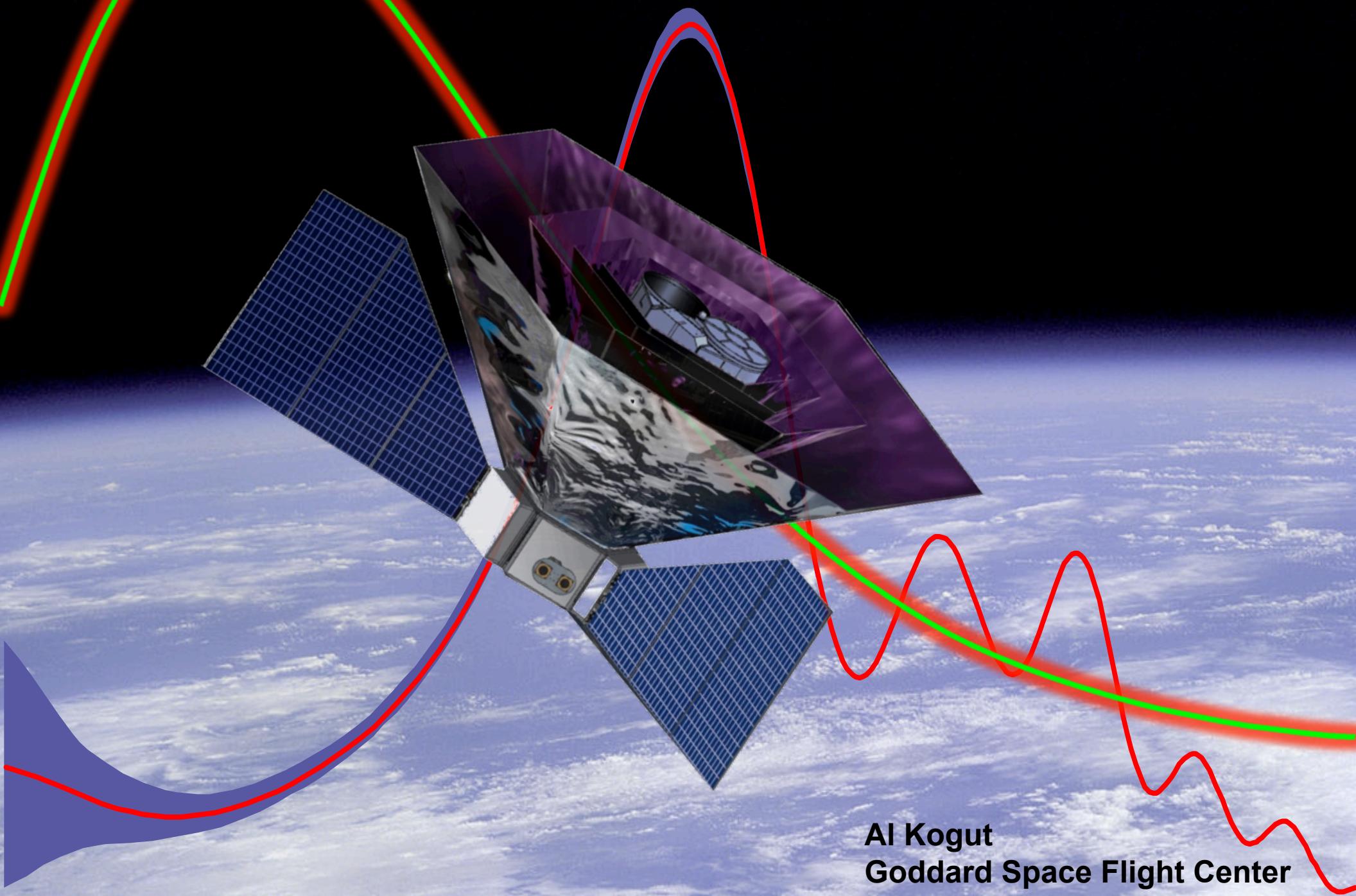
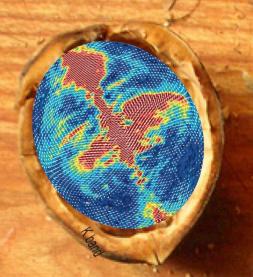


The Primordial Inflation Explorer

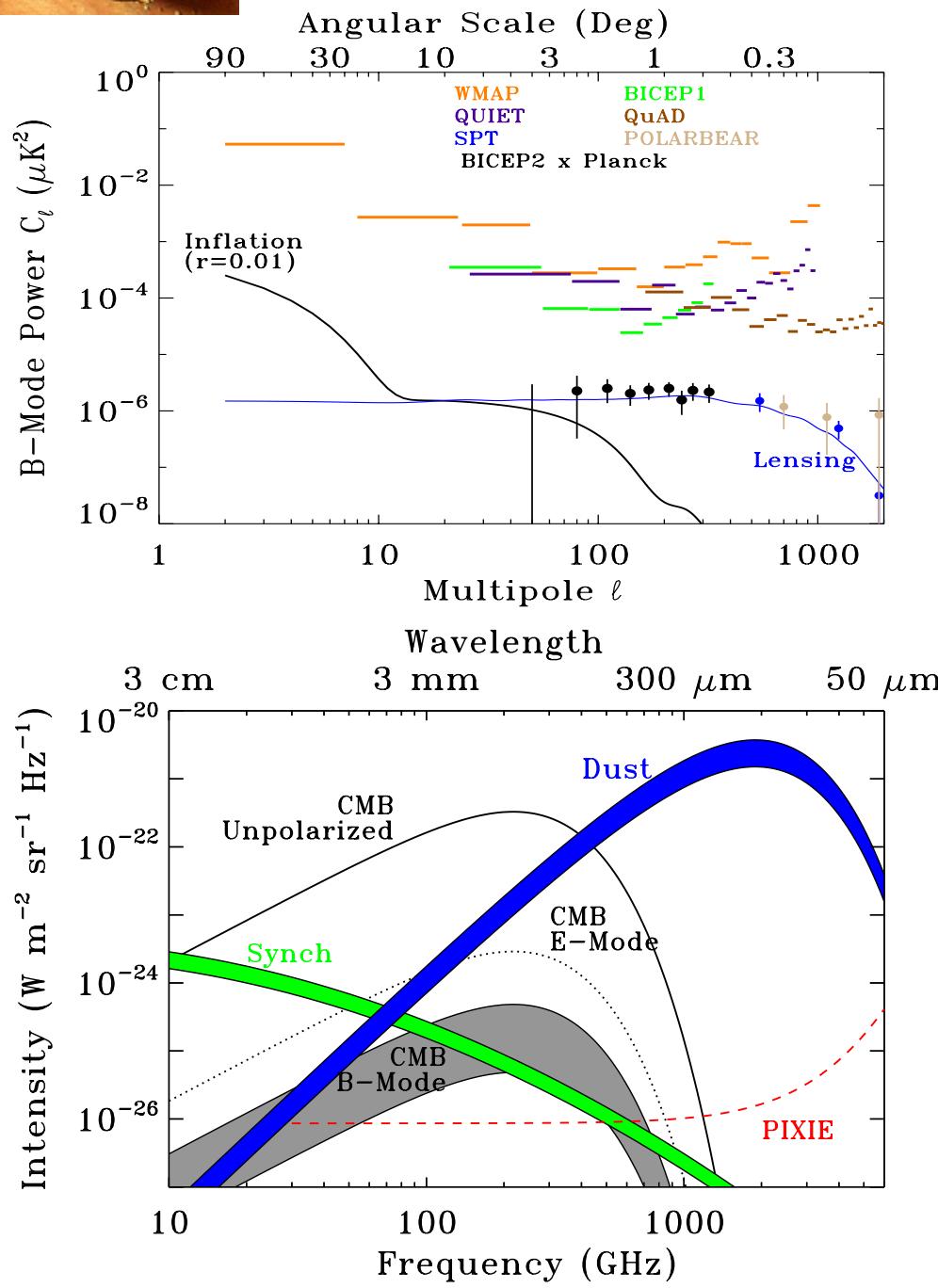
Beyond the Power Spectrum



Al Kogut
Goddard Space Flight Center

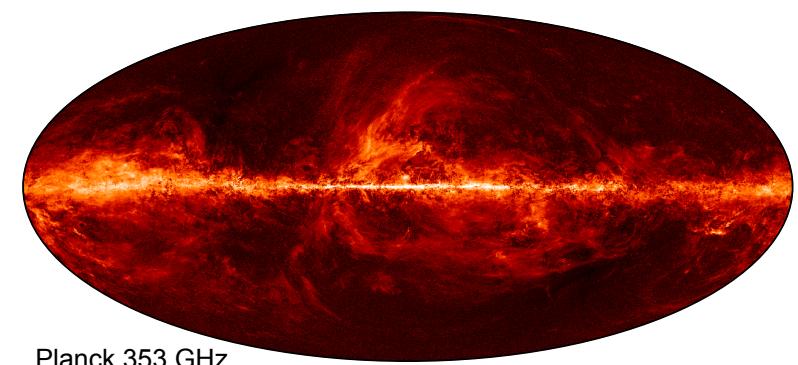


B-modes in a Nutshell



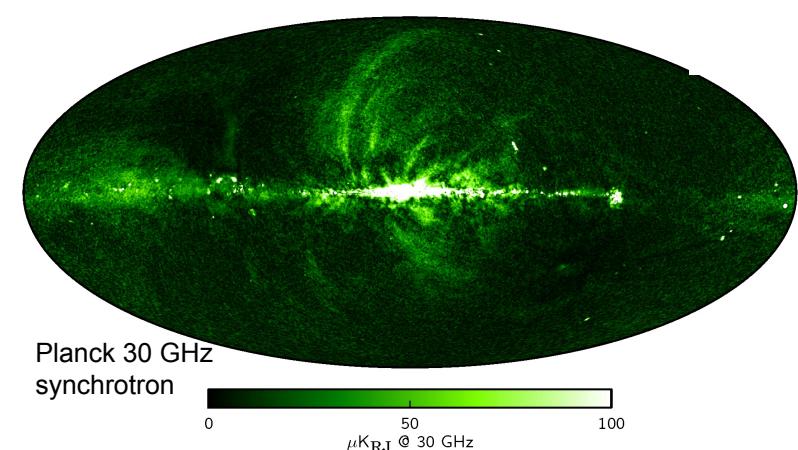
B-Mode Requirements

- Sensitivity
- Foreground Discrimination
- Systematic Error Rejection



Planck 353 GHz

dust



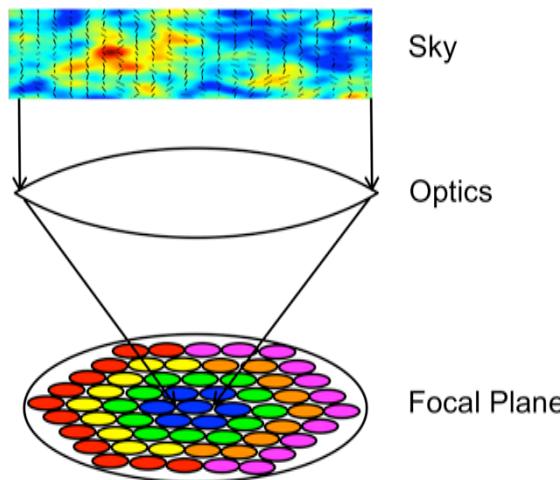
Planck 30 GHz

synchrotron

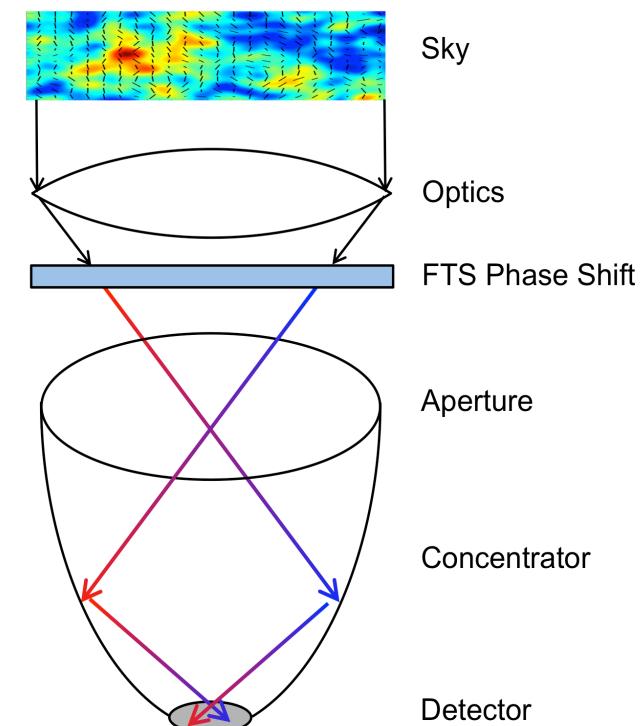


PIXIE Solution: Multi-Moded FTS

Single-Moded Optics



Multi-Moded Optics



Diffraction Limit: $A\Omega = \lambda^2$

Single mode on each of 10,000 detectors

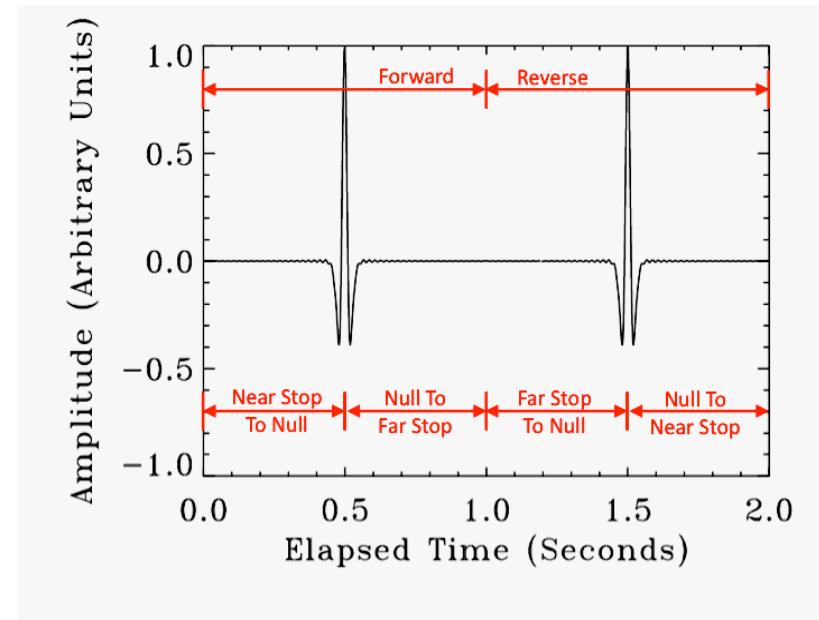
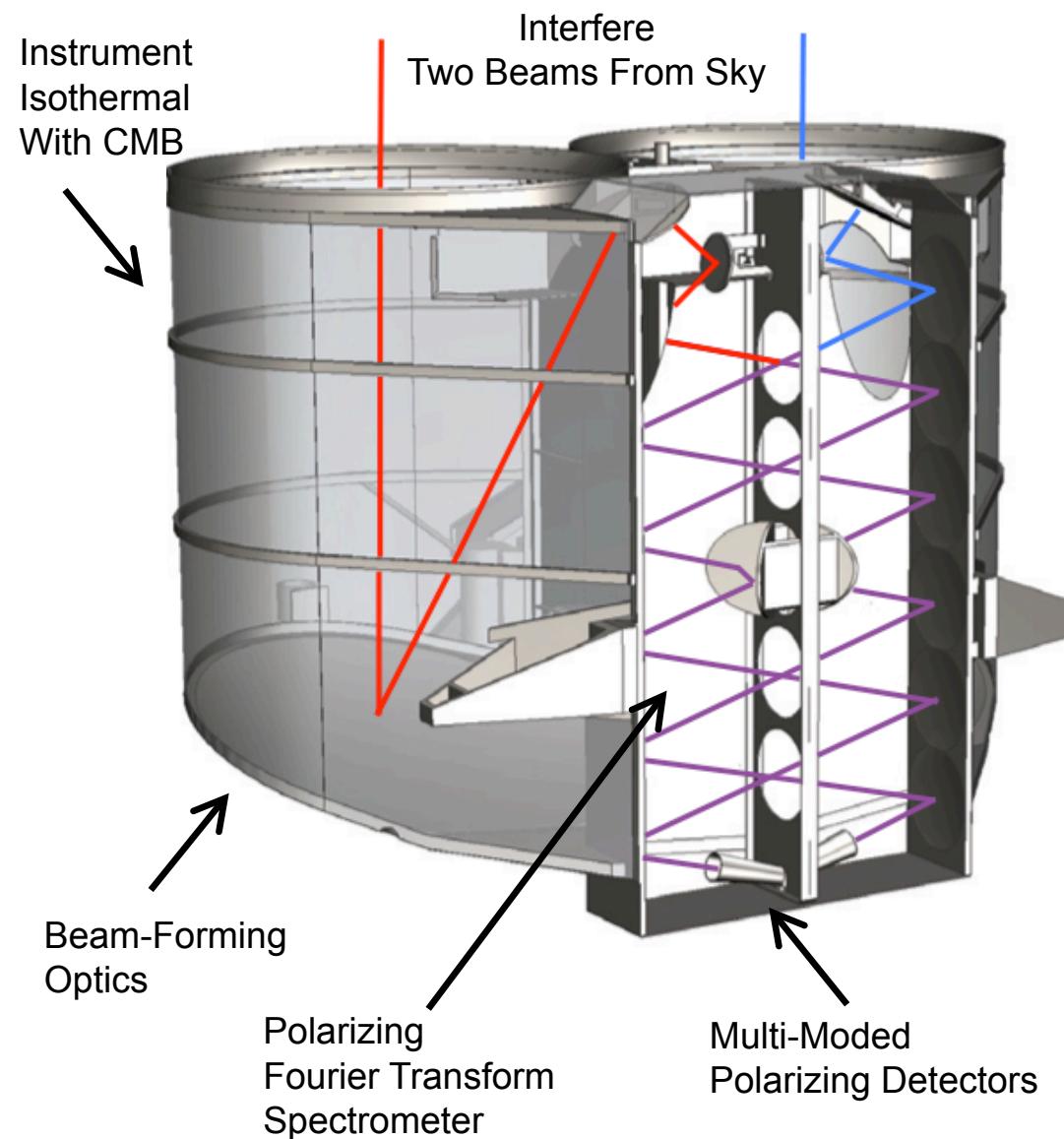
Conserve etendu: $N_{\text{mode}} = A\Omega / \lambda^2$

22,000 modes on each of 4 detectors

***Trade angular resolution
for frequency coverage and systematic error control***

Only possible from space!

PIXIE Nulling Polarimeter



**Measured Fringe Pattern
Samples Frequency Spectrum
of Polarized Sky Emission**

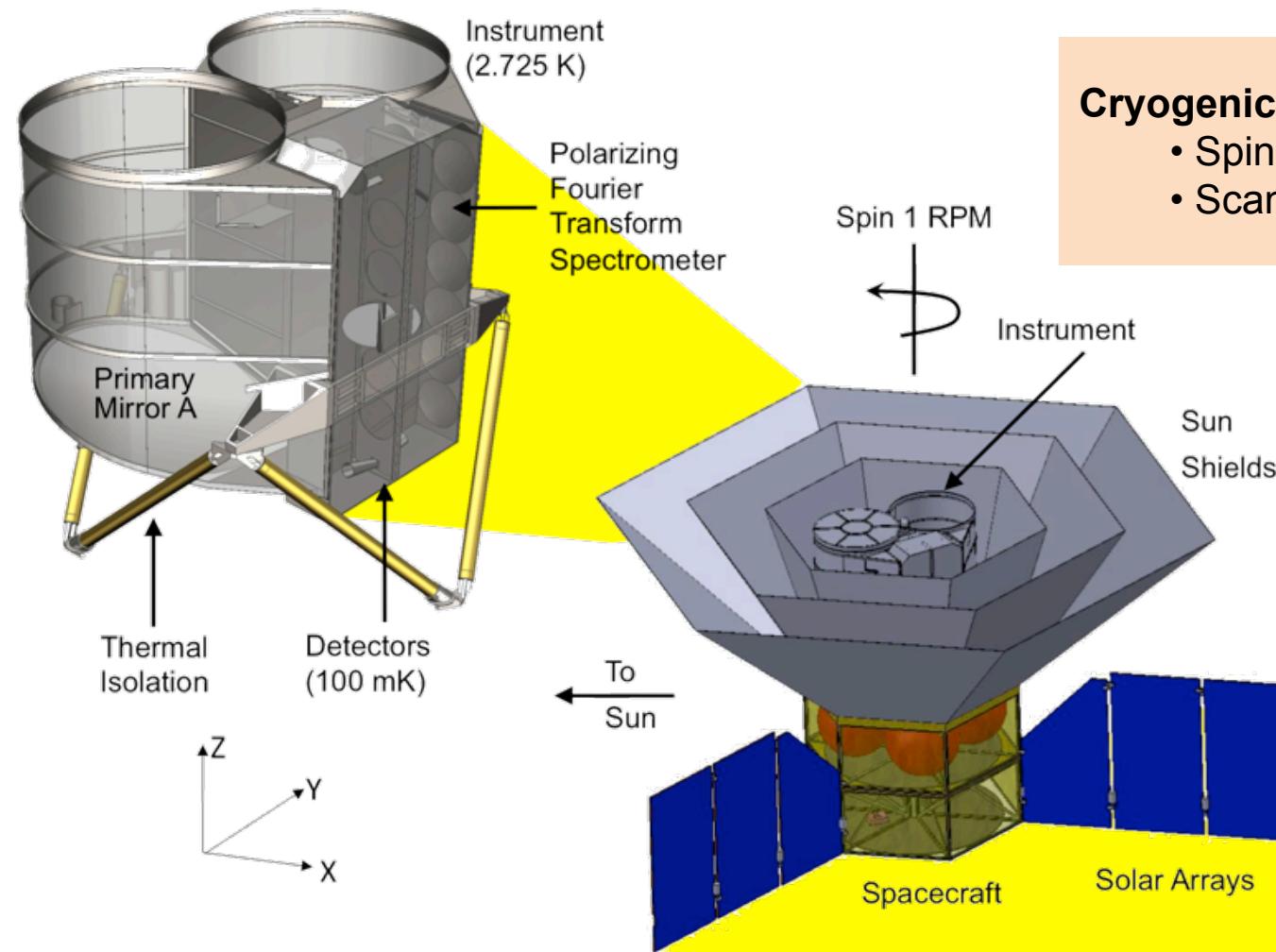
$$P_{Lx} = \frac{1}{2} \int (E_{Ay}^2 + E_{Bx}^2) + (E_{Bx}^2 - E_{Ay}^2) \cos(z\omega/c) d\omega$$

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

Stokes Q

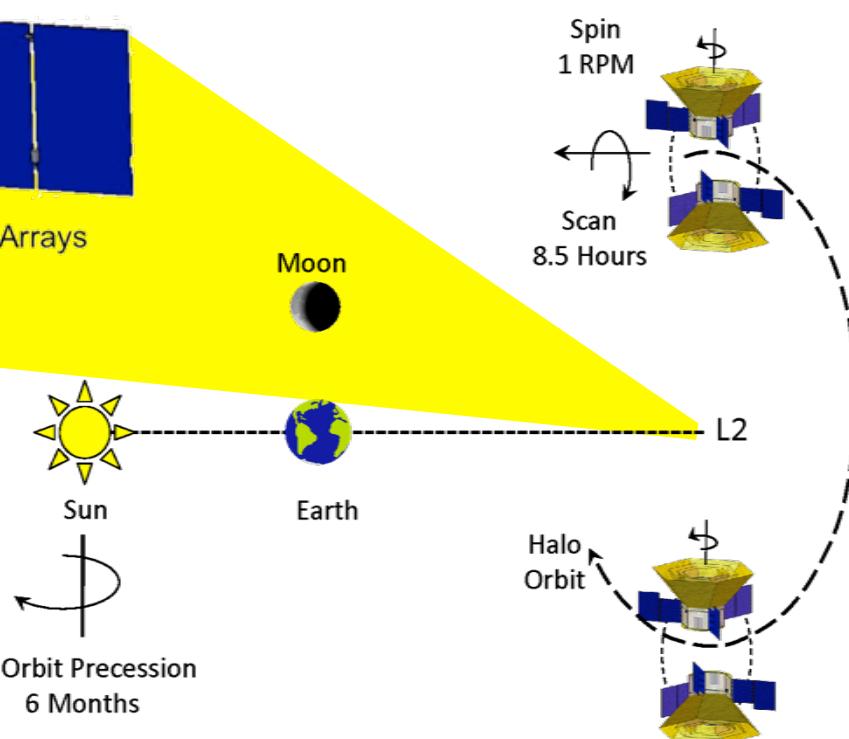
FIRAS With Polarization!

Instrument and Observatory



Cryogenic instrument at L2 halo orbit

- Spin at 1 RPM about instrument boresight
- Scan once every 8.5 hours about sun line



L2 Halo Orbit

- Spin axis 91 deg to sun line
- Precess scan plane to follow sun line
- Full-sky coverage every 6 months



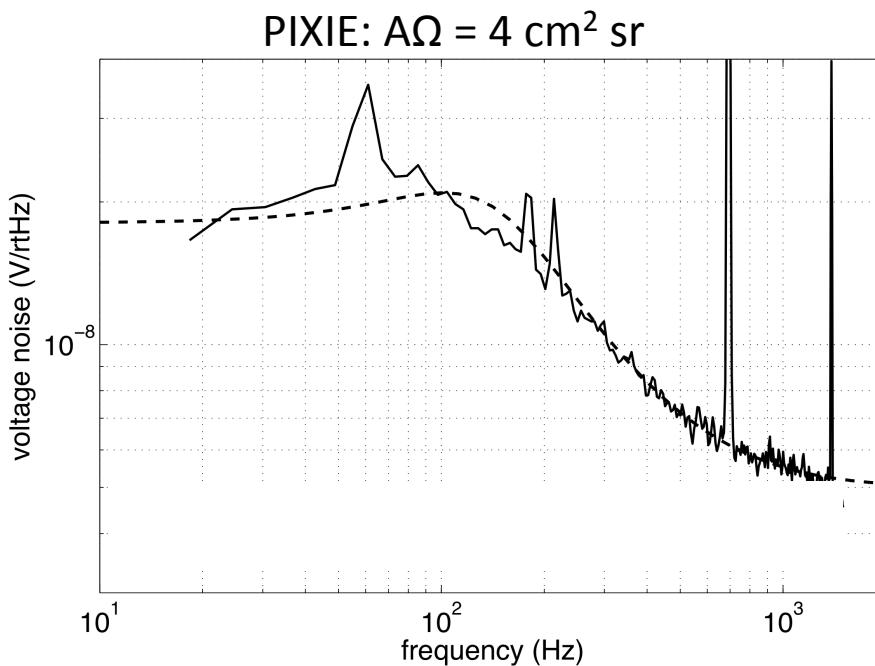
Sensitivity the Easy Way

Big Detectors in Multi-Moded Light Bucket

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

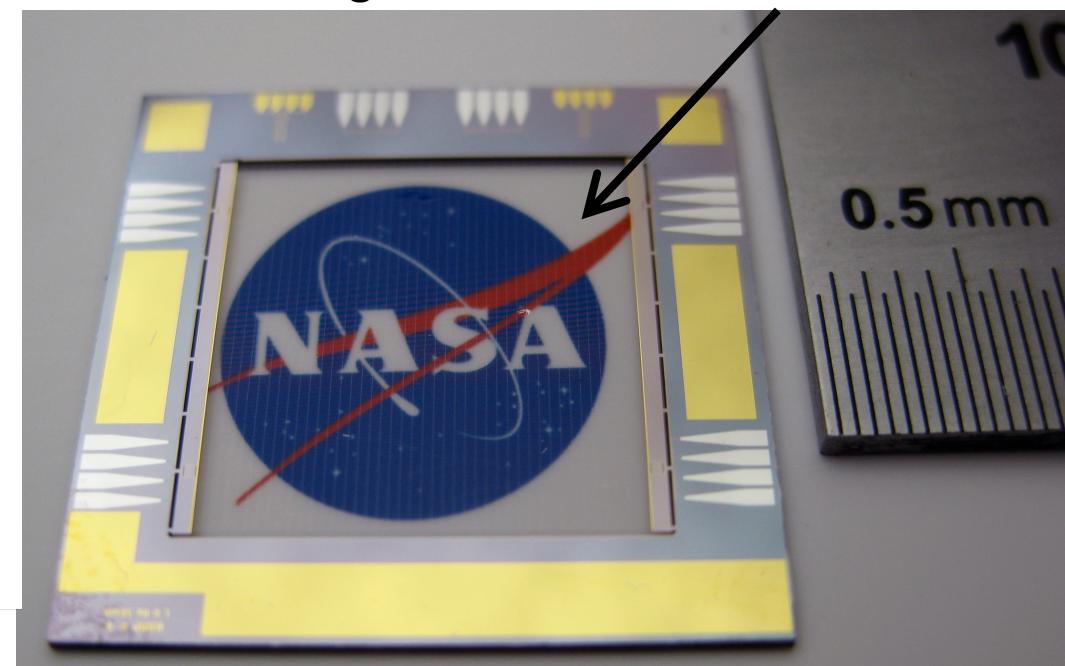
$$\delta I_\nu = \frac{\delta P}{A\Omega \Delta\nu (\alpha\epsilon f)}$$

- Photon noise $\sim (A\Omega)^{1/2}$
 Big detector: Negligible phonon noise
- Signal $\sim (A\Omega)$
 Big detector: S/N improves as $(A\Omega)^{1/2}$



Sensitivity 70 nK per $1^\circ \times 1^\circ$ pixel

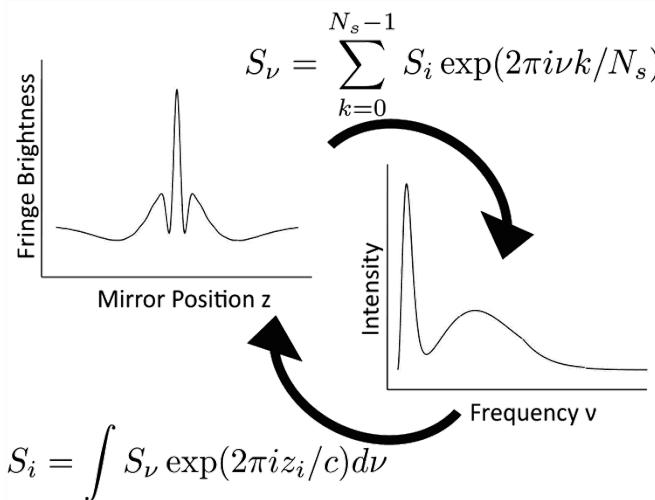
30x collecting area as Planck bolometers



PIXIE polarization-sensitive bolometer



Foregrounds the Easy Way

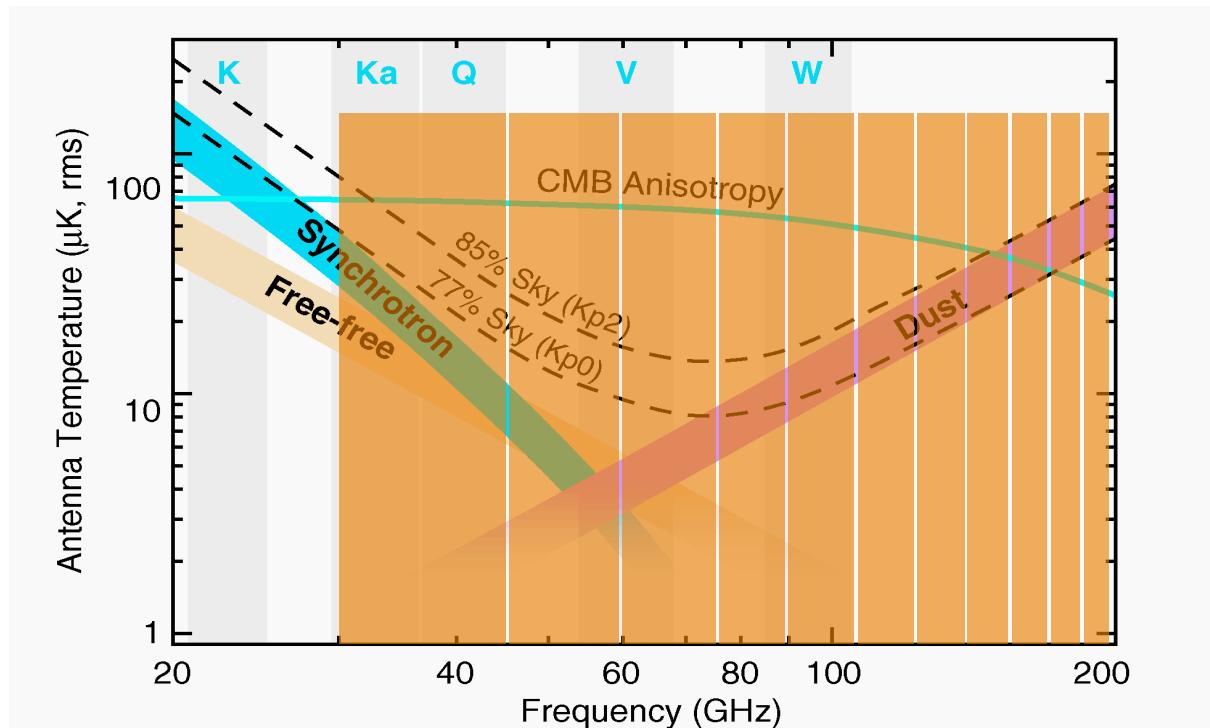


Phase delay L sets channel width

$$\Delta\nu = c/L = 15 \text{ GHz}$$

Number of samples sets frequency range

$$\nu_i = 15, 30, 45, \dots (N/2)*\Delta\nu$$

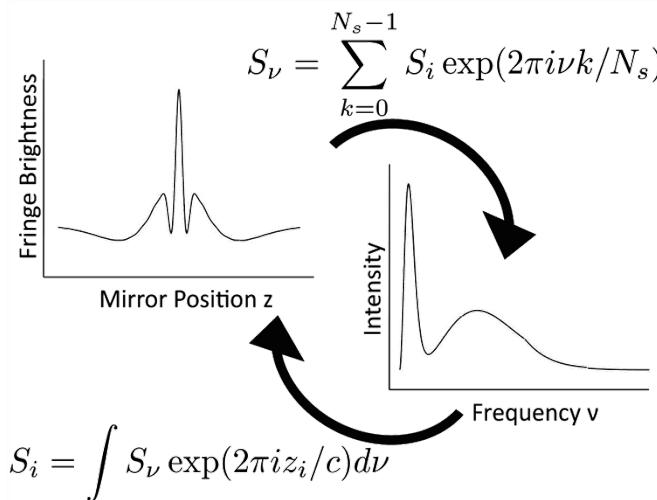


Example:
24 samples during fringe sweep
12 channels 15 GHz to 180 GHz

But why stop there?



Foregrounds the Easy Way

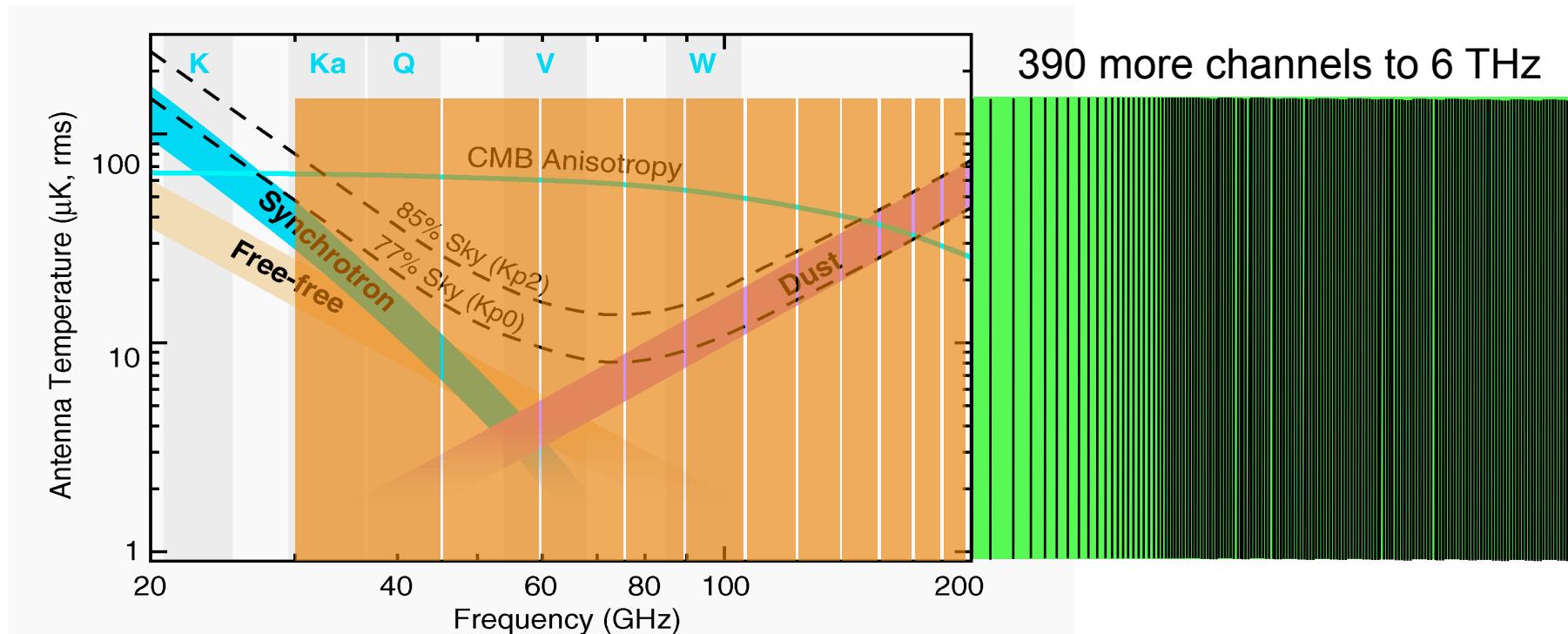


Phase delay L sets channel width

$$\Delta\nu = c/L = 15 \text{ GHz}$$

Number of samples sets frequency range

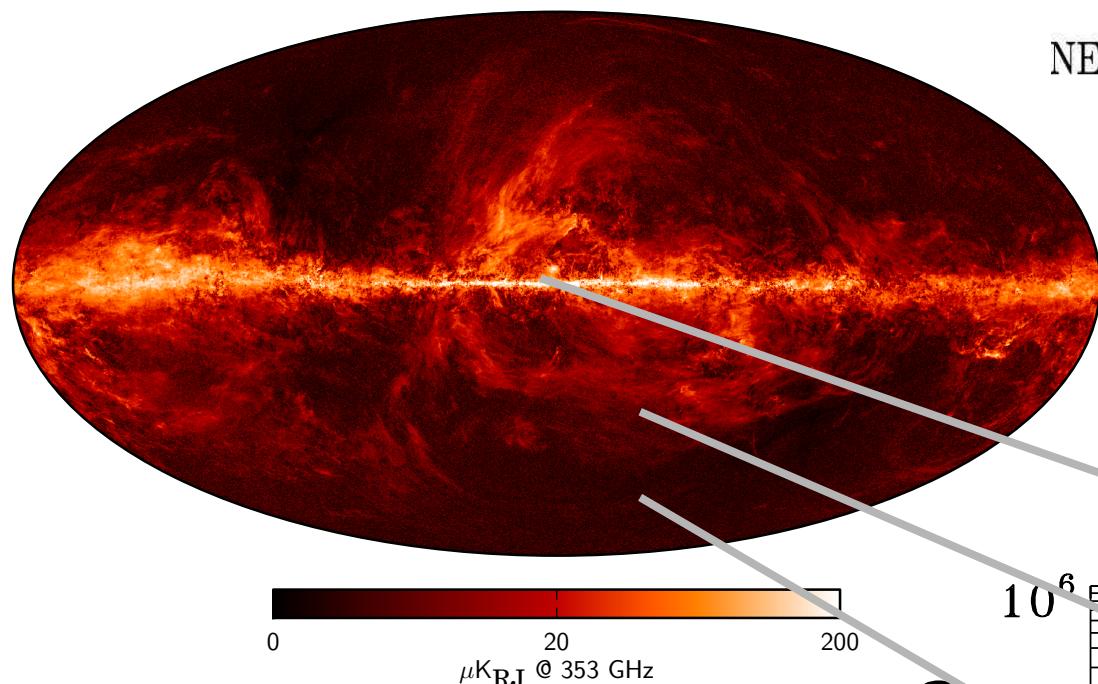
$$\nu_i = 15, 30, 45, \dots (N/2)^*\Delta\nu$$



Sample more often: Get more frequency channels!

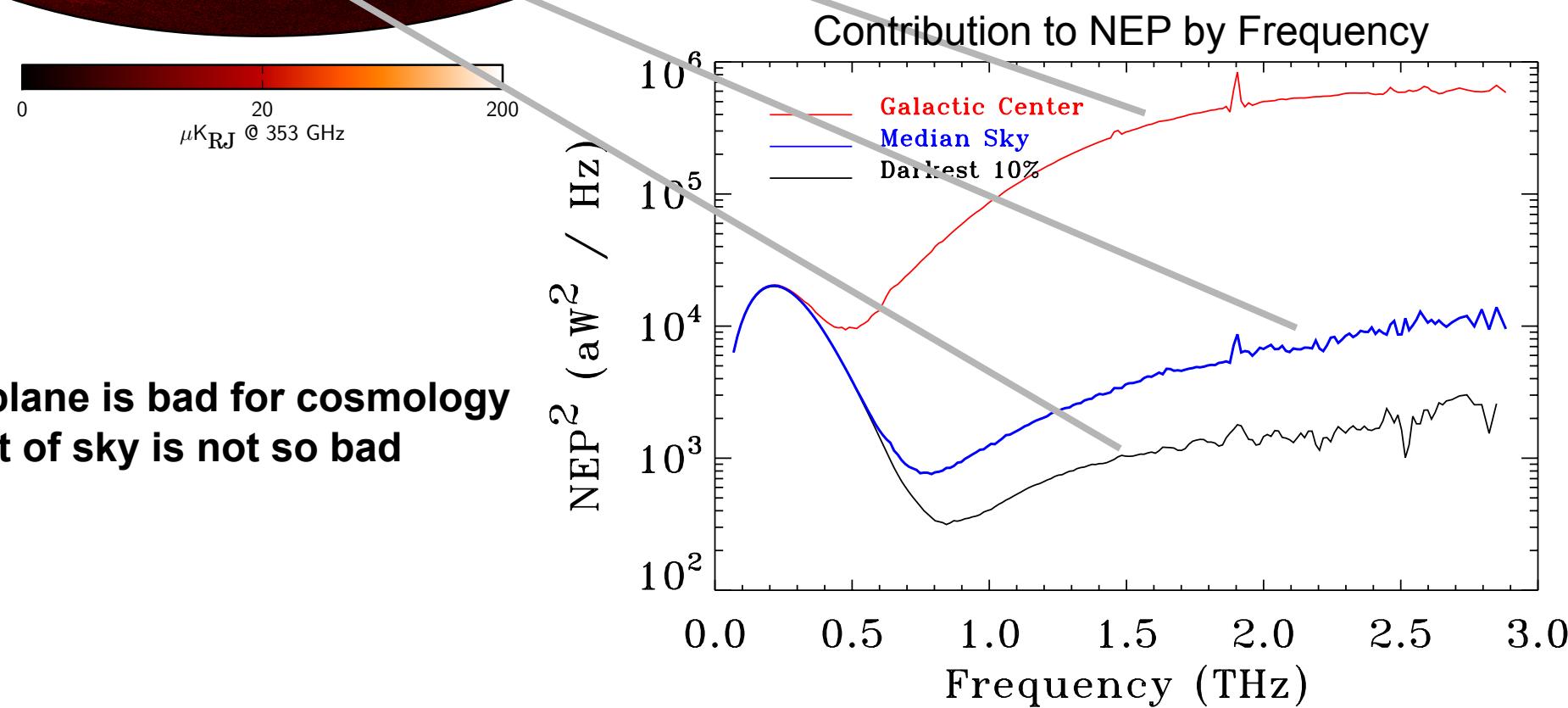


PIXIE Photon Noise



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

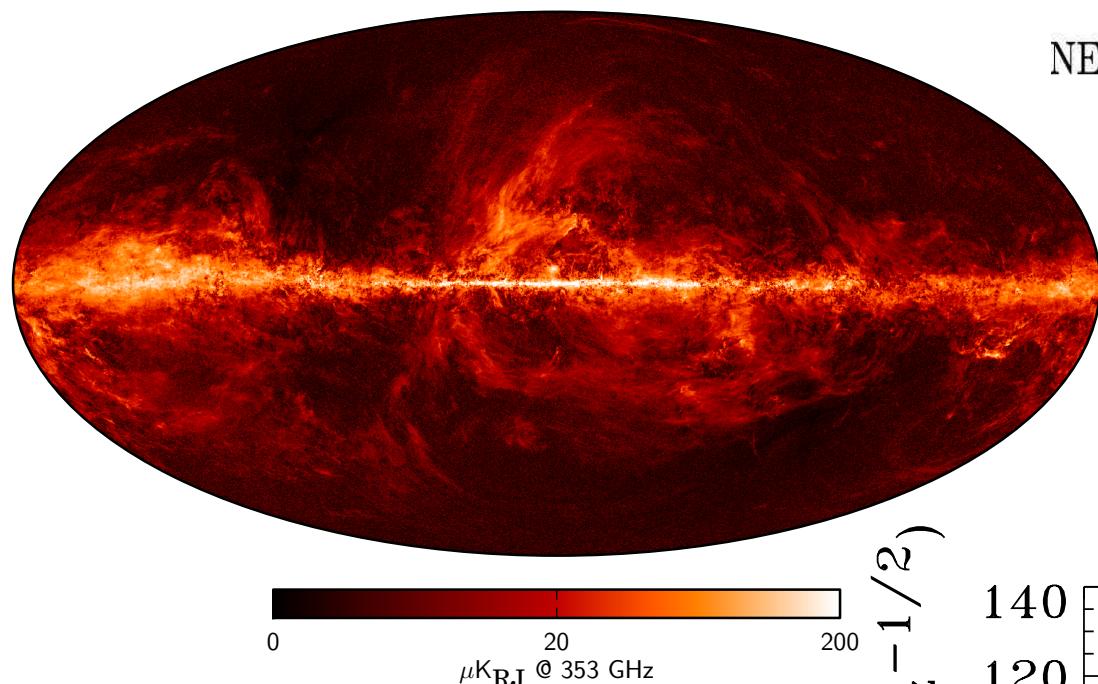
Compute NEP² from photon noise
Include CMB, dust, CIB, zodiacal light



Galactic plane is bad for cosmology
Rest of sky is not so bad

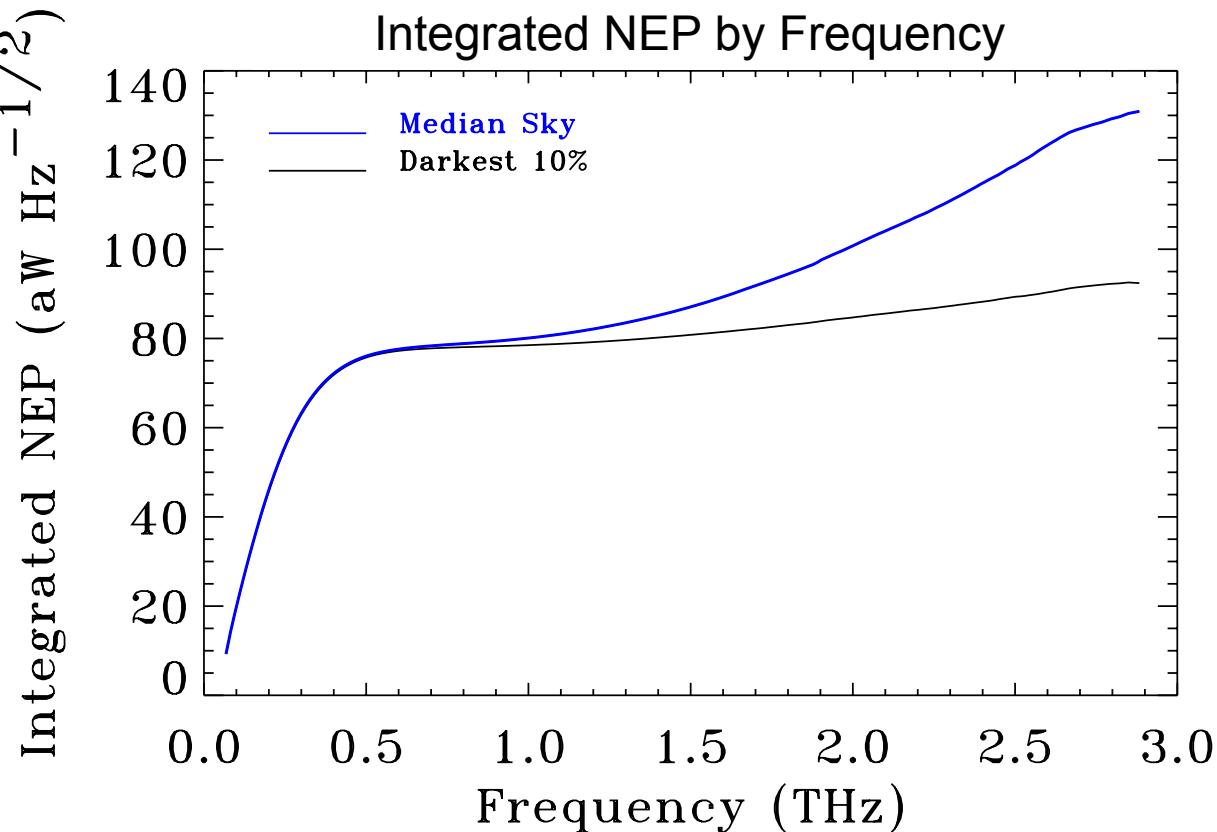


PIXIE Photon Noise



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

Compute NEP² from photon noise
Include CMB, dust, CIB, zodiacal light

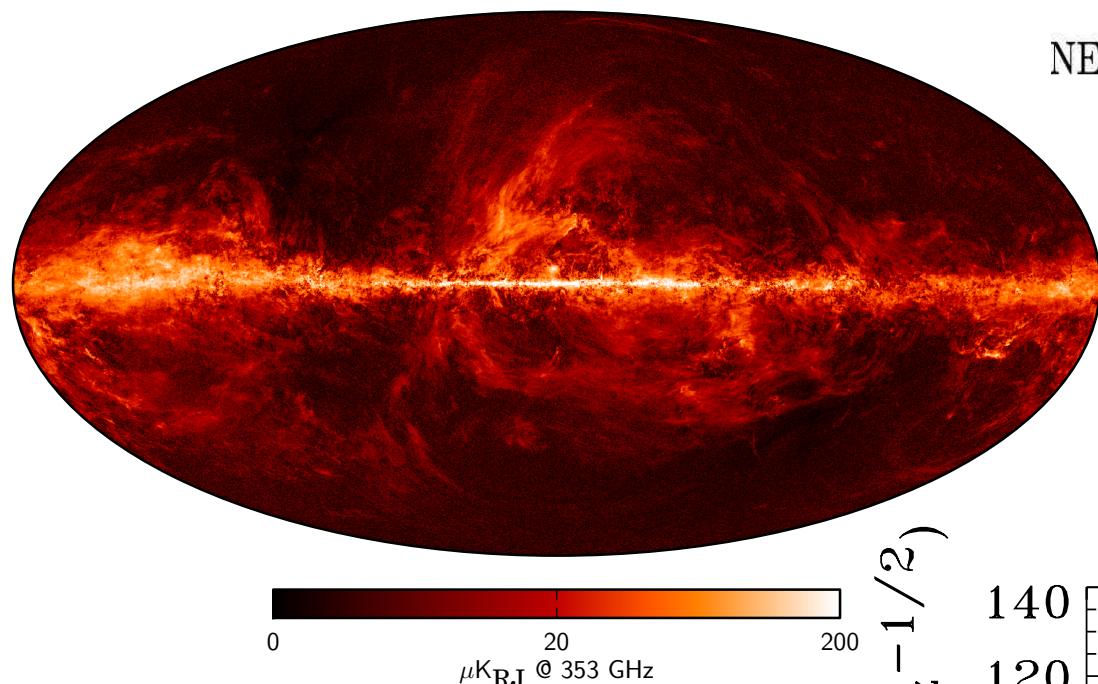


Galactic plane is bad for cosmology
Rest of sky is not so bad

No filter on optics:
Increase CMB noise by factor ~2



PIXIE Photon Noise

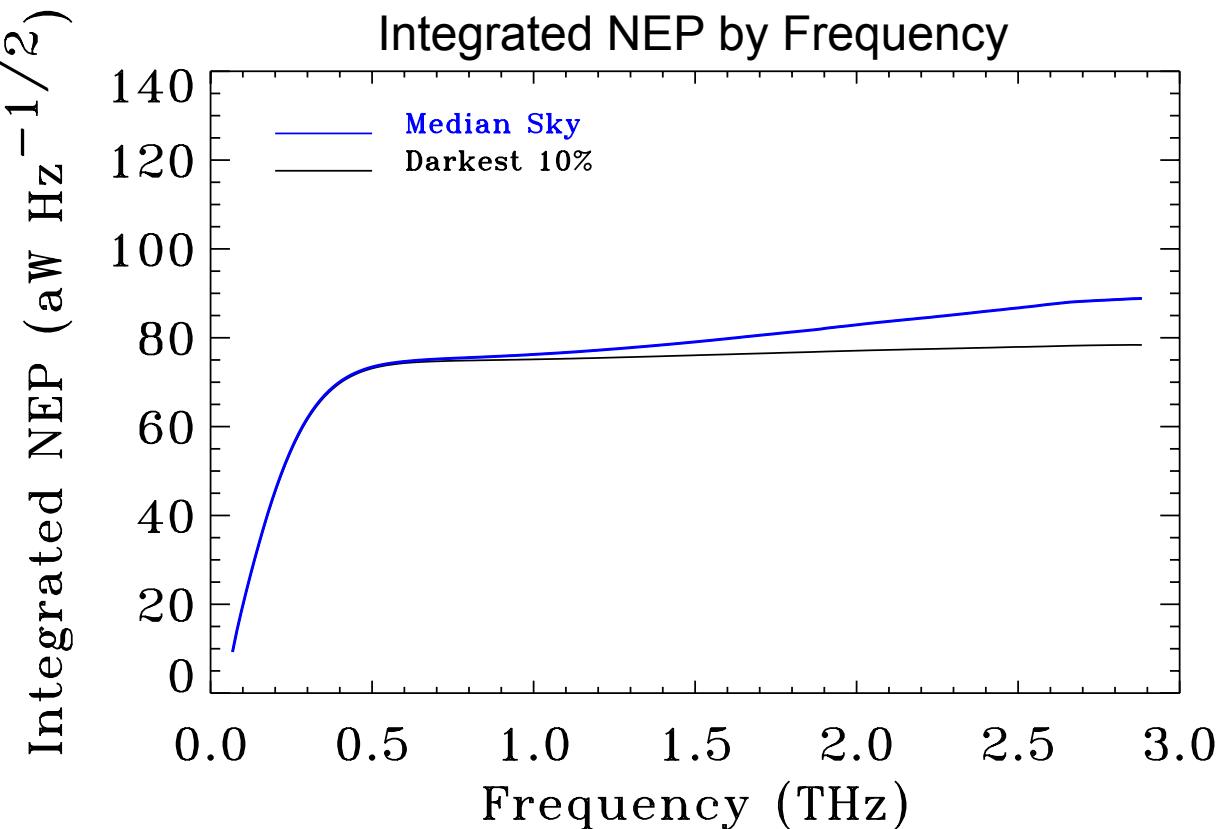


**Galactic plane is bad for cosmology
Rest of sky is not so bad**

**Lowpass filter on optics:
Increase CMB noise by ~20%**

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

Compute NEP² from photon noise
Include CMB, dust, CIB, zodiacal light





Why Add THz Channels?

The Usual Prescription



Put a zebra
into your sim ...



... Fit for
zebra parameters
Nfeet, NStripes, B/W ratio...



Why Add THz Channels?

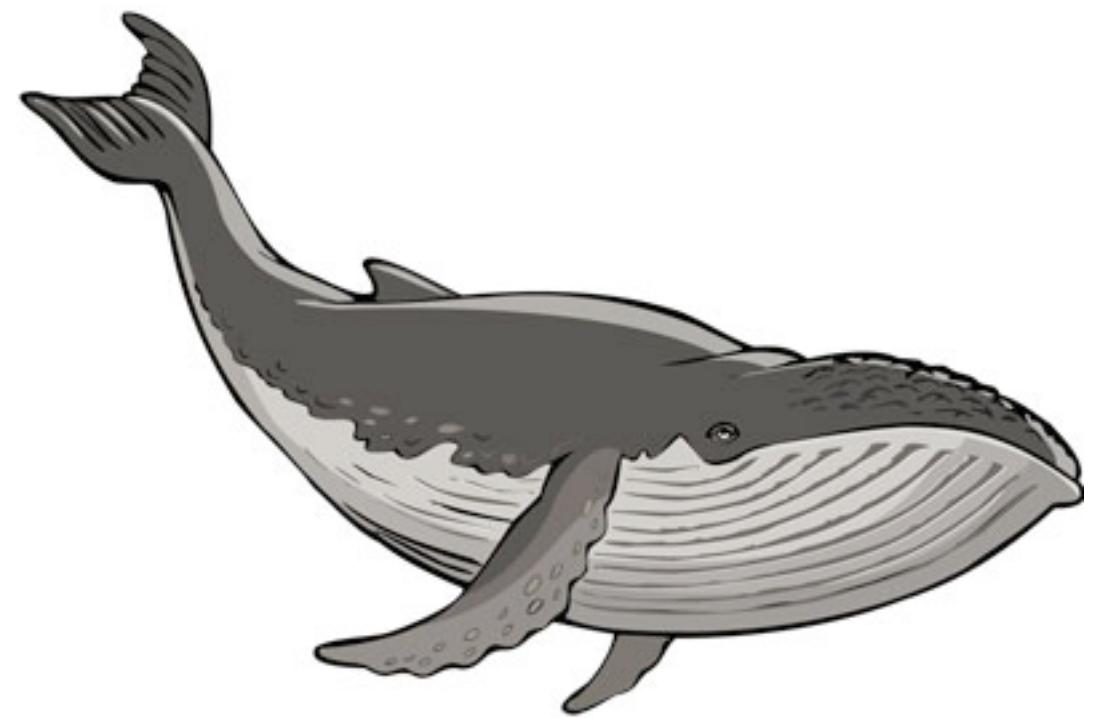
The Usual Prescription



Put a zebra
into your sim ...



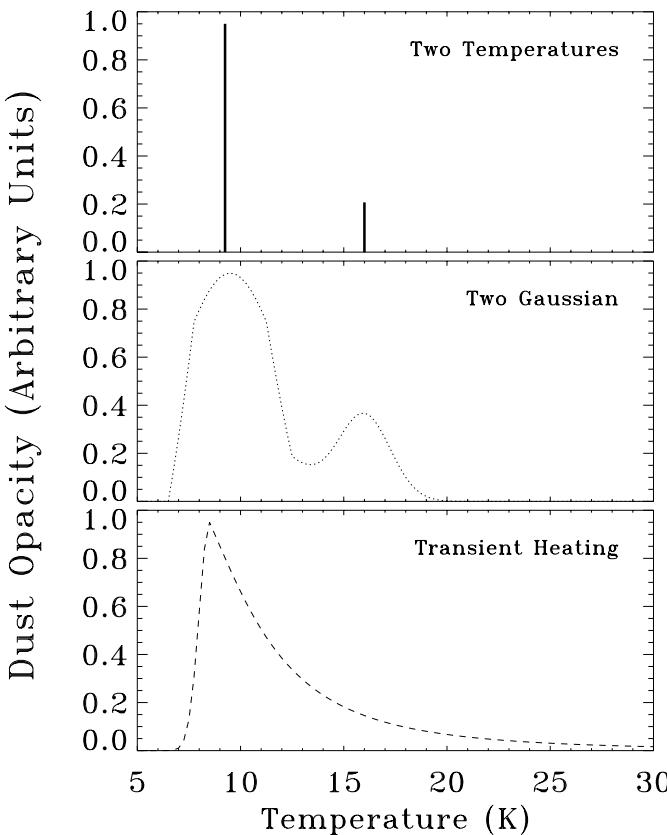
... Fit for
zebra parameters
Nfeet, NStripes, B/W ratio ...



What if Nature had something else in mind?



Why Add THz Channels?

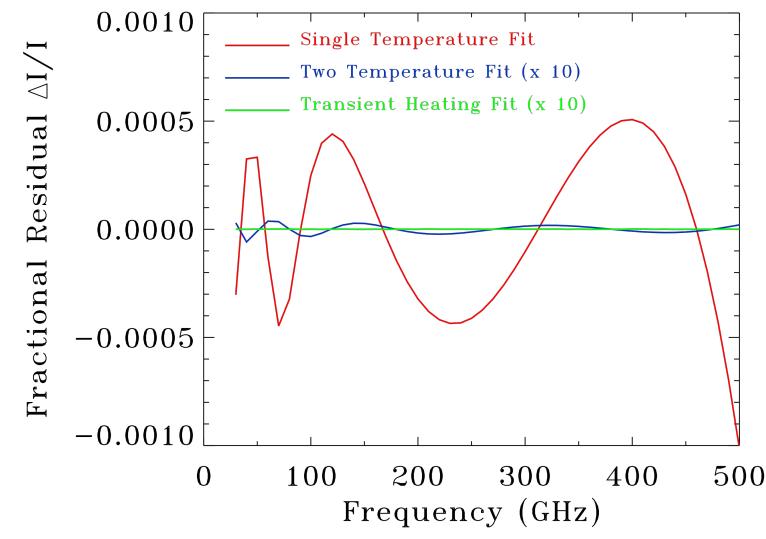
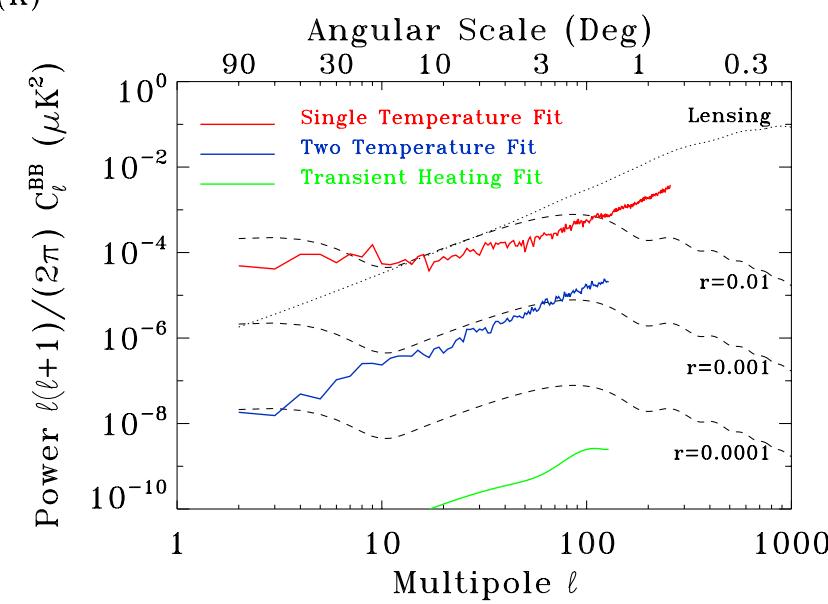


CMB residuals when
Input = transient model
Output = other model
45 channels, 30 to 500 GHz

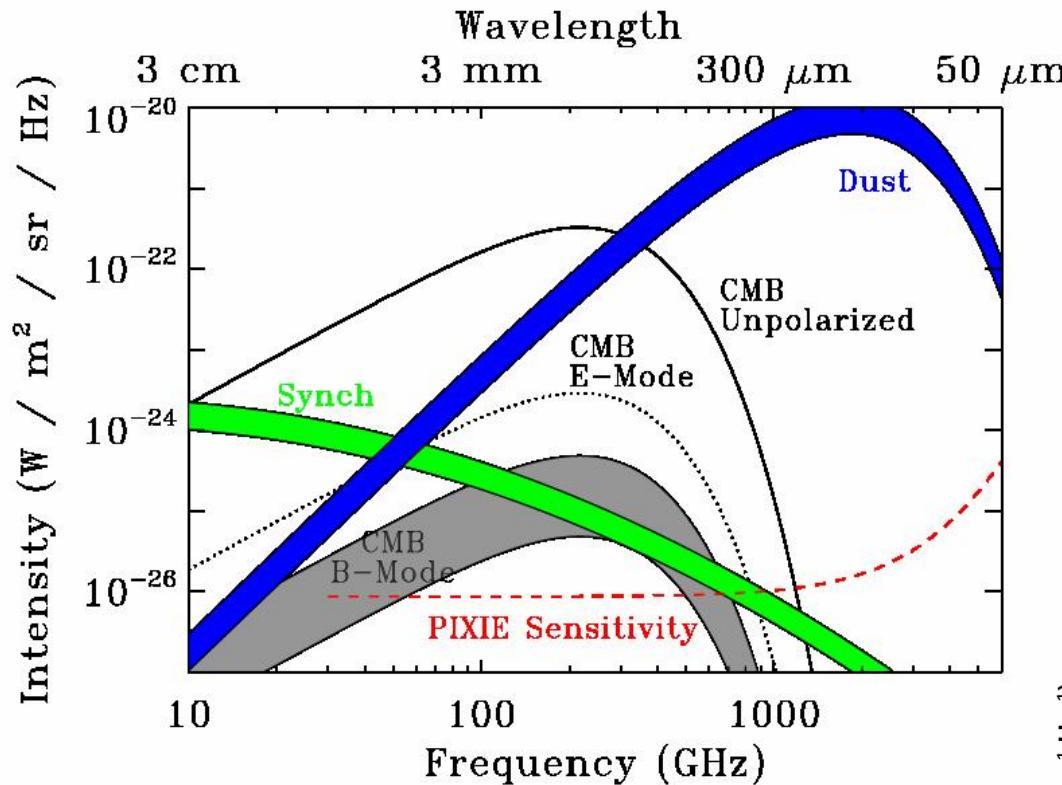
Pick one dust model for simulation input
Fit sim using different dust model

Easy to get non-trivial CMB bias ($\Delta r > 10^{-3}$)
Despite excellent fit to combined sky emission

Need THz data to distinguish dust models



PIXIE “Foreground Machine”



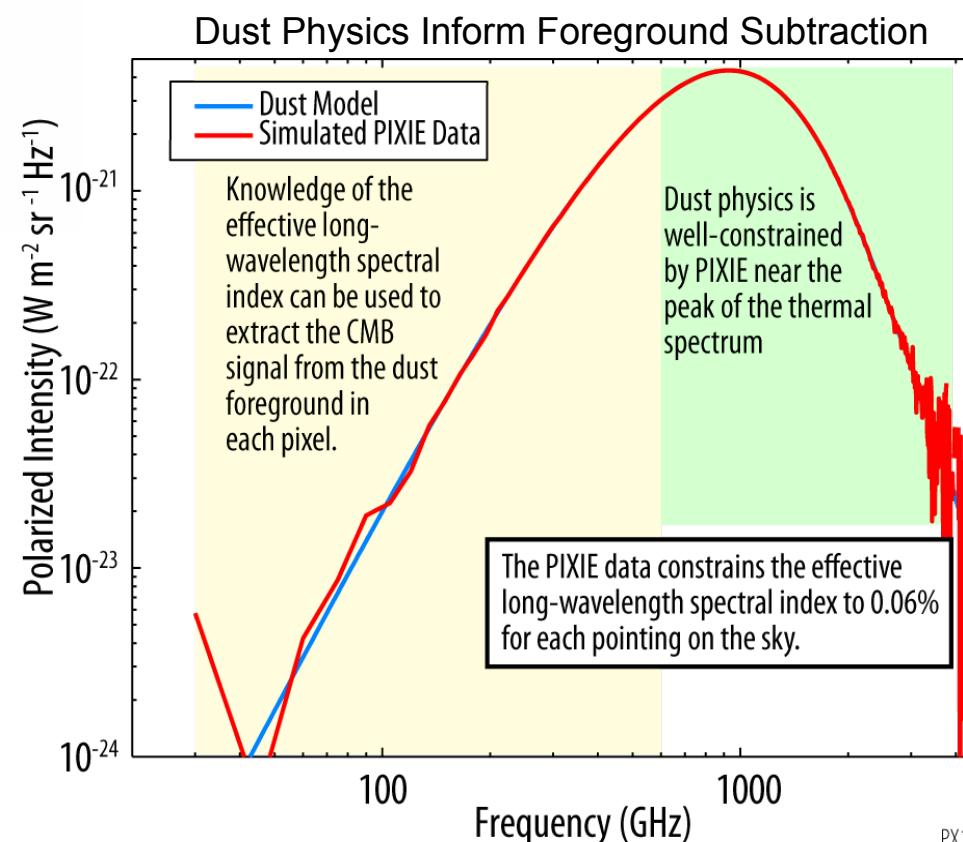
Sensitivity plus broad frequency coverage

Foreground S/N > 100 in each pixel and freq bin
Spectral index uncertainty ± 0.001 in each pixel

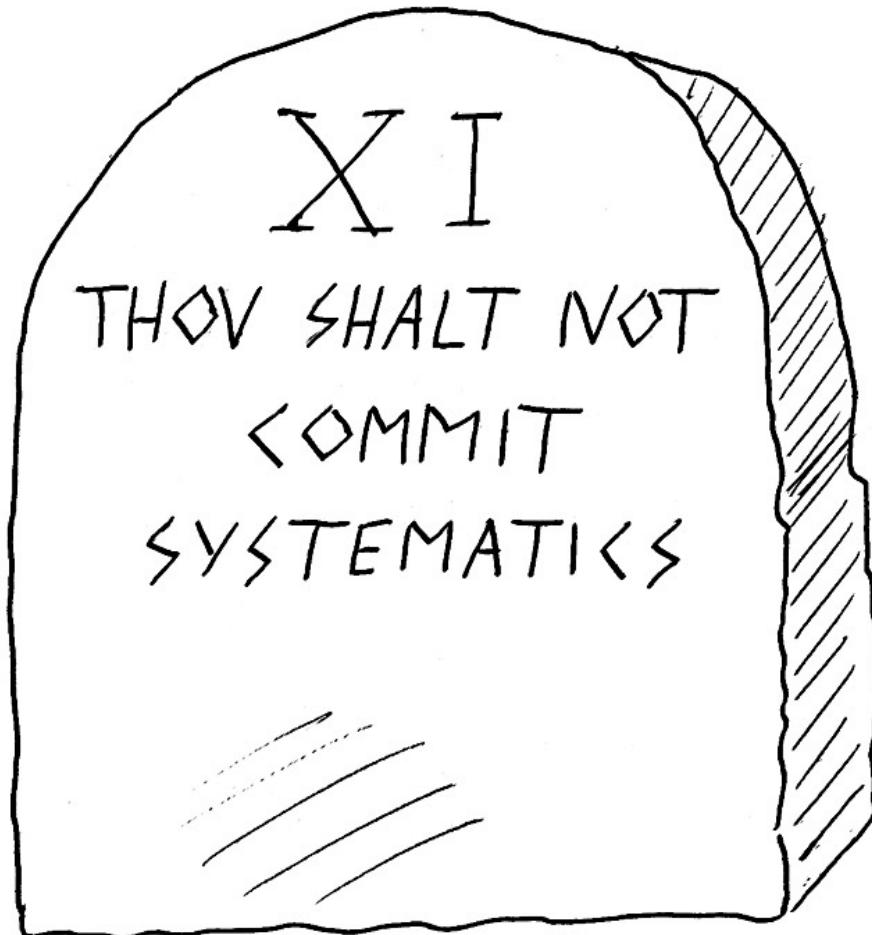
If PIXIE can't figure out the foregrounds,
it probably can't be done!

Spectral coverage spanning 7+ octaves

Polarized spectra from 30 GHz to 6 THz
400 channels with mJy sensitivity per channel



Systematic Error Control



Lesson from FIRAS:

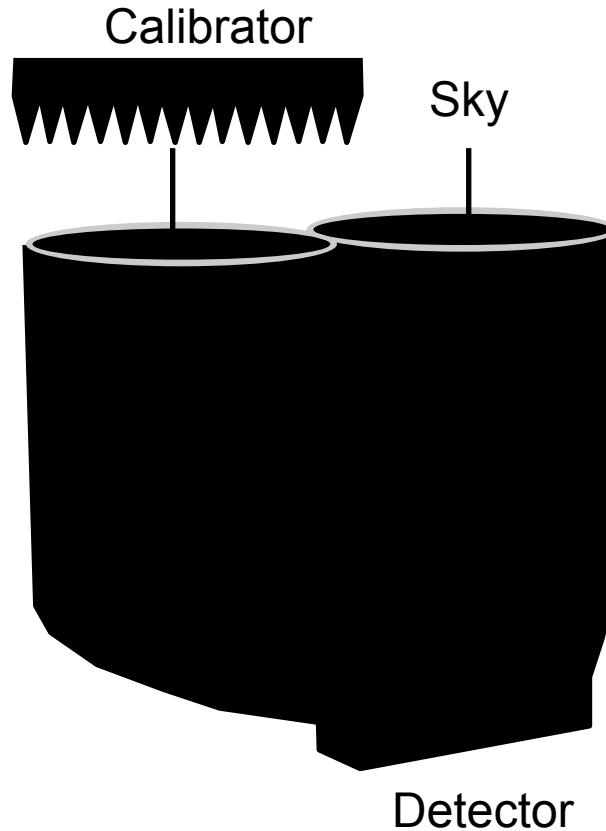
Parts-per-billion measurement requires null measurement plus multiple levels of modulation

The 11th Commandment



Systematic Errors I

Keep Instrument Isothermal With Sky



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 error signal

Imager: Telescope at 4 K

PIXIE: Instrument at 2.725 K

$\Delta T = 1.3 \text{ K}$ lever for systematics

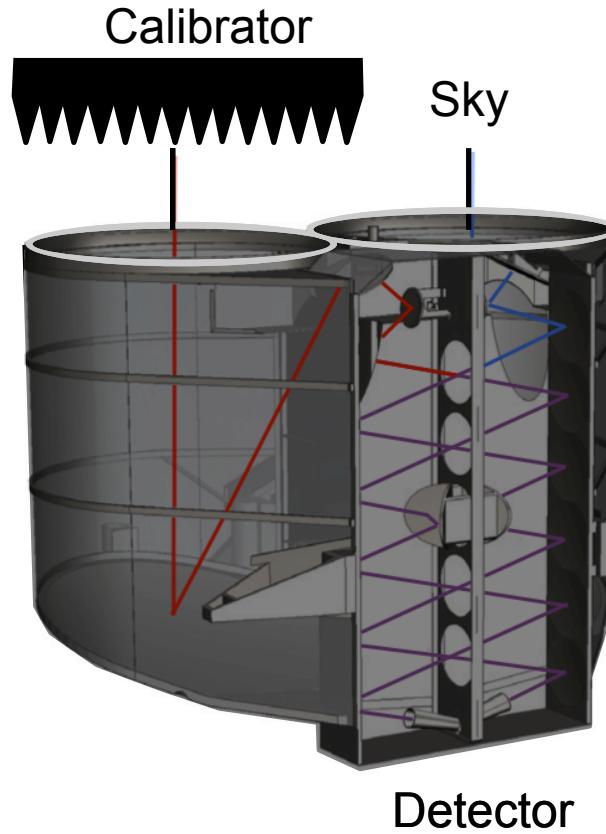
$\Delta T = 0.005 \text{ K}$ lever for systematics

Isothermal operation alone reduces systematic errors by factor 300!



Systematic Errors II

Chain Multiple Nulls Together



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

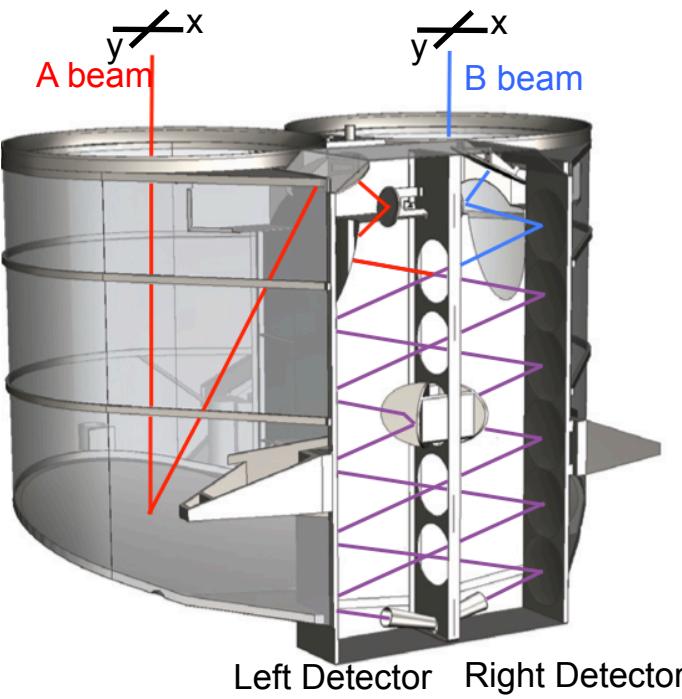
Multiple levels of nulling reduce systematics to negligible levels without relying on any single null

Symmetry and Systematic Error

20 Ways to Fix An Error

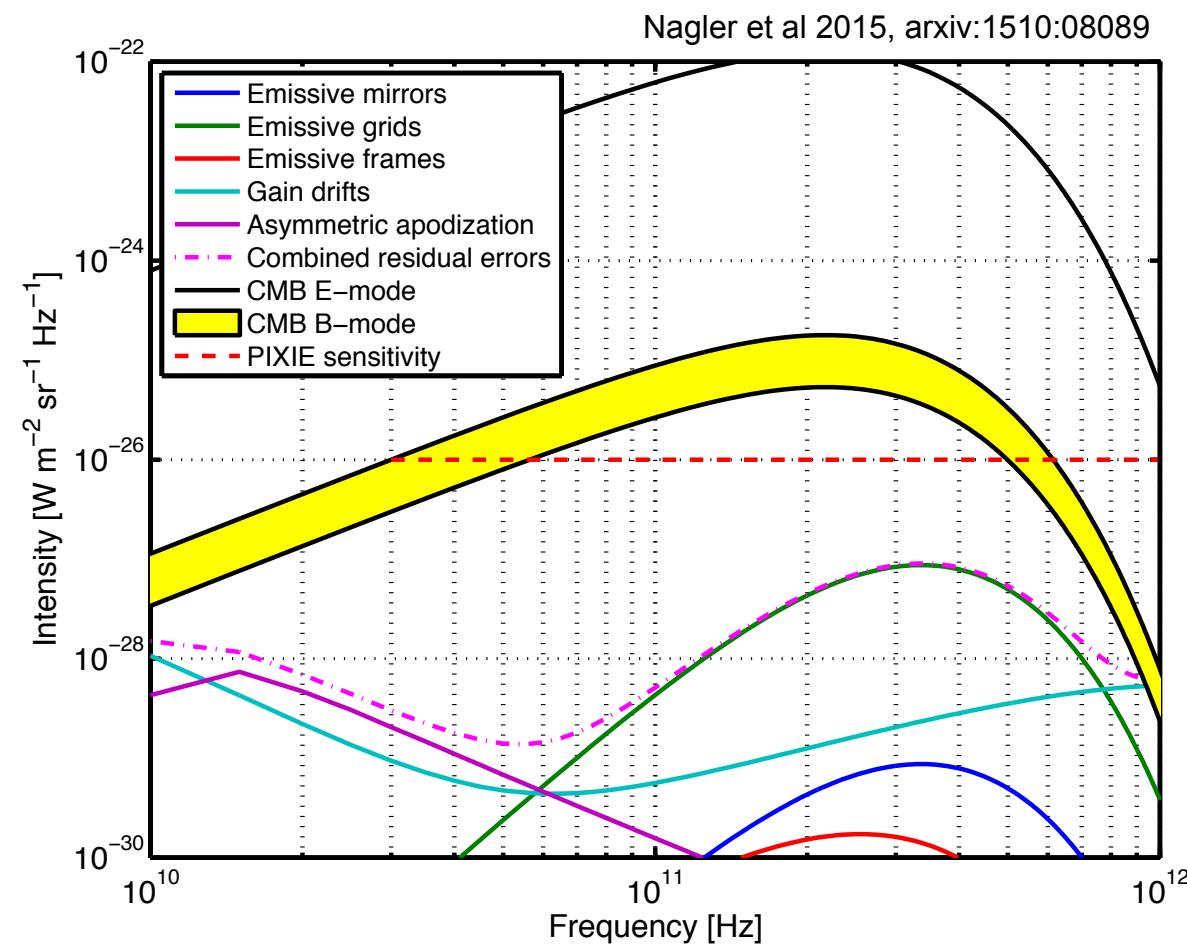


Symmetry	Mitigates
x vs y Polarization	Pointing
Left vs Right Detector	Particle Hits
A vs B Beam	Differential loss
Real vs Imaginary FFT	Detector heat capacity
Forward vs Backward FTS	Microphonics
Calibrator over A vs B	Calibration, Beam
Calibrator Hot vs Cold	Non-Linearities
Ascending vs Descending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



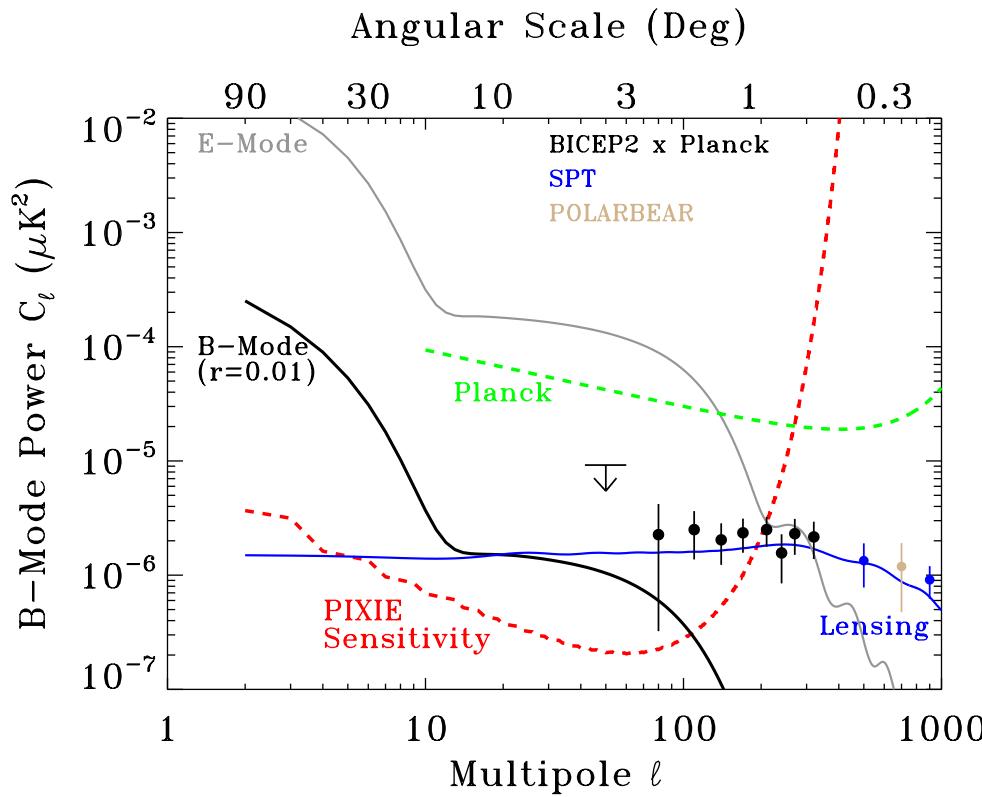
Multiple nulls combine to reduce systematic errors

- Isothermal instrument: 300x better than FIRAS
- Multiple symmetries: no reliance on any single one
- Estimated systematic errors < 1 nK





PIXIE and Polarization



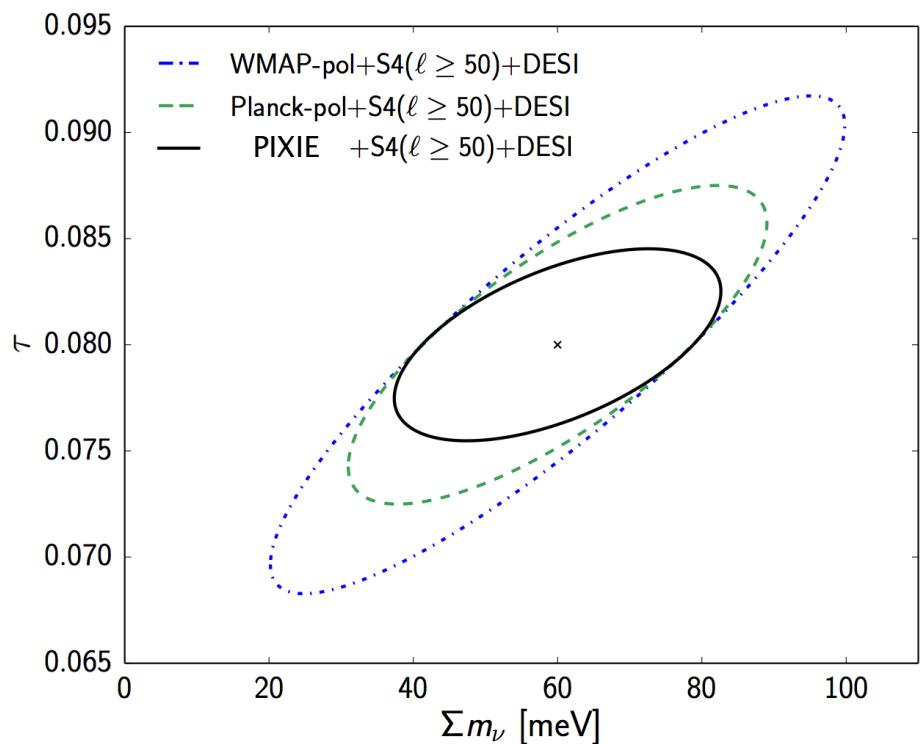
Complement Ground-Based Efforts

- Large angular scales ($2 < \ell < 300$)
- Legacy dust foreground
- EE to get reionization / tau
- Improve limits on neutrino mass
- Legacy data for mm & sub-mm calibration

Sensitivity $r < 2 \times 10^{-4}$ (68% CL)

CMB sensitivity 70 nK per 1° pixel
Test / characterize minimal inflationary models

Cosmic-variance-limited EE spectrum
Characterize astrophysical foregrounds



Do From Space That Which Can Only Be Done From Space

BUT WAIT,
there's more!

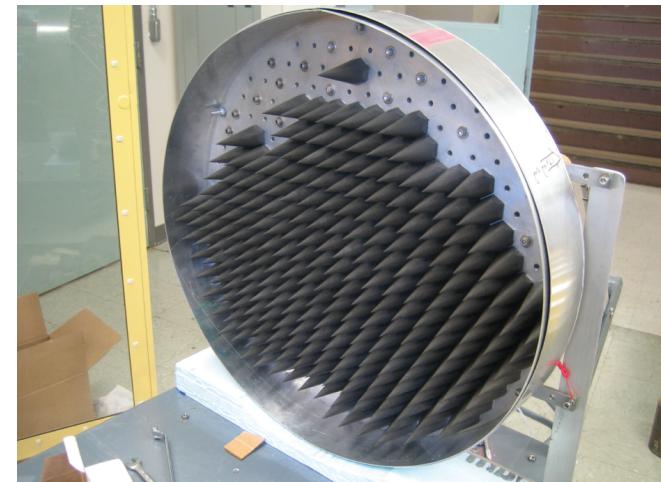
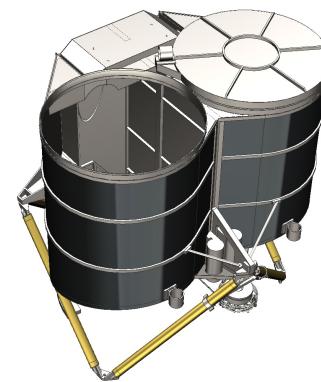


Blackbody Calibrator Tests Blackbody Distortions



**Calibrator stowed:
Polarization only**

$$\left\{ \begin{array}{l} P_{Lx} = \frac{1}{2} \int (E_{Ay}^2 + E_{Bx}^2) + (E_{Bx}^2 - E_{Ay}^2) \cos(z\omega/c) d\omega \\ P_{Ly} = \frac{1}{2} \int (E_{Ax}^2 + E_{By}^2) + (E_{By}^2 - E_{Ax}^2) \cos(z\omega/c) d\omega \end{array} \right. \quad \text{Sky Stokes Q}$$



Partially-assembled
blackbody calibrator

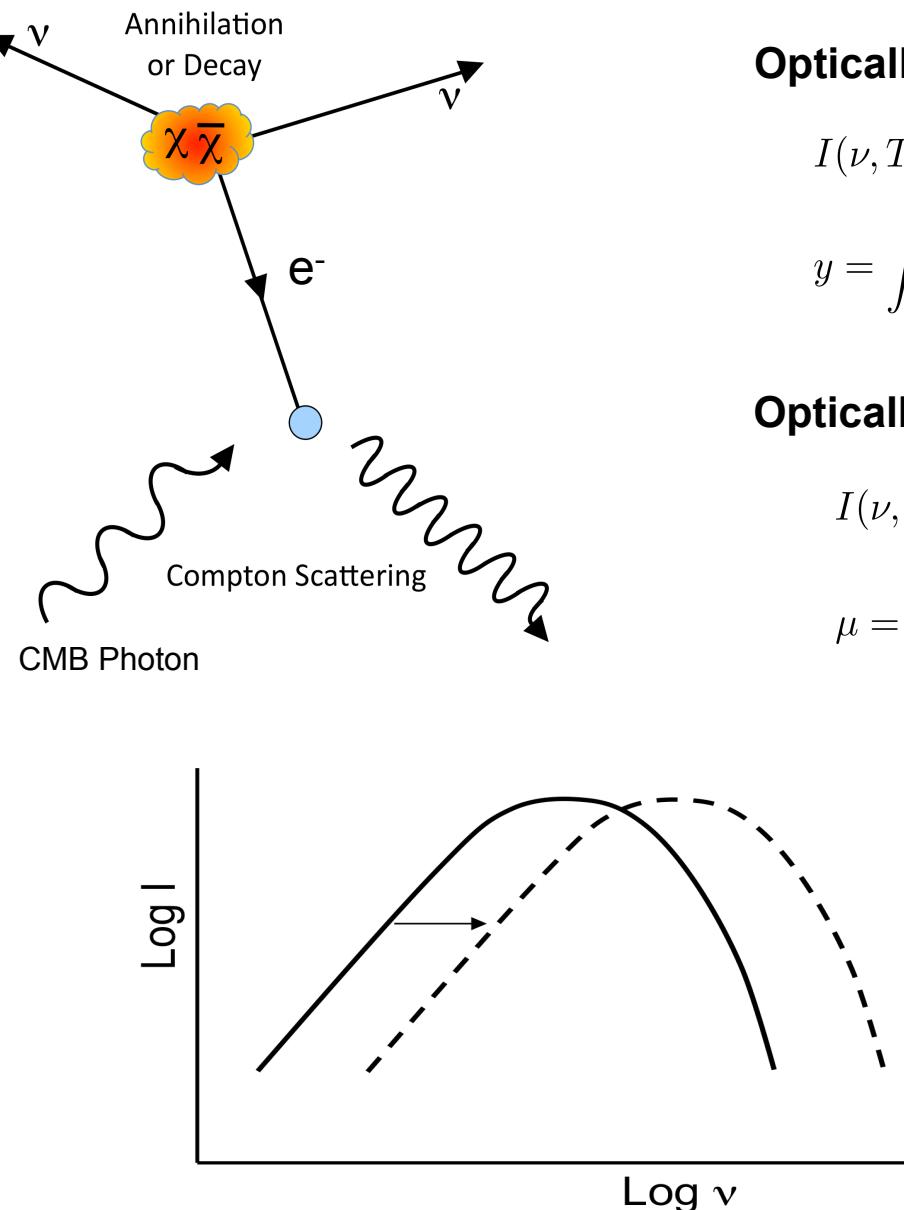
**Calibrator deployed:
Spectral distortions!**

$$\left\{ \begin{array}{l} P_{Lx} = \frac{1}{2} \int (E_{Cal,y}^2 + E_{Sky,x}^2) + (E_{Sky,x}^2 - E_{Cal,y}^2) \cos(z\omega/c) d\omega \\ P_{Ly} = \frac{1}{2} \int (E_{Cal,x}^2 + E_{Sky,y}^2) + (E_{Sky,y}^2 - E_{Cal,x}^2) \cos(z\omega/c) d\omega \end{array} \right. \quad \text{[Calibrator-Sky] Spectral Difference}$$

Like FIRAS,
But 1000x
More Sensitive!



Spectral Distortion from Energy Release



Optically thin case: Compton y distortion

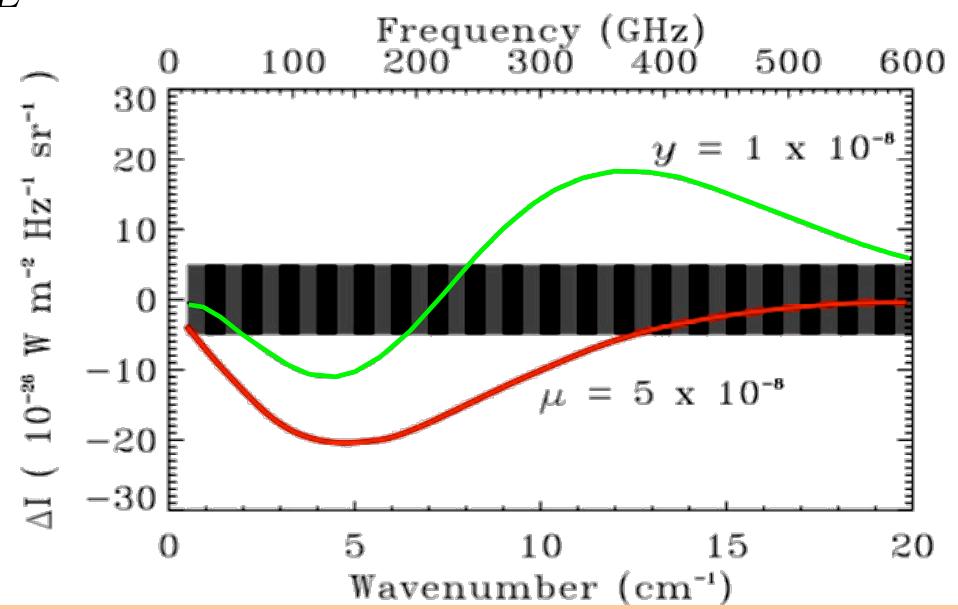
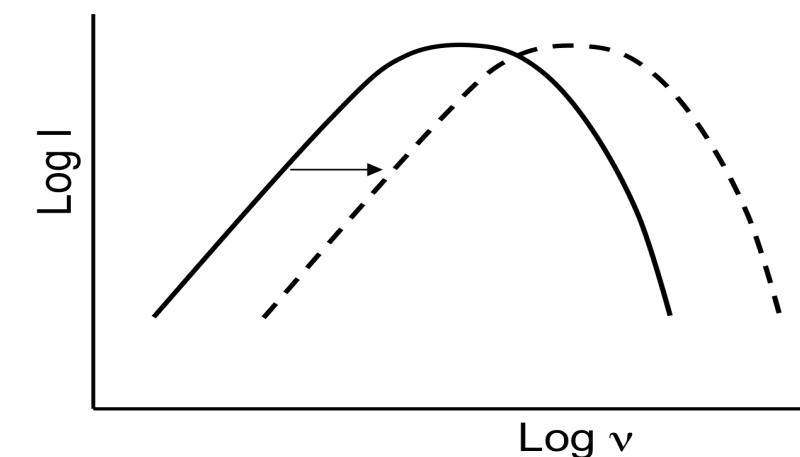
$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(x) - 1} \left[1 + \frac{y x \exp(x)}{\exp(x) - 1} \left(\frac{x}{\tanh(x/2)} - 4 \right) \right]$$

$$y = \int \frac{kT_e}{mc^2} n c \sigma_T dt$$

Optically thick case: Chemical potential distortion

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

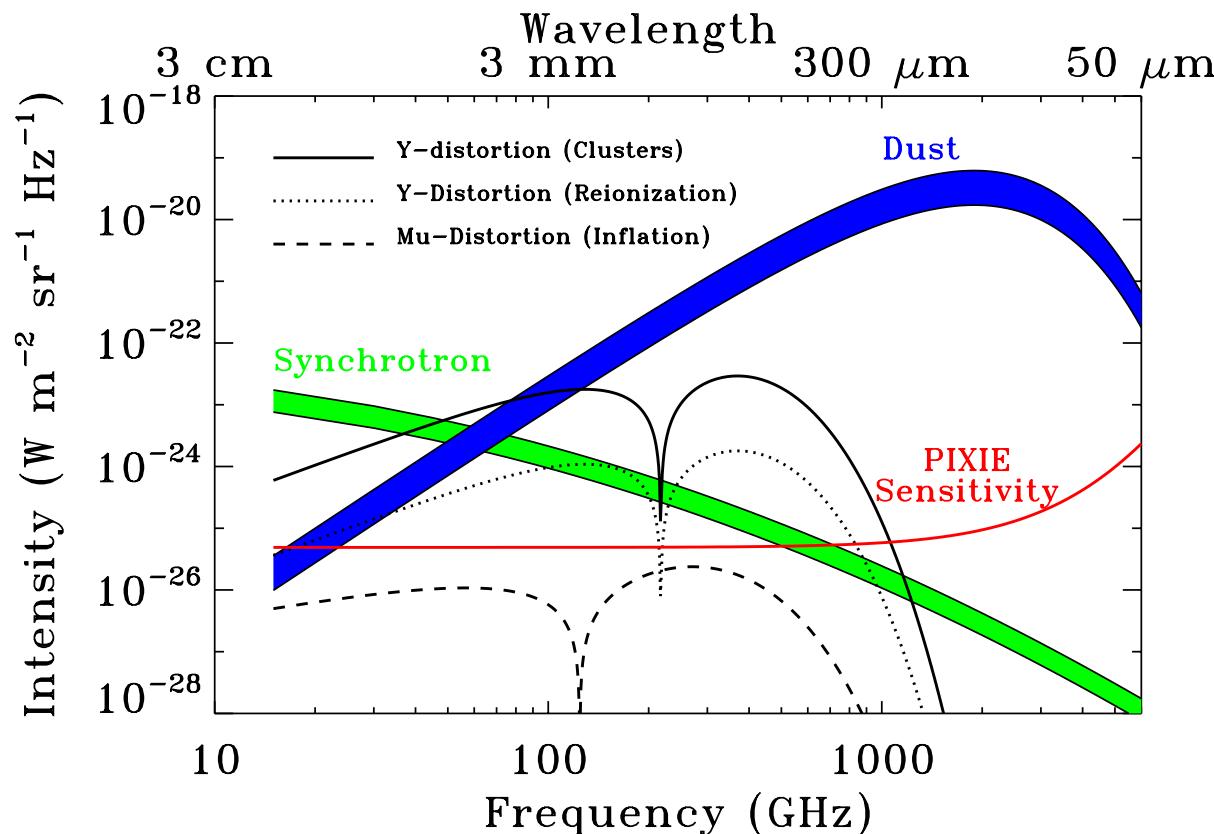
$$\mu = 1.4 \frac{\Delta E}{E}$$



Distortion to blackbody spectrum proportional to integrated energy release



PIXIE Spectral Capability



Improve COBE by factor of 1000
 $|\mu| < 10^{-8}$
 $|y| < 2 \times 10^{-9}$

Expect significant detections

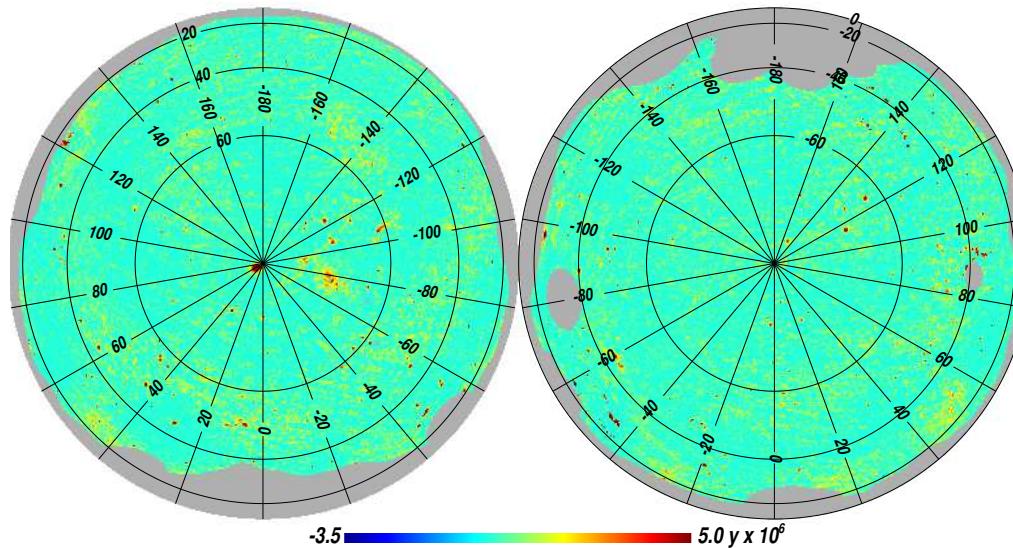
- 1500σ for cluster y distortion
- 95σ for reionization y distortion
- 3σ for inflation μ distortion

Open new discovery space

- Dark matter annihilation
- Exotic physics

Bring spectral distortions to same precision as B-mode polarization

Spectral Distortions: Structure Formation



Contribution from unresolved sources

Total monopole: $y = 1.6 \times 10^{-6}$

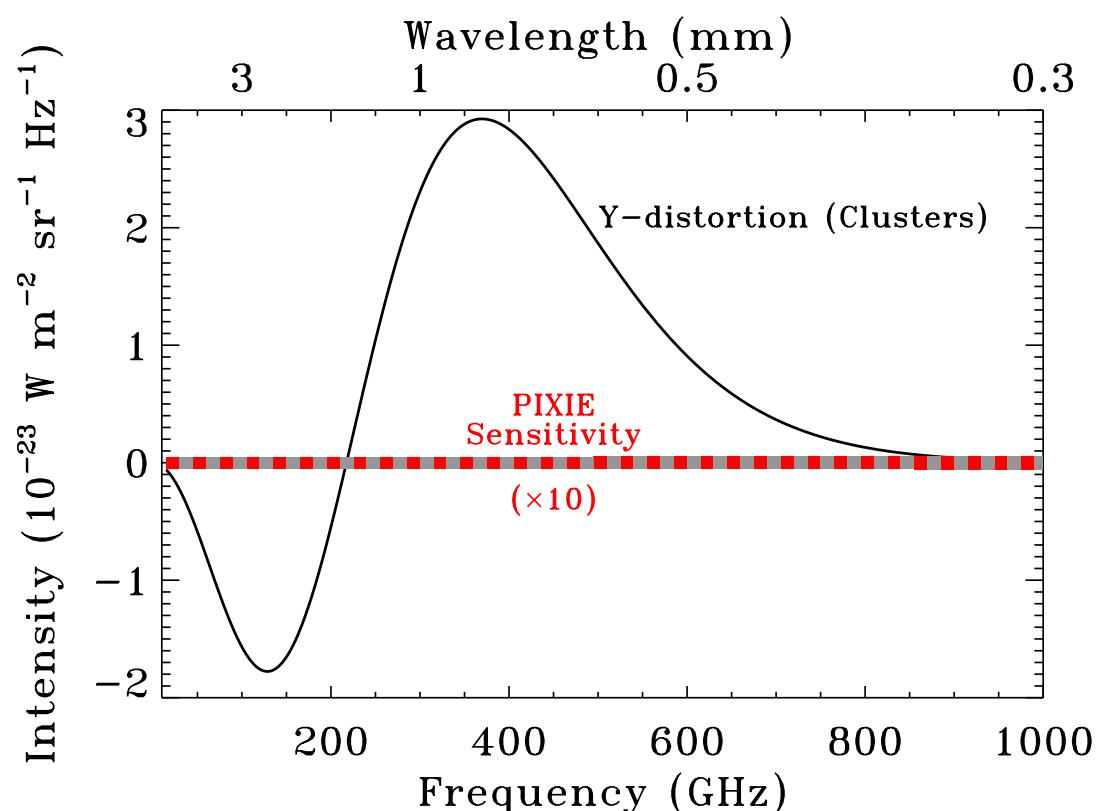
PIXIE 1500-sigma detection

- Dipole: Compare to CMB at $z=1000$
Gravitational accelerations
- Cross-correlate vs redshift surveys
Growth of structure

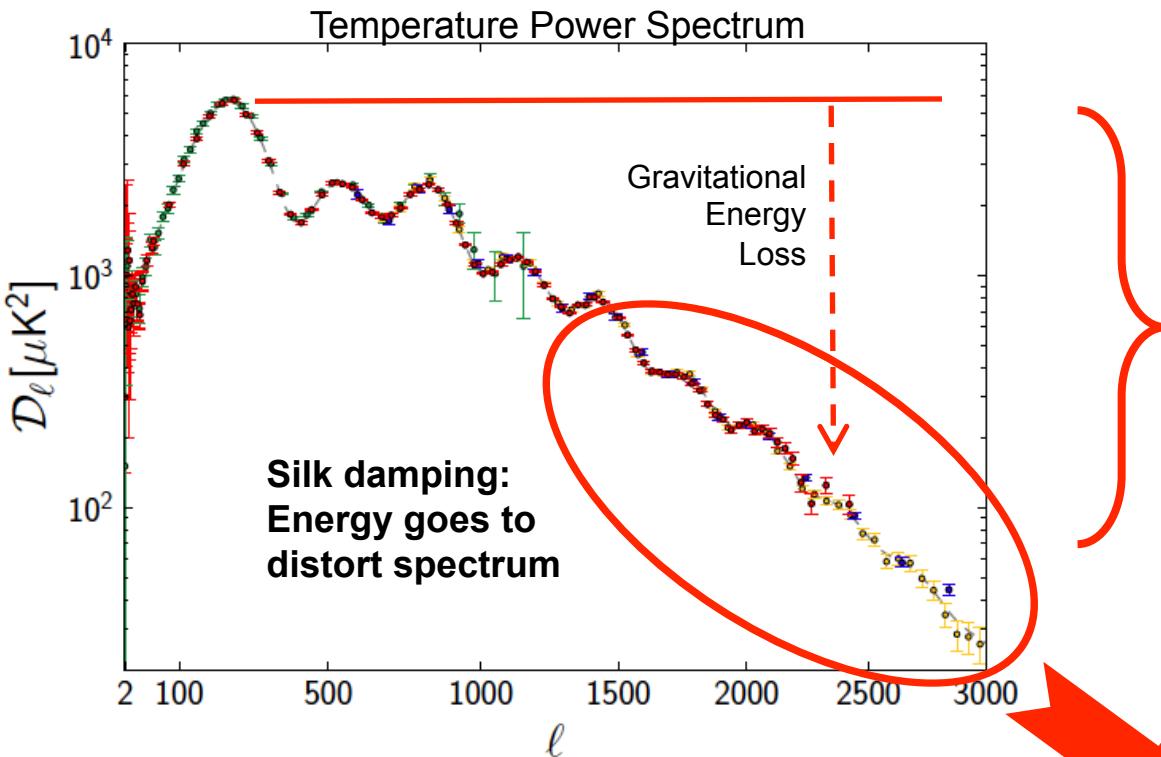
Planck measures thermal SZ effect

Monopole floor: $y > 5.4 \times 10^{-8}$

PIXIE 50-sigma detection



Spectral Distortions: Inflation



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

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

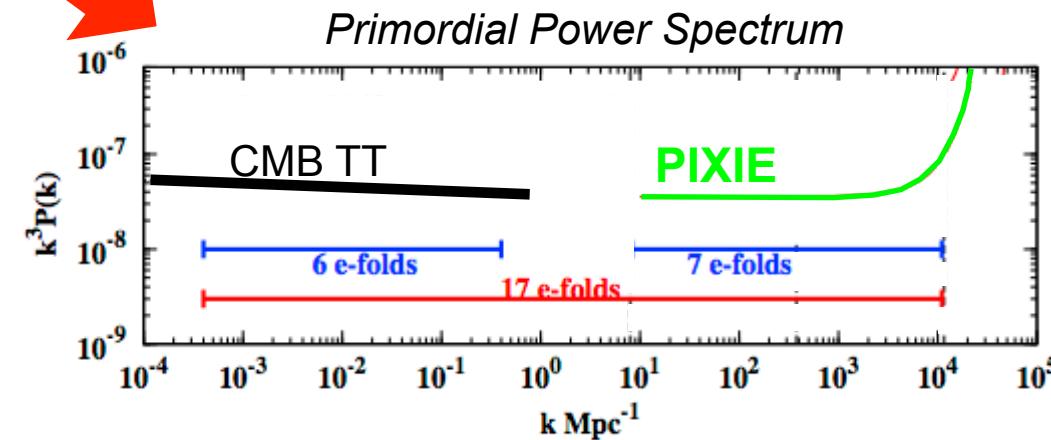
PIXIE limit $\mu < 10^{-8}$

PIXIE 3-sigma detection

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

Test inflation at solar-mass scales!



Triple the number of e-folds from inflation

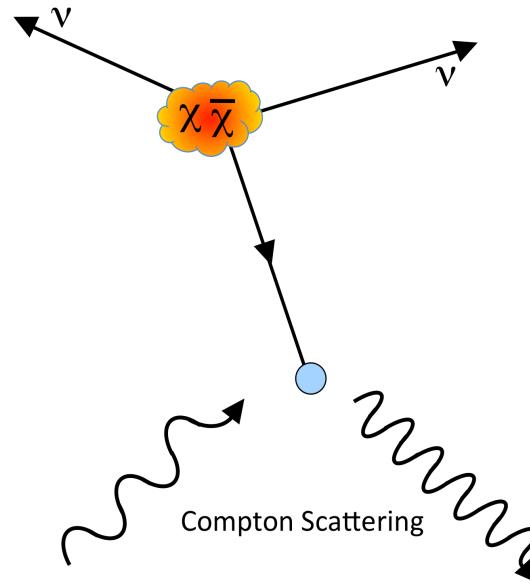
Daly 1991

Hu, Scott, & Silk 1994

Chluba, Erickcek, & Ben-Dayan 2012

Sunyaev & Khatri 2013

Spectral Distortions: Dark Matter Annihilation



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

Dark matter annihilation

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

Neutralino mass limit $m_\chi > 80 \text{ keV}$

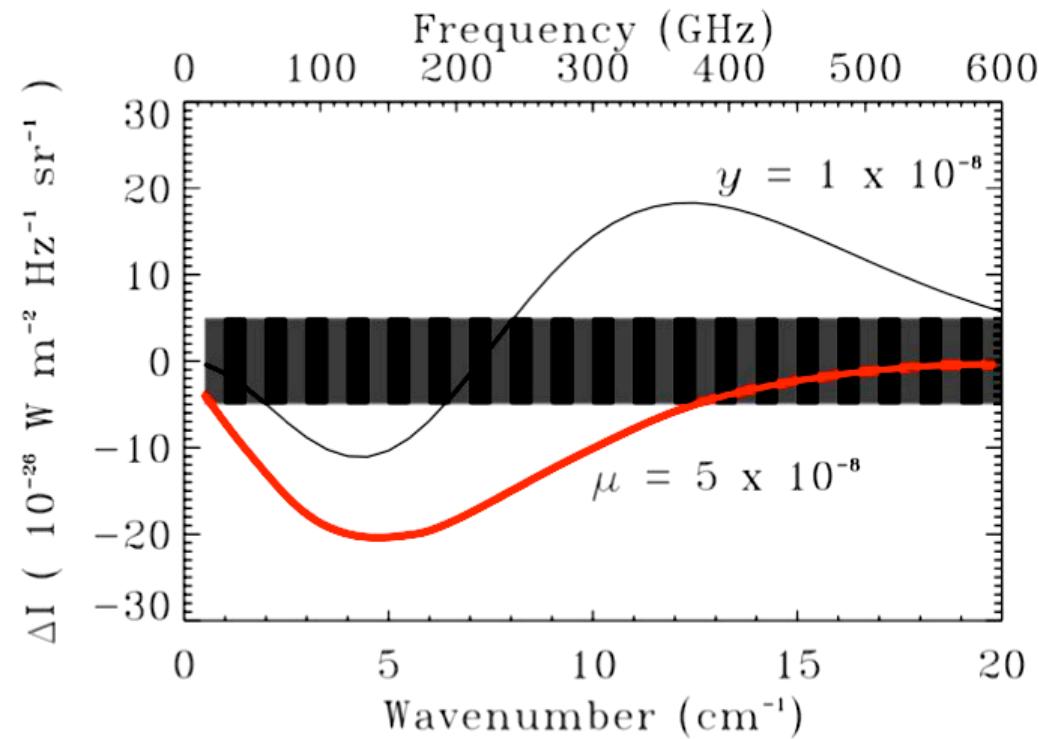
Definitive test for warm dark matter

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

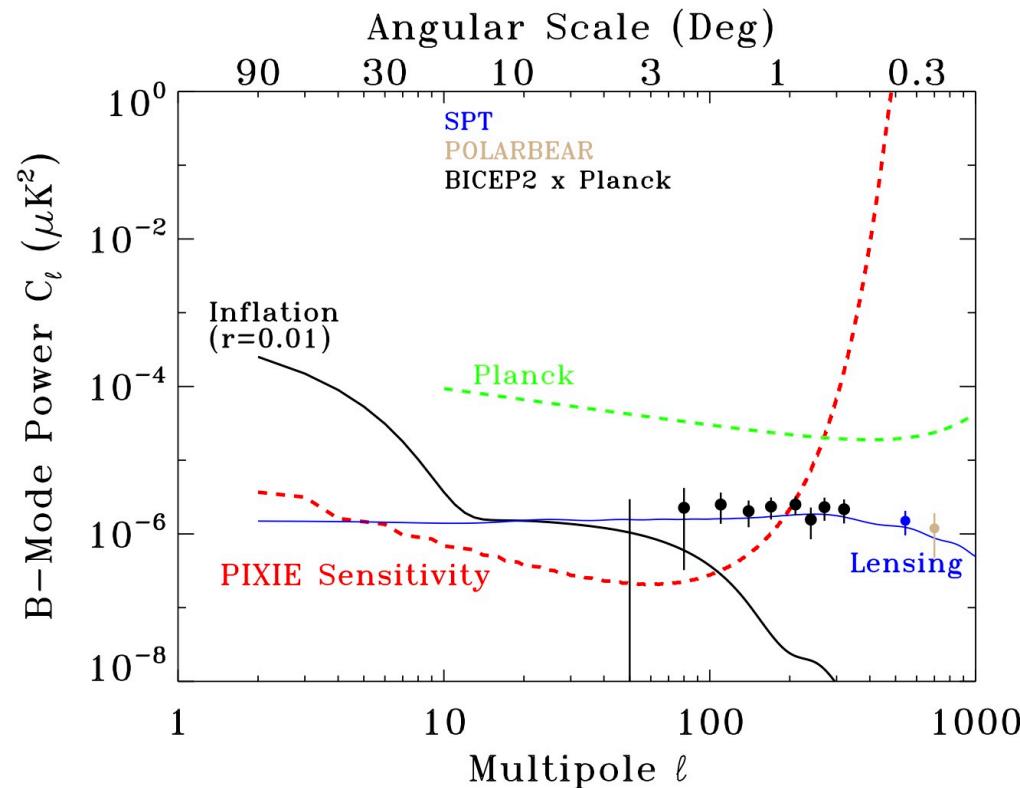
$$\text{Annihilation rate} \sim n^2 \sim z^6$$

$$\text{Number density } n \sim m^{-1}$$

$$m_\chi > 80 \text{ keV} \left[f \left(\frac{\mu}{5 \times 10^{-8}} \right) \left(\frac{\sigma v}{6 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}} \right) \left(\frac{\Omega_\chi}{0.112} \right)^2 \right]^{1/2}$$



Unique Science Capability



Multiple Science Goals

- Polarization / inflation
- Tau / neutrino mass
- Spectral distortions / growth of structure
- ISM and Dust Cirrus

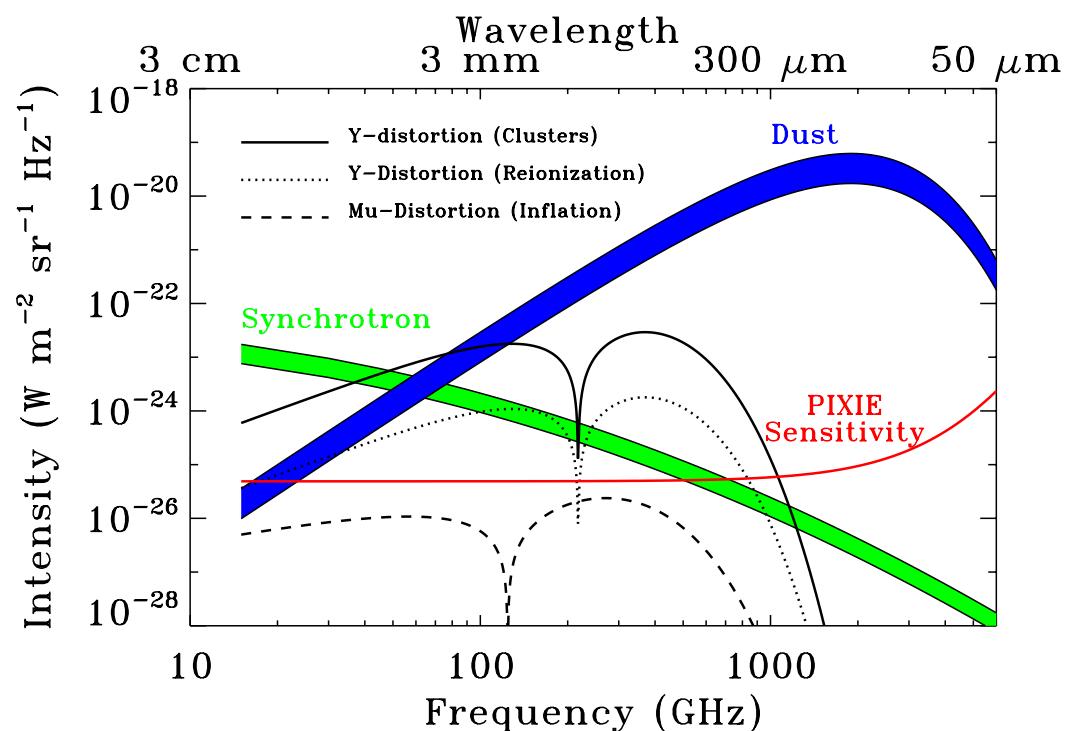
B-mode: $r < 2 \times 10^{-4}$ (1σ)

Distortion $|\mu| < 10^{-8}$, $|y| < 5 \times 10^{-9}$

Full-Sky Spectro-Polarimetric Survey

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

Legacy Archive for far-IR Astrophysics



NASA Explorer Program



Small PI-led missions

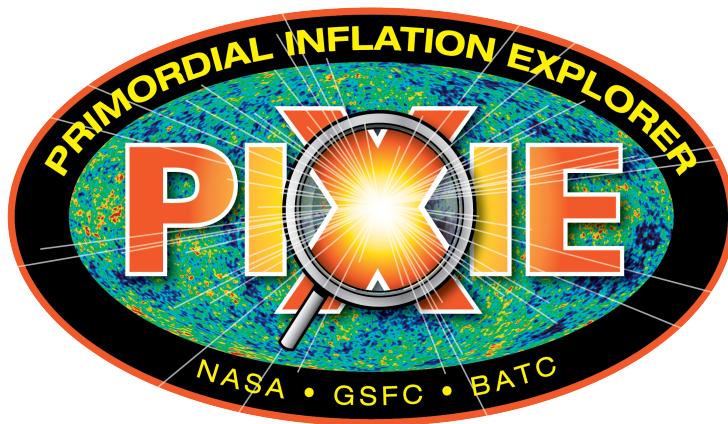
- 22 full missions proposed Feb 2011
- \$200M Cost Cap + launch vehicle

PIXIE not selected; urged to re-propose

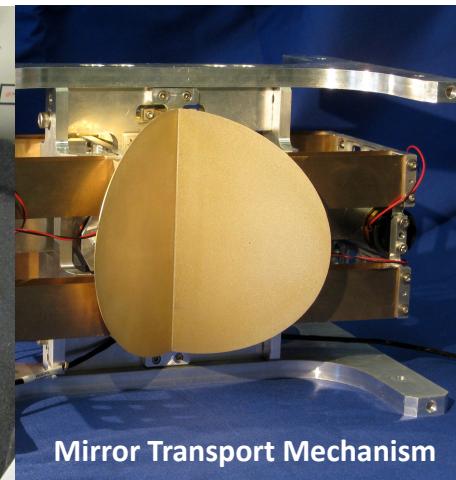
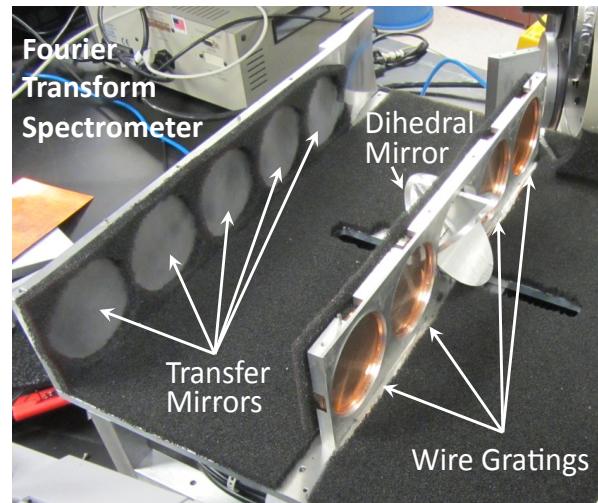
- Top (Category I) science rating
- Broad recognition of science appeal

Re-propose to next MIDEX AO (2016)

- Technology is mature
- Launch early next decade

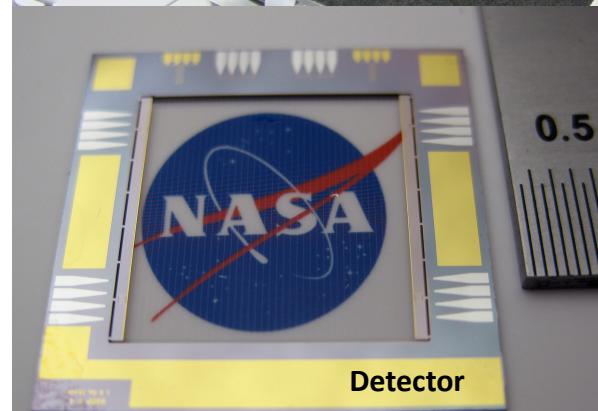


"PIXIE's spectral measurements alone justify the program"
-- NASA review panel

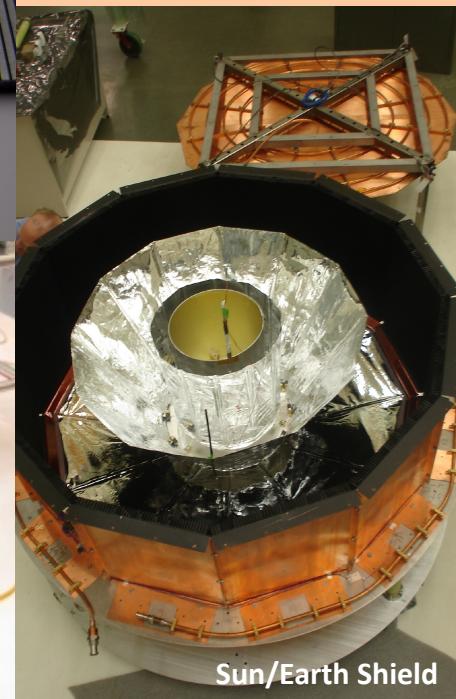


Mirror Transport Mechanism

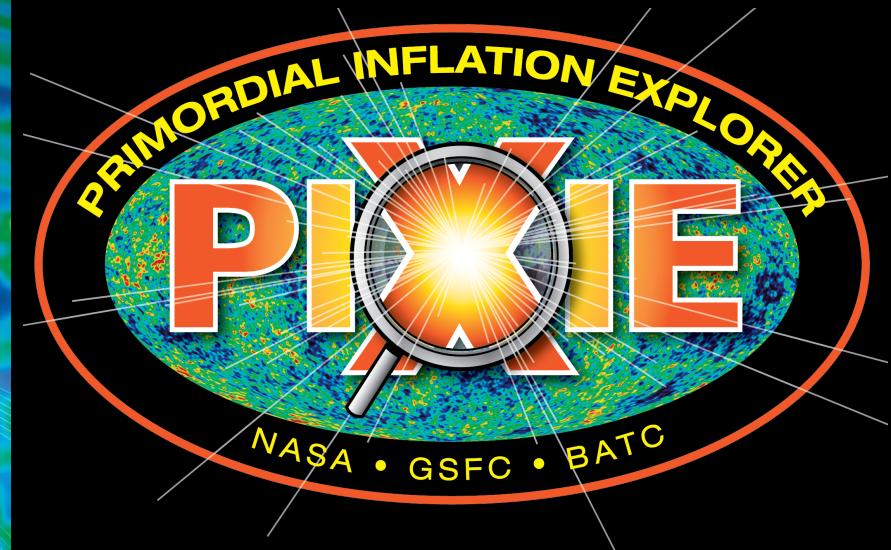
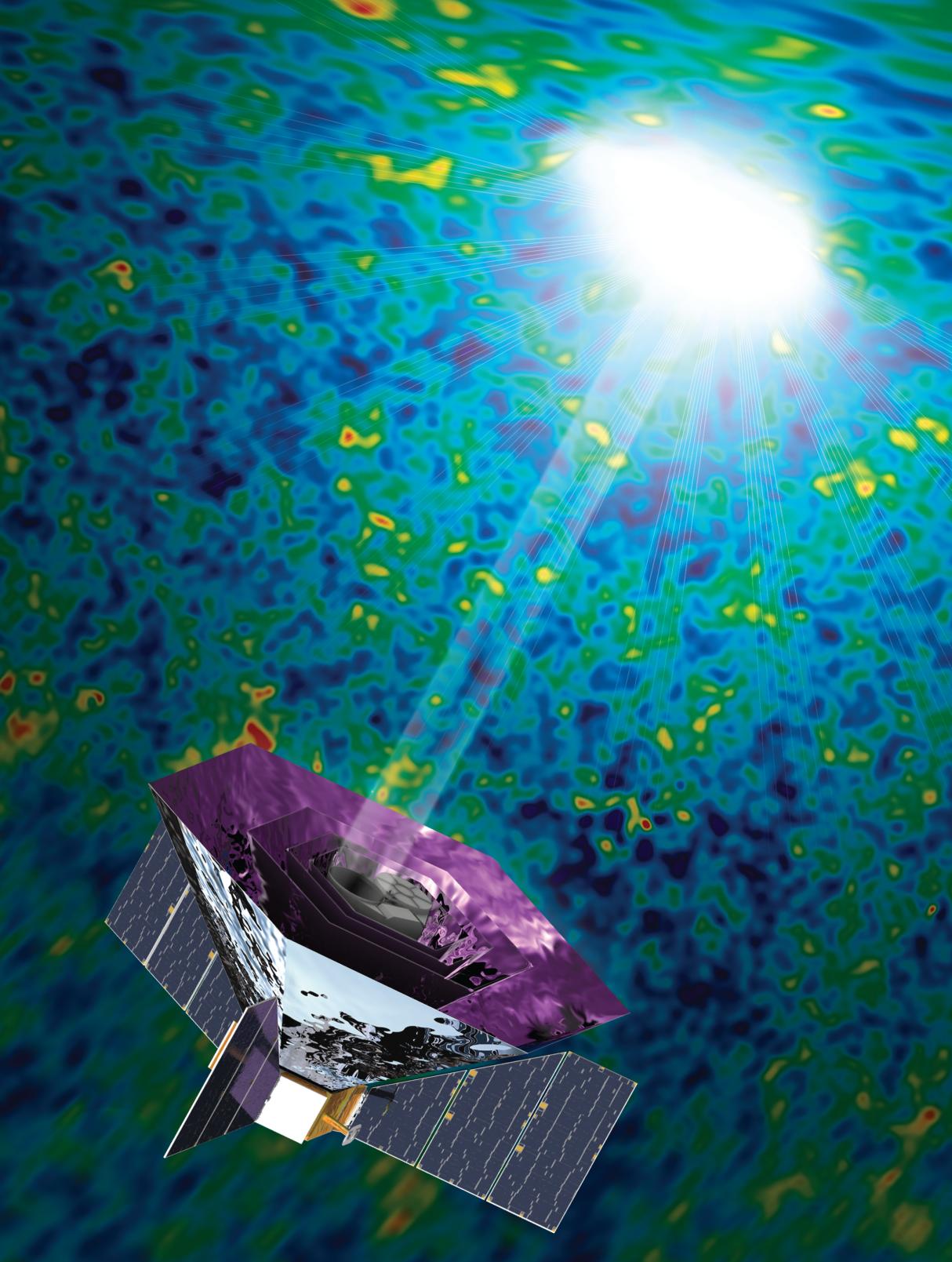
Mature technology



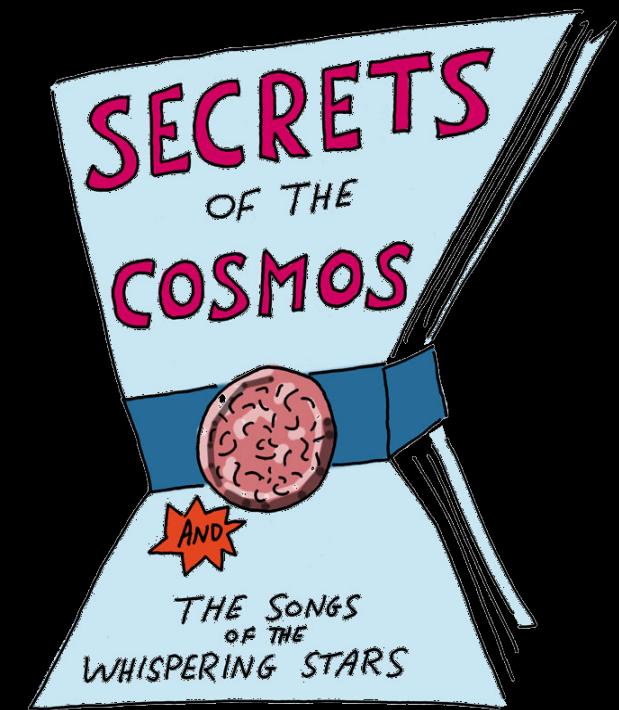
Calibrator



Sun/Earth Shield

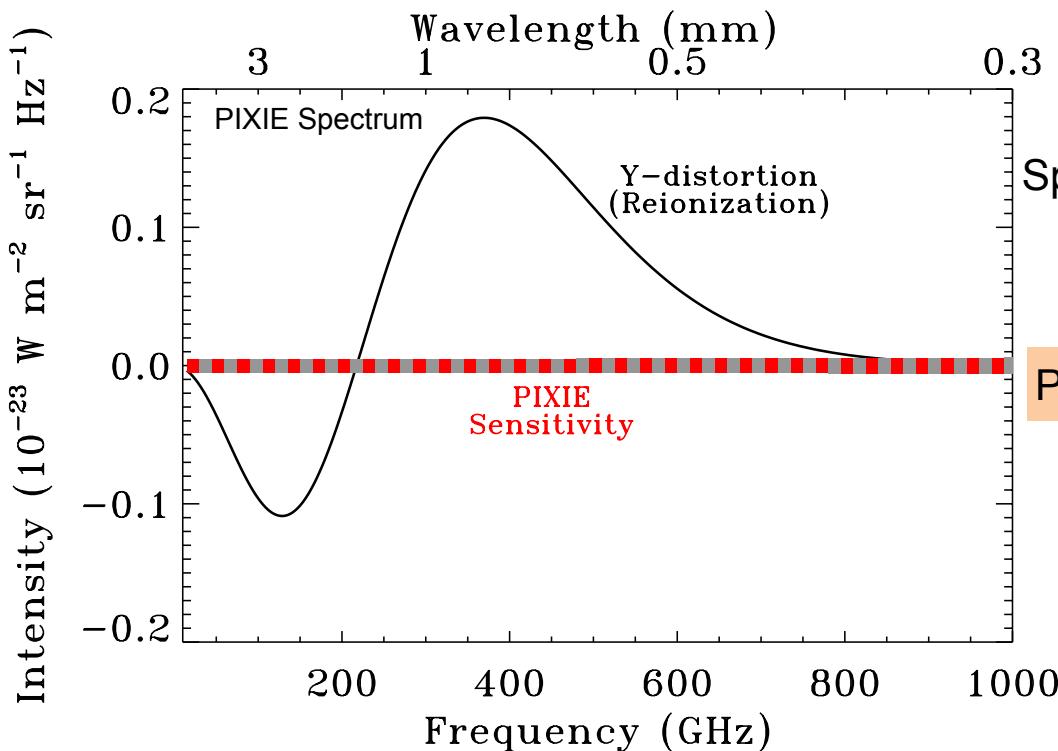


*Coming Soon From a
Spacecraft Near You!*



Backup Slides

Spectral Distortions: Reionization



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

- PIXIE limit $y < 5 \times 10^{-9}$
- Signal $y \sim 10^{-7}$

PIXIE 95-sigma detection (but buried under IGM)

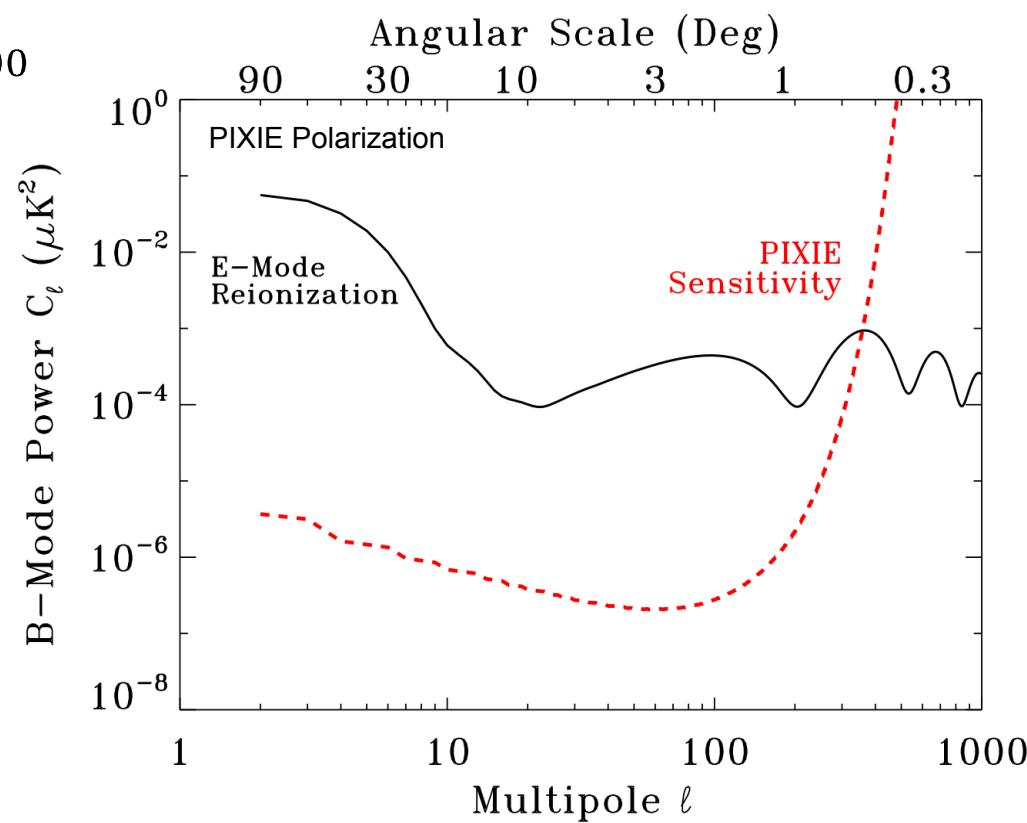
E-mode optical depth \sim Electron density n

Same scattering for both signals

Combine to get n and T_e

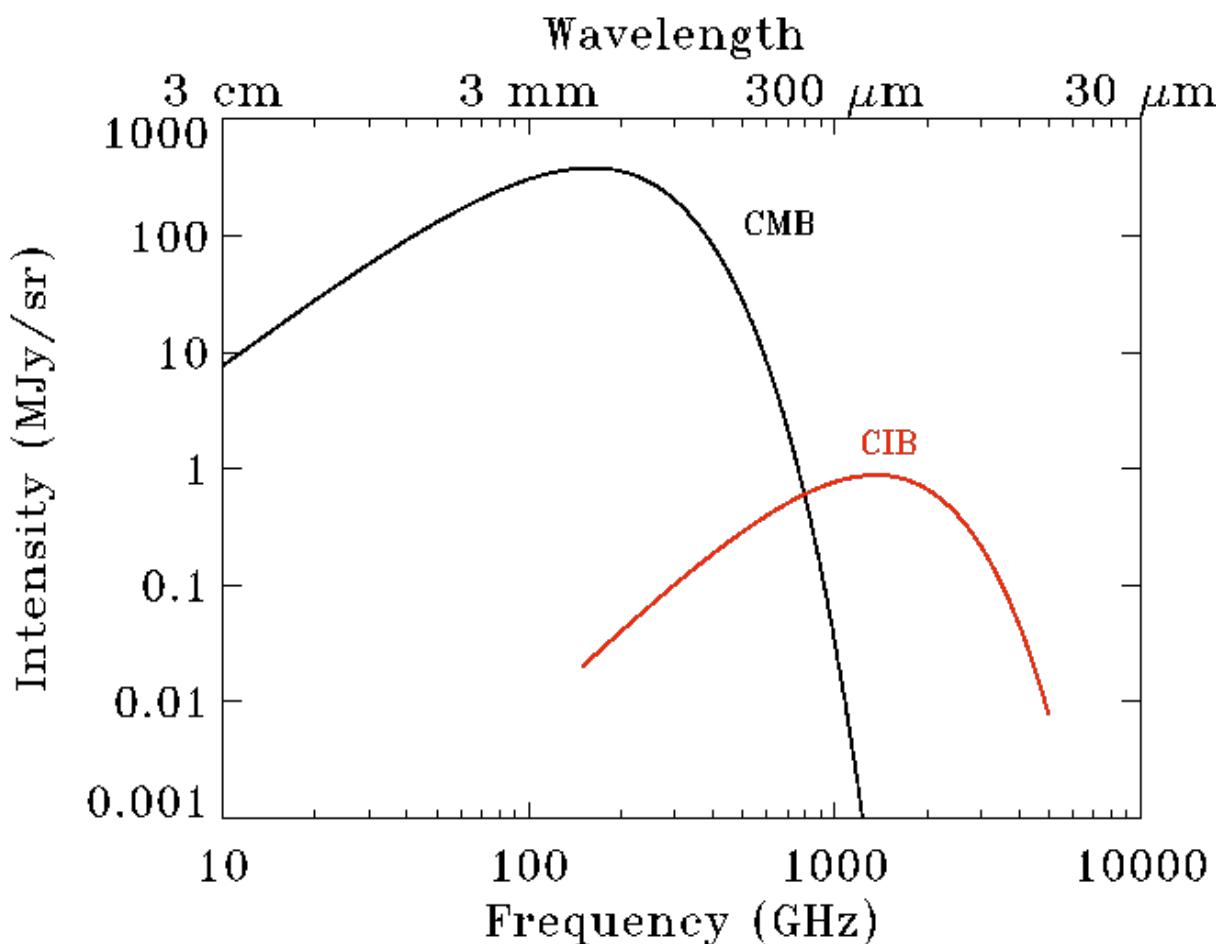
- T_e probes ionizing spectrum
- Distinguish Pop III, Pop II, AGN

Determine nature of first luminous objects





Cosmic Infrared Background



PIXIE noise is down here!

Thermal Dust Emission from $z \sim 1-3$

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

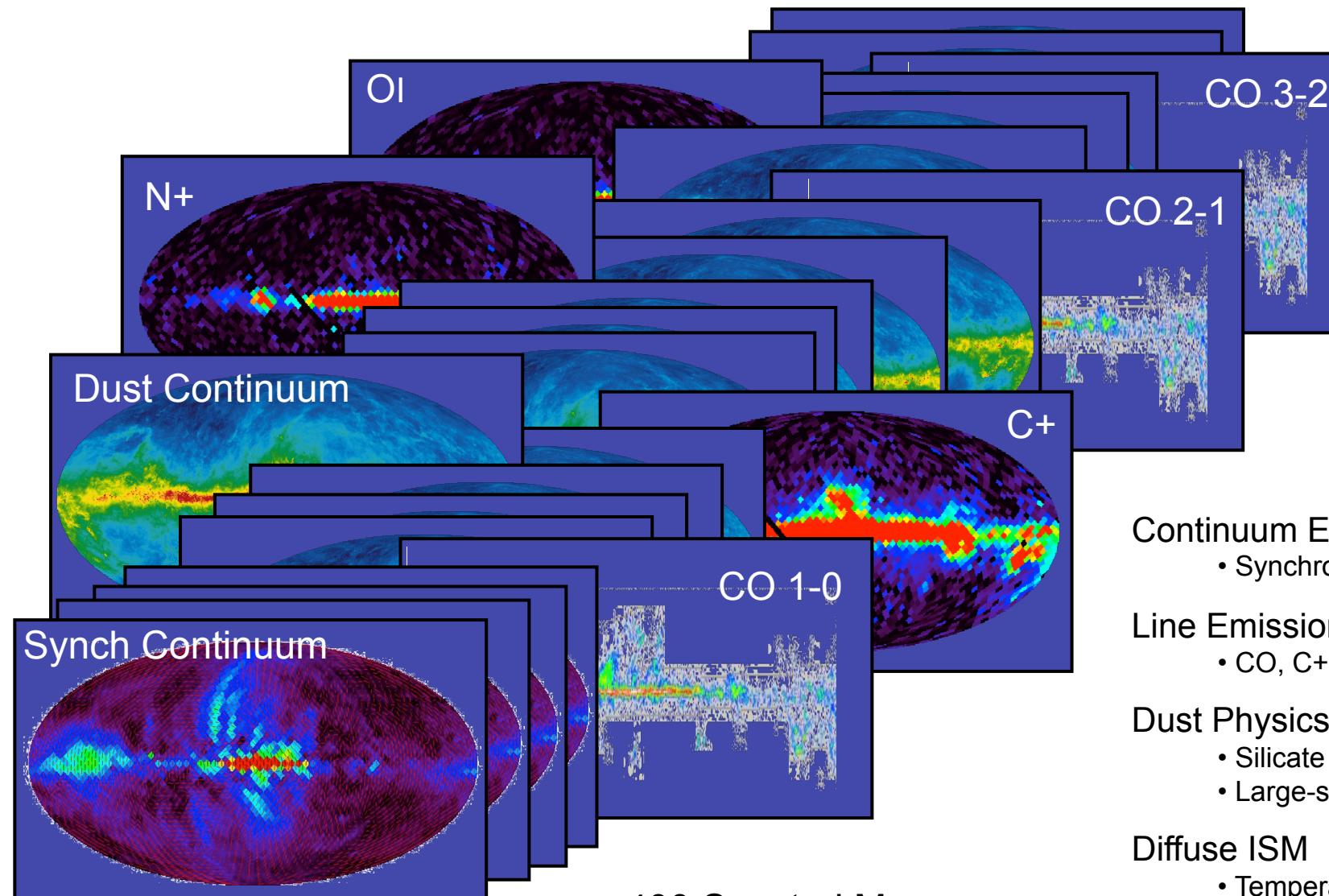
Frequency coverage over CIB peak

- Complement Herschel, Planck

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



Spectral Line Emission



Continuum Emission

- Synchrotron, Dust

Line Emission

- CO, C+, N⁺, O, ...

Dust Physics

- Silicate vs carbonaceous dust
- Large-scale magnetic field

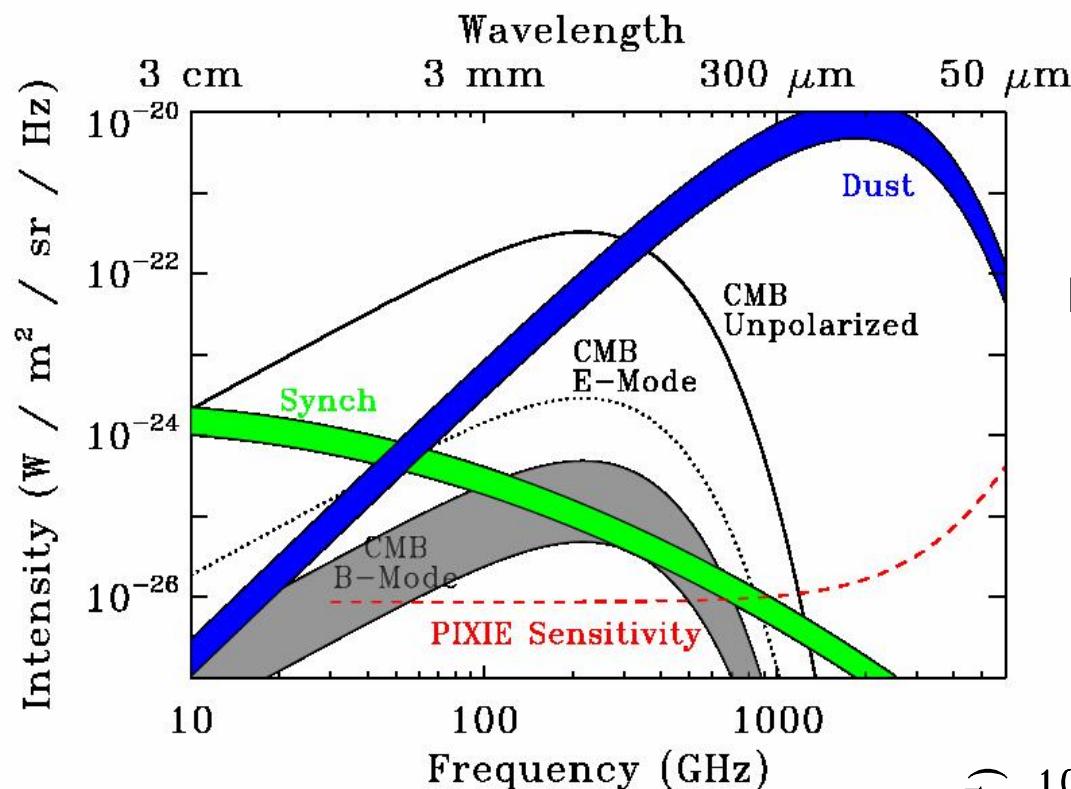
Diffuse ISM

- Temperature, Density
- Energy Balance
- Metalicity

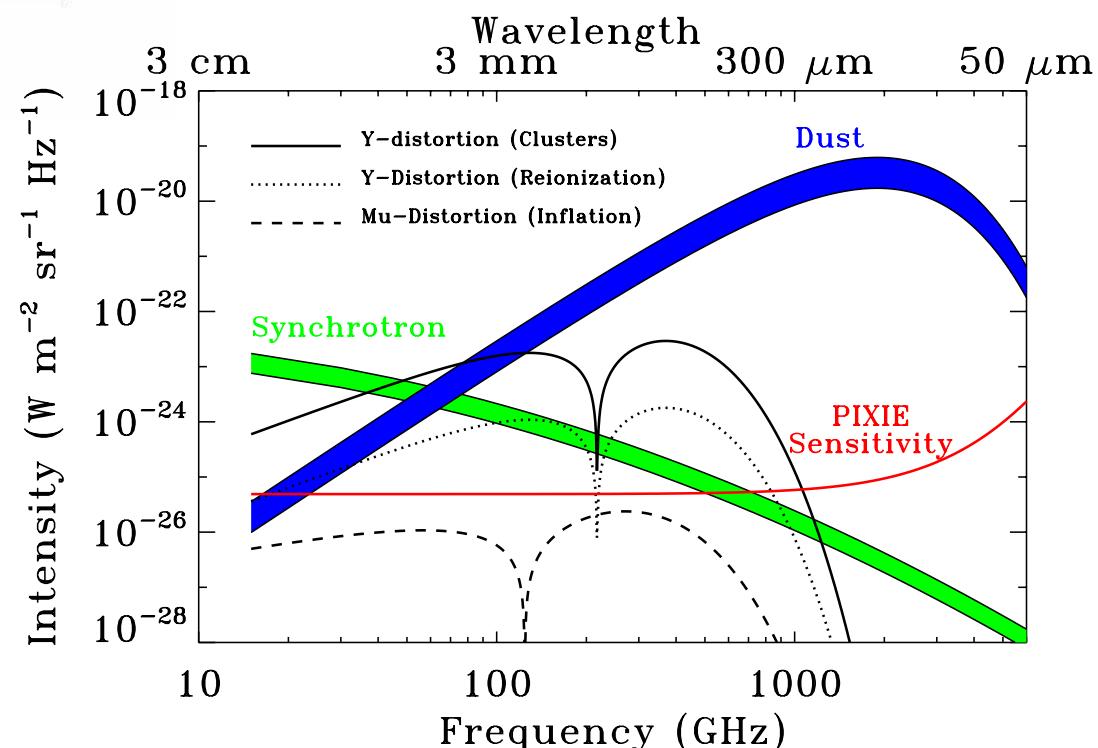
Extremely Rich Data Set!



Foreground Comparison



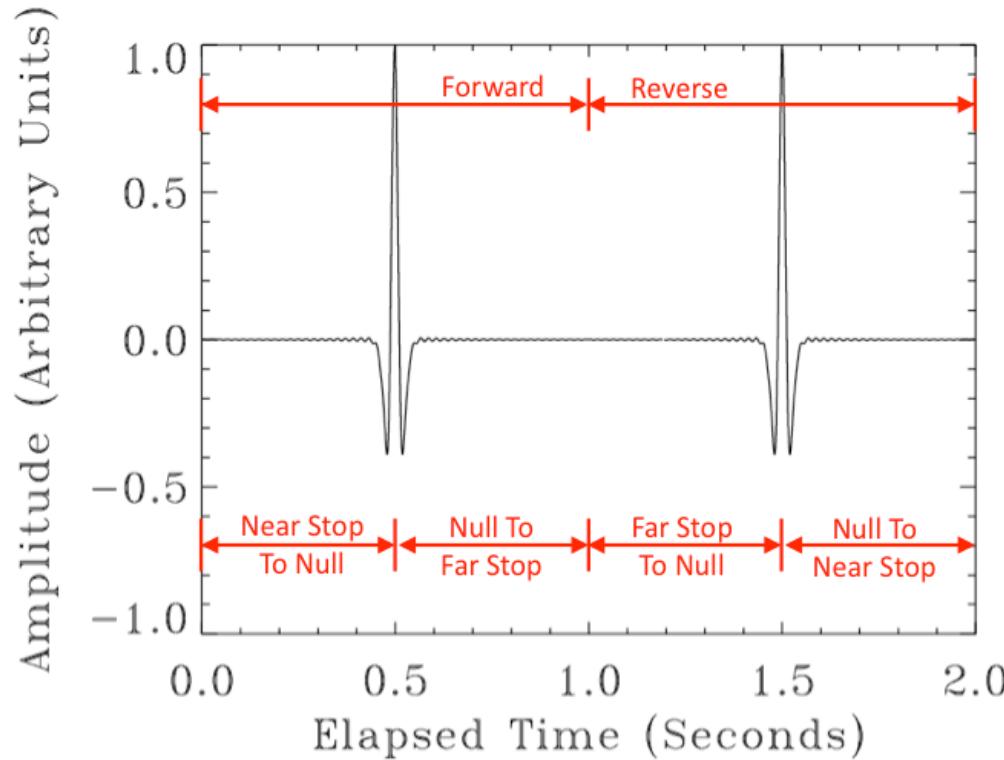
Unpolarized Foregrounds





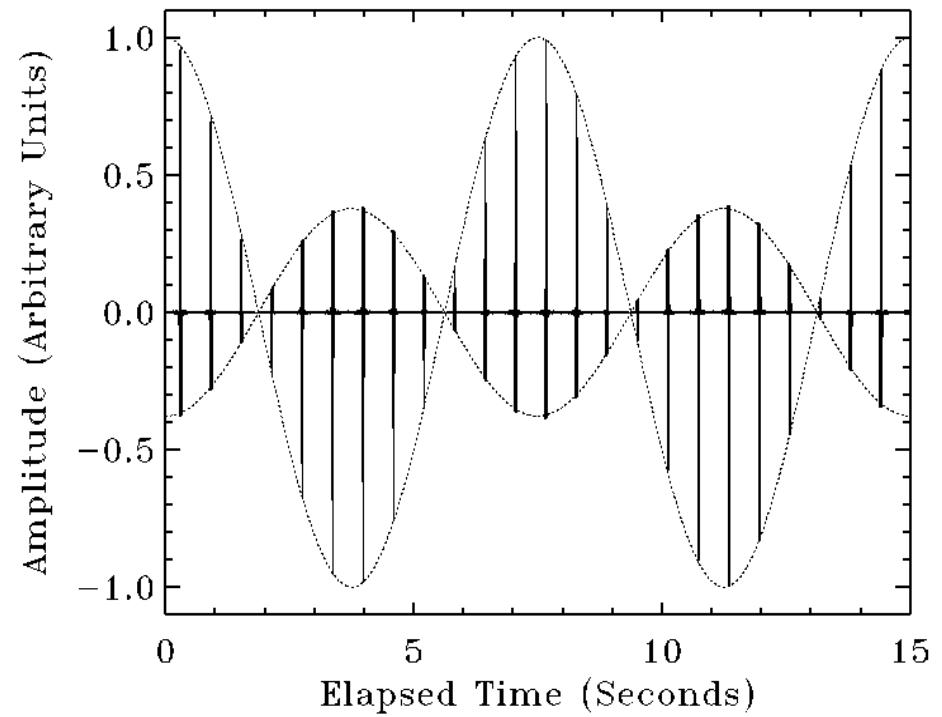
Systematic Error Control

Multiple Instrumental Symmetries



Spacecraft spin imposes amplitude modulation of entire fringe pattern

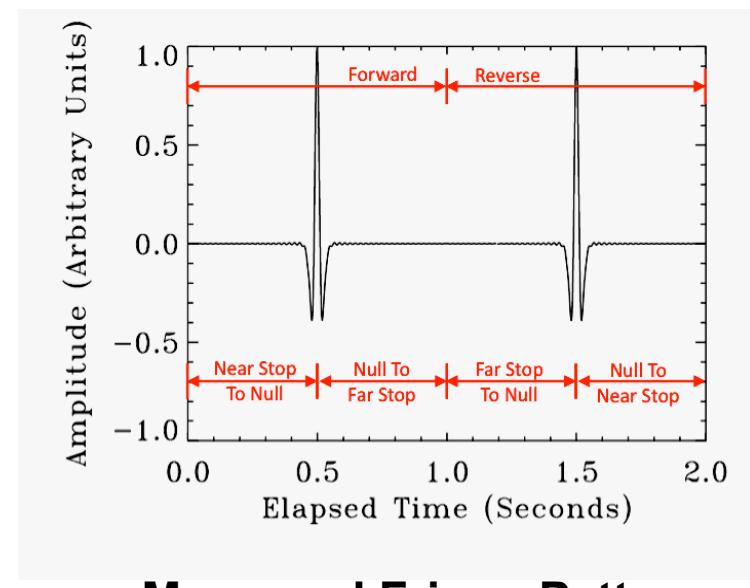
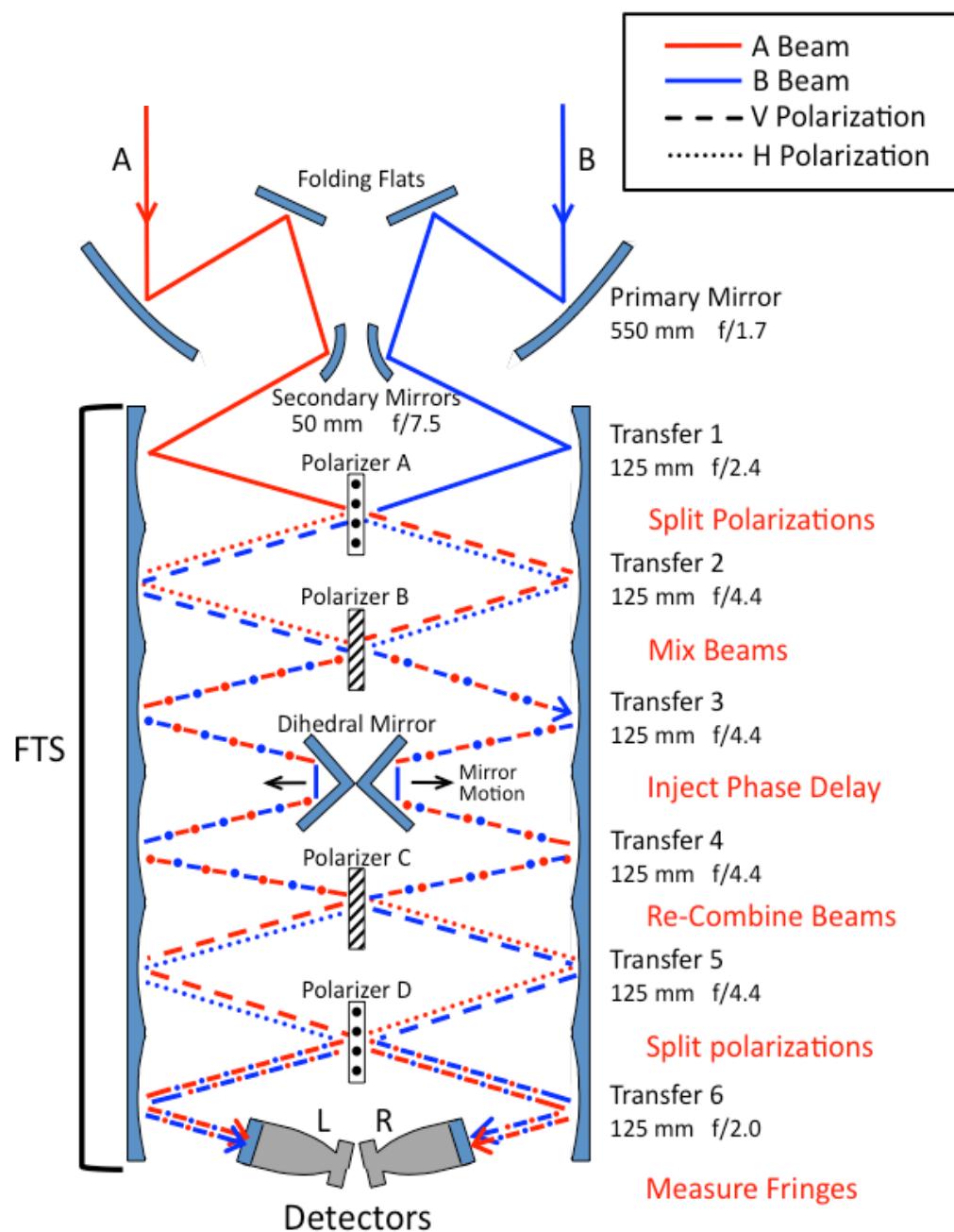
Same information 4x per stroke with different time/space symmetries



Multiple Redundant Symmetries Allow Clean Instrument Signature



PIXIE Nulling Polarimeter



Measured Fringe Pattern Samples Frequency Spectrum of Polarized Sky Emission

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

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

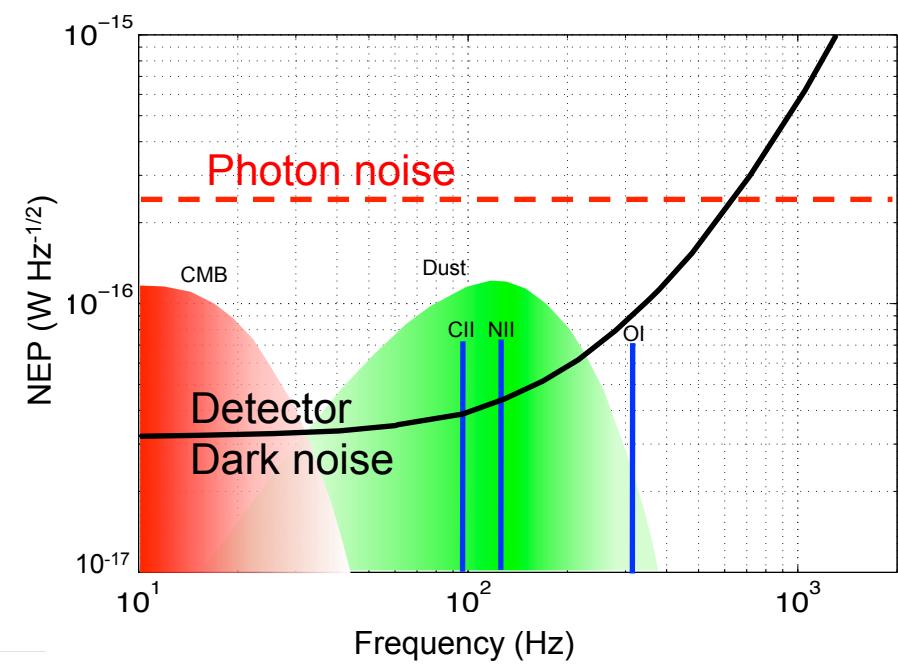
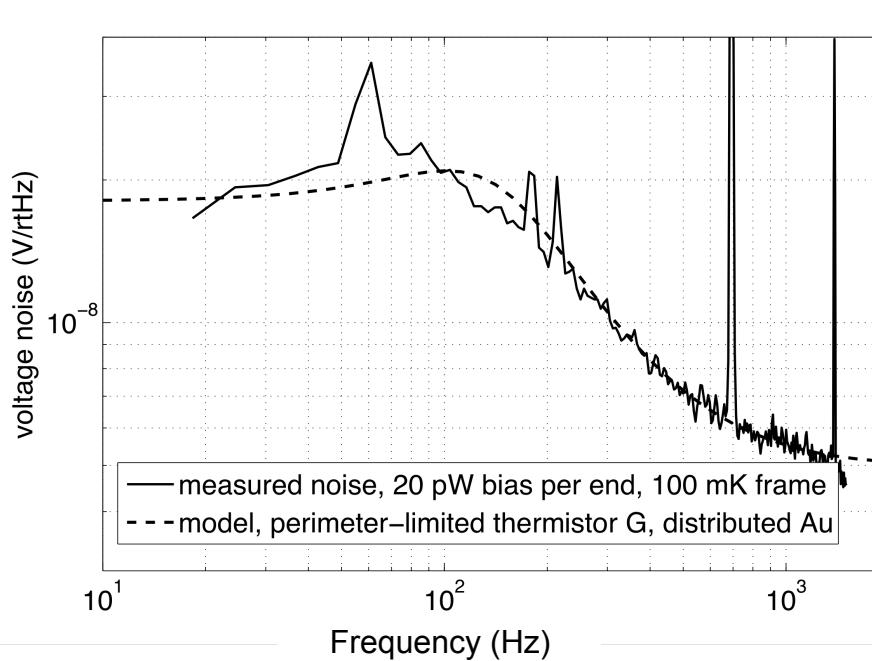
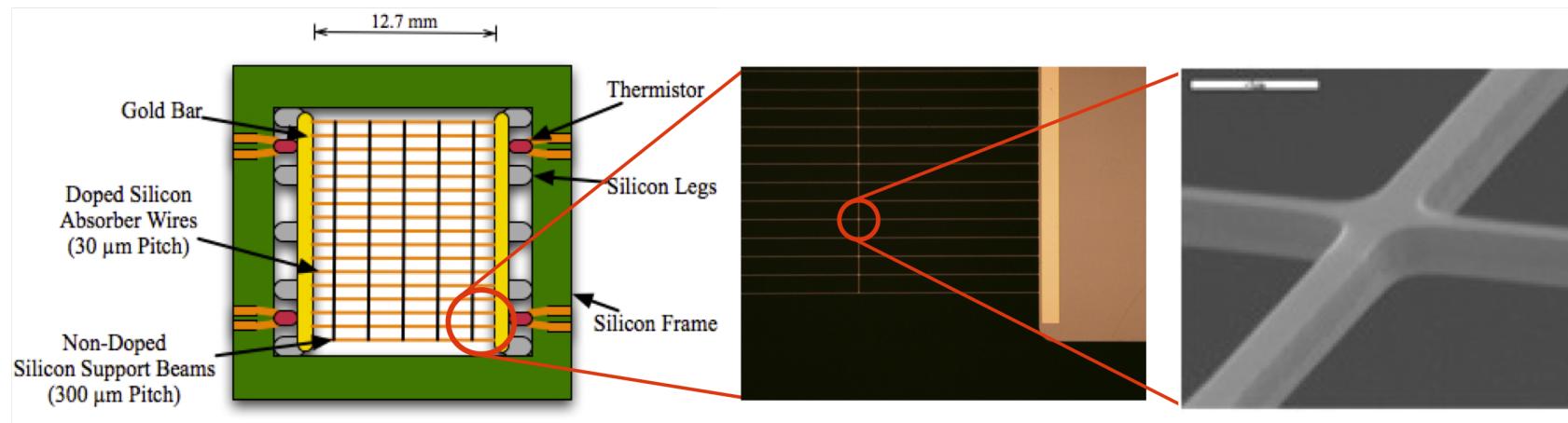


Stokes Q

Nulling Polarimeter: Zero = Zero

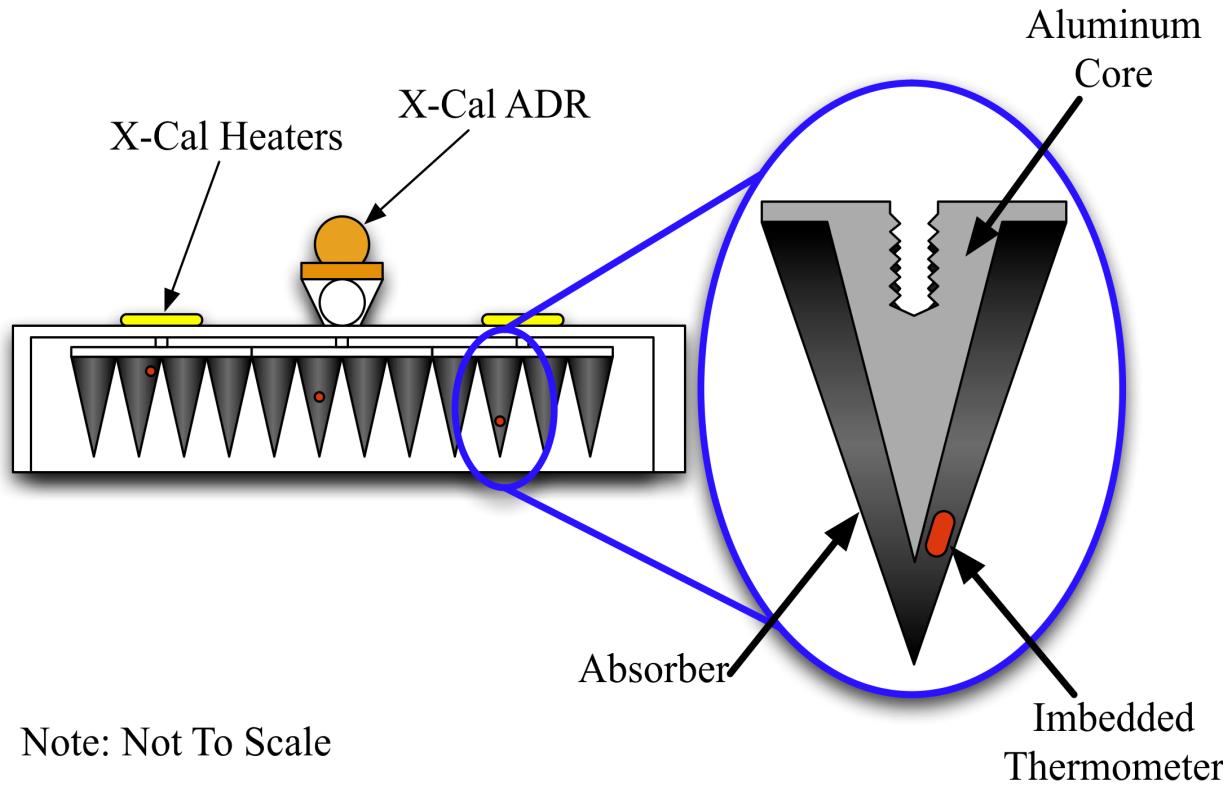


PIXIE Detectors



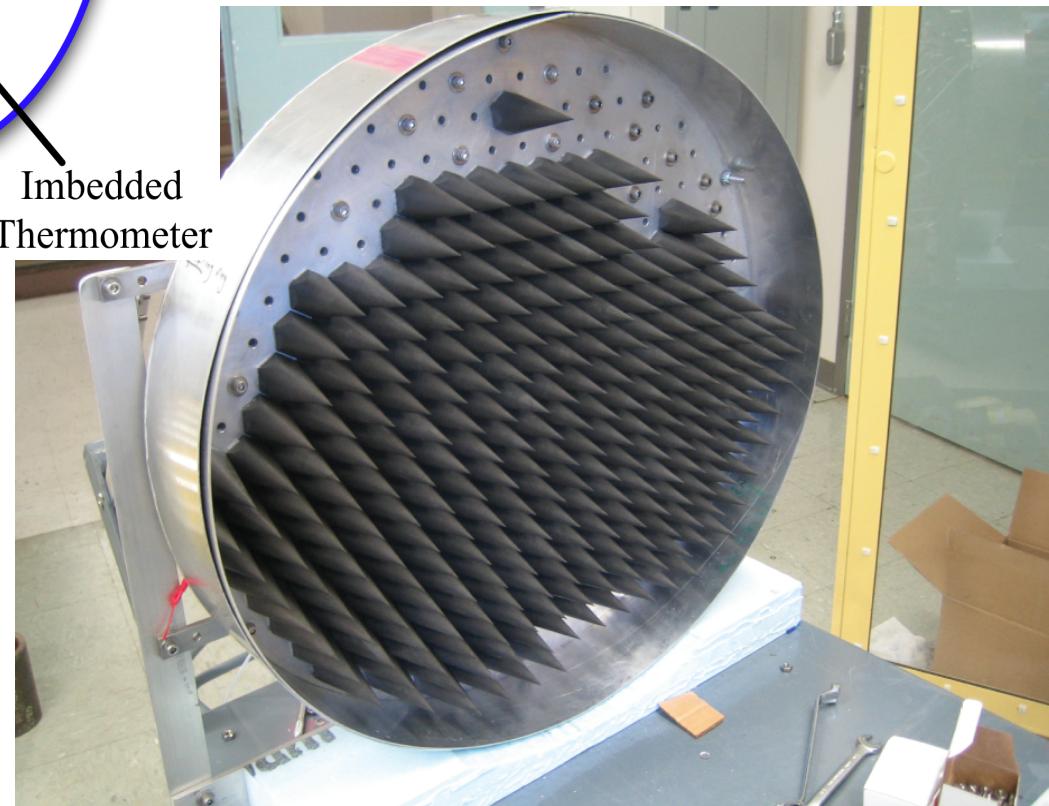
Demonstrate multi-moded single-polarization photon-limited detectors

Blackbody Calibrator



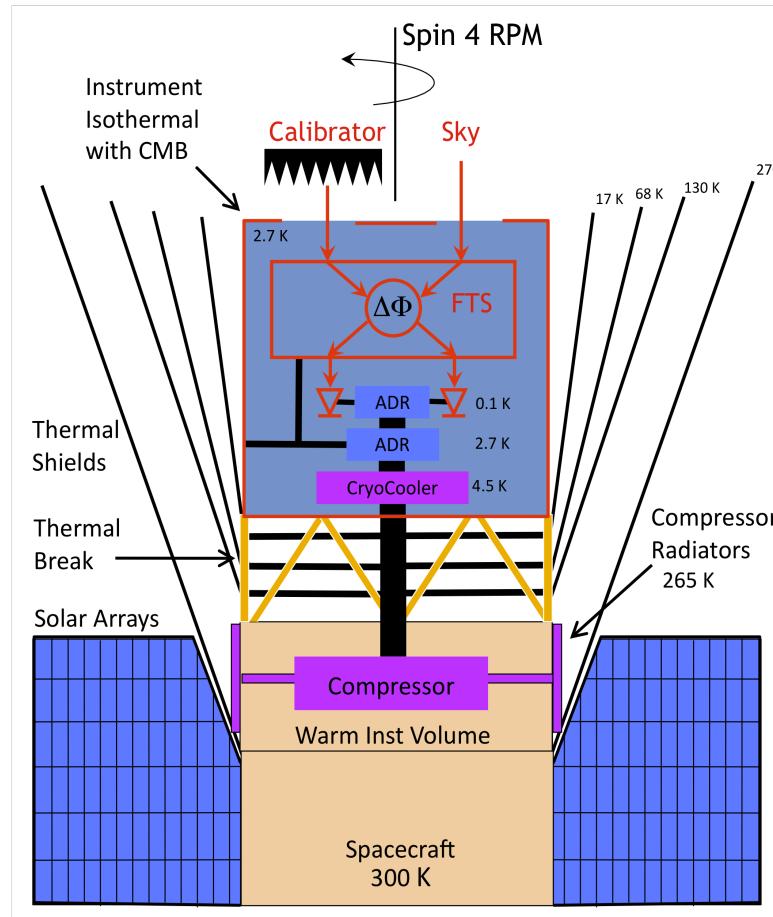
Note: Not To Scale

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 - 3.5 K
Temperature Range (Single Cone)	2.6 - 20 K	2.6 - 20 K
Temperature Gradient	< 3 μ K	< 1 μ K

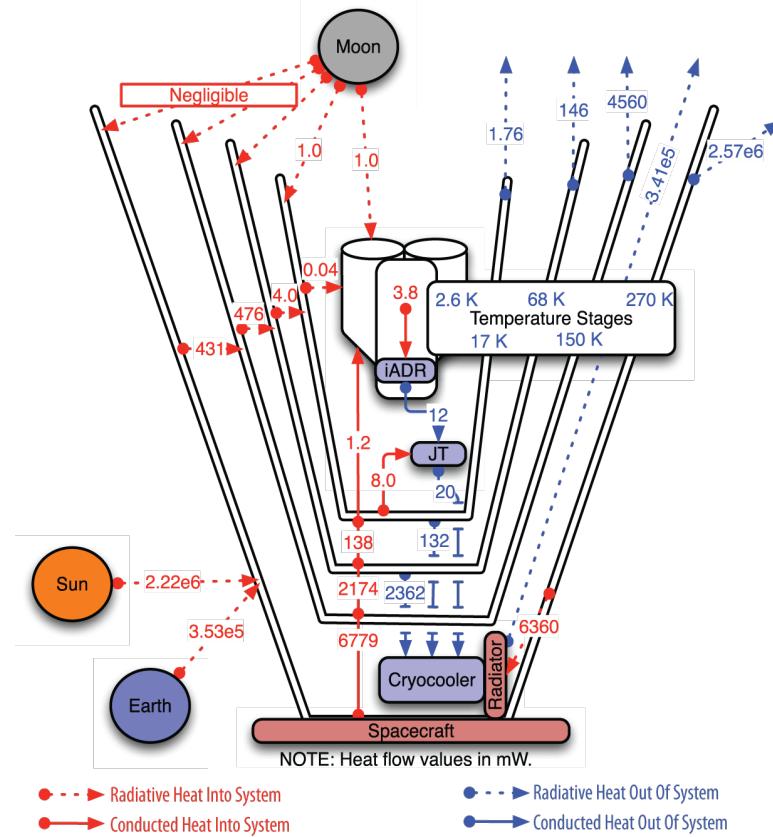
Instrument Cryogenics



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



Fully cryogenic instrument

Cryo-cooler to 4.5 K

ADR to 2.7 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