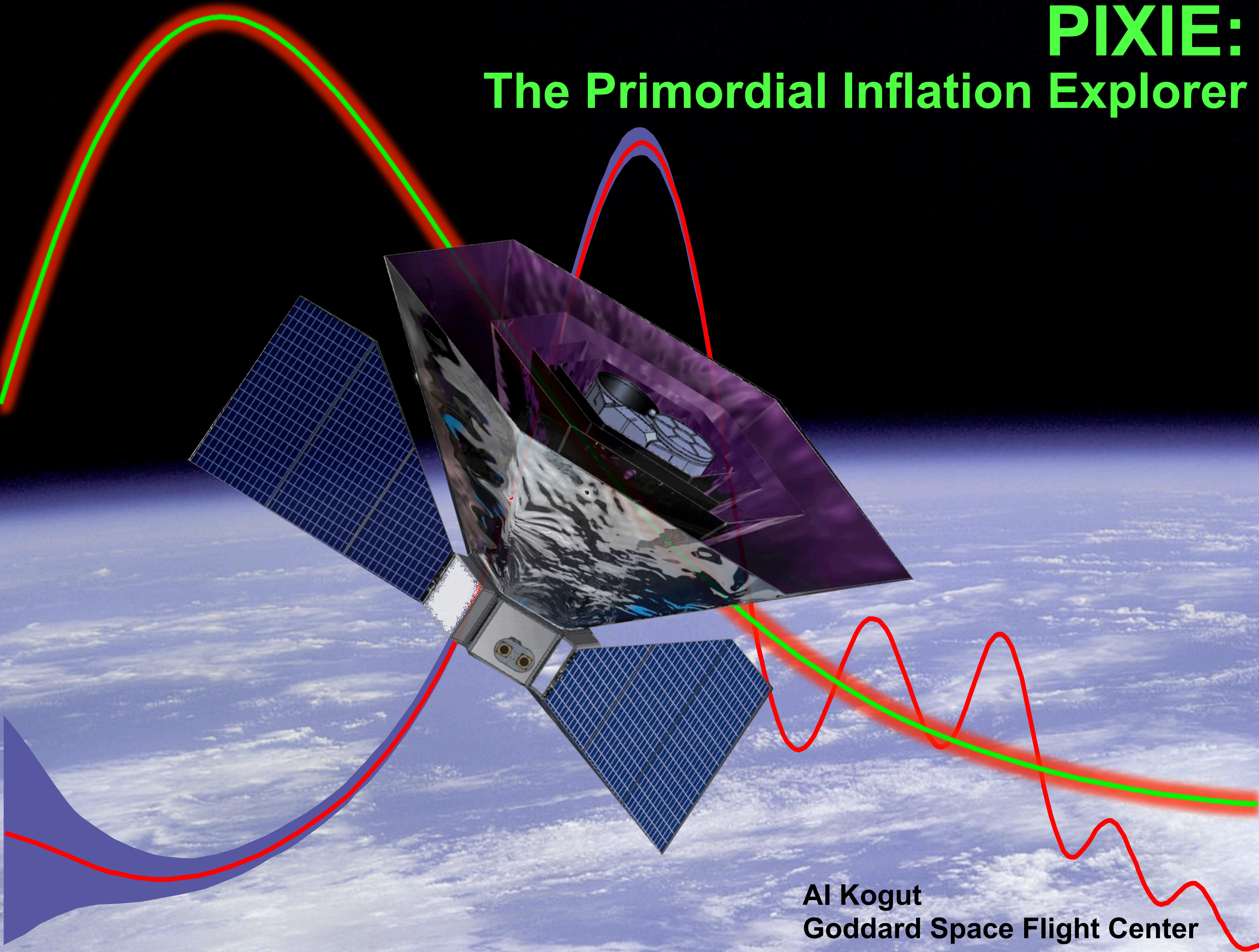
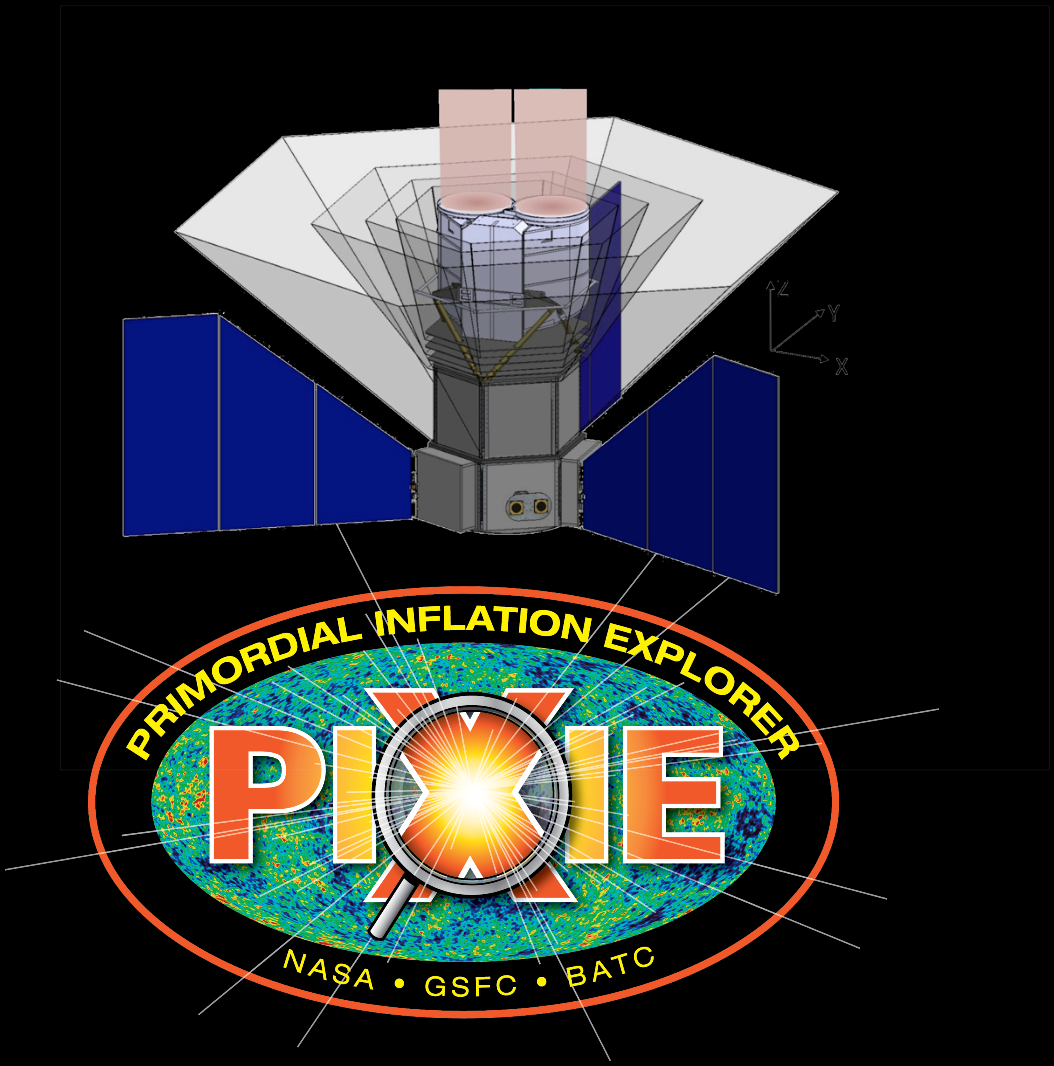
PIXIE:

The Primordial Inflation Explorer



Al Kogut
Goddard Space Flight Center

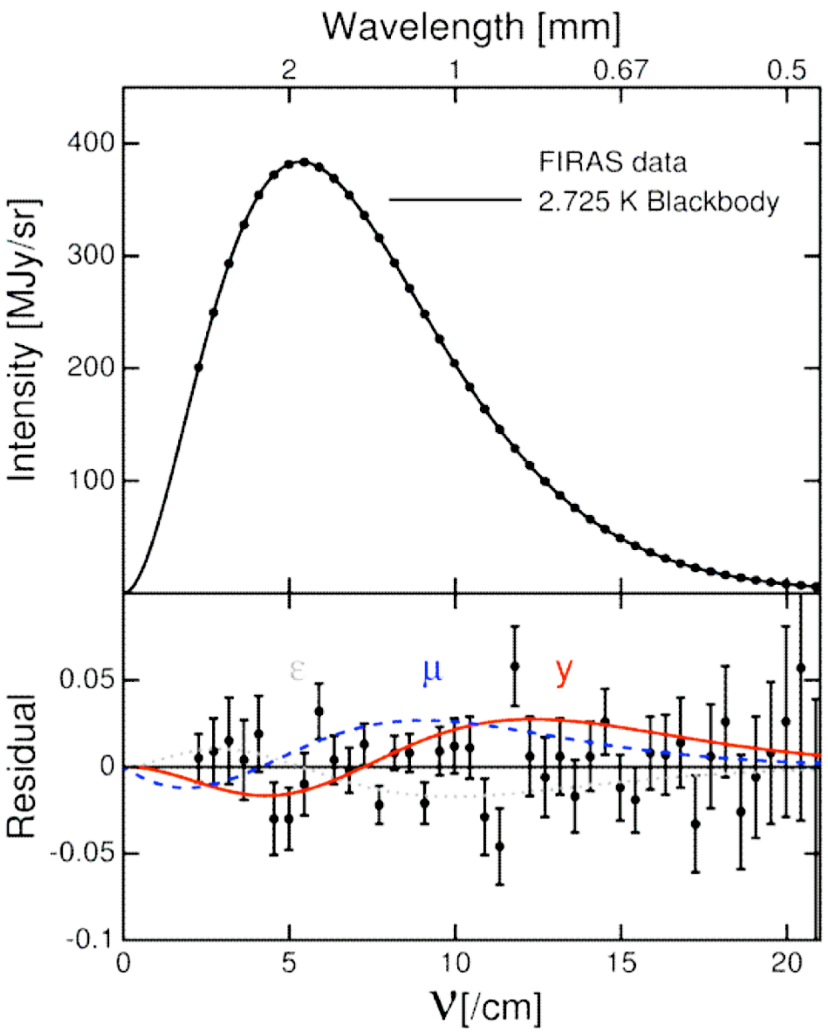
Primordial Inflation Explorer



Name	Role	Institution
A. Kogut	PI	GSFC
D. Fixsen	IS	UMD
D. Chuss	Co-I	GSFC
J. Dotson	Co-I	ARC
E. Dwek	Co-I	GSFC
M. Halpern	Co-I	UBC
G. Hinshaw	Co-I	UBC
S. Meyer	Co-I	U. Chicago
H. Moseley	Co-I	GSFC
M. Seiffert	Co-I	JPL
D. Spergel	Co-I	Princeton
E. Wollack	Co-I	GSFC

Spectral Distortions Provide New Window to Early Universe

The Ideal Instrument



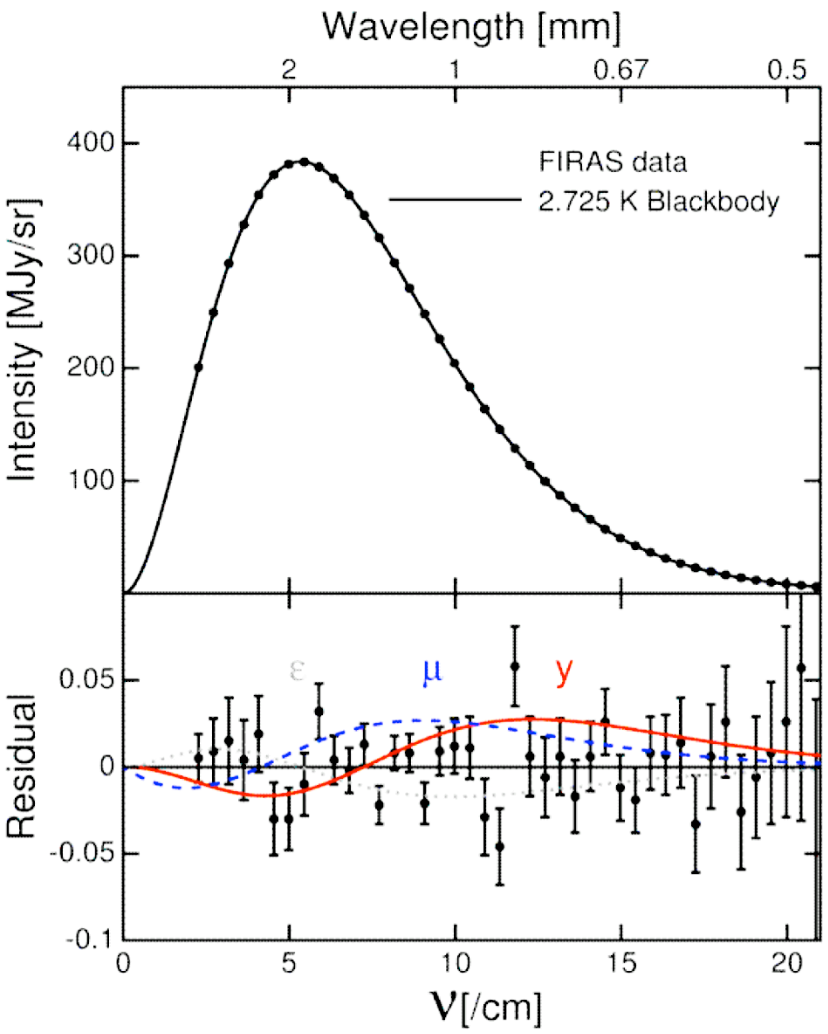
FIRAS: Sky is black to 50 ppm. How can we improve?

Sensitivity: Background-limited detectors

Foregrounds: Many frequency channels
Band-to-band calibration

Systematics: Space mission (continuum)
Blackbody cavity
Maximize internal symmetries

The Ideal Instrument



FIRAS: Sky is black to 50 ppm. How can we improve?

Sensitivity: Background-limited detectors

1.4 K → 0.1 K

Foregrounds: Many frequency channels
Band-to-band calibration

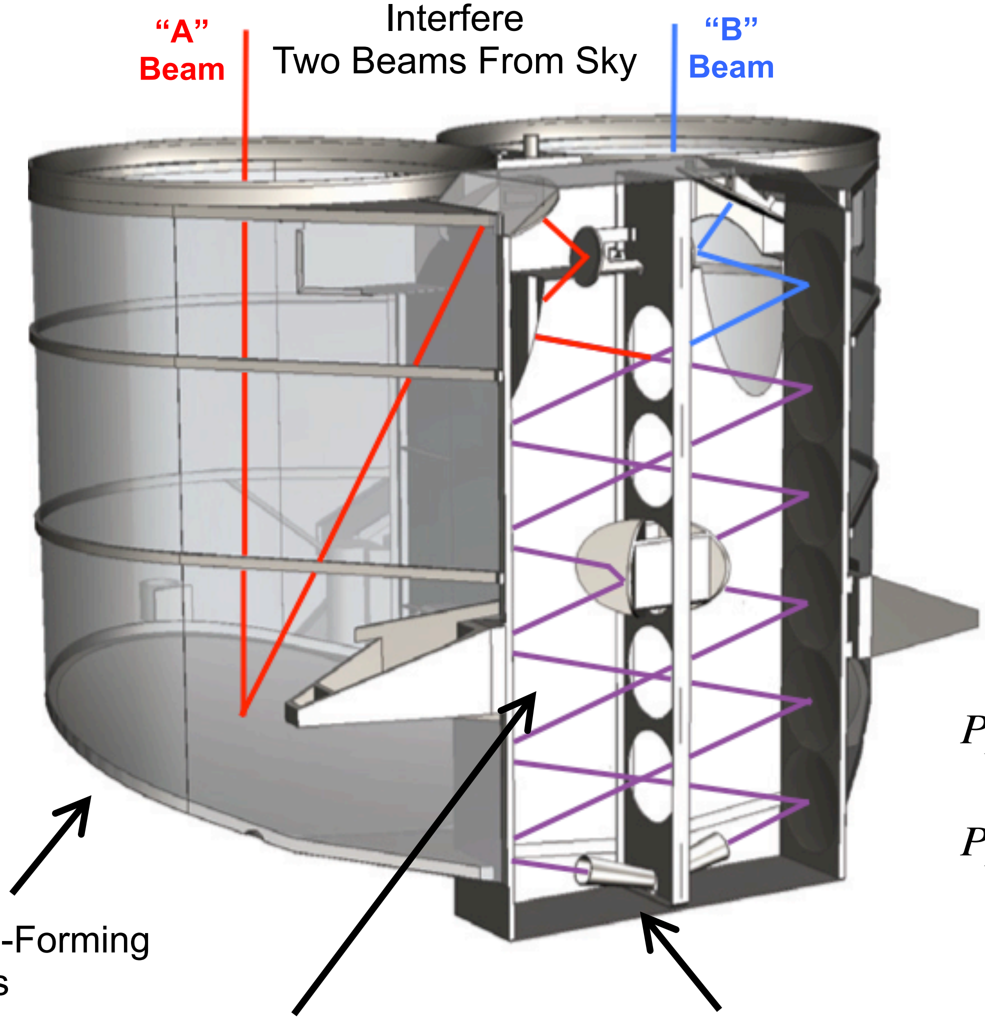
Fourier Transform Spectrometer

Systematics: Space mission (continuum)
Blackbody cavity
Maximize internal symmetries

Multiple levels of symmetry

Solution: Cryogenic Fourier Transform Spectrometer

PIXIE Instrument



"A" Beam

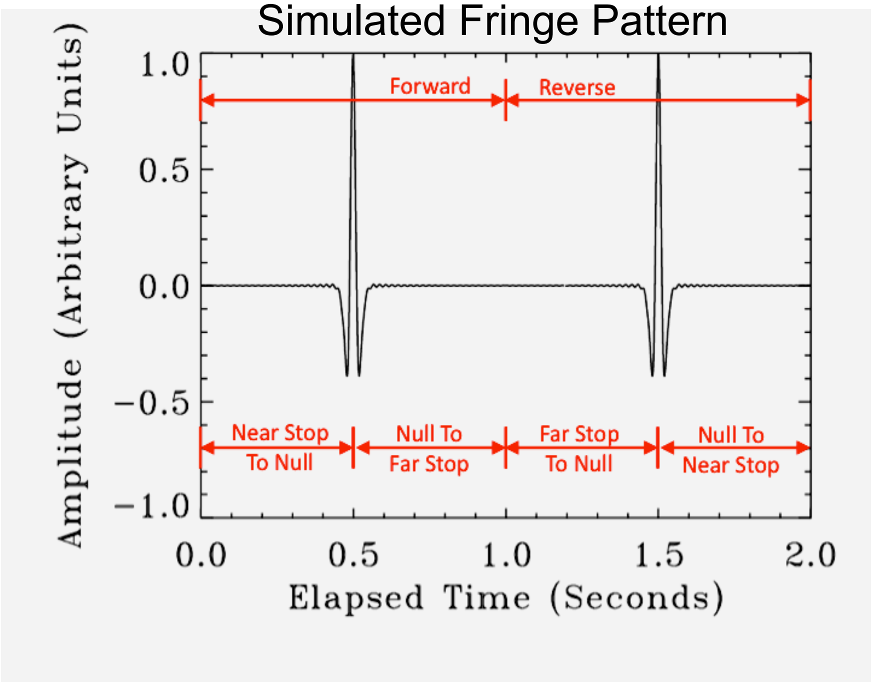
Interfere
Two Beams From Sky

"B" Beam

Beam-Forming
Optics

Polarizing
Fourier Transform
Spectrometer

Multi-Moded Detectors
Maximize Sensitivity



$$P_{Lx} = \frac{1}{2}\int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx}^2 - E_{Ay}^2\right)\cos(z\omega/c)\, d\omega$$

$$P_{Ly} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \underbrace{\left(E_{By}^2 - E_{Ax}^2\right)}_{\text{Stokes Q}}\cos(z\omega/c)\, d\omega$$

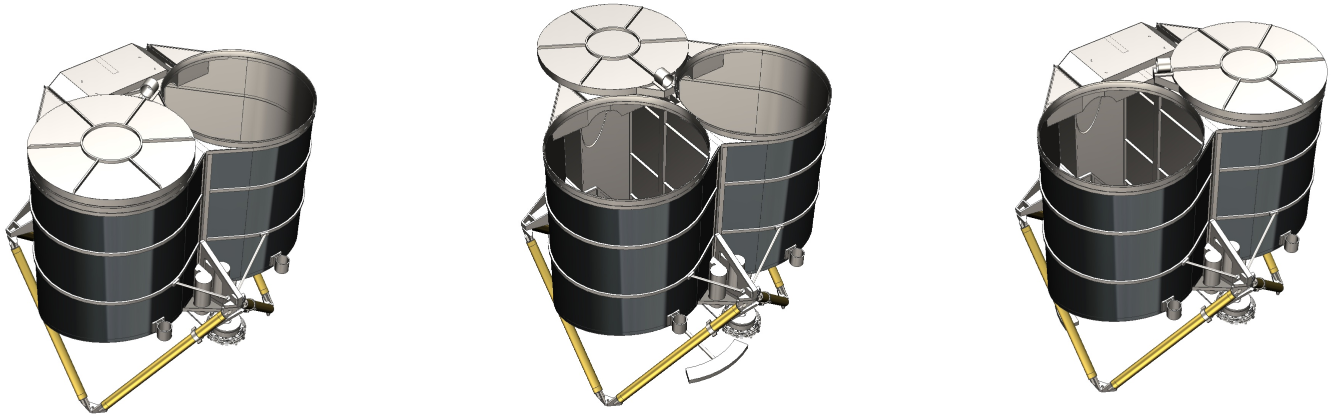
Measured Fringes Sample Frequency Spectrum of Polarized Sky

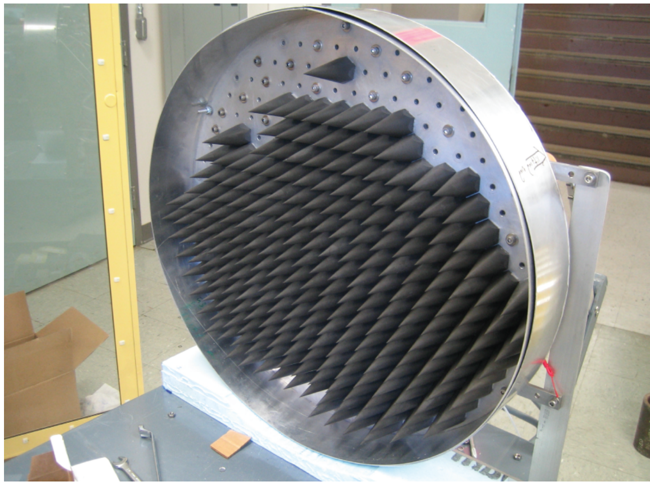
Blackbody Calibrator Adds Spectrum Science

Calibrator stowed: Polarization only

$$P_{Lx} = \frac{1}{2}\int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx}^2 - E_{Ay}^2\right)\cos(z\omega/c)\, d\omega$$

$$P_{Ly} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \underbrace{\left(E_{By}^2 - E_{Ax}^2\right)}_{\text{Sky Stokes Q}}\cos(z\omega/c)\, d\omega$$





Partially-assembled blackbody calibrator

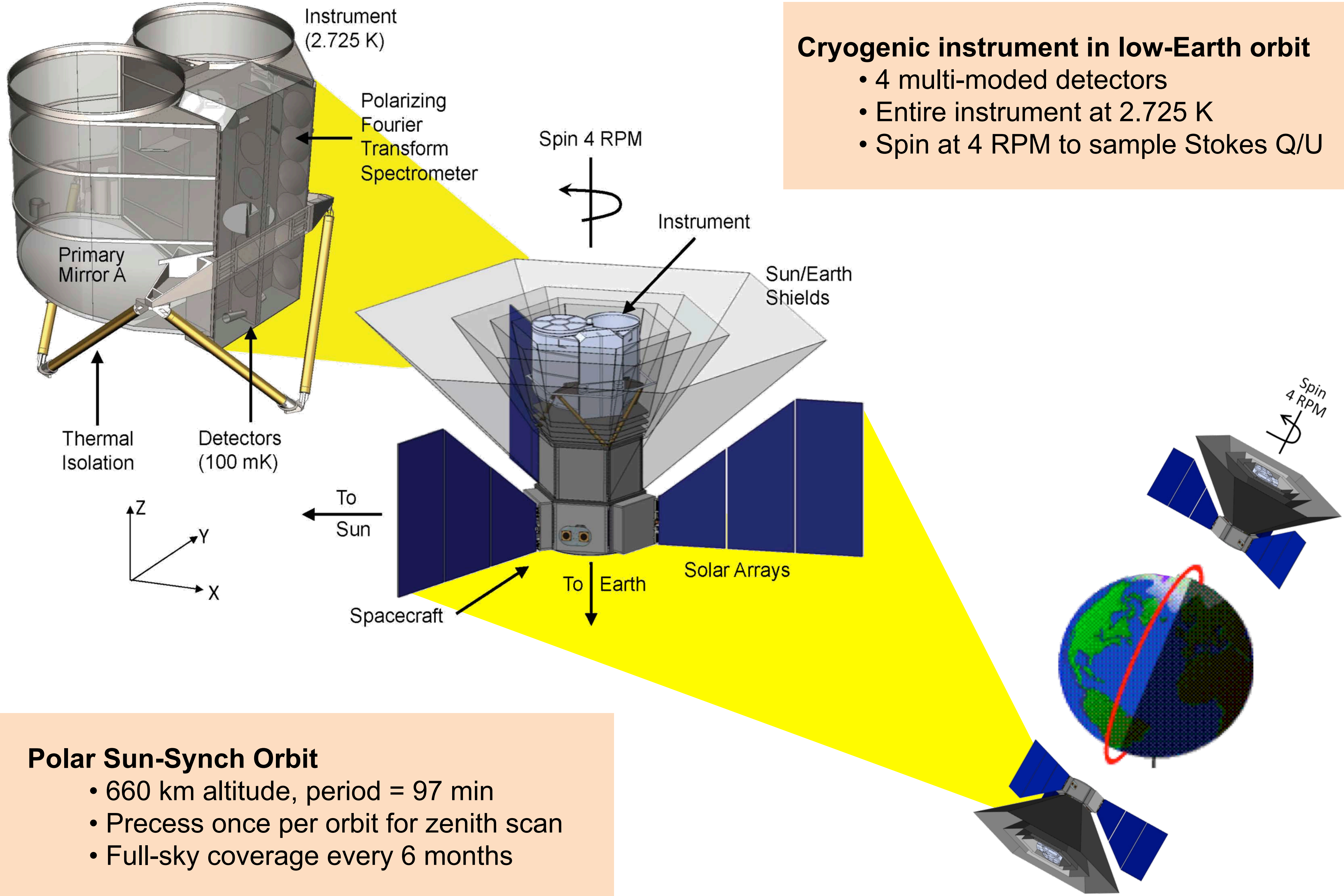
Calibrator deployed: Spectral distortions!

$$P_{Lx} = \frac{1}{2}\int \left(E_{Cal,y}^2 + E_{Sky,x}^2\right) + \left(E_{Sky,x}^2 - E_{Cal,y}^2\right)\cos(z\omega/c)\, d\omega$$

$$P_{Ly} = \frac{1}{2}\int \left(E_{Cal,x}^2 + E_{Sky,y}^2\right) + \underbrace{\left(E_{Sky,y}^2 - E_{Cal,x}^2\right)}_{\substack{\text{[Calibrator-Sky]}\\ \text{Spectral Difference}}}\cos(z\omega/c)\, d\omega$$

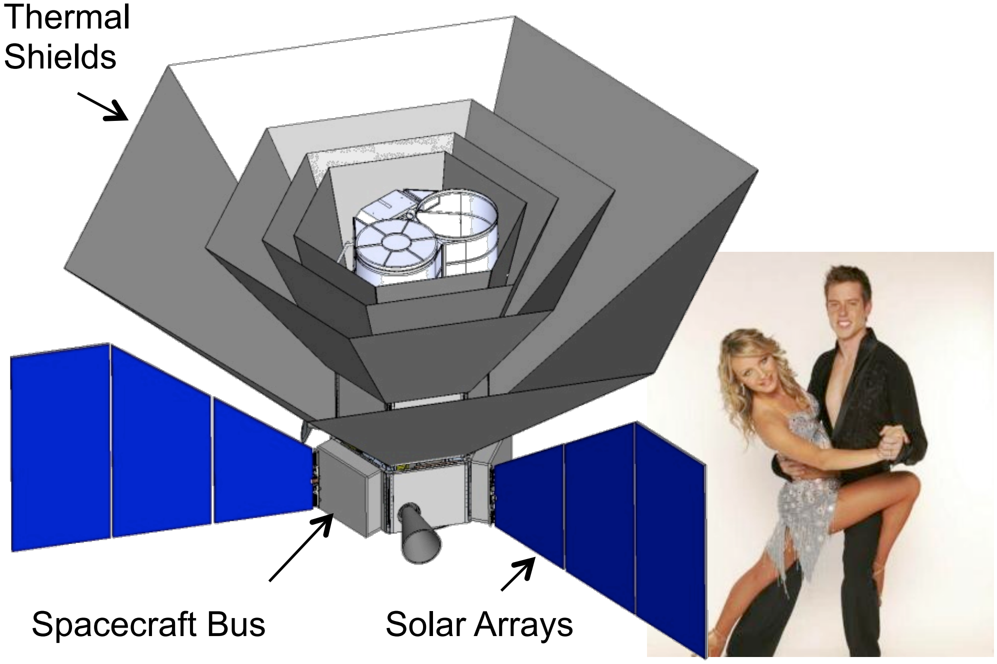
Instrument and Observatory

Cryogenic instrument in low-Earth orbit
- 4 multi-moded detectors
- Entire instrument at 2.725 K
- Spin at 4 RPM to sample Stokes Q/U



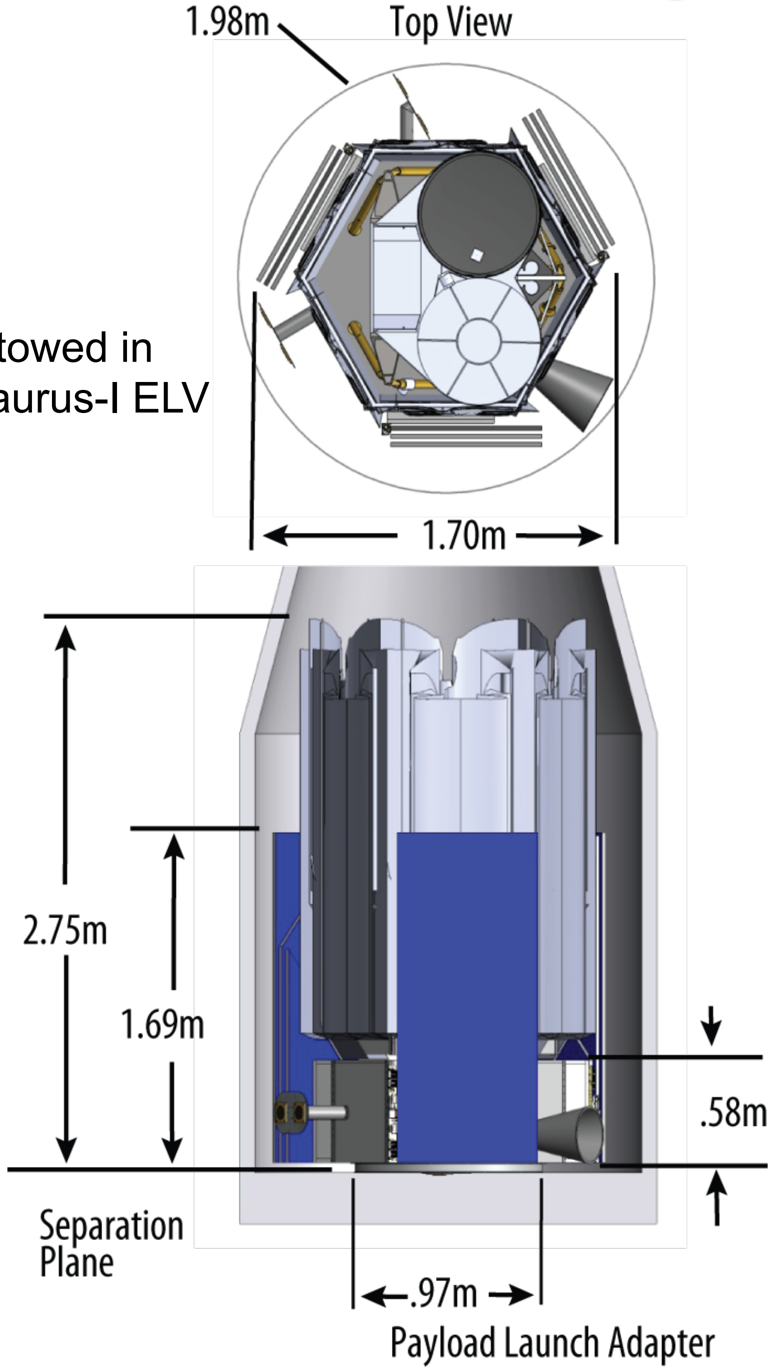
Polar Sun-Synch Orbit
- 660 km altitude, period = 97 min
- Precess once per orbit for zenith scan
- Full-sky coverage every 6 months

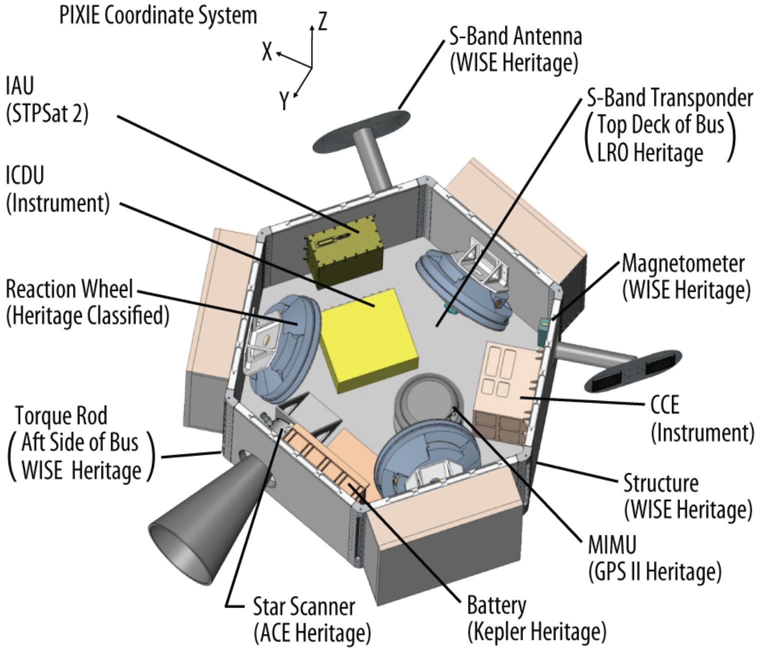
Observatory



Star Power (for scale)

Stowed in Taurus-I ELV





PIXIE Fourier Transform

Phase delay L sets channel width

$\Delta\nu = c/2L$

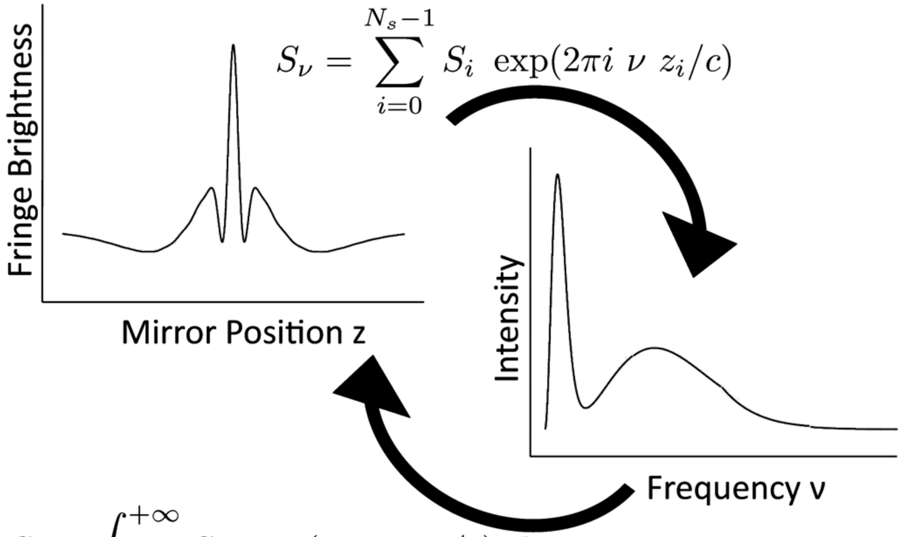
Number of samples sets frequency range

N_chan = N_samp / 2

PIXIE: ~400 usable channels

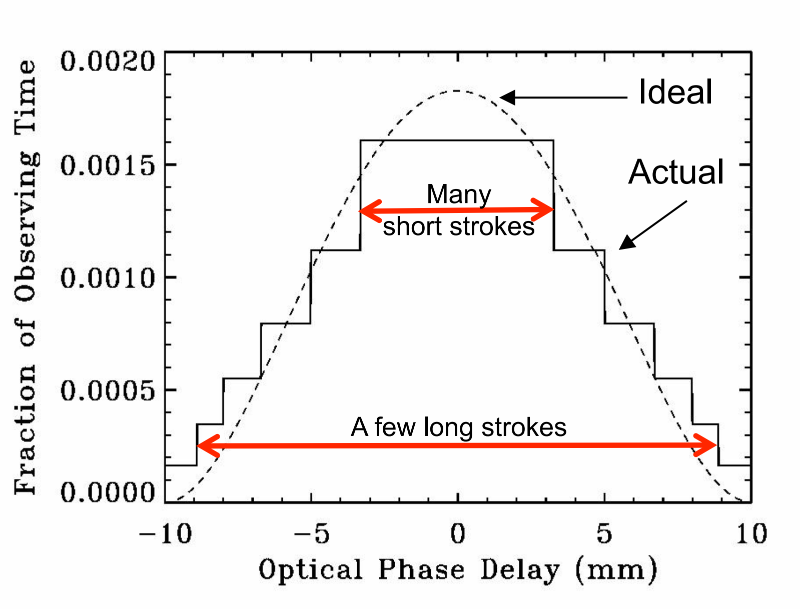
$\Delta\nu = 15$ GHz

30 GHz to 6 THz (1 cm to 50 μm)



$$S_\nu = \sum_{i=0}^{N_s-1} S_i \; \exp(2\pi i \; \nu \; z_i/c)$$

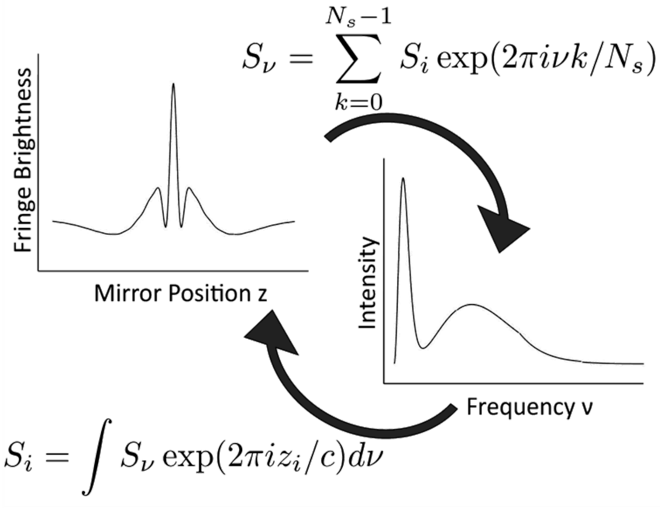
$$S_i = \int_{-\infty}^{+\infty} S_\nu \; \exp(2\pi i \; \nu \; z_i/c) \; d\nu$$



Optical Delay	Physical Stroke	Samples per Stroke	Strokes per Spin
±10 mm	±2.5 mm	1024	8
±8.9 mm	±2.3 mm	910	9
±8.0 mm	±2.1 mm	819	10
±6.7 mm	±1.7 mm	683	12
±5.0 mm	±1.3 mm	512	16
±3.3 mm	±0.9 mm	341	24

Vary stroke length to apodize Fourier transform

FTS vs Foregrounds

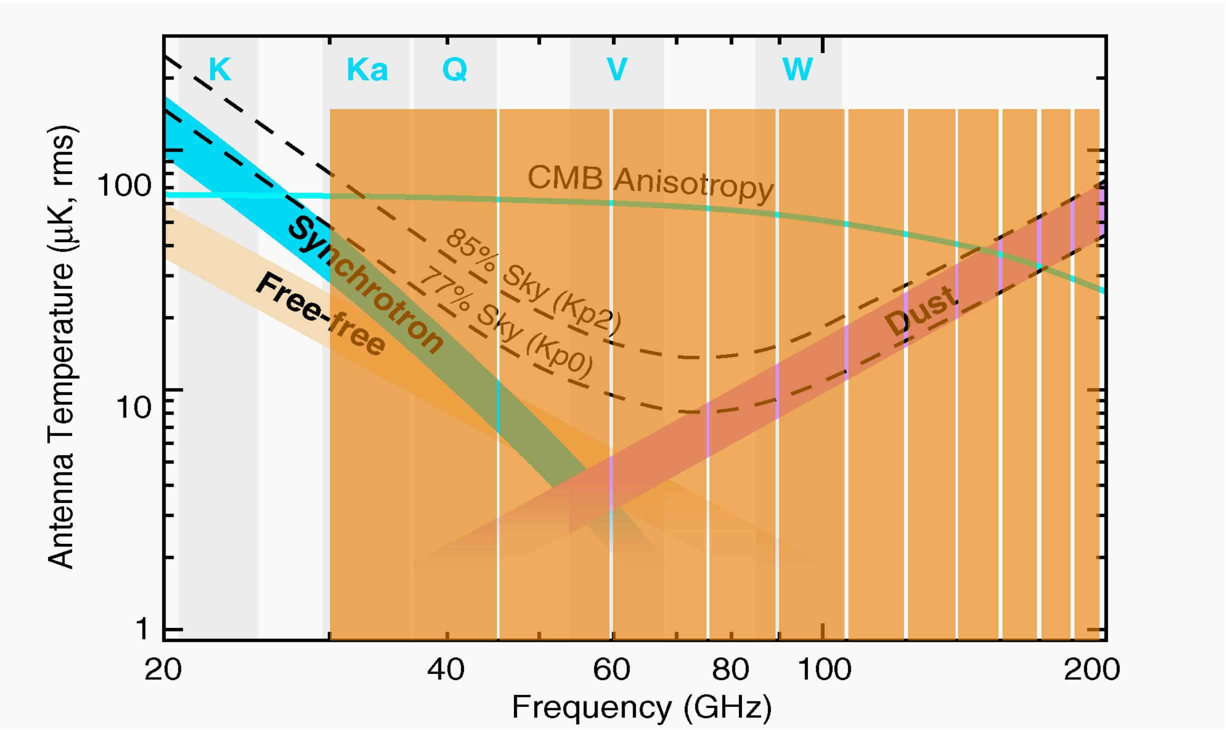


$$S_\nu = \sum_{k=0}^{N_s-1} S_i \exp(2\pi i \nu k / N_s)$$

$$S_i = \int S_\nu \exp(2\pi i z_i / c) d\nu$$

Phase delay L sets channel width
$\Delta\nu = c/2L = 15$ GHz

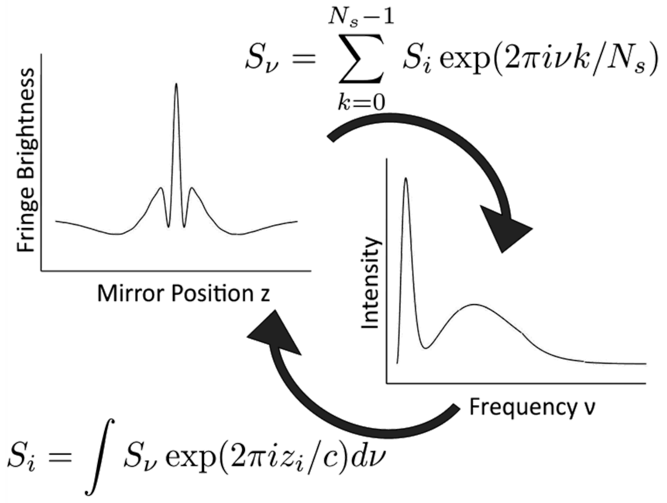
Number of samples sets frequency range
$\nu_i = 15, 30, 45, \ldots (N/2)^*\Delta\nu$



Example:
24 samples during fringe sweep
12 channels 15 GHz to 180 GHz

But why stop there?

FTS vs Foregrounds

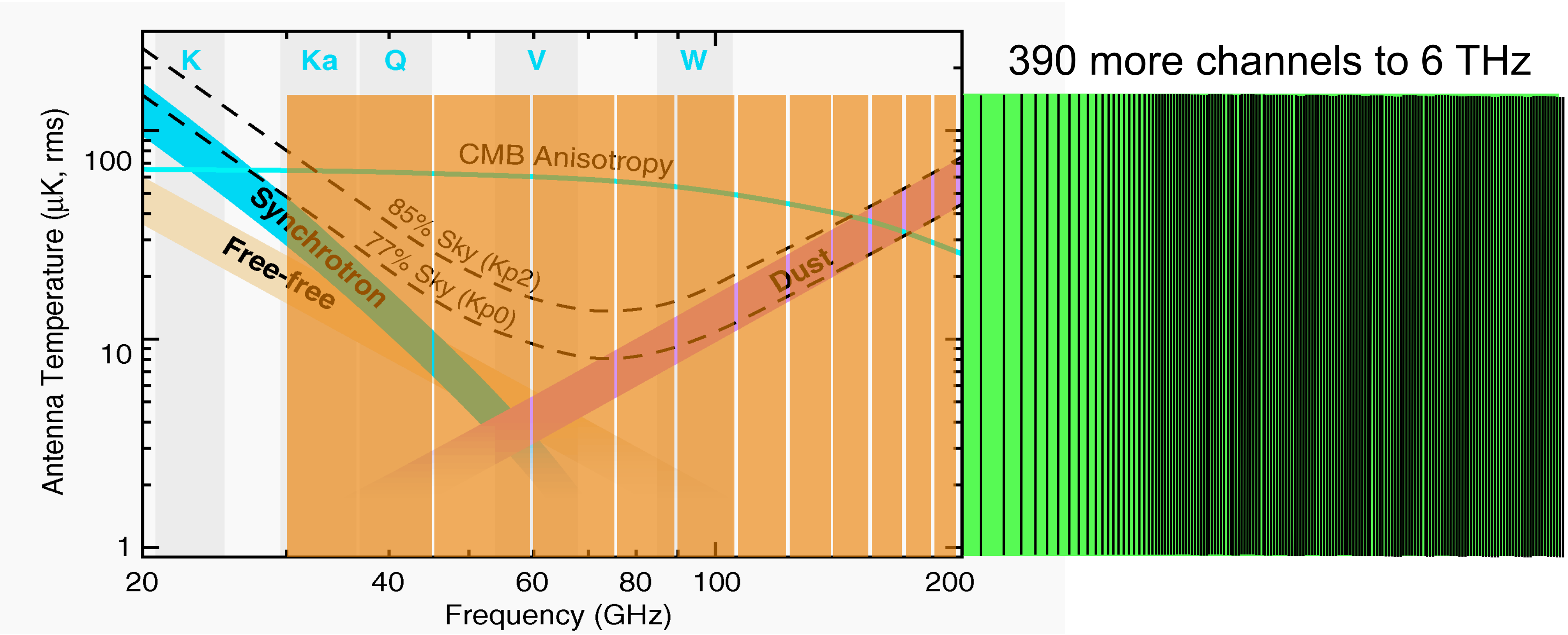


$$S_\nu = \sum_{k=0}^{N_s-1} S_i \exp(2\pi i \nu k / N_s)$$

$$S_i = \int S_\nu \exp(2\pi i z_i / c) d\nu$$

Phase delay L sets channel width
$\Delta\nu = c/2L = 15$ GHz

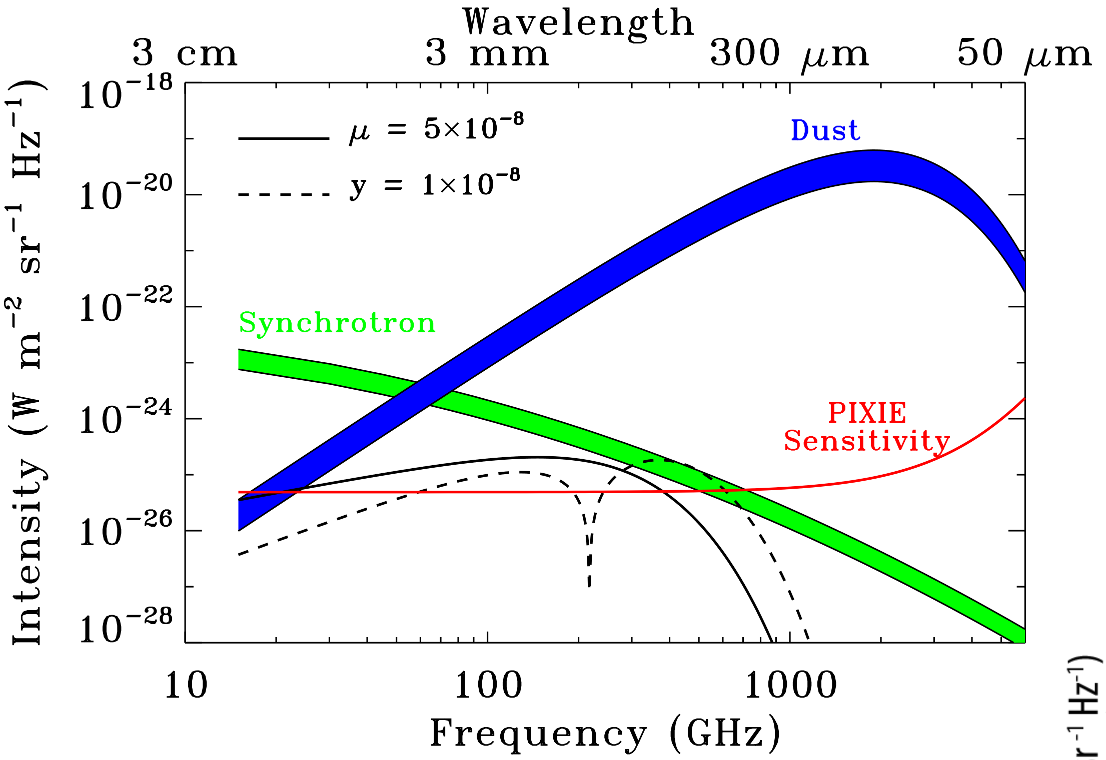
Number of samples sets frequency range
$\nu_i = 15, 30, 45, \ldots (N/2)^*\Delta\nu$



390 more channels to 6 THz

Sample more often: Get more frequency channels!

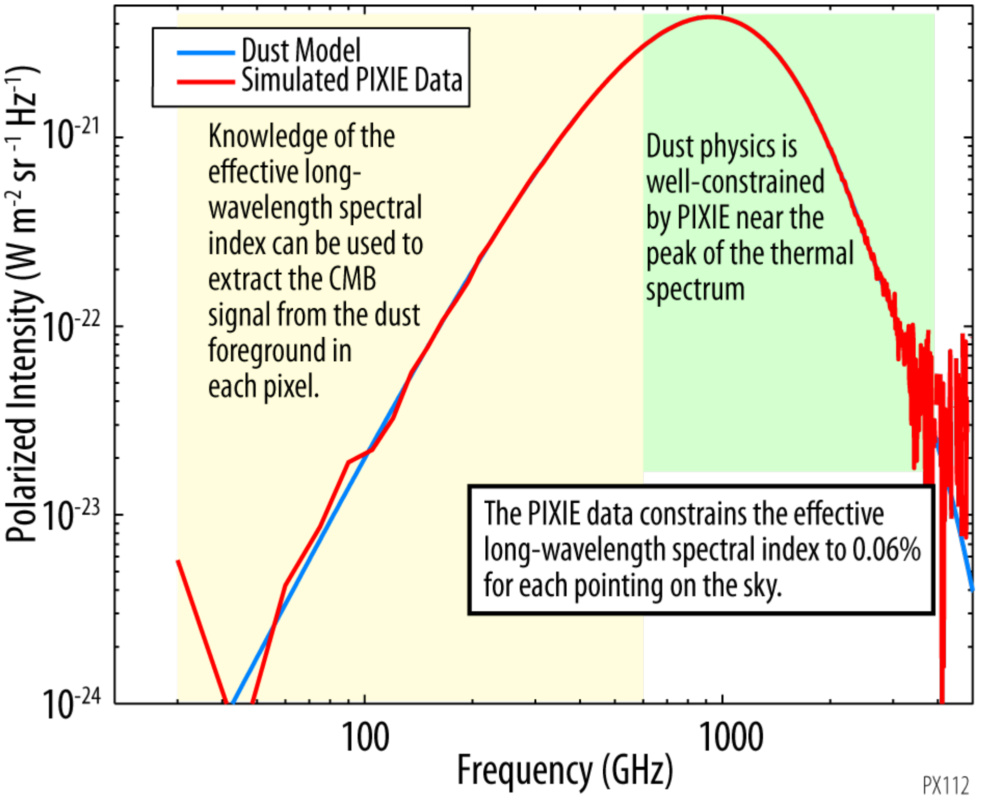
PIXIE “Foreground Machine”



Spectral coverage spanning 7+ octaves
Polarized spectra from 30 GHz to 6 THz
400 channels with mJy sensitivity per channel

Sensitivity plus broad frequency coverage
Foreground S/N > 100 in each pixel and freq bin
Spectral index uncertainty ±0.001 in each pixel

Dust Physics Inform Foreground Subtraction



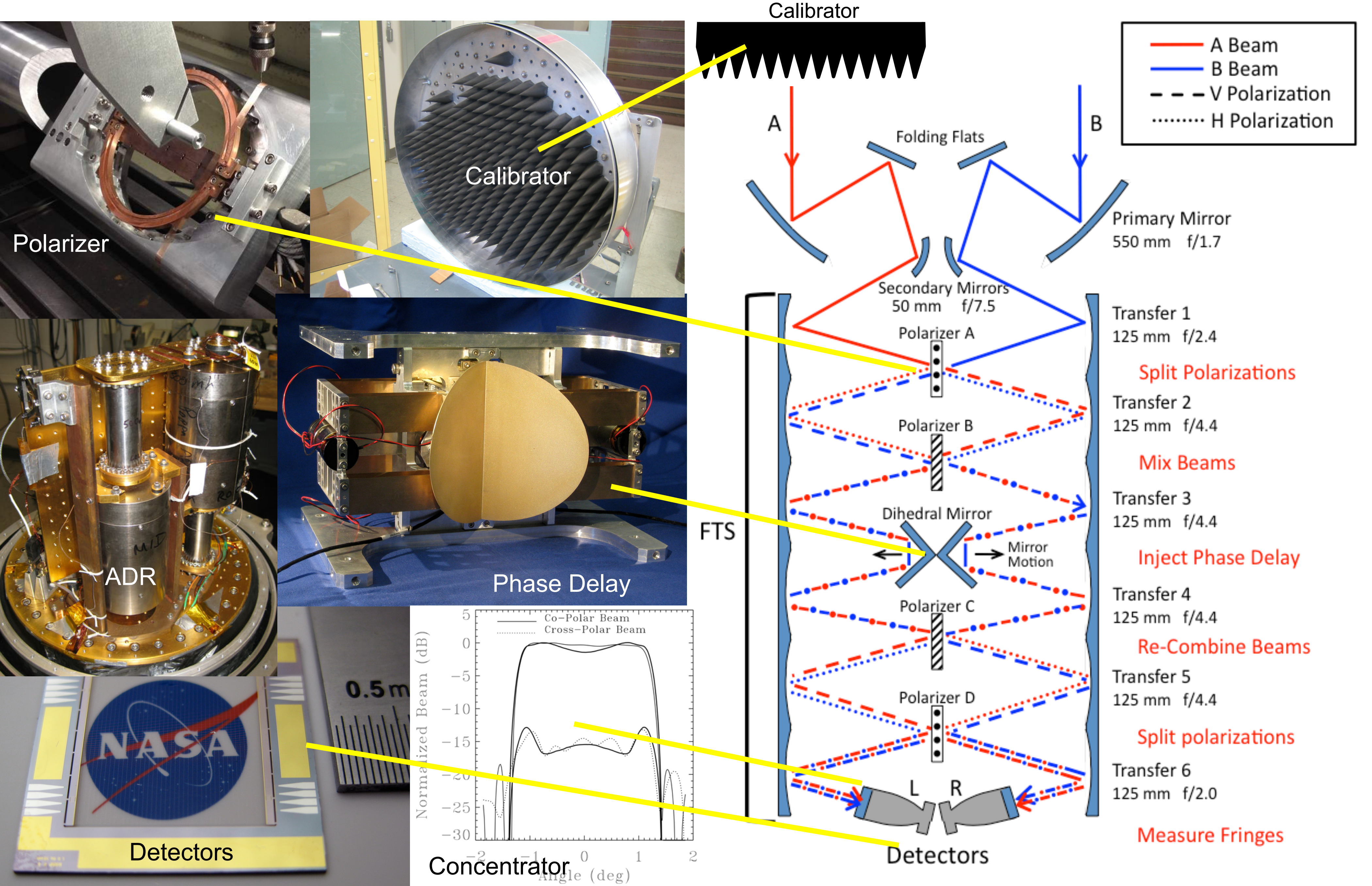
Knowledge of the effective long-wavelength spectral index can be used to extract the CMB signal from the dust foreground in each pixel.

Dust physics is well-constrained by PIXIE near the peak of the thermal spectrum

The PIXIE data constrains the effective long-wavelength spectral index to 0.06% for each pointing on the sky.

If PIXIE can’t figure out the foregrounds, it probably can’t be done!

PIXIE Implementation



Sensitivity: Background Limit the Easy Way

Big Detectors in Multi-Moded Light Bucket

$$\mathrm{NEP}^2_{\mathrm{photon}} = \frac{2A\Omega}{c^2}\frac{(kT)^5}{h^3}\int \alpha\epsilon f\,\frac{x^4}{e^x-1}\left(1+\frac{\alpha\epsilon f}{e^x-1}\right)dx$$

Photon noise ~ $(A\Omega)^{1/2}$
Big detector: Negligible phonon noise

$$\delta I_\nu = \frac{\delta P}{A\Omega\,\Delta\nu\,(\alpha\epsilon f)}$$

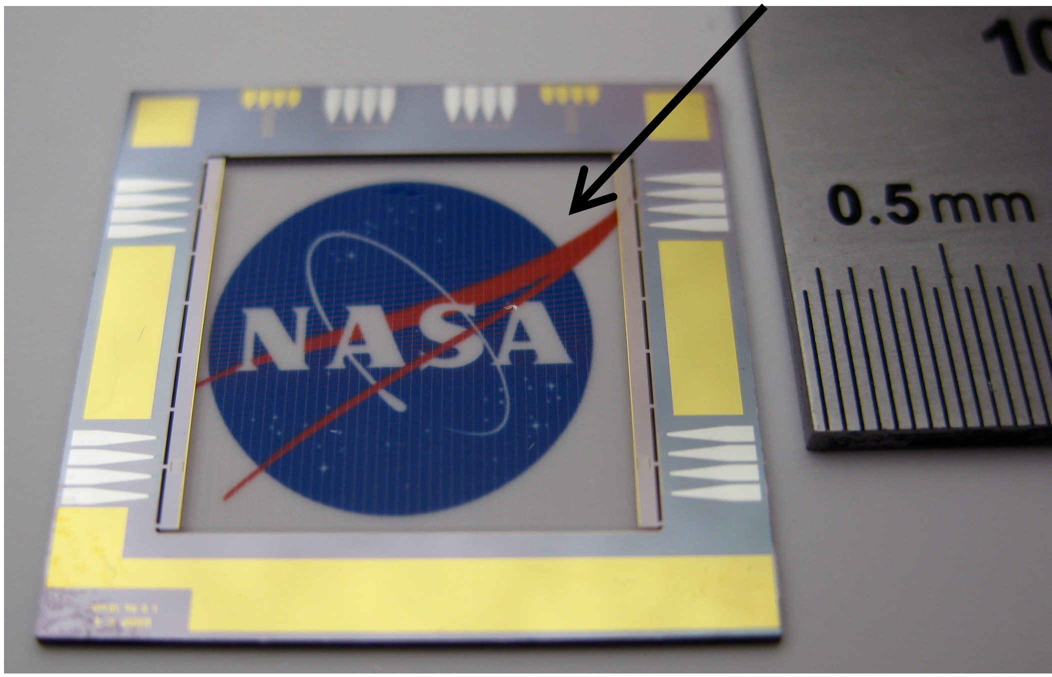
Signal ~ $(A\Omega)$
Big detector: S/N improves as $(A\Omega)^{1/2}$

PIXIE: $A\Omega = 4\ \mathrm{cm}^2\ \mathrm{sr}$

Parameter	**Units**	**Calibrator Deployed**	**Calibrator Stowed**
Stokes I (per bin)	$\mathrm{W\,m^{-2}\,sr^{-1}\,Hz^{-1}}$	2.4×10^{-22}	---
Stokes Q (per bin)	$\mathrm{W\,m^{-2}\,sr^{-1}\,Hz^{-1}}$	3.4×10^{-22}	0.5×10^{-22}
NET (CMB)	$\mu\mathrm{K\,s}^{-1/2}$	13.6	---
NEQ (CMB)	$\mu\mathrm{K\,s}^{-1/2}$	19.2	5.6

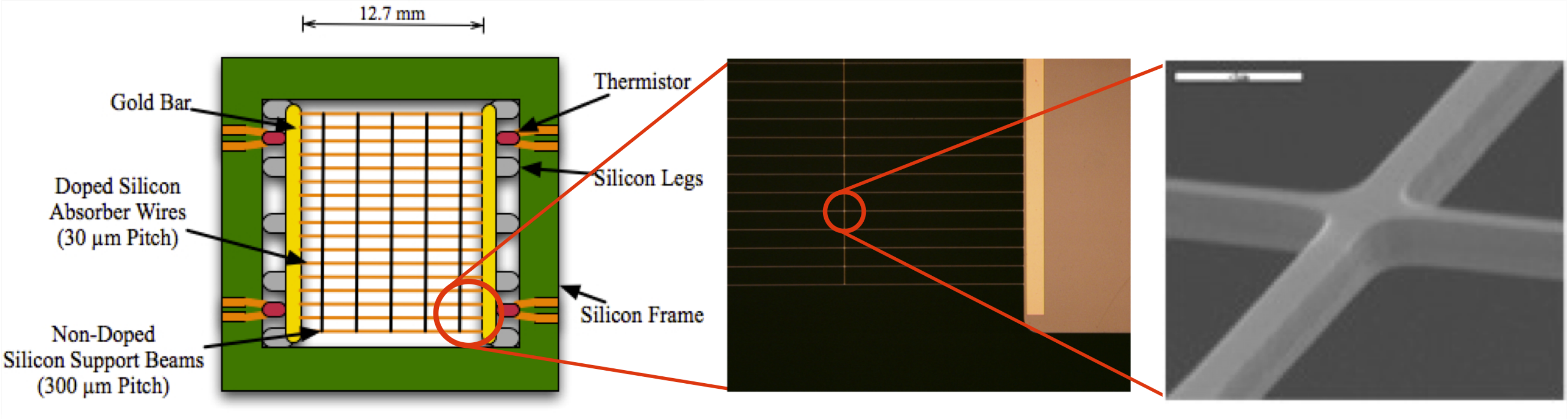
Sensitivity 70 nK per 1° x 1° pixel

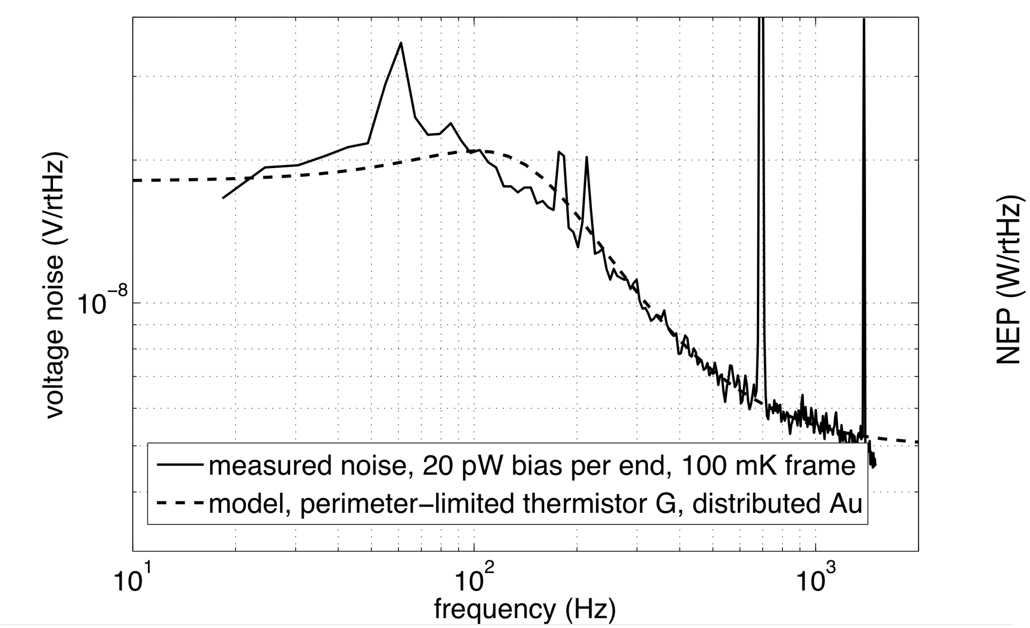
30x collecting area as Planck bolometers

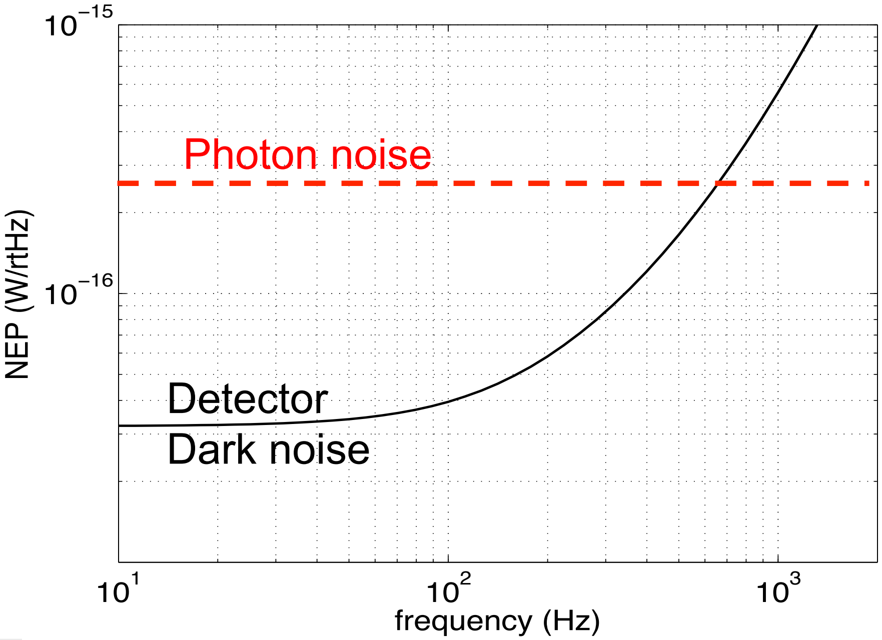


PIXIE polarization-sensitive bolometer

PIXIE Detectors







Demonstrate multi-moded single-polarization photon-limited detectors

Microwave vs Audio Frequencies

Given spectrum S(ν) and mirror position z, get interferogram I(z)

$$I(z) = \int_{-\infty}^{+\infty} S(\nu)\exp(2\pi i\,\nu\, z/c)\, d\nu$$

For single spectral line $S(\nu) = S_0\,\delta(\nu-\nu_0)$ this becomes

$$I(z) = S_0 \exp(2\pi i\,\nu_0\, z/c)$$

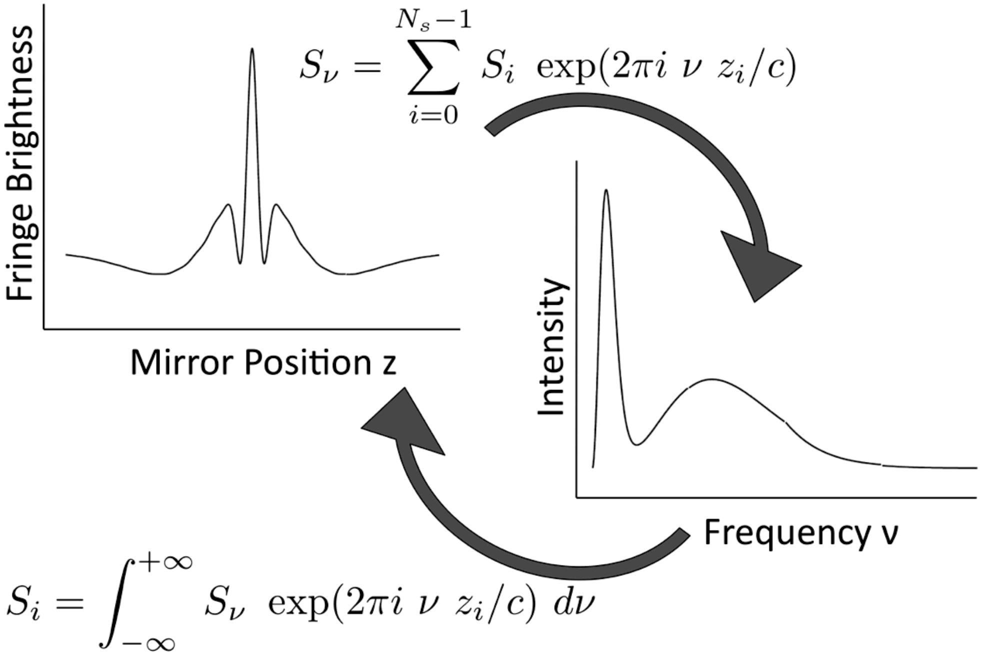
If mirror moves at constant velocity b, then z = vt
The interferogram may then be written

$$I(z) = S_0 \exp(2\pi i\,\nu_0\, \mathrm{v}/c\ t)$$

Defining β = v/c, the interferogram becomes

$$I(z) = S_0 \exp(2\pi i\,\beta\nu_0\, t)$$

which only has power at audio frequency $\beta\nu_0$

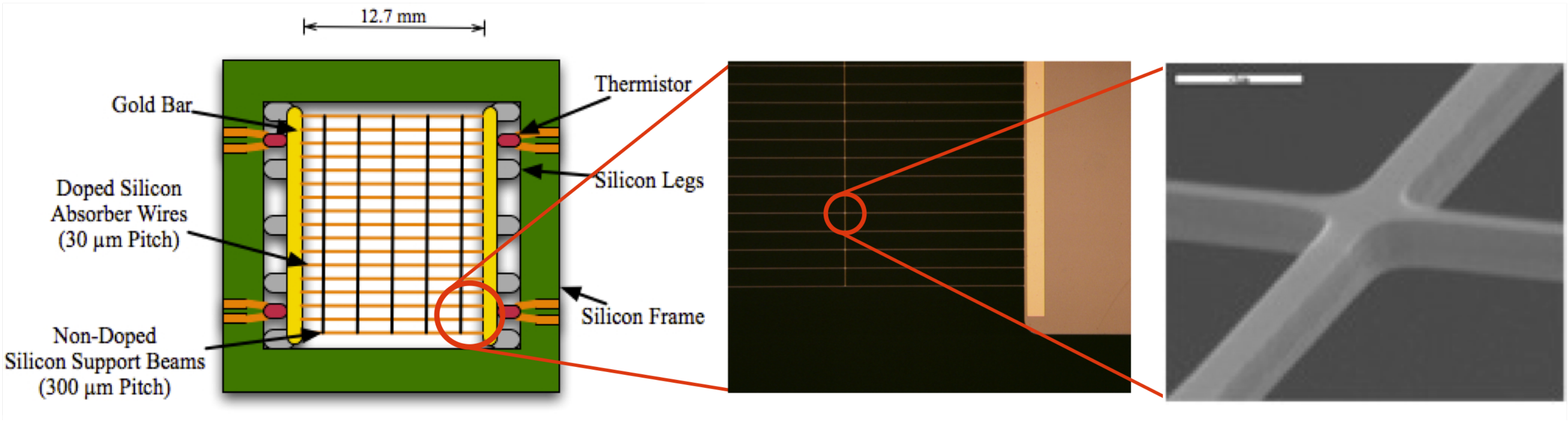


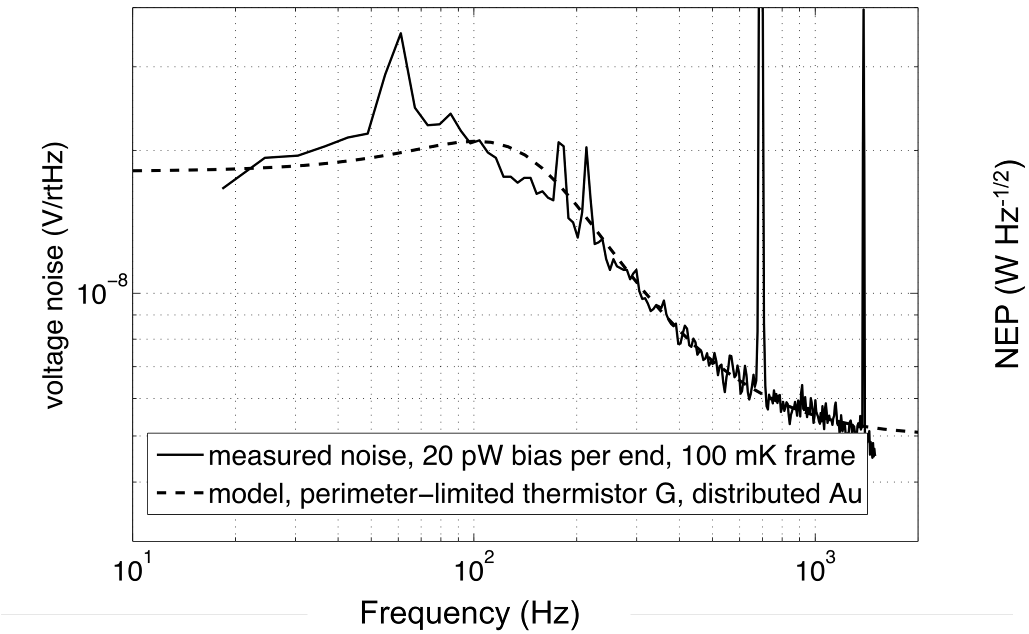
$$S_\nu = \sum_{i=0}^{N_s-1} S_i\ \exp(2\pi i\ \nu\ z_i/c)$$

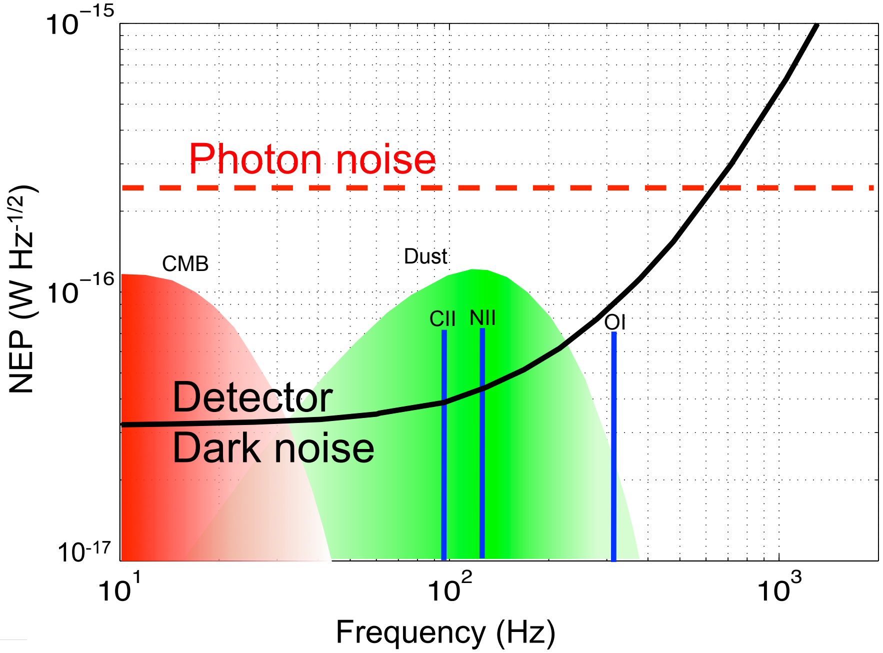
$$S_i = \int_{-\infty}^{+\infty} S_\nu\ \exp(2\pi i\ \nu\ z_i/c)\ d\nu$$

	Microwave	Audio
CMB	30 – 300 GHz	2 – 20 Hz
Dust	300 – 3000 GHz	20 – 200 Hz

PIXIE Detectors

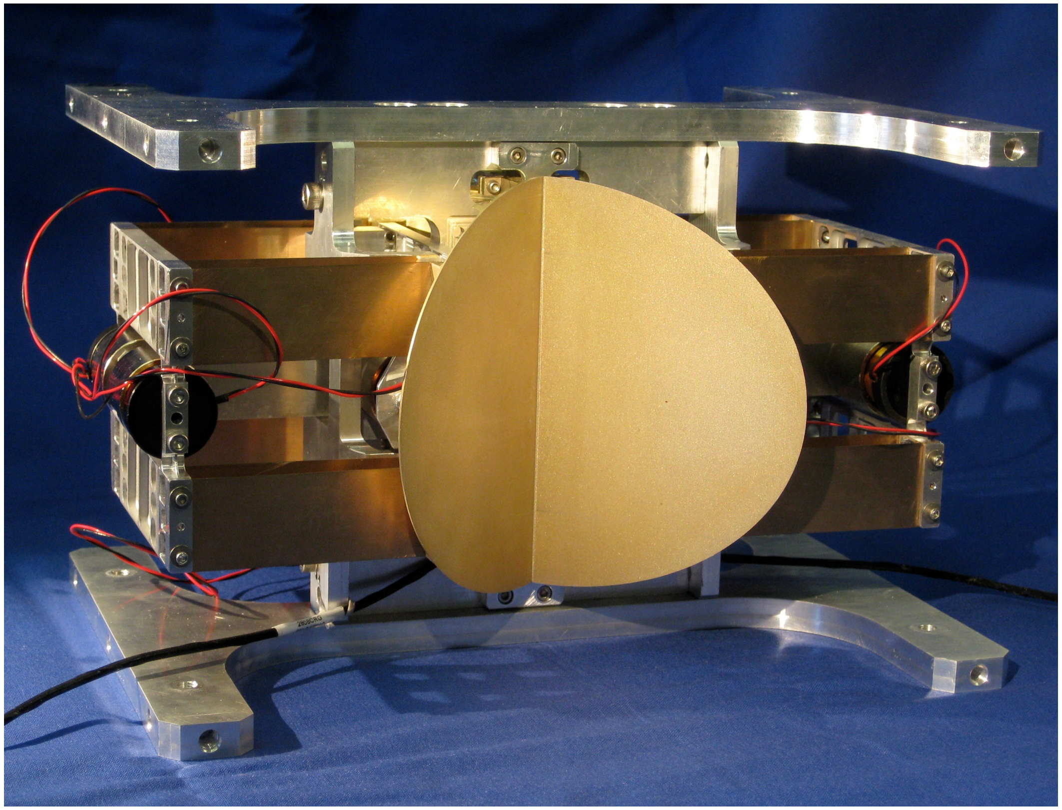






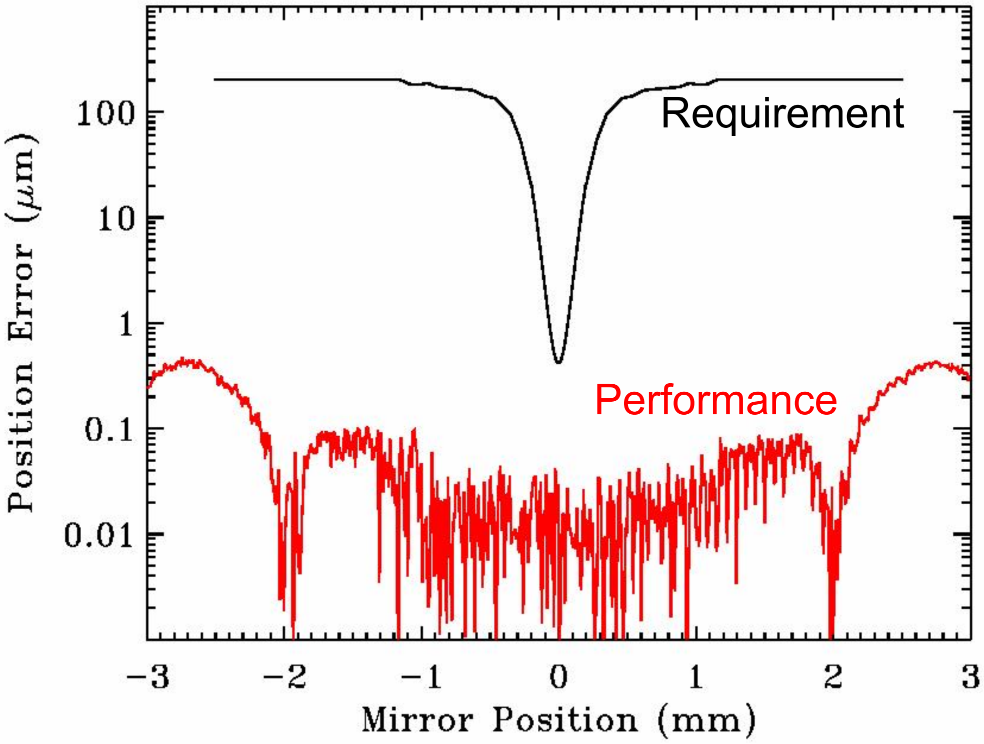
Demonstrate multi-moded single-polarization photon-limited detectors

Mirror Transport Mechanism



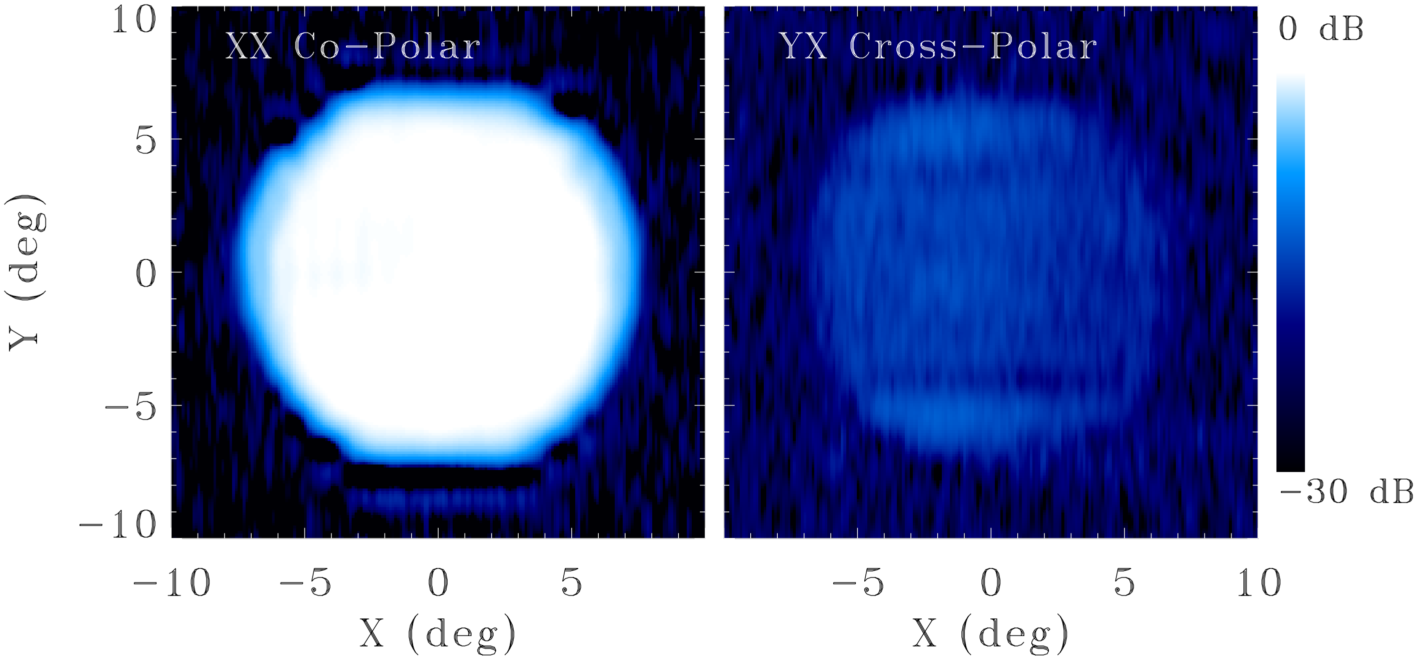
Engineering prototype

Translate ±2.54 mm at 0.5 Hz
Optical phase delay ±1 cm
Repeatable cryogenic position



Demonstrated performance
exceeds requirement by factor of ten

Measured Beam Patterns

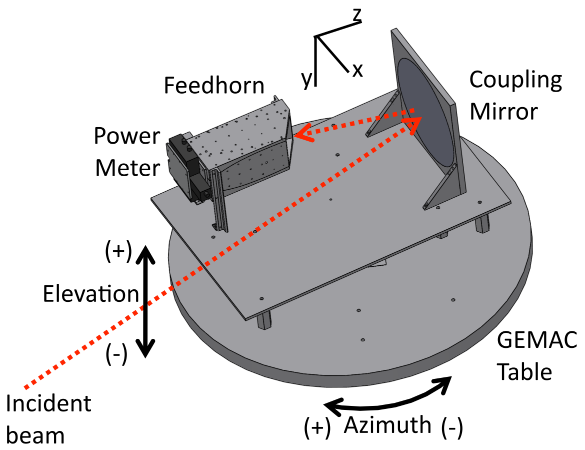


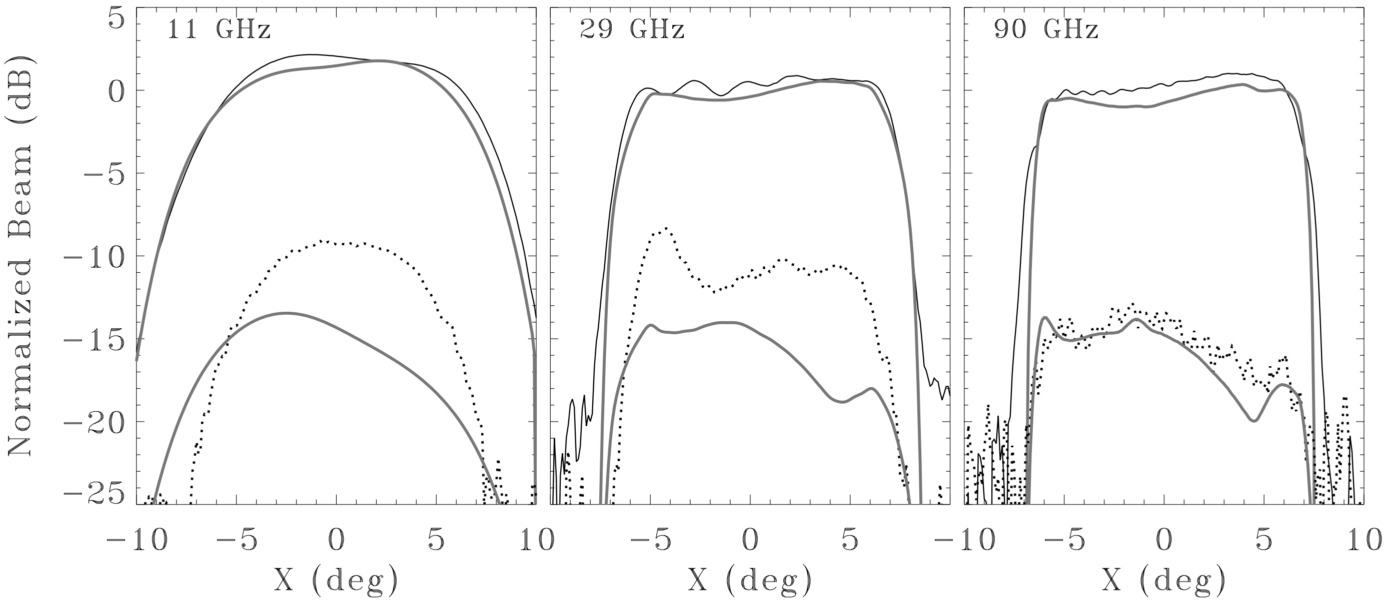
Measured co-polar and cross-polar beams for multi-moded feed

Choose wavelengths to span few-mode (N=6) case to multi-mode (N=500) case

Good agreement between model and measurements

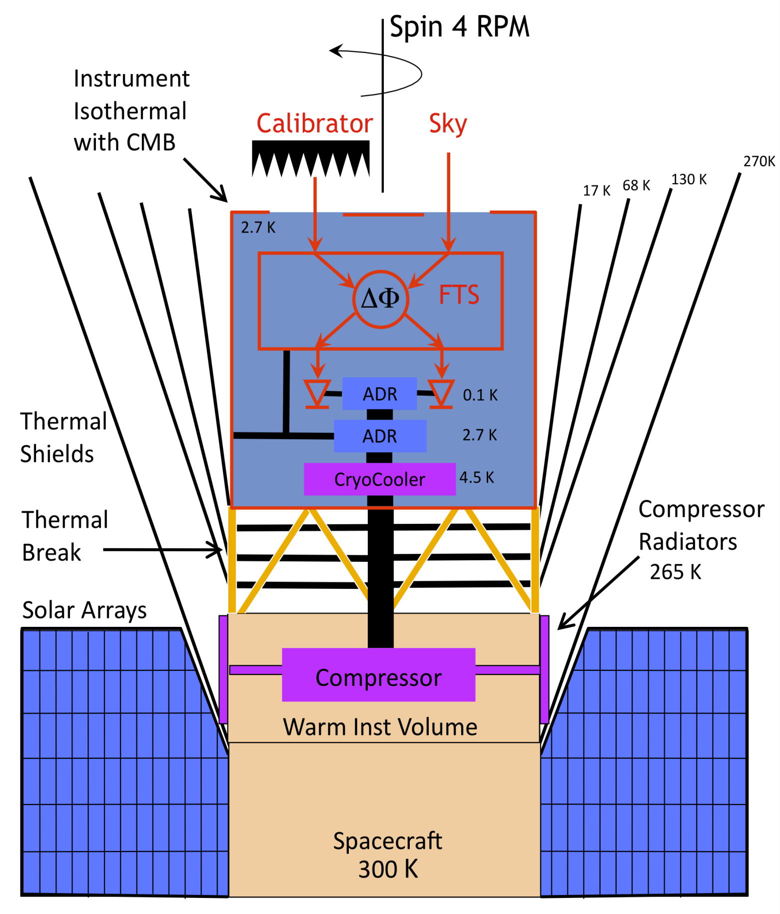
Typical cross-polar response -18 dB, can reduce to -25 dB in 2nd-gen feed





Kogut et al. 2015, JOS-A, arXiv:1503.04206

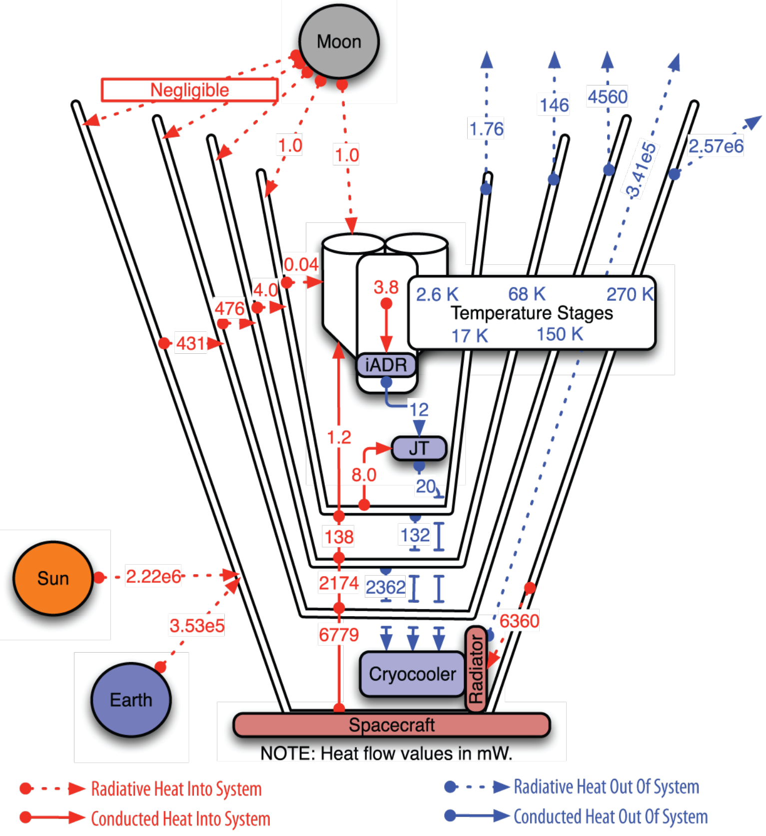
Instrument Cryogenics



INSTRUMENT THERMAL LIFT BUDGET

Cooler Stage	Stage Temp (K)	CBE Loads (mW)	Derated Capability (mW)	Contingency & Margin (%)
Stirling (Upper Stage)	68	2362	4613	95%
Stirling (Lower Stage)	17	132	278	111%
Joule-Thomson	4.5	20	40	100%
iADR	2.6	6	12	100%
dADR	0.1	0.0014	0.03	2043%

PIXIE INSTRUMENT HEAT FLOW



NOTE: Heat flow values in mW.

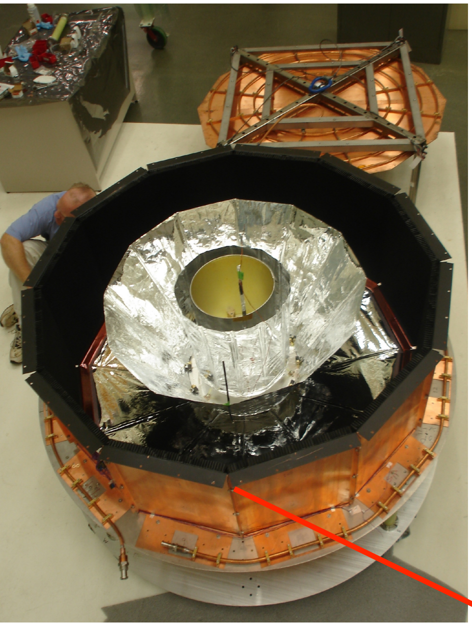
Fully cryogenic instrument

- Cryo-cooler to 4.5 K
- ADR to 2.6 K (instrument body)
- ADR to 0.1 K (detectors)

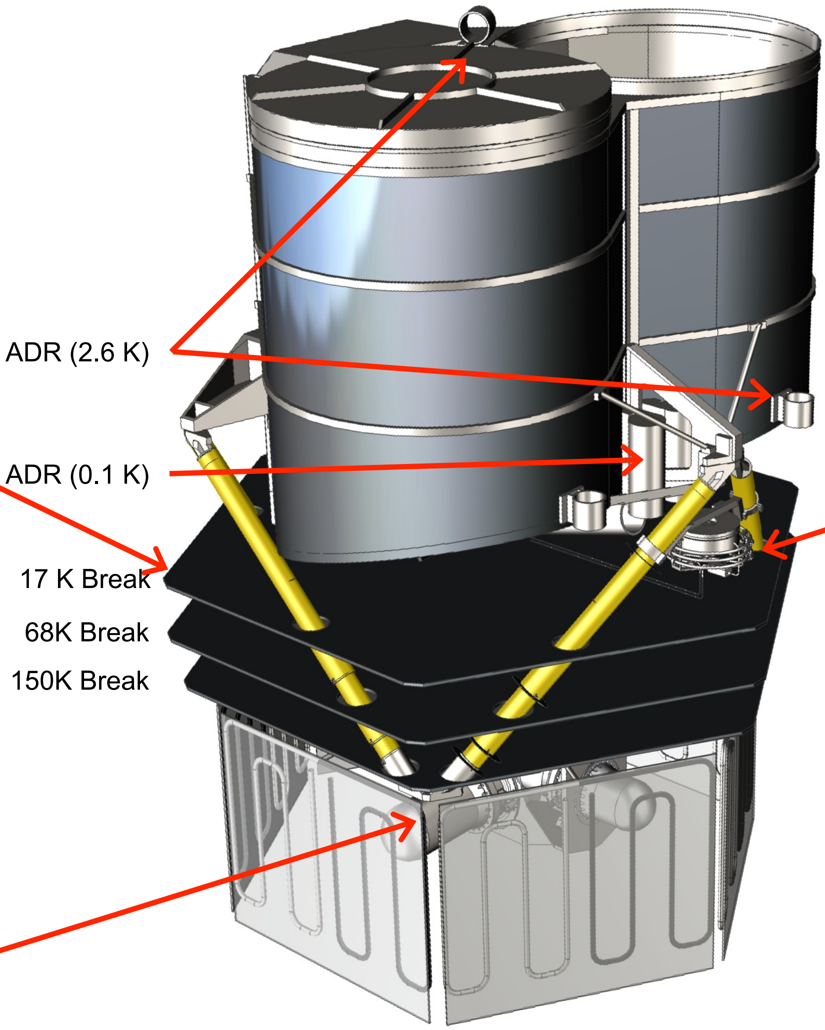
Tolerant thermal design

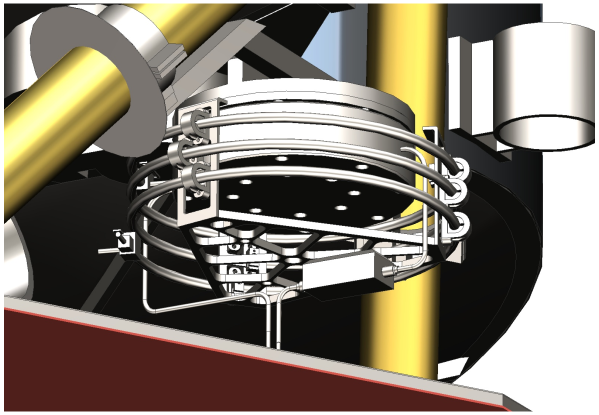
- Robust design/performance margins
- Active thermal control for all optical surfaces
- Thermal “backbone” tolerant vs temperature excursions

Cryogenics

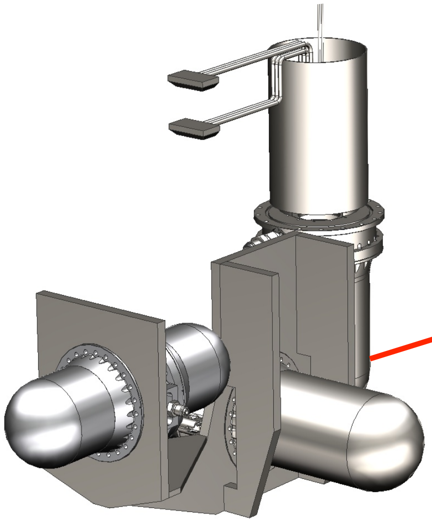


Sun Shield / Radiators





J-T Cold Head (4.5 K)



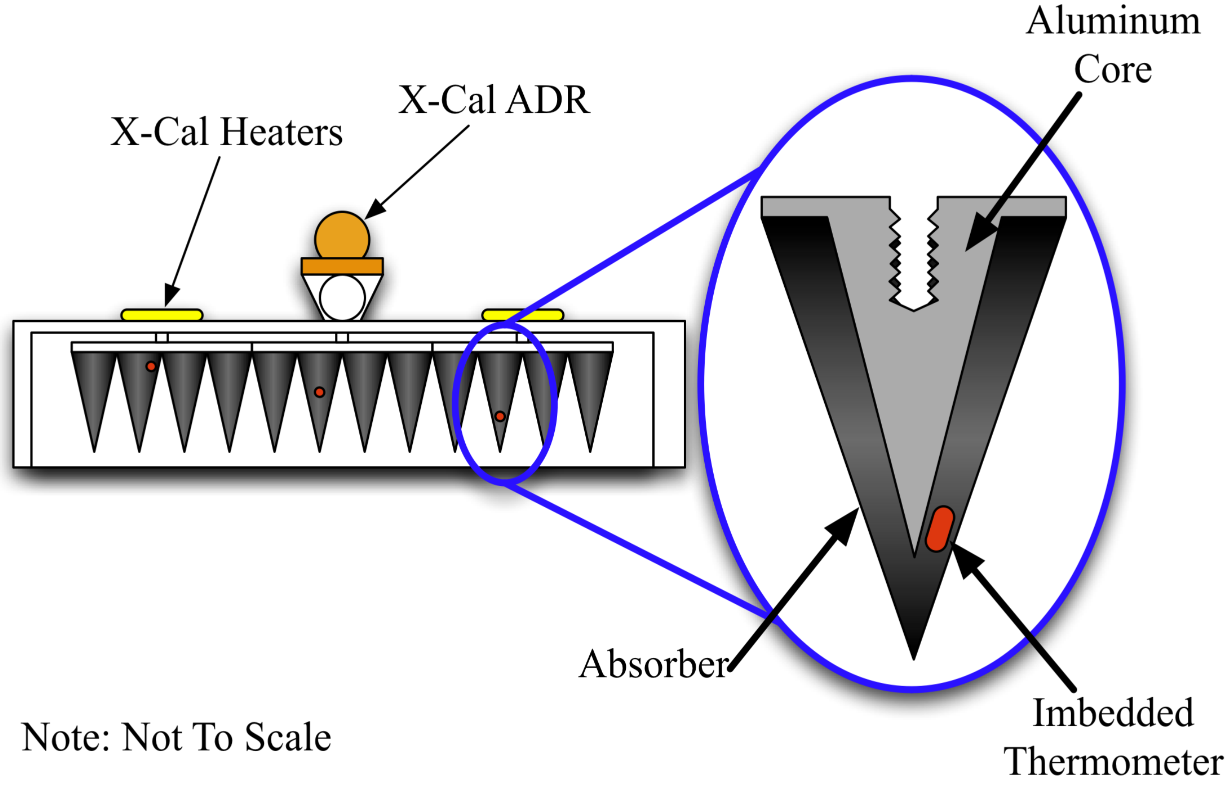
Cryo-Cooler Compressor (280 K)

Multi-Stage Cryogenic Design
- Passive Sun Shades (not shown)
- 4.5 K Cryo-cooler
- 2.6 K ADR
- 0.1 K ADR

Thermal Lift Budget

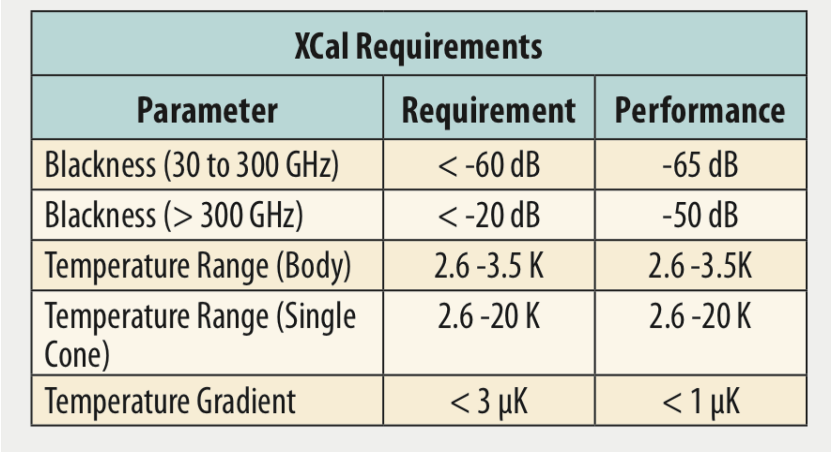
Cooler Stage	Stage Temp (K)	CBE Loads (mW)	Derated Capability (mW)	Contingency & Margin
Stirling (Upper)	68	2362	4613	95%
Stirling (Lower)	17	132	278	111%
Joule-Thomson	4.5	20	40	100%
ADR	2.6	6	12	100%
ADR	0.1	0.0014	0.03	2043%

Blackbody Calibrator

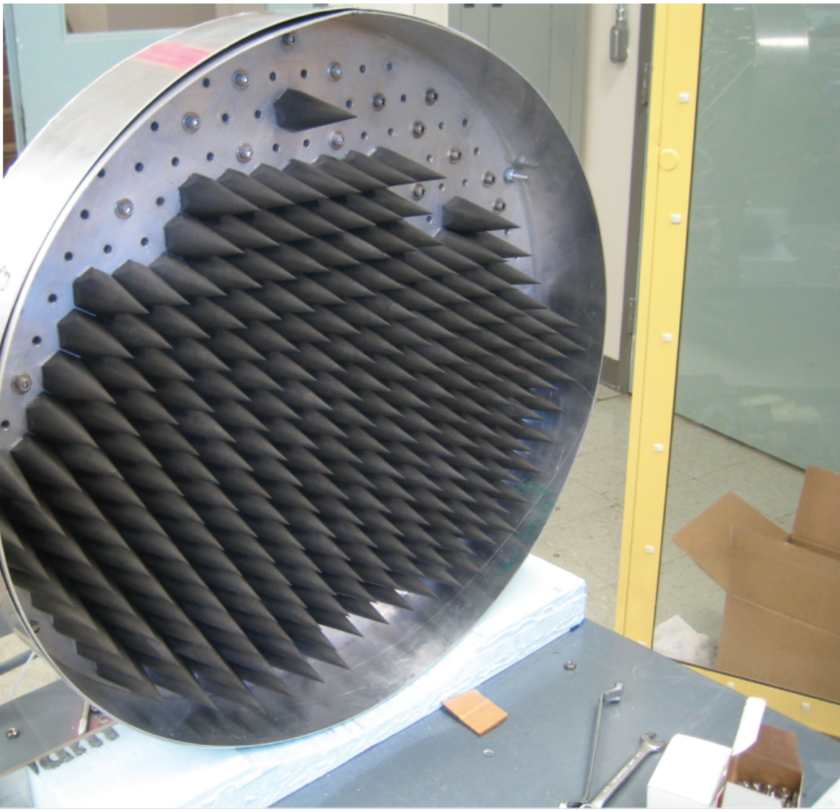


Note: Not To Scale

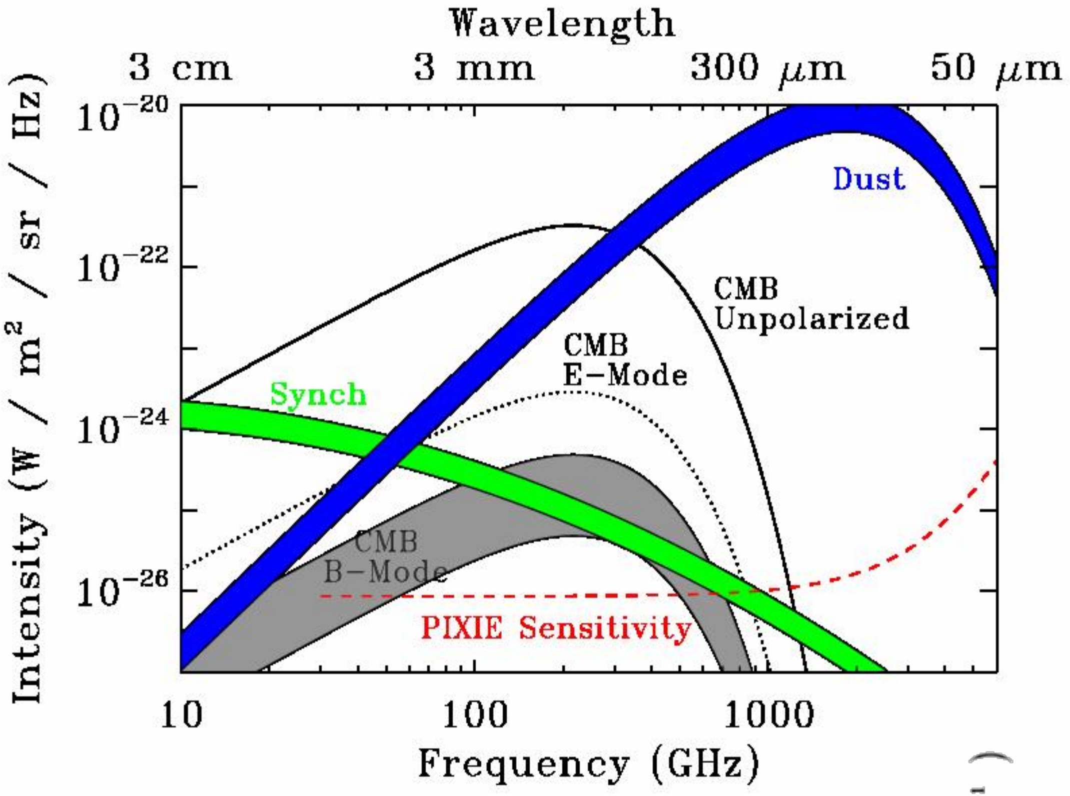
Based on successful ARCADE calibrator



XCal Requirements		
Parameter	**Requirement**	**Performance**
Blackness (30 to 300 GHz)	< -60 dB	-65 dB
Blackness (> 300 GHz)	< -20 dB	-50 dB
Temperature Range (Body)	2.6 -3.5 K	2.6 -3.5K
Temperature Range (Single Cone)	2.6 -20 K	2.6 -20 K
Temperature Gradient	< 3 μK	< 1 μK



Baseline Science Capability



Full-Sky Spectro-Polarimetric Survey

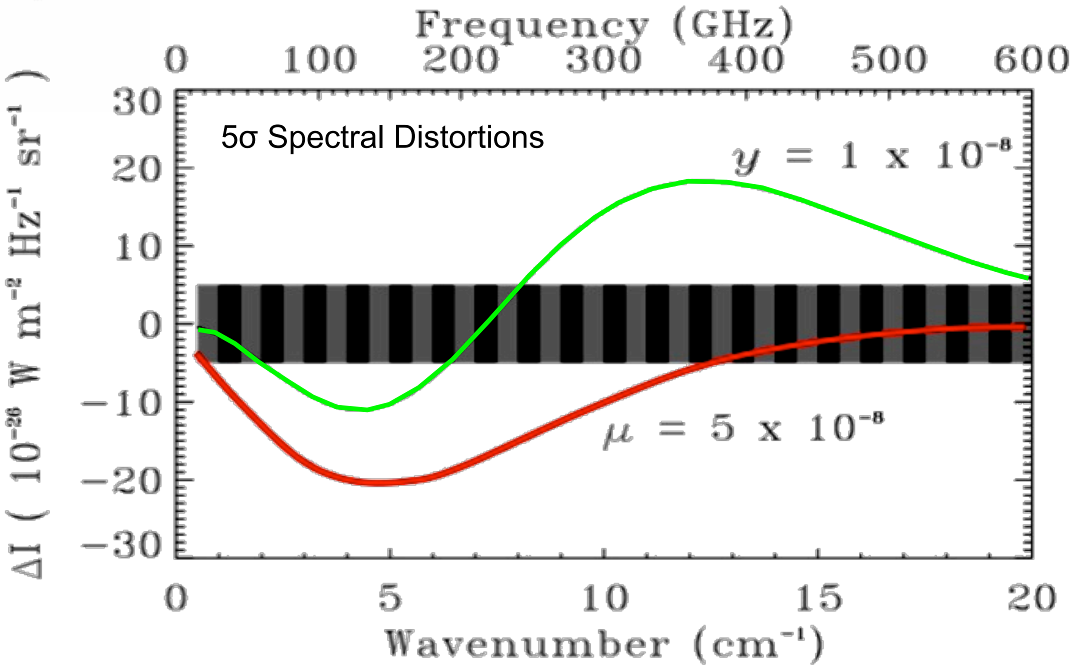
- 400 frequency channels, 30 GHz to 6 THz
- Stokes I, Q, U parameters
- 49152 sky pixels each 0.9° × 0.9°
- Pixel sensitivity 6 x 10^{-26} W m^{-2} sr^{-1} Hz^{-1}
- CMB sensitivity 70 nk RMS per pixel

Multiple Science Goals

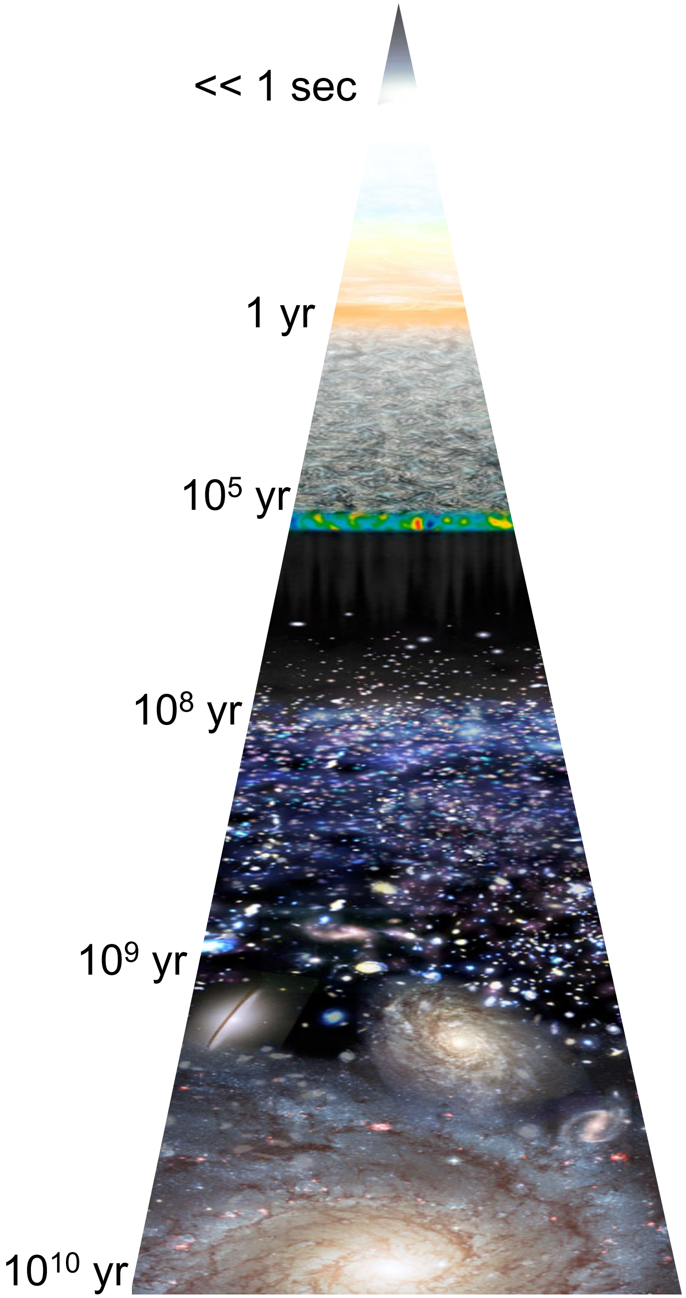
- Inflation/GUT Physics
- Dark Matter
- Reionization/First Stars
- ISM and Dust Cirrus

B-mode: $r < 1 \times 10^{-4}$ (1σ)

Distortion $|\mu| < 10^{-8}$, $|y| < 2 \times 10^{-9}$



PIXIE: Testing The Standard Model



Primary Science

Big Bang Cosmology *
- Inflation
- GUT physics
- Quantum gravity

Secondary Science

Early Universe
- Dark matter decay/annihilation
- Primordial density perturbations

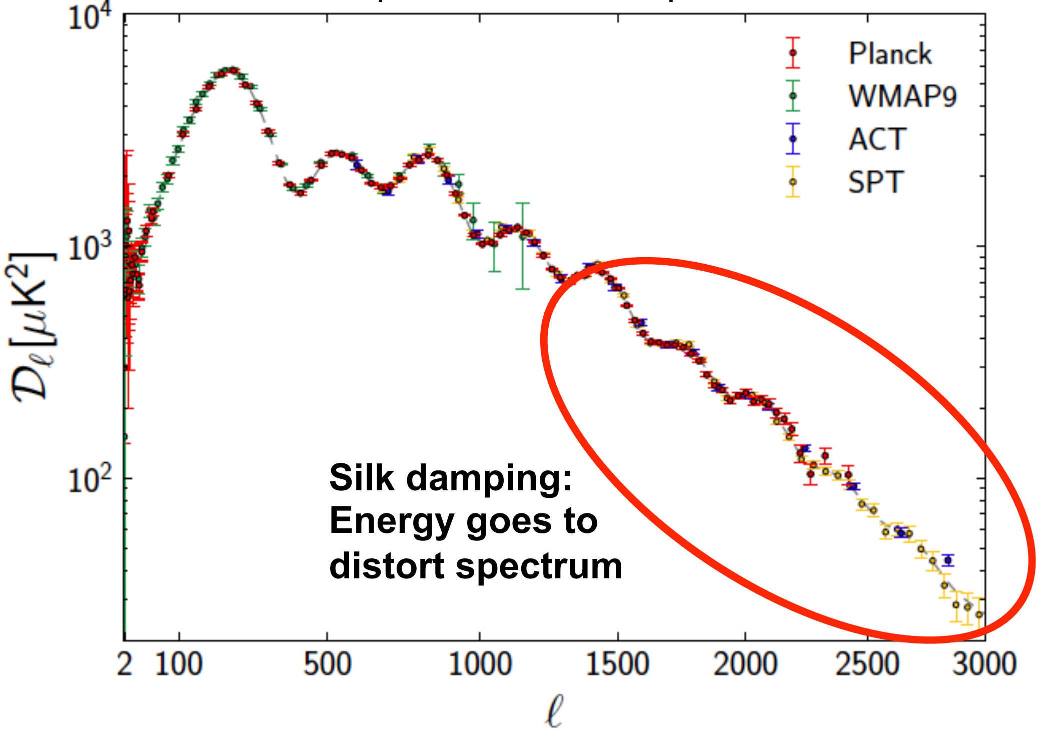
Reionization and First Stars *
- Ionization history at end of Dark Ages
- Nature of first stars

Large-scale Structure
- Galaxy bias vs dark matter density
- Star formation at redshift 2--3

Galactic Structure
- Assembly history of the Galaxy
- Dust & chemical separation

* Specifically called out in Astro-2010 Decadal Survey

Spectral Distortions: Inflation


Temperature Power Spectrum

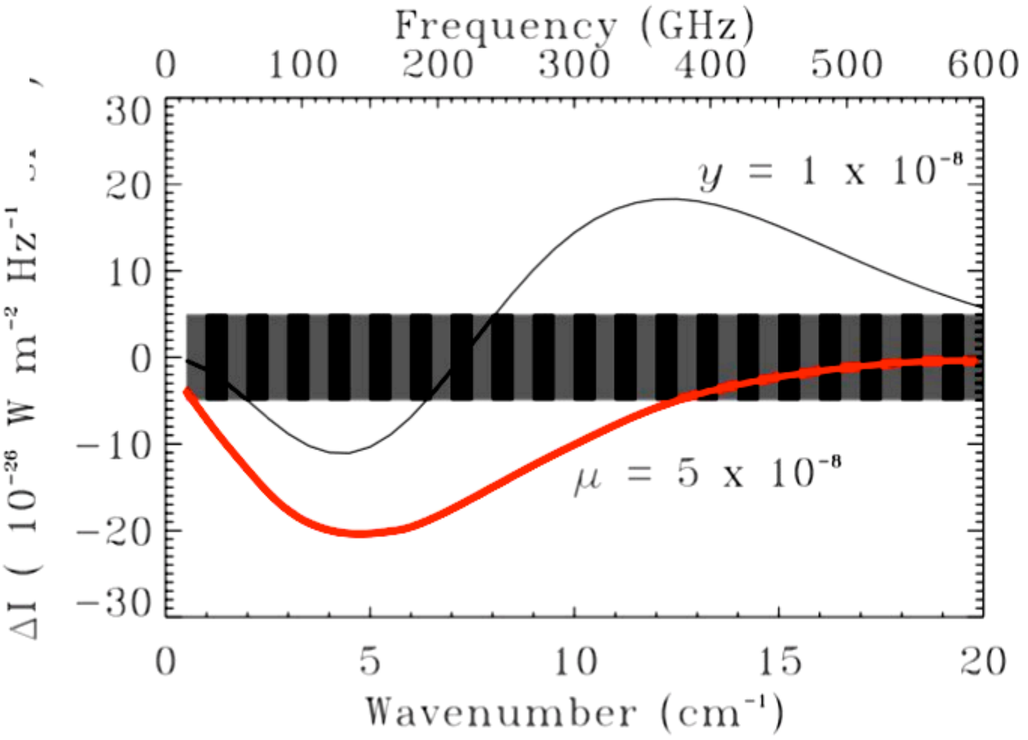
Silk damping:
Energy goes to
distort spectrum

Energy release at $10^4 < z < 10^6$

Chemical potential $\mu = 1.4 \frac{\Delta E}{E}$

PIXIE limit $\mu < 10^{-8}$

Distort CMB from blackbody spectrum

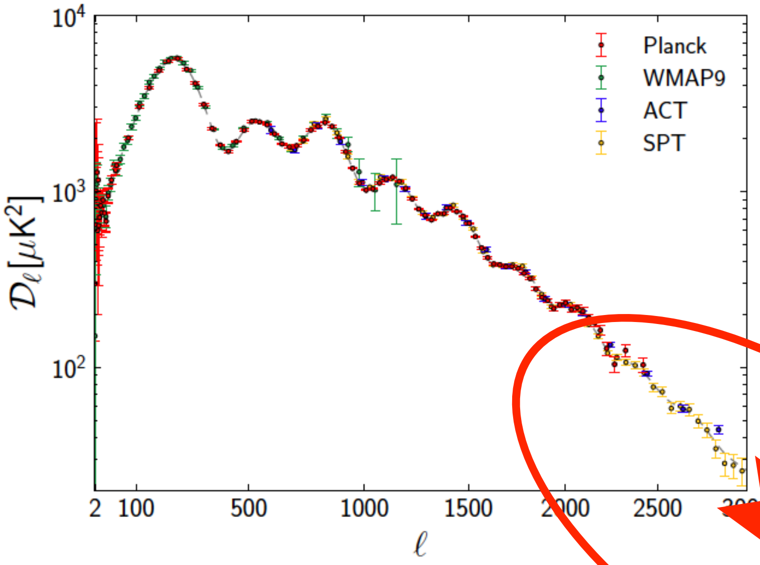


Silk damping of primordial perturbations

- Scalar index n_s and running dln n_s/dln k
- Physical scale ~1 kpc ($1M_\odot$)

Daly 1991
Hu, Scott, & Silk 1994
Chluba, Erickcek, & Ben-Dayan 2012

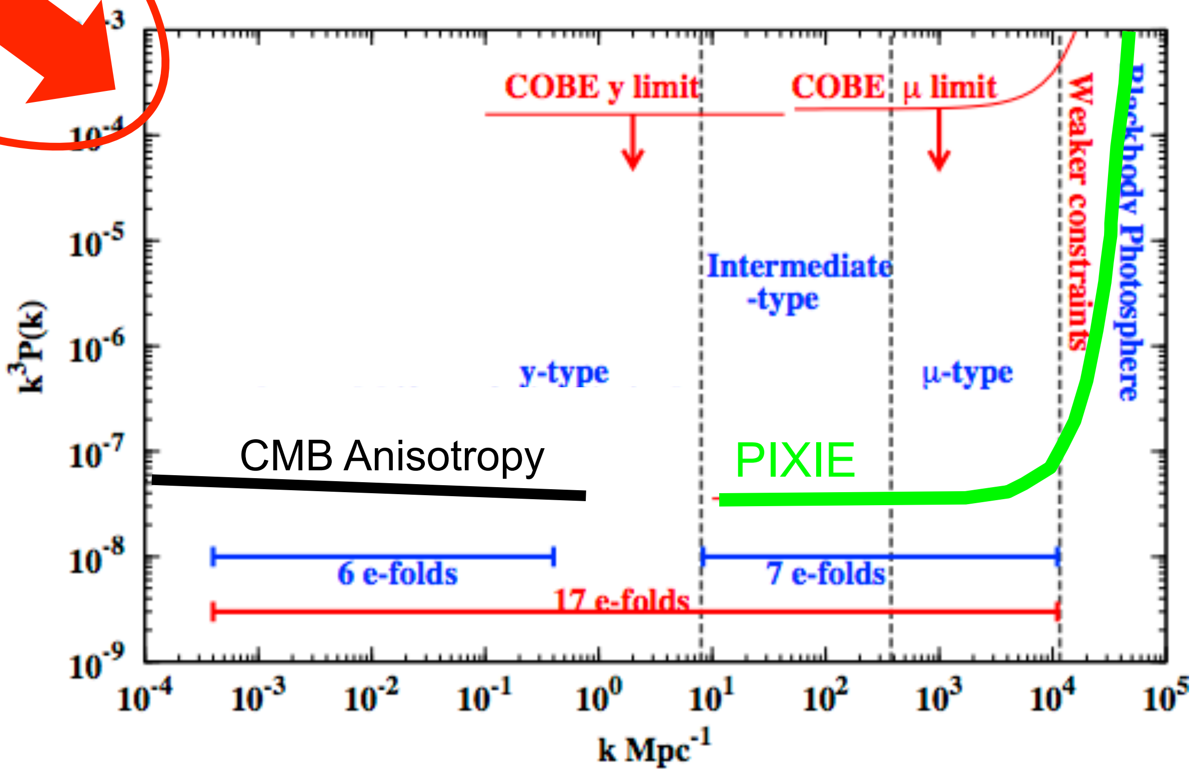
Beyond the Power Spectrum



Spectral distortions extend tests of inflation by 4 orders of magnitude in physical scale

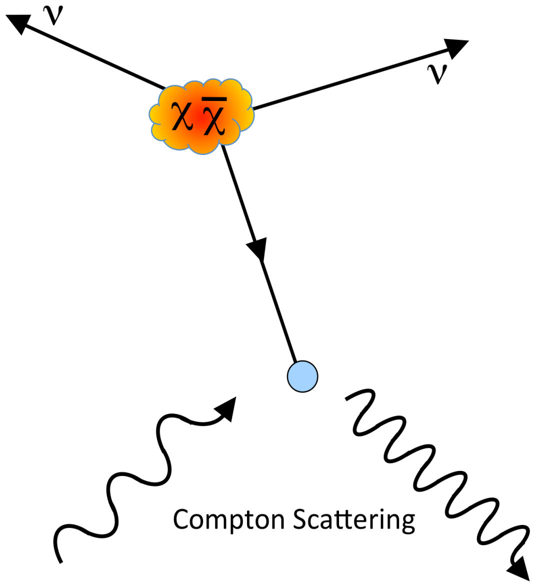
- Scalar index and running
- Non-Gaussian f_{NL}
- Tensor index and running

Complementary to both CMB anisotropy and polarization



Sunyaev & Khatri 2013

Spectral Distortions: Dark Matter Annihilation



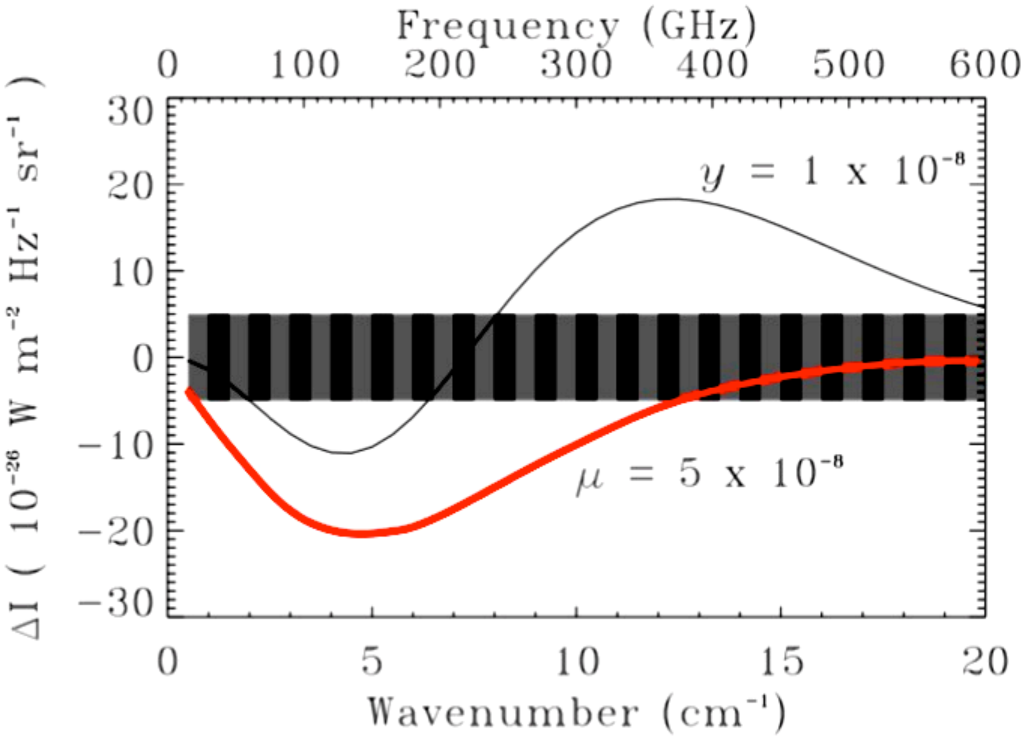
$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp(\frac{h\nu}{kT}+\mu)-1}$$

Chemical potential $\mu = 1.4\frac{\Delta E}{E}$

Annihilation rate ~ n^2 ~ z^6

Number density n ~ m^{-1}

$$m_\chi > 80\ \mathrm{keV}\left[f\left(\frac{\mu}{5\times10^{-8}}\right)\left(\frac{\sigma v}{6\times10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}\right)\left(\frac{\Omega_\chi}{0.112}\right)^2\right]^{1/2}$$



Dark matter annihilation

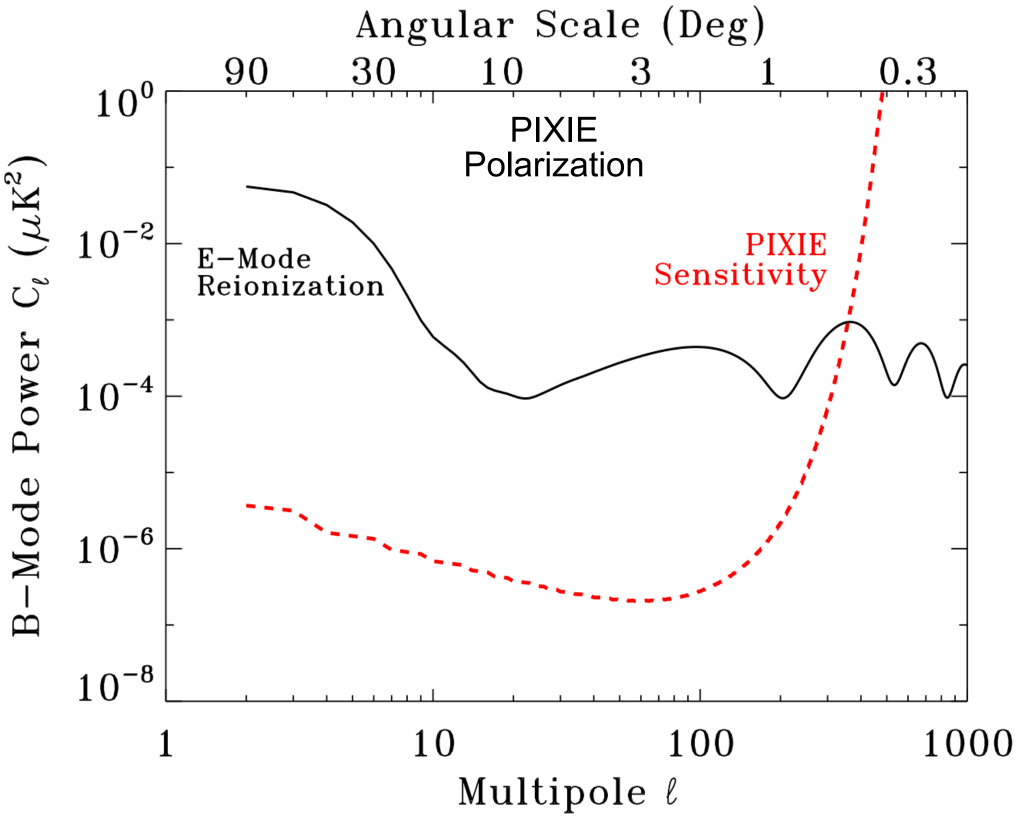
PIXIE limit μ < 10^{-8}

Neutralino mass limit m_χ > 80 keV

Definitive test for warm dark matter

McDonald et al 2001
de Vega & Sanchez 2010

Spectral Distortions: Reionization



Spectrum: y distortion ~ Electron pressure $\int nkT_e$

- PIXIE limit $y < 5 \times 10^{-9}$
- Distortion must be present at $y \sim 10^{-7}$

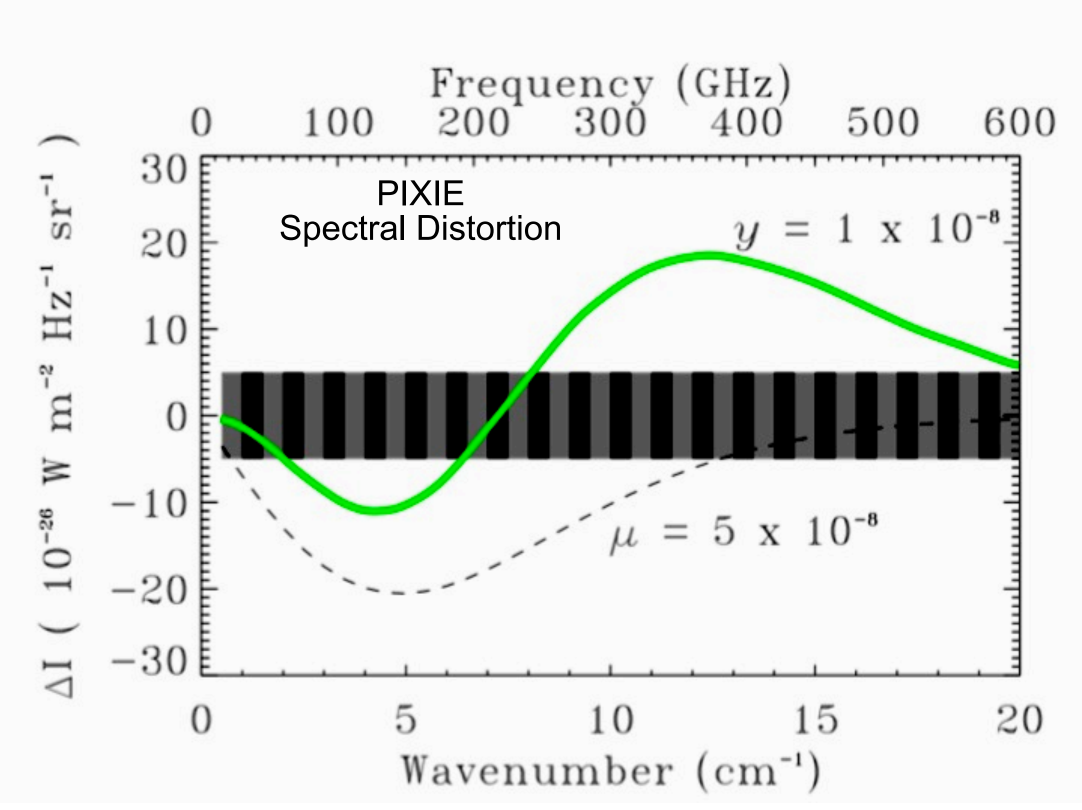
Polarization: Optical depth ~ Electron density n

Same scattering for both signals

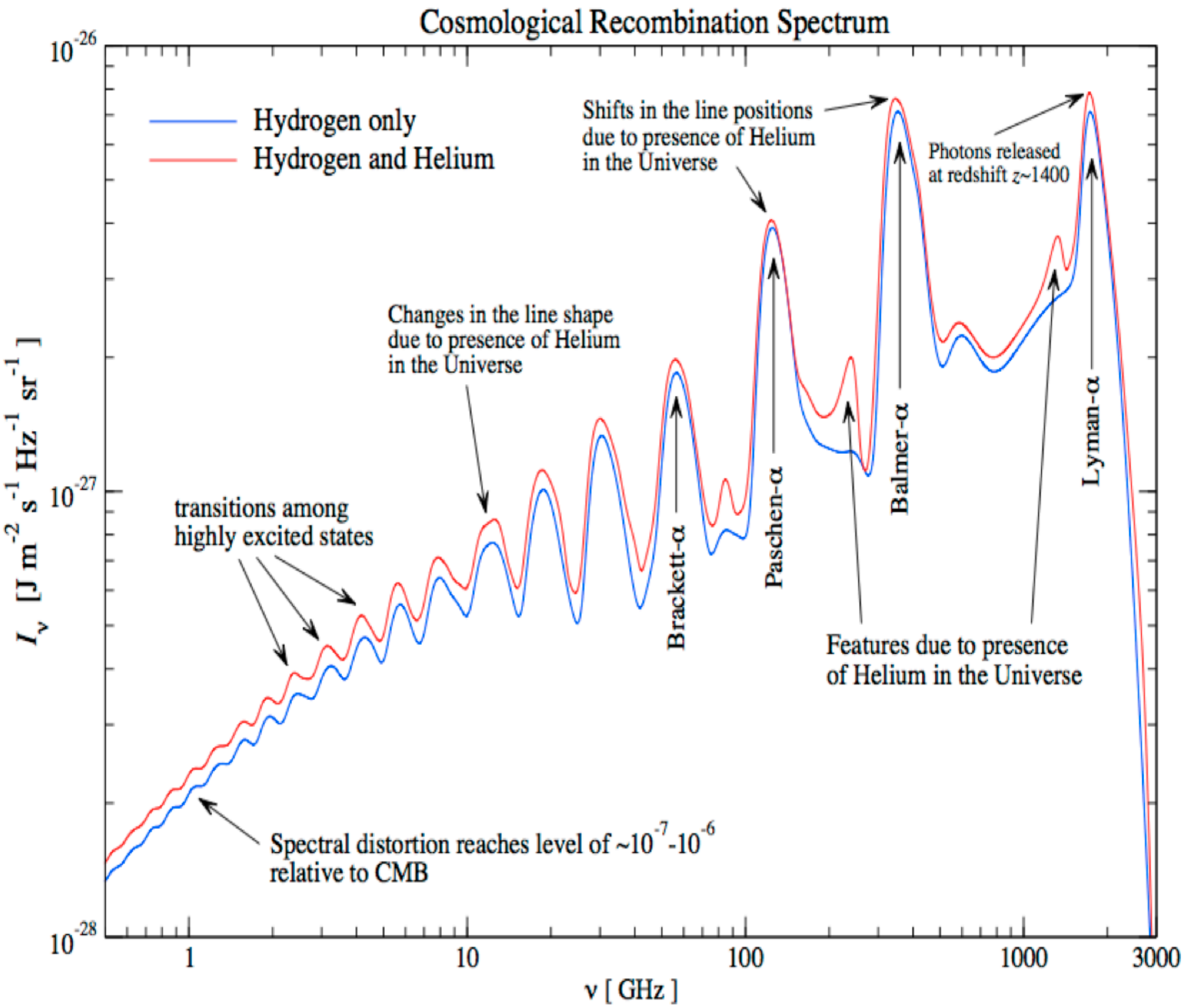
Combine to get n and T_e

- T_e probes ionizing spectrum
- Distinguish Pop III, Pop II, AGN

Determine nature of first luminous objects



Spectral Distortions: Recombination



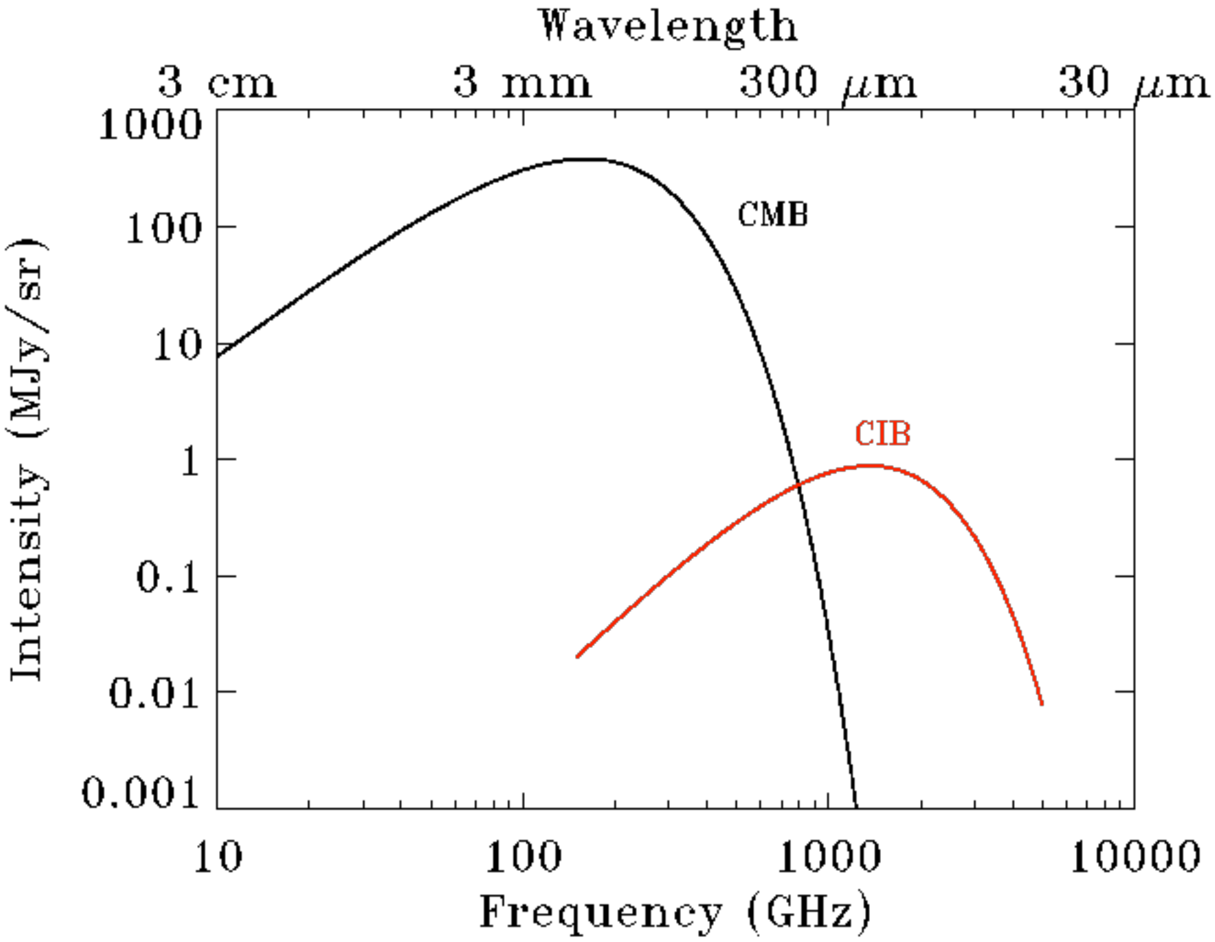
Line emission at recombination yields complex spectral features

- Physics at recombination
- Primordial He abundance

Baseline PIXIE mission: 2σ detection of modified spectrum

Sunyaev & Khatri 2013

Cosmic Infrared Background



Thermal Dust Emission from z ~ 1--3

- Monopole: Galaxy Evolution
- Dipole: Bulk Motion
- Anisotropy: Matter power spectrum

Frequency coverage over CIB peak

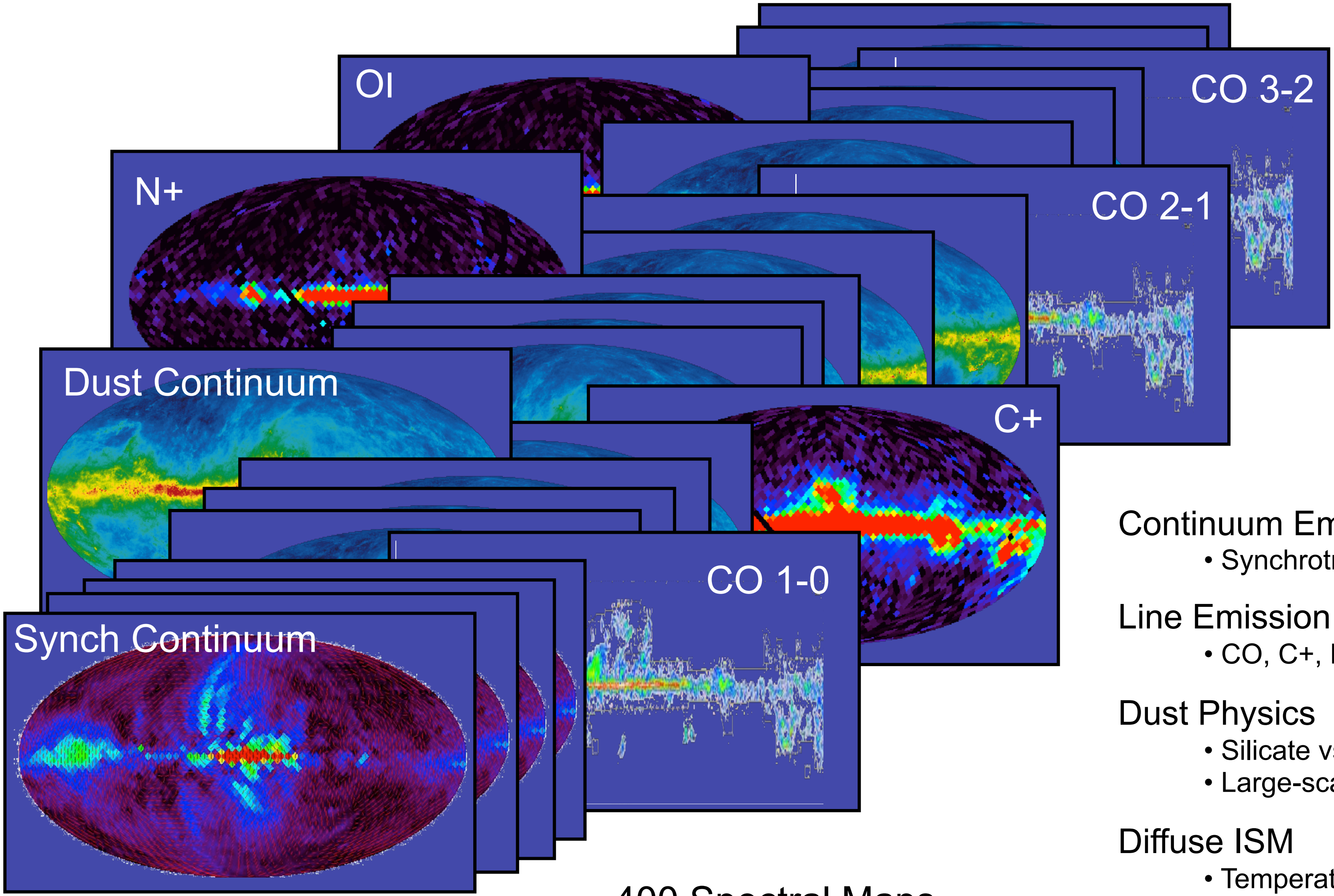
- Complement Herschel, Planck

PIXIE noise is down here!

Measure the frequency spectrum,
the power spectrum,
and the
frequency spectrum of the power spectrum

Knox et al. 2001
Fixsen & Kashlinsky 2011

Spectral Line Emission



Continuum Emission
- Synchrotron, Dust

Line Emission
- CO, C+, N+, O, …

Dust Physics
- Silicate vs carbonaceous dust
- Large-scale magnetic field

Diffuse ISM
- Temperature, Density
- Energy Balance
- Metalicity

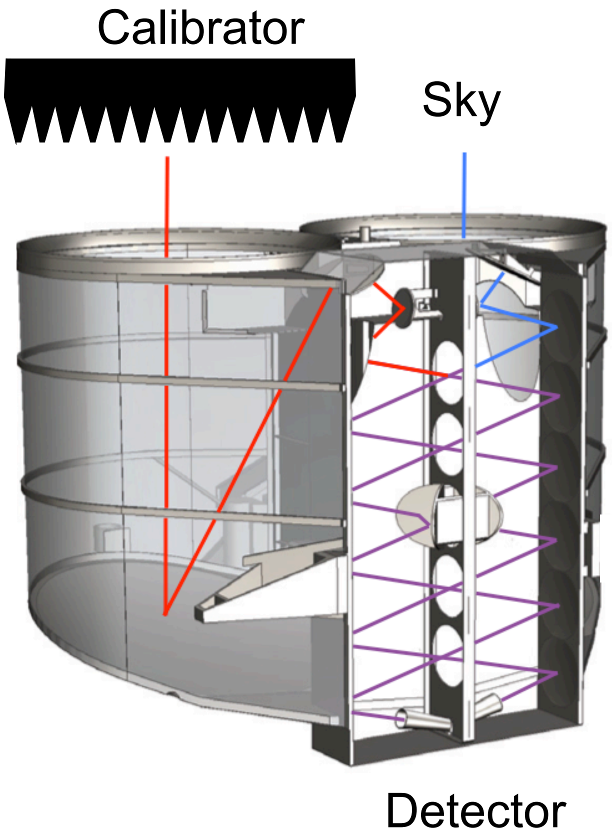
400 Spectral Maps
Stokes I, Q, U
$\Delta\nu$ = 15 GHz

Extremely Rich Data Set!

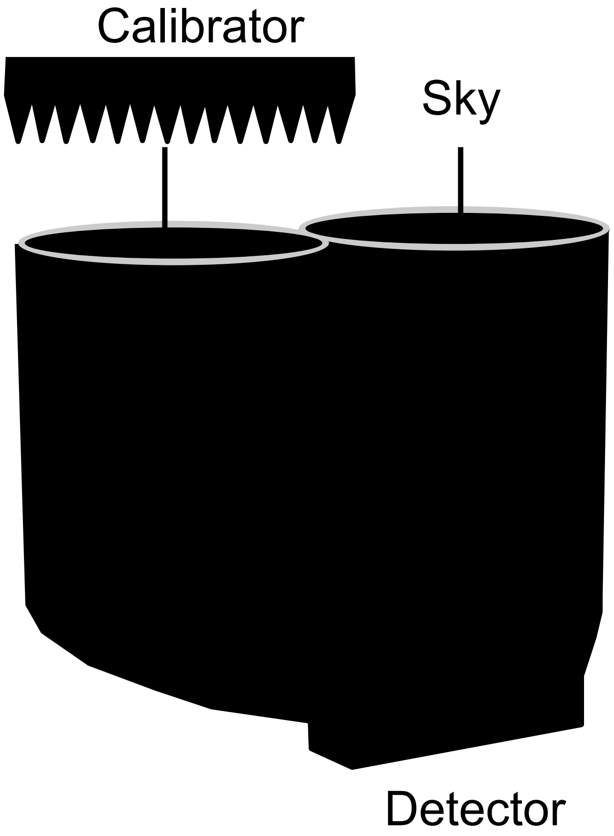
Systematic Errors:
What You Don't Know Can Hurt You

Can we ***really***
control systematics
at the nK level?

A Thought Experiment



A Thought Experiment

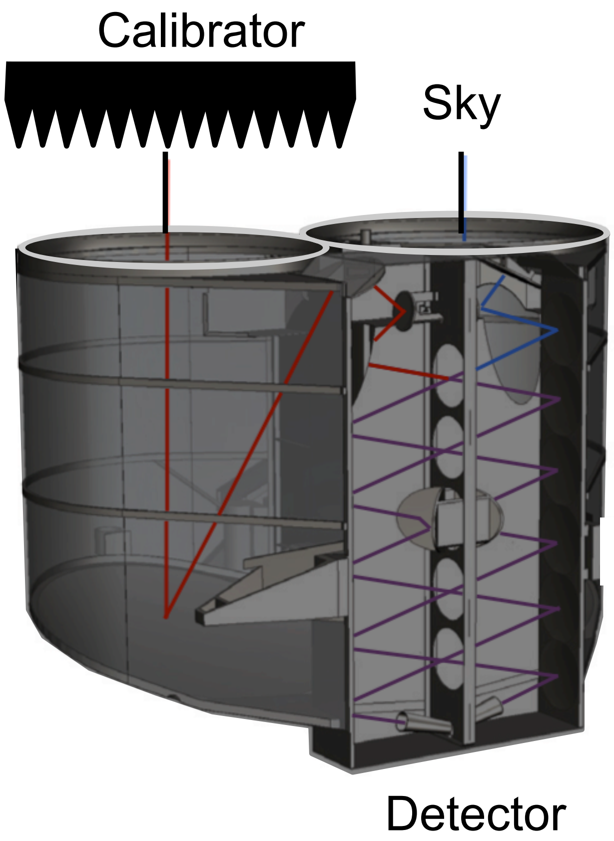


Thermal Physics:
Blackbody spectrum depends on temperature,
and ***only*** on temperature!

If the sky, calibrator, and instrument
are all maintained at the same temperature,
then the system can not generate fringes

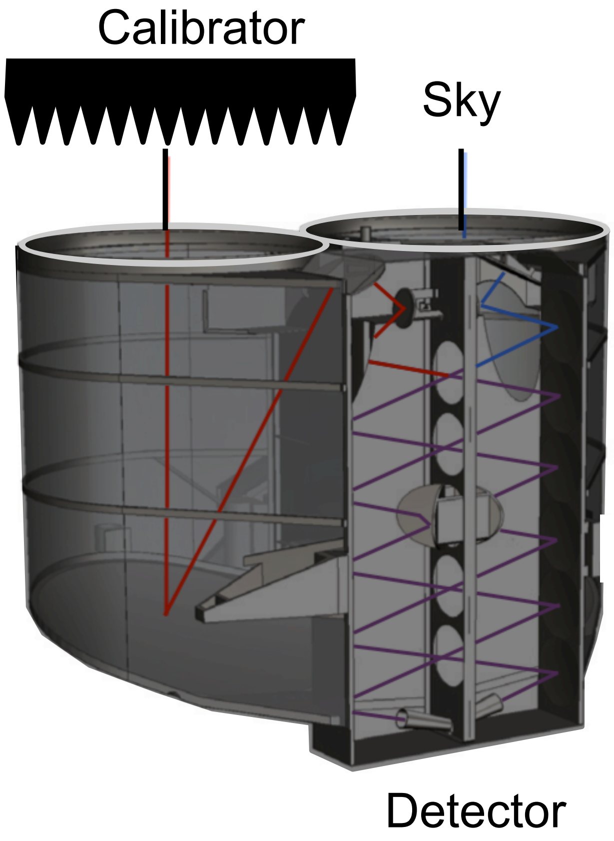
Expand Signal To First Order About Ideal Case

A Thought Experiment



Maximum ΔT few mK

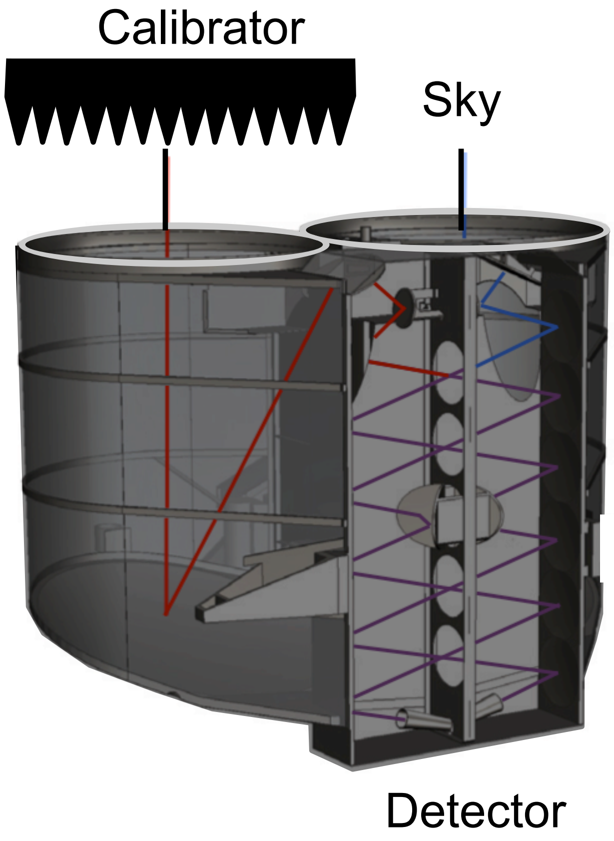
A Thought Experiment



Maximum ΔT few mK

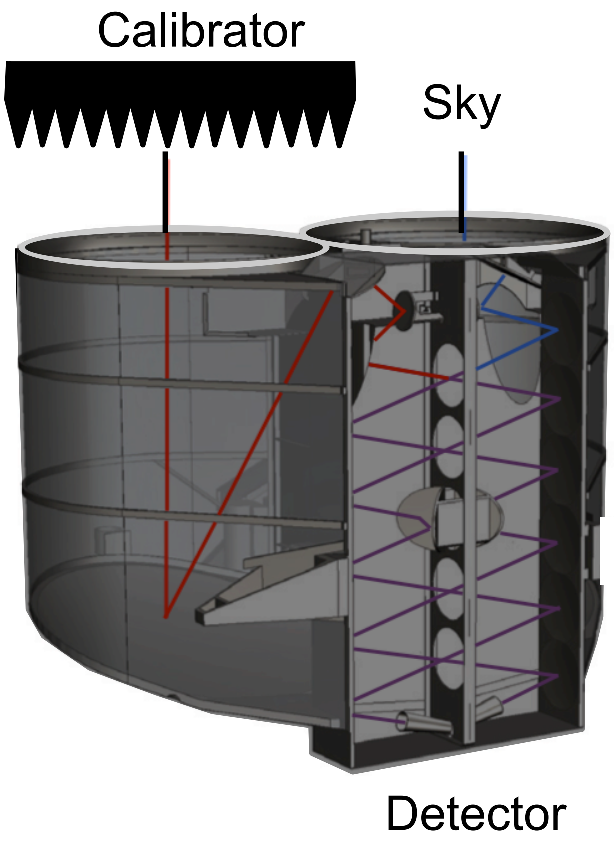
Mirror Emissivity x 0.01 → tens of uK

A Thought Experiment



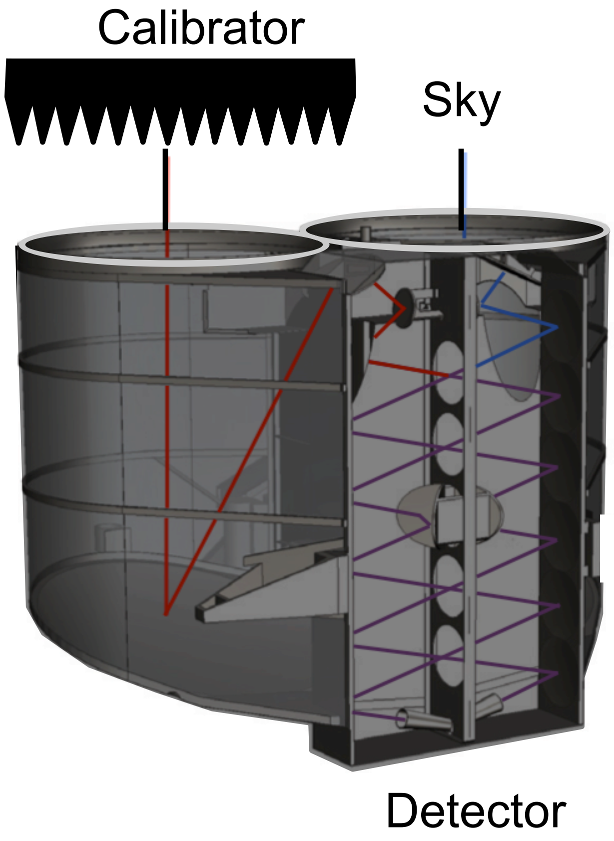
Maximum ΔT	few mK		
Mirror Emissivity		x 0.01 ⇨	tens of uK
Left/Right Asymmetry		x 0.01 ⇨	few hundred nK

A Thought Experiment



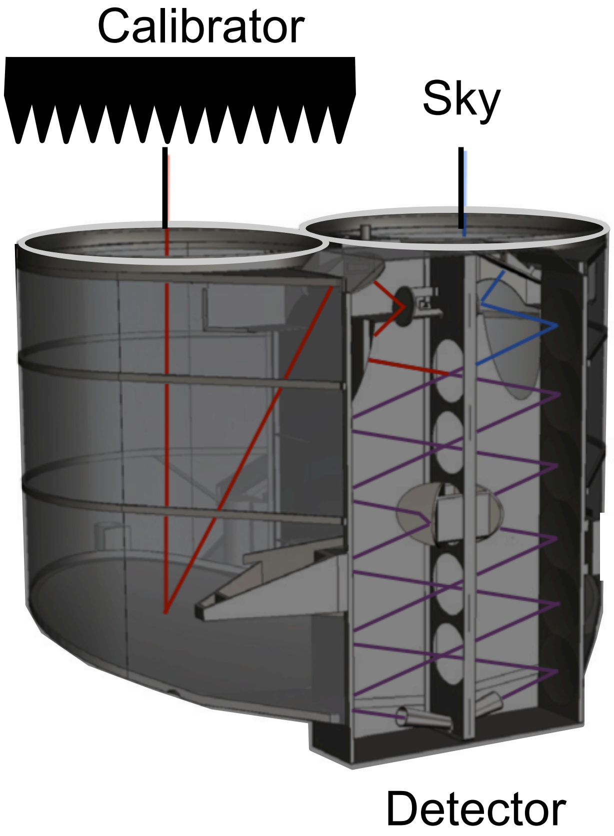
Maximum ΔT	few mK		
Mirror Emissivity	x 0.01	→	tens of uK
Left/Right Asymmetry	x 0.01	→	few hundred nK
Swap hot vs cold	x 0.01	→	few nK

A Thought Experiment



Maximum ΔT	few mK		
Mirror Emissivity	x 0.01	→	tens of uK
Left/Right Asymmetry	x 0.01	→	few hundred nK
Swap hot vs cold	x 0.01	→	few nK
Uncorrected Error	few nK (with blue-ish tinge)		
Corrected Error	<< 1 nK		

An Imperfect Instrument



The temperature will not match the CMB ***precisely***
but good enough to limit the signals to a few mK

The instrument will not be ***perfect***
but good enough to reduce the emission to tens of uK

The symmetry will not be ***exact***
but good enough to reduce the imbalance to ~few 100 nK

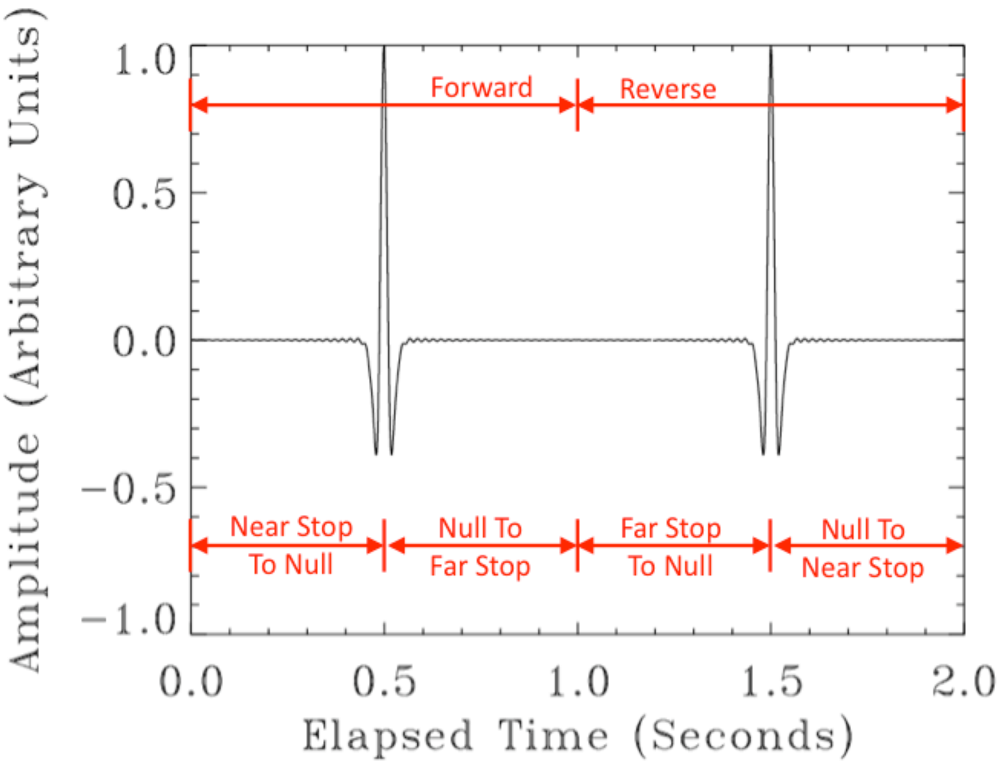
The operational balance will not be ***ideal***
but good enough to reduce the bias to a few nK

The correction is limited by the ***total data set*** so it
will be able to reduce the residual to <1 nK

Residual errors at sub-nK level after accounting for real-world imperfections

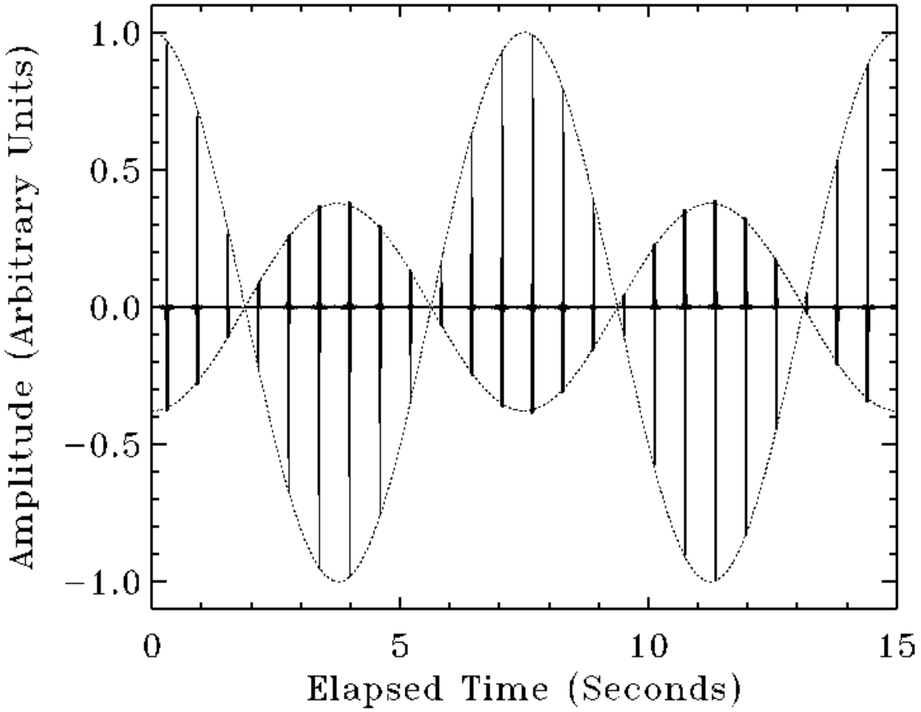
Systematic Error Control

Multiple Instrumental Symmetries



Spacecraft spin imposes amplitude modulation of entire fringe pattern

Same information 4x per stroke with different time/space symmetries



Multiple Redundant Symmetries Allow Clean Instrument Signature

Symmetry and Systematic Error

20 Ways to Fix An Error

Symmetry	Mitigates
x vs y Polarization	Pointing
Left vs Right Detector	Particle Hits
A vs B Beam	Differential loss
Real vs Imaginary FFT	Detector heat capacity
Forward vs Backward FTS	Microphonics
Calibrator over A vs B beam	Calibration, Beam
Calibrator Hot vs Cold	Non-Linearities
Ascending vs Descending	Far sidelobes, calibration
Spin m=2	Electronics
Spin m=1, 3 to 12	Beam asymmetries

$$P_{Lx} = \frac{1}{2}\int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx}^2 - E_{Ay}^2\right)\cos(z\omega/c)\, d\omega$$

$$P_{Ly} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{By}^2 - E_{Ax}^2\right)\cos(z\omega/c)\, d\omega$$

$$P_{Rx} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{Ax}^2 - E_{By}^2\right)\cos(z\omega/c)\, d\omega$$

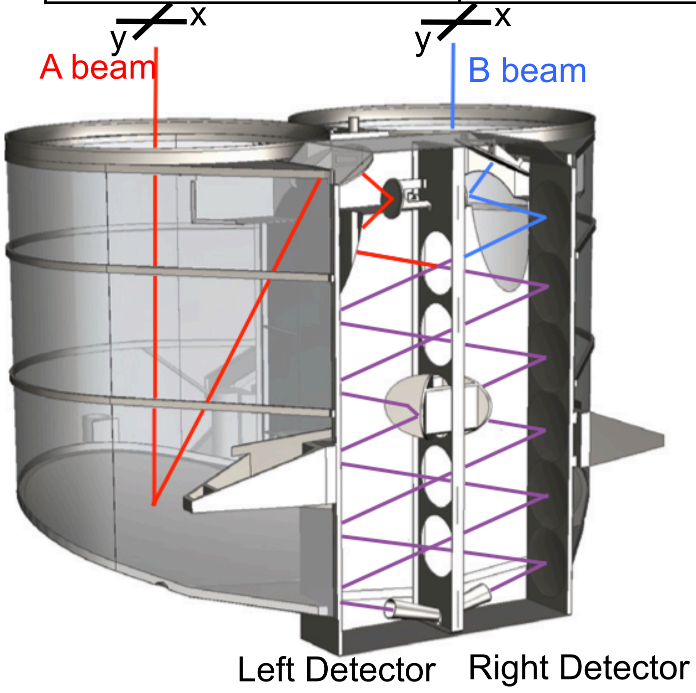
$$P_{Ry} = \frac{1}{2}\int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Ay}^2 - E_{Bx}^2\right)\cos(z\omega/c)\, d\omega$$

Add : Sky cancels, leaving systematics

Subtract : Instrument cancels, leaving sky

No assumptions about sky or instrument

Identify & model systematics at **first** order in sum $\alpha \pm \delta\alpha$
Residuals only appear at **second** order in difference $\delta\alpha^2$



Effect	Leakage	PIXIE Mitigation						Residual
		FTS	Spin	Orbit	XCal	Symmetry	Preflight	(nK)
Cross-polar beam	$E \to B$		√			√	√	*1.5*
Beam ellipticity	$\nabla^2 T \to TB$		√	√		√	√	*2.7*
Polarized sidelobes	$\Delta T \to B$		√	√		√	√	*1.1*
Instrumental polarization	$\Delta T \to B$		√	√	√	√	√	*<0.1*
Polarization angle	$E \to B$			√		√	√	*0.7*
Beam offset	$\Delta T \to B$		√	√	√	√	√	*0.7*
Relative gain	$\Delta T \to B$	√			√	√		*<0.1*
Gain drift	$T \to B$	√			√	√		*<0.1*
Spin-synchronous emission	$\Delta T \to B$	√	√		√	√	√	*<0.1*
Spin-synchronous drift	$T \to B$	√			√	√	√	*<0.1*

A Non-Cosmological Problem

Will a future Congress fund a $1B Inflation Probe?

Low-cost alternative within existing NASA budget line

NASA Explorer Program

Small PI-led missions
- 22 full missions proposed Feb 2011
- $200M Cost Cap + launch vehicle

PIXIE not selected; urged to re-propose
- Category I Science rating
- Broad recognition of science appeal

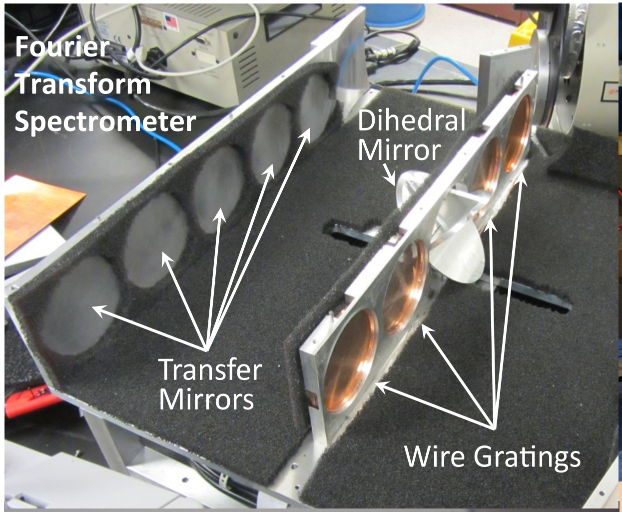
Re-propose to next MIDEX AO (2017)
- Technology is mature
- Launch early next decade

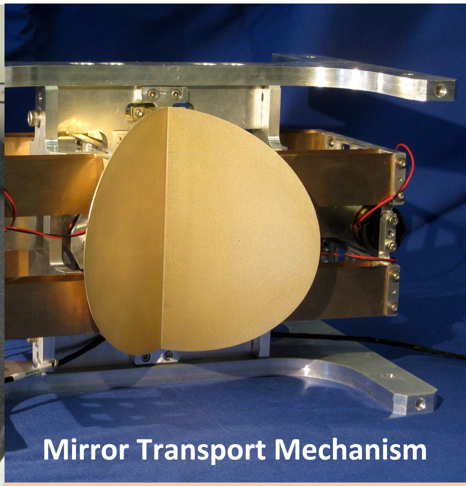
PRIMORDIAL INFLATION EXPLORER

PIXIE

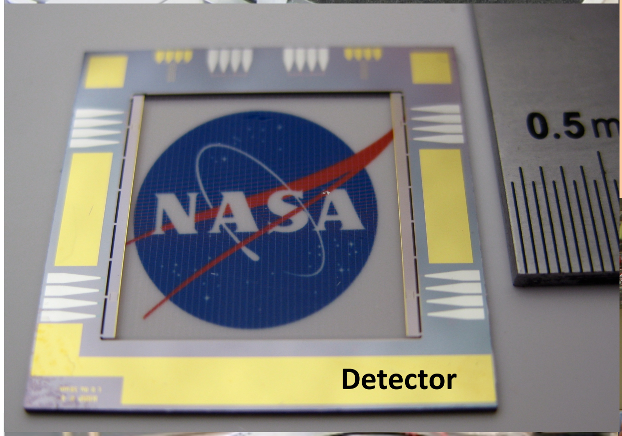
NASA • GSFC • BATC

> "PIXIE's spectral measurements alone justify the program"
>
> -- NASA review panel

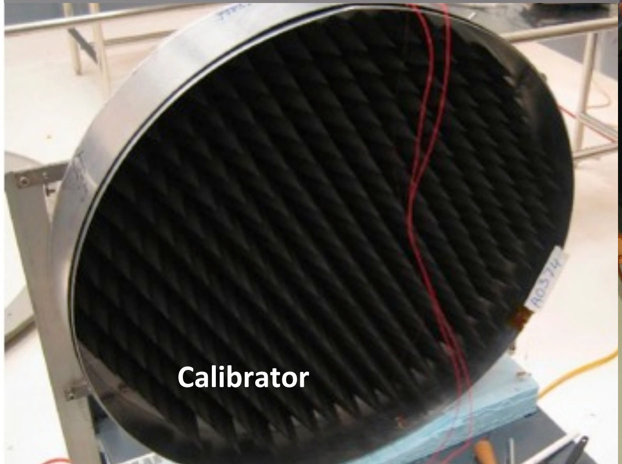


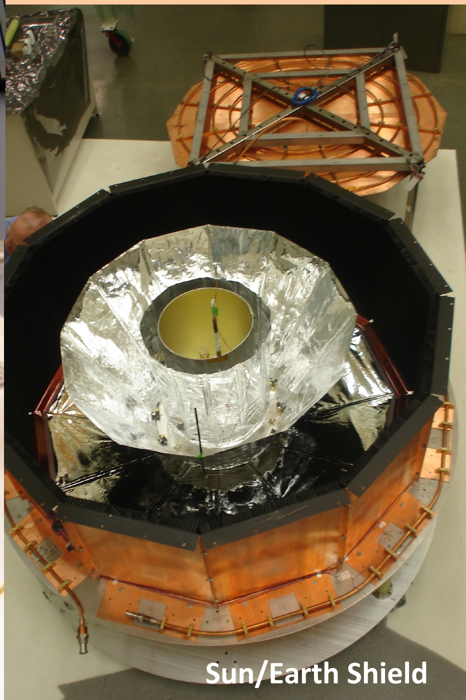

Mirror Transport Mechanism

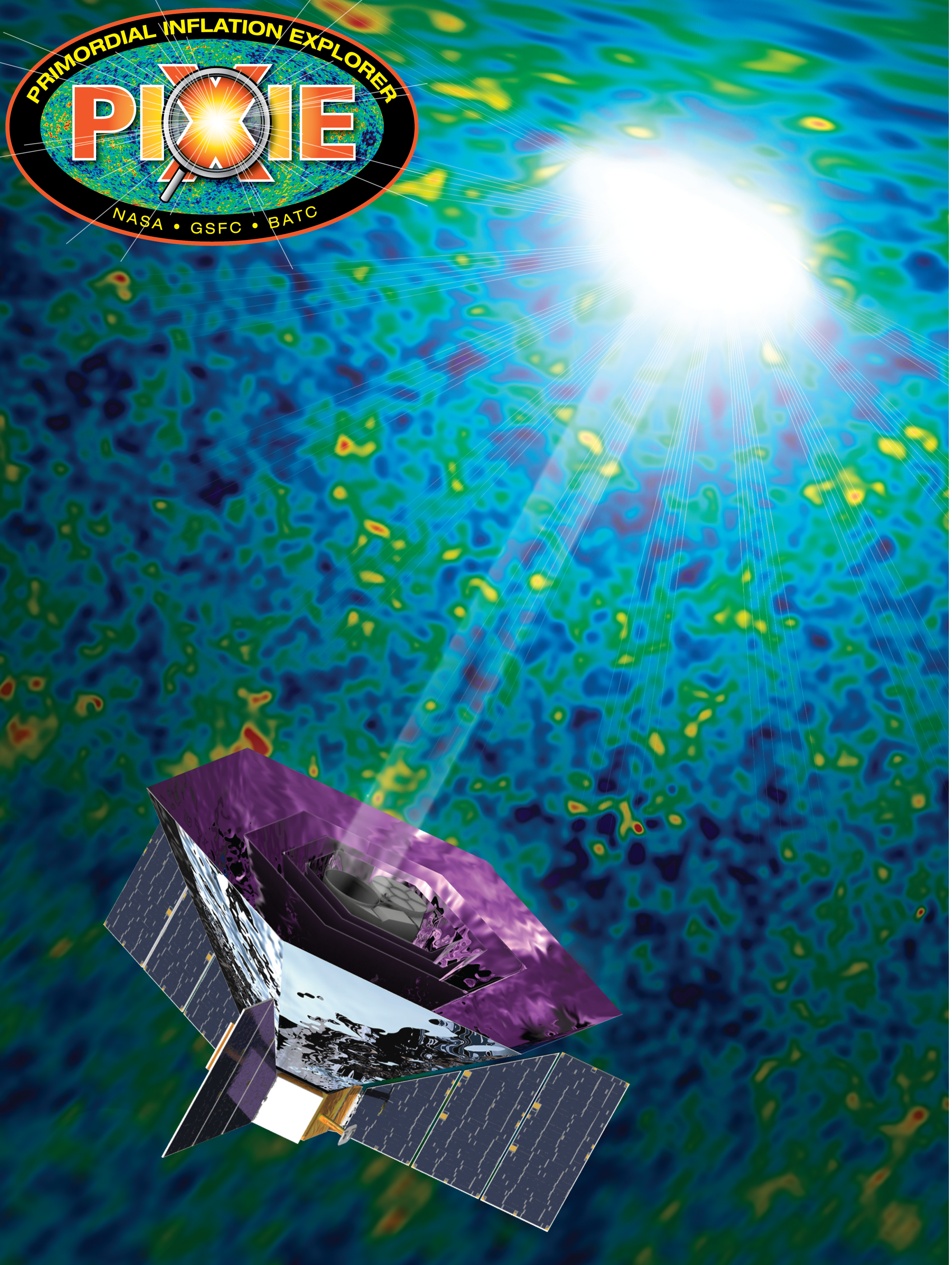
Mature technology



Detector


Calibrator


Sun/Earth Shield



Some Questions ...

- Optimum channel width?

  Noise penalty ~ $(\Delta v)^{-1/2}$
  On-orbit ops can only increase Δv

- Optimum noise floor?

  Improve sensitivity at cost of complexity
  More detectors, greater etendu, ...

- Optimum angular resolution?

  Fixed etendu, so Ω ~ 1 / Area
  Foreground structure within beam

- Additional science?

  Reionization / early universe
  Spectral/spatial maps of CIB
  Intensity mapping of far-IR lines
  ISM / dust physics