Future Prospects for Anisotropy Measurements in Space

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Scope

- I'll only talk about anisotropy measurements
- Tomo will talk about LiteBIRD, which aims to get to $r \sim 10^{-3}$
- I'll take for granted that there is a need to:
  - measure or put limits on r *below* 10^{-3}
  - measure or put limits on the B-mode power spectrum for $\ell <\sim 30$

    $\Rightarrow$ As a practical matter, I do not think either of these is possible from the ground, ever.

- My question for today: is there a path to achieve such levels?

Possibilities?

- Only ESA, NASA, and CNSA can do missions of the scale required
  - CNSA — CMB is not mentioned in the development program announced last October (but that was a very broad summary)
  - ESA — Voyage 2050 L-class candidate is for spectral distortions
  - NASA — a real possibility in the Probe line of missions

The expected second NASA Probe call in ∼2031 offers the only credible opportunity in the foreseeable future for an $r \lesssim 10^{-4}$ anisotropy mission.

Astro2020 and "Probes"

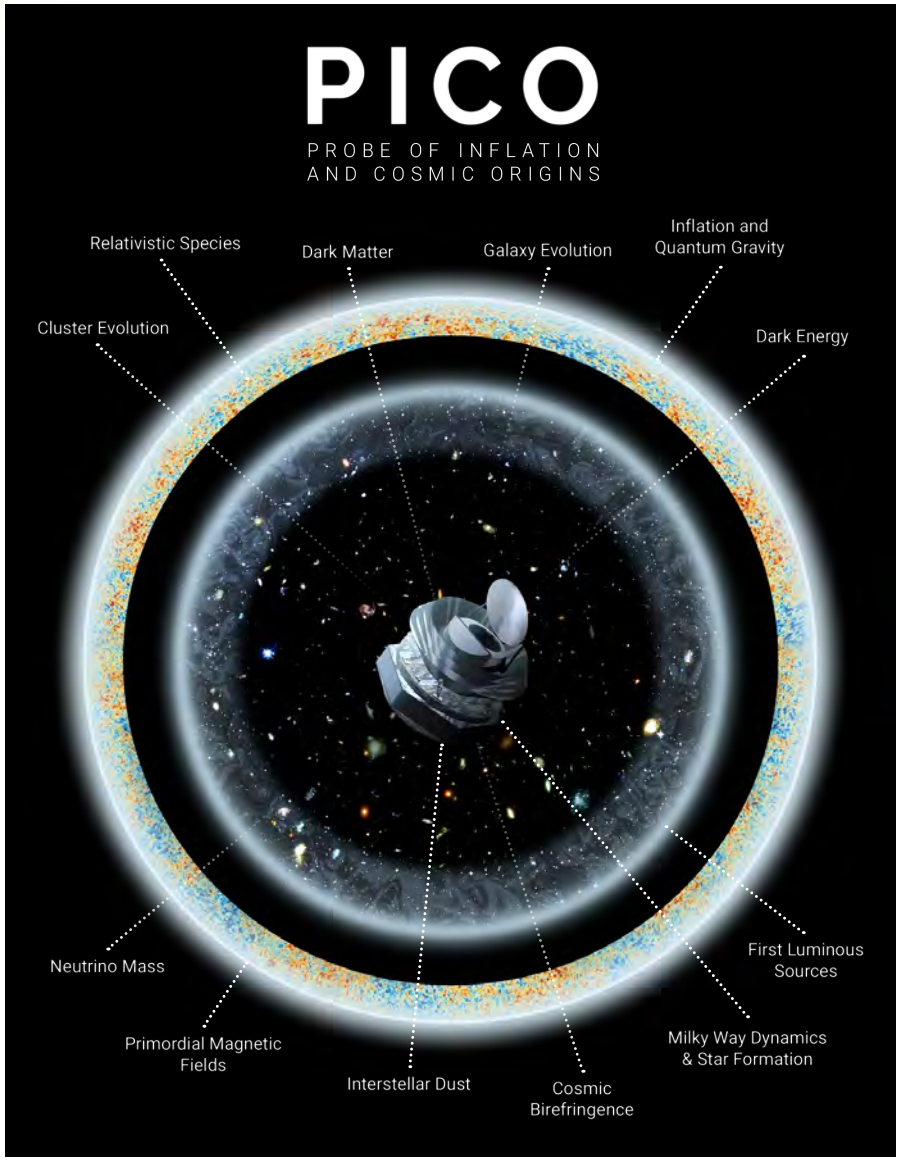
- During the 2010's, there was a growing recognition that the gap between "Explorer" missions, with cost caps up to about $350 M, and "flagships", costing many $B, provided a huge opportunity for science
- To demonstrate this, NASA funded 11 mission concept studies with a "PI cost cap" of $1 B

  Which along the way became known as "Probe" class
- Astro2020 recommended

  "Institution of a Probe-class line of missions with a cost cap of ∼$1.5 B per mission, a cadence of ∼one per decade, and competed within selected priority areas identified by this and future decadal surveys, is a crucial addition to NASA's astrophysics portfolio. The two priorities for the first Probe-cass mission competition are a far-IR probe or an X-ray probe to complement the Athena mission."

Astro2020 and the CMB — I

- One of the probe mission concept studies was PICO,



https://science.nasa.gov/wp-content/uploads/2023/04/PICO_Study_Rpt.pdf?emrc=30c7fb)

- For the ground, CMB-S4 was well-advanced, and in 2014 the Particle Physics Project Prioritization Panel (P5) had recommend CMB research for increased funding.

- Astro2020 had a lot to say about the CMB, e.g.,
  - "... higher angular resolution and sensitivity CMB observations from the ground and in space will be needed given the difficulty of detecting the small B-mode signal amidst the polarized galactic foreground."
  - "Higher sensitivity and higher resolution CMB observations motivated to a significant extent by cosmology (Section 2.2) will have a large impact on the understanding of galaxy formation as well."

Astro2020 and the CMB — II

- Put simply, CMB-S4 was ready to go, PICO wasn't, so...
- Astro2020 recommended CMB-S4 as its second-highest priority for new projects on the ground (after the much bigger ELT Program)
  - Jointly funded by DOE and NSF
  - Start of observations nominally 2027
- It also said:

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.

Why PICO Wasn't Ready

- More development was required to demonstrate it could deal with realistic foregrounds and systematics at the target 10^{-4} level
  - Foregrounds

    CMB-S4 Concept Definition Taskforce report in 2017 first showed that equivalent angular resolution was needed at low and high frequencies to deal with non-Gaussian structure in the synchrotron background

    PICO had $\theta \propto \lambda$, so big beams at low frequencies

    Likely could not deal with realistic, non-Gaussian, synchrotron foregrounds at the 10^{-4} level
  - Detector coupling

    PICO used three-color sinuous antenna/lenslet pixels for the 2–462 GHz bands
    [Edwards, O'Brient, Lee, Rebeiz, IEEE Transactions on Antennas and Propagation (Volume: 60, Issue: 9, September 2012)]

    Plane of polarization of sinuous antennas rotates with frequency, $\pm 5^\circ$ over two octaves in frequency. Scary!

    Never demonstrated in the field. Scary.
- Both problems driven by the 5.2-m Falcon 9 rocket shroud
  - Limited the volume and design of the telescope...
  - ...and in turn the size of the focal plane

What's Changed? — I

- In May 2024 the NSF said it would undertake no new experiments at Pole "for at least a decade"
  - CMB-S4 has spent the last year redesigning to be an all-Chile experiment, with first data now no earlier than 2035 (see Francois Bouchet's talk)

What's Changed? — II

https://universemagazine.com/en/daytime-splashdown-spacex-announces-date-for-new-starship-mission/

https://eu.floridatoday.com/picture-gallery/tech/science/space/2025/01/16/blue-origin-launches-first-new-glenn-rocket-from-cape-canaveral-space-force-station-in-florida/77718136007/

An Opportunity

- Astro2020 strongly affirmed the importance of CMB science
  - Ground first (CMB-S4 data in 2027)
  - Space next ("potentially a compelling candidate for the future probe call in the 2030's")

    The current probe missions in Step 2 (= phase A) show launch in 2031. Add 10 years...?
  - But CMB-S4 is delayed by at least 8 years
- We should definitely update the previous probe study, PICO, focusing first on the following:
  - The telescope

    Design — three-mirror-anastigmats have much larger undistorted focal plane than PICO's open-Dragone design

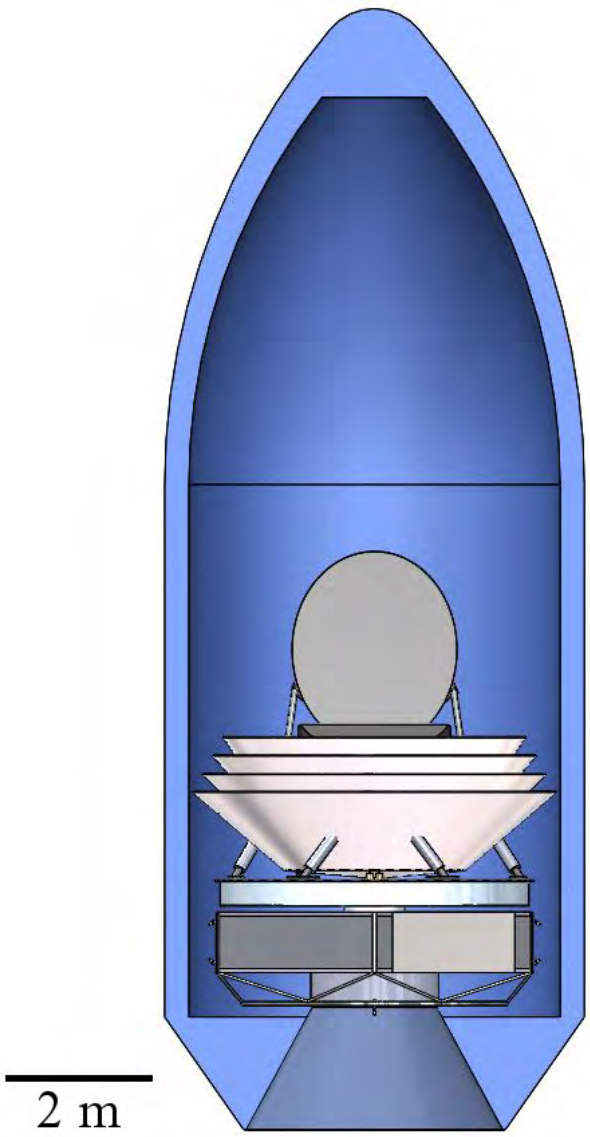
    $\Rightarrow$ much more space for detectors, no more multichroic feeds

    Size

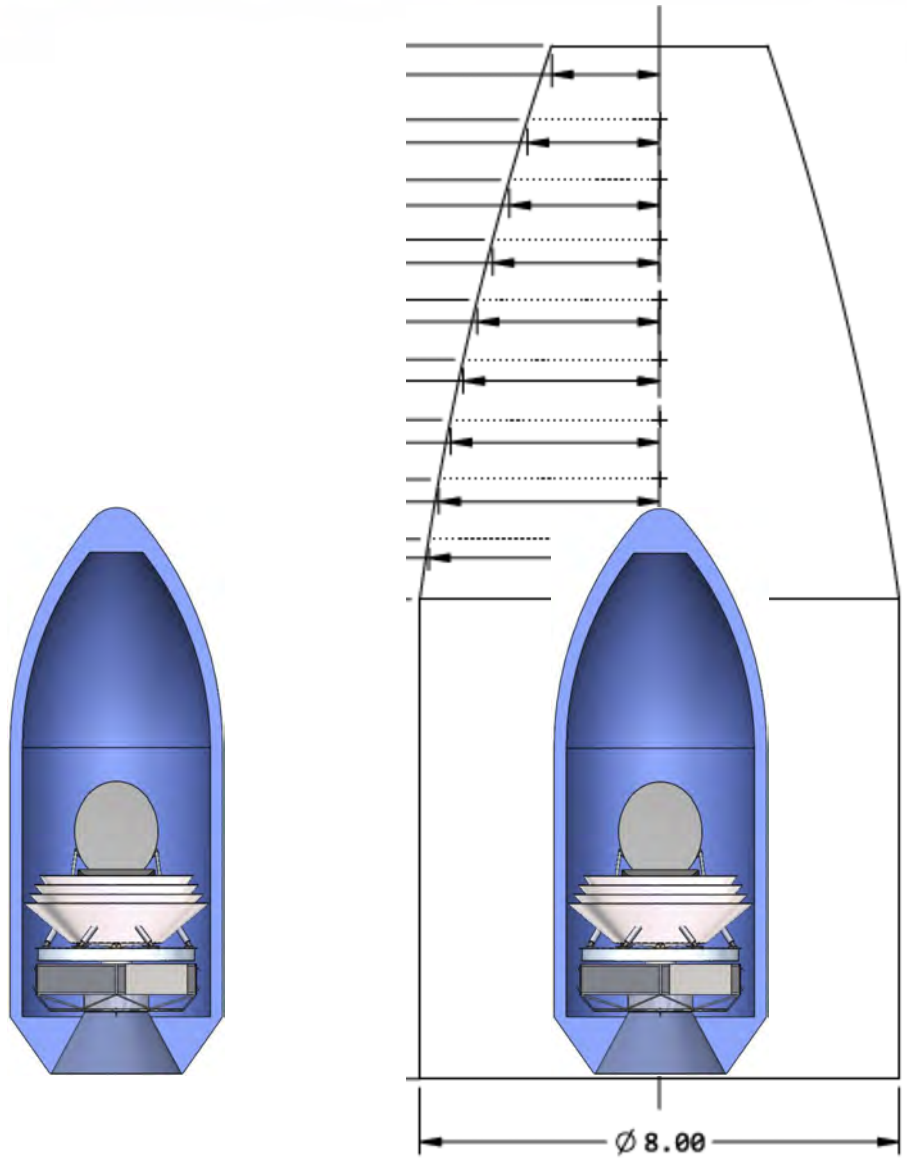
    $\Rightarrow$ enough resolution at low frequencies to deal with non-Gaussian synchrotron foregrounds

    $\Rightarrow$ the prospect to go to $\ell > 5000$, even higher

PICO in Falcon 9 Shroud



PICO in Starship Shroud

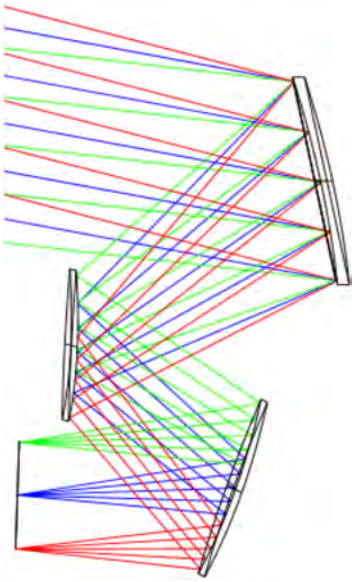


https//www.spacex.com/media/starship_users_guide_v1.pdf

How Large a Telescope Will Fit in a Starship?

- I don't know
- To explore, start with the 5-m TMA that Steve Padin designed for CMB-S4 at the South Pole

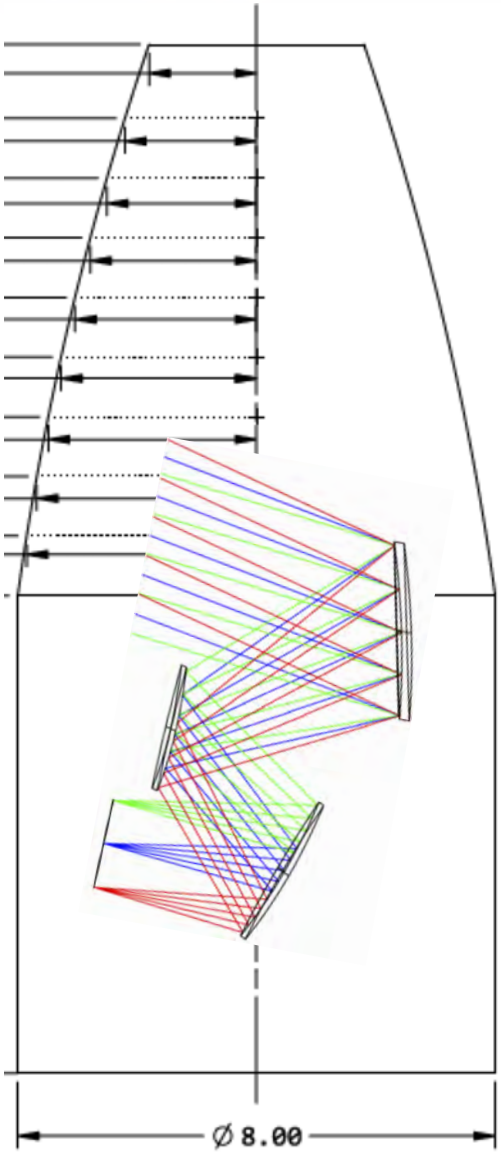
S. Padin, Applied Optics Vol. 57, Issue 9, pp. 2314-2326 (2018) https://doi.org/10.1364/AO.57.002314



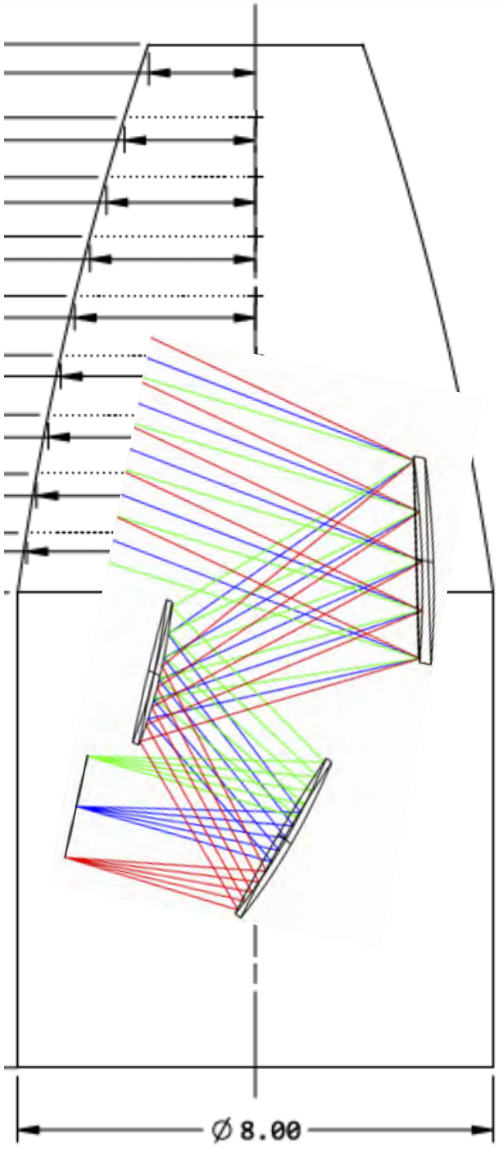
  - FOV $12 \times 8^\circ$ at $\lambda = 3$ mm
  - Can accommodate 424k / 136 k / 63 k $F\lambda$ pixels at $\lambda = 1/2/3$ mm
  - PICO only had 13 k detectors, scrunched up in di- and trichroic pixels. TMA focal plane larger than necessary.

- In subsequent slides, scale to
  - 3 m
  - 3.5 m
  - 4 m
  - and rotate so that principal ray is 69° from spin axis, as in PICO

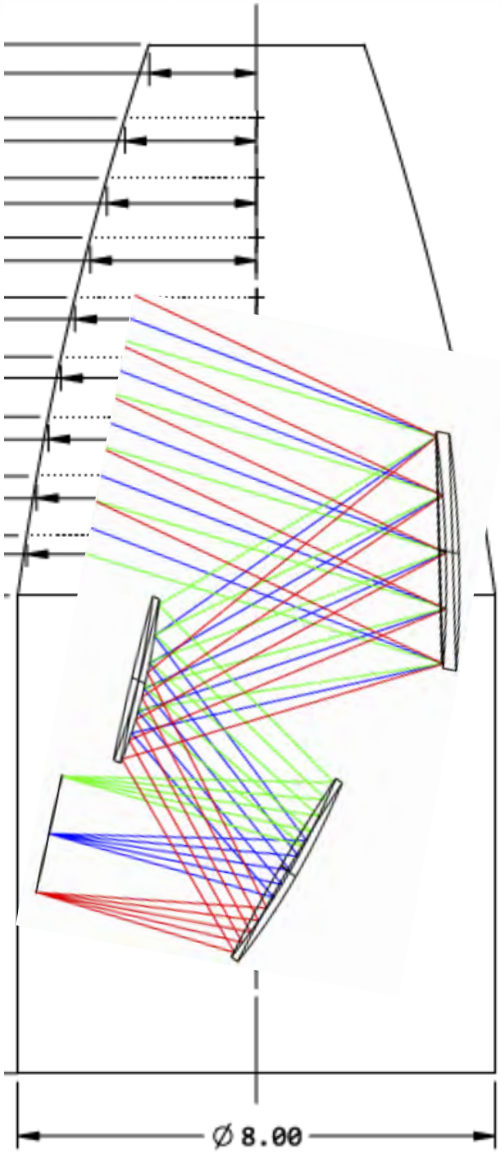
3-m TMA in Starship



3.5-m TMA in Starship



4-m TMA in Starship



Summary

- There is a credible programmatic path to a space mission that could get to $r < 10^{-4}$
  - With angular resolution at low frequencies to deal with non-Gaussian synchrotron foregrounds
  - With angular resolution to deal very effectively with delensing, cluster science, other astrophysics, time-domain observations, etc.
- Taking advantage of much larger rockets, there is design space to investigate to realize such a mission
- There no guarantees and many uncertainties
- I hope many of you here today will be interested in helping with that investigation.