FY2017 Symposium Conference for "Cosmic Acceleration" Research Grant program

Latest Results of POLARBEAR and Future Measurements of CMB Polarization with Simons Array and LiteBIRD

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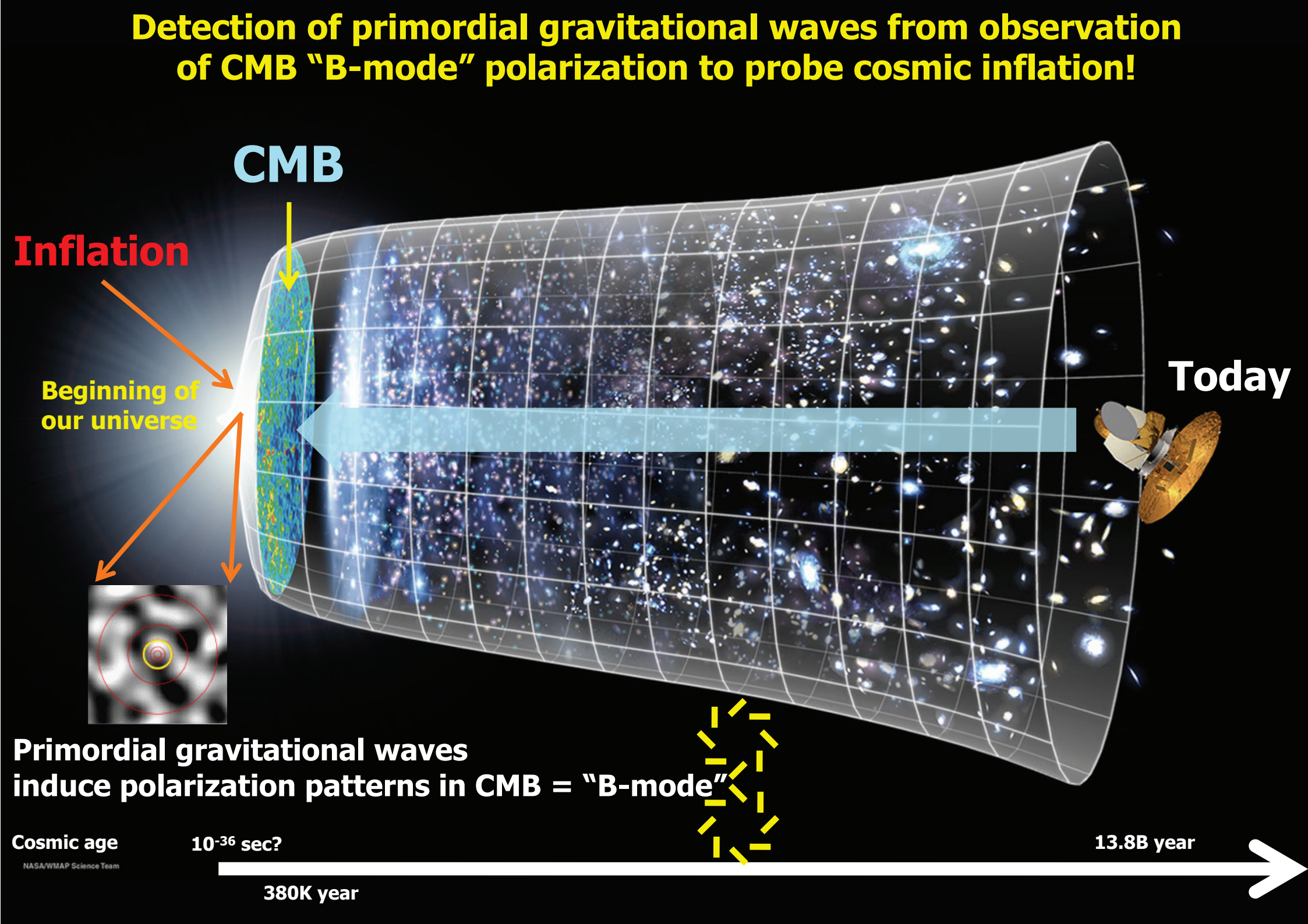
University of California, Berkeley

Kavli IPMU

11th Feb, 2018

Detection of primordial gravitational waves from observation of CMB "B-mode" polarization to probe cosmic inflation!

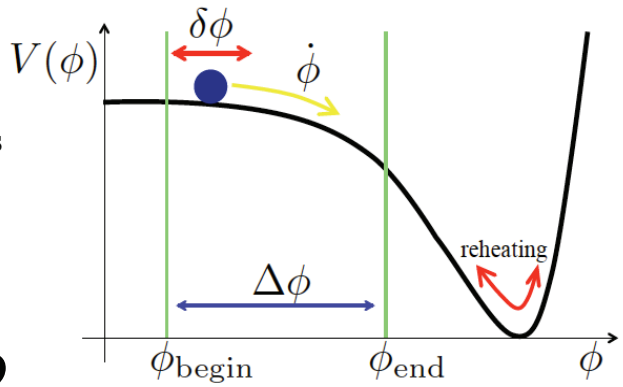


About Prediction on PGW (r: Tensor-to-Scalar Ratio)

- **Many model predict r>0.01**
- More general prediction
  - focus on the simplest models based on "Occam's razor" principle
  - "**single field slow-roll**" models give Lyth relation

$$r \simeq 0.002 \left(\frac{60}{N_{\rm e}}\right)^2 \left(\frac{\Delta\phi}{m_{\rm pl}}\right)^2$$

$N_{\rm e}$: e-folding
$m_{\rm pl}$: Planck mass

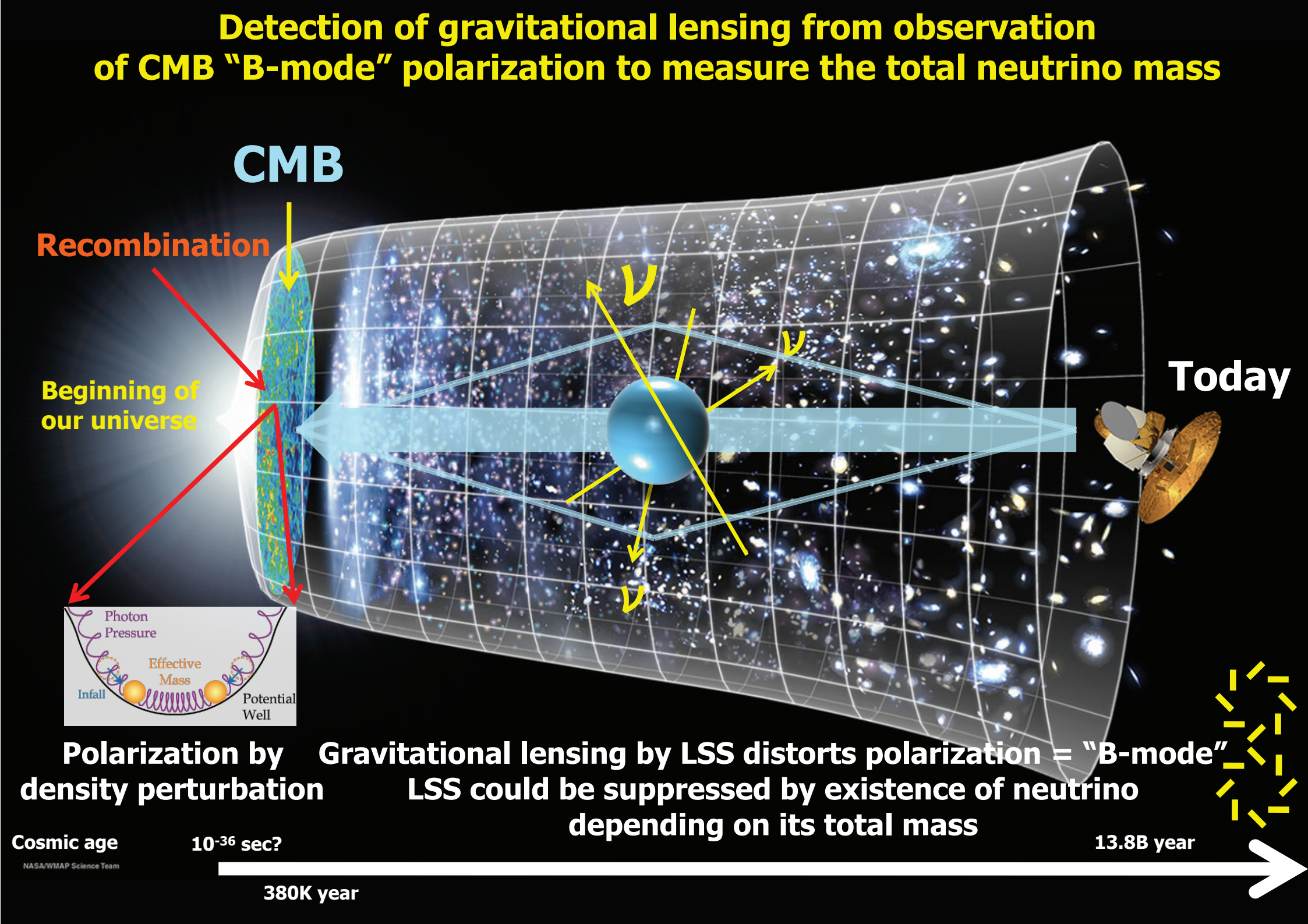


  - Large-field inflation ($\Delta\phi > m_{\rm pl}$), which is well motivated phenomenologically, leads **r>0.002**
  - **Detection of r>0.002 establish large-field inflation**
  - Ruling out large-field inflation is also a significant impact on cosmology and fundamental physics

r<0.07 (Planck+BK14)

To achieve σ(r)<10^{-3} is a natural target

Detection of gravitational lensing from observation of CMB "B-mode" polarization to measure the total neutrino mass



About Prediction on Total Neutrino Mass

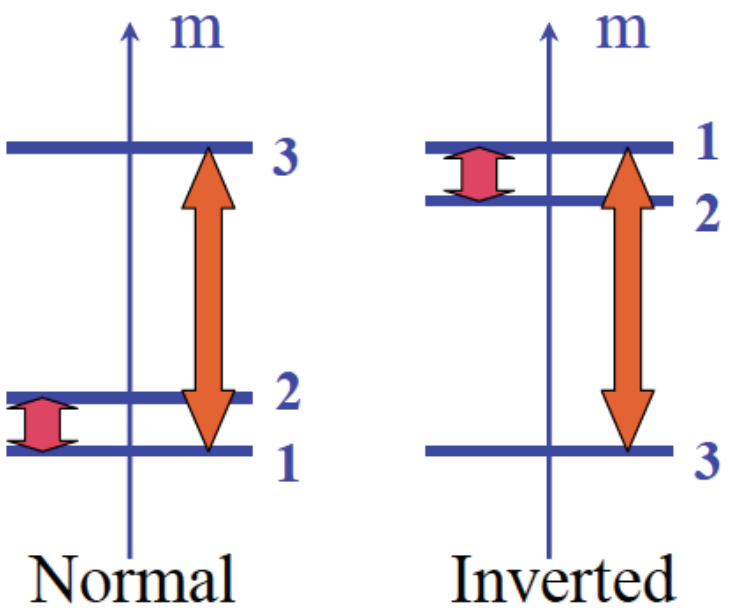
The current lower limit on the sum of neutrino masses imposed by oscillation experiments

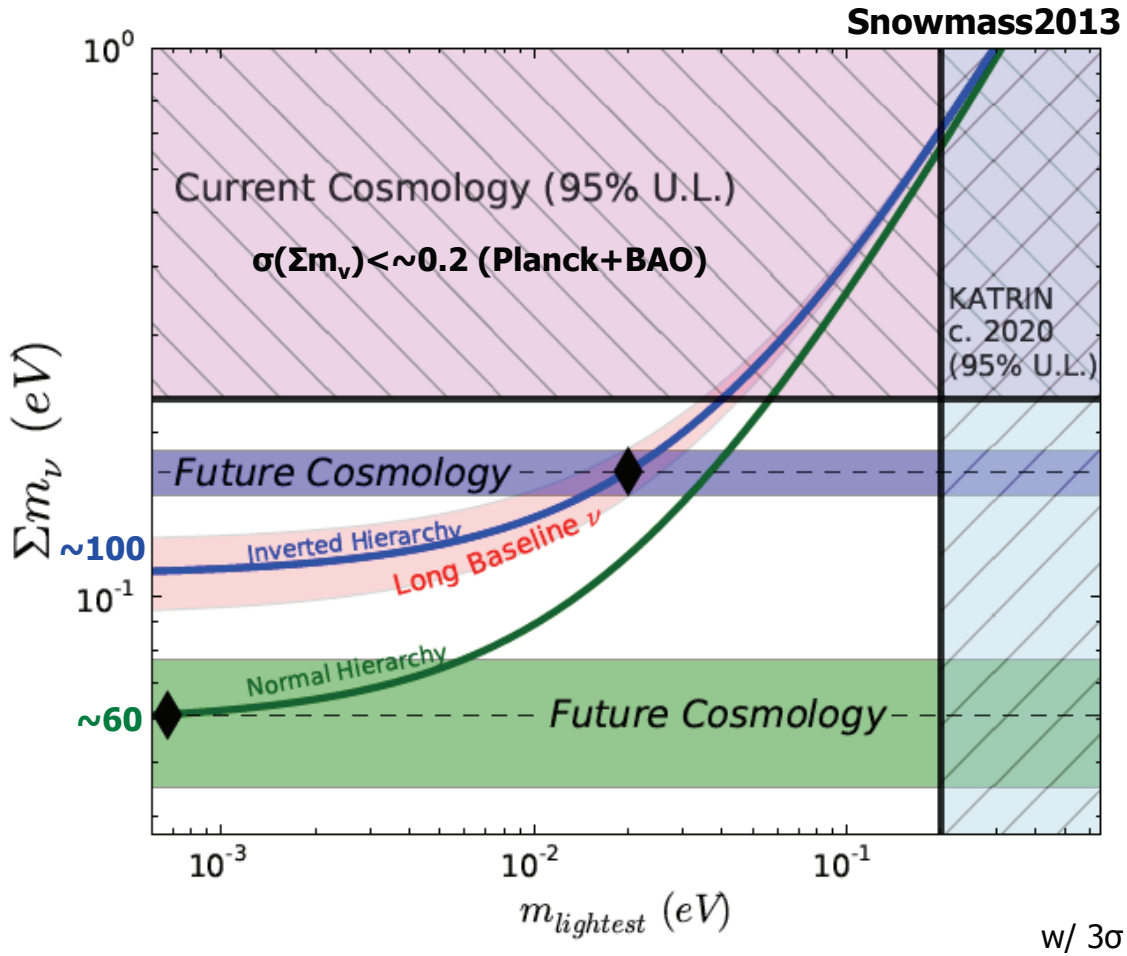
Normal hierarchy:

$$\sum m_\nu > 58\,\mathrm{meV}$$

Inverted hierarchy:

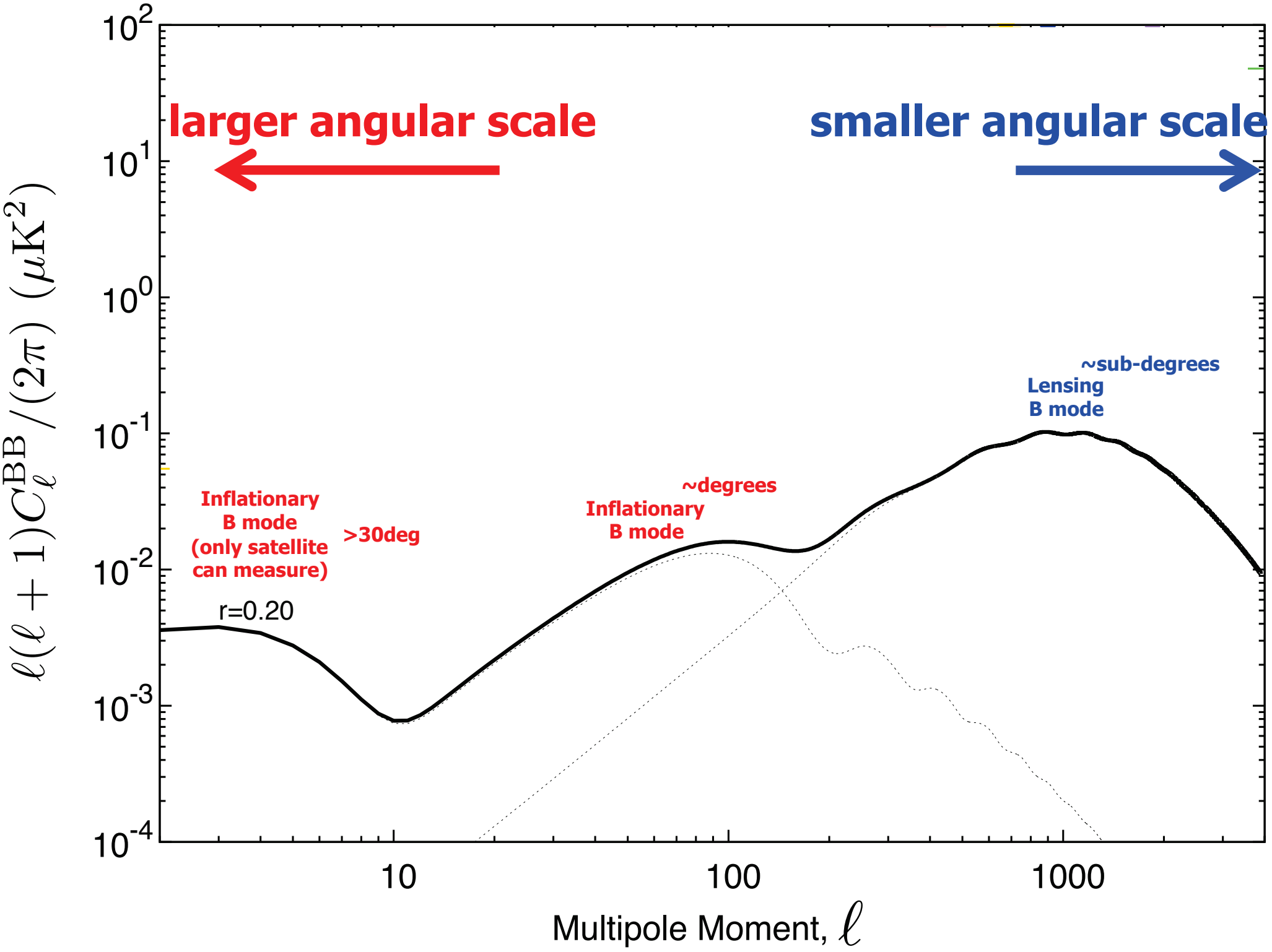
$$\sum m_\nu > 100\,\mathrm{meV}$$

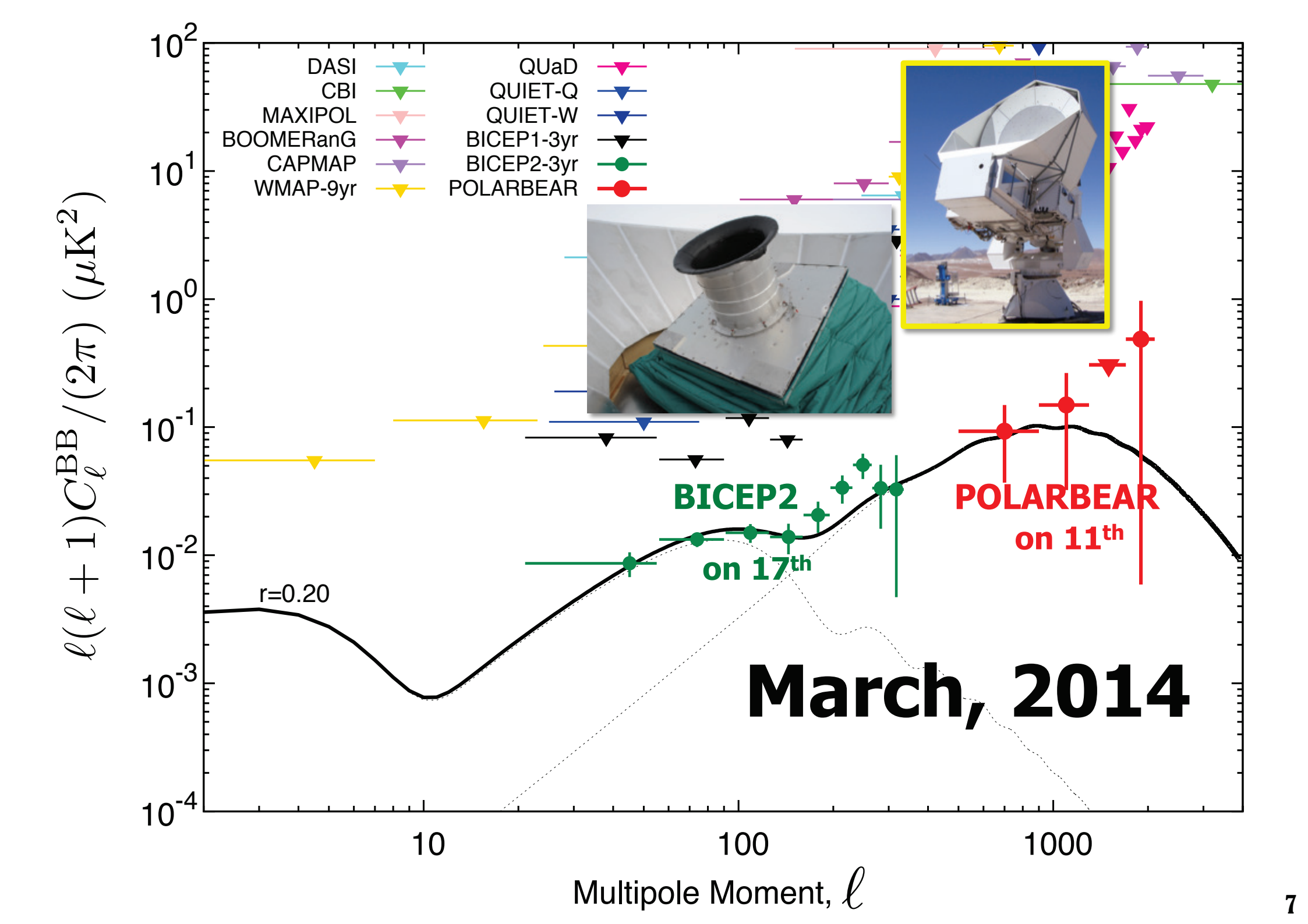


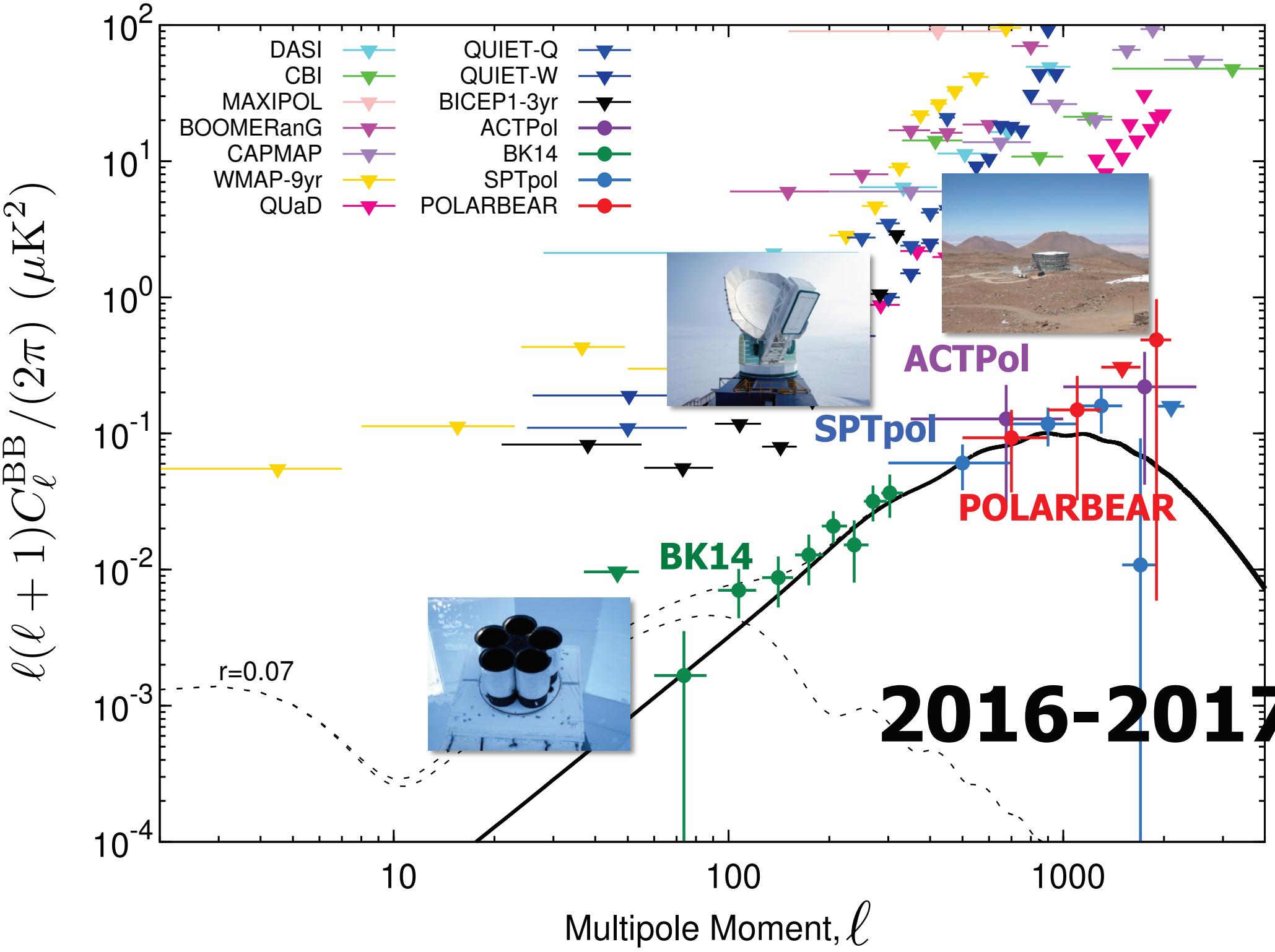


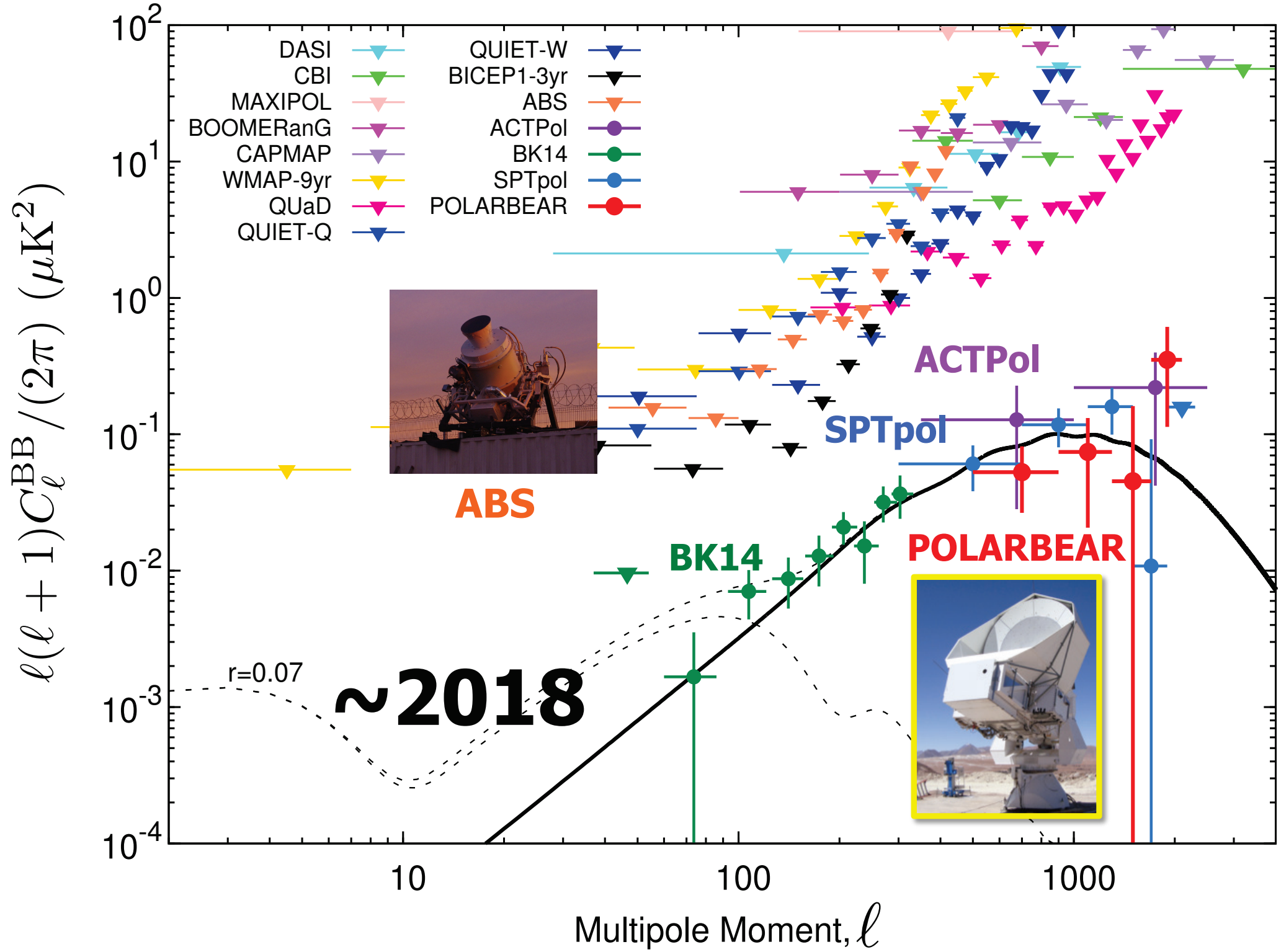
w/ 3σ

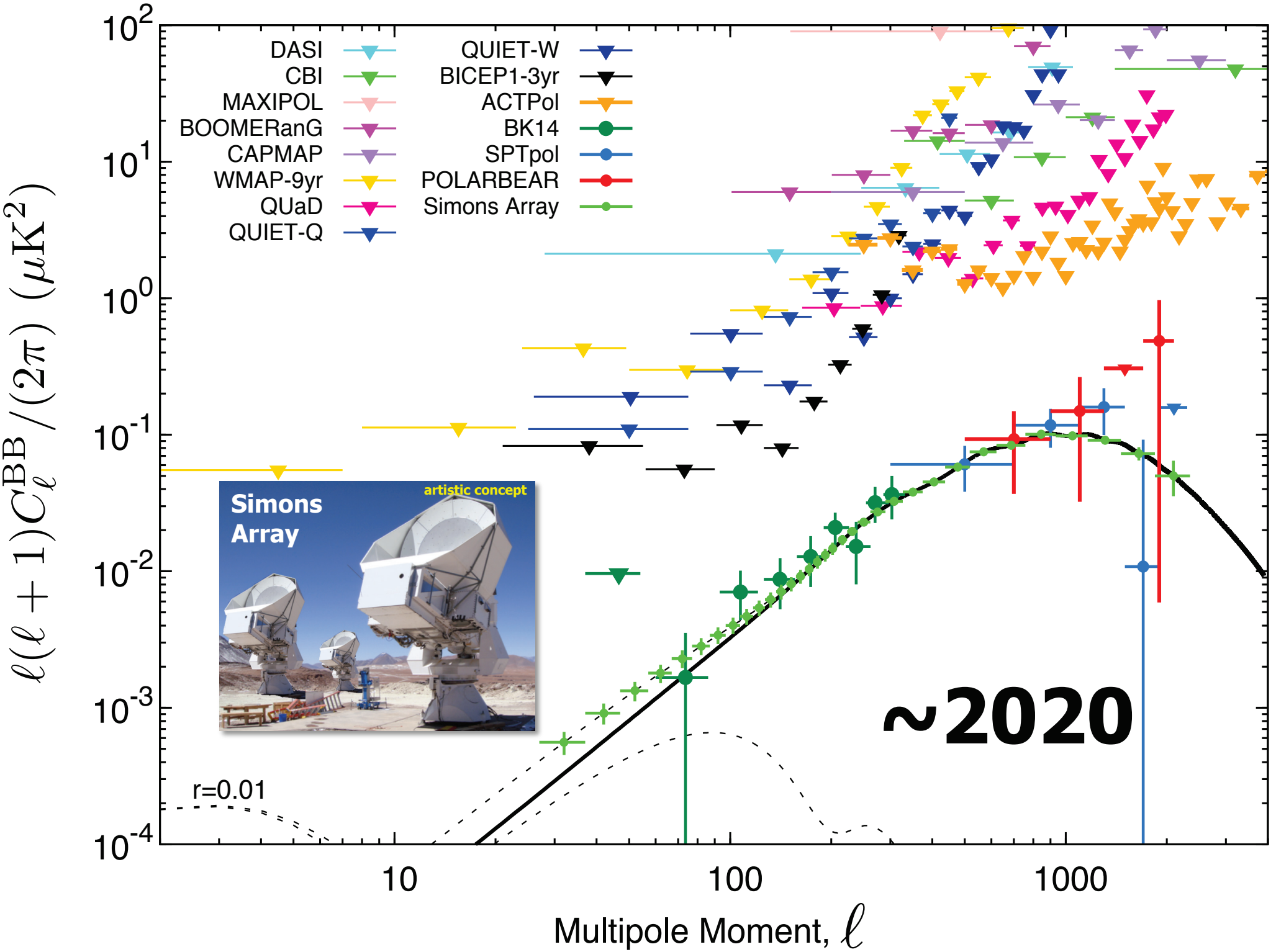
Need σ(Σm$_\nu$)<20 meV to determine hierarchy


larger angular scale
smaller angular scale
$\ell(\ell+1)C_\ell^{BB}/(2\pi)$ (μK^2)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Inflationary
B mode
(only satellite
can measure)
>30deg
r=0.20
~degrees
Inflationary
B mode
~sub-degrees
Lensing
B mode
10
100
1000
Multipole Moment, ℓ


DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
BICEP2-3yr
POLARBEAR
BICEP2
on 17th
POLARBEAR
on 11th
r=0.20
March, 2014
$\ell(\ell+1)C_\ell^{BB}/(2\pi)\ (\mu K^2)$
Multipole Moment, ℓ
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000


DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ACTPol
BK14
SPTpol
POLARBEAR
ACTPol
SPTpol
POLARBEAR
BK14
r=0.07
2016-2017
$\ell(\ell+1)C_\ell^{BB}/(2\pi)\ (\mu K^2)$
Multipole Moment, ℓ
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000


DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ABS
ACTPol
BK14
SPTpol
POLARBEAR
ACTPol
SPTpol
ABS
BK14
POLARBEAR
r=0.07
~2018
$\ell(\ell+1)C_\ell^{BB}/(2\pi)\ (\mu K^2)$
Multipole Moment, ℓ
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000


DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ACTPol
BK14
SPTpol
POLARBEAR
Simons Array
Simons Array
artistic concept
~2020
r=0.01
$\ell(\ell+1)C_\ell^{BB}/(2\pi)\ (\mu K^2)$
Multipole Moment, ℓ
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000

POLARBEAR

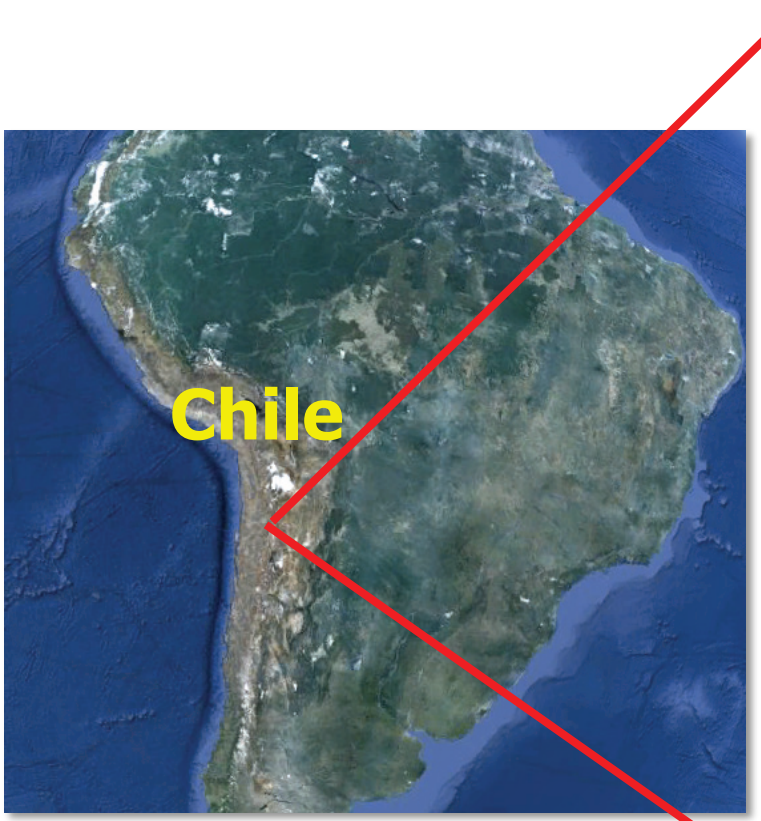
Simons Array

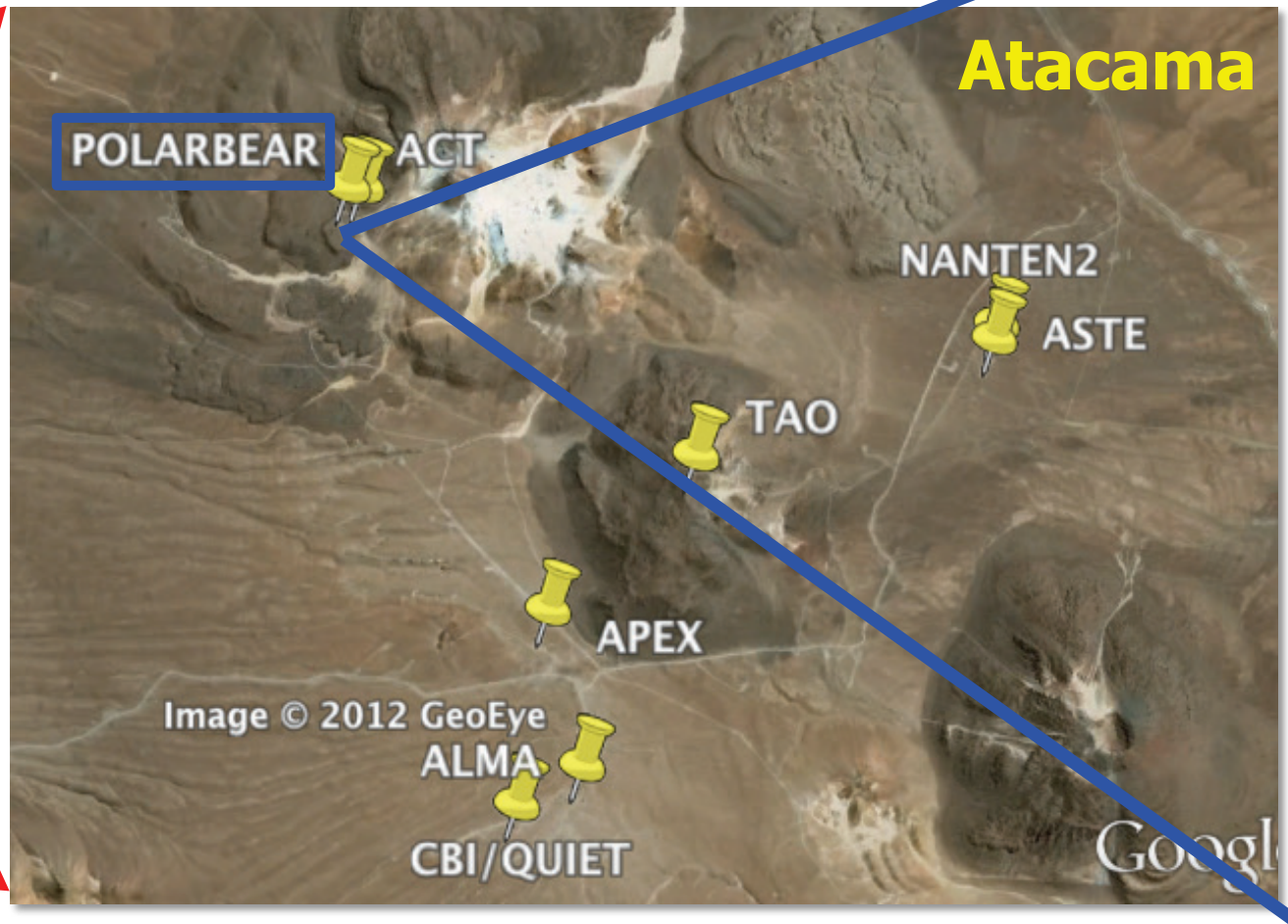
POLARBEAR/Simons Array Collaboration

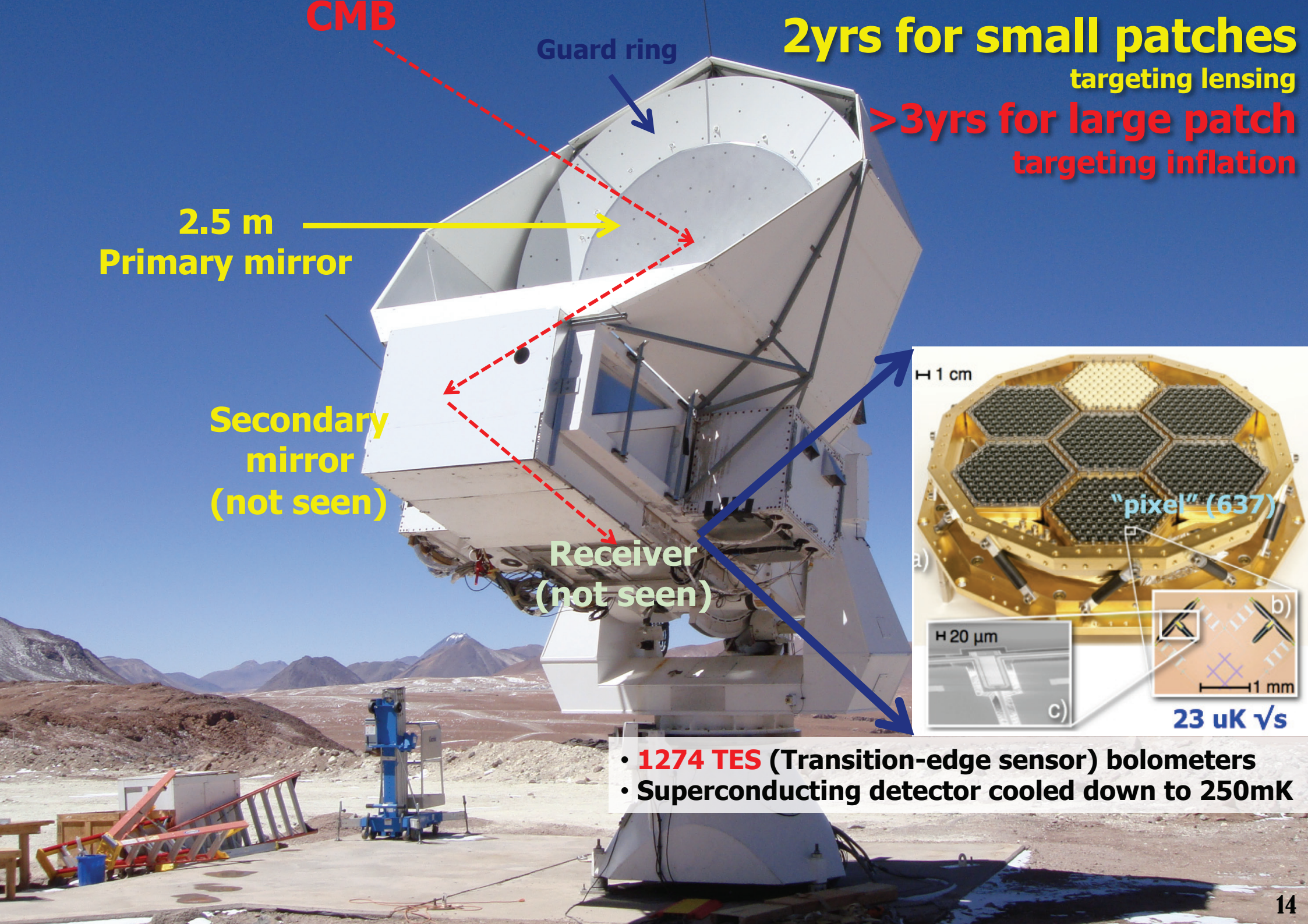
~100 collaborators & many from JAPAN!

POLARBEAR since 2012 (deployed in 2011)

- Observing CMB polarization on Atacama desert in Northern Chile at an altitude of 5,200m since January 2012





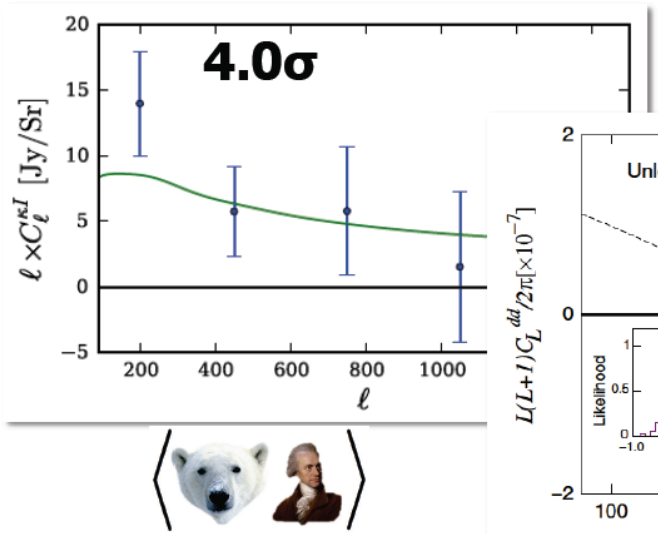

CMB
Guard ring
2yrs for small patches
targeting lensing
>3yrs for large patch
targeting inflation
2.5 m
Primary mirror
Secondary
mirror
(not seen)
Receiver
(not seen)
1 cm
"pixel" (637)
20 µm
1 mm
23 uK √s
• 1274 TES (Transition-edge sensor) bolometers
• Superconducting detector cooled down to 250mK

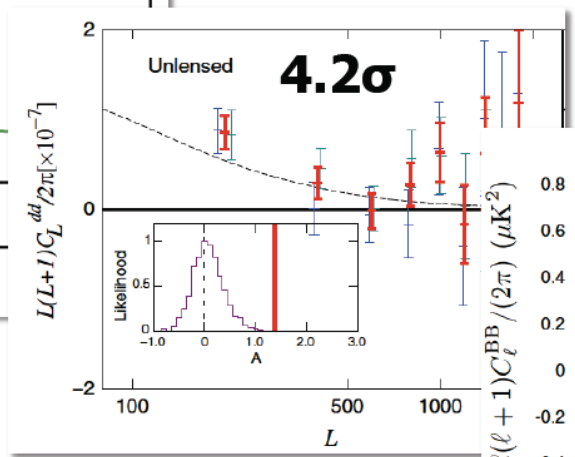
Slide From The Previous Conference (Mar 2017)

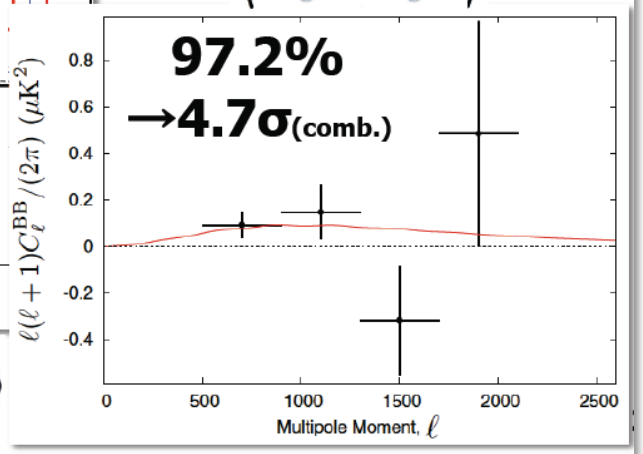
Science Results

- **23rd Dec, 2013: Detection of lensing by POLARBEAR x CIB**
- **23rd Dec, 2013: Detection of lensing by POLARBEAR w/ 4pt**
- **10th Mar, 2014: Measurement of lensing B modes by POLARBEAR w/ 2pt**
- 9th Sep, 2015: Constraint on Cosmic birefringence & Primordial magnetic field by **POLARBEAR**

POLARBEAR is the first experiment to successfully implement a "blind analysis" w/ enough sensitivity to measure B modes



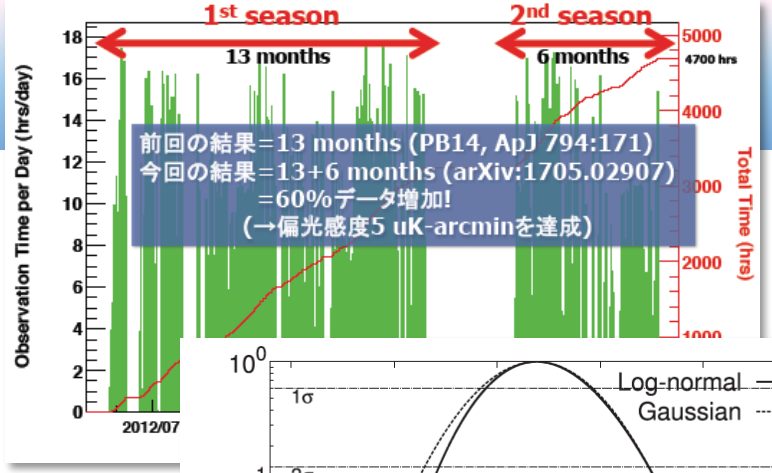


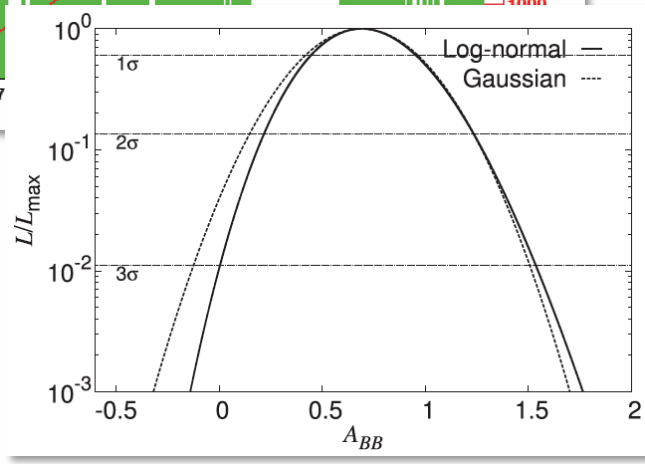


We have published a new lensing B-mode paper w/ better sensitivity on Oct. 2017!

What's New?

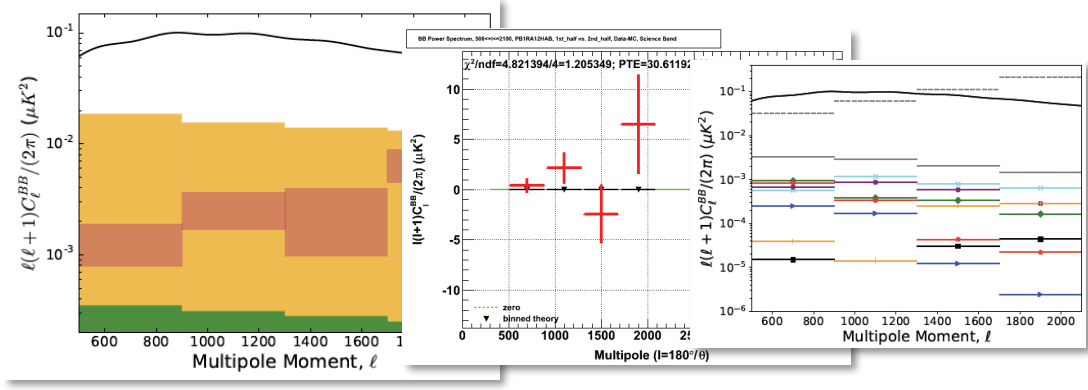
- 60% more data
  - new dataset & improved data selection
- Improved noise model & estimate
  w/ Monte Carlo





has doubled the previous sensitivity

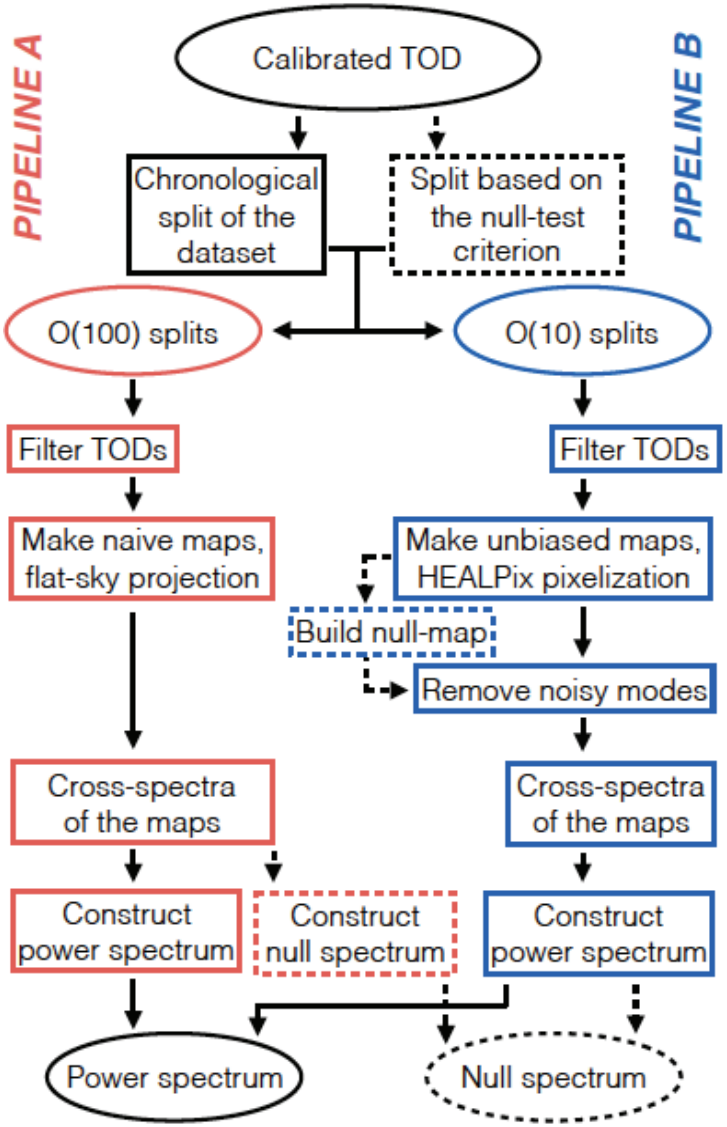
- More realistic estimation
  of foreground contamination
  w/ Planck 353 GHz

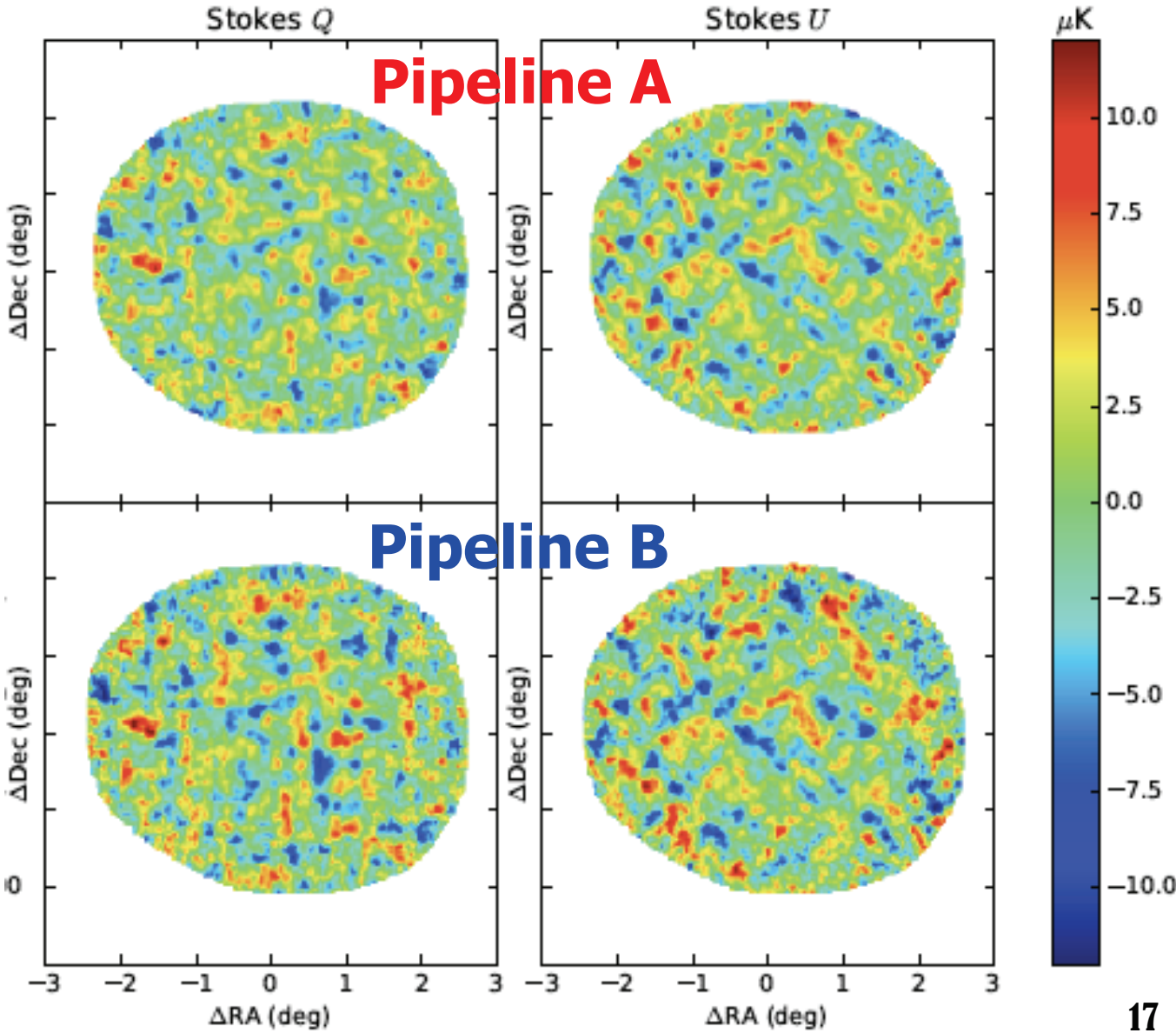


- **Validated data, systematics & analysis *blindly***
  - w/ dedicated "Null" tests
  - realistic instrument simulation

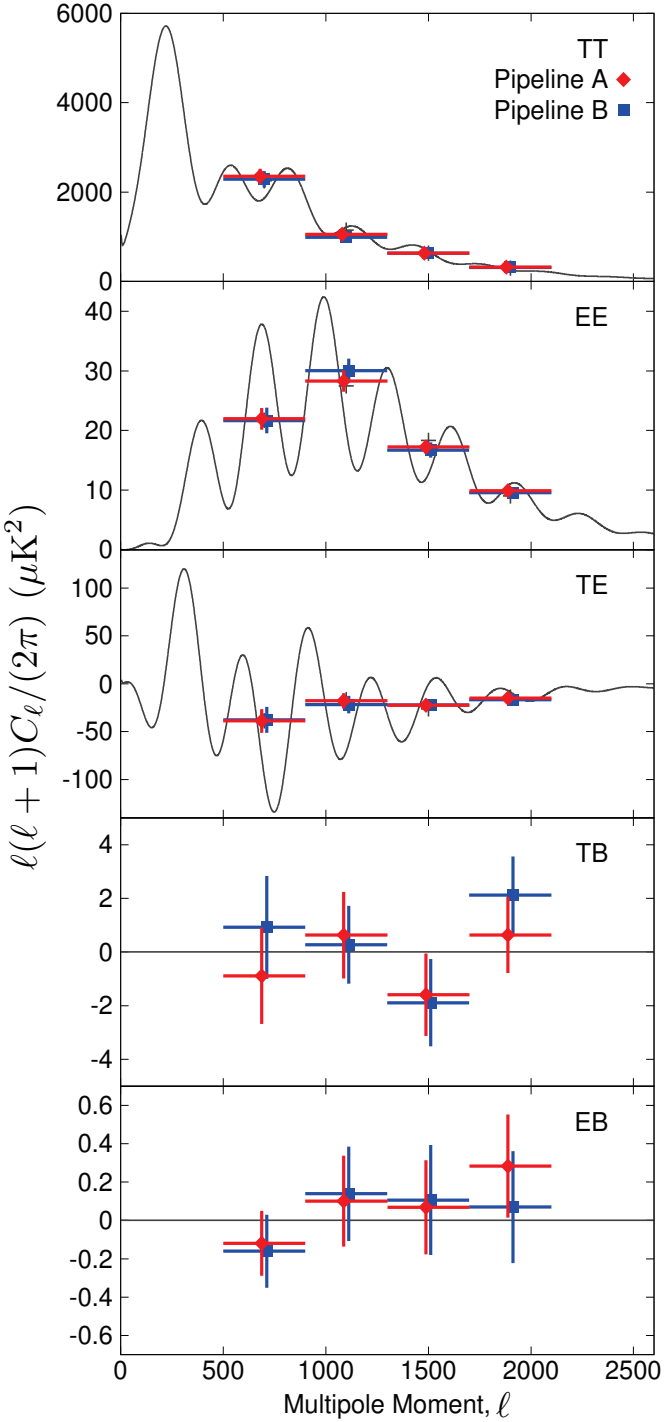
What's New? Independent Pipeline

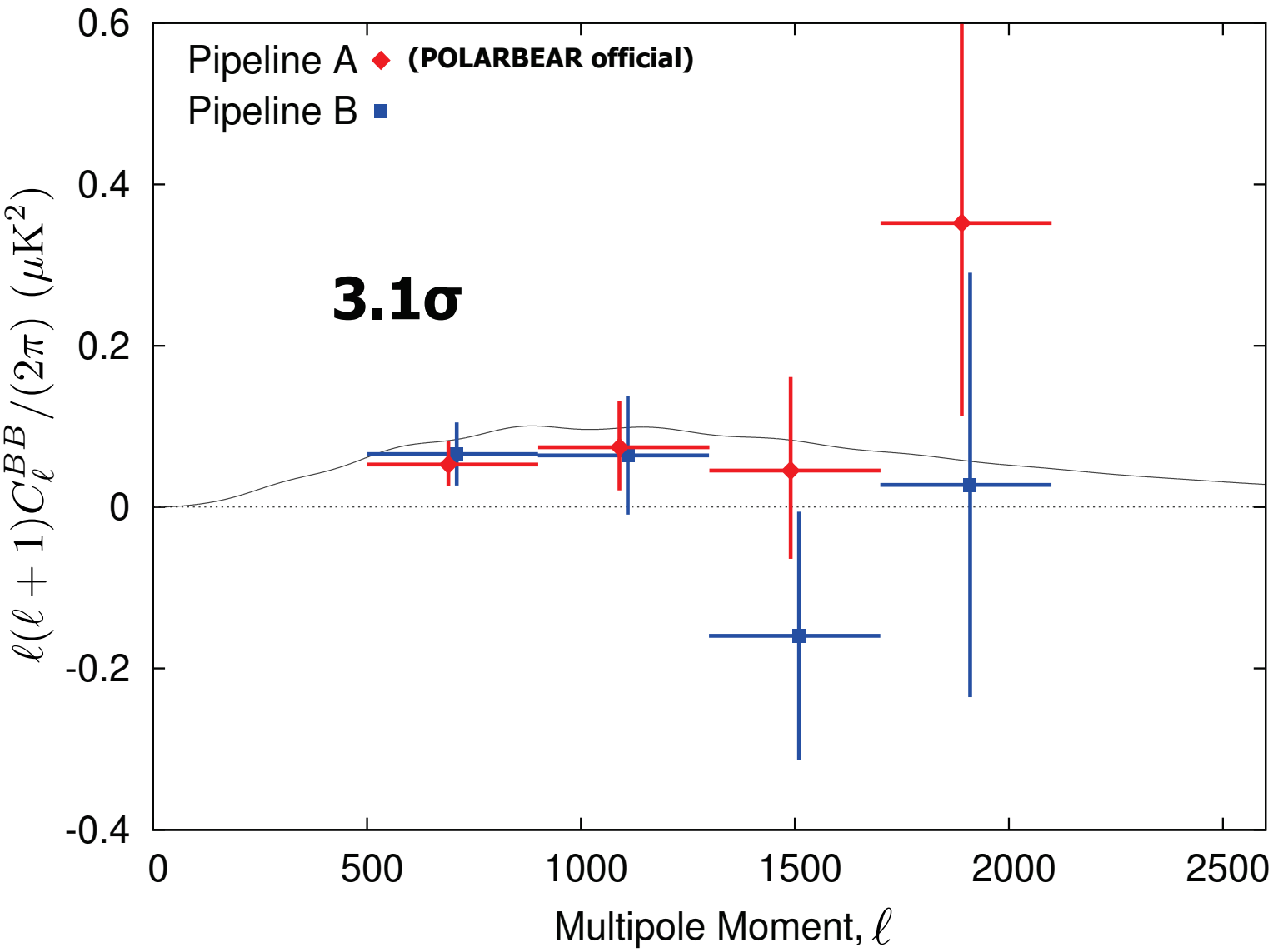
- Two independent pipelines performed TOD into maps & power spectrum estimate ⇨ Make our analysis more robust





New Results: x2 better than 2014

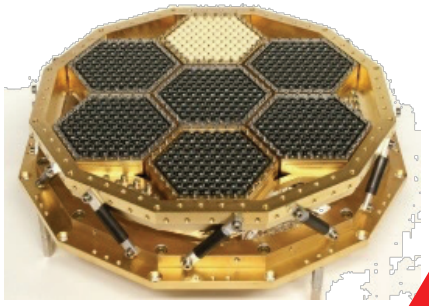




We reject the null hypothesis of no B-mode polarization at a confidence of 3.1σ including both statistical and systematic uncertainties.

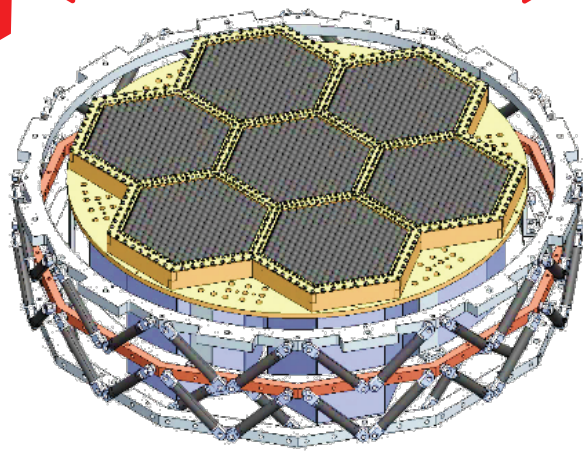
$$A_L = 0.60^{+0.26}_{-0.24}(\mathrm{stat})^{+0.00}_{-0.04}(\mathrm{inst}) \pm 0.14(\mathrm{fg}) \pm 0.04(\mathrm{multi})$$

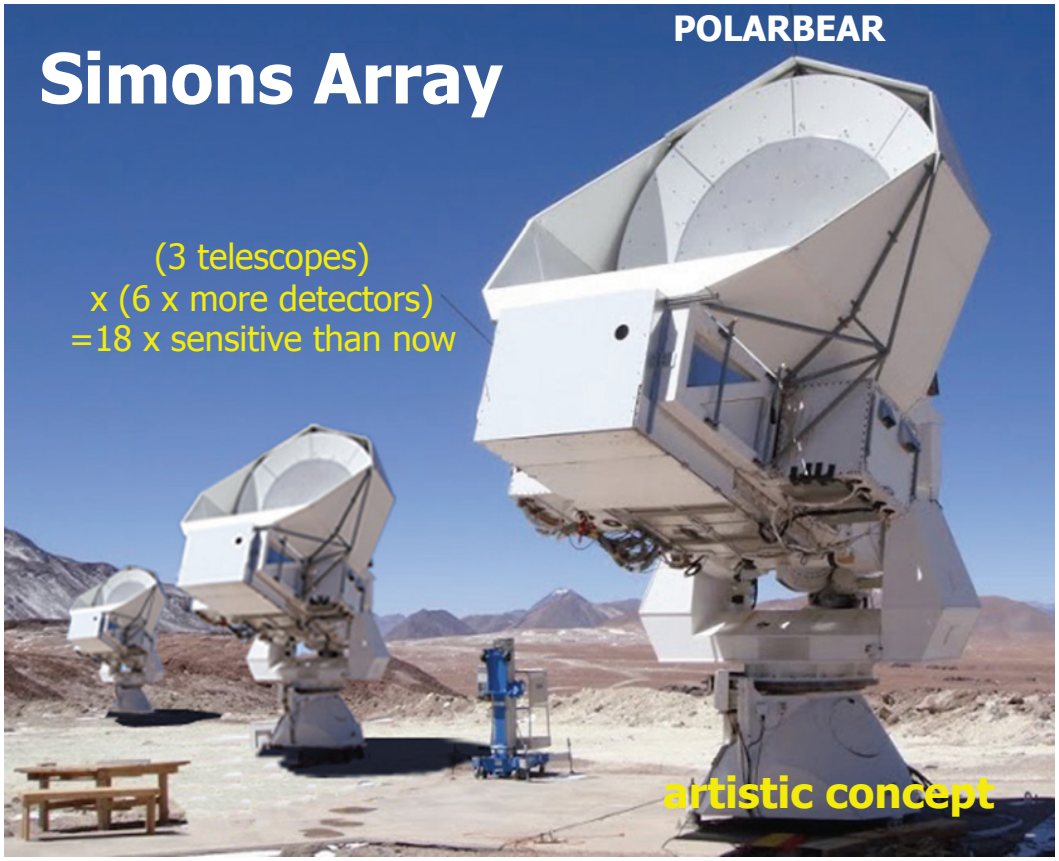
Simons Arrays



x6 more detectors

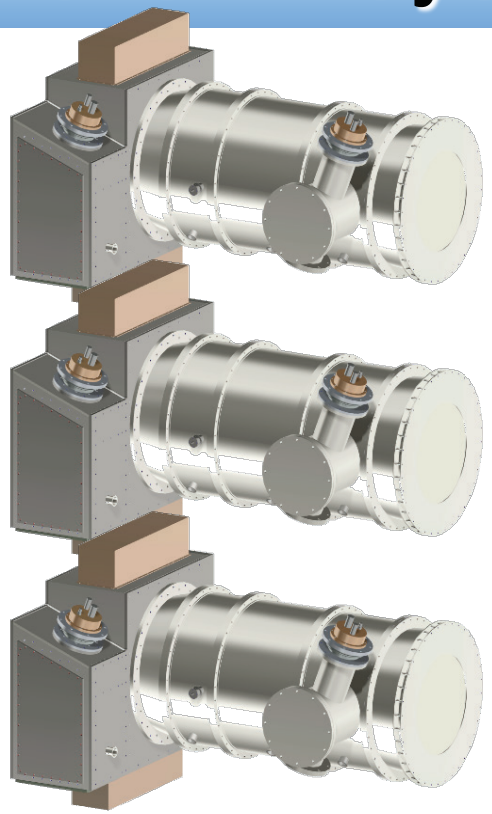
dual freq.





- 7,588 bolometers per receiver, factor of **6** increase from current receiver
- **Three telescopes** (two new telescopes + one current one)
- **→ (3 telescopes) x (6 x more detectors) = 18 x sensitive than now**

Simons Arrays

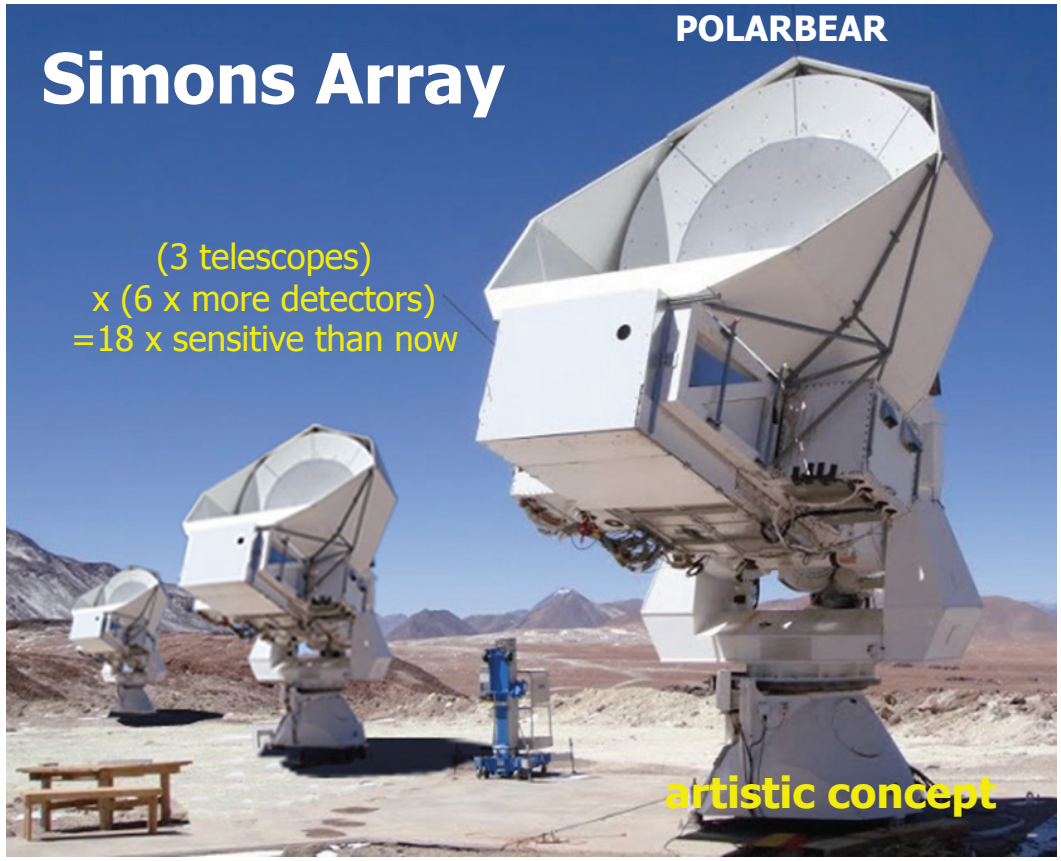


POLARBEAR-2A
95/150 GHz

POLARBEAR-2B
95/150 GHz

POLARBEAR-2C
220/270 GHz

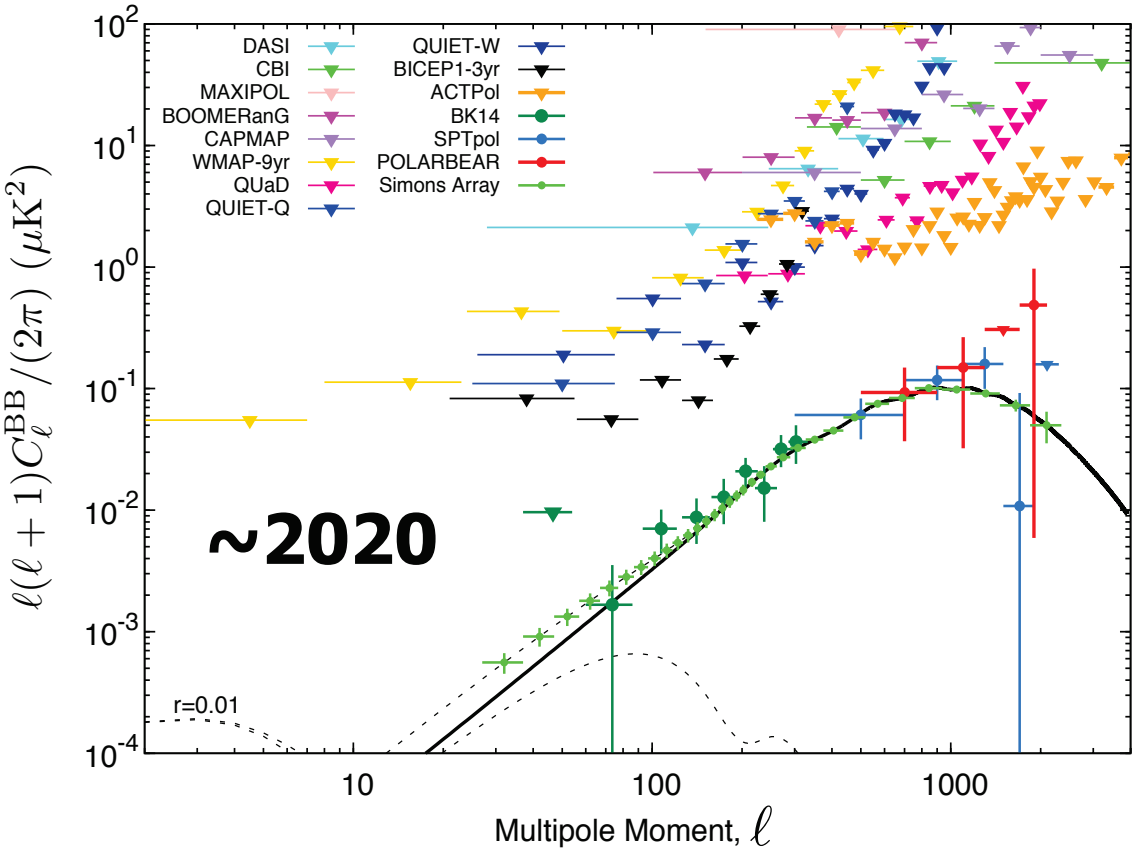
POLARBEAR-2 Receiver Frequency Plan

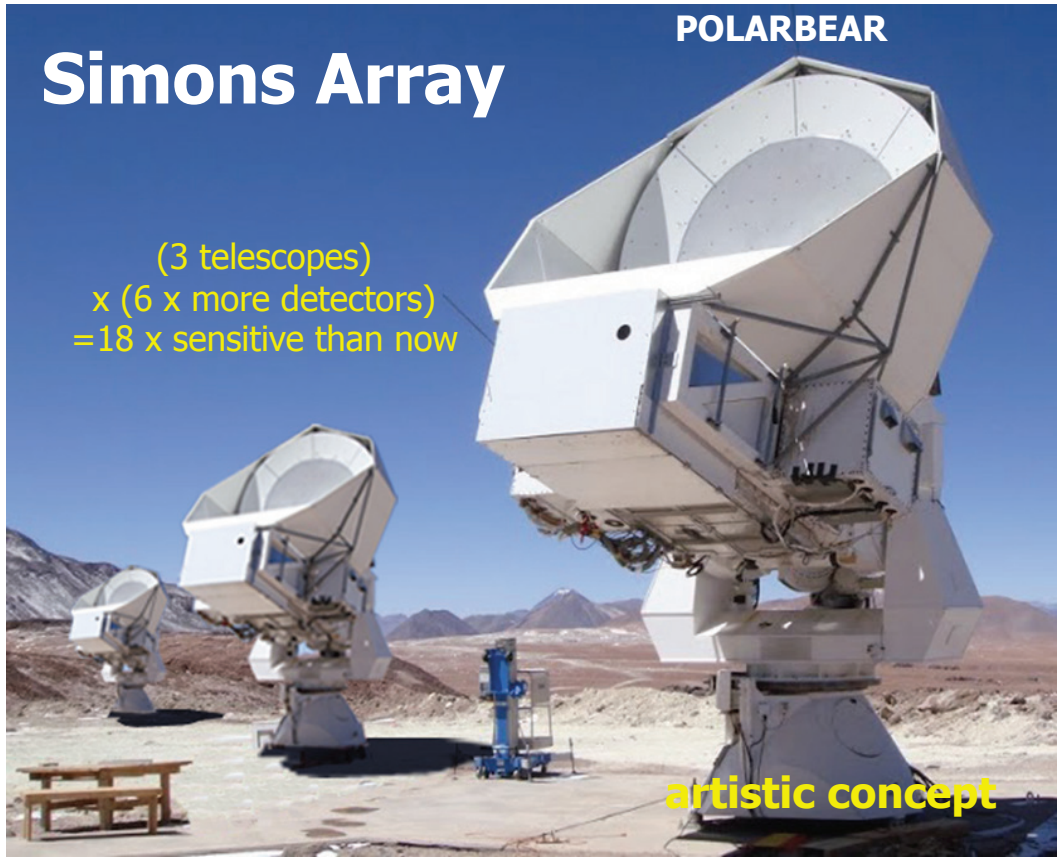


- 7,588 bolometers per receiver, factor of **6** increase from current receiver
- **Three telescopes** (two new telescopes + one current one)
- **→ (3 telescopes) x (6 x more detectors) = 18 x sensitive than now**
- Expand frequency coverage for FG removal (**95/150/220/270 GHz**)
- Deploy first receiver (PB2A) soon
- Deploy two more receivers (PB2B, PB2C) in **2018**

Daisuke will talk more!

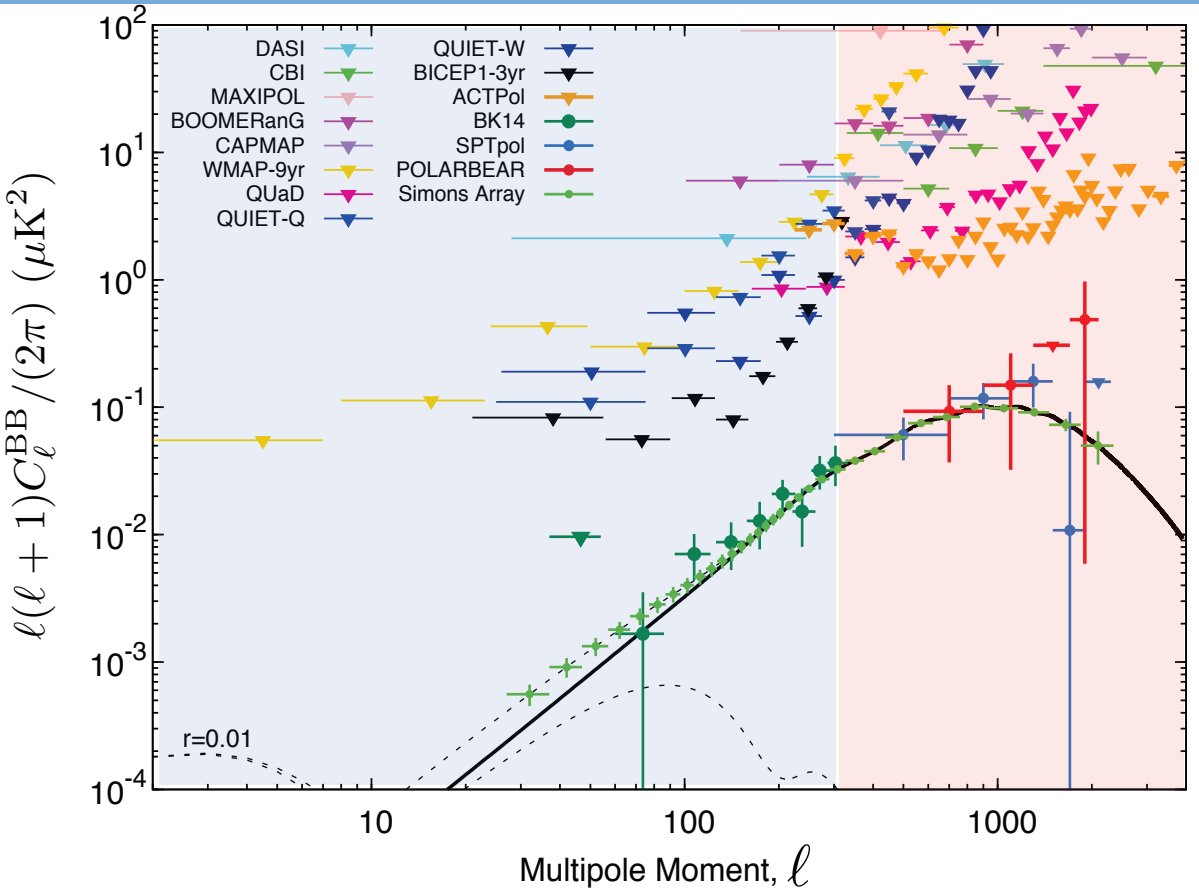
Simons Arrays





- **Inflation: σ(r=0.1) = 6×10^{-3} (4×10^{-3} stat.)**
- **Neutrino mass: σ(Σmν) = 40 meV (19 meV stat.)** **w/ BAO from DESI**
- **Light relic: σ(N$_{eff}$) = 0.04**

Success & Concern



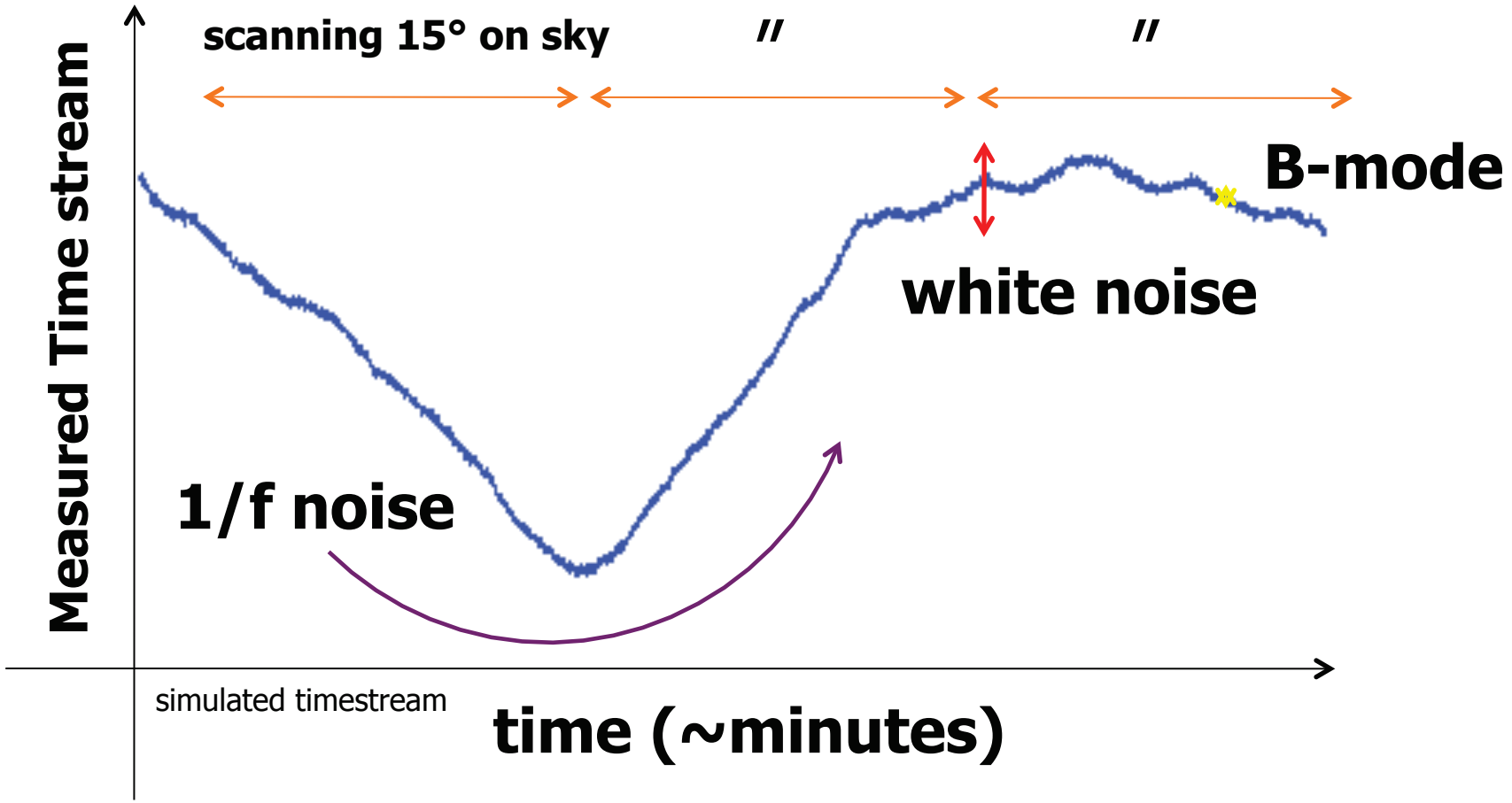
- POLARBEAR successfully measured B modes @ high ell (small angular scales) & Simons Array will inherit what POLARBEAR has achieved (inst. & ana.)
  - How about sensitivity to achieve $\sigma(r)<10^{-3}$ & $\sigma(\Sigma m_\nu)<20$ meV?
  - How about low ell (large angular scales) for inflationary B modes **(ell<200)**?

Need a next-generation ground exp & satellite & new technology to make low-ell measurement possible

Simons Array to Simons Observatory

- Simons Array & ACT will be combined to "Simons Observatory" (SO)
  - The Simons Foundation is providing $40M in support for the Simons Observatory
  - Can observe ~80% of the sky from Chile
    - ✓ then can provide rich astronomical probes & lensing info
- SO/S4 is targeting to achieve $\sigma(r)<0.001$; $\sigma(\Sigma m_\nu)\sim 20$ meV
  - actively studying design of instrument (& data analysis)

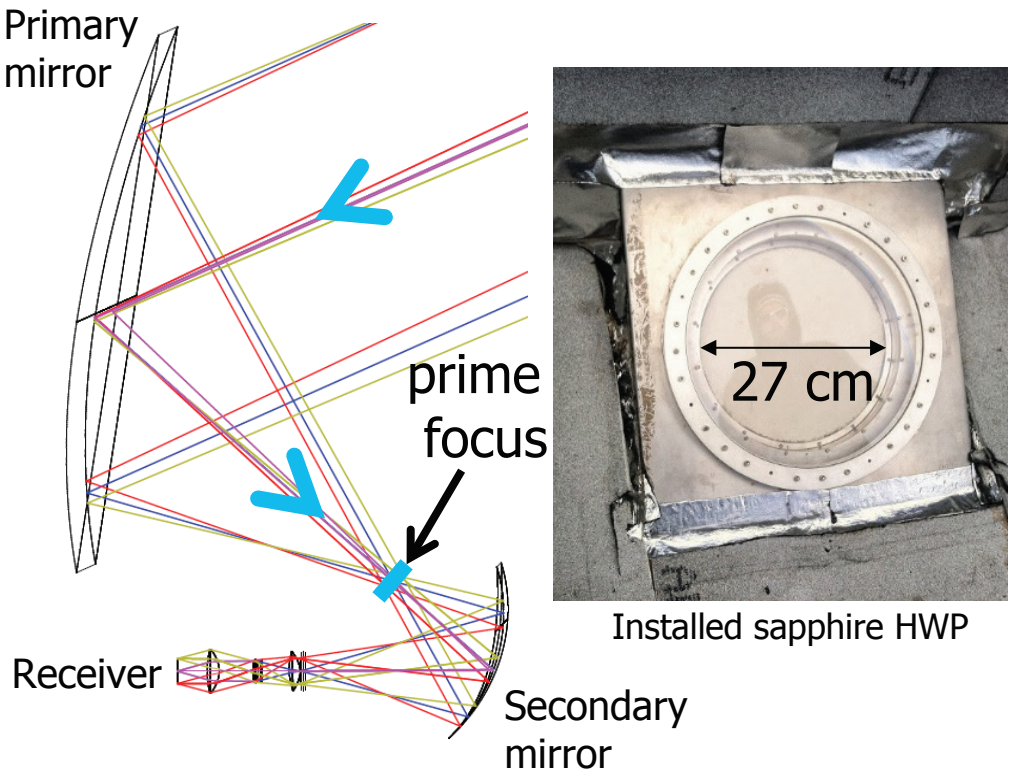
How Much Low Ell We Can Measure? Atmospheric 1/f Noise



- Measured data @ large angular scales are dominated by atmospheric 1/f noise, which is NOT suppressed by averaging
  - Make it difficult to measure inflationary B modes
- Need "modulation" to recover inflationary B modes

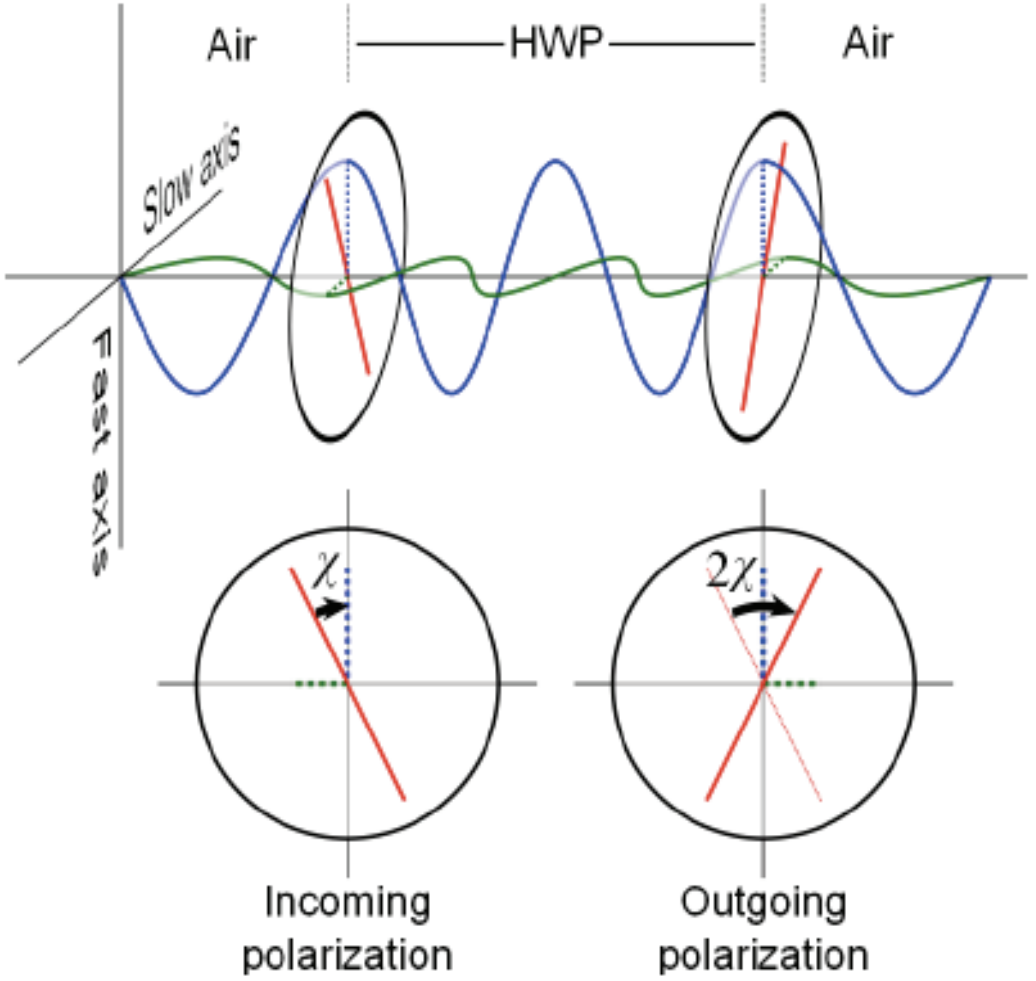
Modulation by Continuously Rotating Half-wave Plate

HWP is optical element made of a birefringent material whose thickness is set to make the path difference between birefringent axes half of a wave length.



Installed sapphire HWP

Kusaka et. al (2014)

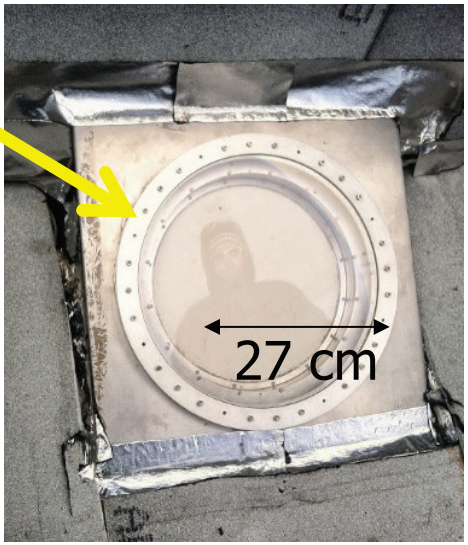


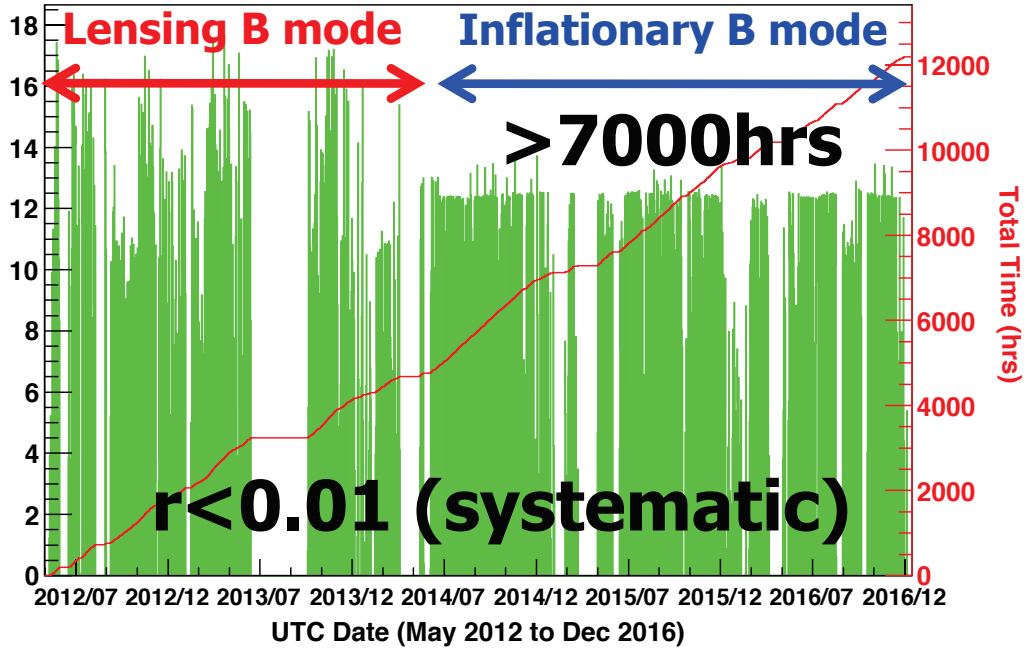
- HWP can rotate incoming polarization signal as we want
  - given an angle between HWP axis & incoming polarization of χ, outgoing polarization angle will be 2χ
- By rotating HWP, we can modulate incoming signal as we want!

Half-wave Plate on Simons Array & Simons Observatory

HWP on POLARBEAR

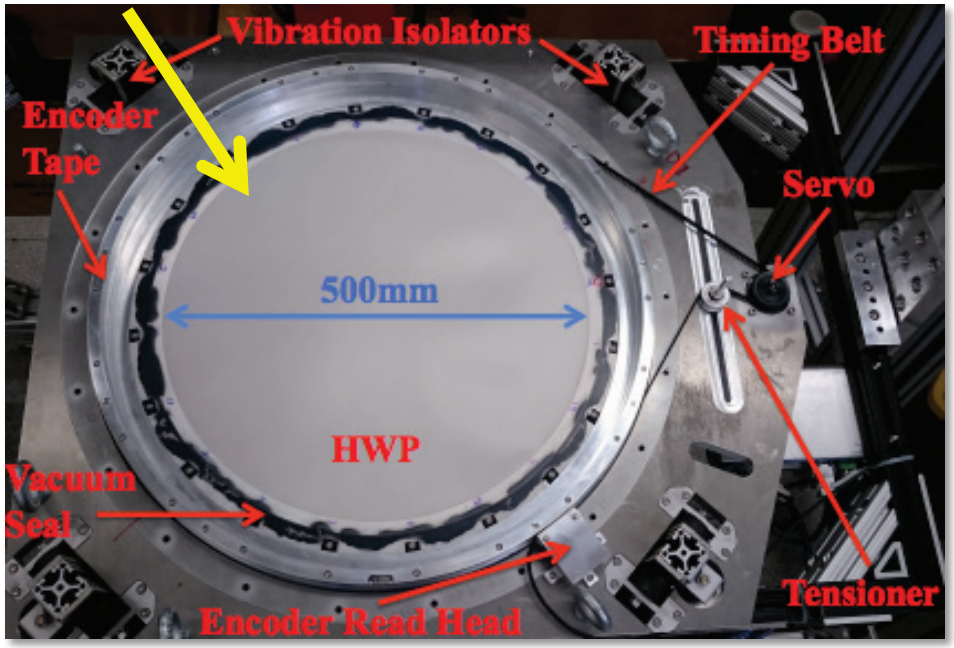
arXiv:1702.07111
S. Takakura et. al. (PB Collab.)





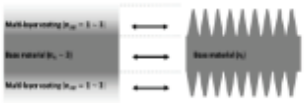
HWP on Simons Array

arXiv:1607.07399; CA Hill, S Beckman, Y. Chinone et. al.

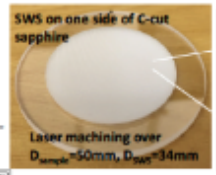


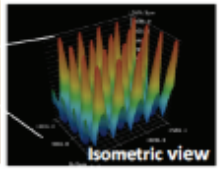
Polarization Modulator

broadband AR coating and polarization modulation efficiency

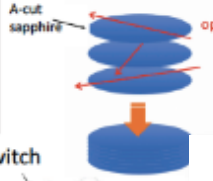


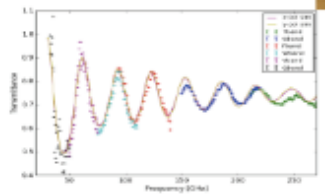
Comparison between the data from the one-side machined sample and the prediction.

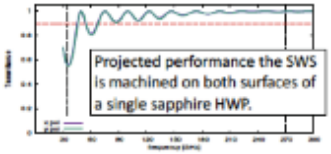


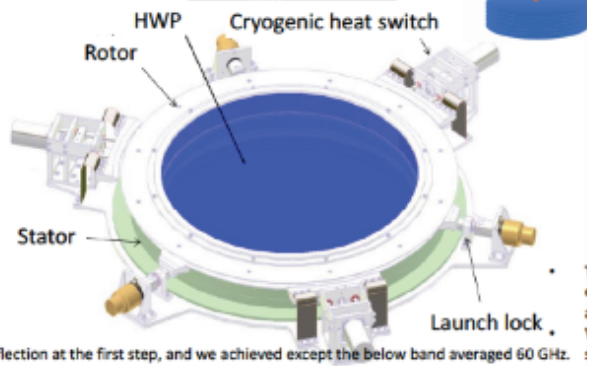


Sapphire based 9 layer achromatic HWP









- We set the goal to achieve below 10 % of reflection at the first step, and we achieved except the below band averaged 60 GHz.
- We now move towards the reflection below 1 % by 1) higher aspect ratio and/or optimized SWS shape.
- The further develop is in progress to increase the process speed.

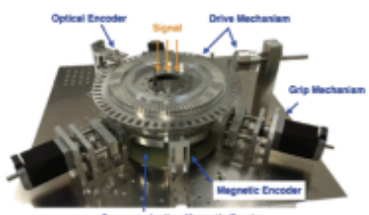
from LTD17 poster (T. Matsumura et al.)

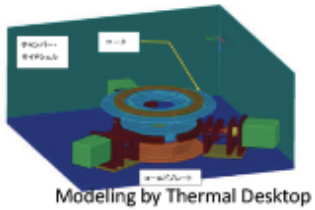
Polarization Modulator

Thermal model

from LTD17 poster (T. Matsumura et al.)

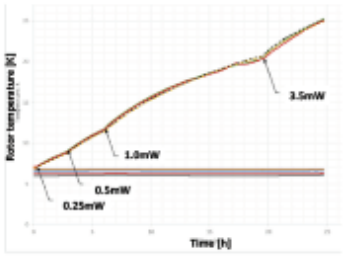
A scale model of the polarization modulator and the thermal model

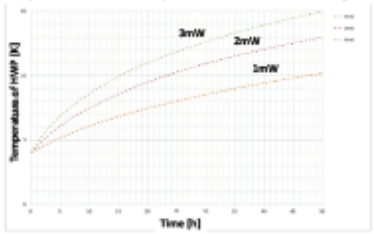




Modeling by Thermal Desktop

Projected thermal performance for a flight size



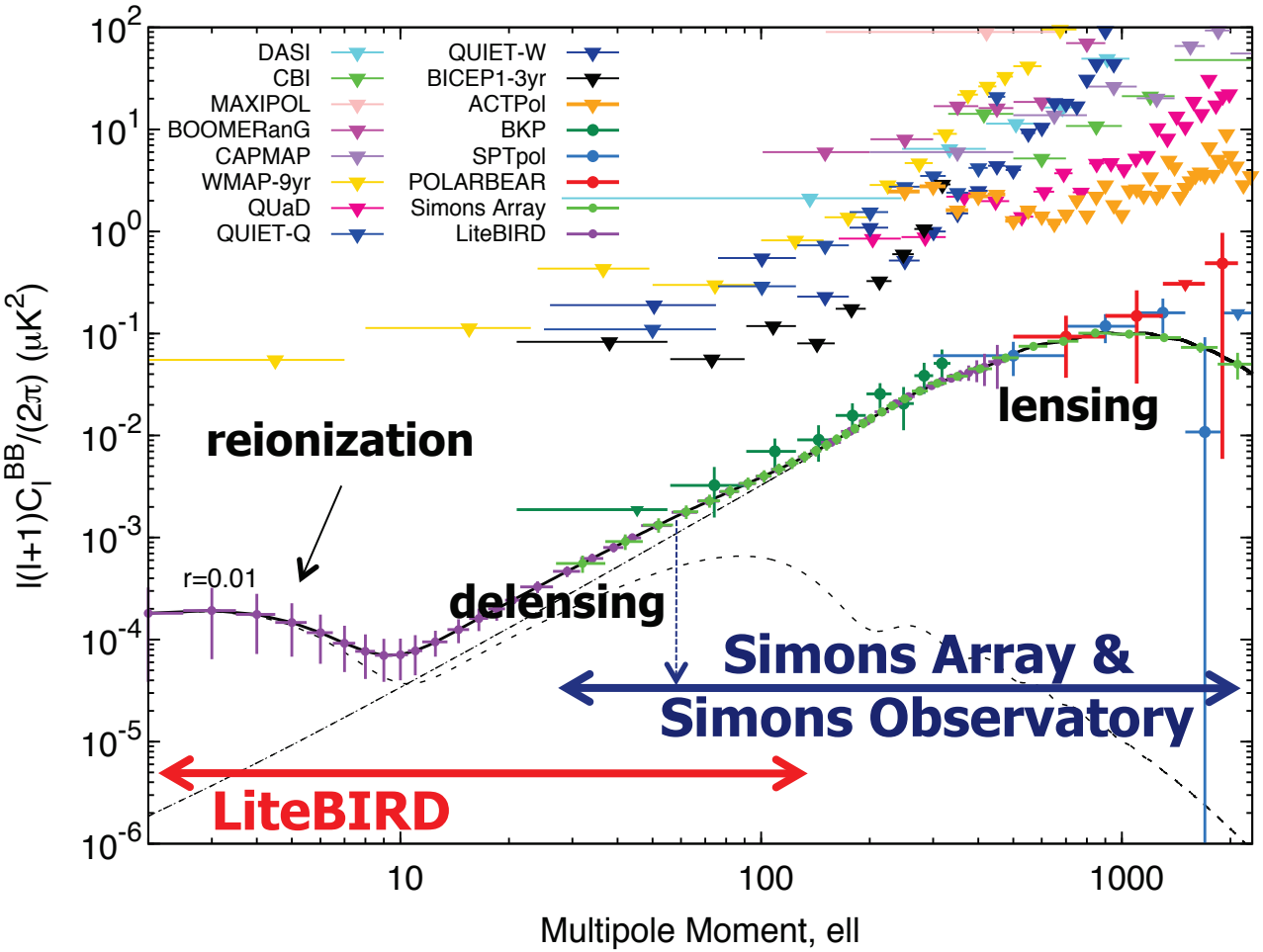


The rotor temperature with the resistive heat on the rotor and the fit with the thermal model. We apply this thermal model to the flight size, and evaluate the temperature profile given the heat input. Left) When the rotor is levitating with the heat input, Right) the rotor is held and cooled down conductively. The projected estimate of the heat input is about a few mW and we are in the progress to

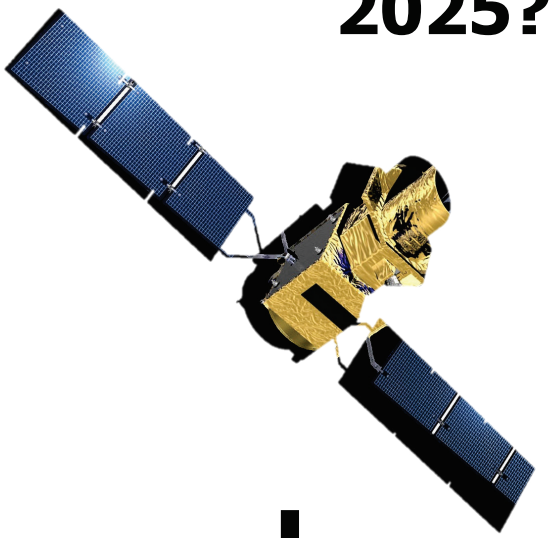
LiteBIRD also uses HWP for low-ell measurement. Hiroaki will talk more!

Collaboration & Synergy Among PB/SA/SO/LB

- POLARBEAR has validated HWP & Simons Array and Simons Observatory will inherit its achievement
  - **LiteBIRD is an only experiment can access the full sky & also needs HWP to measure reionization bump**
- SA/SO can "delens" LiteBIRD for "extra" success

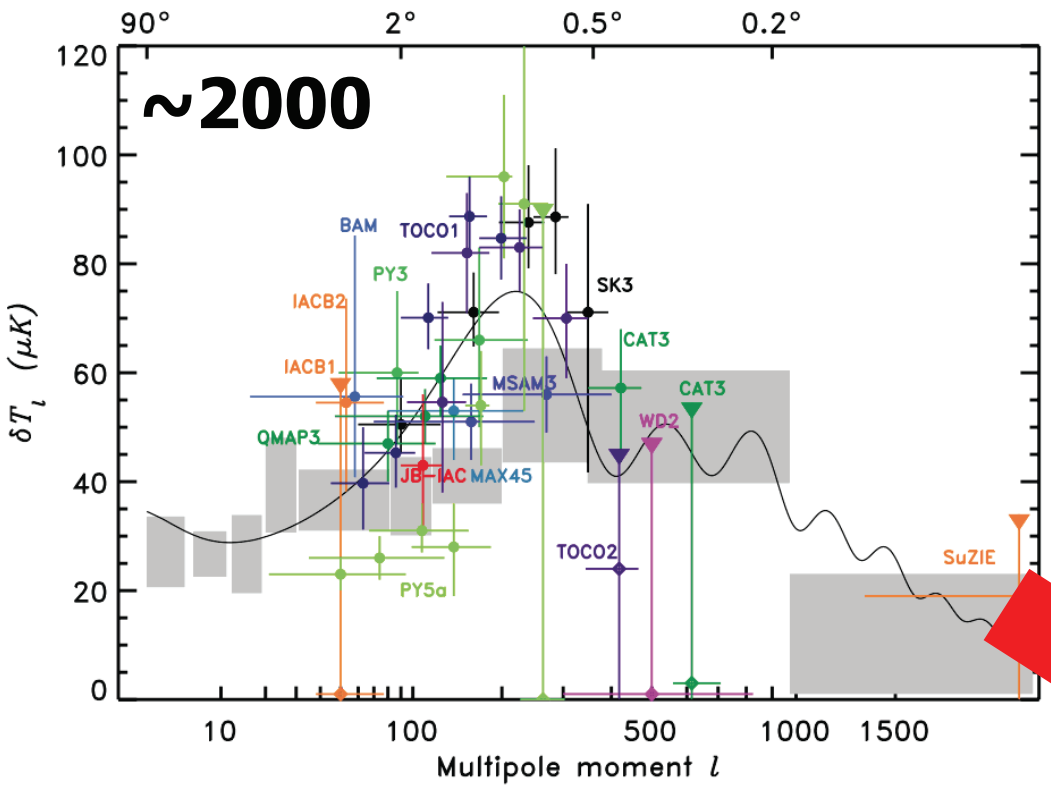


2025?~

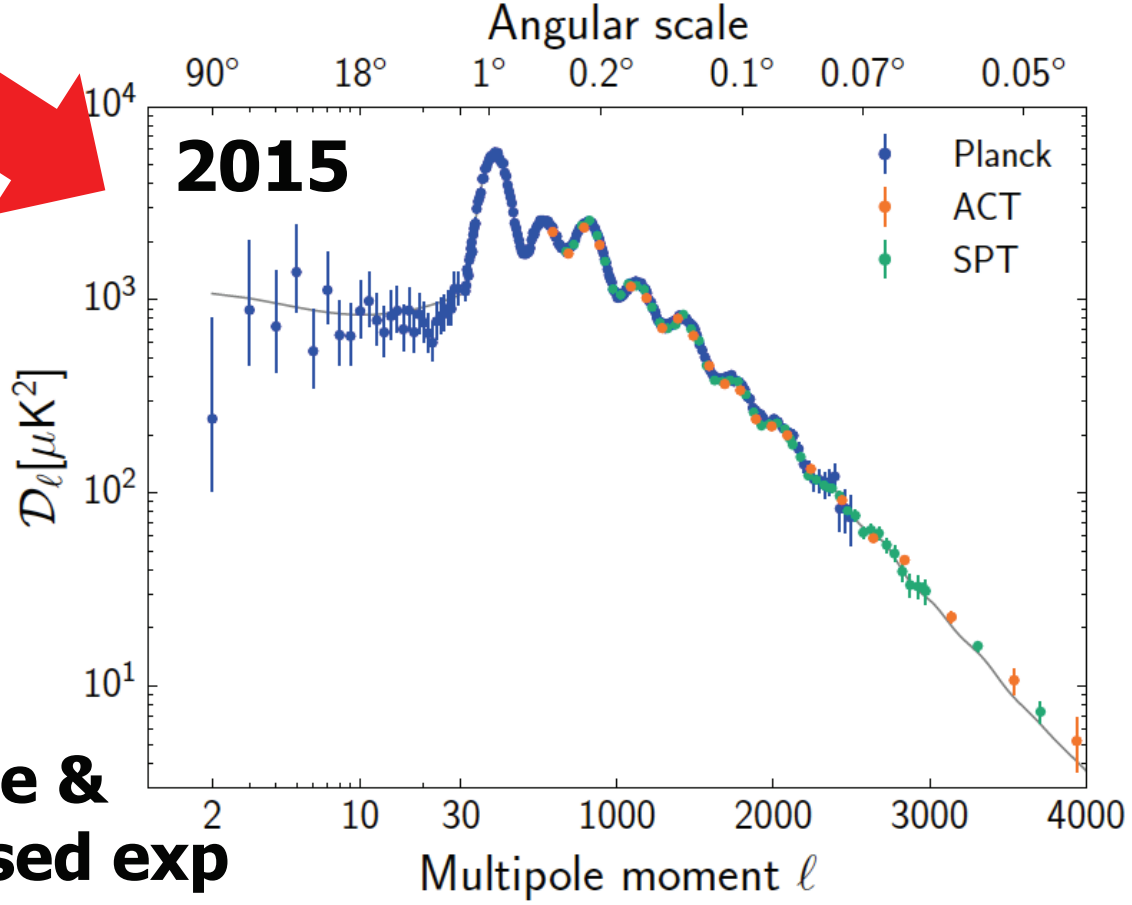


2018 & 2020~

Analogy to Temperature Measurement 15yrs Ago

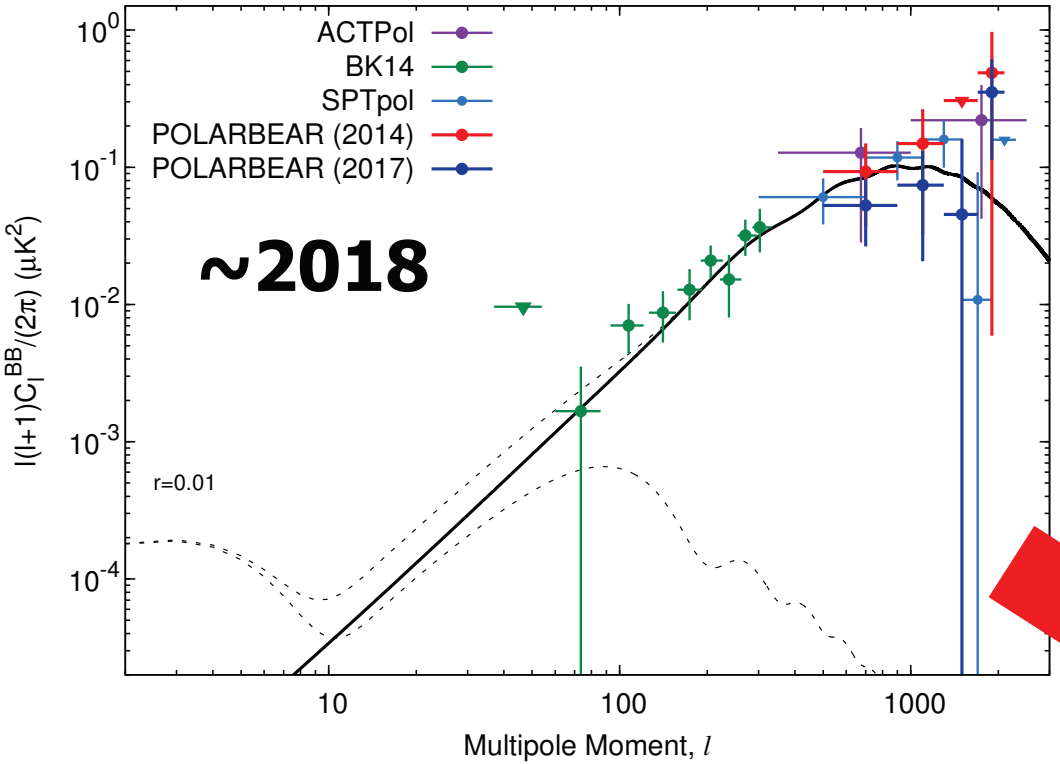


Old generation ground-based (balloon) exps.

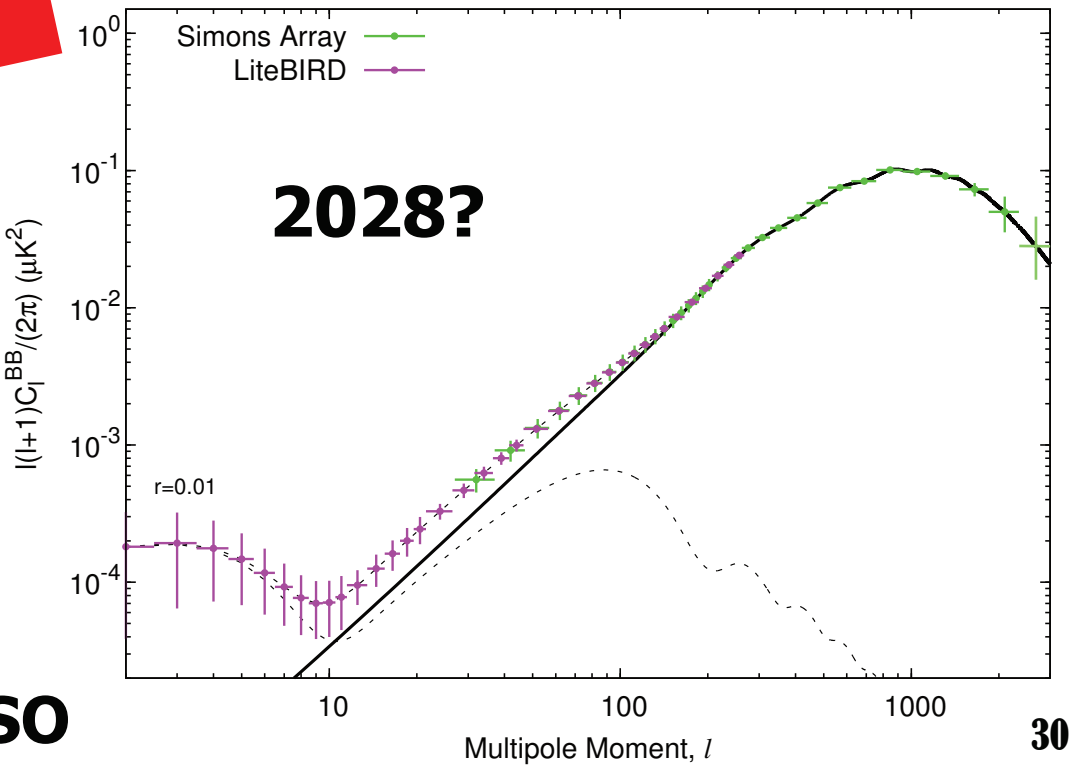


Dedicated satellite & advanced ground-based exp

Analogy to Temperature Measurement 15yrs Ago



Old generation ground-based (balloon) exps. =PB/SPT/ACT/BK

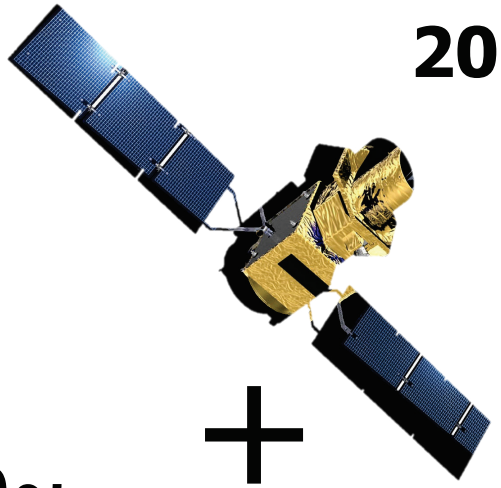


Dedicated satellite=LiteBIRD & advanced ground-based exp=SA/SO

Summary

- POLARBEAR is a "stage 2" CMB experiment, which successfully measured B-mode lensing; Updated the result achieving 2x better
- Upgrading POLARBEAR to Simons Array, which is a "stage 3" CMB experiment; Deploy in 2018!
- Staring Simons Observatory & developing LiteBIRD w/ heritages that POLARBEAR have achieved

2025~



+

Now

σ(r)<0.1

2018~

σ(r)<0.01; σ(Σm$_\nu$)~40 meV

2020~

σ(r)<0.001; σ(Σm$_\nu$)~20 meV