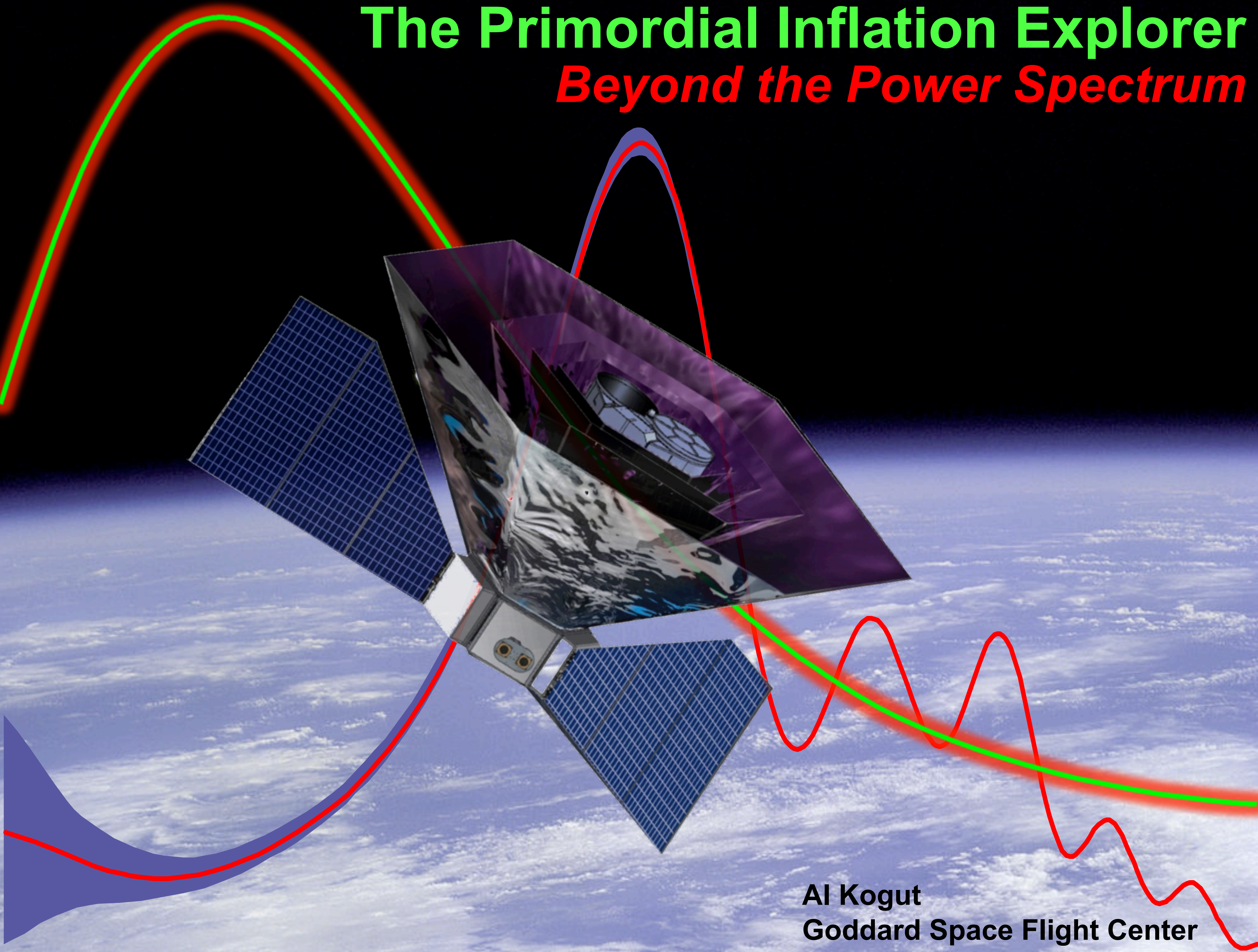
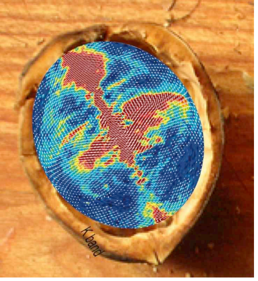
The Primordial Inflation Explorer

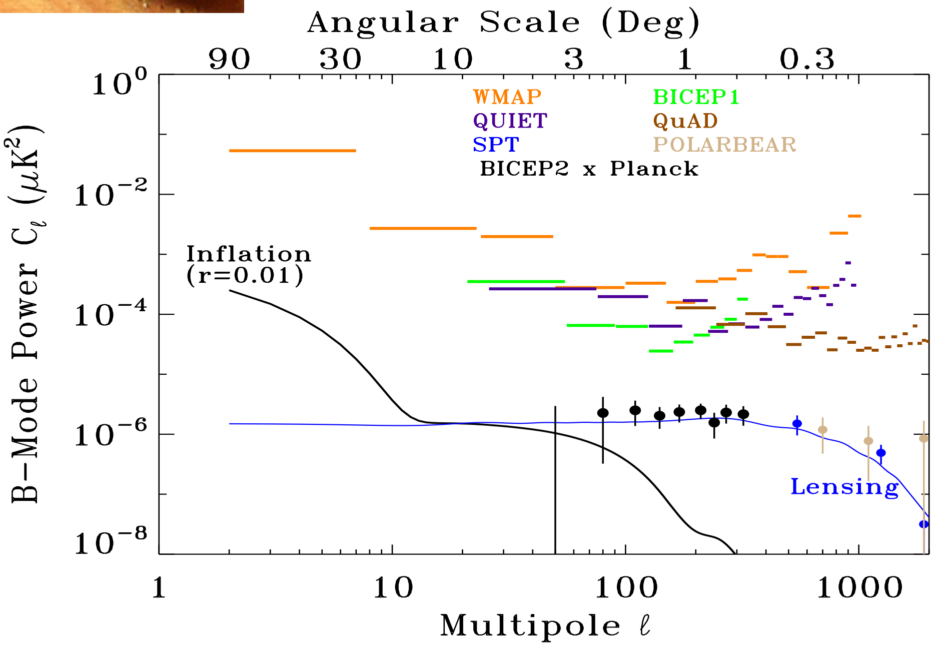
Beyond the Power Spectrum

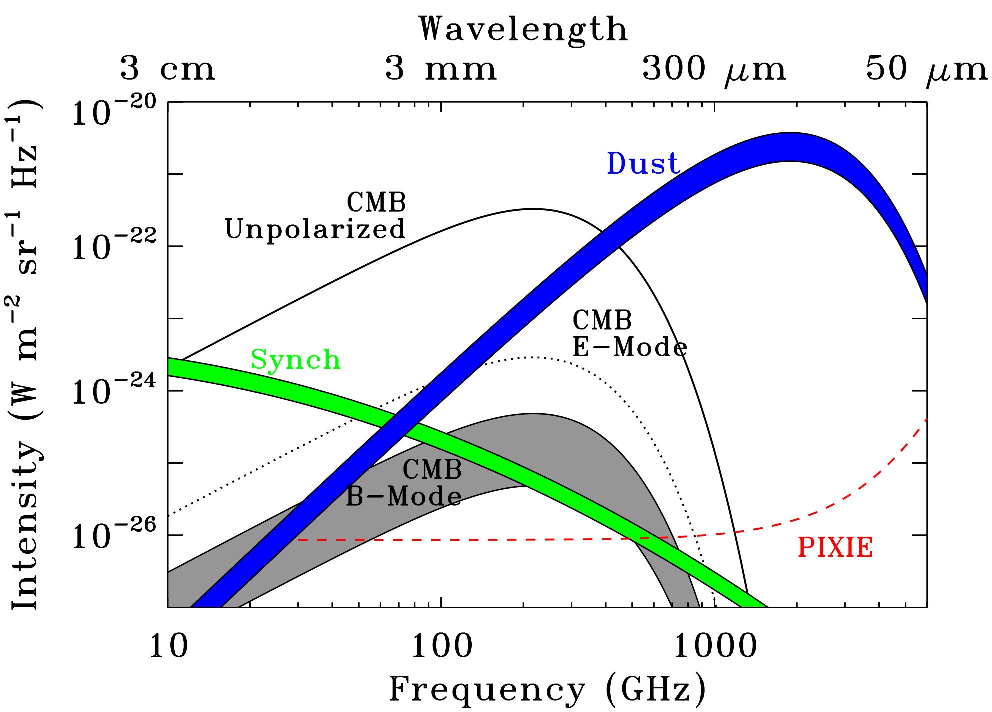


Al Kogut
Goddard Space Flight Center



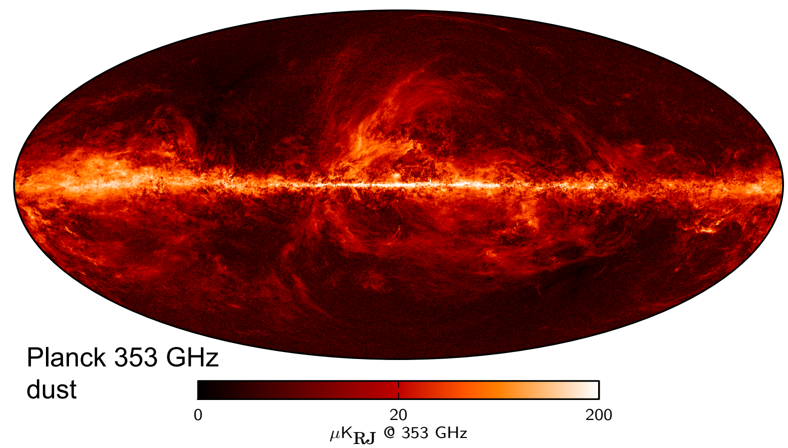
B-modes in a Nutshell



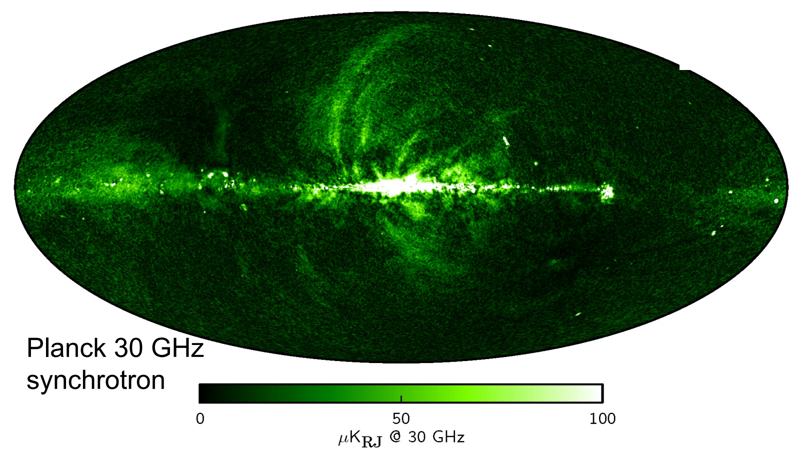


B-Mode Requirements

- Sensitivity
- Foreground Discrimination
- Systematic Error Rejection

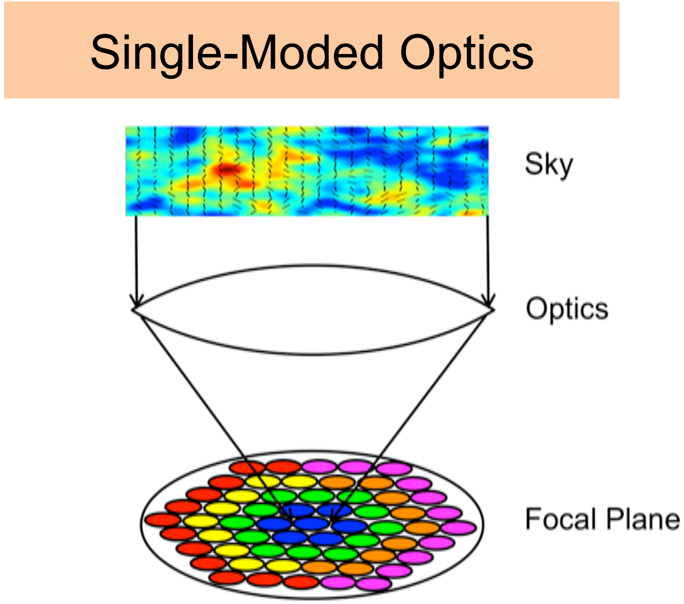


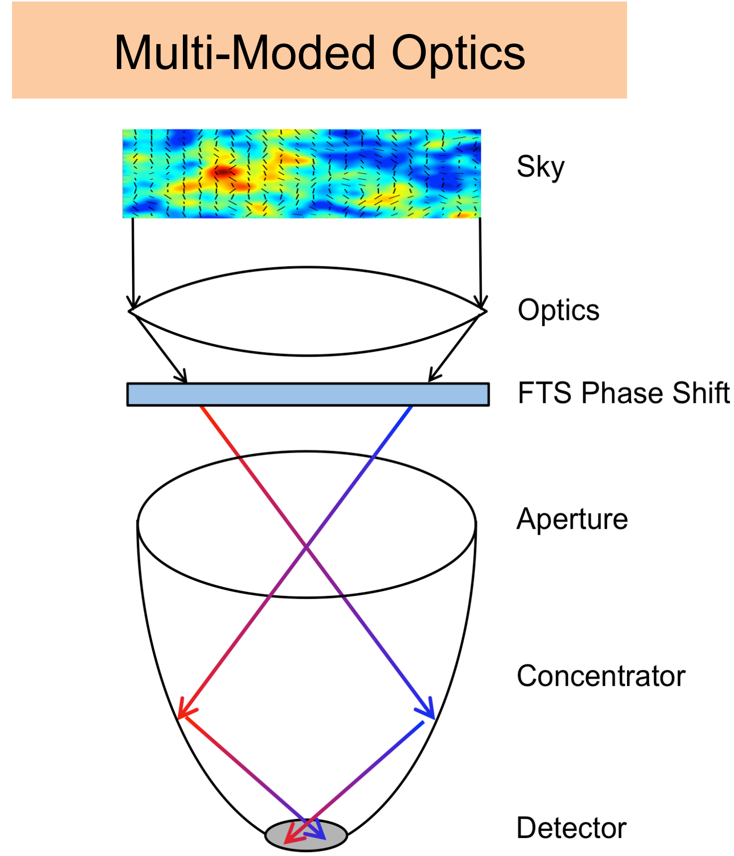
Planck 353 GHz
dust



Planck 30 GHz
synchrotron

PIXIE Solution: Multi-Moded FTS





Diffraction Limit: $A\Omega = \lambda^2$
Single mode on each of 10,000 detectors

Conserve etendu: $N_{mode} = A\Omega / \lambda^2$
22,000 modes on each of 4 detectors

Trade angular resolution
for sensitivity, frequency coverage, and systematic error control

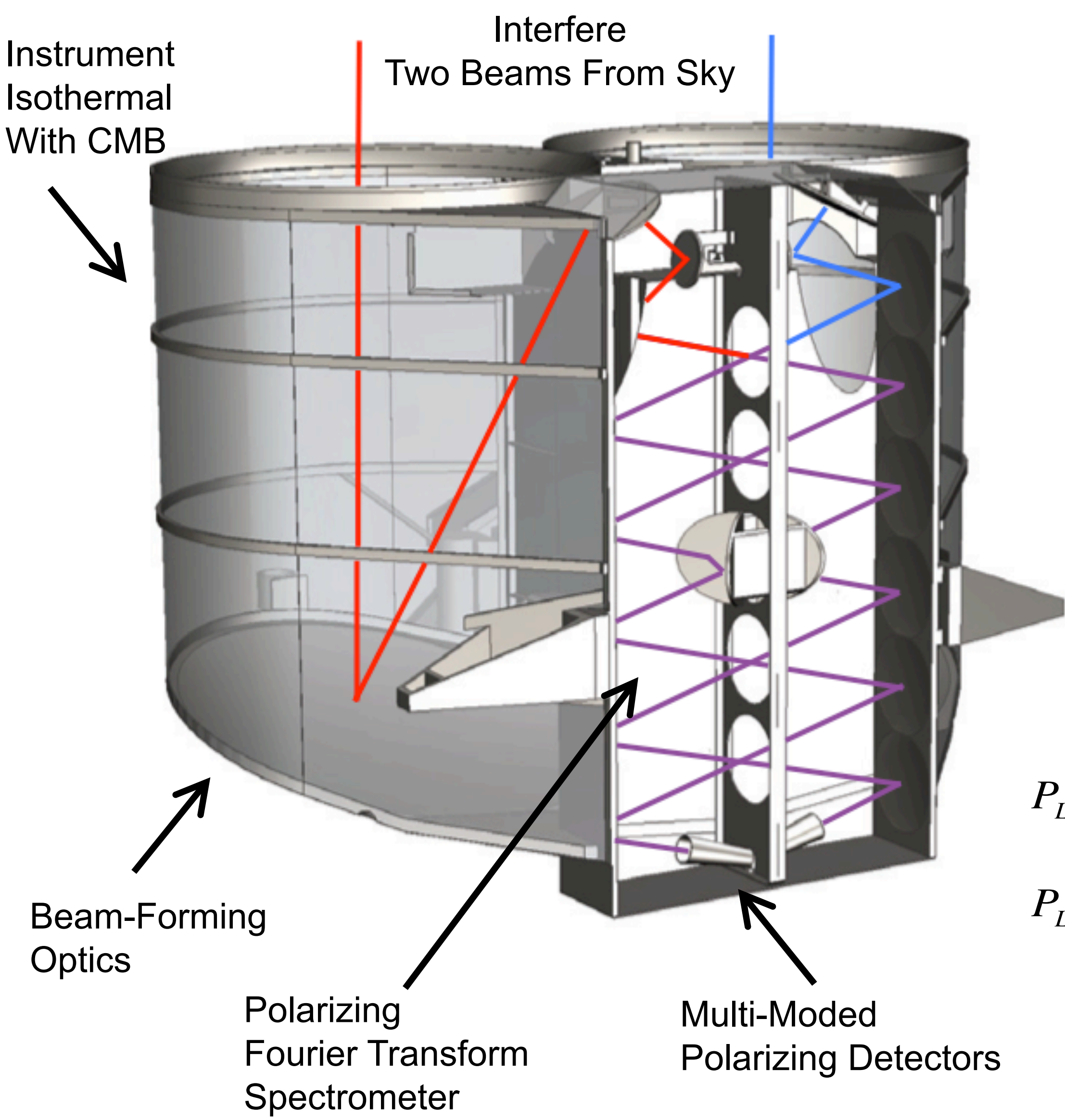
Updating a Classic Solution

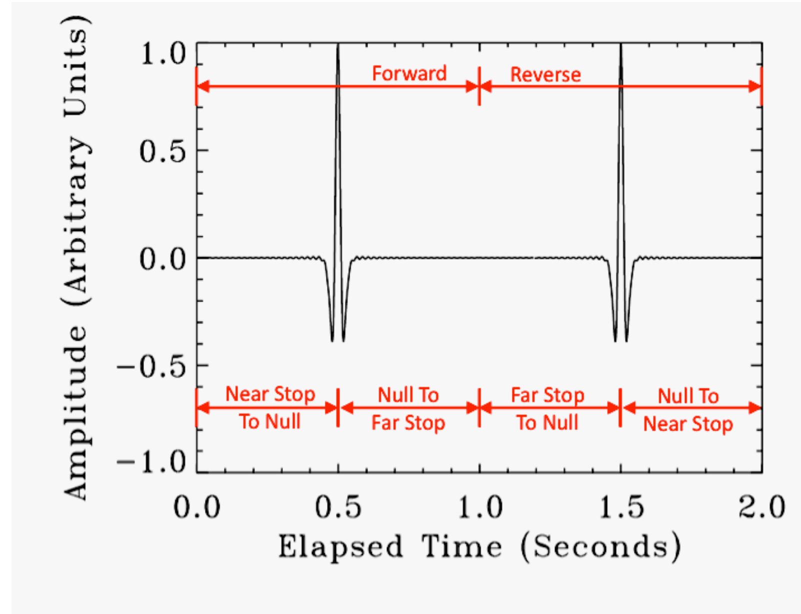
COBE/FIRAS
The Best of 1980's Technology

- CMB blackbody spectrum
- Limit distortions to 50 ppm
- Map CMB primary anisotropy
- dB/dT Spectrum of CMB anisotropy

What Could You Do With Today's Technology?

PIXIE Nulling Polarimeter





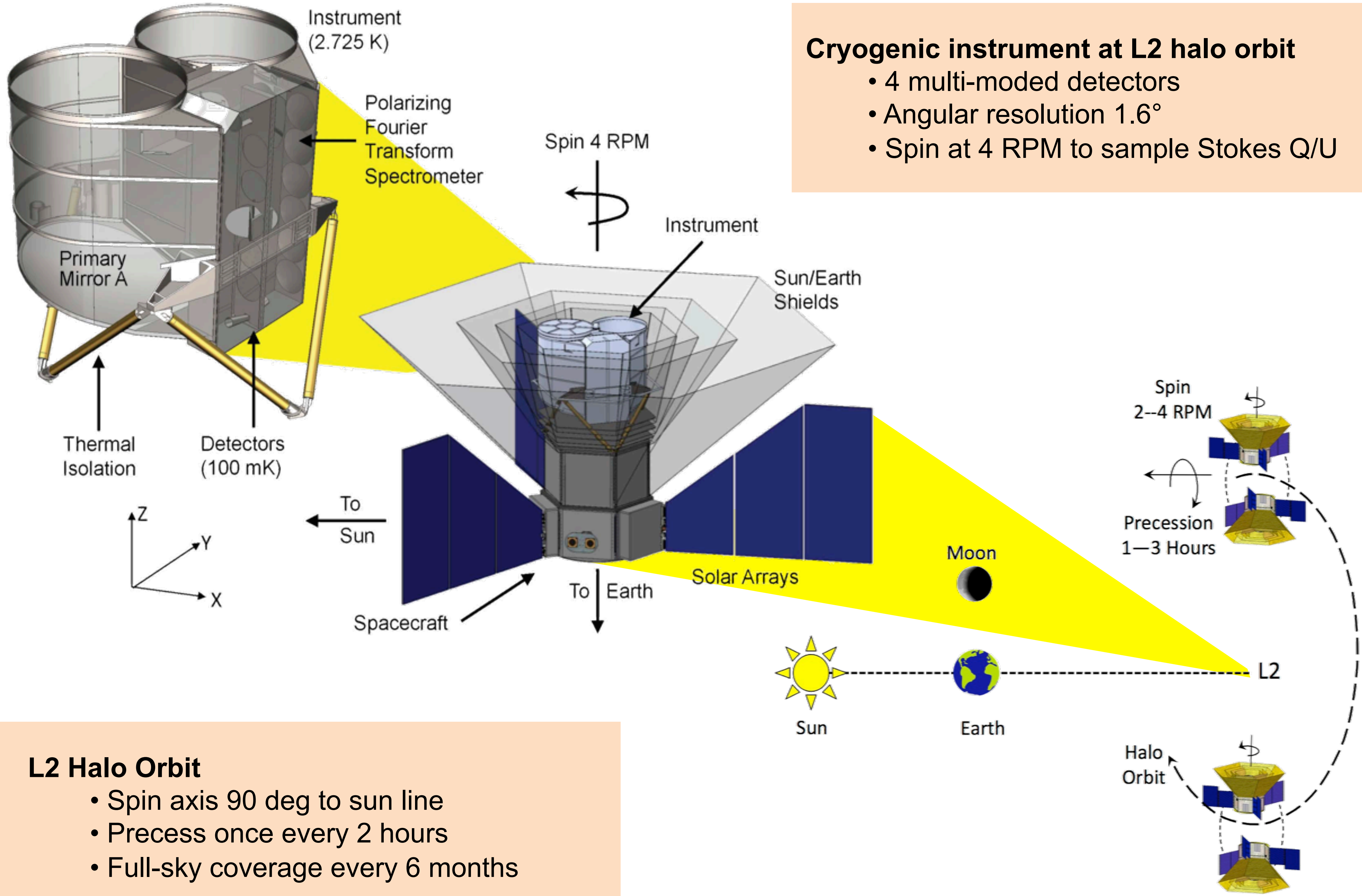
Measured Fringe Pattern Samples Frequency Spectrum of Polarized Sky Emission

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

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

FIRAS With Polarization!

Instrument and Observatory



Cryogenic instrument at L2 halo orbit

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

L2 Halo Orbit

- Spin axis 90 deg to sun line
- Precess once every 2 hours
- Full-sky coverage every 6 months

Sensitivity the Easy Way

Big Detectors in Multi-Moded Light Bucket

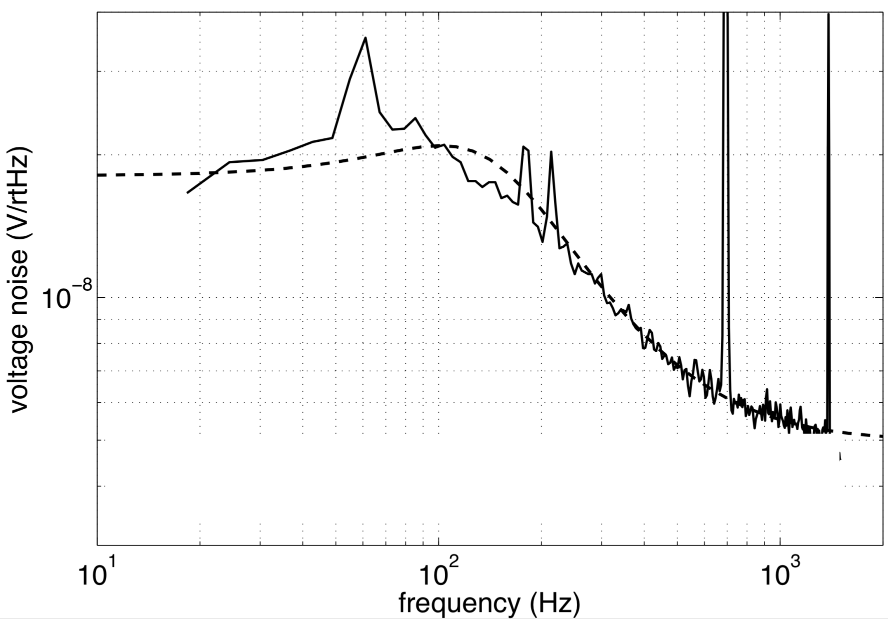
$$\mathrm{NEP}^2_{\mathrm{photon}} = \frac{2A\Omega}{c^2}\frac{(kT)^5}{h^3}\int \alpha\epsilon f \, \frac{x^4}{e^x - 1}\left(1 + \frac{\alpha\epsilon f}{e^x - 1}\right) dx$$

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

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

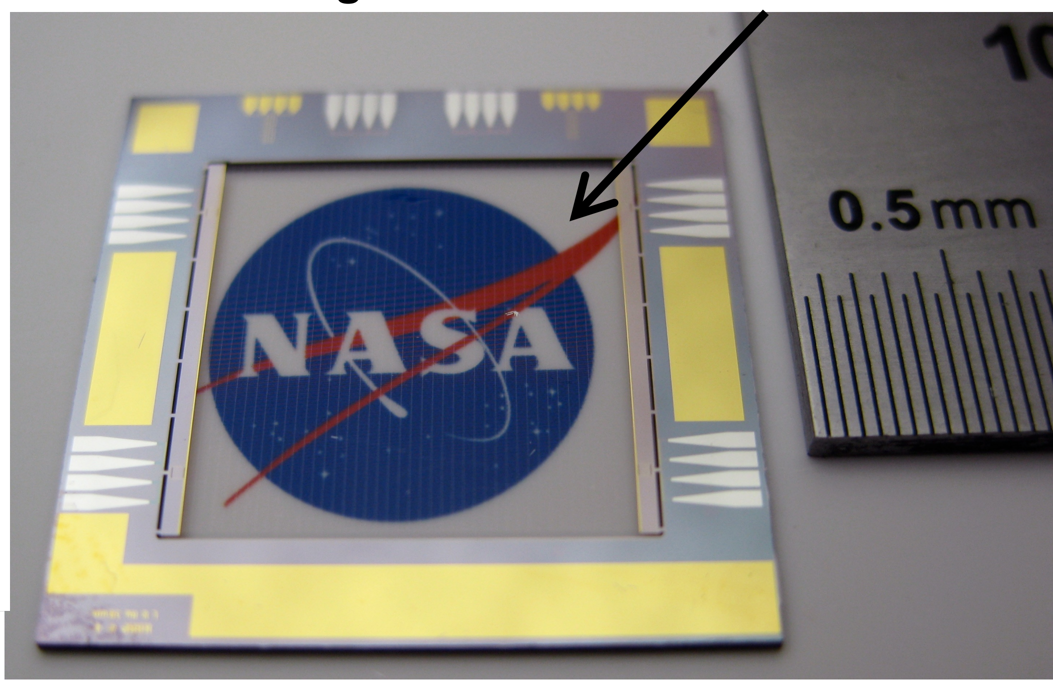
Signal ~ $(A\Omega)$
Big detector: S/N improves as $(A\Omega)^{1/2}$

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



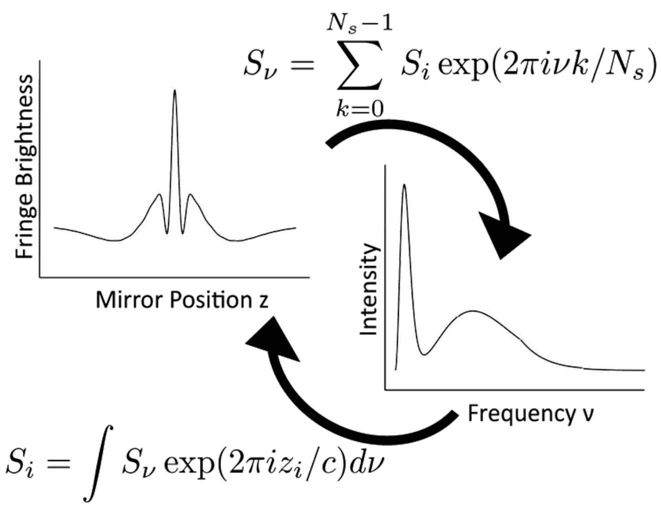
Sensitivity 70 nK per 1° x 1° pixel

30x collecting area as Planck bolometers



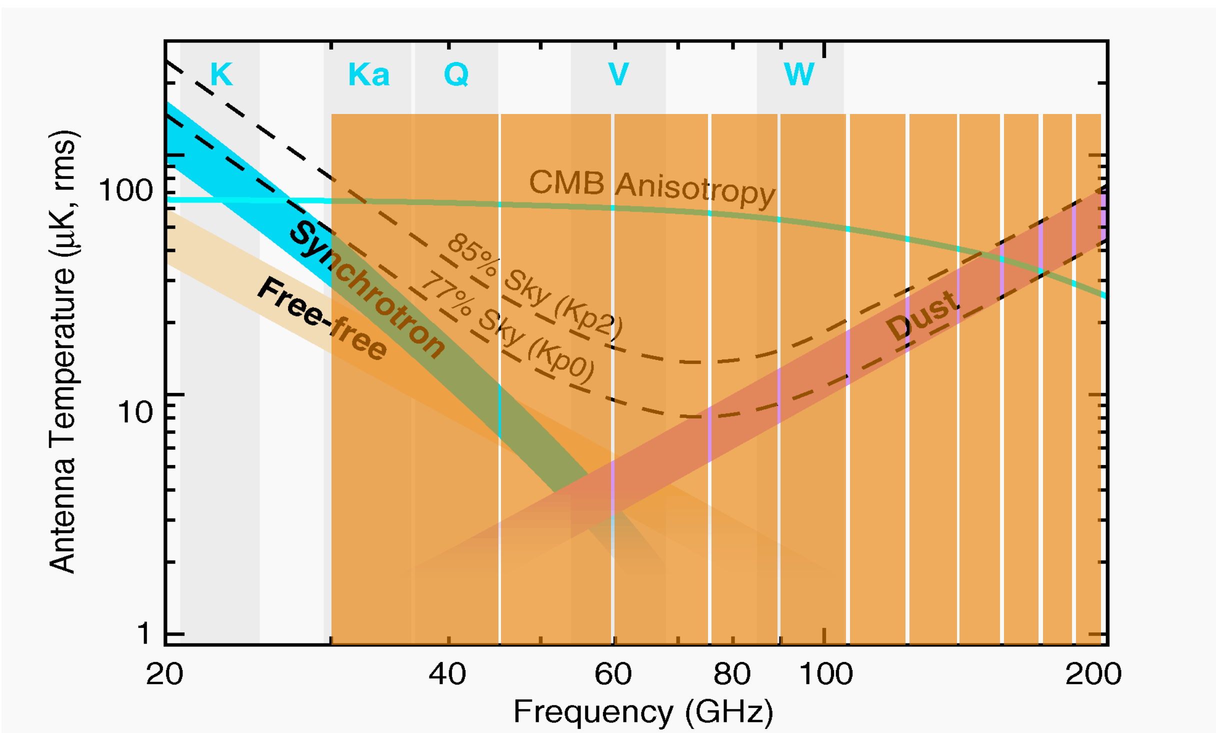
PIXIE polarization-sensitive bolometer

Foregrounds the Easy Way



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

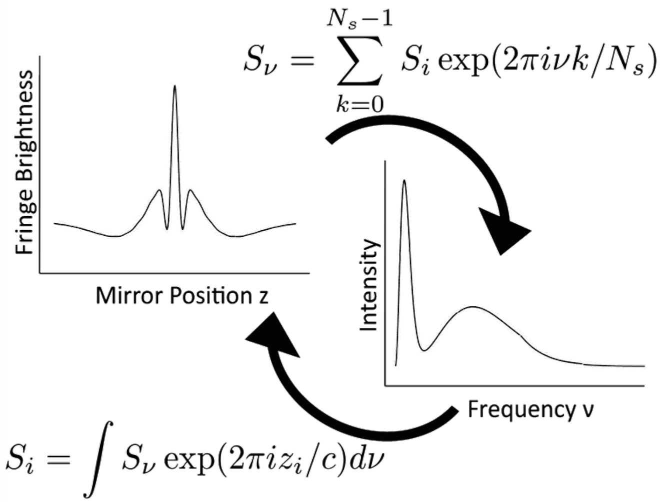
Number of samples sets frequency range
$\nu_i = 15, 30, 45, \ldots (N/2)*\Delta\nu$



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

But why stop there?

Foregrounds the Easy Way



Phase delay L sets channel width

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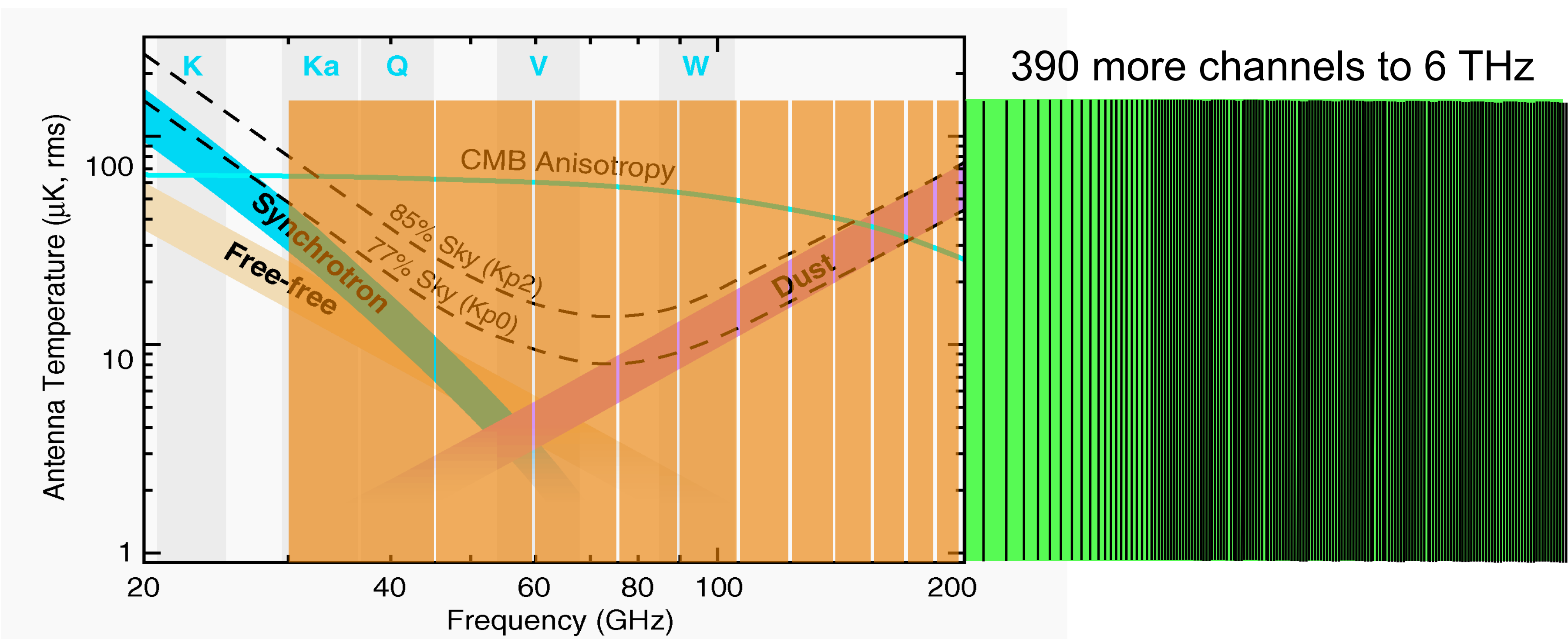
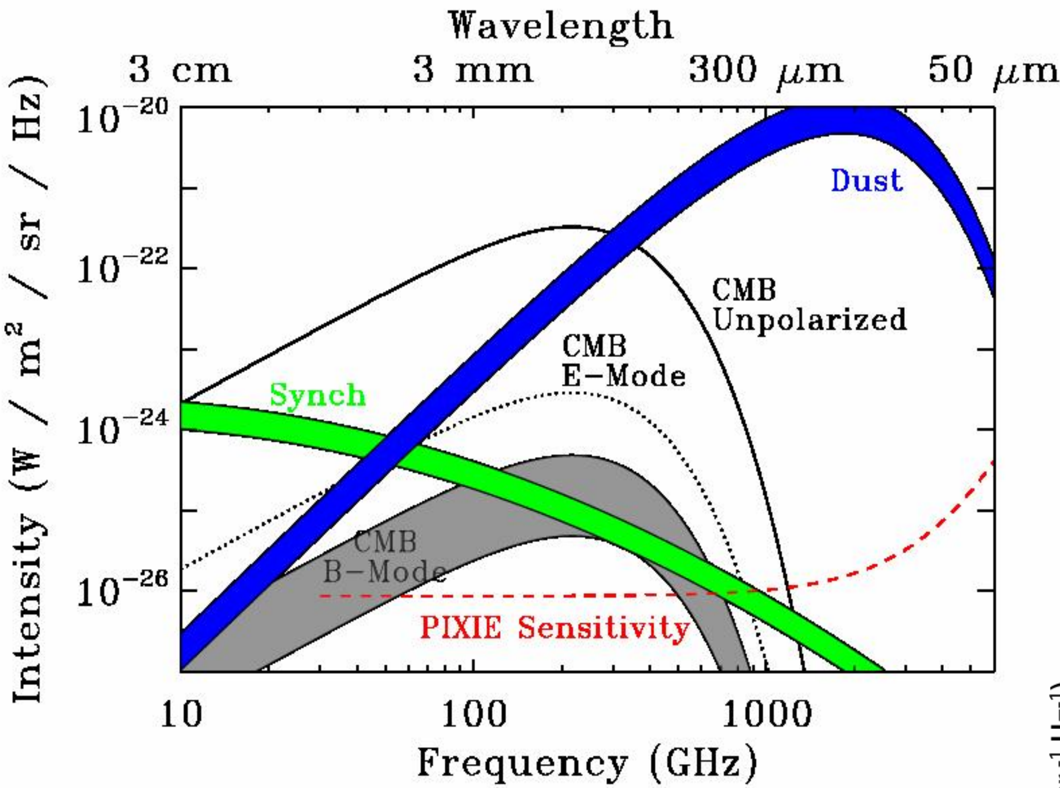


Sample more often: Get more frequency channels!

PIXIE "Foreground Machine"



Spectral coverage spanning 7+ octaves

Polarized spectra from 30 GHz to 6 THz

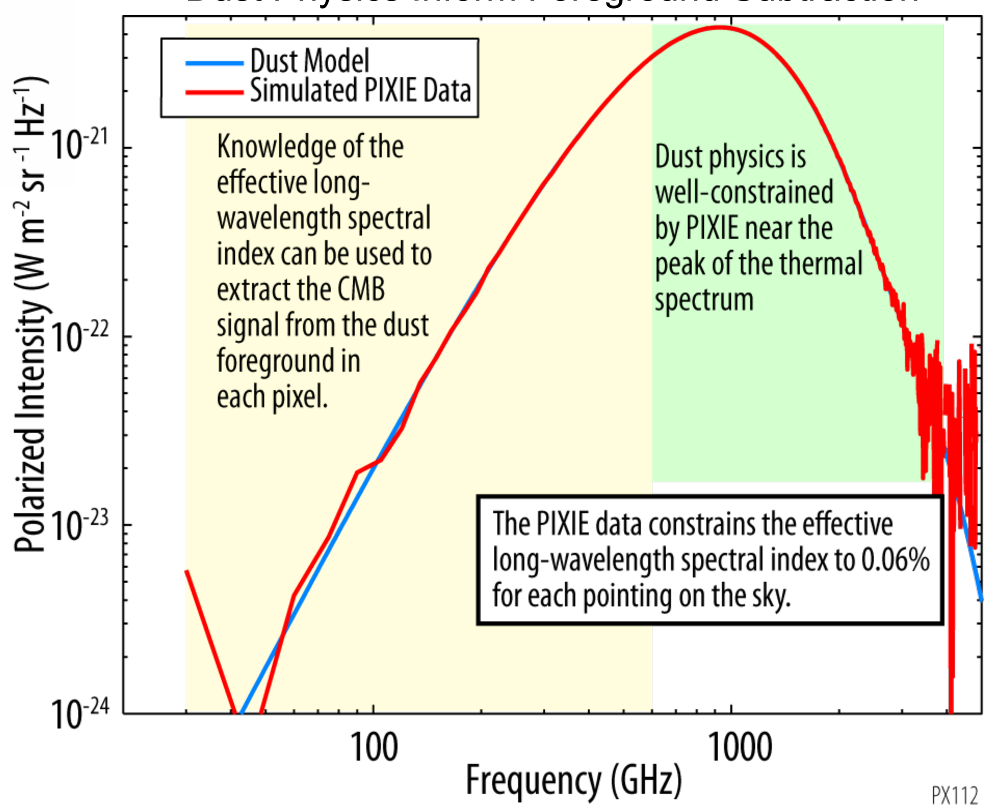
400 channels with mJy sensitivity per channel

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



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

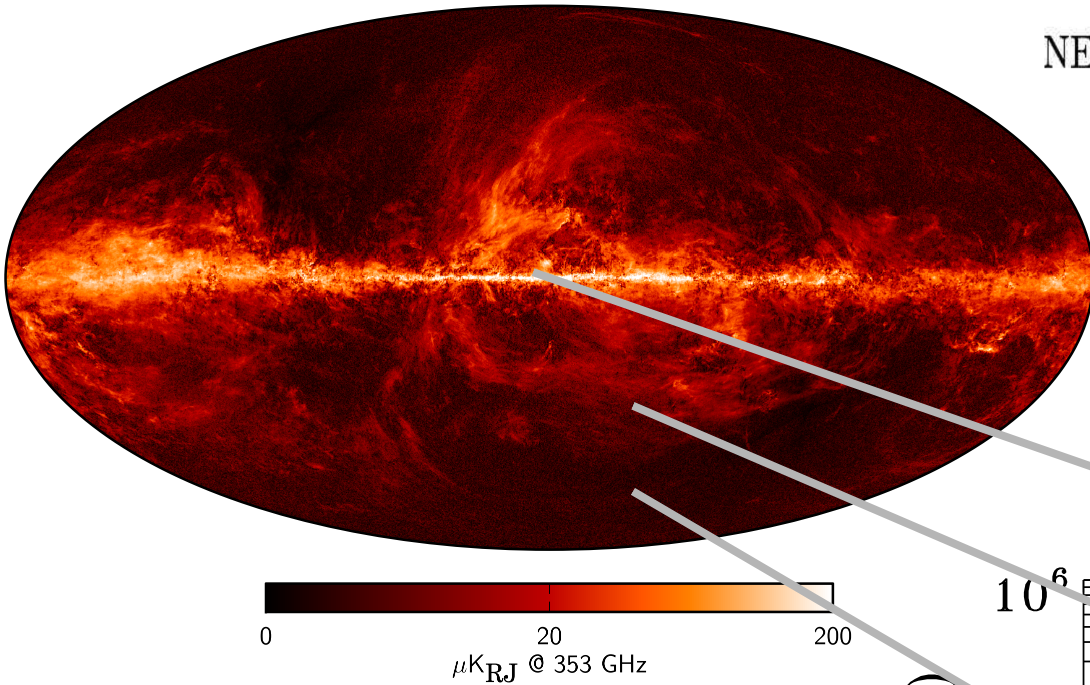
PX112

PIXIE Photon Noise

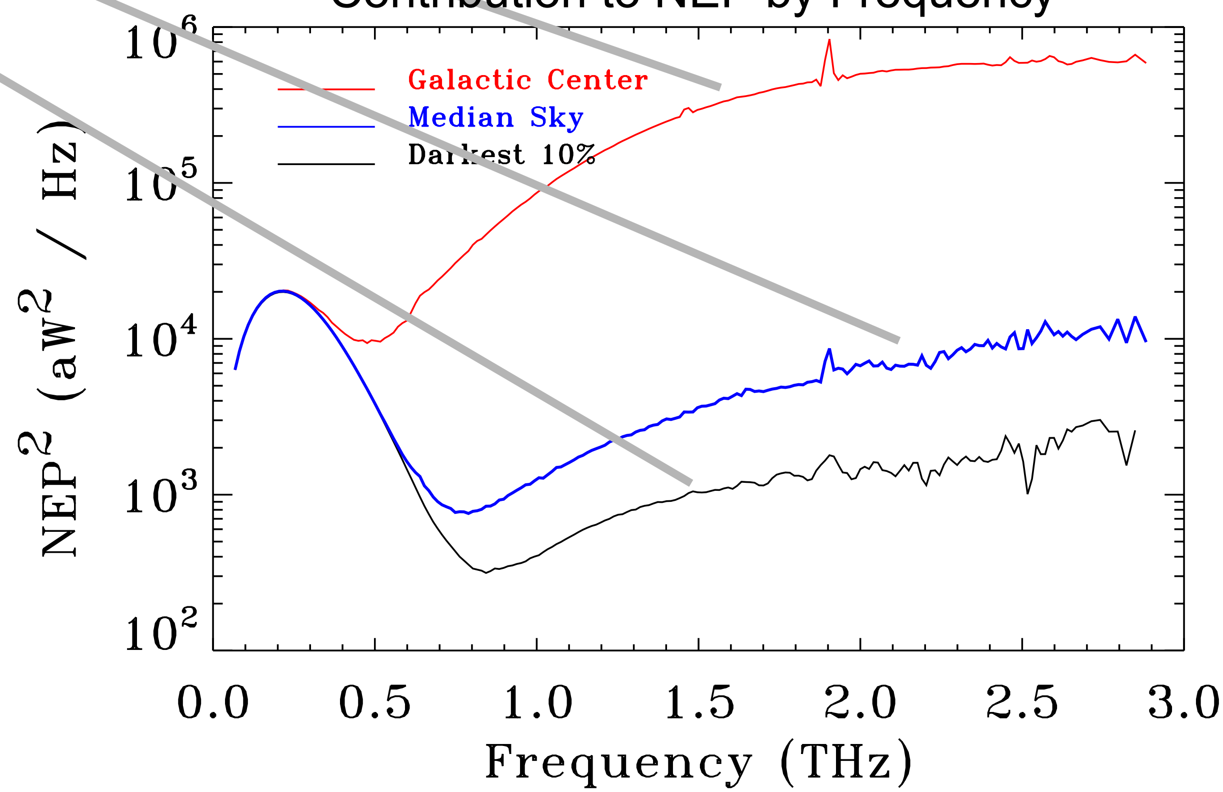
$$\mathrm{NEP}^2_{\mathrm{photon}} = \frac{2A\Omega}{c^2}\frac{(kT)^5}{h^3}\int \alpha\epsilon f \,\frac{x^4}{e^x-1}\left(1+\frac{\alpha\epsilon f}{e^x-1}\right)\,dx$$

Compute NEP² from photon noise

Include CMB, dust, CIB, zodiacal light



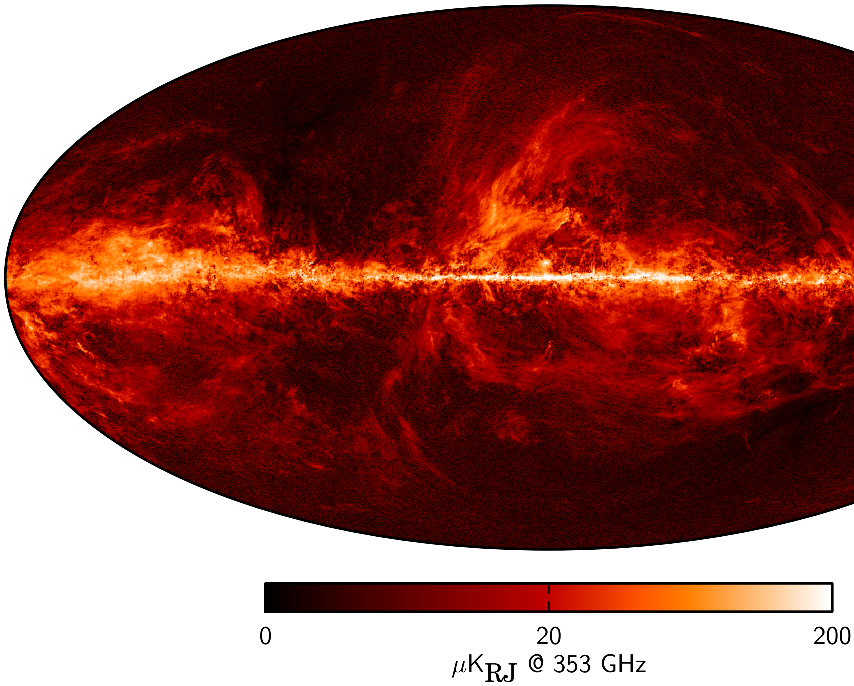
Contribution to NEP by Frequency



Galactic plane is bad for cosmology

Rest of sky is not so bad

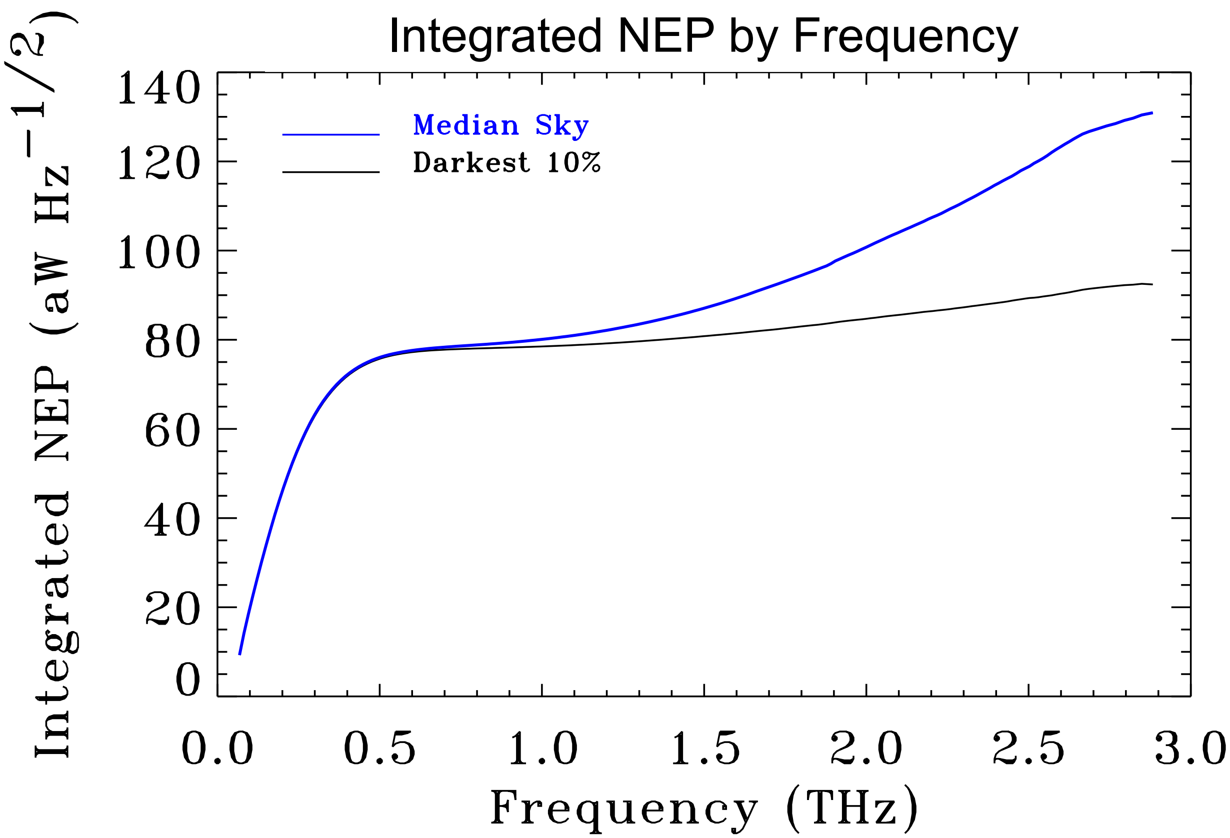
PIXIE Photon Noise



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

Compute NEP² from photon noise

Include CMB, dust, CIB, zodiacal light

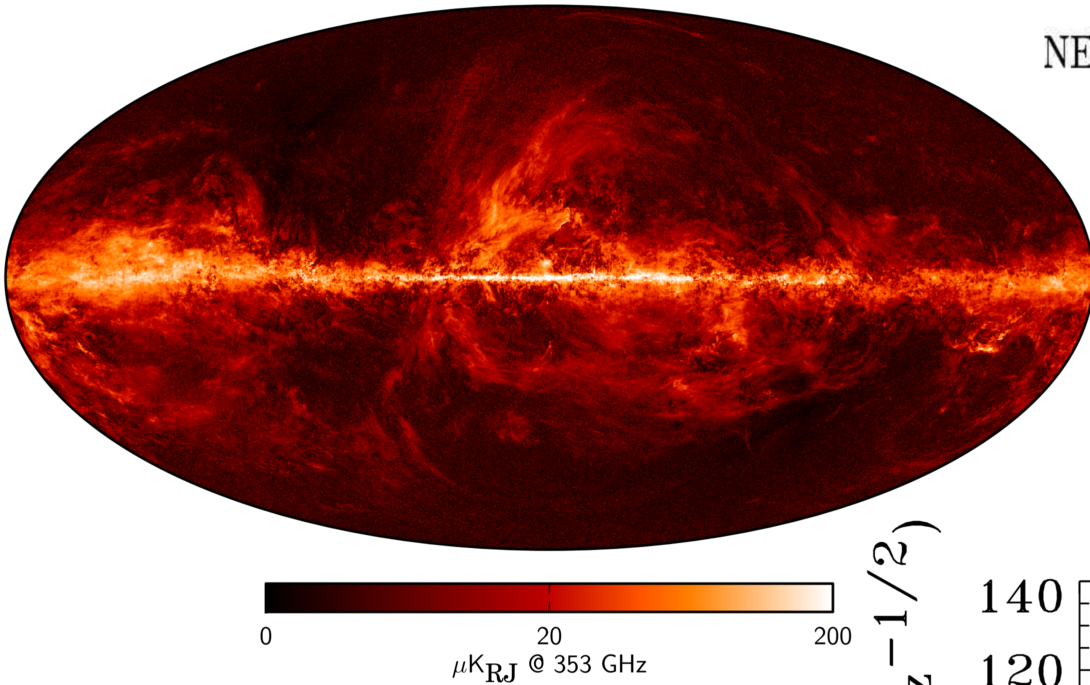


Galactic plane is bad for cosmology
Rest of sky is not so bad

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

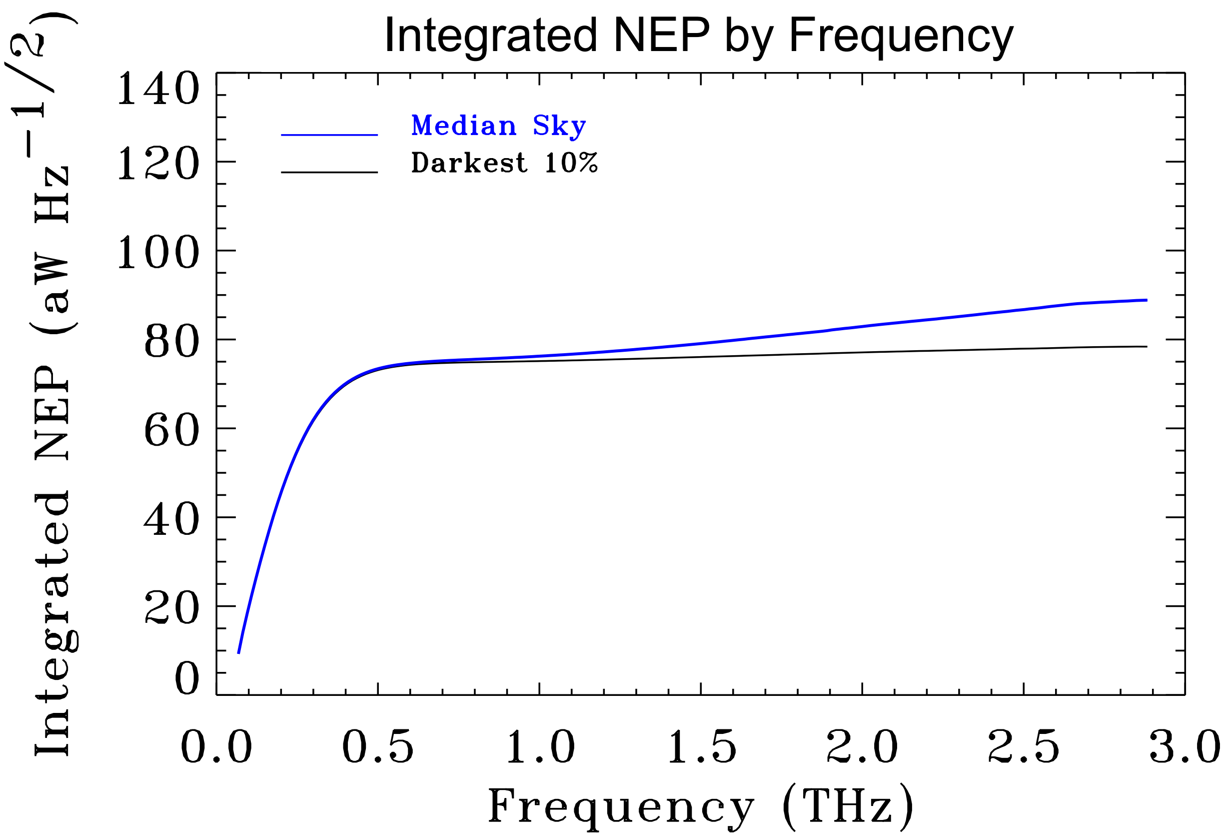
PIXIE Photon Noise

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



Compute NEP² from photon noise

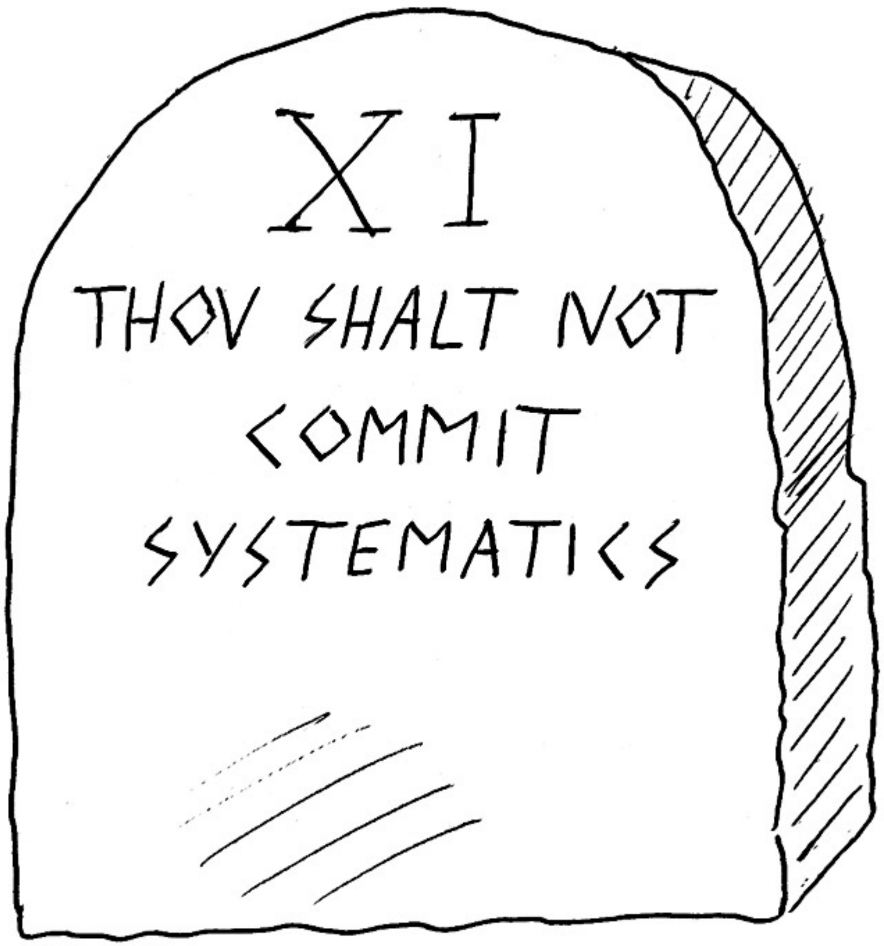
Include CMB, dust, CIB, zodiacal light



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

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

Systematic Error Control



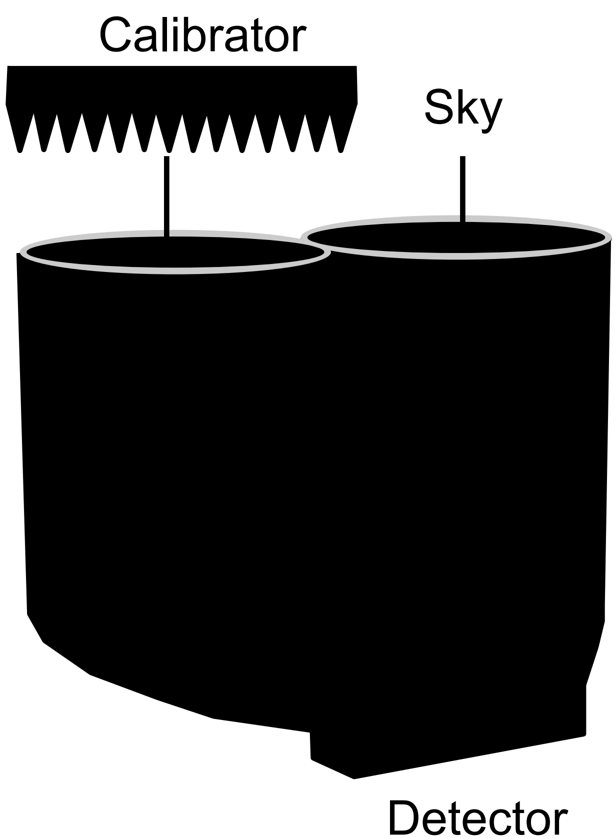
Lesson from FIRAS:

Parts-per-billion measurement requires multiple nulling

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

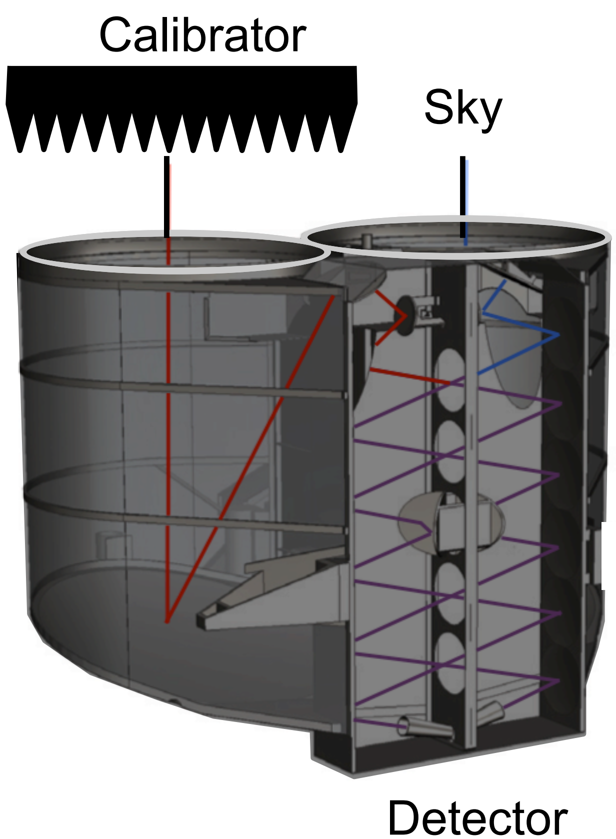
FIRAS: Instrument at 1.4 K — ΔT = 1.3 K lever for systematics

PIXIE: Instrument at 2.725 K — ΔT = 0.005 K lever for systematics

Isothermal operation alone reduces systematic errors by factor 300!

Systematic Errors II

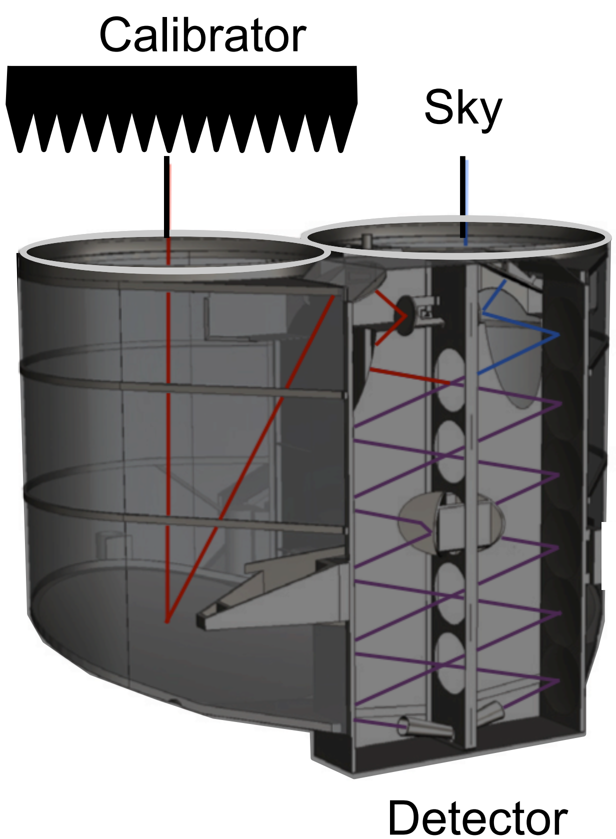
Chain Multiple Nulls Together



Maximum ΔT few mK

Systematic Errors II

Chain Multiple Nulls Together

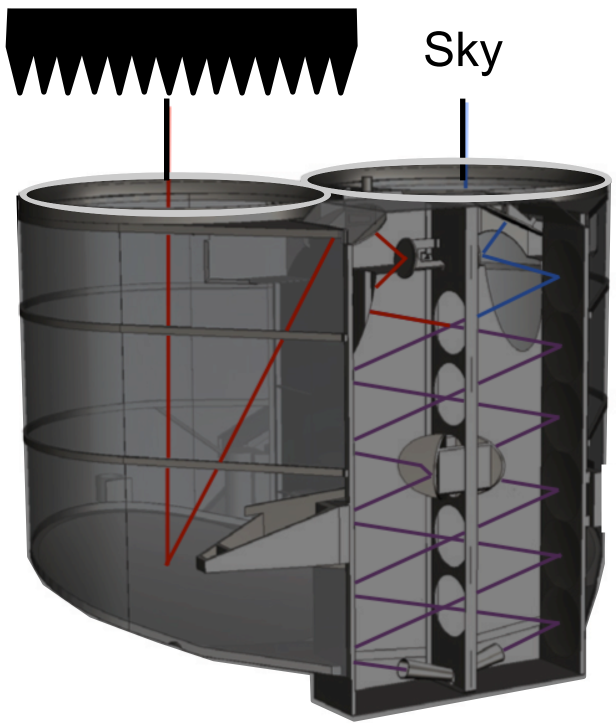


Maximum ΔT few mK

Mirror Emissivity x 0.01 → tens of uK

Systematic Errors II

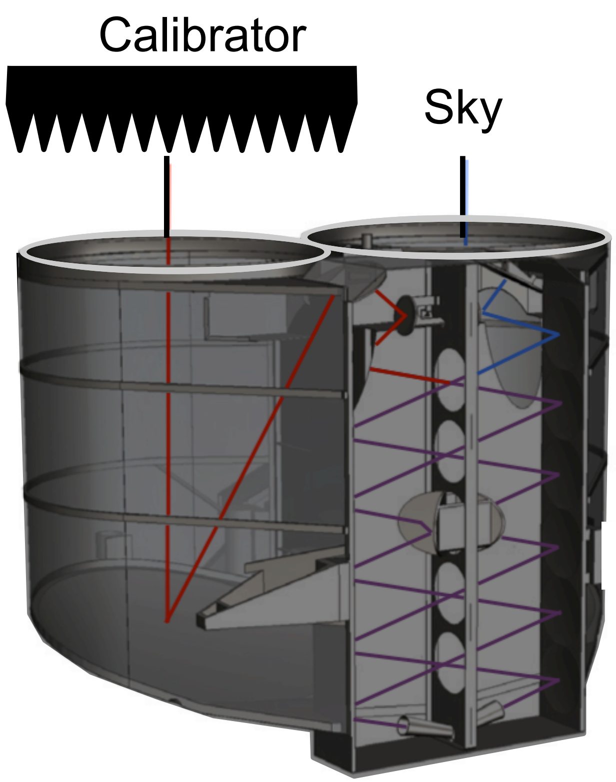
Chain Multiple Nulls Together



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

Systematic Errors II

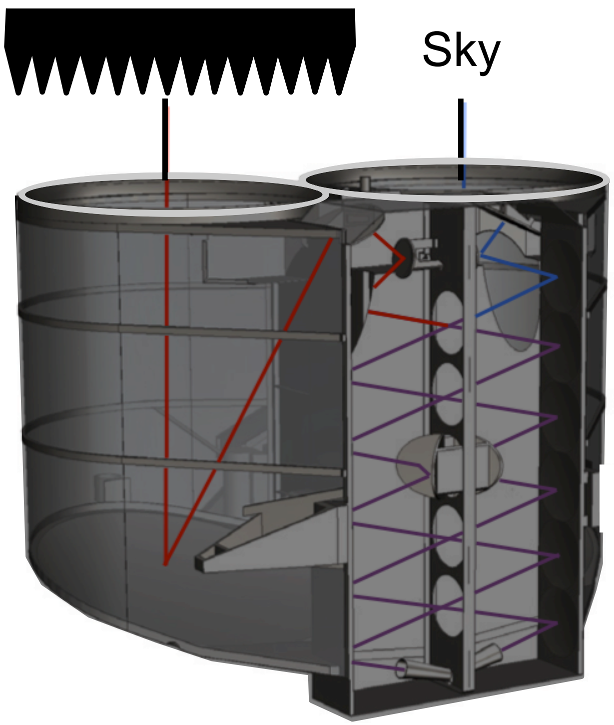
Chain Multiple Nulls Together



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)	

Systematic Errors II

Chain Multiple Nulls Together



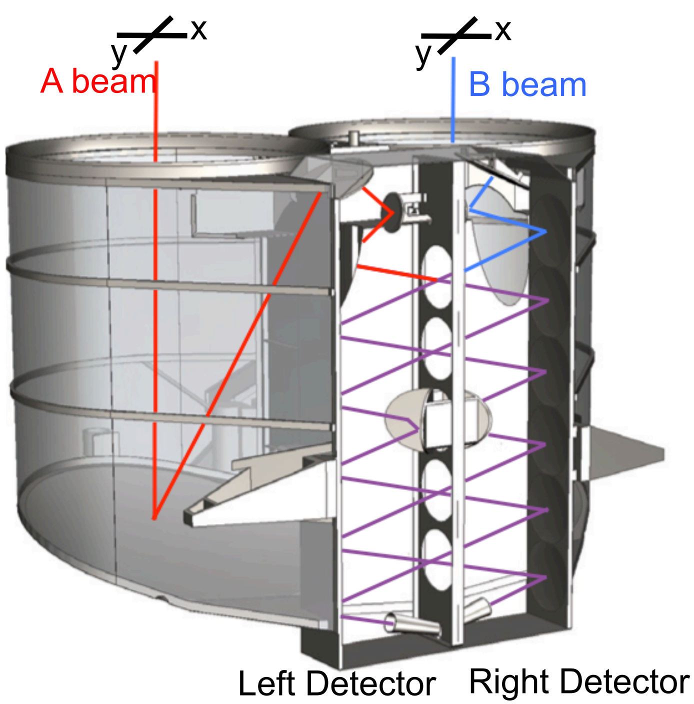
Maximum ΔT	few mK		
Mirror Emissivity		x 0.01 →	tens of uK
Left/Right Asymmetry		x 0.01 →	few hundred nK
Swap hot vs cold		x 0.01 →	few nK
Uncorrected Error	few nK (with blue-ish tinge)		
Corrected Error	<< 1 nK		

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

Symmetry and Systematic Error

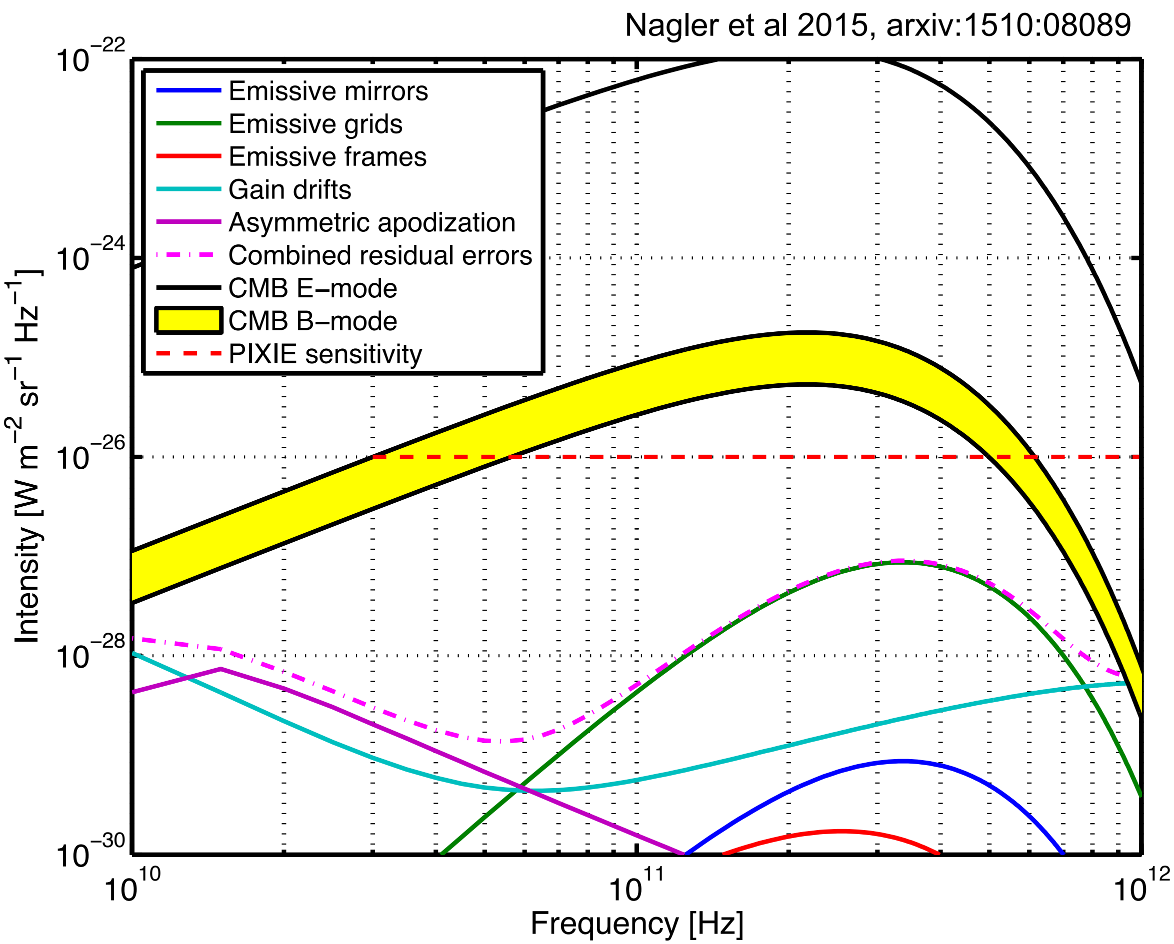
20 Ways to Fix An Error

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

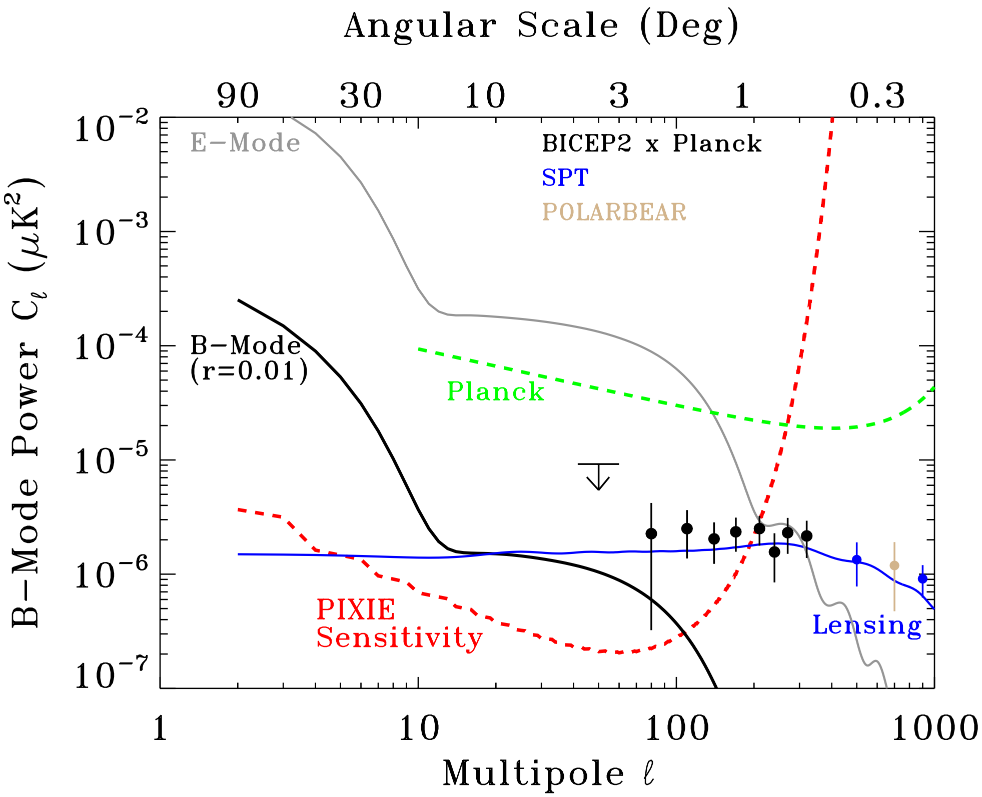


Multiple nulls combine to reduce systematic errors

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



PIXIE and Polarization

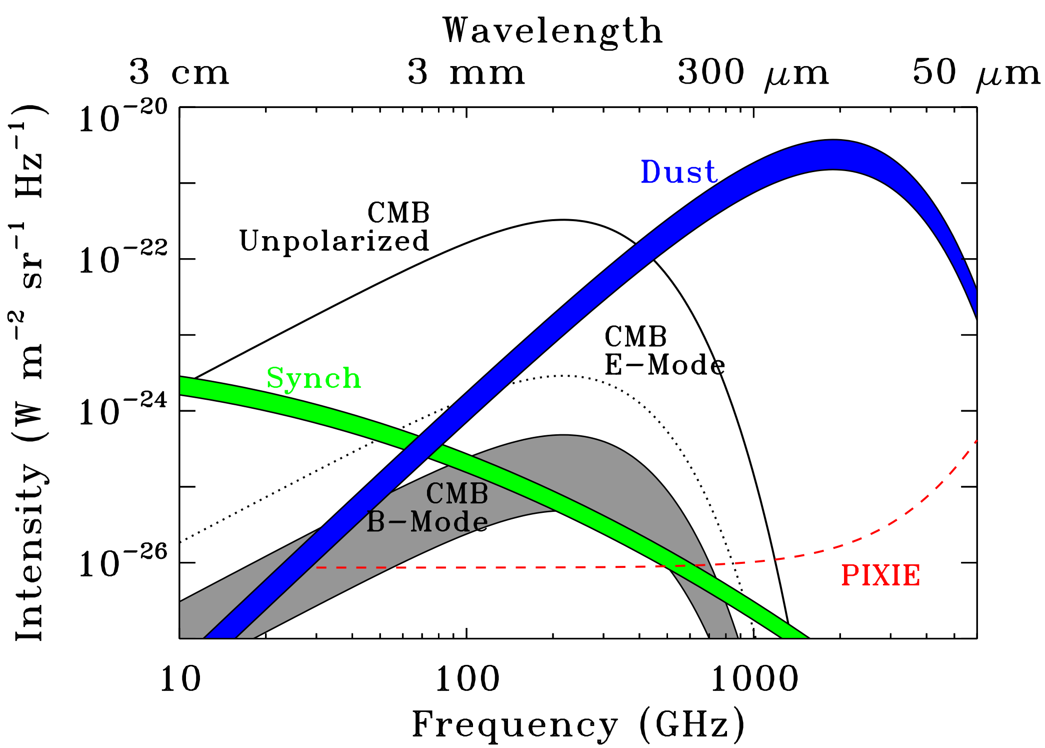


Sensitivity r < 4 x 10^{-4} (95% CL)

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

Cosmic-variance-limited EE spectrum

Characterize astrophysical foregrounds



Complement Ground-Based Efforts

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

Do From Space That Which Can Only Be Done From Space


BUT WAIT,
there's more!

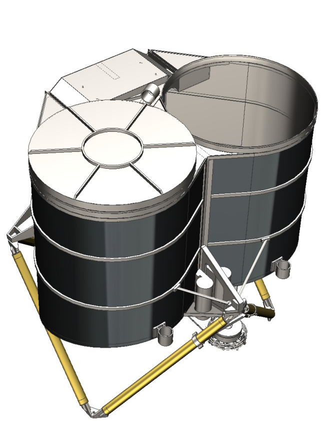
Blackbody Calibrator Tests Blackbody Distortions

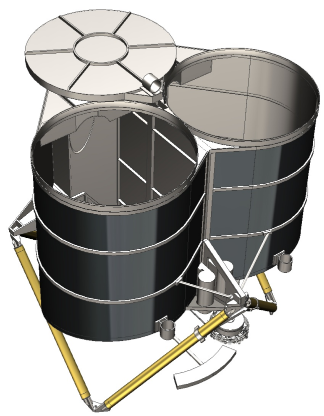
Calibrator stowed:
Polarization only

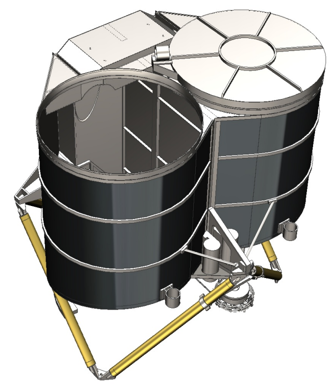
$$P_{Lx} = \frac{1}{2}\int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx}^2 - E_{Ay}^2\right)\cos(z\omega/c)\, d\omega$$

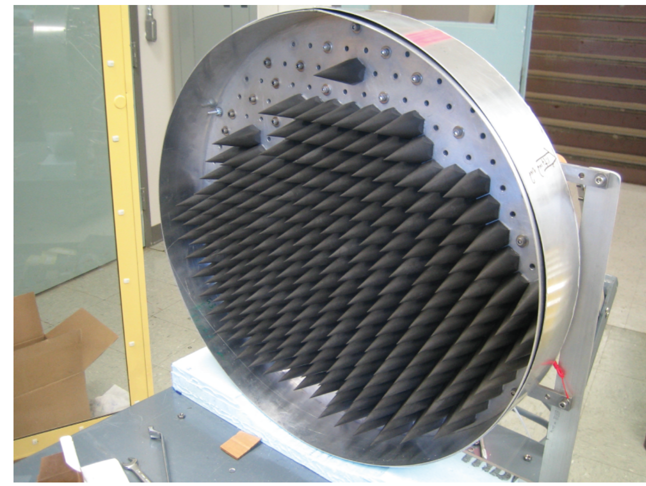
$$P_{Ly} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{By}^2 - E_{Ax}^2\right)\cos(z\omega/c)\, d\omega$$

Sky Stokes Q









Partially-assembled blackbody calibrator

Calibrator deployed:
Spectral distortions!

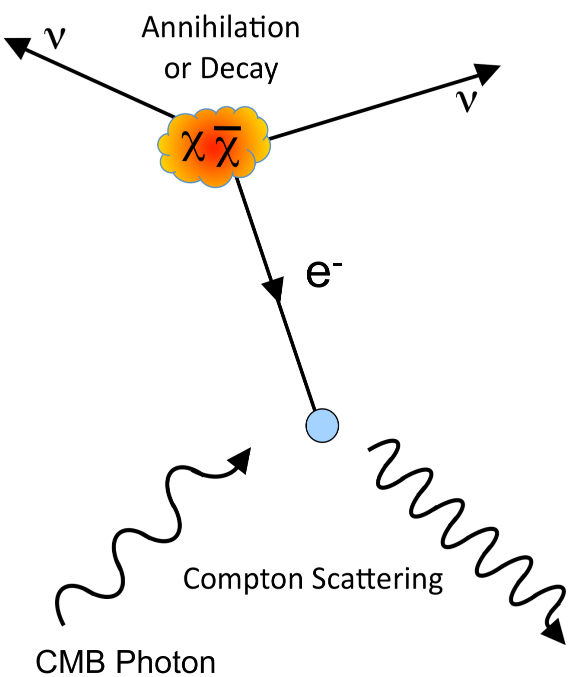
$$P_{Lx} = \frac{1}{2}\int \left(E_{Cal,y}^2 + E_{Sky,x}^2\right) + \left(E_{Sky,x}^2 - E_{Cal,y}^2\right)\cos(z\omega/c)\, d\omega$$

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

[Calibrator-Sky]
Spectral Difference

Like FIRAS,
But 1000x
More Sensitive!

Spectral Distortion from Energy Release



Optically thin case: Compton y distortion

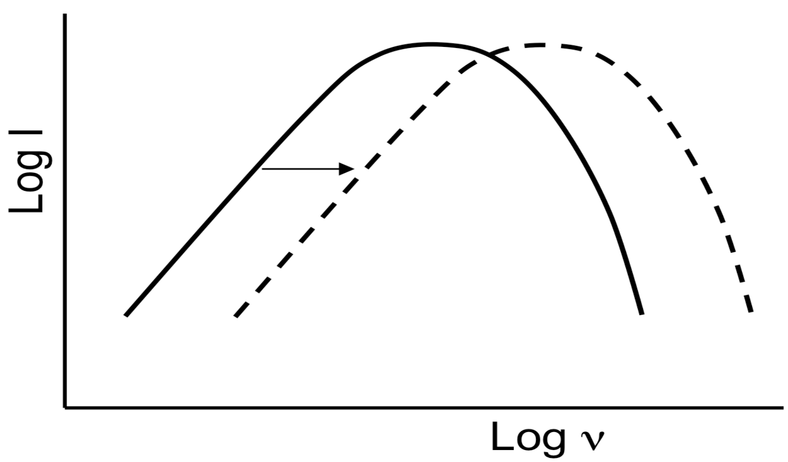
$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp(x)-1}\left[1+\frac{y\,x\,\exp(x)}{\exp(x)-1}\left(\frac{x}{\tanh(x/2)}-4\right)\right]$$

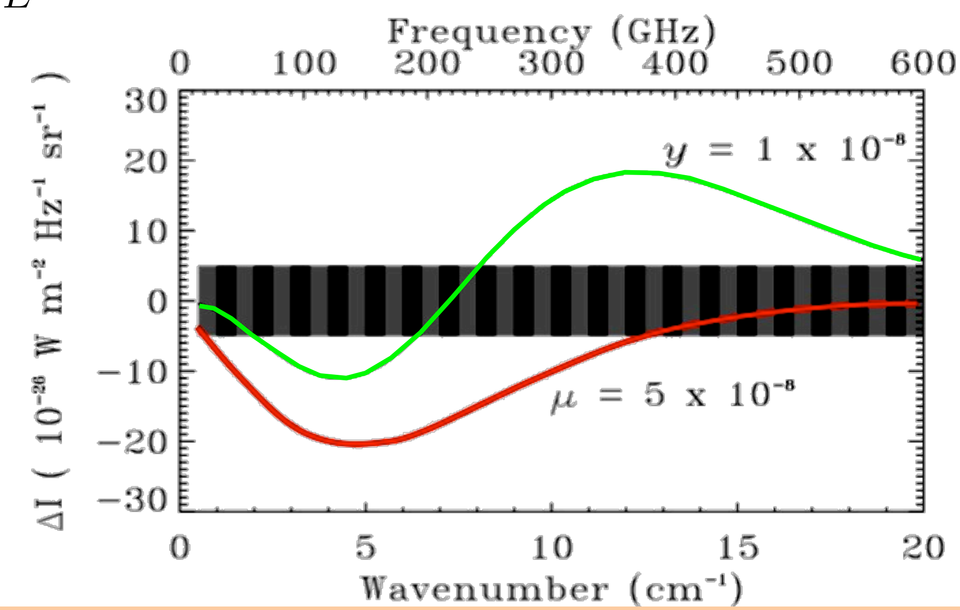
$$y = \int \frac{kT_e}{mc^2}\, nc\sigma_T\, dt$$

Optically thick case: Chemical potential distortion

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

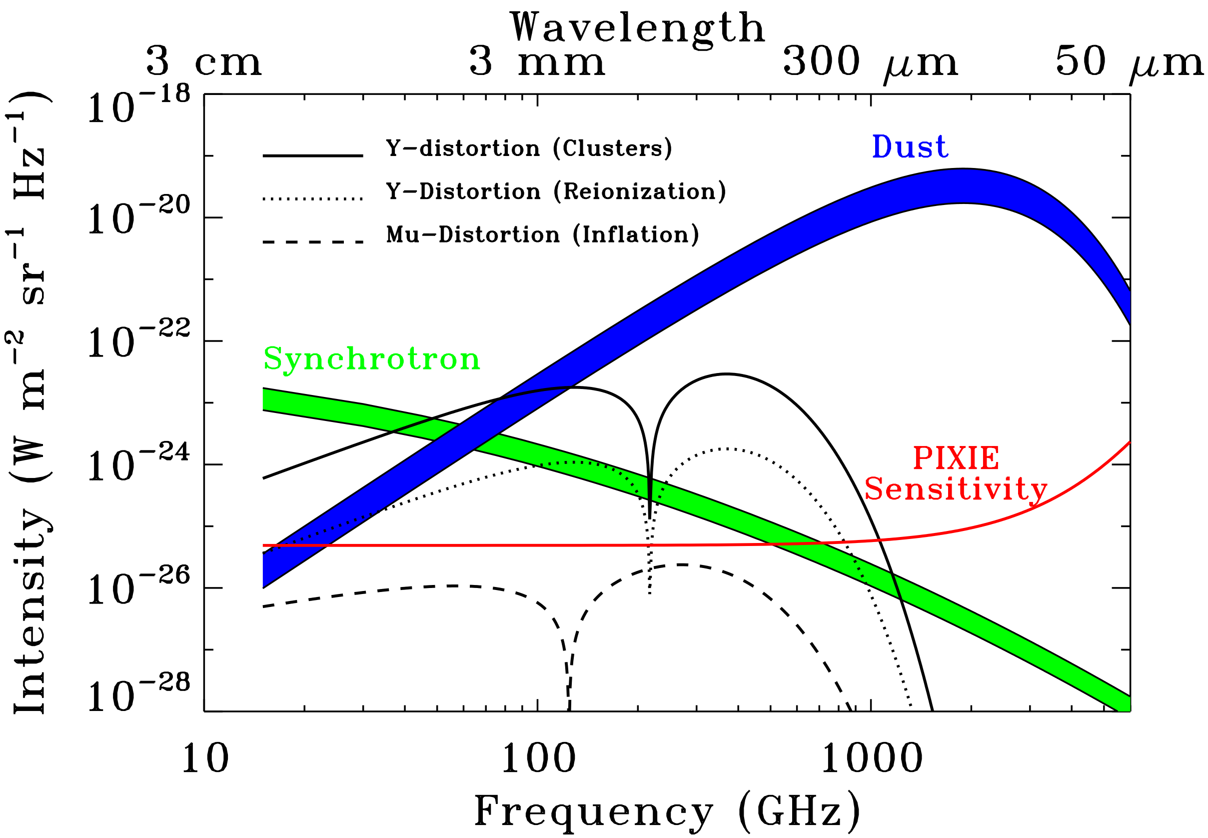
$$\mu = 1.4\,\frac{\Delta E}{E}$$





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

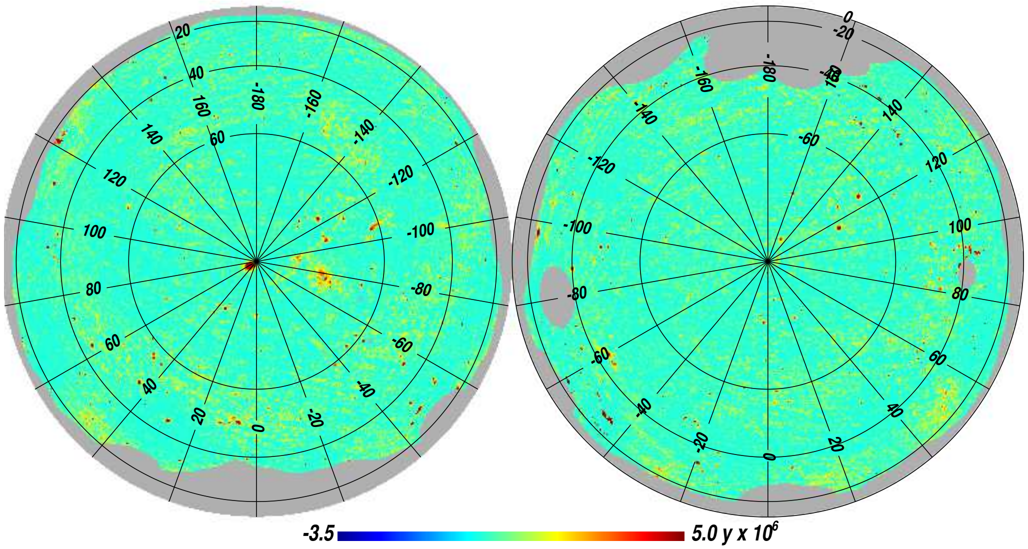
- 1500σ for cluster y distortion
- 95σ for reionization y distortion
- 3σ for inflation μ distortion

Open new discovery space

- Dark matter annihilation
- Exotic physics

Bring spectral distortions to same precision as B-mode polarization

Spectral Distortions: Structure Formation



Planck measures thermal SZ effect

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

PIXIE 50-sigma detection

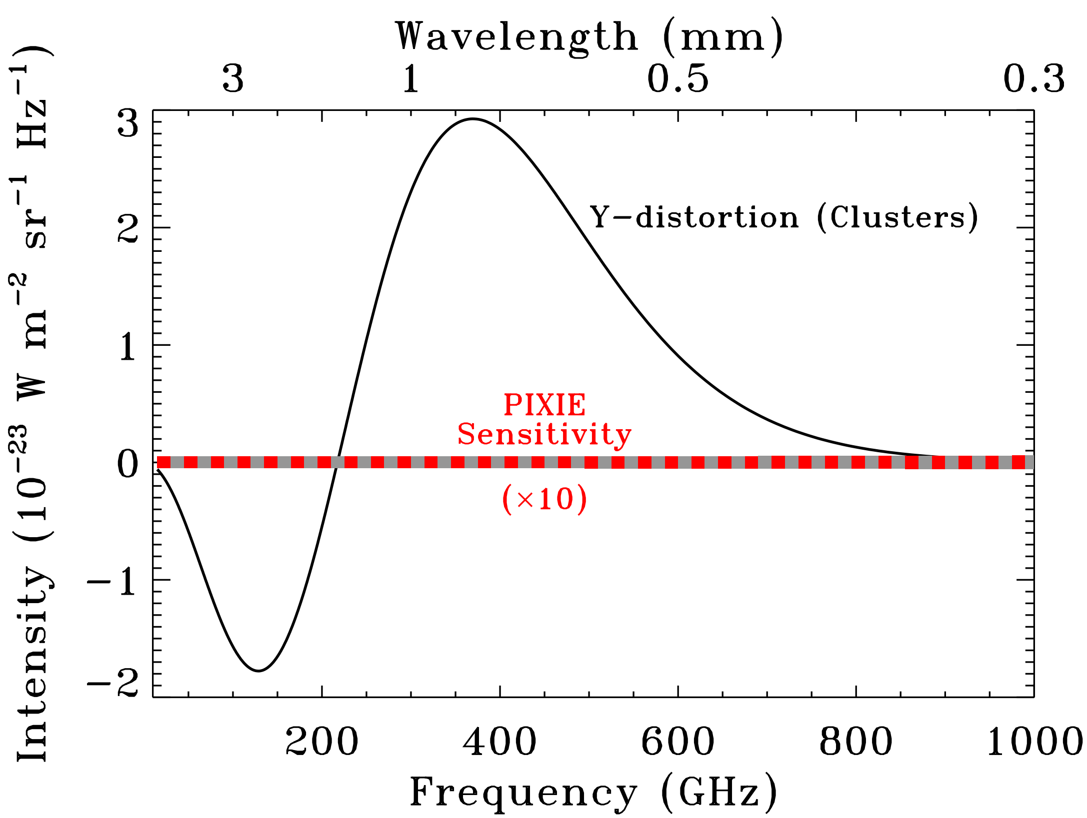
Contribution from unresolved sources

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

PIXIE 1500-sigma detection

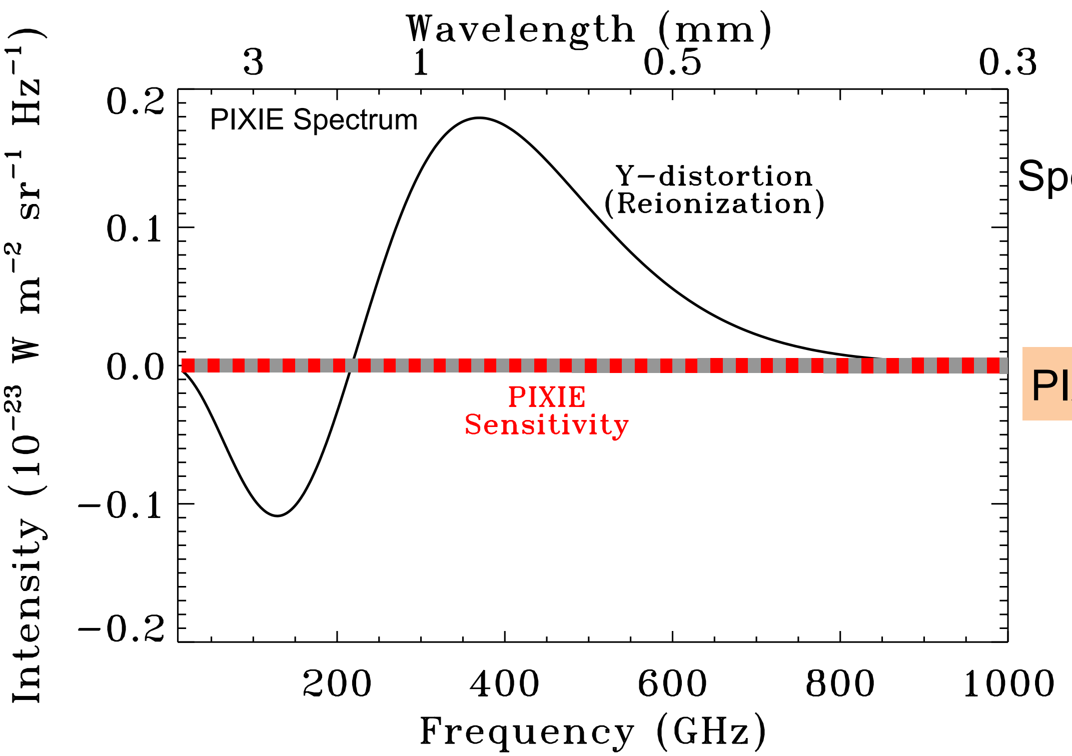
- *Dipole: Compare to CMB at z=1000*
  Gravitational accelerations

- *Cross-correlate vs redshift surveys*
  Growth of structure



Planck 2015 XXII, arXiv:1502.01596
Khatri & Sunyaev 2015, arXiv:1505.00781
Hill et al. 2015, PRL, in prep

Spectral Distortions: Reionization



Spectrum: y distortion ~ 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)

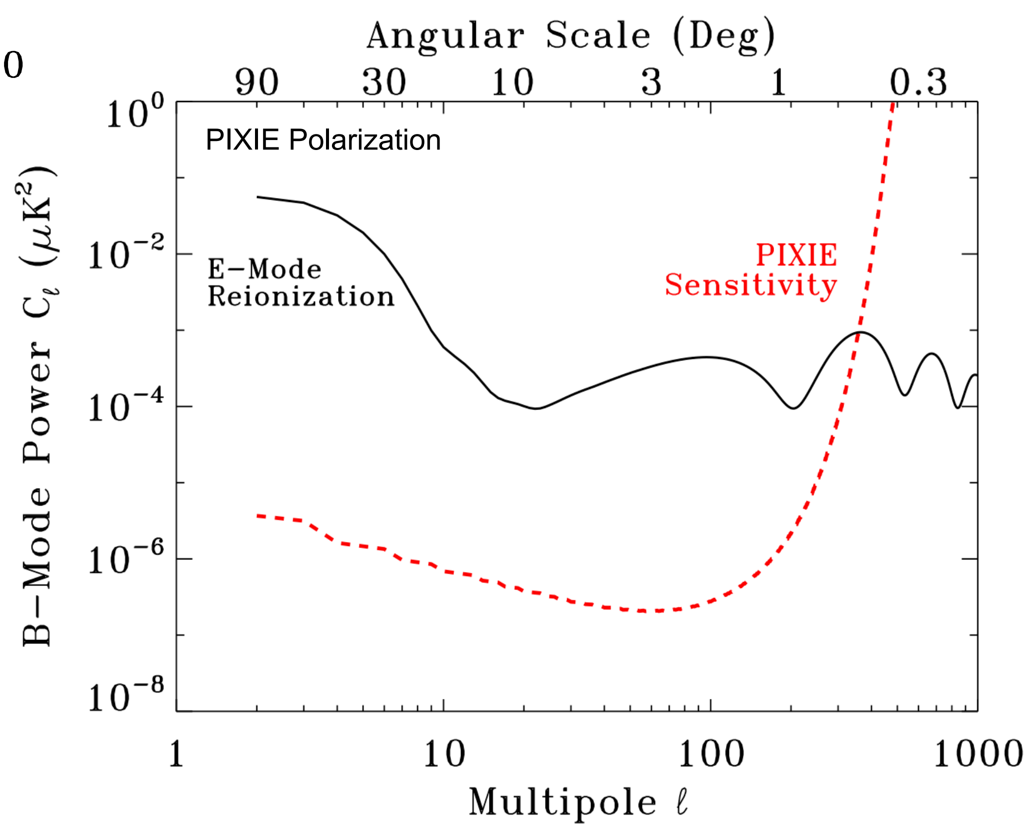
E-mode optical depth ~ Electron density n

Same scattering for both signals

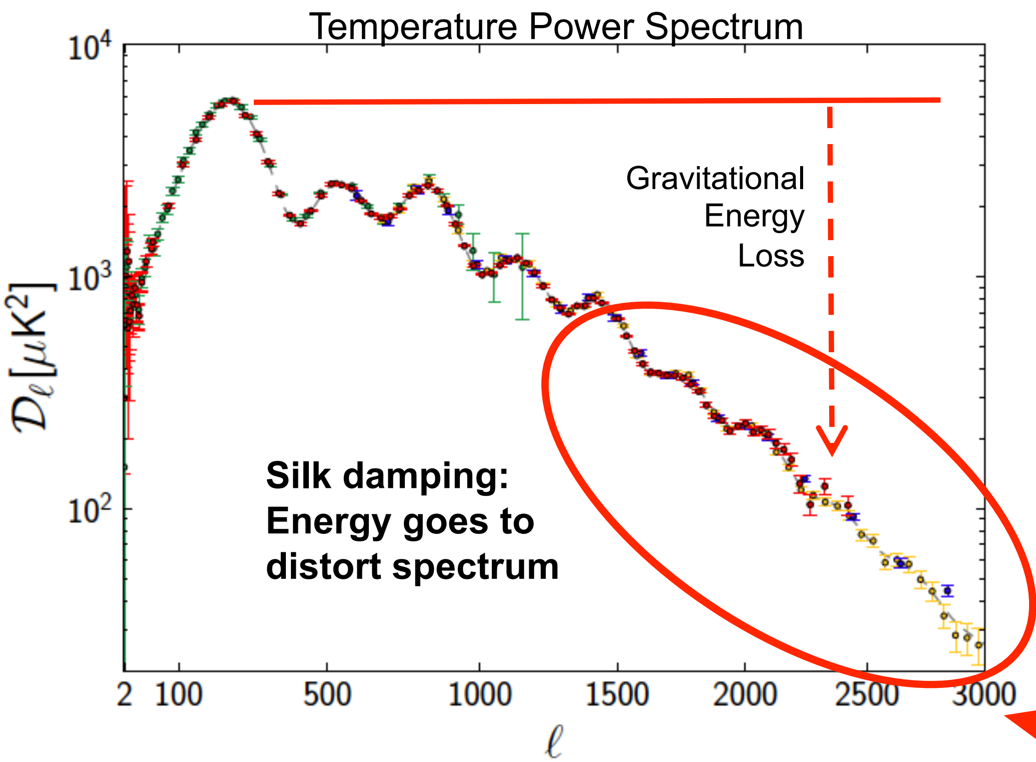
Combine to get n and T_e

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

Determine nature of first luminous objects



Spectral Distortions: Inflation



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

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

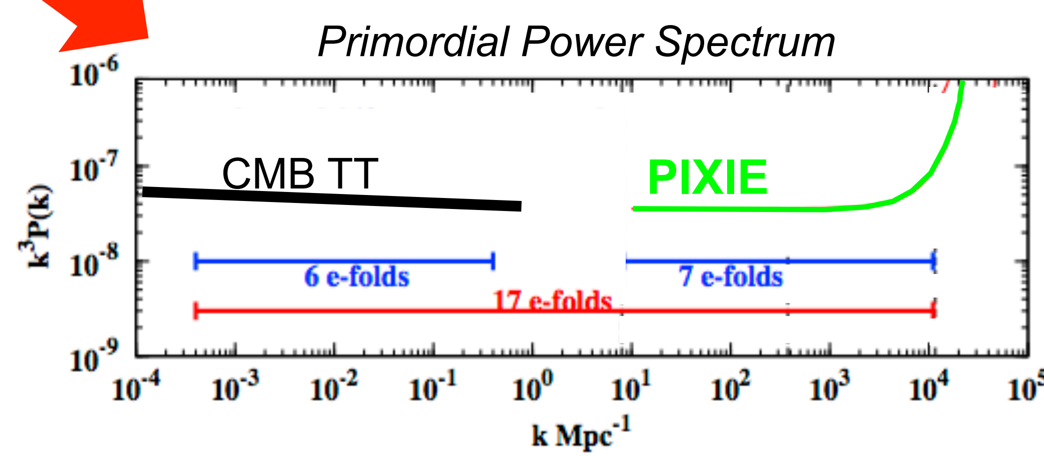
PIXIE limit $\mu < 10^{-8}$

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

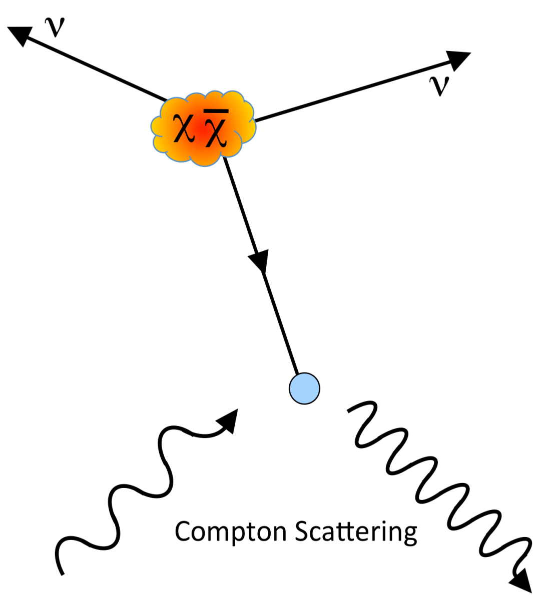
Test inflation at solar-mass scales!



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



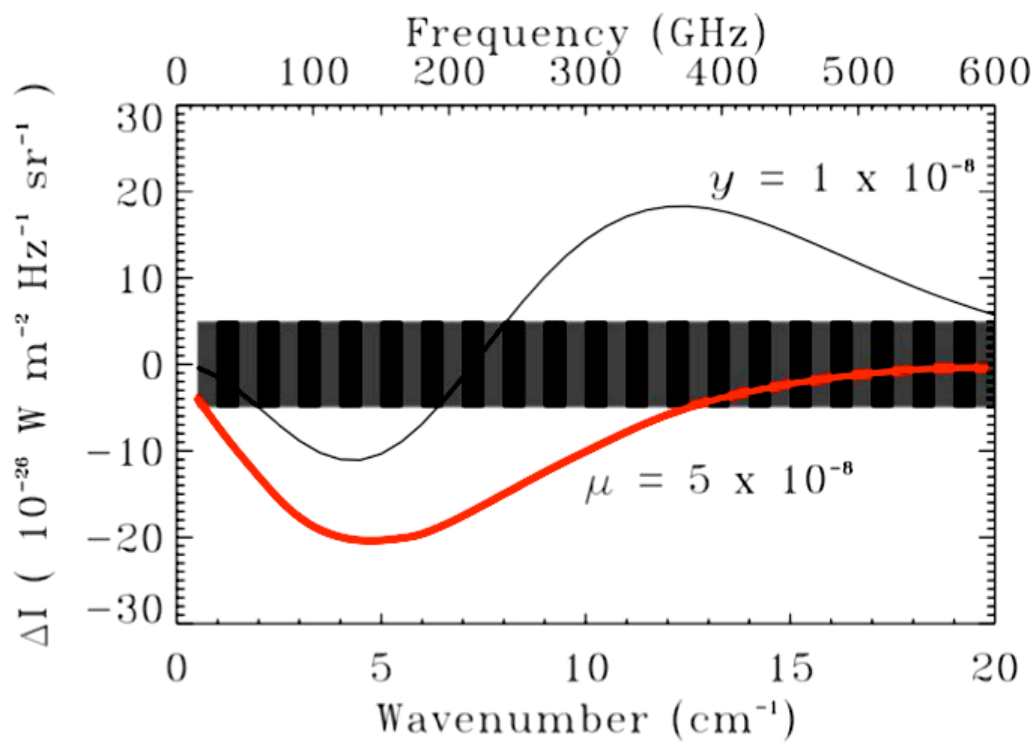
$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp(\frac{h\nu}{kT}+\mu)-1}$$

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

Annihilation rate ~ n^2 ~ z^6

Number density n ~ m^{-1}

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



Dark matter annihilation

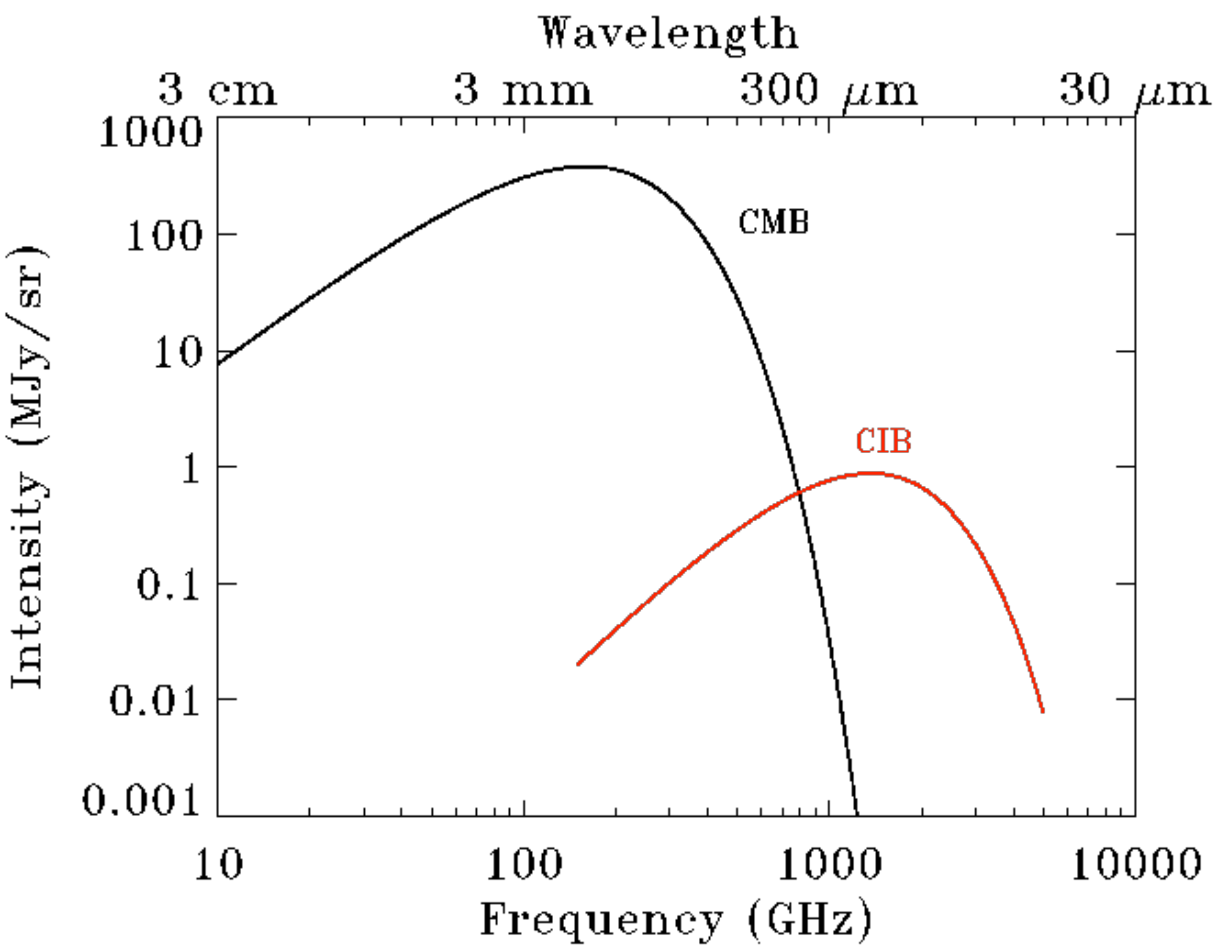
PIXIE limit $\mu < 10^{-8}$

Neutralino mass limit m_χ > 80 keV

Definitive test for warm dark matter

McDonald et al 2001
de Vega & Sanchez 2010

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

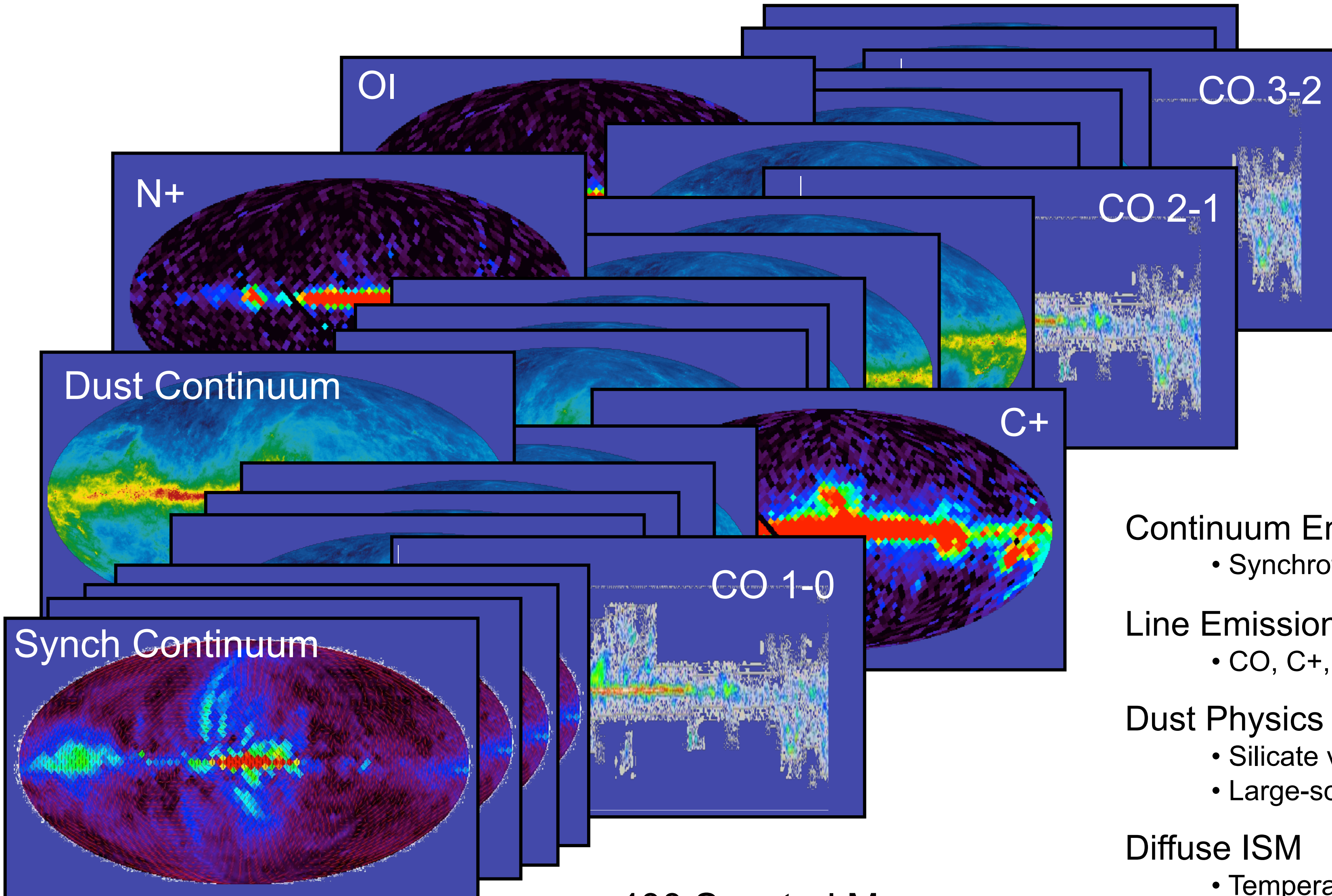
- Complement Herschel, Planck

PIXIE noise is down here!

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

Knox et al. 2001
Fixsen & Kashlinsky 2011

Spectral Line Emission



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

Extremely Rich Data Set!

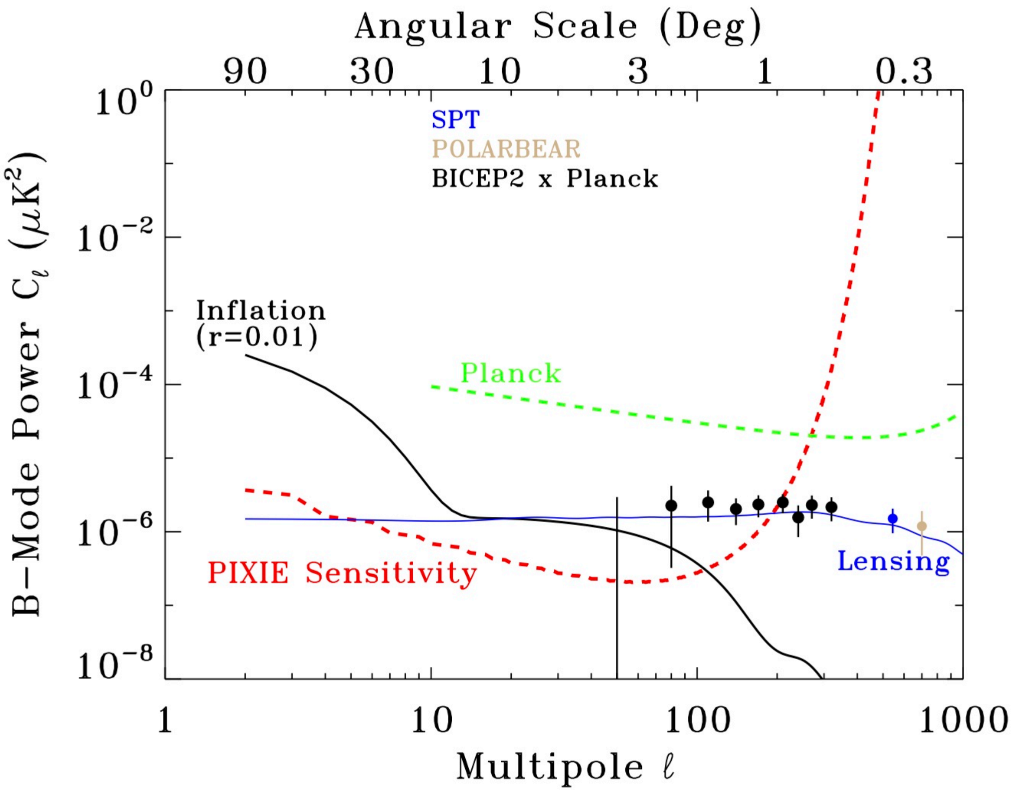
Continuum Emission
- Synchrotron, Dust

Line Emission
- CO, C+, N+, O, …

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

Diffuse ISM
- Temperature, Density
- Energy Balance
- Metalicity

Unique Science Capability



Full-Sky Spectro-Polarimetric Survey

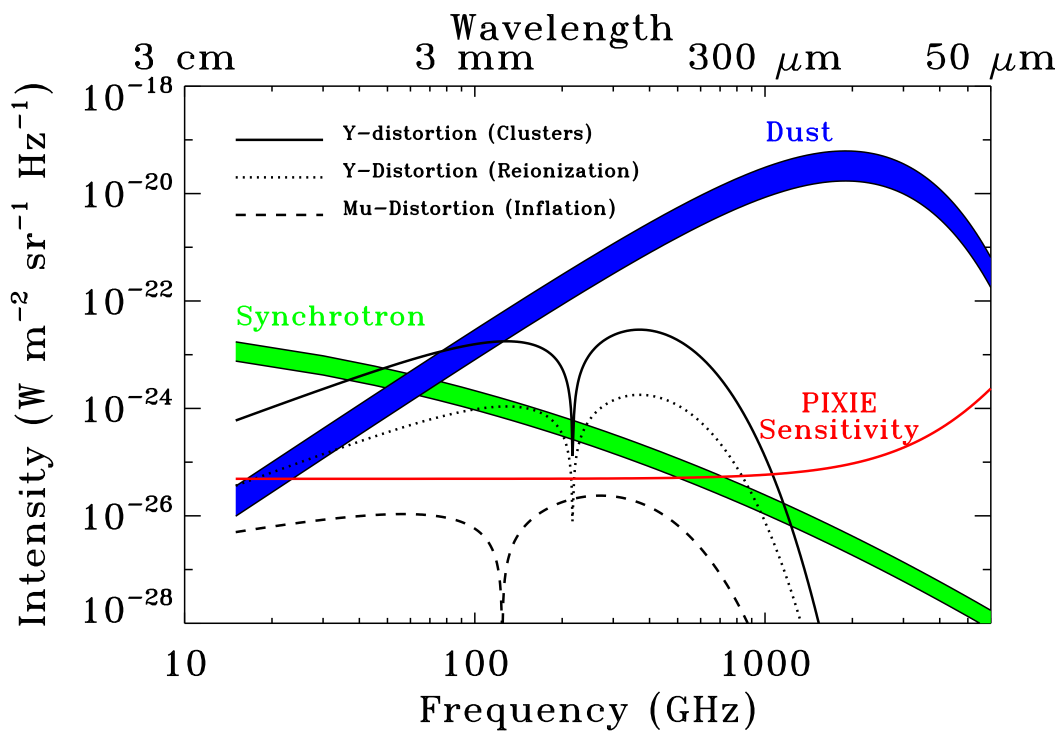
- 400 frequency channels, 30 GHz to 6 THz
- Stokes I, Q, U parameters
- 49152 sky pixels each 0.9° × 0.9°
- Pixel sensitivity 6 x 10^{-26} W m^{-2} sr^{-1} Hz^{-1}
- CMB sensitivity 70 nk RMS per pixel

Multiple Science Goals

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

B-mode: $r < 2 \times 10^{-4}$ (1σ)

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



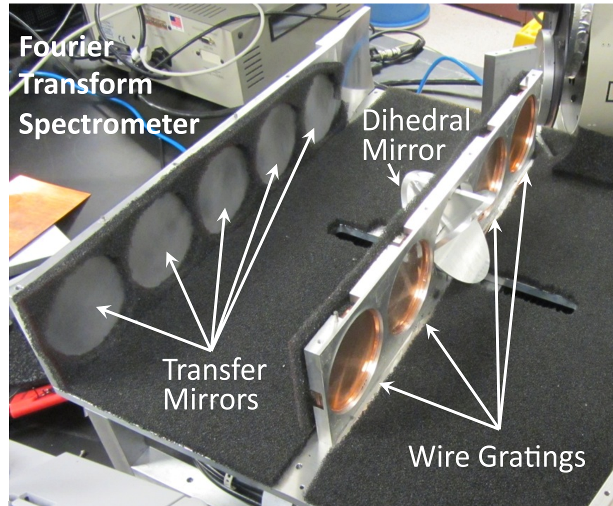
NASA Explorer Program

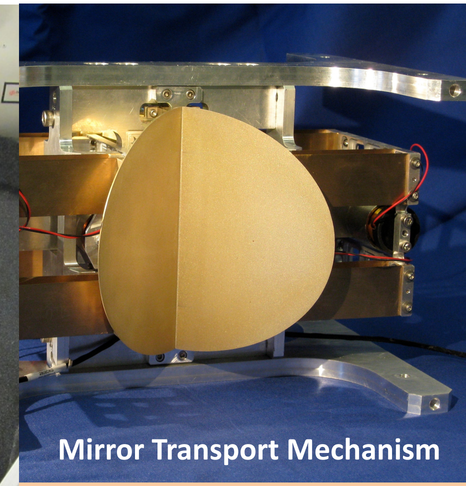
Small PI-led missions
- 22 full missions proposed Feb 2011
- $200M Cost Cap + launch vehicle

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

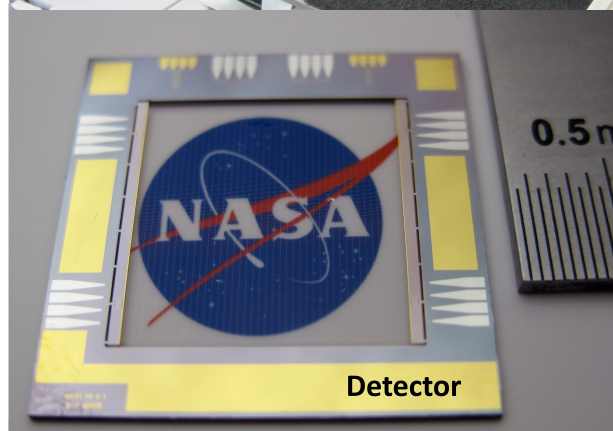
Re-propose to next MIDEX AO (2016)
- Technology is mature
- Launch early next decade

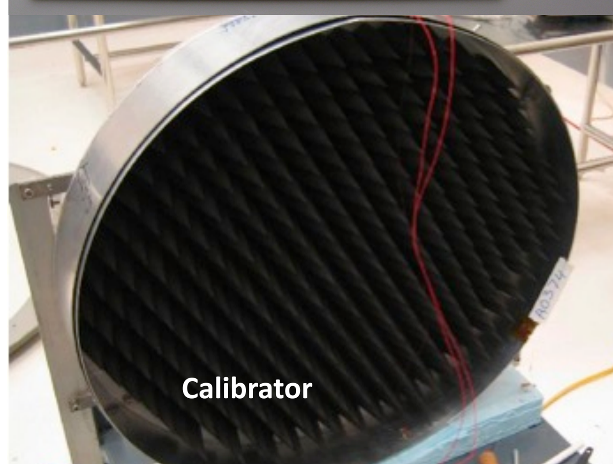
"PIXIE's spectral measurements alone justify the program"
-- NASA review panel

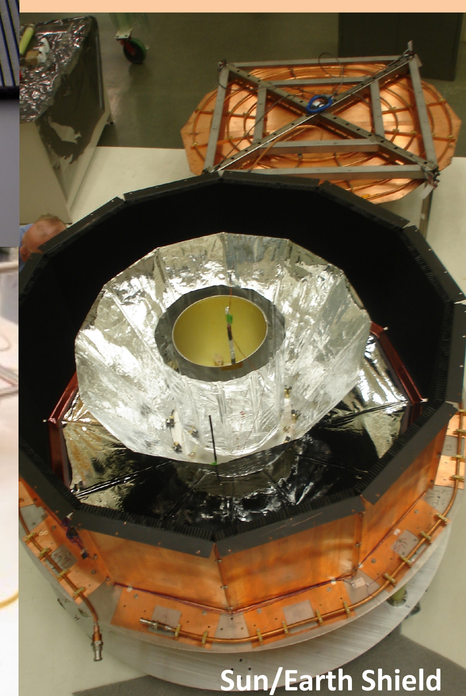


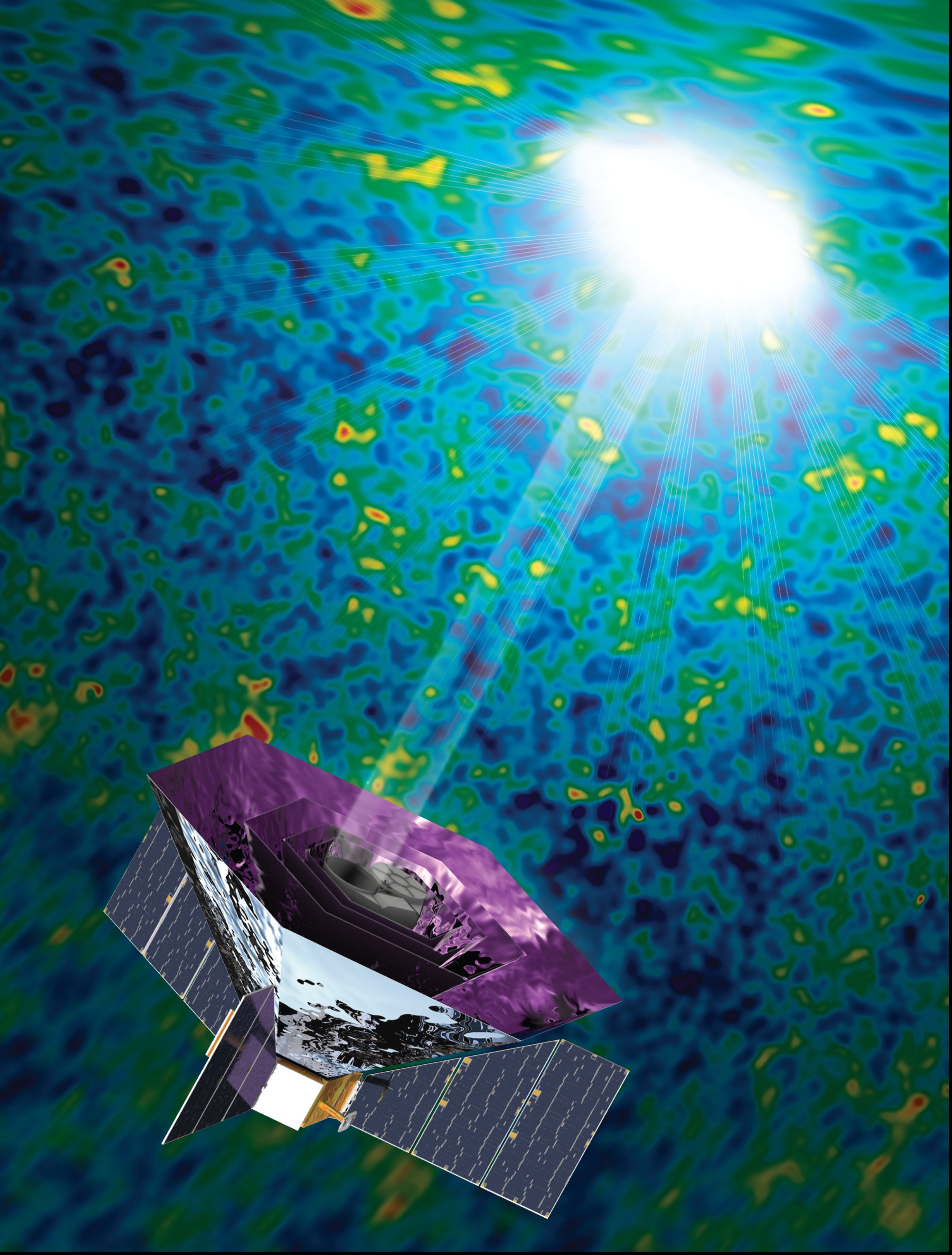


Mature technology









PRIMORDIAL INFLATION EXPLORER

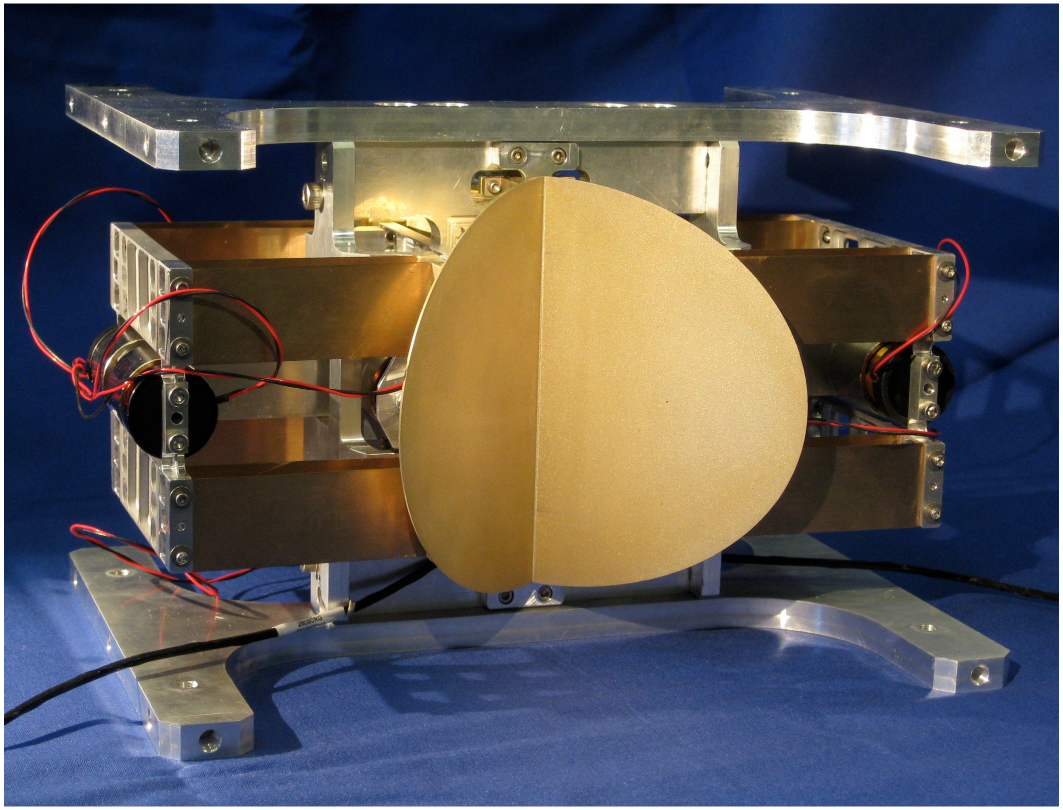
PIXIE

NASA • GSFC • BATC

Coming Soon From a Spacecraft Near You!

Backup Slides

Mirror Transport Mechanism

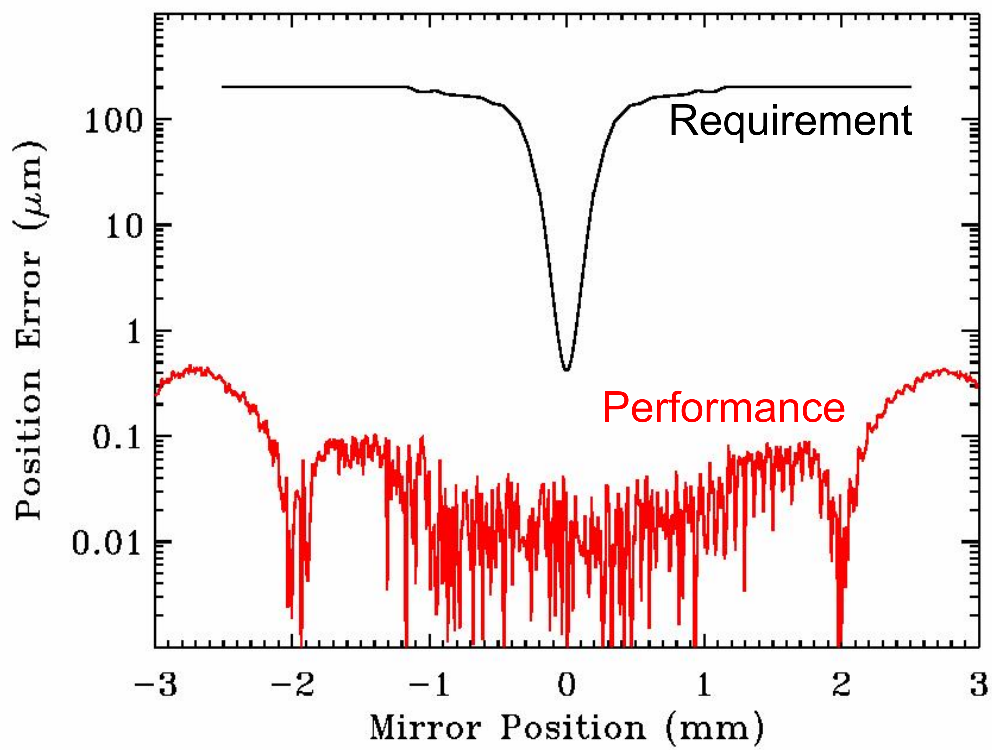


Engineering prototype

Translate ±2.54 mm at 0.5 Hz

Optical phase delay ±1 cm

Repeatable cryogenic position



Demonstrated performance
exceeds requirement by factor of ten