Multimode detectors for cosmic microwave background studies

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Note: I am not Peter!

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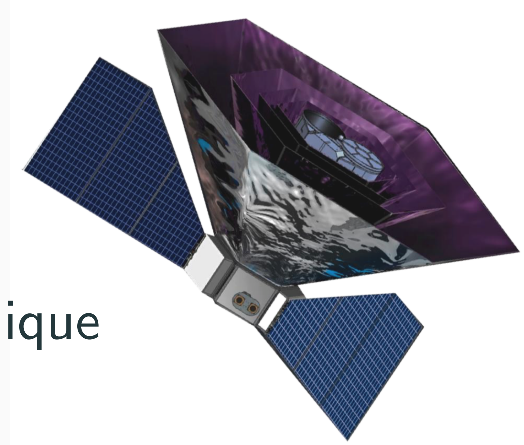
Outline

Introduction

Introduction - the PIXIE experiment

The Primordial Inflation Explorer (PIXIE)

- Space-based polarizing Fourier transform spectrometer (FTS).



Detectors designed for a FTS like PIXIE require unique optimization:

- Large etendue ($A\Omega = 4$ cm^2 sr).
- Handle large and constant optical load (120 pW).
- Large and mechanically robust absorber structure (30x larger than the spider web bolometers on Planck).
- Limited sensitivity to particle hits.
- Sensitive to all optical frequencies of interest (30 GHz - 6 THz).
- Photon-noise limited $\left(\mathrm{NEP_{phot}} \simeq 2.7 \times 10^{-16}\ \mathrm{W}/\sqrt{\mathrm{Hz}}\right)$.

Key difference: 4 multimoded bolometers instead of thousands of single moded bolometers.

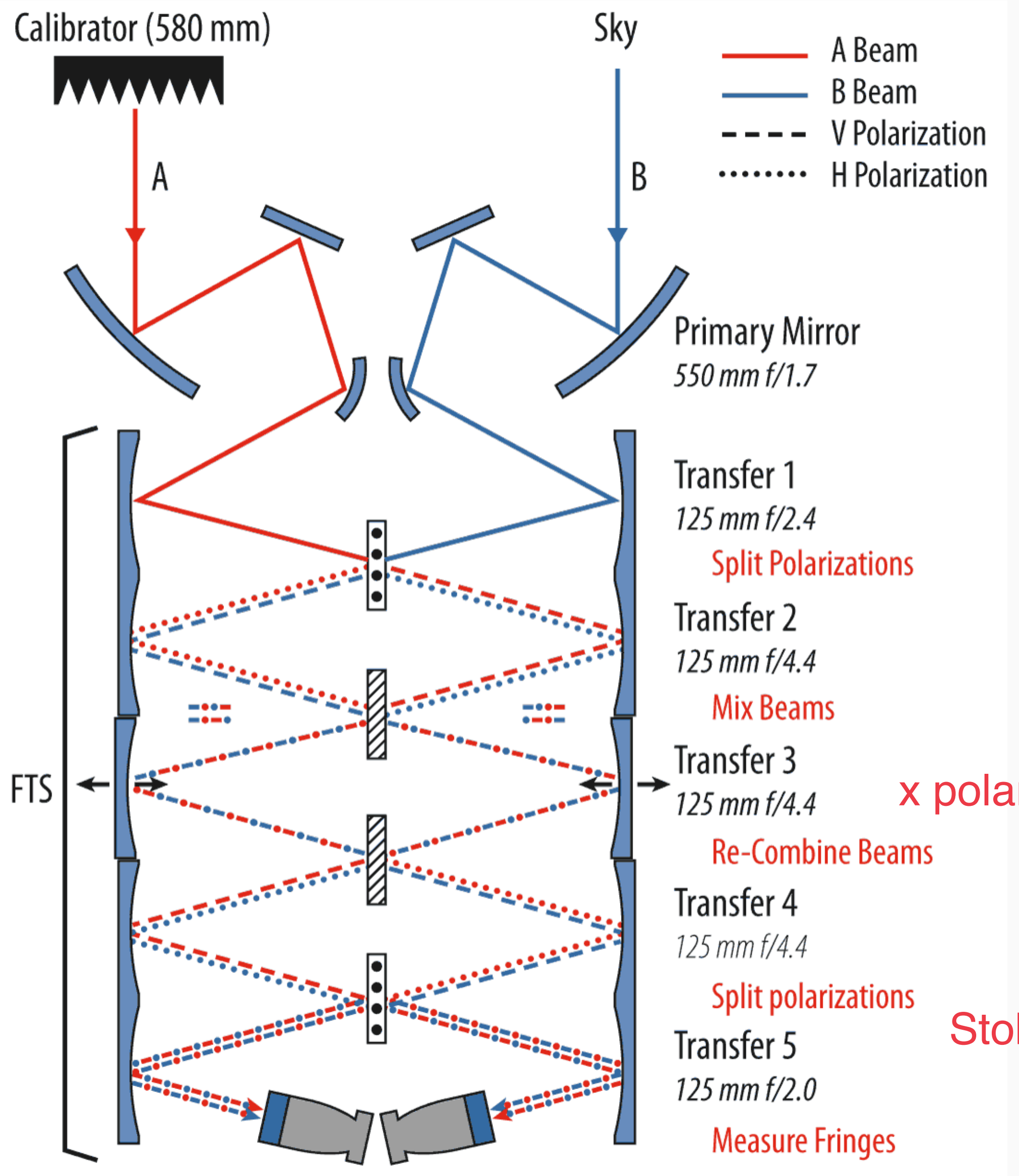
$$\mathrm{NEP_{phot}} \propto A \times \Omega.$$

Photon noise equivalent power

Detector area

Solid angle

Introduction - Fourier transform spectroscopy



Instrument computes the Fourier transform.

Incident light:

$$\mathbf{E}_{left} = A_x \hat{x} + A_y \hat{y}.$$
$$\mathbf{E}_{right} = B_x \hat{x} + B_y \hat{y}.$$

Power at detectors:

$$\mathbf{P} = \frac{1}{2} \int (A_x^2 + B_y^2) + (A_x^2 - B_y^2) \cos\left(\frac{4\nu z}{c}\right) d\nu.$$

Difference spectrum

Mirror modulation

Inverse Fourier transform:

$$\mathbf{S}_x^L(\nu) = A_x^2(\nu) - B_y^2(\nu).$$

x polarization from left

y polarization from right

Sky-fixed coordinates:

$$\mathbf{S}_x^L(\nu) = Q_{sky} \cos(2\gamma) + U_{sky} \sin(2\gamma).$$

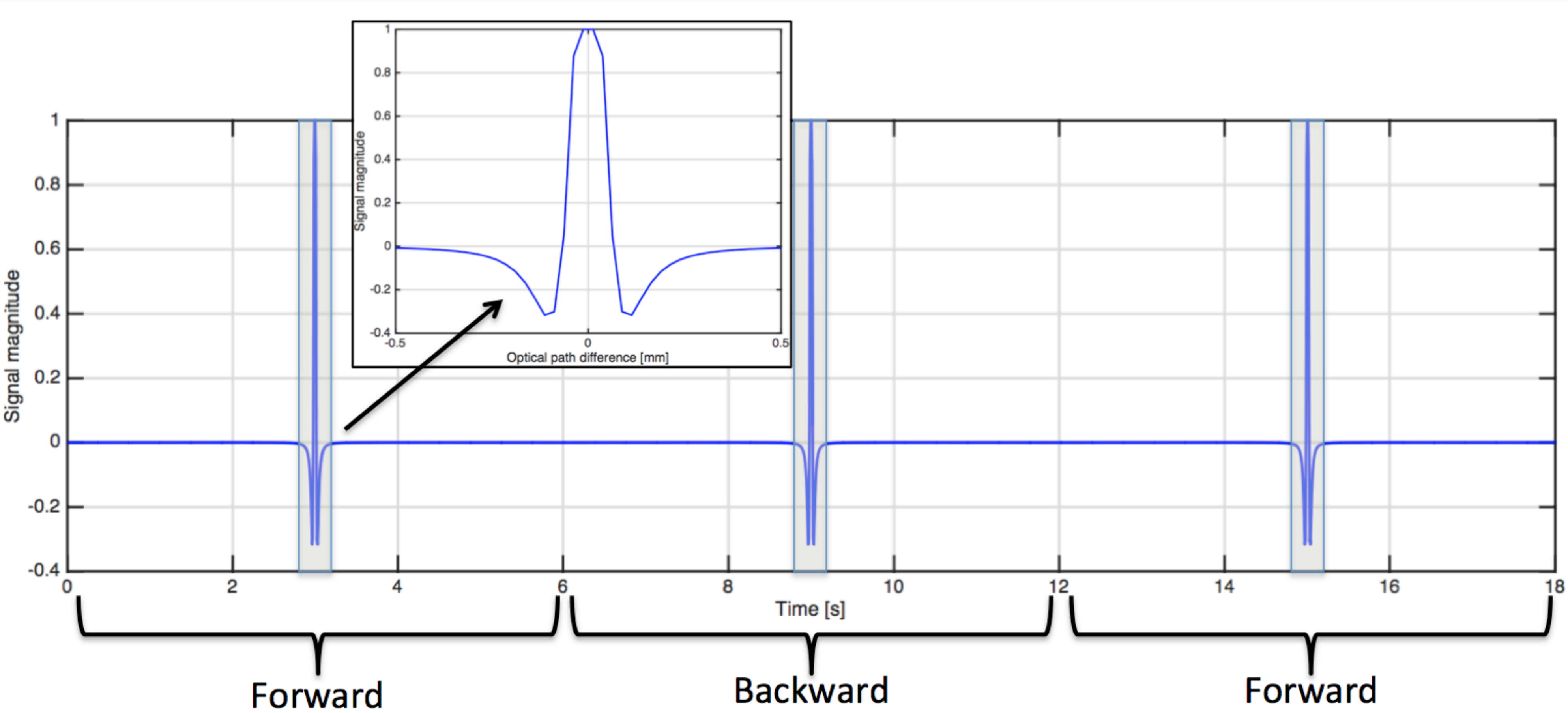
Stokes Q   Spacecraft spin angle   Stokes U

Completely specifies linear polarization.

Using a FTS is the *ideal* way to measure polarization.

Introduction - Fourier transform spectroscopy

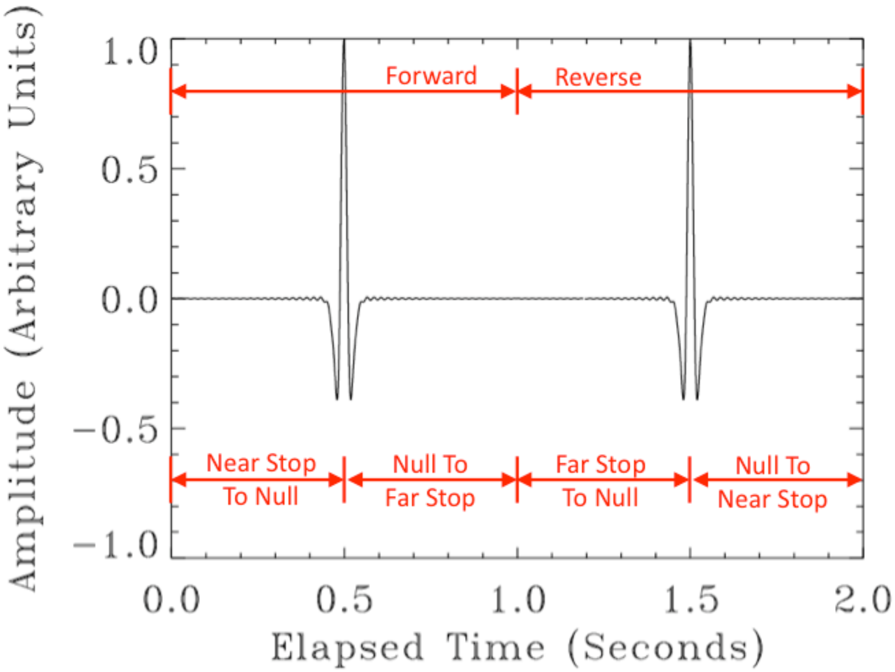
Signal is the Fourier transform of the sky. What does it look like?



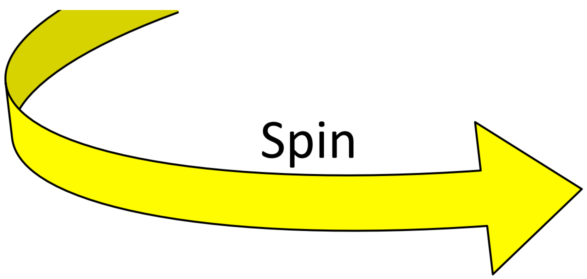
Details of FTS operation give bolometer bias and bandwidth requirements.

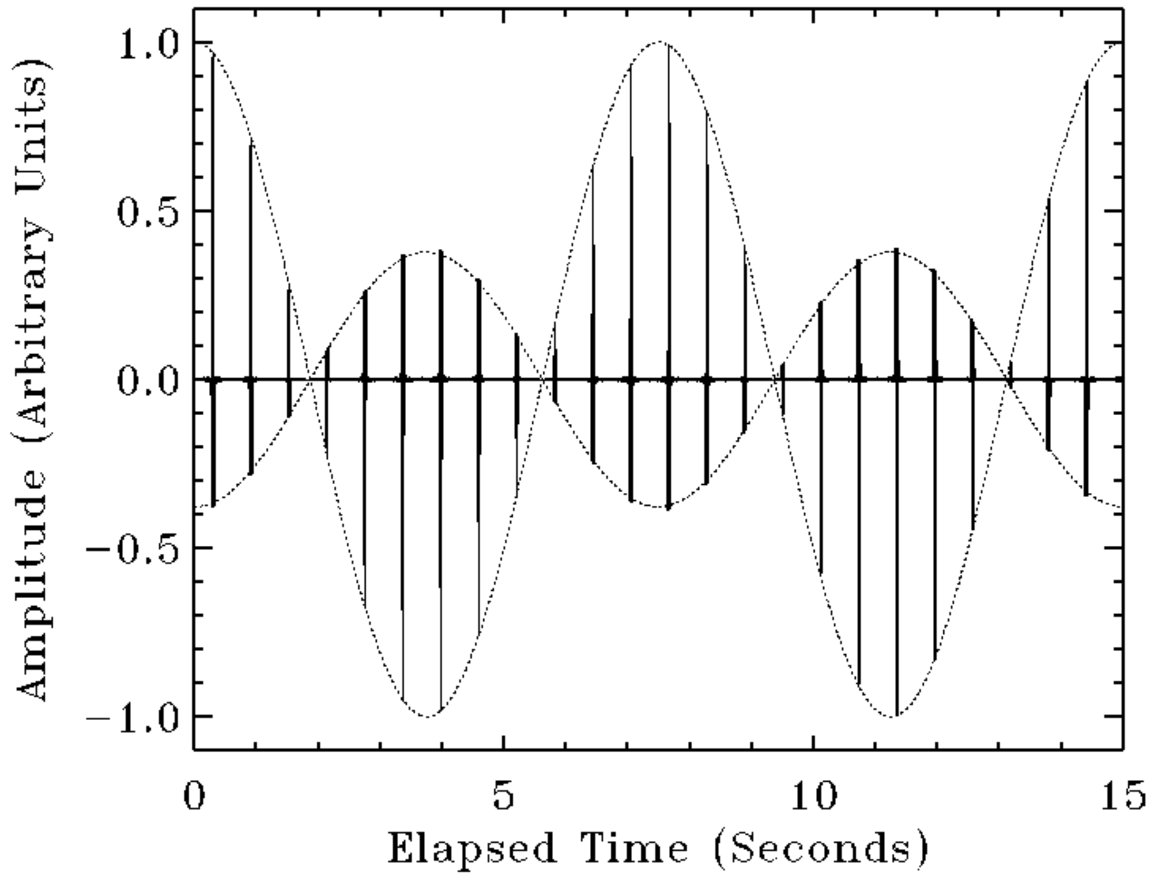
For PIXIE: photon noise limited $\left(\mathrm{NEP}_{\mathrm{phot}} \simeq 2.7 \times 10^{-16}\,\mathrm{W}/\sqrt{\mathrm{Hz}}\right)$ across all FTS frequencies $(0 - 100\,\mathrm{Hz})$ under large, near-constant $(\sim 120\,\mathrm{pW})$ optical bias.

Introduction - Fourier transform spectroscopy



Spacecraft rotation creates
amplitude modulation
of polarization fringe pattern



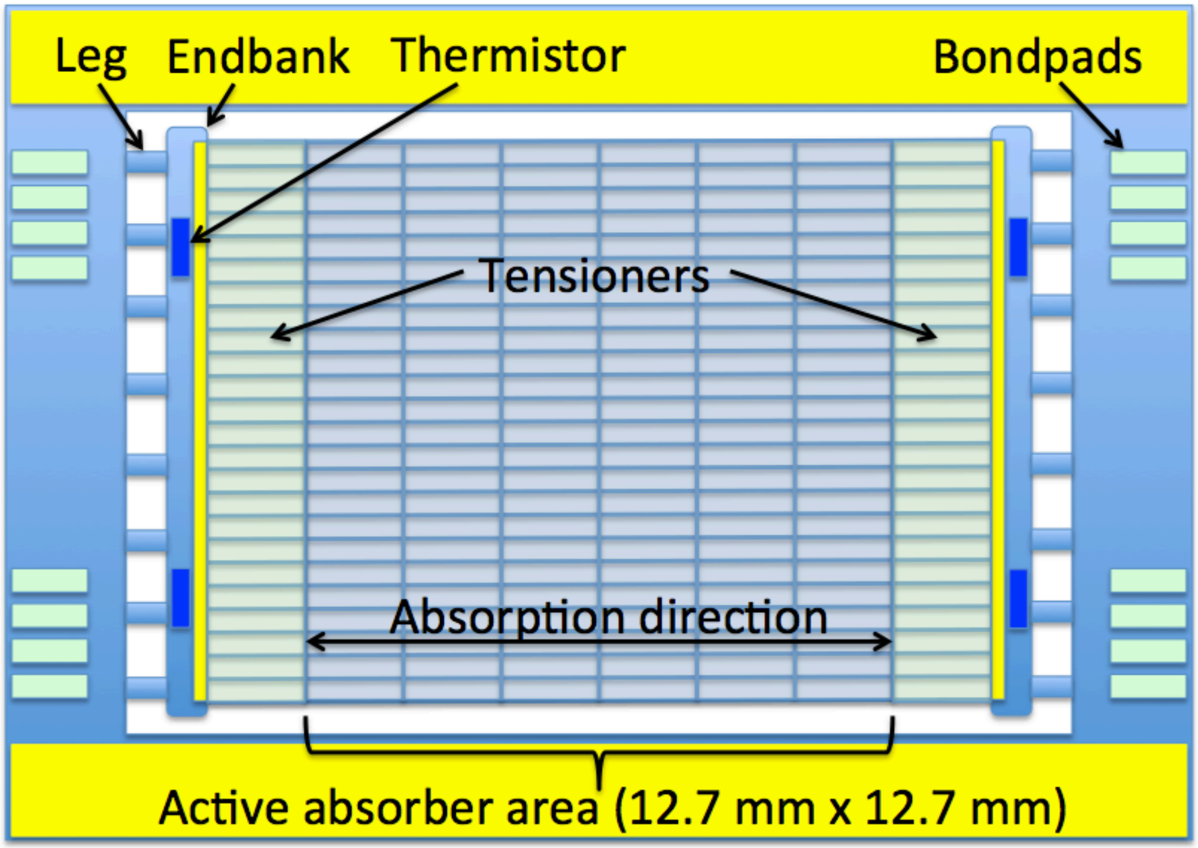


Instrumental drifts in time domain are
Fourier transformed to
lowest bins in frequency domain

No striping in polarization sky maps

Multimode bolometers for PIXIE

PIXIE bolometers - Introduction

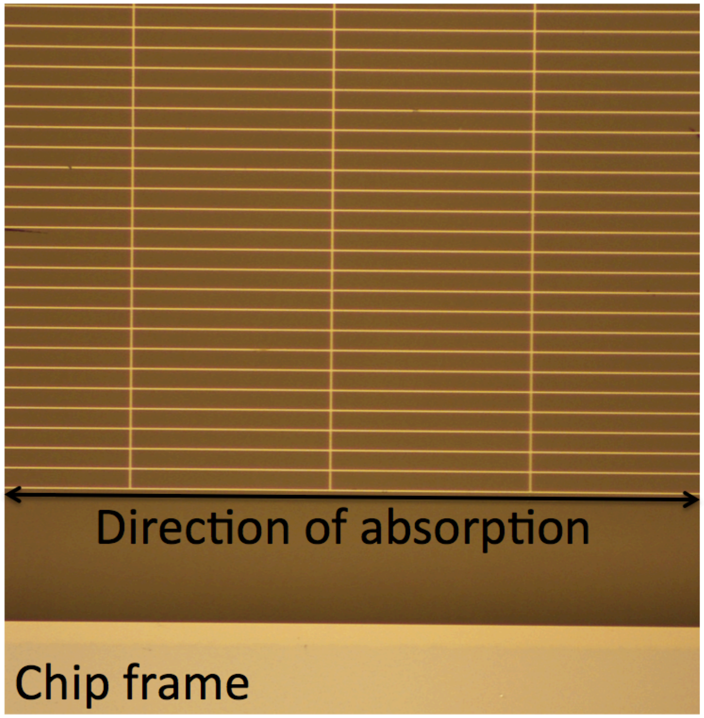


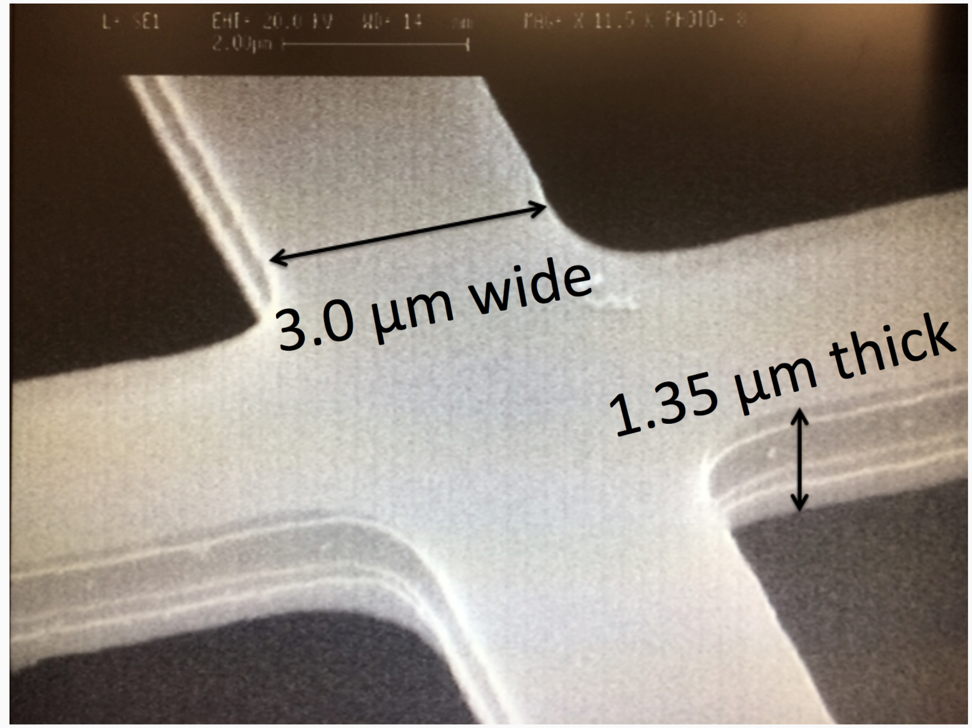
Key components:

- Absorber structure - absorb single linear polarization
- Endbanks - measure incident optical power with silicon thermistors
- Frame - thermal sink, indium bumps, and interface to readout

Single-crystal silicon instead of SiN to control time constants
Gold plate frame to eliminate back-loading from cosmic ray hits

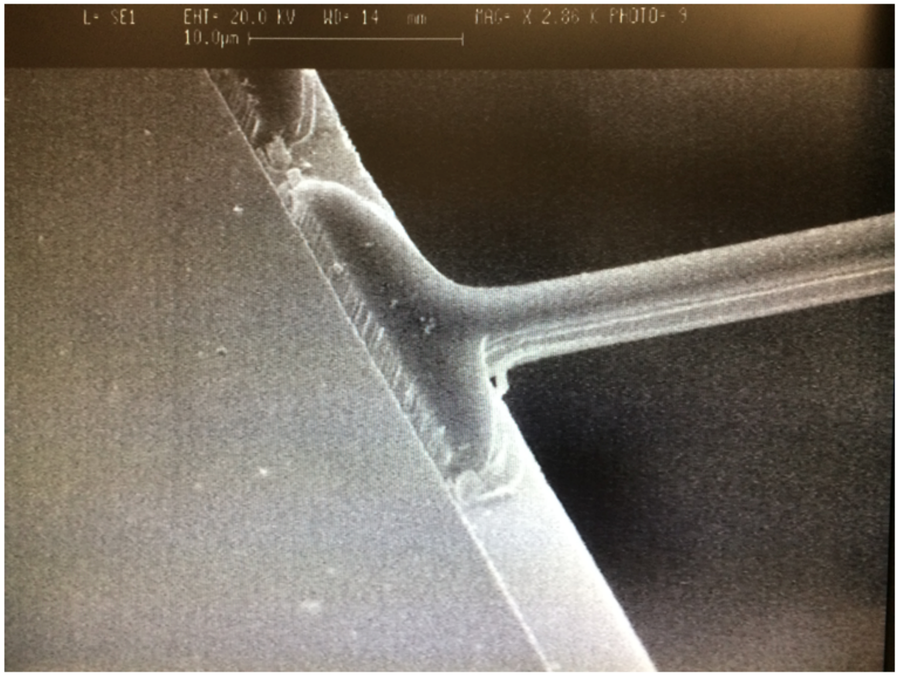
PIXIE bolometers - Absorber structure

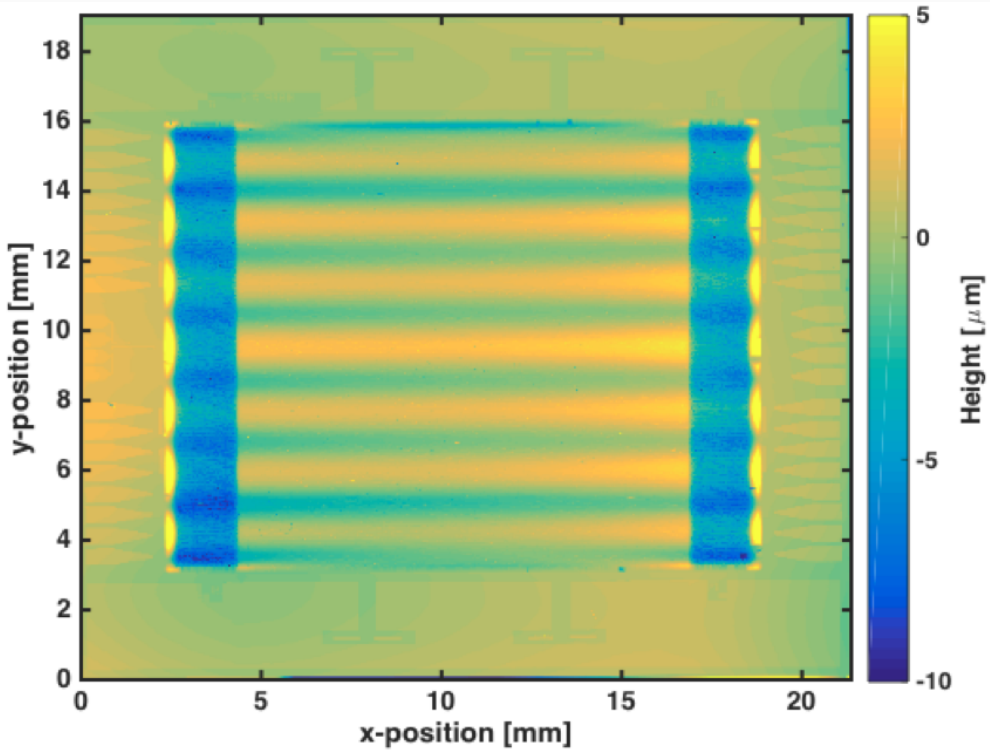




- Grid of degenerately-doped Si wires.
- Metallic at all temperatures; $R_s^{eff} \sim 377\,\Omega/\square$.
- Absorber area A sets low frequency cutoff of instrument ($\sim$ 15 GHz); grid spacing (30 μm) sets high frequency cutoff ($\sim$ 5 THz).
- Wire widths and thicknesses are highly uniform across the array.
    - Thickness set by starting SOI device layer thickness (1.35 μm).
    - Wires are etched to width with an ICP RIE process.

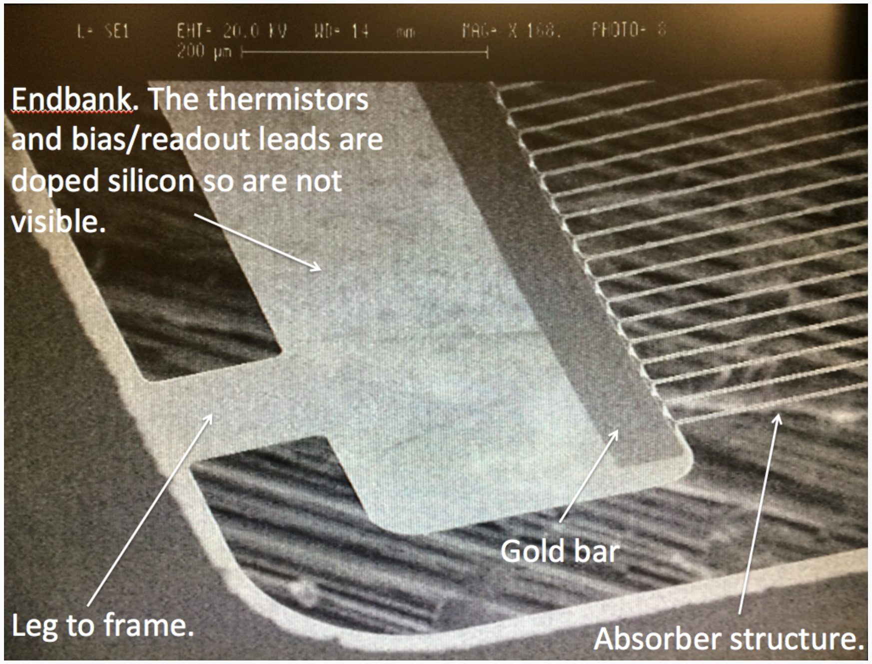
PIXIE bolometers - Absorber structure





- Doping induces compressive stress in absorber wires.
- Detectors subject to vibrations and acoustic excitations at launch.
- Solution: deposit highly tensile $\mathrm{Al_2O_3}$ film on absorbers outside of active optical region.
  $\rightarrow$ Fabricated absorbers are flat and expected to oscillate with amplitudes of $< 0.4\ \mu$m rms during launch.

PIXIE bolometers - Endbanks



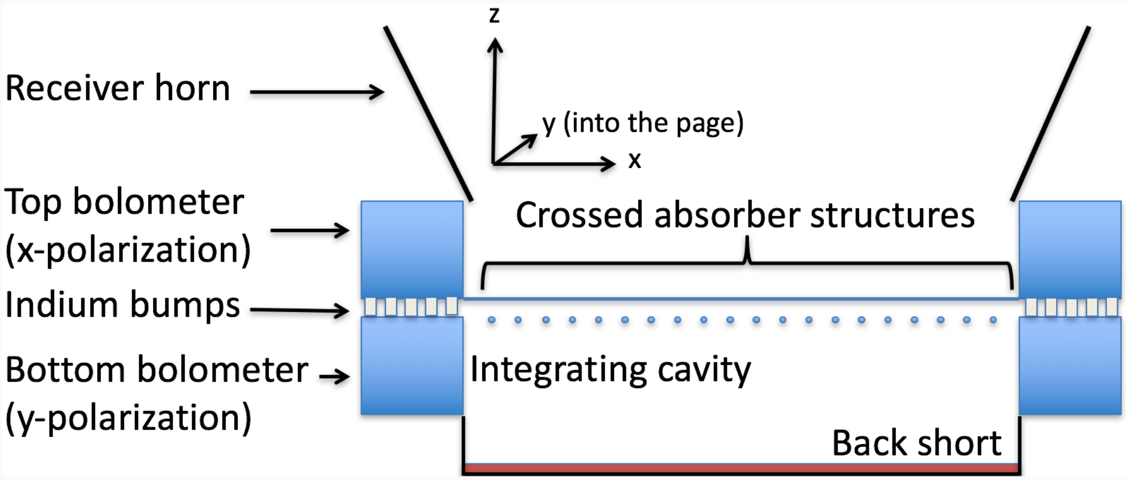
- Consists of a gold bar for thermalization and two doped silicon thermistors on a crystalline silicon membrane.
- The gold bar also sets the heat capacity of the endbank.
- Endbank is formed from the device layer of the SOI substrate.
- Endbanks are connected to the chip frame through eight silicon legs.
- Thermistors are doped to operate below metal-insulator transition. Electron transport mechanism is variable range hopping:

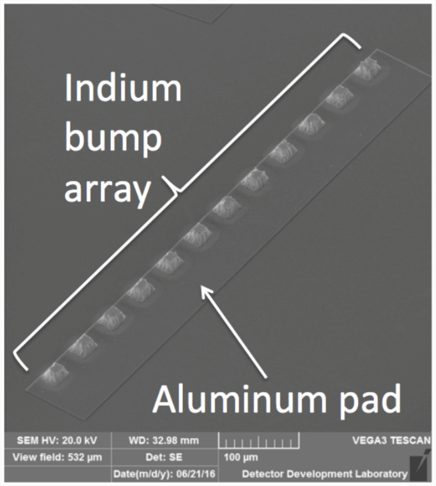
$$R(T) = R_0 \times \exp\sqrt{\frac{T_0}{T}},$$

where R_0 and T_0 are constants largely determined by geometry and doping, respectively.

PIXIE bolometers - Chip frame

Focal plane: two In bump-hybridized detectors mounted $< 20\ \mu$m apart with their absorbers orthogonal.



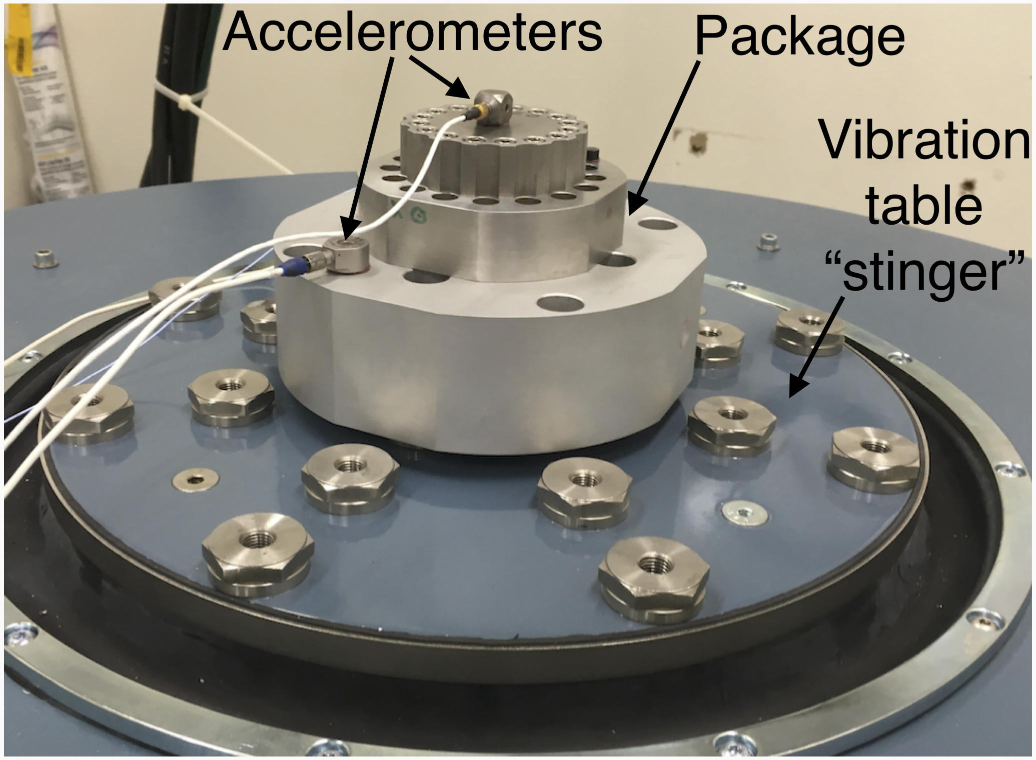


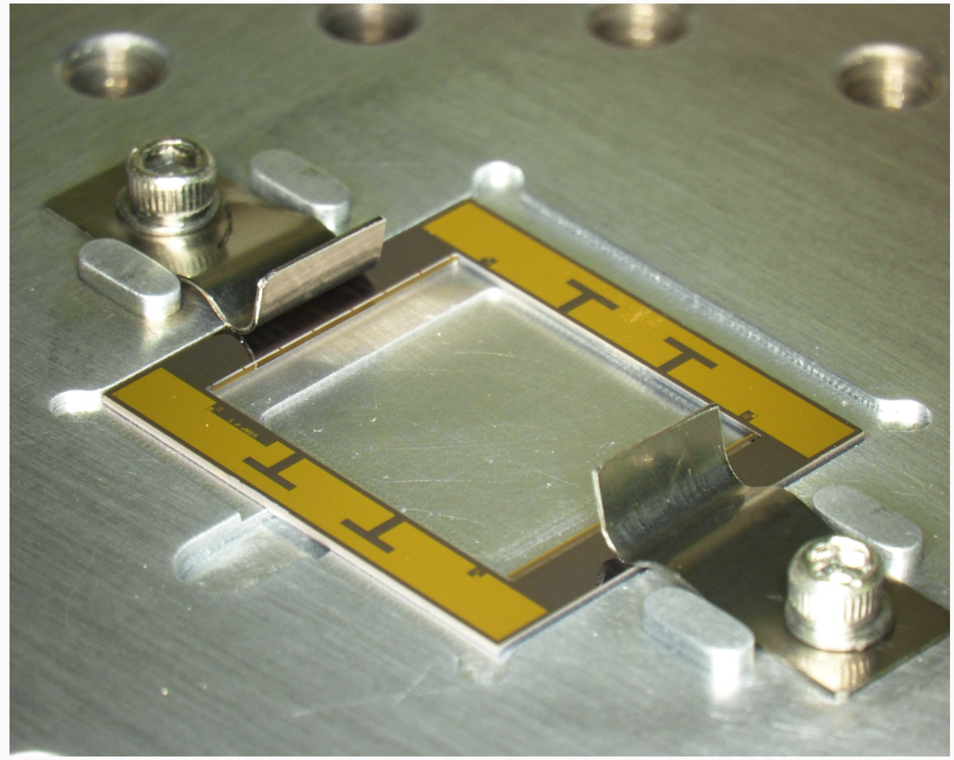
- Any two bolometer chips can be hybridized together.
- Large gold-covered areas serve as heat sinks.
- Al pads alloyed to degenerately-doped Si leads form wirebond and In bump pads.

Prototypes: achieved chip separation of $13 \pm 1\ \mu$m.

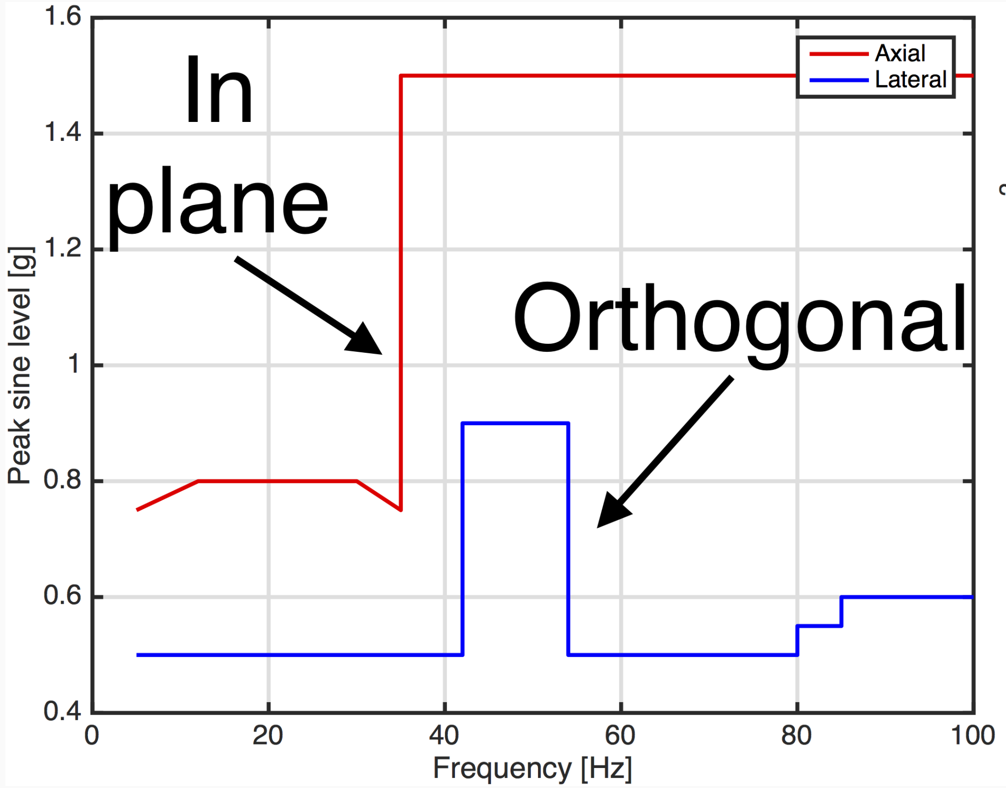
PIXIE bolometers - Environmental tests

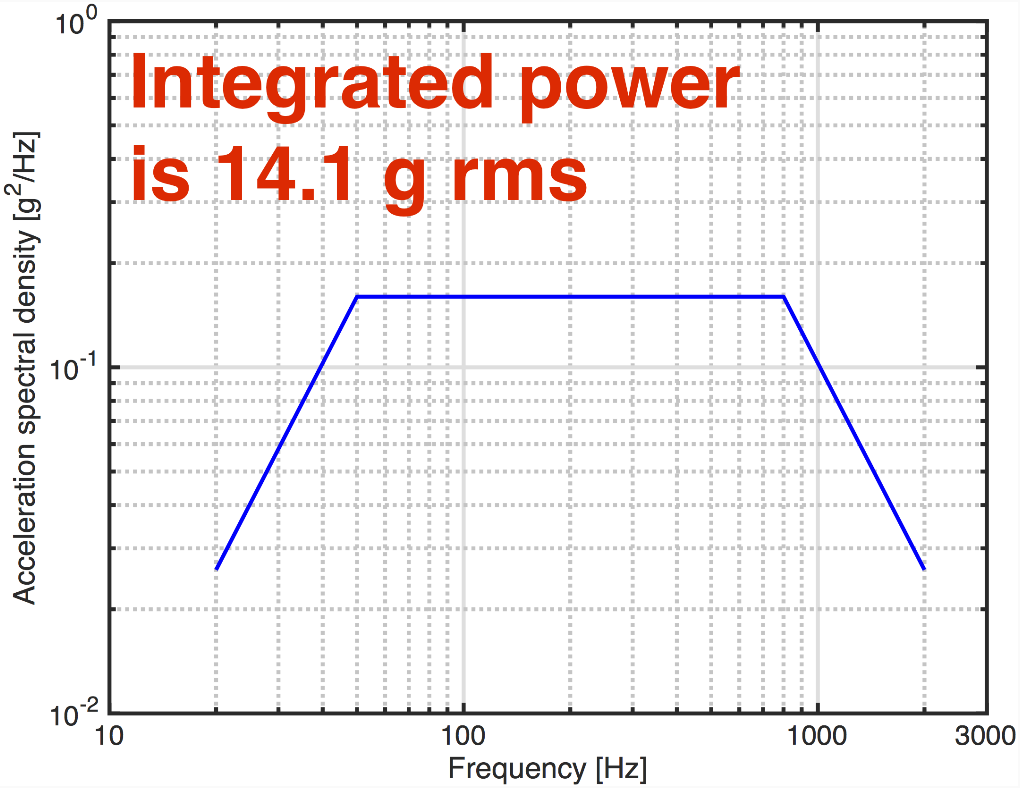
To advance TRL of PIXIE bolometers, we performed vibration testing.





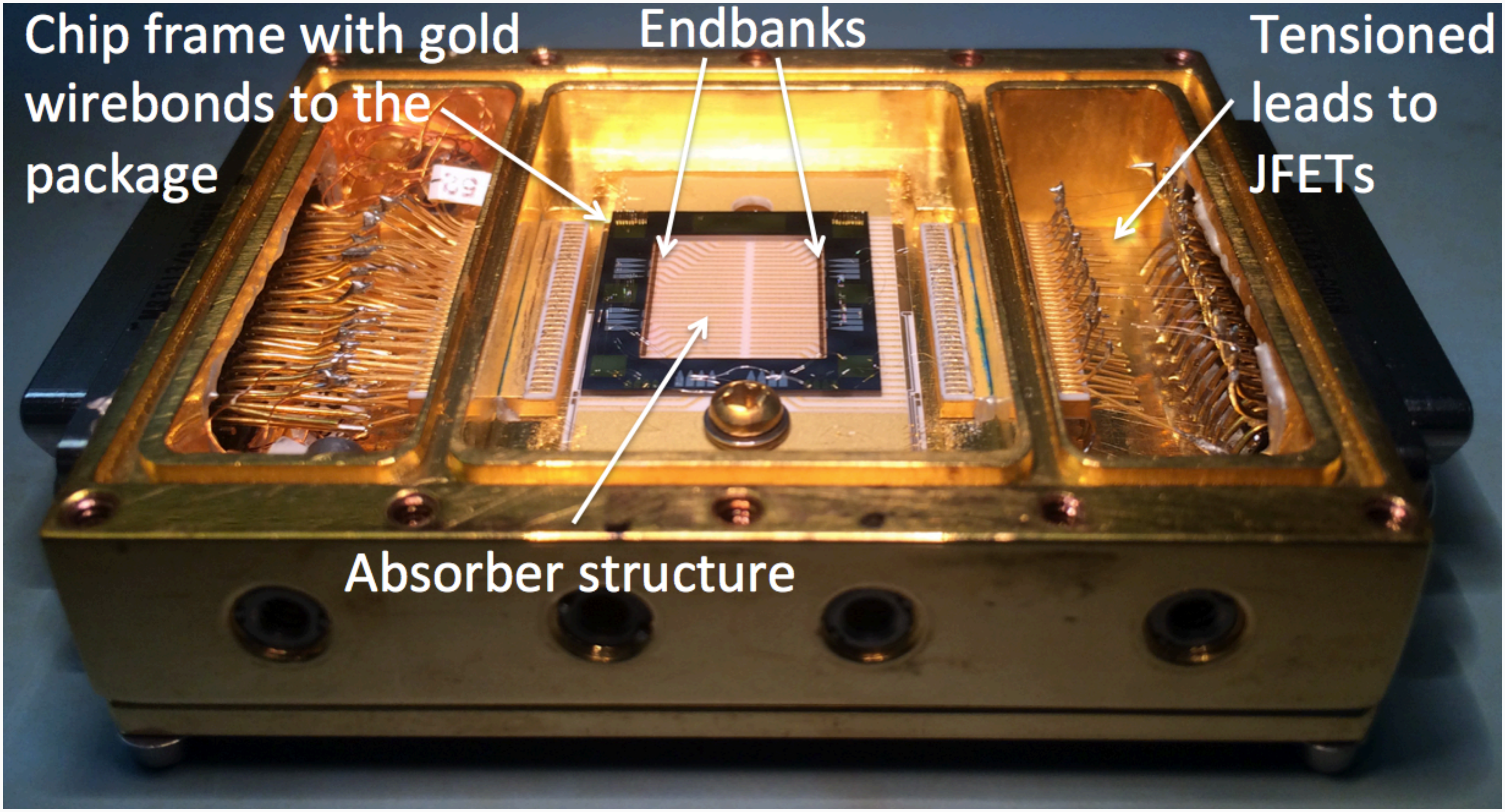
PIXIE bolometers - Environmental tests





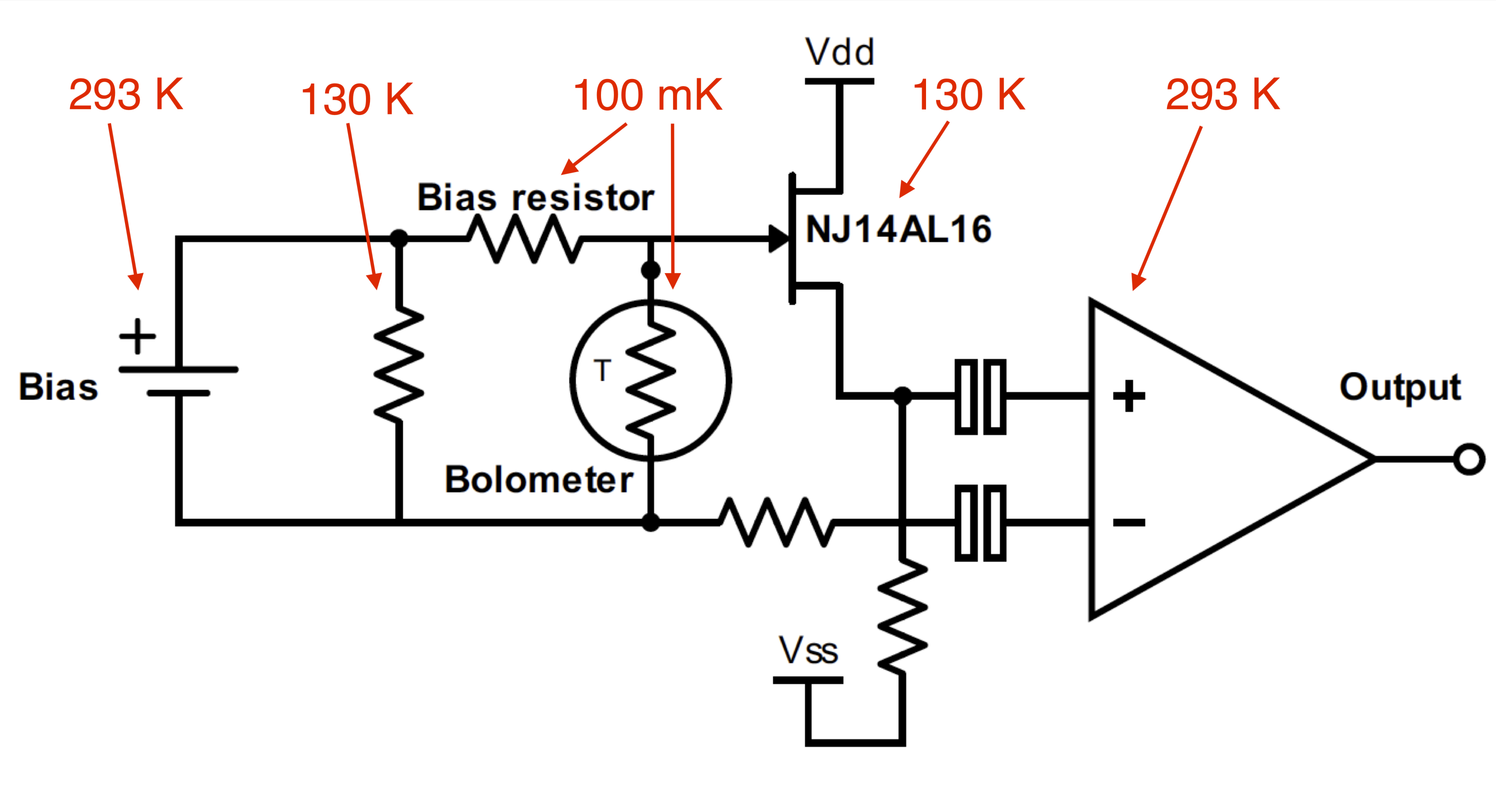
PIXIE bolometers - Environmental tests

PIXIE bolometers - Cryogenic test package



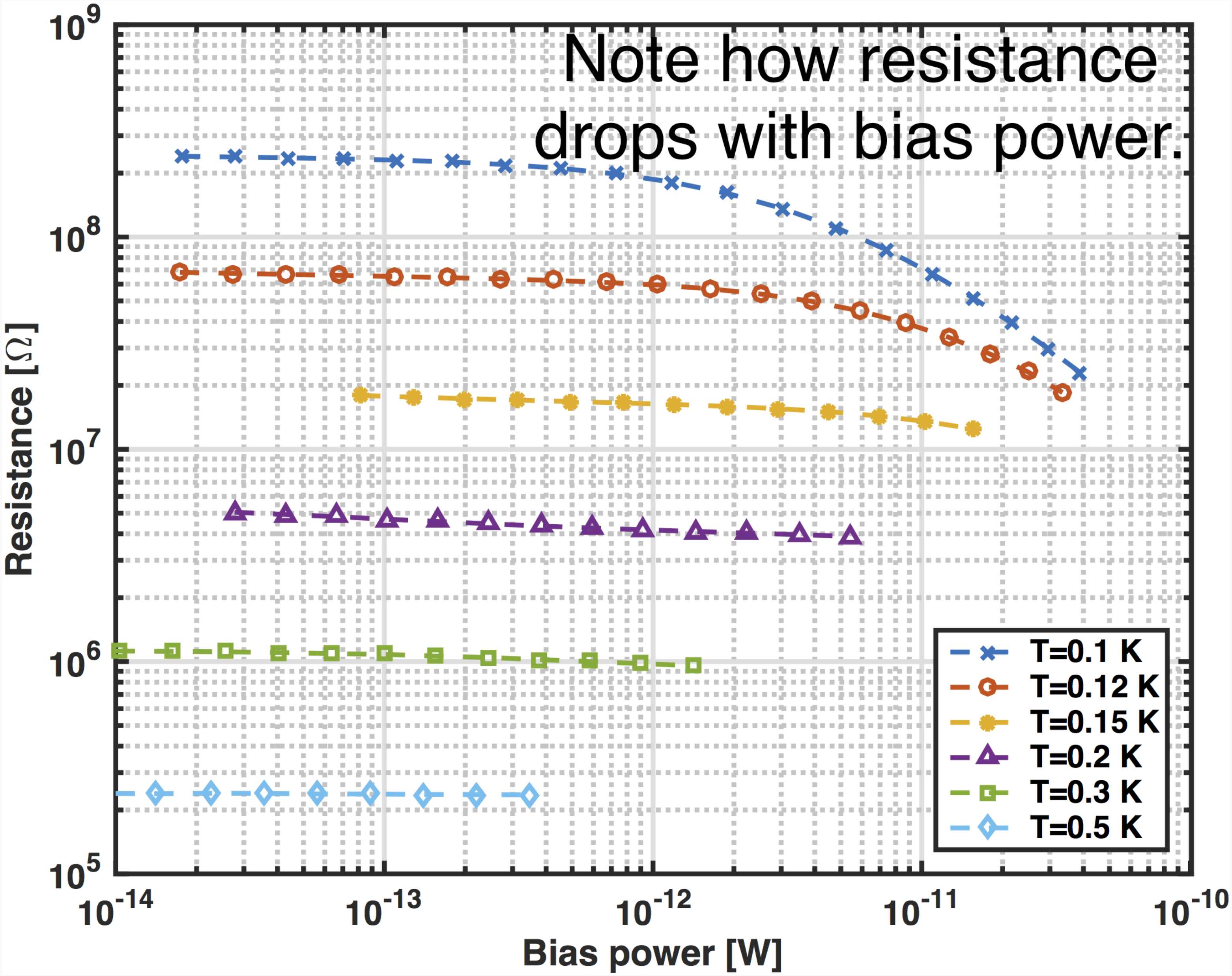
- Bolometer is connected to a cryogenic (130 K) JFET amplifier with tensioned leads, mitigating capacitive microphonic contamination of the signal band. Shamelessly borrowed from Hitomi.

PIXIE bolometers - Readout circuit



- Thermistor operates under current bias ($R_{bias} >> R_{therm}$).
- We use Interfet NJ14AL16 JFETs that are screened for low noise performance at 130 K (5.5 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ at 100 Hz).
- Amplifier converts the high source impedance of the thermistors (MΩ-scale) to the low output impedance of the JFETs (1.8 kΩ).
- Low impedance signal is AC coupled to a room temperature amplifier.

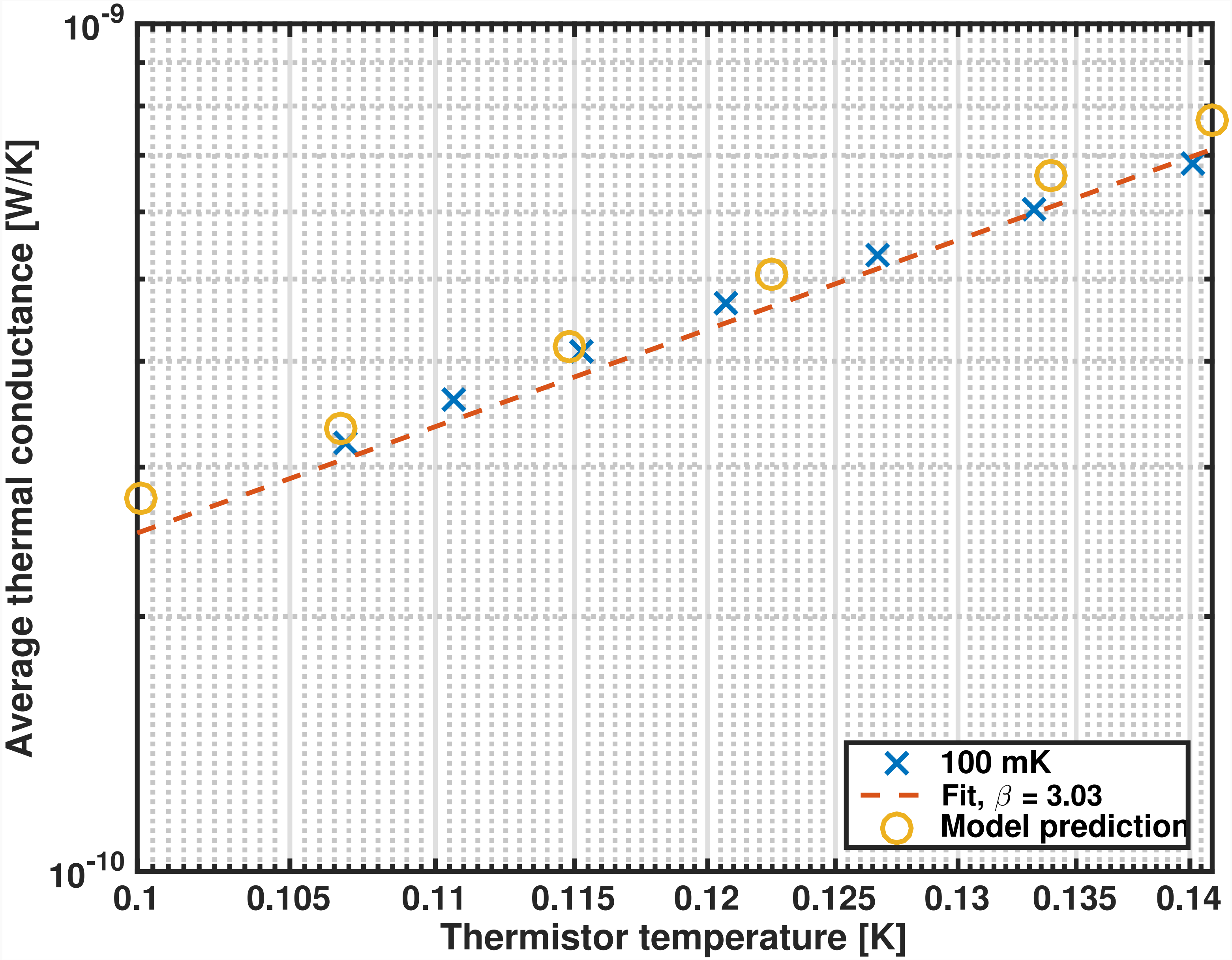
PIXIE bolometers - Load curves



$T_0 = 15.11$ K. $R_0 = 911\ \Omega$. Operating resistance: 5.42 MΩ.

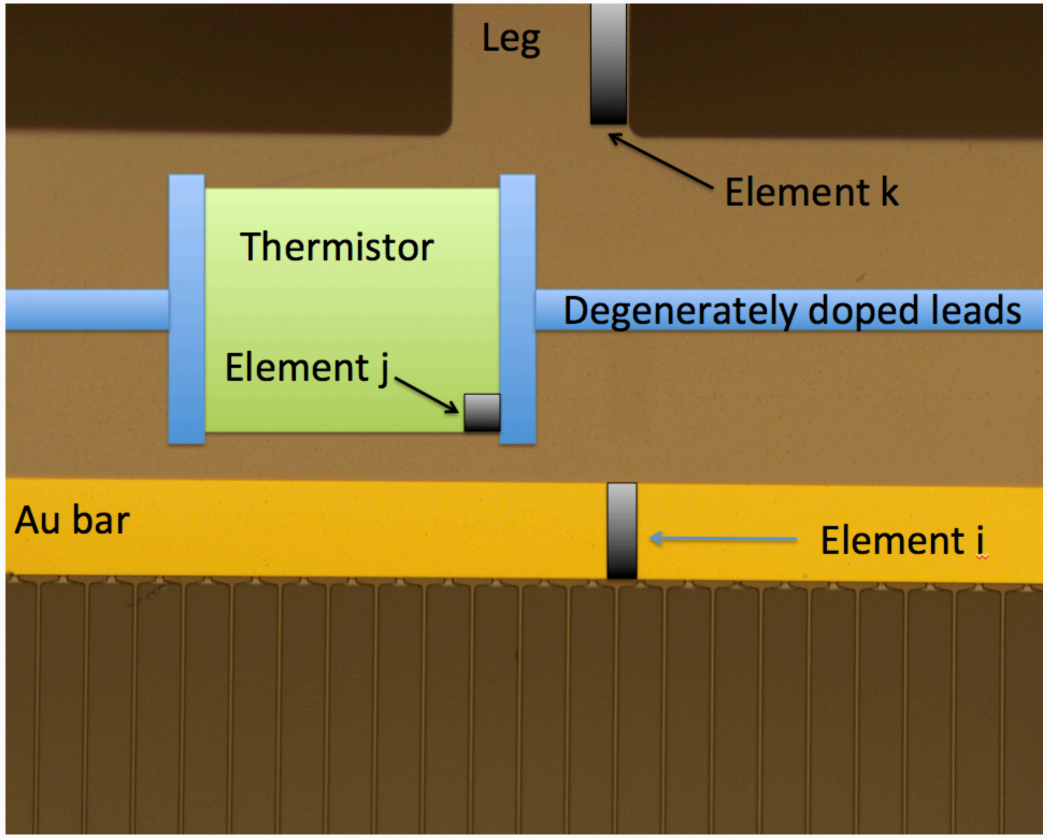
Old school detectors: Robust vs loading (but hard to multiplex)

PIXIE bolometers - Thermal conductance



- $\bar{G} = P_{\text{bias}} / (T_1 - T_2)$; fit with function $\tilde{G} = G_0 \times T^{\beta}$.

PIXIE bolometers - Thermal model

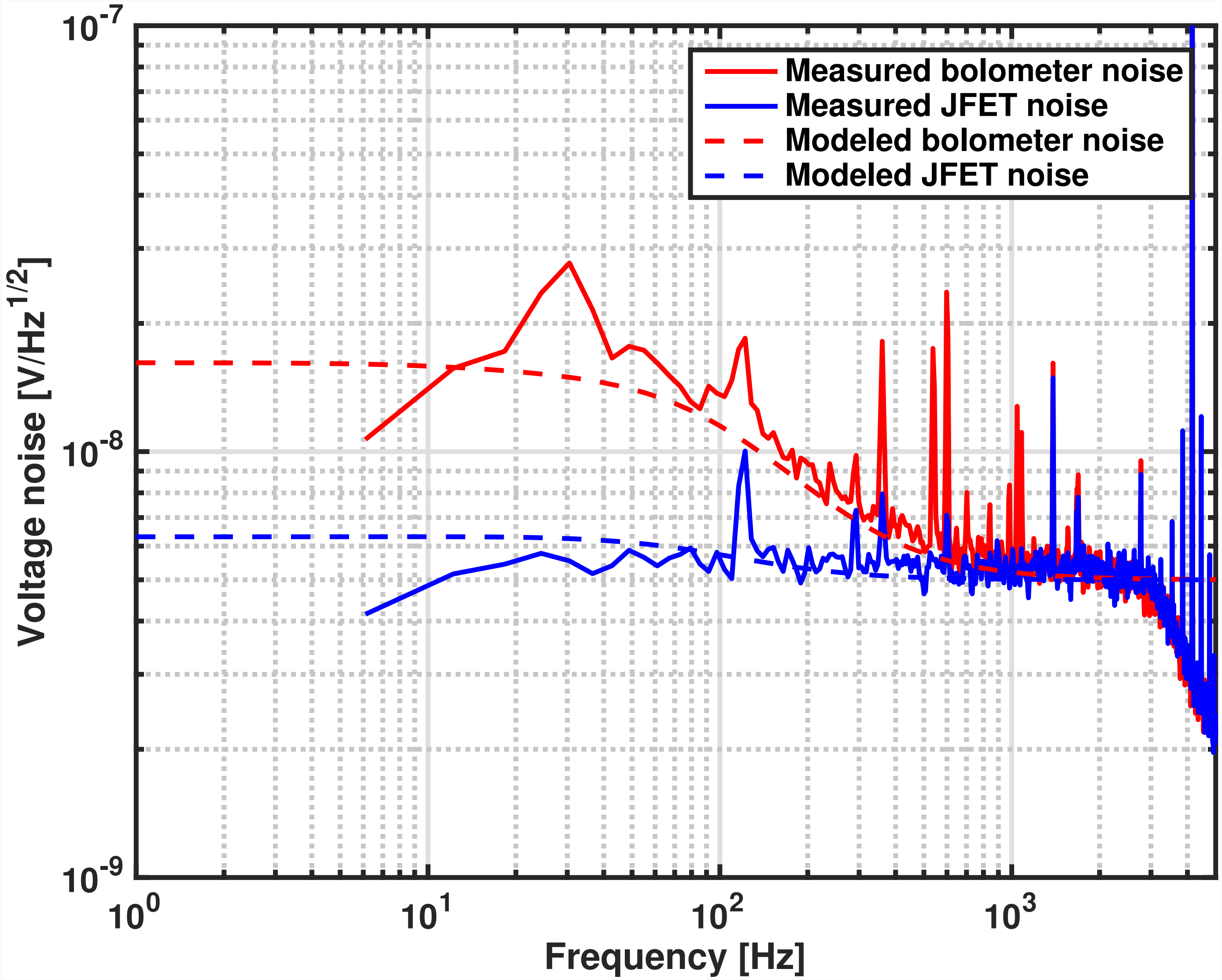


Solve for non-equilibrium bolometer noise:

$$\mathrm{NEP_{bolometer}}^2 = \gamma_1 4 k_b T^2 G + \frac{1}{S^2}\left(\gamma_2 4 k_b T R + e_n^2 + \gamma_3 i_n^2 R + \gamma_4 \mathrm{NEP_{excess}}^2\right).$$

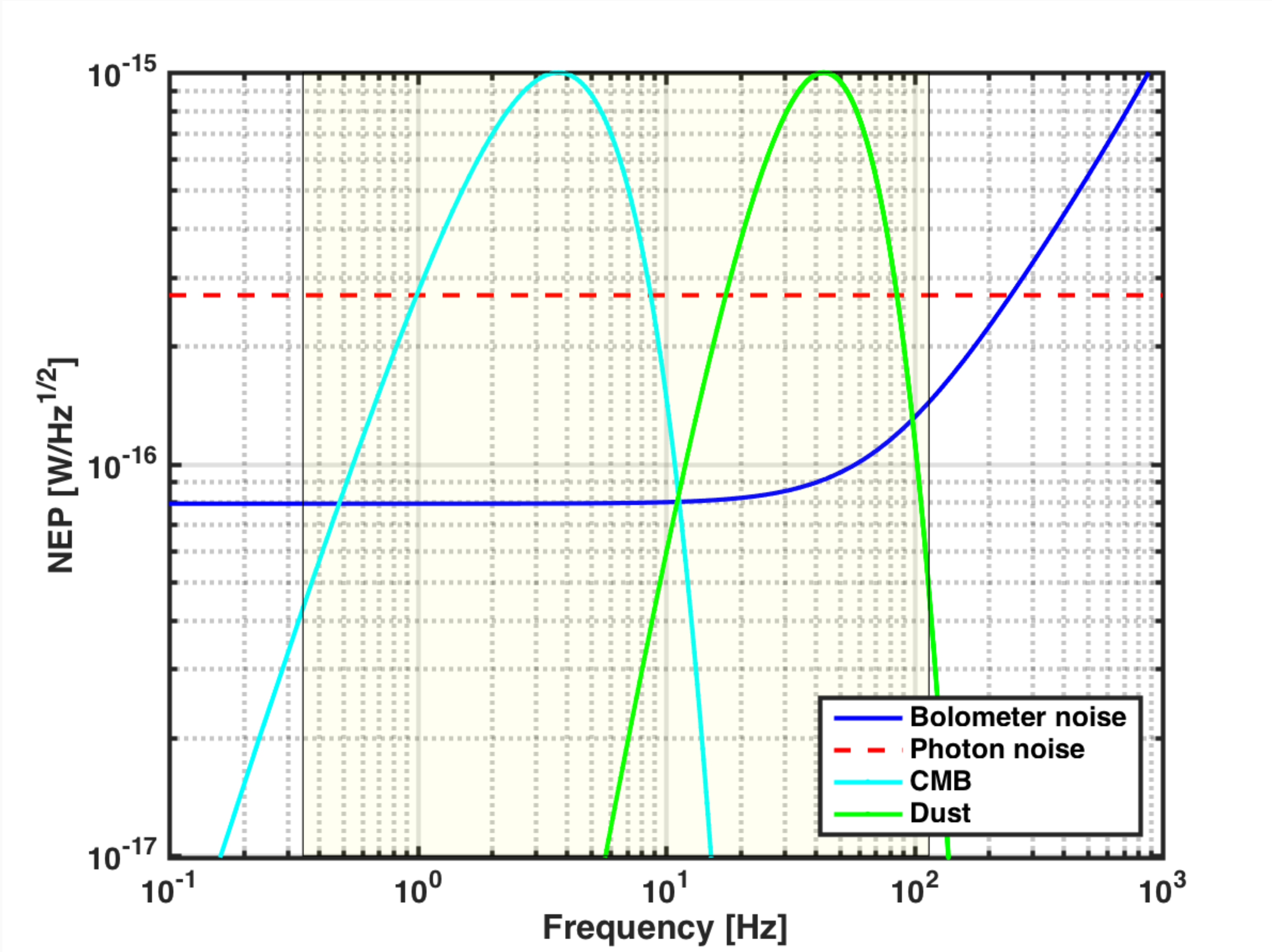
Total NEP — Phonon noise — Responsivity — Johnson noise — Amplifier noise — Excess noise

PIXIE bolometers - Noise



- Modeled noise fits the measured noise well for multiple bias conditions.

PIXIE bolometers - Noise



Expect to be photon noise limited across the entire PIXIE bandwidth.

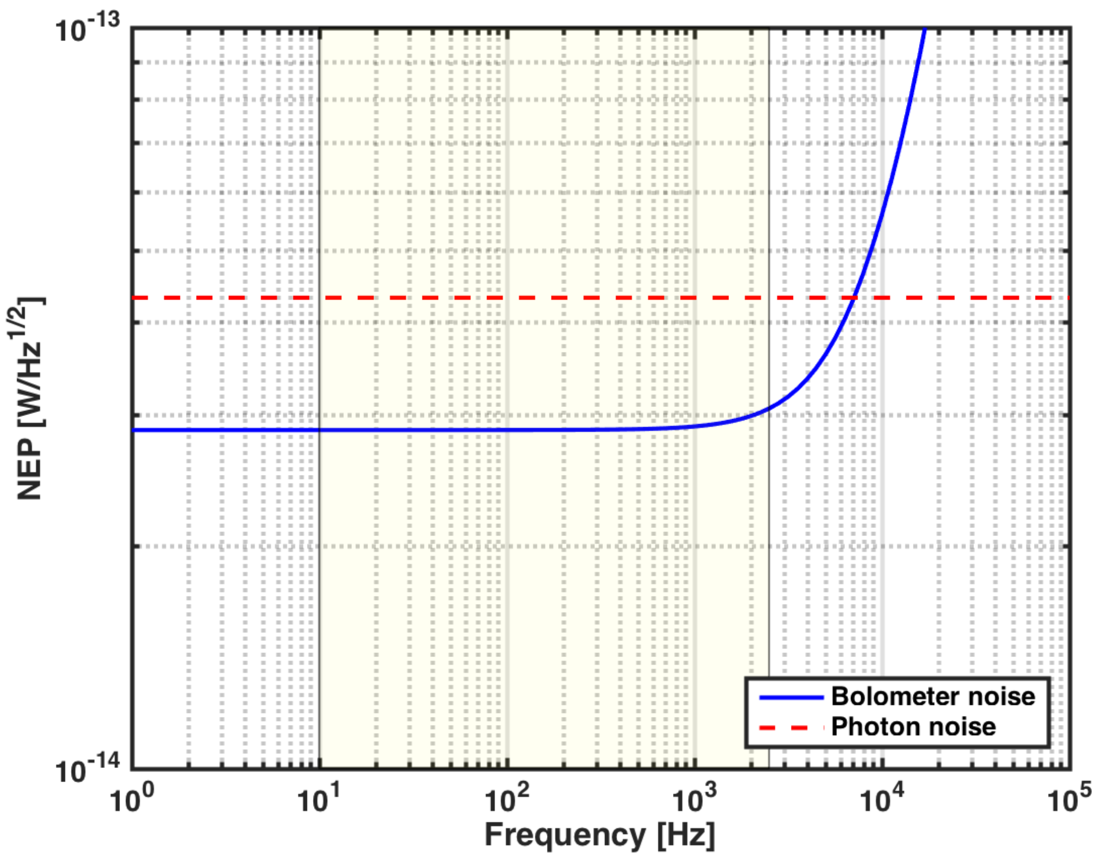
Multimode bolometers for sub-orbital applications

Bolometers for Dust Buster

Thermistor-based bolometers can operate over a wide temperature and load range. Preliminary sensitivity for Dust Buster-like operating conditions:

- $\nu_{max} = 2.5$ THz.
- $P_{optical} = 1.2\ \mu$W.
- $T_{bath} = 0.3$ K.

Balloon mission to measure dust SED
along individual lines of sight
over frequency range 100 GHz — 2.5 THz



Conclusions

Conclusions

We designed, built, and tested detectors suitable for a space-based FTS like PIXIE

- Optimization is different from single-mode bolometers.
- Fabrication process is high-yield and detectors are mechanically robust.
- Readout system is mature and well-understood.
- Cryogenic testing indicates performance meets requirements for a PIXIE-like instrument.

Thermistor-based bolometers are tolerant of wide operating conditions

- Minimal changes are needed to make a multimode bolometer suitable for a sub-orbital FTS.

Acknowledgements

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Special thanks to all who contributed to this development effort.

Questions?