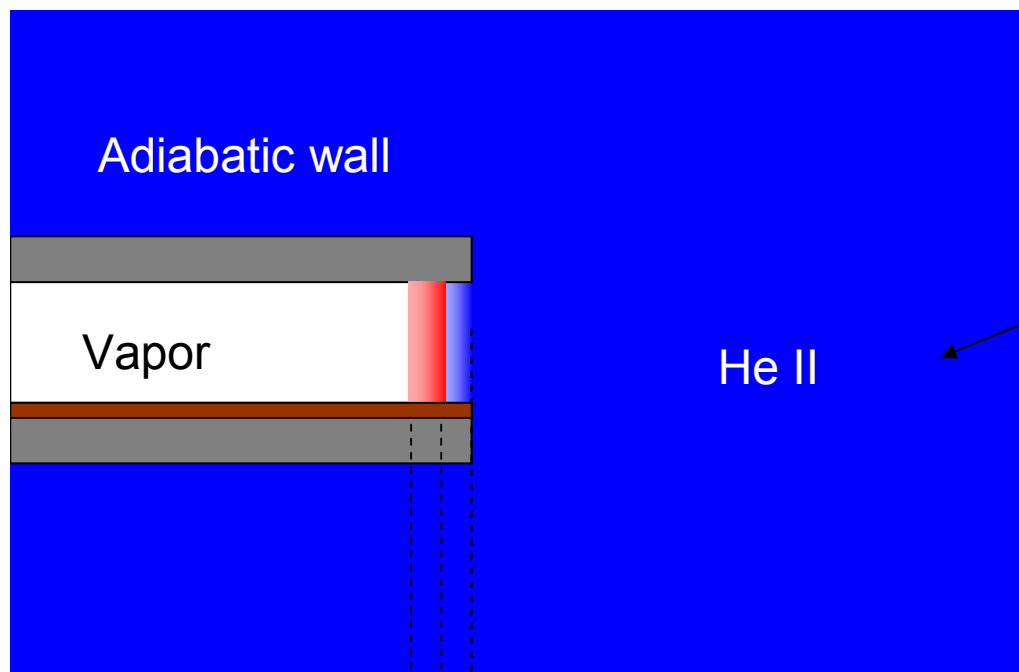




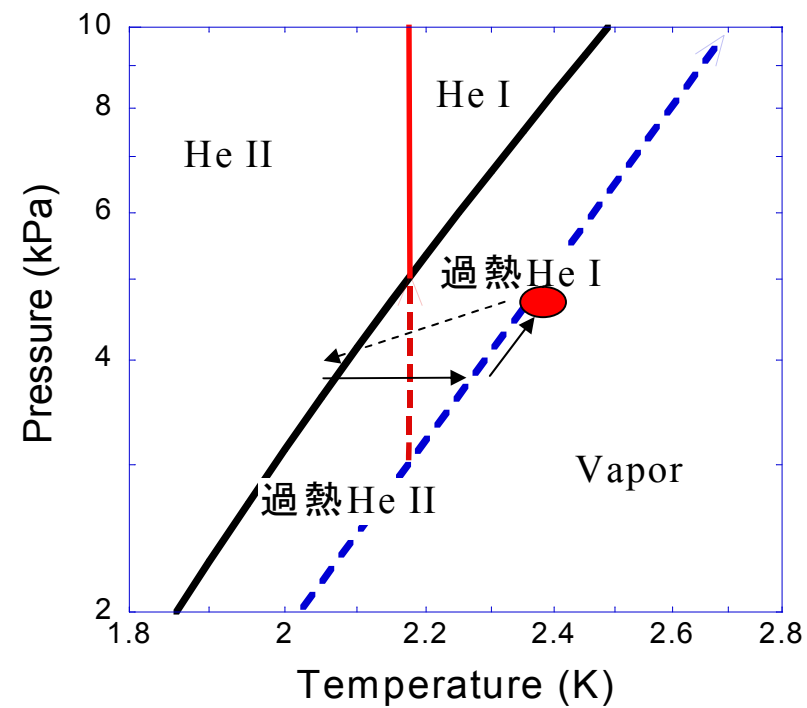
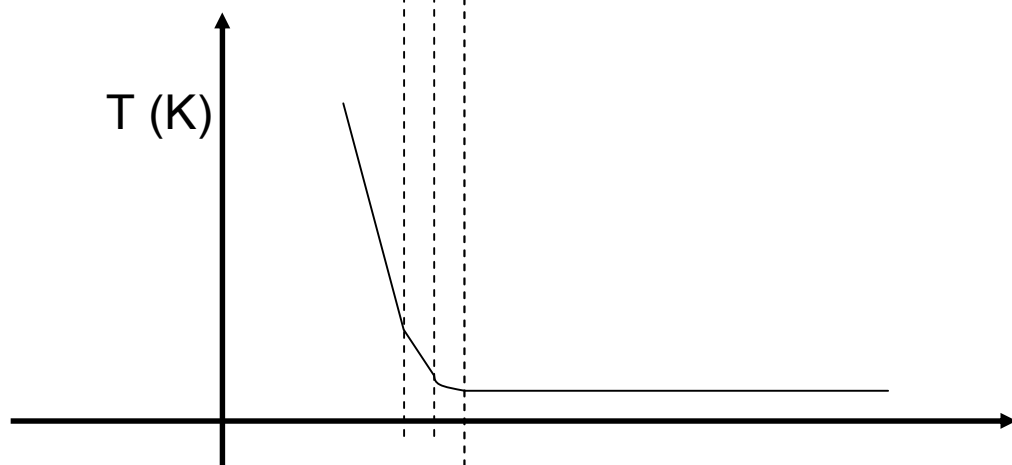


非常に広い流路幅を持ったHe II

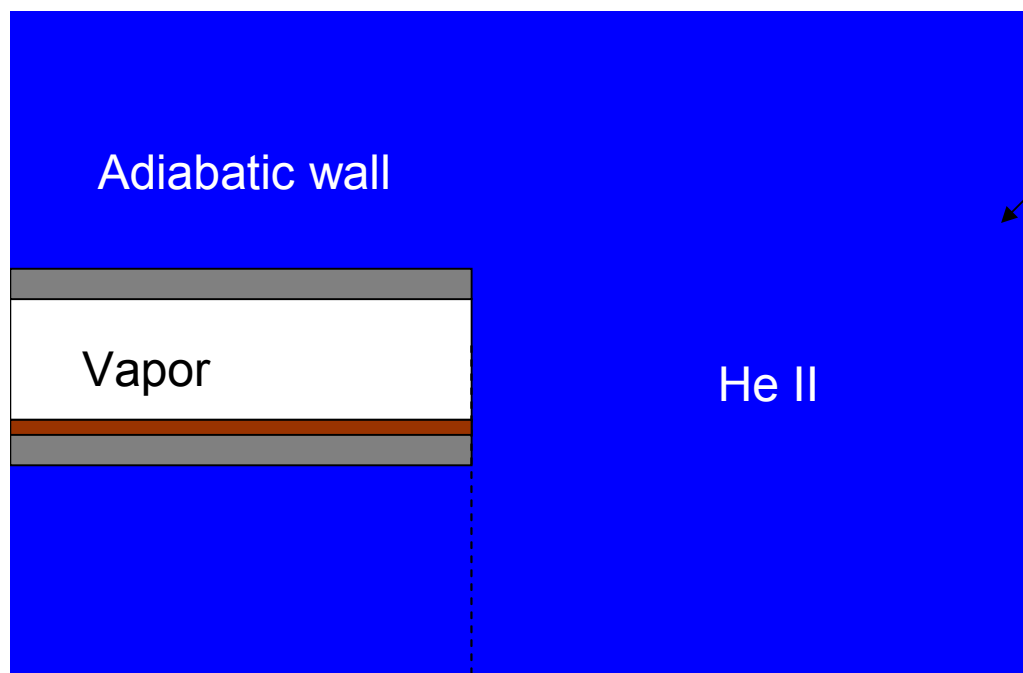




非常に広い流路幅を持ったHe II



非常に広い流路幅を持ったHe II



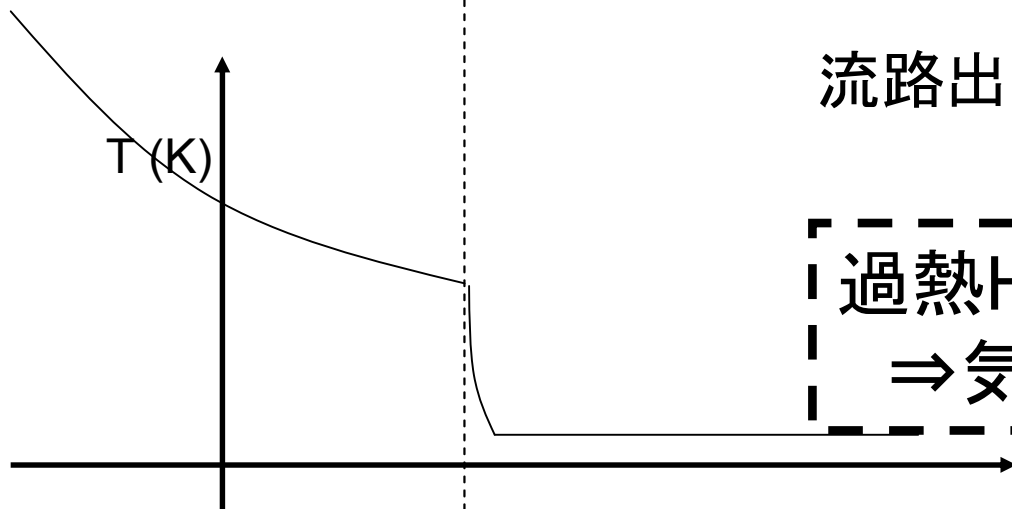
He II 超熱伝導性

$$\nabla T = f(T) \cdot q^m$$

有効熱伝導率

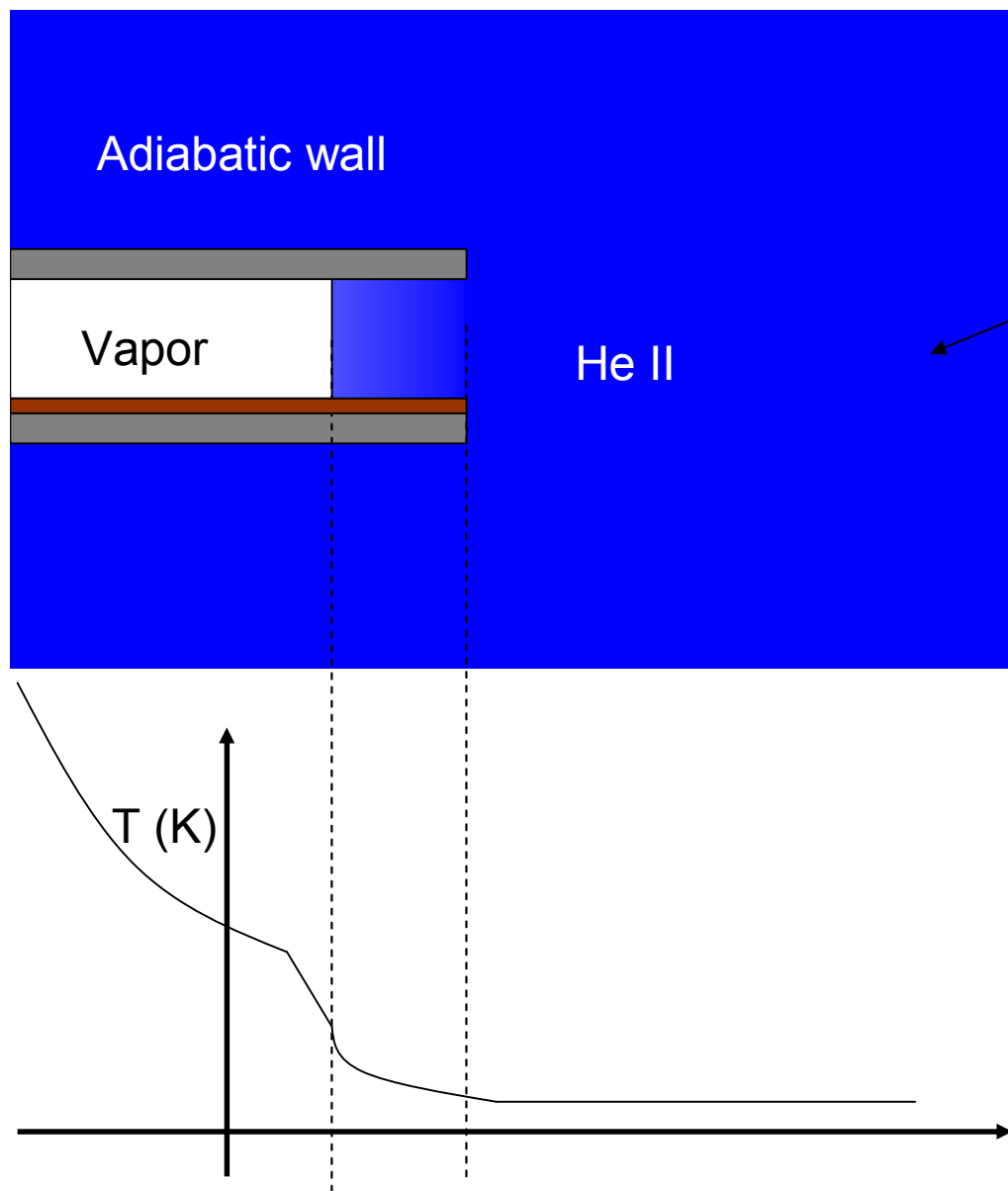
$$\lambda = \frac{1}{f(T)} \left(\frac{1}{q} \right)^{m-1}$$

流路出口で急増する有効熱伝導率！！

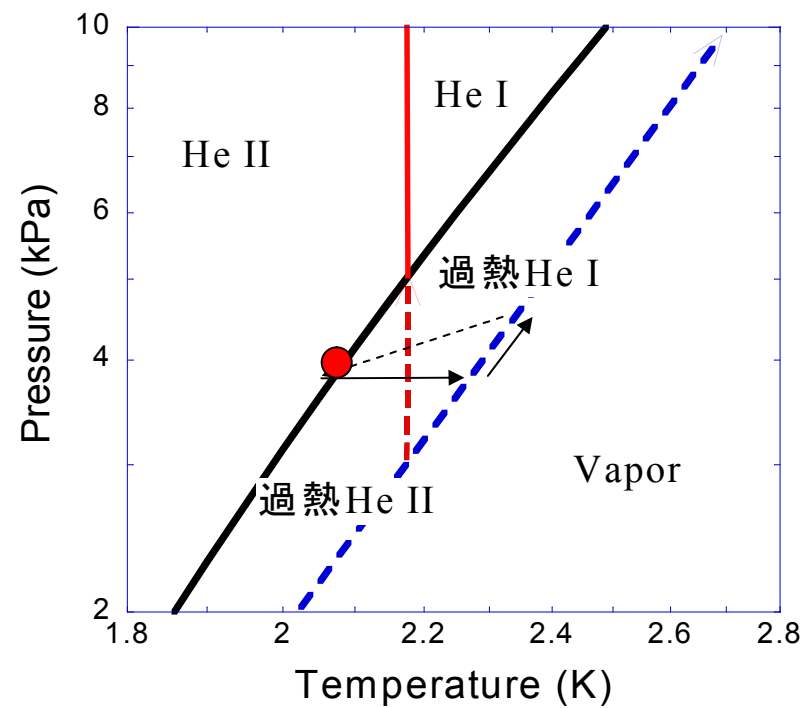


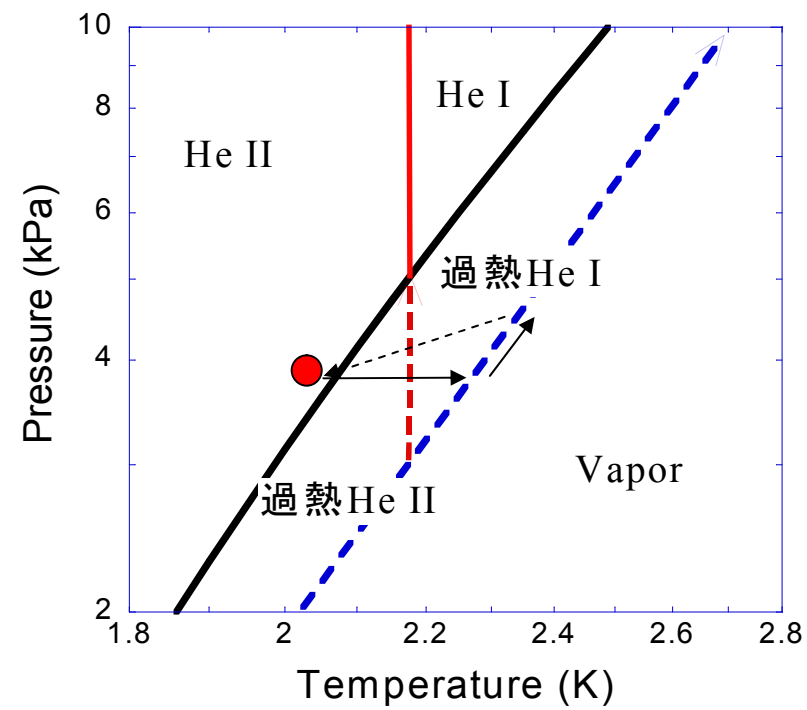
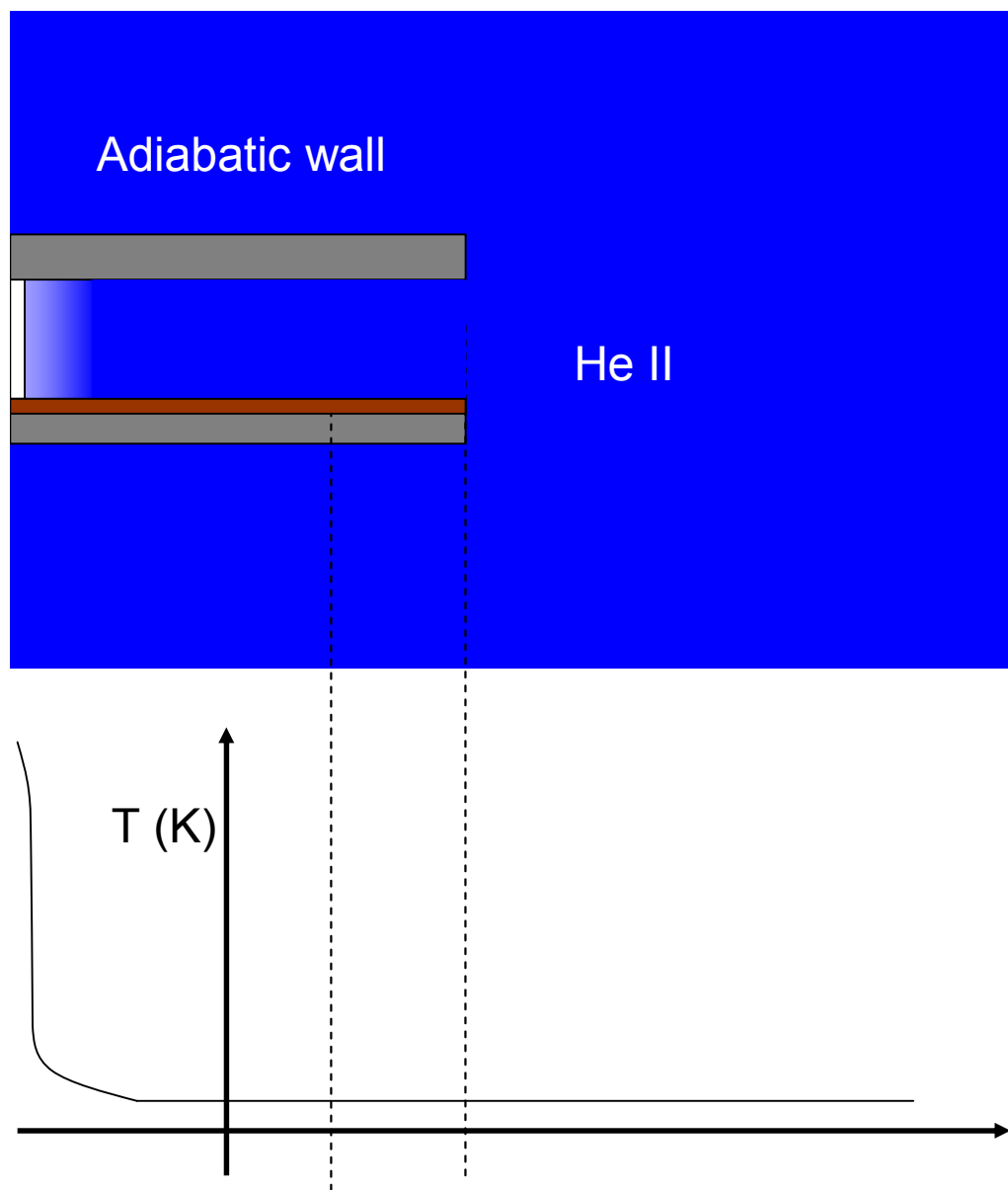
過熱He Iが消失

⇒気液界面外側がHe IIに交換

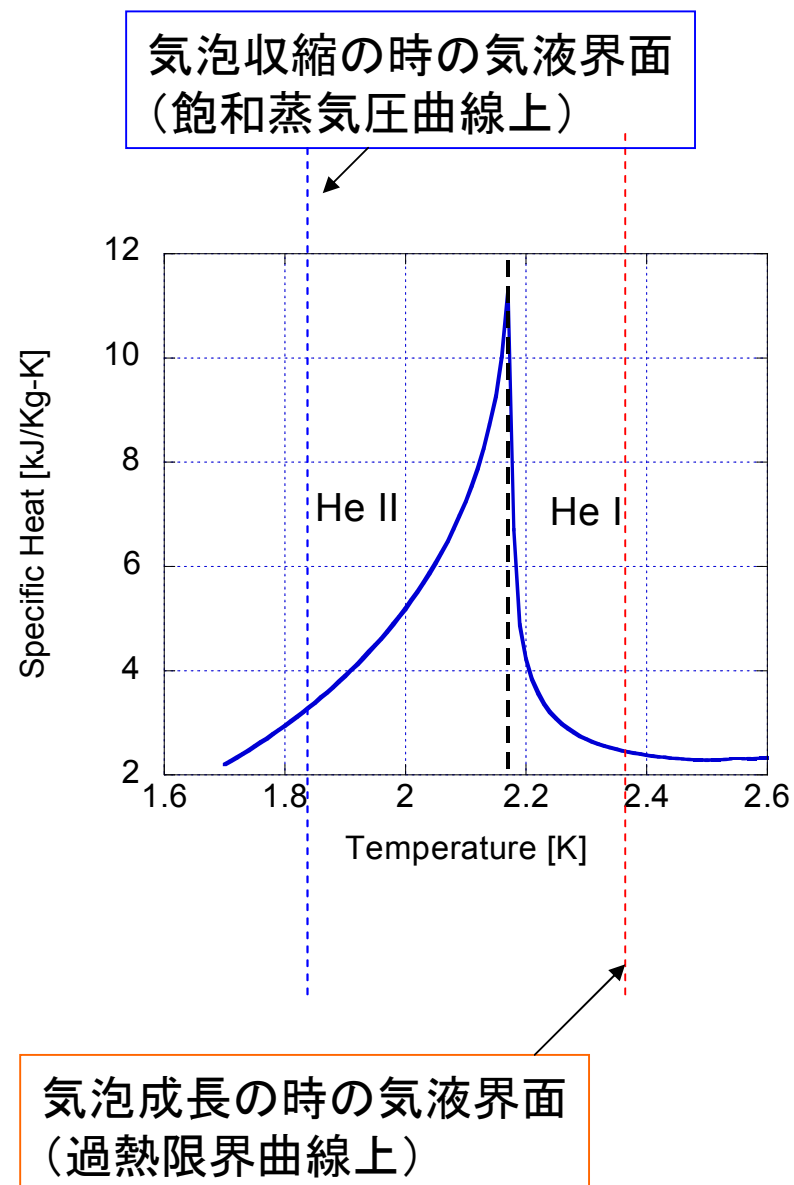
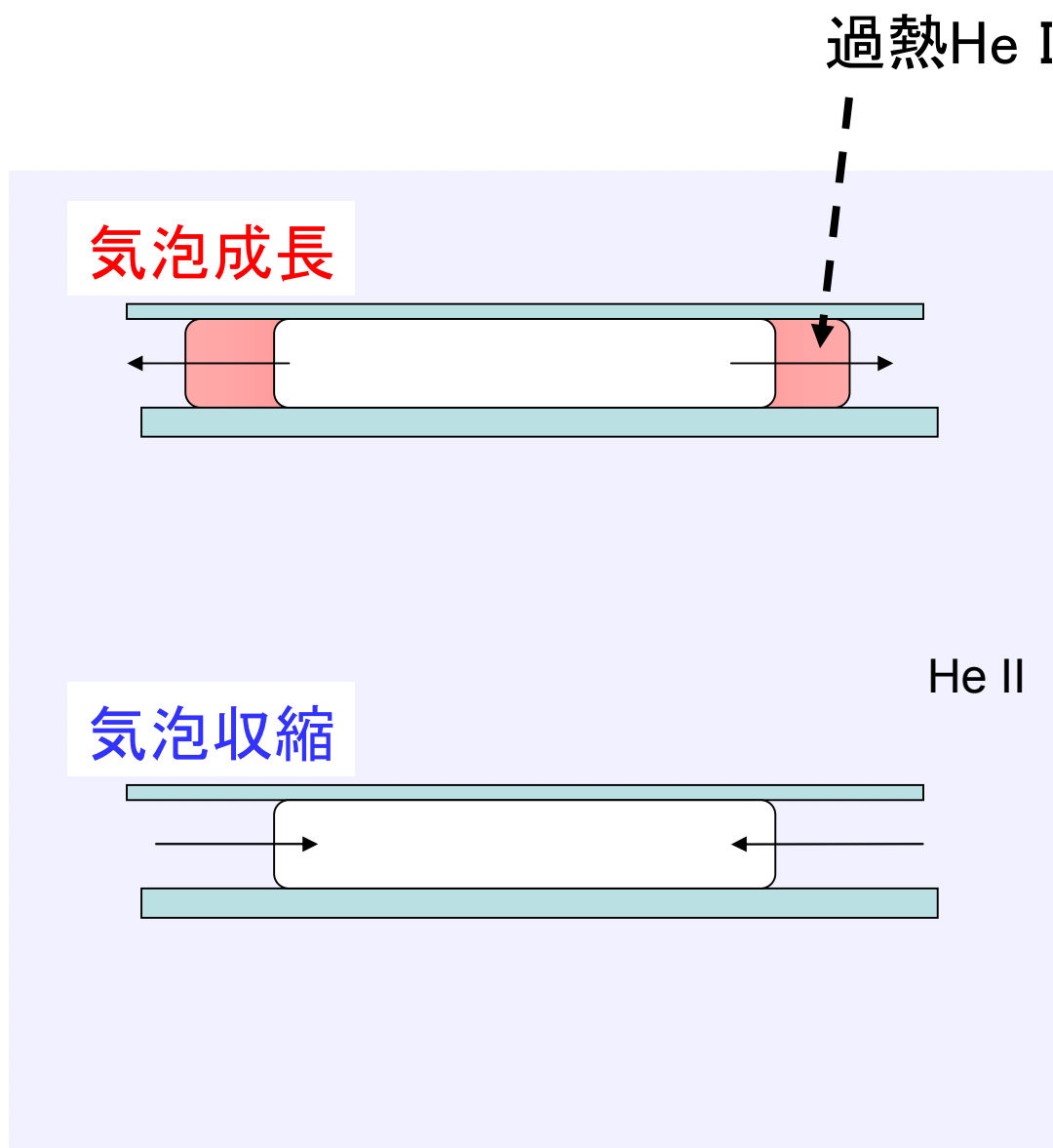


凝縮 >> 蒸発
 圧力は低下し一気に液に戻る



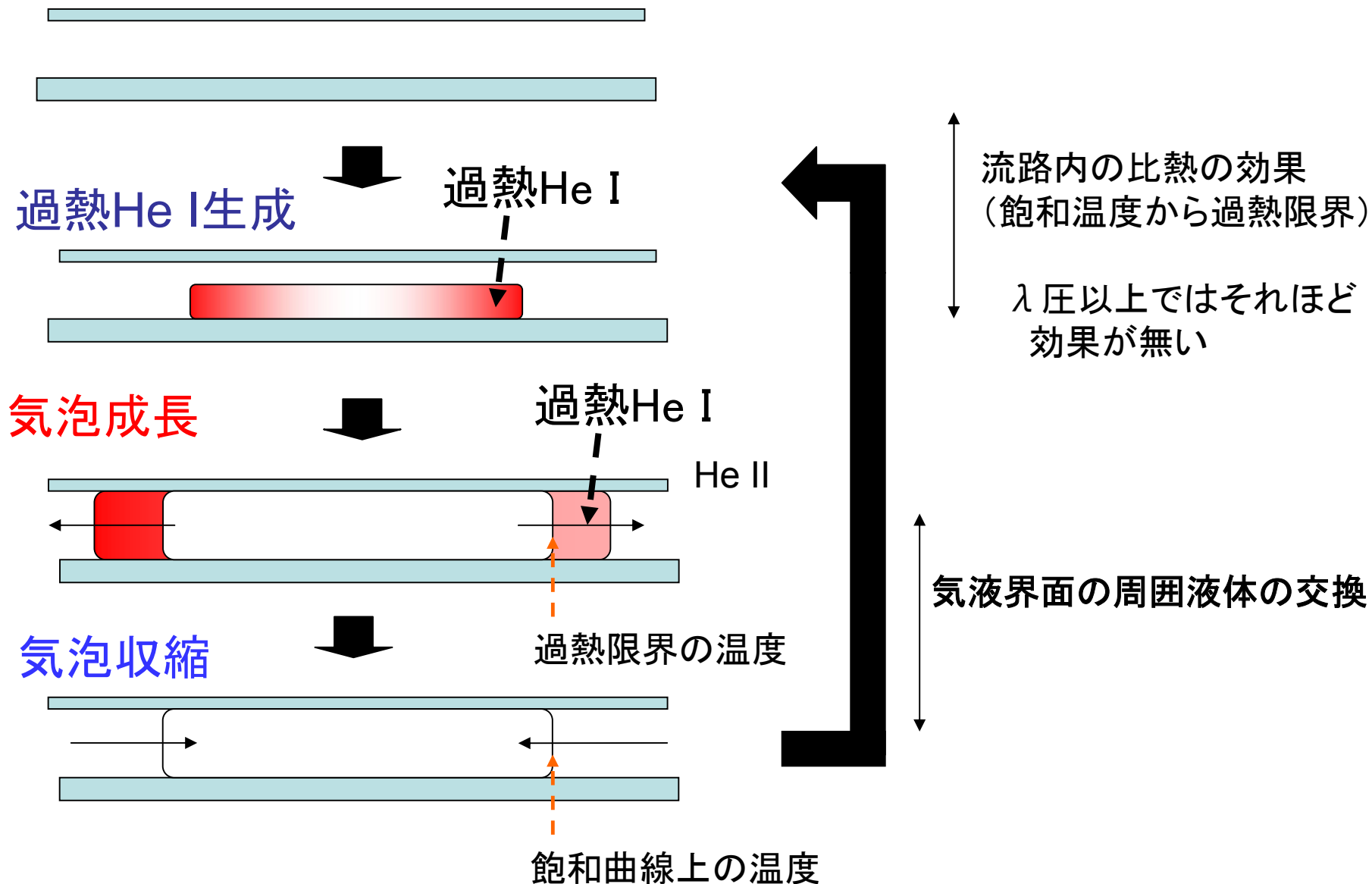


比熱異常を効率的に利用する過熱液体の放出

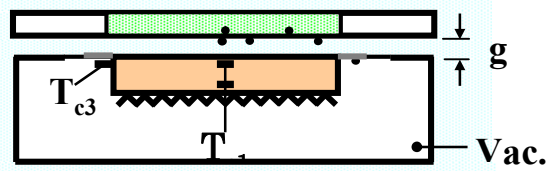
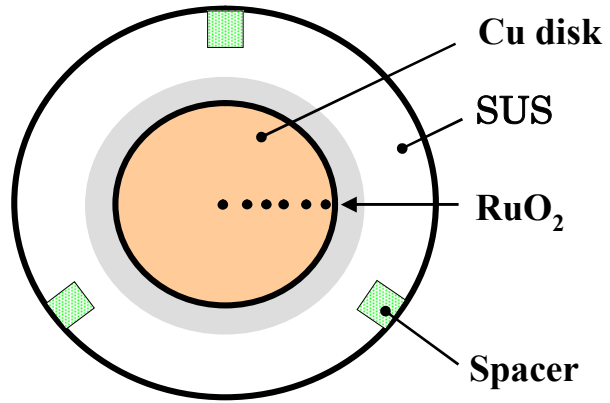


比熱異常を効率的に利用する過熱液体の放出

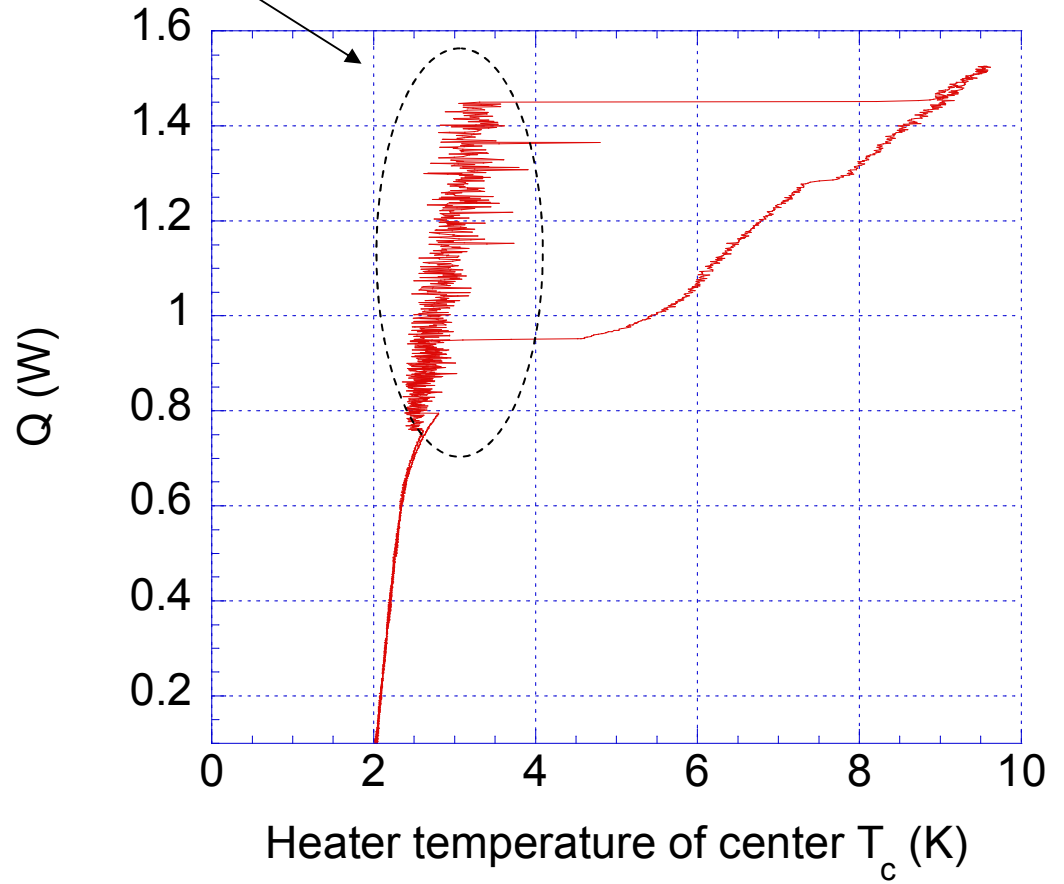
加熱開始



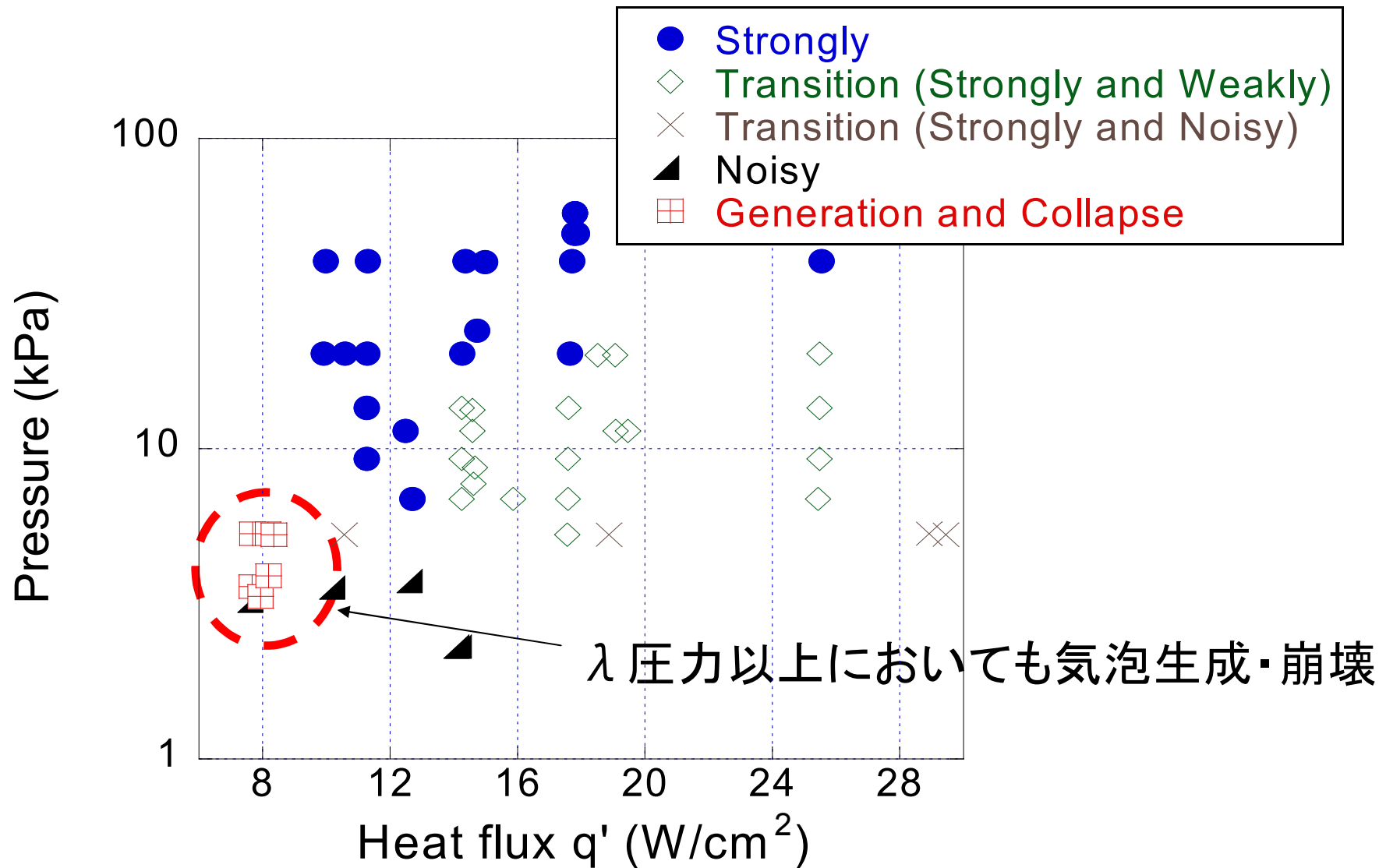
気泡の生成崩壊のサイクルが起きている部分



2

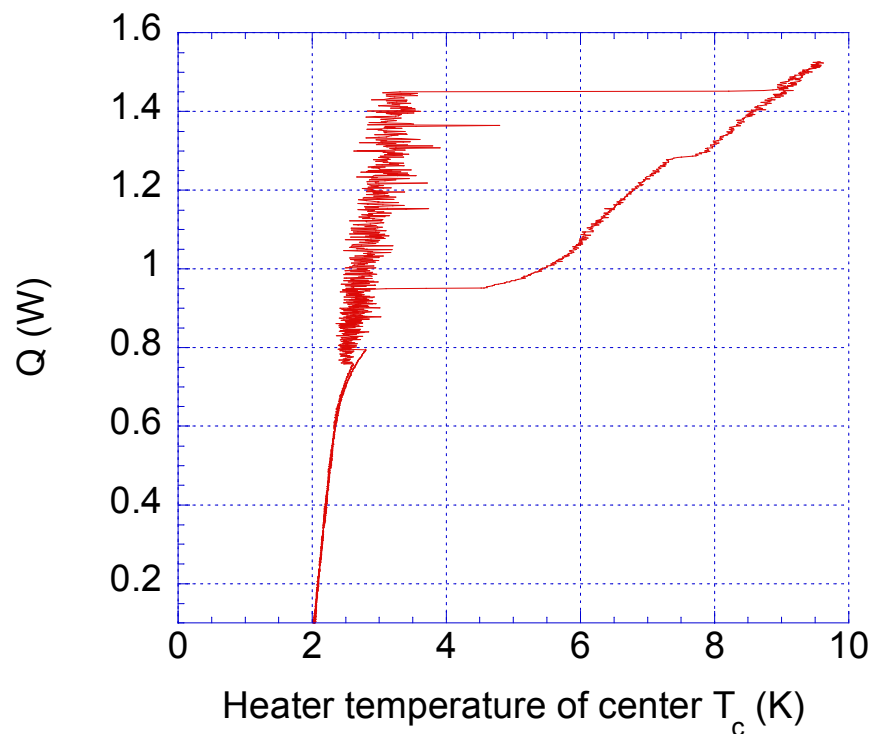


1.9 Kにおける沸騰モードマップ (q-p図)

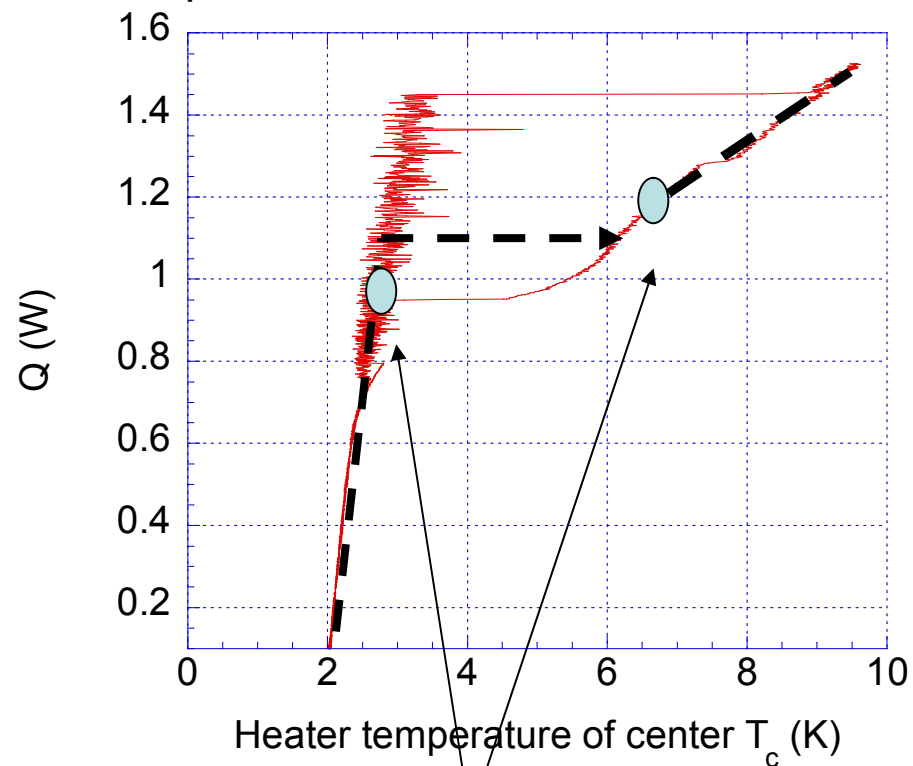


2つの実験系におけるヒータ加熱の違い

約2時間かけてSweep



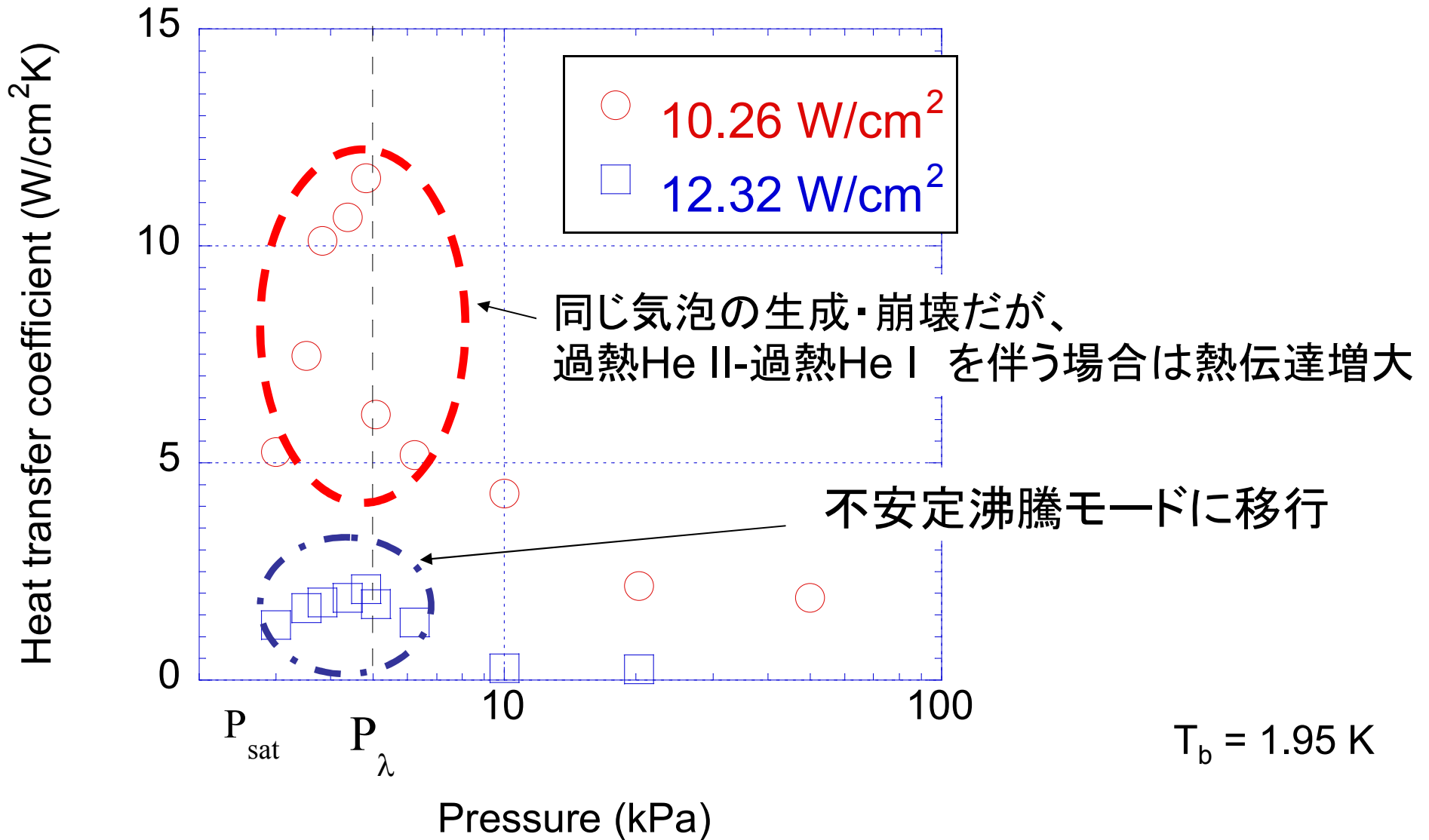
Step加熱



2つの熱流束に固定して
熱伝達率を調査

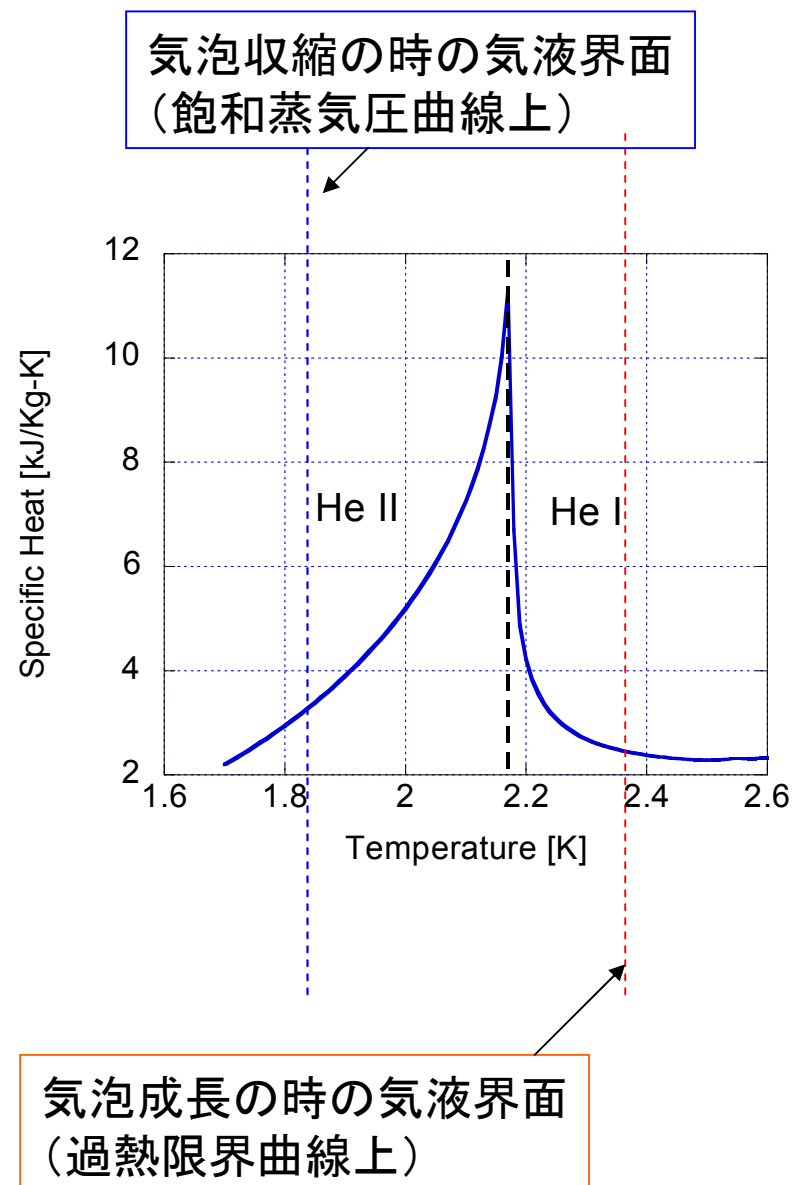
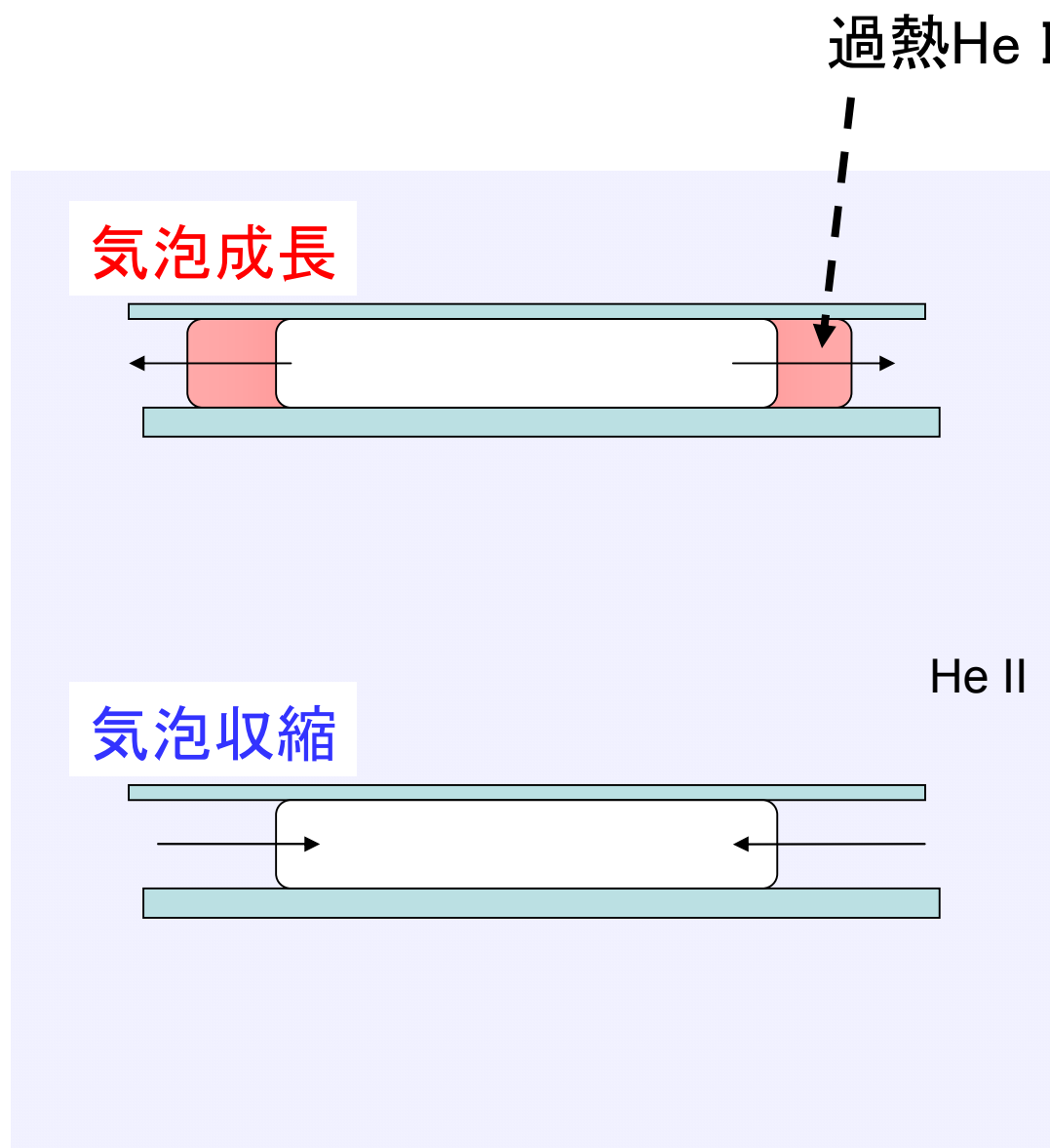


狭隘流路中の沸騰熱伝達率の圧力依存性

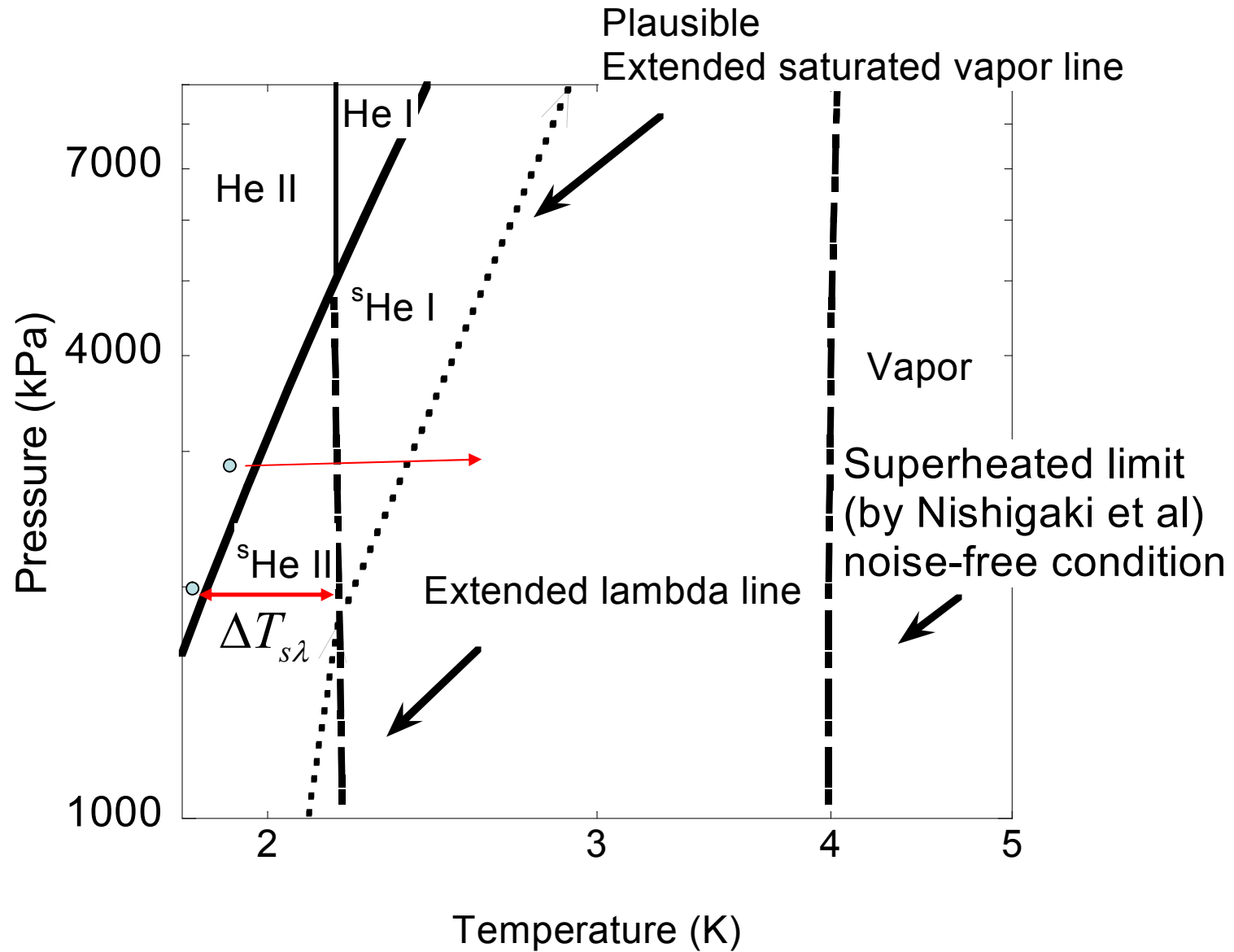


結論： λ 圧力において運用することが最適である！！

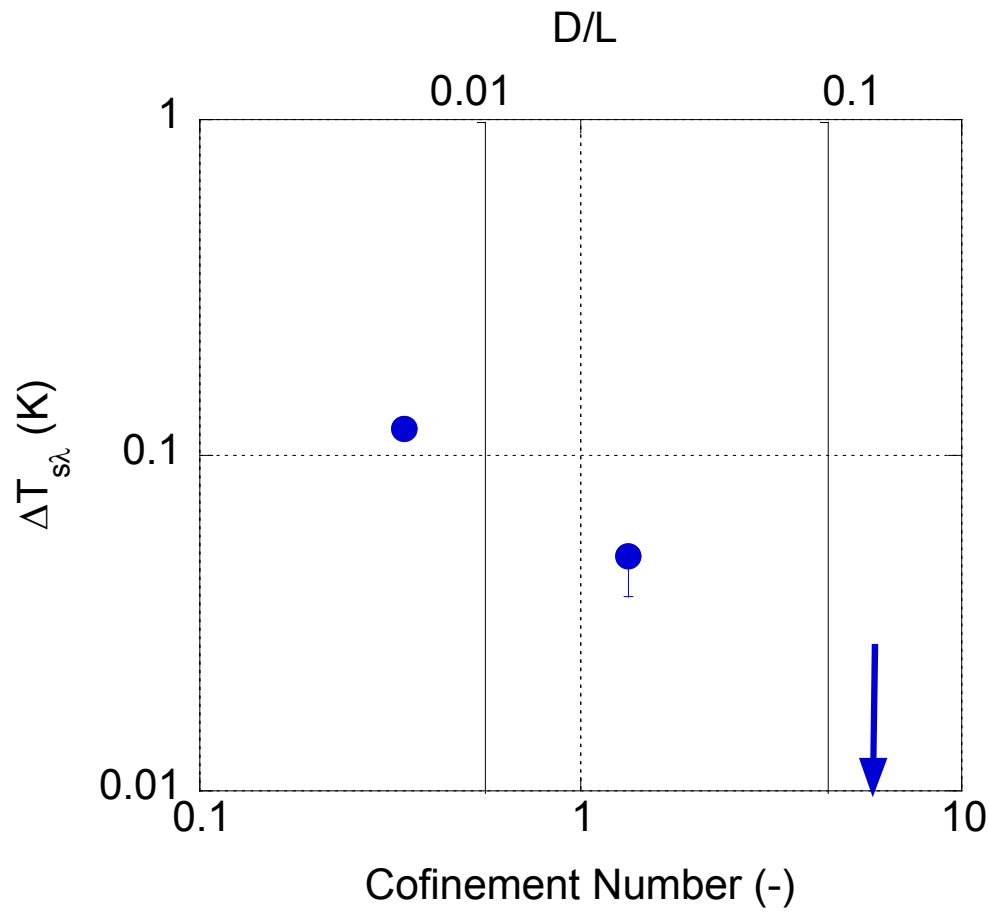
比熱異常を効率的に利用する過熱液体の放出



流路幅と過熱限界



流路幅と過熱限界の相関



● 0.155 mm: 6.2×10^{-3} (D/L)

特徴的な沸騰モード発現 2.0 K以上
過熱He II-He I 界面ははっきりと観測される

● 0.6mm: 2.4×10^{-2} (D/L)

特徴的沸騰モード発現 2.1 K以上
過熱He II-He I 界面ははっきりとは見えない

● 3mm: 1.2×10^{-1} (D/L)

観測されず

D: ギャップ厚さ L: ヒーター長

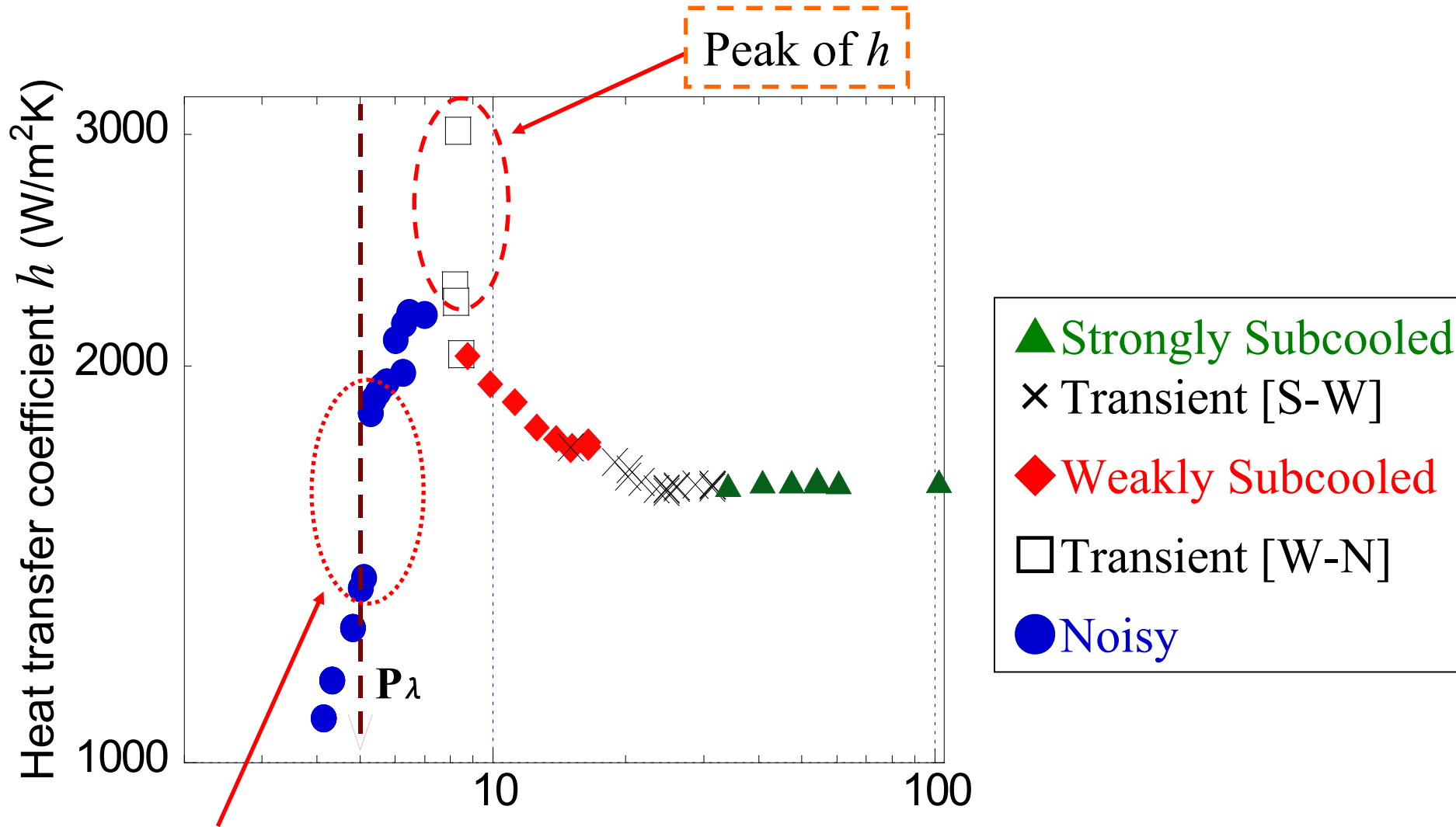
流路形状が3次元に近づくほど過熱限界は減少する

結論

狭隘2次元流路中のHe II沸騰について、
可視化実験を中心に研究を進めた結果
狭隘流路内においては、過熱状態が容易に出現し、
特徴的な振る舞いを示すことがわかった。

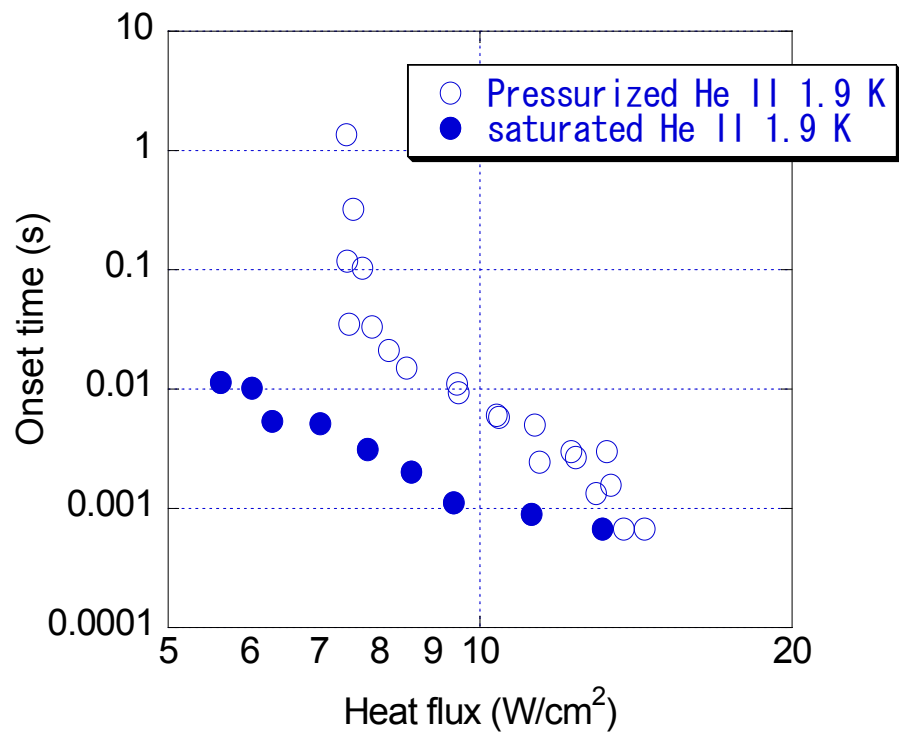
- ・気泡の生成崩壊を起こし、未発達な沸騰領域については、
λ 圧力を僅かに下回る圧力領域において熱伝達率が上昇
← 沸騰に過熱したHe II-He I 相転移が含む

沸騰熱伝達率の圧力依存性

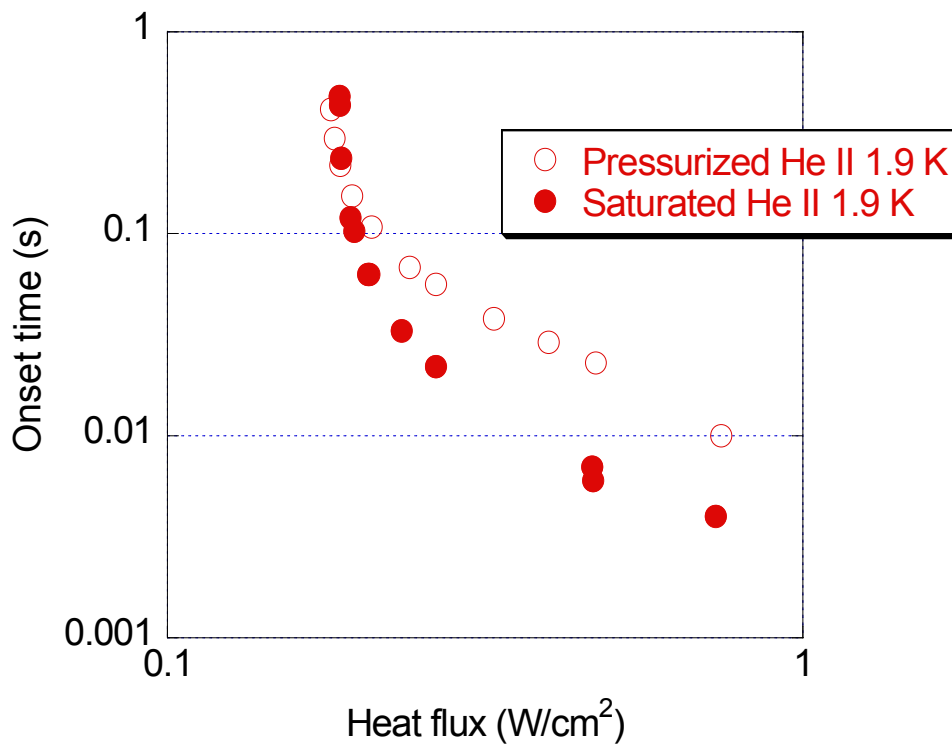


$q = 11.2 \times 10^4 \text{ W}/\text{m}^2$ at 1.9 K

開放空間と狭小流路 (155 μm)



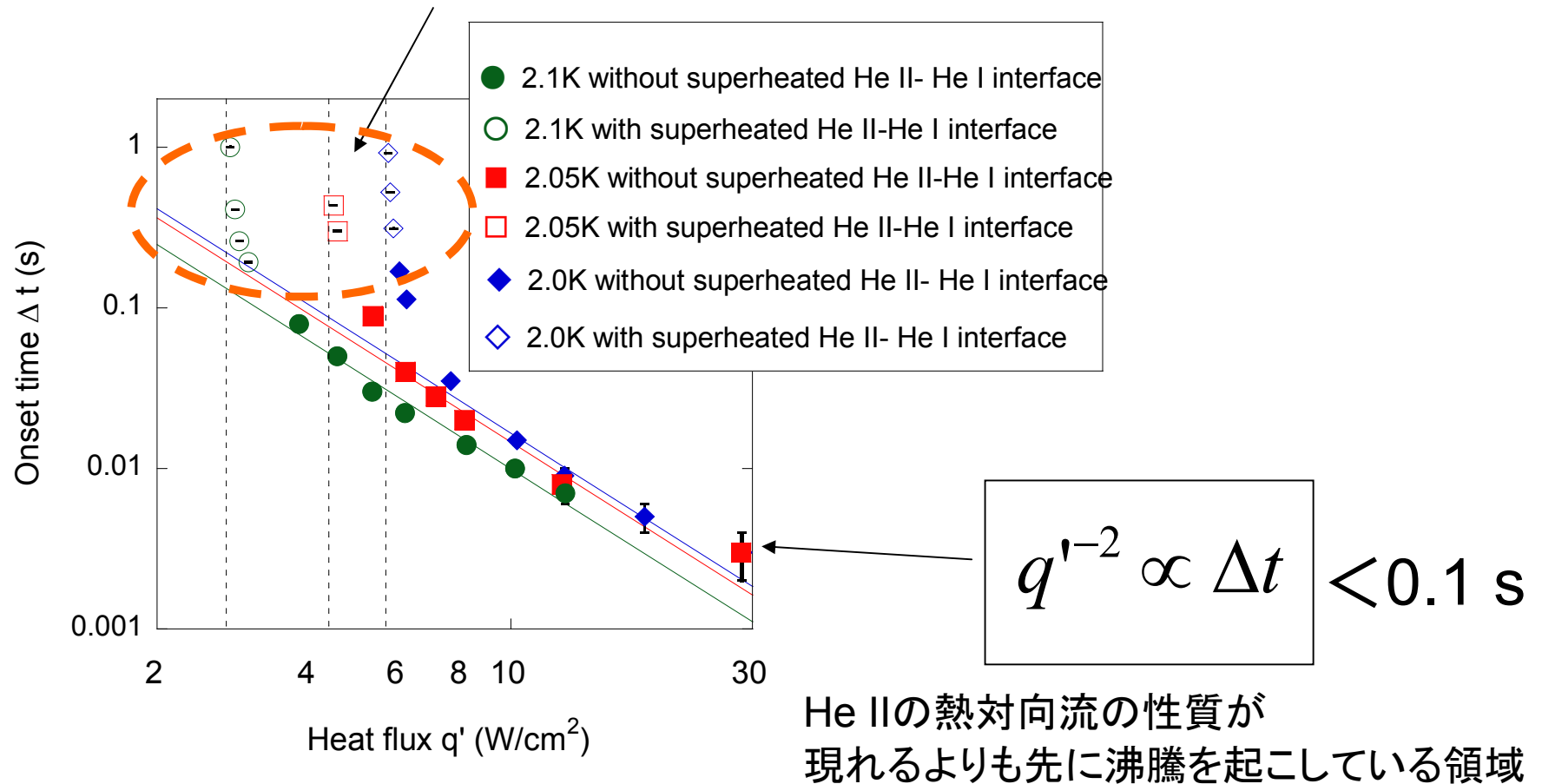
3-D open system



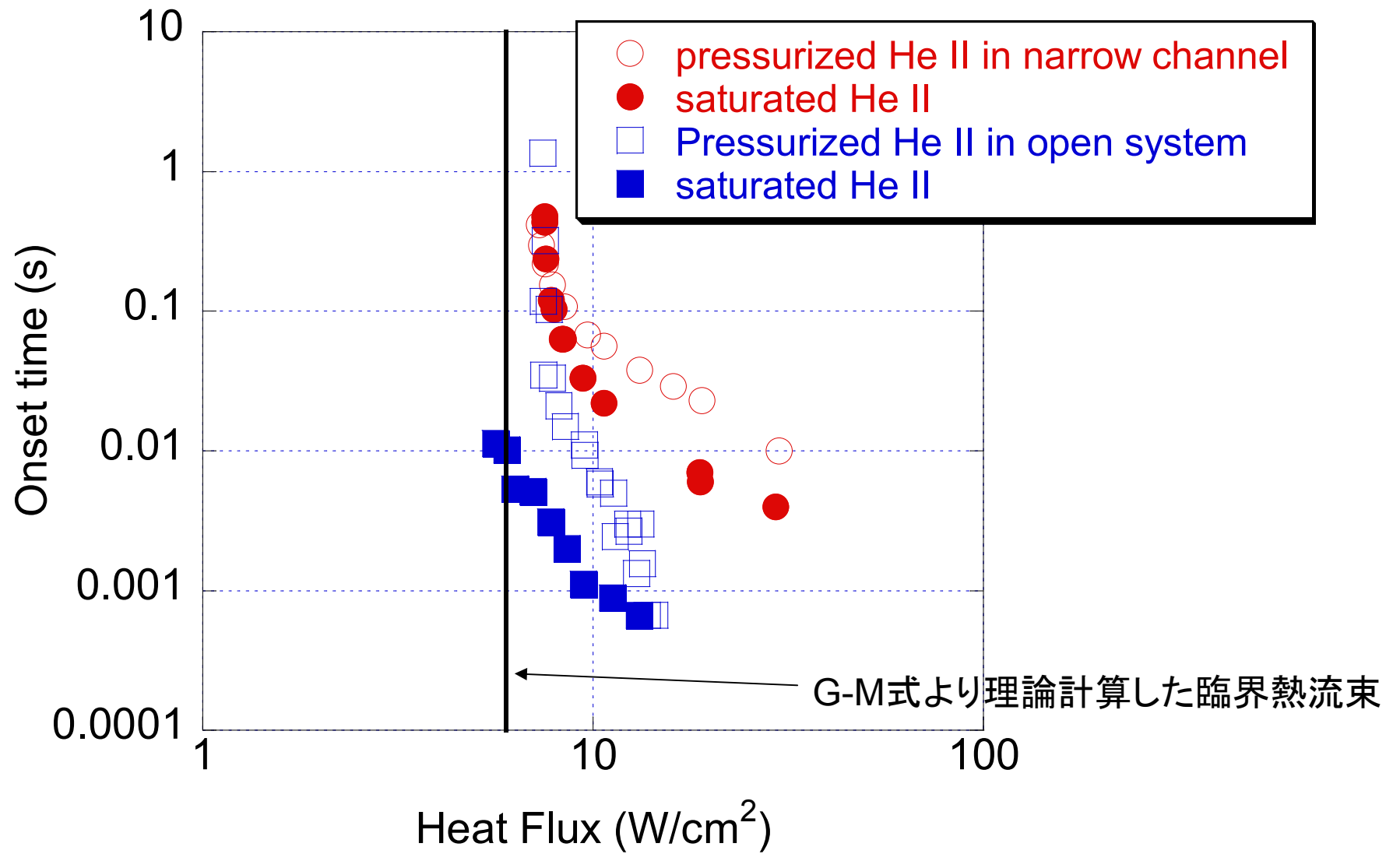
Narrow Channel $d = 0.155 \text{ mm}$

Gap thickness $d = 0.155$ mm

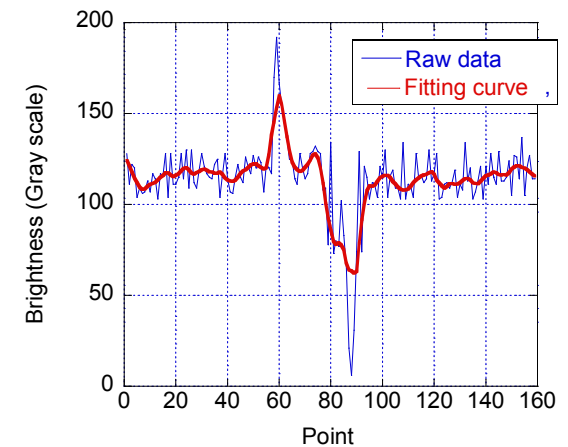
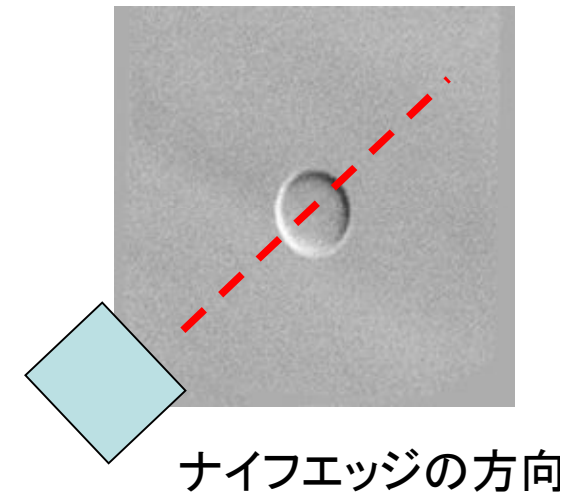
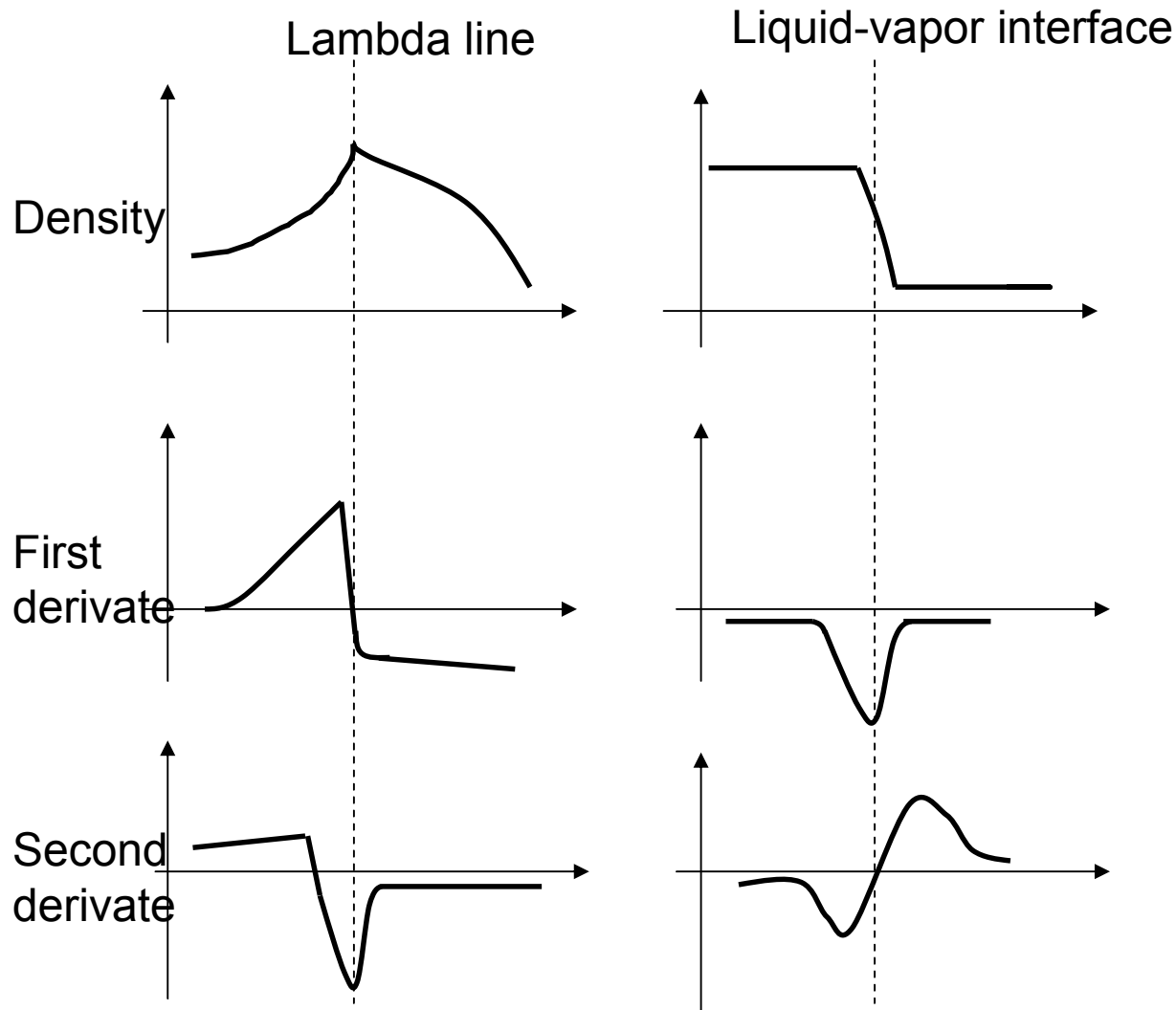
低熱流束のみで過熱He II-過熱He I界面出現



The onset time Δt of boiling depending on heat flux q'

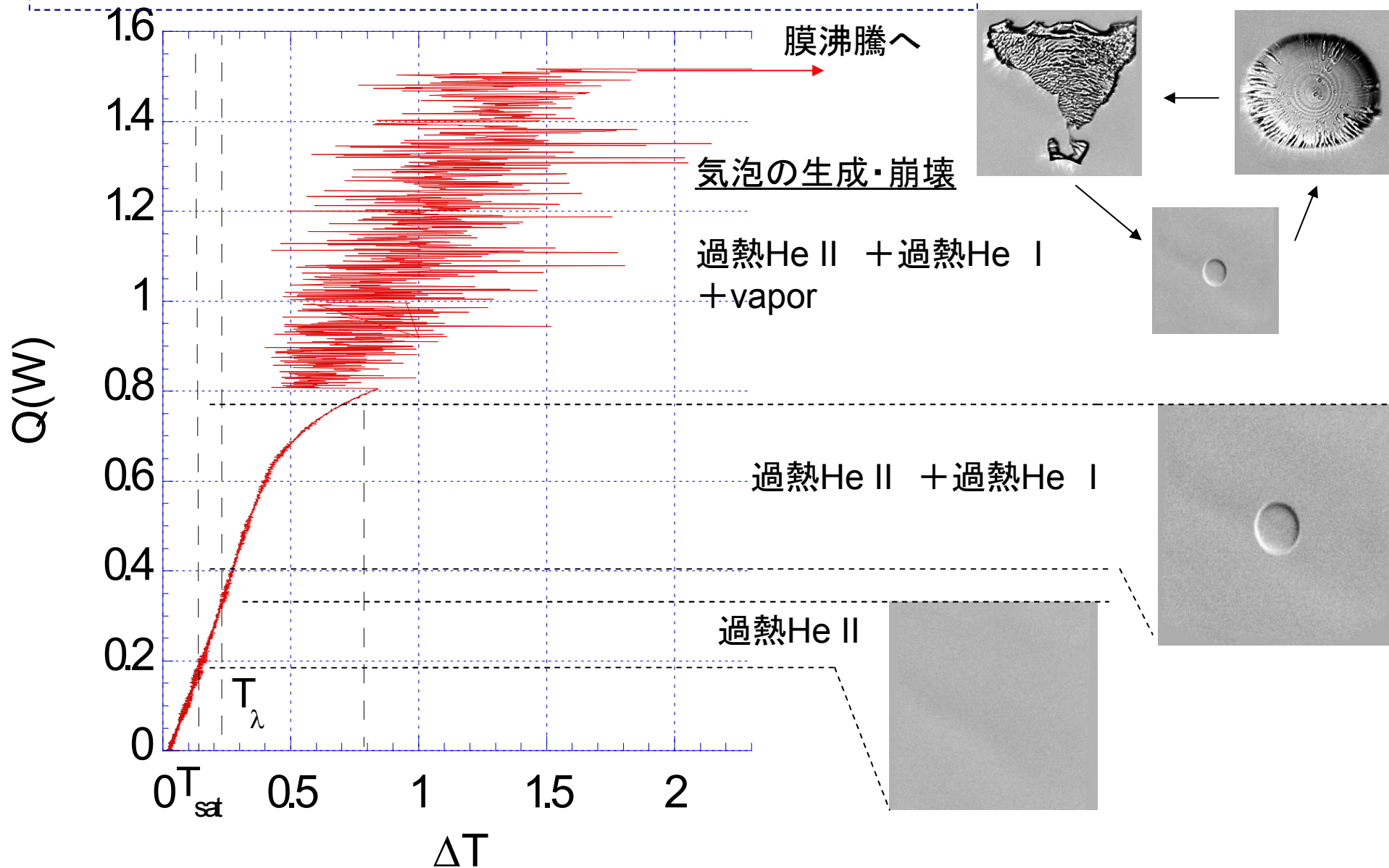


He II中でのシャドウグラフ / シュリーレン法

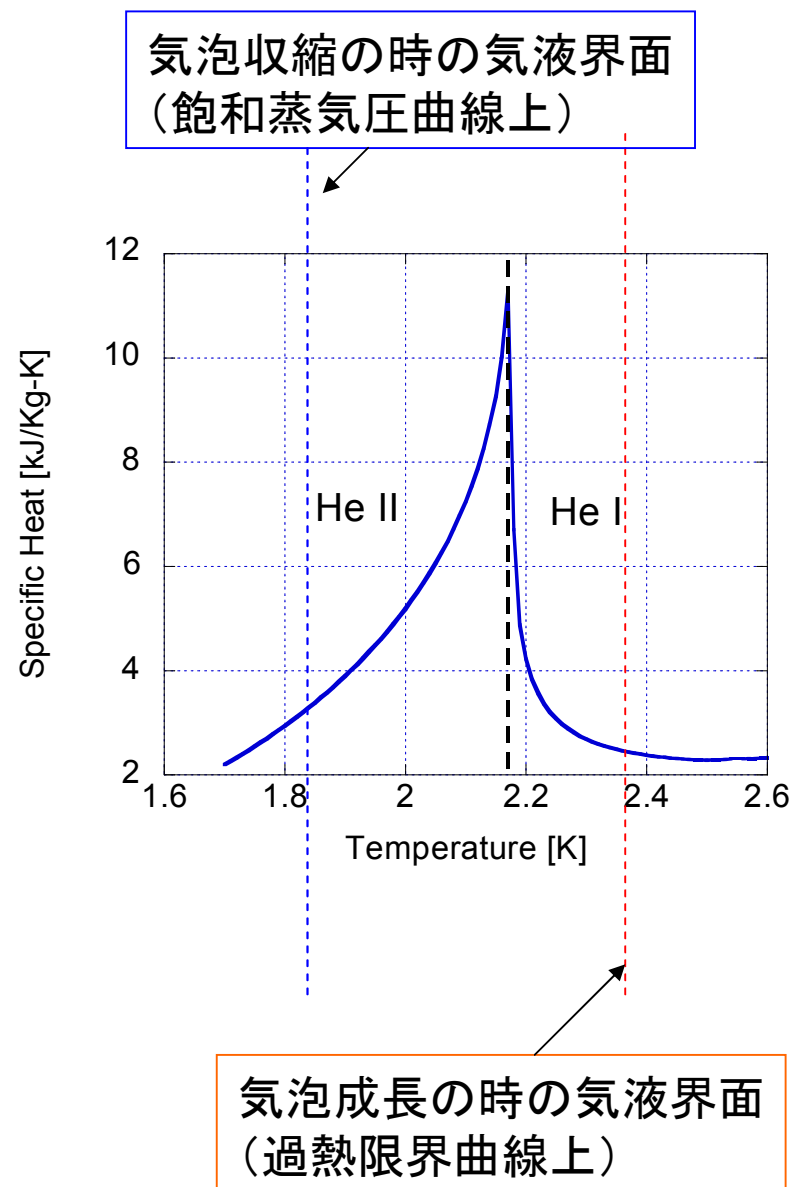
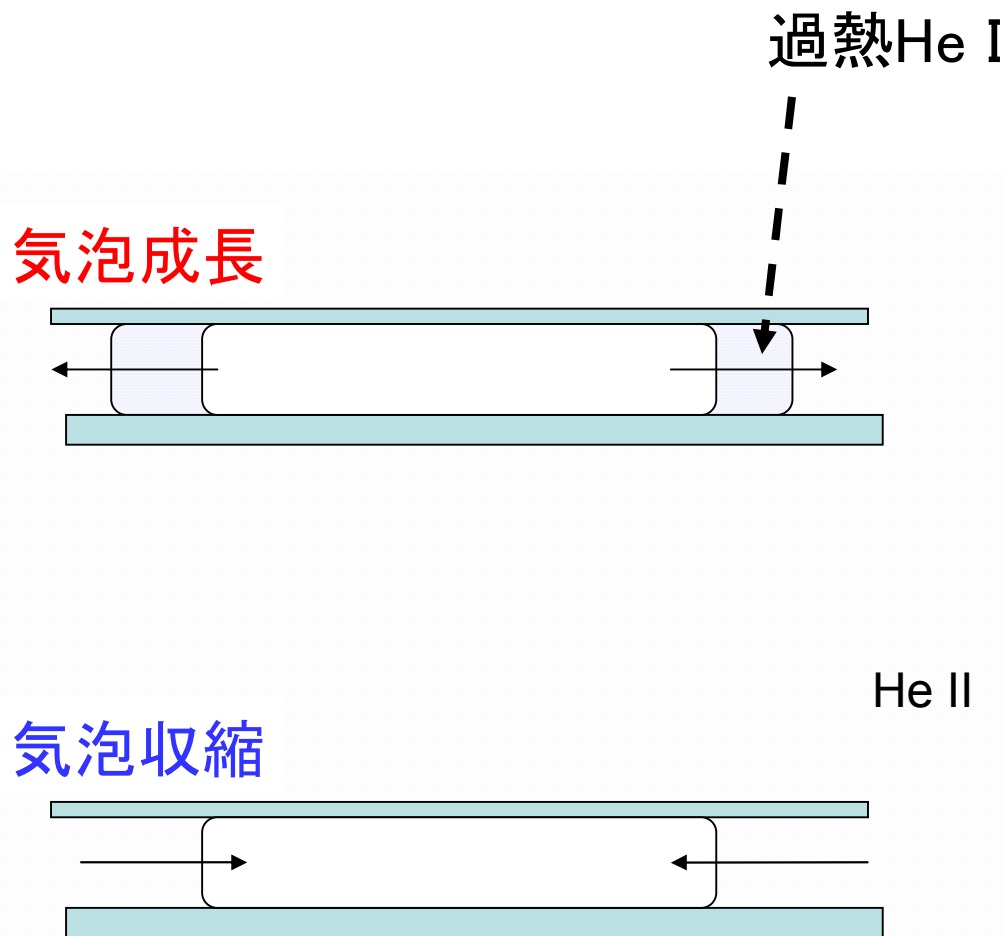


He II-He I相転移界面、気液界面の可視化が可能

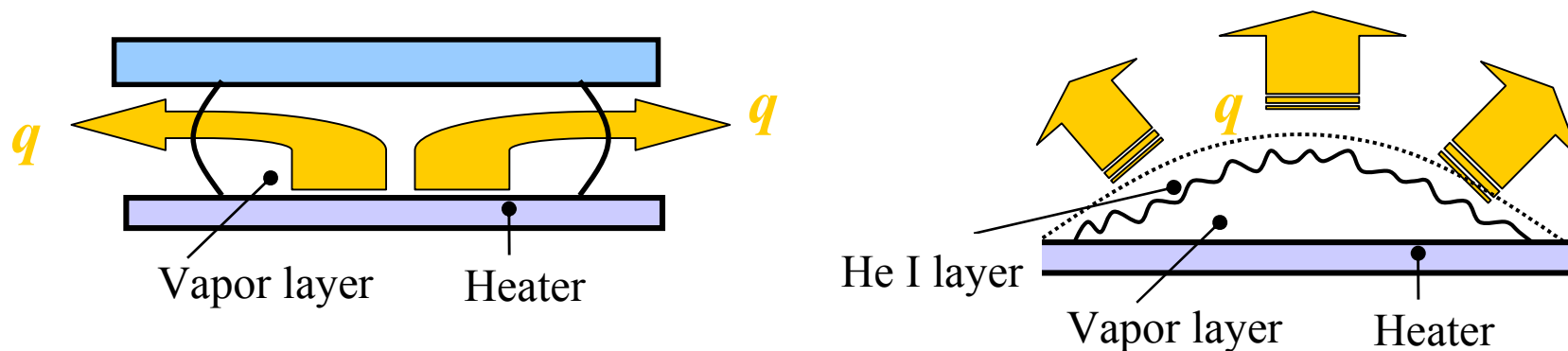
温度測定実験との比較： 共同研究者（日大・小林教授）の厚意による



比熱異常を効率的に利用する過熱液体の放出



狭小流路における熱流束の取り扱い



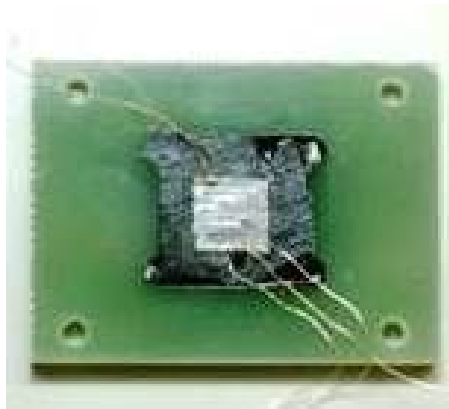
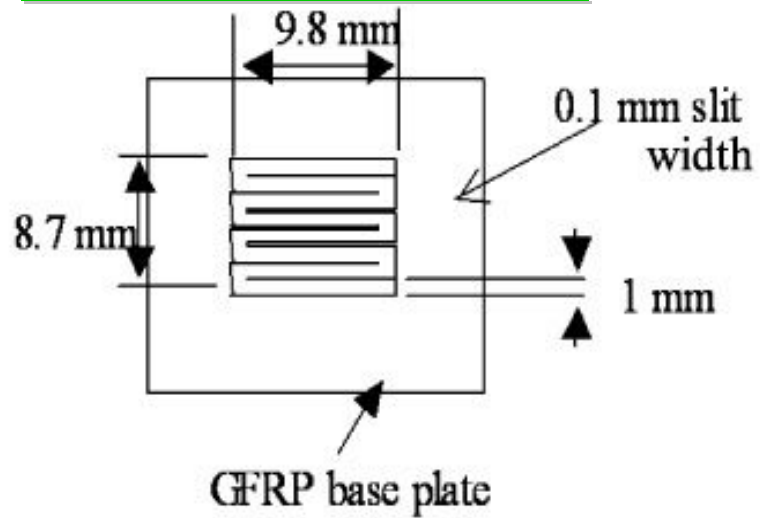
2次元流路の熱流束

$$q' = \frac{Q}{R \cdot d}$$

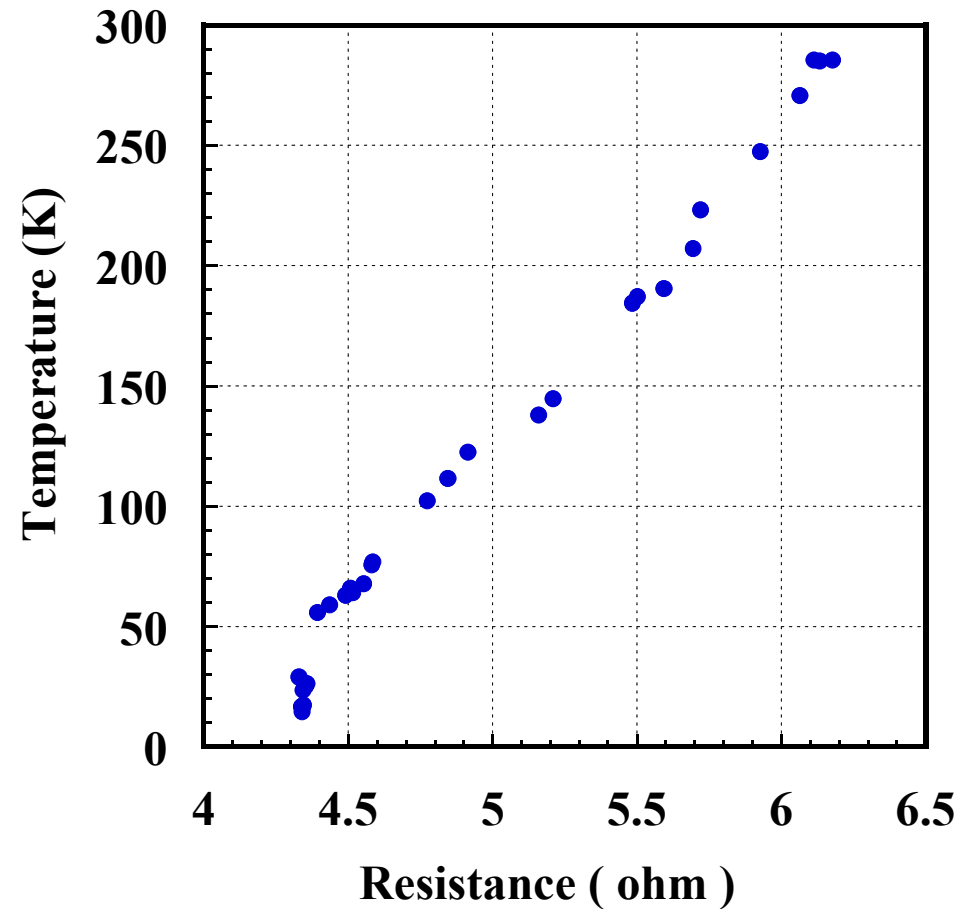
R ; ヒータ周長, d ; 流路厚さ

平板ヒータ

* ステンレス箔ヒーター

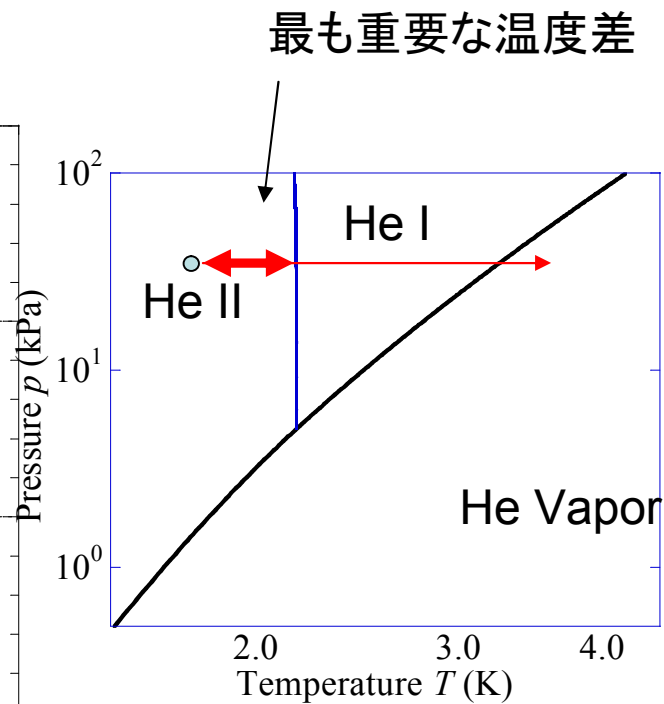
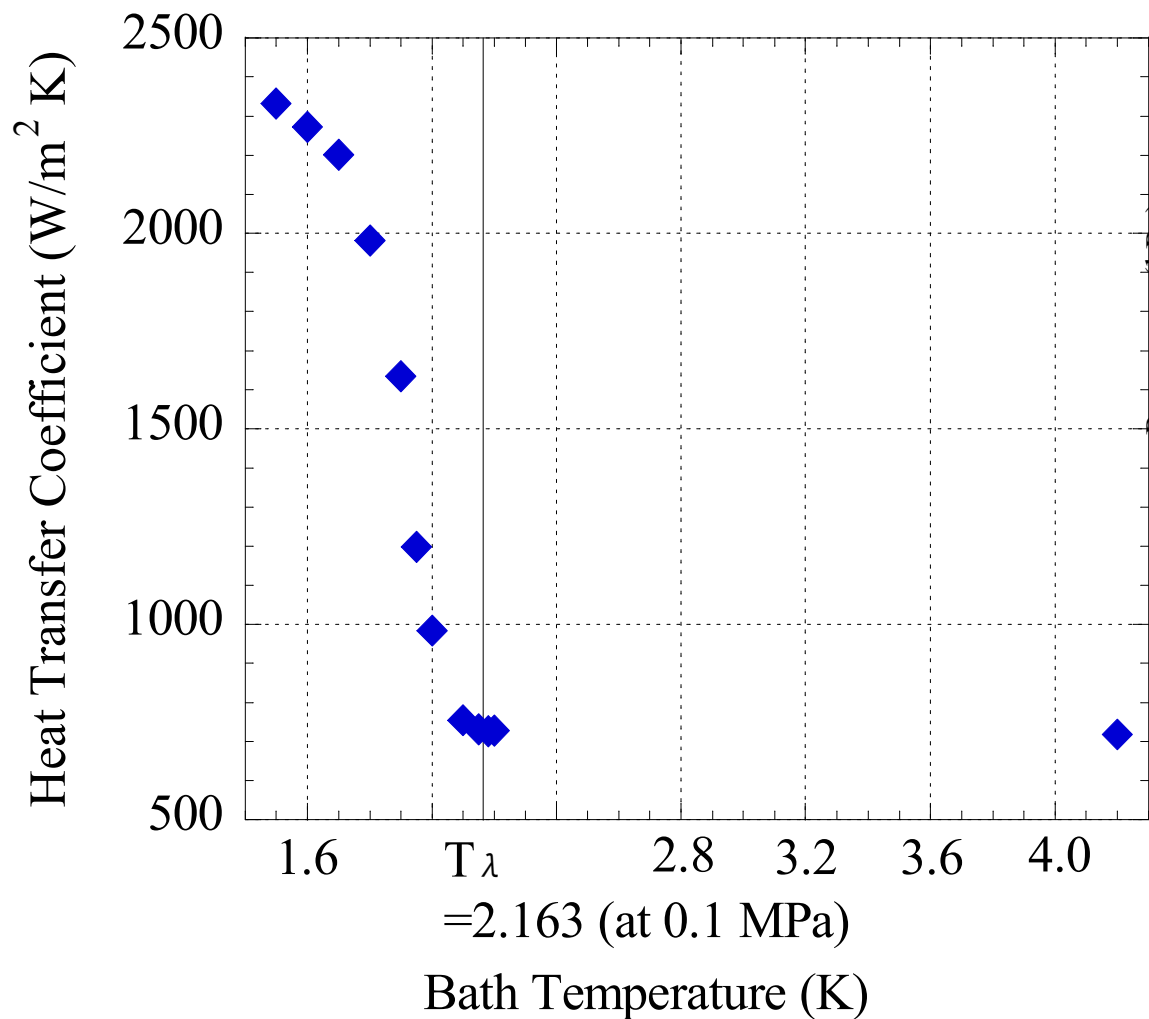


Thickness $8 \mu\text{m}$ の薄膜



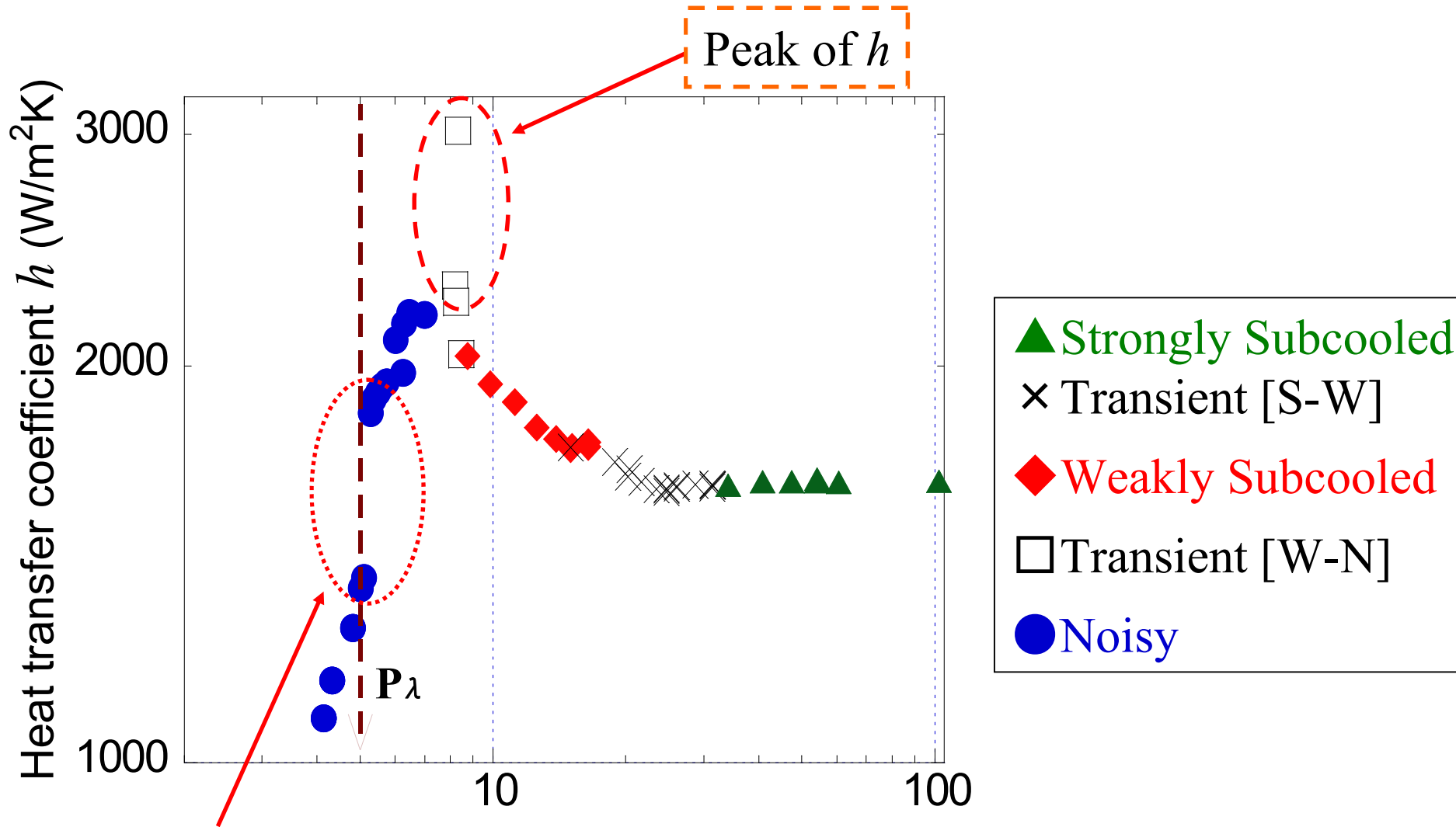
先行研究との整合性: 平板ヒータ・圧力振動・可視化

沸騰熱伝達率のHe II温度依存性



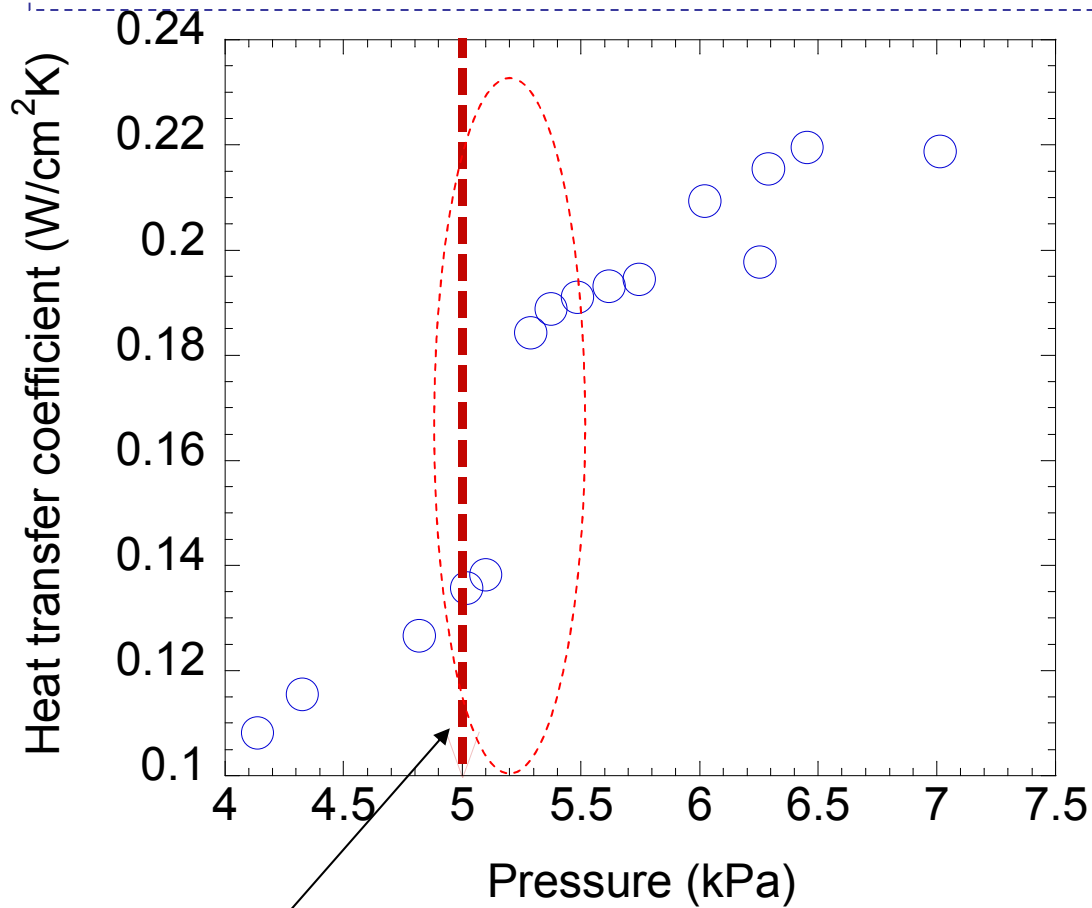
$$q = 11.2 \times 10^4 \text{ W/ m}^2 \text{ K}, \quad p = 101.13 \text{ kPa}$$

沸騰熱伝達率の圧力依存性



$q = 11.2 \times 10^4 \text{ W}/\text{m}^2$ at 1.9 K

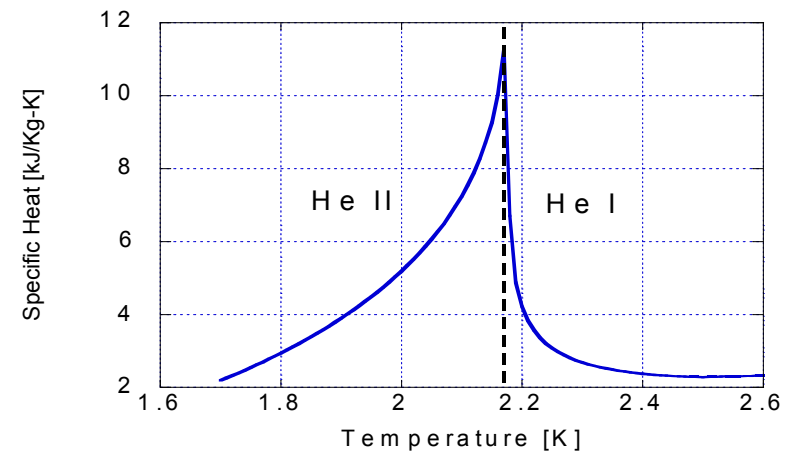
λ 圧力における特徴的な熱伝達率のジャンプ



僅かにλ 圧力より上でジャンプ

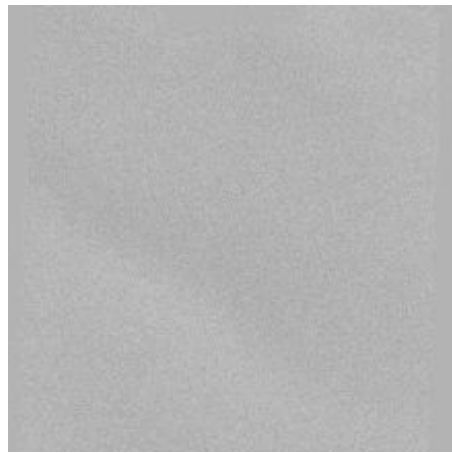
⇒ 蒸気膜周りのHe I相が十分に発達するため

λ 温度における比熱異常

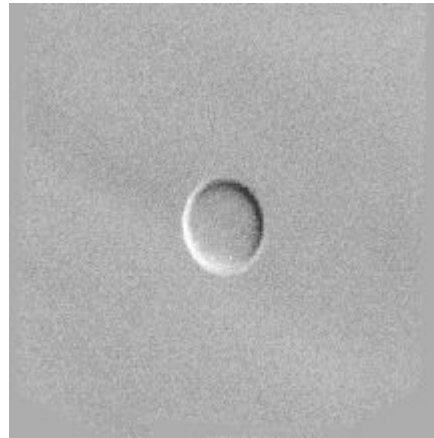
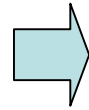


特徴的サイクル

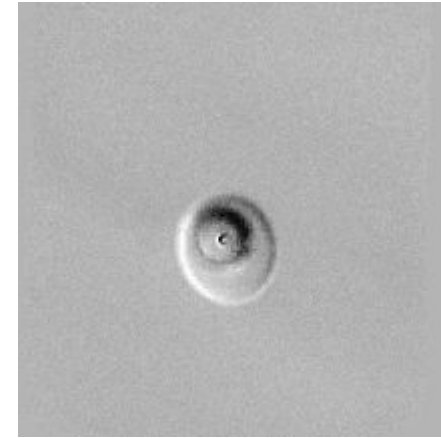
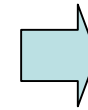
saturated He II, 2.1 K, $q' = 2.64 \text{ W/cm}^2$



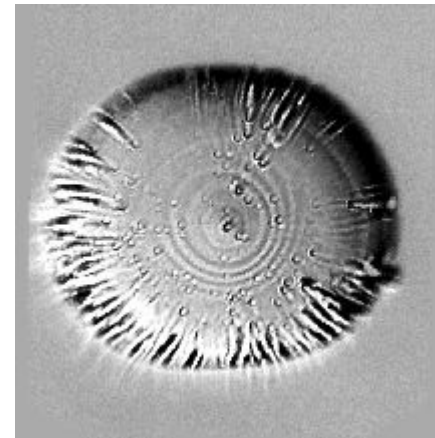
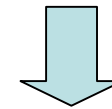
①初期状態



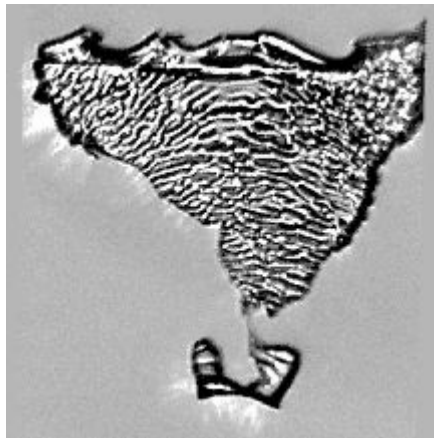
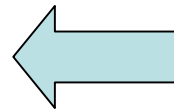
②過熱He II-過熱He I



③過熱He II-過熱He + Vapor



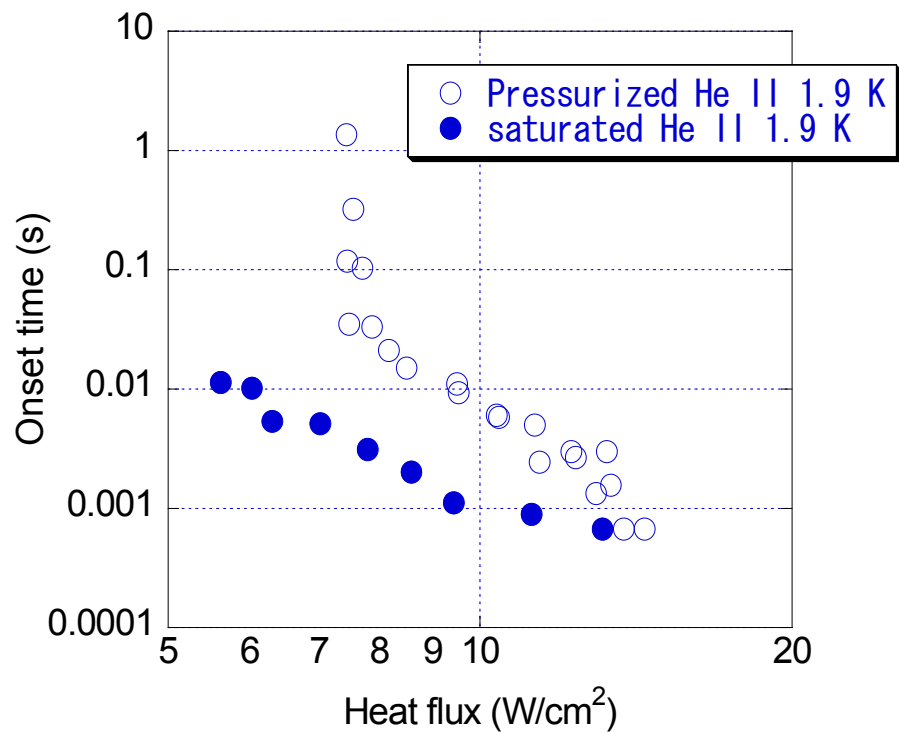
④気泡成長



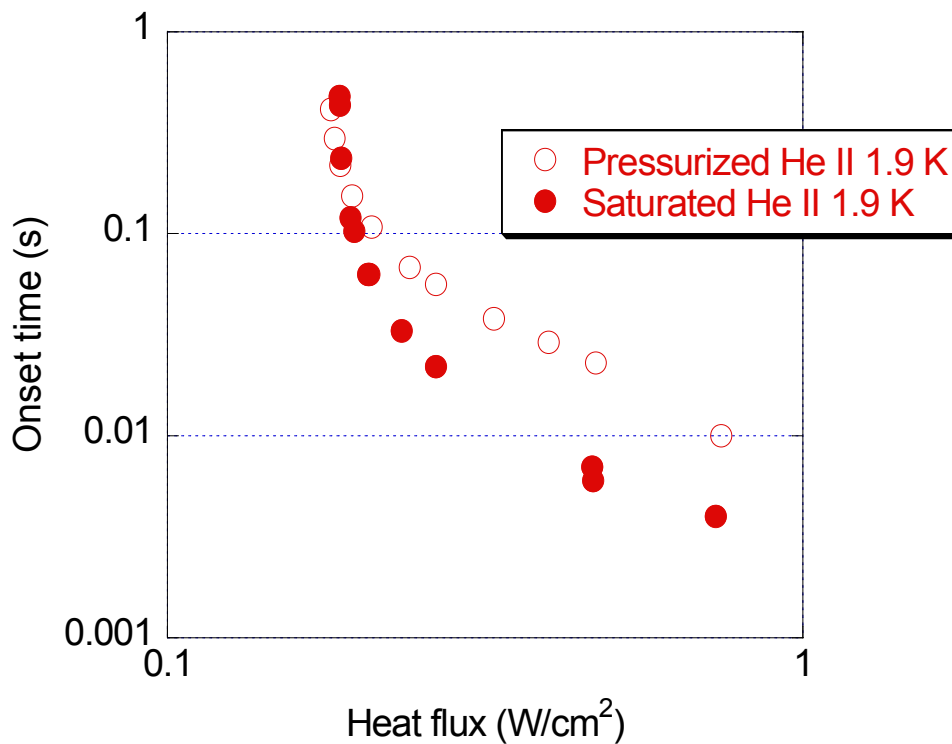
⑤気泡崩壊



開放空間と狭小流路 (155 μm)



3-D open system



Narrow Channel $d = 0.155 \text{ mm}$