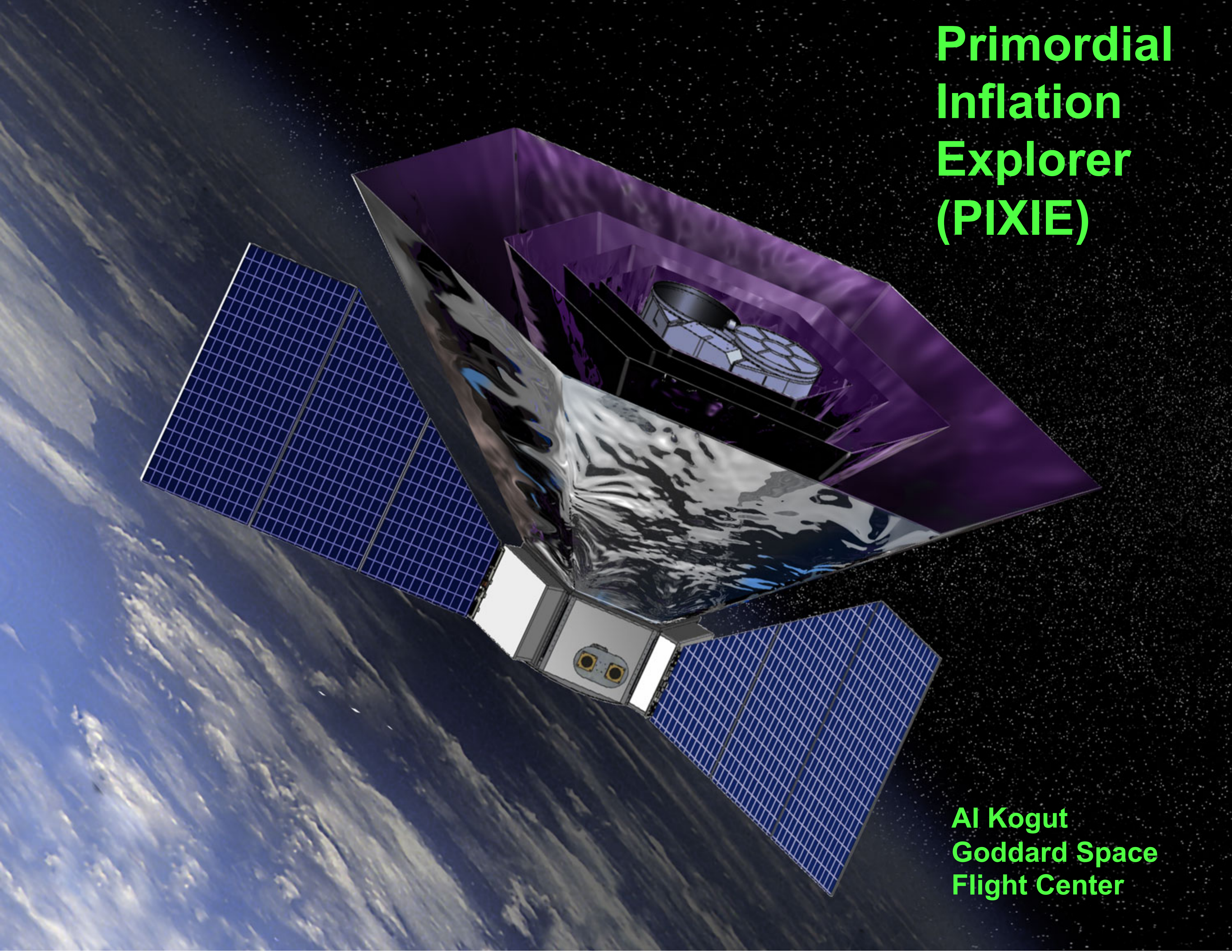
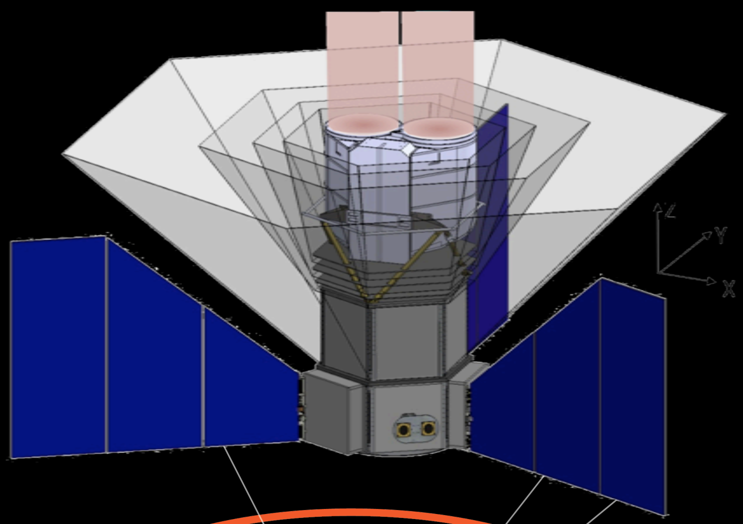
Primordial Inflation Explorer (PIXIE)



Al Kogut
Goddard Space
Flight Center

Primordial Inflation Explorer



PRIMORDIAL INFLATION EXPLORER

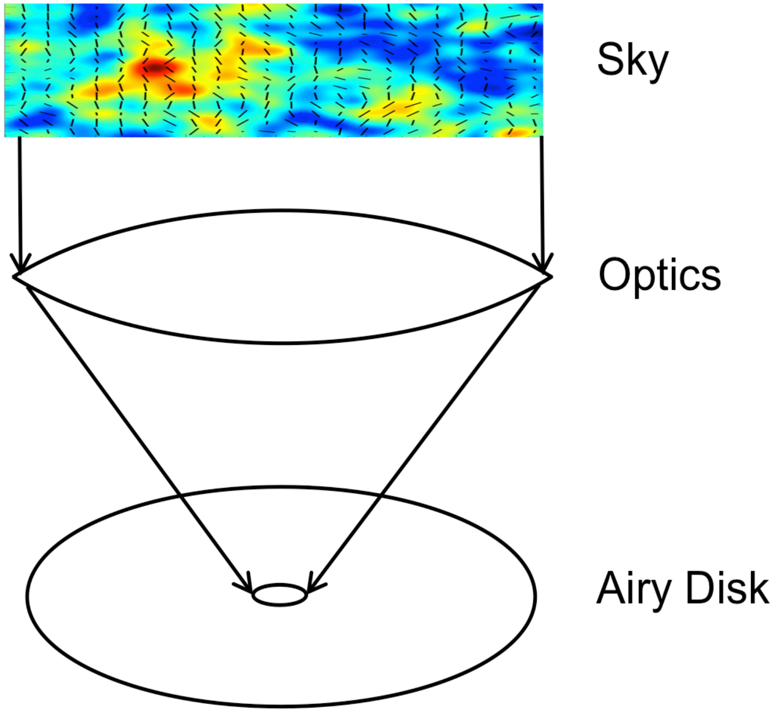
PIXIE

NASA • GSFC • BATC

Name	Role	Institution
A. Kogut	PI	GSFC
D. Fixsen	IS	UMD
D. Chuss	Co-I	GSFC
J. Dotson	Co-I	ARC
E. Dwek	Co-I	GSFC
M. Halpern	Co-I	UBC
G. Hinshaw	Co-I	UBC
S. Meyer	Co-I	U. Chicago
H. Moseley	Co-I	GSFC
M. Seiffert	Co-I	JPL
D. Spergel	Co-I	Princeton
E. Wollack	Co-I	GSFC

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

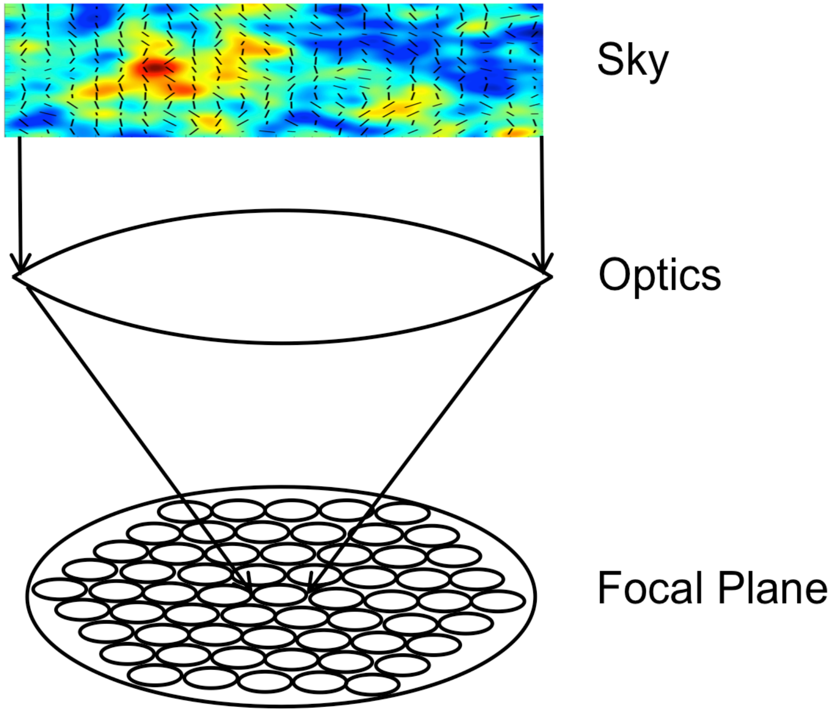
Optical Design for CMB



Conventional
Focal Plane

Single-Moded Pixel

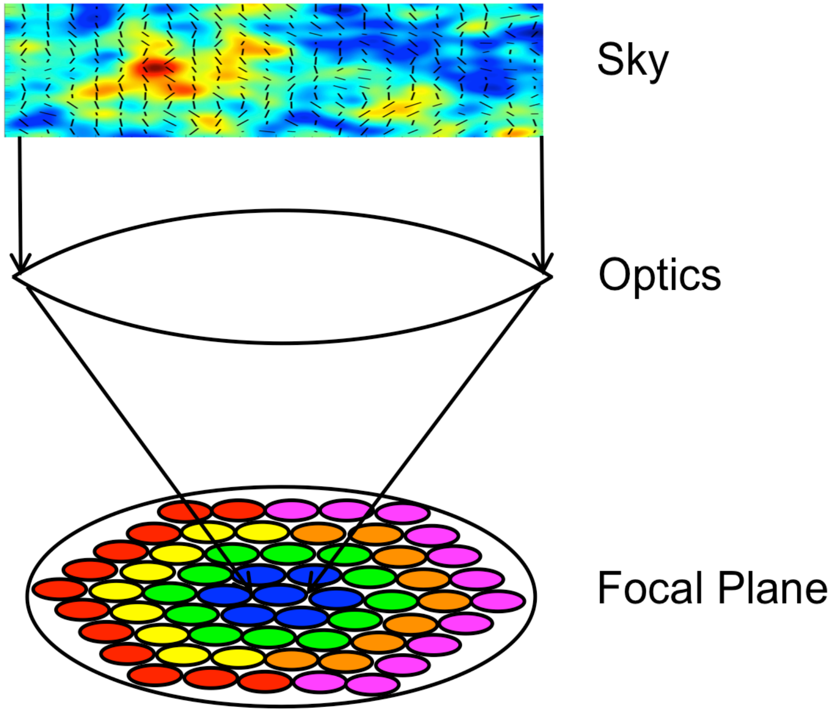
Optical Design for CMB



Conventional Focal Plane

Photon Limit: Add Detectors

Optical Design for CMB

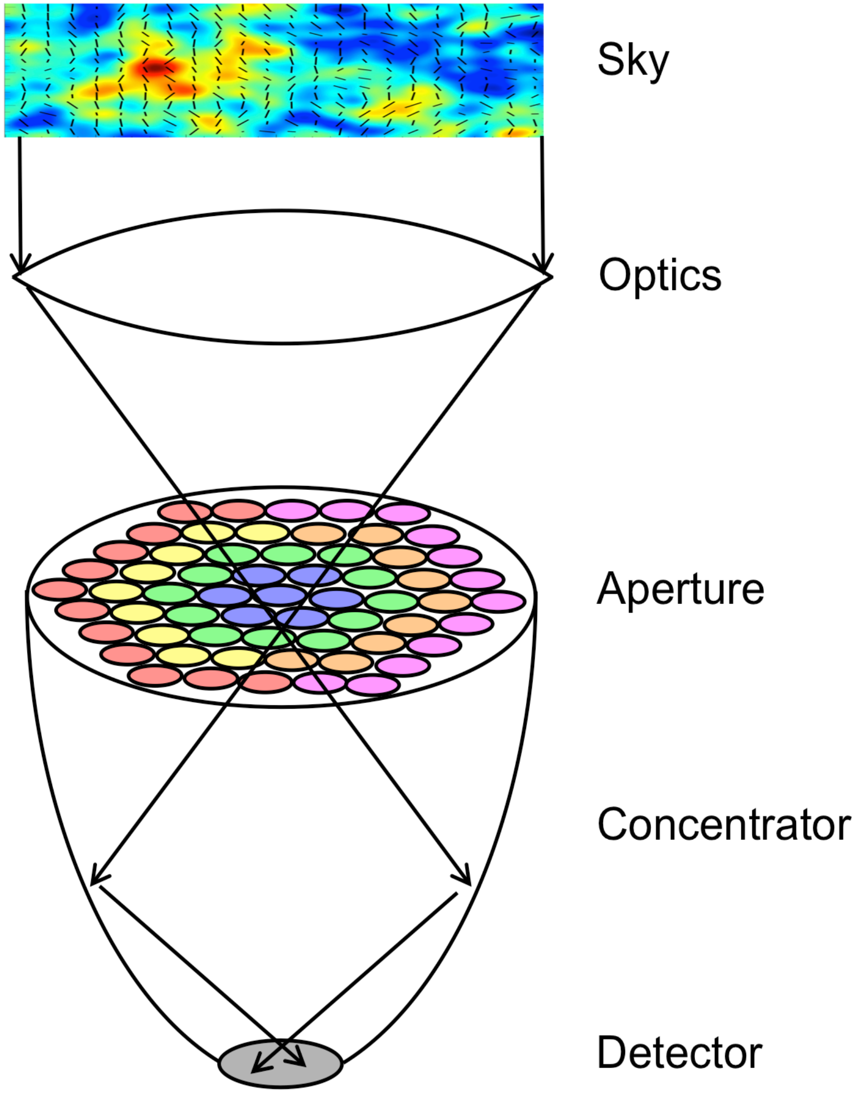


Conventional Focal Plane

Foregrounds: Separate Bands

Problem: Getting enough sensitivity in enough frequency bands requires ~10,000 background-limited detectors!

PIXIE Optical Solution

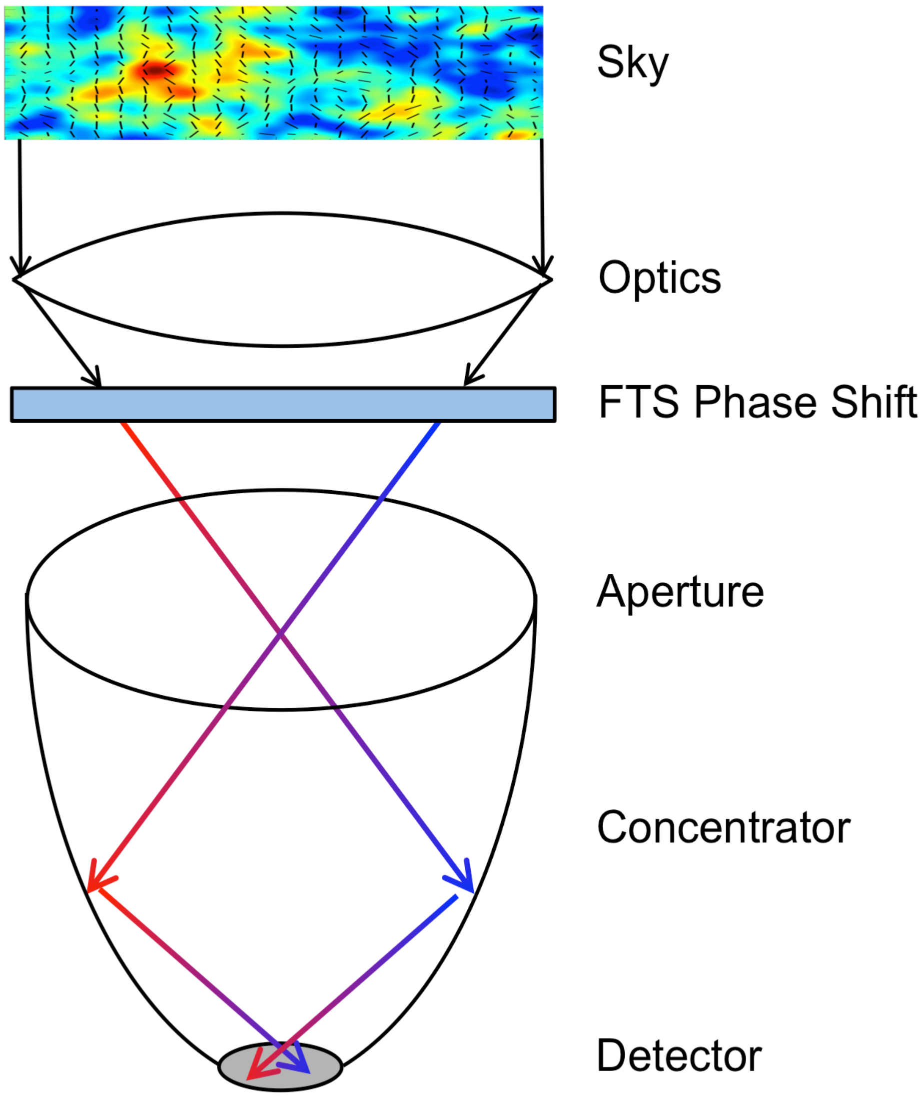


PIXIE

Need more photons,
not more detectors!

Replace tiled focal plane
with
multi-moded concentrator

PIXIE Optical Solution



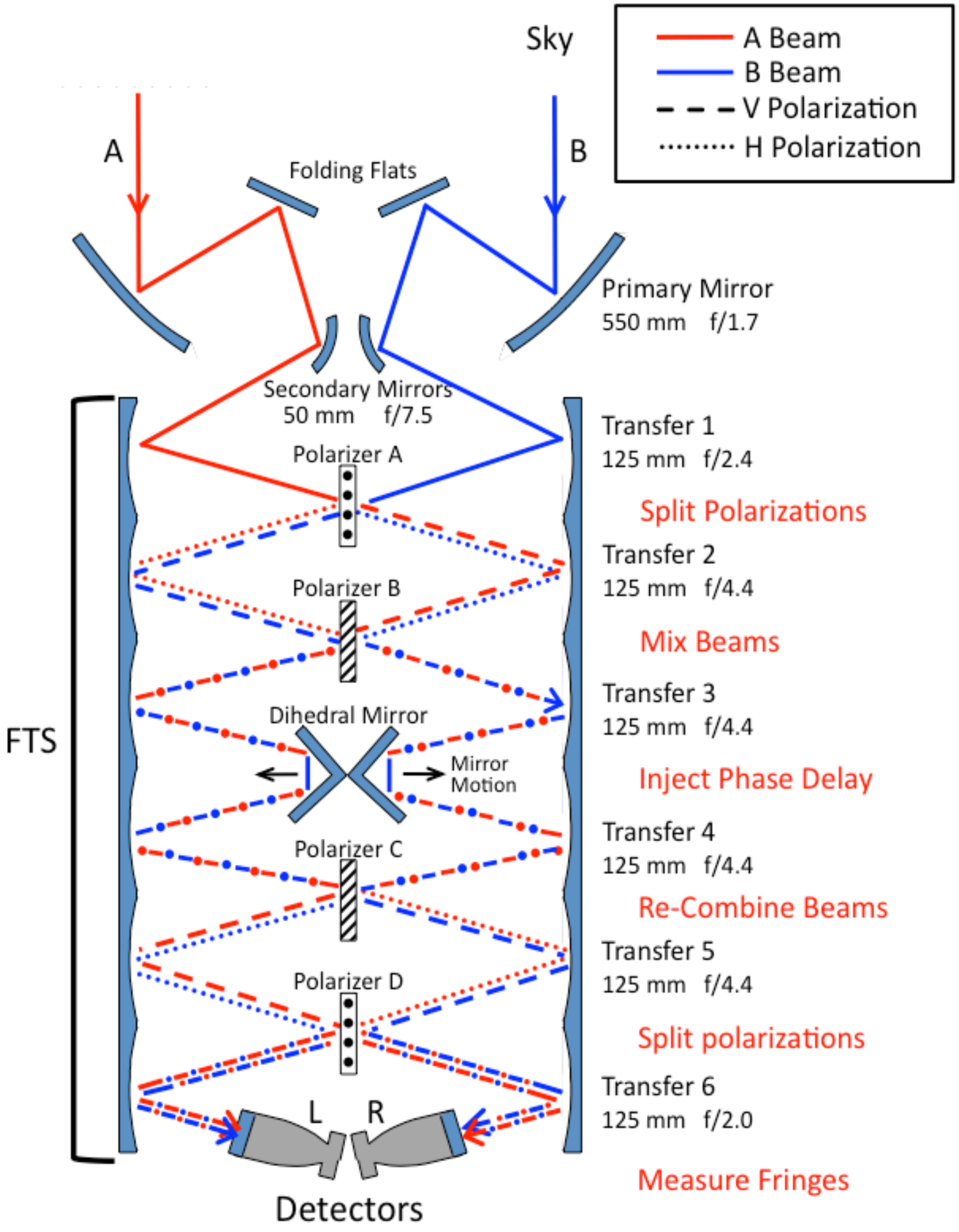
PIXIE

Replace multi-color detectors
with
Fourier transform spectrometer

Replace tiled focal plane
with
multi-moded concentrator

Win-Win: Sensitivity and spectra from a single detector

PIXIE Nulling Polarimeter



Measured Fringe Pattern Samples Frequency Spectrum of Polarized Sky Emission

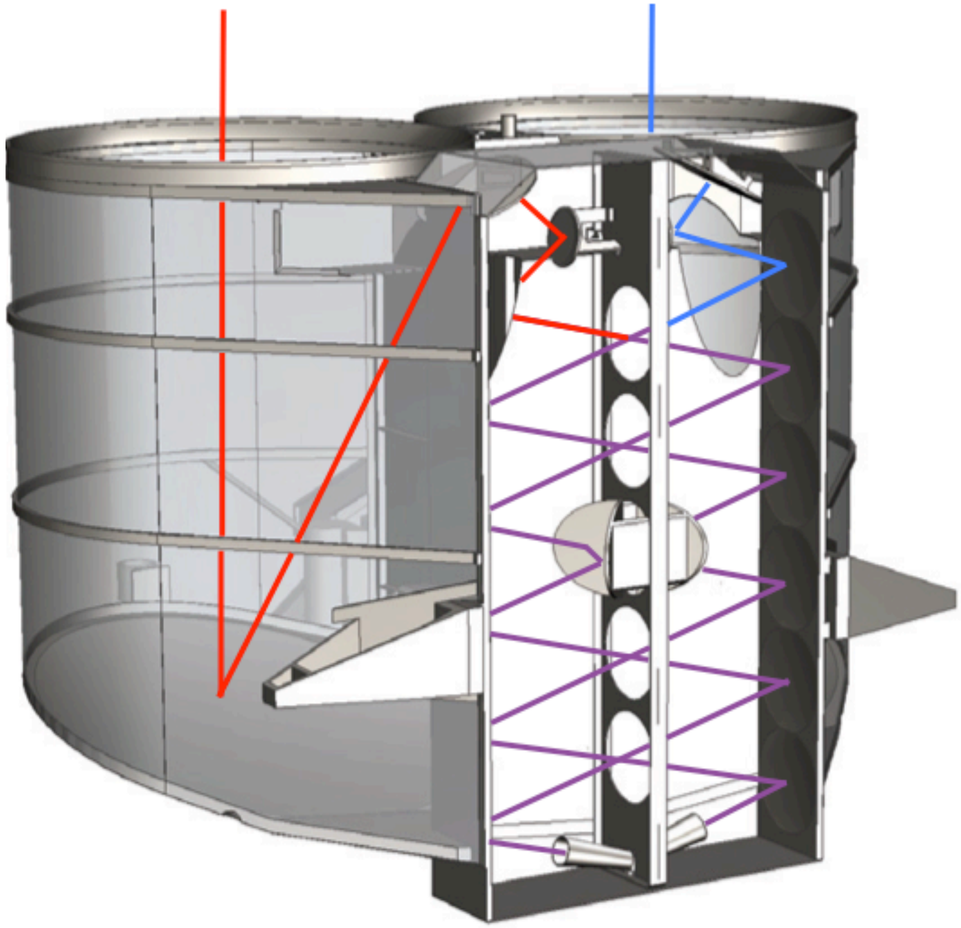
$$P_{Lx} = \frac{1}{2}\int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx}^2 - E_{Ay}^2\right)\cos(z\omega/c)\,d\omega$$

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

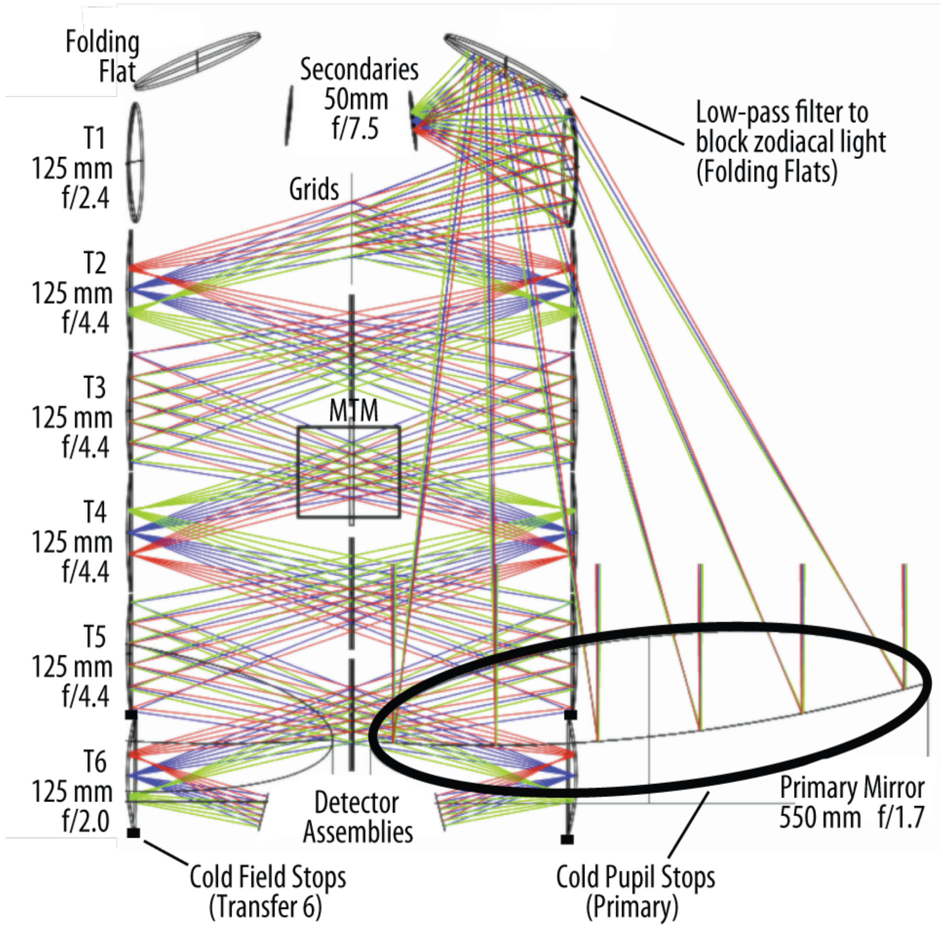
Nulling Polarimeter: Zero = Zero

Kogut et al. 2011, JCAP, 7, 025
Kogut et al. 2011, SPIE, 7731, 77311S

PIXIE Non-Imaging Optics



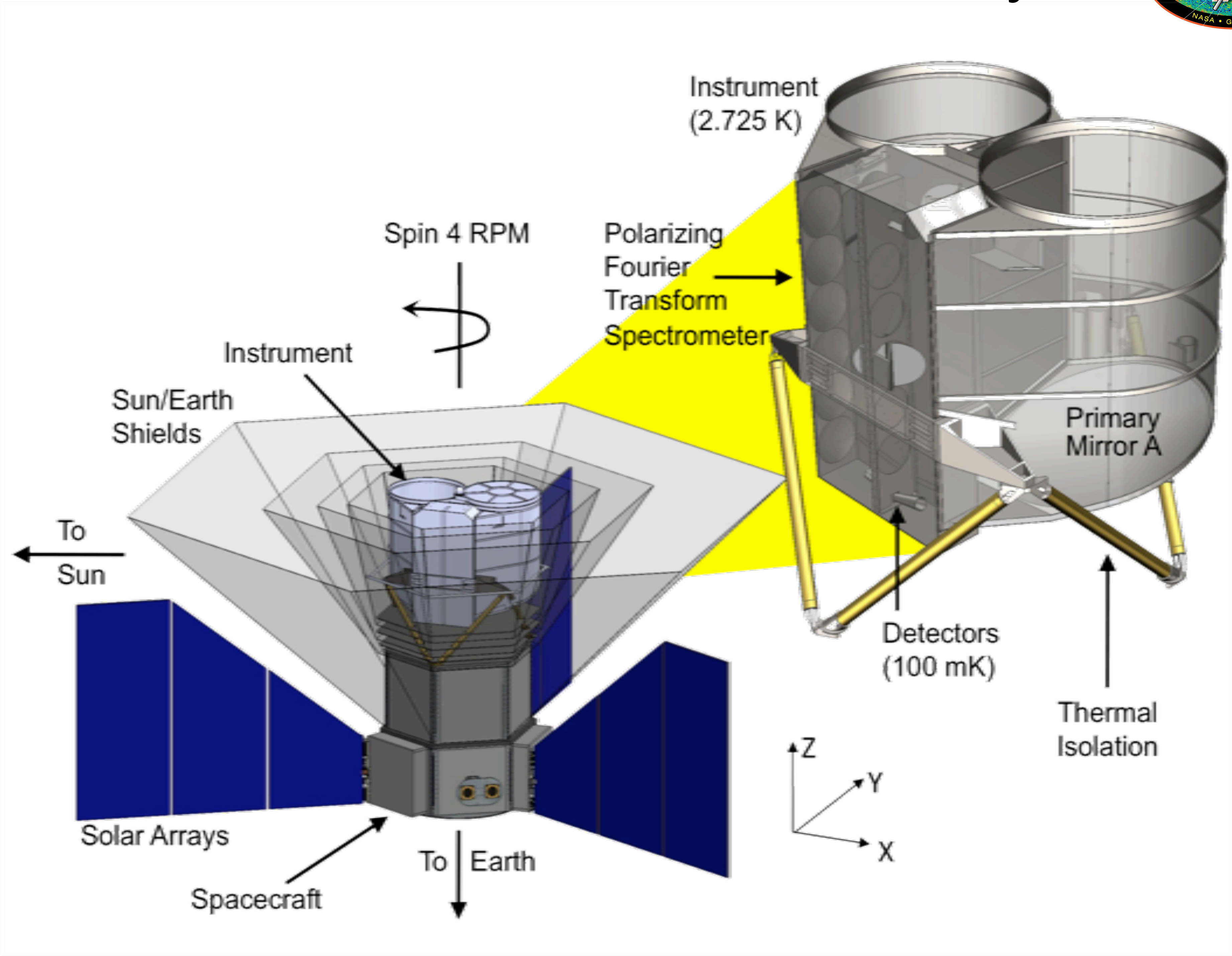
Parameter	Value
Primary Mirror Diam	550 mm
Etendu	4 cm^2 sr
Beam Diam	2.6° Tophat
Throughput	82%



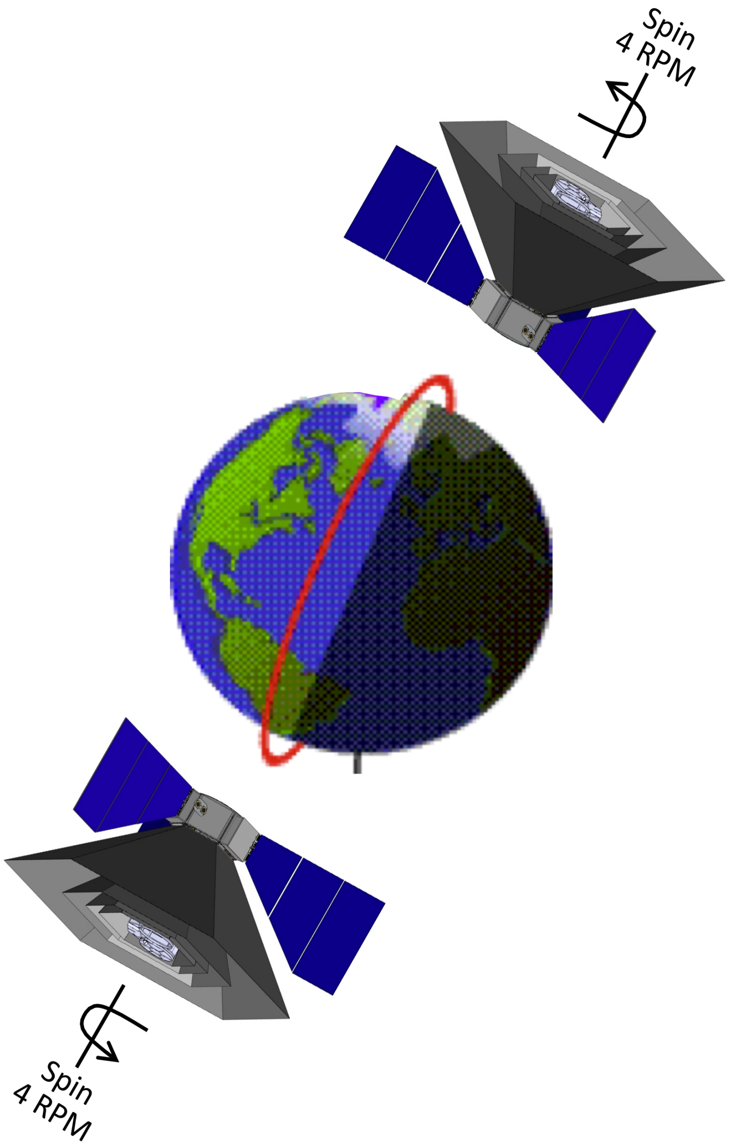
PX108

44,000 modes
on 4 detectors

Instrument and Observatory



PIXIE Mission Concept



Polar Sun-Synch Orbit
- 6 AM or 6 PM ascending node
- 660 km altitude

Like COBE, but lower

3-Axis Control
- Spin at 4 RPM
- Spin axis 90° to sun line
- Zenith view (precess axis once/orbit)

COBE, WMAP

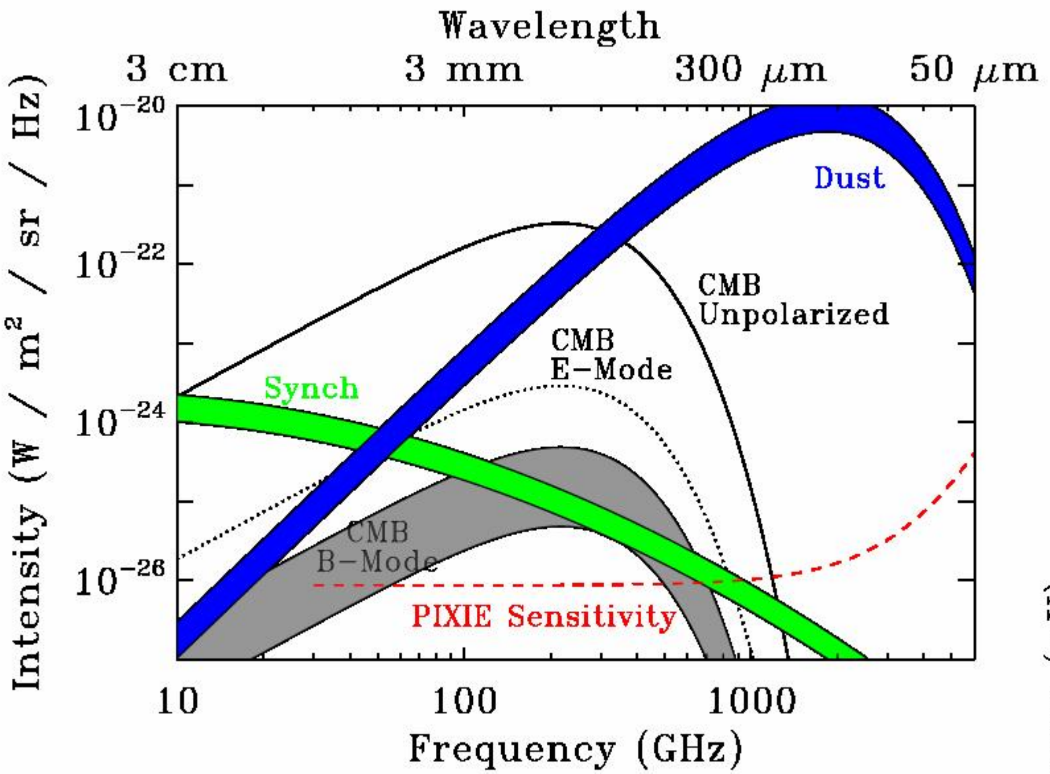
Routine Observations
- Spin and stare
- Move calibrator every 2nd orbit
- 2 year baseline mission
- 4 year extended mission

COBE, WMAP, Planck

Small observatory fits multiple launch vehicles
- Taurus-I ELV

Full-Sky Maps in Stokes IQU in 400 Channels 30 GHz to 6 THz

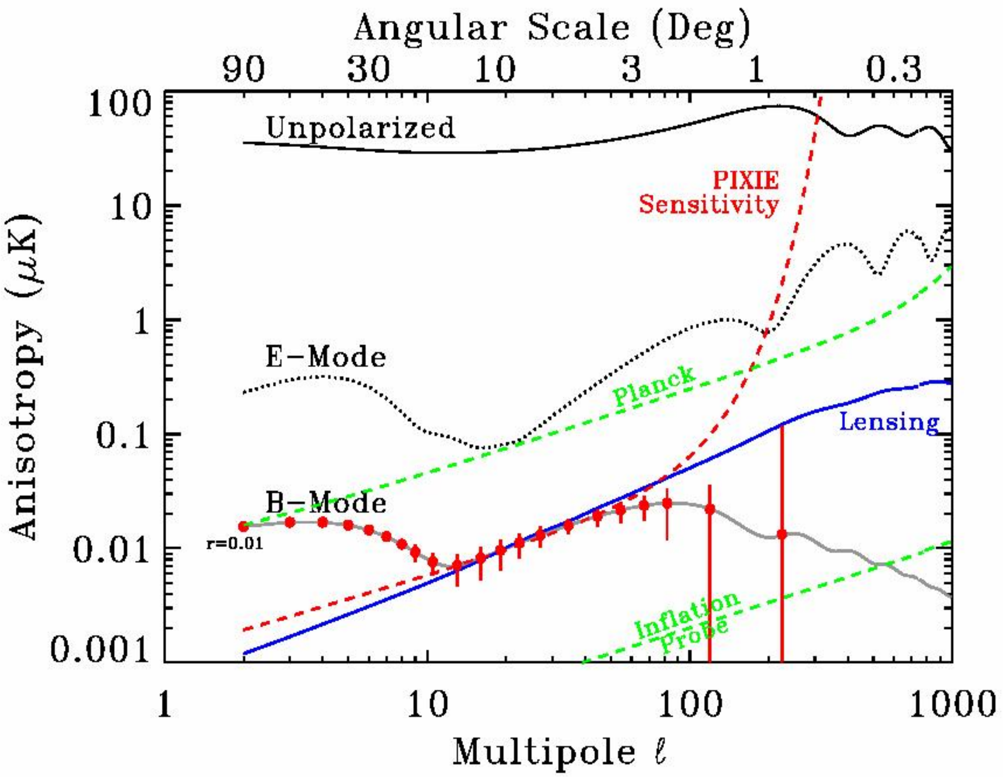
PIXIE B-Mode Science



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

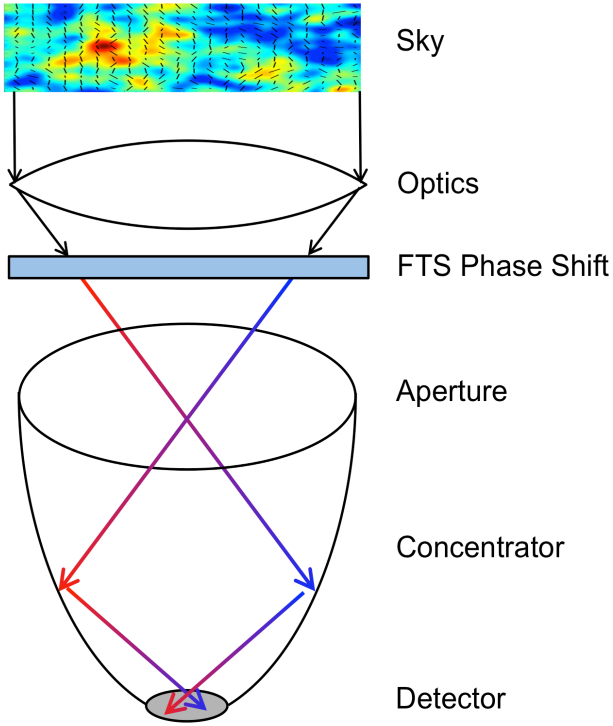
Full-Sky Spectro-Polarimetric Survey

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



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

Design Trades (No Free Lunch)



PIXIE Multi-Moded Optics

Penalties

Concentrator vs Focal Plane Array
Angular Resolution (x6 at 2 mm)

FTS vs Bandpass Filters
Noise (x2)

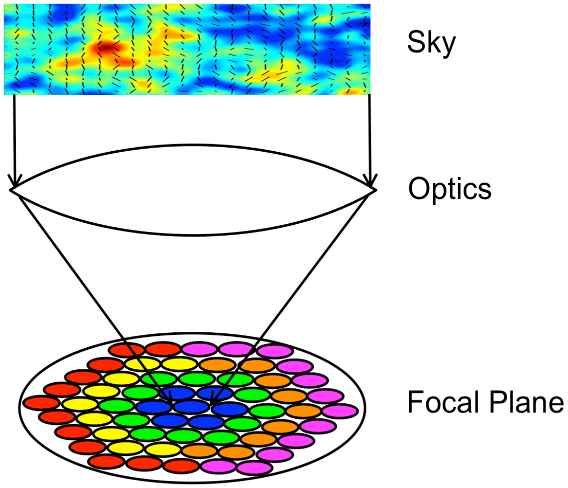
Advantages

Fewer Detectors (x1000)

More Frequency Channels (x25)

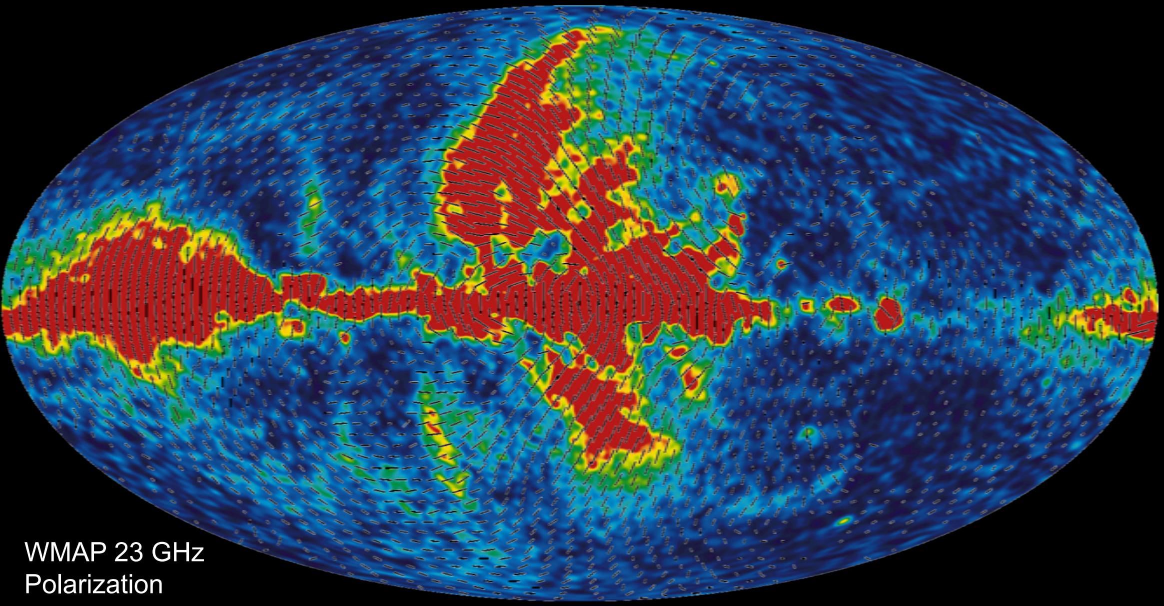
Broader Frequency Range (x8)

Smaller Cold Area (x500)



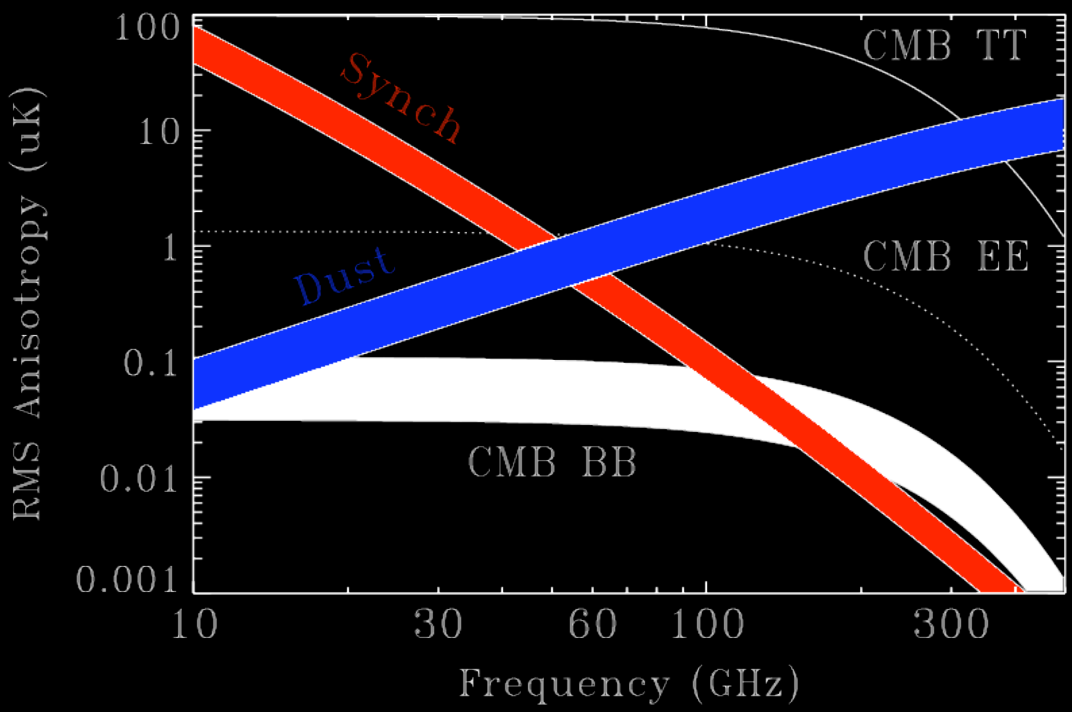
Single-Moded Focal Plane

B-Mode Fundamentals



WMAP 23 GHz
Polarization

Signal is faint
Foregrounds are bright
Everything is confusing



Requirements for B-Mode Detection
- Sensitivity
- Foreground Subtraction
- Systematic Error Control

Sensitivity: Background Limit 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

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

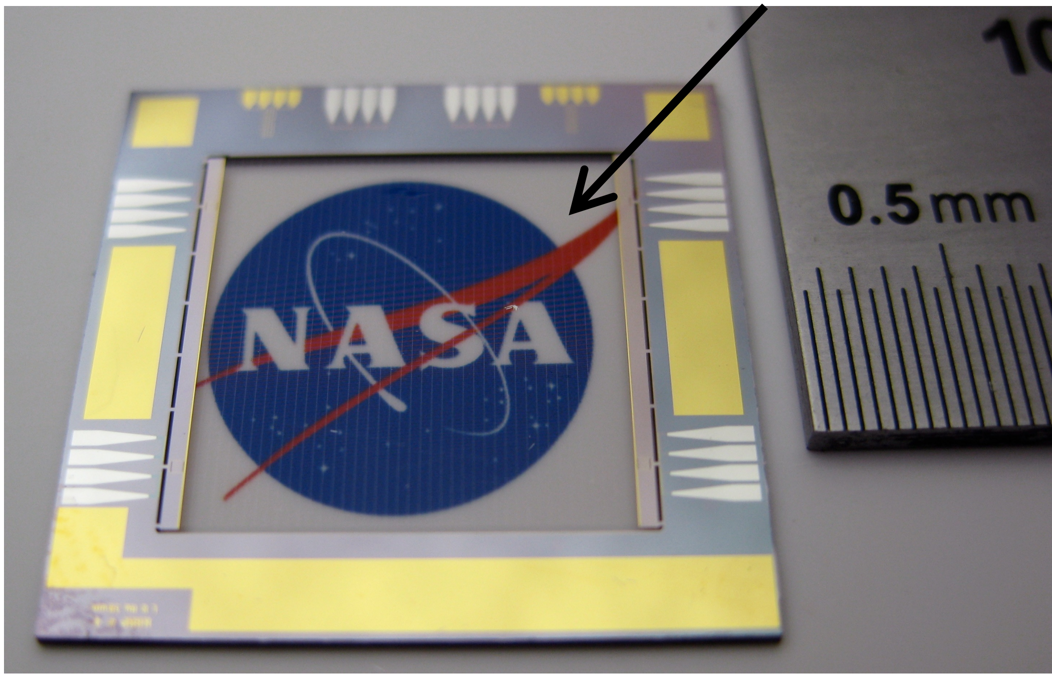
Signal ~ $(A\Omega)$
Big detector: S/N improves as $(A\Omega)^{1/2}$

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

Parameter	Units	Calibrator Deployed	Calibrator Stowed
Stokes I (per bin)	W m^{-2} sr^{-1} Hz^{-1}	2.4 x 10^{-22}	---
Stokes Q (per bin)	W m^{-2} sr^{-1} Hz^{-1}	3.4 x 10^{-22}	0.5 x 10^{-22}
NET (CMB)	μK s$^{-1/2}$	13.6	---
NEQ (CMB)	μK s$^{-1/2}$	19.2	5.6

Sensitivity 70 nK per 1° x 1° pixel

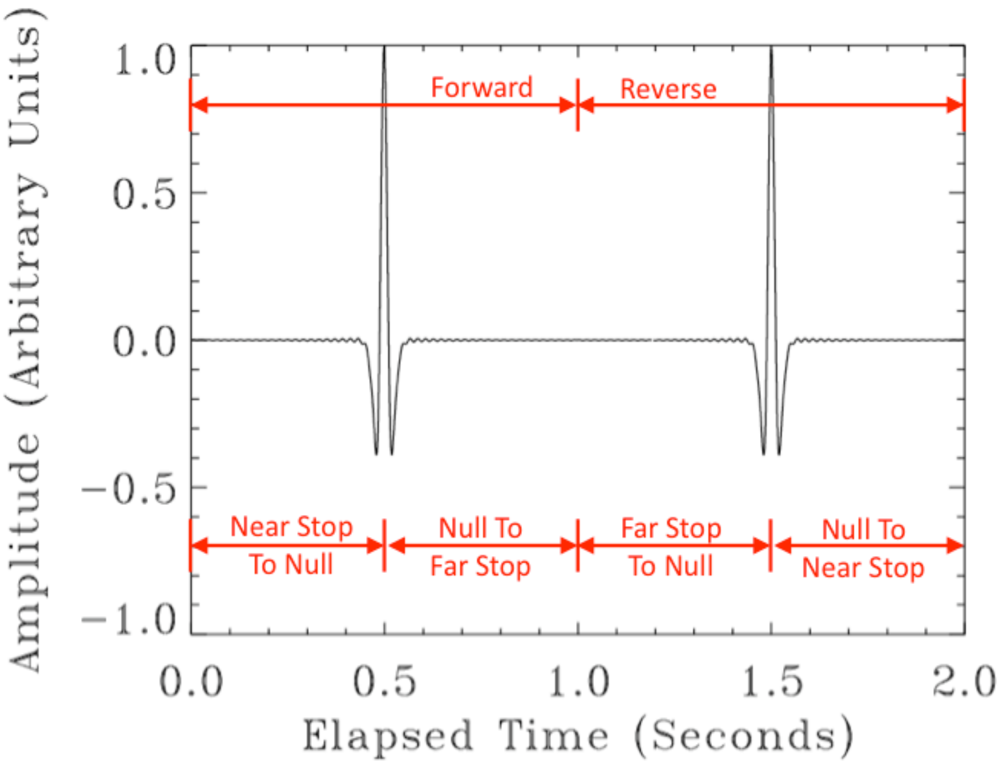
30x collecting area as Planck bolometers



PIXIE polarization-sensitive bolometer

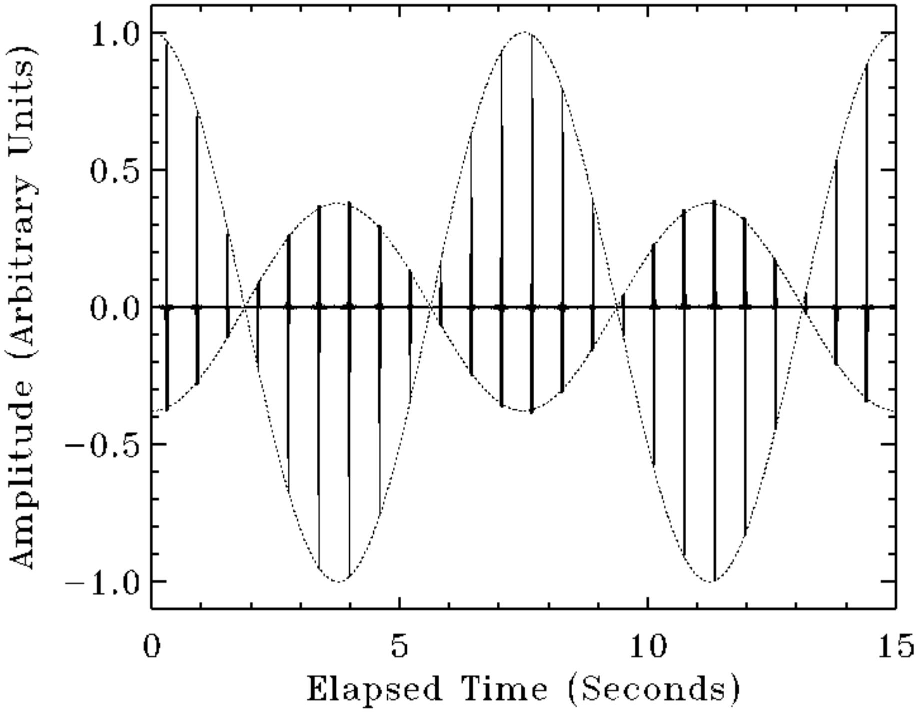
Systematics: Error Control The Easy Way

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 Error Budget

Efficient suppression of potential systematic errors

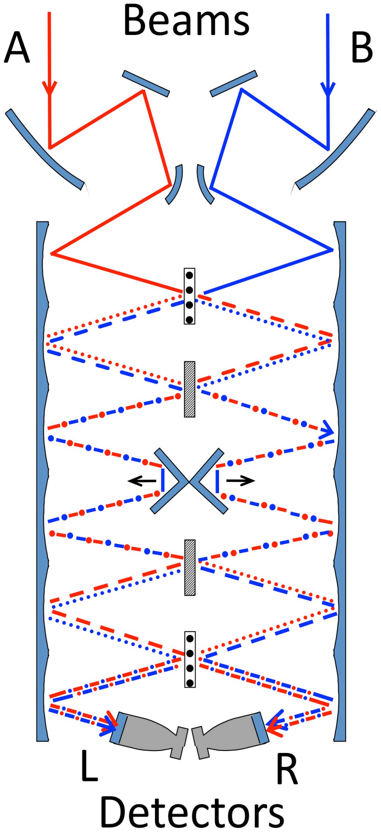
Symmetry	**Mitigates**
x vs y Polarization	Beam/pointing
Left vs Right Detector	Beam/pointing
A vs B Beam	Differential loss
Real vs Imaginary FFT	1/f noise, relative gain

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

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

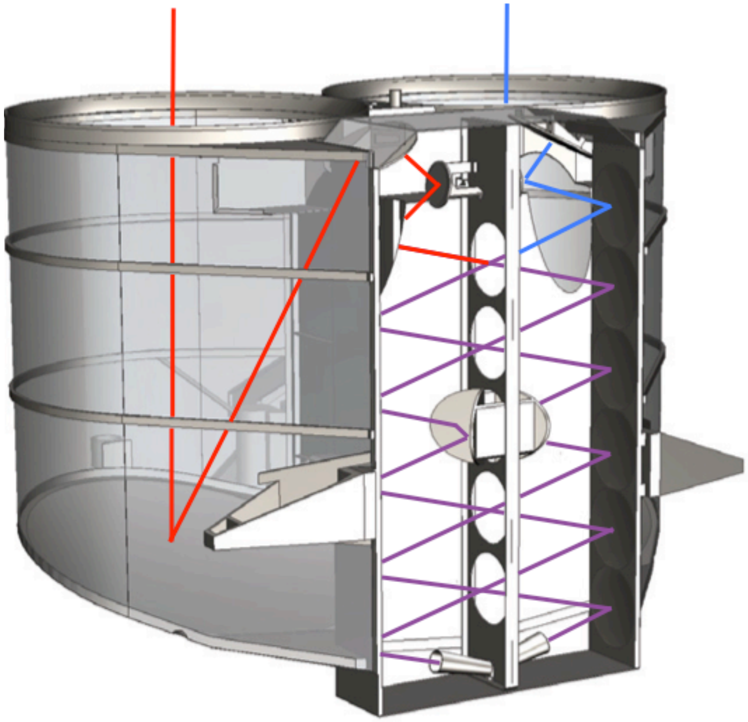
$$P_{Rx} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{Ax}^2 - E_{By}^2\right)\cos(z\omega/c)\ d\omega$$

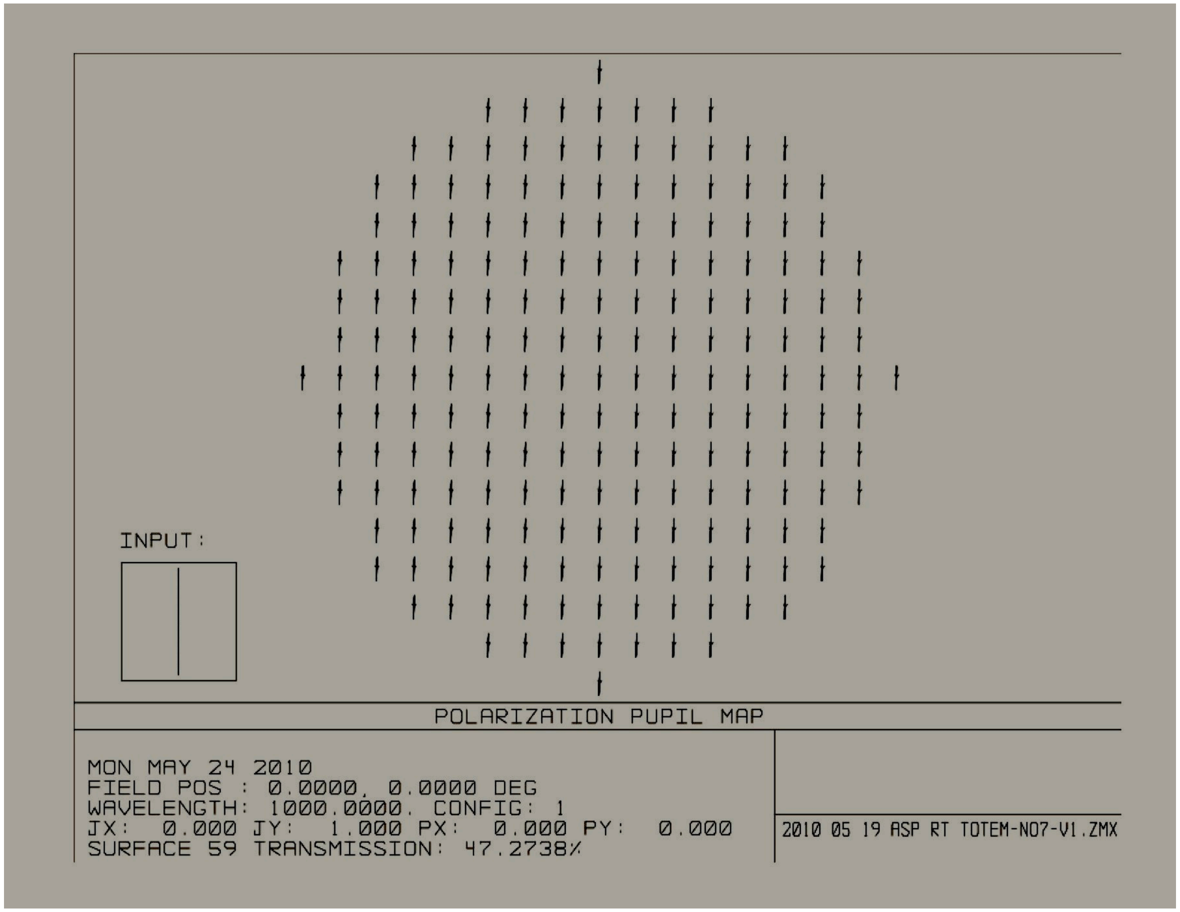
$$P_{Ry} = \frac{1}{2}\int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Ay}^2 - E_{Bx}^2\right)\cos(z\omega/c)\ d\omega$$



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

PIXIE Beam Pattern



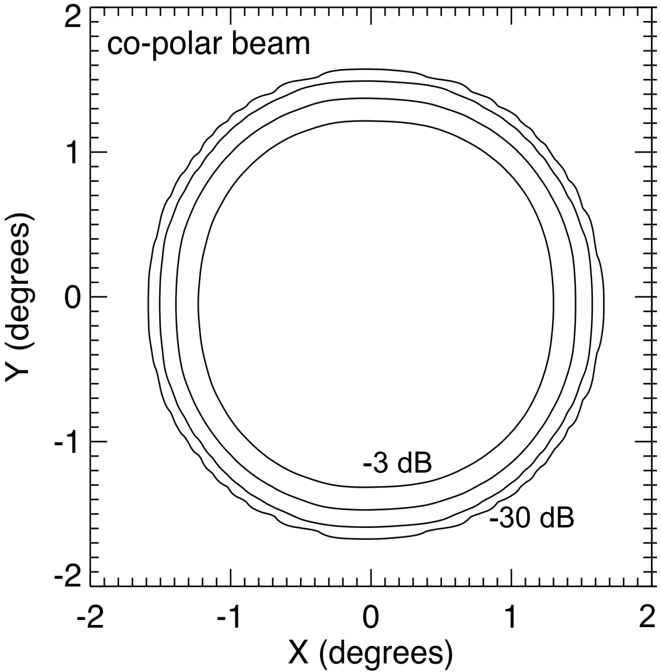


```
INPUT:

POLARIZATION PUPIL MAP

MON MAY 24 2010
FIELD POS : 0.0000, 0.0000 DEG
WAVELENGTH: 1000.0000, CONFIG: 1
JX:  0.000 JY:  1.000 PX:  0.000 PY:  0.000
SURFACE 59 TRANSMISSION: 47.2738%

2010 05 19 ASP RT TOTEM-N07-V1.ZMX
```



Co-Polar Beam (T → B Systematics)

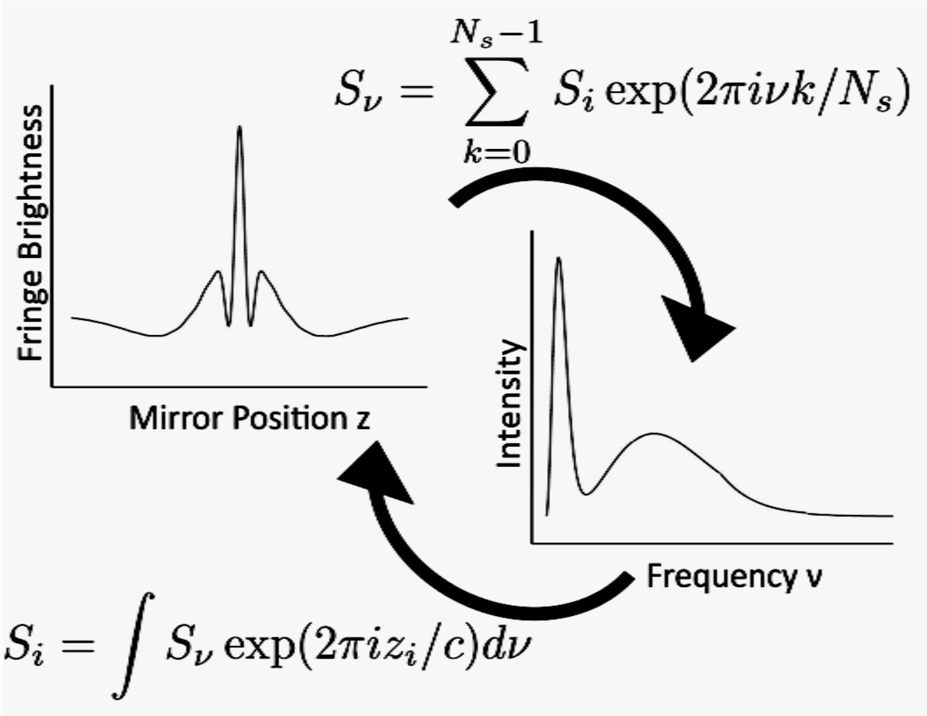
Round: m=2 ellipticity < 10^{-3} of m=0 monopole power

Symmetric: A/B difference appears only at second order

Small: Systematic error < 3 nK in sky maps

Foregrounds: Multiple Channels the Easy Way

Fourier Transform Spectrometer



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

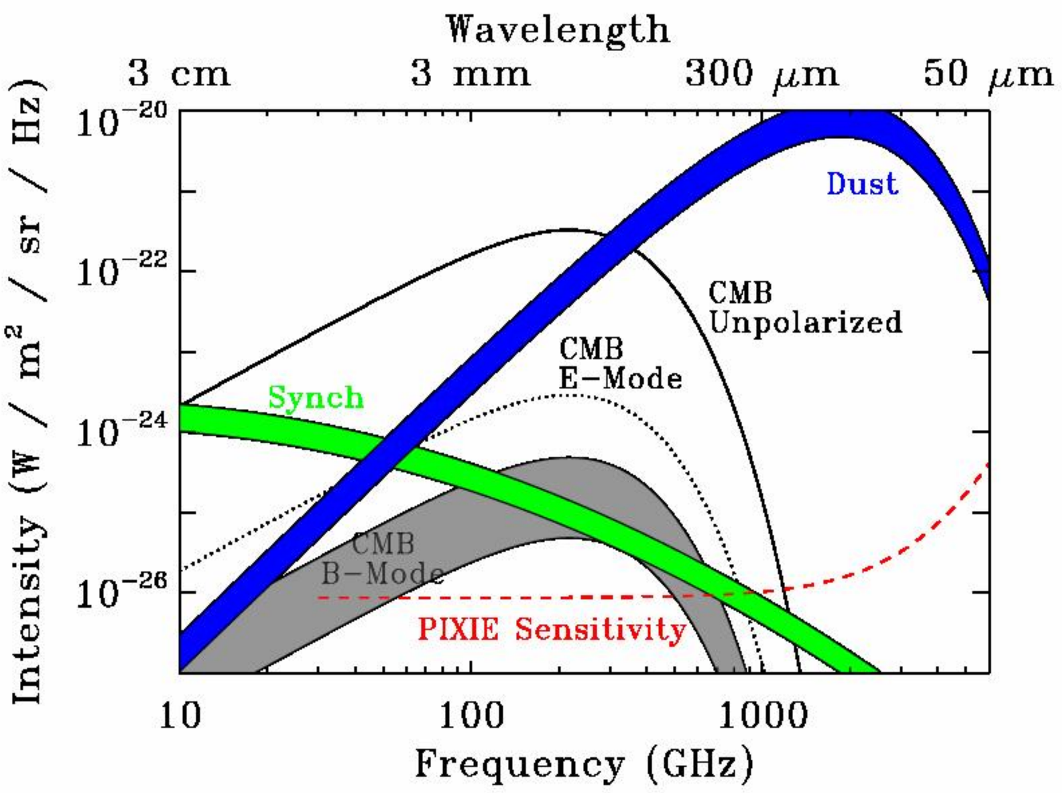
$$S_i = \int S_\nu \exp(2\pi i z_i / c) d\nu$$

Frequency Spectrum vs Fringe Pattern

- Largest optical phase delay (1 cm) sets channel width
- Number of samples (1024) sets number of channels
- Apodization sets channel bandpass

PIXIE: 512 channels each 15 GHz wide

- Lowest effective channel = 30 GHz (1 cm)
- Highest effective channel ~ 6 THz (50 μm)

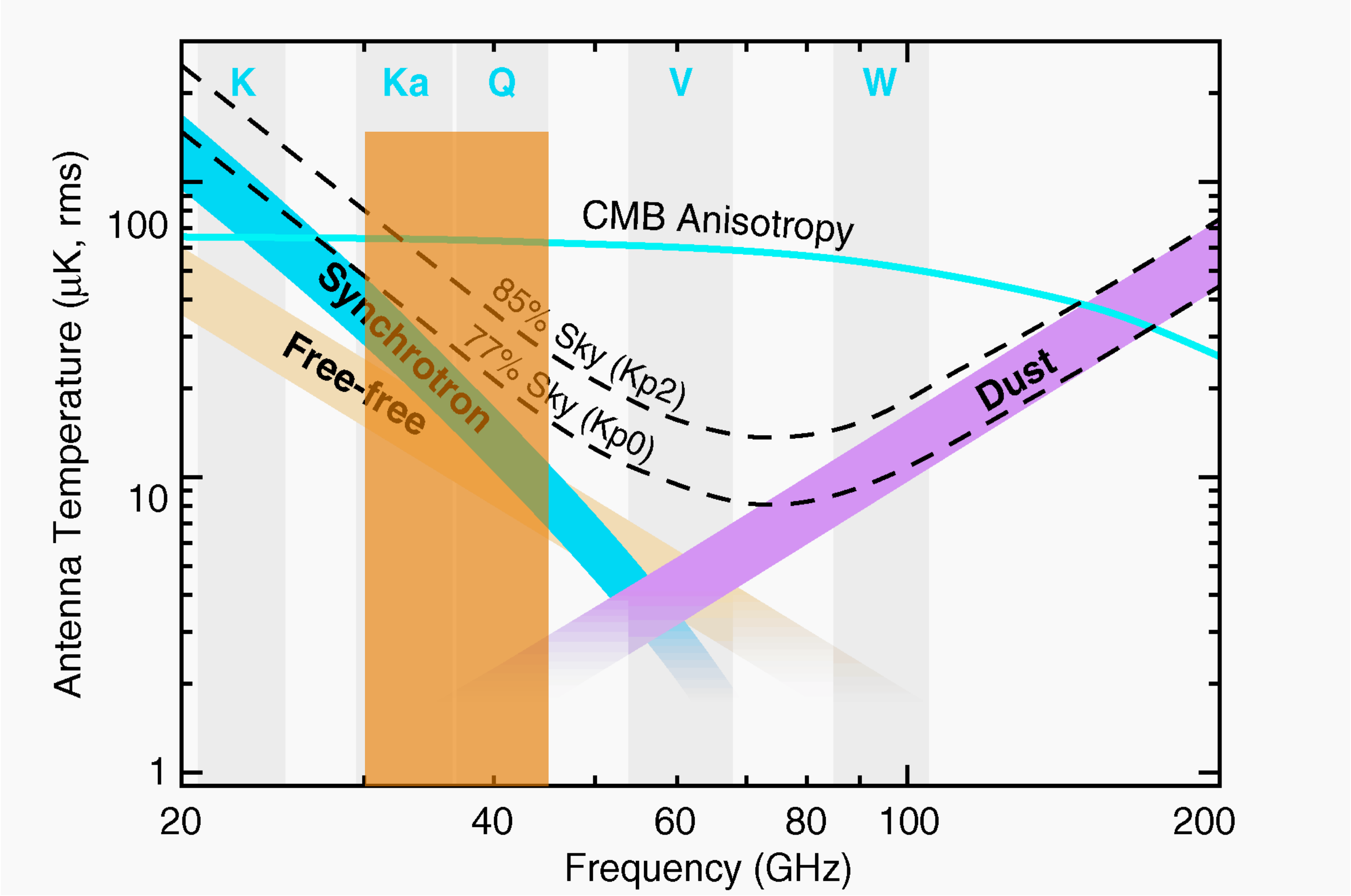


Pixel-by-pixel foreground subtraction

- 400 effective channels to fit ~15 free parameters
- Spectral index uncertainty ±0.001 in each pixel
- Continuum spectra: curvature, multiple components, ...

Only 2% "noise penalty" for foreground subtraction

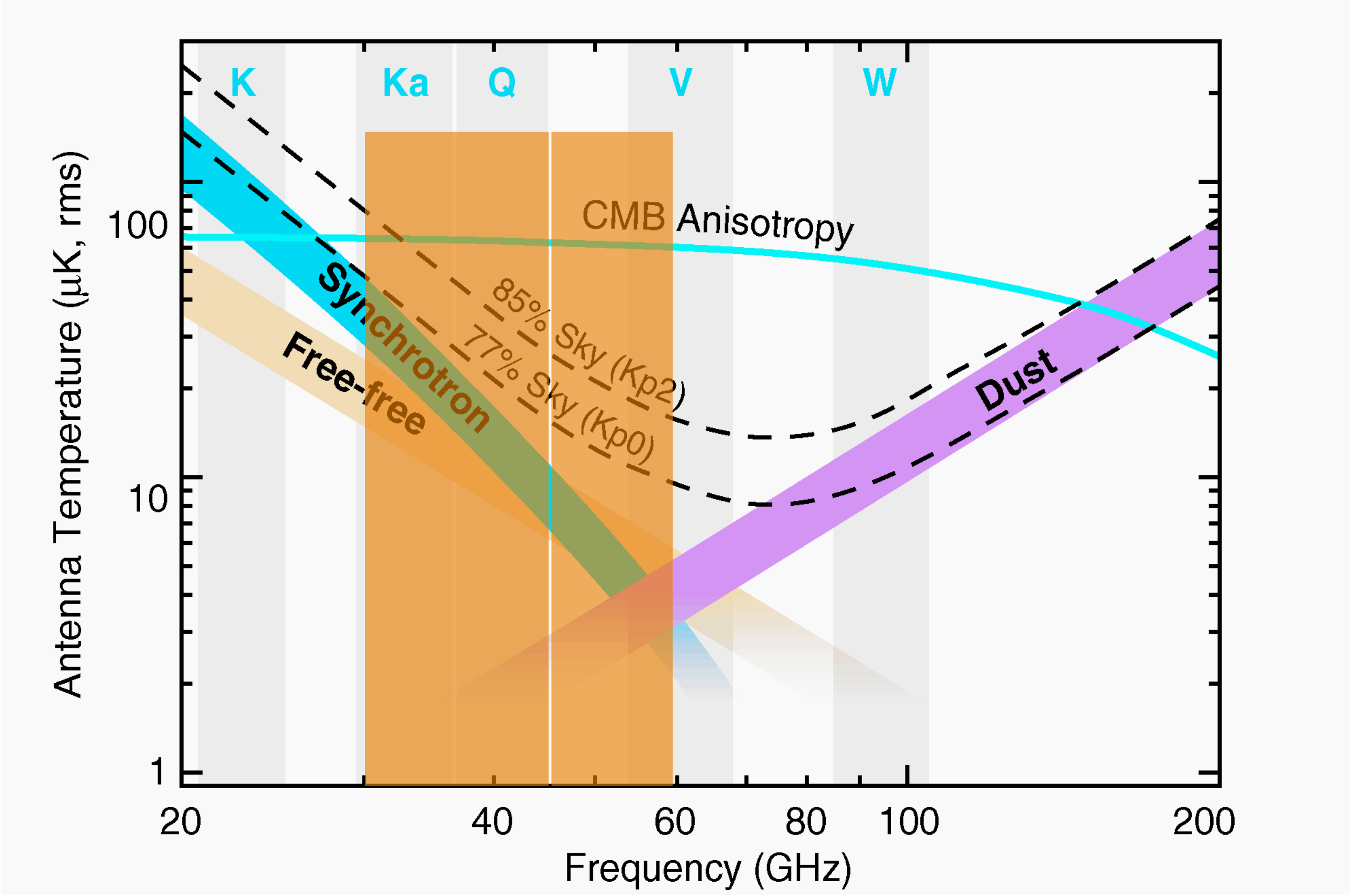
PIXIE vs HKEPol



Synthesized Channels:

N x 15 GHz

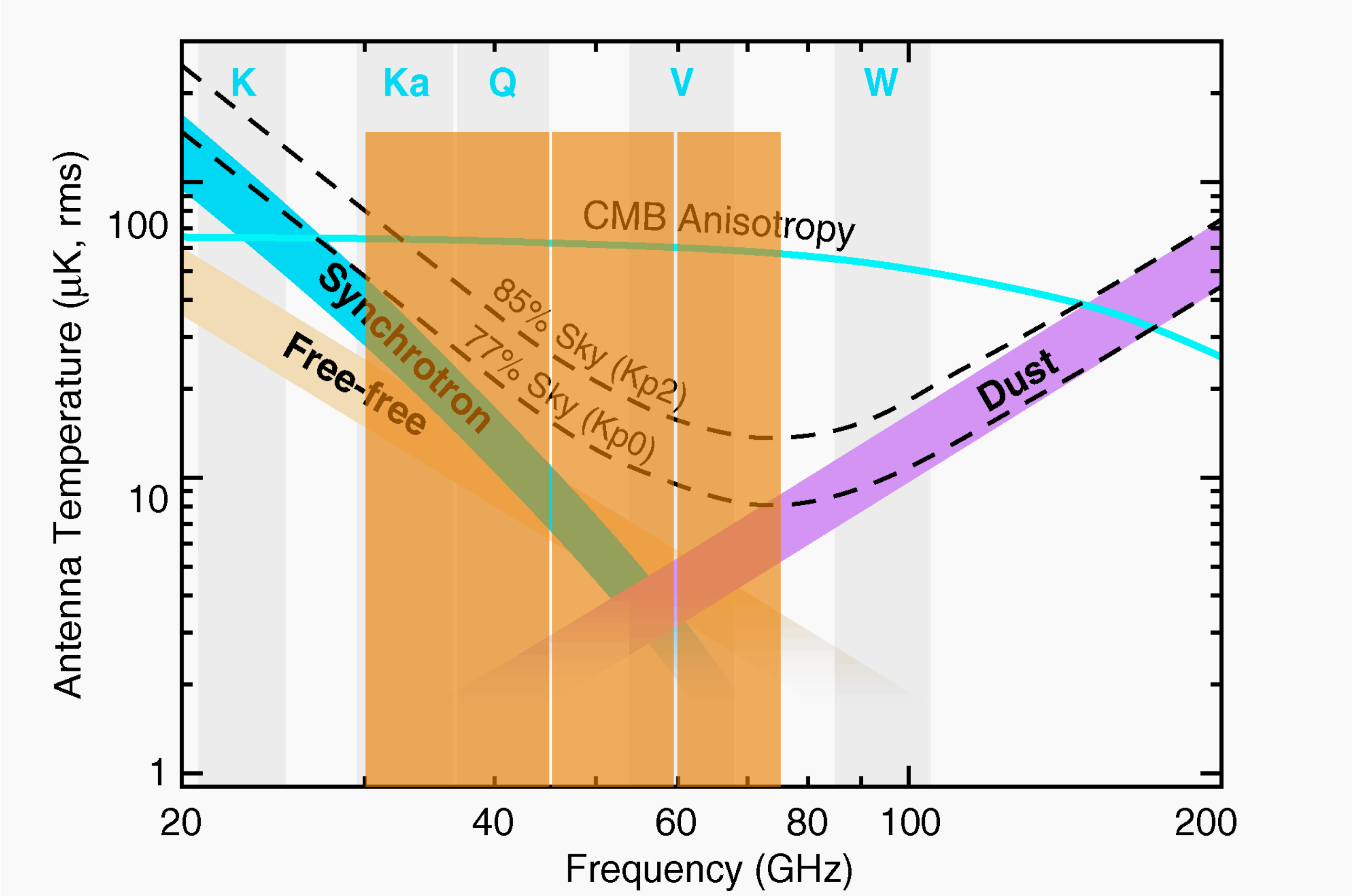
PIXIE vs HKEPol



Synthesized Channels:

N x 15 GHz

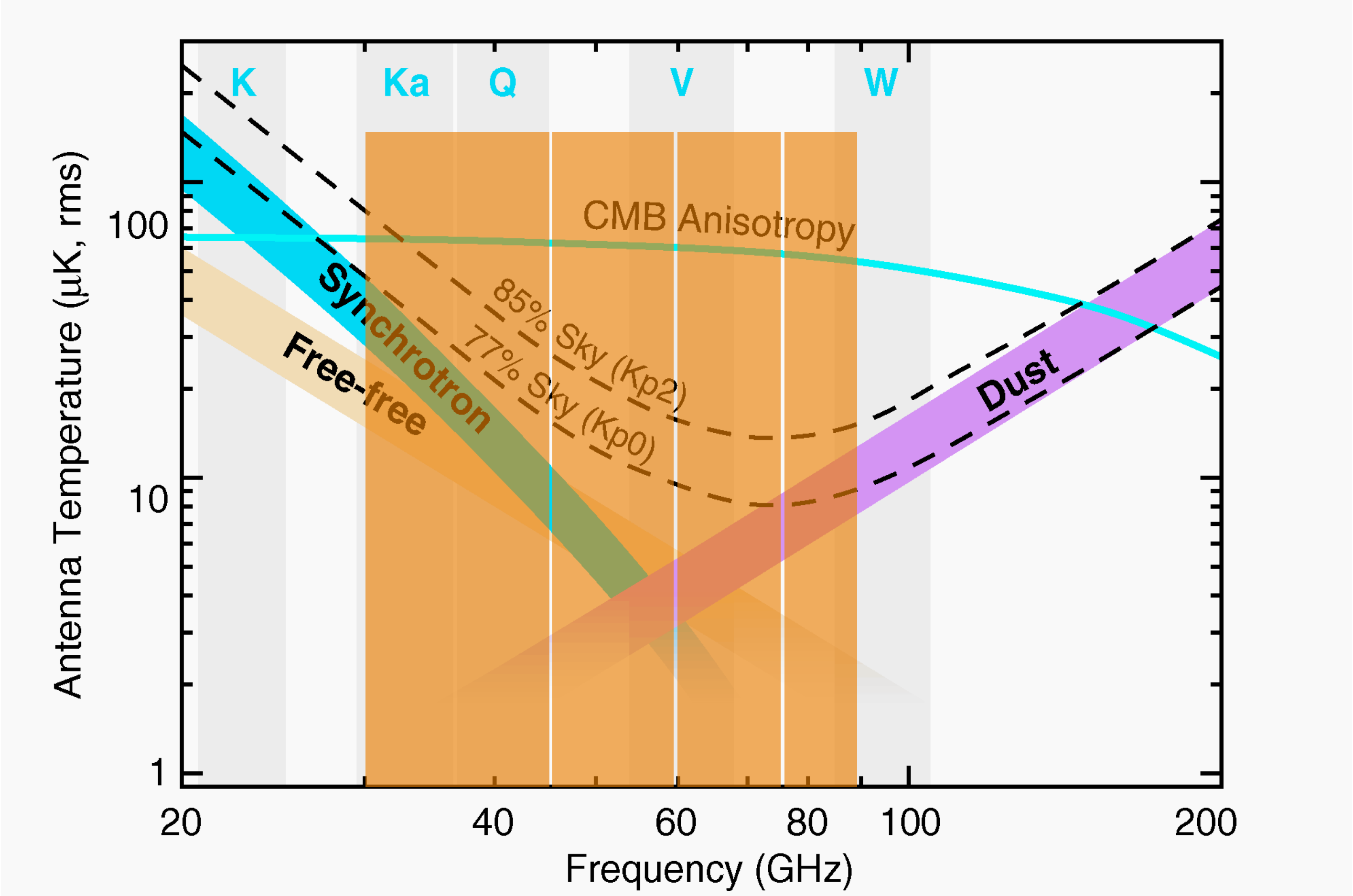
PIXIE vs HKEPol



Synthesized Channels:

N x 15 GHz

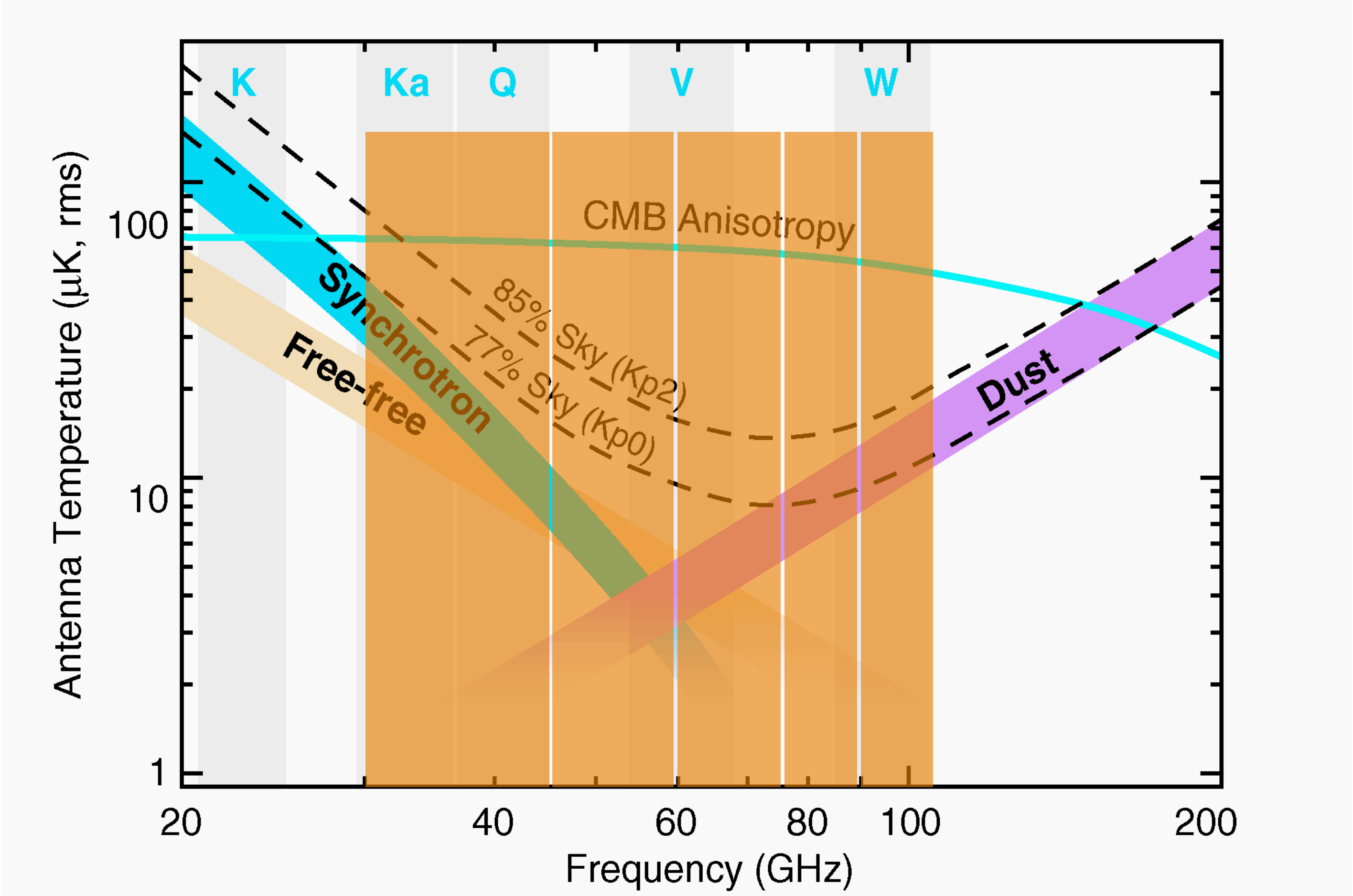
PIXIE vs HKEPol



Synthesized Channels:

N x 15 GHz

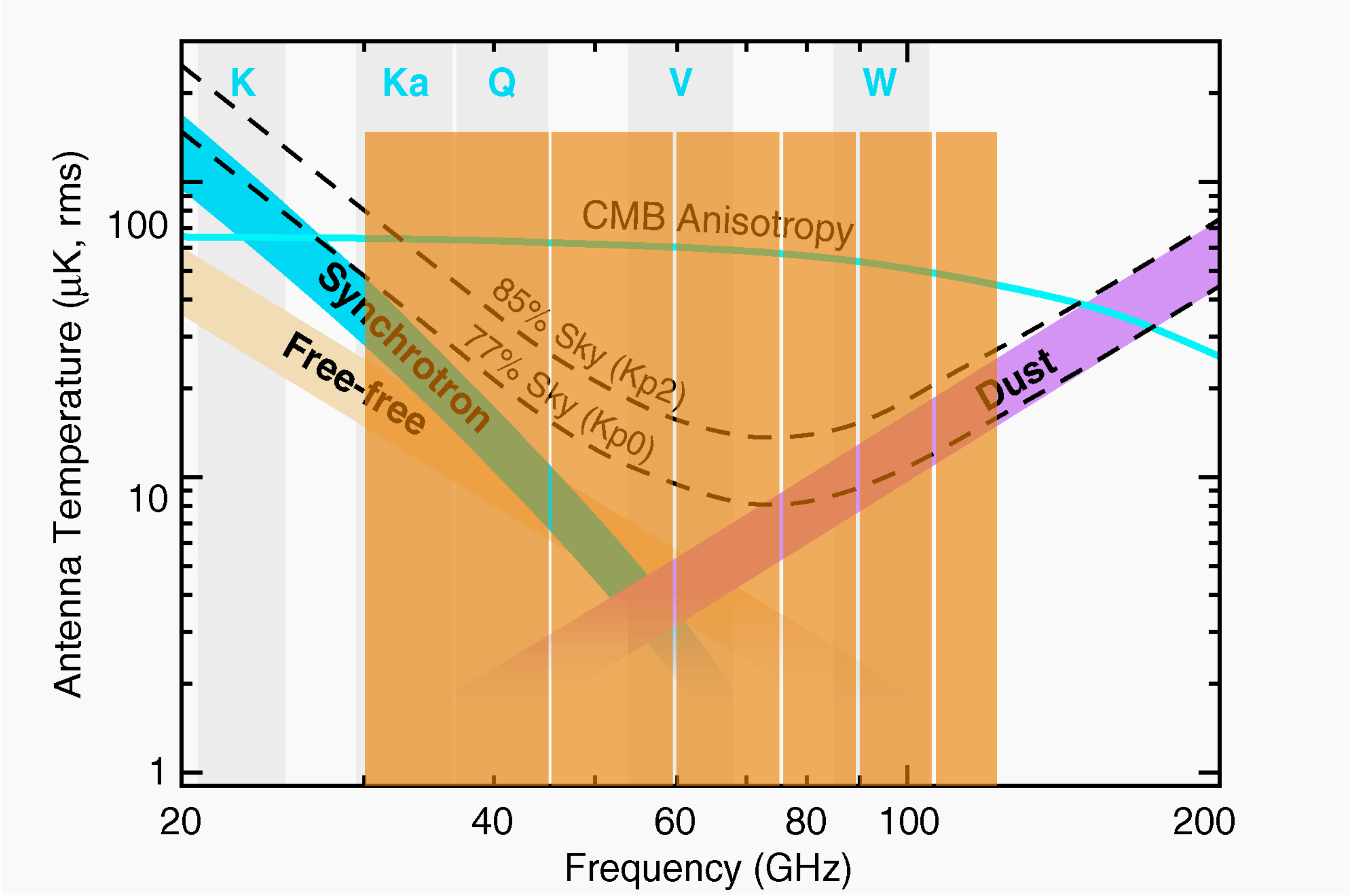
PIXIE vs HKEPol



Synthesized Channels:

N x 15 GHz

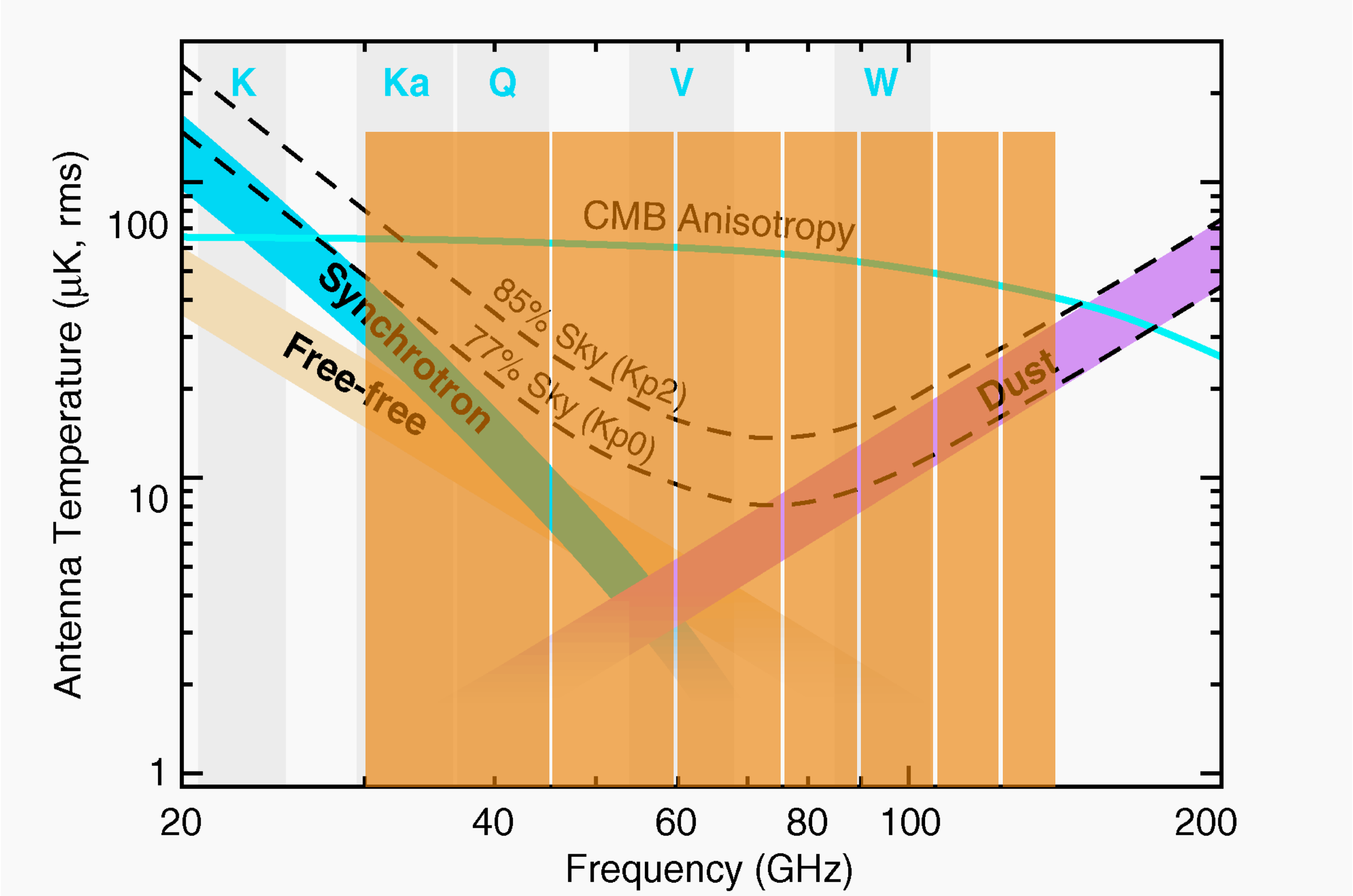
PIXIE vs HKEPol



Synthesized Channels:

N x 15 GHz

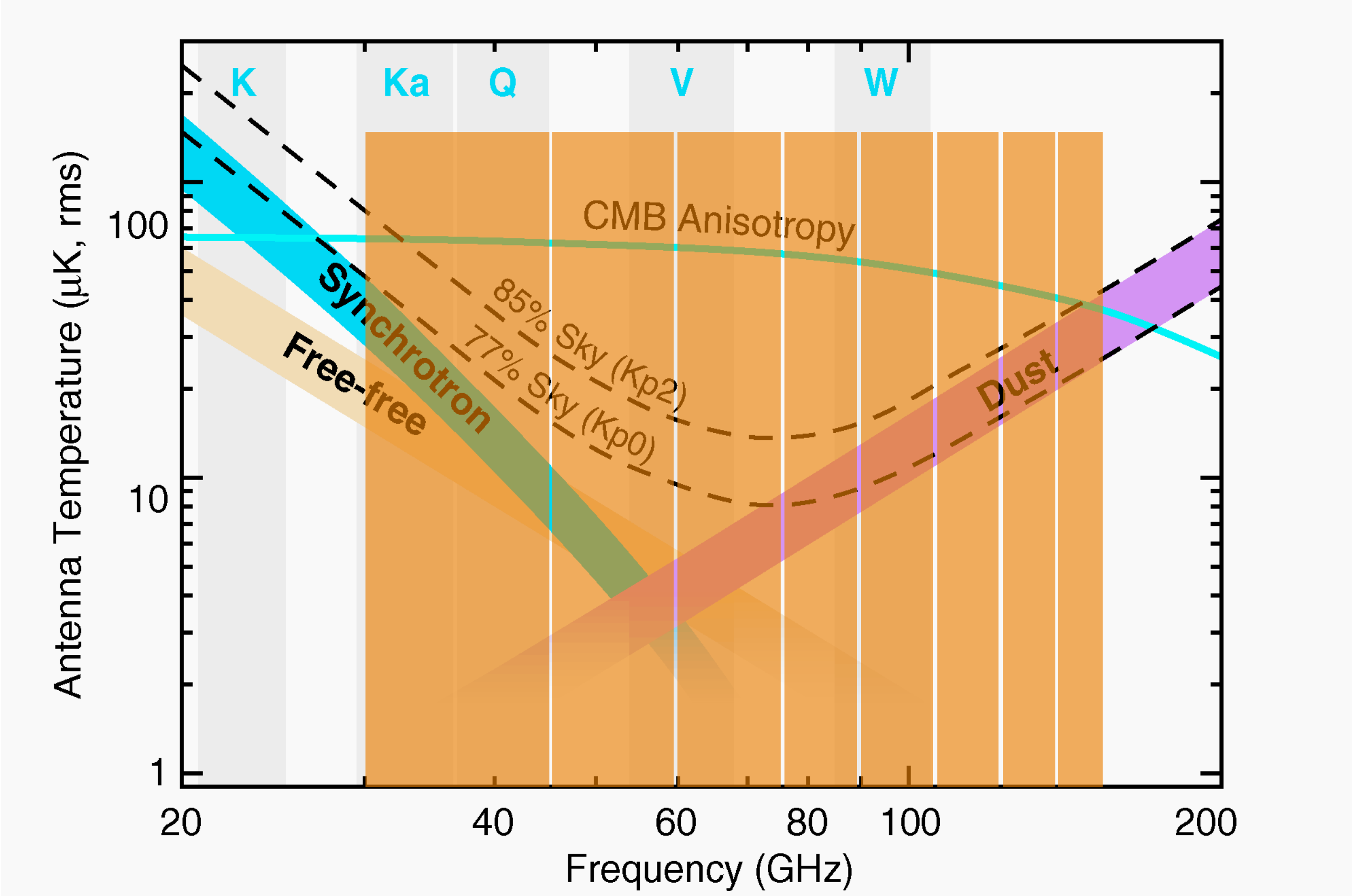
PIXIE vs HKEPol



Synthesized Channels:

N x 15 GHz

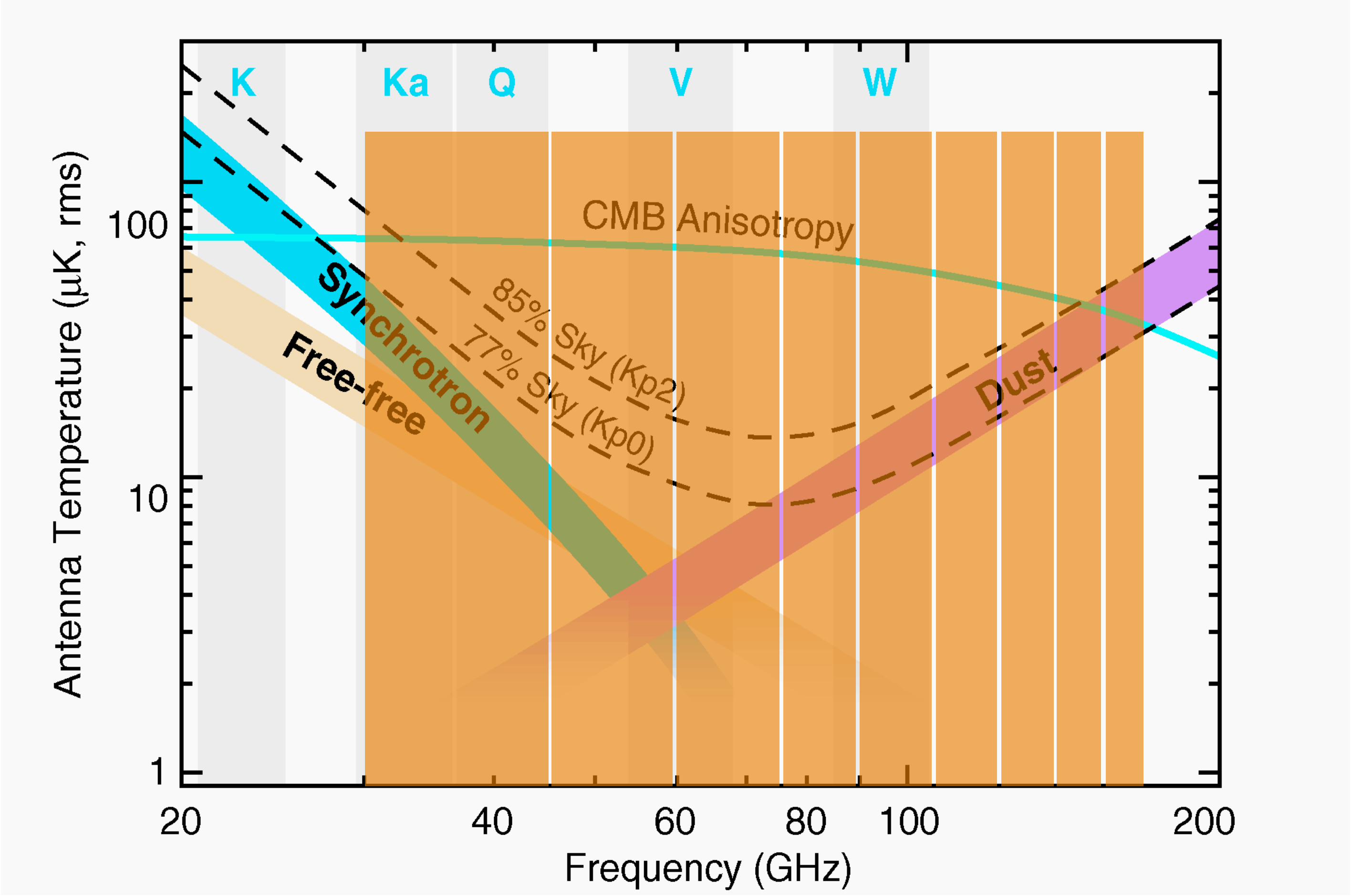
PIXIE vs HKEPol



Synthesized Channels:

N x 15 GHz

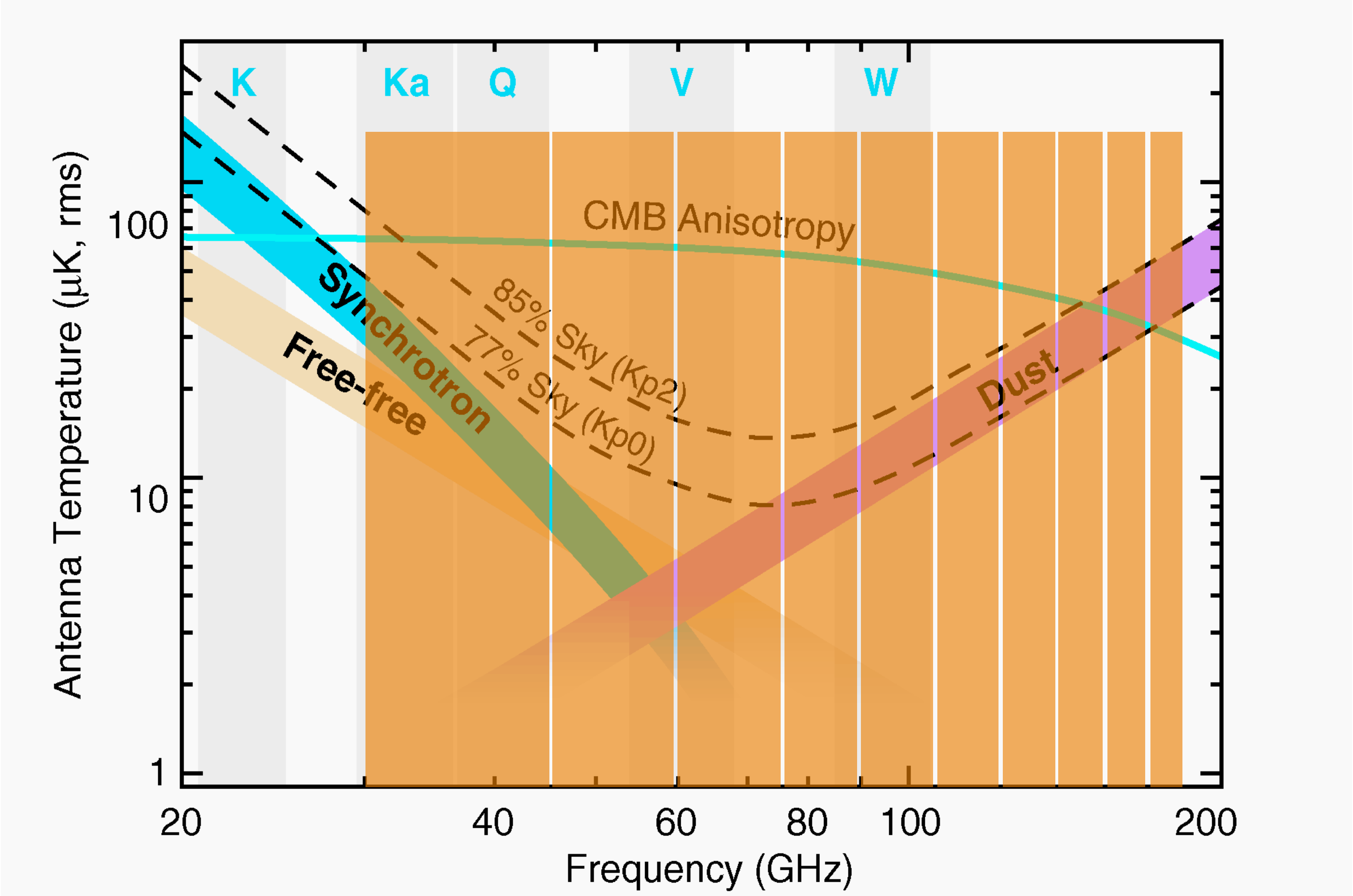
PIXIE vs HKEPol



Synthesized Channels:

N x 15 GHz

PIXIE vs HKEPol

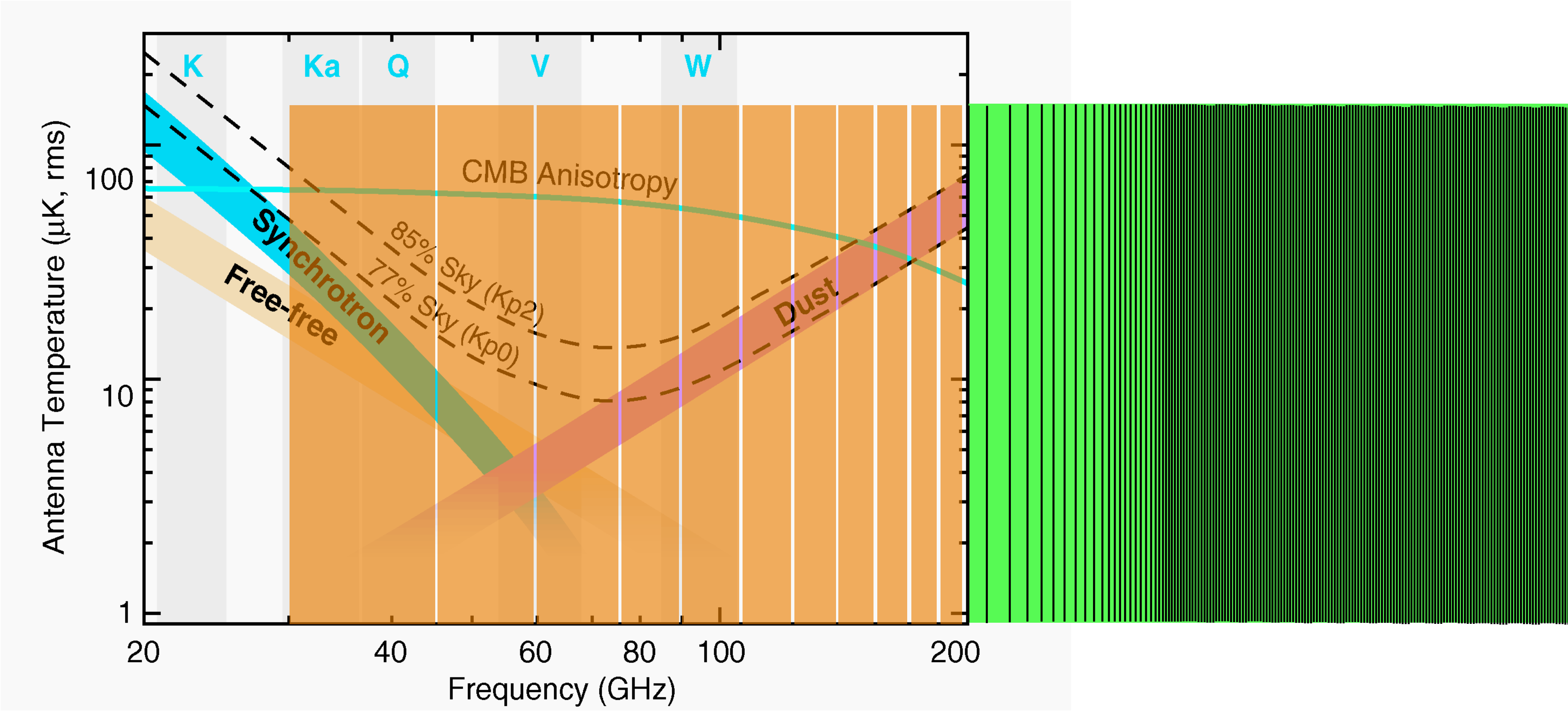


10 bands 30 GHz through 200 GHz ...

Synthesized Channels:

N x 15 GHz

PIXIE vs HKEPol

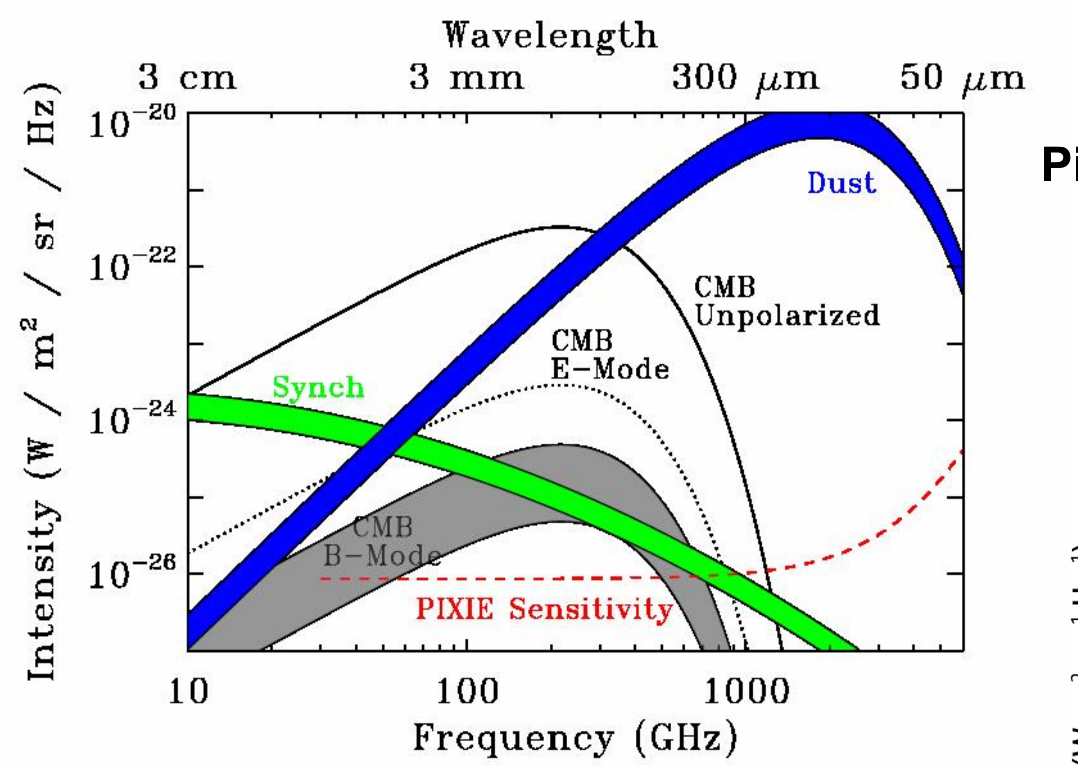


10 bands 30 GHz through 200 GHz ... **PLUS** 390 more bands to 6 THz

FTS gets extra bands for free: why not use them?

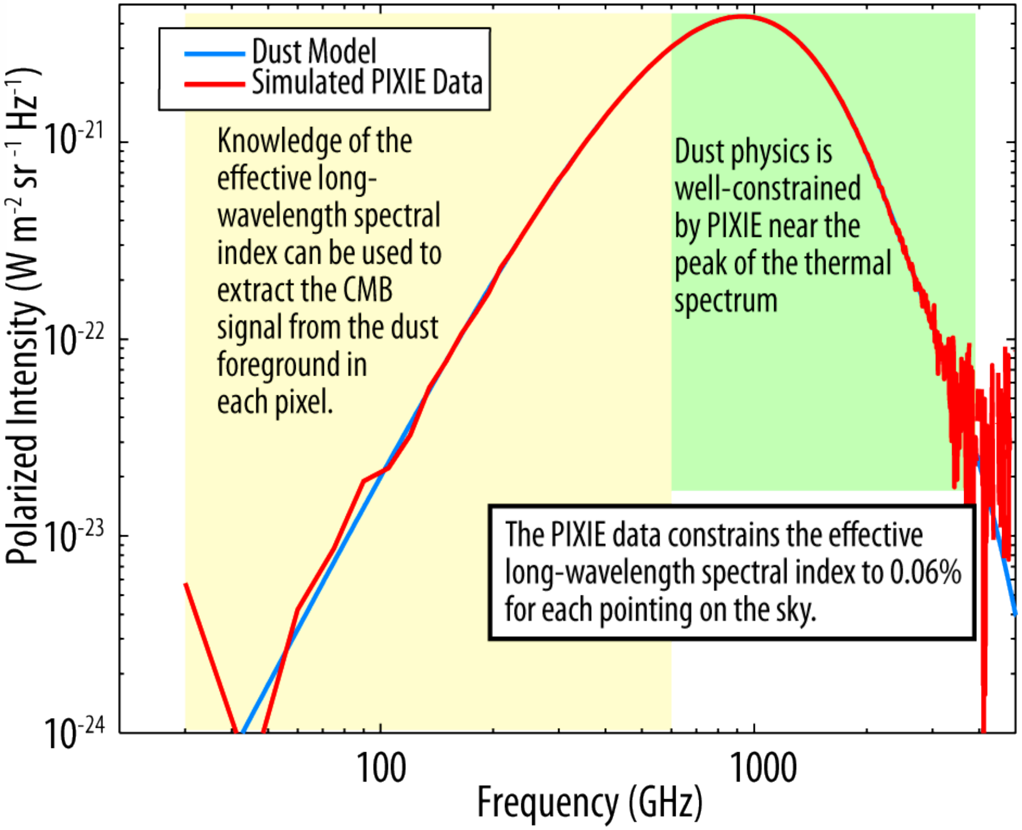
Foreground Science: Interstellar Dust

Science from high-frequency channels informs low-frequency fitting



Pixel-by-pixel dust characterization

- 400 channels to fit models of far-IR dust emission
- Spectral index uncertainty ±0.001 in each pixel
- Dust physics for foreground subtraction



Knowledge of the effective long-wavelength spectral index can be used to extract the CMB signal from the dust foreground in each pixel.

Dust physics is well-constrained by PIXIE near the peak of the thermal spectrum

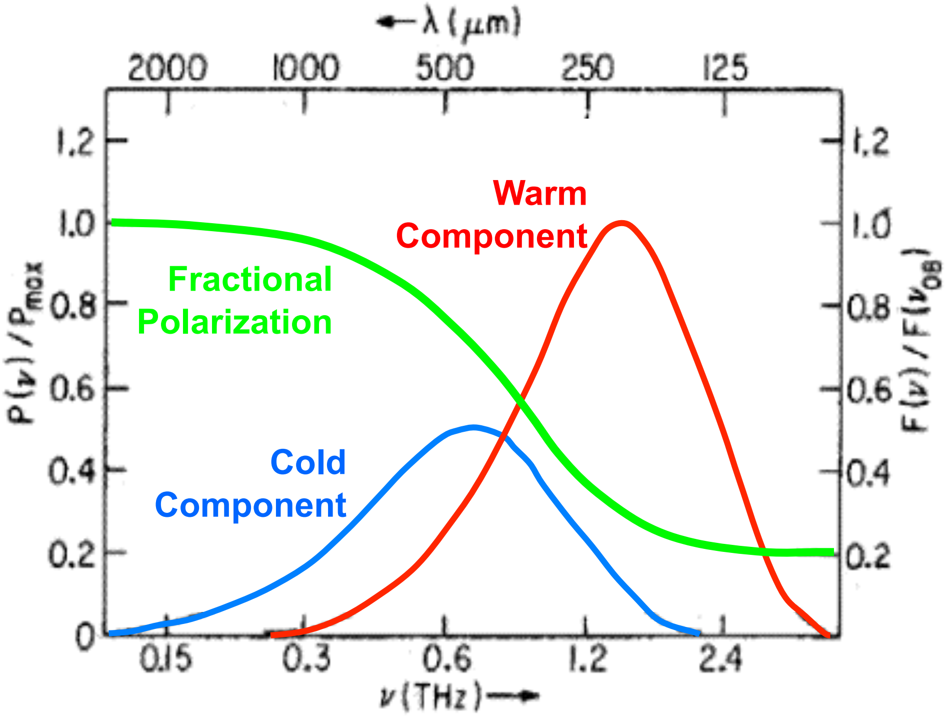
The PIXIE data constrains the effective long-wavelength spectral index to 0.06% for each pointing on the sky.

One person's foreground is another person's science

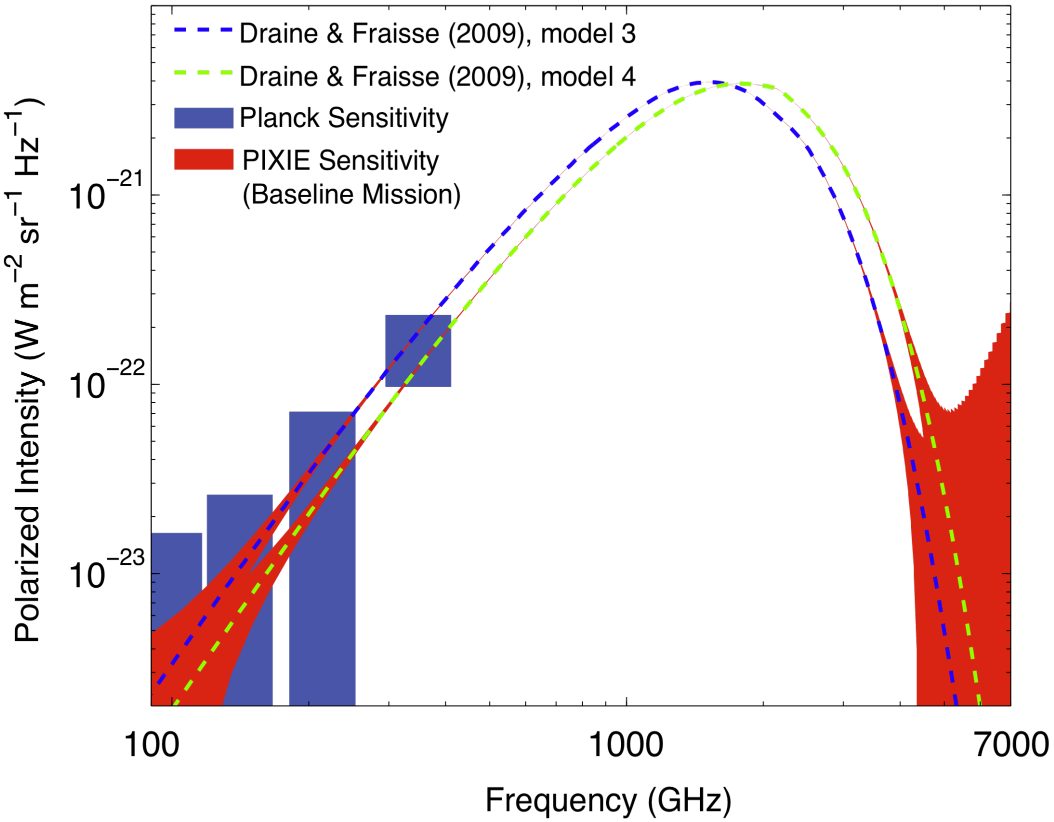
Dust Parameters (Modified Greybody)

Polarization depends on composition
  - Silicate: Colder, More polarized
  - Carbonaceous: Warmer, Less polarized

Sensitive probe of dust composition



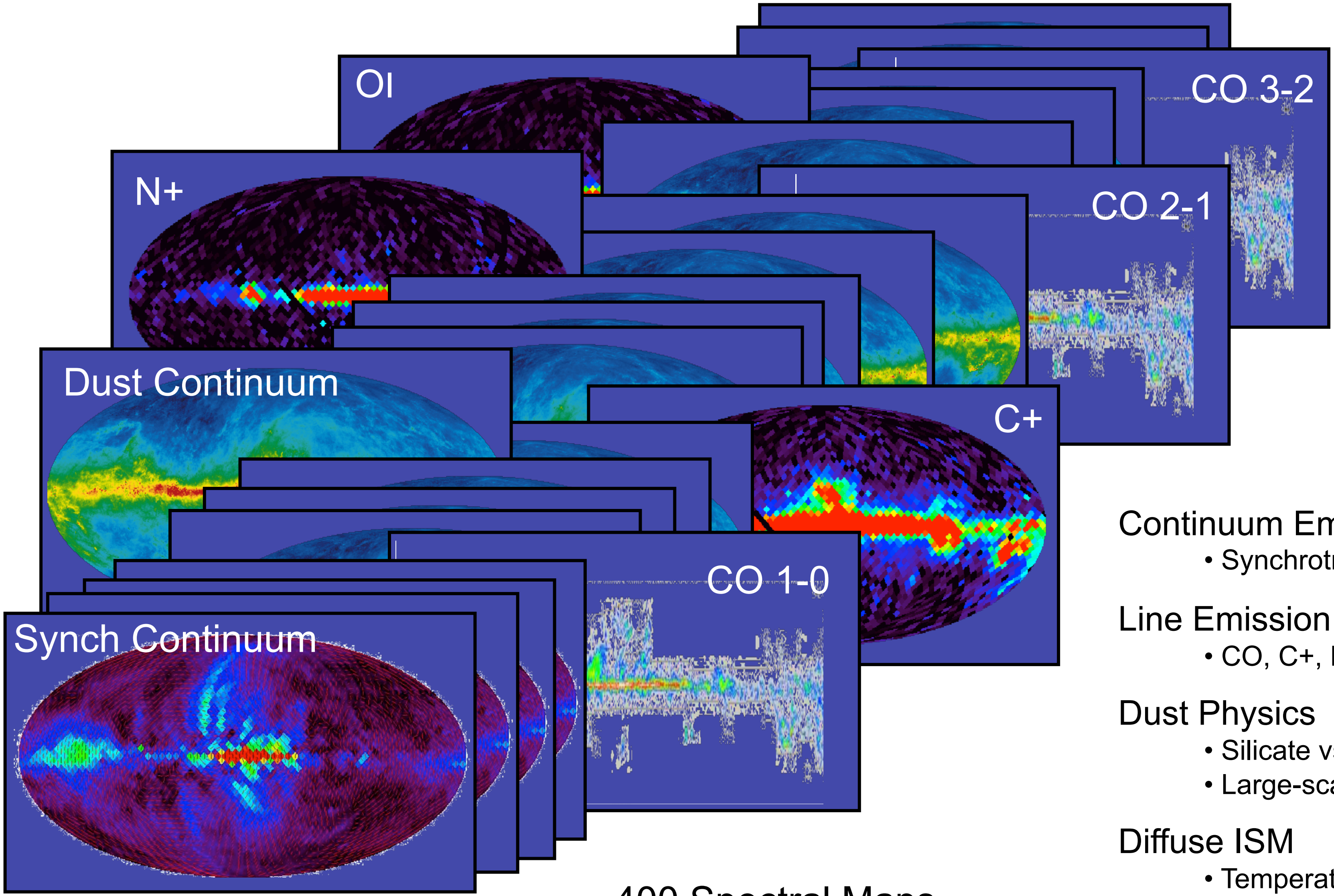
Hildebrand & Kirby 2004



PIXIE data from 30 GHz to 6 THz
  - Temperature(s)
  - Fractional polarization
  - Chemical composition

Constrain dust properties for each line of sight

PIXIE and Interstellar Medium



Continuum Emission
  - Synchrotron, Dust

Line Emission
  - CO, C+, N+, O, …

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

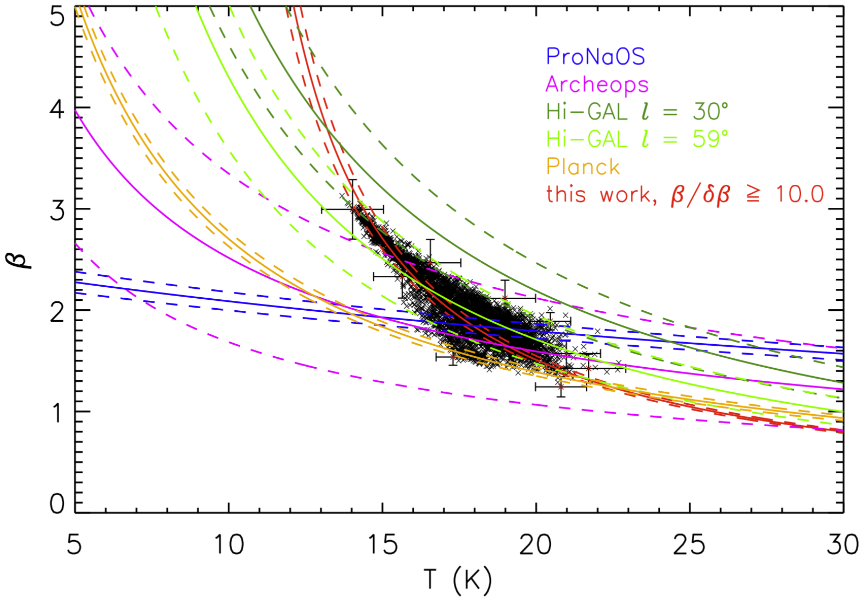
Diffuse ISM
  - Temperature, Density
  - Energy Balance
  - Metalicity

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

Extremely Rich Data Set!

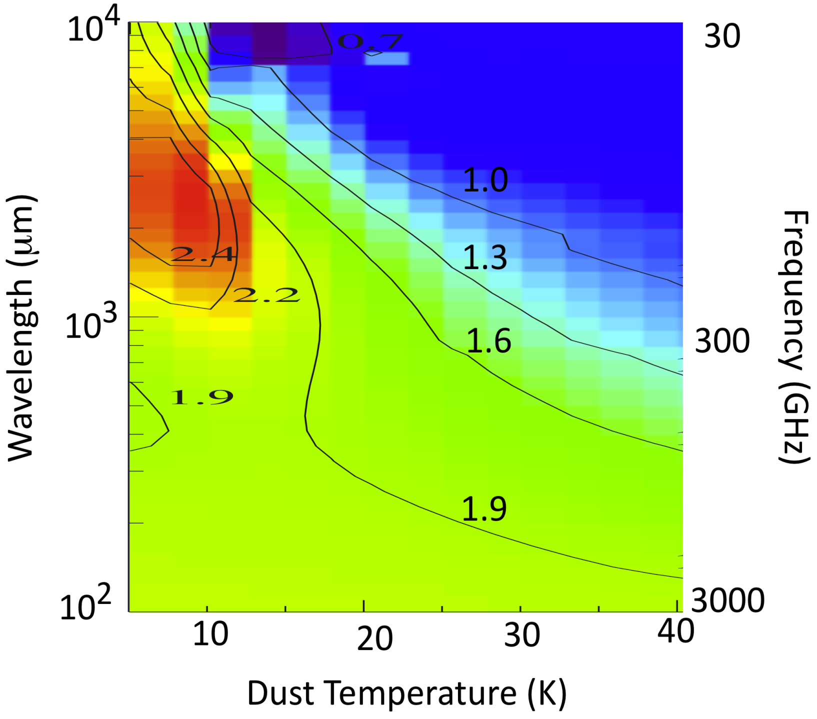
Parametric Dust Models

A Cautionary Tale



Empirical fits show correlation between T and β
Greybody model, pixel-to-pixel variation

Liang et al. 2012, arXiv:1201.0060



Solid-state model of disordered medium
Two-level system predicts variation in β

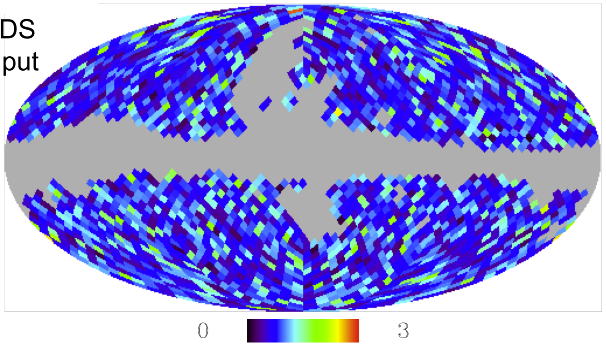
- Steeper β for colder T at fixed frequency
- Flatter β for lower freq at fixed temperature

Meny et al. 2007, A&A, 468, 171
Paradis et al. 2011, A&A, 534, A118
Paradis et al. 2012, A&A, 537, A113

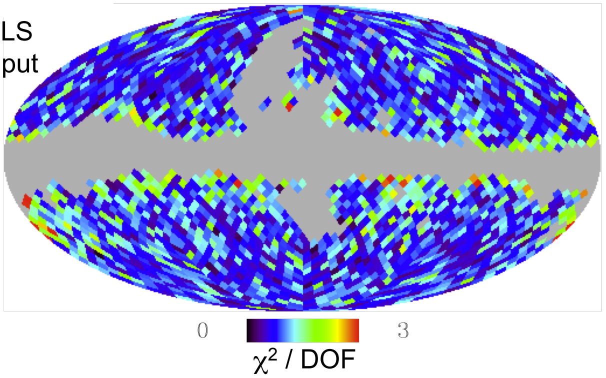
Is either model the correct description?
How can we tell?

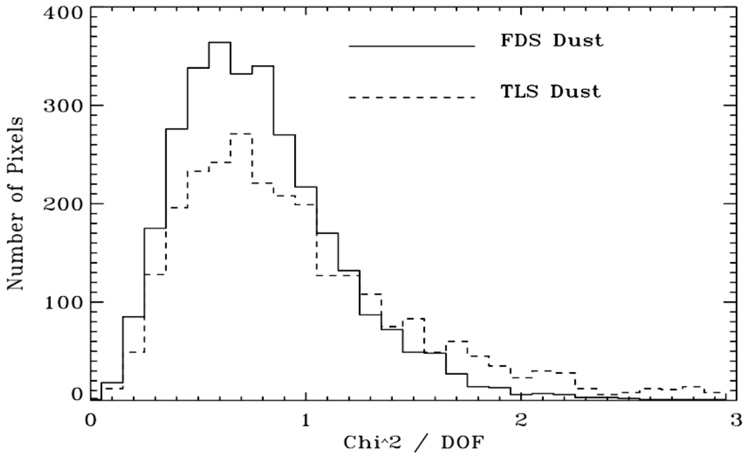
A Tale Of Two Models

FDS
Input



TLS
Input





Input Sky: CMB + Dust (either FDS or TLS) + Noise

9 EPIC Channels (30, 45, 70, 100, 150, 220, 340, 500, 850 GHz)

Fit 8 parameters to 18 maps using FDS model

- CMB amplitude (Q and U)
- Cold dust amplitude (Q and U) and spectral index
- Warm dust amplitude (Q and U) and spectral index

Compare Output to Input CMB Maps

A Tale Of Two Models

Input Sky: CMB + Dust (either FDS or TLS) + Noise

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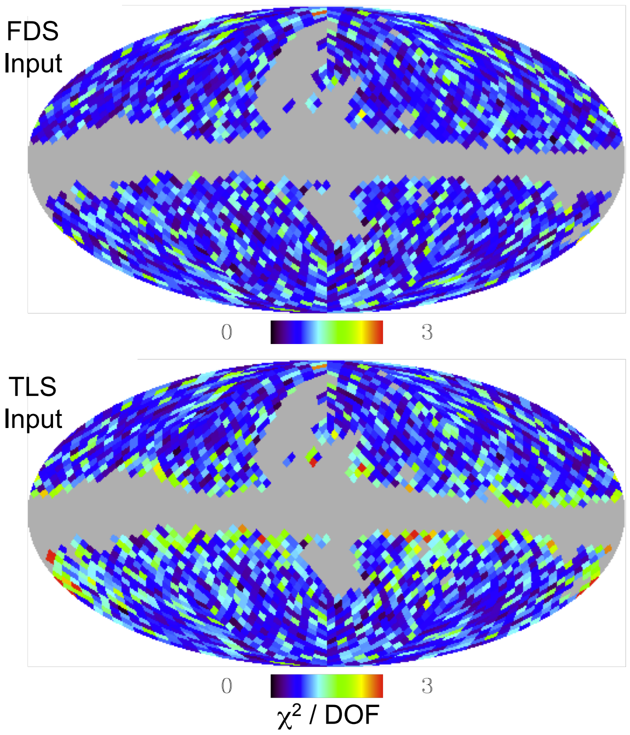
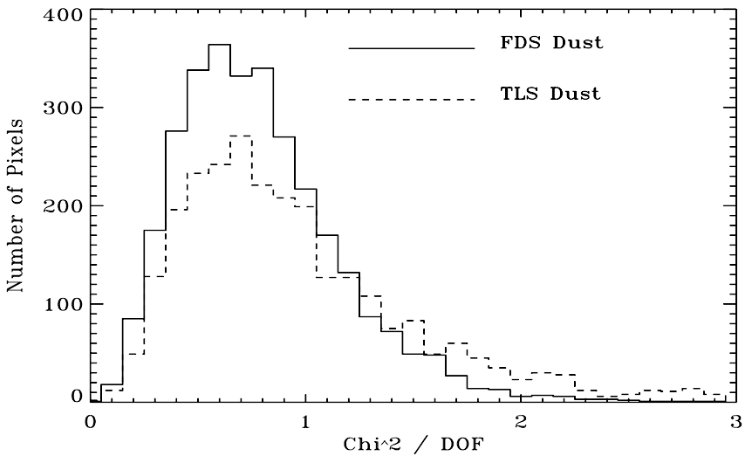
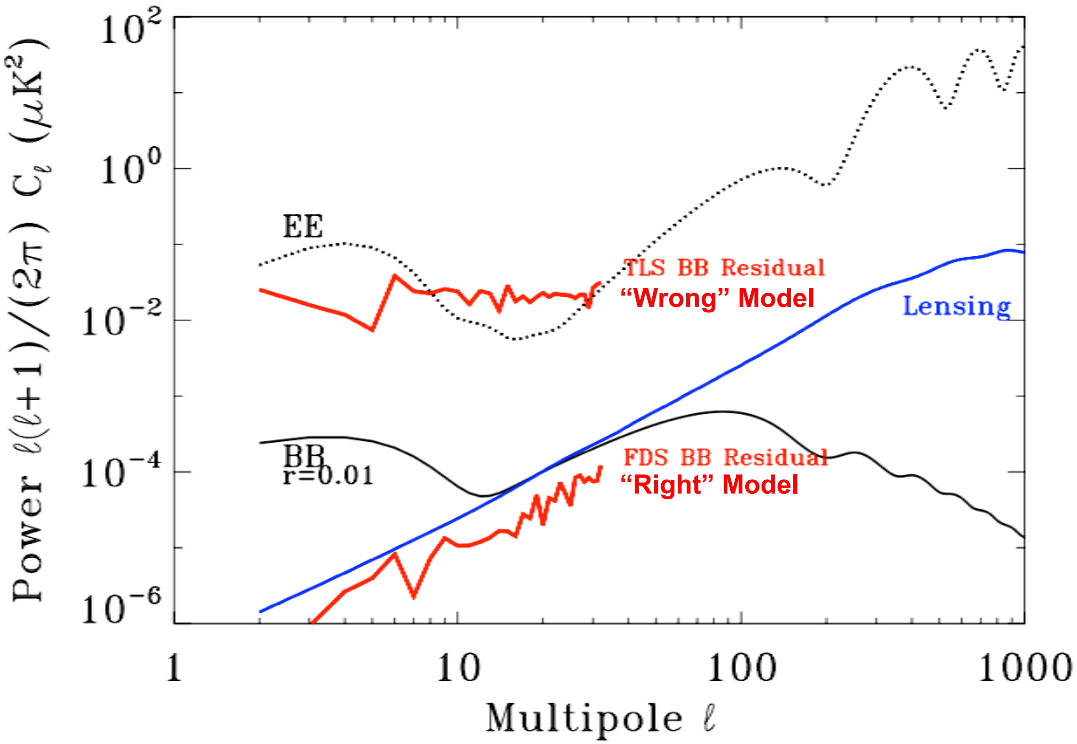






Same χ^2 But Different C_l: Worst-Case Scenario!

The Problem With Parametric Models

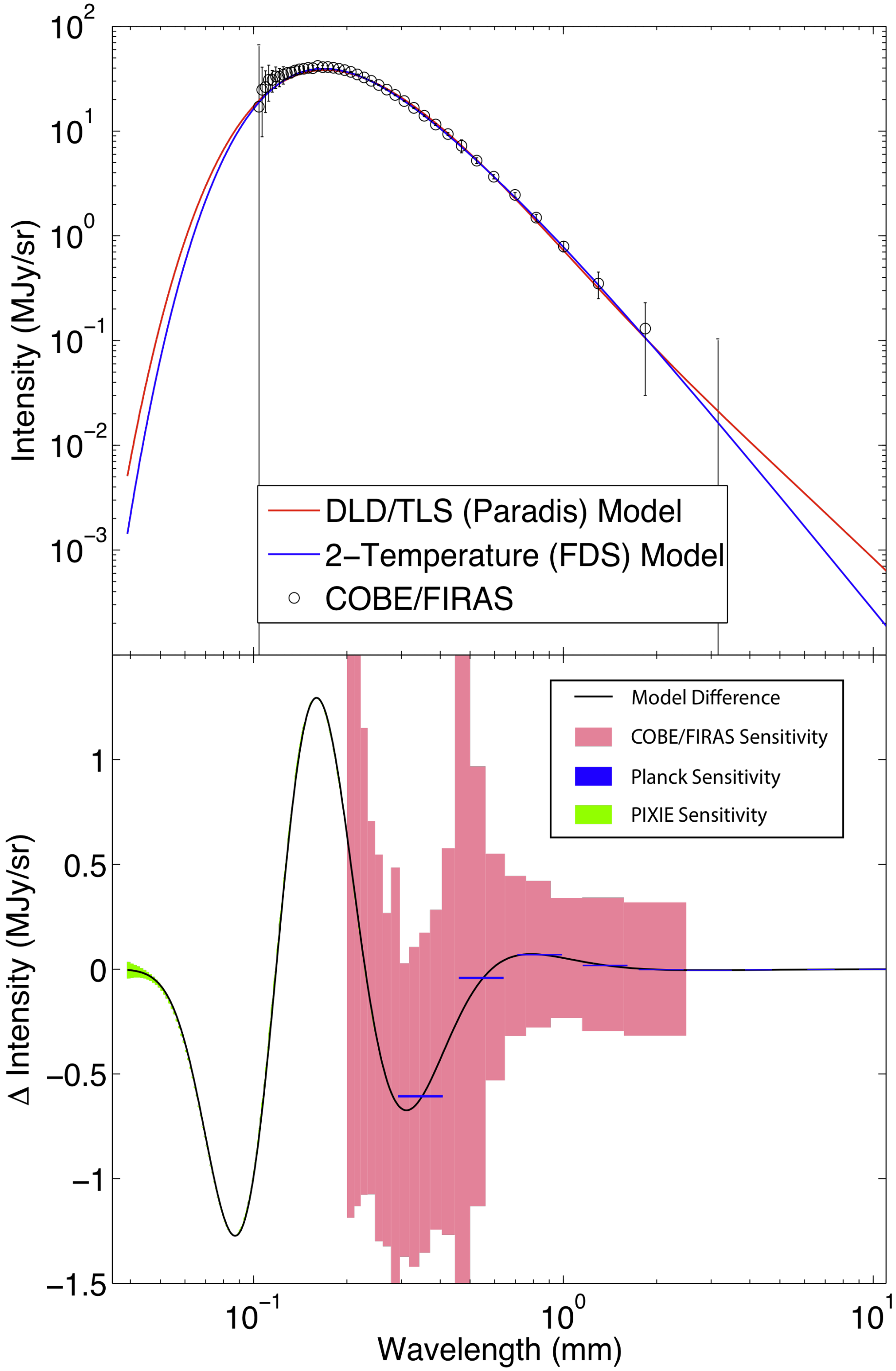
With seven free parameters,
you can fit a charging rhino.

Solution:

Don't try to think more
about the same data,

Think about getting more data!

PIXIE vs Dust Models

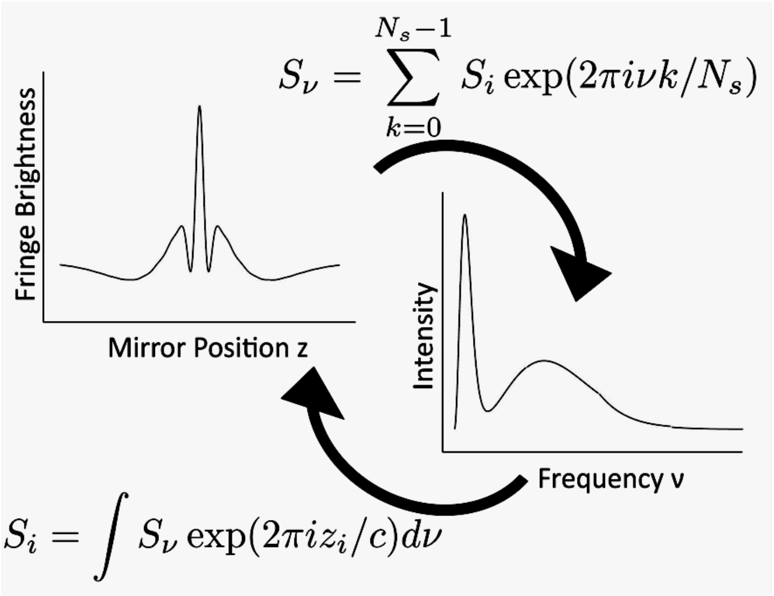


400 frequency channels from 30 GHz to 6 THz

- Distinguish FDS from TLS emission model
- Determine correct parametric model
- Use THz data to inform low-freq CMB fit

Get channels almost for free

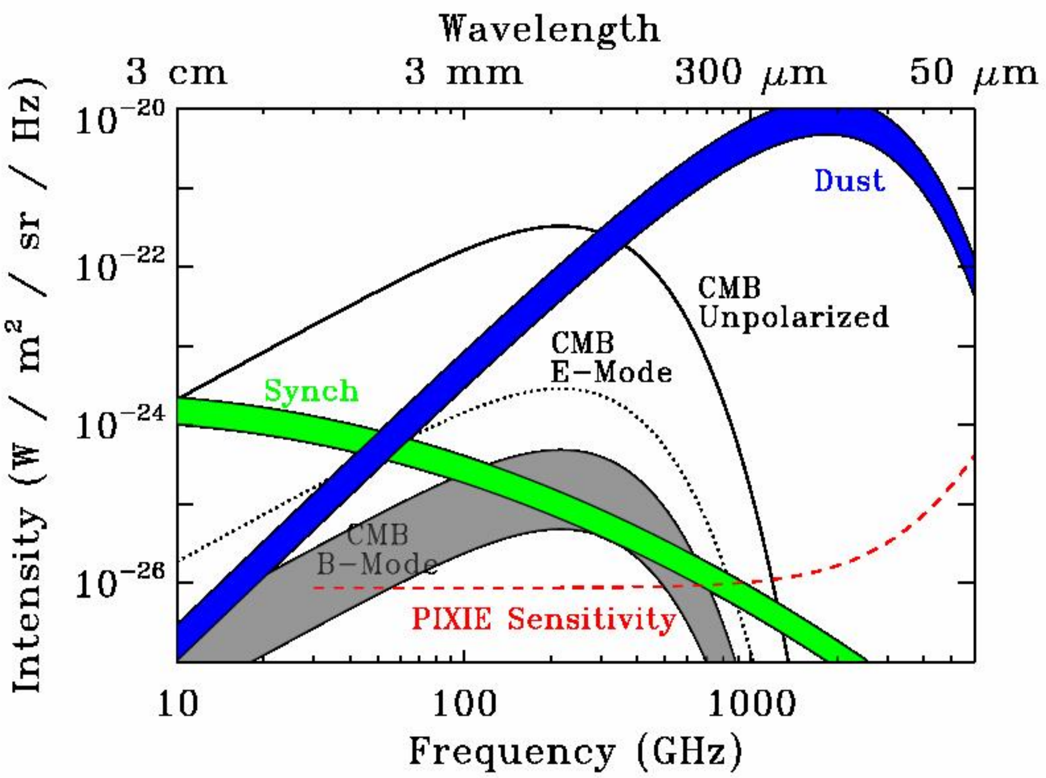
- Longest mirror stroke sets channel width
- Sampling rate sets number of channels
- No messy focal plane allocations



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

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

PIXIE Foreground 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

Number of channels >> Fitted parameters

- Model physics of foreground emission
- Synchrotron and dust spectral curvature
- Dust spectral index ±0.001 within each pixel
- FDS vs TLS emission spectra

If you can’t remove foregrounds with PIXIE,
it probably can’t be done at all

NASA Explorer Program

Small PI-led missions

- $200M Cost Cap + launch vehicle

22 full missions proposed Feb 2011

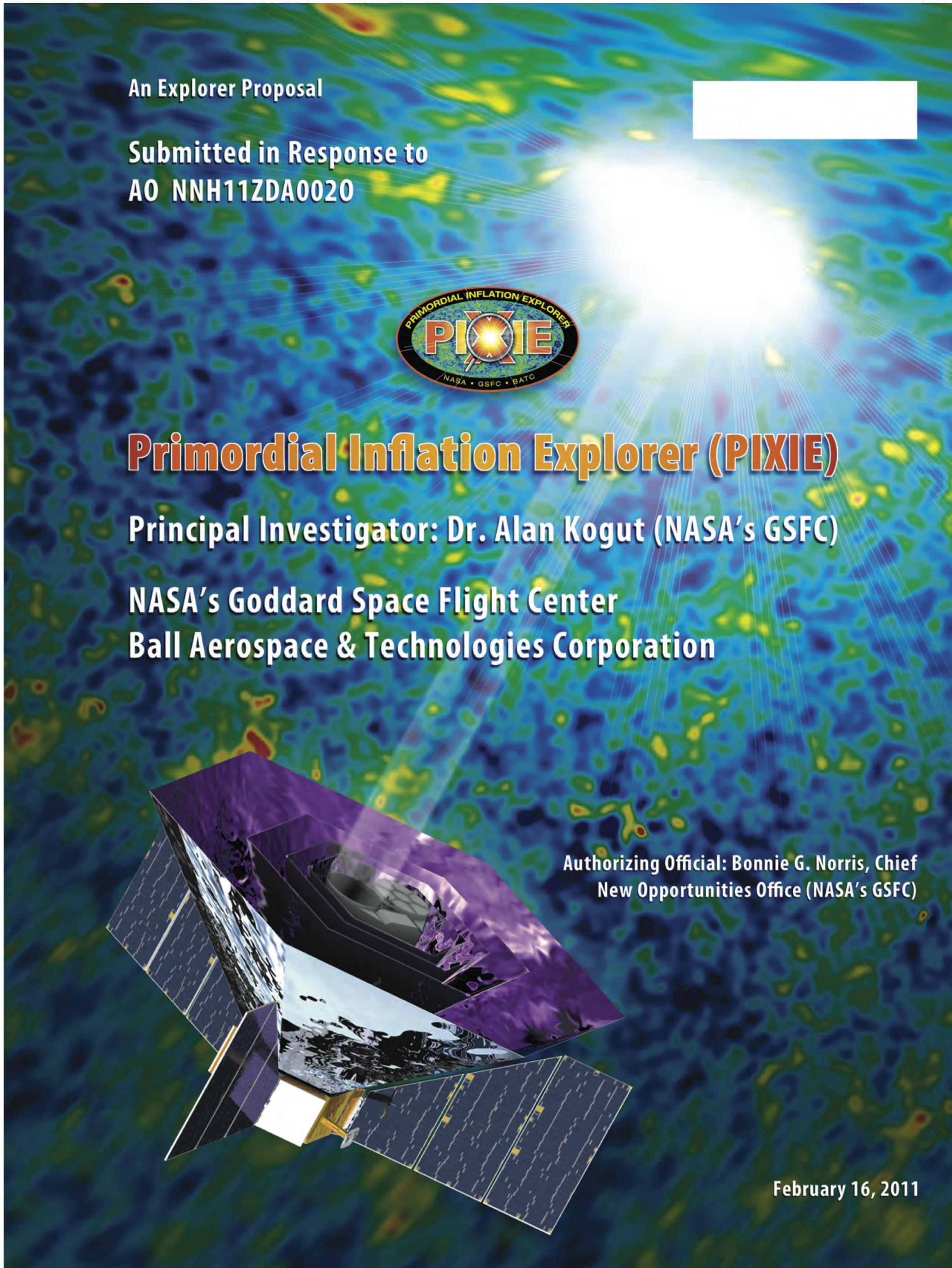
PIXIE not selected; urged to re-propose

- Category I Science rating
- Broad recognition of science appeal

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

PRIMORDIAL INFLATION EXPLORER
PIXIE
NASA • GSFC • BATC

Gloomy budget realities:
Best shot at inflationary physics?



An Explorer Proposal

Submitted in Response to
AO NNH11ZDA0020

PRIMORDIAL INFLATION EXPLORER
PIXIE
NASA • GSFC • BATC

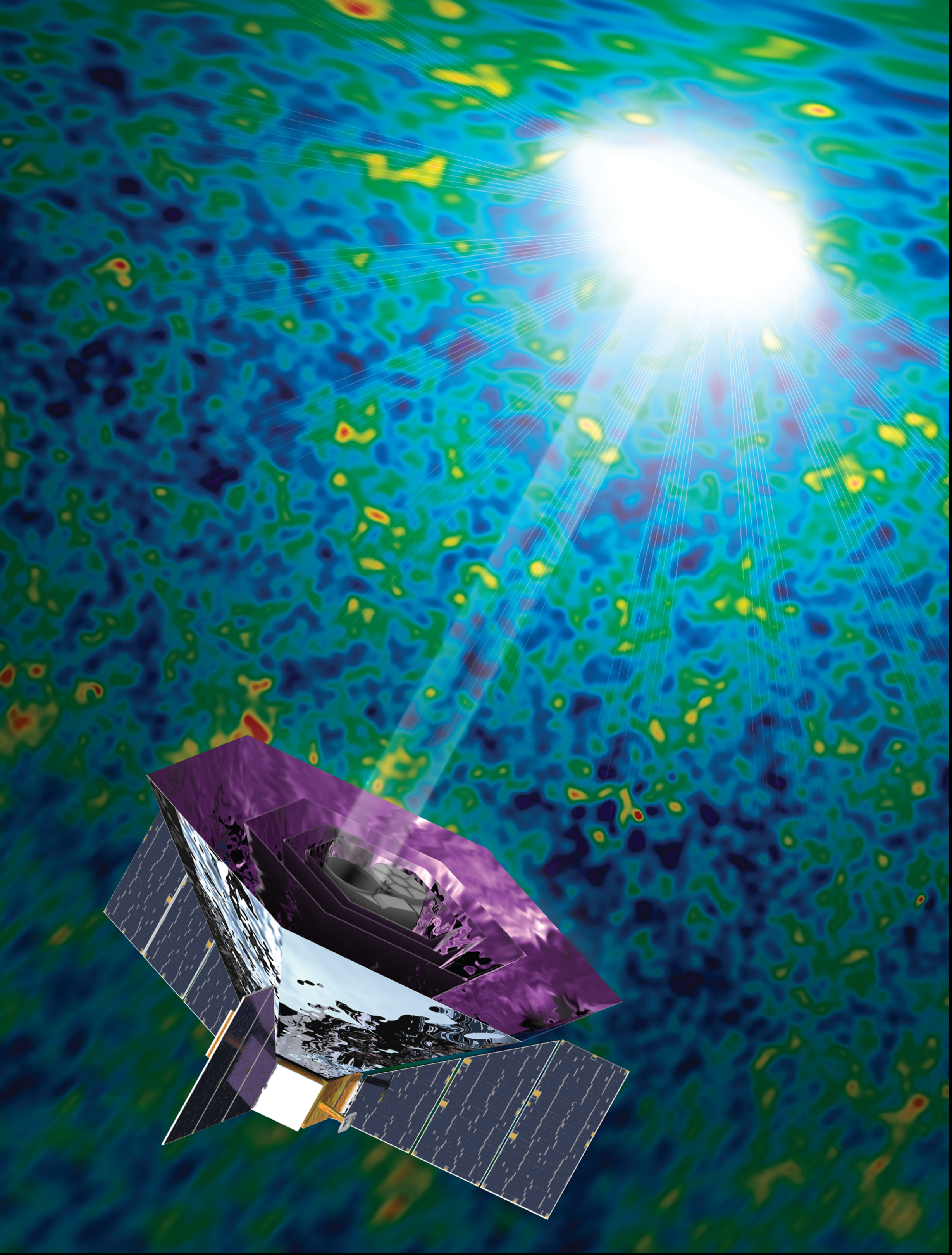
Primordial Inflation Explorer (PIXIE)

Principal Investigator: Dr. Alan Kogut (NASA's GSFC)

NASA's Goddard Space Flight Center
Ball Aerospace & Technologies Corporation

Authorizing Official: Bonnie G. Norris, Chief
New Opportunities Office (NASA's GSFC)

February 16, 2011

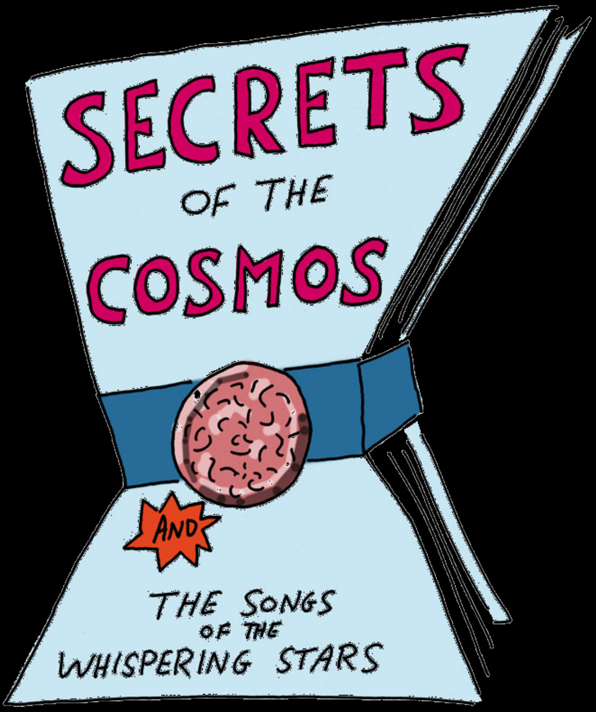


PRIMORDIAL INFLATION EXPLORER

PIXIE

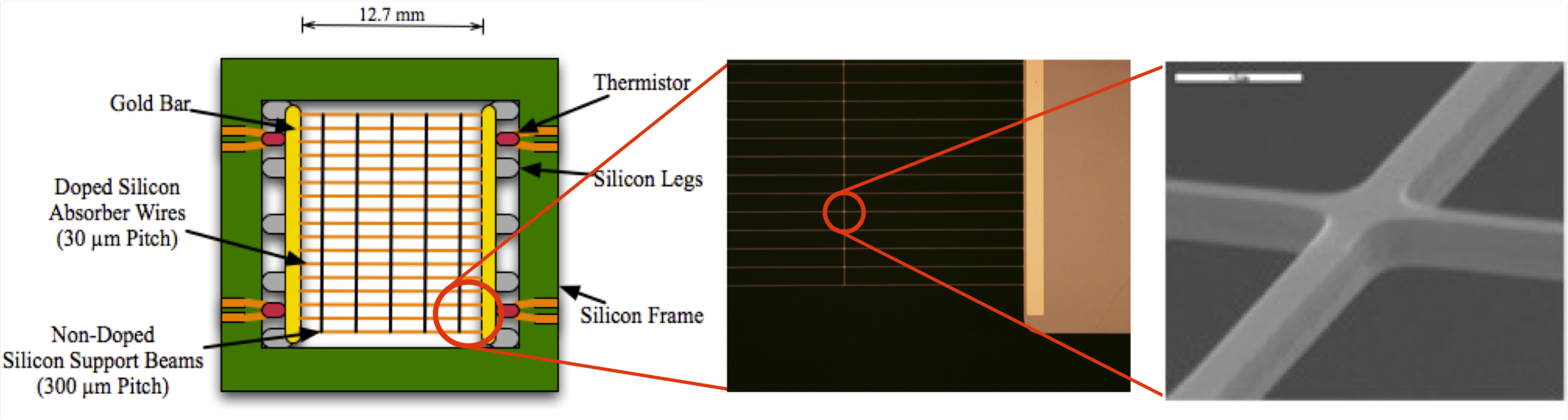
NASA • GSFC • BATC

Coming Soon From a Spacecraft Near You!



Backup Slides

PIXIE vs Cosmic Rays

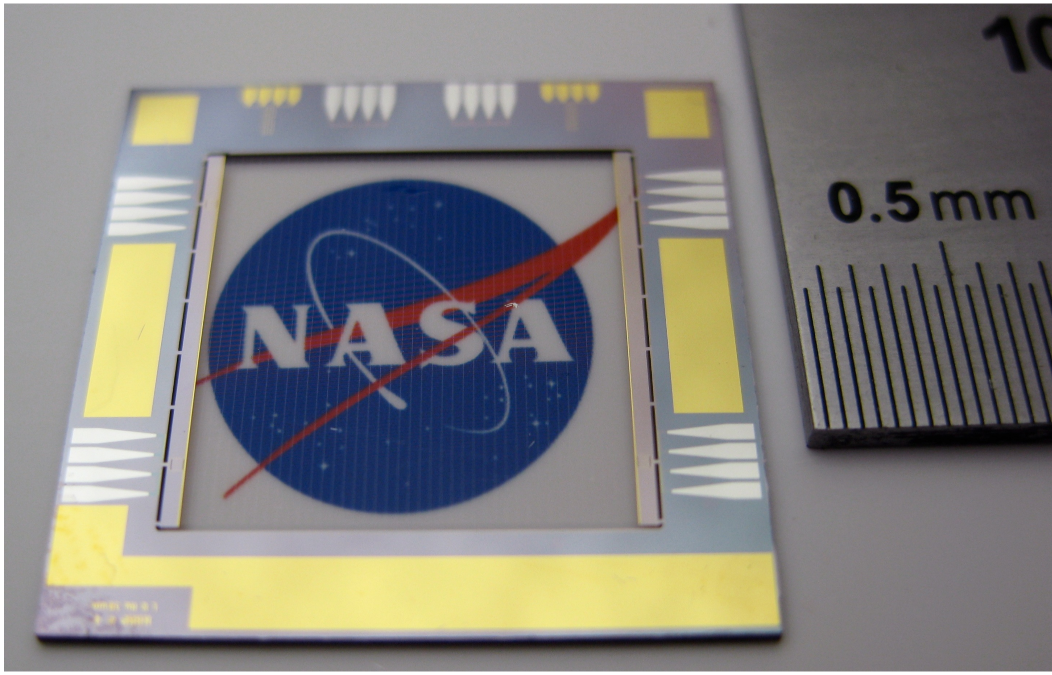


PIXIE detectors 30x Planck area
But ...

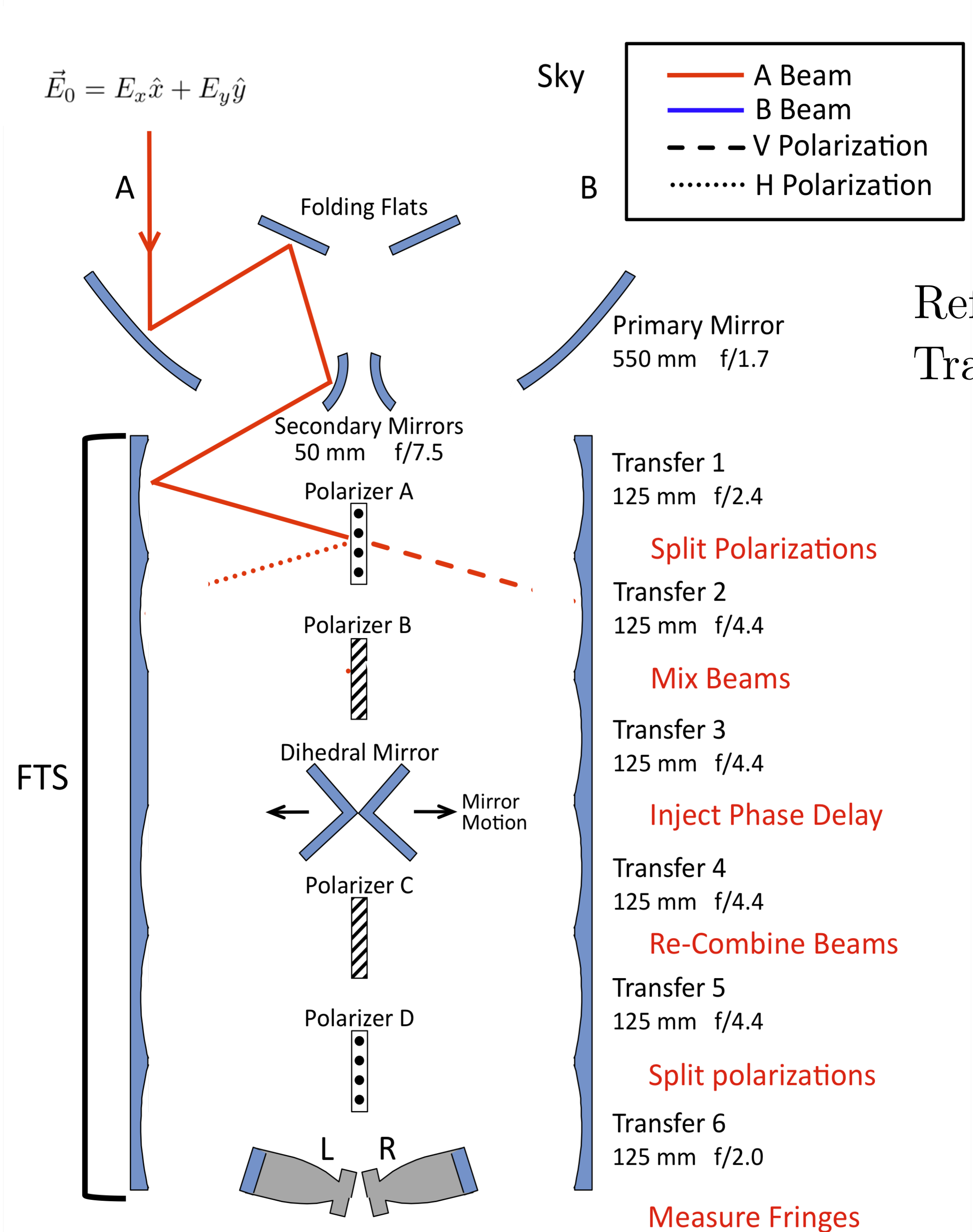
- Anchor silicon frame to 100 mK bath
- Crystalline silicon for fast time constant
- No on-board lossy compression
- Higher NEP → Higher threshold
- Fast (1 second) interferogram scans

Scale from FIRAS, Astro-E, Planck

- Astro-E: 0.3 hits /sec on 11 mm^2
- PIXIE: 0.5 hits / sec on 17 mm^2
- Data loss < 0.5%



Systematic Error from Asymmetries

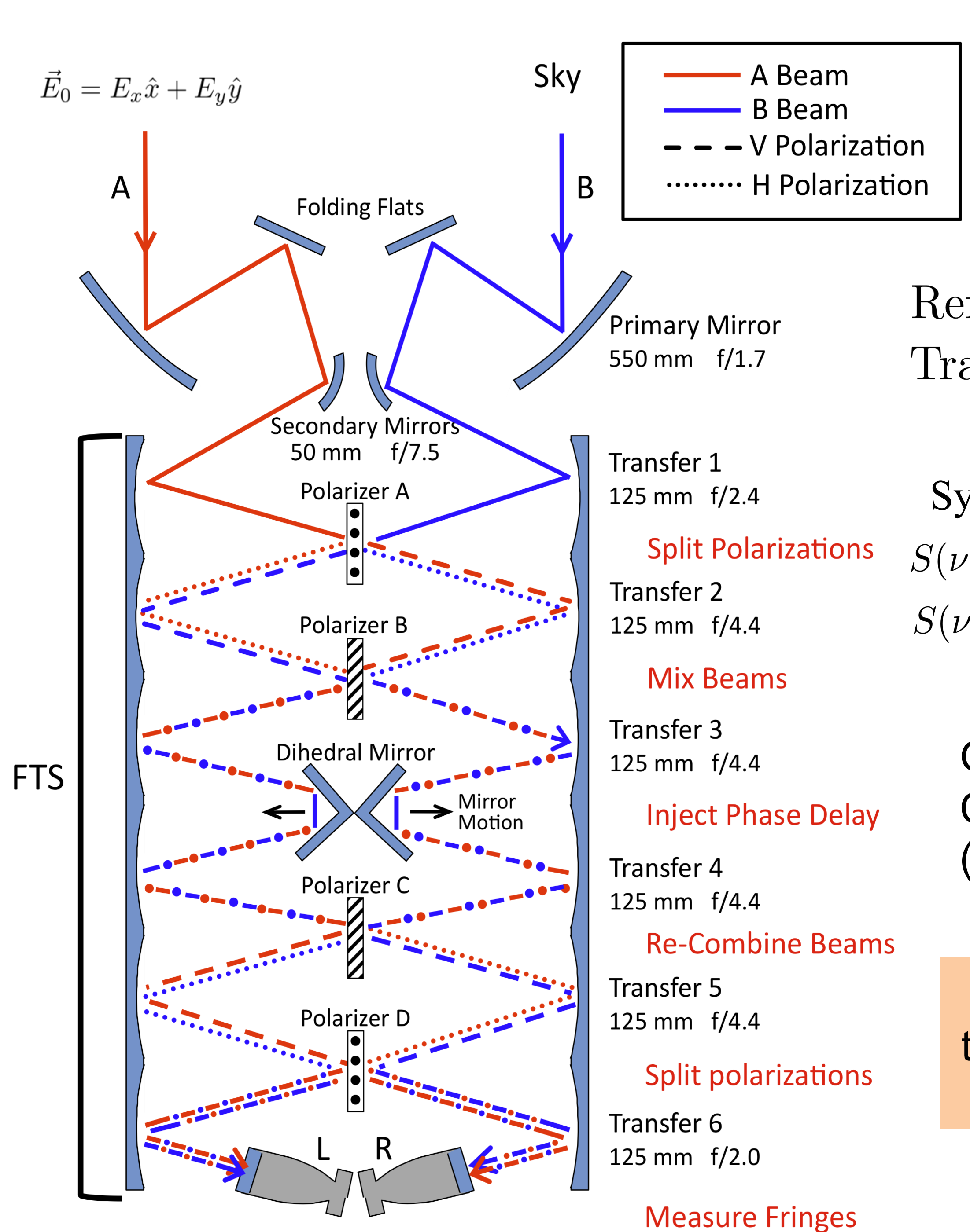


Absorption At Grid

$$\text{Reflected} : \vec{E}_r = -E_y \; \hat{y}$$

$$\text{Transmitted} : \vec{E}_t = [(1-\alpha)E_x + \alpha E_g] \; \hat{x}$$

Systematic Error from Asymmetries



Absorption At Grid

$$\text{Reflected}: \vec{E}_r = -E_y\ \hat{y}$$

$$\text{Transmitted}: \vec{E}_t = [(1-\alpha)E_x + \alpha E_g]\ \hat{x}$$

Synthesized Spectra:

$$S(\nu)_{Lx} = 1/4\left[-\alpha^2(Q_\nu \cos 2\gamma + U_\nu \sin 2\gamma) + \alpha^2 \Delta I_\nu\right]$$

$$S(\nu)_{Ry} = 1/4\left[\ \alpha^2(Q_\nu \cos 2\gamma + U_\nu \sin 2\gamma) - \alpha^2 \Delta I_\nu\right]$$

Gain Correction (< 3 nK)

Inst Coupling (not spin modulated)

ARCADE: Change component temperatures to measure α_i continuously throughout mission

PIXIE Fourier Transform

Phase delay L sets channel width

$\Delta\nu = c/L$

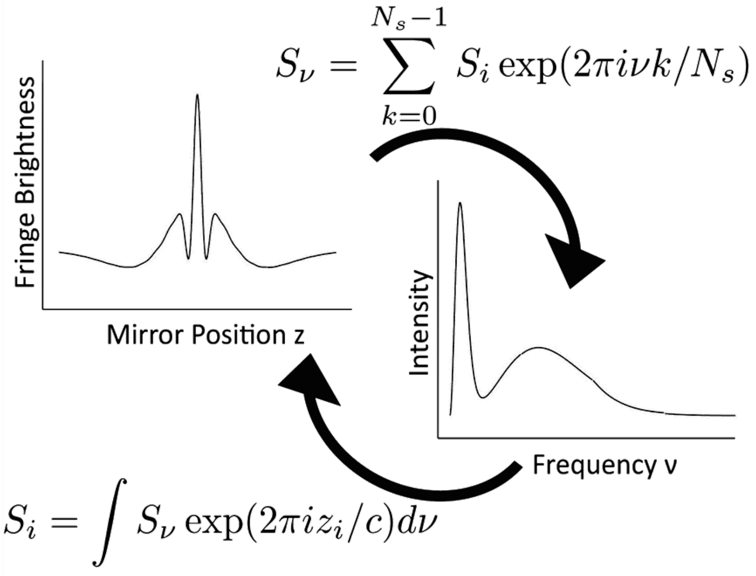
Number of samples sets frequency range

N_chan = N_samp / 2

PIXIE: ~400 usable channels

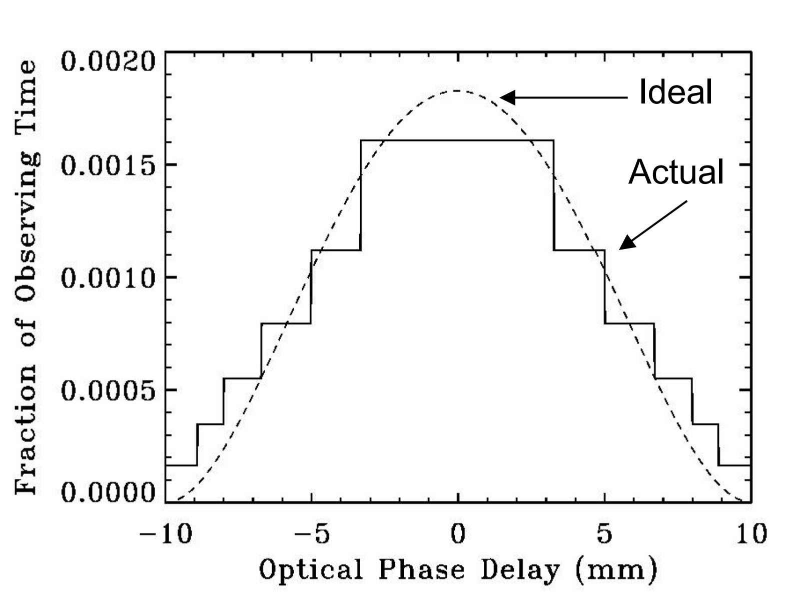
$\Delta\nu$ = 15 GHz

30 GHz to 6 THz (1 cm to 50 μm)



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

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

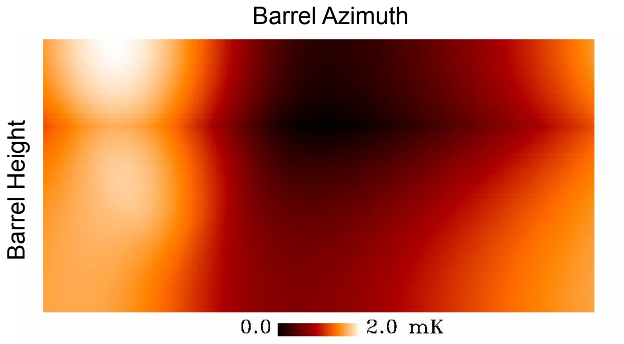


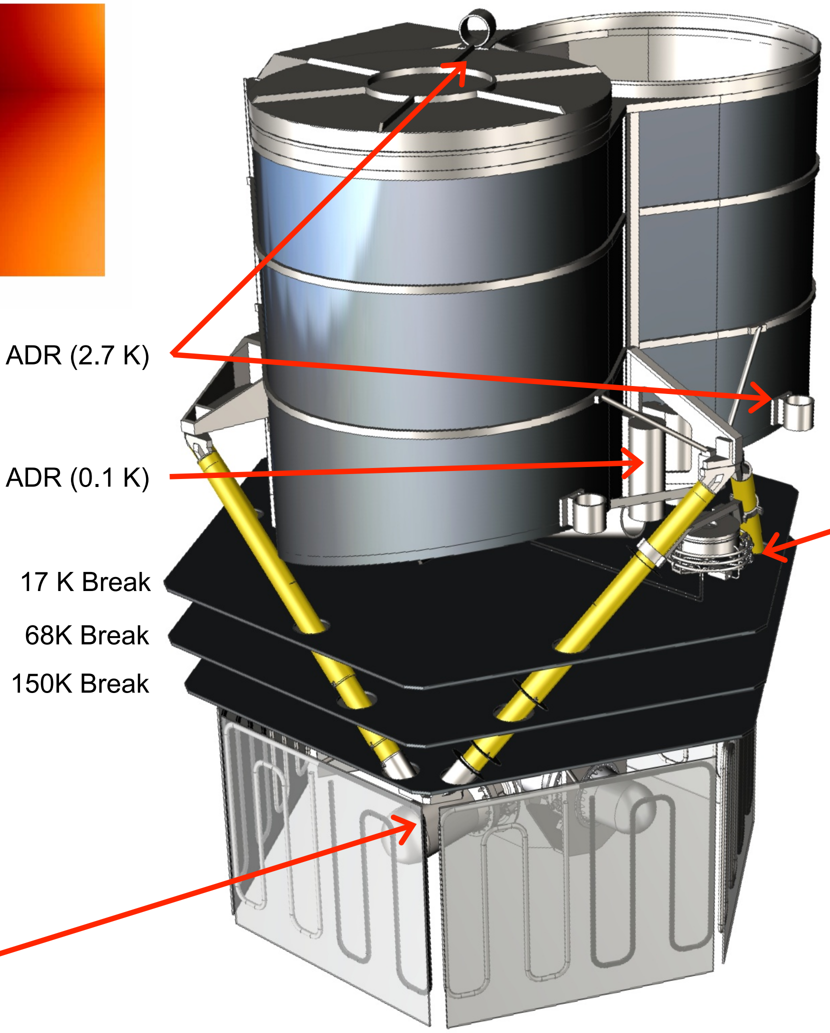
Optical Delay	Physical Stroke	Samples per Stroke	Strokes per Spin
±10 mm	±2.5 mm	1024	8
±8.9 mm	±2.3 mm	910	9
±8.0 mm	±2.1 mm	819	10
±6.7 mm	±1.7 mm	683	12
±5.0 mm	±1.3 mm	512	16
±3.3 mm	±0.9 mm	341	24

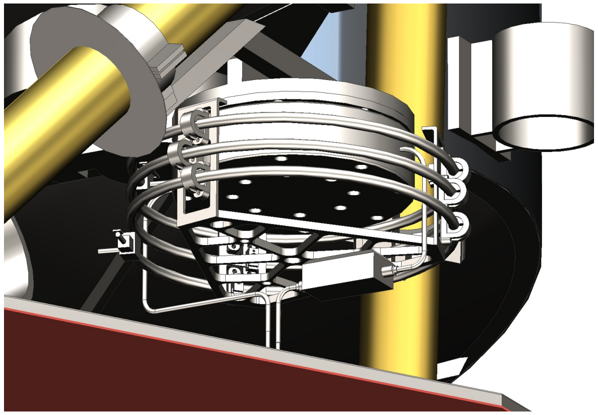
Vary stroke length to apodize Fourier transform

Cryogenics

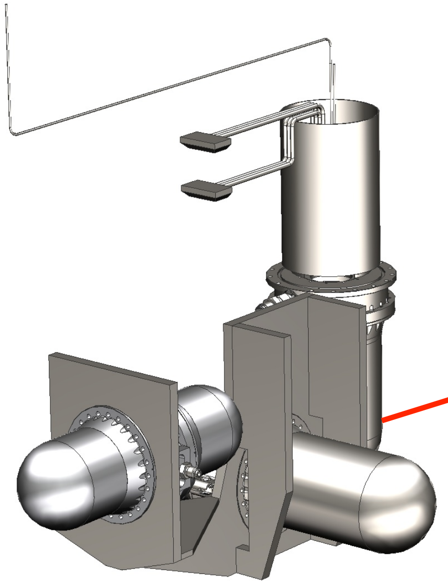
Moonshine Thermal Gradient







J-T Cold Head (4.5 K)



Cryo-Cooler Compressor (280 K)

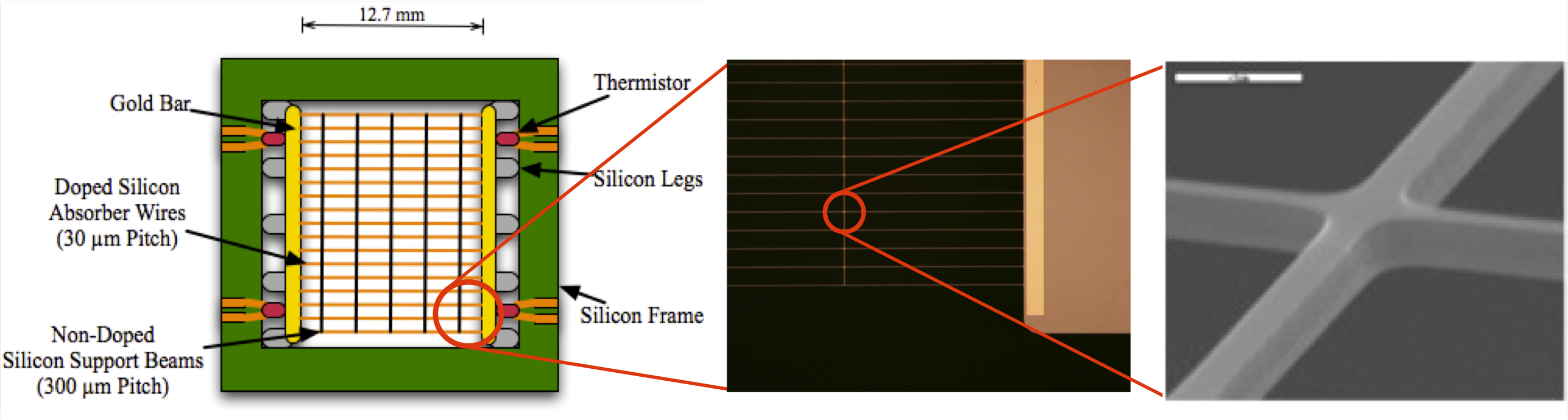
Multi-Stage Cryogenic Design

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

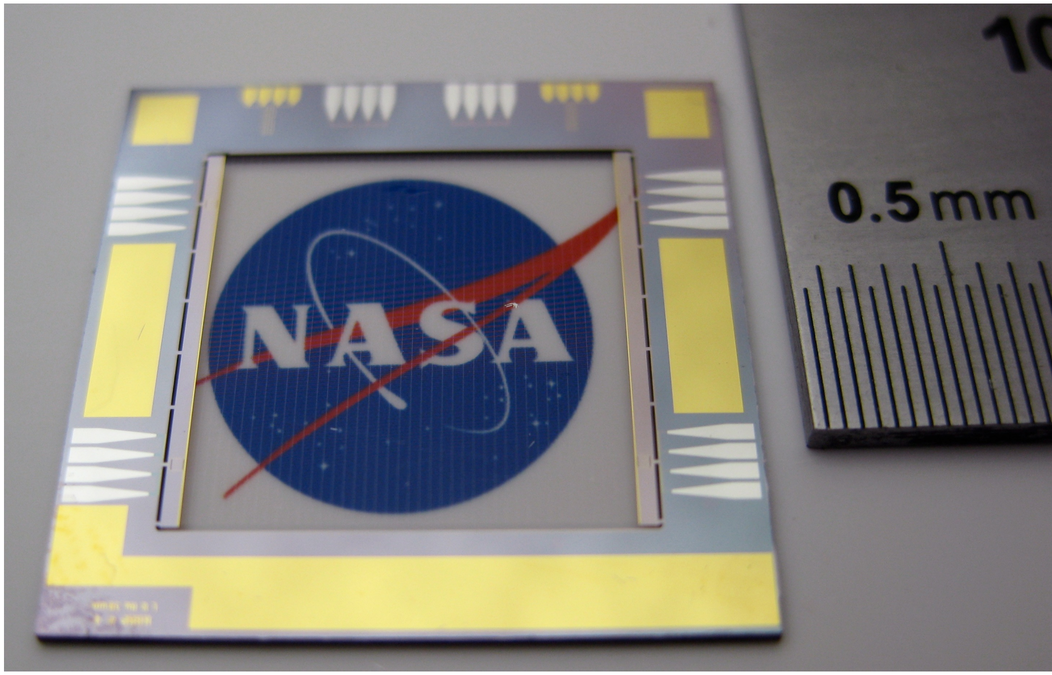
Thermal Lift Budget

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%

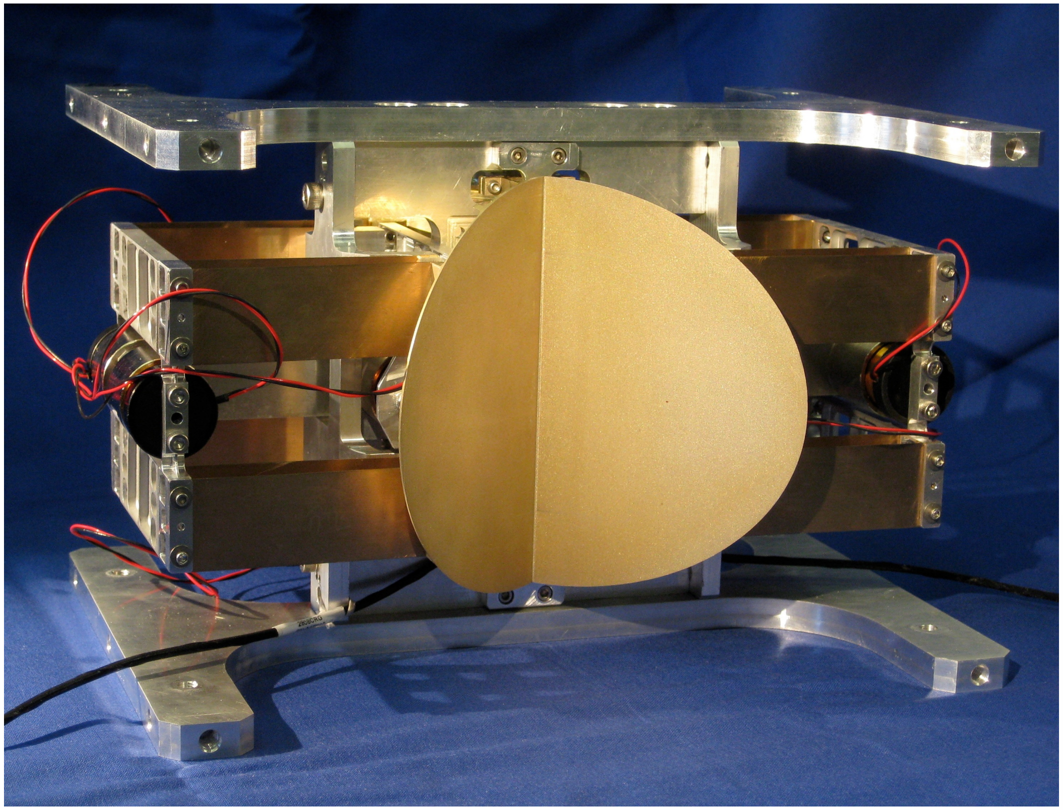
Polarization-Sensitive Detectors



Parameter	Design	
Area	160 mm^2	
Fill Fraction	11%	
Frame Temperature	100 mK	
Absorber Temperature	140 mK	
	Requirement	**Performance**
NEP (W Hz$^{-1/2}$)	<10^{-16}	0.7 x 10^{-16}
Time Constant (ms)	<4	1
Cross-Pol at 150 GHz	<1%	0.1%



Mirror Transport Mechanism

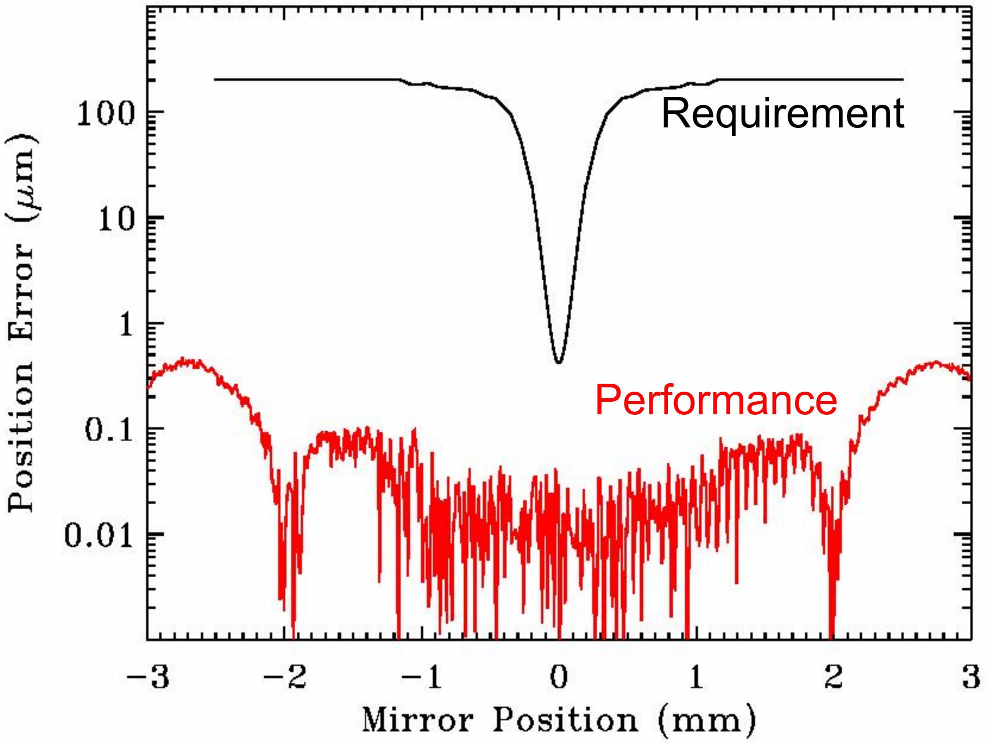


Engineering prototype

Translate ±2.54 mm at 0.5 Hz

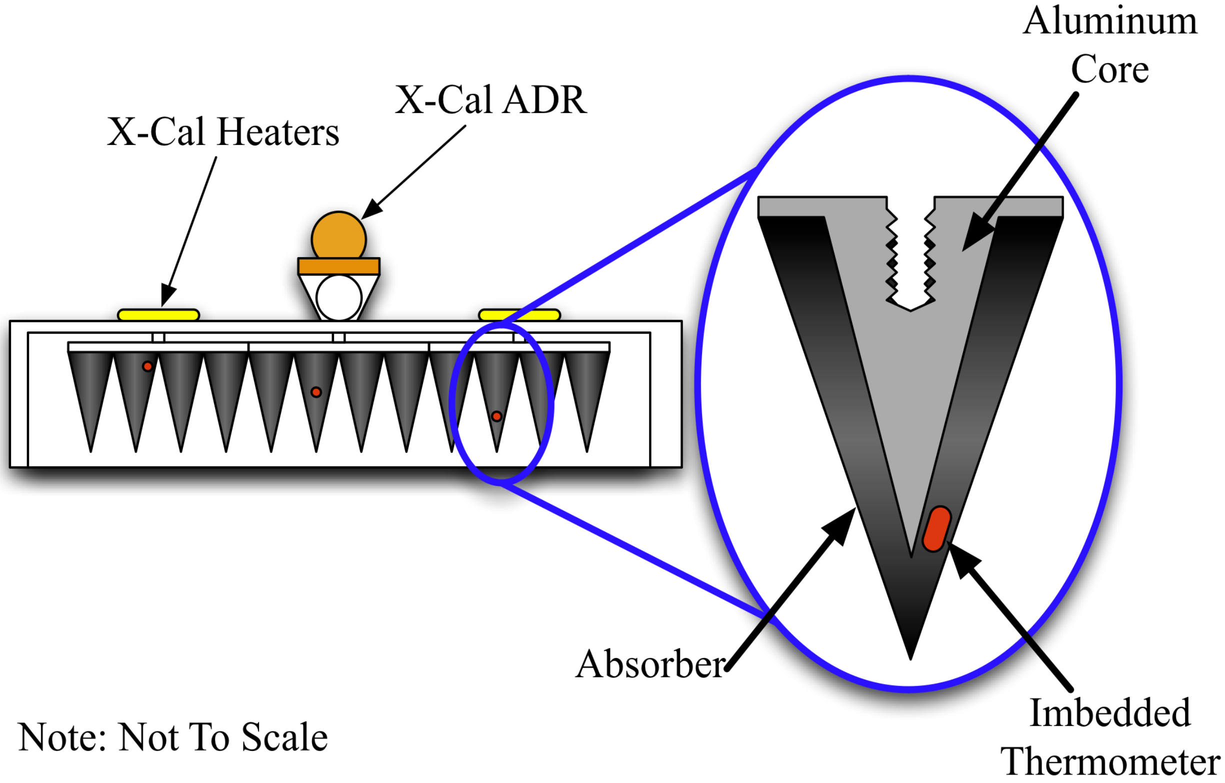
Optical phase delay ±1 cm

Repeatable cryogenic position



Demonstrated performance
exceeds requirement by factor of ten

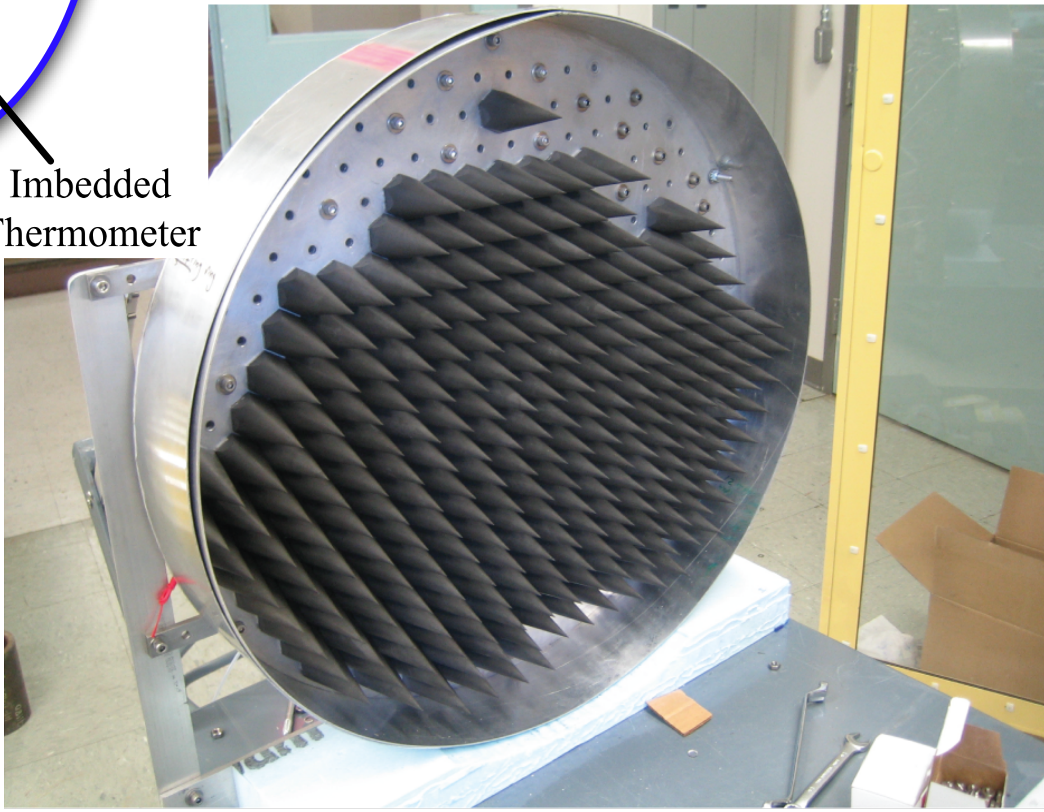
Blackbody Calibrator



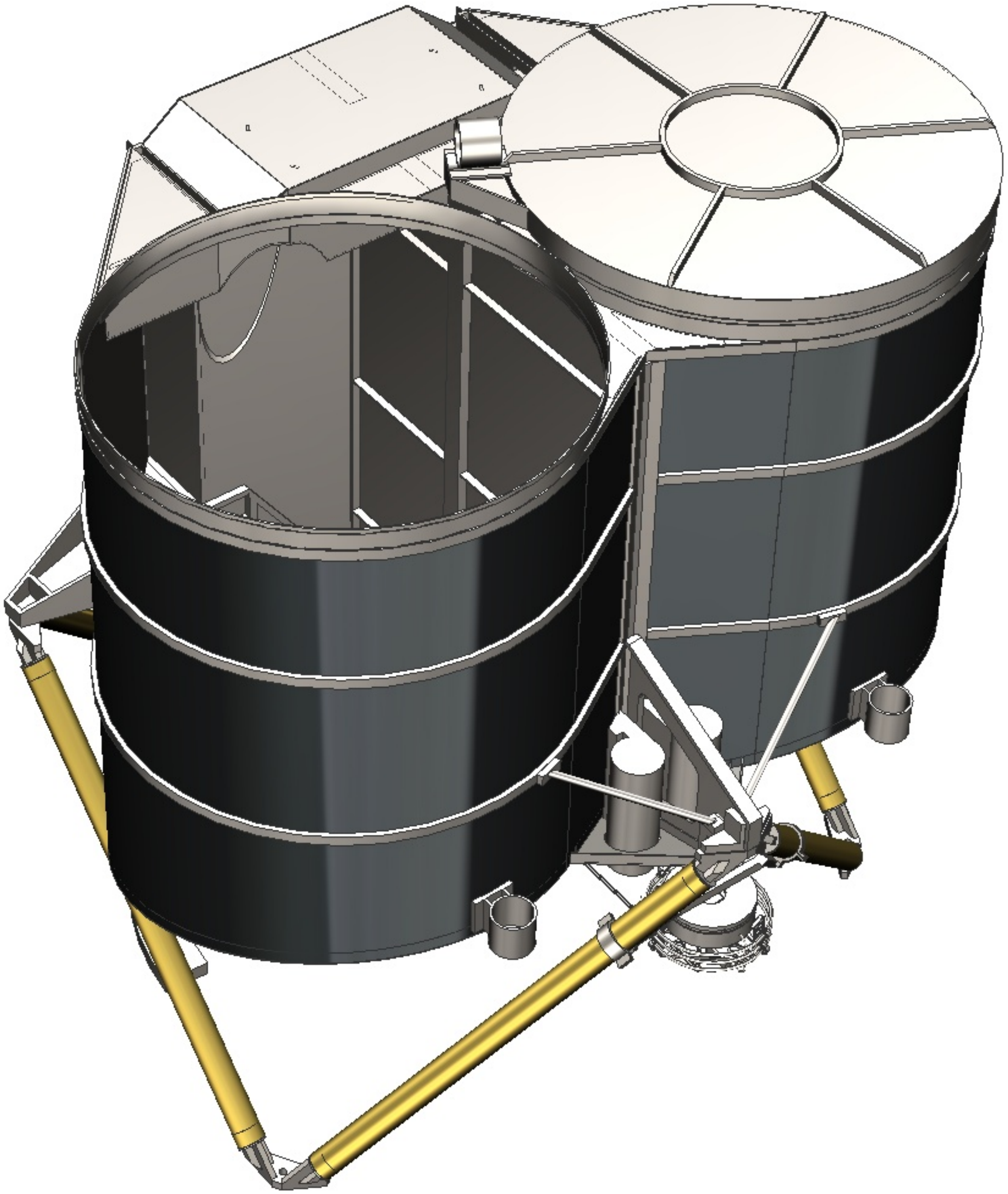
Note: Not To Scale

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



External Calibrator



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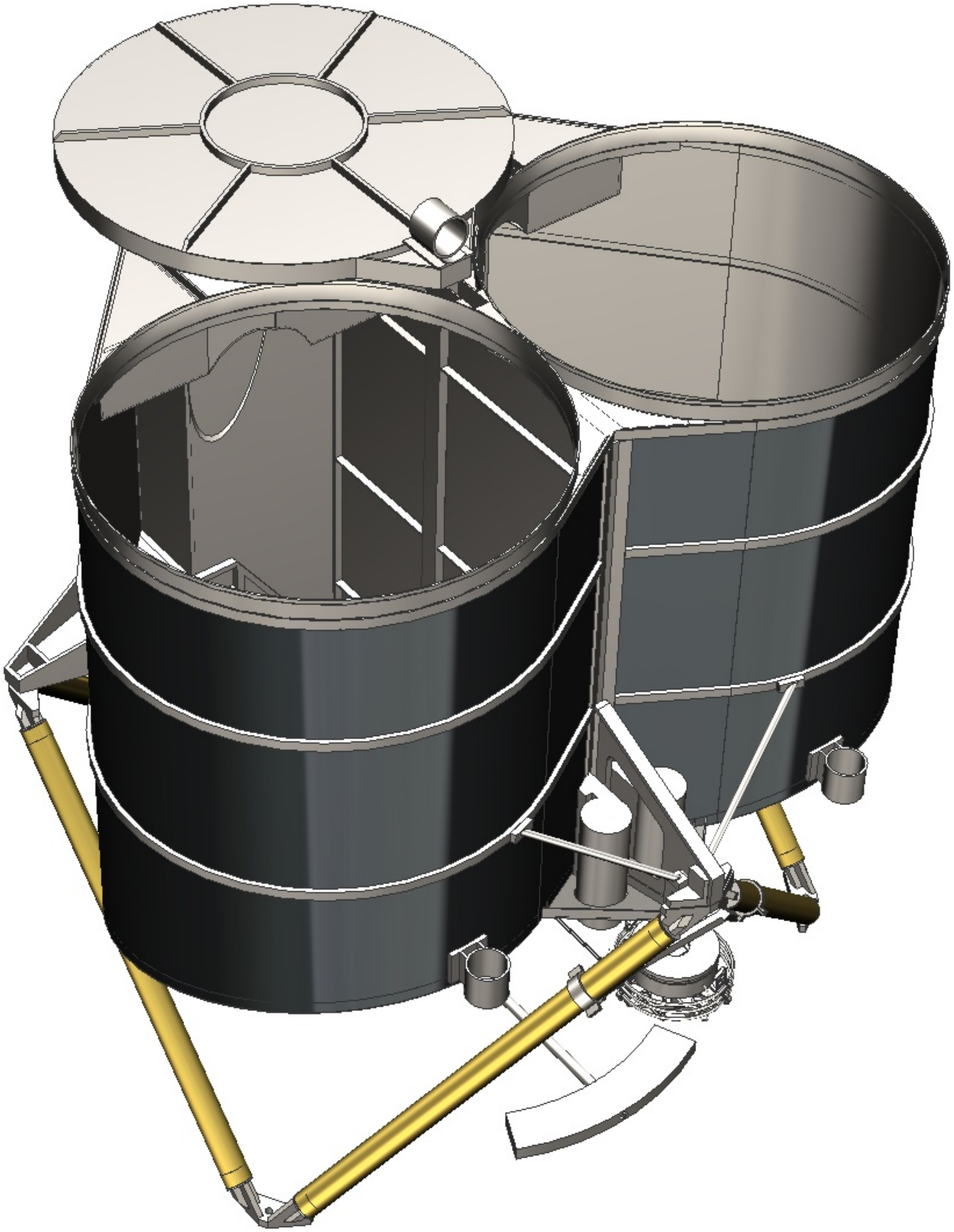

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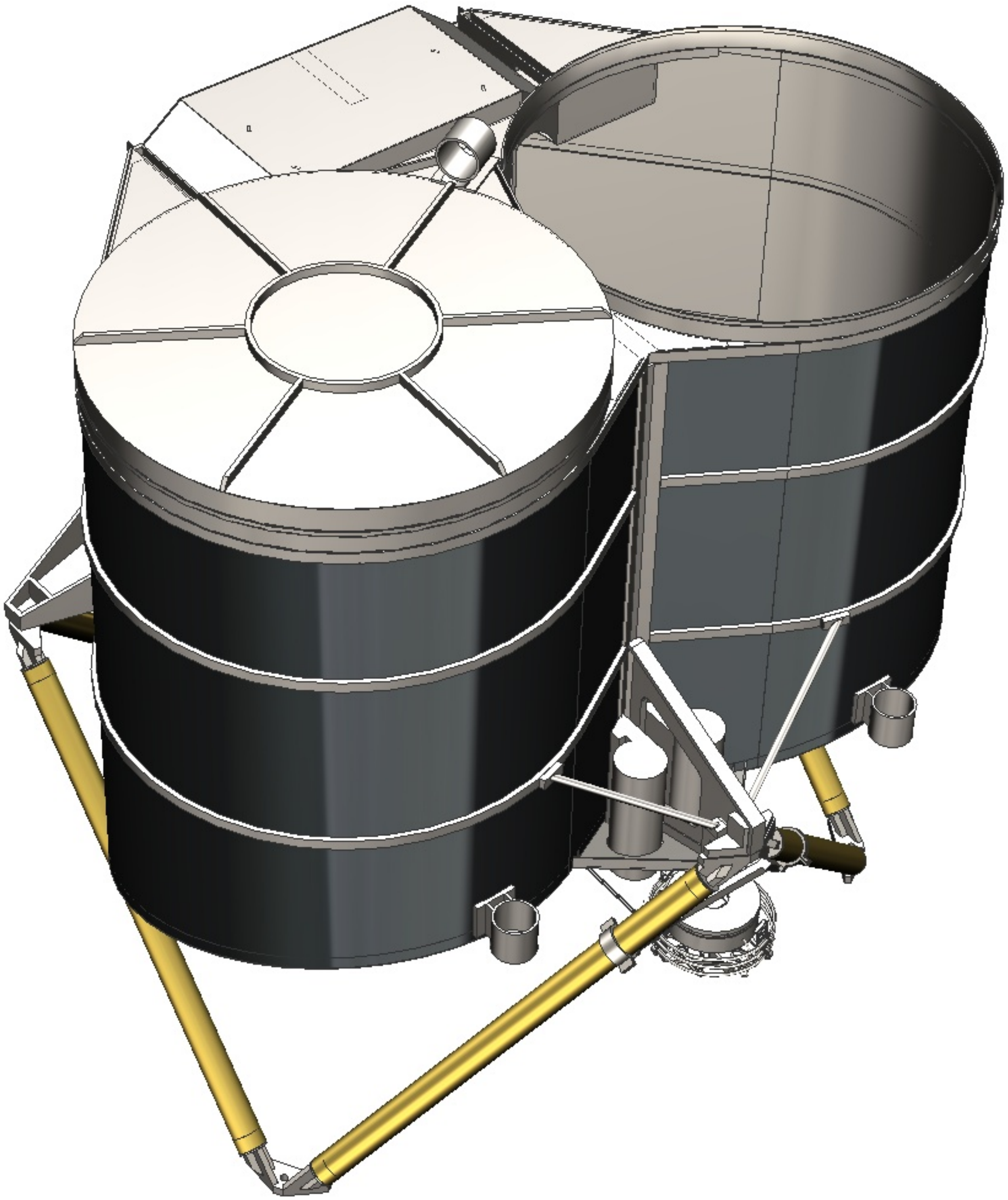
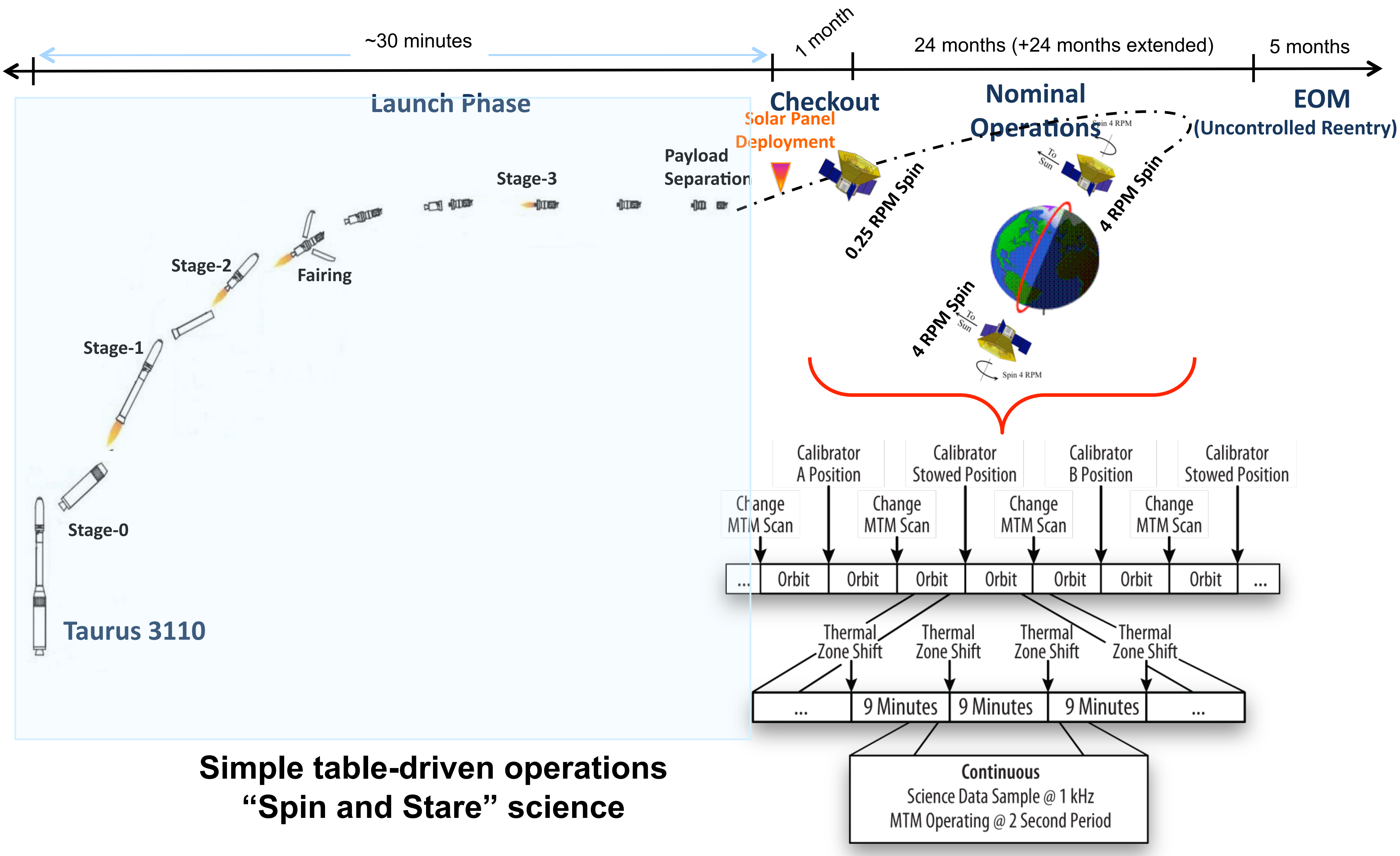
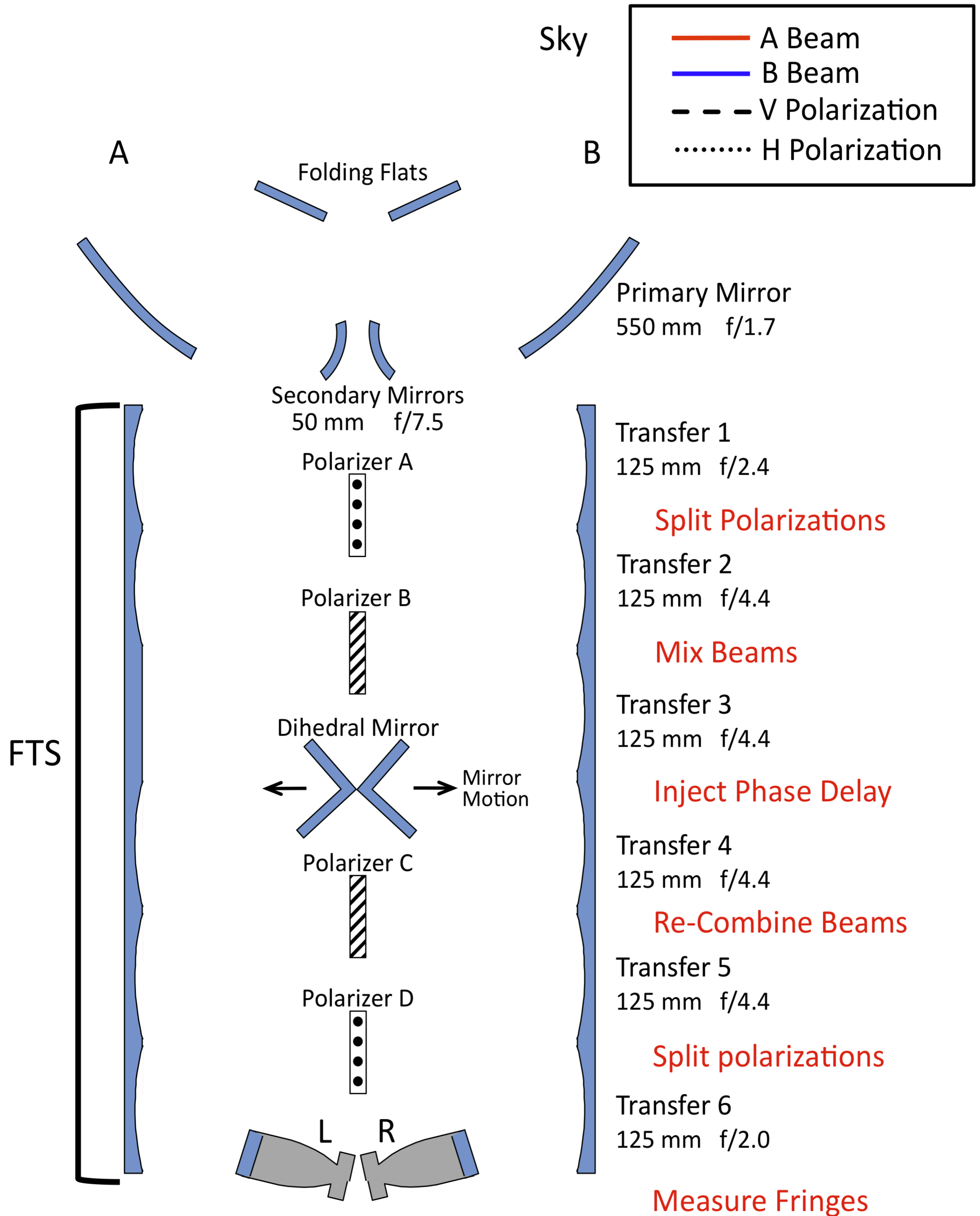


Mission Operations



Simple table-driven operations
“Spin and Stare” science

PIXIE Optical Path



Sky

A Beam
B Beam
V Polarization
H Polarization

A

Folding Flats

B

Primary Mirror
550 mm f/1.7

Secondary Mirrors
50 mm f/7.5

Polarizer A

Transfer 1
125 mm f/2.4

Split Polarizations

Polarizer B

Transfer 2
125 mm f/4.4

Mix Beams

Dihedral Mirror

Mirror Motion

FTS

Transfer 3
125 mm f/4.4

Inject Phase Delay

Polarizer C

Transfer 4
125 mm f/4.4

Re-Combine Beams

Polarizer D

Transfer 5
125 mm f/4.4

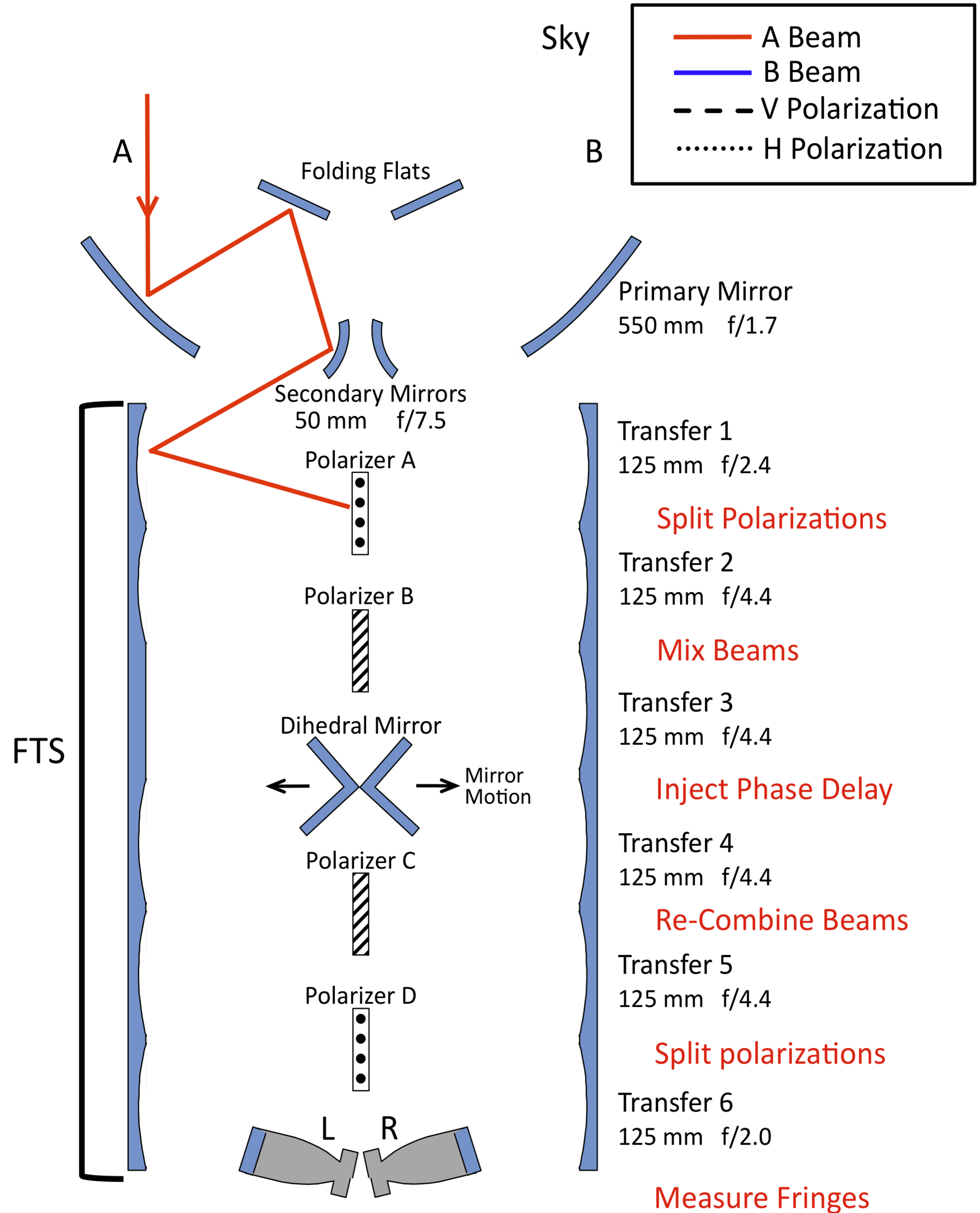
Split polarizations

L R

Transfer 6
125 mm f/2.0

Measure Fringes

PIXIE Optical Path



━━ A Beam
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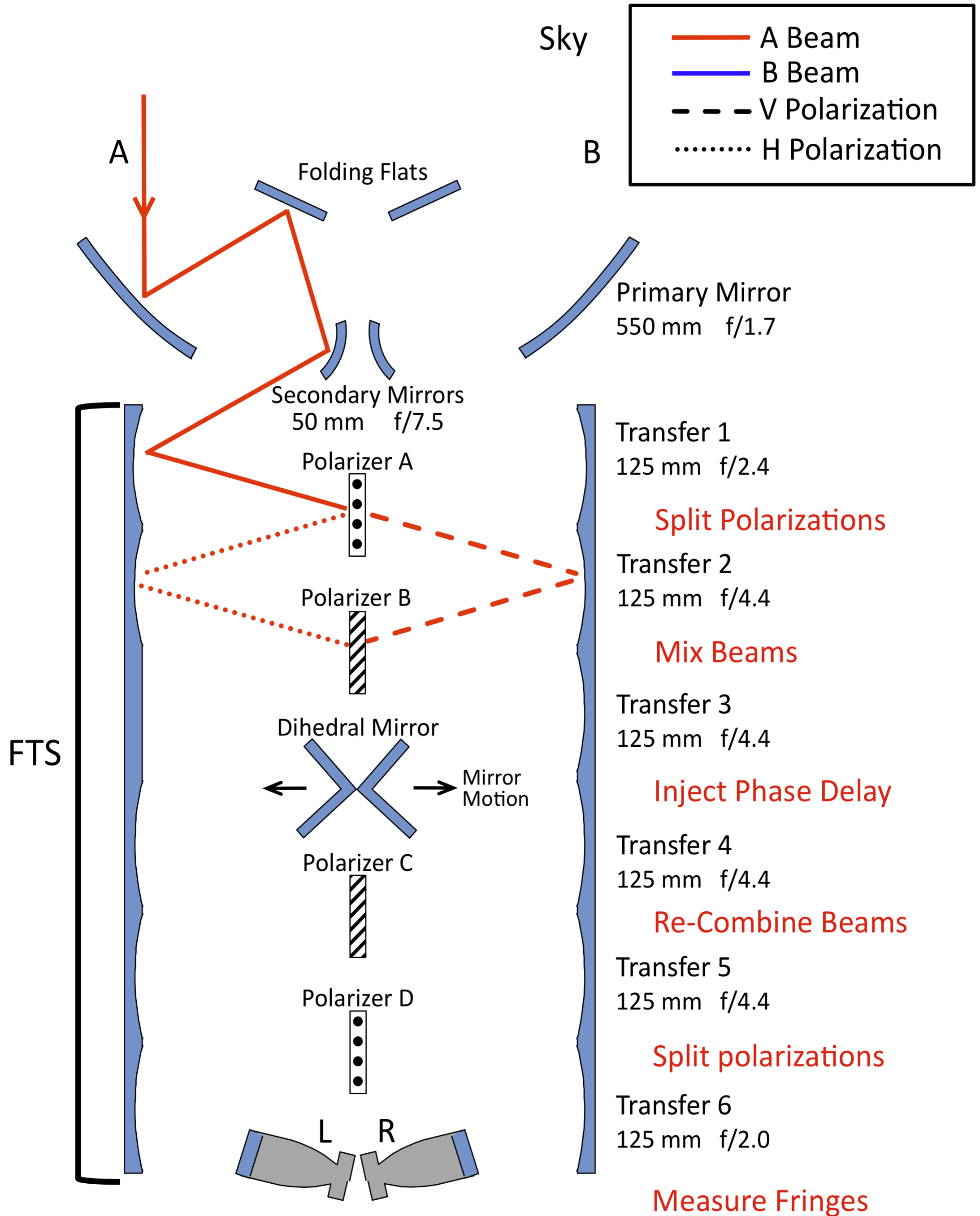

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Transfer 4
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Polarizer C

Re-Combine Beams

Transfer 5
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Split polarizations

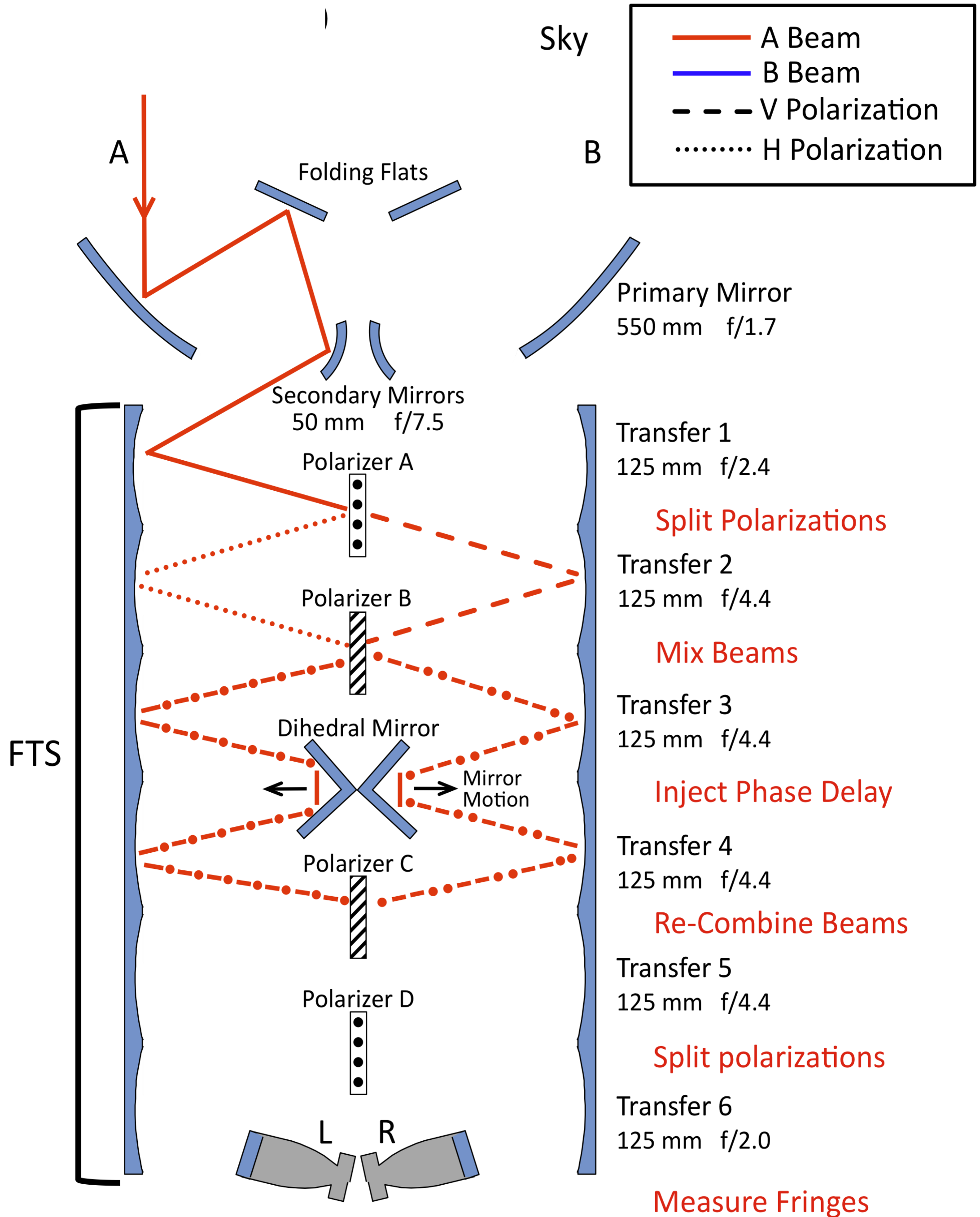
Transfer 6
125 mm f/2.0

L

R

Measure Fringes

PIXIE Optical Path



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Polarizer A

Split Polarizations

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Polarizer B

Mix Beams

Transfer 3
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Dihedral Mirror

Mirror Motion

Inject Phase Delay

FTS

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Split polarizations

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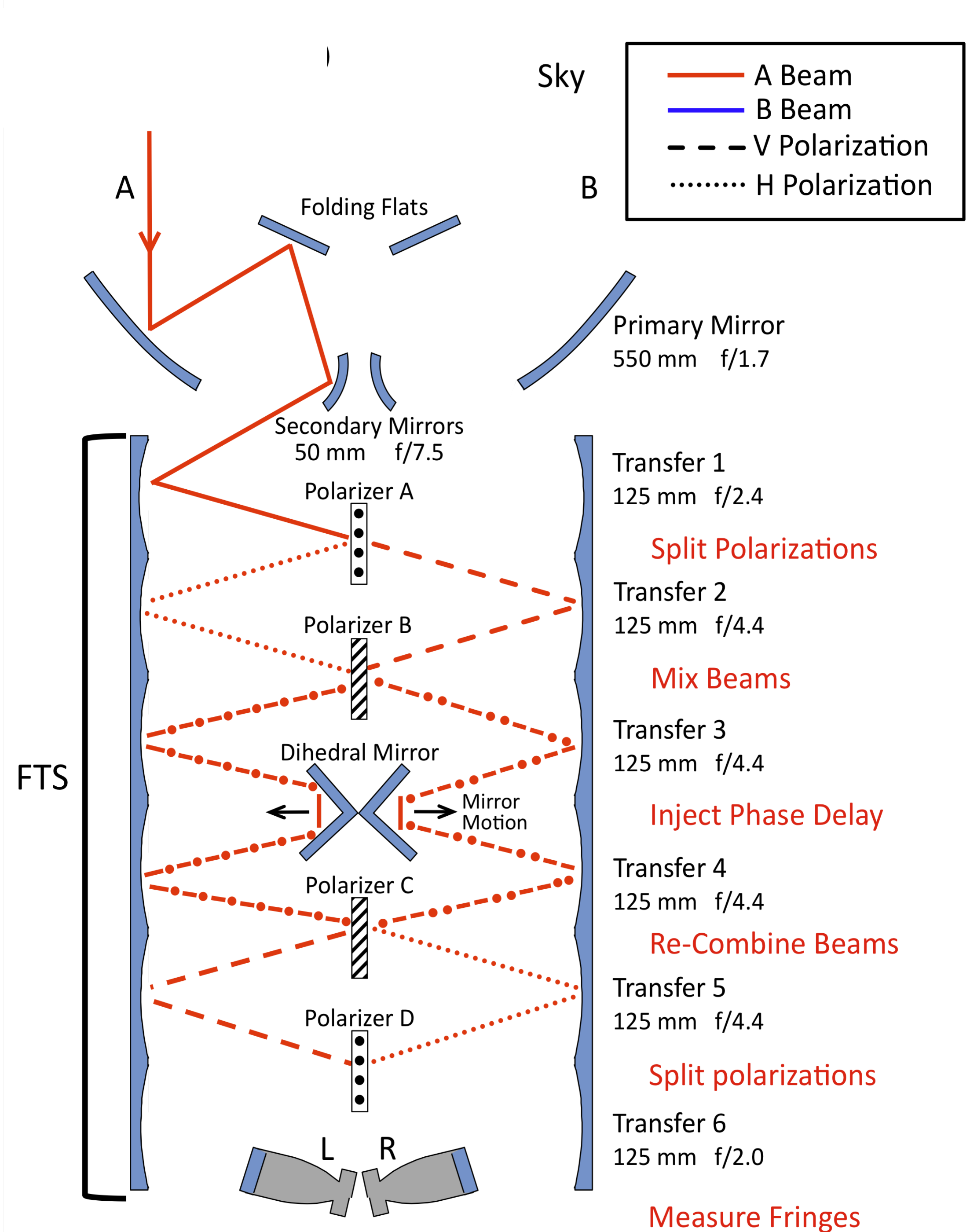
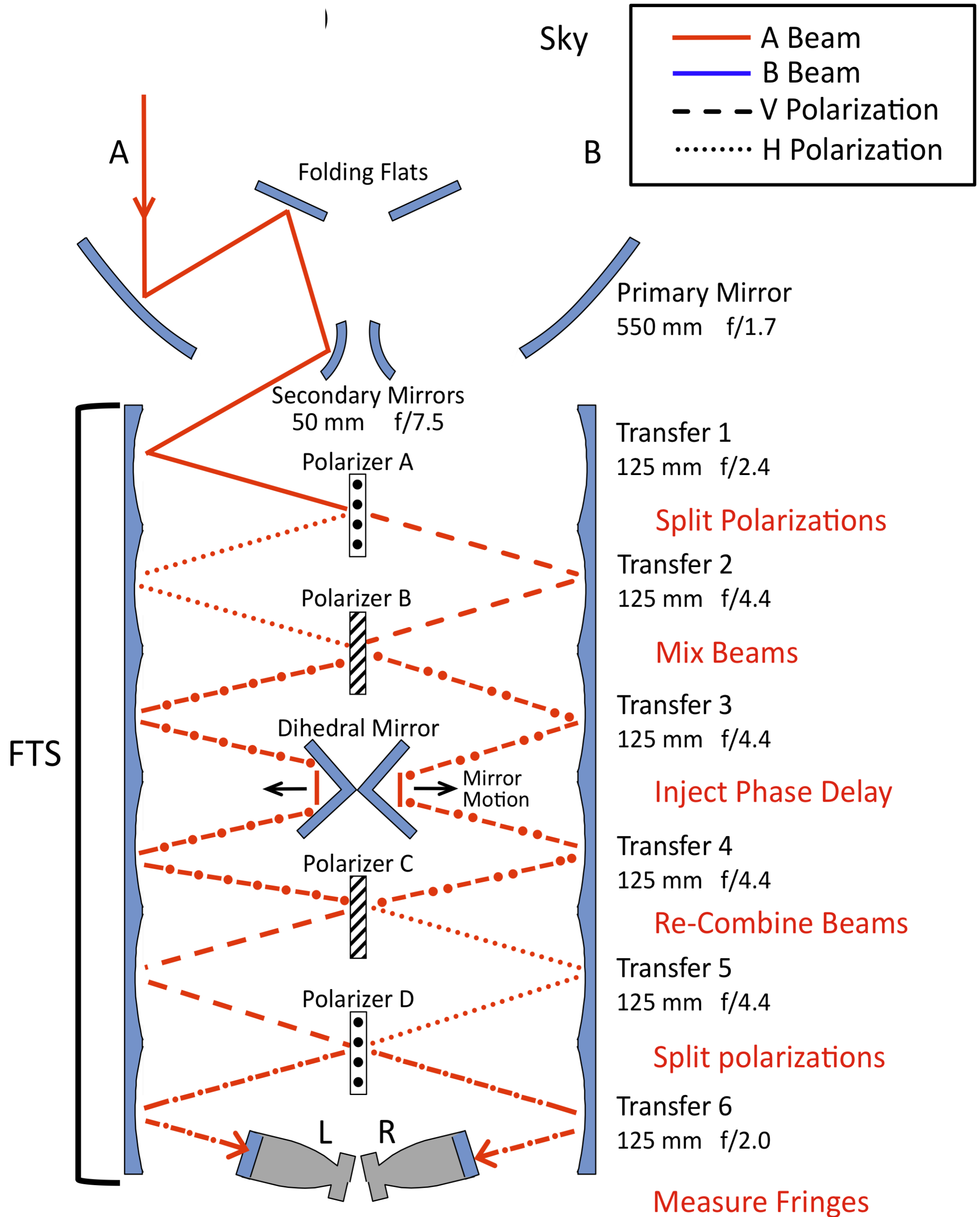
L R

Measure Fringes

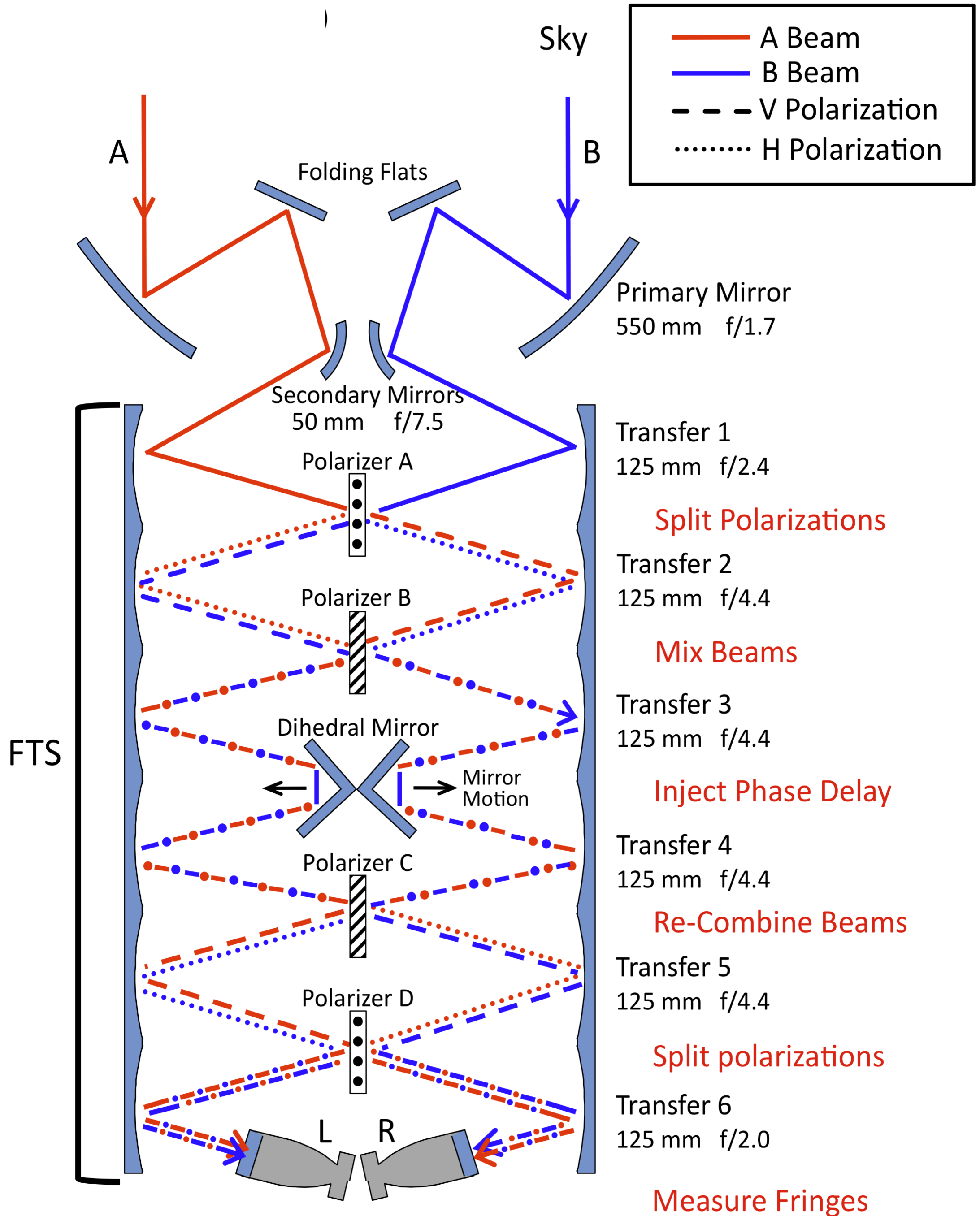
PIXIE Optical Path



PIXIE Optical Path



PIXIE Optical Path



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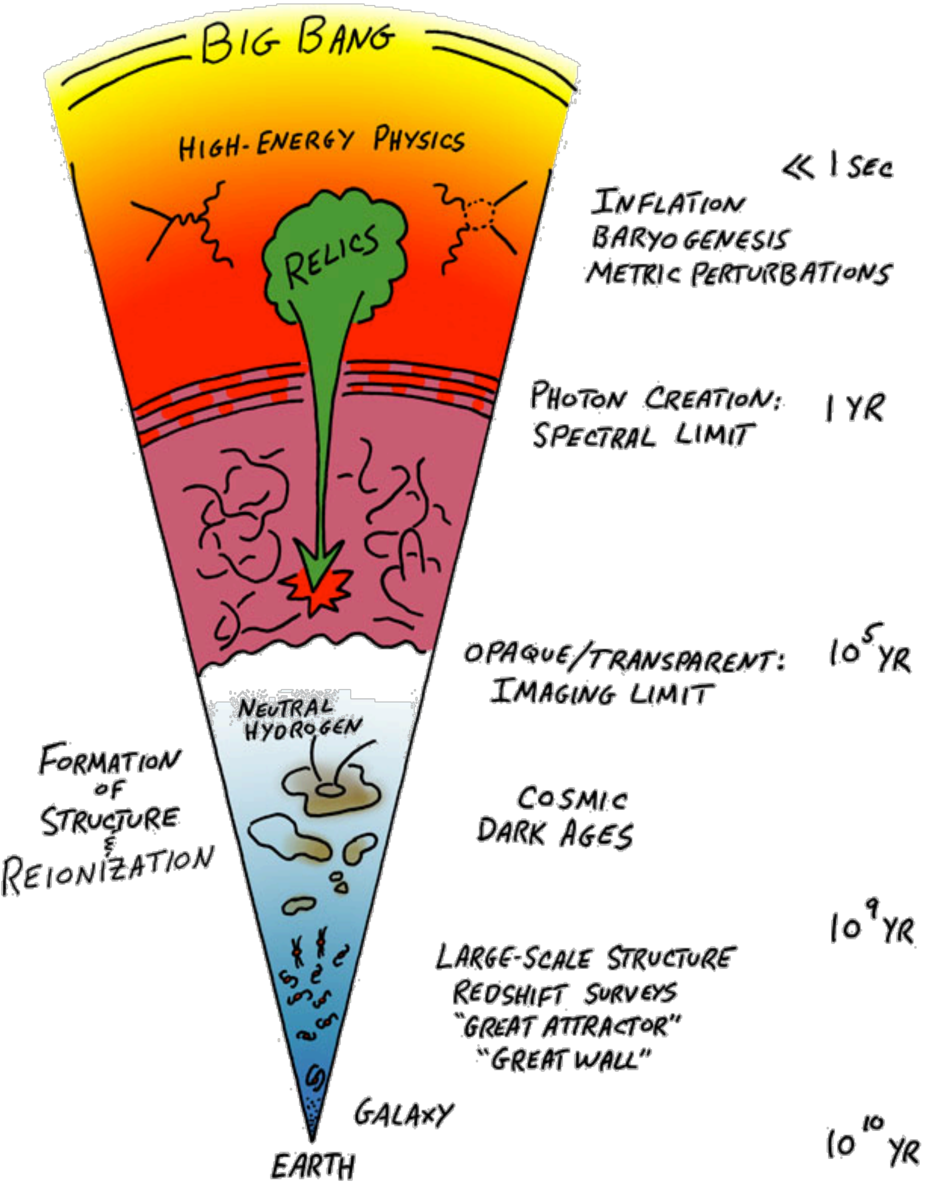
L

R

Measure Fringes

PIXIE Samples Cosmic History



Big Bang Cosmology *

Inflation
GUT physics
Quantum gravity

Primary Science

Early Universe

Dark matter decay/annihilation
Primordial density perturbations

Reionization and First Stars *

Ionization history at end of Dark Ages
Nature of first stars

Large-scale Structure

Galaxy bias vs dark matter density
Star formation at redshift 2--3

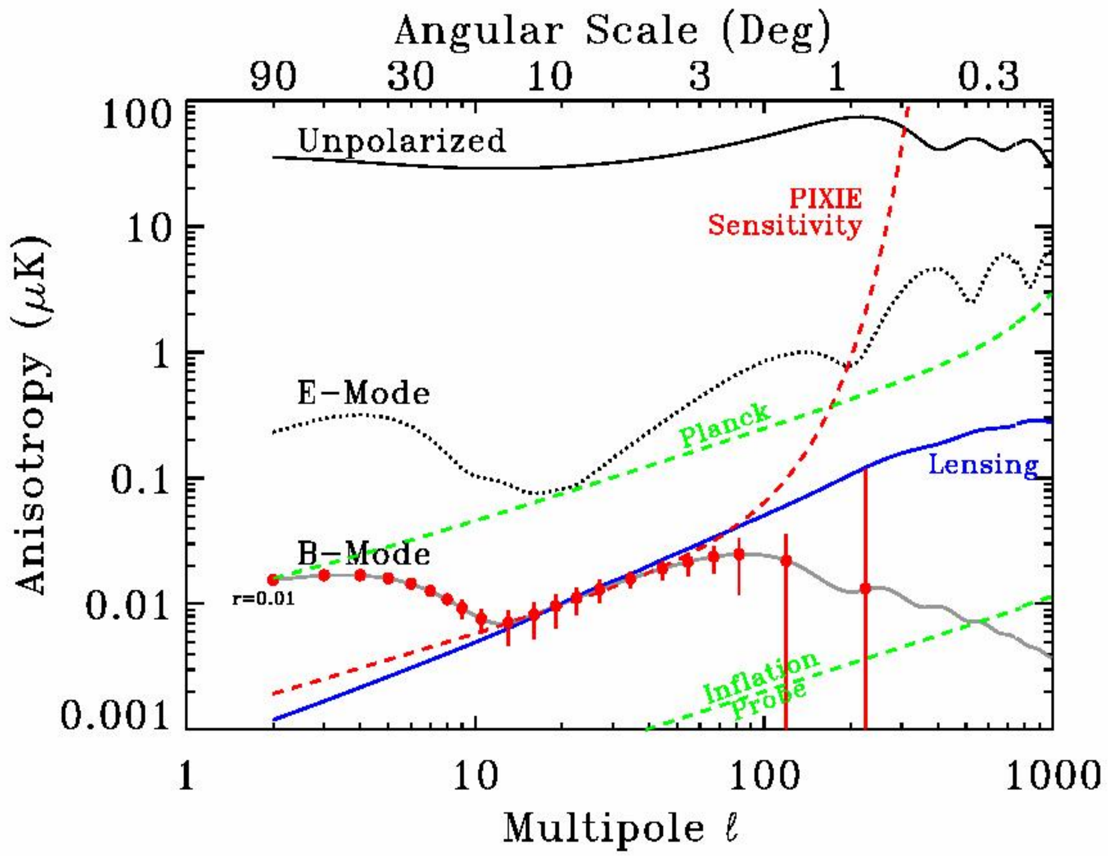
Galactic Structure

Assembly history of the Galaxy
Dust & chemical separation

**Secondar
y Science**

* Specifically called out in Astro-2010 Decadal Survey

Primary Science: Inflation

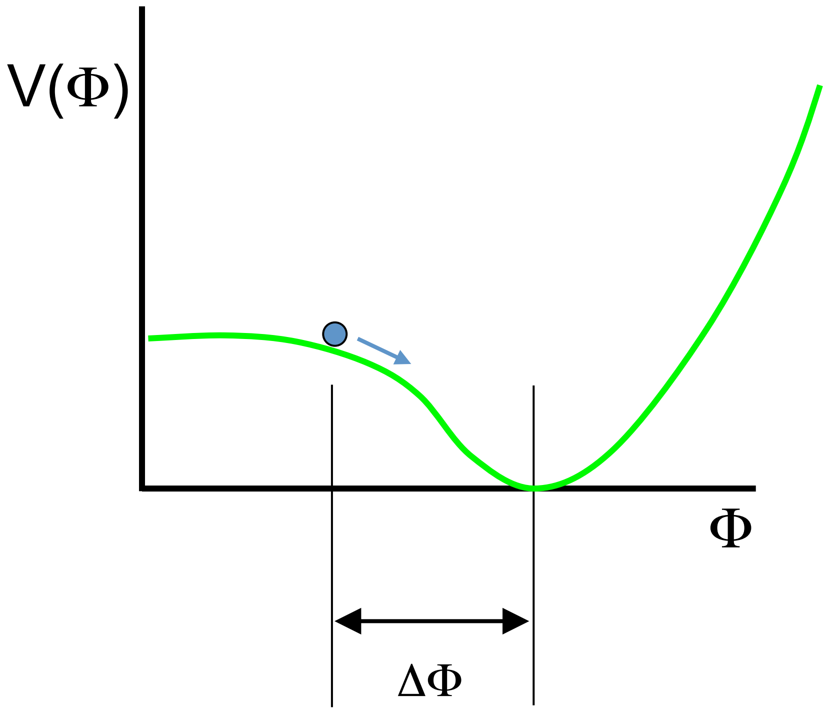


GUT-Scale Physics: $r < 10^{-3}$ at 5σ

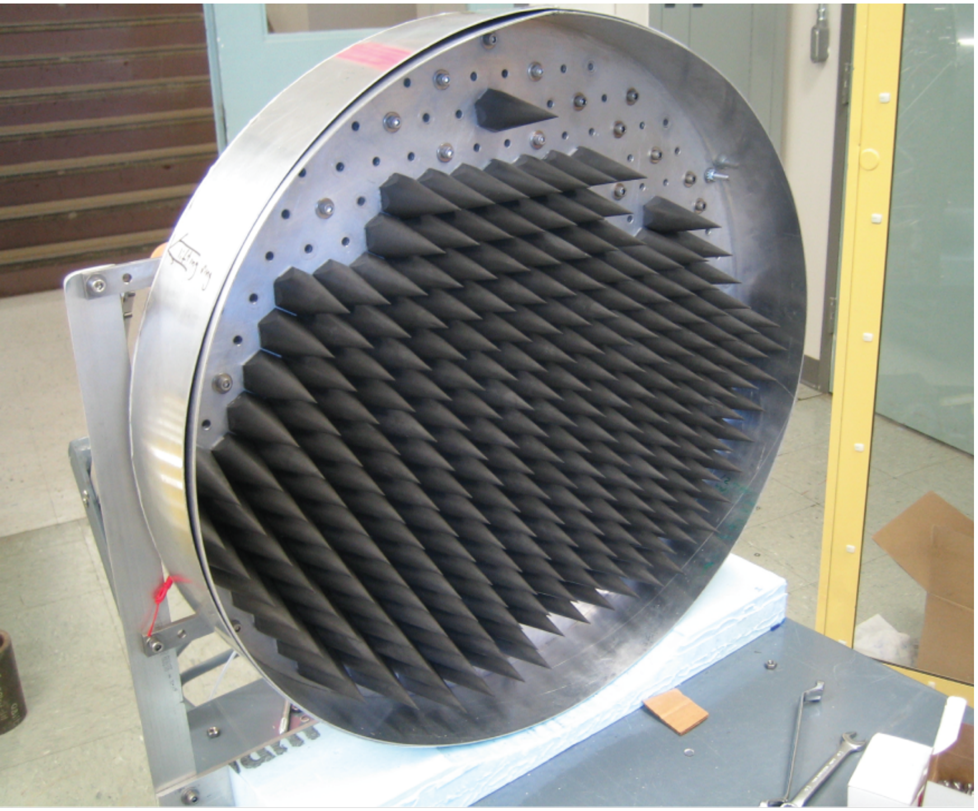
- Detect ~all large-field models
- Power spectrum to l~100
- Reach limit of lensing foreground

Planck-Scale Physics: Map B-Mode Polarization

- Consistency relation $r = -6.2\, n_t$
- Statistics of B-mode polarization field



Secondary Science: Inflation

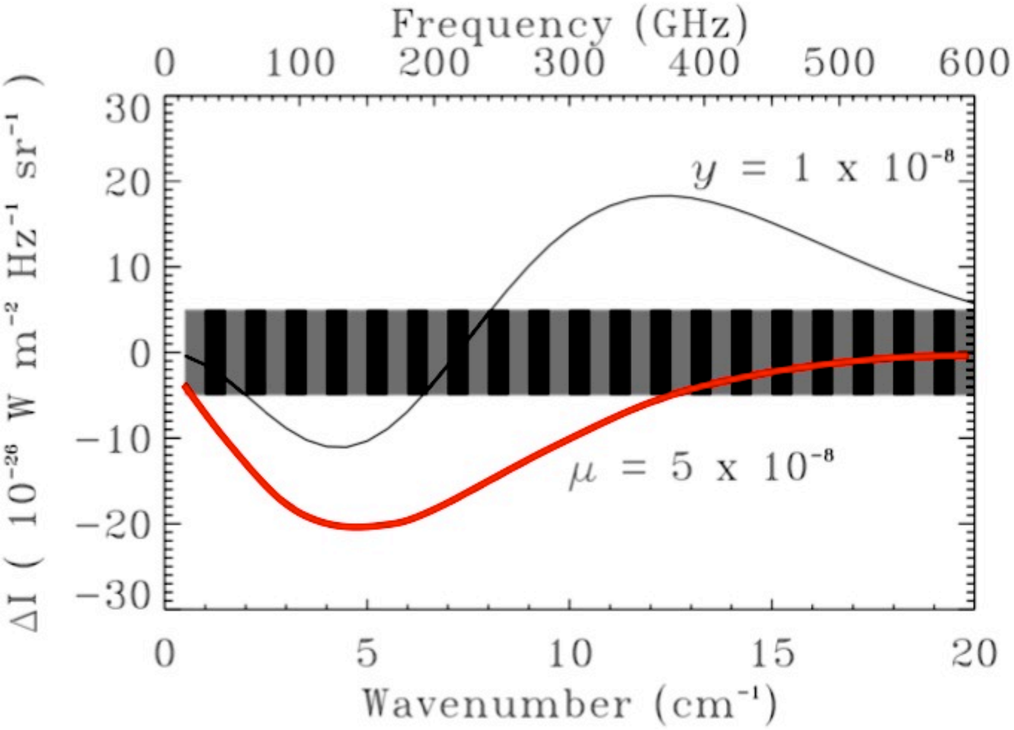


Blackbody calibrator: Spectral distortions

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

Energy release at $10^6 < z < 10^8$

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



Silk damping of primordial perturbations

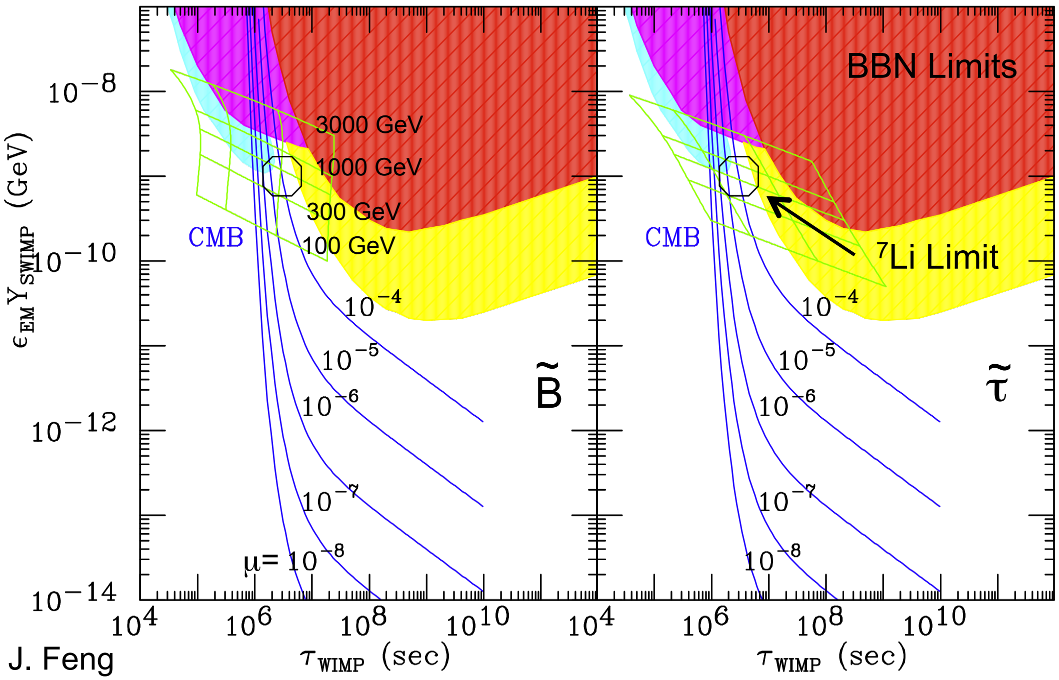
- Scalar index n_s and running dln n_s/dln k
- Physical scale ~1 kpc ($1M_{\odot}$)

Daly 1991
Hu, Scott, & Silk 1994
Khatri, Sunyaev, & Chluba 2011

Secondary Science: Dark Matter

Blackbody distortion from dark matter decay or annihilation

slepton decay



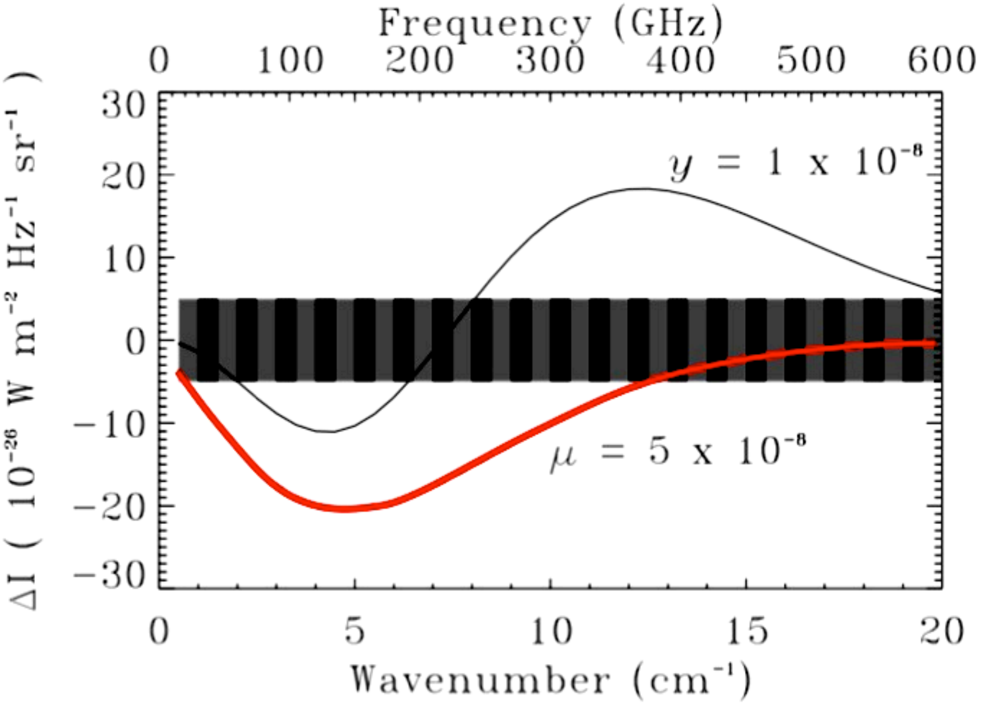
J. Feng

Energy release at $10^6 < z < 10^8$

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

Energy release $\Delta E \sim \Omega_{DM} \Gamma \Delta m$

Distort CMB from blackbody spectrum



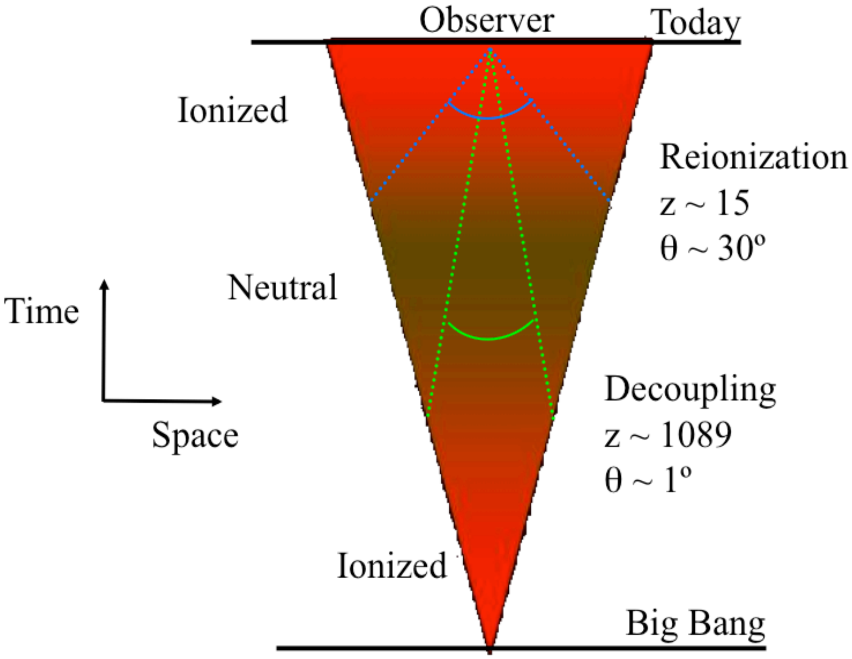
PIXIE limit $\mu < 10^{-8}$

Reach cosmological limit $\tau < 3 \times 10^6$ sec

Test of gravitino dark matter

McDonald et al 2001
de Vega & Sanchez 2010
Feng 2010

Secondary Science: Reionization

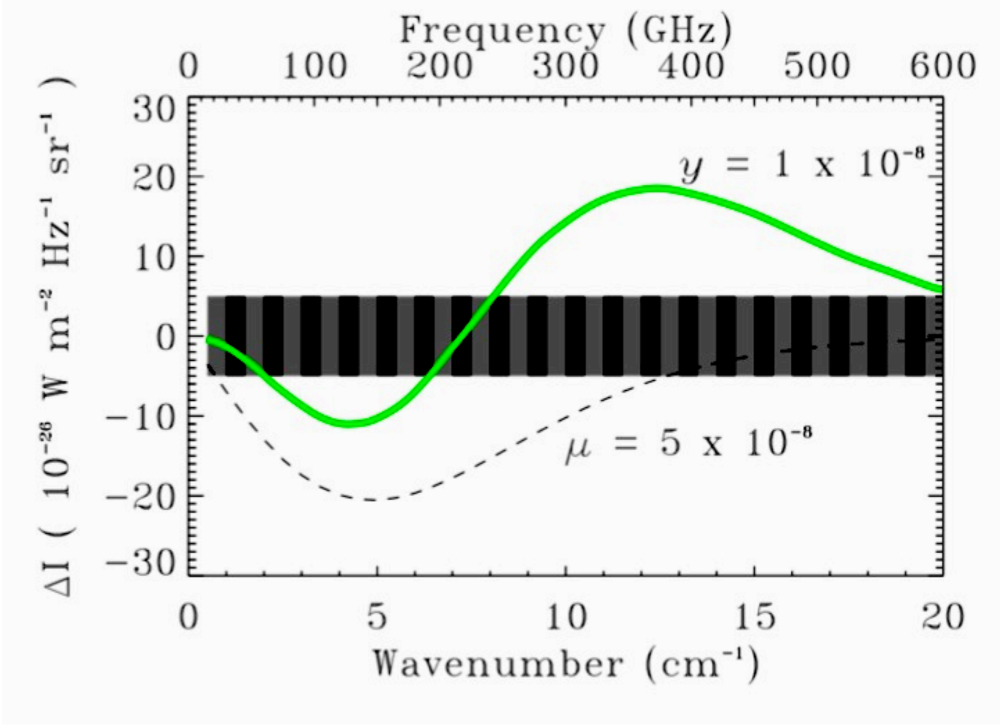


Polarization: Optical depth ~ Electron density n(z)

Angular scale ←→ Horizon at redshift *z*

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

- PIXIE limit $y < 5 \times 10^{-9}$
- Distortion must be present at $y \sim 10^{-7}$



Same scattering for both signals:

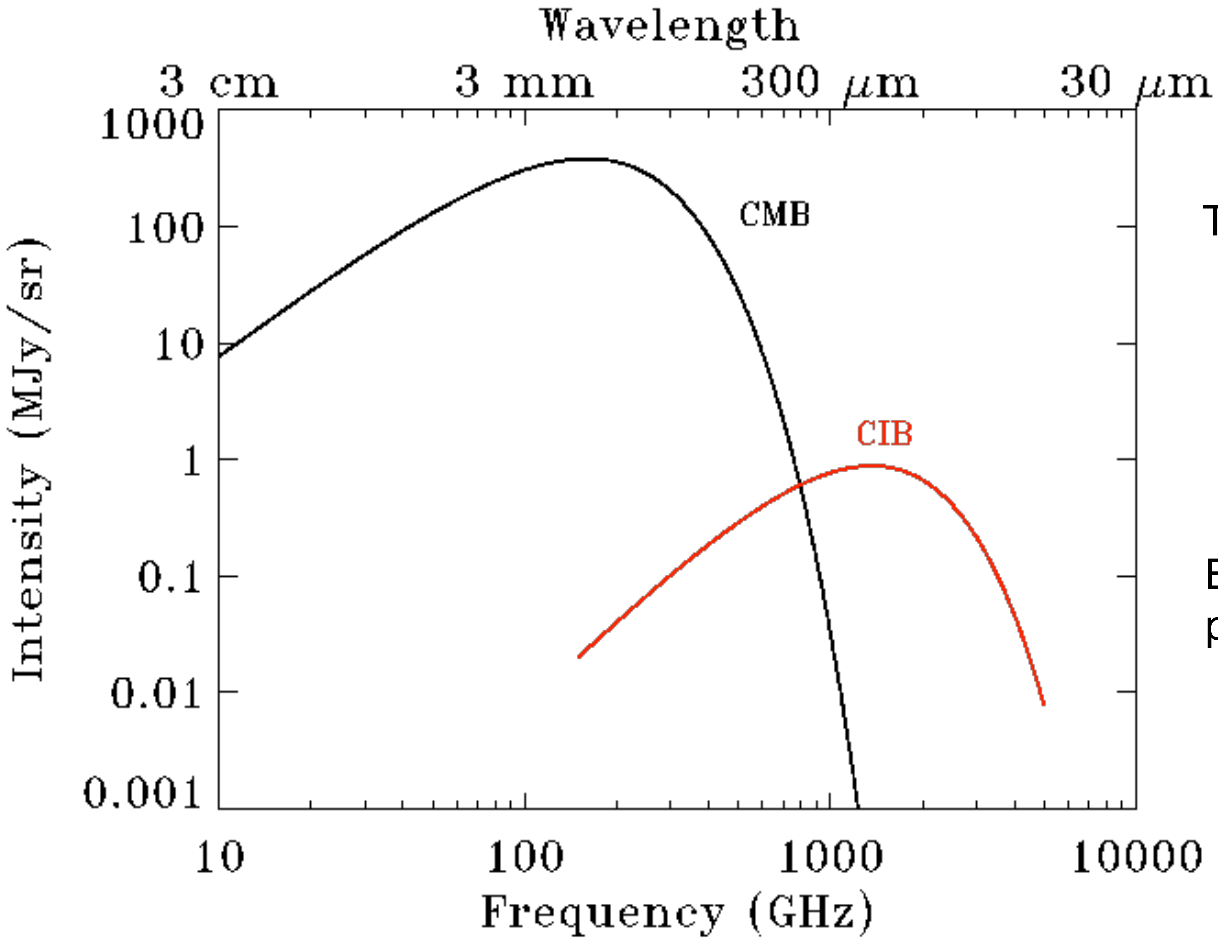
Combine to get n(z) and T_e

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

Determine nature of first luminous objects

Hu & Holder 2003

Secondary Science: Cosmic Infrared Background



Thermal Dust Emission from z ~ 1--3

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

Broad frequency coverage over CIB peak

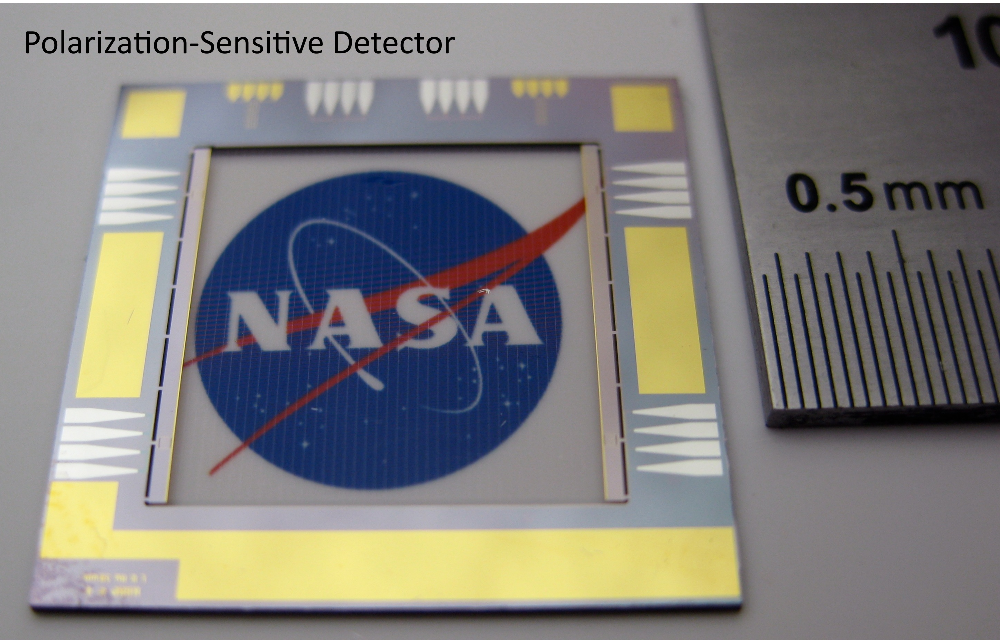
- Complement Herschel, Planck

PIXIE noise is down here!

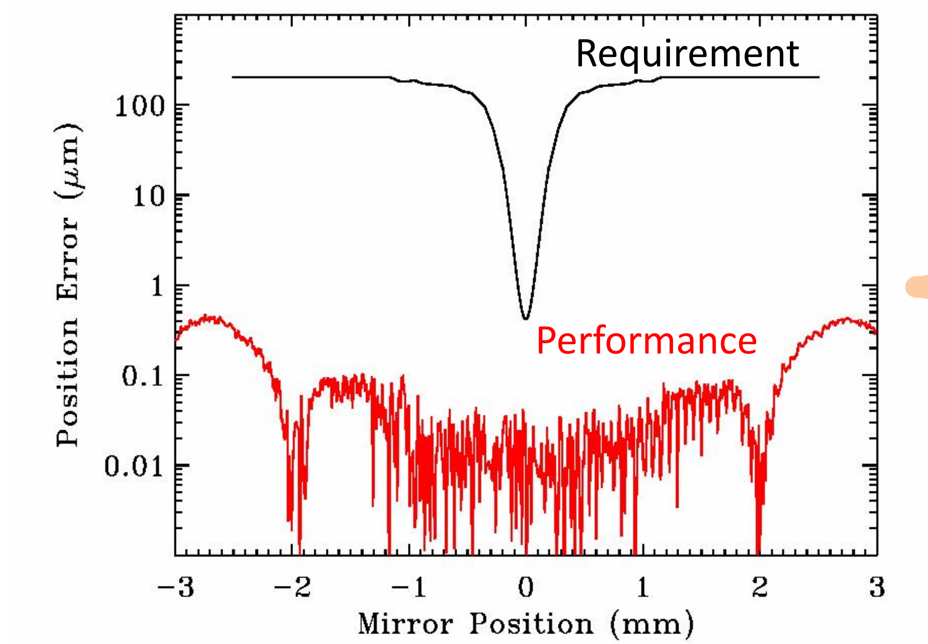
Knox et al. 2001
Fixsen & Kashlinsky 2011

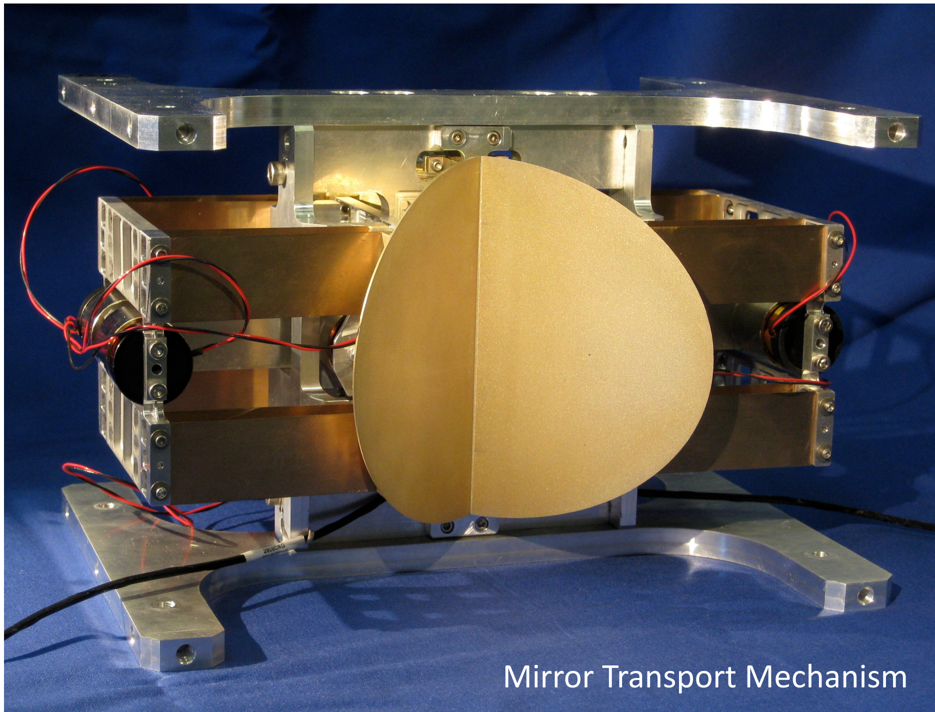
PIXIE Technology

Technologically Mature Implementation

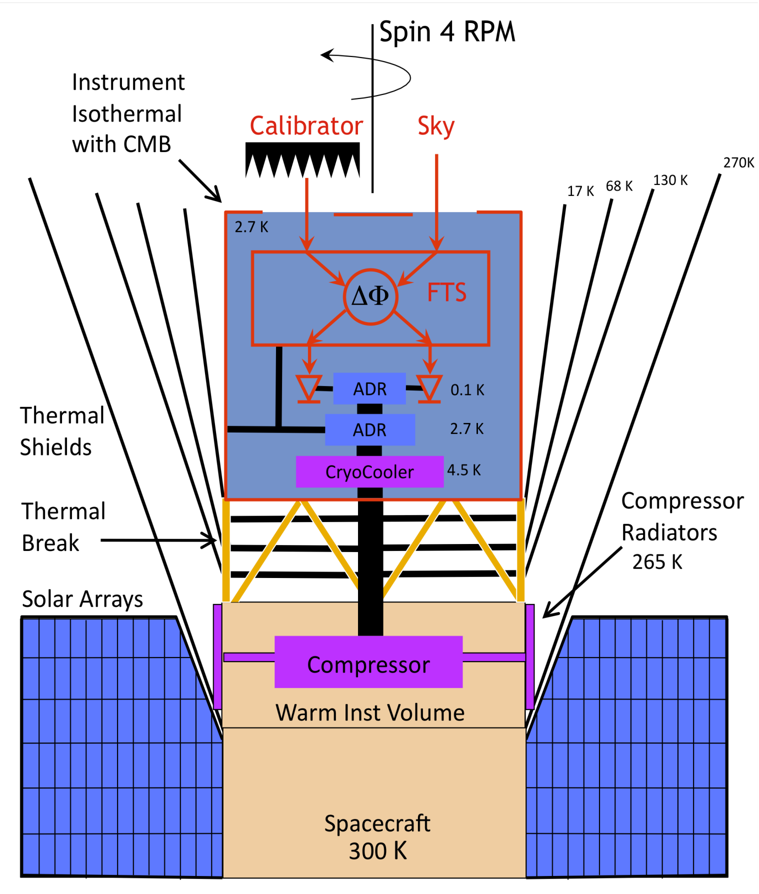

Polarization-Sensitive Detector

Parameter	Design	
Area	160 mm^2	
Fill Fraction	11%	
Frame Temperature	100 mK	
Absorber Temperature	140 mK	
	Requirement	**Performance**
NEP (W Hz$^{-1/2}$)	$<10^{-16}$	0.7×10^{-16}
Time Constant (ms)	<4	1
Cross-Pol at 150 GHz	<1%	0.1%




Mirror Transport Mechanism

Instrument Cryogenics



Fully cryogenic instrument

- Cryo-cooler to 4.5 K
- ADR to 2.7 K (instrument body)
- ADR to 0.1 K (detectors)

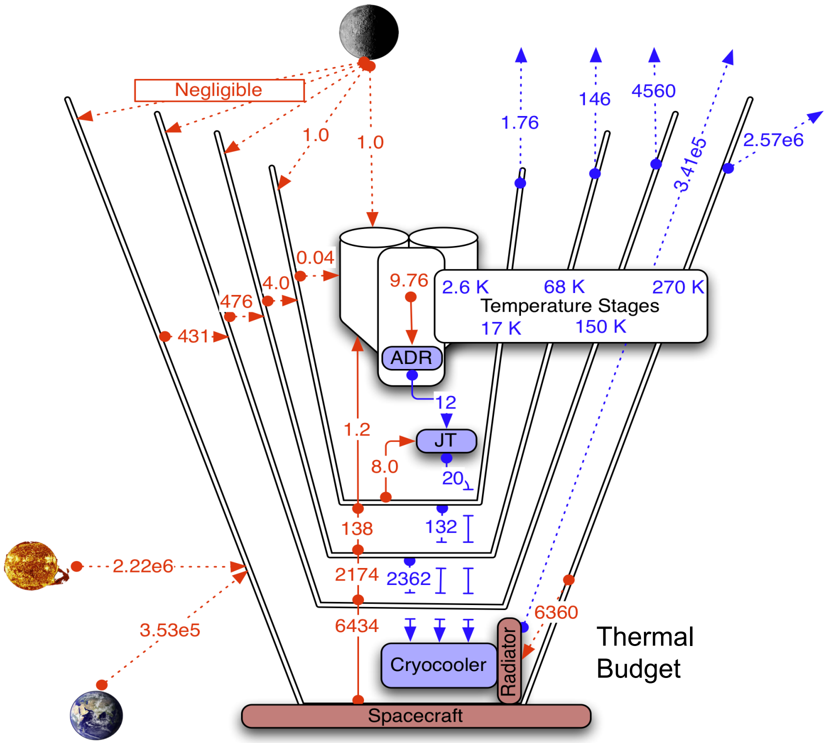
Active + Passive Cooling

- Cryo-cooler + ADR
- Radiator cools shields & compressor
- No view to Sun or Earth

Active control of cryogenic temps

- Instrument bus ~ 2.6 K
- Individual PID control of optical elements
- ADR entropy reserve

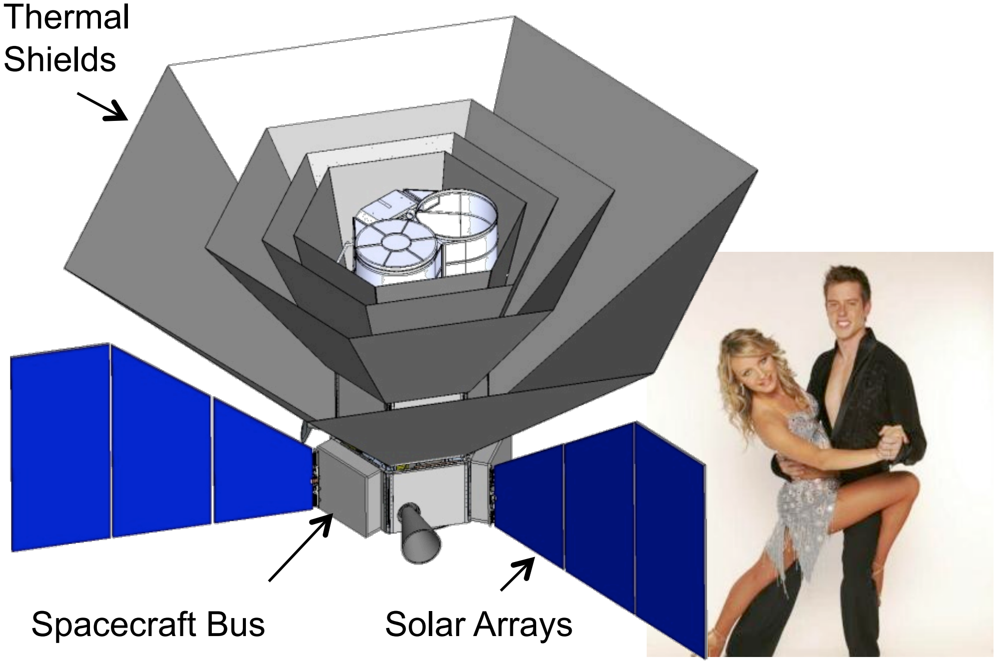
Cooler Stage	Stage Temp (K)	CBE Loads (mW)	Derated Capability (mW)	Contingency & Margin (%)
Stirling (Upper Stage)	68	2362	4613	95%
Stirling (Lower Stage)	17	132	278	111%
Joule-Thomson	4.5	20	40	100%
iADR	2.6	6	12	100%
dADR	0.1	0.0014	0.03	2043%



Thermal Budget

NOTE: Heat flow values in mW.

Observatory



Star Power (for scale)

Stowed in Taurus-I ELV