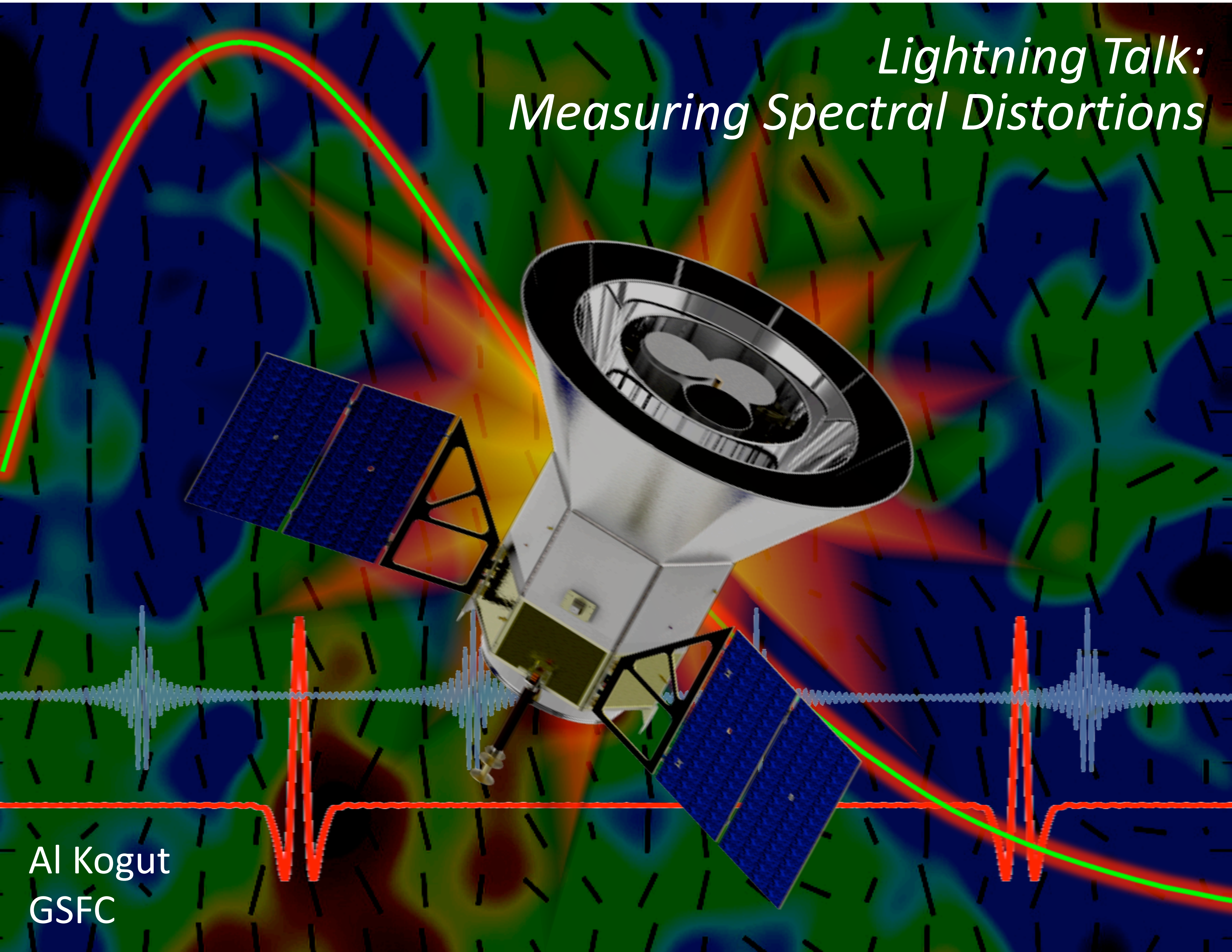
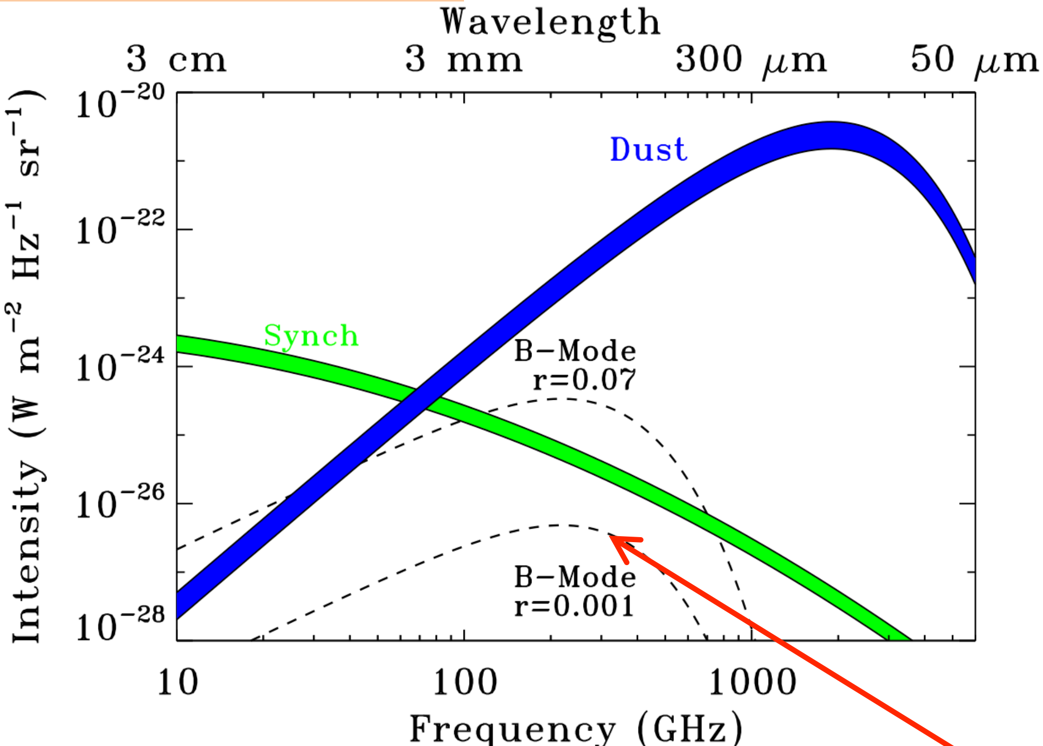
Lightning Talk: Measuring Spectral Distortions



Al Kogut
GSFC

B-Mode Comparison

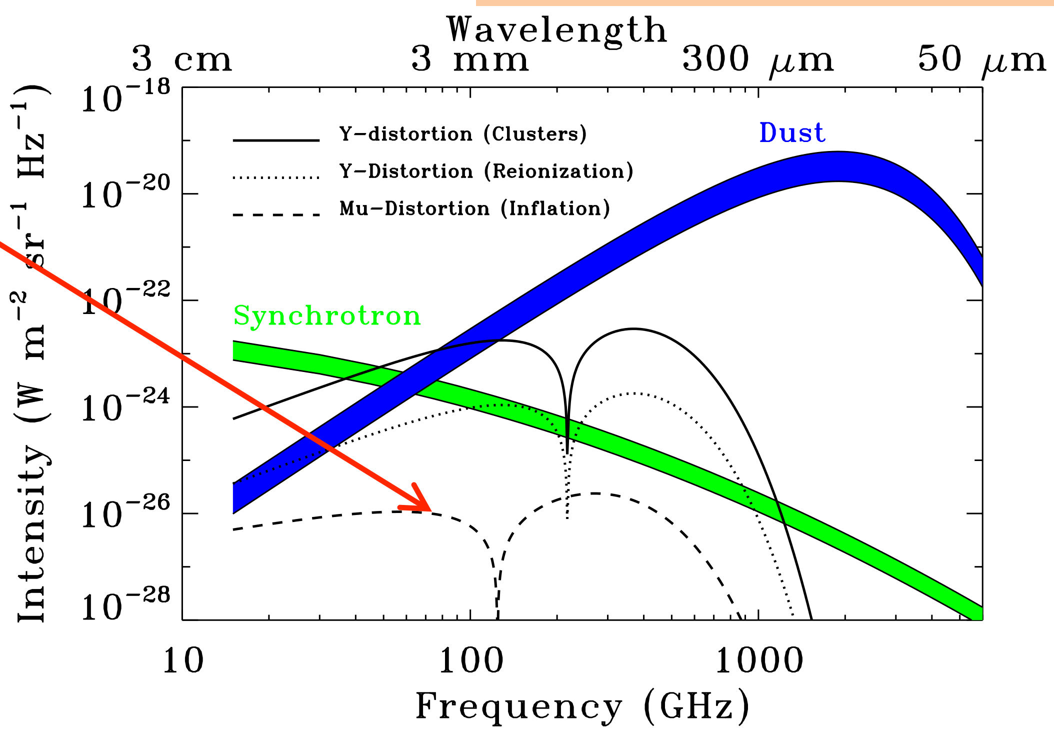
Polarization vs foregrounds



Cosmic Coincidence:
Signal amplitude and
relation to foregrounds ...

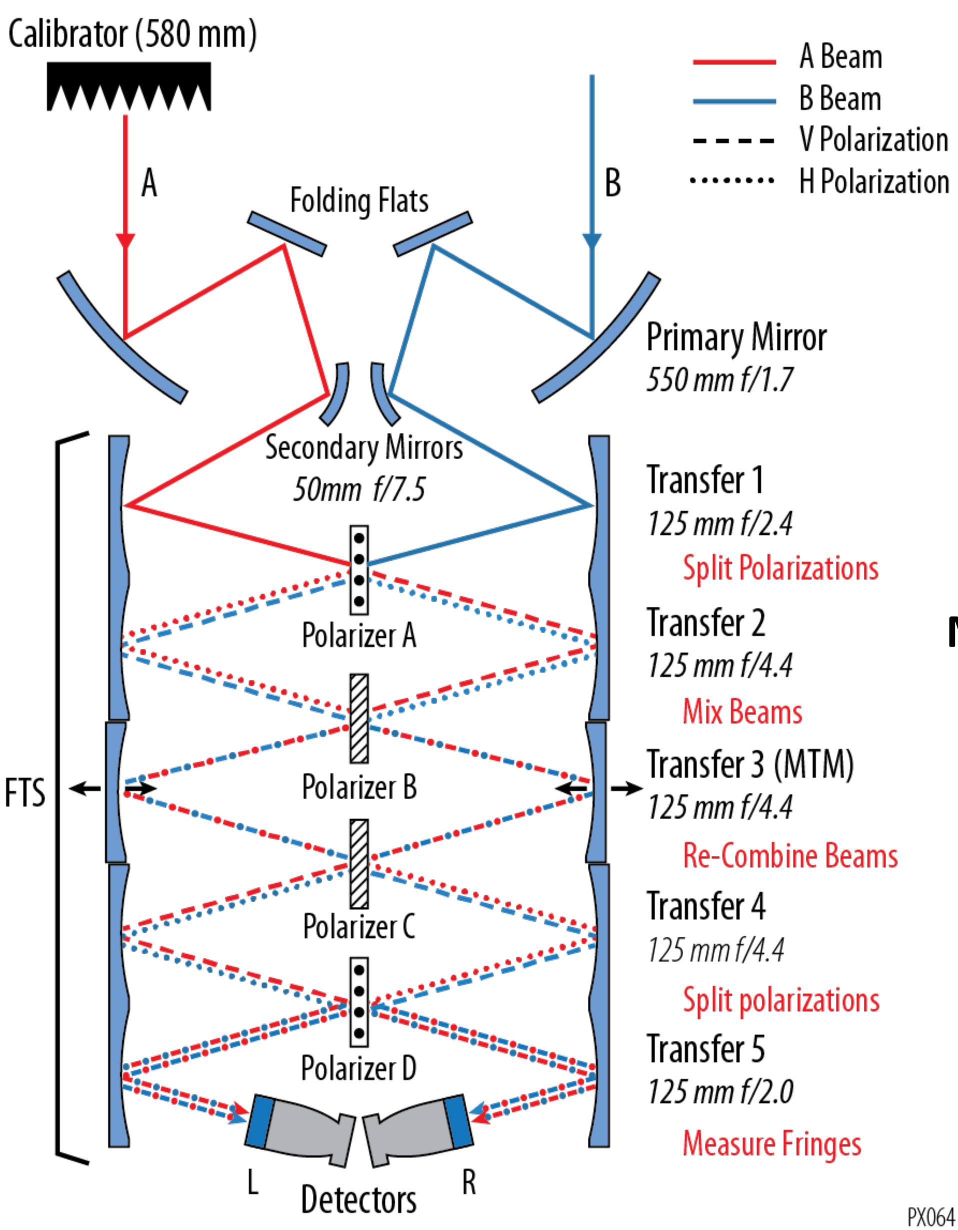
Same Amplitude!

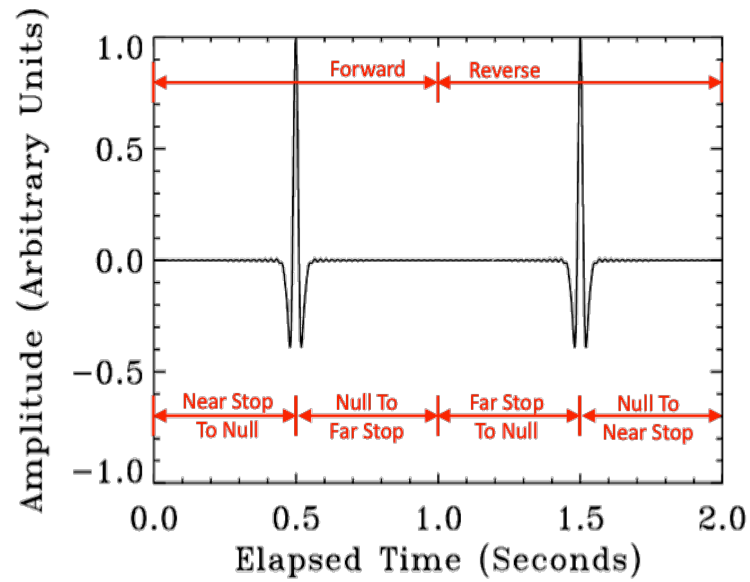
Spectral distortions vs foregrounds



... Similar for spectral distortions
as for B-modes

Martin-Puplett Nulled Interferometer





Measured Fringe Pattern Samples Frequency Spectrum Of (Sky-Calibrator) Difference

$$P_{Lx} = 1/2 \int\{ (E_{Ax}^2 + E_{By}^2) + (E_{Ax}^2 - E_{By}^2)\cos(4z\omega/c) \}d\omega$$

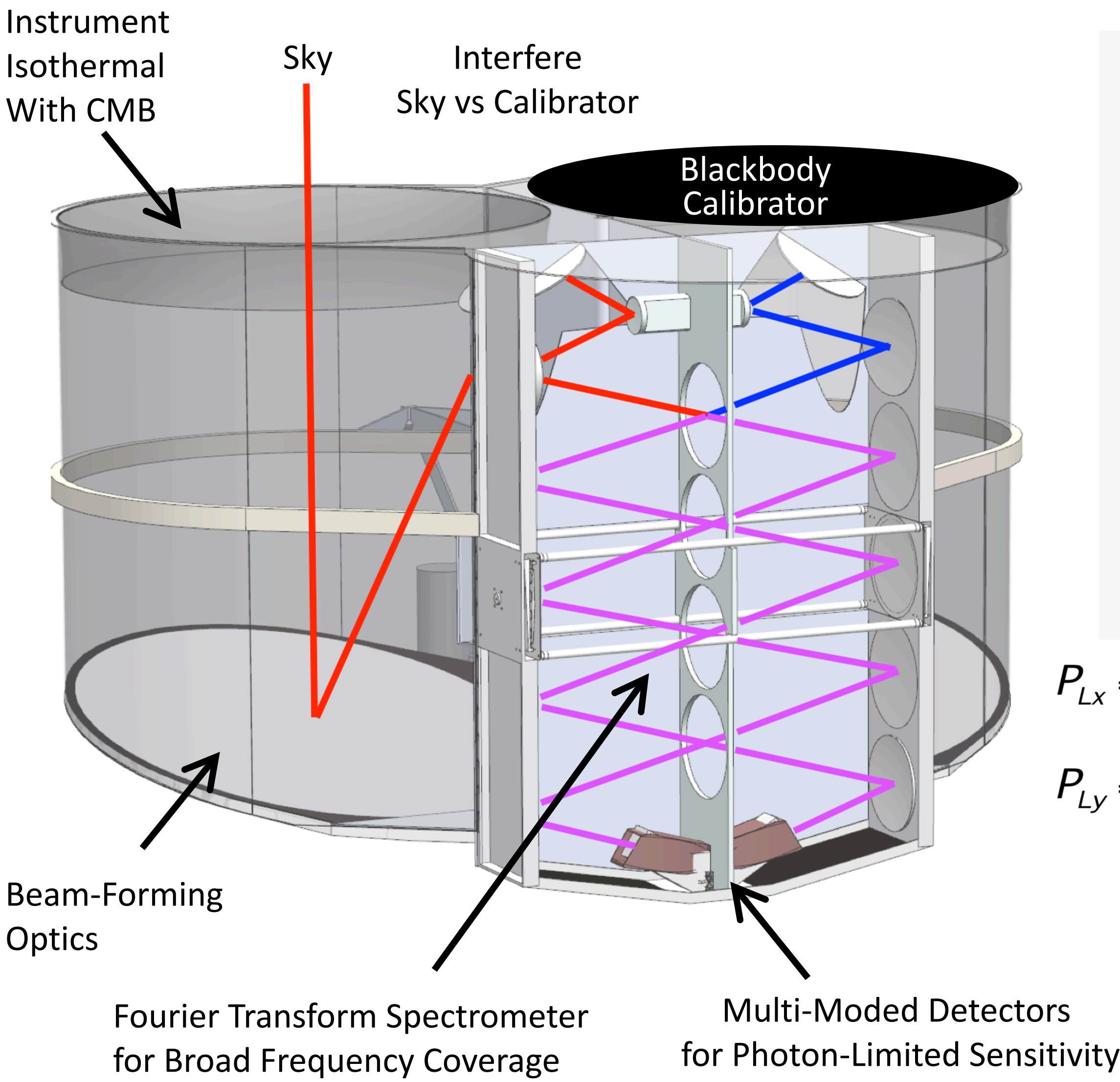
$$P_{Ly} = 1/2 \int\{ (E_{Ay}^2 + E_{Bx}^2) + (E_{Ay}^2 - E_{Bx}^2)\cos(4z\omega/c) \}d\omega$$

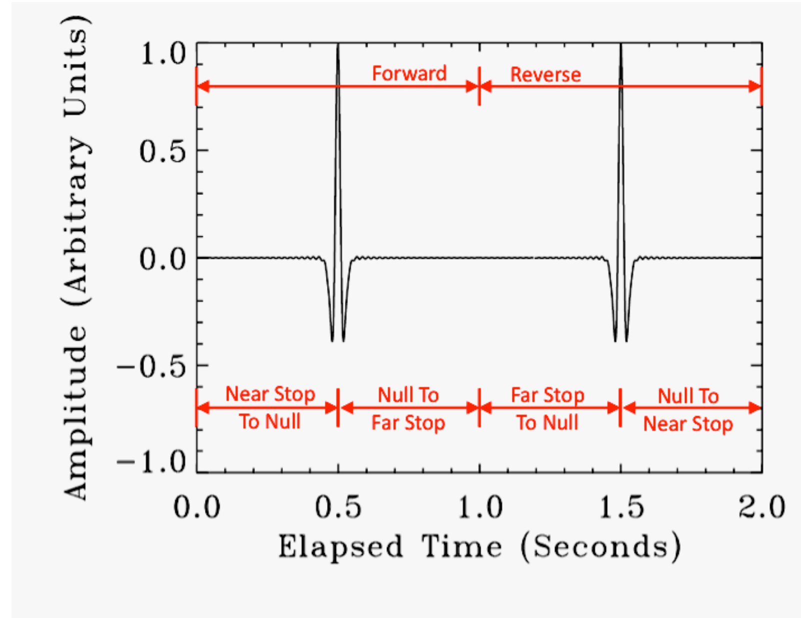
$$P_{Rx} = 1/2 \int\{ (E_{Ay}^2 + E_{Bx}^2) + (E_{Bx}^2 - E_{Ay}^2)\cos(4z\omega/c) \}d\omega$$

$$P_{Ry} = 1/2 \int\{ (E_{Ax}^2 + E_{By}^2) + (E_{By}^2 - E_{Ax}^2)\cos(4z\omega/c) \}d\omega$$

Nulling Instrument: Zero = Zero

PIXIE and Spectral Distortions





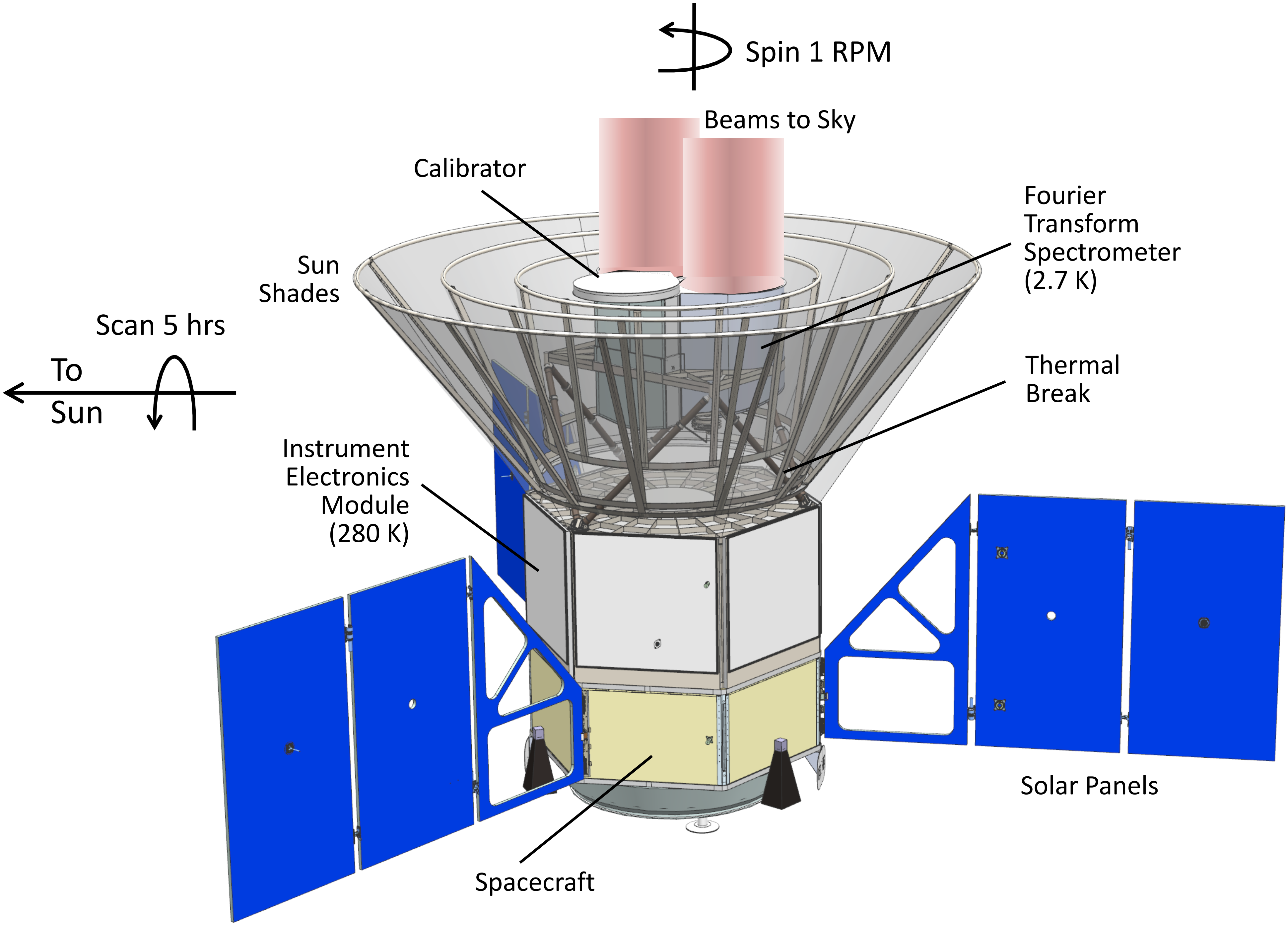
$$P_{Lx} = \frac{1}{2}\int \left(E^2_{Cal,y} + E^2_{Sky,x}\right) + \left(E^2_{Sky,x} - E^2_{Cal,y}\right)\cos(z\omega/c)\, d\omega$$

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

[Calibrator-Sky]
Spectral Difference

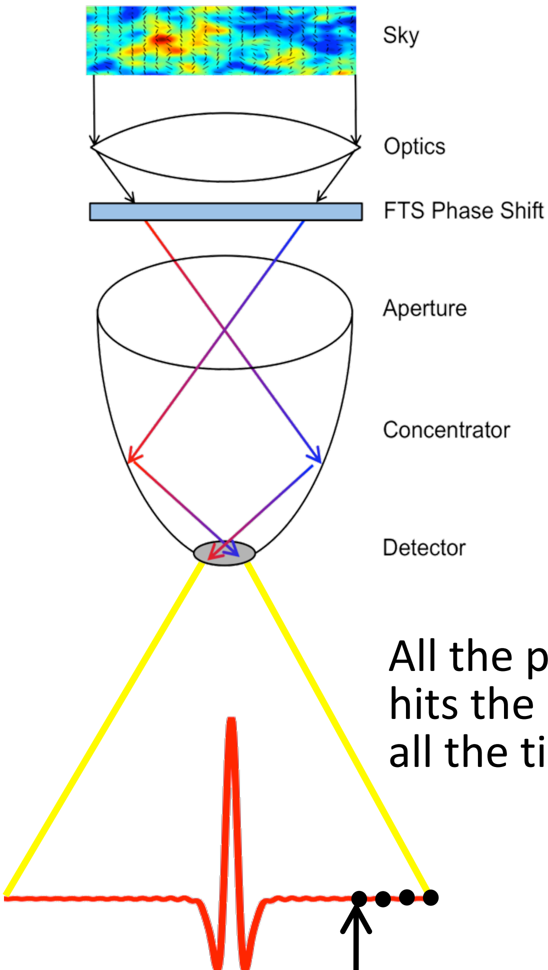
Zero means zero: No fringes if sky is a blackbody

PIXIE Observatory

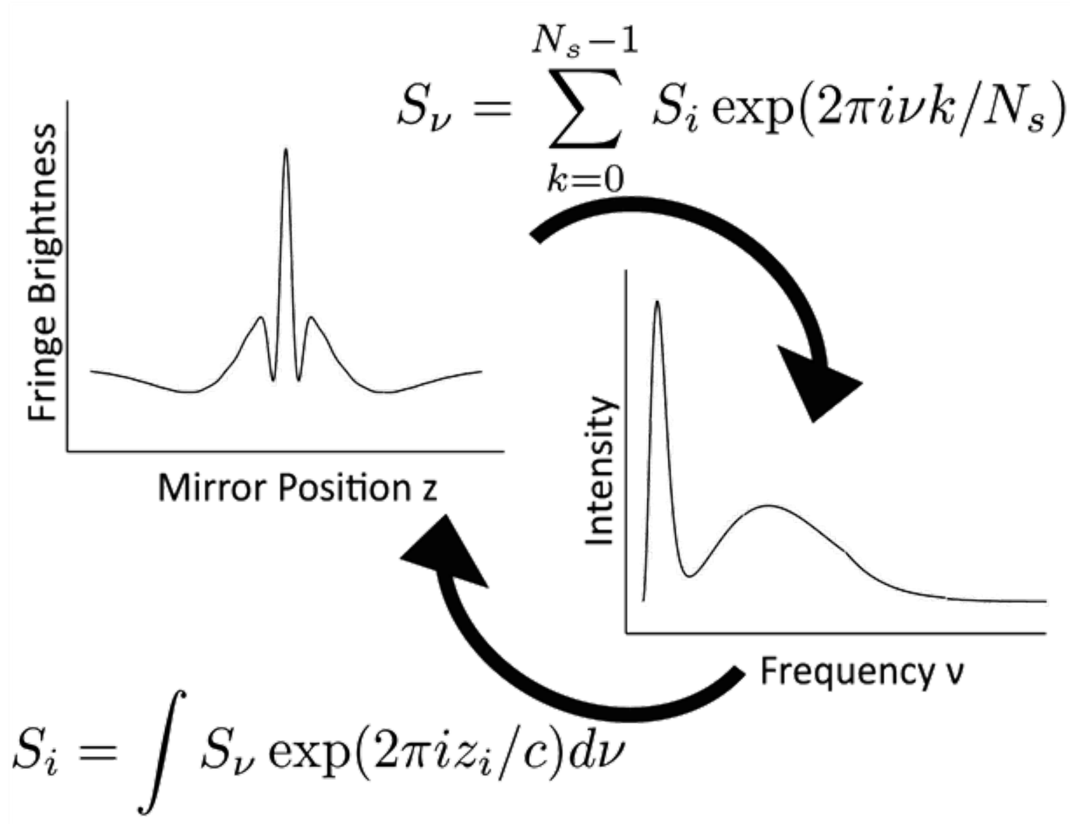


Adventures in Fourier Space

Fringe Pattern vs Frequency Spectrum



All the power hits the detector all the time



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

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

Sample Fringe Pattern

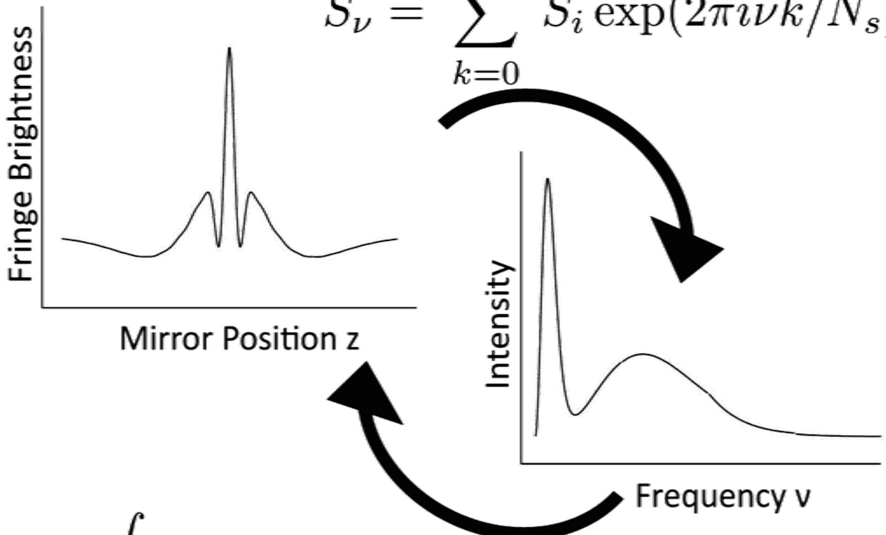
Fit sampled fringe pattern to Fourier series cos(k*x)

$a_0 + a_1\cos(x) + a_2\cos(2x) + a_3\cos(3x) + \ldots + a_N\cos(Nx)$

Adventures in Fourier Space

Channel Selection

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



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

Get N samples of fringe pattern
as phase delay goes from –L to +L

Maximum phase delay sets channel width
(hence lowest frequency)

$$\Delta\nu = {}^{c}/_{L}$$

Number of samples N sets highest frequency

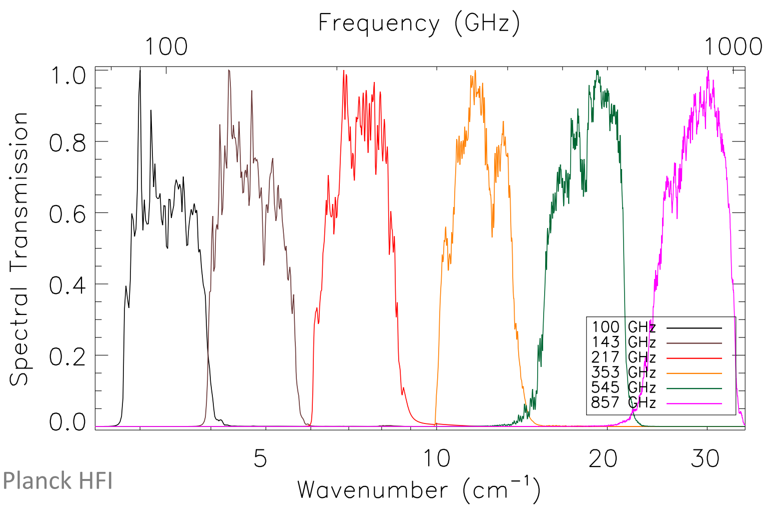
$$\nu_i = \Delta\nu, 2\Delta\nu, 3\Delta\nu, \cdots, \frac{N}{2}\Delta\nu$$

Sample more often → Get more (higher frequency) channels
Increase mirror throw → Decrease channel width (go to lower frequencies)

More frequency channels ←→ Higher sampling rate (data rate)

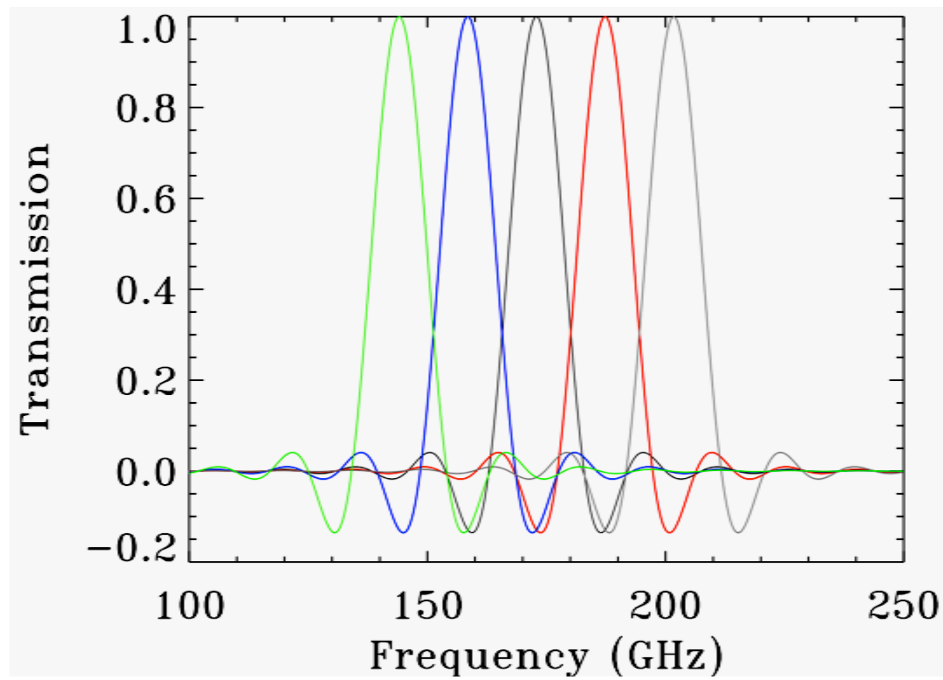
Adventures in Fourier Space

Channel Shape



Planck HFI

Photometer passbands set by filters
Complicated shape
Hard to control at few-percent level

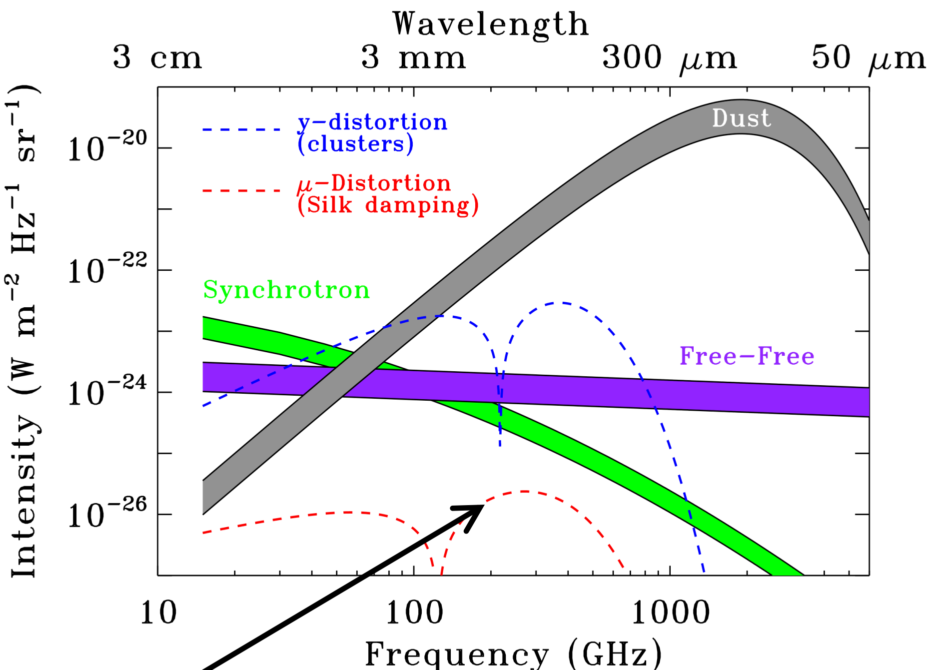


FTS channel shape set by apodization
Trade resolution vs channel-to-channel correlations
- Uniform sampling → Sync function (ugly)
- Weighted sampling → Nearest-neighbors (nice)

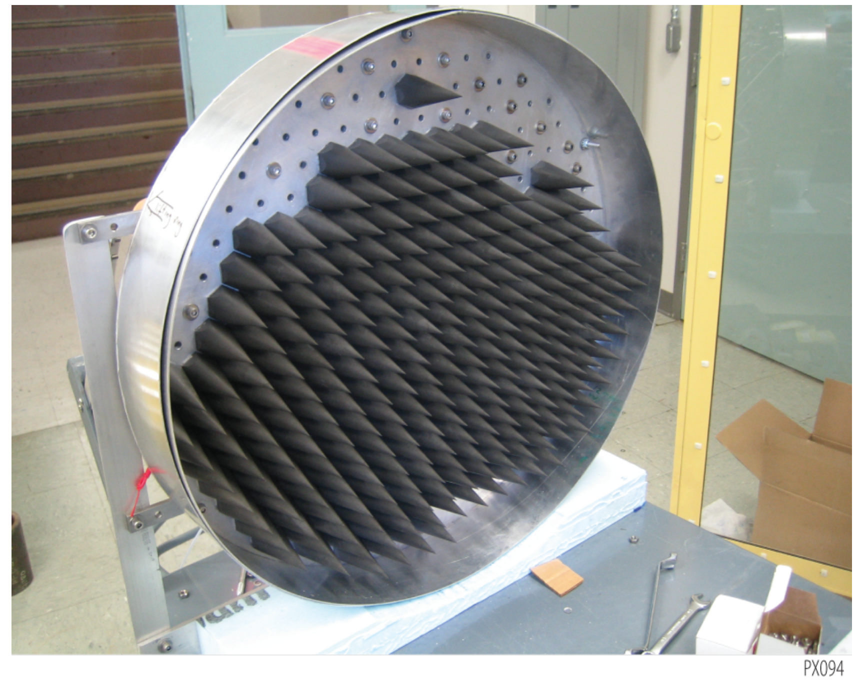
Channel shape and channel-to-channel correlations are entirely deterministic!
Bonus: Pick bands to force CO lines into center of every Nth channel

Systematic Errors I

How Black is Black Enough?

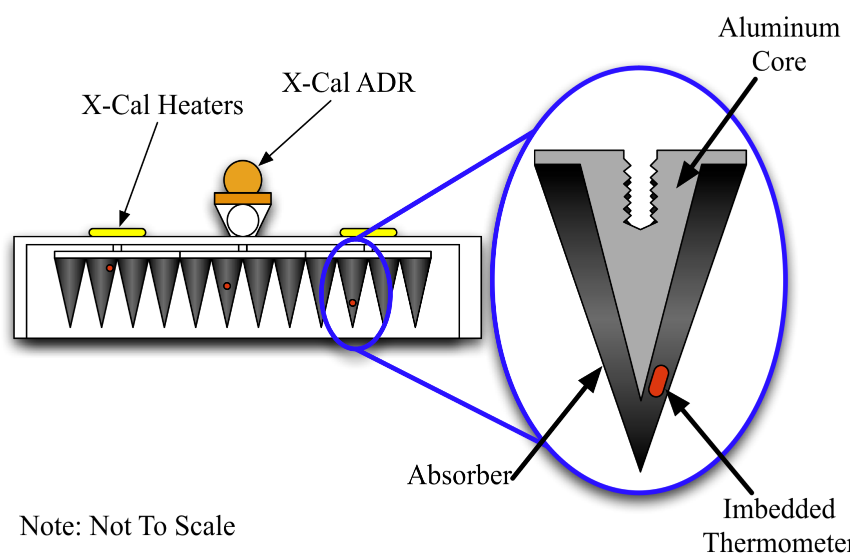


Distortion science is at nK signal levels



Calibrator is based on ARCADE design
Measured black to -60 dB

Is this good enough?



Systematic Errors I

The Importance of Nulling

Where does the reflected ray go?

Reflected ray "sees" instrument wall instead of calibrator

But ...

Instrument, calibrator, and sky are all within a few mK of each other

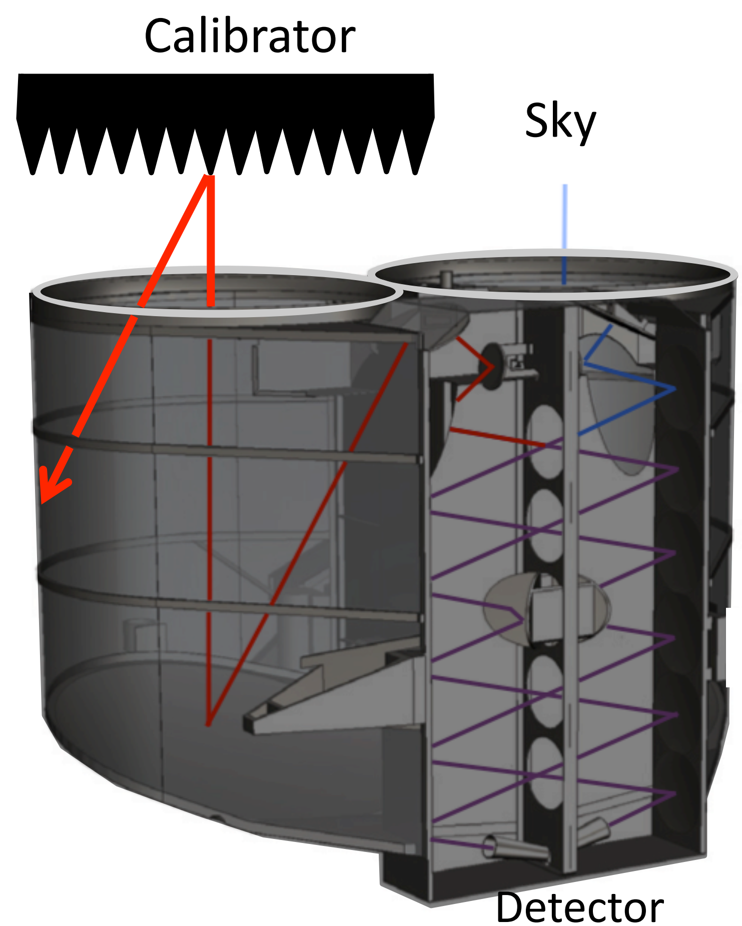
So ...

Error signal is 10^{-6} x (few mK difference) or just a few nK (before correction)

Bonus: Error signal flips sign when calibrator is hotter/colder than wall

Vary calibrator and wall temps to isolate and remove error signal

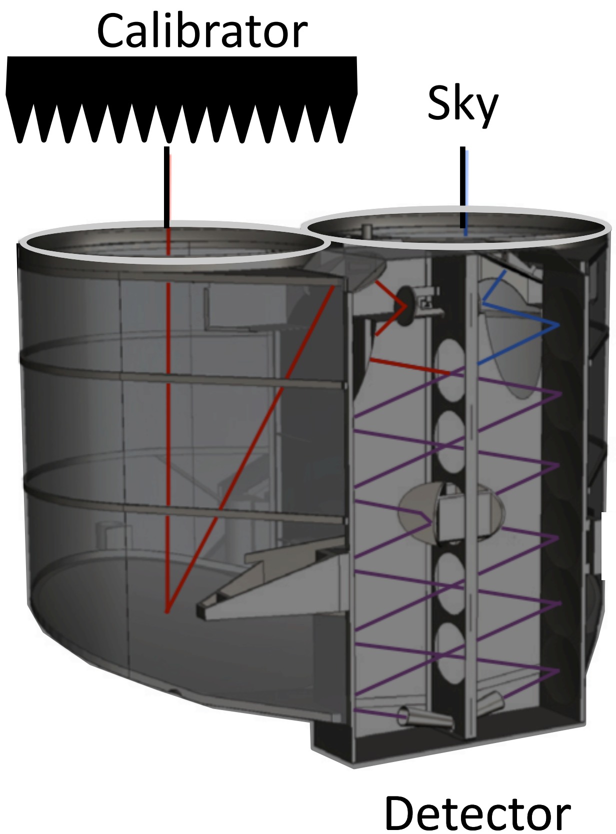
Sub-nK residual at noise limit of entire mission



Backwards ray trace: From detector to calibrator

Systematic Errors II

Chain Multiple Nulls Together

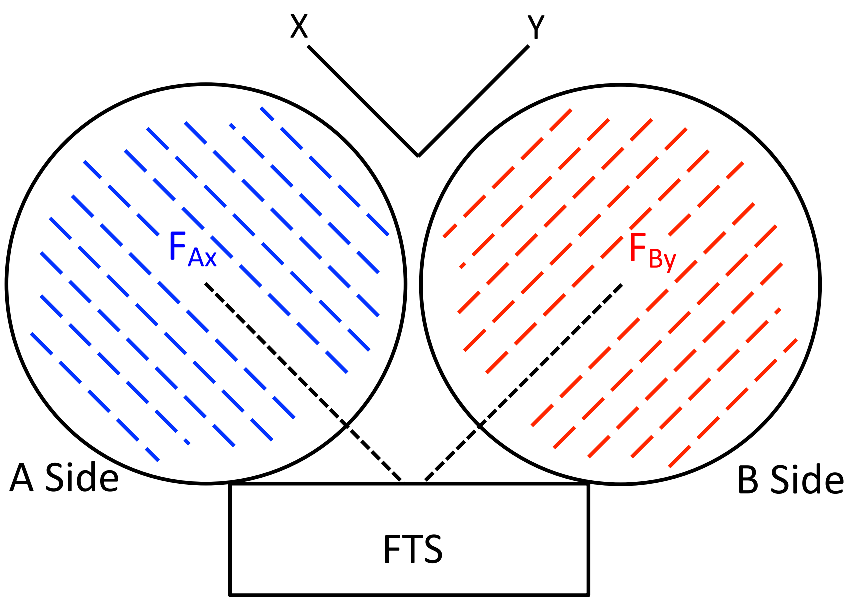


Maximum ΔT	few mK		
Mirror Emissivity		x 0.01	tens of uK
Left/Right Asymmetry		x 0.01	few hundred nK
Swap hot vs cold		x 0.01	few nK
Uncorrected Error	few nK (with blue-ish tinge)		
Corrected Error	<< 1 nK		

Never rely on any single cancellation

Systematic Errors III

Beam Patterns



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$$P_{Ry} = 1/2 \int \{ (E_{Ax}^2 + E_{By}^2) + (E_{By}^2 - E_{Ax}^2)\cos(4z\omega/c) \} d\omega$$

Signals depend on differential beam pattern
x pol on A side – y pol on B side

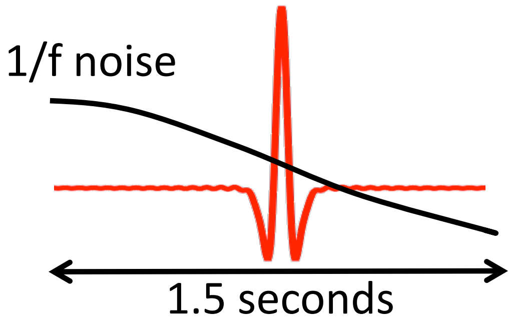
By design, roles of x and y are reversed in A side vs B side
Systematic errors are thus ***second-order***
Depend on the (A-B) difference of the (x-y) polarization

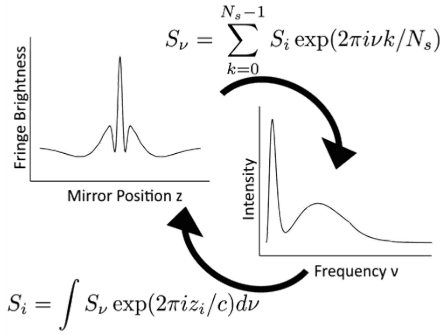
Note that double-difference cancellation occurs in hardware
Post-detection differences of individual detectors allow additional cancellations

Kogut & Fixsen 2018, arXiv:1801.08971

Systematic Errors IV

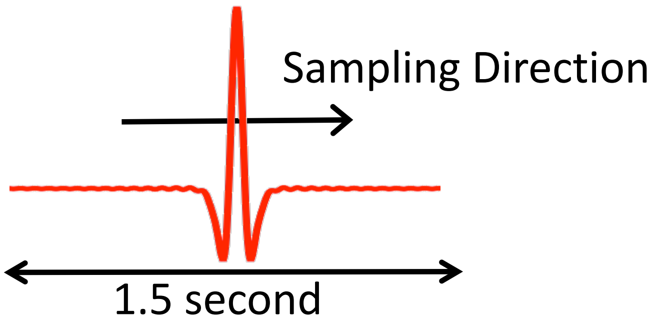
A Grab Bag of Symmetries

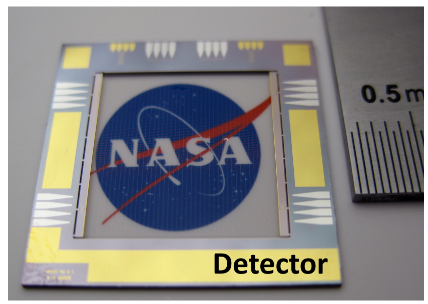




1/f noise gets Fourier-transformed into lowest bins of synthesized spectra

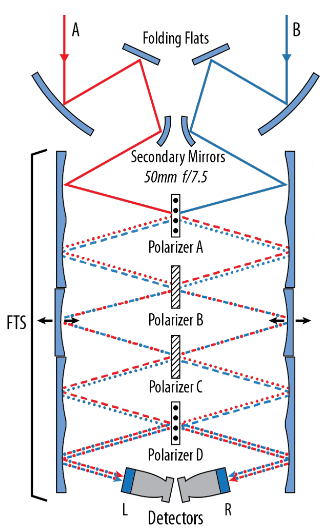
No striping in CMB maps





Peak at zero phase delay provides before-and-after reference for detector time constants

126,000,000 times per detector



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$$P_{Ry} = 1/2 \int \{ (E_{Ax}^2 + E_{By}^2) + (E_{By}^2 - E_{Ax}^2)\cos(4z\omega/c) \} d\omega$$

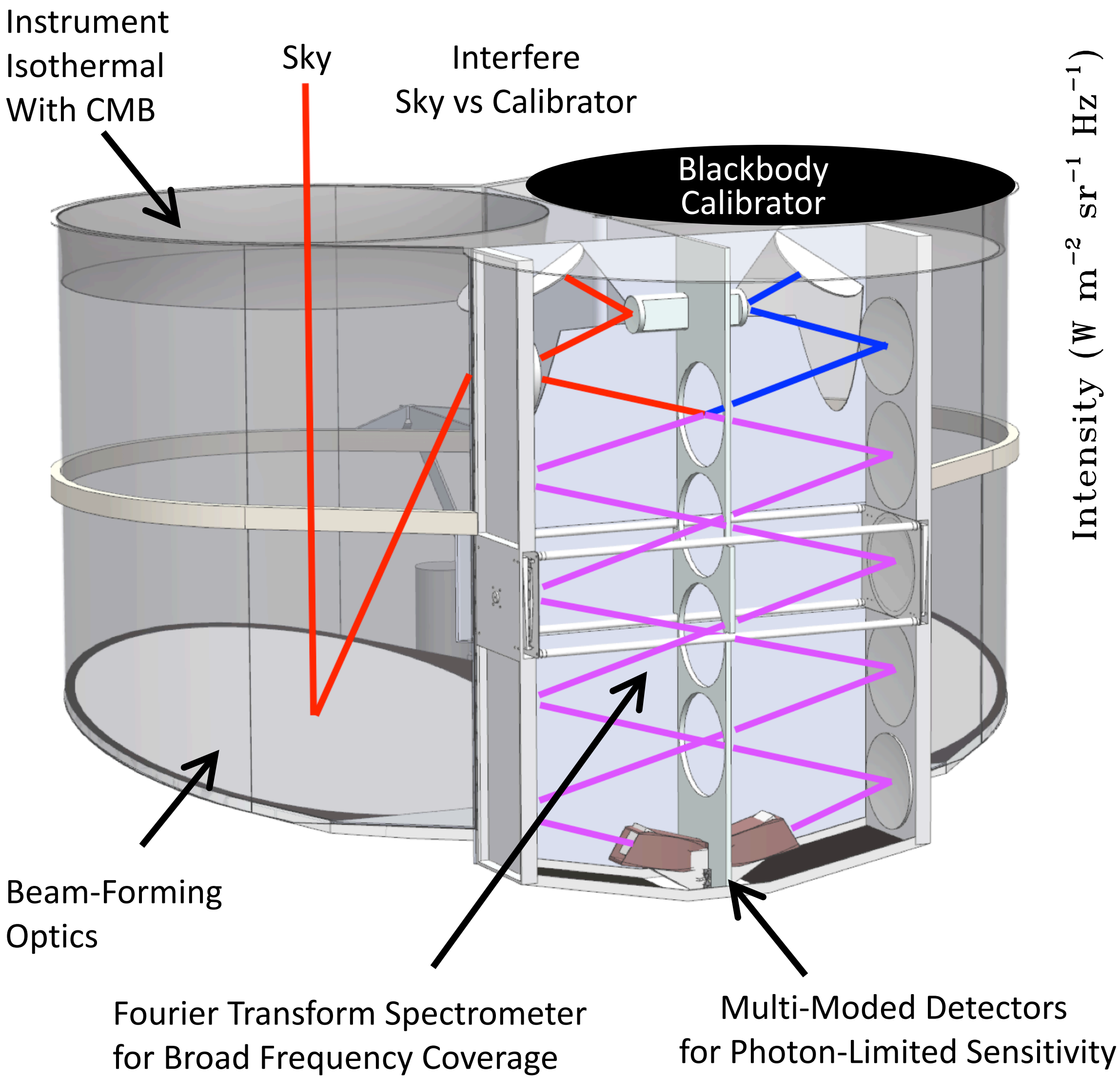
Permutations!

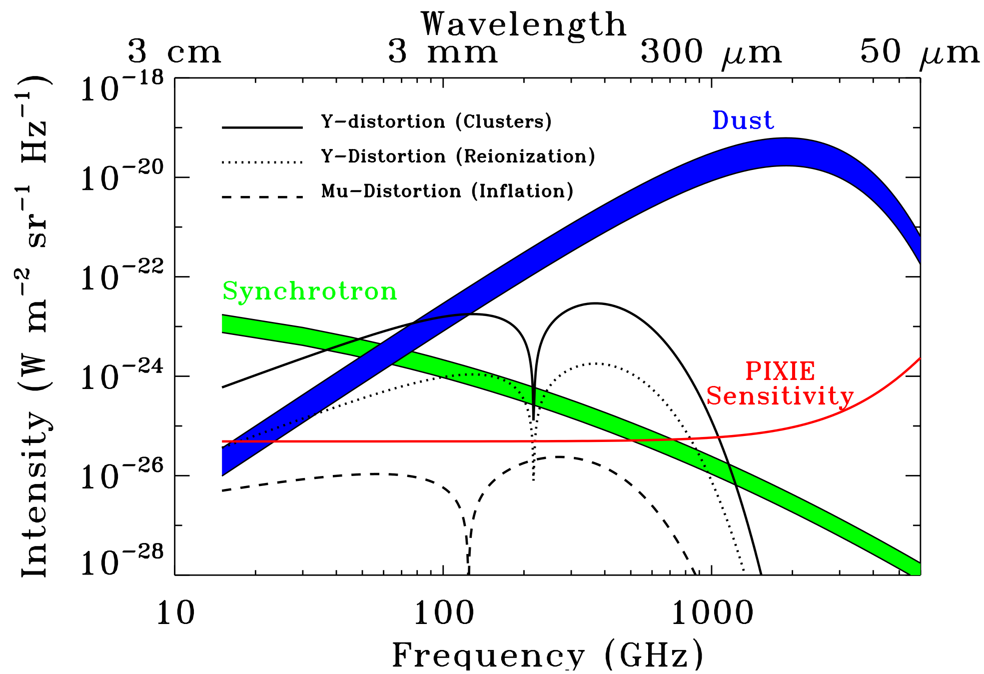
Exploit multiple internal symmetries

- x vs y polarization
- L vs R concentrators
- A vs B beams
- Real vs imaginary FFT

Jackknife tests use full data set

PIXIE and Spectral Distortions





PIXIE Sensitivity (4 years)

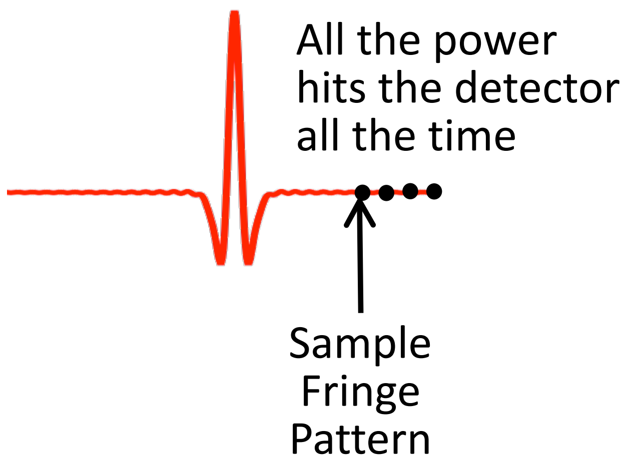
Noise only (no foregrounds)
$y = 1 \times 10^{-9}$
$\mu = 1 \times 10^{-8}$

After foreground subtraction
$y = 2 \times 10^{-8}$
$\mu = 2 \times 10^{-7}$

The Path to Sensitivity

How Low Can You Go?

FTS Penalty for Low-Frequency Channels



Mirror throw sets channel width (lowest freq)

$$\Delta\nu = c/L$$

Test: Increase throw by factor of 2

This decreases integration time per sample, increasing noise per sample by root(2)

But there are now twice as many samples in FTS, so noise in frequency domain increases by another root(2)

Noise per synthesized bin larger by factor of 2
Continuum sources can co-add over bins
Integrated noise then larger by only root(2)

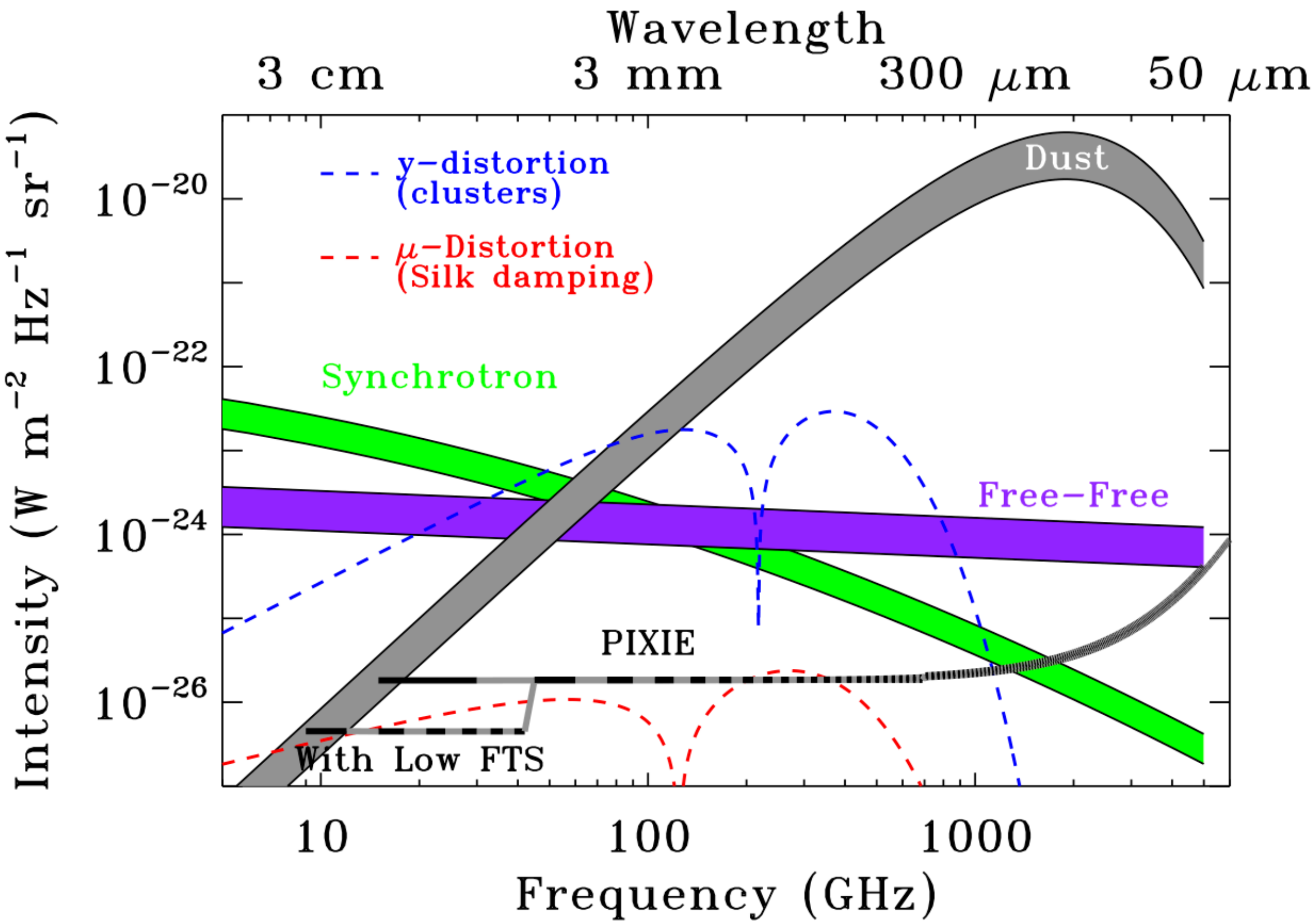
Spectral Distortion Sensitivity Scales as Sqrt{ $\Delta\nu$ }
Hard to win by adding low-frequency channels while keeping full range*

* Aha! A loophole!

Adding Low-Frequency Sensitivity

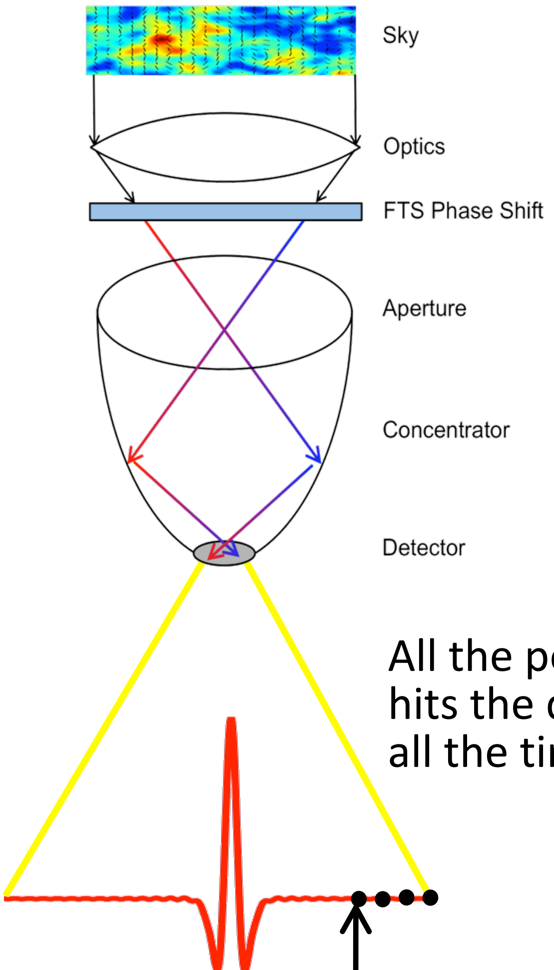
Add second low-freq FTS using FTS loopholes

- 3 GHz channel width → 20 mm mirror throw
- 14 synthesized channels → 28 fringe pattern samples (not 1024)
- Lowpass filter at 42 GHz → Minimize photon NEP
- Waveguide cutoff ~ 7 GHz → Lowest usable channel at 9 GHz
- Shortest wavelength 7mm → Dispersion not a problem at f/4



Adventures in Fourier Space

Signal to Noise Ratio



All the power hits the detector all the time

Sample Fringe Pattern

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

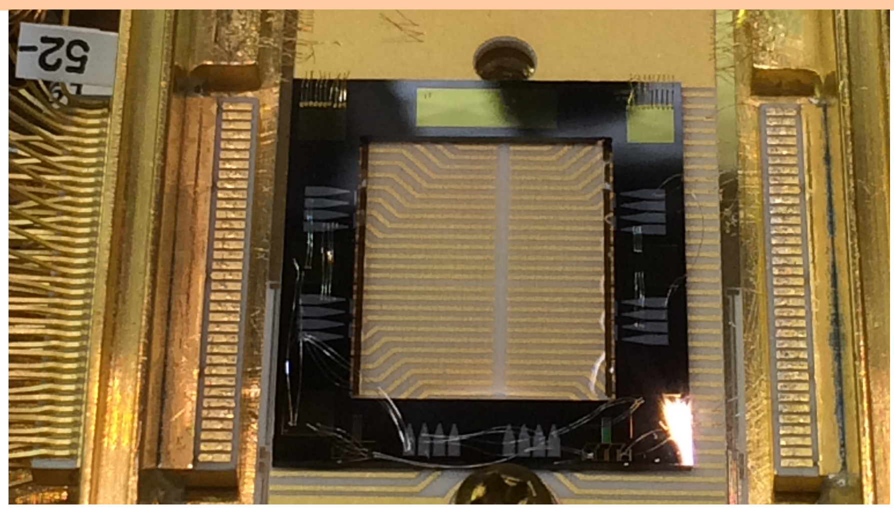
Photon noise ~ $(A\Omega)^{1/2}$

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

Signal ~ $(A\Omega)$

Good news: Signal to noise ratio improves as $(A\Omega)^{1/2}$

Better news: nK sensitivity using only 4 bolometers

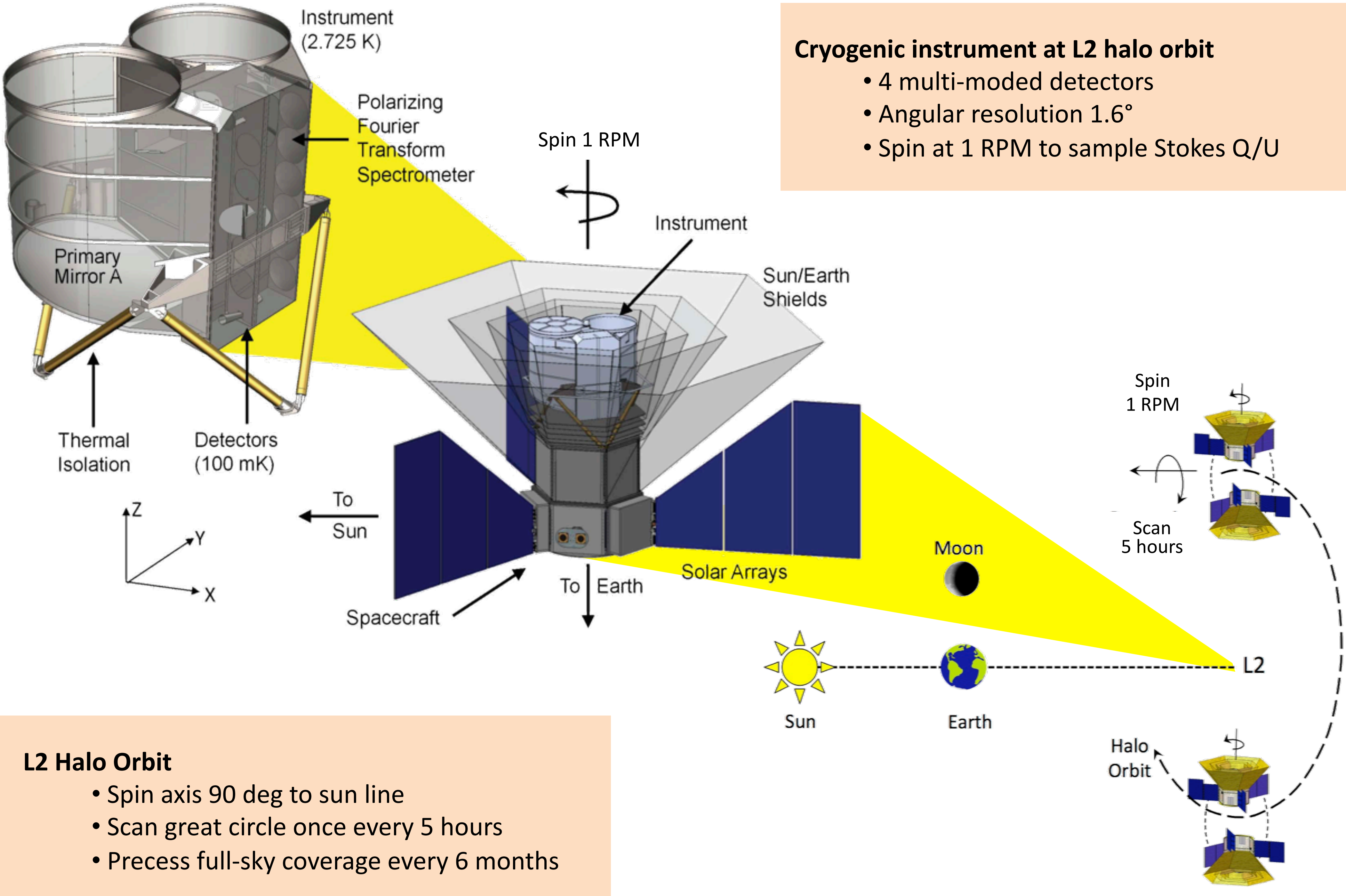


PIXIE polarization-sensitive bolometer
30x collecting area as Planck bolometers

Instrument and Observatory

Cryogenic instrument at L2 halo orbit

- 4 multi-moded detectors
- Angular resolution 1.6°
- Spin at 1 RPM to sample Stokes Q/U



L2 Halo Orbit

- Spin axis 90 deg to sun line
- Scan great circle once every 5 hours
- Precess full-sky coverage every 6 months

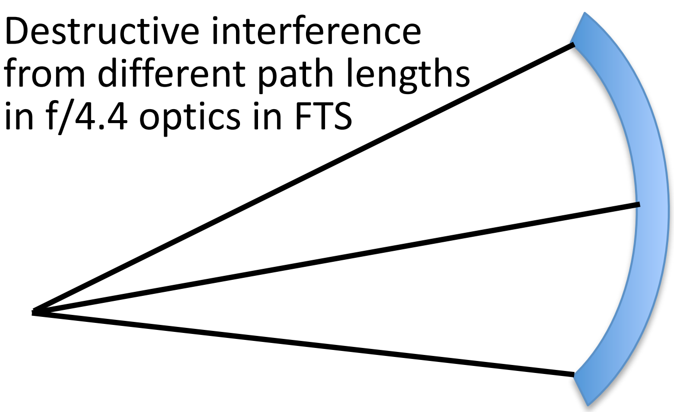
The Path to Sensitivity

How Big Can You Grow?

Photon Noise Limit: Sensitivity improves as $(A\Omega)^{1/2}$

Can we just make PIXIE bigger?

Test: Increase all dimensions x3 (area x9)
Problem: Dispersion washes out signal
Solution: Slower optics



But slower optics reduces solid angle Ω, requiring increase in area to compensate (or accept some loss in sensitivity)

50 cm primary mirrors	→	3 meters diameter each
13 cm FTS mirrors	→	1 meter each
FTS box 50 cm x 20 cm x 80 cm	→	4 x 2 x 6 meters

Bad: FTS grows from of size carry-on luggage to size of a bus!
Better to adopt ground-based approach and clone the instrument