‘Heat from Above’ heat capacity measurements in liquid ^{4}He

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We have made heat capacity measurements of superfluid ^{4}He at temperatures very close to the lambda point, T_λ, in a constant heat flux, Q, when the helium sample is heated from above. In this configuration the helium enters a self-organized (SOC) heat transport state [1] at a temperature $T_{SOC}(Q)$, which for $Q \geq 100\,\mathrm{nW/cm^2}$ lies below T_λ. At low Q we observe little or no deviation from the bulk $Q = 0$ heat capacity up to $T_{SOC}(Q)$; beyond this temperature the heat capacity appears to be sharply depressed, deviating dramatically from its bulk behaviour. This marks the formation and propagation of a SOC/superfluid two phase state, which we confirm with a simple model. The excellent agreement between data and model serves as an independent confirmation of the existence of the SOC state. As Q is increased (up to $6\,\mu\mathrm{W/cm^2}$) we observe a Q dependant depression in the heat capacity that occurs just below $T_{SOC}(Q)$, when the entire sample is still superfluid. This is due to the emergence of a large thermal resistance in the sample, which we have measured and used to model the observed heat capacity depression. Our measurements of the superfluid thermal resistivity are a factor of ten larger than previous measurements by Baddar *et al.*[2].

[1] W. A. Moeur, P. K. Day, F-C. Liu, S. T. P. Boyd, M. J. Adriaans and R. V. Duncan, *Phys. Rev. Lett.* **78**, 2421 (1997).

[2] H. Baddar, G. Ahlers, K. Kuehn and H. Fu, *J. Low Temp. Phys.* **119**, 1 (2000).

‘Heat from Above’ heat capacity measurements in liquid in ^{4}He

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This work has resulted from development of:

The CQ Experiment

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Robert V. Duncan (U.N.M.)
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Peter K. Day (J.P.L.)

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The CQ Experiment: Enhanced Heat Capacity of Superfluid Helium in a Heat Flux

- Guest experiment on DYNAMX (critical dynamics in μg).
- NASA flight experiment.
- 2008 flight on International Space Station (μg environment).

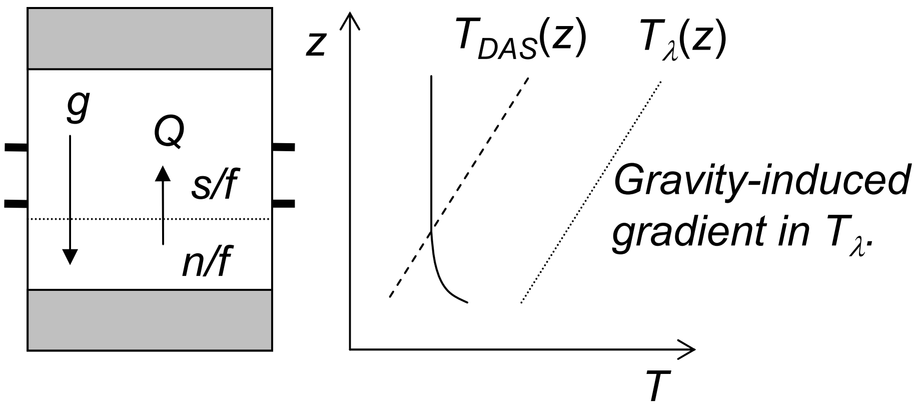
<u>Purpose</u>:

- Test predictions of the dynamic renormalization group theory.
- When one applies a heat flux, Q, to a sample of superfluid:
  - Transition temperature is <u>depressed</u>, $T_c(Q) < T_\lambda$
  - Heat capacity is <u>enhanced</u>, $\Delta C_Q = C_Q - C_0$, and <u>diverges</u> at $T_c(Q)$

- <u>Ground-based experiments (disagree with theory)</u>:
  - $T_{DAS}(Q) < T_c(Q)$, **<u>D</u>**uncan, **<u>A</u>**hlers and **<u>S</u>**teinberg, *PRL,* **60**, 1522(1988).
  - $\Delta C_{Q\_Harter.} \approx 10 \times \Delta C_{Q\_theory}$, Harter *et al*., *PRL,* **84**, 2195 (2000).

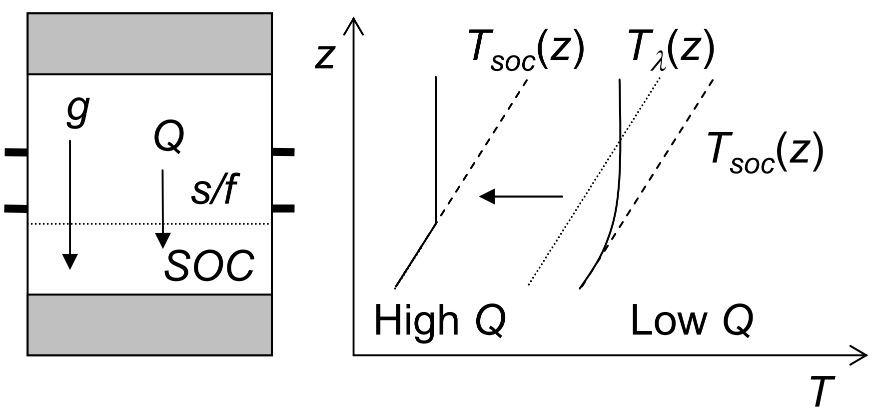
‘Heat from Below or Above’ – ground based

– ‘Heat from Below’ configuration



g = gravity, Q = Heat flux, z = height

– ‘Heat from Above’ configuration



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- ‘Heat from Above’ produces:
- **<u>S</u>**elf **<u>O</u>**rganized **<u>C</u>**ritical State:
  Mouer *et. al.*, *PRL*, **78**, 2421 (1997)
- At low Q the SOC state exists on the normal-fluid side of T_λ, where the diverging thermal conductivity causes the sample to ‘self-organize’ at a fixed reduced temperature from T_λ.
  – For $Q < 0.1\ \mu W/cm^2$: $T_{soc} > T_\lambda$

$$\kappa(Q, t_{soc}) = \frac{|Q|}{\nabla T_\lambda}$$

  – For $Q > 0.5\ \mu W/cm^2$: $T_{soc} \approx T_{DAS}$

$$t_{soc}(Q) = \frac{T_\lambda - T_{soc}}{T_\lambda} = \left(\frac{Q}{638\ \mathrm{W/cm^2}}\right)^{0.813}$$

Measurement technique

- Heat pulse method

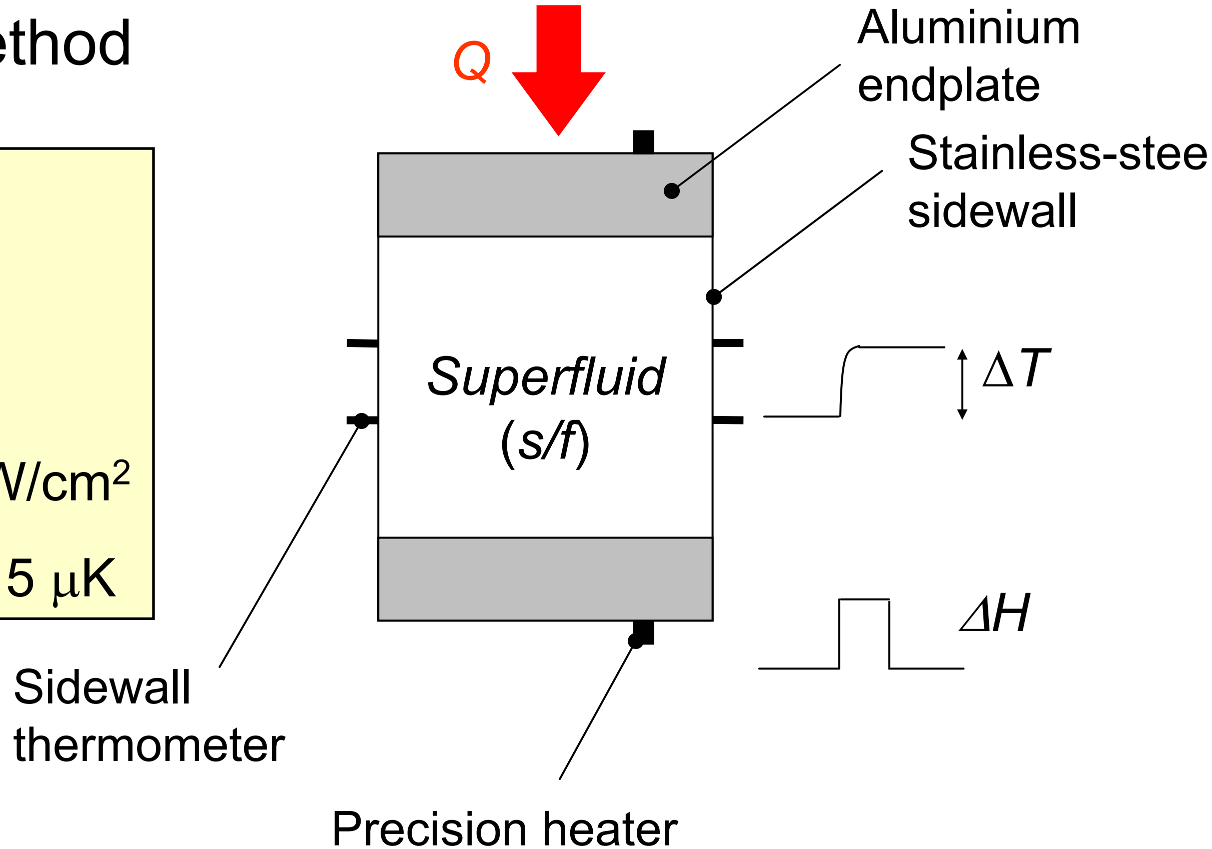
$C = \Delta H/\Delta T$

ΔH = 500 nJ

ΔT = 30 nK

Q range: 0 - 6 μW/cm^2

T range: $T_\lambda - T \leq 5\ \mu$K



- Pulse sample, raising its temperature, until $T = T_{soc}(Q)$, and look for ΔC_Q.

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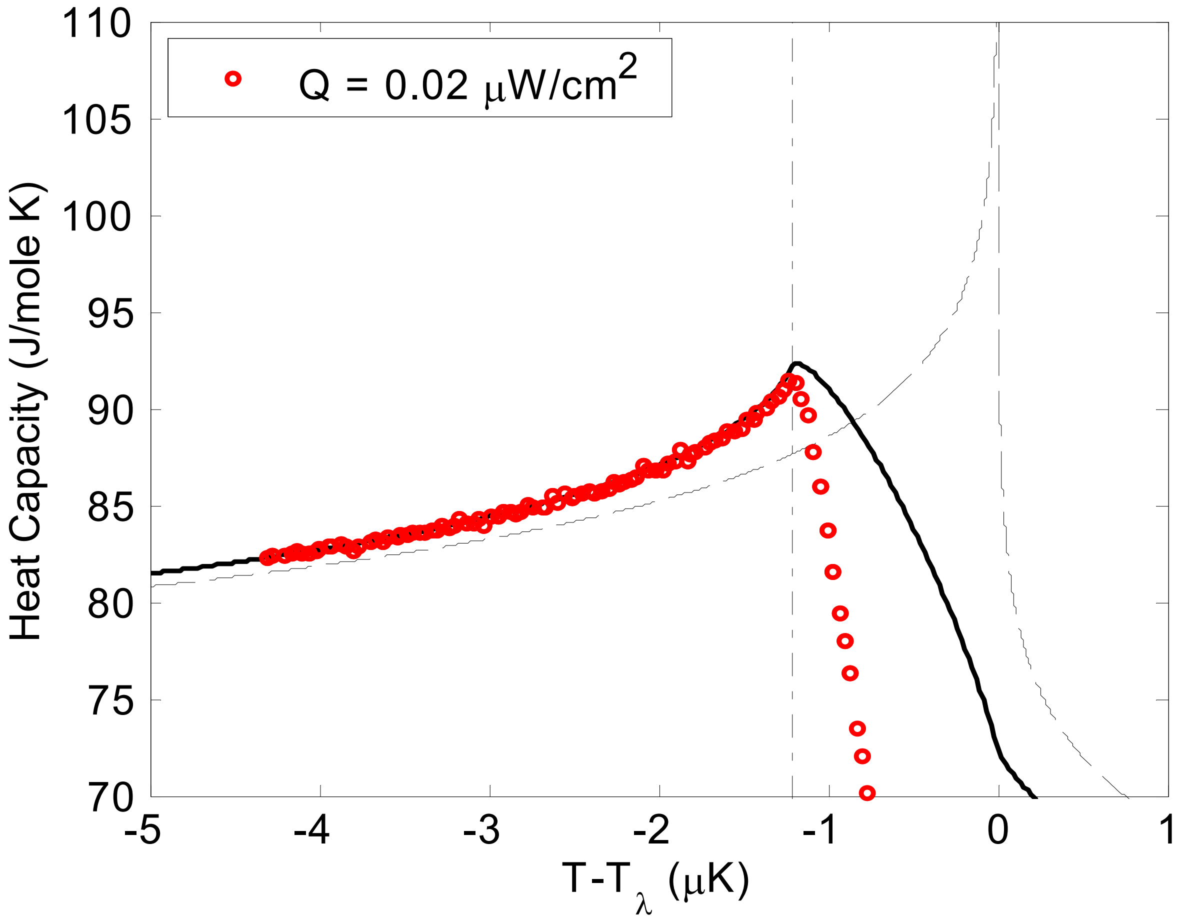
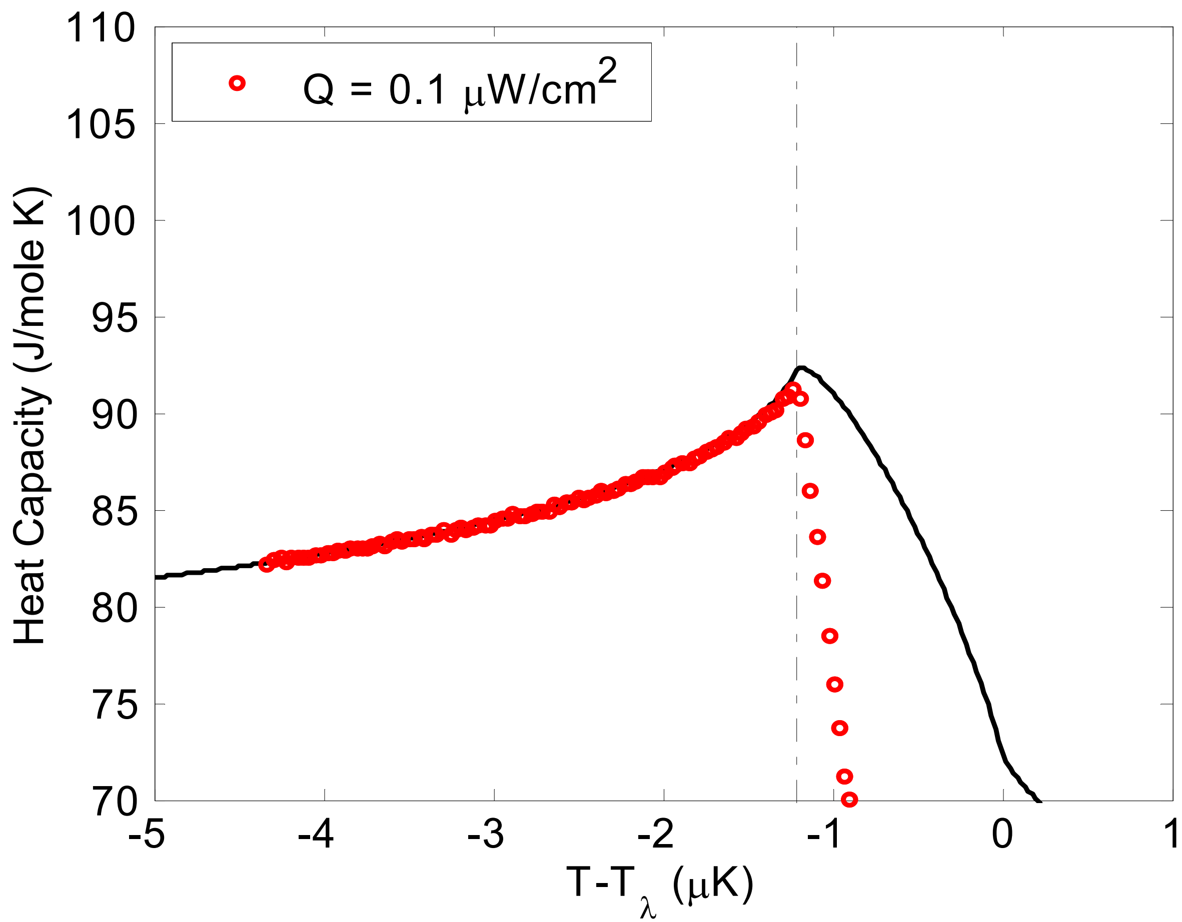
Results - ‘Heat from Above’



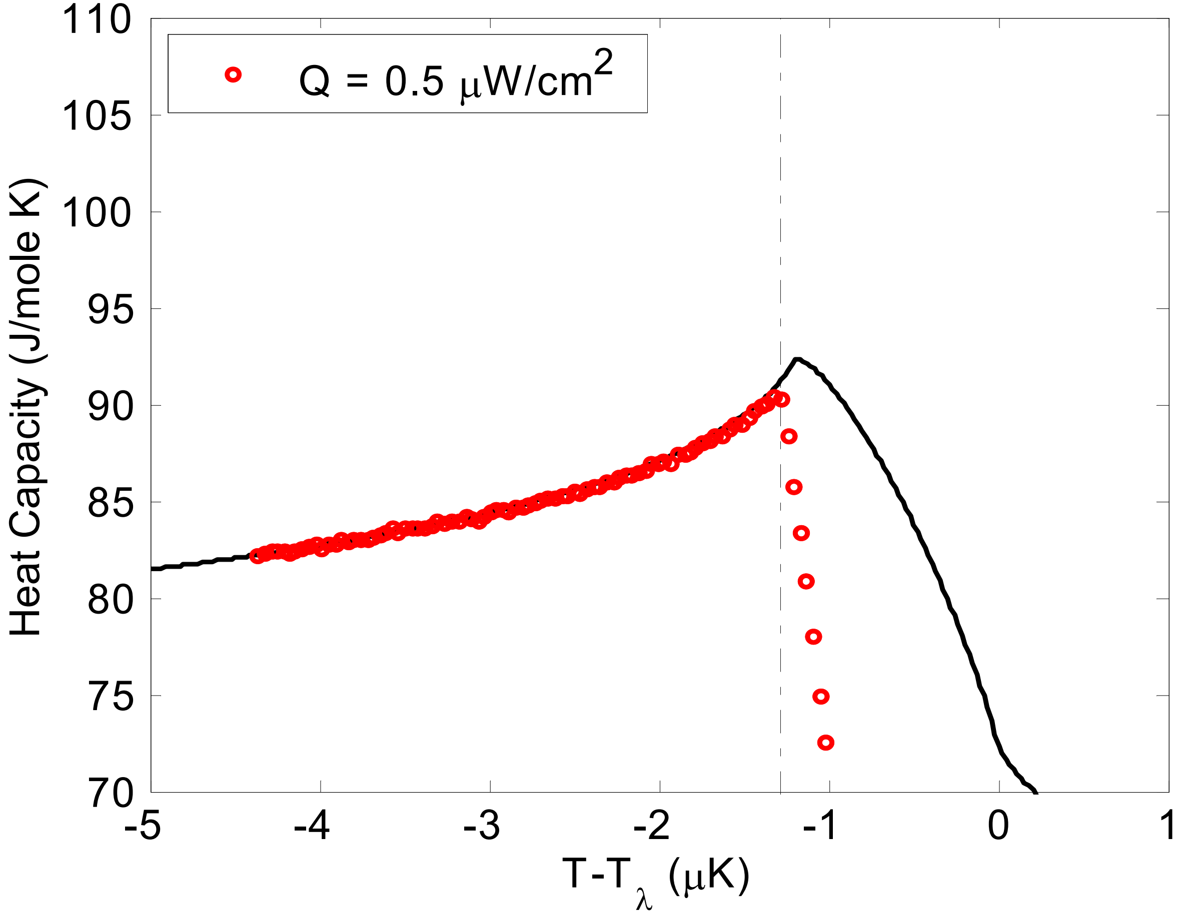
- Sample depth = 9 mm, so T_λ(top) - T_λ(bottom) = 1.2 μK
- Severe gravity rounding (black line). Compare with μg (dashed line).

Results - ‘Heat from Above’



- Red circle points = ‘Heat from Above’ heat capacity data.
- Black line = calculated gravity rounded, Q = 0, heat capacity
- Dot-dashed line = measured $T_{soc}(Q)$.[34]

Results - 'Heat from Above'



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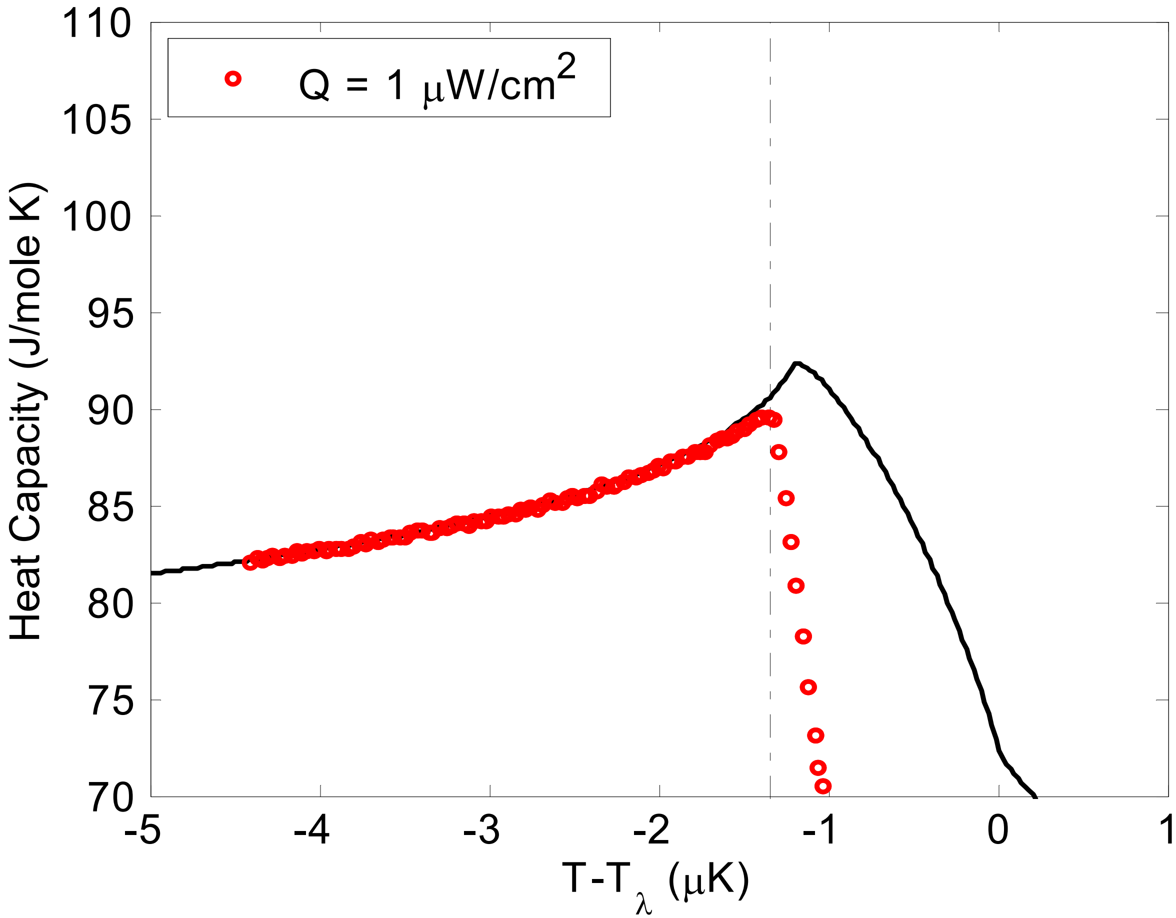
Results - ‘Heat from Above’



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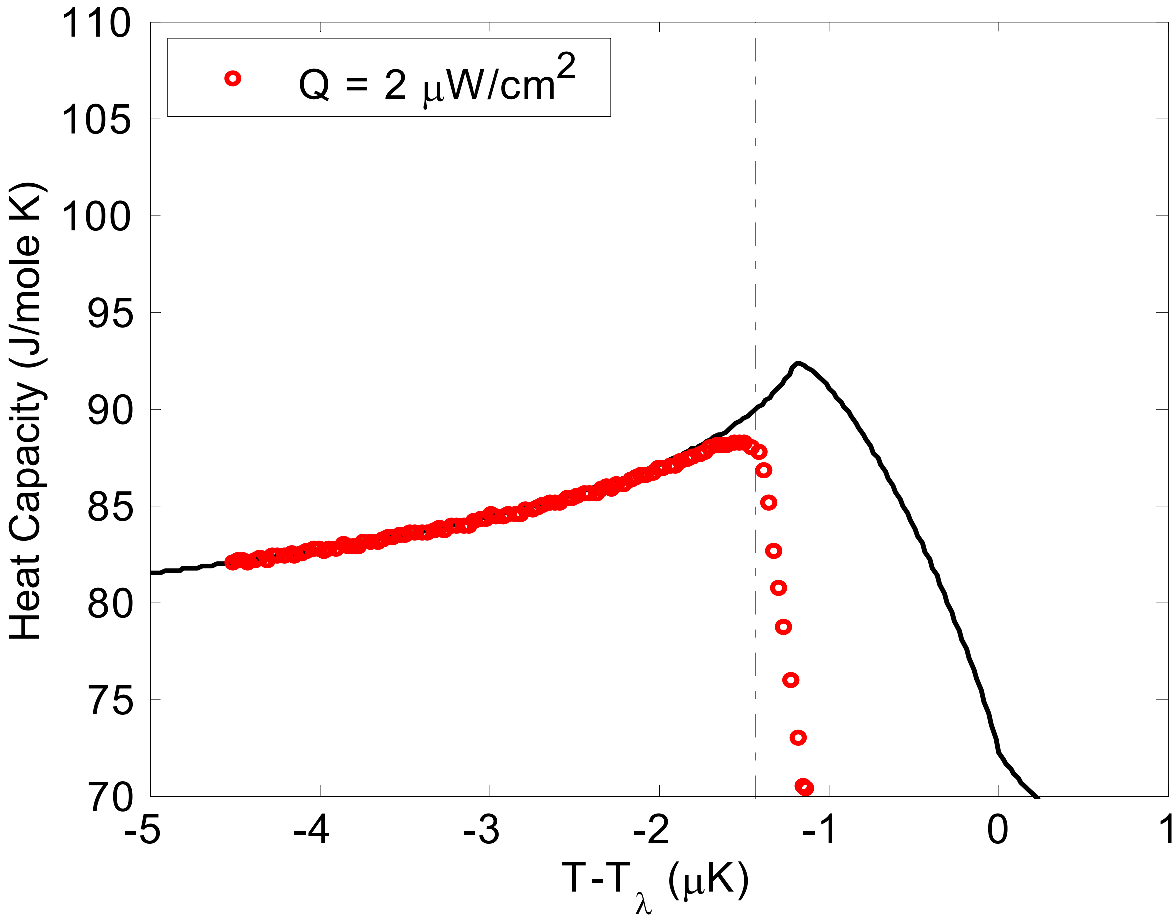
Results - 'Heat from Above'



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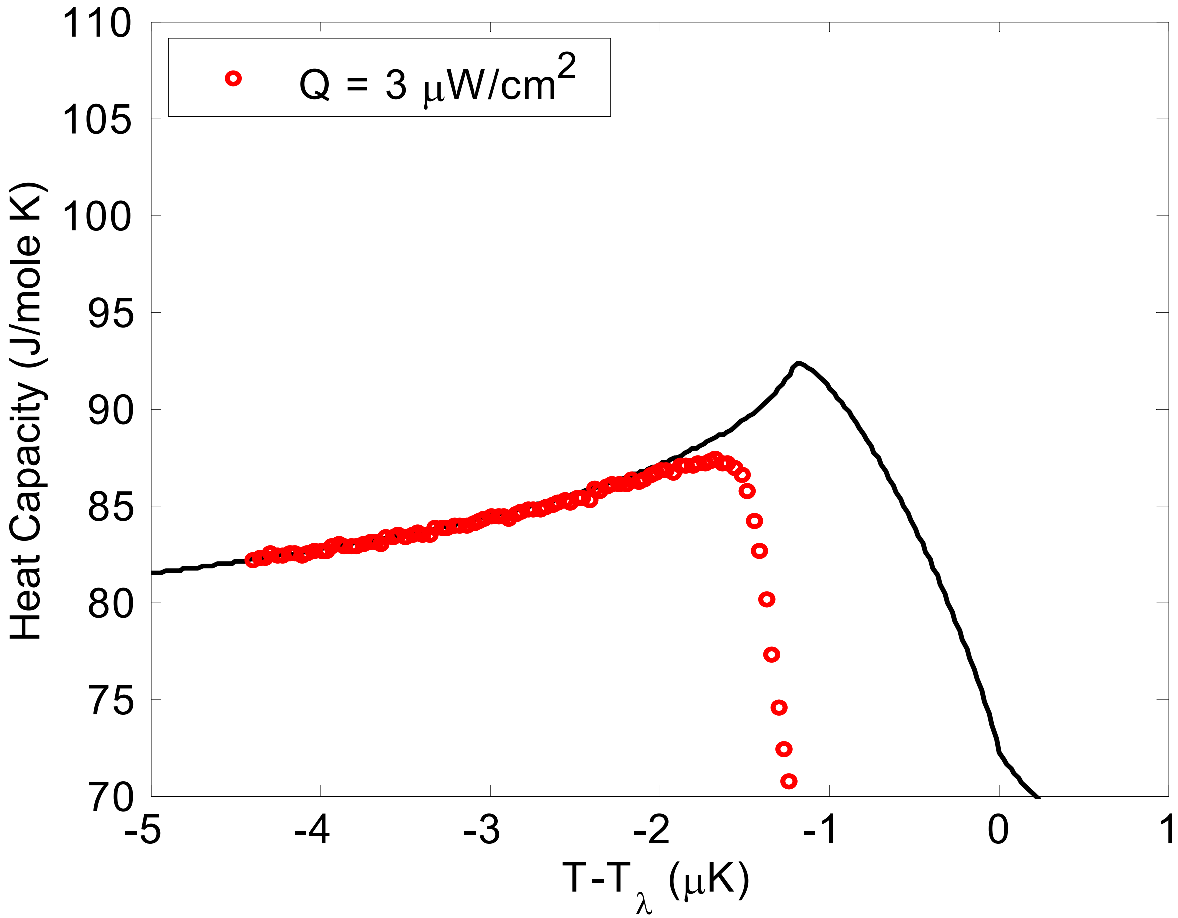
Results - 'Heat from Above'



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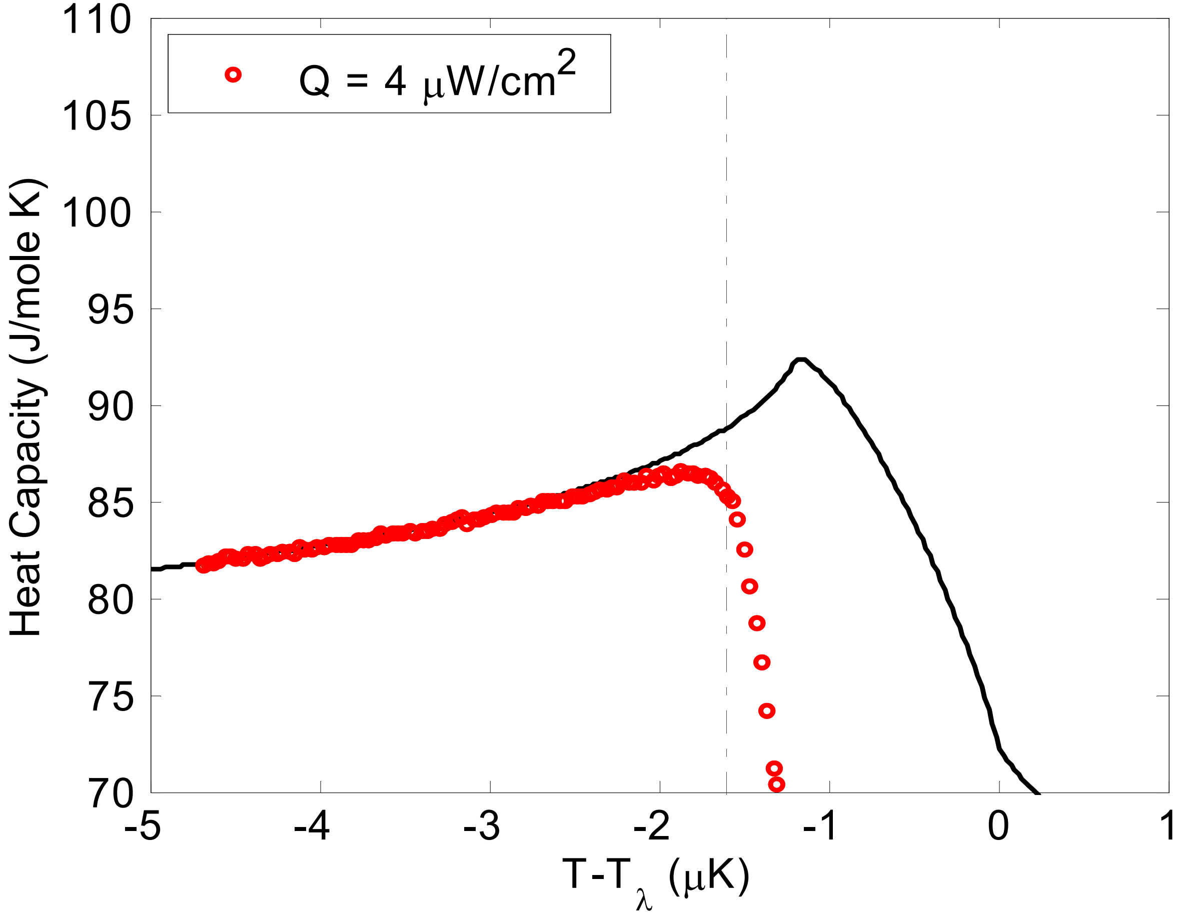
Results - ‘Heat from Above’



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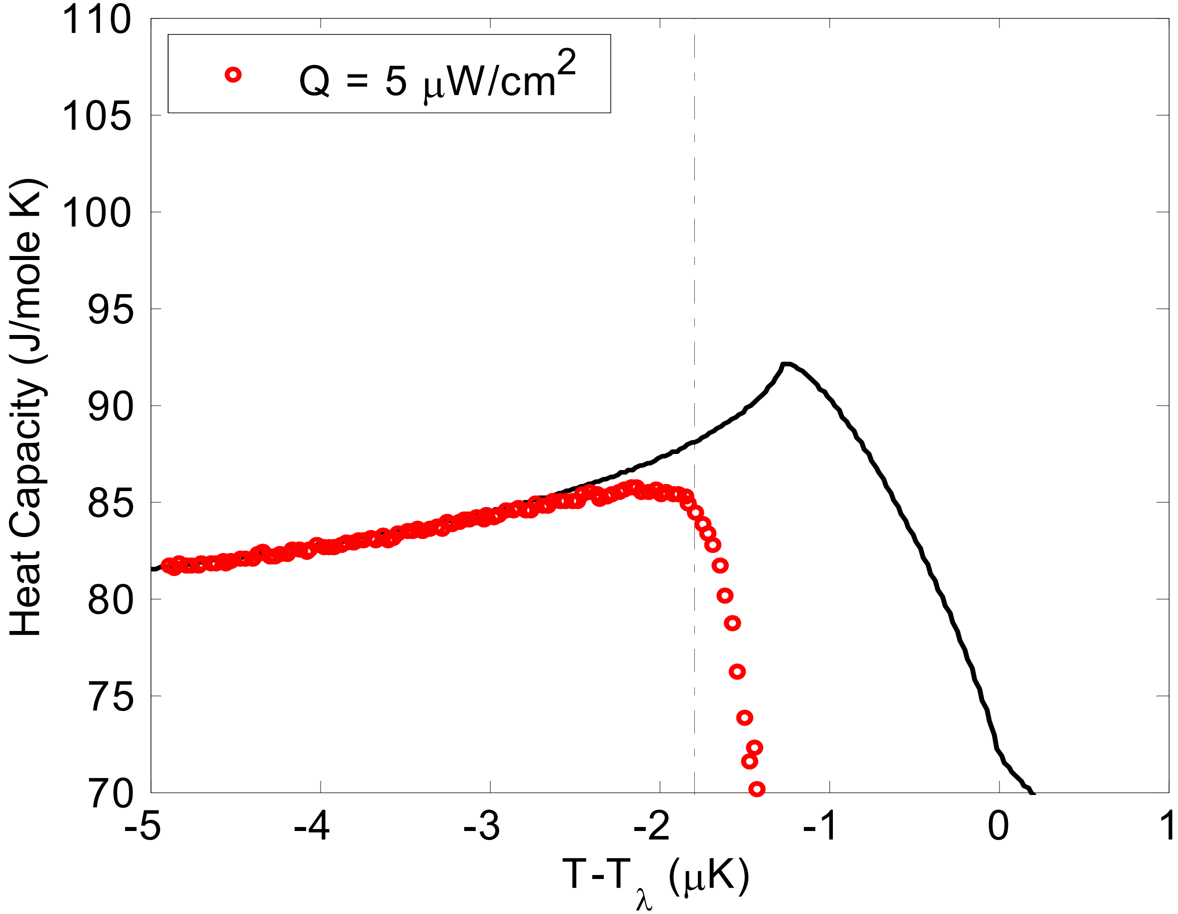
Results - 'Heat from Above'



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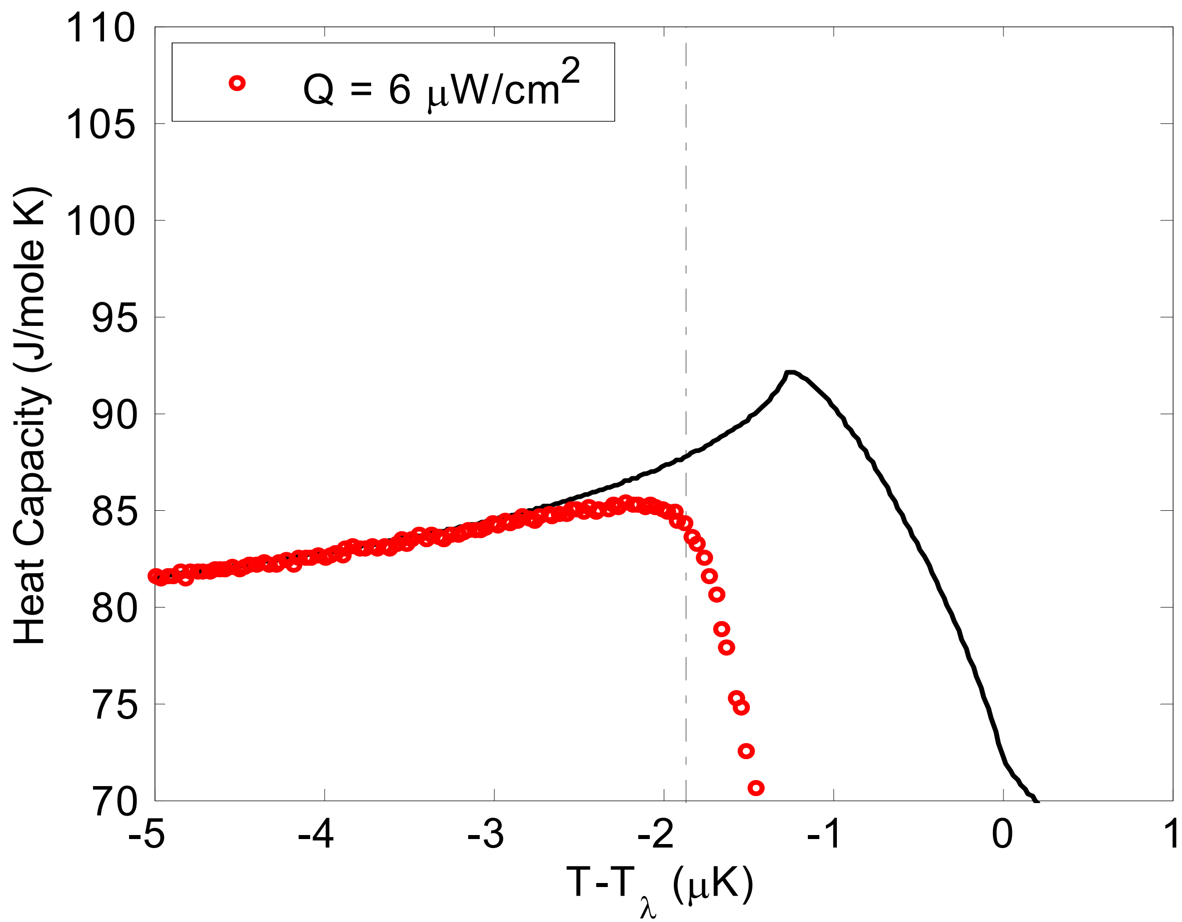
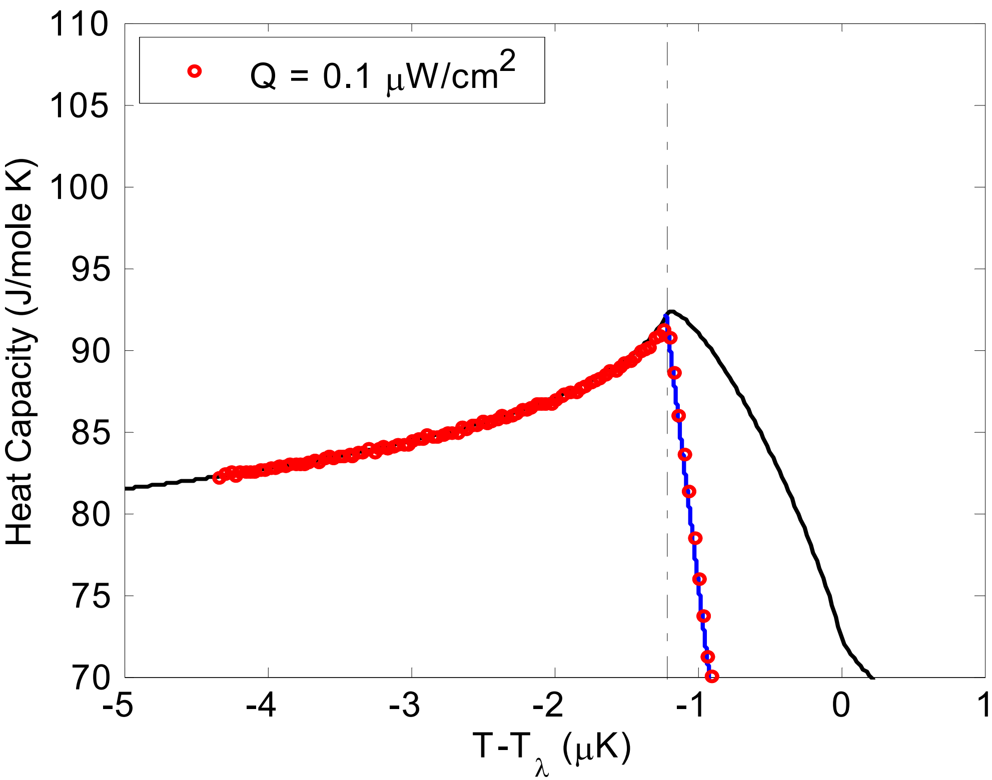
Results - 'Heat from Above'

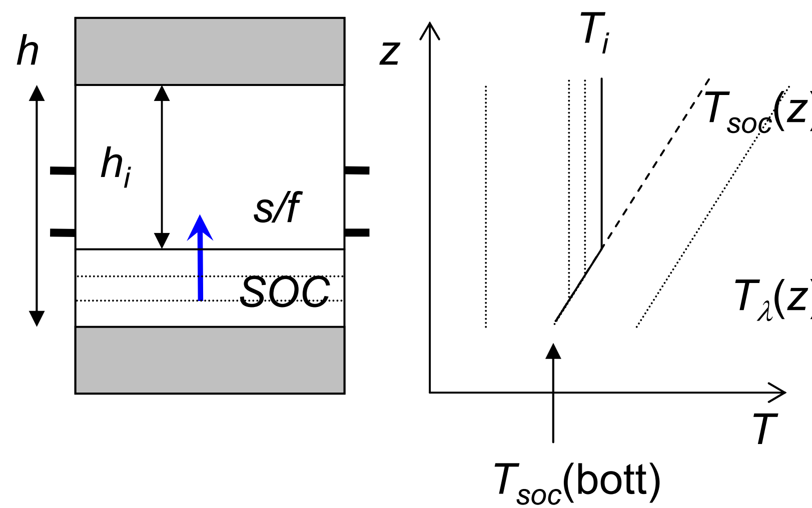


- Our measured $T_{soc}(Q)$ agrees with Moeur *et al.,* for $Q > 0.5\ \mu W/cm^2$:

$$t_{soc}(Q) = \left(\frac{Q}{Q_0}\right)^{0.813}, Q_0 = 745 \pm 39\ \mathrm{W/cm^2}, Q_0 = 638 \pm 178\ \mathrm{W/cm^2}_{\text{(Moeur } et\ al.\text{)}}$$

Explanation – the sharp depression

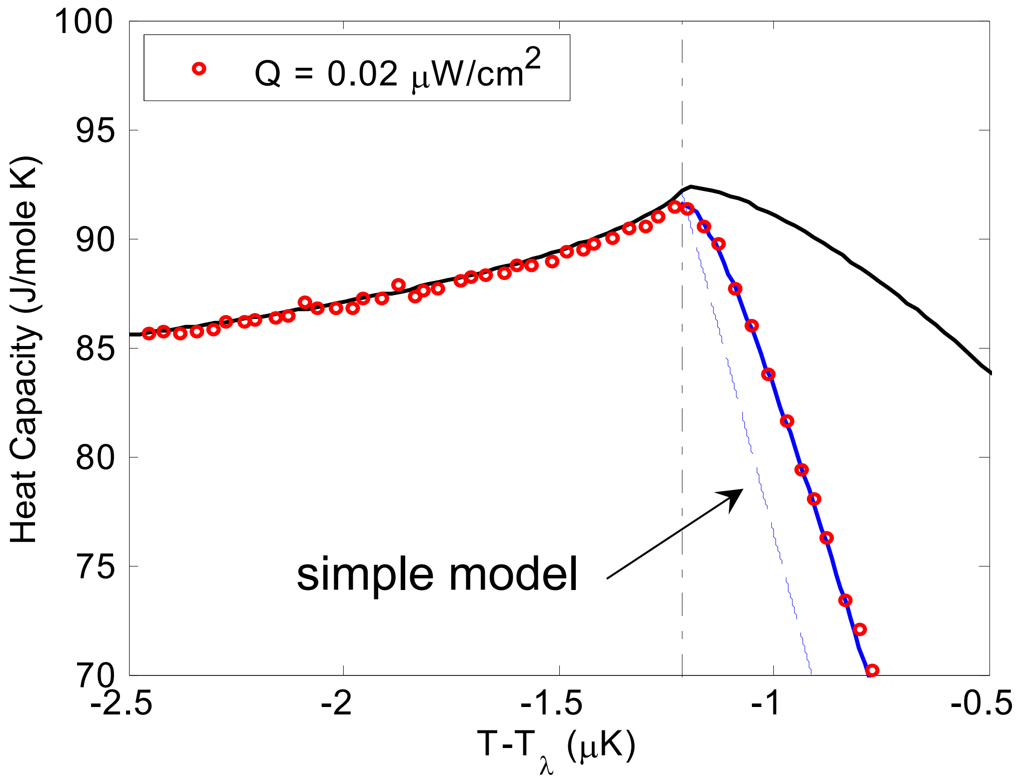


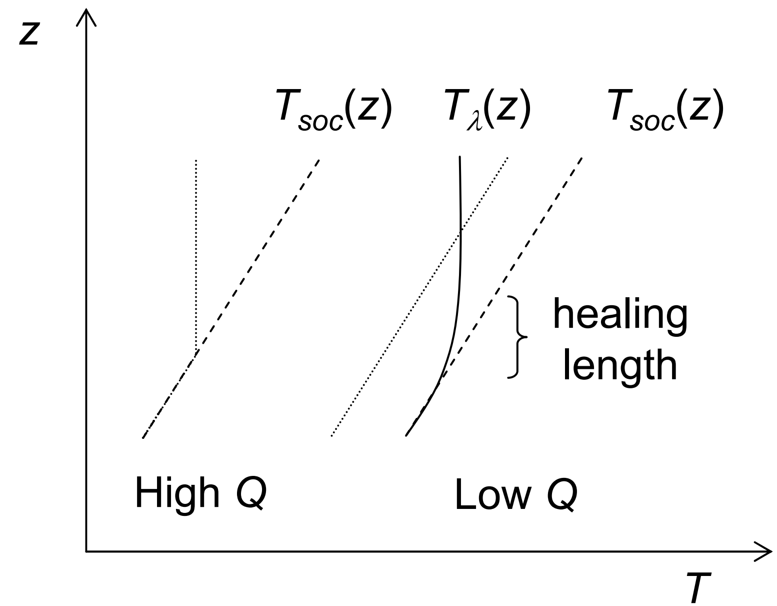


$$c_{\text{model}}\left(T_i\right) = c_{s/f}\left(T_i, h_i\right).\frac{V_i}{V}$$

- This is due to an advancing SOC/superfluid interface. We can model this:
  - Assume the sample's heat capacity is dominated by the shrinking superfluid phase, with zero heat capacity contribution from the SOC phase.
  - Reasonable assumption: t_{soc} is fixed because Q is fixed, therefore the SOC state does not absorb any of the heat pulse energy.
  - The model (blue line) works very well for Q = 1 to 0.1 μW/cm², however …

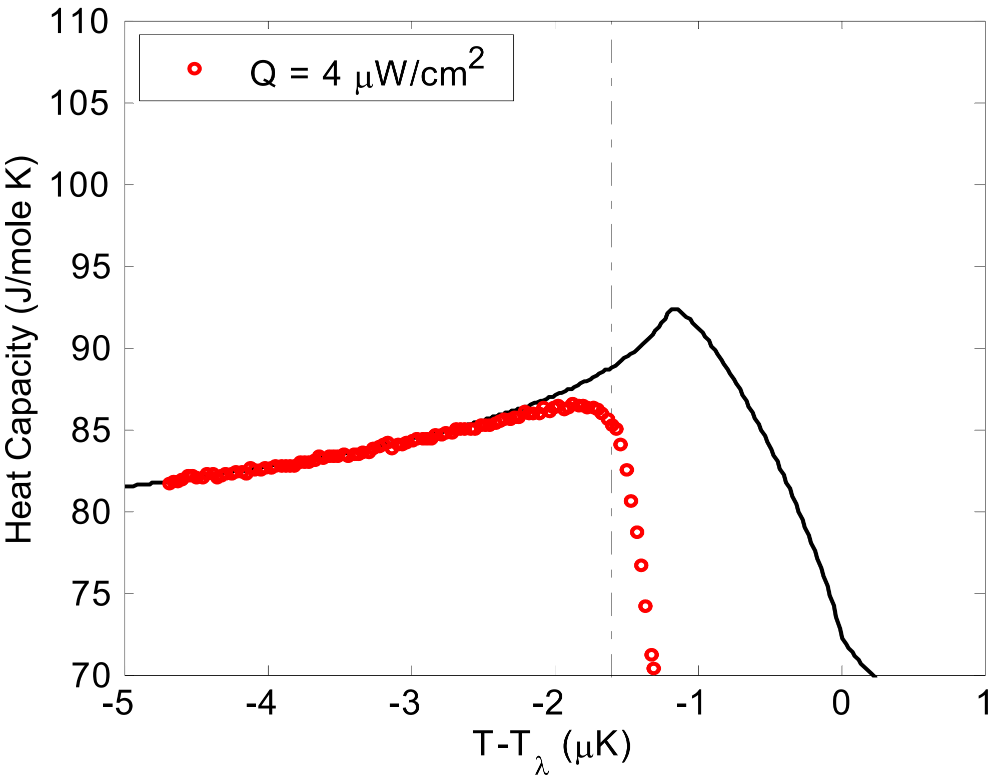
Simple model fails at low Q due to the 'healing length'

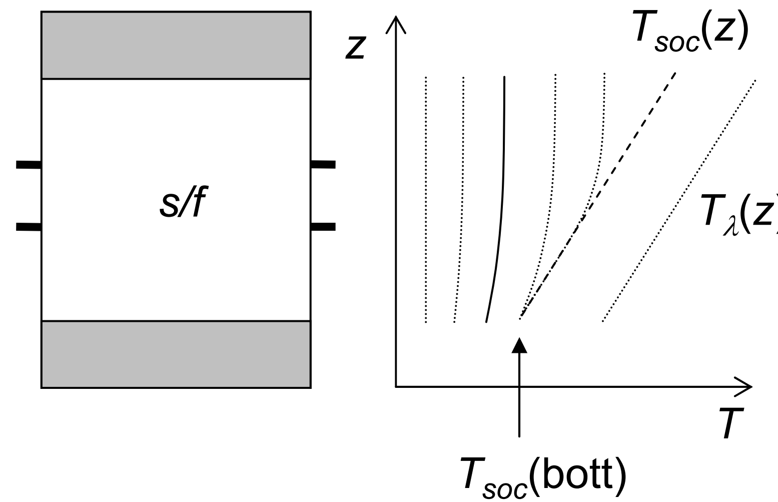




- For Q < 0.1 μW/cm² (T_{soc} > T_λ) develop a 'healing length' between SOC/normal-fluid, due to the finite κ. Also observed by Moeur *et al*.
- We can model this:
  - Integrate the heat flow equation: $\nabla T = -Q/\kappa\,(Q, t)$, using $\kappa(t) = \kappa_0\, t^{-x}$.
  - We generate a thermal profile → increment T → generate a new thermal profile → integrate total energy →49 compute heat capacity point → repeat …
  - Improved model = blue line. κ_0 the only adjustable parameter.

The *Q* dependant depression





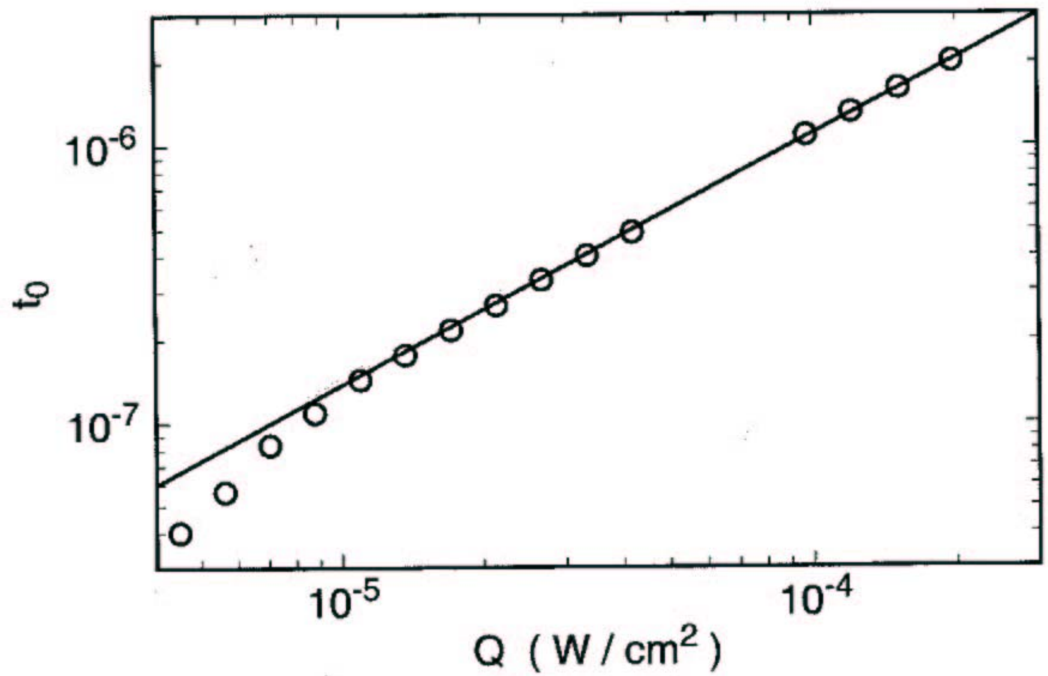
- Remember CQ is looking for an <u>*enhancement*</u> and we see a depression, why?
- Well, the depression occurs in the <u>superfluid</u> phase for $T < T_{soc}$(bott)
  - Maybe it's due to a large superfluid thermal resistivity causing a <u>thermal gradient</u> in the sample and a <u>reduced bulk heat capacity</u>?

Previous s/f thermal resistivity measurements

- Baddar *et al*., *J. Low Temp. Phys*., **119**, 1 (2000)
  - 'Heat from Below' experiment. For $Q \geq 10\ \mu\text{W/cm}^2$, they observed a power law behaviour:

$$R = \left(\frac{t}{t_0}\right)^{-2.8} \text{ K cm/W}$$

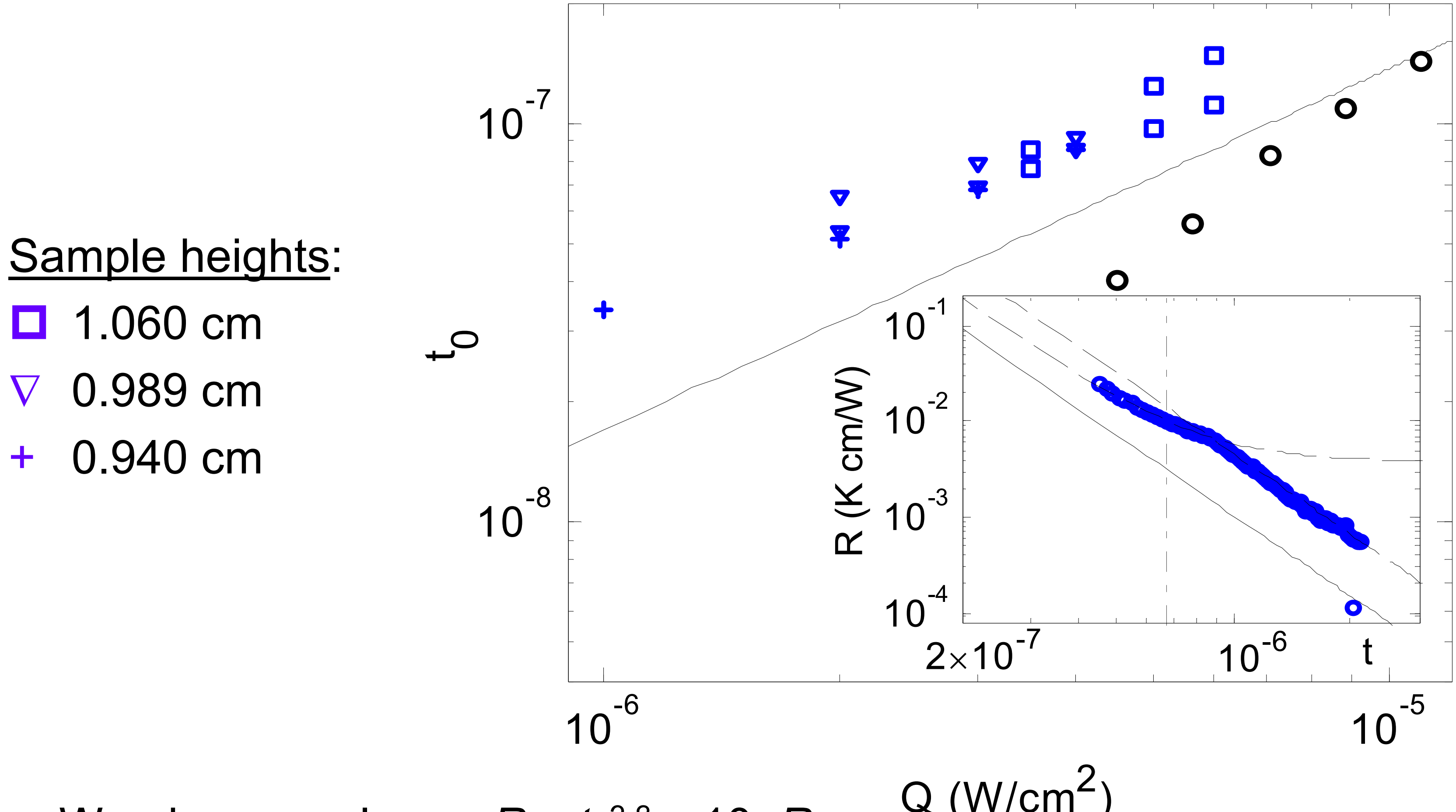
$$t_o = \left(\frac{Q}{393\ \text{W/cm}^2}\right)^{0.904}$$



- However, these previous measurements proved to be too small to explain our observed depression.
- We made our own measurements, using the sidewall thermometers.

s/f thermal resistivity measurements

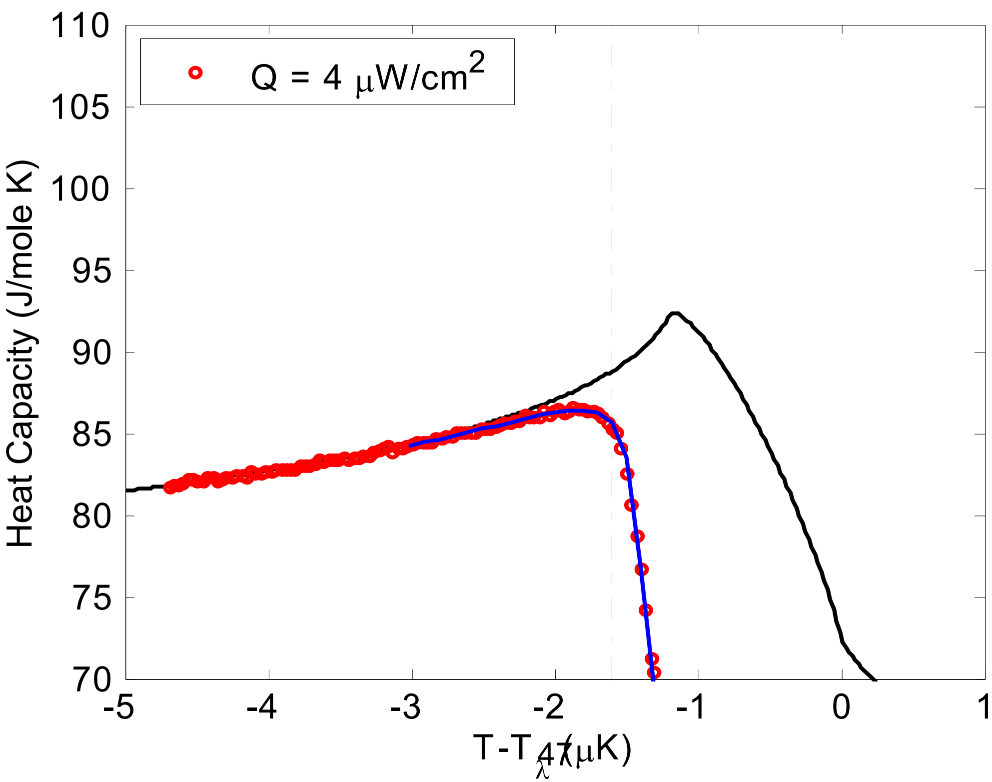
- We fit our data to $R = (t/t_0)^{-2.8}$ and extracted t_0 at each value of Q.



- We observe a larger $R \sim t_0^{2.8} \approx 10 \times R_{Baddar}$
- In addition, our high Q data show a clear change in thermal resistivity (insert: data at Q = 6 μW/cm^2), giving two values of t_0 at each value of Q.

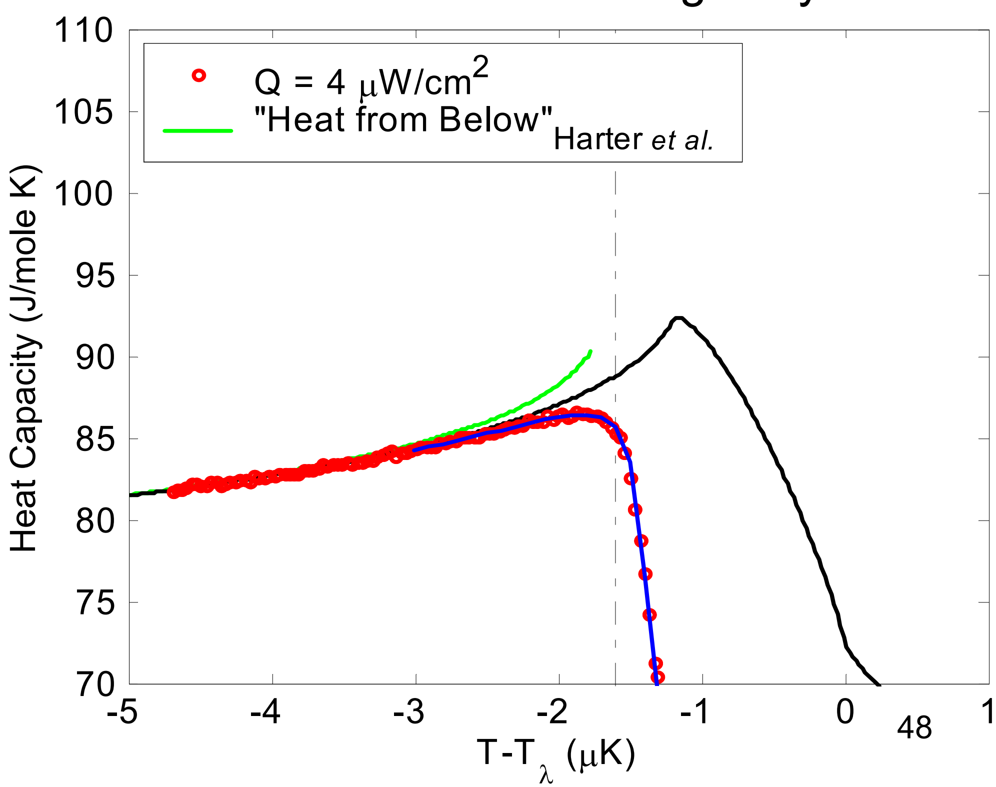
Explanation – the Q dependant depression

- So the depression is due to an anomalously large superfluid thermal resistivity. Again, we can model this:
  - As before we integrate the heat flow equation, $\nabla T = -Q/\kappa\,(Q, t)$, using our <u>measured</u> $\kappa\,(Q, t)$.
  - The model works very well for all of our data (blue line).



Interesting implication

- In our model, when we integrate the total energy, we use the $c_{Q=0}$ (black line) and <u>not</u> the enhanced c_{Q_Harter} (green line) - Harter *et al*., *PRL,* **84**, 2195 (2000).
  - This <u>implies</u> that in ‘Heat from Above’ experiments there is no, or very little, heat capacity enhancement.
  - It does not rule out c_{Q_theory} that may still be there, but which would be too small to resolve due to gravity rounding.



$$c_{\text{model}} = \frac{\text{Total Energy}}{n.\Delta T}$$

$$c_{\text{model}} = \frac{1}{n.\Delta T}.\sum_{i}^{N} n_i.\Delta T_i.c_{Q=0}(T_i)$$

Conclusions

We have made the first measurements of the heat capacity of liquid ^{4}He in a 'Heat from Above' configuration:

- We can explain all the features of our data.
- Our measurements provide independent confirmation of the existence of the Self Organized Critical state.
- We are in agreement with Mouer *et al.*, *PRL*, **78**, 2421 (1997).
  - We measure the same $t_{soc}(Q)$ dependence,
  - and observe 'healing length' effects at low Q values.

Conclusions

Our ‘Heat from Above’ measurements differ with those made in ‘Heat from Below’ as follows:

1. Our modelling implies no large heat capacity enhancement
   - Harter *et al*., *PRL,* **84**, 2195 (2000).
2. We observe a large superfluid thermal resistivity
   - 10x larger than Baddar *et al*., *J. Low Temp. Phys*., **119**, 1 (2000).
3. We observe a sharp kink/change in *R*, seen clearly in our deeper samples and at large *Q* values.

This leads to the question:

- Why do such seemingly similar experimental configurations produce such different behaviour …. ?