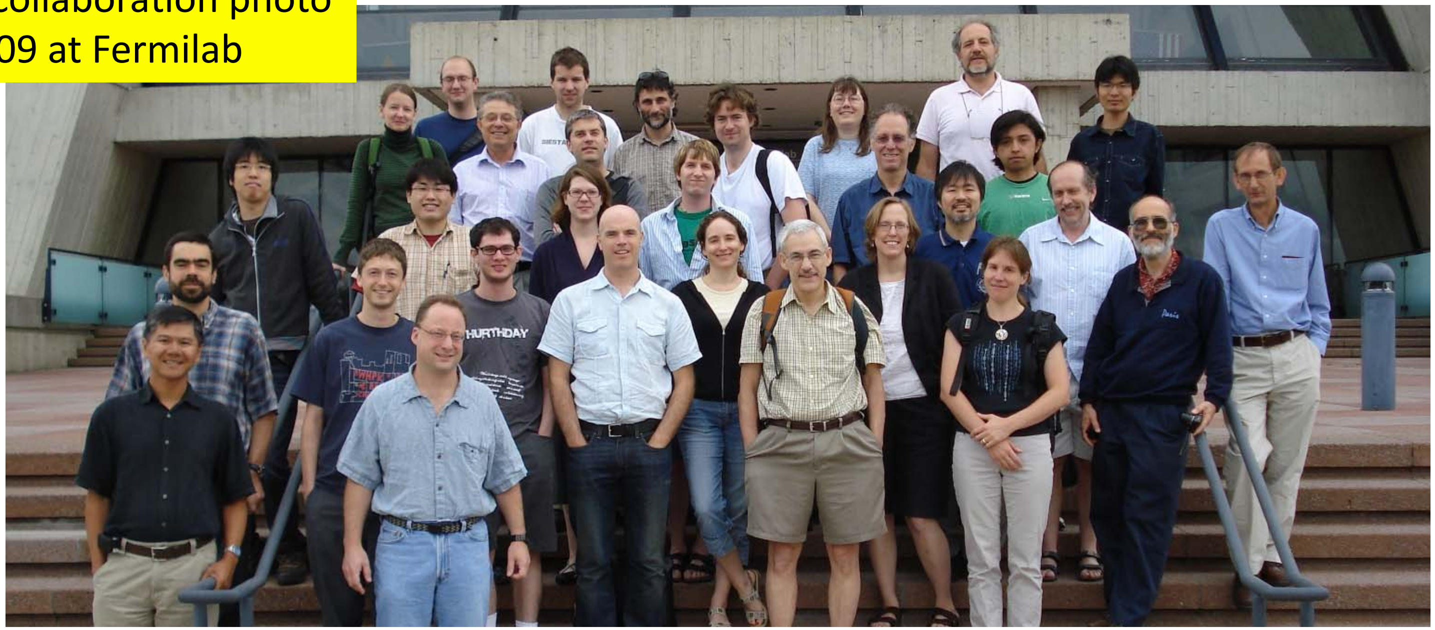
インフレーション宇宙の痕跡を探す！
－CMB偏光の精密観測実験

QUIET collaboration photo
Jun. 2009 at Fermilab



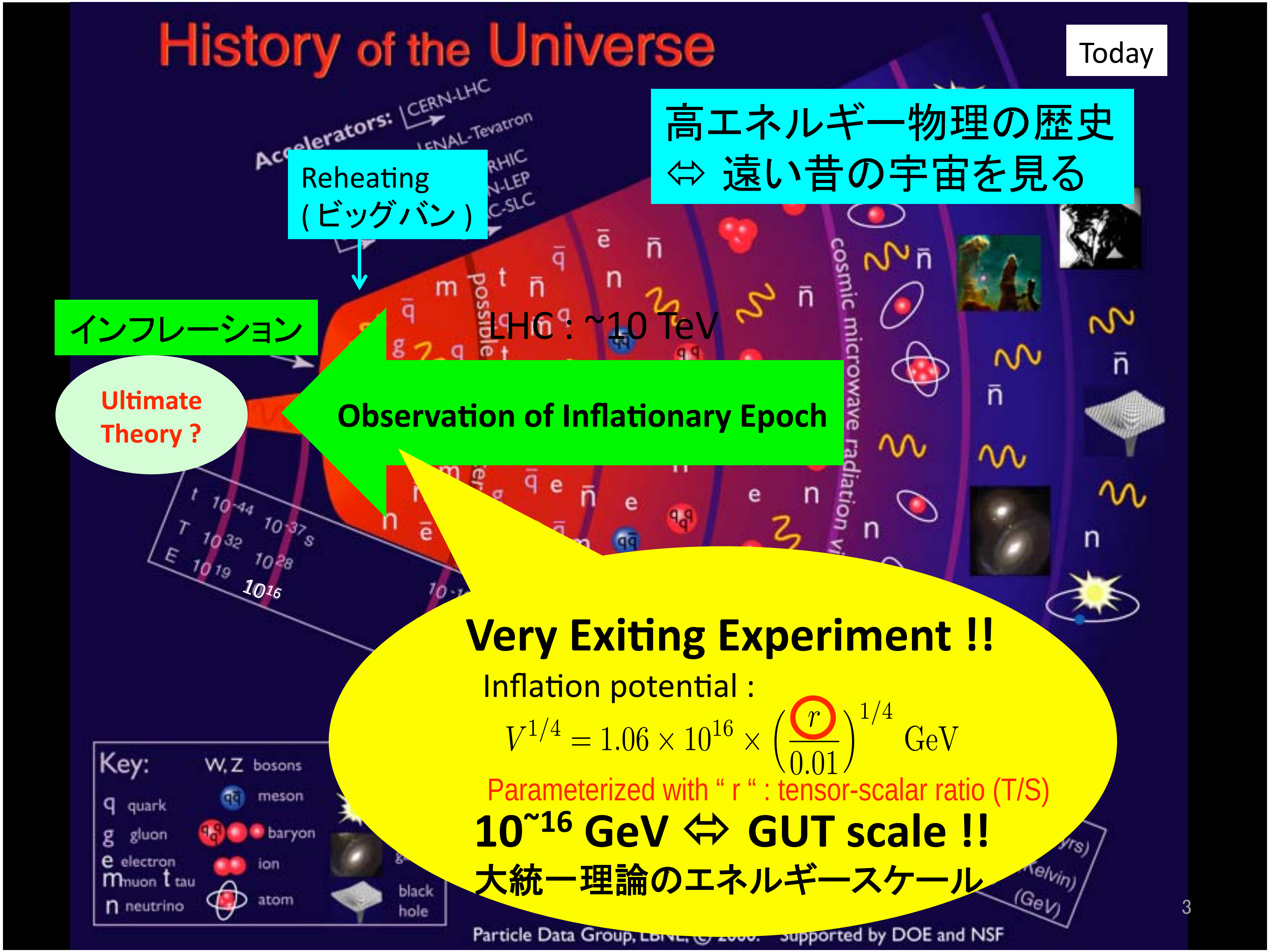
田島　治
高エネルギー加速器研究機構 (KEK)

インフレーション宇宙の痕跡を探す！
– CMB偏光の精密観測実験

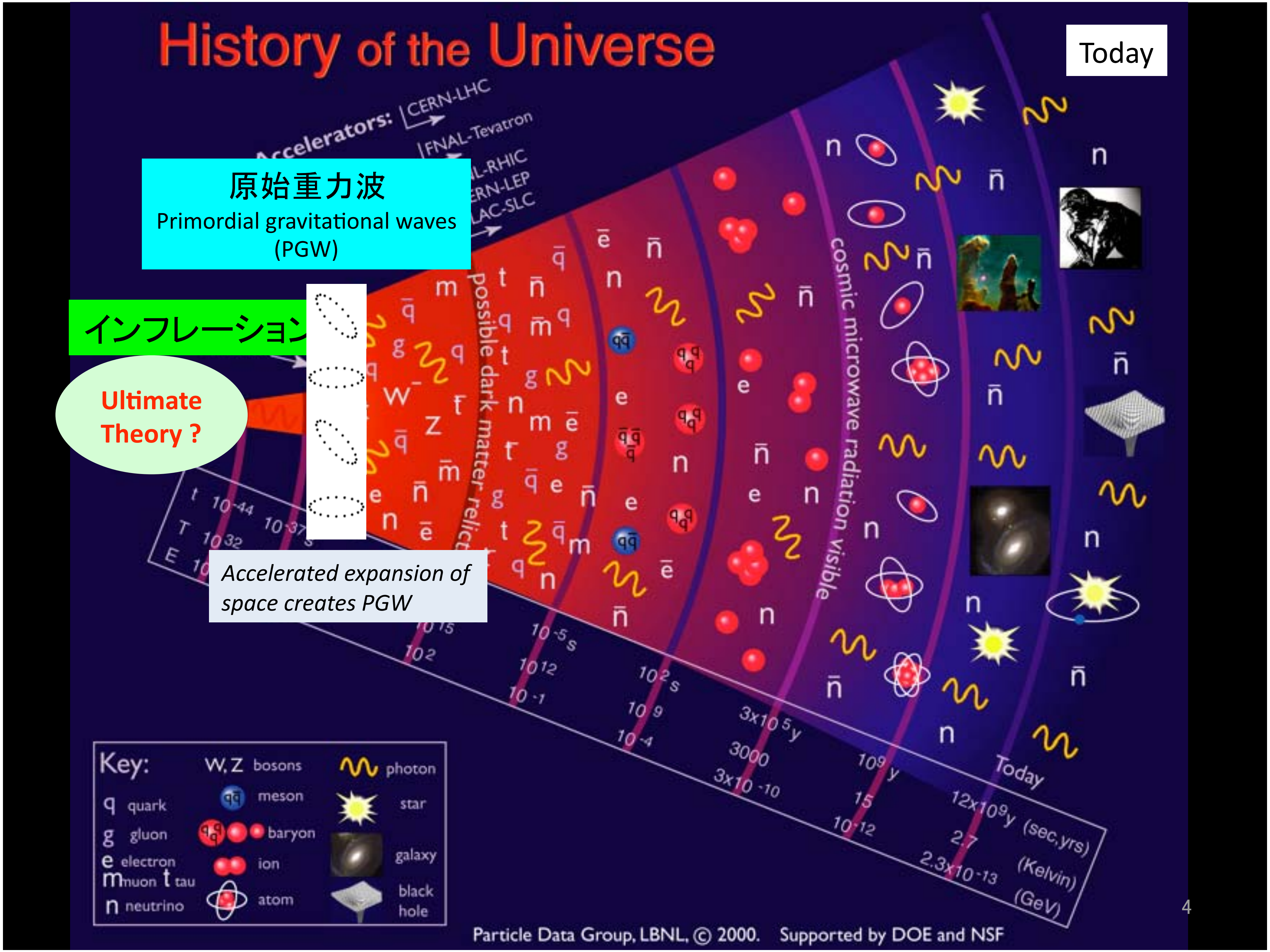
Contents:
- インフレーション宇宙とCMB偏光の「Bモード」
- Bモードをどうやって、観測するのか？
- 最近のBモード結果と展望
- まとめ

QUIET実験の話題を中心に（上記2項目）

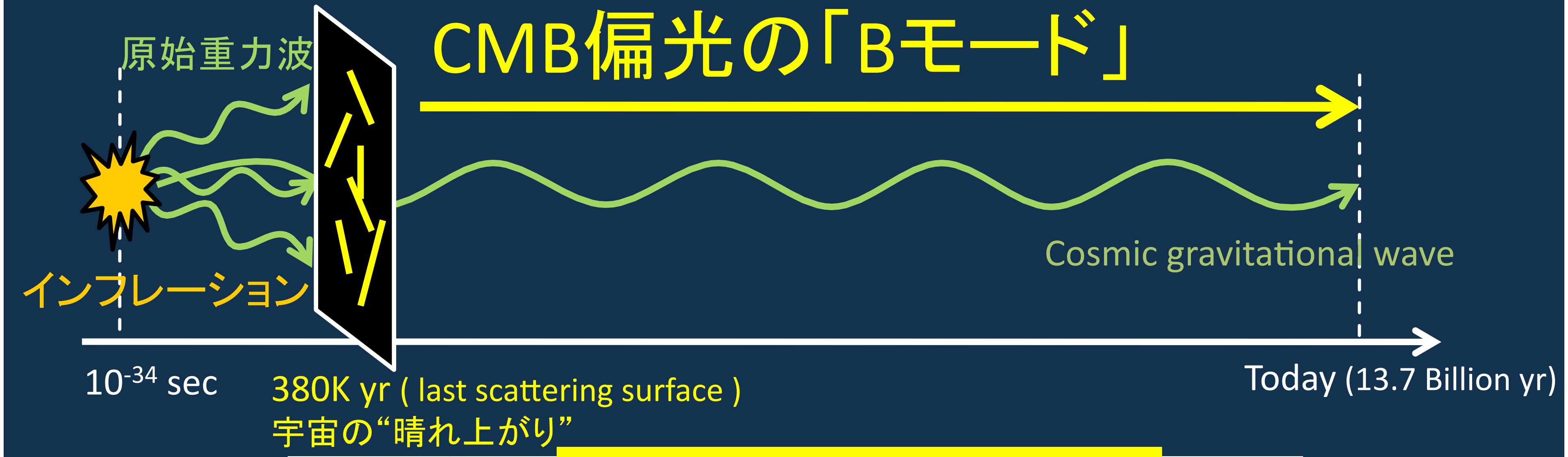
田島　治
高エネルギー加速器研究機構 (KEK)

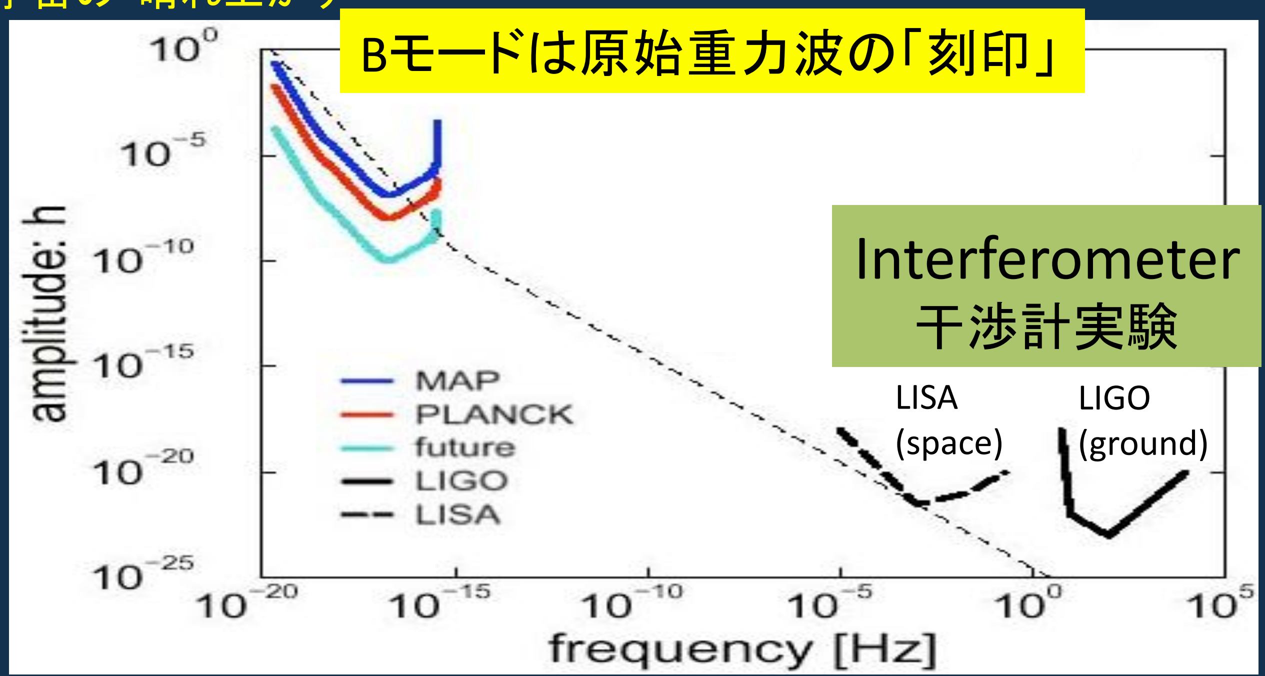


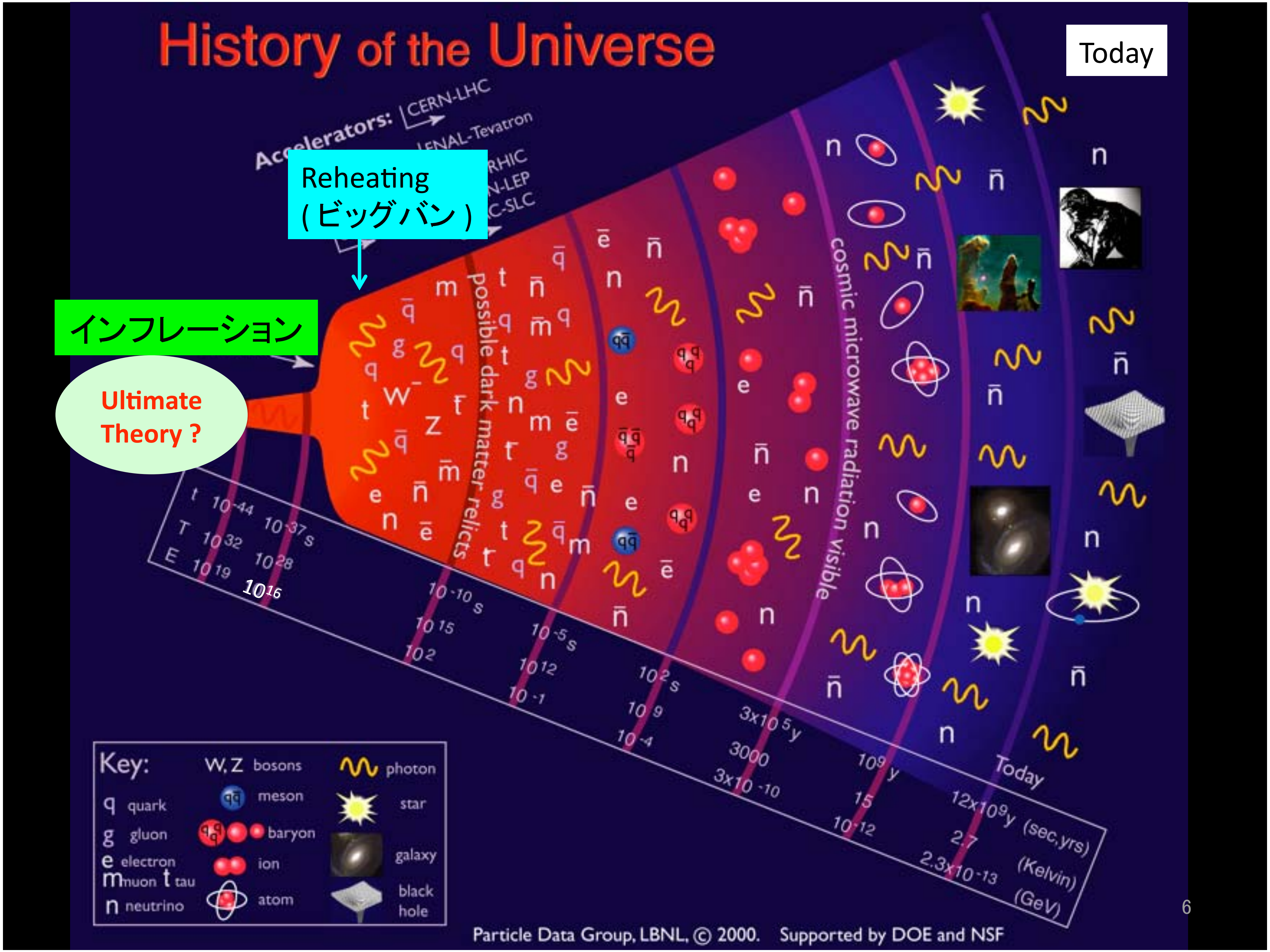
History of the Universe
Today
高エネルギー物理の歴史
⇔ 遠い昔の宇宙を見る
Accelerators: CERN-LHC
FENAL-Tevatron
RHIC
N-LEP
C-SLC
Reheating
(ビッグバン)
インフレーション
Ultimate
Theory ?
LHC : ~10 TeV
Observation of Inflationary Epoch
cosmic microwave radiation
possible
t 10-44 10-37 s
T 10 32 10 28
E 10 19
1016
Very Exiting Experiment !!
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)
10~16 GeV ⇔ GUT scale !!
大統一理論のエネルギースケール
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
black
hole
(Kelvin)
(GeV)
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


History of the Universe
Today
Accelerators: CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
原始重力波
Primordial gravitational waves (PGW)
インフレーション
Ultimate Theory ?
Accelerated expansion of space creates PGW
possible dark matter relics
cosmic microwave radiation visible
t
T
E
10^-44
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
q quark
g gluon
e electron
m muon t tau
n neutrino
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

原始重力波を観測する2つのアプローチ







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t 10-44 10-37 s
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E 1019 1016
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
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Key:
q quark
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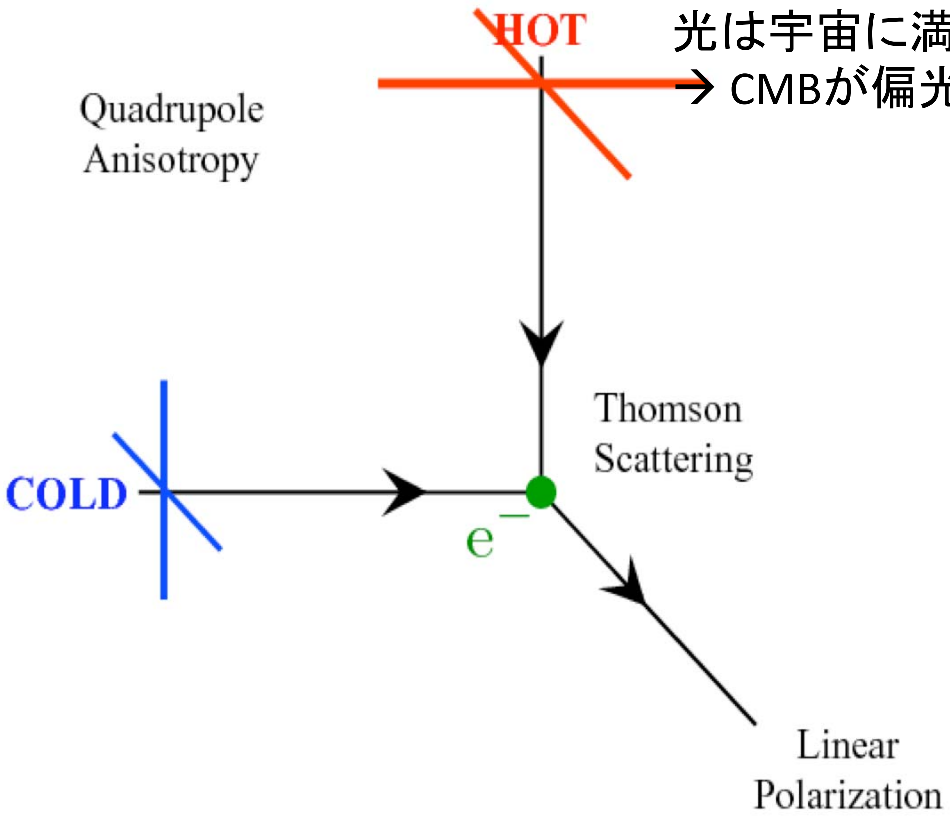
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

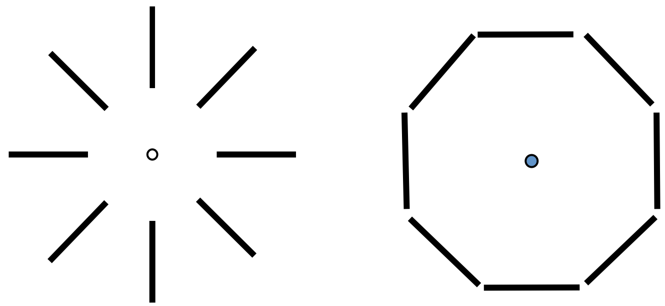
もし、原始重力波がなかったら？
E-modes only

晴れ上がり以前（38万年以前）の宇宙では、
光は宇宙に満ち満ちていた自由電子に散乱されていた
→ CMBが偏光する



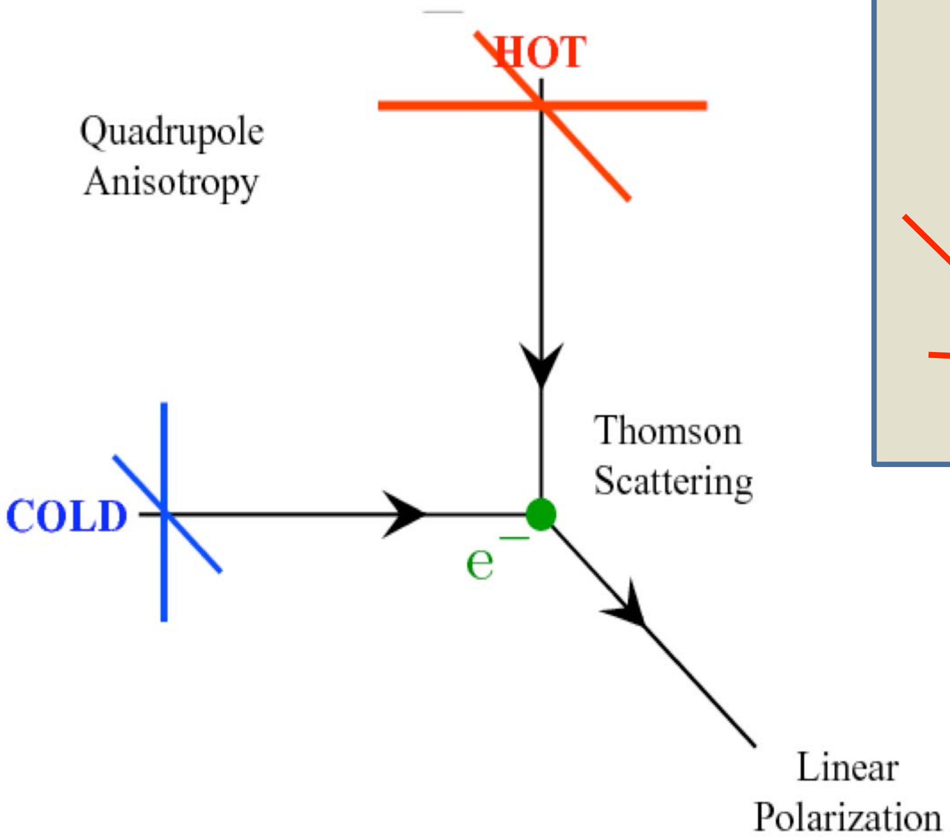
宇宙は完全に一様でない
Anisotropy of universe（10万分の1の揺らぎ）
→対称（偶パリティ）な偏光パターンを作る

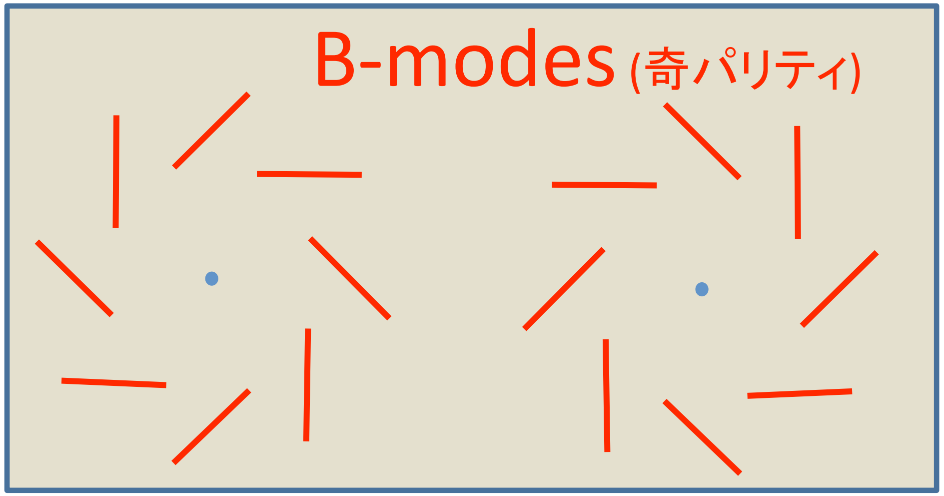
E-modes (偶パリティ)



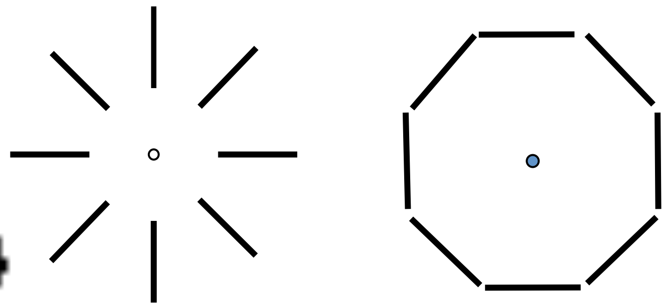
原始重力波があれば…

Bモードは原始重力波(⇔インフレーション)の決定的証拠



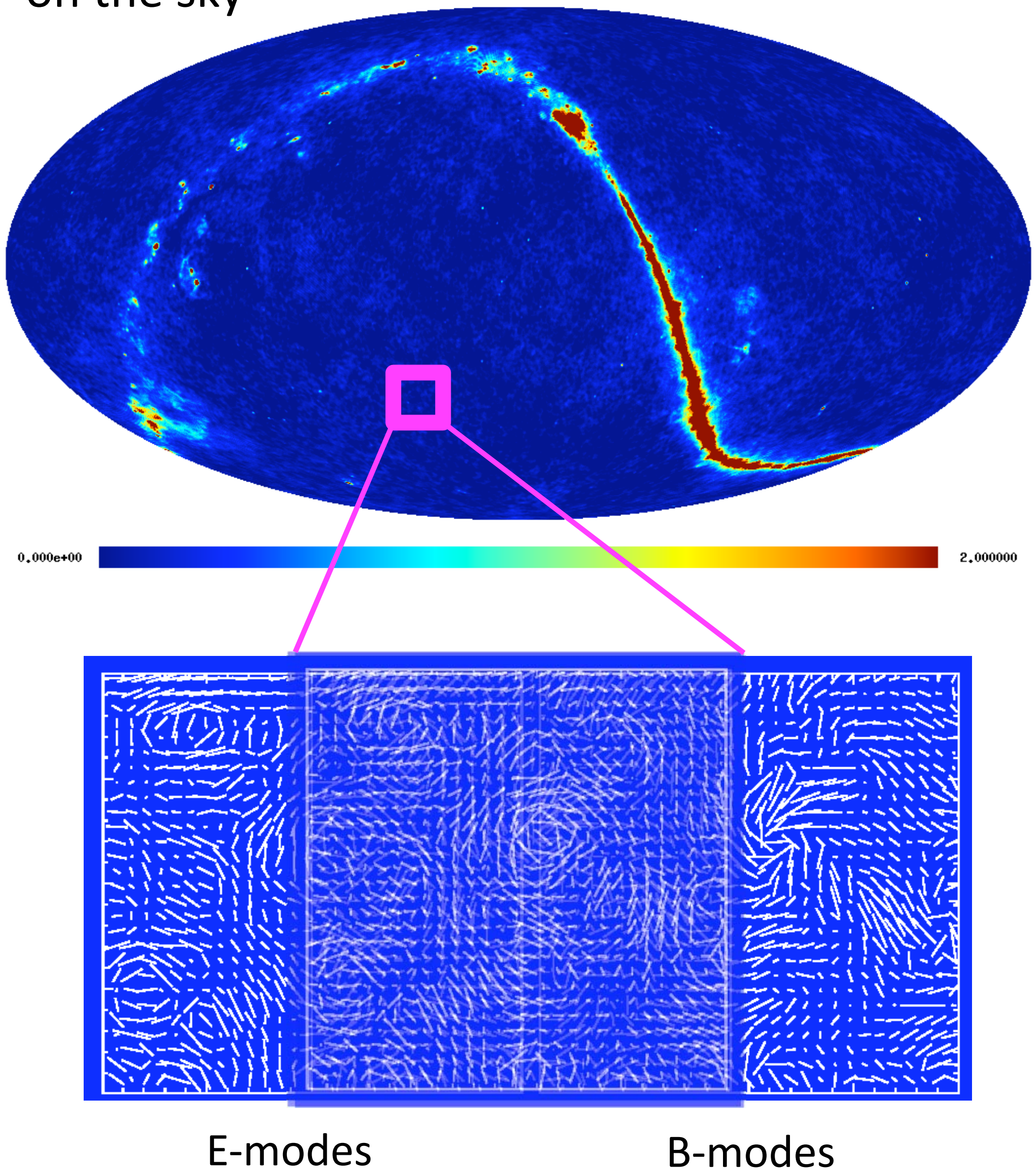


E-modes (偶パリティ)



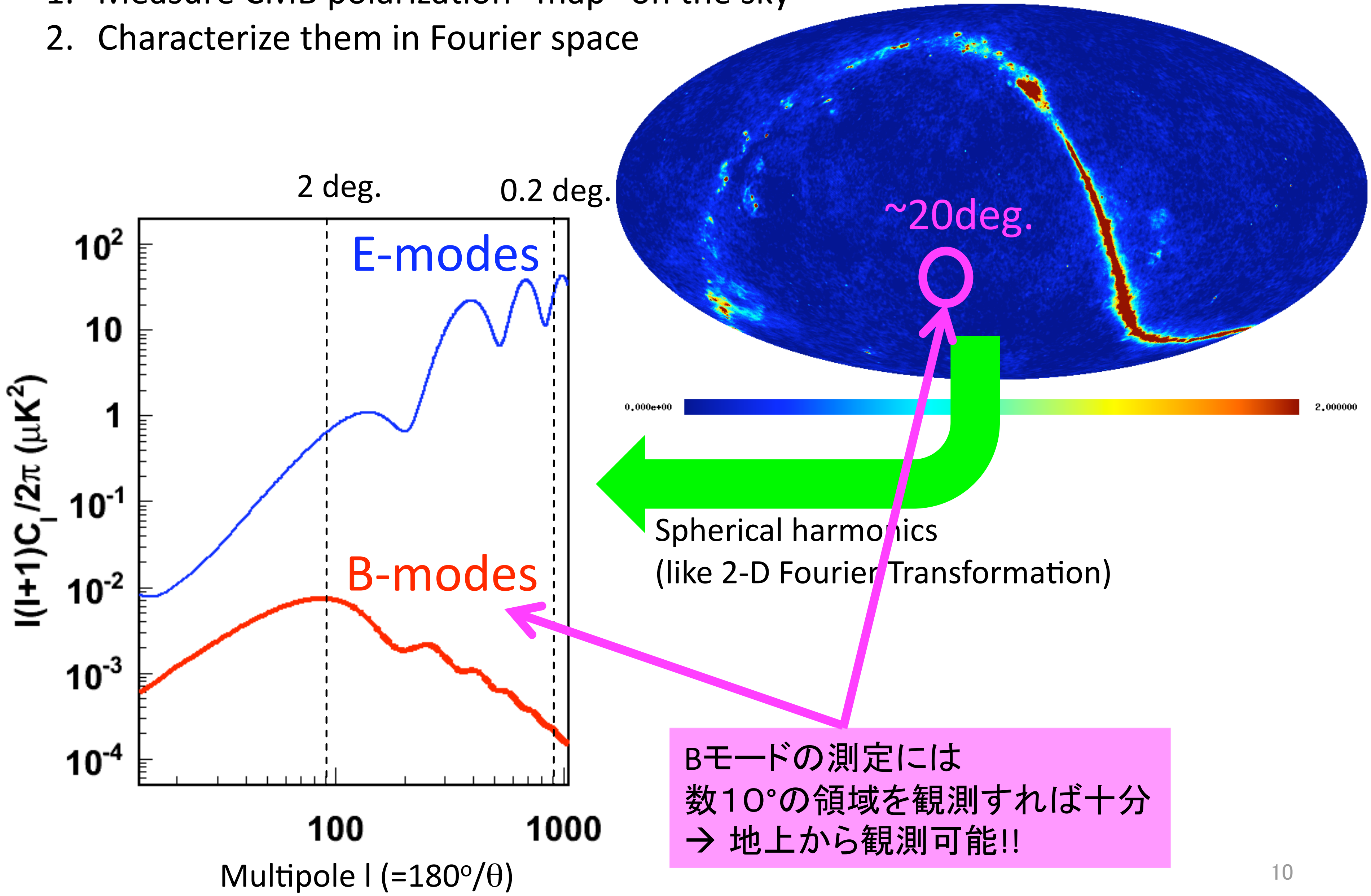
Since B-modes are pattern in CMB polarization, experimental approach is;

1. Measure CMB polarization "map" on the sky



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

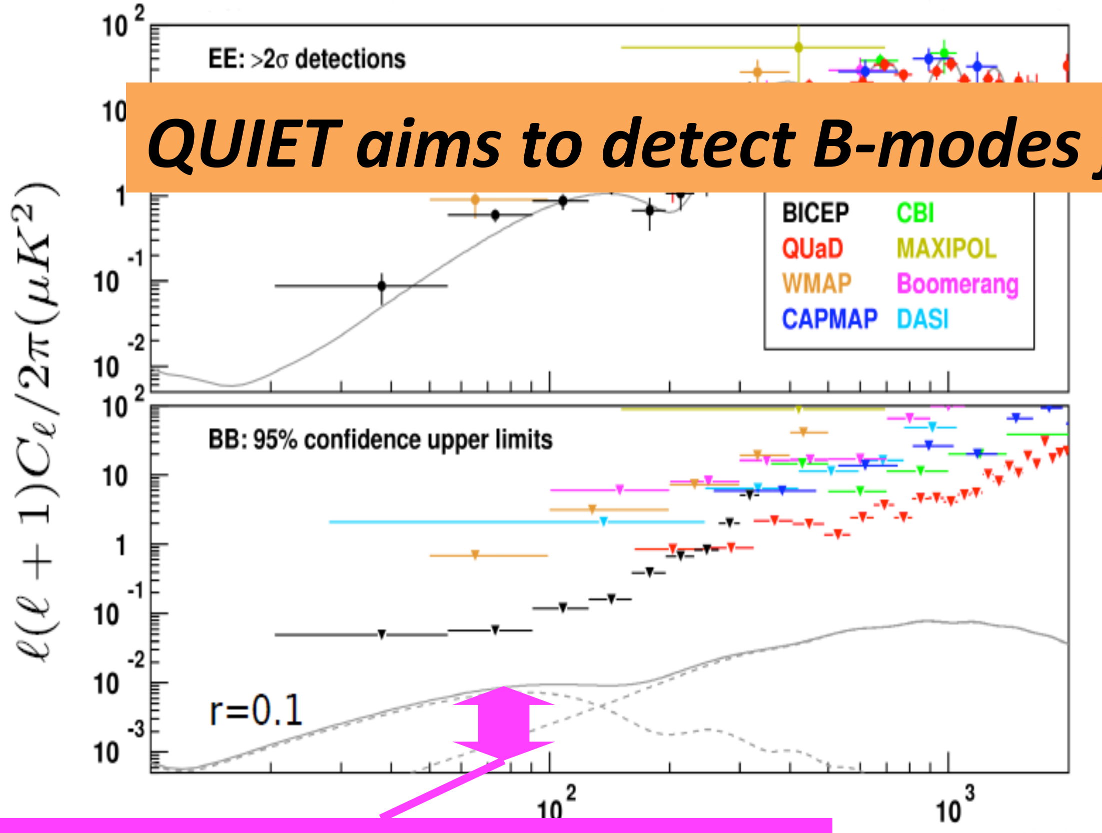
1. Measure CMB polarization “map” on the sky
2. Characterize them in Fourier space



これまでのBモード探索結果

最新の検出器を搭載できる、地上実験が発見競争を牽引している！

QUIET aims to detect B-modes from ground !



…t al, 0906.1181

インフレーションの証拠！

B-modes
（U.L. 95%C.L.）

Direct bound
r < 0.7 (BICEP)

Regions favored by many
inflationary models r = 0.01 ~ 0.1
r = T/S : Tensor-Scalar ratio

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

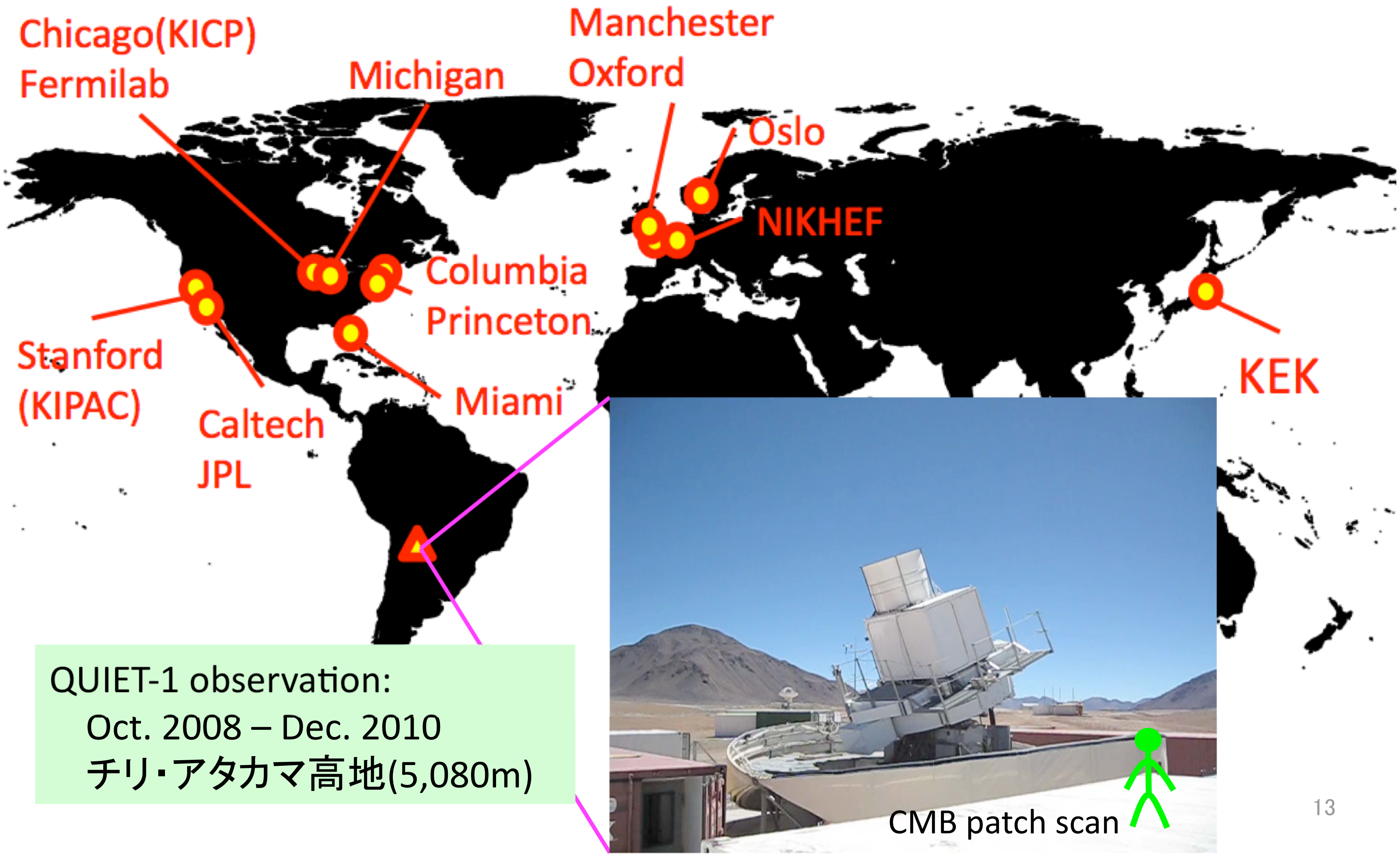
The QUIET Collaboration

5 countries, 14 institutes, ~35 scientists

QUIET collaboration photo
Jun. 2009 at Fermilab

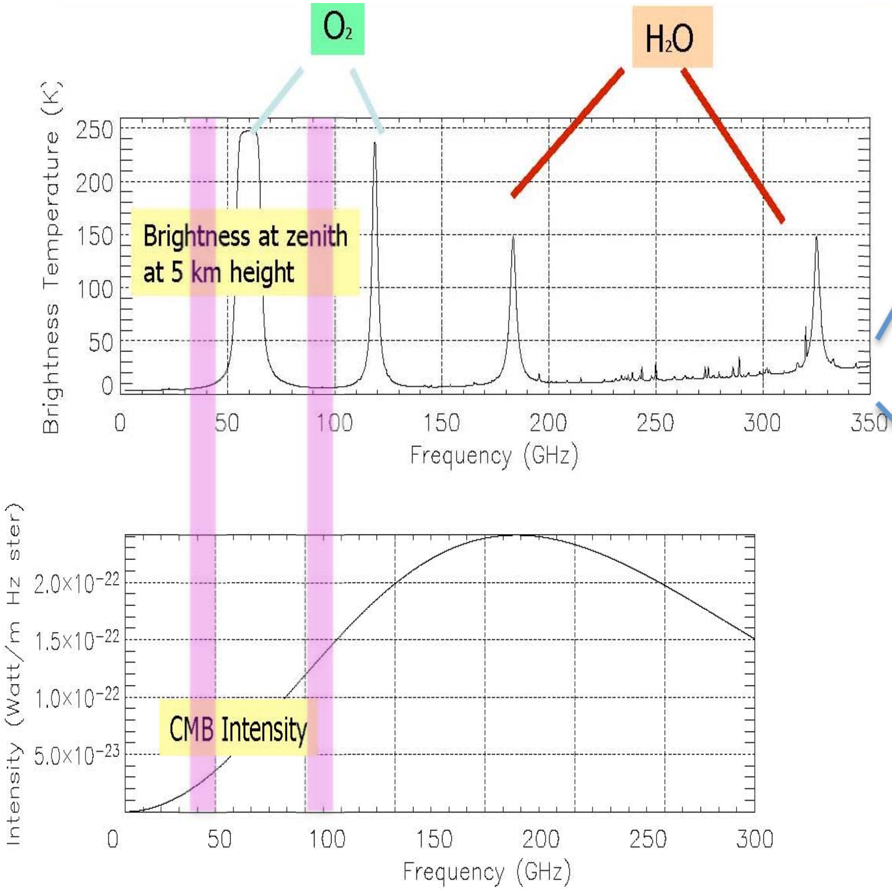
The QUIET Collaboration

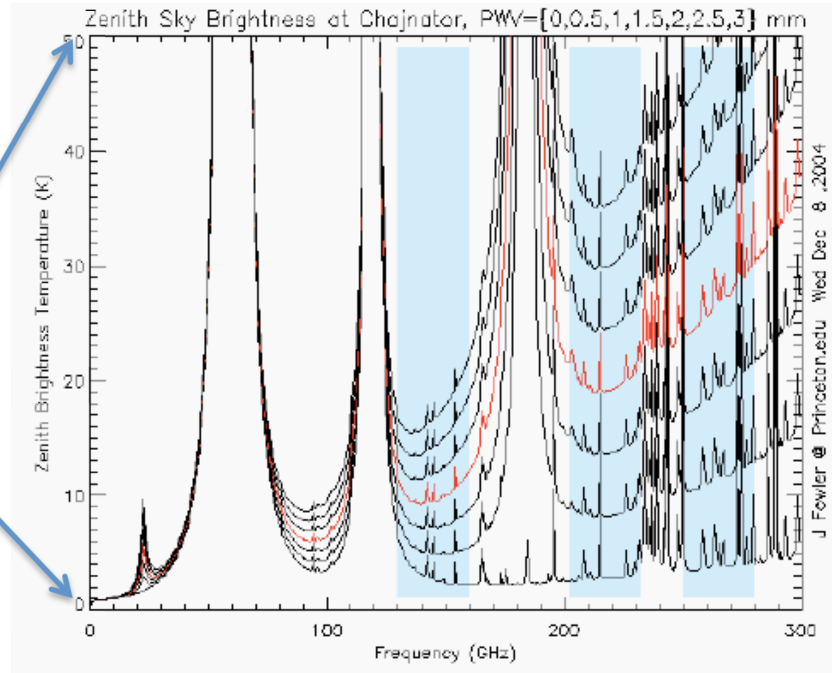
5 countries, 14 institutes, ~35 scientists



QUIET-1 observation:
Oct. 2008 – Dec. 2010
チリ･アタカマ高地(5,080m)

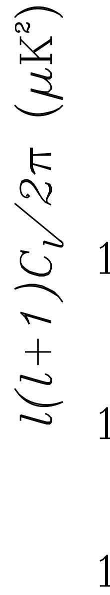
ナゼこんなところで観測するかというと



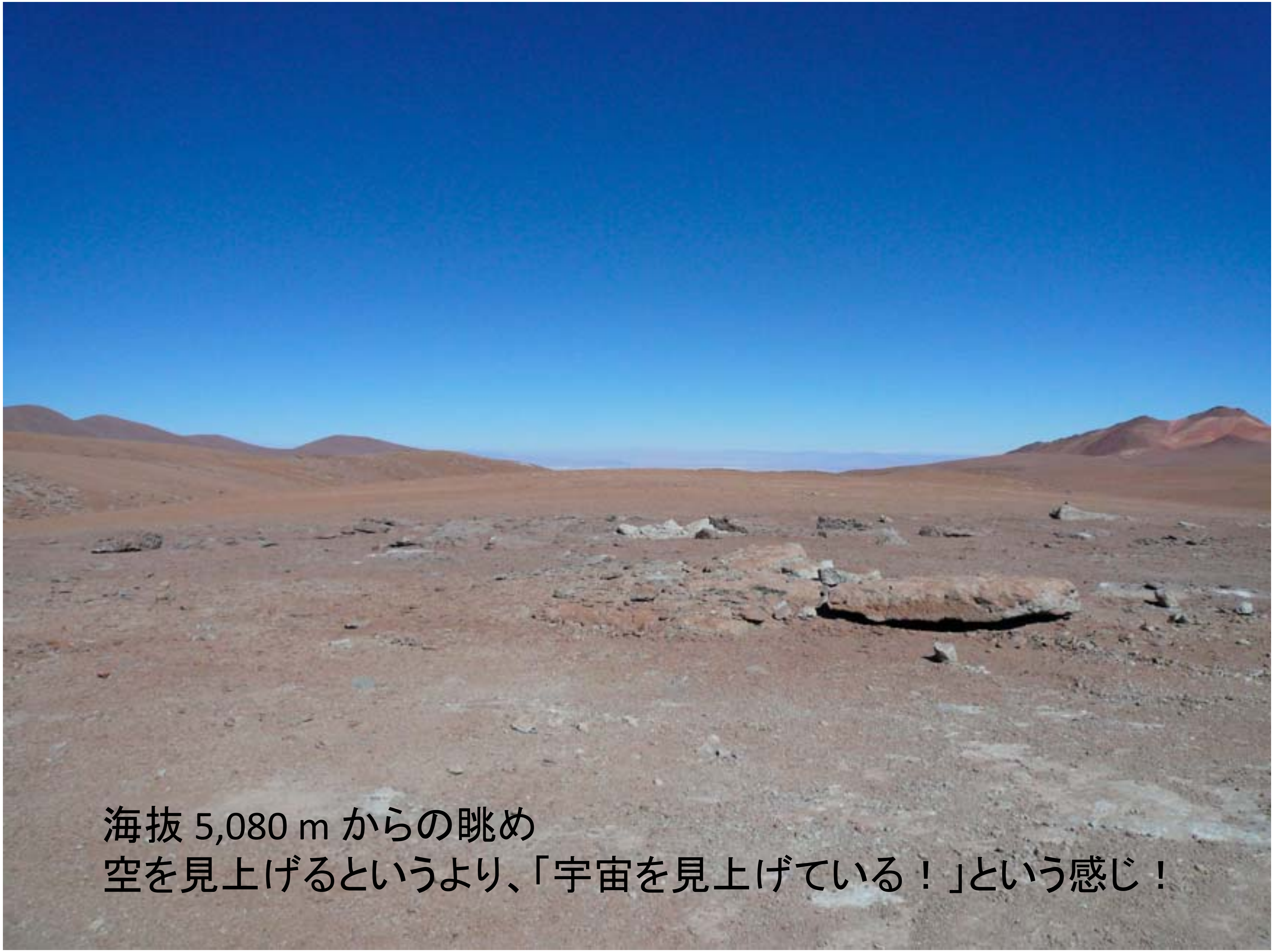


- *大気の輻射熱は周波数依存大*
- *酸素、水の吸収線の間をぬって観測*
- *Tailの寄与があるので、*
  空気が薄く、乾燥した場所が良い

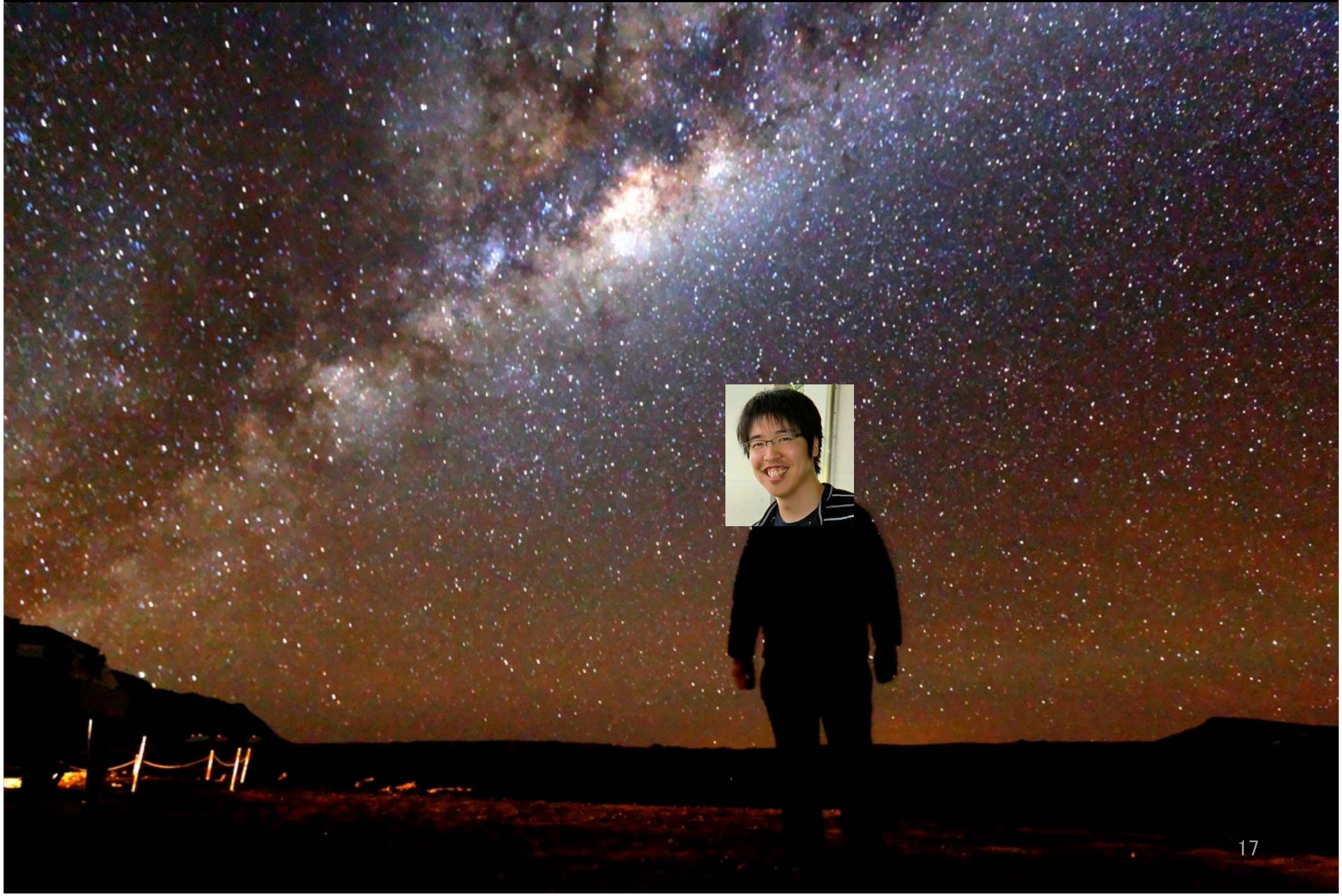
Chile Atacamaは地上で最もCMB観測に適した場所！
QUIETではQ-band(43GHz帯)とW-band(95GHz帯)を観測する



QUIET observation site


海抜 5,080 m からの眺め
空を見上げるというより、「宇宙を見上げている！」という感じ！

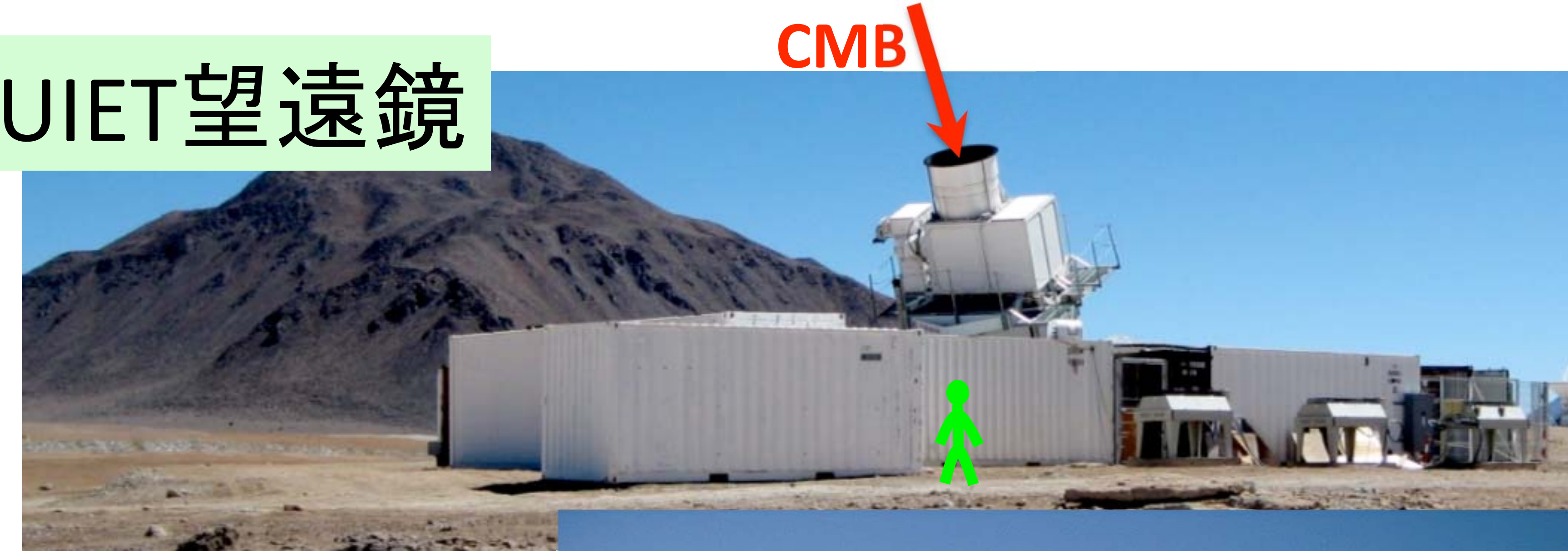
Beautiful Sky at 5,080m

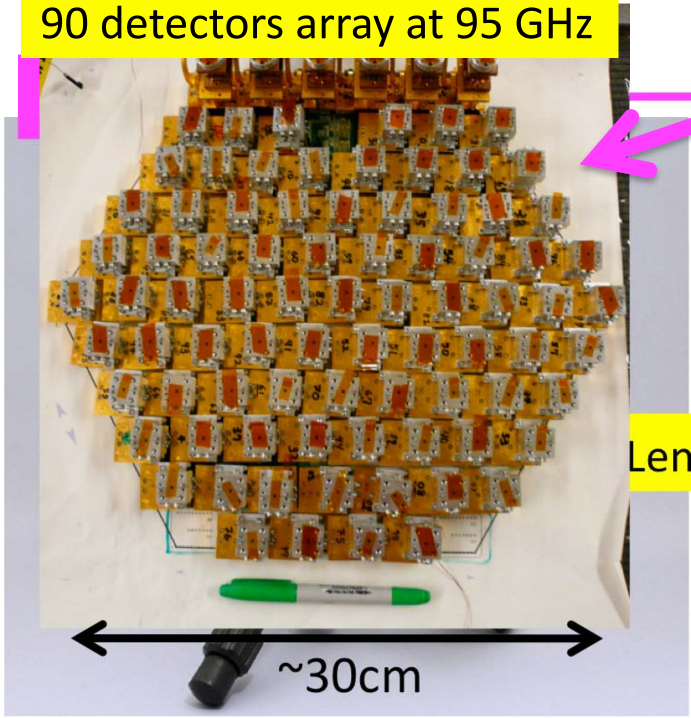


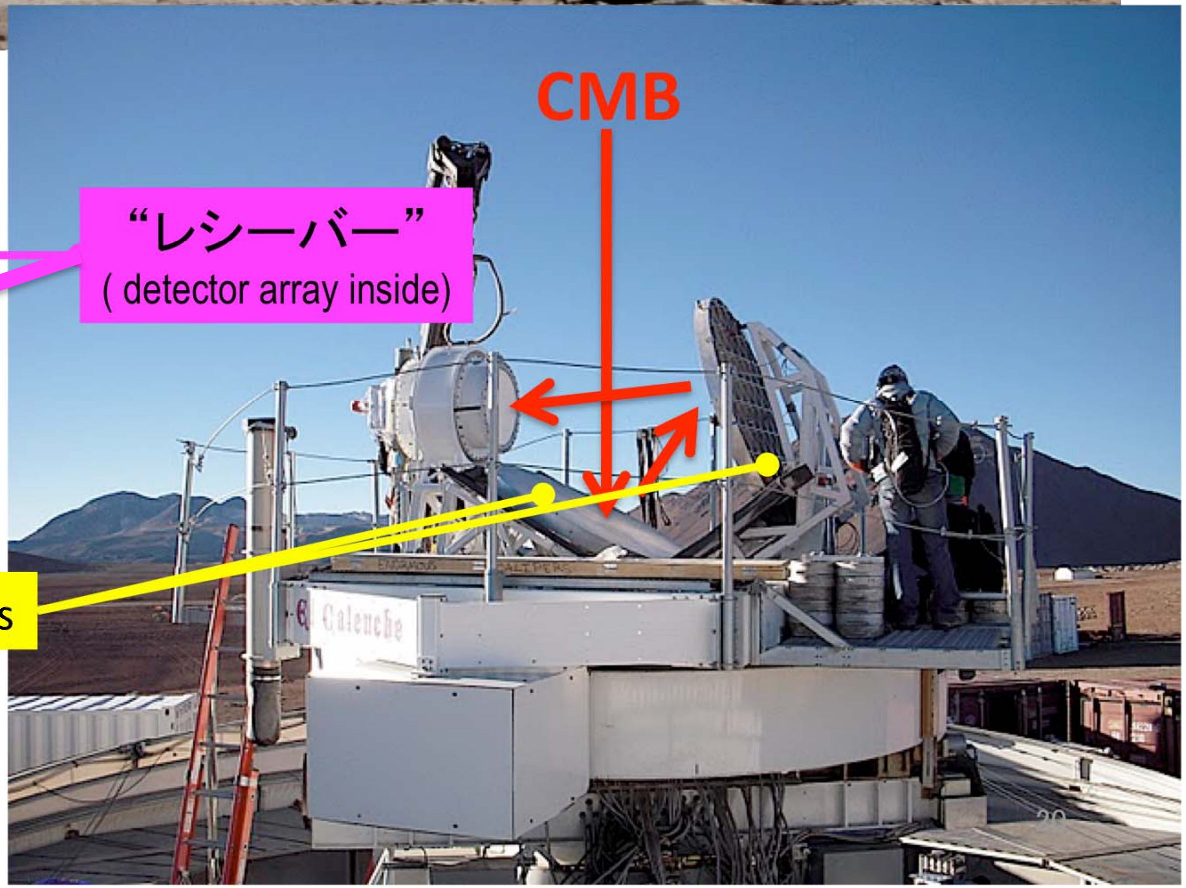

ふもと町（2,400m）のレストランにて


ふもと町（海抜2,400m）から5,000m級の山々を見上げる
地平線の下から、照らされる夕日に映える山々

QUIET望遠鏡

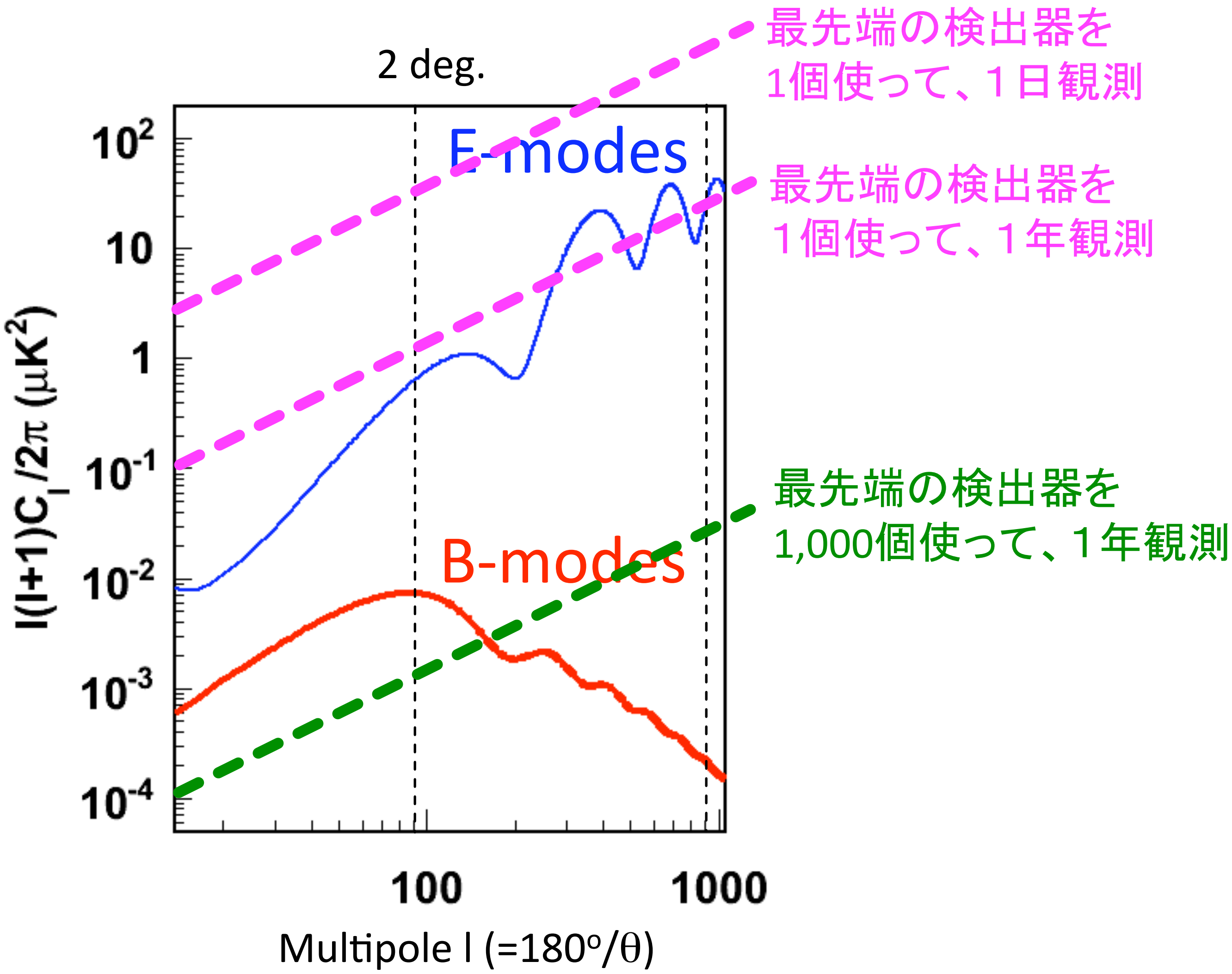

CMB


QUIET偏光検出器
90 detectors array at 95 GHz
~30cm


CMB
“レシーバー”
(detector array inside)
Lens

“Detector Array” is essential

無偏光成分
検出器１個の性能はCMB(3K)自身の熱雑音で頭打ちされている



Large number of detectors

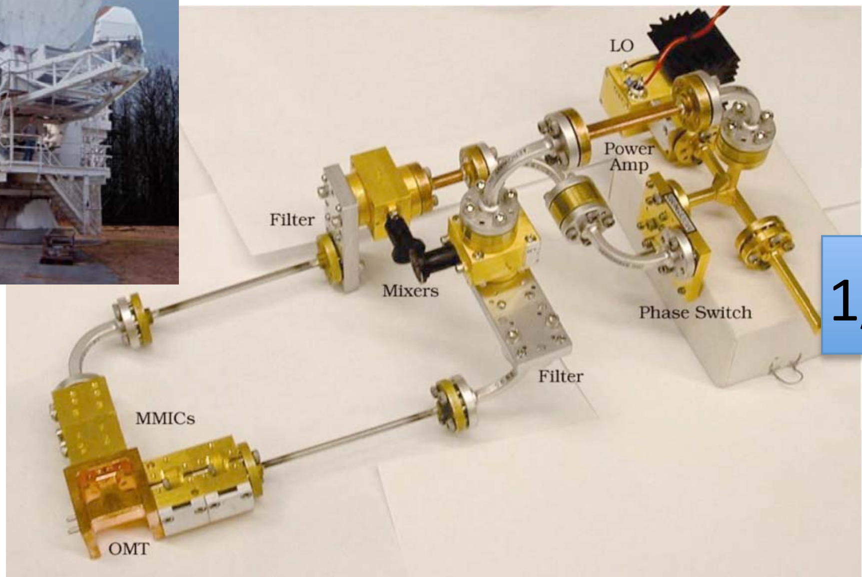
"Detector Array" is essential

for all CMB-pol. experiments

Limitation of single detector sensitivity

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

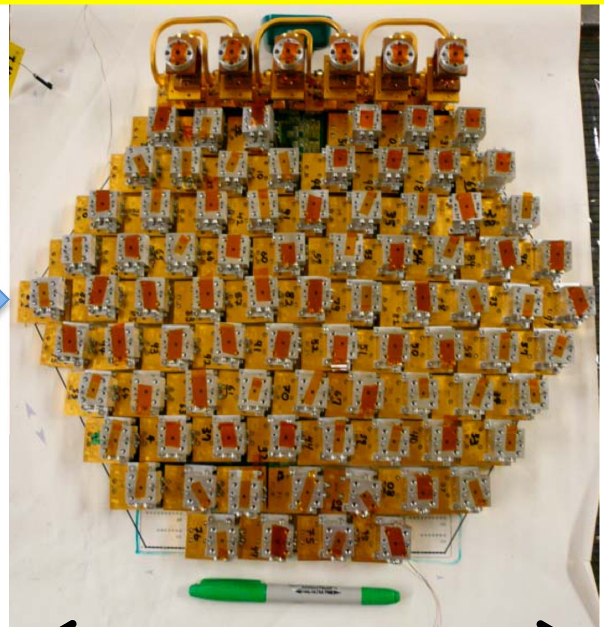
CAPMAP (2003-2005)
偏光検出器 at 95GHz



~30cm

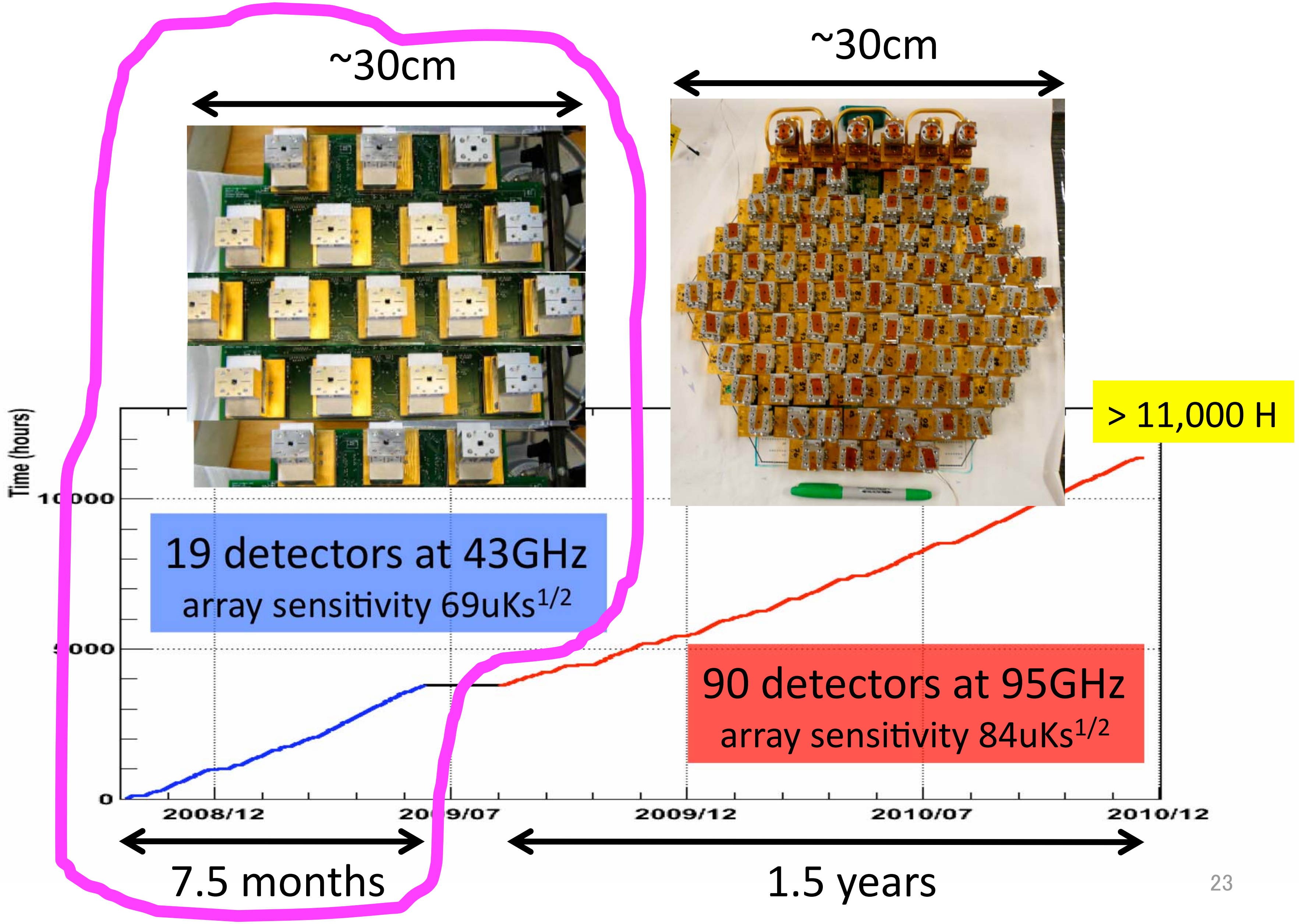
1/10 size

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



~30cm

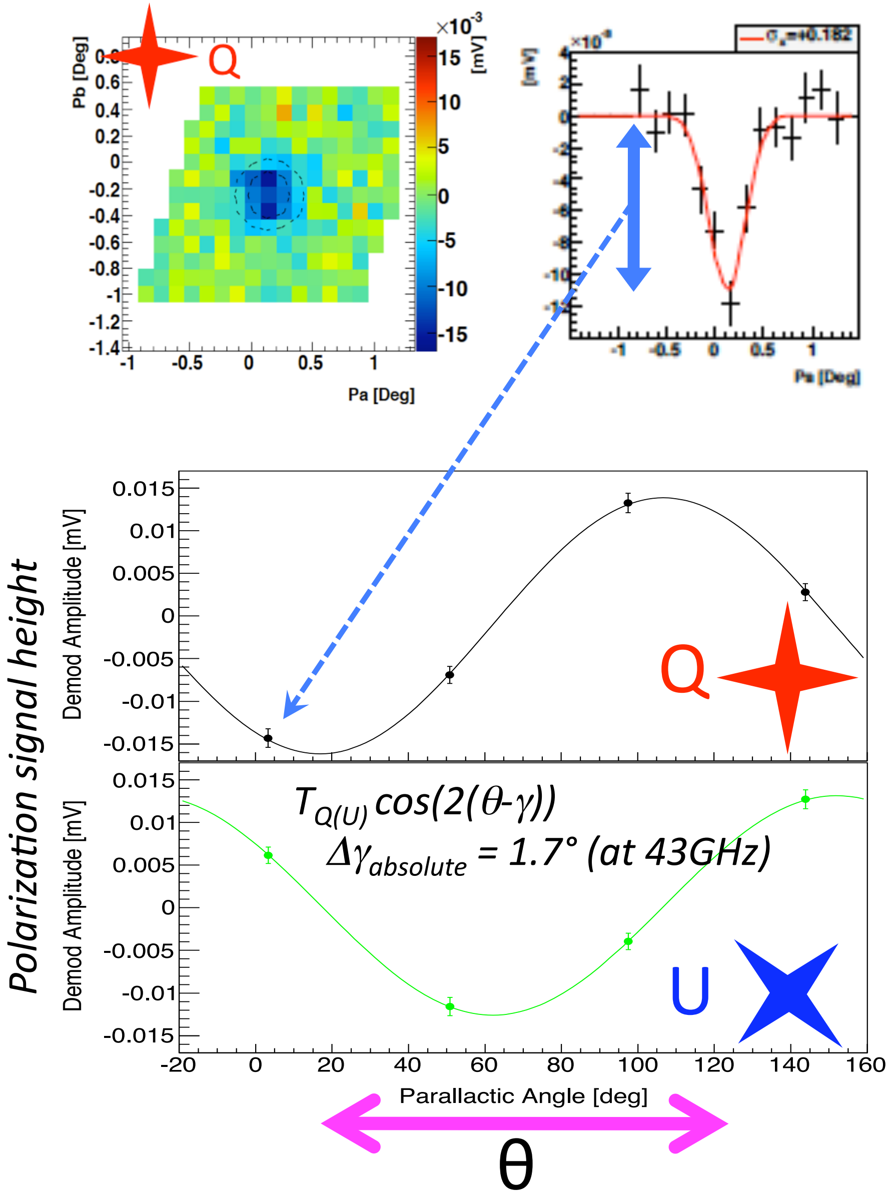
QUIET-1 観測履歴 @ チリ・アタカマ（5,080m）

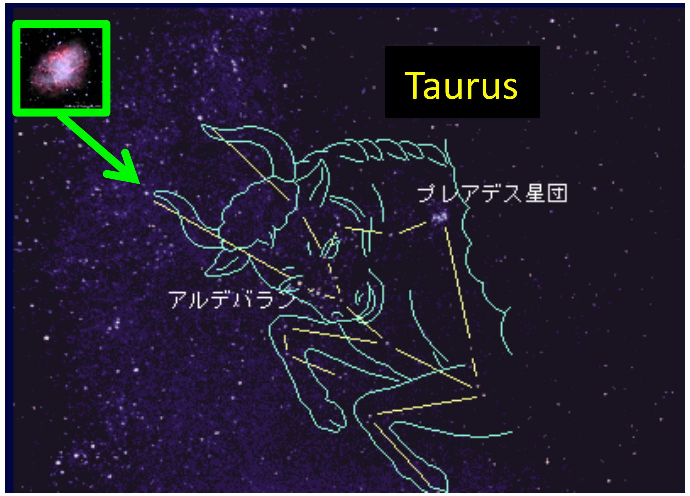


偏光検出器のキャリブレーション

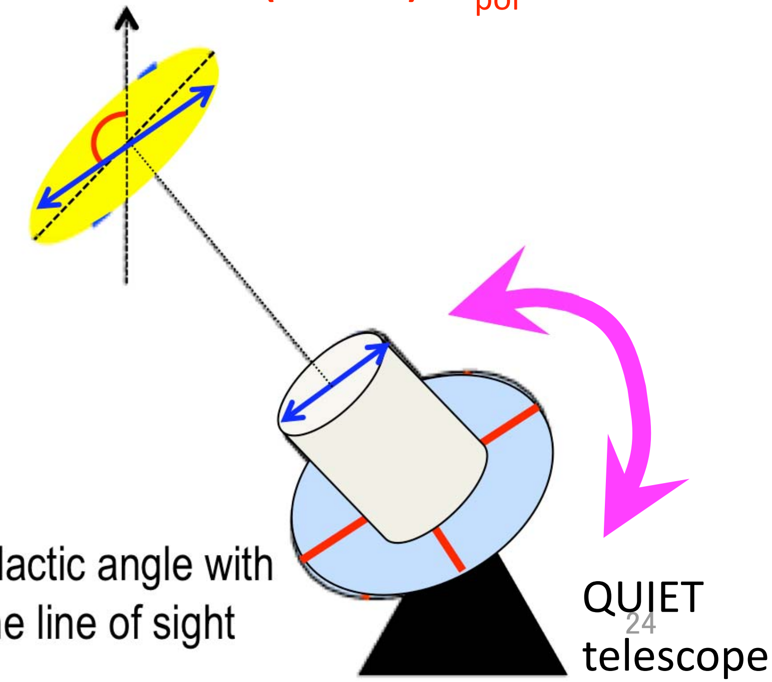
[arXiv:1012.3191]

~4 min scan time for each



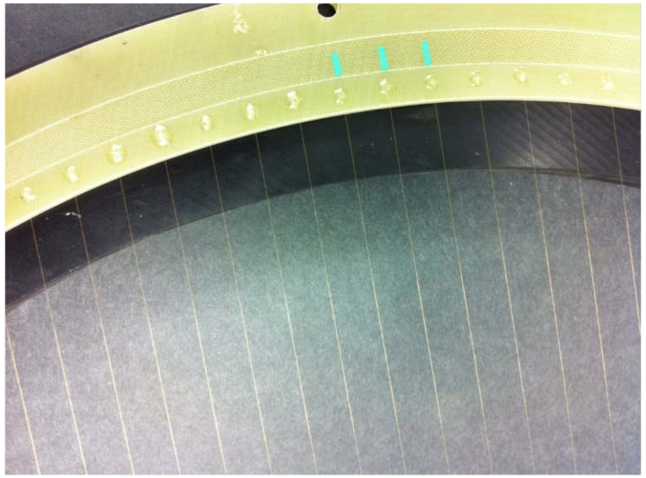


Crab nebula (TauA) T_{pol} = 5mK

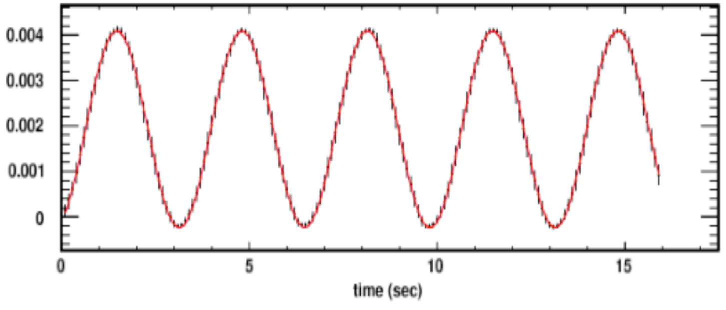


Rotate parallactic angle with
keeping the line of sight

“まばらな”ワイヤーをつかった、
人工的なcalibration



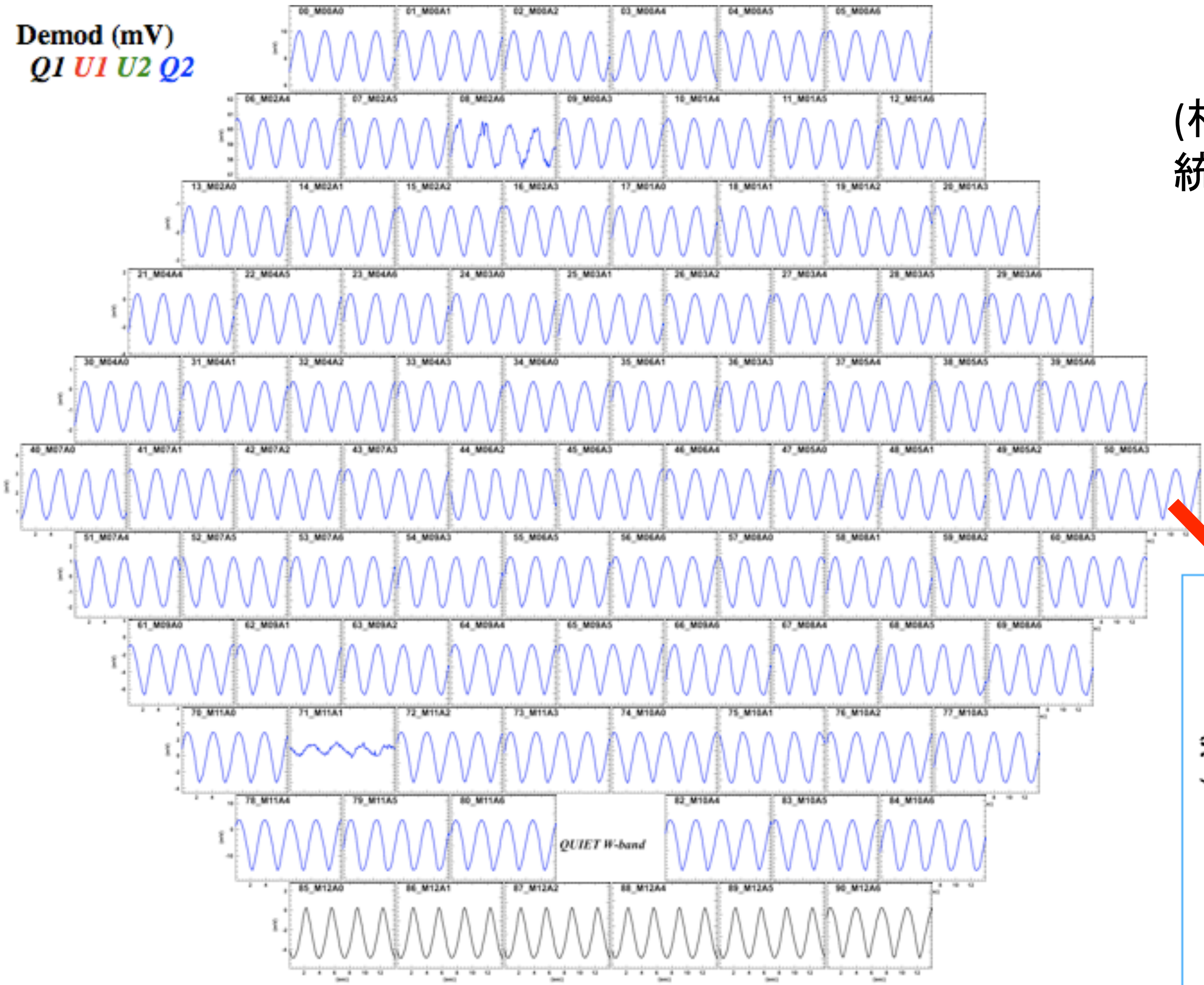
Grid rotates to modulate the polarization

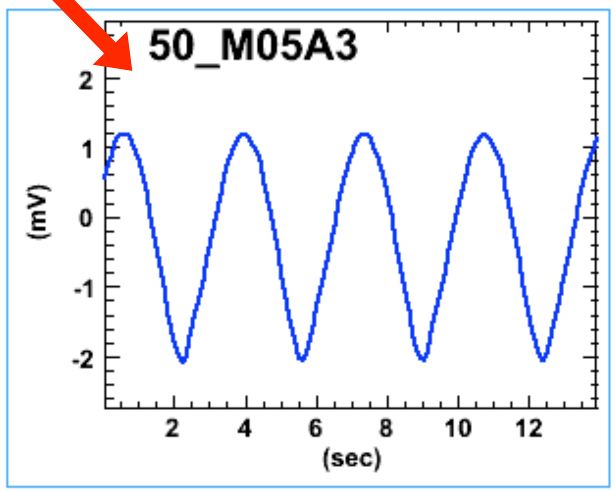


“まばらな”ワイヤーを使ったCalibration

全チャンネル同時にCalibration！

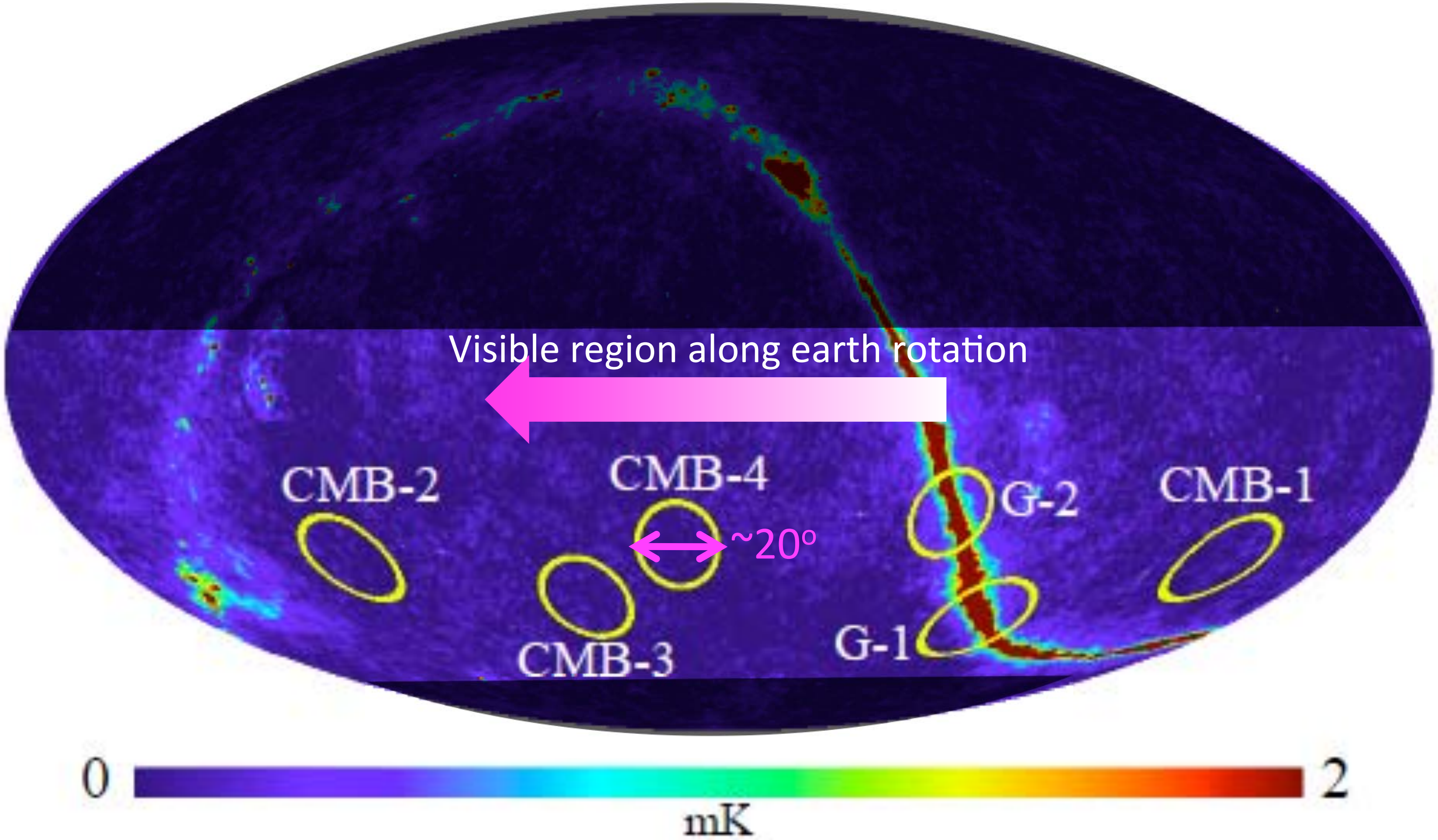
(相対)偏光角度決定精度
統計誤差: 0.4deg (30sec data)





CMB偏光の観測ストラテジー

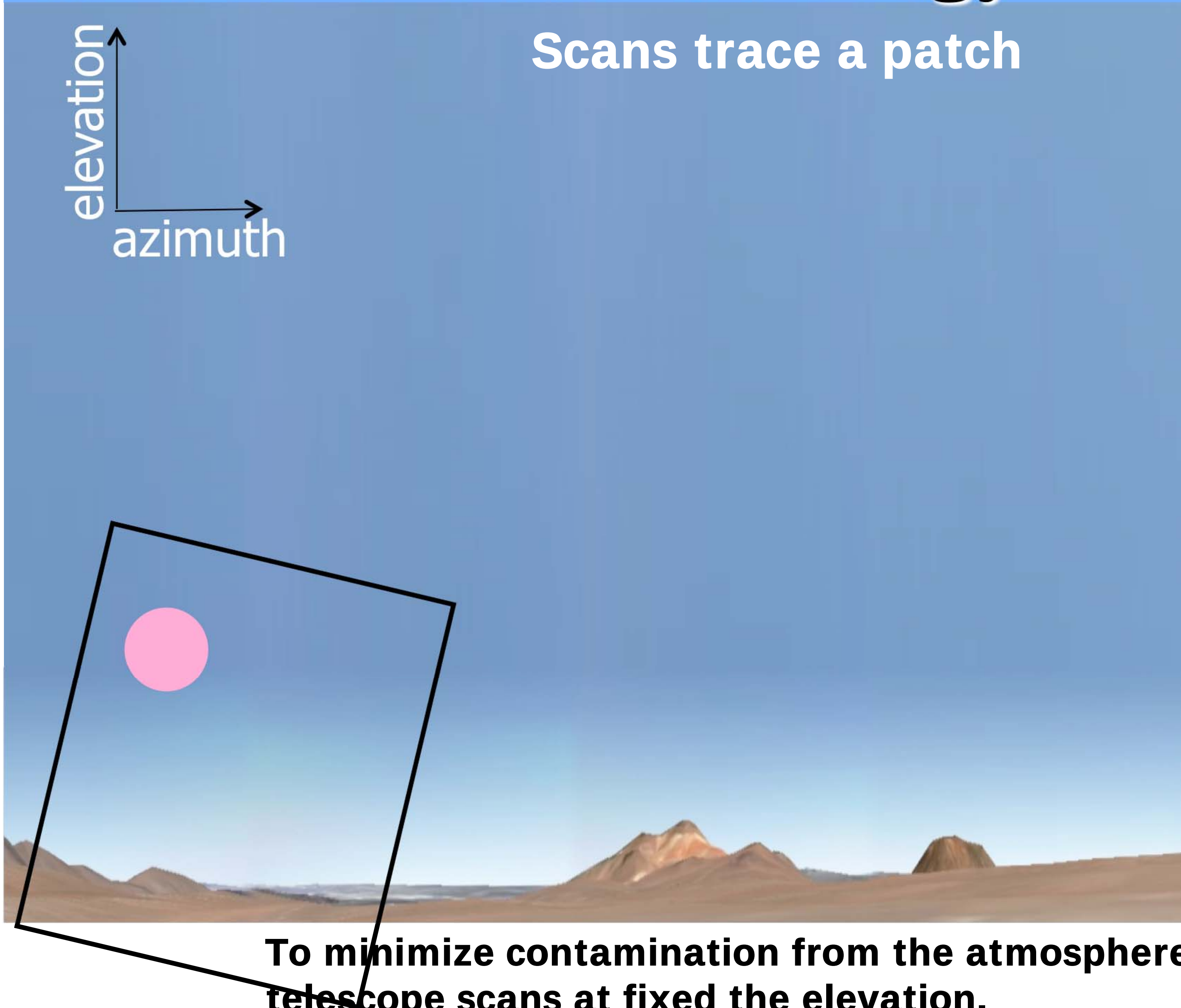
Observation Patches

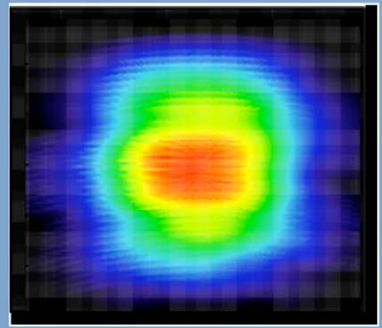


4 CMB patches were chosen (~3% of full sky)
Observing them DEEPLY (Galaxy observation when CMB patches are not visible)
Map precision on 1°x1°: ~1μK (7.5 months at 43GHz)

QUIET's Scan Strategy

Scans trace a patch



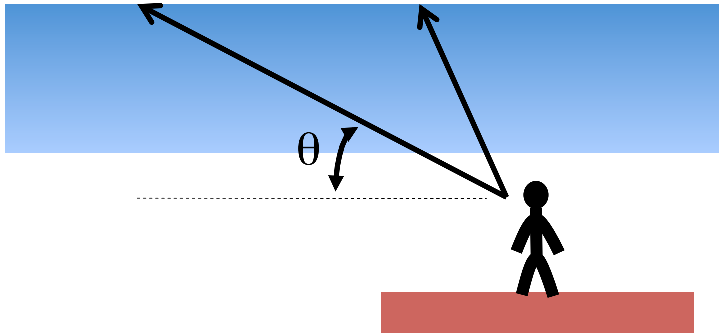


exposure map for one patch

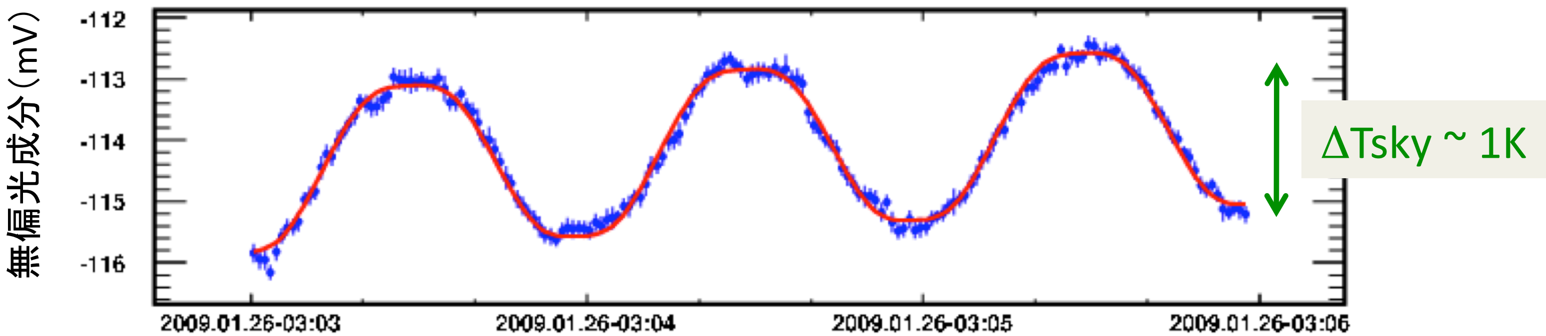
To minimize contamination from the atmosphere, telescope scans at fixed the elevation.

縦に首をふると大気からの放射強度が変わる

縦に首を振ると....
→ 視野方向の大気の厚みが変わる
⇔ 大気の放射強度が変わる



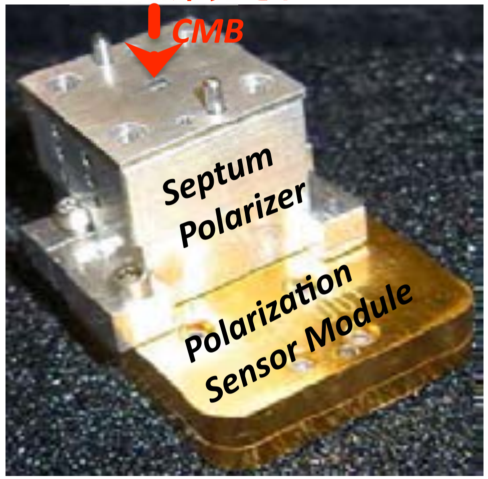
縦に±3°ふった時の無偏光成分信号の出力変化



大気の放射は無偏光なので、
一見すると偏光測定には影響がないように見えるが...

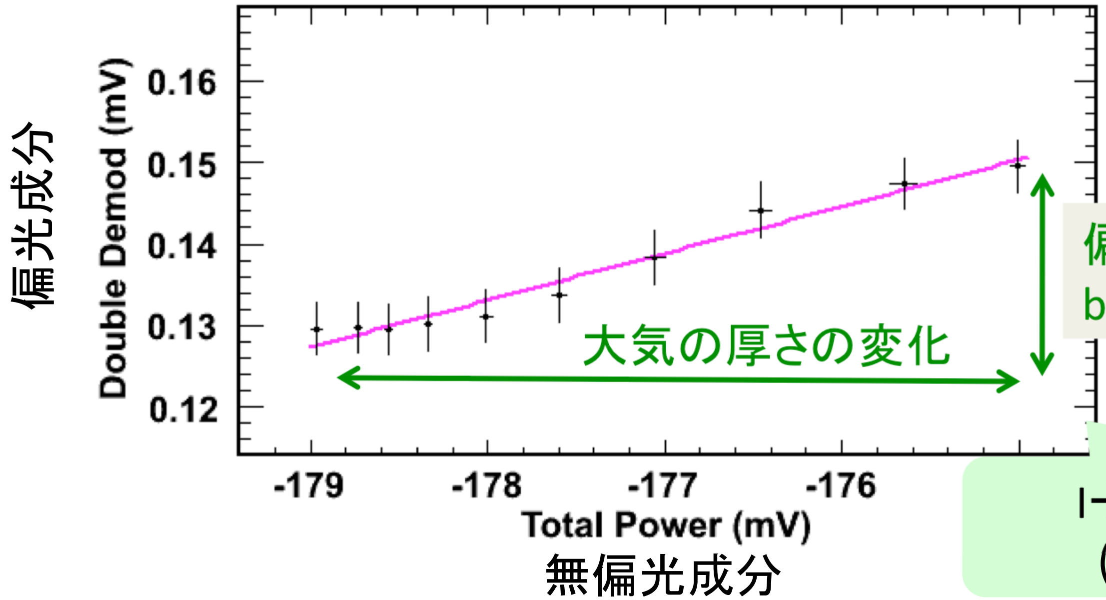
無偏光(I)→偏光(Q/U)への”クロストーク”

I → Q/U Leakage



Septum Polarizerでの微小なクロストーク
（導波管の世界の出来事なので時間変化しない）

首を縦にふる較正スキャン

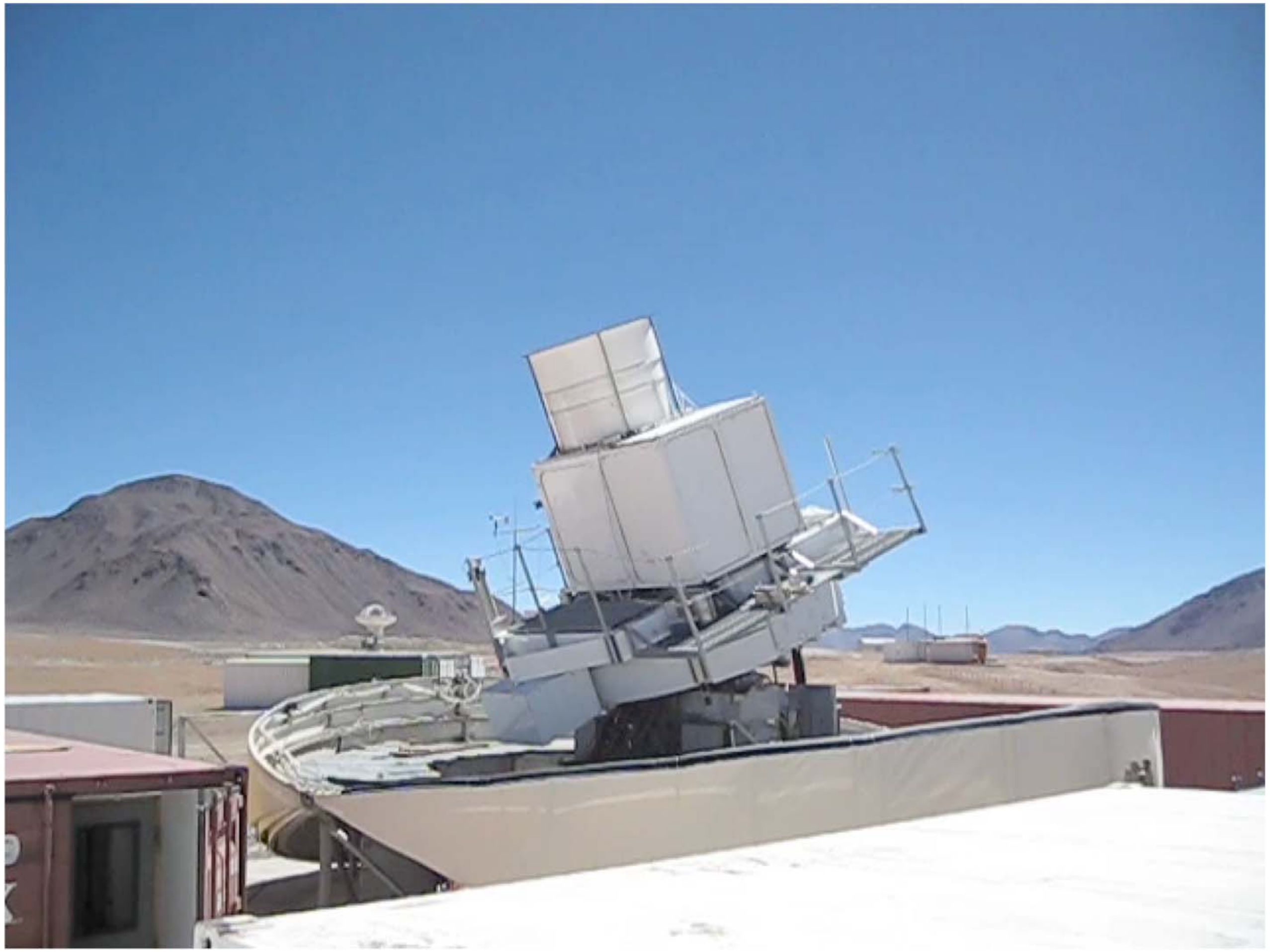


偏光信号出力のbaselineの変化

I→Q/U leakage : 0.6 ±0.1 %
(Q-bandレシーバー平均)

縦に首を振ると偽の偏光信号がbaselineを揺るがす，
e.g. ΔT_{sky}=1K → 600uK >> ~uK (E-modes) >> B-modes
→ Constant Elevation Scanの採用して、偏光信号の揺らぎを抑制！

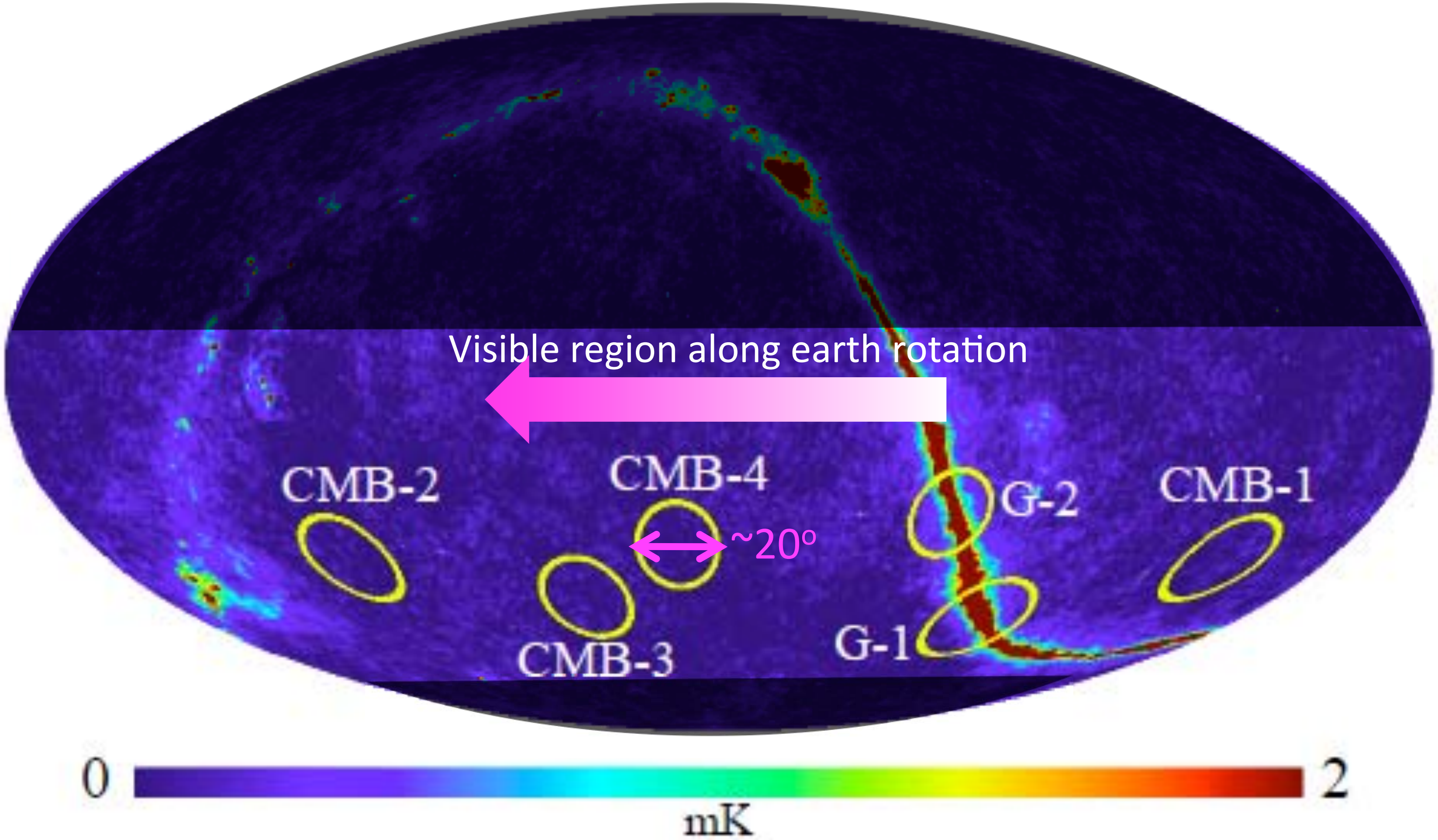
実際の観測の様子



Constant Elevation Scan

検出器のクロストーク(I→Q/U leakage)の影響を最小限にするスキャンストラテジー

Observation Patches



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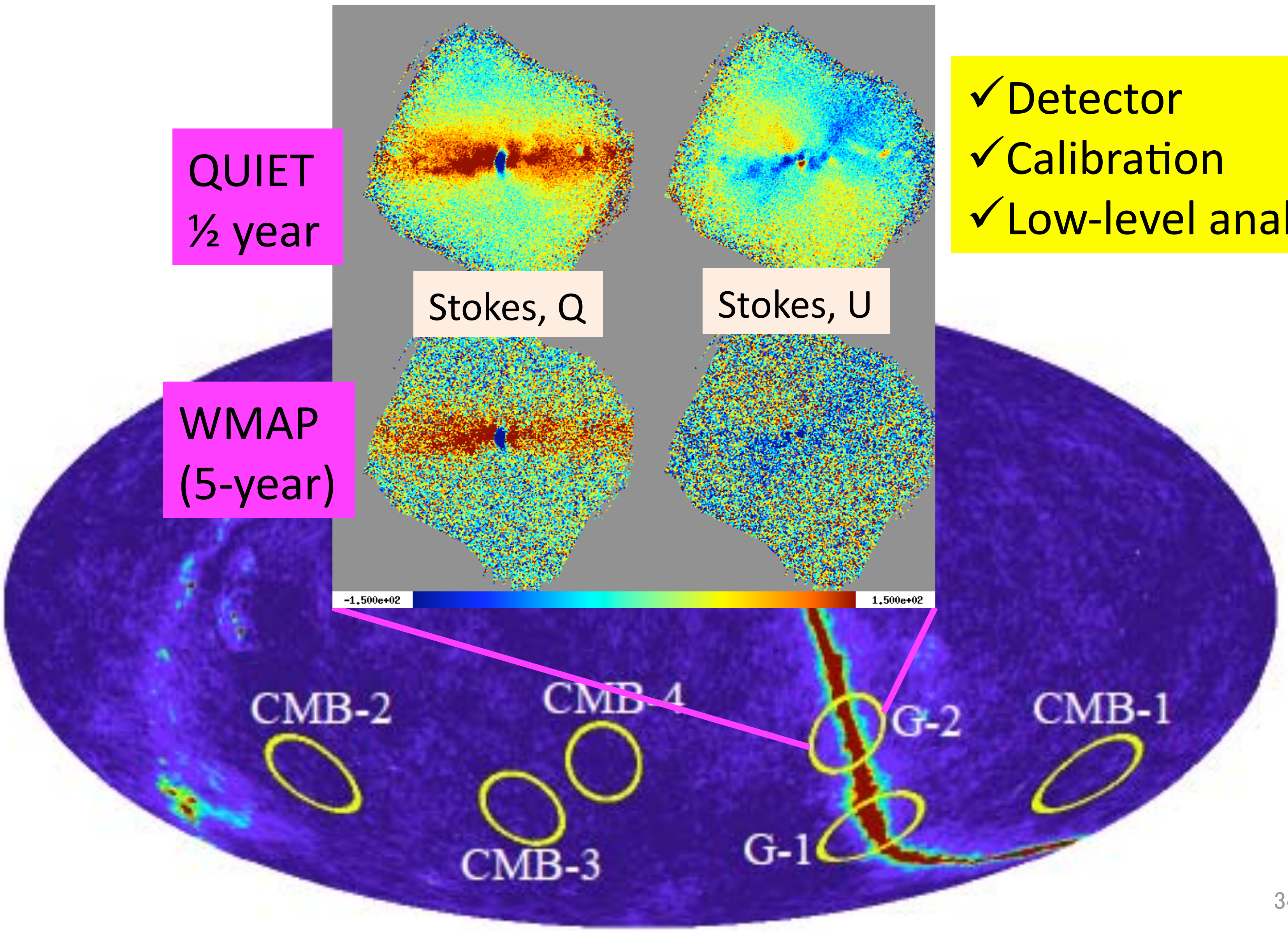
Map precision on 1°x1°: ~1μK (7.5 months at 43GHz)

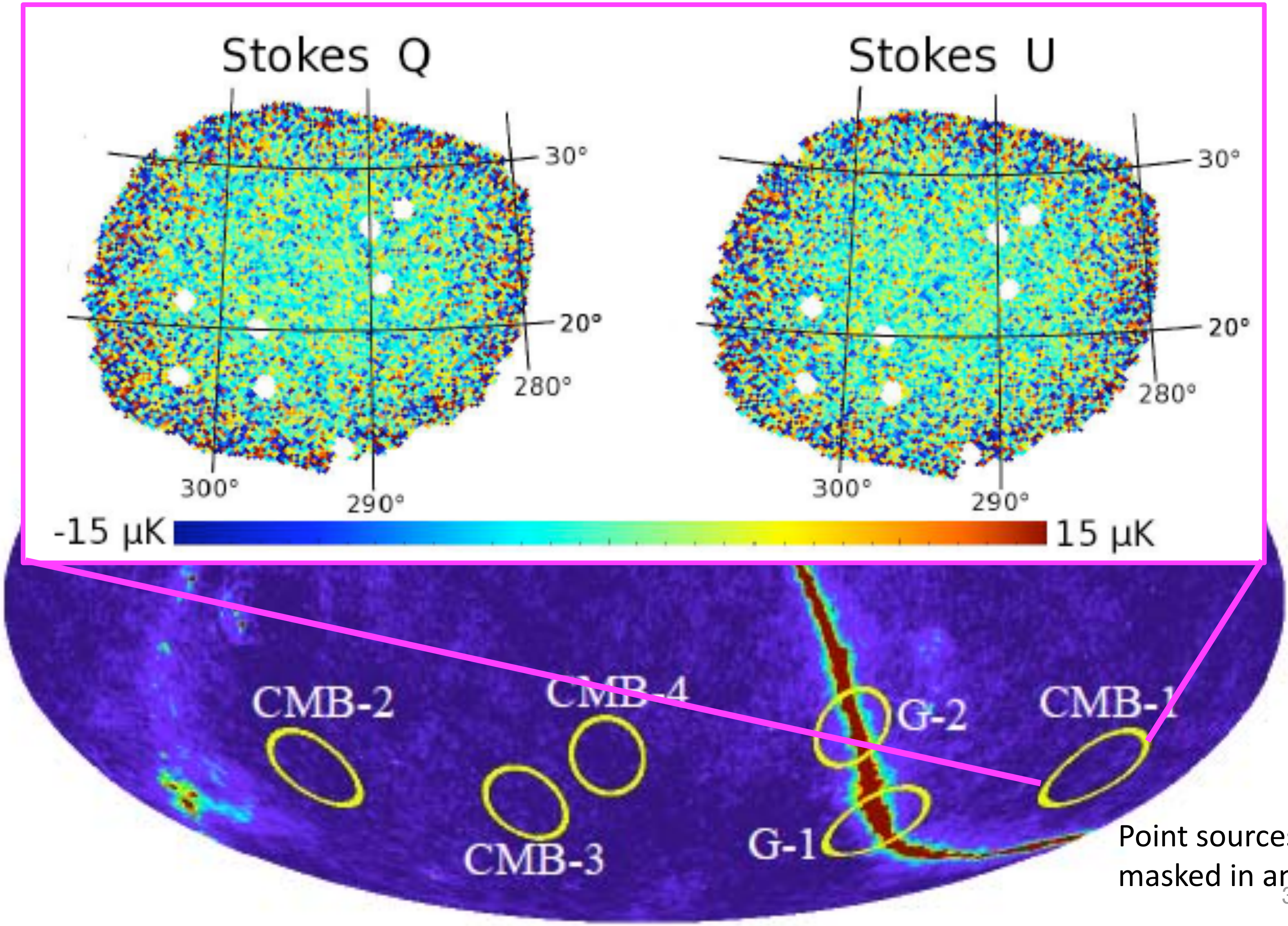
QUIET Polarization Map for Galactic Center

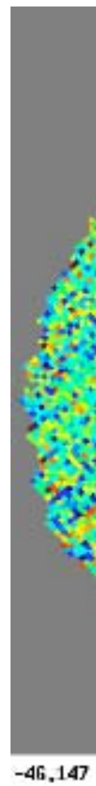


✓Detector
✓Calibration
✓Low-level analysis

[arXiv:1012.3191]

QUIET CMB Polarization Map

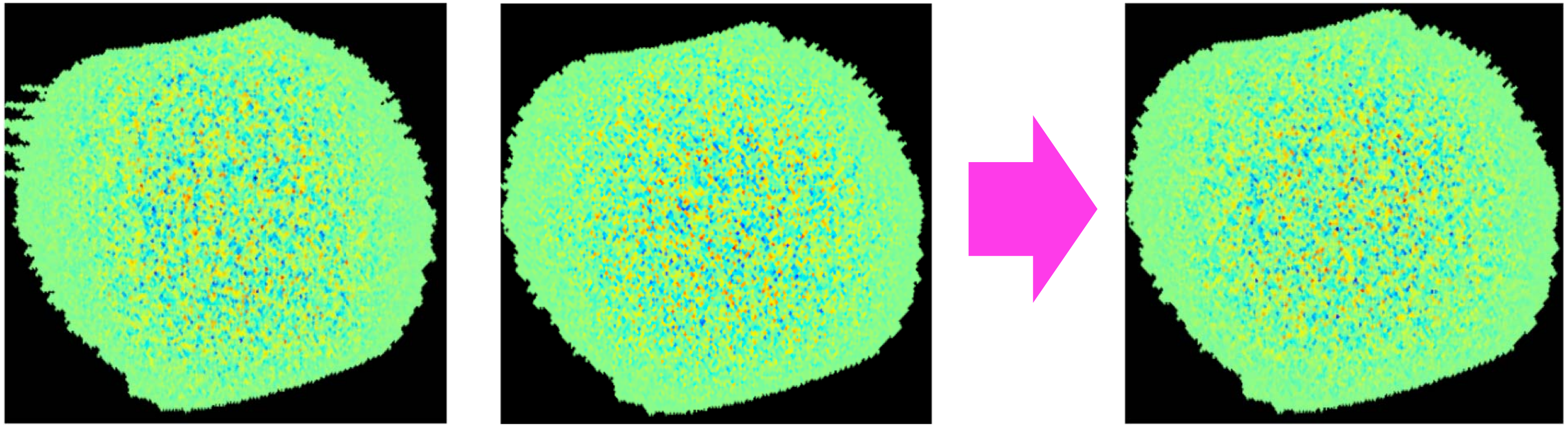




Point sources are masked in analysis

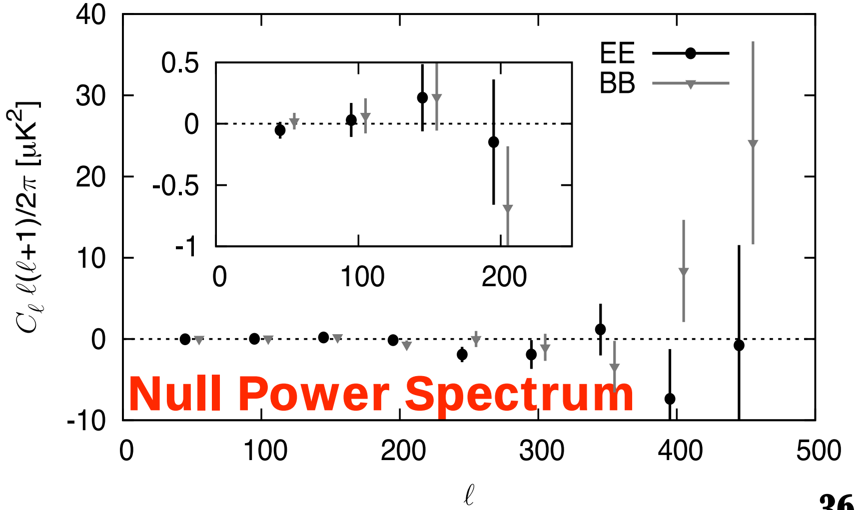
Analysis Validation: Null Test

- Divide data set into two maps, difference them.



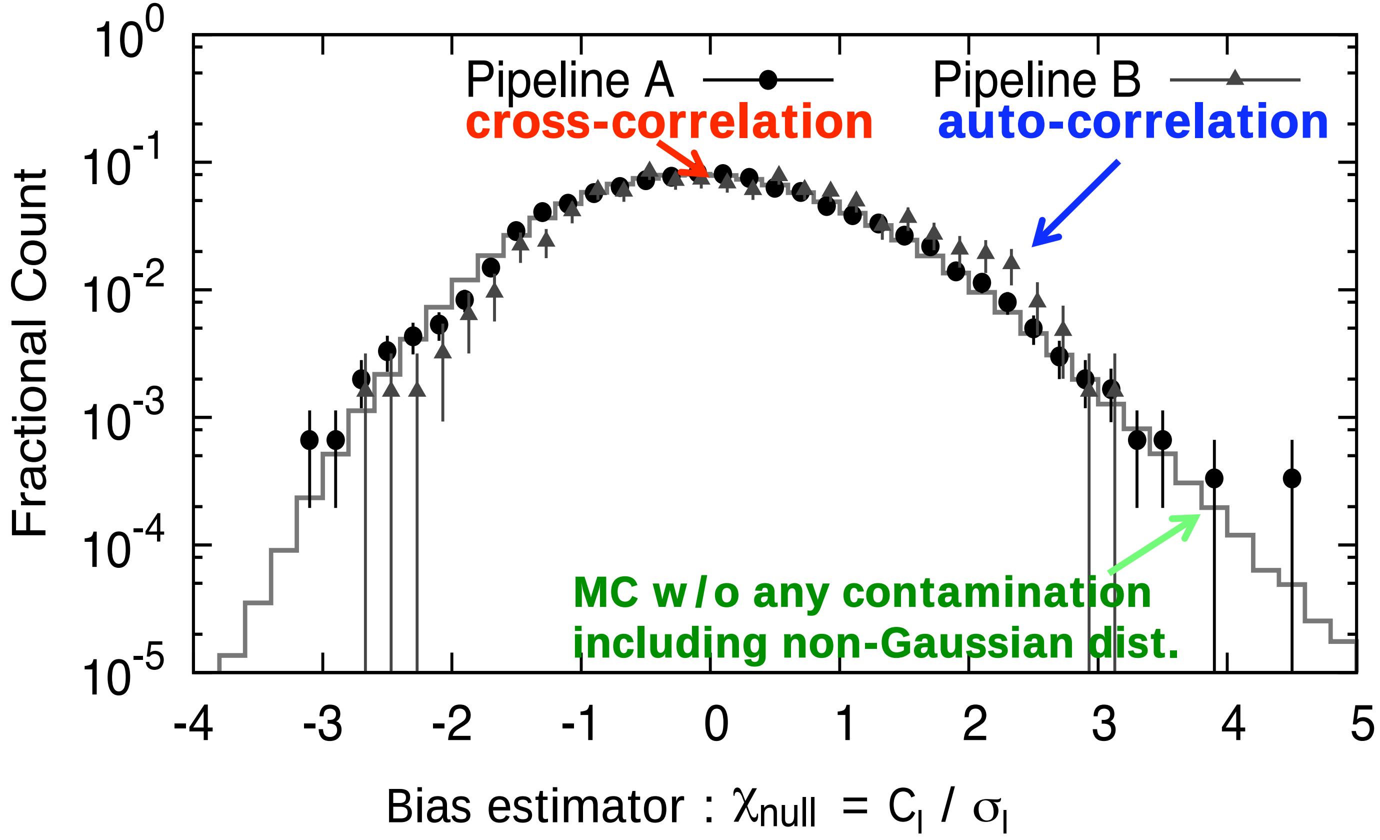
(CMB+Noise$_A$) - (CMB+Noise$_B$) (Noise$_A$-Noise$_B$)

- Calculate “null” power spectrum
- Perform 42 data divisions
  - Q vs. U channels
  - weather conditions
  - cryostat temperature



Null Test: χ_{null} distribution

- Mean shift of **χ_{null} dist.** is sensitive to detect biases which have not been removed



- Cross-correlation successfully removed the residual bias

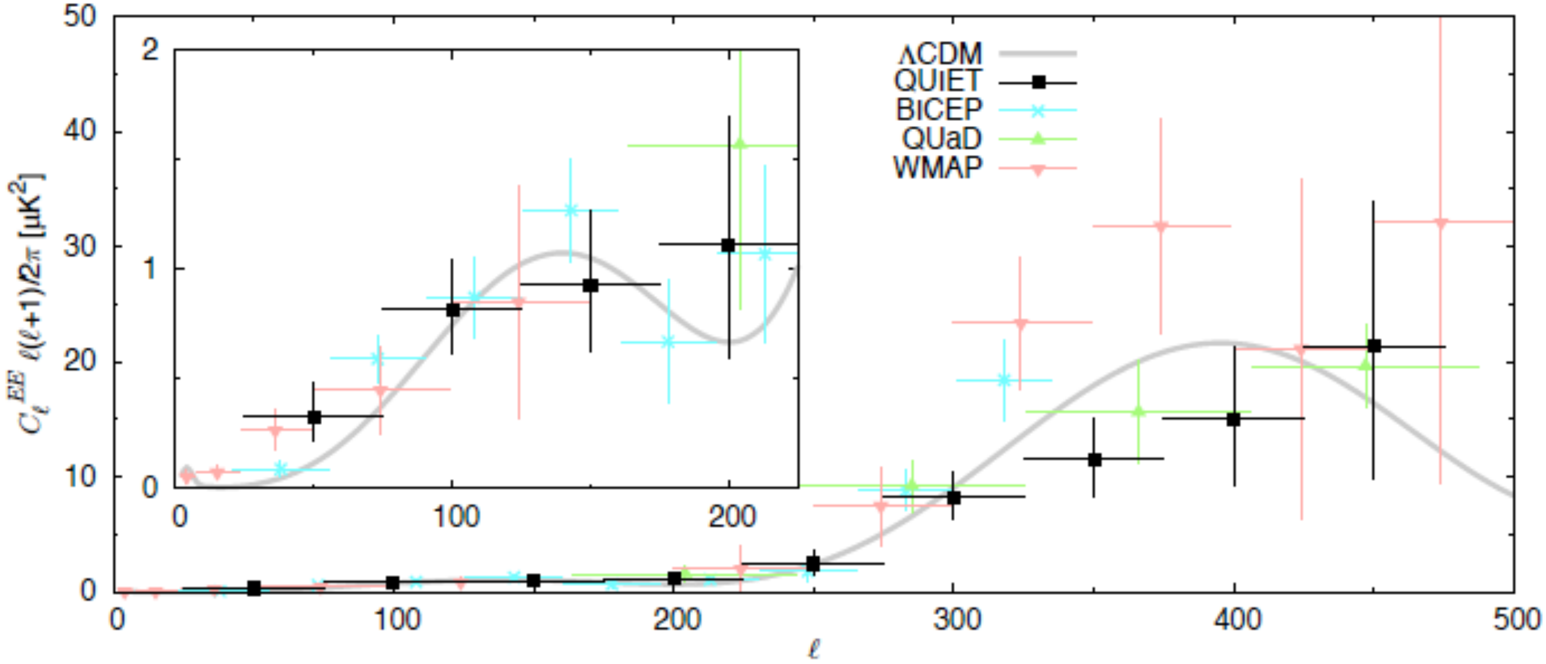
We passed null test ! Ready to open the box !!

[arXiv:1012.3191]

E-modes

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

Strong proof of instrument and analysis



Significant power is detected at 1st , 2nd peak region

Consistent with ΛCDM model

QUIET / ΛCDM = 0.87 ± 0.10

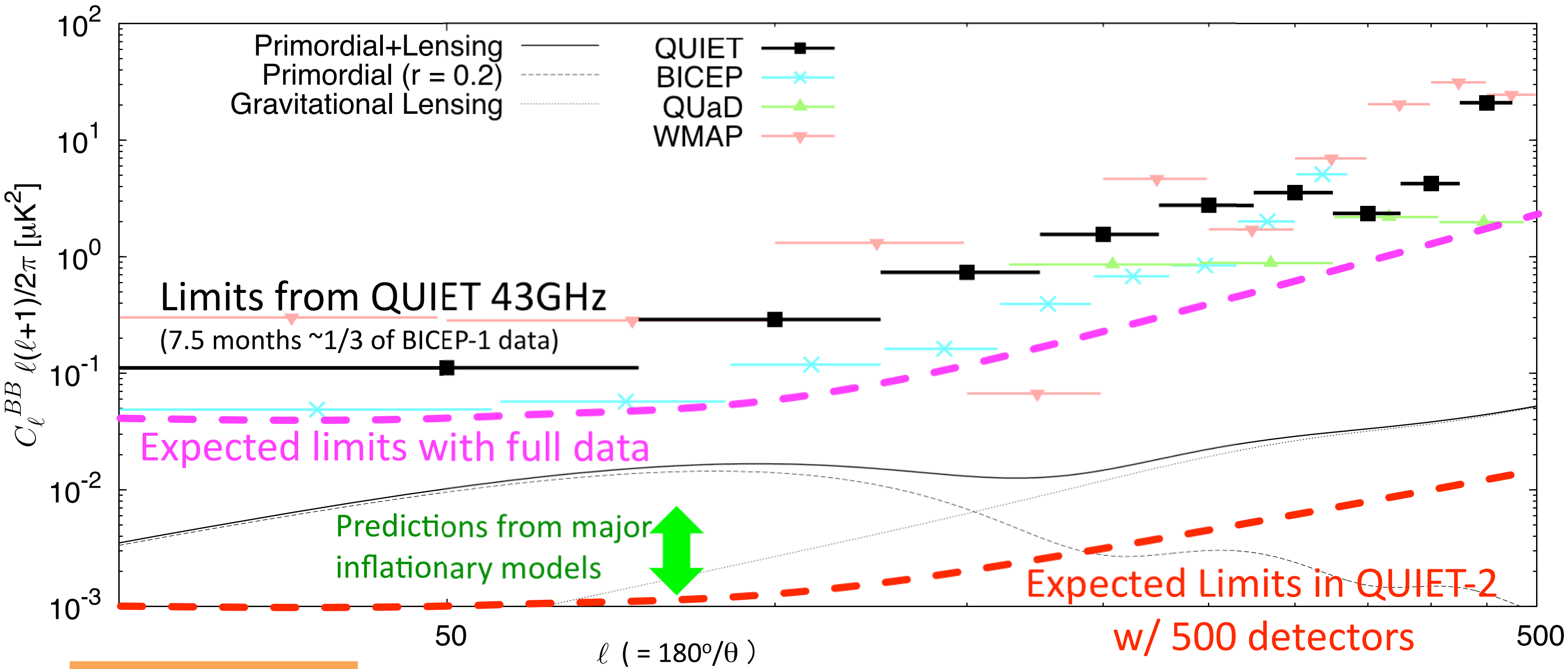
PTE from ΛCDM 14% for EE + BB + EB

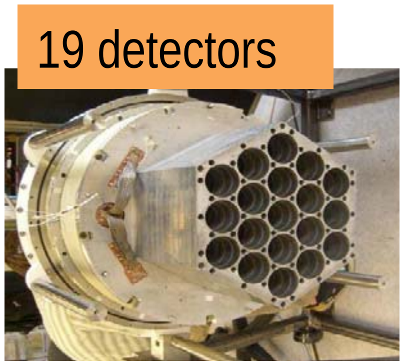
B-modes : r < 2.2 @95%CL

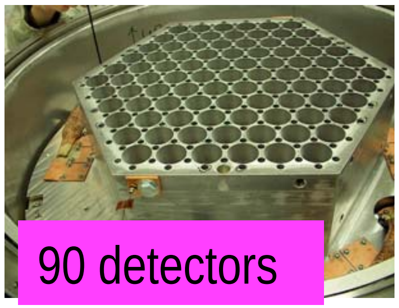
[arXiv:1012.3191]

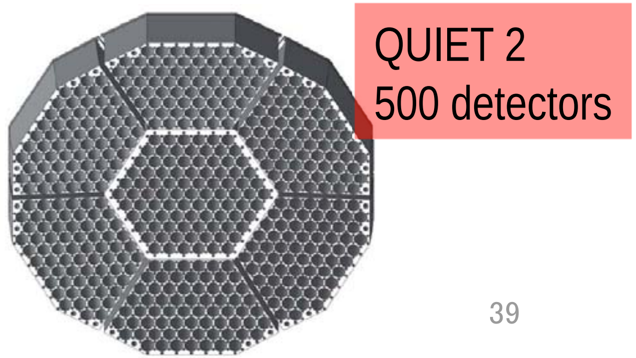
(zero-consistent : $r=0.35^{+1.06}_{-0.87}$)

Second best upper limits whereas short observation time



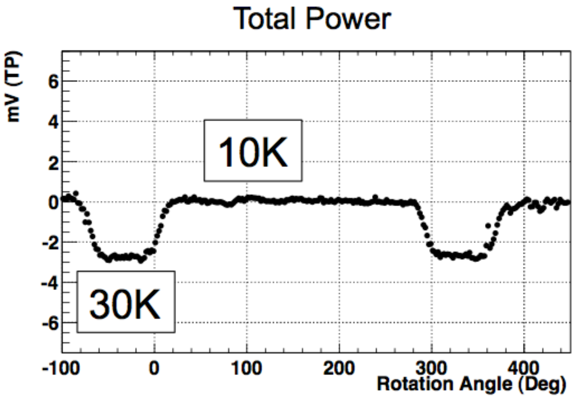


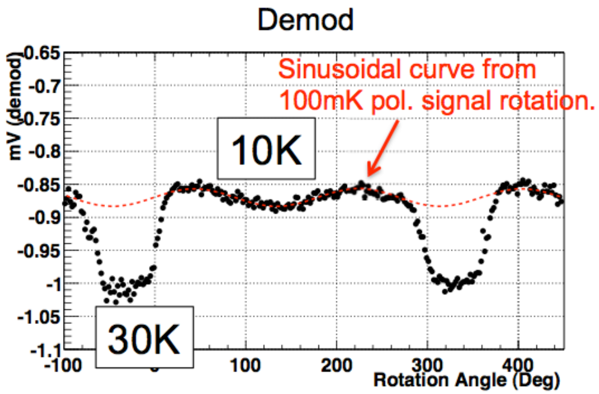


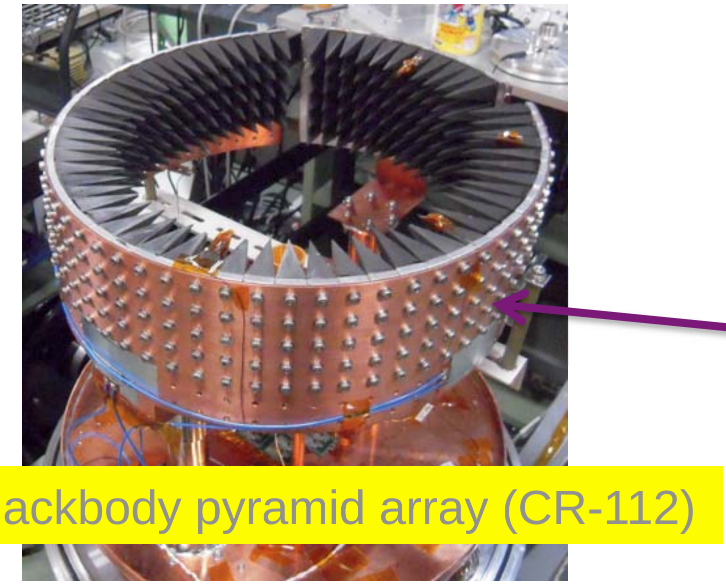


QUIET-IIへ向けたR&D @ KEK

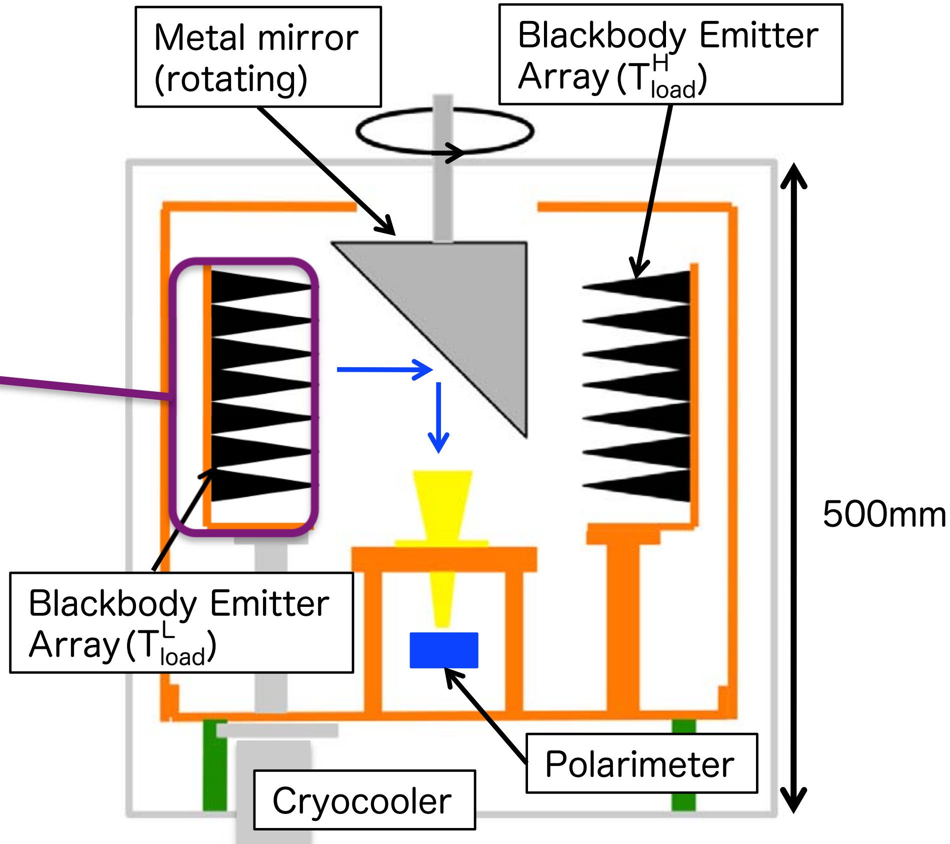
その1：検出器の性能評価・チューニングシステム





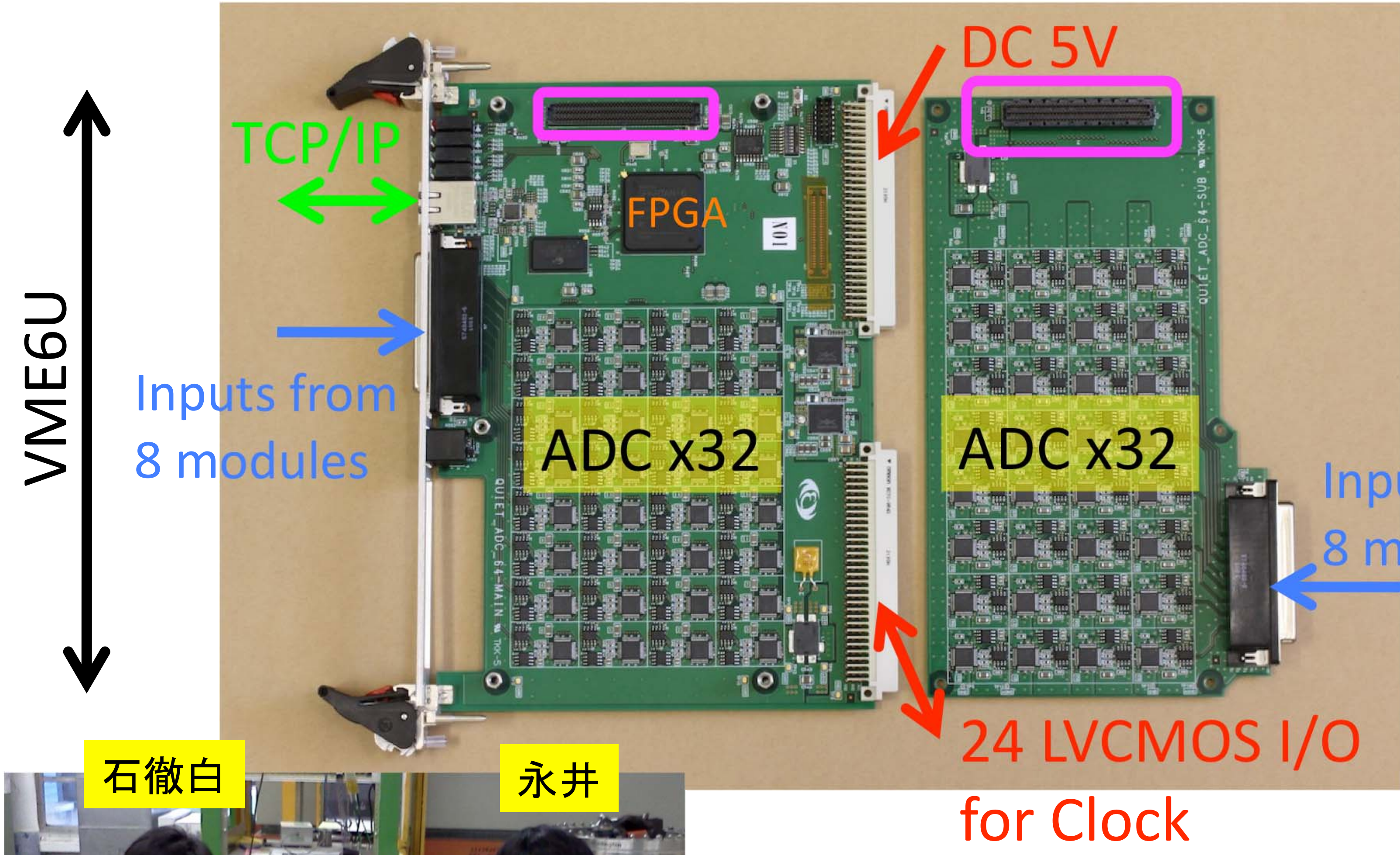


Blackbody pyramid array (CR-112)



初めての日本CMBコミュニティ発の論文
M. Hasegawa, O. Tajima *et al.*,
Rev. Sci. Instru. 82, 054501 (2011).

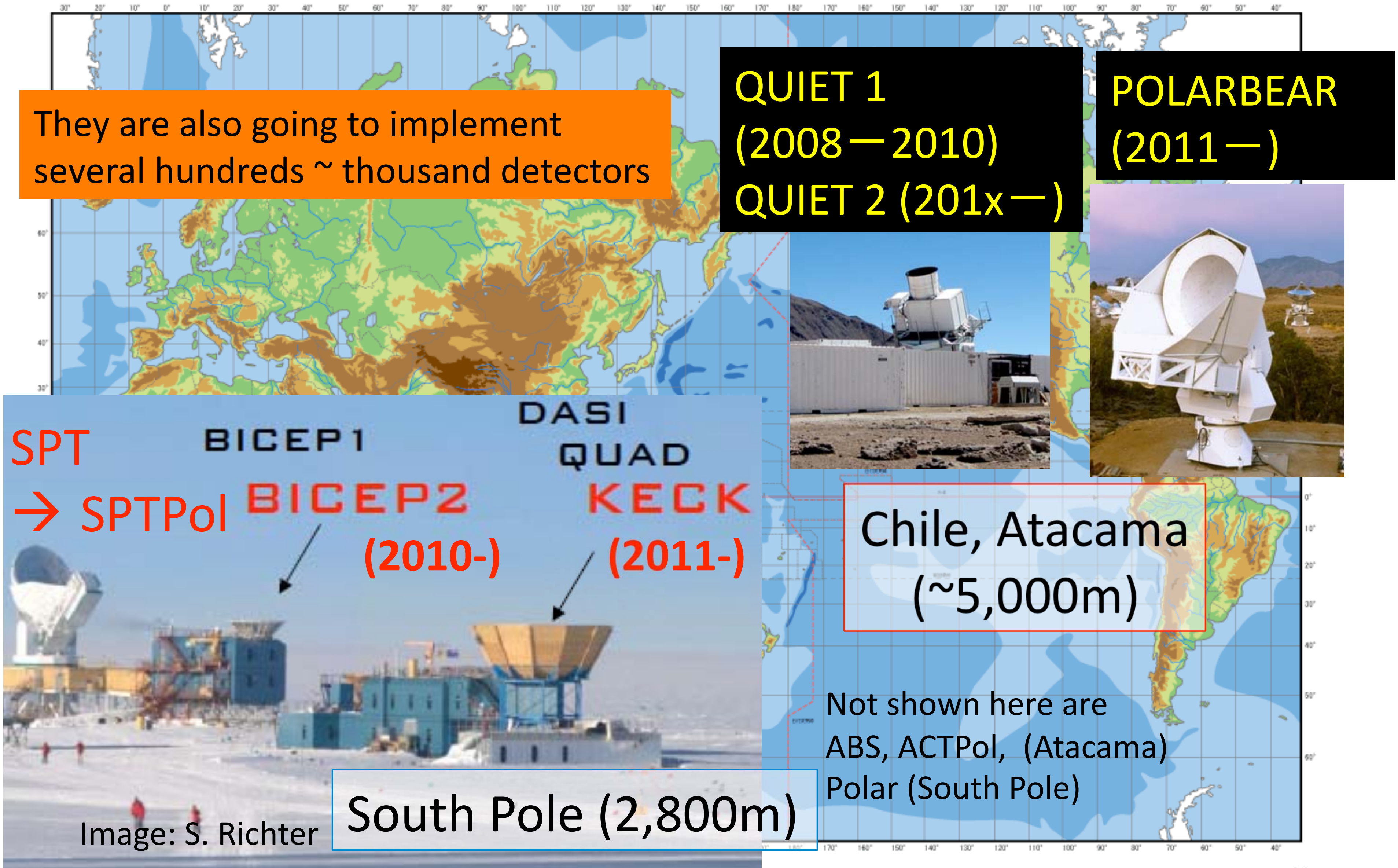
その2：読み出しエレキ(ADC board)



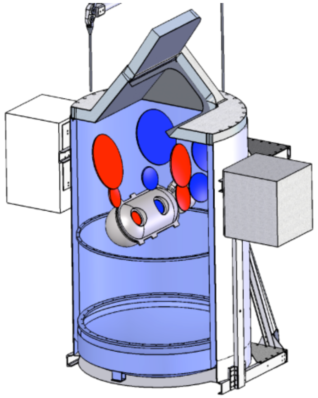
board
z, Resolutions18 bits
ation

x2 density
⇔ phase-1 ADC board

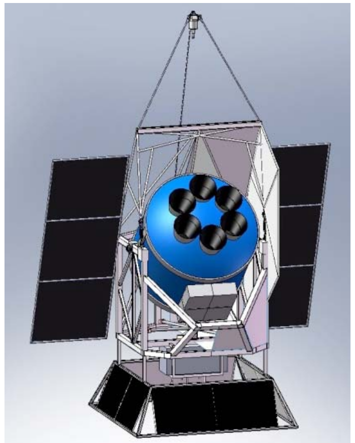
Ground-based telescopes



Balloon-borne telescopes



PIPER（2013-）



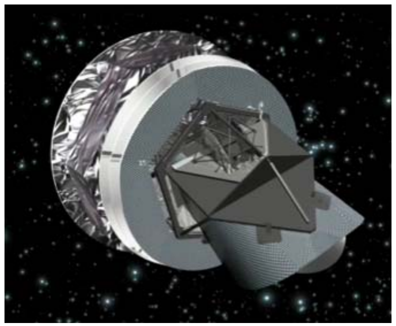
SPIDER（2011, 2012）

EBEX（2009-2011）

Satellite Telescopes

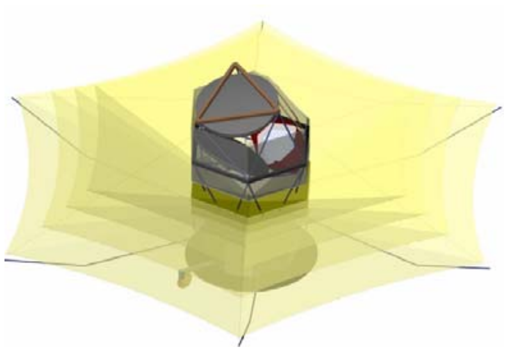
~2020 –

Planck (2009-)

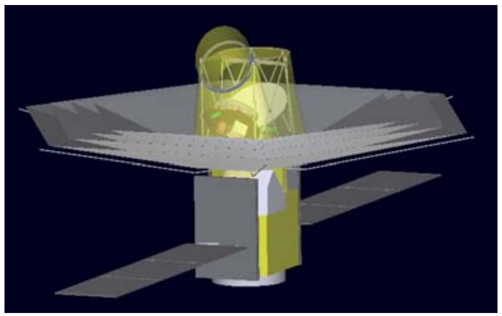


Not optimized for
polarization meas.

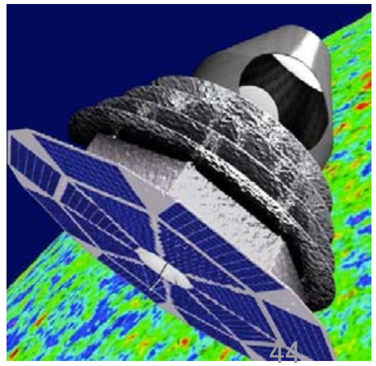
EPIC



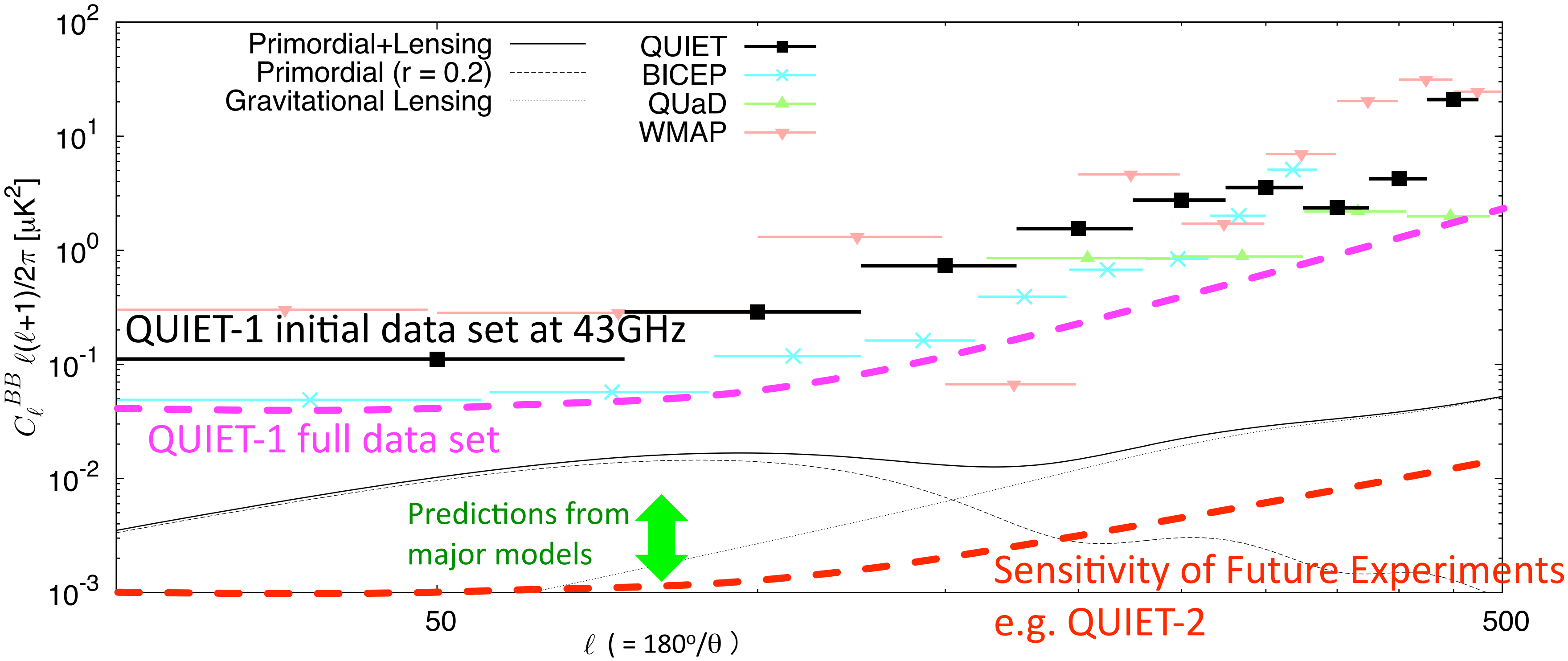
LiteBIRD (日本の計画)



COrE



B-mode Search in Future

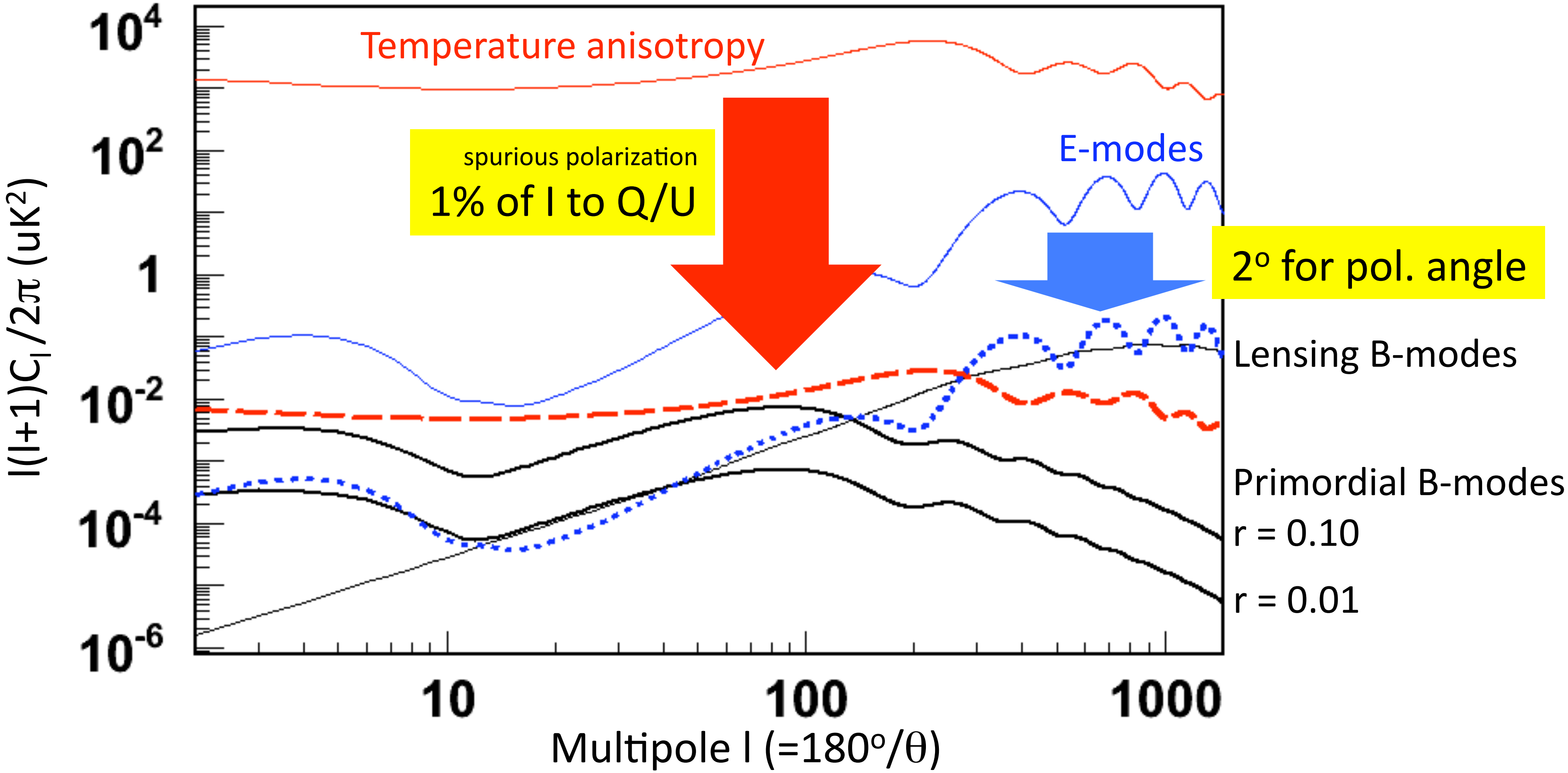


All coming experiments claim good sensitivity r = O(0.01)
or better sensitivity with several hundreds to thousand detectors

The most important subject for future:
Good systematic error control

Impact of **systematic error**

In case of 1% precision of calibrations …



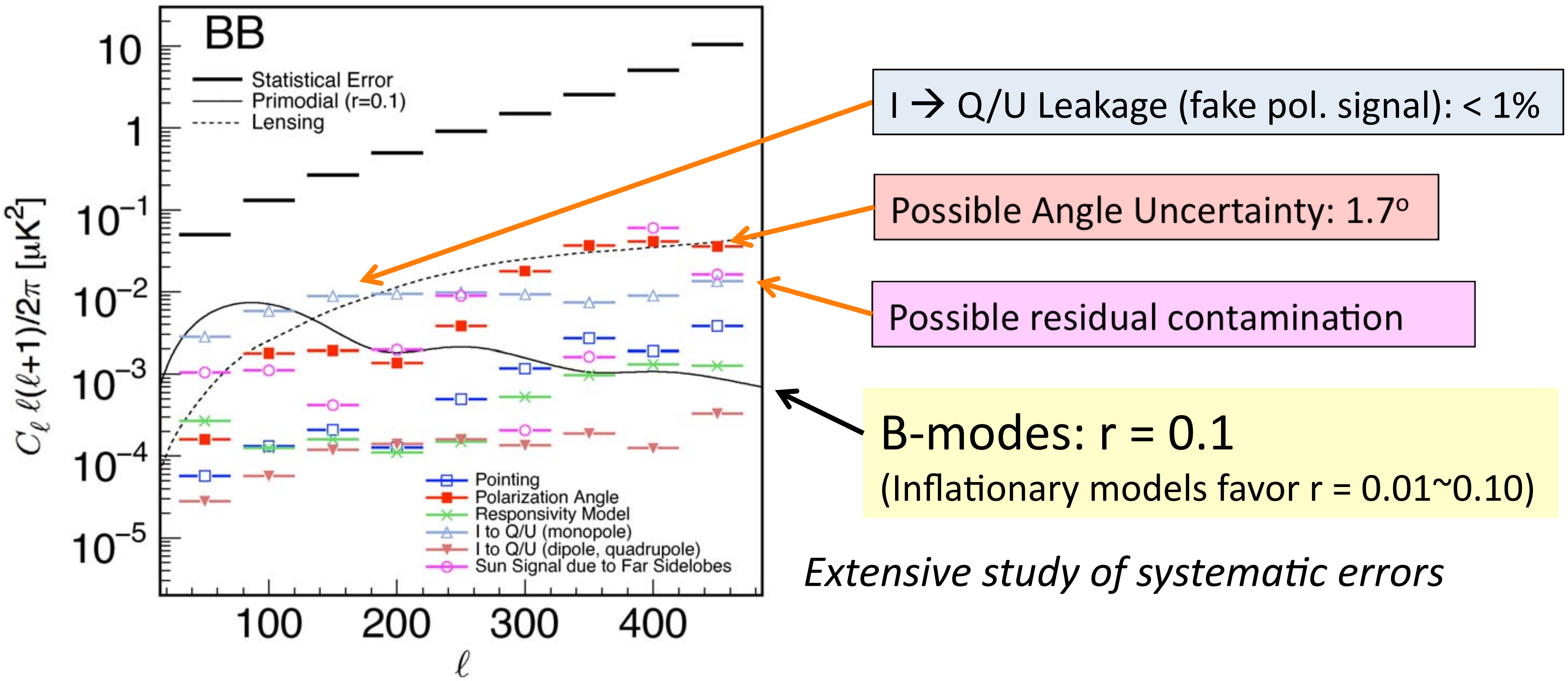
Have to minimize spurious polarization: ~0.1%

Have to achieve angle precision: ~0.1º

QUIET-1 initial results at 43GHz

[arXiv:1012.3191]

Least systematic error to date



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

Summary

- CMB偏光の「Bモード」はインフレーション宇宙論の決定的証拠
  - そして、インフレーションは究極の高エネルギー物理でもある : $10^{\sim 16}$ GeV

- 多くの実験が本格的なBモード探索に入りつつある
  - 明日にでも、大発見のニュースが飛び交っても不思議ではない!

- ひかえめに言えば、実験手法の確立はいまだ手探り状態
  - 系統誤差の理解など、精密測定に至るための課題は多い
  - QUIET-1は従来実験で最良の系統誤差を達成
    [arXiv:1012.3191] e.g. fake polarization signal: < 1%

- 後発の我々が世界のトップに食い込む余地は大いにある！
- 地上実験の予算規模は5~15億円