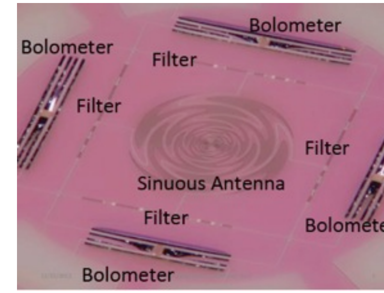
The LiteBIRD Satellite Project

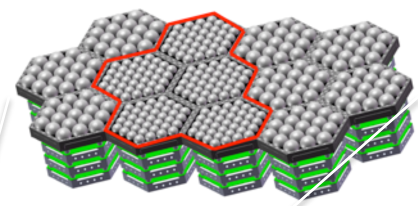
Masashi Hazumi
(KEK CMB Group)

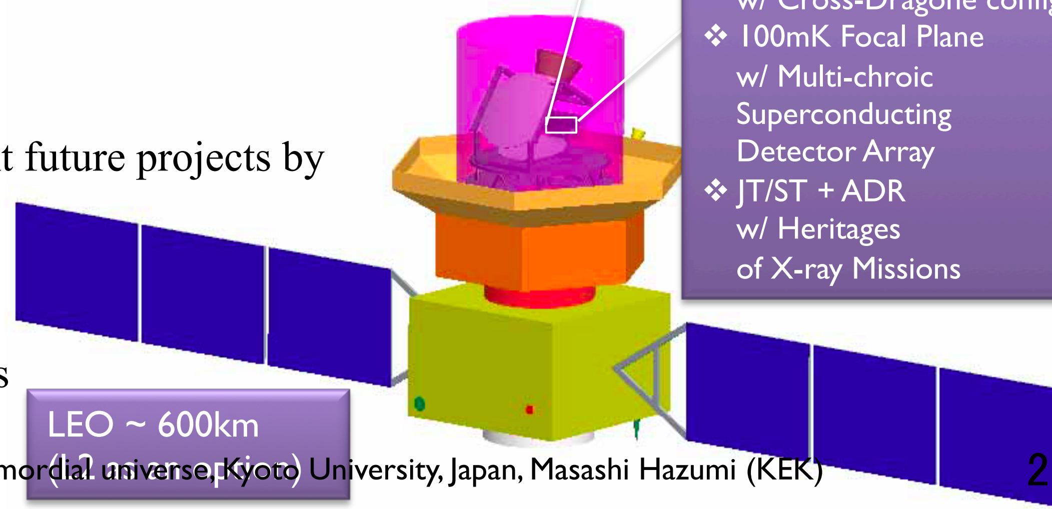
LiteBIRD

Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

- JAXA-based working group (more than 60 members from JAXA, Kavli IPMU, KEK, NAOJ, Berkeley/LBNL, McGill, Riken, MPA and Japanese universities)
- Scientific objectives
  - Tests of cosmic inflation and quantum gravity theories
  - ***Full success: $\delta r < 0.001$ (stat. $\oplus$ syst. $\oplus$ foreground $\oplus$ lensing)***
    - ***δr is the total error on tensor-to-scalar ratio***
- Observations
  - Full-sky CMB polarization survey at a degree scale (30arcmin @ 150 GHz)
  - 6 bands b/w 50 and 320 GHz
- Strategy
  - Part of technology verification from ground-based projects
  - Synergy with ground-based super-telescopes
  - Synergy with X-ray mission R&D
- Project status/plan
  - Selected as one of eight most important future projects by astronomy/astrophysics division of Science Council of Japan
  - Recognized as one of key future JAXA missions in fundamental physics
  - Target launch year ~2020







❖ Continuously-rotating HWP w/ 30cm diameter
❖ 60cm Primary Mirror w/ Cross-Dragone config.
❖ 100mK Focal Plane w/ Multi-chroic Superconducting Detector Array
❖ JT/ST + ADR w/ Heritages of X-ray Missions

LiteBIRD working group

- 67 members (as of June. 1, 2013)
- International and interdisciplinary

KEK
Y. Chinone
K. Hattori
M. Hazumi (PI)
M. Hasegawa
K. Kimura
N. Kimura
T. Matsumura
H. Morii
R. Nagata
S. Oguri
N. Sato
T. Suzuki
O. Tajima
T. Tomaru
M. Yoshida

SOKENDAI
Y. Akiba
Y. Inoue
H. Ishitsuka
A. Shimizu
H. Watanabe

Osaka U.
S. Takakura

JAXA
H. Fuke
I. Kawano
H. Matsuhara
K. Mitsuda
T. Nishibori
A. Noda
S. Sakai
Y. Sato
K. Shinozaki
H. Sugita
Y. Takei
T. Wada
N. Yamasaki
T. Yoshida
K. Yotsumoto

Okayama U.
H. Ishino
A. Kibayashi
Y. Kibe

National Inst. for Fusion Science
S. Takada

UC Berkeley
A. Ghribi
W. Holzapfel
A. Lee (US PI)
P. Richards
A. Suzuki

McGill U.
M. Dobbs

LBNL
J. Borrill

Tsukuba U.
M. Nagai

MPA
E. Komatsu

IPMU
N. Katayama
H. Nishino

Yokohama NU.
S. Murayama
S. Nakamura
K. Natsume

ATC/NAOJ
K. Karatsu
T. Noguchi
Y. Sekimoto
Y. Uzawa

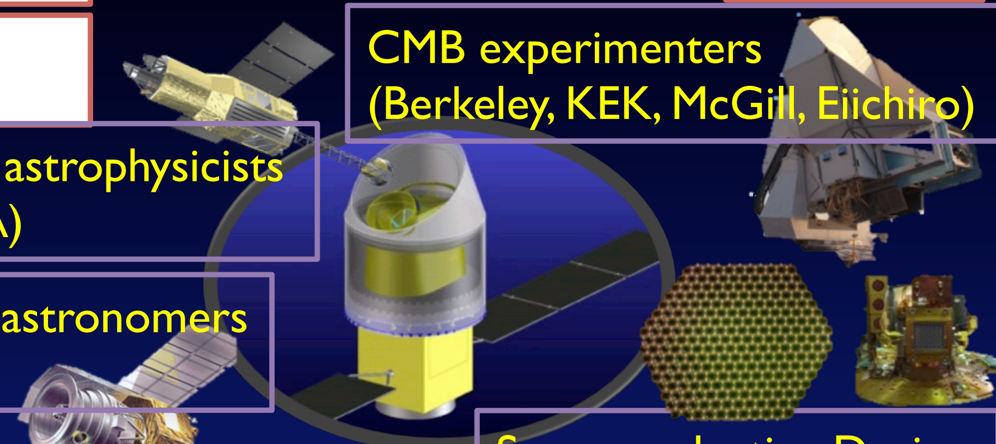
Saitama U.
M. Naruse

Osaka Pref. U.
H. Ogawa

RIKEN
K. Koga
S. Mima
C. Otani

Tohoku U.
M. Hattori
K. Ishidoshiro
K. Morishima

Kinki U.
I. Ohta



CMB experimenters (Berkeley, KEK, McGill, Eiichiro)

X-ray astrophysicists (JAXA)

Infrared astronomers (JAXA)

JAXA engineers, Mission Design Support Group, SE office

Superconducting Device (Berkeley, RIKEN, NAOJ, Okayama, KEK etc.)

Outline

1. Introduction
2. Pre LiteBIRD Era
3. LiteBIRD Era
4. Post-LiteBIRD Era
5. Conclusion

1. Introduction

CMB polarization projects

1. Ground

2. Balloon

3. Satellite

In addition, QUIJOTE in Canary island, AMiBA in Hawaii

Why so exciting ?

Experimental cosmologists dream of

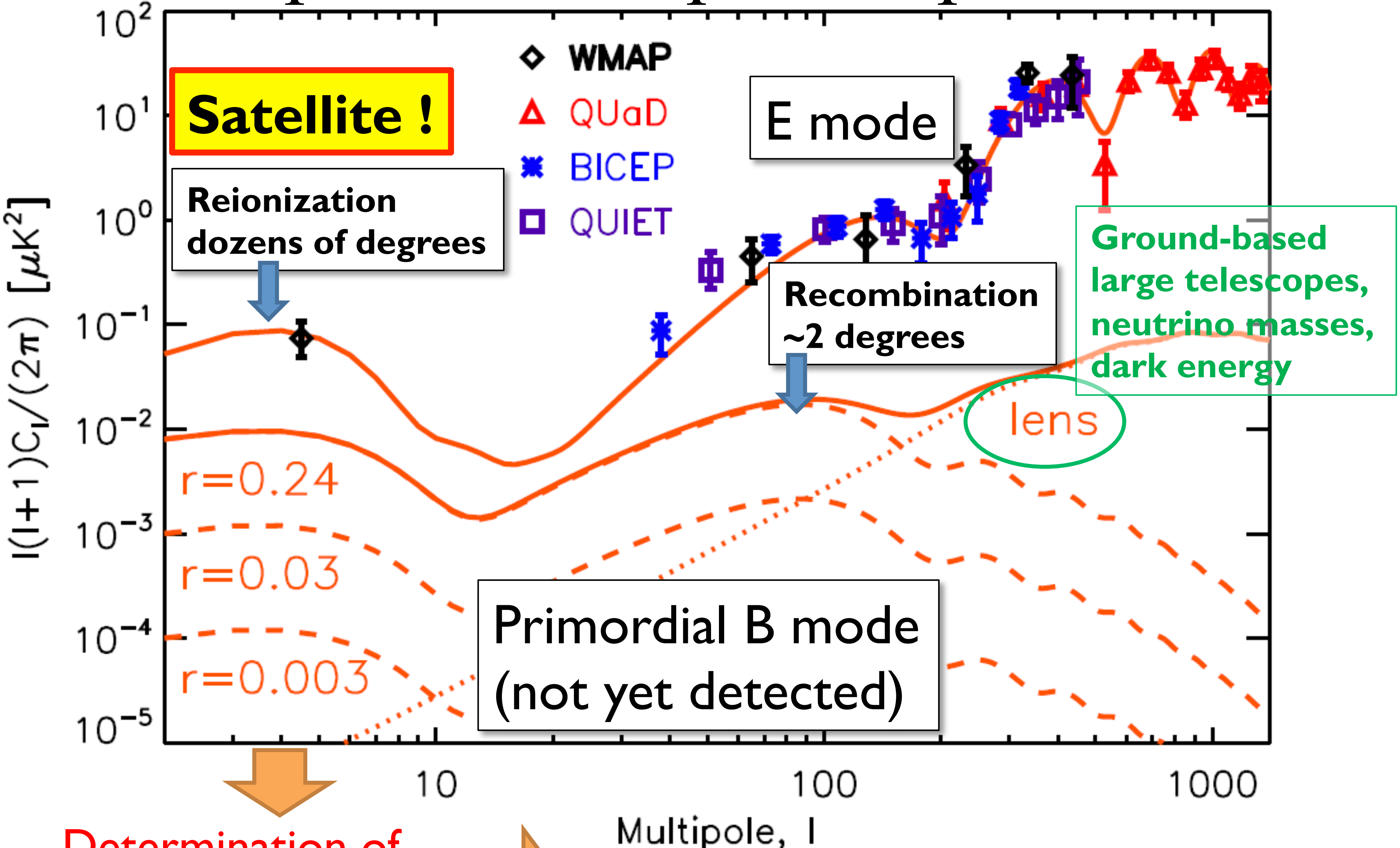
- Discovery of Primordial Gravitational Waves (PGW) !
- Determination of energy scale of inflation !
- Experimental quantum gravity !

Measuring CMB polarization is the only neat thing to do !

	Sun. 6/9	Mon. 6/10	Tue. 6/11	Wed. 6/12	Thu. 6/13	Fri. 6/14
8:00		Registration	Registration		Registration	Registration
9:00		Welcome (Dorfan) Goals (Hazumi) CMB science introduction (Sugiyama)	SPIDER (Jones, remote) EBEX (Hanany)	Free discussion	Cross correlations (Das) r values and ultimate theory (Yokoyama)	Foreground science (Finkbeiner) AMIBA (Lin)
10:00		WMAP (Larson) Coffee	QUIJOTE (Genova-Santos) ABS (Kusaka)		CLASS (Marriage) BICEP-3/POLAR-1 (Thompston) GroundBIRD (Tajima)	NANTEN2 (Fukui) S-PASS (Bernardi) C-BASS (Jones)
11:00		Planck instrumentation (Piacentini) Planck results (Tristram)	Coffee POLARBEAR-1 (Lee)		Coffee POLARBEAR-2 (Tomaru) Simons Array (Arnold)	Coffee PIPER (Fixsen) LSPE/SWIPE (Piacentini)
12:00		Discussion	ACTPol (Staggs) Foreground separation (Dickinson) Group photo		MuSE (Kusaka) QUBIC (Hamilton) Announcement etc.	Discussion Closing
13:00		Lunch	Lunch		Lunch, poster, OIST tour & free discussion	
14:00		Poster	Poster			
15:00		ACT (Devlin) SPT/SPTpol/SPT3G (Reichardt)	Intro (Hazumi) EPIC (Bock, remote) PIXIE (Fixsen)		OIST seminar Cosmology (Komatsu) Astronomy (de Graauw)	
16:00		BICEP/BICEP2/Keck Array (Buder)	LiteBIRD (Matsumura) Discussion		OIST tea time	
17:00	Registration	Coffee QUIET (Tajima)	Coffee COrE (Bouchet)			
18:00	Reception Sun Marina Hotel	CMB polarization (Komatsu)	L-Class mission (Delabrouille) Discussion	Welcome drink		
19:00				Conference dinner (buffet style) Kafuu Resort Fuchaku Condo Hotel		
20:00						
21:00						

timetable_v23, May 24, 2013

CMB polarization power spectra



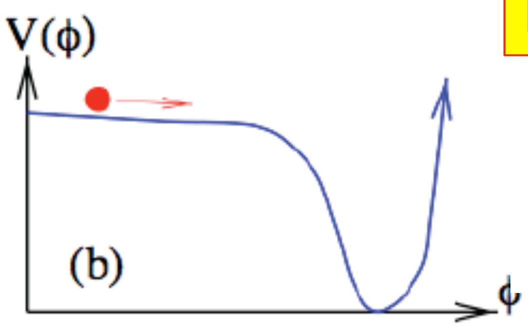
Determination of r (tensor-scalar ratio)

Shed light on inflation energy scale

Physics of inflation

Leading hypothesis = new scalar field "Inflaton"
In case of single-field slow-roll inflation
(= so-to-speak "standard model Higgs" in cosmology)

r (tensor-to-scalar ratio) is a key parameter



$$\varepsilon = \frac{m_{PL}^2}{16\pi}\left(\frac{V'(\phi)}{V(\phi)}\right)^2 ; \eta = \frac{m_{PL}^2}{8\pi}\left(\frac{V''(\phi)}{V(\phi)}\right)$$

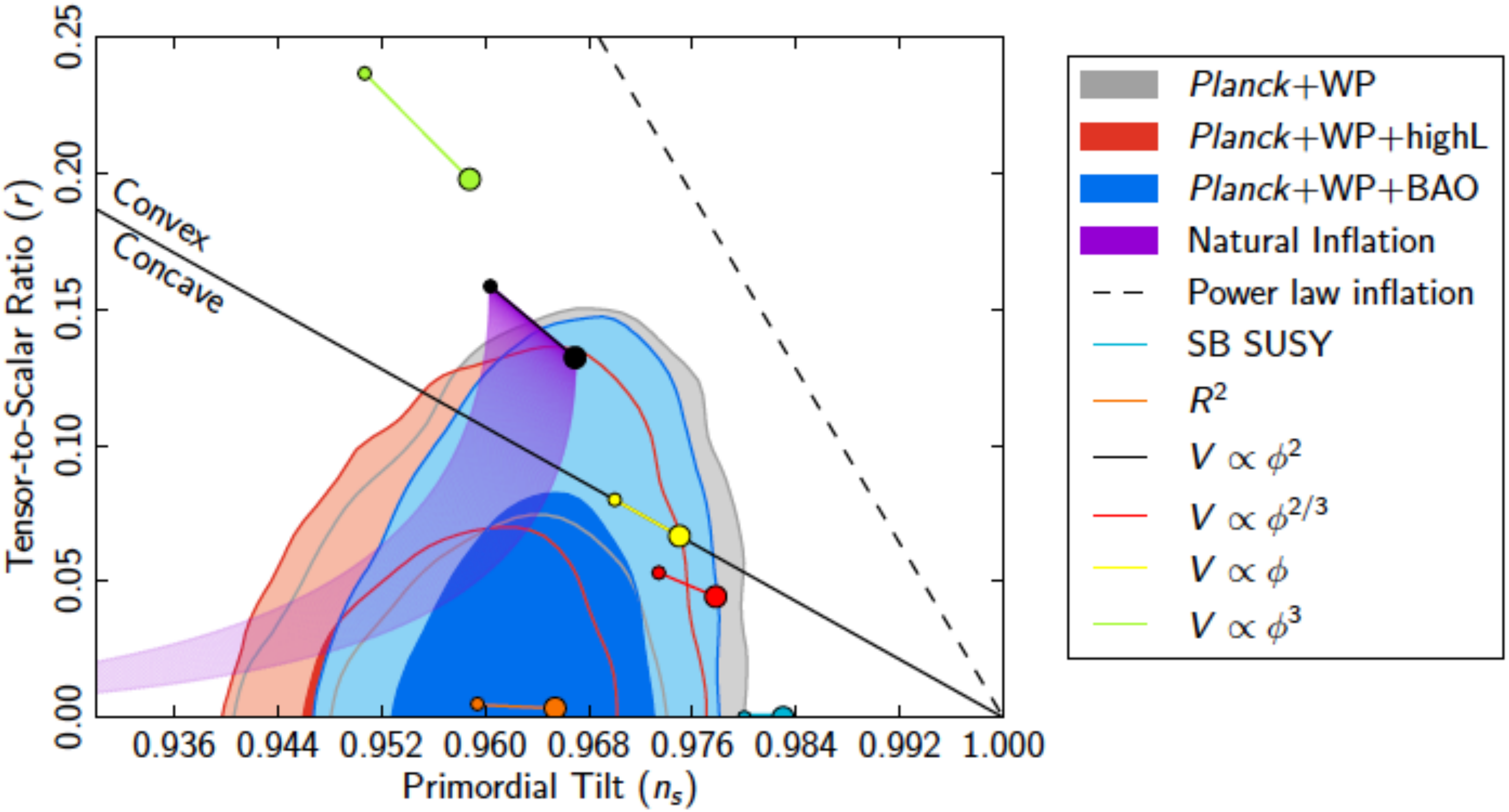
$$n_S \approx 1 - 6\varepsilon + 2\eta$$
$$r \equiv T/S = 16\varepsilon$$
$$n_S \neq 1 \Rightarrow r \neq 0$$

Inflation potential proportional to r

$$V^{1/4} = 1.06 \times 10^{16} \times (r/0.01)^{1/4}\ \text{GeV}$$

Unique probe of GUT scale physics !

Current limit on r from CMB temperature



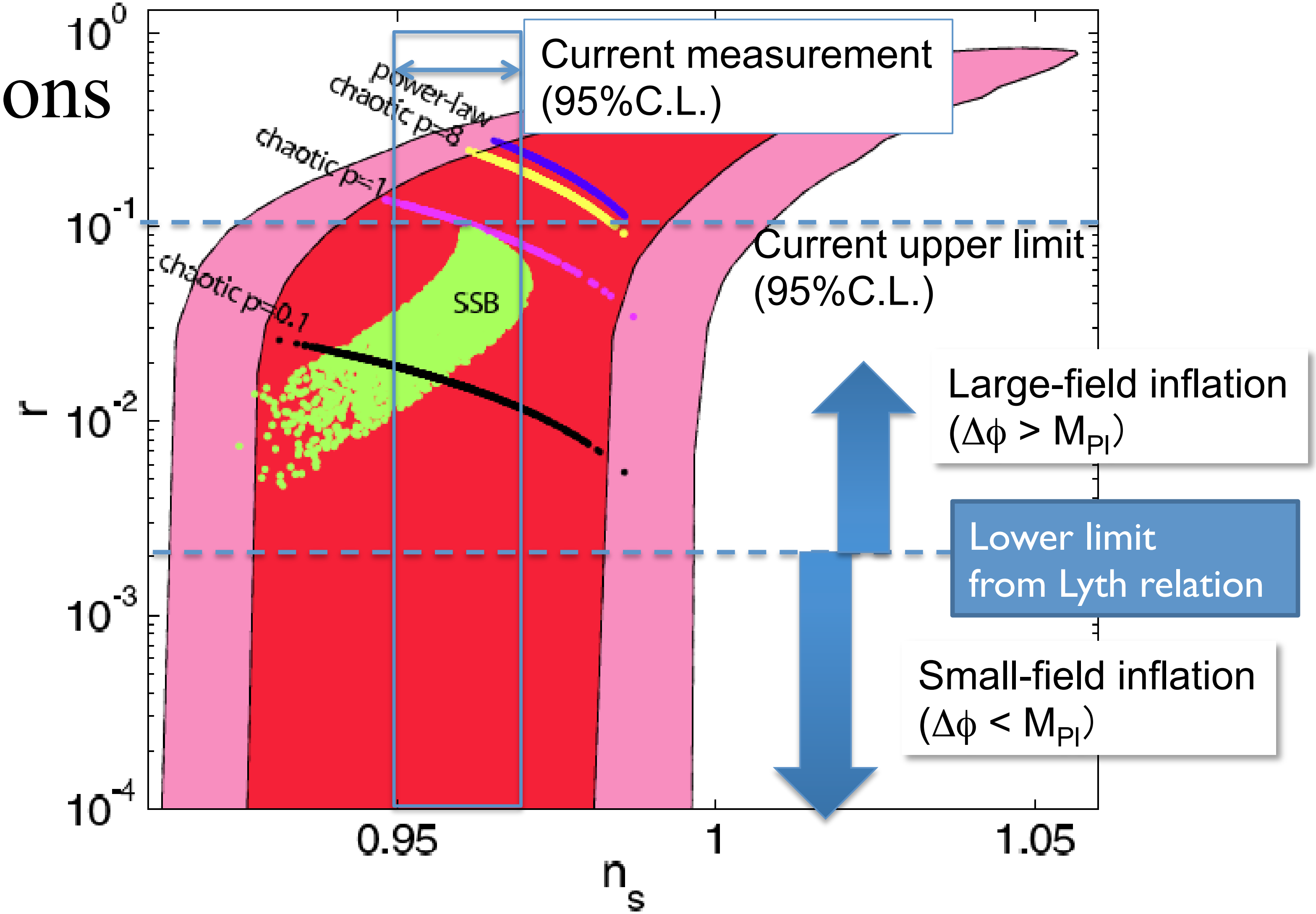
$r < 0.11$ (95% C.L.)

Cosmic variance limited

→ Hope is in polarization measurements.

Predictions on r

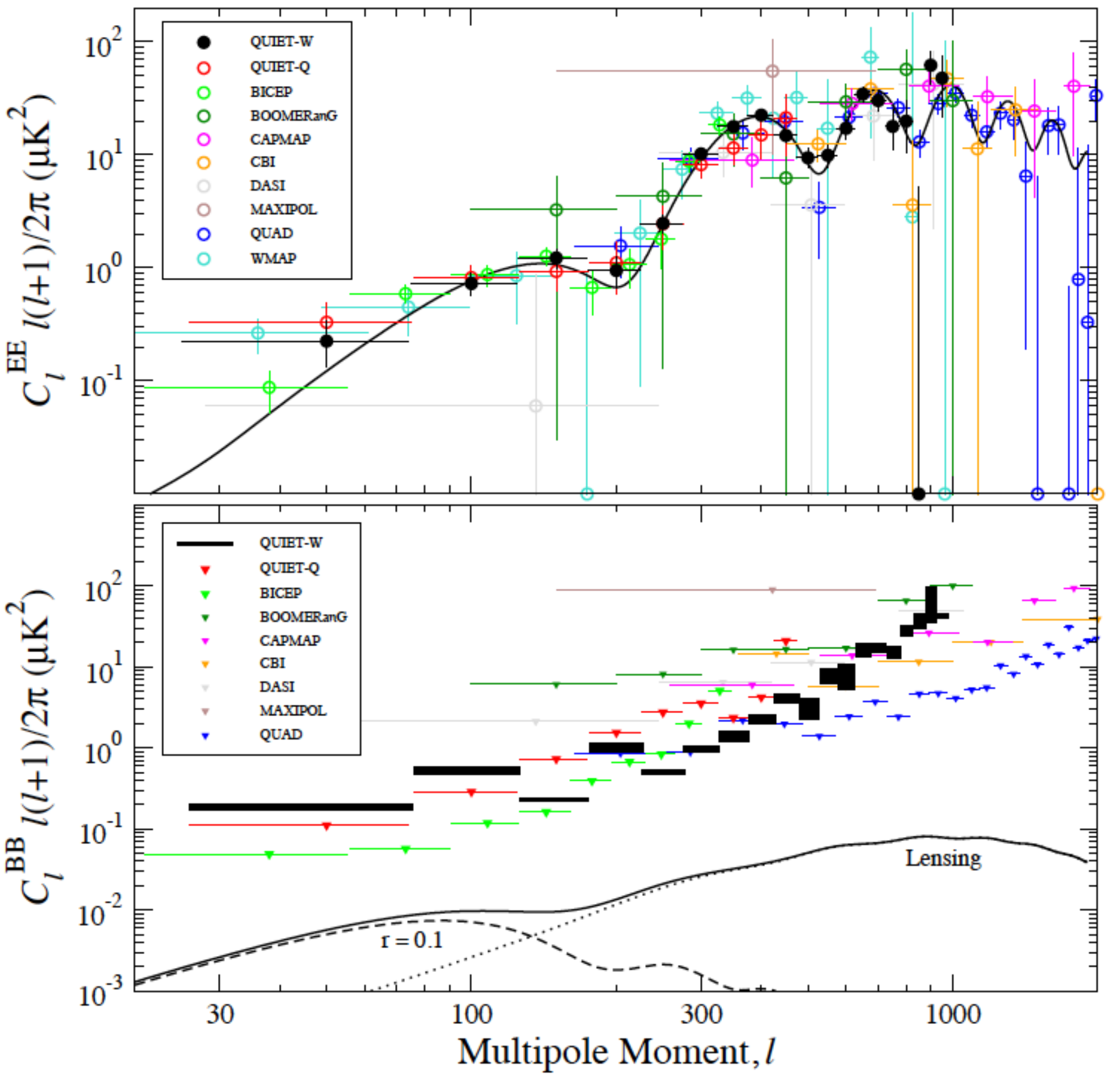
Pagano-Cooray-Melchiorri-Kamionkowski 2007



- Targeting r=0.01 is well motivated.
- Targeting r=0.001 is needed to fully test large-field models.

2. Pre-LiteBIRD Era

Current Status of polarization measurements



E-mode
- Observed
- Consistent with ΛCDM

B-mode
- Not observed yet
- Best limit on r from B-mode is $r < 0.7$ (95%C.L.) by BICEP (3yr data, preliminary)

CMB Polarization Data in the Can

- BICEP-2/Keck Array
- Planck
- POLARBEAR-1
- SPTpol
- ABS
- QUIJOTE
- EBEX

These experiments will publish results in the near future with sensitivity at r~0.1 or even better.

Four obstacles

Statistics

Systematics

Goal

$\delta r < 0.01$

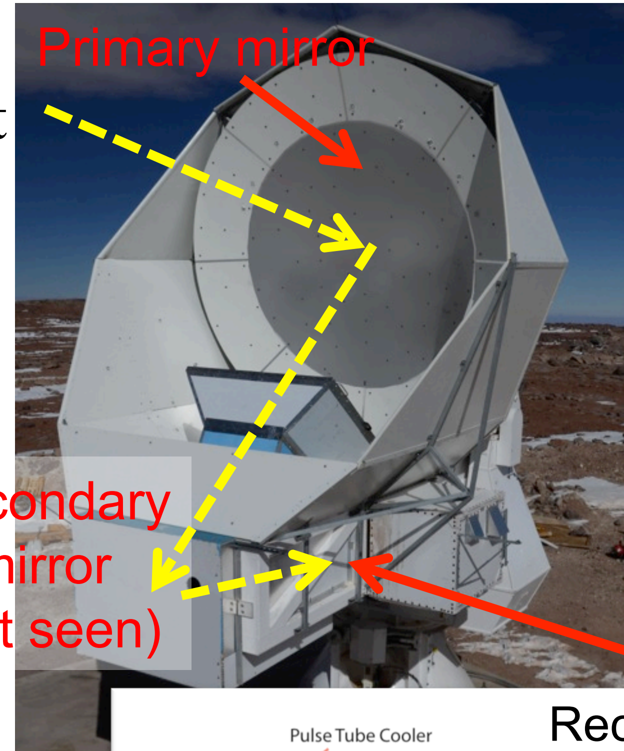
Foreground

Lensing

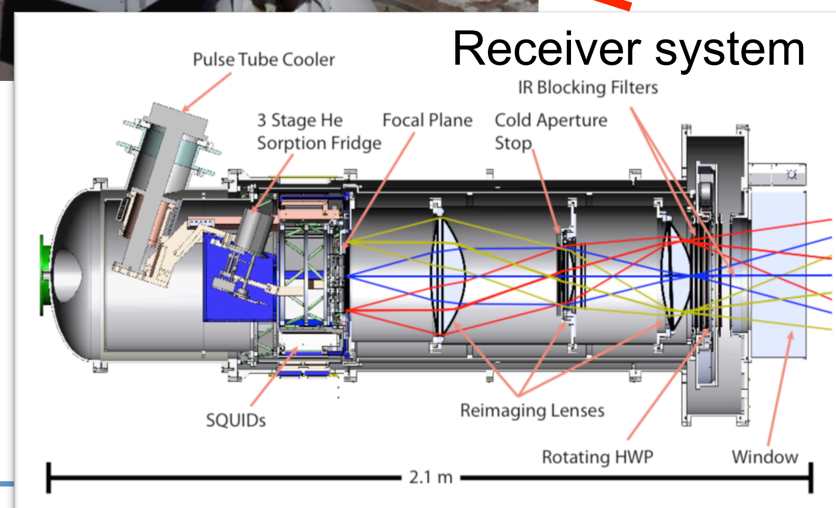
POLARBEAR

International collaboration including KEK, Kavli IPMU, UCSD, UC Berkeley from Asia Pacific regions
POLARBEAR-1 project led by UC Berkeley

- Search for inflationary B-modes to r=0.025 (95%C.L.) *and* detect gravitational lensing B-modes
- 3.5m primary mirror and large focal plane with 1274 TES bolometers
- First light in Chile in Jan. 2012 and large amount of data already recorded
- Roadmap:
  - 7588 TESes in 2014 (POLARBEAR-2)
    - r<0.01 (95%C.L.)
  - >22000 TESes in 2016(Simons Array)

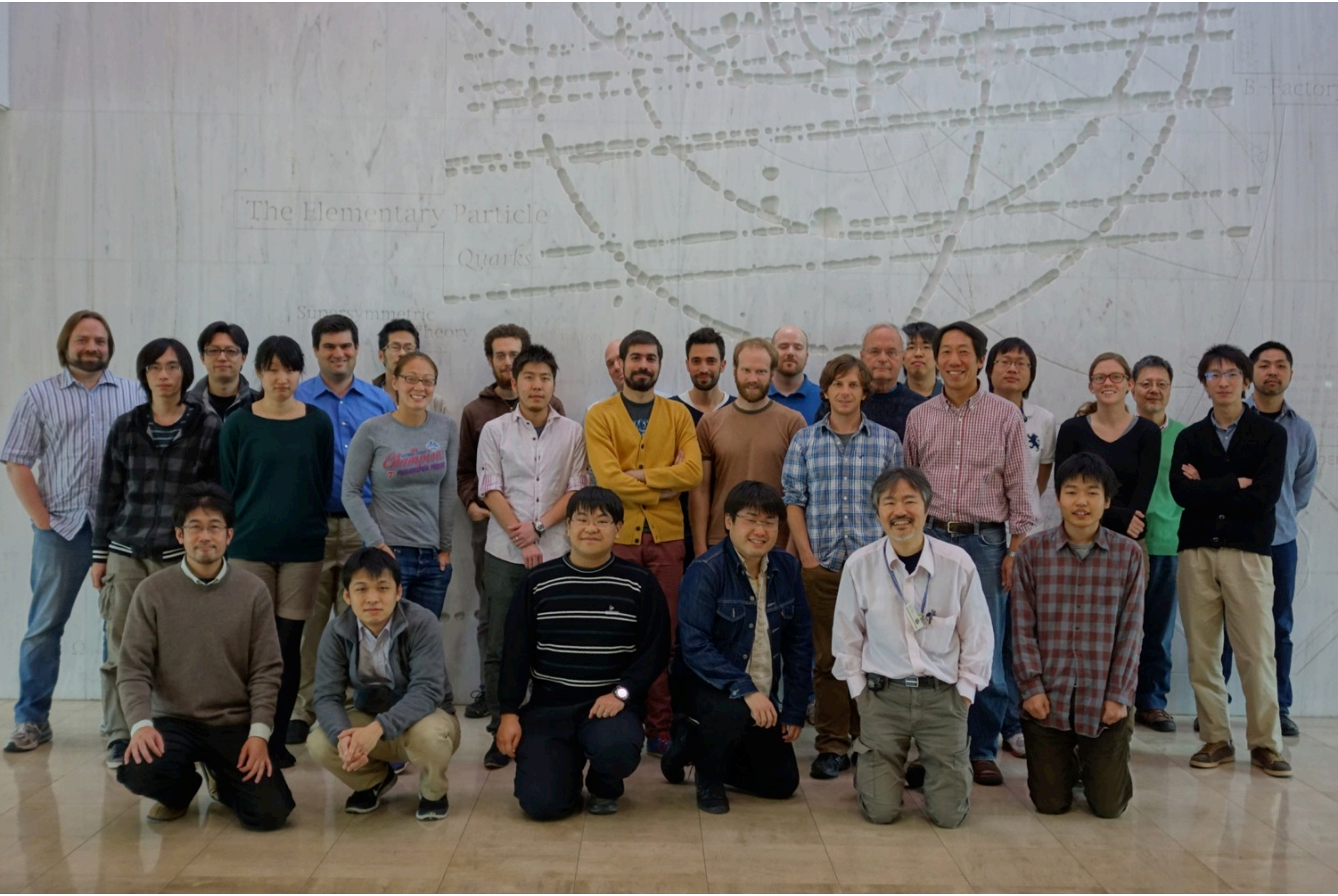


POLARBEAR Site: Atacama, Chile (5150m above sea level)

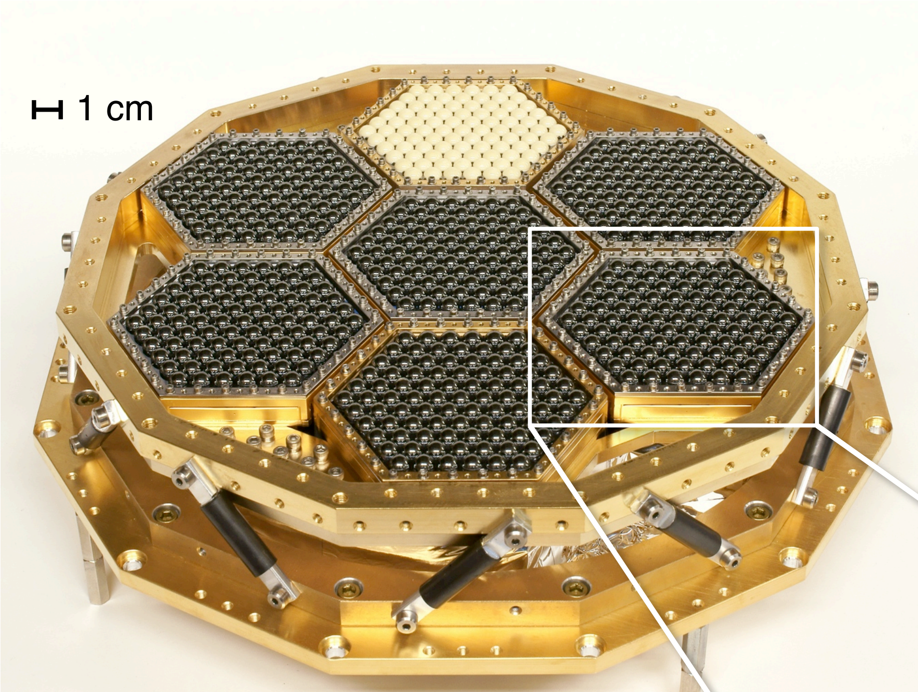


Overview

POLARBEAR Site:
Atacama, Chile
(5150m above sea level)

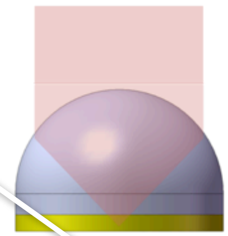

The Elementary Particle
Quarks
B Factory

POLARBEAR-1 Focal Plane

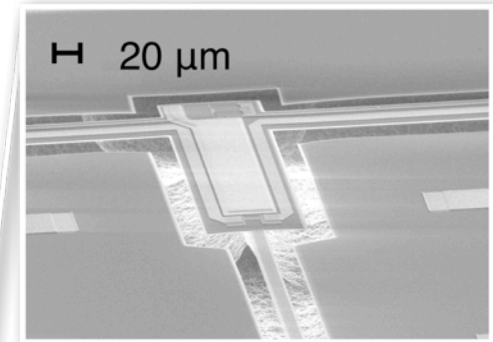


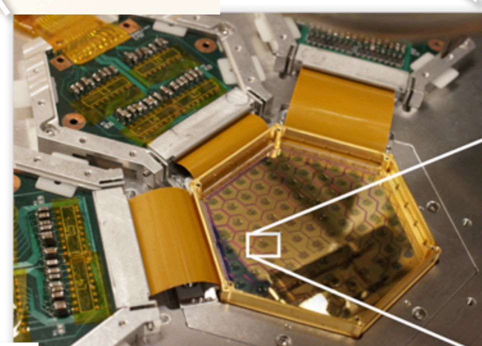
637 pixels
(91 pixels/wafer x 7 wafers)
1274 TES bolometers

Lenslet

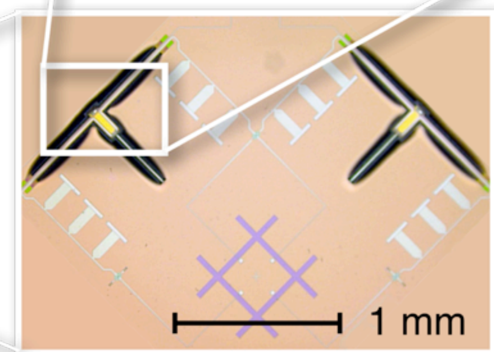


TES





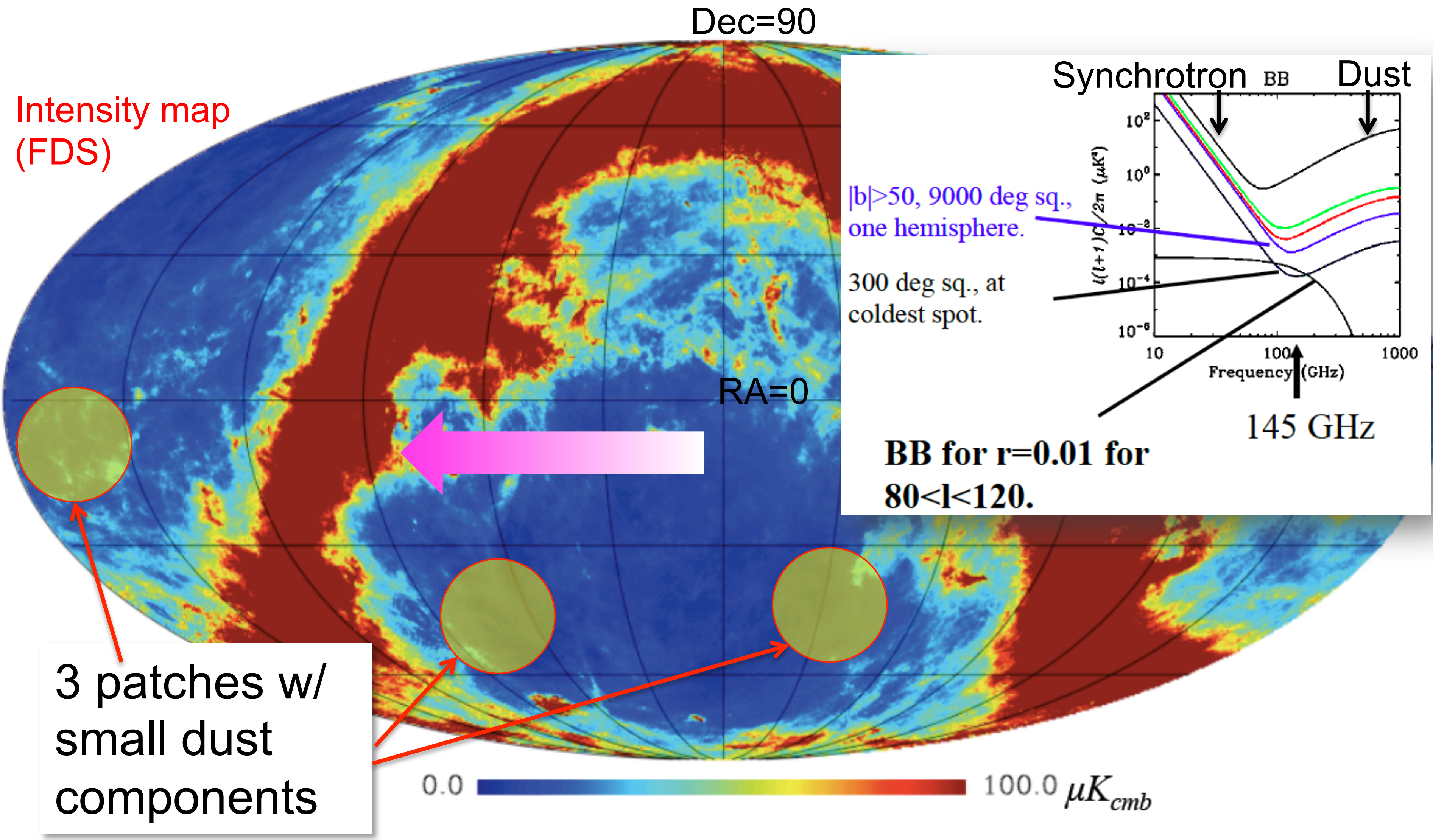
Wafer module assembly



2 TES bolometers/pixel with dual-polarization double-slot dipole antenna

21 μK√s array NET
(achieved typically during observations)

Observation (36 hour cycle)

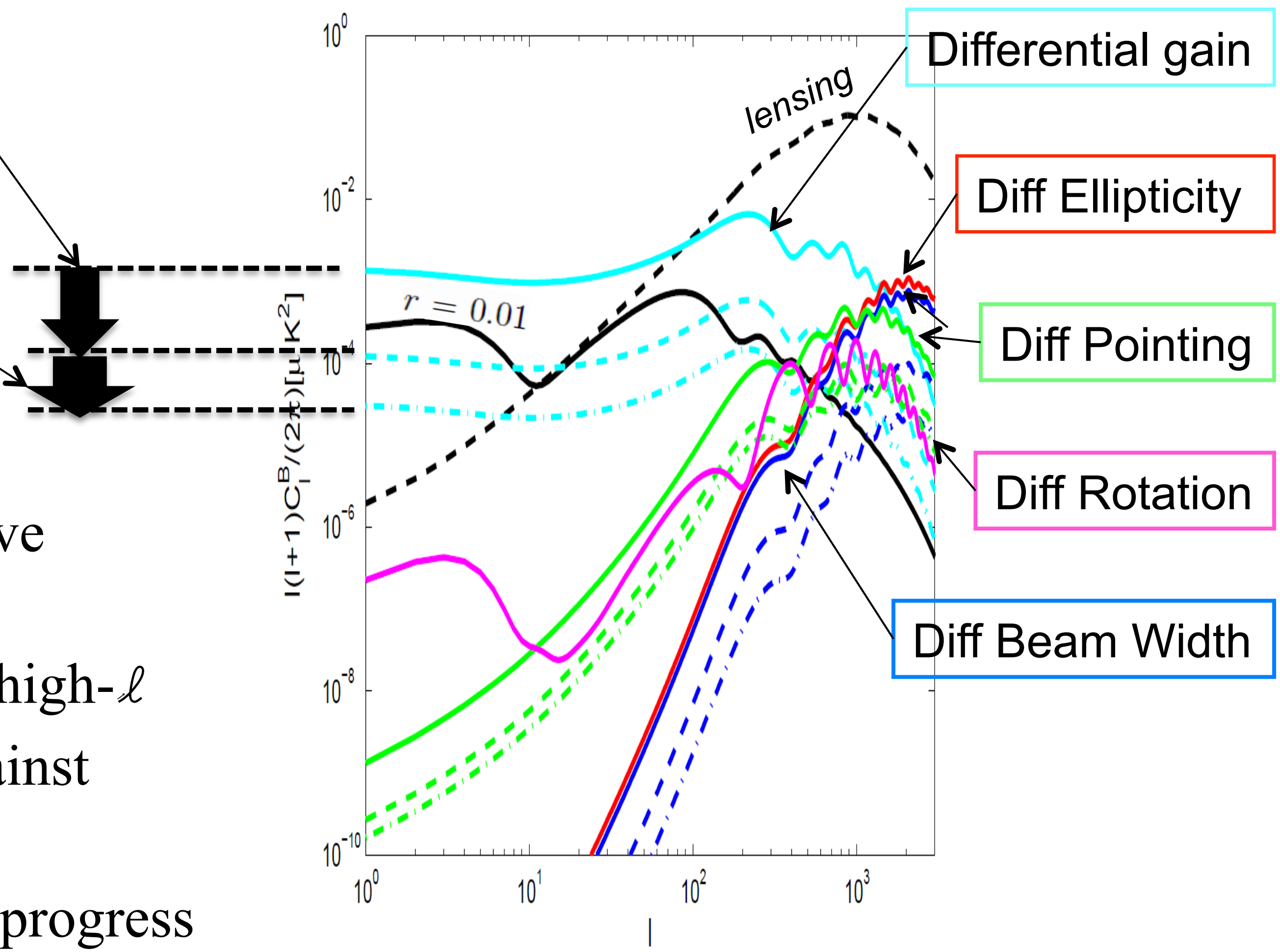


Systematic Error Mitigation

Suppression with sky rotation

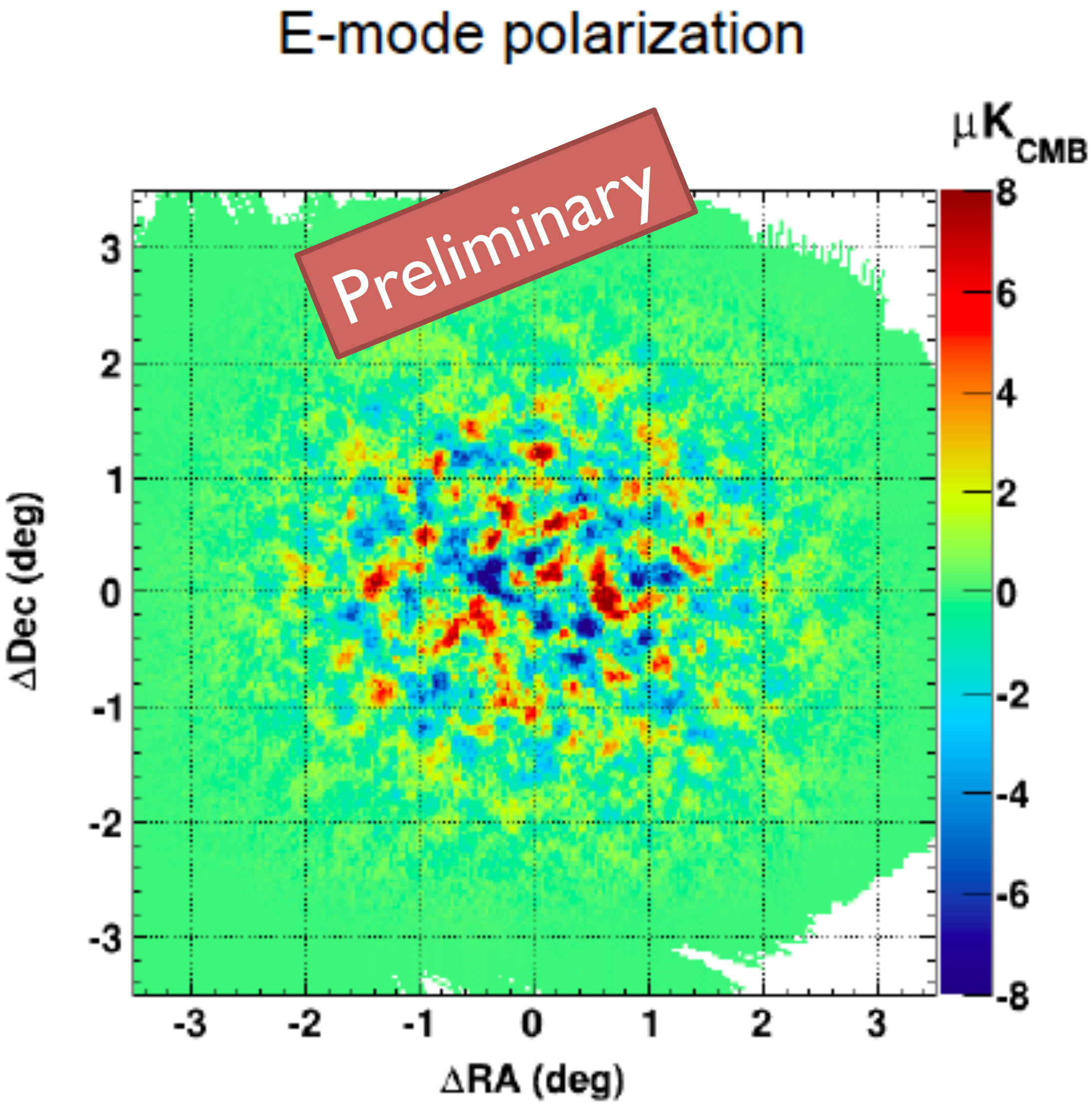
Suppression w/ stepped HWP

Beam effect forecast

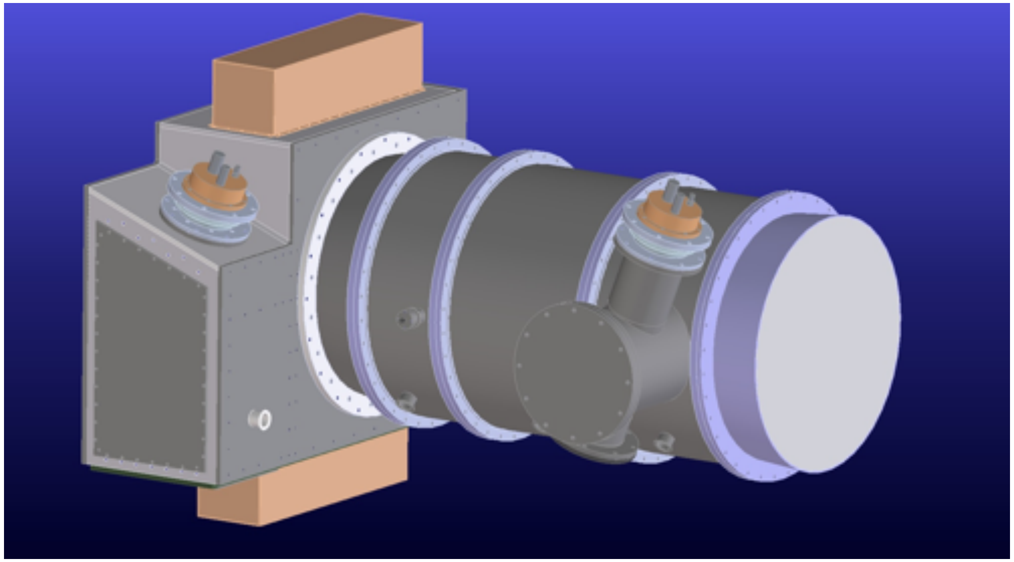


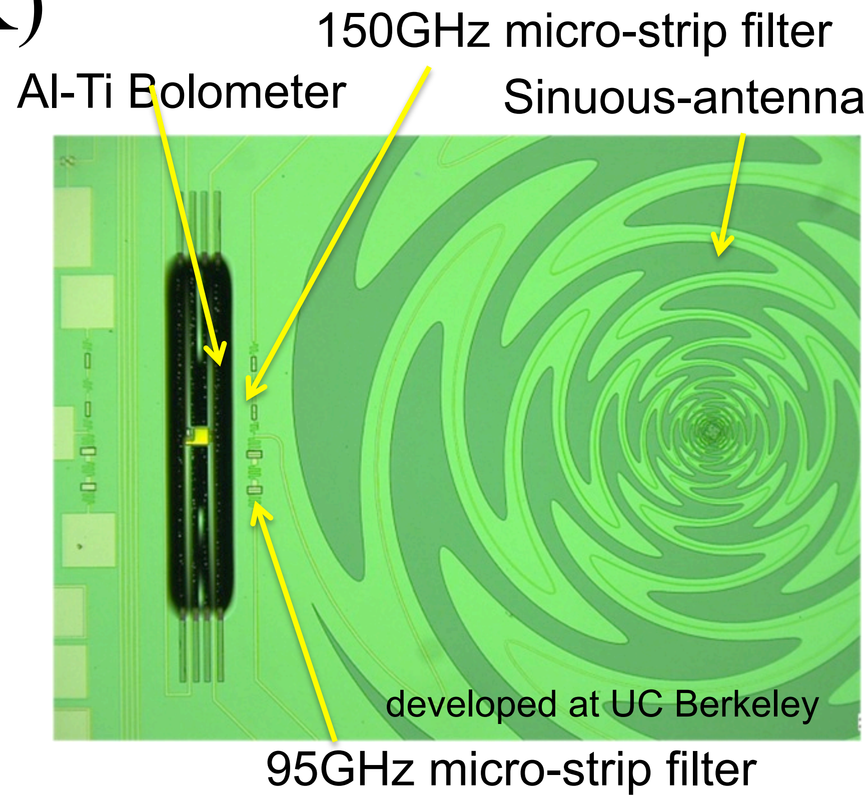
- Sky rotation is effective
- Small-enough beams → peak in leakage at high-ℓ
- Comoving shields against sidelobes
- Evaluation w/ data in progress

POLARBEAR-1 (First year of data)

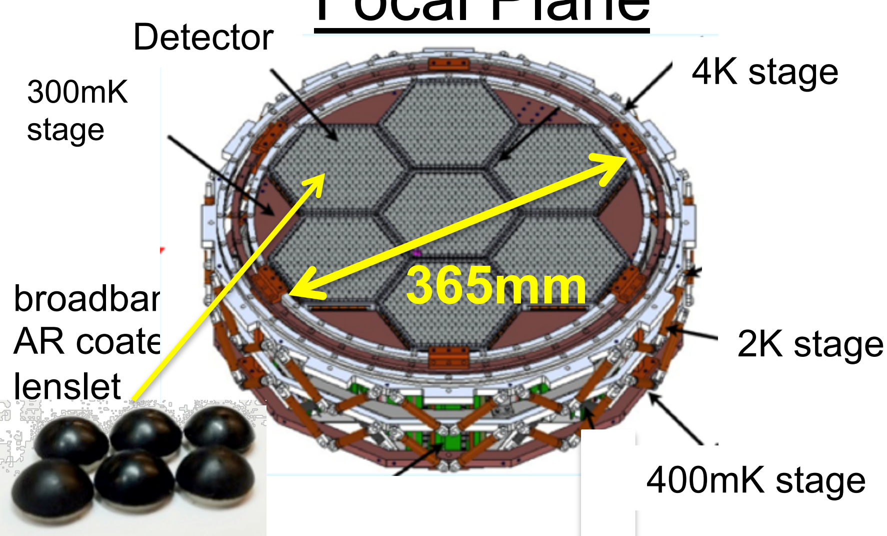


POLARBEAR-2 (led by KEK)





Focal Plane



- 7588 TES bolometers
- 95GHz and 150GHz

- r<0.01 @ 95%C.L.
- $\sigma(\Sigma m_\nu)$=65meV (w/ Planck)

Solutions

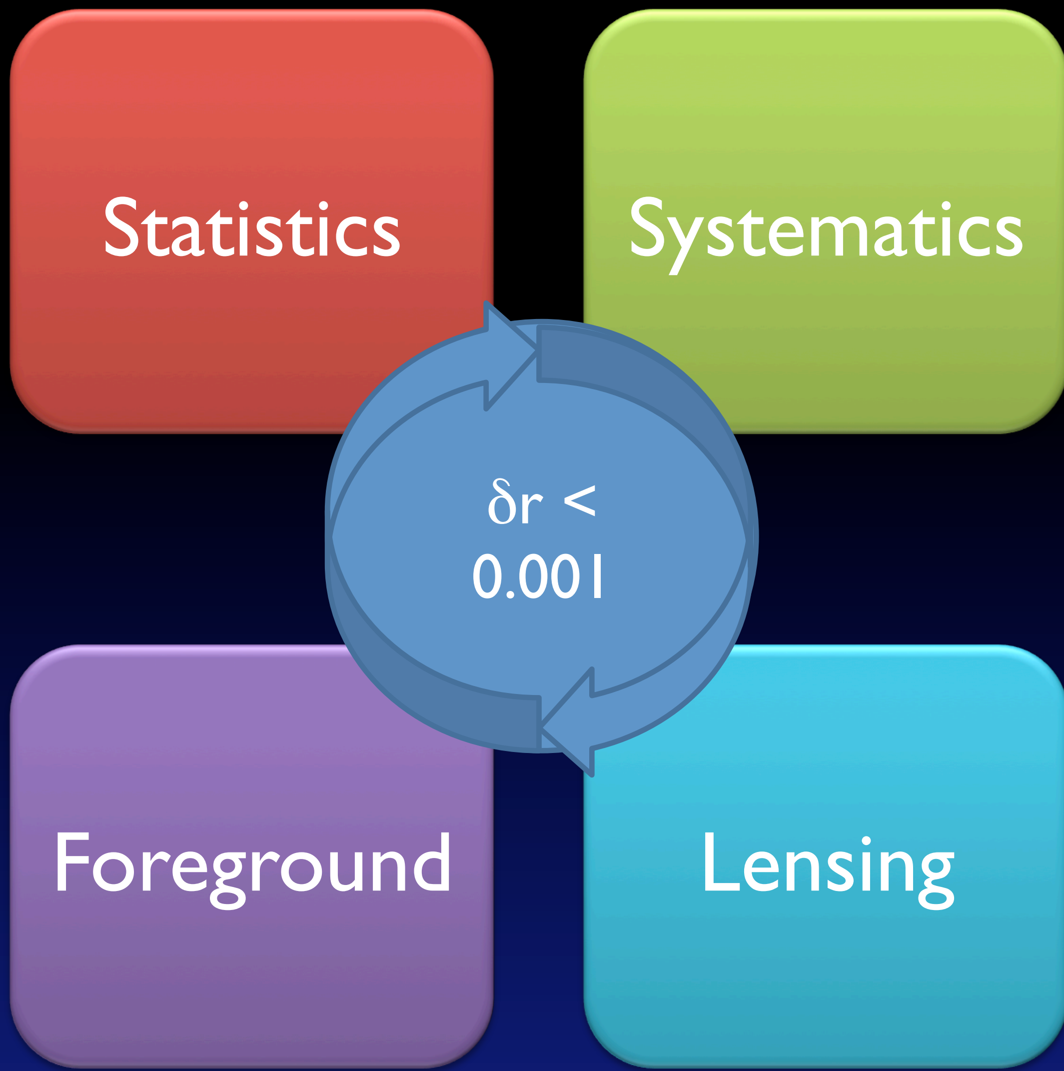
- Cryogenic Detector Array

- Gaussian beam
- Modulation
- Calibrations

- Multi-band
- Clean patches

- Delensing
- Large sky

How to reach r=0.001 ?



Satellite(s) !

- All sky → at low l, lensing is subdominant even at r=0.001
- No atmospheric fluctuation
- No limitation in observing frequency
- Long observing time

End of ground-based CMB projects in ~5 years ?

No !

CMB polarization with large telescopes (l>500 + Planck)

- Sum of neutrino masses to ~0.05ev
  - Hierarchy may be understood
- Constrain other new particles (e.g. gravitinos)
- (Early) dark energy
- Modified gravity

Dish size: 3.5m → 6m → 10m

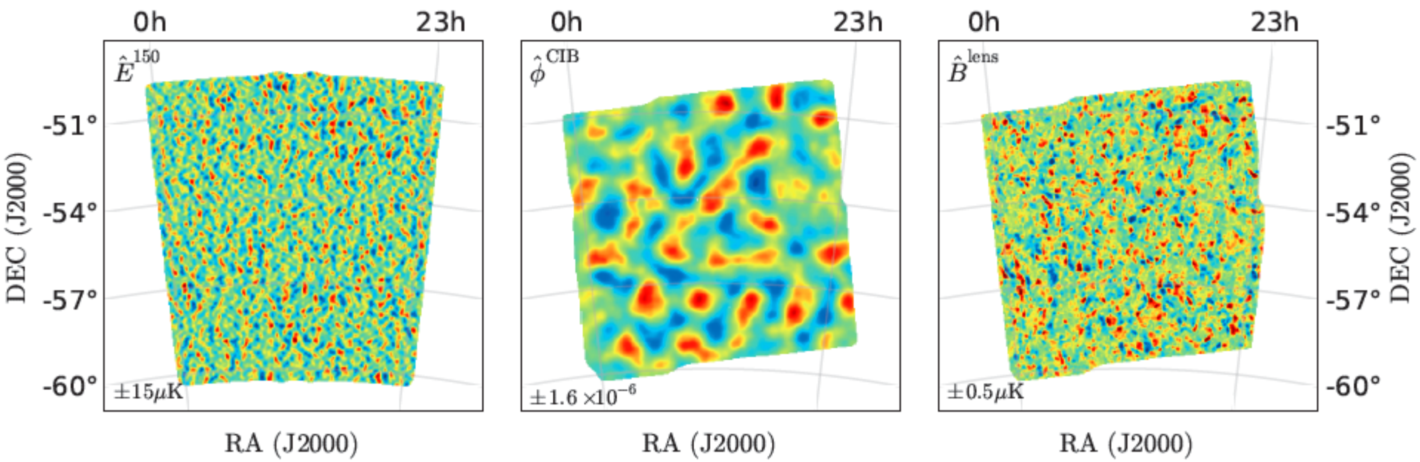
# of detectors: 1000 → 10000

3.5m	6m	10m
POLARBEAR POLARBEAR-2 Simons Array	ACTpol Advanced-ACTpol	SPTpol SPT3G

Discovery of lensing B-mode could be at any time soon
High precision neutrino mass results in a few years

Lensing B-mode Discovery by SPTPol

arXiv:1307.5830



South Pole Telescope (SPT)

E map from SPTPol 150GHz

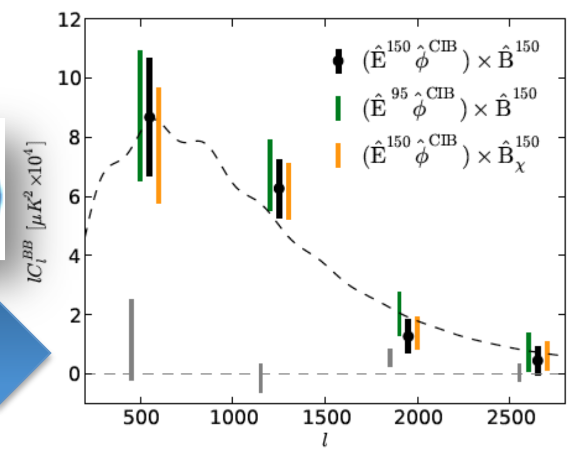
Lensing potential "ϕ" from Herschel 500μm

Reconstructed B map, or "Eϕ"

$$\text{“E}\phi\text{”} = B^{\rm lens}(\vec{l}_B) = \int d^2\vec{l}_E \int d^2\vec{l}_\phi W^\phi(\vec{l}_E, \vec{l}_B, \vec{l}_\phi) E(\vec{l}_E)\phi(\vec{l}_\phi)$$

Correlation b/w B map from SPTPol ("B") and reconstructed B map ("Eϕ") examined

Eϕ x B



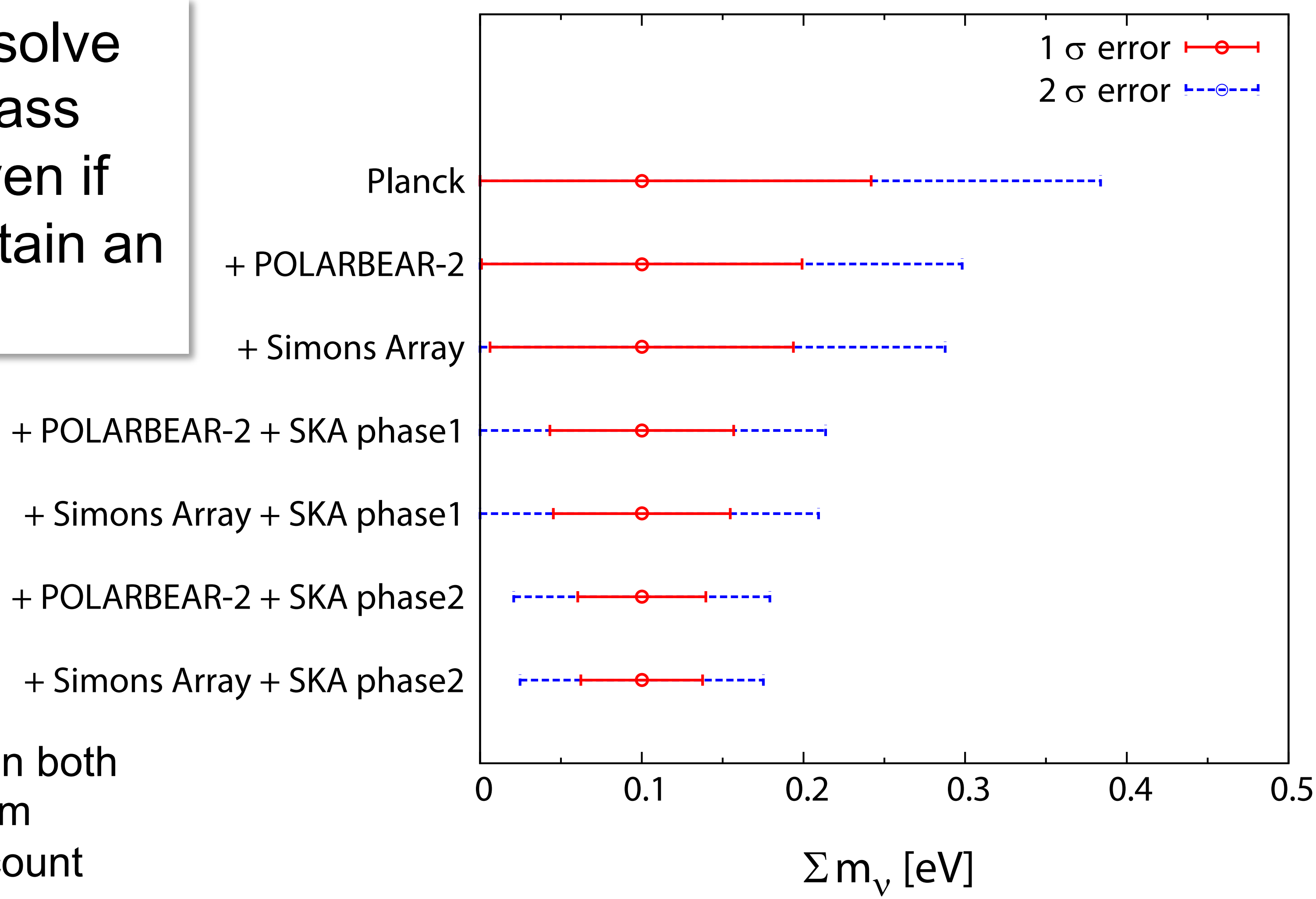
7.7σ (EϕxB and EBxϕ combined)

Next Step

- Cl_BB from CMB data alone is the next big step
  - The discovery will truly open up the new era of cosmology with lensing B-mode.
  - The discovery will give us promise for precision B-mode measurements toward r=0.01.

Synergy w/ 21cm

Hope to resolve neutrino mass hierarcy even if we only obtain an upper limit

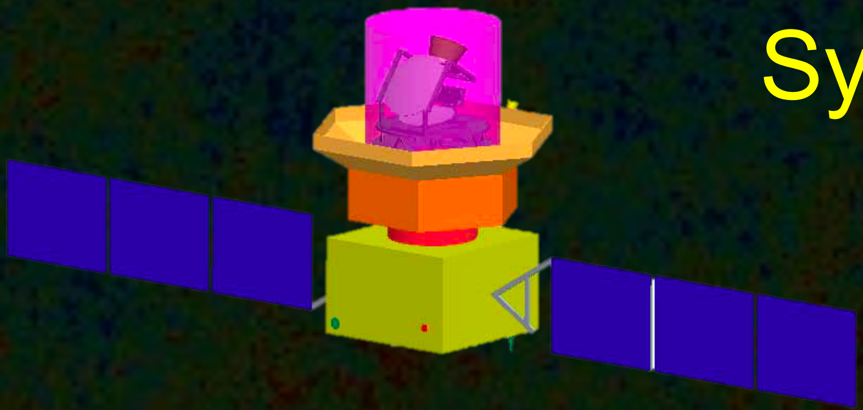


Foregrounds in both CMB and 21cm taken into account

Oyama, Kohri and Hazumi (2013) in preparation

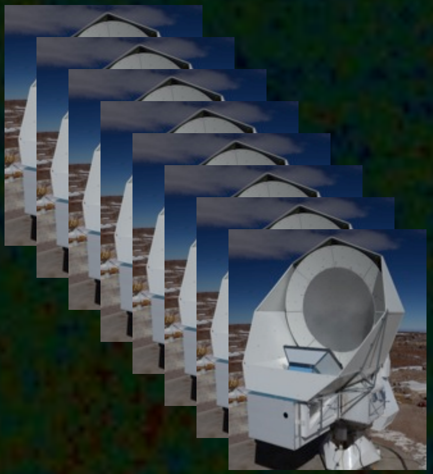
3. LiteBIRD Era

Strategy



Synergy

X



Small Satellite for ultimate meas. of r ($\delta r<0.001$)

Super telescope array on ground
$40 < l < 3000 \sim 10000$

Powerful Duo

LiteBIRD mission

- Check representative inflationary models
  - ***requirement on the uncertainty on r***

    (stat. ⊕ **syst.** ⊕ **foreground** ⊕ **lensing**) **$\delta r < 0.001$**

No lose theorem of LiteBIRD

- ➢ Many inflationary models predict r>0.01 → >10sigma discovery
- ➢ Representative inflationary models (single-large-field slow-roll models) have a lower bound on r, r>0.002, from Lyth relation.

$$r = \frac{1}{N^2}\left(\frac{\Delta\phi}{m_{\rm pl}}\right)^2 \approx 2\cdot 10^{-3}\left(\frac{\Delta\phi}{m_{\rm pl}}\right)^2$$

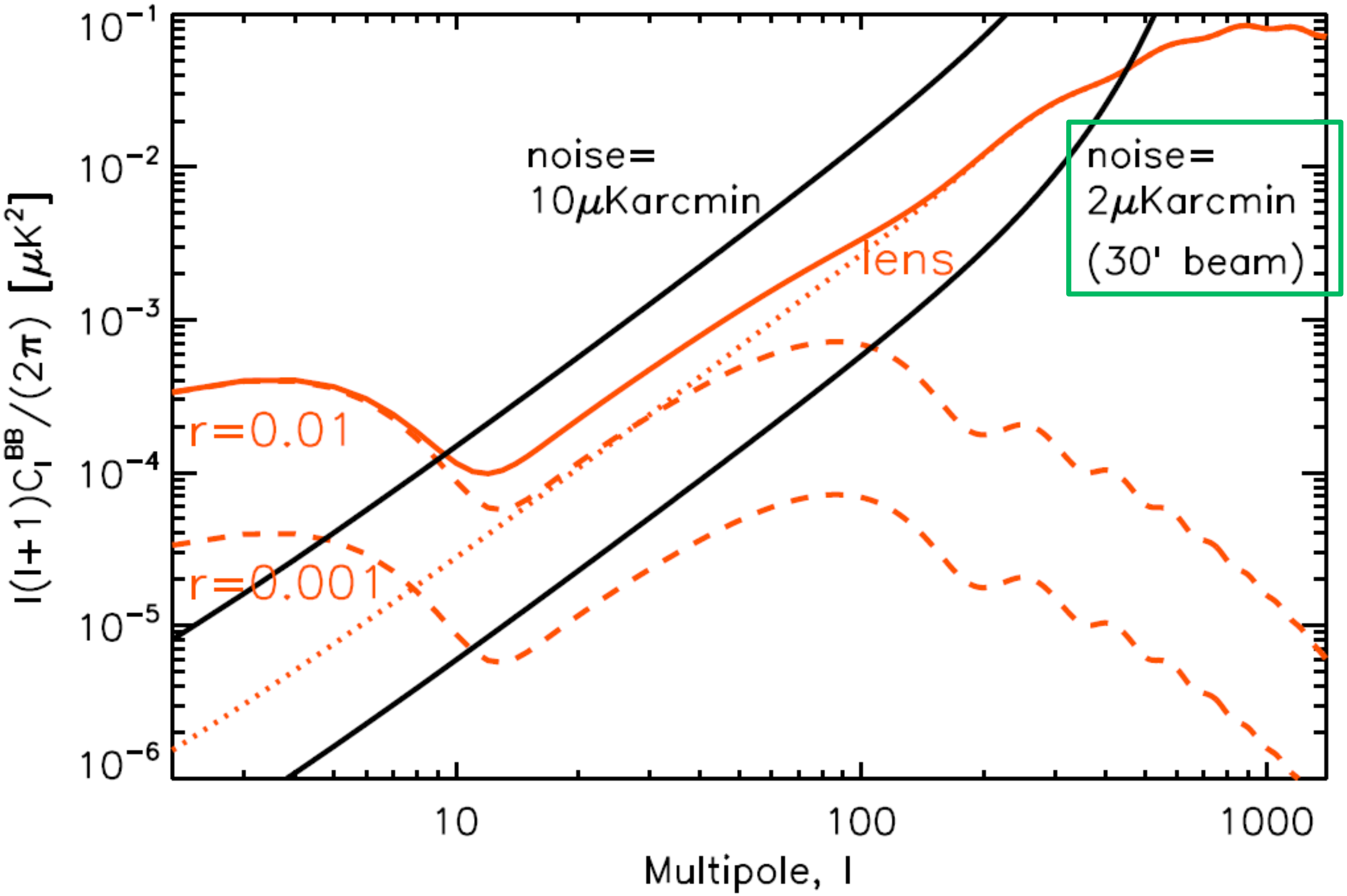
  - ➢ no gravitational wave detection at LiteBIRD → exclude representative inflationary models (i.e. r<0.002 @ 95% C.L.)
- ➢ Early indication from non-space-based projects → power spectra at LiteBIRD !

Similar to LHC Higgs case (Occam's razor)

Focal plane requirement

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

To be well below "lensing floor"



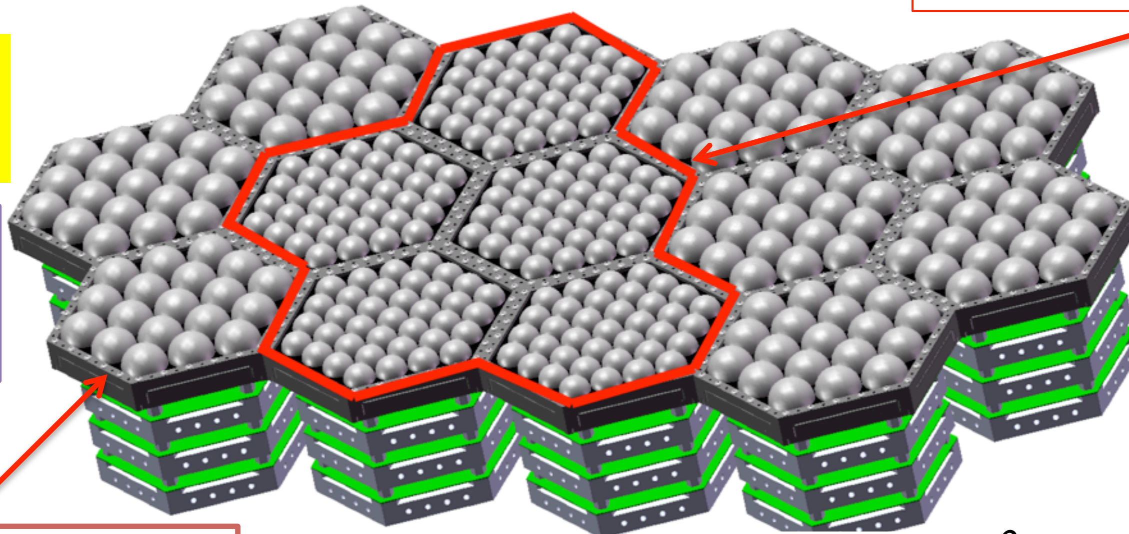
LiteBIRD focal plane design

UC Berkeley TES option

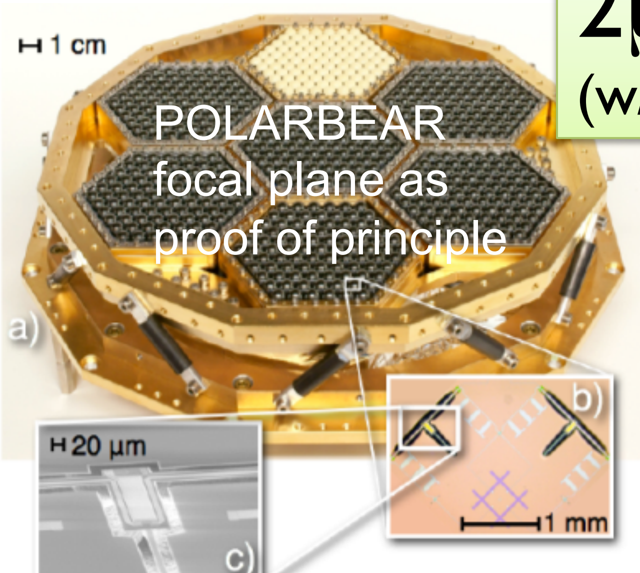
2022 TES bolometers

T_{bath} = 100mK

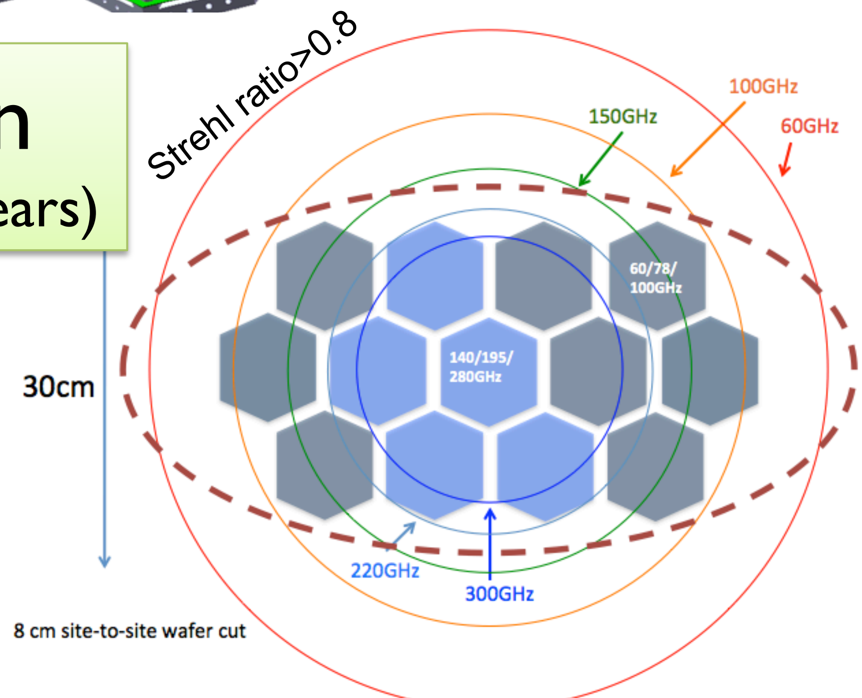
tri-chroic (140/195/280GHz)



tri-chroic (60/78/100GHz)



2μKarcmin
(w/ 2 effective years)



LiteBIRD focal plane design

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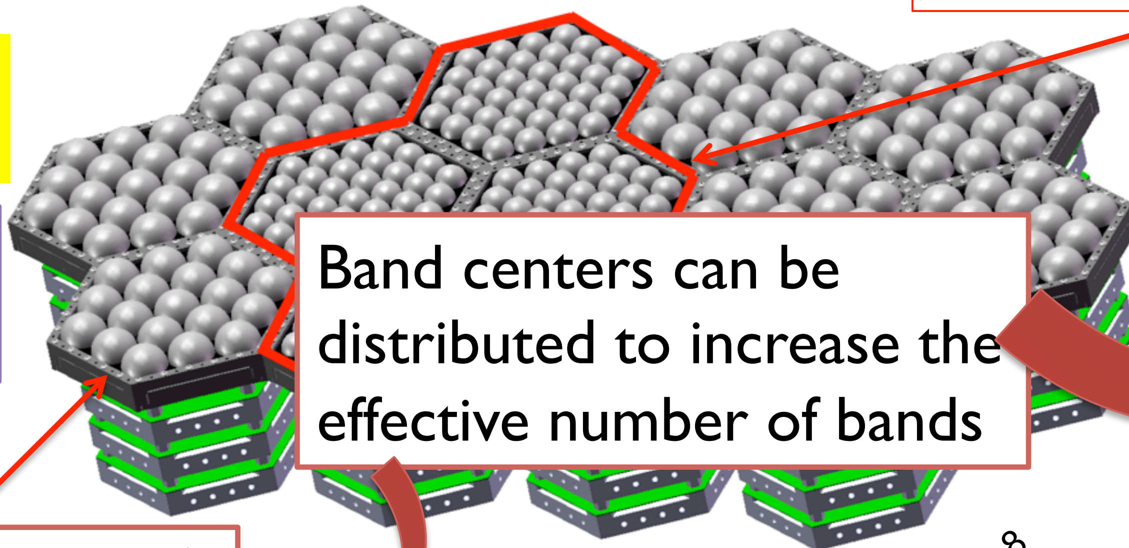
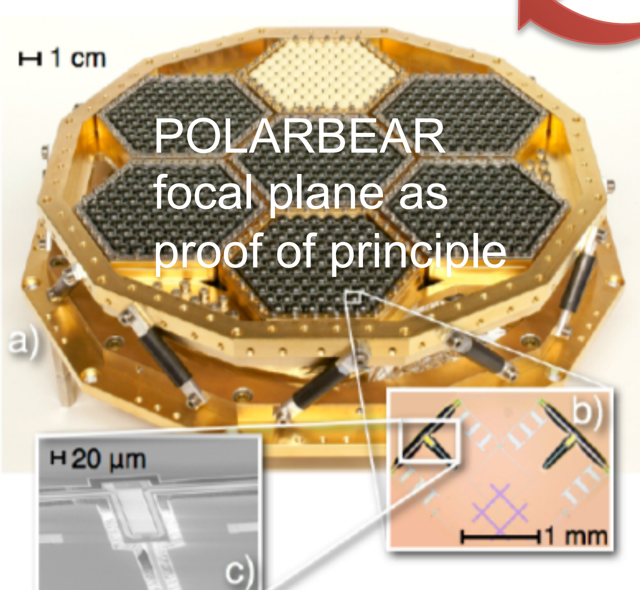
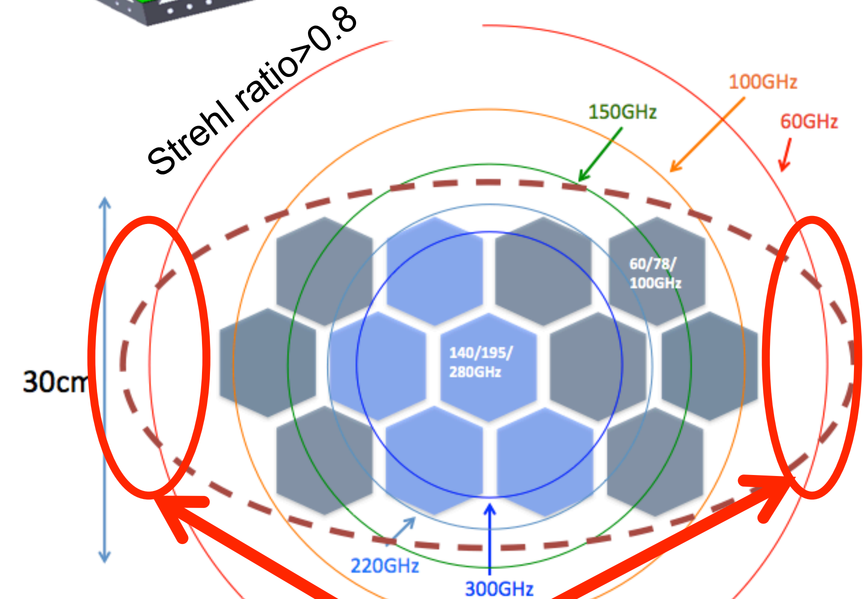


Band centers can be distributed to increase the effective number of bands

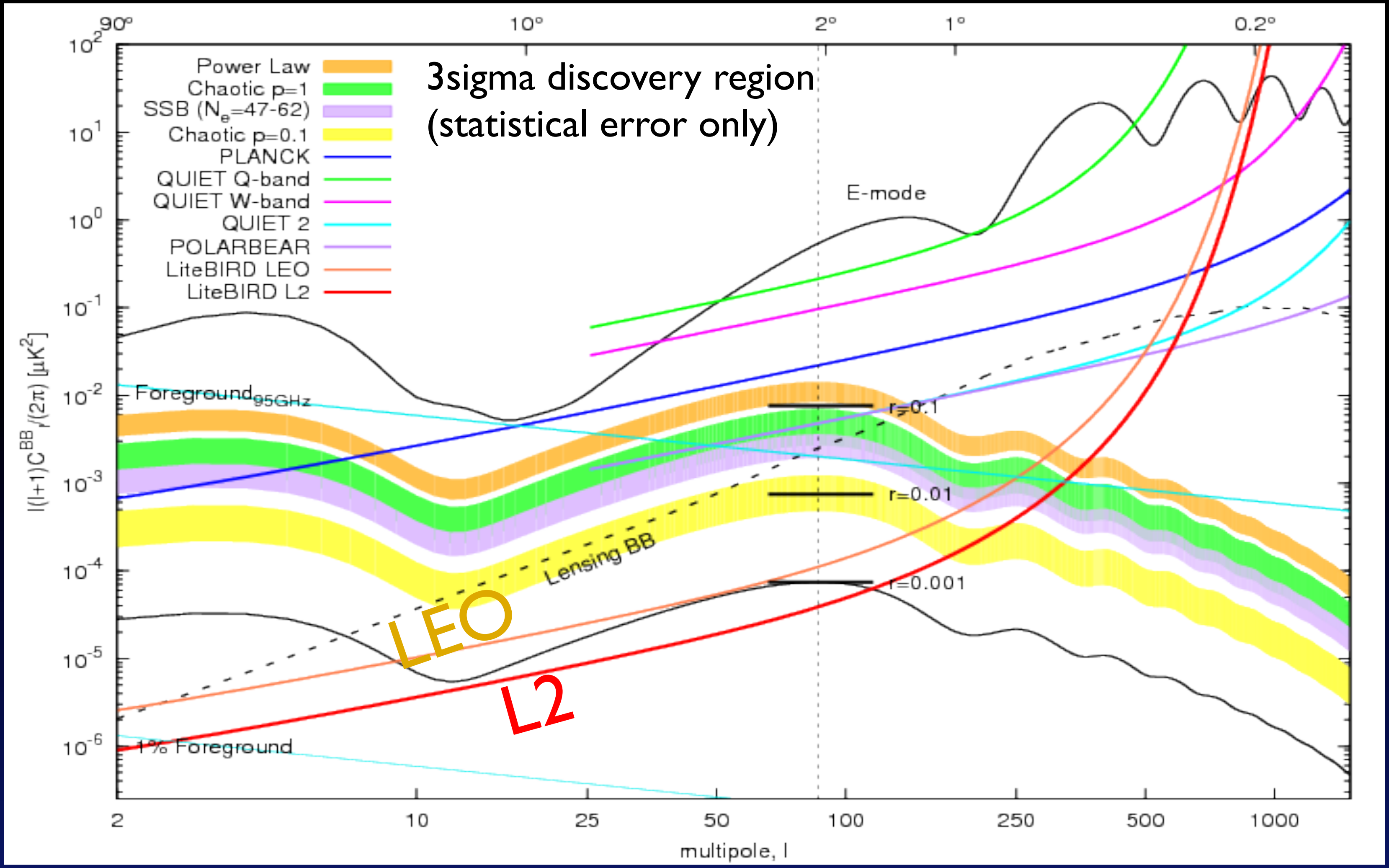
tri-chroic（60/78/100GHz）





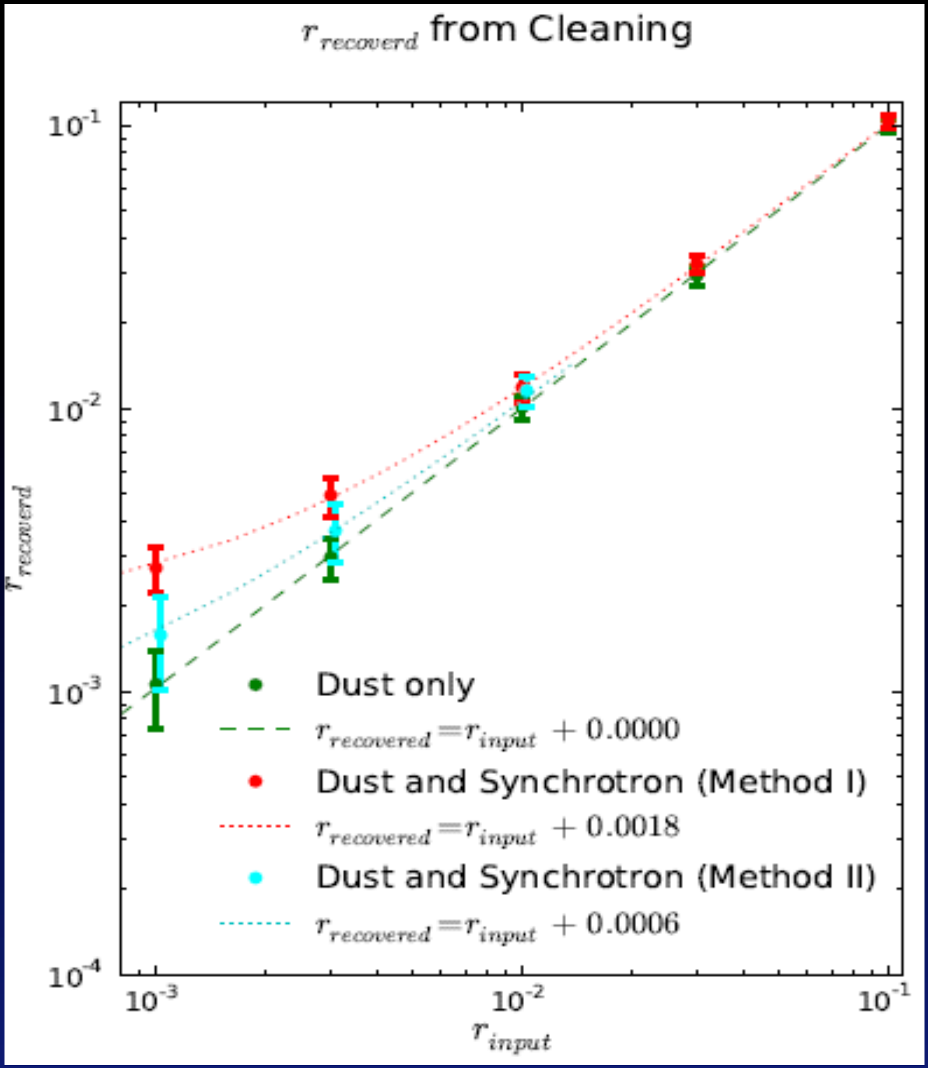
More space to place <60GHz detectors

L2 vs. LEO



Both cases satisfy the requirement on statistical error

Foreground removal and observing bands



- Foreground removal
  → ≥4 bands in 50-270GHz

N. Katayama and E. Komatsu, ApJ 737, 78 (2011) **(arXiv:1101.5210)**

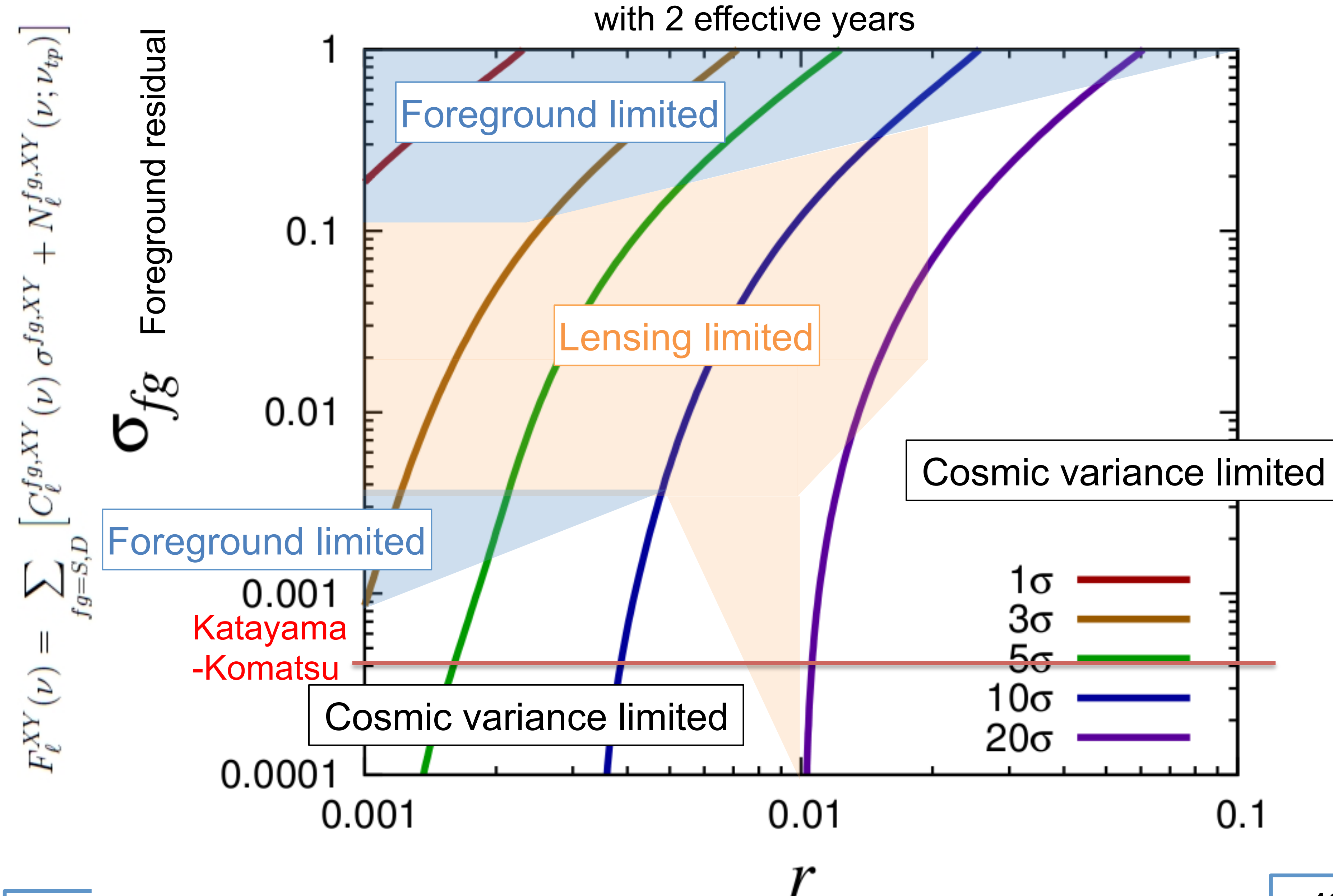
pixel-based polarized foreground removal **(model-independent)**

very small bias

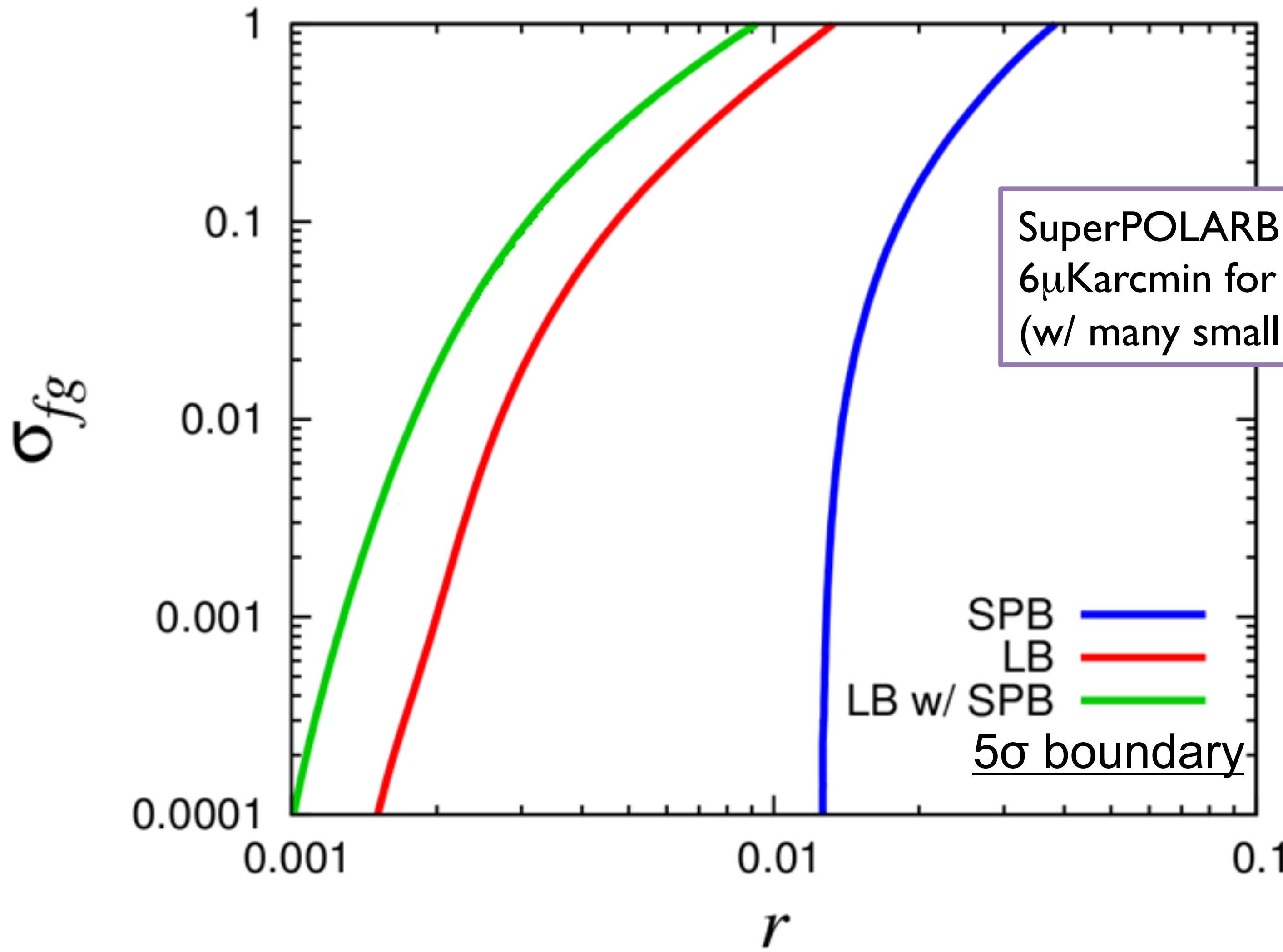
r~0.0006

with 60,100,240GHz (3 bands)

Expected sensitivity on r



Delensing with SuperPOLARBEAR



SuperPOLARBEAR assumes 6μKarcmin for f_sky = 0.75 (w/ many small patches)

Other scientific objectives

- Tensor tilt (n_t): $\delta n_t \sim 0.07$ (@r=0.1)
- Other non-standard cosmology with BB, EB, EE
    - Tests of superstring theory (e.g. non-zero Cl_EB)
    - Power spectra deviation from standard cosmology
        - Loop quantum gravity ? Primordial magnetic field ? Cosmic strings ?
    - Isocurvature
    - Non Gaussianity
    - etc.

No dedicated studies so far
You are welcome to contribute !

- Astronomy
    - Reionization w/ EE, TE correlations
    - Galactic magnetic field
    - Galactic haze emission

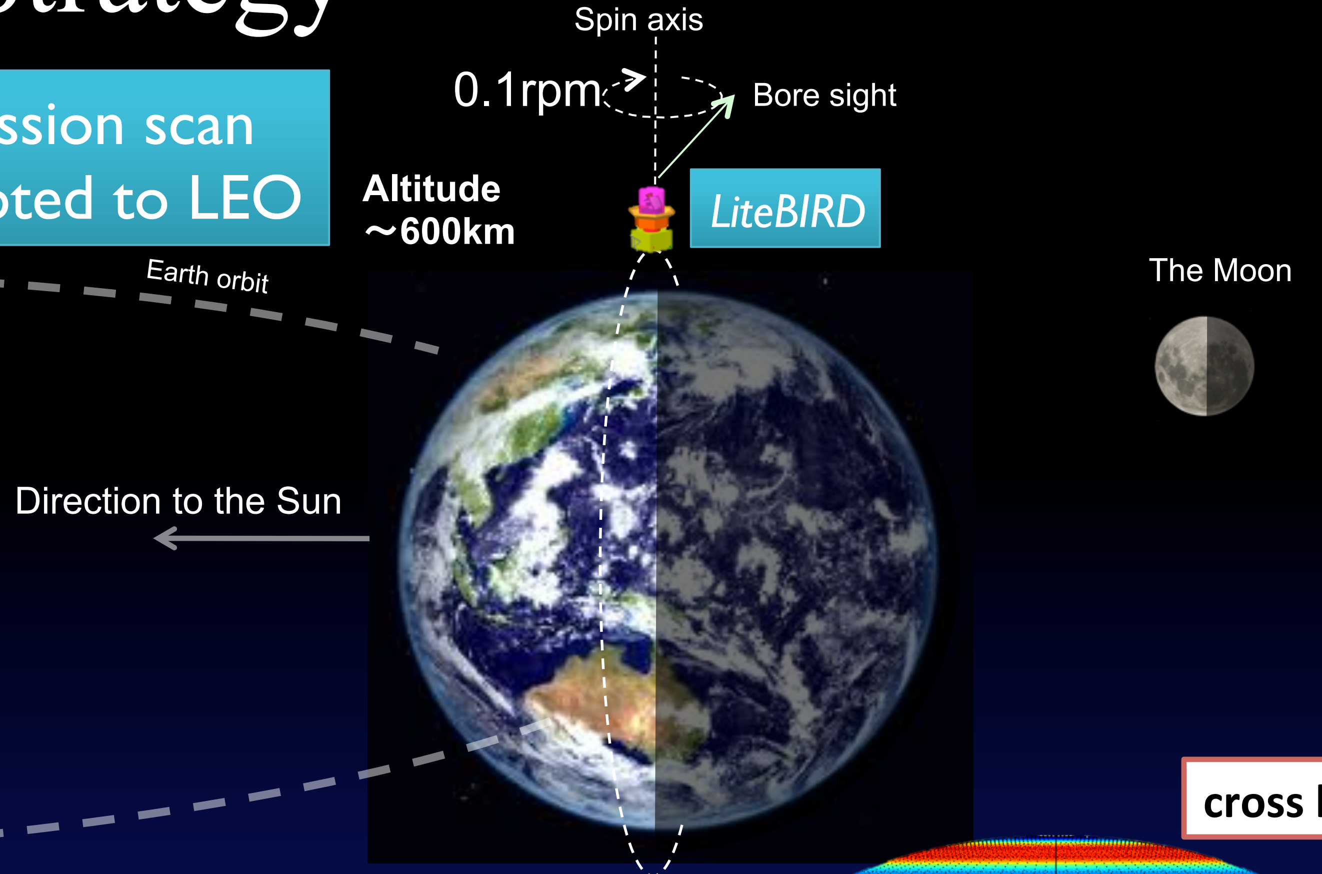
Systematic effect requirements

We set the required level of each systematic effect as 1% of lensing floor in C_l at all l range.

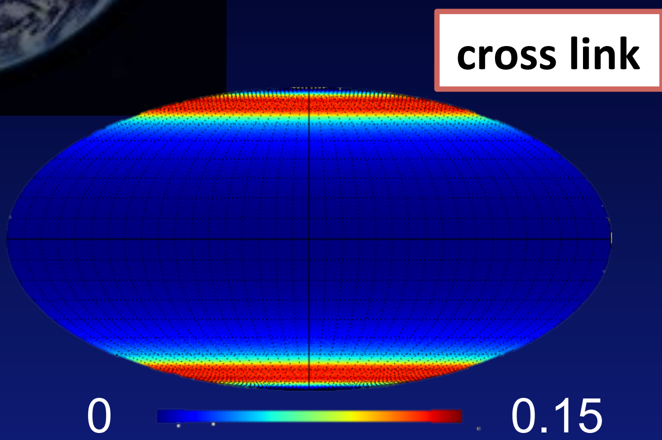
Effects	Types	Requirement (bias)	Requirement (random)	Comments	Mitigation
Absolute gain	$E \rightarrow B$	Cancel on r	3%	Calibration in every 10 min.	Dipole, planets
Polarization angle	$E \rightarrow B$	1 arcmin.	24 arcmin.		
Beam size stability	$E \rightarrow B$		O(10%)		Scan strategy
Absolute pointing	$E \rightarrow B$	6 arcmin.	25 arcmin.	20degx30deg FOV	Scan strategy
Diff. pointing	$T \rightarrow B$	5 arcsec.	16 arcsec.		Continuous HWP
Diff. gain	$T \rightarrow B$	0.01%	0.3%		Continuous HWP
Diff. beam size	$T \rightarrow B$	0.7%	2%		Continuous HWP
Diff. beam ellipticity	$T \rightarrow B$	7% @l=2 0.04% @ l=300	2.7 %		Continuous HWP

Scan Strategy

Spin & precession scan strategy adapted to LEO

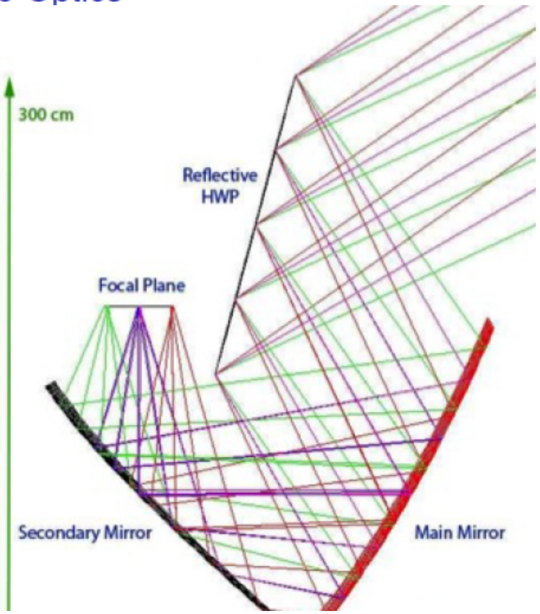


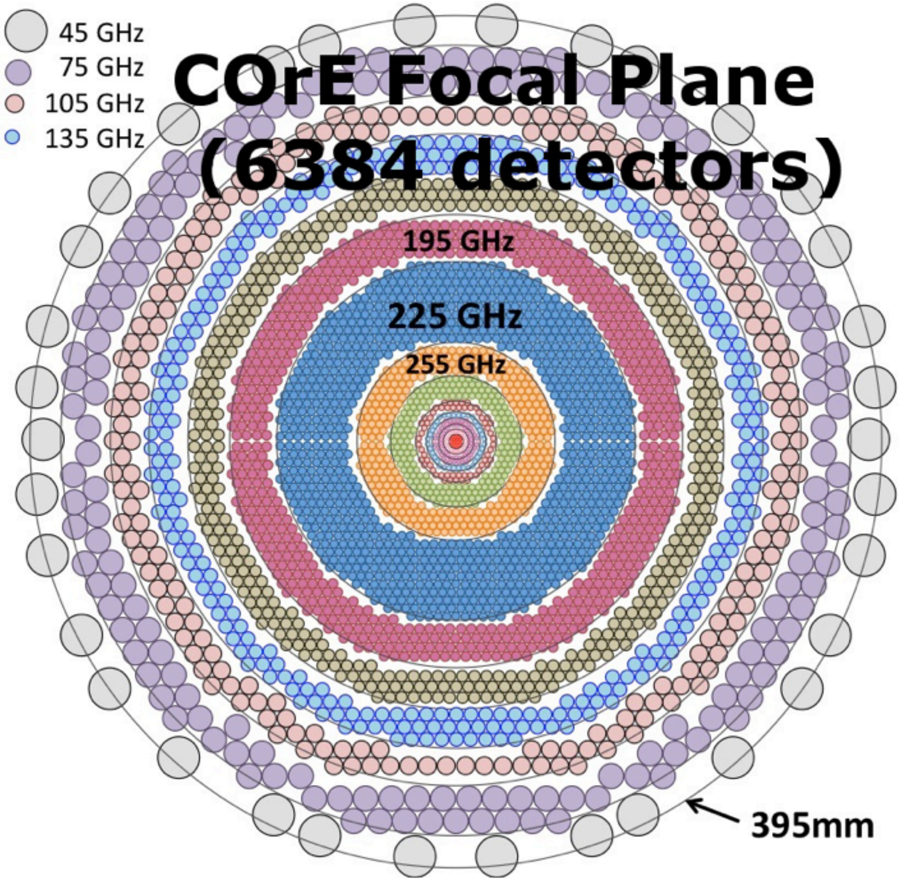
Uniformity and cross link as good as the case for L2

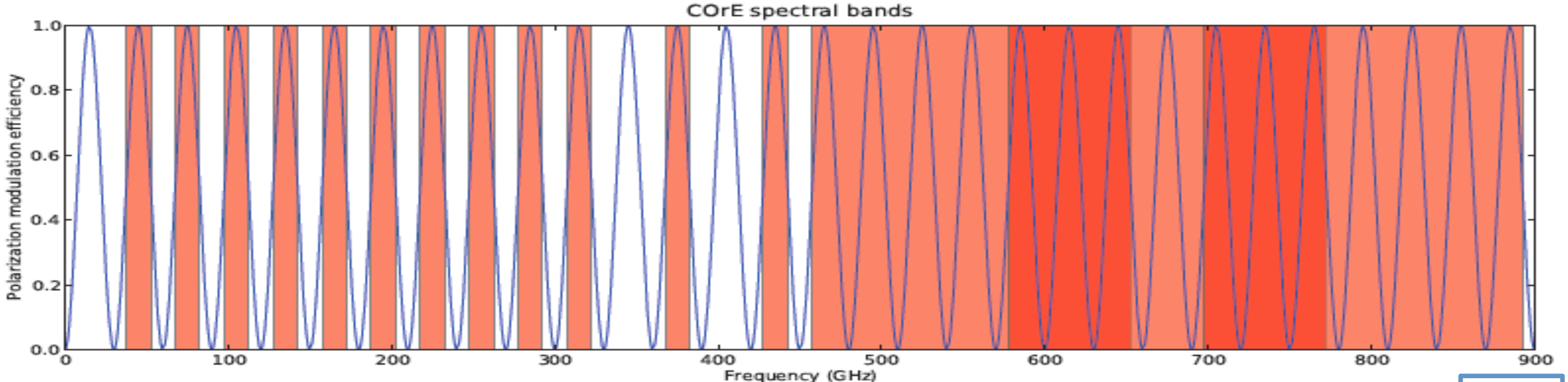


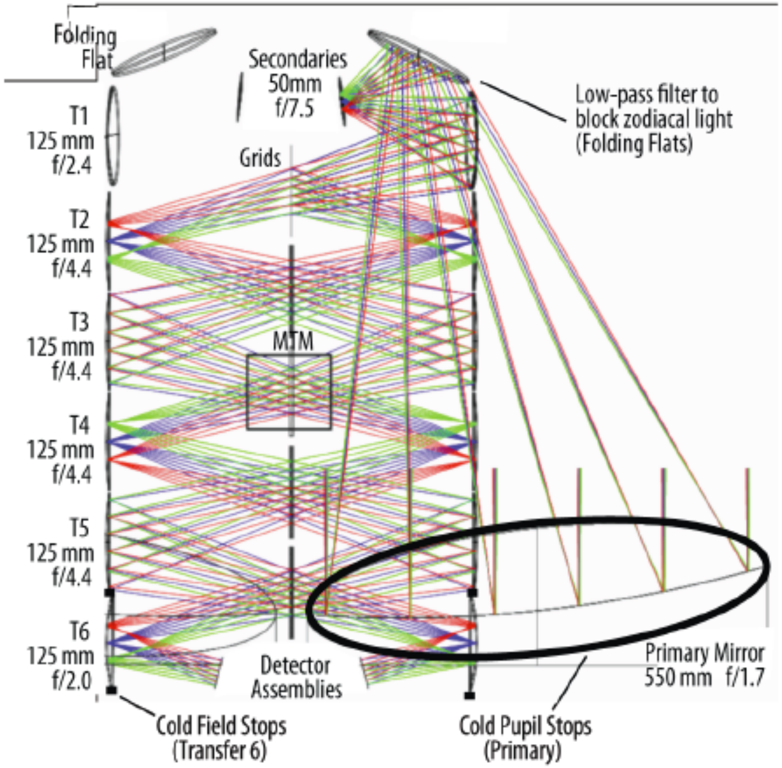
COrE (ESA)

Core Optics

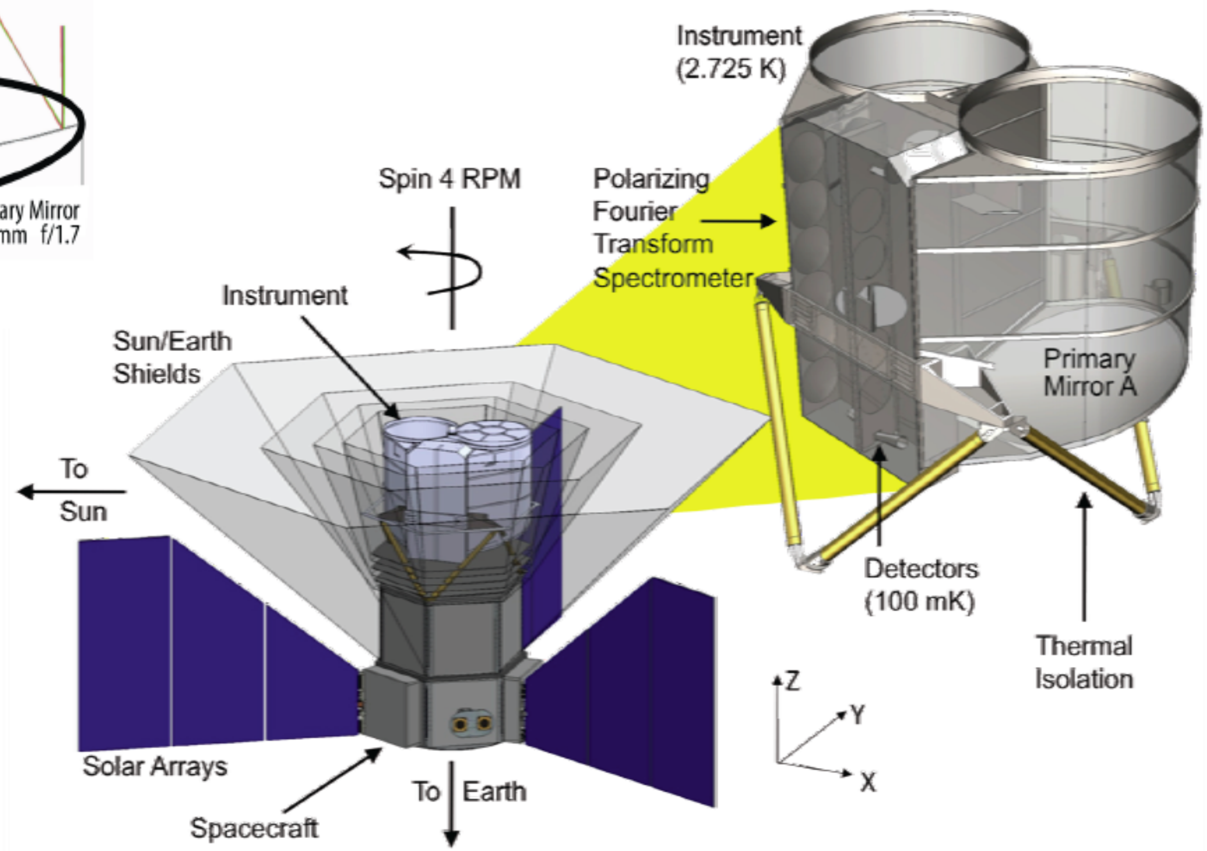








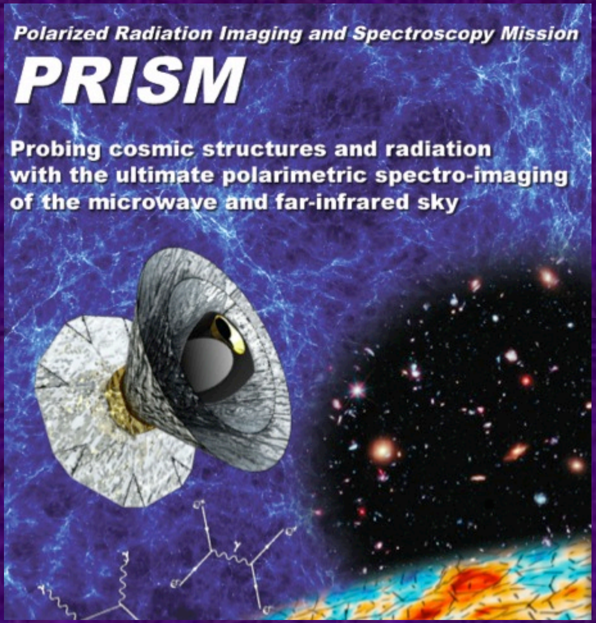
- Just 4 detectors !
- Multi-mode
- FTS
- 30GHz ~ 6THz



PIXIE

(NASA)

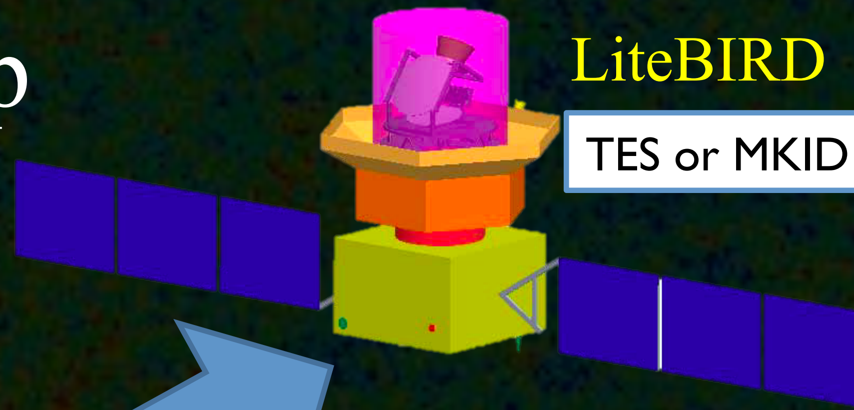
4. Post-LiteBIRD Era



- Large mission in ~2030
  - European proposal: PRISM
- CMB-alone will not be enough
  → Synergy w/ other measurements will be crucial
- Measurements of nt and slow-roll consistency !
  - CMB + 21cm + pulsar timing + Space interferometer (such as Ultimate DECIGO)
  - Understanding of systematic errors and foregrounds in each measurements will decide the game

We have a lot to do next 100 years ☺

5. Conclusion
LiteBIRD Roadmap

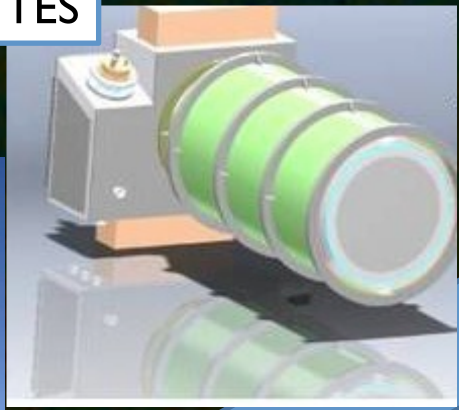


LiteBIRD

TES or MKID

POLARBEAR-2

TES



POLARBEAR

TES

GroundBIRD

MKID

- Ground-based projects as important steps
  - Verification of key technologies
  - Good scientific results
- International projects

5. Conclusions

- We are at the dawn of the new era of "cosmology with CMB polarization"
  - Big discovery "r>0" awaits us !
  - Neutrino masses to ~0.05ev
  - And more (dark energy, new particles, etc.)
- Many new results will come in next ~5 years
  - r ~ 0.01
- Studies with future satellites are MUST, regardless of the value of r
  - r ~ 0.001 from LiteBIRD

CMB polarization measurements are exciting !