CMB Lensing with POLARBEAR

Michael Myers
UC Berkeley

POLARBEAR Collaboration

University of California at Berkeley
Kam Arnold
Daniel Flanigan
Wlliam Holzapfel
Jacob Howard
Zigmund Kermish
Adrian Lee P.I.
Marius Lungu
Mike Myers
*Haruki Nishino
Roger O'Brient
Erin Quealy
Christian Reichardt
Paul Richards
Chase Shimmin
Bryan Steinbach
Aritoki Suzuki
Oliver Zahn

Lawrence Berkeley National Lab
Julian Borrill
Christopher Cantalupo
Theodore Kisner
Eric Linder
Mike Sholl
Helmuth Spieler

University of Colorado at Boulder
Aubra Anthony
Nils Halverson

University of California at San Diego
David Boettger
Brian Keating
George Fuller
Nathan Miller
Hans Paar
Ian Schanning
Meir Shimon
Nathan Stebor

Imperial College
Andrew Jaffe
Daniel O'Dea

Laboratoire Astroparticule & Cosmologie
Josquin Errard
Giulio Fabbian
Radek Stompor

KEK
Yuji Chinone
Masaya Hasegawa
Masashi Hazumi
Tomo Matsumura
Hideki Morii
Akie Shimizu
Takayuki Tomaru

McGill University
Peter Hyland
Matt Dobbs

Cardiff University
Peter Ade
Will Grainger
Carole Tucker

*Supported by JSPS

Outline

- Overview
  - Science goals
  - Experiment design
- 2010 Engineering run
- Current status (Deployment soon!)
- Future plans
  - POLARBEAR-II
  - POLARBEAR-Extended

POLARBEAR Science Goals

Measure E-mode polarization to high precision

Deep search for g-wave B-modes

- r = 0.025 for PB-I (2σ)

Detect and characterize B-mode lensing signal

- Neutrino masses
- Cross-correlation science
- Early dark energy

This requires:

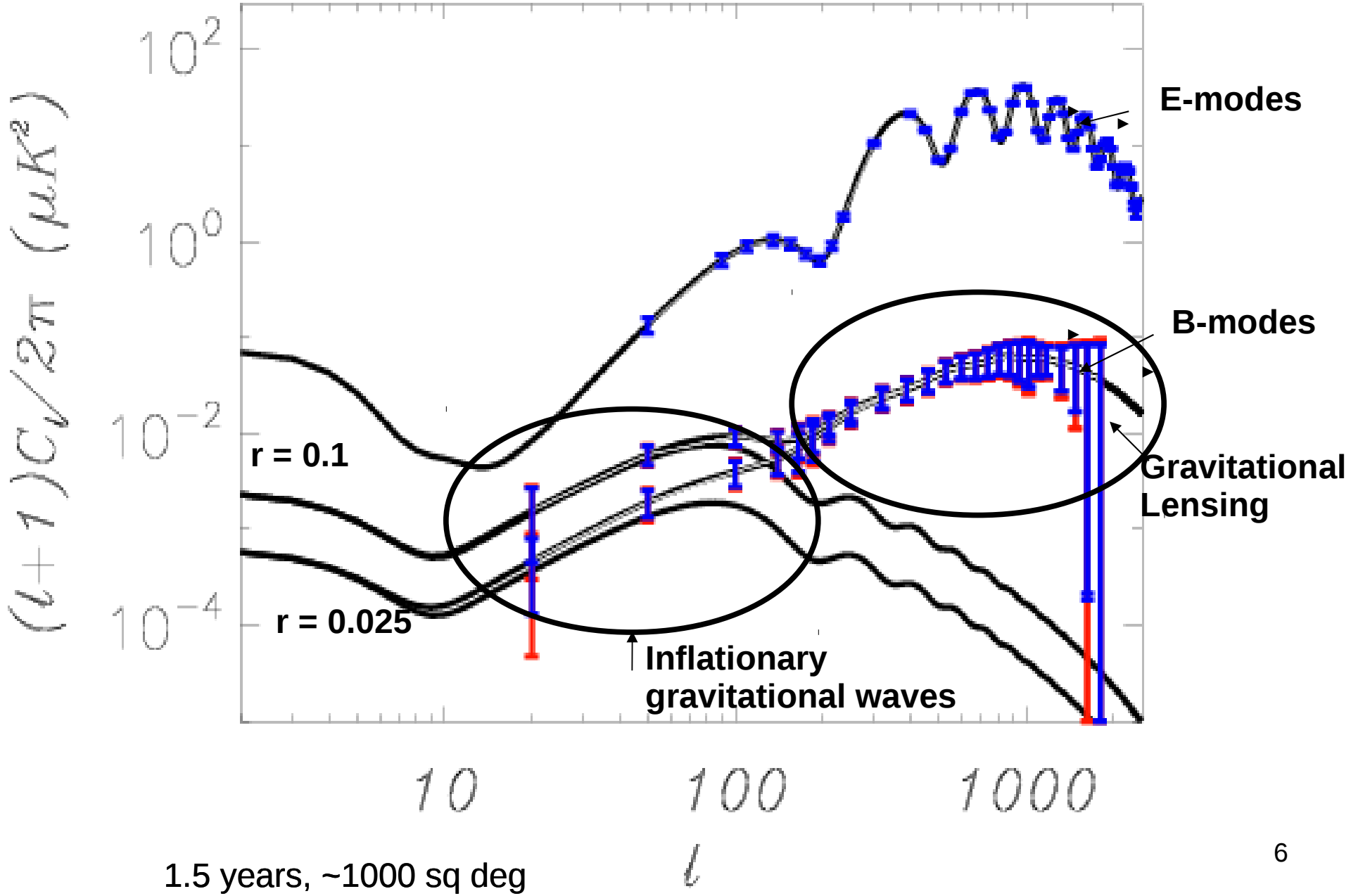
Sensitivity

- Large-format TES bolometer arrays
- High quality mm-wave site (Atacama Desert, Chile)

Systematic error control

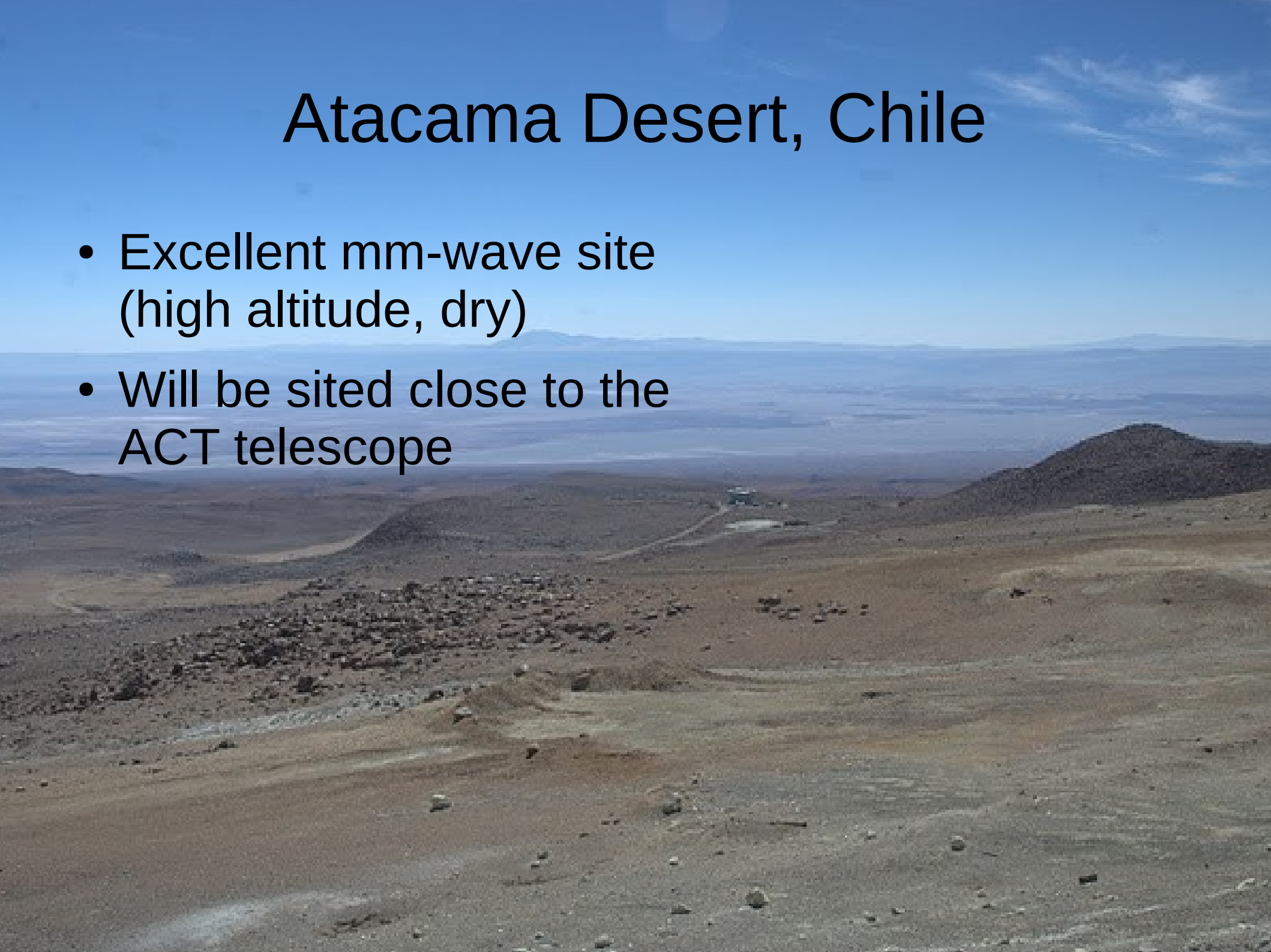
- Pol. Modulation (HWP, sky rotation)
- 4' beam @ 150 GHz
- Low sidelobe optical design

POLARBEAR-I Expected Polarization Power Spectra



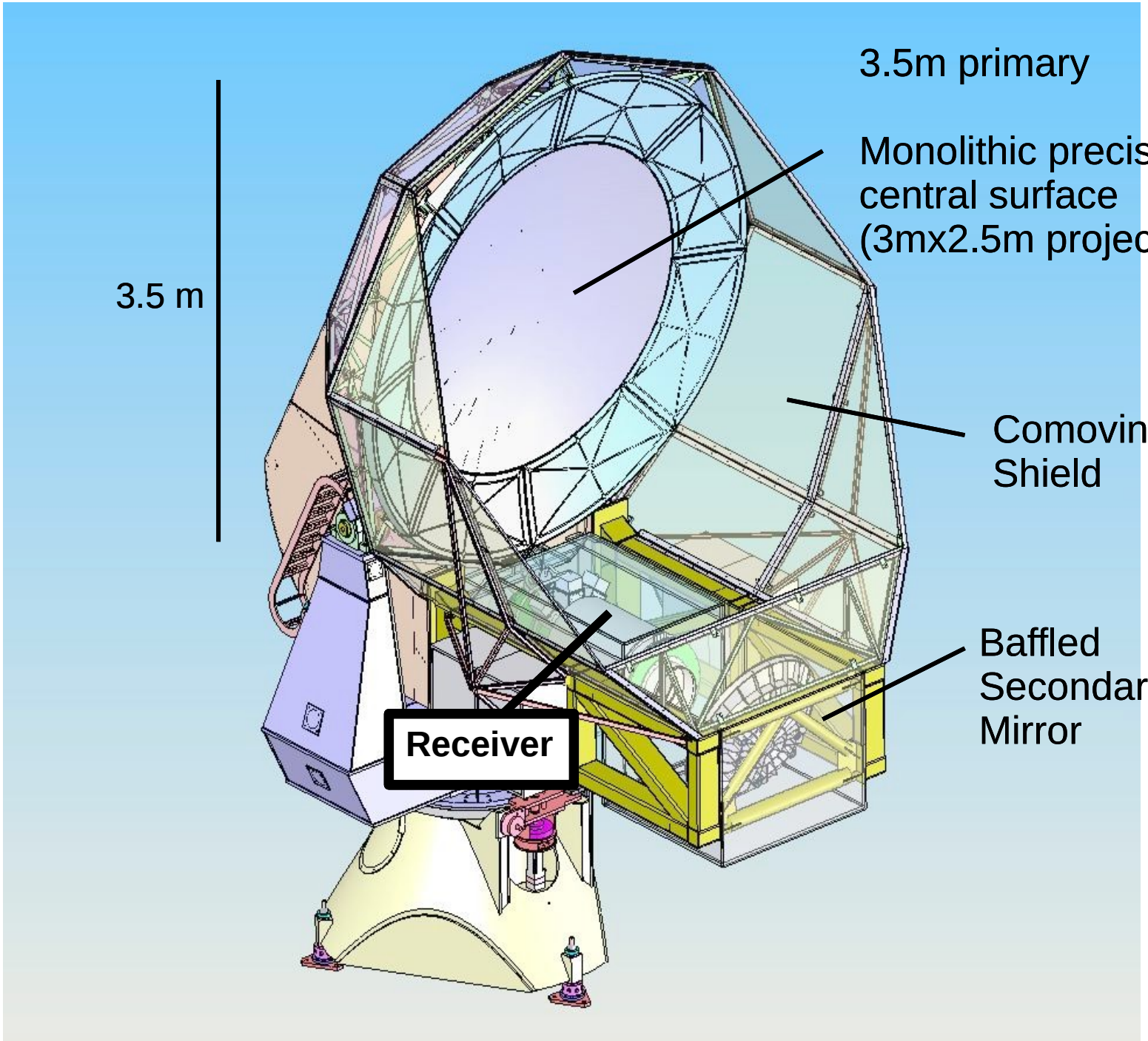
1.5 years, ~1000 sq deg

Atacama Desert, Chile

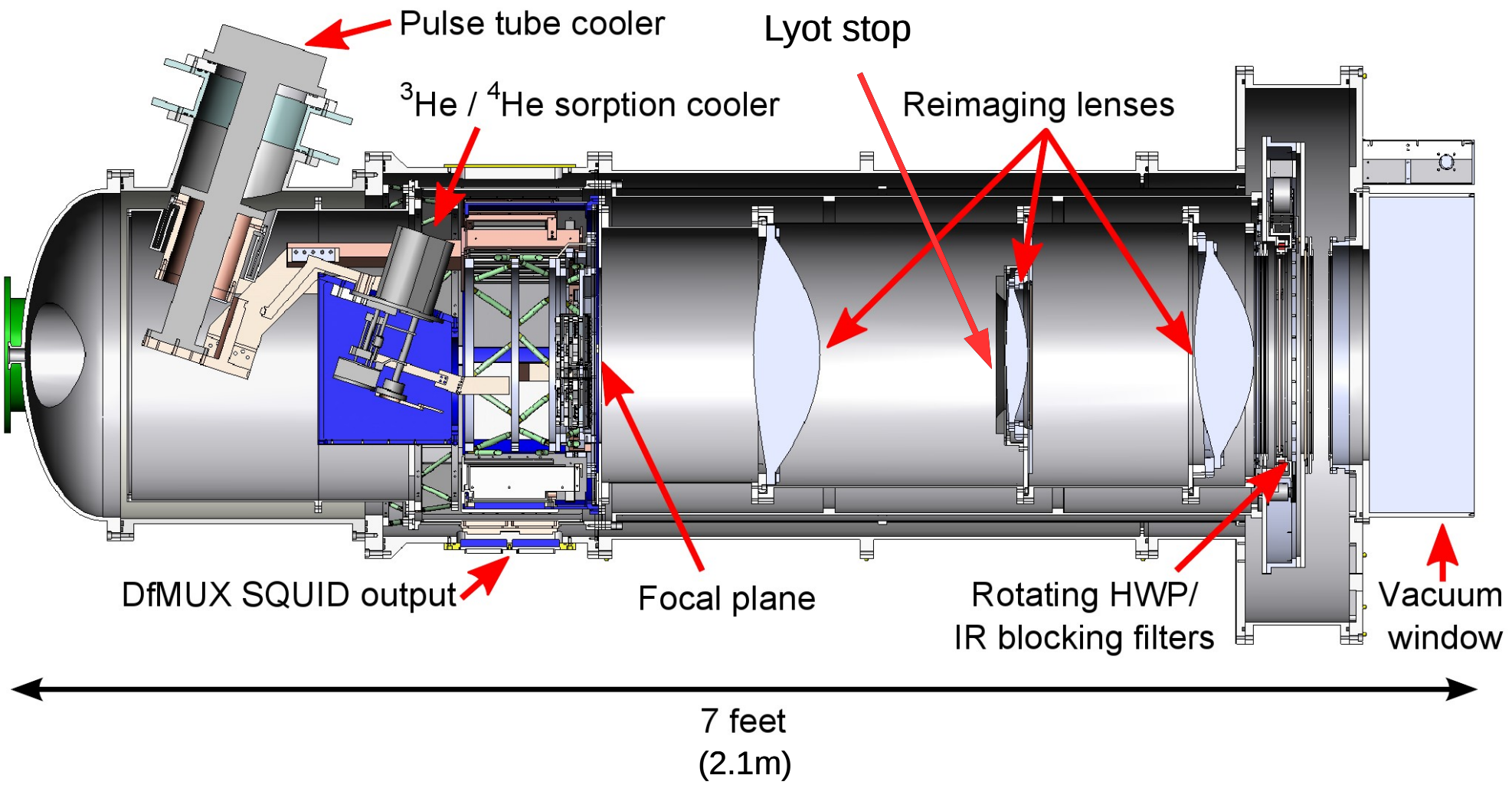


- Excellent mm-wave site (high altitude, dry)
- Will be sited close to the ACT telescope

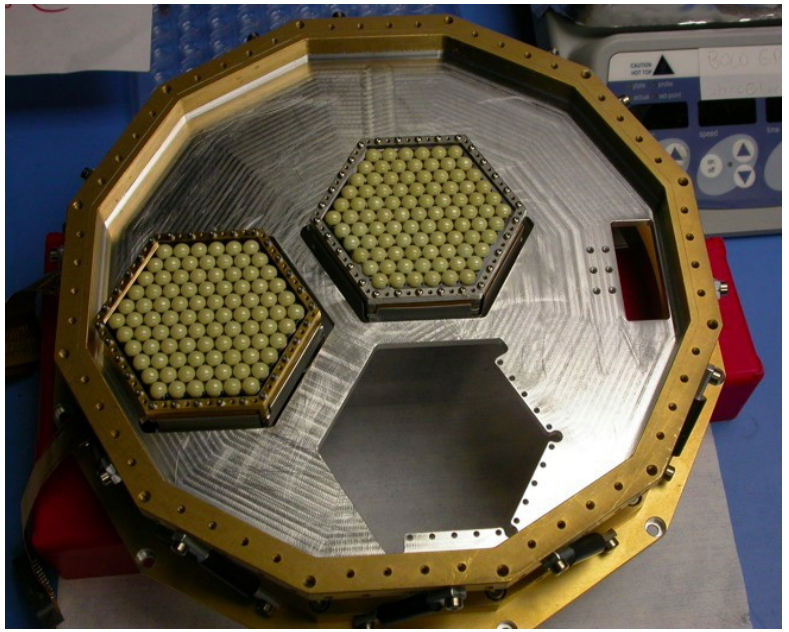
Telescope design

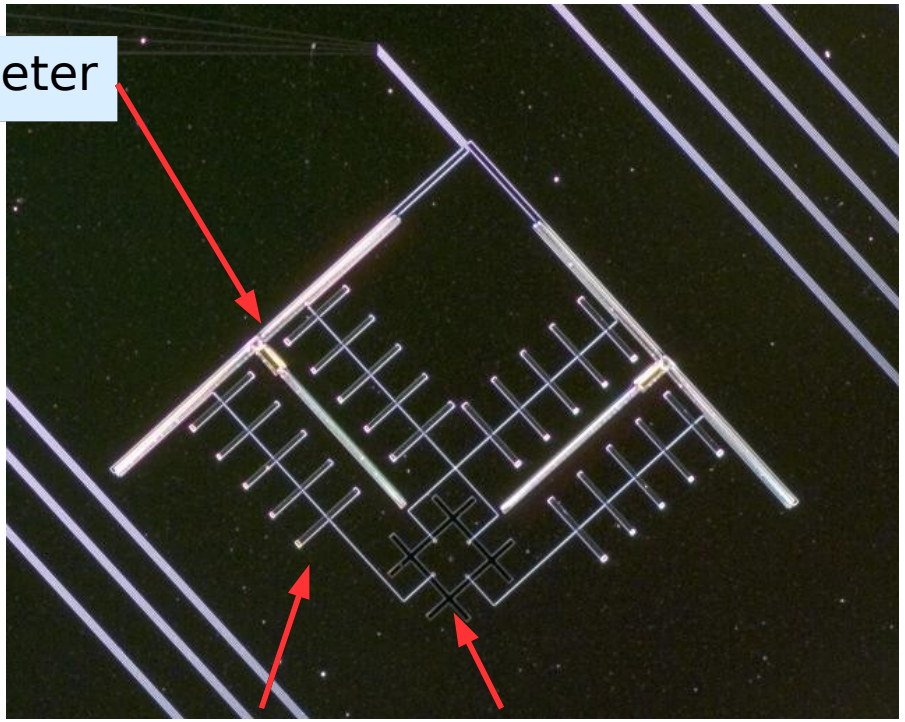


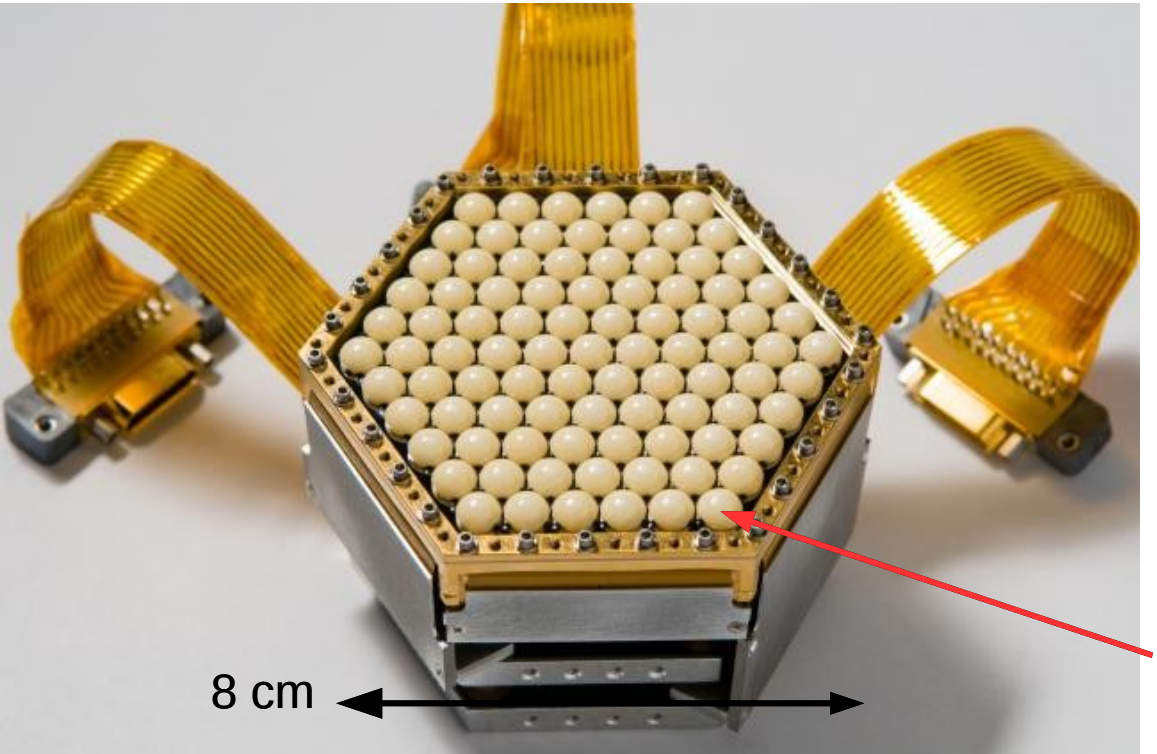
POLARBEAR-I Receiver



POLARBEAR: Antenna-coupled Arrays





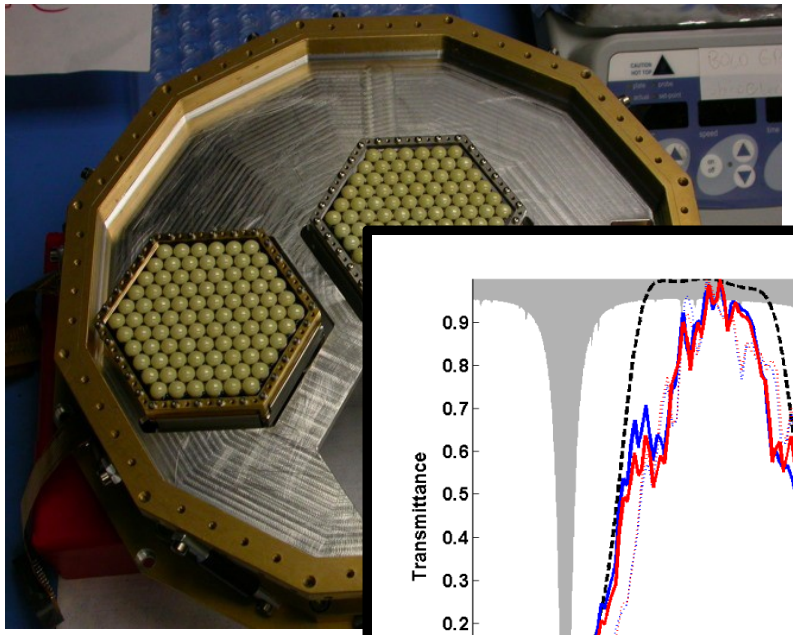


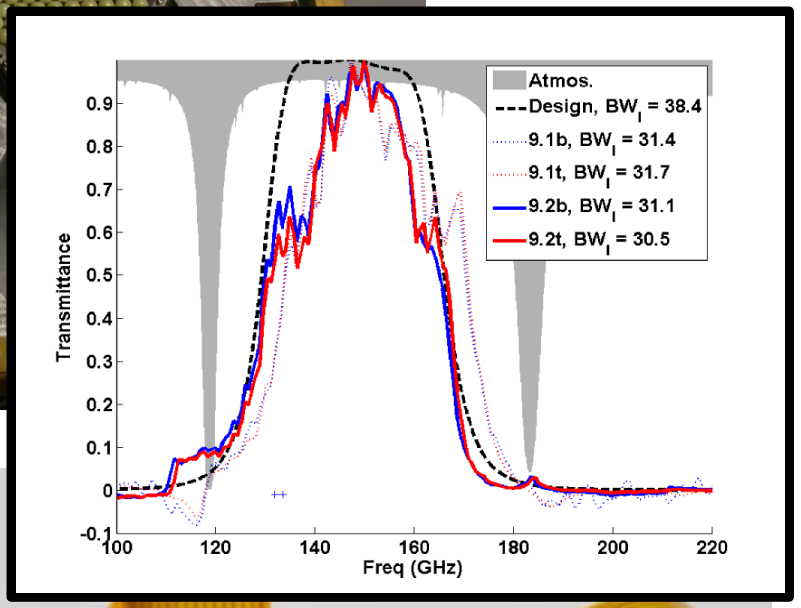
1274 bolos @ 150 GHz (PB-I)

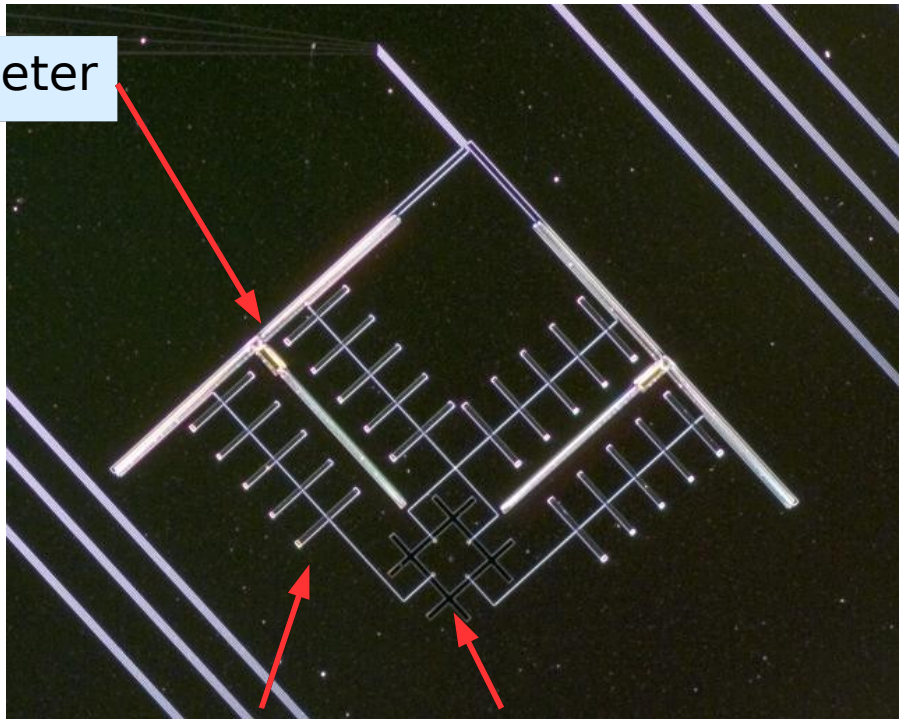
Monolithic wafer

Scalable

POLARBEAR: Antenna-coupled Arrays



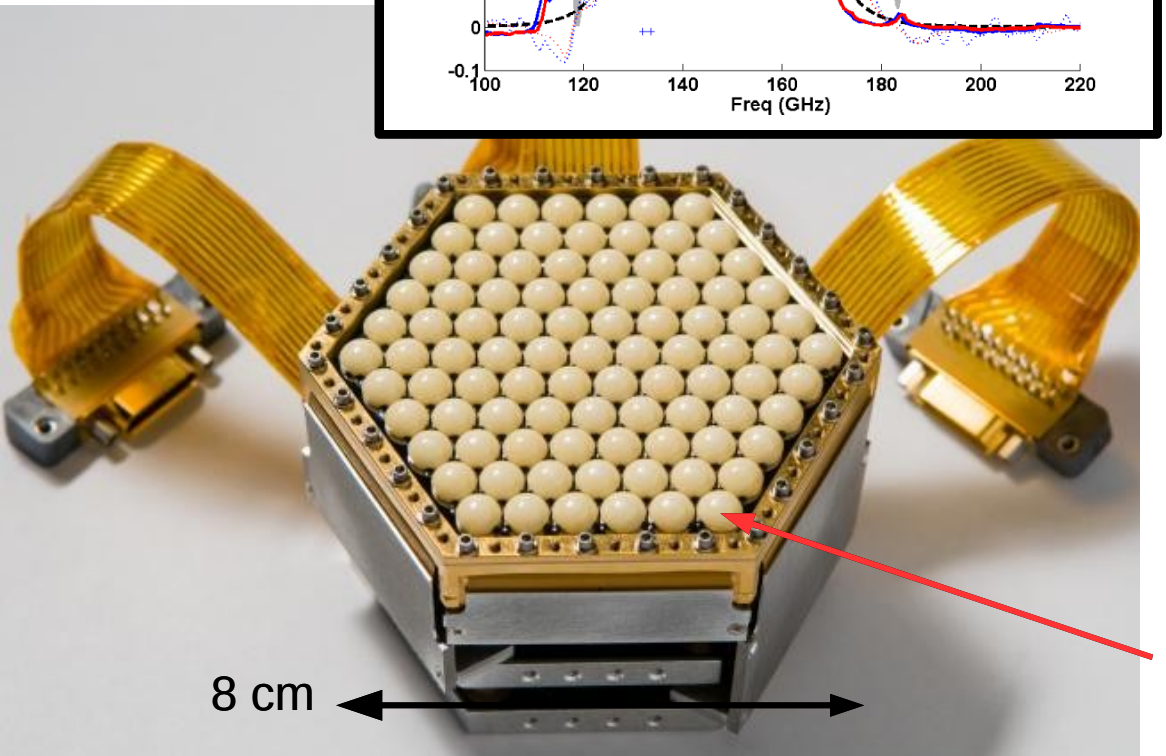




Bolometer

Filter

Antenna



1274 bolos @ 150 GHz (PB-I)

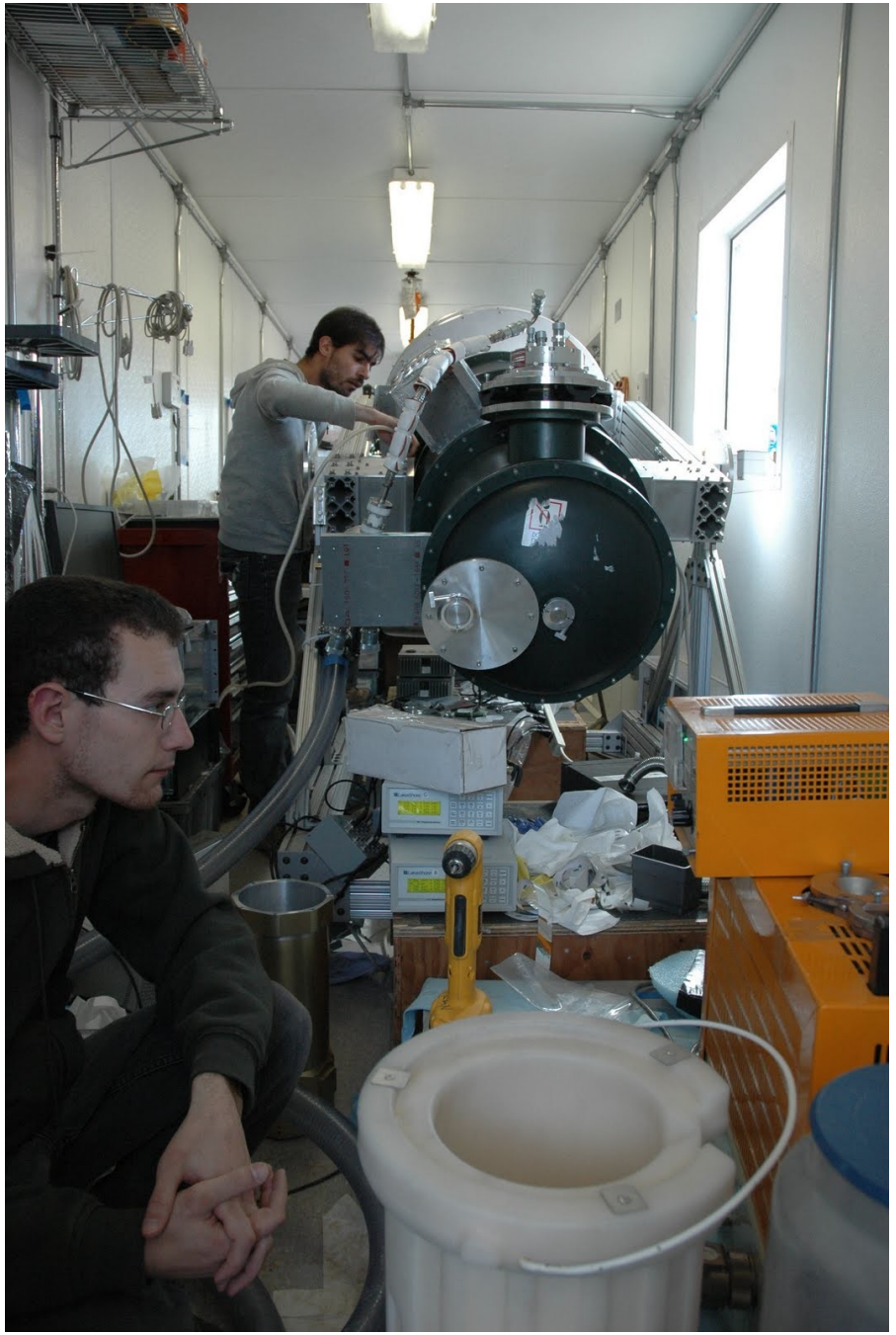
Monolithic wafer

Scalable

6mm Lenslet

POLARBEAR-I Engineering Run
2010 Cedar Flat, CA

Huan Tran Telescope at the James Ax Observatory

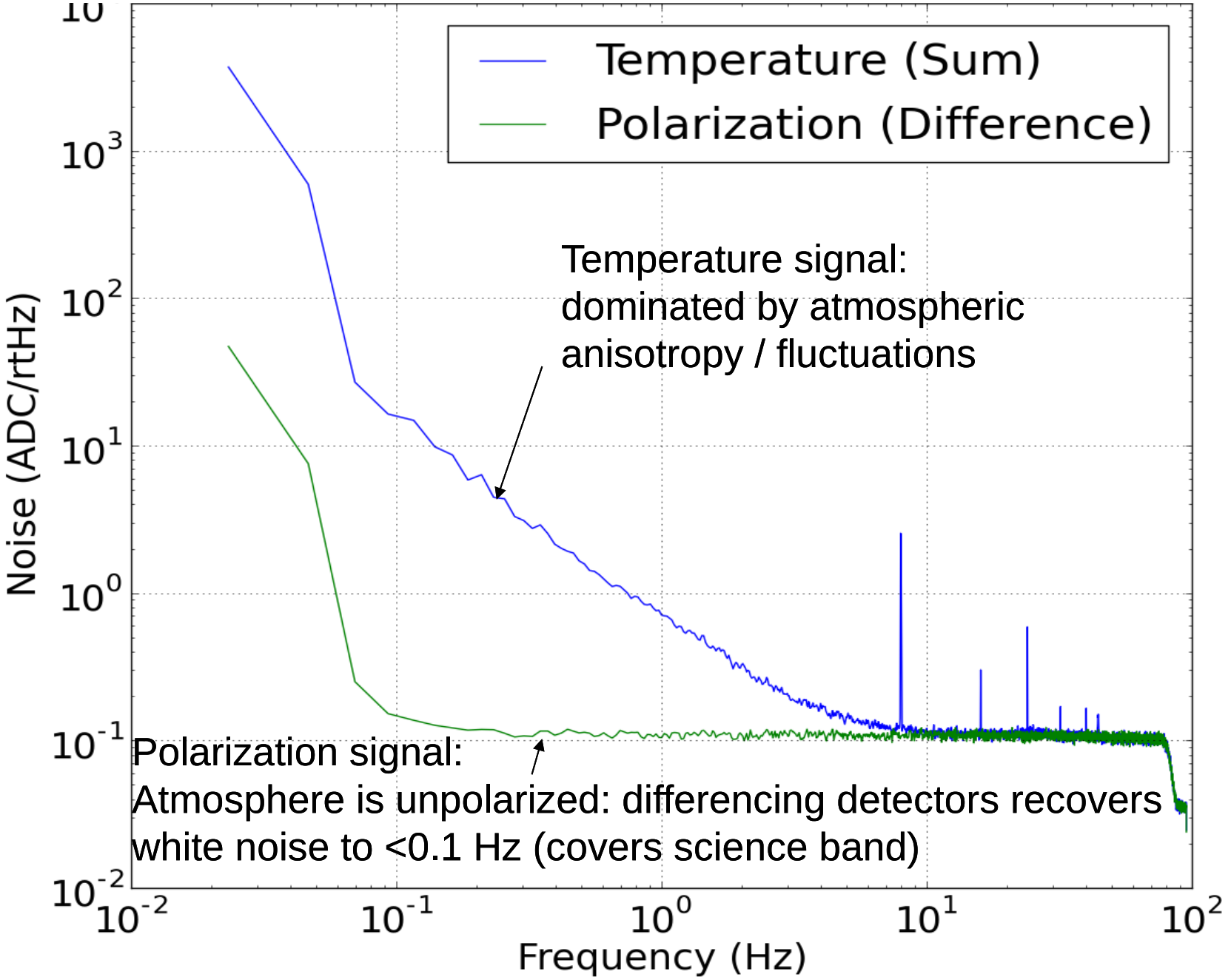


First Light: April 2010

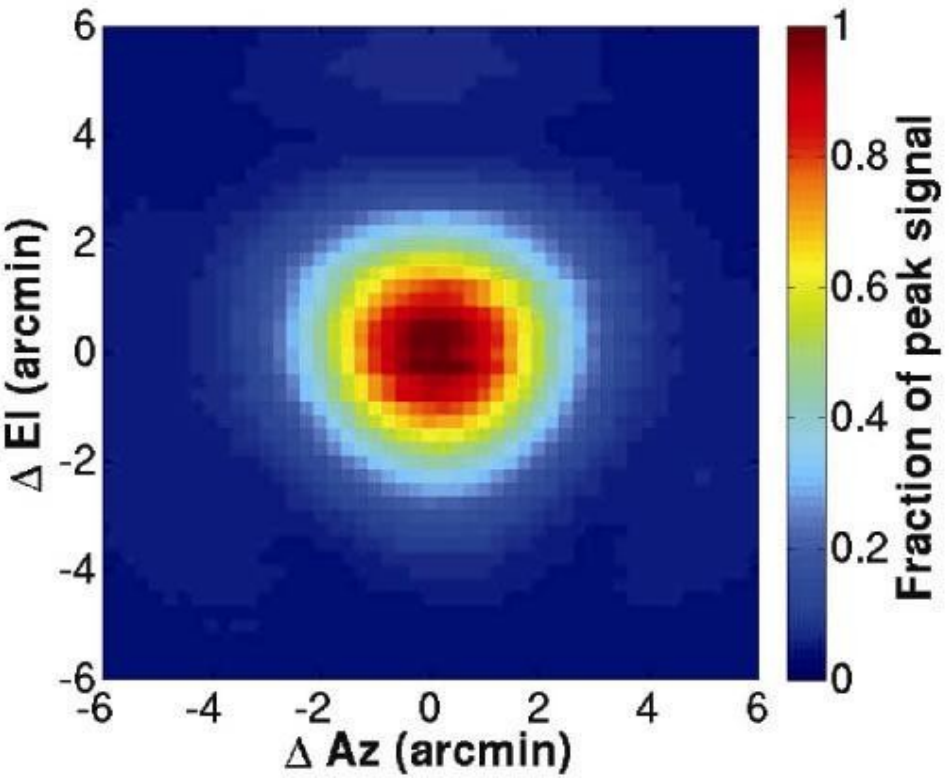
PB-I Focal Plane Sensitivity

- Engineering run noise limited by Cedar Flat sky temperature
- Typical measured optical efficiency ~50% (implies 75% at focal plane)
- Projected NET_{PIXEL} = 340 $\mu K \sqrt{s}$ in Chile

Atmospheric noise in Temperature is suppressed in polarization



Beam Properties



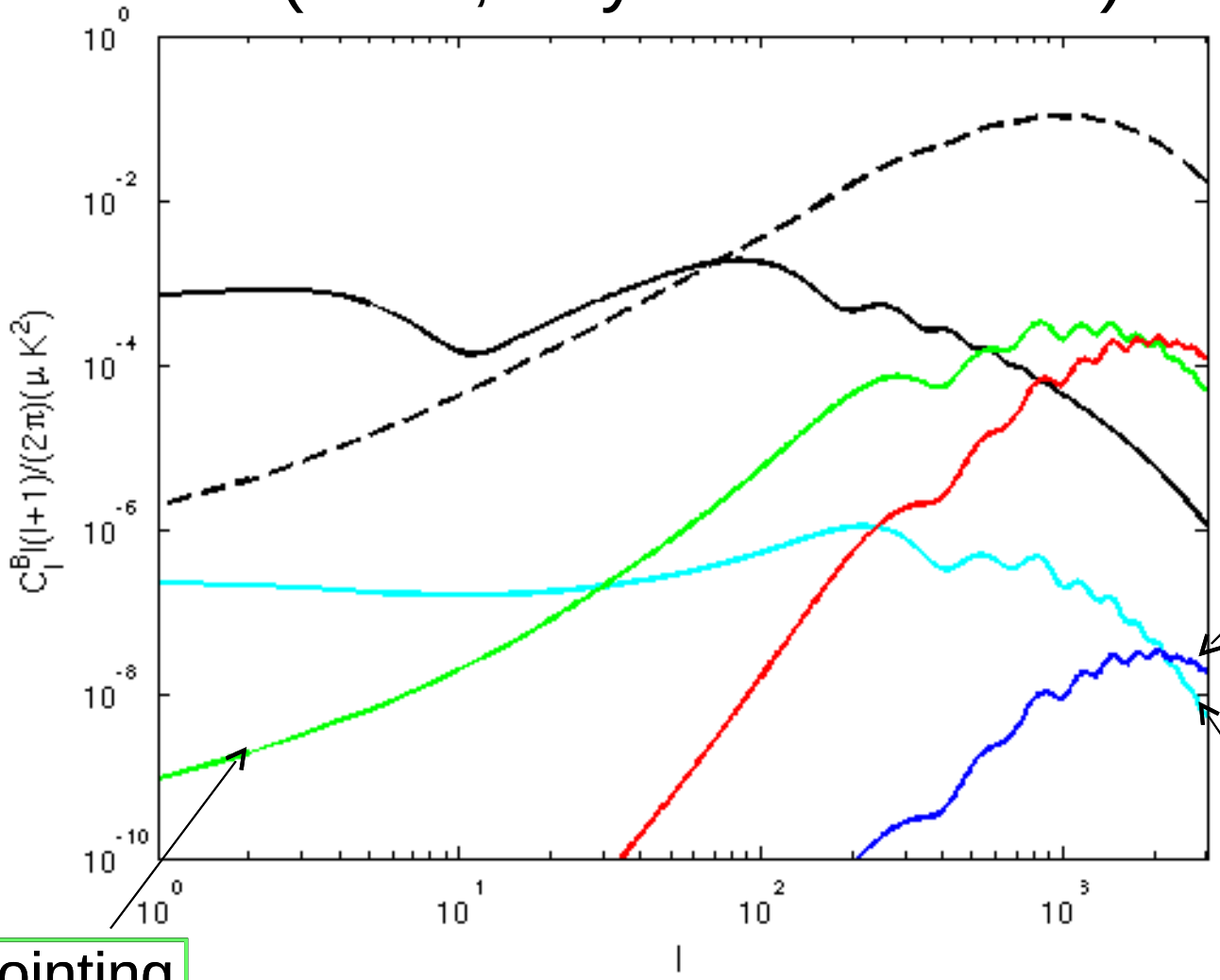
Co-added map of Jupiter

(recall N. Miller's talk Thursday)

Effect	Measured (Eng. run)	Required for r = 0.025*
Differential Gain	0.4%	0.03%
Differential Pointing	0.41”	1.1”
Differential Ellipticity	0.5%	2.9%
Differential Beam Size	0.4%	1.5%
Polarization Angle Uncertainty	1.5º	0.52º

* Requirements are relaxed when HWP, sky rotation included

Systematic Error Power Spectra
(HWP, Sky Rot. included)



Diff Ellipticity

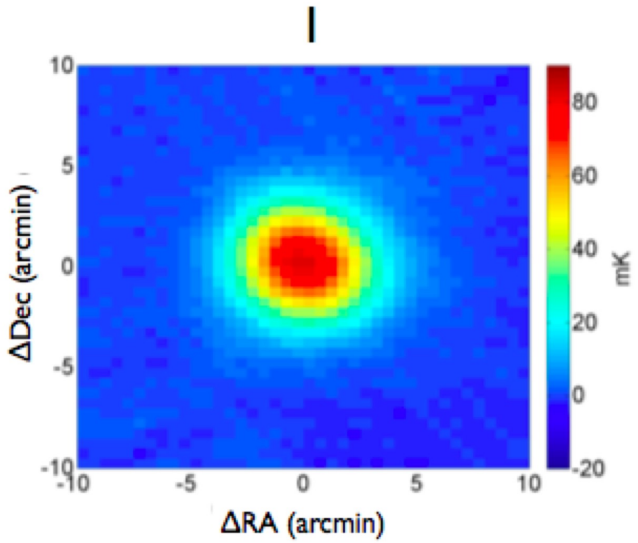
Diff Beam Width

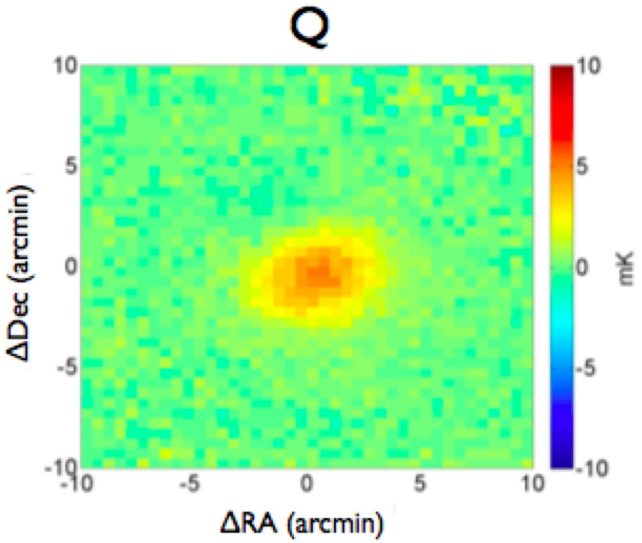
Differential gain

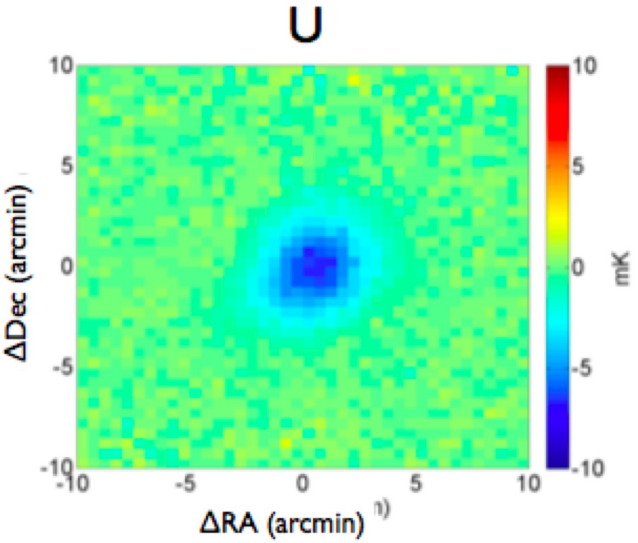
Diff Pointing

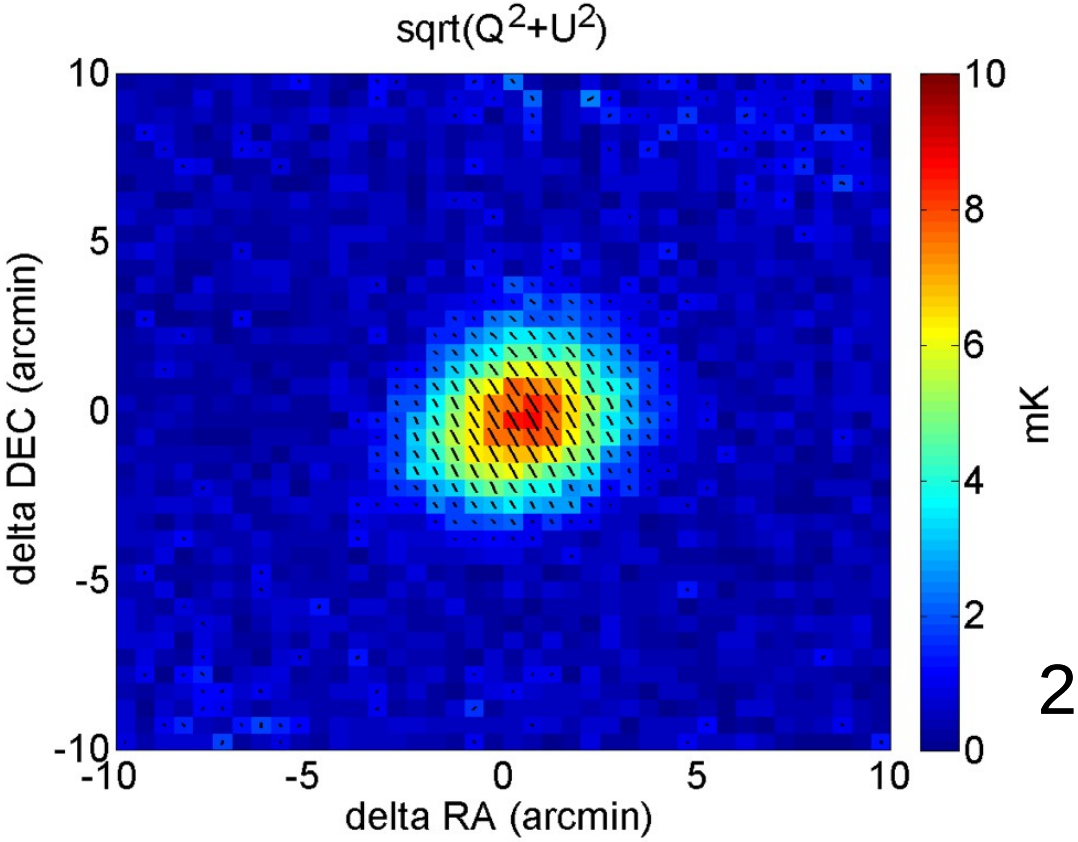
Measured POLARBEAR beams meet the systematic error requirements

POLARBEAR Measurements of TauA



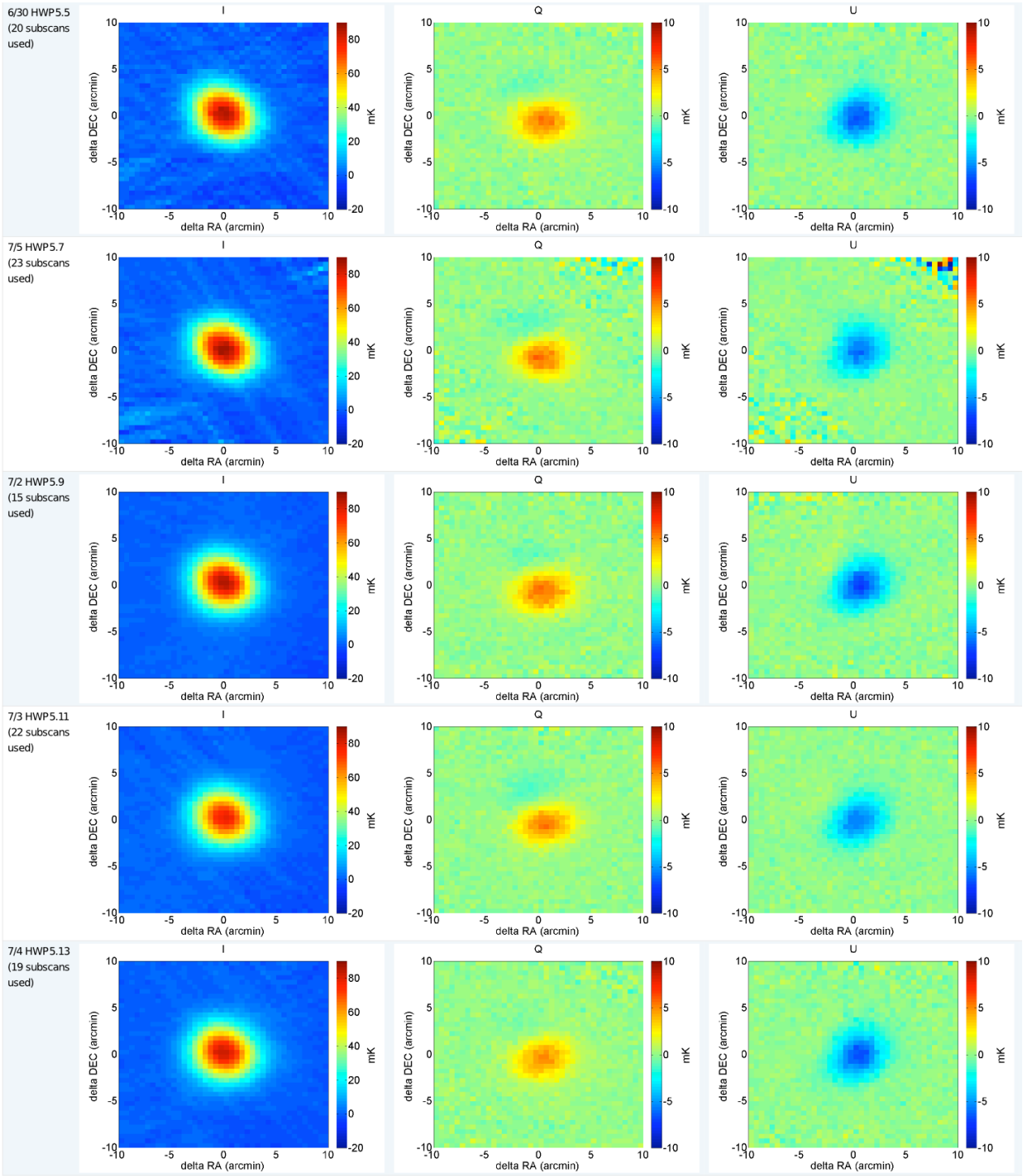






Pol. Magnitude and angle agree with Aumont et al., A&A 514 A70 (2010)

2 hours of data



Tau A I, Q, U

Taken at several Half Wave Plate positions

POLARBEAR-I status

Receiver in Berkeley for upgrade to full readout/focal plane

Telescope in Chile, foundation under construction

Analysis team working hard on Cedar Flat data (calibration, pointing, etc.), preparing pipeline for Chile data set

Chile deployment mid-2011!

POLARBEAR - II

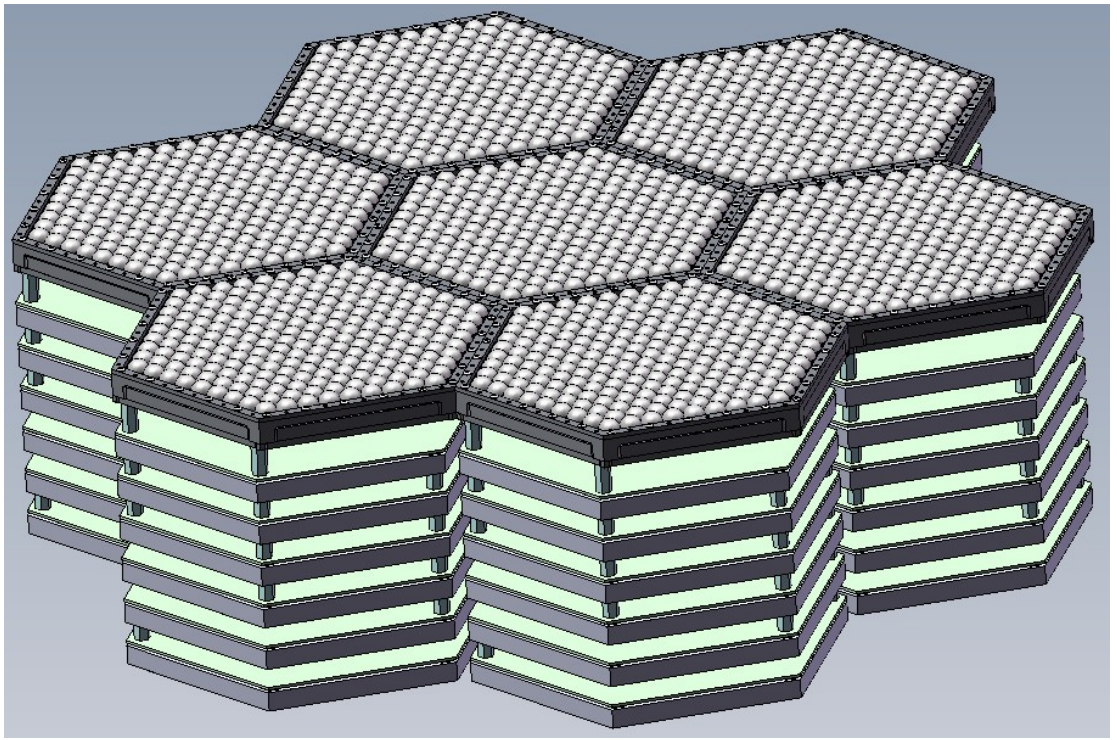
POLARBEAR-II

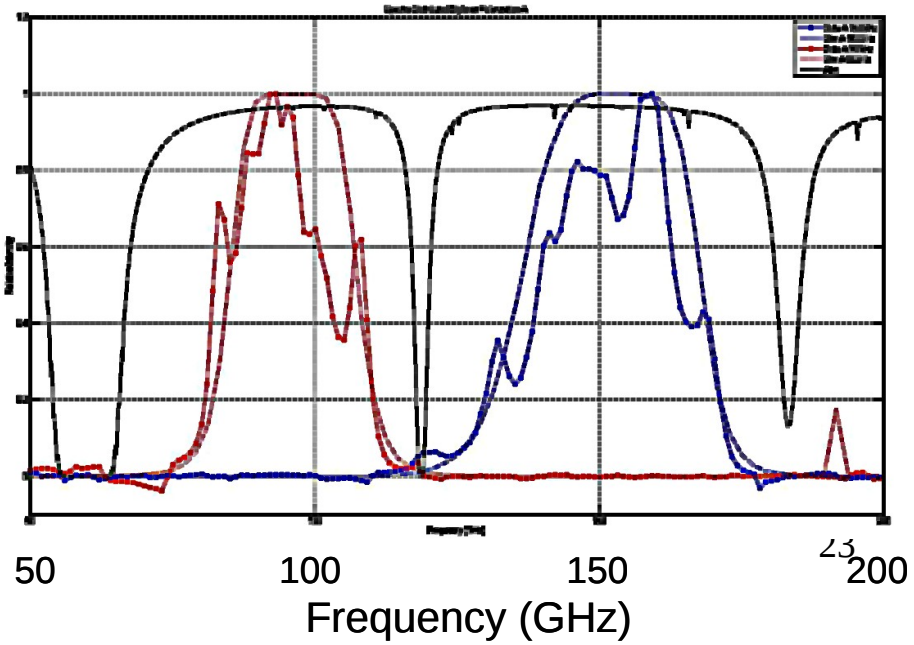
Receiver upgrade for the existing telescope

- 36 cm diam. focal plane (22 cm for PB-I)
- Two-color pixels (90 GHz, 150 GHz)
- 6076 bolometers (4.8x PB-I)
- 100 mK operation

Scheduled to deploy in late 2013 on HTT

POLARBEAR-II focal plane

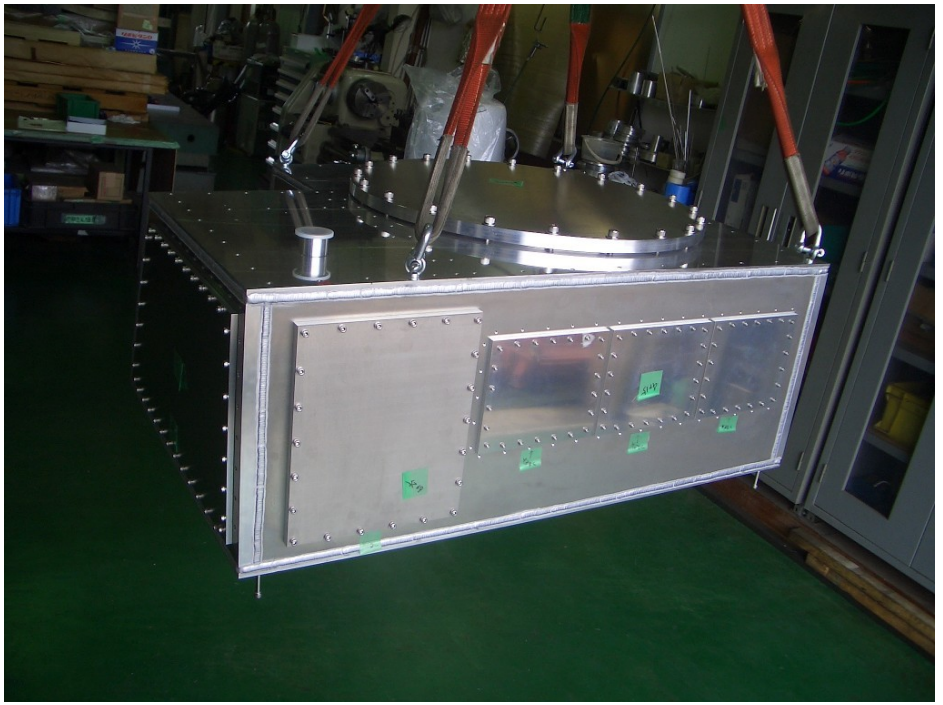




Above: Full PB-II focal plane
Top Right: Detector test chip
Right: Measured spectral response
For 90 GHz/ 150 GHz bands

PB-II Receiver (KEK)

- Receiver under construction
- Backend machined (right), contains cryogenics, focal plane
- Optics tube waiting for final optical design (soon)



POLARBEAR - Extended

POLARBEAR-Extended

- Investigating 3-6 telescopes at PB site in Chile
- Each telescope uses a PB-II type receiver

  (90/150 GHz or 150/220 GHz)

- Will produce high-quality lensing maps over a large fraction of the sky
- Overlap with optical surveys for cross-correlation science (BOSS, Herschel, etc)

Telescopes 2,3 fully funded by the James Ax Foundation

Sensitivity Comparison

	# bolos	Deep (3y)	Wide (3y)
PB-I	1274	1000 sq deg @ 8 μK arcmin	-
PB-II	6076	1000 sq deg @ 3 μK arcmin	4000 sq deg @ 6 μK arcmin
(PB–II) x 3	18228	1000 sq deg @ 1.7 μK arcmin	16000 sq deg @ 7 μK arcmin
(PB–II) x 6	36456	1000 sq deg @ 1.2 μK arcmin	16000 sq deg @ 5 μK arcmin

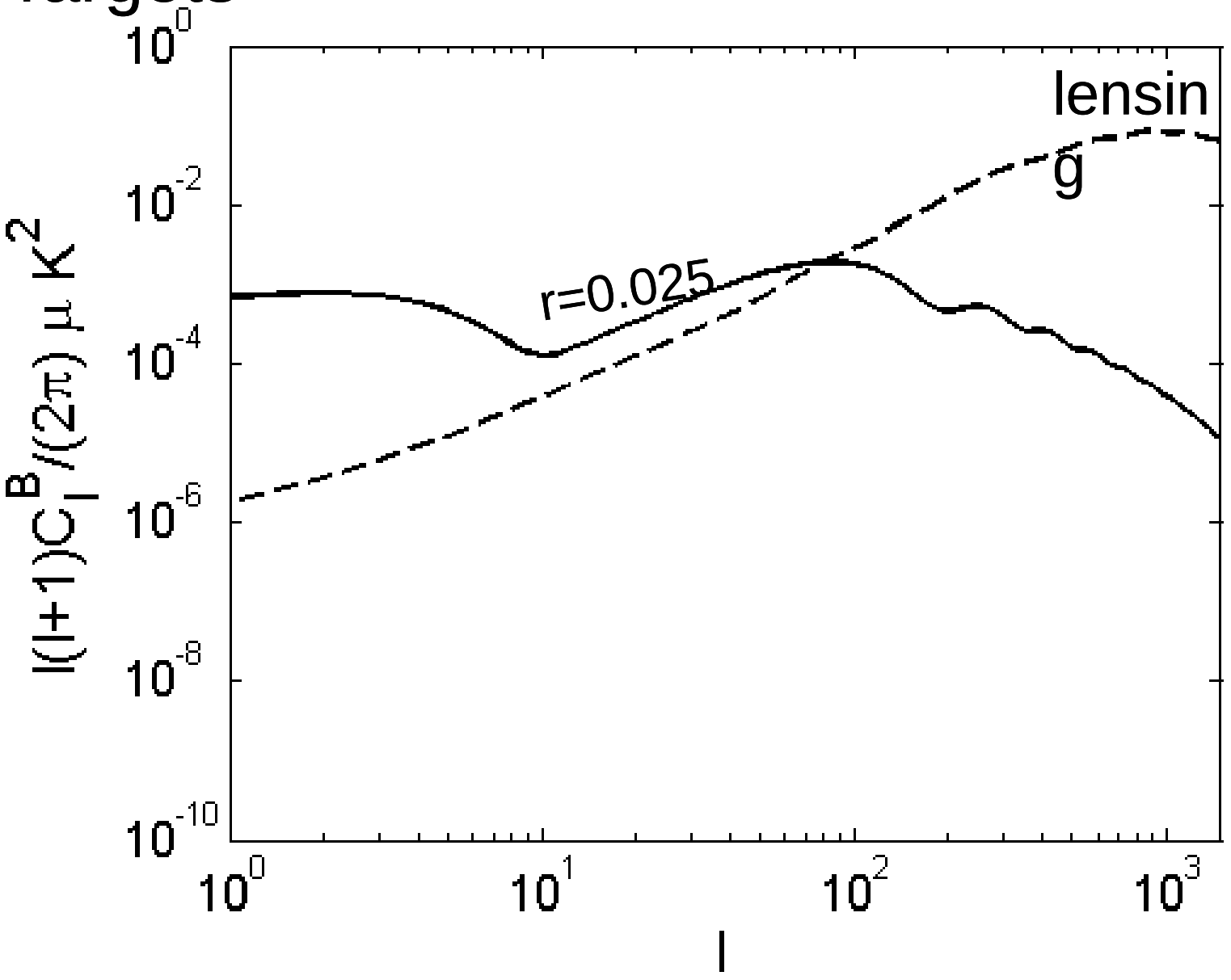
See Oliver Zahn's talk for lensing science applications of PB-extended

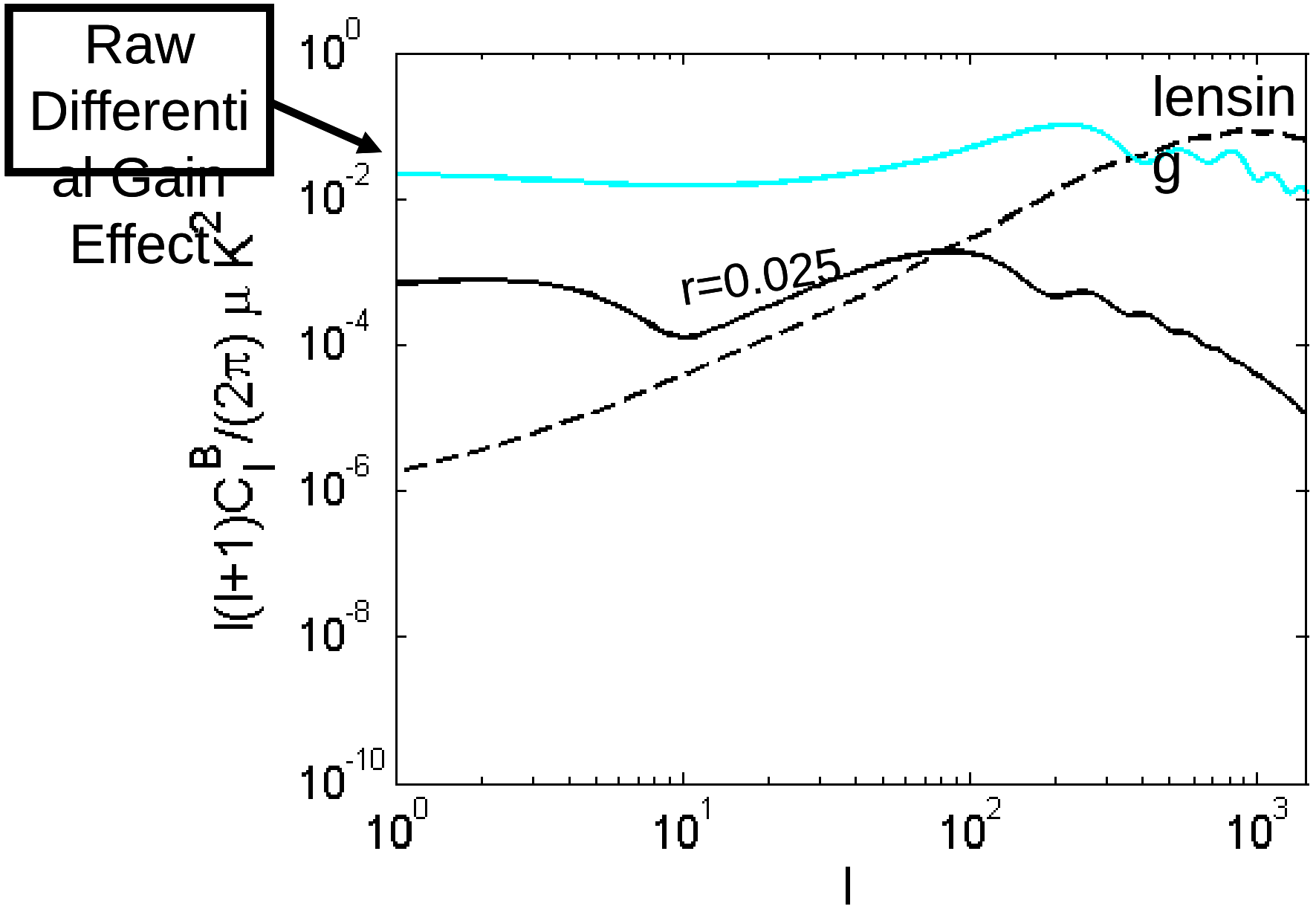
Conclusion

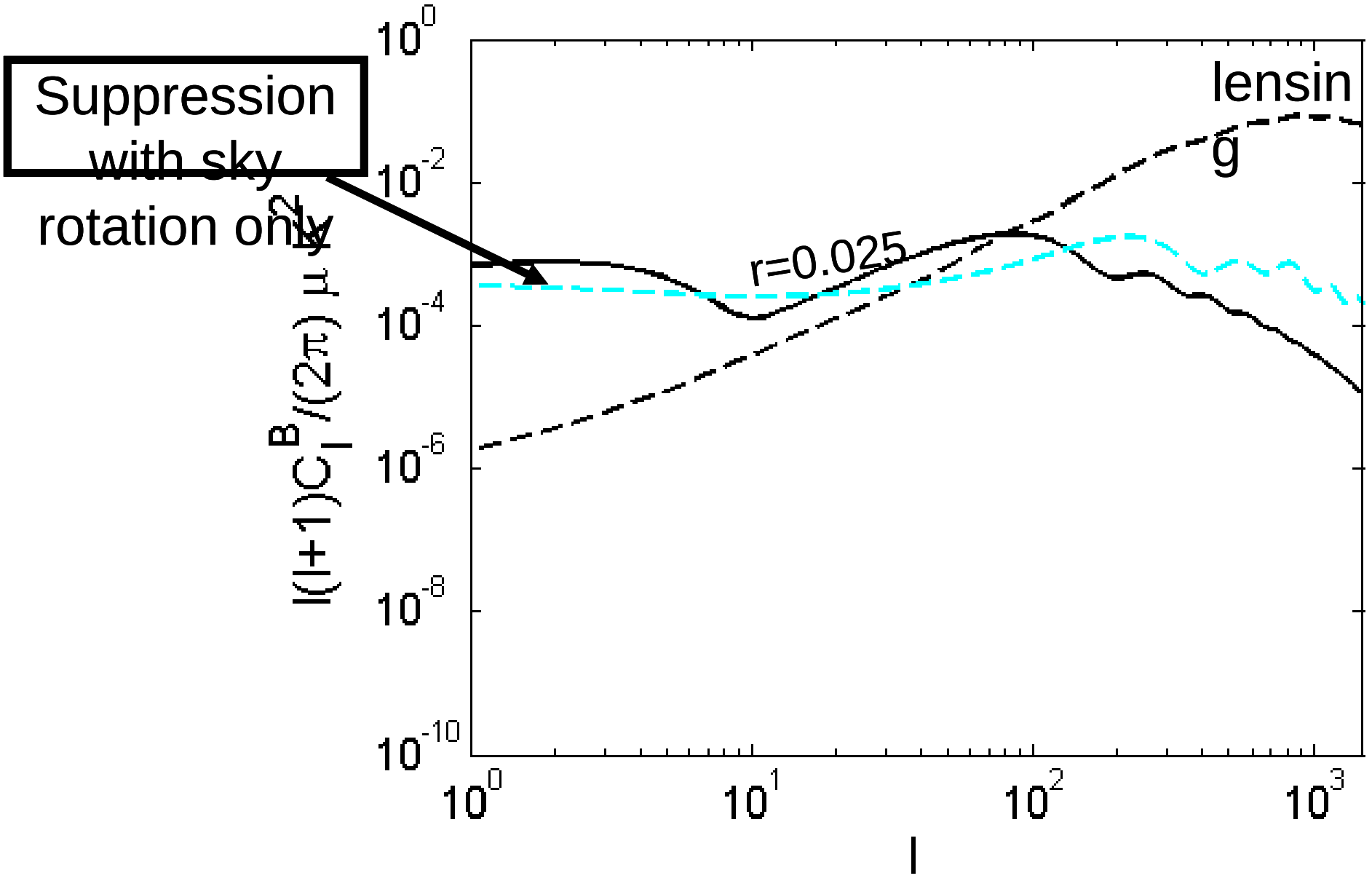
- POLARBEAR-I deploys mid-2011
  - Successful engineering run, meets requirements!
  - Should reach r ~ 0.025, detect B-mode lensing
- POLARBEAR-II on schedule for 2013 deployment
- POLARBEAR - “Extended” will follow
  - Expand to 3 – 6 telescopes

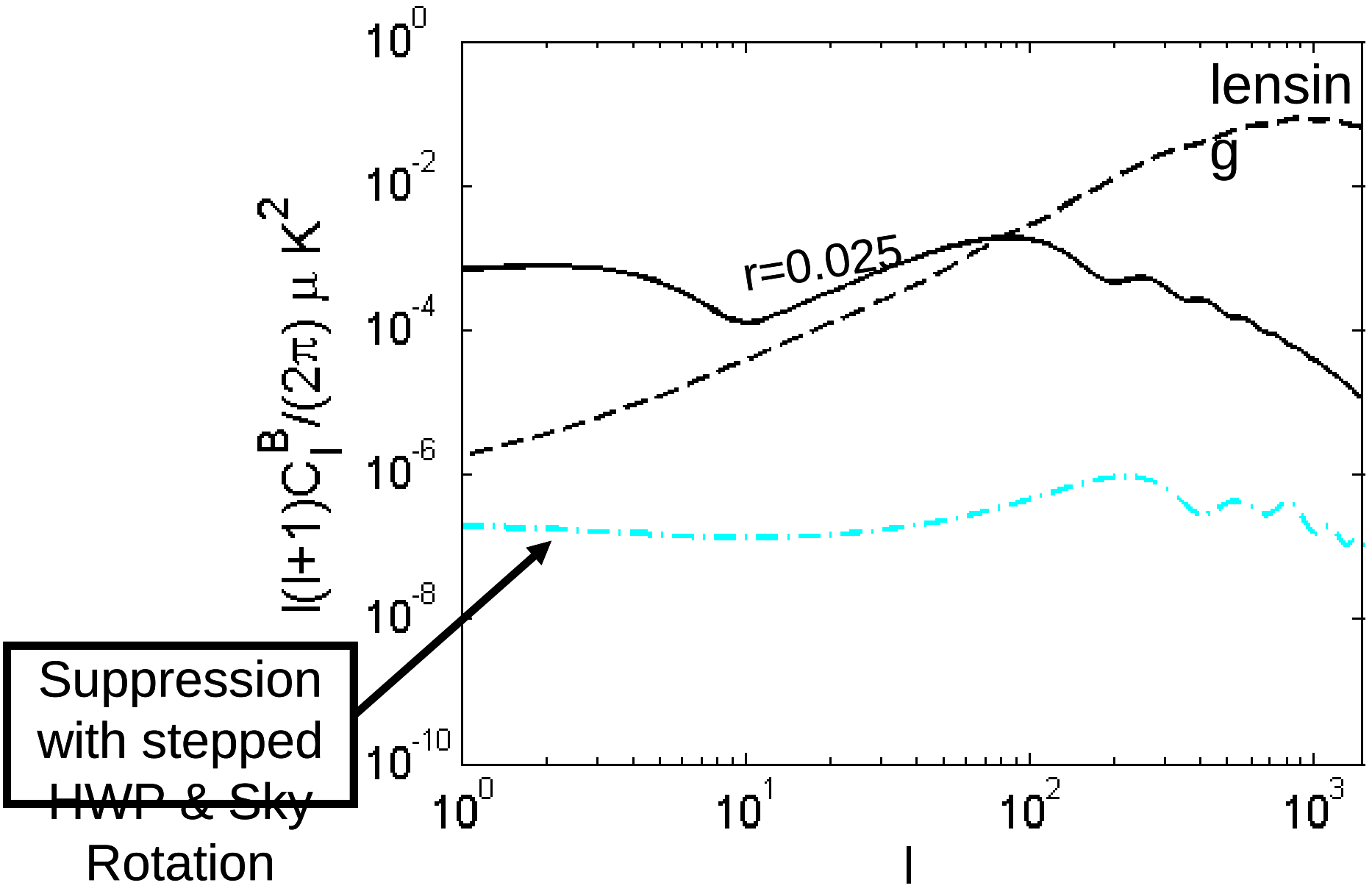
End.

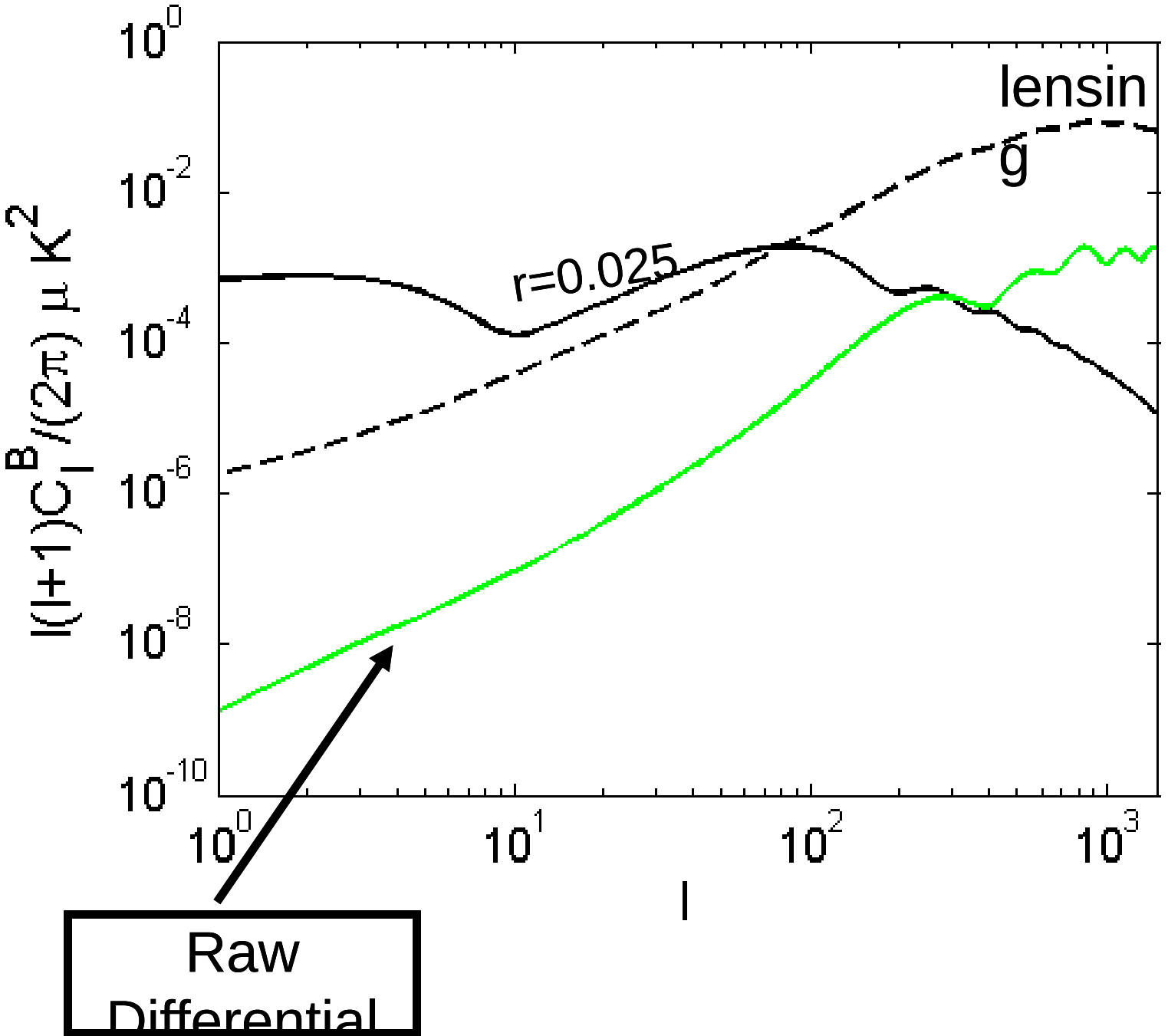
Systematic Power Spectra Compared to CMB Science Targets

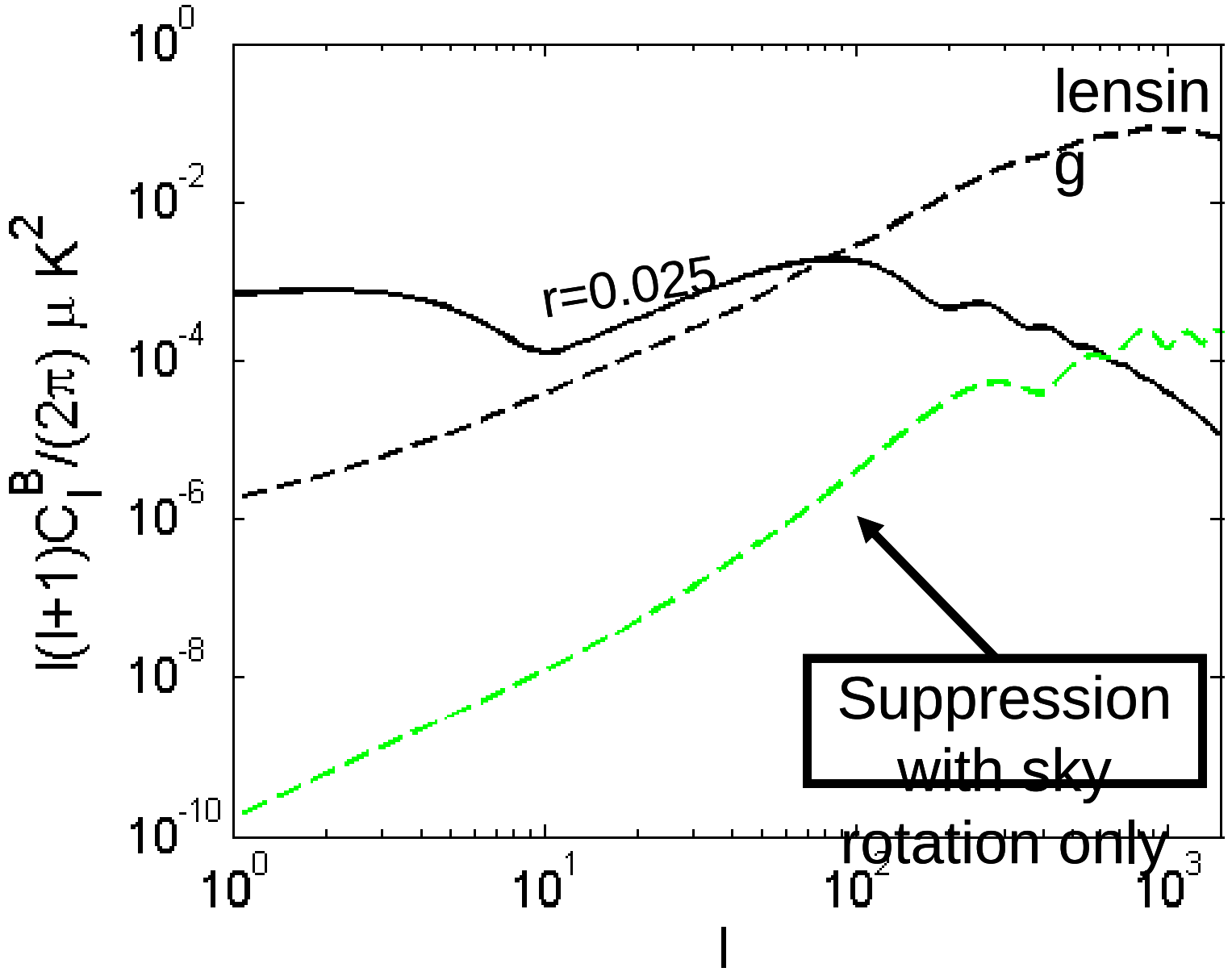


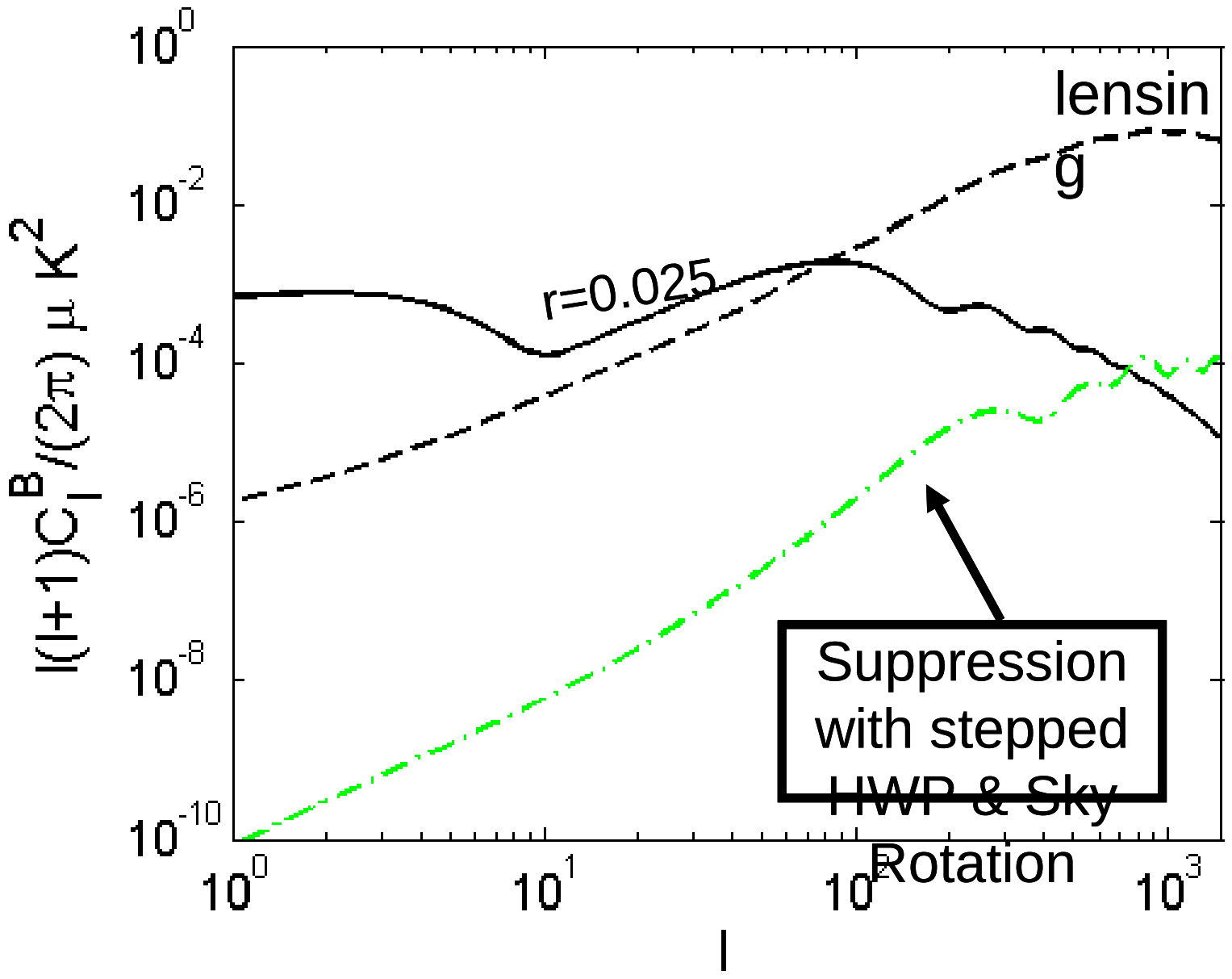

Raw Differential Gain Effect
lensing
r=0.025
$l(l+1)C_l^B/(2\pi)\ \mu K^2$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^1
10^2
10^3
l

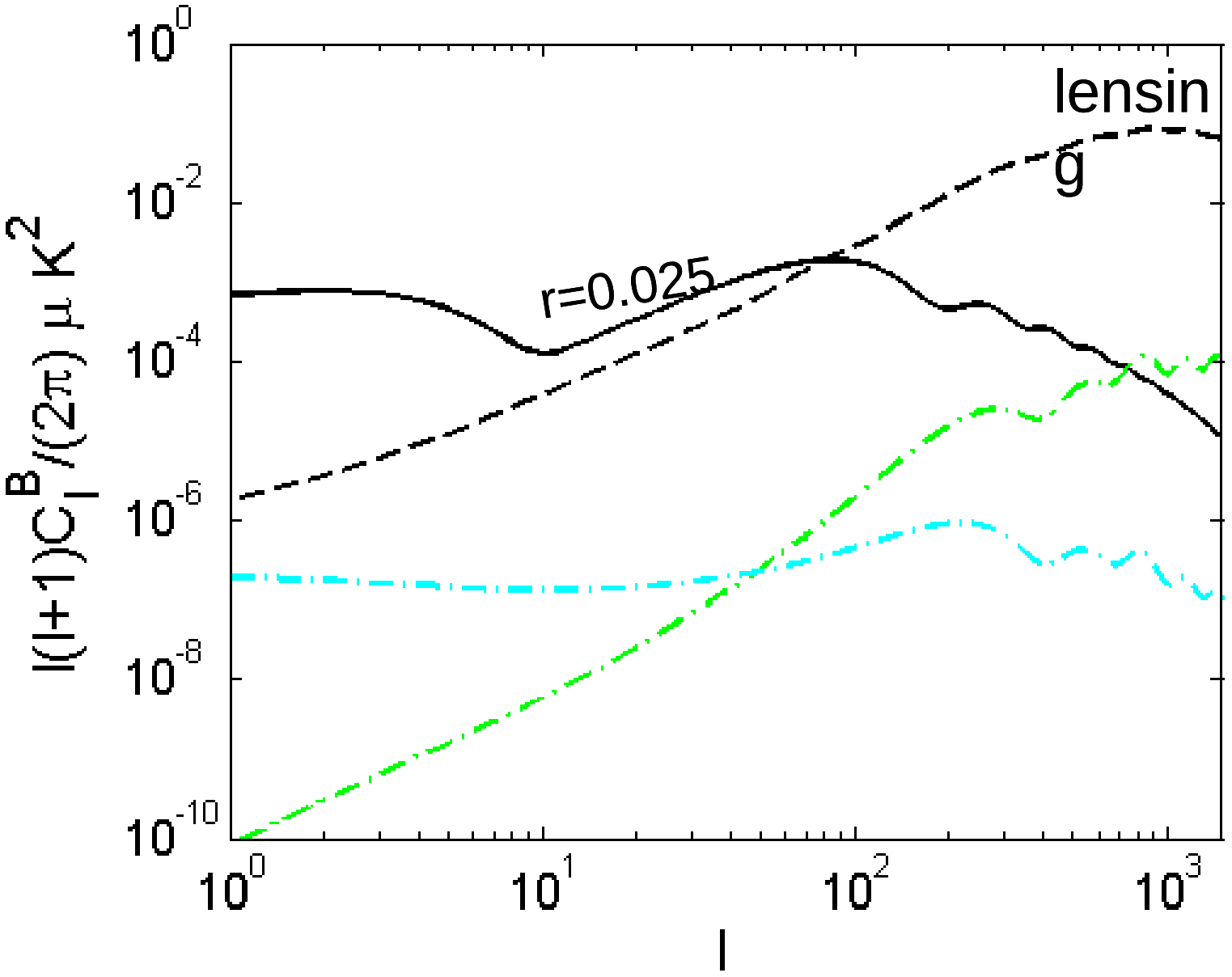

Suppression with sky rotation only
lensing
r=0.025
$l(l+1)C_l^B/(2\pi)\ \mu K^2$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^1
10^2
10^3
l

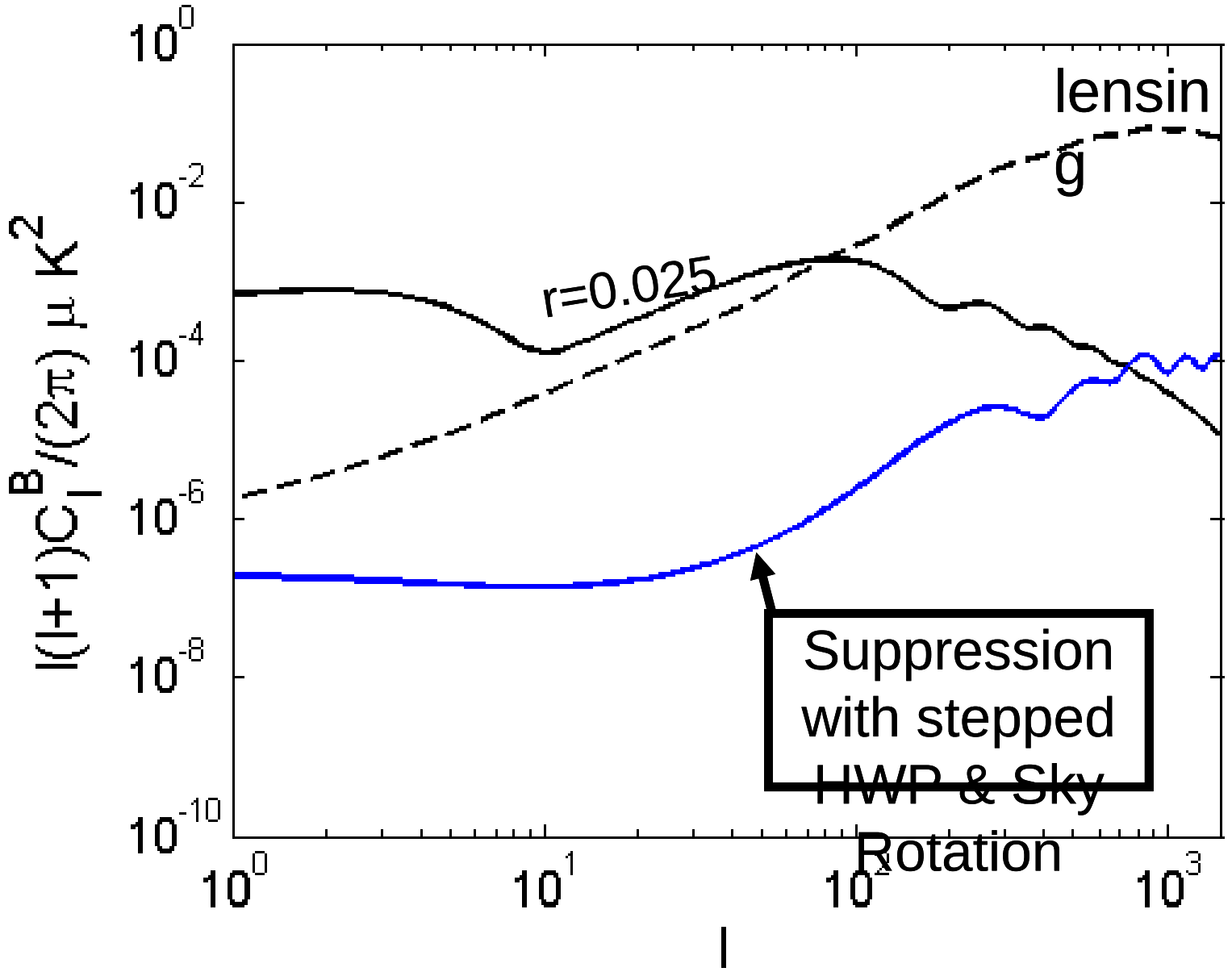

lensing
r=0.025
$l(l+1)C_l^B/(2\pi)\ \mu K^2$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^1
10^2
10^3
l
Suppression with stepped HWP & Sky Rotation


lensing
r=0.025
$l(l+1)C_l^B/(2\pi)\ \mu\ K^2$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^1
10^2
10^3
l
Raw
Differential


lensing
r=0.025
Suppression with sky rotation only
l(l+1)C_l^B/(2π) μ K^2
l
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^0
10^1
10^2
10^3


lensing
r=0.025
Suppression with stepped HWP & Sky Rotation
l(l+1)C_l^B/(2π) μ K^2
l
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^0
10^1
10^2
10^3


lensing
r=0.025
$l(l+1)C_l^B/(2\pi)\ \mu\ K^2$
l
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^1
10^2
10^3


lensing
r=0.025
Suppression with stepped HWP & Sky Rotation
l(l+1)C_l^B/(2π) μ K^2
l
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^0
10^1
10^2
10^3