COrE++ : The Competition

Martin Bucher, APC, Université Paris 7/CNRS

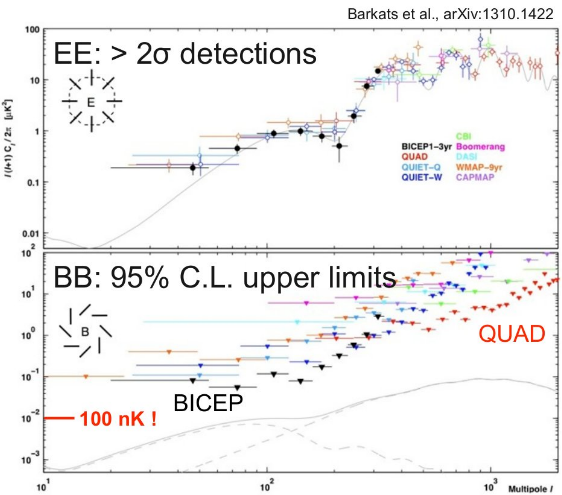
COrE/PRISM M4 Planning Meeting
Paris, 10 February 2014

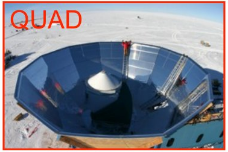
The Context

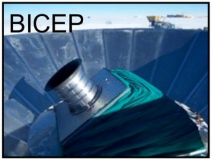
The mission selected for the M4 slot is likely to be launched around 2028. This means that the science proposed does not only need to be competitive vis-à-vis present experiments, but also vis-à-vis future experiments that will take place before ≈ 2028. To make our case, we must argue persuasively that COrE++ will be interesting and competitive in 2028, by anticipating the future development of the field. We must be able to prove that even if r is detected from the ground, a space mission will be worthwhile. We must also explain how our mission compares the two other related (presently unfunded) space missions, PIXIE and LiteBird.

“Stage 4 CMB" — The ultimate ground-based challenge from our American colleagues

Status of B-mode experiments







CMB timeline

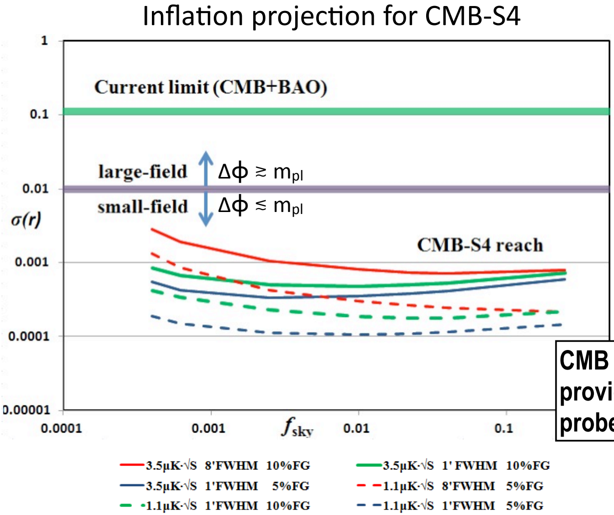
- 2009: $r < 0.7$ (BICEP) Chiang et al, 0906.1181

- 2013: Stage II experiments detect lensing B-modes
- 2014: $r \lesssim 0.1$ from Inflationary B-modes (BICEP 2) ?
- 2013-2016: Stage II experiments
  $\sigma(r) \sim 0.03$, $\sigma(N_{eff}) \sim 0.1$, $\sigma(\Sigma m_\nu) \sim 0.1$eV
- 2016-2020: Stage III experiments
  $\sigma(r) \sim 0.01$, $\sigma(N_{eff}) \sim 0.06$, $\sigma(\Sigma m_\nu) \sim 0.06$eV;

- 2020-2025: Stage IV experiment, **CMB-S4**
  $\sigma(r) = 0.001$, $\sigma(N_{eff}) = 0.020$, $\sigma(\Sigma m_\nu) = 16$ meV

On an ambitious path forward and producing a steady flow of scientific results

CMB-S4 What it will deliver



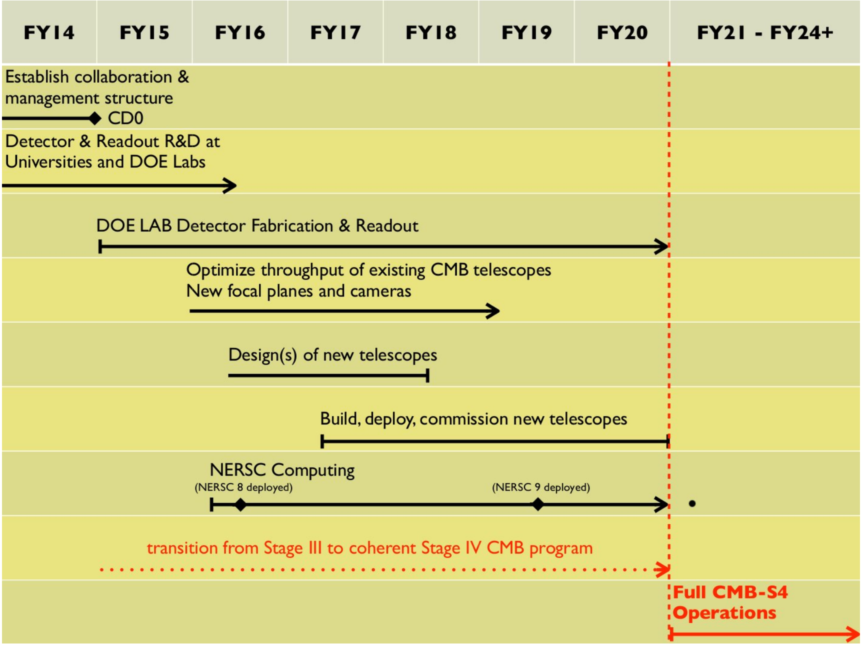
CMB polarization provides the only probe for r < 0.1

CMB-S4 What it will take

- **CMB-S4 Survey:**
  - Maximum return on Inflation, Neutrino, and Dark Energy science requires an optimized survey which includes a range of resolution and sky coverage from deep to wide.
- **Sensitivity of ~1 uK-arcmin over half the sky**
- **Experimental Configuration:**
  - 200,000+ detectors on multiple platforms
  - spanning 40 - 240 GHz for foreground removal
  - $\lesssim$ 3 arcmin resolution required for CMB lensing & neutrino science,

    (***higher resolution leads to amazing and complementary dark energy constraints and gravity tests on large scales via the SZ effect)***

See Snowmass planning document arxiv:1309.5383


FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21 - FY24+
Establish collaboration & management structure
CD0
Detector & Readout R&D at Universities and DOE Labs
DOE LAB Detector Fabrication & Readout
Optimize throughput of existing CMB telescopes
New focal planes and cameras
Design(s) of new telescopes
Build, deploy, commission new telescopes
NERSC Computing
(NERSC 8 deployed)
(NERSC 9 deployed)
transition from Stage III to coherent Stage IV CMB program
Full CMB-S4 Operations

NOTIONAL BUDGET		FY15	FY16	FY17	FY18	FY19	FY20	
DOE ANL/LBNL/SLAC Detector	project capital $*	0.5M	1M	1.5M	1.5M	1.5M	1.5M	
	FTE†	5	7	10	14	16	16	
DOE (LBNL/NERSC) Computing	project capital $	-	-	-	-	-	0.5M	
	FTE	-	1	2	2	3	3	
DOE Receiver test facilities, hardware & electronics	project capital $	-	3M	4.5M	7.5M	7.5M	7.5M	
	FTE	4	8	10	12	12	12	
NSF University CMB Dev, Test, Ops and Analysis	Σ $	(7M) current	7M	7M	7M	8M	9M	
new telescopes (NSF) site/deploy (NSF/DOE)	project capital $	-	2M	7M	7M	7M	7M	
NSF & DOE new telescope operations	$	-	0.5M	2M	3M	4M	5M	
DOE Lab & Univ Analysis (converts)	*FTE*	*6*	*10*	*16*	*24*	*30*	*30*	
*2013 dollars †DOE Particle Physicist FTE								

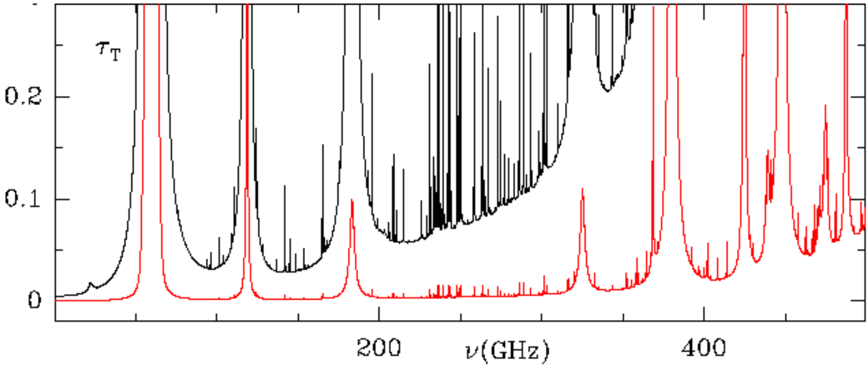
NOTIONAL BUDGET		FY15	FY16	FY17	FY18	FY19	FY20	Capital $+FTEyr
DOE ANL/LBNL/SLAC Detector	project capital $	0.5M	1M	1.5M	1.5M	1.5M	1.5M	**7.5M**
	FTE	5	7	10	14	16	16	**68 yr**
DOE (LBNL/NERSC) Computing	project capital $	-	-	-	-	-	0.5M	**0.5M**
	FTE	-	1	2	2	3	3	**11 yr**
DOE Receiver test facilities, hardware & electronics	project capital $	-	3M	4.5M	7.5M	7.5M	7.5M	**31M**
	FTE	4	8	10	12	12	12	**58 yr**
NSF University CMB Dev, Test, Ops and Analysis	Σ $	(7M) current	7M	7M	7M	8M	9M	
†new telescopes (NSF) site/deploy (NSF/DOE)	project capital $	-	2M	7M	7M	7M	7M	**30M**
NSF & DOE new telescope operations	$	-	0.5M	2M	3M	4M	5M	
DOE Lab & Univ Analysis (converts)	*FTE*	*6*	*10*	*16*	*24*	*30*	*30*	

†Roughly 2:1 ratio of cost of telescopes to costs of site prep and deployment

Total Project Capital: $69M and 137 FTE • yr
(not including 25% contingency)

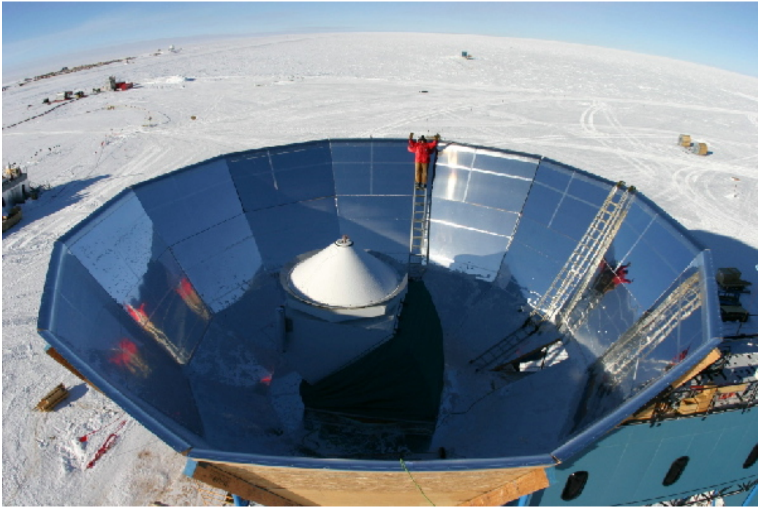
NOTIONAL BUDGET		FY15	FY16	FY17	FY18	FY19	FY20	Ops/yr Analysis/yr
DOE ANL/LBNL/SLAC Detector	project capital $	0.5M	1M	1.5M	1.5M	1.5M	1.5M	
	FTE	5	7	10	14	16	16	
DOE (LBNL/NERSC) Computing	project capital $	-	-	-	-	-	0.5M	**0.5M/ 3yr**
	FTE	-	1	2	2	3	3	**4 FTE**
DOE Receiver test facilities, hardware & electronics	project capital $	-	3M	4.5M	7.5M	7.5M	7.5M	
	FTE	4	8	10	12	12	12	
NSF University CMB Dev, Test, Ops and Analysis	Σ $	(7M) current	7M	7M	7M	8M	9M	**9M**
new telescopes (NSF) site/deploy (NSF/DOE)	project capital $	-	2M	7M	7M	7M	7M	
NSF & DOE new telescope operations	$	-	0.5M	2M	3M	4M	5M	**5M**
DOE Lab & Univ Analysis (converts)	*FTE*	*6*	*10*	*16*	*24*	*30*	*30*	*30+FTE*
		2020+ yearly ops and analysis: $14.2M and 34+ FTE						

Atmospheric optical depth vs. ν (GHz)



Red=South pole, black=stratospheric balloon

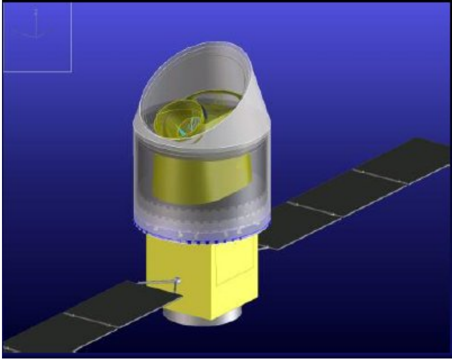
Earth and balloon based experiments need ground shields



LiteBird

ビッグバン以前の宇宙を探るLiteBIRD衛星

Lite (light) Satellite for the studies of **B**-mode polarization and **I**nflation from cosmic background **R**adiation **D**etection



高エネルギー加速器研究機構(KEK)
素粒子原子核研究所
宇宙背景放射(CMB)実験グループ
羽澄昌史(はずみまさし)
for the LiteBIRD Working Group

第1回小型科学衛星シンポジウム
2011年3月1日

This talk is dedicated to Bruce Winstein.

Focal plane sensitivity

LiteBIRD

30cm mirror

Claim: r=1e-3 at 5sigma

Integration time = 2 effective years

T_{mirror} = 4 K

No dark bolo is included in the count.

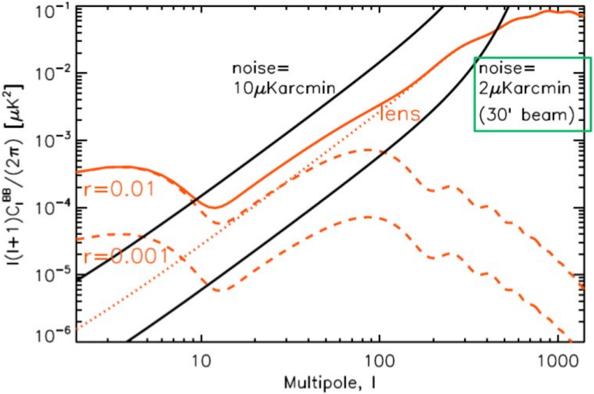
Band [GHz]	Pixel size [mm]	Pixel#/ wafer	Bolo#/ wafer	Sensitivity per wafer [uKarcmin]	# of wafer (total # of bolo on FP)	Sensitivity per band [uKarcmin]
60	18	19	38	29	8	10.3
78	18	19	38	18	8	6.4
100	18	19	38	13	8	4.6
Sub total			**114**		**(912)**	**3.5**
140	12	37	74	8.8	5	4.0
190	12	37	74	7.0	5	3.1
280	12	37	74	9.2	5	4.1
Sub total			**222**		**(1110)**	**2.1**
All					**(2022)**	**1.8** ???

We limit the total number of detectors as ~2000. The MUX factor of 64 (2W/SQUID) will keep the readout power below 70W.

Focal plane requirement

Noise level: goal = 2μK・arcmin
(requirement: < 3μK・arcmin)

To be well below "lensing floor"



ν	n_{unpol}	n_{pol}	θ_{fwhm}	Temp (I) $\mu K\cdot$arcmin		Pol (Q,U) $\mu K\cdot$arcmin	
GHz			arcmin	RJ	CMB	RJ	CMB
30	4	4	32.7	198.5	203.2	280.7	287.4
44	6	6	27.9	228.0	239.6	322.4	338.9
70	12	12	13.0	186.5	211.2	263.7	298.7
100	8	8	9.9	23.9	31.3	33.9	44.2
143	11	8	7.2	11.9	20.1	19.7	33.3
217	12	8	4.9	9.4	28.5	16.3	49.4
353	12	8	4.7	7.6	107.0	13.2	185.3
545	3	0	4.7	6.8	1.1×10^3	—	—
857	3	0	4.4	2.9	8.3×10^4	—	—

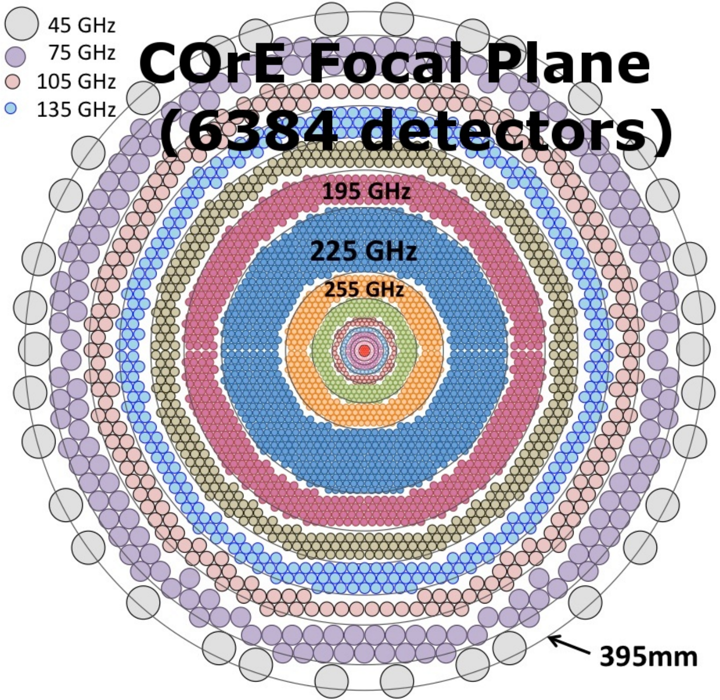
PLANCK (30 month mission)

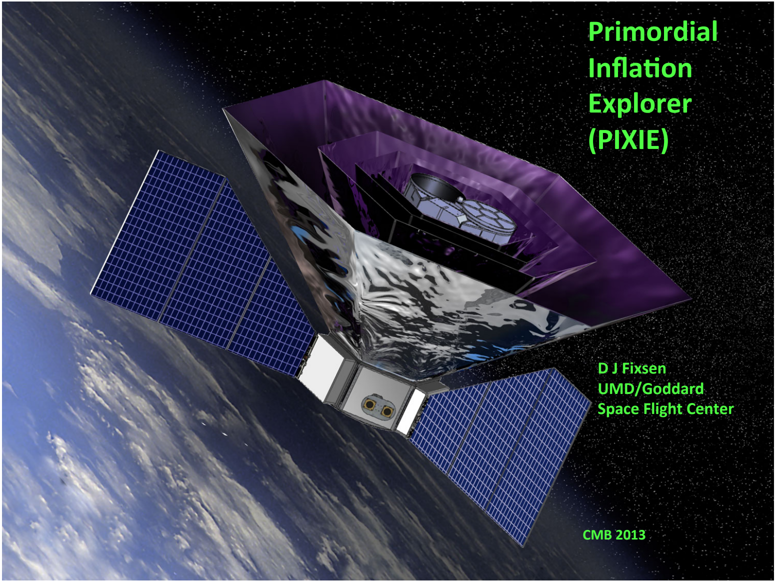
ν	$(\Delta\nu)$	n_{det}	θ_{fwhm}	Temp (I) $\mu K\cdot$arcmin		Pol (Q,U) $\mu K\cdot$arcmin	
GHz	*GHz*		arcmin	RJ	CMB	RJ	CMB
45	15	64	23.3	4.98	5.25	8.61	9.07
75	15	300	14.0	2.36	2.73	4.09	4.72
105	15	400	10.0	2.03	2.68	3.50	4.63
135	15	550	7.8	1.68	2.63	2.90	4.55
165	15	750	6.4	1.38	2.67	2.38	4.61
195	15	1150	5.4	1.07	2.63	1.84	4.54
225	15	1800	4.7	0.82	2.64	1.42	4.57
255	15	575	4.1	1.40	6.08	2.43	10.5
285	15	375	3.7	1.70	10.1	2.94	17.4
315	15	100	3.3	3.25	26.9	5.62	46.6
375	15	64	2.8	4.05	68.6	7.01	119
435	15	64	2.4	4.12	149	7.12	258
555	195	64	1.9	1.23	227	3.39	626
675	195	64	1.6	1.28	1320	3.52	3640
795	195	64	1.3	1.31	8070	3.60	22200

COrE summary (4 year mission)

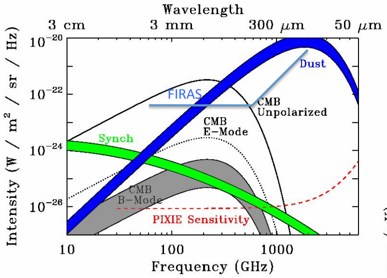
Table: **COrE performance compared to WMAP and PLANCK.**

COrE Focal Plane (6384 detectors)



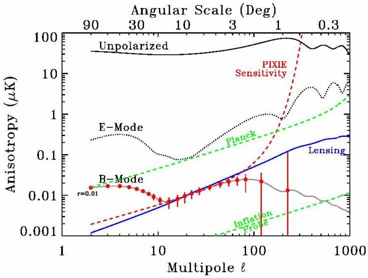

Primordial
Inflation
Explorer
(PIXIE)
D J Fixsen
UMD/Goddard
Space Flight Center
CMB 2013

PIXIE B-Mode Science



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



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

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

The FIRAS Experience

Results

Temperature to 2.72548 +/-57

Fixsen ApJ 707:916 (2009)

Black Body (+/- 50 PPM)

Fixsen etal ApJ 473:567 (1996)

Dipole Spectrum (+/- 1%)

Fixsen etal ApJ 473:567 (1996)

CIB Spectrum (+/- 30%)

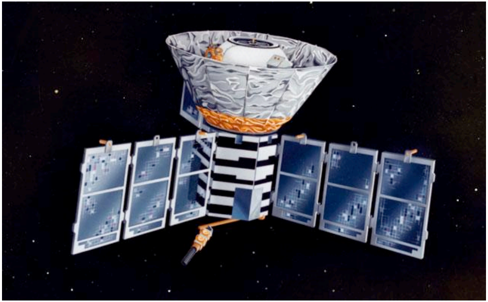
Fixsen etal ApJ 508:123 (1998)

CMB Anisotropy

Fixsen etal ApJ 486:623 (1997)

Spectrum of CMB Anisotropy

Fixsen ApJ 594:L67 (2003)



The Instrument

Fourier Transform Spectrometer

Cold External Calibrator

Internal Nulling

1.4 K detector

7 Degree beam

Limitations

1.4 K detector (one good)

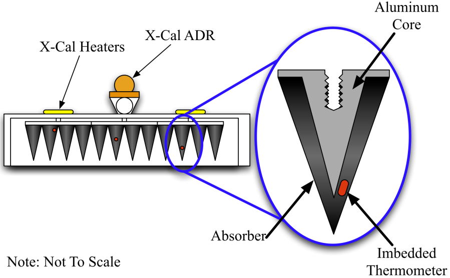
Particle hits

Averaged before fitting

Limited Calibration Data

Limited Thermometry

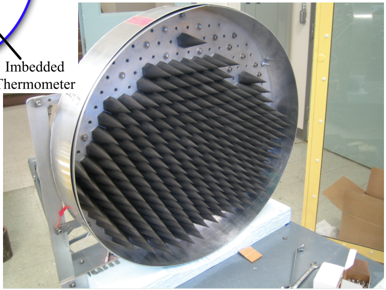
Blackbody Calibrator



Note: Not To Scale

3 Positions Left Right Out
40 thermometers to measure gradients

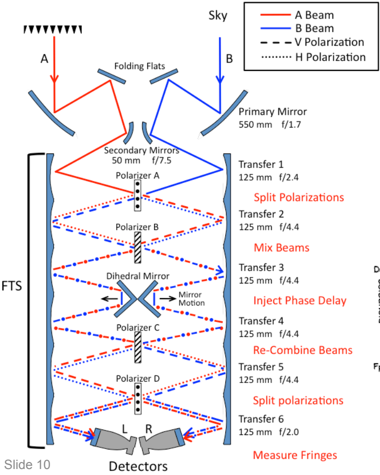
Based on successful ARCADE calibrator



PX094

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

PIXIE Nulling Polarimeter



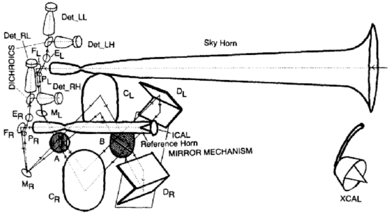
AC Readout

Nulling Polarimeter: Zero = Zero

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

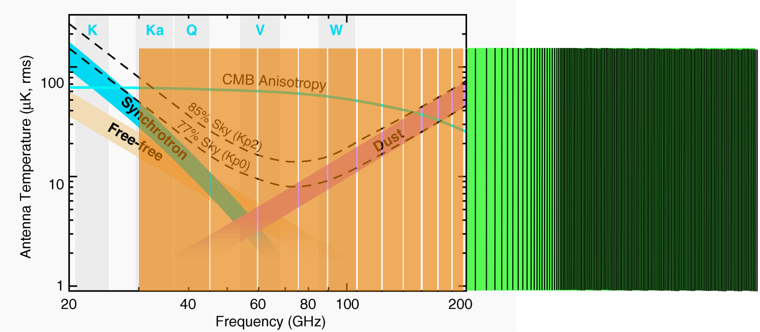
$$P_{Ly} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{By}^2 - E_{Ax}^2\right)\cos(z\omega/c)\, d\omega$$

Stokes Q



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

PIXIE vs Typ Pol

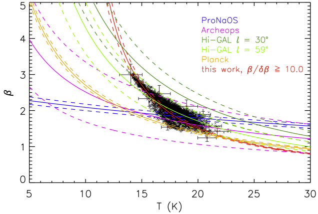


10 bands 30 GHz through 200 GHz ... **PLUS** 390 more bands to 6 THz

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

Parametric Dust Models

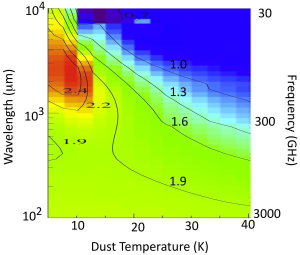
A Cautionary Tale



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?

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!

Conclusions :

- Our ability to be selected will depend crucially on how well we explain how our M4 proposal relates to the competing proposals both from the ground and from space.
- Ground-based experiments face formidable challenges, particularly at large angular scales, although some science may benefit from a larger mirror, and hence better angular resolution. Need to assess what realistically can be achieved from the ground.
- COrE++ would fly later but be high-end compared to our space competitors.
- The competition makes favorable assumptions about foregrounds. Nature may not be so kind, and new complexity is likely to emerge with vastly better sensitivity.
- Further study is required.