Experimental Landscape

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- A Bit of History
- Satellites
- Balloons
- Ground-Based

Ground-Based Experiments

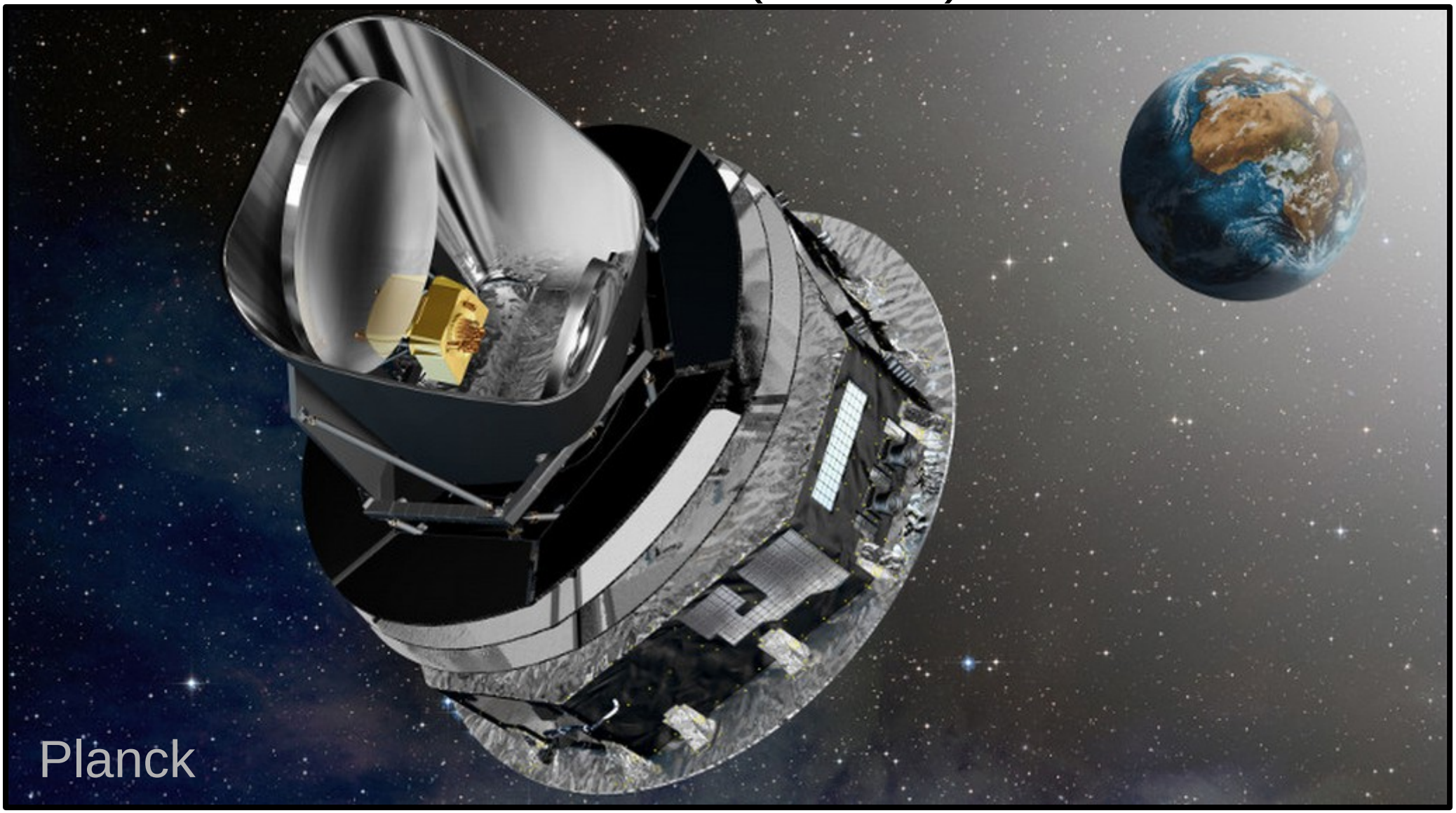
There have been many:
ABS, ACBAR, ACME, ACT, AMI, AMiBA, APEX, ATCA, BEAST, BICEP[2|3]/Keck, BIMA, CAPMAP, CAT, CBI, CLASS, COBRA, COSMOSOMAS, DASI, MAT, MUSTANG, OVRO, Penzias & Wilson, etc., PIQUE, Polatron, Polarbear, Python, QUaD, QUBIC, QUIET, QUIJOTE, Saskatoon, SP94, SPT, SuZIE, SZA, Tenerife, VSA, White Dish & more!

Balloons

There have been a number: 19 GHz Survey, Archeops, ARGO, ARCADE, BOOMERanG, EBEX, FIRS, MAX, MAXIMA, MSAM, PIPER, QMAP, Spider, TopHat, &

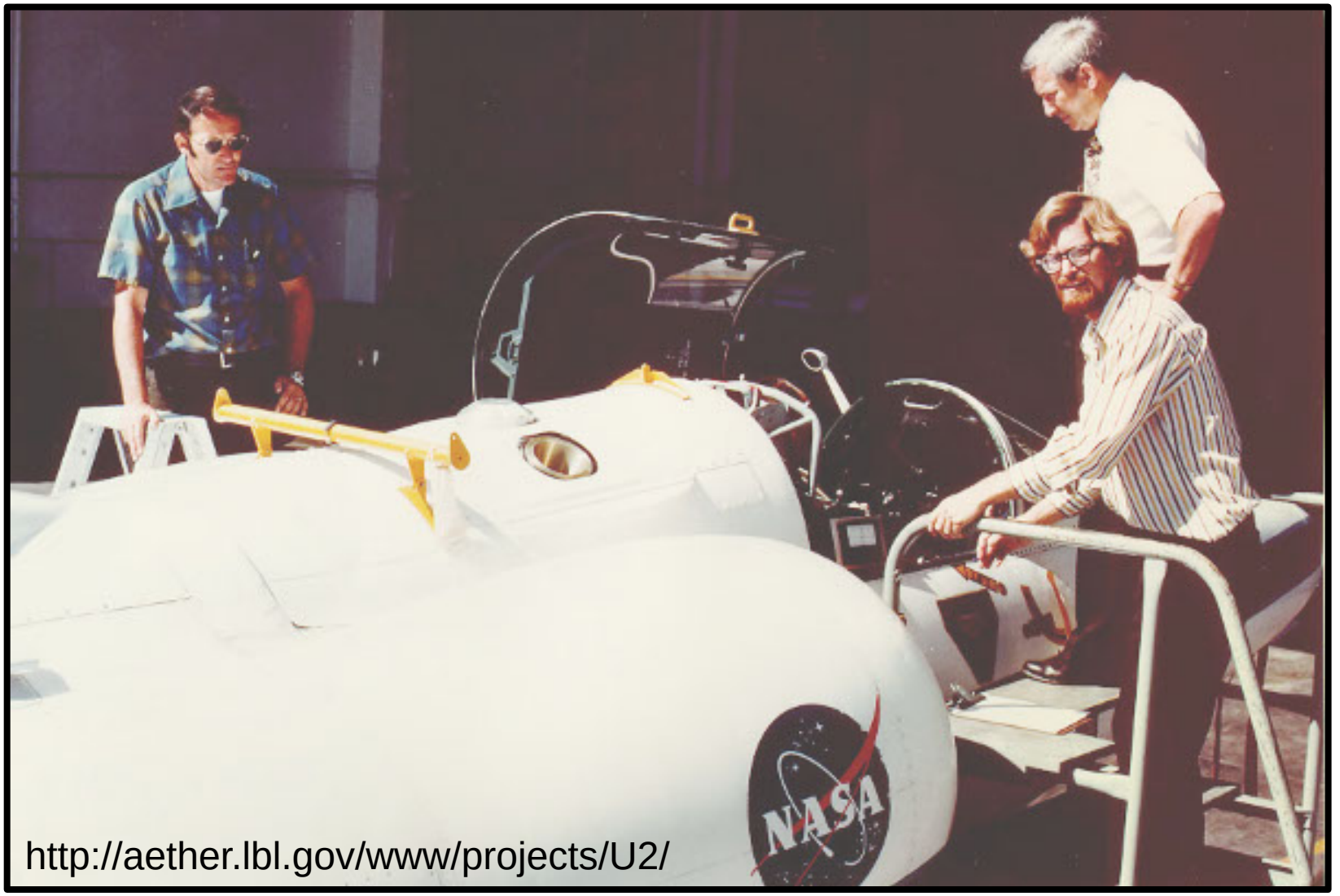
Satellites

There have been 4 (or 5?): Relikt, *COBE*, *WMAP*, *Planck* (+*IRTS*!)



Rockets & Airplanes

For example, COBRA, Berkeley-Nagoya Excess, U2 Anisotropy Measurements & others...



http://aether.lbl.gov/www/projects/U2/

It's difficult to get integration time on these platforms, so while they are still used in the infrared, they are no longer often used for the CMB.

LiteBIRD (from R. Stompor)

- 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

Radek Stompor LAL, Sept 29, 2017 http://litebird.jp/eng/ 36

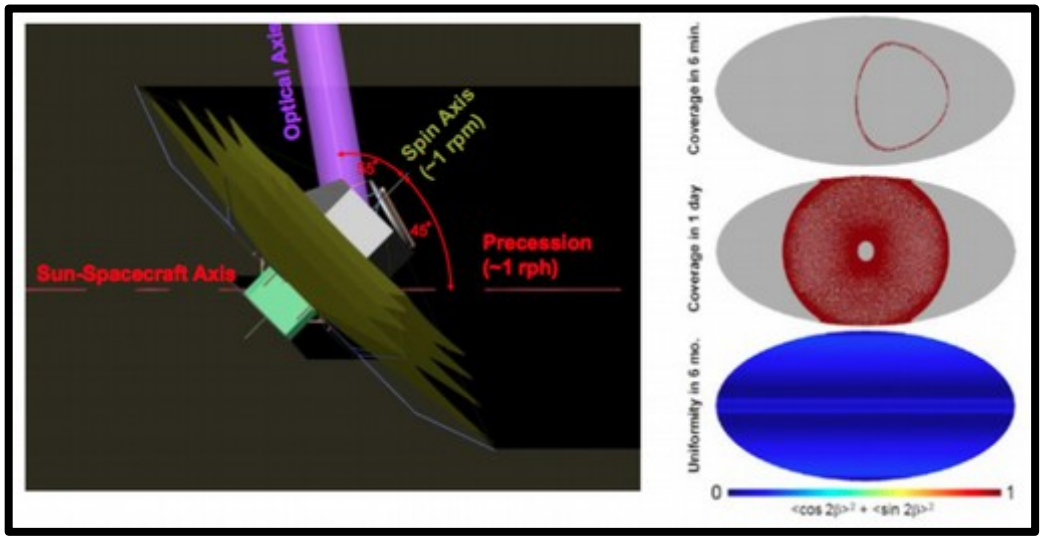
Other Satellite Possibilities

- US “CMB Probe”
  - Studying two possibilities
    - Imager
    - Spectrophotometer
  - Inputs being prepared for the Decadal Process

https://zzz.physics.umn.edu/ipsig/

- CORE-like
  - Discussions ongoing with India/ISRO & others
  - Could include imager AND low-angular-resolution spectrophotometer?

Search arXiv for “Exploring Cosmic Origins with CORE”



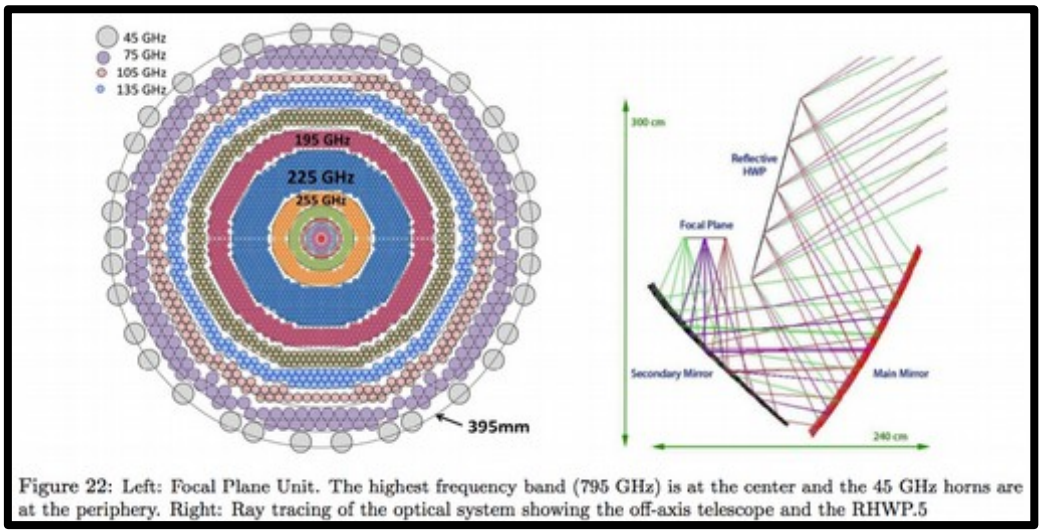
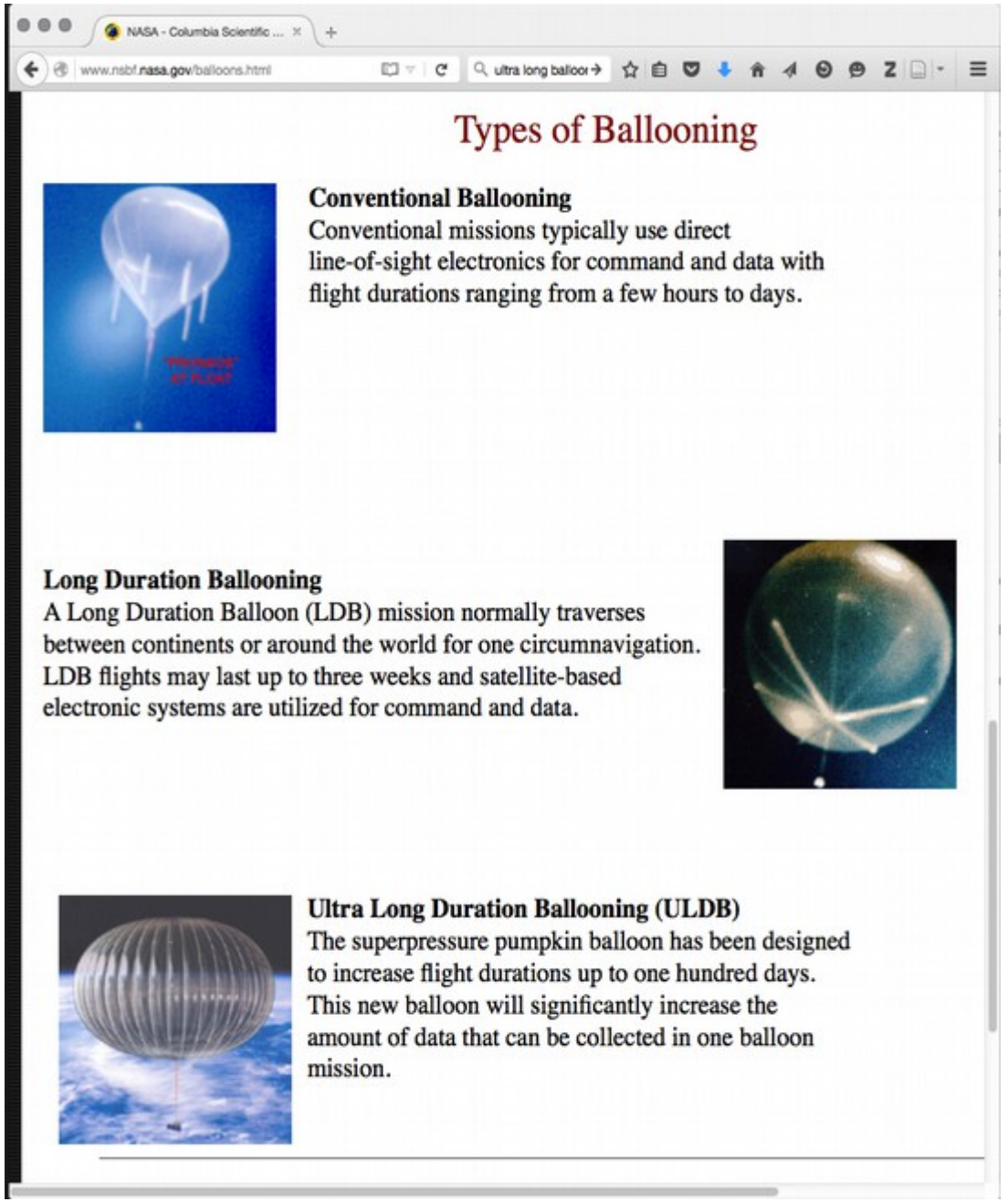


Figure 22: Left: Focal Plane Unit. The highest frequency band (795 GHz) is at the center and the 45 GHz horns are at the periphery. Right: Ray tracing of the optical system showing the off-axis telescope and the RHWP.5

Satellite Summary

- LiteBIRD is the most probable satellite possibility on the horizon, but we must remember that there is still a down-select soon
- It is large-angular-scale, in the “discovery spirit” of *COBE*/DMR, for example, but will need to be analyzed in concert with suborbital experiments
- Other, larger, more comprehensive, possibilities are being explored, but are probably longer term (~2030?)

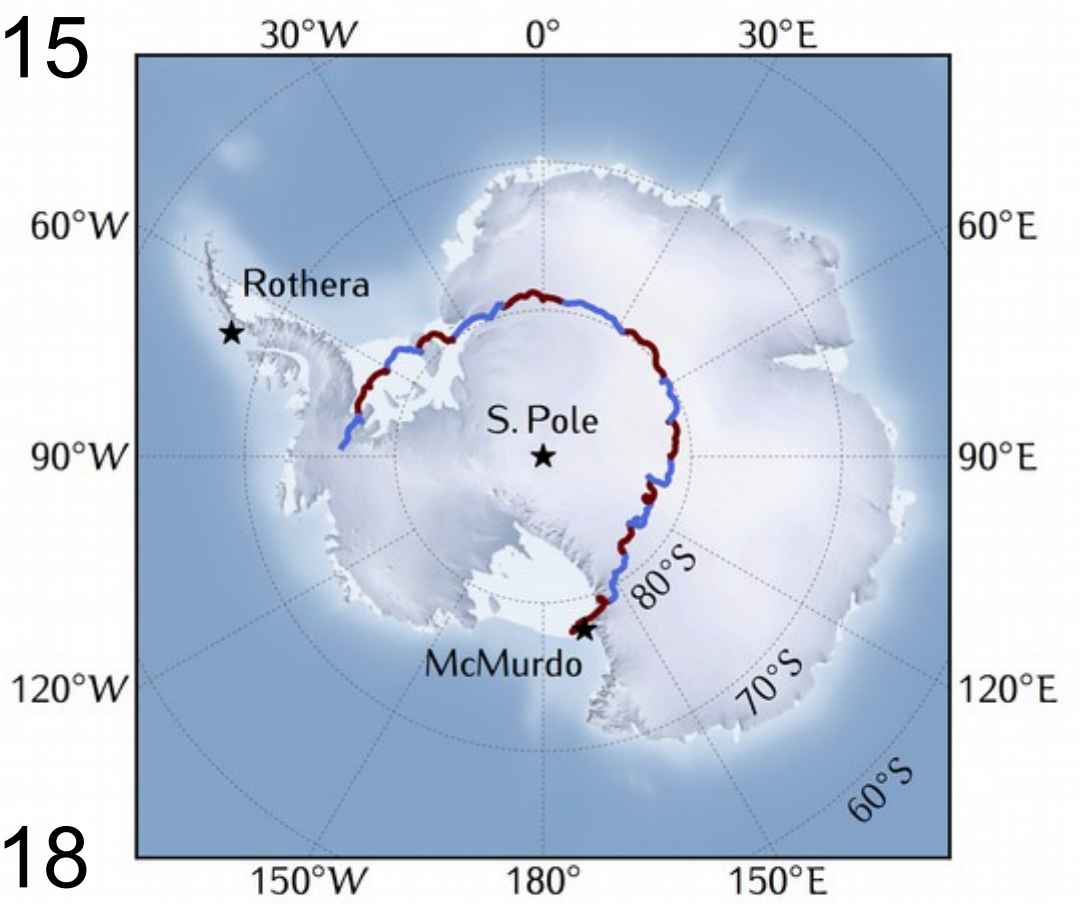
Balloons



- Conventional Ballooning
  - ~1 day
- Long Duration Ballooning
  - ~15 days
- Ultra-Long-Duration Ballooning
  - Also called “Super-Pressure Balloons”
  - 100 days?

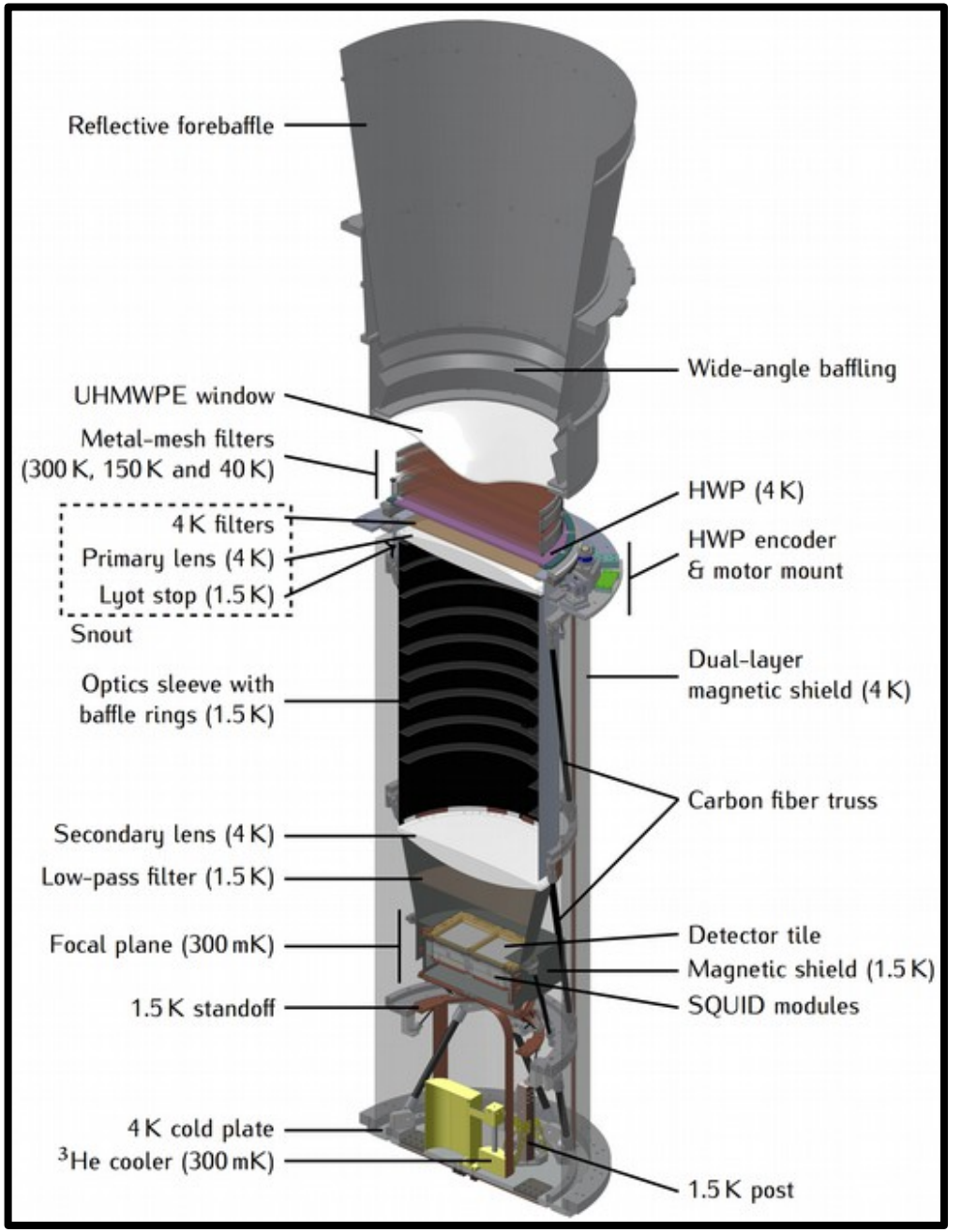
Spider Flight Summary (from S. Rahlin)

- Launched January 1, 2015
- 16 days at float
- 1.6 TB data
- Data recovered, February 2015
- Hardware recovered November 2015
- Next flight December 2018



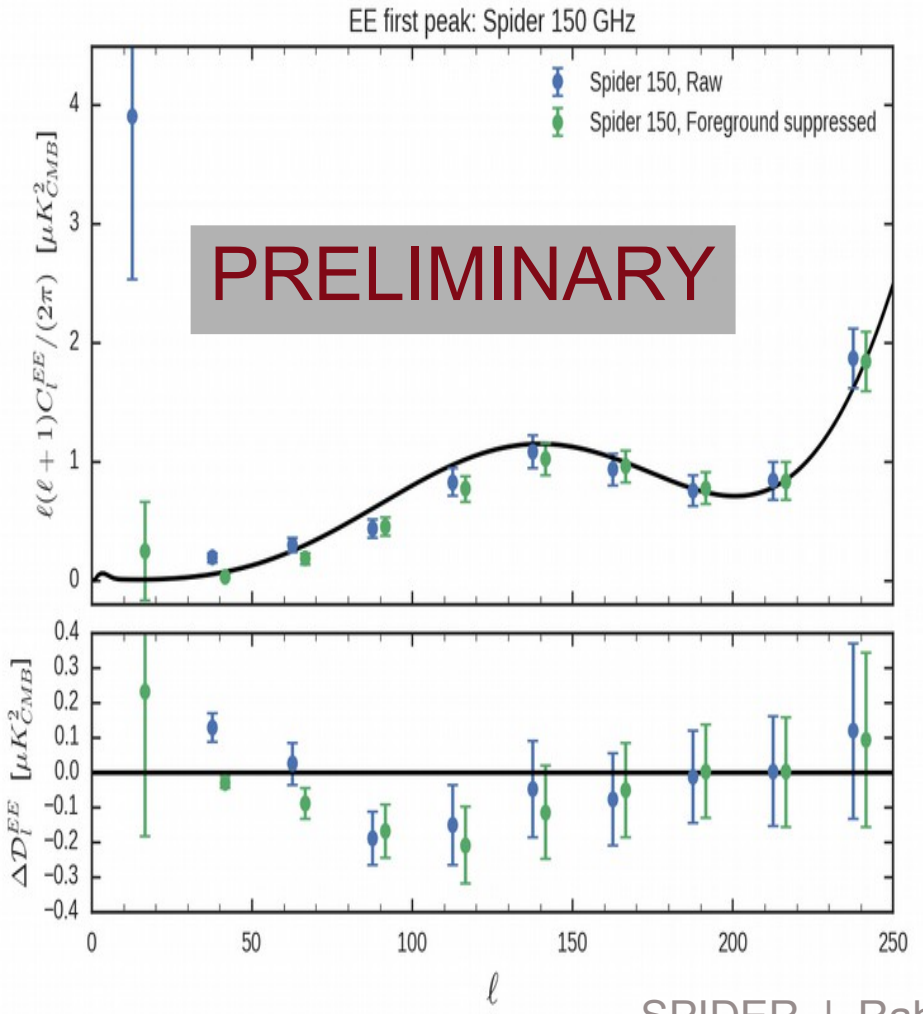
Spider Receiver (by S. Rahlin)

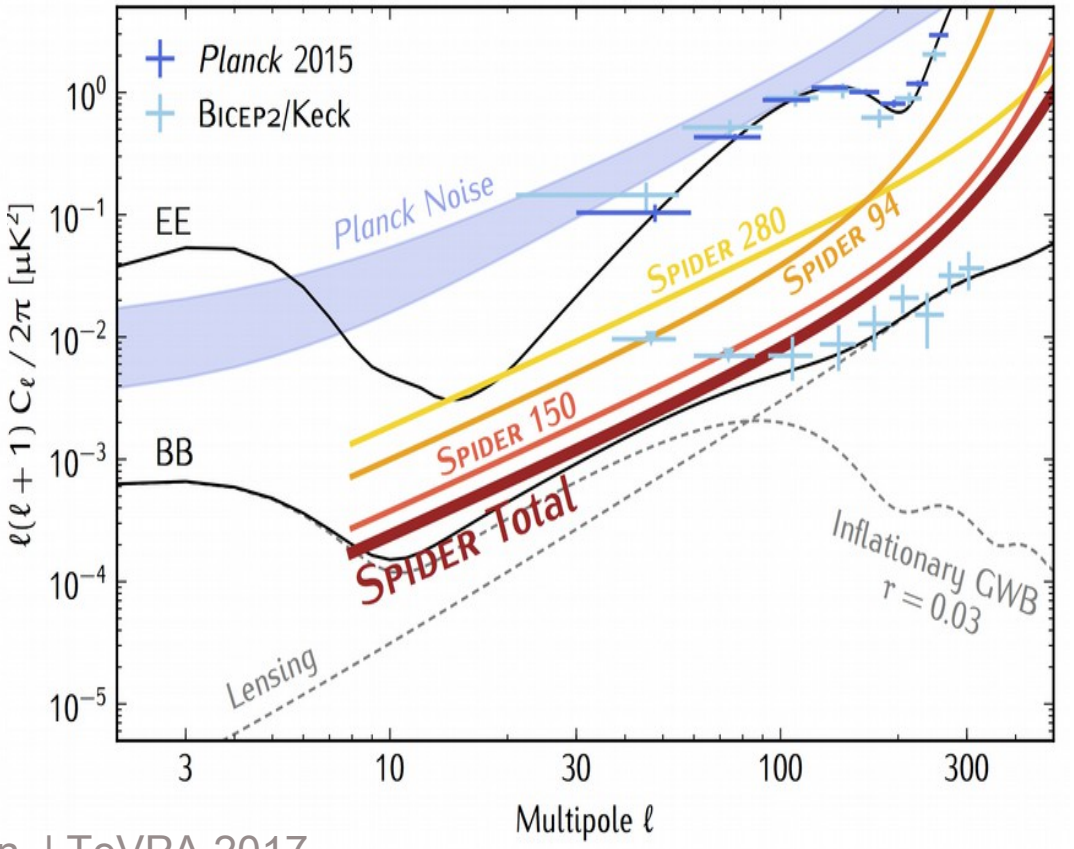
SPIDER | Rahlin | TeVPA 2017



SPIDER-2 Development (by S. Rahlin)

- Evidence of foregrounds at large angular scales
- 280 GHz receivers to characterize Galactic dust
- Expected sensitivity after two flights:





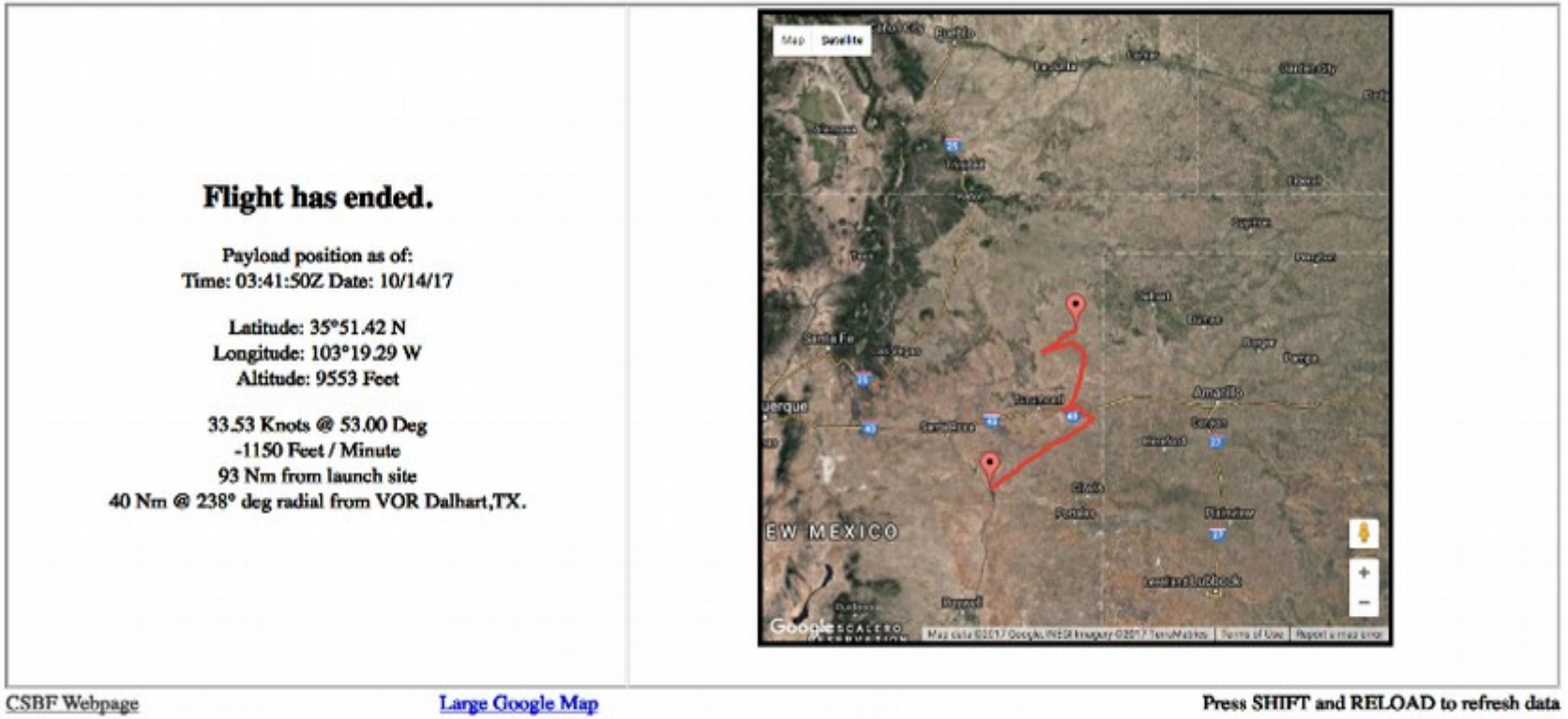
SPIDER | Rahlin | TeVPA 2017

PIPER (asd.gsfc.nasa.gov/piper/)

1st engineering flight was (finally) October 13

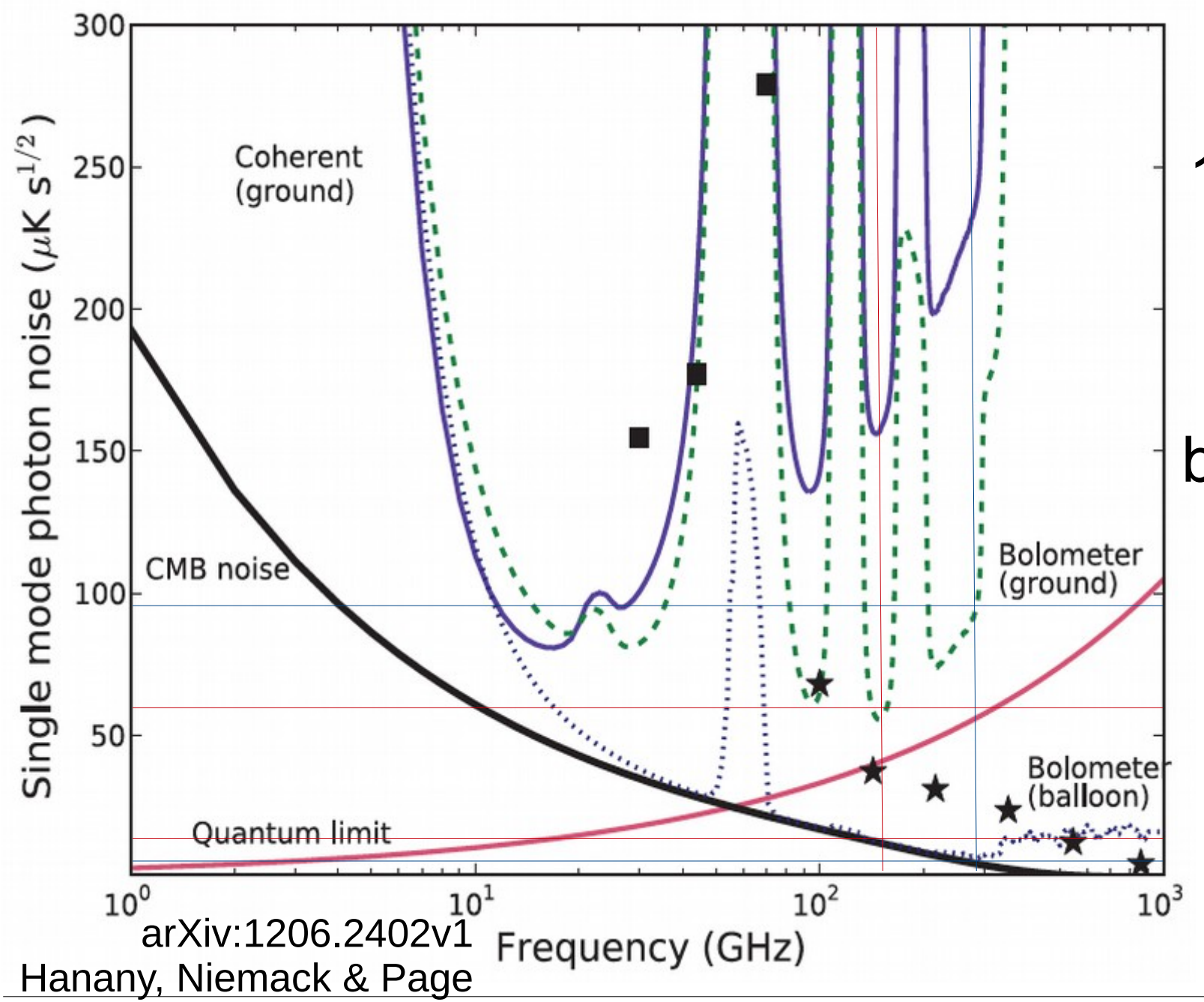
- Landing was a bit rough (http://stratocat.com.ar/news20171101-e.htm)

- 200, 270, 350, 600 GHz
- ~5000 NIST detectors
- Multiple single-night flights to cover multiple frequencies



GSFC (PI), Hopkins, NIST
UBC, Cardiff, Villanova, Ames, College Park MD, Stanford, Wyle STE, Michigan, ADNET

Photon Noise



arXiv:1206.2402v1
Hanany, Niemack & Page

Photon noise from 1-1000 GHz for 1 mode of radiation for a 20% bandwidth in frequency.

Ground/ Balloon (/det/time):
150: ~5
280: ~30

Photon Limited Ground vs. Balloon

- Satellites/Balloons have limited focal plane space
  - Assume all focal planes are about the same size.
- A balloon is just a short-lived satellite
  - Assume both are CMB limited
- Balloon Experiments are bigger & more complicated than before
  - We're having fewer flights
- Ground-based experiments are lasting longer and longer

- 150 GHz
  - Ground Noise ~5^2=25x Balloon
  - 2 Weeks of Balloon focal plane ~ 1 year of ground focal plane
  - With ~25 ground focal planes, balloons would need ~2 launches/month to compete
- 280 GHz
  - Ground noise 30^2~900x Balloon
  - 2 Weeks of Balloon focal plane ~35 yrs. of ground focal plane
  - With ~25 ground focal planes, balloons would need ~launch/2-3 years to compete

Balloon vs. Ground vs. Satellite

150 GHz	Satellite	Balloon	Ground-Based Focal Plane	25 Ground-Based Focal Planes
2 Weeks	***100***	100	500	100
1 Year	20	100	98	20
5 Years	8.8	63	44	8.8
10 Years	6.2	45	31	6.2

280 GHz	Satellite	Balloon	Ground-Based Focal Plane	25 Ground-Based Focal Planes
2 Weeks	***100***	100	3000	600
1 Year	20	100	590	118
5 Years	8.8	63	263	53
10 Years	6.2	45	186	37

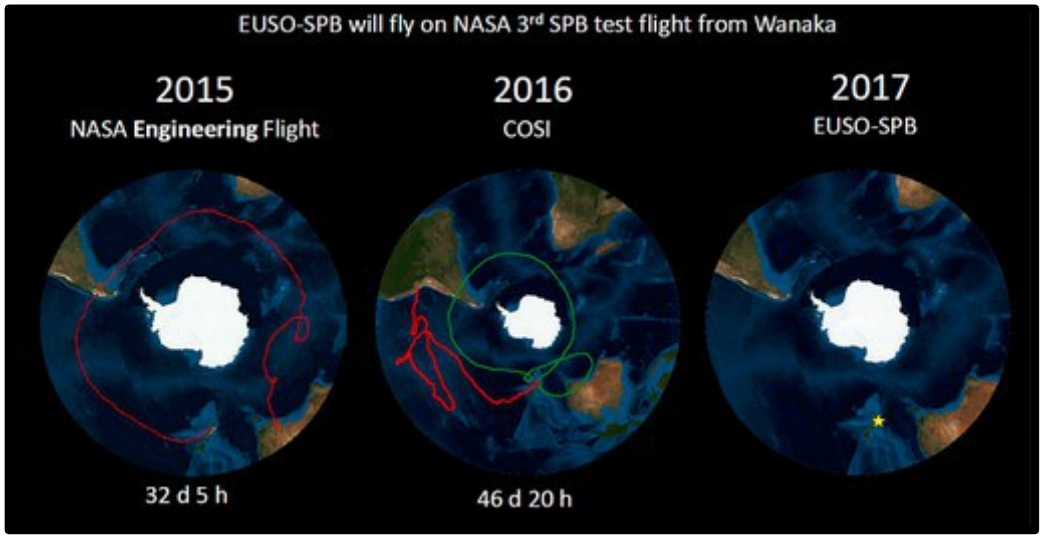
Super-Pressure Balloons (SPB~ULDB)

There have now been 3 SPB flights. The first two lasted about a month and a month-and-a-half.

These have weight and power constraints that are hard to meet (for the CMB)

EUSO-SPB (not CMB!) launched in April and got a couple of weeks of data before falling into the sea.

I'm told that they have been given support for another flight



http://astroserve.mines.edu/euso_spb/FlightPath.html

http://stratocat.com.ar/spb17_map_final.jpg

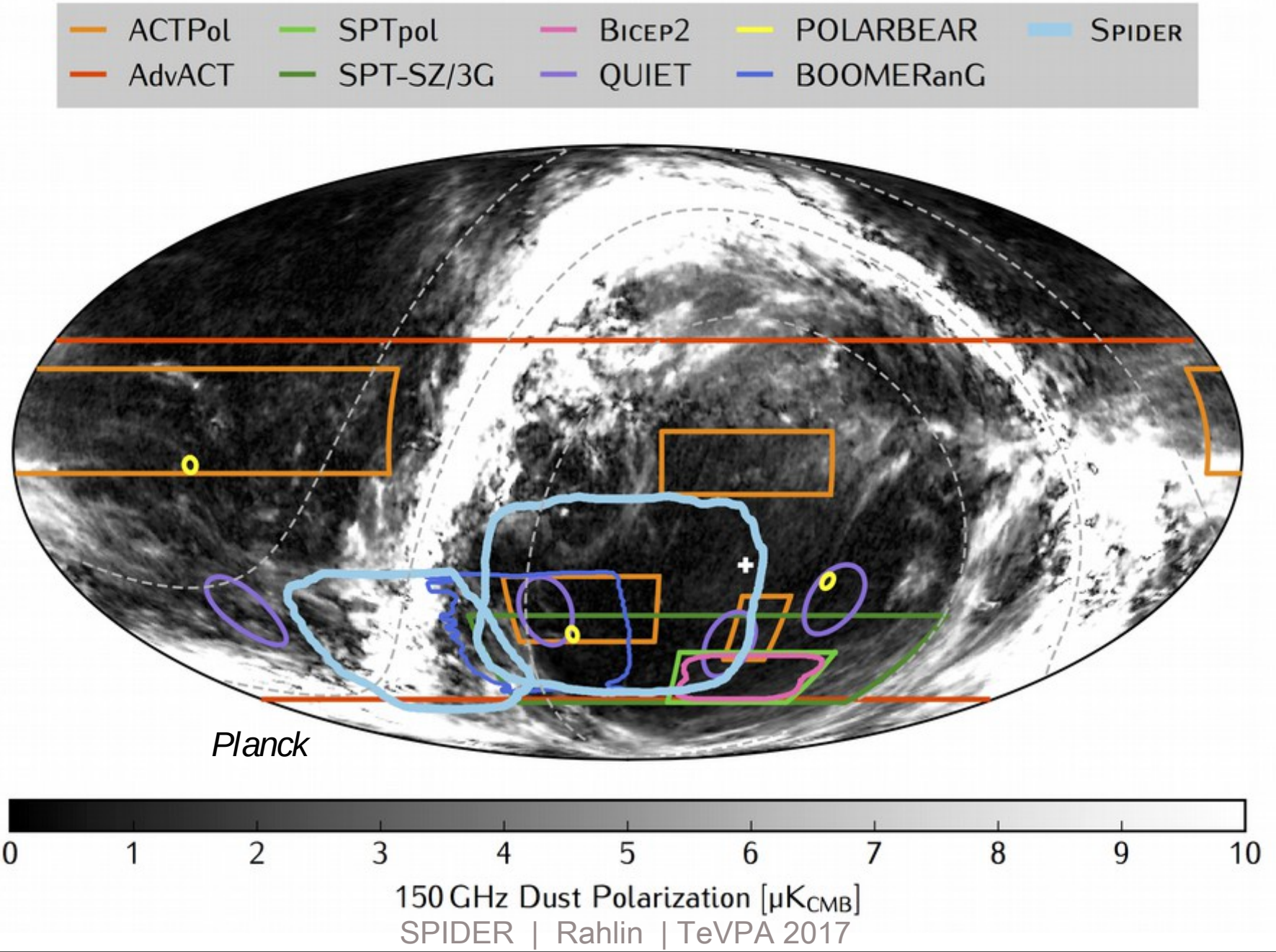
Future Balloon Landscape

- SWIPE is the high-frequency part of LSPE, led by Paolo de Bernardis at La Sapienza, Rome.
- Olimpo: An SZ experiment which has been waiting for a northern launch for years. Also led by Paolo de Bernardis at La Sapienza, Rome.
- BFore: a ULDB CMB+Foreground mission, has not been fully funded, but got some support for development.
- EBEX: was not selected
- There are also high-frequency astrophysics balloon missions such as BLAST & PILOT

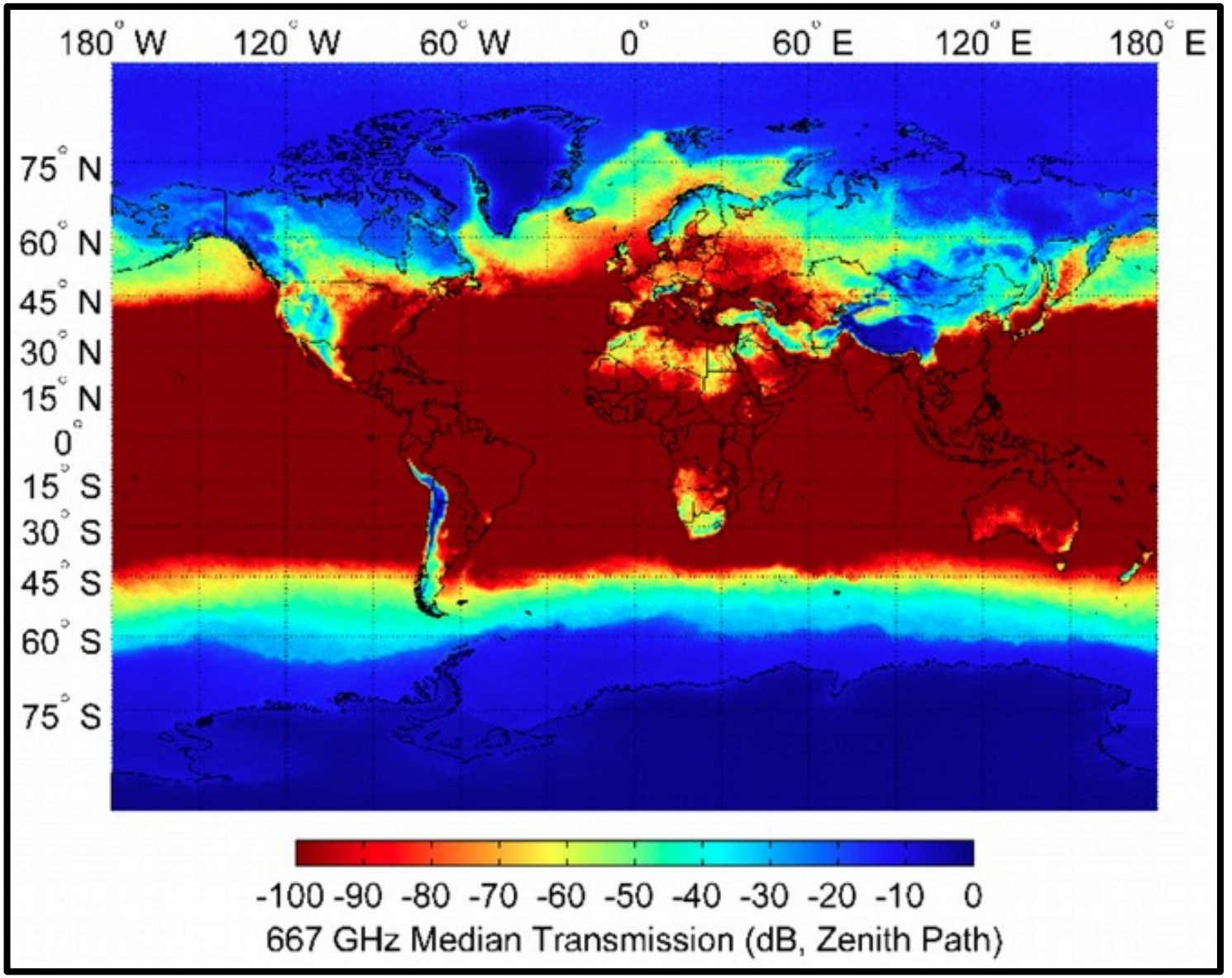
Balloons

- Balloons play a key role in the CMB “between ground and space”:
  - among the first to measure the dipole, the 1st peak & polarization
  - Key for large sky areas, high frequencies, & technology qualification
- ULDB or “rapid-fire” flights may help address integration time limitations.
- CNES (France) seems reluctant to expand (or continue?) their scientific balloon program
- More complicated instruments increase time between flights
- PIPER, Spider & Olimpo have have all had delays
- EUSO-SPB leak is a ULDB schedule setback
- EBEX/BFore/BSide not fully funded (or not funded at all)

Sky Coverage (by S. Rahlin for Spider)



Choice of Sites



Suen, Fang & Lubin

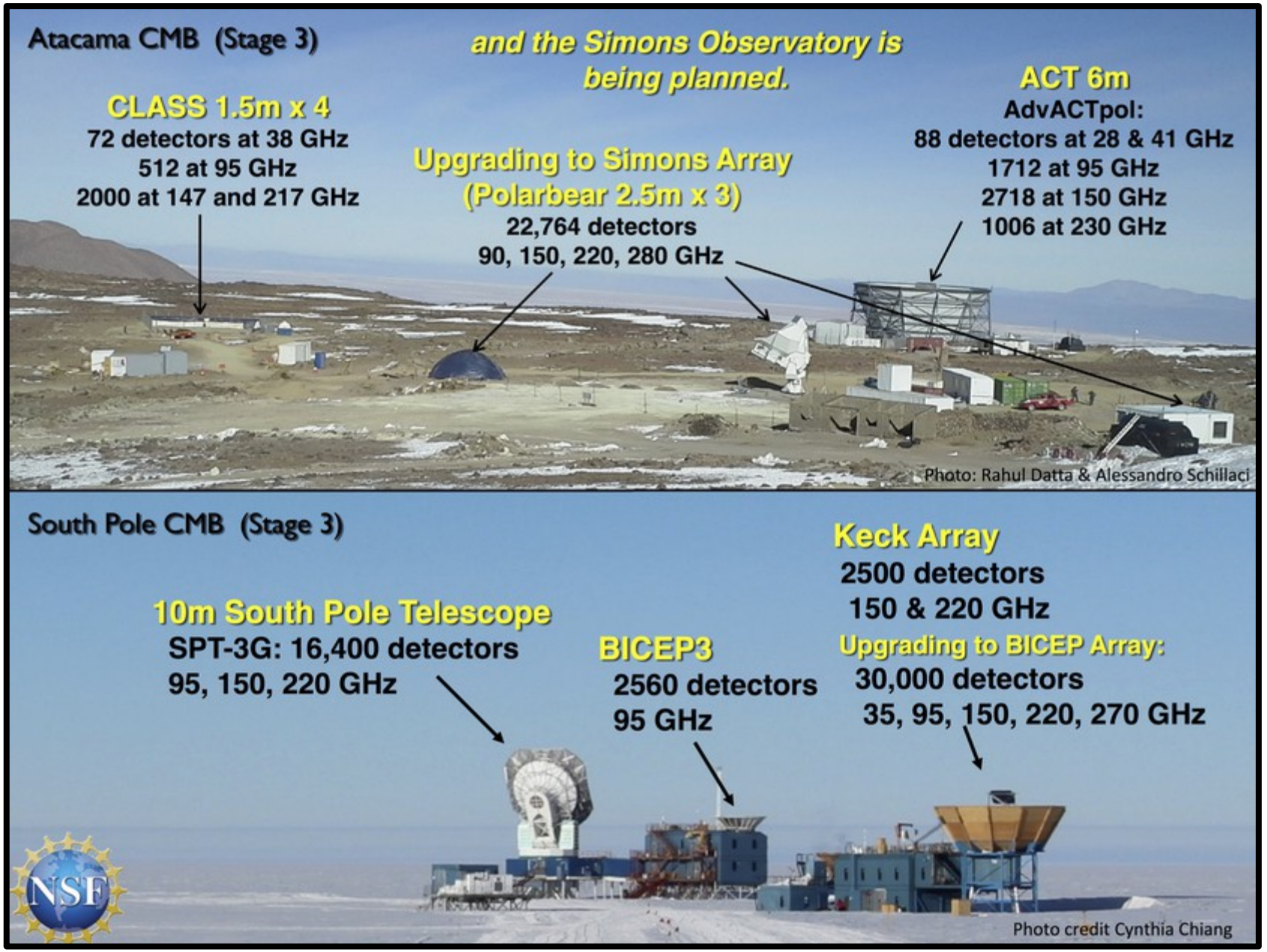
South Pole & Chile are the "traditional" sites

Ali could go to 6000 m in Tibet

Vieregg, Barkats *et al.* are doing monitoring in, for example, Greenland.

CMB Stage 3

The current S4 thinking is to have only these two sites, though further sites would probably be welcome if they could increase the Northern sky coverage.



Graphic from John Carlstrom

https://indico.in2p3.fr/event/14661/contributions/19246/attachments/43767/54161/Carlstrom_CMB-S4_Update.pdf

Fielded Anisotropy Experiments

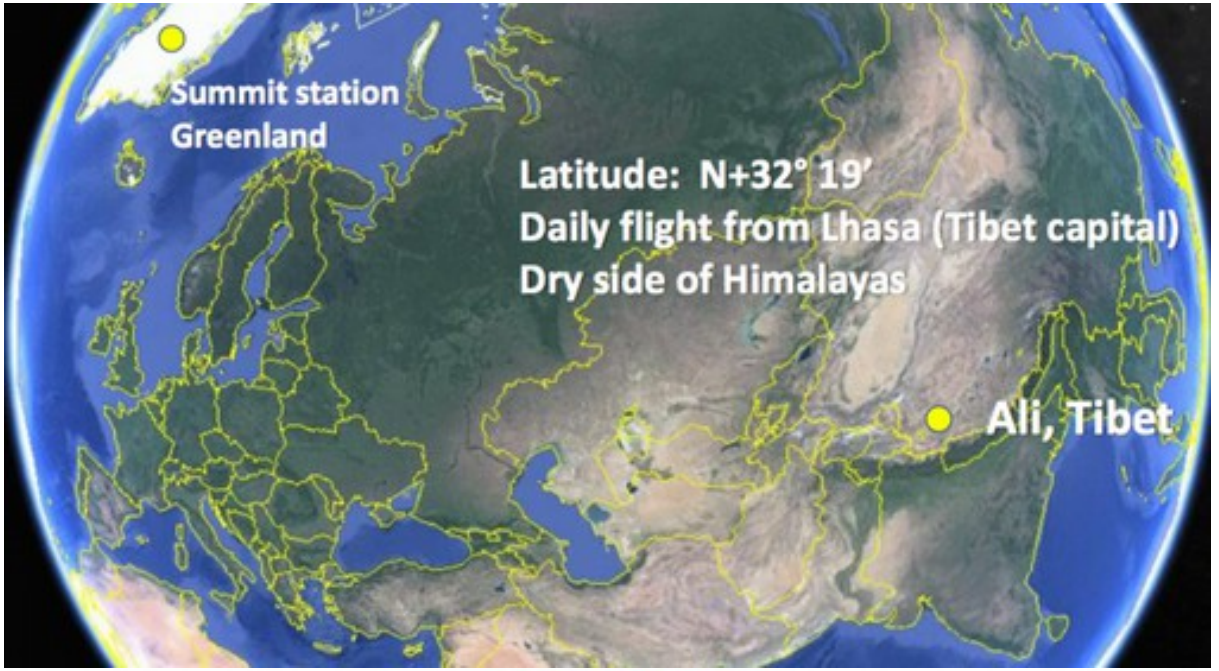
- Small Aperture/Pole
  - BICEP/Keck: Adding more cameras/detectors and going to higher frequencies
- Small Aperature/Chile
  - CLASS commissioning at $\nu<90$ GHz

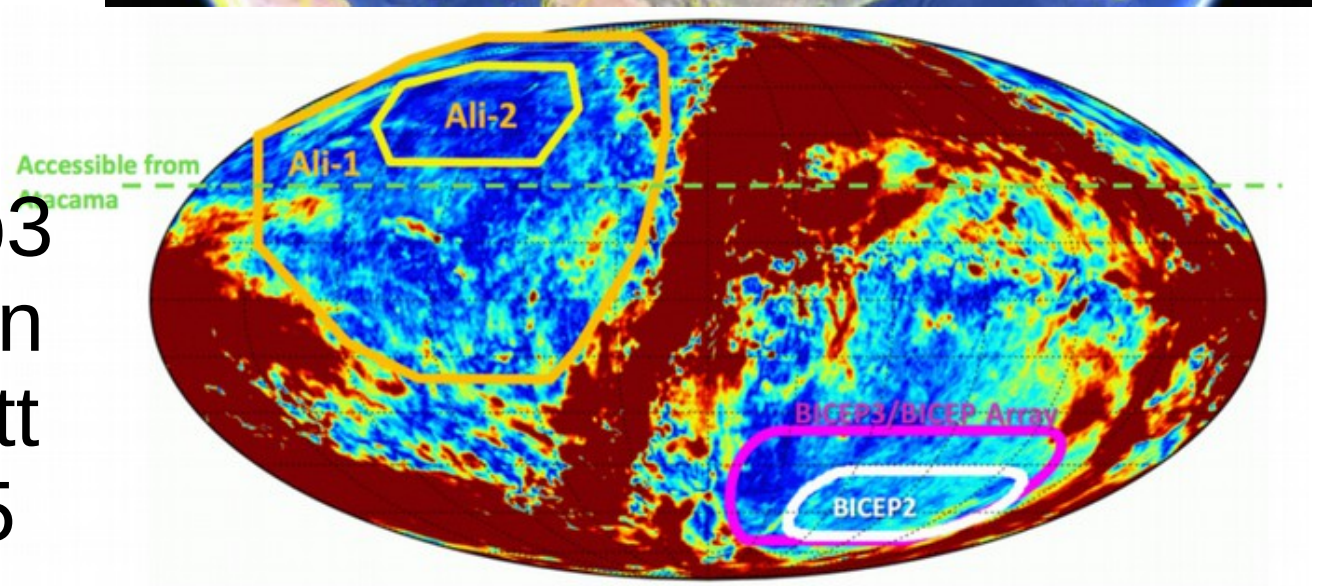
Tenerife: QUIJOTE

- Large Aperture/Pole
  - South Pole Telescope has 15000 detectors on the telescope now
- Large Aperture/Chile
  - ACT
  - Simons Array

Other Ground-Based Locations

- Ali would be in Tibet mountains with a possibility of 6000 m
- Sino-SLAC collaboration
- See C.-L. Kuo presentation at : (https://indico.in2p3.fr/event/14661/contributions/19261/attachments/43751/54261/KuoV2.pdf)



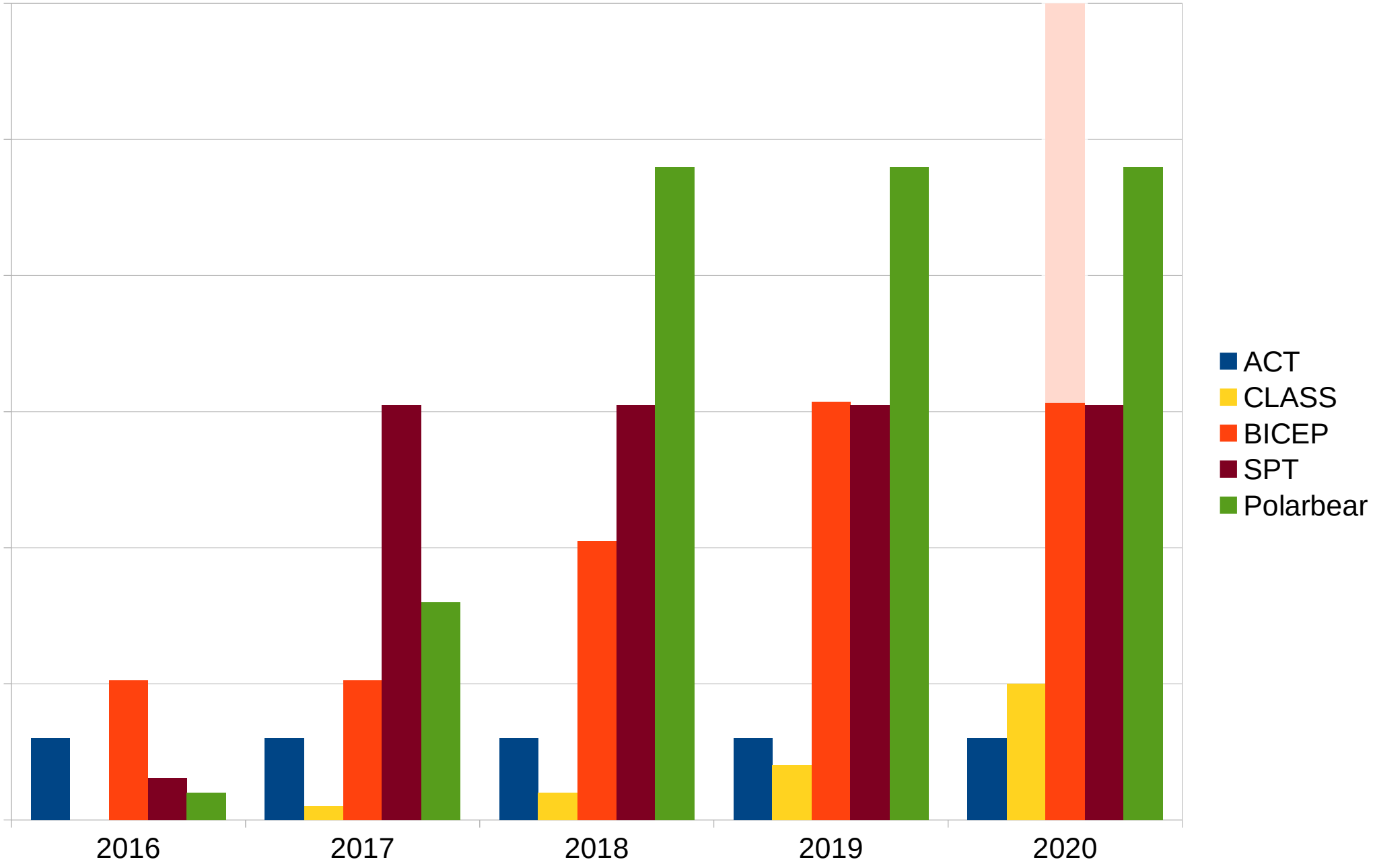


1. There will be lots of lessons learned with better statistics
2. Staged wedding cake strategy may be advantageous (e.g. Kovetz & Kamionkowski PRD 91, 081303R,2015)

European Ground

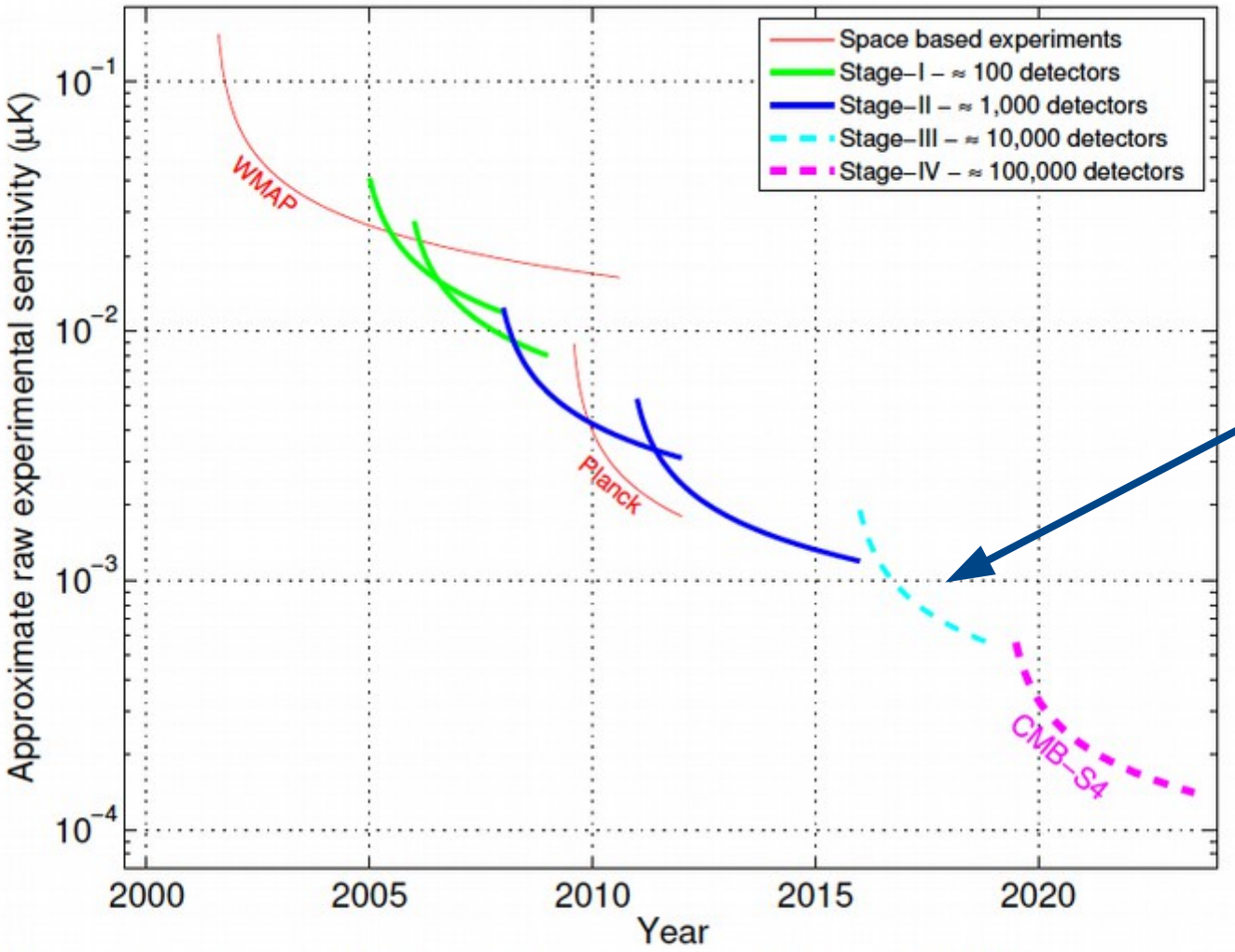
- COSMO: New, small, spectrum measurement at Dome C. Silvia Masi
- KISS: A low-resolution, KIDs, mm spectrometer under construction to field at Tenerife in 2018
- NIKA2: Just finished commissioning the first 1000+ KIDs focal plane as a facility instrument at the IRAM 30 m
- QUBIC: Observations in Argentina with 1 TES array next year. Upgrade to all TES arrays in early 2019.
- QUIJOTE: 10-20 GHz running since 2012. 30 GHz commissioning now. 40 GHz next year.
- STRIP: Low-frequency part of LSPE. It was originally going to fly on a balloon, but has now been re-designed to observe from Tenerife.

American Experiment Detector #s



Moore's Law for CMB Detectors

This is focused on detectors in the 100+ GHz range.



The largest, American experiments have O(10k) detectors & expect O(100k) for S4

Figure 2. *Plot illustrating the evolution of the raw sensitivity of CMB experiments, which scales as the total number of bolometers. Ground-based CMB experiments are classified into Stages with Stage II experiments having O(1000) detectors, Stage III experiments having O(10,000) detectors, and a Stage IV experiment (such as CMB-S4) having O(100,000) detectors. Figure from Snowmass CF5 Neutrino planning document.*

CMB-S4 Science Book – arXiv://1610.02743

Top-Line CMB-Stage IV Goals

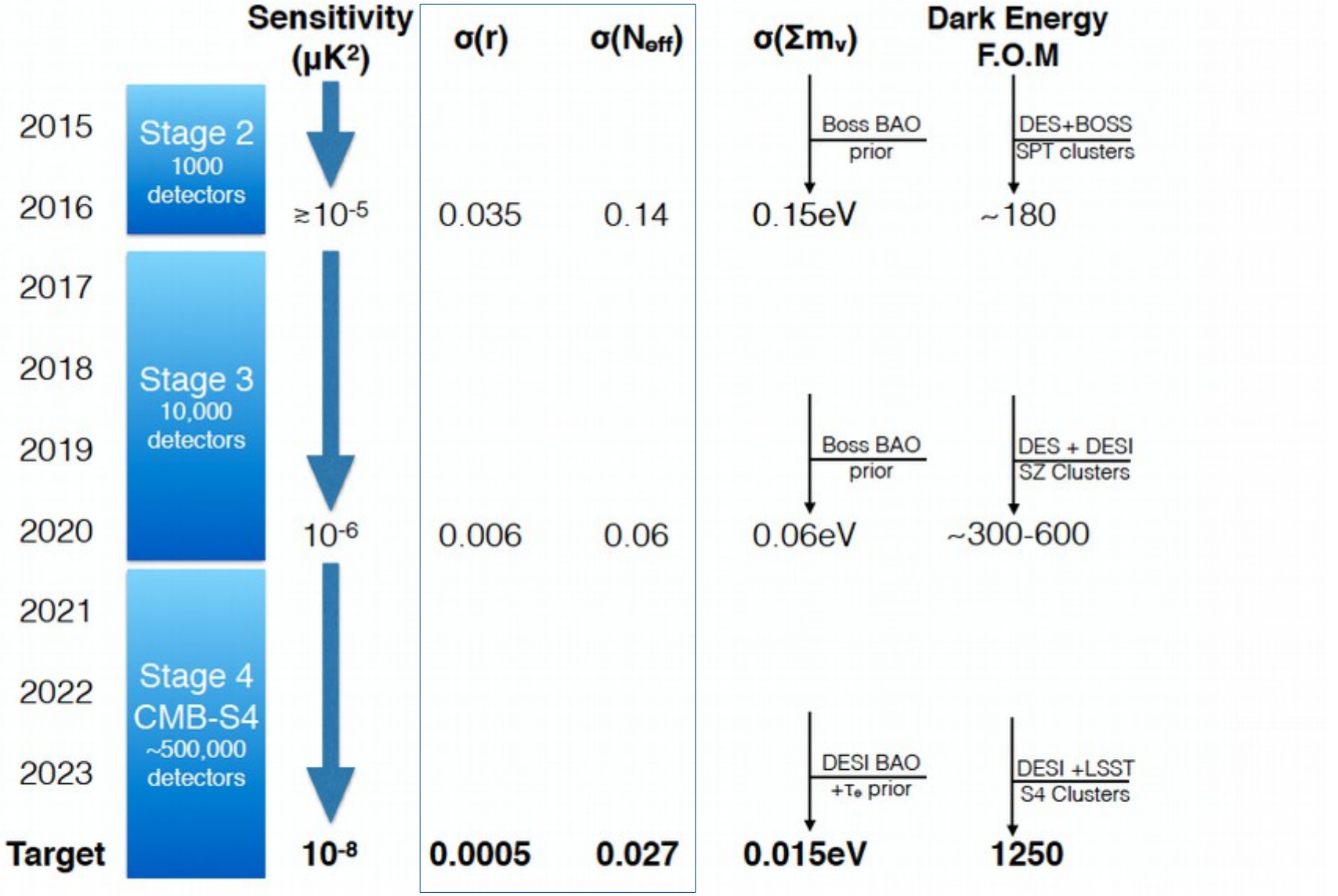


Figure 3. *Schematic timeline showing the expected increase in sensitivity (μK^2) and the corresponding improvement for a few of the key cosmological parameters for Stage-3, along with the threshold-crossing aspirational goals targeted for CMB-S4.*

CMB-S4 Science Book – arXiv://1610.02743

CMB Stage IV

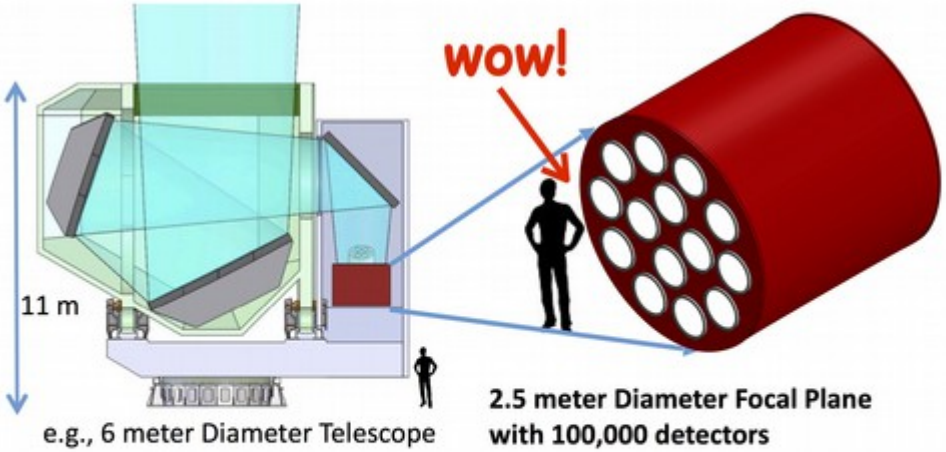
The current S4 thinking is to have a modular design. Here is Europe some of us are hoping that we can provide some of these modules.

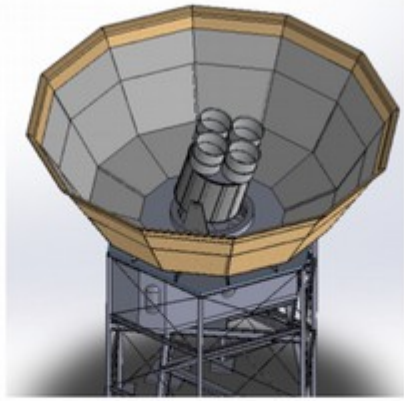
Graphic from John Carlstrom

CMB-S4
Next Generation CMB Experiment

CMB-S4 concept

- One collaboration, one project, with two sites: South Pole and Atacama, Chile
- Small and large telescopes for B-mode, de-lensing, high-ℓ cosmic structure science
- 500,000 detectors (300k on 3 large telescopes; 200k on 14 small telescopes)
- Order 8 frequency bands for CMB and foreground mitigation on small telescopes
- Two surveys: 4 yr deep B-mode w/ de-lensing (f_{sky} ~ few %)
  7 yr broad for N_{eff} and cosmic structure science (f_{sky} = 40%)





High resolution Science + de-lensing:
300,000 detectors on 3 large telescopes

Figure from Simons Obs, Mark Devlin / Mike Niemack

Low resolution B-mode Science:
200,000 det. on 14 small telescopes

Figure from BICEP Array

https://indico.in2p3.fr/event/14661/contributions/19246/attachments/43767/54161/Carlstrom_CMB-S4_Update.pdf

CMB Stage-IV

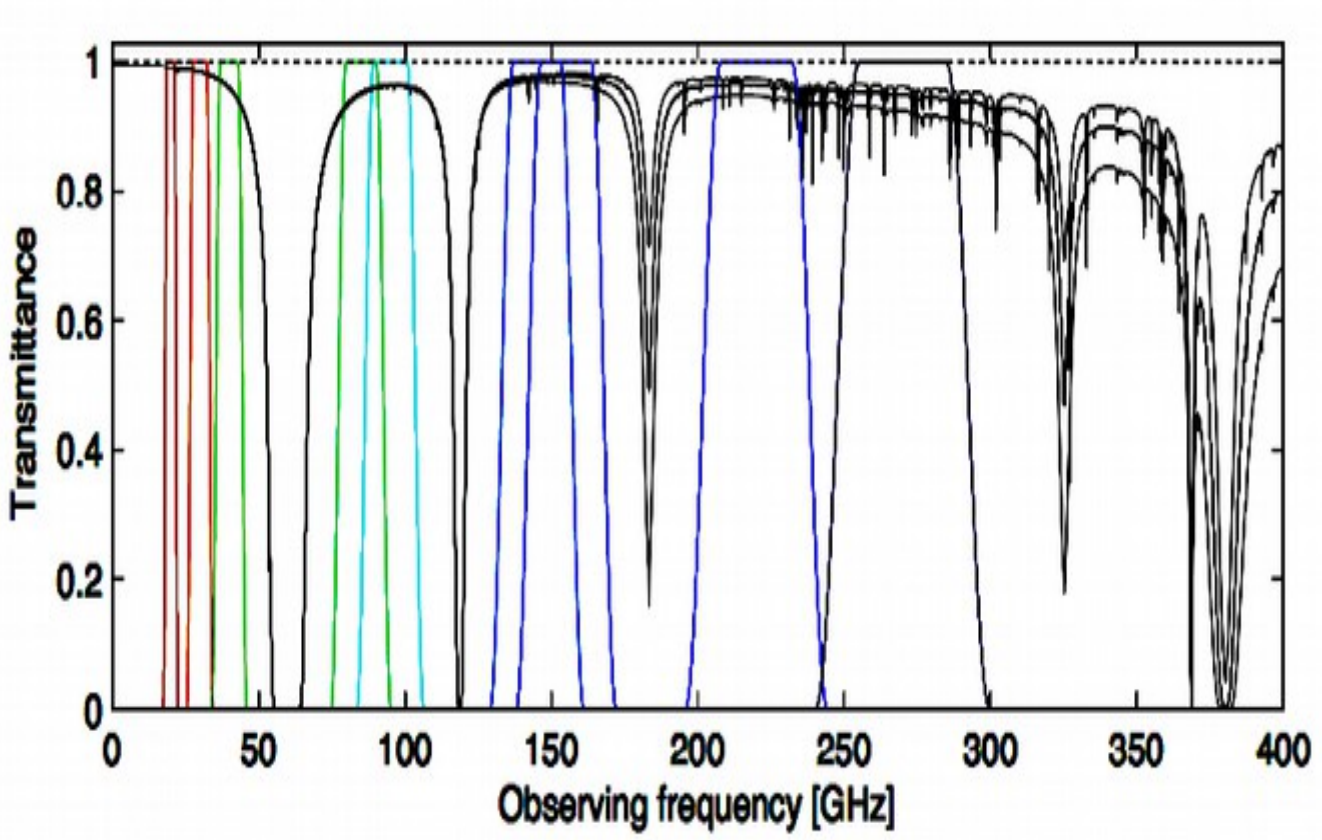
- r & N_{eff} will be the design drivers
  - But it will still do other work
- Cost ~$412M
- 7 years construction
- 4/7 years observation
- ~1-2 uK arcminute (cf Antony's 5 uK-arcminute lensing noise)

From S4CDT Report

Science	Item	Frequency [GHz] 20	30	40	85	95	145	155	220	270	Total
r	**14 x 0.5-m cameras**										
	# detectors	. . .	260	470	17 k	21 k	18 k	21 k	34 k	54 k	168 k
	Angular resolution [FWHM]		77′	58′	27′	24′	16′	15′	11′	8.′5	
	1 x 6-m telescope										
	# detectors	130	250	500	. . .	25 k	25 k	. . .	8.7 k	8.7 k	68 k
	Angular resolution [FWHM]	11′	7.′0	5.′2	. . .	2.′2	1.′4	. . .	1.′0	0.′8	
$N_{\rm eff}$											
	2 x 6-m telescopes										
	# detectors	290	640	1.1 k	. . .	50 k	50 k	. . .	17 k	17 k	136 k
	Angular resolution [FWHM]	11′	7.′0	5.′2	. . .	2.′2	1.′4	. . .	1.′0	0.′8	

S4 Frequency Choices

- Except for the 270/350 GHz channel, the bands are quite similar to those of Planck. Is it enough?



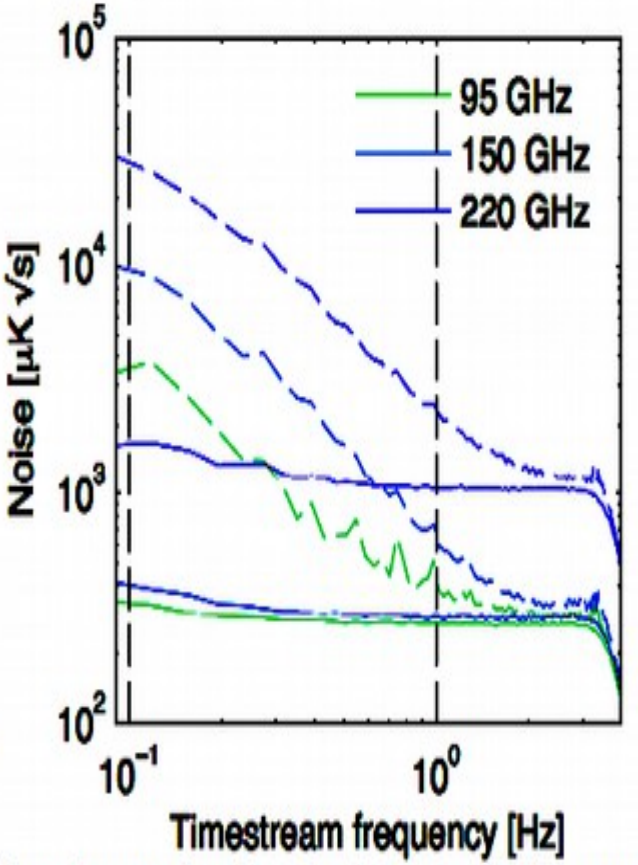
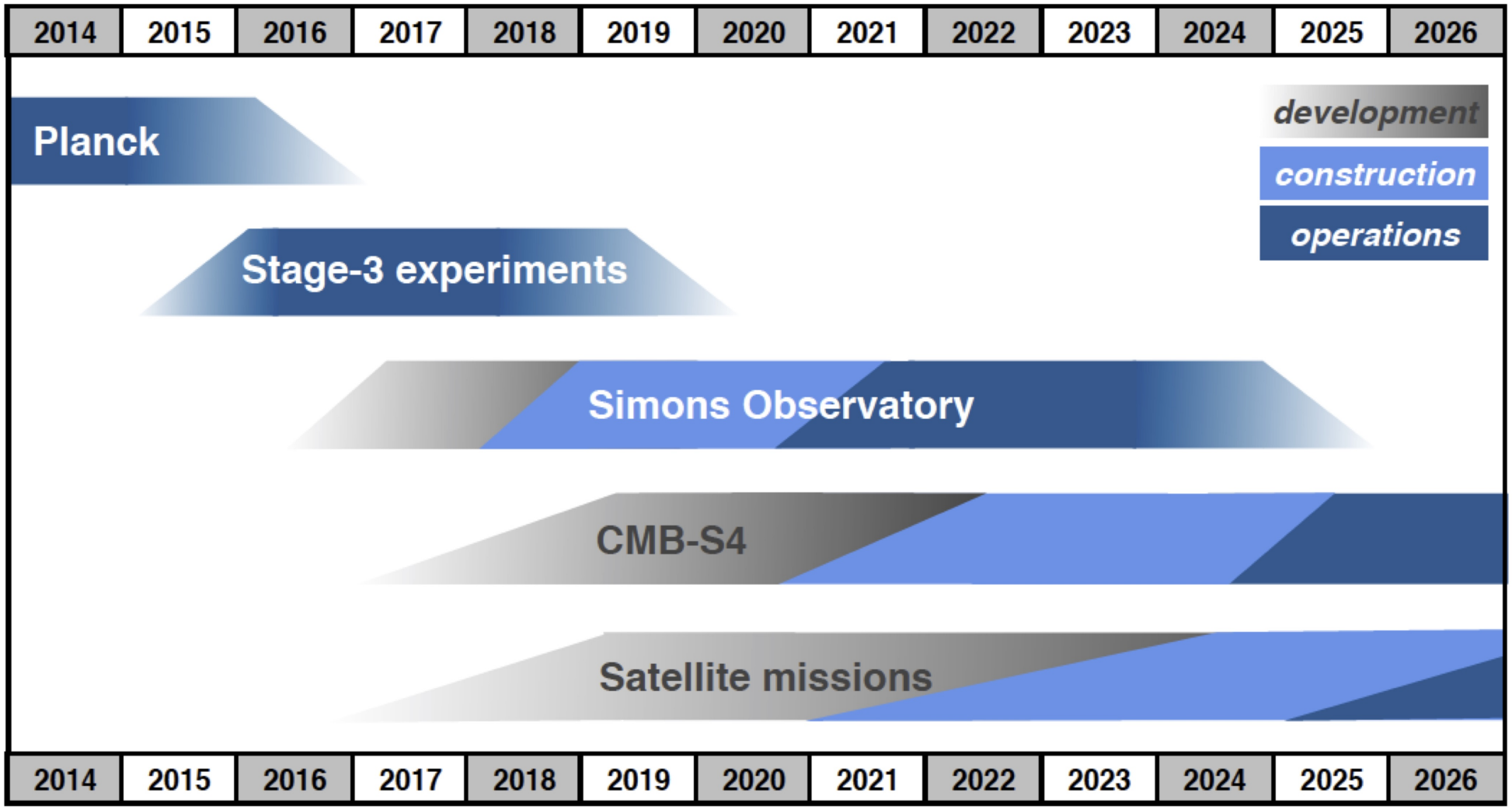


Figure 2: *Left:* Atmospheric transmission as a function of frequency showing the atmospheric windows and the pass-bands chosen for CMB-S4. *Right:* The power spectral density of detector timestream data showing that atmospheric $1/f$ noise is largely unpolarized (solid lines are polarization, dashed are total intensity).

Proposed UK CMB Roadmap



From M. Brown's presentation at last week's Florence meeting (https://indico.in2p3.fr/event/14661/)

Summary

- Traditionally, A healthy CMB field mounts a “triad” of ground-, balloon-, and satellite-based experiments
- Ground-based CMB is advancing rapidly! “Stage 3” experiments have O(10k) detectors and Stage 4 experiments should have O(100k) near 2027
- LiteBIRD and other efforts are underway to mount the next generation satellite experiments
- Balloons have had a hard time recently, but continue to push for longer (ultra-long!) flights and higher frequencies.
- Europe has put significant resources into the CMB in recent years with Planck, but must continue to do so to continue to have access to leading-edge CMB cosmology