Pressure Driven Flow of normal and superfluid through a single nanopipe

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Outline

Physics motivations and issues:

In **normal fluid**: what is the slip length?
(inspired by carbon nannotube results)
In **superfluid**: what is the critical velocity? Is it intrinsic or extrinsic?
How does it depend on ΔP and pipe geometry ?
How does a superfluid dissipate energy?

Nanopipes: Single ion etch tracks in polymers and mica 20 -80 nm dia, 20 microns long
Glass tubes, 200 nm dia 30 mm long

Flows are detected with a mass spectrometer (RGA)
Basic measurement is flow rate Q as function of ΔP

Prospects for nanopipes made using new technologies

Example: Carbon Nanotubes

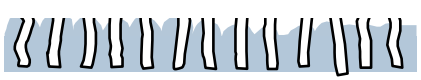
Air
Water

1

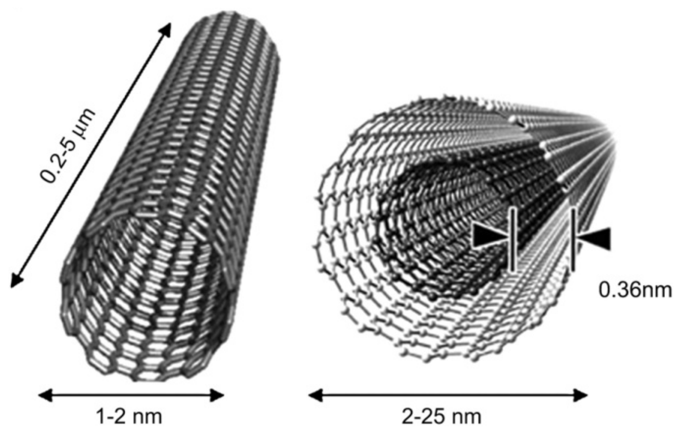
Membrane	Pore diameter (nm)	Pore density (cm^{-2})	Thickness (μm)	Enhancement over Knudsen model* (minimum)	Enhancement over no-slip, hydrodynamic flow† (minimum)	Calculated minimum slip length‡ (nm)
DWNT 1	1.3 to 2.0	$\leq 0.25 \times 10^{12}$	2.0	40 to 120	1500 to 8400	380 to 1400
DWNT 2	1.3 to 2.0	$\leq 0.25 \times 10^{12}$	3.0	20 to 80	680 to 3800	170 to 600
DWNT 3	1.3 to 2.0	$\leq 0.25 \times 10^{12}$	2.8	16 to 60	560 to 3100	140 to 500
Polycarbonate	15	6×10^{8}	6.0	2.1	3.7	5.1

*From (*18*). †From (*26*). ‡From (*29*).

2

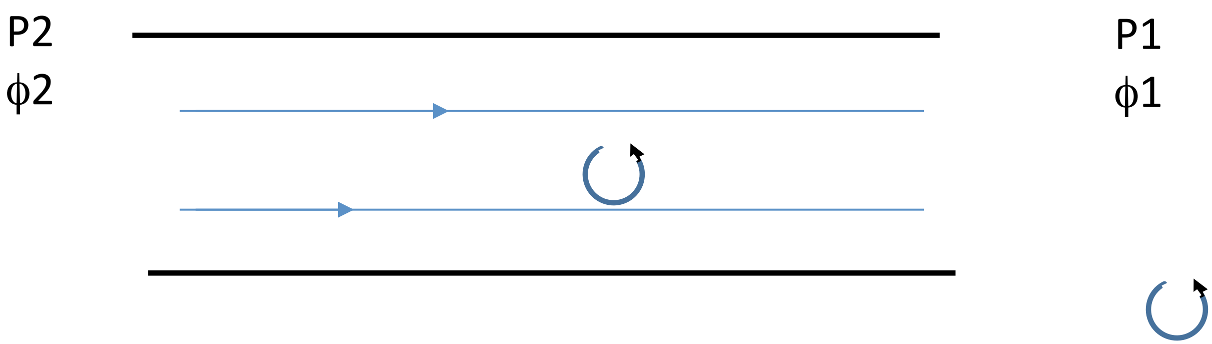


10^{11}/cm^2



1. Holt et al. Science **312**, 2006
2. Reilly J Nucl Med. **48**,7 2007

Vortices in a pipe carrying an ideal classical fluid

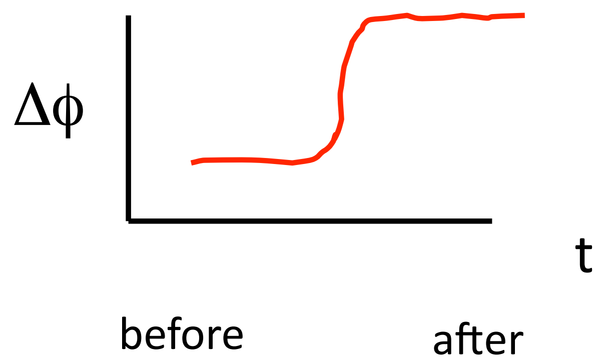


Potential flow

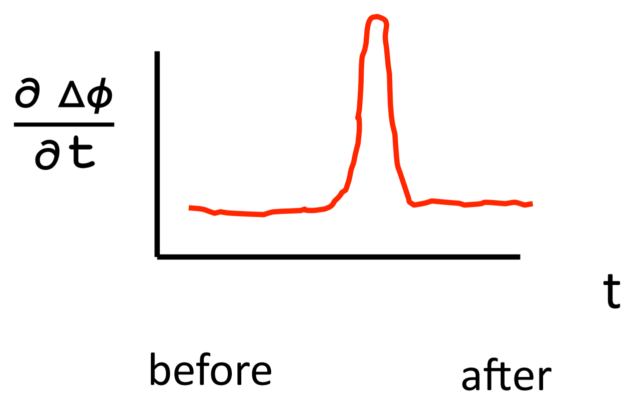
$$V = \nabla\phi$$

Bernoulli

$$\frac{\partial \phi}{\partial t} + \frac{1}{2}\nabla\phi \cdot \nabla\phi + \frac{P}{\rho} = 0$$

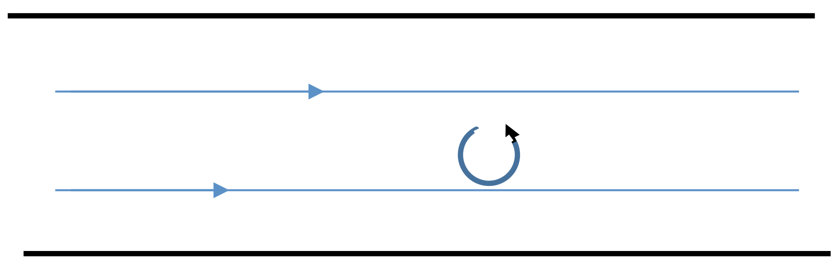


$$\Delta\phi = \phi 2 - \phi 1 = \int_1^2 \nabla\phi \cdot \mathbf{ds}$$



$$\Delta P = \rho \left\langle \frac{\partial\, \Delta\phi}{\partial t} \right\rangle = \rho\, \dot{N} \kappa$$

Anderson-Josephson relation



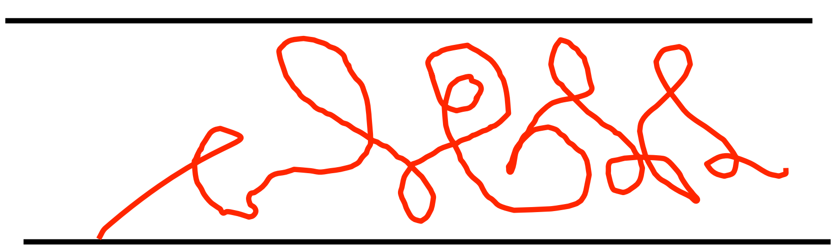
$$\Delta P = \rho \, \dot{N} \kappa$$

Why does vortex cross flow lines?

Ideal fluid : Kelvin Theorem (no Magnus force; go with the flow)

With mutual friction : Magnus force

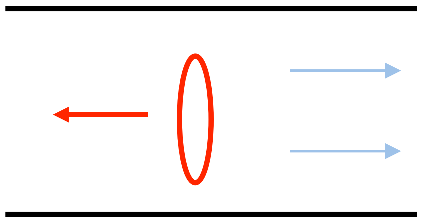
At very low temperatures: vortex tangle, pinning, reconnection and turbulence



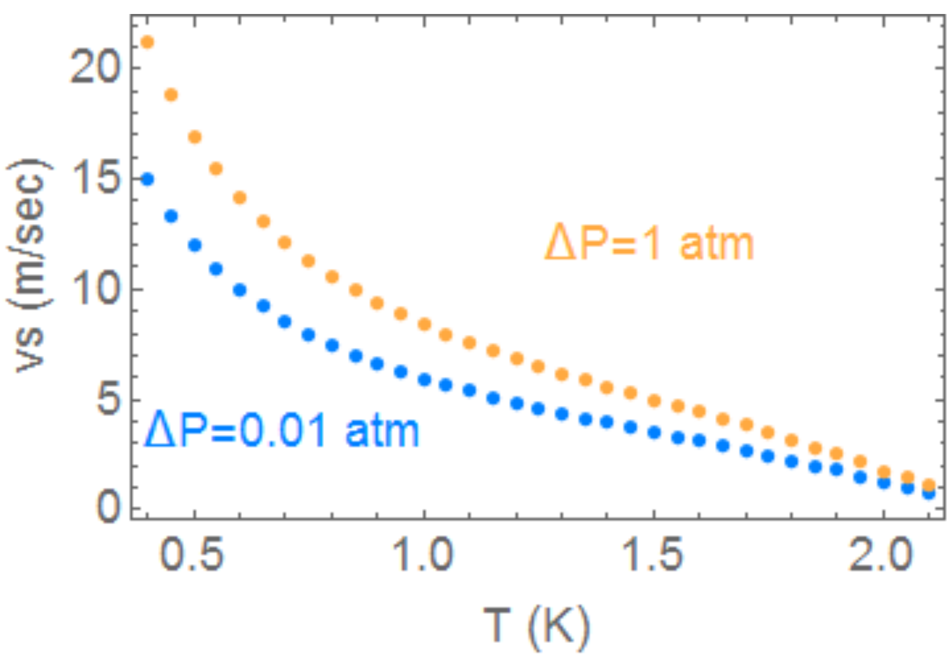
In mm scale pipes, turbulent superfluid flows just like water

Where do the vortices come from?

Nucleation: energy of critical vortex ring= $\frac{\beta\,\rho s}{\rho\,\mathbf{vs}}$



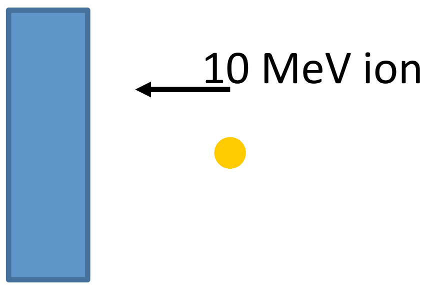
$$\Delta P = \rho\,\kappa\,\dot{N} = \rho\,\kappa\,V\,f_0\,e^{-\frac{\beta\,\rho s}{\rho\,\mathbf{vs}\,T}}$$

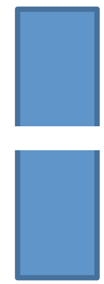


Logarithmic dependence on ΔP, L, and R

10^{13} vortices/atm

Measuring pressure driven flow through single nanopipes



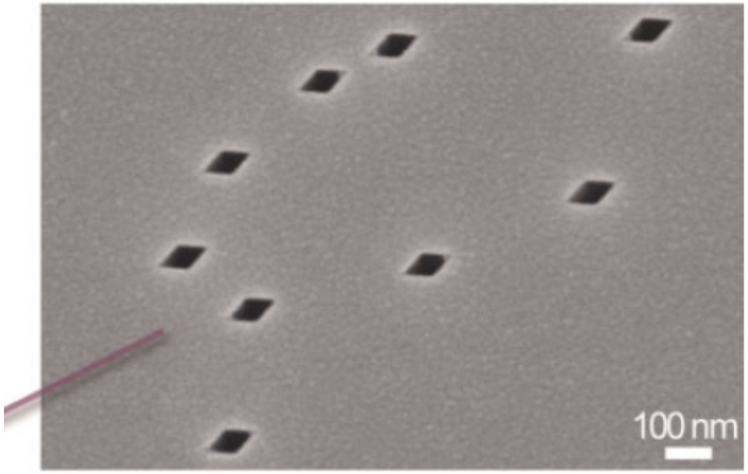


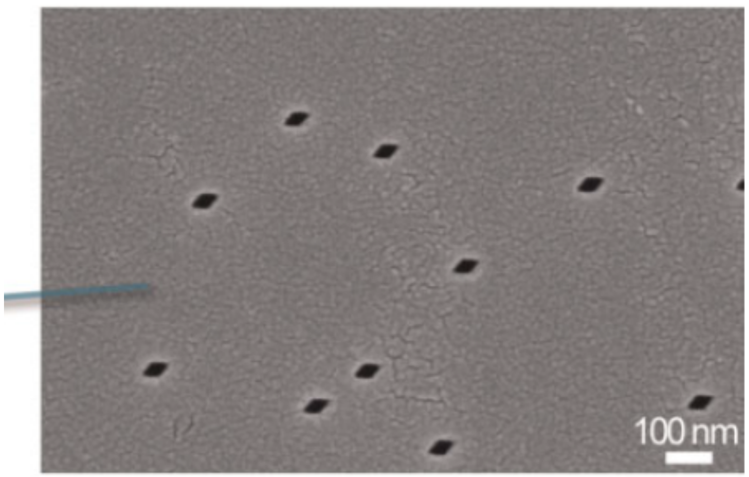
Chemical etch
Diameter= 20 - 200 nm

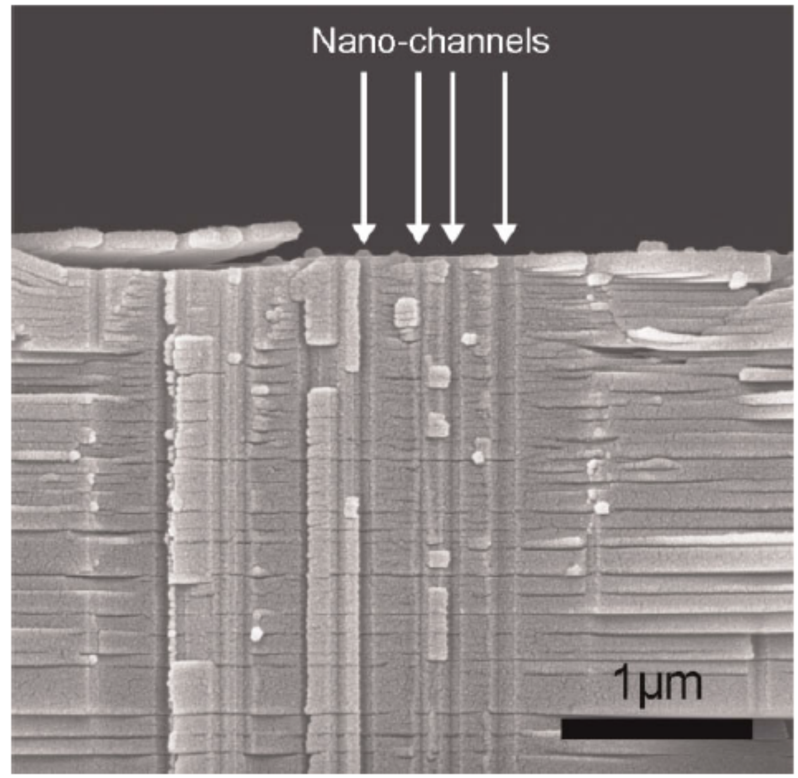
10-20 microns
PET or mica

Glass tubes : 200 nm diameter, meters long

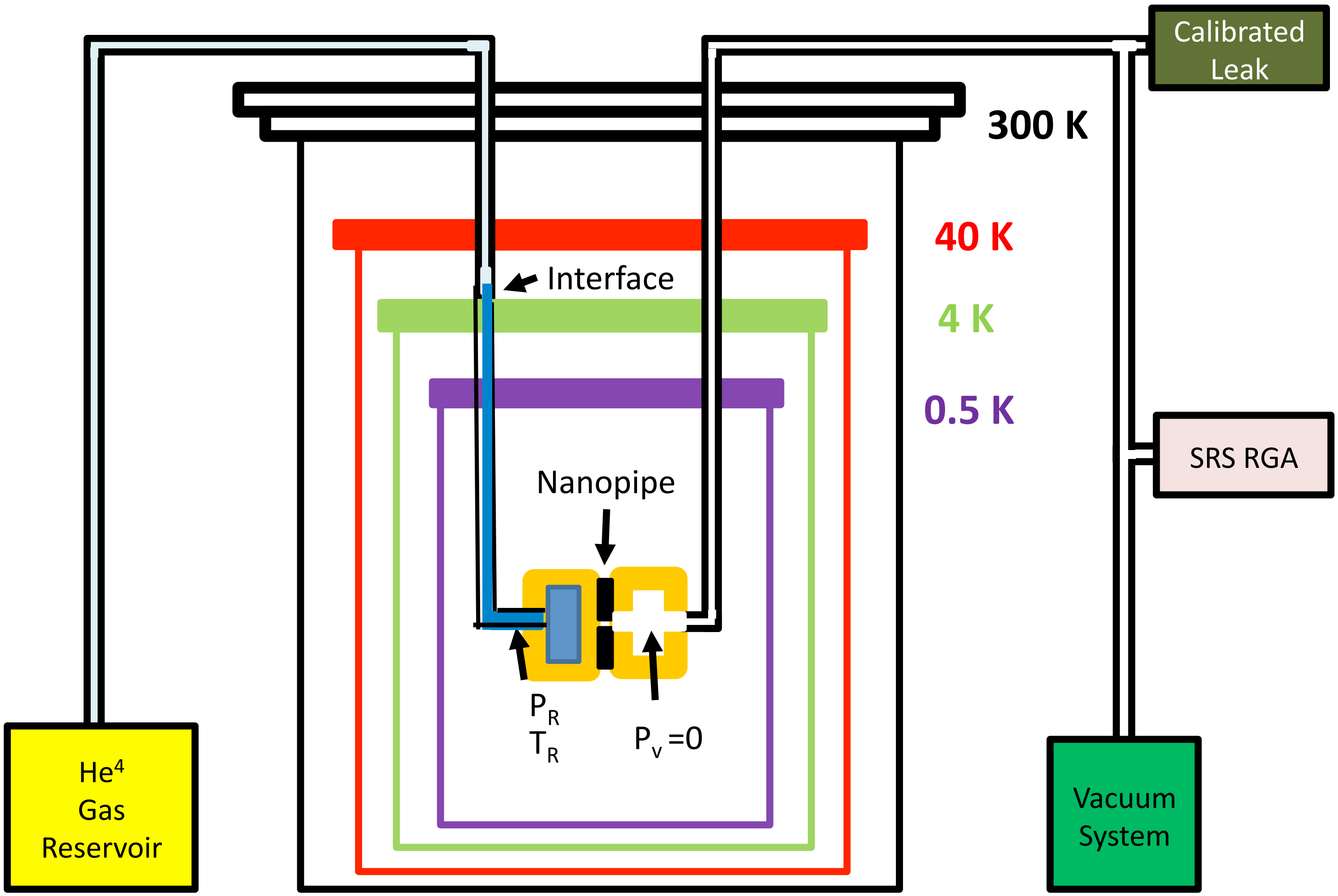
Detection of flow: mass spectrometry with detection limit of 10^6 particles/sec



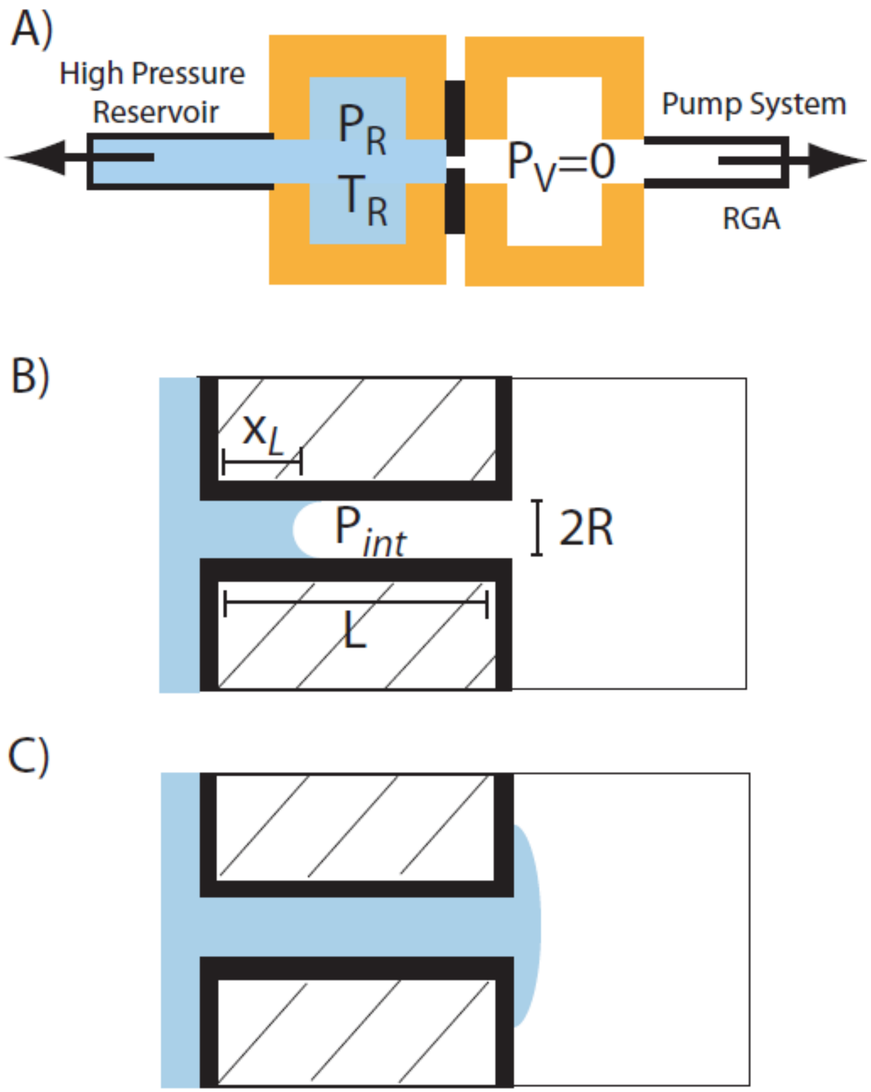




3. Pezzagna et al. Phys. Status Solidi A **9**,
2017-2022 (2011)


Calibrated Leak
300 K
40 K
Interface
4 K
0.5 K
SRS RGA
Nanopipe
P_R
T_R
P_v =0
He4 Gas Reservoir
Vacuum System

Liquid Flow into Vacuum



Mass Flow

$$Q = \frac{\pi\,\rho\Delta P}{8\eta x_L}(R^4 + 4bR^3)$$

$$Q_{Evap} > Q_{flow}$$

$$\Delta P = P_R + \frac{2\gamma}{R} - P_{int}$$

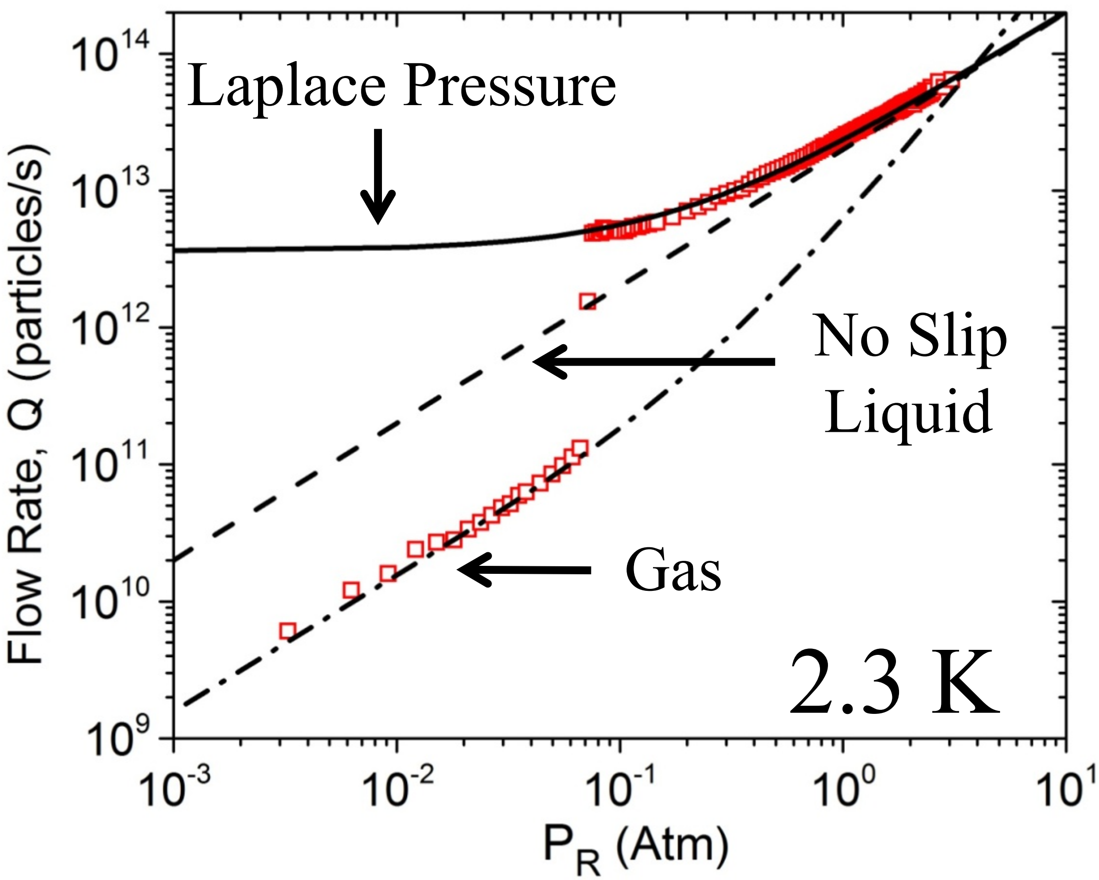
$$Q_L(x_L) = Q_G(L - x_L)$$

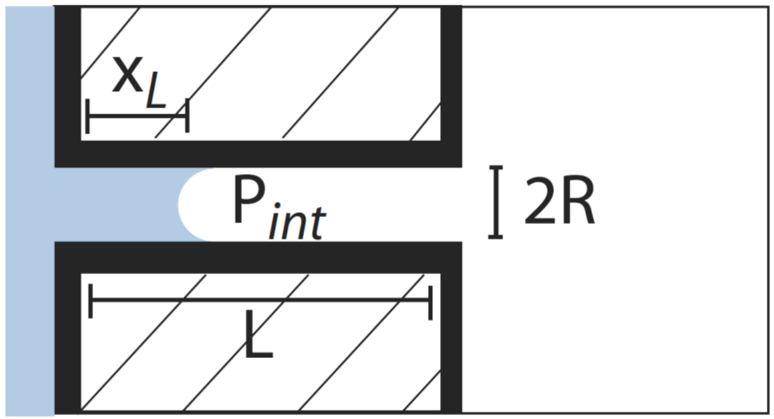
$$Q_{Evap} < Q_{flow}$$

$$\Delta P = P_R$$

$$x_L = L$$

Normal ^{4}He: 60 nm PET

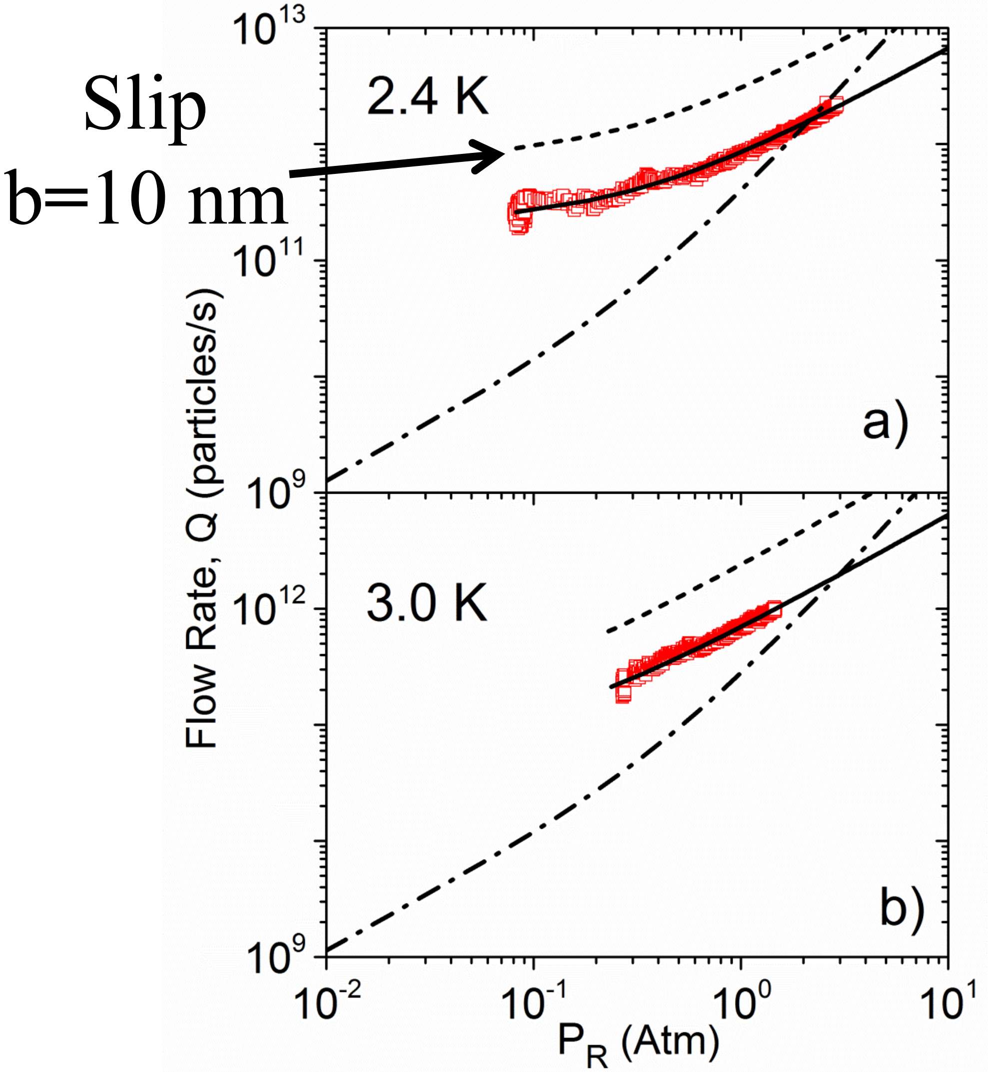




$$Q = \frac{\pi\,\rho\Delta P}{8\eta\, x_L}(R^4 + 4bR^3)$$

$$\Delta P = P_R + \frac{2\gamma}{R} - P_{int}$$

31 nm Mica Nanopore



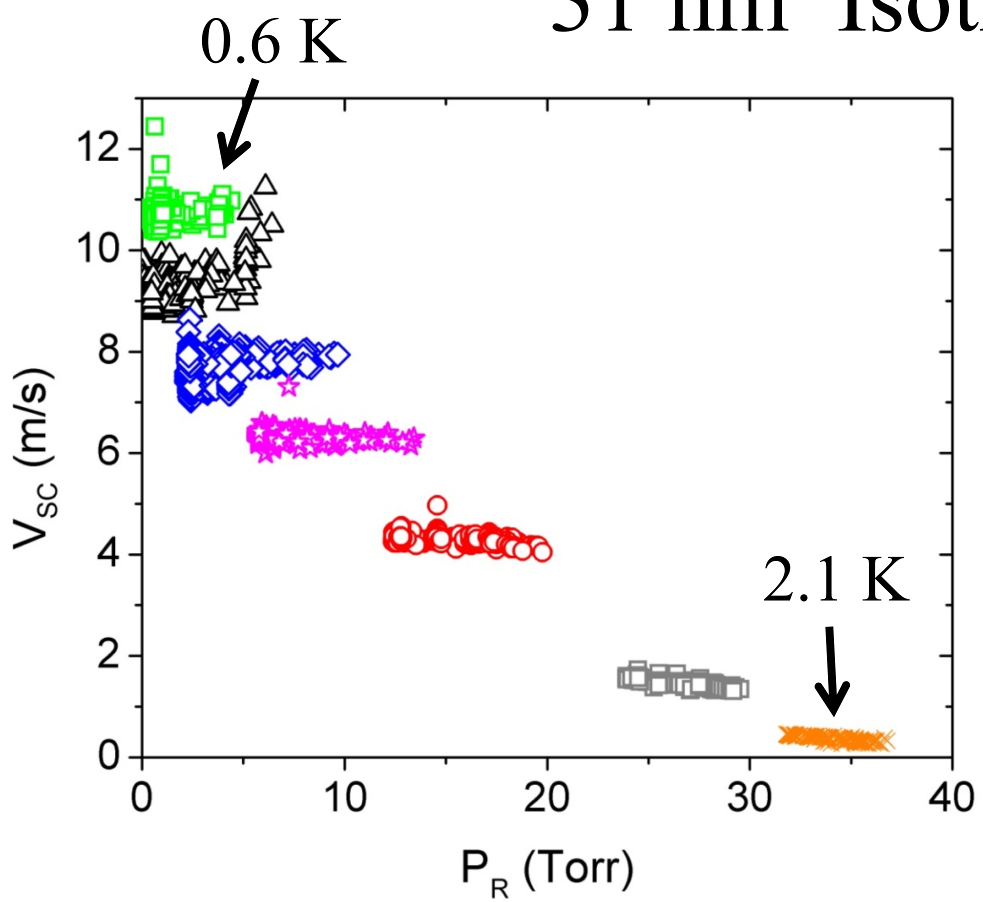
$$P_{int} < \frac{2\gamma}{R}$$

$19.6\ \mu m < x_L < 19.9\ \mu m$

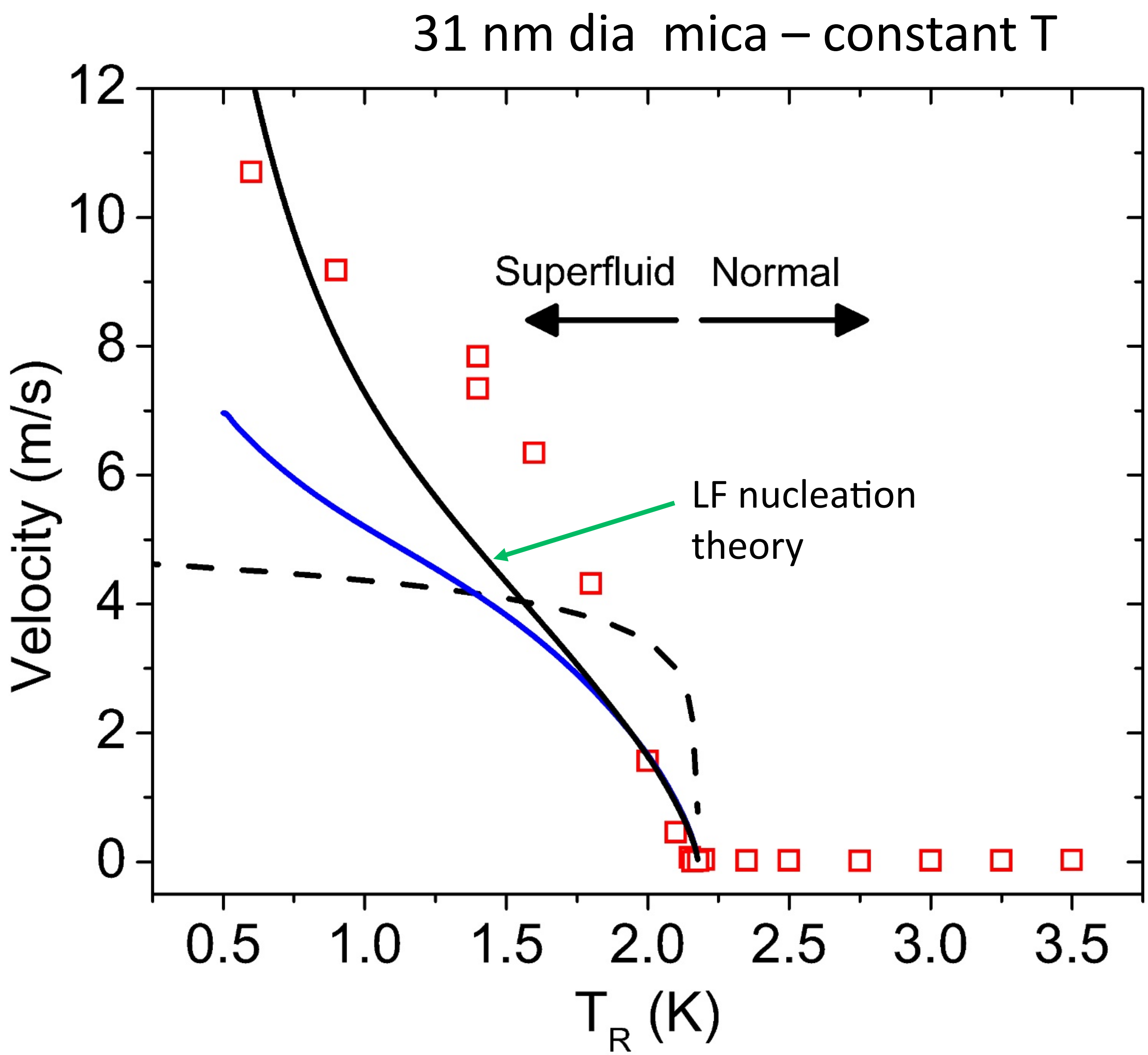
$$P_{int} \sim \frac{2\gamma}{R}$$

$17\ \mu m < x_L < 19.4\ \mu m$

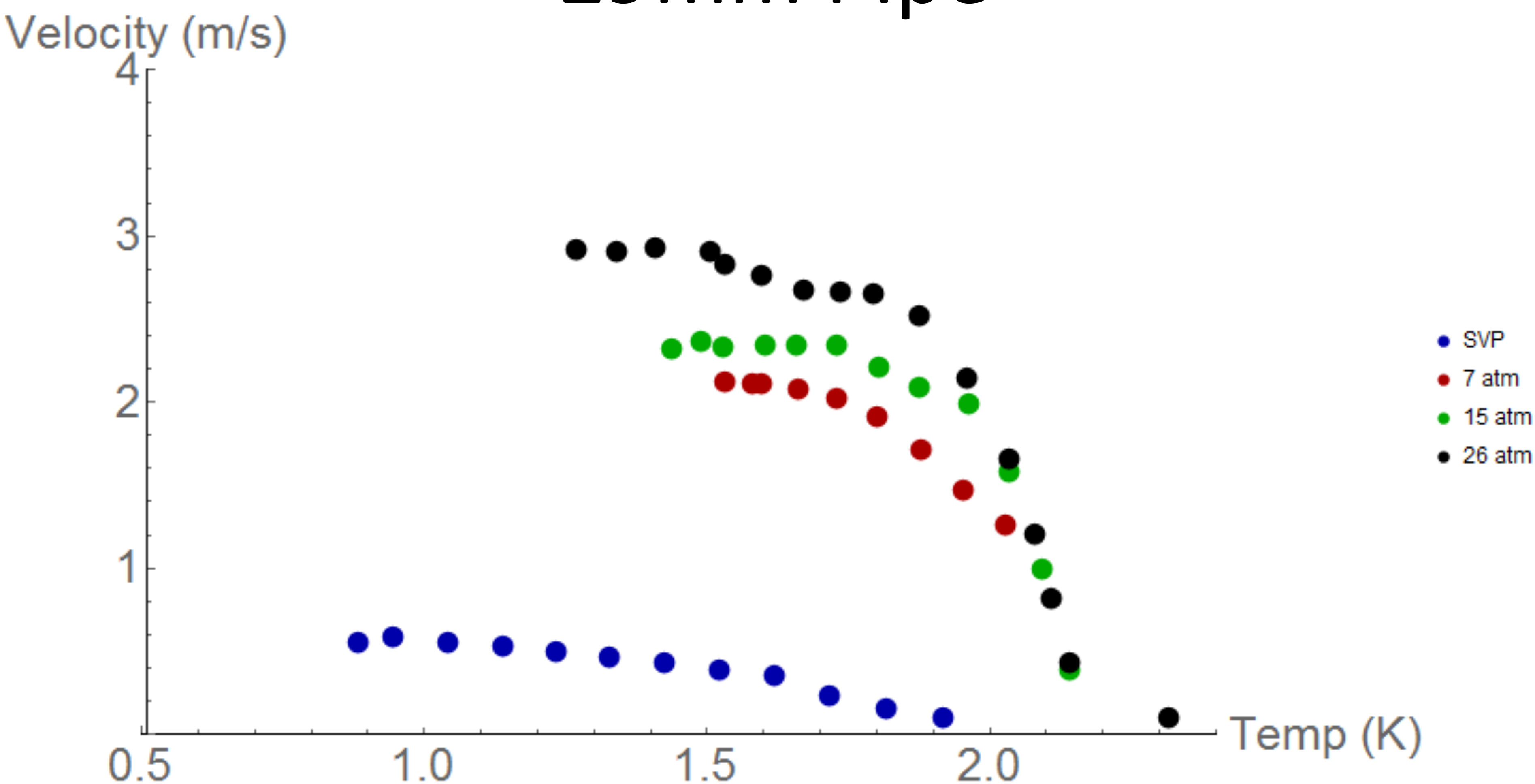
31 nm Isotherms



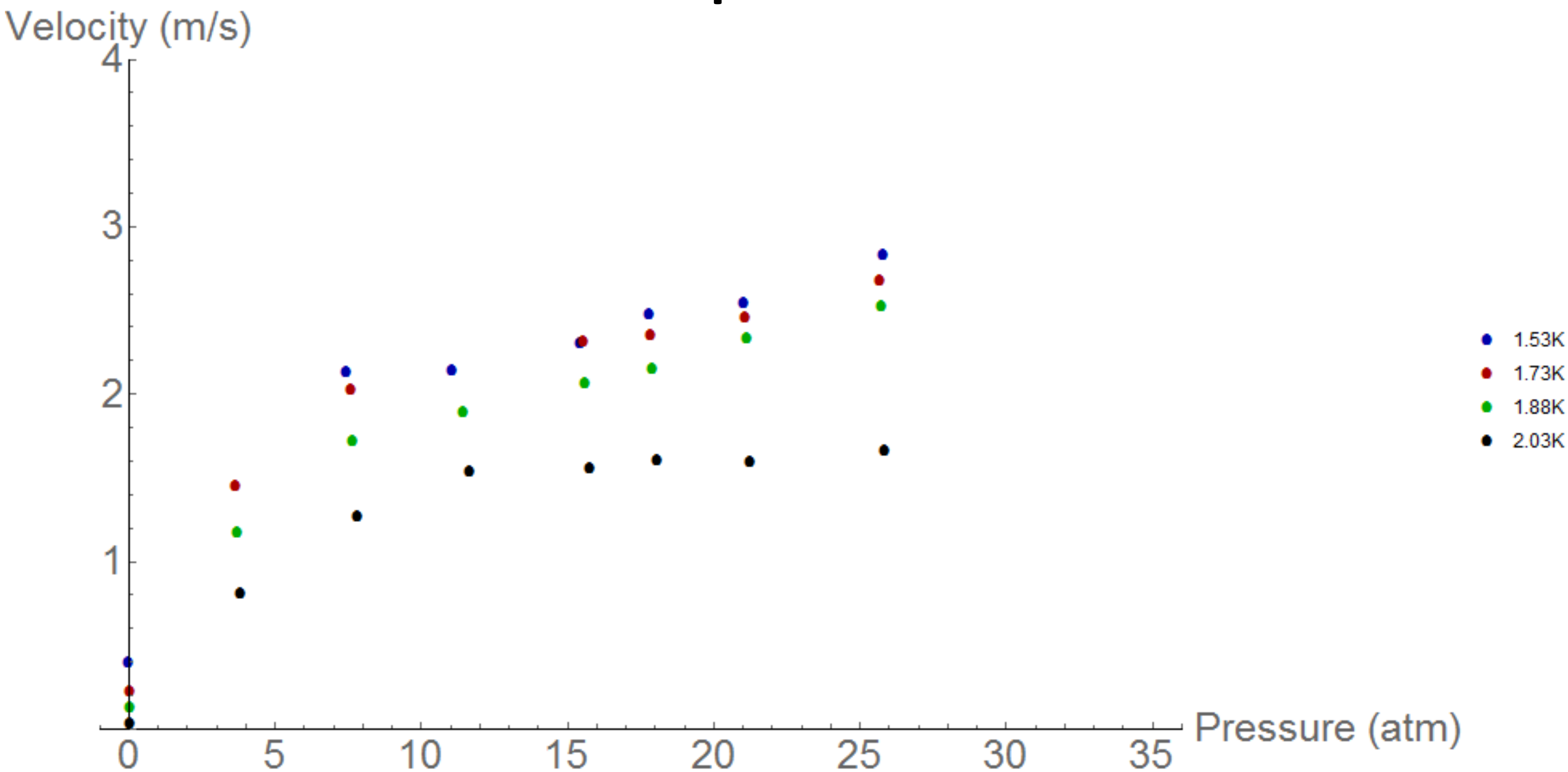
T(K)	V (m/sec)
0.6	10.6
0.9	9.2
1.4	7.9
1.6	6.4
1.8	4.6
2.0	2.6
2.1	1.5


31 nm dia mica – constant T
Superfluid
Normal
LF nucleation theory
Velocity (m/s)
T_R (K)
12
10
8
6
4
2
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

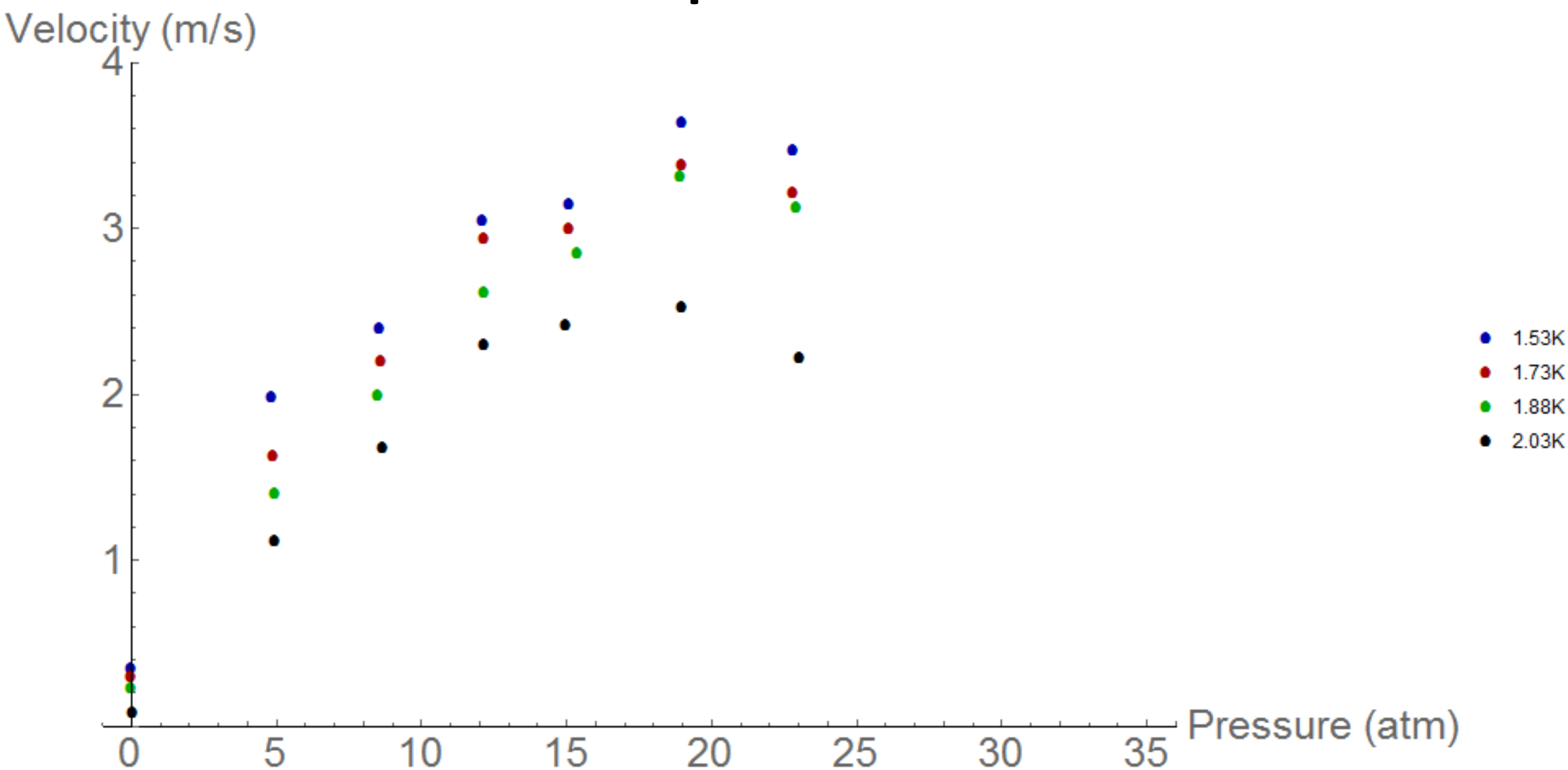
29mm Pipe



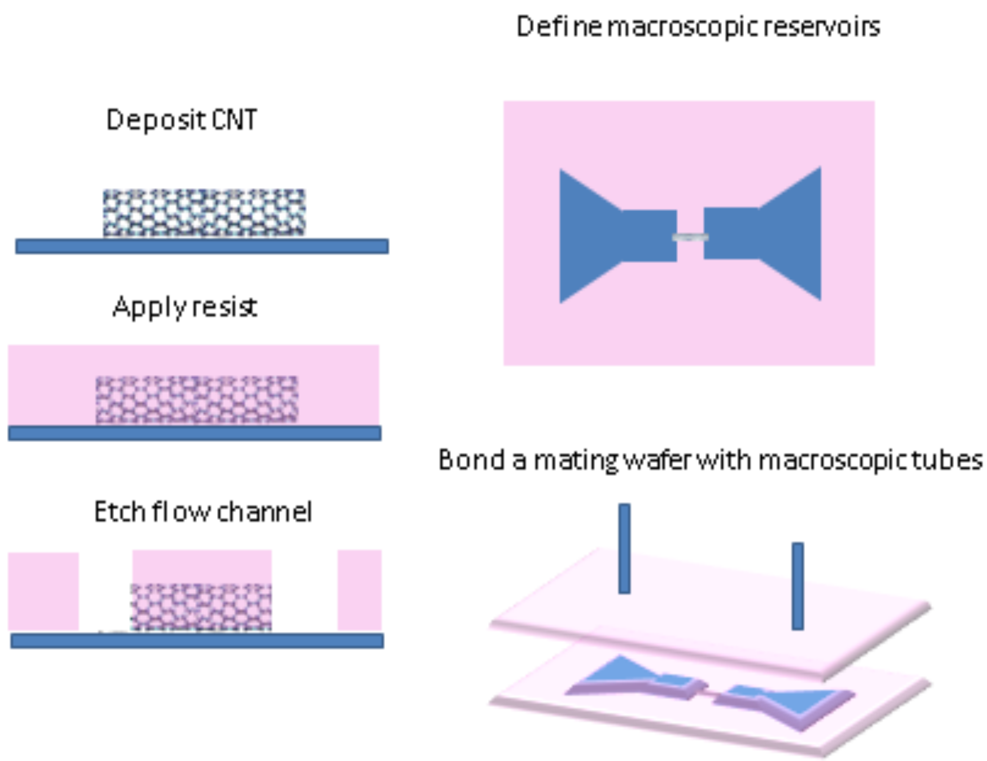
29mm Pipe Isotherms



1mm Pipe Isotherms

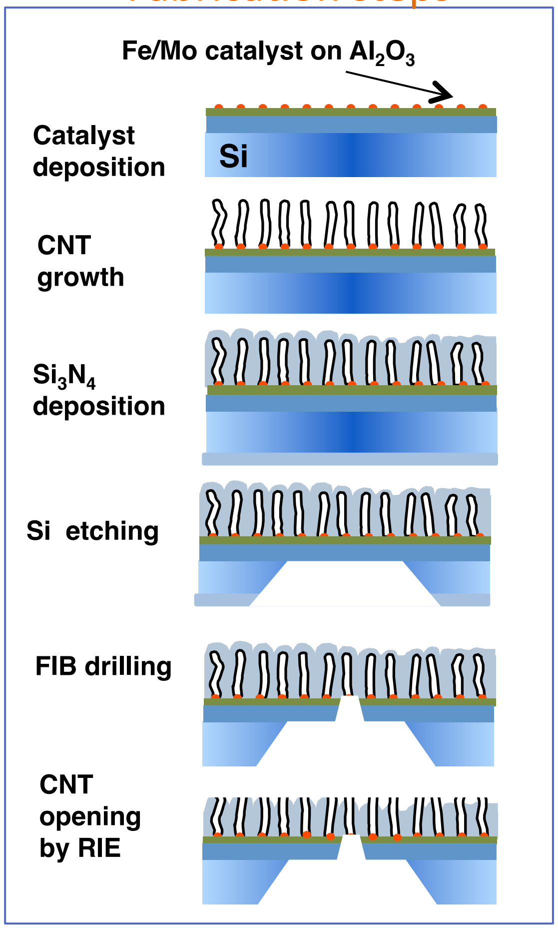


New nanopipe fabrication technologies: making a single nanotube flow device

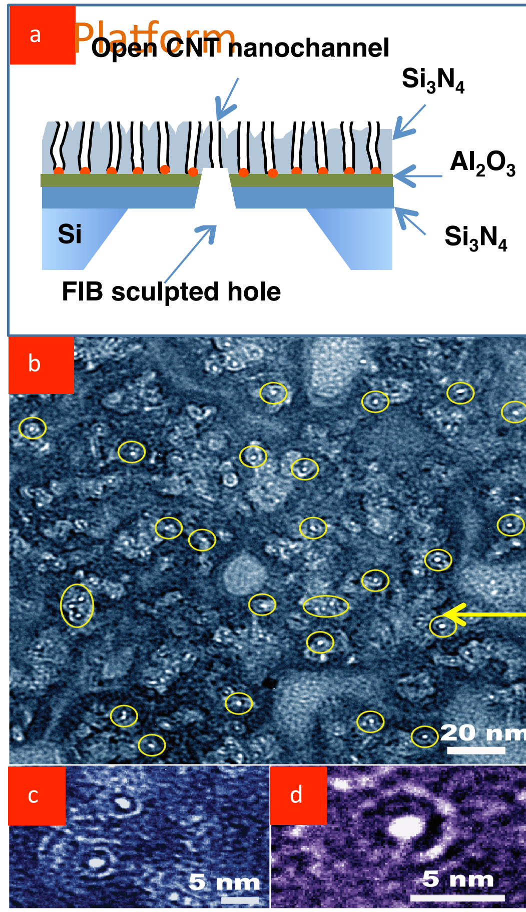


Nanofluidic platform for fluid transport in a single or a few CNTs

Fabrication steps



Nanofluidic Platform



UNIQUE APPROACH

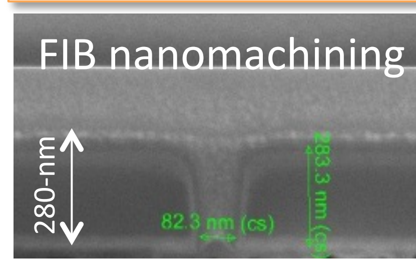
In the same device,

- single pore or
- billions of pores (membrane)

can opened at will.

TEM cross-sectional image of CNT-Si_3N_4 composite

White dot in yellow circle = CNT

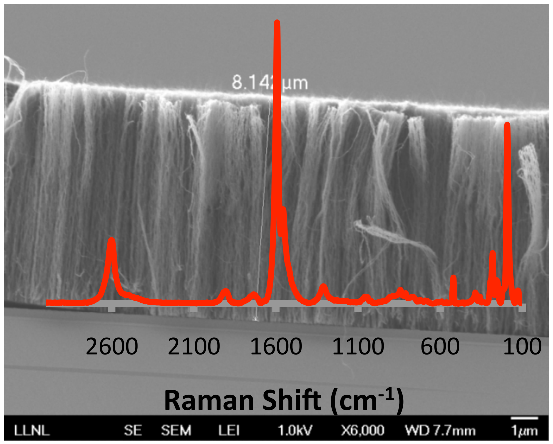


From: Francesco Fornasiero, LLNL, *fornasiero1@llnl.gov*

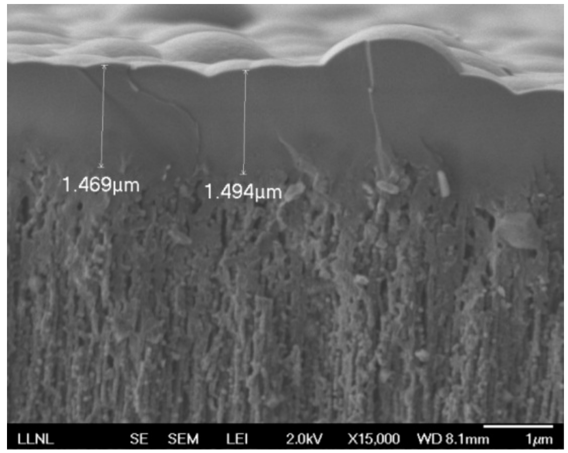
Nanofluidic device fabrication

From: Francesco Fornasiero, LLNL, *fornasiero1@llnl.gov*

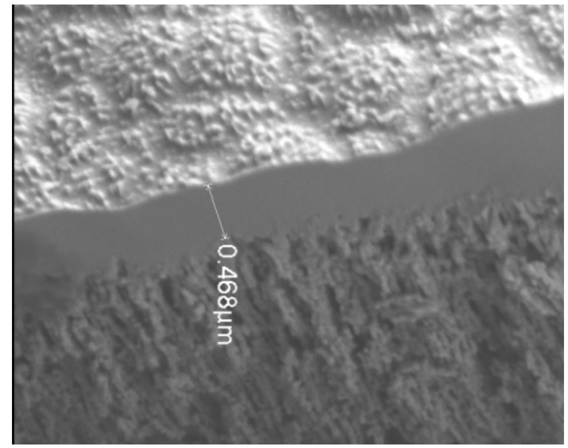
CNT growth



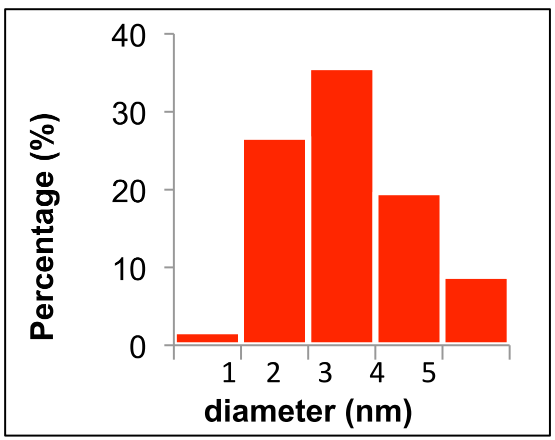
SiN infiltration



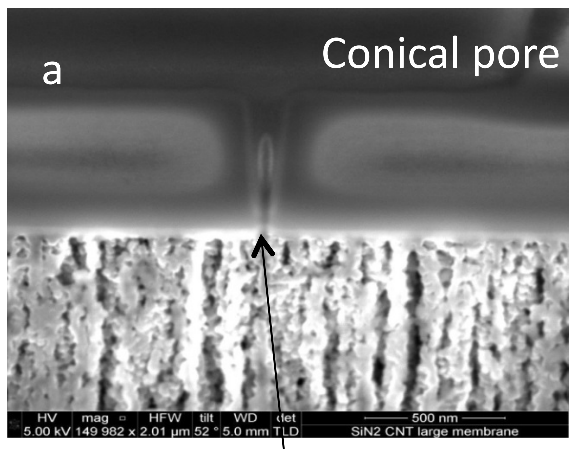
RIE etching



CNT pore distribution

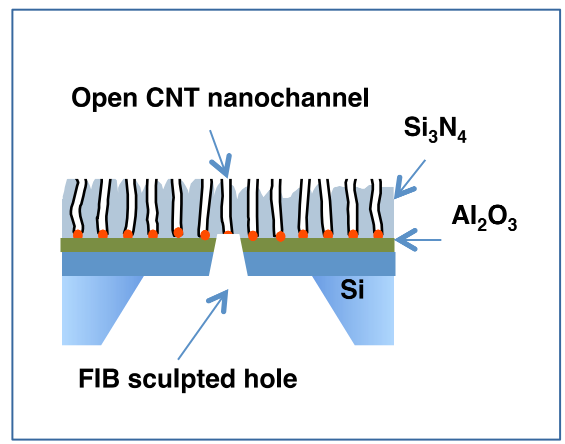


FIB Sculpting

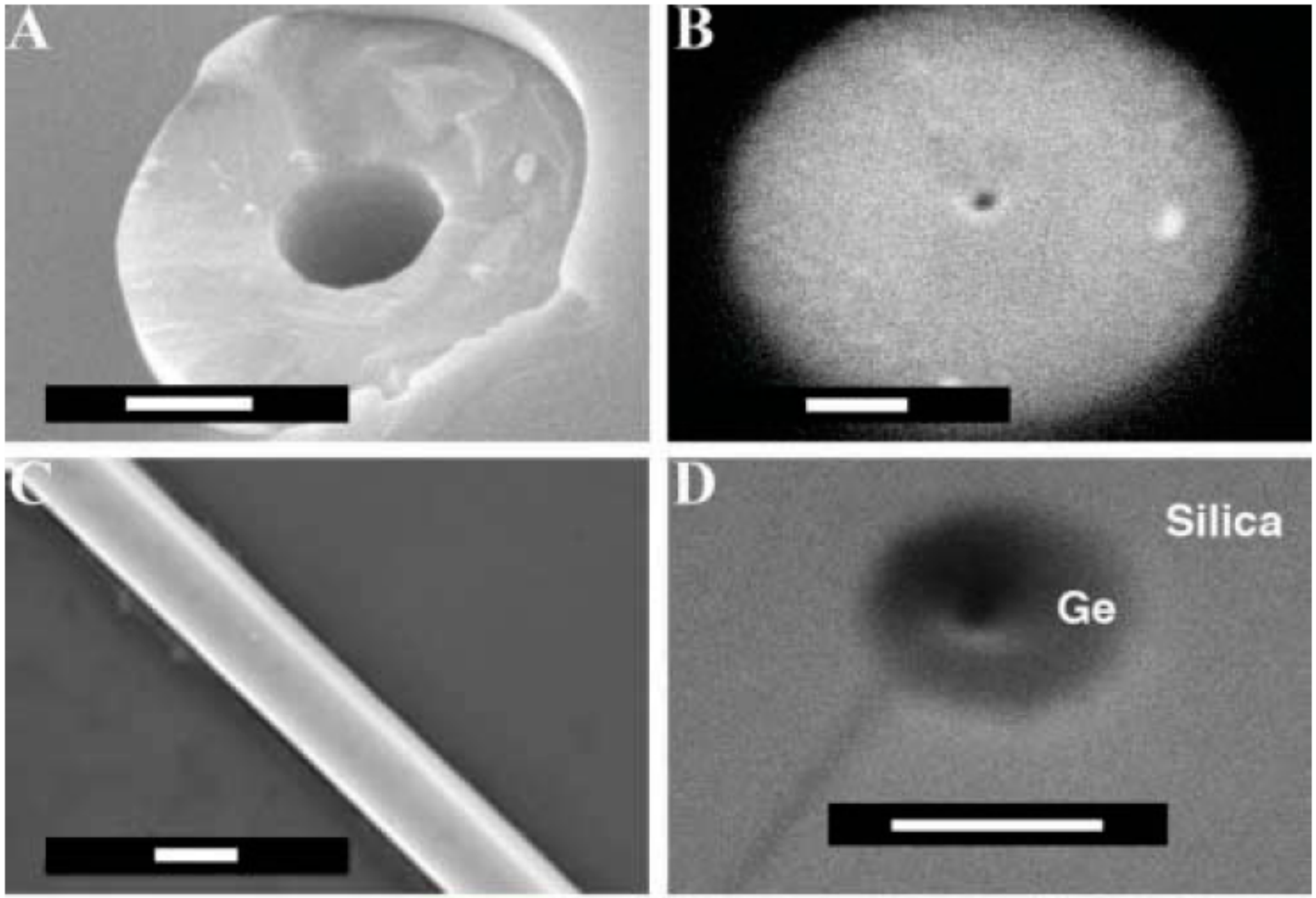


Pore is small enough to open only one or a few CNTs

Final device



Making smaller glass tubes: start with nanometer diameter glass tubes and fill them with germanium



500 nm

25 nm

2 μ

100 nm

Sazio et al , Science 311, 1583 (2006)

These recent advances in materials science will allow us to explore new regimes of superfluid flows.