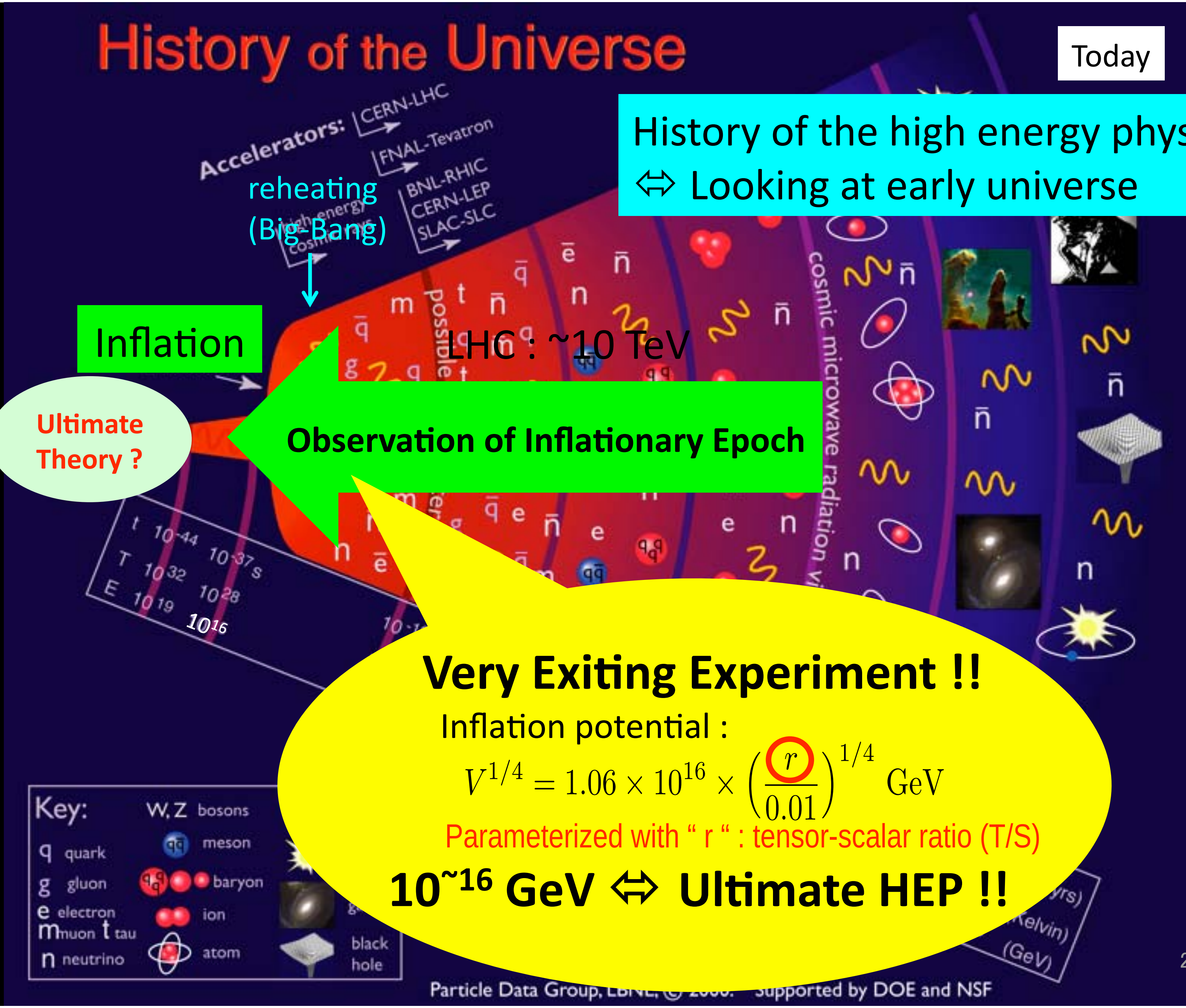
Ultimate High Energy Physics

Quest for signal from inflationary universe
- precise measurement of CMB polarization

QUIET collaboration photo
Jun. 2009 at Fermilab

Osamu Tajima (KEK)



Today

History of the high energy physics
⇔ Looking at early universe

reheating
(Big-Bang)

Inflation

Ultimate Theory ?

LHC : ~10 TeV

10^{16}

Observation of Inflationary Epoch

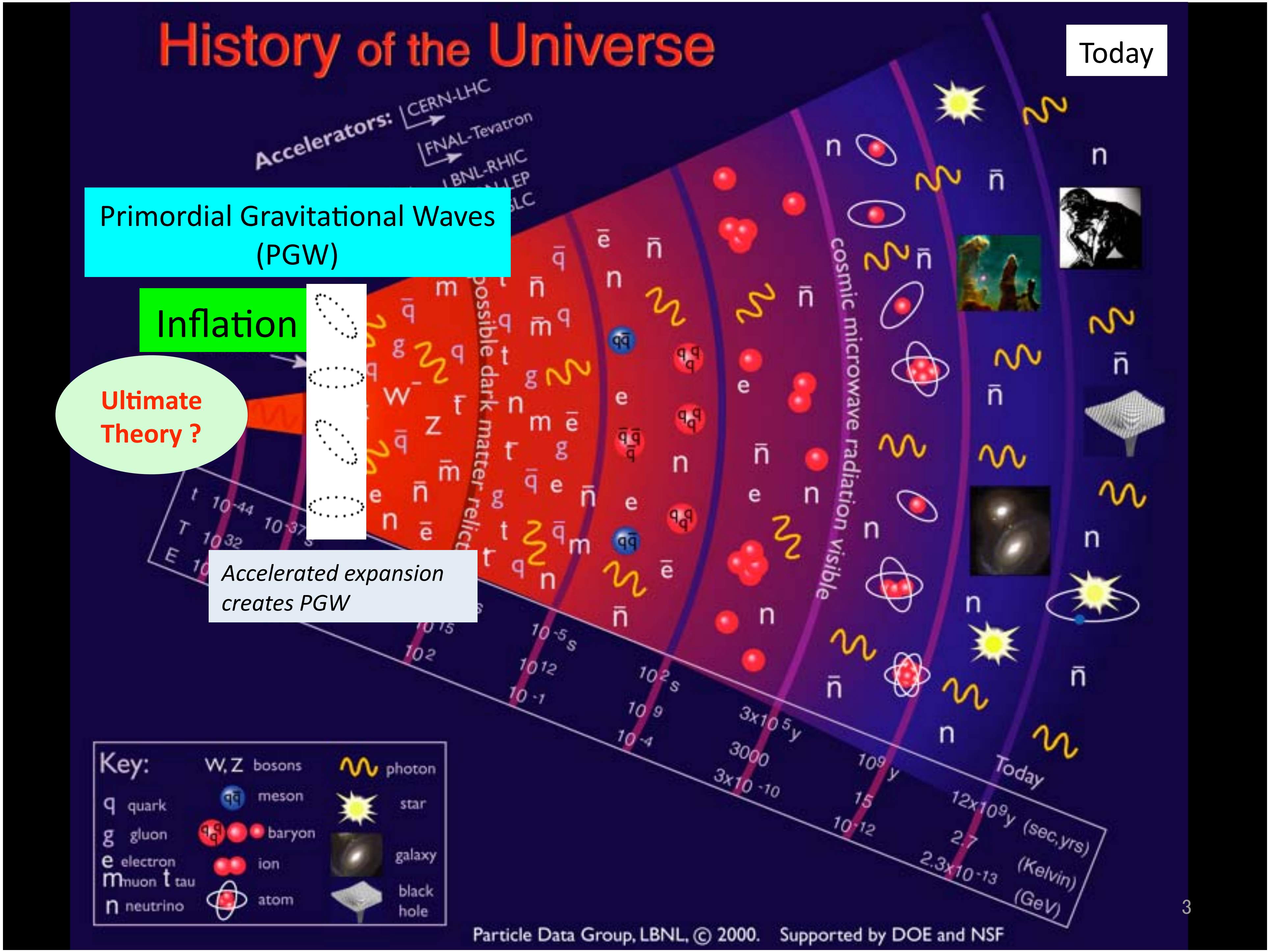
Very Exiting Experiment !!

Inflation potential :

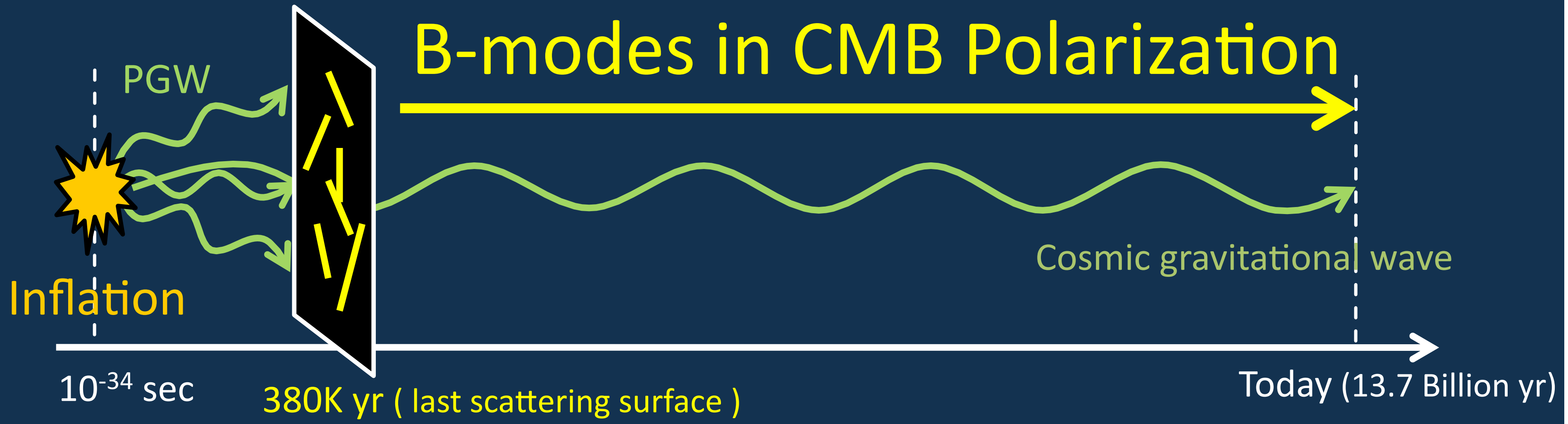
$$V^{1/4} = 1.06 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} \text{ GeV}$$

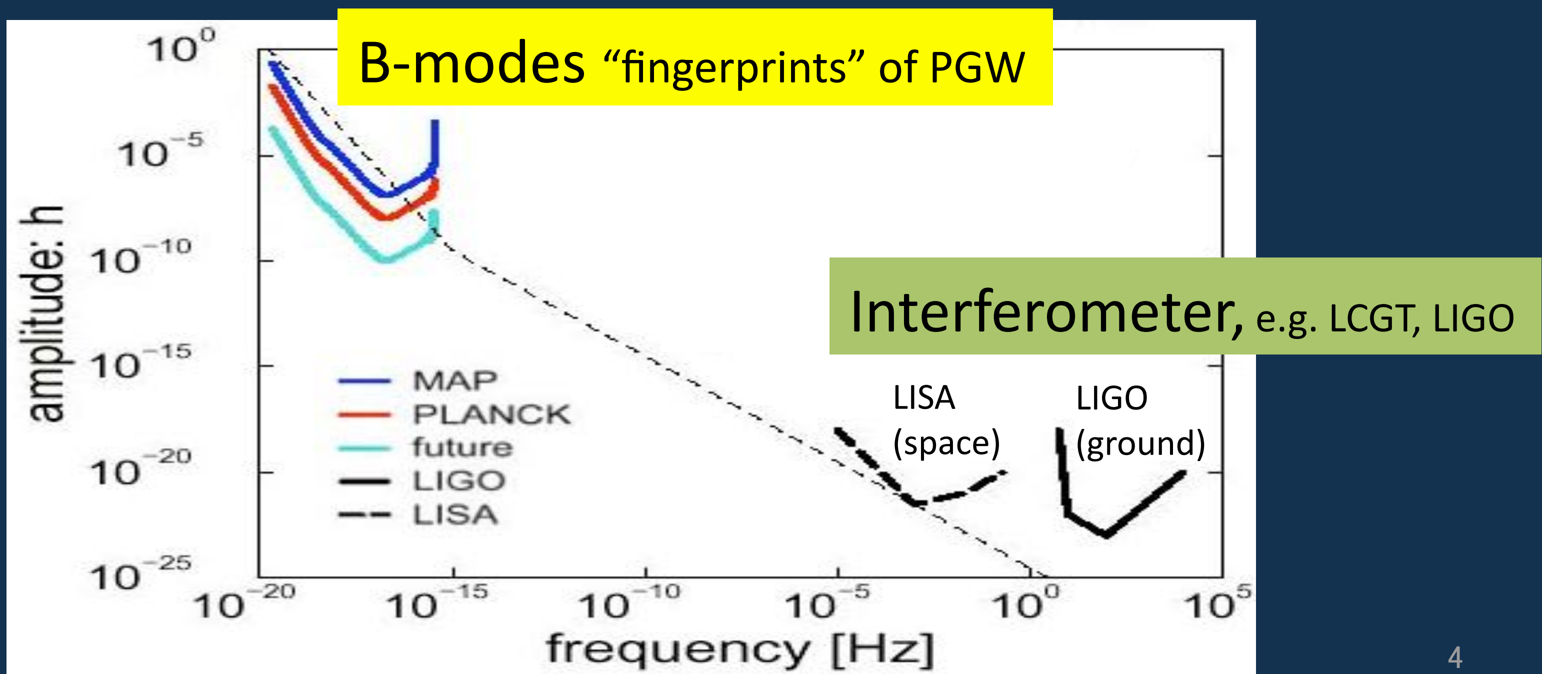
Parameterized with " r " : tensor-scalar ratio (T/S)

$10^{\sim 16}$ GeV ⇔ Ultimate HEP !!


History of the Universe
Today
Accelerators: CERN-LHC
FNAL-Tevatron
BNL-RHIC
Primordial Gravitational Waves (PGW)
Inflation
Ultimate Theory ?
Accelerated expansion creates PGW
possible dark matter relics
cosmic microwave radiation visible
t 10^-44
T 10^32
10^-37 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
galaxy
e electron
ion
m muon t tau
n neutrino
atom
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

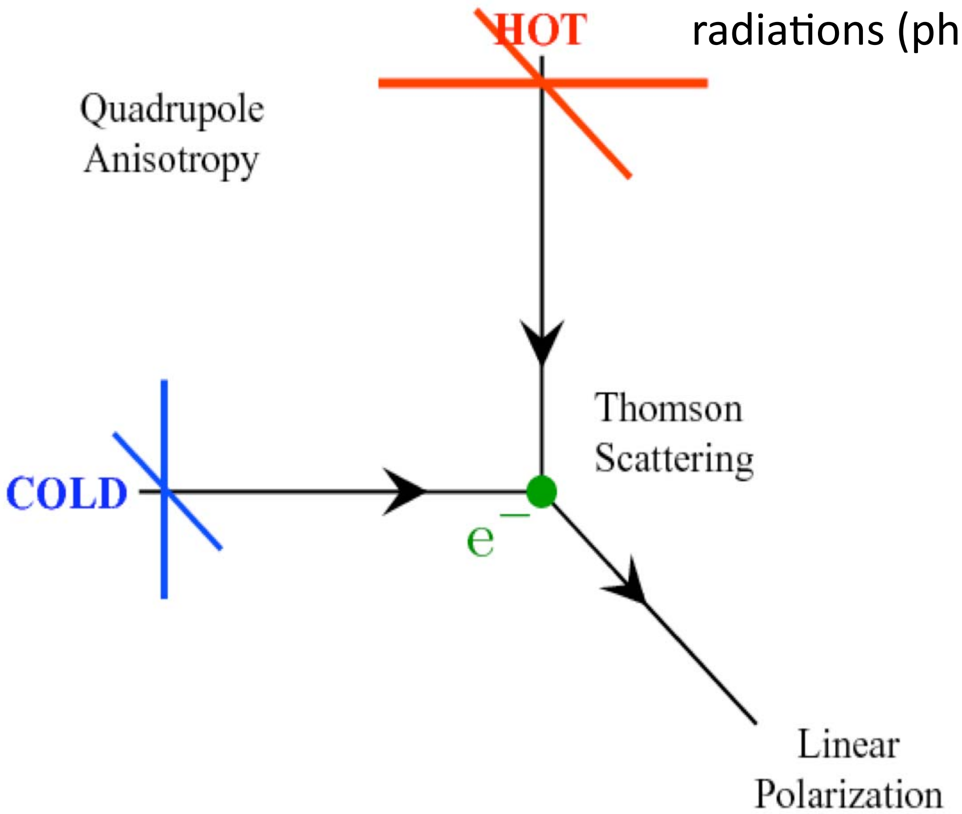
Two approaches for PGW observation





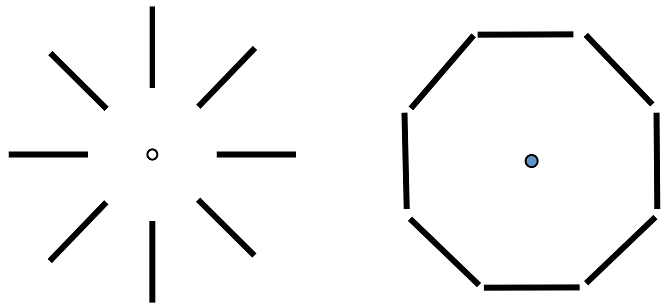
No PGW, E-modes only

At the early stage of universe,
radiations (photons) were scattered by free electrons



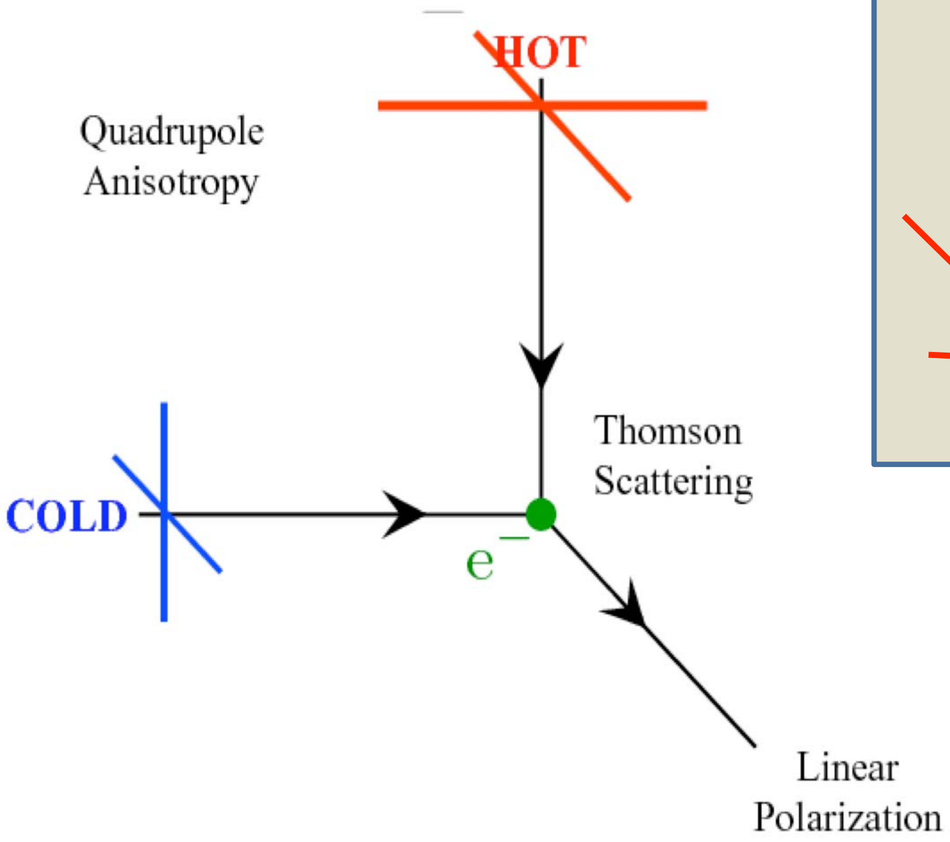
Anisotropy of universe
(scalar perturbation ~0.001%)
→ Parity even polarization pattern

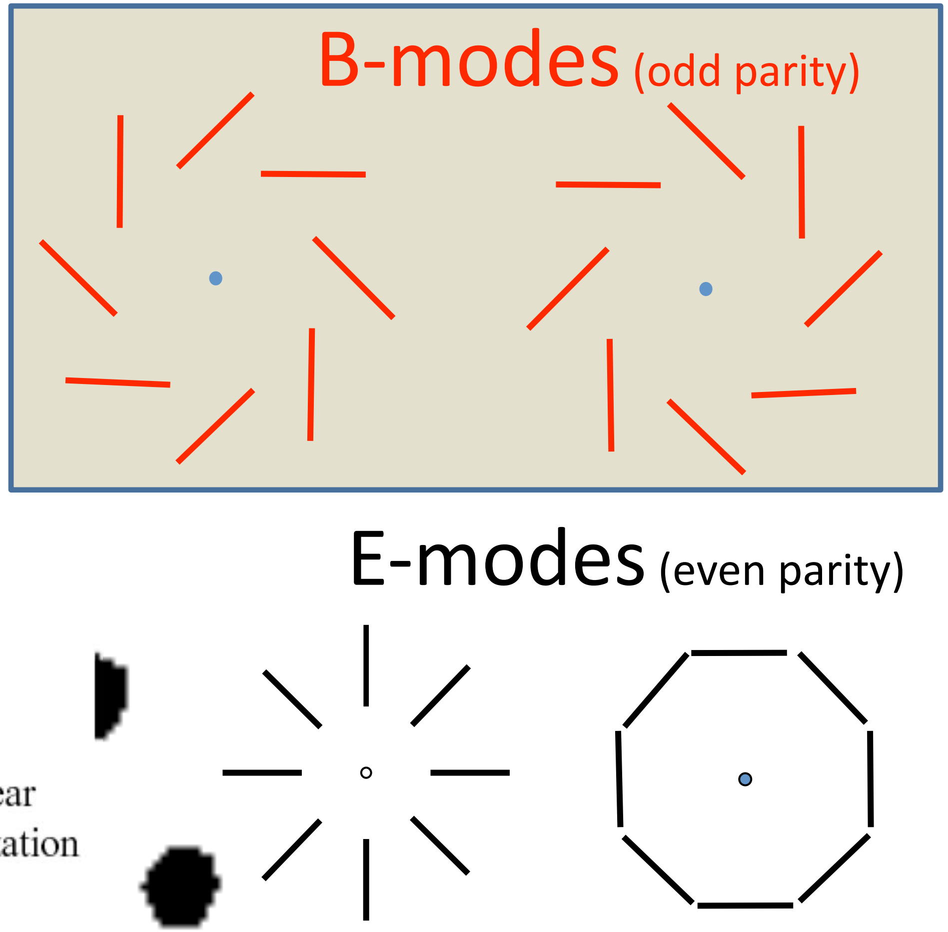
E-modes (even parity)



With PGW, B-modes and E-modes

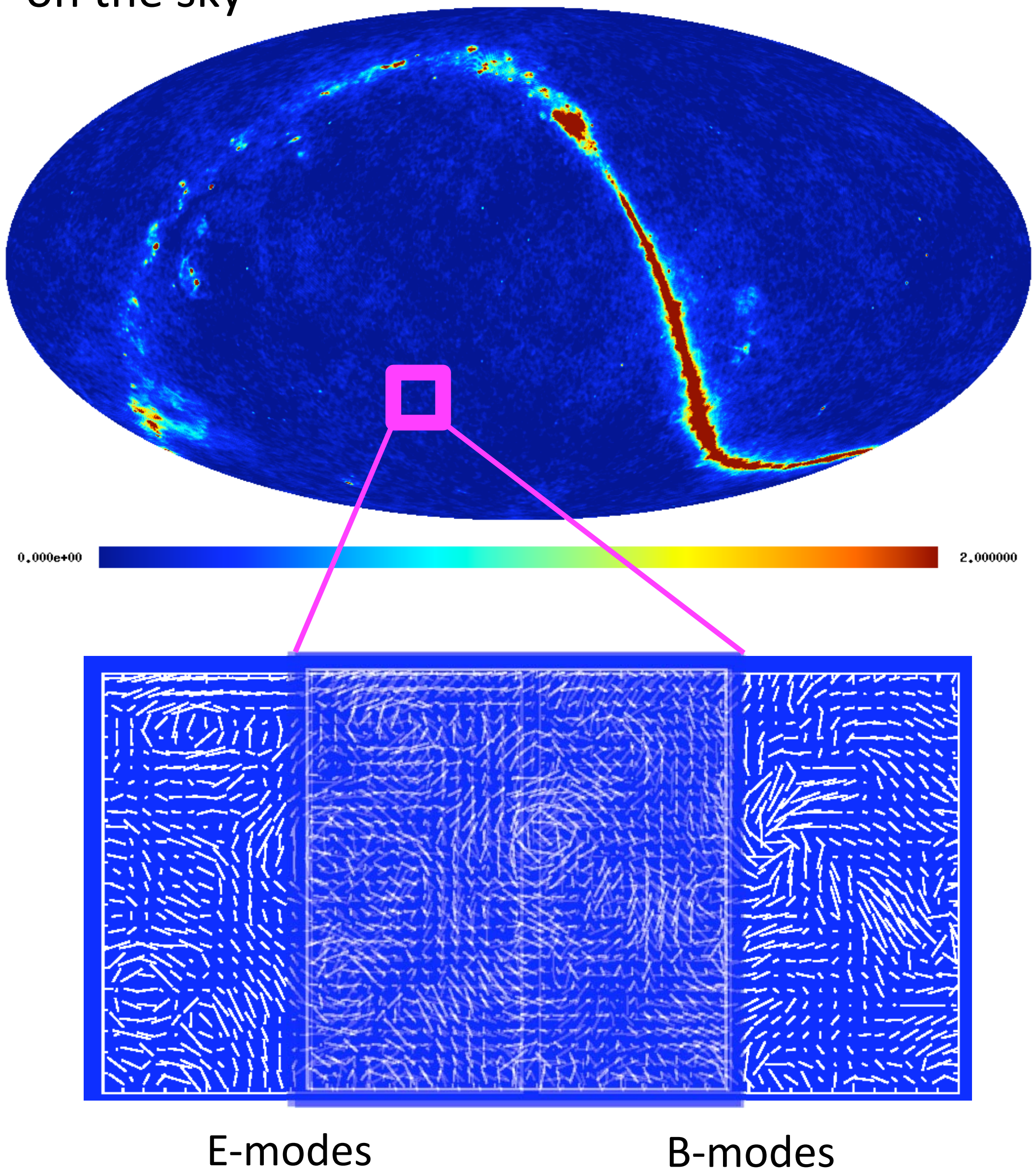
B-modes: Smoking gun signal of PGW





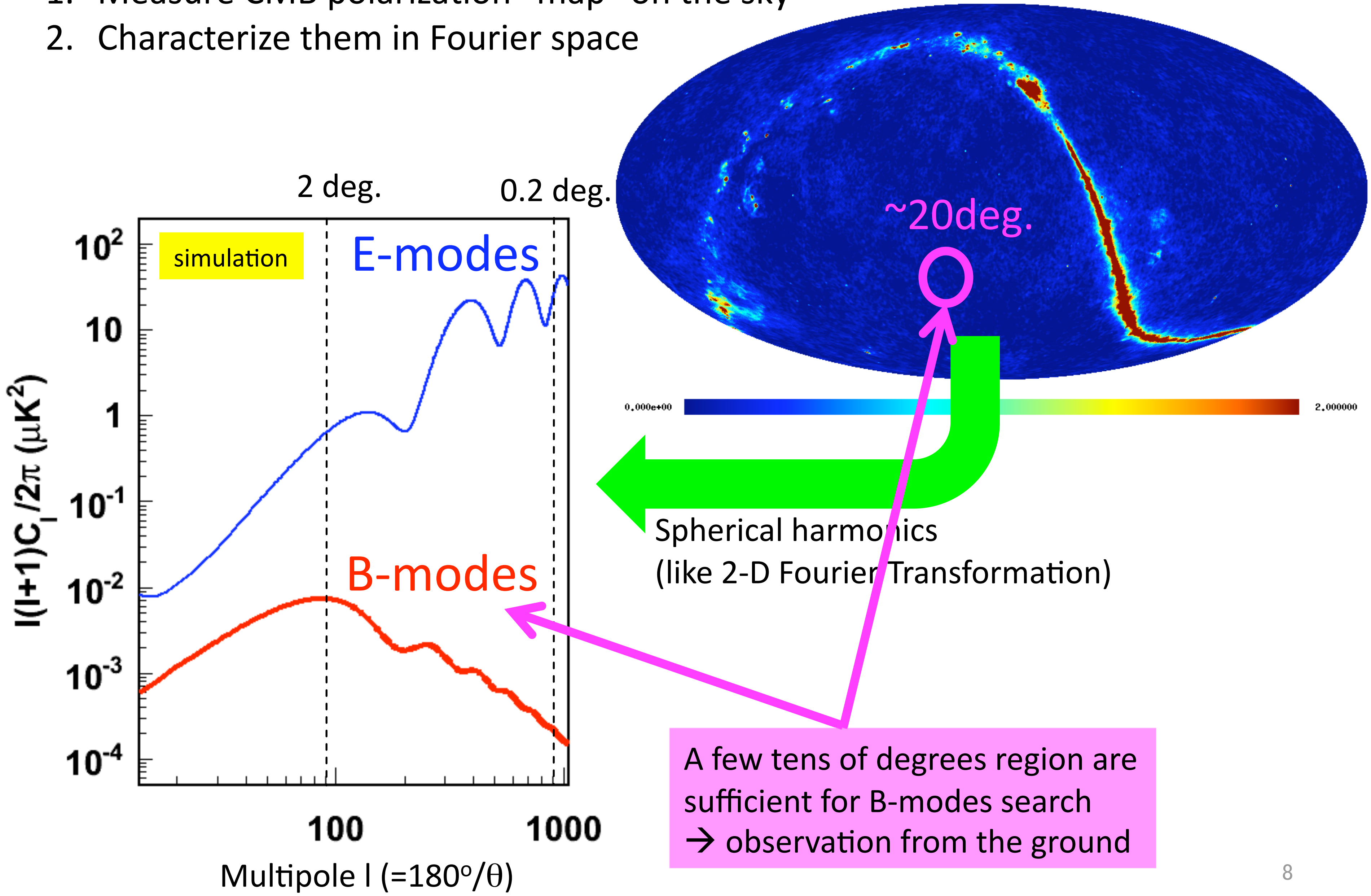
Since B-modes are patterns in CMB polarization, experimental approach is;

1. Measure CMB polarization "map" on the sky



Since B-modes are patterns in CMB polarization, experimental approach is;

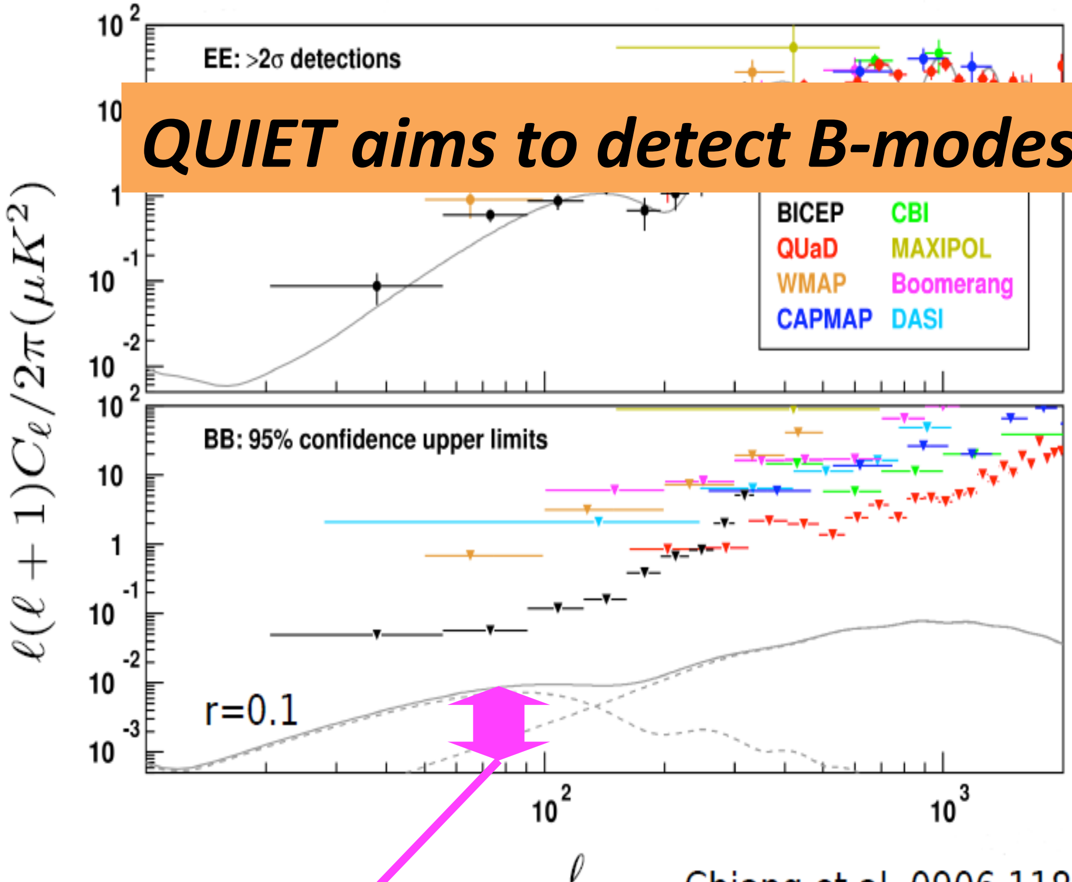
1. Measure CMB polarization "map" on the sky
2. Characterize them in Fourier space



Experimental results at present

Currently, ground base experiments lead this competition
Because they can use cutting edge polarization detectors

QUIET aims to detect B-modes from ground !



Chiang et al, 0906.1181

Smoking gun signal of PGW

B-modes
(U.L. 95%CL)

Direct bound
r < 0.7 (BICEP)

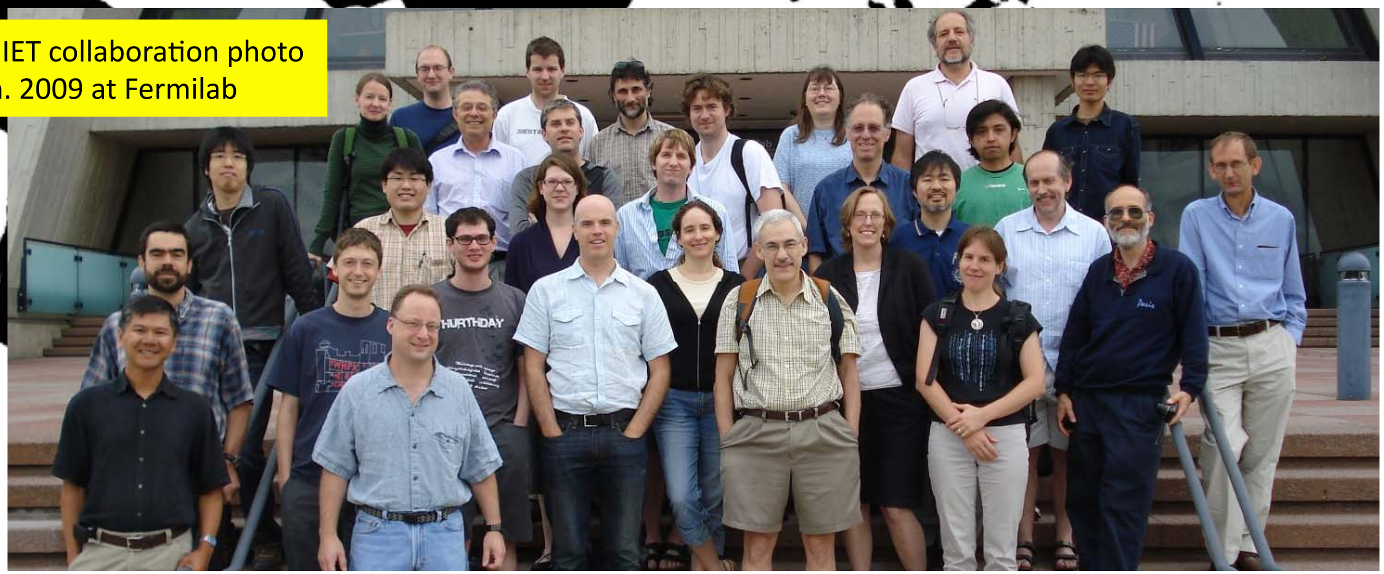
Regions favored by many inflationary models r = 0.01 ~ 0.1

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

Parameterized with " r " : tensor-scalar ratio (T/S)

The QUIET Collaboration

5 countries, 14 institutes, ~35 scientists



QUIET collaboration photo
Jun. 2009 at Fermilab

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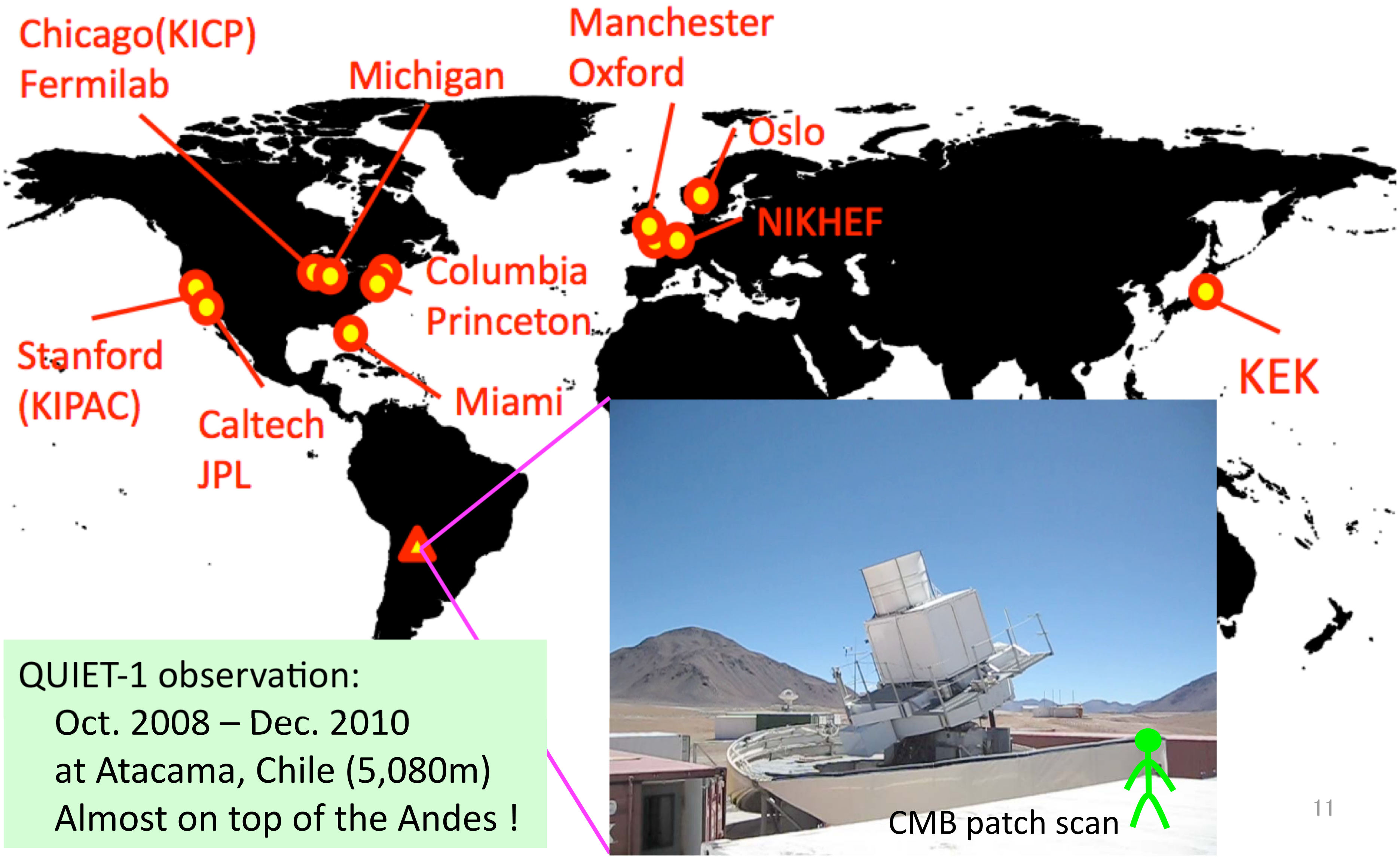
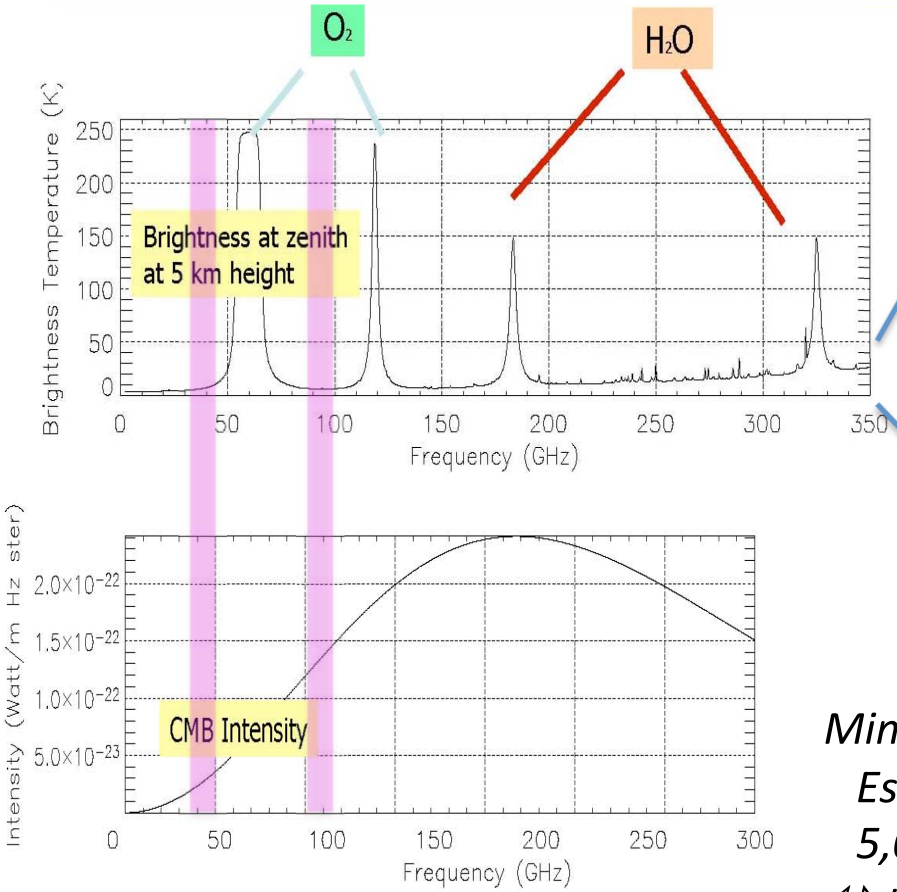


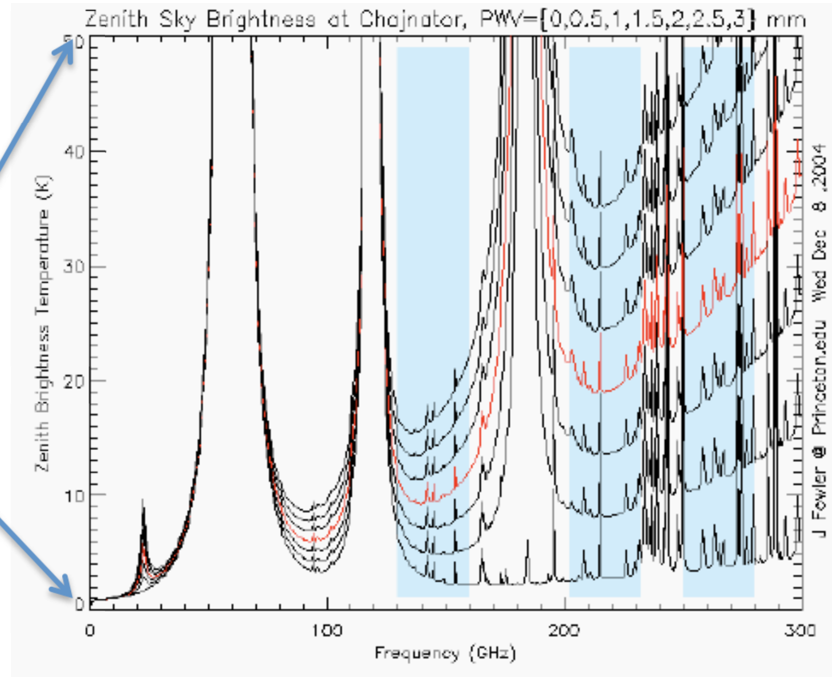
QUIET-1 observation:
- Oct. 2008 – Dec. 2010
- at Atacama, Chile (5,080m)
- Almost on top of the Andes !

QUIET observation site

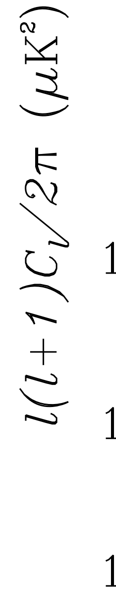

Above the forest line.
NO grass, NO green at all

Why are we observing at 5,000m ?





Minimizing the atmosphere emission
Especially, Oxygen and water vapor
5,000m
⇔ *thickness of atmosphere is ~1/2 of the sea level*

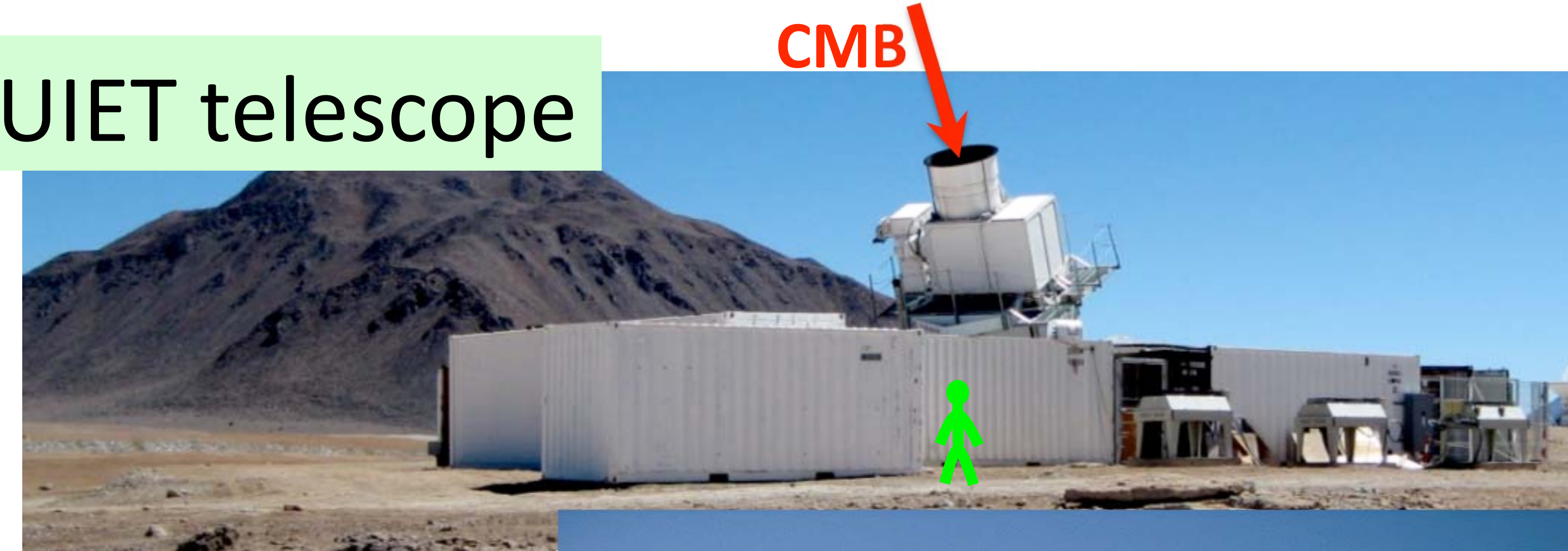


Atacama plateau is the best place to observing CMB from the ground
43GH, 95GHz, 150GHz, and 220GHz are major frequency bands
(QUIET has 43GHz and 95GHz bands)


You could imagine
"Looking at the Universe, directly !"

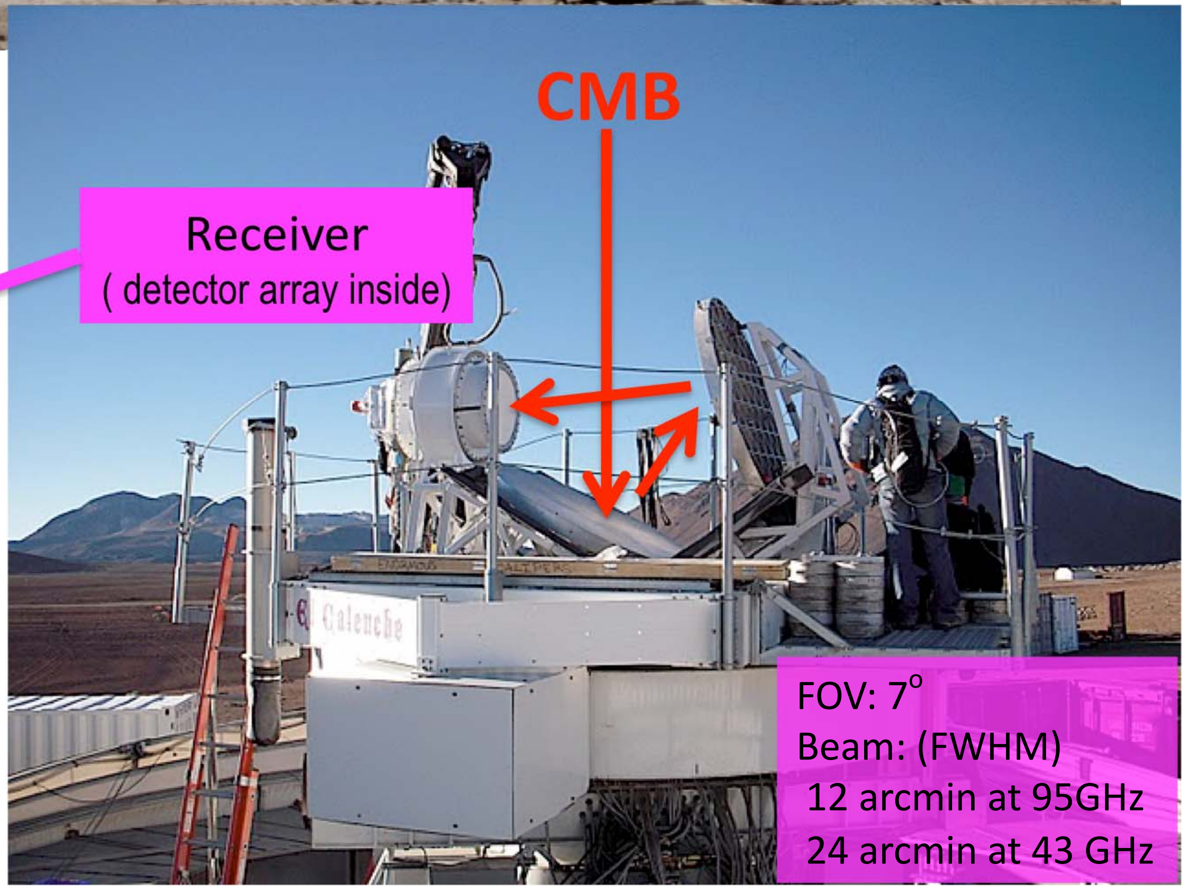
Beautiful Sky at 5,080m

QUIET telescope



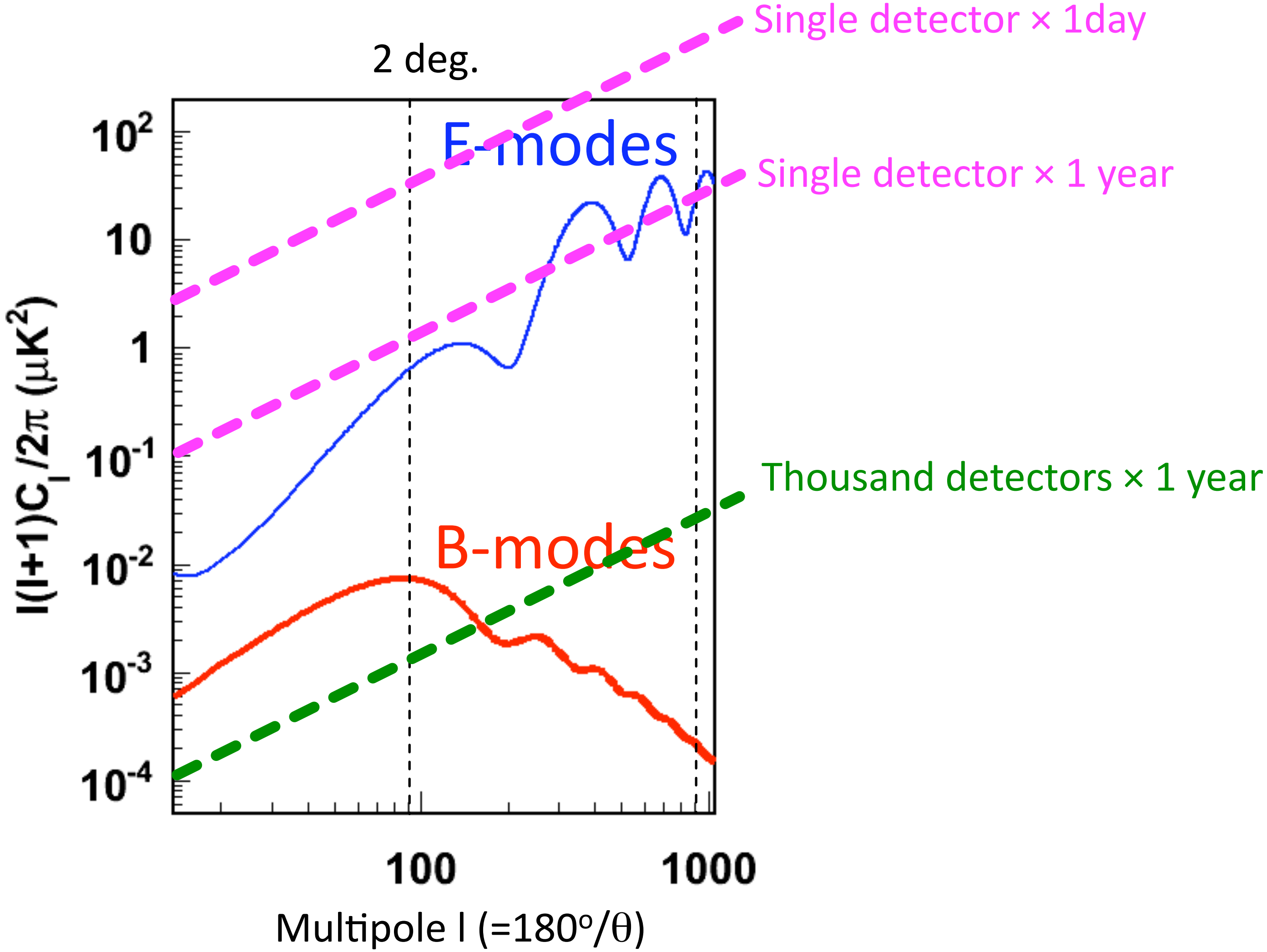
QUIET polarization detector
90 detectors array at 95 GHz

~30cm



“Detector Array” is essential

Single detector sensitivity is limited by finite photon statistics of the CMB itself as well as noise from atmospheric emission



Large number of detectors

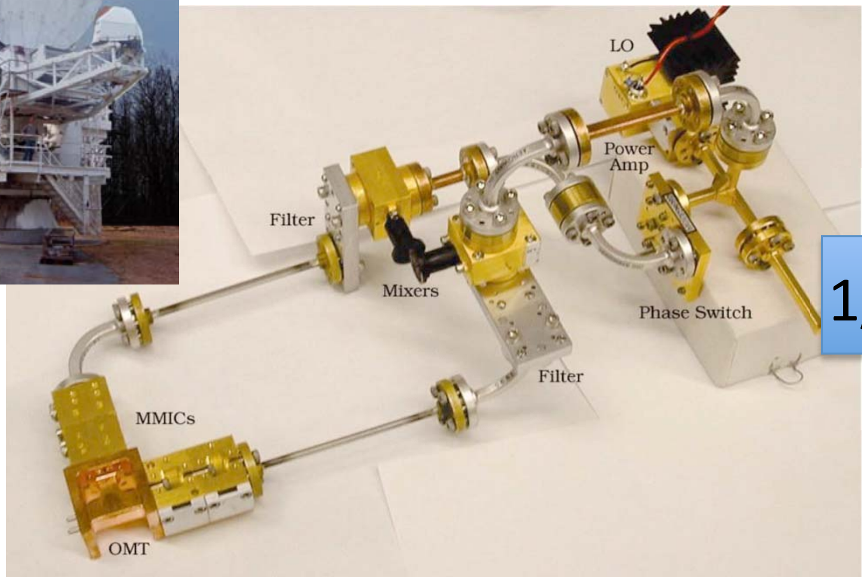
"Detector Array" is essential

for all CMB-pol. experiments

Limitation of single detector sensitivity

Several hundreds ~ thousand detectors are necessary
to cover the model favored region: r ~ 0.01
⇔ QUIET-1 is intermediated phase to proof of technology

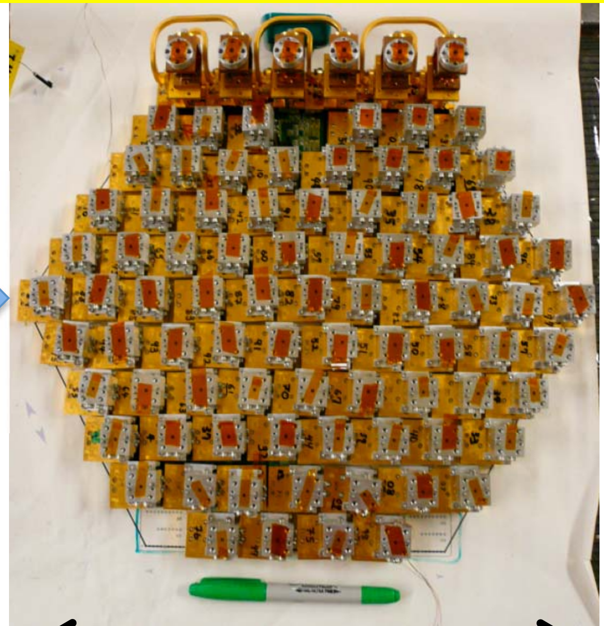
CAPMAP (2003-2005)
Pol. detector at 95GHz



~30cm

1/10 size

QUIET-1 (2008-2010)
90 detectors array at 95 GHz



~30cm

Principle of “polarization” measurements

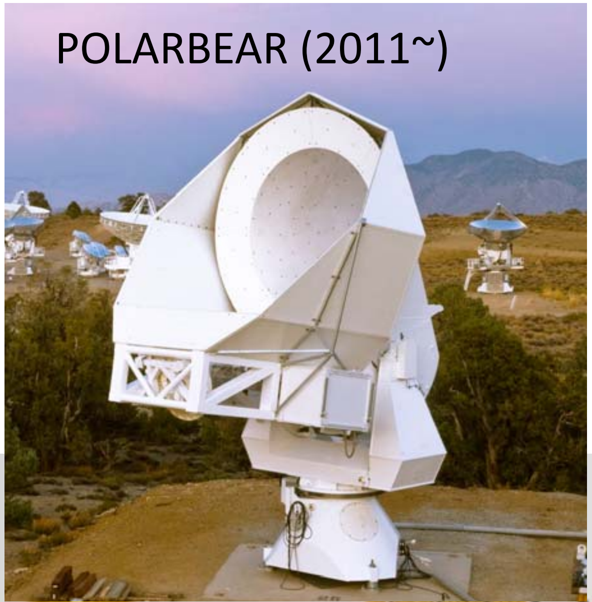
The simplest approach : Antenna-coupled bolometers

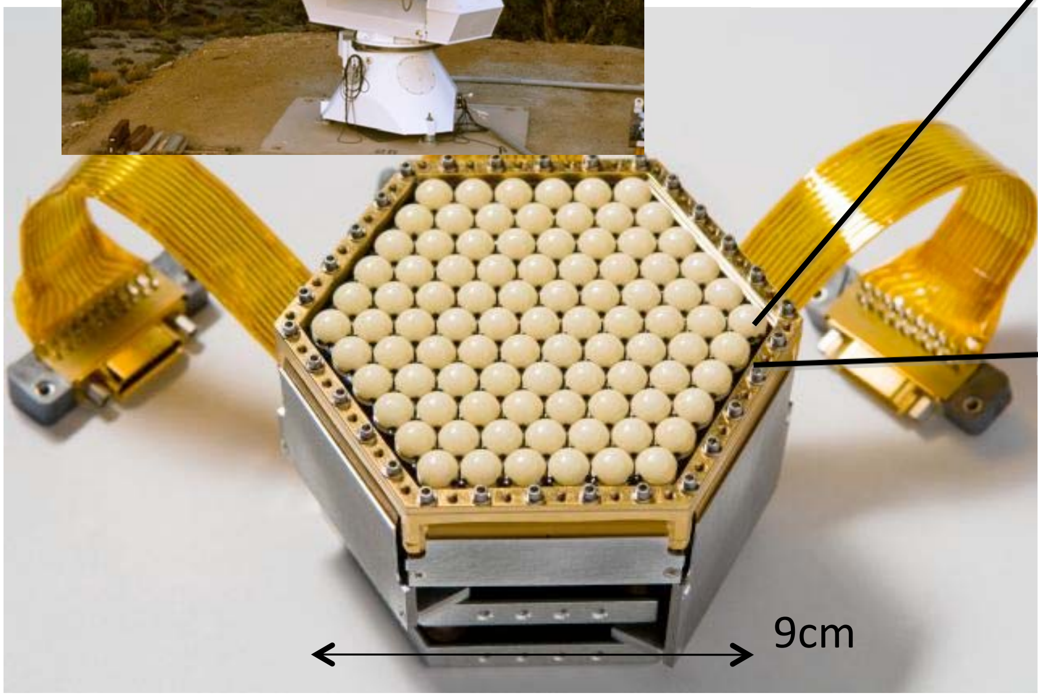
Detector response for Stokes Q & U

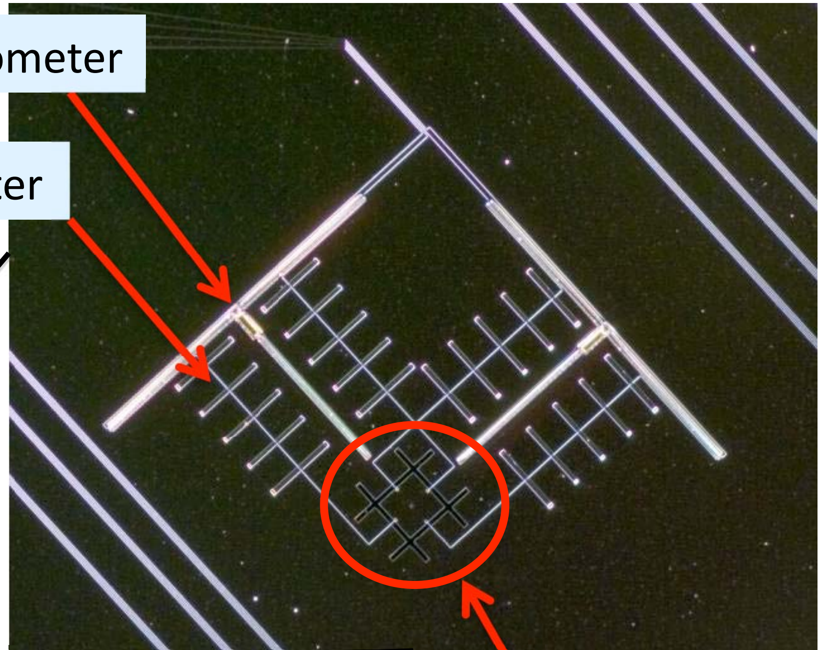
$Q \propto T_x G_x - T_y G_y$

$(U \propto T_a G_a - T_b G_b)$

G_k (k=x,y, a,b) are detector responsivities

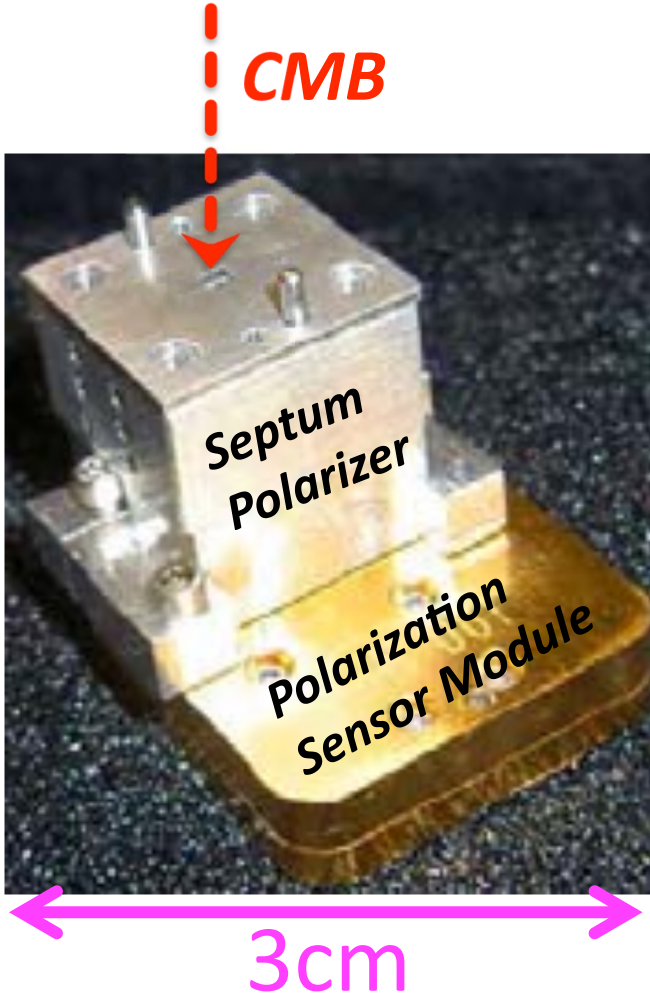




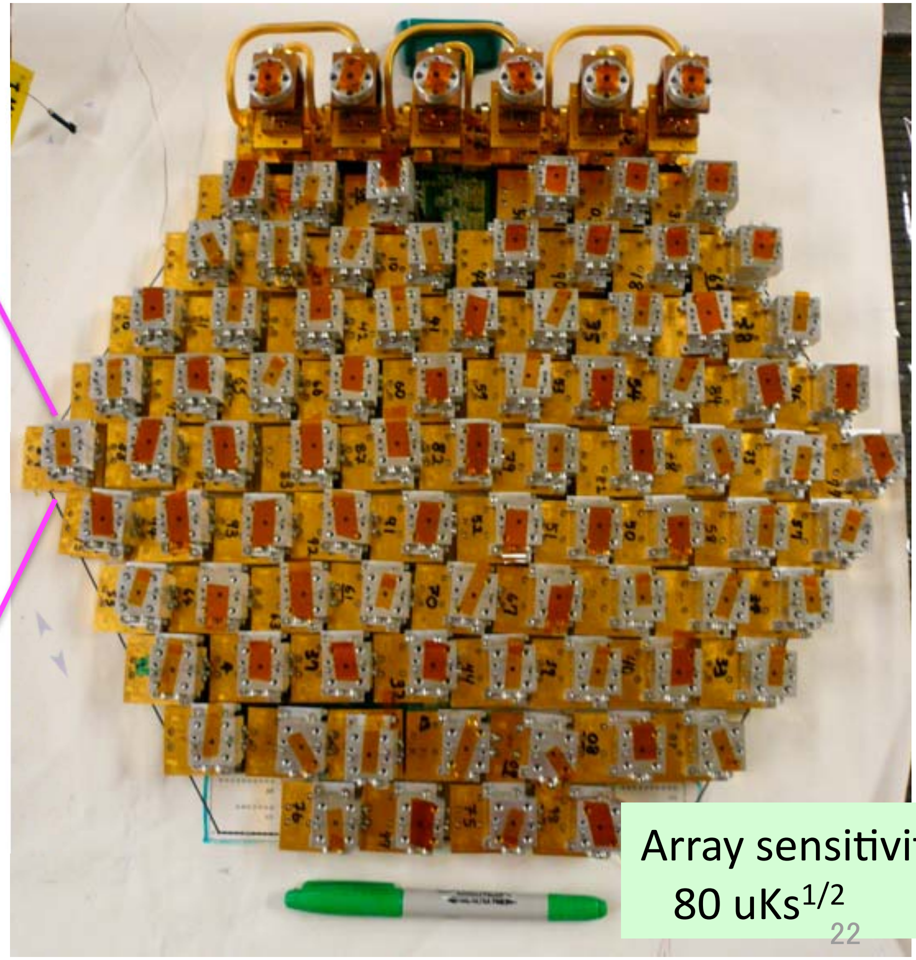


Robust detector against to the systematic biases

QUIET polarization detector array

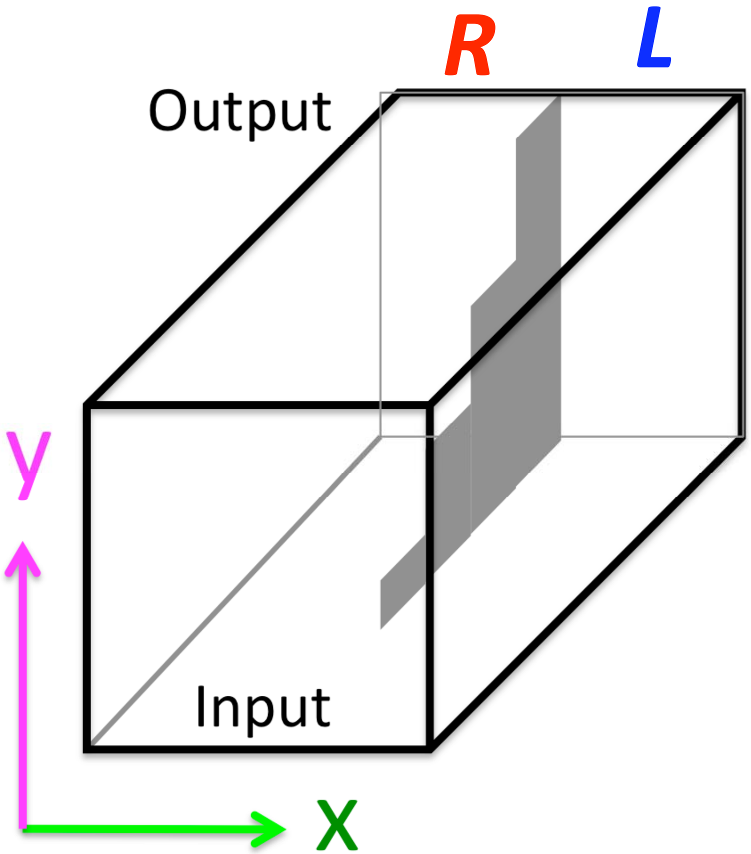


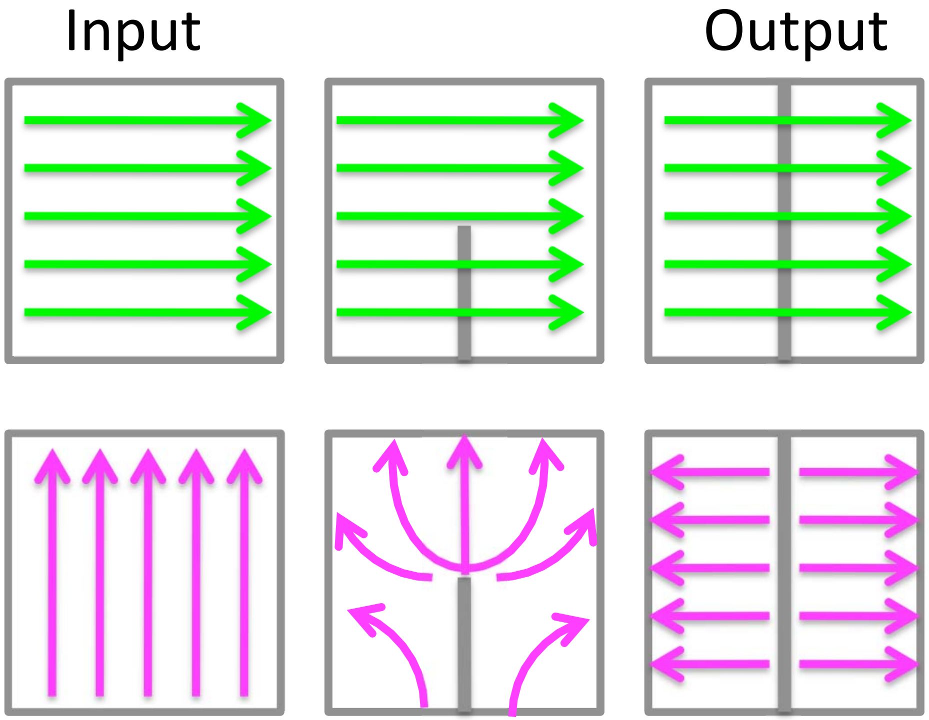
90 detector array for 95 GHz



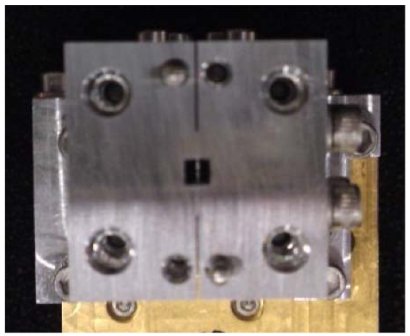
Array sensitivity 80 uKs$^{1/2}$

Septum Polarizer





Electrostatic induction oppositely rotates E_y components



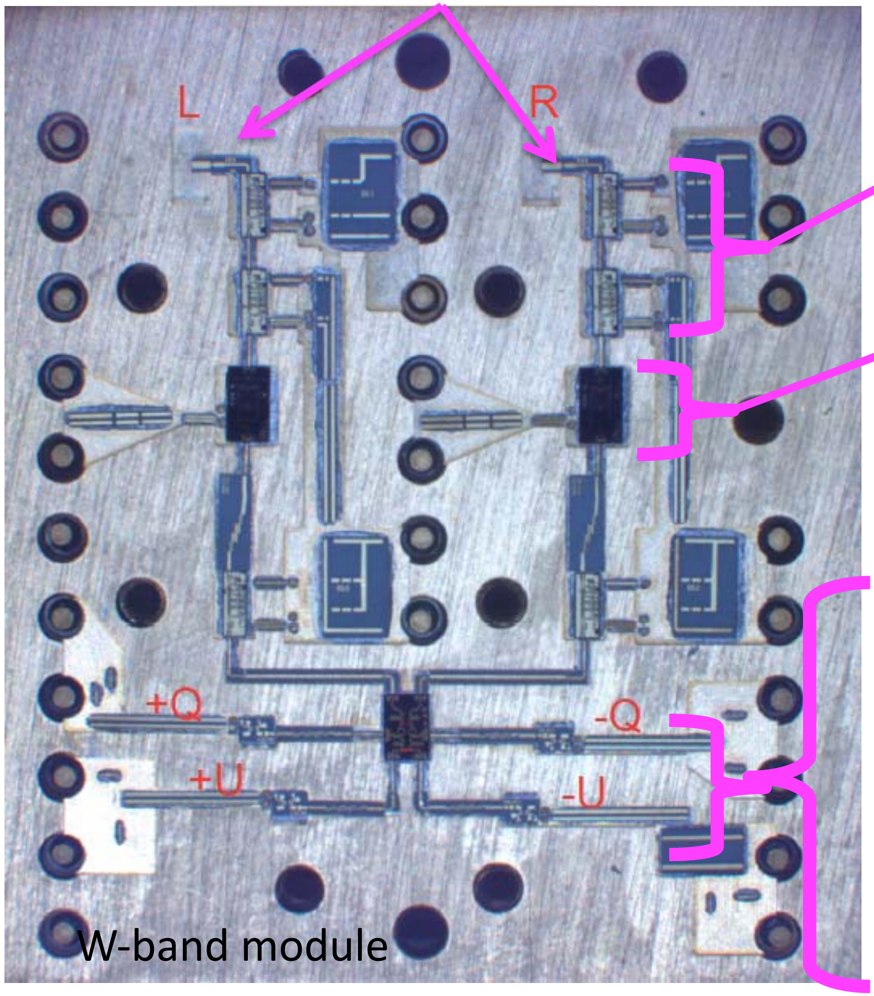
$$R = E_X - iE_Y$$

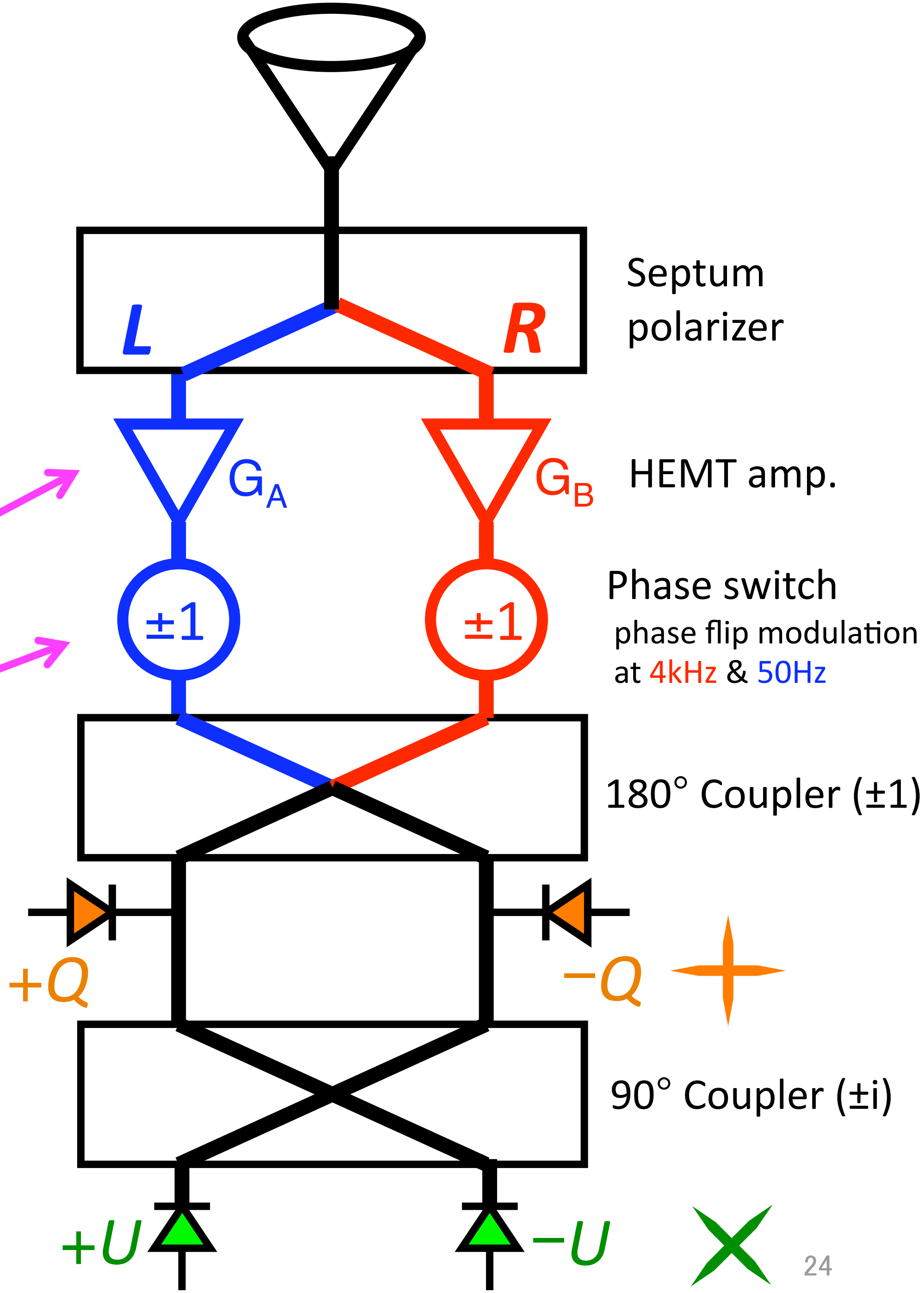
$$L = E_X + iE_Y$$

Opposite phase
for Y-components

Polarization Sensor Module

Antenna to pick up "L", "R"

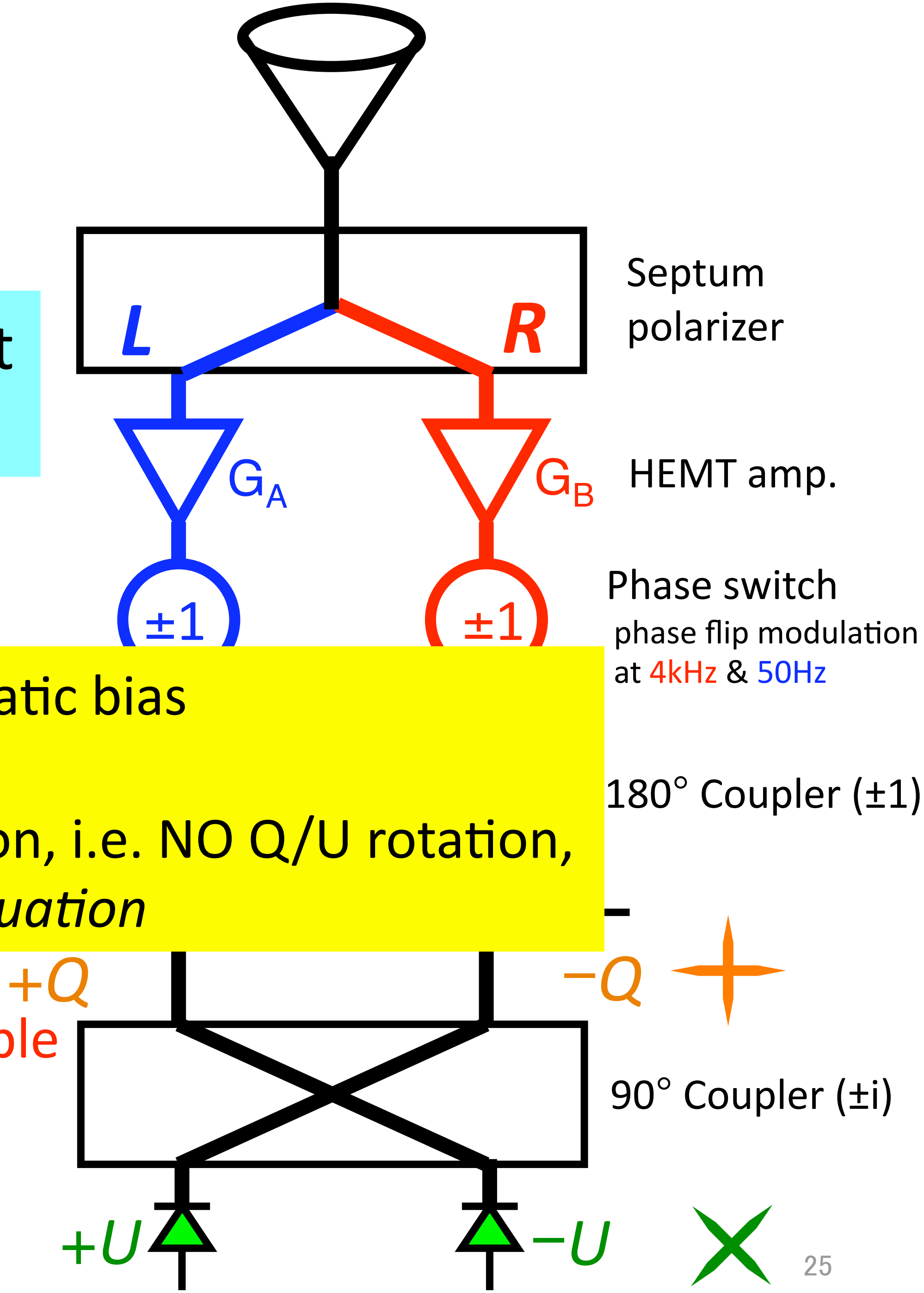




Polarization Sensor Module

Simultaneous measurement of Stokes Q and U

Polarization (Q, U) α $G_A \times G_B$



Strong immunity against systematic bias

NO spurious polarization,

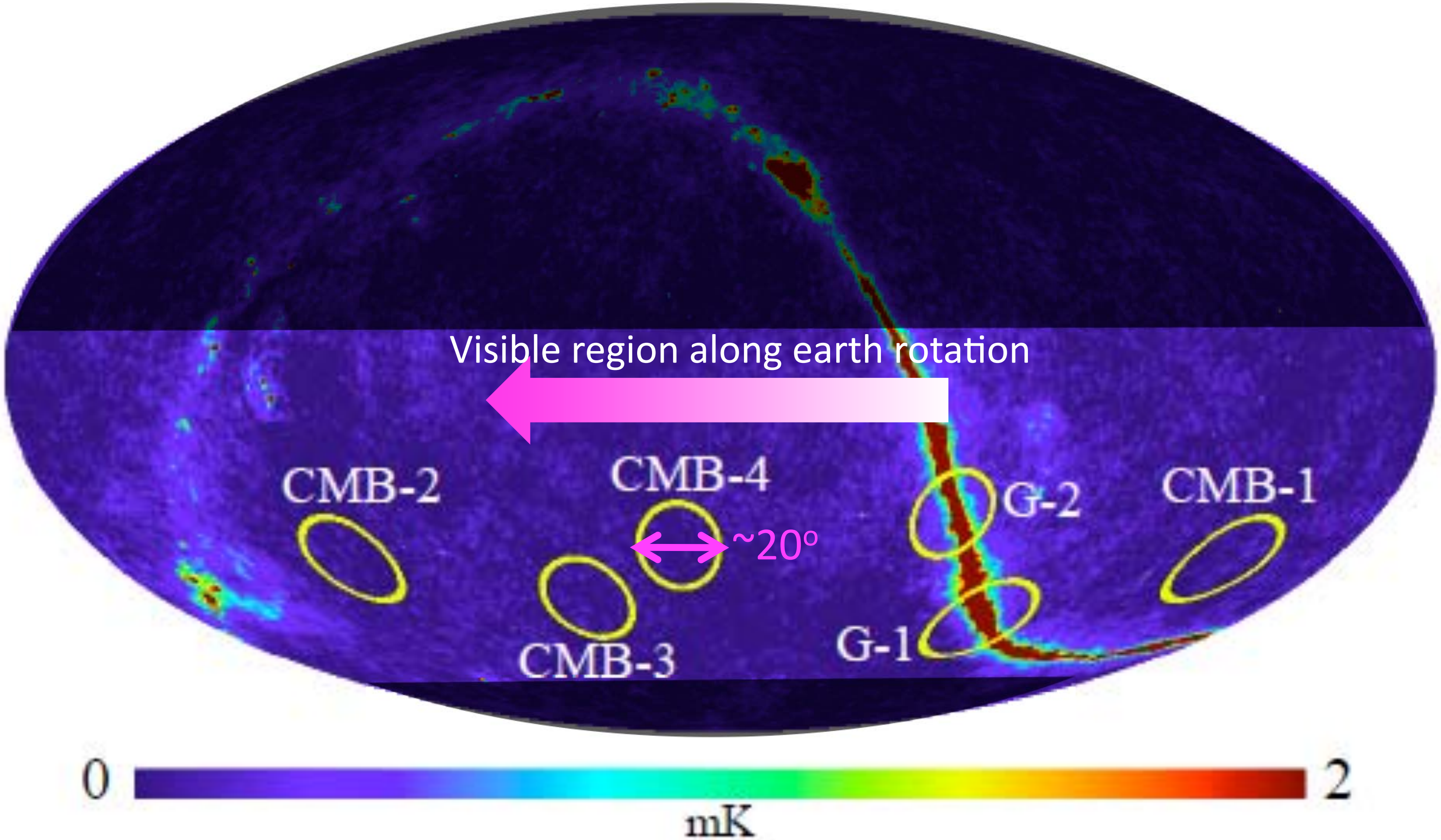
NO polarization angle rotation, i.e. NO Q/U rotation,

even though there is gain fluctuation

QUIET detector is extremely stable for the polarization response

Scan strategy of CMB polarization experiments

Observation Patches

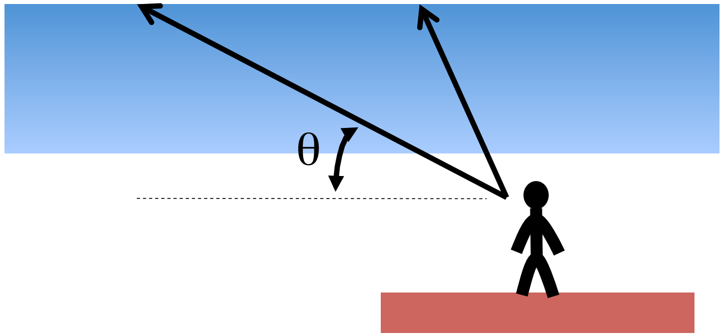


4 CMB patches were chosen (~3% of full sky)
Observing them DEEPLY (Galaxy observation when CMB patches are not visible)
Map precision on 1°x1°: ~1μK (7.5 months at 43GHz)

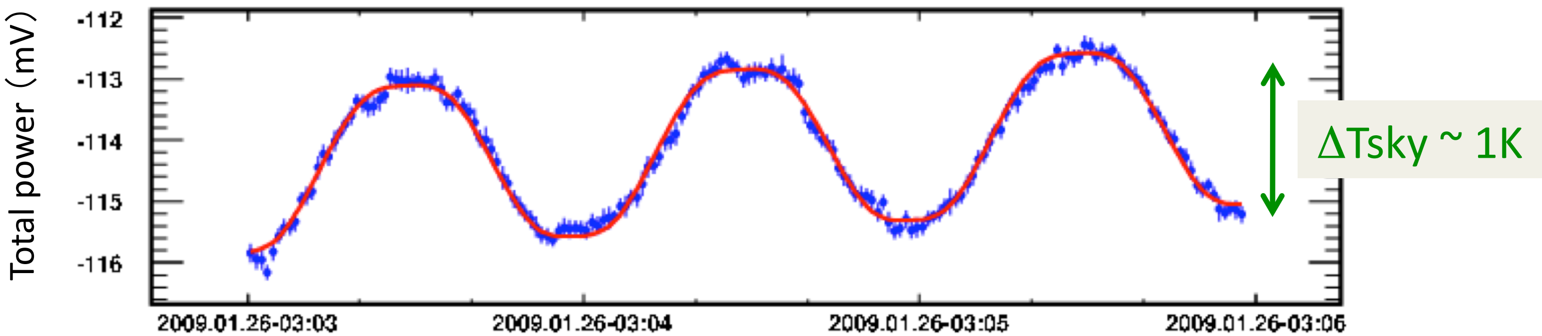
Each CMB patch rises from east, then set to the west

Atmosphere emission varies with elevation change

Thickness atmosphere varies with the elevation angle.



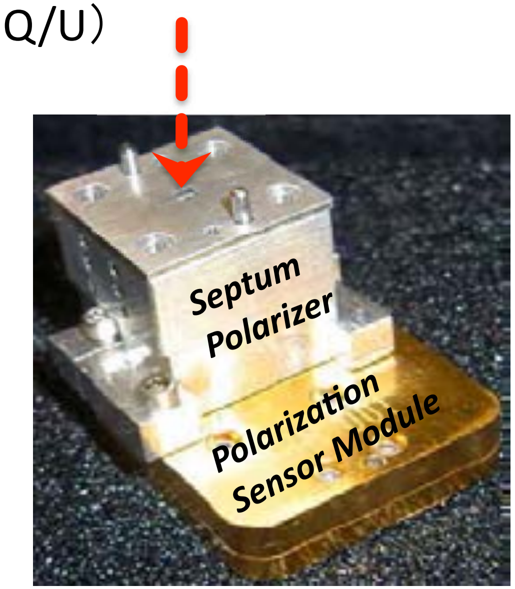
Total power response with ±3° elevation change



Ideally, variation of unpolarized radiation, i.e. atmosphere, does not make any effect for polarization measurements…

There is tiny "crosstalk" from unpolarized (I) to polarized (Q/U)

I → Q/U Leakage

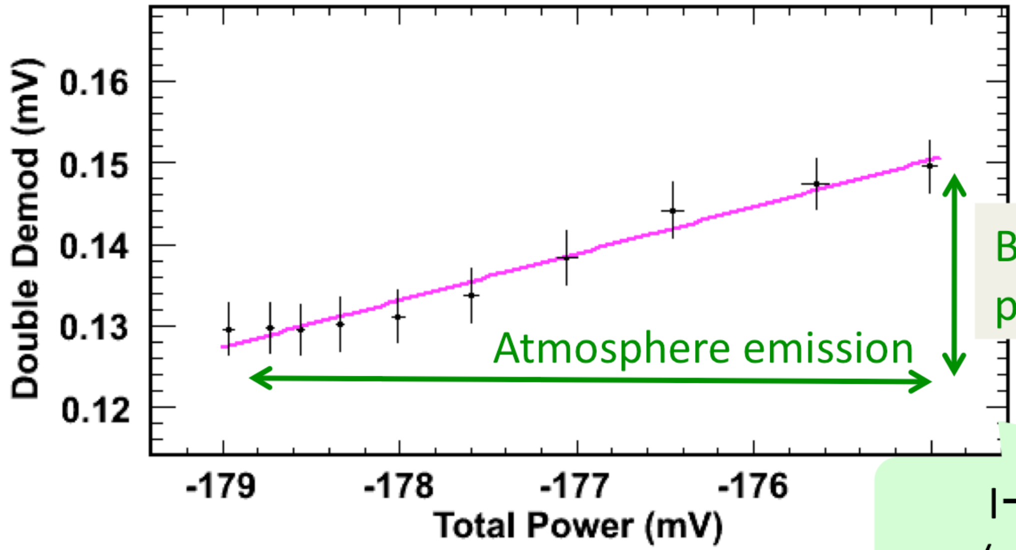


Tiny crosstalk in the septum polarizer

(NO time variation since this is the waveguide components)

$\pm 3^{o}$ scan for the elevation

Polarization response



Unpolarized

Baseline variation for polarization response

I→Q/U leakage : 0.6 ±0.1 %
(average for 43GHz receiver)

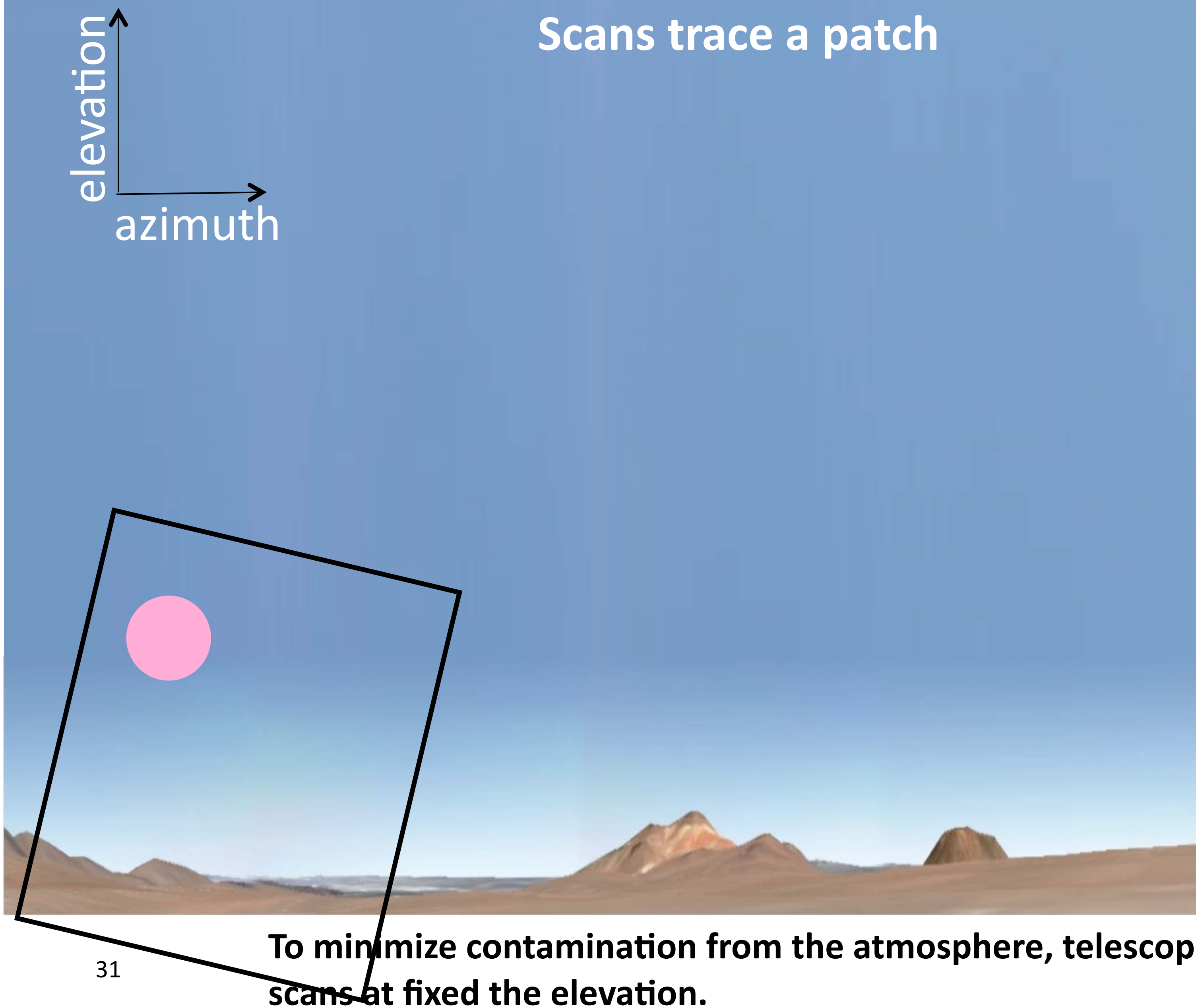
Even though it is "tiny", it is serious for B-mode detection,

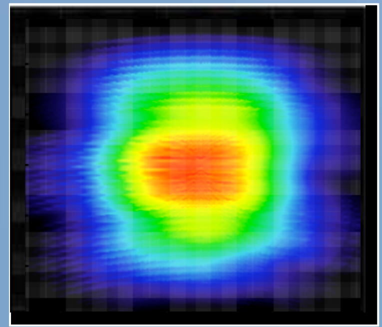
e.g. ΔT_{sky}=1K → 600uK >> ~uK (E-modes) >> B-modes

➔ Having special scan strategy to minimize the effect (NEXT PAGE)

QUIET's Scan Strategy

Scans trace a patch

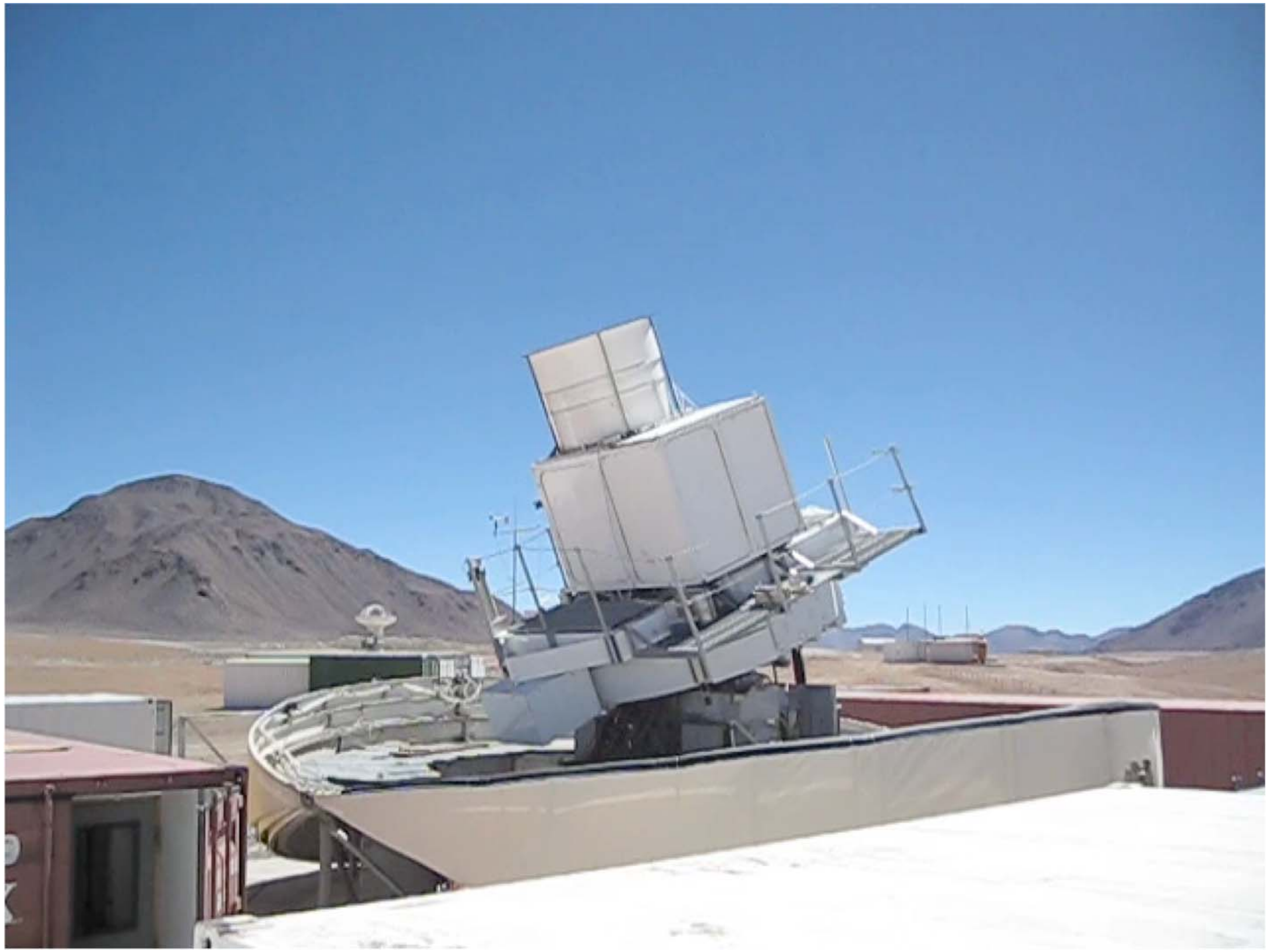




exposure map for one patch

To minimize contamination from the atmosphere, telescope scans at fixed the elevation.

QUIET's scan at 5,080m

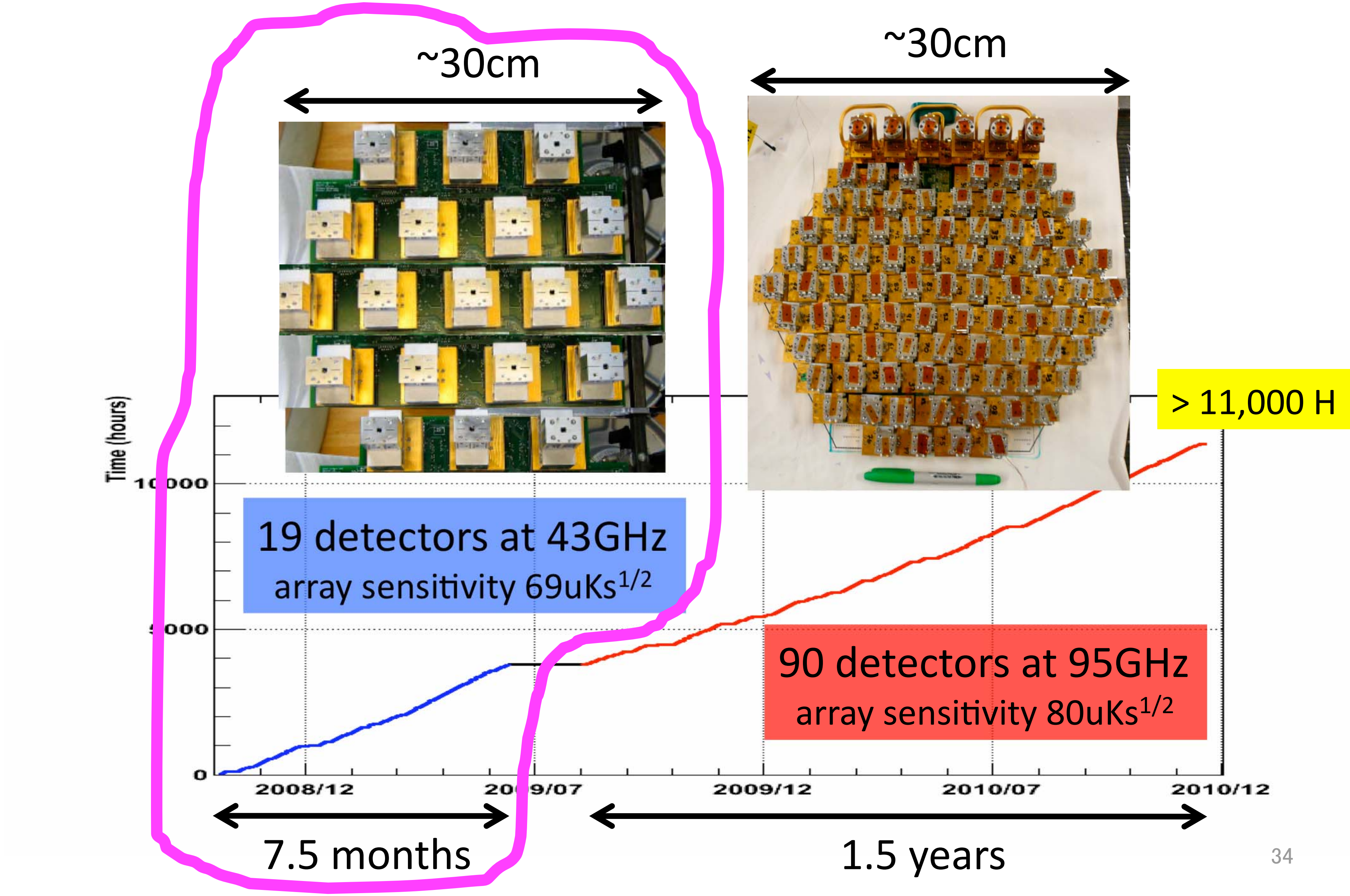


Constant Elevation Scan

Scan strategy to minimize the systematic bias

Initial results from QUIET

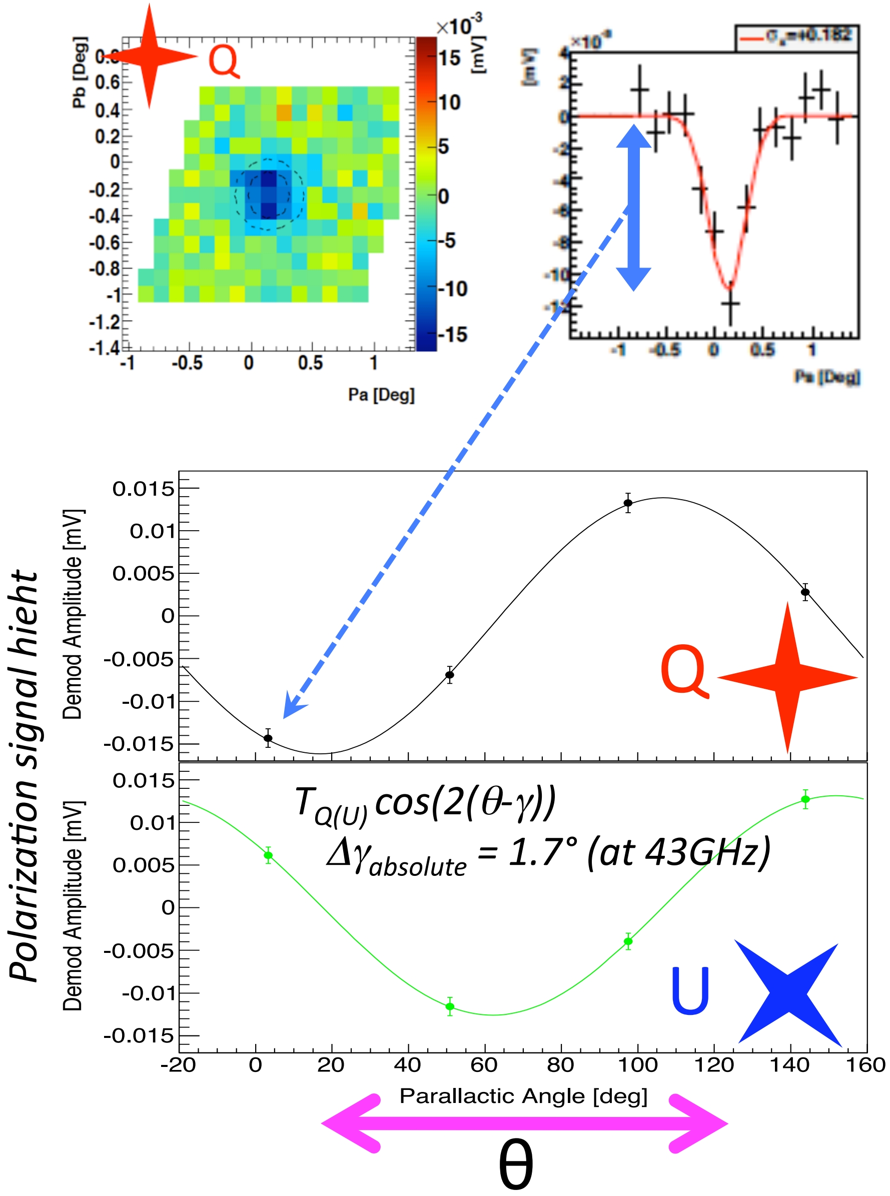
QUIET-1 observation at Atacama, Chile 5,080m

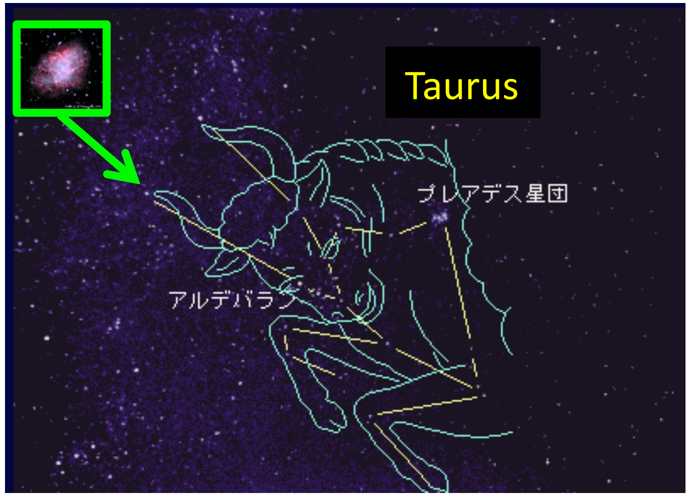


[arXiv:1012.3191]

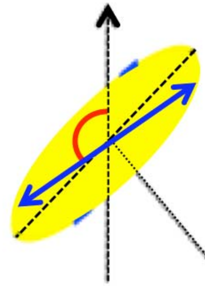
Astronomical Calibrator

~4 min scan time for each

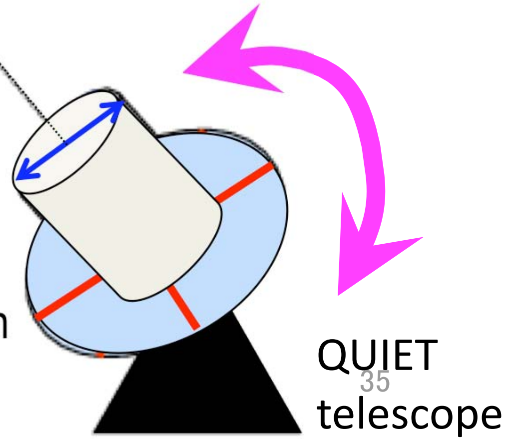




Crab nebula (TauA) T_{pol} = 5mK

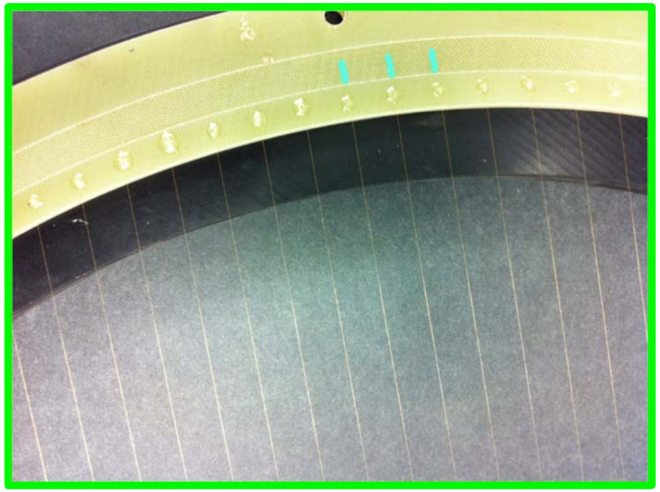


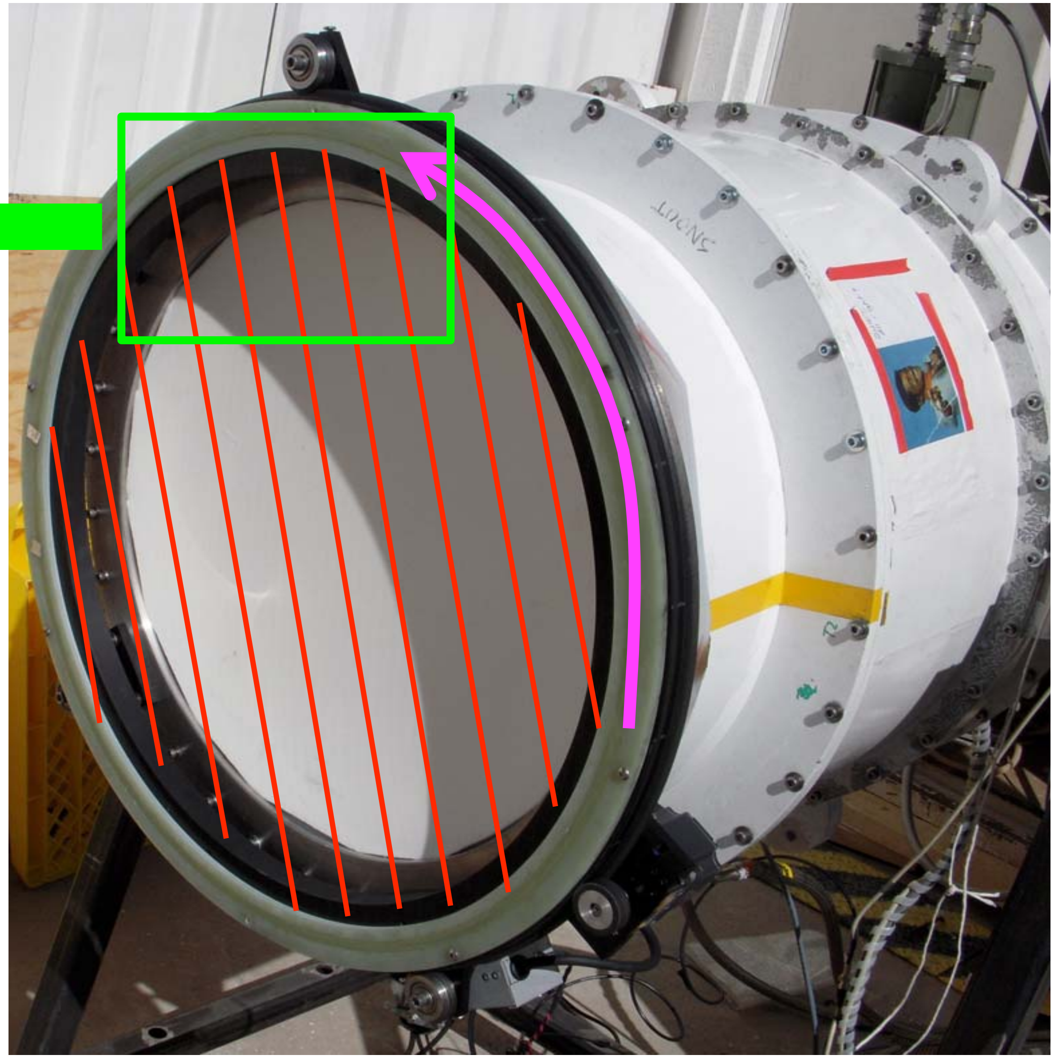
Rotate parallactic angle with keeping the line of sight



by

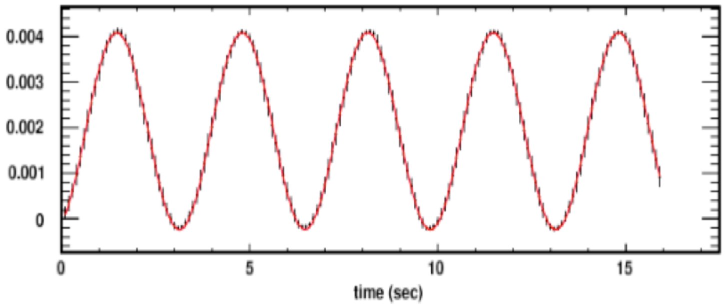
Artificial Calibrator with "Sparse" Wires





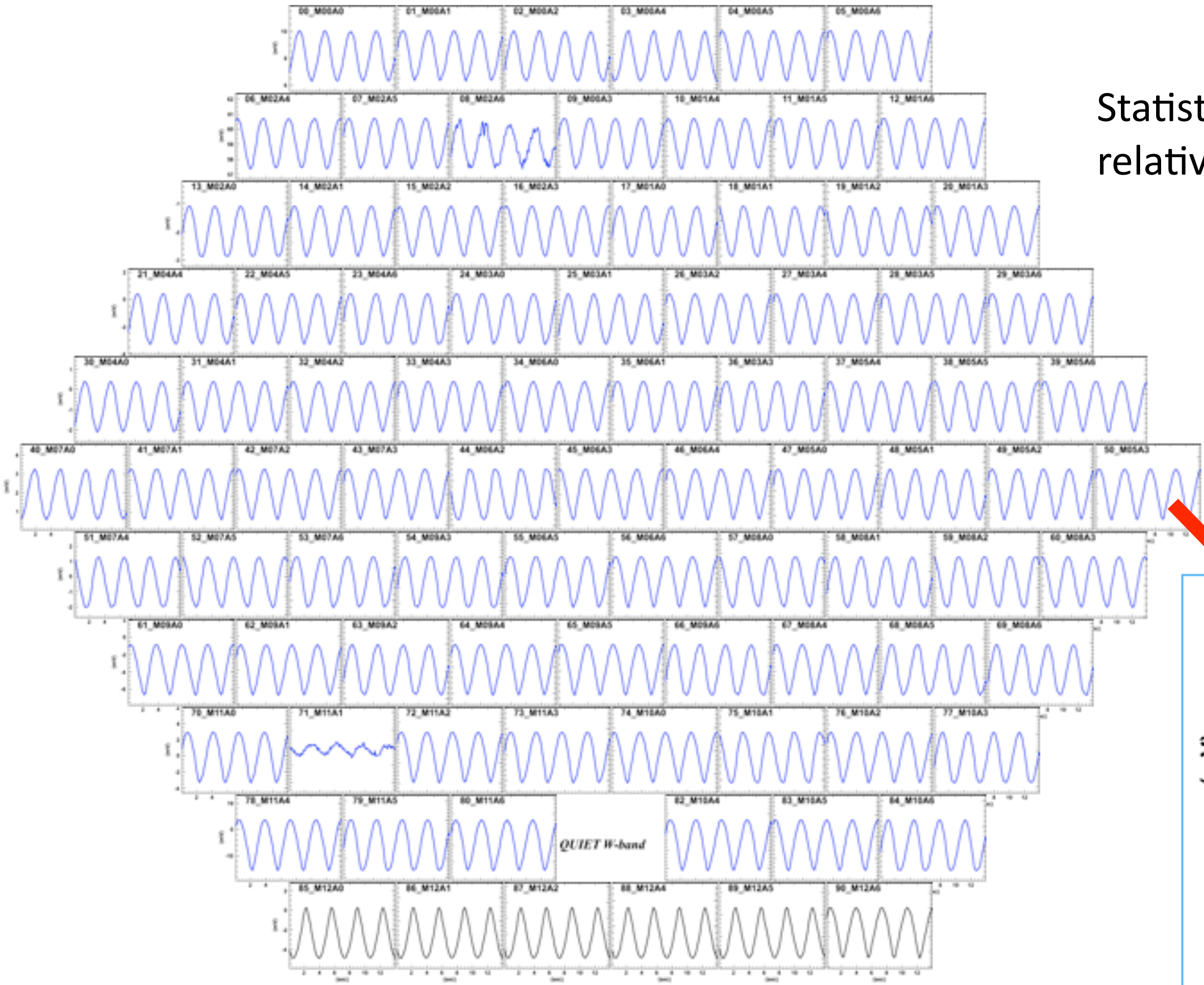
Polarized radiation (≈2K) is created via the reflection of ambient temperature from the metal wire surface

Detected polarization response should be sinusoidal curve

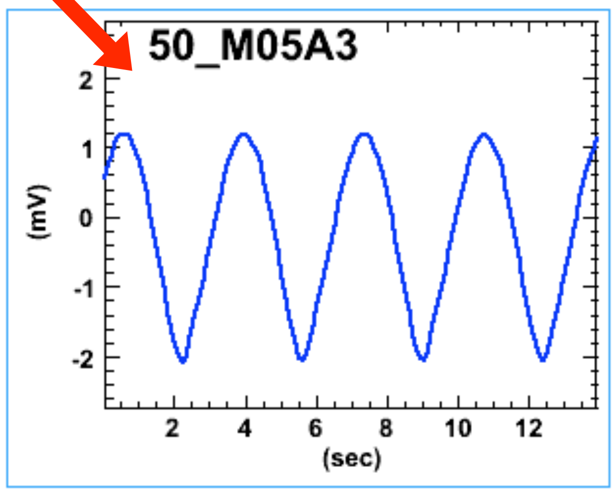


Artificial Calibration with "Sparse" Wires

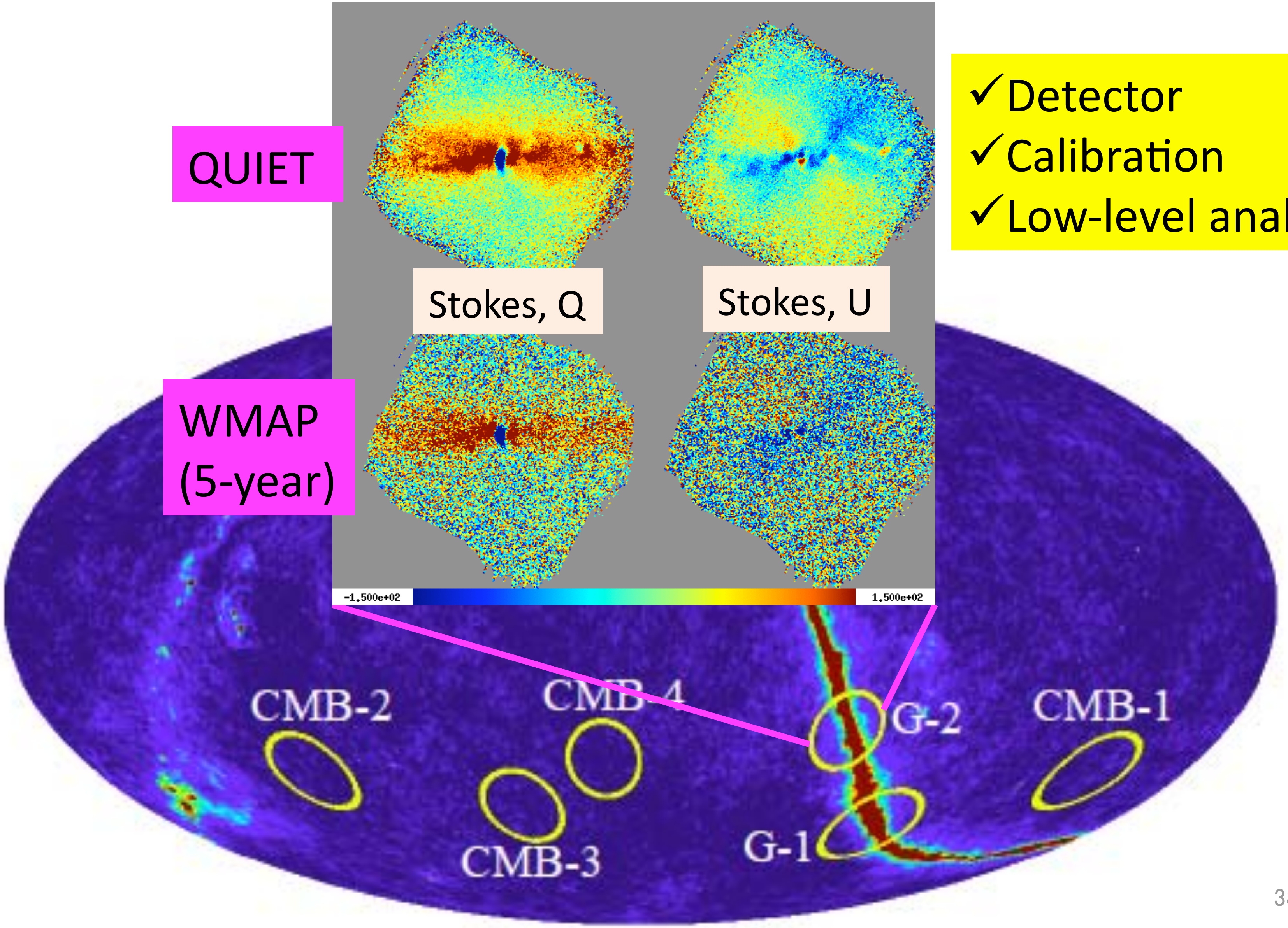
"Simultaneous" & "rapid" calibration for all detectors



Statistical precision of relative angle: 0.4deg (30sec data)



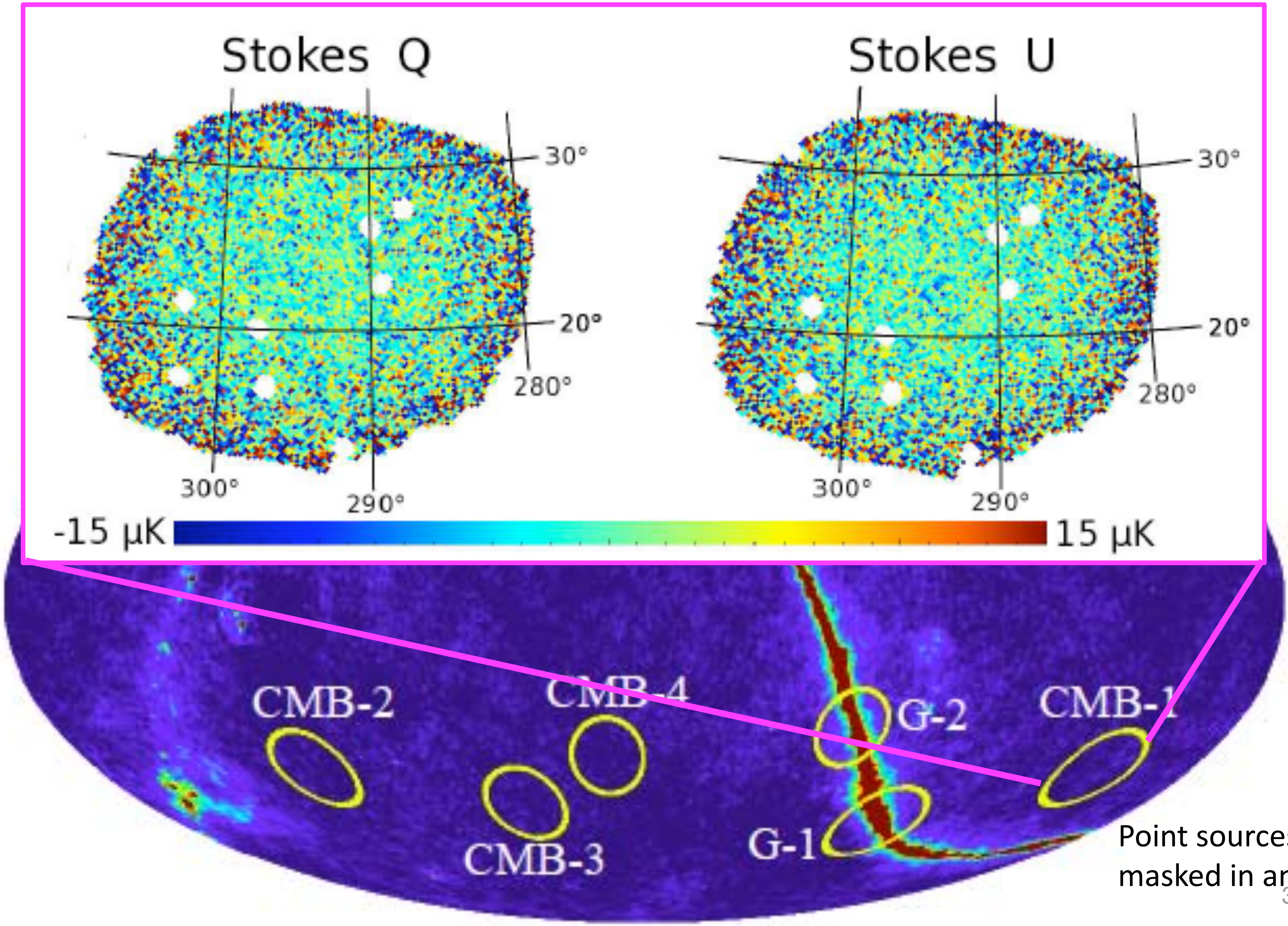
QUIET Polarization Map for Galactic Center

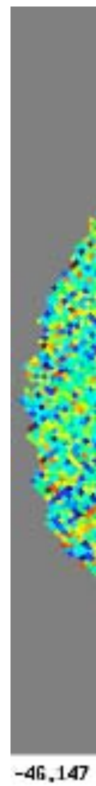


- ✓Detector
- ✓Calibration
- ✓Low-level analysis

[arXiv:1012.3191]

QUIET CMB Polarization Map





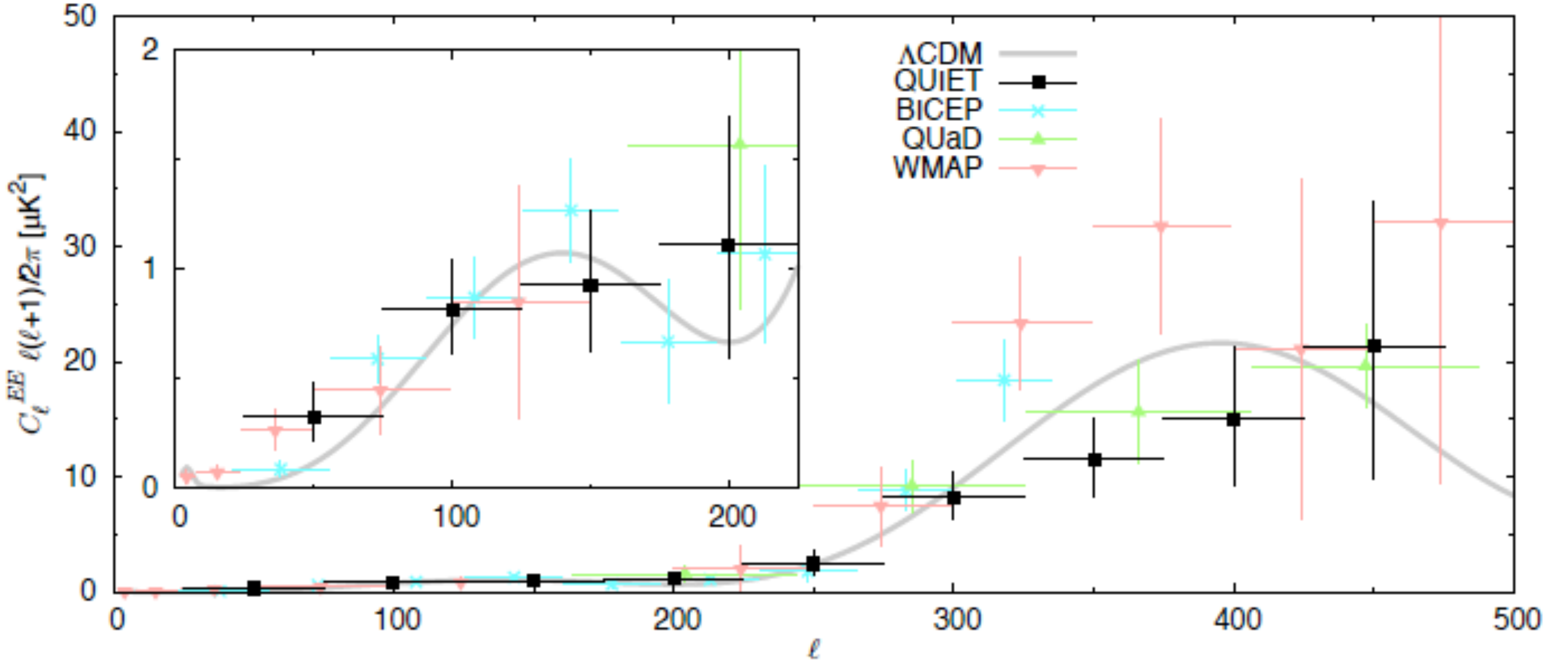
Point sources are masked in analysis

[arXiv:1012.3191]

E-modes

✓Detector
✓Calibration
✓Low-level analysis
✓High-level analysis

Consistency check with “standard model”
Strong proof of instrument and analysis



Significant power is detected at 1st , 2nd peak region
Consistent with ΛCDM model

QUIET / LCDM = 0.87 ± 0.10

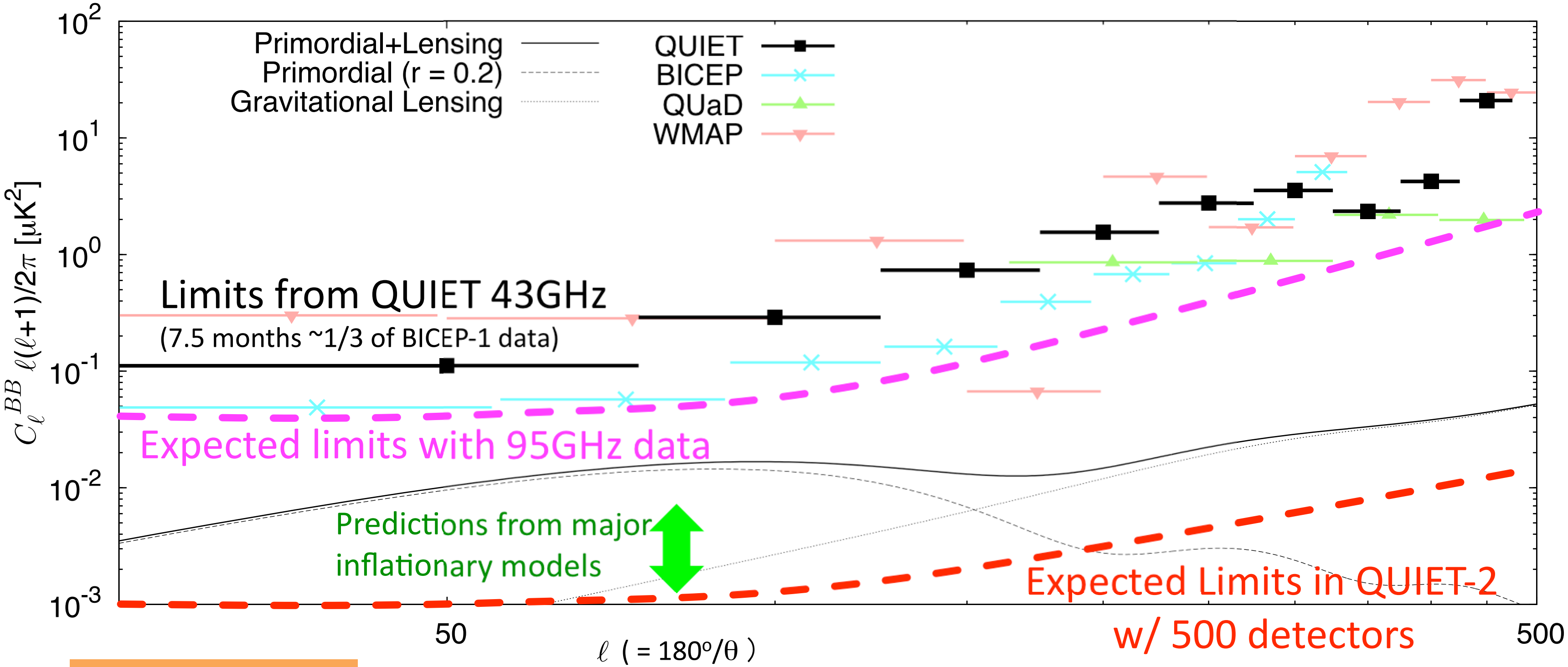
PTE from LCDM 14% for EE + BB + EB

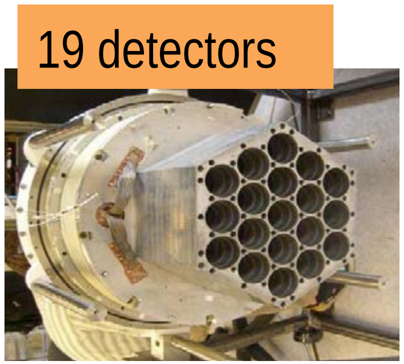
B-modes : r < 2.2 @95%CL

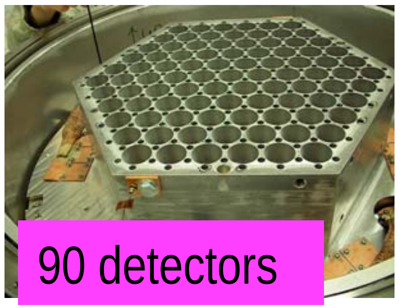
[arXiv:1012.3191]

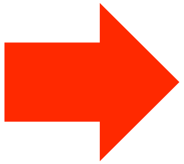
(zero-consistent : $r=0.35^{+1.06}_{-0.87}$)

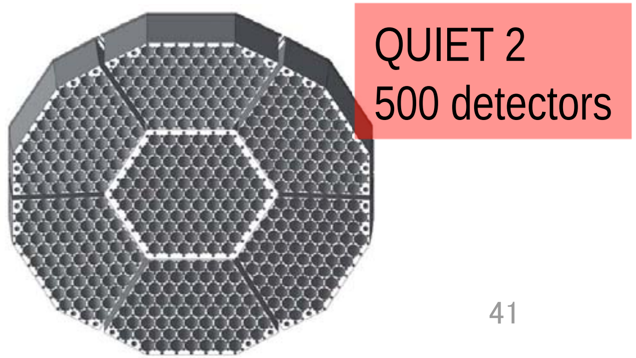
Second best upper limits whereas short observation time



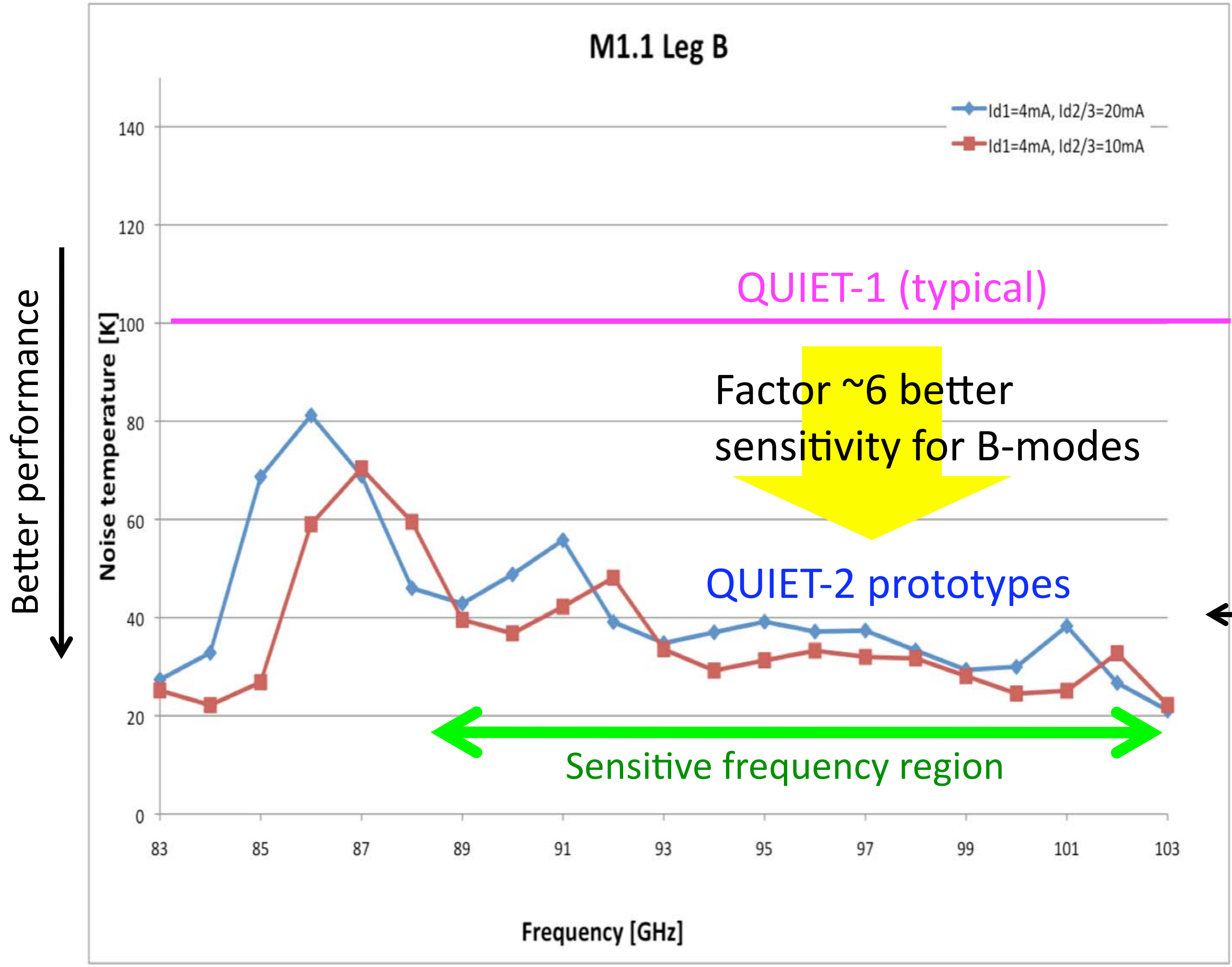




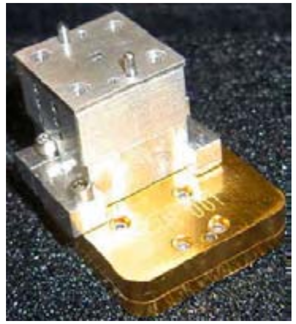




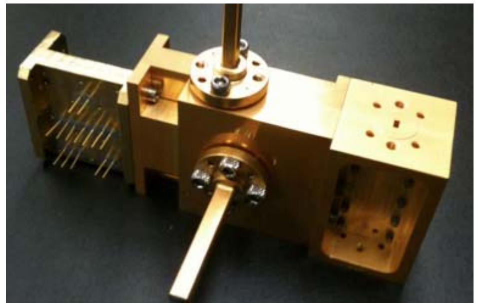
Prototype of QUIET-2 detectors



QUIET-1



Developed by JPL

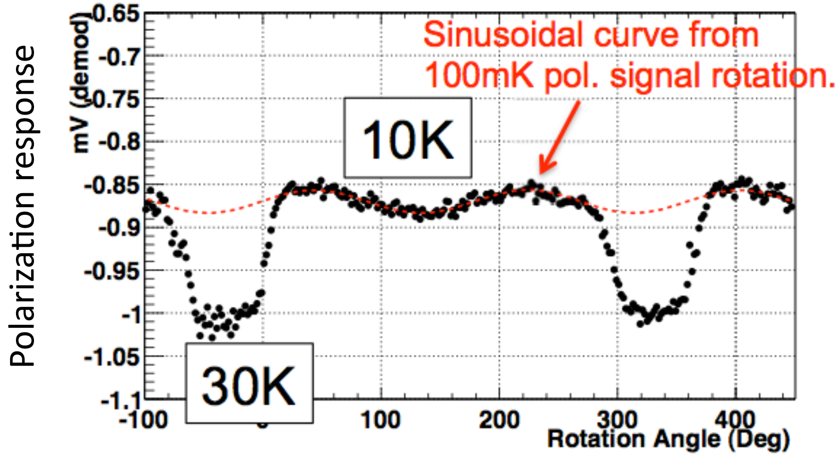


QUIET-2 prototype

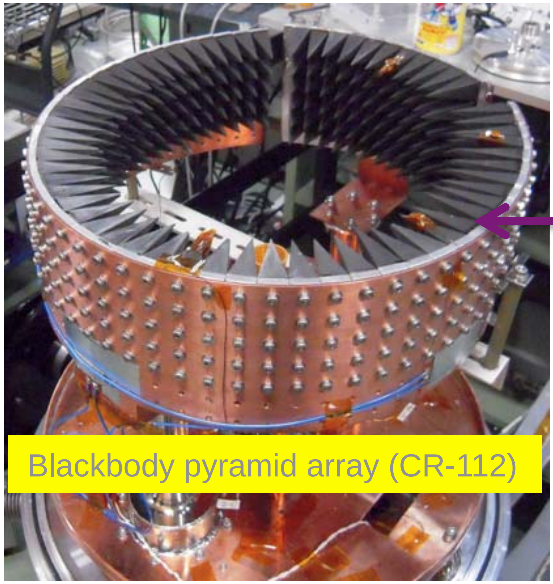
Much better performance (factor ~6) than the QUIET-1 !

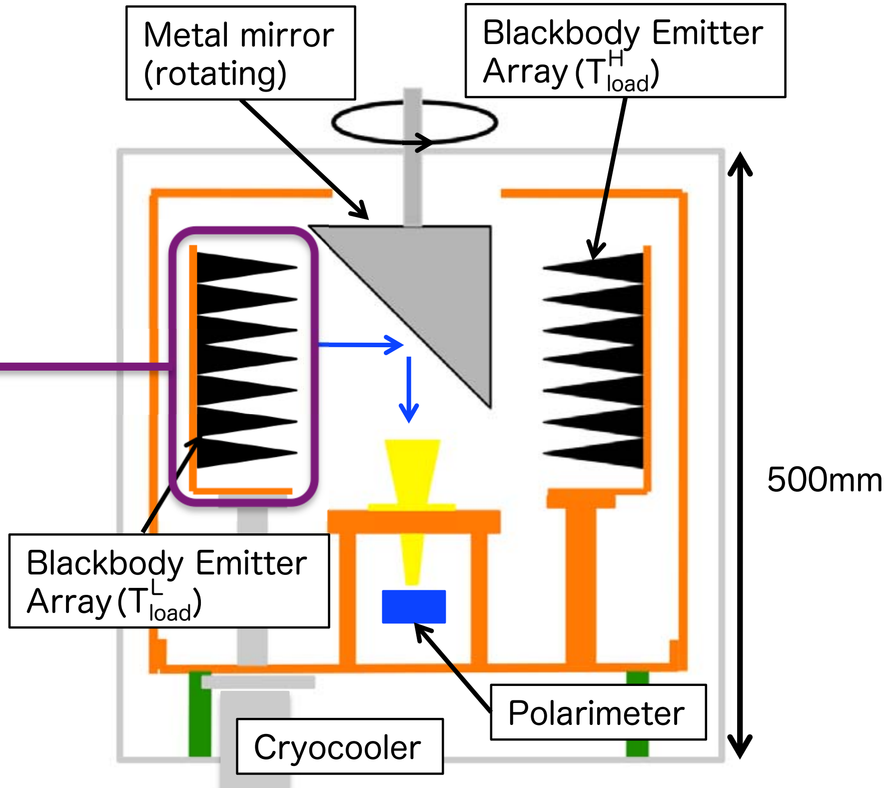
precise Detector Calibration system for QUIET-2 in KEK

M. Hasegawa, O. Tajima *et al.*, Rev. Sci. Instru. 82, 054501 (2011).

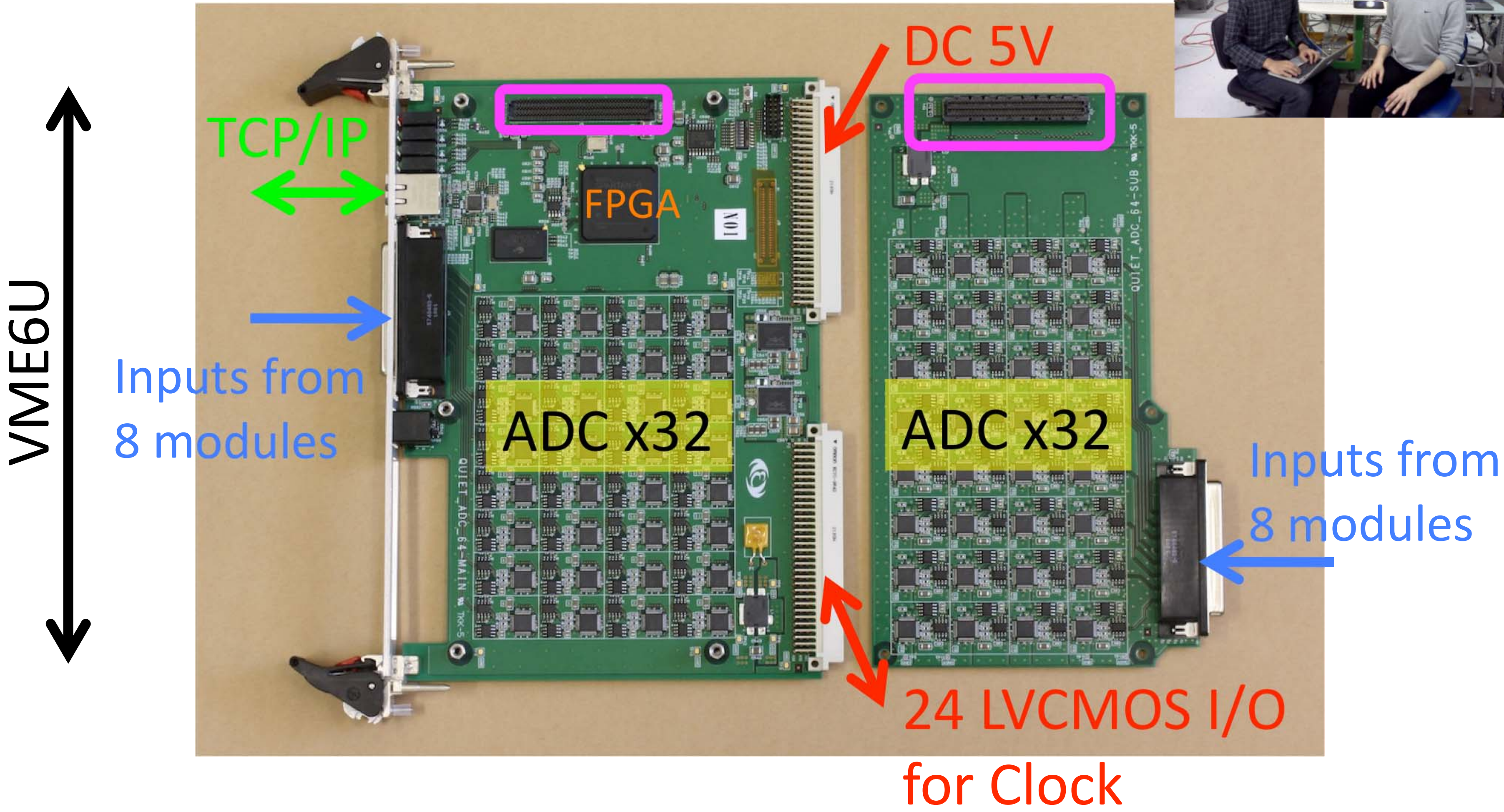


"Reproduce the condition of Atacama sky (10K) even in the laboratory"





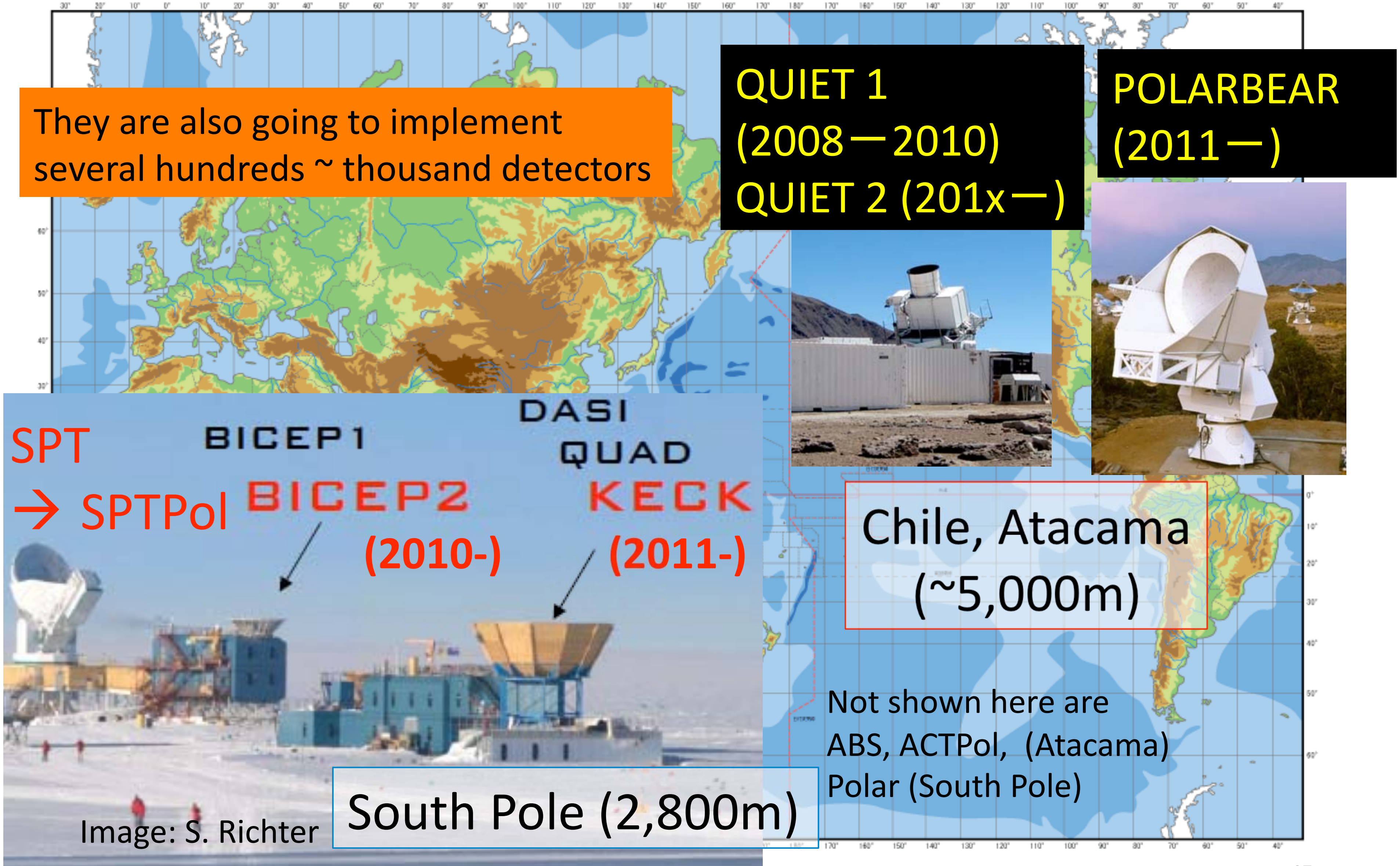
ADC system developed in KEK



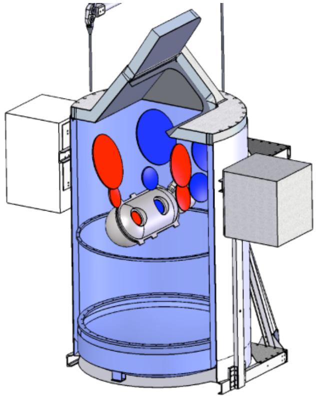
- 64 inputs ⇔ 16 modules / board
- Each ADC: Sampling 800kHz, Resolutions18 bits
- On board double-demodulation

x2 density
of QUIET-1 ADC board

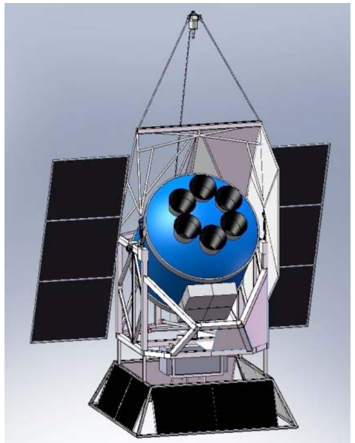
Ground-based telescopes



Balloon-borne telescopes



PIPER（2013-）



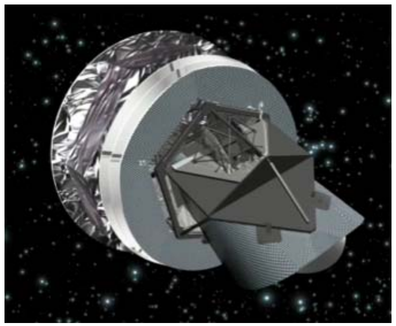
SPIDER（2011, 2012）

EBEX （2009-2011）

Satellite Telescopes

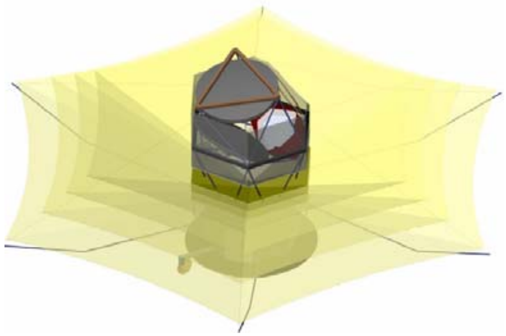
~2020 –

Planck (2009-)

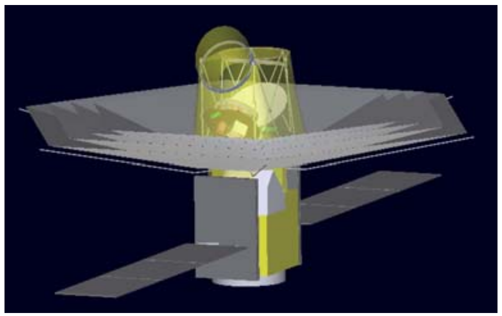


Not optimized for
polarization meas.

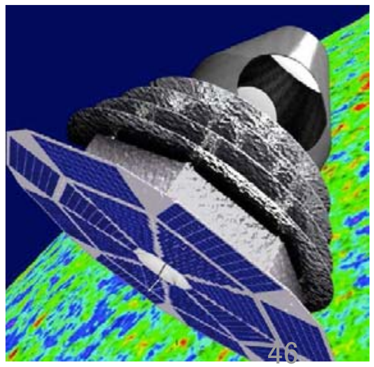
EPIC



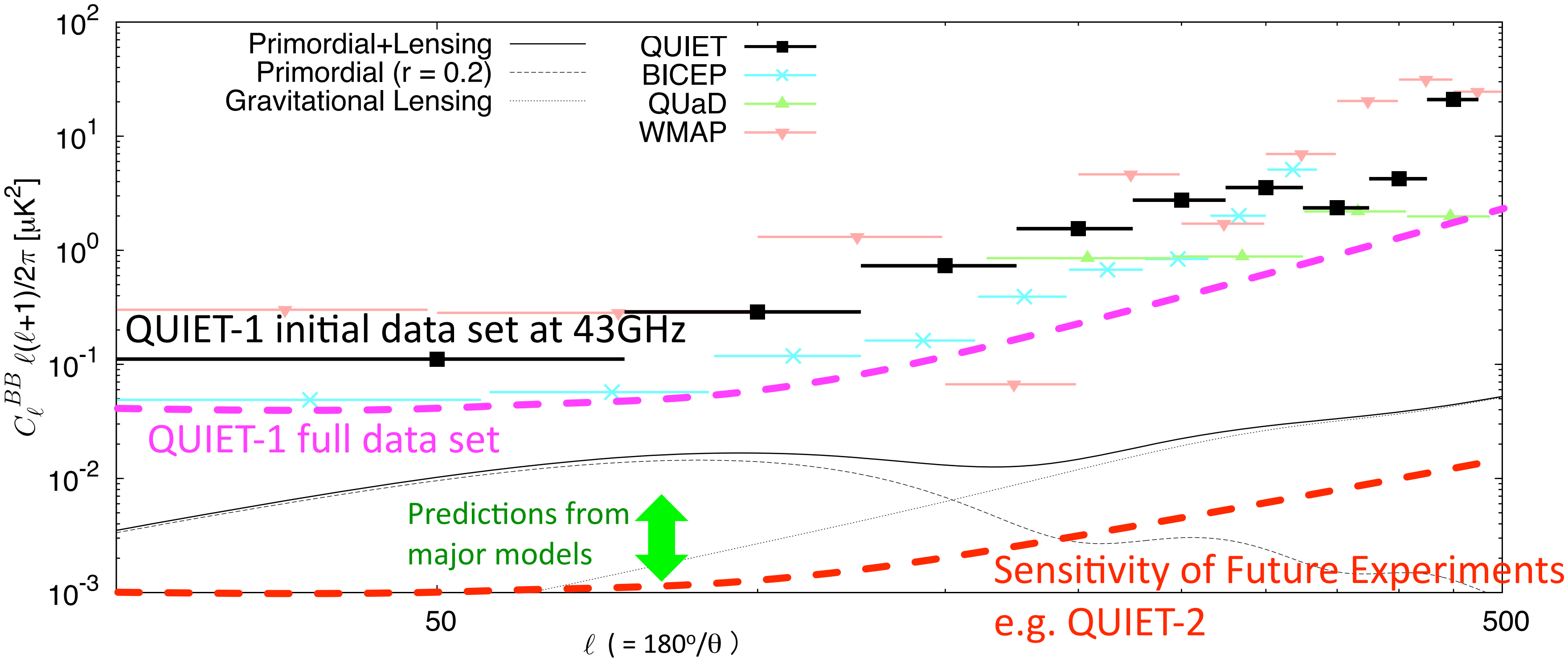
LiteBIRD



COrE



B-modes Search in Future

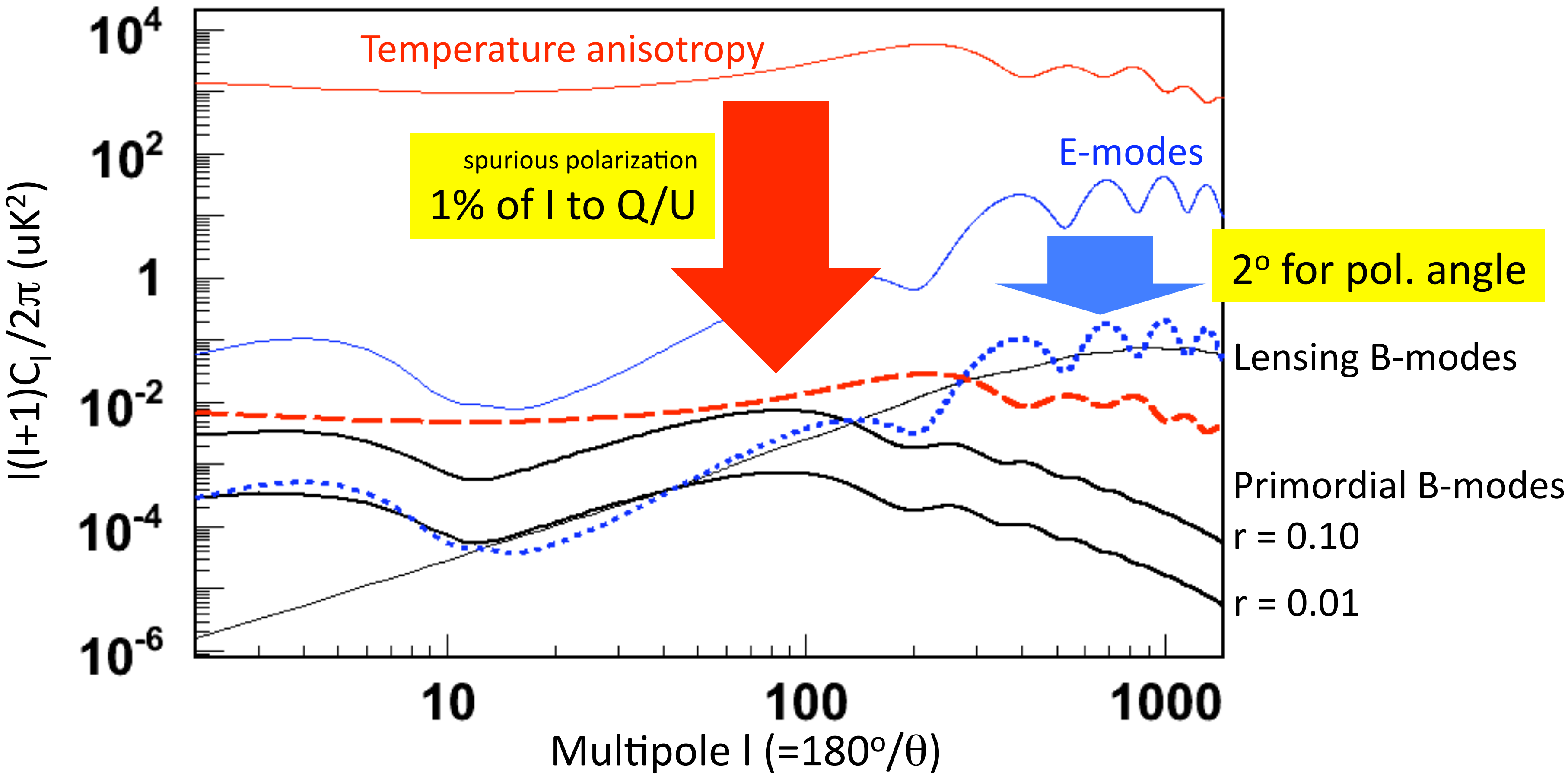


All coming experiments claim good sensitivity r = O(0.01)
or better sensitivity with several hundreds to thousand detectors

The most important subject for future:
Good systematic error control

Impact of **systematic error**

In case of 1% precision of calibrations …

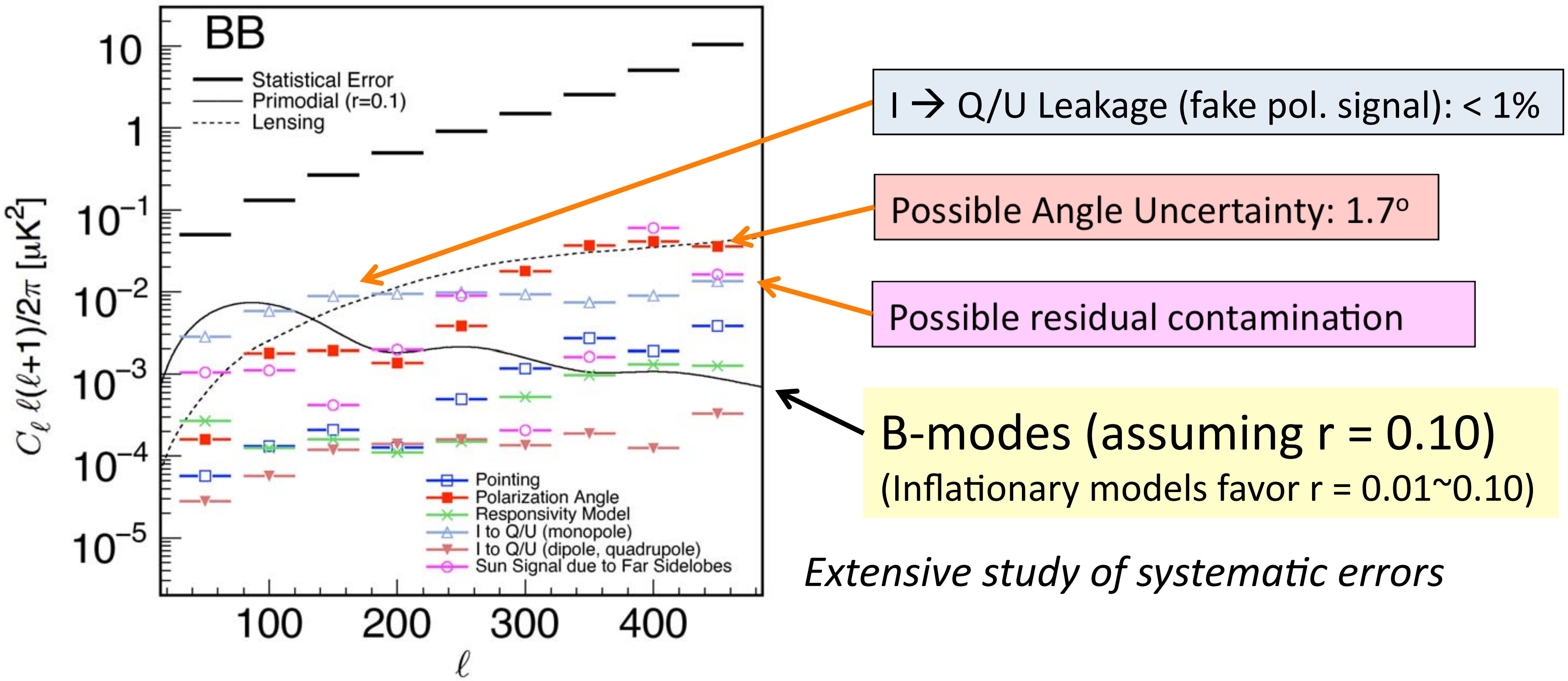


Have to minimize spurious polarization: ≈0.1%
Have to achieve angle precision: ≈0.1°

QUIET-1 initial results at 43GHz

[arXiv:1012.3191]

Least systematic error to date (r≈0.06)



Extensive study of systematic errors

- Strong proof of our technology for future
- Good prospects for further syst. error reduction
  – We improved 95GHz instruments and calibrations

Ground-based Experiment from Japan

GroundBIRD

Japan-oriented ground-base experiment

Targets:

Start commissioning within 3 years

Compact & Small

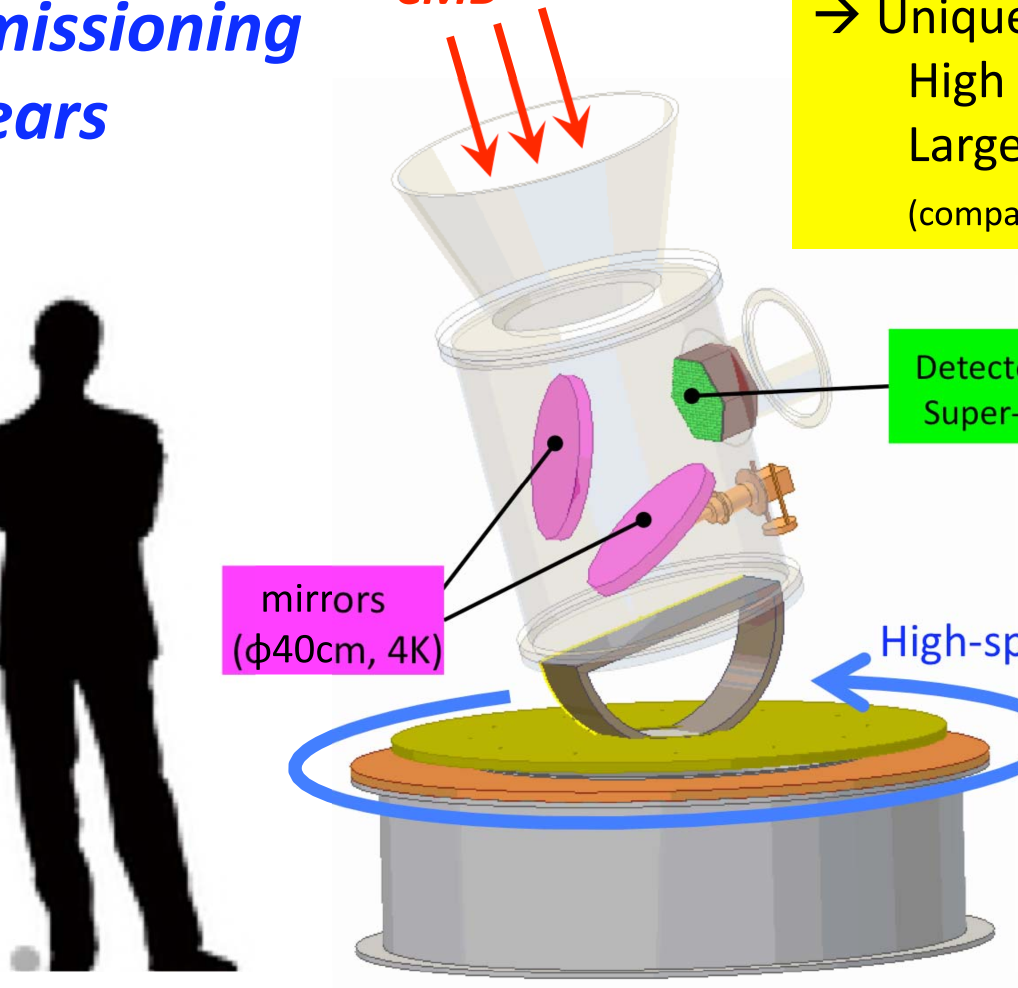
→ Unique scan strategy

High speed: x100

Large field: x10

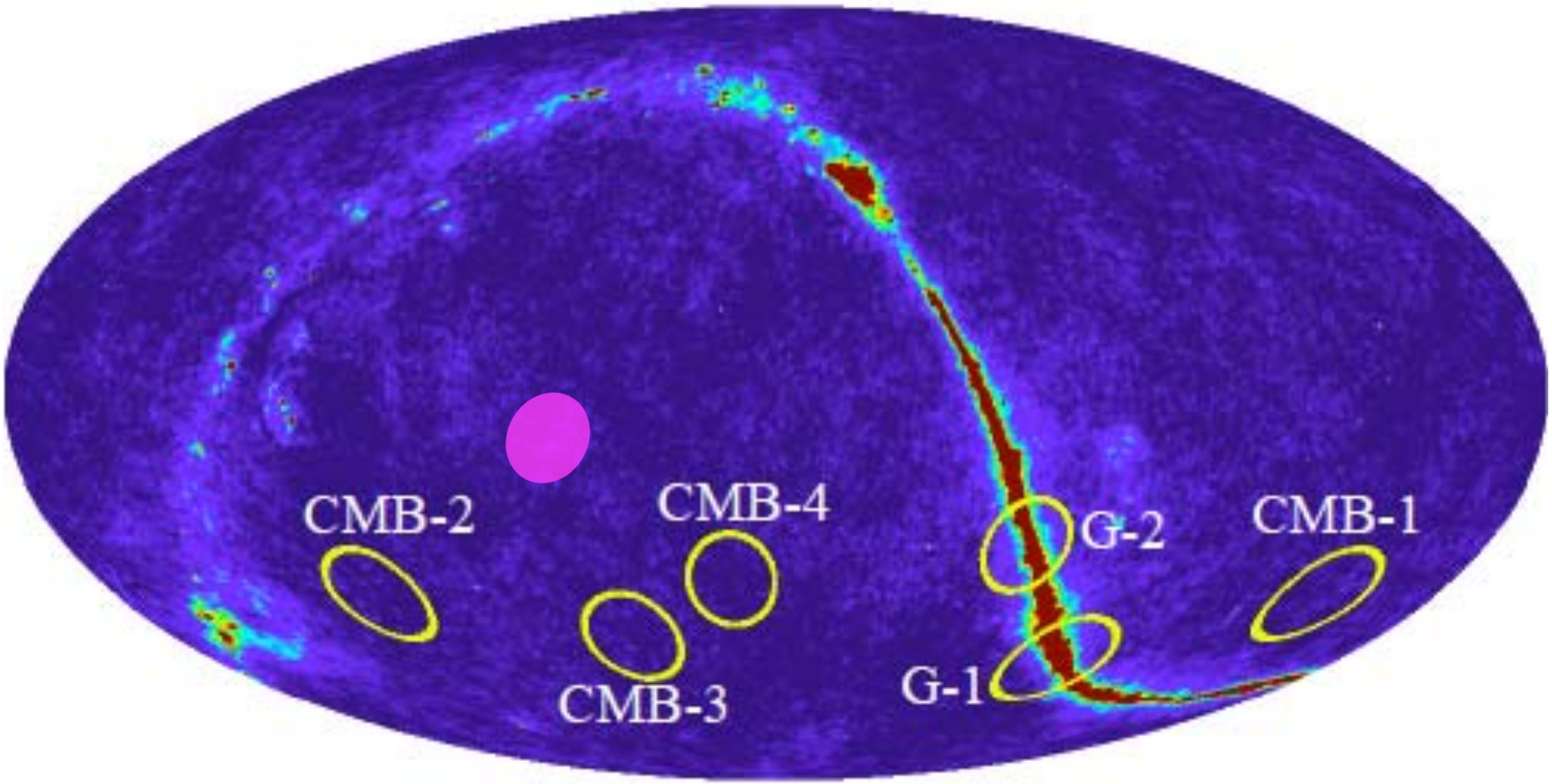
(compared with other experiments)

Almost all other experiments are LARGE instruments

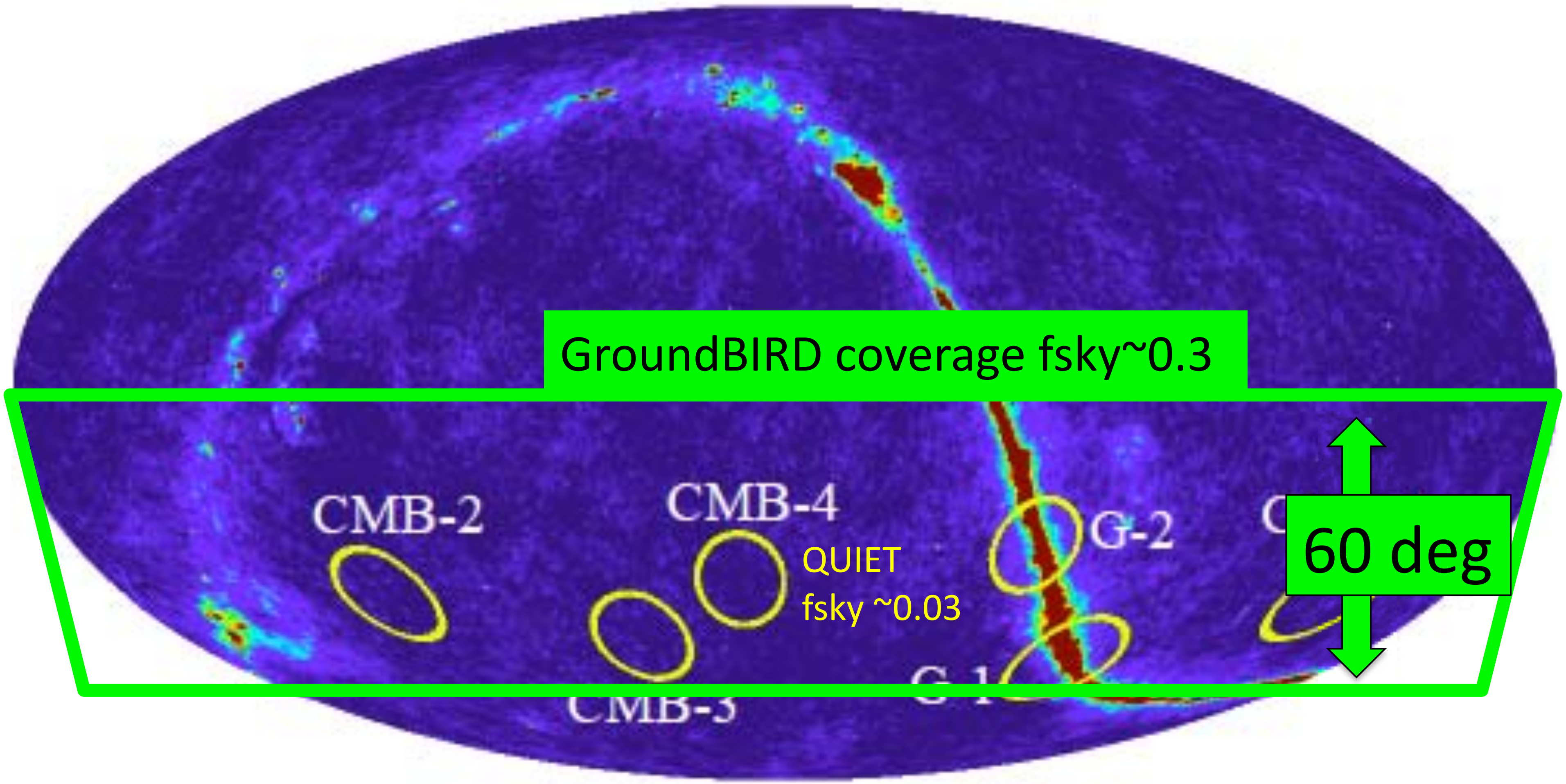


Detector array (ϕ12cm)
Super-conducting detectors, 1626ch

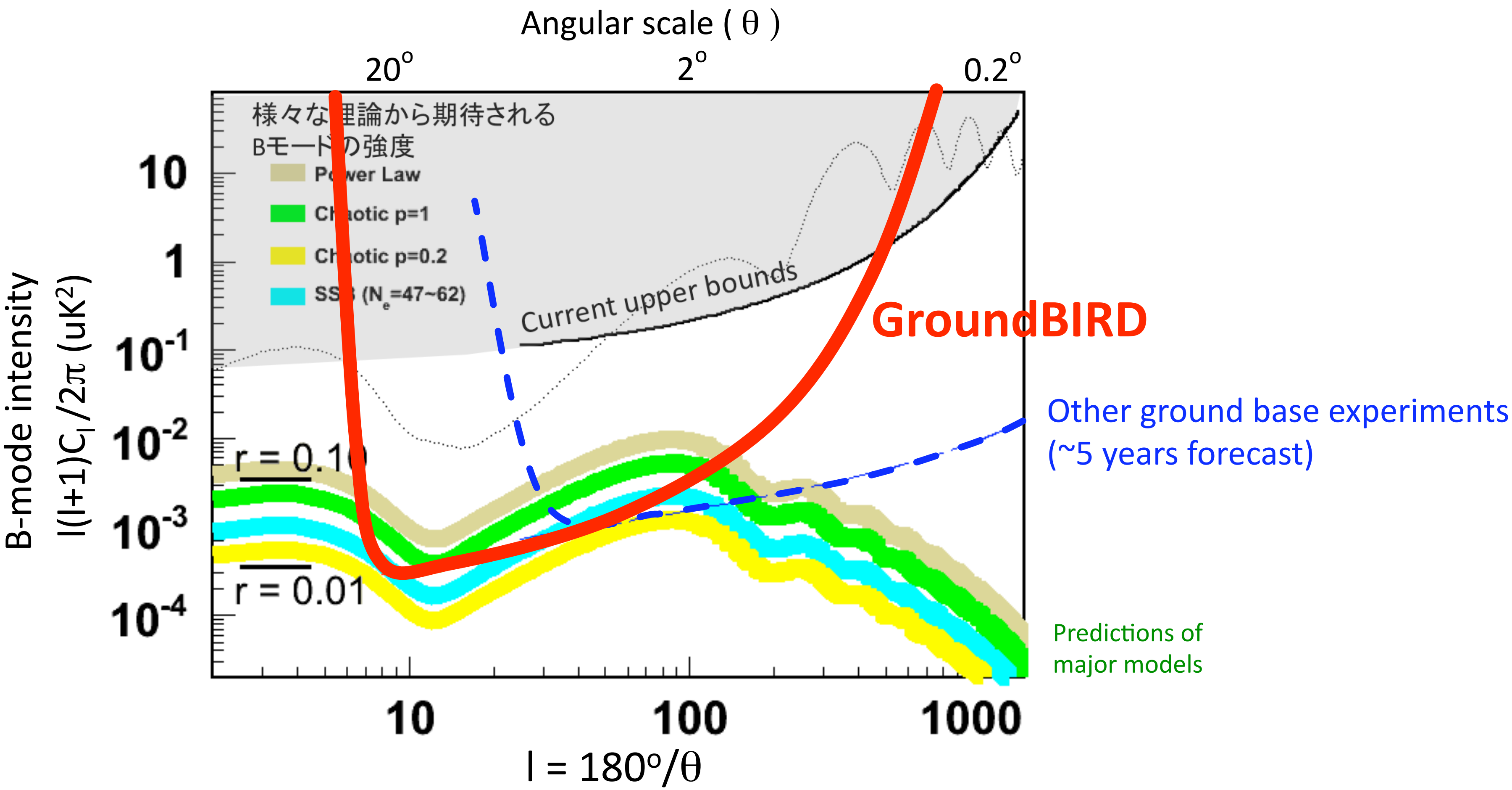
Scan strategy of GroundBIRD



Scan strategy of GroundBIRD



High-speed & Large field scan provides competitive B-mode detection sensitivity with other experiments



Summary

- "B-modes" in CMB polarization are a smoking gun signature of inflationary universe
  - Ultimate High Energy Physics: $10^{\sim 16}$ GeV
- Many experiments are going on, search limits are improved almost year-by-year
  - It is very exciting period now
- Experimental technique is still in its infancy
  - Especially, systematic error control
  - QUIET-1 initial results achieved least systematic error to date

    [arXiv:1012.3191] e.g. fake polarization signal: < 1%

    「インフレーション宇宙の痕跡を探す – QUIET実験の初期結果」

    田島治　高エネルギーニュース Vol.30 No.1

    http://www.jahep.org/hepnews/2011/116Tajima-04final.pdf

- Many rooms to be top of the exciting (B-mode search) race, even if we are new comers.