Jet Propulsion Laboratory
California Institute of Technology

The University of New Mexico

Superfluid Transition in ^{4}He Driven Far From Equilibrium

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Outline

- Introduction
- Nonlinear dynamics of the superfluid transition
  - Singular boundary resistance
  - Breakdown under a heat flux
  - Nonlinear region
  - Correlation length effects
  - Self-organized criticality and a new sound mode
- Experimental
- Future directions

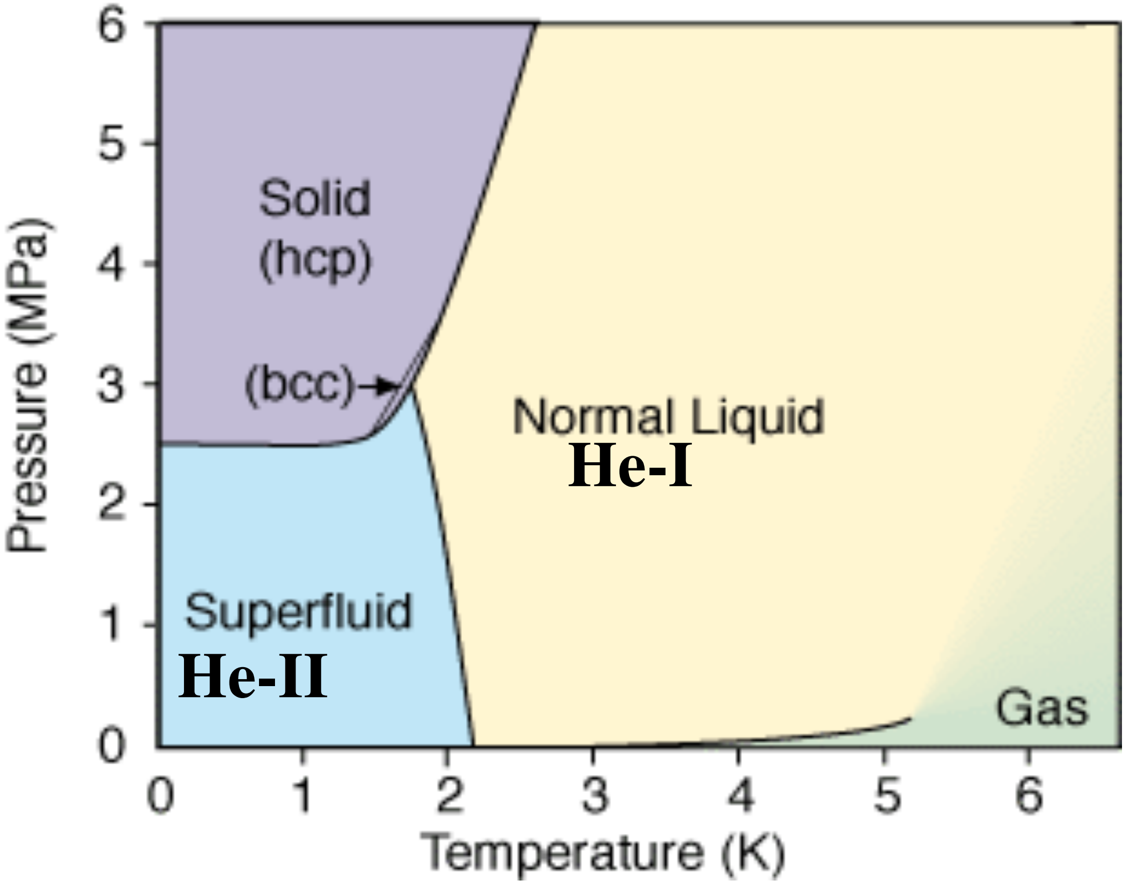
Unique Properties of Liquid Helium

- **Only liquid that never freezes under it's own vapor pressure**

- **Instead, it forms a new phase of long-range quantum order, called a 'superfluid'**

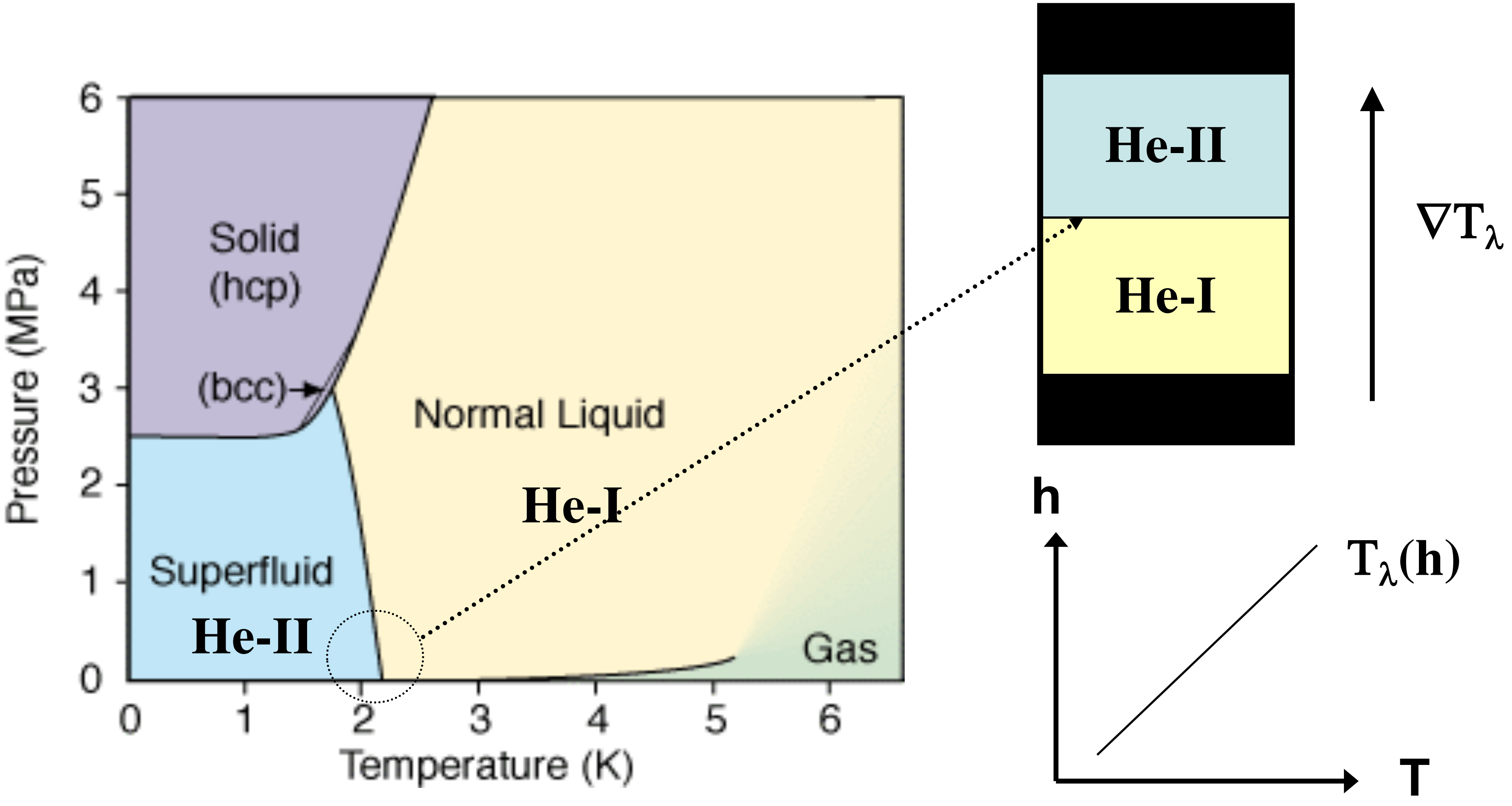
- **The phase diagram of ^{4}He (boson) is radically different from that of ^{3}He (fermion) at very low temperatures**

Helium-4 (^{4}He)



$\lambda = h/p$, at 2K, λ = d between ^{4}He atoms

Pressure dependence of T_λ breaks 'up-down' symmetry and stabilizes an interface on Earth



Non-equilibrium interface stabilizes without gravity!
See Weichman *et al*., Phys. Rev. Lett. 80 4923 (1998)

$|\nabla T_\lambda| = 1.3\ \mu\text{K/cm}$

‘Two Fluid’ Model of Superfluids and the Landau tie to Quantum Physics

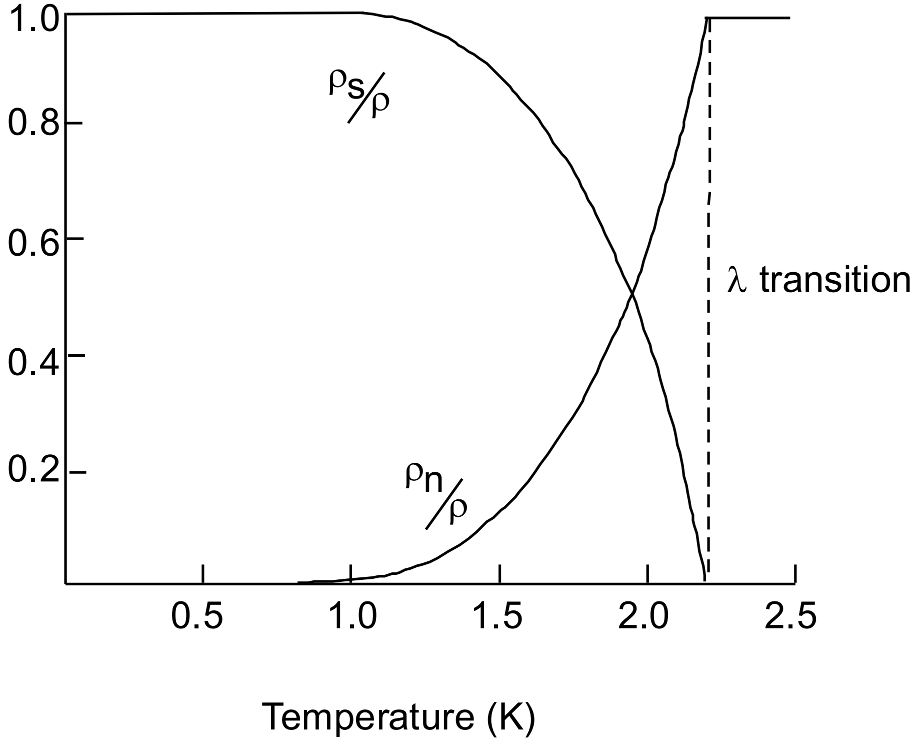
$\rho = \rho_n + \rho_s$

$\mathbf{j} = \mathbf{j}_n + \mathbf{j}_s$ $(\rho v = \rho_n v_n + \rho_s v_s)$

$\psi = \psi_o e^{i\varphi}$

$\rho_s = m_4 \psi_o^* \psi_o$ and

$v_s = (\hbar/m_4) \nabla\varphi$



Counterflow: the Flow of Heat Without Resistance!

$\rho = \rho_n + \rho_s$ $\qquad$ $j = \rho v$ $\qquad$ $j = j_n + j_s$ $(\rho v = \rho_n v_n + \rho_s v_s)$

$j = 0$ (no convection, no mass flow), $j_n = -j_s$, Counterflow!

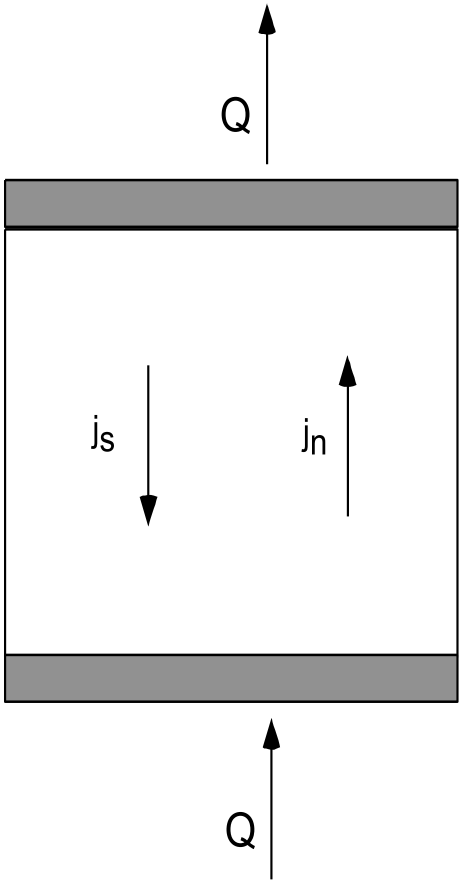
So $\rho_n v_n = -\rho_s v_s$ $\qquad$ $v_n = -\rho_s/\rho_n\, v_s$

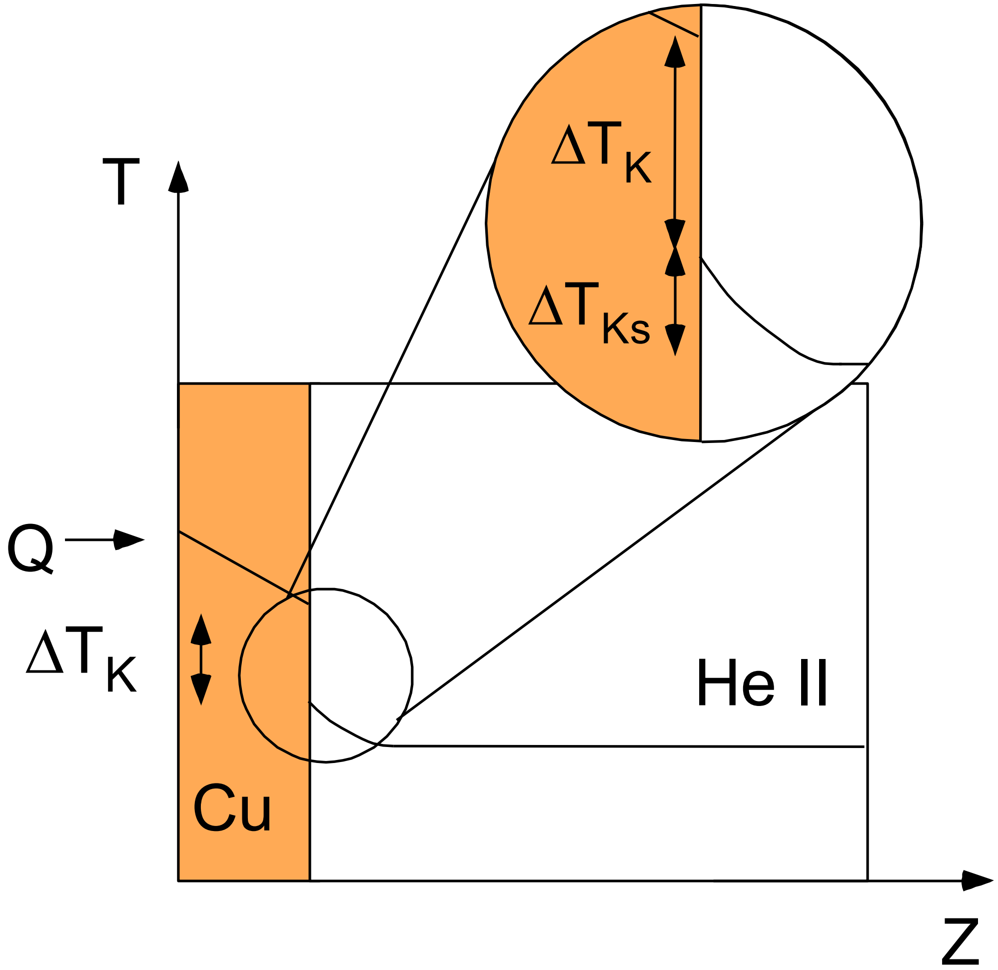
Q = heat flux $= \rho\, S\, T\, v_n = -\, S\, T\, \rho\rho_s/\rho_n\, v_s$

Singular Boundary Resistance

Usually called the ‘Kapitza Resistance’

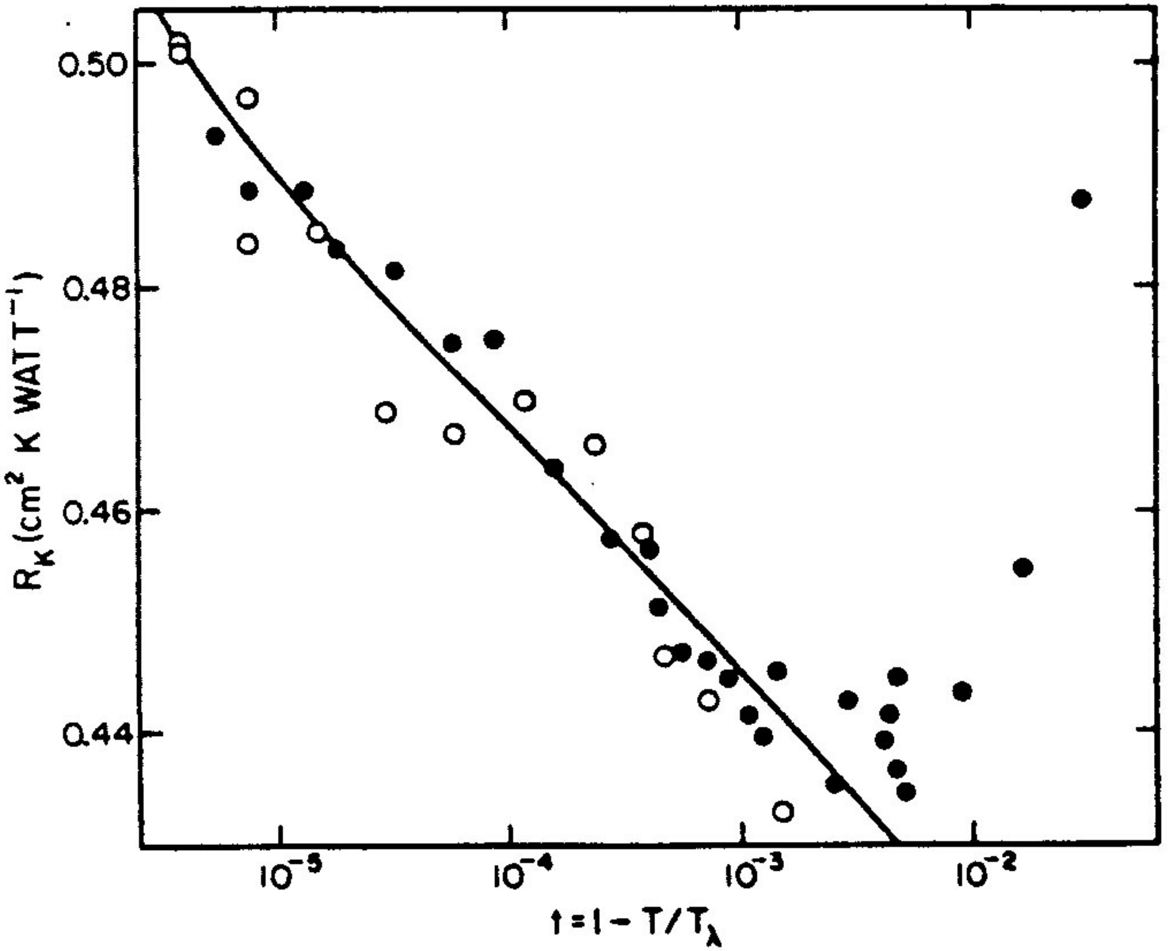
Figures from Ray Nelson’s Ph.D. Thesis…





Weak Boundary Resistance Singularity

Duncan, Ahlers, and Steinberg, Phys. Rev. Lett. **58**, 377 (1987)



Predicted by Landau
In 1941

$R_{Ks} = \Delta T_{Ks}/Q$

$R_{Ks} \sim t^{-0.2}$

Theory: Frank and Dohm, Phys. Rev. Lett. **62**, 1864 (1989)

Superfluid Near Criticality: Counterflow Breakdown

$Q = \rho S T v_n$ If $\rho v = 0$, then $Q = [-\rho\rho_s/\rho_n]\ ST\, v_s \approx -S_\lambda T_\lambda\, \rho_s(v_s)\, v_s$

but ρ_s decreases with increasing v_s, resulting in sudden breakdown when $dQ/dv_s = 0$. This breakdown occurs at temperature $T_c(Q) < T_\lambda$
Invert to obtain $Q_c(T)$.

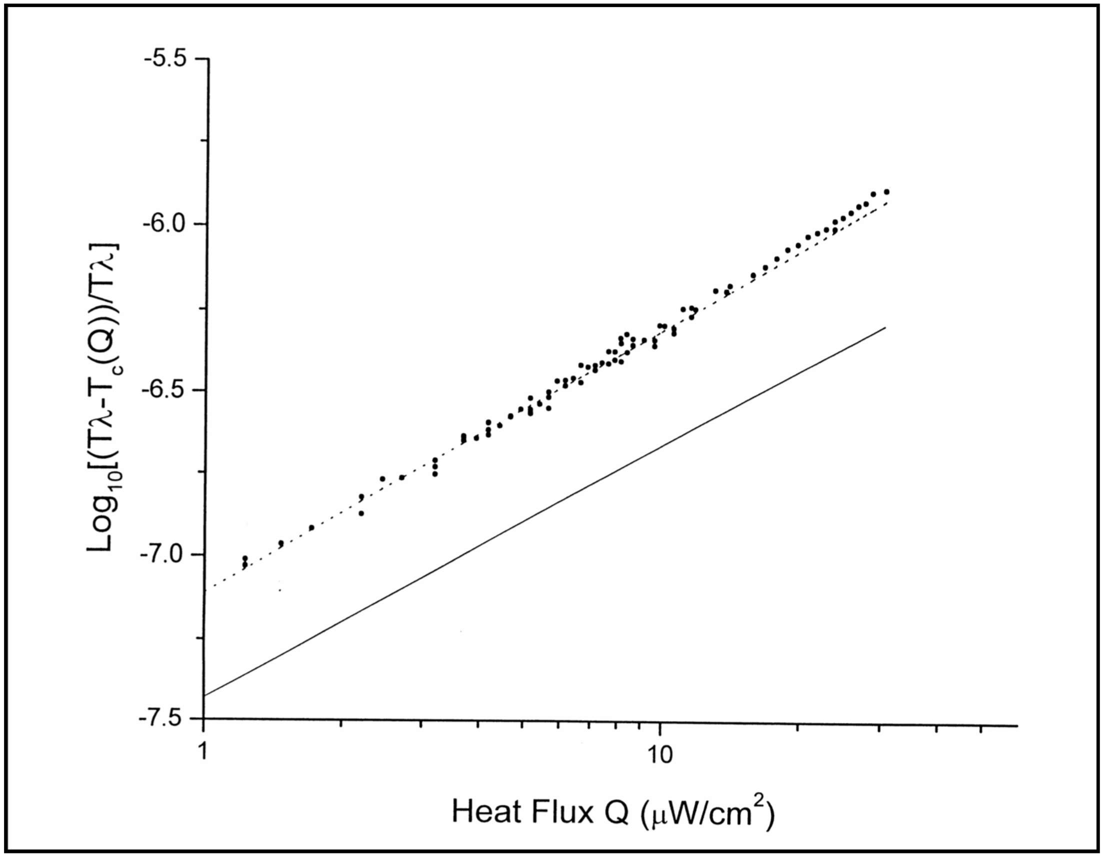
Correlation length
$\xi = \xi_o\, t^{-\nu}$, where $t = |T - T_\lambda|/T_\lambda$ with $\xi_o = 2\mathrm{x}10^{-8}$ cm and $\nu = 0.671$

Thermal conductivity
Diverges due to fluctuations: $\kappa = \kappa_o\, t^{-x}$ with $x \approx ½$

Field-Theory: 'Model F' of Halperin, Hohenberg, and Siggia
See Hohenberg and Halperin, Rev. Mod. Phys. 49, 435 (1977)

Superfluid Breakdown

Duncan, Ahlers, and Steinberg, Phys. Rev. Lett,. **60**, 1522 (1988)

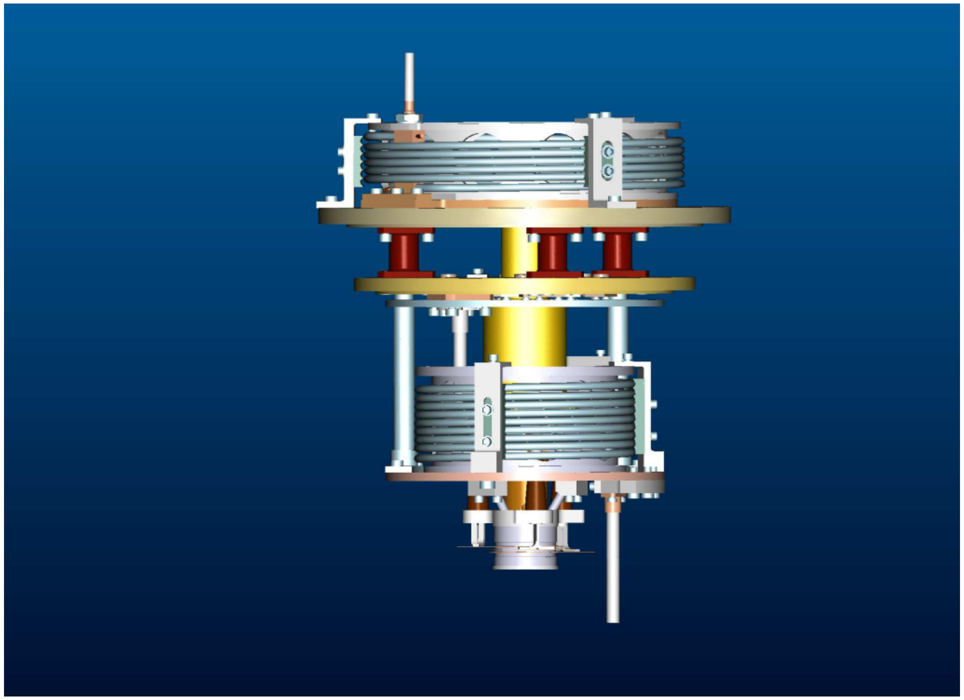


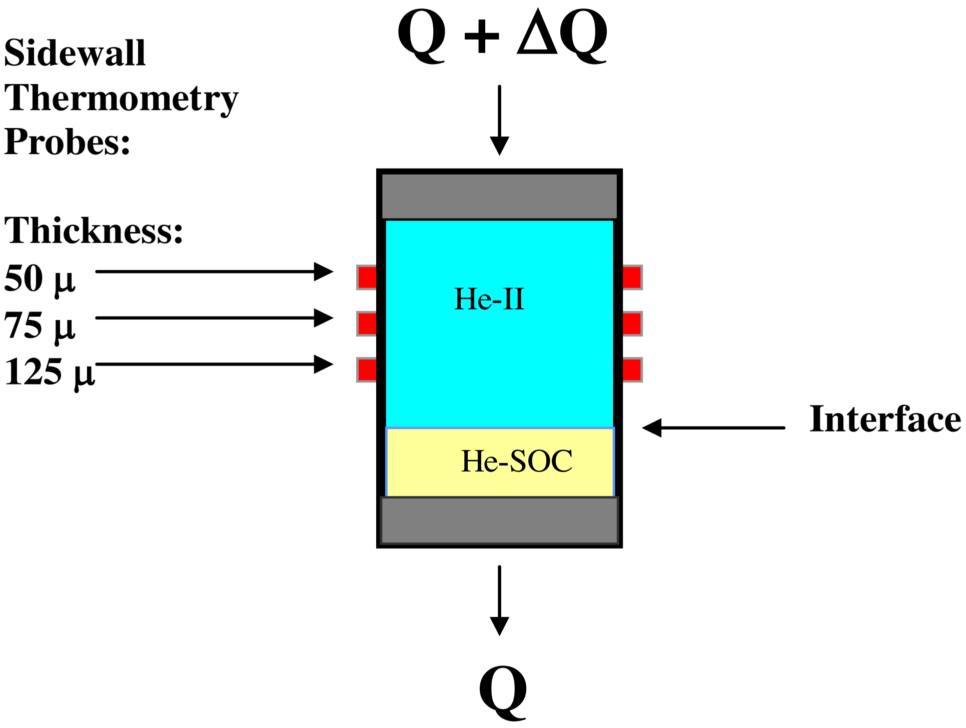
$[T_\lambda\text{-}T_c(Q)]/T_\lambda = (Q/Q_c)^y$

Theory (Dohm, Onuki, etc.)
$y = 1/2\nu = 0.744$
$Q_c = 7{,}000$ W/cm^2

Experiment:
$y = 0.81 \pm 0.01$
$Q_c \approx 600$ W/cm^2

Experimental Concept





Sidewall Thermometry Probes:

Thickness:

50 μ

75 μ

125 μ

$Q + \Delta Q$

He-II

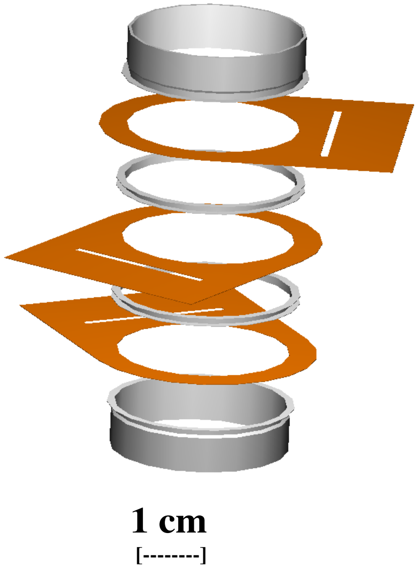
He-SOC

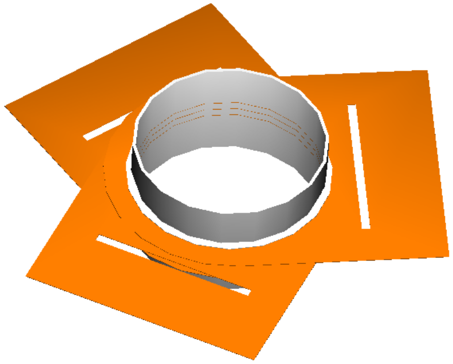
Interface

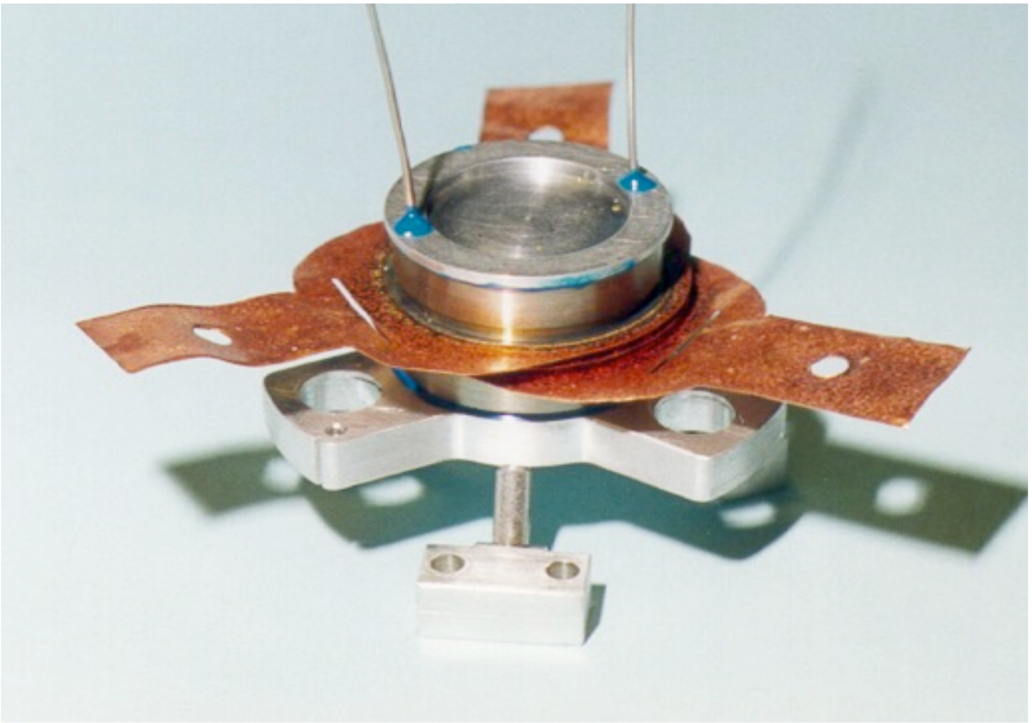
Q

Science objectives are obtained from the thermal profile data (noise level of < 100 pK/$\sqrt{\text{Hz}}$), while the heat flux is extremely well controlled to $\delta Q \sim 1$ pW/cm^2

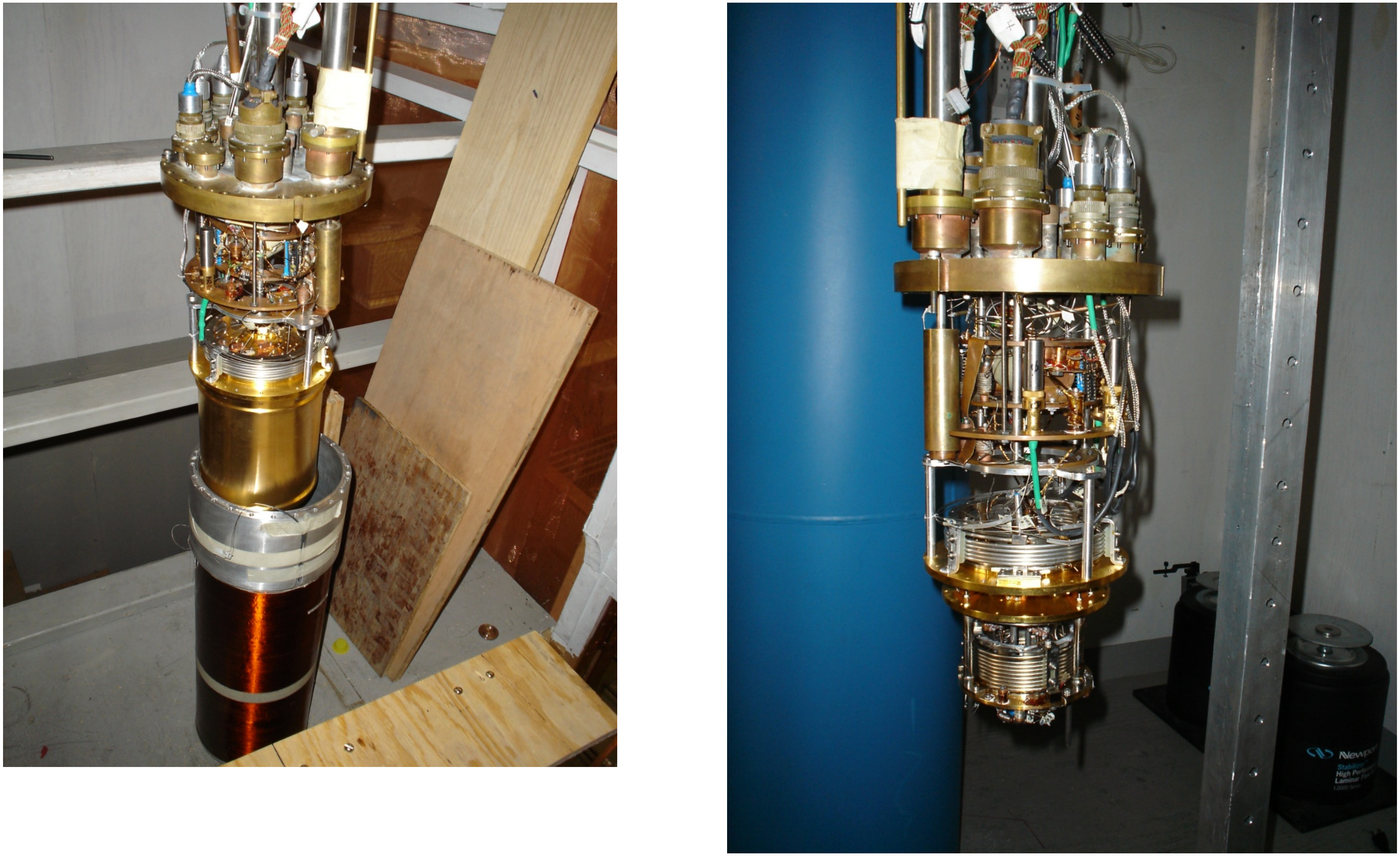
DYNAMX Sample Cell wall with Thermal Probes, End Caps, and Structural Supports



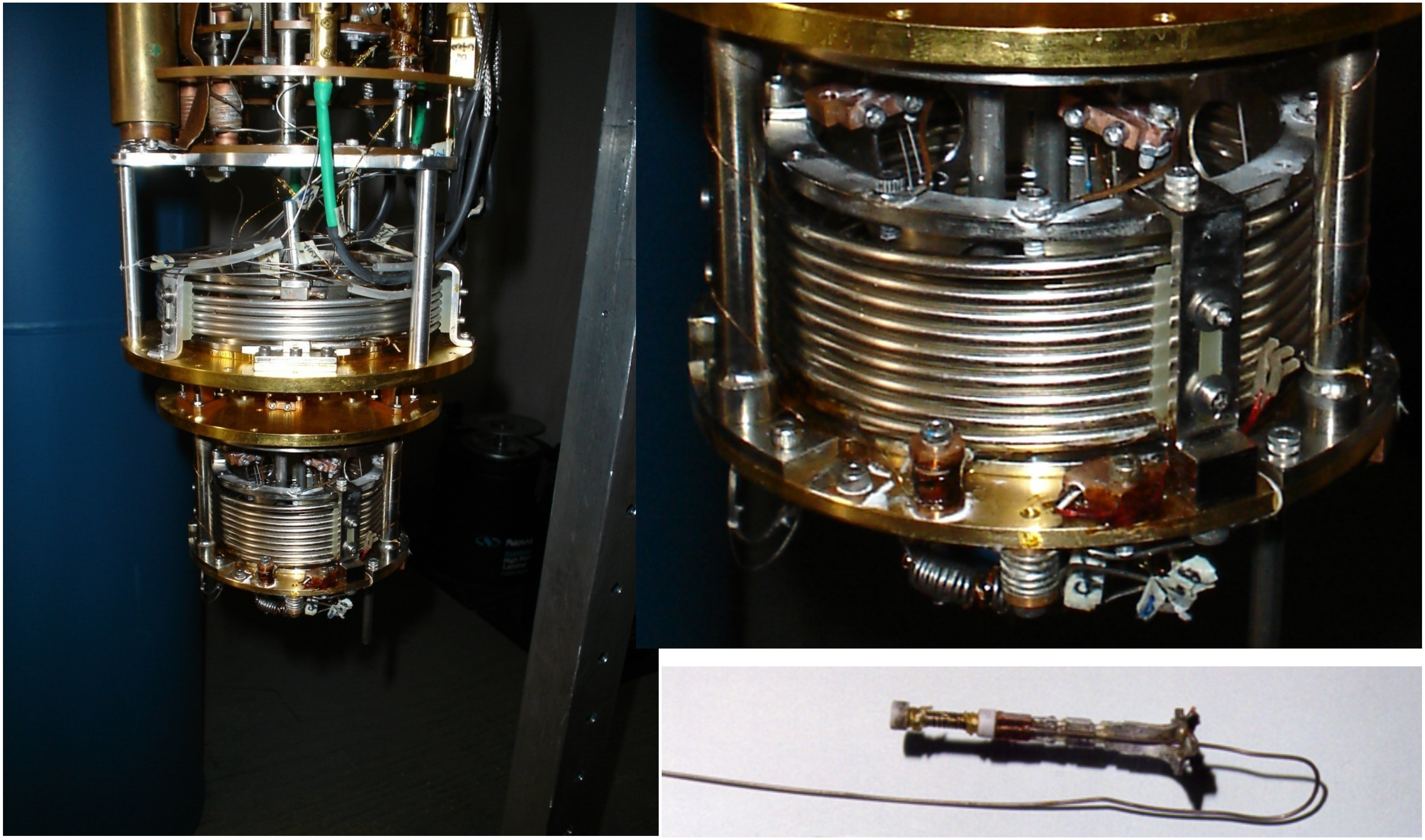




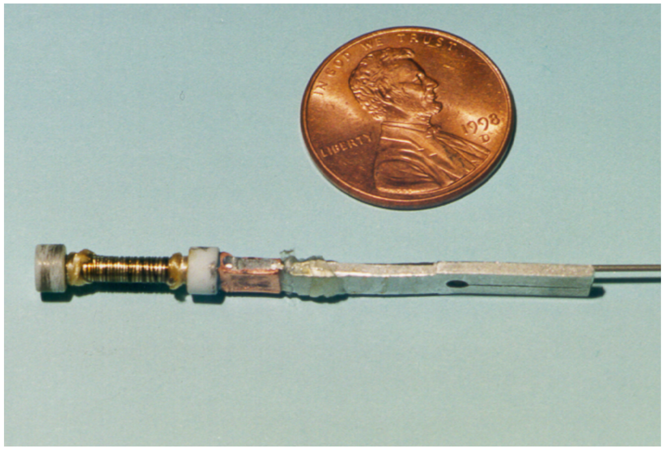
Experimental ‘T5’ Apparatus

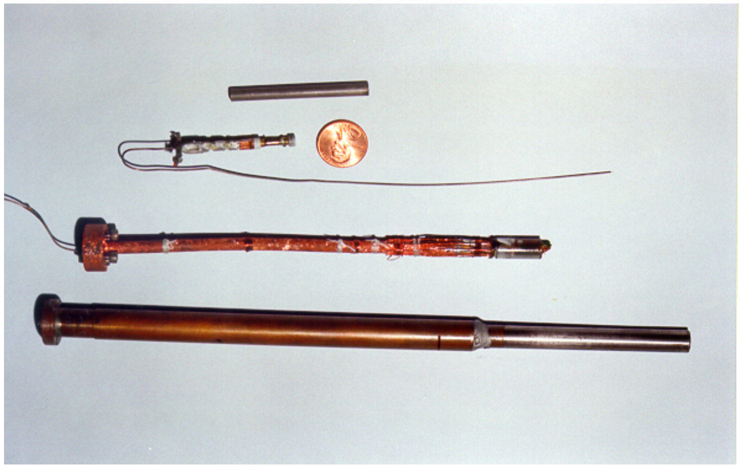


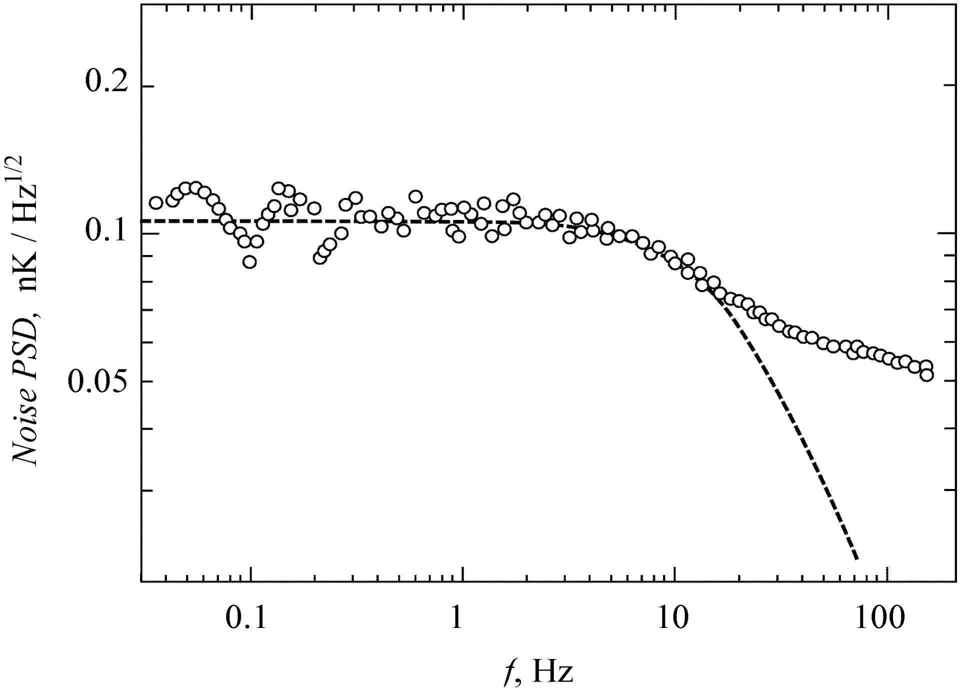
‘T5’ Critical Thermal Path



Mini-High Resolution Thermometer



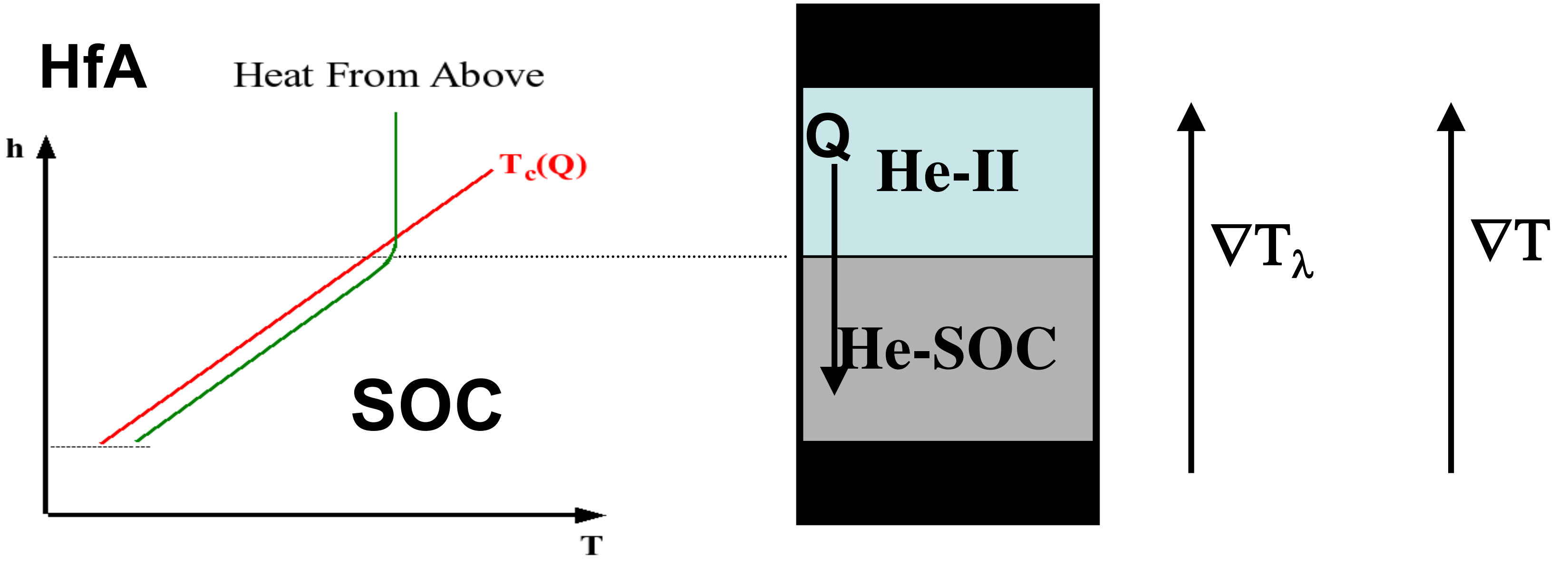




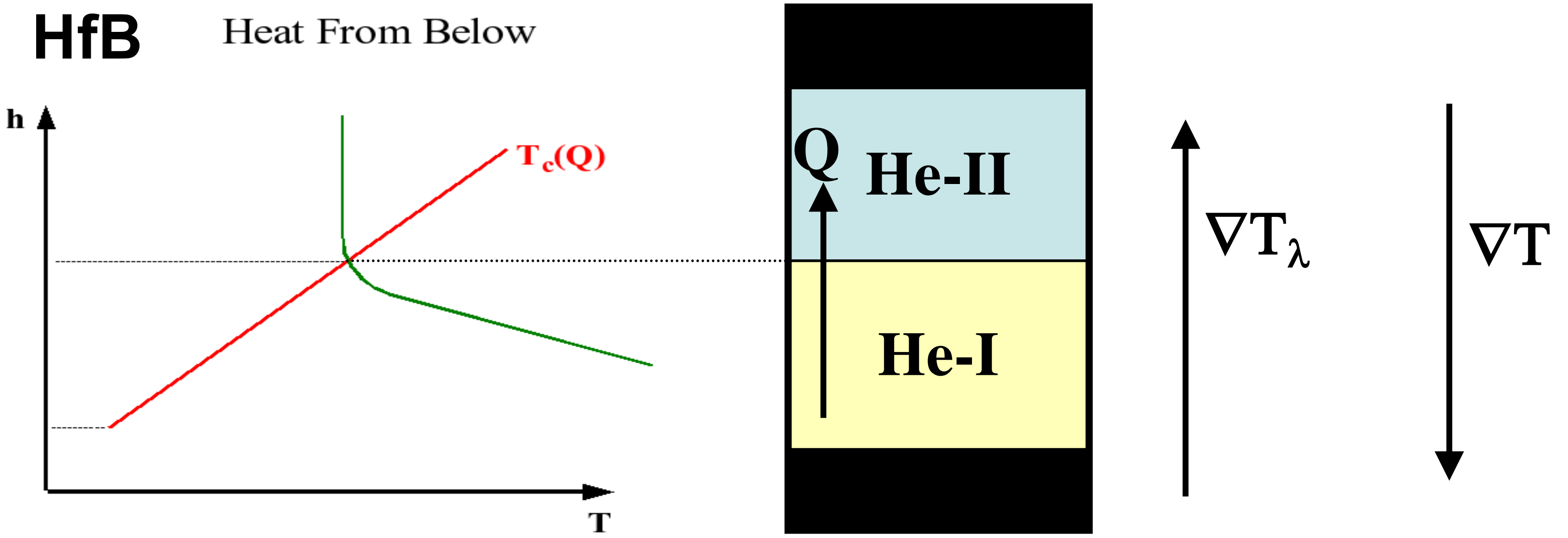
Demonstrated Drift = 2.9 x 10^{-15} K/s (0.25 nK/day, 0.1μK/year).

The Direction of Q is Important :

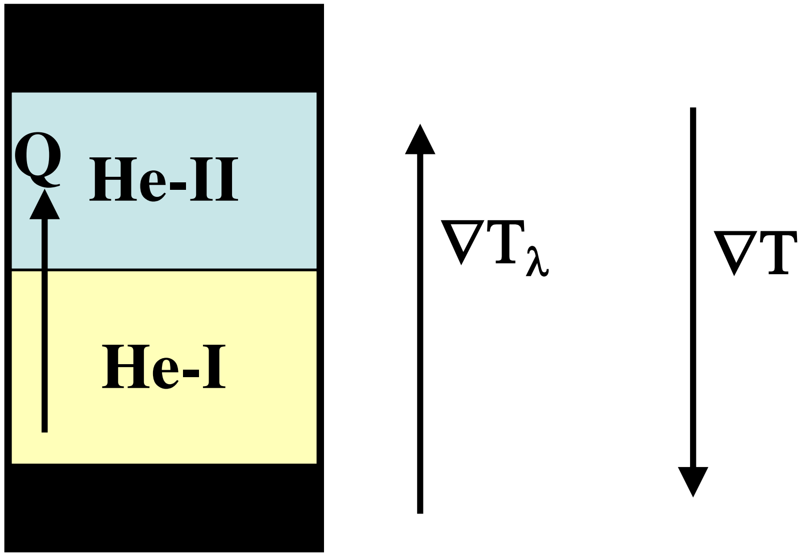
HfA Heat From Above



HfB Heat From Below

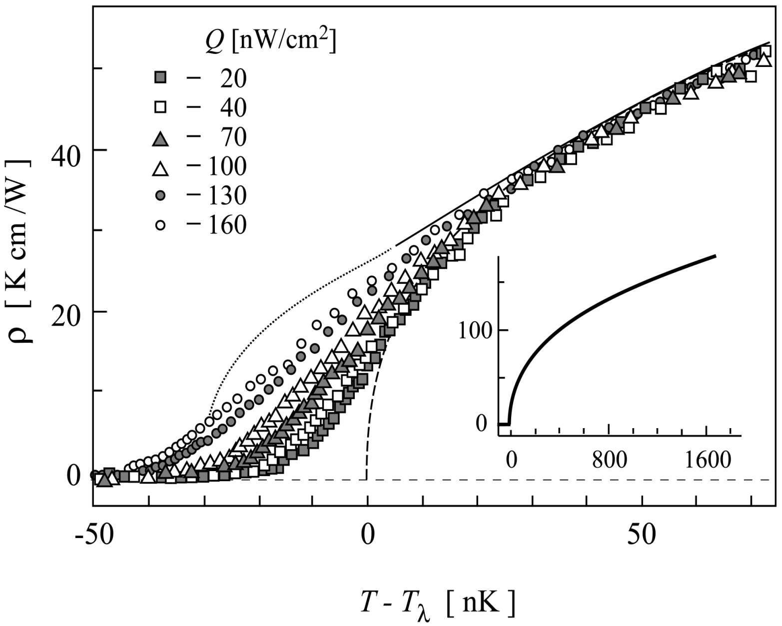


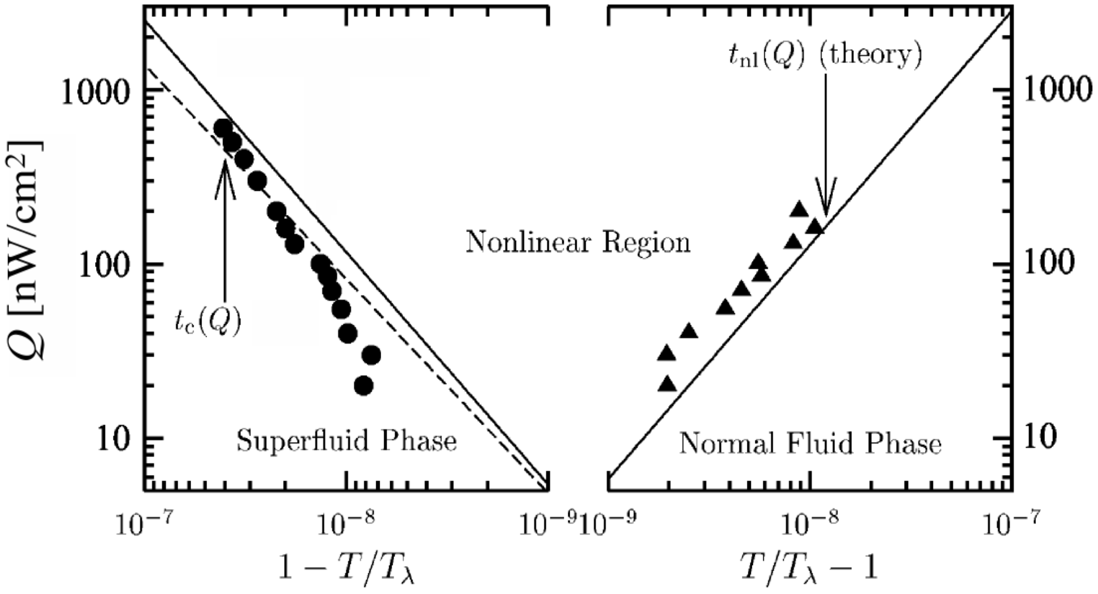
HfB: 'Heat from Below'



- Correlation length divergence is cut-off on Earth
- Nonlinear thermal resistivity near T_λ

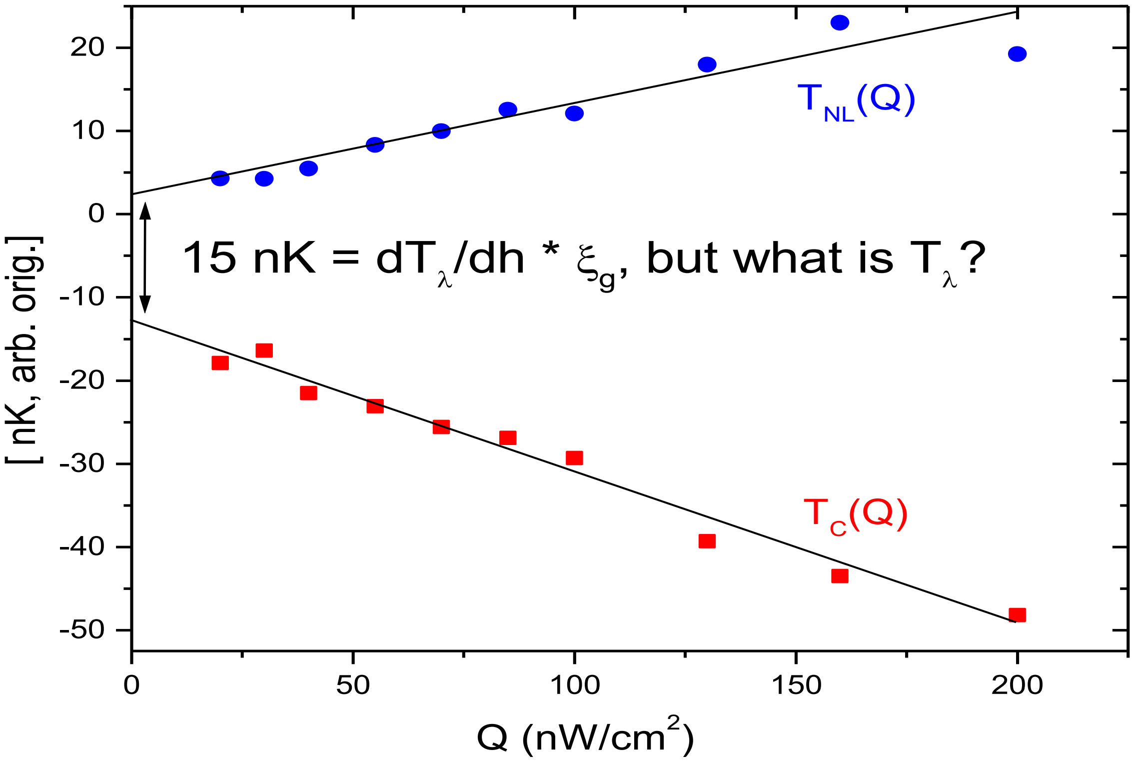
HfB: The Nonlinear Region





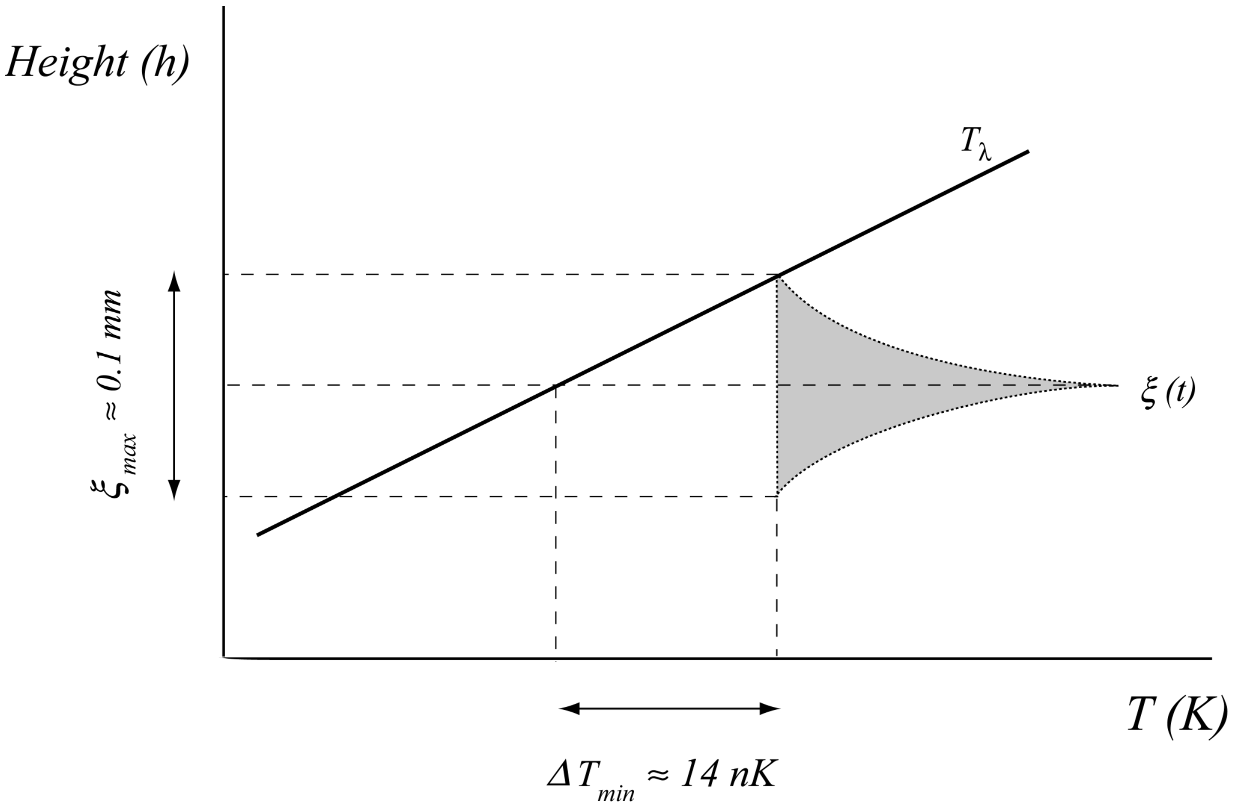
Theoretical prediction of the nonlinear region [Haussmann and Dohm, *PRL* **67**, 3404 (1991); *Z. Phys. B* **87**, 229 (1992)] with our data [Day *et al*., *PRL* **81**, 2474 (1998)].

HfB: $T_c(Q)$, $T_{NL}(Q)$, T_λ



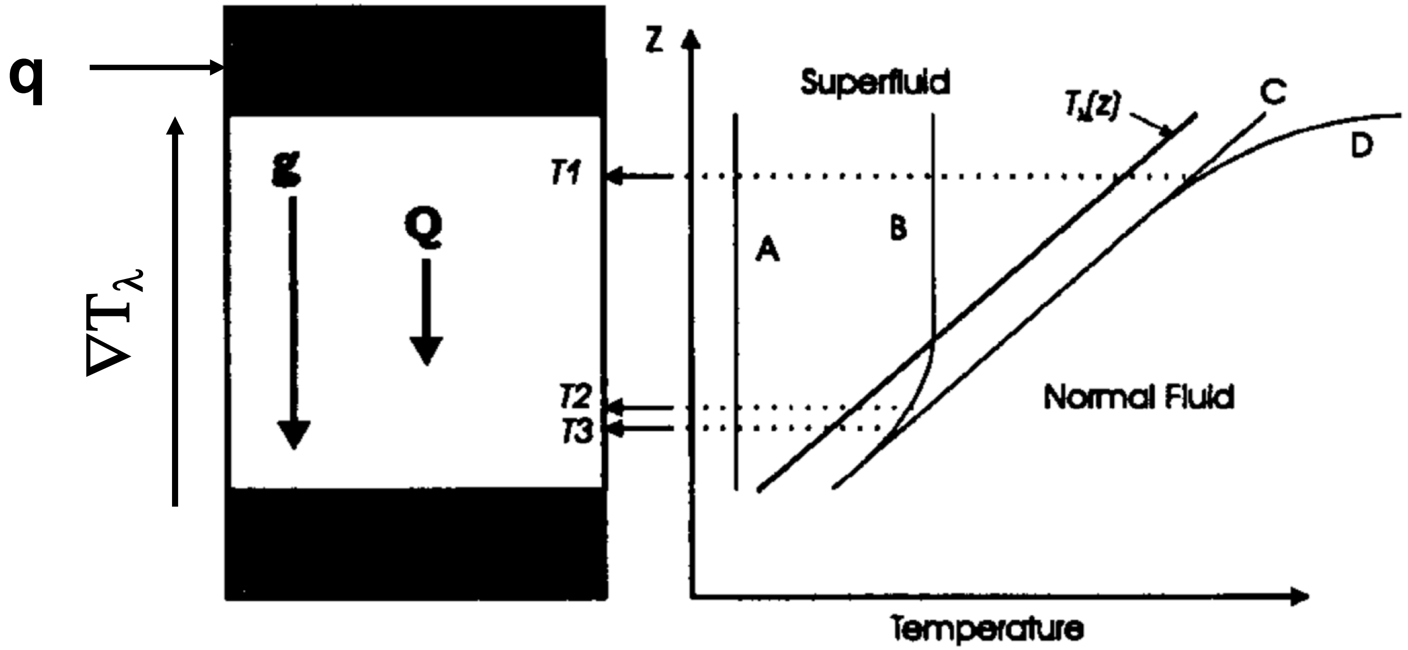
$T_c(Q)$ and $T_{NL}(Q)$ are expected to extrapolate to T_λ as Q goes to zero in microgravity, but not on Earth, as explained by Haussmann.

Gravitational Effect: ξ_g



As the superfluid transition is approached from above, the diverging correlation length eventually reaches its maximum value $\xi_g = 0.1$ mm, at a distance of 14 nK from T_λ.

HfA: Heat from Above



A: Cell is superfluid (hence isothermal), and slowly warming at about 0.1 nK/s
B: SOC state has formed at the bottom and is passing T3 as it advances up the cell, invading the superfluid phase from below
C: Cell is completely self-organized
D: As heat is added the normalfluid invades the SOC from above

(Suggested by A. Onuki and independently by R. Ferrell in Oregon, 1989)

What is $T_{soc}(Q)$?

$\kappa\nabla T = Q$, so $\kappa_{soc} = Q / \nabla T_\lambda$

$\kappa_{soc} = \kappa_o\, \varepsilon_{soc}^{-x} = Q / \nabla T_\lambda$

$\varepsilon_{soc} = [Q/(\kappa_o\, \nabla T_\lambda)]^{-1/x}$

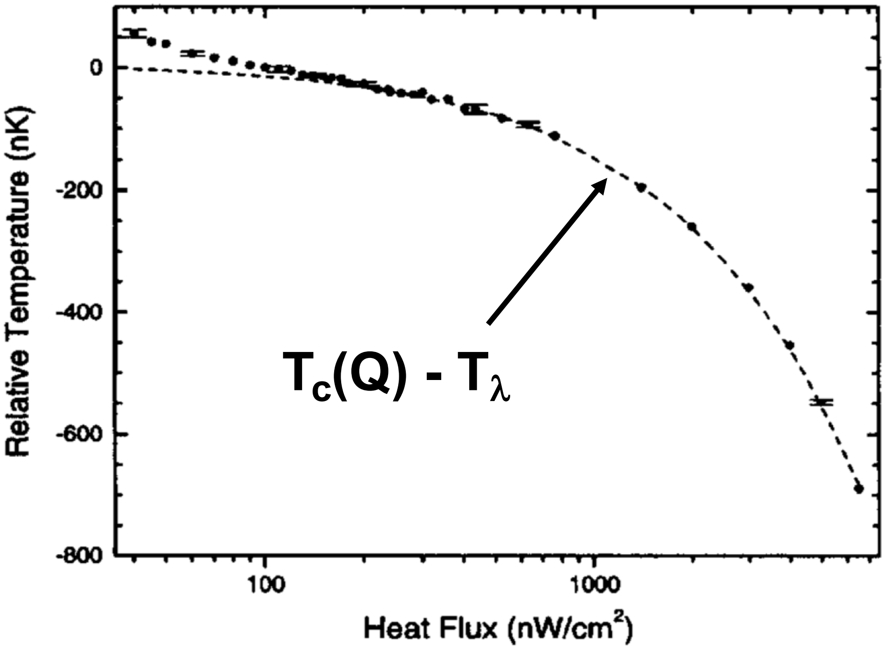
$T_\lambda\, \varepsilon_{soc} = T_{soc}(Q,z) - T_c(Q,z)$

$T_{soc} - T_c = T_\lambda\, [Q/(\kappa_o\, \nabla T_\lambda)]^{-1/x}$

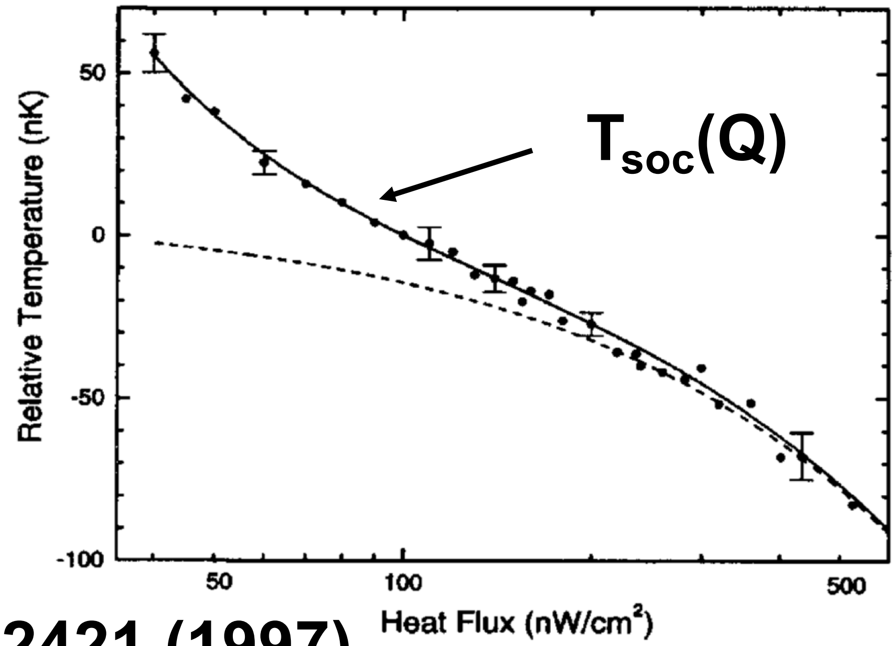
$\kappa_o \approx 10^{-5}$ W/(cm K), $x \approx 0.48$

$\nabla T_\lambda \approx 1.27\ \mu$K / cm

$T_{soc} - T_c = T_\lambda\ [Q / (12.7\ \text{pW/cm}^2)]^{-2.083}$



$T_c(Q) - T_\lambda$



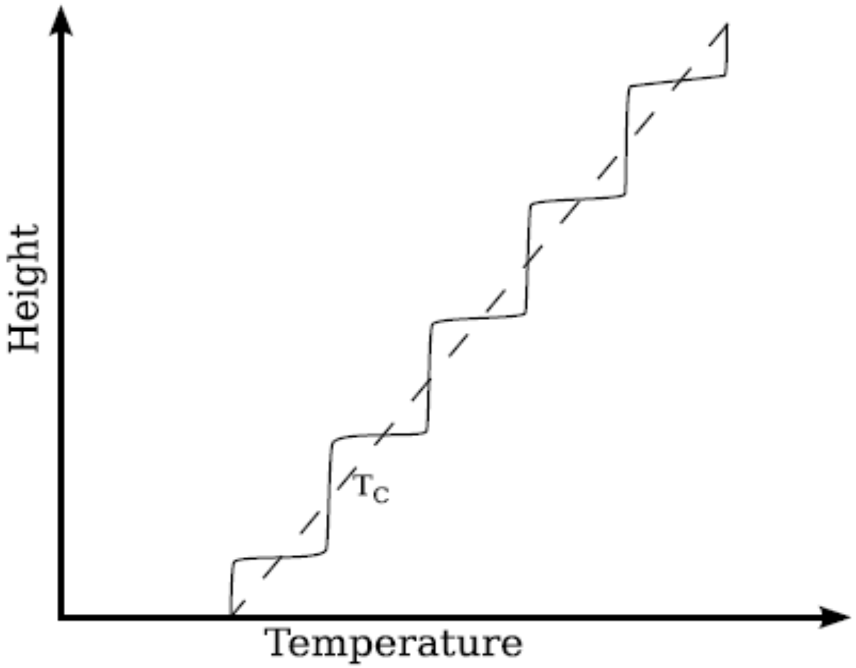
$T_{soc}(Q)$

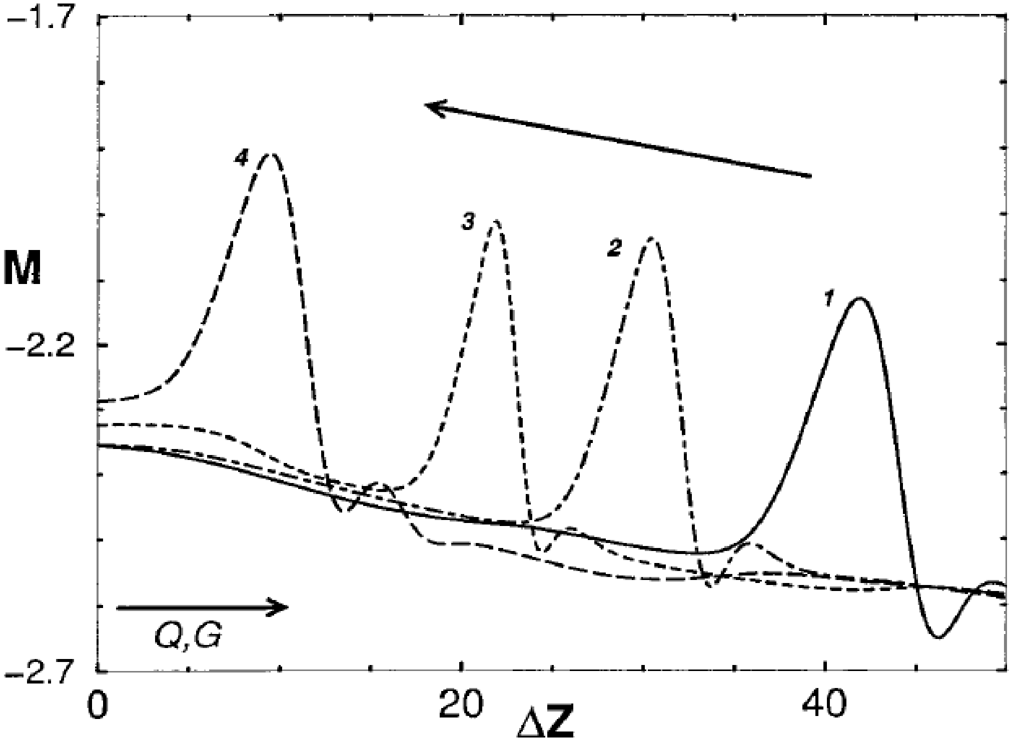
Moeur *et al.,* Phys. Rev. Lett. 78, 2421 (1997)

How does He-II do this?

Synchronous phase slips – each slip creates a sheet of quantized vortices

See: Weichman and Miller, JLTP 119, 155 (2000):





Diffusive Anisotropic Wave Propagation

"New Propagating Mode Near the Superfluid Transition in 4He",
Sergatskov *et. al., Physica* **B 329 – 333**, 208 (2003), and
"Experiments in ^{4}He Heated From Above, Very Near the Lambda Point",
Sergatskov *et. al*., *J. Low Temp. Phys*. **134**, 517 (2004), and
Chatto, Lee, Day, Duncan, and Goodstein, *J. Low Temp. Phys.* (2007)

The basic physics is very simple:

$$C\frac{dT}{dt} = -\vec{\nabla}\bullet\vec{Q}$$

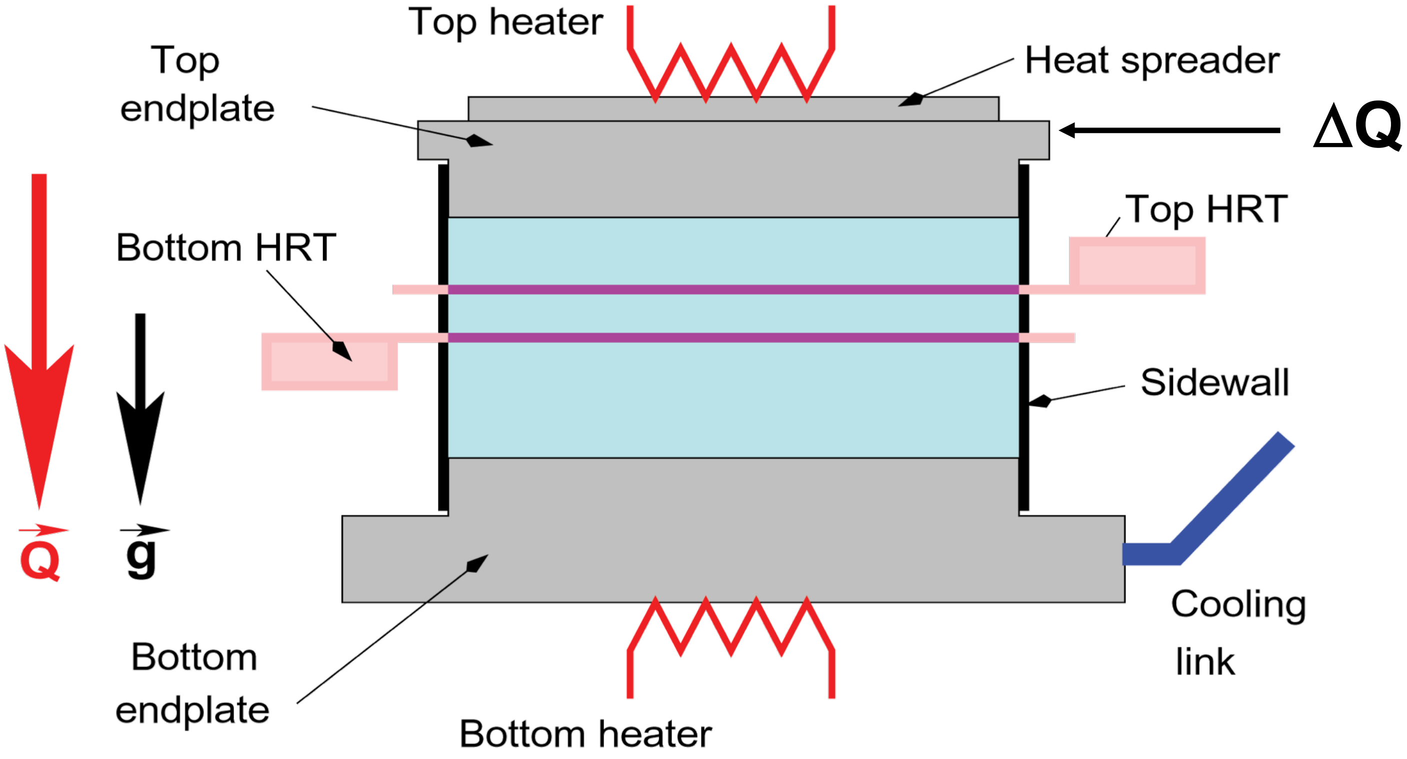
$$\vec{Q} = -\kappa\vec{\nabla}T$$

$$C\frac{dT}{dt} = \vec{\nabla}\kappa\bullet\vec{\nabla}T + \kappa\nabla^2 T$$

Wave speed $v = \nabla\kappa/C$

If C ~ constant
then $v = \nabla D$
where $D = \kappa/C$

A New Wave on the SOC State



Wave travels only against Q, so 'Half Sound'

Sergatskov *et al*., JLTP 134, 517 (2004)

Weichman and Miller, JLTP 119, 155 (2000)

And now Chatto et al., JLTP (2007)

Wave Speed v(Q)

Following Chatto et al., 2007

$$C\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\kappa\frac{\partial T}{\partial Z}\right).$$

$\varepsilon = (T - T_\lambda)/T_\lambda$

$$CT_\lambda\frac{\partial \epsilon}{\partial t} = \frac{dT_\lambda}{dz}\frac{\partial \kappa}{\partial \epsilon}\frac{\partial \epsilon}{\partial z} + \left(\frac{dT_\lambda}{dz}\frac{\partial \kappa}{\partial \epsilon'} + \kappa T_\lambda\right)\frac{\partial^2 \epsilon}{\partial z^2}.$$

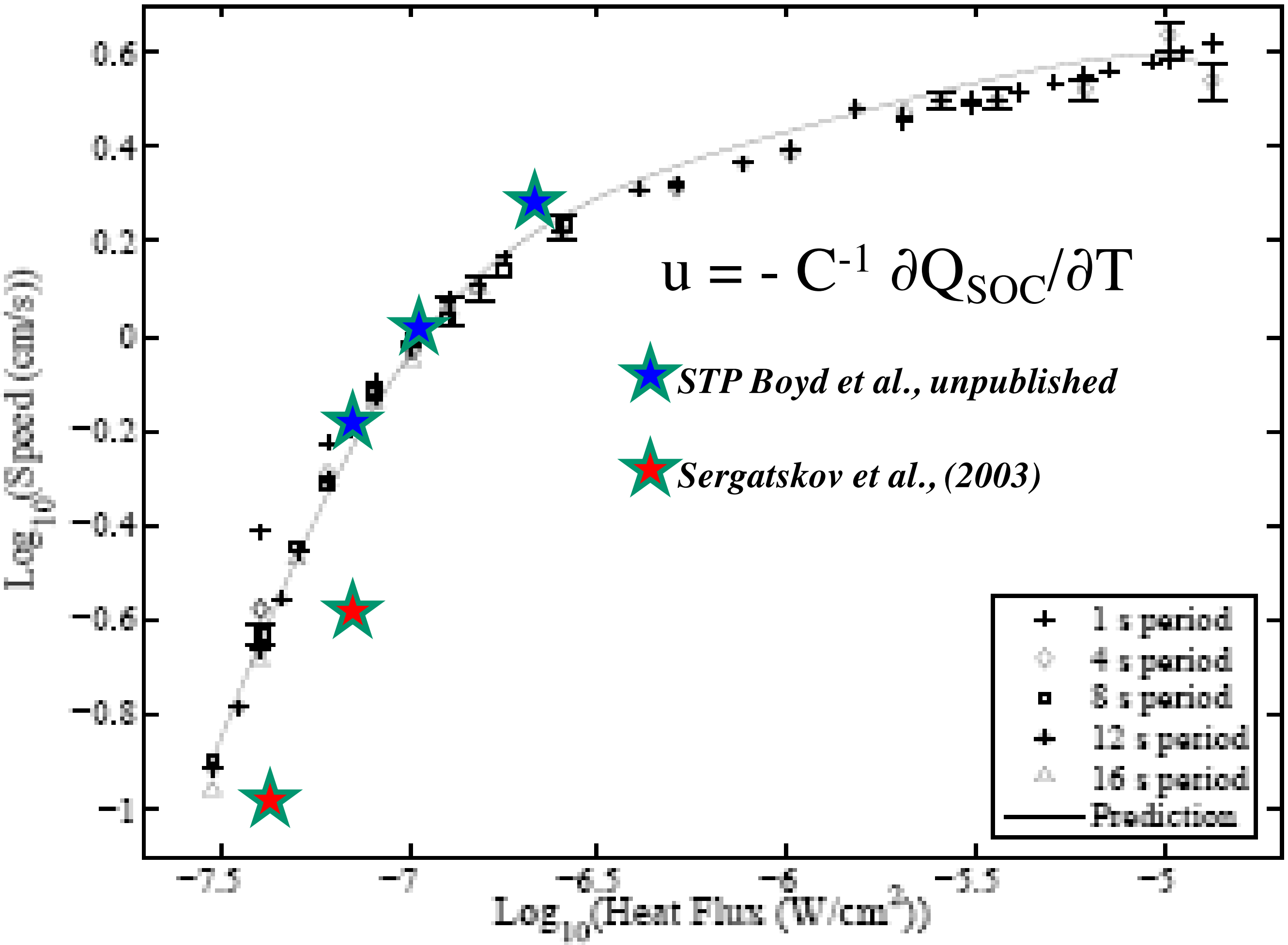
$$\epsilon(z,t) = \epsilon_0 + \delta_0 e^{-Dk^2 t} e^{ik(z-vt)}$$

$$v = -\frac{1}{CT_\lambda}\frac{dT_\lambda}{dz}\frac{\partial \kappa}{\partial \epsilon}.$$

$$\boxed{v = -\frac{1}{C}\frac{\partial Q_{\mathrm{SOC}}}{\partial T}}$$

New Anisotropic Wave Speed

Chatto, Lee, Duncan, and Goodstein, JLTP, 2007.

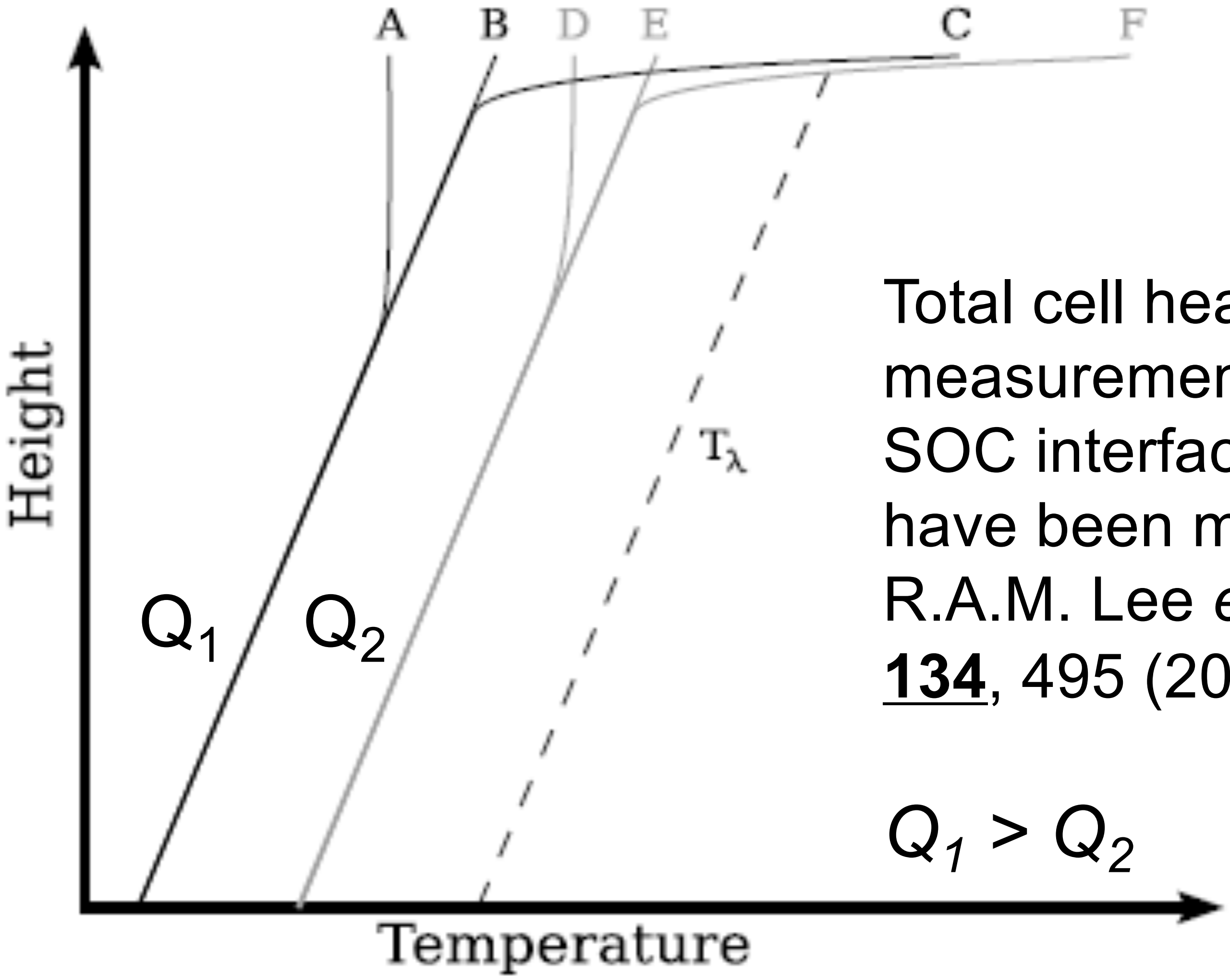


$$u = - C^{-1}\ \partial Q_{SOC}/\partial T$$

★ *STP Boyd et al., unpublished*

★ *Sergatskov et al., (2003)*

How do we measure C_{soc}?

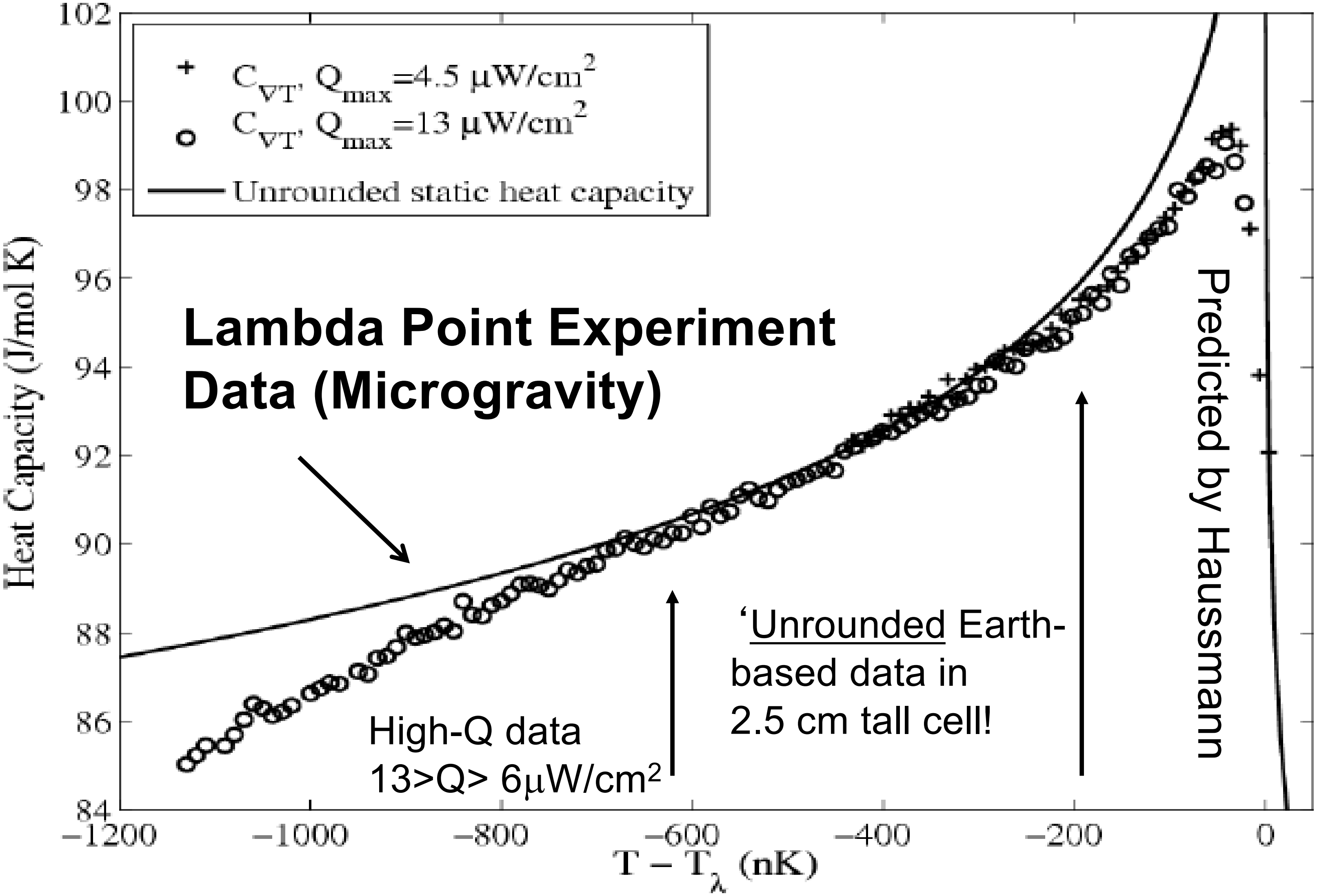


Total cell heat capacity measurements as the SOC interface advances have been made by R.A.M. Lee *et al., JLTP* **134**, 495 (2004).

$Q_1 > Q_2$

Heat Capacity on the SOC State

Chatto, Lee, Duncan and Goodstein, *JLTP (2007)*
R. Haussmann, Phys. Rev. B 60, 12349 (1999).



Lambda Point Experiment Data (Microgravity)

High-Q data
13>Q> 6μW/cm^2

'Unrounded Earth-based data in 2.5 cm tall cell!

Predicted by Haussmann

Summary

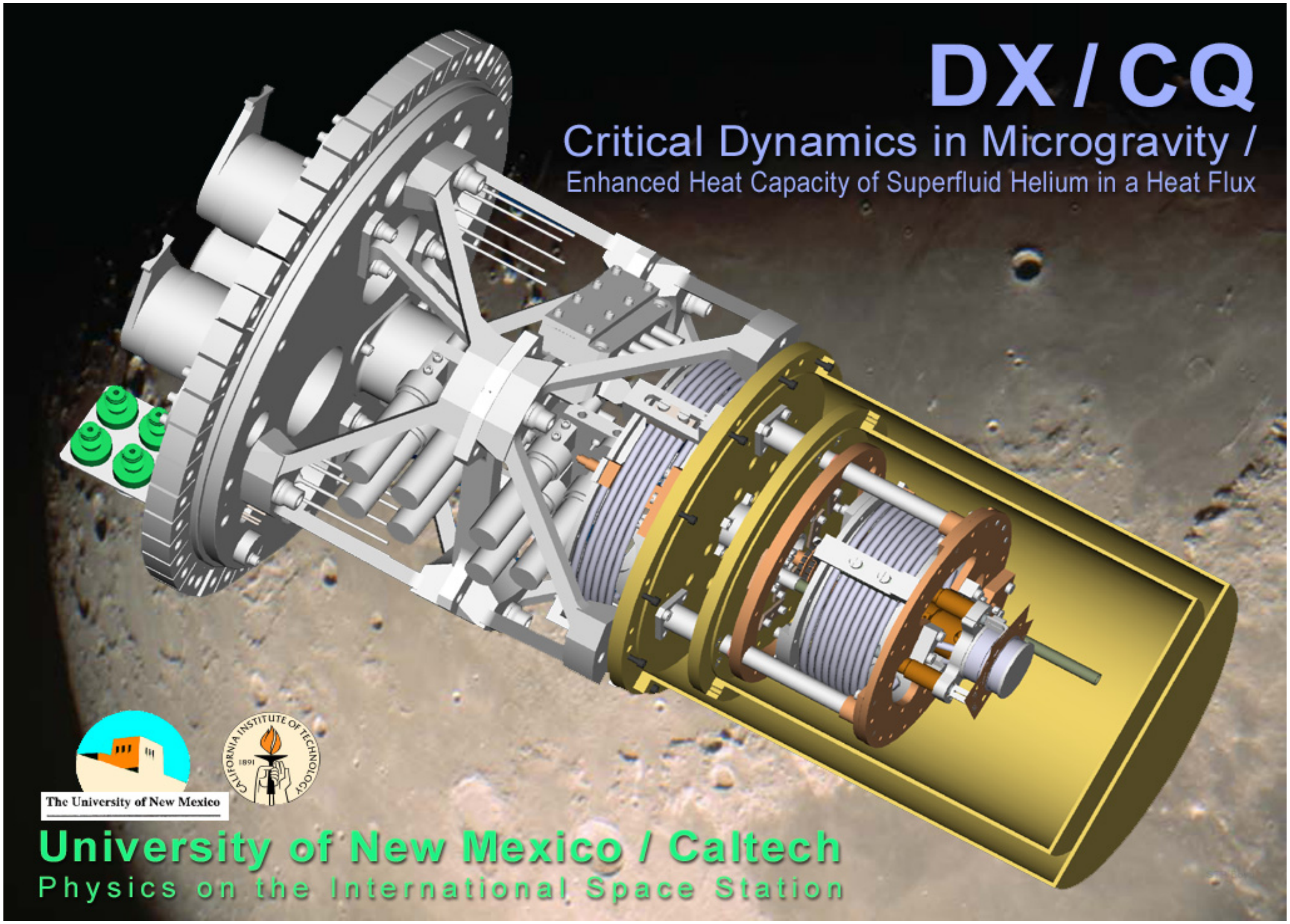
The study of the nonlinear dynamics of the superfluid transition is interesting for many fundamental reasons, including:

- model system to study the onset of long range quantum order while driven far from equilibrium
- test of renormalized, field theoretic models of the dynamical properties of the superfluid under phase change
- general applicability to the understanding of phase change in systems far from equilibrium
- ideal system in which to study self-organized criticality
- opportunity to study fluctuations and other thermodynamic properties in an exceptionally well controlled system

Today's science will become tomorrow's superior metrology, as we have seen so many times before

Space flight is the only way to avoid ξ_g

See Barmatz, Hahn, Lipa, and Duncan, "Critical Phenomena Measurements In Microgravity: Past, Present, and Future", Reviews of Modern Physics 79, 1 (2007)



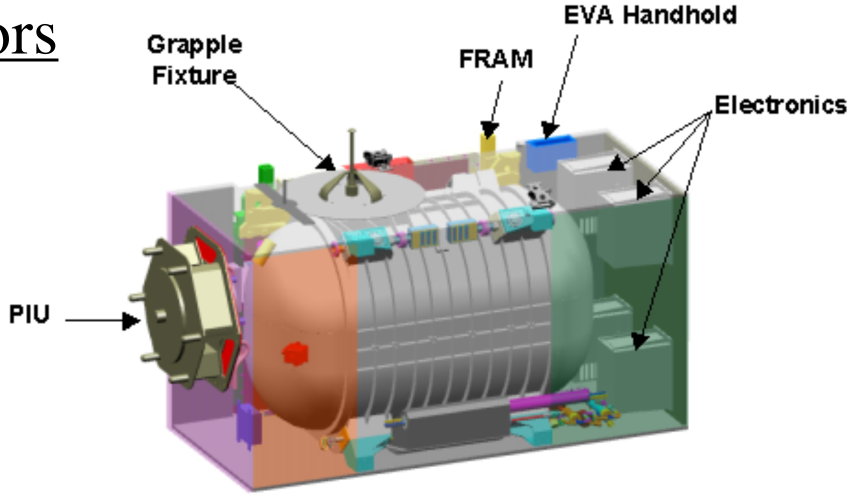
Successful CDR in 2003

Cancelled in 2004

All 117 'ClassB' approved hardware drawings are in place.

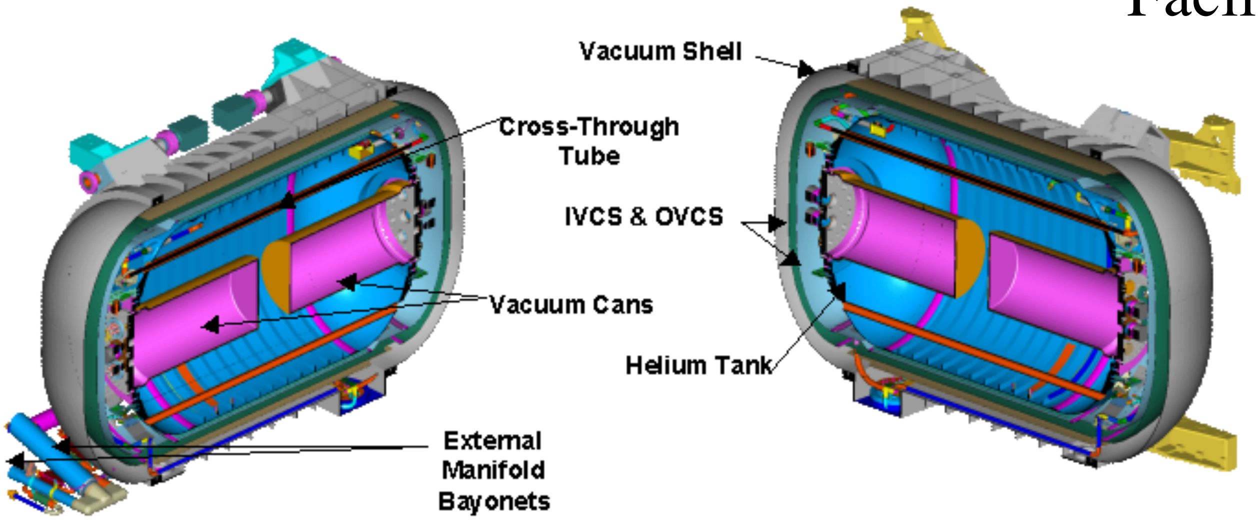
Low Temperature Microgravity Physics Facility (LTMPF)

‘M1’ Contractors
JPL (lead)
Ball Aerospace
Design Net
Stanford
Caltech
UNM



Flight planned
In 2008

ISS attach on the
Japanese Experiment
Module’s Exposed
Facility



Jet Propulsion Laboratory
California Institute of Technology

Future Directions

- Could we ever measure the cooling rate of the CMB?
  - CMB cooling rate may be about 200 pK/year
  - To resolve T_{CMB} to within 20 pK will require about a year of averaging
  - Foreground sources are huge (~ 100 nK) compared to this level
  - Pointing accuracy and cosmic radiation limitations are daunting
- Measurement Approach
  - Maintain peak C_V at the superfluid transition ($T_\lambda = 2.1768\ldots$ K) for years
    - Modulate heat input to the ^4He cell using a Josephson junction source
    - Synchronously demodulate the cell temperature change ΔT (at 0.005 Hz)
    - Adjust cell cooling with 0.5 pW resolution to maintain minimum ΔT
    - Hold average cell temperature to within one pK of T_λ for years
  - Measure the radiated power into this ultra-stable platform from the relatively unstable CMB, $T_{CMB} - T_\lambda \sim 0.5$ K
  - Do this for 10+ years as the Pluto Fast Flyby travels away from the Sun

Also… Interested in the Fundamental Measurement Limits of Thermometry?

Statistically, $\delta T/T \sim 1/\sqrt{N}$

Other limits:

Electronic Johnson noise / shot noise…
if resistive, but our thermometers are too good to resist!

Thermal energy fluctuation limits

Paramagnetic Susceptibility Thermometry

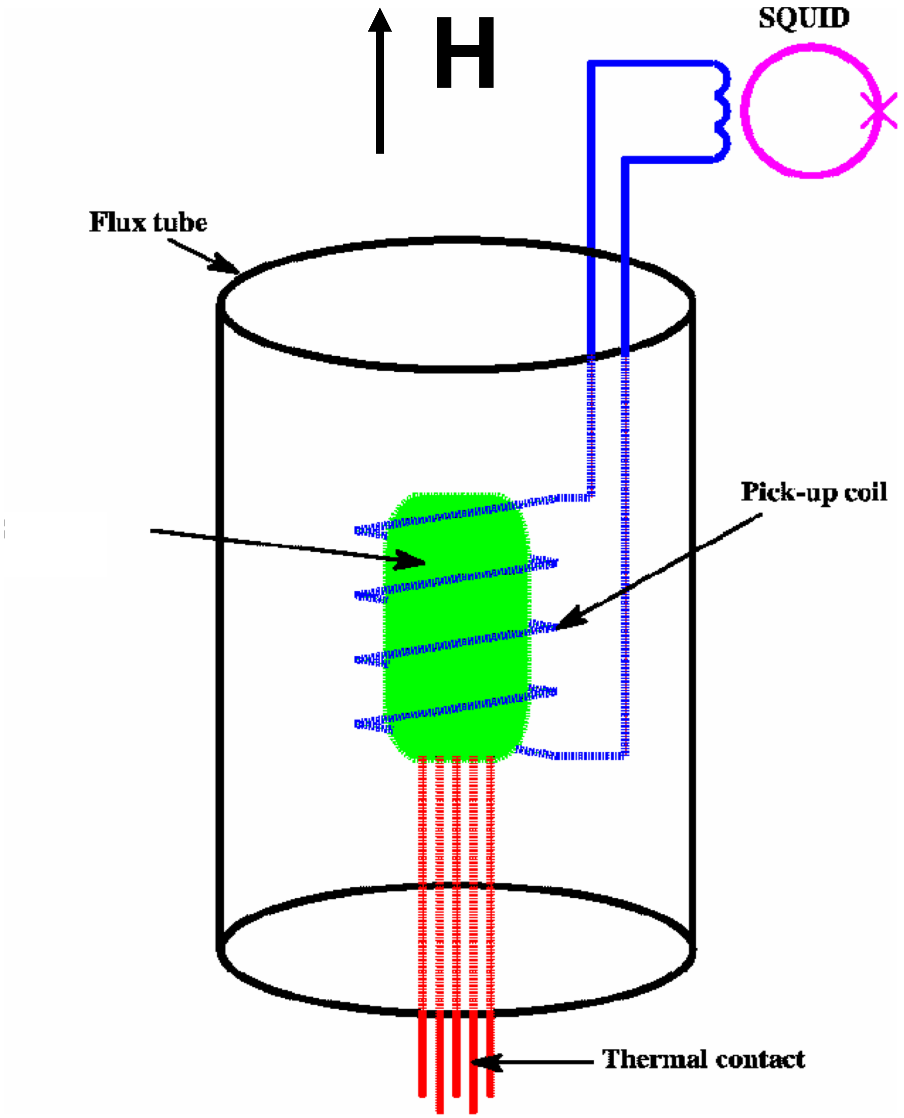
Magnetic flux is trapped in a niobium tube

A paramagnetic substance with $T > T_c$ is thermally anchored to the platform

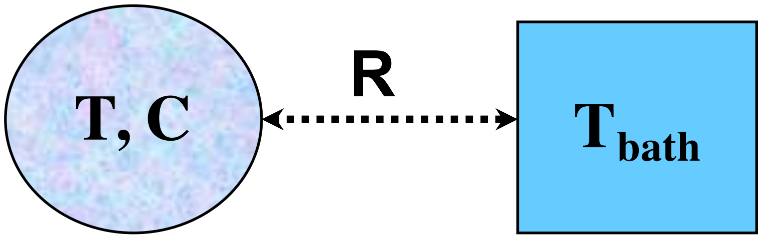
$M = H\,\chi(T)$

$\chi(T) = \Gamma\,[(T - T_c)/T_c]^{-\gamma}$ so small changes in T create large changes in M, and hence in the flux coupled to the SQUID

Gifford, Web, Wheatley (1971)
Lipa and Chui (1981)

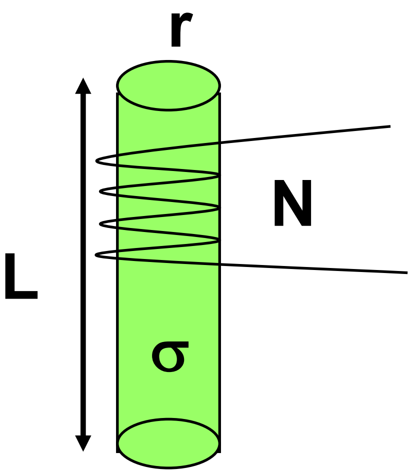


Fundamental Noise Sources



Heat fluctuations in the link

one independent measurement
per time constant τ, τ = RC
(noise)$^2 \sim \tau / C$
$\langle(\delta T_Q)^2\rangle = 4Rk_BT^2$
so $\delta T_Q \sim \sqrt{R}$ and $\delta T_Q \sim T$
See: Day, Hahn, & Chui, JLTP 107, 359 (1997)



Thermally induced electrical current fluctuations

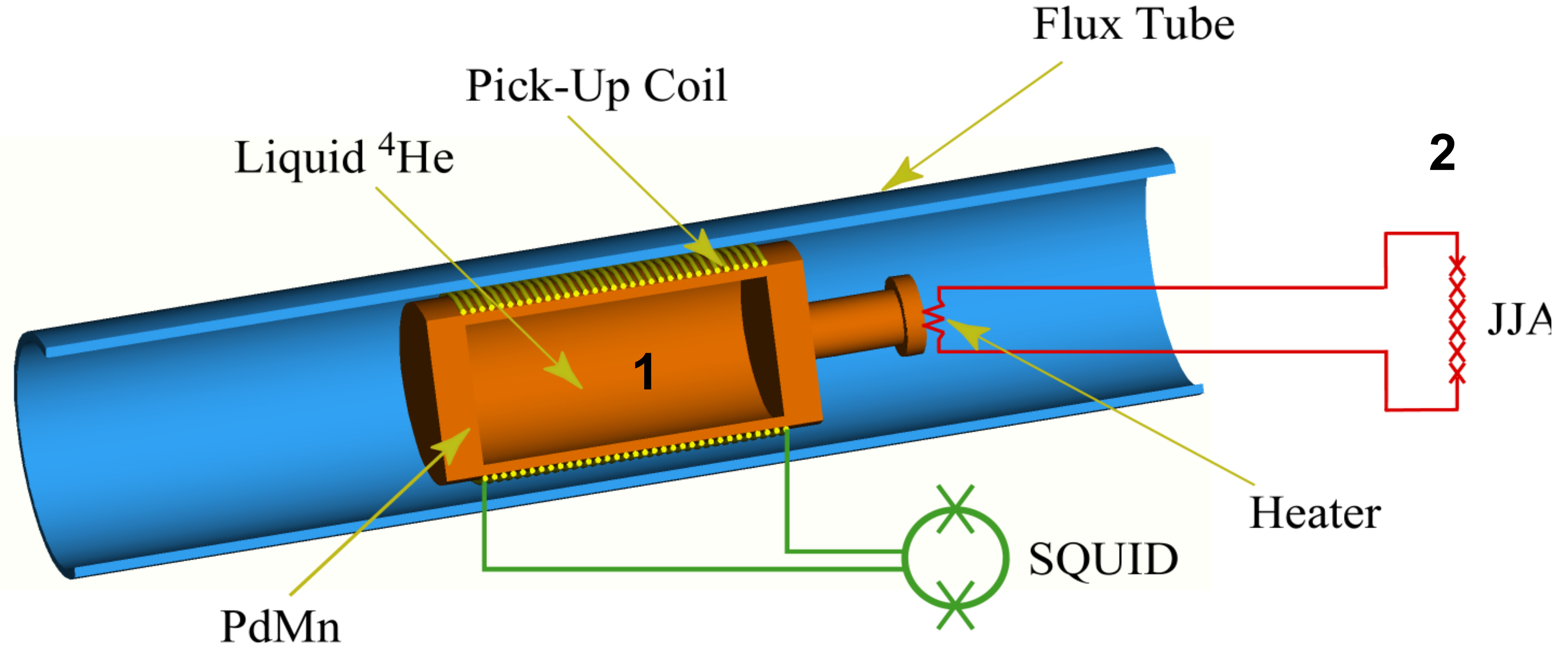
mutual inductance creates flux noise
$\langle(\delta\Phi)^2\rangle \sim T\, N^2 \sigma\, r^4 / L$
$\delta T_M = \delta\Phi / s$, $s \approx 1\ \phi_o/\mu K$
so $\delta T_M \sim \delta\Phi \sim \sqrt{T}$

SQUID noise

$\langle(\Delta\Phi_{SQ})^2\rangle^{1/2} \approx 4\ \mu\phi_o/\sqrt{Hz}$ with shorted input
external circuit creates about three times this noise level
so $\Delta\Phi \approx 12\ \mu\phi_o/\sqrt{Hz}$ and $\delta T_{SQ} \approx 12\ pK/\sqrt{Hz}$

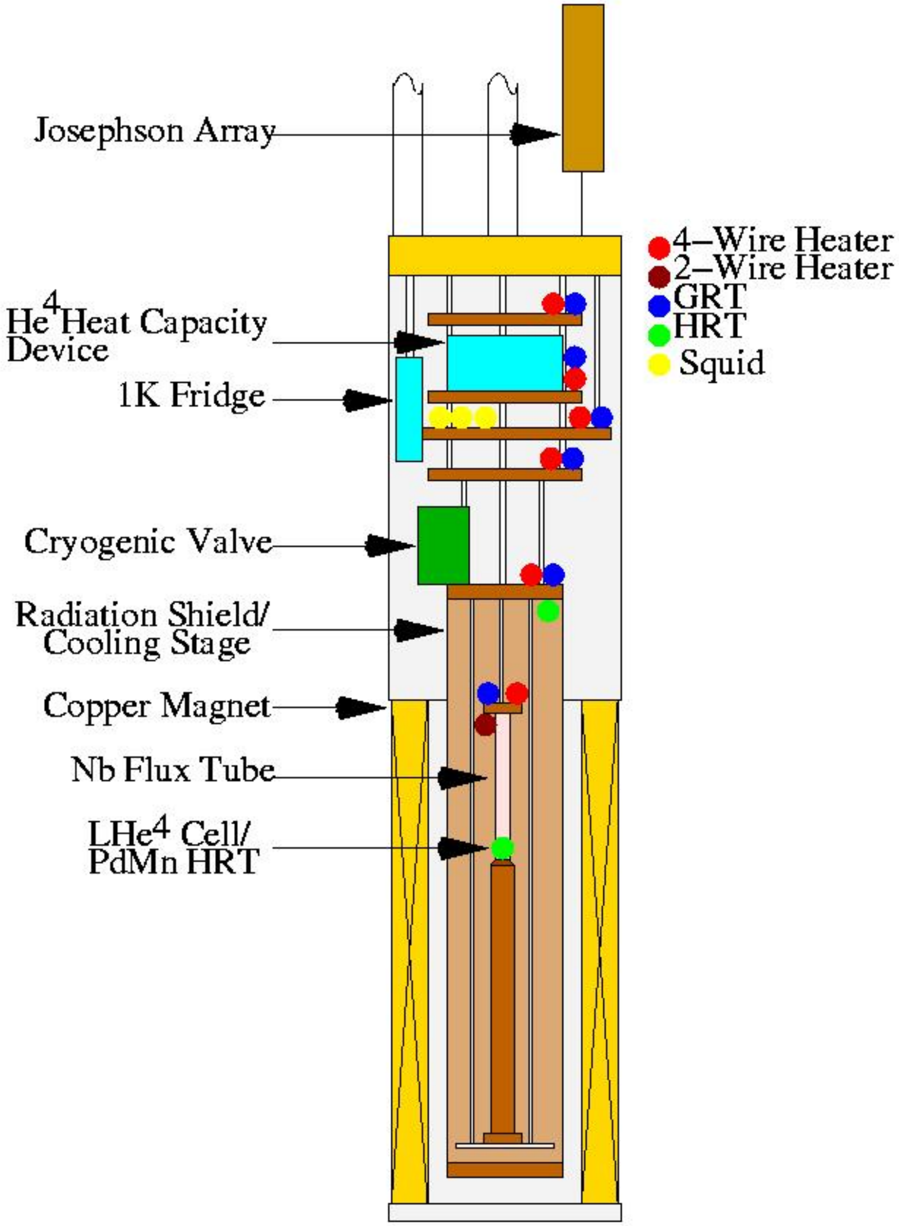
New Ultra-Stable Platform

Green, Sergatskov, and Duncan, J. Low Temp. Phys. 138, 871 (2005)

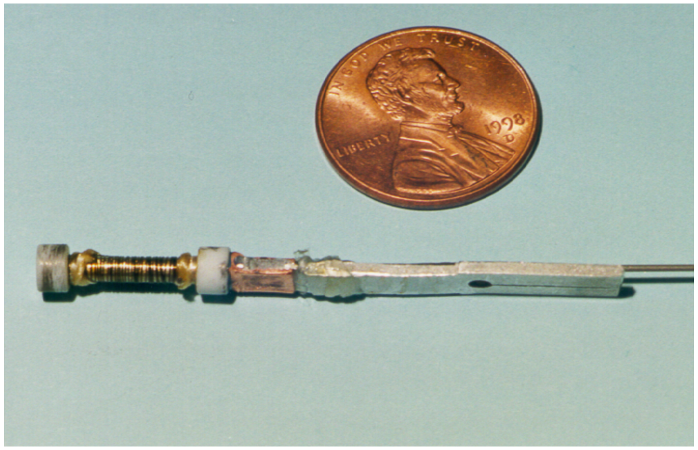


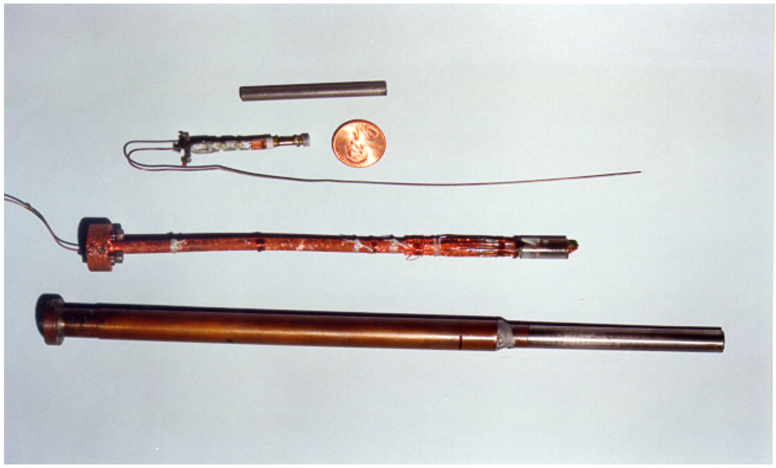
The helium sample is contained within the PdMn thermometric element. Power dissipation is precisely controlled with the rf-biased Josephson junction array (JJA). Stabilized to $\delta T \sim 10^{-11}$ K.

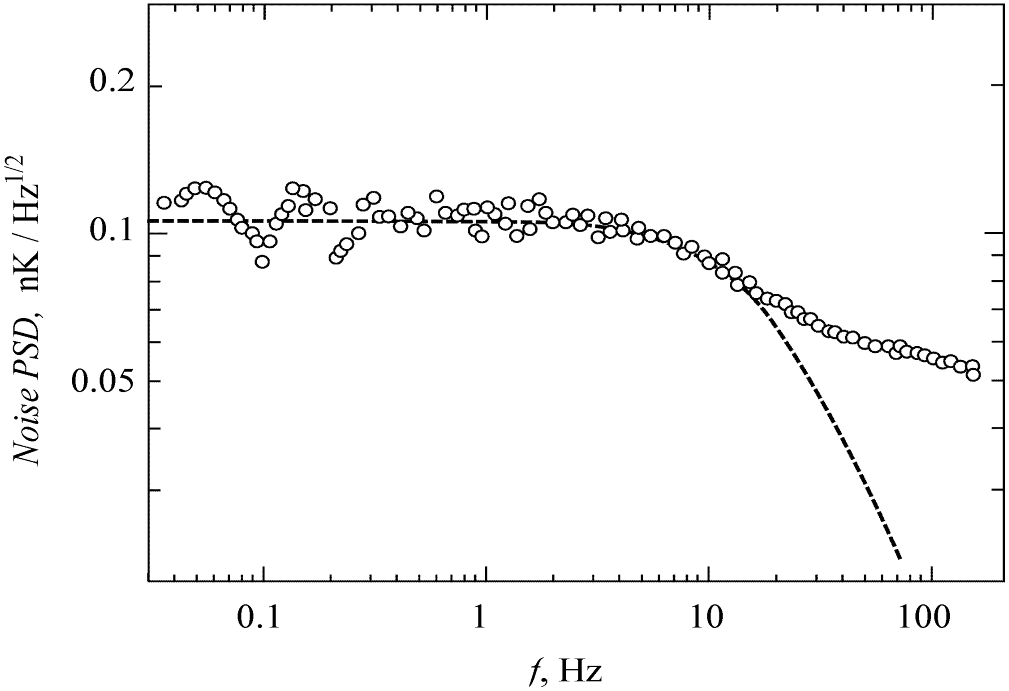
Next Generation Hardware



Heat Fluctuation Noise Across the Link







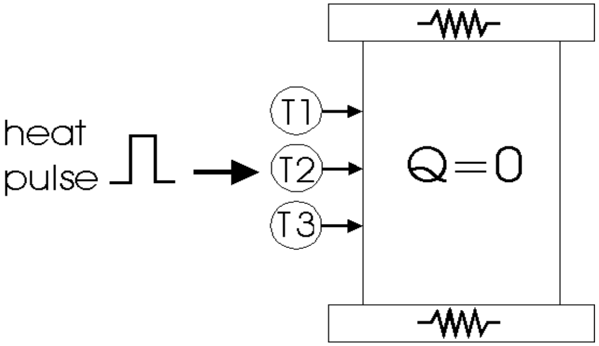
R = 40 K/W

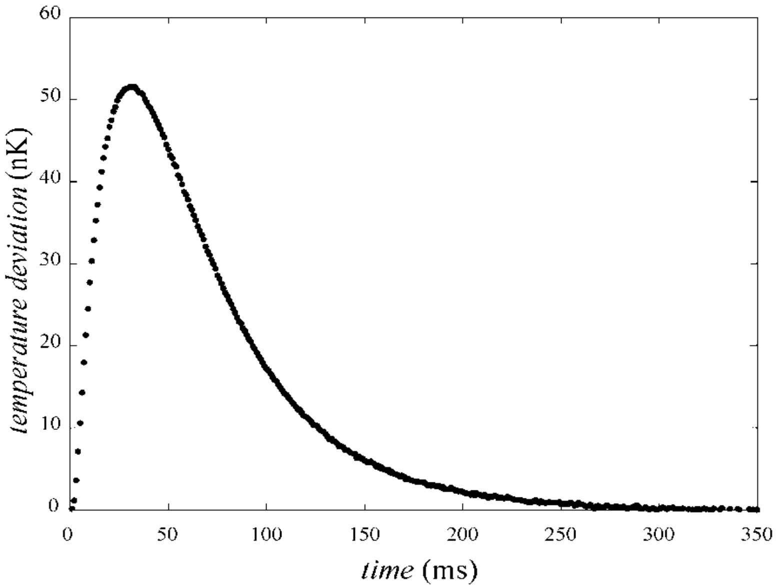
$\langle(\delta T_Q)^2\rangle = 4Rk_BT^2$
so $\delta T_Q = 0.10$ nK/√Hz

3 dB point at 10 Hz,
suggesting $\tau \approx 50$ ms

(collaboration with Peter Day)

HRT Time Constant





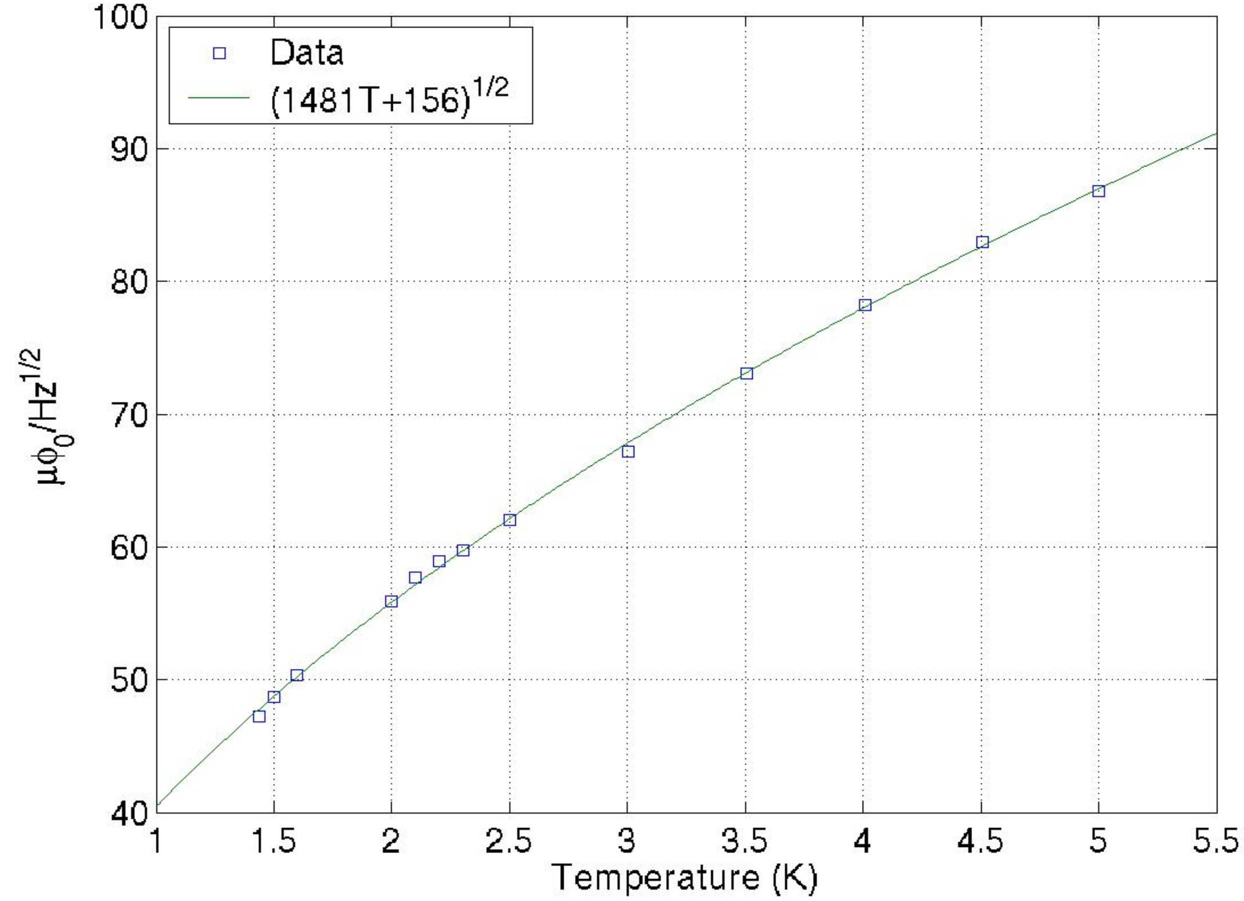
Method:

- **Controlled cell temperature with T1**
- **Pulsed a heater located on T2**
- **Cell in superfluid state**
- **Contact area of only 0.05 cm^2**

- **Rise time ~ 20 ms**
- **Decay time = 48 ms**

Collaboration with Peter Day

Noise: Thermally Driven Current Fluctuations



Thermal current fluctuations: $\delta\Phi = 38\ \mu\phi_o/(\mathrm{Hz\ K})^{1/2}\ \sqrt{T}$

SQUID circuit noise: $\delta\Phi_{SQ} = 12.5\ \mu\phi_o/\sqrt{\mathrm{Hz}}$

Reduce the Heat Fluctuation Noise

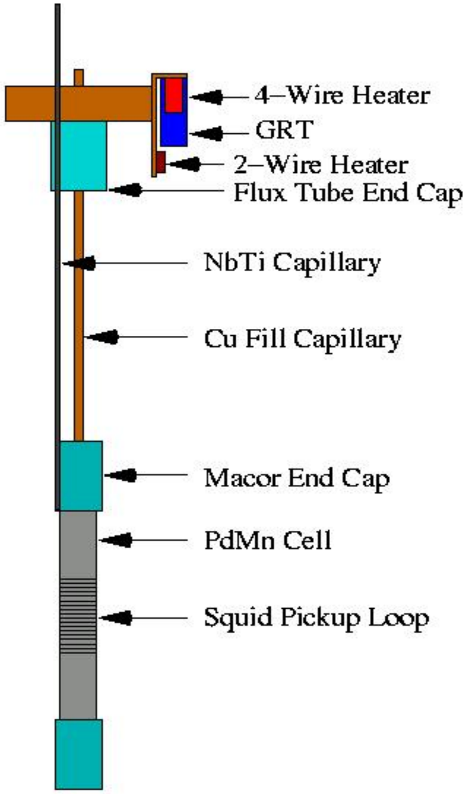
Reduce R from 40 to 0.25 K/W

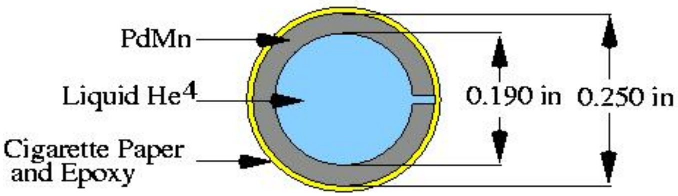
Now $\delta T_Q \approx 7\ \mathrm{pK}/\sqrt{\mathrm{Hz}}$

Minimize δT_M with a gap to reduce mutual inductance to the SQUID loop

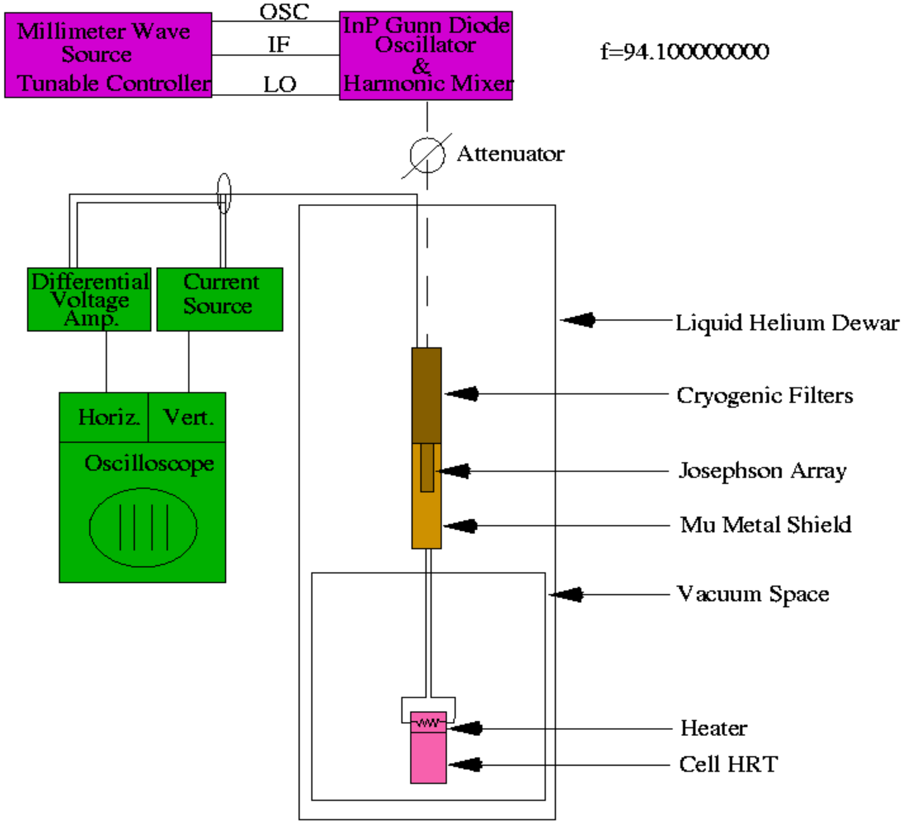
γ is PdMn thickness = 0.76 mm

$r^4 \rightarrow 4\, r\, \gamma^3 \qquad r^3/(4\gamma^3) \approx 18$





RF-biased Josephson Junctions for Heater Control



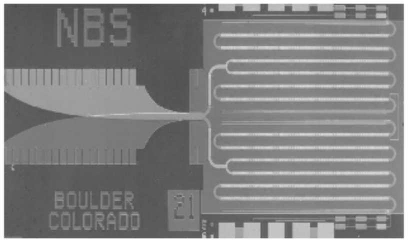
$V_n = n\,(h/2e)\,f$

$h/2e = \phi_o = 2.07\ \mu V/GHz$

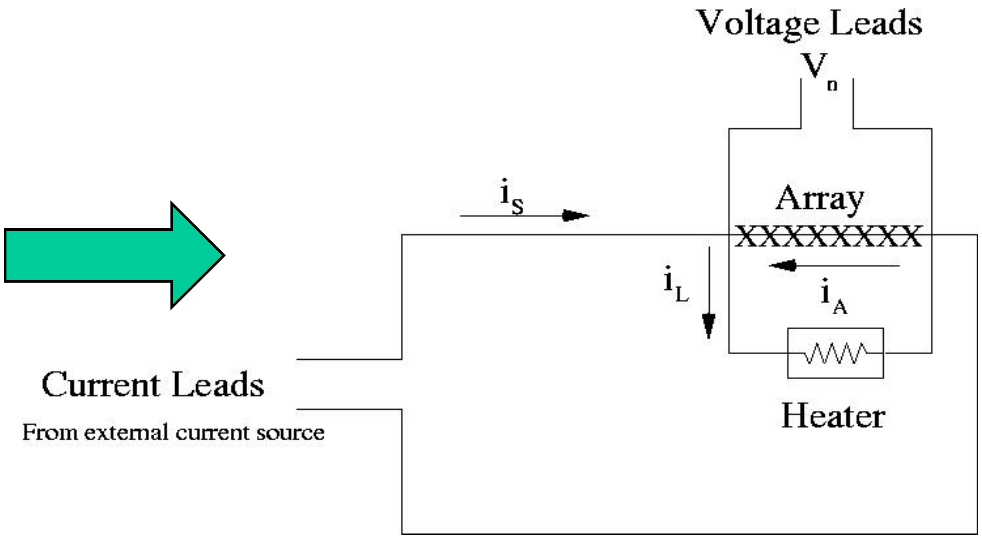
$f = 94.100000000\ GHz$

$R_{el} = 1{,}015\ \Omega$

$P_n = V_n^2 / R_{el} = 37.3\ n^2\ pW$



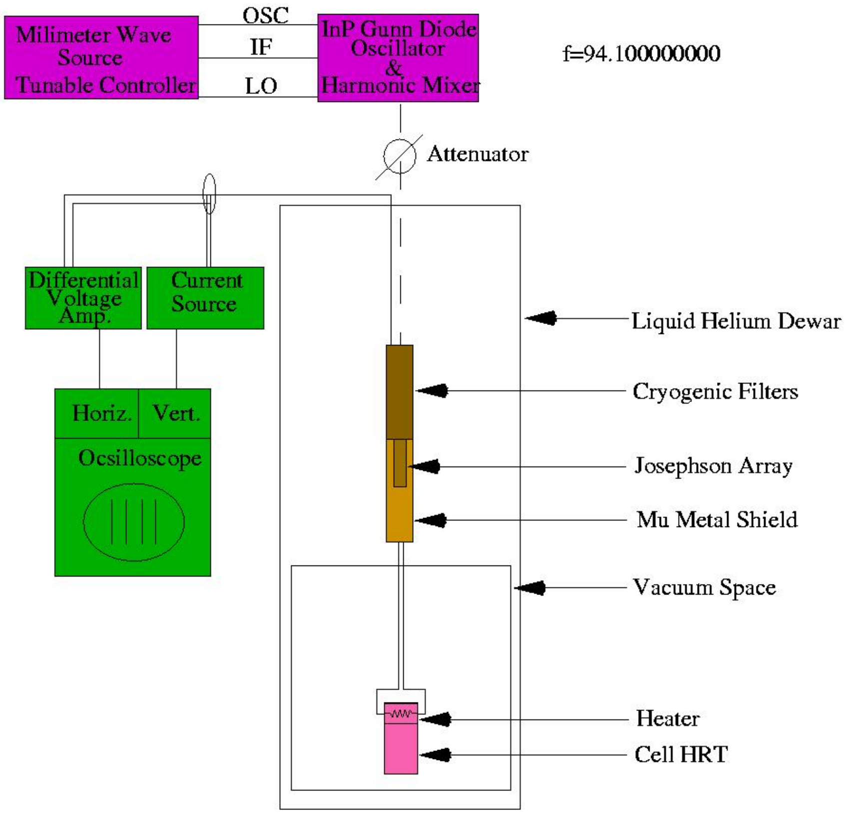
A one–volt NIST Josephso junction array standard having 3020 junctions, similar to the one used in this experiment.



RF-biased Josephson Junctions for Heater Control

$$V_n = n\,(h/2e)\,f$$

$$P_n = V_n^2 / R \approx 40\, n^2 \text{ pW}$$



Milimeter Wave Source Tunable Controller

OSC

IF

LO

InP Gunn Diode Oscillator & Harmonic Mixer

f=94.100000000

Attenuator

Differential Voltage Amp.

Current Source

Horiz.

Vert.

Ocsilloscope

Liquid Helium Dewar

Cryogenic Filters

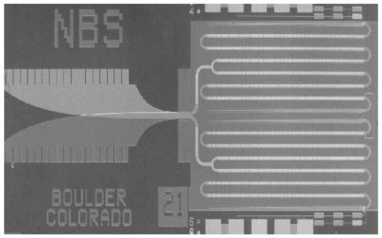
Josephson Array

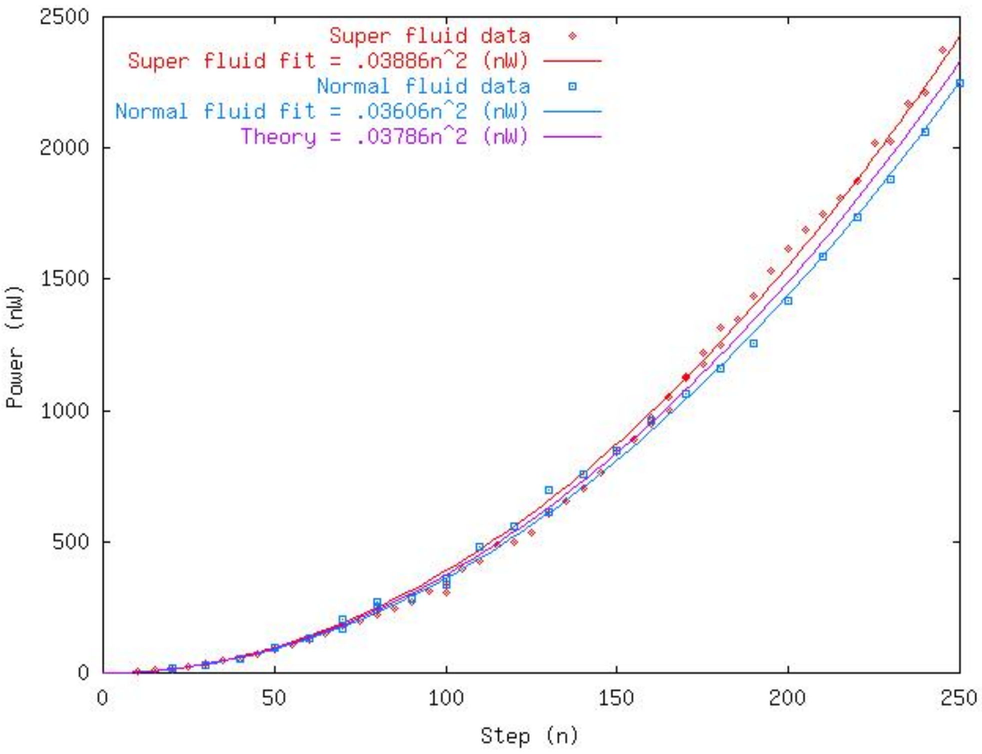
Mu Metal Shield

Vacuum Space

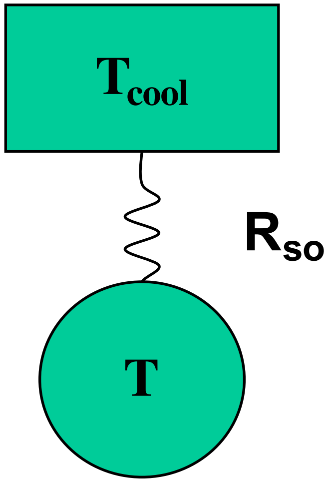
Heater

Cell HRT



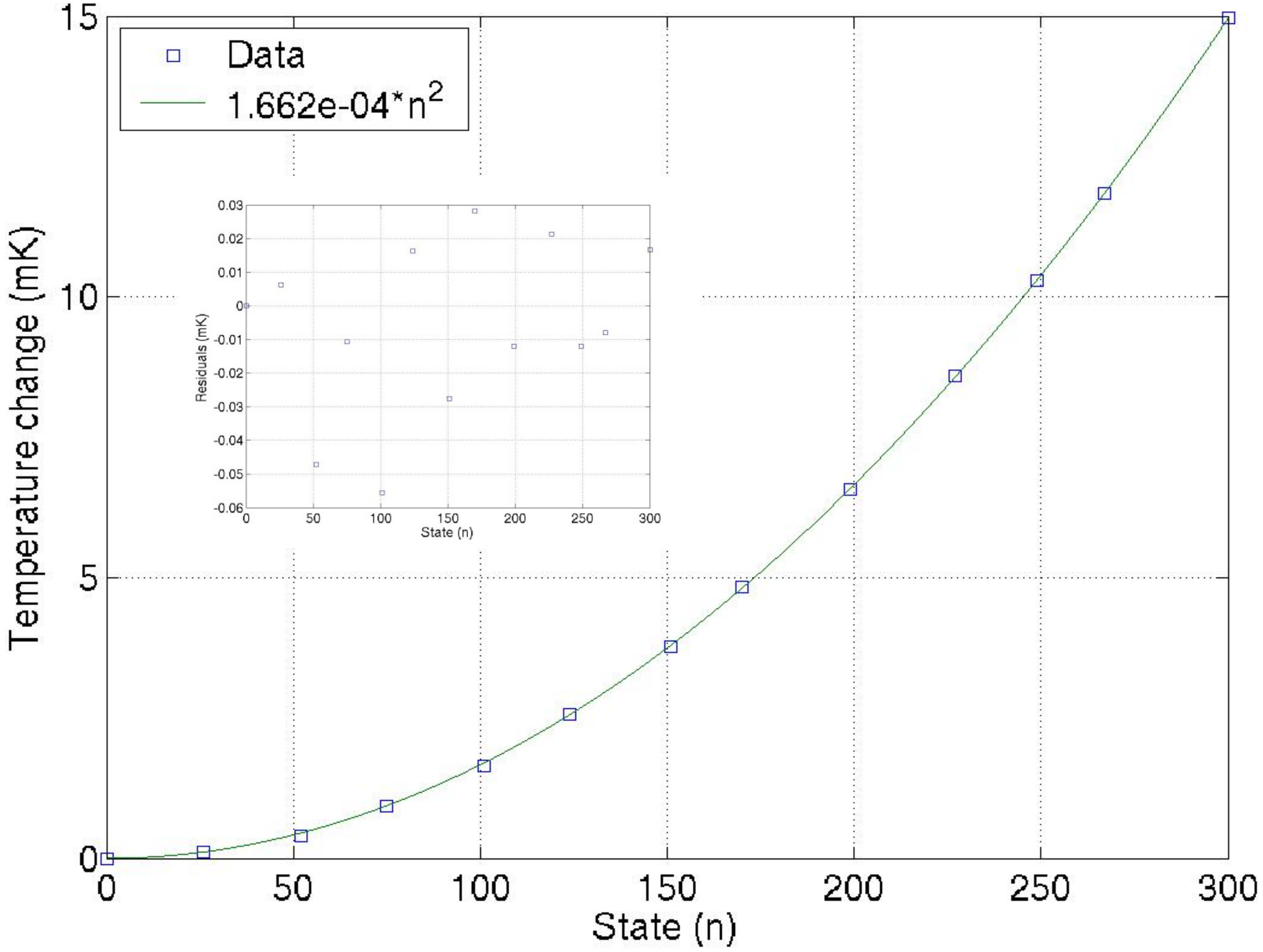


Standoff vs. Josephson Quantum Number n

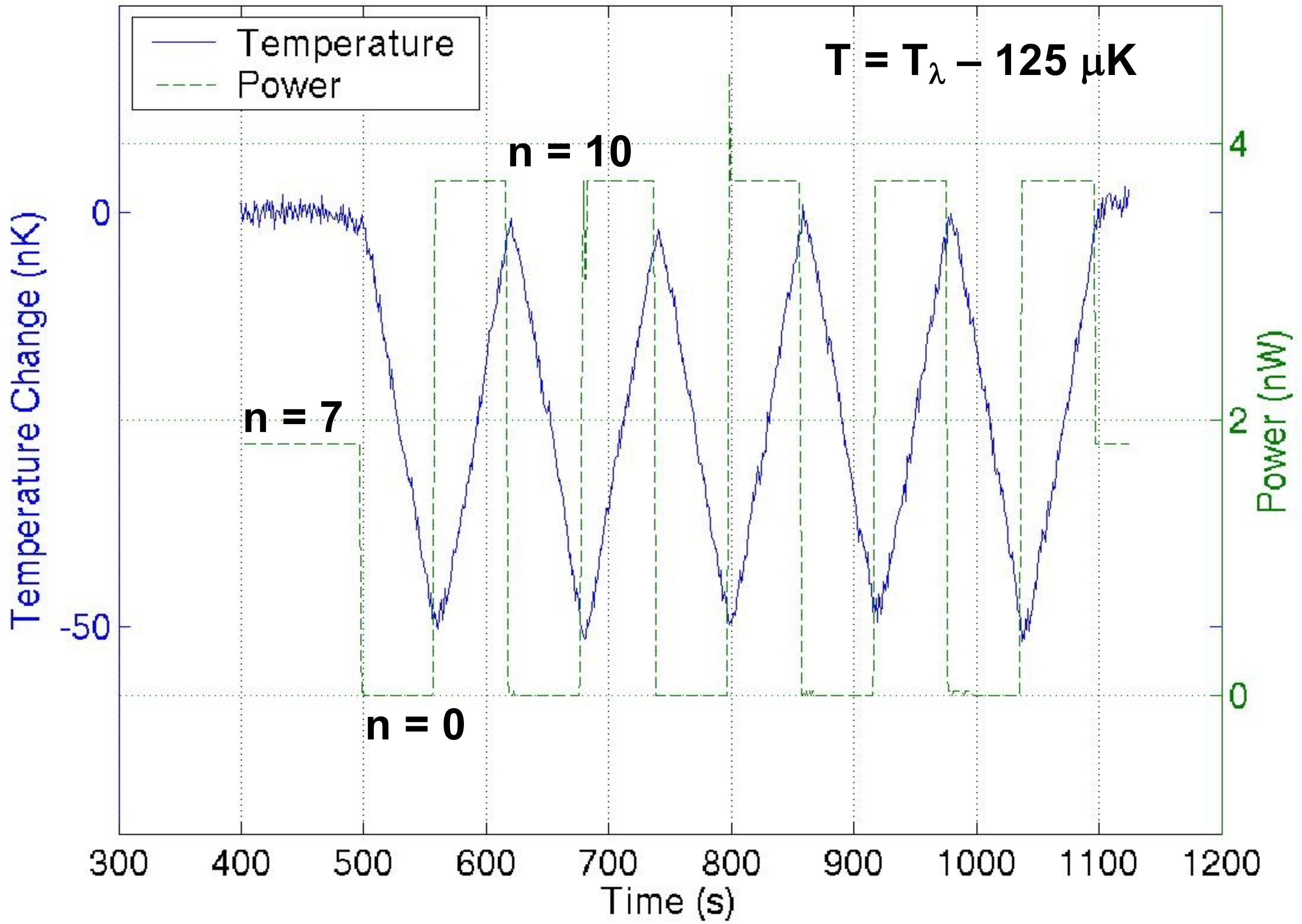


R_{el} = 1,015 Ω

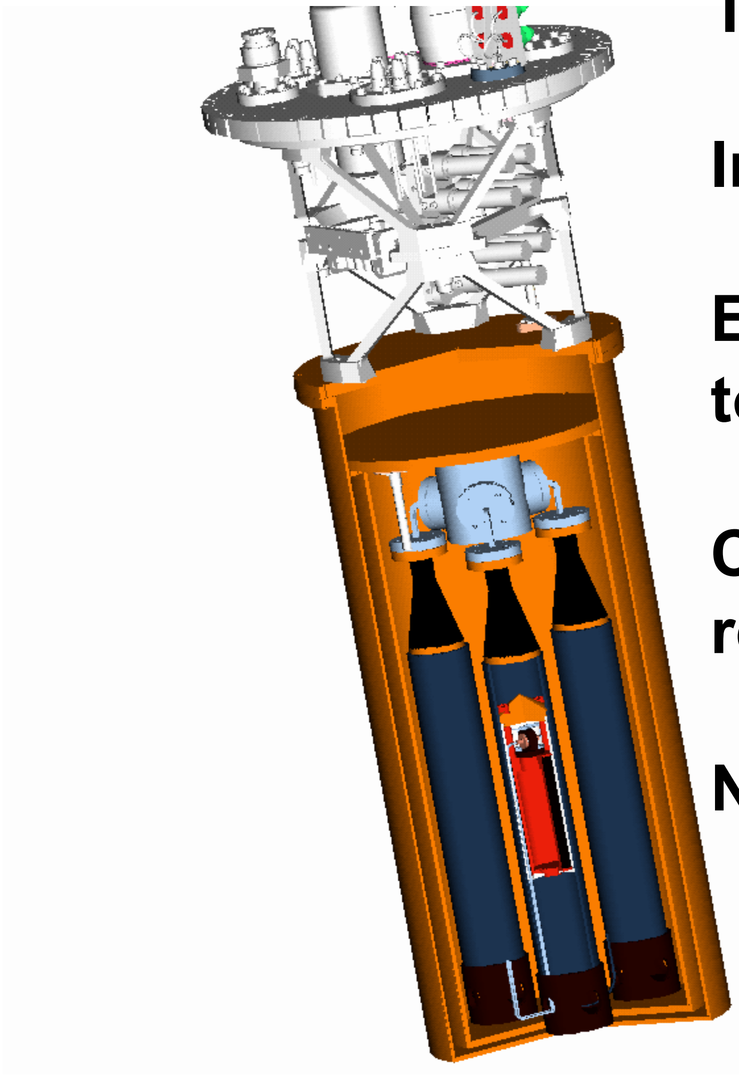
R_{so} = 4,456 K/W



A New ‘Fixed-Point’ Standard



Future Work: Radiometric Comparisons



Three independent BB references

Inner shield maintained at $T_\lambda \pm 50$ pK

Each reference counted up from T_λ
to 2.7 K using Josephson heater control

Compare to each other with 0.1 nK
resolution in a well controlled cryostat

New control theory has been developed

(Discussions with Phil Lubin, UCSB
and with George Seidel at Brown)

Conclusions

- Fundamental noise sources in PST identified and reduced
- Lowest noise ~ 25 pK/√Hz at 1.6 K
- New rf-biased Josephson junction heater controller developed
- Technology in place now to develop a reference standard more stable than the CMB temperature (< 200 pK/year drift) in a weightless lab, provided that T_λ does not vary with the cosmic expansion