Internal thermal fluctuation noise in Mo/Au TES’s

Nick Wakeham

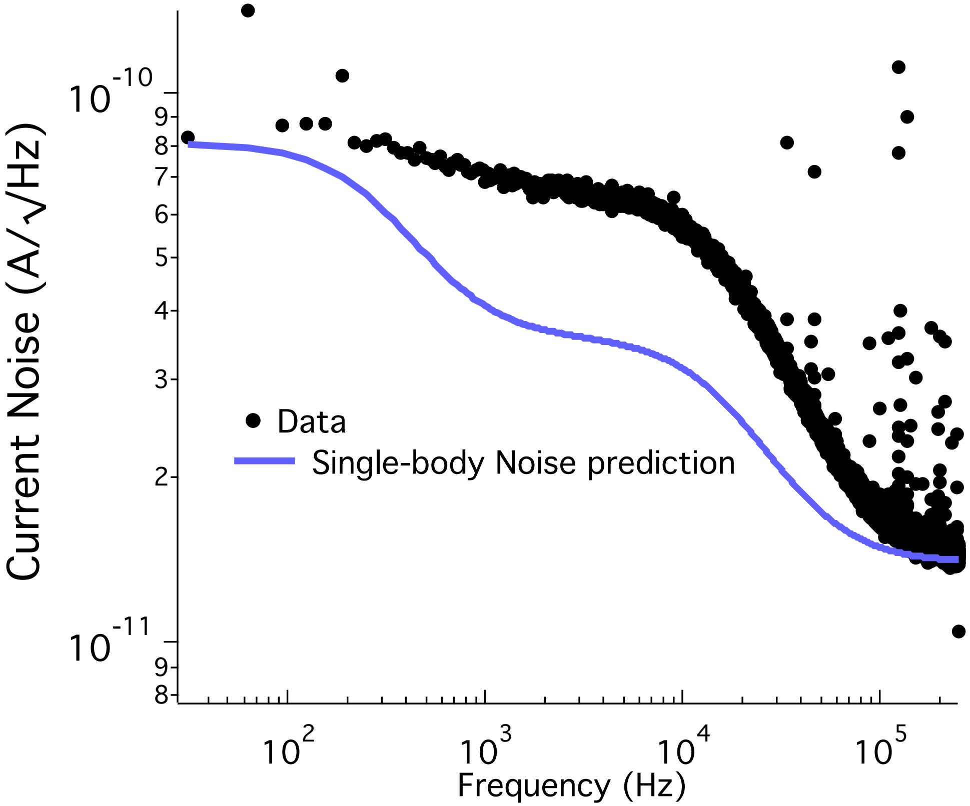
NASA-Goddard Space Flight Center

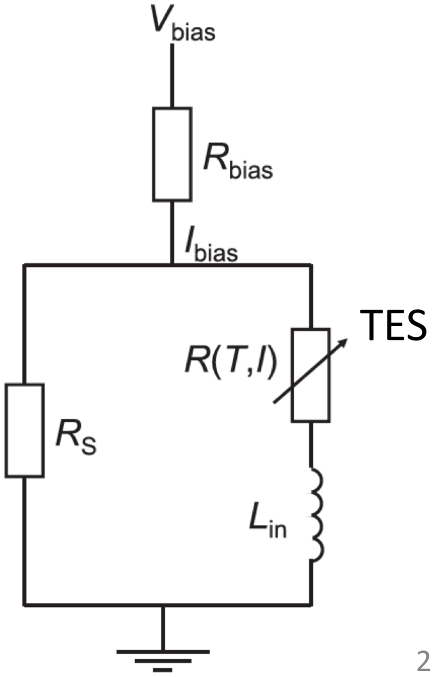
Joseph Adams, Simon Bandler, Sophie Beaumont, James Chervenak, Aaron Datesman, Megan Eckart, Fred Finkbeiner, Ruslan Hummatov, R. Kelley, Caroline Kilbourne, Antoine Miniussi, F. Porter, John Sadleir, Kazuhiro Sakai, Stephen Smith, Edward Wassell

Noise in excess of single-body model

Simplest model of TES is a single body connected to bath by thermal conductance G_{bath}

Measured noise is in excess of single body prediction





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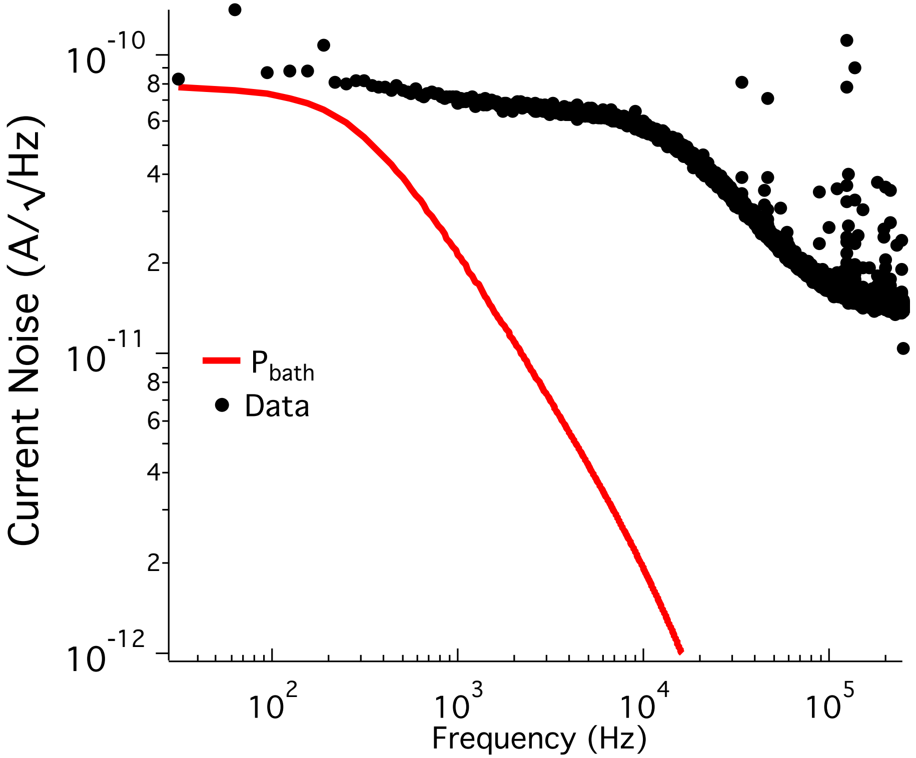
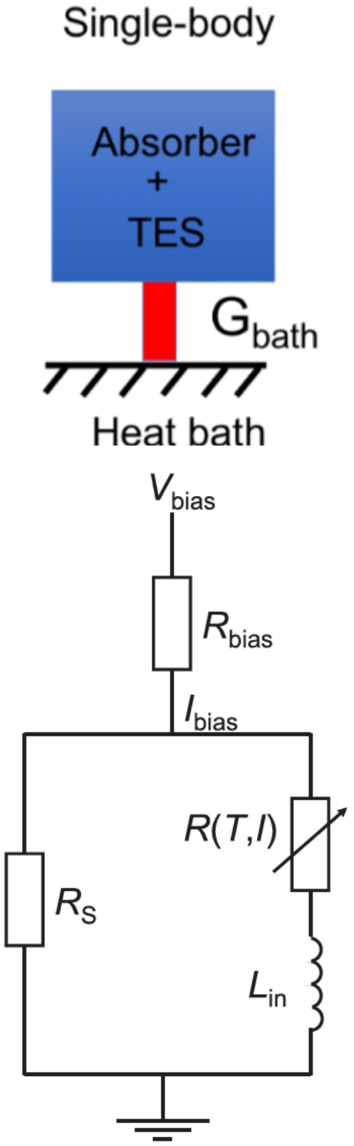
3 contributions to current noise:

1. Thermal fluctuation noise between single body and bath - P_{bath}





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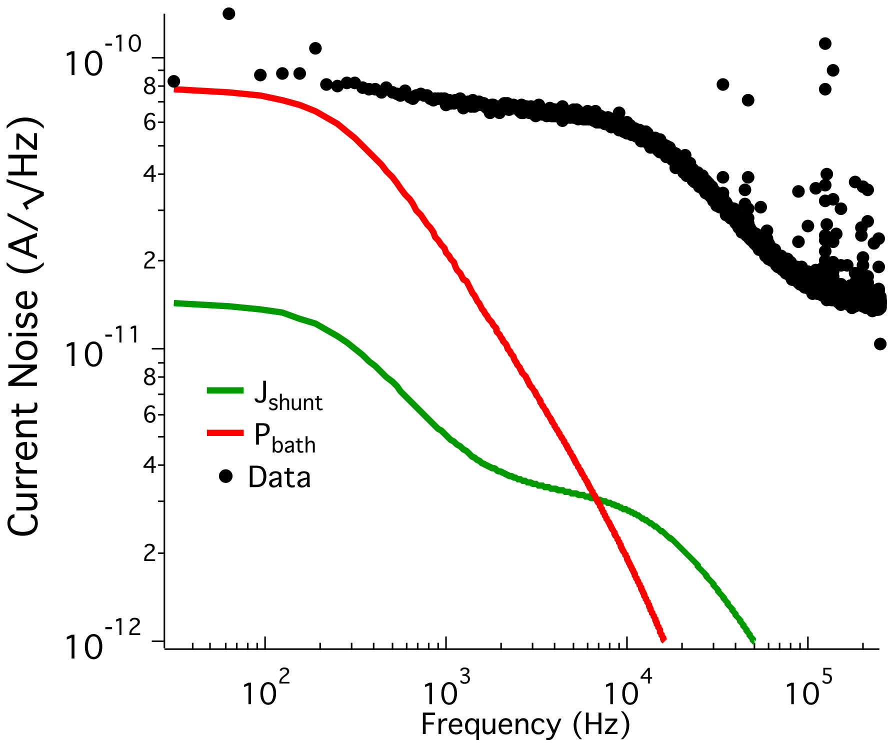
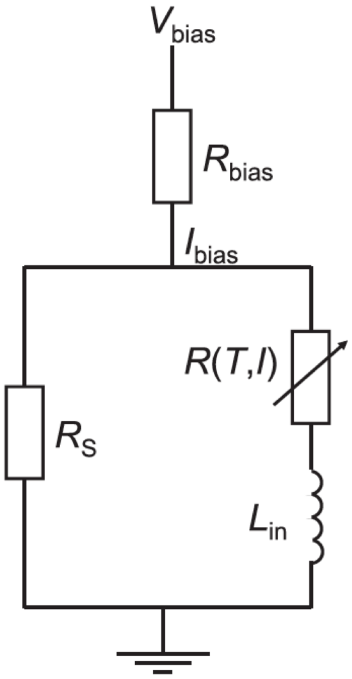
1. Thermal fluctuation noise between single body and bath
2. Johnson noise of shunt resistor J_{shunt}





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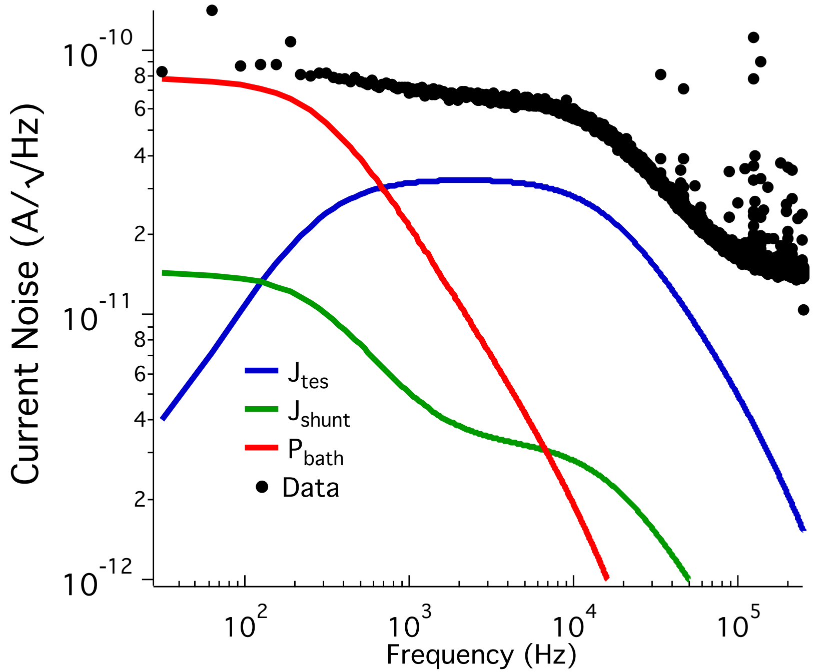
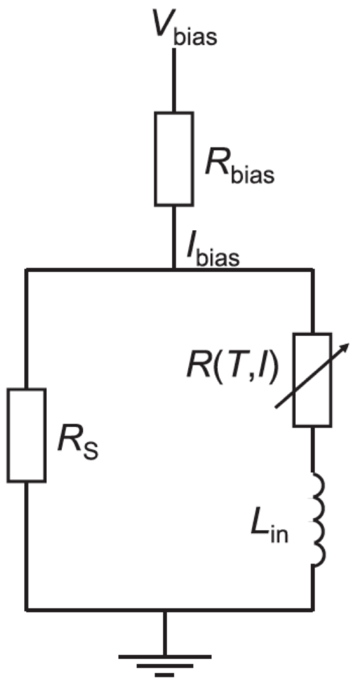
Simplest model of TES is a single body connected to bath by thermal conductance G_{bath}

3 contributions to current noise:

1. Thermal fluctuation noise between single body and bath
2. Johnson noise of shunt resistor
3. (non-equilibrium) Johnson noise of TES J_{tes}

K. D. Irwin Nuclear Instruments and Methods in Physics Research A 559 (2006) 718–720





Noise in excess of single-body model

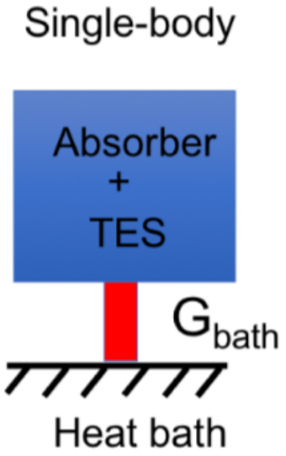
Can fit to measured data by adding another term $M^2\ J_{tes}$

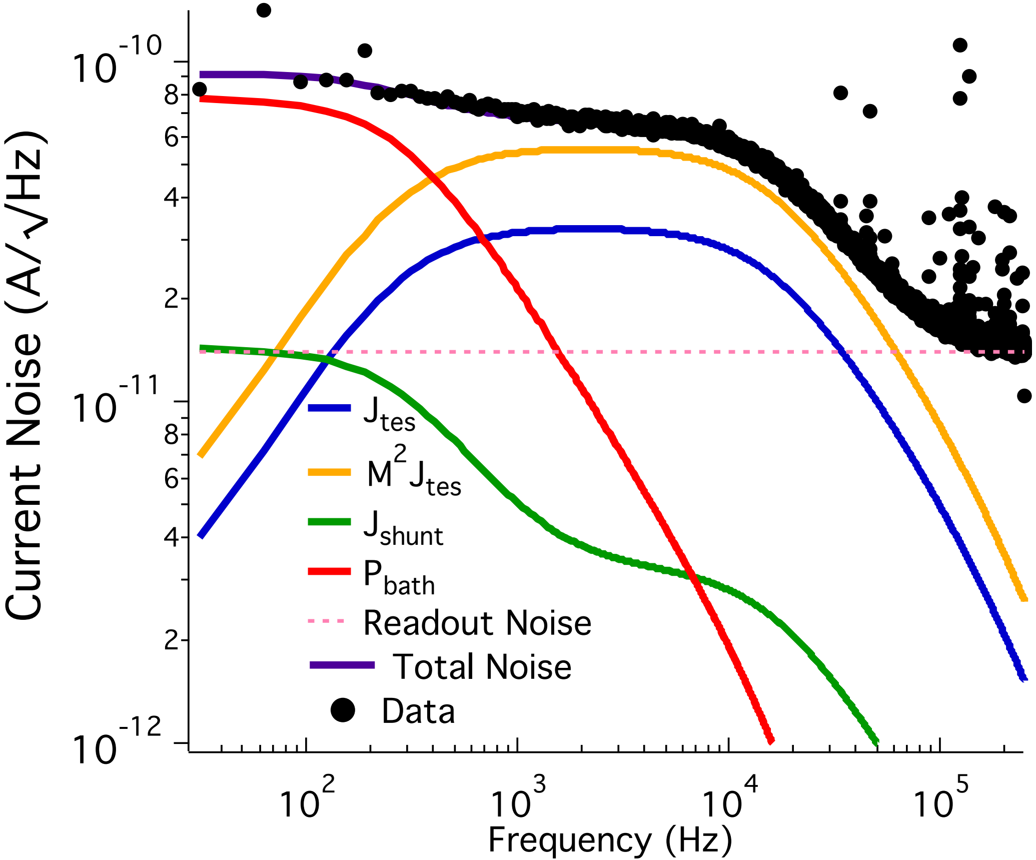
Smith et al. J. Appl. Phys. 114, 074513 (2013);

$$V_n = \sqrt{(4K_BTR)(1+2\beta)(1+M^2)}$$

M^2 then parameterizes the magnitude of the excess noise in the device.

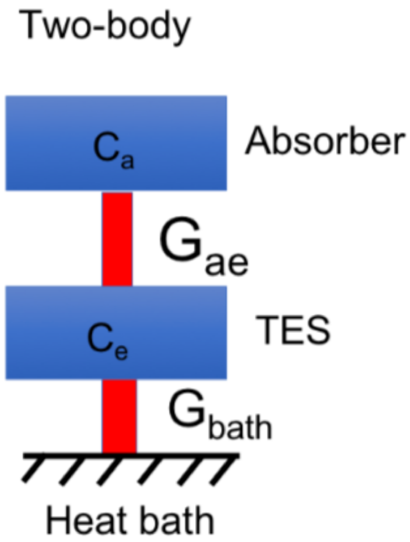
But what is the origin of this excess noise term?





Two-body model

In two-body model, absorber and TES (for example) are separated by thermal conductance G_{ae}



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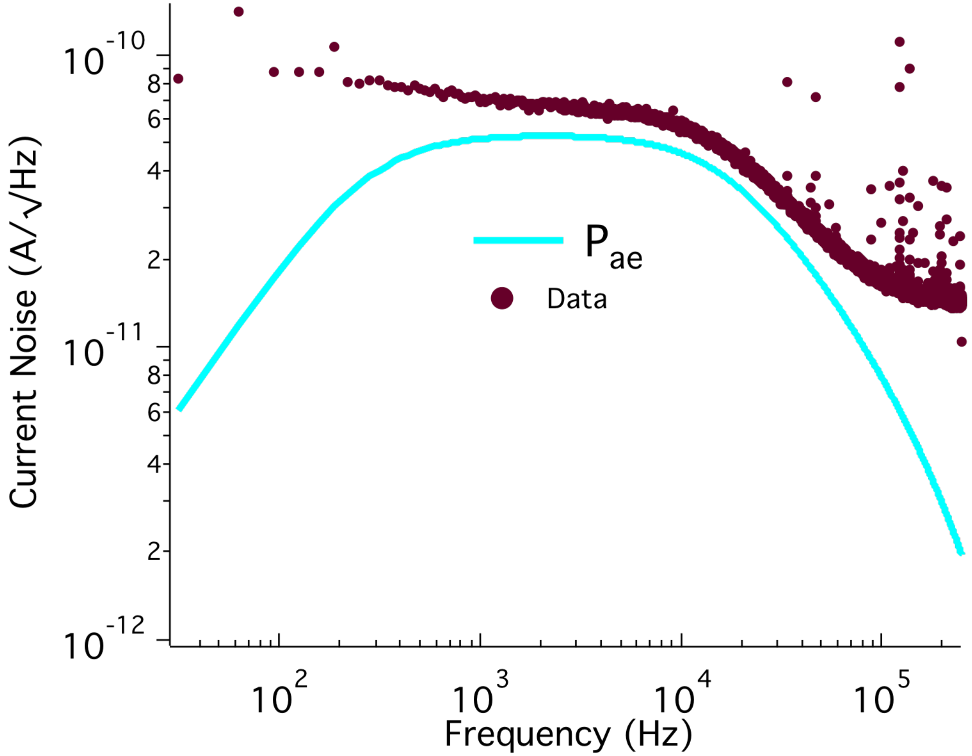
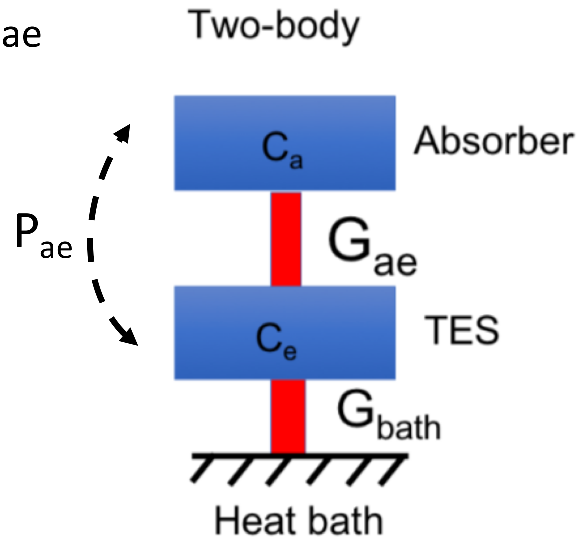
- Internal thermal fluctuation noise between the two bodies. - P_{ae}





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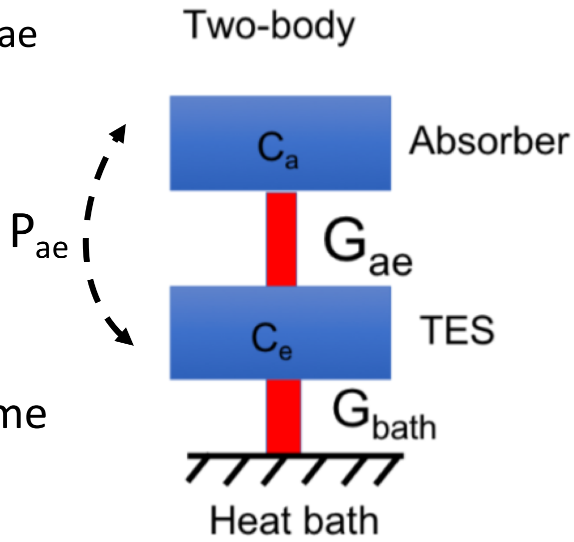

No new theory here. It has been described by many others…

M. A. Lindeman, Ph.D. thesis, UC Davis, 2000;
Lindeman et al. Review of Scientific Instruments 75, 1283 (2004)
I. J. Maasilta AIP Advances 2, 042110 (2012);
E Figueroa-Feliciano et al. Journal of Applied Physics 99 , 114513 (2006);
…………et al.

This additional noise has also been found to be significant in some cases

H. F. C. Hoevers et al. Appl. Phys. Lett. 77 , 4422 (2000);
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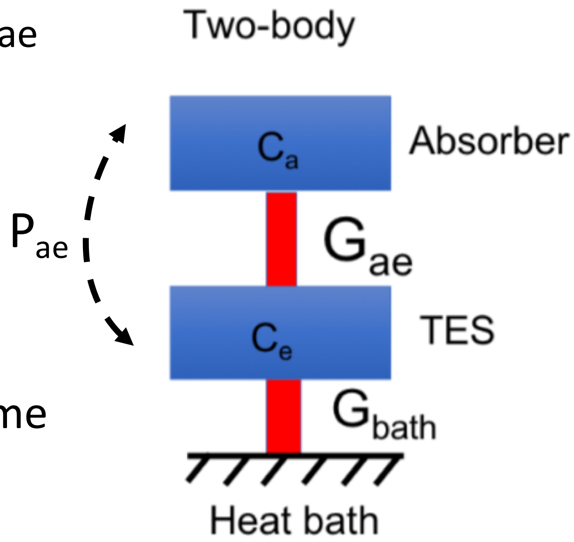

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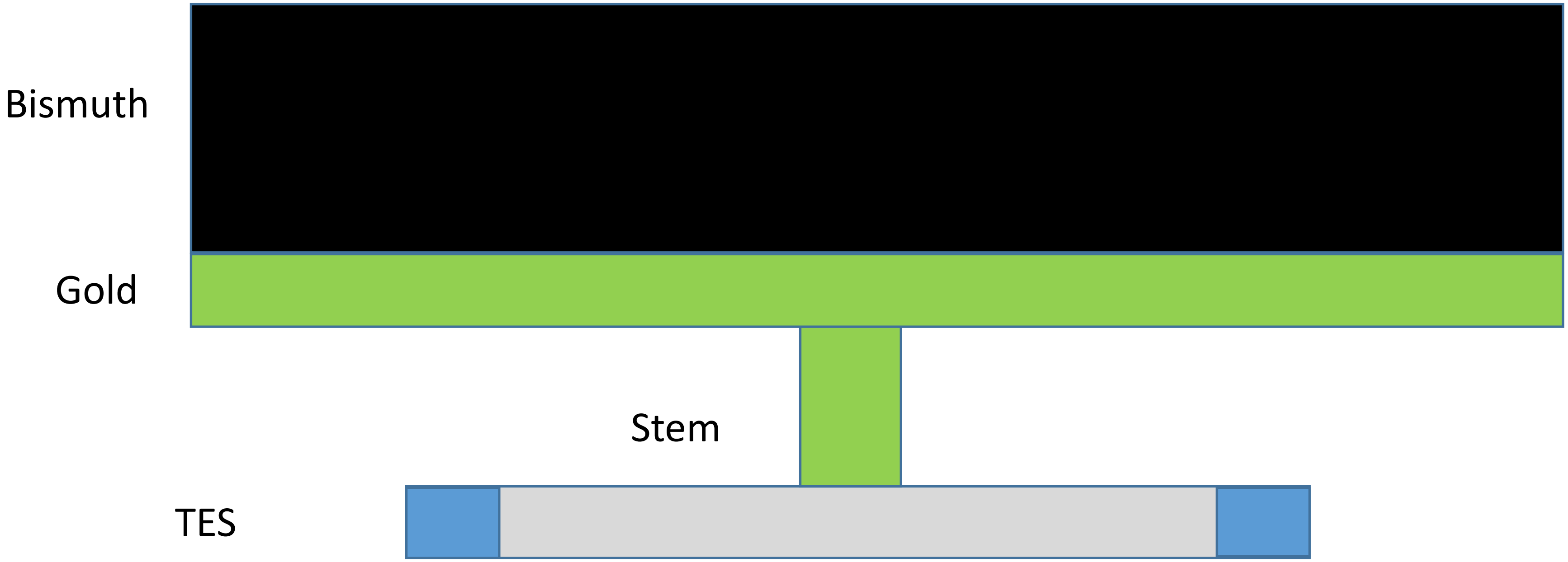
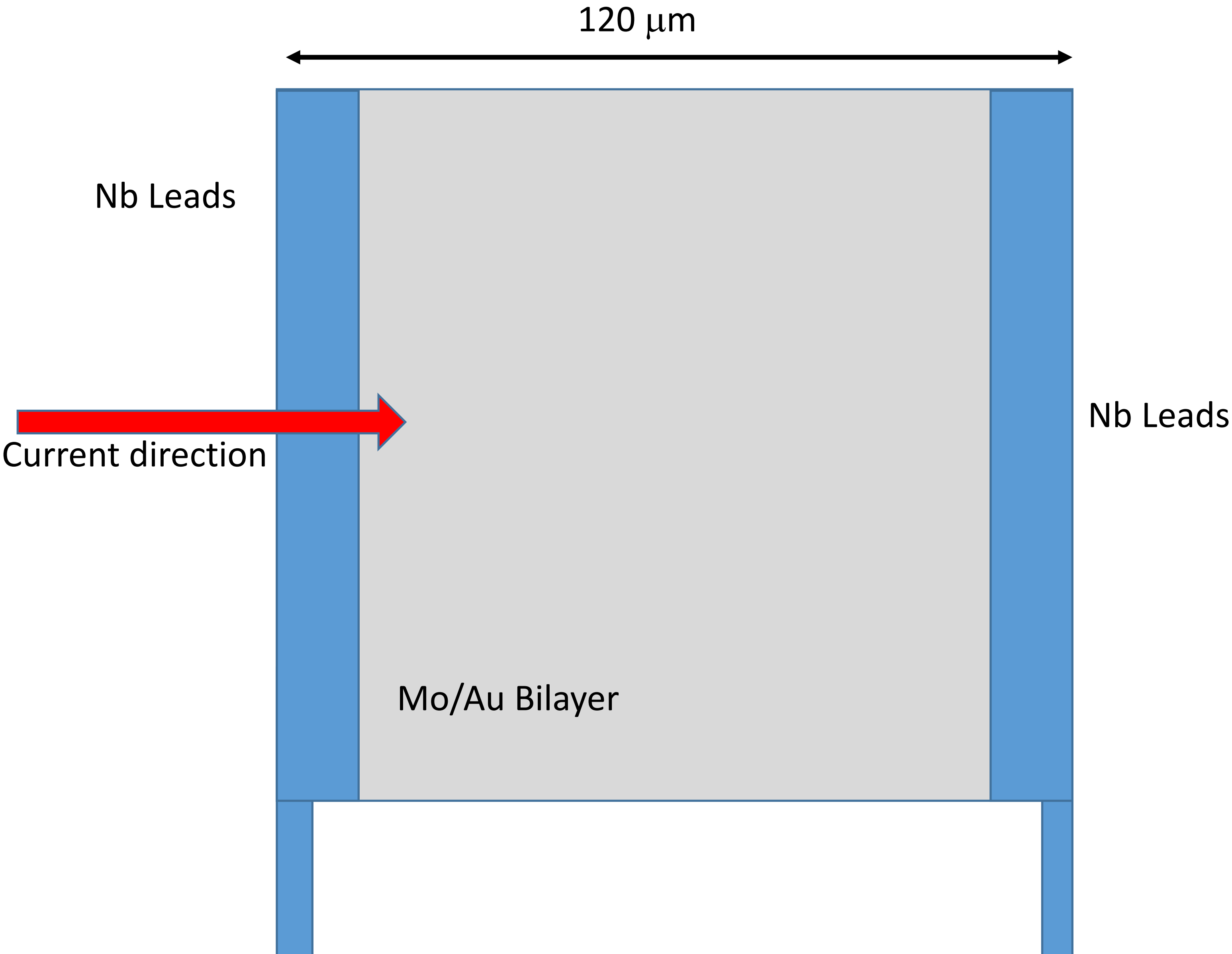
Central question:
In latest NASA Mo/Au bilayer TESs is internal thermal fluctuation noise significant?

TES design - Side view

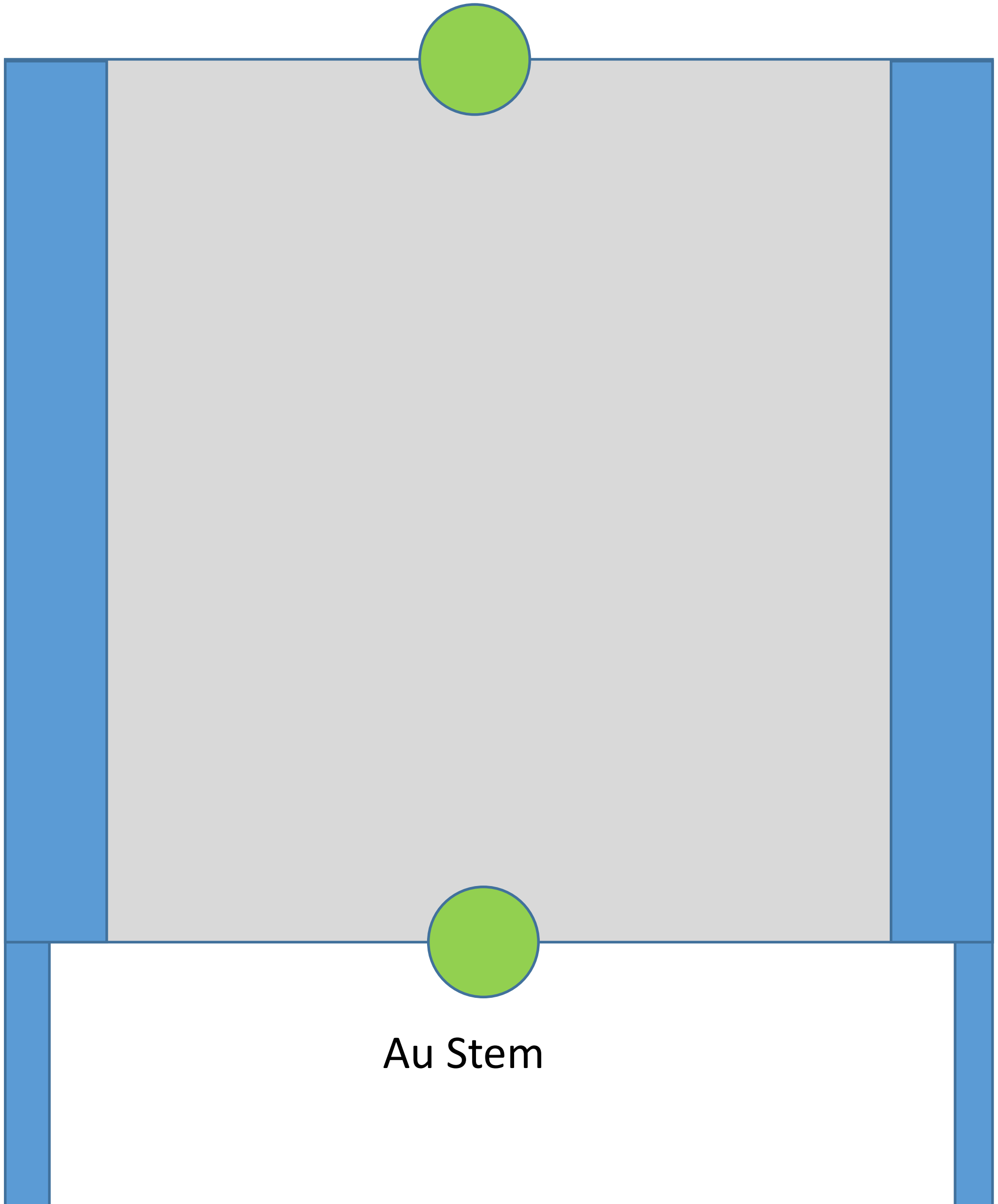


TES design – Top View



Top view

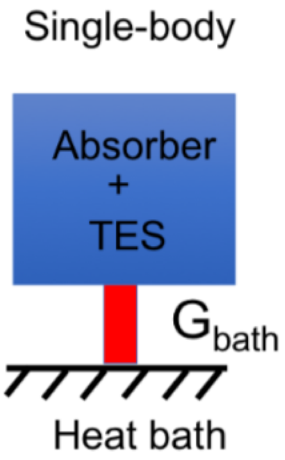
Absorber stems are pillars



We have measured complex impedance and noise

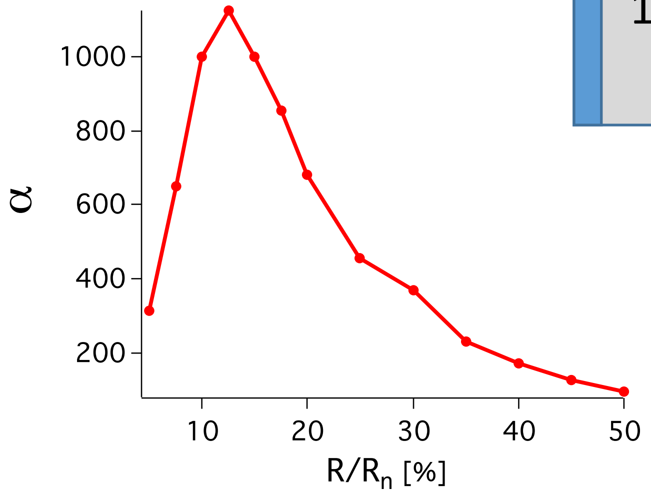
Extract transition properties and estimate noise contributions

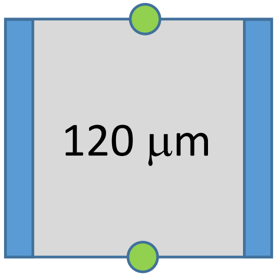
Single-body



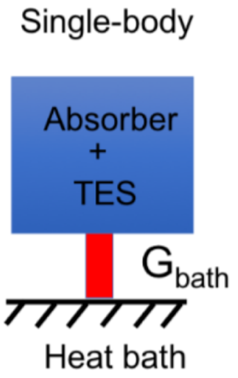
Complex Impedance

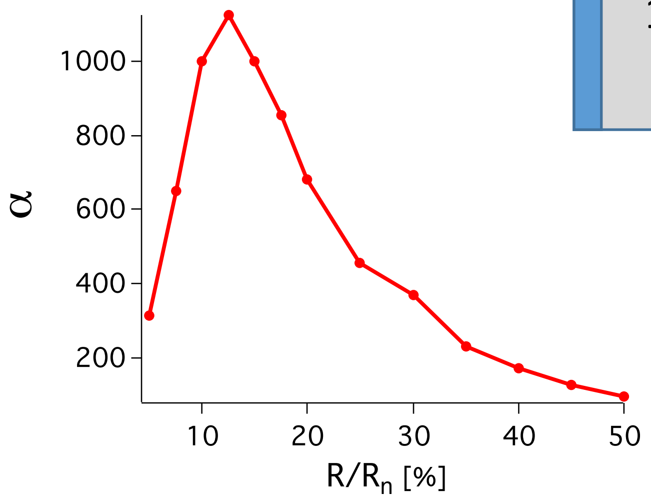
$\alpha = T/R \, \mathrm{d}R/\mathrm{d}T$

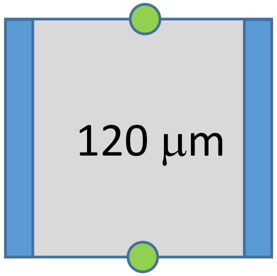


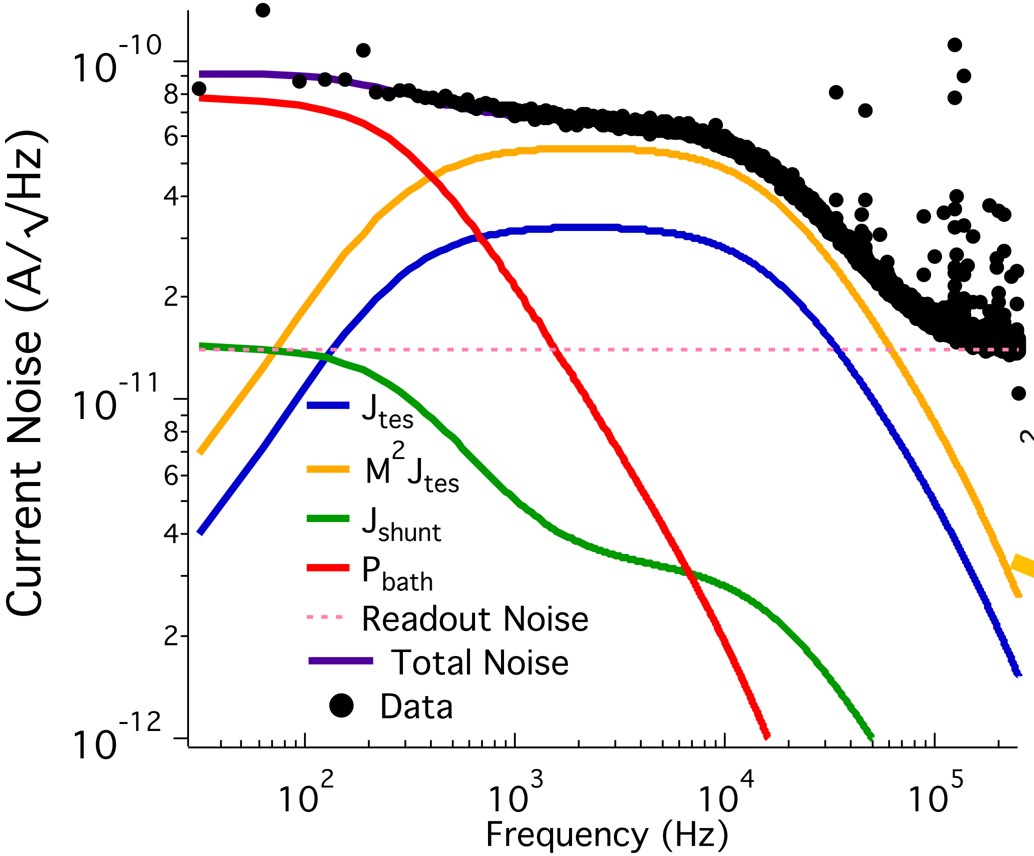


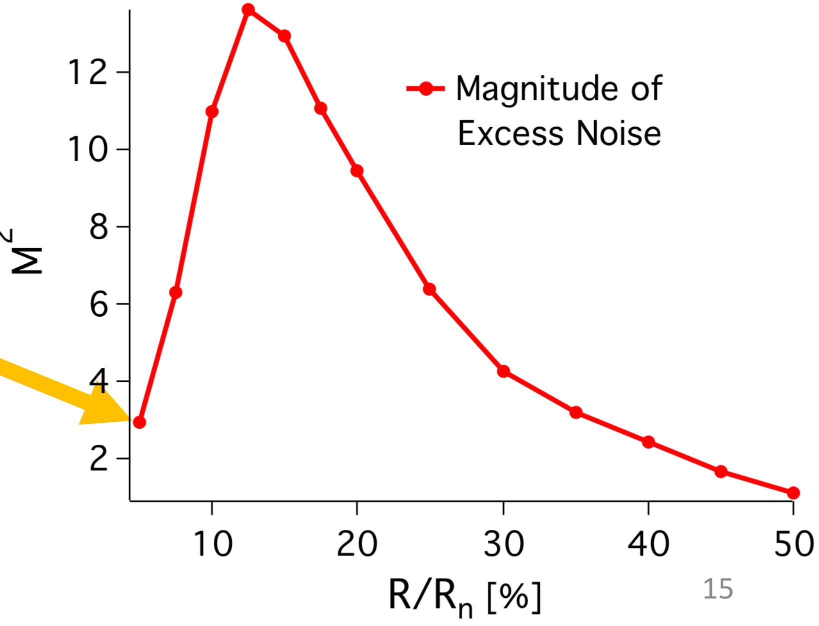
Single-body


Single-body
Absorber
+
TES
G$_{bath}$
Heat bath

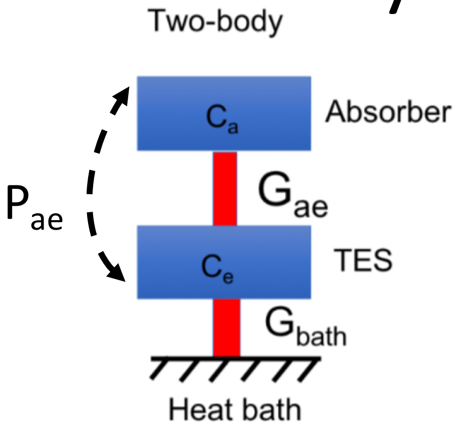

α
1000
800
600
400
200
10
20
30
40
50
R/R$_n$ [%]


120 μm


Current Noise (A/√Hz)
10^{-10}
8
6
4
2
10^{-11}
8
6
4
2
10^{-12}
10^{2}
10^{3}
10^{4}
10^{5}
Frequency (Hz)
J$_{tes}$
M^{2}J$_{tes}$
J$_{shunt}$
P$_{bath}$
Readout Noise
Total Noise
Data


M^2
12
10
8
6
4
2
10
20
30
40
50
R/R$_n$ [%]
Magnitude of Excess Noise

Two-body

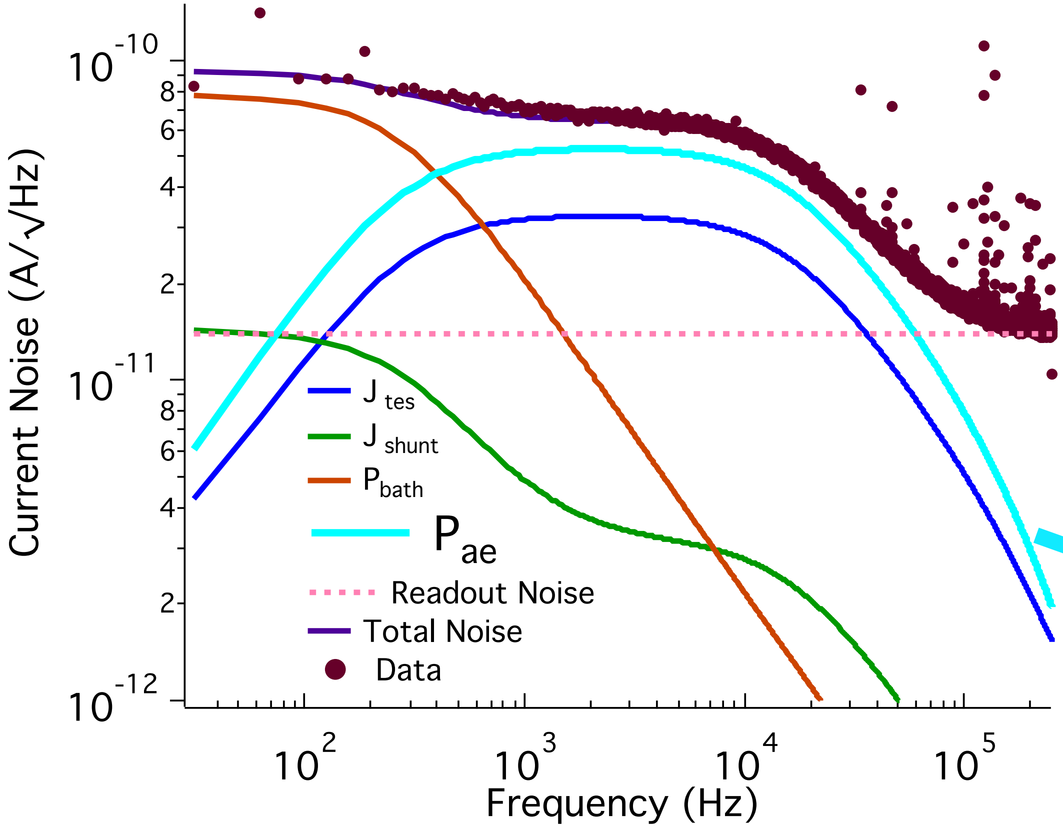


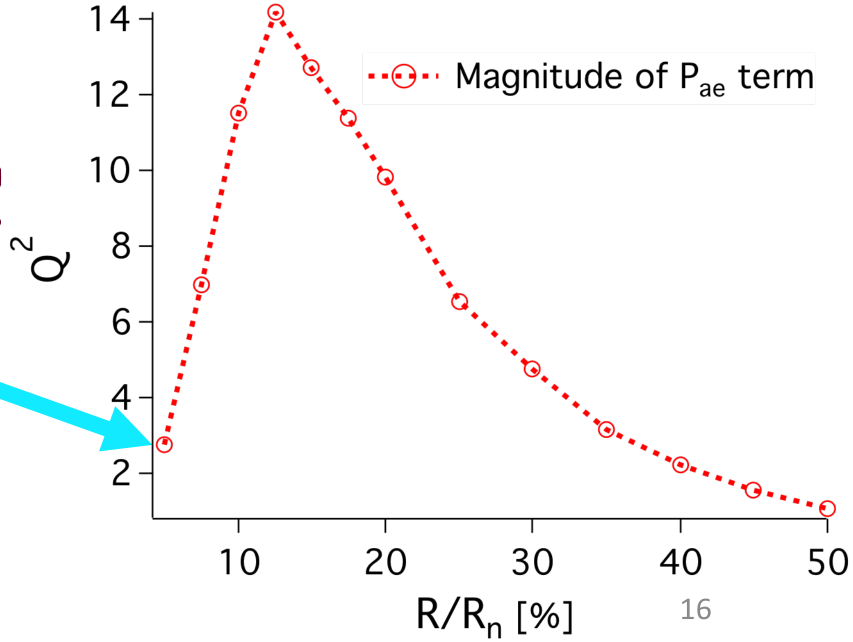
Attribute excess noise to internal thermal fluctuation noise - P_{ae}

No need for additional Johnson noise

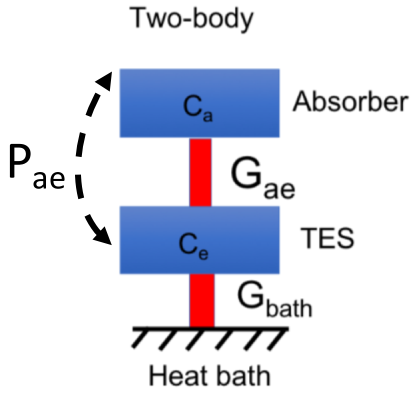
For convenience: Parameterize magnitude of P_{ae} term relative to the Johnson noise.

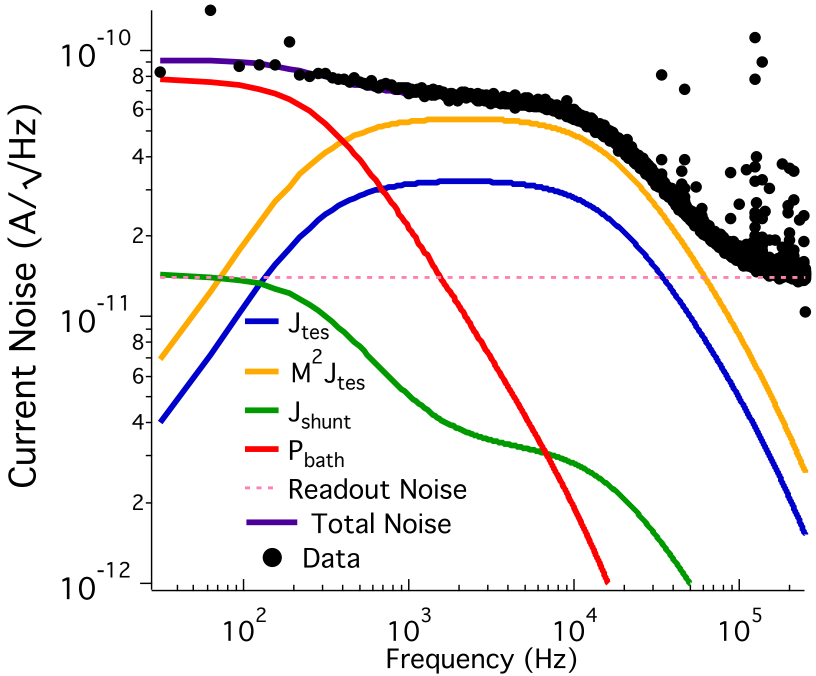
$$P_{ae} \simeq Q^2 J_{tes}$$

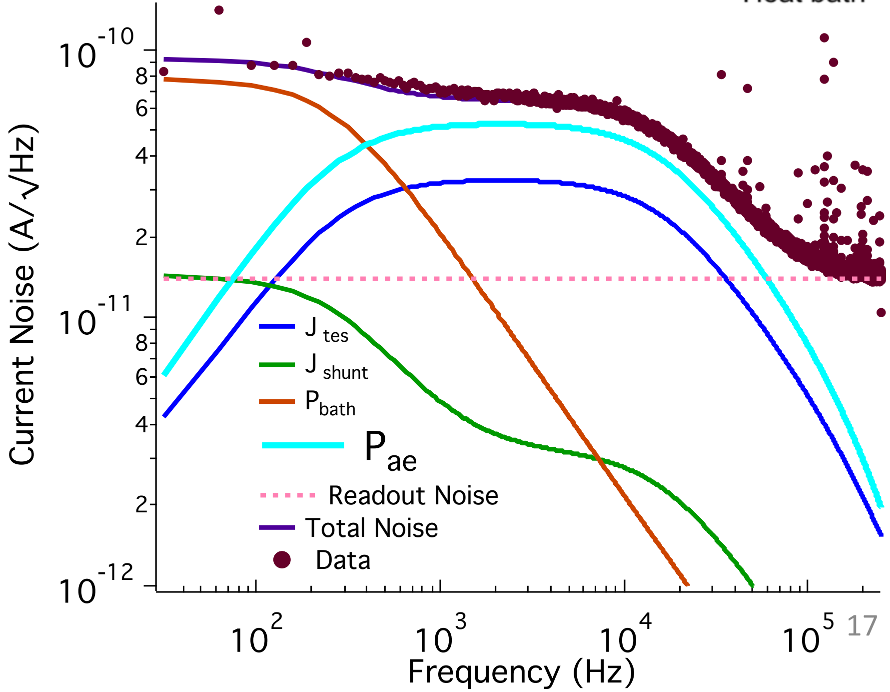




Single-body Vs Two-body







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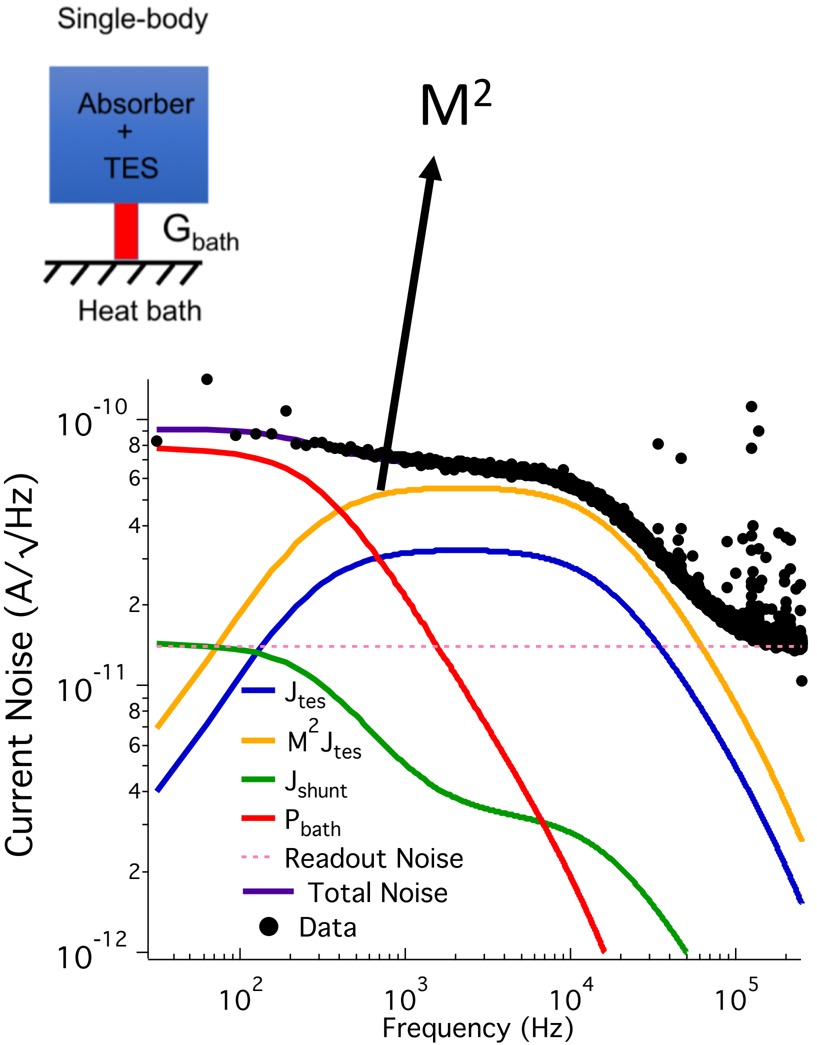

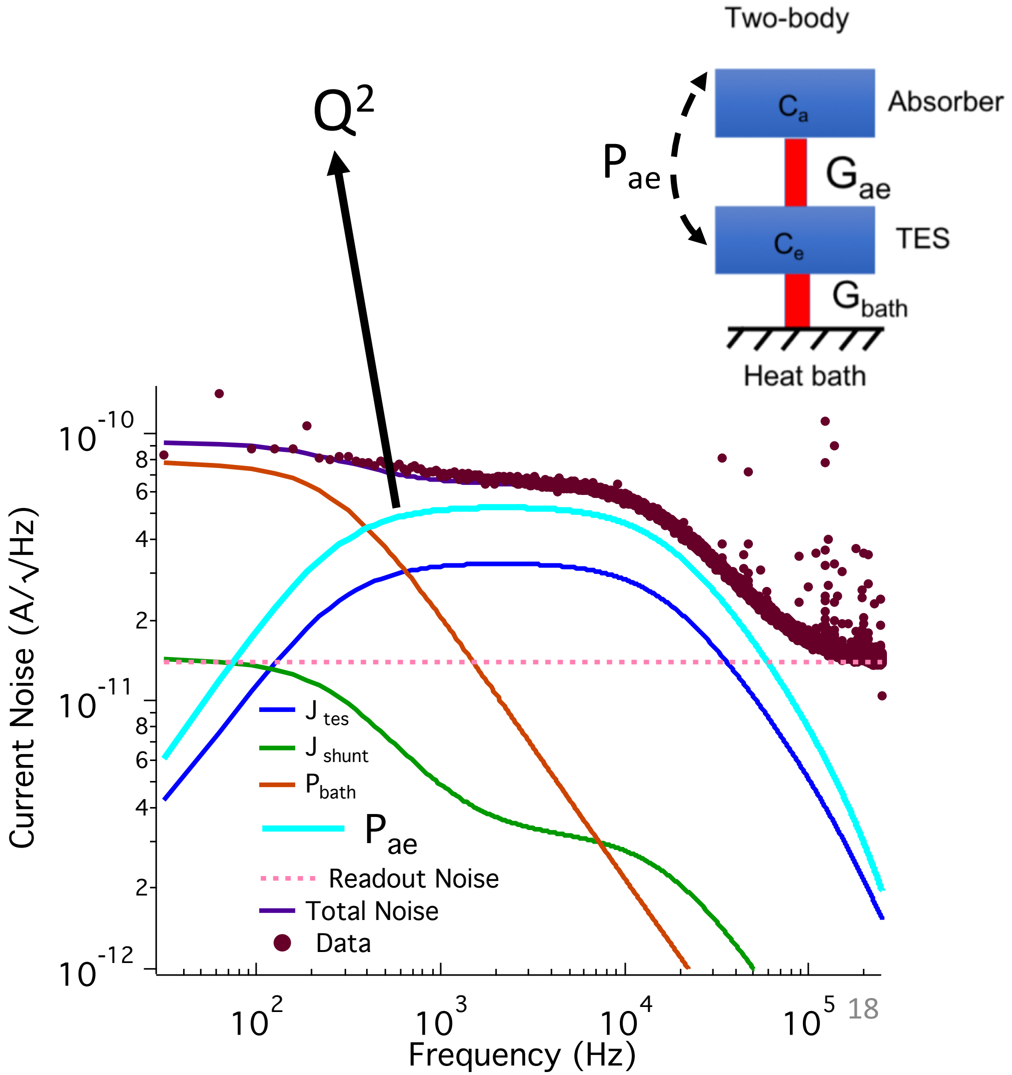

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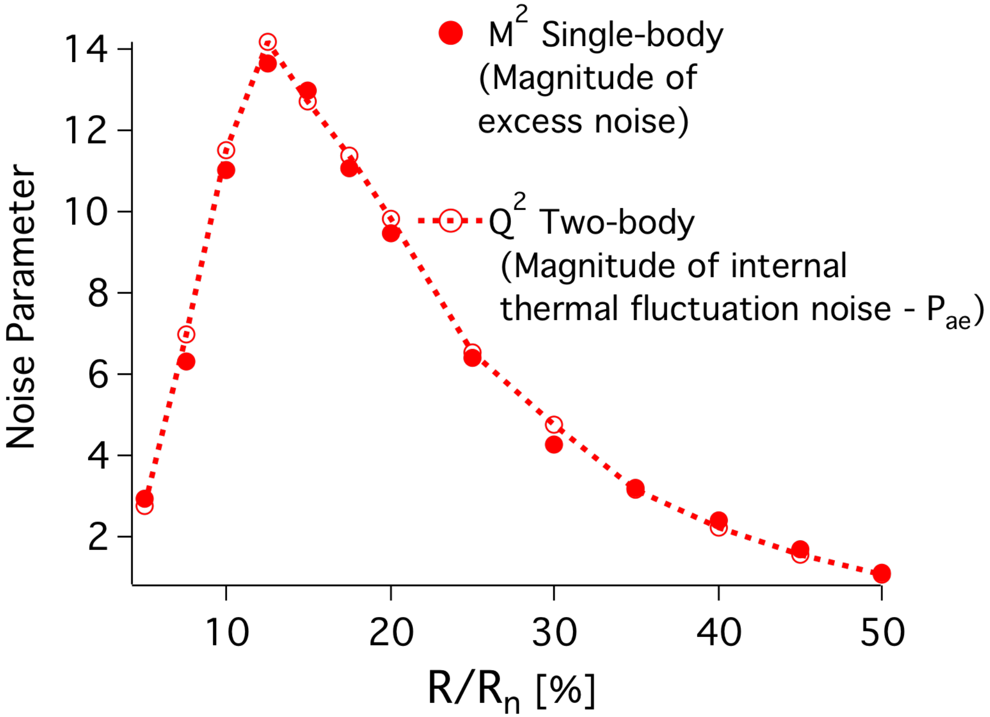

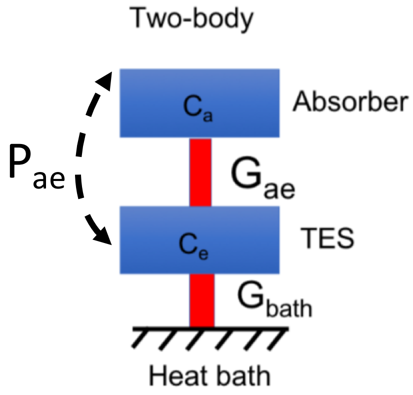

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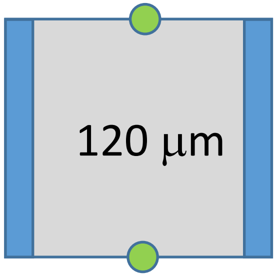
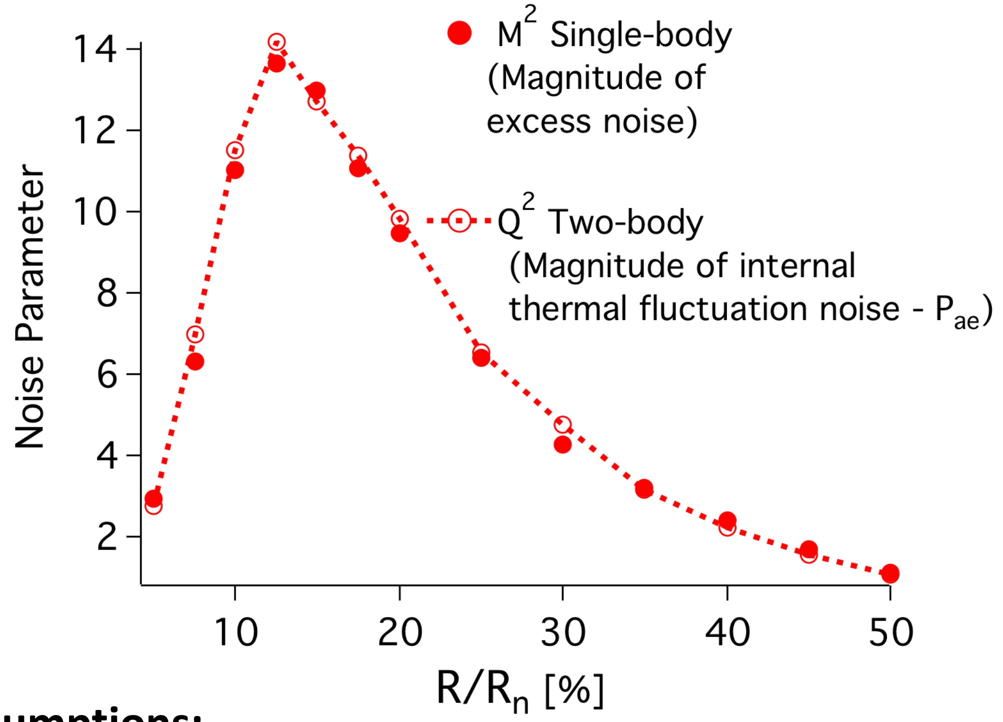
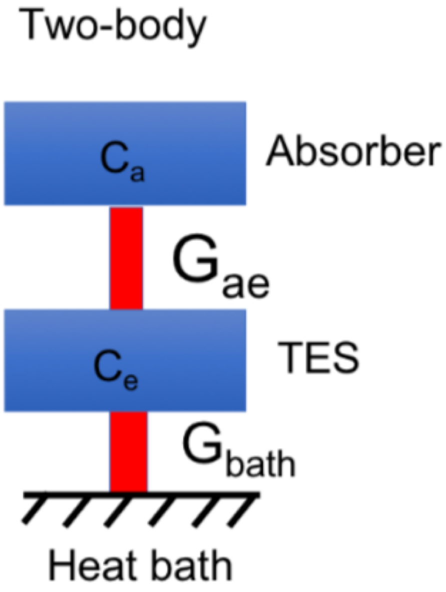






Two-body assumptions:

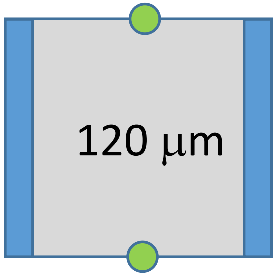
C_e = BCS Predicted C of TES including jump from superconductivity (+ membrane). **Relatively insensitive.**

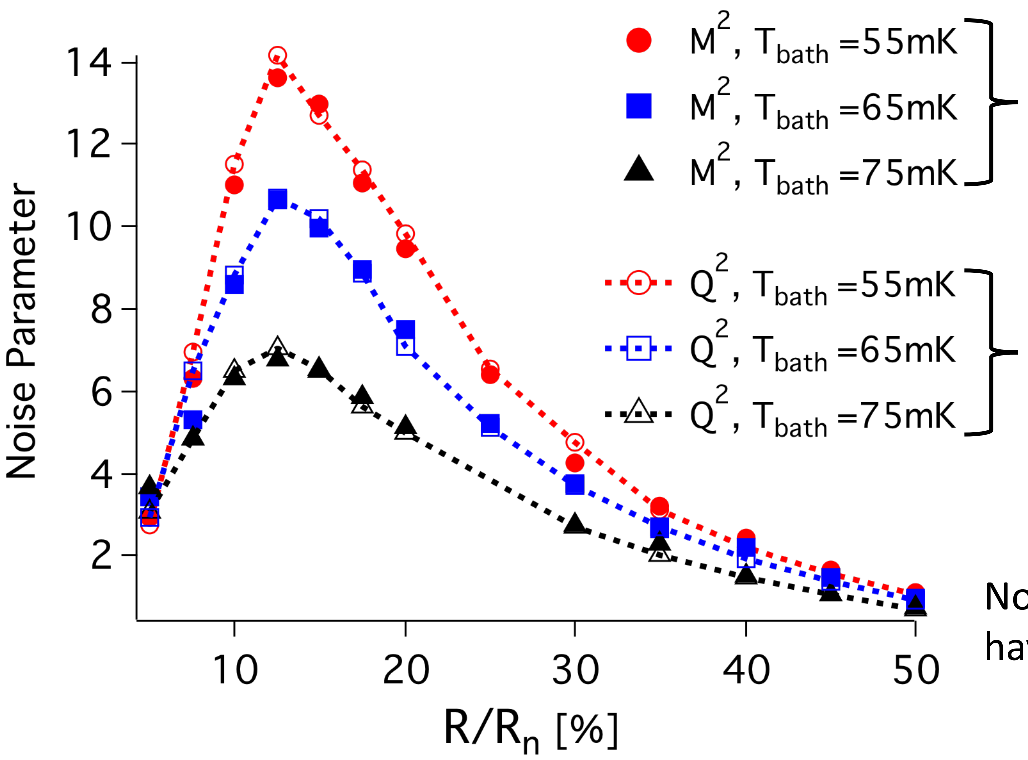
$C_a + C_e$ = measured heat capacity of device

G_{bath} is measured value

G_{ae} = constant in R/R_n

Variation with T_{bath}

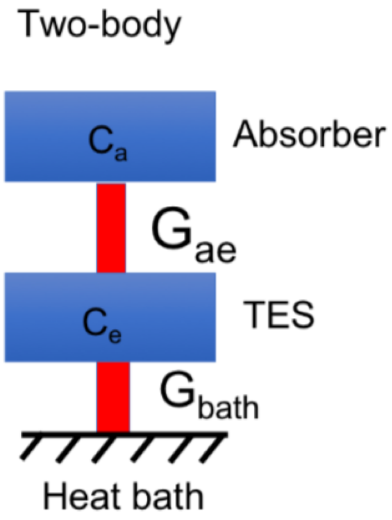




Single-body
(Excess Noise)

Two-body
(Internal Thermal
Fluctuation Noise)

Note: T_{bath} does not have big impact on α



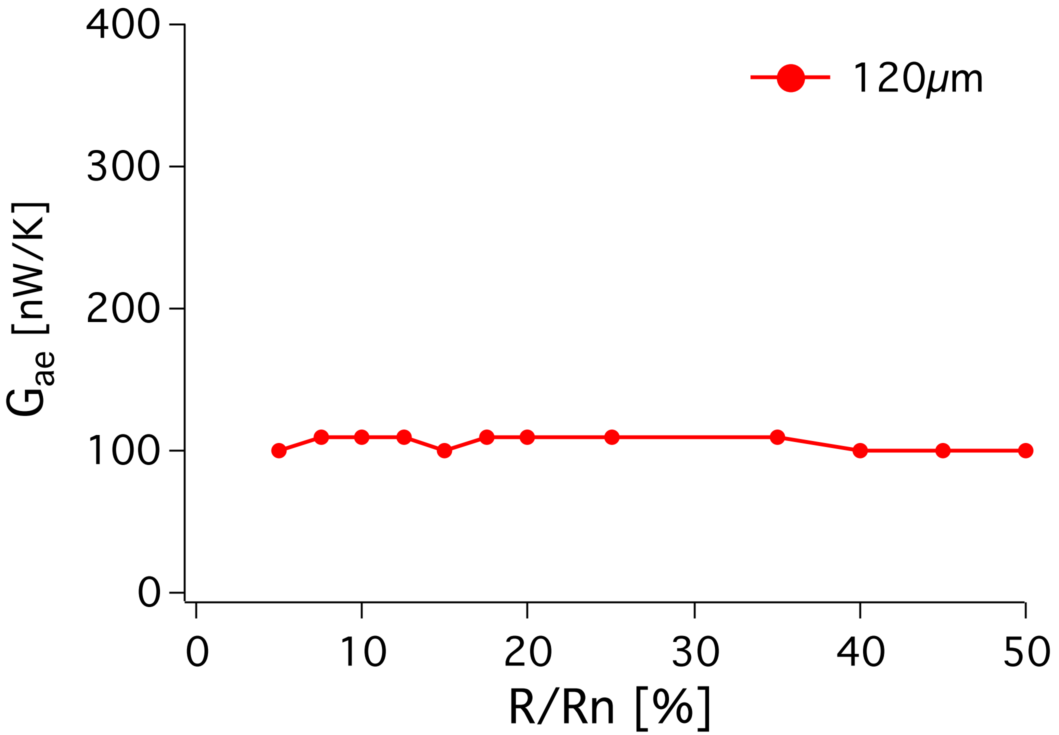
G_{ae} is a constant for all points on graph.

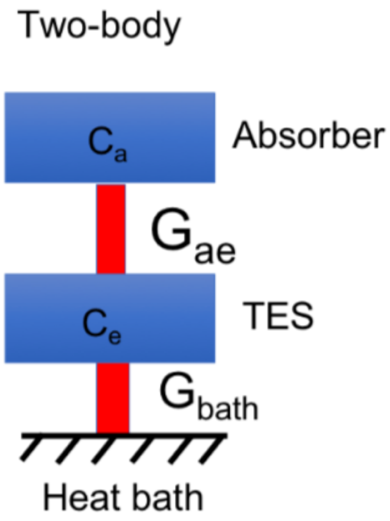
Measured excess noise well described by two-body model with fixed parameters over wide range of T_{bath} and R/R_n.

Variable G_{ae}

Allow G_{ae} to float in fitting of two-body model.

Largely independent of bias point



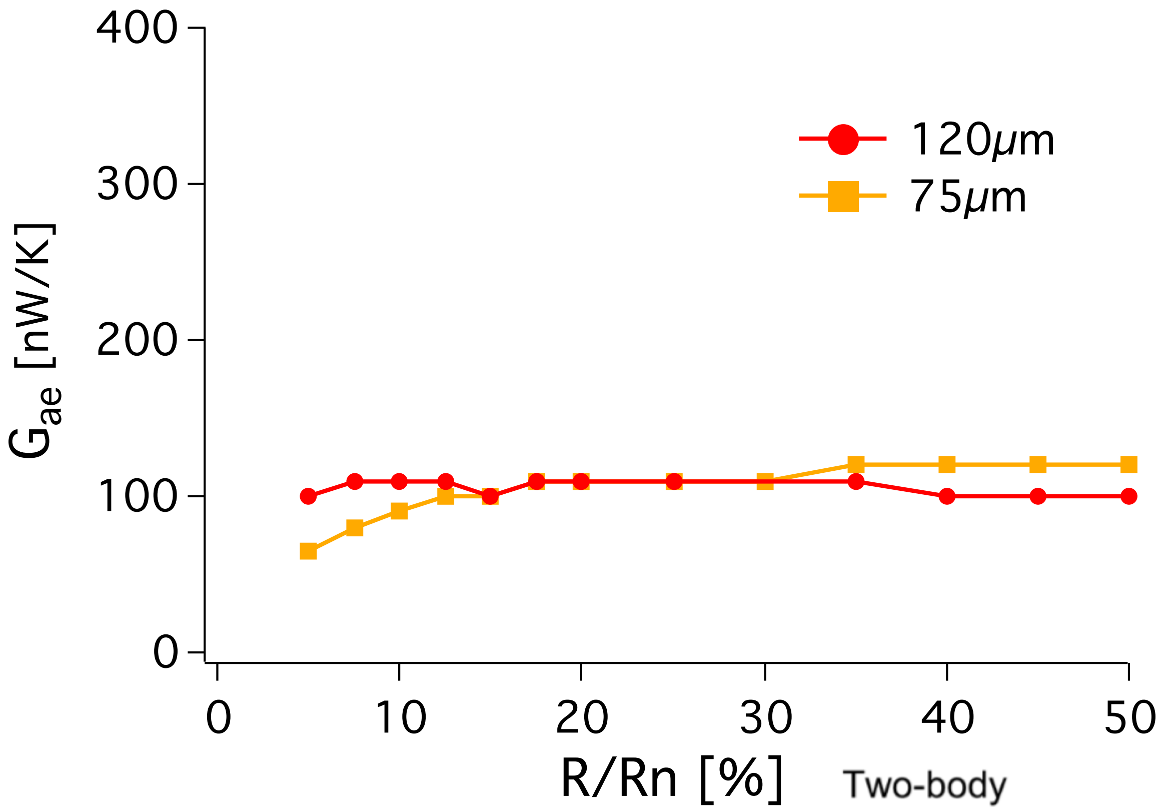


Variable G_{ae}

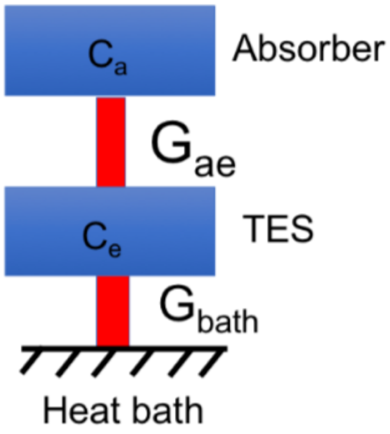
Allow G_{ae} to float in fitting.

Can then do same analysis on other devices

75µm TES



Two-body

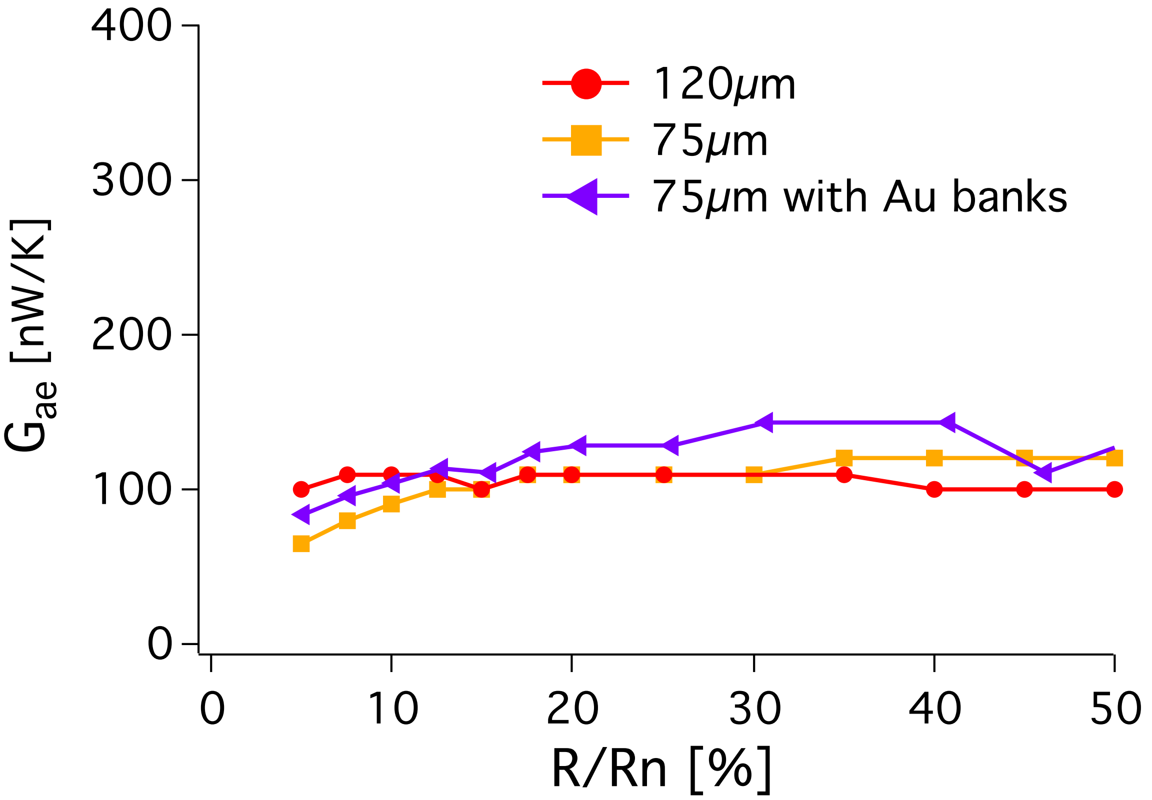


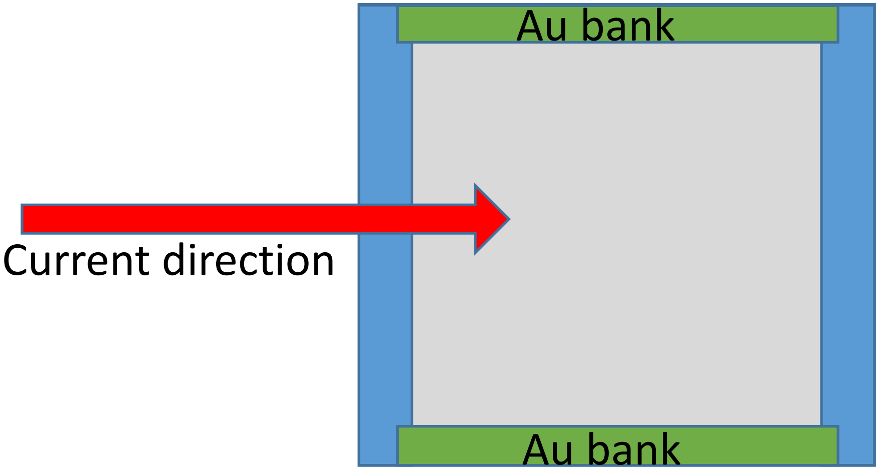
Variable G_{ae}

Allow G_{ae} to float in fitting.

Can then do same analysis on other devices

75μm TES with Au banks



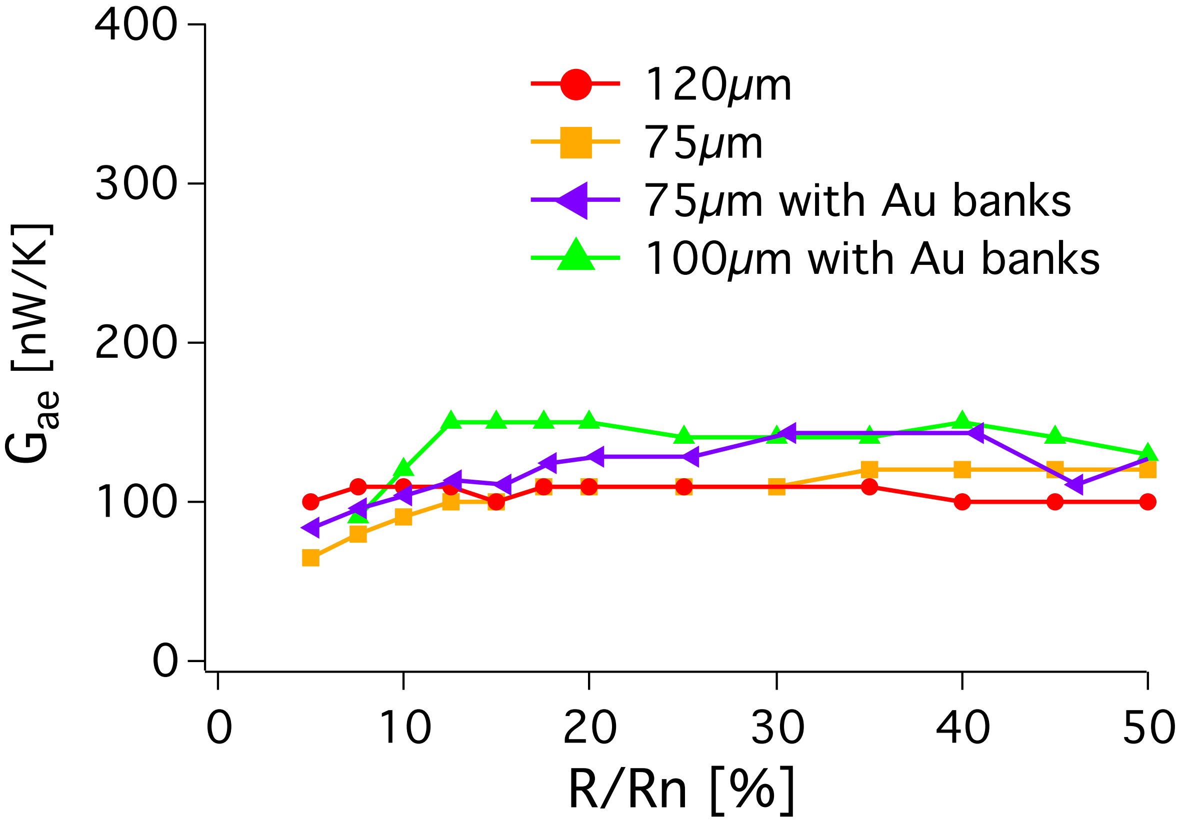


Variable G_{ae}

Allow G_{ae} to float in fitting.

Can then do same analysis on other devices

100µm TES with Au banks



- ➢ Little variation in fitted value G_{ae} ~ 100 nW/K

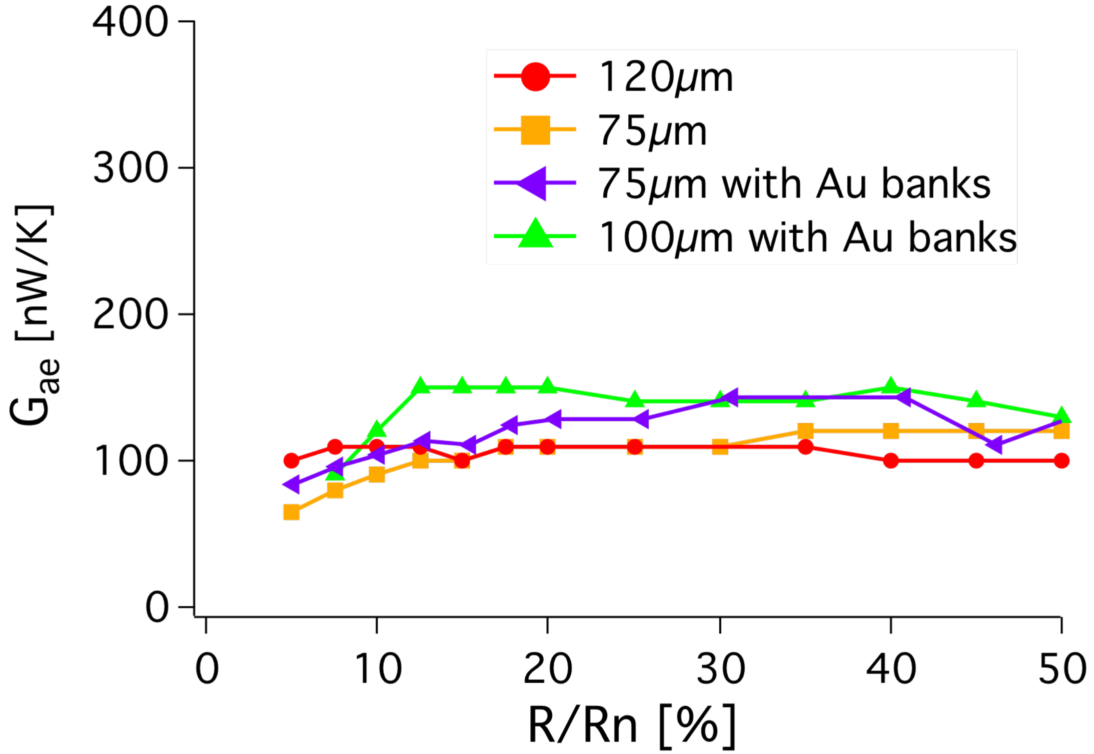
Variable G_{ae}

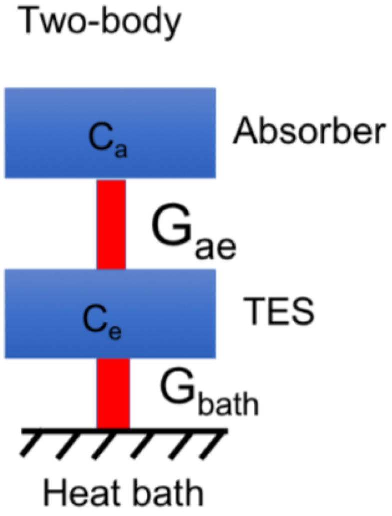
What is origin of finite G_{ae}?

Estimated G from stem pillars 90 μW/K
→ Too large

Estimated G from electron-phonon interaction 2 nW/K
→ Too small

Estimated G of bilayer from Wiedemann-Franz law and measured sheet resistance (50 mΩ/□)
→ 50 nW/K.





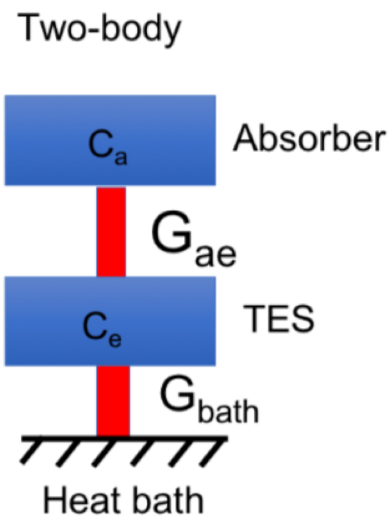
Suggests finite thermal conductance (G_{ae}) is from finite resistance of bilayer itself

Reported before in 200 mΩ Ti/Au bilayers *H. F. C. Hoevers et al. Appl. Phys. Lett. 77 , 4422 (2000);*

Low R bilayer

If bilayer resistance is responsible for internal thermal fluctuation noise.

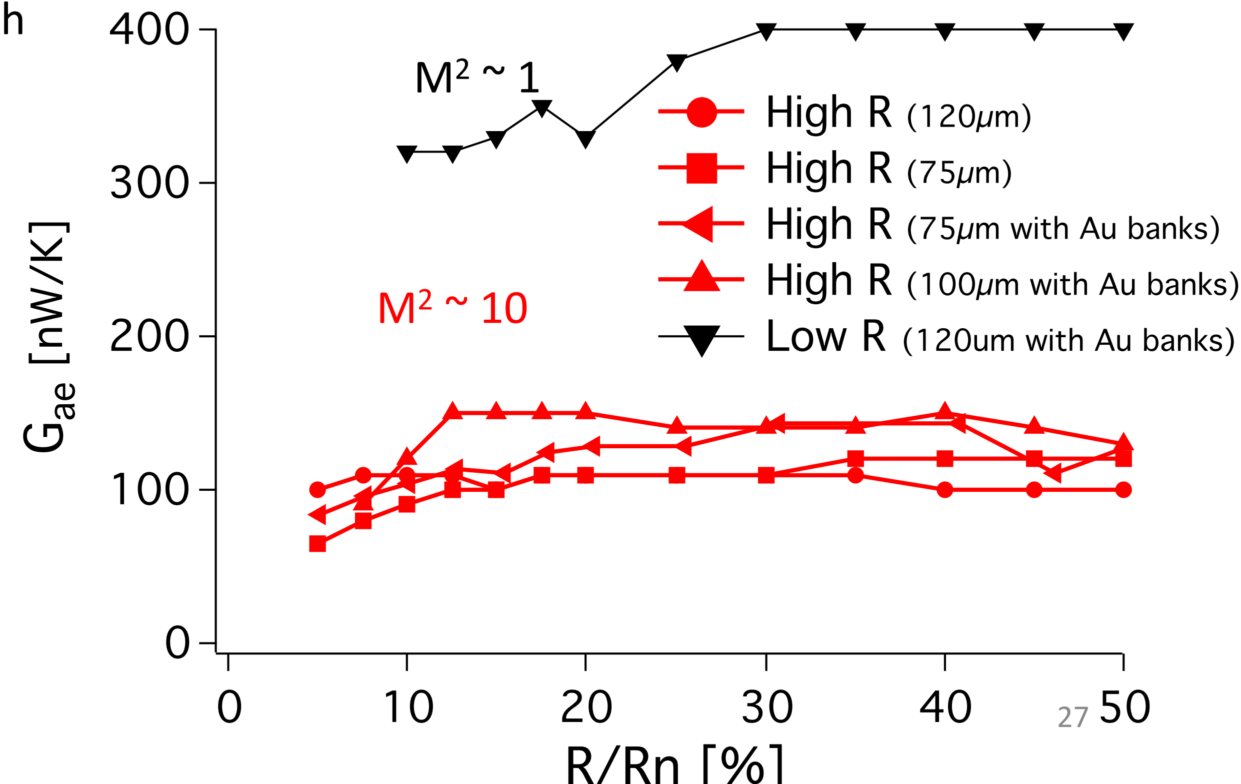
EXPECT: Lower R□ bilayer → Higher G_{ae}



Measured and fitted devices with bilayer with factor ~4 smaller R□

Fitted G_{ae} ~ factor 4 larger

Clearly a crude estimate of thermal conductance of TES but captures coarse trends.



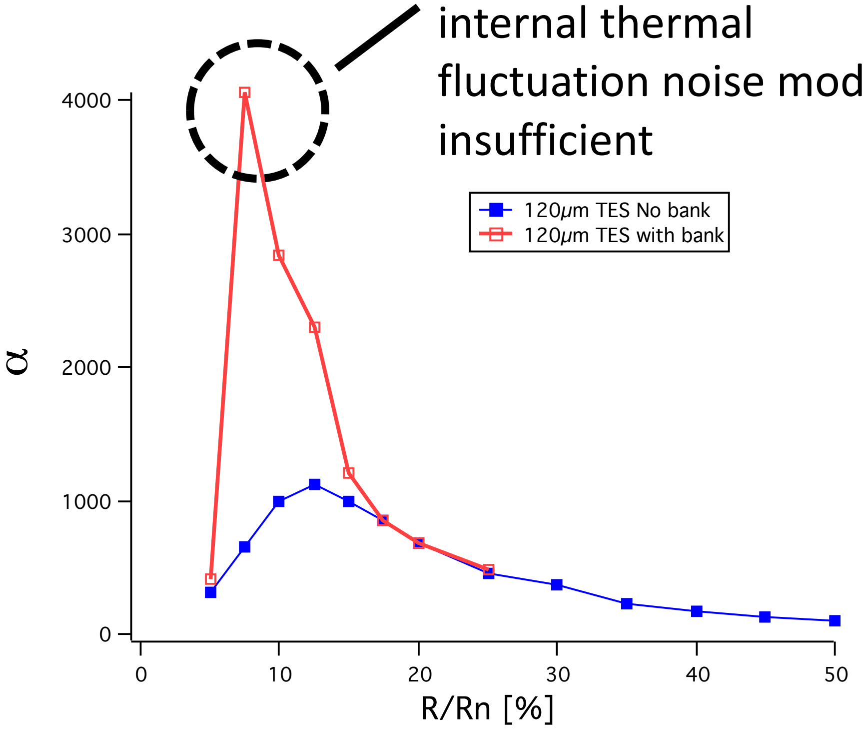
Where two-body model doesn’t work…

Cannot fit within our assumptions around kinks

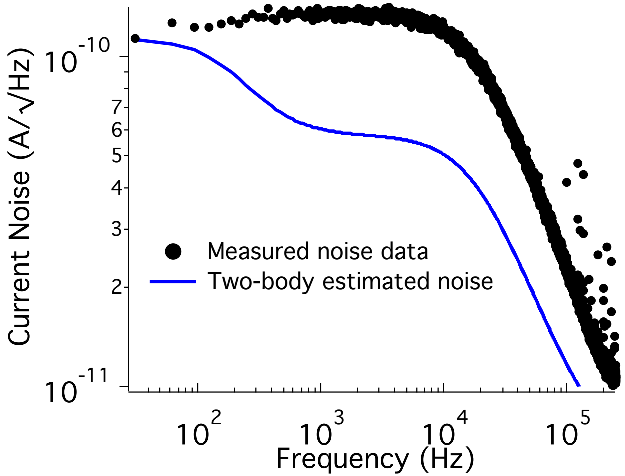
- Regions with rapid changes in α.
- For example in this 120μm device with banks.

No stripes → smoother transitions.

Perhaps in other devices small transition features may have given additional noise largely not present in our small no-stripe devices



Around spike like this in α internal thermal fluctuation noise model is insufficient



Conclusion

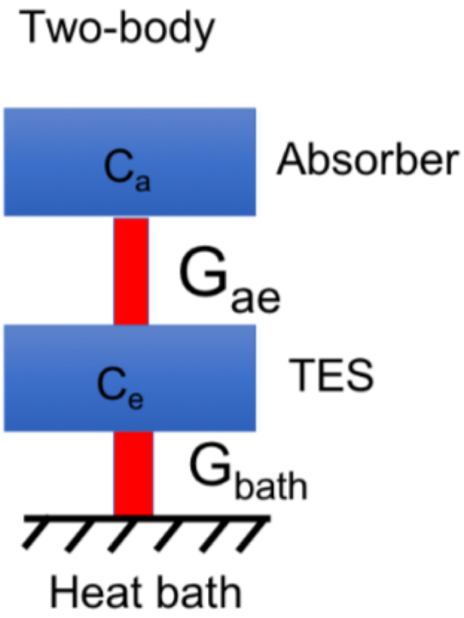
Fit measured noise in our “no-stripe” devices with a two-body model.

Internal thermal fluctuation noise appears to dominate excess noise

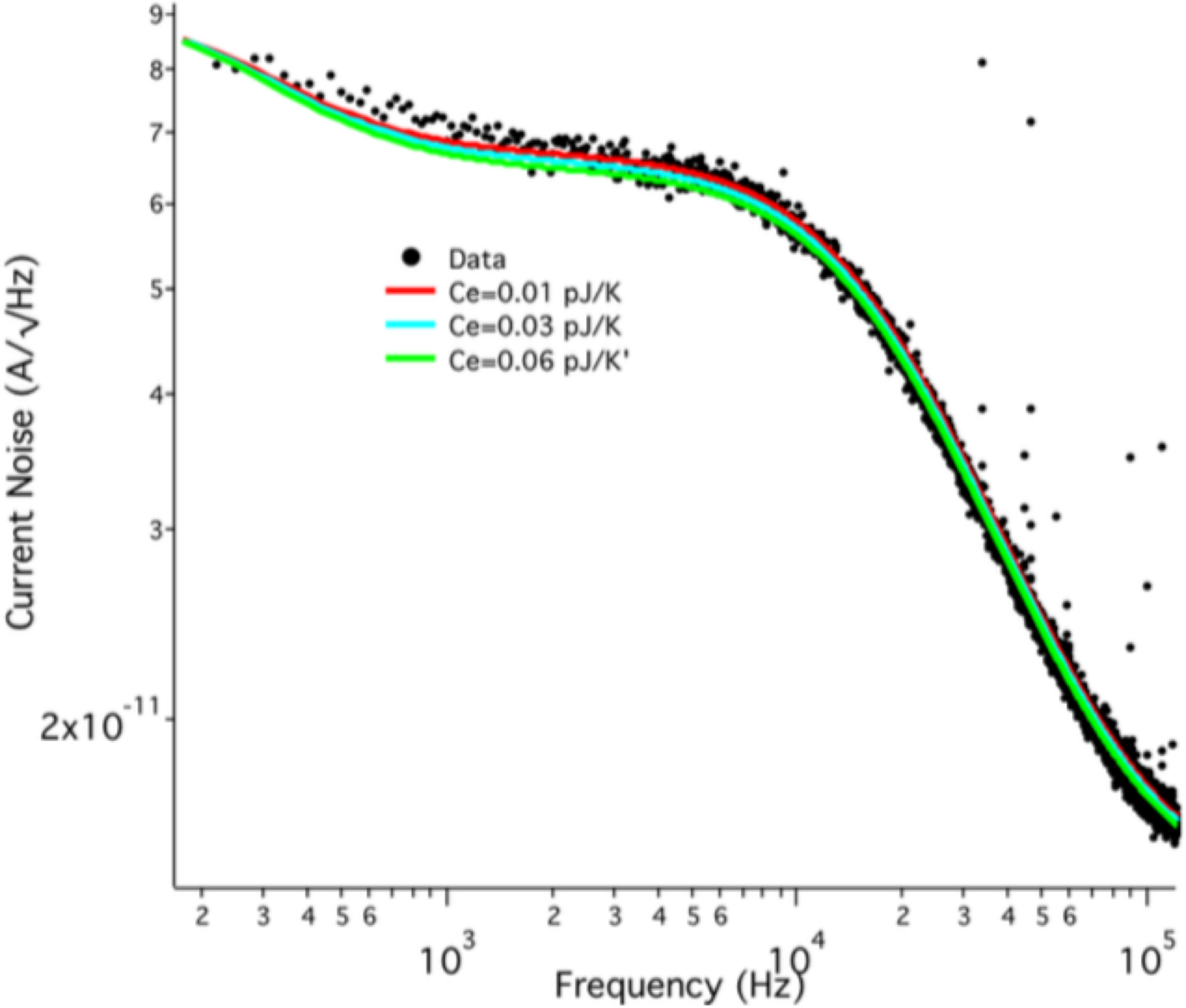
Finite thermal conductance responsible appears to be from resistance of the bilayer.

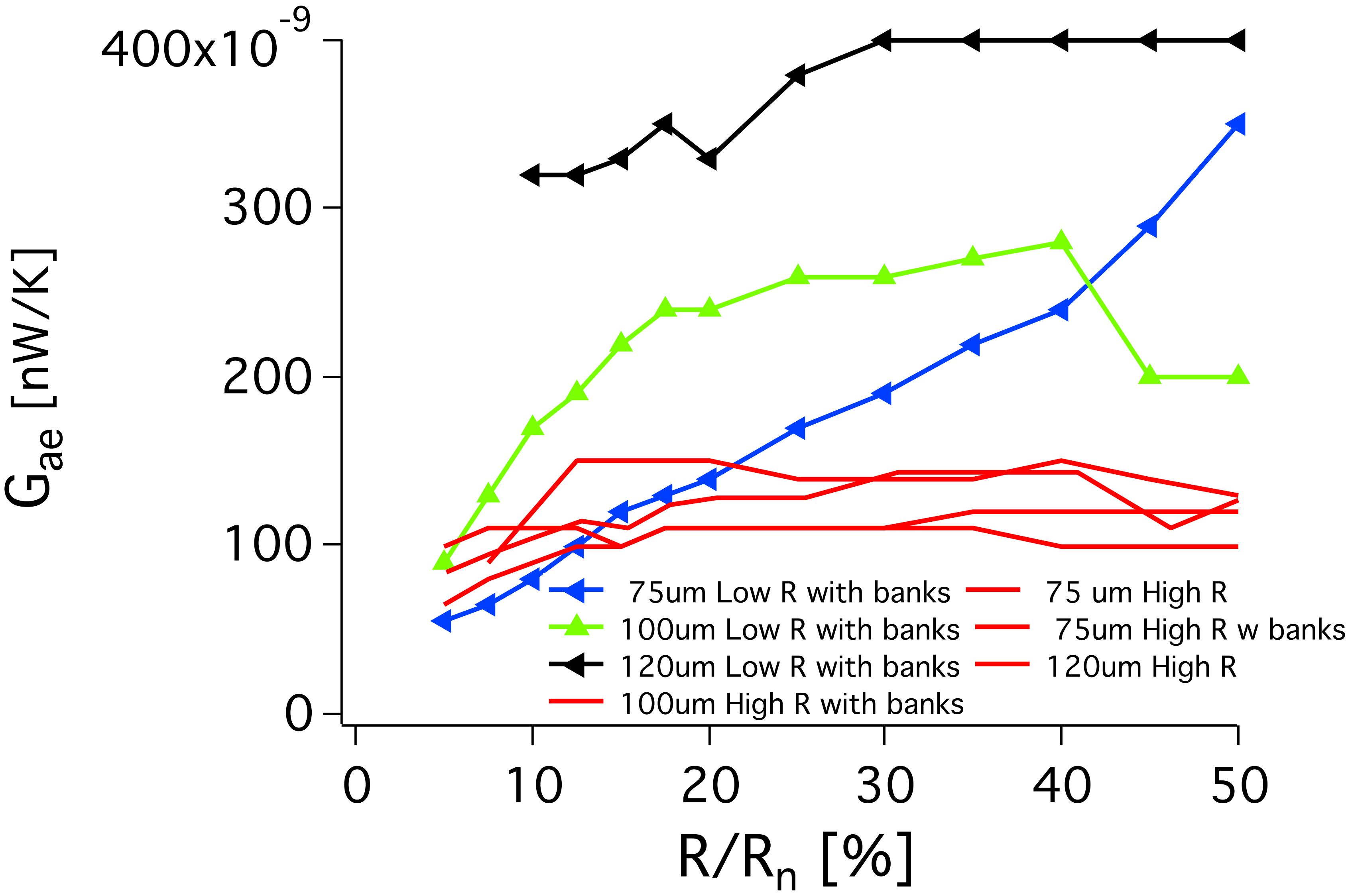
In regions with rapidly changing α this model is insufficient.

It’s likely there that an additional noise mechanism may be present in that case.



Insensitivity to C_e



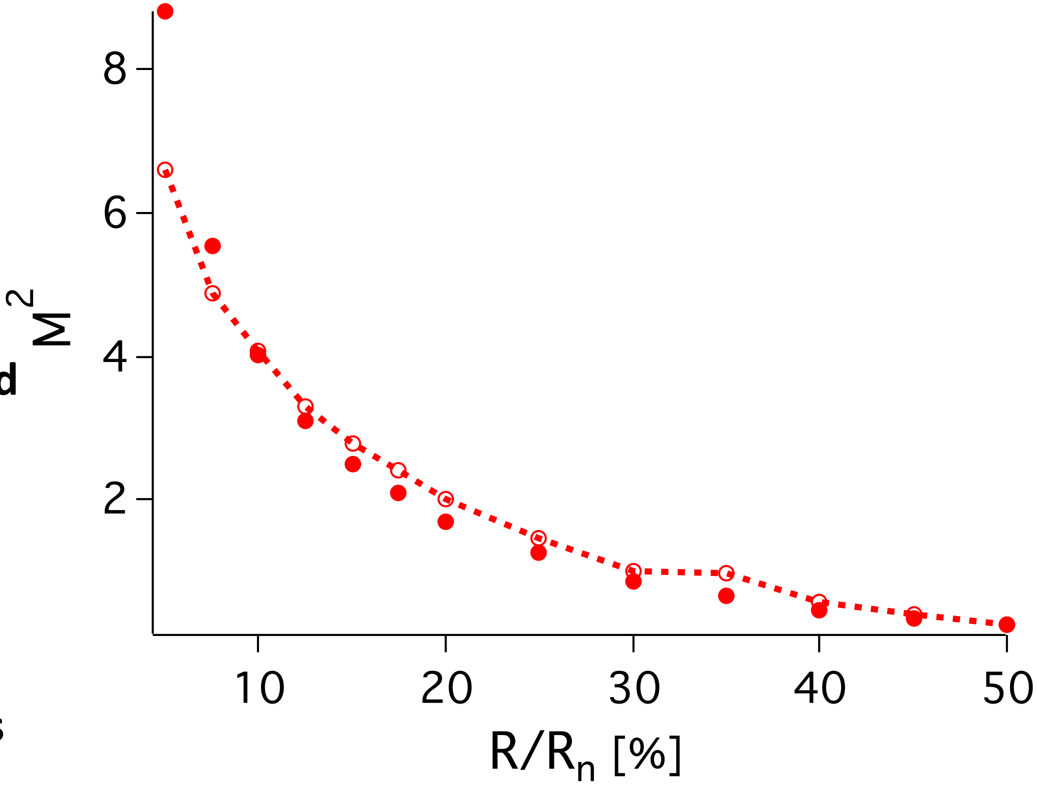


400x10^{-9}
300
200
100
0
G_{ae} [nW/K]
0
10
20
30
40
50
R/R$_n$ [%]
75um Low R with banks
100um Low R with banks
120um Low R with banks
100um High R with banks
75 um High R
75um High R w banks
120um High R

75um TES

With constant Gae through the transition. M^2 calculated from two body model is only partial agreement with measured values.

If we allow Gae to vary then we are able to fit at all points



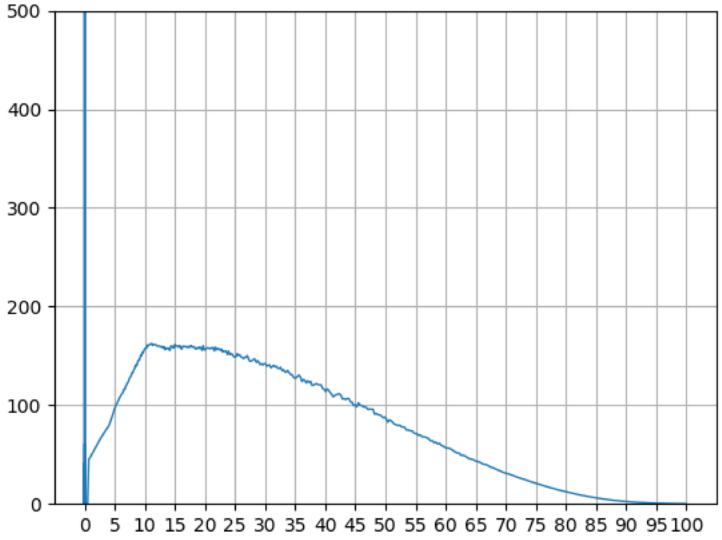
Where this doesn’t work

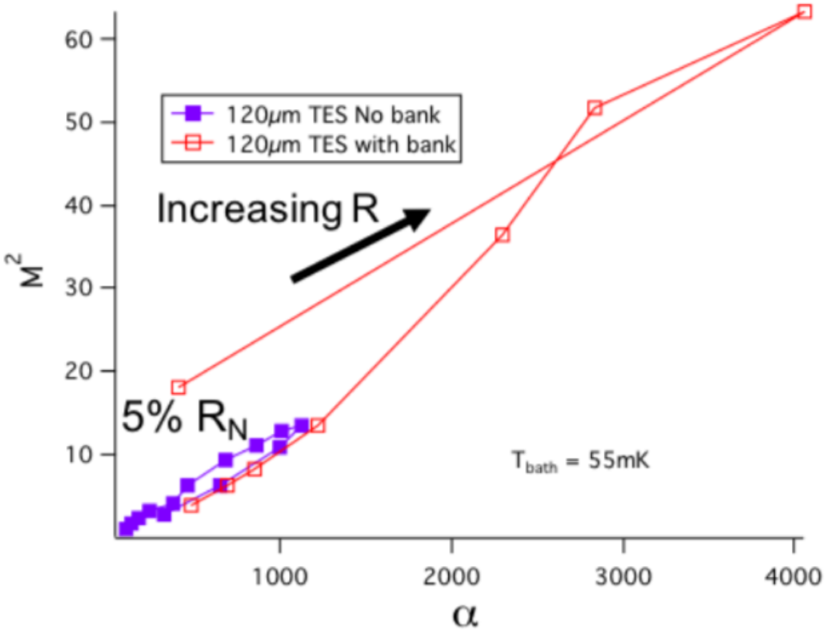
In kink-like region excess noise far exceeds expectation from our two-body model with reasonable value of Gae.

In fact noise fits can not be good within our assumptions even with very low Gae.

Speculate that in this region there is a separate noise term.

This other noise term may have dominated in older devices (e.g. with normal metal stripes)





Where this doesn’t work

Why does this fitting work in these devices?

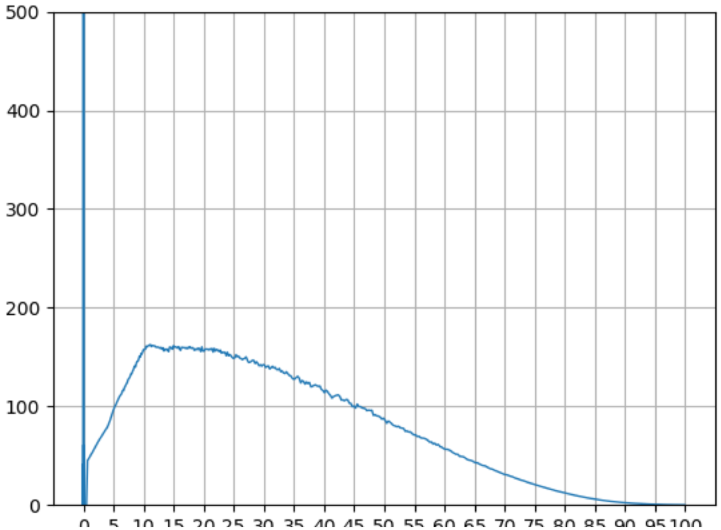
Removing stripes in general produces smoother transitions.

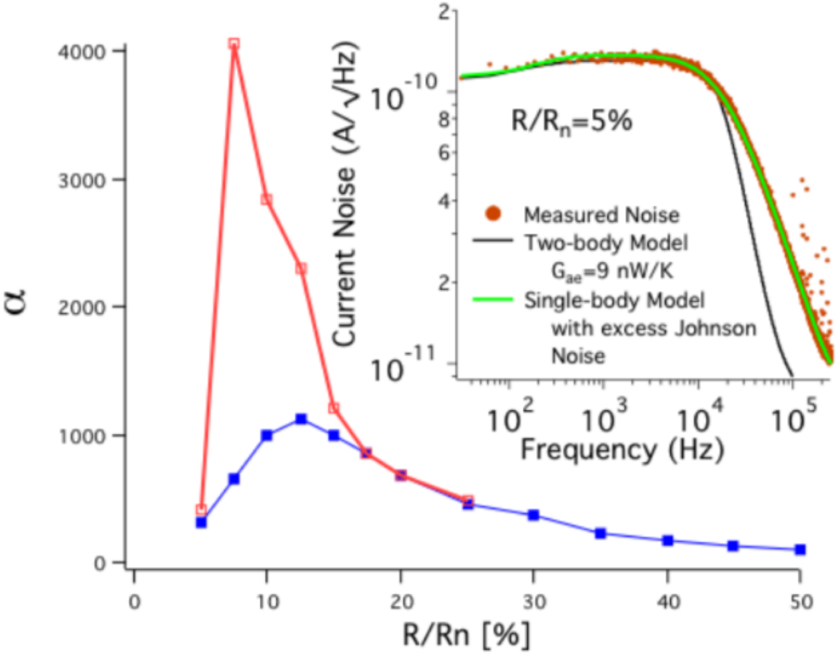
But sometimes see ”kinks” low in transition

For example in this 120um device with banks.

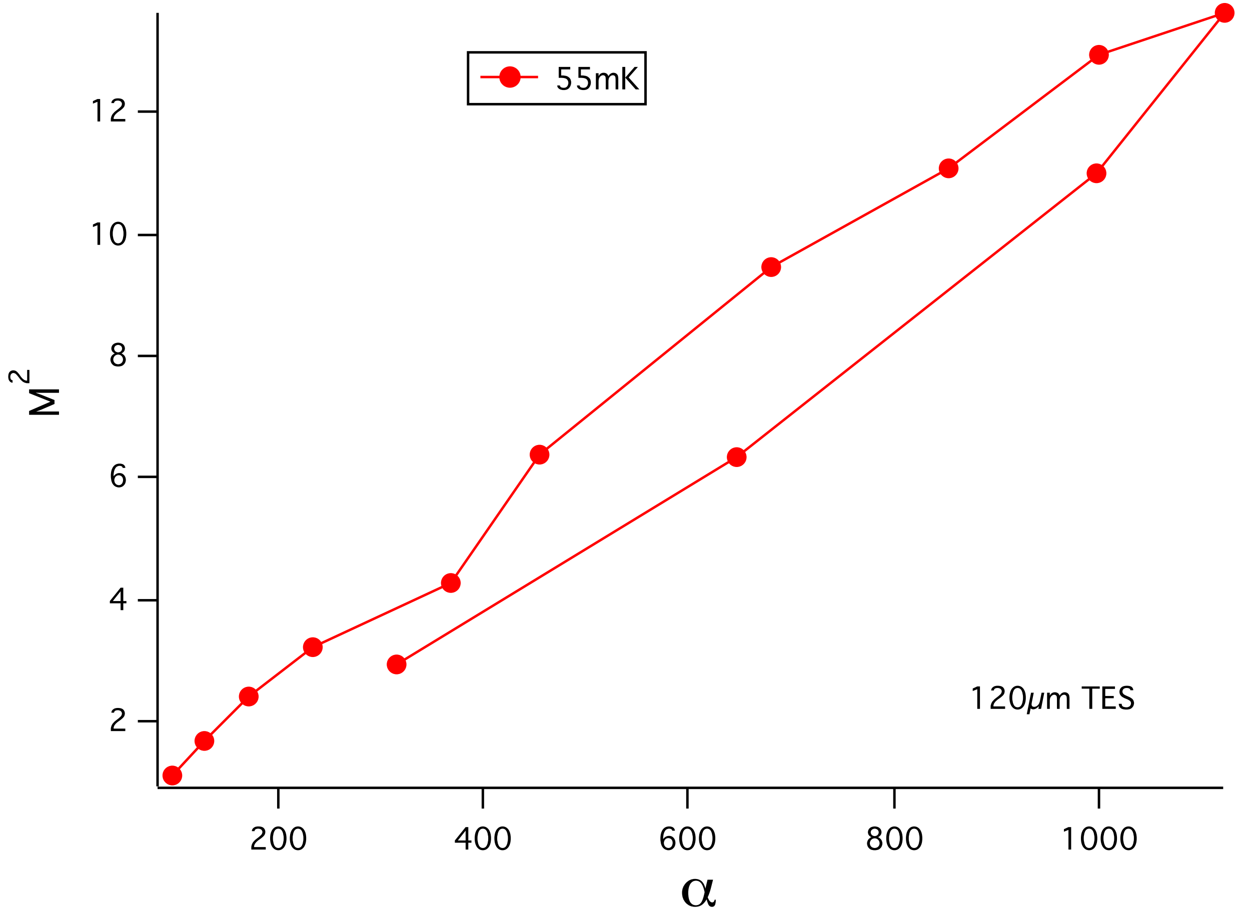
Subtle features is alpha_IV

Dramatic spike in Alpha.



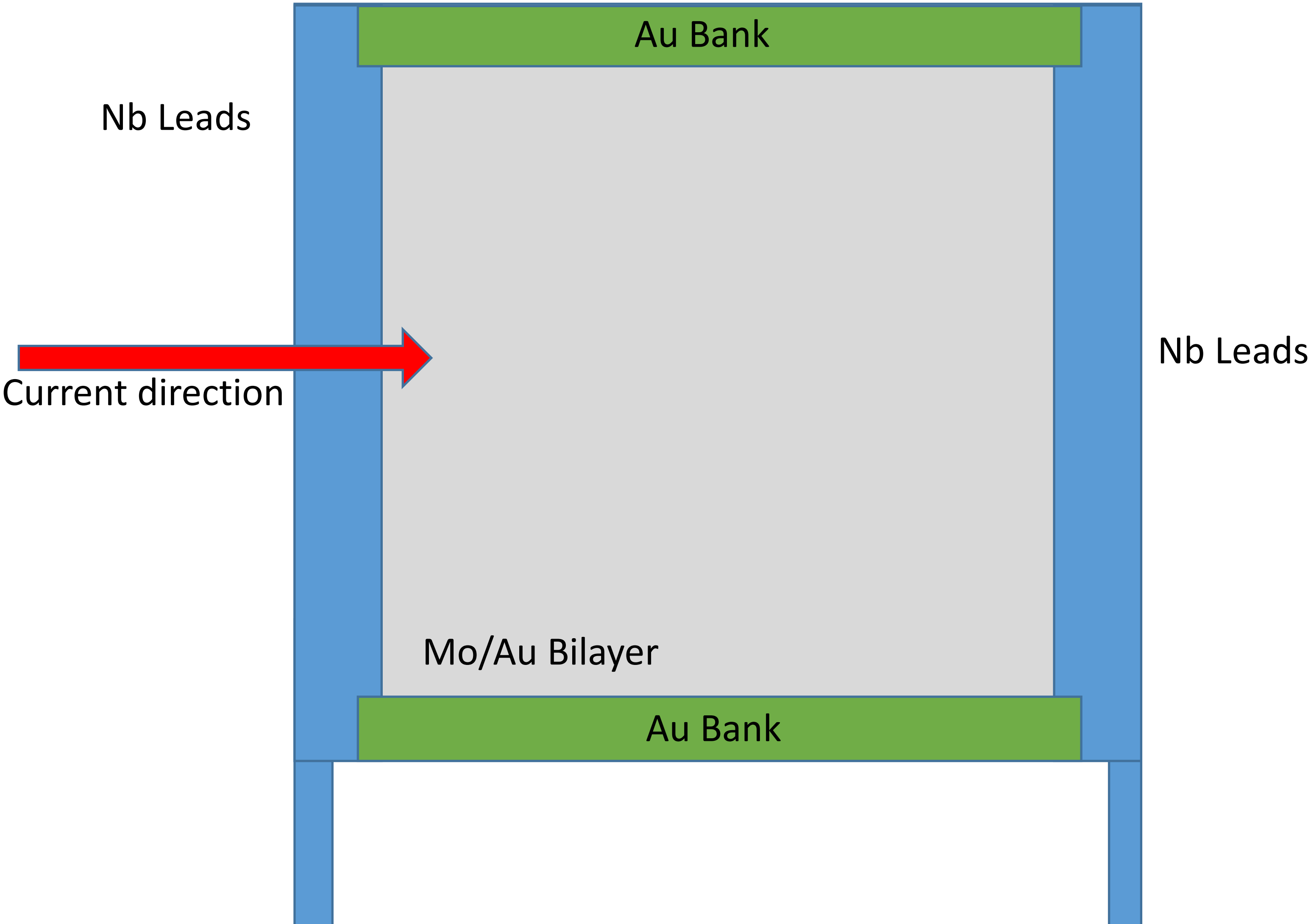


Assumptions



Our simple TES design

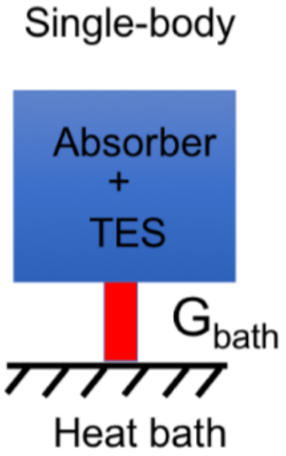
Some have Au banks

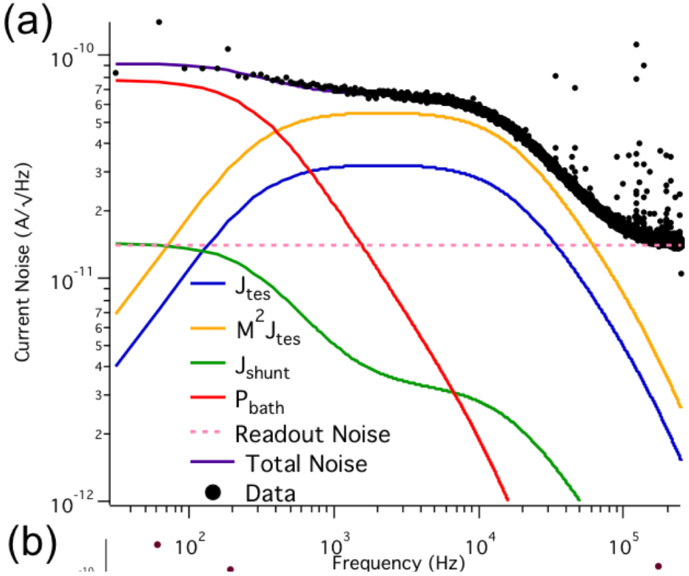


Noise in excess of single-body model

What is the origin of this additional noise?

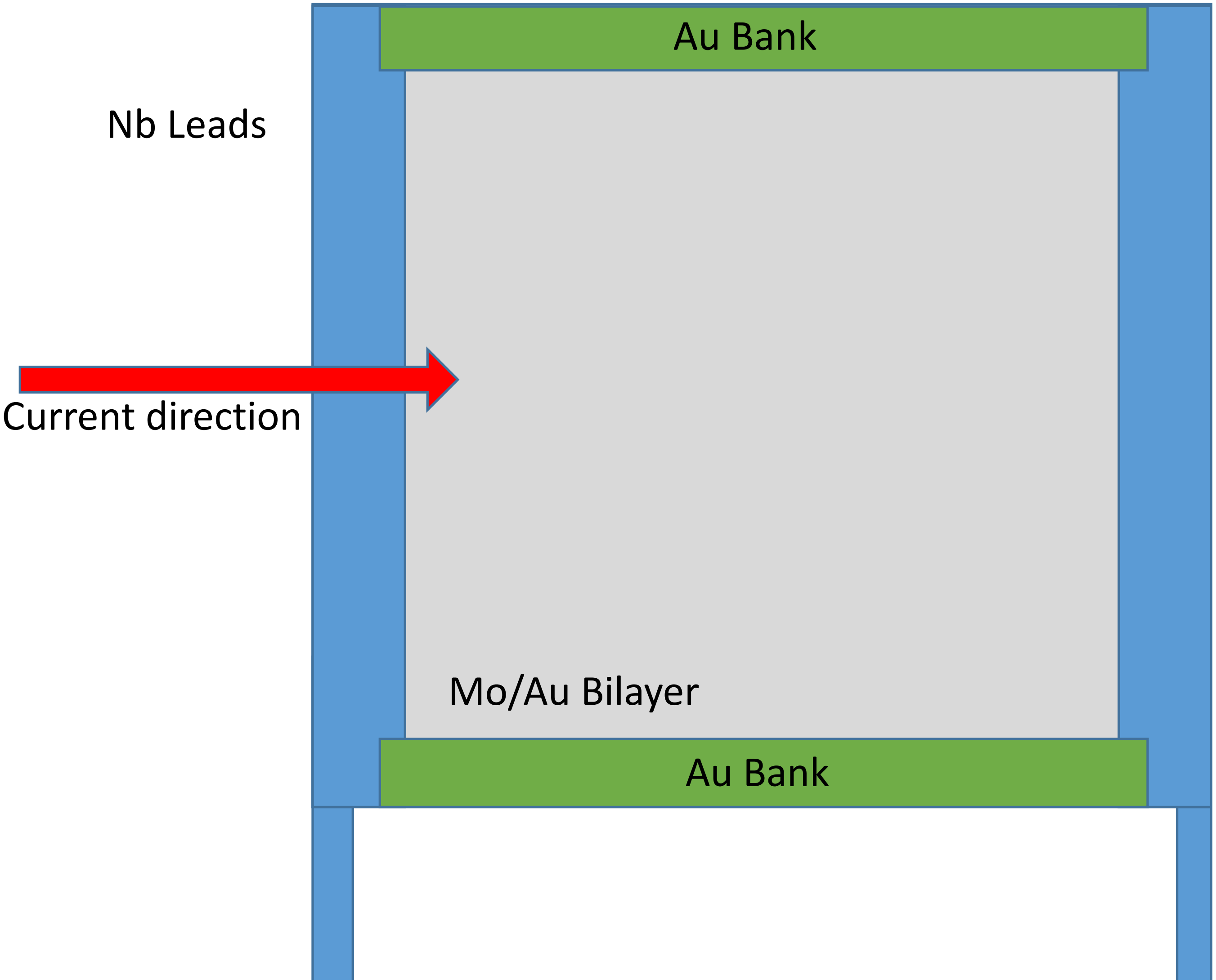
Is it related to the Johnson noise (higher order terms)?
Is it related to phase-slip line behavior?
Or is it additional thermal fluctuations noise not captured in single-body model?





TES design

Some have Au banks



Au Bank

Nb Leads

Nb Leads

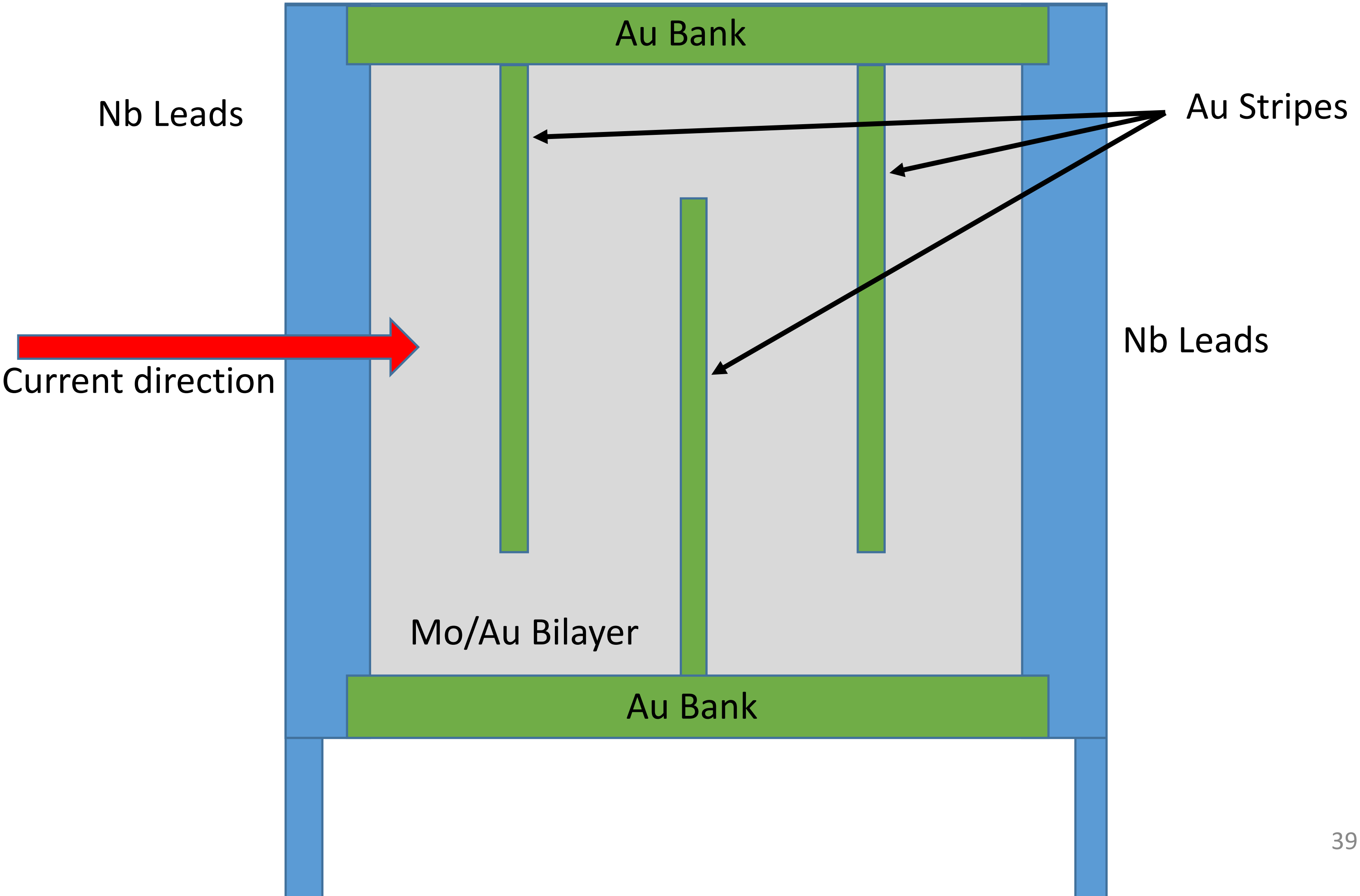
Current direction

Mo/Au Bilayer

Au Bank

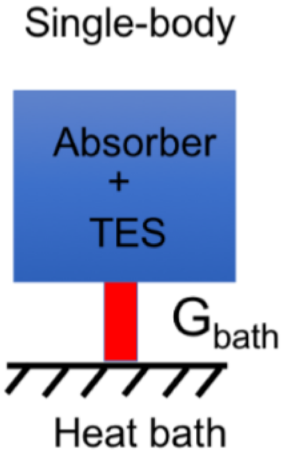
Typical TES design

Au stripes reduce unexplained (excess) noise



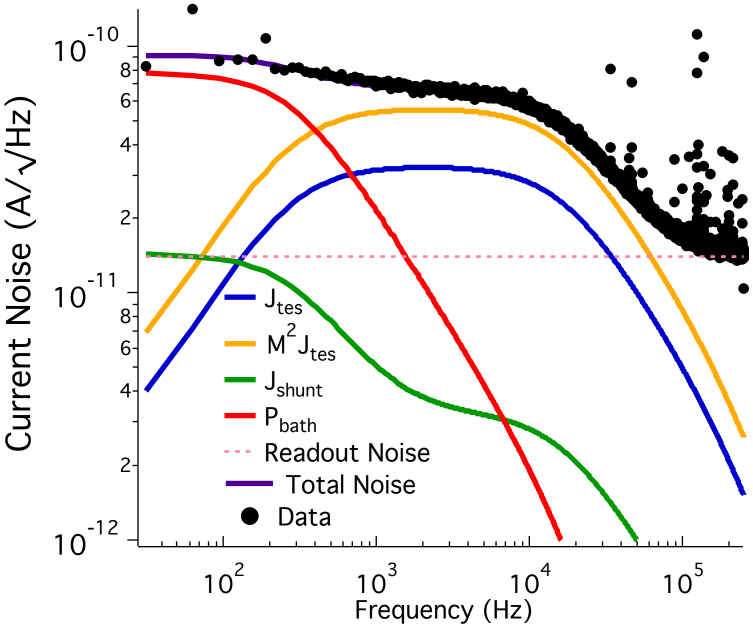
Noise in excess of single-body model

Simplest model of TES is a single body connected to bath by thermal conductance G_{bath}



3 noise sources:

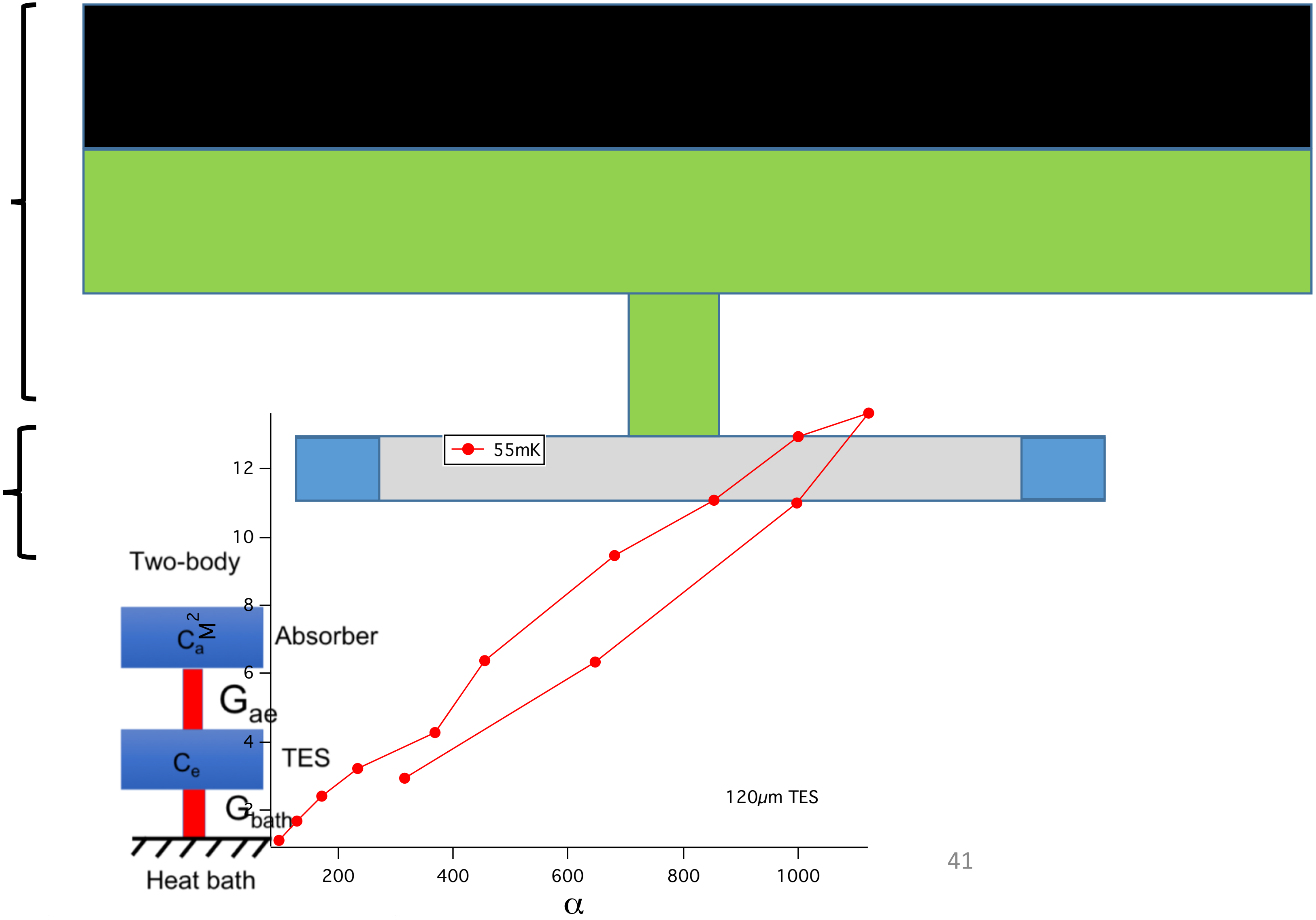
1. Johnson noise of TES
2. Johnson noise of shunt resistor
3. Thermal fluctuation noise between TES/Absorber and bath
4. **Quantify magnitude of excess noise by adding another TES Johnson noise term - $M^2 J_{tes}$**



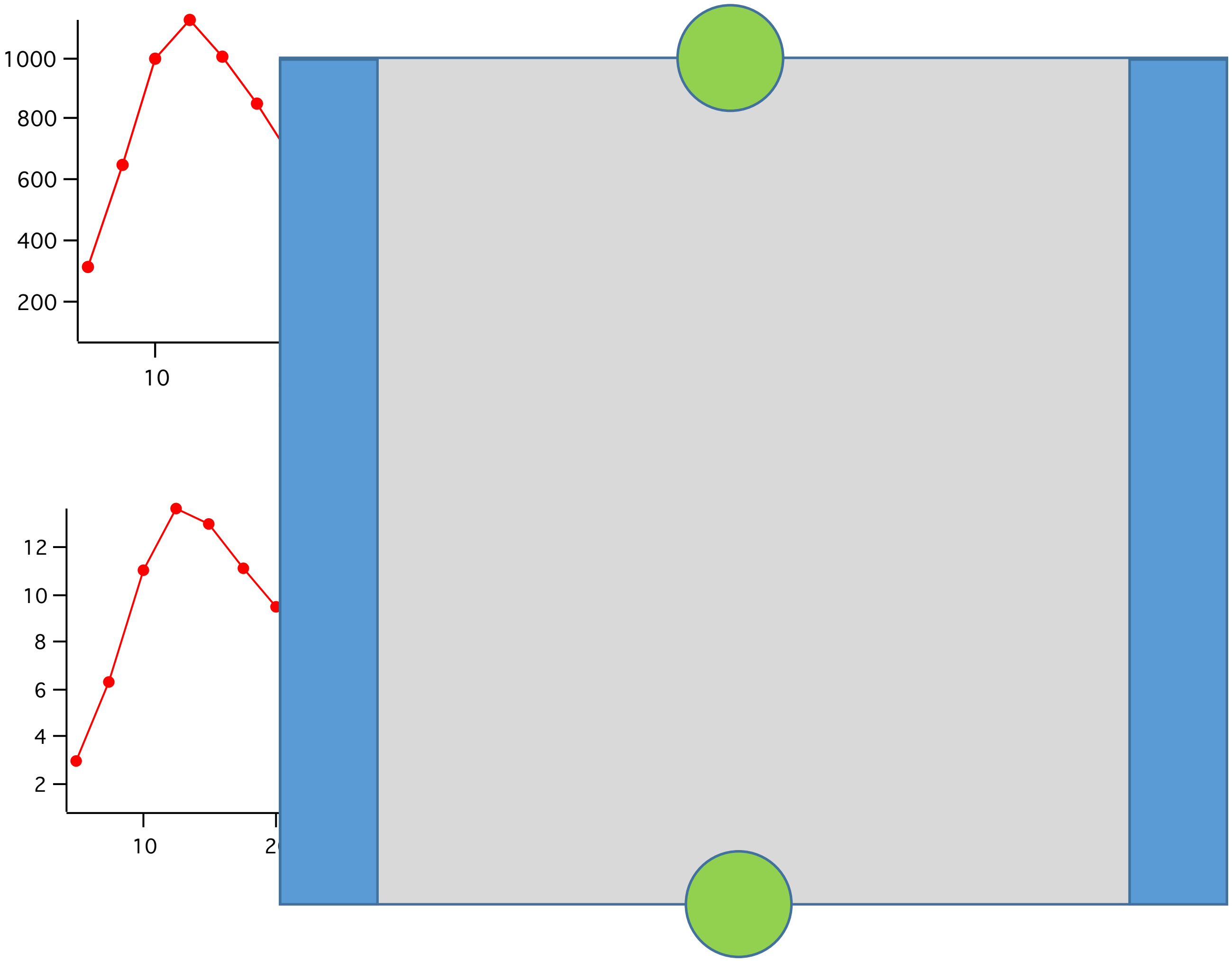
Assumptions

Body 1

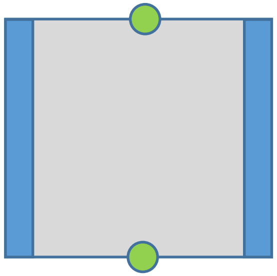
Body 2



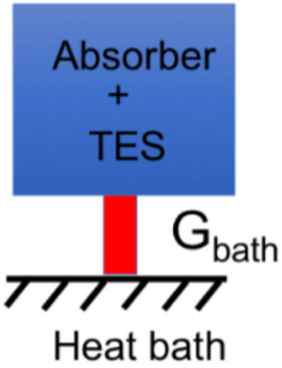
Fitted M^2 for 120um TES

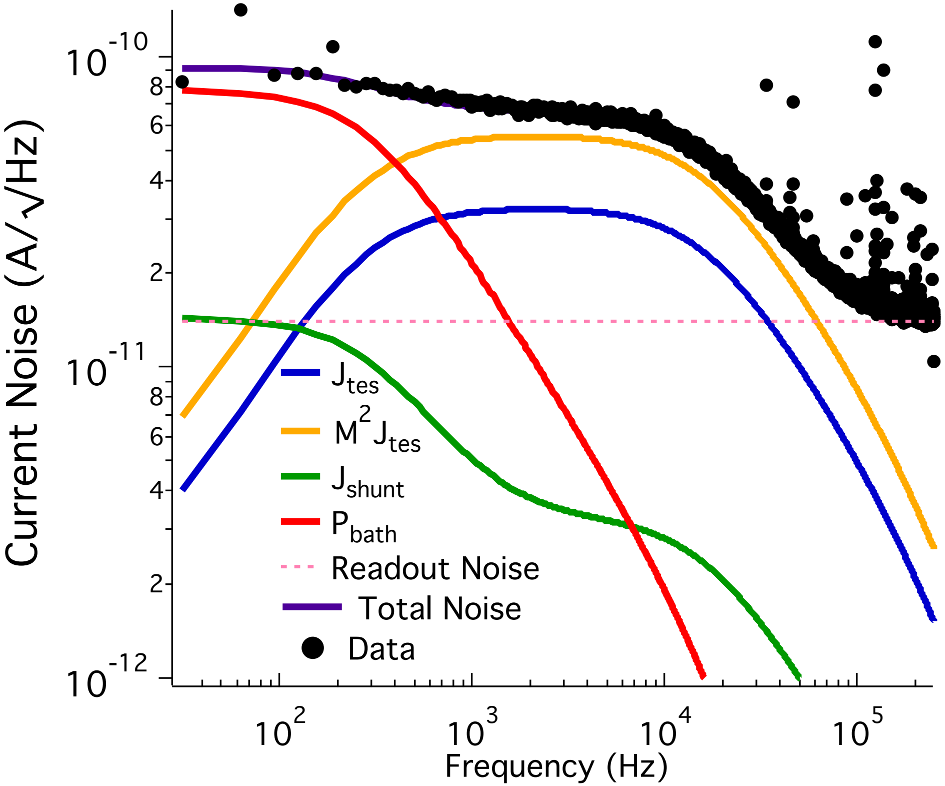


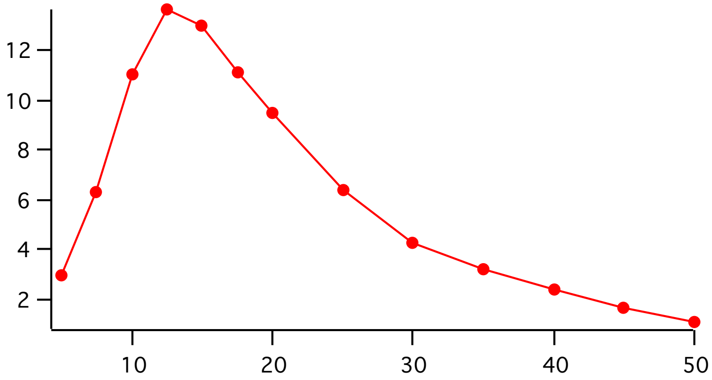
Single-body Vs Two-body



Single-body





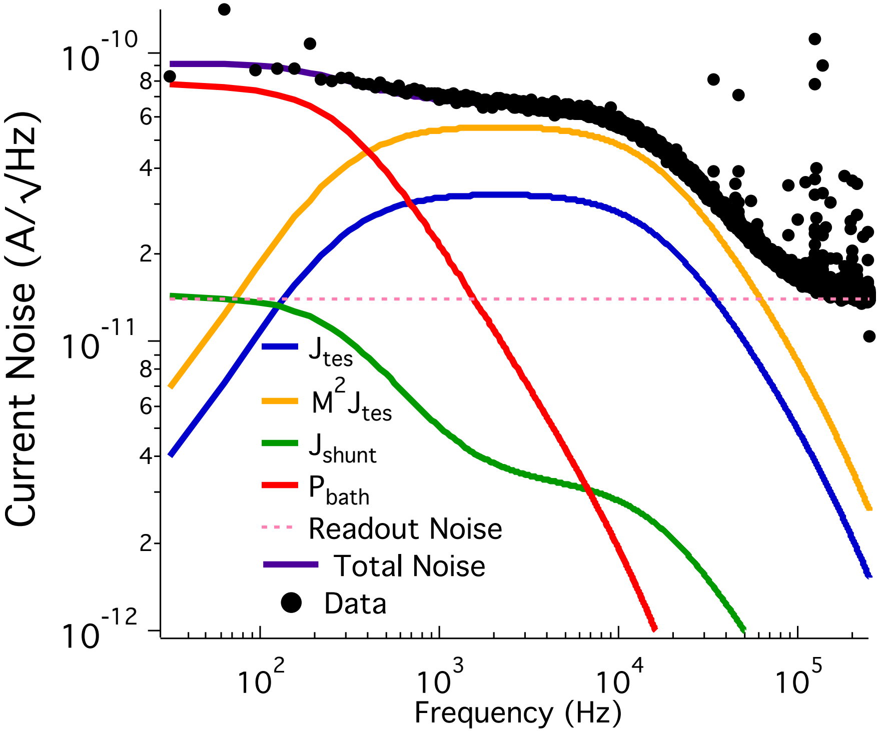


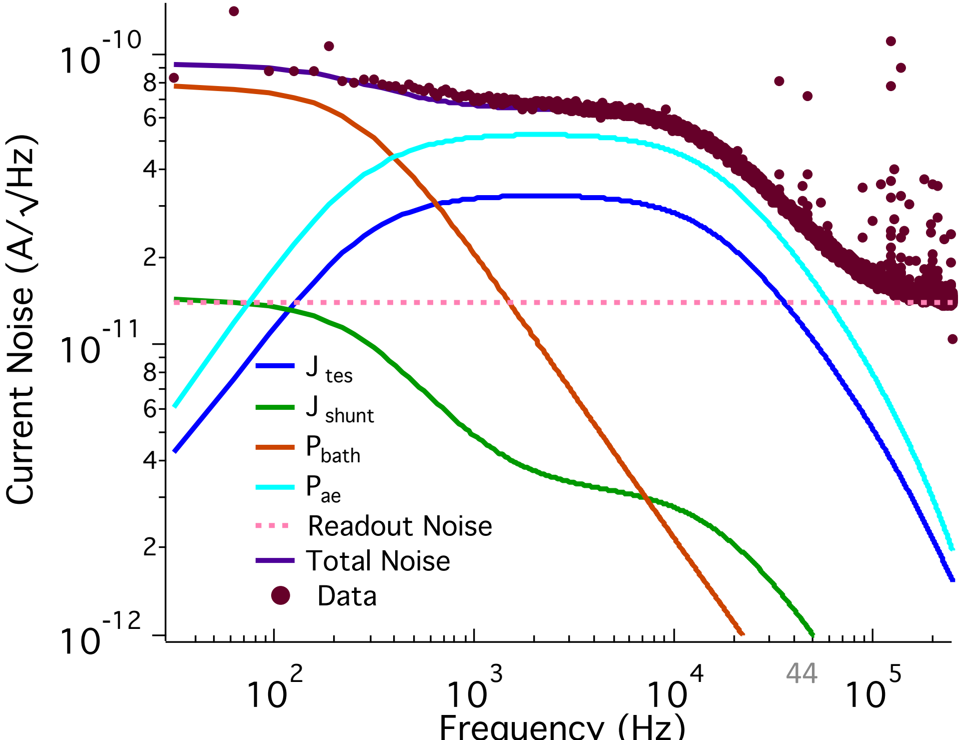
Single-body Vs Two-body

Internal thermal fluctuation noise can also be used to fit data.

Frequency dependence very similar to J_{tes}

Therefore, I will still quantify magnitude of this excess noise term with M^2



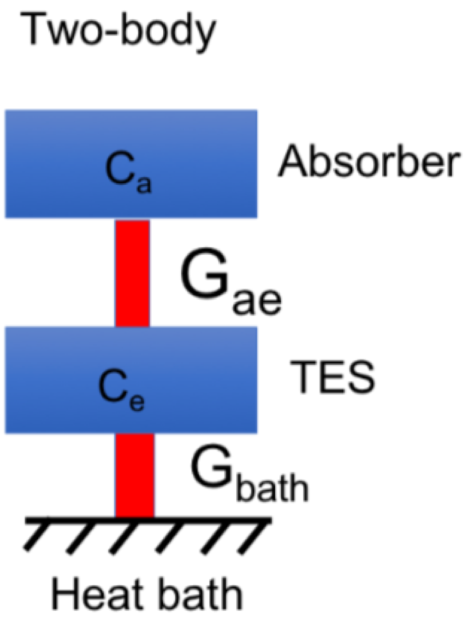


Assumptions:

Ce = BCS Predicted heat capacity of TES including jump from superconductivity (+ membrane). Relatively insensitive

Ca+Ce = measured heat capacity of device

G_{bath} is measured value



Fit for Gae

but initially assume Gae is not a function of R/Rn or T_{bath}