Future Satellite Missions

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CMB-S4 Collaboration Meeting

UIUC

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Why Space?

- All sky
  - Can measure largest angular scales
  - Absolute calibration from orbital dipole
- All frequencies
  - Good for foregrounds
- No atmosphere
- No ground
  - From Sun-Earth L_2, Sun, Earth, and Moon are relatively close in the sky and can be blocked "easily"

    No problem from comm satellits orbiting Earth
- Space is cold

- Rule of thumb: one detector in space is worth 100 on the ground

Opportunities in Space

- Space agencies have discrete categories of mission
- ESA has nothing in preparation at this time, at any scale
- JAXA has LiteBIRD, which you just heard about
- NASA

  "Flagship or Strategic missions": BIG, $>$\$1 B (JWST almost \$10 B, Roman $\sim$\$4 B. . .) Decadal review

  "Probes": \$1 B PI cost cap — Competed

  "Mid-sized Explorer – Midex'': $\sim$\$350 M PI cost cap — Competed

  "mall-size Explorer – Smex": $\sim$\$170 M PI cost cap — Competed

  Smaller things — Competed

- We have tried multiple times to fit a compelling CMB mission into a Midex cap, and failed
  - With a maxed-out non-NASA contribution (30%), it *might* be possible to do something good, but it's a long shot
- In the mid-2010s, NASA (Paul Hertz) posed the question to the community

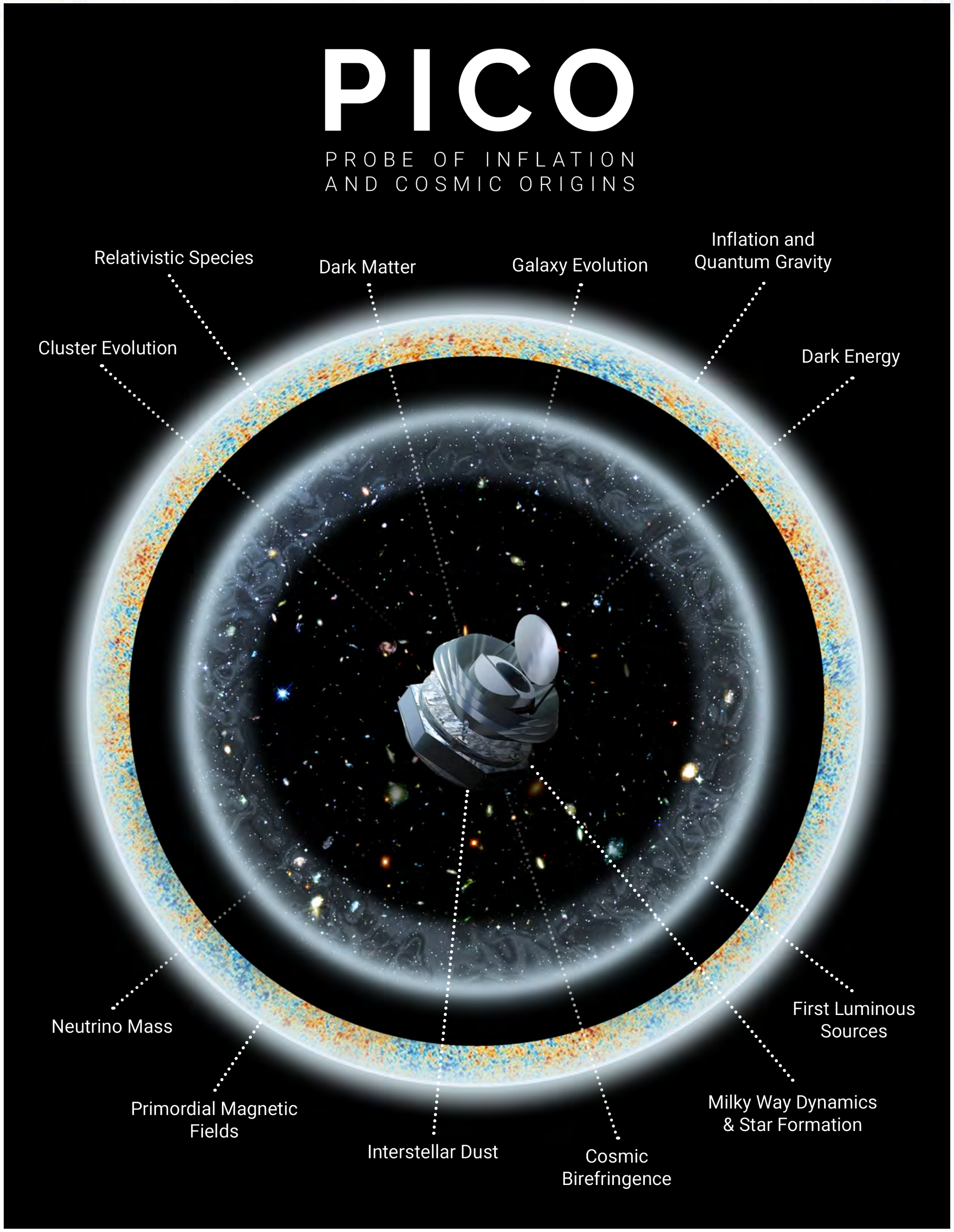
  "Does the CMB need a flagship-scale mission?"

- The answer was "no", and attention in preparation for Astro2020 turned to a possible new class of mission, Probes

Probes

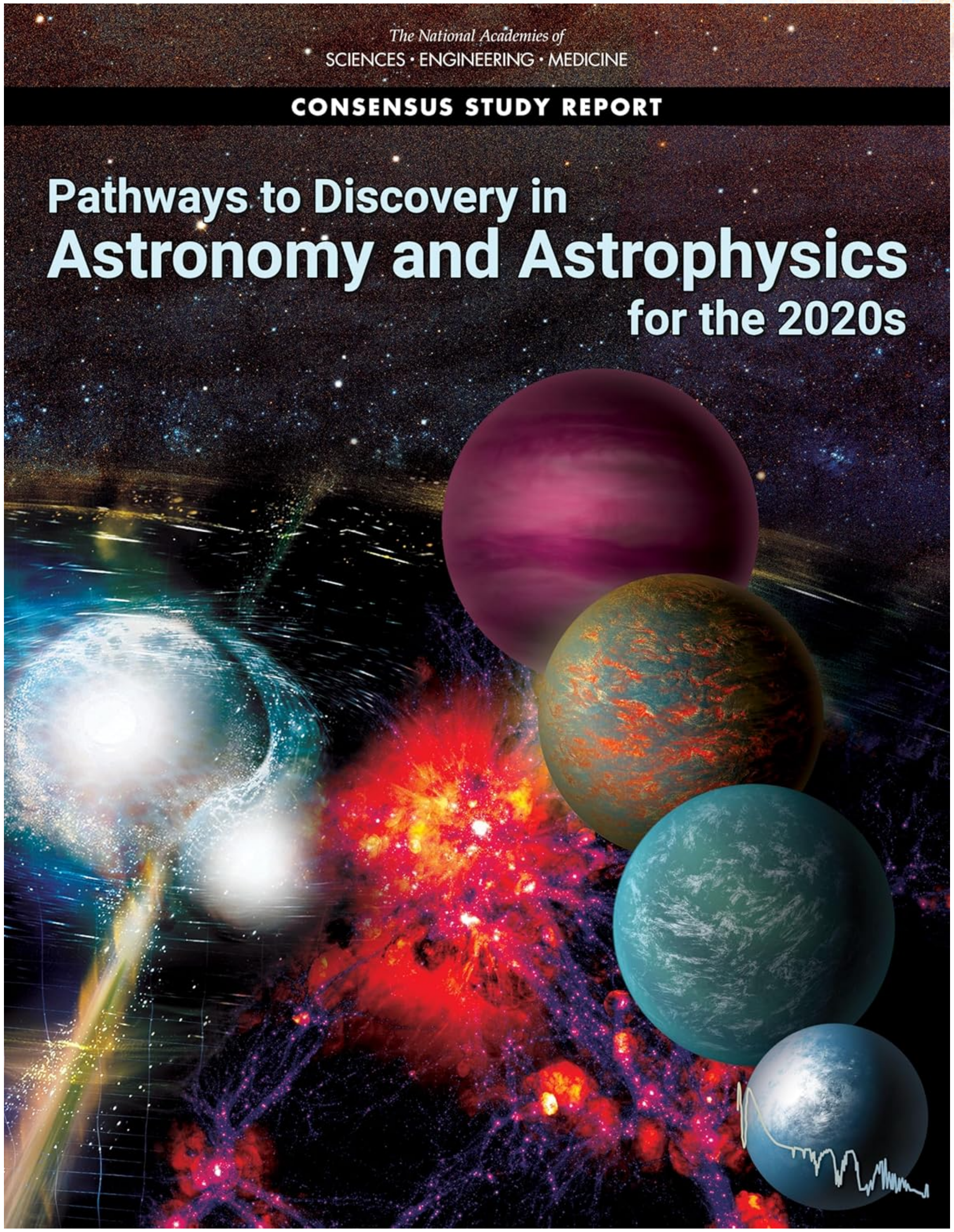
- Before Astro2020, the answer to the question "What's between a Midex and a flagship in astrophysics?" was "Nothing"
- The potential and need for missions in that OOM cost diffence between Midex and Flagship was widely discussed
- To put some thought behind the idea, NASA held a pre-decadal competition for "Probe-scale" mission concepts, and selected 11 for study.

One of Them Was . . .



Astro2020 Delivered

"In addition, the survey recommends a new line of probe missions to be competed in broad areas identified as important to accomplish the surveys scientific goals. For the coming decade, a far-IR mission, or an X-ray mission designed to complement the European Space Agency (ESAs) Athena mission, would provide powerful capabilities not possible at the Explorer scale. With science objectives that are more focused compared to a large strategic mission, and a cost cap of $1.5 billion, a cadence of one probe mission per decade is realistic."



PICO, 2019

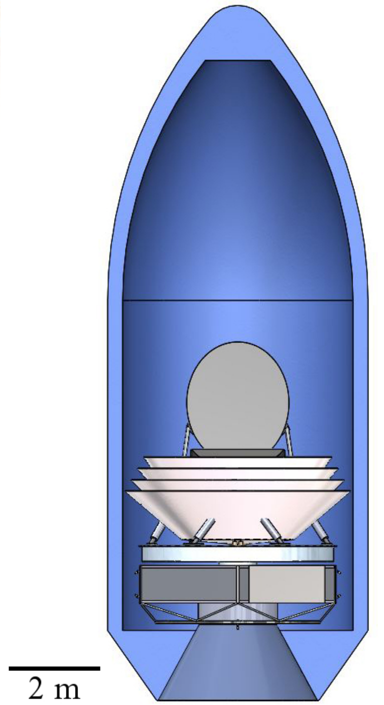


Figure 4.1: PICO is compatible with the Falcon 9.

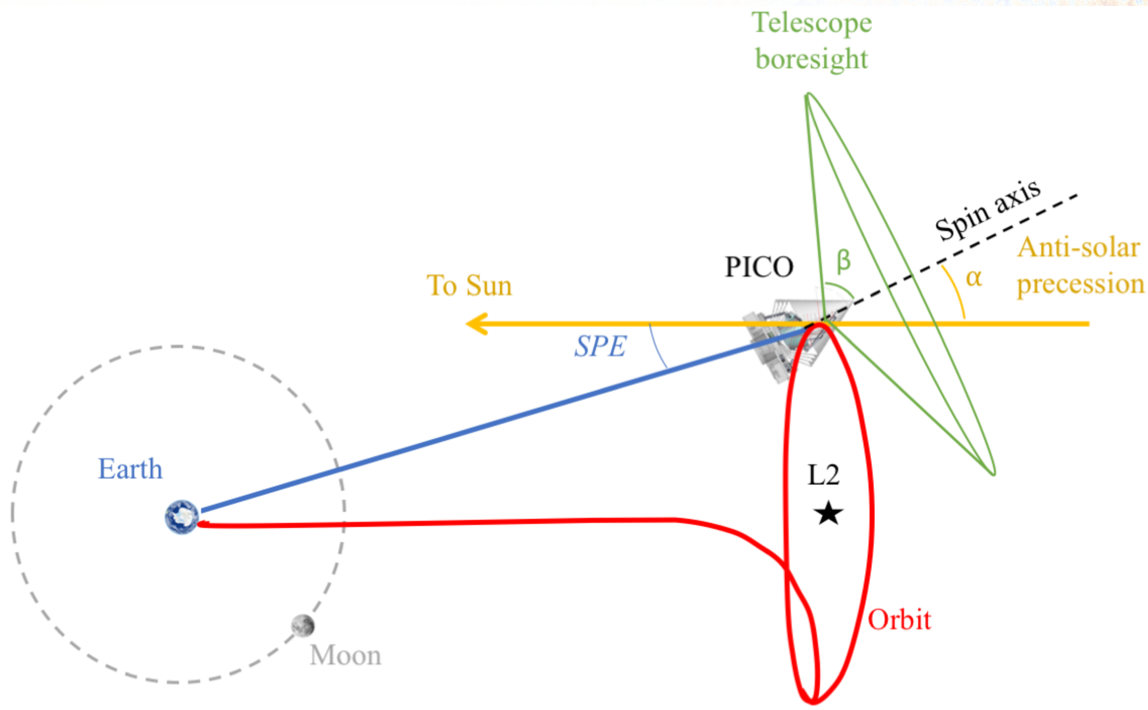


Figure 4.2: PICO surveys by continuously spinning the instrument about a precessing axis.

PICO Mission Parameters, 2019

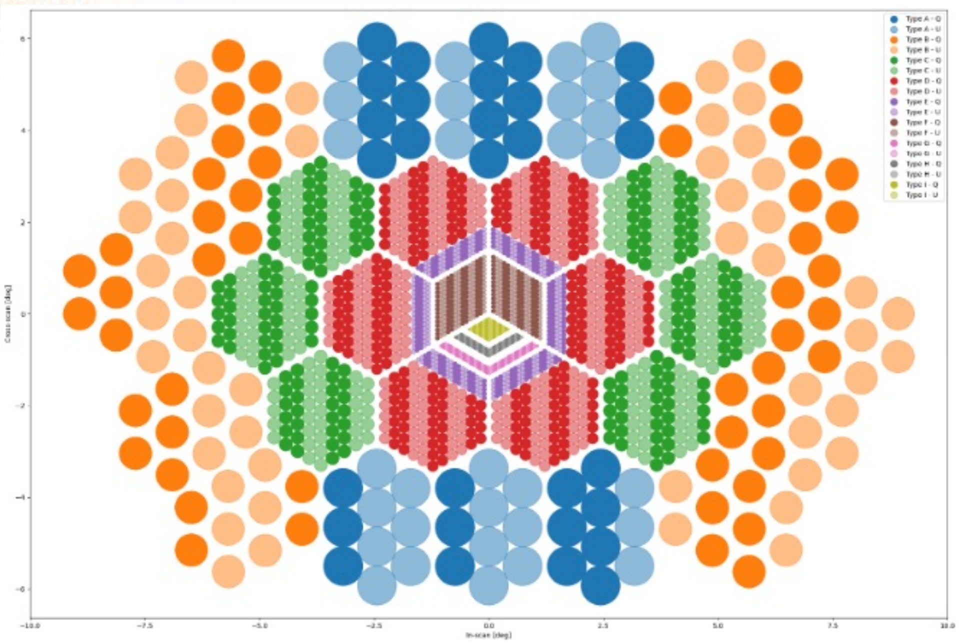
Table 1.1: **Mission Parameters**

Combined polarization map depth (rms noise in 1×1 arcmin^2 pixel):	
Baseline	0.87 μK_{CMB} arcmin equivalent to 3300 *Planck* missions
CBE[a]	0.61 μK_{CMB} arcmin equivalent to 6400 *Planck* missions
Survey duration / start	5 yrs / 2029
Orbit type	Sun-Earth L2
Launch mass	2147 kg
Total power	1320 W
Data rate	6.1 Tbits/day
Cost	$ 958M

[a] CBE = Current best estimate.

Table 3.2: PICO has 21 partially overlapping frequency bands with band centers (ν_c) from 21 GHz to 799 GHz and each with bandwidth $\Delta\nu/\nu_c = 25\,\%$. The beams are single mode, with FWHM sizes of $6\farcm2 \times (155\,\mathrm{GHz}/\nu_c)$. The CBE per-bolometer sensitivity is photon-noise limited (§ 3.2.4). The total number of bolometers for each band is equal to (number of tiles) × (pixels per tile) × (2 polarizations per pixel), from Table 3.1. Array sensitivity assumes 90 % detector operability. The map depth assumes 5 yr of full sky survey at 95 % survey efficiency, except the 25 and 30 GHz frequency bands, which are conservatively excluded during 4 hr/day Ka-band (26 GHz) telecom periods (§ 4.2).

Band center [GHz]	Beam FWHM [arcmin]	CBE bolo NET [$\mu K_{CMB}\,s^{1/2}$]	N_{bolo}	CBE array NET [$\mu K_{CMB}\,s^{1/2}$]	Baseline array NET [$\mu K_{CMB}\,s^{1/2}$]	Baseline polarization map depth [μK_{CMB} arcmin]	[Jy sr^{-1}]
21	38.4	112	120	12.0	17.0	23.9	8.3
25	32.0	103	200	8.4	11.9	18.4	10.9
30	28.3	59.4	120	5.7	8.0	12.4	11.8
36	23.6	54.4	200	4.0	5.7	7.9	12.9
43	22.2	41.7	120	4.0	5.6	7.9	19.5
52	18.4	38.4	200	2.8	4.0	5.7	23.8
62	12.8	69.2	732	2.7	3.8	5.4	45.4
75	10.7	65.4	1020	2.1	3.0	4.2	58.3
90	9.5	37.7	732	1.4	2.0	2.8	59.3
108	7.9	36.2	1020	1.1	1.6	2.3	77.3
129	7.4	27.8	732	1.1	1.5	2.1	96.0
155	6.2	27.5	1020	0.9	1.3	1.8	119
186	4.3	70.8	960	2.0	2.8	4.0	433
223	3.6	84.2	900	2.3	3.3	4.5	604
268	3.2	54.8	960	1.5	2.2	3.1	433
321	2.6	77.6	900	2.1	3.0	4.2	578
385	2.5	69.1	960	2.3	3.2	4.5	429
462	2.1	133	900	4.5	6.4	9.1	551
555	1.5	658	440	23.0	32.5	45.8	1580
666	1.3	2210	400	89.0	126	177	2080
799	1.1	10400	360	526	744	1050	2880
Total			12 996	0.43	0.61	0.87	



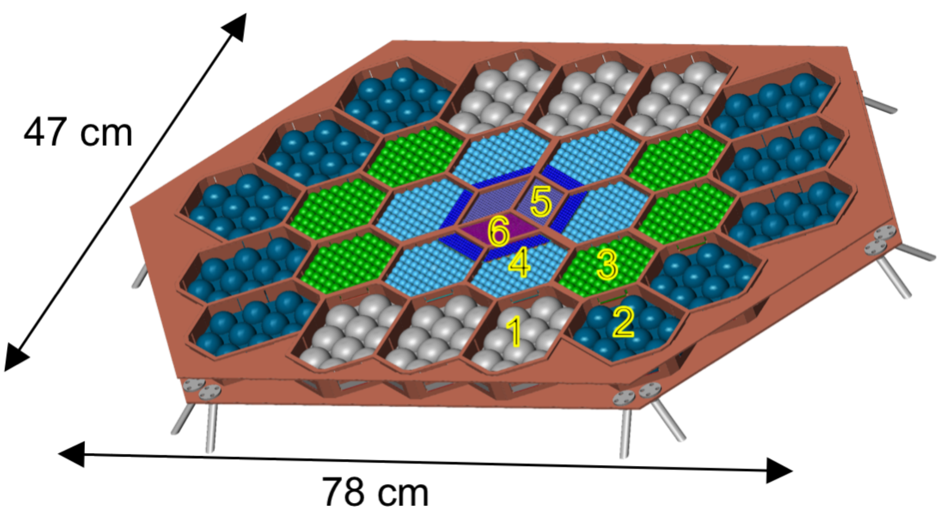


Table 3.1: PICO makes efficient use of the focal area with multichroic pixels (three bands per pixel, § 3.2.1). The sampling rate is based on the smallest beam (Table 3.2), with 3 samples per FWHM at a scan speed $(360^\circ/\text{min})\sin(\beta = 69^\circ) = 336^\circ/\text{min}$. Scaling from suborbital experience, we anticipate that TES bolometers can support these sampling rates with $\sim 4\times$ margin.

Tile type	N_{tile}	Pixels/ tile	Pixel type	Band centers [GHz]	Sampling rate [Hz]
1	6	10	A	21, 30, 43	45
2	10	10	B	25, 36, 52	55
3	6	61	C	62, 90, 129	136
4	6	85	D	75, 108, 155	163
		80	E	186, 268, 385	403
5	2	450	F	223, 321, 462	480
6	1	220	G	555	917
		200	H	666	
		180	I	799	

7.5.3.5 An Early Universe Cosmology and Fundamental Physics Probe

As detailed in the report of the Panel on Cosmology, studies of the cosmic microwave background continue to provide data that address profound and fundamental questions about the universe on the largest scales and during its earliest moments. As noted by the EOS-2 panel report, “space observations will unquestionably be needed for the best foreground separation and the lowest systematic errors on all angular scales, and especially on angular scales of greater than about ten degrees.” With investment in technologies this decade, combined with ground-measurements, cosmic microwave background (CMB) probe mission could potentially be a compelling candidate for the future probe call in the 2030’s, complementing the survey’s ground-based CMB-S4 recommendation.

- This is the **only** mention of a 2030 Probe candidate by Astro2020

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Foreground separation and constraints on primordial gravitational waves with the PICO space mission

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Results: PICO r constraints for different sky models

r = 0 and r = 0.003 after 73% delensing

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Sky model	r = 0: $r_{95\%}$	r = 0.003: [r ± σ(r)]
Planck Baseline: dust + sync	2.6 x 10^{-4}	(3.15 ± 0.16) x 10^{-3} ✓
Two component dust model + sync + AME	1.5 x 10^{-4}	(3.09 ± 0.13) x 10^{-3} ✓
Physical Dust + sync + AME	1.3 x 10^{-4}	(3.09 ± 0.11) x 10^{-3} ✓
Tigress MHD simulation (dust, sync) + AME	2.7 x 10^{-4}	(3.09 ± 0.11) x 10^{-3} ✓
Multi-Layer Dust + sync + AME	13.2 x 10^{-4}	(3.93 ± 0.32) x 10^{-3} ✗

r = 0.003 Recover input r value with ~ 20σ confidence
→Strongest for any proposed instrument

⇒ 3σ bias

Why is it biased for the Multi-Layer Dust?
→ Foreground residuals
→ Full sky: some patches of sky more contaminated than others → Multipatch analysis

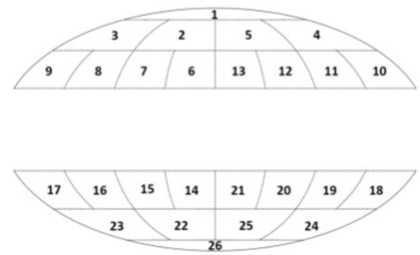
10

Multipatch analysis

- MultiLayer sky model: Biased estimation of r
- Mitigation of the bias → compare independent

constraints on r from independent sections of the sky

Equal area sky sections with fsky = 2.5%



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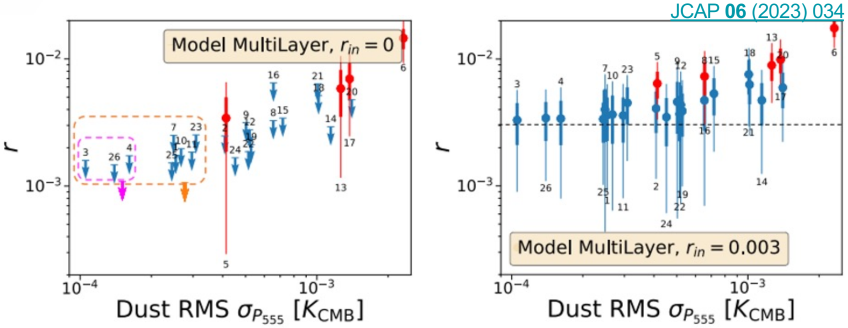


95% confidence limits for r = 0 and r = 0.003 per patch

⇒ Need a space mission with high sensitivity

- Dust → Bias
- Tracer of dust: 555 GHz
- Least contaminated patches:
  For r = 0, $r_{95\%} = 1.9\text{x}10^{-3}$ (magenta) $r_{95\%} = 1.6\text{x}10^{-3}$ (orange)

11

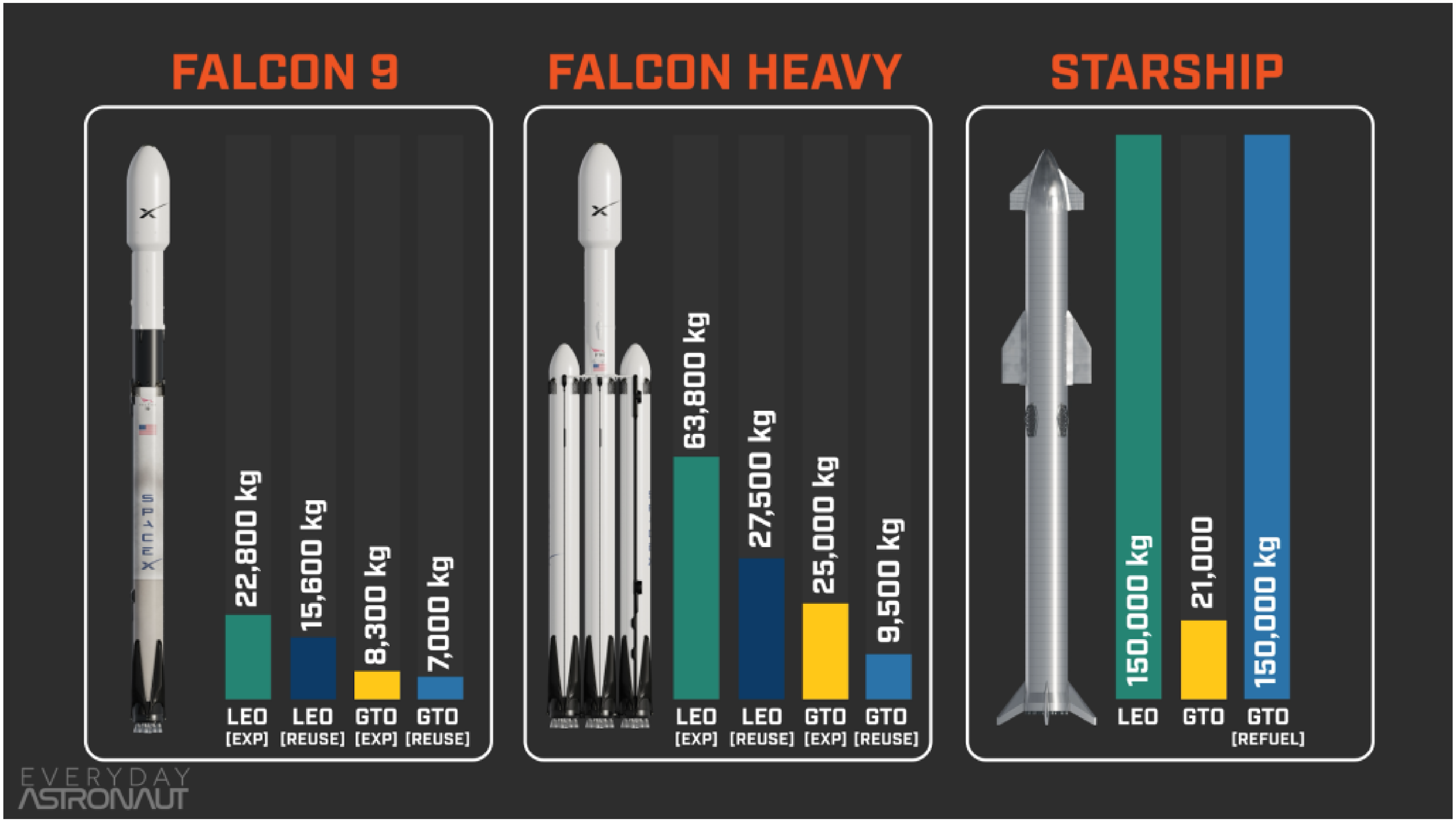
555GHz: frequency channel close to CMB channels and dominated by dust

The bias comes from the areas of sky with high polarized intensity from dust.

If we estimate r on the patches which are least contaminated by dust, r estimation is no longer biased for r= 0. What about r = 0.003?

WHAT'S CHANGED SINCE 2019? — I

- Rockets are getting bigger and cheaper



https://everydayastronaut.com/definitive-guide-to-starship/

What's Changed Since 2019? — Ia

https://impulso.space/blog/posts/falcon-heavy-vs-starship/

What's Changed Since 2019? — II

- Foregrounds and delensing are becoming better understood
- Superconducting parametric amplifiers have been demonstrated at centimeter wavelengths, with noise about 2X the quantum limit
- The schedule for CMB-S4 has slipped. Instead of taking data in 2027 or so, the expectation at the time of Astro2020, the current estimate.
  - The scheme of "ground first" then "Probe-scale space in 2030" has to be rethought
  - Also, the first Probe call was in 2023, not 2020

Summary

- Space is still there
- Work on foreground separation and delensing for a Probe-scale mission continues at a low level
- NASA is supporting some relevant technology development
- Ground-space complementarity should be reassessed as part of studies being undertaken