Technology Development Needs for the Inflation Probe

Detector arrays & focal-plane coupling –

Harvey Moseley

Multiplexing -

Kent Irwin

- What are the key immediate areas for development?
- Where is the technology heading in the near term (<2015) and mid-term (>2015)?

The Inflation Probe Technology Roadmap

Technology	Priority	Timescale	Candidates	TRL
Detector Arrays	**High**	**Sub-orbital experiments**	**TES+SQUID+Antenna** **HEMT / MMIC**	**4-5**
Optics	Medium	Sub-orbital experiments	Polarization modulators AR coatings	2-5
Coolers	Low	Develop for space	Passive+mechanical+sub-K	3-9
Advanced Arrays		Develop for simplified space implementation. Connects to X-ray, far-IR and optical astronomy	MKID+RF resonator TES+RF resonator	3

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CMB Polarization Satellite Mission Concepts

Experimental Probe of Inflationary Cosmology

CMB community mission developed for Decadal

1.4 m Crossed Dragone Telescope

- Resolution to measure lensing signal cosmic limits

Large Focal Plane

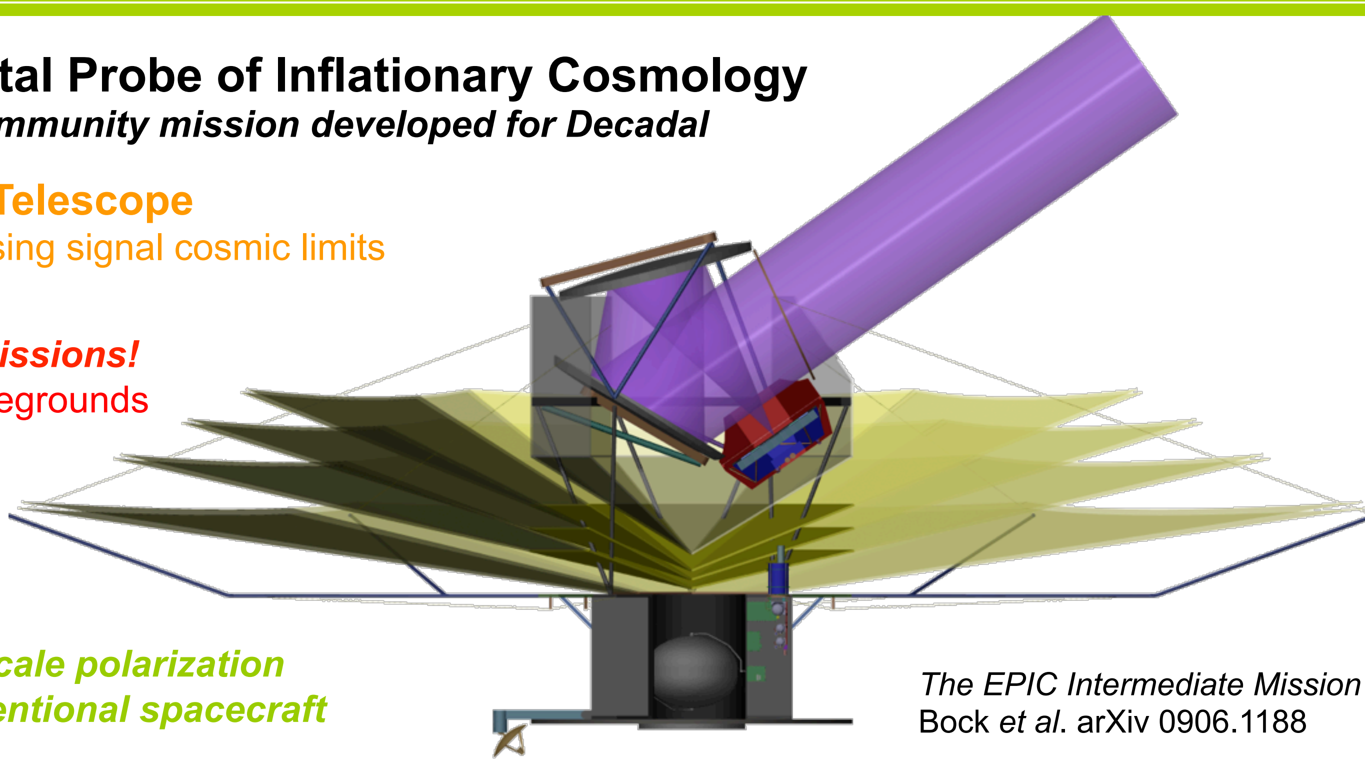
- ***equates to 1000 Planck missions!***
- Wide band coverage for foregrounds

Cooling system

- 100 mK
- ***Improved Planck system***

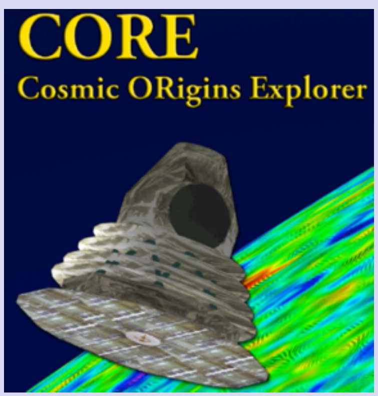
L2 Halo Orbit

- ***Scan strategy for large-scale polarization***
- ***Simple operations, conventional spacecraft***

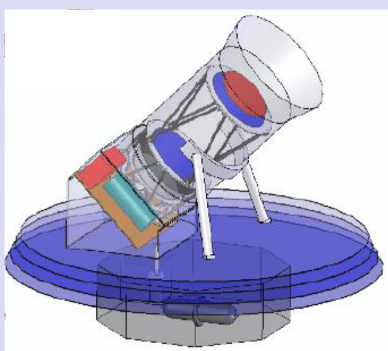


The EPIC Intermediate Mission
Bock *et al*. arXiv 0906.1188

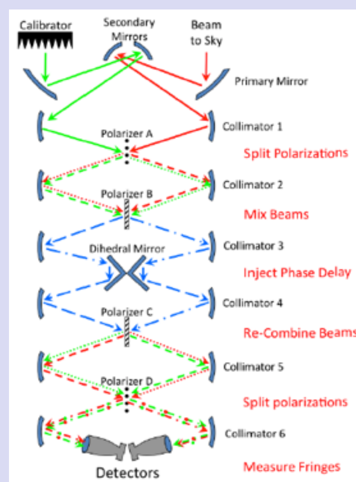
Alternative Concepts



CORE
ESA 2010 proposal
1.2 m aperture

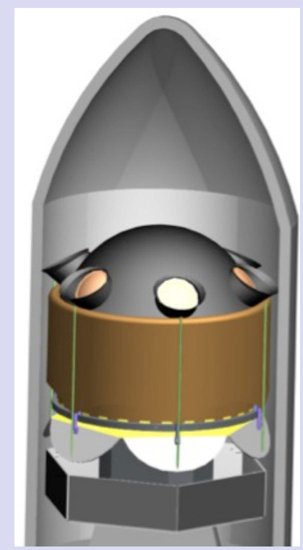


LITEBIRD
Japanese concept
30 cm aperture



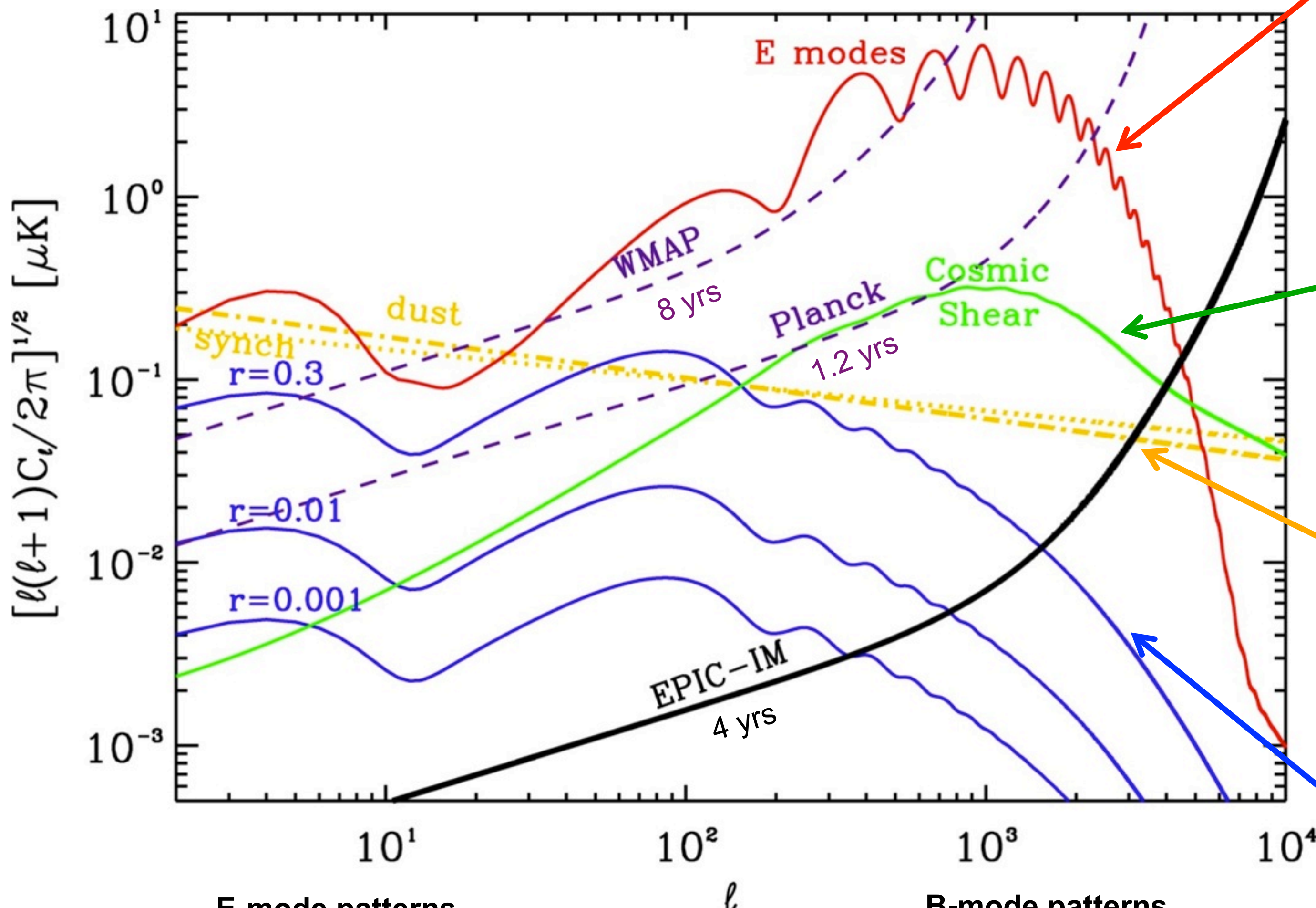
EPIC-*Low Cost*
JPL concept
30 cm apertures

PIXIE
SMEX proposal
Multi-mode FTS



CMB Polarization Science is Deep and Broad

CMB Polarization Spatial Power Spectra



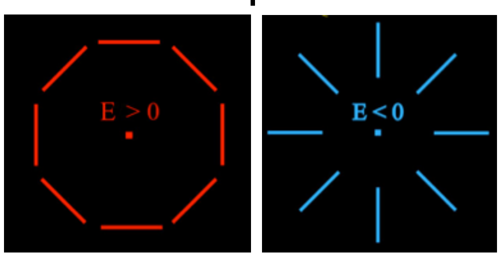
Scalar Perturbations
E-modes
- Precision cosmology
- Departure from scale inv.
- Reionization history

Gravitational Lensing
B-Modes
- Neutrino mass hierarchy
- Dark energy at z > 2

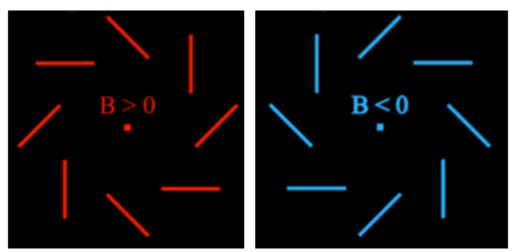
Galactic Magnetic Fields
E & B-Modes
- Star formation
- Large-scale fields

Inflationary Gravitational Waves
B-modes
- GUT energy scale
- Large field inflation
- n_t / r consistency test

E-mode patterns



B-mode patterns



Detectors for CMB Polarization

- The detection of B-mode polarization of the CMB requires large numbers of high efficiency polarimetric detectors operating at the background limit aganst the CMB.
- Detectors with adequate thermal sensitivity are well developed. The primary technical challenges are to provide highly integrated polarimeters with uniform characteristics in large arrays (~10^4 detectors)

Primary Detector Requirements

- High optical efficiency
- Polarization sensitivity
- Integrated filtering
  - Uniform across array, adaptable for all required bands
- Beam formation
  - Matching for the two polarization states
  - Uniform across array

Additional Requirements

- Noise characteristics
  - Allowable 1/f corner depends on implementation
- Environmental sensitivity
  - Particle events
    - SEU – dead time
    - Parametric changes
  - Sensitivity to experimental parameters
    - Should be logged at required rate and sensitivity

Additional Requirements

- Ease of integration
  - – Independently testable integrated focal plane
    - Choices of scales of modularity depend on experimental details
  - – Simple electrical interface (microwave multiplexing?)
  - – Thermal interfaces may be challenging for large focal surfaces
  - – Filtering to limit radiative loads probably easier if telescope is cold

Areas for Immediate Development

- Arrays for current ground based and balloon borne experiments
  - ~ 10^3 element
  - SQUID MUX readouts
- Optimization of feed structures and coupling
- Optimization of Detector Production Process
  - Uniformity of parameters across wafer and from run to run

Current CMB Research: Sub-Orbital and Ground-Based

	Experiment	Technology	Resolution (arcmin)	Frequency (GHz)	Detector Pairs	Modulator
US-led Balloon	COFE	HEMT/MMIC	83/55/42	10/15/20	3/6/10	wire grid
	EBEX	TES	8	150/250/410	398/199/141	HWP
	PIPER	TES	21/15/12/7	200/270/350/600	2560	VPM
	SPIDER	TES	60/40/30	90/150/280	288/512/512	HWP
US-led Ground	ABS	TES	30	150	200	HWP
	ACTpol	TES	2.2/1.4	90/145	1500	-
	BICEP2	TES	40	150	256	-
	C-BASS	HEMT	44	5	1	ϕ-switch
	CLASS	TES	80/34/22	40/90/150	36/300/60	VPM
	Keck	TES	60/40/30	96/150/220	288/512/512	HWP
	POLAR	TES	5.2	150	2000	-
	POLARBeaR	TES	7/3.5/2.4	90/150/220	637	HWP
	QUIET	HEMT/MMIC	42/18	44/90	19/100	ϕ-switch
	SPTpol	TES	1.5/1.2	90/150	768	-
Int'l Ground	AMiBA	HEMT	2	94	20	Int.
	QUBIC	TES	60	90/150	256/512	Int.
	QUIJOTE	HEMT	54-24	10-30	38	-

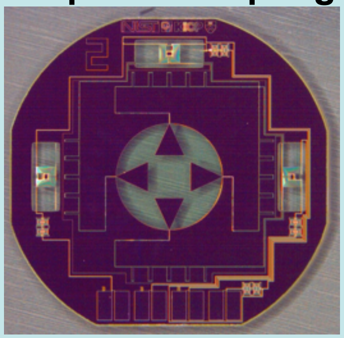
- **Push to higher sensitivity than Planck: new detector array technologies**
- **Focused on B-mode science: target small, deep fields**
- **Explore the diversity of technology approaches**
- **Test new methodologies for systematic error control**
- **Expect rapid progress in Inflationary B-mode limits in next few years**

Elements of Detector Design

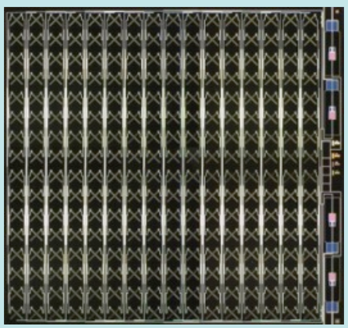
- Optical Coupling
  - Horns, lenslet + antenna, phased array
- Polarization sensitivity
- Microwave circuitry
  - Transmission lines
  - Filters
  - Components – Hybrids, etc.
  - Detector coupling
    - Distributed vs lumped

Sensor Arrays

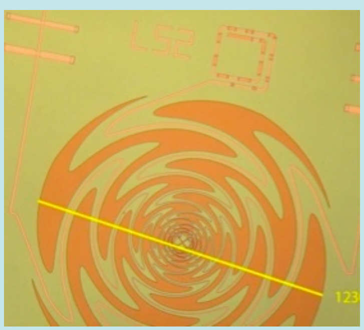
Optical Coupling



Feed Coupled

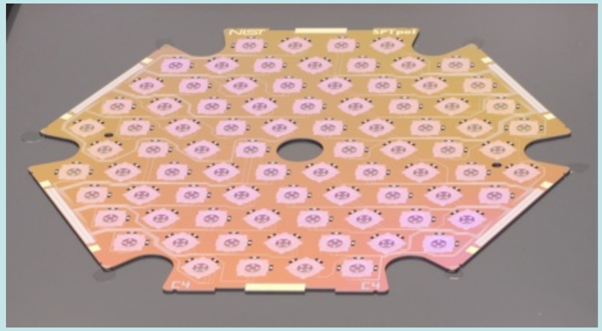


Planar Antennas

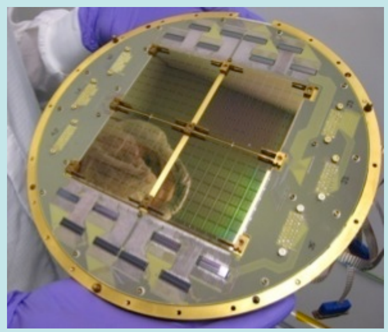


Lens-Coupled Antennas

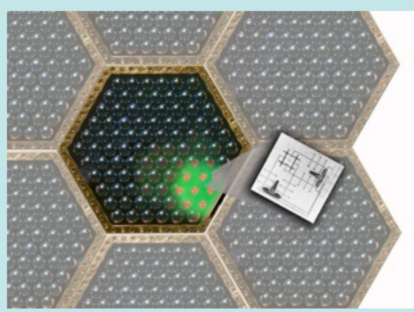
SPTpol 150 GHz



BICEP-2 150 GHz



POLARbear



To reach the sensitivity required for the Inflation Probe, we need

- Polarized detectors with noise below the CMB photon noise (much lower NEP).
- Large frequency coverage with many bands over 30 GHz-1 THz
- Large numbers of detectors (1->10 kpixel)
- Exquisite control of systematics

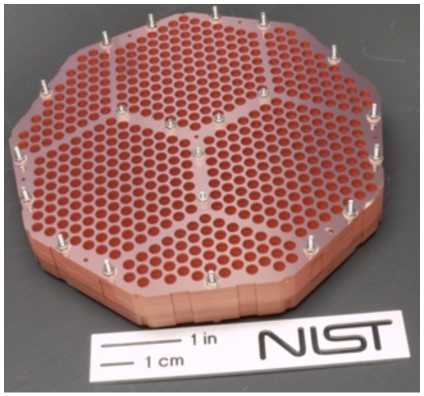
• The most mature large polarimeter array sensor, the superconducting transition-edge sensor, is now being fielded in ground-based and suborbital experiments.

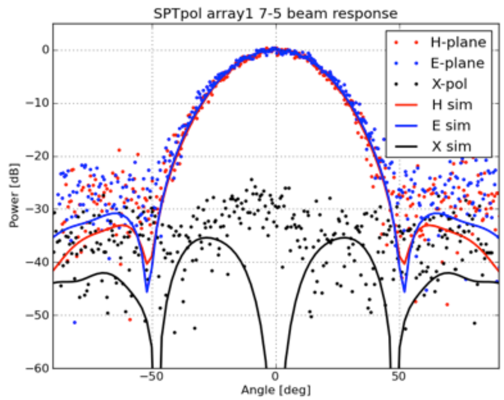
• Three optical coupling options are being developed and deployed. New work will be required to project the performance of these options in a satellite environment.

• MMICs are also being developed at a lower level

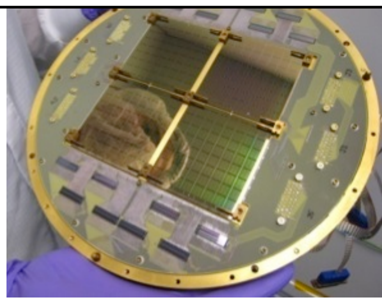
Optical coupling / beam forming

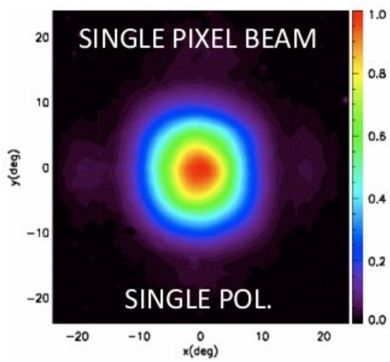
ACTpol feeds



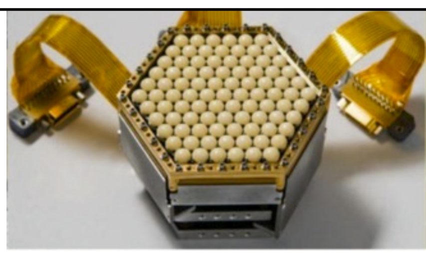


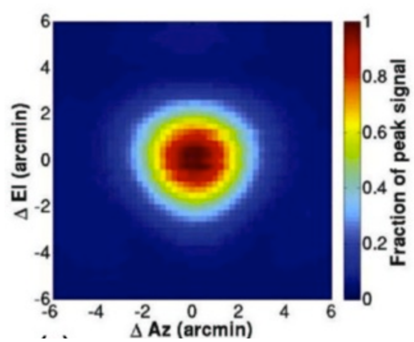
BICEP-2 phased arrays





POLARbear lenselets





<u>Feedhorn arrays</u>

- Long heritage in flight missions
- Excellent beam symmetry & crosspol
- ACTpol, SPTpol, ABS, CLASS

<u>Phased antenna arrays</u>

- Compact; very low mass, simple
- BICEP-2, Keck, SPIDER, POLAR

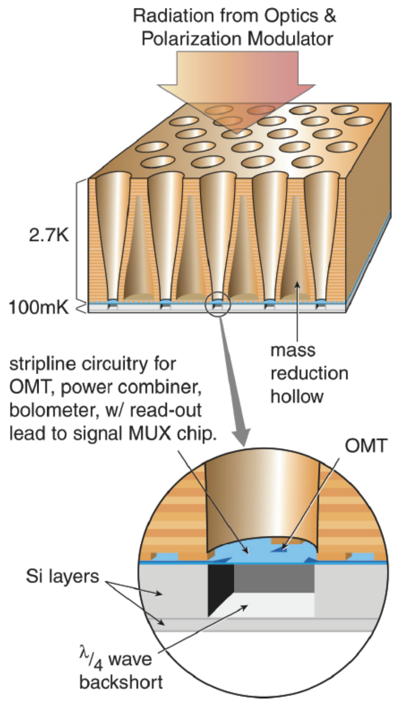
<u>Lenselet arrays</u>

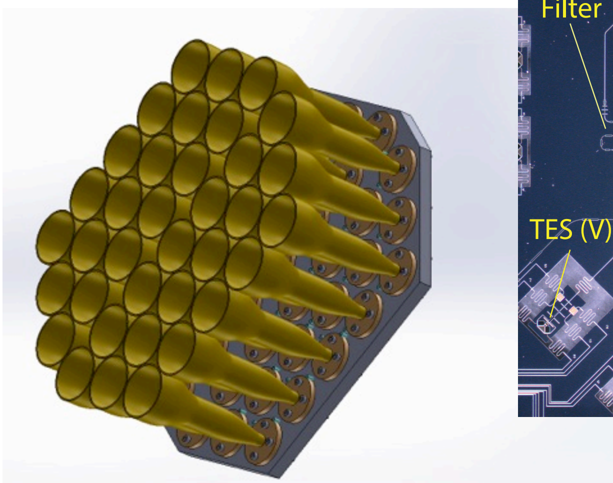
- Large bandwidth
- POLARbear

Three options are being pursued to meet Inflation Probe requirements

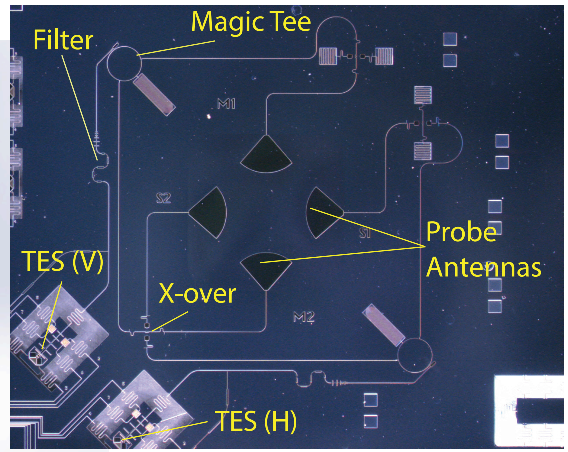
Feedhorn-coupled Polarized Detectors

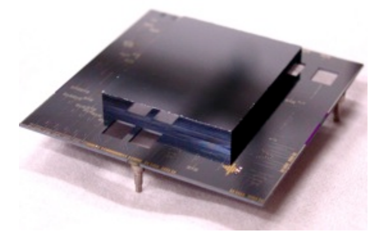
Wollack, Moseley, Denis, Stevenson, Chuss, Rostem, U-Yen (GSFC)



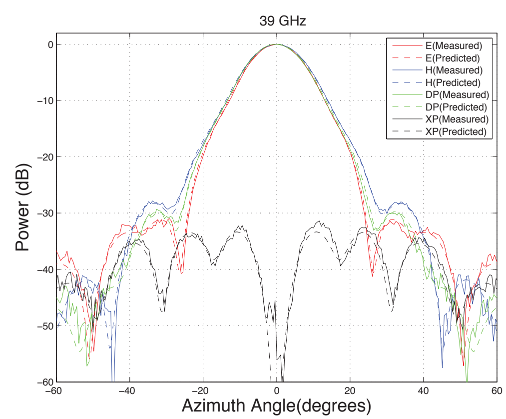


CLASS 40 GHz
Focal Plane

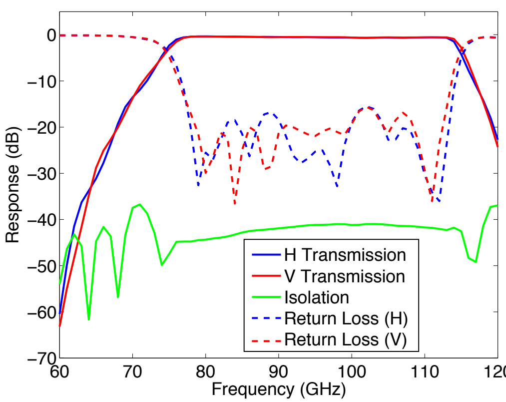


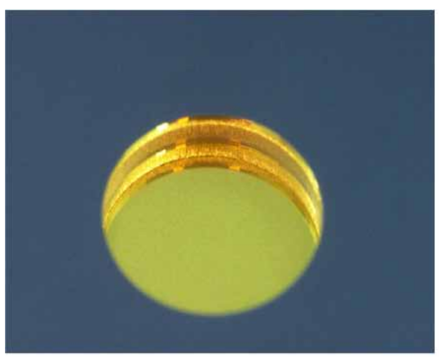


40 GHz Prototype Sensor



Smooth-walled Feedhorns
(Zeng et al. 2010)

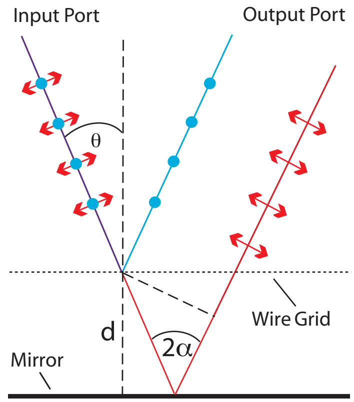




90 GHz Backshort Assembly

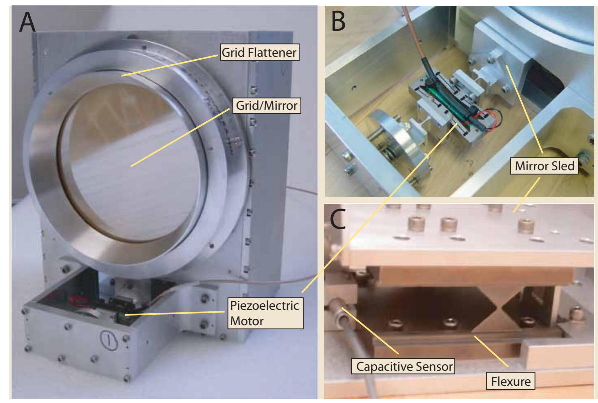
IPSAG 90 GHz Sensors

Variable-delay Polarization Modulators (VPMs)

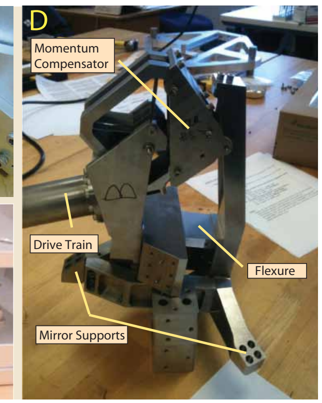


Concept

Vary the phase delay
Between orthogonal
Linear polarizations-
Leads to a modulation
Of a single linear
Stokes parameters with
Residuals & systematics
Confined to the circular
Polarization channel

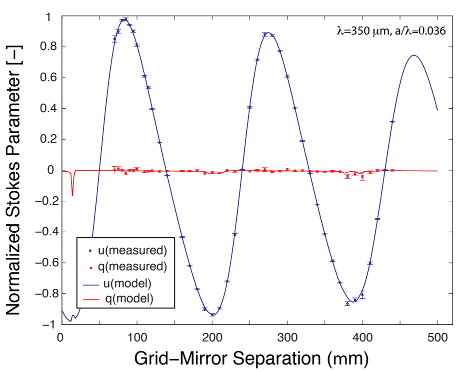


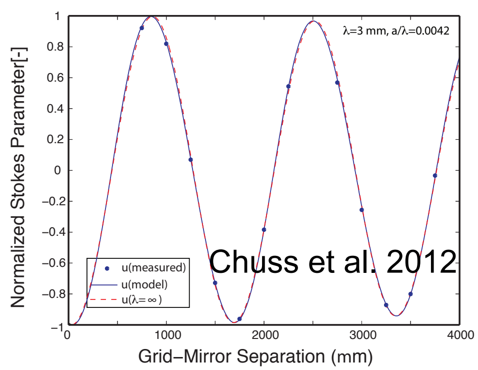
Prototype

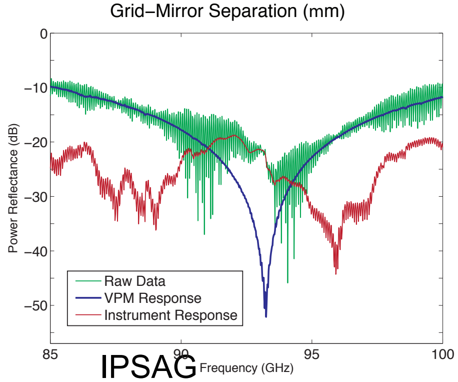


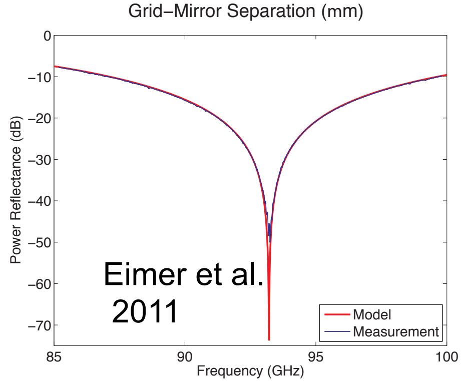
PIPER

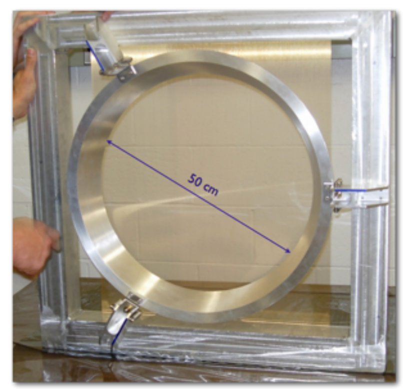
Validation



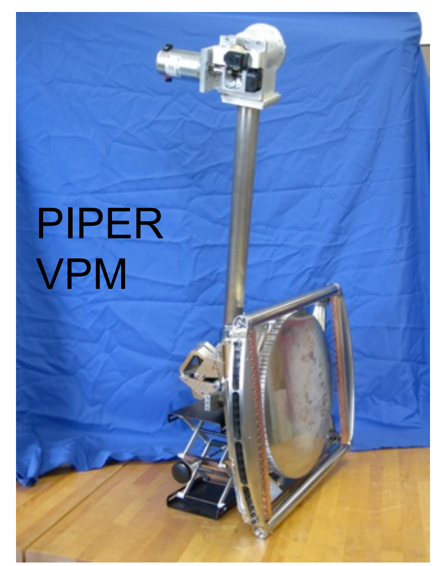




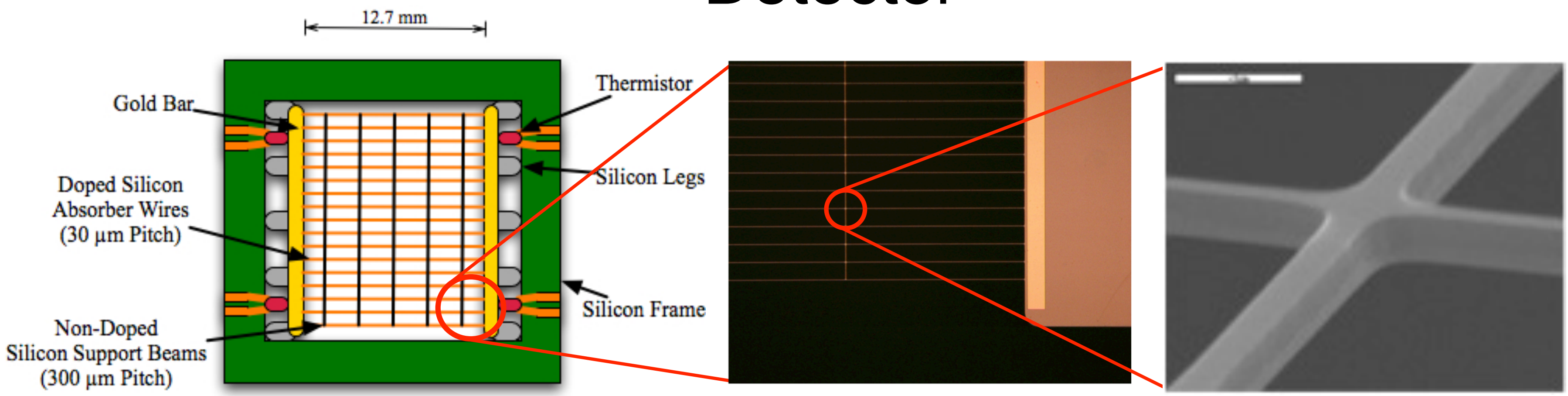




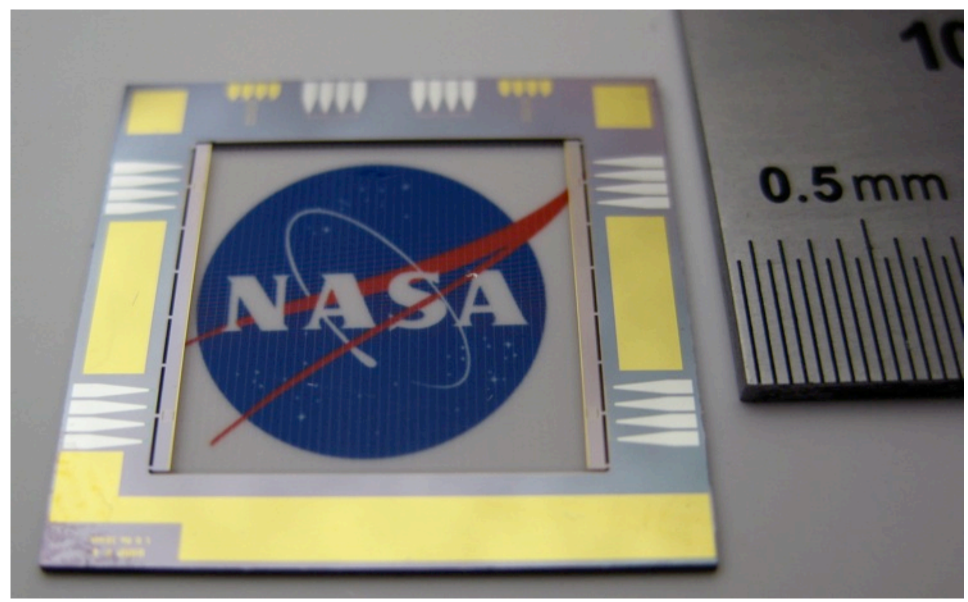
CLASS
Prototype grid



Multi-Moded Polarization-Sensitive Detector



30x collecting area as Planck bolometers



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

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

PIXIE detector:

- $A\Omega = 4\ \mathrm{cm}^2\ \mathrm{sr}$
- Fill factor = 11%
- NEP = $0.7 \times 10^{-16}\ \mathrm{W\ Hz}^{-1/2}$

Detector Element Challenges

- TES
  - Conductance – Saturation Power
    - Process control on large spatial scales
    - A priori prediction of conductance to minimize iteration
  - Sensor Noise
    - Develop designs with predictable and understandable noise to facilitate optimization.
      - Should reduce time required to optimize a system

Near Term Progress

- Many fielded polarimeters, some with second and third iteration focal planes
  - Significant design, production, test, and operation experience
- Improving understanding TES thermometers, allowing improved designs
- Improved RF circuit designs and production
- Better test capabilities for focal planes
- Better understanding of best ways to organize focal planes

Bolometers at Low Frequencies

- TES bolometers operating at low temperatures can reach the sensitivity required for background limited operation for low frequency bolometers (40 GHz, e.g.)
- Given demonstrated high efficiency coupling, there is no reason to doubt they will function at fundamental limits at these low frequencies
  - CLASS has robust demonstrations of efficiency

Beyond 2015

- Existence of quantum limited amplifiers allows vastly simplified detector arrays of many kinds – TES, MKIDs, and semiconducting bolometers
- Production on larger wafers may change approaches for focal planes
- Spectropolarimeters made possible by improved microstrip circuits and greater ease of multiplexing

Beyond 2015

- The role of MKIDs in this high power, long wavelength application is not yet clear, but should be within the next 5-10 years.
- Potential benefits are:
  - Possibly simpler production process
    - Complexity may be dominated by other circuit elements
  - High speed of response
    - Less dead time from particle events
    - Operation in ionizing radiation field must be demonstrated

Conclusions

- An active ground and balloon program is driving the development of the first generation of CMB polarization focal planes
- This work, combined with a robust detector development program can produce vastly simplified high performance arrays with can be flown in a CMB space mission at low risk.