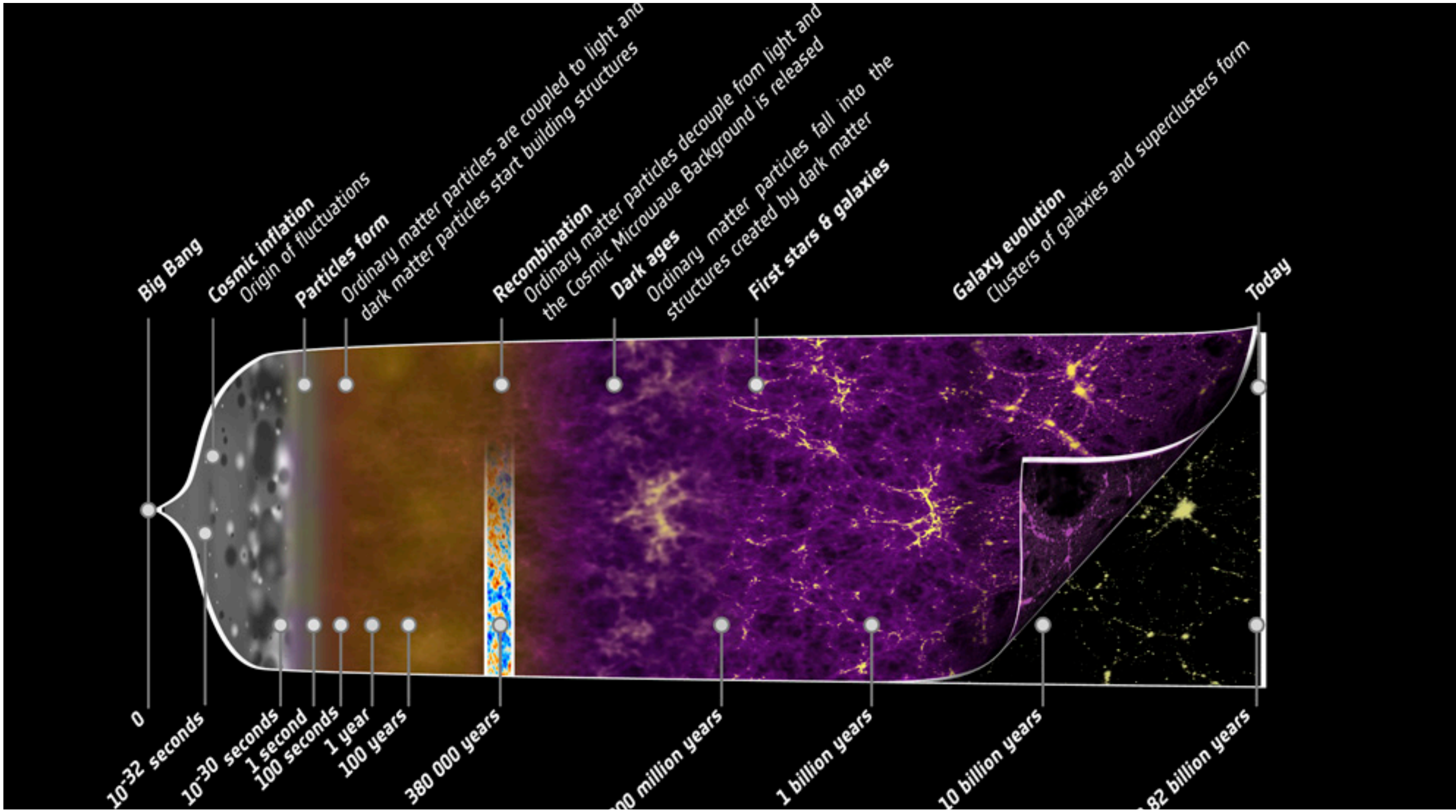
Quest for CMB B-modes:
from POLARBEAR, to Simons Array and Observatory, and to LiteBIRD

R. Stompor (APC)

Cosmology has its standard model …



And it is called … hot big bang cosmology

Are we done then ?

- Three major features of the model,

  – dark matter
  – dark energy
  – source of the initial perturbations …

are essentially unknown …

Hasn't inflation been already established ?!

- Well it does explain all it was designed for (flatness, no monopoles, homogeneity, isotropy, etc).

  it also explains things which came about only later !

- Indeed, single-field slow-roll inflation looks so far remarkably good:
  - Super-horizon fluctuation
  - Adiabaticity
  - Gaussianity
  - $n_s<1$

- All as we had asked for !!!

- An outstanding success by many measures.

What else then ?

- Gravitational waves ….

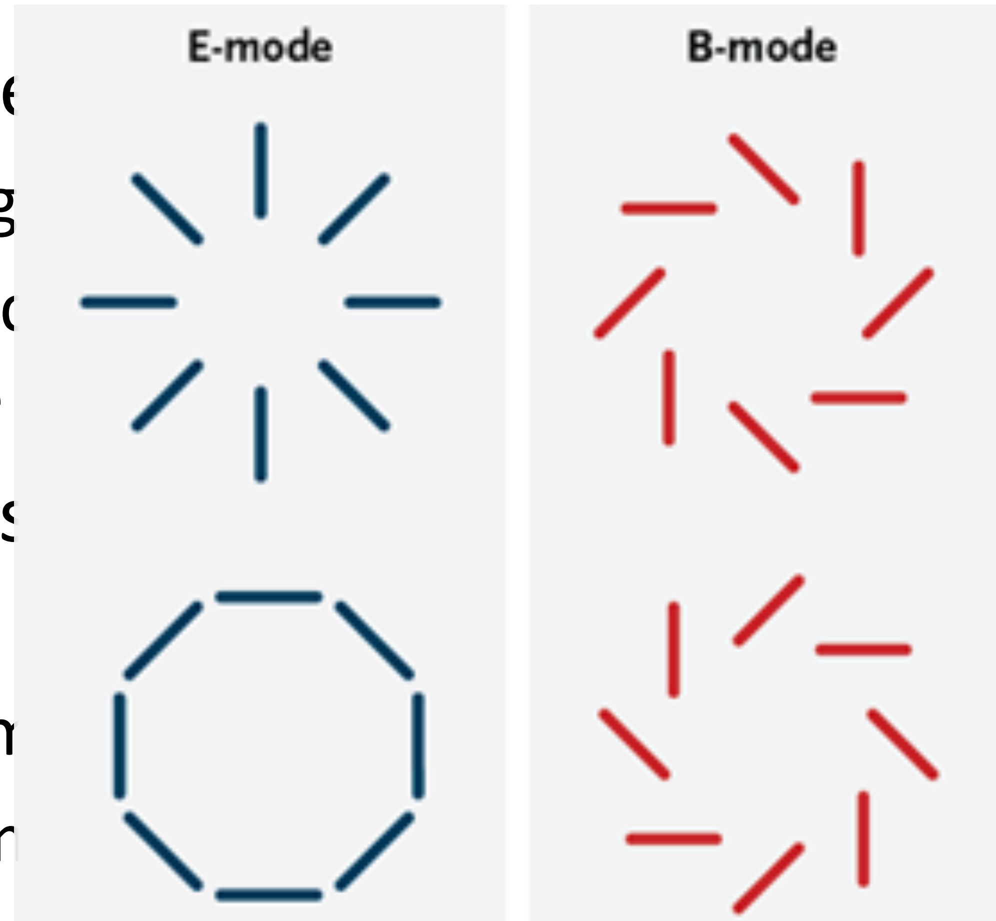
- Why ?
  - Should be there;
  - If detected,
    - would be a great confirmation of overall picture;
      and we need that to zoom on the right model.
    - they would provide a unique insight into high energy physics at the energy scales 10^{12} higher than accessible in the man-made laboratories (LHC);

  - if not,
    - well then assuming the overall picture would help to reject some of the specific models …

  - In either case this is our only way at this time to "witness" the first moments of the Universe as we know it (however indirect this may be ...)

How CMB can help with this ? (1)

- CMB light is polarize
  - Thomson scattering
  - Inhomogeneities (sc
    present at the time
- There are two types
  patterns:
  - a gradient type (E-m
  - a curl-free type (B-m



How CMB can help with this ? (2)

- The scalar perturbations (dominating the total density measurements) generate only E-modes.
- Need ~~vorticity or~~ gravitational waves present at the time of decoupling to generate B-modes.

➔ B-mode pattern on scales larger than the horizon would indicate presence of the primordial gravity waves !

if Gaussian, parity invariant, scale-invariant, etc ….

Primordial GW 'detection chain'

Primordial gravity waves generated at inflation

↓

Primordial gravity waves at the time of recombination

↓

quadrupolar distortion of photons

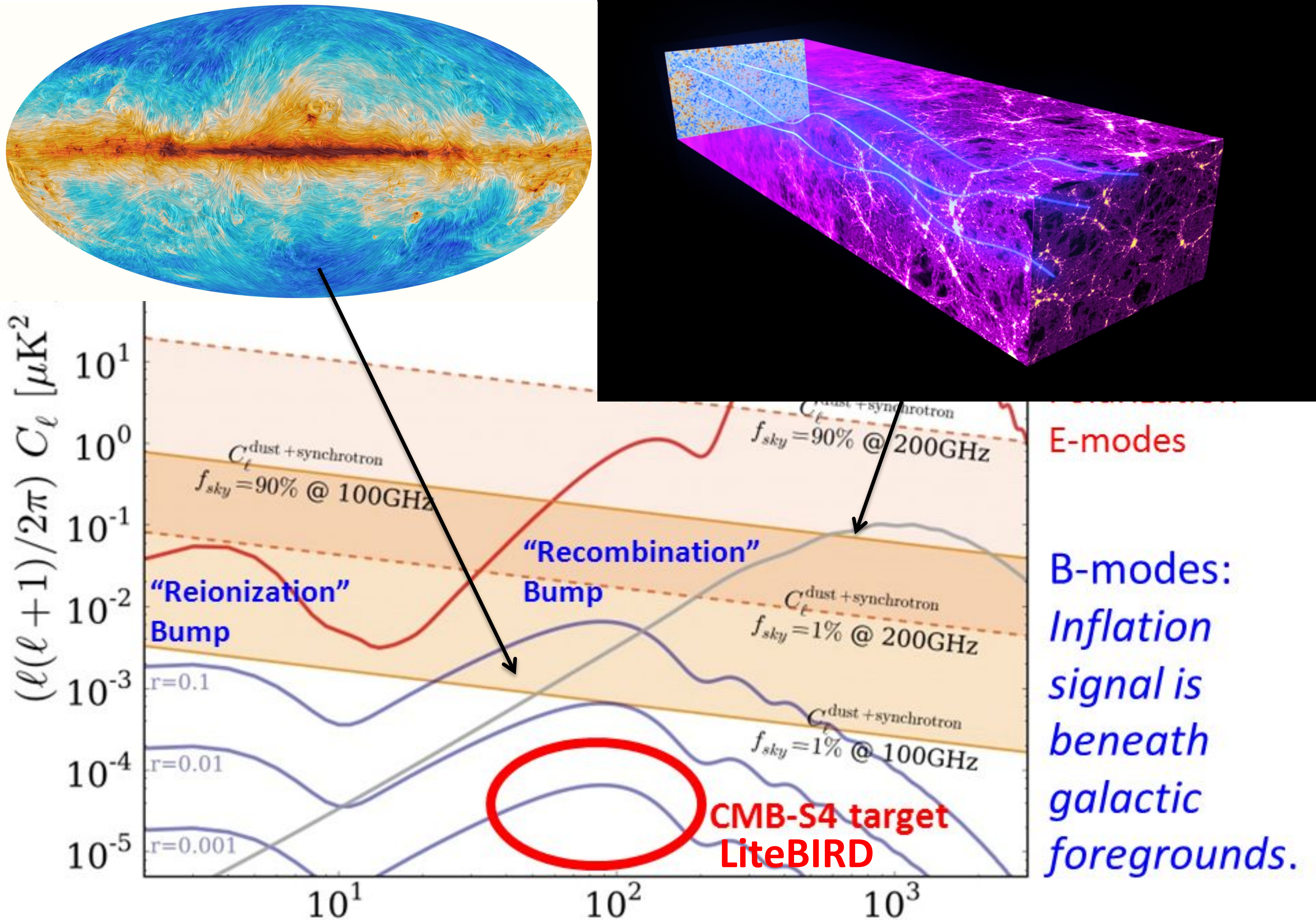
Genetrates the CMB photon polarization (Thomson scattering) →

CMB polarization

↓

GW detected if B-mode pattern found

Truly cosmological laboratory …



Errard, Feeny, Peiris, and Jaffe, arXiv:1509.06770

How to detect primordial B-modes ?

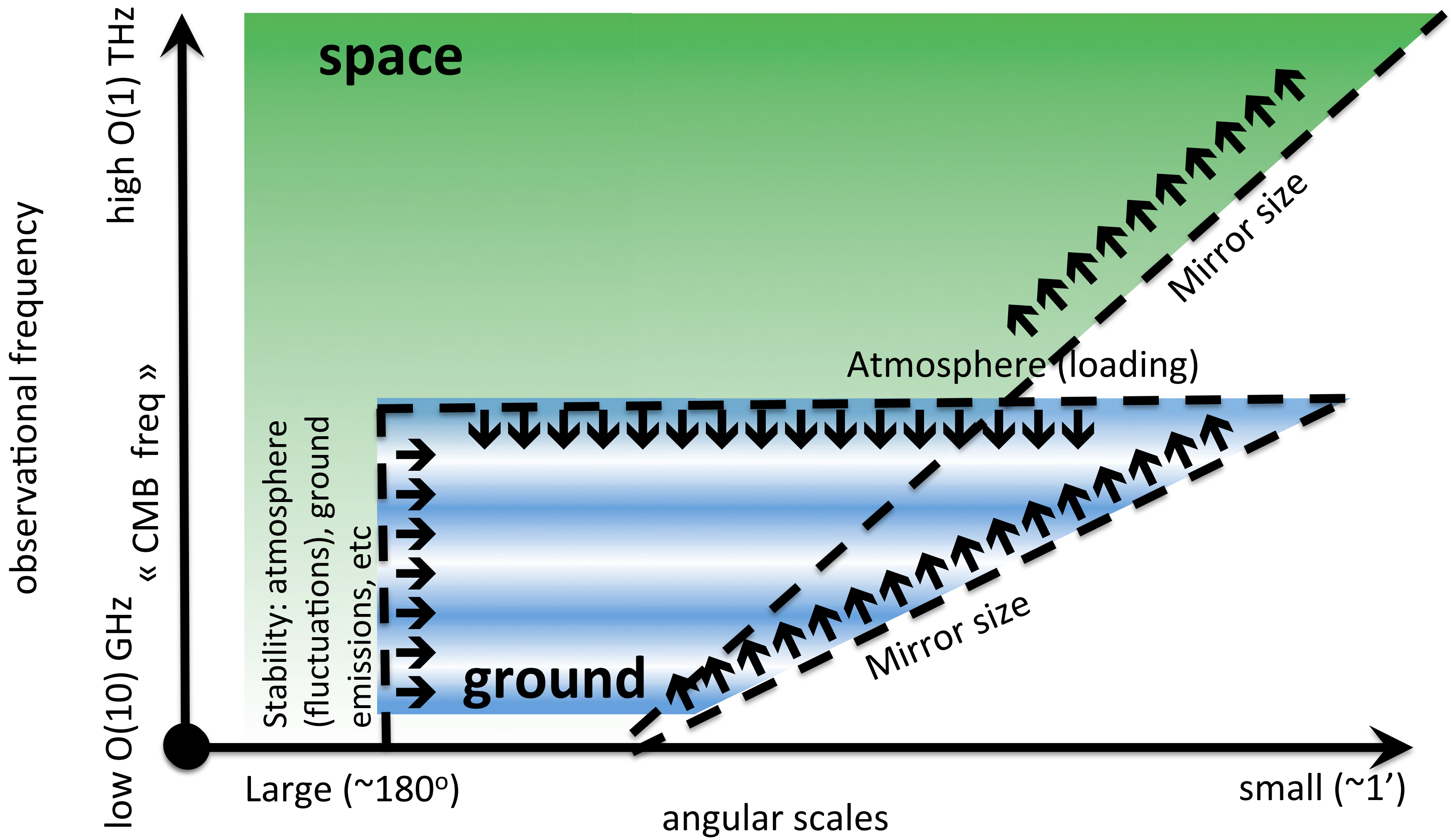
- High sensitivity ➔ huge data sets (in particular for the ground-based experiments);
- Exquisite control of instrumental effects;
- Removal of non-cosmological contributions, e.g., foregrounds
- Removal of non-primordial B-modes, lensing B-modes, others ?!

What it takes to detect primordial B-modes ?

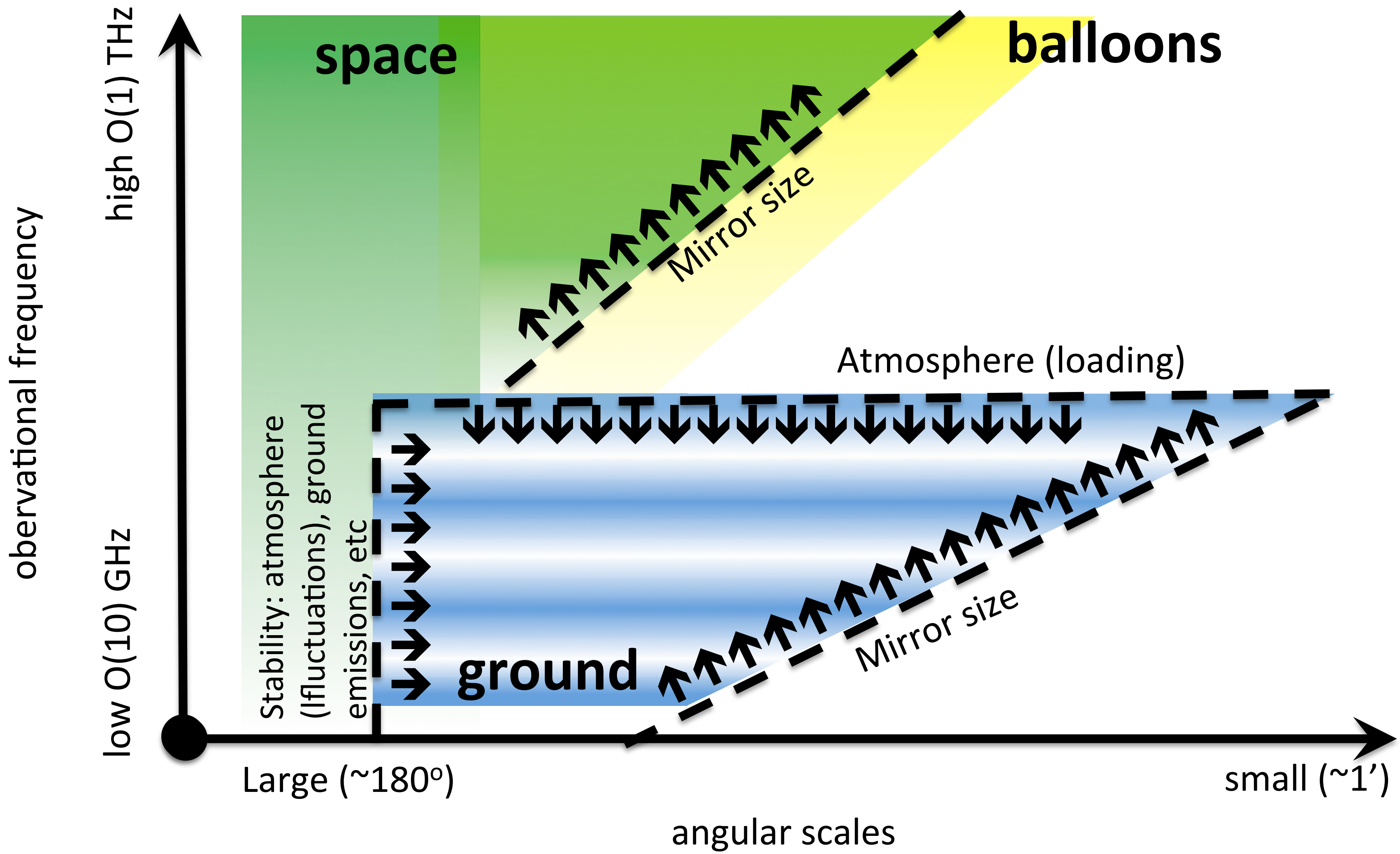
- Large telescopes furnished with high-sensitivity huge arrays of cutting-edge multi-frequency detectors;
- Long-term, sustained observational campaigns;
- Advanced data analysis employing high performance numerical algorithms and statistical inference.

Money, time and effort

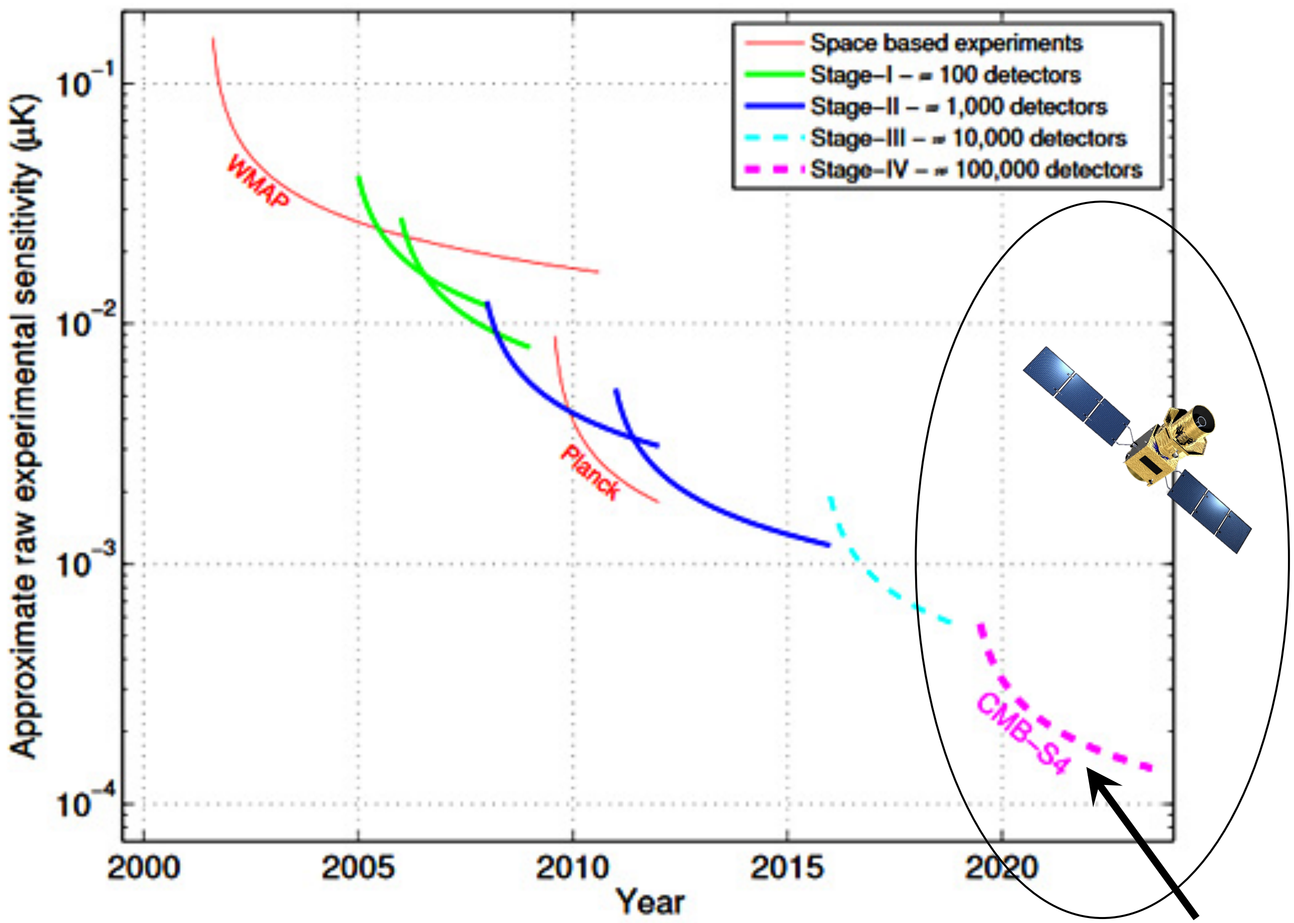
Experimental complementarity (1)



Experimental complementarity (2)

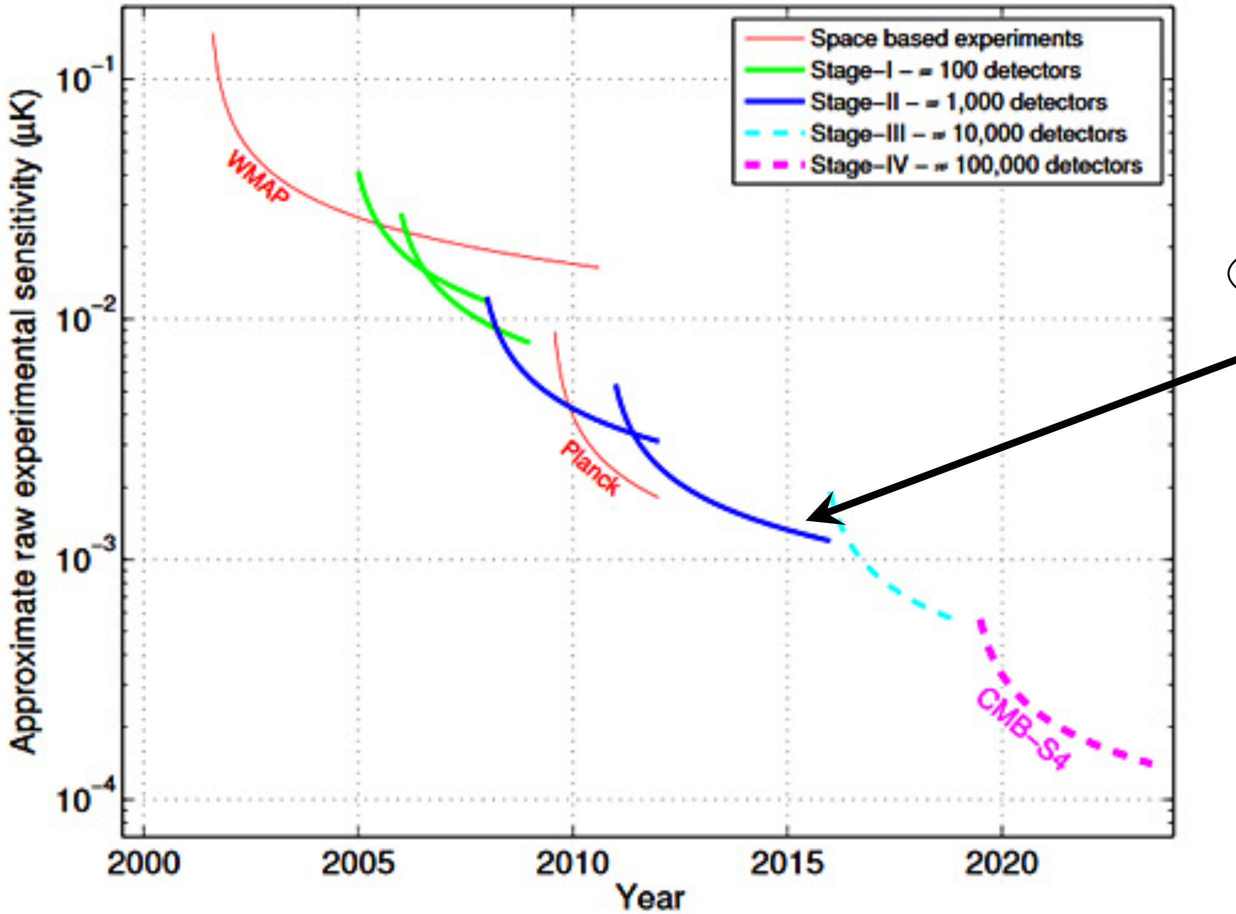


CMB ground deployment stages



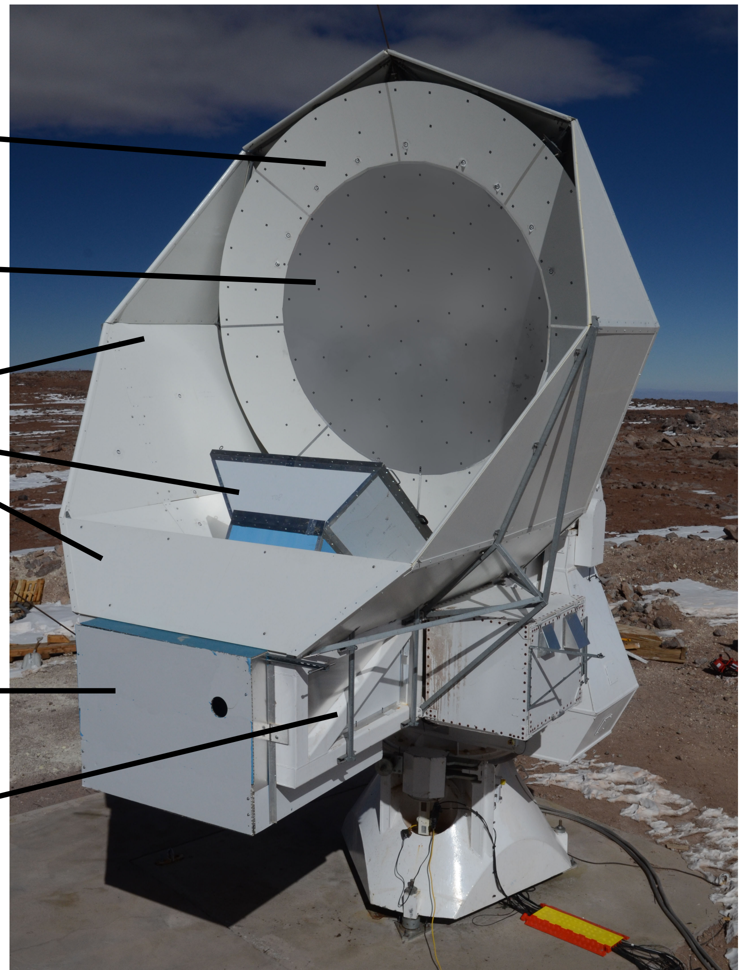
the « ultimate »
ground experiment

CMB Stage -II



POLARBEAR-I
SPTpol
BICEP3
ACTpol

POLARBEAR-I



Guard ring

2.5 meter precision primary

Shielding

Secondary mirror

Receiver enclosure

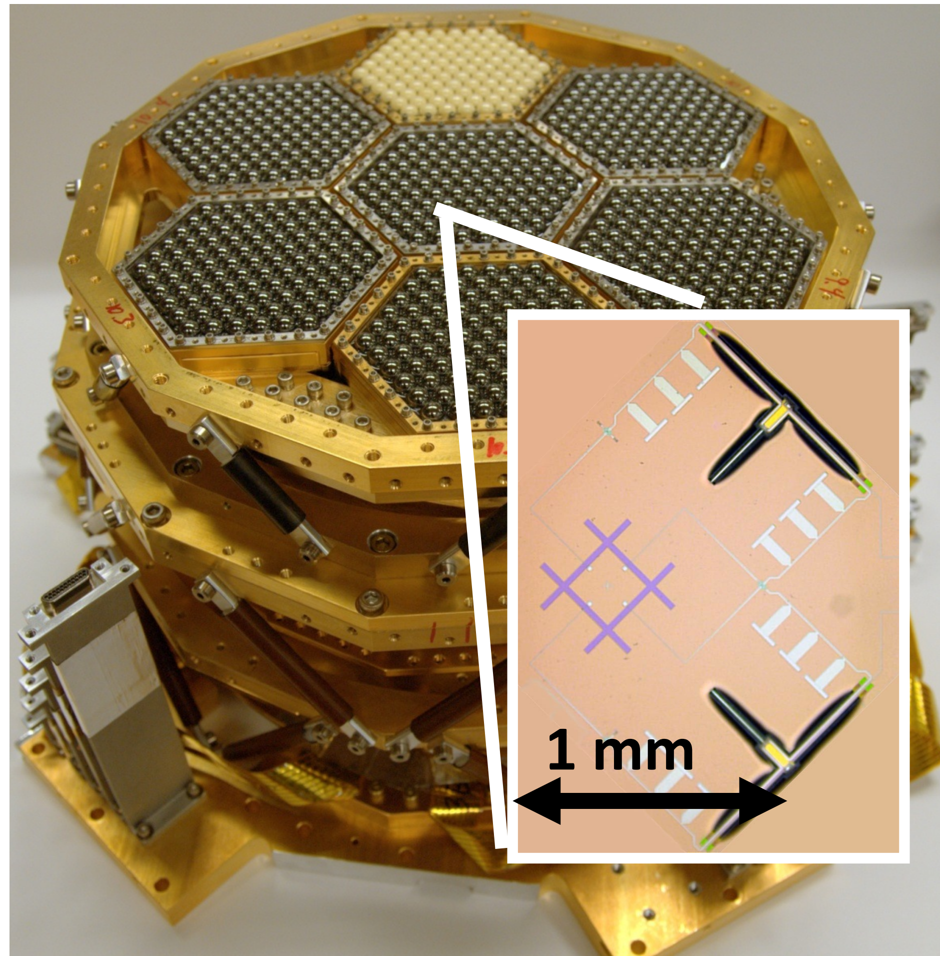
- Off-axis Gregorian- Dragone design
  - Low cross-polarization
  - Large field-of-view
- 3.5’ FWHM beams @ 150 GHz

- Single frequency (150GHz)
- Observing from the Atacama Desert in Chile (~5150m) since 2013

- 3 observational campaigns,
- 2 small patch published (2014, 2017),
- the 3rd, large patch data still analyzed.

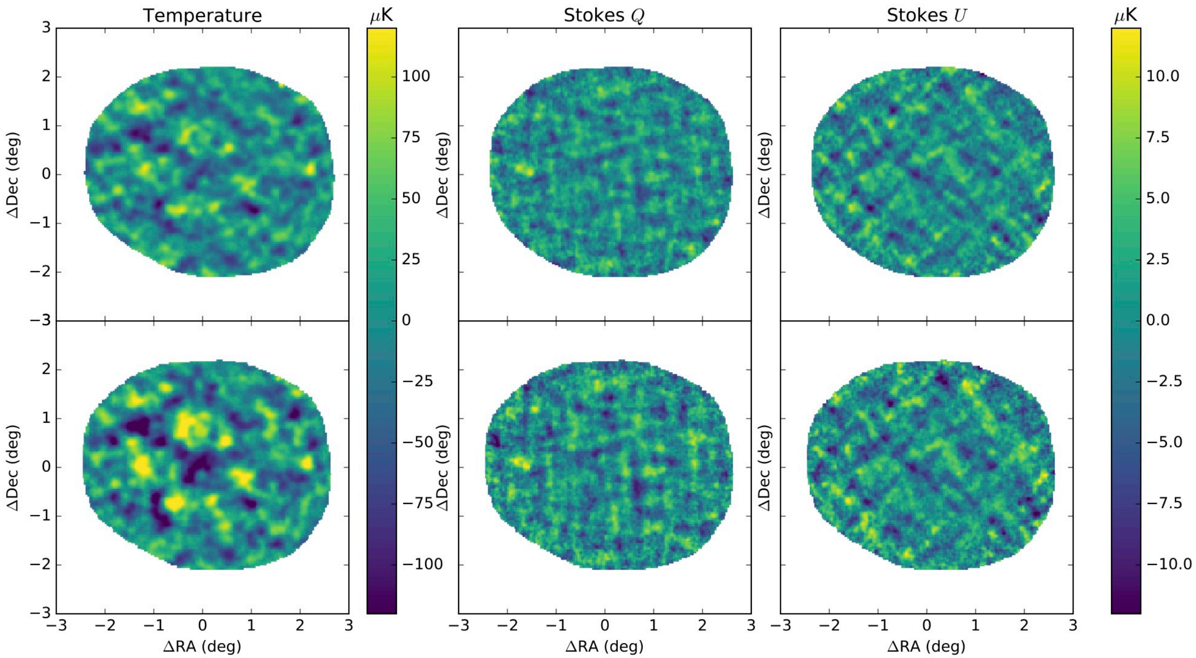
POLARBEAR-I: Focal Plane

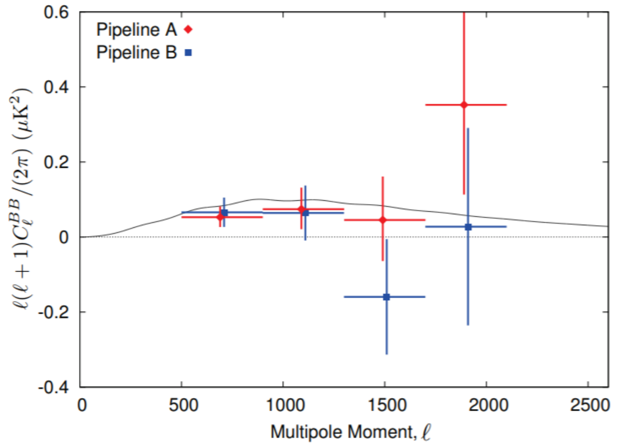
- 637 dual polarization pixels
- Beam-forming lenslet coupled to each pixel
- 1274 superconducting transition-edge sensor bolometers
- Frequency-domain multiplexing readout (8x)
- Cooled down to 250mK



POLARBEAR Team

First two sets of results (small patch)

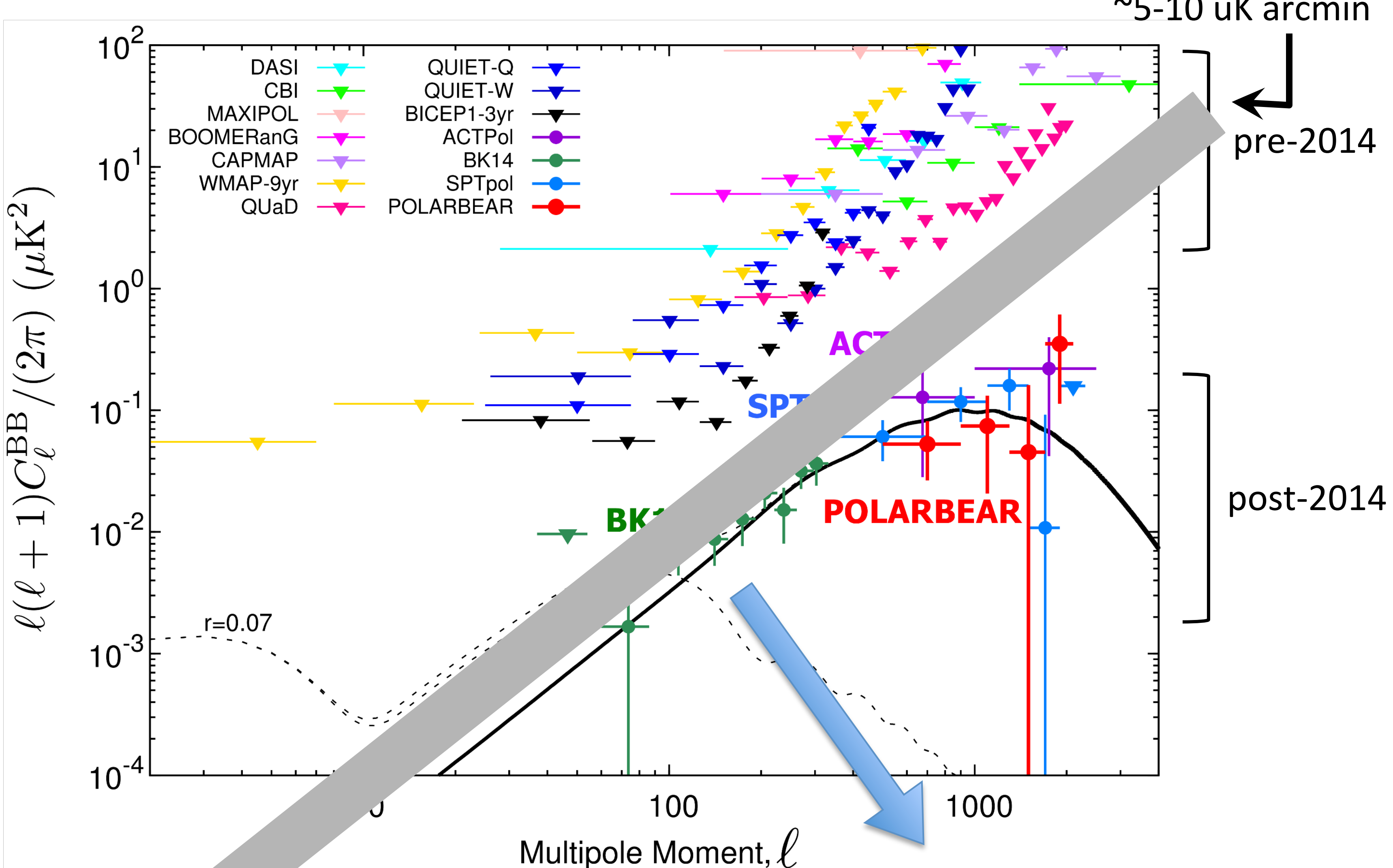




2014/15:
Angular power spectrum: ApJ 794, 171 (2014)
Deflection power spectrum: PRL 113, 021301 (2014)
Galaxy cross-correlation: PRL 112, 131302 (2014)
Constraints on cosmic birefringence and primordial magnetic fields: PRD 92, 123509, (2015);

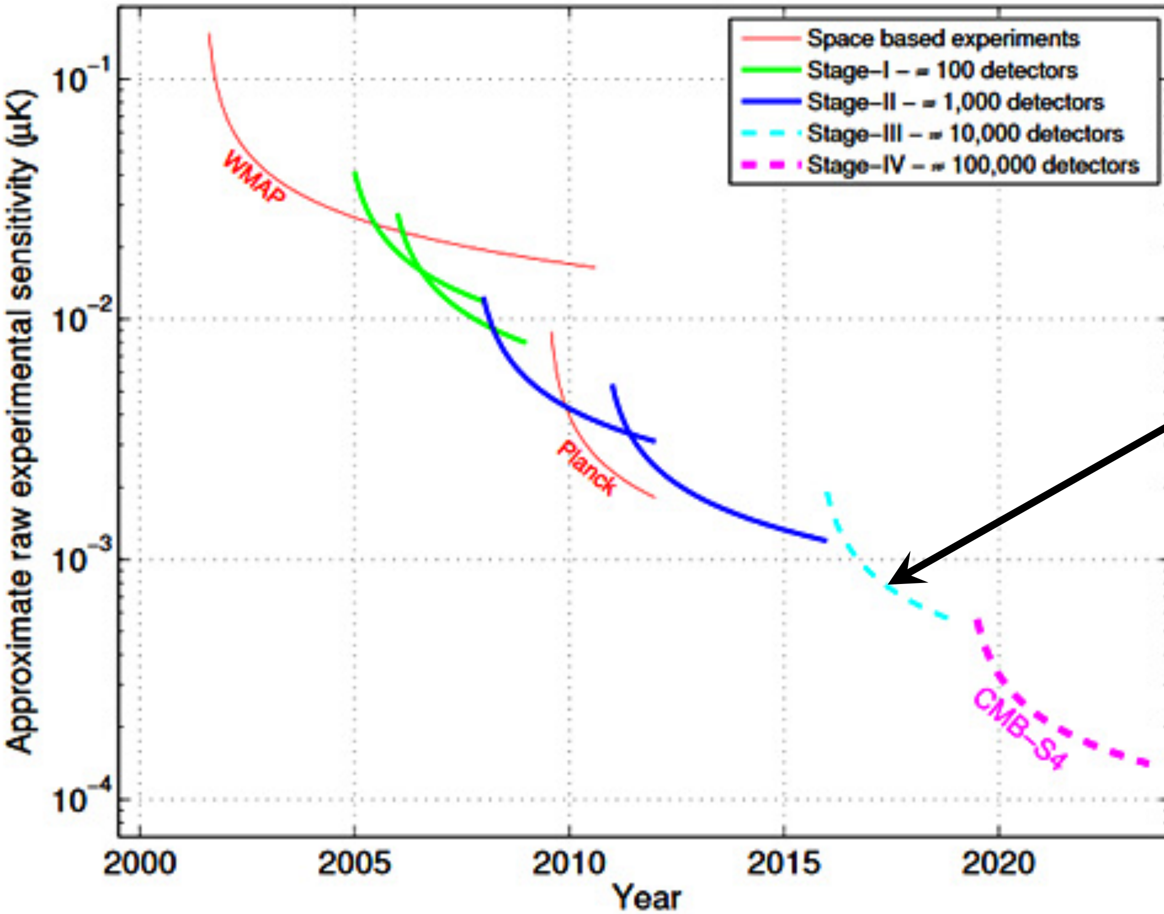
2017:
Updated on angular power spectrum: ApJ to be published, (2017)

Current (post-Stage II) status:



r < 0.07 95% c.l.

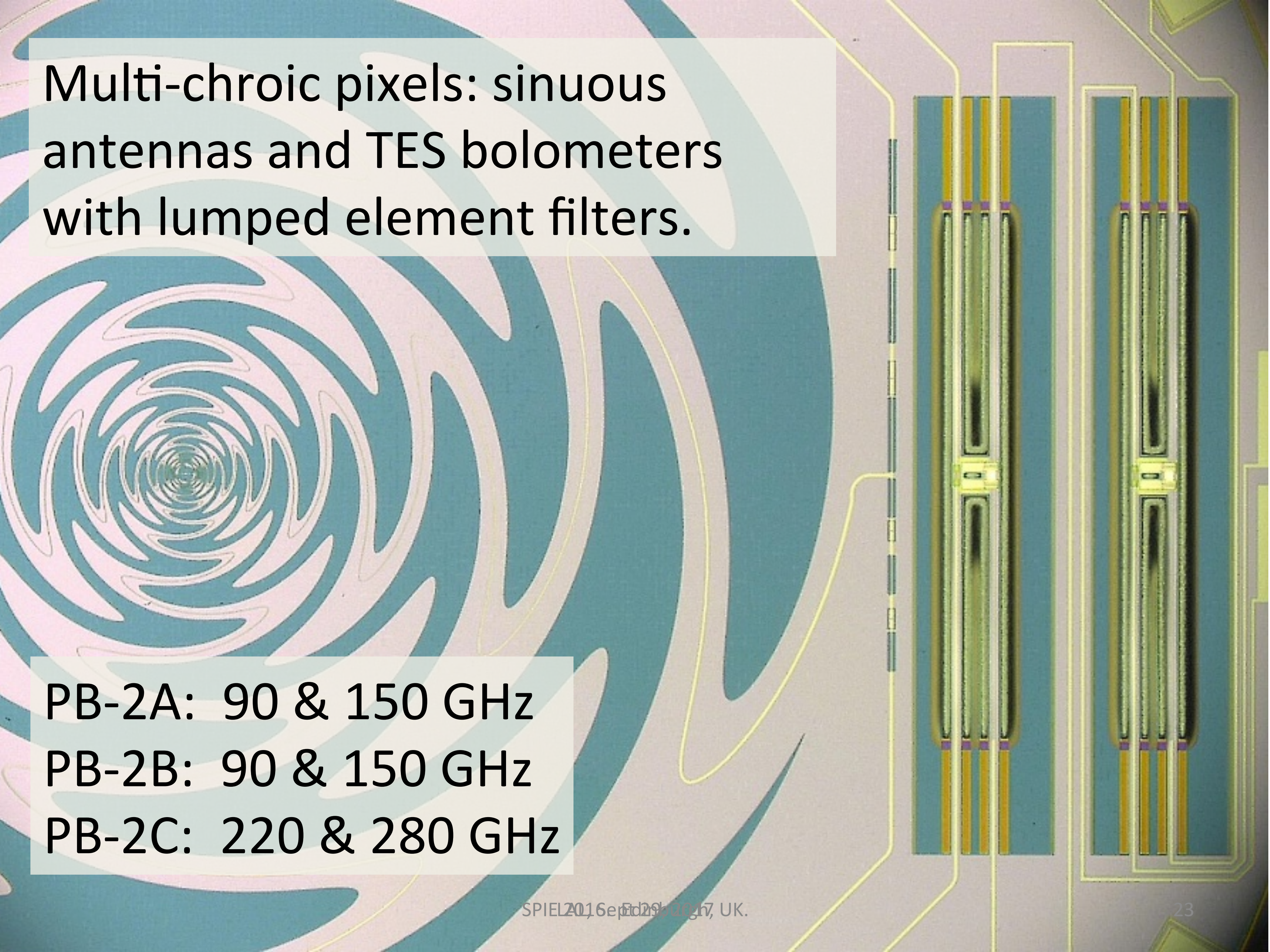
CMB Stage -III



PB/SA
SPT3G
BICEP Array
advACT
CLASS

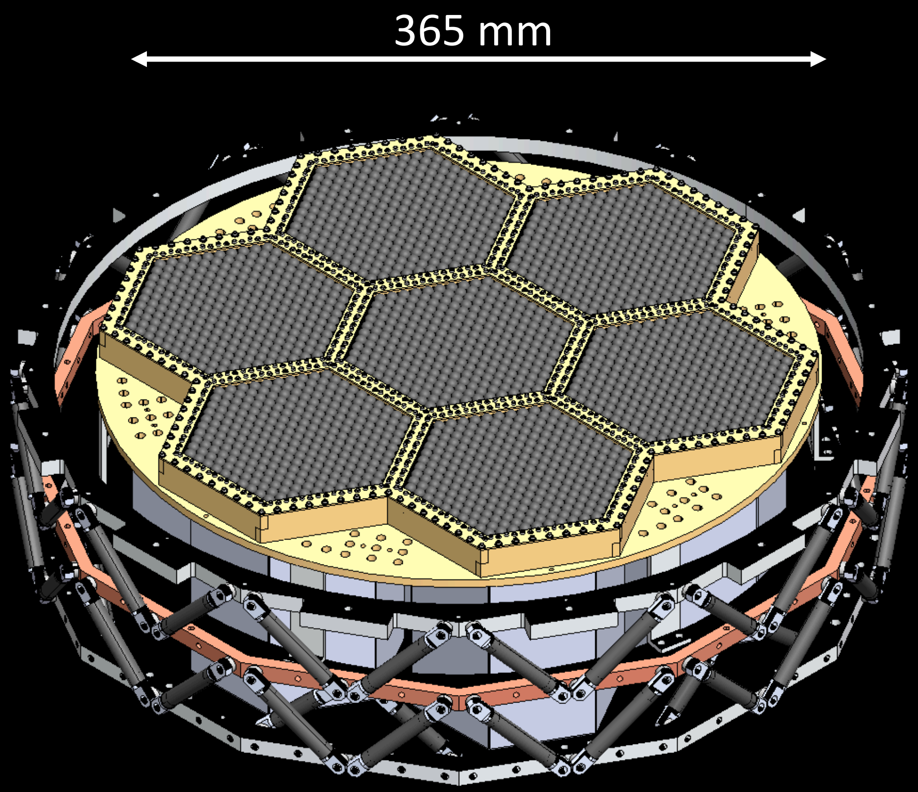
How to increase the mapping speed: Simons Array

Multi-chroic pixels: sinuous antennas and TES bolometers with lumped element filters.

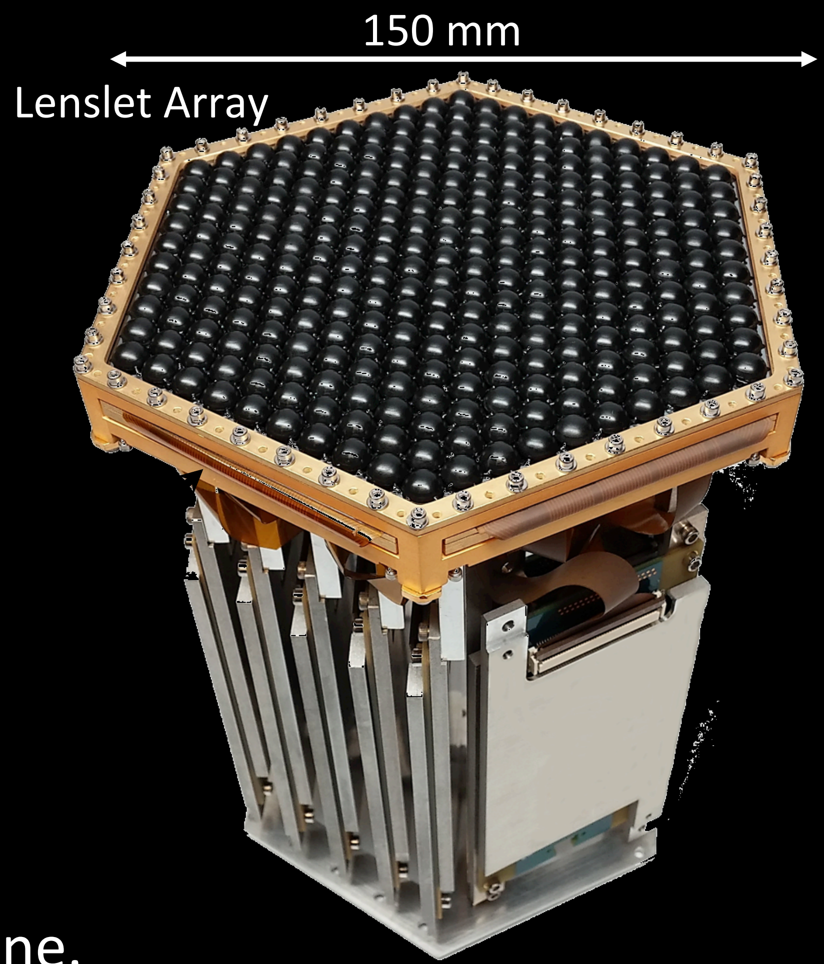


PB-2A: 90 & 150 GHz
PB-2B: 90 & 150 GHz
PB-2C: 220 & 280 GHz

Multi-chroic Focal Planes



POLARBEAR-2 Focal Plane CAD



7 Detector modules in each focal plane.

Detector module: Lenslet Array, Detector Array, Readout electronics.

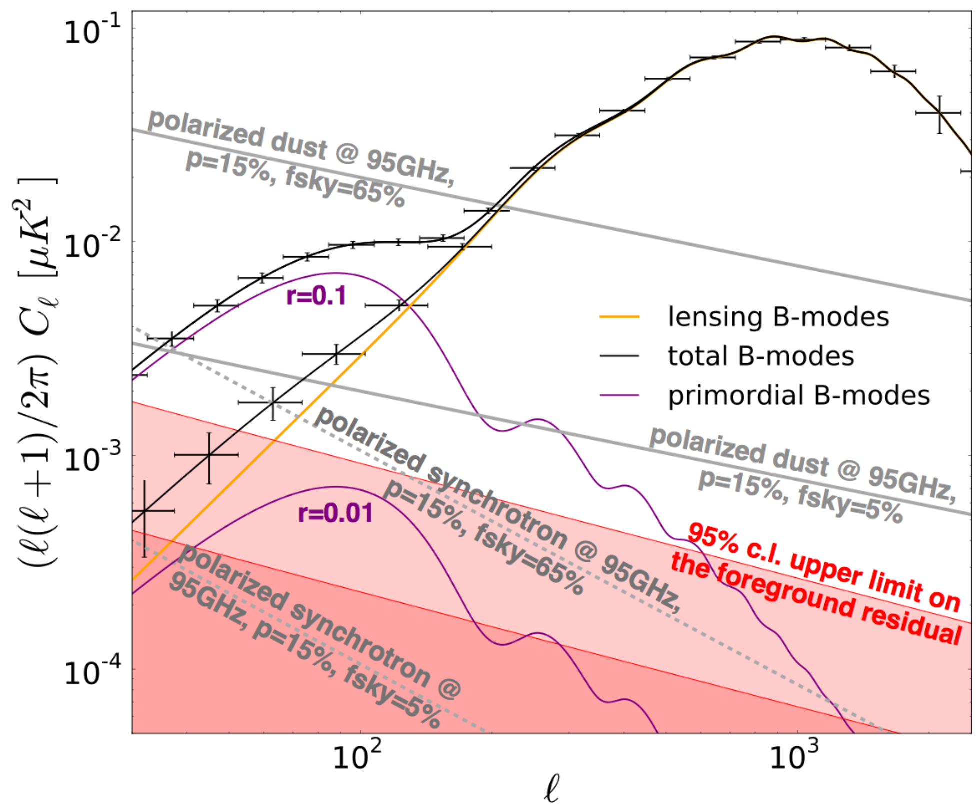
7,588 detectors per focal plane. 22,764 detectors full Simons Array.

Simons Array: Projected sensitivity

Foreground rejection with multi-frequency Simons Array data

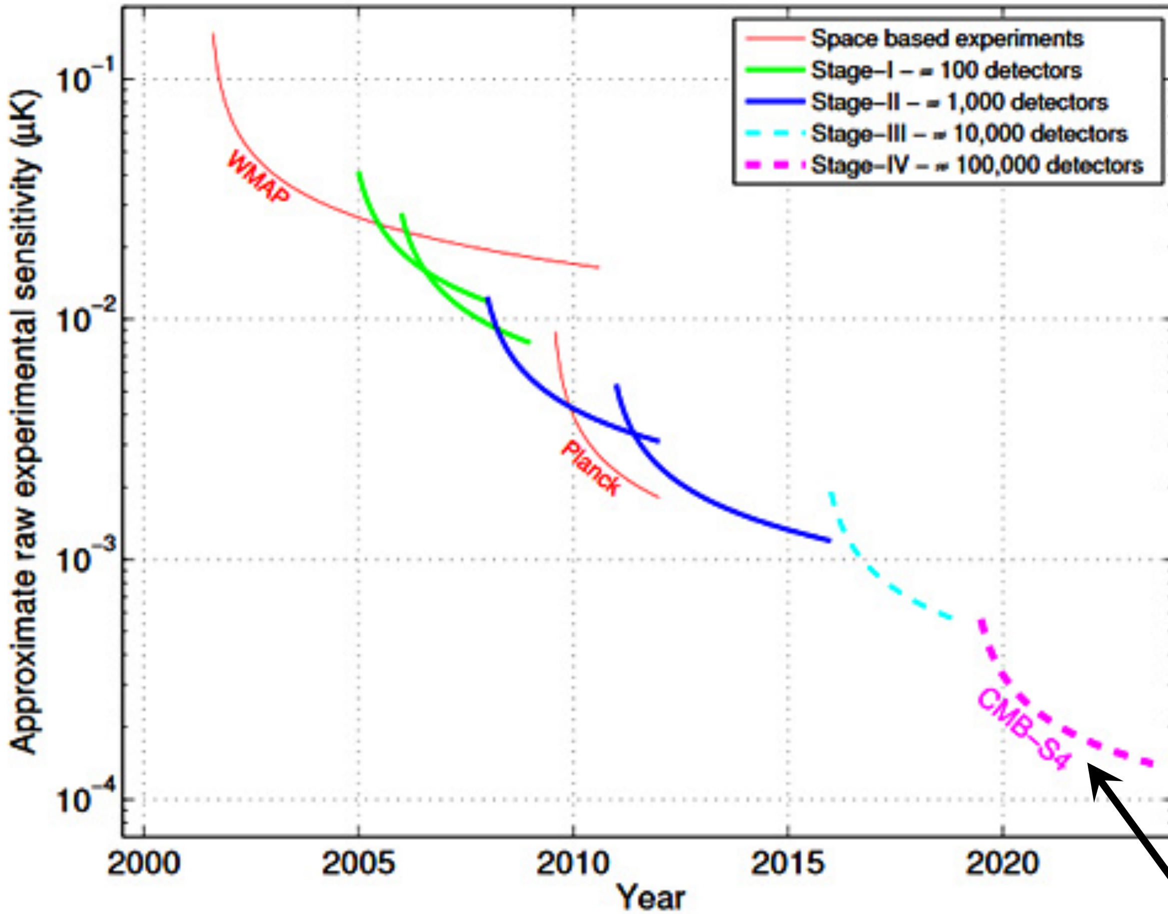
$\sigma(\boldsymbol{\Sigma m_\nu})$ = 40 meV
w/ DESI BAO,
including foreground contamination

$\sigma(\boldsymbol{r} = 0.1)$ = 0.006



Residual computation method:
Errard, Stivoli, Stompor. 2011, Phys. Rev. D 84, 063005
Stompor, Errard, Poletti 2016, Phys.Rev.D 94, 083526

CMB Stage -IV



the « ultimate » ground experiment

Long term goal: Stage-IV

ULTIMATE GROUND-BASED EXPERIMENT:

- Shallow (high resolution) maps of big parts of the sky
- Deep (low resolution) maps of selected patches

  ➔ $\sigma(r) \sim 1 \times 10^{-3}$ (for r=0)

- Multi-frequency (limited by the Earth's atmosphere);
- Broad science goals (lensing, clusters, inflation, etc)

➔ 10^5 – 5×10^5 detectors;

➔ Multiple telescopes (apertures ?!)

➔ Multiple sites (?!)

➔ Bigger focal planes

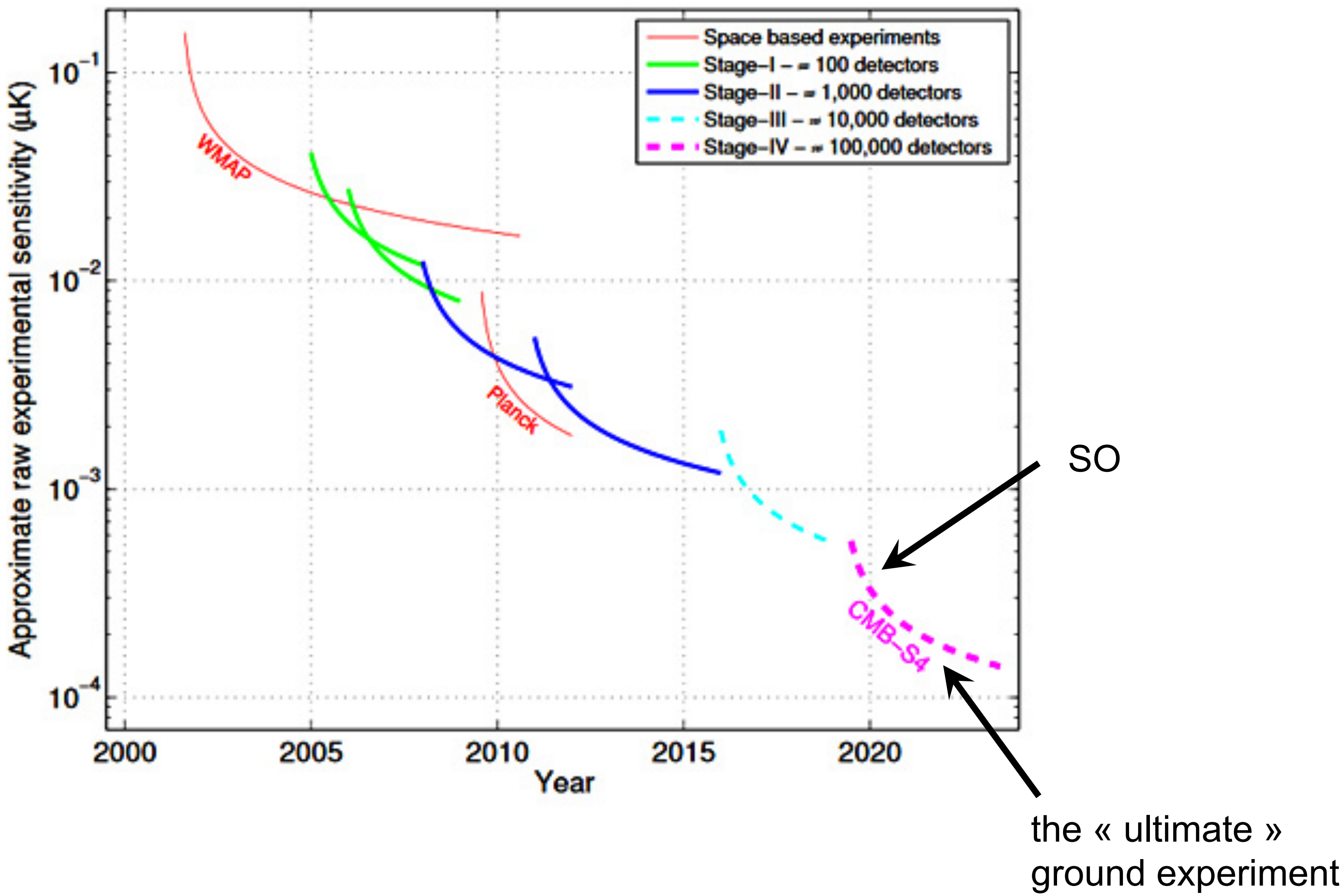
➔ Operations: ~2025+

More a concept at this time than a project yet.

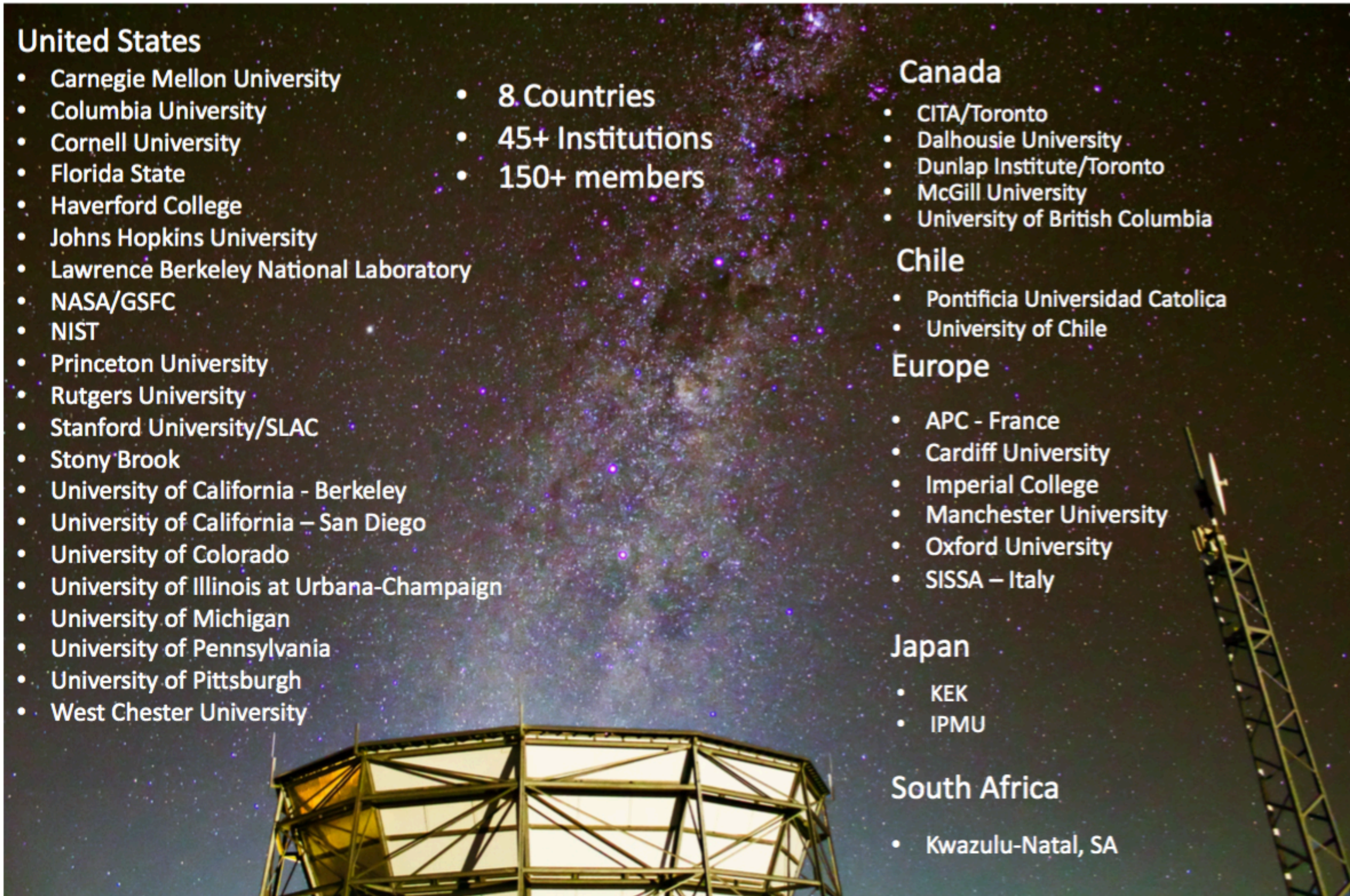
Simons Observatory - a CMB-Stage IV pathfinder

- US-led, funded by Simons Foundation+ project
  ➔ spokesperson: M. Devlin (UPenn)
- Combines PB/SA and ACTpol teams;
- To deploy multiple telescopes on the Atacama Desert within the next 5 years;
- Multi-frequency and multi-resolution.
- Stage-IV like science goals but with lower sensitivity. (few sigma on r = 0.01)
- Will test technology and build infrastructure for a fully-fledged Stage IV effort at Atacama.

CMB Stage -IV


Space based experiments
Stage–I – ≈ 100 detectors
Stage–II – ≈ 1,000 detectors
Stage–III – ≈ 10,000 detectors
Stage–IV – ≈ 100,000 detectors
WMAP
Planck
CMB–S4
Approximate raw experimental sensitivity (μK)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
2000
2005
2010
2015
2020
Year
SO
the « ultimate » ground experiment

SO collaborations

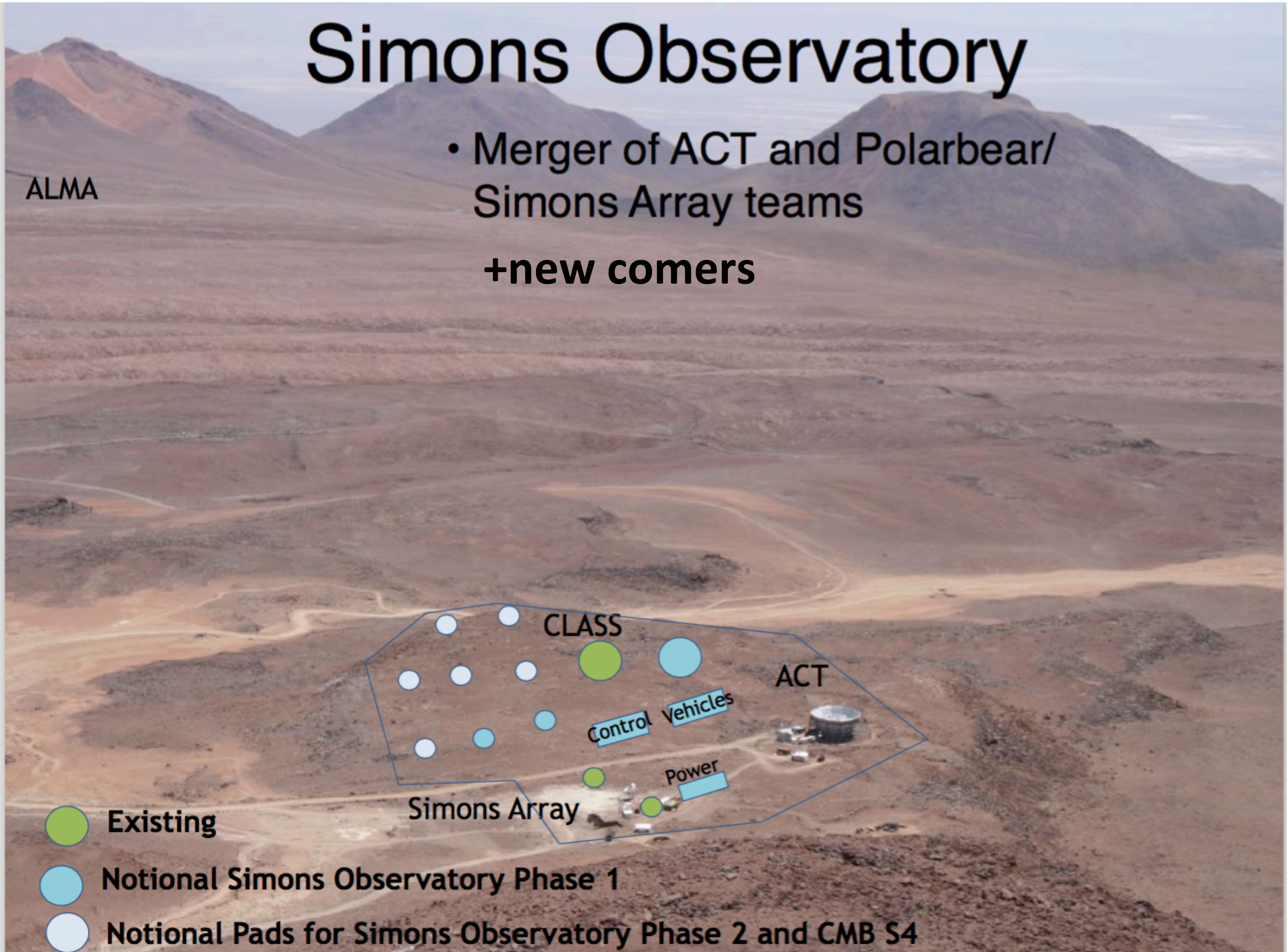


Atacama desert

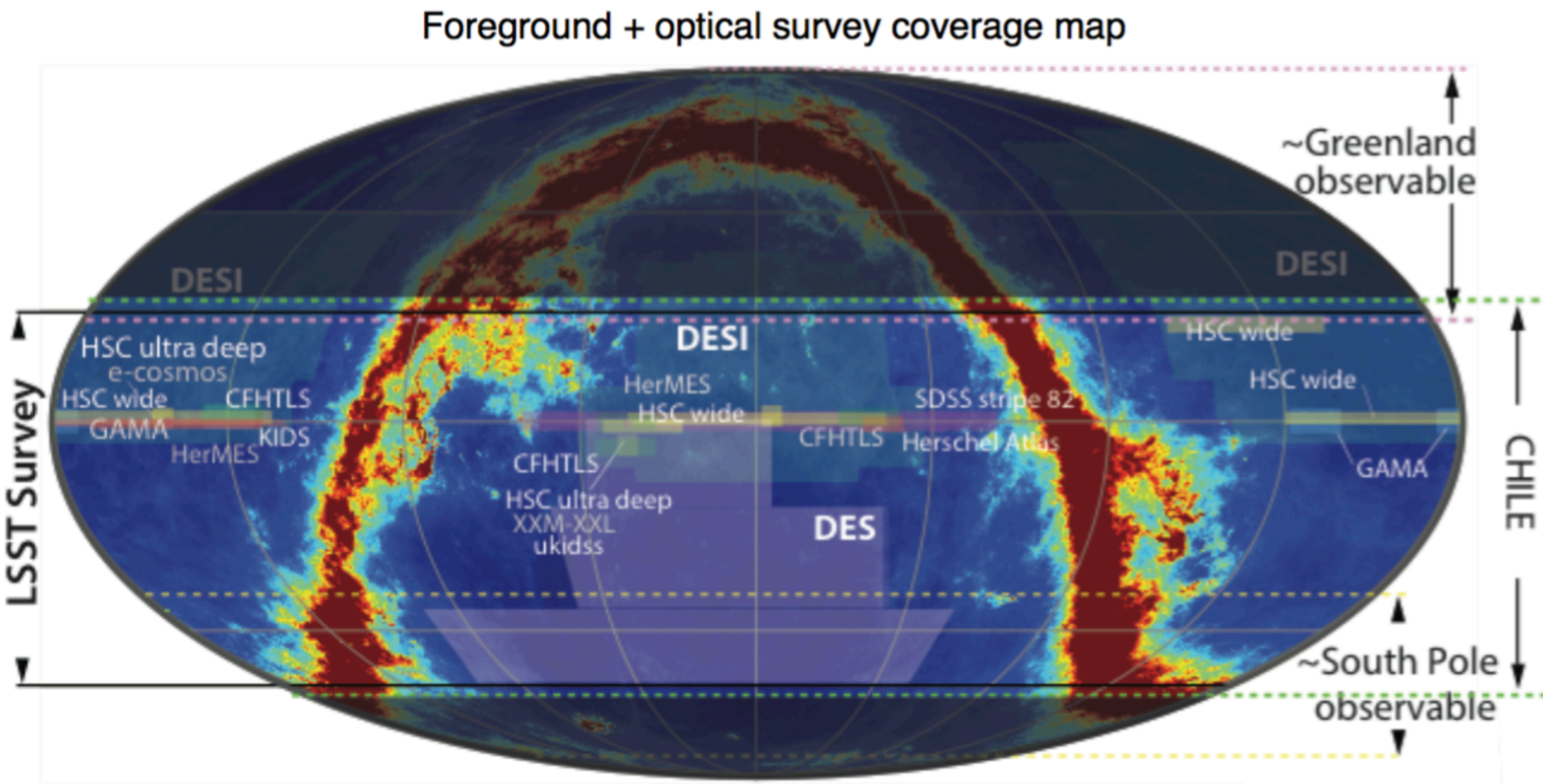
Simons Observatory

- Merger of ACT and Polarbear/ Simons Array teams

+new comers



Sky observability



Large Surveys:
(1) Access to Large Low Foreground Regions
(2) Overlap with optical surveys
(3) Overlap with ALMA

SO tentative timeline

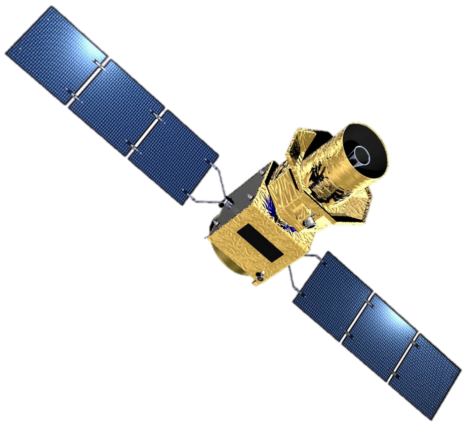
- 2016-17: Planning and technology development
- 2016-18: Logistical upgrades to the site infrastructure
- By end of 2020: Construction and installation of telescopes
- By end of 2020: Production of new CMB-S4-type receivers with partially filled focal planes
- 2021 and beyond: Observing!

A thought …

- Stage-II data sets where ≅ 10 x bigger than Planck's (at 20th of its budget and 10th of its human resources) …
- Stage-III data sets ≅ 10-30 x (Stage-II data sets)
- Stage-IV data sets ≅ 10-20 x (Stage-III data sets)
- Craving a challenge ?!

And now the space …

- LiteBIRD
  - Focused mission optimized for inflation search
    - large angular scales;
    - High sensitivity;
    - Systematic, astrophysical/ instrumental effects control.
  - 30’ resolution @ 150 GHz
  - Broad frequency coverage: 40GHz - 400 GHz
  - Fast polarization modulation (HWP)
  - Advanced scanning strategy

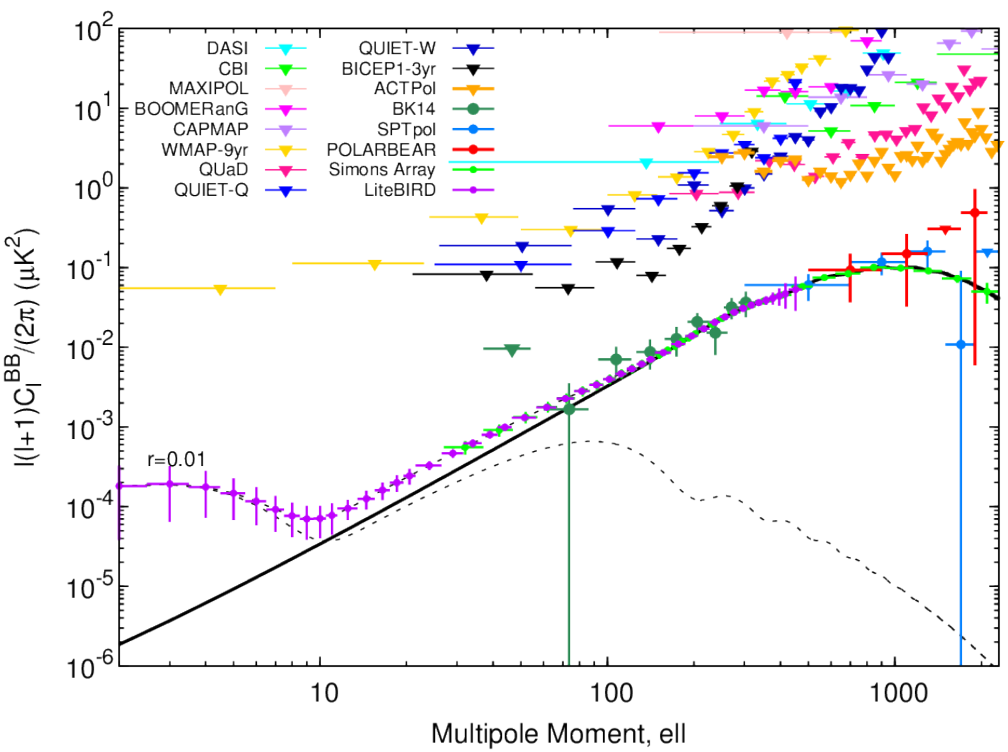


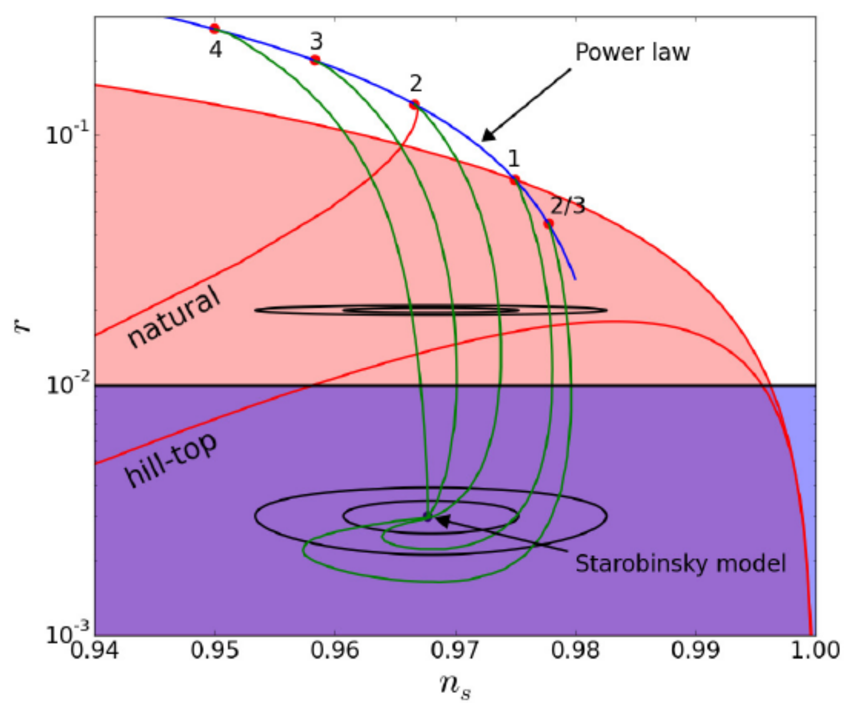
  - JAXA-led (PI: M. Hazumi (KEK)) phase A1 study on-going to be completed in Aug 2018
  - NASA MO: Phase A completed
  - Canada, Europe …. ?!

  - To be launched in 2026/27

Full success defined as

- $\sigma(r) < 1 \times 10^{-3}$ (for r=0)
- All sky survey (for $2 \le \ell \le 200$)

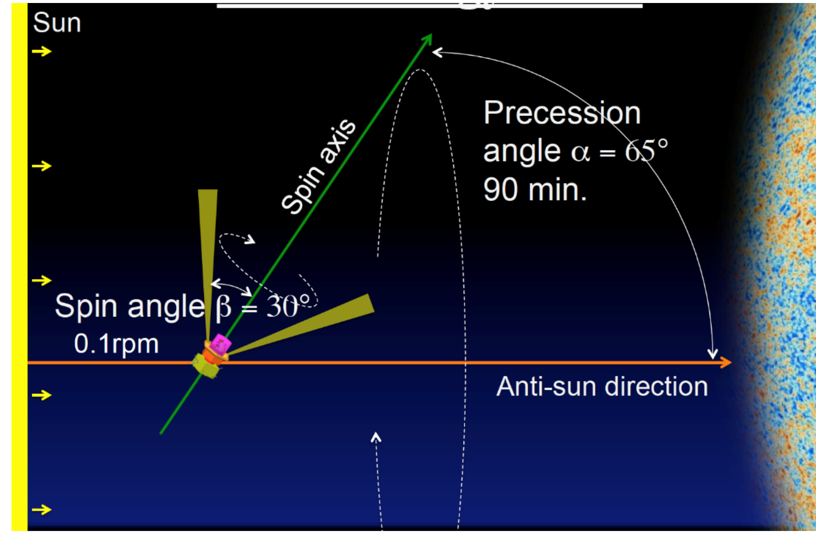


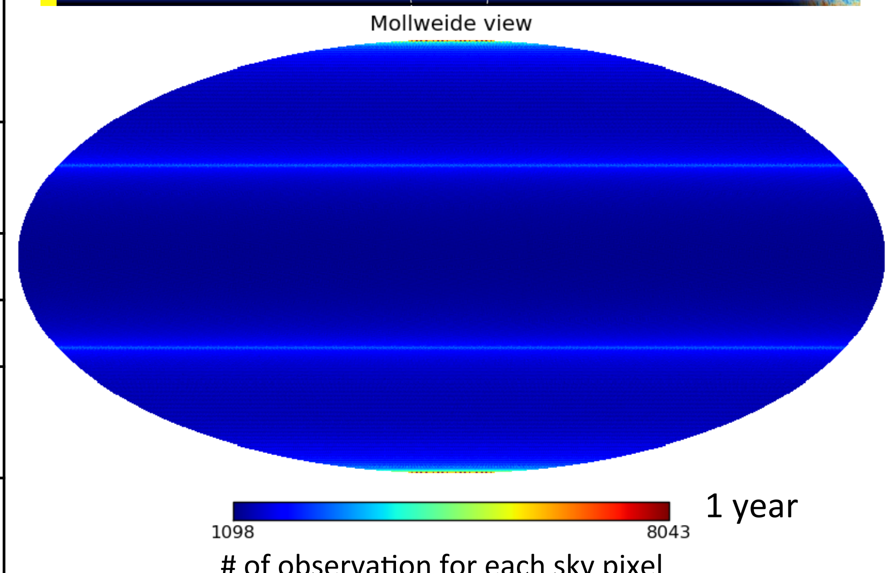


LiteBIRD Phase A1 baseline specifications/operations

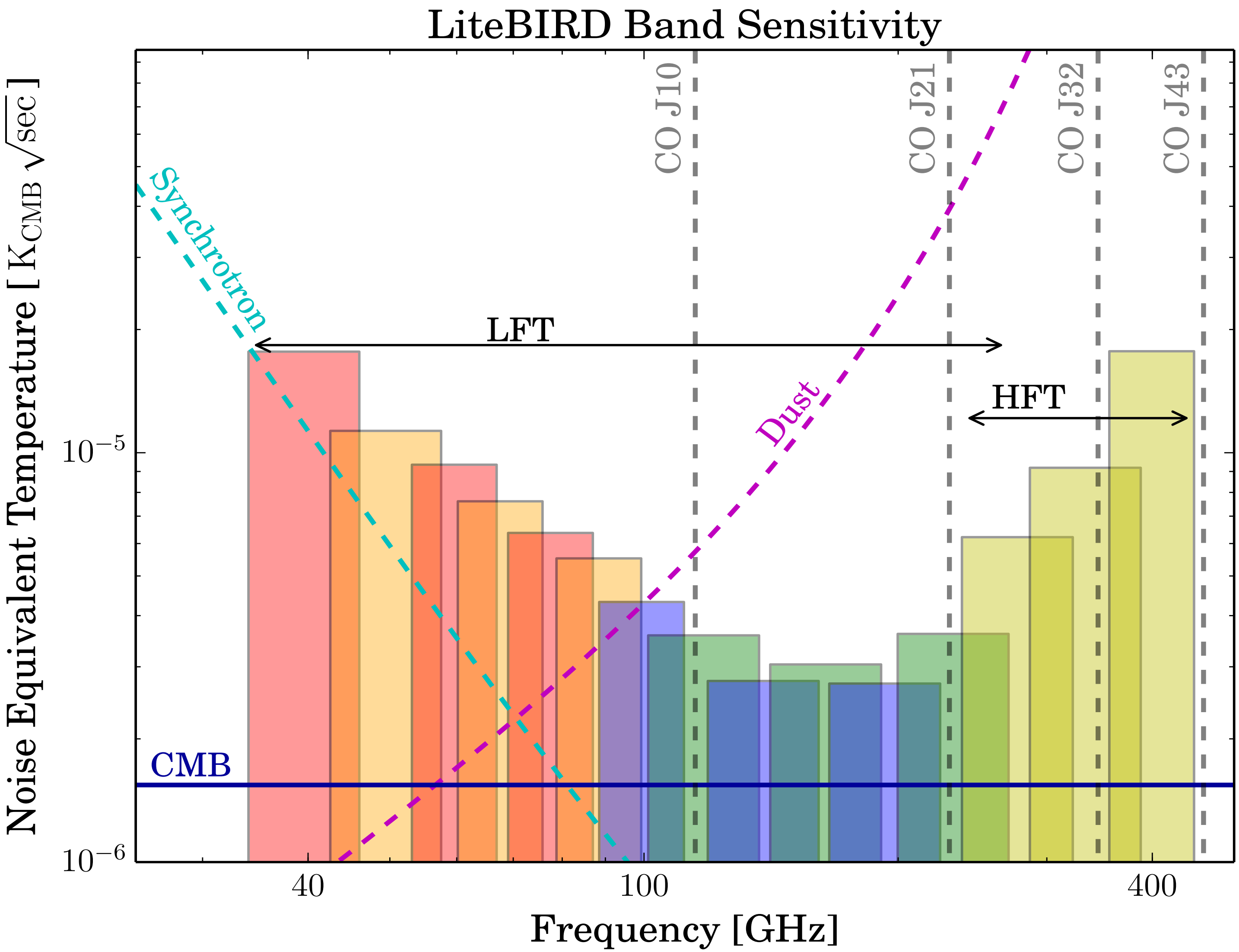
Main specifications (Phase-A baseline design)	
Item	**Specification**
Orbit	L2 halo orbit
Launch	In 2026-2027, JAXA H3 rocket
Observation (time)	All-sky CMB survey (3 years)
Mass / Power	2.2 t / 2.5 kW
Mission instruments	• Superconducting detector arrays • Continuously-rotating half-wave plate (HWP) • Crossed-Dragone mirrors (LFT) + small refractive telescope (HFT) • 0.1K cooling system (ST/JT/ADR)
Frequencies	34 – 448 GHz (15 bands, 40/402 GHz lowest/highest band center)
Data size	4 GB/day
Sensitivity	2.5 microKarcmin (3 years)
Angular resolution	0.5deg @ 100 GHz (FWHM)
Development Model	DM/EM/FM

All-sky surveys in L2 halo orbit





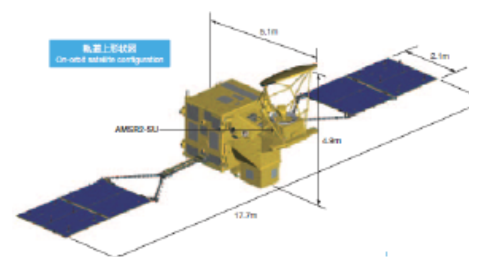
LiteBIRD: Measurements with 15 Overlapping Bands for Powerful Foreground Control

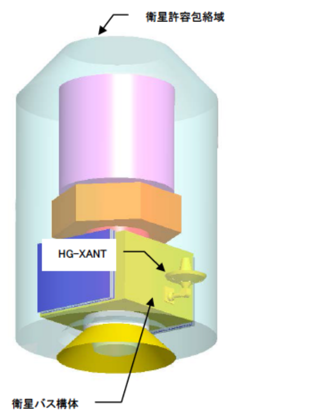


LiteBIRD Phase-A baseline design

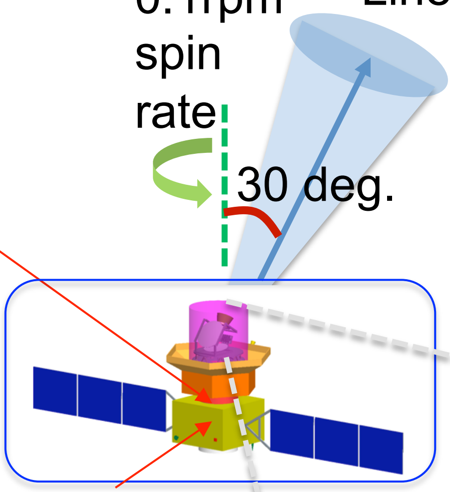
- Japan: LFT, HWP, precoolers, spacecraft, launch, operation
- US: Focal-plane units, Sub-K cooler, cold readout
- Canada: warm readout (DfMUX)

Slip-ring technology used for Shizuku





(Fit in H2 envelope)
Now H3 is assumed, with bigger envelope

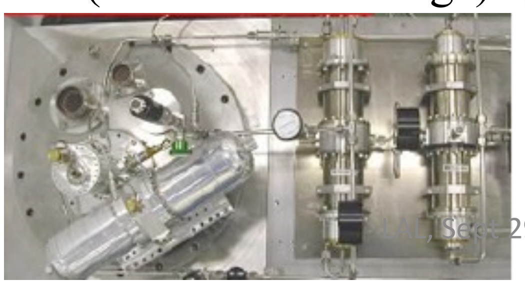


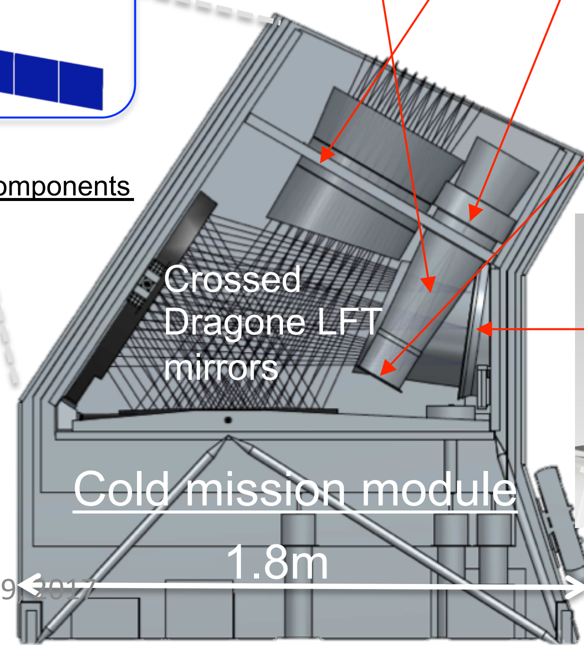
Bus module
(based on high TRL components

Small refractive HFT system

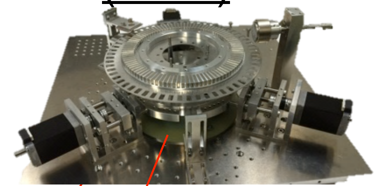
Cryogenics

■ JT/ST and ADR (ASTRO-H heritage)

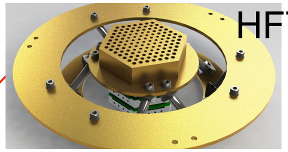


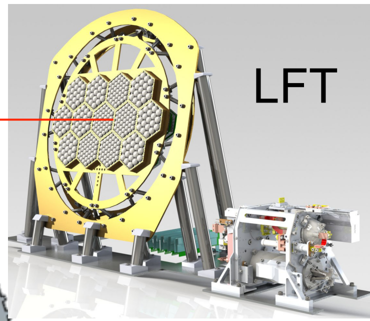


Continuously-rotating half wave plate (HWP)



Multi-chroic TES focal plane detectors





LiteBIRD summary

- LiteBIRD aims at doing what has to be done from space
  ➔cost-effective;

- LiteBIRD alone has a potential to revolutionize our understanding of cosmology and physics.
  Though 'focused' on B-modes will also:
  - Constraint τ;
  - Set constraints on non-Gaussianity on large scales;
  - Set constraints on other sources of B-modes in the Universe;
  - Provide multi-frequency maps of the full sky.

- It is also a perfect match to ground-based efforts promising excellent, extra science from joint analysis

- In Europe: the interest is growing and the status quo is evolving very quickly … so stay tuned.

Summary

- CMB has been a key in establishing the current standard model of cosmology
- It continues to hold significant potential for the future: stand alone or combined with other surveys
- B-mode polarization provide a window onto the physics at extreme energies and the very first moments of the Universe
- B-mode observations are coming off age with new exciting efforts on the ground and in space are developed and/or planned …

- Expect new significant results within the next decade …