B is for BIRD

Nobu Katayama
IPNS, KEK

July 13, 2010

IPMU seminar

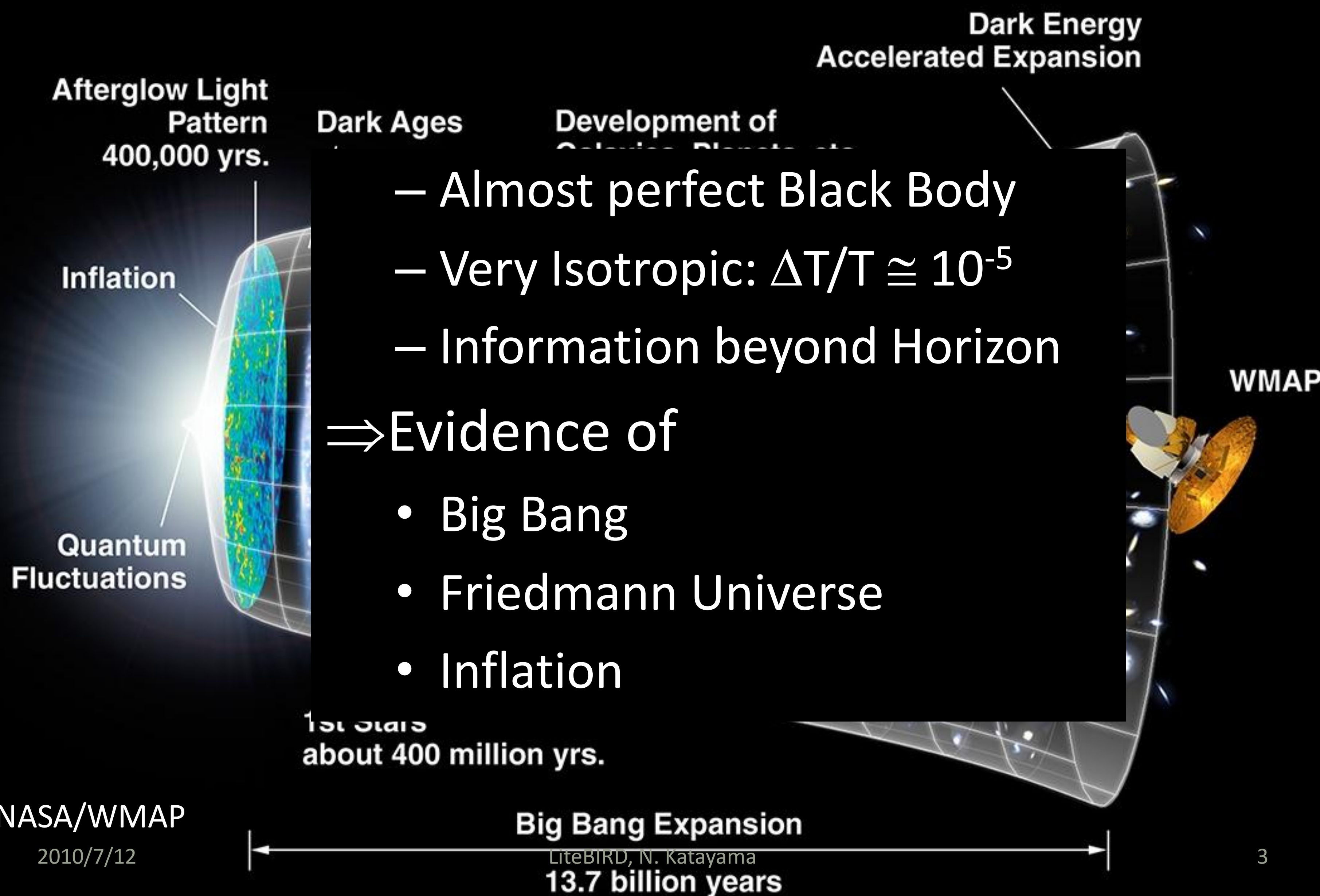
Outline

- Introduction
  - CMB Science
- Feasibility studies for LiteBIRD
  - Simple foreground removal (E. Komatsu/nk)
- LiteBIRD project

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

  - Conceptual design
  - Detector, Optics, cooling, scan

CMB is the fossil light from the Big Bang



- – Almost perfect Black Body
- – Very Isotropic: $\Delta T/T \cong 10^{-5}$
- – Information beyond Horizon

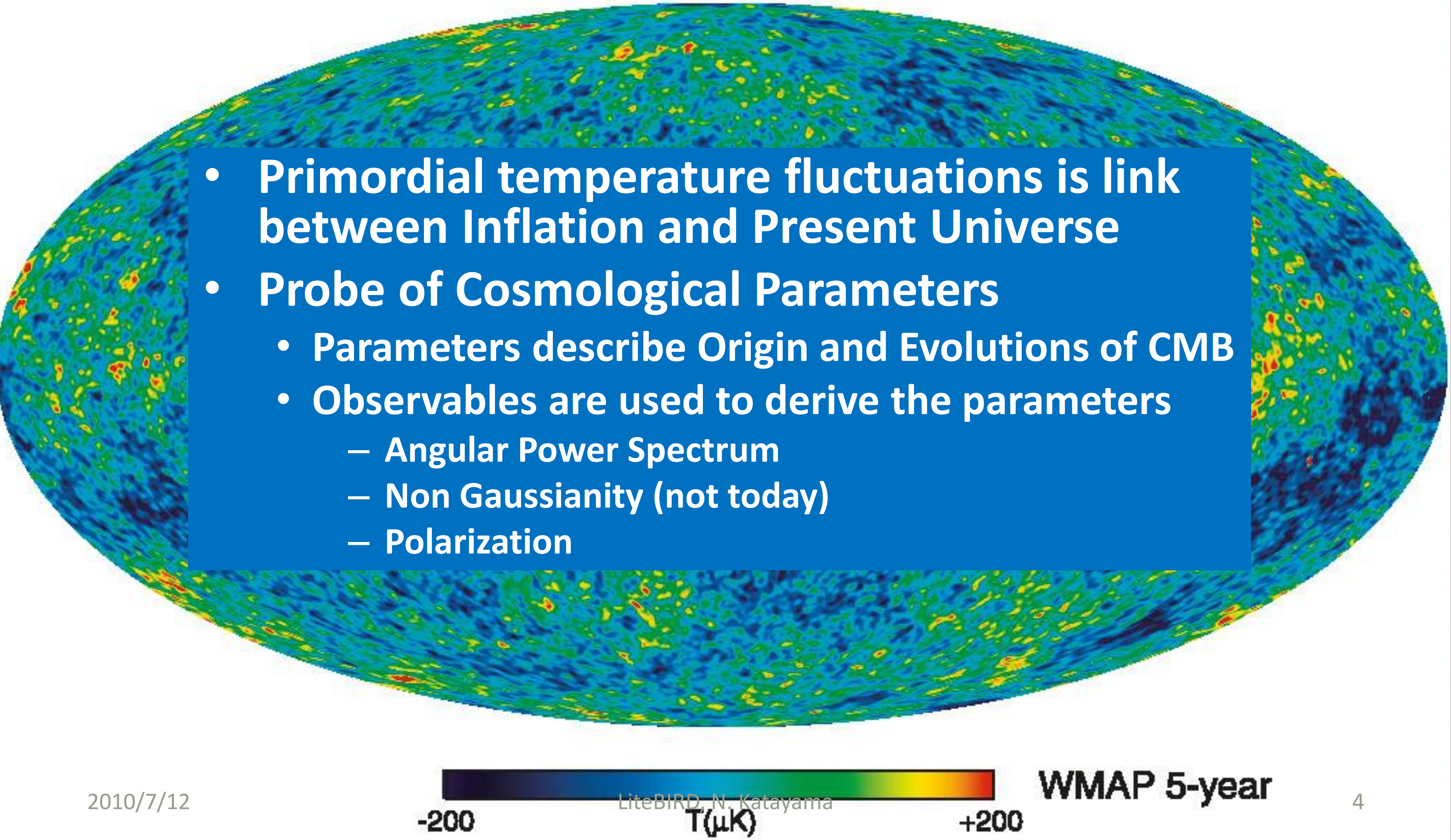
$\Rightarrow$Evidence of

- Big Bang
- Friedmann Universe
- Inflation

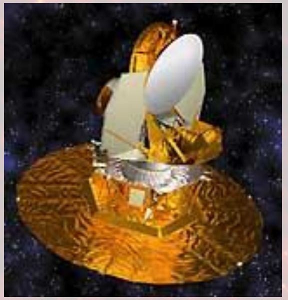
NASA/WMAP

Spatial anisotropy of CMB

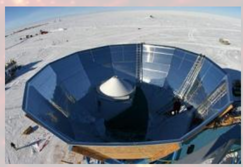
- **Primordial temperature fluctuations is link between Inflation and Present Universe**
- **Probe of Cosmological Parameters**
  - **Parameters describe Origin and Evolutions of CMB**
  - **Observables are used to derive the parameters**
    - **Angular Power Spectrum**
    - **Non Gaussianity (not today)**
    - **Polarization**

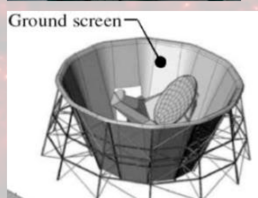


CMB Experiments







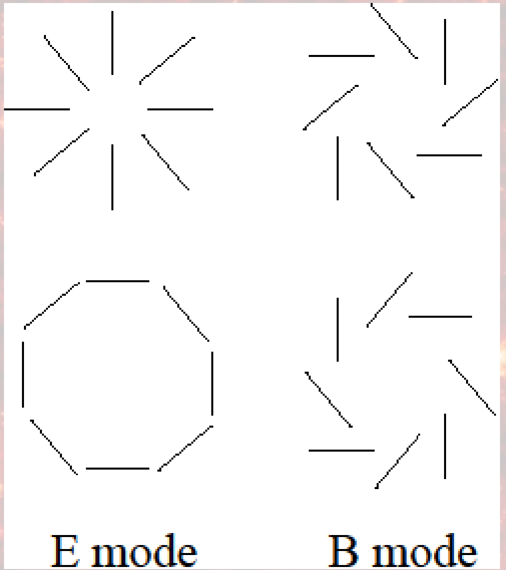


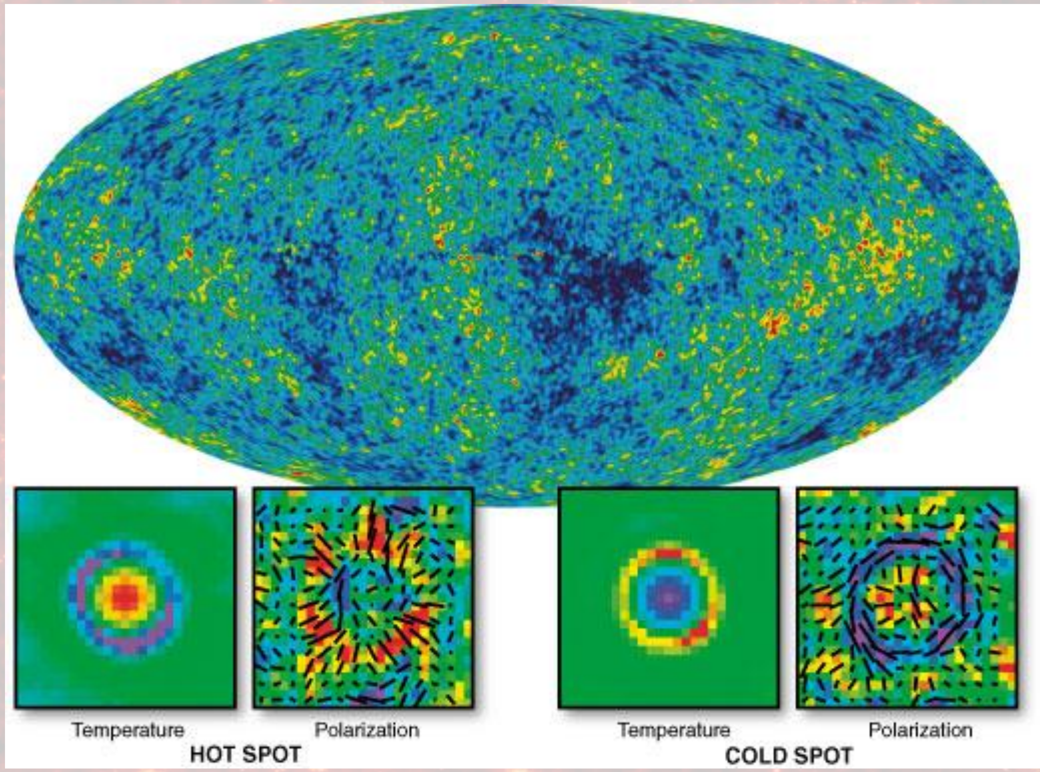
- WMAP (2001-2010), Space, D=1.5m, ν=23, 33, 41, 61, 96GHz
  – l=2-1000; T&Pol, 10 detectors(HEMT)
- PLANCK (2009-), Space, D=1.5m, ν=30, 33, 70, 100, 143, 217, 353, 545, 857GHz
  – L=2-3000; T&Pol, 22HEMT, 52bolo
- ACBAR (2001-2005), South Pole, D=2.1m, ν=150GHz
  – l=470-2600; T only, 16 detectors(bolo)
- QUaD (2005-2007), South Pole, D=2.6m, ν=100, 150GHz
  – l=200-3000; T&Pol, 31 detectors (bolo)
- ACT (2007-), Chile, D=6m, ν=148, 218, 277GHz
  – l=200-8000; T only, 3072 detectors(bolo)

KEK has joined QUIET and POLERBEAR

  – l=2000-9000; T only, 960 detectors (bolo)
- **QUIET (2009-), Chile, ν=40, 90GHz**
  – **l=50-2500; Pol, 90 detectors (HEMT)**
- **POLERBEAR (2010-), Chile, ν=150, 220GHz**
  – **l=20-2000; Pol, 1284 detectors (bolo)**

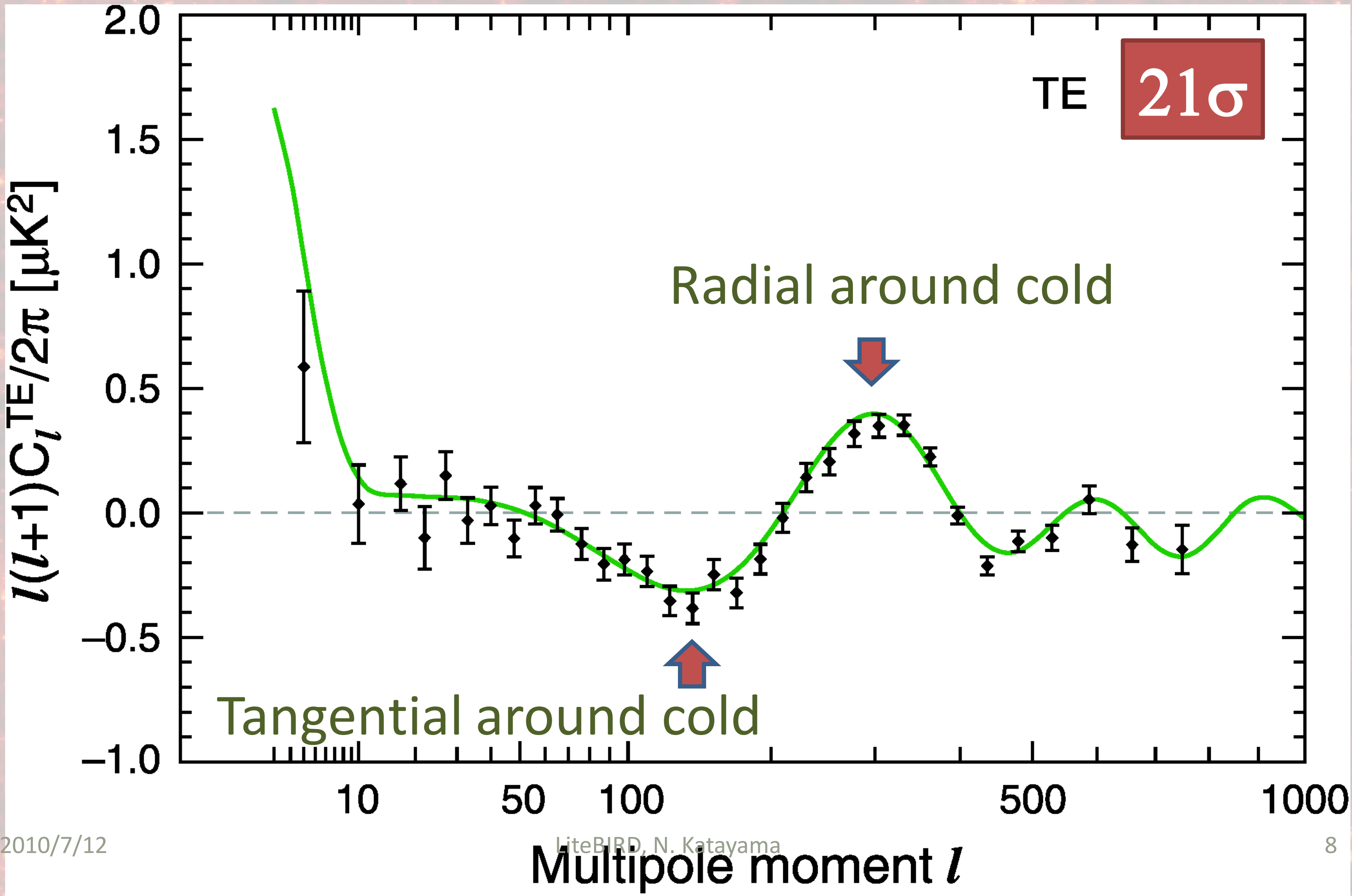
CMB can be polarized





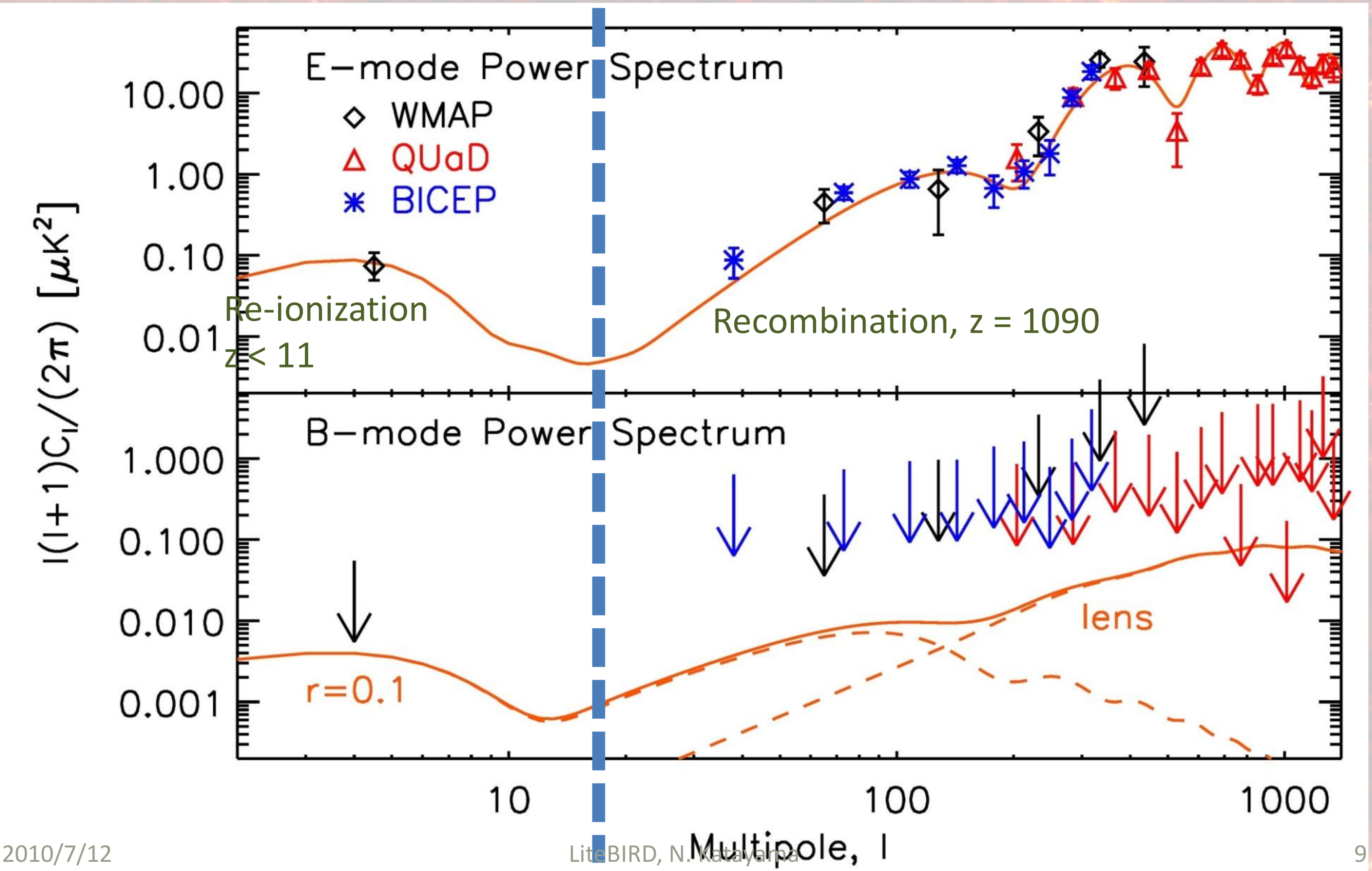
- Thomson Scattering and CMB quadrupole anisotropies produce linear polarization
- Overlay many hot and cold spots and see polarization around the spots
- A clear correlation of temperature and E-mode seen

WMAP 7yr TE correlation



B mode not detected yet

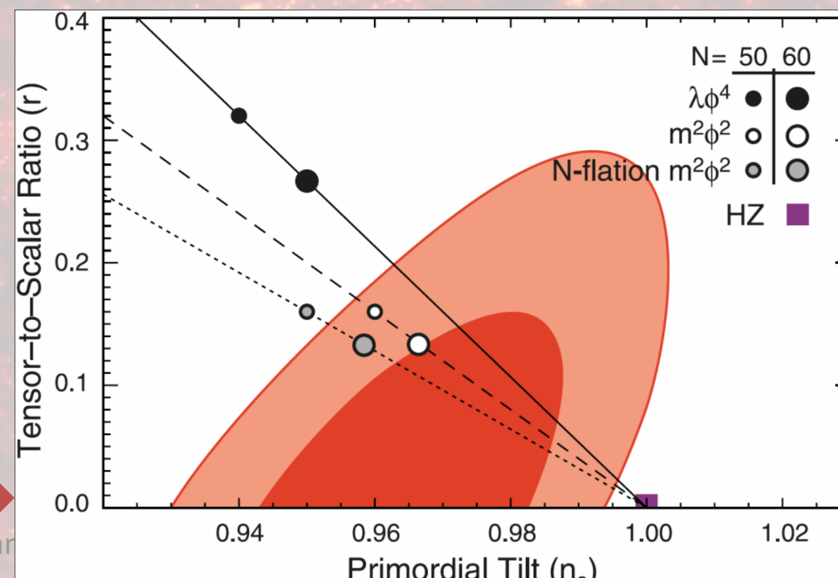
E mode polarization observed at 8σ (WMAP 7yrs)



B mode polarization and inflation

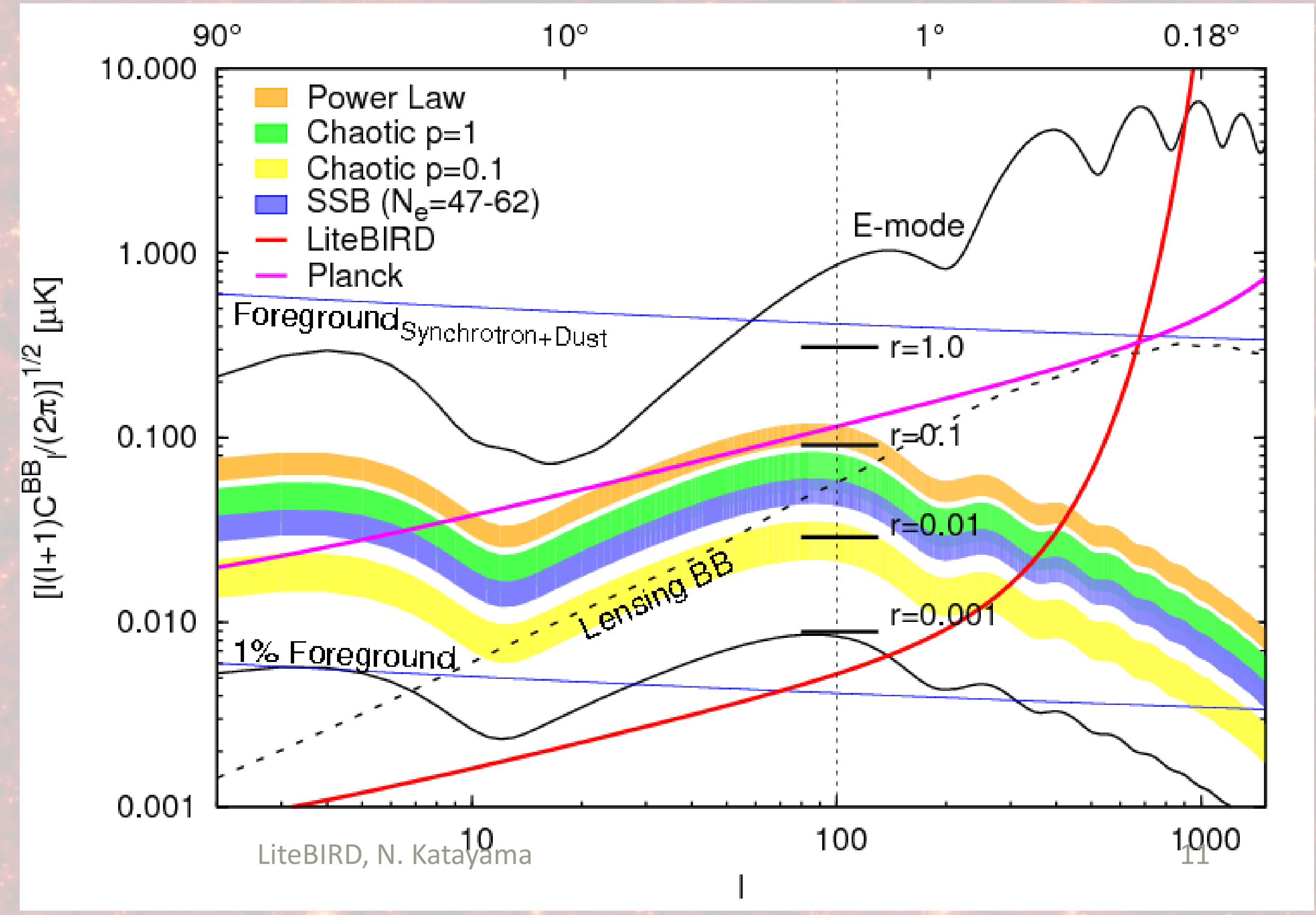
- Quantum fluctuation $\Rightarrow$ Space-time fluctuation $\Rightarrow$ (thru Inflation) $\Rightarrow$ Gravitational wave
- Gravitational wave h_x (h_+) produces B (E) mode polarization
- r = ratio of primordial gravitational wave to curvature perturbations
  - Energy scale
    - 0.93×10^{16} Gev $(r/0.01)^{1/4}$
  - Current limit: r < 0.24 (95% C.L.)

WMAP+BAO+H_0



B mode spectrum

- Gravitational wave
  - Models predict different values of r
- Re-ionization
- Lensing
- Noise
- Foreground



Feasibility studies for r detection

E. Komatsu and nk

Motivation

- Low ℓ very important
  - ℓ to be limited to ~100
  - need exact likelihood distribution for low ℓ
- **r** is the only cosmological parameter for LiteBIRD
  - In the following study, only **r** is "measured"
- CMB analysis: new to me
  - write out own pipeline (in Python)
  - CMB analysis is known to be compute intensive
- Eventually, we need to include many systematic effects

Significance of r measurement

- If we could observe B mode polarization with
  - full sky
  - C_ℓ^{BB} spectrum known
  - Noise white (and small)
  - No lensing
  - Gaussian approx.

$$\delta r \quad \propto \quad (\sum_{l=2}^{l=l_{max}} (2\ell+1))^{-\frac{1}{2}}$$

$$\Rightarrow \quad \frac{r}{\delta r} \sim \frac{l_{max}}{\sqrt{2}}$$

- With N_ℓ and $C_\ell^{lensing}$ (C_ℓ^{BB} is for r=1)

$$\frac{r}{\delta r} = \sqrt{\frac{f_{sky}}{2} \sum_{\ell=2}^{\ell=\ell_{max}} (2\ell+1)(\frac{rC_\ell^{BB}}{rC_\ell^{BB} + C_\ell^{lensing} + N_\ell})^2}$$

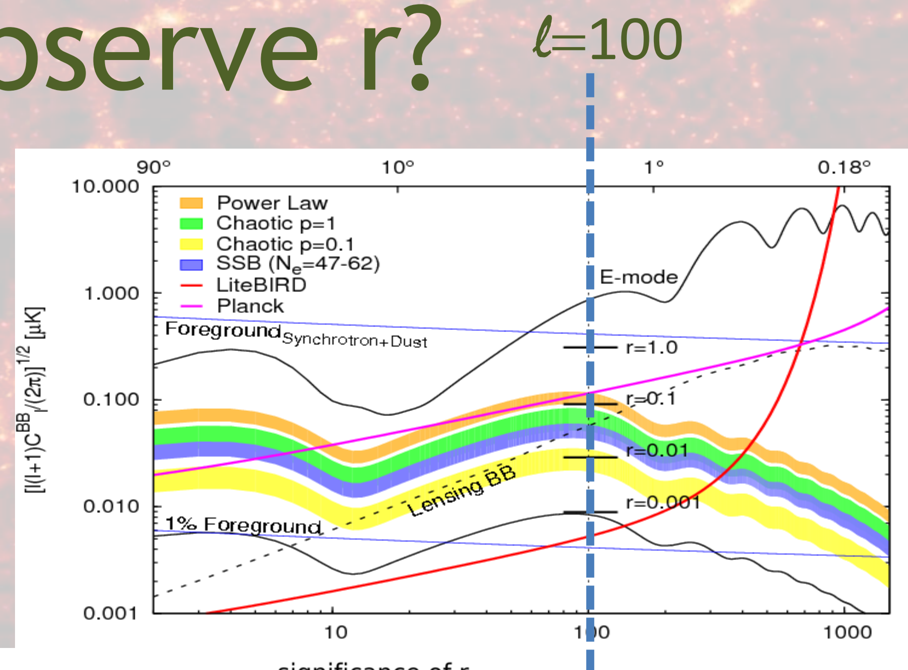
Can we observe r?

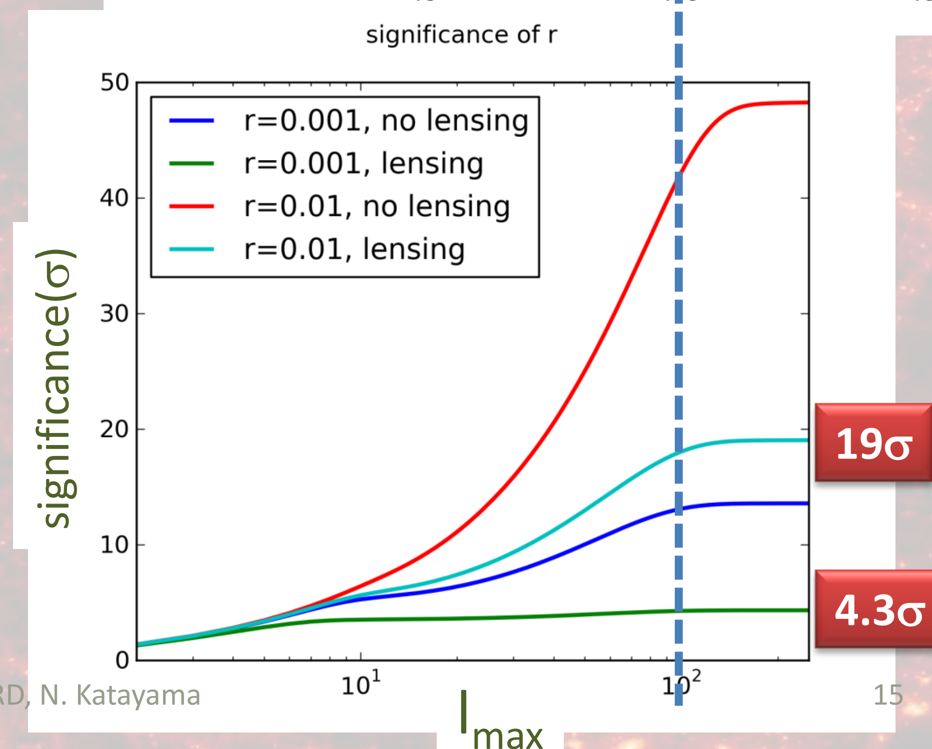
- Noise: 2μK arcmin
- Spectra known
- No foreground
- f_{sky}: 0.75
- lensing

⇒For r=0.01, ~19σ

⇒For r=0.001, ~4.3σ

- Saturation at ℓ~100 due to lensing





Likelihood method

- CMB is Gaussian on pixels
- Pixel space likelihood ⇒ most sensitive, unbiased but computationally intensive (Large factor $\times n_p^3$)

$$L(\boldsymbol{m}|r)d\boldsymbol{m} = \frac{\exp\left[-\frac{1}{2}\boldsymbol{m}^t(S(r)+N)^{-1}\boldsymbol{m}\right]}{|S(r)+N|^{1/2}}\frac{d\boldsymbol{m}}{(2\pi)^{2n_p/2}}$$

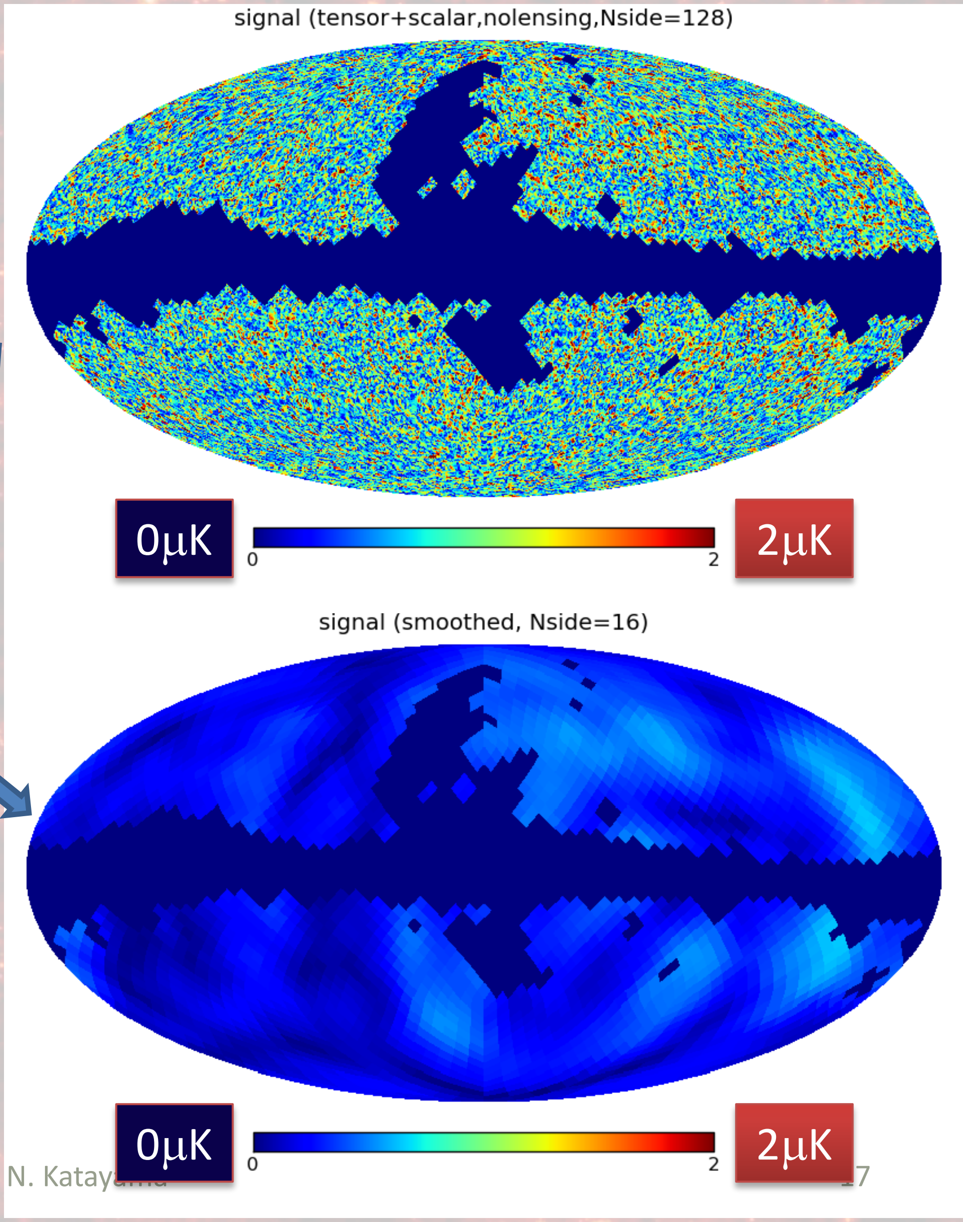
where

- ***m*** is Q and U map vector of length $2n_p$
- S is signal covariance matrix of ($2n_p \times 2n_p$)
  - S is a function of cosmological parameters
- N is noise covariance matrix
  - N is not diagonal due to smoothing

n_p = 3072 (N_{side}=16)

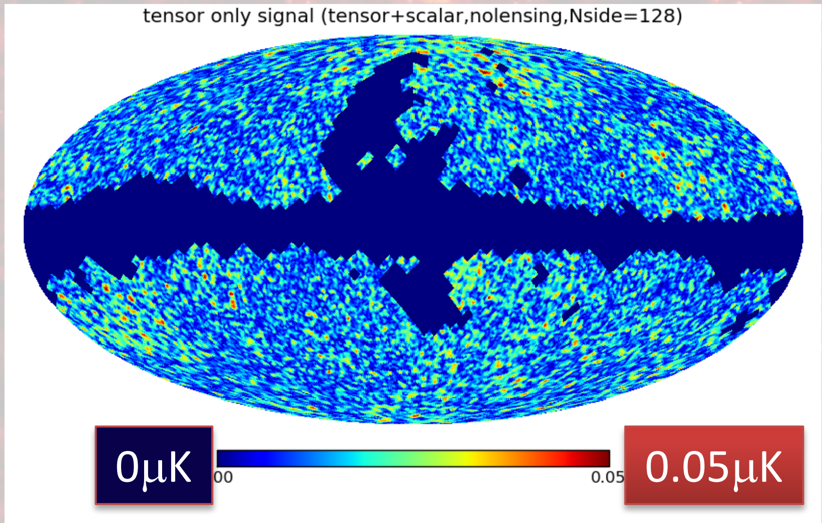
E mode signal

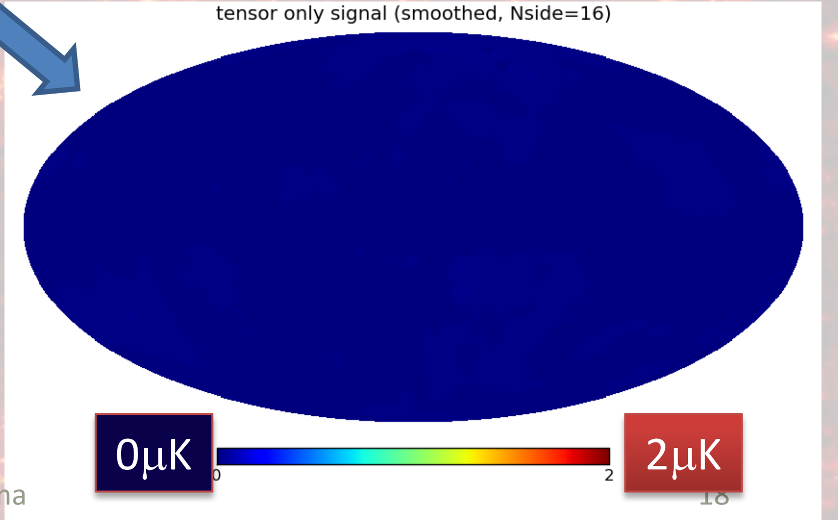
- E mode signal ~0.3μK
- E mode dominated by the curvature fluctuation origin
- generate at N_{side}=128 corresponding to LiteBIRD's beam size of 30'
- Smooth down to N_{side}=16
- $\sqrt{Q^2+U^2}$ plotted
  - same for all figures in this talk
  - WMAP P06 masked



B mode signal

- B mode signal $\sim (0.17 \times \sqrt{r})\mu K$
- C_ℓ^{BB} (ℓ<10, r=0.01) is less than 1/300 of C_ℓ^{EE}
- B mode is originated from the primordial gravitational wave
- Map using the same scale as E mode (as in previous page)
- For r=0.01, lensing C_ℓ^{BB} >> g.w. C_ℓ^{BB} even for $\ell \approx 100$
- We look at region of $2 \leq \ell \leq 47$
- No lensing for now





Exact covariance matrix

- Elements of S can be written in terms of spin-weighted $Y_{\ell m}$ and C_ℓ
  - S can be written as r × S^tensor + S^scalar
  - but need to compute $(S+N)^{-1}$ each time

$$
\begin{aligned}
C_{QQ}(x,y) &= \sum_l C_l^{EE} \sum_m W_{lm}(x) W_{lm}^*(y) + C_l^{BB} \sum_m X_{lm}(x) X_{lm}^*(y) \\
C_{QU}(x,y) &= \sum_l C_l^{EE} \sum_m (-W_{lm}(x) X_{lm}^*(y)) + C_l^{BB} \sum_m X_{lm}(x) W_{lm}^*(y) \\
C_{UQ}(x,y) &= \sum_l C_l^{EE} \sum_m (-X_{lm}(x) W_{lm}^*(y)) + C_l^{BB} \sum_m W_{lm}(x) X_{lm}^*(y) \\
C_{UU}(x,y) &= \sum_l C_l^{EE} \sum_m X_{lm}(x) X_{lm}^*(y) + C_l^{BB} \sum_m W_{lm}(x) W_{lm}^*(y)
\end{aligned}
$$

$$
\begin{aligned}
W_{lm}(x) &= (-1)({}_2Y_{lm}(x) +_{-2} Y_{lm}(x))/2 \\
X_{lm}(x) &= (-i)({}_2Y_{lm}(x) -_{-2} Y_{lm}(x))/2
\end{aligned}
$$

Likelihood fit procedure

- Assume r is the only unknown cosmological parameter
  - Pre-compute ${}_{+2}Y_{\ell m}$ (p), $C_\ell^{[Q,U]}$(p,p') for $2 \leq \ell \leq 47$

The results are as expected and will be shown later ☺

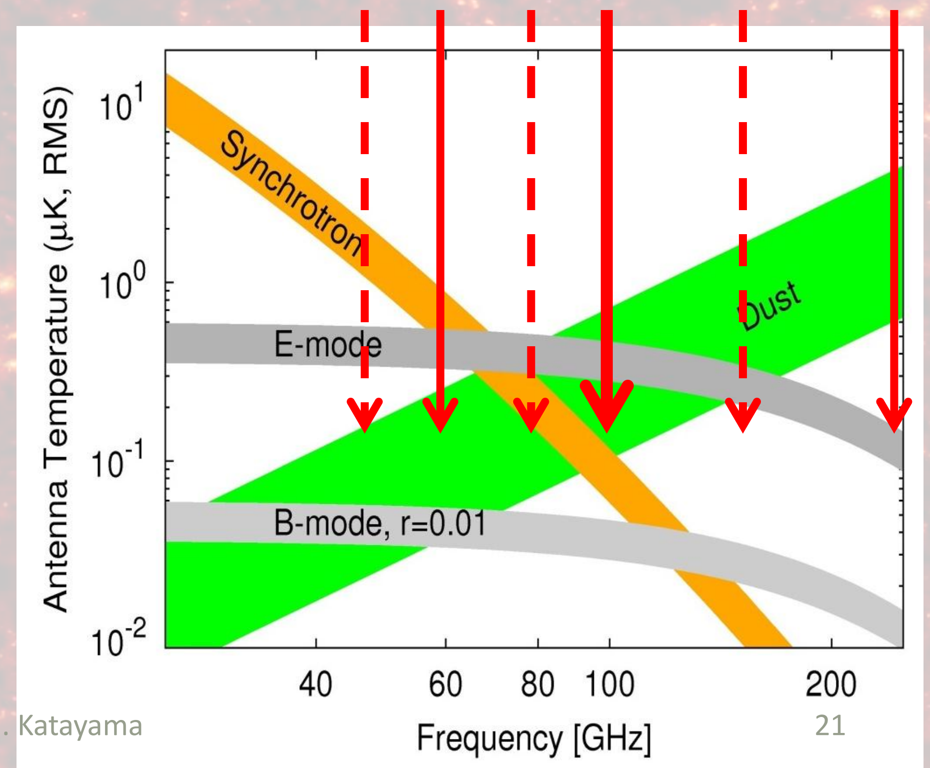
- Generate map (N_{side}=128) assuming $r=r_{input}$, add noise, smooth to N_{side}=16, apply P06 mask
- Compute ln L(**m**|r) for r=0.0001, 0.0002, 0.0003 and find r which gives max. ln L(**m**|r)
  - repeat for many realizations
  - get Δr from 0.5 = Δln L
- Plot resulting r, compute mean of r and Δr, etc.
  - repeat for r_{input} = 0.001, 0.003, 0.01,,,

Foregrounds

- Polarized photons everywhere!
- Originated from inside our galaxy
  - Dust
  - Synchrotron
  - Others (not today)
- Measured, modeled but still not well known
- Foregrounds will be the biggest obstacles when observing B mode signal from pgw (by good detector in space)

- Measure at many frequencies
  - Spatial distribution
  - Frequency dependence

$\Rightarrow \propto f(\theta, \phi)\ \nu^{\beta(\theta, \phi)}$

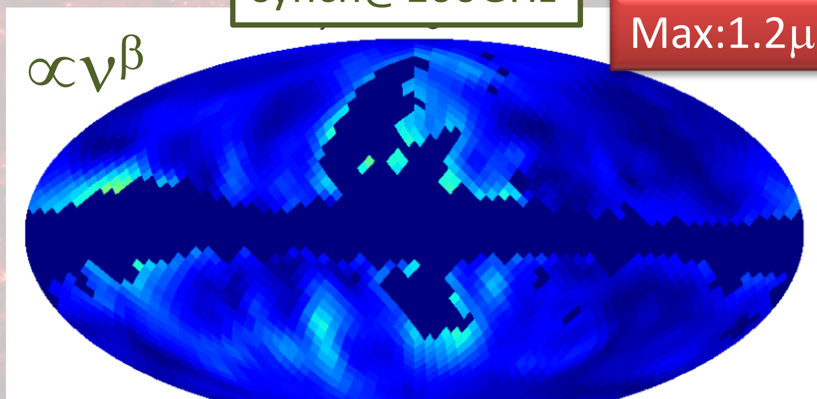


Spatial dist. of Synch. and Dust

synch@100GHz

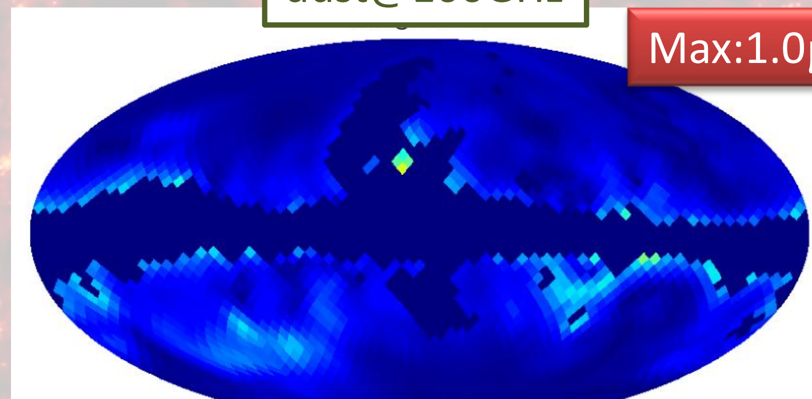
Max:1.2μK

$\propto \nu^{\beta}$

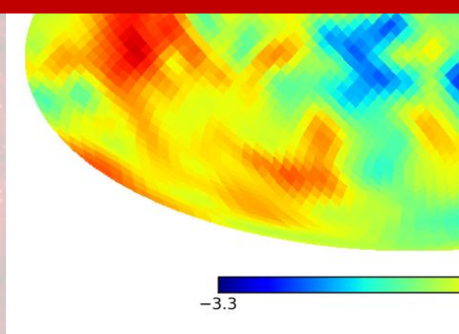


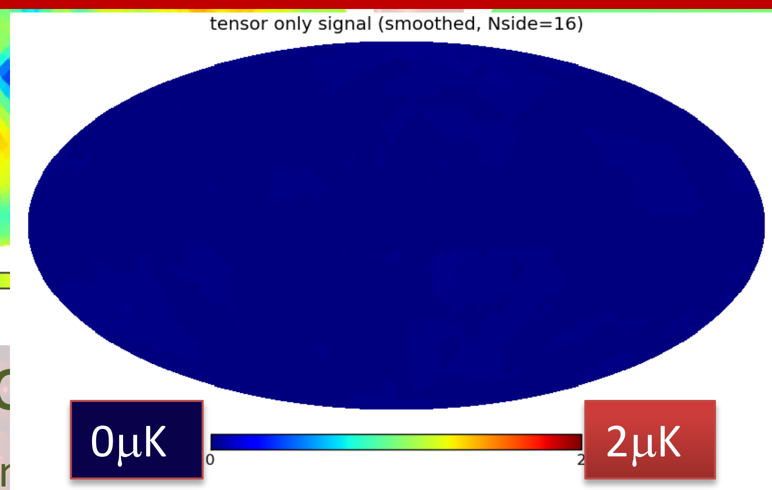
dust@100GHz

Max:1.0μK



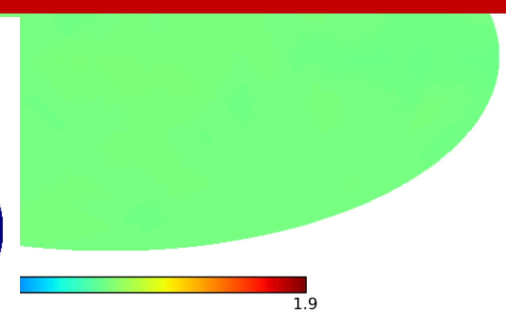
Remove foregrounds with multiband maps assuming morphology





0μK

2μK



Synchr

Dust

Maps from Plan

nd FDS(dust)

Dust cleaning with 2 bands

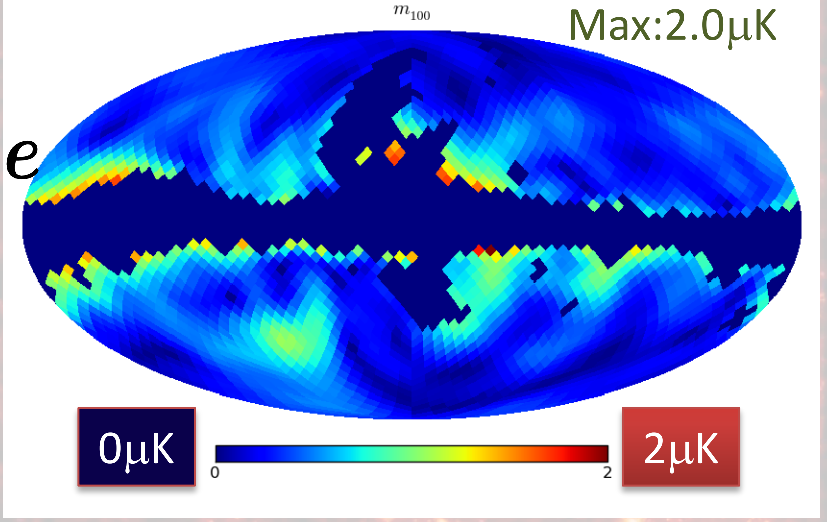
- Simple cleaning (E. Komatsu)

$$\boldsymbol{m}_{100} = \boldsymbol{cmb} + \boldsymbol{dust}_{100} + \boldsymbol{noise}$$

$$\boldsymbol{m}_{240} = \boldsymbol{cmb} + \boldsymbol{dust}_{240}$$

$$\boldsymbol{dust}(\nu) = \boldsymbol{dust}_0\left(\frac{\nu}{\nu_0}\right)^{\beta}$$

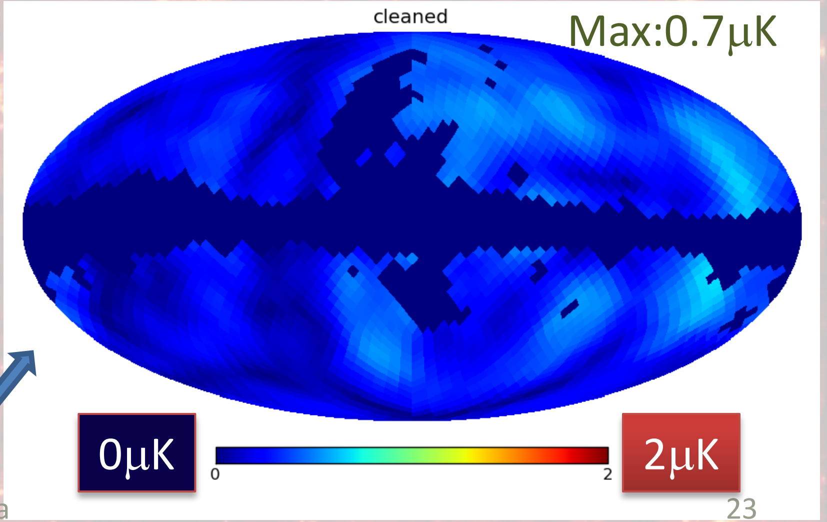
$$\chi^2 = (\boldsymbol{m}_{100} - \alpha\boldsymbol{m}_{240})^T (S+N)^{-1} (\boldsymbol{m}_{100} - \alpha\boldsymbol{m}_{240})$$



- minimize χ^2 with respect to α
- In L

$$\boldsymbol{m} \Rightarrow \frac{\boldsymbol{m}_{100} - \alpha\boldsymbol{m}_{240}}{1-\alpha}$$

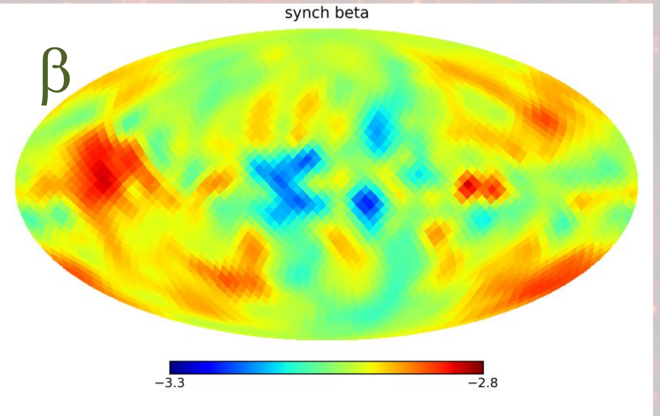
$$N \Rightarrow \frac{N}{(1-\alpha)^2}$$

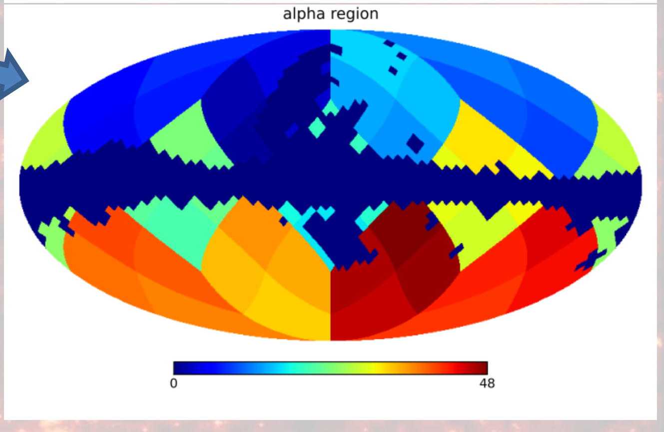


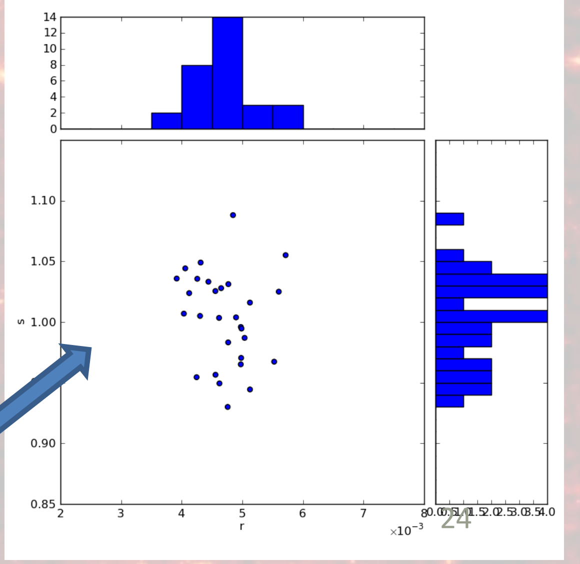
Note: These map include both dust and synch

Dust+Synch cleaning

- Try cleaning dust+synch using 3 bands
- Make $\alpha_{synch}(\theta, \phi)$ dependent
  - 48 alpha regions
- Maximization using 51 parameters
- $(S+N)^{-1}$ depends on all parameters because of $N/(1-\alpha)^2$
- It is computationally prohibitive to maximize L using exact $(S+N)^{-1}$
- Use "nominal alphas" by analytically solving $\dfrac{\partial \chi^2}{\partial \alpha_i} = 0$ and use it in $N/(1-\alpha)^2$
- $(S+N/(1-\alpha)^2)^{-1}$ is a function of r and s

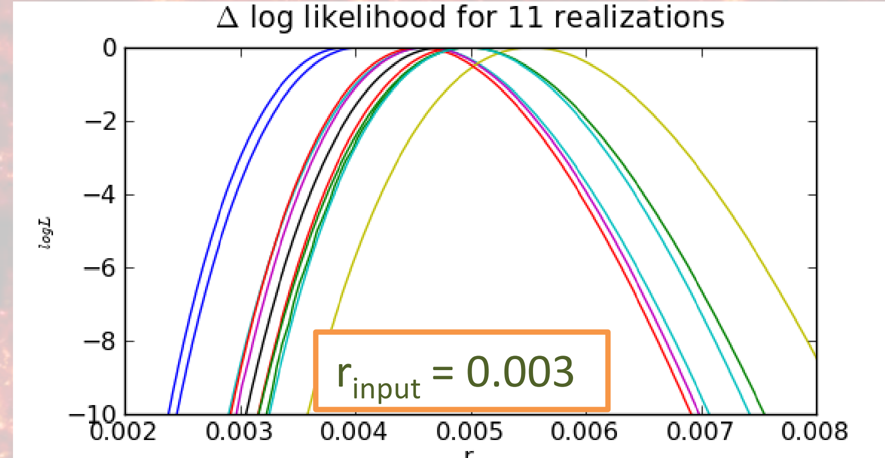




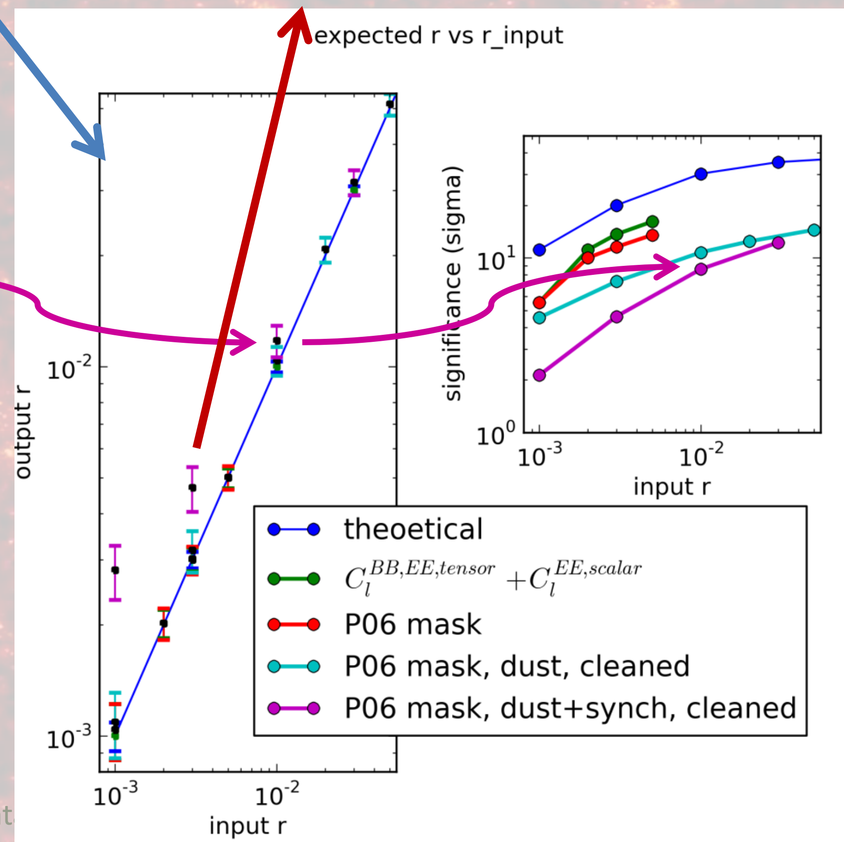


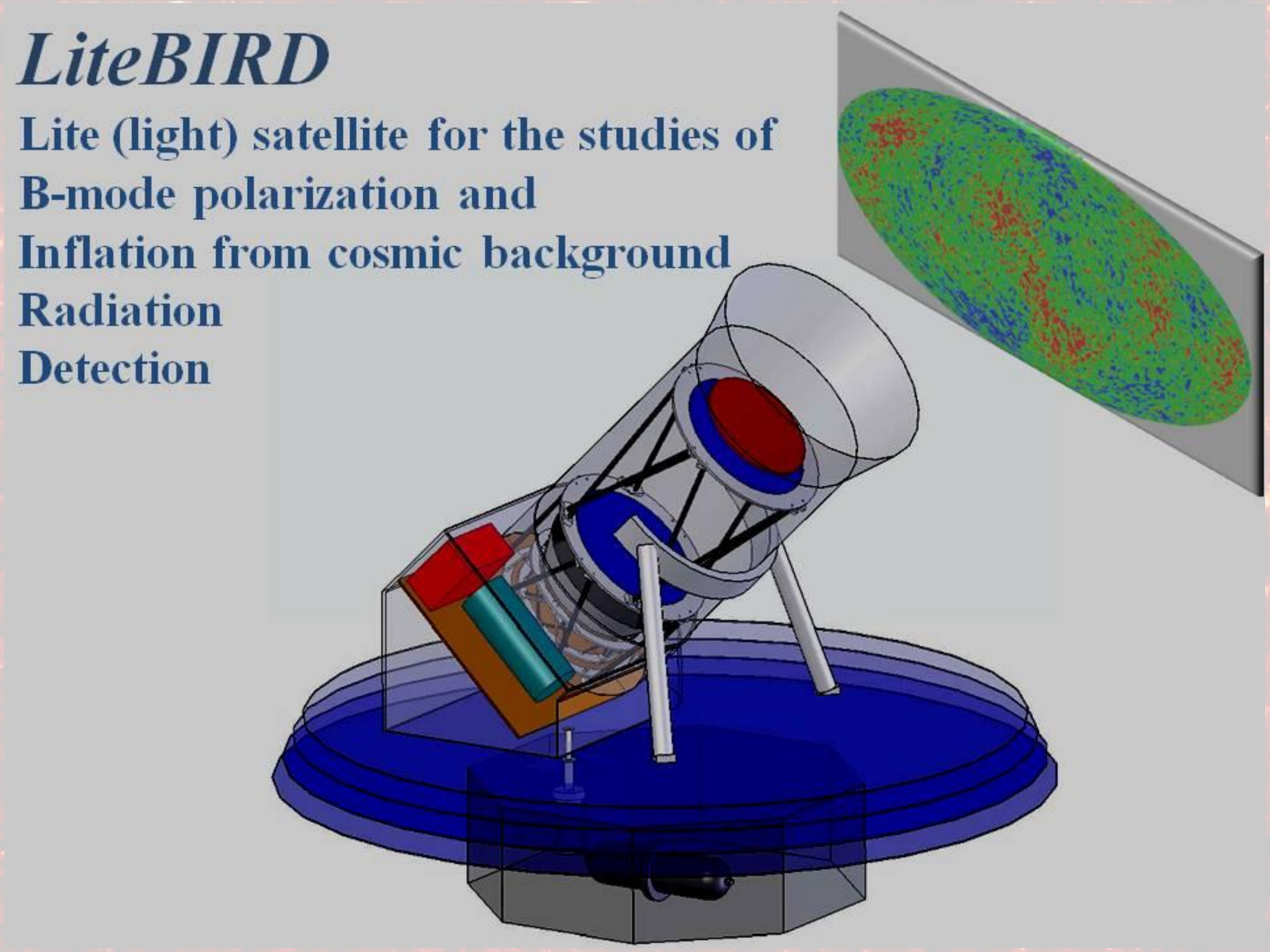
Results and plan

- Full sky
- Masked
- Dust
- Dust + Synchrotron
  - has an offset
  - r ~> 0.01 OK with this simple cleaning method
- Improve foreground removal
  - Though we think it is not a time to build complicated analysis techniques
- Add experimental details



(r=0: many σ away)





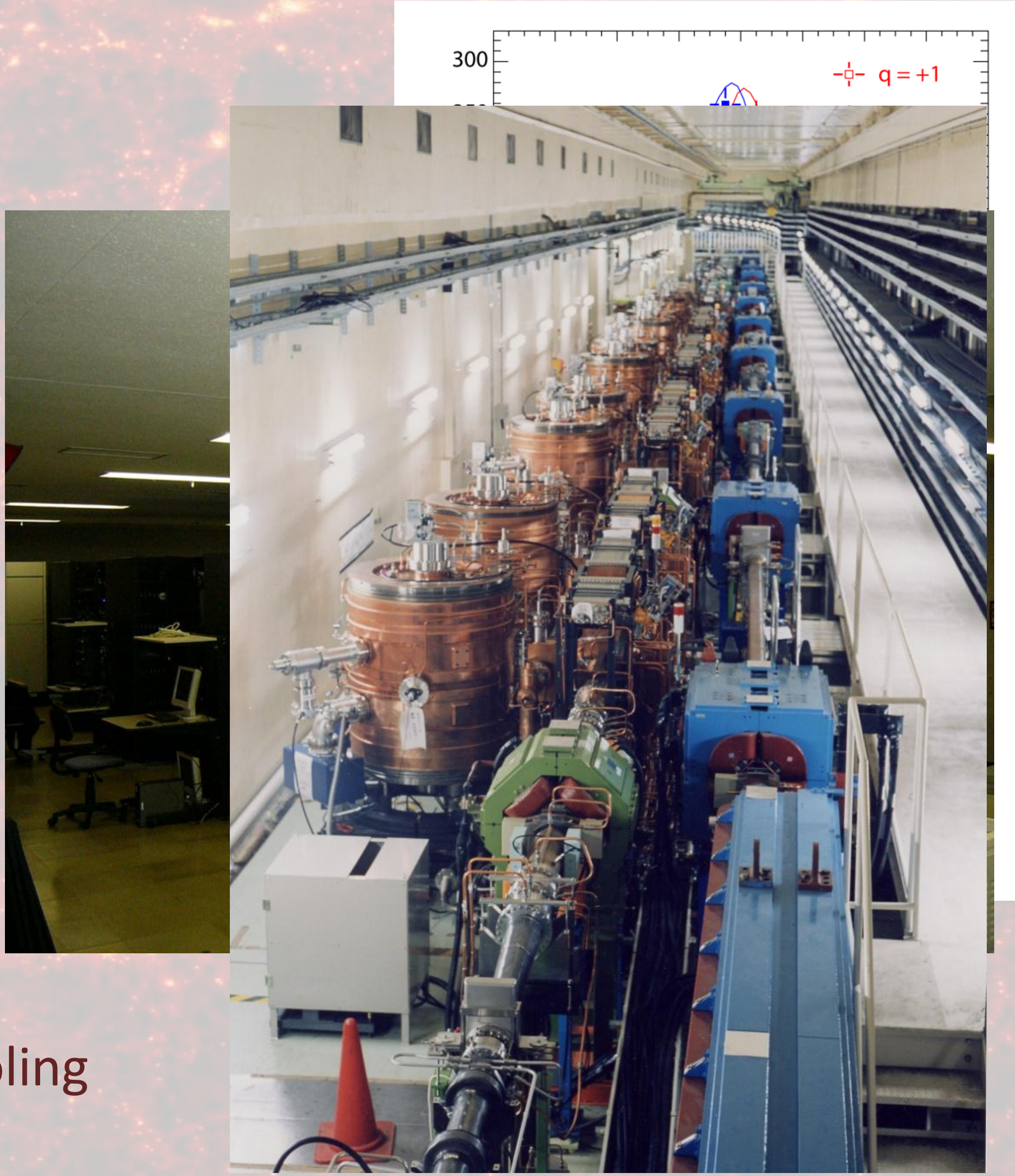
Lite (Light) satellite for the studies of

B-mode polarization and **I**nflation

from cosmic background **R**adiation **D**etection

Why KEK?

- Physics interests
- Technologies
  - Experiment
    - Sensor/Detector
    - DAQ (in radiation environment!)
    - Computing
    - Data Analysis
  - Accelerator
    - RF
    - Superconducting/cooling
    - Optics
    - Vacuum
      - Gravitational wave experiment at Kamioka



The LiteBIRD concept

- Use latest detector and cooling technologies

$\Rightarrow$ Very low noise, multichroic detector

- Limit ourselves to $2 \leq \ell \leq \sim 100$

$\Rightarrow$ Compact optics, warm launch

- Launch as soon as possible before American and European flagships go up

$\Rightarrow$ Be the first to claim **r** is non-zero

LiteBIRD: Project History

1. Approved as a small satellite working group (Sep. 2008)
2. JPS: CMB session (Mar. 2009)
3. Kaken-hi H21-25 (Research on Innovative Areas) (Jul. 2009)
   "The Physical Origin of the Universe viewed through the Cosmic Background Radiation" (From Cosmological Inflation to Dark Ages)
   1. Main objectives are the scientific outcome from ground based experiments
   2. R&D for focal plane detectors of LiteBIRD
4. Approved to continue as a small satellite working group (Jan. 2010)
5. JPS: CMB symposium (Mar. 2010)
6. Ground based CMB experiments (QUIET, POLARBEAR)
   – Detector technologies, systematic errors
7. Collaborations with other projects
   – DIOS： Cooling systems
   – ASTE： TES bolometer readout
8. Science Council of Japan mentioned in the perspectives and long-term plan report for astronomy and cosmology

LiteBIRD Working Group

- Y. Sato, K.. Shinozaki, H. Sugita （ARD/JAXA）
- T. Matsumura （Caltech）
- H. Fukuya, H. Matsuhara, K. Mitsuta, T. Yoshida （ISAS/JAXA）
- N. Katayama, M. Kimura, N. Sato, T. Suzuki, K. Sumisawa, O. Tajima, T. Tomaru, M. Hazumi, M. Hasegawa. T. Higuchi, H. Nishino, M. Yoshida (KEK)
- I. Ohta (Kinki U.)
- Y. Uzawa, Y. Sekimoto, T. Noguchi (NAOJ)
- Julian Borrill （LBNL）
- H. Ishino, A. Kibayashi, K. Hattori, S. Mima, T. Misawa (Okayama U.)
- T. Ohtani (Riken)
- E. Yaginuma (Soken-dai)
- Y. Chinone, M. Hattori (Tohoku U.)
- T. Takada (U. Tsukuba)
- William L. Holzapfel, Bradley R. Johnson, Adrian T. Lee, Paul L. Richards, Huan T. Tran, Aritoki Suzuki （UC Berkeley）
- E. Komatsu （UT Austin）

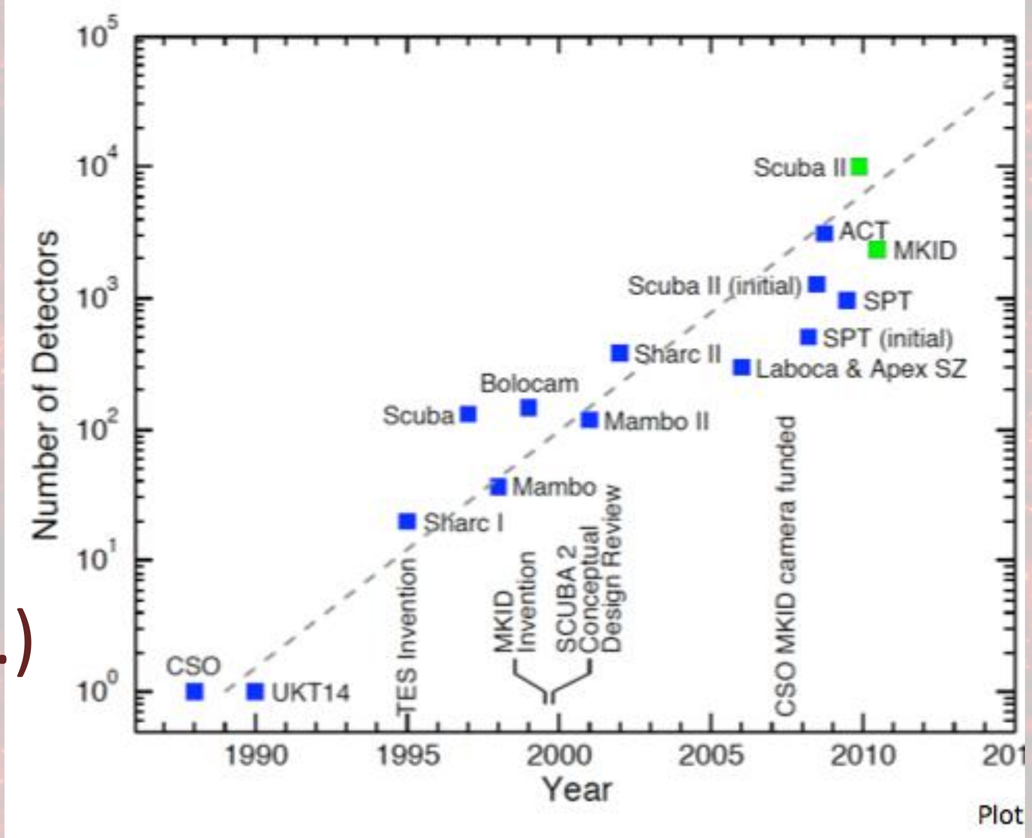
Consultants

- H. Kodama (KEK), T. Nakagawa (JAXA), Y. Kawabe (NAOJ)

Some are members of:
ALMA
APEX
BICEP
EBEX
Planck
PolarBear
QUIET
SPT
WMAP

Advances in detector technology

- TES bolometer
  - Berkeley group
- MKID, STJ
  - Riken + KEK
- $10^{3\sim5}$ detectors
- Multichroic
- Lower threshold(freq.)
- Low power read out
- Very low noise
- Compact antenna, focal plane



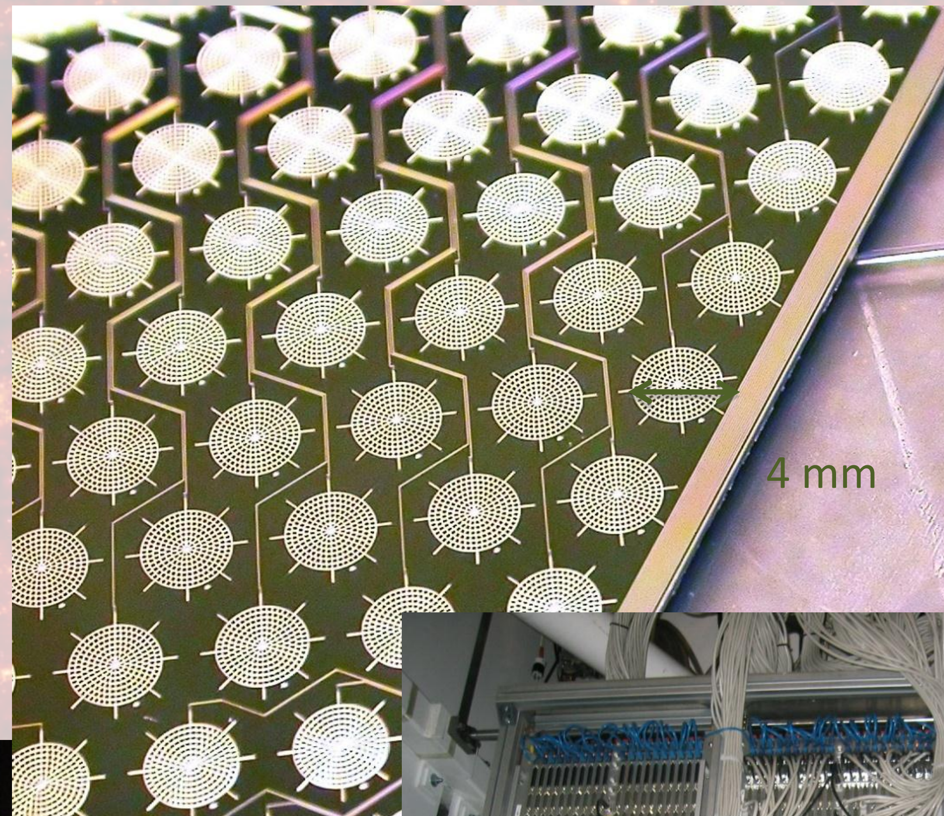
Plot from J. Zmuidzinas

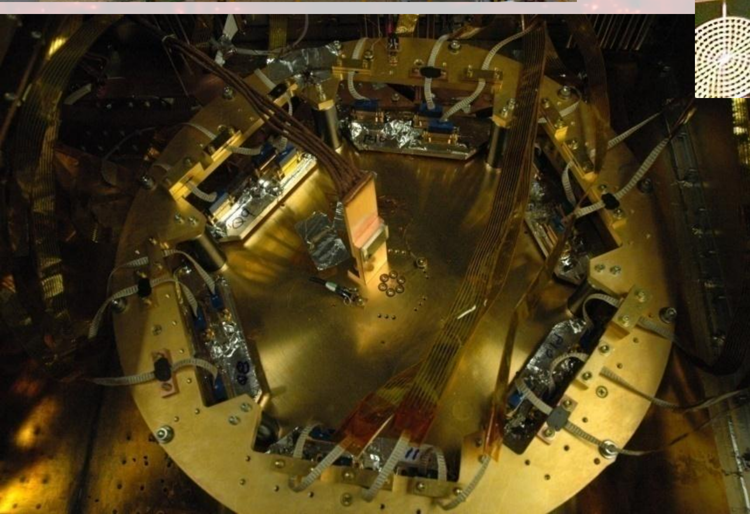
⇒Technology has matured to get down to ~μK arcmin noise level

N.B.: I used 2 μK arcmin in my simulation

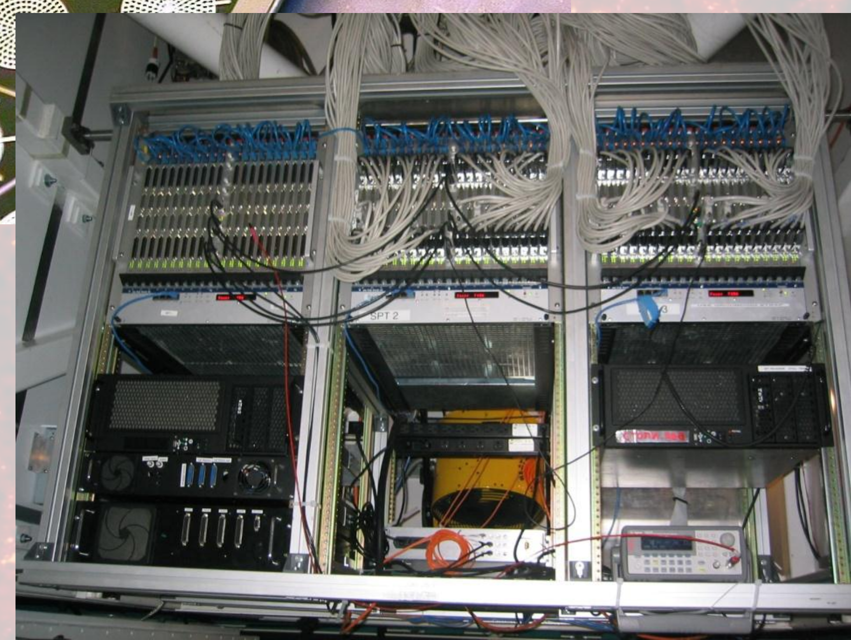
South Pole Telescope Spider TES Arrays

Berkeley, CWRU, Cardiff, Chicago, Colorado, Davis, Illinois, JPL, McGill, SAO





960 Pixel fMUX wiring



Adrian Lee
(Berkeley)

Digital FPGA fMUX

M. Dobbs (McGill University)

- Primary motivation for DfMUX was power consumption → goal was 1/10 power reduction.

2004
64W for 16 channels

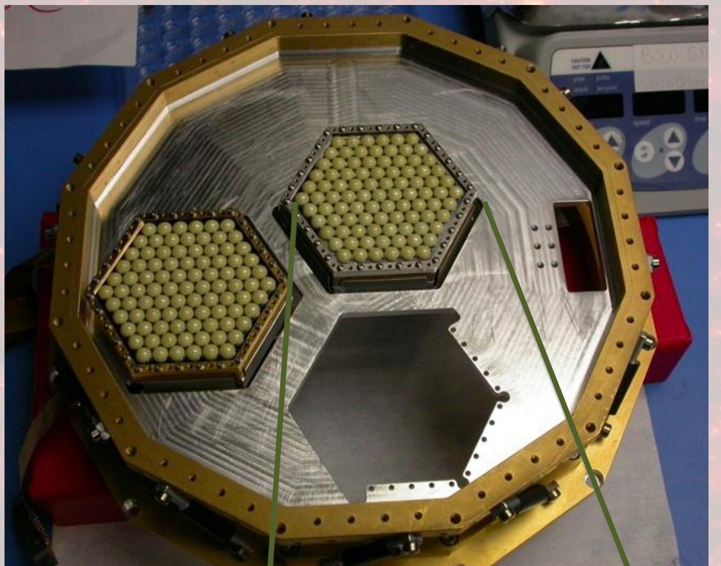
1/12 Power

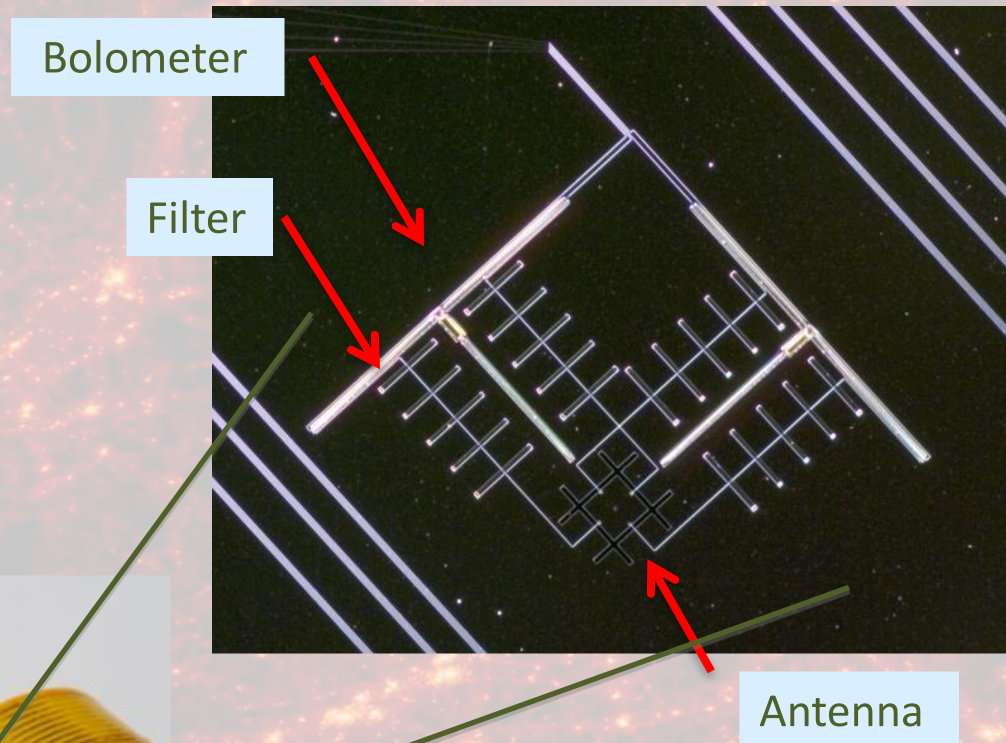
1/10 Form Factor

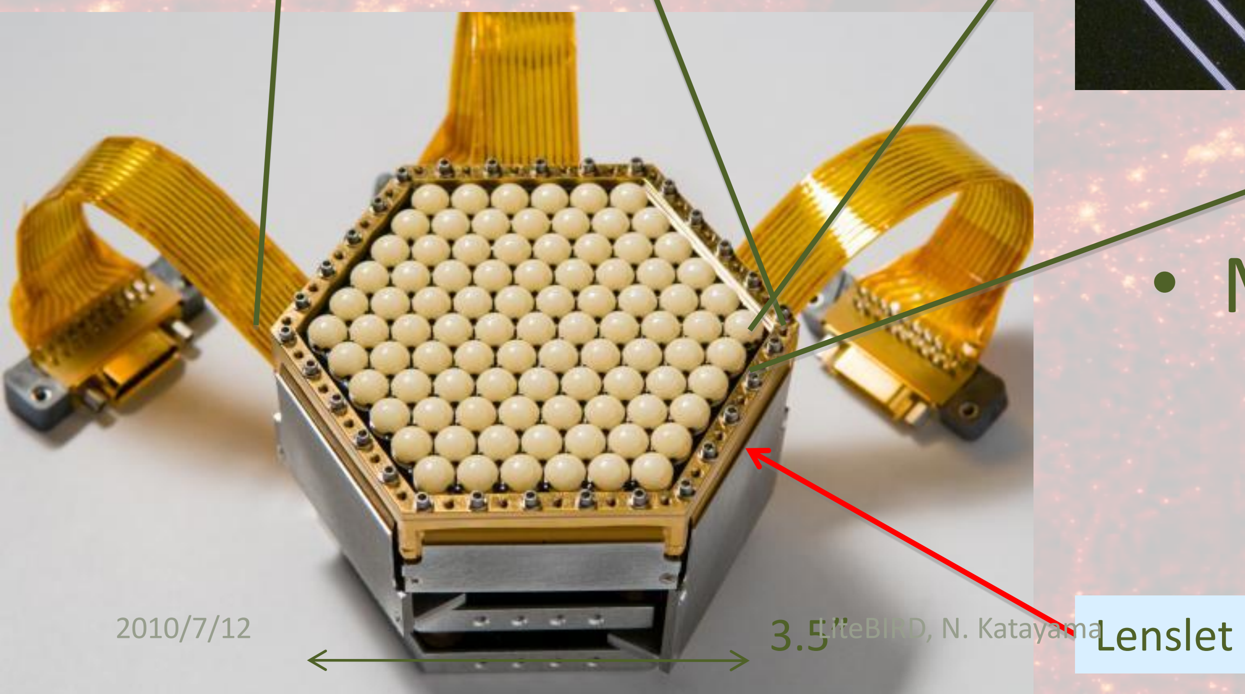
2006/12
~16W for 48 channels

We need another factor of 10 for LiteBIRD

POLARBEAR: Antenna-coupled Arrays





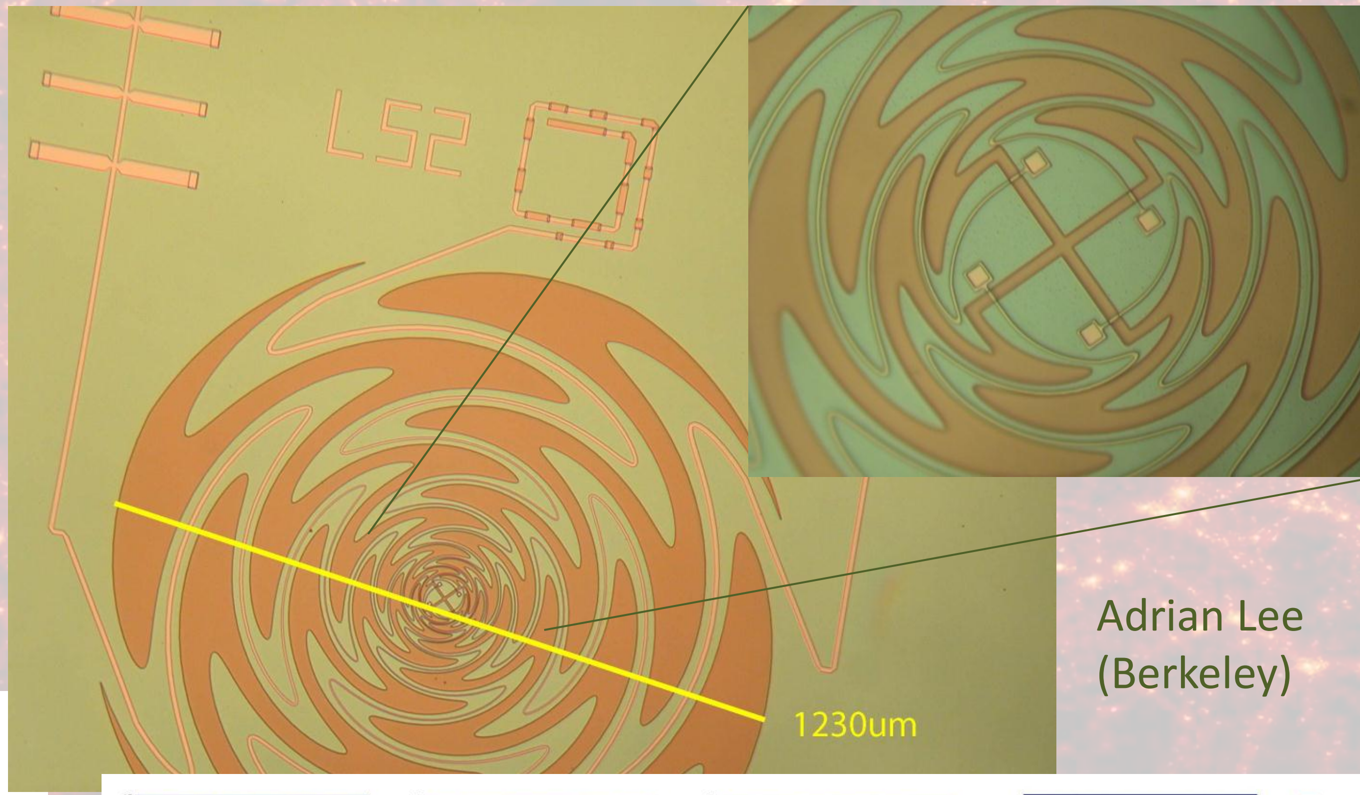


- Monolithic wafer
  - Scalable
  - 1284 bolos (PB-I)

Adrian Lee (Berkeley)

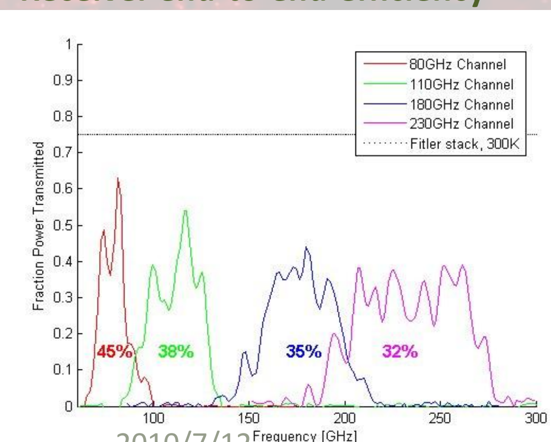
Dual-pol. Multichroic Sinuous Antenna

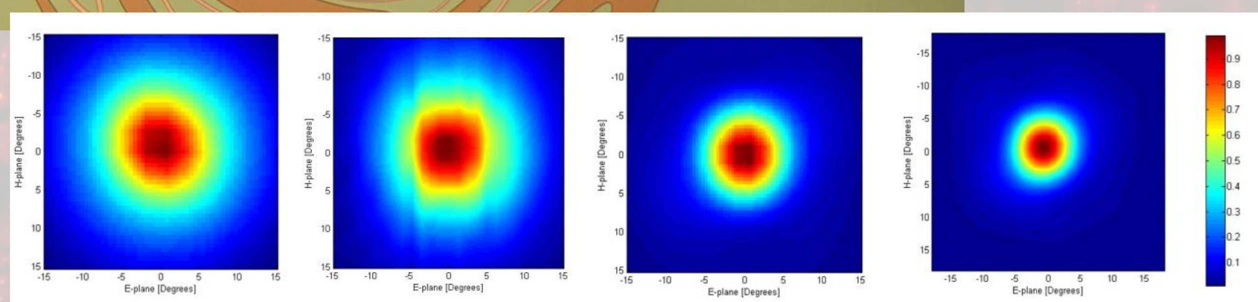
- Opposite arms couple to linear polarizations
- Adjustable parameters: Geometric scaling factor, arm opening angle
- Self-complimentary: Constant impedance, “wire” or “slot” operation



Adrian Lee (Berkeley)

Receiver *end-to-end* efficiency

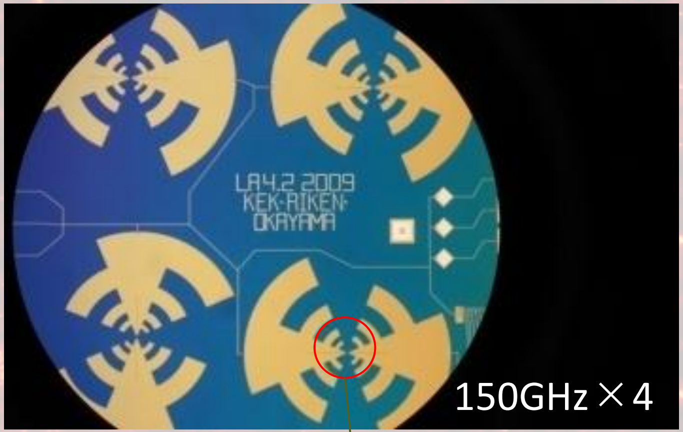




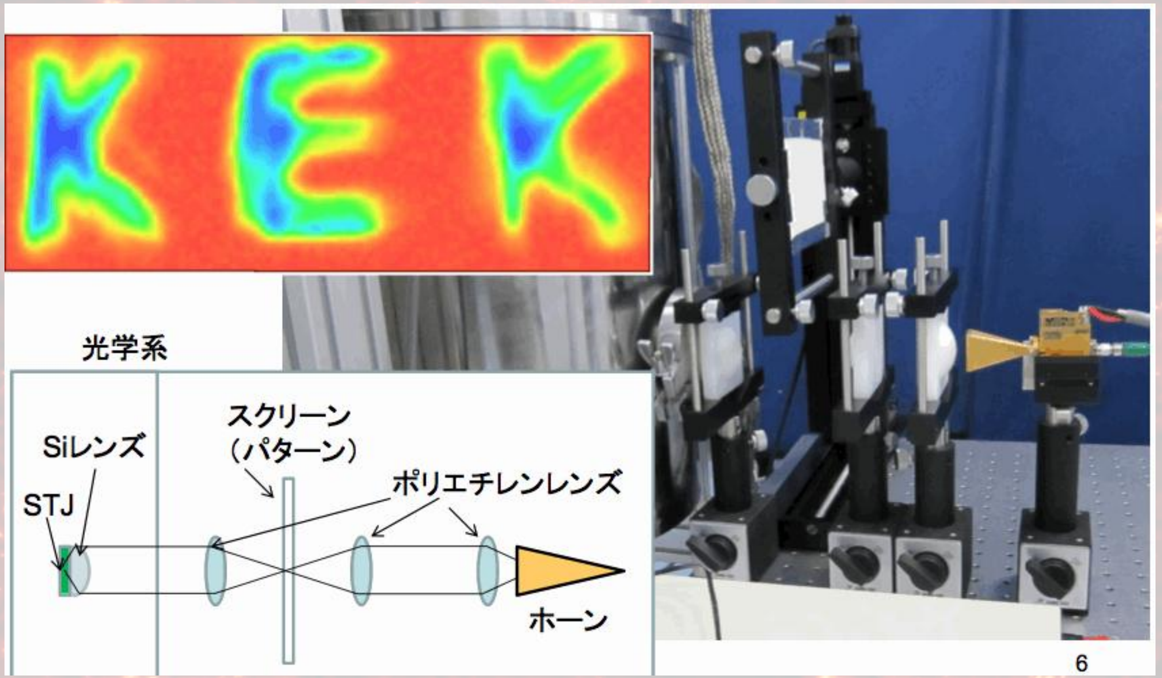
4:1 Bandwidth, Symmetric beams, low cross-pol

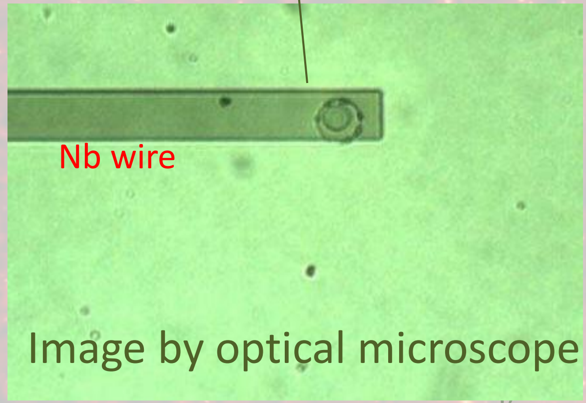
STJ (Superconducting Tunnel Junction)

- Advantages of STJ
  - Large dynamic range
  - Small NEP expected～10^{-18}W/√Hz
  - Fast time constant ～μsec



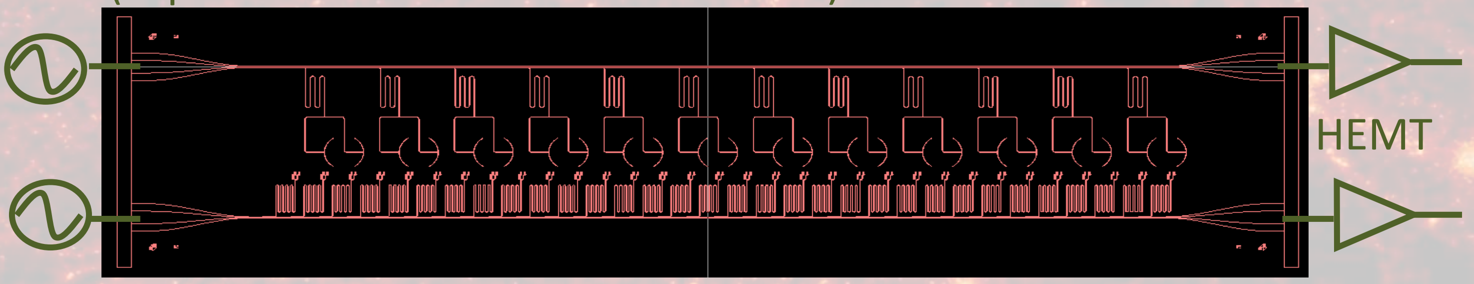
First STJ built at KEK

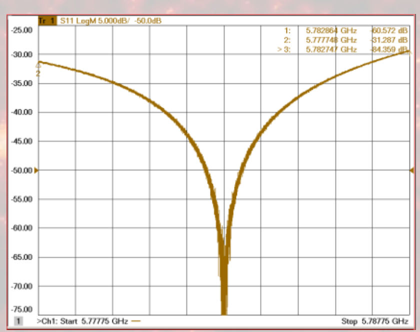


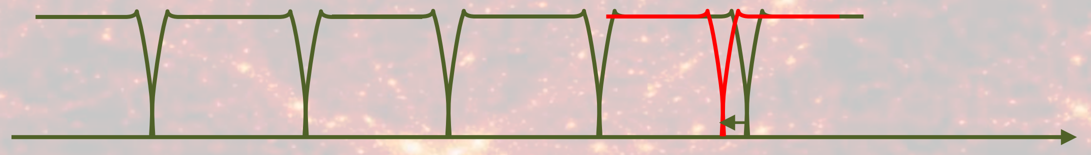


Microwave Kinetic Inductance Detector

(Experimental Photo Mask for MKIDs)



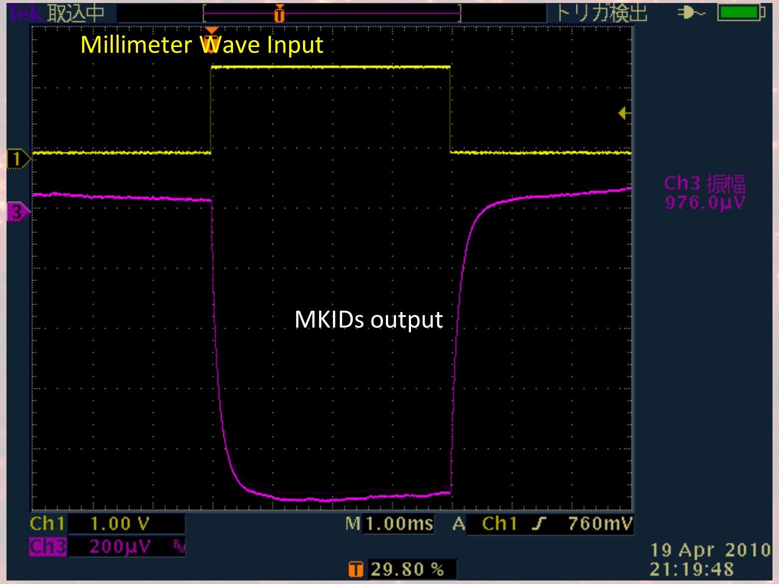




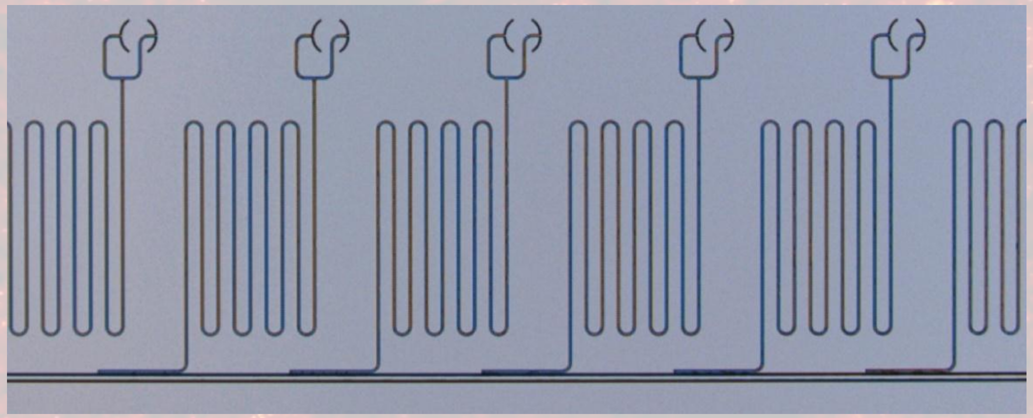
Advantages for a Satellite Application:

- Multi channel readout by one HEMT.
- No bias required.
- Easy structure avoids defects at satellite operation.

Pulse Response of MKIDs



Resonance of MKIDs

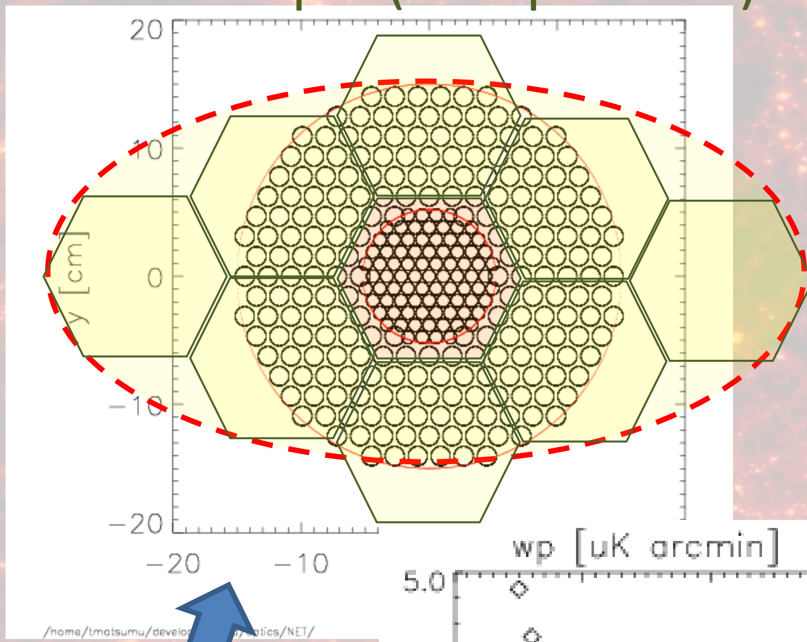


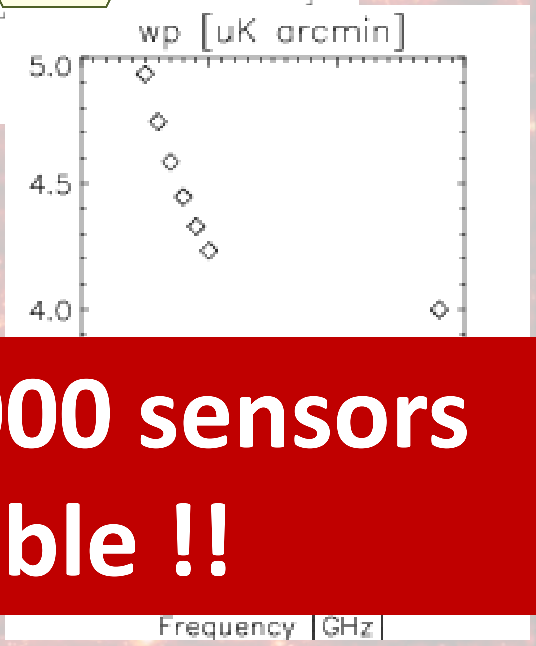
Focal plane design

- Effective use of focal plane:60-250GHz detectors

  Traditional detector
  1 pixel → 1 band
  LiteBIRD
  1 pixel → *N band*

Example (oval possible)



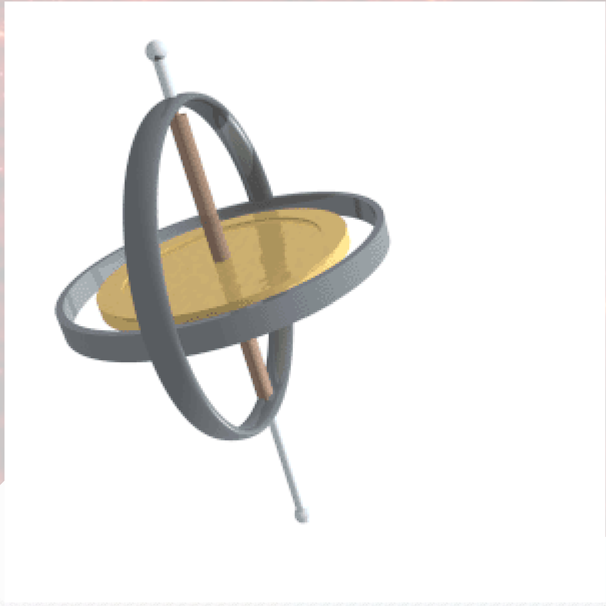


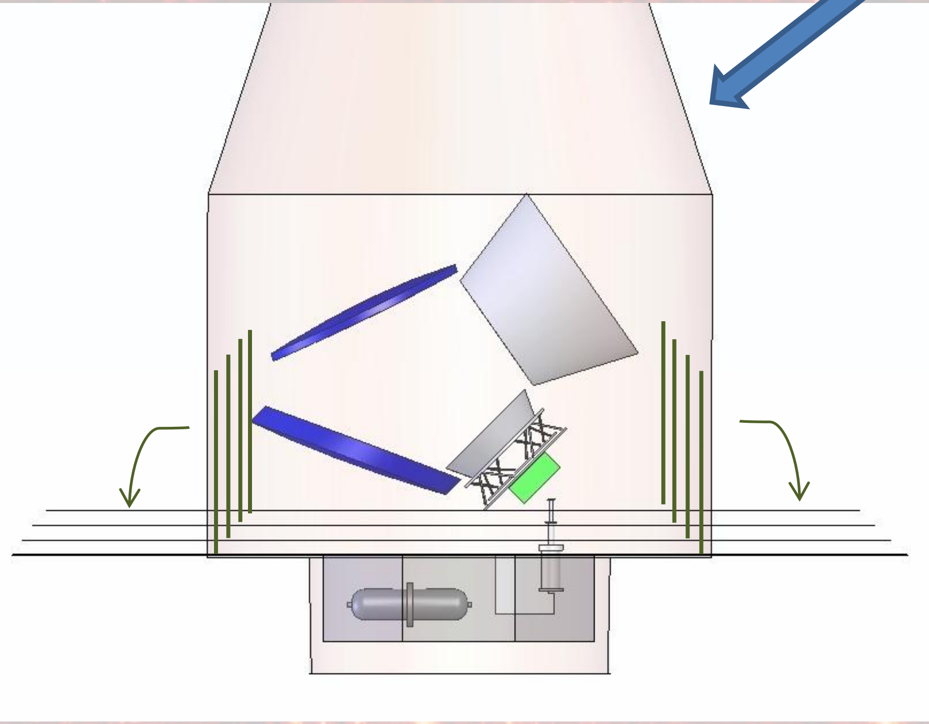
- Focal plane Optimization
- Pixel size
- No. pixels
- Areas for each set of bands
- What to optimize ?
- r significance (discussed later)
- (Noise/Foregrounds vs Signal)

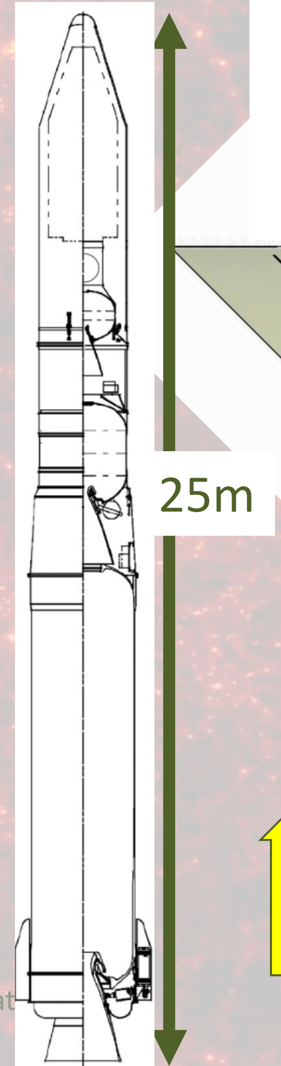
30 cm dia. focal plane with 1000 sensors at 100mK in space possible !!

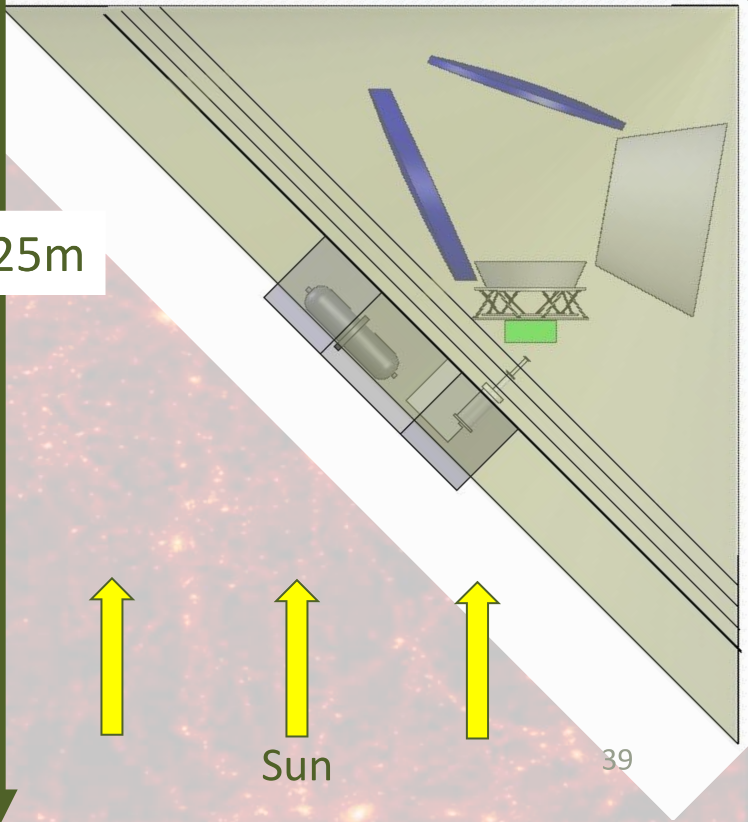
Satellite design

- Size, weight and power consumption of the satellite is limited by the specification of the rocket for small satellites
- Compact optics and focal plane
- Cooling, DAQ
- Bus (other things)

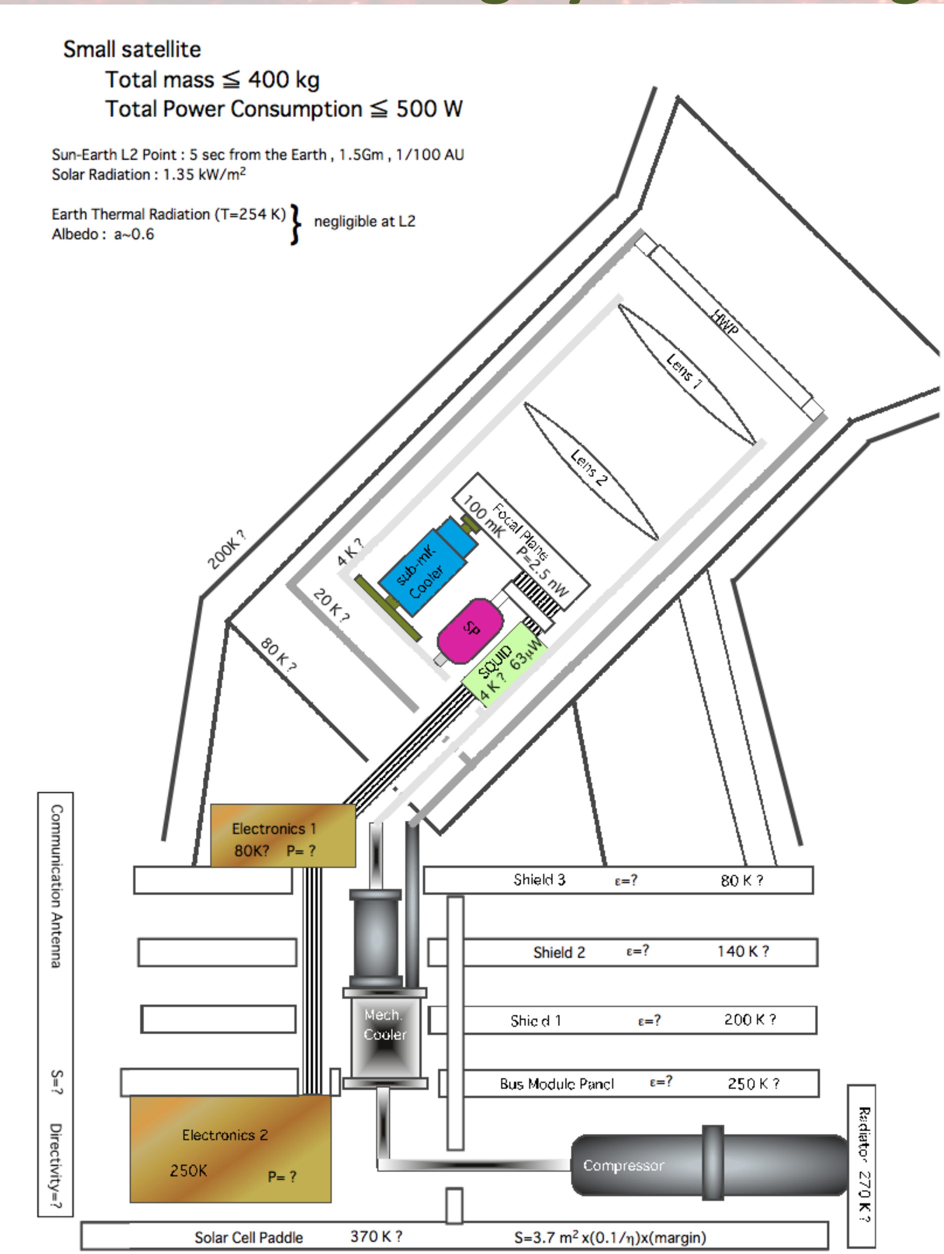




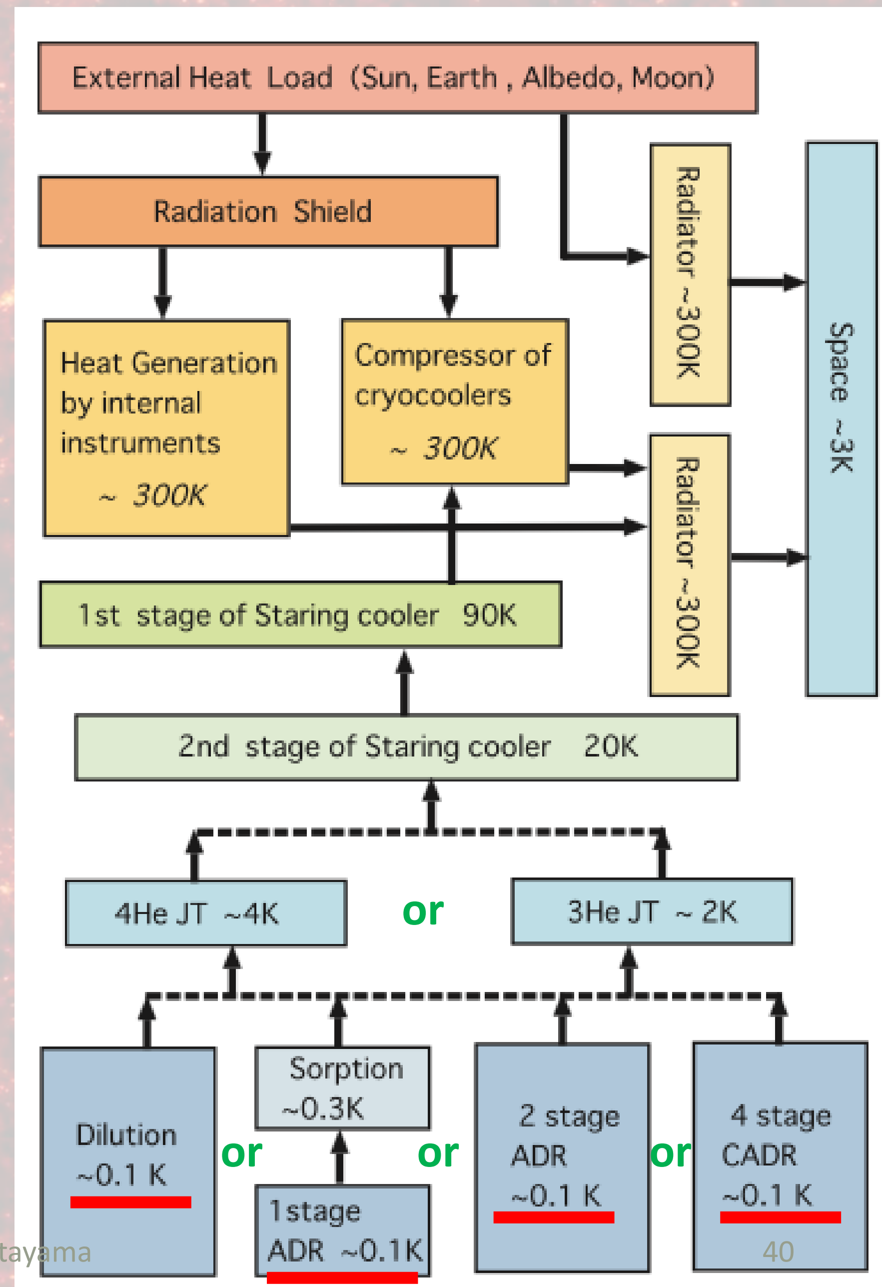




LiteBird Cooling system design

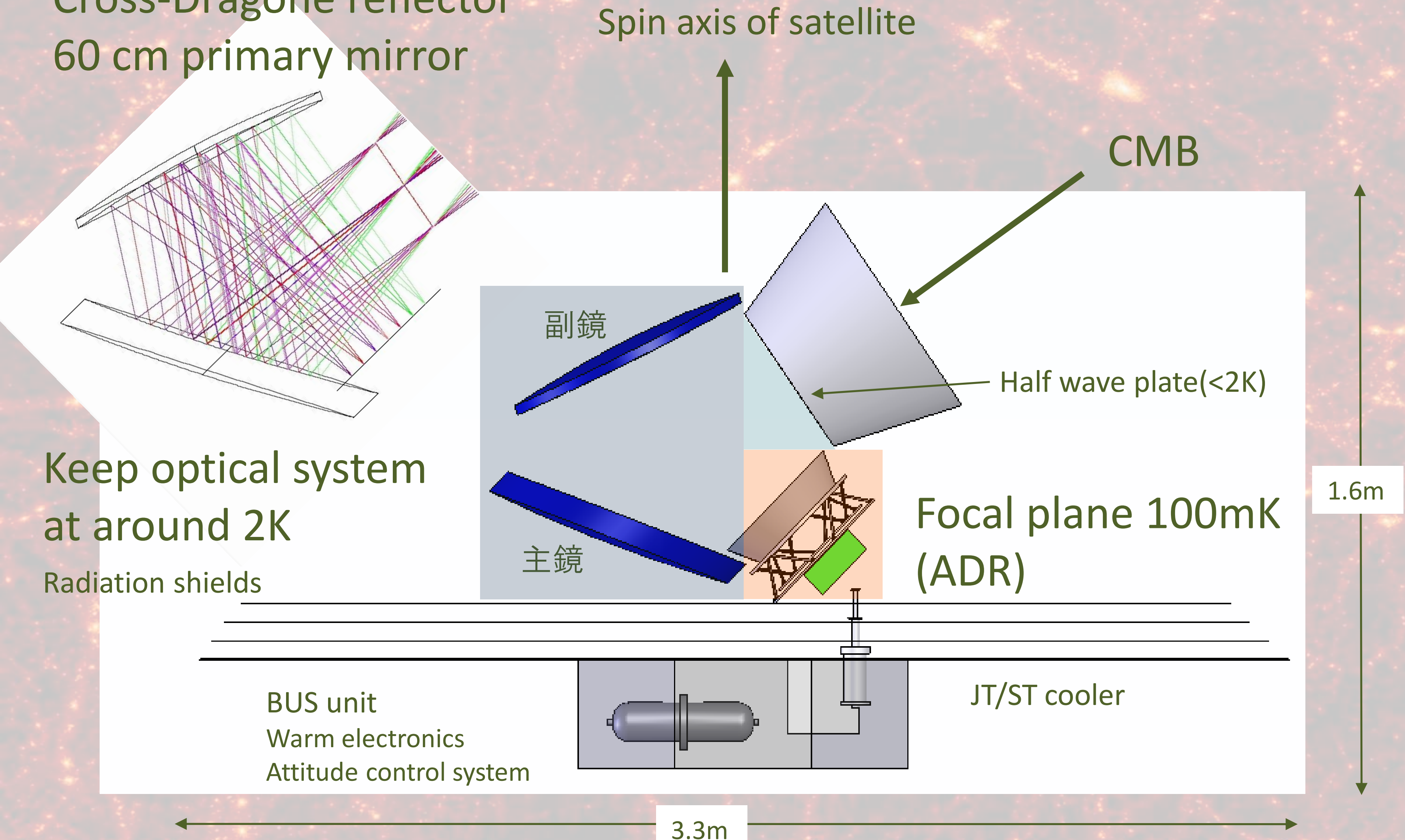


Cooling system diagram and heat flow



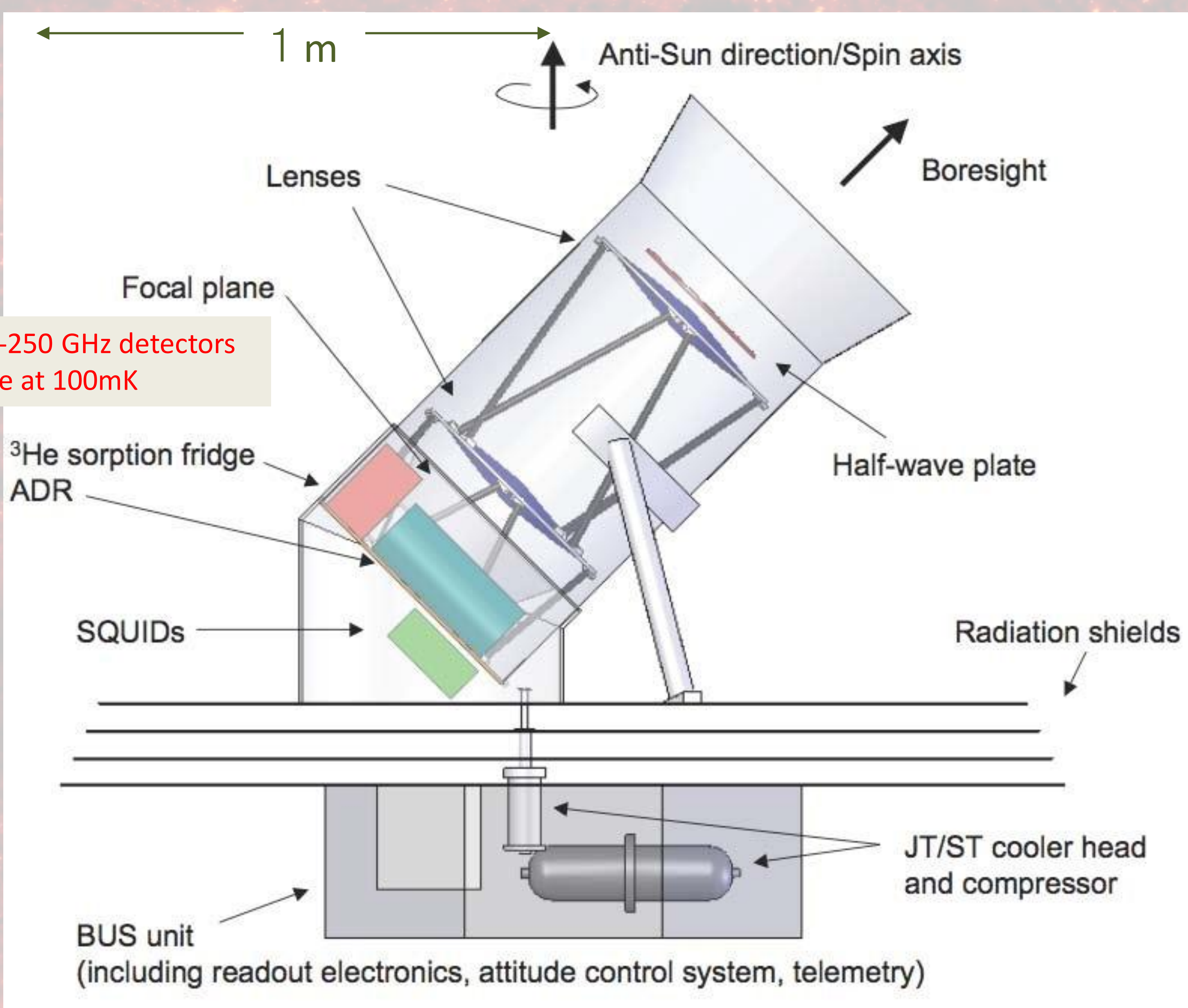
Optics design: Reflective optics

Cross-Dragone reflector
60 cm primary mirror



Keep optical system
at around 2K

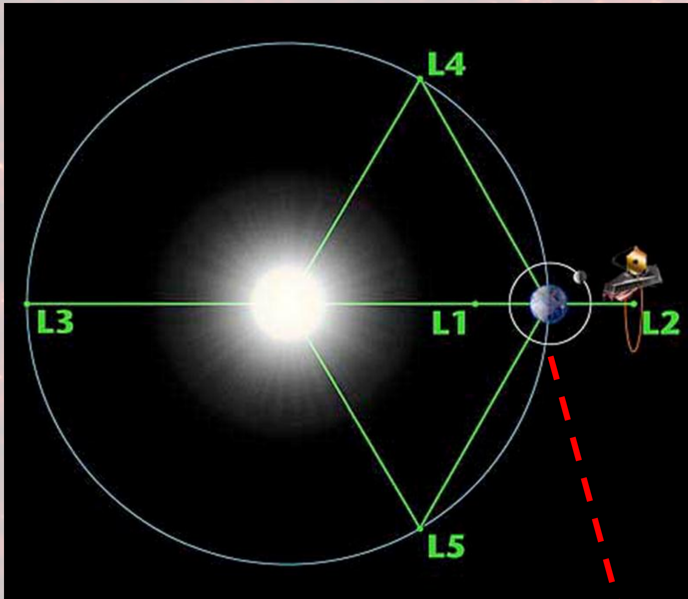
Overall satellite design: Refracting optics

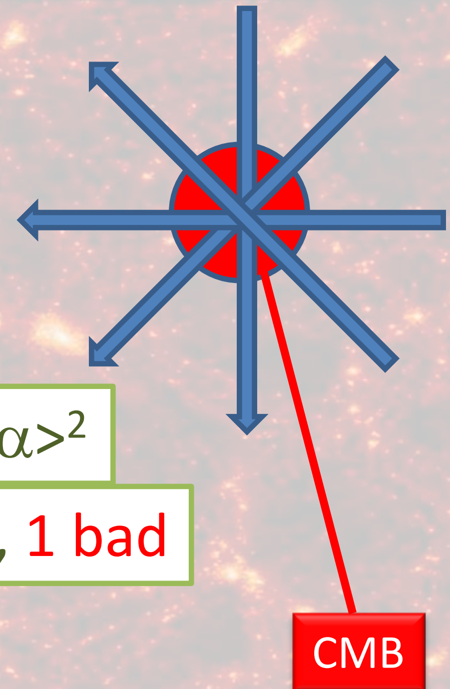


O(10^3) 60-250 GHz detectors
Focal plane at 100mK

Scan at L2

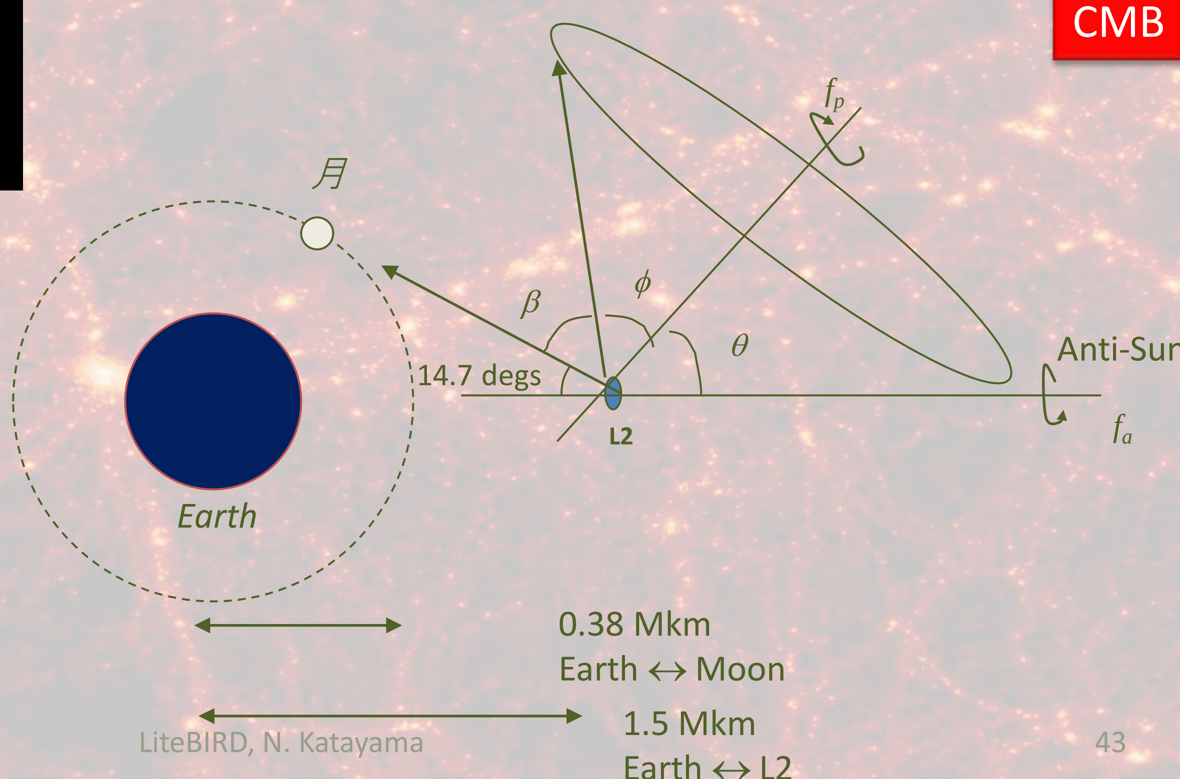
- We want to observe the full sky evenly
- We want to observe CMB pol. from all directions to reduce the systematic error





Crosslink:=$\langle \sin 2\alpha \rangle^2 + \langle \cos 2\alpha \rangle^2$

0 good, 1 bad

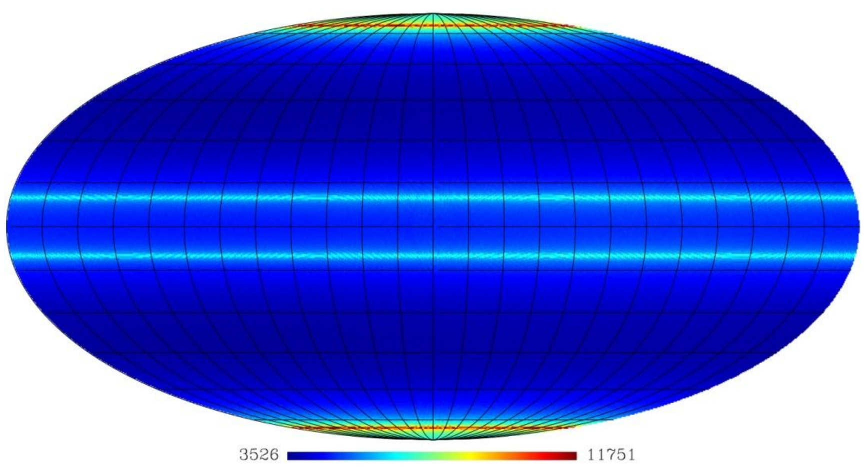


Better (stable) environment

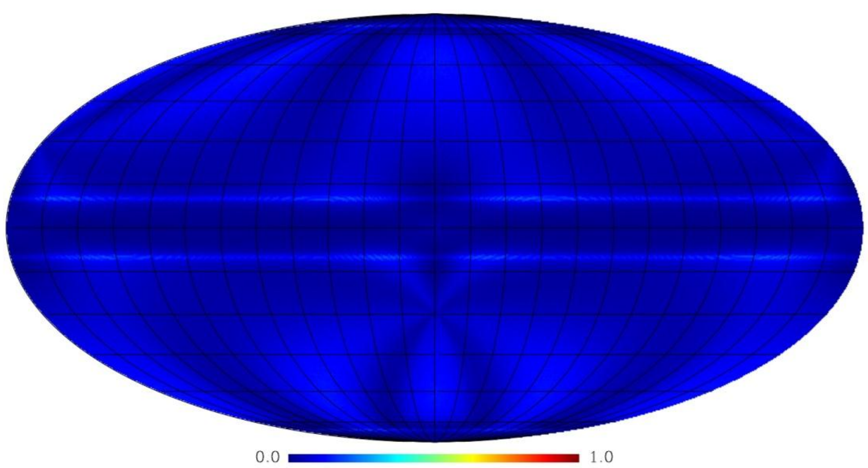
Sun, moon, earth can entirely be out of view

Scan at L2

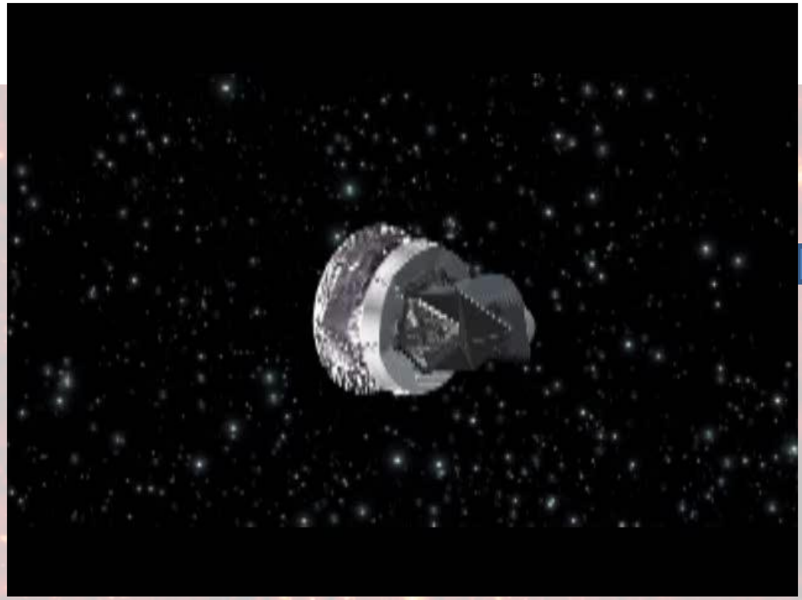
N_{obs}

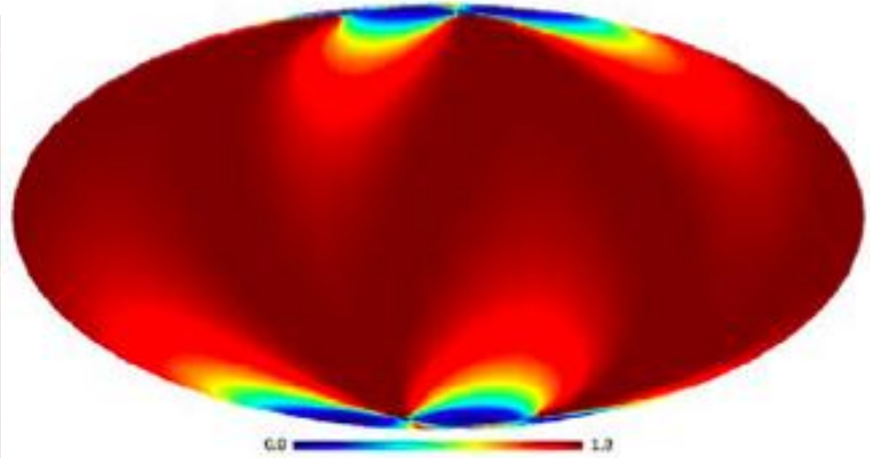


Cross link



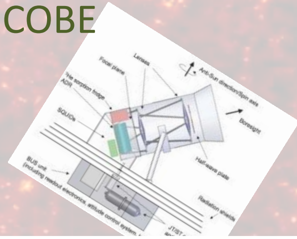
Planck's cross link

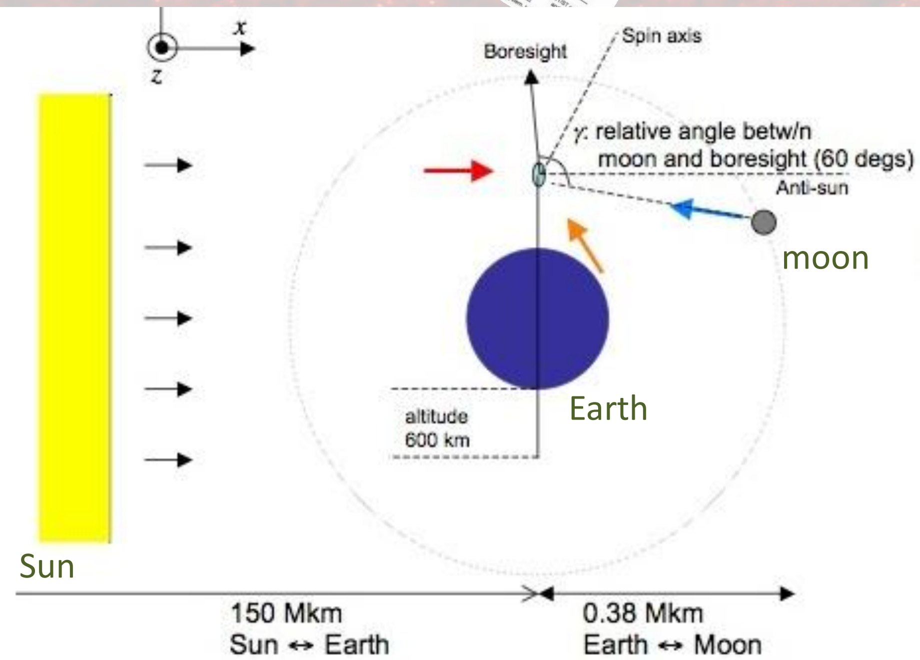


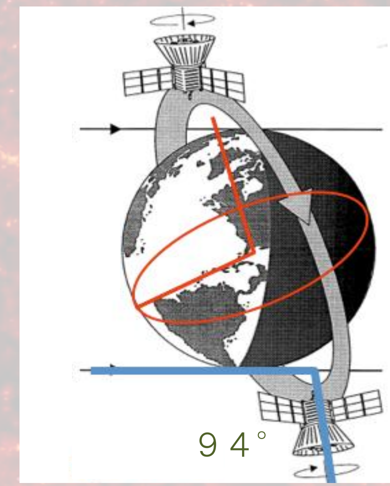


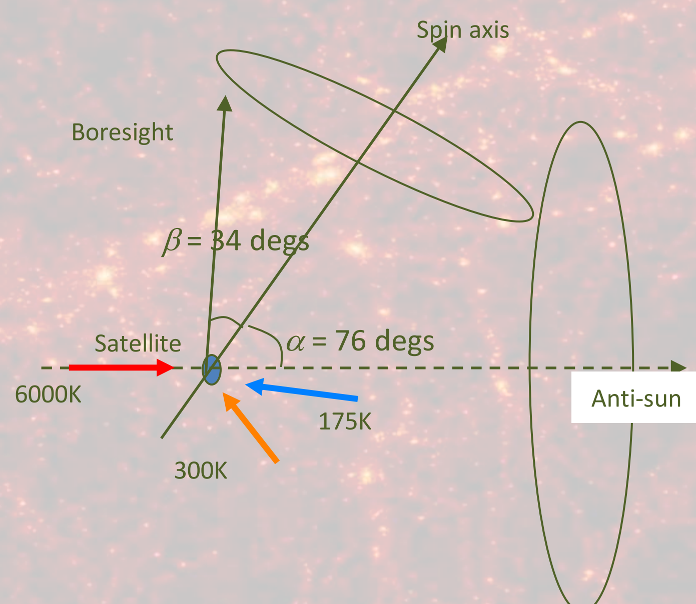
Low earth orbit

Scan for Orbit like COBE









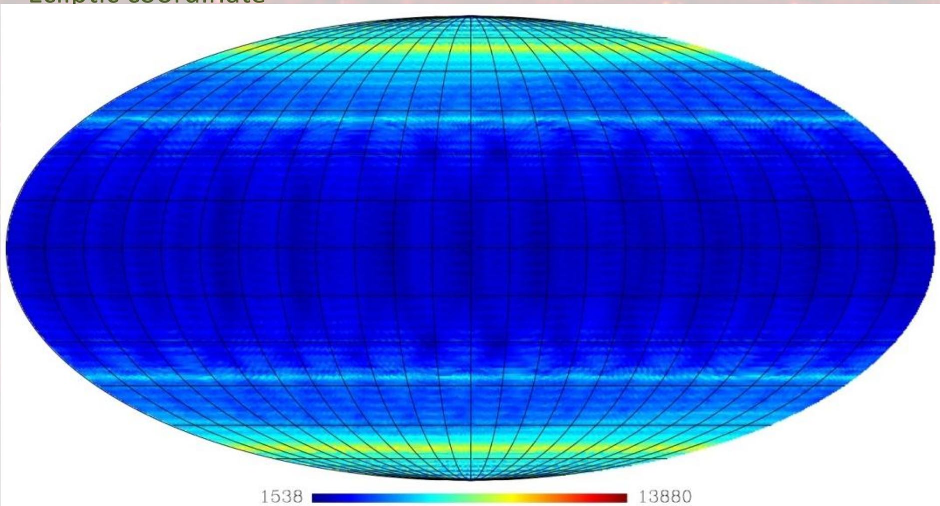
Low earth orbit

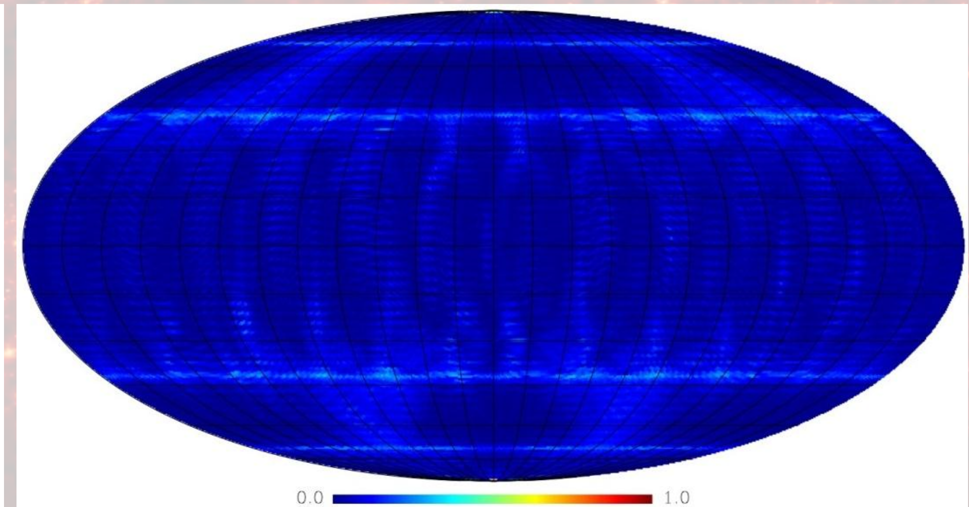
LEO scan ver1: 1 year

Ecliptic coordinate

Nhits

Angular Cross link

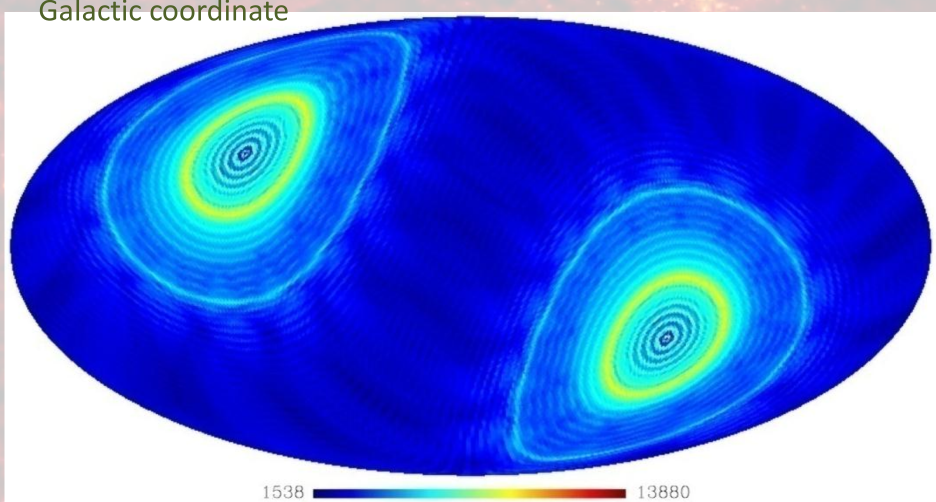


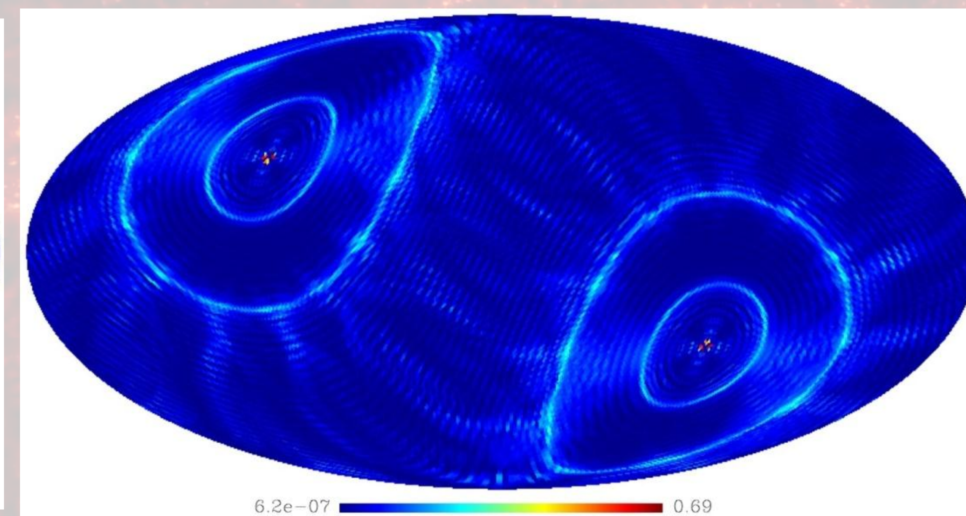


1538 13880

0 1

Galactic coordinate





1538 13880

6e-7 .69

Summary

- LiteBIRD is a small satellite dedicated to detect CMB B mode polarization originated from primordial gravitational wave
  - We are hoping to launch in 2018-2020
  - Basic detector technologies have become matured
  - STJ/MKID/Cooling system actively being developed
- Simple simulation study has begun
  - It looks promising
  - Very important for optimization of the conceptual design of the satellite

LiteBIRD Specifications

Item	Specification
Lifetime	> 2 years (5 years for the mission part)
Orbit	Sun-Earth L2, or near-earth sun-synchronous orbit
Attitude control	< 5 arcmin (i.e. < 1/10 x beamsize)
Telemetry	2Mbps
Weight	Mission part < 200kg, total < 400kg
Power	Mission part < 200W, total < 500W
Cooling	100mK w/ SPICA-type JT+starling (+ He3 sorption) + ADR
Focal plane	Superconducting detector (TES, STJ or MKID)
Sensitivity	Total NET < 1μK$\sqrt{s}$
Frequencies	90GHz and 150GHz with a sufficient number of pixels and angular resolution (< 1 deg), + 45GHz + 300GHz as much as possible
Modulation	Satellite rotation + more modulation methods

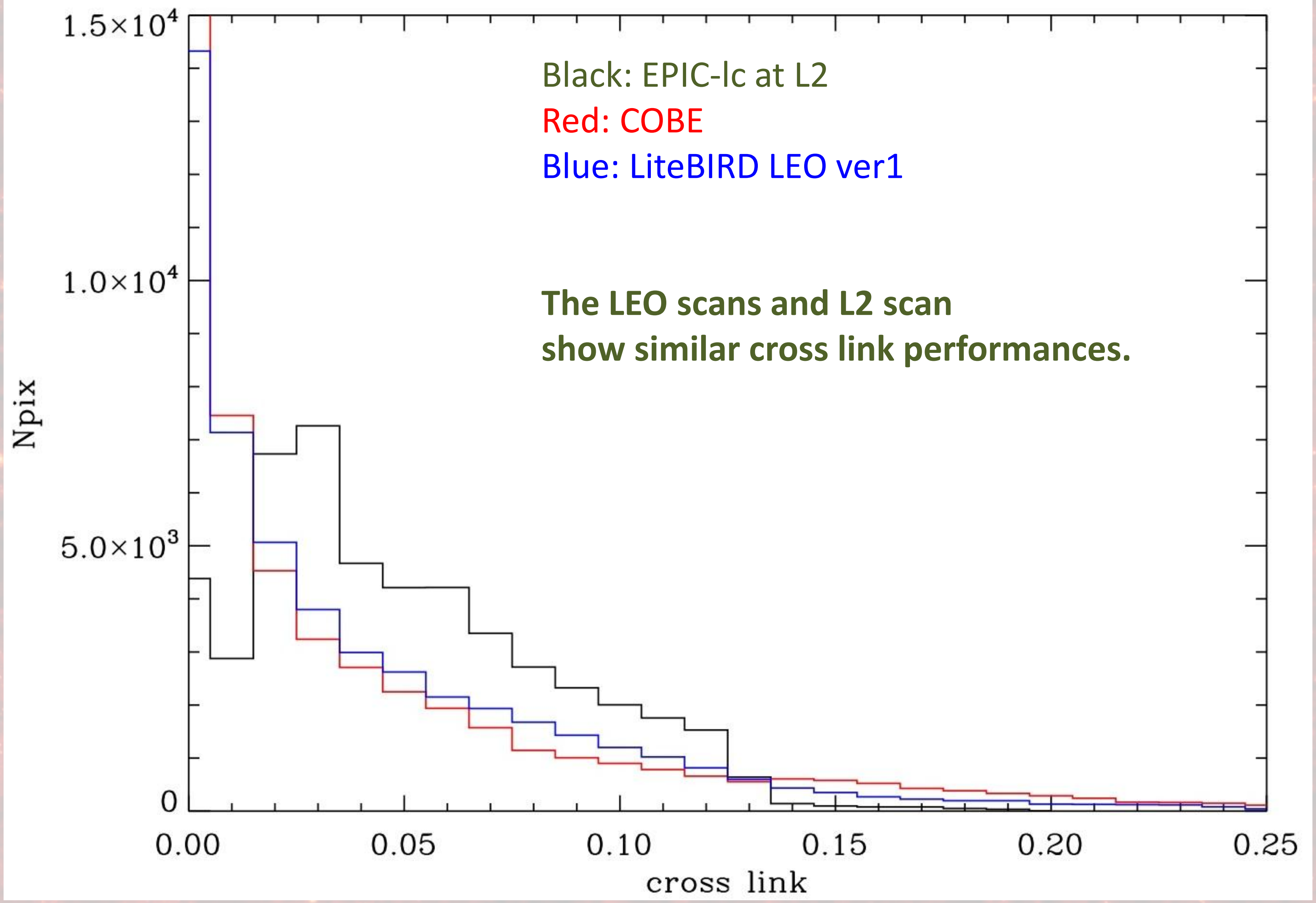
Power and weight guesstimation

Mission part	Weight(kg)	Power (W)
Focal plane (detector,optics)	60	
Mission part electronics (for detector)	20	100
Baffle,		
Cryo-h		
Sub-K		20
2K refr		160
Total for mission part	175	280
Bus part	**Weight(kg)**	**Power (W)**
Structure, thermal control, etc.	50	30
Solar panel, electronics	30	20
Data acquisition, telemetry	20	60
Attitude control (AC)	50	100
Total for bus part	150	210
Total (mission + bus)	**325**	**490**

Requirements for small satellite

~400Kg/500W

Comparison of cross link



Sampling rate and telemetry

L2

Sampling rate

Freq [GHz]	Beam [arcmin]	N_{det} [#]	t_{req} [ms]	sample rate [Hz]	data rate [kbps]
60	77	400	14	92	147.2
100	46	600	8	154	369.6
250	19	200	3	384	307.2
total		1200			824

4 bit/bolometer; data compression at the same rate as Planck
2 × Nyquist sampling spin rate 6 rpm
1/fknee ～ 100 mHz (TES bolometer assumed)

✓L2
6 hours/day down link possible
X band 4 Mbps; detector data rate < 1 Mbps

✓LEO
40 min./day/Tracking station
Using two stations,
datarate < 10 Mbps × 2 × 40/(60 × 24) = 0.56 Mbps