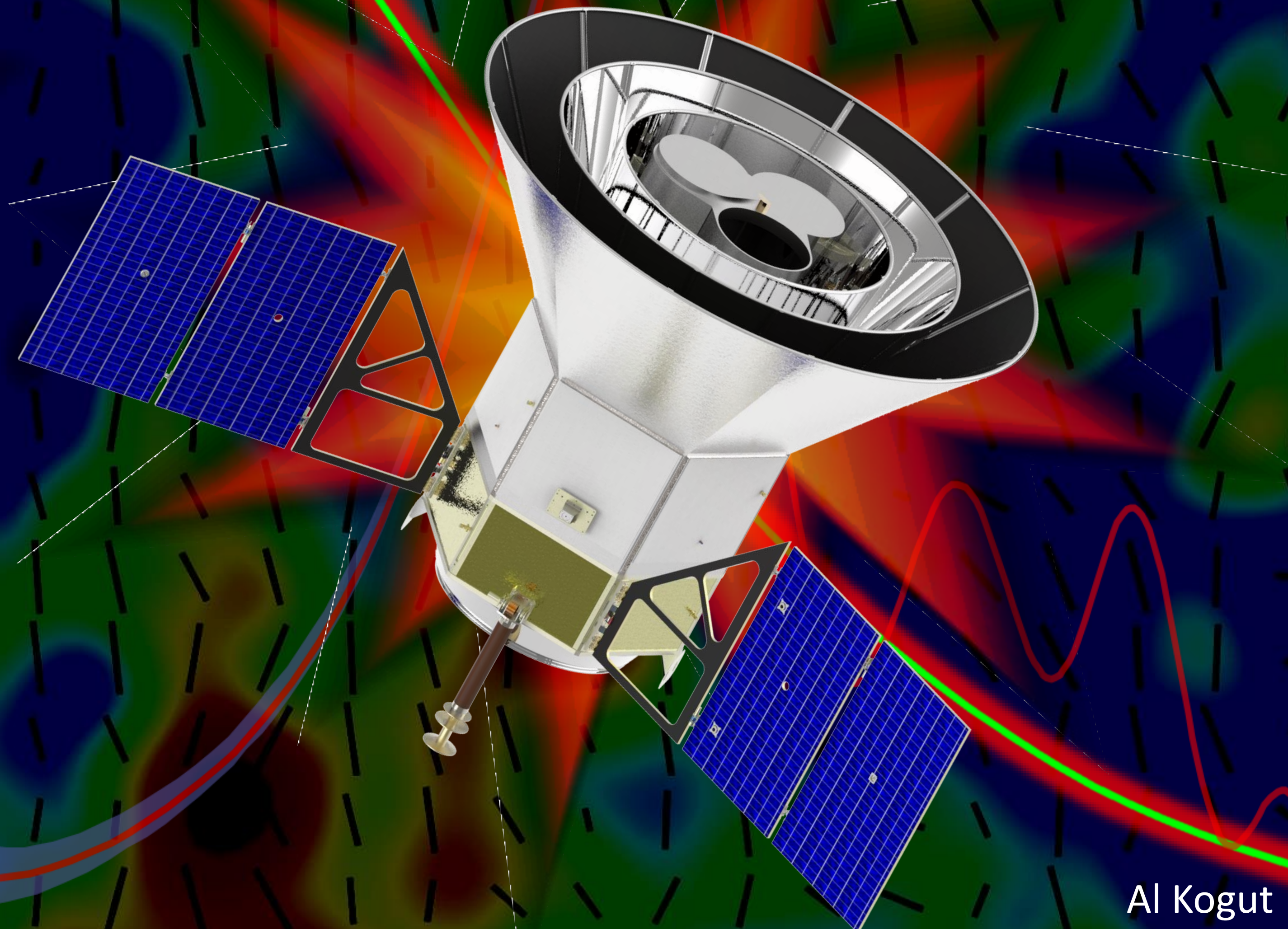
PIXIE:

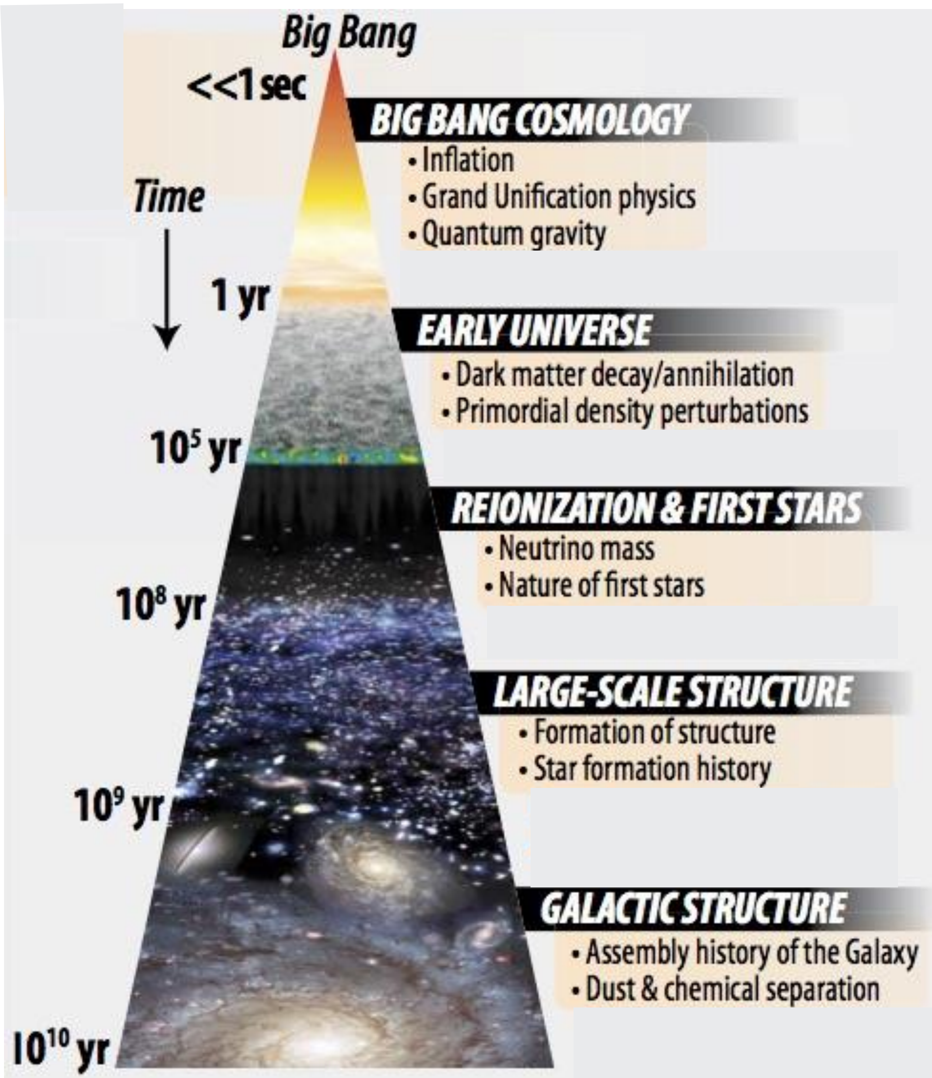
The Primordial Inflation Explorer



Al Kogut
GSFC

History of the Universe

Standard model leaves many open questions



NASA Strategic Guidance:
2010 Astrophysics Decadal Survey

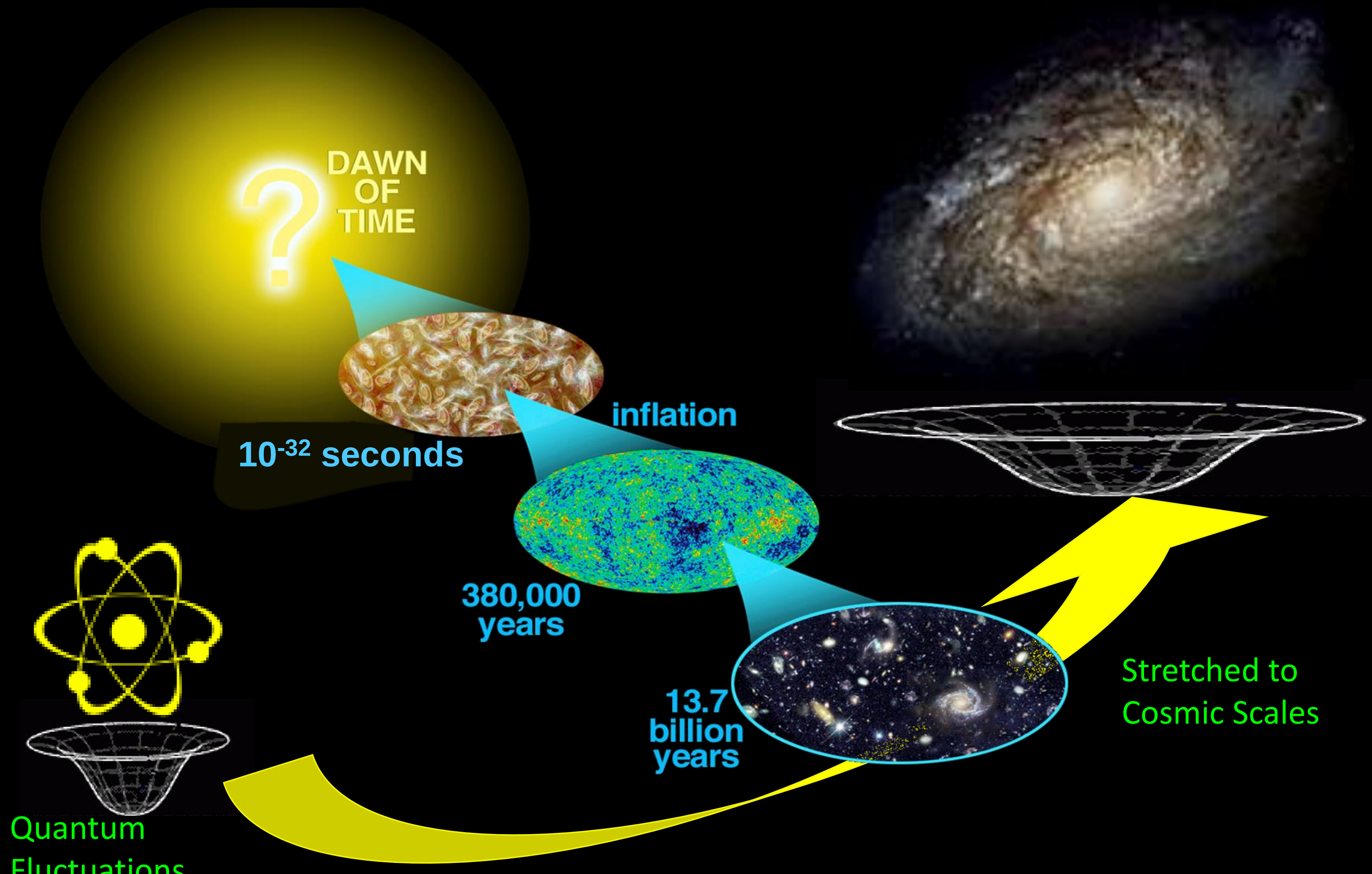
Top Mid-Scale Priorities
- #1: Exoplanets (TESS)
- #2: Inflation

Use cosmic microwave background as backlight for thermal history of universe

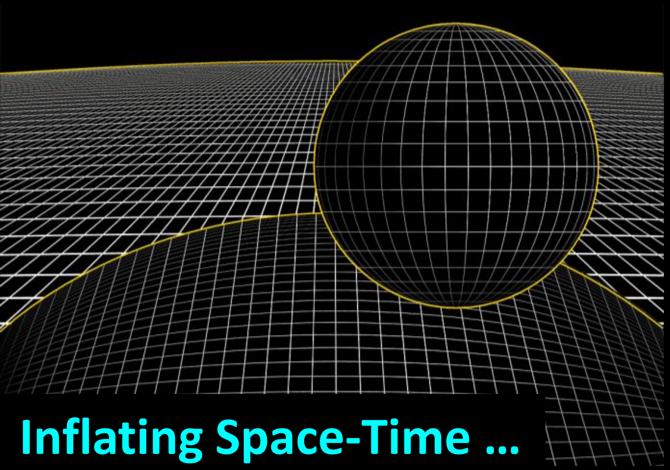
Panel	Question	
Cosmology and Fundamental Physics	CFP1	How did the universe begin?
	CFP3	What is dark matter?
	CFP4	What are the properties of neutrinos?
Galaxies Across Cosmic Time	GCT1	How to cosmic structures form and evolve?
	GCT4	What were the first objects to light up the universe and when did they do it?
Galactic Neighborhood	GAN1	What are the flows of matter and energy in the circumgalactic medium?

Inflationary Paradigm

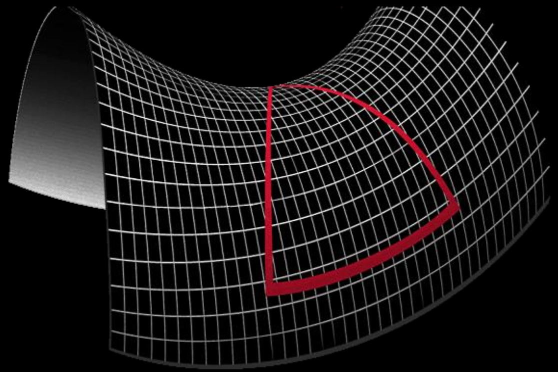
Quantum Physics Meets Cosmology



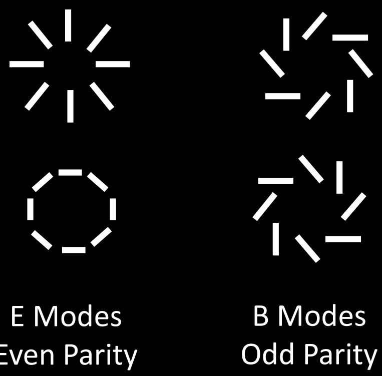
Testing Inflation with CMB Polarization

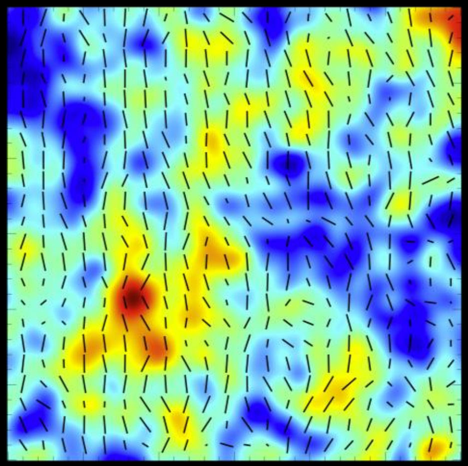


Inflating Space-Time ...



Creates Gravity-Wave Background ...

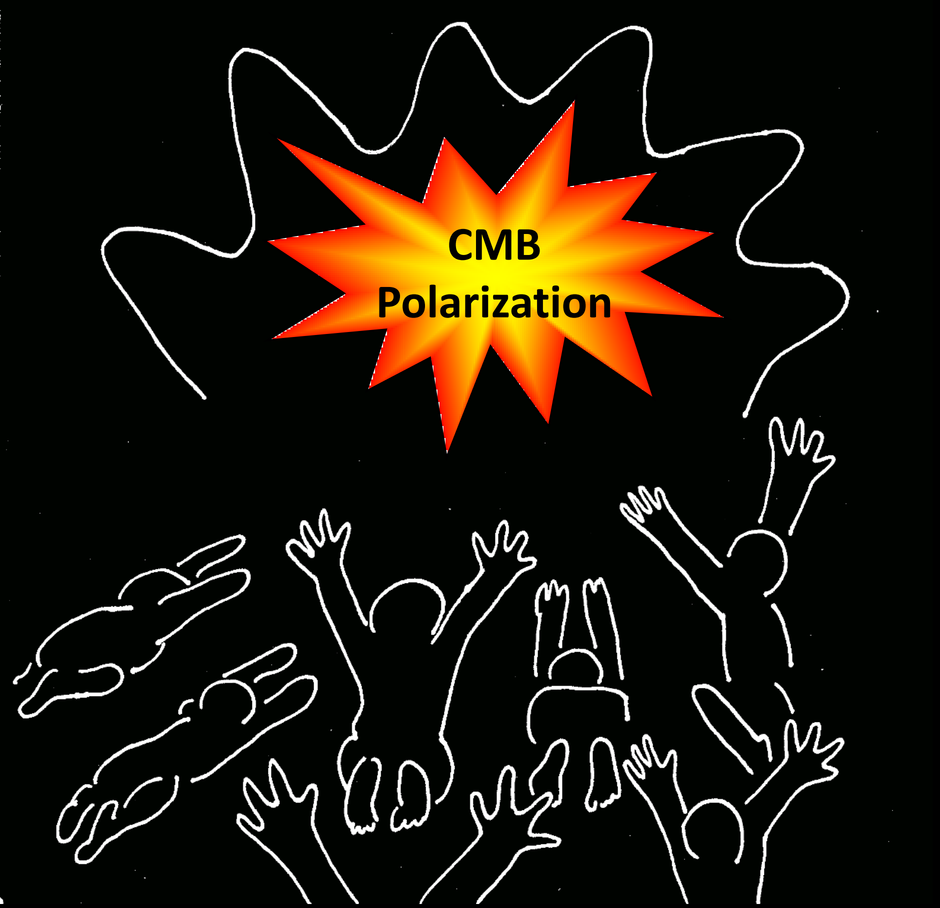




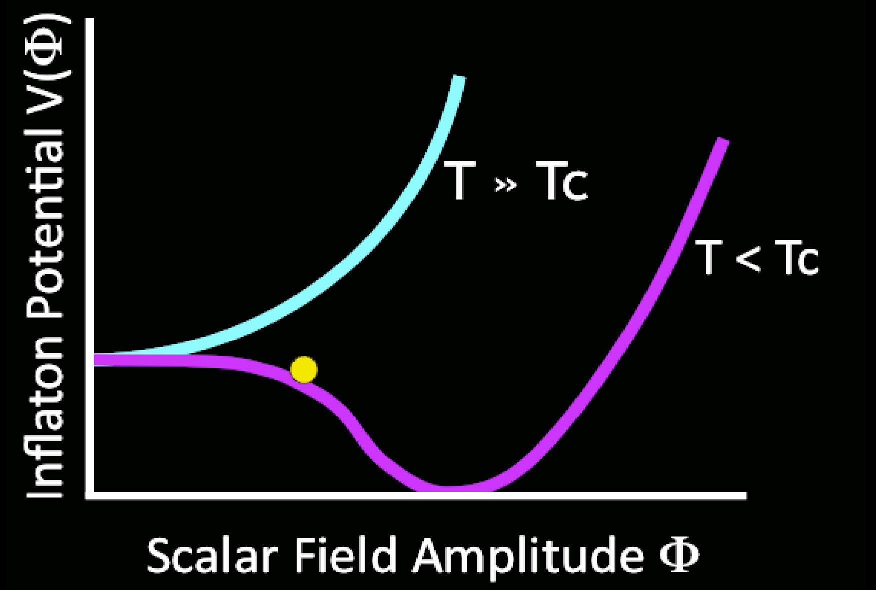
Which Sources CMB Polarization

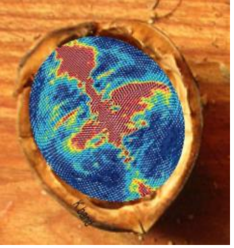
B-Mode Polarization:
"Smoking Gun" Signature of Inflation

Why Study CMB Polarization?

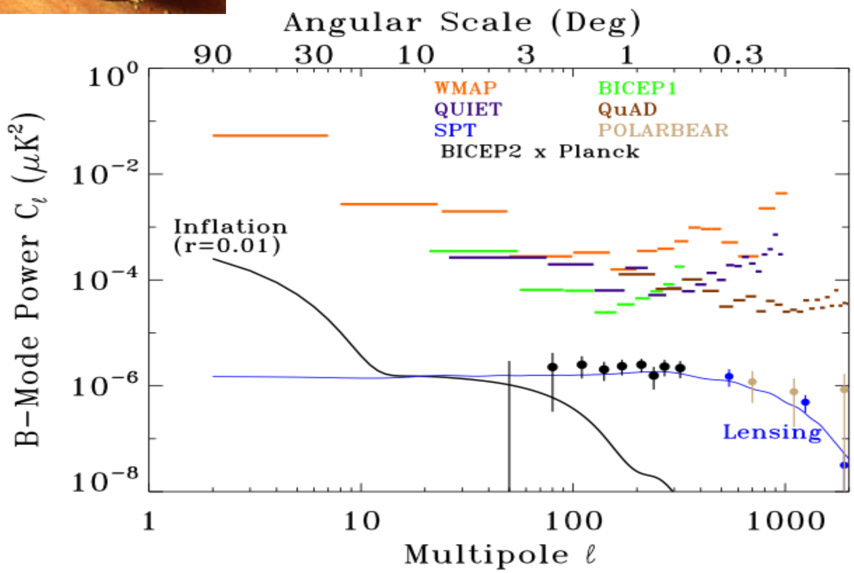


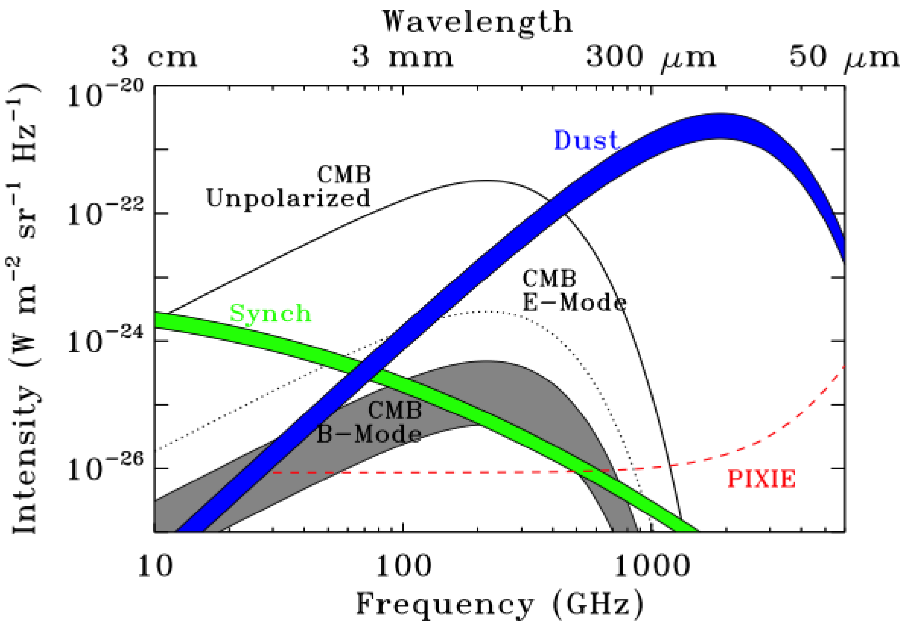
- **Demonstrate inflation as physical reality**
  - Trace evolution back to single quantum system
  - Oldest information in the universe
- **Measure inflationary energy scale**
  - 10^{16} GeV : Grand Unification theory
  - Trillion (!) times higher energy than Higgs boson
- **Observable "Theory of Everything"**
  - LIGO: Classical gravitational radiation
  - CMB: Proof that gravity obeys quantum mechanics





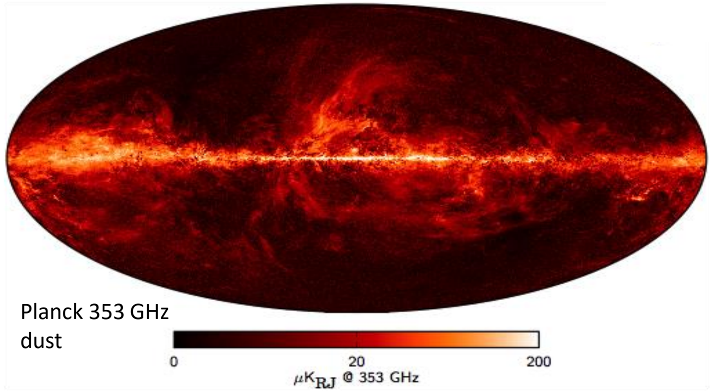
B-modes in a Nutshell



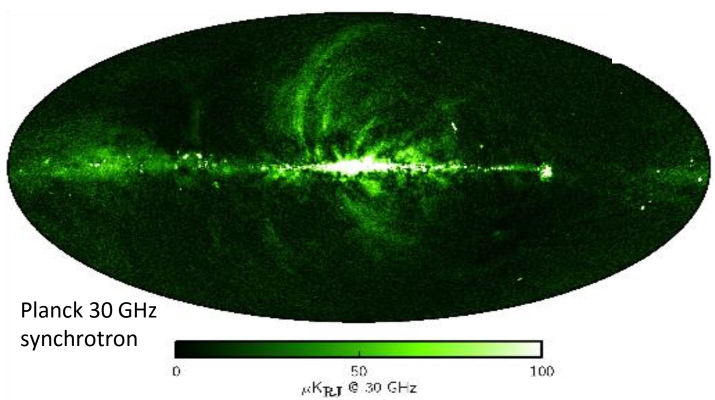


Requirements for Detection

- Photon-Limited Sensitivity
- Accurate Foreground Subtraction
- Immunity to Instrumental Effects

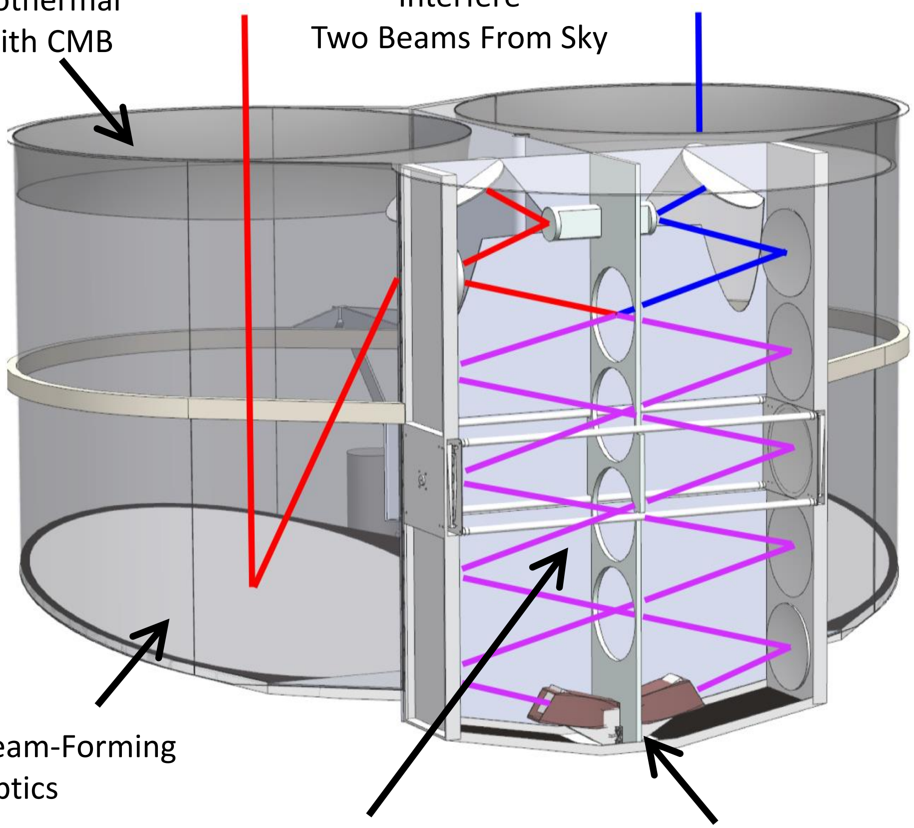


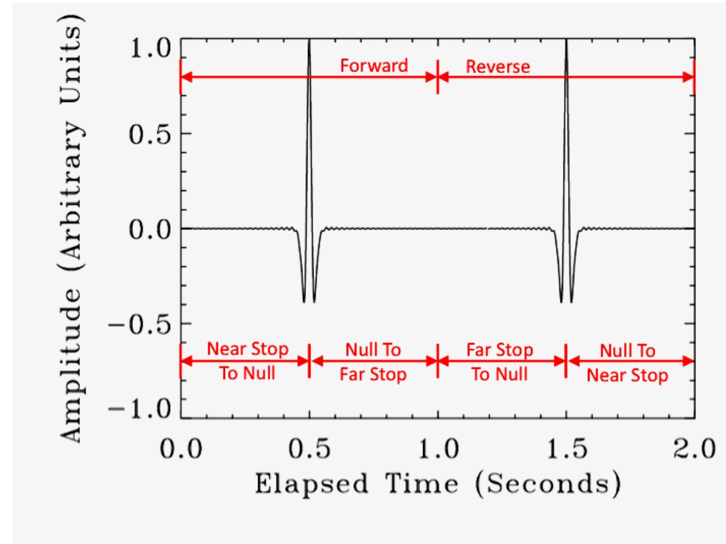
Planck 353 GHz
dust



Planck 30 GHz
synchrotron

PIXIE Nulling Polarimeter





Measured Fringe Pattern
Samples Frequency Spectrum
of Polarized Sky Emission

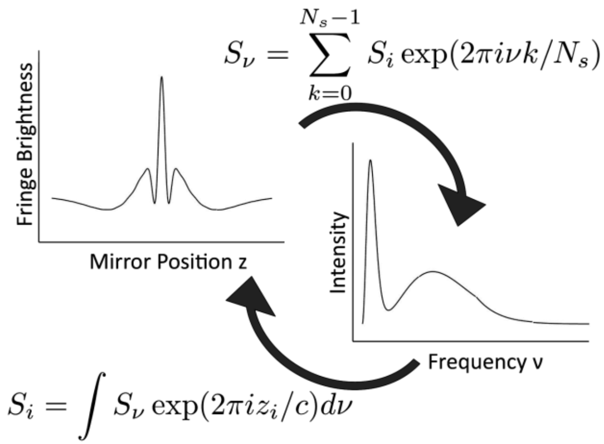
$$P_{Lx} = \frac{1}{2} \int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx}^2 - E_{Ay}^2\right) \cos(z\omega/c)\, d\omega$$

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

Stokes Q Polarization

Zero means zero: No fringes if sky is not polarized

Frequency Coverage



Phase delay L sets channel width

$\Delta\nu = c/L = 14.41$ GHz

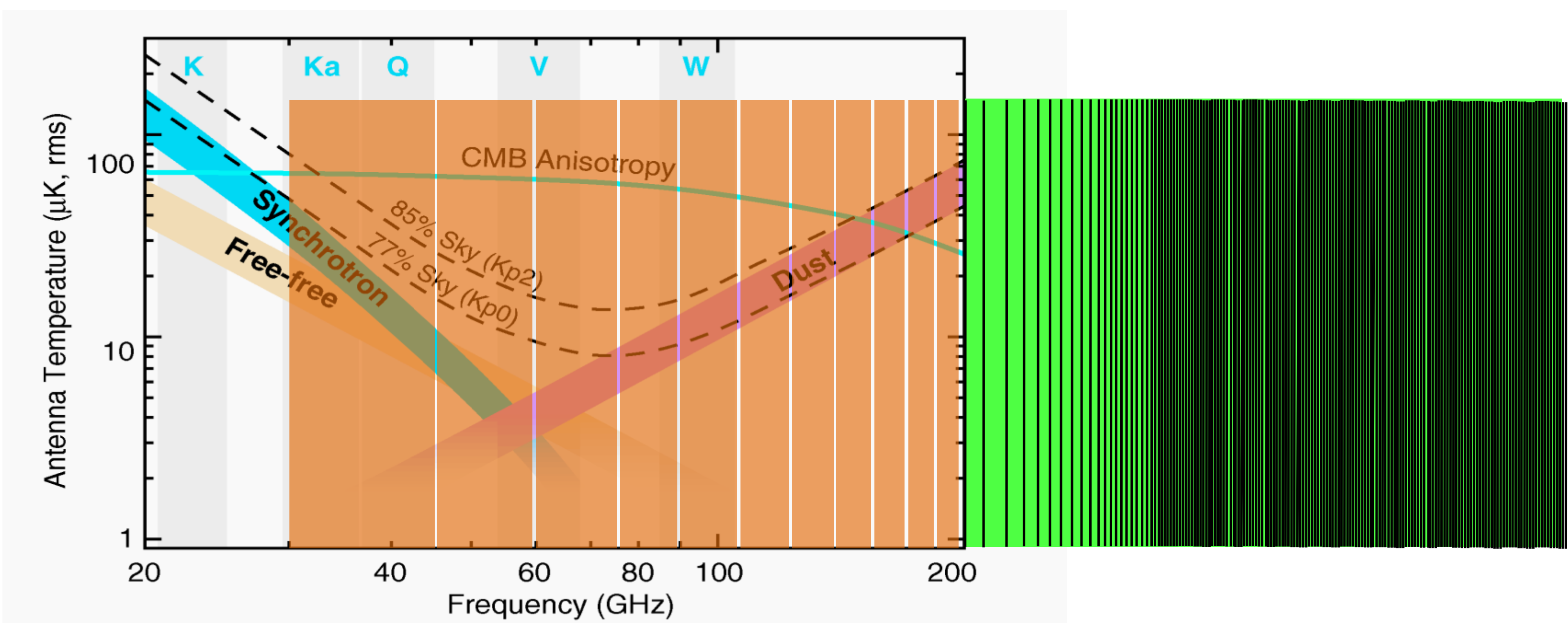
Number of samples sets frequency range

$\nu_i = [\, 1, 2, 3 \ldots N/2 \,] * \Delta\nu$

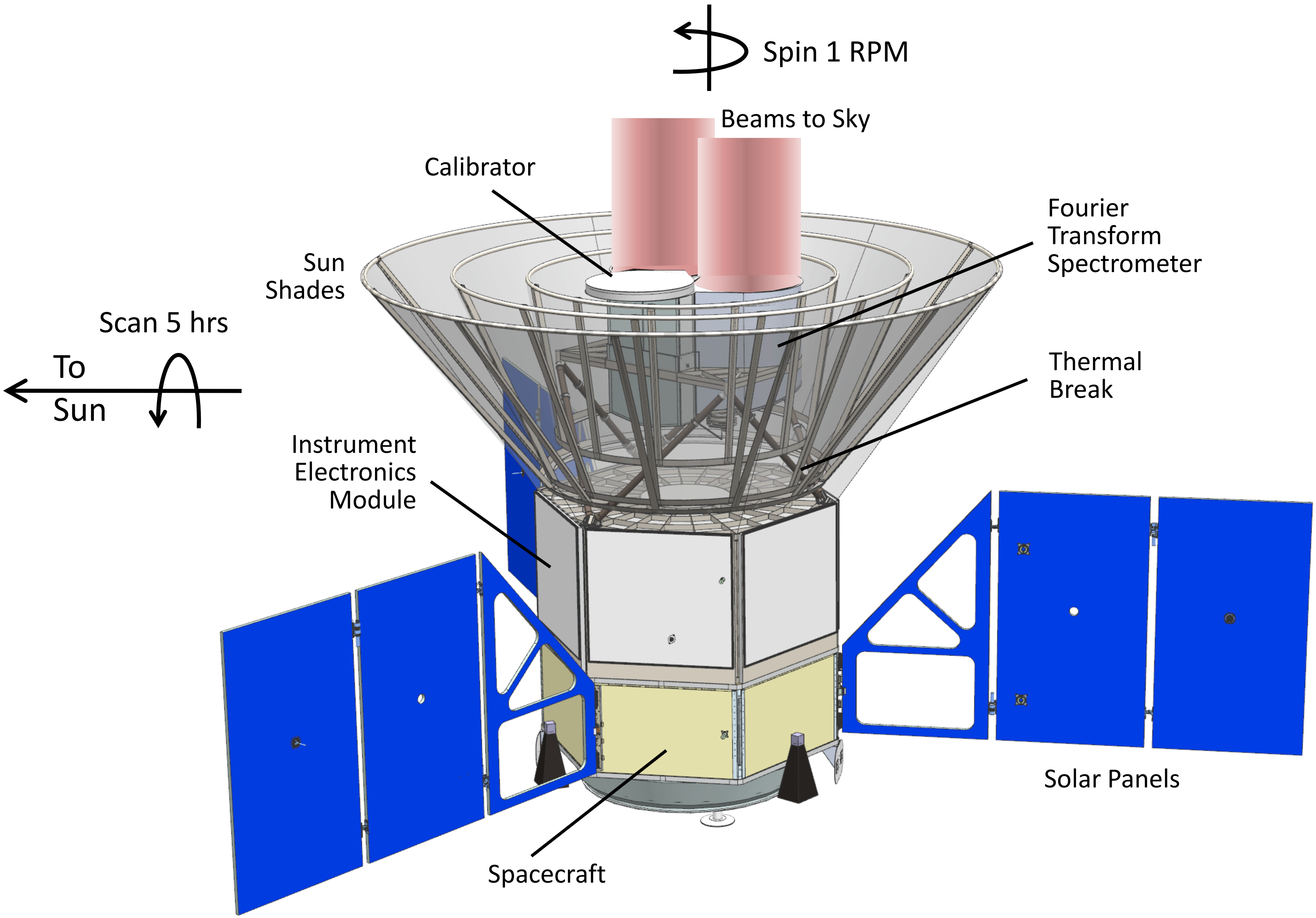
400 Frequency Channels across 7 octaves

- 30 GHz to 6 THz
- 14 GHz frequency resolution

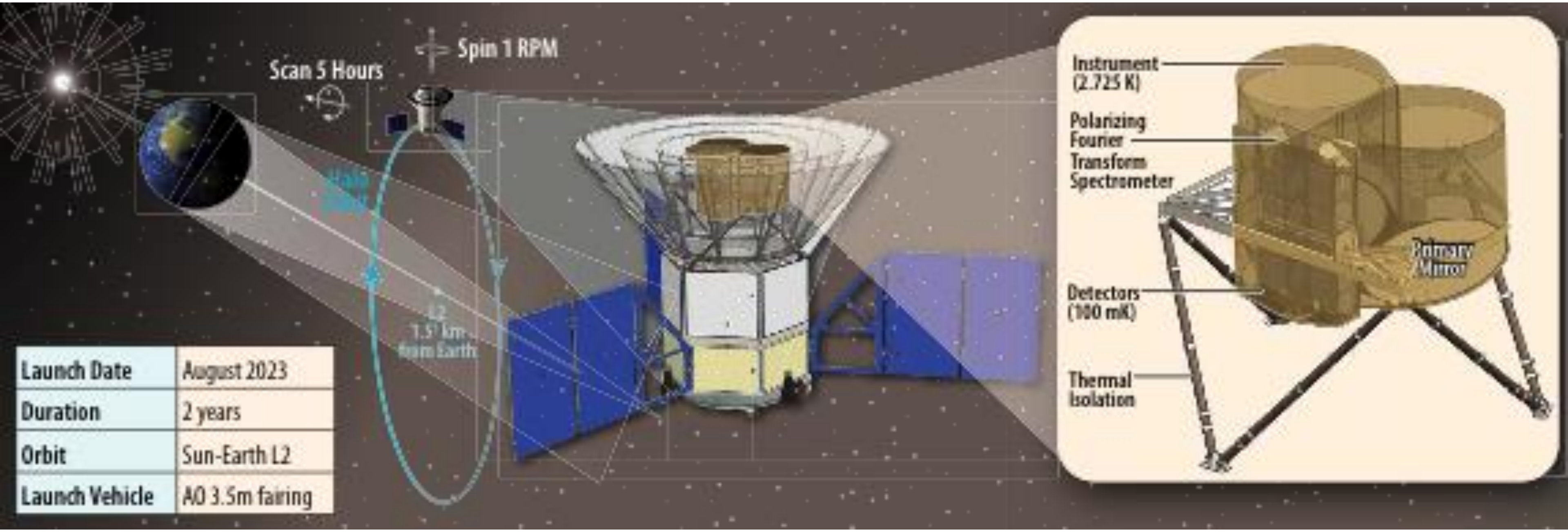
Legacy dataset for far-IR astrophysics



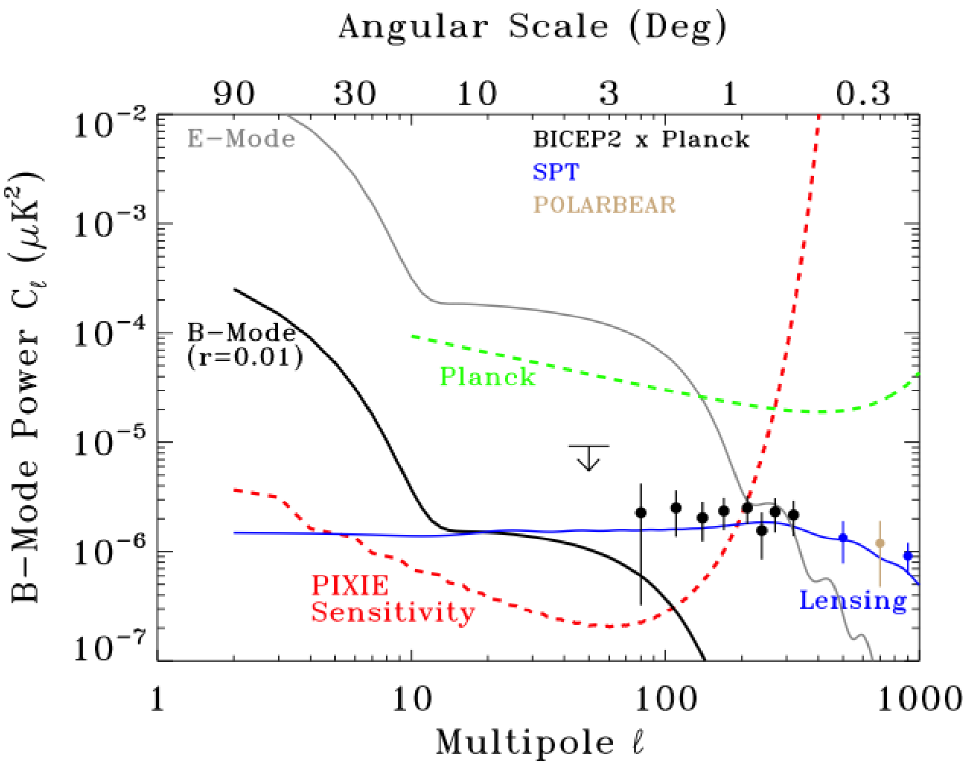
PIXIE Observatory



PIXIE Mission



PIXIE and Polarization

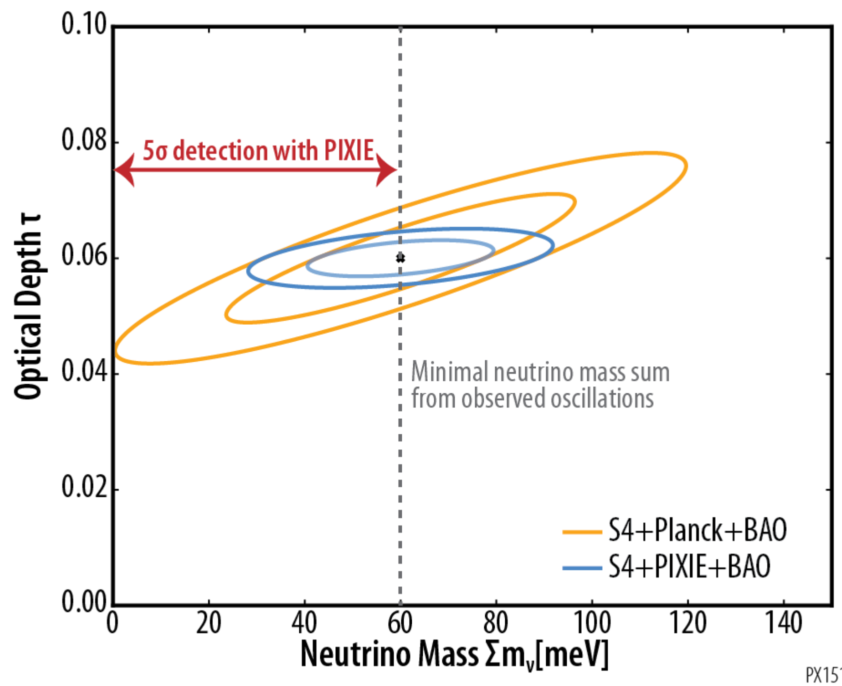


Definitive test for large-field inflation

CMB sensitivity 70 nK per 1° pixel
Limit r < 2 x 10^{-4} for inflation amplitude

Determine neutrino mass scale

Characterize astrophysical foregrounds



Complement Ground-Based Efforts

- Large angular scales (2 < ℓ < 300)
- Legacy dust foreground
- Legacy data for mm & sub-mm calibration


BUT WAIT,
there's more!

PIXIE and Absolute Sky Spectra

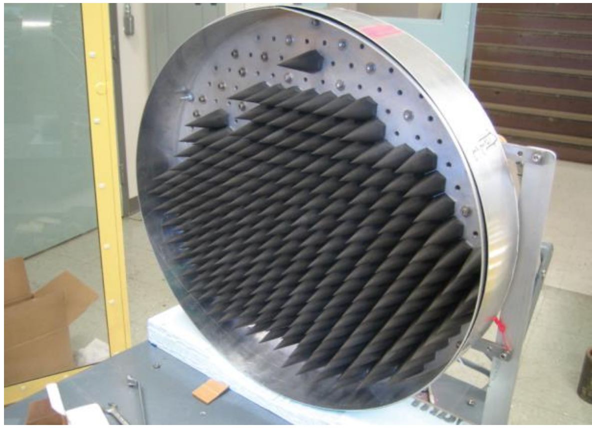
On-Board Calibrator Measures Unpolarized Sky Spectrum

Calibrator stowed:
Polarization only

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

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

Sky Polarization



Partially-assembled blackbody calibrator

Calibrator deployed:
Spectral distortions!

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

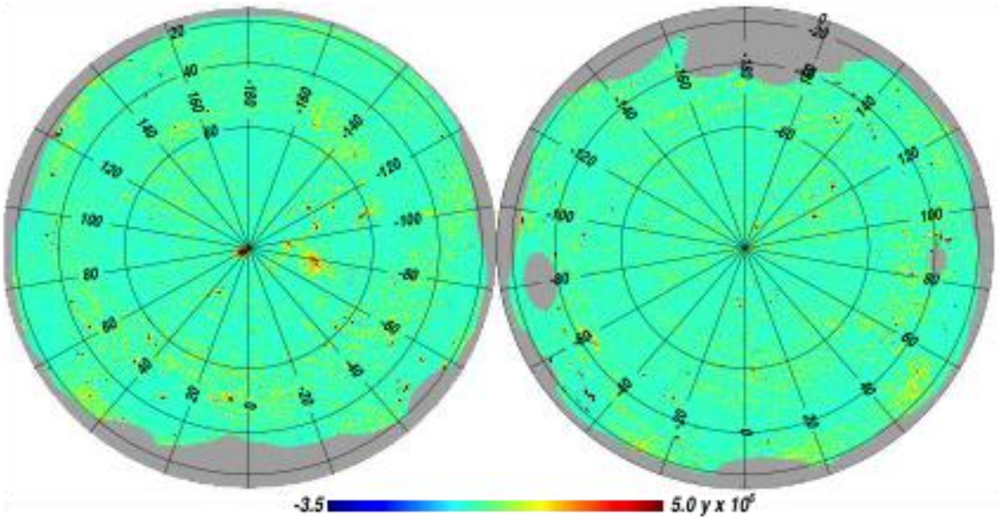
$$P_{Ly} = \frac{1}{2}\int \left(E_{Cal,x}^2 + E_{Sky,y}^2\right) + \underbrace{\left(E_{Sky,y}^2 - E_{Cal,x}^2\right)}_{\text{[Calibrator-Sky] Spectral Difference}}\cos(z\omega/c)\, d\omega$$

[Calibrator-Sky]
Spectral Difference

Like COBE/FIRAS,
But 1000x
More Sensitive!

Precision Survey for Extragalactic Backgrounds

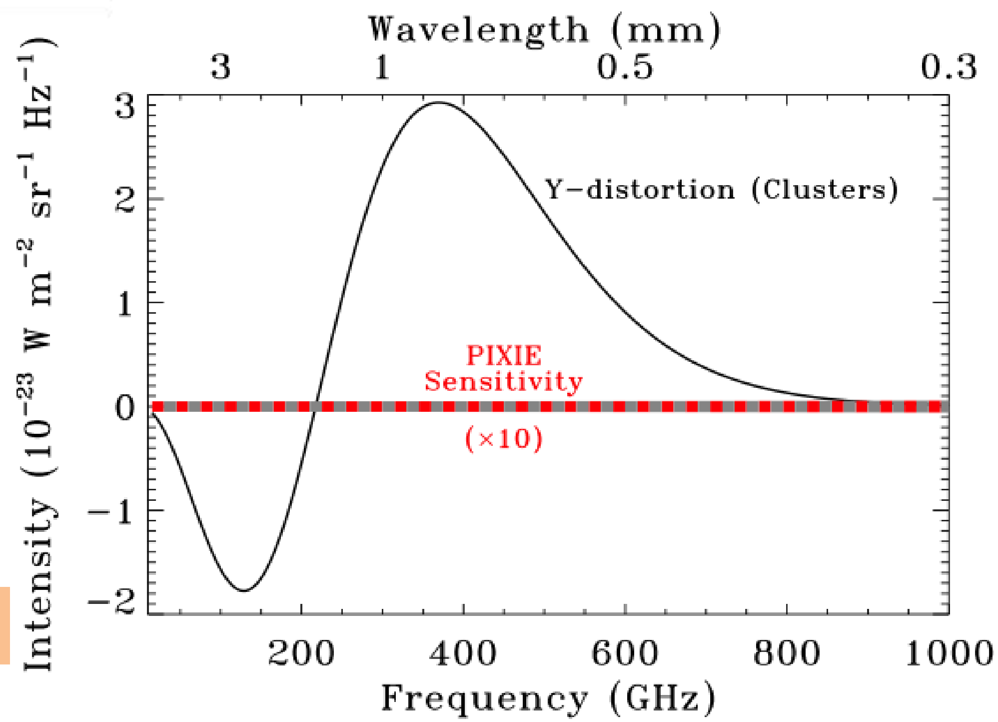
Spectral Distortions: Structure Formation



Integrated signal from CMB photons scattering off relativistic electrons

Dominated by intracluster gas in groups and clusters

Constraints on relativistic electrons



High signal-to-noise detection

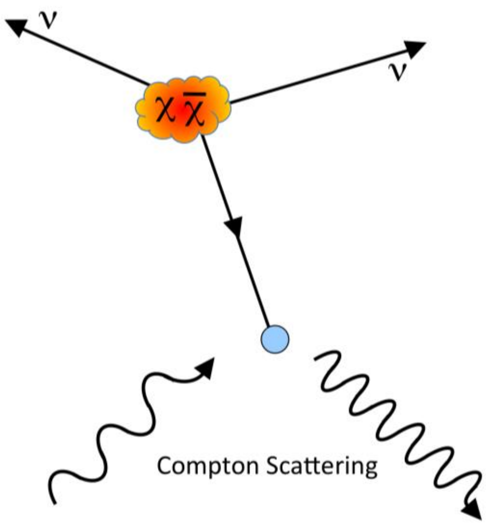
- Monopole: 194σ detection
- Relativistic correction: 11σ detection

Mean thermal energy in electrons
Integral constraint on feedback

Dominated by faint unresolved sources

Hill et al 2015

Spectral Distortions: Dark Matter Annihilation



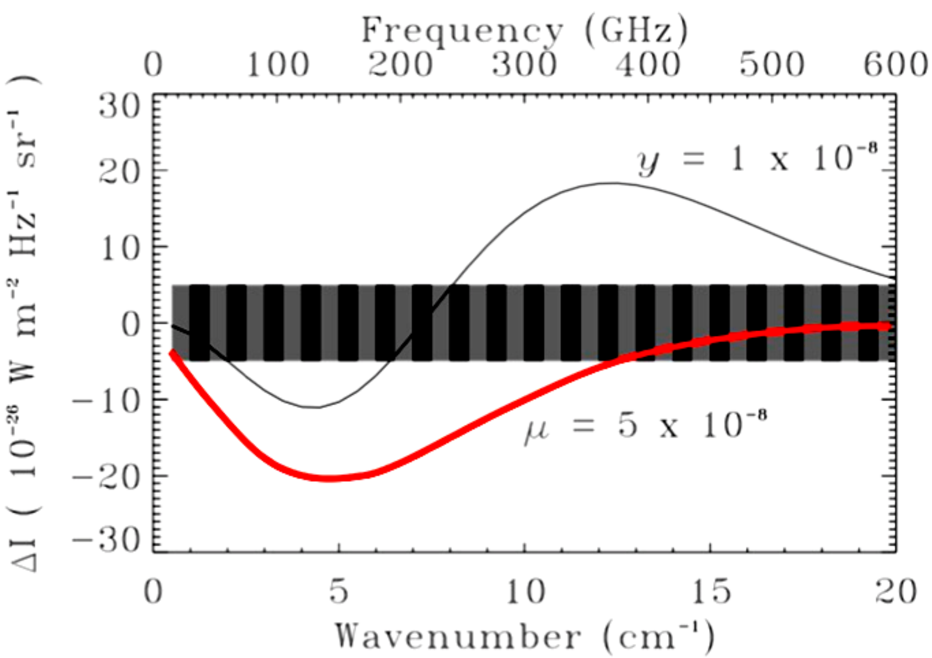
$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(\frac{h\nu}{kT} + \mu) - 1}$$

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

Annihilation rate ~ n^2 ~ z^6

Number density n ~ m^{-1}

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



Dark matter annihilation

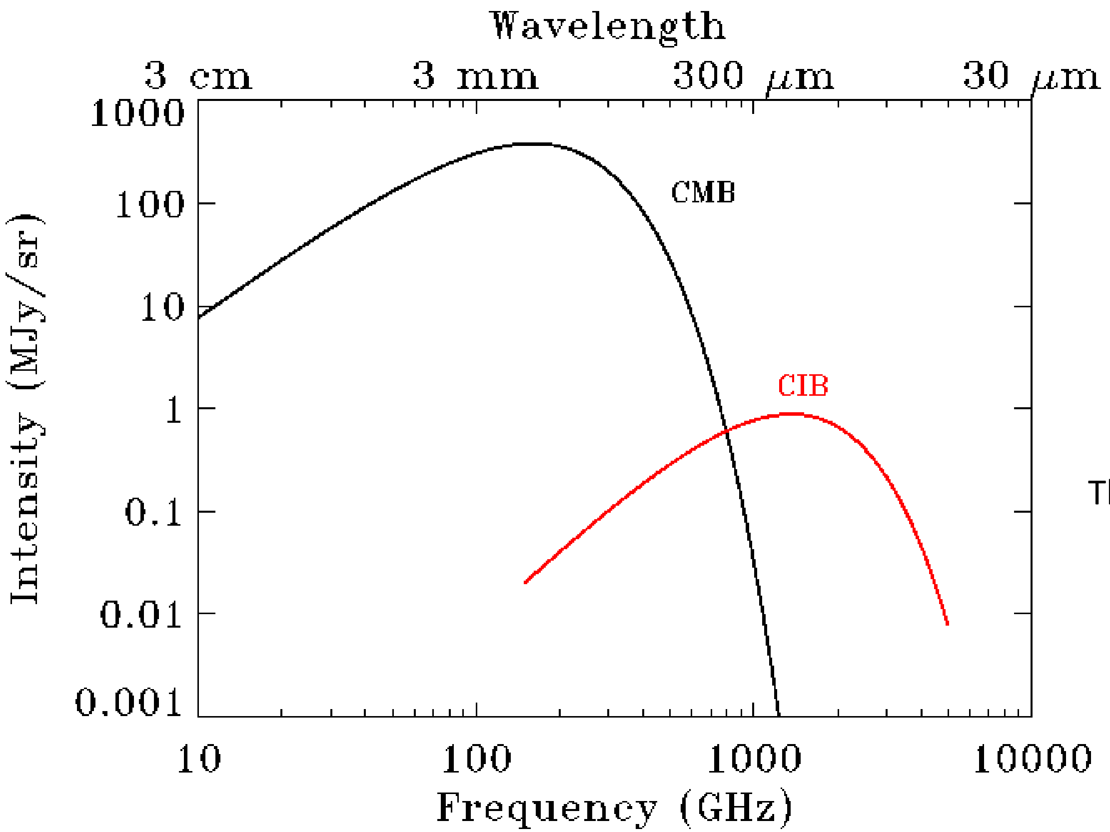
PIXIE limit $\mu < 10^{-8}$

Neutralino mass limit $m_\chi > 80$ keV

Definitive test for warm dark matter

McDonald et al 2001
de Vega & Sanchez 2010

Cosmic Infrared Background



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

Thermal Dust Emission from z ~ 1--3

- Monopole: Galaxy Evolution
- Dipole: Bulk Motion
- Anisotropy: Primordial non-Gaussianity

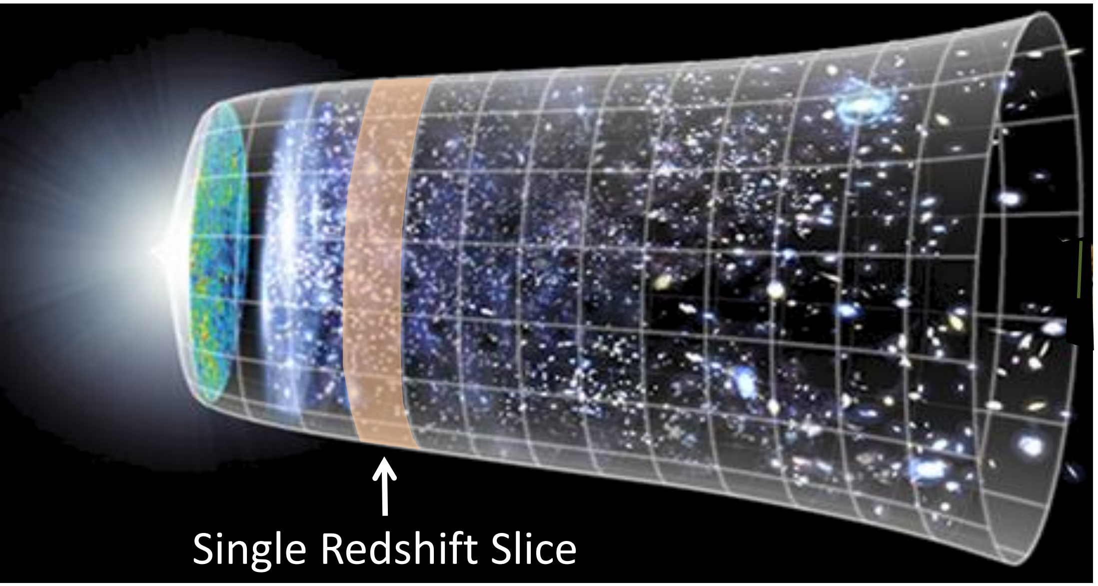
Limits to non-Gaussianity $f_{NL} < 1$

PIXIE noise is down here!

Knox et al. 2001
Fixsen & Kashlinsky 2011
Tucci et al 2016

Far-IR Tomography

Intensity Mapping with C+, N+, CO lines



Low spatial resolution

Integrated emission from many sources

Multiple frequency bins

Multiple redshift slices

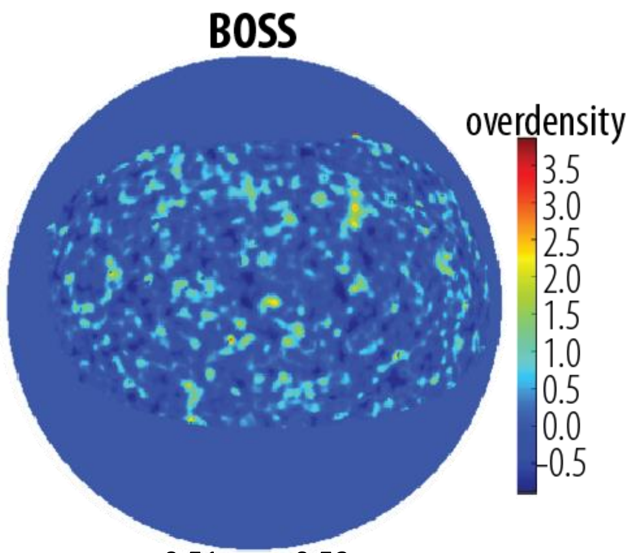
Red-shifted far-IR lines

C+ 158 um → Star formation rate

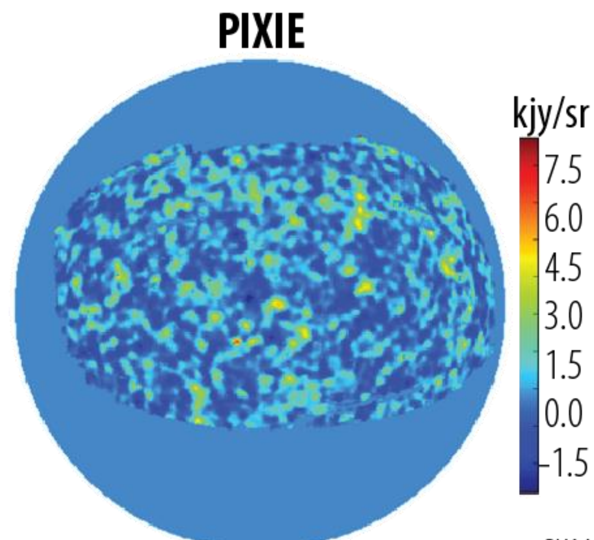
CO ladder → Cold gas reservoir

Cross-correlate PIXIE with redshift-tagged galaxy surveys

- Track star formation vs redshift
- 5—10% redshift bins at z=2—3
- Compare to continuum CIB



0.51 < z < 0.53

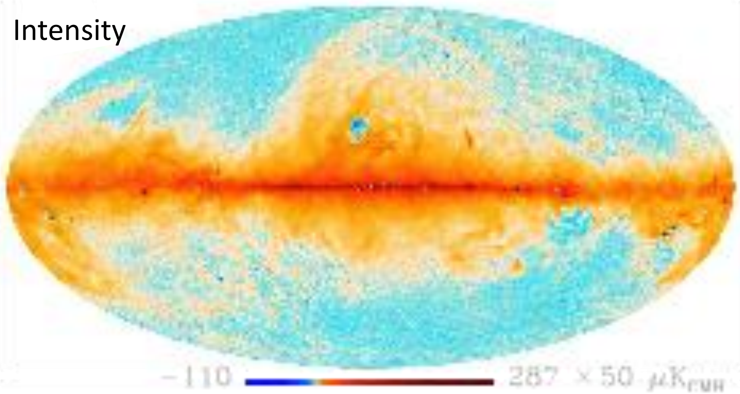


Single Channel 1245 GHz

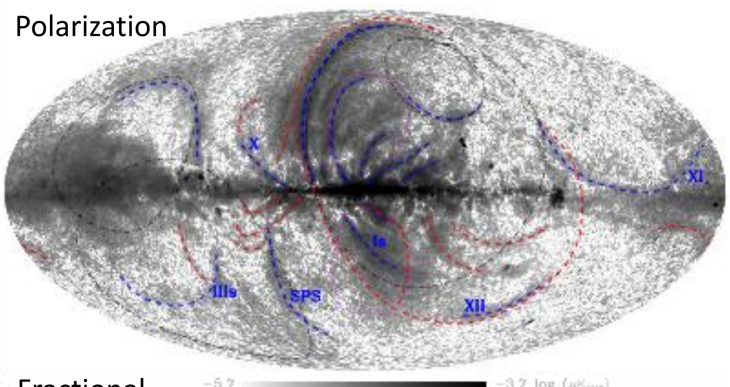
Switzer 2017

Radio Synchrotron

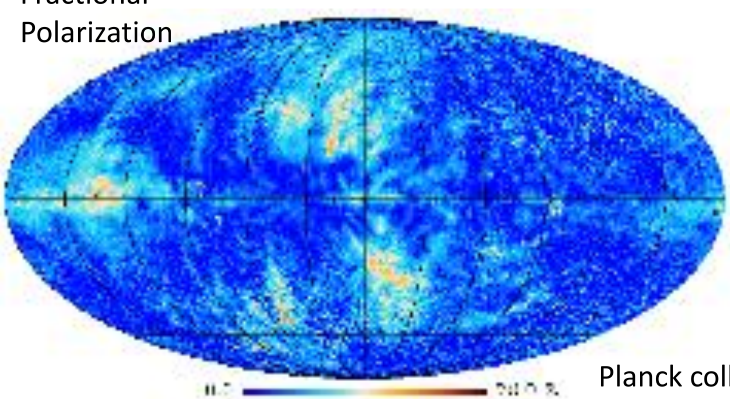
Intensity



Polarization



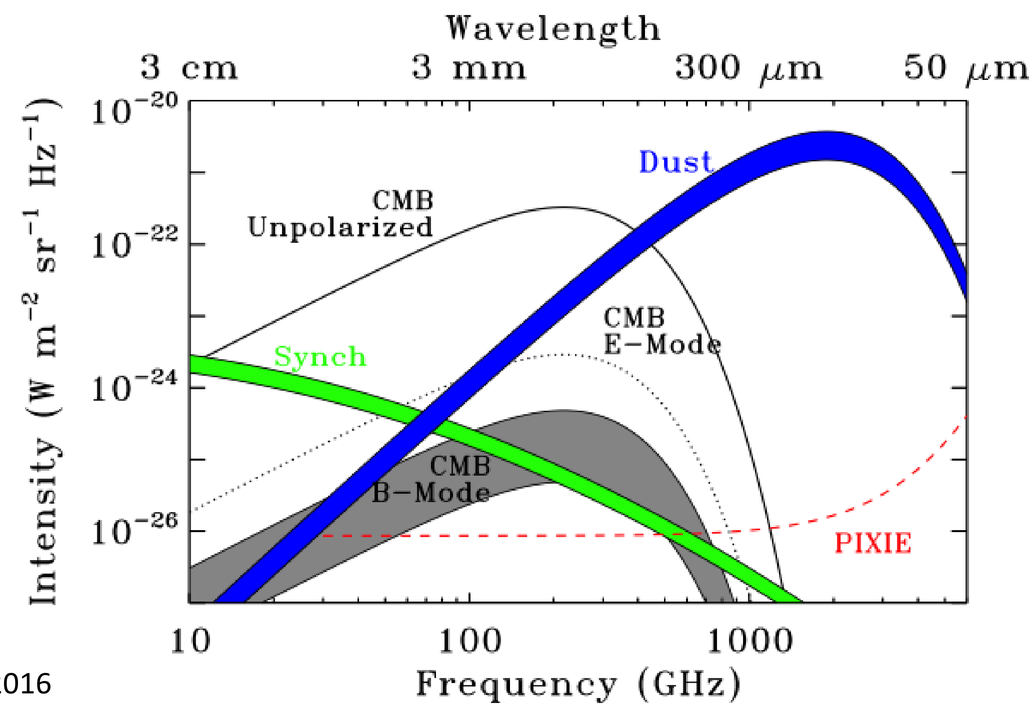
Fractional Polarization



PIXIE Improvements to Synchrotron Model

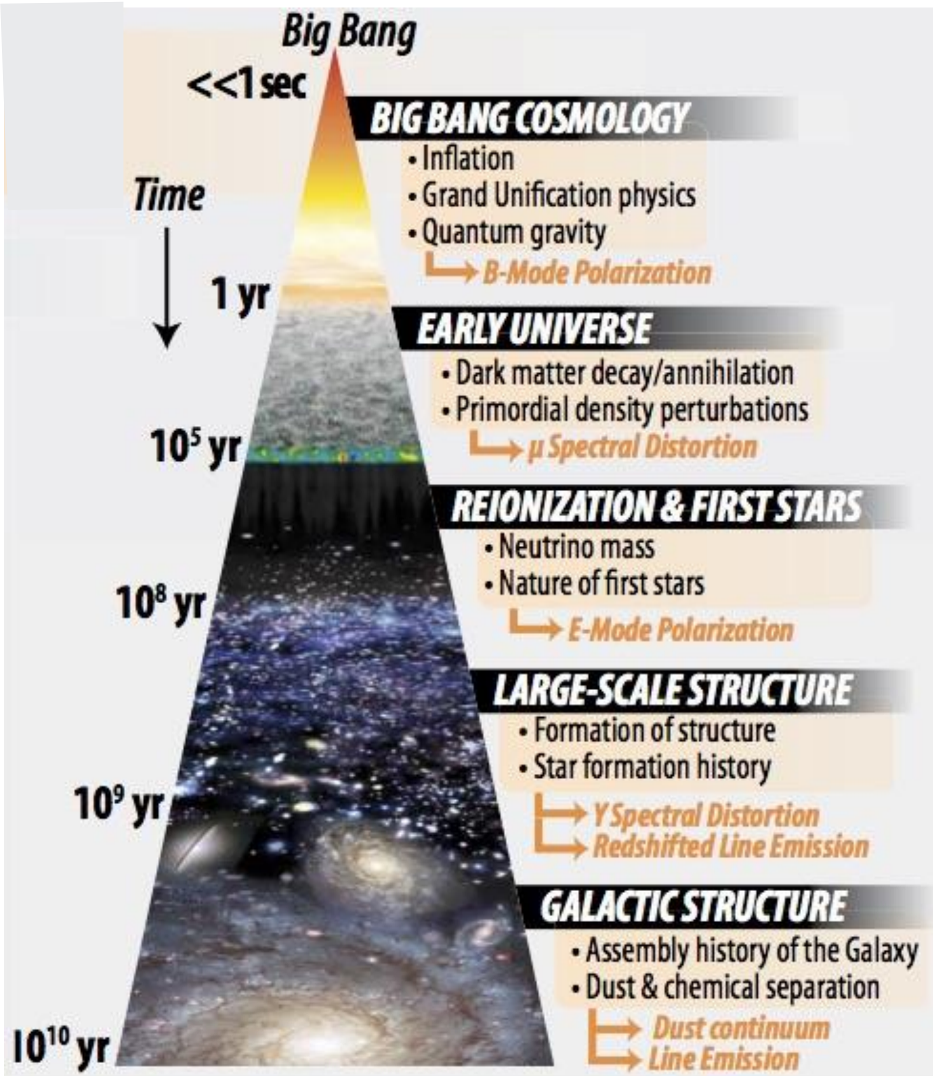
- Polarization amplitude in faint regions
- Zero level for intensity + polarization

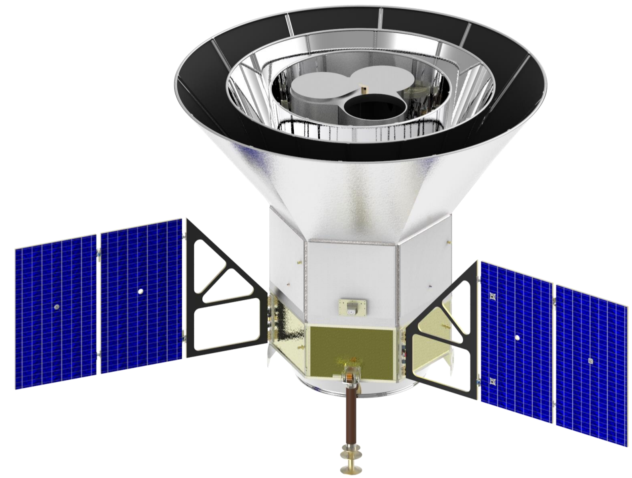
Test for local-bubble synchrotron model



Planck collaboration 2016

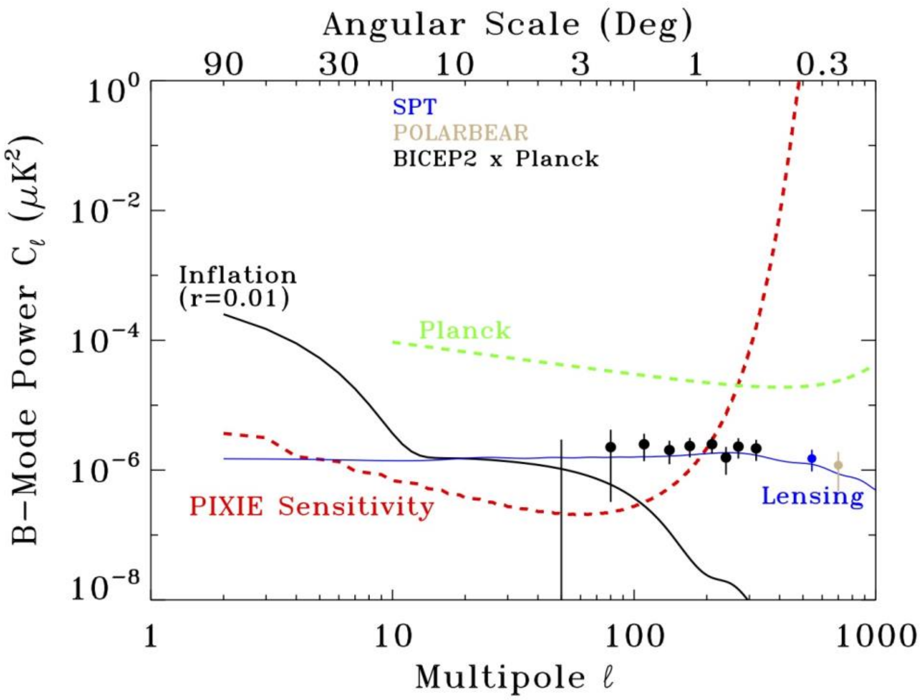
Multiple Decadal Goals in One MIDEX Mission





Science Goal	PIXIE Measurement
Inflation	Polarization B-modes
Neutrino Mass	Polarization E-modes
Reionization	Polarization E-modes
Dark Matter	Spectral Distortion (y)
Large-Scale Structure	Spectral Distortion (μ)
Star Formation History	Far-IR Intensity Mapping
Radio Background	Synchrotron intensity + polarization

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

Legacy Archive for far-IR Astrophysics

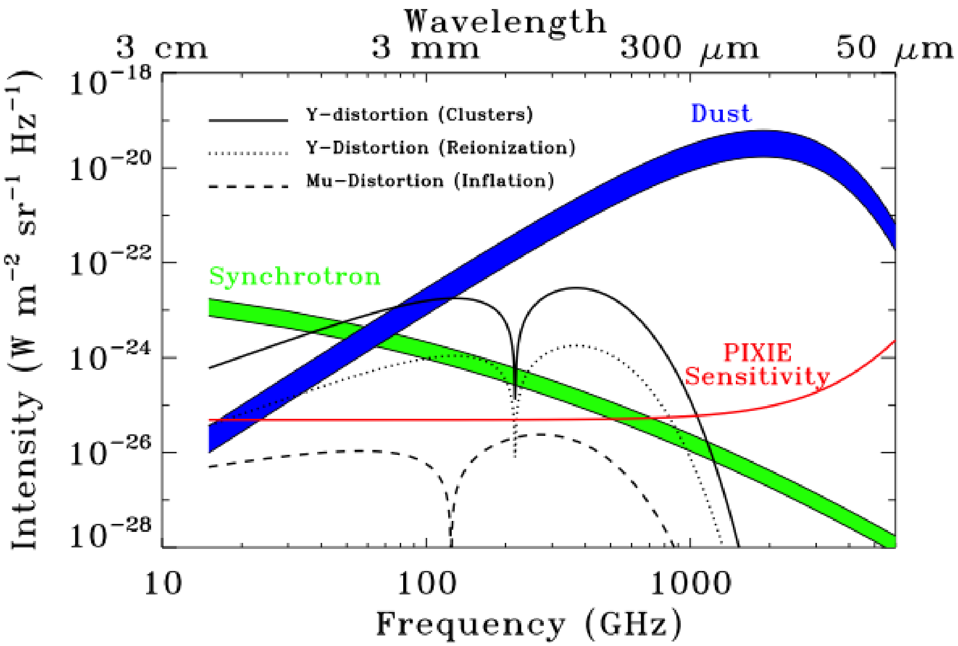
Multiple Science Goals

- Inflation
- Neutrino Mass
- Galaxy Evolution
- Interstellar Medium

95% CL Limits:

B-mode: $r < 4 \times 10^{-4}$

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



Now how much would you pay?

A Non-Cosmological Problem

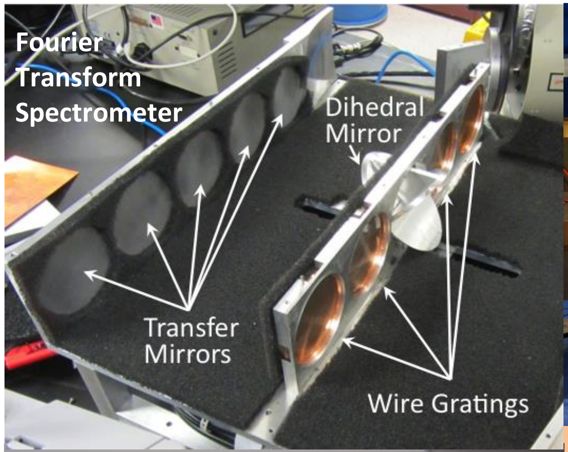
Will a future Congress fund a $1B Inflation Probe?
Low-cost alternative within existing NASA budget line

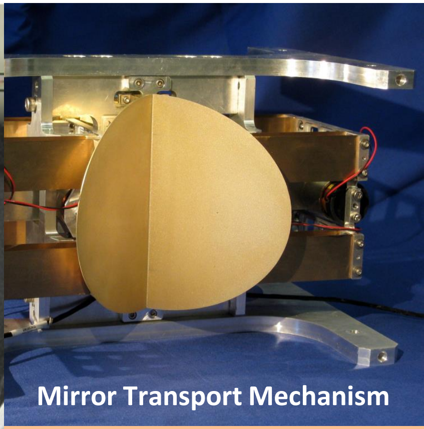
NASA Explorer Program

Small PI-led missions
- 11full missions proposed Dec 2016
- $250M Cost Cap + launch vehicle

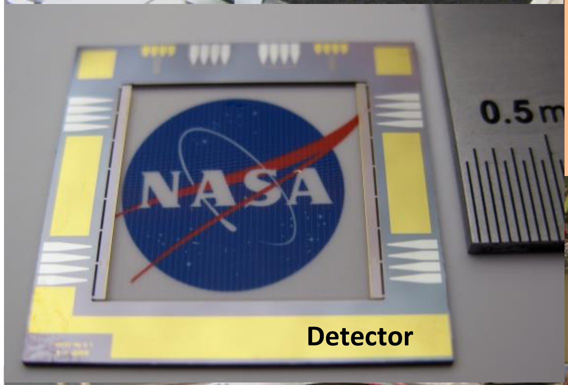
PIXIE submitted with mature technoloigy
- All technology TRL 6 or higher
- Cost & schedule based on flight missions

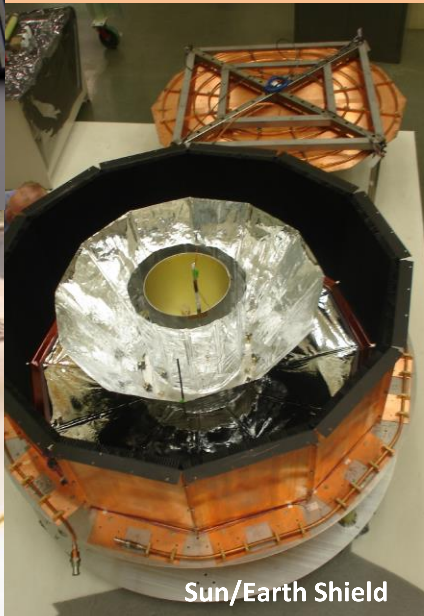
Step-1 proposal submitted Dec 2016
- Phase A down-select "Summer 2017"
- Phase B down-select late 2018
- Launch 2023



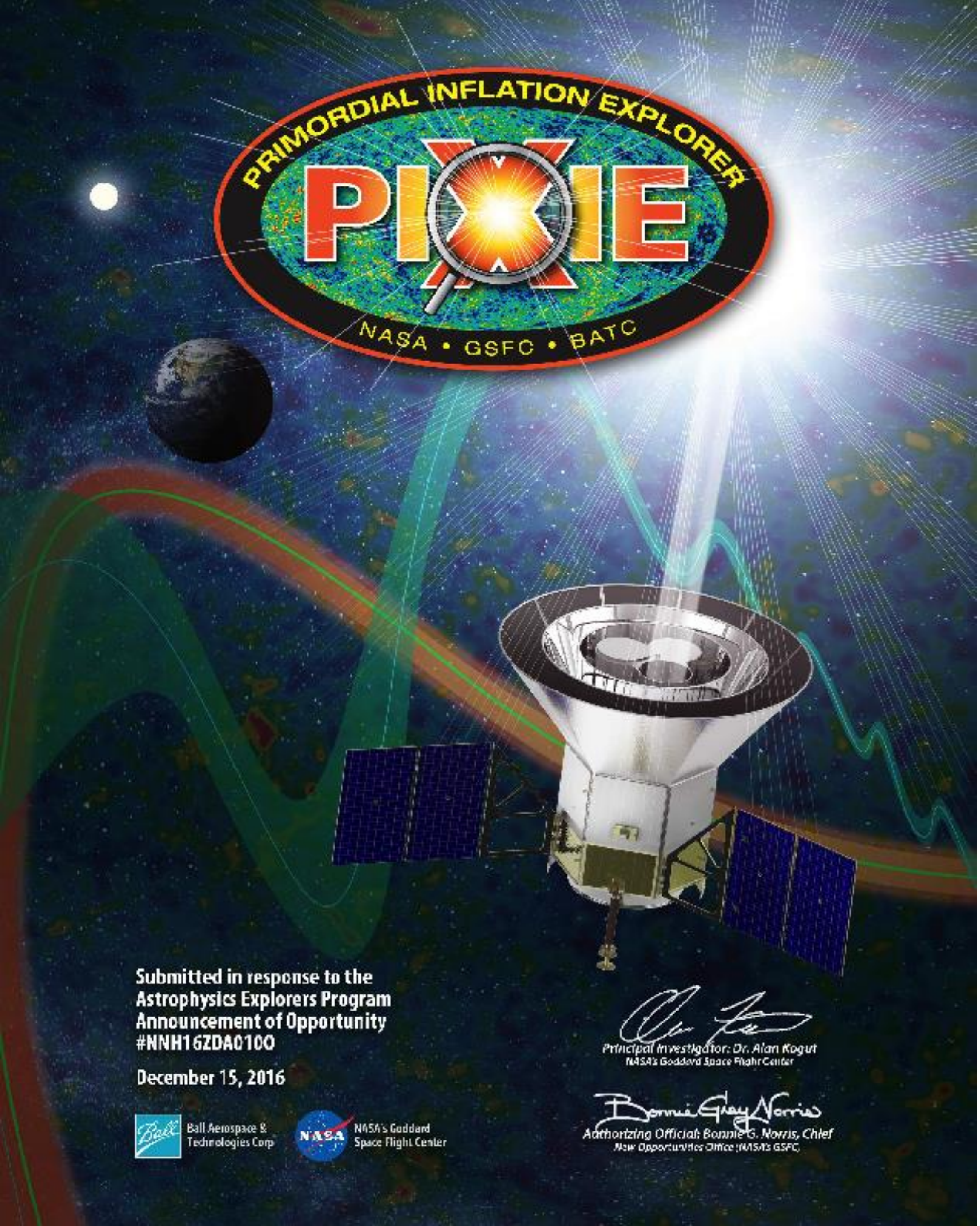


Mature technology

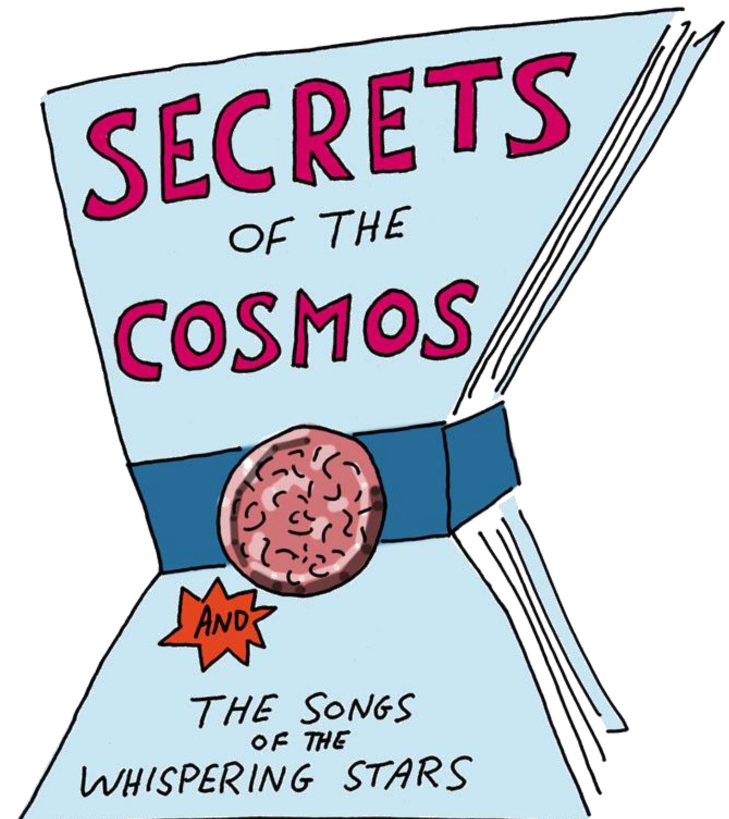




PRIMORDIAL INFLATION EXPLORER
PIXIE
NASA • GSFC • BATC



Coming Soon From a Spacecraft Near You!



Sensitivity the Easy Way

Big Detectors in Multi-Moded Light Bucket

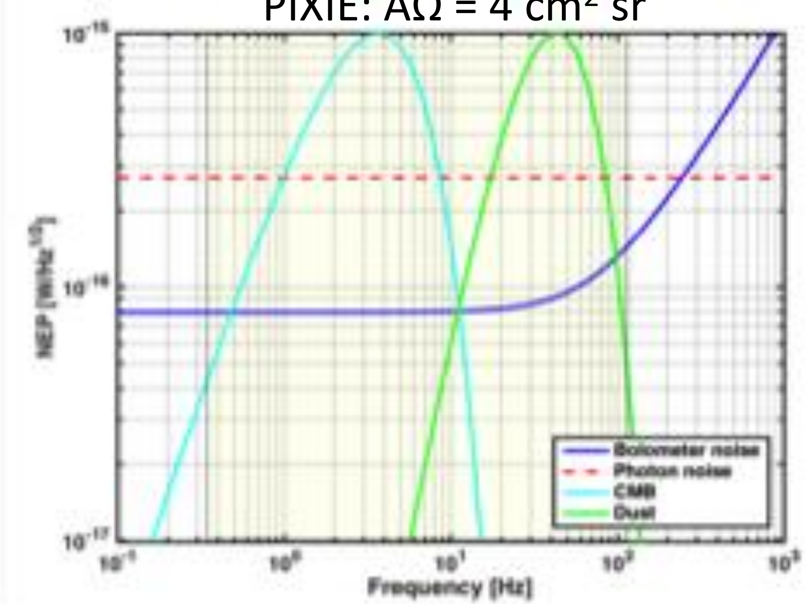
$$\mathrm{NEP}^2_{\mathrm{photon}} = \frac{2A\Omega}{c^2}\frac{(kT)^5}{h^3}\int \alpha\epsilon f \, \frac{x^4}{e^x - 1}\left(1 + \frac{\alpha\epsilon f}{e^x - 1}\right) dx$$

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

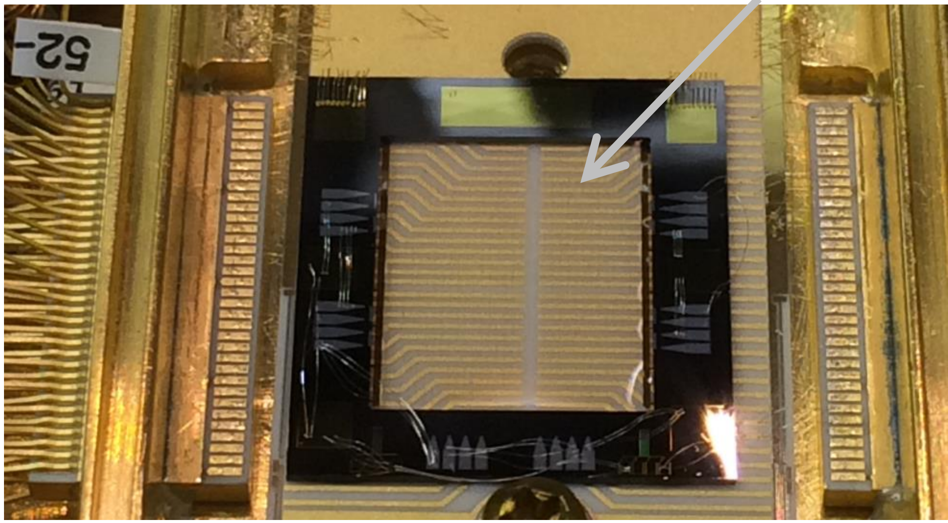
$$\delta I_\nu = \frac{\delta P}{A\Omega\,\Delta\nu\,(\alpha\epsilon f)}$$

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

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



30x collecting area as Planck bolometers

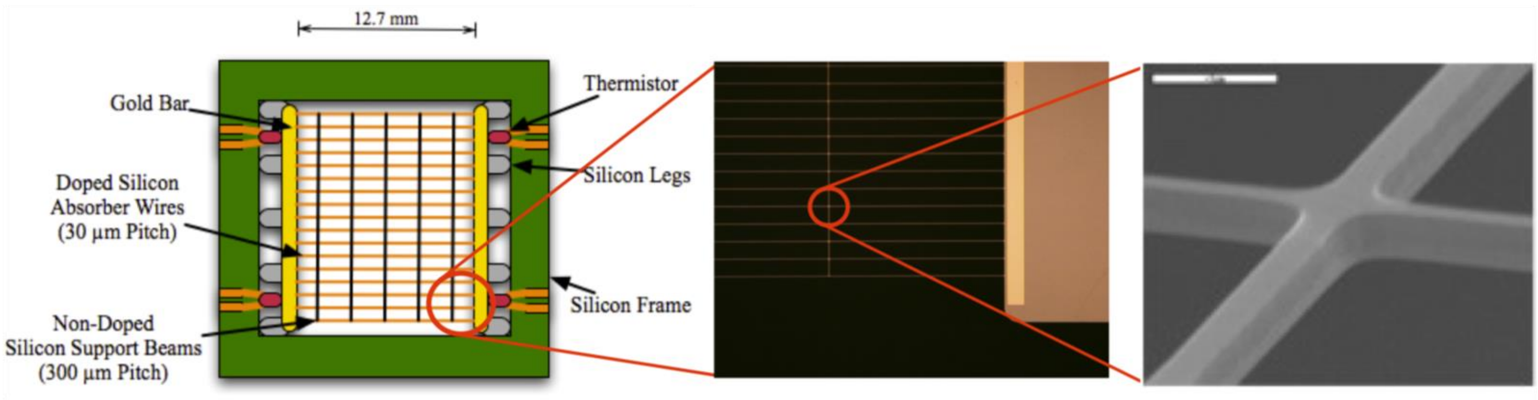


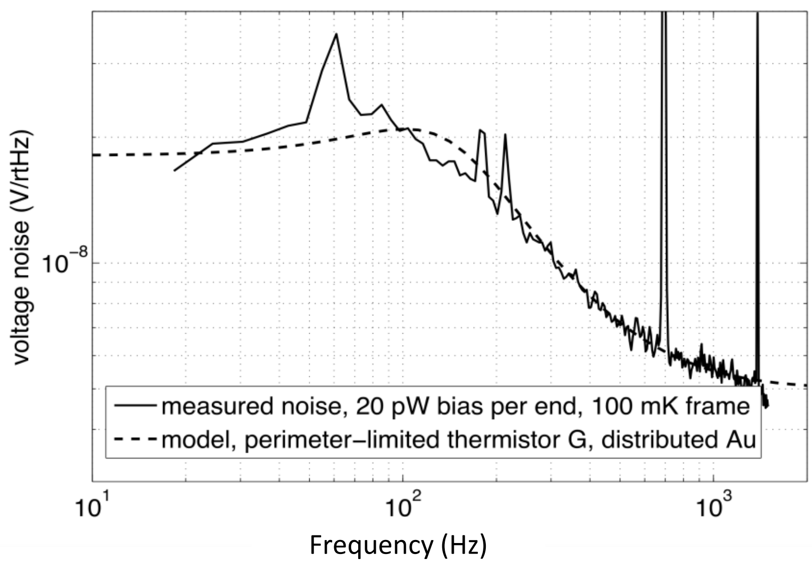
PIXIE polarization-sensitive bolometer

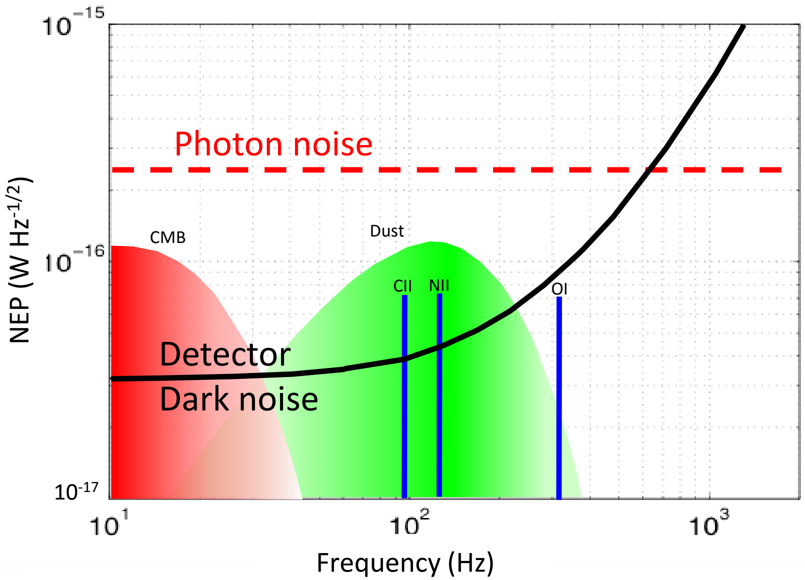
Sensitivity 70 nK per 1° x 1° pixel

See P. Nagler detector talk Thursday afternoon (9914-47)

PIXIE Detectors

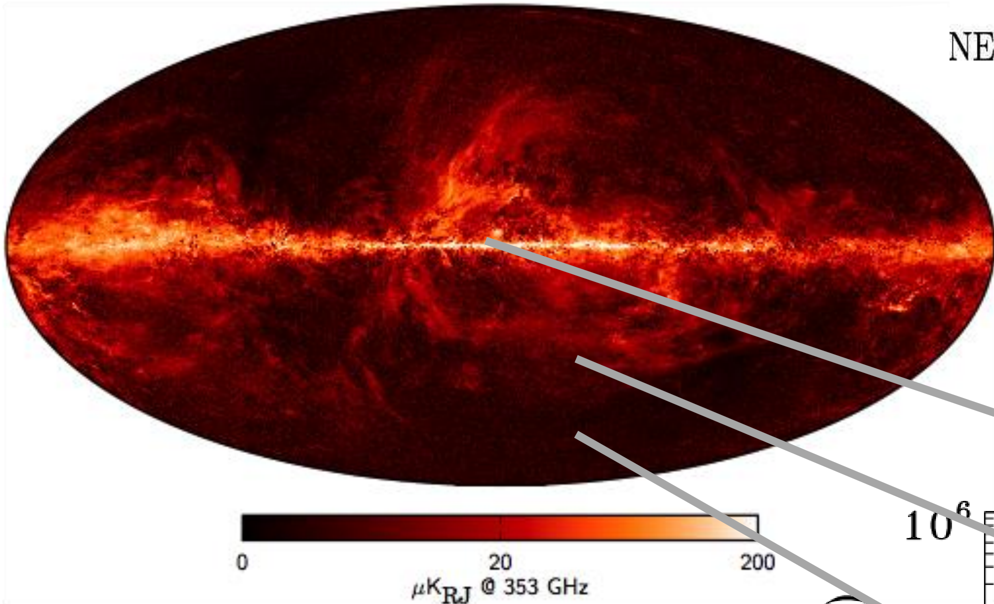






Demonstrate multi-moded single-polarization photon-limited detectors

PIXIE Photon Noise

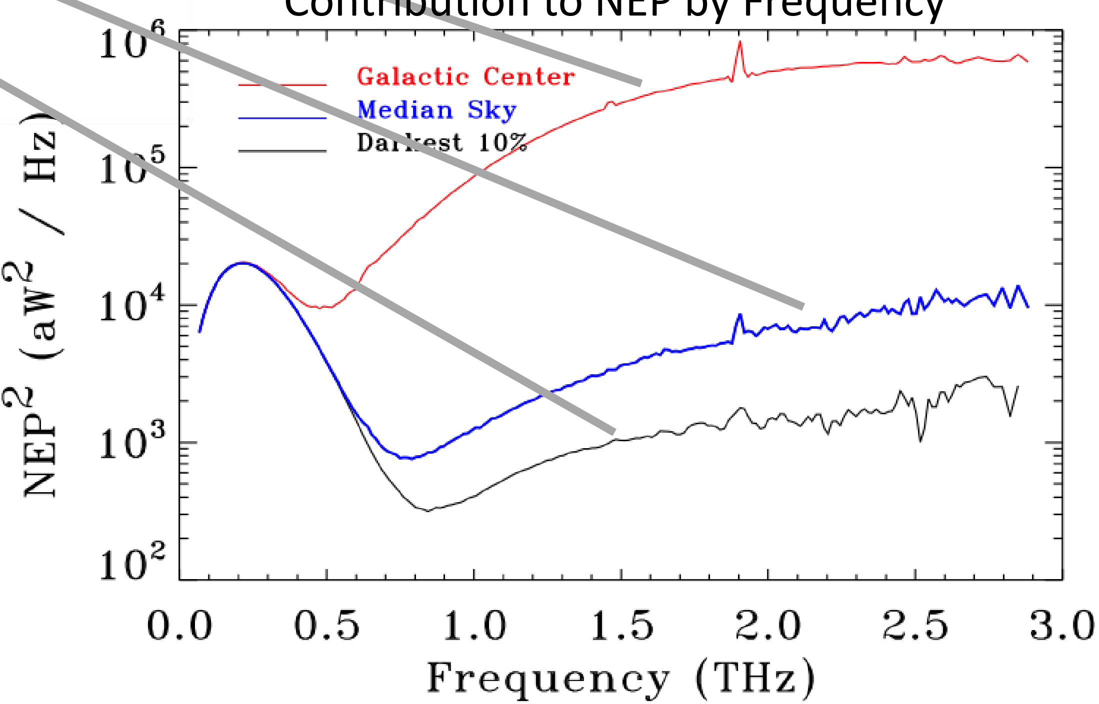


$$\mathrm{NEP}^2_{\mathrm{photon}} = \frac{2A\Omega}{c^2}\frac{(kT)^5}{h^3}\int \alpha\epsilon f\ \frac{x^4}{e^x-1}\ \left(1+\frac{\alpha\epsilon f}{e^x-1}\right)\ dx$$

Compute NEP^2 from photon noise

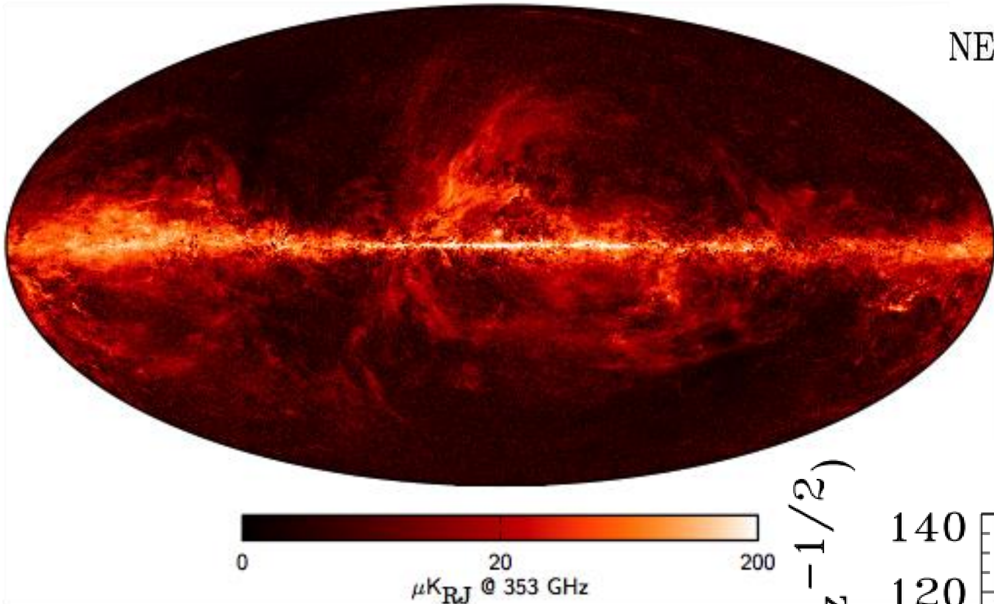
Include CMB, dust, CIB, zodiacal light

Contribution to NEP by Frequency



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

PIXIE Photon Noise

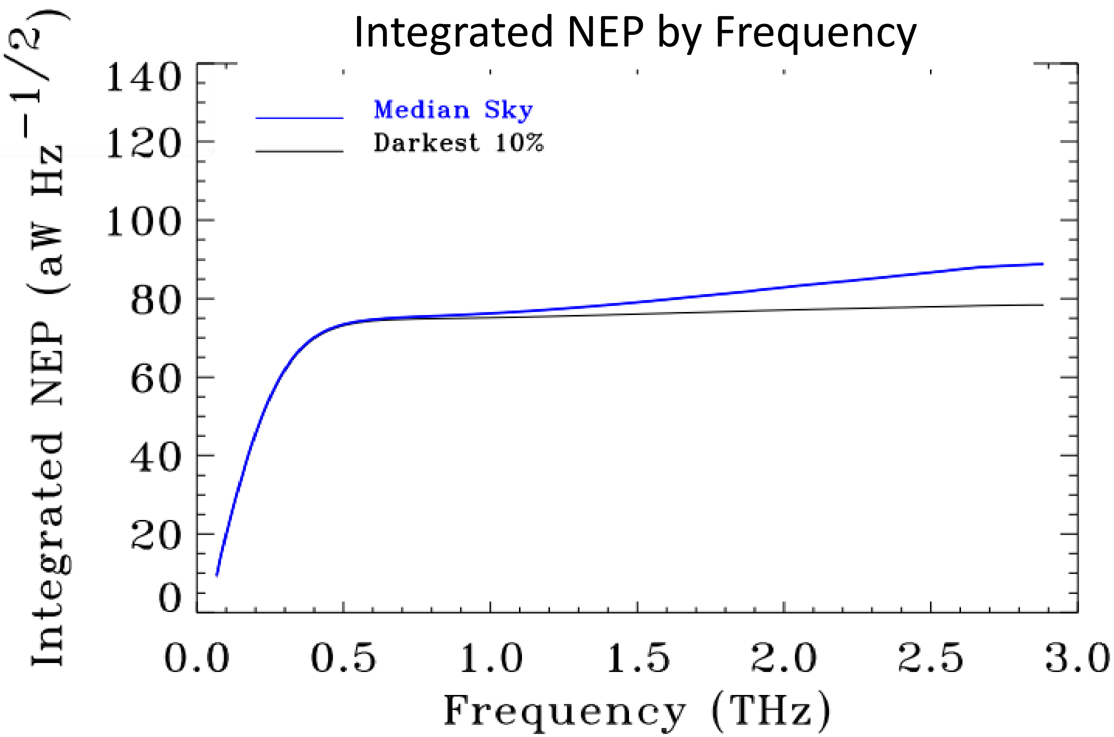


$$\mathrm{NEP}^2_{\mathrm{photon}} = \frac{2A\Omega}{c^2}\frac{(kT)^5}{h^3}\int \alpha\epsilon f\,\frac{x^4}{e^x-1}\left(1+\frac{\alpha\epsilon f}{e^x-1}\right)dx$$

Compute NEP^2 from photon noise

Include CMB, dust, CIB, zodiacal light

Integrated NEP by Frequency

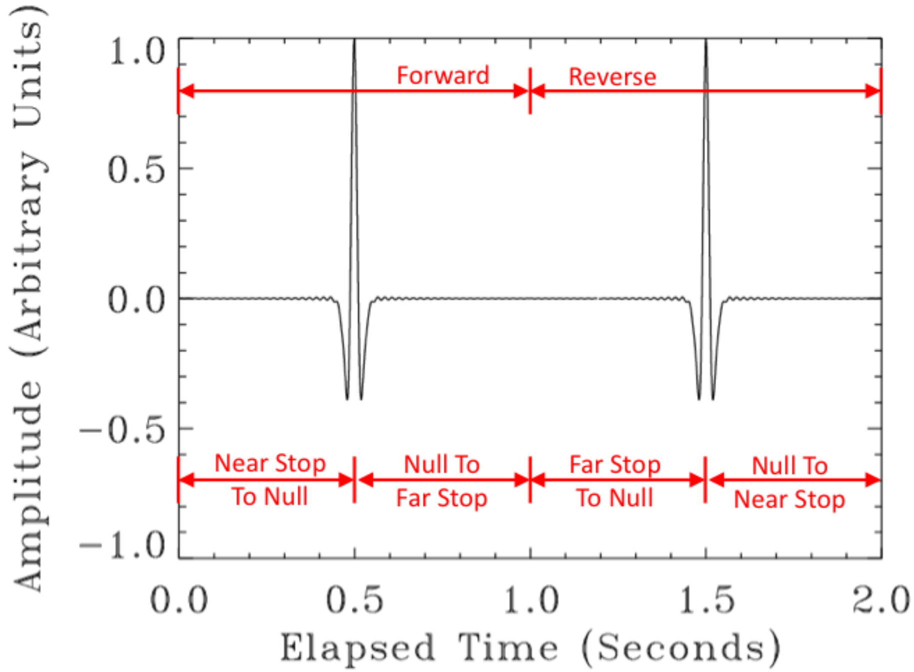


Galactic plane is bad for cosmology
Rest of sky is not so bad

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

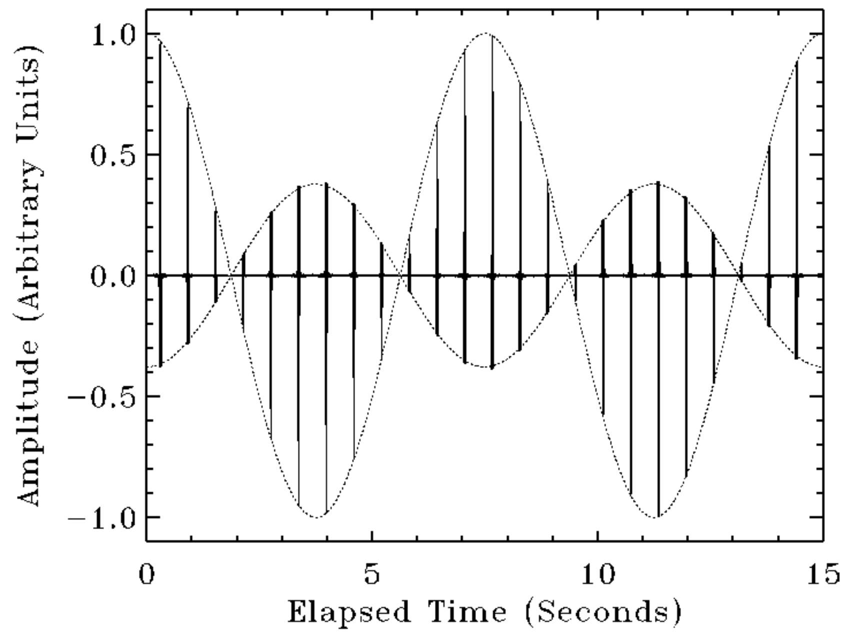
Systematic Error Control

Multiple Instrumental Symmetries



Spacecraft spin imposes amplitude modulation of entire fringe pattern

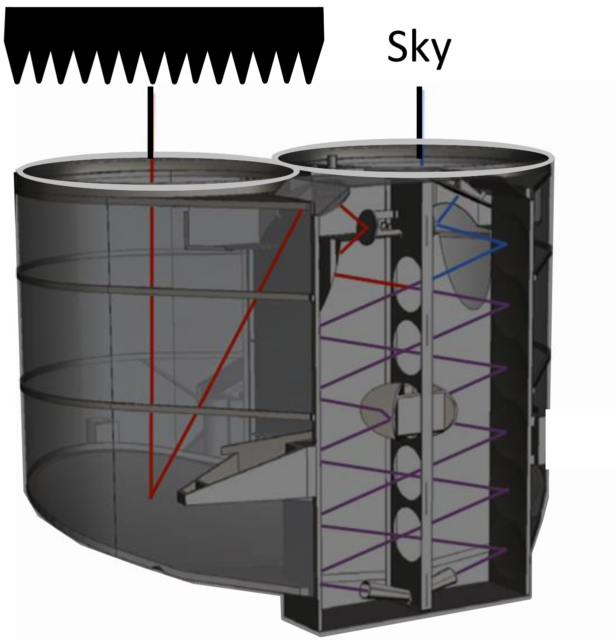
Same information 4x per stroke with different time/space symmetries



Multiple Redundant Symmetries Allow Clean Instrument Signature

Systematic Errors II

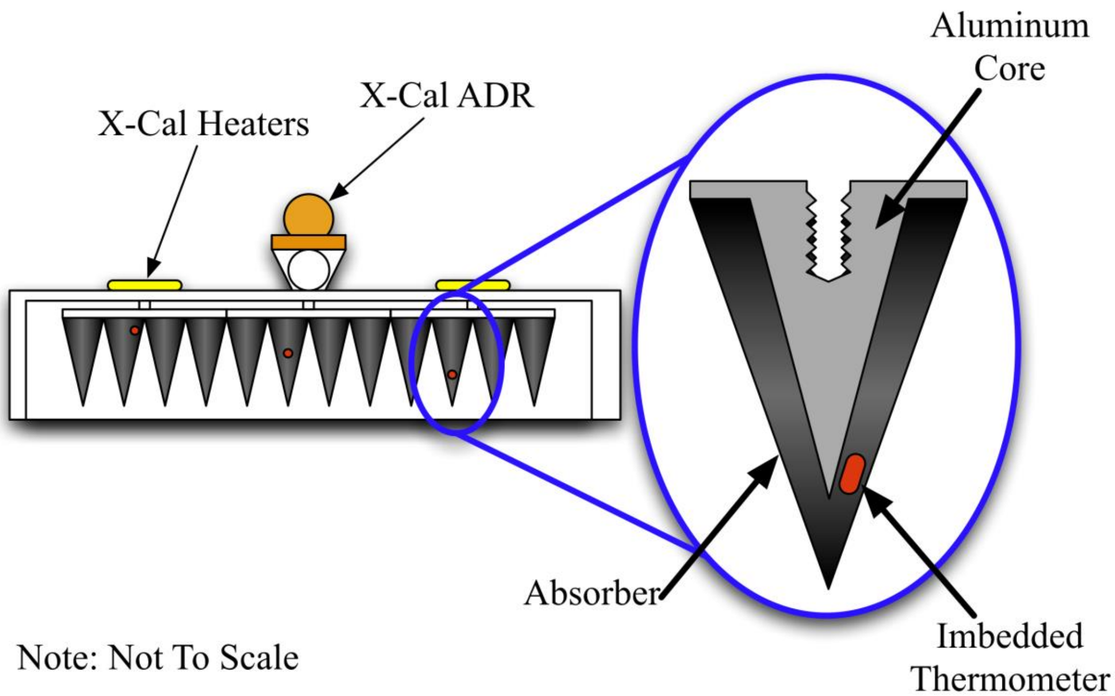
Chain Multiple Nulls Together



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	

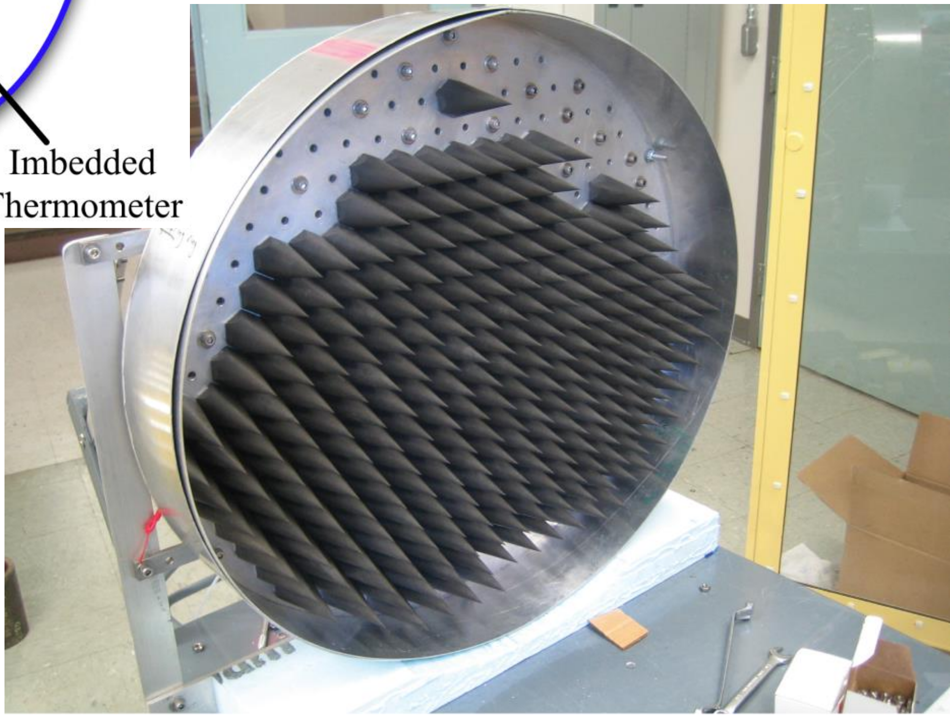
Multiple levels of nulling reduce systematics to negligible levels without relying on any single null

Blackbody Calibrator



Note: Not To Scale

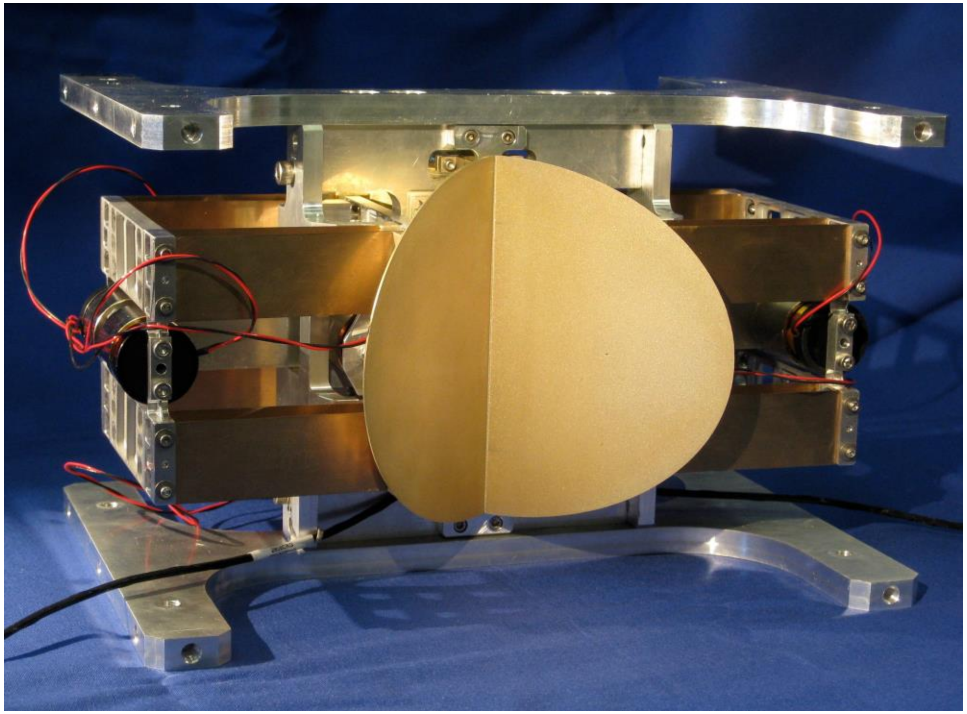
Based on successful ARCADE calibrator



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

PX094

Mirror Transport Mechanism

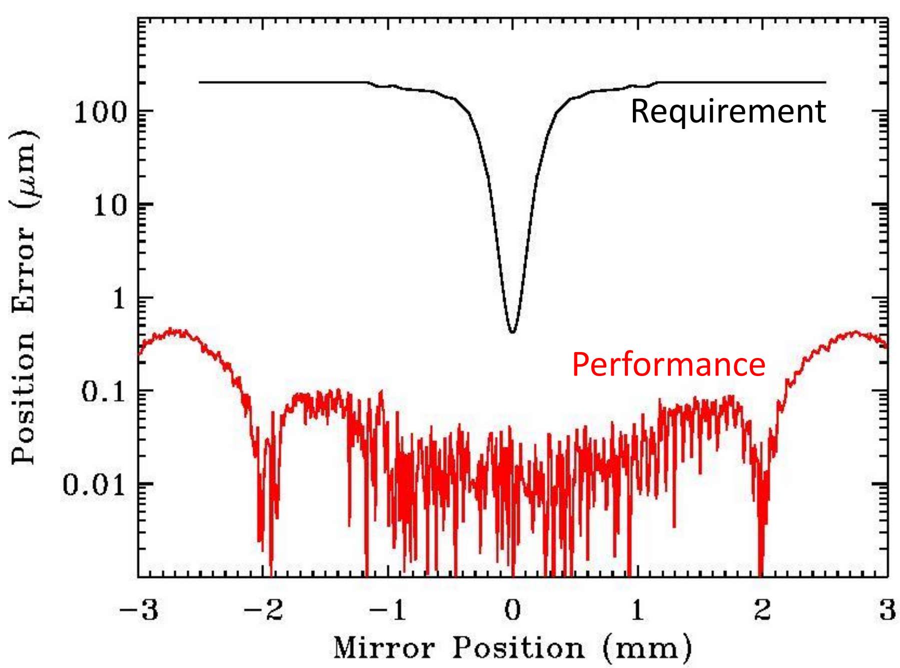


Engineering prototype

Translate ±2.54 mm at 0.5 Hz

Optical phase delay ±1 cm

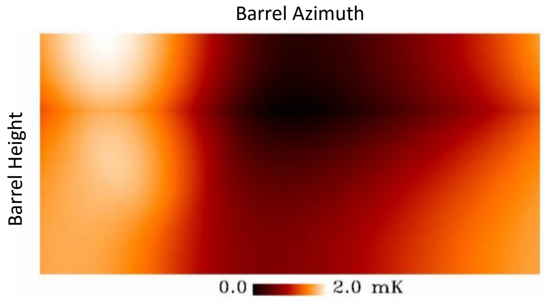
Repeatable cryogenic position

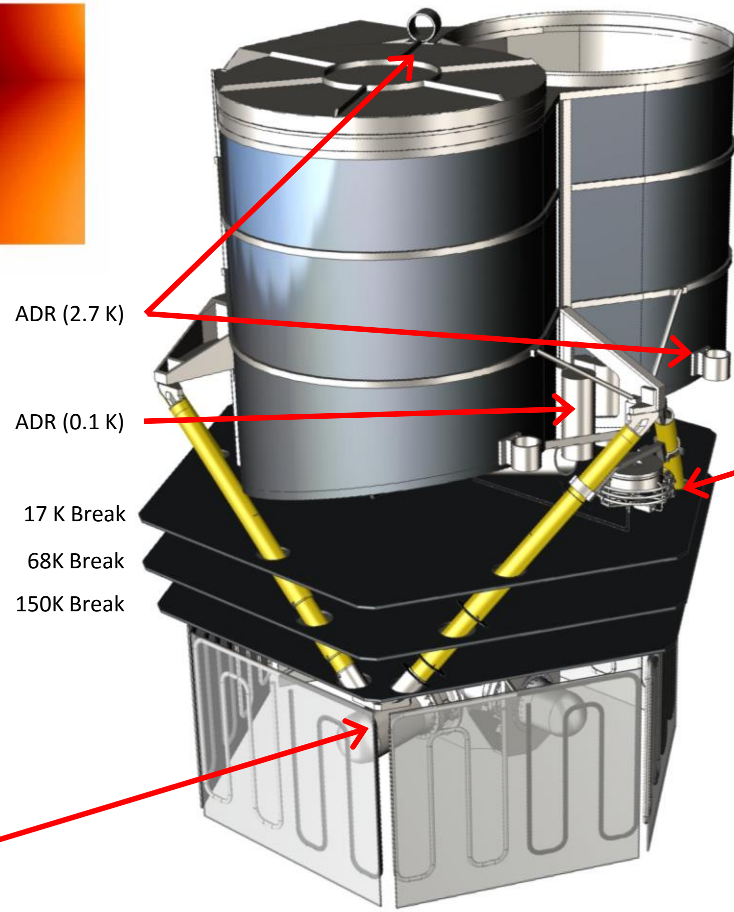


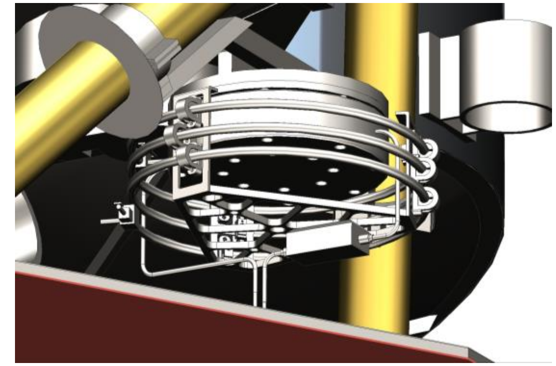
Demonstrated performance
exceeds requirement by factor of ten

Cryogenics

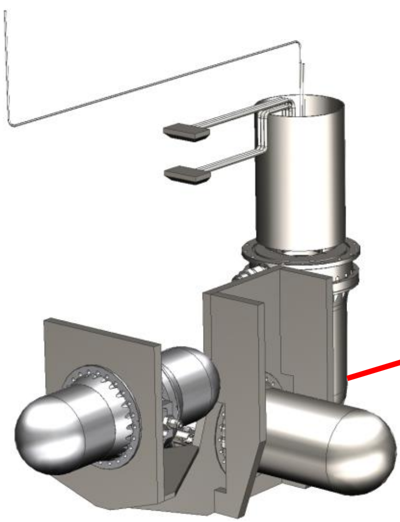
Moonshine Thermal Gradient







J-T Cold Head (4.5 K)



Cryo-Cooler Compressor (280 K)

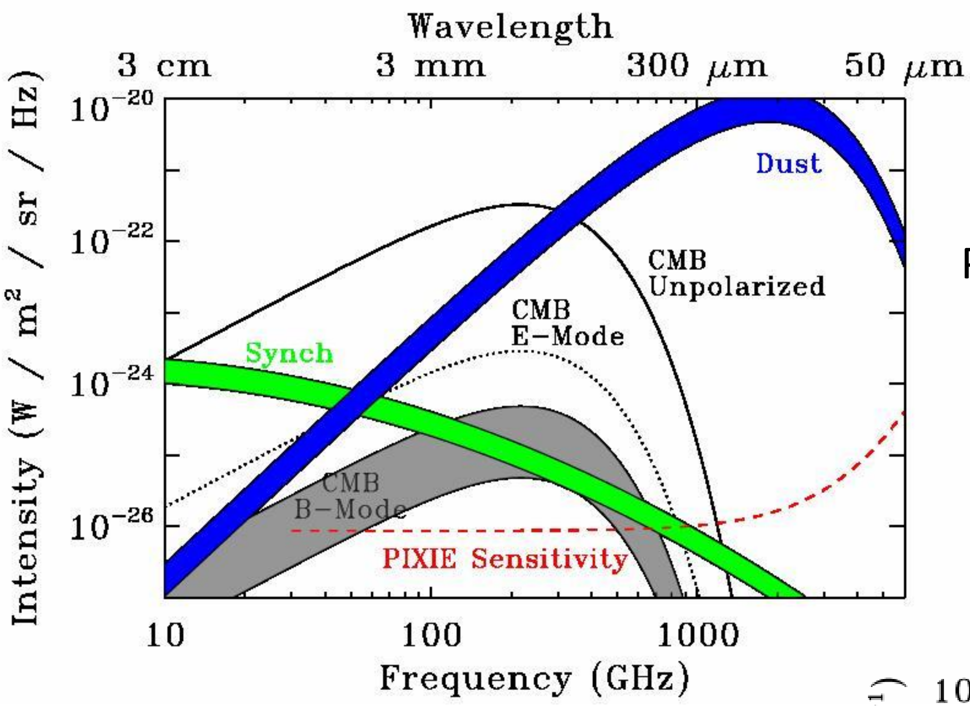
Multi-Stage Cryogenic Design

- Passive Sun Shades (not shown)
- 4.5 K Cryo-cooler
- 2.7 K ADR
- 0.1 K ADR

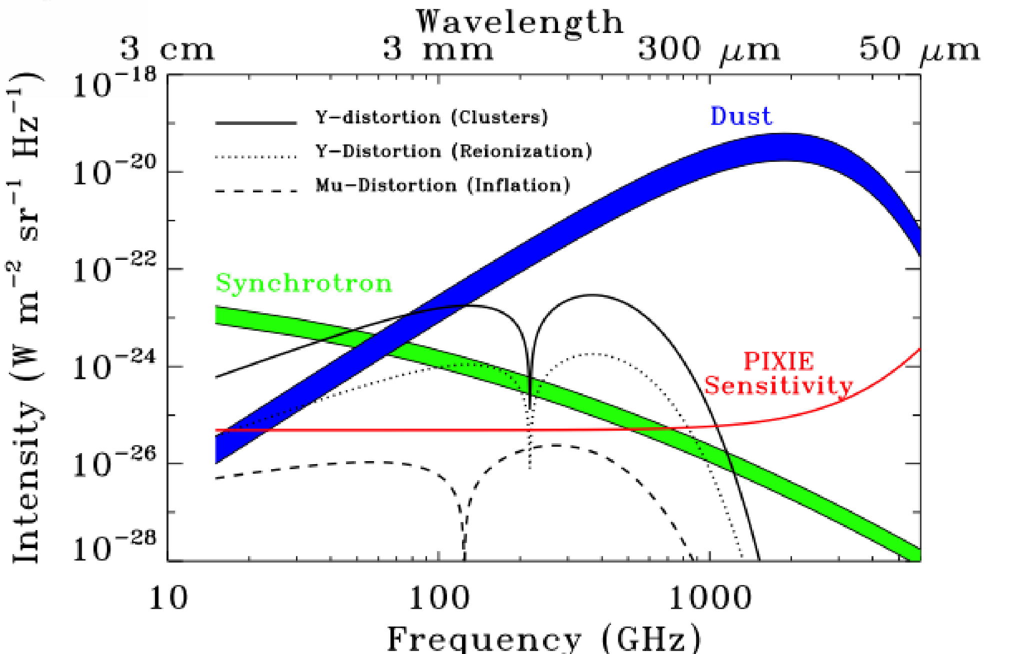
Thermal Lift Budget

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%

Foreground Comparison



Polarized Foregrounds



Unpolarized Foregrounds