COSPAR 2018

PICO

PROBE OF INFLATION AND COSMIC ORIGINS

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PASADENA CONVENTION CENTER
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“Probes”

Probe Mission $\equiv$ a NASA astronomy mission costing between \$400 M and \$1 B

- There is at present no Probe line
  - NASA Planetary Science has two mission lines in this cost range

    Discovery — $\leq \$500$ M; science open

    New Frontiers — $\leq \$1$ B; science in five specified areas
- The 2010 Decadal did not recommend space missions between \$250 M and \$1 B
- In preparation for the 2020 Decadal, NASA set up ten “Probe Mission Studies”

NASA Preparation for 2020 — I

The Astrophysics Probe Mission Concept Studies Portfolio:

• Inflation Probe (PICO)	Hanany, U Minn
• Galaxy Evolution Probe	Glenn, U Colorado
• STROBE-X	Ray, NRL
• Cosmic Evolution through UV Spectroscopy (CETUS)	Danchi, GSFC
• Transient Astrophysics Probe	Camp, GSFC
• AXIS	Mushotzky, U Maryland
• Cosmic Dawn Intensity Mapper	Cooray, UC Irvine
• Probe of Extreme Multi-Messenger Astrophysics (POEMMA)	Olinto, U Chicago
• (EarthFinder)	Plavchan, George Mason
• (Starshade Rendezvous)	Seager, MIT

NASA Preparation for 2020 — II

- Studies are to produce 50-page reports + cost estimates to be submitted to NASA and the Decadal Panel in December 2018
- Possible outcomes
  - Panel recommends a Probe line of competed missions
  - Panel recommends specific missions
  - Some combination of the above
  - Panel does what it did in 2010

- Our desired outcome
  - Panel recommends a competed Probe line, and also recognizes in some way that a 4th-generation space CMB mission is a high priority

The PICO Collaboration

- Open to all — subscribe!, contribute!
- Wiki: https://z.umn.edu/cmbprobe
- Mailing list: cmbprobe@lists.physics.umn.edu

Spectrometer, Imager, or Both?

- We considered both imagers and spectrometers
- And concluded that there is a strong case for both. . .
- . . .but not combined in a single mission
- PICO will be designed and costed as an imaging mission

Ambition

- Energy scale of inflation, $r \sim 10^{-4}$
- $N_{\rm eff}$ and Σm_ν
- τ
- Cosmic star formation history
- Physics of the Galactic magnetic field

THIS AMBITION DEMANDS A SPACE MISSION

N.B.—PICO is a lightly-funded concept study, not a mission proposal.

Goal: convince the decadal committee to recommend a Probe line.

The study is in progress, not finished. Things will change.

Figures here are from:

Young et al., Proc. SPIE 10698-143 (2018)

Sutin et al., Proc. SPIE 10698 (2018)

PICO in Brief

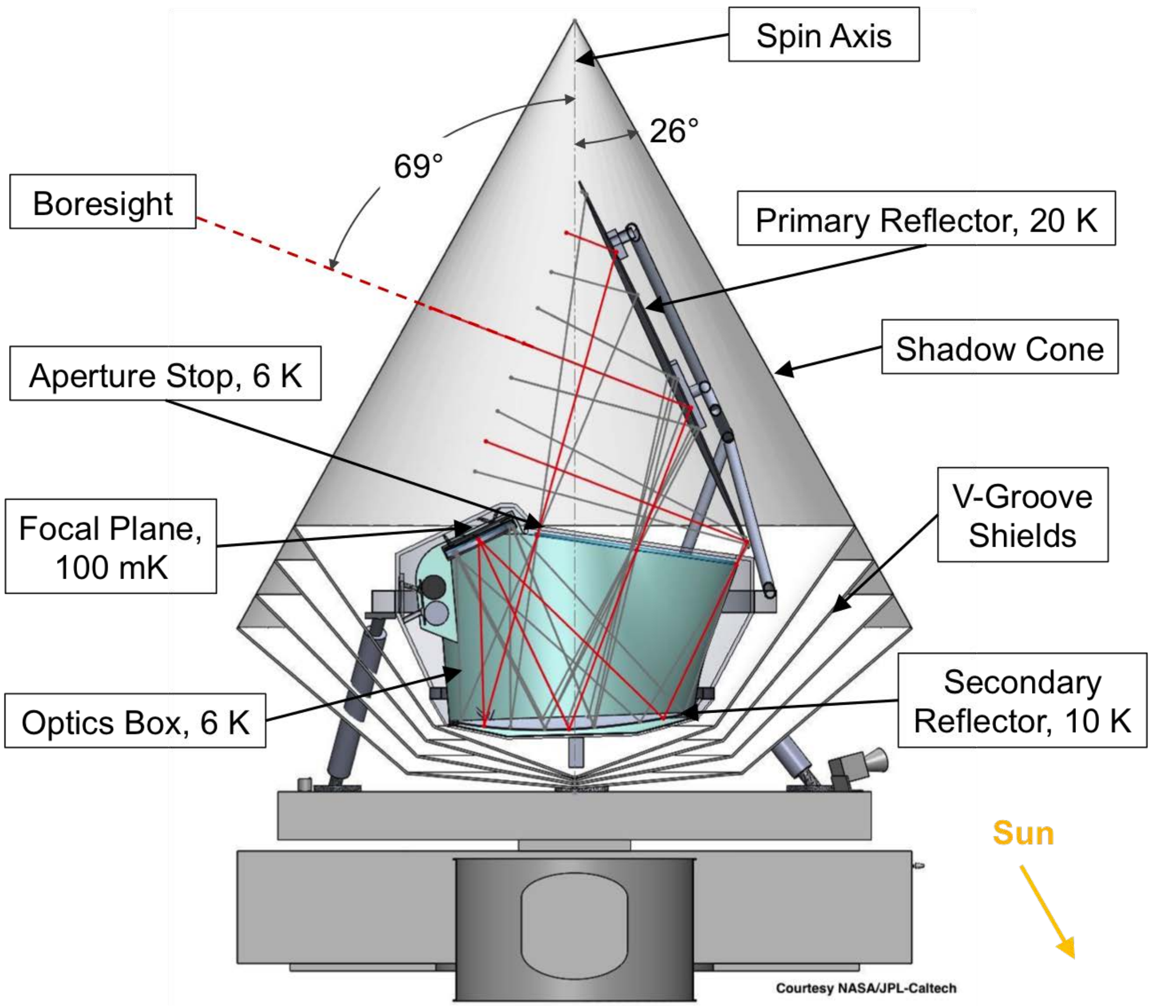
- All-sky polarimetry
- 21 bands from 20 to 800 GHz
- 1.4-m aperture telescope
- Diffraction-limited resolution:

  38′ to 1′
- 12,996 TES bolometers
  - Multichroic pixels up to 464 GHz

    Three bands per pixel

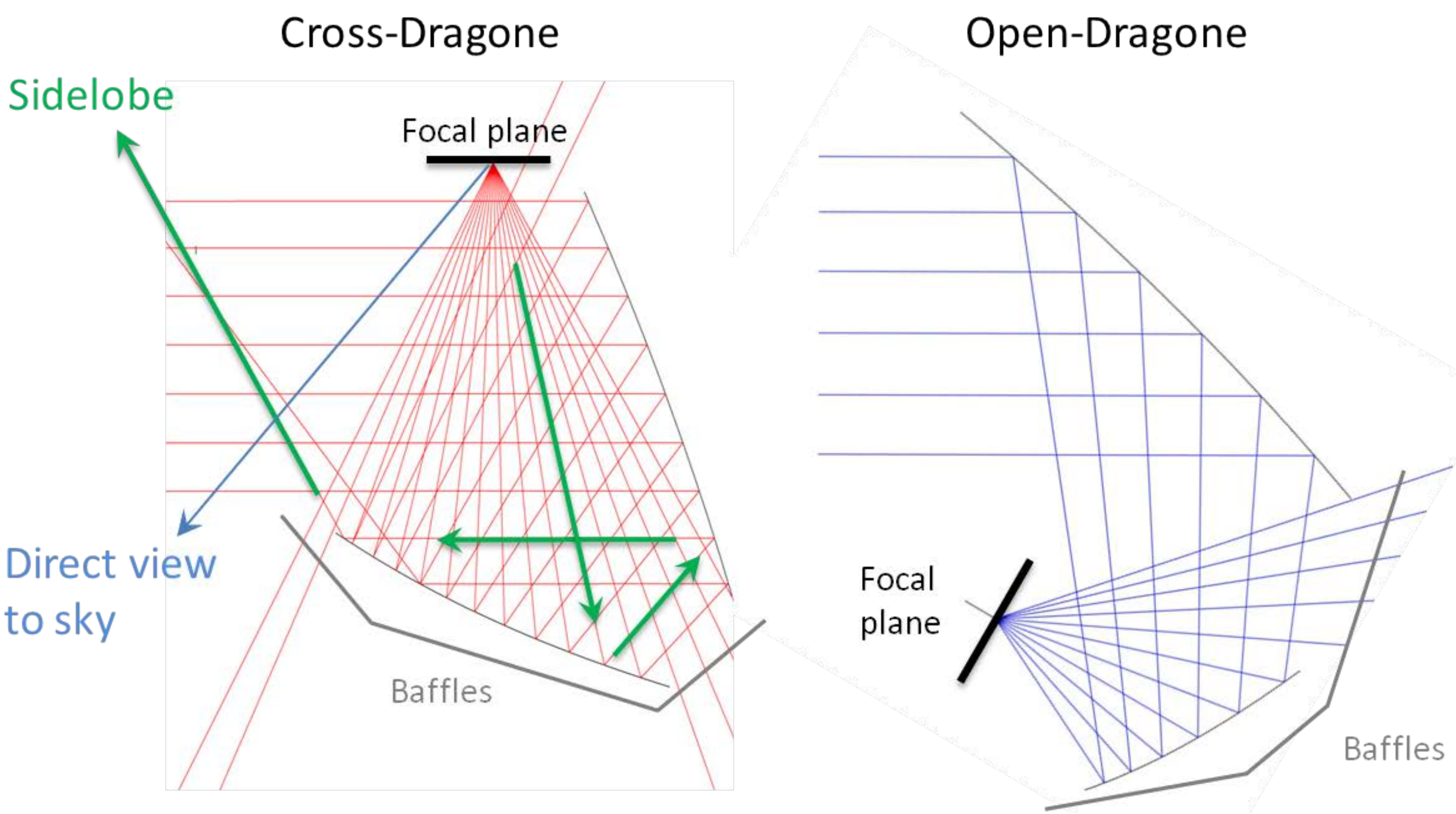
    Two TESs per band

    Six bolos/pixel
- 5-year survey from L_2
  - Falcon 9 launch
- 0.6 μK_{CMB} arcmin map depth
  - $\approx$ Planck/80



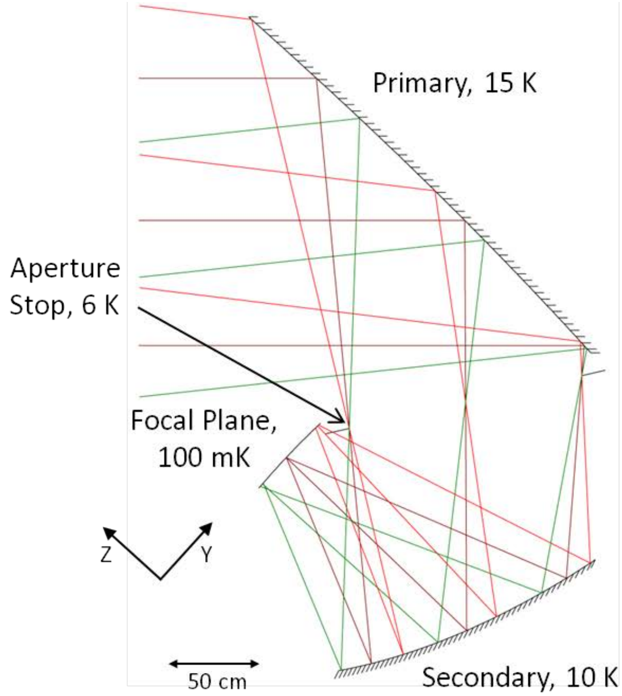
The 1-rpm spin axis precesses around the satellite-Sun axis with an angle of 26°, defining the shadow cone. Precession periods between 10 and 48 hours are being considered.

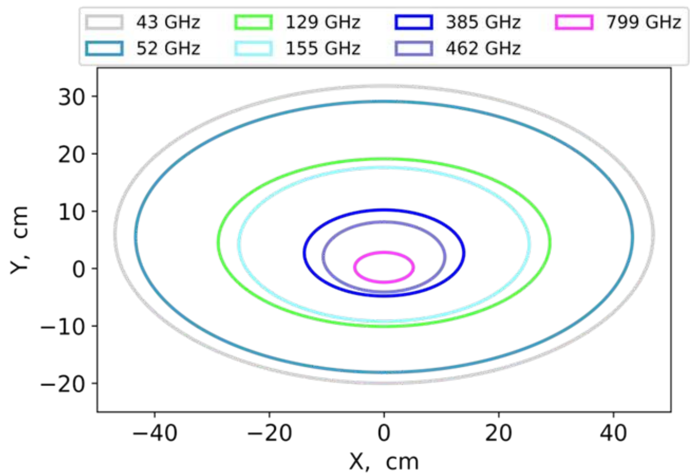
Telescope — Open Dragone vs. Cross-Dragone



- Open Dragone had 1/4 the diffraction-limited field of view (DLFOV) of the cross Dragone, but was easier to pack inside the spacecraft volume while avoiding sidelobes
- Largest cross Dragone that met PICO volume constraints had a 1.2-m aperture and $f/D = 2.5$, while the largest open Dragone had a 1.4-m aperture and $f/D = 1.42$.
- Smaller f/D means smaller focal plane for same number of pixels $\Rightarrow$ lower mass and cost

Telescope and Focal Plane



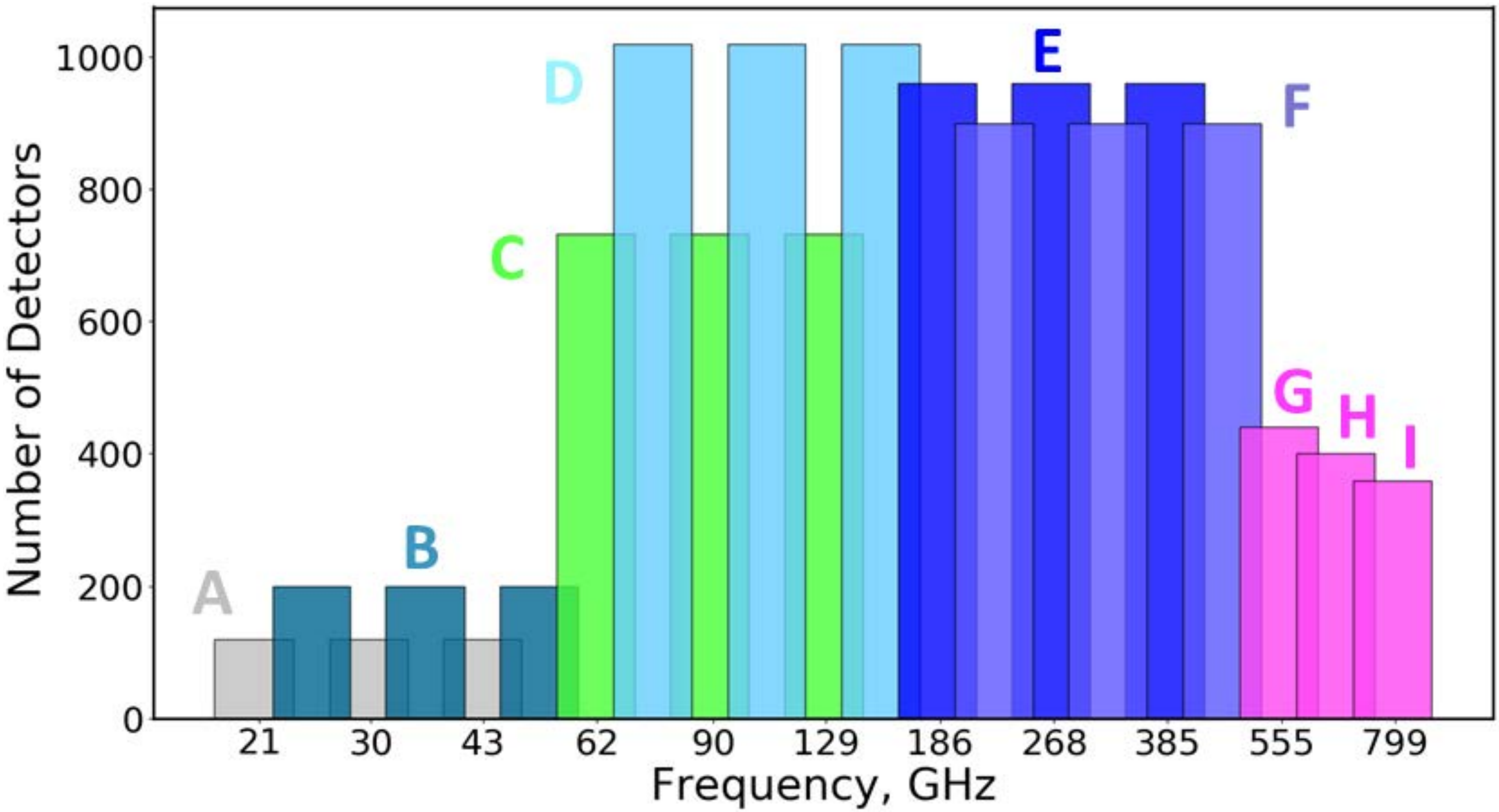


Strehl = 0.8 contours

PICO optical system					Initial Open-Dragone[b]	
	Primary	Secondary	Telescope parameters[b]		Fundamental design parameters	
Reflector size[a] (cm)	270 × 205	160 × 158	Aperture (cm)	140	Aperture (cm)	140
Radius of curvature (cm)	∞	136.6	F-number	1.42	θ_0 (deg)	90
Conic constant, k	0	-0.926	h (cm)	624.2	θ_e (deg)	20
Normalization radius (cm)	524.8	194.1	α (deg)	74.2	θ_p (deg)	140
4th Zernike Coefficient (cm)	2018.4	-61.1	β (deg)	62.3	L_m (cm)	240
9th Zernike Coefficient (cm)	-37.0	16.7	L_m (cm)	229.3		
10th Zernike Coefficient (cm)	-2919.8	-15.1	L_s (cm)	140.5	Derived parameters	
11th Zernike Coefficient (cm)	-1292.7	22.3			F-number	1.42
12th Zernike Coefficient (cm)	120.6	-3.8	Focal Surface		h (cm)	624.2
13th Zernike Coefficient (cm)	-74.5	4.9	Ellipse major axes (cm)	69 x 45	α (deg)	38.6
19th Zernike Coefficient (cm)	-75.8	3.4	Ellipse major axes (deg)	19 x 13	β (deg)	101.4
20th Zernike Coefficient (cm)	-398.9	6.3	Radius of curvature (cm)	455	L_s (cm)	122.2
21st Zernike Coefficient (cm)	-319.5	23.3			Primary, f (cm)	312.1
22nd Zernike Coefficient (cm)	-276.6	-8.5			Secondary, a (cm)	131
23rd Zernike Coefficient (cm)	-201.6	-3.2			Secondary, e	1.802
24th Zernike Coefficient (cm)	-127.4	-1.9				
25th Zernike Coefficient (cm)	-55.0	0.1				

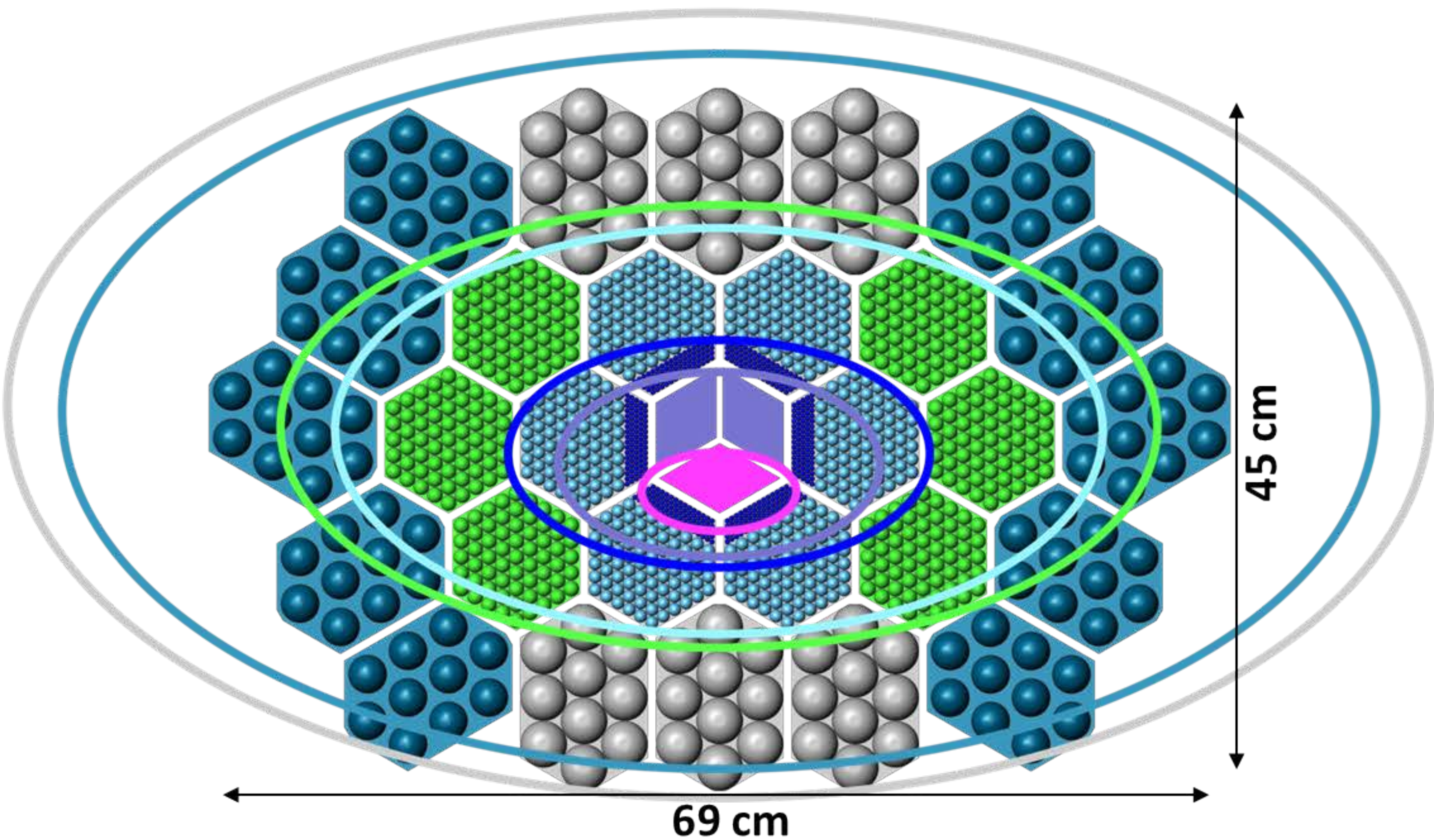
[a] The maximum physical size of the reflectors.
[b] Telescope parameters follow the definitions in Granet 2001.[11]

Frequency Coverage

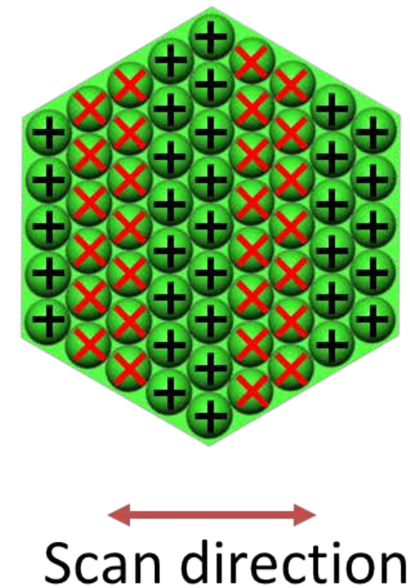


- Multichroic pixels up to 462 GHz. Single-color pixels in bands G, H, and I.
- 25% bandwidth, all bands

Focal Plane

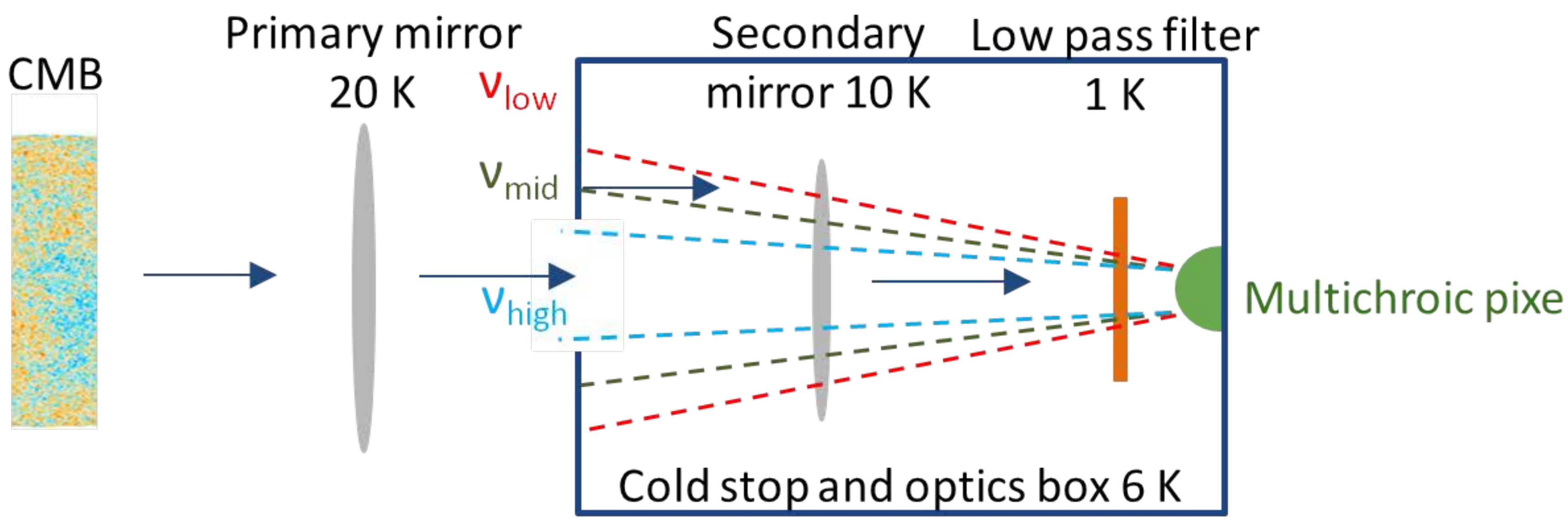


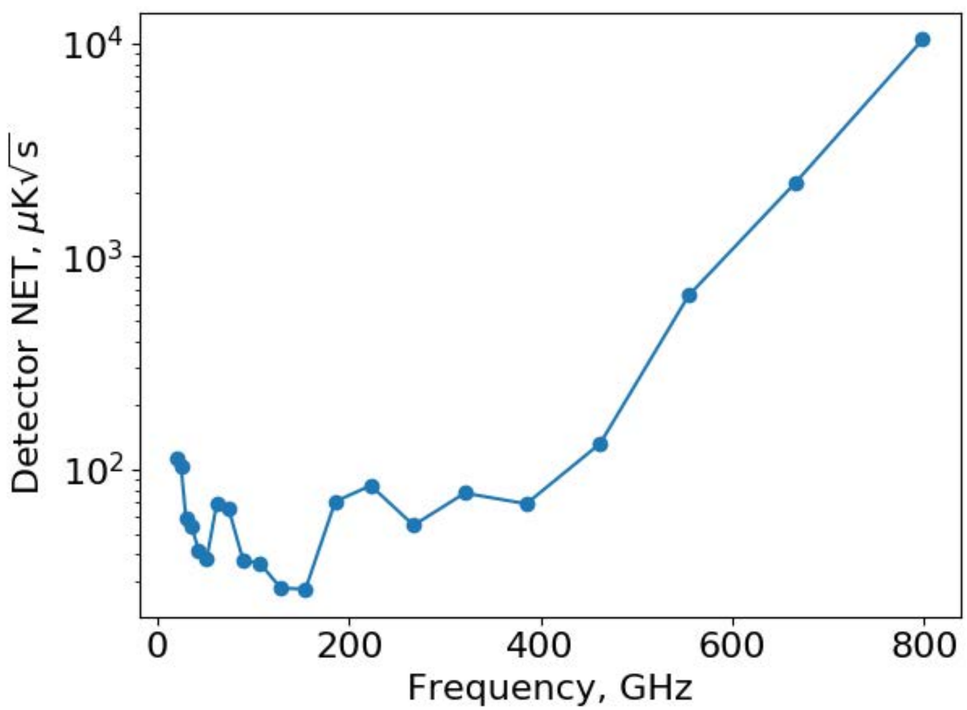
Strehl = 0.8 contours shown for each pixzel type



Stokes Q (black crosses) Stokes U (red Xs) for an example wafer

Optical Loading and NET





Noise

Table 3. PICO frequency channels and noise.

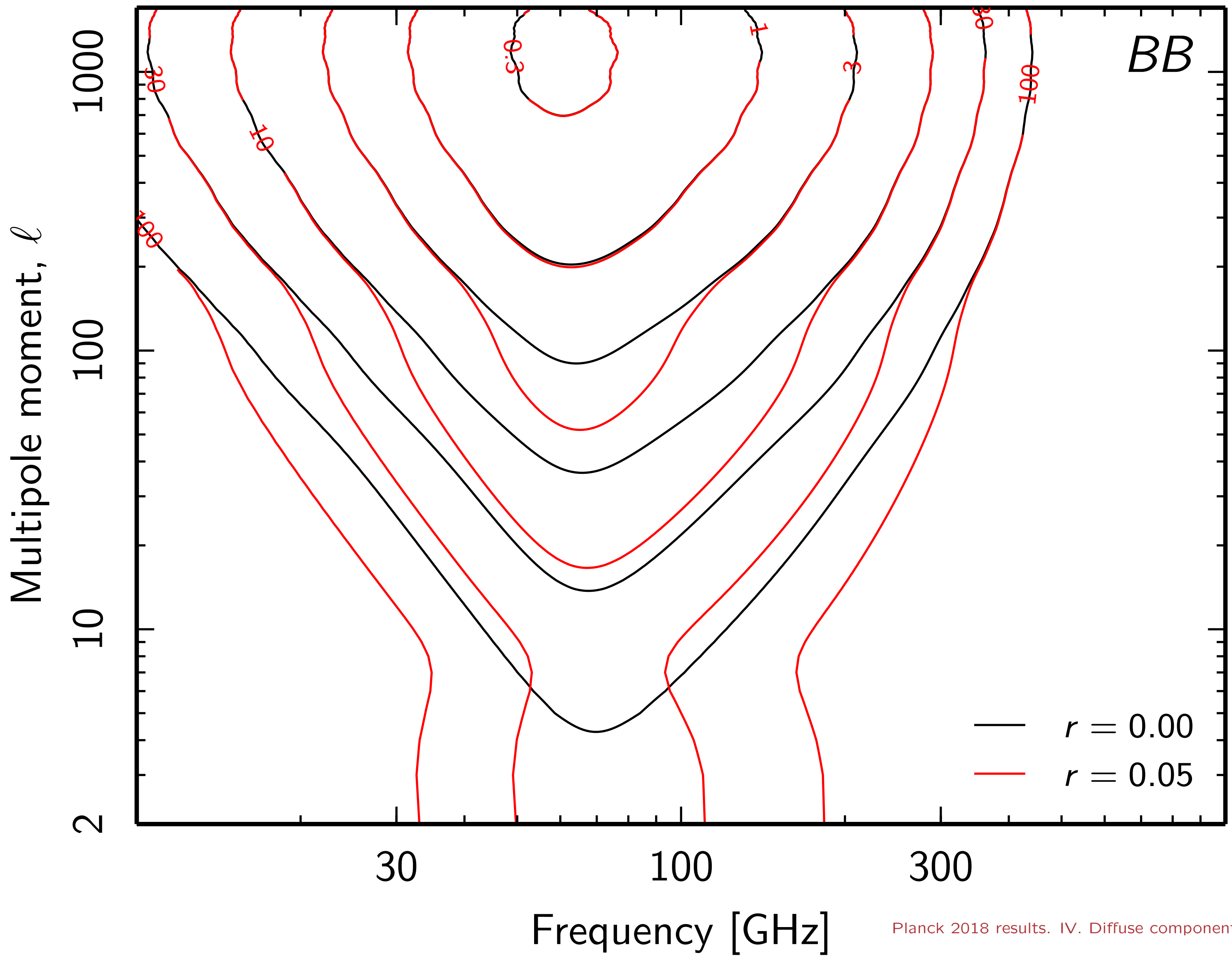
Pixel Type	Band GHz	FWHM arcmin	Bolometer NEP $aW/\sqrt{Hz}$	Bolometer NET $\mu K_{CMB}\sqrt{s}$	N_{bolo}	Array NET $\mu K_{CMB}\sqrt{s}$	Polarization map depth μK_{CMB}-arcmin	Jy/sr
A	21	38.4	4.89	112.2	120	13.6	19.2	6.69
B	25	32.0	5.33	103.0	200	9.56	13.5	7.98
A	30	28.3	4.92	59.4	120	5.90	8.31	7.93
B	36	23.6	5.36	54.4	200	4.17	5.88	9.59
A	43	22.2	5.33	41.7	120	4.01	5.65	13.9
B	52	18.4	5.73	38.4	200	2.86	4.03	16.8
C	62	12.8	8.29	69.2	732	3.13	4.42	37.0
D	75	10.7	8.98	65.4	1020	2.47	3.47	48.1
C	90	9.5	7.76	37.7	732	1.49	2.10	44.5
D	108	7.9	8.18	36.2	1020	1.21	1.70	57.0
C	129	7.4	7.35	27.8	732	1.09	1.53	69.7
D	155	6.2	7.36	27.5	1020	0.91	1.28	84.6
E	186	4.3	12.30	70.8	960	2.52	3.54	383
F	223	3.6	12.70	84.2	900	3.05	4.29	579
E	268	3.2	8.55	54.8	960	1.87	2.62	369
F	321	2.6	8.16	77.6	900	2.73	3.84	518
E	385	2.5	4.54	69.1	960	2.35	3.31	318
F	462	2.1	4.00	132.6	900	4.66	6.56	403
G	555	1.5	6.47	657.8	440	33.1	46.5	1569
H	666	1.3	5.74	2212	400	117	164	1960
I	799	1.1	4.97	10430	360	560	816	2321
Total					12996	0.46	0.65	

- Noise is equivalent to Planck/80 (!!)

But. . .

- Raw sensitivity is necessary, but not even close to sufficient
- Foregrounds and systematics will determine what a mission can do
- To justify spending most of $1 B to reach two orders of magnitude below Planck, we the CMB community will have to demonstrate feasibility in a way that we have never done before
  - Simulations starting from time-ordered data with realistic (i.e., nasty, complicated, numerous) instrument and mission systematics, and foregrounds are necessary.
- We can't yet do this, but we're getting closer.

Foregrounds



Planck 2018 results. IV. Diffuse component separation

Amplitude ratio between total polarized foregrounds and CMB as a function of both multipole moment and frequency, as defined by $f(\ell,\nu) = [C_\ell^{\rm fg}(\nu)/C_\ell^{\rm CMB}]^{1/2}$, with parameters derived from 78 % of the sky as estimated by Commander.

One Example

- The CMB-S4 Concept Definition Task Force (CDT) found that the introduction of non-Gaussian, small-scale structure in the synchrotron foreground model led to substantially greater foreground residuals.
- For CMB-S4, the problem was solved by moving the 20 GHz channel to one of the 6-m telescopes.
  - Having roughly the same angular resolution at the lowest frequency as at higher frequencies worked in simulations
- The same solution is not available to PICO!
- Moreover, we still haven't quite got a valid way to introduce non-Gaussian small-scale structure into our all-sky simulated foreground.
- There's still a lot left to do...

Possible Probe Schedule

- December 2020 — Decadal review recommends Probe line in astrophysics
- 2021, maybe into 2022 — NASA gets approval for Probe line
- 2022, maybe into 2023 — NASA drafts call for proposals
- 2023 — call for proposals, and proposals due
- 2023, maybe into 2024 — step 1 selection
- 2024 — step 1 (Phase A) studies
- 2025 — selection
- 2025–2029,2030 — build
- 2030 — launch

Conclusion

- Great science
- Demanding hardware and software
- It will happen. . .

  . . .but it will take a while