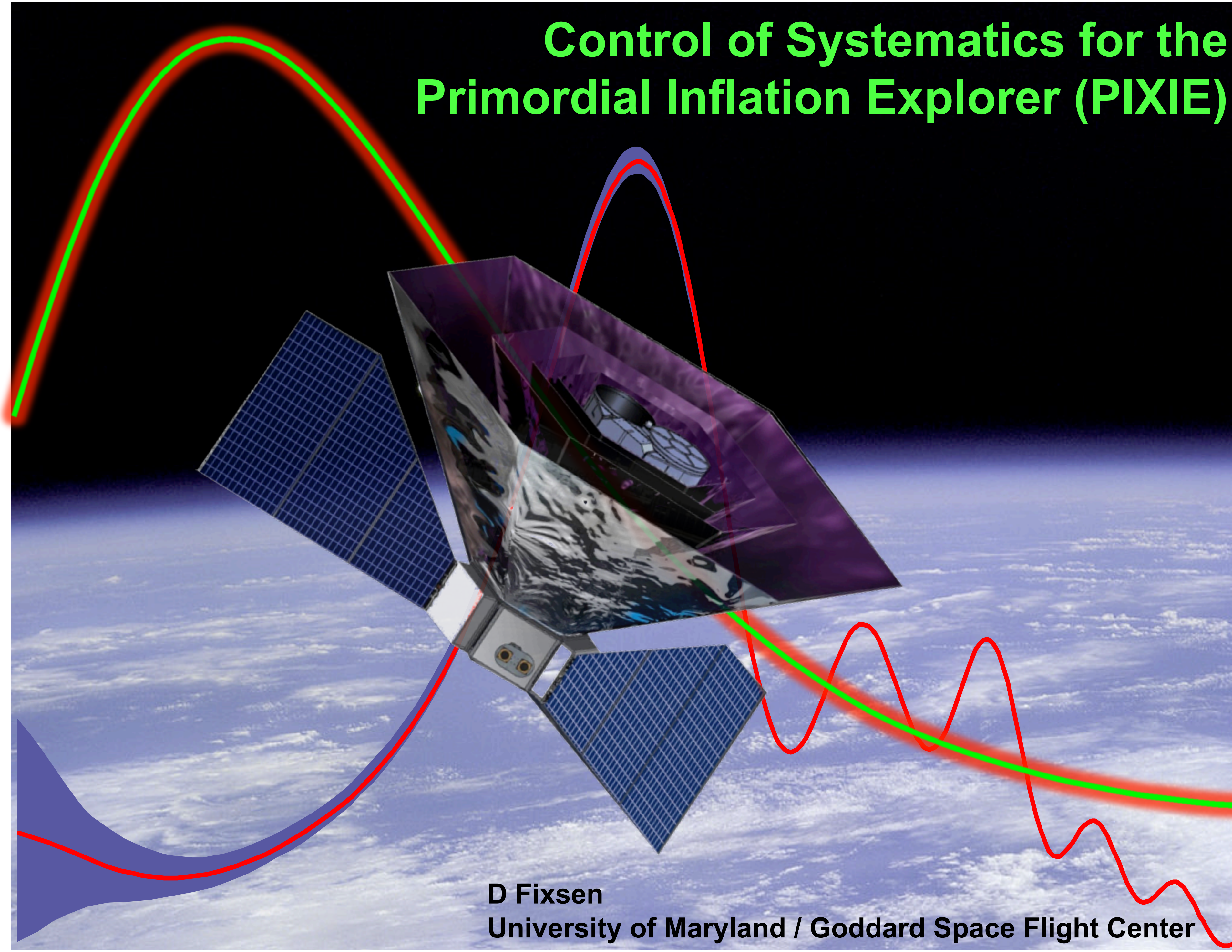
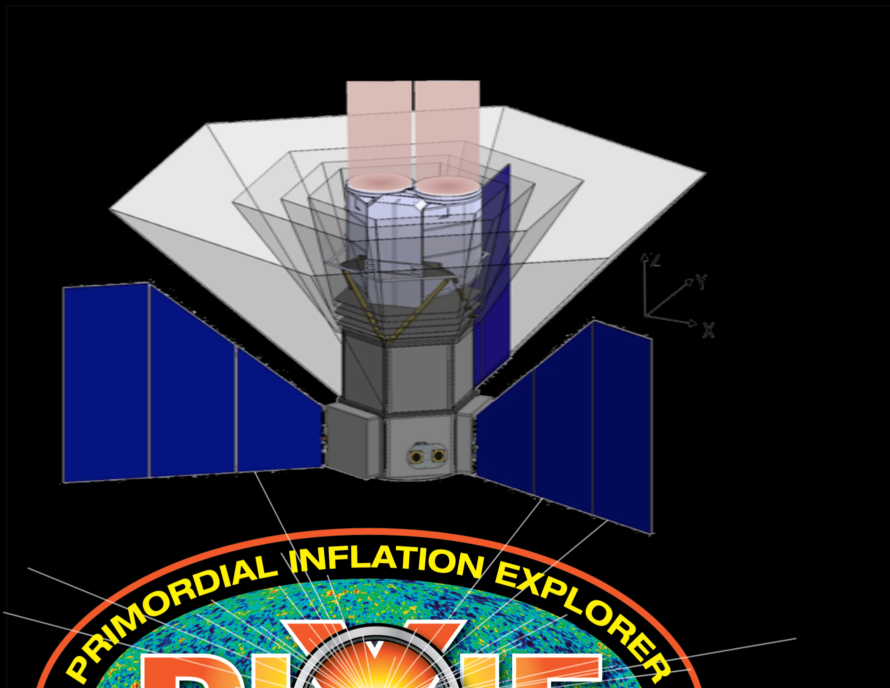
Control of Systematics for the Primordial Inflation Explorer (PIXIE)



D Fixsen
University of Maryland / Goddard Space Flight Center

Primordial Inflation Explorer



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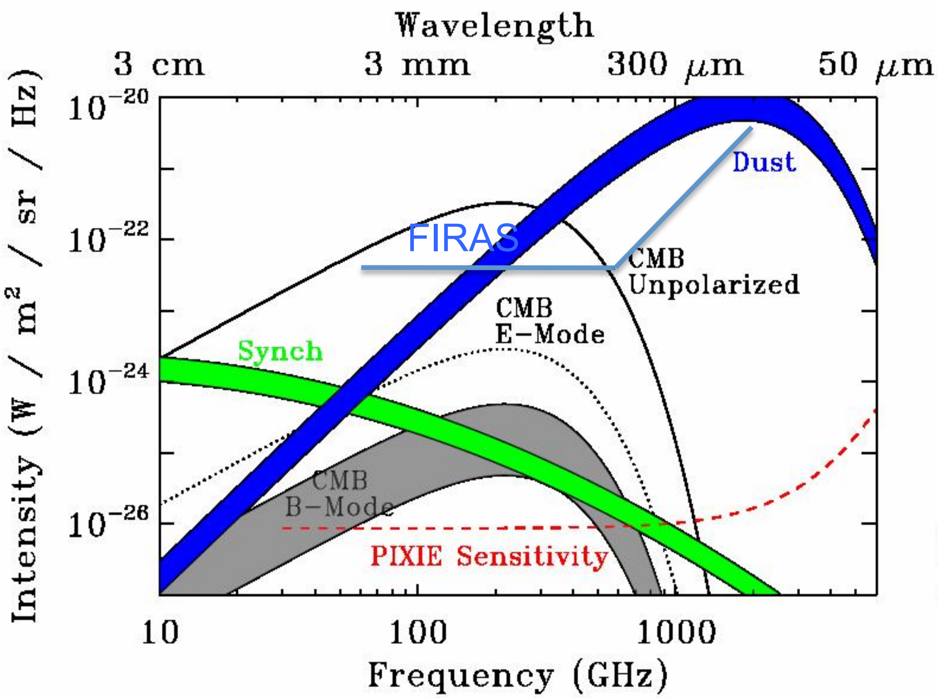
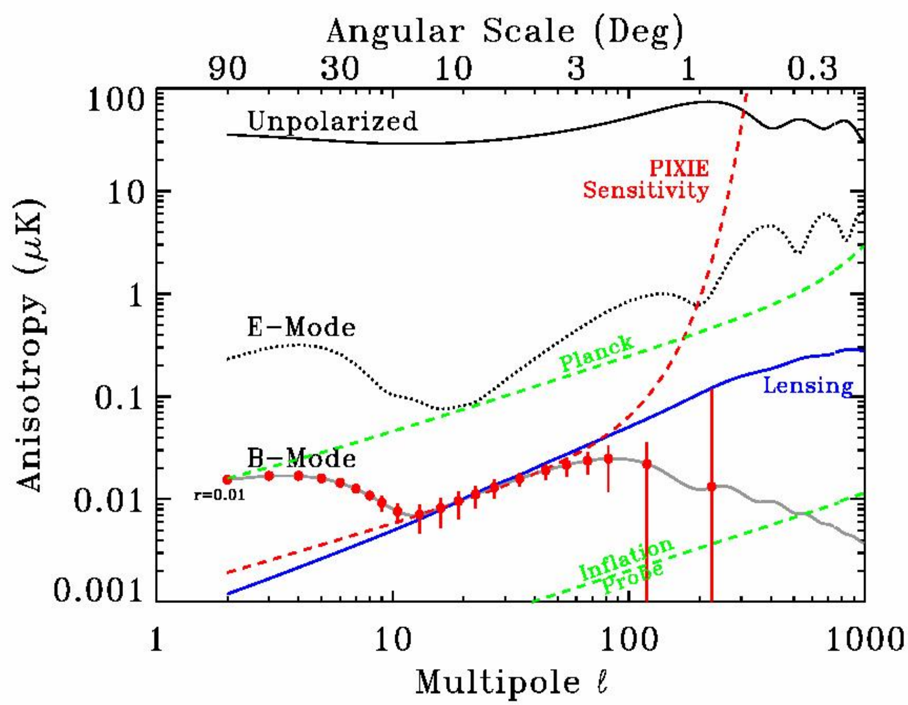
Measure B-Mode Polarization
To Limits Imposed By Astrophysical and Cosmological Foregrounds

PIXIE B-Mode Science



Full-Sky Spectro-Polarimetric Survey

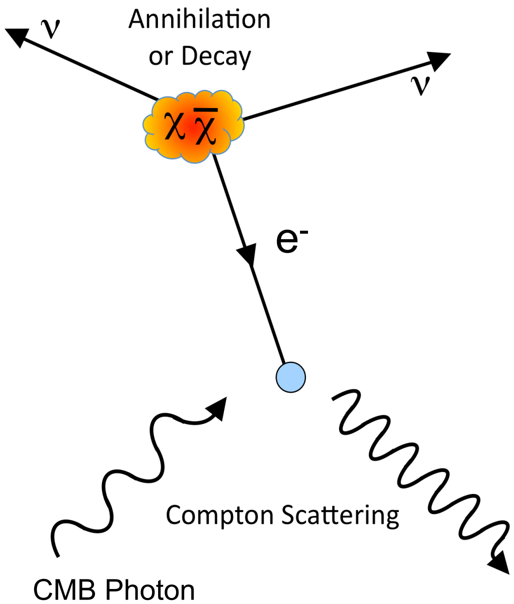
- 400 frequency channels, 30 GHz to 6 THz
- Stokes I, Q, U parameters
- 49152 sky pixels each 0.9° × 0.9°
- Pixel sensitivity 6 x 10^{-26} W m^{-2} s^{-1} sr^{-1}
- CMB sensitivity 70 nk RMS per pixel



- Detect ~all large-field models
- Power spectrum to l~200
- Reach limit of lensing foreground

Measure r < 0.001 at 5σ (after foreground subtraction)

Spectral Distortion from Energy Release



Optically thin case: Compton y distortion

$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp(x)-1}\left[1+\frac{y\,x\,\exp(x)}{\exp(x)-1}\left(\frac{x}{\tanh(x/2)}-4\right)\right]$$

$$y = \int \frac{kT_e}{mc^2}\, nc\sigma_T\, dt$$

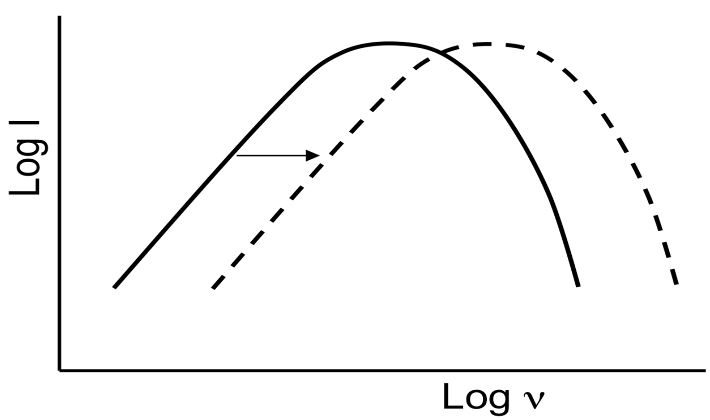
FIRAS limit $1.5\text{x}10^{-5}$

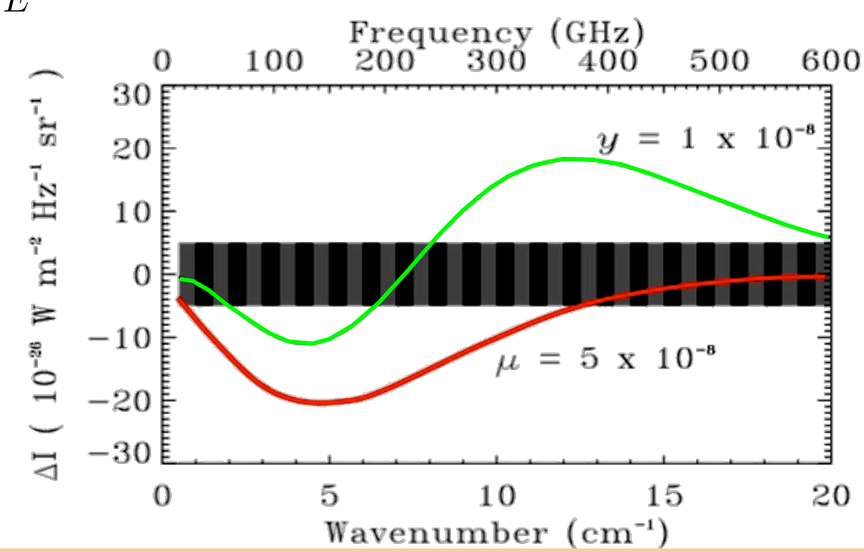
Optically thick case: Chemical potential distortion

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

$$\mu = 1.4\,\frac{\Delta E}{E}$$

FIRAS limit 9 $\text{x}10^{-5}$

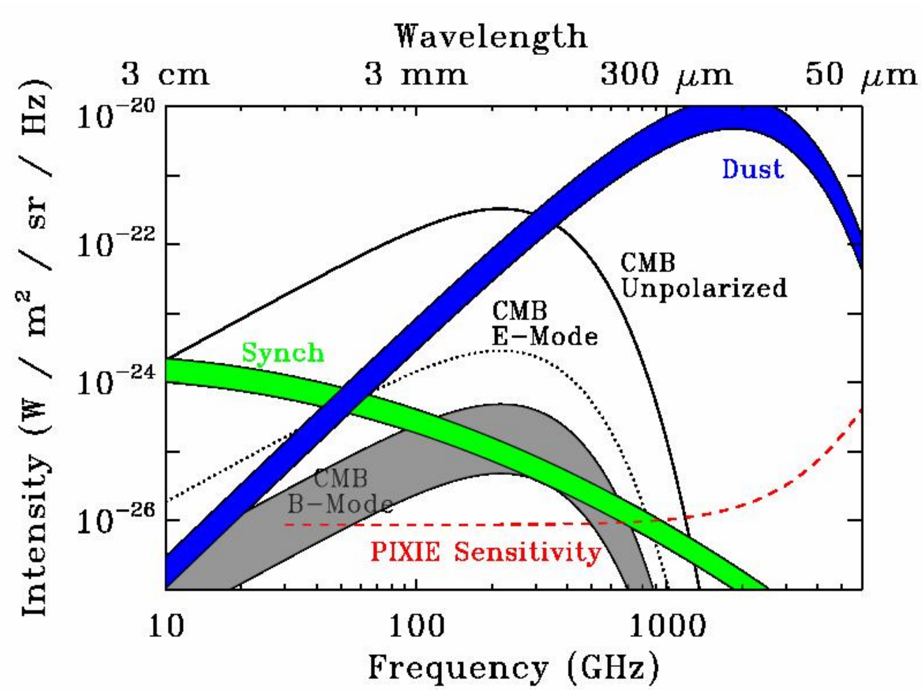




Distortion to blackbody spectrum proportional to integrated energy release

Foreground Science: Interstellar Dust

Science from high-frequency channels informs low-frequency fitting

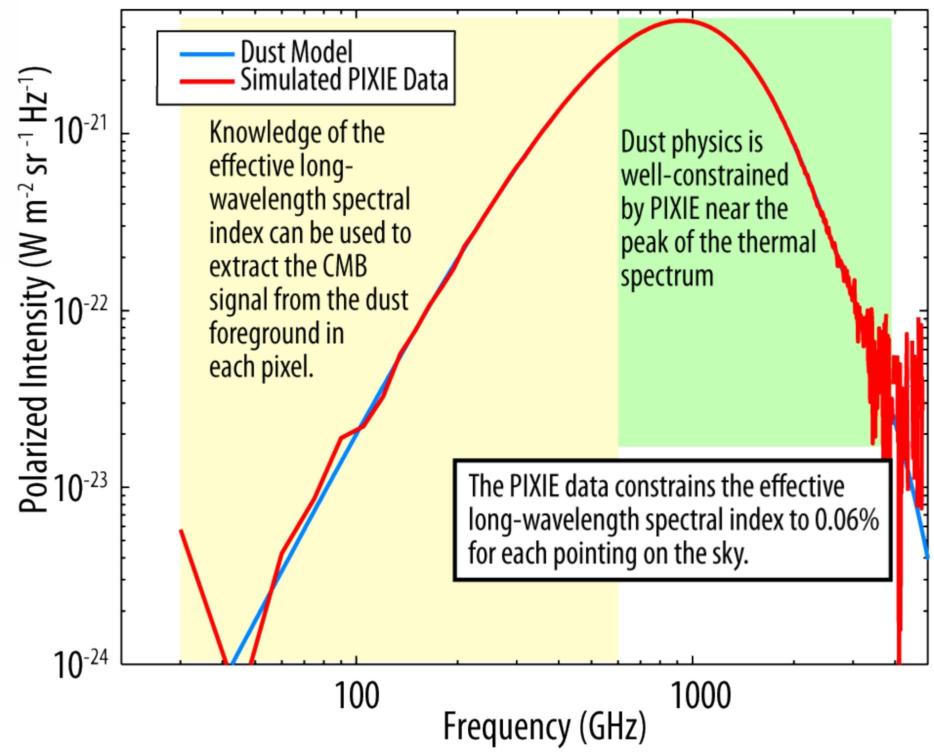


Pixel-by-pixel dust characterization

400 channels to fit models of far-IR dust emission

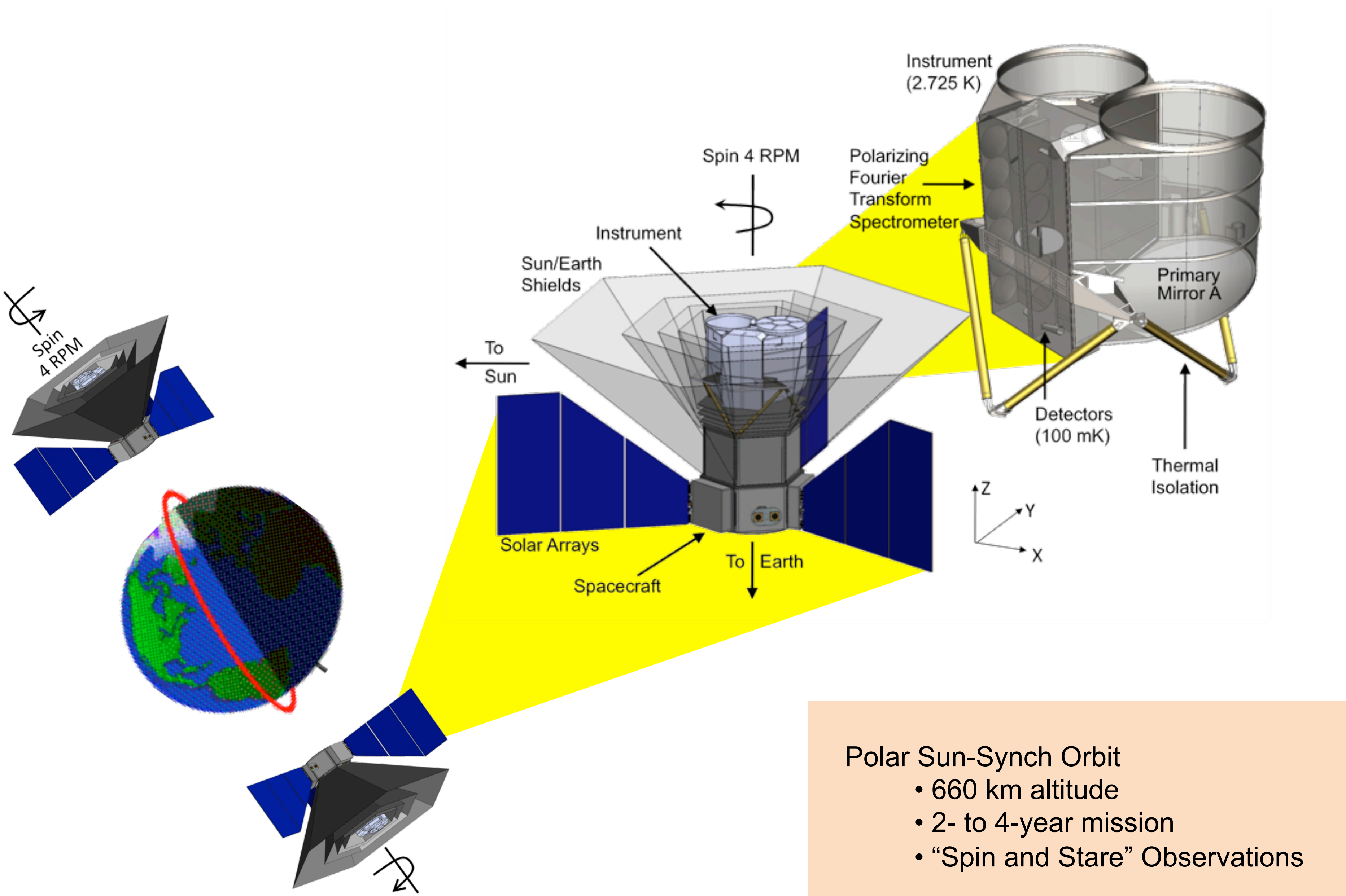
Spectral index uncertainty ±0.001 in each pixel

Dust physics for foreground subtraction



One person's foreground
is another person's science

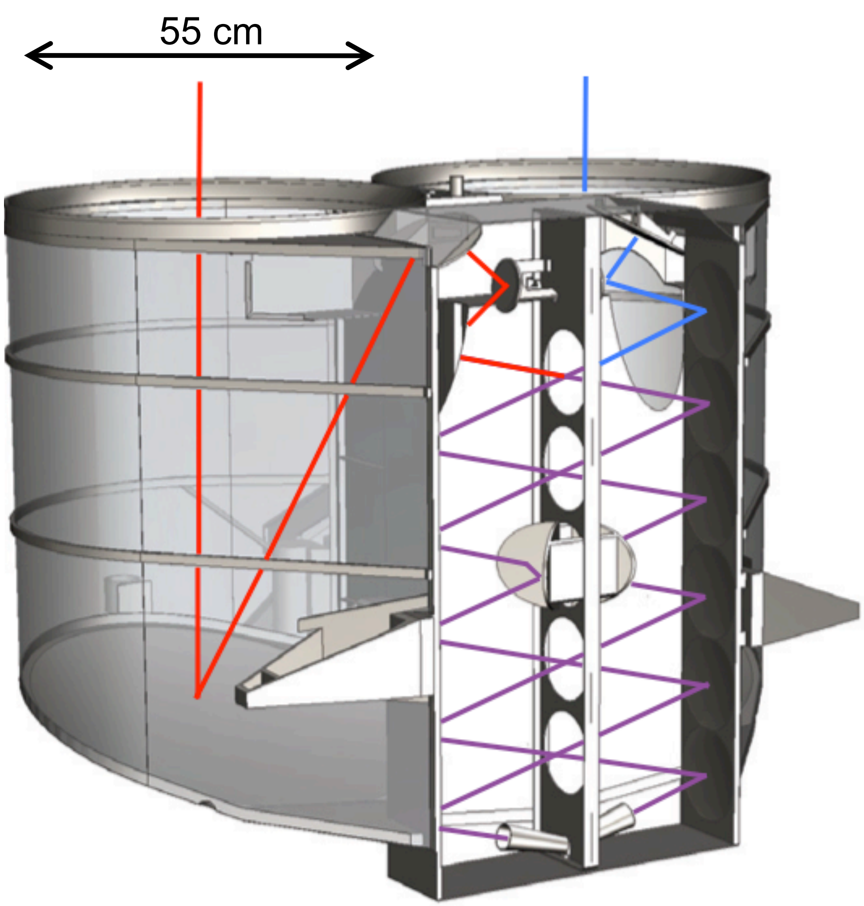
Instrument and Observatory



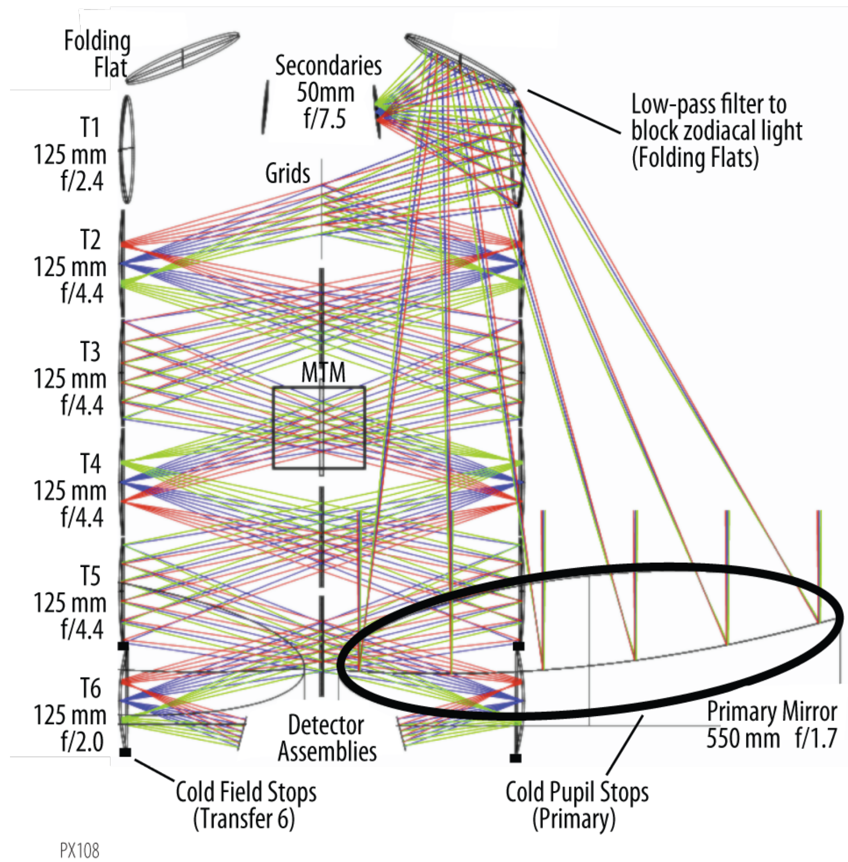
Polar Sun-Synch Orbit

- 660 km altitude
- 2- to 4-year mission
- “Spin and Stare” Observations

PIXIE Non-Imaging Optics

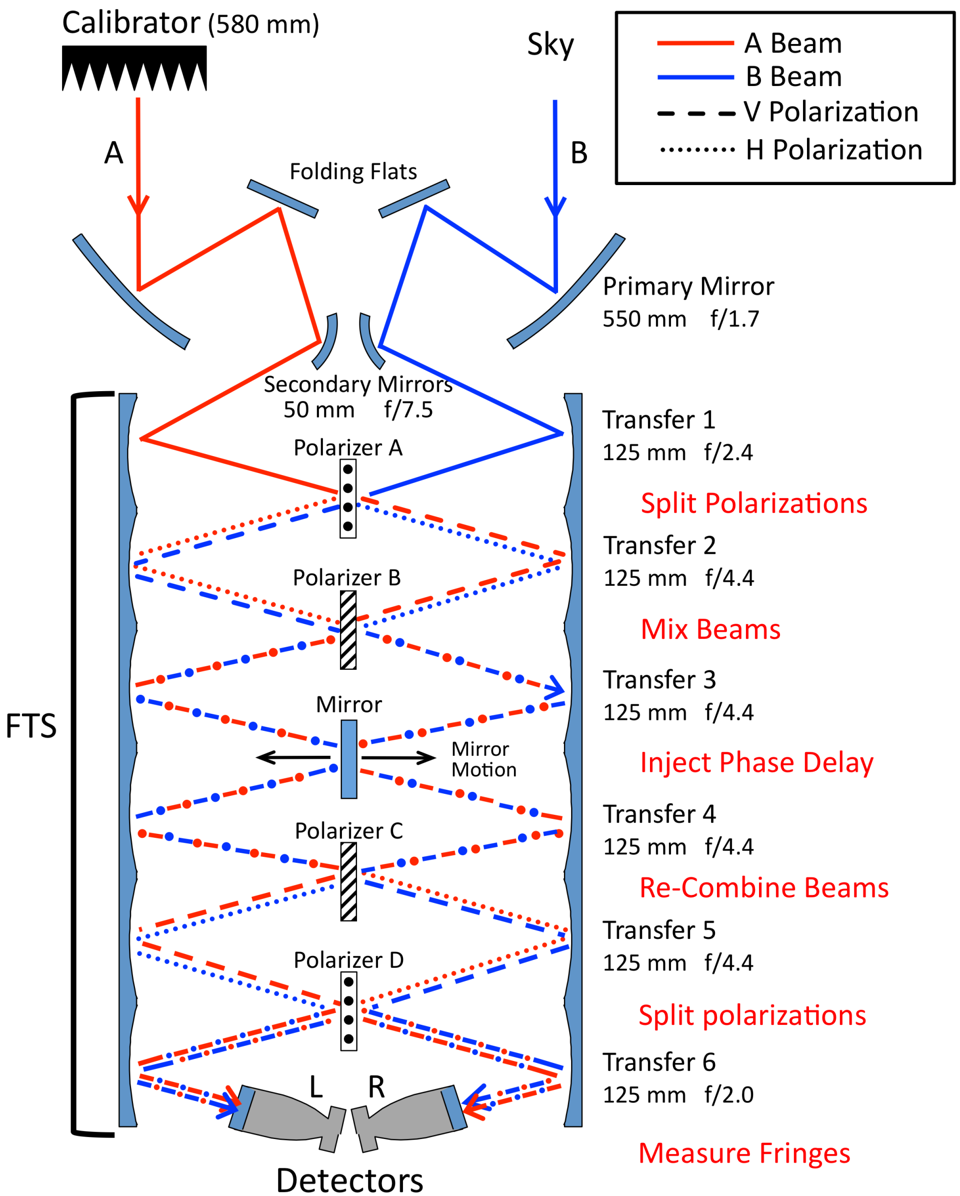


Parameter	Value
Primary Mirror Diam	550 mm
Etendu	4 cm^2 sr
Beam Diam	2.6° Tophat 1.6° Gaussian approx
Efficiency	82%



44,000 modes
on 4 detectors

PIXIE Nulling Polarimeter



AC Readout

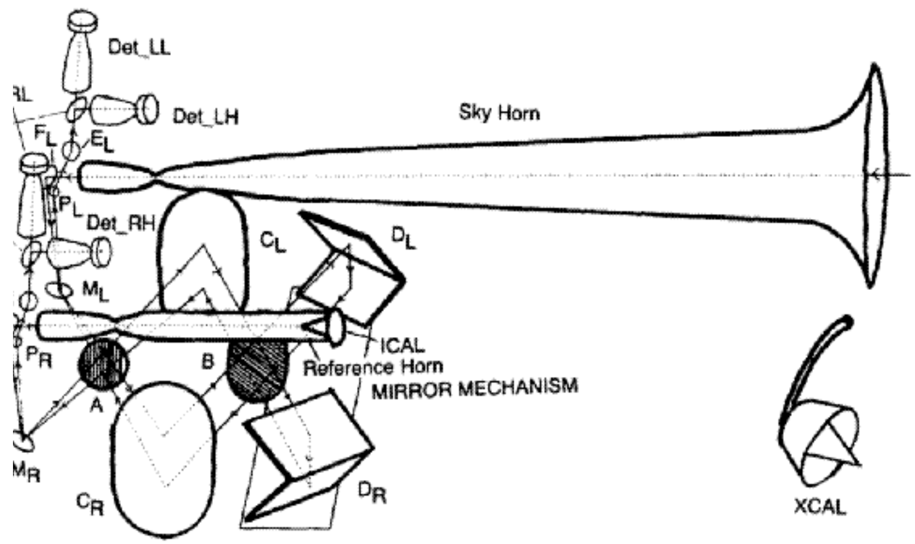
Nulling Polarimeter: Zero = Zero

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

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

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

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



Fourier Transform

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

$$P_{Lx}(\omega) = g_{Lx}(\omega)\left(S_{Bx}(\nu) - S_{Ay}(\nu)\right), \qquad \omega = \nu * u/c$$

$$P_{Ly}(\omega) = g_{Ly}(\omega)\left(S_{By}(\nu) - S_{Ax}(\nu)\right)$$

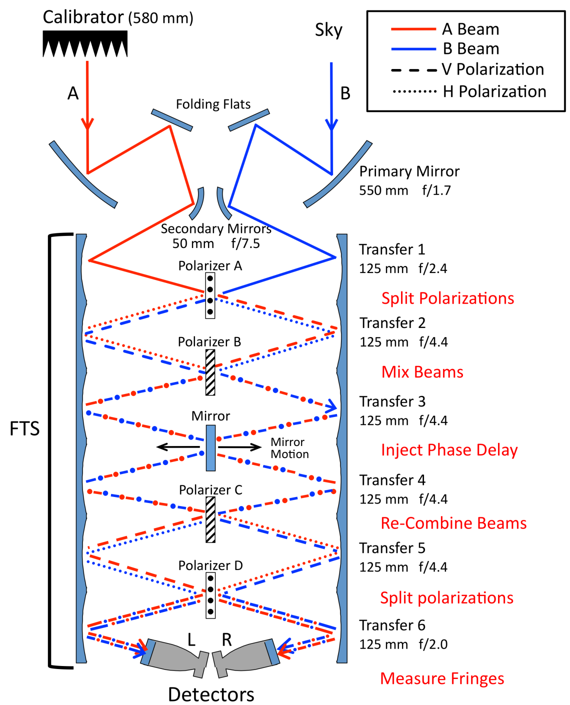
$$P_{Rx}(\omega) = g_{Rx}(\omega)\left(S_{Ax}(\nu) - S_{By}(\nu)\right)$$

$$P_{Ry}(\omega) = g_{Ry}(\omega)\left(S_{Ay}(\nu) - S_{Bx}(\nu)\right)$$

Resolution set by maximum excursion,

highest frequency set by sample spacing

Systematics: Mirrors



Signal = few mK (the mirror is 2.725+/-.005 K)

x ~.01 (Mirror emissivity)

x ~.01 (Left / Right asymmetry)

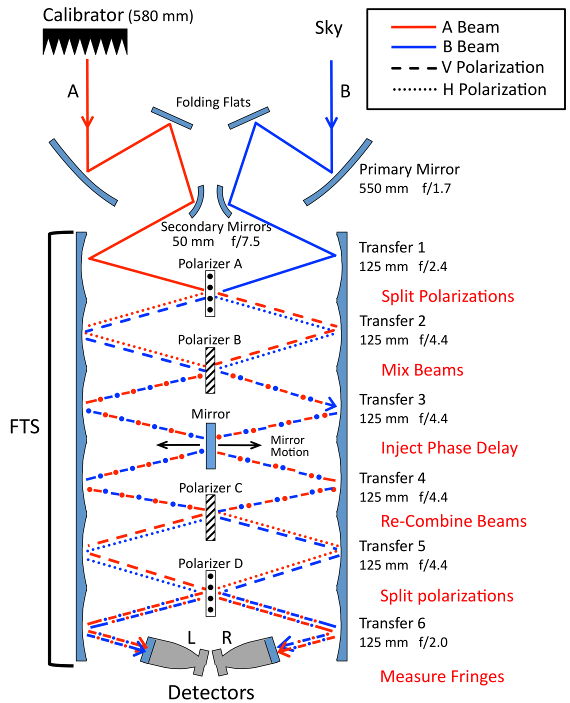
x ~.01 (Move Calibrator, switch sign)

= few nK bluish tinge, ***before correction***

Calibration allows measurement and correction of mirror emission during observations, **with full observational data set**. Allows data selection/weighting to match precisely. Errors <1 nK after correction.

Identical arguments for flats, secondary, T1, T2 and T3.
T4, T5 and T6 are not modulated and so produce no signal.

Systematics: Instrument



Signal = few mK (the Instrument is ~2.725)

x ~.01 (Beam fraction missing mirrors)

x ~.01 (Left / Right asymmetry)

x ~.01 (Other mirror has opposite sign)

= few nK reddish tinge, ***before correction***

Calibration allows measurement and correction of instrument emission during observations, **with full observational data**. Also allows data selection/weighting to match precisely. Errors <1 nK after correction.

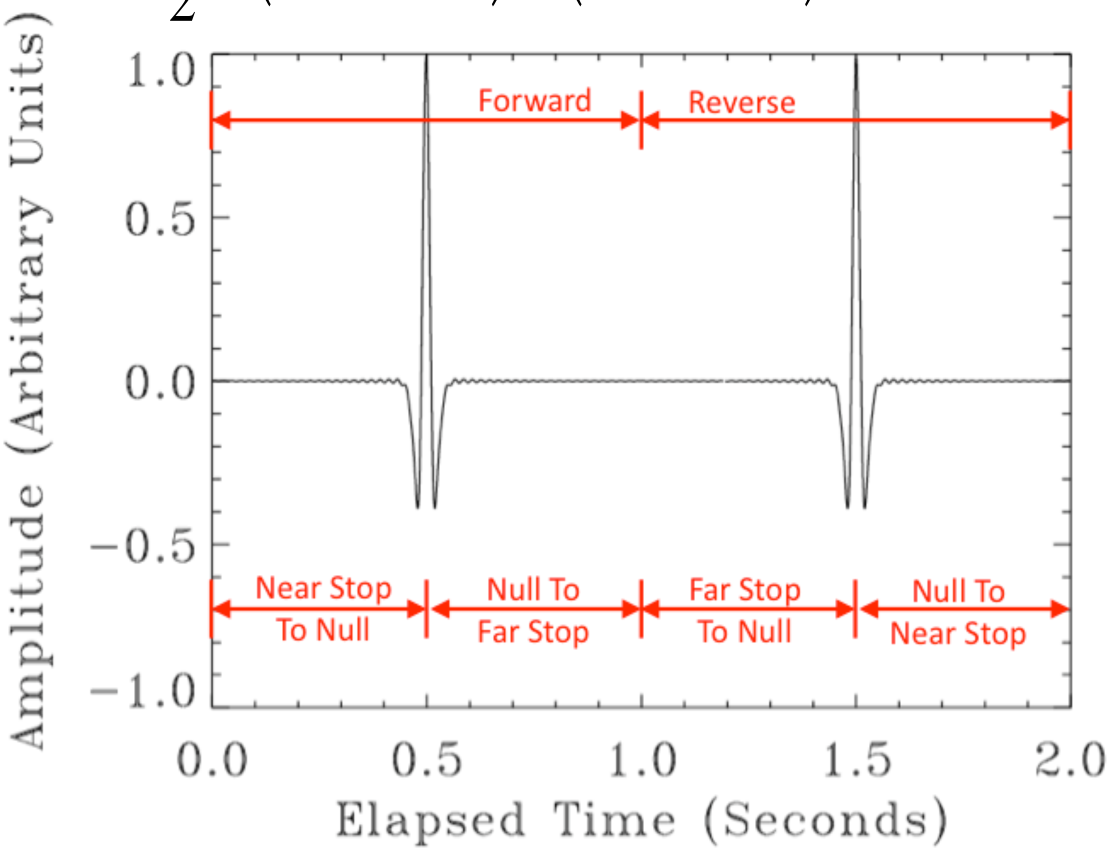
Identical arguments totems, septum and other areas. Areas close to the detectors are not modulated and so produce no signal.

Systematics: Stroke

Fully symmetric stroke

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

Signal is ~10^{-3} of DC



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

Fourier Transform:

Real (cosine)=Signal

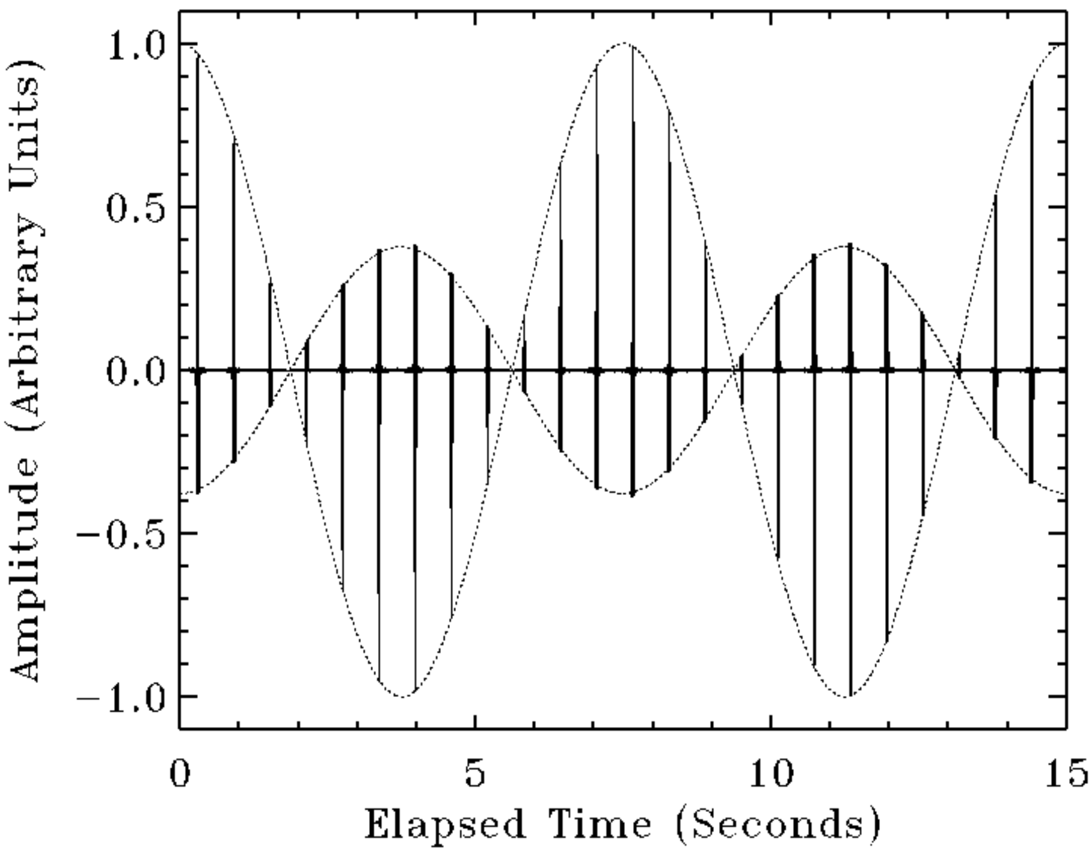
Imaginary (sine)=Phase shift

The key detector transfer function, heat capacity and thermal conductance show linearly in the imaginary part of the Fourier transform and quadraticaly in the real part

The forward and reverse stroke allow unambiguous untangling of effects in time, with effects from different sides. ~100,000,000 samples to compare

Systematics: Spin

Spacecraft Spin



Spacecraft spin imposes amplitude modulation of entire fringe pattern

For "perfect beam" only m=0 components are nonzero

Spin allows sampling of the beam
At m=0-12.
Only m=2 is degenerate with polarization
m=1,3-12 can be used to study the beam.

ONLY the m=2 DIFFERENTAL Asymmetries lead to Polarization errors.

~6,000,000 Rotations to compare

Symmetries and Systematic Errors

20 Ways to Find 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
Left vs Right XCal	Calibration, Beam
Hot vs Cold	Non-Linearities
Ascending vs Descending	Far sidelobes, calibration
Spin m=2	Electronics
Spin m=1, 3 to 12	Beam asymmetries

$$P_{Lx}(\omega) = g_{Lx}(\omega)\left(S_{Bx}(\nu) - S_{Ay}(\nu)\right)$$

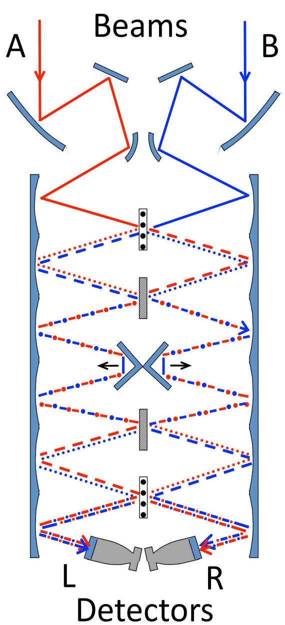
$$P_{Ly}(\omega) = g_{Ly}(\omega)\left(S_{By}(\nu) - S_{Ax}(\nu)\right)$$

$$P_{Rx}(\omega) = g_{Rx}(\omega)\left(S_{Ax}(\nu) - S_{By}(\nu)\right)$$

$$P_{Ry}(\omega) = g_{Ry}(\omega)\left(S_{Ay}(\nu) - S_{Bx}(\nu)\right)$$

Add them: Sky cancels, leaving only systematics
Subtract them: Instrument cancels, leaving only sky

No assumptions about sky or instrument model



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

Summary

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 calibration is limited by the ***total data set*** so it
will be able to reduce the residual to ~1 nK