The measurement

$$C = \frac{\Delta Q}{\Delta T}$$

How to measure Cp ?

- Principle : apply P, read T and time
- adiabatic : isolated sample and pt by pt $C = \dfrac{\Delta Q}{\Delta T}$
  quasi-adiabatic, continuous heating $P = C\, dT/dt$
- relaxation : heat pulse, thermal link to T bath
  large relaxation, dual slope, ...
- modulation : alternative heating at ω $T_{ac} = \dfrac{P}{K + jC\omega}$

very demanding T measurements !!

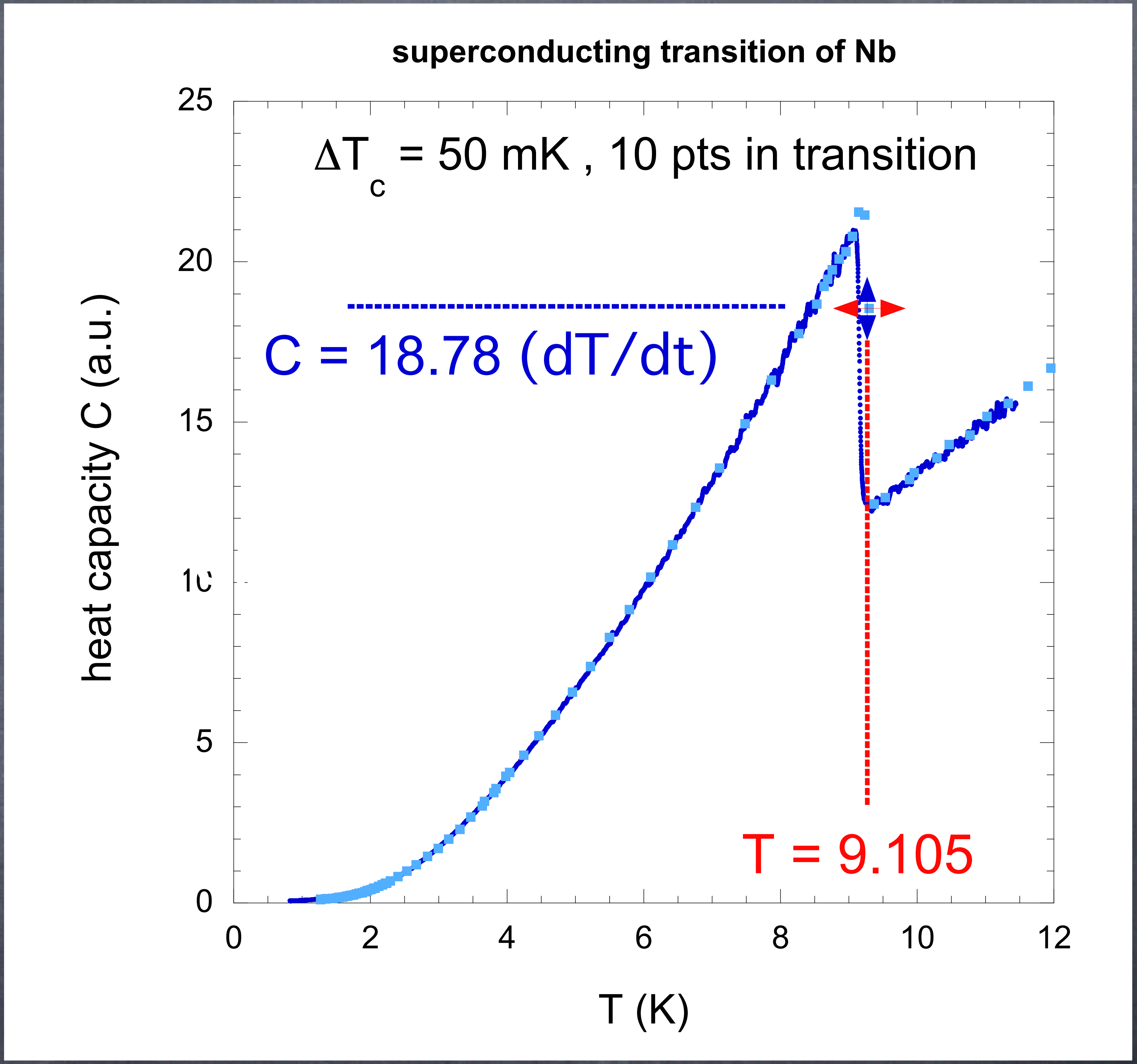
DC/C ~ 10^{-3}

T = 9.104785

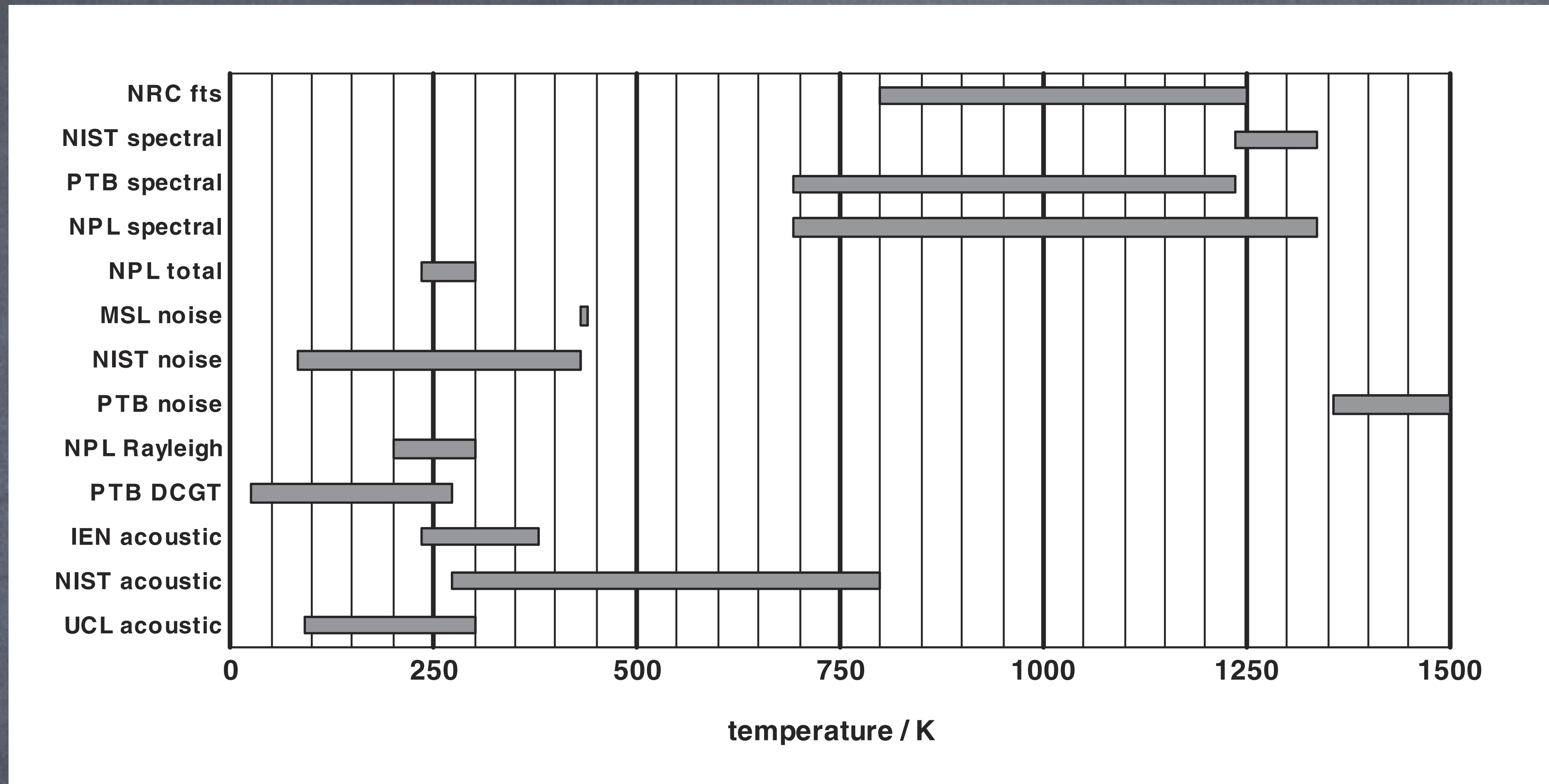
DT/T ~ 10^{-3}

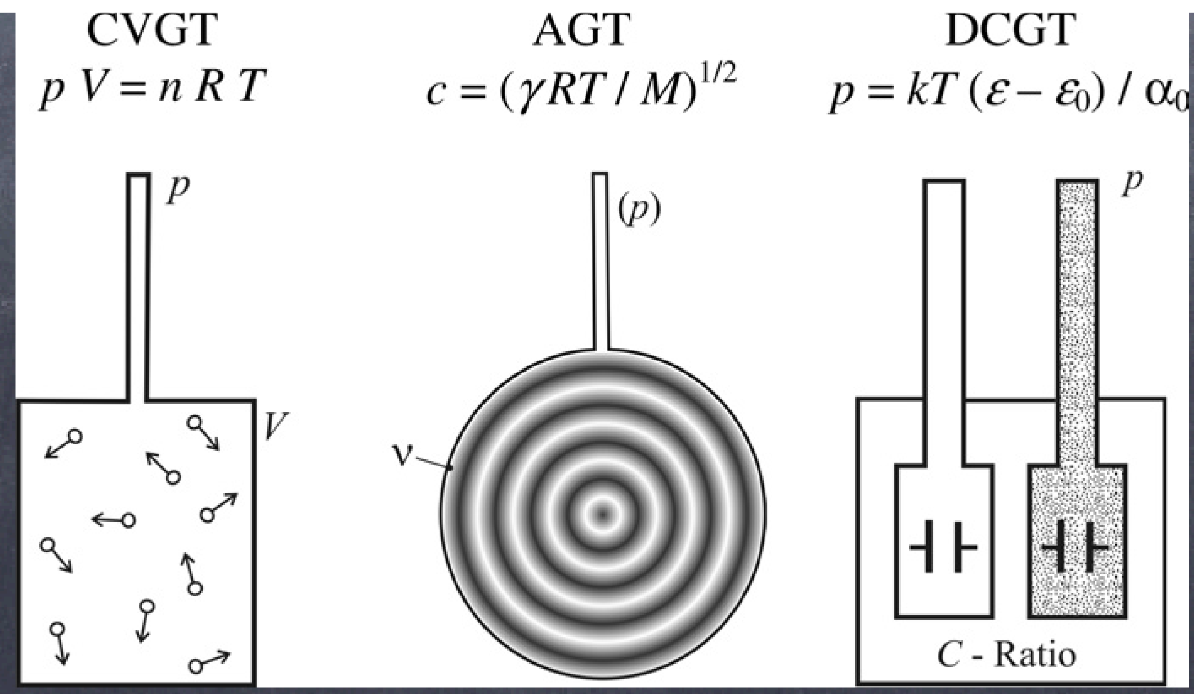
and TIME

calibrations of thermometers is a nightmare !!
and fitting procedure



Thermodynamic thermometers

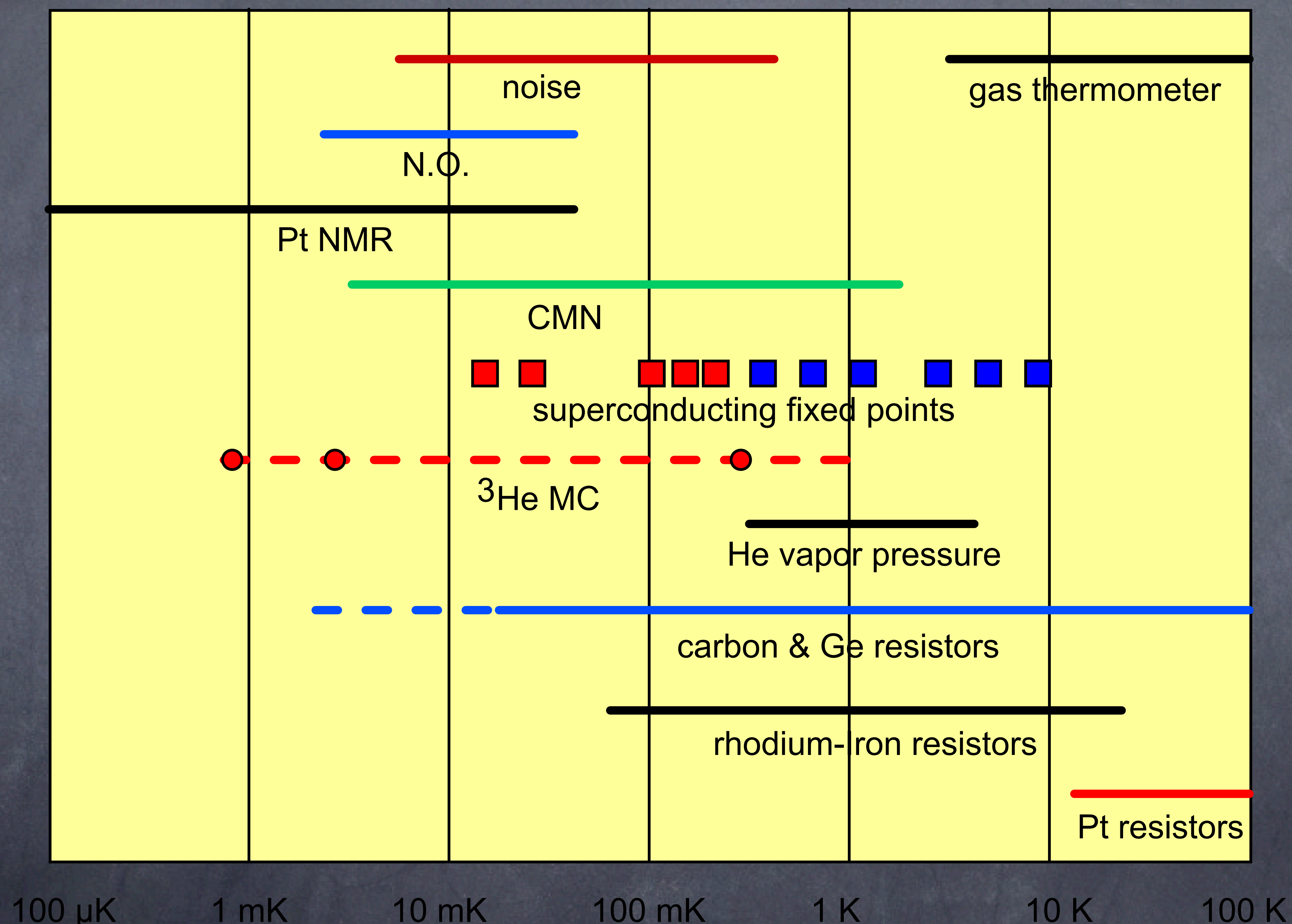




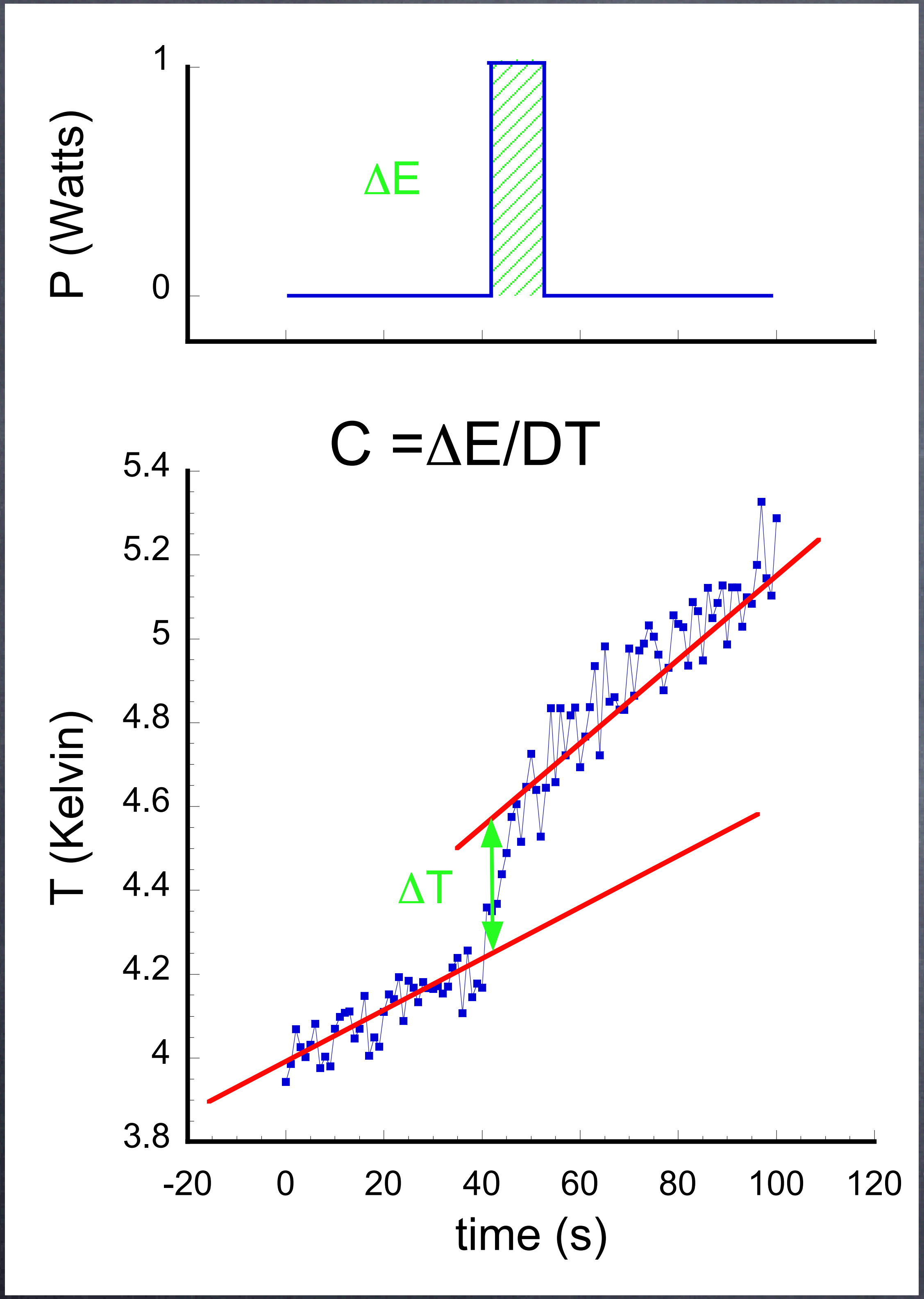
Thermometers

- What is a good thermometer ?
- primary / secondary
- accuracy
- resolution/sensitivity
- reproducibility
- easy to use
- time response

Thermometers actually used in low temperature laboratory



ADIABATIC



heat pulse and isolated sample

- Excellent precision and accuracy

λ transition in space shuttle

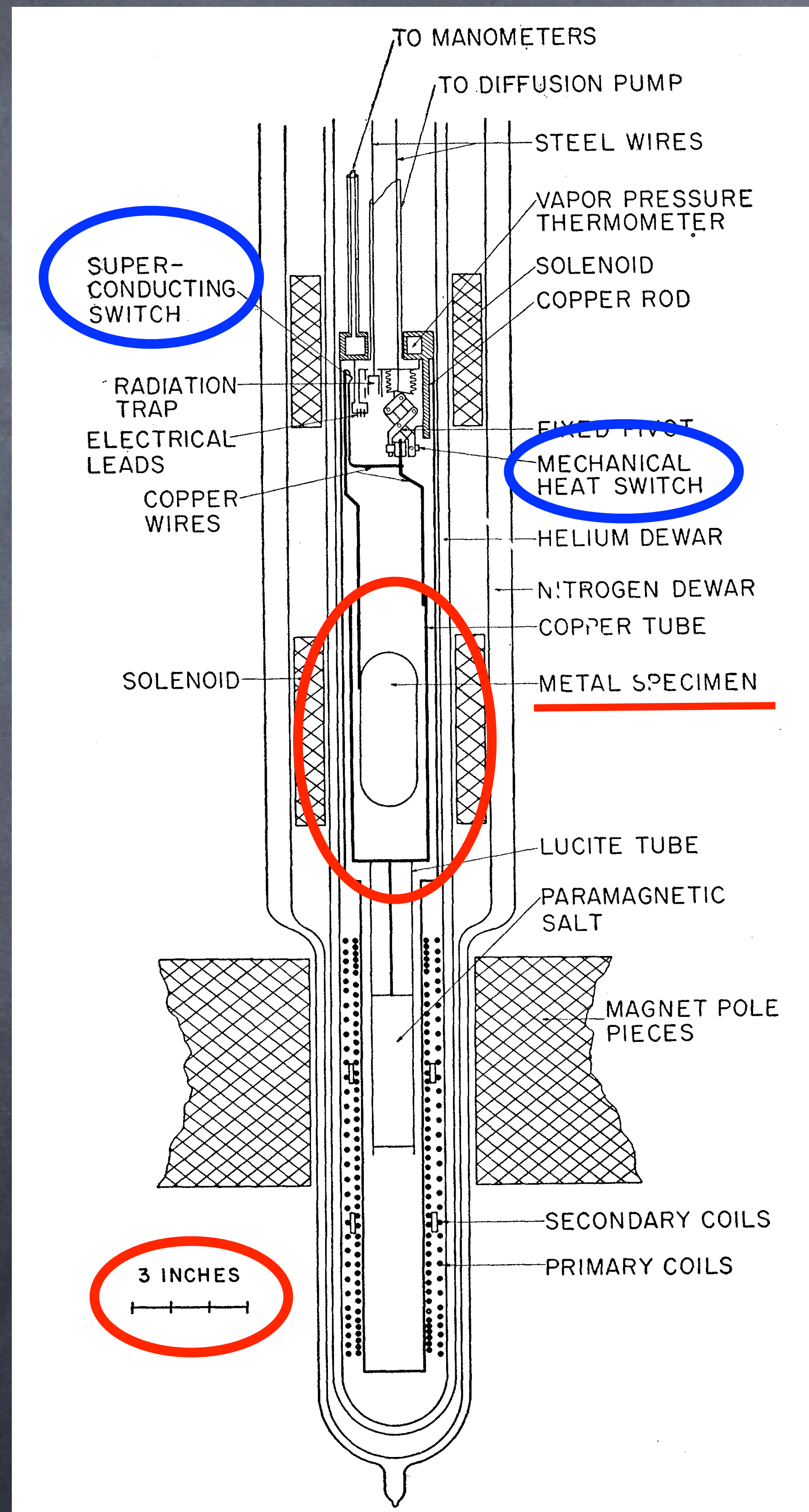
but

- method point by point (tenuous)
- how to cool the sample ?
- limited to large samples (parasitic non-adiabaticity)

Apparatus used for calorimetric measurements in the adiabatic demagnetization range

Prof. N.E.Phillips
University of California
BERKELEY

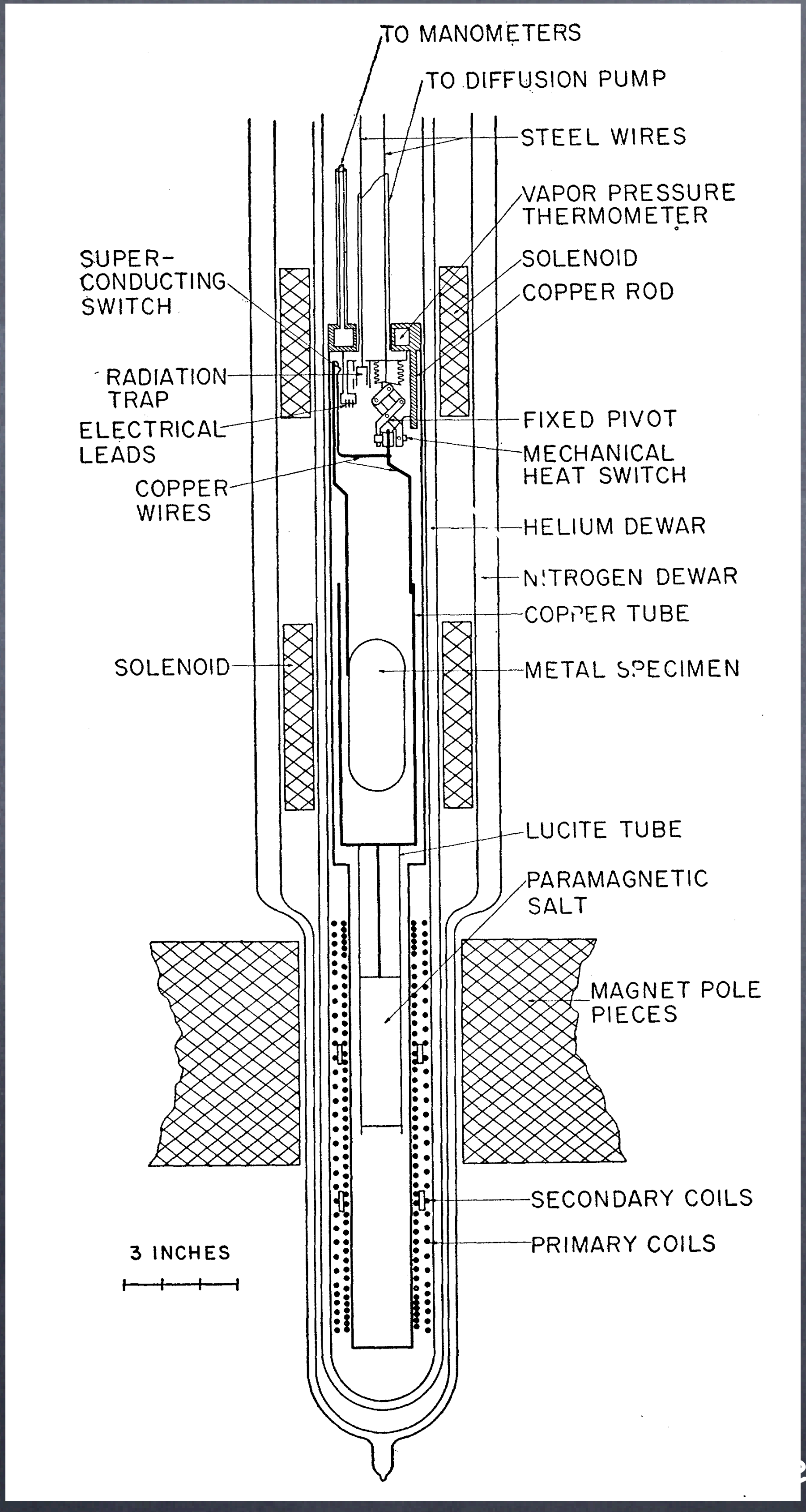
Superconducting switch



Mechanical heat switch

Sample

Apparatus used for calorimetric measurements in the adiabatic demagnetization range



Prof. N.E.Phillips
University of California
BERKELEY

100mK-40K

accuracy a few %

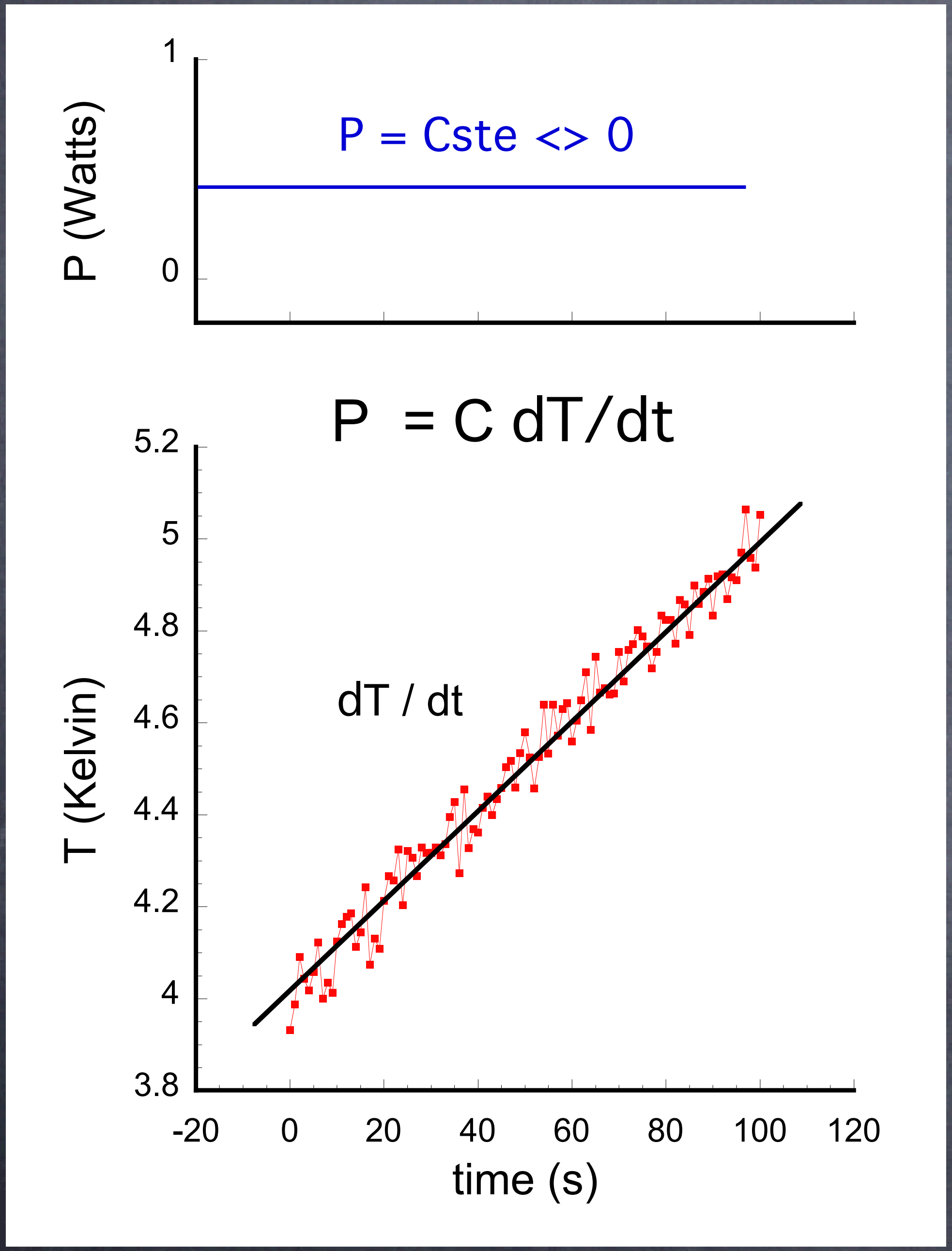
$\Delta C/C$ a few 10^{-3}

100mg-1g Heavy Fermion

QUASI-ADIABATIC

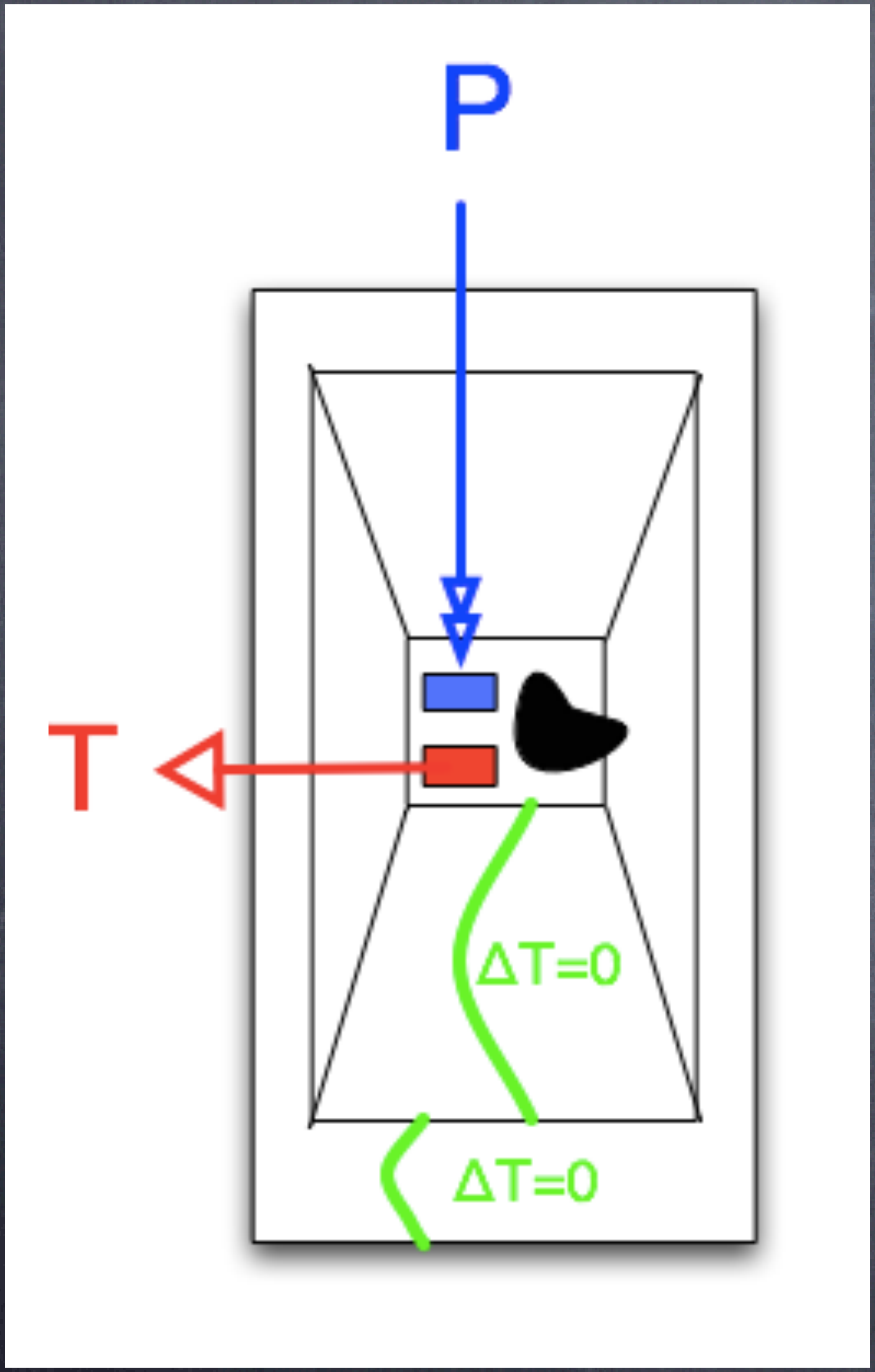
Prof. A. Junod
University of Geneva

~~heat pulse~~ continuous heating and still isolated sample



QUASI-ADIABATIC

Prof. A. Junod
University of Geneva



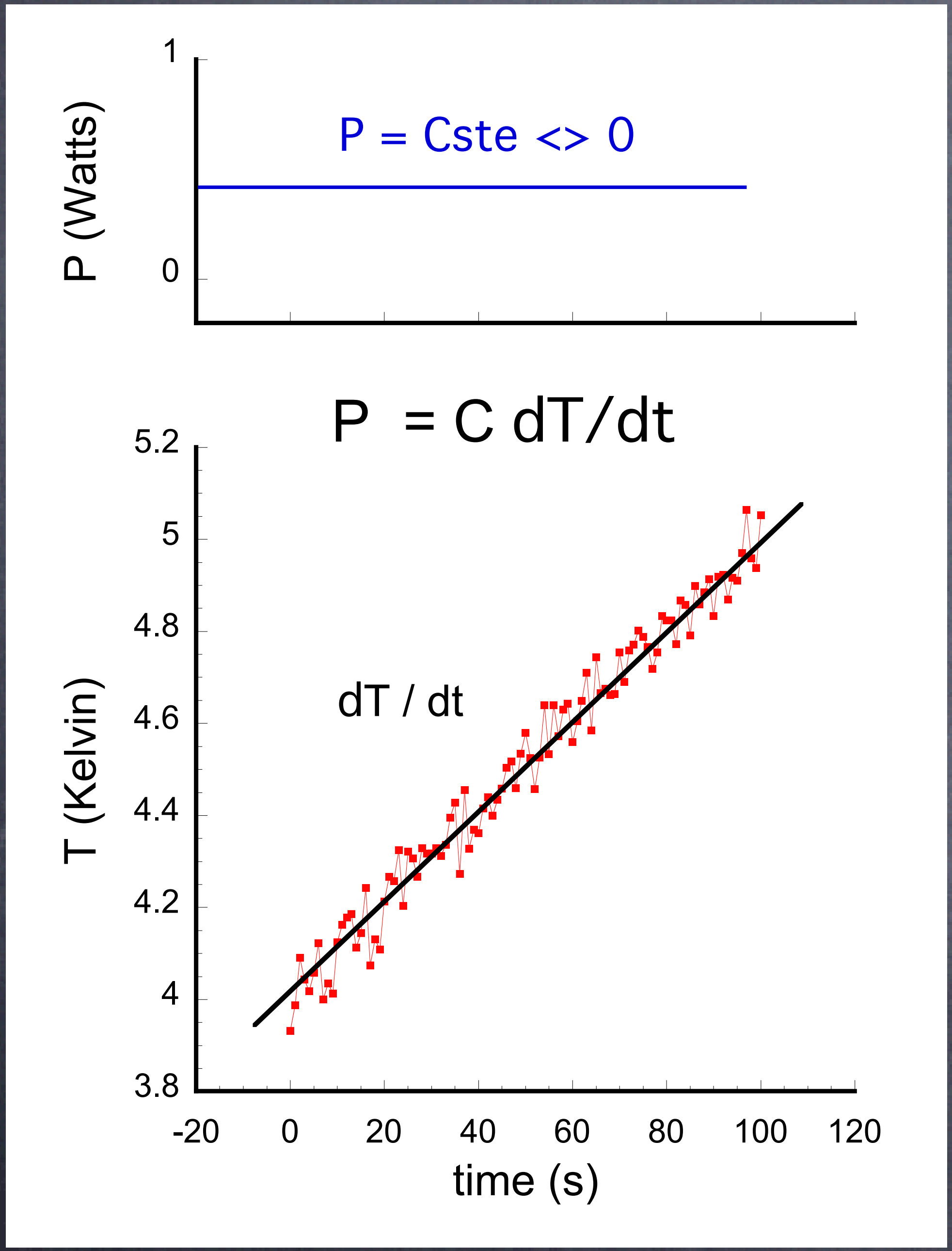
~~heat pulse~~ continuous heating and still isolated sample

Double radiation shields
but still
$P_{parasitic}$ a few 10^{-7}W
with
ΔT measured via
Cr-Cn thermocouples
and nanovoltmeter

QUASI-ADIABATIC

Prof. A. Junod
University of Geneva

~~heat pulse~~ continuous heating and still isolated sample



10K-300K

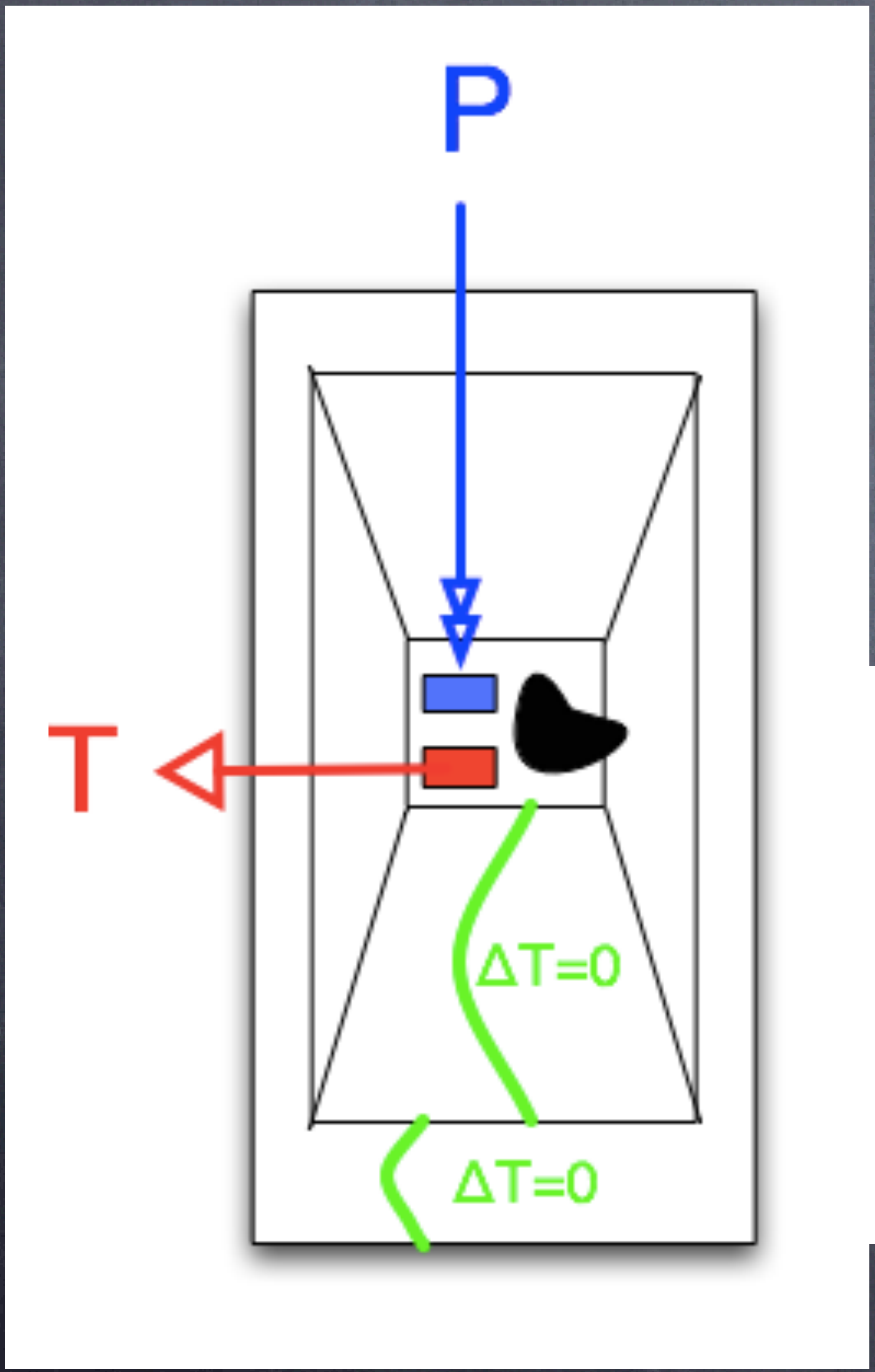
accuracy 1-5 %

$\Delta C/C$ a few 10^{-3}

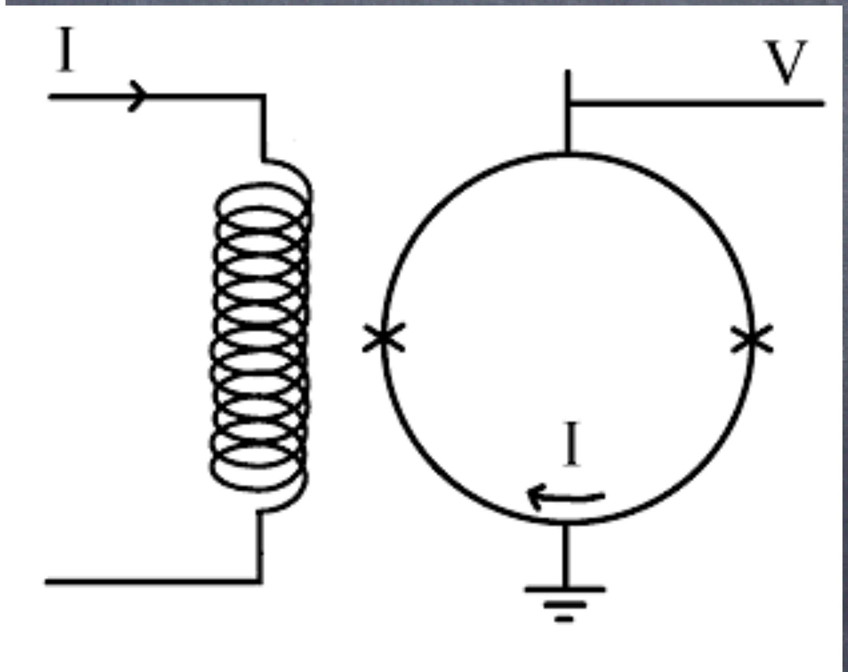
10mg-100g HTSC

QUASI-ADIABATIC in dilution range

R. Calemczuk
CEA-grenoble



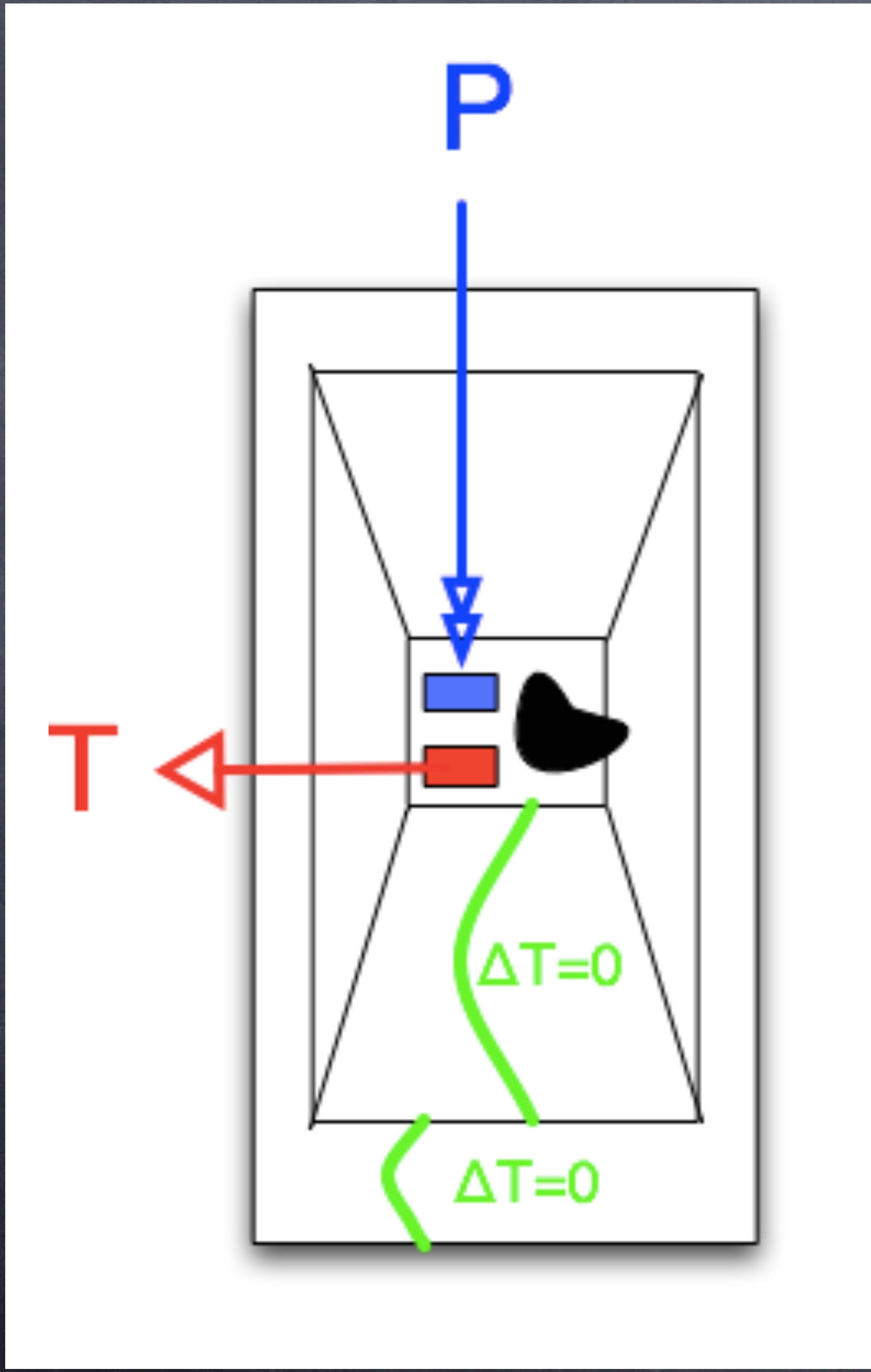
ΔT measured via
Au:Fe thermocouples
and SQUID !!



SQUID + Chopper = 1-2 $pA/(Hz)^{1/2}$

QUASI-ADIABATIC in dilution range

R. Calemczuk
CEA-grenoble

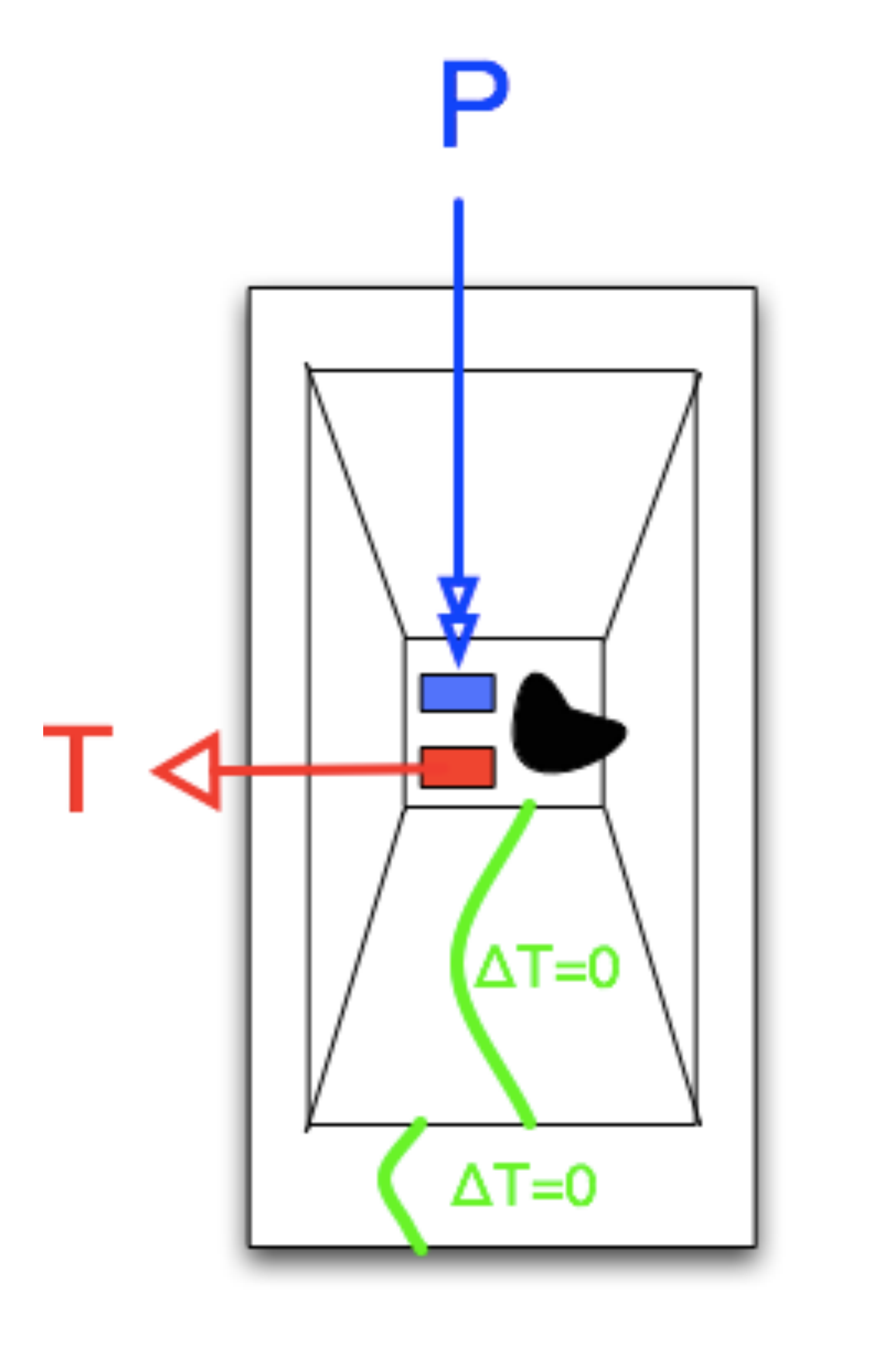


at 100 mK

$$\sqrt{V^2} = \sqrt{4k_B T R} = 0.5 \text{ pV}/\sqrt{Hz}$$
$$\sqrt{I^2} = \sqrt{4k_B T/R} = 10 \text{ pA}/\sqrt{Hz}$$
$$\sqrt{\Delta T^2} = 2 \ \mu\text{K}/\sqrt{Hz}$$
$$\text{P}_{parasitic} = \frac{L}{S/T}\sqrt{I^2} = 10^{\ -13} \text{ W}$$

QUASI-ADIABATIC in dilution range

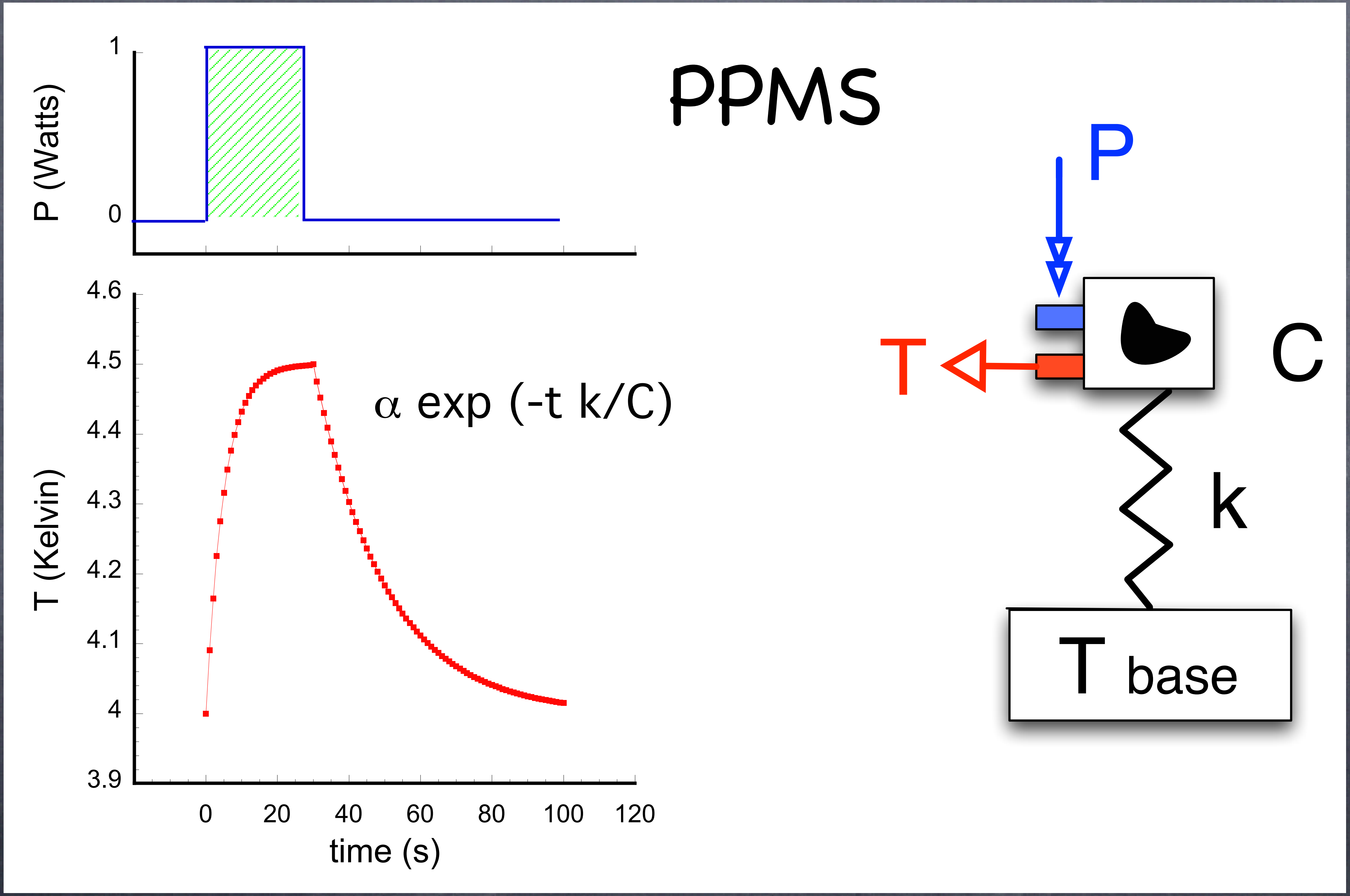
R. Calemczuk
CEA-grenoble



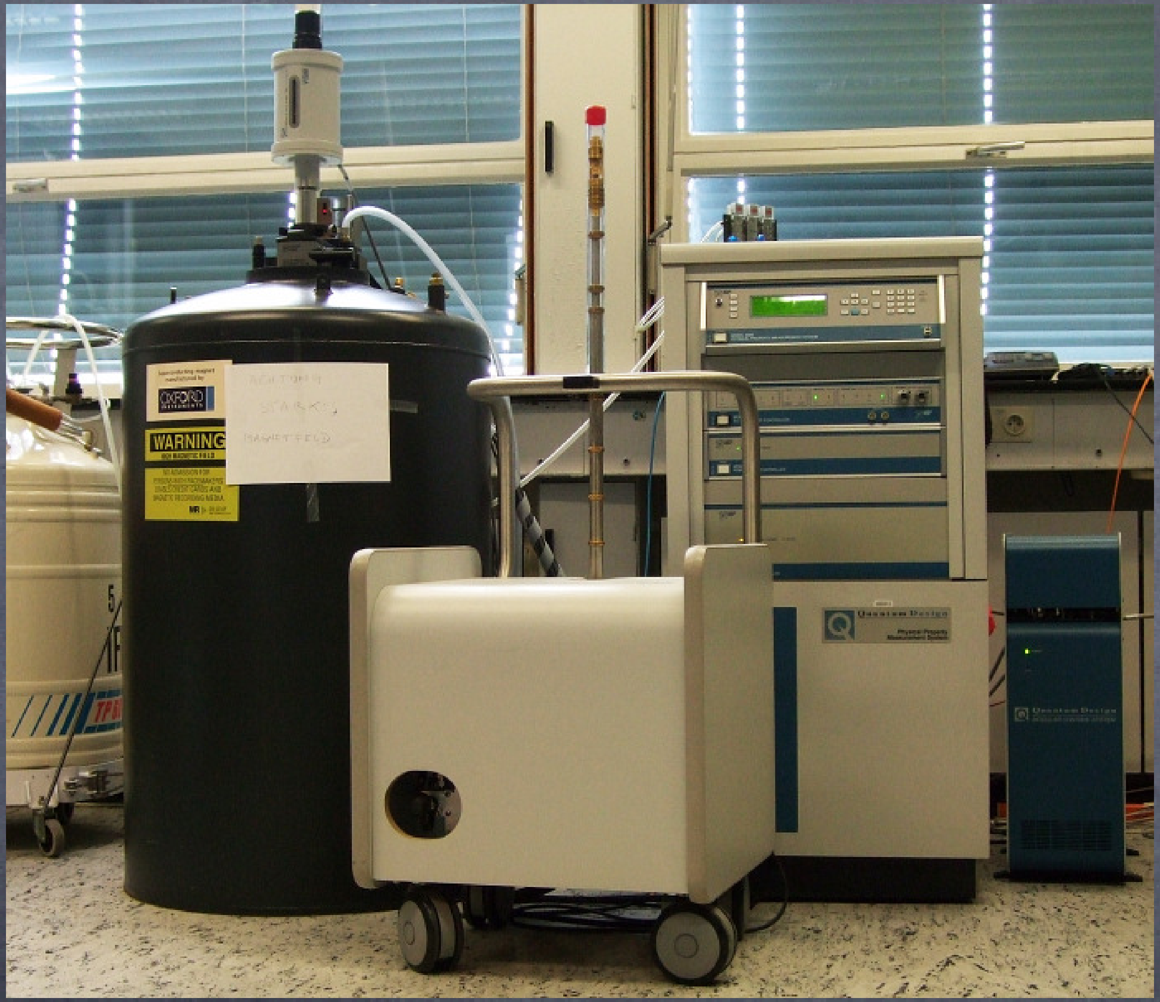
1-10% of 10mg Cu
BUT !!
no calibration of S
(null detector)
$\Delta T = 0$
therefore thermometer
in compensated area

RELAXATIONS Methods

heat pulse or steplike, heat link to thermal bath at T_b

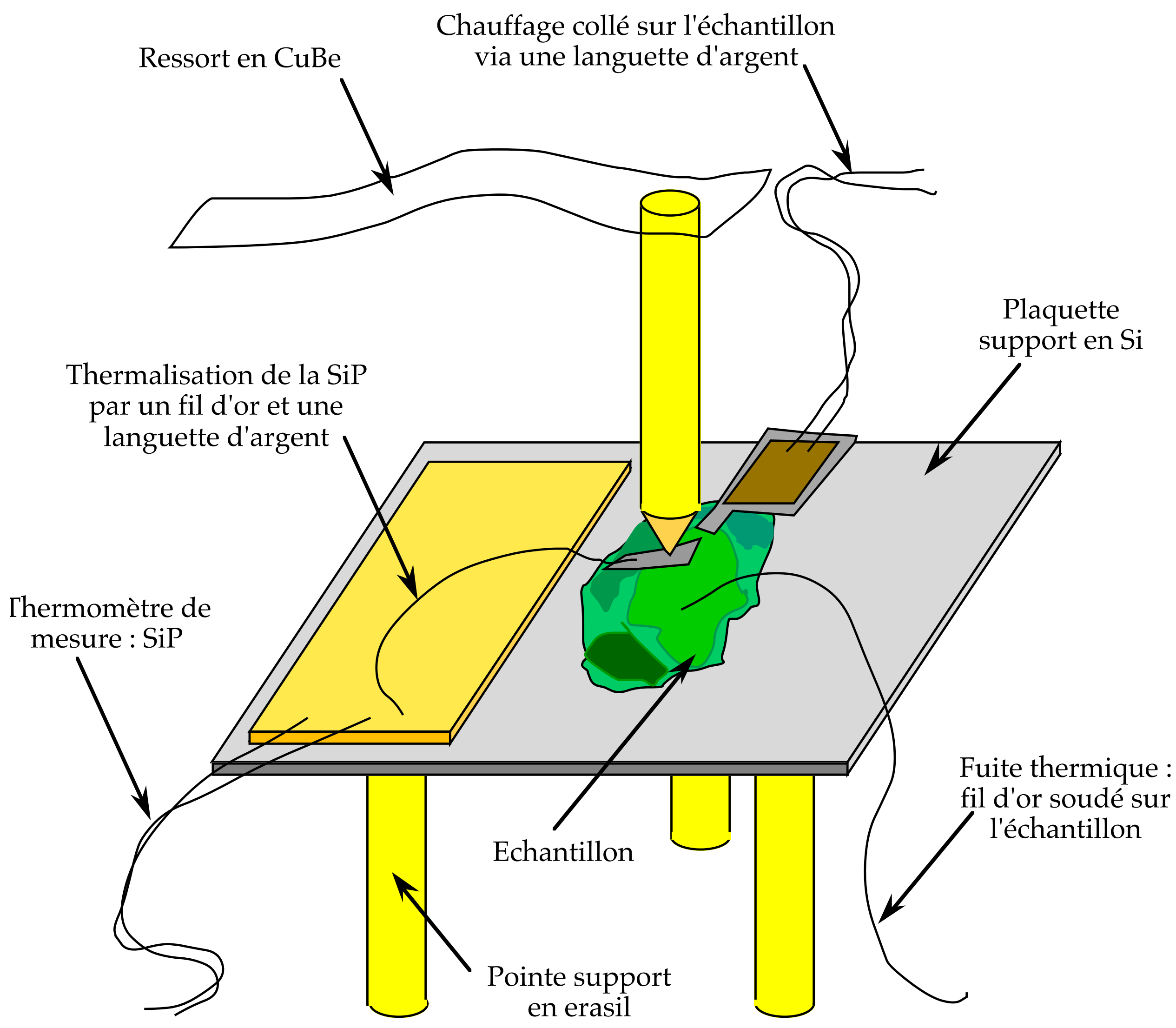


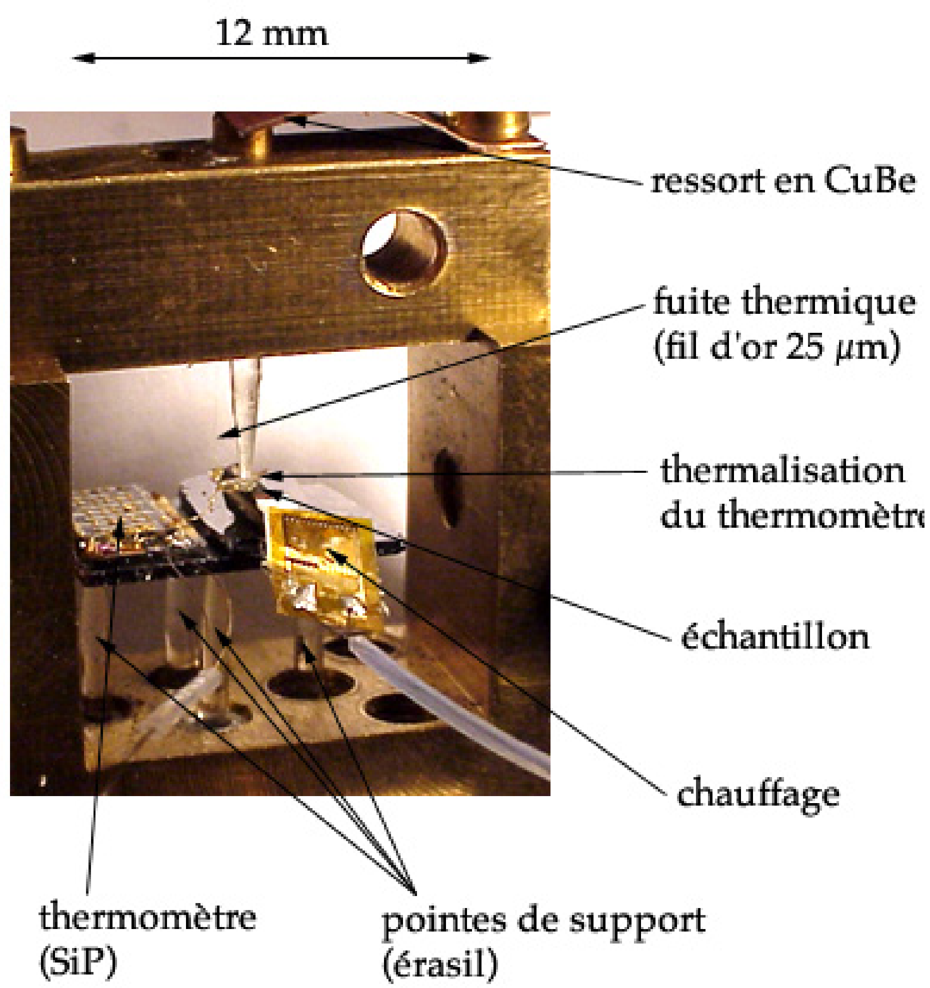
PPMS Quantum Design : ^{4}He and ^{3}He



Set-up at ultra-low T (10mk-1K)

J.P. Brison
CEA-grenoble



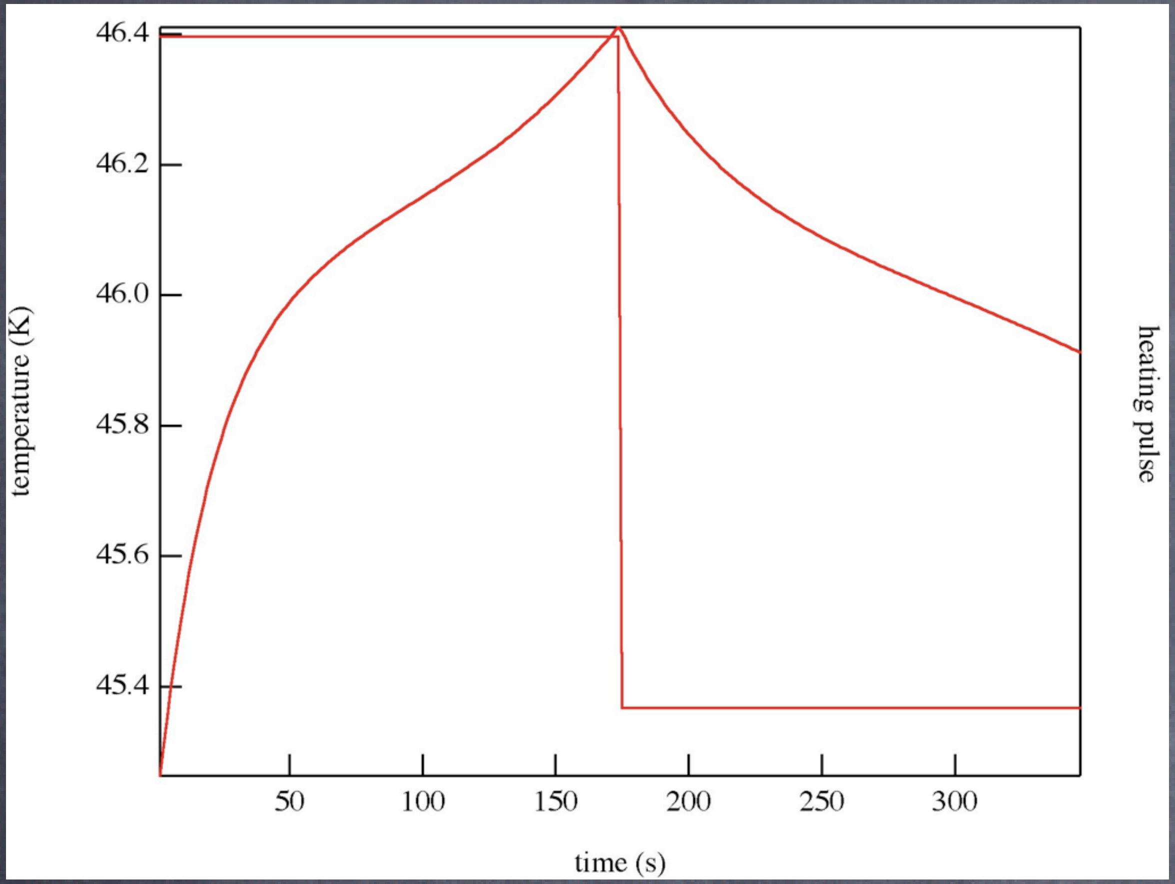


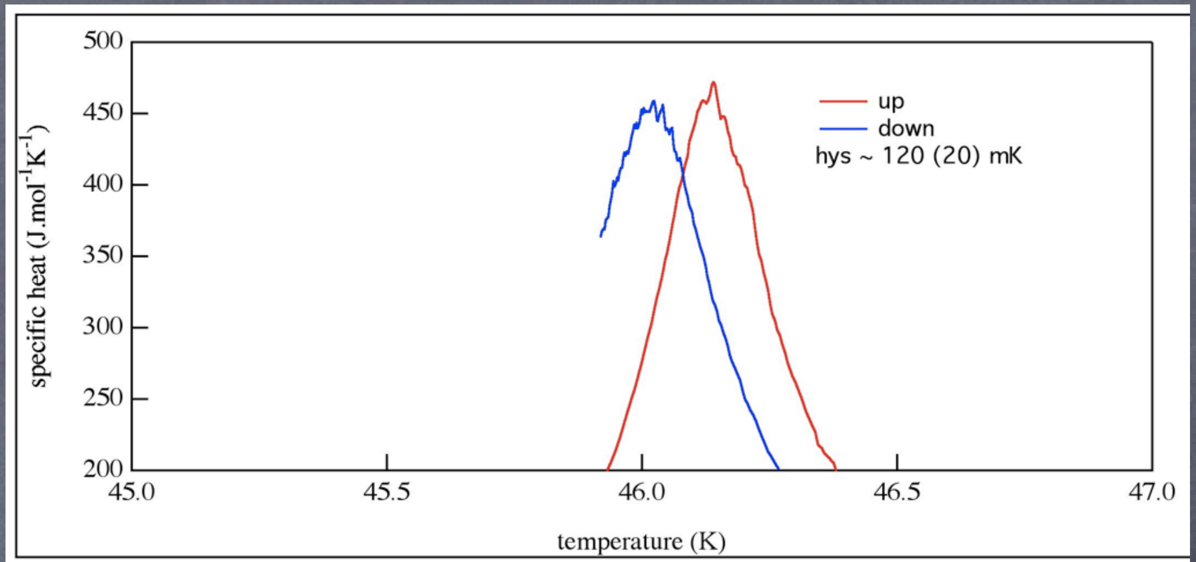
(Dis)Advantages,

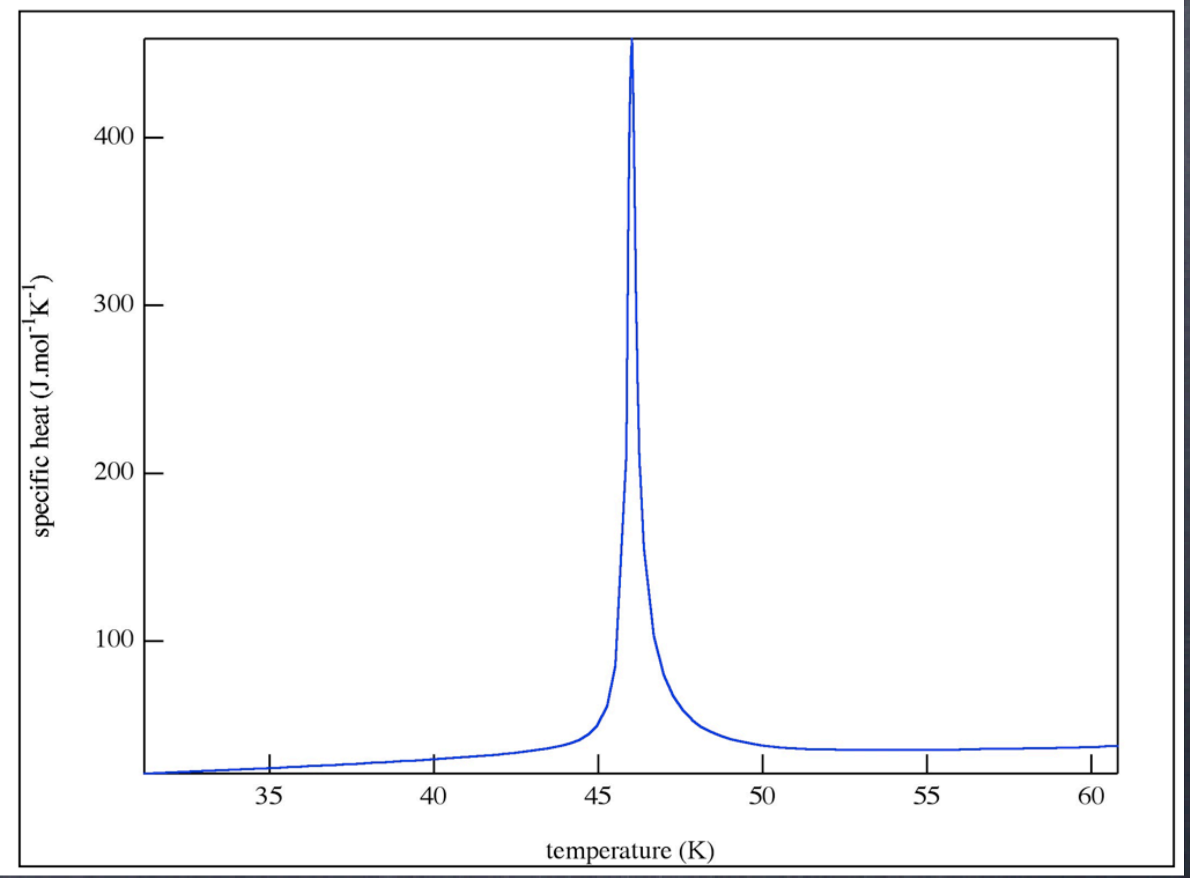
- popular, reliable, and widely used at low T
- extended down to below 10mK (J.P. Brison)
- good accuracy (5%), but not excellent resolution
- mass down to a fraction of a mg
- relaxation time >= 1s
- Cp can vary by orders of magnitude between the interesting T-range, <u>so does relaxation time</u>
- Point by point, long and tenuous, 1pt at 100K=20mns

$AuCrS_2$: antiferromagnetic + structural

Courtesy:
F. levy
CNRS-grenoble





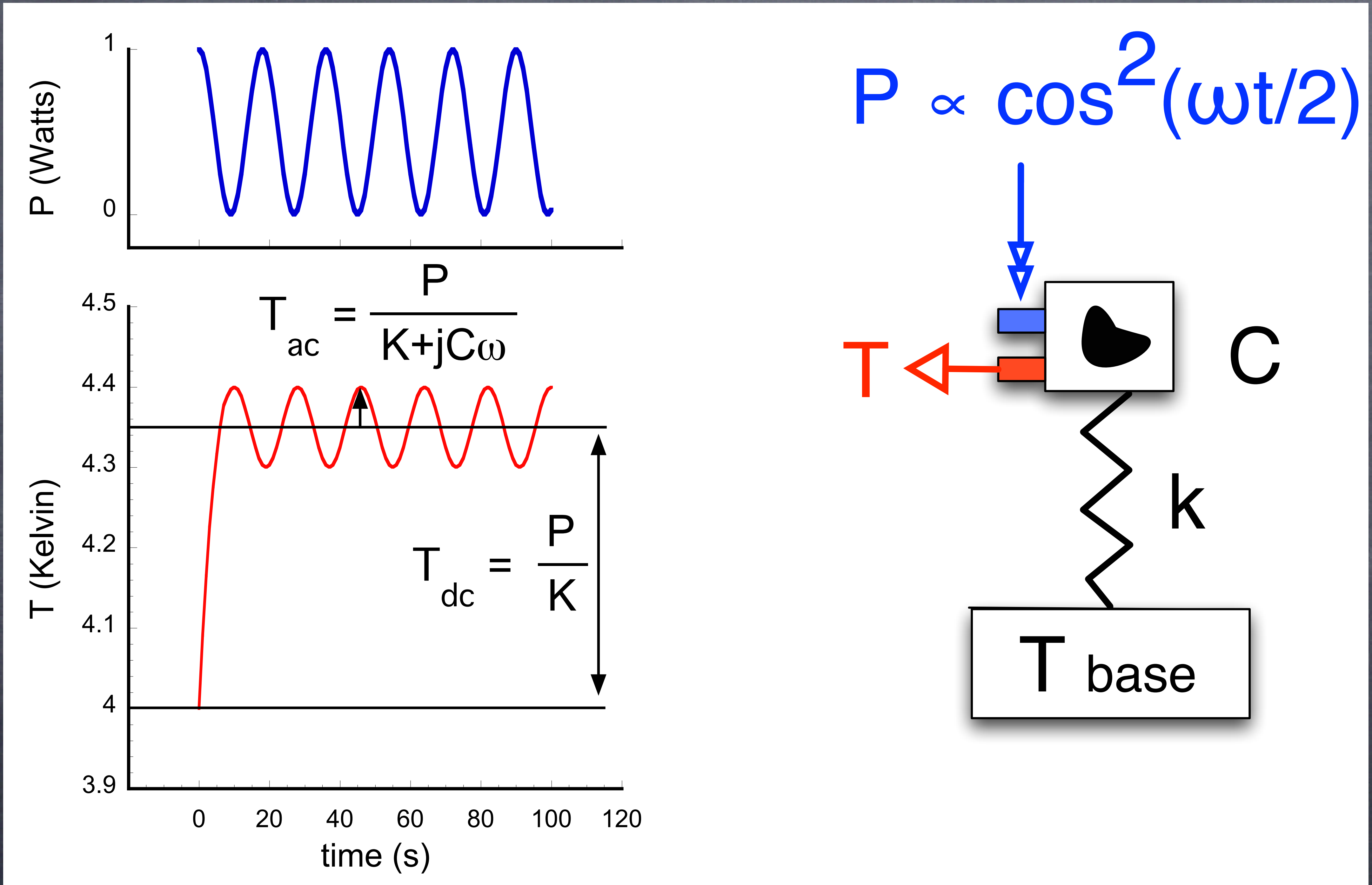


Options

- define internal and external time constants
- choose duration time vs τ_{int} and τ_{ext}
- fitting procedure : introduce constrains
- Large relaxations and local dT/dt (A. Demuer) faster, larger current,...
- Dual Slope method (dynamic, no calibration of κ)

Modulation (alternative)

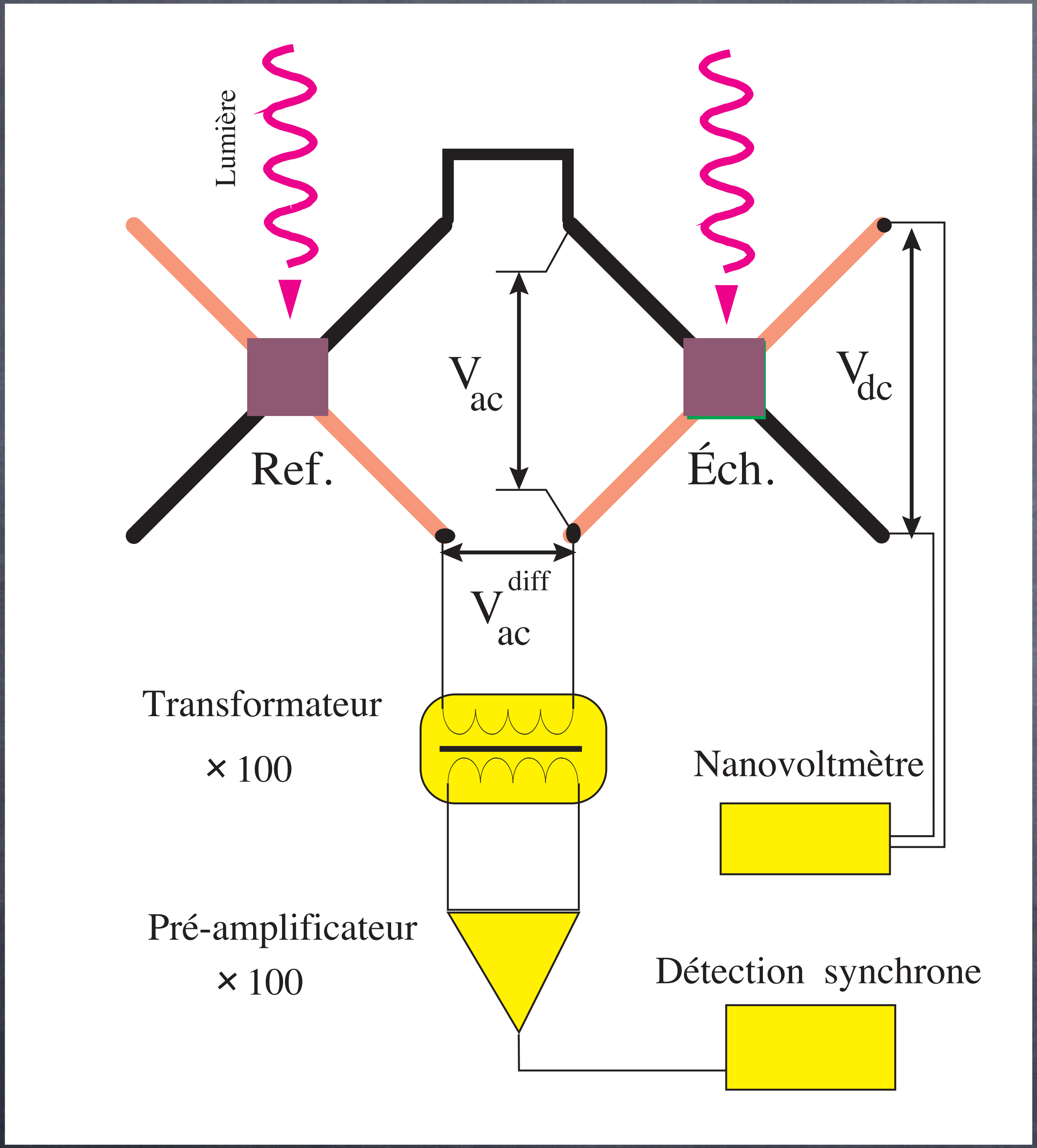
ac-power



Characteristics

- lock-in detection, filters, noise rejection (true for all modulation technics)
- excellent resolution (typical 10^{-4}), lesser accuracy but ΔC = a few 10^{-12} J/K
- 100 nanogram < m < a few milligram
- continuous: during H and/or T sweeps
- easy to extend a differential configuration
- extrem conditions: 45T-DC, pulsed 60T, 15Gpa, 10kHz

Schematic



- transformer at room T: a few 0.1 mK/(Hz)$^{1/2}$
- transformer at 4K: a few 10 μK/(Hz)$^{1/2}$
- Squid detection: a few 0.1 μK/(Hz)$^{1/2}$