Texas A&M
Department of Physics and Astronomy

SOURCES OF NOISE IN THE CDMS EXPERIMENT

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MOTIVATION AND EXPERIMENTAL OVERVIEW

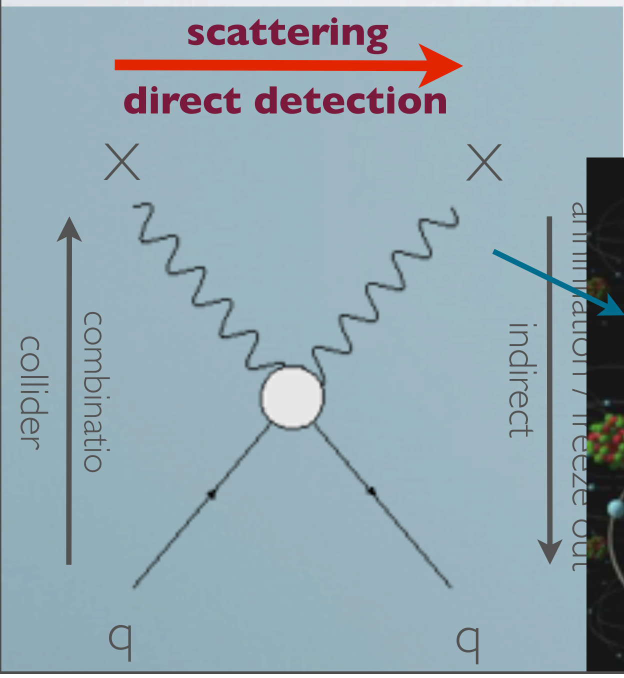
- The Cryogenic Dark Matter Search (CDMS) detector is composed of Ge crystals kept at superconducting (transition) temperatures

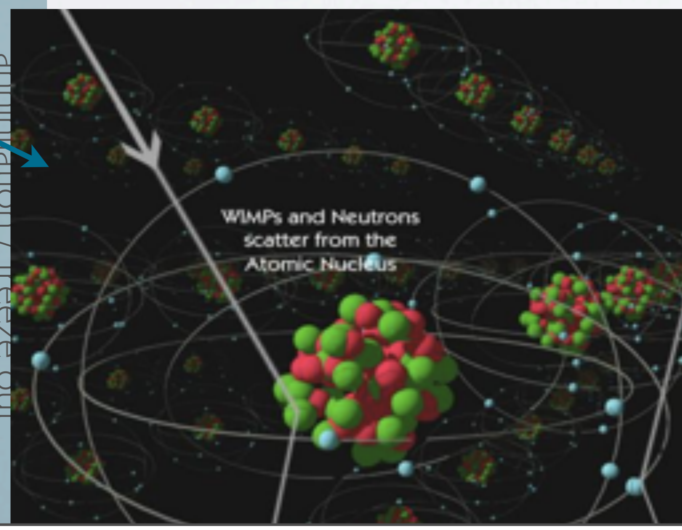
- Designed to be sensitive to small deposits of energy from a dark matter particle interaction, using phonons produced in the lattice, and ionization collection (will focus in phonon noise)

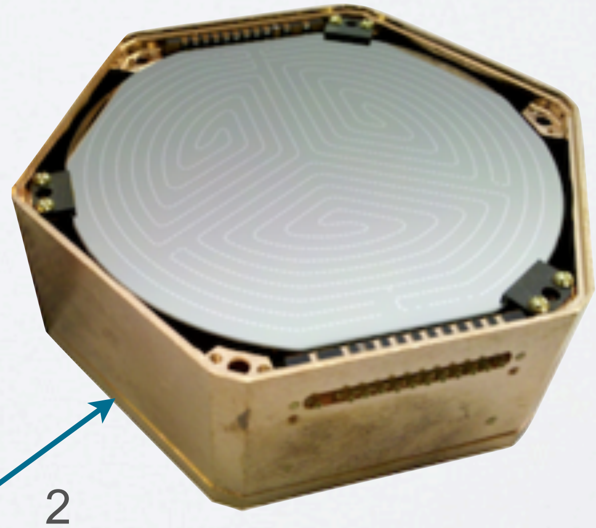
- When a particles interacts:
  - Can measure how much energy the particle deposited
  - Dark Matter interactions are expected around ~10keV (or less)
  - Sensitivity is determined by the ability to separate real-particle-phonon-pulses from noise
  - Amount of noise also affects our ability to measure the deposited energy

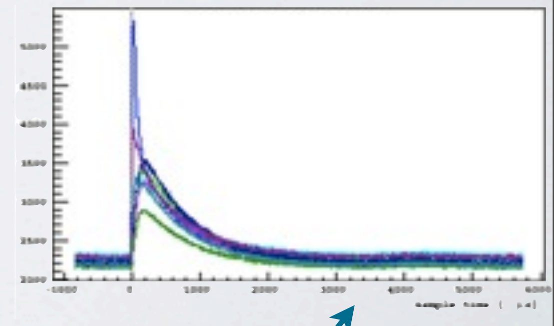
GOALS:

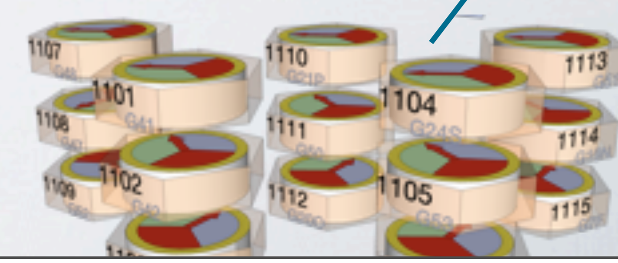
- **Understand the sources of noise**
- **Make suggestions on how to reduce them**











OUTLINE

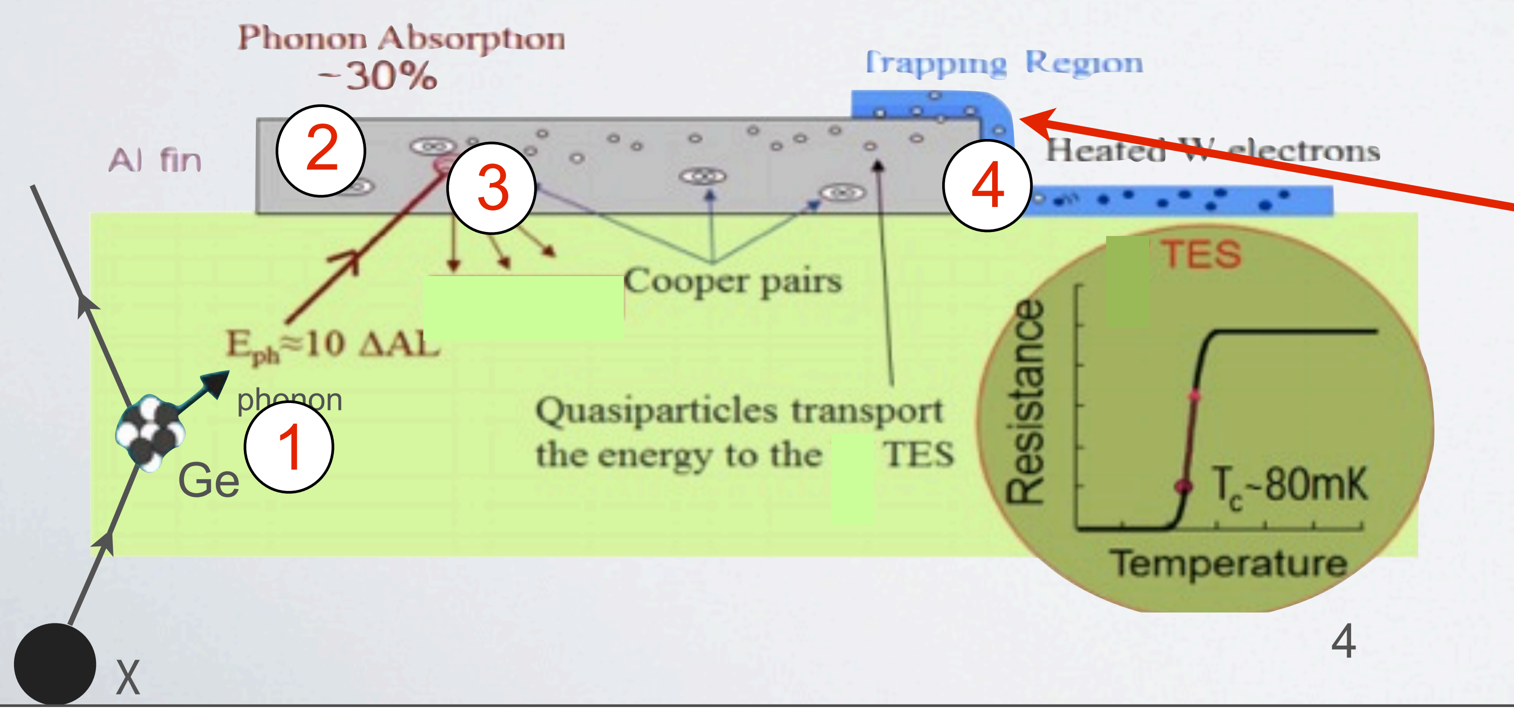
- I. Detecting Phonons with the SuperCDMS Soudan detectors: From a Particle Interaction to a Phonon Pulse
- II. Separating Real Pulses from Noise
- III. Identifying Potential Sources of Noise: Methods and Results
- IV. Looking Towards the Future
- V. Conclusions

GE CRYSTALS AND PHONONS IN THE DETECTOR: FROM A PARTICLE INTERACTION TO A SIGNAL OUT OF THE **T**RANSITION **E**DGE **S**ENSOR (**TES**)

- Phonon production and collection process:

1. Phonons created in a particle interaction with the lattice
2. Phonons travel to the aluminum
3. Phonons break up Cooper pairs, leaving single, unpaired electrons
4. Electrons are absorbed by the Transition Edge Sensor (TES) changing it's temperature (which changes its resistance, and the amount of current that flows through it)

Phonon Trap



Transition Edge Sensor (TES):

Resistance as function of temperature in the transitioning phase (Super/Normal - conducting) → the changing resistance creates a signal

OVERVIEW OF THE PHONON SIGNAL READ-OUT

1

Electrothermal feedback (V_{bias}) can maintain the TES in 1 of 3 states:
- Normal Conducting
- Superconducting
- Standard Configuration (transitioning phase for normal data taking)

2

After phonons are generated in the crystal, the TES has an increase in temperature which in turn changes its resistance (and the amount of current that can flow)

3

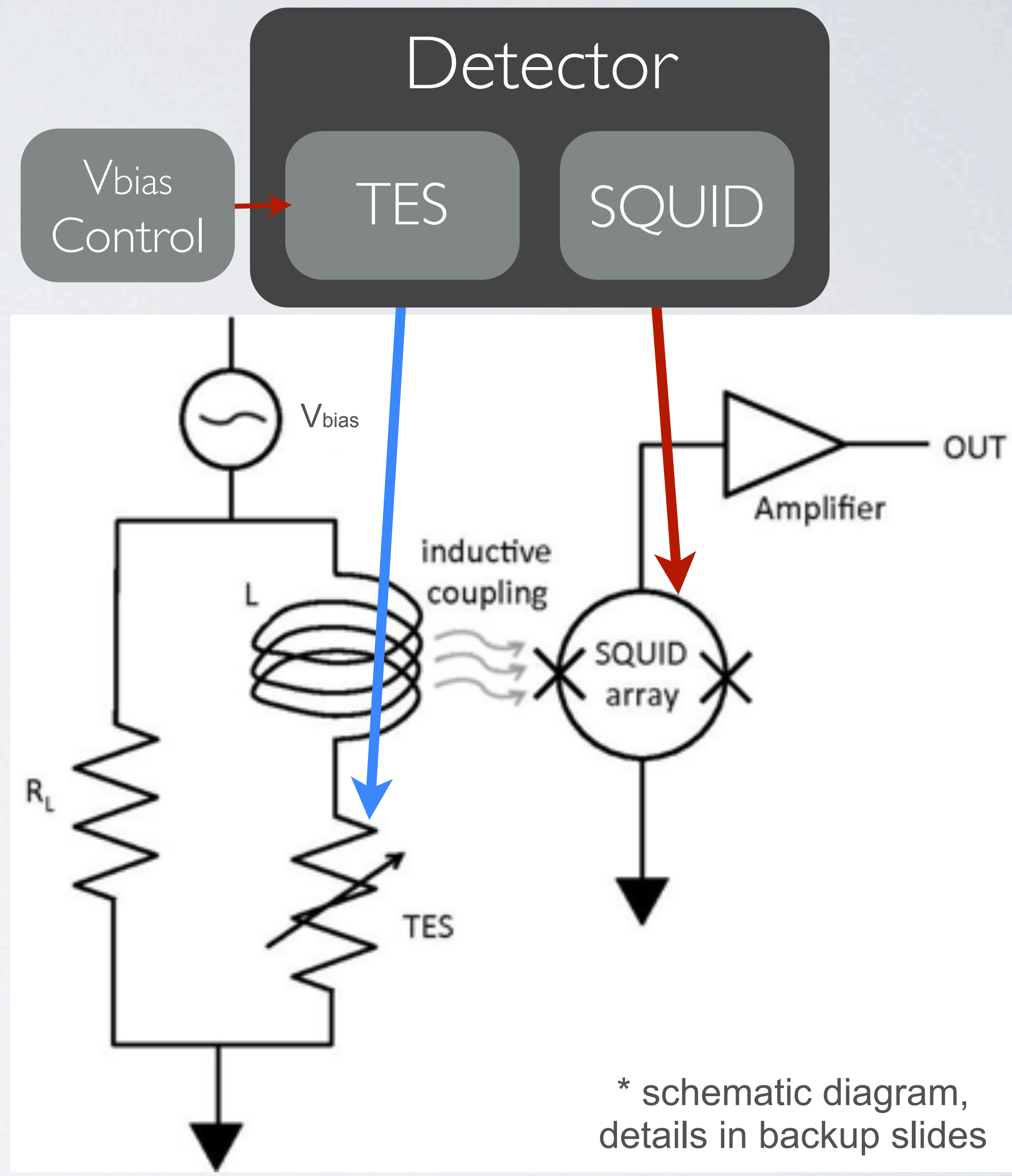
The SQUID amplifies the change in the current of the circuit, so it can be passed to the Other Electronics.

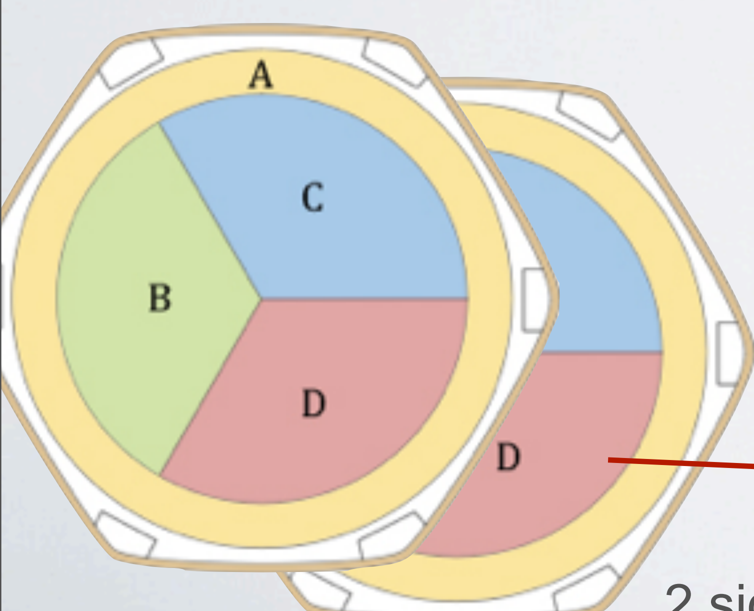
4

Other Electronics take the pulse and do the rest of the data acquisition chain. Amplification, Triggering, Filtering, etc

COLD ELECTRONICS: GETTING SIGNALS OUT OF THE DETECTOR AND INTO THE DAQ

- Superconducting QUantum Interface Device (SQUID): measures the current change of the TES. It's output is what we call the 'phonon pulse'

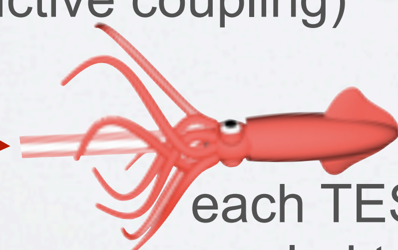




2 sides

each side 4 channels

(inductive coupling)



each TES channel coupled to a SQUID

Each SQUID amplifies a PULSE

PULSE is sent to Downstream Electronics

OUTPUT AFTER THE FULL CHAIN: LOOKING AT PHONON PULSES

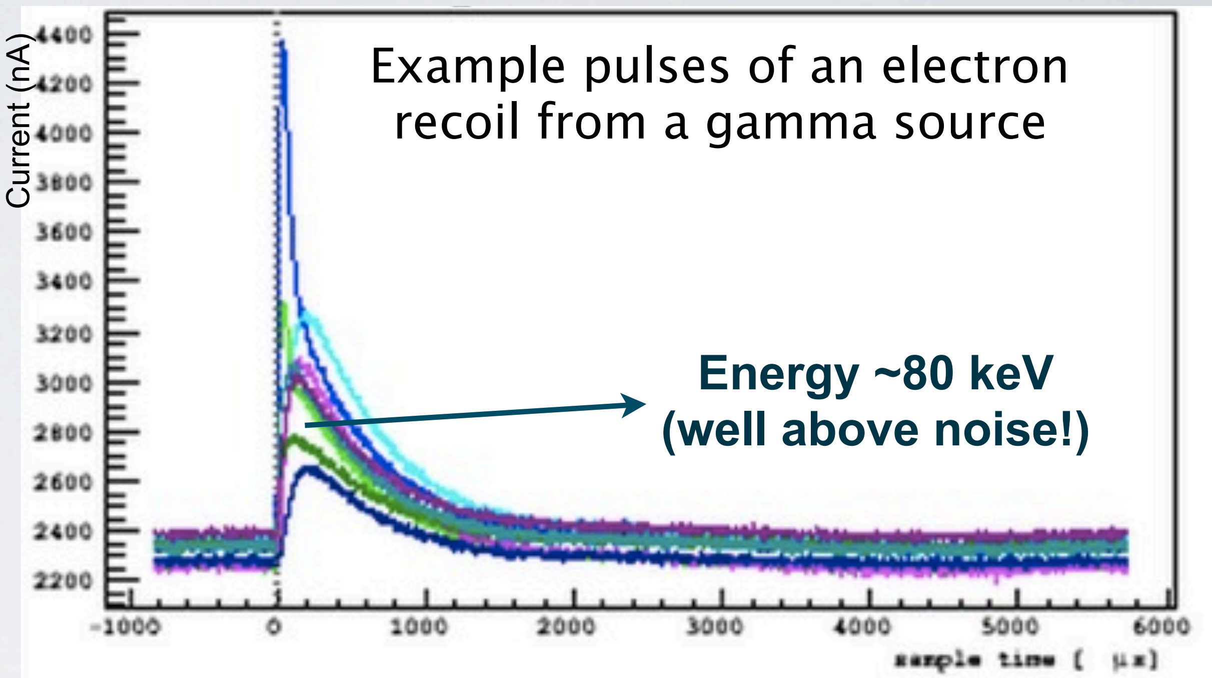
- Dark Matter interactions are expected to deposit a few keV (~5keV or less?)
- Calibrations are well above noise, i.e. electron recoils are in the 10's keV energy range

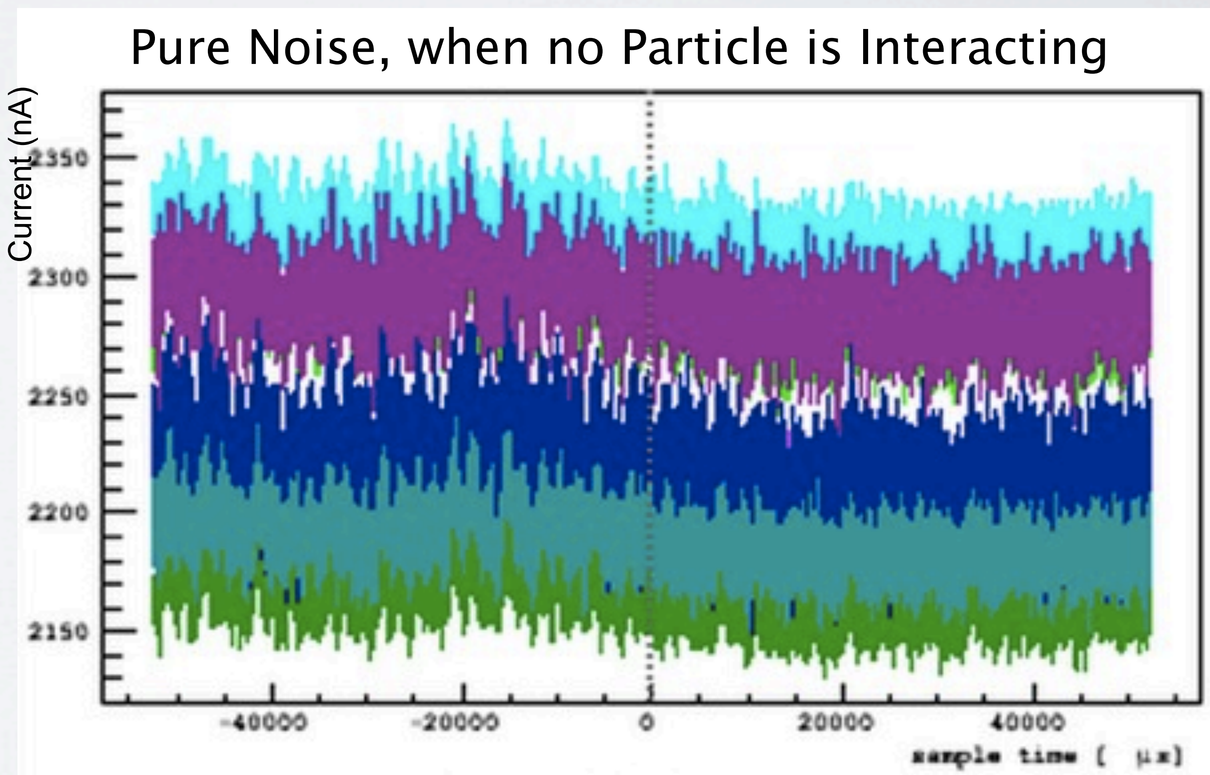
↓

- Given the scale of the expected dark matter interaction, noise can fluctuate to a large enough amplitude to trigger the experiment

↓

- Problem: Signal from a dark matter particle is not as big as above, so we need to be really sensitive and distinguish between a small pulse from the noise (below)
- Will study noise in different TES configurations to help us understand where it is coming from





HOW DO WE OBTAIN THE NOISE DATA FOR ANY CONFIGURATION?

- Randomly select a time to start writing out data:
  - unlikely to have real particles interacting
- The longer the time, the better information we have for noise analysis
  - 750μs is a typical real particle pulse length time
  - Total time > (2x before + 750μs + 5x after)
  - Total time per event ~ 100,000 μs
  - The longer the better because we can probe lower frequencies (Soudan has low frequency noise issues)
- Ratio of interaction of a Cosmogenic particle is ~1 per minute our total time is ok

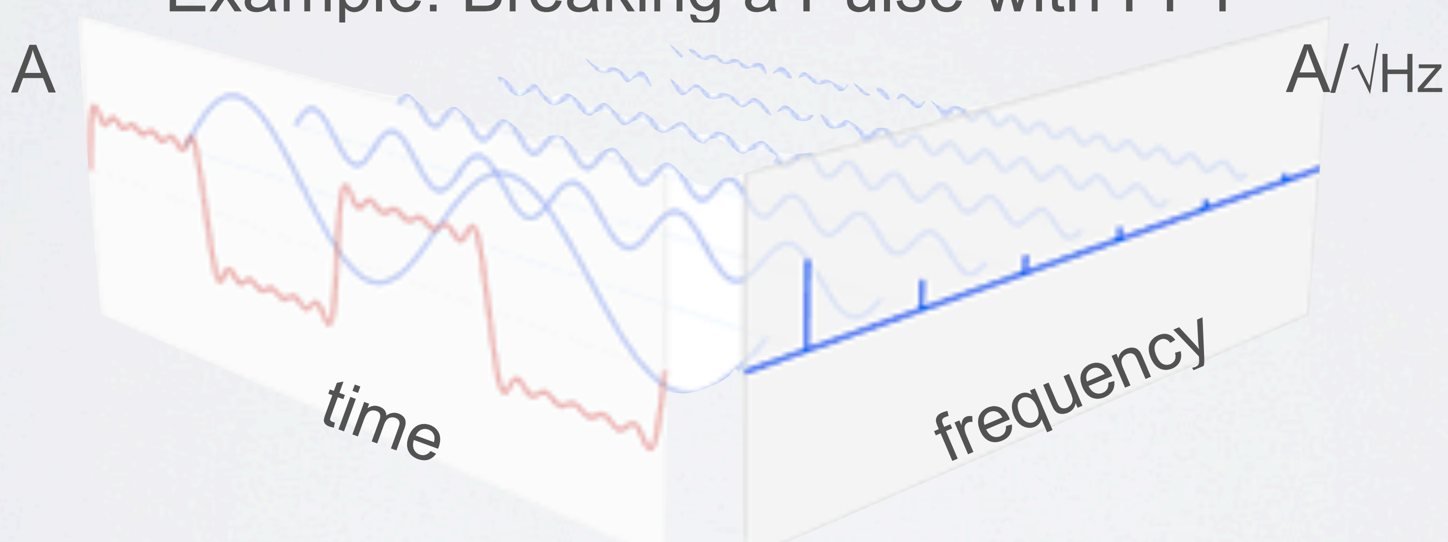
METHODS FOR STUDYING THE AMOUNT OF NOISE

- Sources of noise expected to occur at specific frequencies (actually seen in previous data)
- Look at the data in the Frequency Domain
- Use Fast Fourier Transforms (FFT) → Power Spectral Density Function (PSD)

Example: Breaking a Pulse with FFT

- y: amplitude

- x: time



- y: amplitude in the Power Spectrum

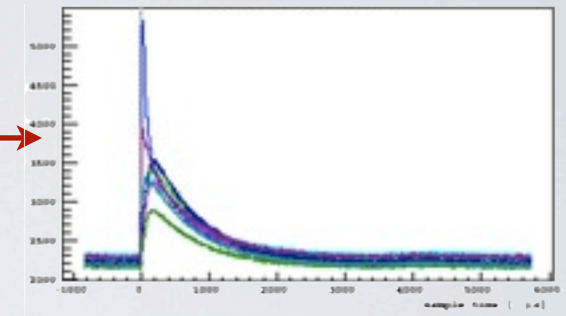
- x: frequency

- Look at many events (lots of noise) to see which frequency is most prevalent

III. Potential Sources of Noise: Method

POSSIBLE SOURCES OF NOISE IN THE EXPERIMENT

V_{bias} Control → Detector (TES, SQUID) → Other Electronics (DAQ: Amplification, Triggering, Filtering...) →



1

V_{bias} Electronics:

Electronics that set the V_{bias} level could inject noise into the experiment

2

Non-interaction Phonon Production:

Vibrations of the detector, occurring in the crystal, measured accurately by the TES, and can be a source of noise

3

Detector Level Inductive Coupling:

Could get noise from the TES-SQUID electronics

4

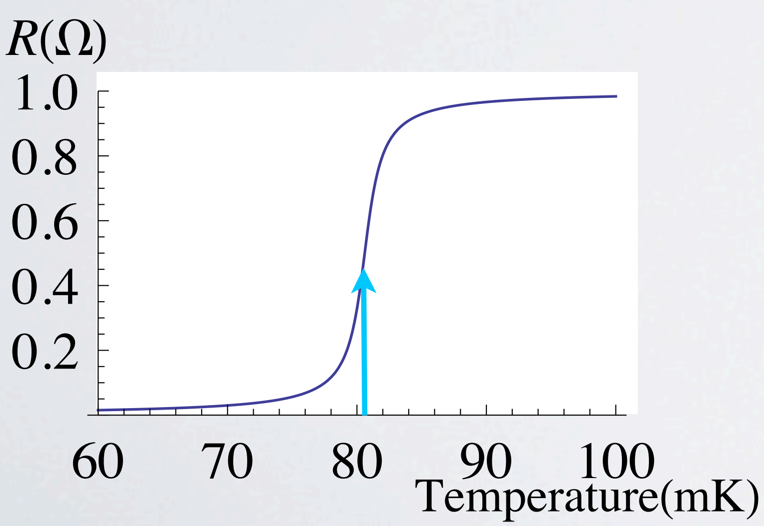
Other Electronics:

Could get noise from the electronics after the detector, for example in the amplification, triggering, or filtering process

COLLECTING SAMPLES OF NOISE IN DIFFERENT DATA TAKING CONFIGURATIONS

A. Standard Configuration
Usual configuration for data
$V_{bias} = V_{threshold}$

- TES is in transitioning phase between normal conducting and superconducting
- Phonons are collected and detector is sensitive to them (gives pulses)

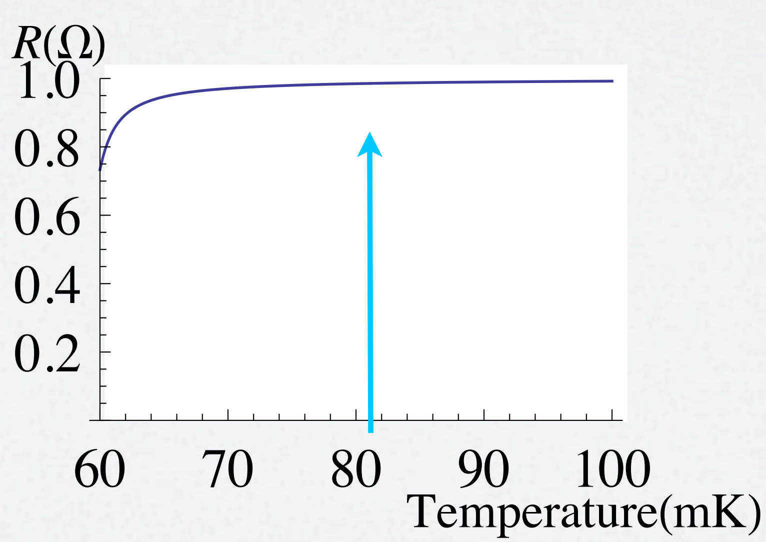


Standard / Transitioning

Sensitive to phonons

B. Normal Conducting
Bias current set at 1000uA
$V_{bias} >> V_{threshold}$

- Resistance never changes much, (amplified) current of SQUID is always small
- Phonons from the detector don't create output signals
- <u>Minimum</u> amplitude of any noise from TES/SQUID electronics

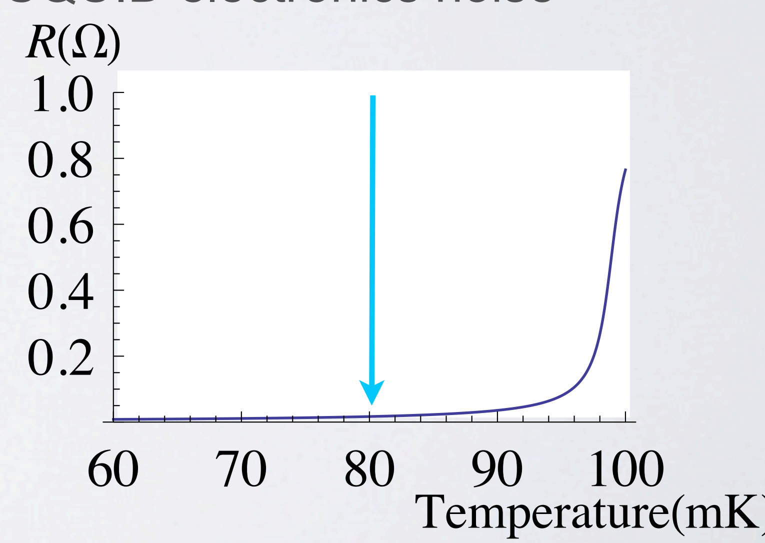


Normal Conducting

Insensitive to phonons

C. Superconducting
Bias current set at 0uA
$V_{bias} << V_{threshold}$

- Resistance never changes much, (amplified) current of SQUID is always large
- Phonons are not amplified so no output signal from phonons
- <u>Maximum</u> amplitude of any TES/ SQUID electronics noise

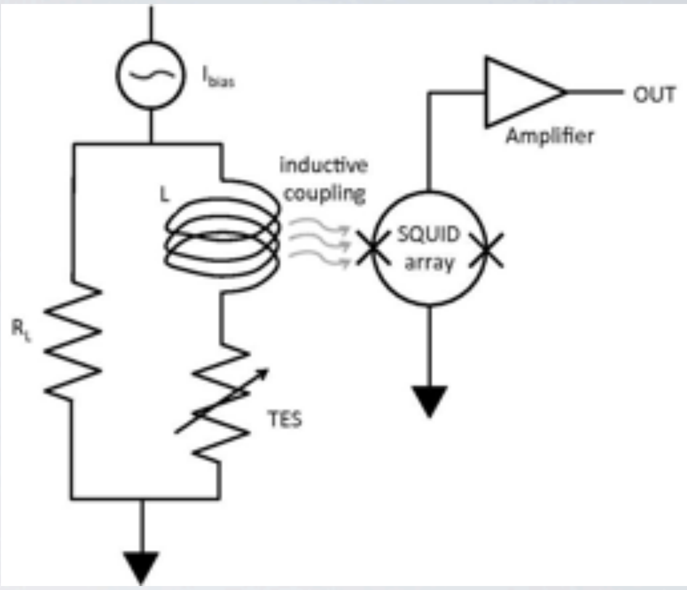


Superconducting

Insensitive to phonons

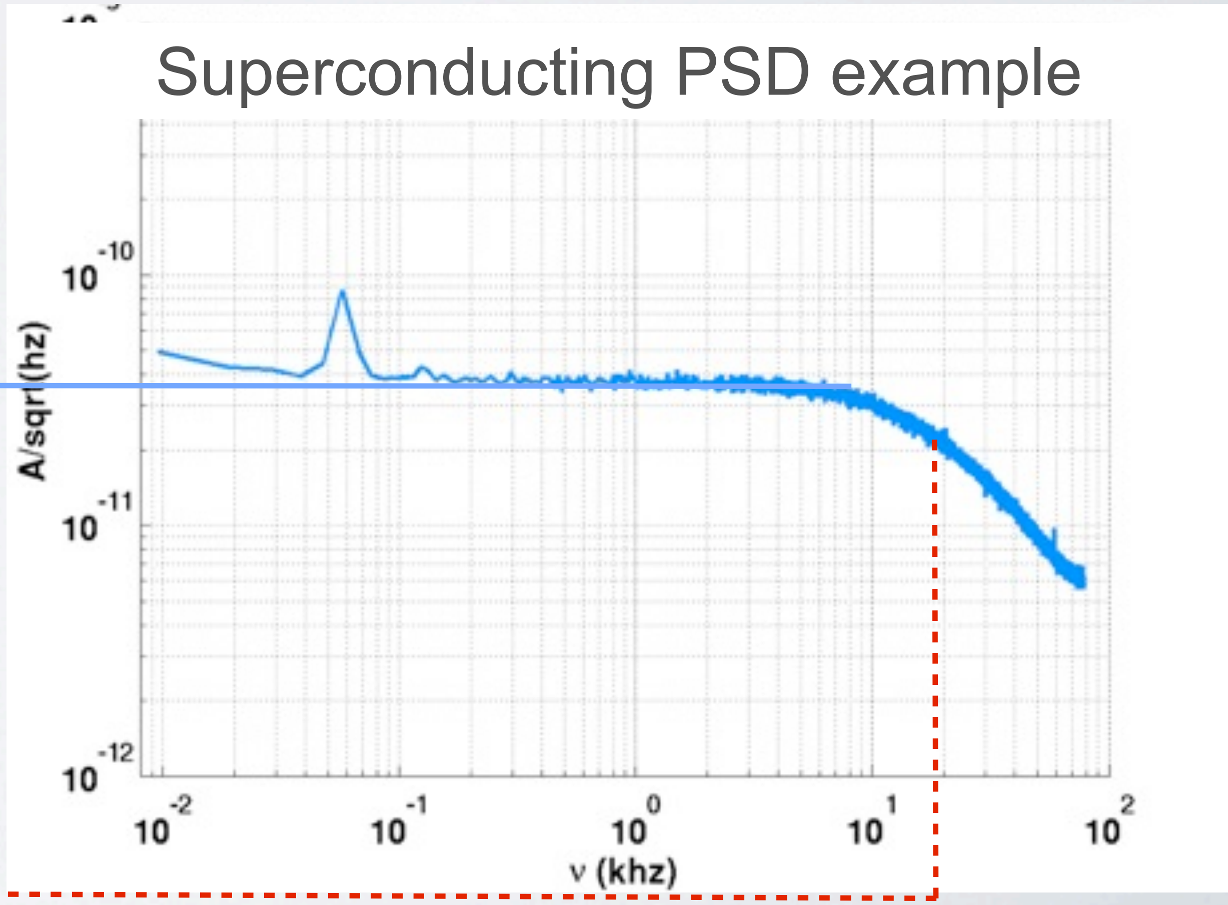
BASE NOISE OF THE TES/SQUID CIRCUIT

(IN SUPERCONDUCTING MODE)



Baseline

- Johnson Noise
  - Random thermal fluctuations
  - Intrinsic to the TES/SQUID circuit
  - Characteristic of the amplification of the TES/SQUID pulse
- Depends on the Resistance and Temperature of the elements in the circuit and is proportional to the product of the Resistance and Temperature of each element



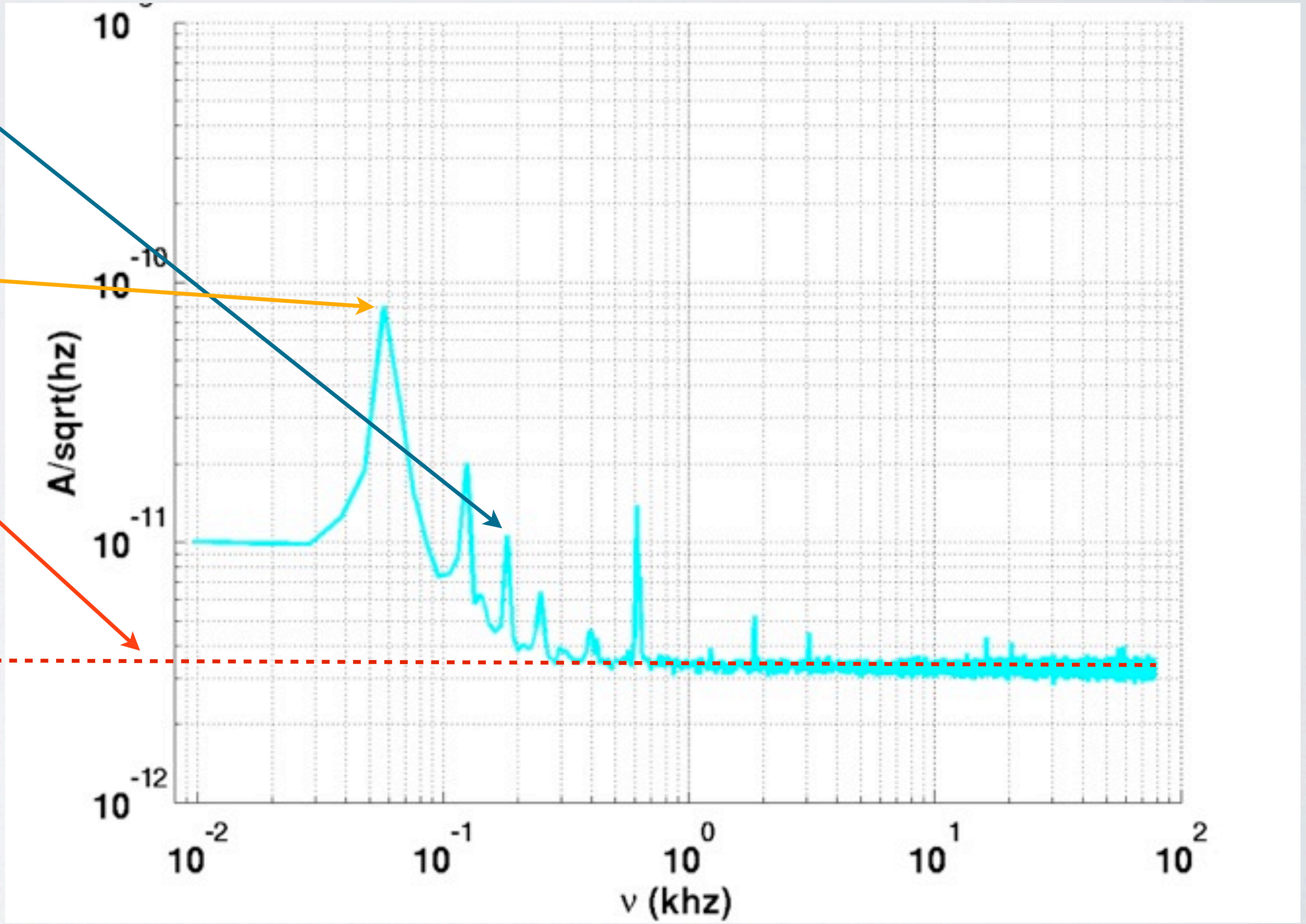
Cut-off frequency

- The cut-off frequency is determined by the impedance of the TES/SQUID circuit to reduce the high frequencies (due to the R/L attenuation)

NORMAL CONDUCTING BASE NOISE

- When the TES has a Temperature/V_{bias} configuration that makes it normal conducting, the readout signal is insensitive to phonons in the detector

- Spikes must NOT be due to phonons, but to some part of the electronics.
- Note the big spike at 60Hz (suggestive number)
- Lower baseline, but that's expected because there is more resistance
- No 'cut-off' here because its off scale.



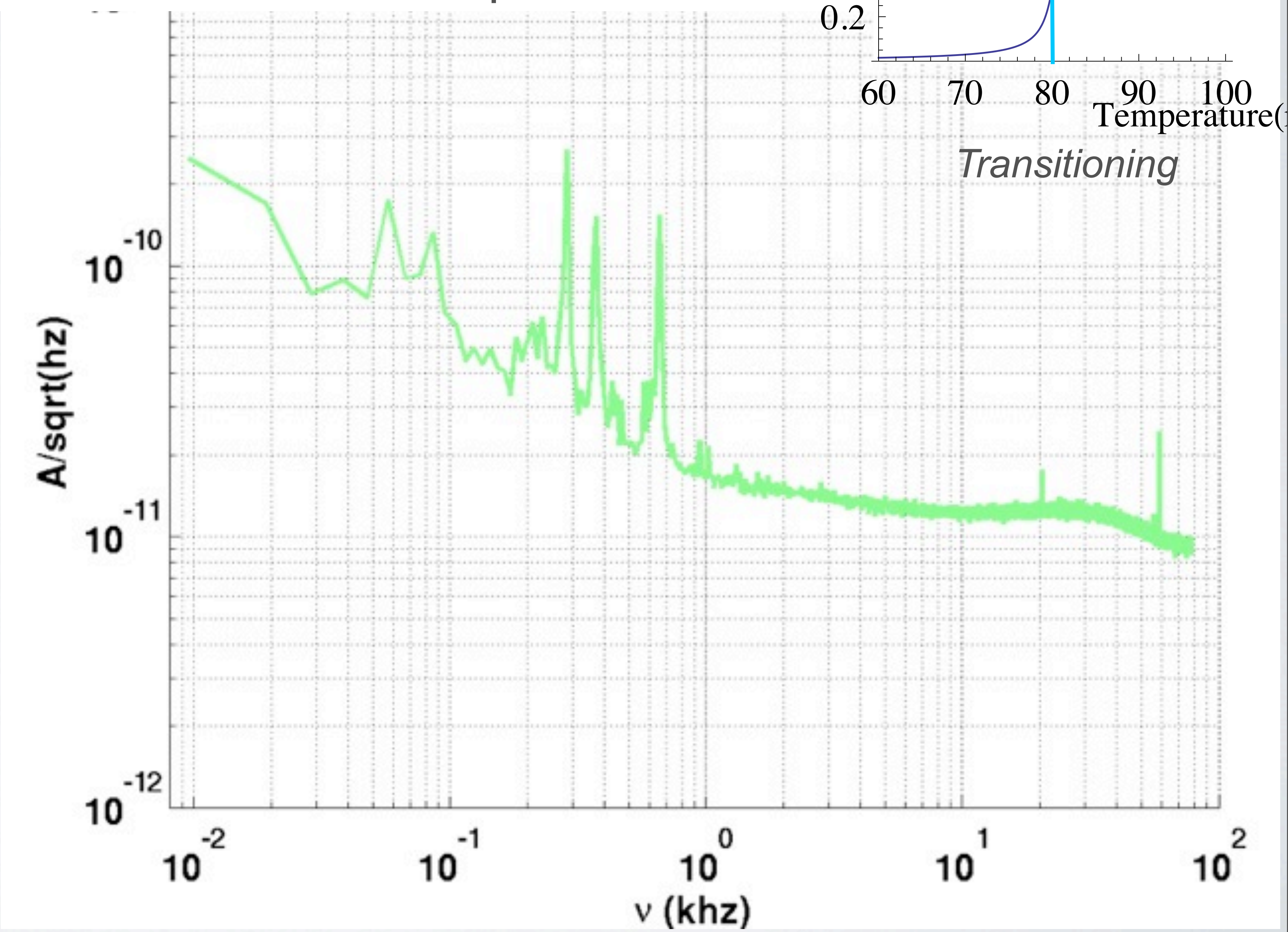
Amplitude Baseline From Johnson Noise: 3.63 pA/√Hz

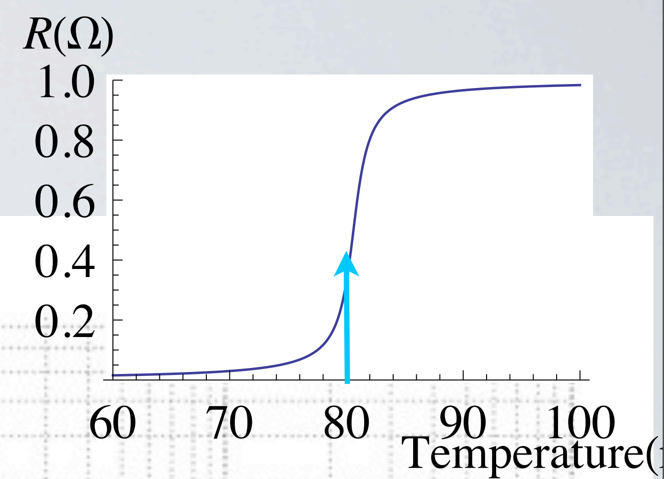
Cut-off frequency from Impedance: 250 kHz (Out of range)

STANDARD CONFIGURATION DATA

(V_{bias} is set so that the TES is in Transitioning Mode)

Data from example detector





Transitioning

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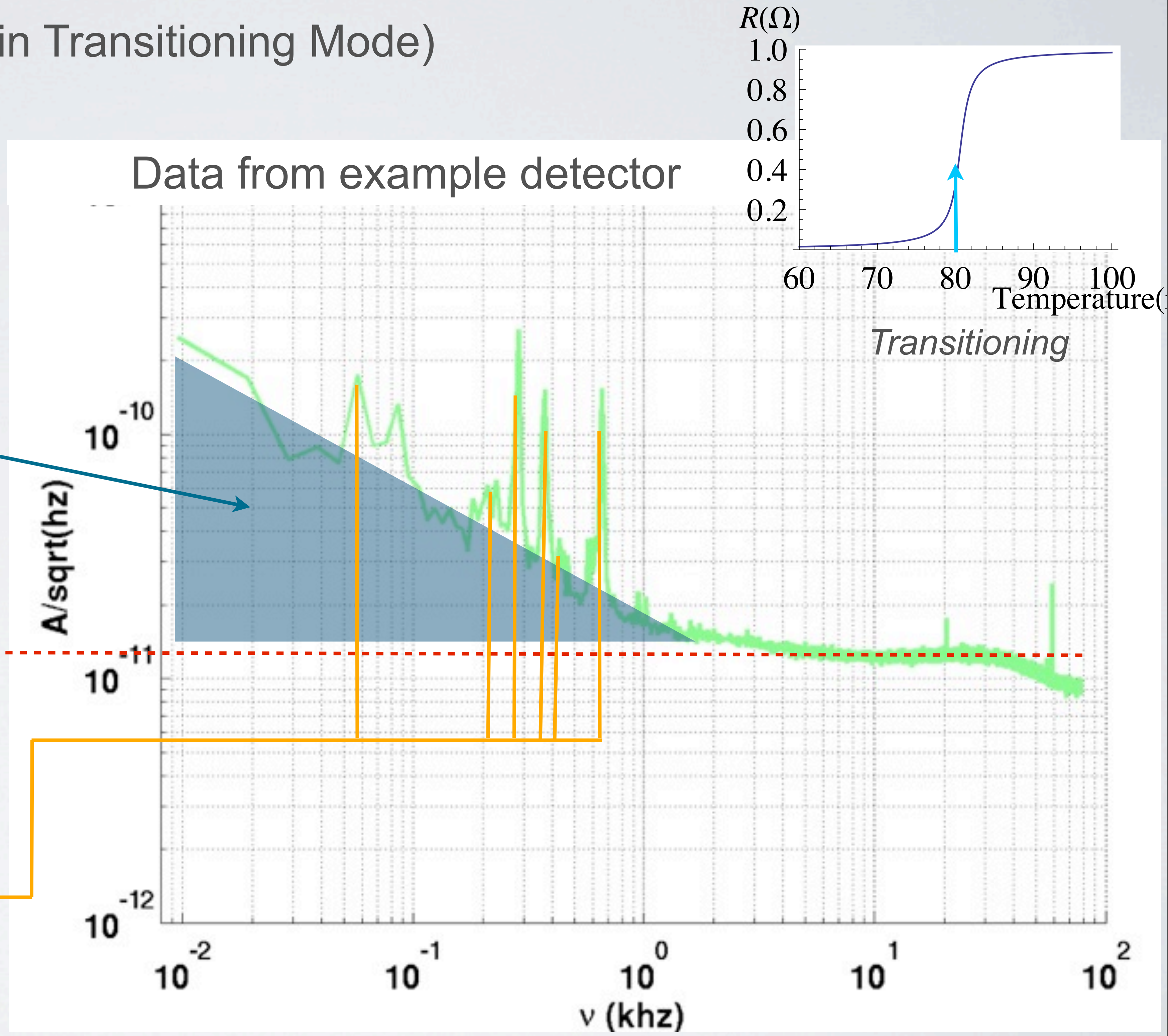
STANDARD CONFIGURATION DATA

(V_{bias} is set so that the TES is in Transitioning Mode)

- Rising region: will show this is from low frequency detector vibrations < 60 Hz
- Baseline Noise: from TES/ SQUID electronics (Johnson Noise)
- Spikes: noise from various sources 100 Hz - 1kHz (phonon, detector electronics, or other electronics noise)



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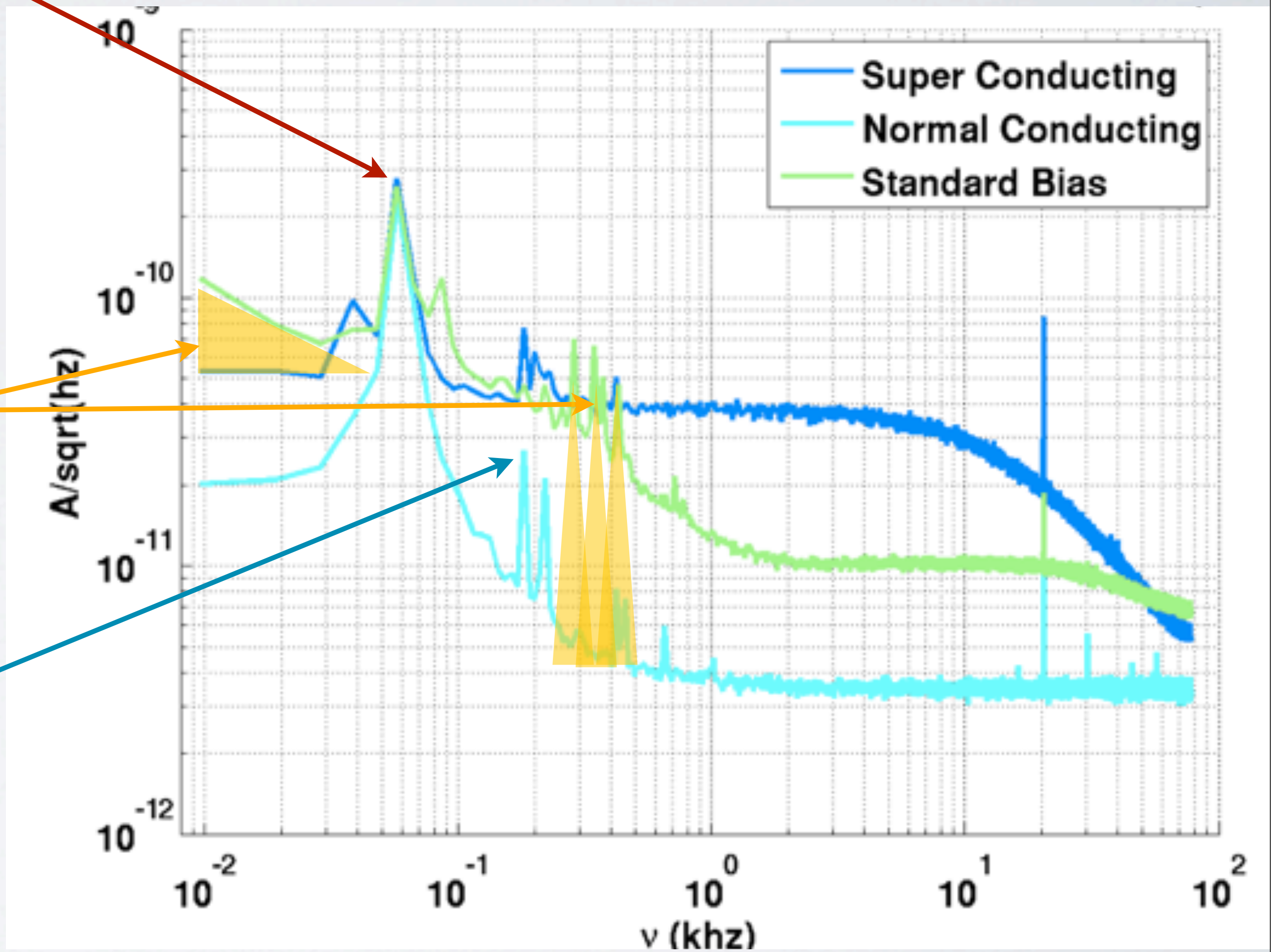
COMPARING ALL THREE SETS OF DATA AT THE SAME TIME (FOR A SINGLE DETECTOR) AND DRAWING QUALITATIVE CONCLUSIONS

- Other Electronics:
  - Peaks of this kind have a noise ratio of 1-to-1 regardless of mode
  - 60 Hz noise always present
  - The amount of noise at this frequency is always the same

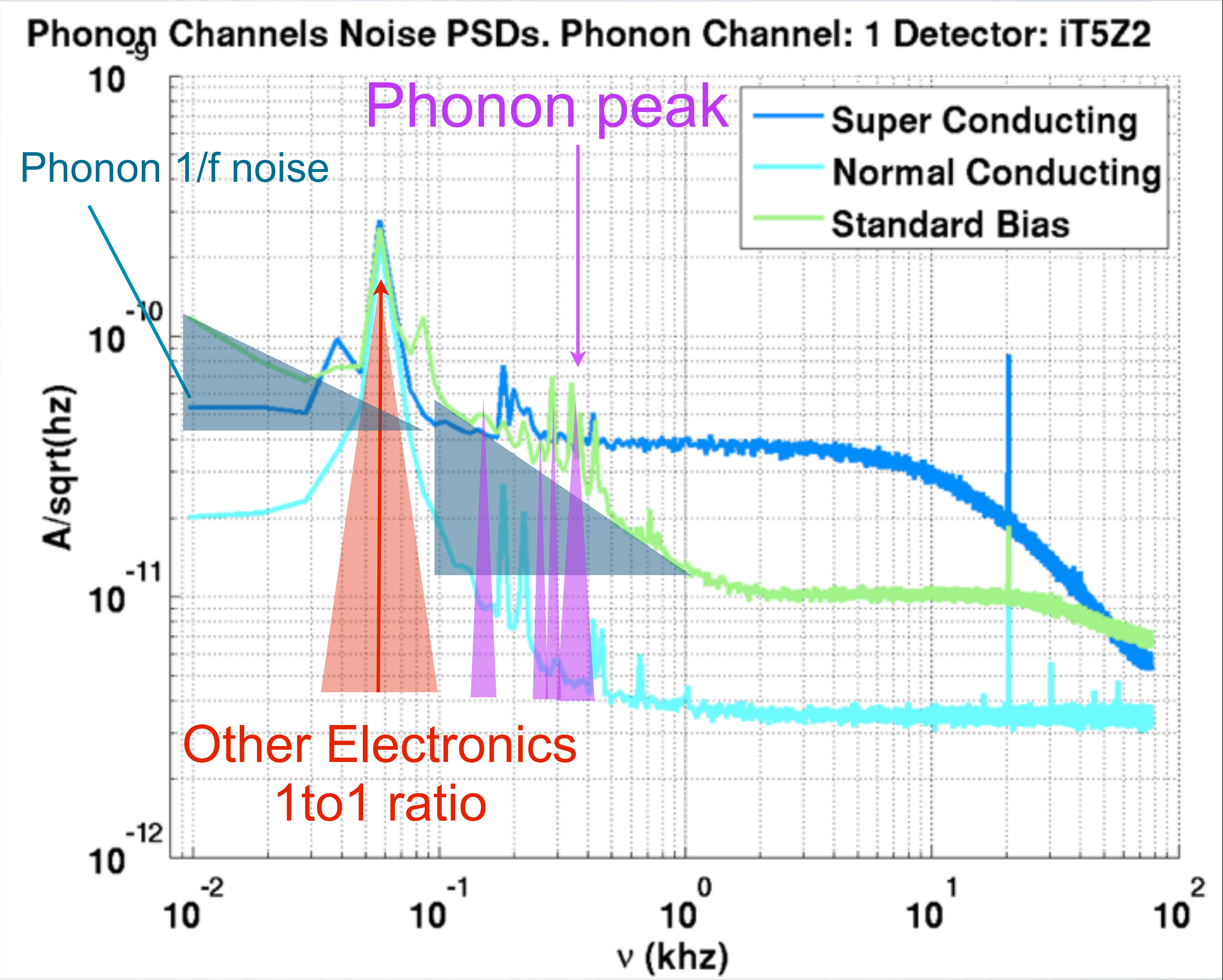
- Noise from Phonons:
  - Only see this noise in Standard Mode (not in Superconducting nor Normal Conducting); noise rises as frequency drops
  - Indicates it is due to phonons that are always present in the detector
  - Also see some phonon spikes (not present in modes insensitive to phonons)

- Spikes due to V_{bias} Electronics / Inductive Coupling:
  - Change in the amplitude of peaks
  - Amplitude depends on resistance ratio of the different experimental modes



MOVING FROM OUR EXAMPLE DETECTOR TO NOISE IN OTHER DETECTORS. NOT ALL DETECTORS ARE THE SAME

- Again see the 60 Hz peak (true for most detectors)
- Some detectors have spikes due to "phonon peaks", not just the slope (1/f noise). Due to cryogenics?
- Many peaks/features are combined electronics noise (from V_{bias}/Inductive and Other Electronics)



RESULTS TRUE FOR SOME DETECTORS

- < 60 Hz Background Results:

  - Most of the detectors (13/15) clearly show real phonon noise

- 100 Hz - 1 kHz peaks:

  - Different detectors show different noise sources, but overall noise is similar in all channels of the same detector (as opposed to some channels)

  - Other Electronics noise doesn't appear in all channels of same detector

  - All detectors show real phonon source peaks

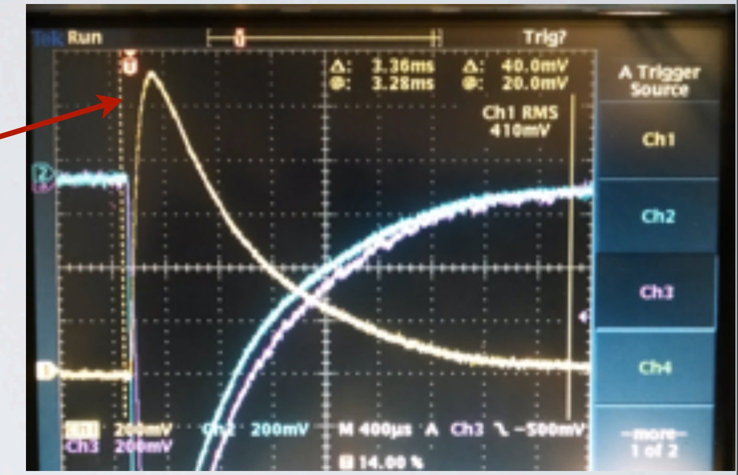
  - Some show additional V_{bias}/Inductive peaks, others show no sources of this kind

  - 6 out of 15 are Phonon dominated

  - 6 out of 15 show Other Electronics peaks

  - 9 out of 15 are V_{bias}/Inductive and Phonon dominated

IDEAS TO REDUCE/CANCEL NOISE IN THE FUTURE



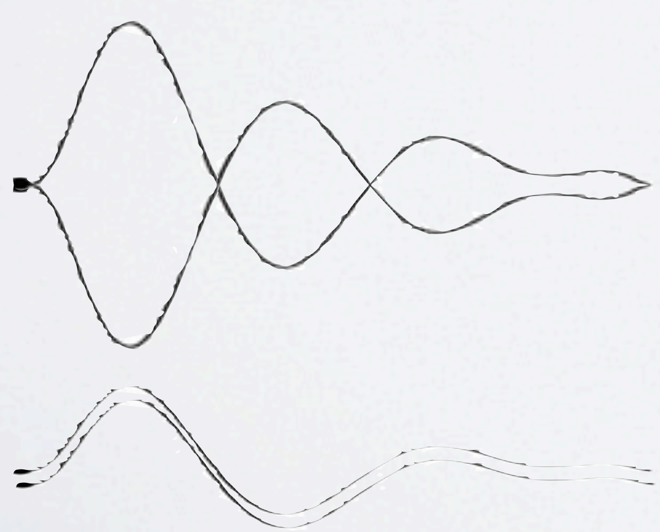
- Flip the Polarity of half of the channels:
  - Invert V_{bias} of 4 out of 8 channels
  - Real phonon signal should flip
  - Electronics noise will not

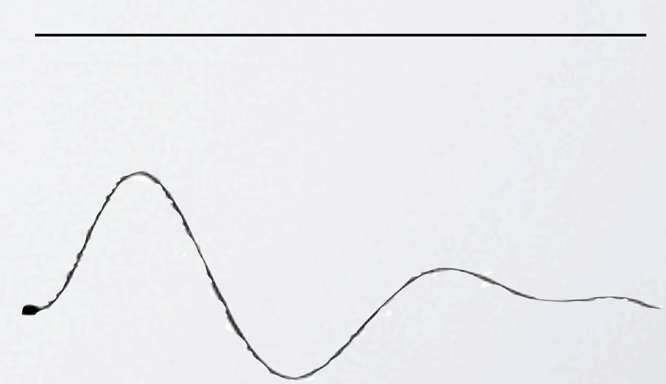
- Potentially cancel the 'Other Electronics' noise

- Complications:
  - Noise should be properly identified and STRONGLY correlated between channels, if not it means that noise doesn't match exactly at such frequency, so we are killing more than just noise

Electric

Phonon





CONCLUSIONS

- We have better understanding of the sources of noise:

  - All detectors have some amount of noise that appears to be due to vibrations, so better casing and supporting structure could really help improve our sensitivity
  (independent studies correlate the Cryocooler noise with the pulses)

  - Better electronics could also help suppress all electronics noise, mostly at TES/squid level, but also downstream. Tighter controls on the detector fabrication and electronics production could also make problems more reproducible and thus straight forward to reduce together

- Inverting Bias on half of the output channels may lead to electronics noise suppression - currently exploring this idea, we are not certain if it is possible to do without suppressing too much signal

- Next generation experiment, located at SNOLAB (Ontario, Canada) is already approved, the upgrades will certainly reduce the noise and improve our sensitivity!

THANKS!

Many thanks to:

Prof. David Toback
(Advisor)
Texas A&M University

Matt C. Pyle
(Collaborating Post-Doc)
U.C. Berkeley

BACKUP

DIRECT DETECTION

Sensitive to 7keV of energy deposit
(LUX: ~3.3 keV , SCDMS-II: 2keV)

- CDMS (Cryogenic DM Search) → Super CDMS
- DAMA (100 kg sodium iodide crystal) → DAMA/LIBRA (250 kg, Gran Sasso, Italy)
- XENON10 (15kg liquid xenon) → XENON100
- KIMS (Korea Invisible Mass Search)
- XMASS (800 kg spherical liquid Xe, Japan)

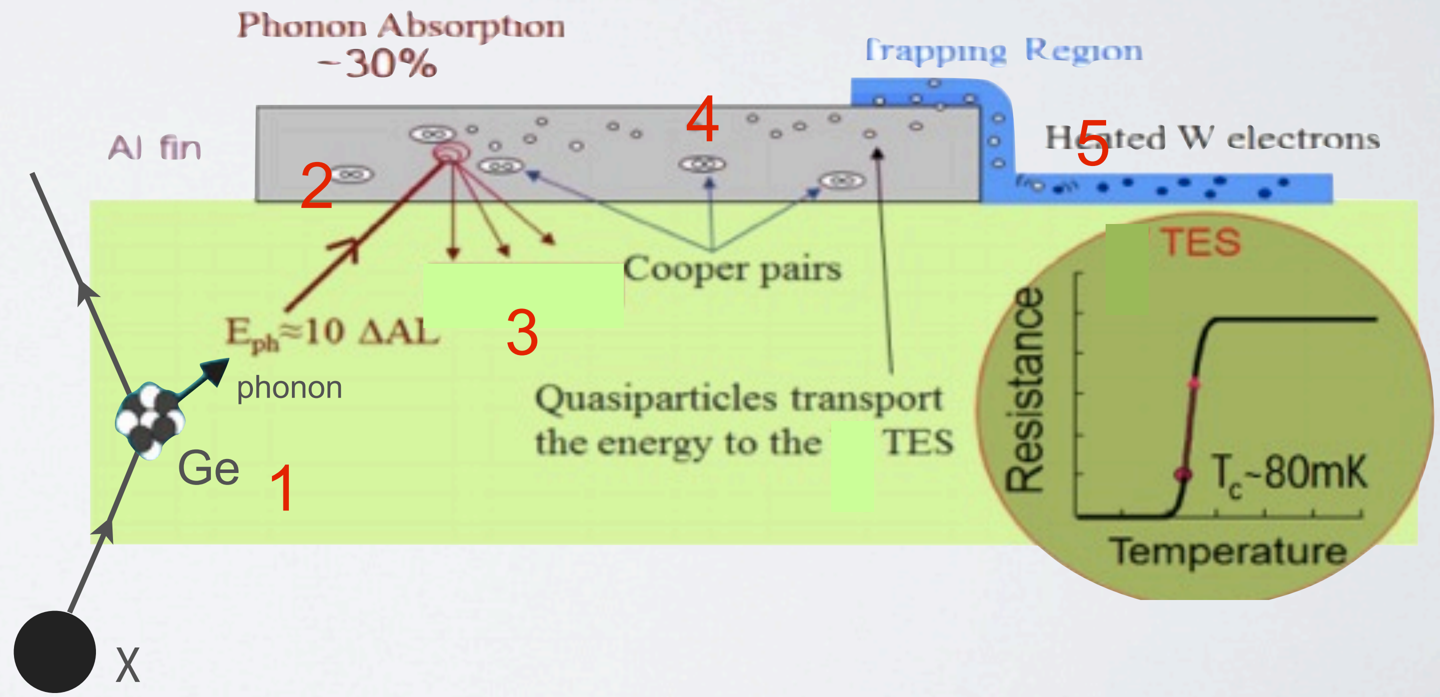
- Ionization (eV, ε~20%)
- Scintillation (keV, ε~1%)
- Phonon (meV, ε~100%)

FROM A PARTICLE INTERACTION TO A SIGNAL OUT OF A **T**RANSITION **E**DGE **S**ENSOR

- A DM particle will interact via vibrations of lattice: Phonons

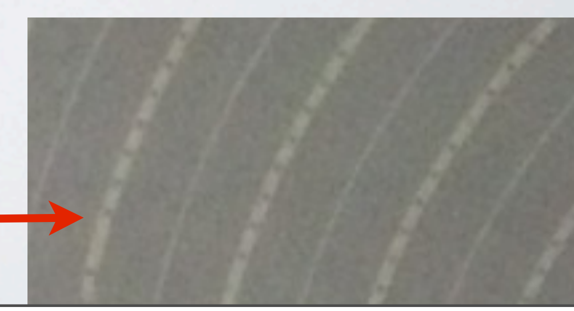
- Phonon production and collection process:

  1 super-rapid phonons (*athermal*)
  2 phonons break superconducting cooper pairs
  3 cascade phonons are produced
  4 phonons couple to freed electrons
  5 finally they diffuse into the tungsten Transistor Edge Sensor (TES)



athermal: more energetic than typical energy; at least 2 superconducting AL gap

Phonon Trap →



COSMOGENIC BACKGROUND

- 750μs is a typical real particle pulse time
- Total time of our samples ~ 100,000 μs
- Cosmogenic background (muons mostly) interact with the detector (passing the scintillating veto)
  - 1 every 64.4 ± 0.1 s
  - energy threshold choice is 1 V (≈ 6.9 MeV)

http://cdms.berkeley.edu/Dissertations/fritts.pdf

BACKUP: SOURCES OF NOISE

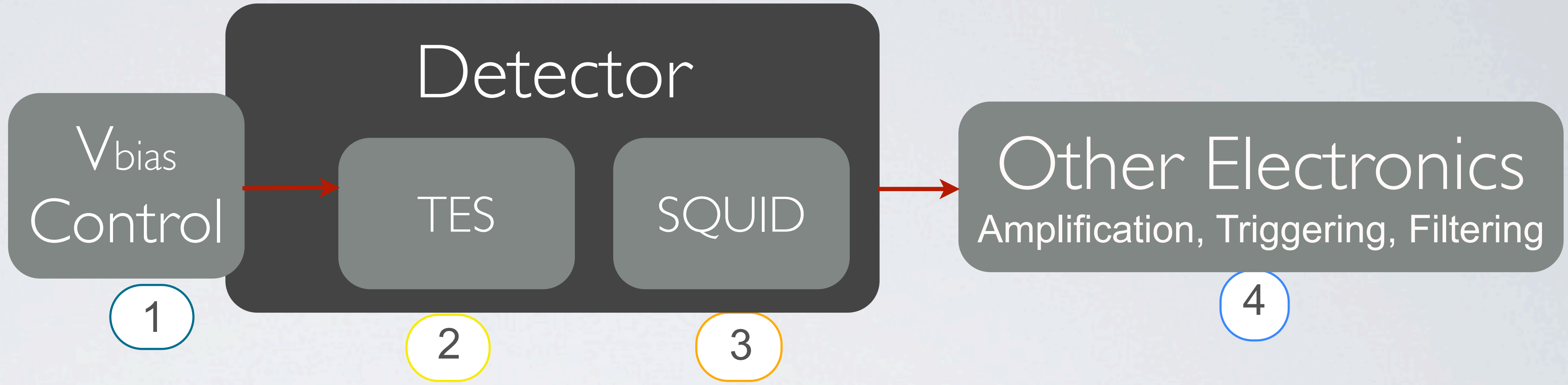
HOW TO UNTANGLE THE SOURCES OF NOISE

Experiment Modes

A. Standard Configuration

B. Normal Conducting

C. Super Conducting



1. V_{bias} Electronics: If peaks are due to noise from the V_{bias} control then they should be bigger or smaller depending on the the overall resistance in the circuit. The amount is known, so the ratio of the peaks should follow this ratio
   A/B ~ 1/3 A/C ~ 7

2. True Phonon Production: If noise is due to detector vibrations, then we should not see any noise when we are not sensible to phonons (modes B & C)

3. Detector Level Inductive Coupling: From PSDs it is the same as Vbias 1 , but we can look at correlation between channels/detectors depending on the connections/card dependencies of the channels within each detector

4. Other Electronics: If the noise is due to the electronics after the SQUID (Other Electronics), then the peaks should be in the same place and have the same size regardless of the experiment mode

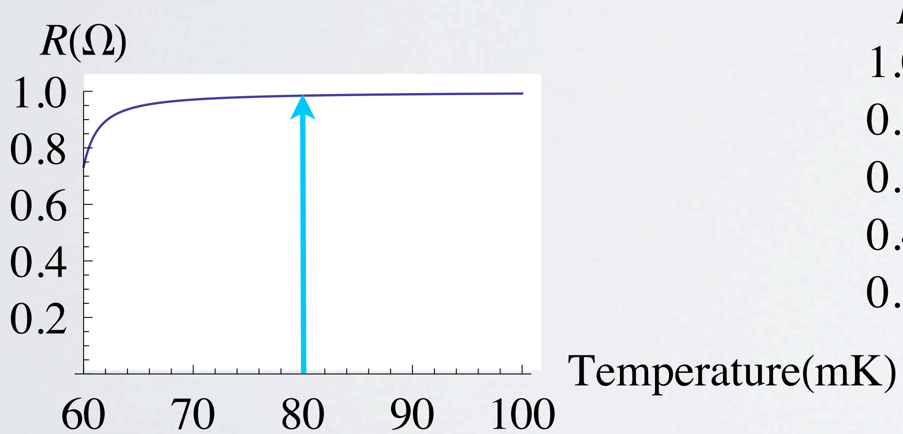
VBIAS AND FRONT END BOARD

- The V_{bias} is actually on the Front End Board, which ALSO does a part of the read-out electronics

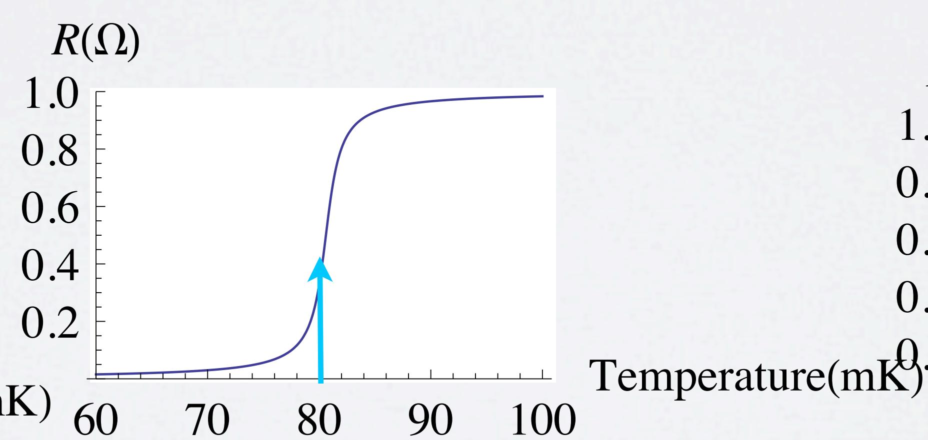
V_{bias} Control → TES needs V_{bias} to operate → Front End Board provides V_{bias}

- Vbias sets the TES R vs. T Curve

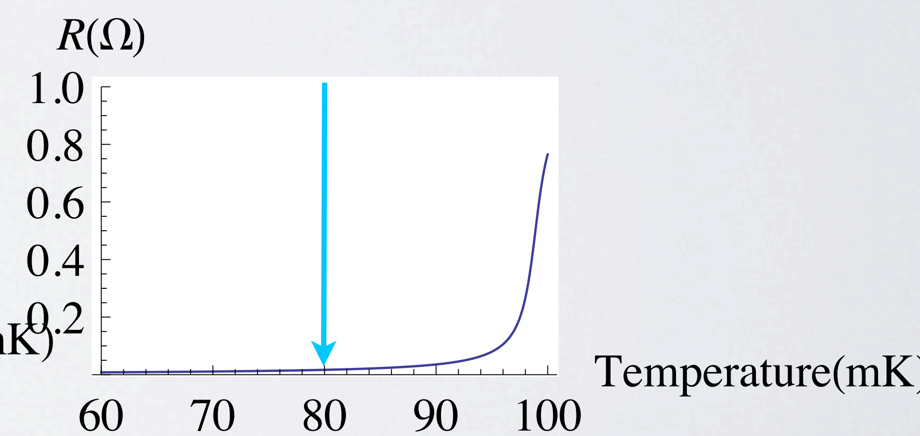
Temperature is fixed at 80mK



Normal Conducting

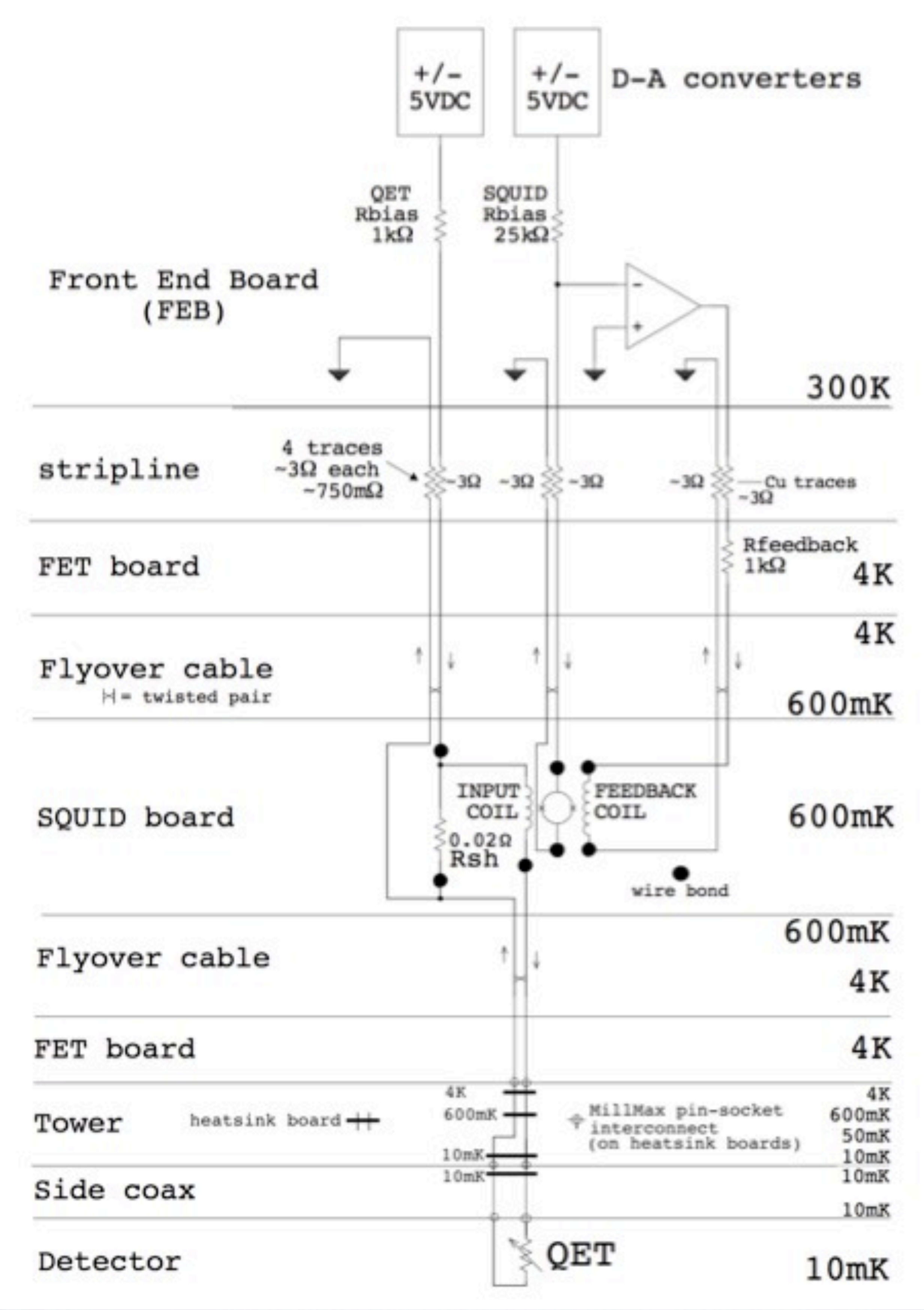


Transitioning



Superconducting

BACKUP: TES/SQUID CIRCUIT



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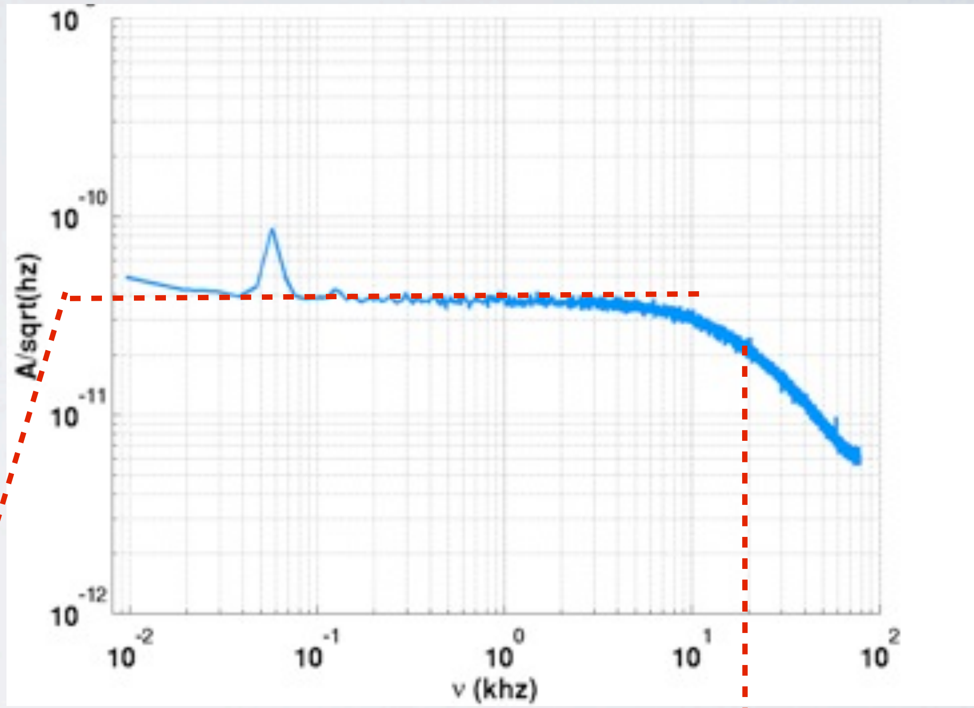
BASE NOISE OF THE TES CIRCUIT

- 'Johnson Noise'
  - Intrinsic of the TES/SQUID circuit
  - Characteristic of the amplification of the TES SQUID pulse

- Depends on the Resistance and Temperature of the elements in the circuit

Amplitude of J-Noise in PSD: $S_I^2 = \frac{4 k_\beta (\Sigma R_i T_i)}{(\Sigma R_i)^2}$



- The cut-off frequency is determined by the impedance

$$\frac{dI}{dV} = \frac{1}{Z} = \frac{1}{(R_L + R_{TES} + \omega L j)}$$

Cut-off frequency

- By setting a Vbias/Ibias (from FEB), we set the TES resistance in the circuit

R and T values of the Circuit

Element	Resistance	Temperature
R_L	34 mΩ	1.2 K
R_{TES}	(0 or 600) m Ω	80 mK

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JOHNSON NOISE AND PARASITIC RESISTANCE

$$S_I{}^2 = \frac{4\,k_\beta\,(\Sigma\,R_i T_i)}{(\Sigma\,R_i)^2}$$

$$S_{II} = \frac{\sim 1\ \text{pA}}{\sqrt{\text{Hz}}}$$

NC: $G_T \approx 3.63\ \text{pA}/\sqrt{\text{Hz}}$.
SC: $G_T \approx 44\ \text{pA}/\sqrt{\text{Hz}}$.

- Johnson Current
- Parasitic Resistance (Average)
-

Element	Resistance	Temperature
R_L	34 mΩ	1.2 K
R_{TES}	(0 or 600) m Ω	80 mK

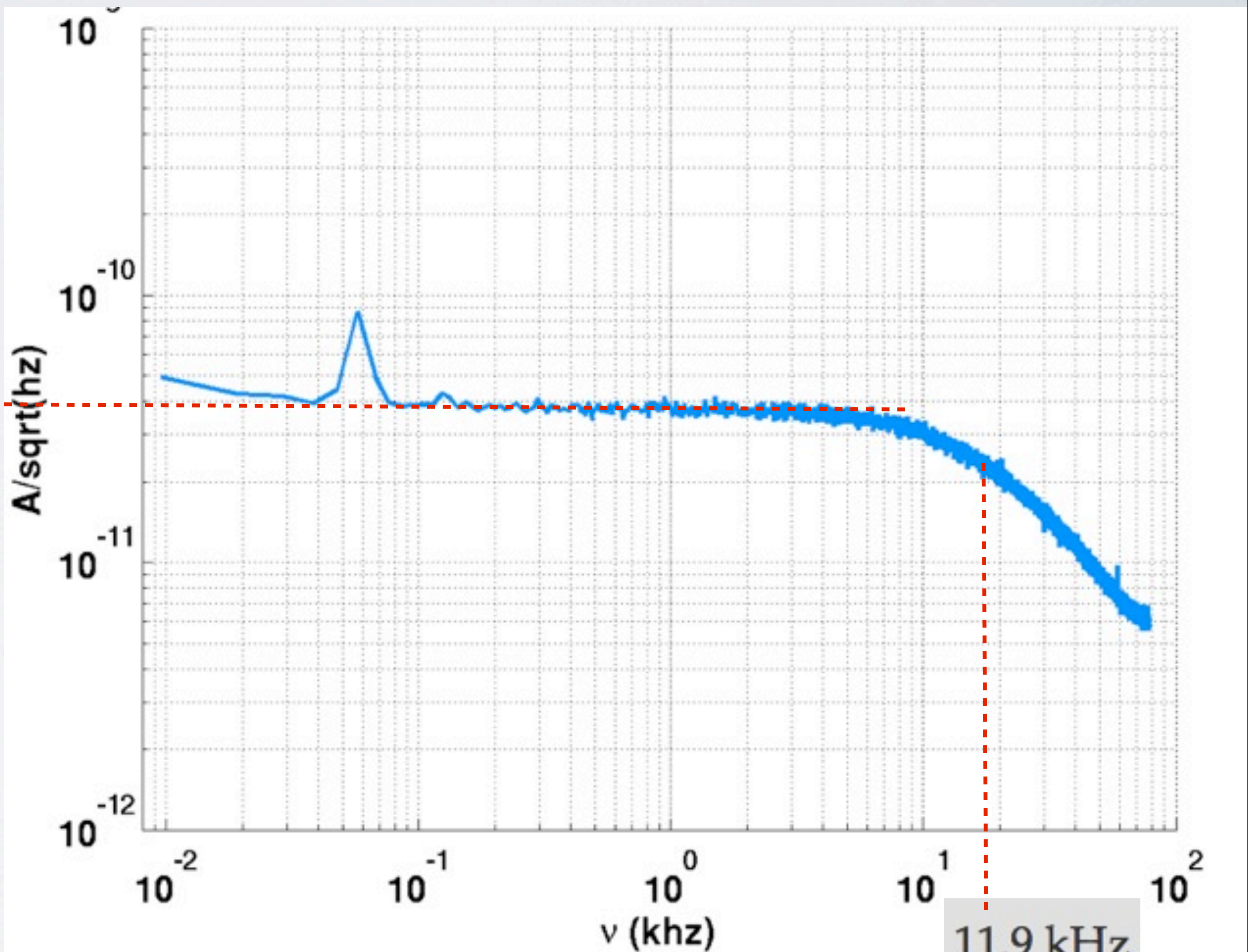
Element	Resistance	Temperature
R_{shunt}	20 mΩ	1.1 K
$R_{Al\ wire\ bonds}$	2 × 4 mΩ	1.1 K
$R_{pins(a)}$	2 × 1 mΩ	4 K
$R_{pins(b)}$	2 × 1 mΩ	1.1 K
$R_{pins(c)}$	2 × 1 mΩ	80 mK
R_L	**34 m Ω**	**1.2 mK**

Std/NC=230mΩ/630mΩ ~ 1/3 Std/SC=230mΩ/30mΩ ~ 7

DETECTOR READOUT IN SUPERCONDUCTING DATA

- When the V_{bias} sets the TES in superconducting mode, again the readout signal is insensitive to phonons in the detector.

- Smaller TES resistance gives greater baseline noise
- Only see one spike at 60Hz again. Other spikes are gone, perhaps swamped with baseline noise?
- Lower threshold Cut-off as expected



Amplitude Baseline From Johnson Noise: $44\ pA/\sqrt{Hz}$

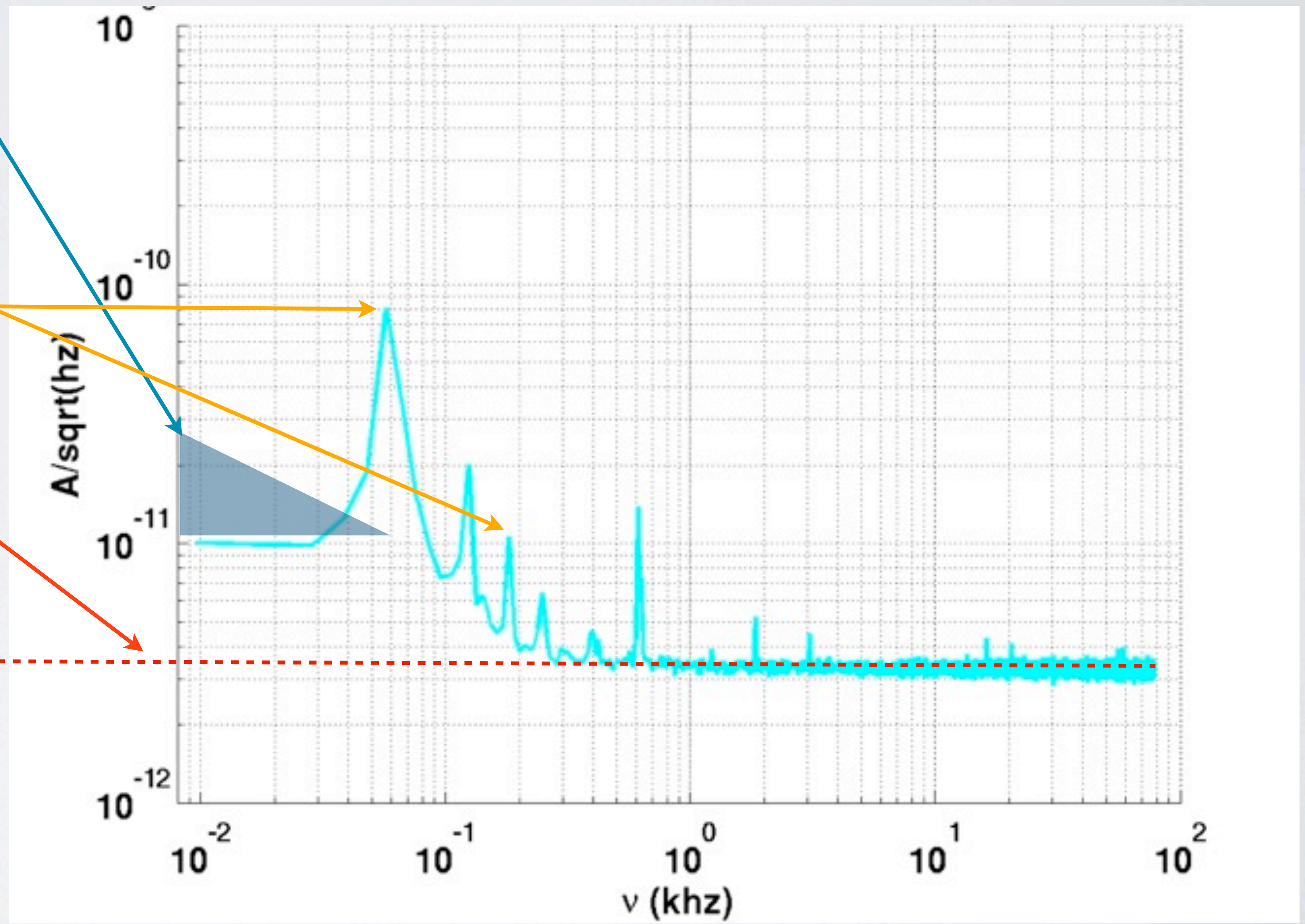
11.9 kHz

Cut-off frequency from Impedance

DETECTOR READOUT IN NORMAL CONDUCTING DATA

- When the TES has a Temperature/V_{bias} configuration that makes it normal conducting, the readout signal is insensitive to phonons in the detector

- No big slope at low frequencies. Noise in the previous plot must be due to phonons 'intrinsic' to the detector somehow
- Spikes still exist, must not be due to phonons, but to some part of the electronics. Note the big spike at 60Hz (suggestive number)
- Lower baseline, but that's expected because there is more resistance
- No 'cut-off' here because its off scale.



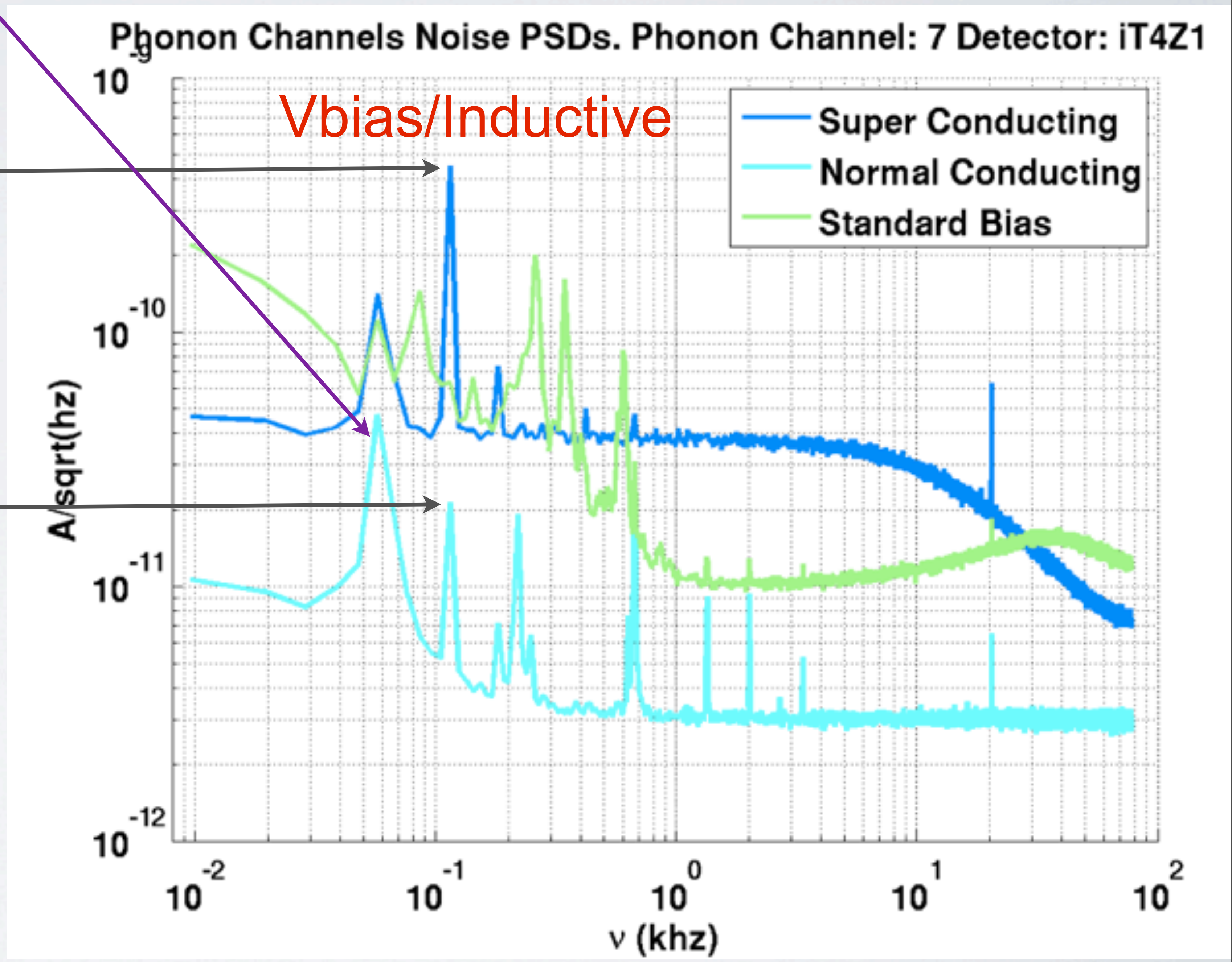
Amplitude Baseline From Johnson Noise: 3.63 pA / √Hz

Cut-off frequency from Impedance: 250 kHz (Out of range)

THIRD EXAMPLE: V_{BIAS}/INDUCTIVE PEAKS

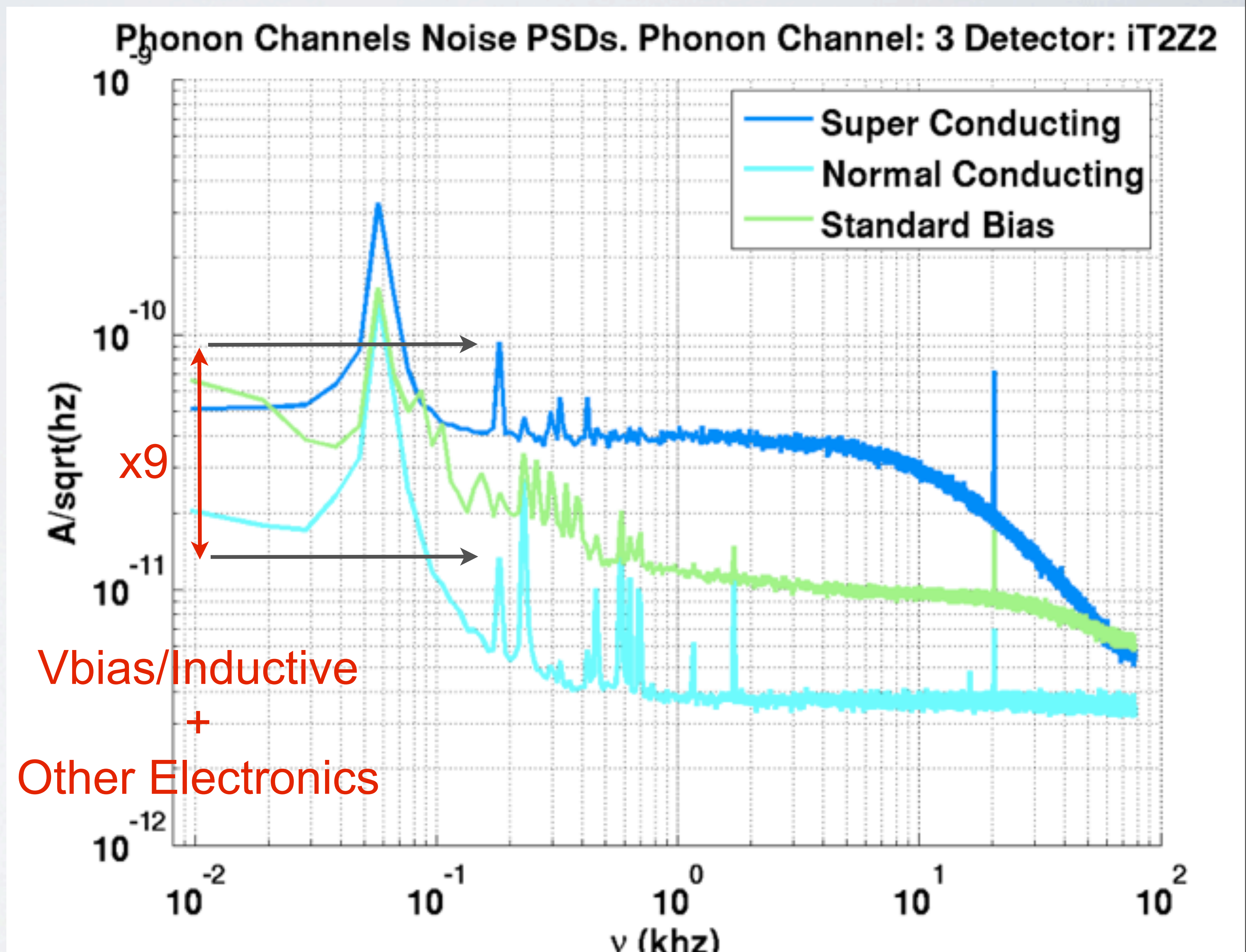
- 60Hz peak is not the same, it is possible that Vbias/ Inductive noise is coupled as well as Other Electronics noise
- Clear peak due to Vbias/ Inductive noise, scales accordingly:
  - Std/SC ~ 7
  - Std/NC ~ 1/3
  - NC/SC ~ 21
- In Standard Bias these peaks could be masked by baseline + phonon noise
- In Superconducting mode peaks must be dominant due to the resistance ratios

x21



4TH EXAMPLE: BORDERLINE V_{BIAS}/ INDUCTIVE PEAKS

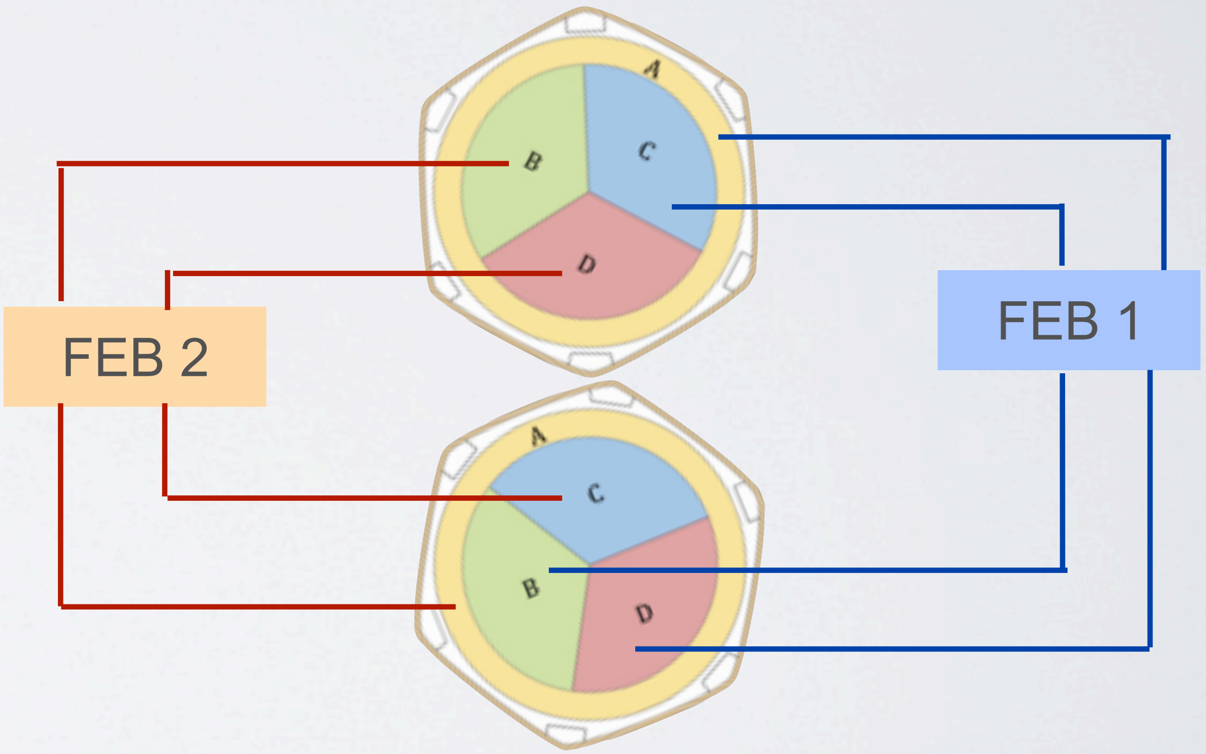
- Vbias/Inductive noise can combine with Other Electronics noise
- Don't see a perfect ratio, the downstream electronics noise adds, but it is clearly not a phonon noise (because it is not dominant in Std)

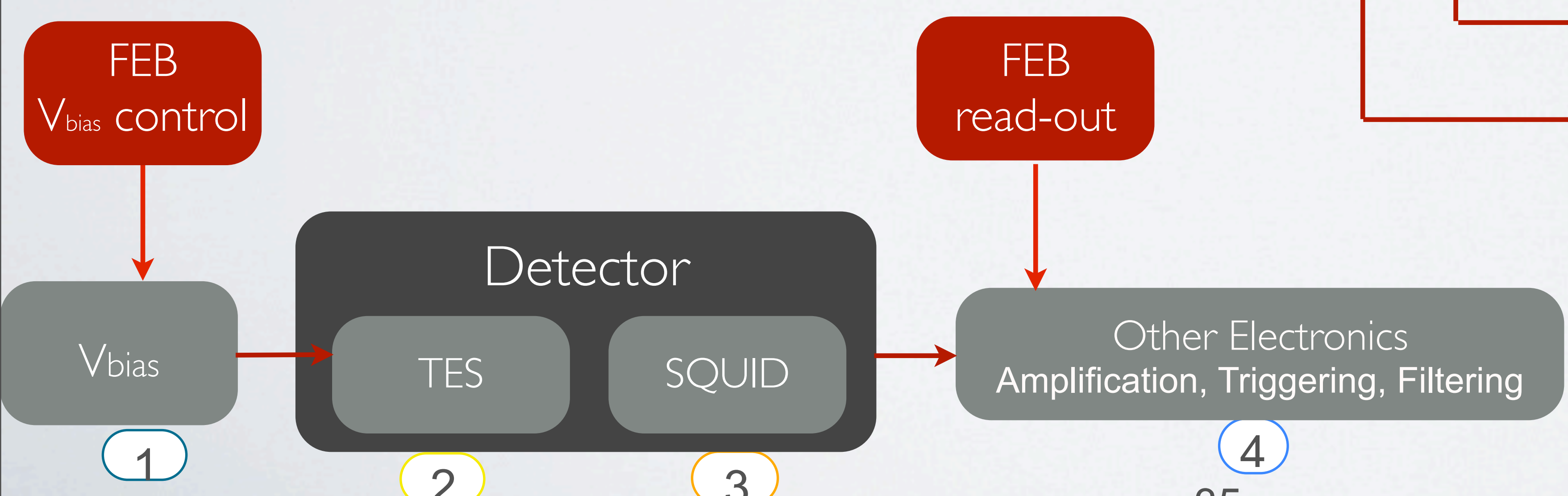


LIMITATIONS OF THE STUDY

- Unfortunately we are not able to discriminate between a capacitively coupled (TES V_{bias}) noise and an inductively coupled (SQUID) noise, but we can see if the noise is common to phonon channels connected to the same electronics board - Front End Board (FEB) - as opposed to a detector

- The FEB connections to the TES channels are combined:
  - 2 cards per detector
  - 2 channels per side in each card





SUMMARY

- Mostly coupled by athermal phonons, or, for non-vibrating detectors through a vbias +downstream coupling mechanism.
  (Of course excluding the ~60Hz Mains Hum, which affects pretty much all detectors).
- The baseline noise (background) in the range < 600Hz (and possibly <500Hz) is phonon coupled, and affects noticeably 13 detectors in all working channels.
- The peaks in the range 100 - 1kHz are both phonon and electronically (vbias +downstream) coupled, a list of dominant mechanism per detector is provided, and few (4/15) detectors include signs of downstream electronics noise (only in some channels 17/28 channels in total).
- Now that we know that the predominant noise is athermal phonon coupled or Vbias +downstream coupled, we can try to make a covariance/correlation study of each phonon channel within the same detector. This can not only tell us effectively if the noise is detector correlated, but it can tell us which frequencies are preferrably correlated between channels, and ultimately it may provide ways of supressing some modes.

http://titus.stanford.edu/cdms_restricted/Soudan/R133/ebook/140707_jm/

REMARKS

- 100 - 1000 Hz peaks:
  - Most cases it is electronically coupled and phonon coupled
  - Some seem like fft harmonics of the 60Hz peak that keep the SC/Std and NC/Std factors, so it is electronically (Vbias) coupled
  - In other cases the noise turns on when the detector is in the transitioning phase, which means there is also a phonon coupling
  - Also, in fewer cases some downstream electronics peaks appear (keeping the 1-to-1 ratio)
- A lot of the noise disappears in the Super Conducting mode, the persisting peaks should be electronically coupled, although only the stronger ones persist, and whenever SC/NC show a factor close to 21 the noise is electronics (Vbias/Inductively) related
- For phonon dominated detectors, since the noise peaks seem to be detector related, not FEB/squet/dib related, this helps to discard the downstream electronics and Vbias coupled electronics, although some exceptions occur in the 60Hz peak

REMARKS

- <60Hz: phonon coupled: most detectors show relatively flat SC and NC PSDs in this range, while the Std shows an intense background (detailed count in the following section)

- Homogenously decreasing background from 10 - 1kHz: again, seems to be a tail from the <60Hz region

- 60Hz peak:
  -Electronically coupled possibly the common 'Mains Hum' affecting all electronics, both downstream electronics and detector electronics
  - In some cases it is also downstream because the peaks are 1-to-1
  - But in other cases it seems like the noise couples inductively (i.e. SC/Std is close to a factor of 7, and NC/Std close to 1/3)

- 100 - 1000 Hz peaks: complicated but most important region

- 2kHz: inductively/vbias coupled (doesn't appear in all detectors/channels)