Bolometry using high sensitivity NTD germanium thermometers

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[*http://woodcraft.lowtemp.org/*](http://woodcraft.lowtemp.org/)

Talk given at the "Low Temperature Thermometry" meeting, Oxford, 24th November 2005, organised by the National Physical Laboratory

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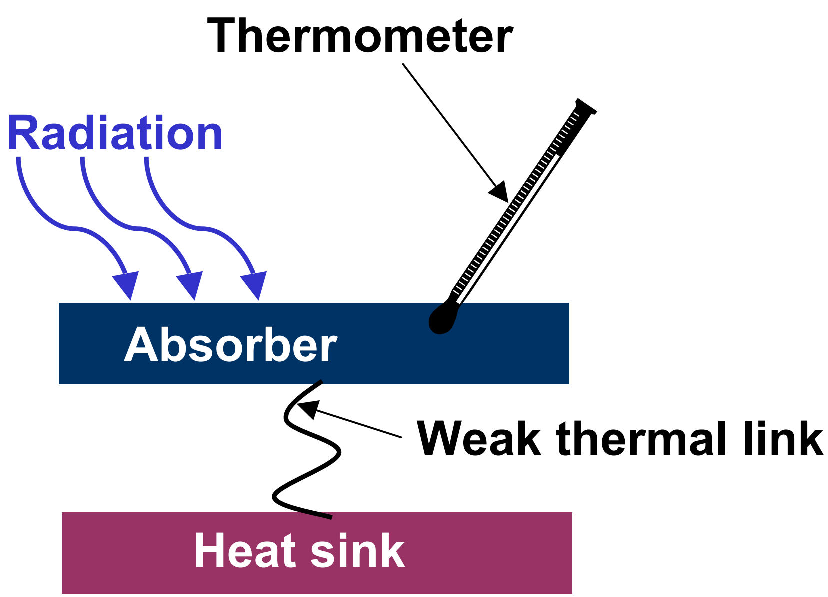
Introduction

Bolometers

A bolometer is conceptually very simple



Absorber temperature is a function of "optical" power

Nearly flat spectral response over wide bandwidth:

- Can define bandwidth using filters/waveguides

Can use simple read-out scheme

Practical to calibrate

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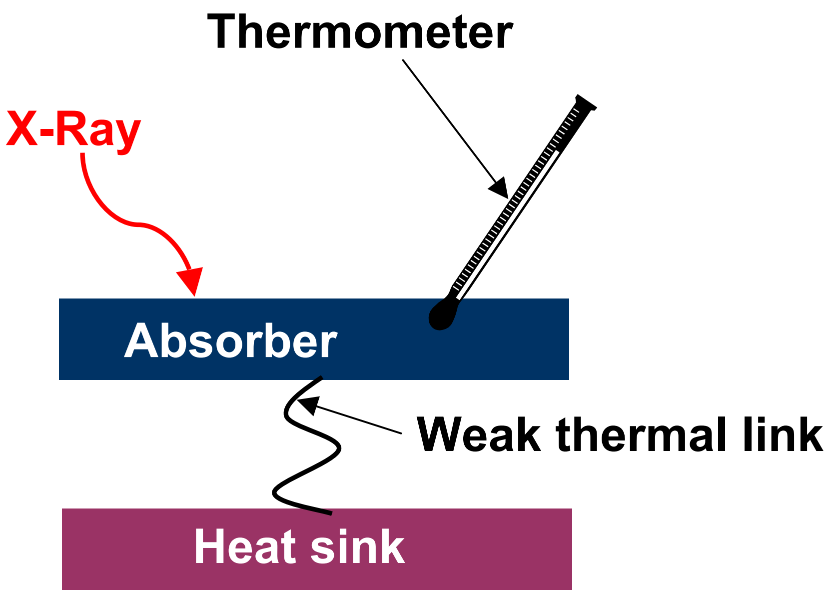
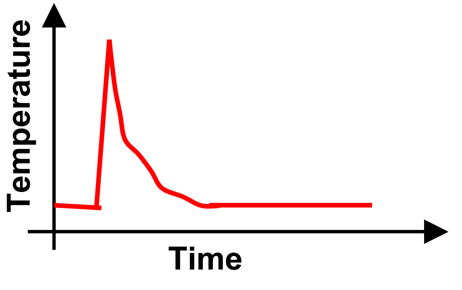
Calorimeters

Measure temperature as a function of time and you have a calorimeter



Uses include:
- Detecting:
  - X-rays
  - Dark matter
  - Double beta decay
- Mass spectroscopy



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Sub-mm astronomy

Astronomy at wavelengths of a few hundred µm
Typically around 450 and 850 µm

Bolometers are the best detectors for continuum ("broadband") measurements

James Clerk Maxwell Telescope, Mauna Kea, Hawaii

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Bolometers for sub-mm astronomy

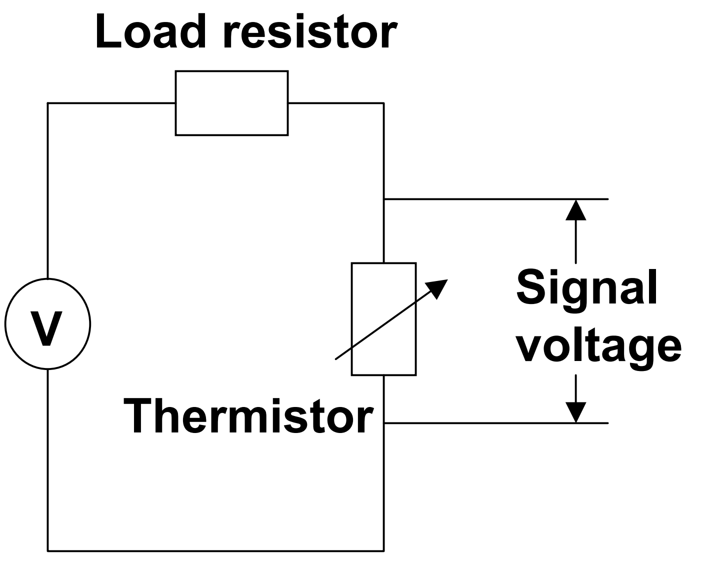
"Classical" design for sub-mm:
Metal-coated dielectric as absorber
Semiconductor resistance thermometer

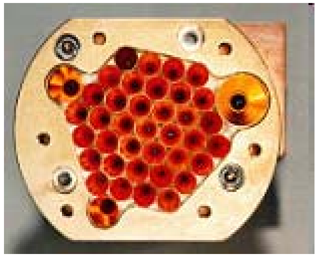
Each pixel illuminated by a feedhorn

Build up focal plane by stacking individual pixels together, each with independent readout

Operate at 100 mK or 300 mK

Readout circuit





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NTD Germanium

Neutron transmutation doping

NTD relies on elements having mix of isotopes; some transmute to acceptor and donor elements in neutron flux

Since isotope distribution is homogenous, doping is uniform and random down to the atomic level

NTD silicon ~ 5% of silicon semiconductor market
Used mainly for power transistors

NTD Ge: made in much smaller quantities; applications more limited – available commercially from Haller-Beeman Associates (http://www.haller-beeman.com/)

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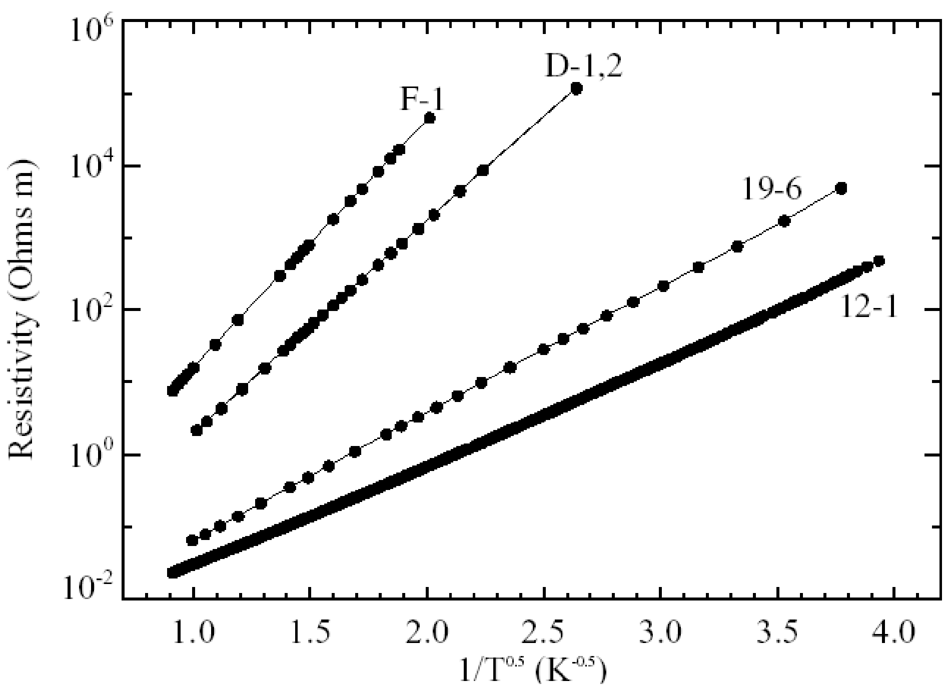
NTD Germanium

Neutron transmutation doping converts ^{70}Ge to ^{71}Ga (acceptor) and ^{74}Ge to ^{75}As (donor)

Doping level depends on neutron flux

Compensation ratio can be changed by altering isotope ratios

Very simple R(T) relation – no Chebychev polynomials!



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VRH

The low temperature conduction method is variable range hopping (VRH). This requires an amorphous structure.

For NTD Ge, the crystal is uniform but the dopant atom positions are random (compare with NbSi which is an amorphous alloy)

Need extremely uniform doping for reproducible behaviour. Other doping methods cannot achieve this

Bolometers

NTD Ge meets all the requirements for cryogenic bolometers and calorimeters:

High sensitivity to temperature – can be tuned for operating temperature from < 20 mK to 4 K

Very good reproducibility (so instruments remain calibrated)

Low "excess" noise

Good (metallic) electrical contacts can be made readily

Can be made very small (-> low heat capacity)

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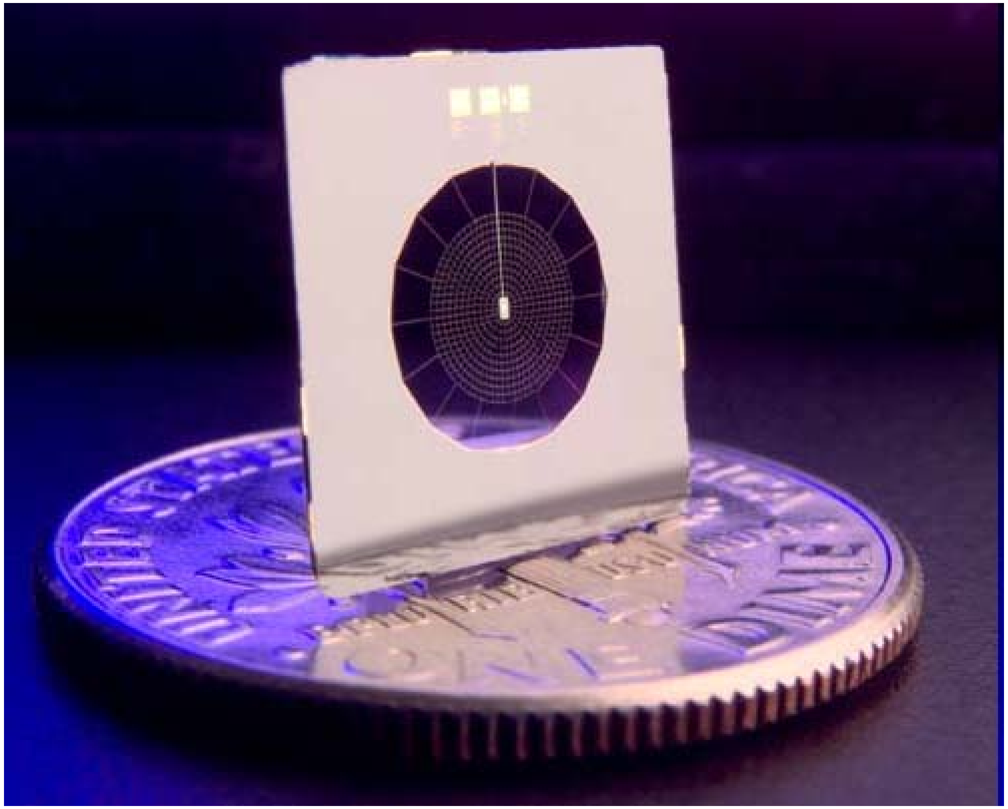
Spiderweb bolometer

Developed at Caltech
Thermistor sits at centre of silicon nitride mesh spiderweb absorber



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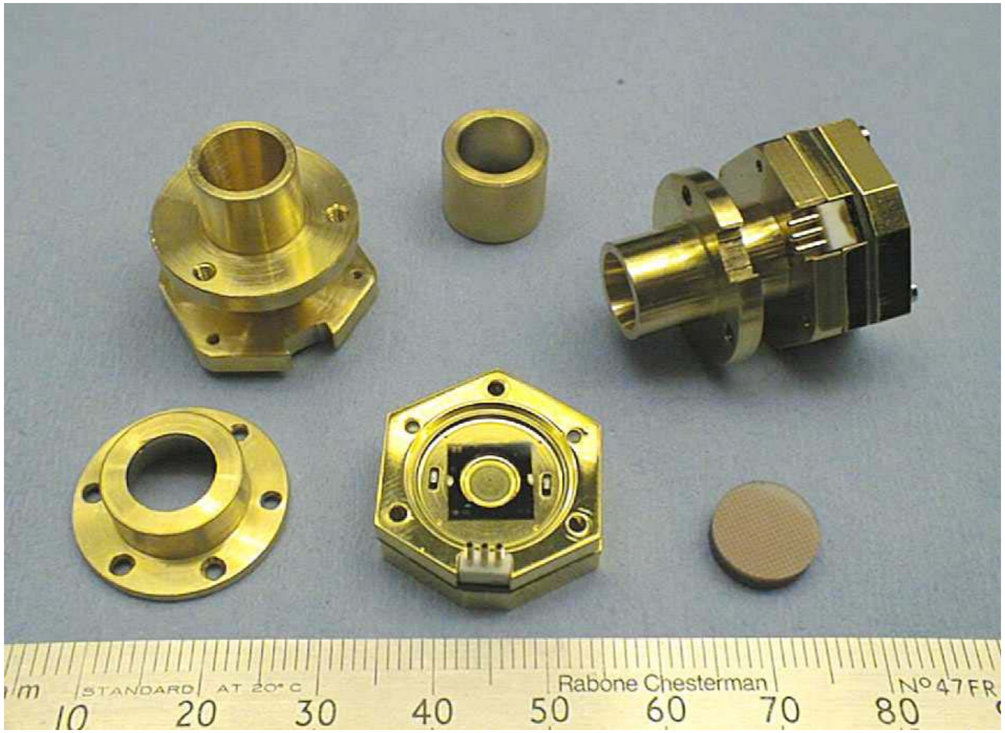
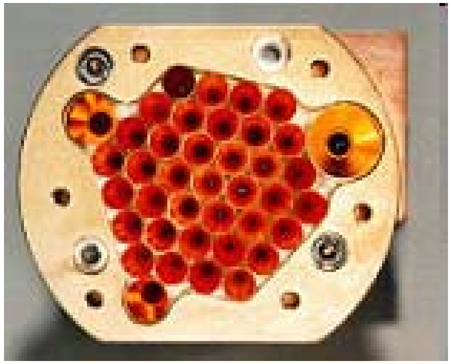
Array made of individual pixels

JPL NTD germanium spiderweb bolometer module with Cardiff feedhorn and metal mesh filter (HFI)



SCUBA bolometer array



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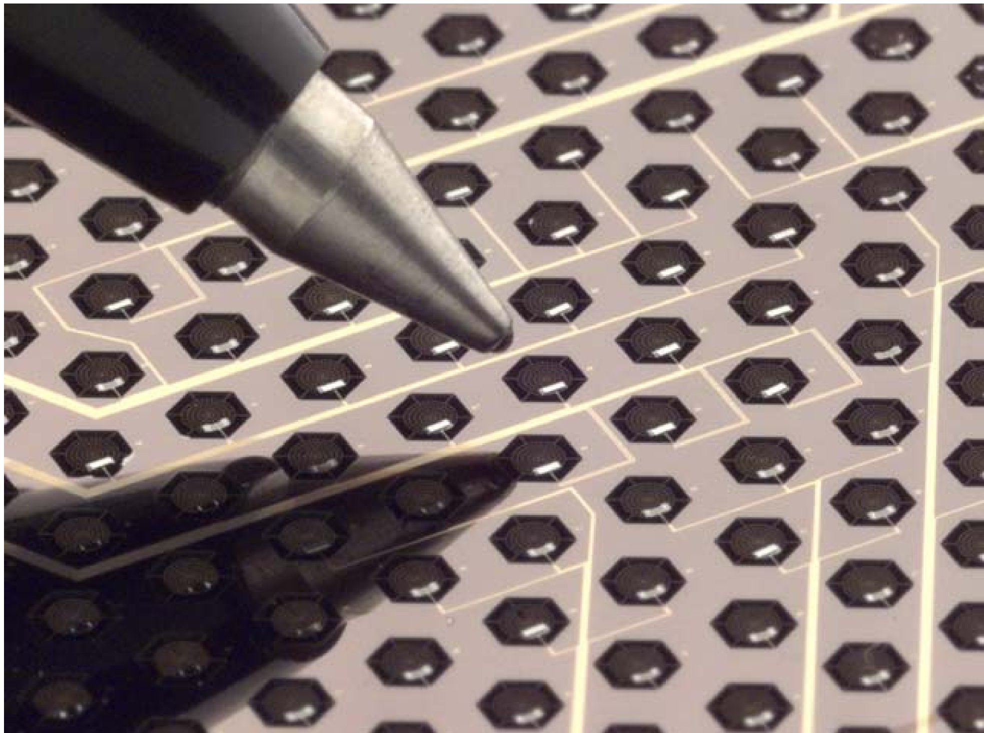
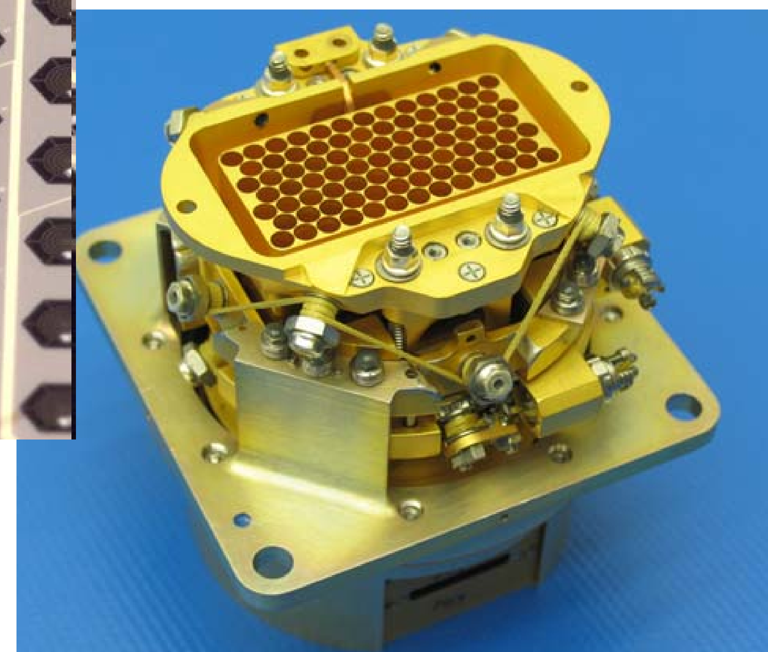
Many pixels on single wafer



Wafer for SPIRE bolometer array



SPIRE bolometer array

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Ge chips stuck on by hand

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Some instruments using NTD Ge

Astronomy
SCUBA
HFI
SPIRE
Boomerang
Bolocam

Dark matter
Eidelweiss
CDMS

Double beta decay
CUORE

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Competing technologies

Ion implanted silicon

+ Similar properties to NTD Ge – very uniform doping
+ Easier to make arrays (no manual steps)
– Traditionally 1/f noise has been a severe problem
    Mitigated by increasing doping thickness
– Not usually used for thermometry

Transition edge sensors

+ Easier to make arrays, multiplexing is practical
+ Better sensitivity
– Stop working completely if optical signal too large
– Read-out much more complex
– Sensitive to magnetic fields
– Don't make good thermometers!

History of ground based sub-mm bolometer arrays

JCMT-UKT14
350μm-2mm

Ge
1

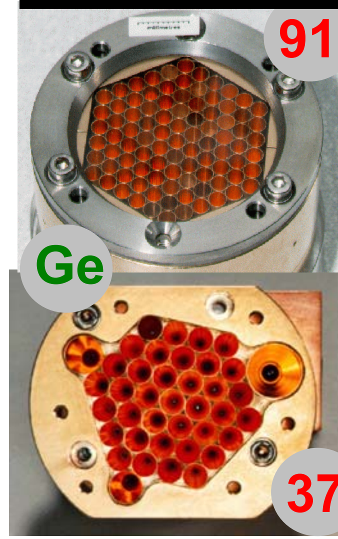
1986-1996

CSO-SHARC
350 μm array

Si
20

1996-

JCMT-SCUBA
350/450 &
750/850μm

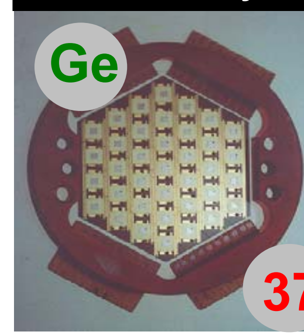


91
Ge
37

1997-

Also 19 pixel 2 mm array at 0.1 K

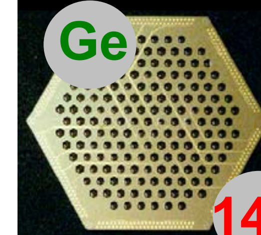
IRAM- MPIfR
1.3mm array



Ge
37

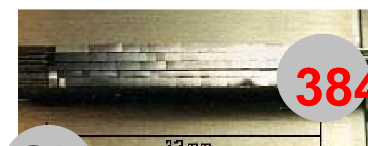
1998-

LMT-BOLOCAM
1.1mm



Ge
144

2001-



384
Si

CSO-SHARC-II
350/450

2004-

91 Number of pixels

Ge Material

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R(T) expressions

VRH

Use NTD Ge on the insulator side of the metal-insulator transition

Conduction is via variable range hopping (VRH) – electrons hop to sites with small ΔE rather than nearest neighbour

For NTD Ge, people normally assume

$$R = R^* \exp\sqrt{\frac{T_g}{T}}$$

R: resistance
T: temperature
*R**, T_g: constants

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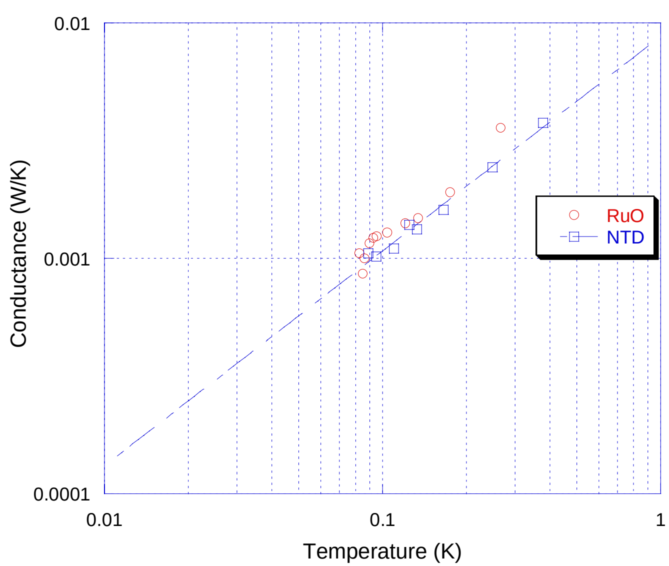
Analytical expressions

Why is a simple analytical expression so useful?

Convenience: don't have to fit complex empirical functions (e.g. Chebychev polynomials)

Improves calibration accuracy – structure in residuals for empirical fits cause systematic errors, especially when measuring very small temperature differences.



Thermal conductance calculated from small temperature differences using NTD Ge (□) and RuO (o) thermometers

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Analytical expressions

Why is a simple analytical expression so useful?

Need fewer points for calibration

Makes measurement errors more obvious – if you depart from the fit, perhaps something is wrong

Makes bolometer models simpler and enables analytical expressions to be written down for properties such as responsivity

Can even extrapolate fits outside range used for calibration with some degree of confidence, especially if using several thermometers from the same batch

VRH

But:

If you use the wrong expression, you make things worse!

In fact, theory suggests $$R = R^{*} \exp\left(\frac{T_g}{T}\right)^{p}$$ $p \sim 0.5$

Or rather $$R = R^{*} T^{q} \exp\left(\frac{T_g}{T}\right)^{p}$$ $q = ???$

But we shall ignore q because experimentally it can generally be absorbed into the p term

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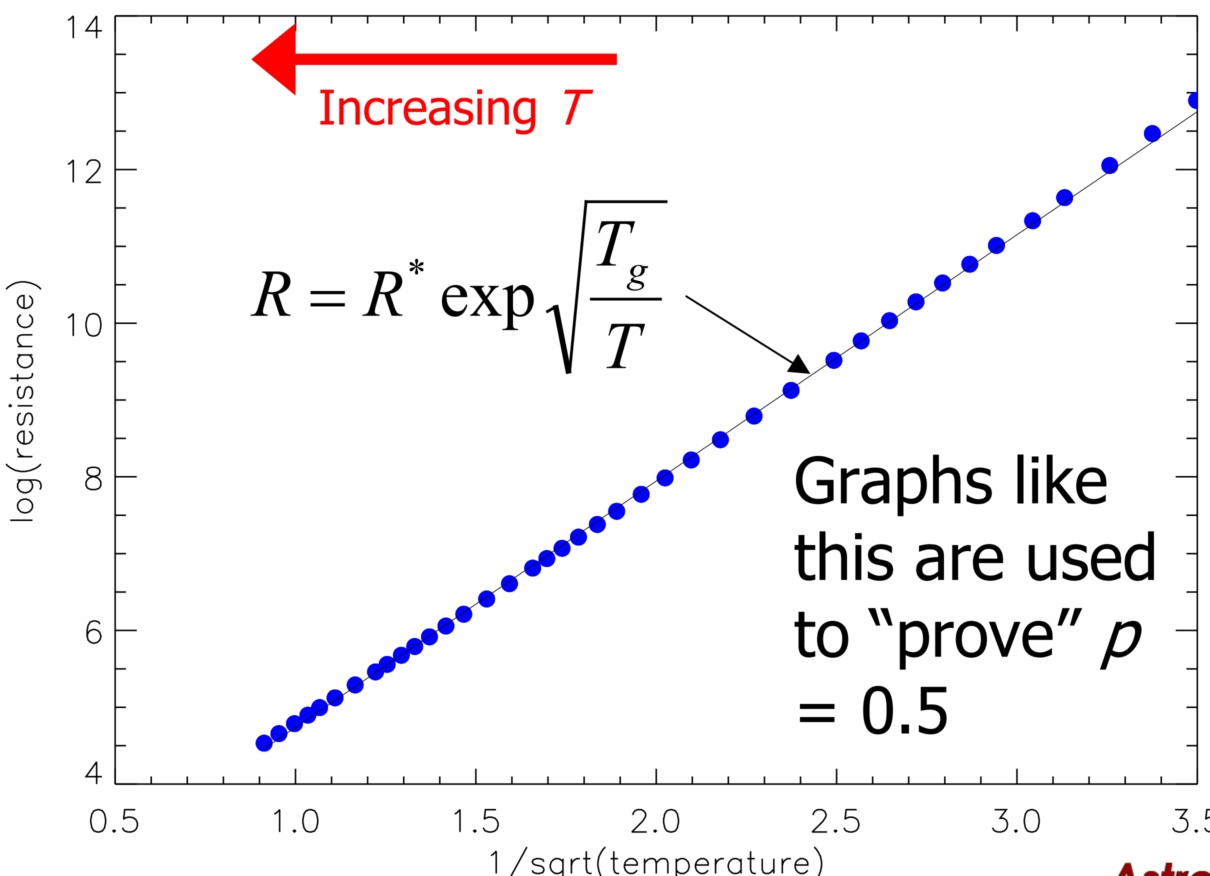
Measurements

Reasonable fit with p=0.5 to data for a 100 mK thermometer…



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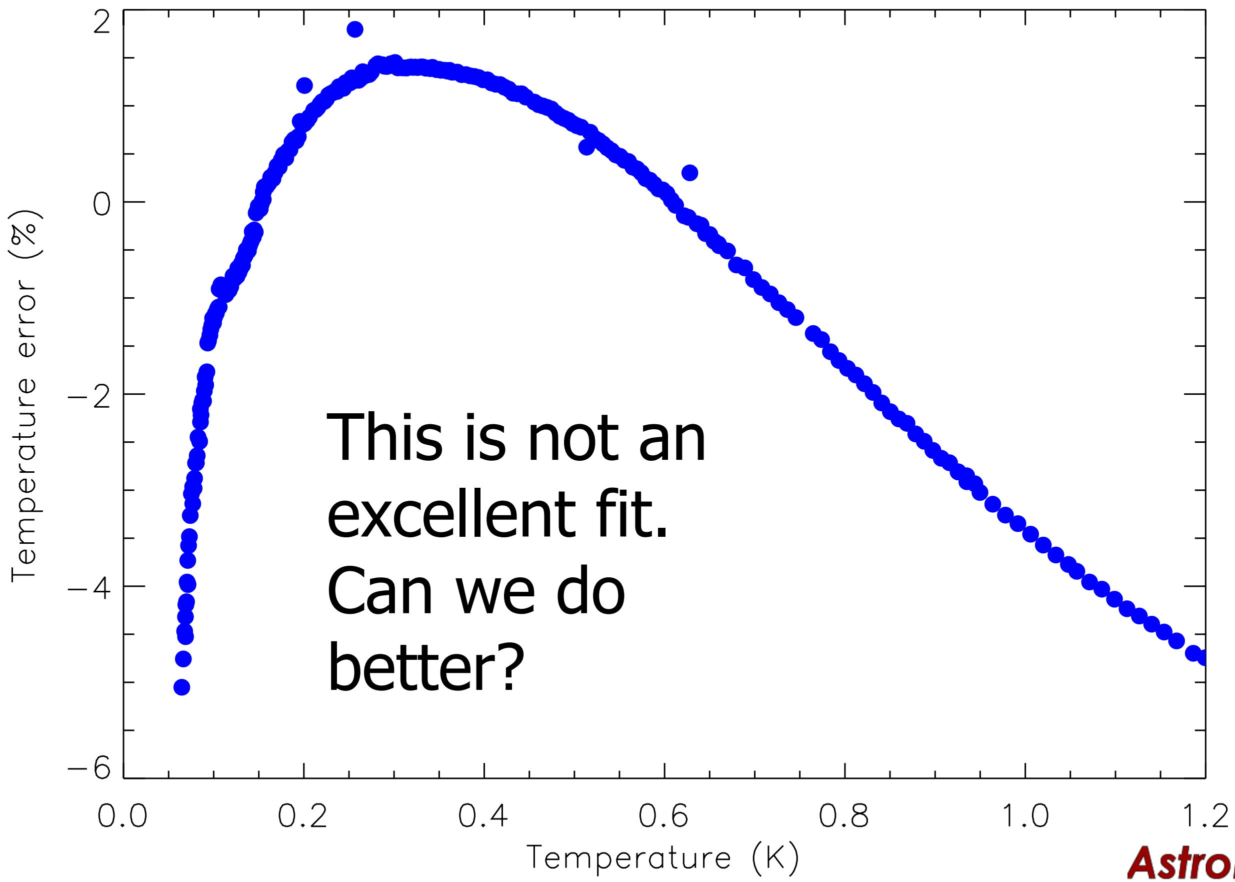
Measurements

...but look at residuals.
(And you should always look at residuals!)



This is not an excellent fit. Can we do better?

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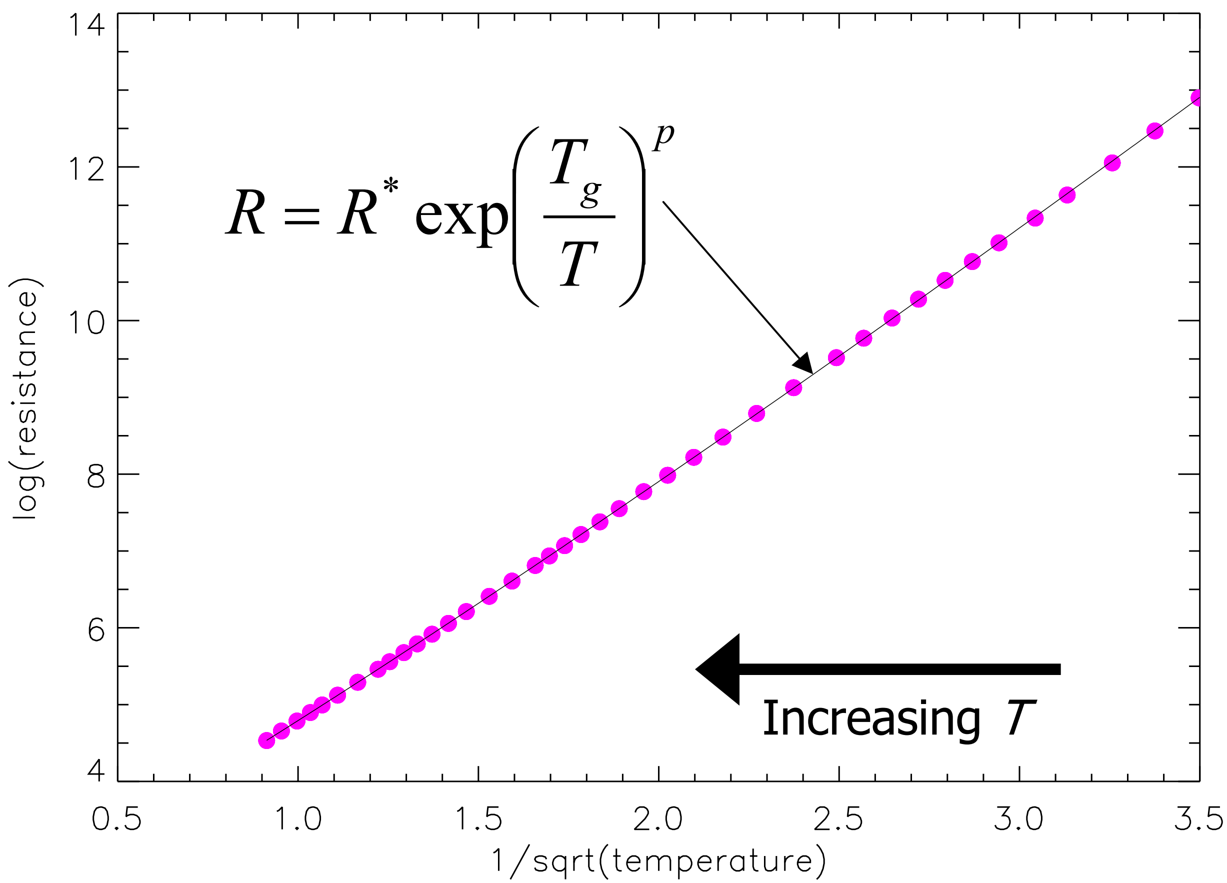
Measurements

With p as adjustable parameter:

p =0.5611 ± 0.004



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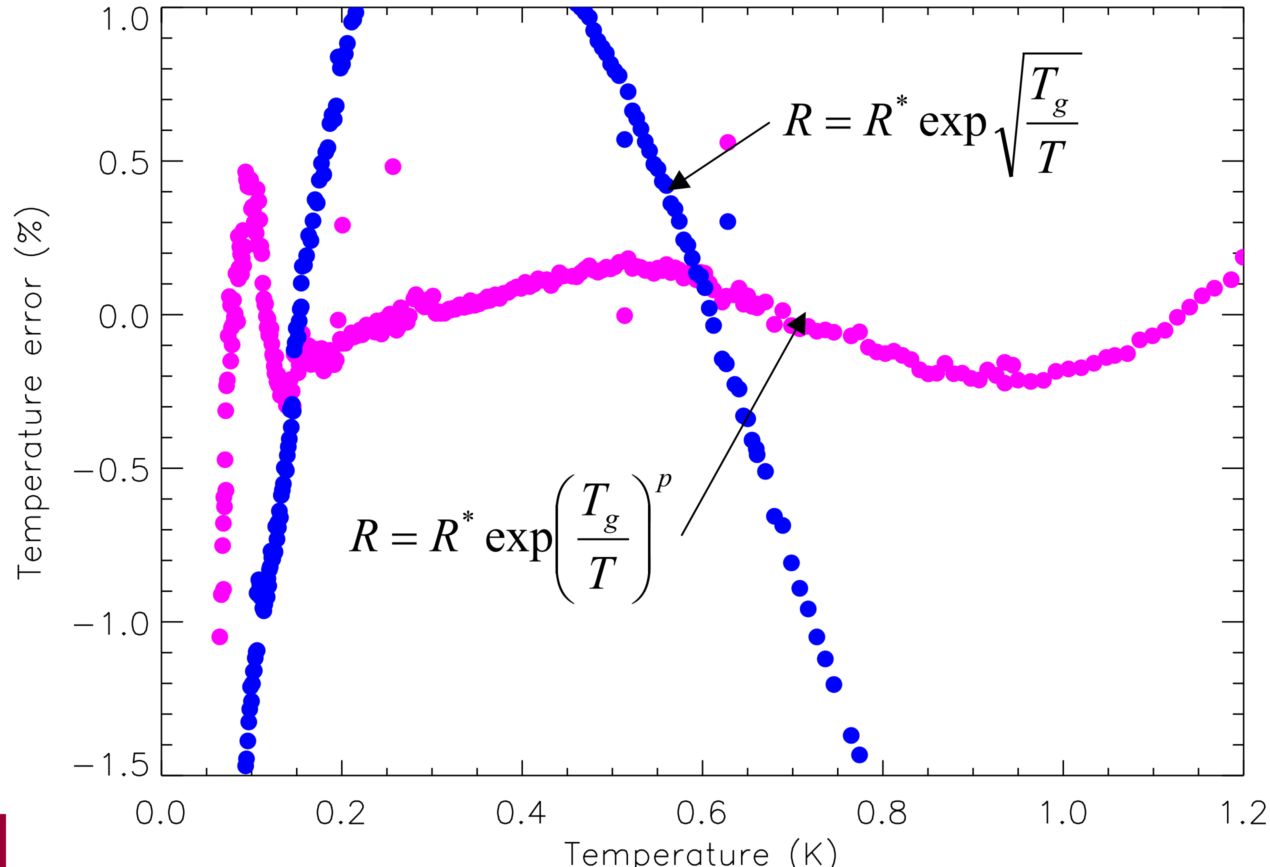
Measurements

Fit is now accurate to better than 0.5% in temperature over almost entire range



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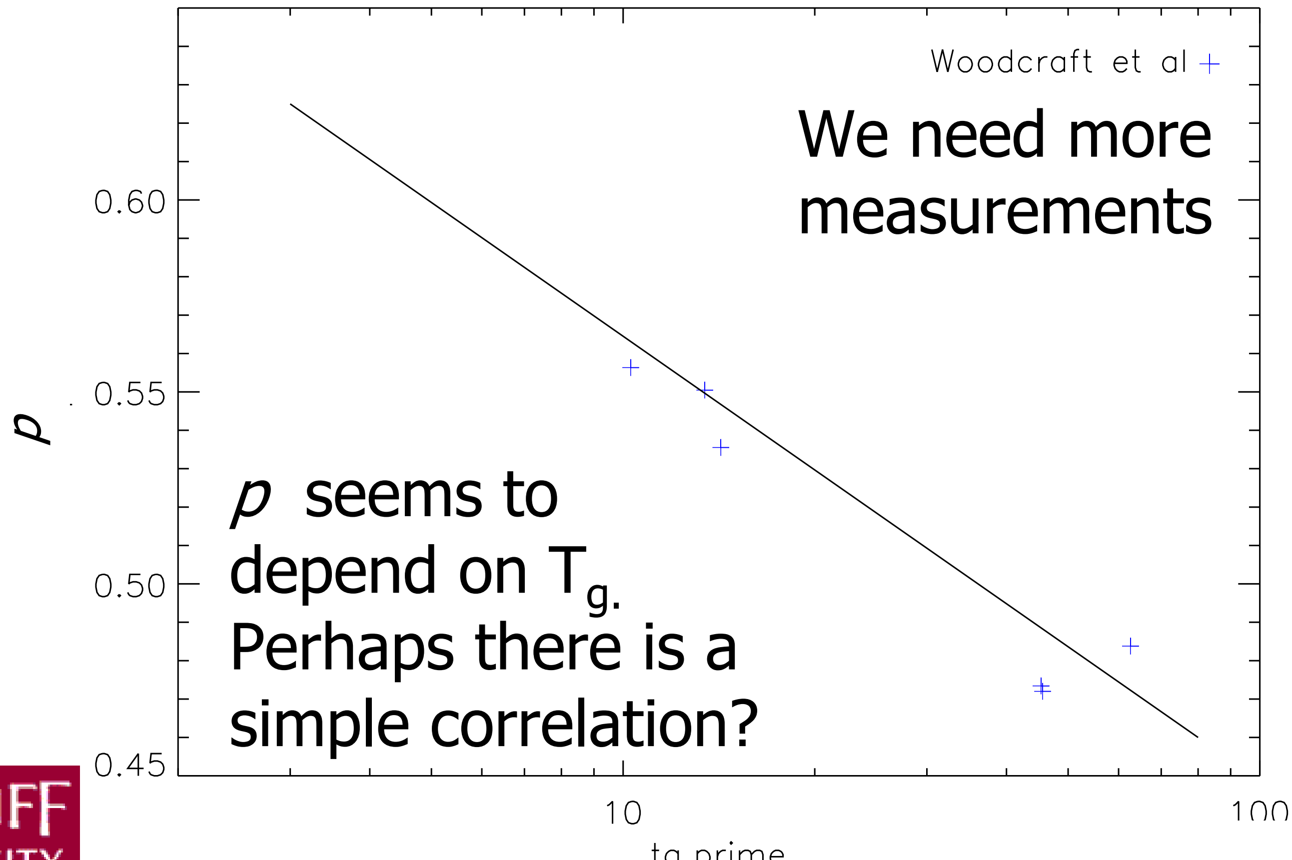
More measurements

Get similar results from examining other thermometers: but get different values of *p*



We need more measurements

p seems to depend on T_g. Perhaps there is a simple correlation?

Woodcraft et al. Journal of Low Temperature Physics 134 (3) 925-944 (2004)

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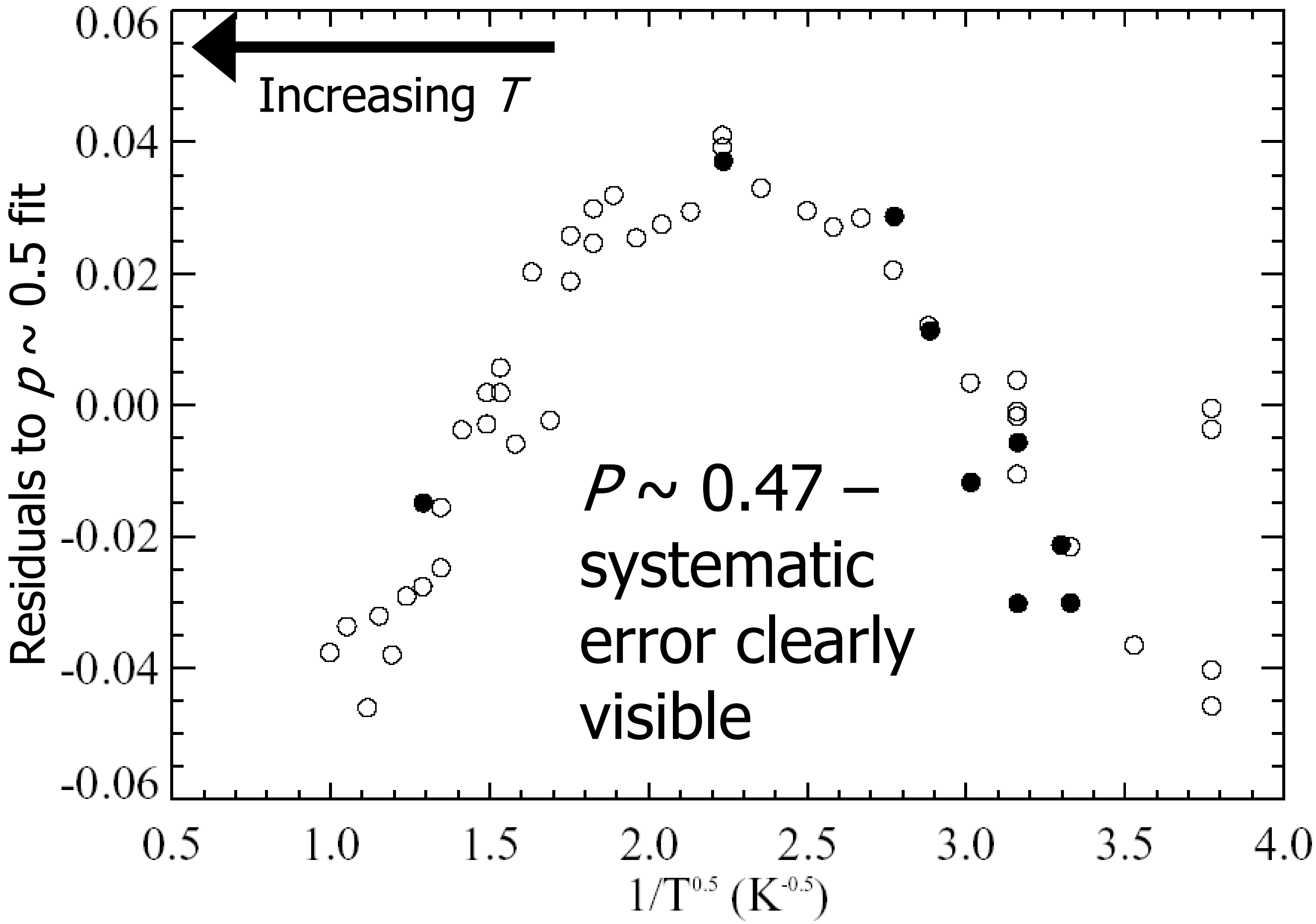
Check

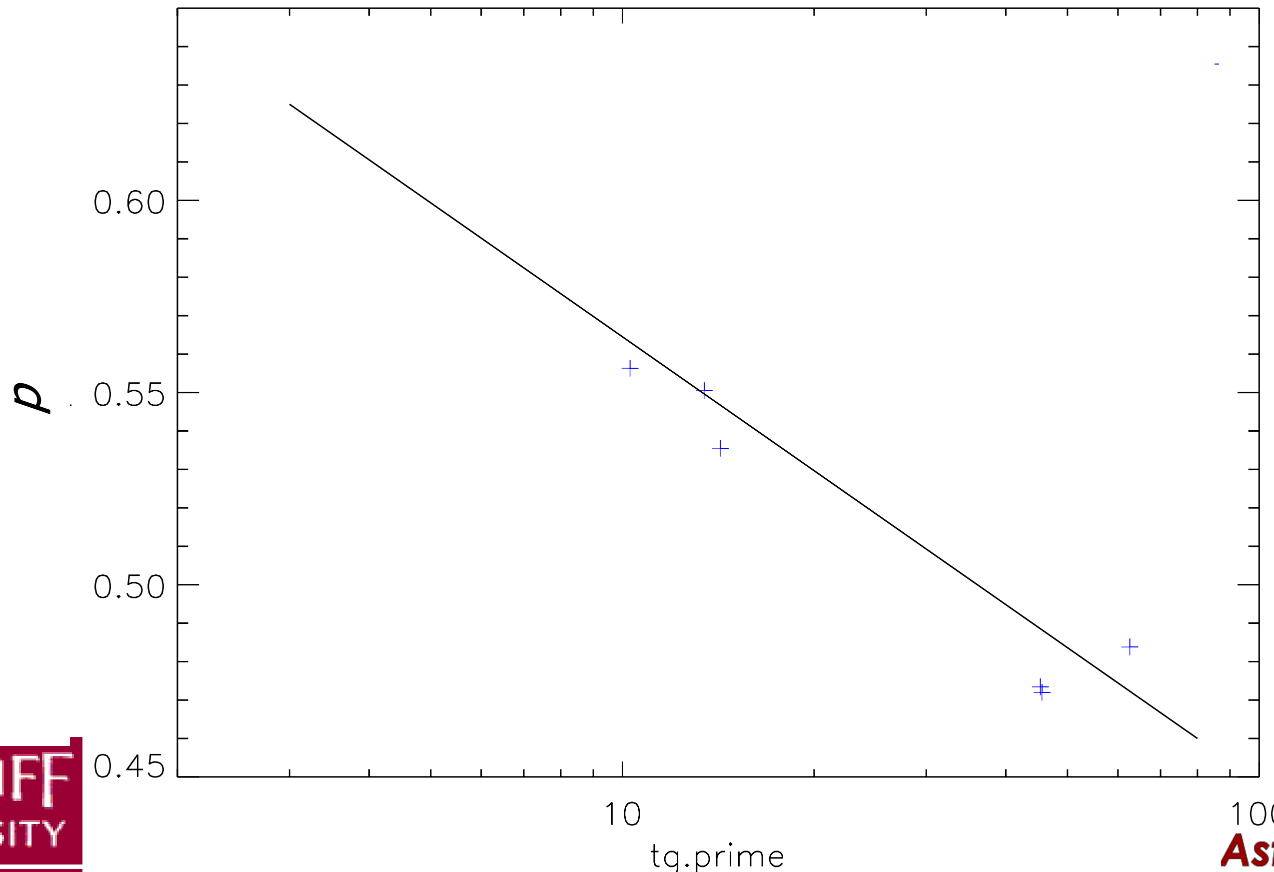
Same thermistor measured in two entirely independent systems (on two different continents)

Other checks confirm results and suggest we really are measuring power-laws (difficult)



$p(T_g)$

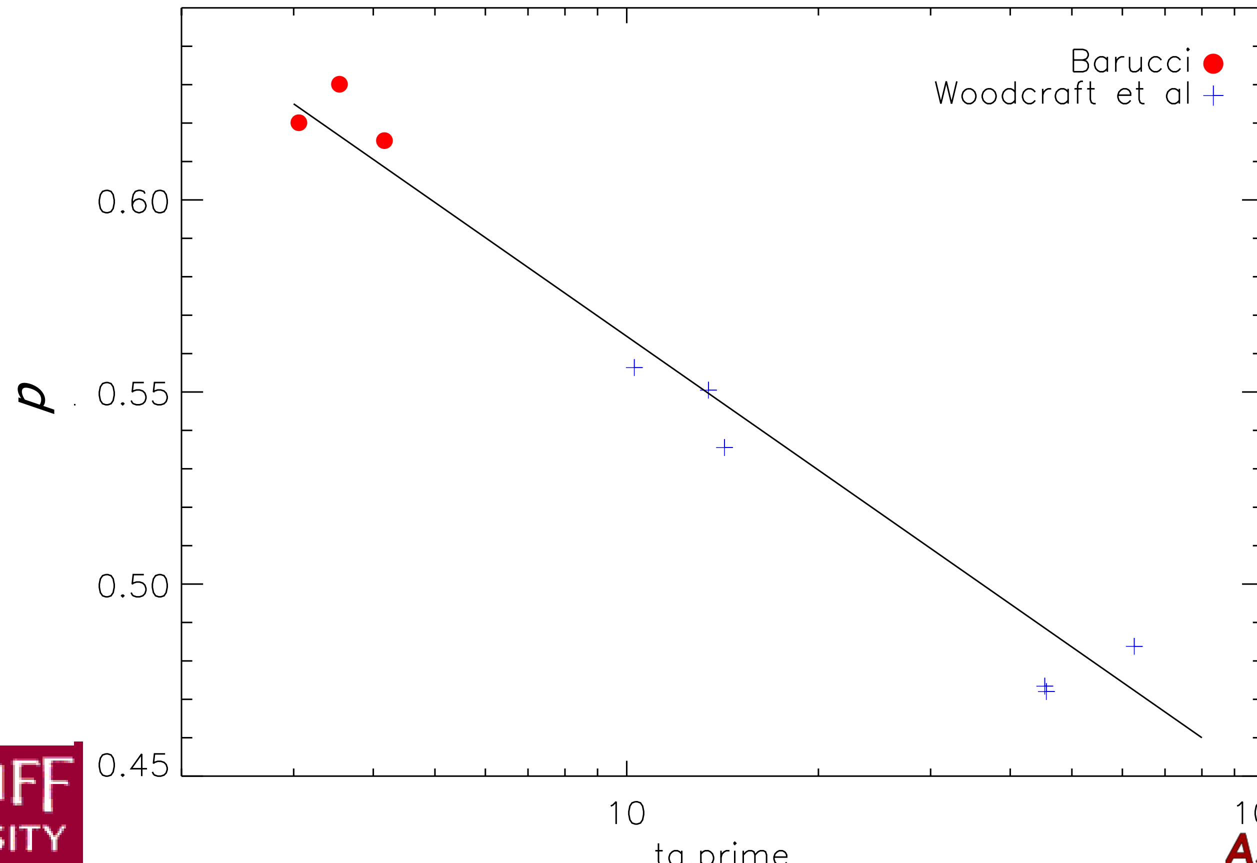
New measurements at lower T_g fall on this line!



$p(T_g)$

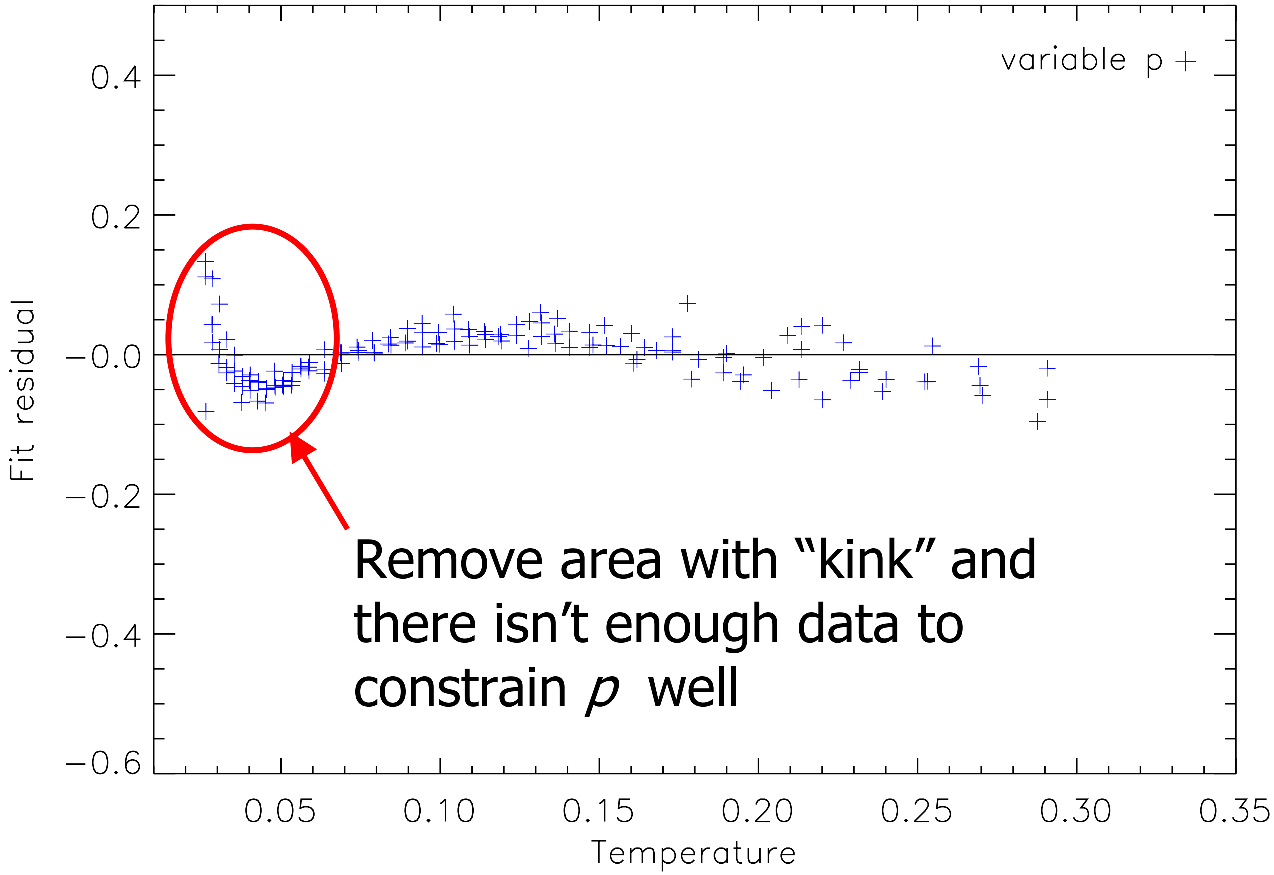
New measurements at lower T_g fall on this line!

Barucci et al. Physica B 368 (2005) 139-142



But…

However, need to treat these values of p with some caution



Alternative expression

We can get good fits by letting *p* vary

McCammon finds this method does *not* work for ion implanted silicon, and suggests a modified equation with no new free parameters: ("Wouter" function)

$$R = R^{*} \exp\sqrt{\frac{T_g}{T}} + R^{*'} \exp\sqrt{\frac{T_g{}'}{T}}$$

$$R^{*'} = R^{*} \exp\left(2.522 T_g{}^{(-0.25)} - 8.733\right)$$

$$T_g{}' = 2.7148 T_g + 1.2328$$

D. McCammon, in Cryogenic Particle Detection, Ed. Enss, Springer 2005

D. McCammon, http://arxiv.org/abs/physics/0503086

He also finds this works well for an NTD Ge sample

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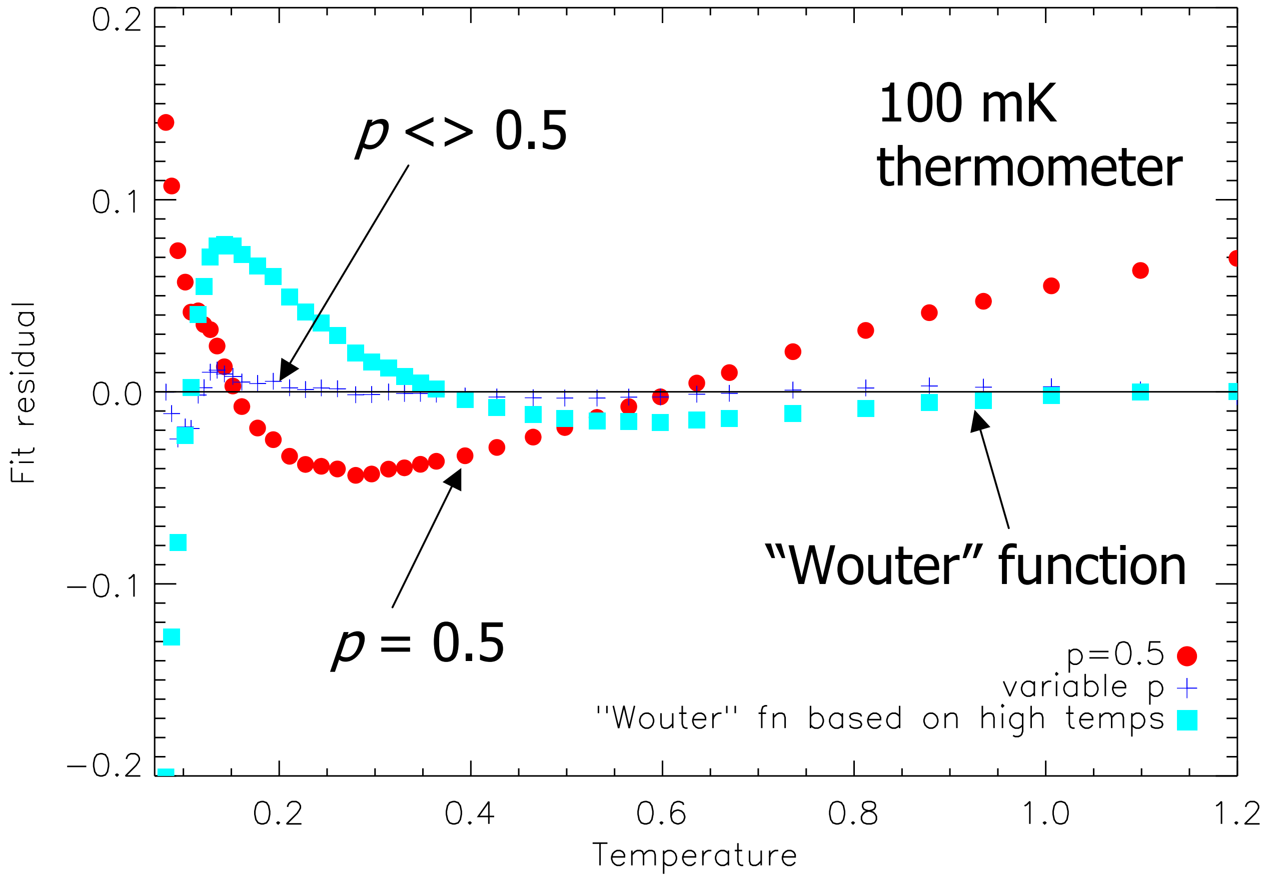
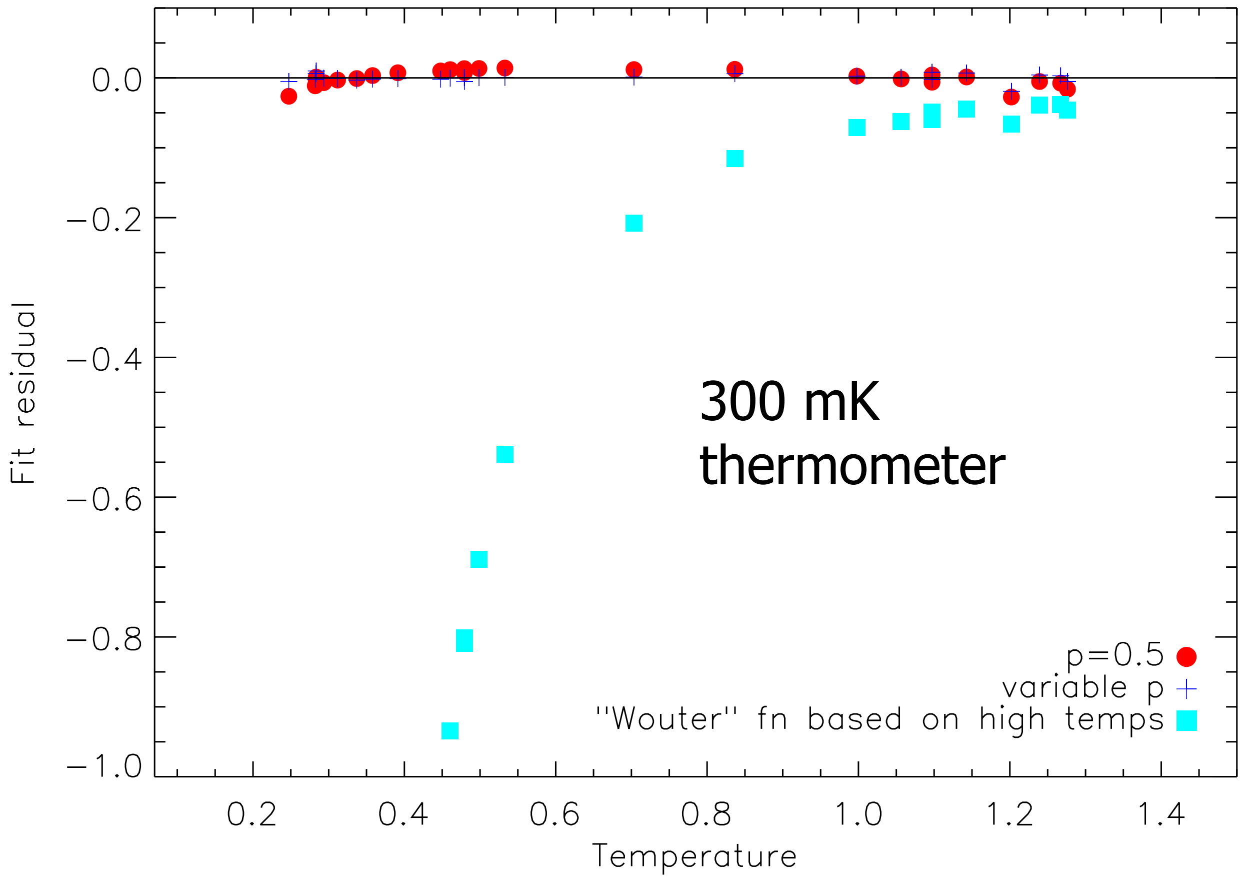
Trying alternative expression

Doesn't work well for 100 mK thermometer measurements



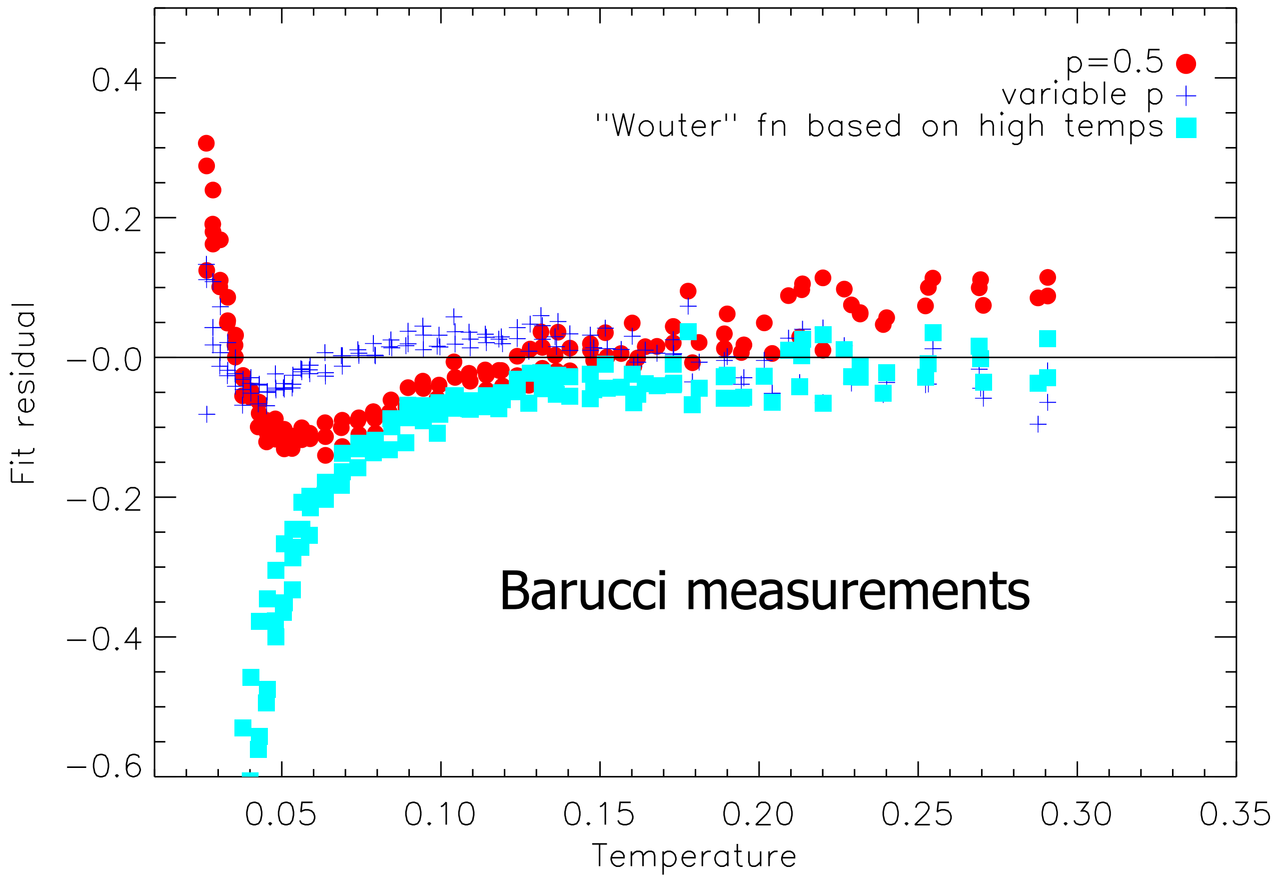
Trying alternative expression

...or for 300 mK thermometers



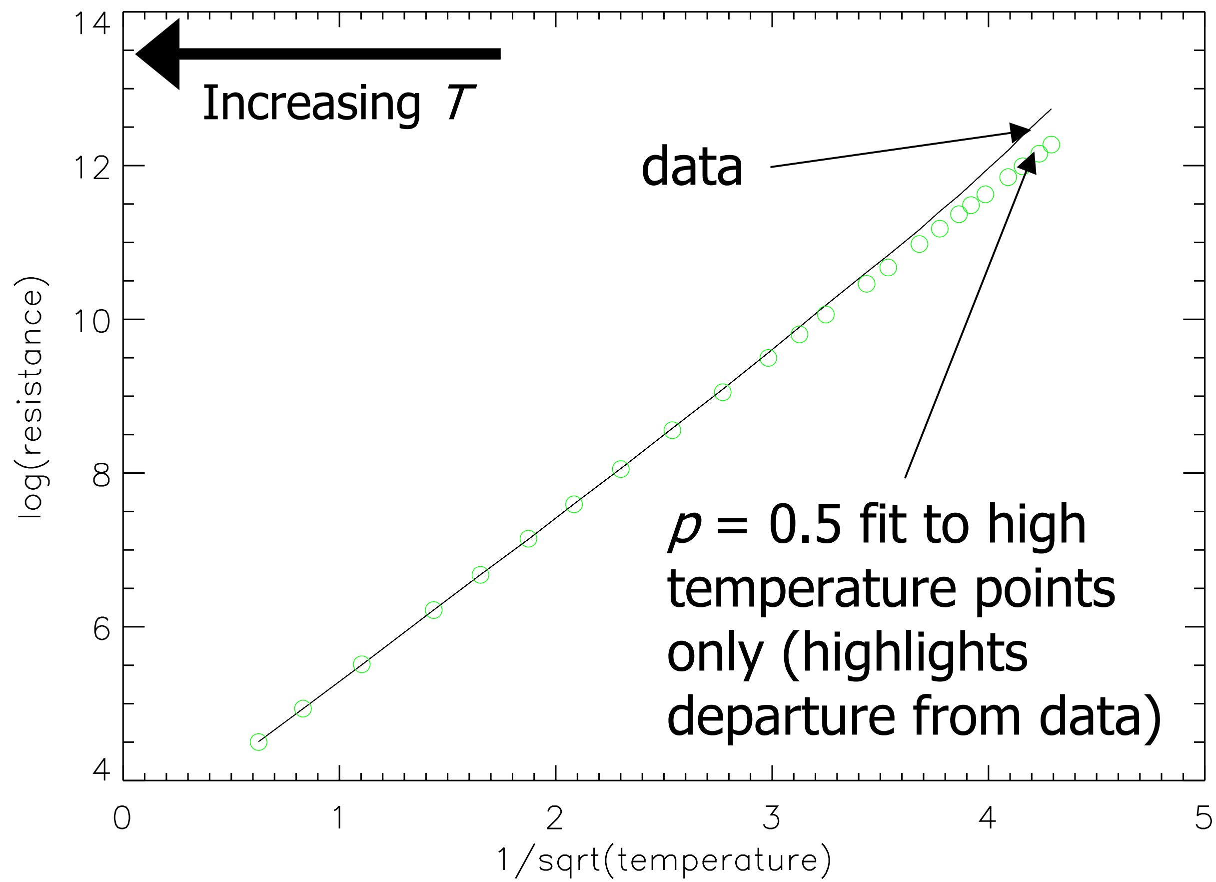
Trying alternative expression

…or for measurements in Barucci et al 2005



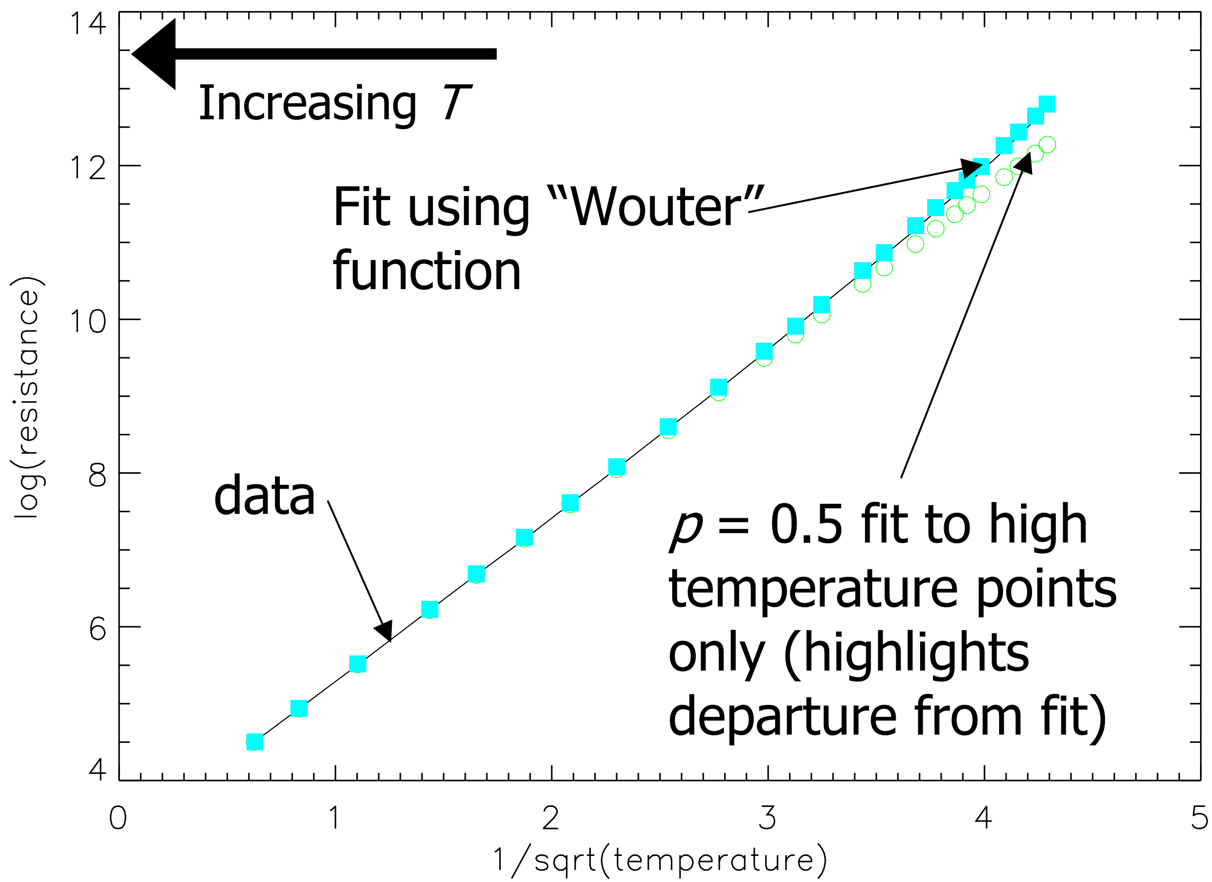
Trying alternative expression

NTD Ge sample from McCammon 2005



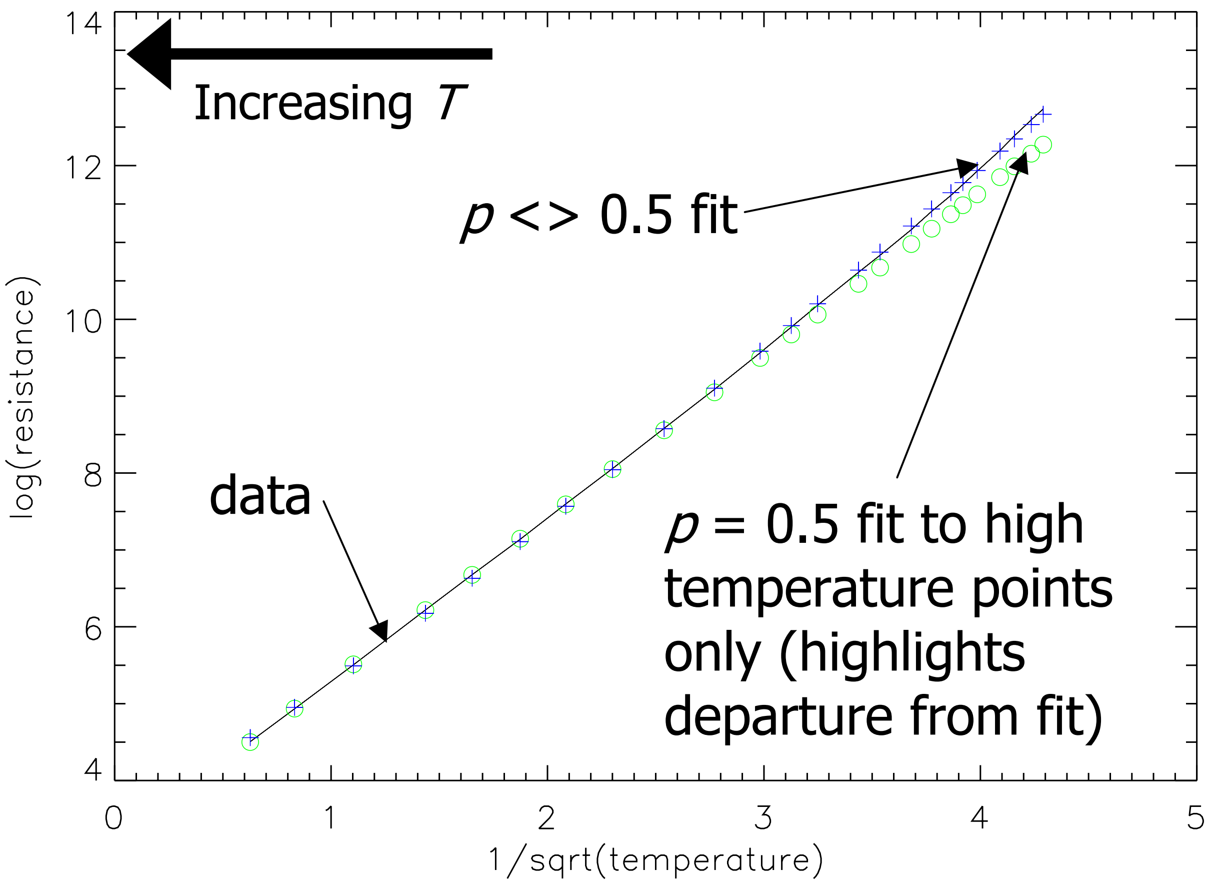
Trying alternative expression

"Wouter" function fits the data well



Trying alternative expression

But variable *p* fit is also good (at the expense of an extra free parameter)



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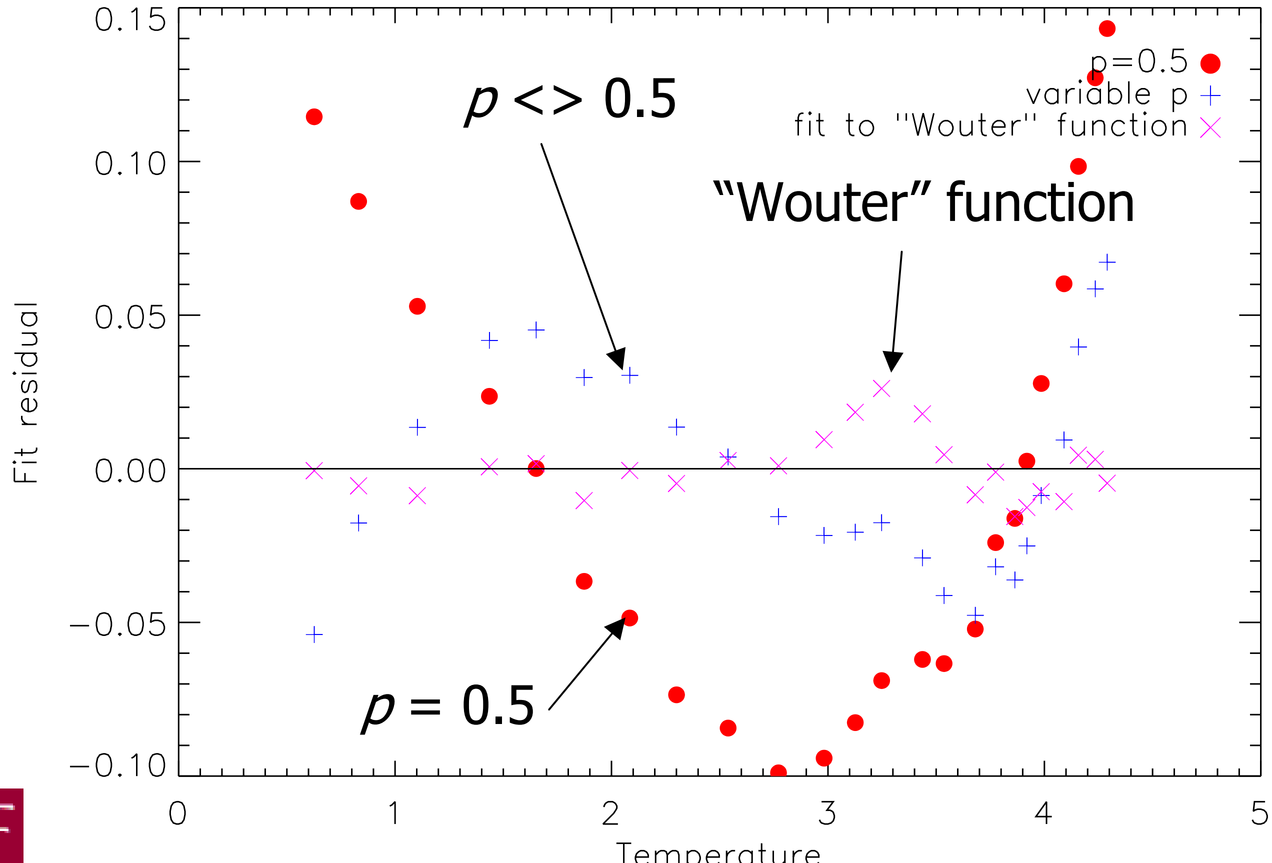
Alternative expression

"Wouter" function seems to do a somewhat better job, but variable p fit is not bad



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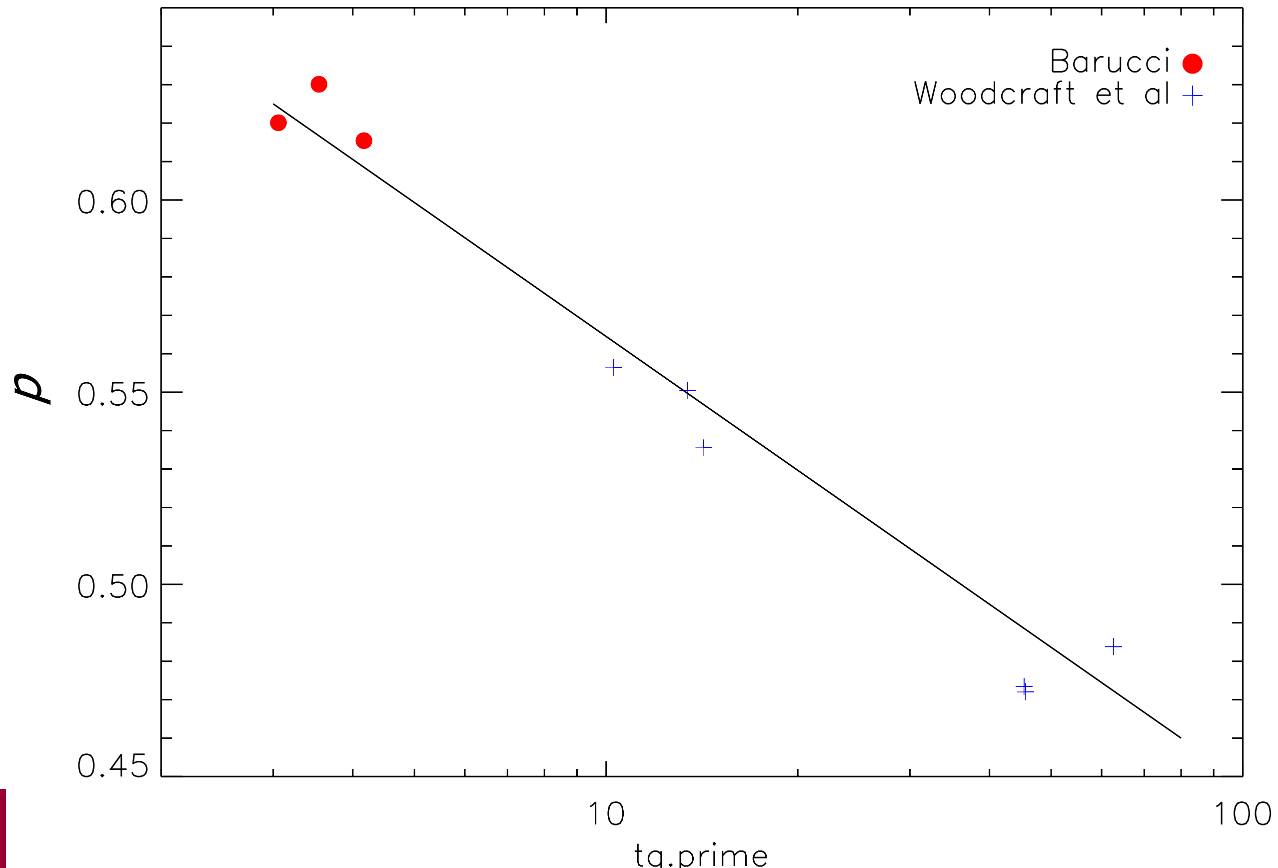
$p(T_g)$

Return to *p* as a function of T_g



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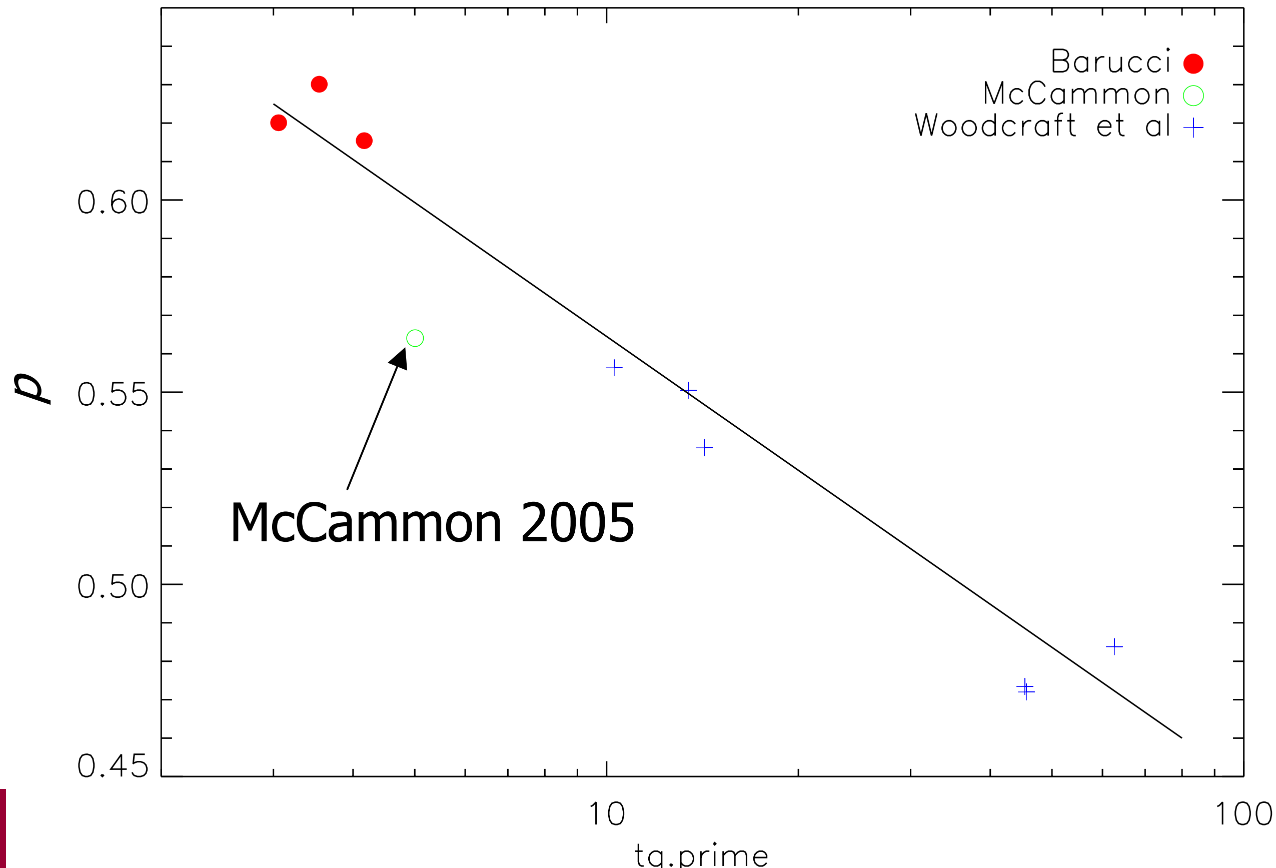
$p(T_g)$

Result from McCammon sample not wildly in disagreement.
Hard to put error bar on – depends on systematic effects



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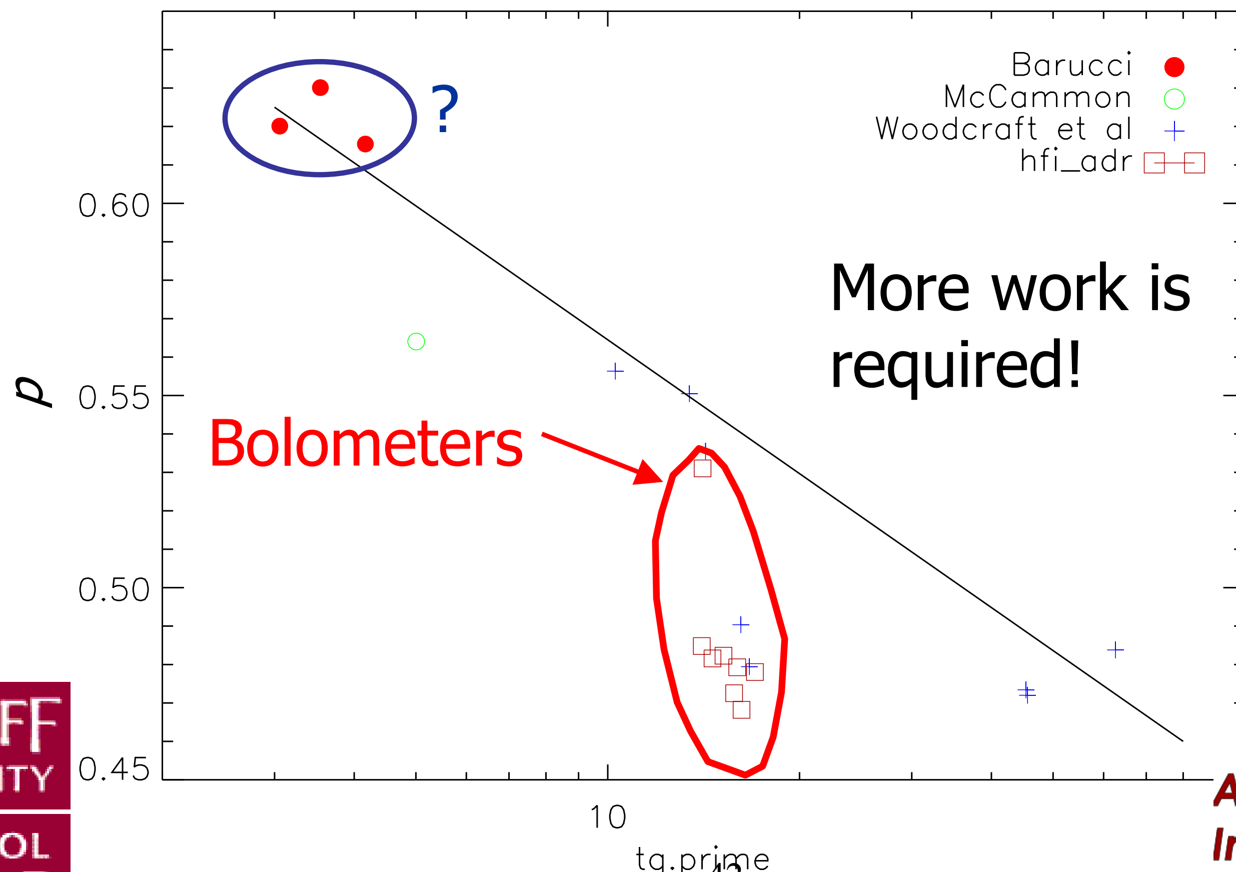
$p(T_g)$

But: measurements on *bolometers* do not agree with the fit!
Mounting in a bolometer shouldn't make a difference
Only significant difference is geometry: contacts on one face not opposite sides – could this make a difference?



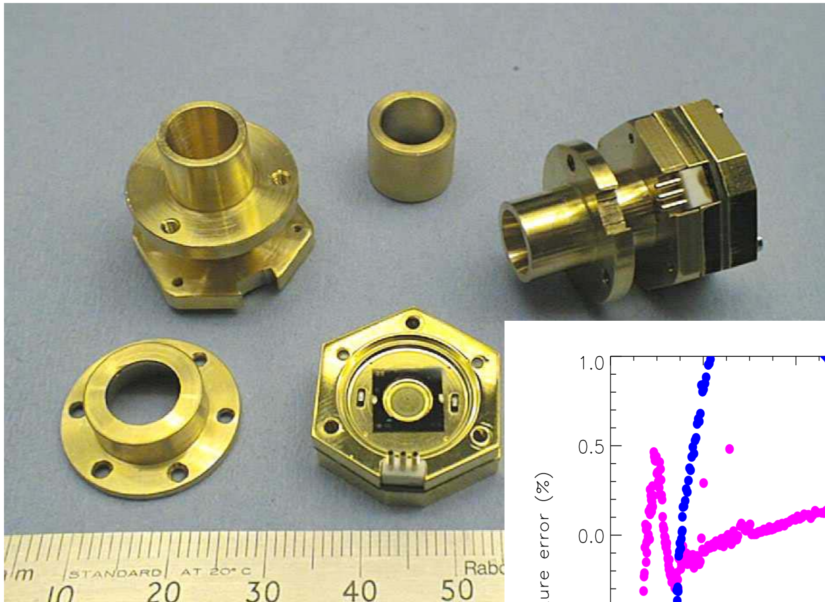
Conclusions

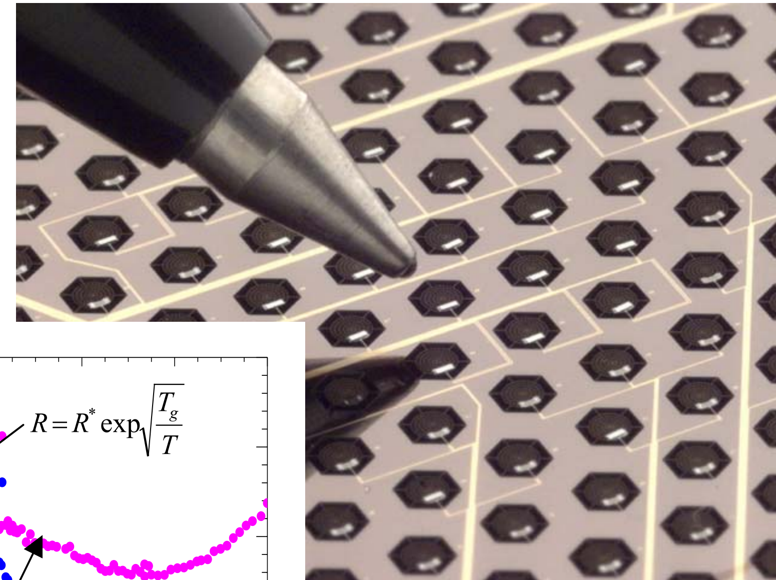
Neutron transmutation doped germanium can be used to make sensitive and reproducible thermometers with a very simple calibration.

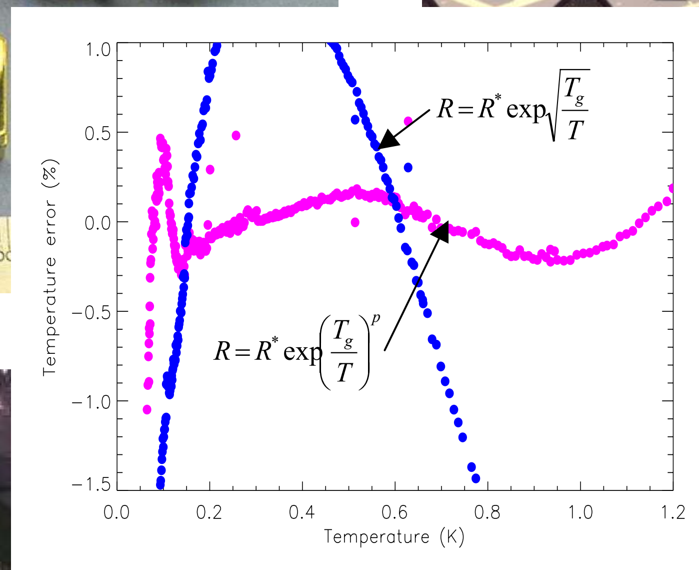
This makes them ideal for use in bolometers and calorimeters

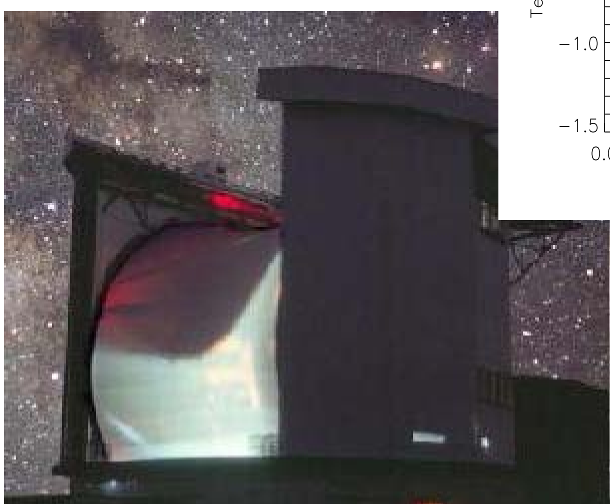
The commonly used calibration expression is often wrong, but adding one more parameter (p) produces good fits for all thermistors examined. There *may* be a correlation between p and T_g – more work is required!

The calibration expression proposed by McCammon based on work on silicon thermistors does *not* appear to be generally appropriate for NTD Ge.









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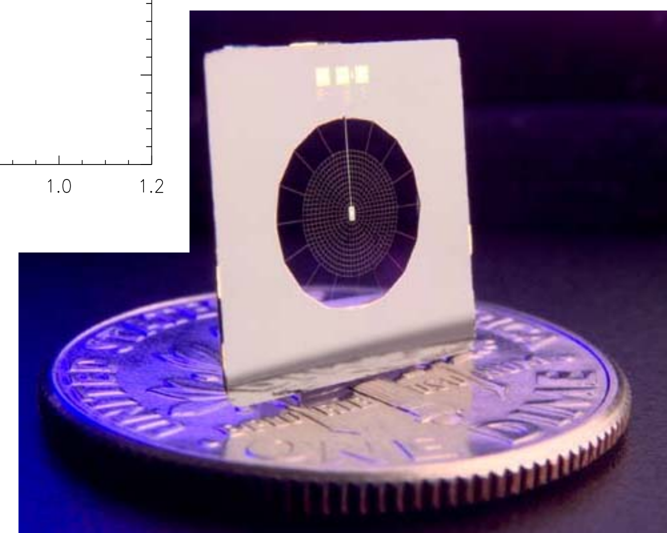

More information: *Woodcraft et al. Journal of Low Temp. Physics 134 925-944 (2004)* [*http://reference.lowtemp.org/woodcraft_ntd.pdf*](http://reference.lowtemp.org/woodcraft_ntd.pdf)