Testing The Standard Model with the Primordial Inflation Explorer

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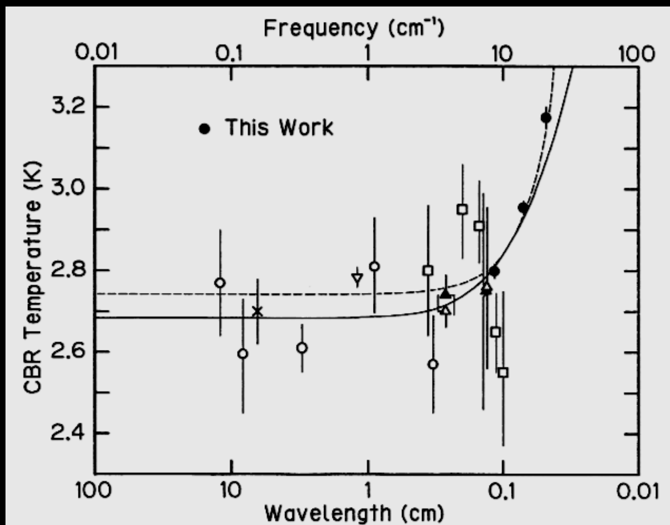
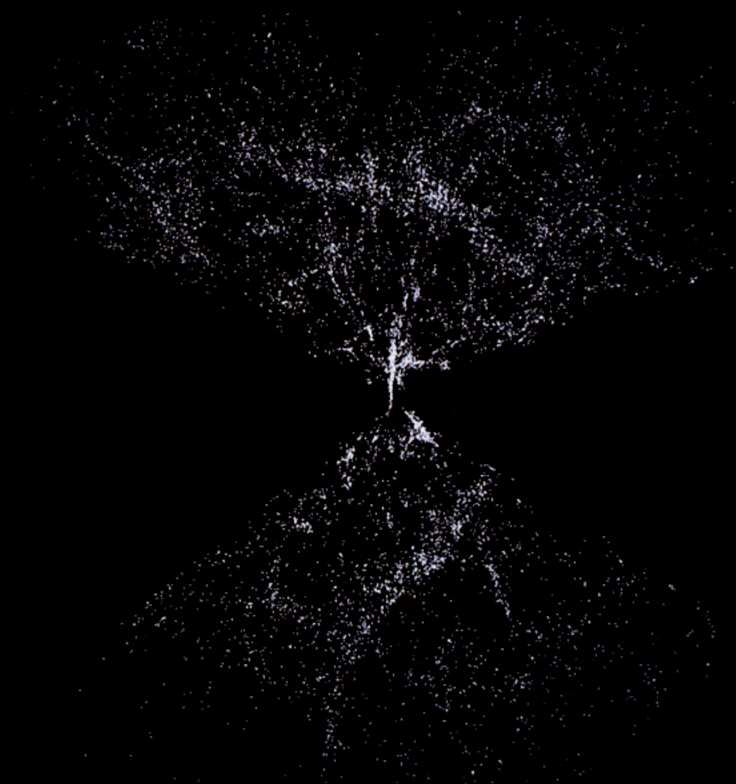
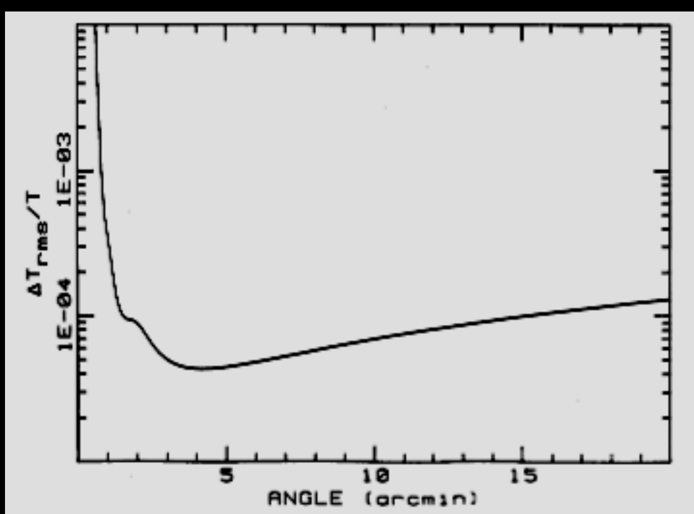
Cosmology at the Dawn of the Chalonge School



More Questions Than Answers (or data!)

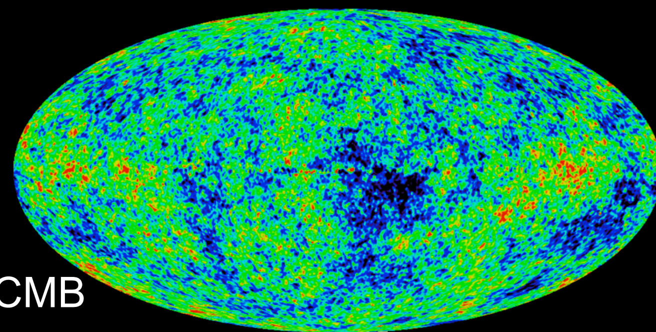
- CMB spectrum: Blackbody (maybe)
- CMB anisotropy: A moving target?
- Large Scale Structure: Open universe?
- Rotation Curves: Dark matter?



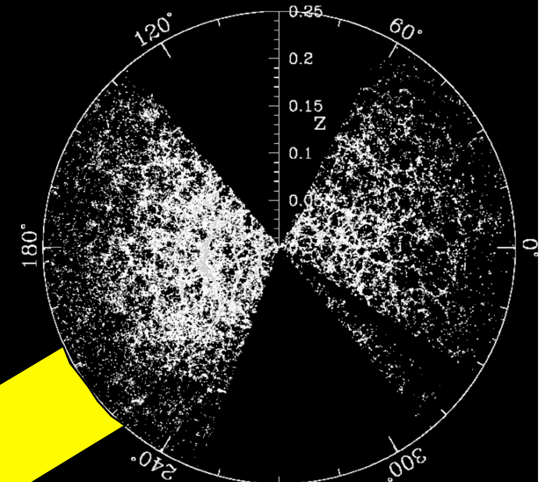


Today: "Precision Cosmology"

Lensing



CMB



Galaxy Surveys

ΛCDM

"Standard Model" for cosmology

$\Omega_b h^2 = 0.0226 \pm 0.0005$
$\Omega_c h^2 = 0.1123 \pm 0.0035$
$\Omega_\Lambda h^2 = 0.728 \pm 0.015$
$n_s = 0.963 \pm 0.012$
$\tau = 0.087 \pm 0.014$
$\sigma_8 = 0.809 \pm 0.024$

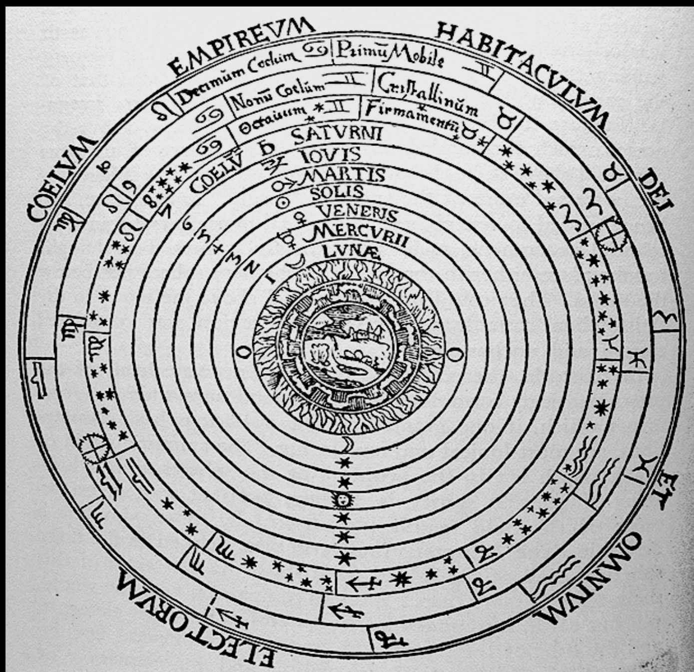
Successfully explains many disparate measurements

Komatsu et al. 2011, ApJS, 192:18

The Problem With Fitting Models

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

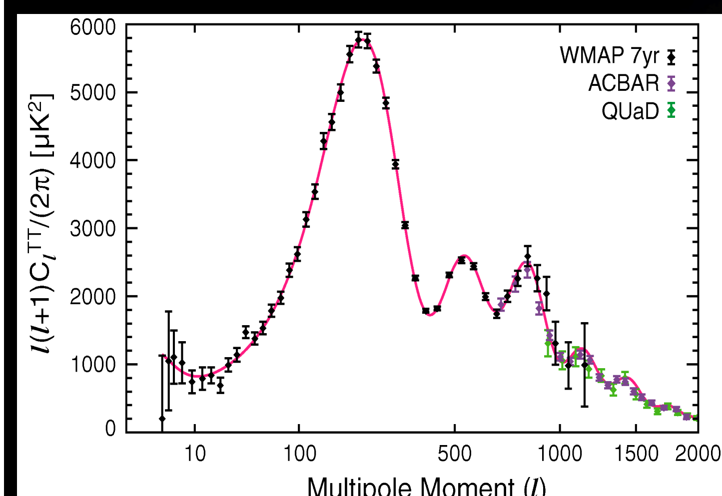
Testing the Standard Model

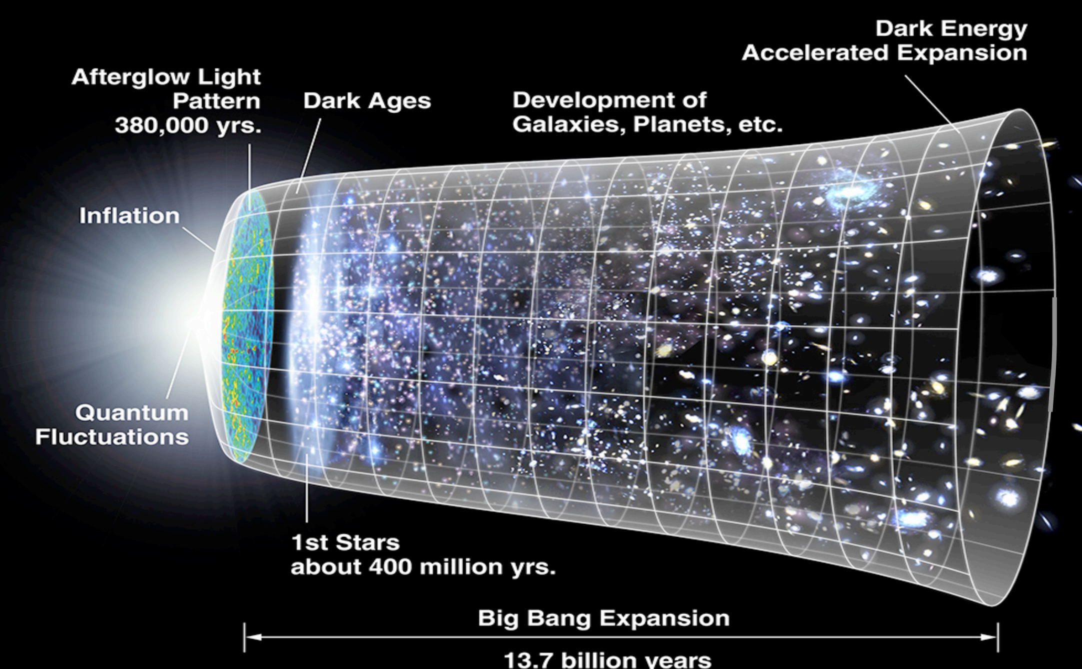


Parameterizing Ignorance

Dark Matter?
Dark Energy?
Inflation?

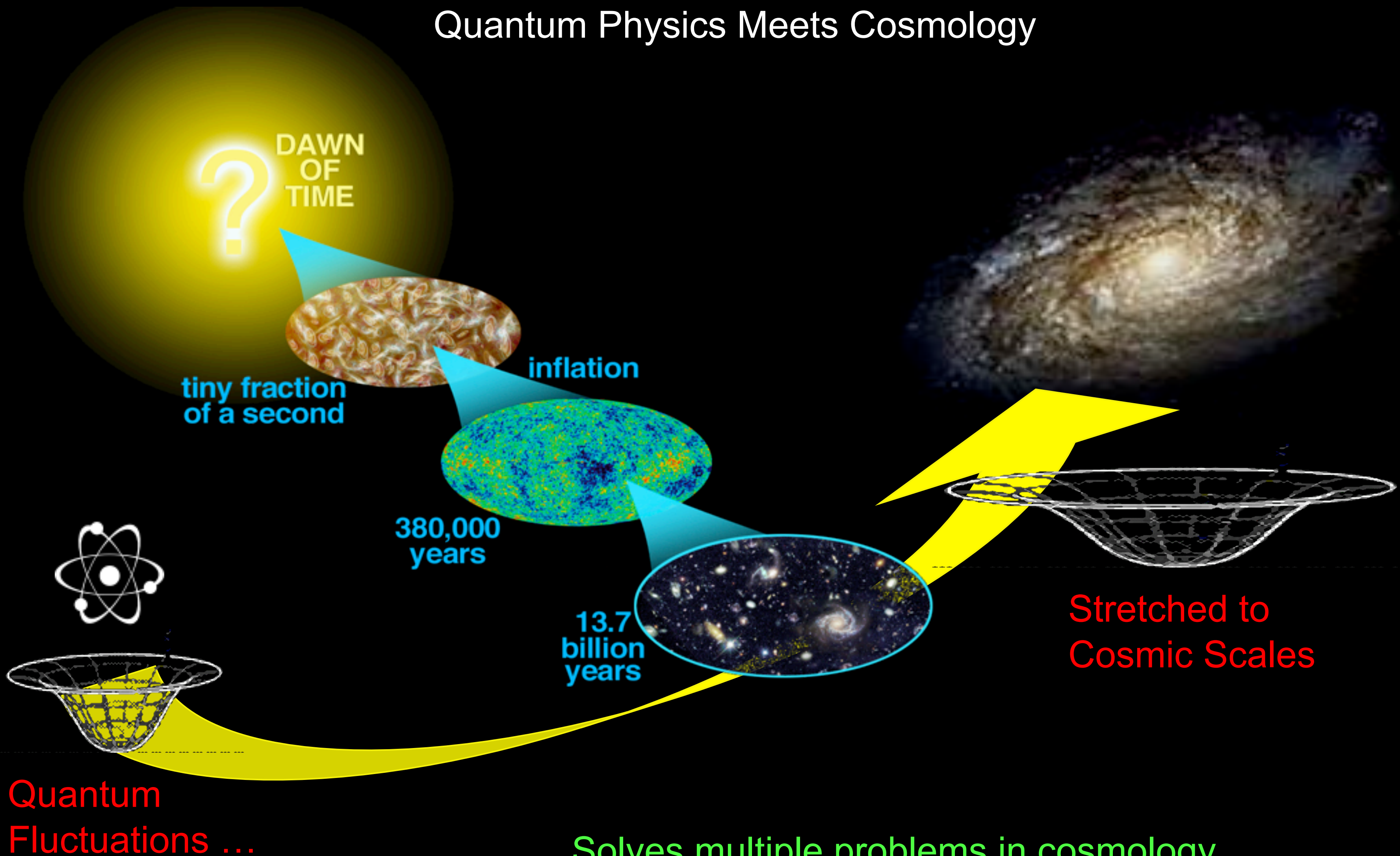
Critical need for New Data





Inflationary Paradigm

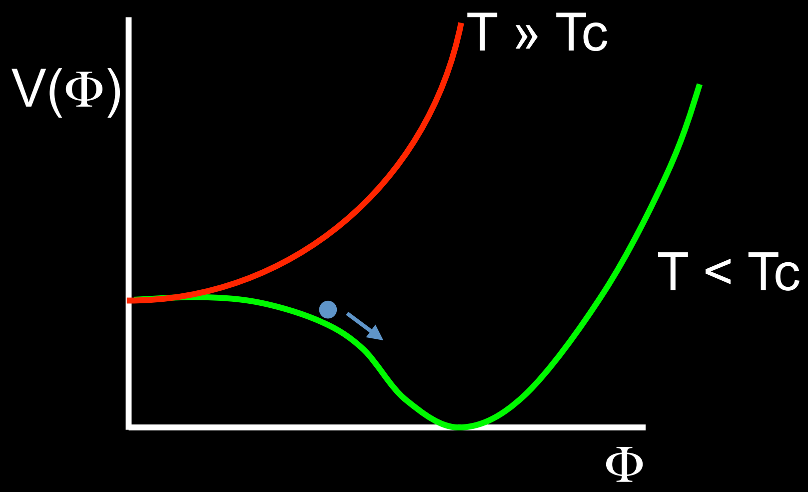
Quantum Physics Meets Cosmology



Solves multiple problems in cosmology (flatness, horizon, scale-invariant spectrum) at cost of bold (!) extrapolation in energy

Gravity Waves and Inflation

Vacuum energy density drives exponential expansion



Inflationary Condition $V >> \dot{\Phi}^2$

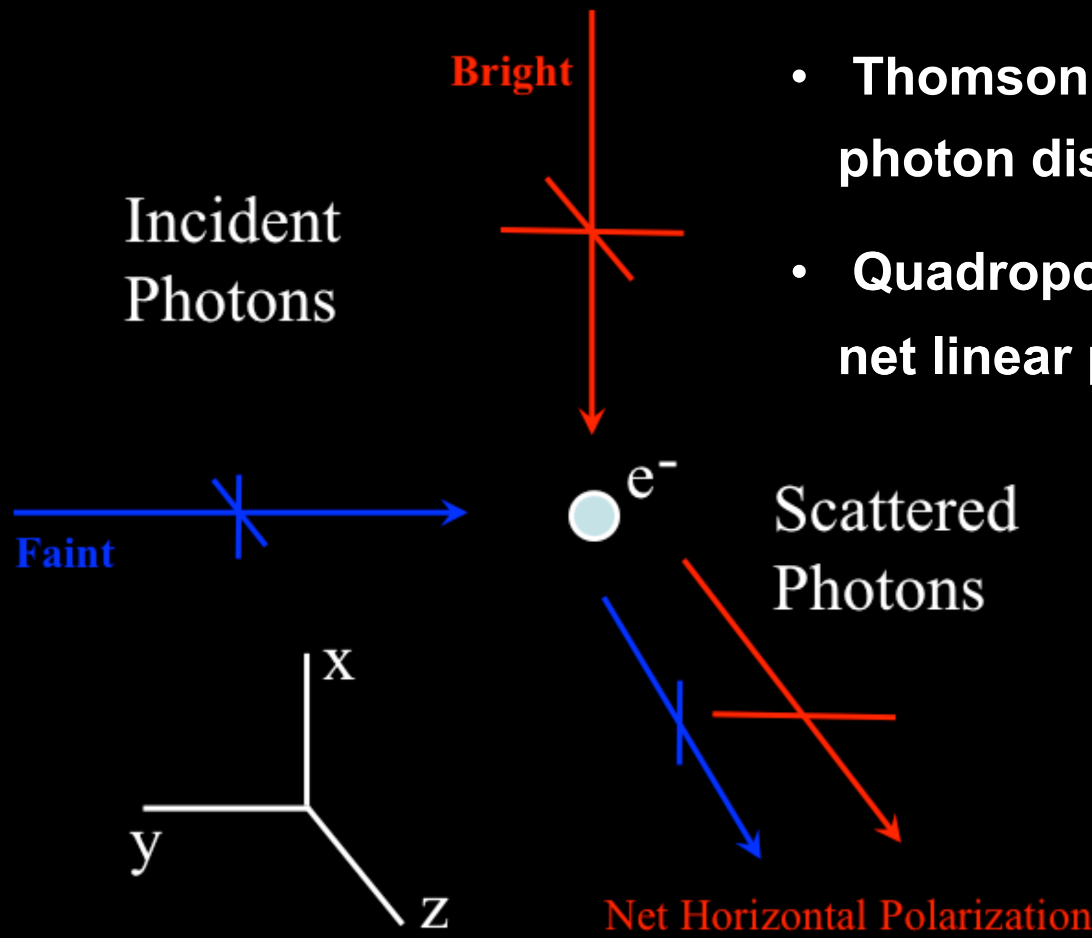
Hubble Constant $H^2 \sim \dfrac{V}{M_{PL}^2}$

Tensor Perturbations $P_T \sim \dfrac{H^2}{M_{PL}^2}$

Energy Scale of Inflation: $P_T \sim V / M_{PL}^4$

$$V^{1/4} \approx 10^{16}\ \text{GeV} \left(\frac{r}{0.01}\right)^{1/4}$$

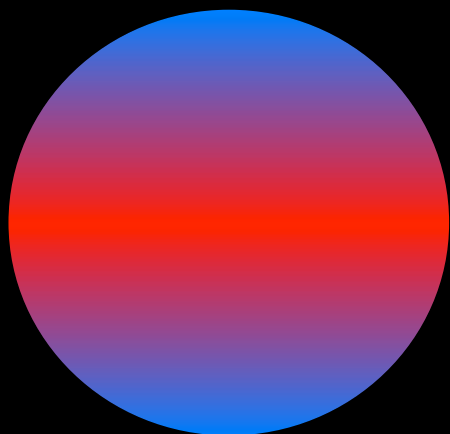
Physics of CMB Polarization



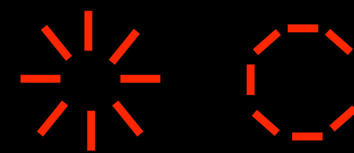
- **Thomson scattering of anisotropic photon distribution by free electrons**
- **Quadropolar anisotropy produces net linear polarization**

Whole New Look at Early Universe

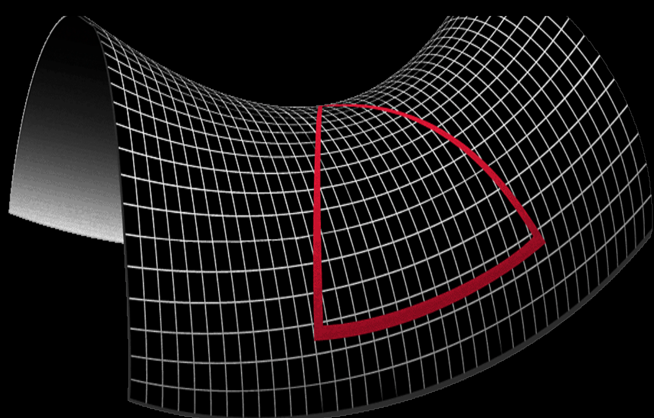
Source Terms for Polarization



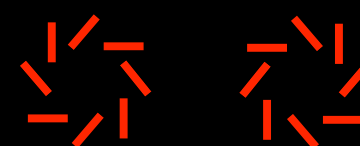
Temperature Quadrupole
Scalar Source
Gradient (“E mode”) Pattern



E Modes
Even Parity

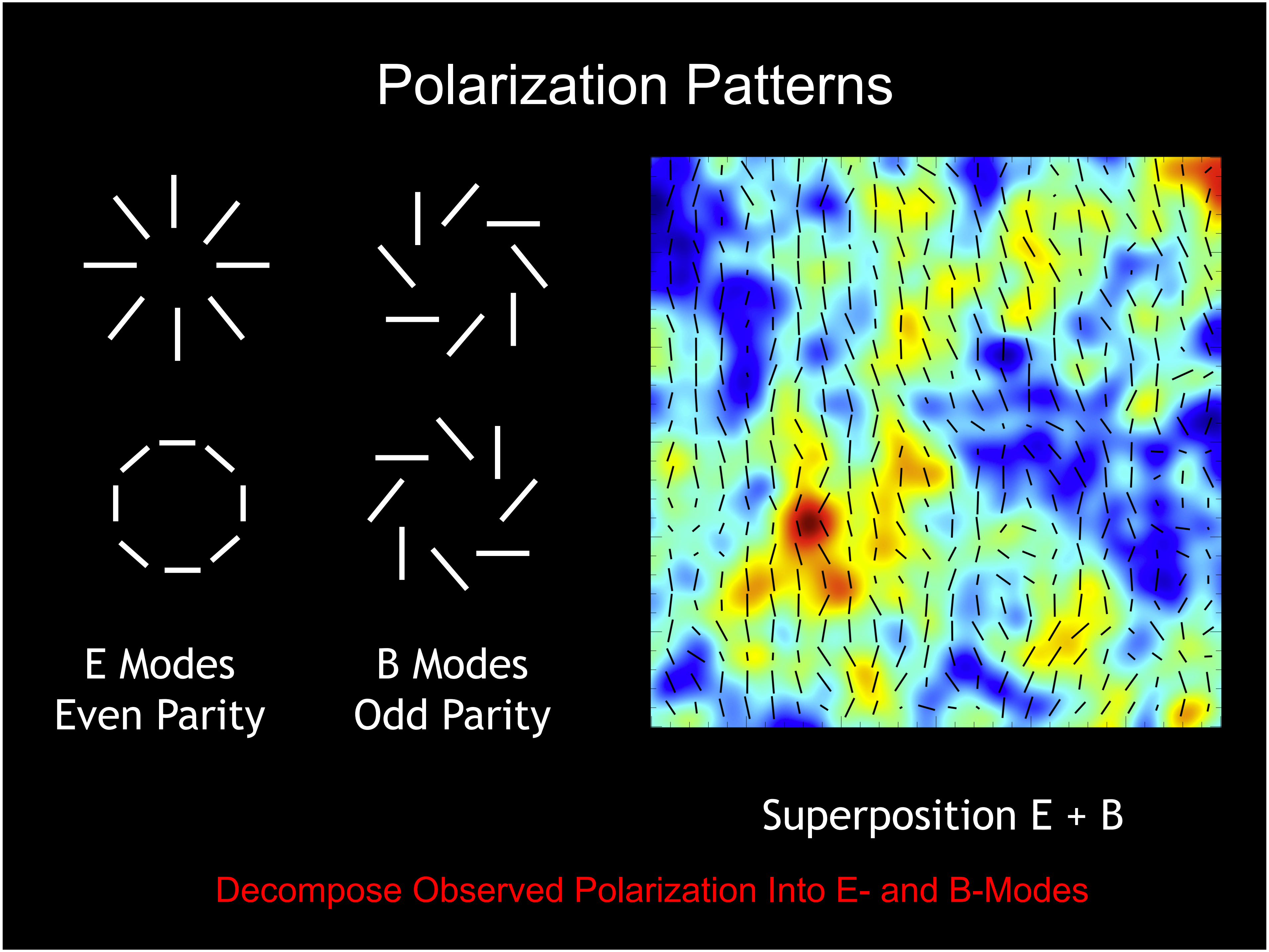


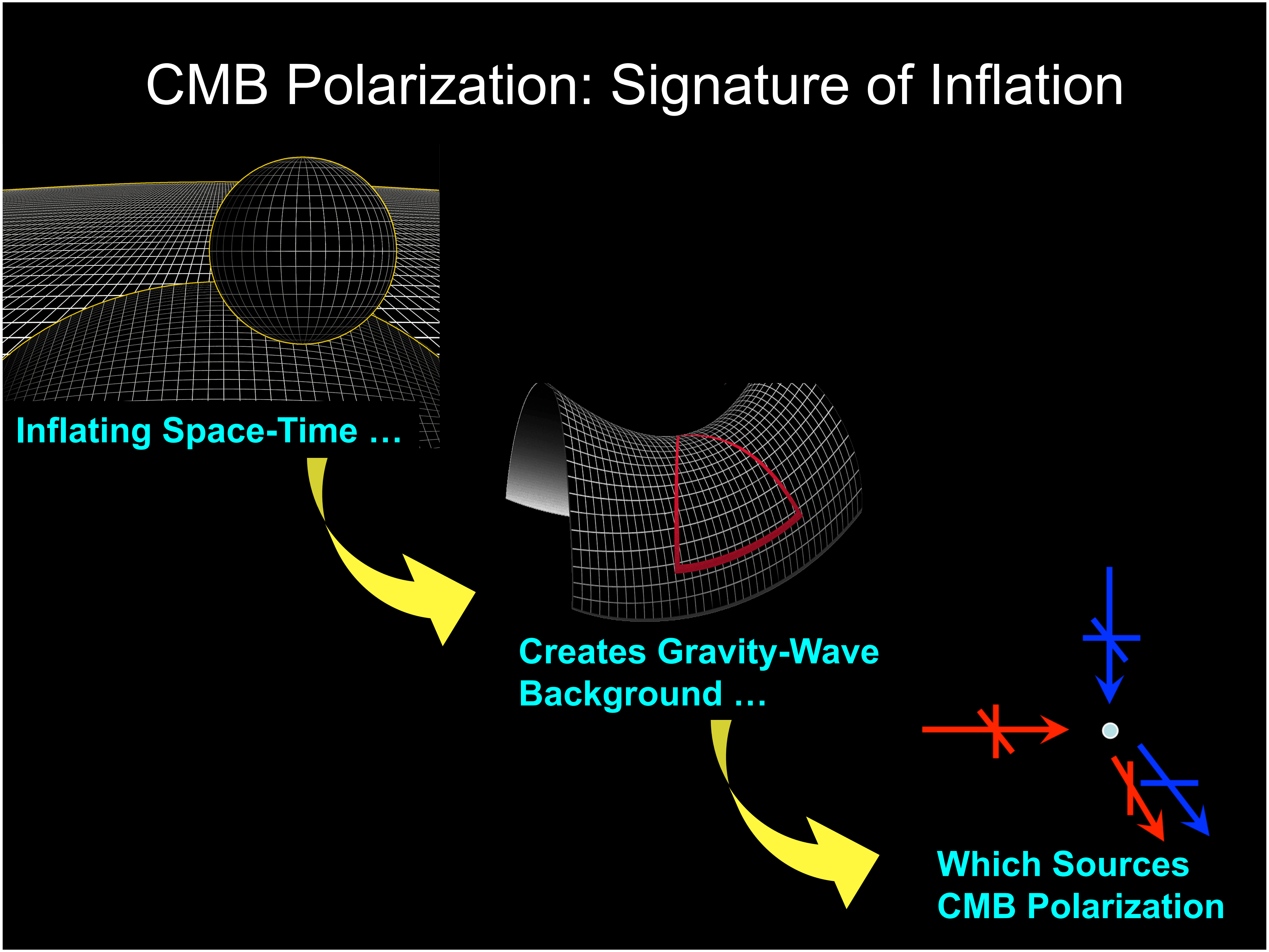
Gravity Wave
Tensor Source
Gradient (“E mode”) Pattern
Curl (“B mode”) Pattern



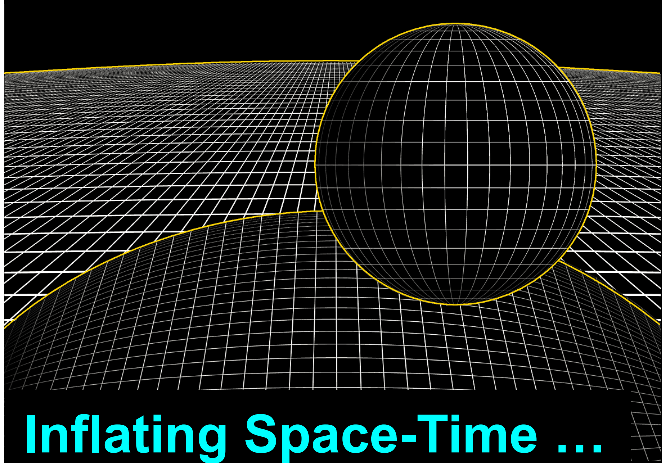
B Modes
Odd Parity

B-mode Polarization: “Smoking Gun” Signature of Inflation


Polarization Patterns
E Modes
Even Parity
B Modes
Odd Parity
Superposition E + B
Decompose Observed Polarization Into E- and B-Modes

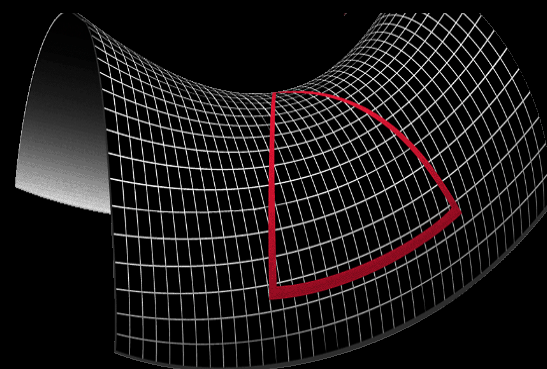

CMB Polarization: Signature of Inflation
Inflating Space-Time …
Creates Gravity-Wave
Background …
Which Sources
CMB Polarization

CMB Polarization: Signature of Inflation

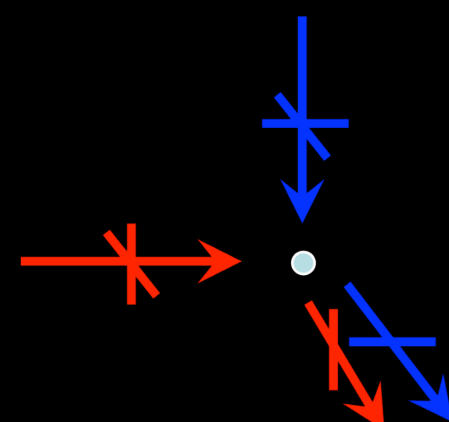


Inflating Space-Time …

So if we detect
B-mode polarization …



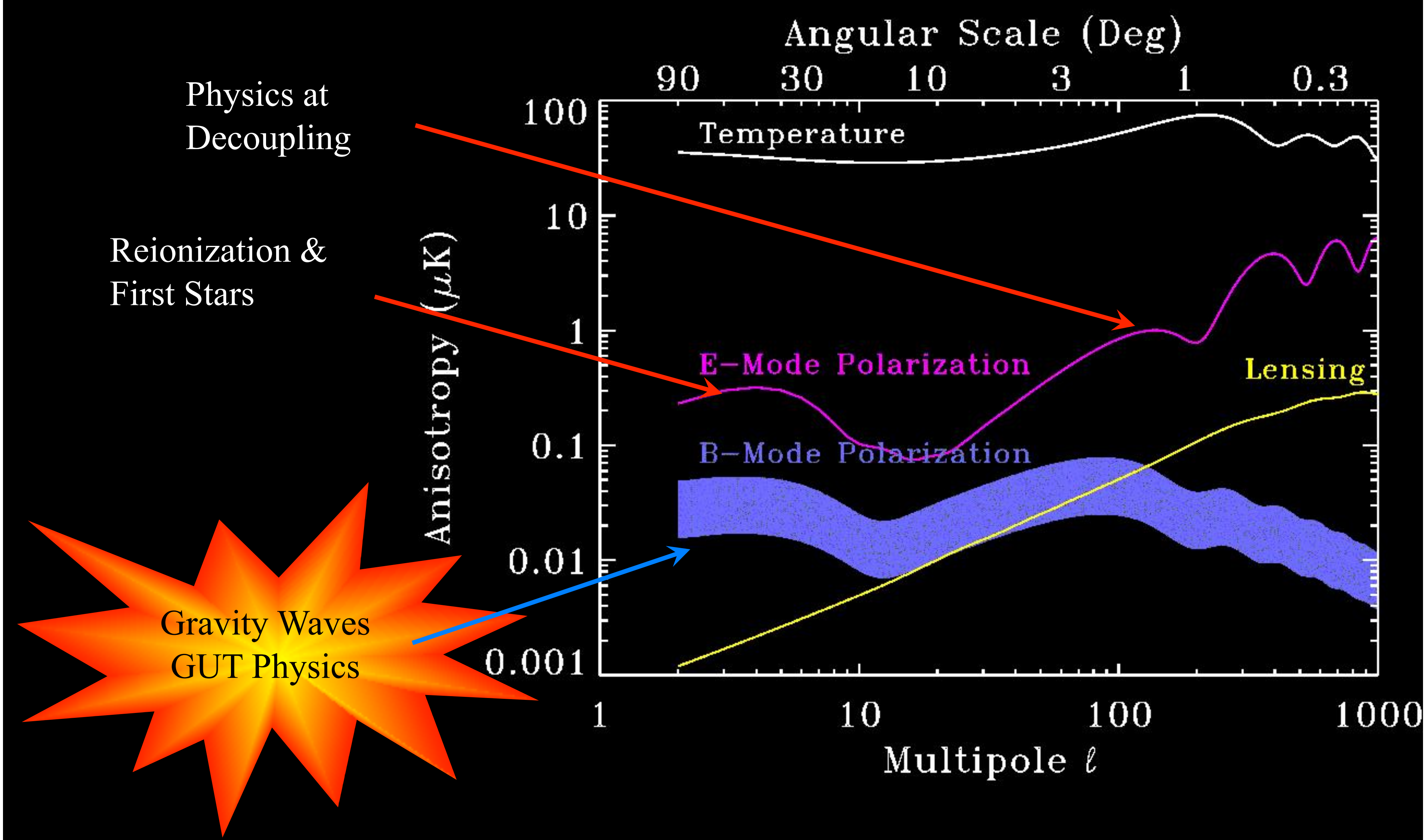
Creates Gravity-Wave Background …



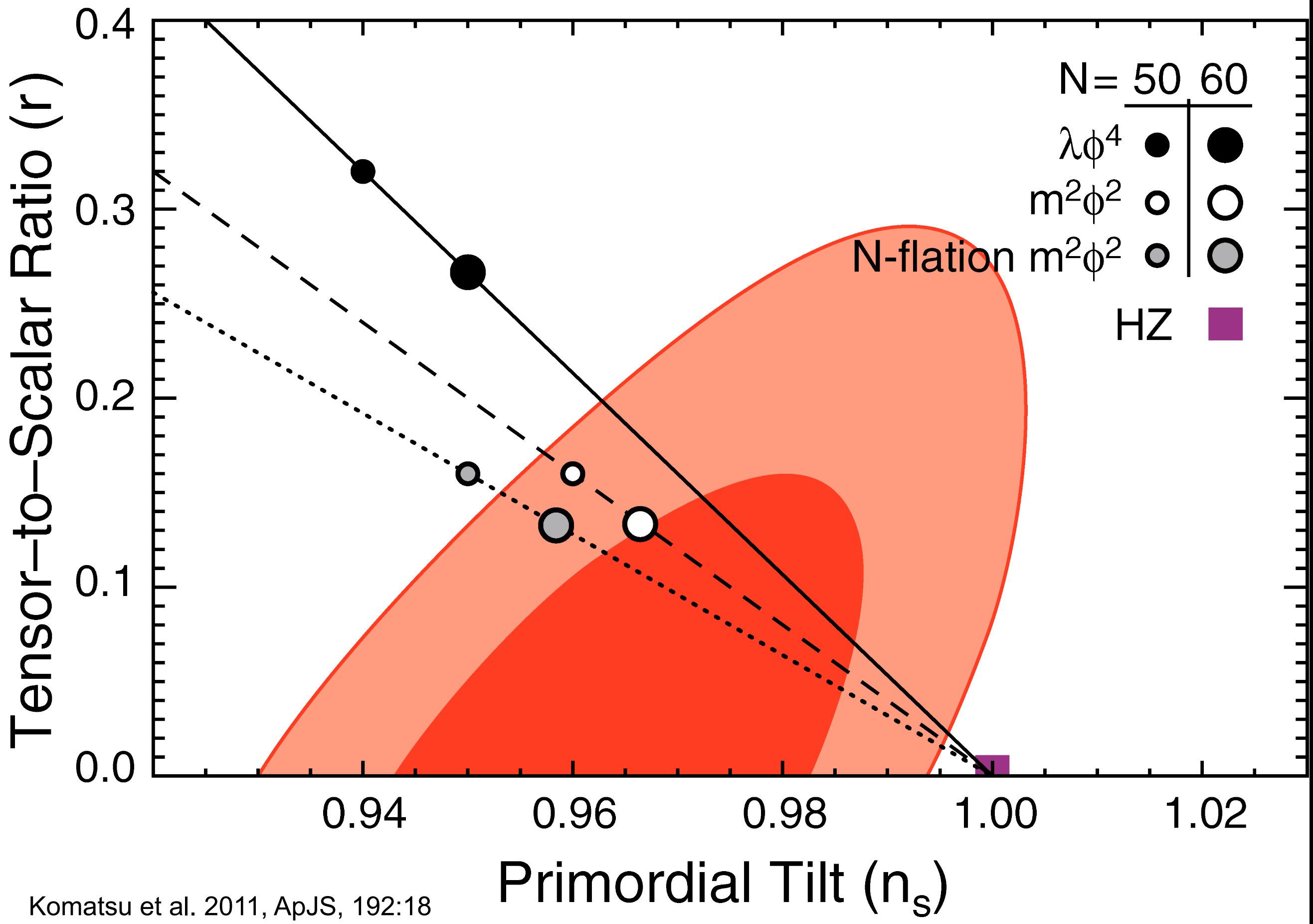
Which Sources CMB Polarization

… Then We Know
- Inflation Is Real
- Determine Energy Scale
- Gravity Near Planck Scale

CMB Polarization: Testing The Standard Model



Theory Predicts Observable Signal

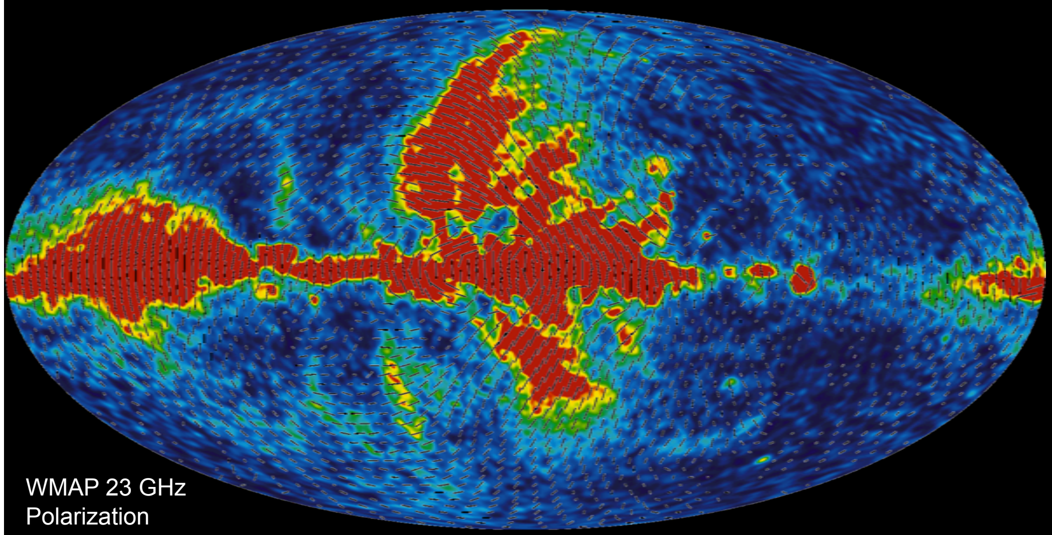


Komatsu et al. 2011, ApJS, 192:18

Departure from scale-invariance predicts $0.02 < r < 0.15$

$r \sim 0.02 \rightarrow \Delta P \sim 30$ nK $\rightarrow \Phi \sim 10^{16}$ GeV

So What's The Problem?

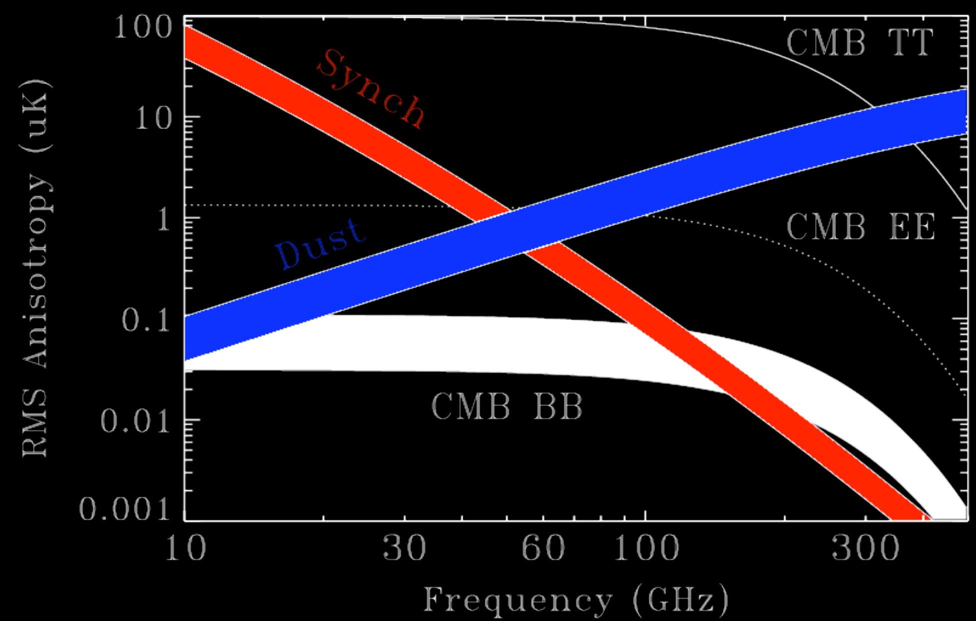


WMAP 23 GHz
Polarization

Signal is faint
Foregrounds are bright
Everything is confusing

Requirements for B-Mode Detection

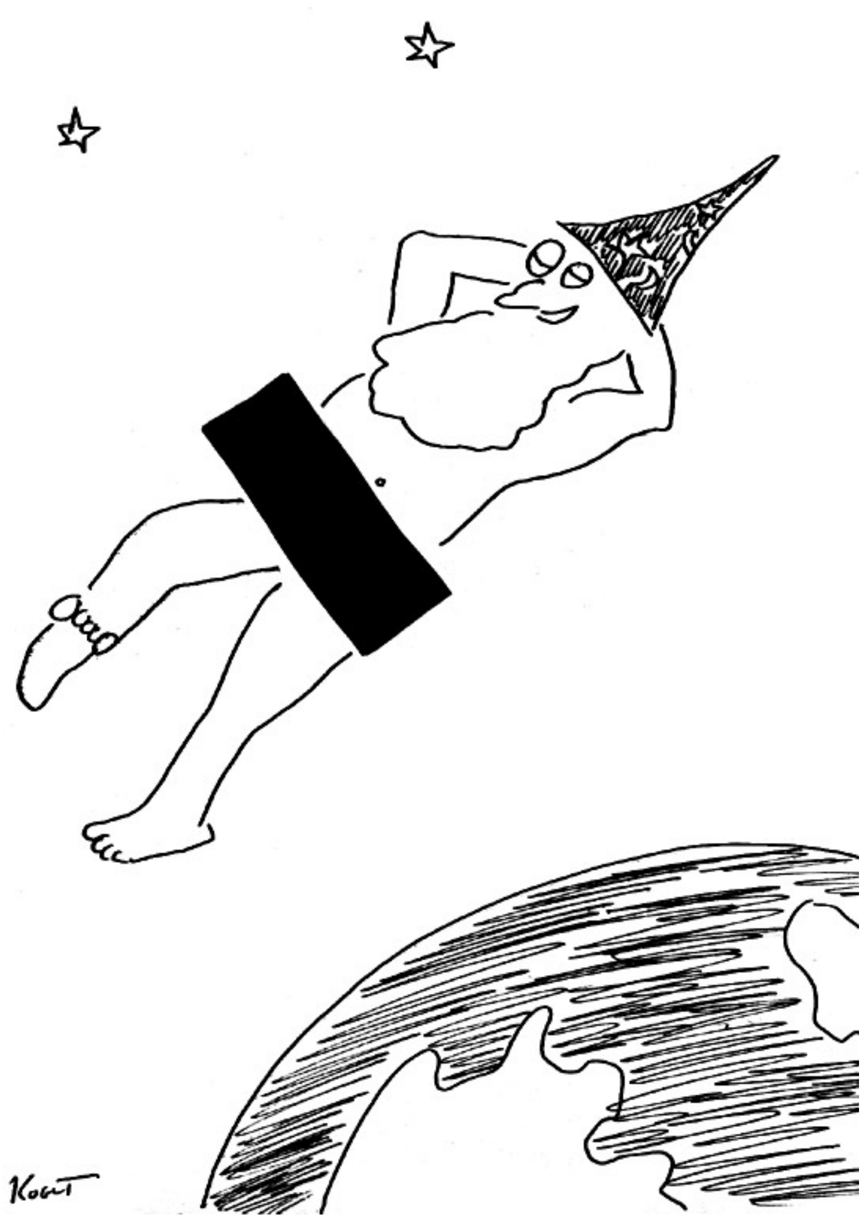
- Sensitivity
- Foreground Subtraction
- Systematic Error Control



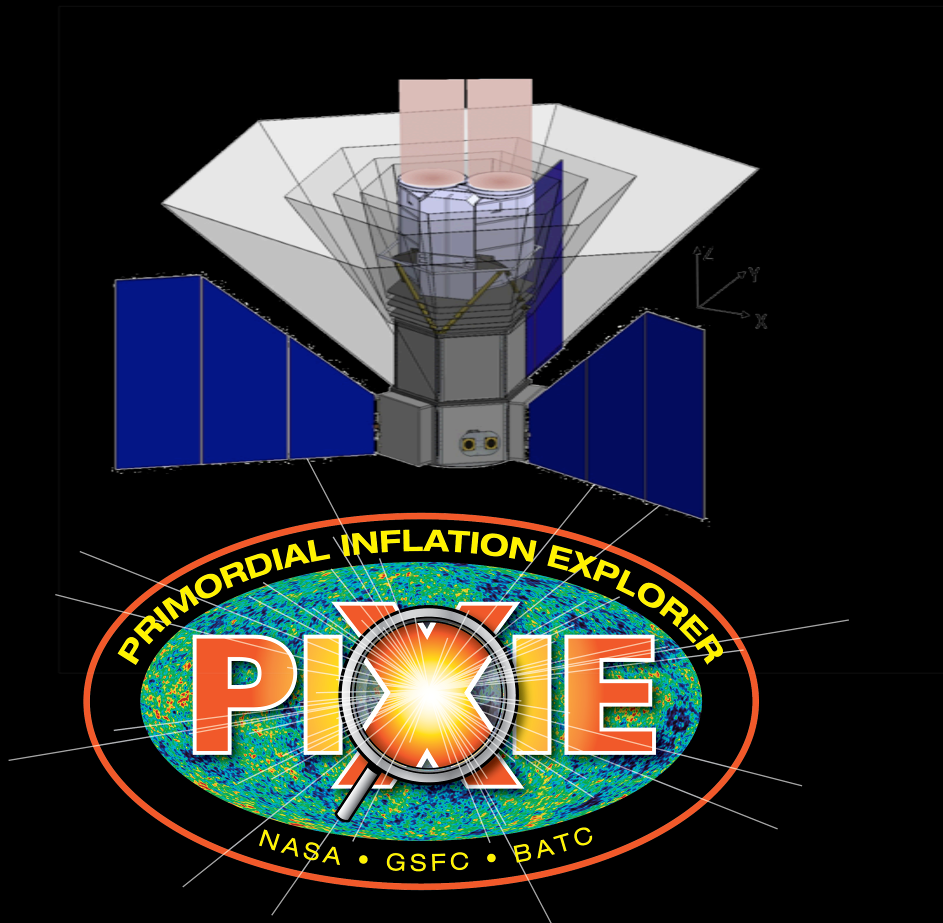
The Problem With Ground-Based Cosmology

Balloons Help, But Only A Little …

The Obvious Solution



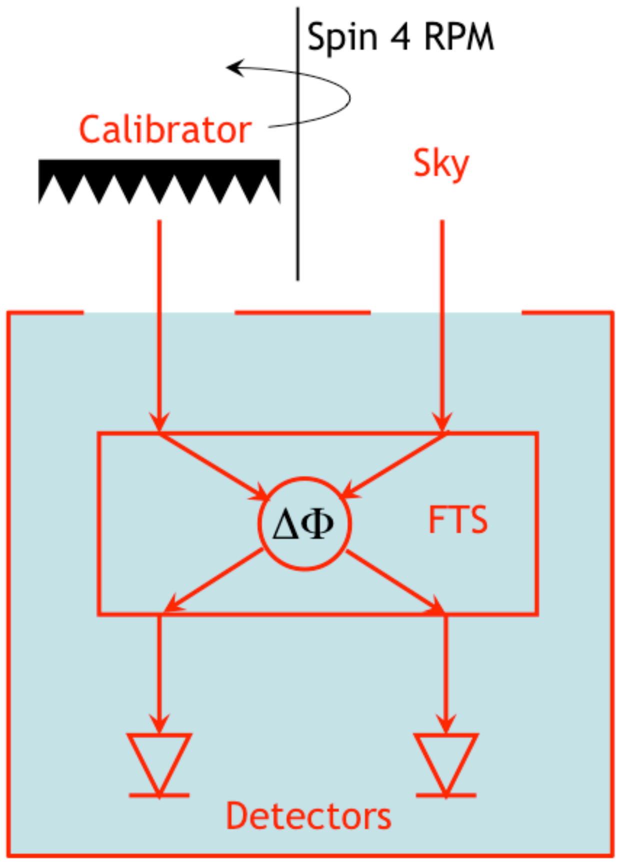
Primordial Inflation Explorer



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 Foreground

PIXIE Nulling Polarimeter



Sensitivity: Photon Shot Noise

Need more photons (not necessarily more detectors)
Solution: Multi-moded "light bucket"
Collect 44,000+ modes on just 4 detectors

Frequency Coverage: Foreground Subtraction

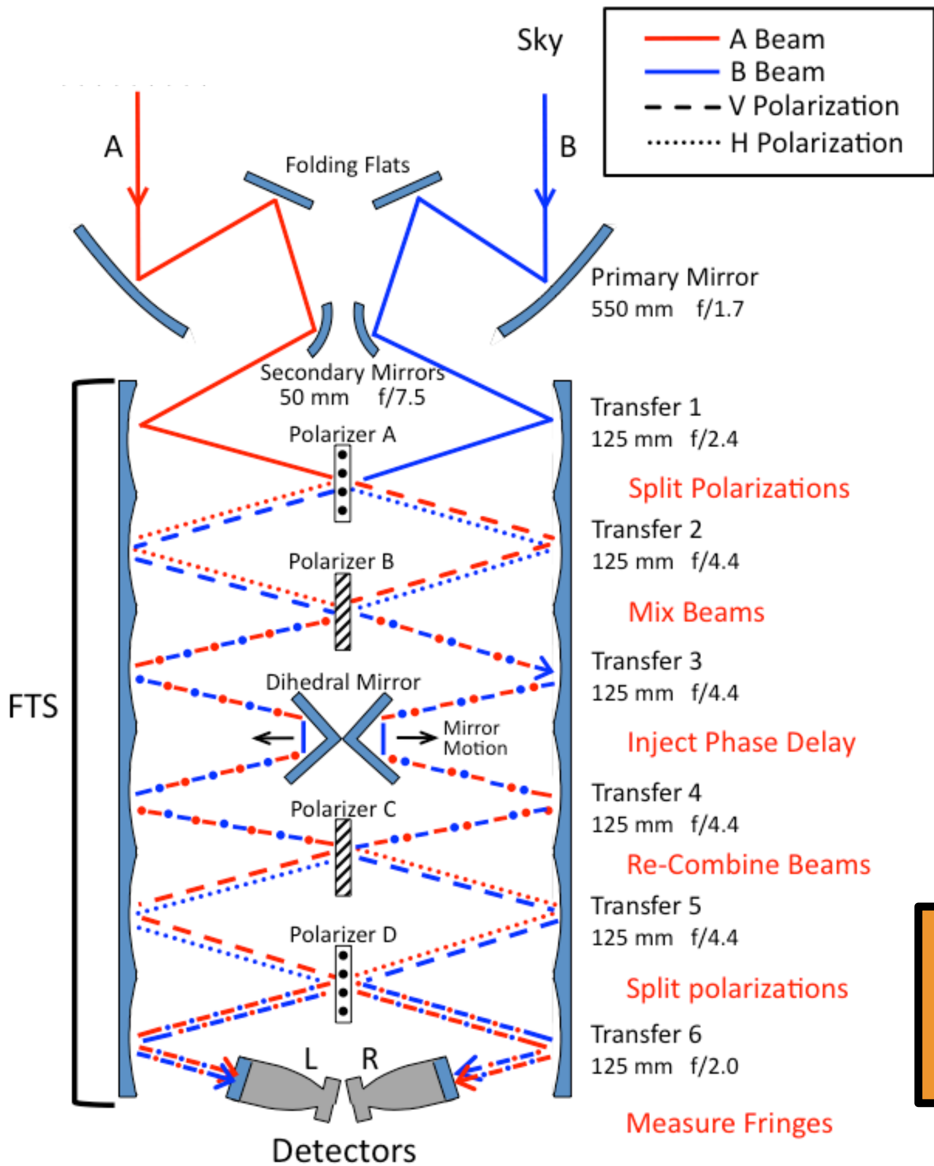
Need more frequency channels than foreground parameters
Solution: Fourier Transform Spectrometer
400 spectral channels from 30 GHz to 6 THz (1 cm to 50 μm)

Systematic Errors: Symmetries

Control instrument signature to few-nK level
Solution: Nulling polarimeter
Multiple symmetries provide multiple rejections

Measure $r < 10^{-3}$ (5σ) Using Only 4 Detectors

Fourier Transform Spectrometer



Take Observed Fringes ...

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

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

... Fourier Transform ...

$$S_\upsilon = \sum_{k=0}^{N-1} P_k \exp(2\pi i k\upsilon/N)$$

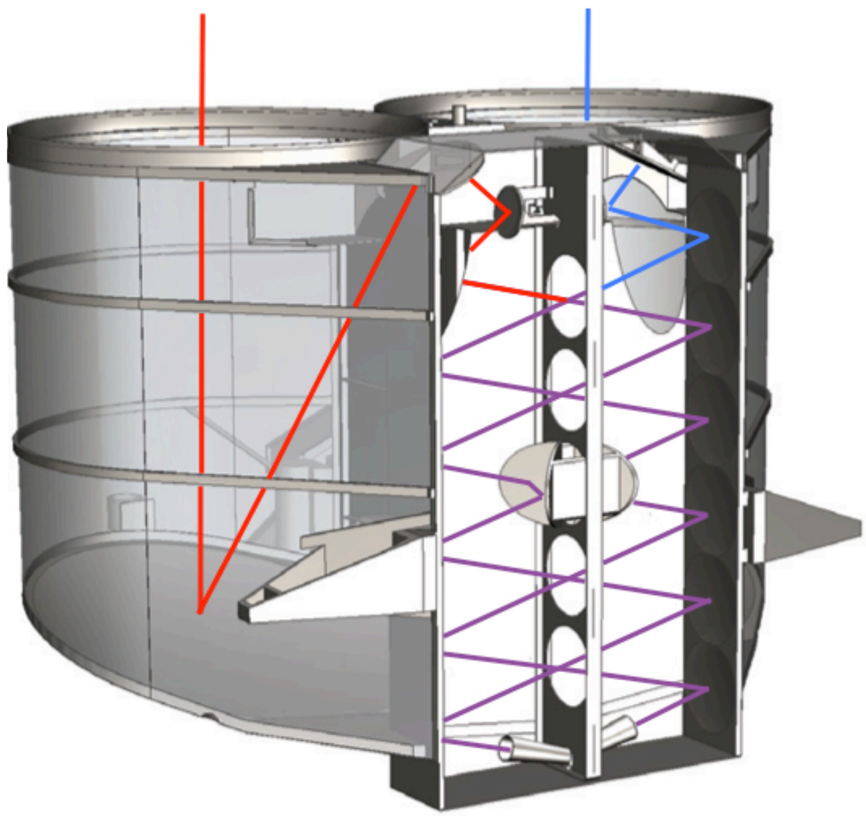
... To get Frequency Spectra

$$S_\upsilon^{Lx} = \frac{1}{4}\left[I_\upsilon^A - I_\upsilon^B + Q_\upsilon\cos(2\gamma) + U_\upsilon\sin(2\gamma)\right]$$

$$S_\upsilon^{Ly} = \frac{1}{4}\left[I_\upsilon^A - I_\upsilon^B - Q_\upsilon\cos(2\gamma) - U_\upsilon\sin(2\gamma)\right]$$

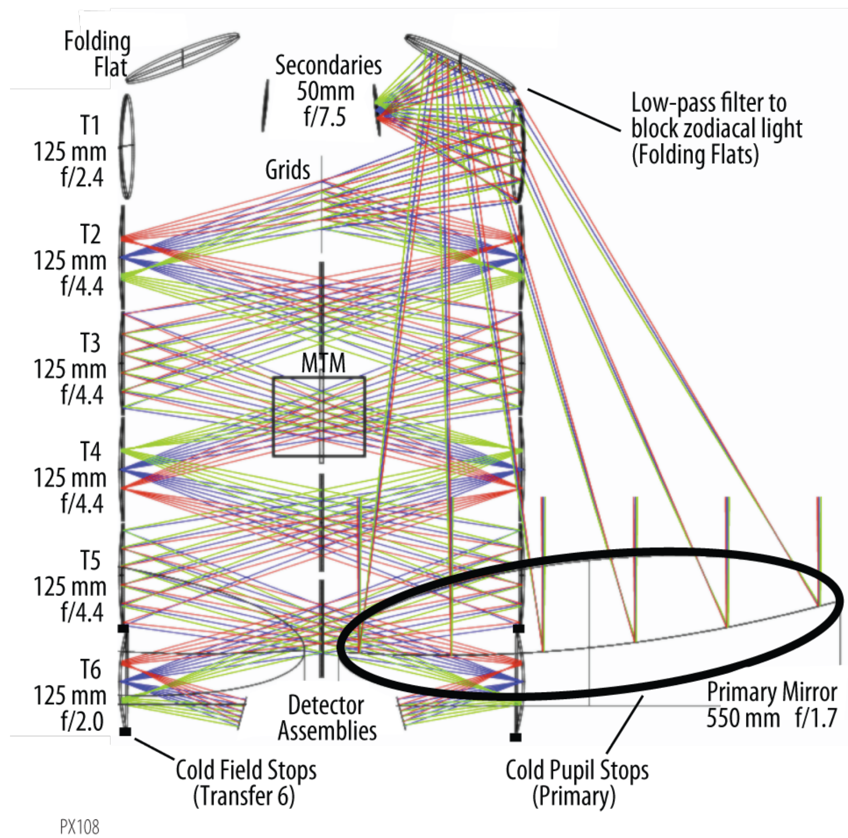
Nulling Polarimeter: Zero = Zero

PIXIE Non-Imaging Optics

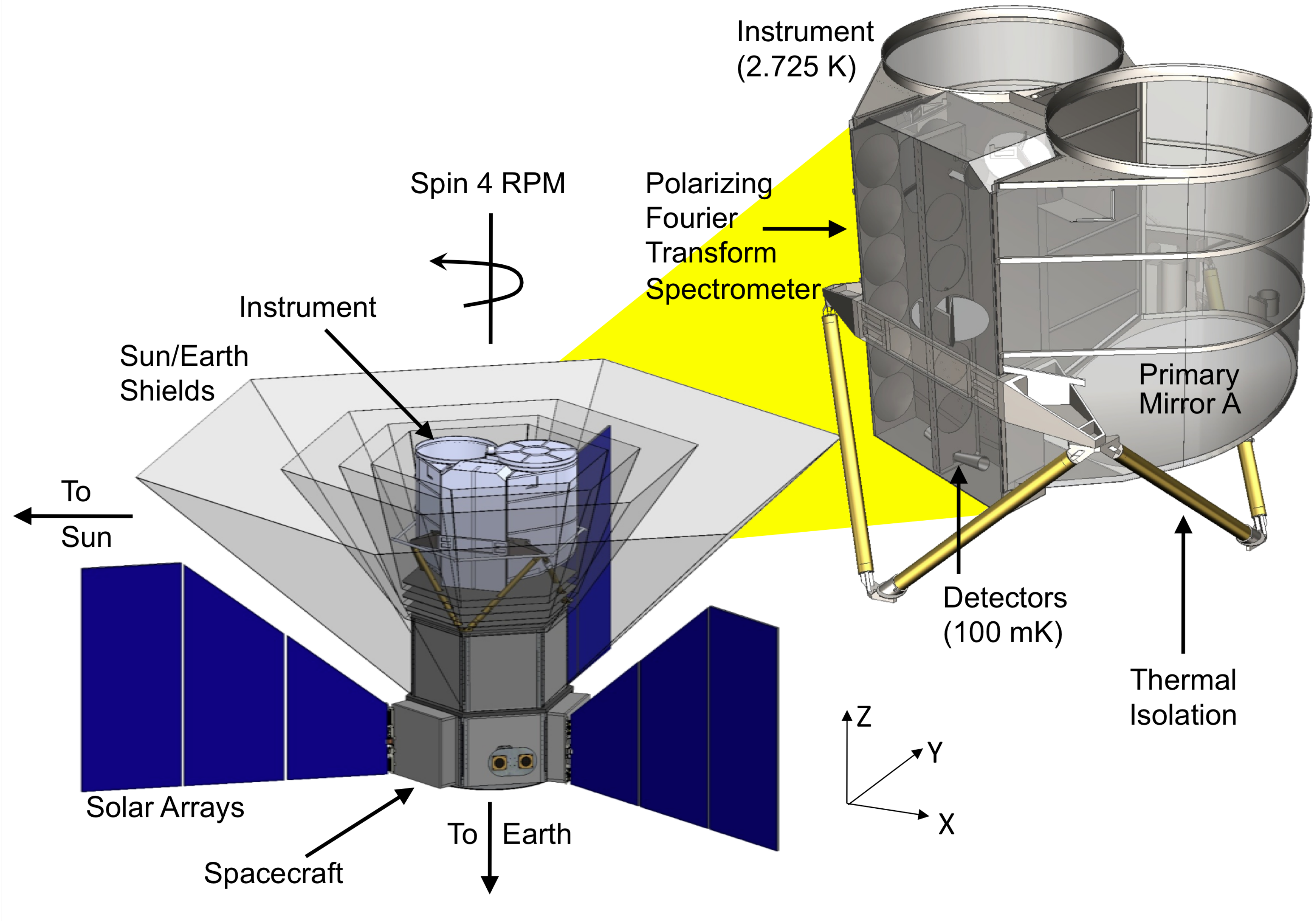


44,000 modes
on 4 detectors

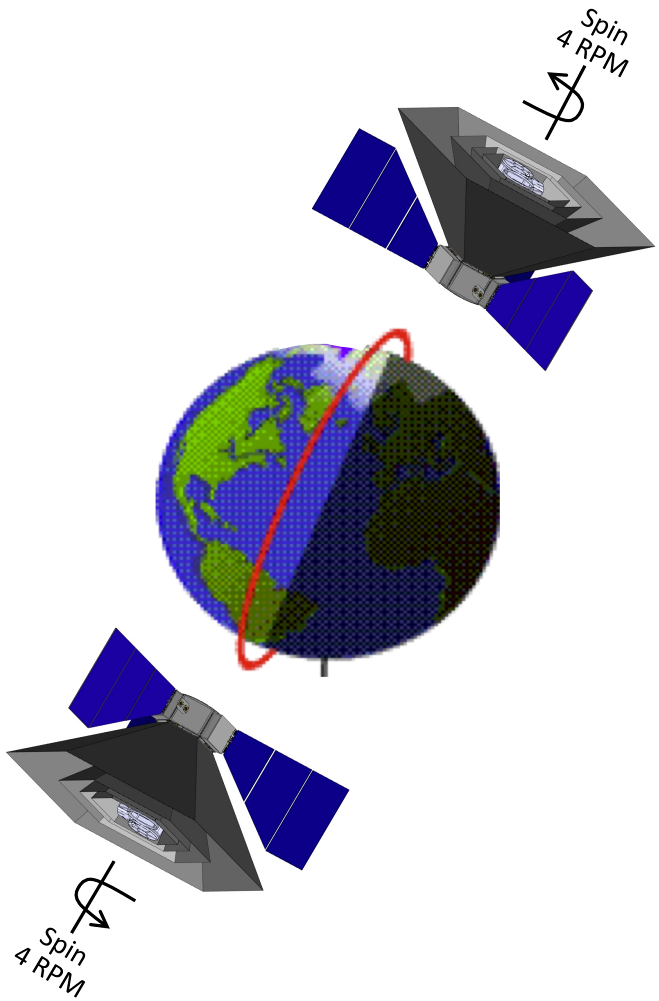
Parameter	Value
Primary Mirror Diam	550 mm
Etendu	4 cm2 sr
Beam Diam	2.6° Tophat
Throughput	82%



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

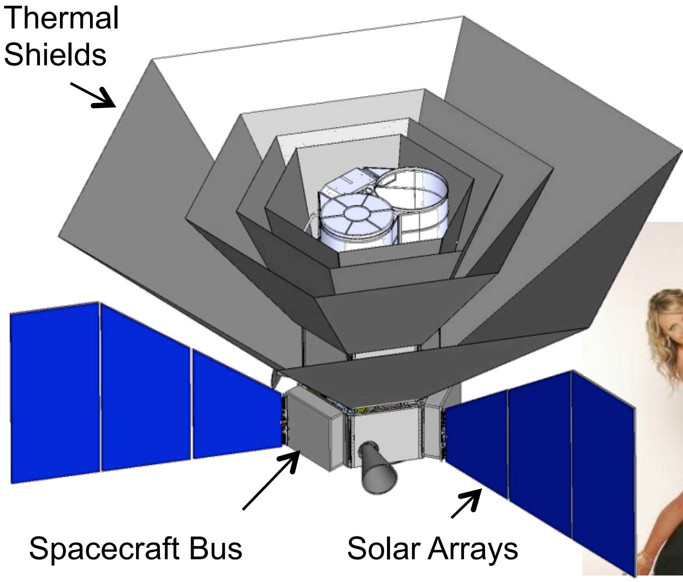
Routine Observations
- Spin and stare
- Move calibrator every 2nd orbit
- 2 year baseline mission
- 4 year extended mission

COBE, WMAP, Planck

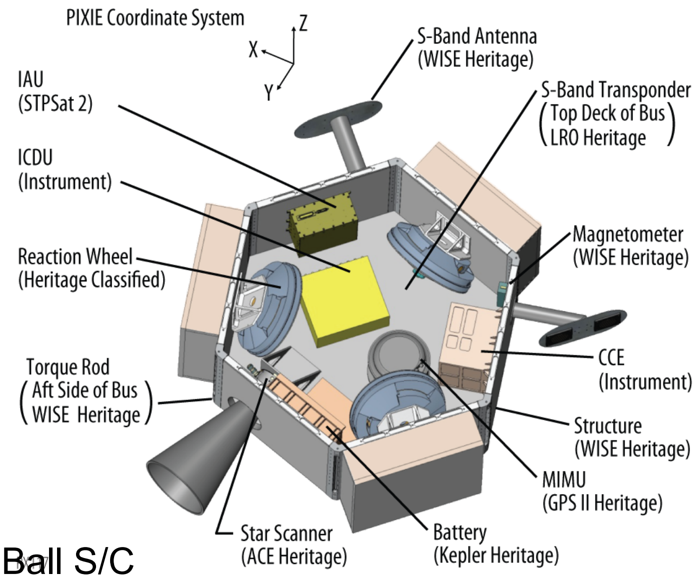
Launch Date Oct 2017
- Taurus-I ELV

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

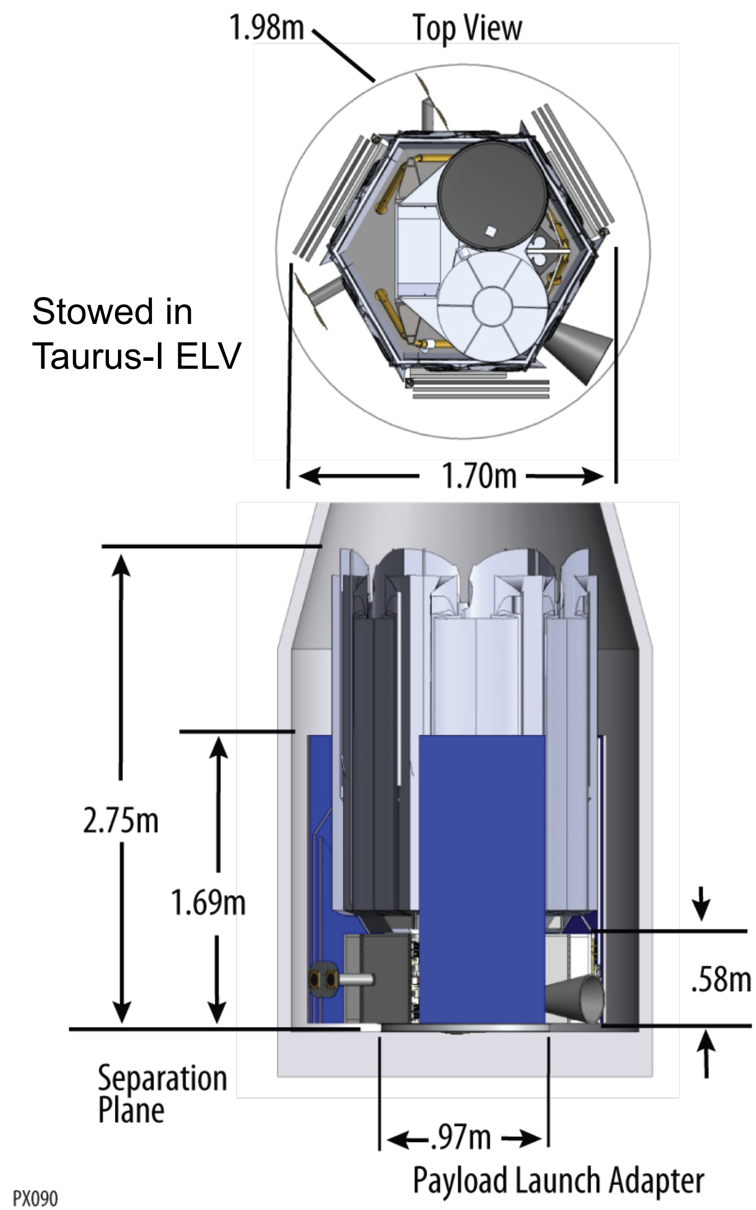
Observatory



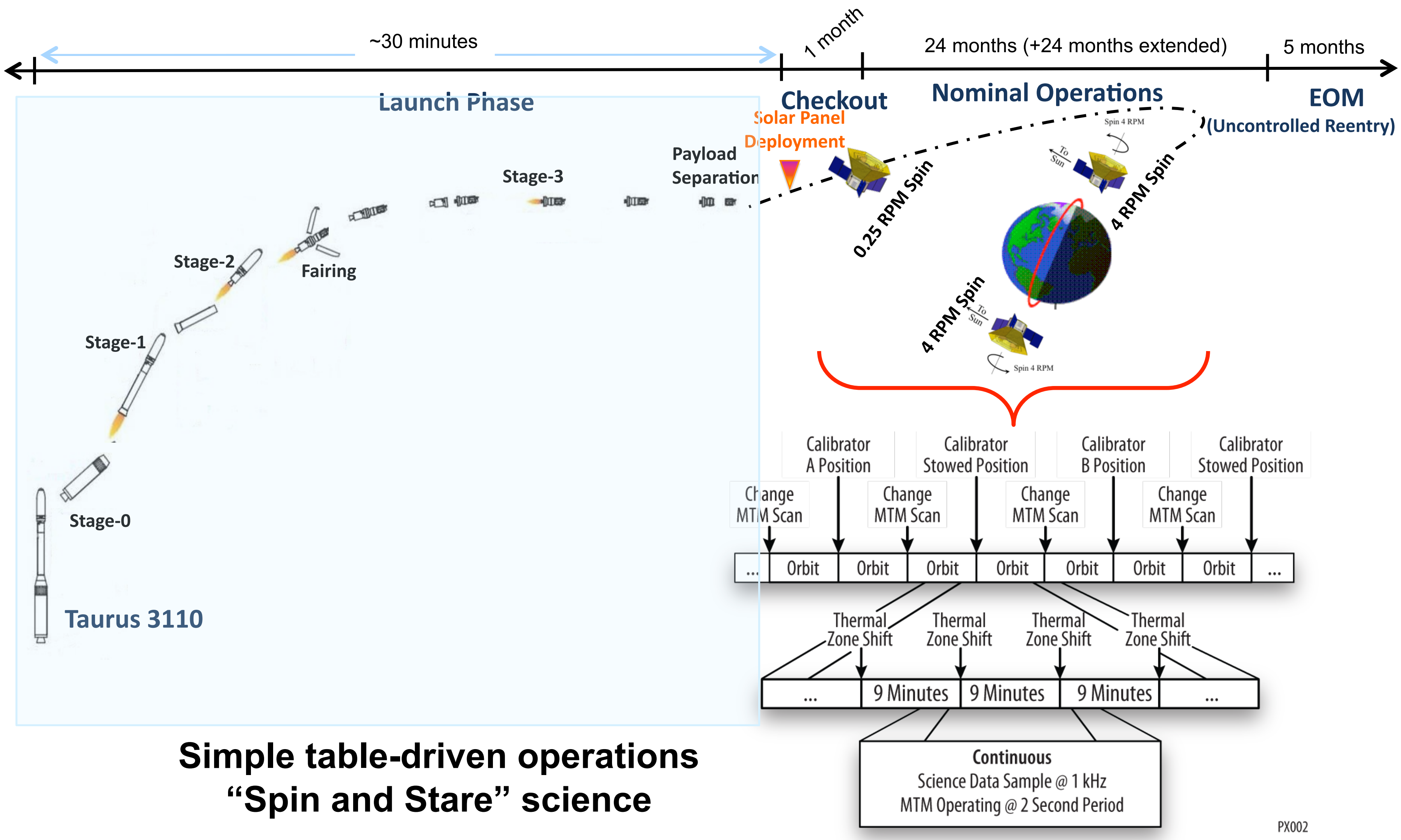
Star Power (for scale)



Ball S/C

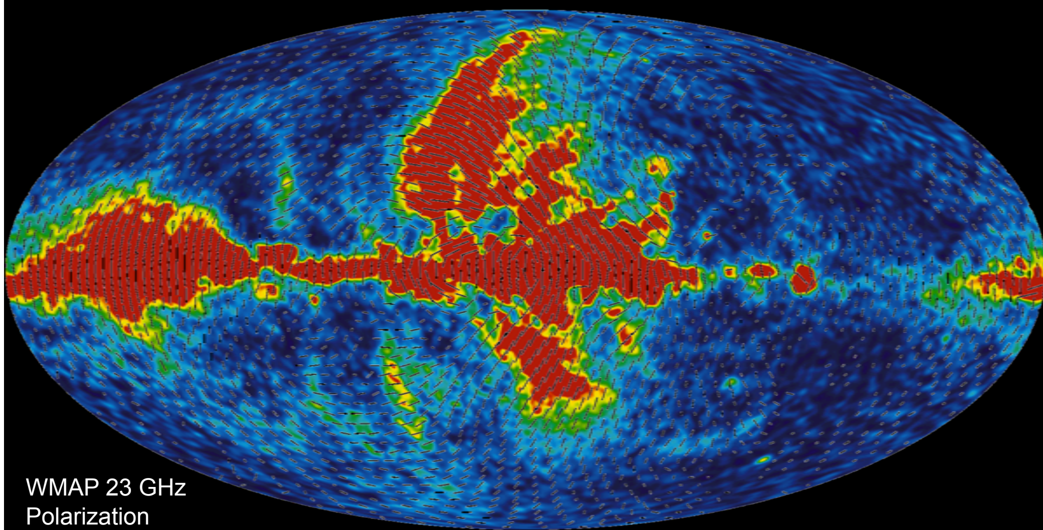


Mission Operations



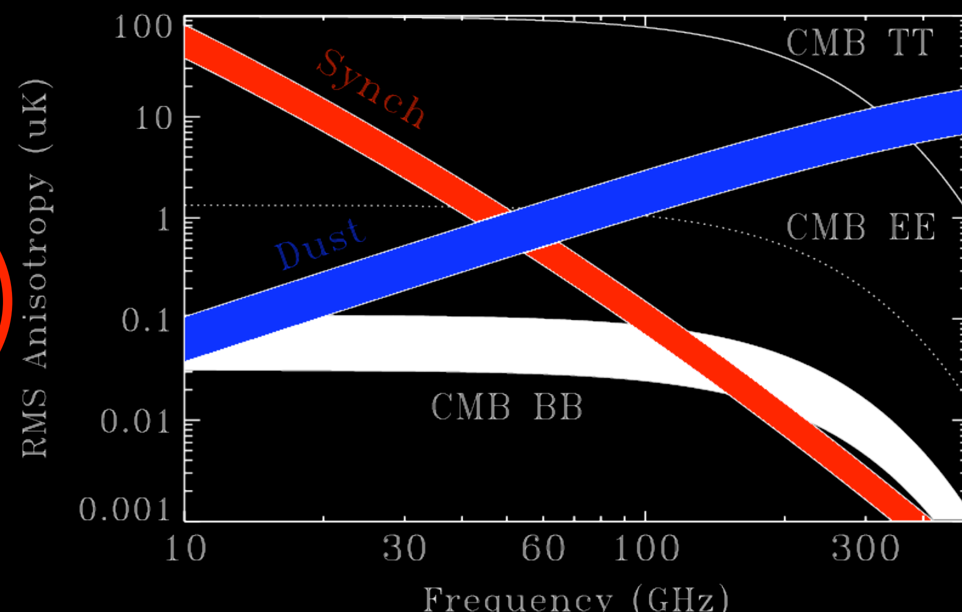
Simple table-driven operations
"Spin and Stare" science

So What's The Problem?



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

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

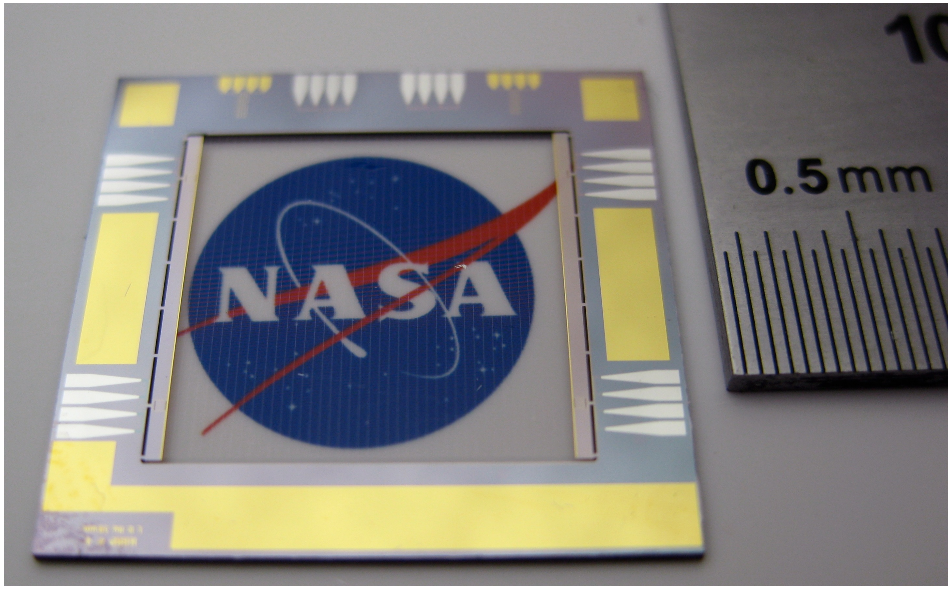
Photon noise ~ $(A\Omega)^{1/2}$
Big detector: Negligible phonon noise

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

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

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

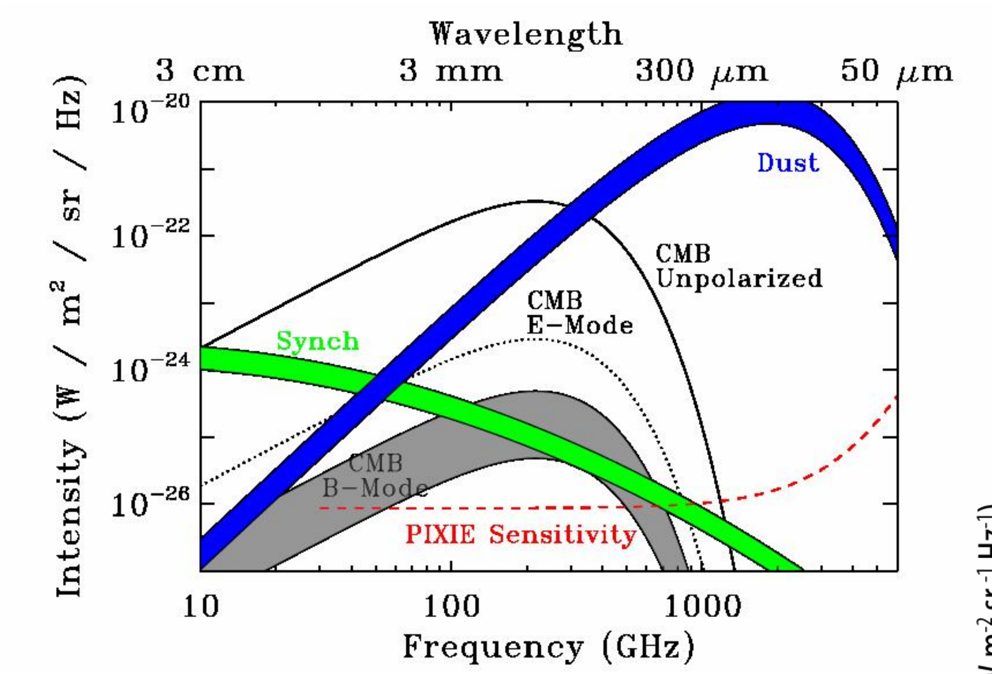
Sensitivity 70 nK per 1° x 1° pixel



PIXIE polarization-sensitive bolometer

Foreground Subtraction: More is Better

Fourier Transform Spectrometer



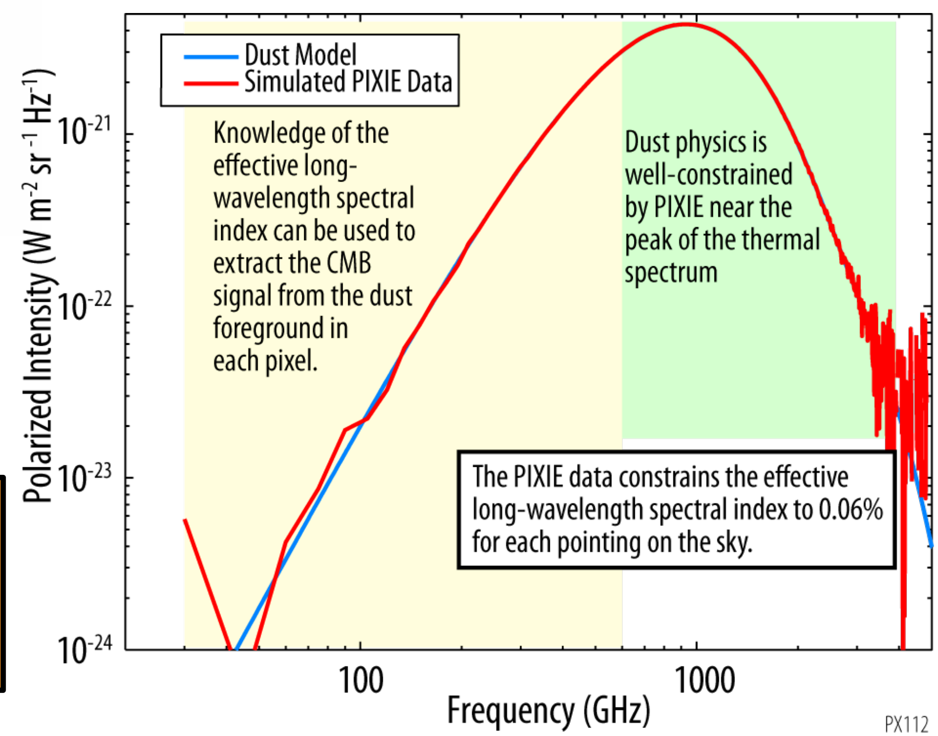
Synthesize 512 channels each 15 GHz wide

- Largest optical phase delay sets channel width
- Number of samples sets number of channels

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

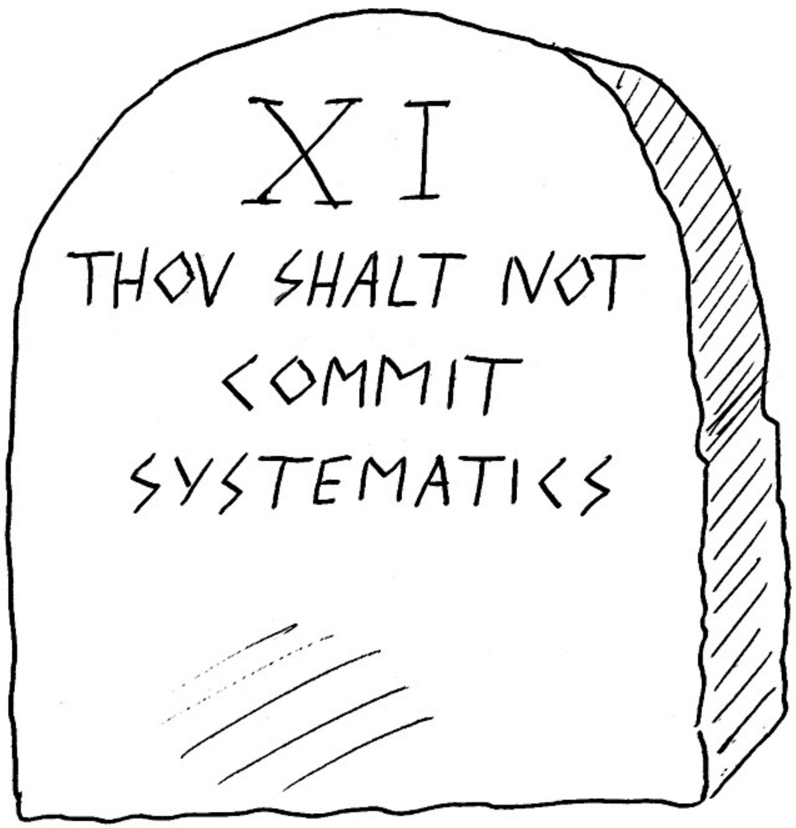
Pixel-by-pixel foreground subtraction

- 400 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

Systematic Errors: The 11th Commandment



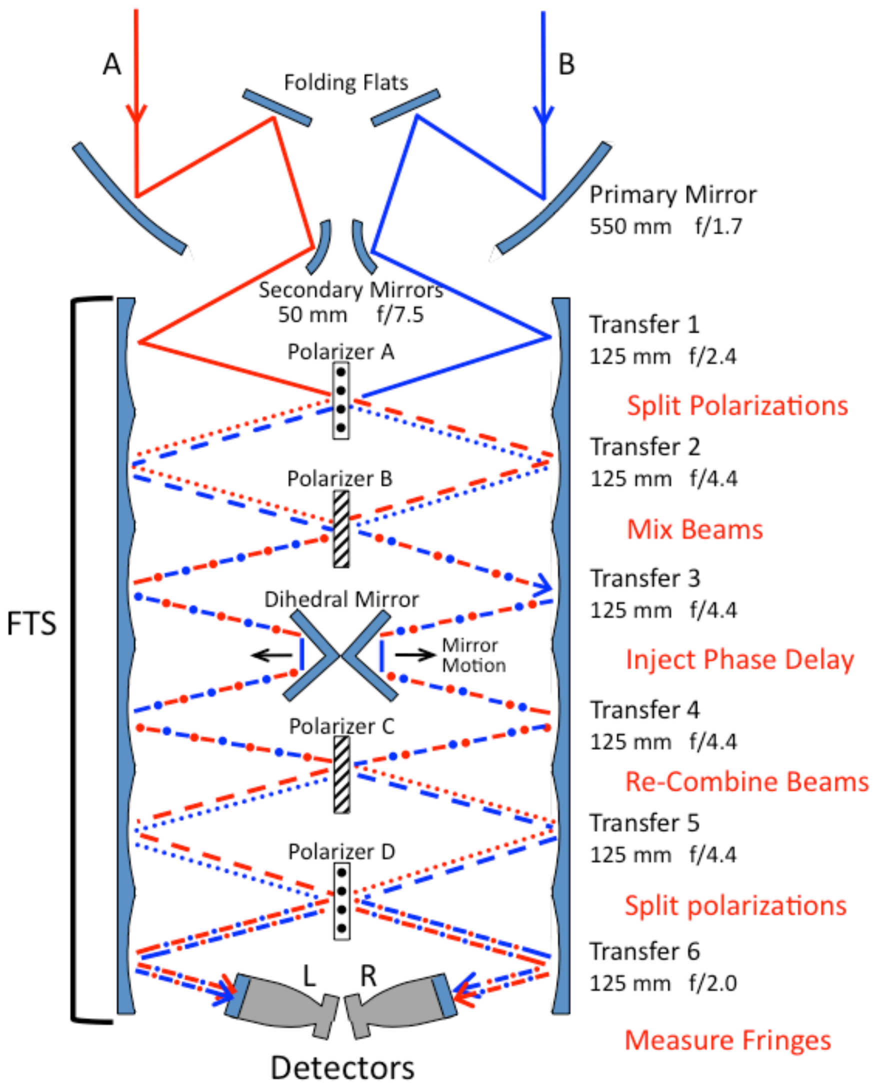
Instrument Design

Multiple Modulations

Multiple Symmetries

Systematic Error Control

Nulling Polarimeter



Observed Fringe Pattern

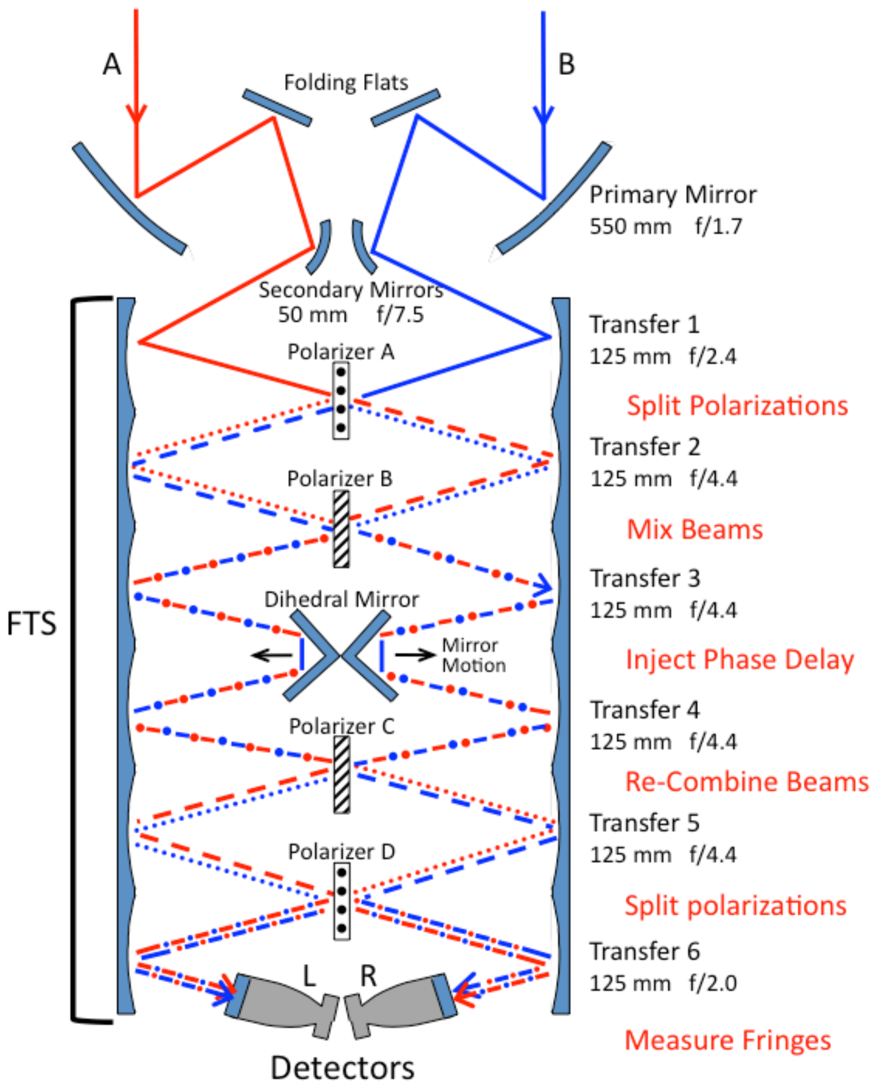
$$P_{Lx} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{Ax}^2 - E_{By}^2\right)\cos(z\omega/c)\, d\omega$$

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

Interfere orthogonal linear polarizations:
Unpolarized sky yields no fringe pattern

Systematic Error Control

Nulling Polarimeter



Observed Fringe Pattern

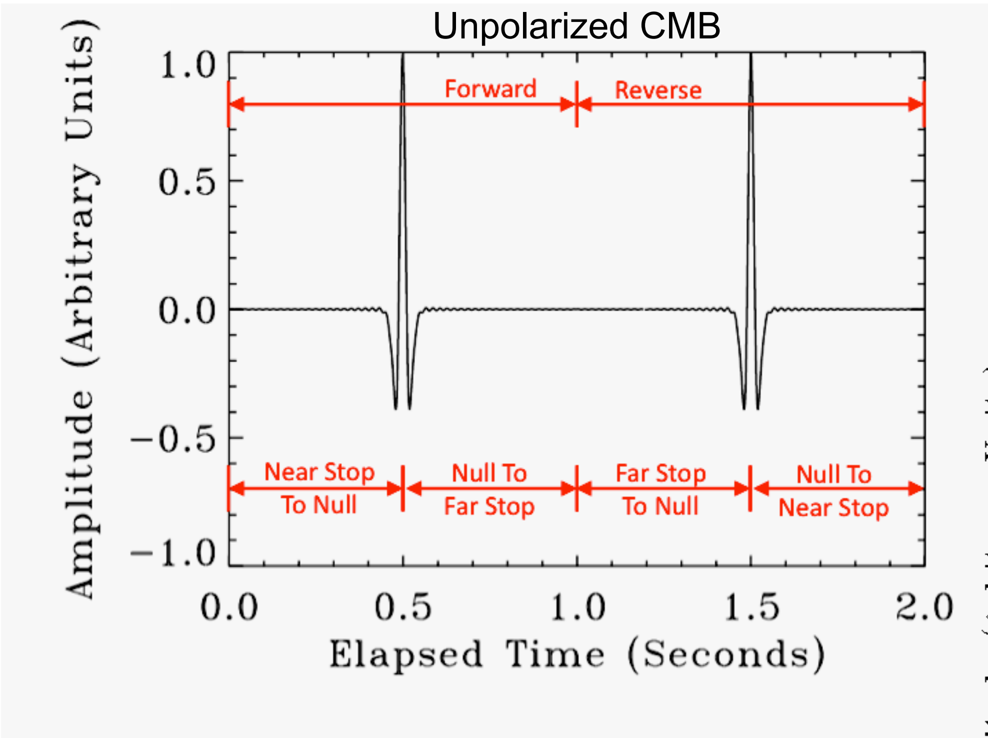
$$P_{Lx} = \frac{1}{2}\int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx} - E_{Ay}^2\right)\cos(z\omega/c)\, d\omega$$

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

Interfere orthogonal linear polarizations:
Unpolarized sky yields no fringe pattern

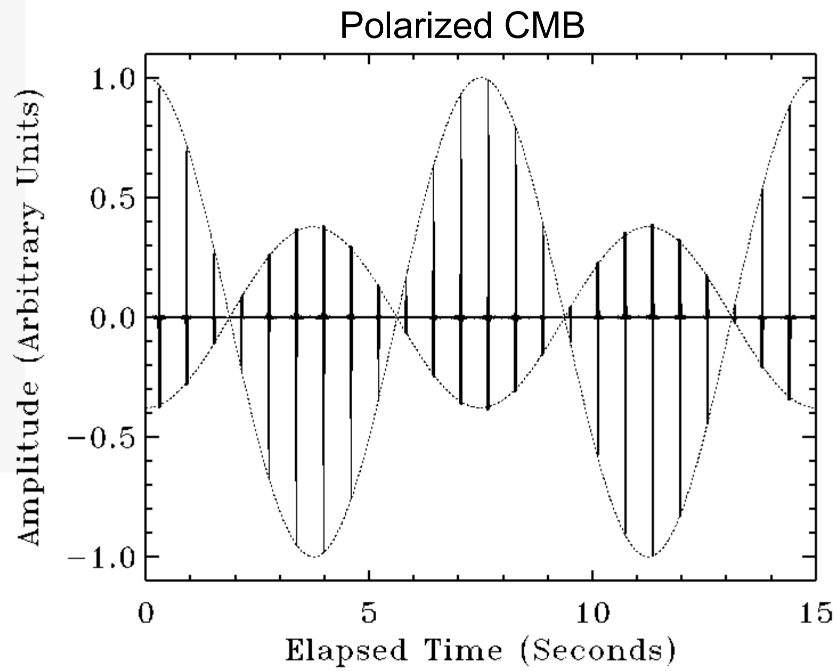
Systematic Error Control

Multiple Instrumental Symmetries



Spacecraft spin imposes amplitude modulation of entire fringe pattern

Multiple Redundancies
Allow Clean Instrument Signature



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

Systematic Error Budget

Multiple symmetries allow 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

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

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

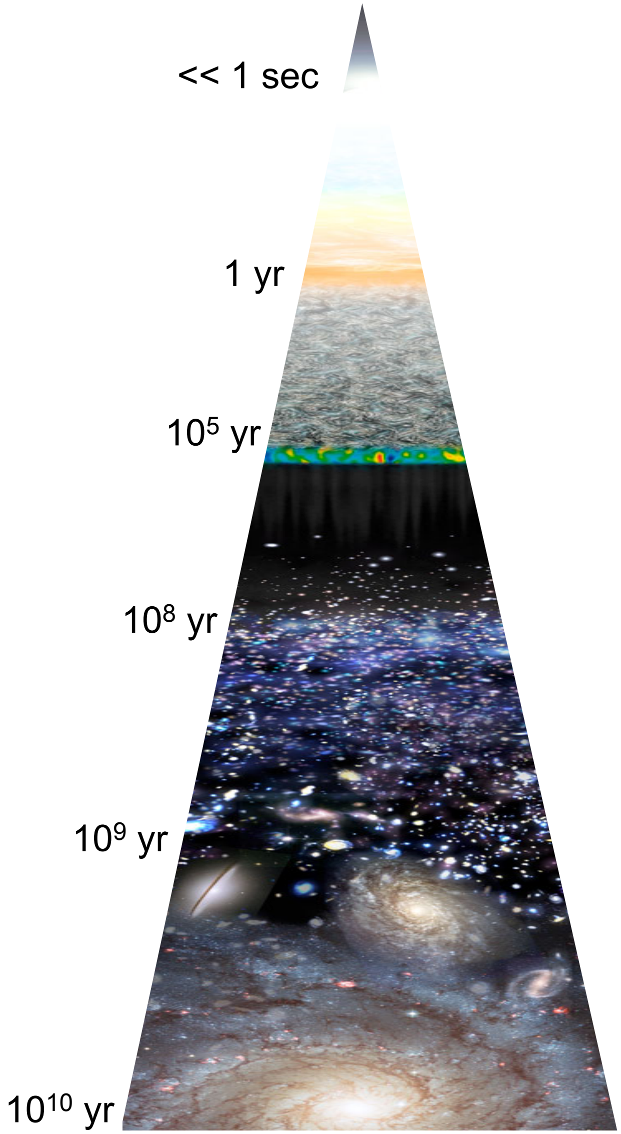
$$P_{Rx} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{Ax}^2 - E_{By}^2\right)\cos(z\omega/c)\, d\omega$$

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

Maintain systematic error budget below 3 nK in Q or U

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: Testing The Standard Model



Primary Science

Big Bang Cosmology *
- Inflation
- GUT physics
- Quantum gravity

Secondary Science

Early Universe
- Dark matter decay/annihilation
- Primordial density perturbations

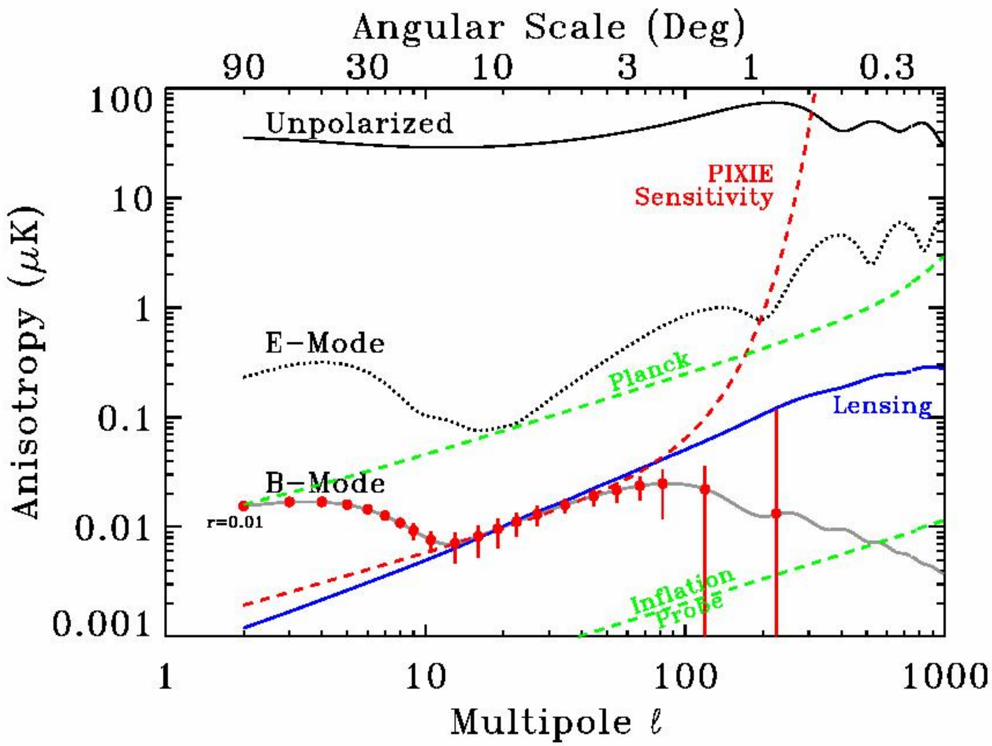
Reionization and First Stars *
- Ionization history at end of Dark Ages
- Nature of first stars

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

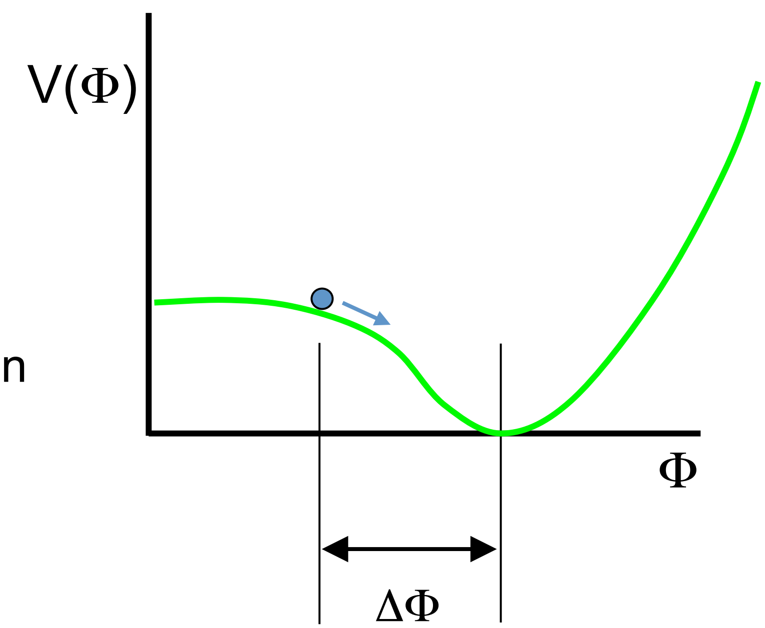
* Specifically called out in Astro-2010 Decadal Survey

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

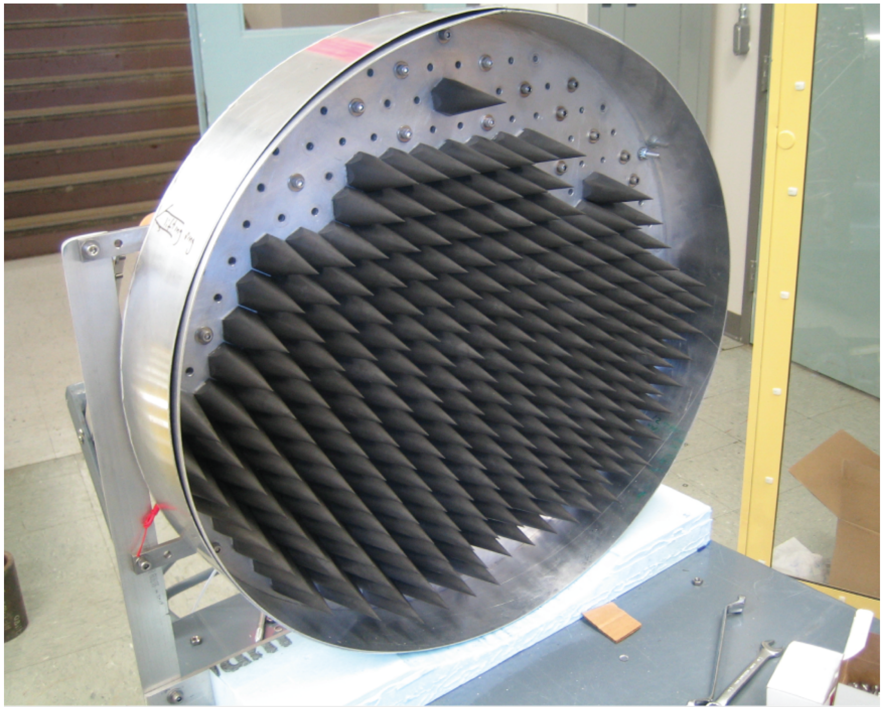


Planck-Scale Physics: Map B-Mode Polarization

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

Noise in CMB maps ~70 nK per 1° x 1° pixel

Secondary Science: Inflation



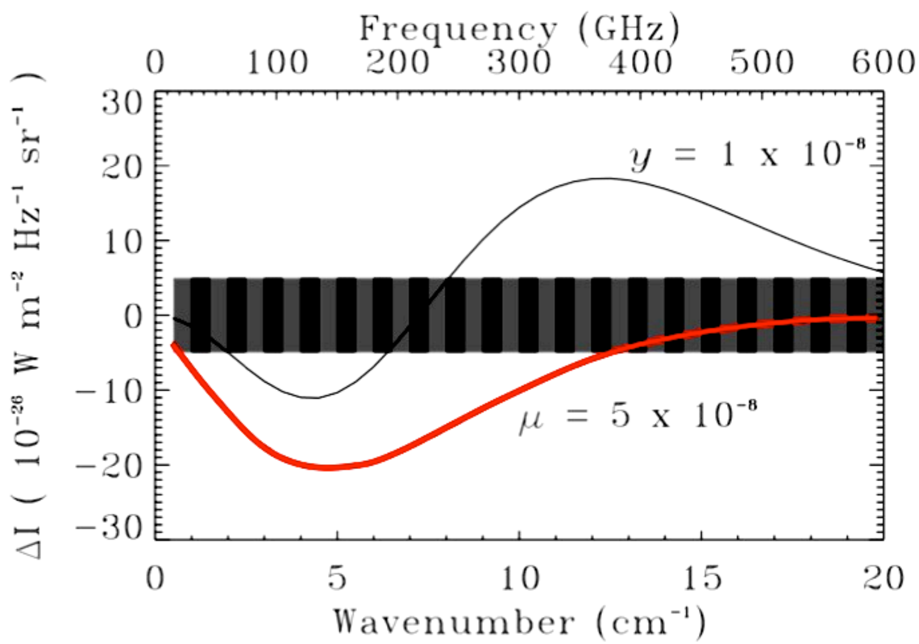
Blackbody calibrator: Spectral distortions

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

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

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

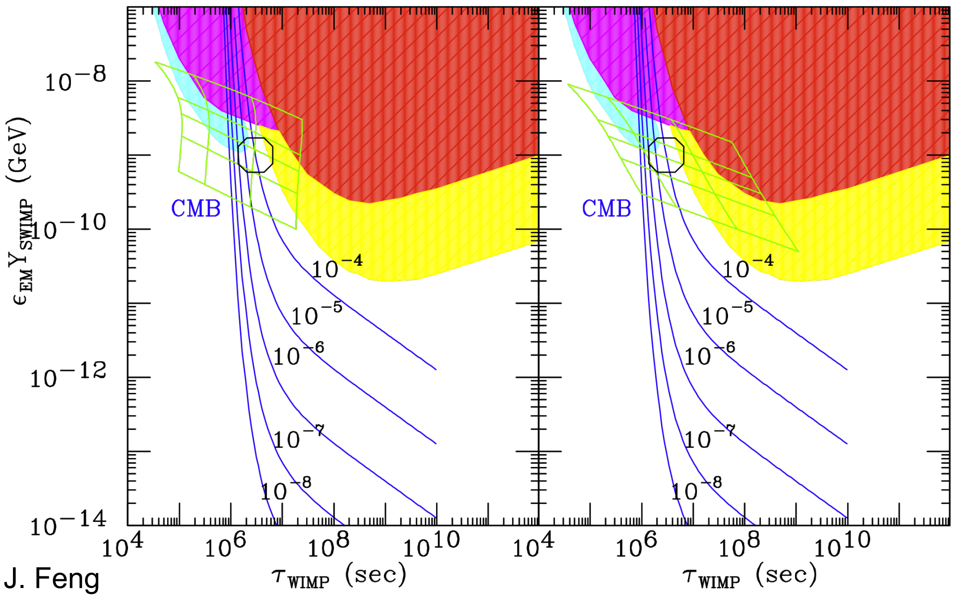
- Scalar index n_s (Silk damping)
- Density perturbations to kpc scales



Daly 1991
Hu, Scott, & Silk 1994

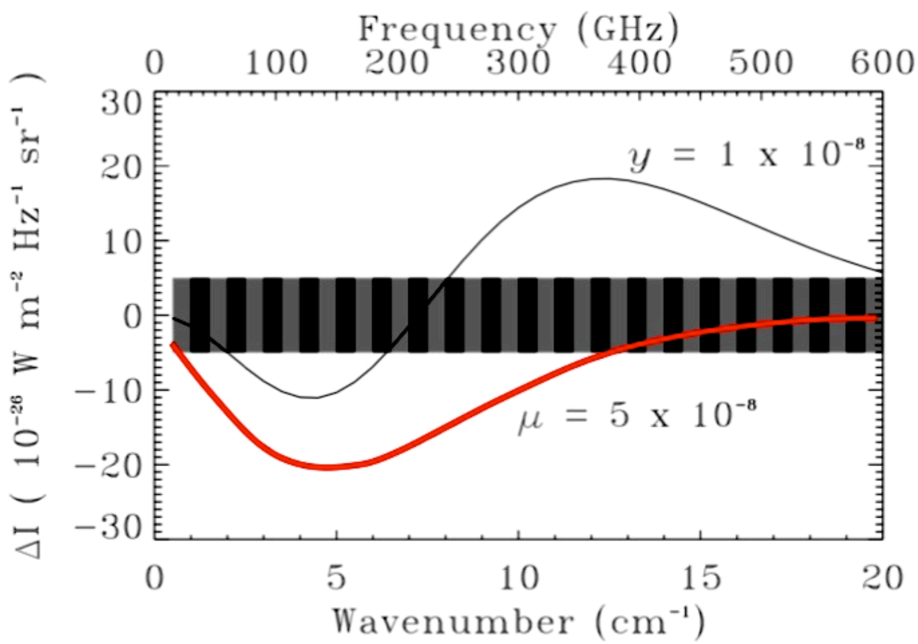
Secondary Science: Dark Matter

slepton decay



J. Feng

Blackbody distortion
from dark matter decay or annihilation

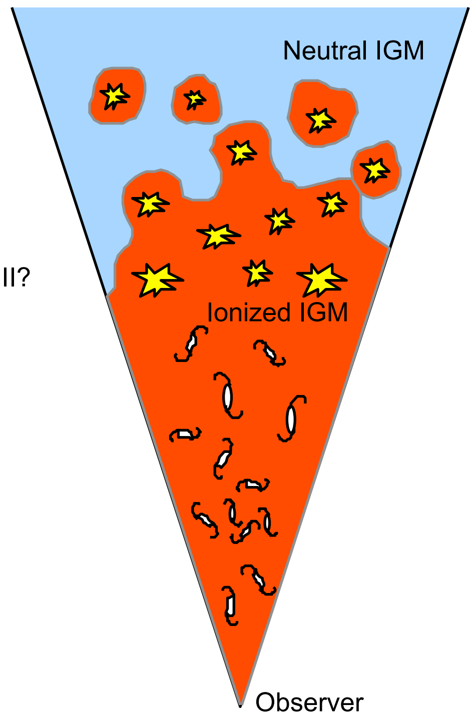


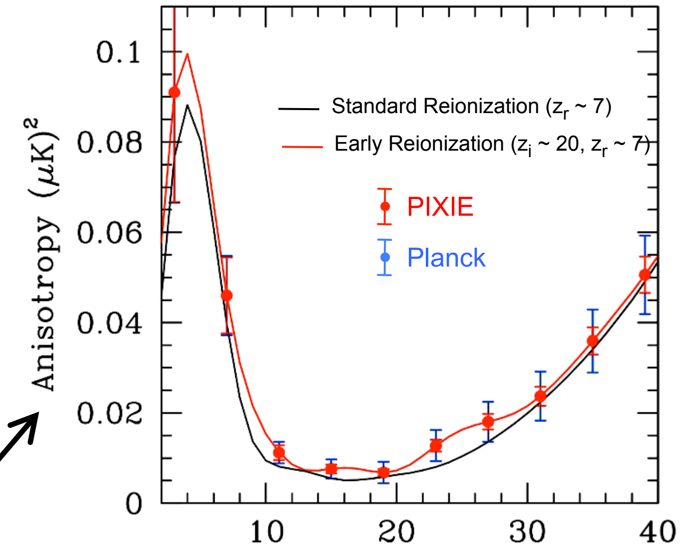
Definitive test for light dark matter

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

McDonald, Scherrer & Walker 2001
de Vega & Sanchez 2010

Secondary Science: Reionization

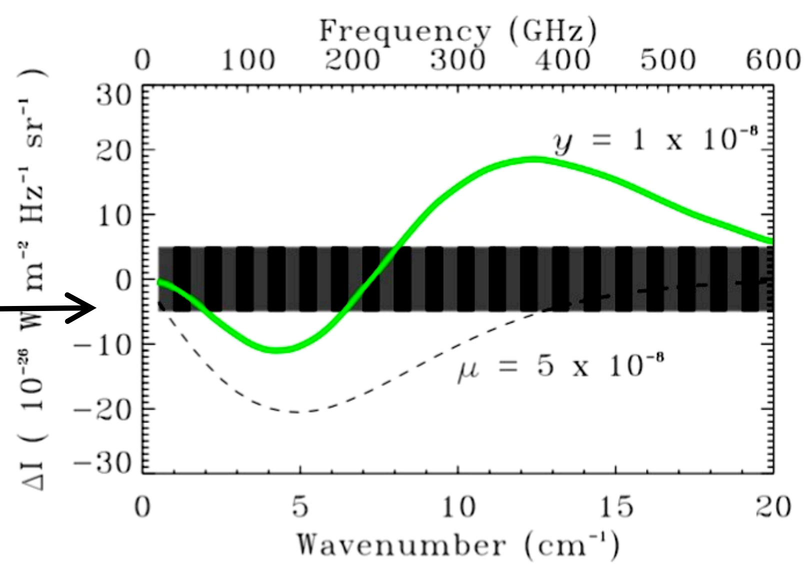




PIXIE and reionization

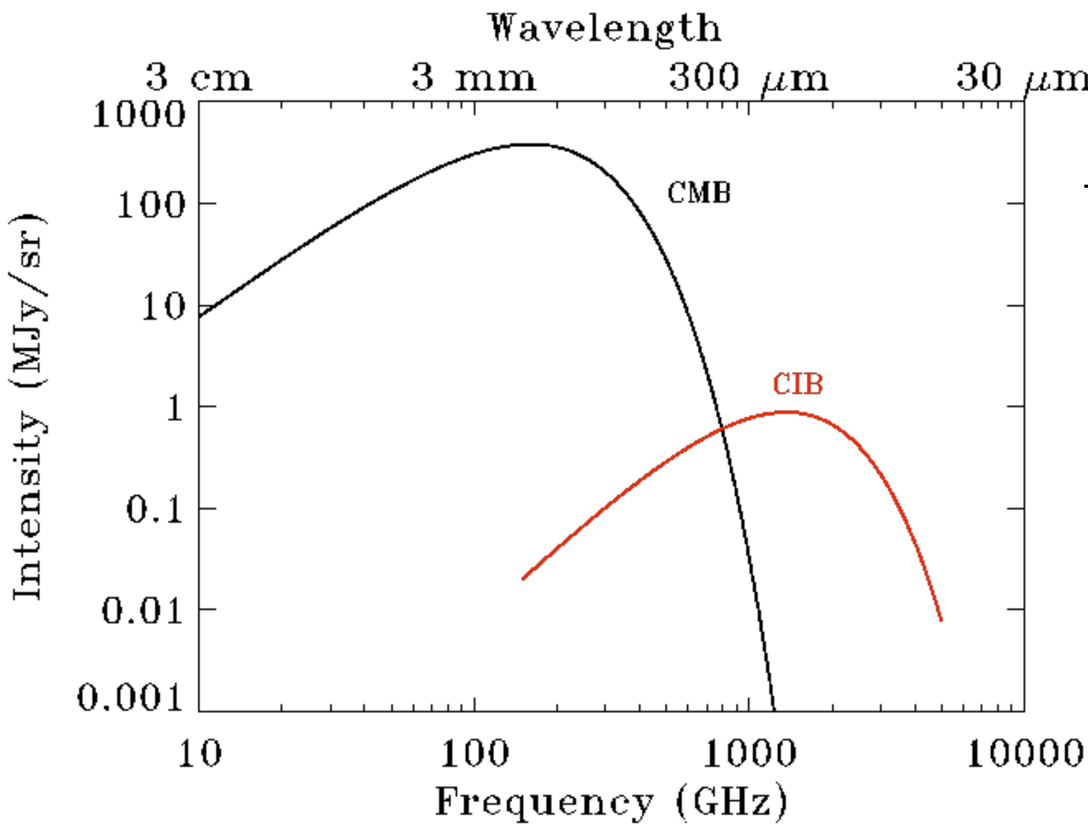
- Polarization: Optical depth τ ~ n(z)
- Spectrum: Compton distortion y ~ $\int nkT_e$

Combine to get n(z) and T_e (ionizing spectra)



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

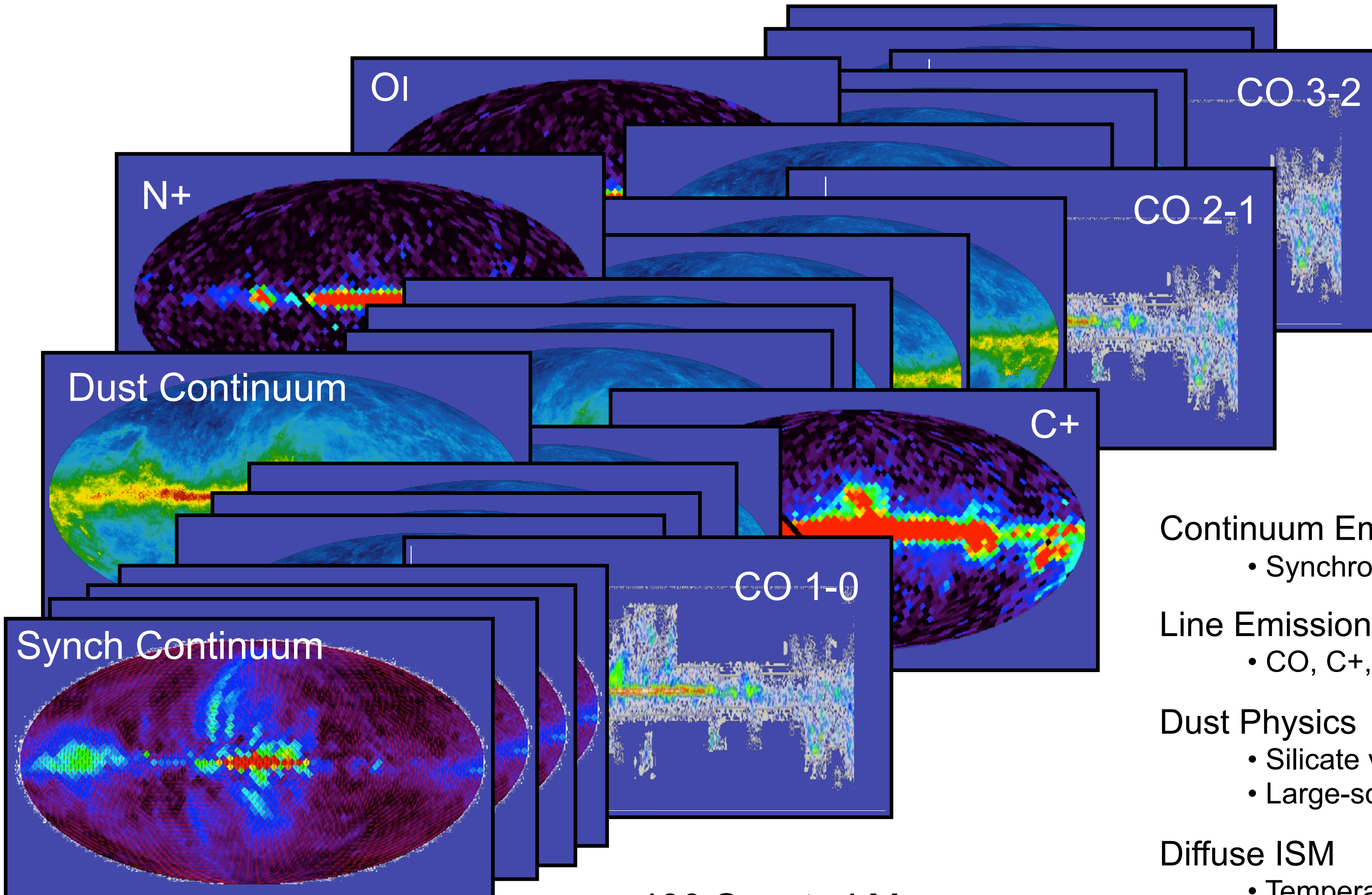
Broad frequency coverage over CIB peak

- Complement Herschel, Planck

PIXIE noise is down here!

Knox et al. 2001
Fixsen & Kashlinsky 2011

Secondary Science: Interstellar Medium



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

Extremely Rich Data Set!

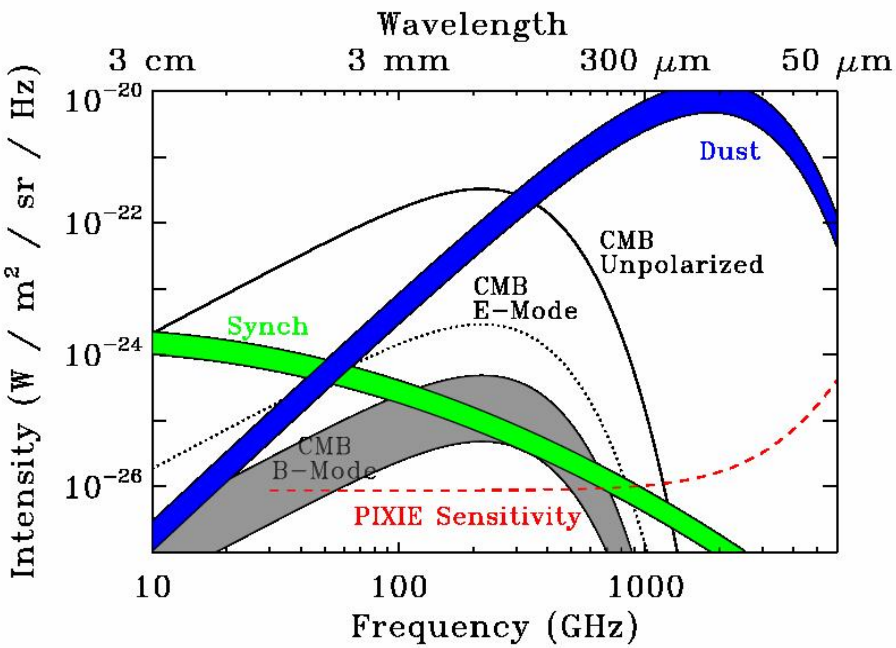
Continuum Emission
- Synchrotron, Dust

Line Emission
- CO, C+, N+, O, …

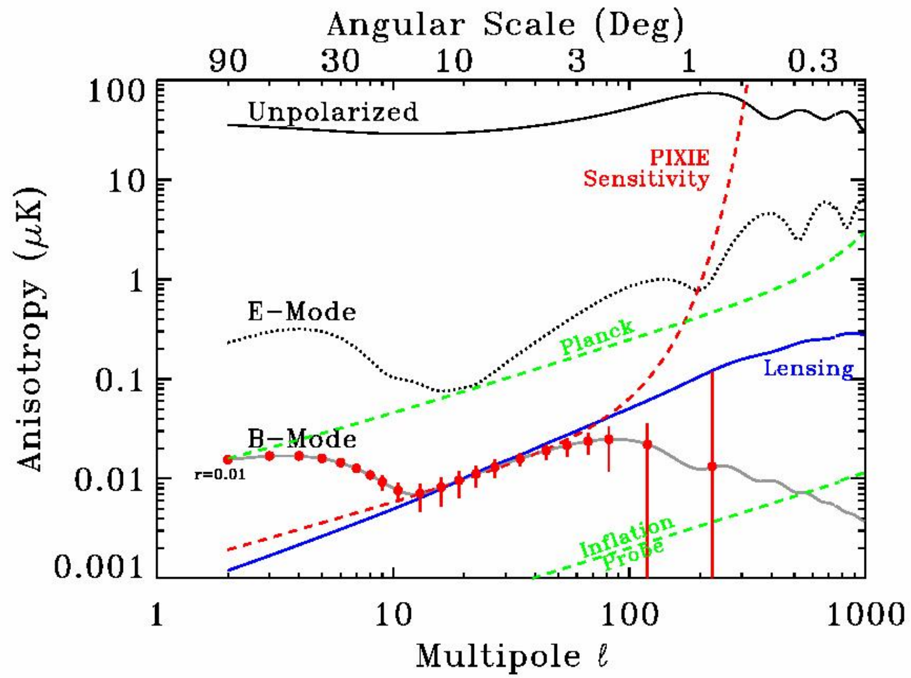
Dust Physics
- Silicate vs carbonaceous dust
- Large-scale magnetic field

Diffuse ISM
- Temperature, Density
- Energy Balance
- Metalicity

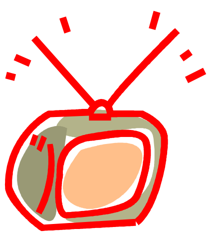
Unique Science Capability



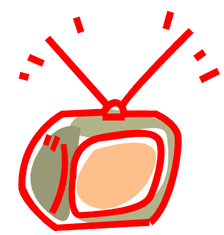
Full-Sky Spectro-Polarimetric Survey
- 400 channels, 30 GHz to 6 THz
- Stokes I, Q, U



- Inflation/GUT Physics
- Dark Matter Annihilation/Decay
- Reionization/First Stars
- CIB/Star Formation History
- ISM and Dust Cirrus



Now how much would you pay?

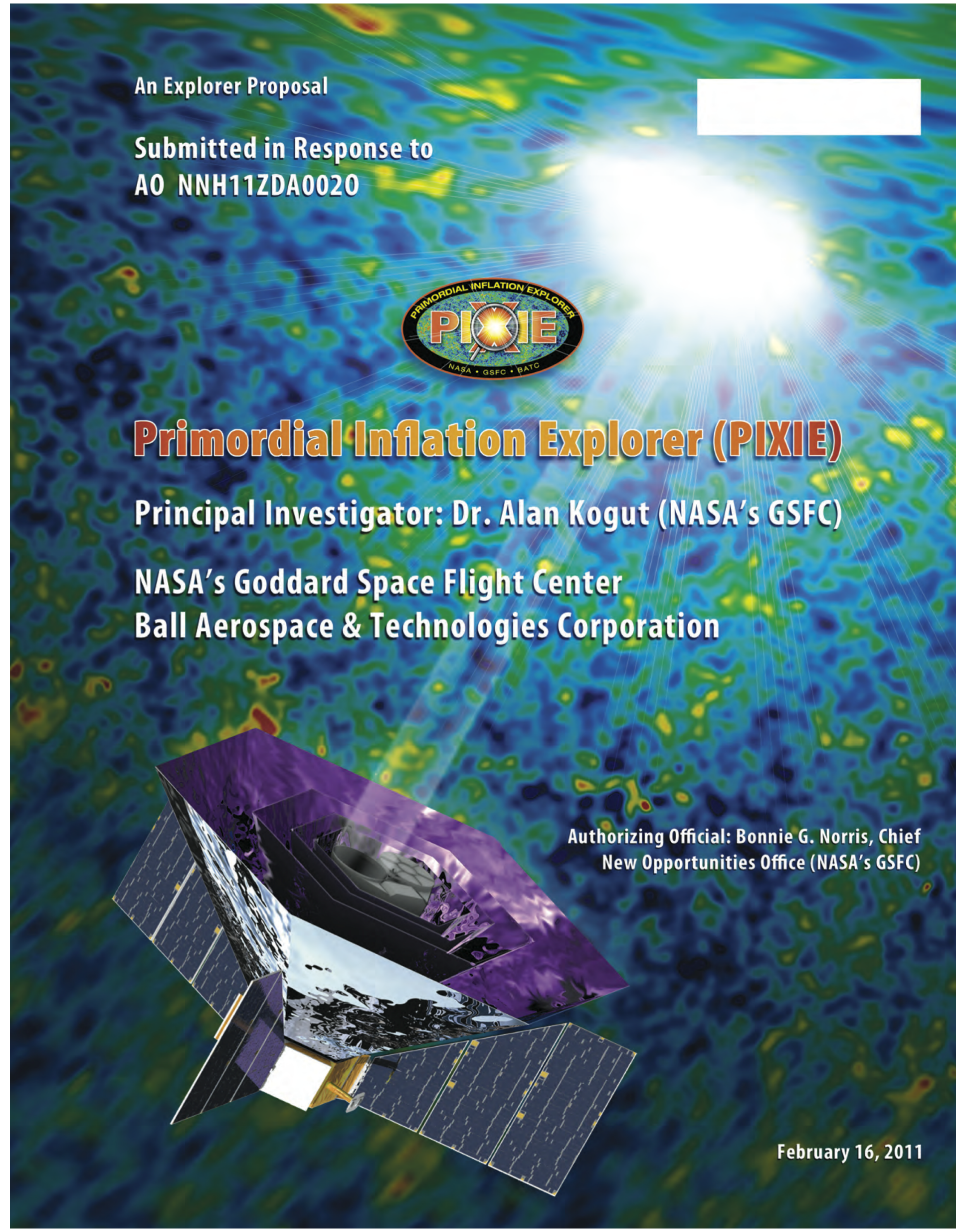


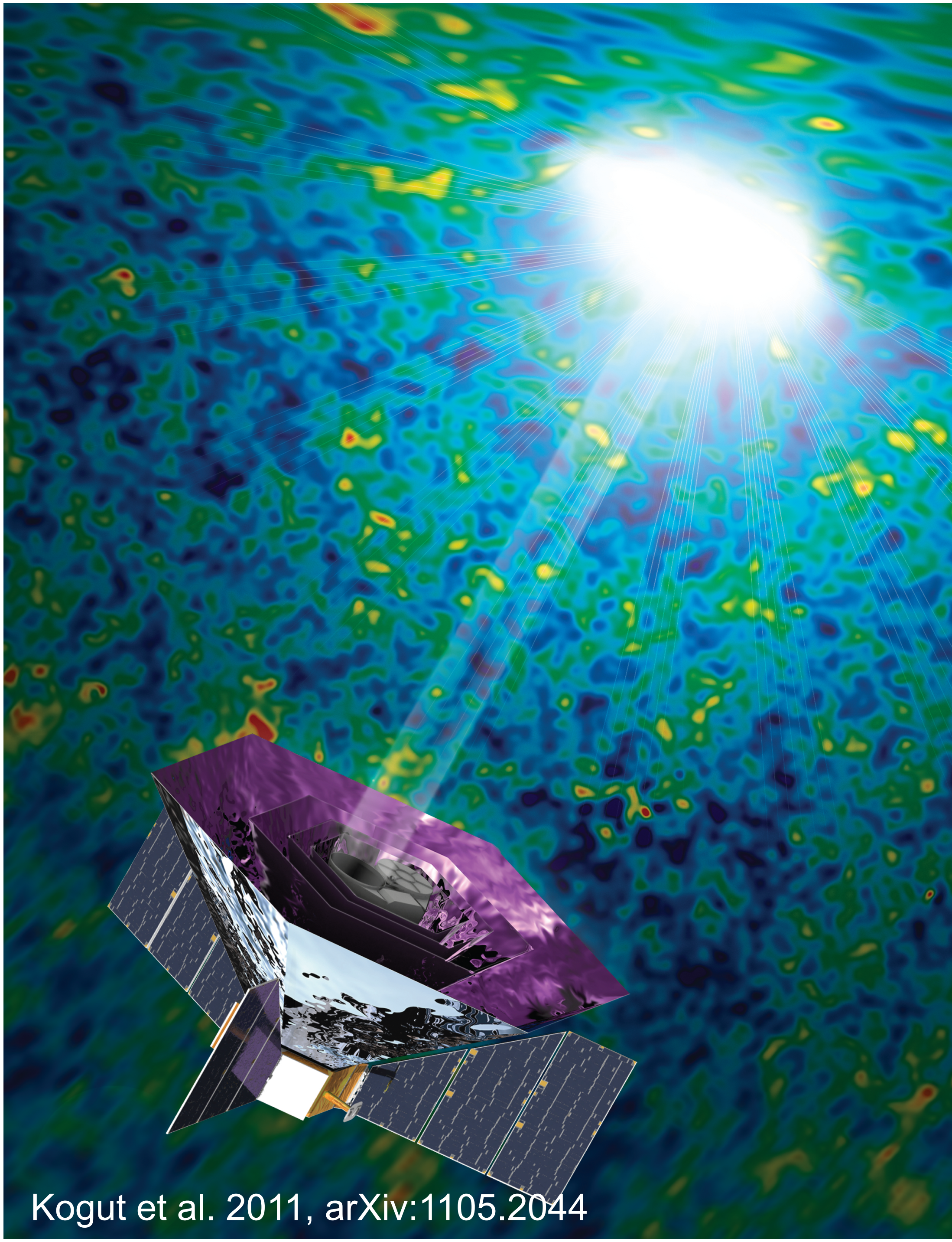
NASA Explorer Program

Small PI-led missions
- $200M Cost Cap
- Taurus/Athena ELV
- Launch by Dec 2018

22 full missions proposed Feb 2011
- 15 Astro, 7 Helio
- Phase A selections Sept 2011
- Down-select for flight Feb 2013

Gloomy budget realities:
Best shot at inflationary physics?





Kogut et al. 2011, arXiv:1105.2044

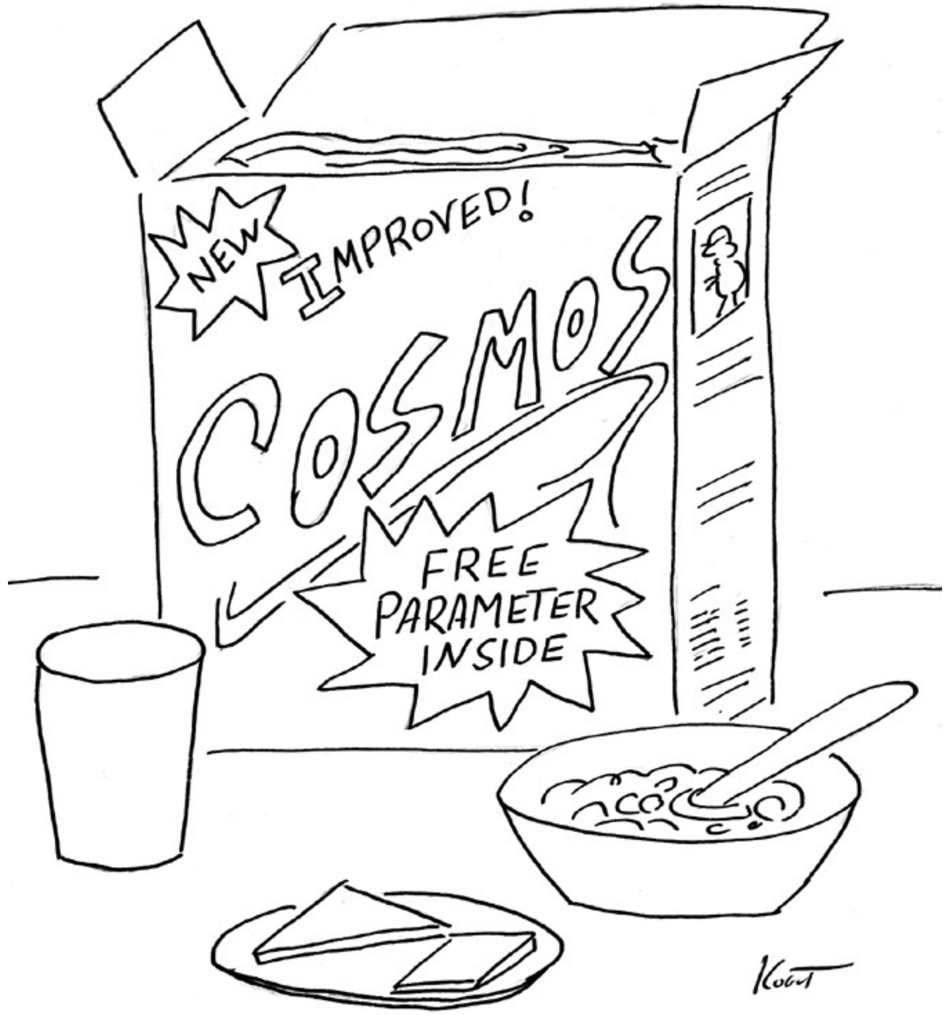
PRIMORDIAL INFLATION EXPLORER

PIXIE

NASA • GSFC • BATC

Coming Soon From a Spacecraft Near You!

Backup Slides



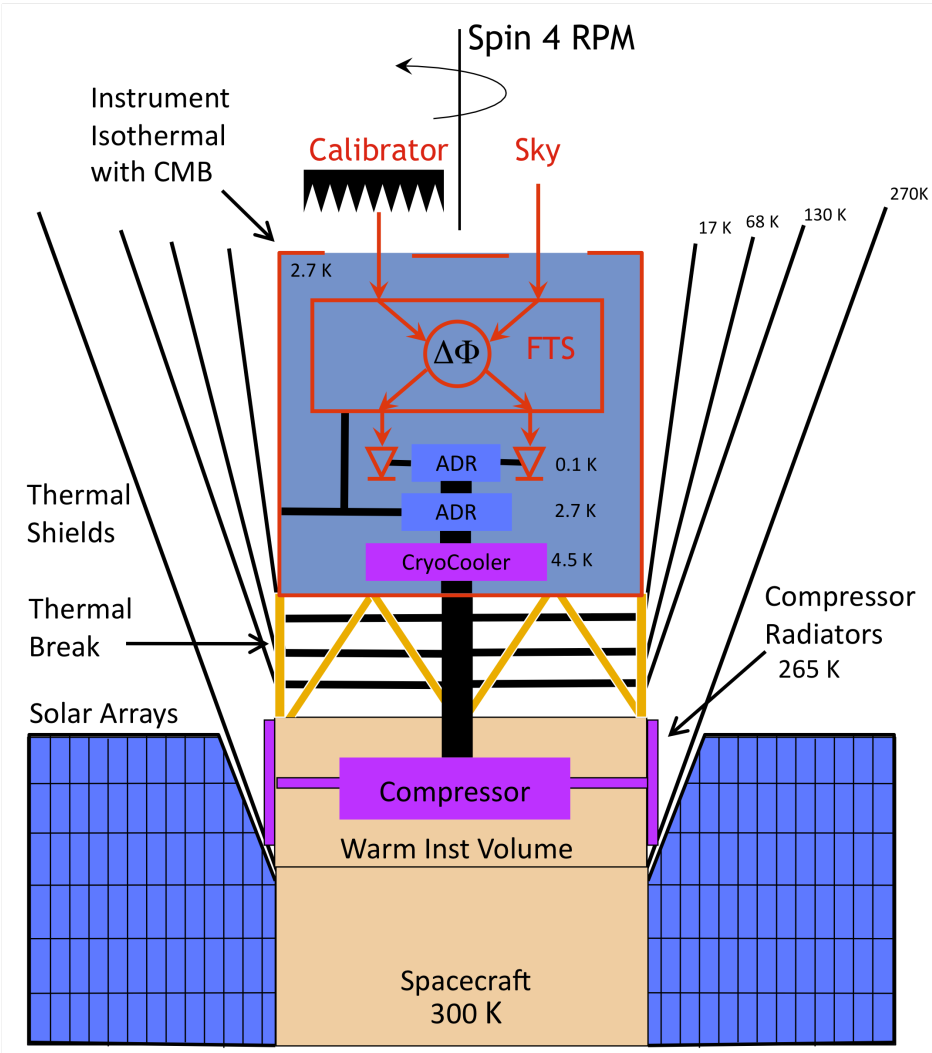
Breakfast of Theorists

Why Bother With CMB Polarization?

- Demonstrate inflation as physical reality
  - Observe universe as quantum system
  - Death to competing models
- Measure inflationary energy scale
  - Energy scale ~ (Observed Signal)$^{1/4}$
  - 10^{16} GeV : GUT physics!
- Observable "Theory of Everything"
  - Physics approaching Planck scale
  - Quantum gravity in action

Oldest Information In The Universe

Cryogenic Instrument

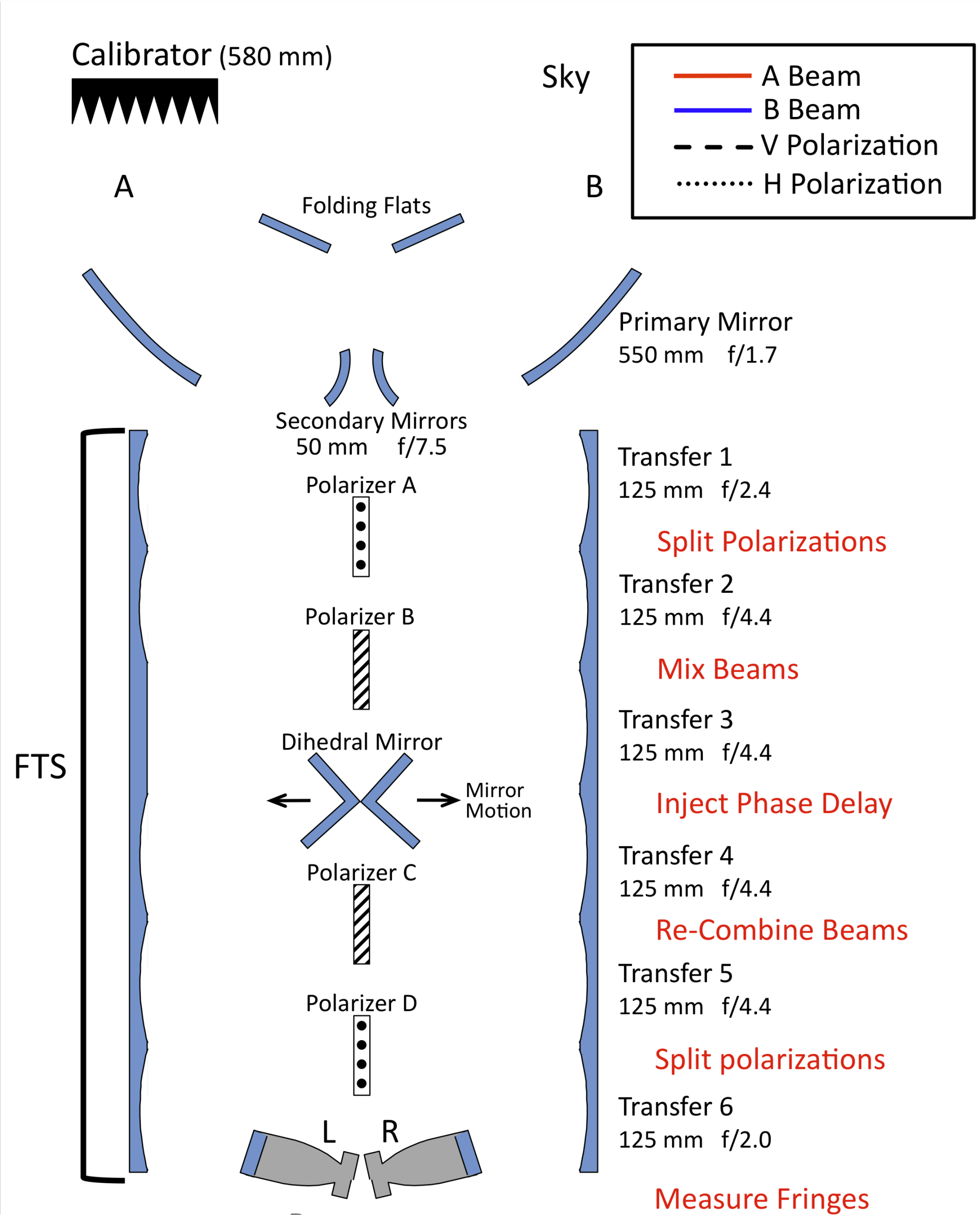


Fully cryogenic instrument
- Cryo-cooler to 4.5 K
- ADR to 2.7 K (instrument body)
- ADR to 0.1 K (detectors)

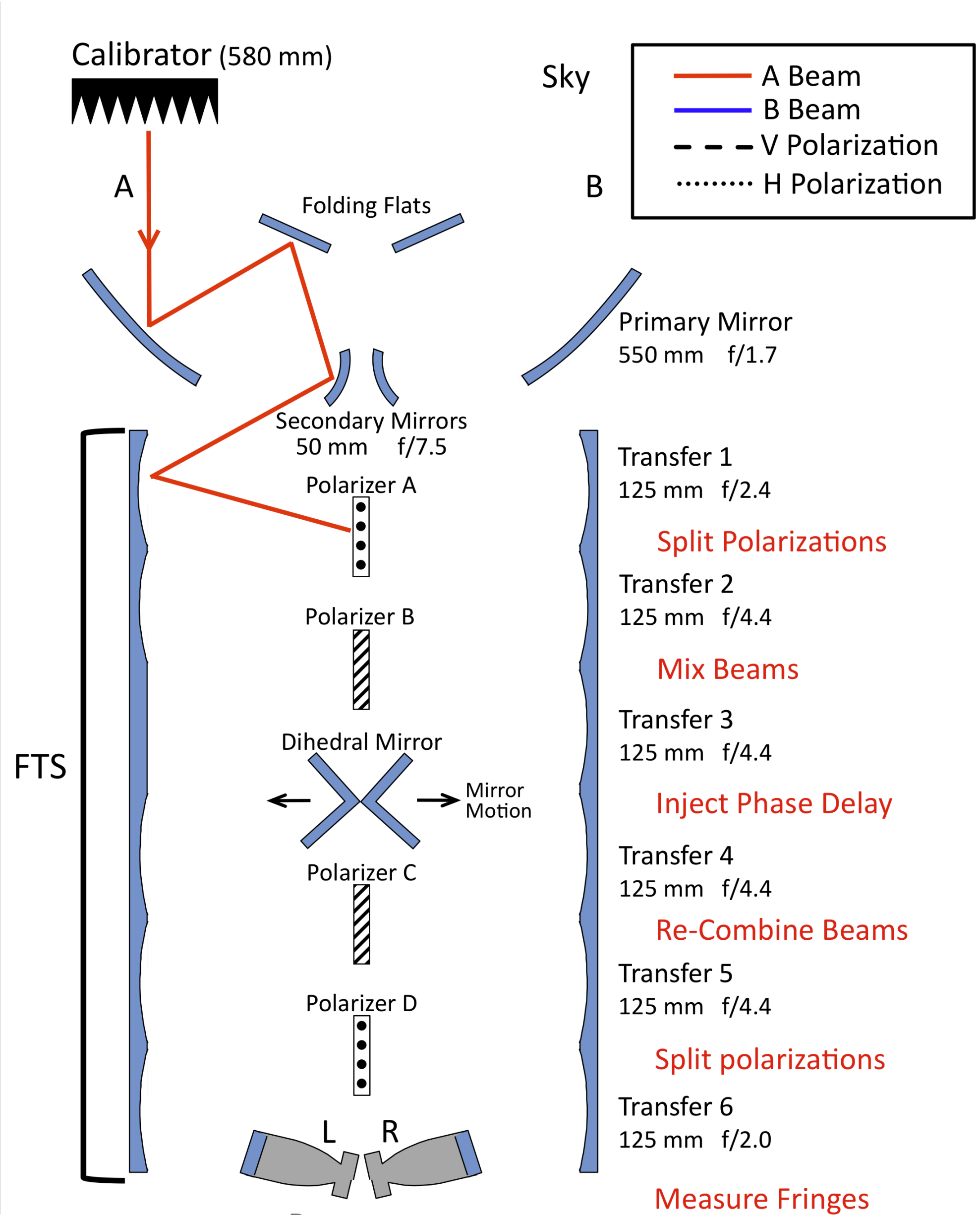
Active control of cryogenic temps
- Knowledge < 1 μK
- Stability < 1 mK
- Multiple cryogenic thermometers

Thermal break between inst & S/C

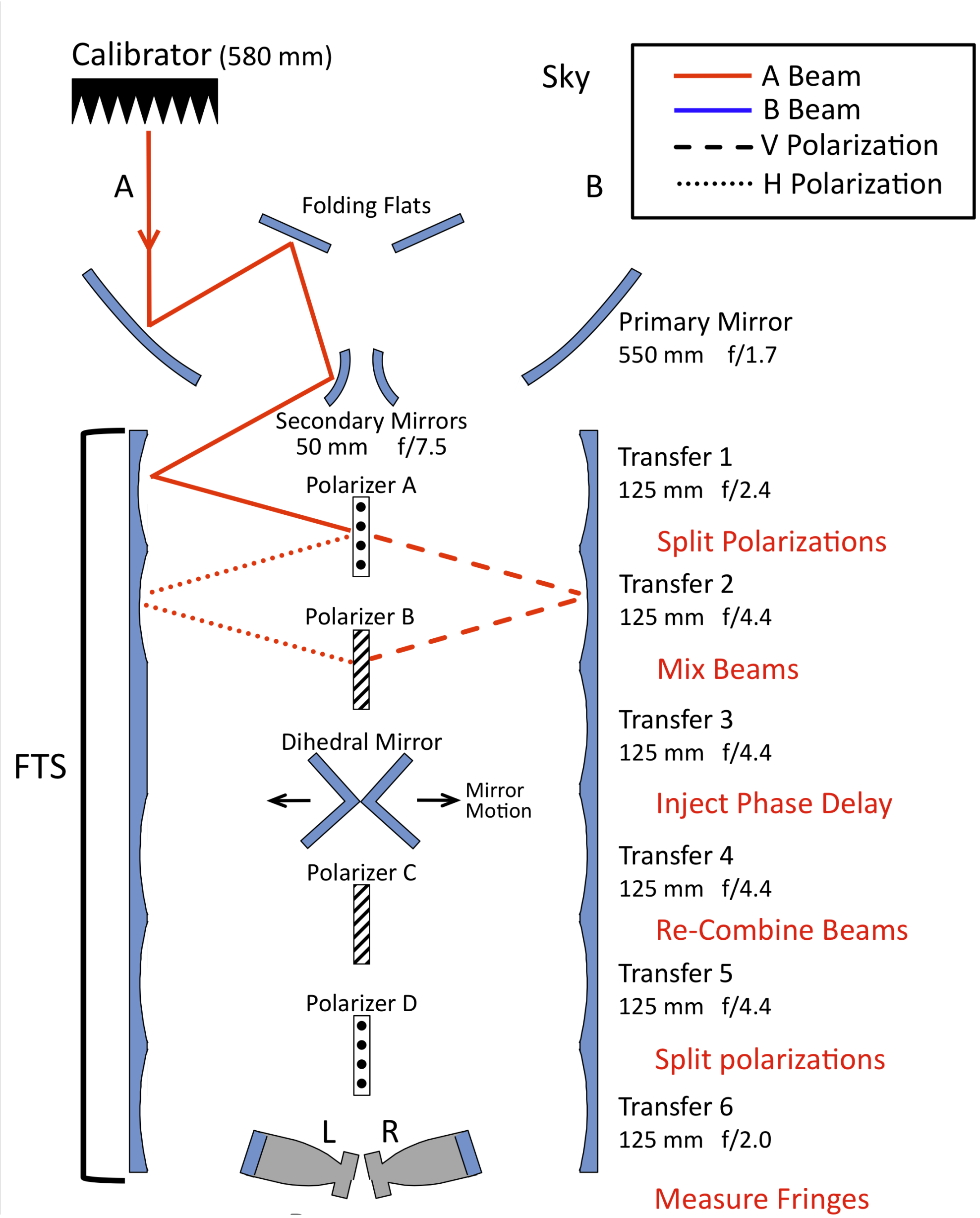
PIXIE Optical Path



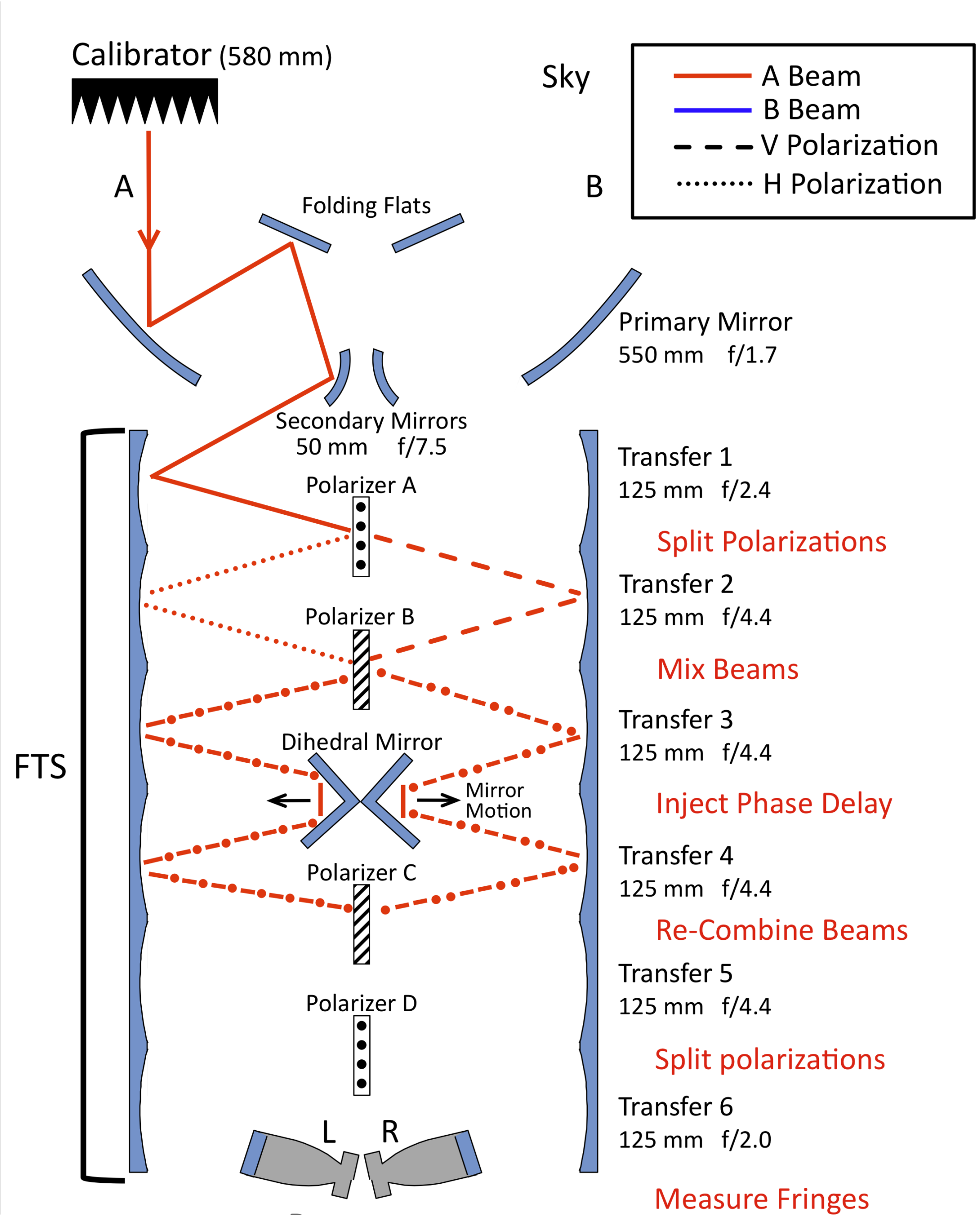
PIXIE Optical Path



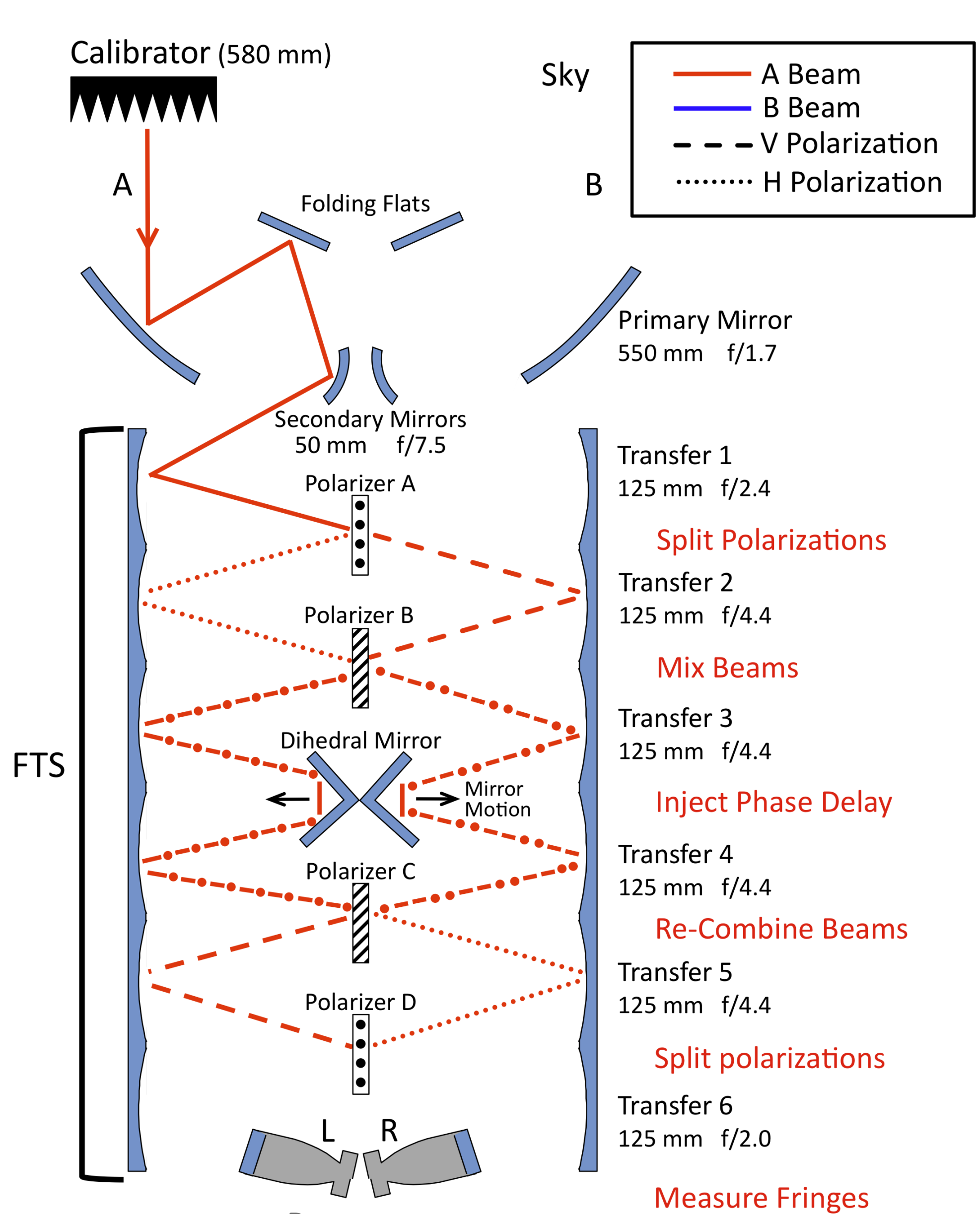
PIXIE Optical Path



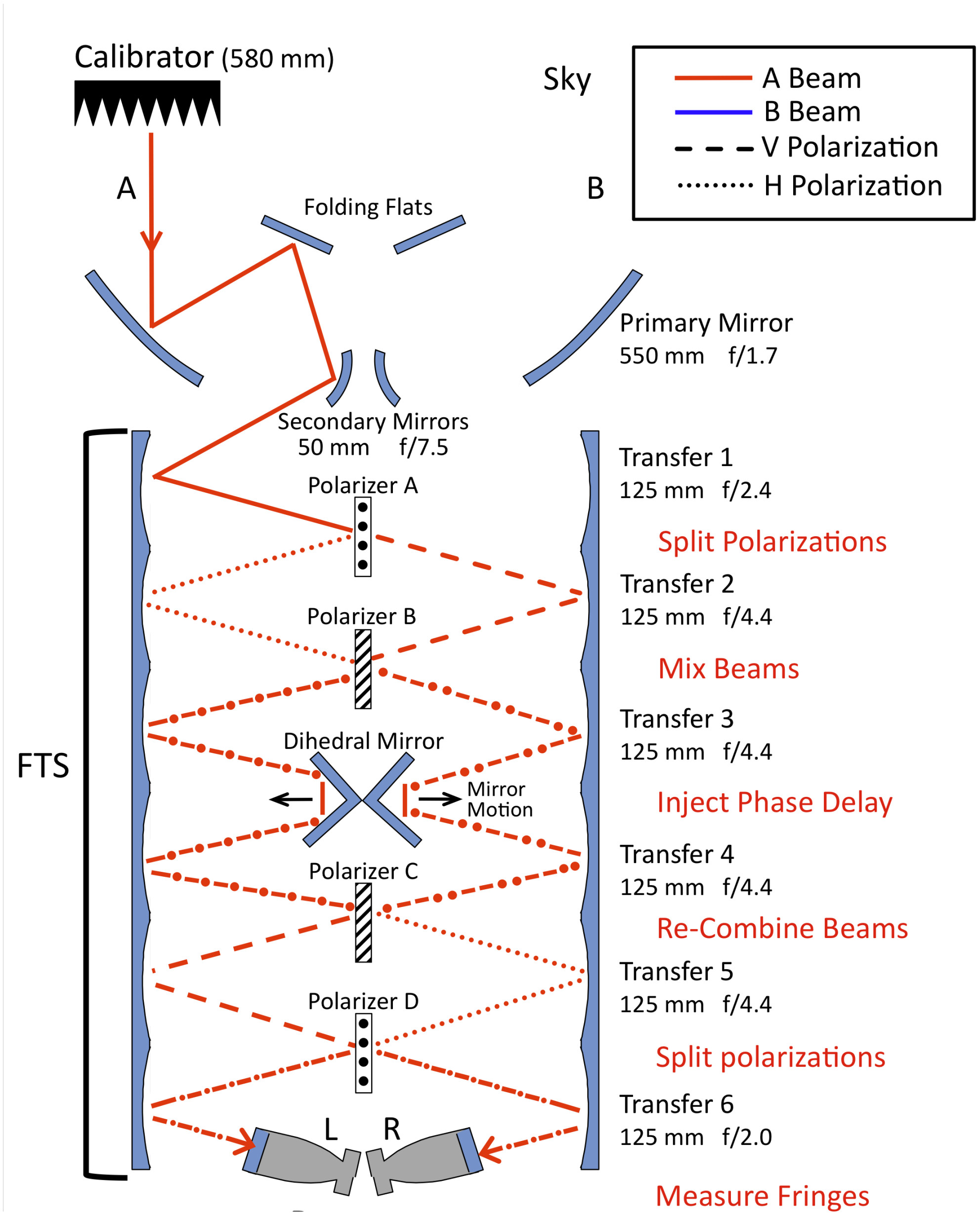
PIXIE Optical Path



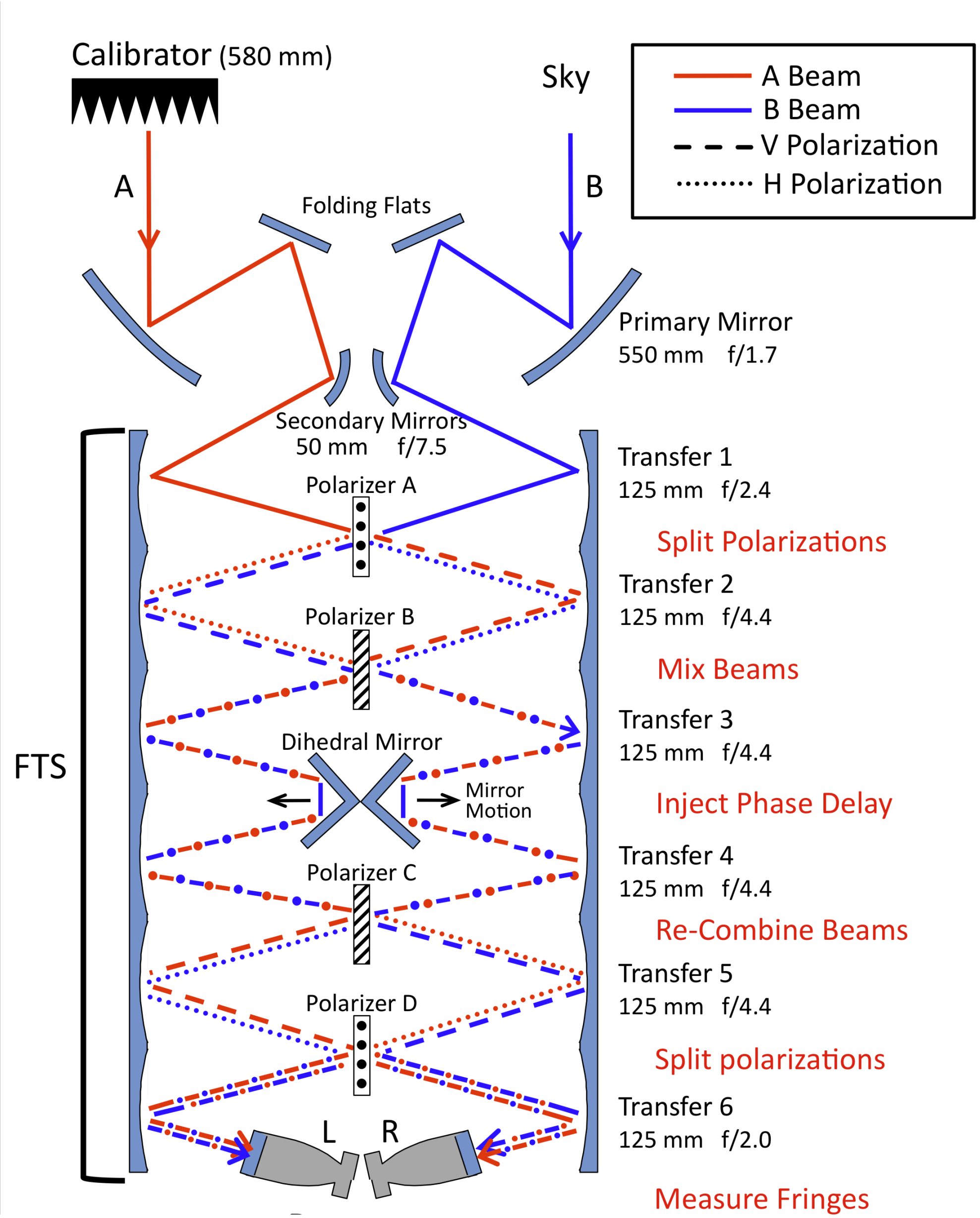
PIXIE Optical Path



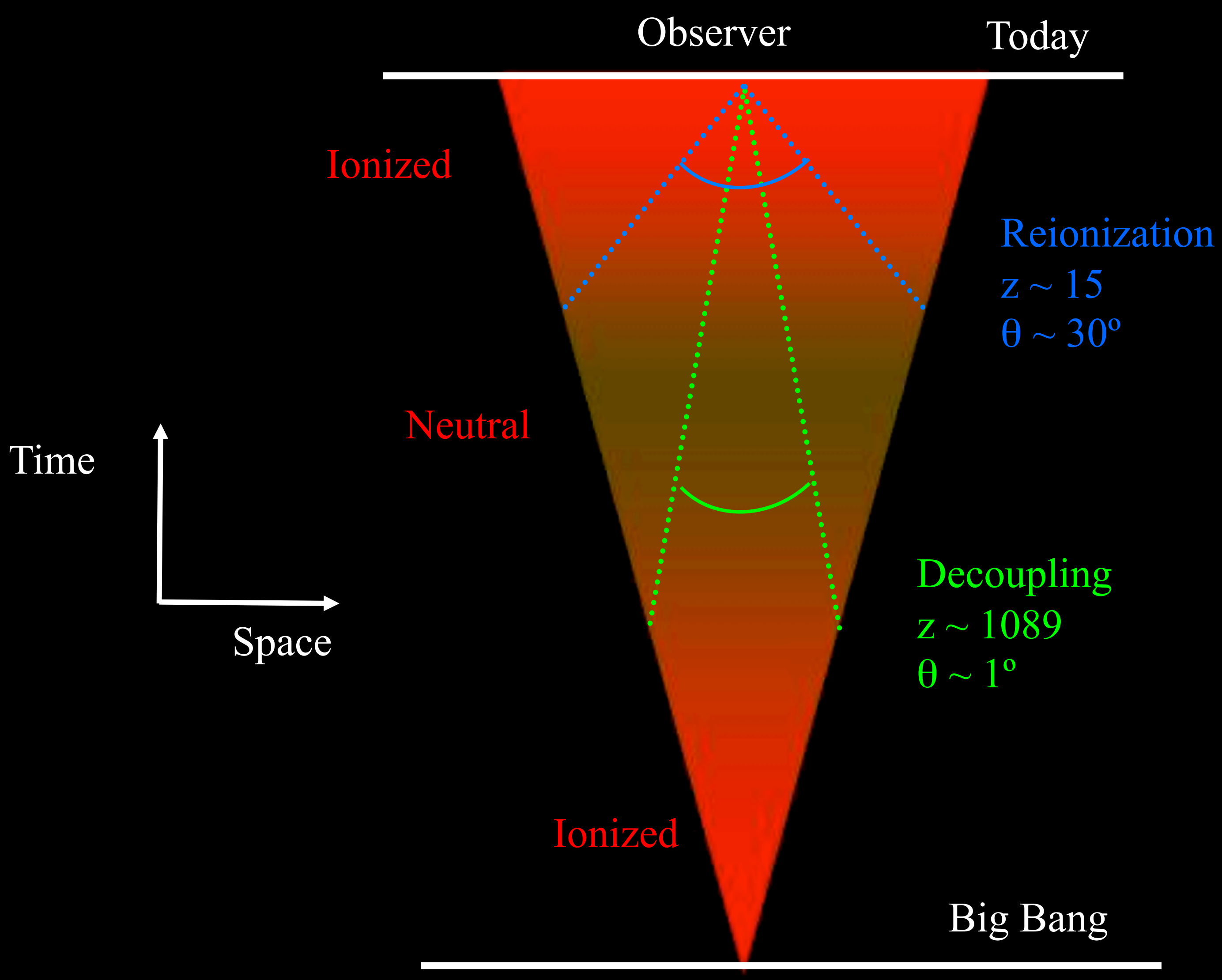
PIXIE Optical Path



PIXIE Optical Path



Angular Scale For Polarization

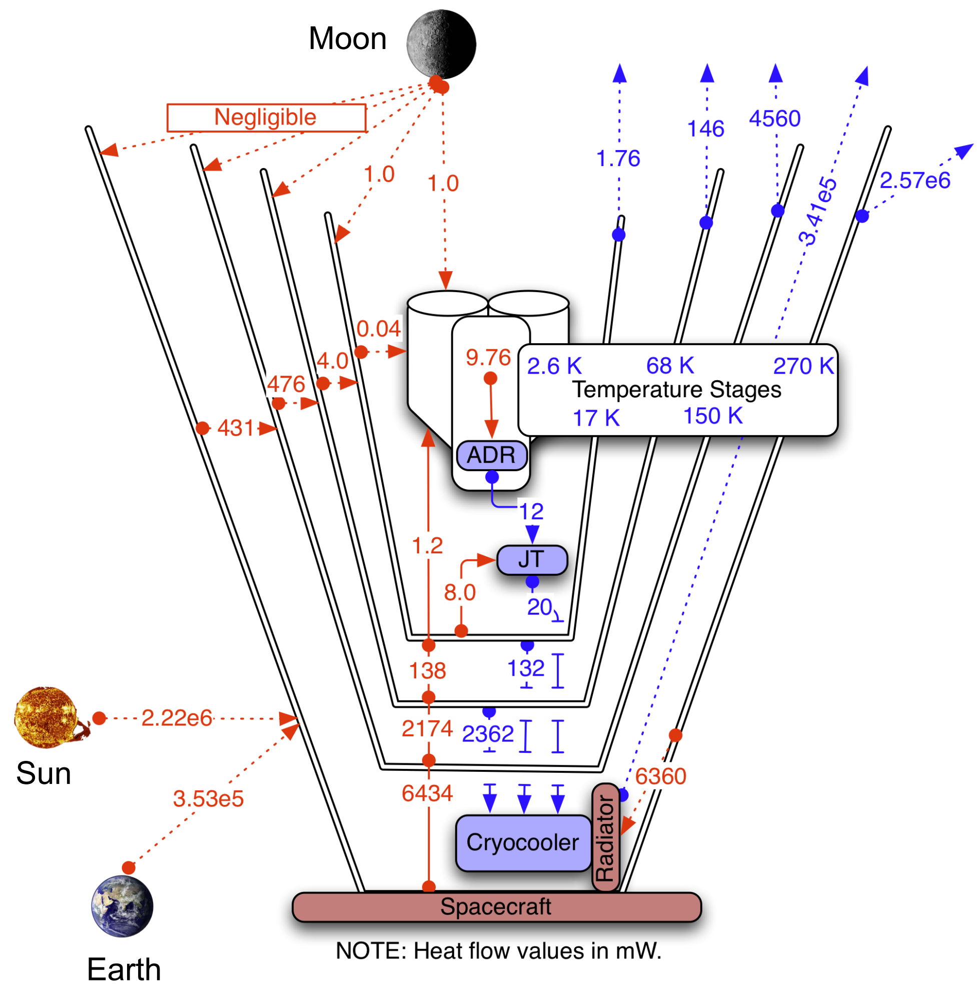


Cryogenic Budget

Layered Hybrid For Maximum Efficiency

- Thermal Shields: Cooling at 150K
- Cryocooler: Cooling at 68, 17, and 4.5K
- ADR: Cooling at 2.6 and 0.1 K

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%

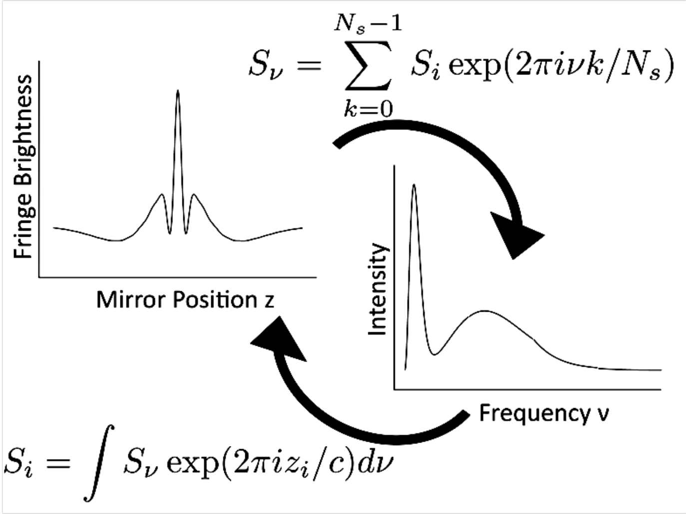


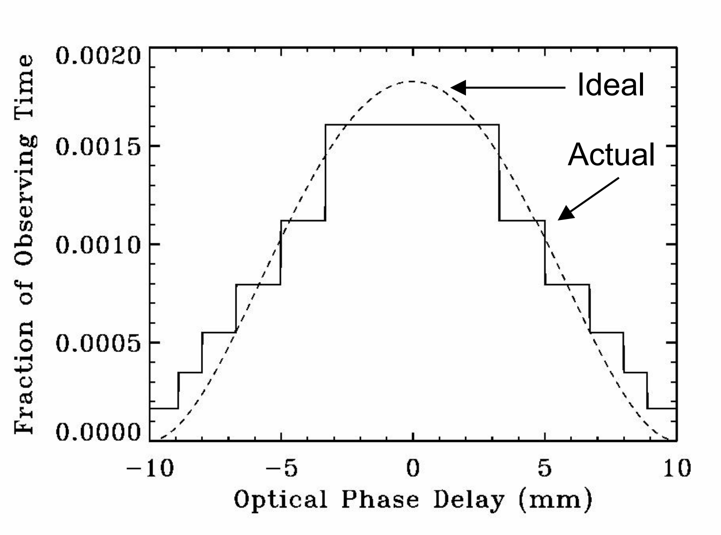
PIXIE Fourier Transform

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)

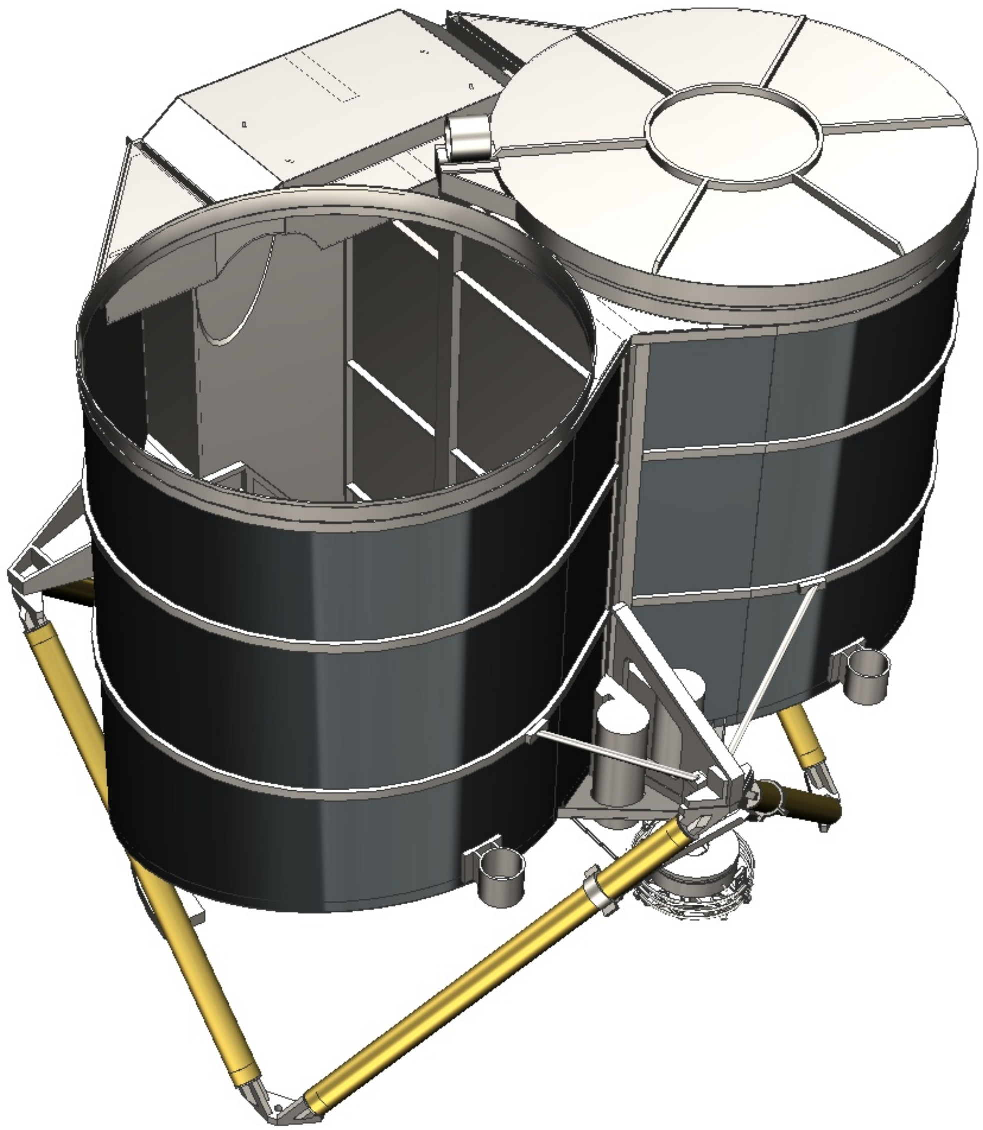




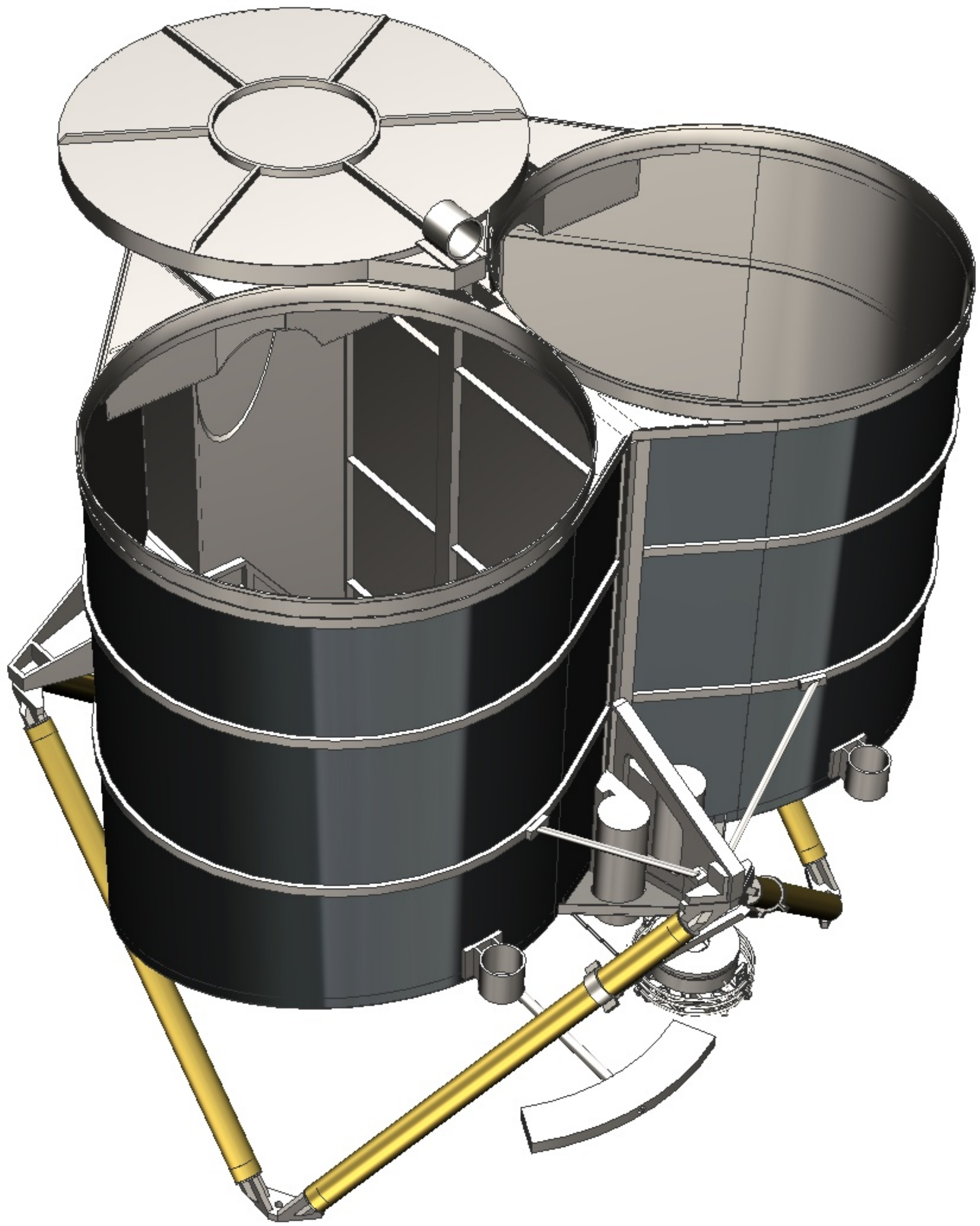
Optical Delay	Physical Stroke	Samples per Stroke	Strokes per Spin
±10 mm	±2.5 mm	1024	8
±8.9 mm	±2.3 mm	910	9
±8.0 mm	±2.1 mm	819	10
±6.7 mm	±1.7 mm	683	12
±5.0 mm	±1.3 mm	512	16
±3.3 mm	±0.9 mm	341	24

Vary stroke length to apodize Fourier transform

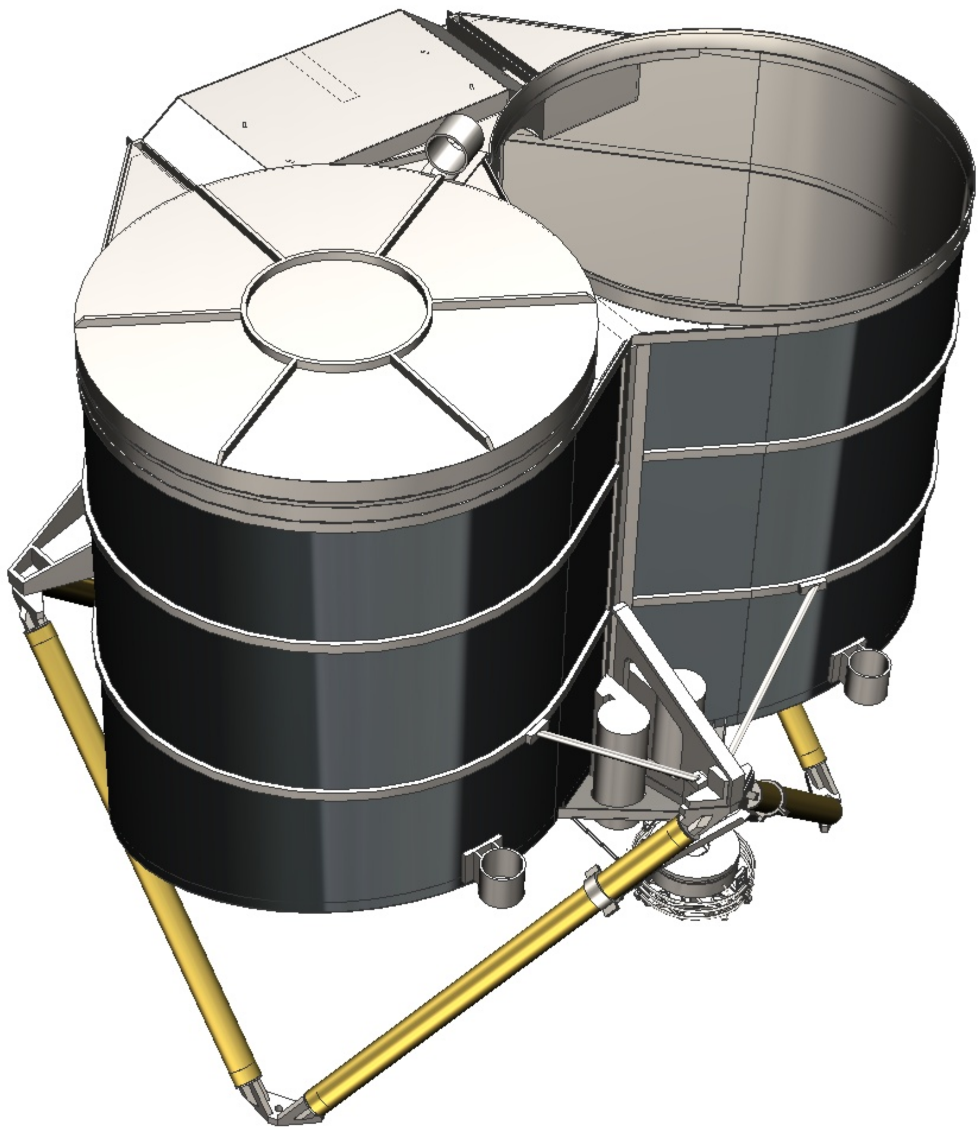
External Calibrator



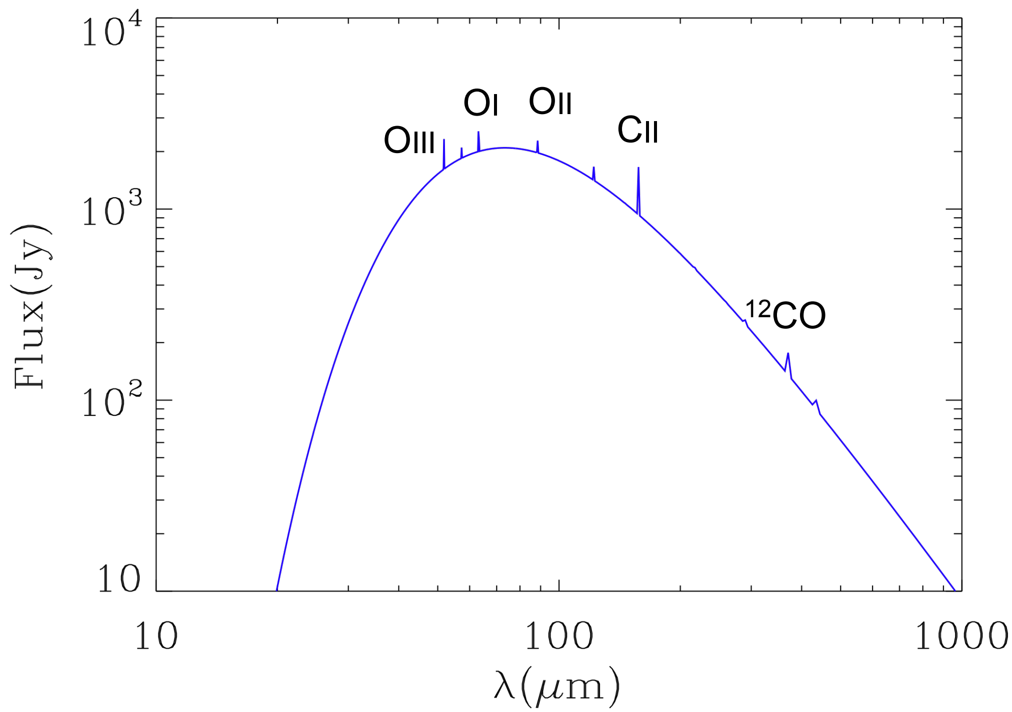
External Calibrator



External Calibrator



Secondary Science: Interstellar Medium

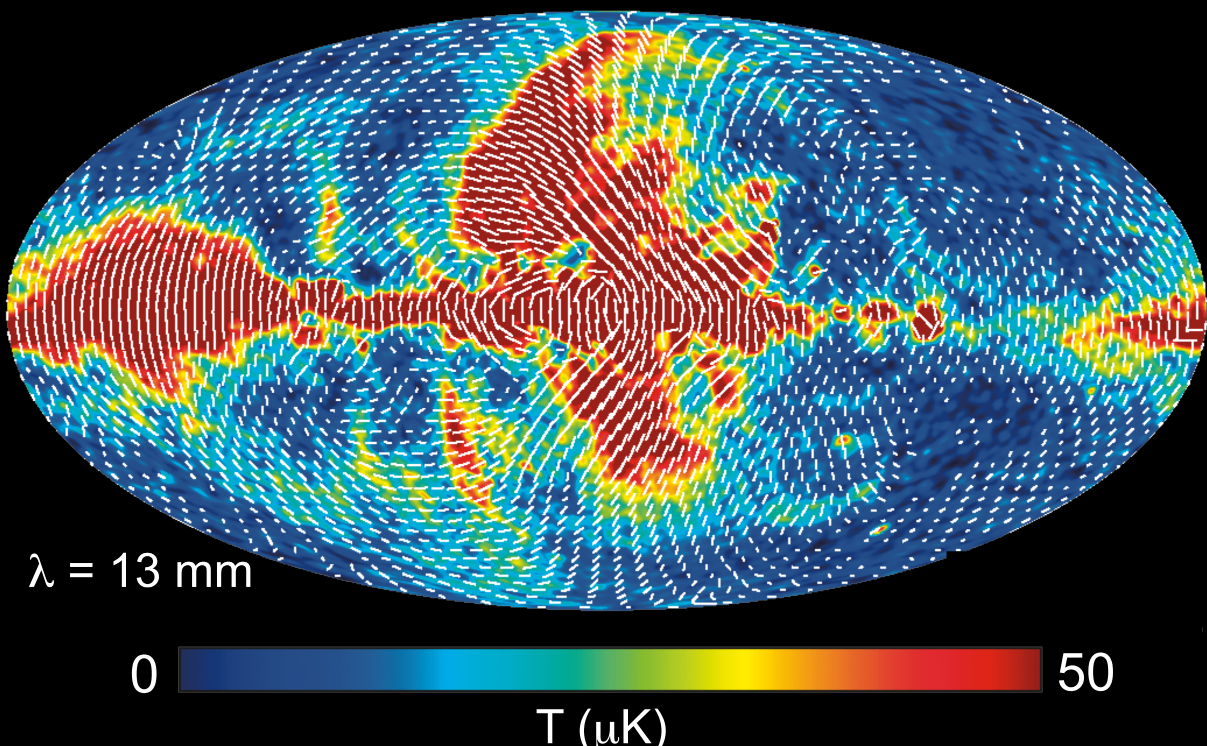


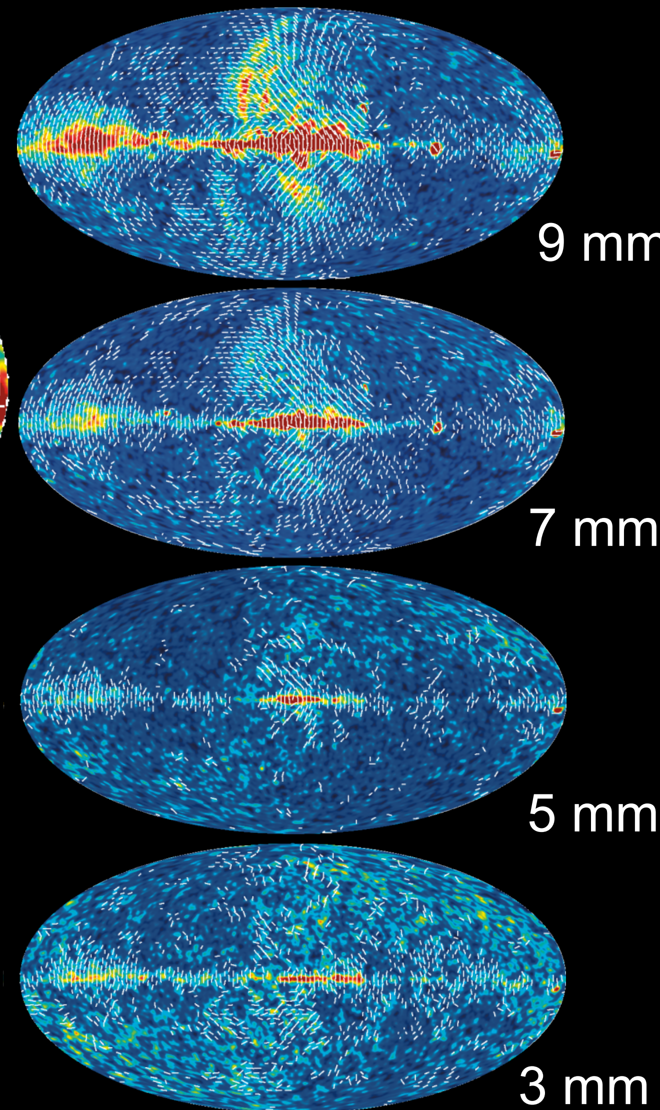
Map temperature and density of each phase in ISM

Metalicity in ISM

Molecular Gas		Photodissociation Regions		H II Regions		Hot ($T > 10^5$ K) Gas	
CO $1 \rightarrow 0$	115 GHz	Fe II	51.3, 87.4 μm	Fe III	51.7 μm	O III	51.8 μm
CO $2 \rightarrow 1$	231 GHz	Fe I	54.3, 111.2 μm	N III	57.3 μm	N III	57.3 μm
CO $30 \rightarrow 29$	3438 GHz	S I	56.3 μm	Fe II	87.4 μm	Fe V	70.4 μm
H_2O	22 GHz	O I	63.2 μm	Fe III	105.4 μm	O III	88.4 μm
H_2O	183 GHz	Si I	68.5, 129.7 μm	N II	121.9 μm		
CS $1 \rightarrow 0$	49 GHz	O I	145.5 μm	Si I	129.7 μm		
CS $2 \rightarrow 1$	98 GHz	C II	157.7 μm	N II	205.2 μm		
CS $4 \rightarrow 3$	196 GHz	C I	370.4, 609.1 μm				

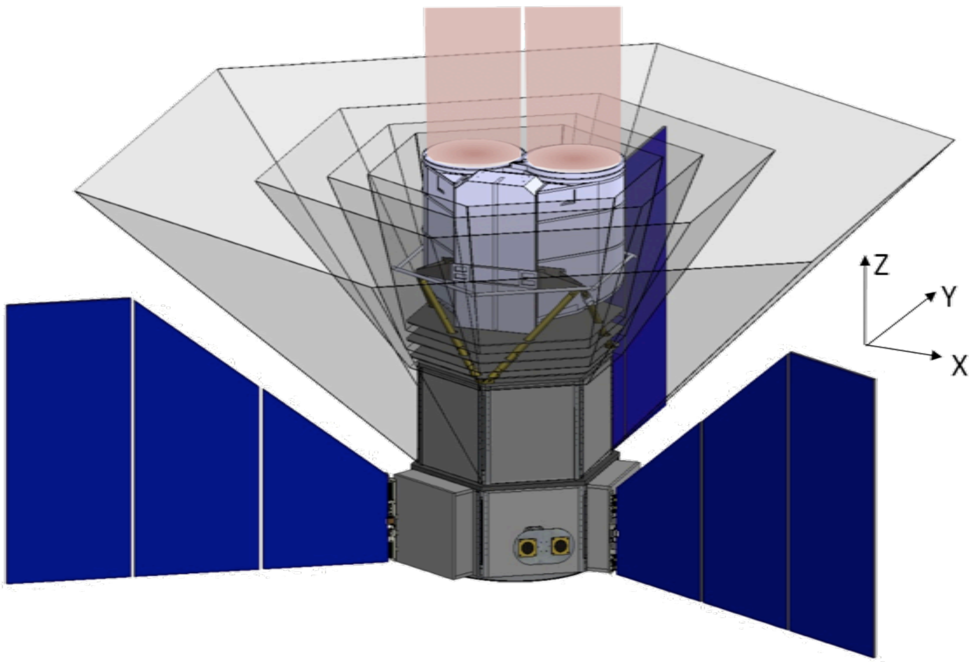
WMAP Full-Sky Polarization





Foregrounds brighter than CMB
E-mode comparable to B-mode

PIXIE Observatory Summary

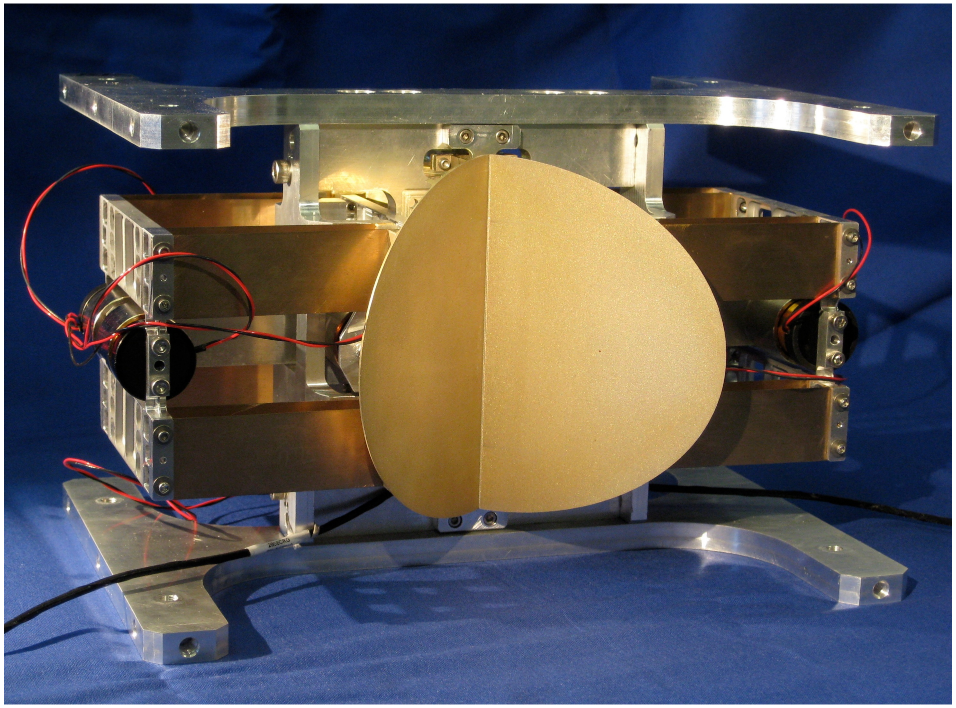


Subsystem	Mass (Kg)			Orbit Average Power (W)		
	CBE	Contin-gency%	MEV	CBE	Cont.	MEV
Mechanical Structure	105.7	26%	132.9			
Mechanisms	8.3	25%	10.4			
Thermal	9.1	25%	11.3	38.0	30%	49.4
Attitude Control	44.4	17%	52.1	98.0	21%	118.3
Command and Data Handling	6.2	20%	7.4	37.0	15%	42.6
RF Communications	10.8	21%	13.1	9.4	5%	9.9
Electrical Power	100.0	22%	122.4	11.0	7%	11.7
Spacecraft Bus Total	284	23%	349	193	20%	232
Payload Total	164.9	30%	214.4	106	30%	137.8
Observatory Total	449.2	26%	563.9	296	24%	369.8
Payload Cryocooler Power	Included in Payload Mass	Included in Payload Mass	Included in Payload Mass	410** (MPV)	100% Cont. and margin	410 (MPV)
Power Sum with Margin Applied						895 W

** Maximum Possible Value for cryocooler. CBE and MEV are not calculated

	Capability	MEV	Margin
Taurus 3210 Launch Capacity	775 kg	563.9 kg	37.5%
Solar Array Power, Avionics	481 W Avionics Allocation	369.7 W	30%
Solar Array Power, Cryocooler	410 W (MPV)	410 W (MPV)	100% Cont & Margin (Heat Lift)
Battery Size	2 X 24 A-h	8.7 A-h	452%
Onboard Data Storage	2 GB	0.76 GB	162%
Uplink Margin	38.4 dB (2 kbps)		
Downlink Margin	6.1 dB (5 Mbps)		
	Requirement	**Prediction**	**Margin**
ADCS Control	1° absolute/axis	0.1°/axis	900%
ADCS Knowledge	9 arcmin, 3 /axis	5.7 arcmin, 3 /axis	58%

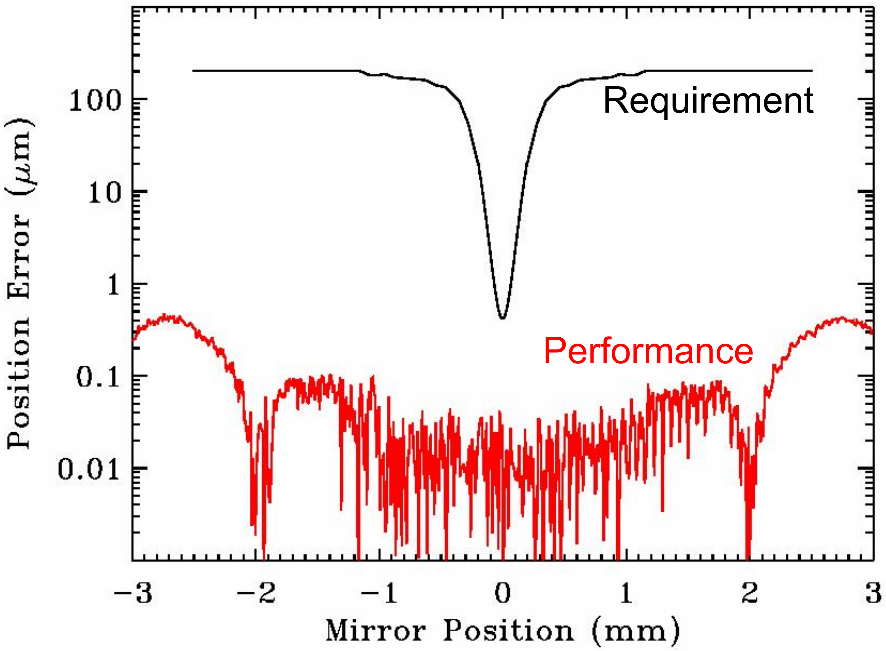
Mirror Transport Mechanism



Engineering prototype

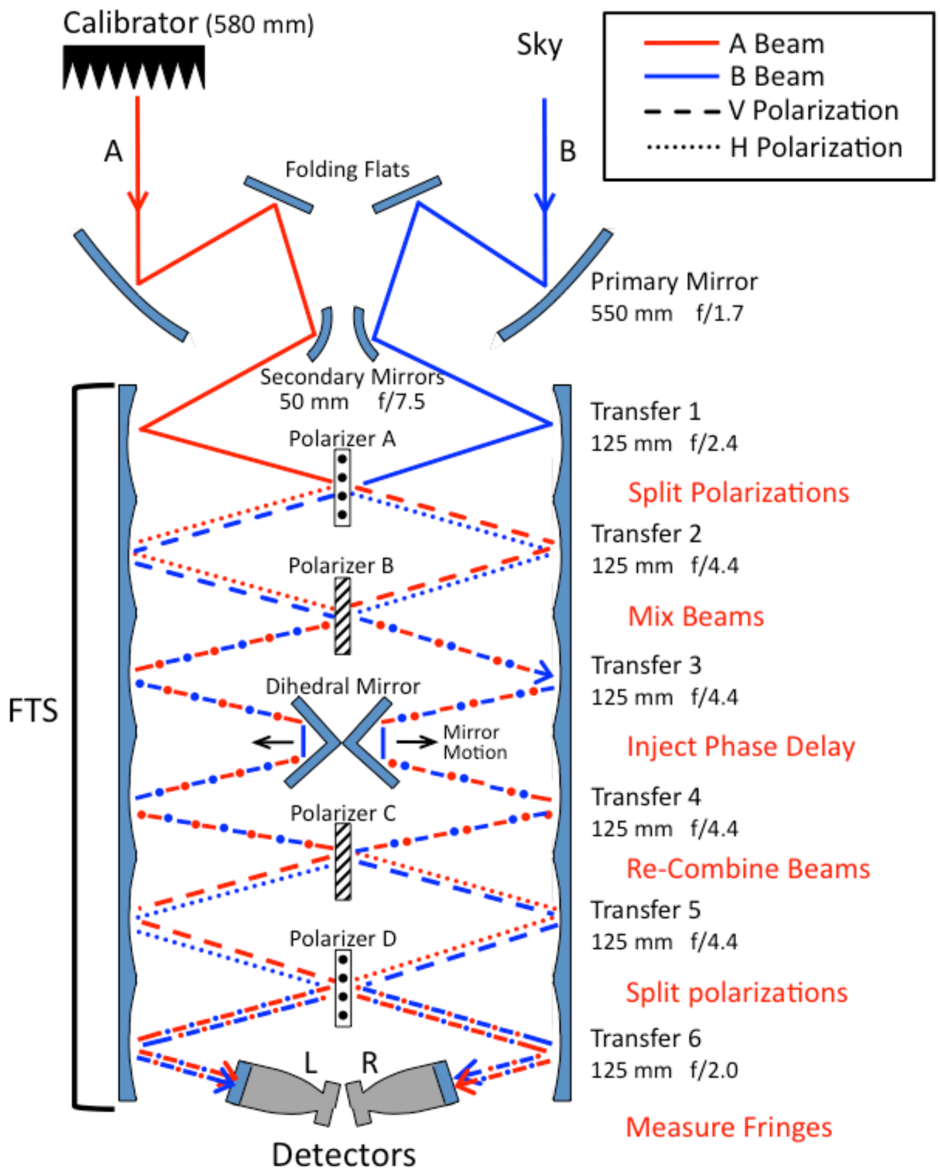
Translate ±2.54 mm at 0.5 Hz

- Optical phase delay ±1 cm
- Repeatable cryogenic position



Demonstrated performance exceeds requirement by factor of ten

Optical Design



Non-Imaging Optics

Primary Mirrors Define Beams
- 55 cm diameter
- 2.6° tophat on sky

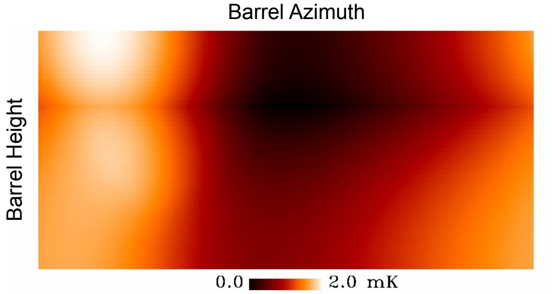
Optics Box Interferes Beams
- Periscope Transfer Mirrors
- Polarizing Grids at 45°

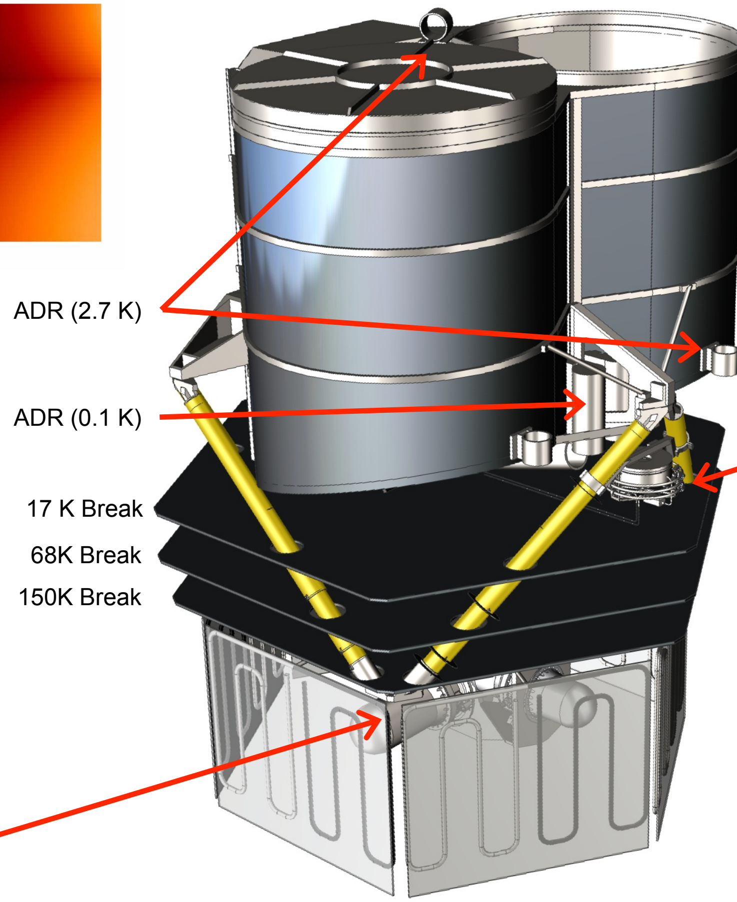
Dihedral Mirror Phase Delay
- ±2.54 mm peak-peak at 1 Hz
- 1 μm position accuracy each 1 ms sample

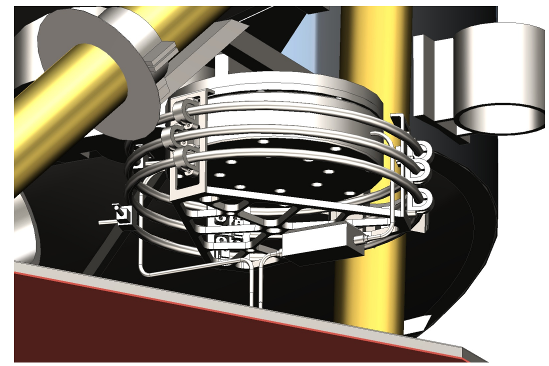
2 Detectors in each concentrator horn
- Measure interference fringes
- 1 kHz detector readout
- 1024 samples per mirror stroke

Cryogenics

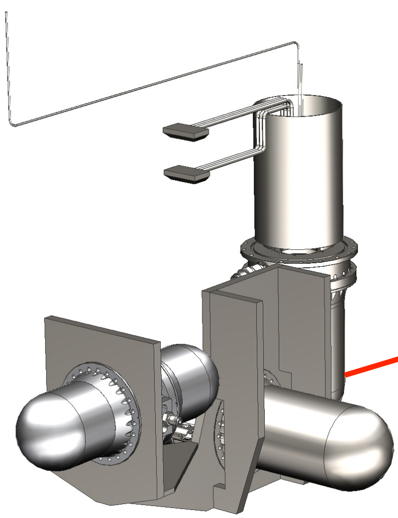
Moonshine Thermal Gradient







J-T Cold Head (4.5 K)



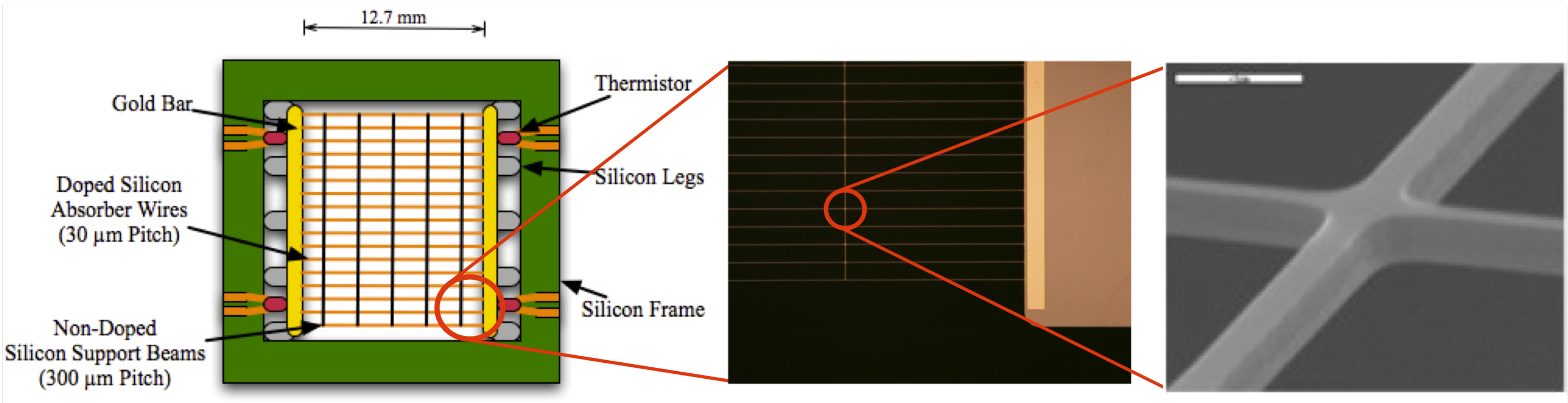
Cryo-Cooler Compressor (280 K)

Multi-Stage Cryogenic Design
- Passive Sun Shades (not shown)
- 4.5 K Cryo-cooler
- 2.7 K ADR
- 0.1 K ADR

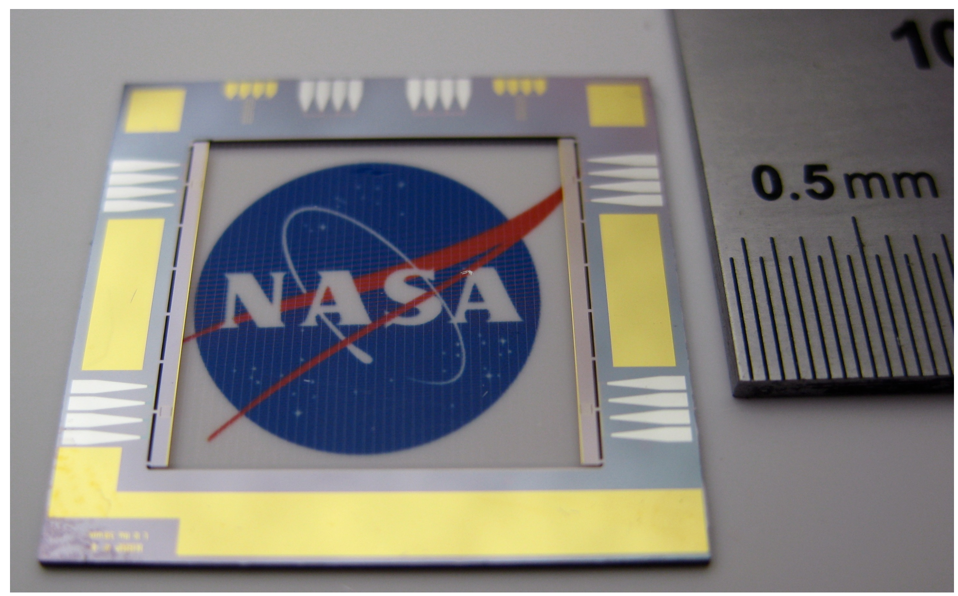
Thermal Lift Budget

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%

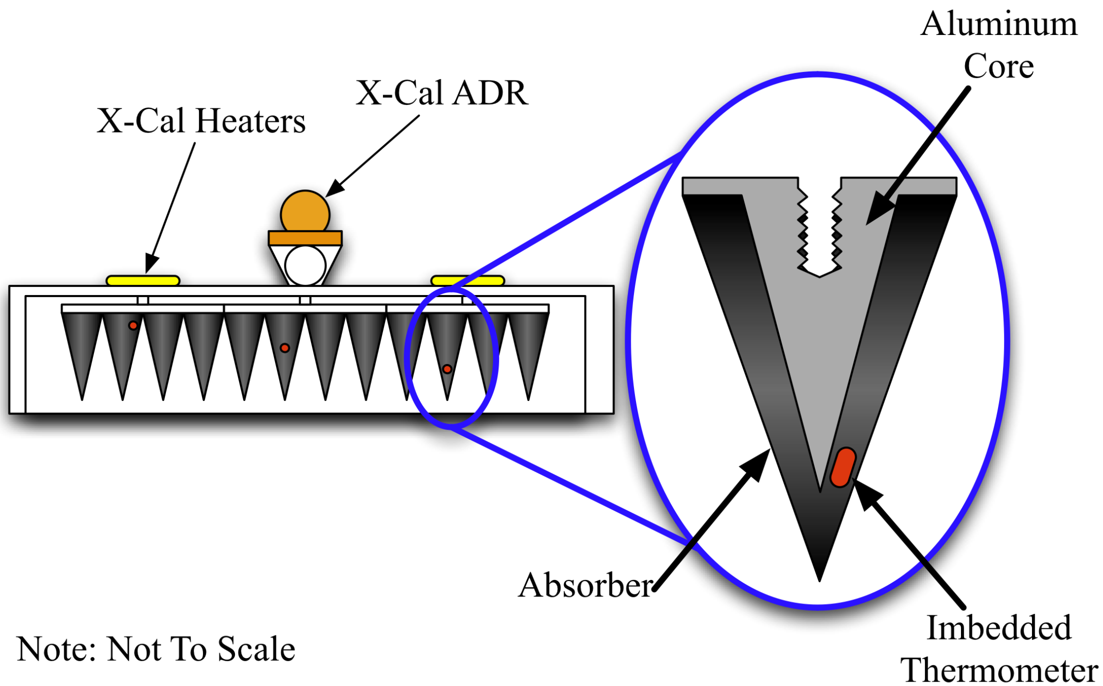
Polarization-Sensitive Detectors



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%

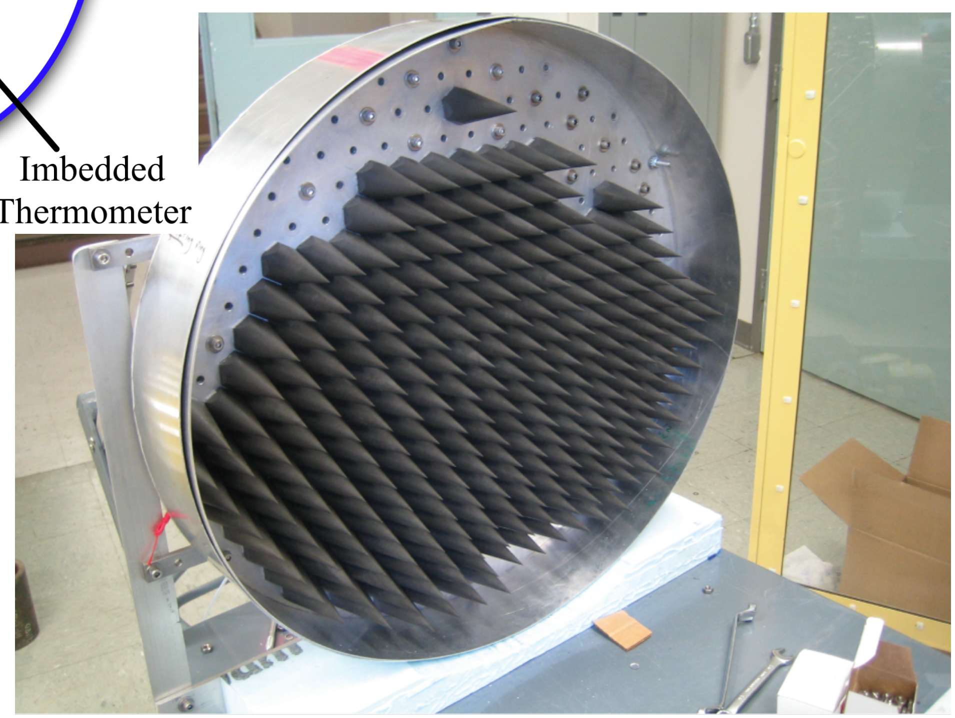


Blackbody Calibrator



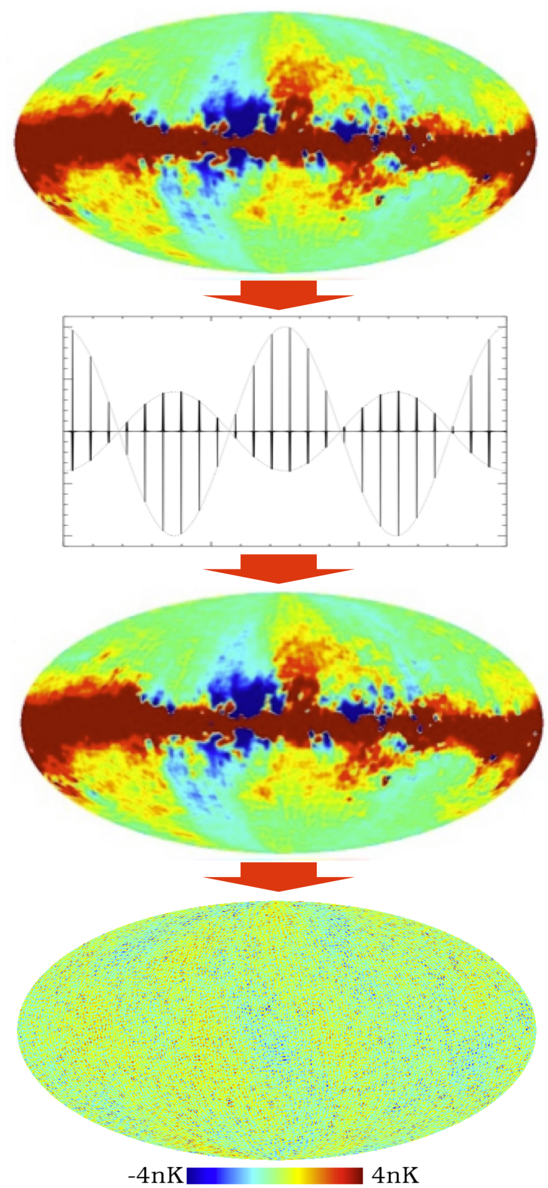
Based on successful ARCADE calibrator

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

End-To-End Simulations



Input Sky Cube
(Stokes Q)

Start with input sky cube, I (Θ,ϕ,v,S)

Simulated
Time-Ordered
Data

“Fly” mission over simulated sky, including desired instrumental effects (cross-pol)

Output Sky Cube
(Stokes Q)

Read time-ordered data and solve for output sky cube

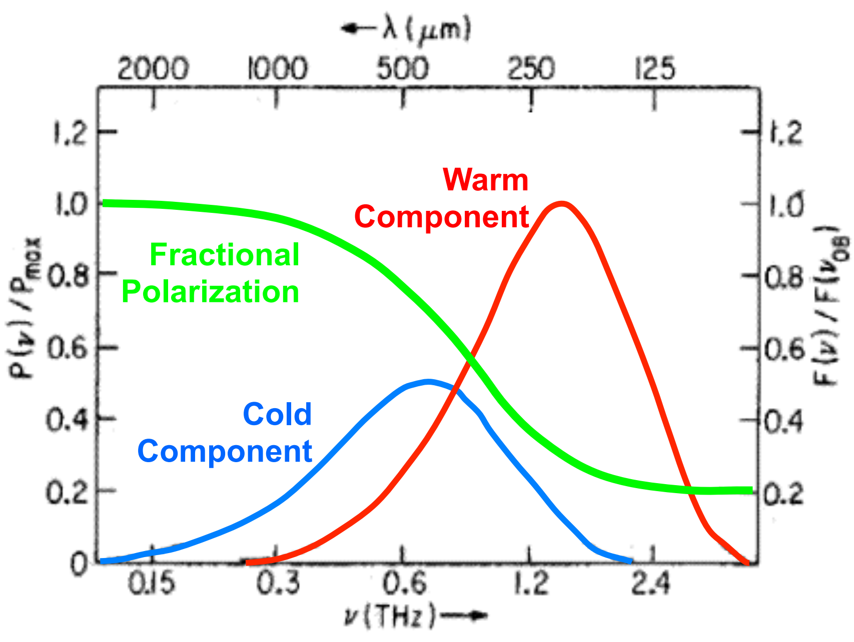
Difference CMB Map
(Stokes Q)

Linear combination of frequency channels generates CMB maps, which are then compared to input CMB maps

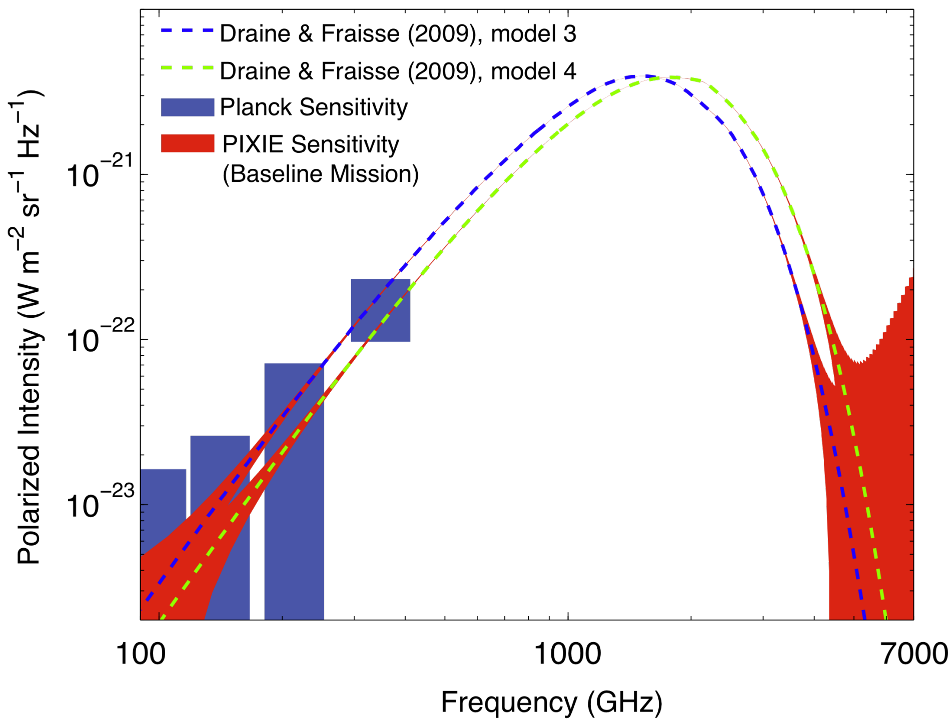
Secondary Science: Interstellar Dust

Polarization depends on composition
- Silicate: More polarized
- Carbonaceous: 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