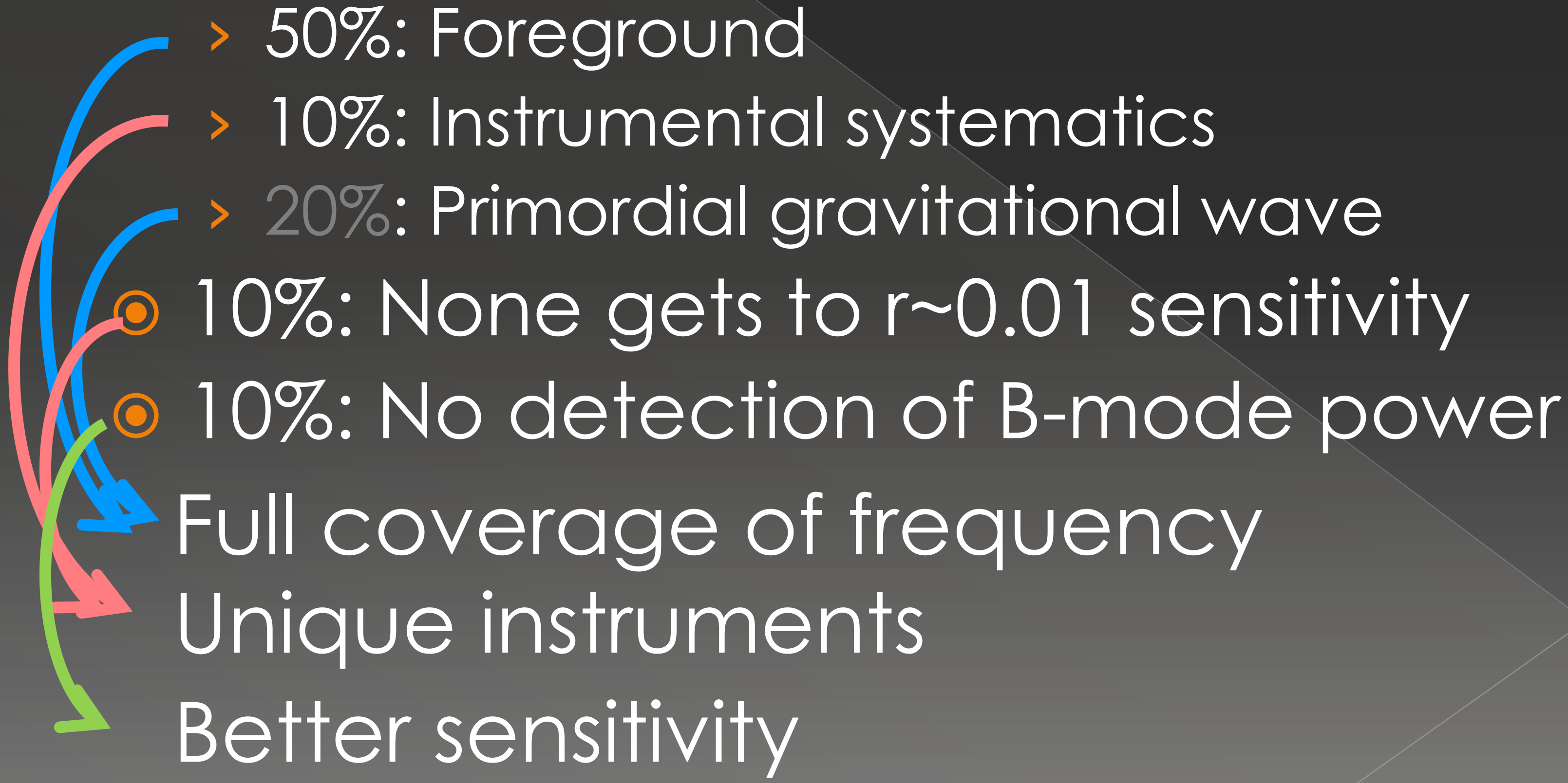
MuSE:
The Multimoded Survey Experiment

CMB 2013
June 13th, 2013, Okinawa, Japan

Akito Kusaka (Princeton University)

B-mode Odds
Next five years…

- 80%: B-mode power will be found at r>0.01
  - 50%: Foreground
  - 10%: Instrumental systematics
  - 20%: Primordial gravitational wave
- 10%: None gets to r~0.01 sensitivity
- 10%: No detection of B-mode power



Full coverage of frequency

Unique instruments

Better sensitivity

MuSE

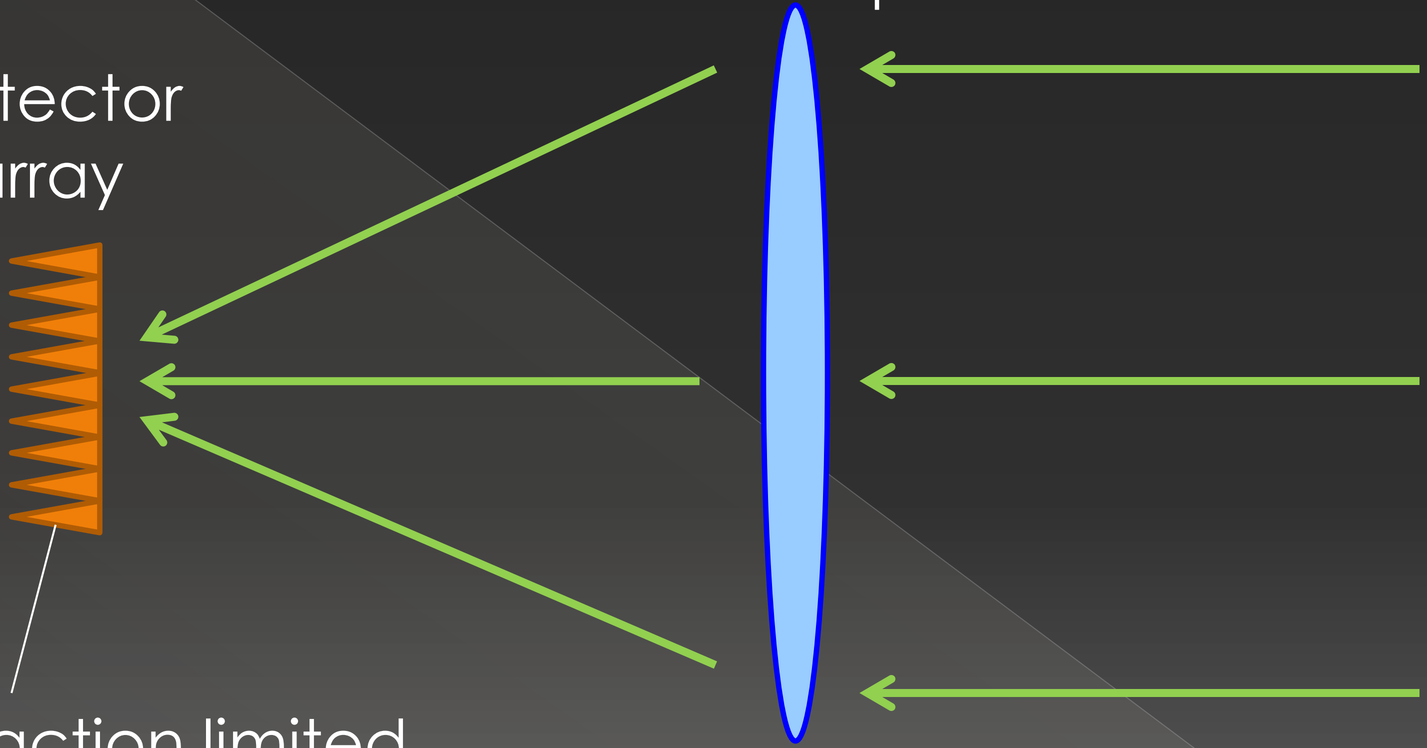
(Multimoded Survey Experiment)

Kusaka et. al. (2012)

Multimoded Survey Experiment (MuSE)

Parameter	Value	Unit	Comment
Multimpole covarage	25 – 250	ℓ	1.4m primary 1.1deg tophat
Frequency	44 / 95 / 145 225 / 275	GHz	
Bandwidth	0.23 / 0.27 / 0.25 0.22 / 0.18	Fractional	
Raw NEQ	4.5	$\mu\mathrm{K}_{CMB}\sqrt{\mathrm{s}}$	95+145GHz
Foreground cleaned NEQ	8.0	$\mu\mathrm{K}_{CMB}\sqrt{\mathrm{s}}$	Linear combination
# of pixels	50		8000 modes
Location	Ground		e.g., Atacama

What are single-mode detectors



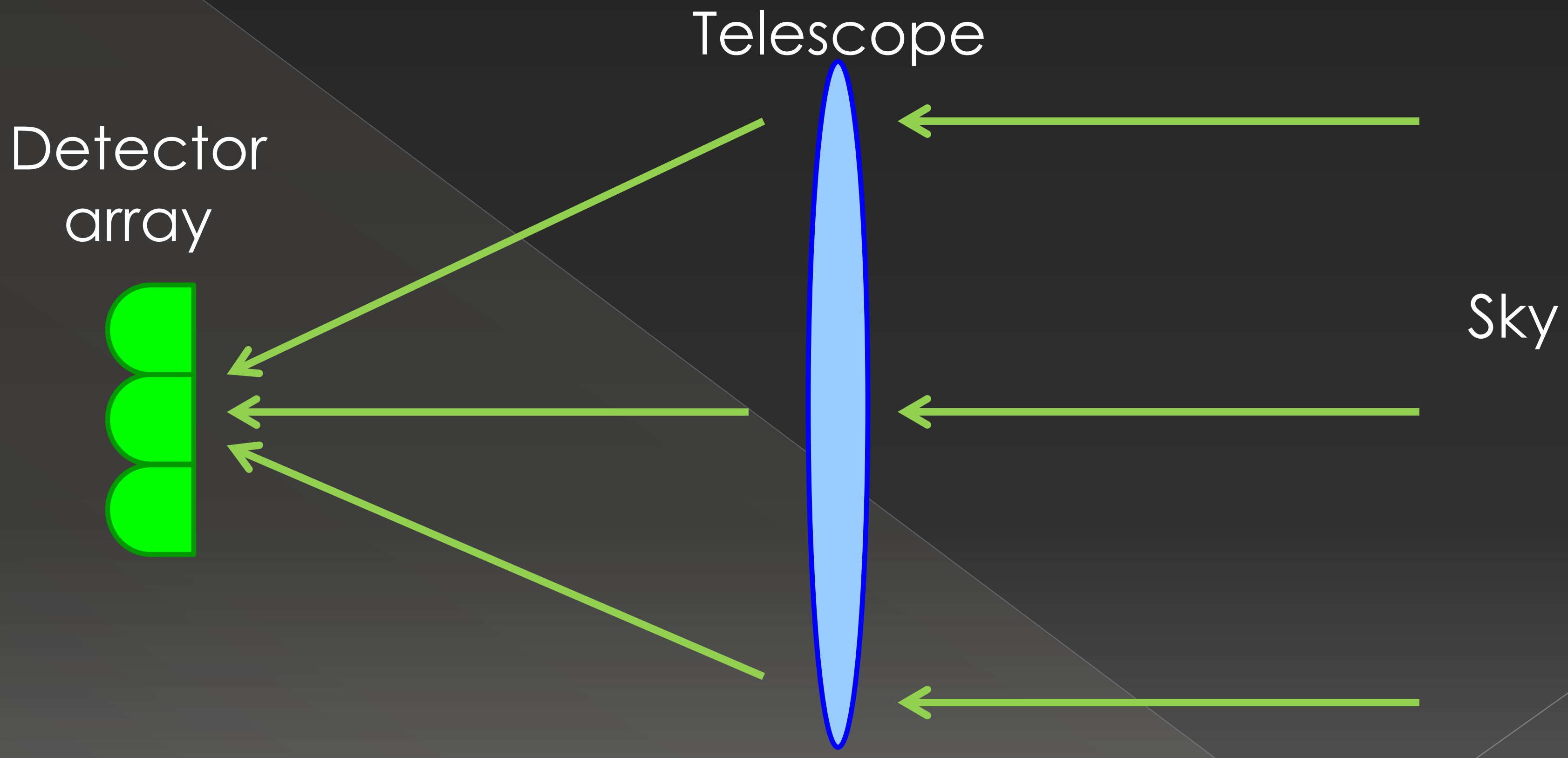
Telescope

Detector array

Sky

Diffraction limited sampling of focal plane

What are multimoded detectors



Conditions
1. Physically large
2. E&M signal does not propagate through a single "line"

Why do I care about the modes?

- Advancement of the detector technology
  - Detector reached the "photon noise limit"
  - Physics limits the information per mode.
- ~~The only way to improve the sensitivity: To increase the number of channels~~
- To increase the number of "modes": more photons!
  - Increasing the number of channels is only one way.
- Multi-moded detector is the other way!

Why Multimoded Instrument?

- No/minimal multiplexing
  - What we need is sensitivity.
  - 100 multimoded bolometers is equivalent to 8000 single-mode bolometers.
- Focal plane packing efficiency
  - Our design is in “Filled Array” category in this context.
  - Many single moded design are similar to “Feedhorn Coupled” category.
  - Gain of ~x2 in mapping speed (see Griffin, Bock, Gear 2002)

Why Multimoded Instrument?

- Larger focal plane
  - Aberration does not reduce antenna gain since each pixel is big.
- High primary aperture illumination eff.
  - No need for edge tapering, since it is not diffraction limited.
  - Lyot stop → well controlled illumination.
- Less need for computational resources.
  - Think about analyzing data from 100 channels, as opposed to those from 8000.

Multimoded Detector Array for CMB Polarimetory: not yet done.

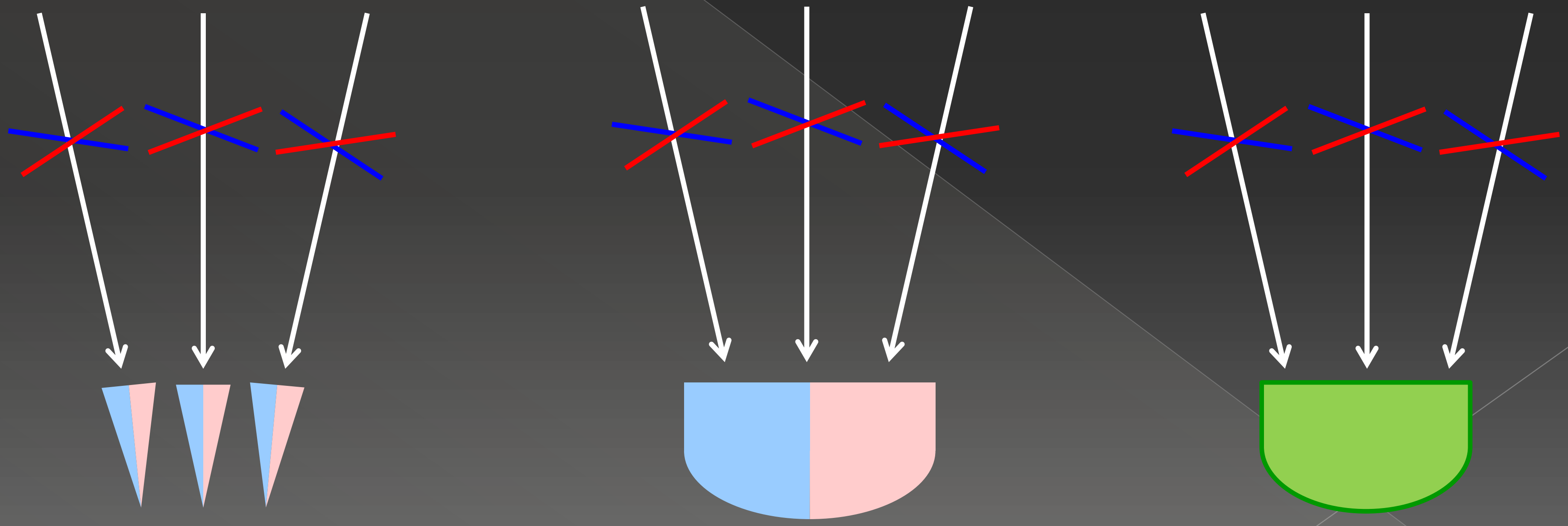
Why?

Disadvantages of multimoded instrument

- Worse angular resolution
  - There are situations where one does not need good resolution.
    - Low l B-mode, high frequency in satellite
  - MuSE concept provides a low-cost option.
- ~~Optics systematics, beam control~~
  - ~~Probably the most compelling reason why single-moded instrument dominates the field.~~
  - ~~We provide a solution for multimoded system.~~

Why is it difficult?

- Multimoded polarization: Difficult intermediate regime

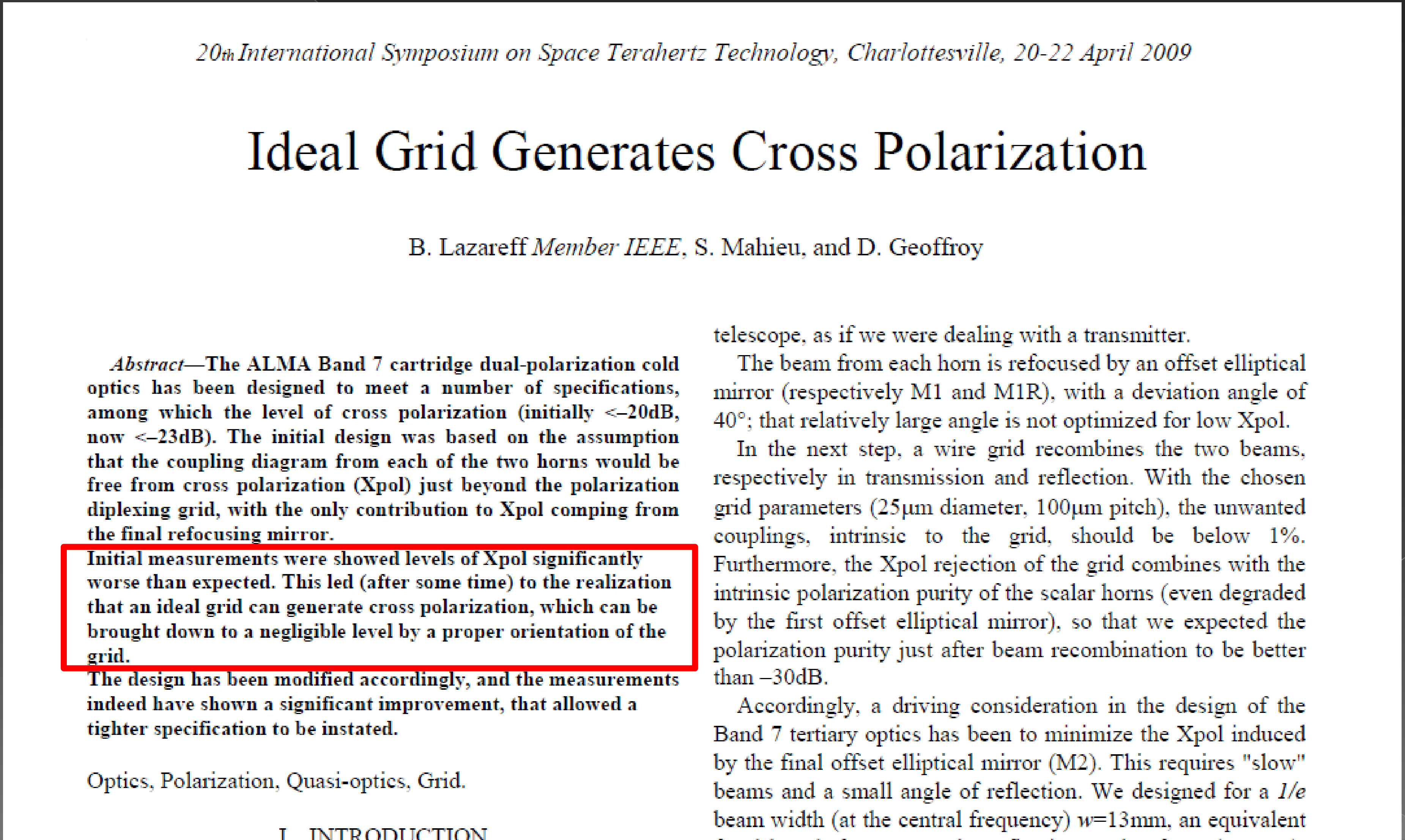


Single-mode polarization

Multimode polarization

Multimode intensity

Why is it difficult?



20th International Symposium on Space Terahertz Technology, Charlottesville, 20-22 April 2009

Ideal Grid Generates Cross Polarization

B. Lazareff *Member IEEE*, S. Mahieu, and D. Geoffroy

Abstract—**The ALMA Band 7 cartridge dual-polarization cold optics has been designed to meet a number of specifications, among which the level of cross polarization (initially <–20dB, now <–23dB). The initial design was based on the assumption that the coupling diagram from each of the two horns would be free from cross polarization (Xpol) just beyond the polarization diplexing grid, with the only contribution to Xpol comping from the final refocusing mirror.**

Initial measurements were showed levels of Xpol significantly worse than expected. This led (after some time) to the realization that an ideal grid can generate cross polarization, which can be brought down to a negligible level by a proper orientation of the grid.

The design has been modified accordingly, and the measurements indeed have shown a significant improvement, that allowed a tighter specification to be instated.

Optics, Polarization, Quasi-optics, Grid.

I. INTRODUCTION

telescope, as if we were dealing with a transmitter.

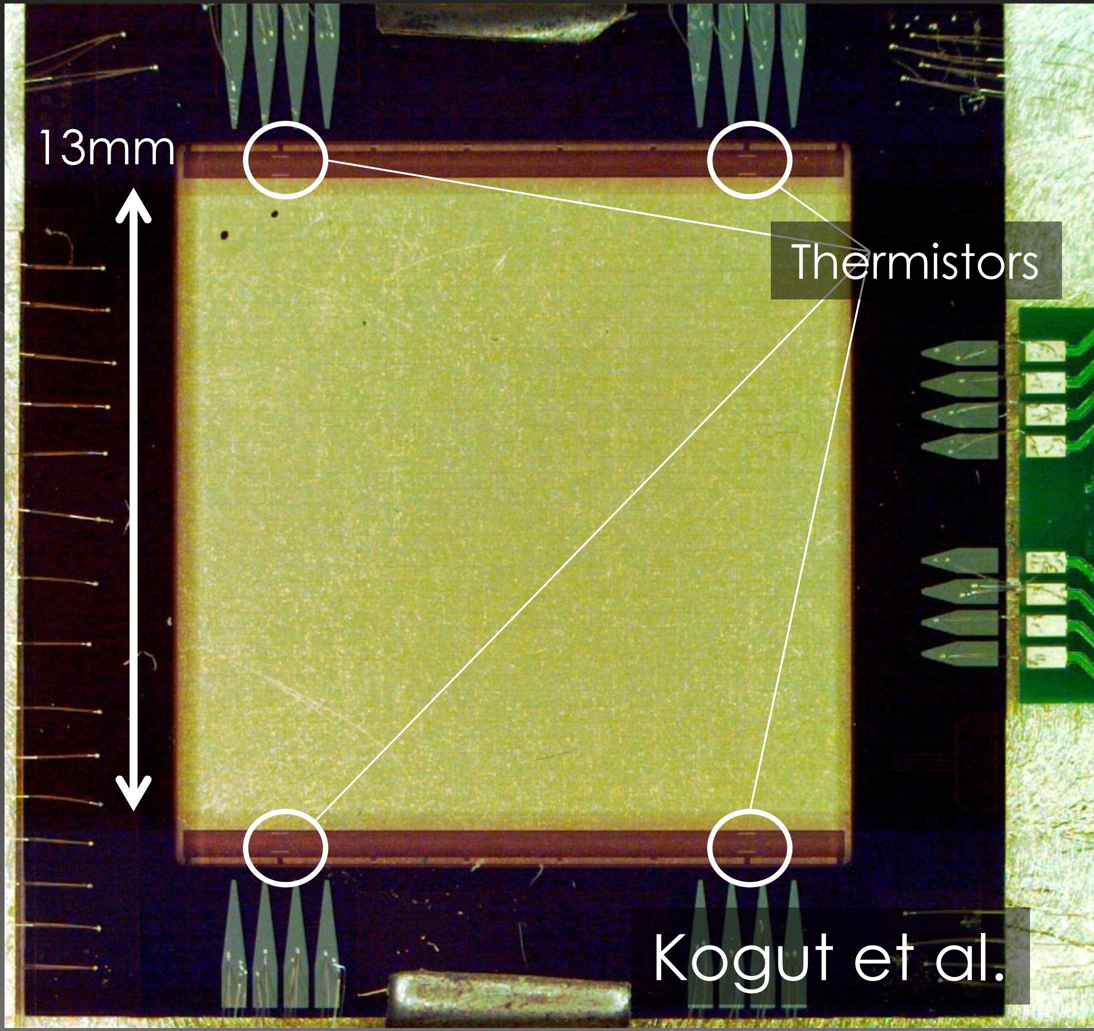
The beam from each horn is refocused by an offset elliptical mirror (respectively M1 and M1R), with a deviation angle of 40°; that relatively large angle is not optimized for low Xpol.

In the next step, a wire grid recombines the two beams, respectively in transmission and reflection. With the chosen grid parameters (25µm diameter, 100µm pitch), the unwanted couplings, intrinsic to the grid, should be below 1%. Furthermore, the Xpol rejection of the grid combines with the intrinsic polarization purity of the scalar horns (even degraded by the first offset elliptical mirror), so that we expected the polarization purity just after beam recombination to be better than –30dB.

Accordingly, a driving consideration in the design of the Band 7 tertiary optics has been to minimize the Xpol induced by the final offset elliptical mirror (M2). This requires "slow" beams and a small angle of reflection. We designed for a *1/e* beam width (at the central frequency) *w*=13mm, an equivalent

Detector developed at NASA GSFC

- Developed for PIXIE satellite proposal (Kogut et. al. 2011)
- Polarization selective absorbing strings
- Can be configured for narrow-band application
  - 87 modes/detector @145GHz
- Cryogenically testing at Princeton



Kogut et al.

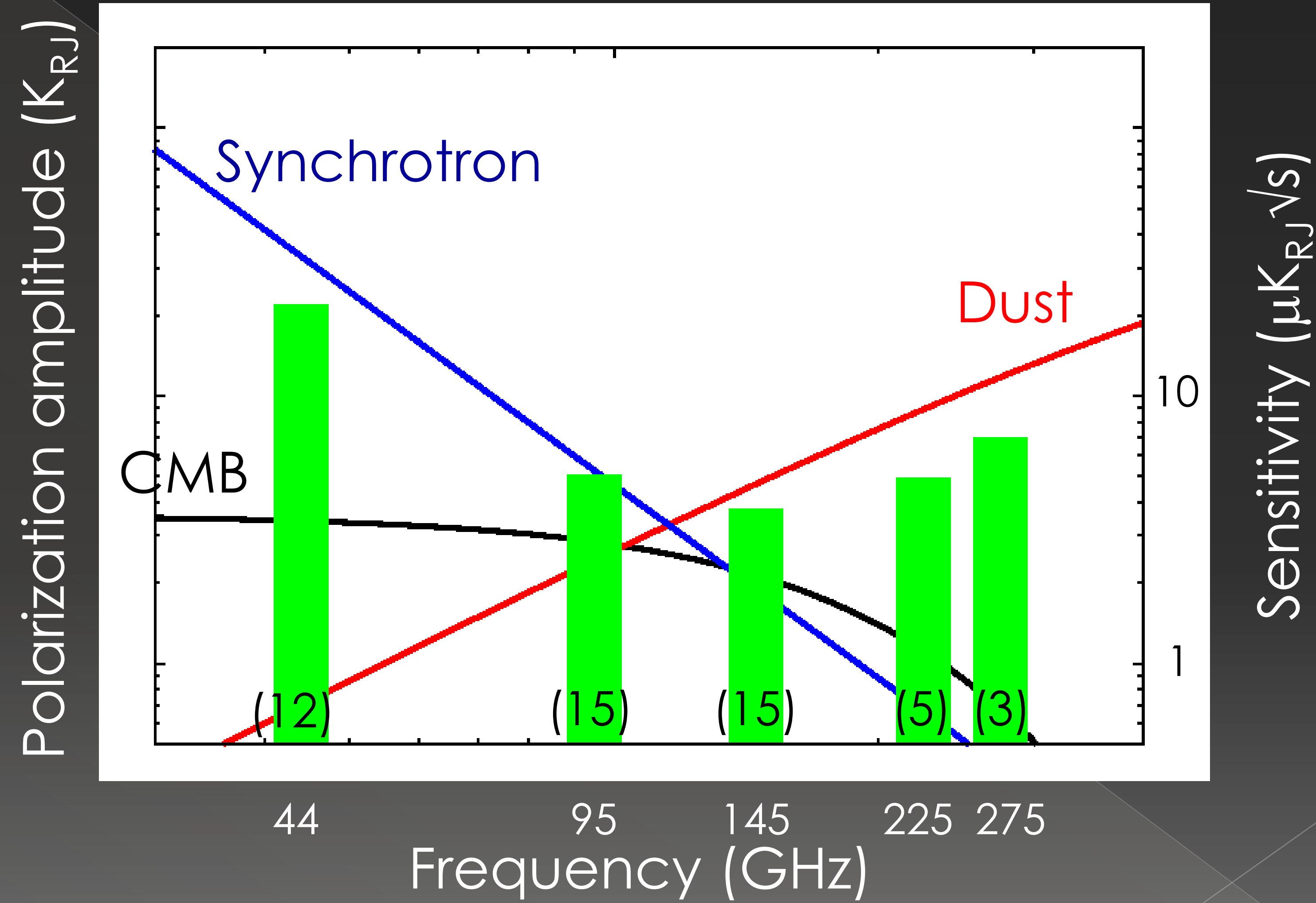
Detector: per-pixel parameters

Frequency (GHz)	44	95	145	225	275
Bandwidth (GHz)	10	26	36	50	50
Optical loading (pW)	9	82	370	1800	3800
NEP (fW/√Hz)	0.09	0.29	0.70	1.8	2.9
NEQ ($\mu K_{CMB}\sqrt{s}$)	79	24	24	36	63
# modes / pol.	8	37	87	210	310
NEQ per mode ($\mu K_{CMB}\sqrt{s}$)	220	150	230	520	1100

T_{bath}=300mK, AΩ=3.7cm^{2}sr, PWV~1mm (e.g., Atacama)

- Benefit from PIXIE R&D
  - Wide-band sensitive, loading~PIXIE (minimum modification)
- Photon noise limited (on the ground)
- HB&T effect ignored, but minor (Zmuidzinas 2003)

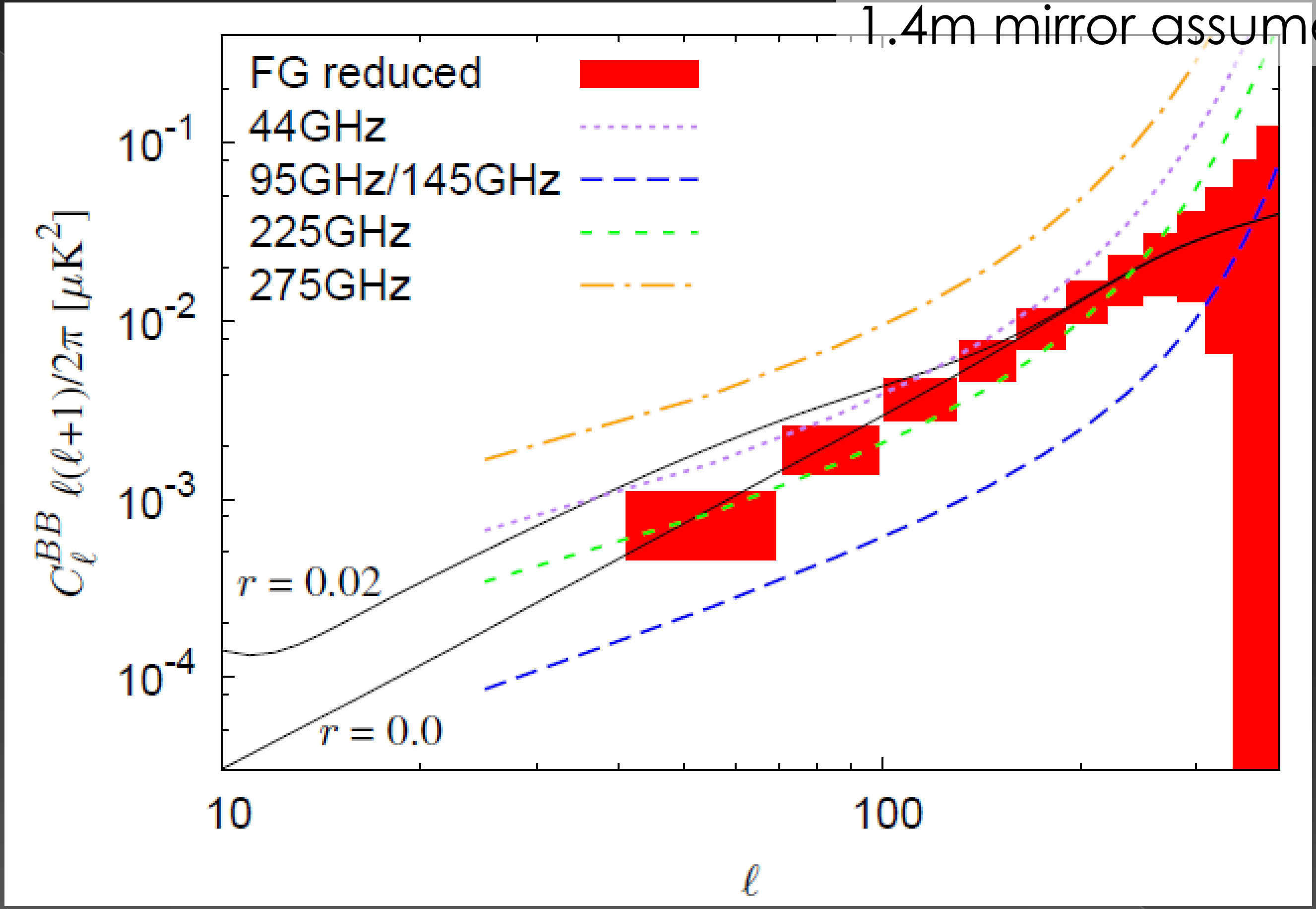
Array configuration



50 pixels distributed to 5 bands.

Raw NEQ (95+145): $4.5\mu K_{CMB}\sqrt{s}$, FG cleaned NEQ: $8.0\mu K_{CMB}\sqrt{s}$

Expected sensitivity



1.4m mirror assumed

Two years of operation, 50% efficiency.
Variance from lensing B-mode included.

Two sigma error on r of 0.009, after foreground reduction.

(sensitivity assumes nominal FG spectrum, to give a FoM.)

Summary

- Requirements for next generation
  - Sensitivity, Frequency, Systematics
- MuSE: Highly multi-moded architecture
  - 100 bolometer experiment equivalent to 8000 single-moded bolometers.
  - Optics design has well controlled systematics
  - With two years of operation, it would achieve two σ error on r of 0.009 with foreground reduced.