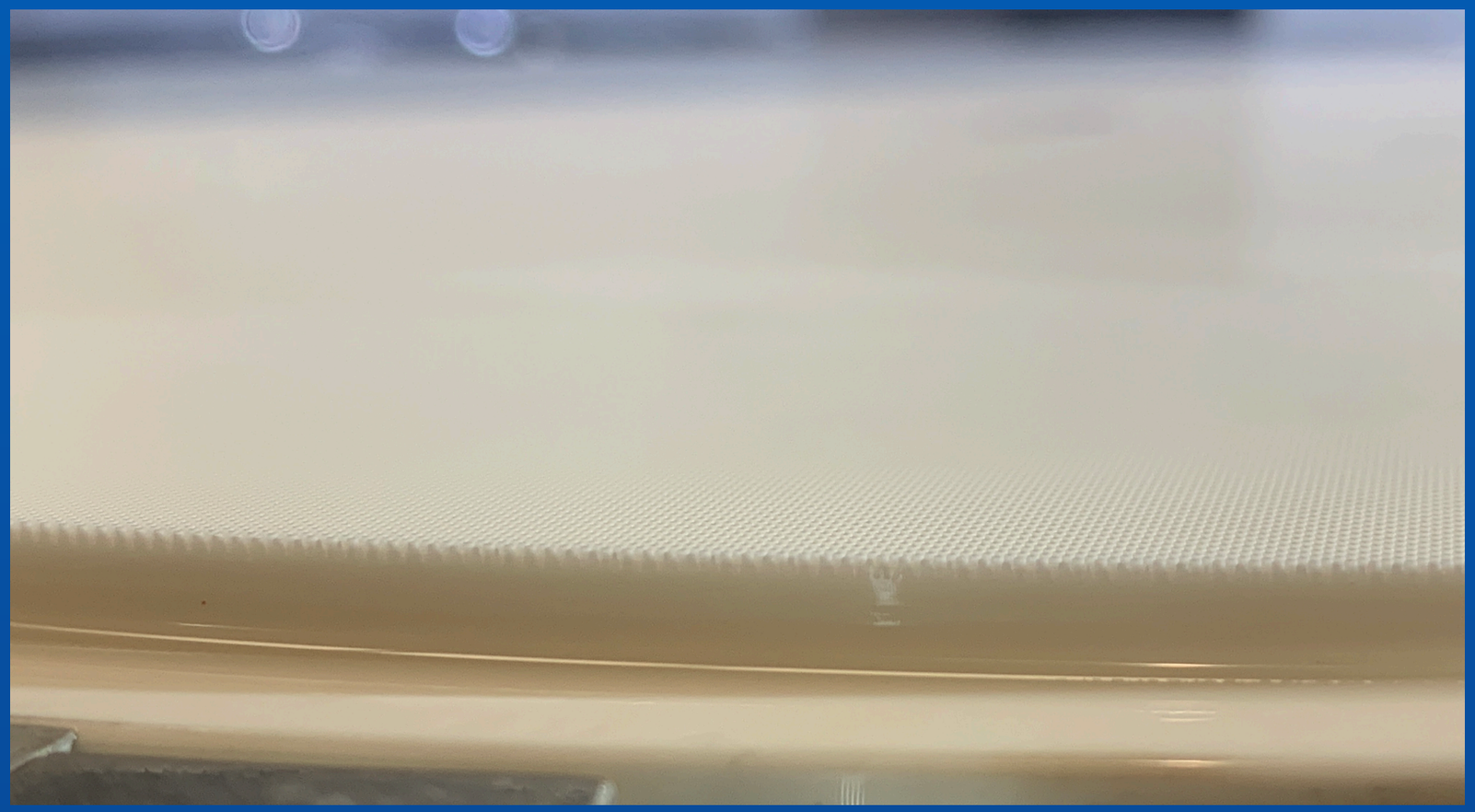
Metamaterial Anti-Reflection Coating Alumina Optics for CMB-S4



Joey Golec

New Prospectives 2021

8/16/21

FERMILAB-SLIDES-21-078-V

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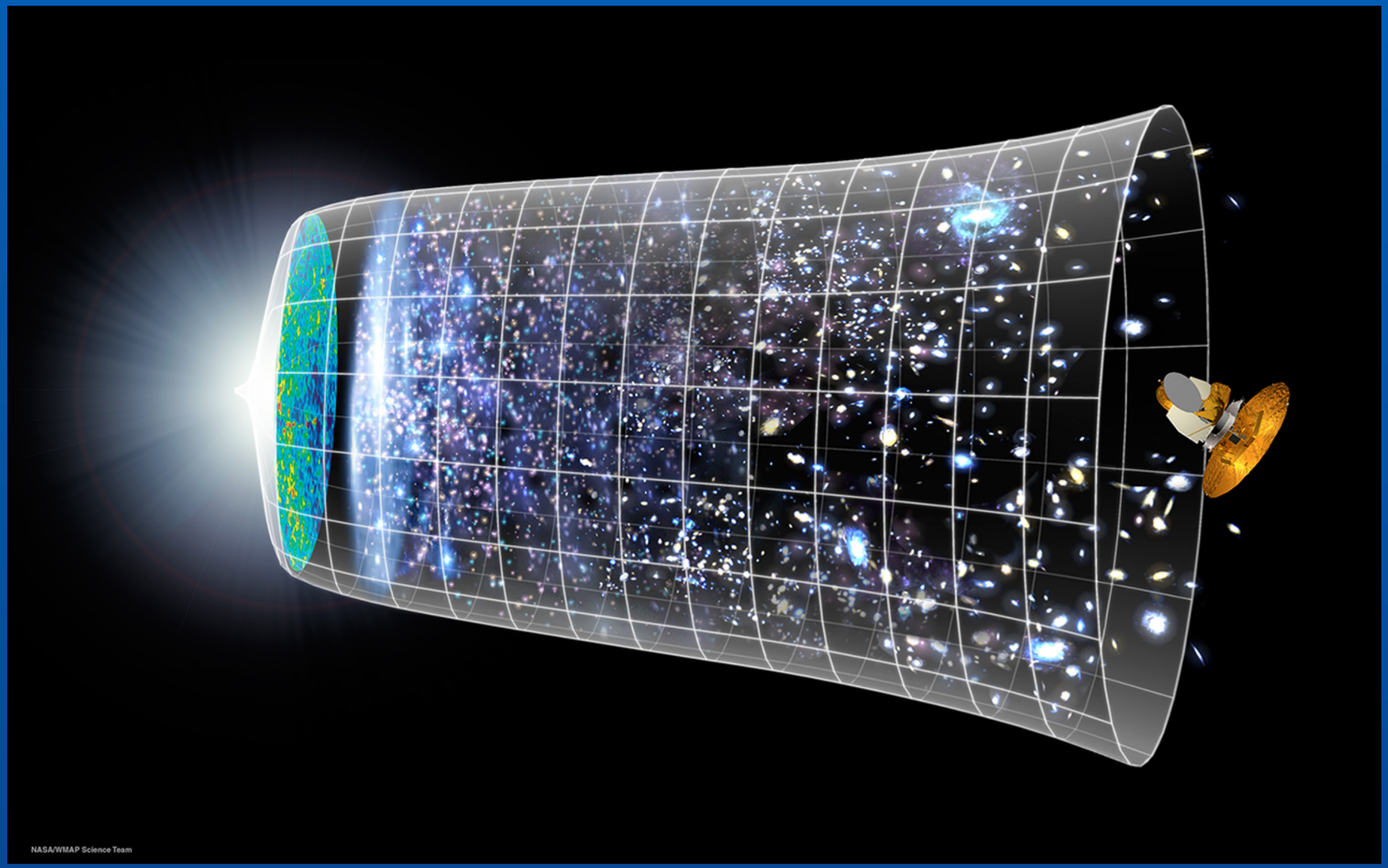
The CMB



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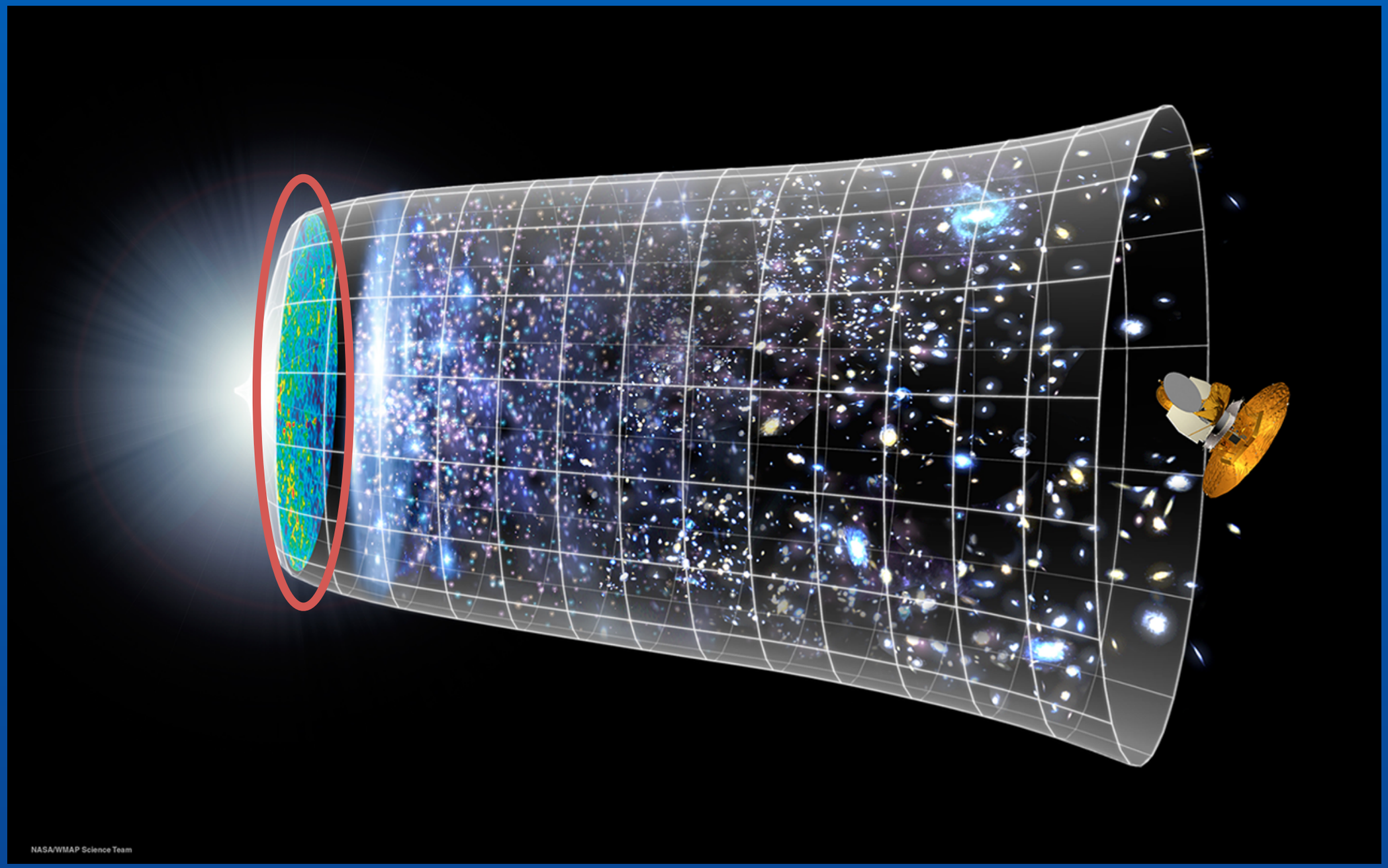

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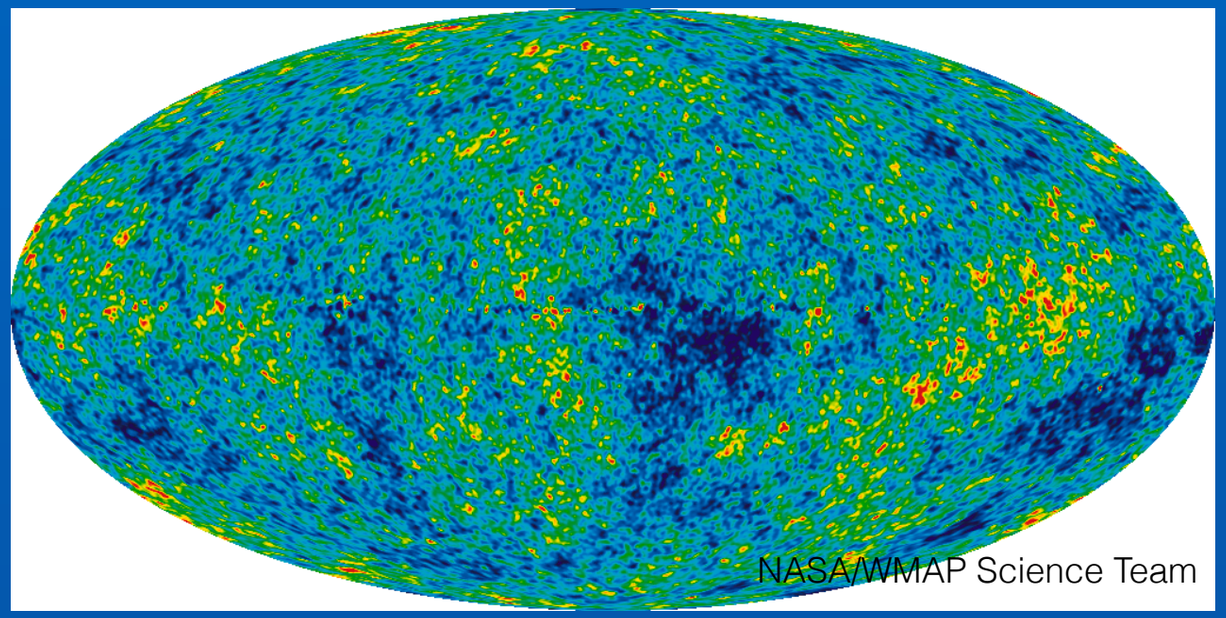

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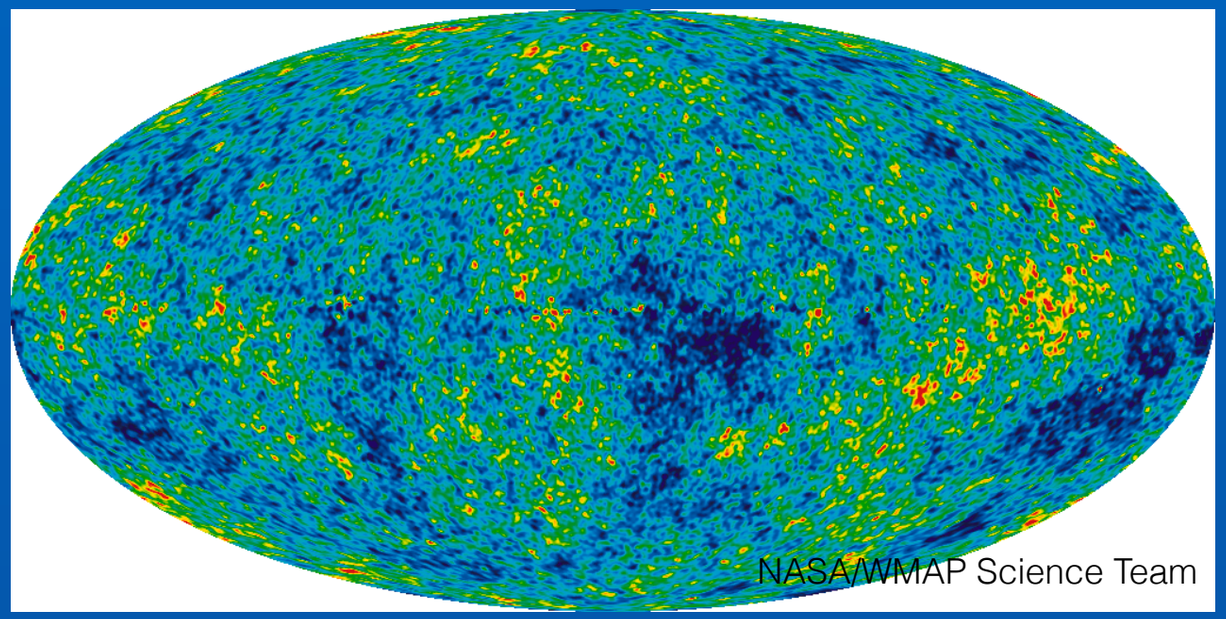
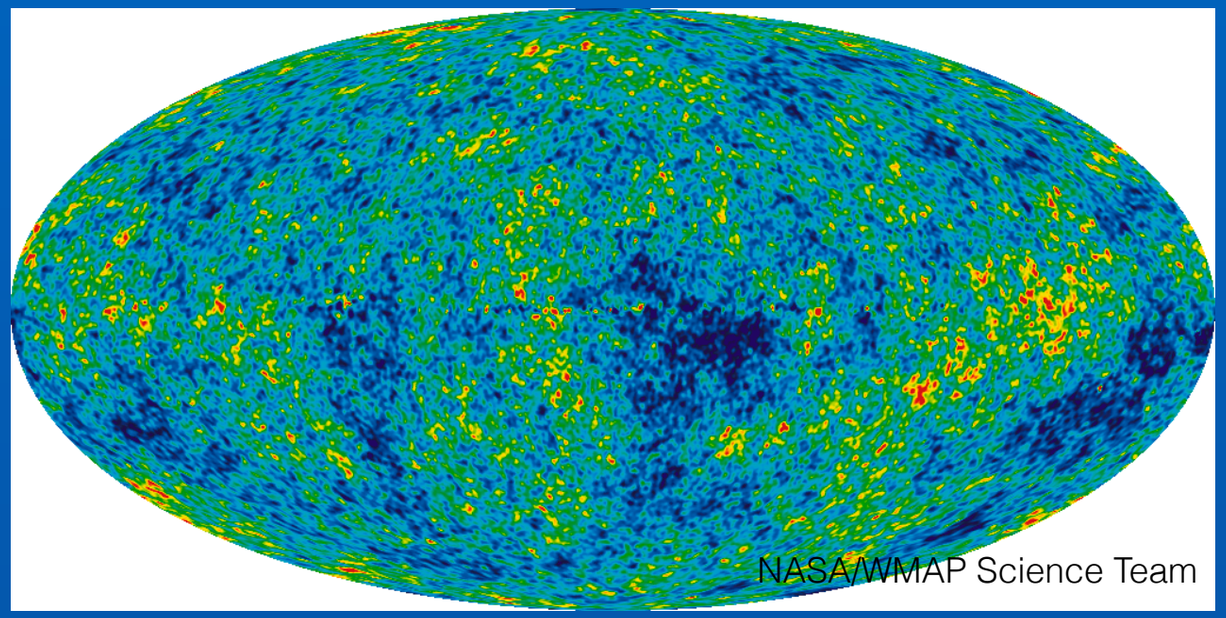


Decompose into spherical harmonics

The CMB



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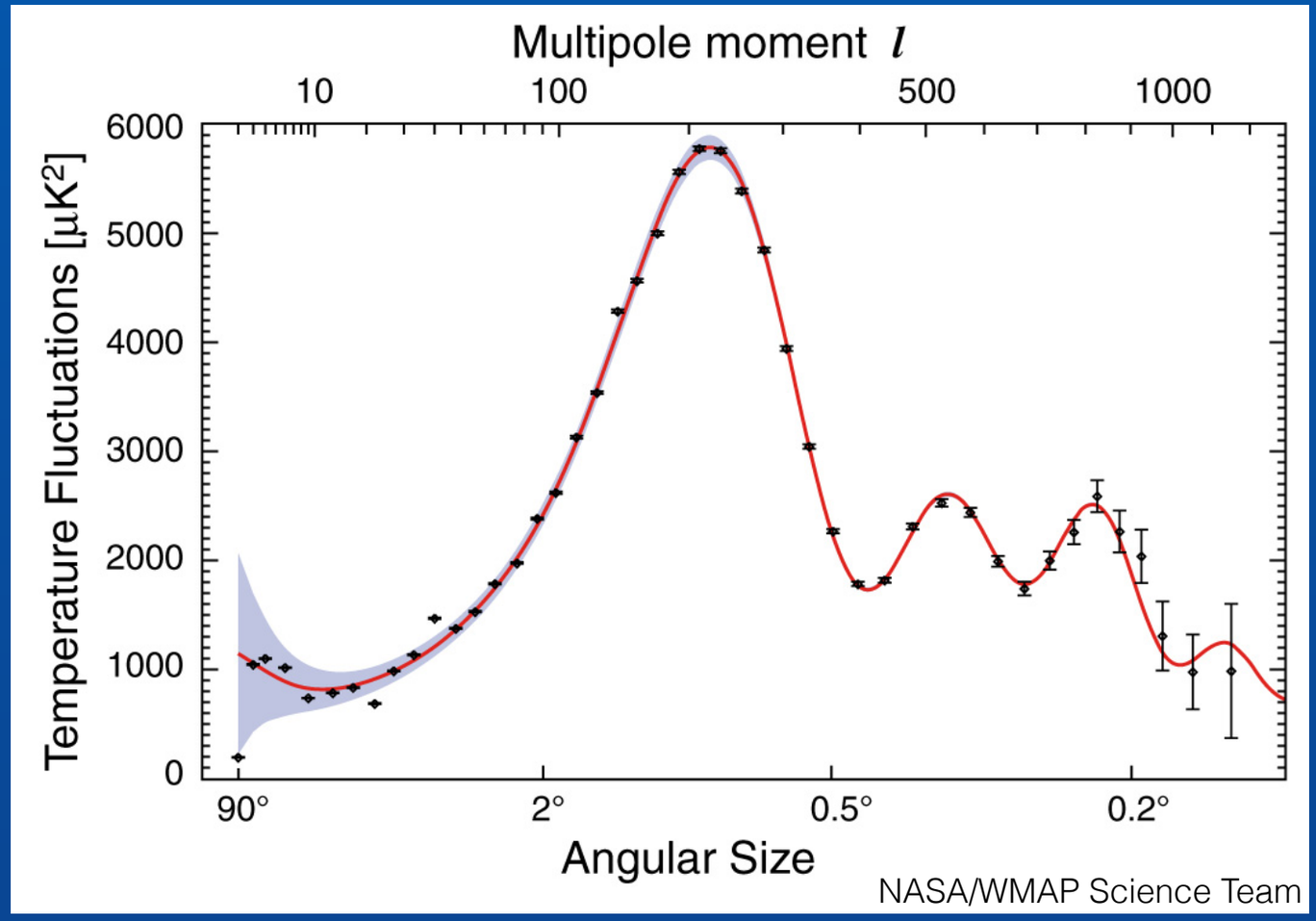
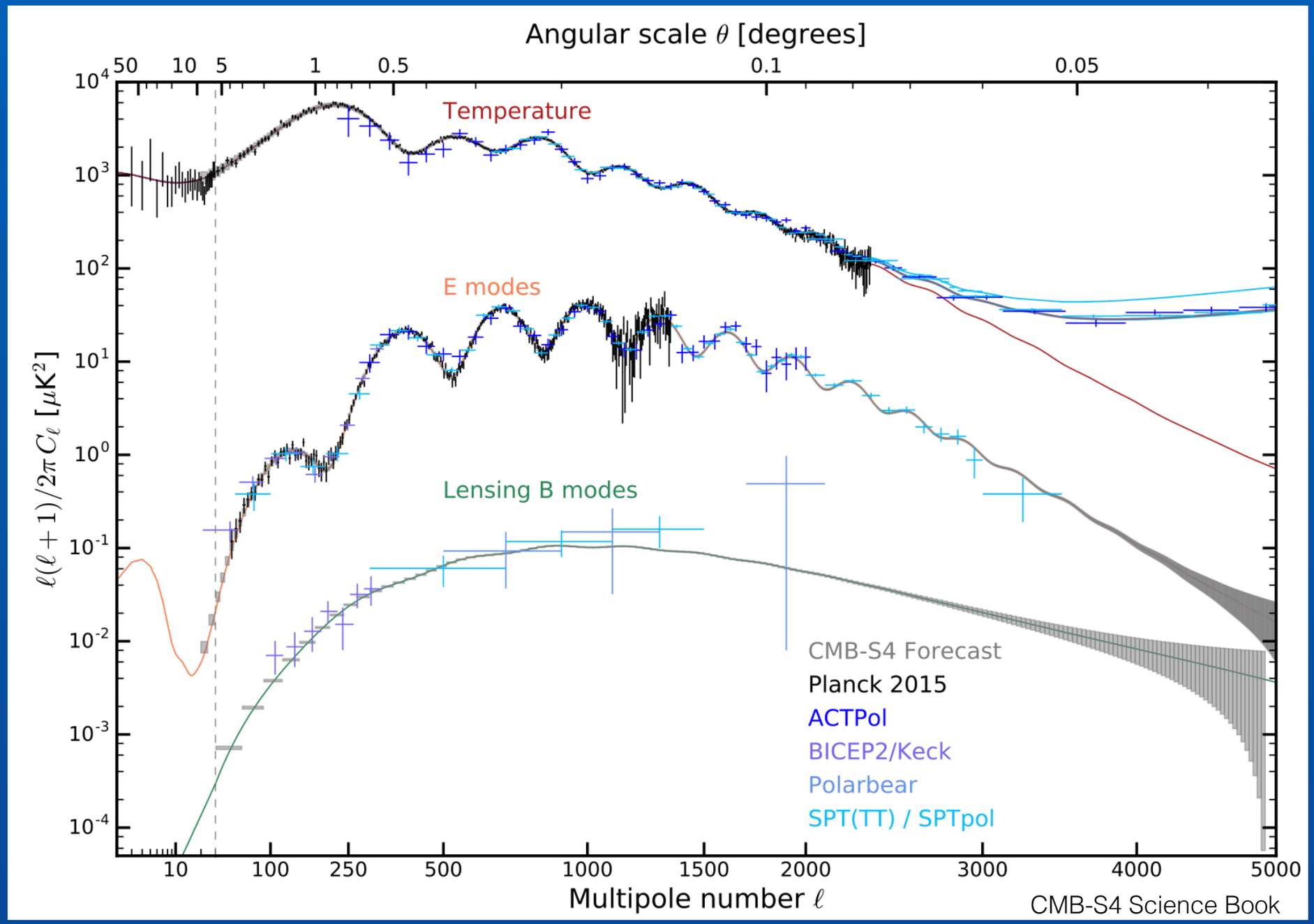
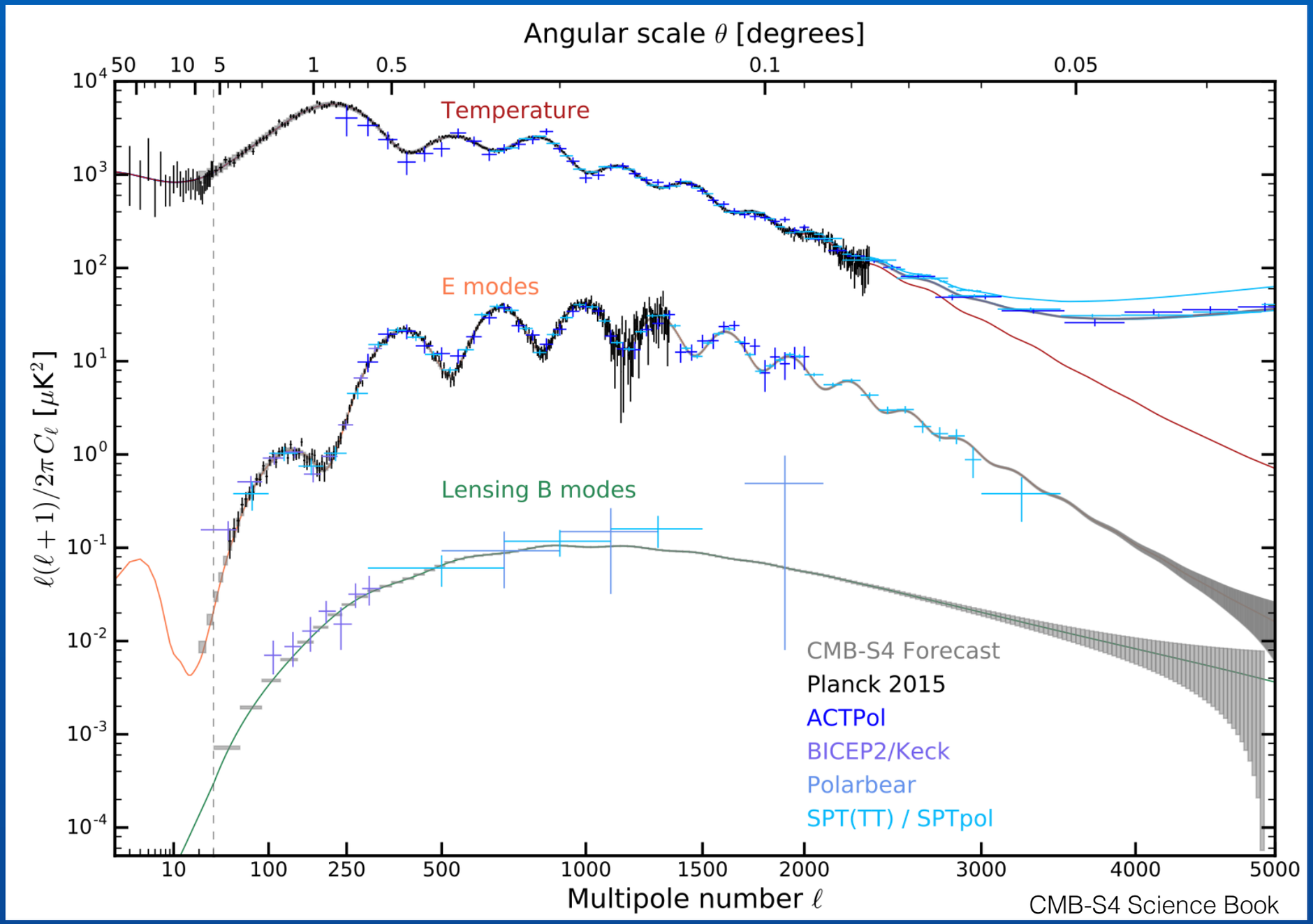


CMB-S4 Science Themes



CMB-S4 Science Themes

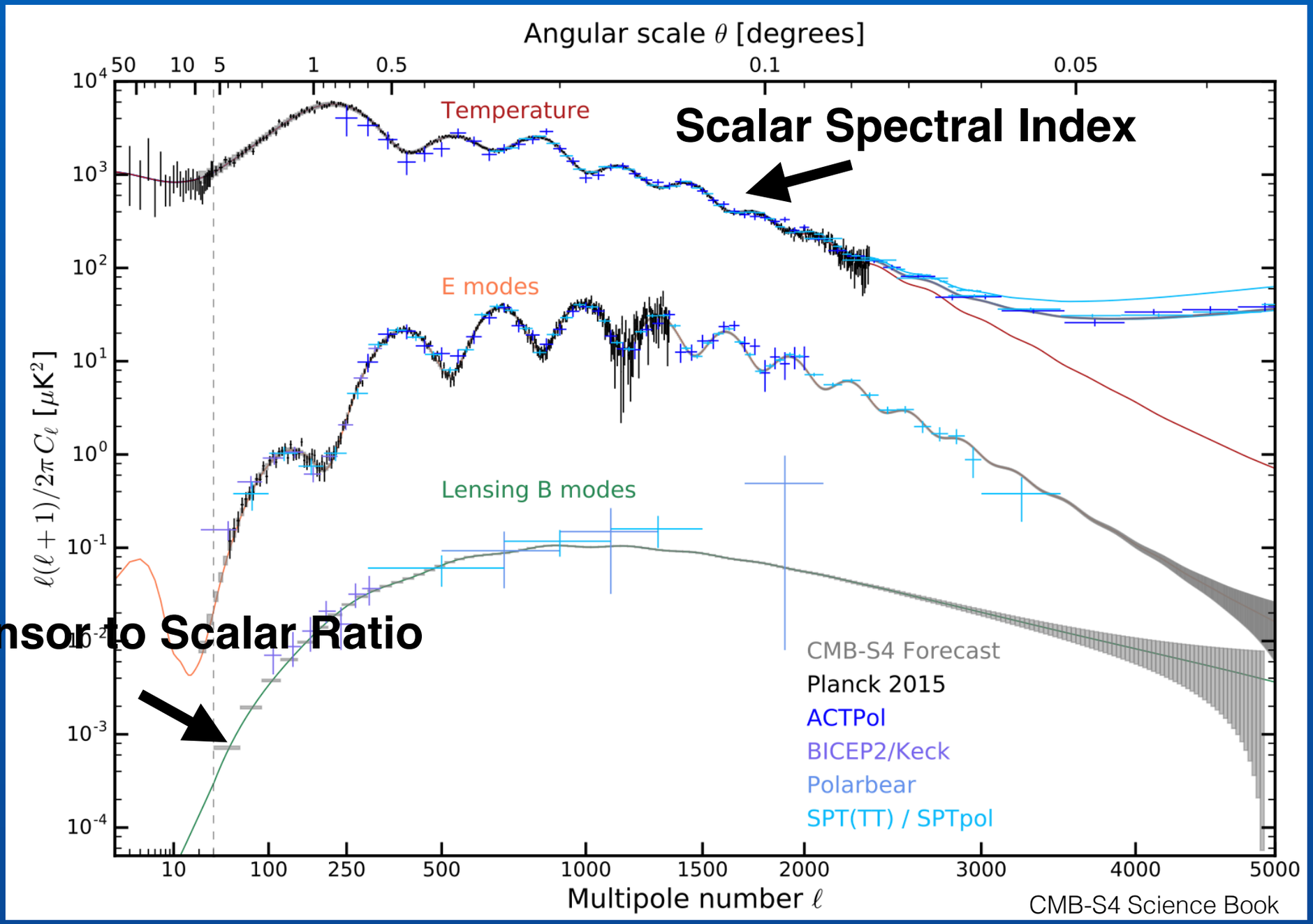
1. Constrain Inflation



CMB-S4 Science Book

CMB-S4 Science Themes

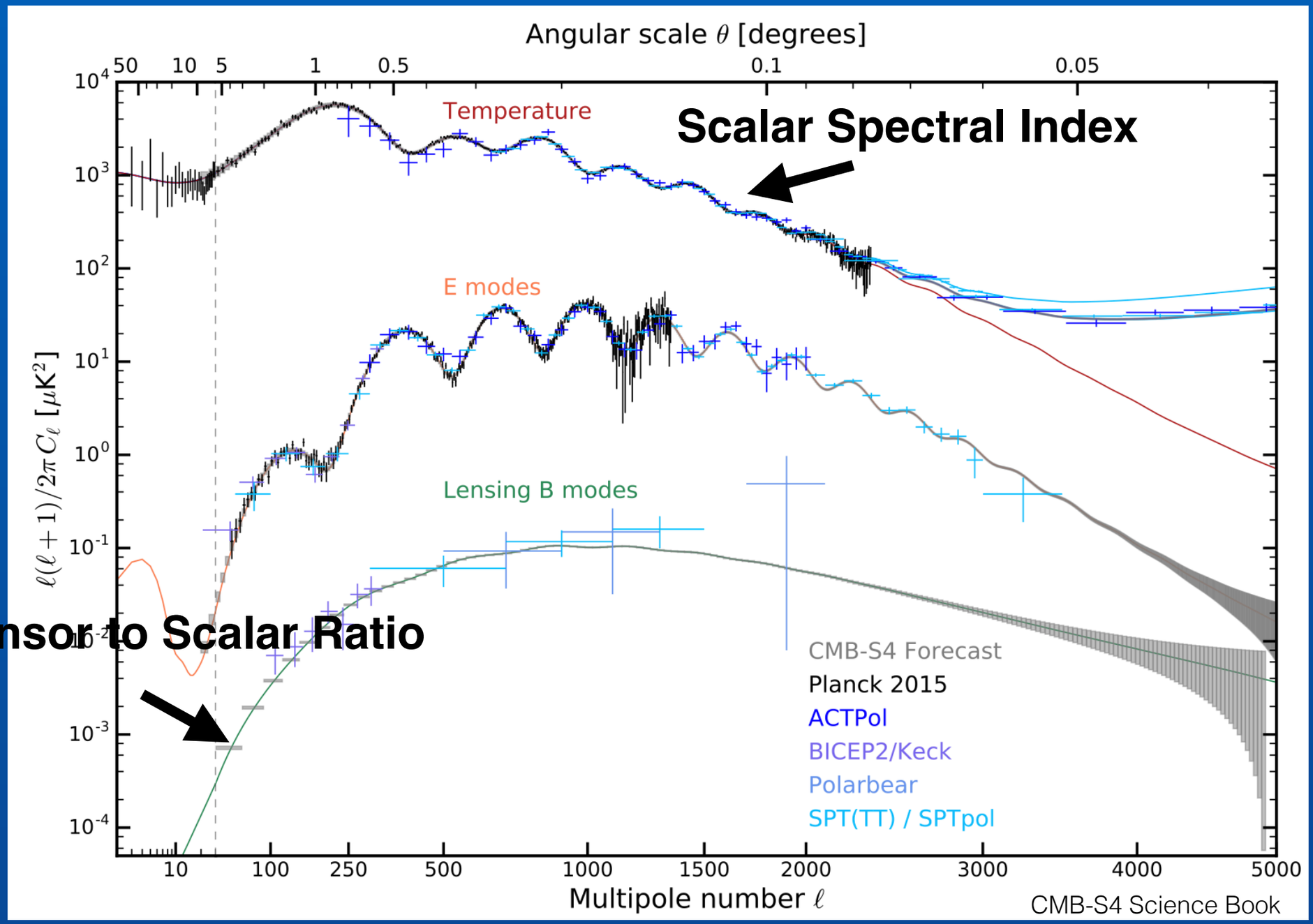
1. Constrain Inflation



CMB-S4 Science Themes

1. Constrain Inflation

2. Investigate the “Dark” Universe



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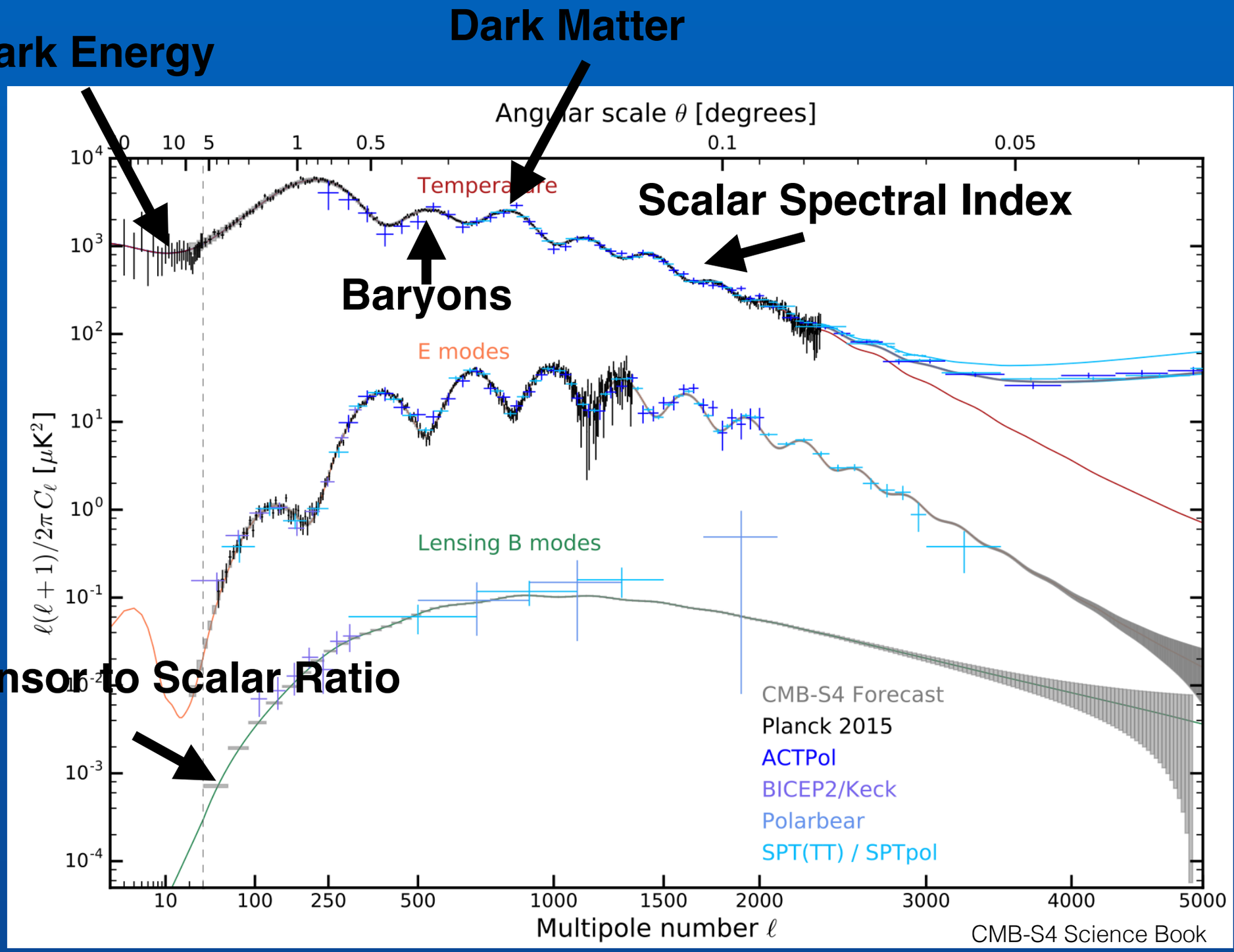
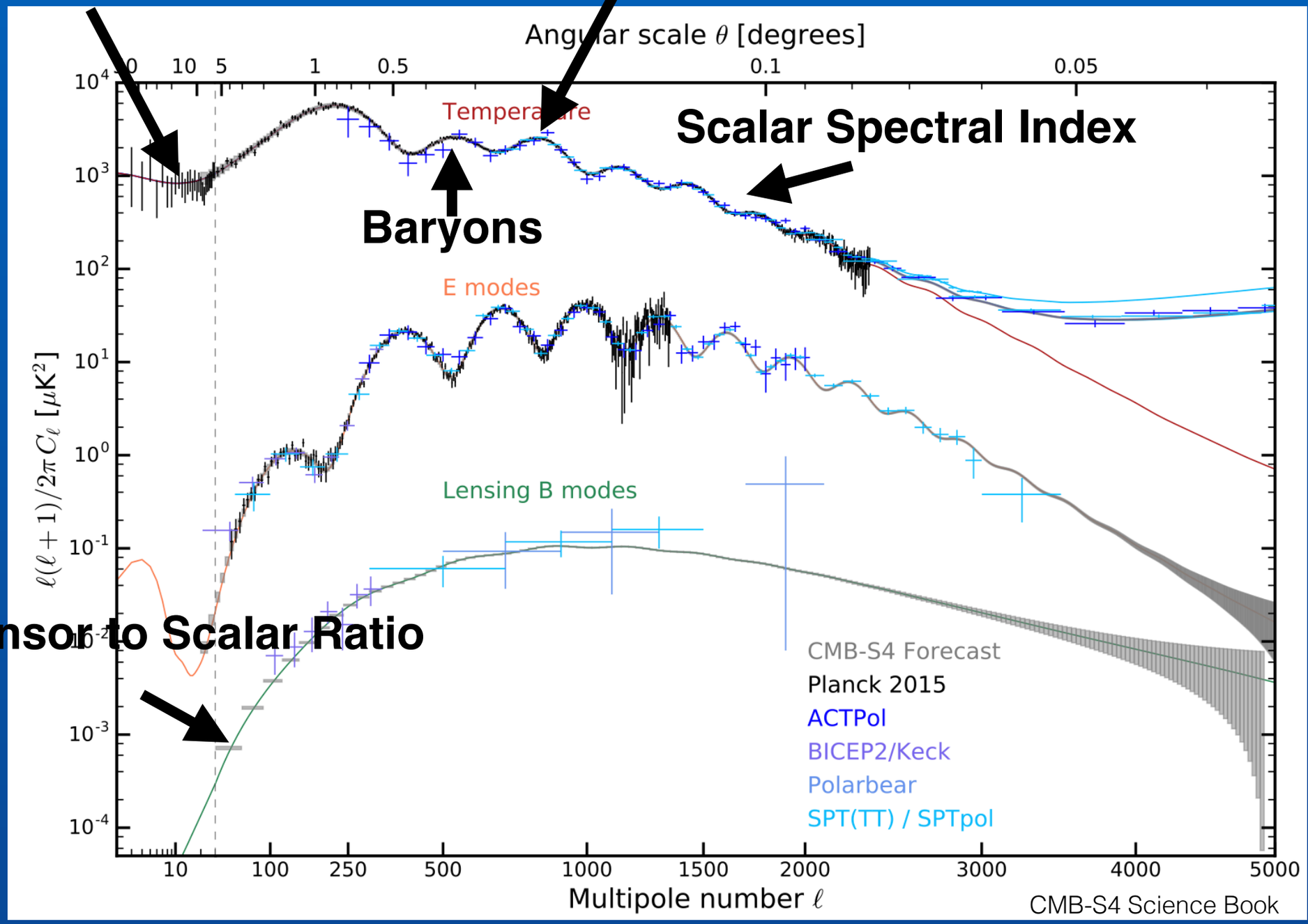


CMB-S4 Science Themes

1. Constrain Inflation
2. Investigate the “Dark” Universe
3. Map the matter distribution in the universe



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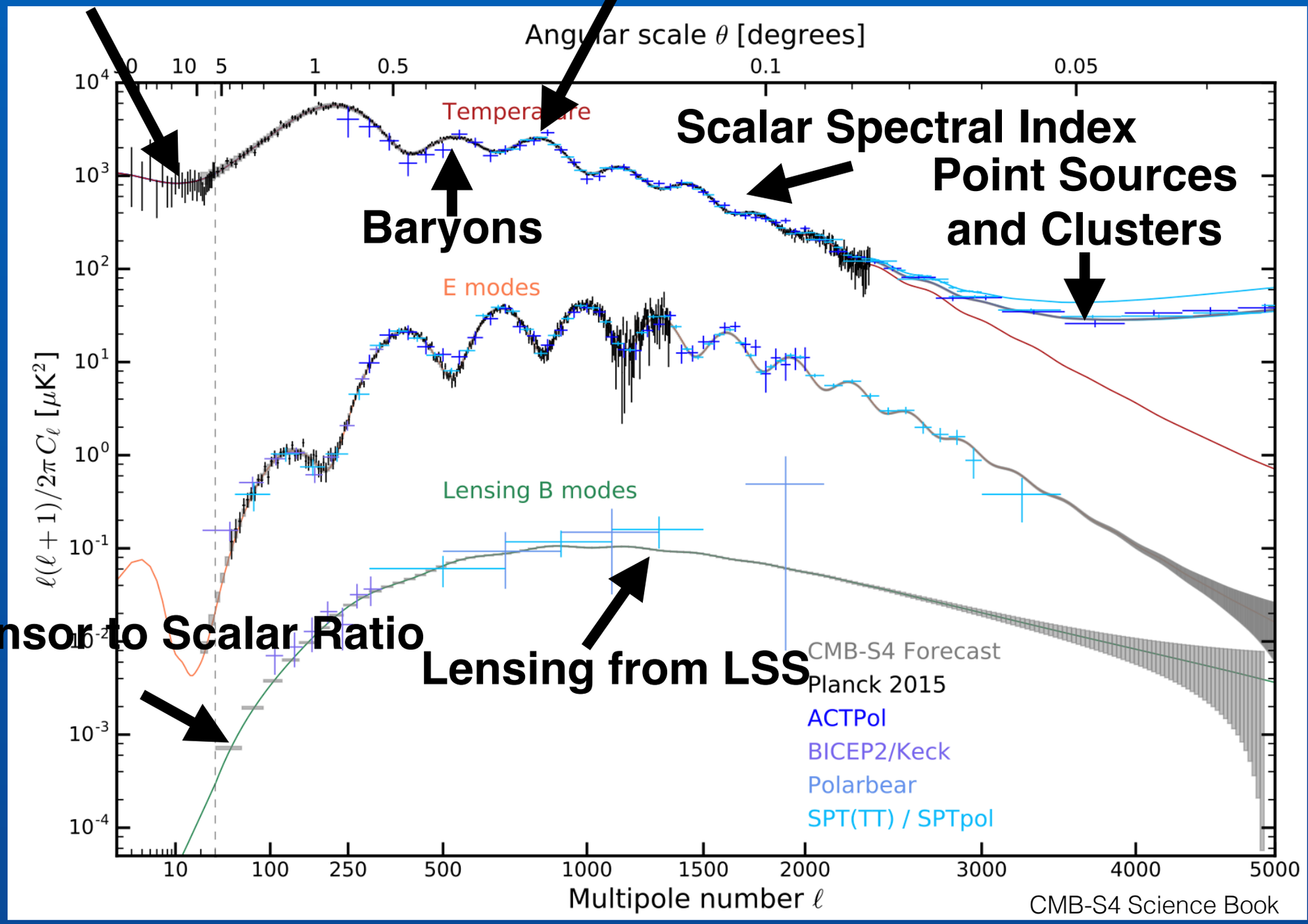
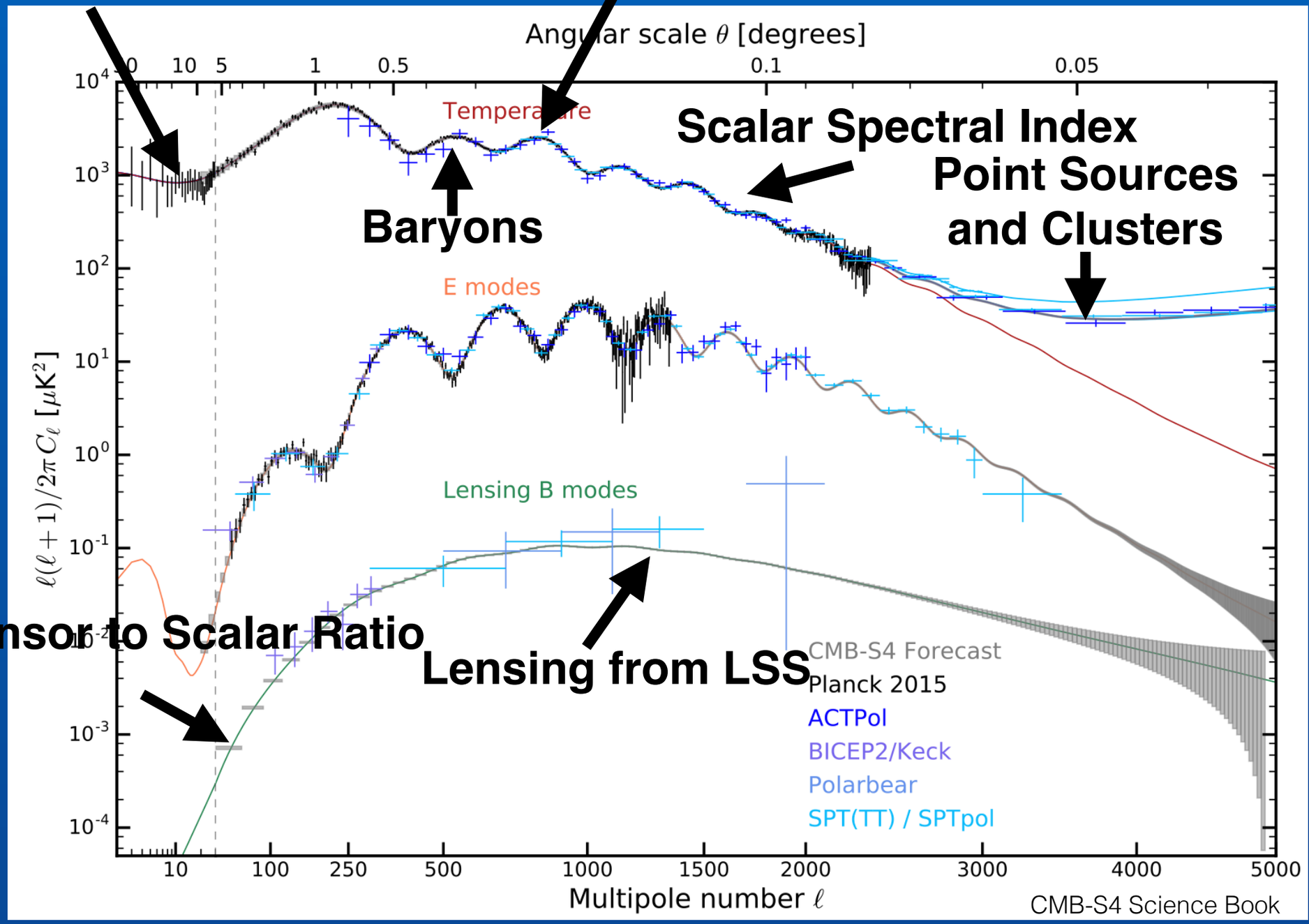


CMB-S4 Science Themes

1. Constrain Inflation
2. Investigate the “Dark” Universe
3. Map the matter distribution in the universe
4. Investigate millimeter-wave transients



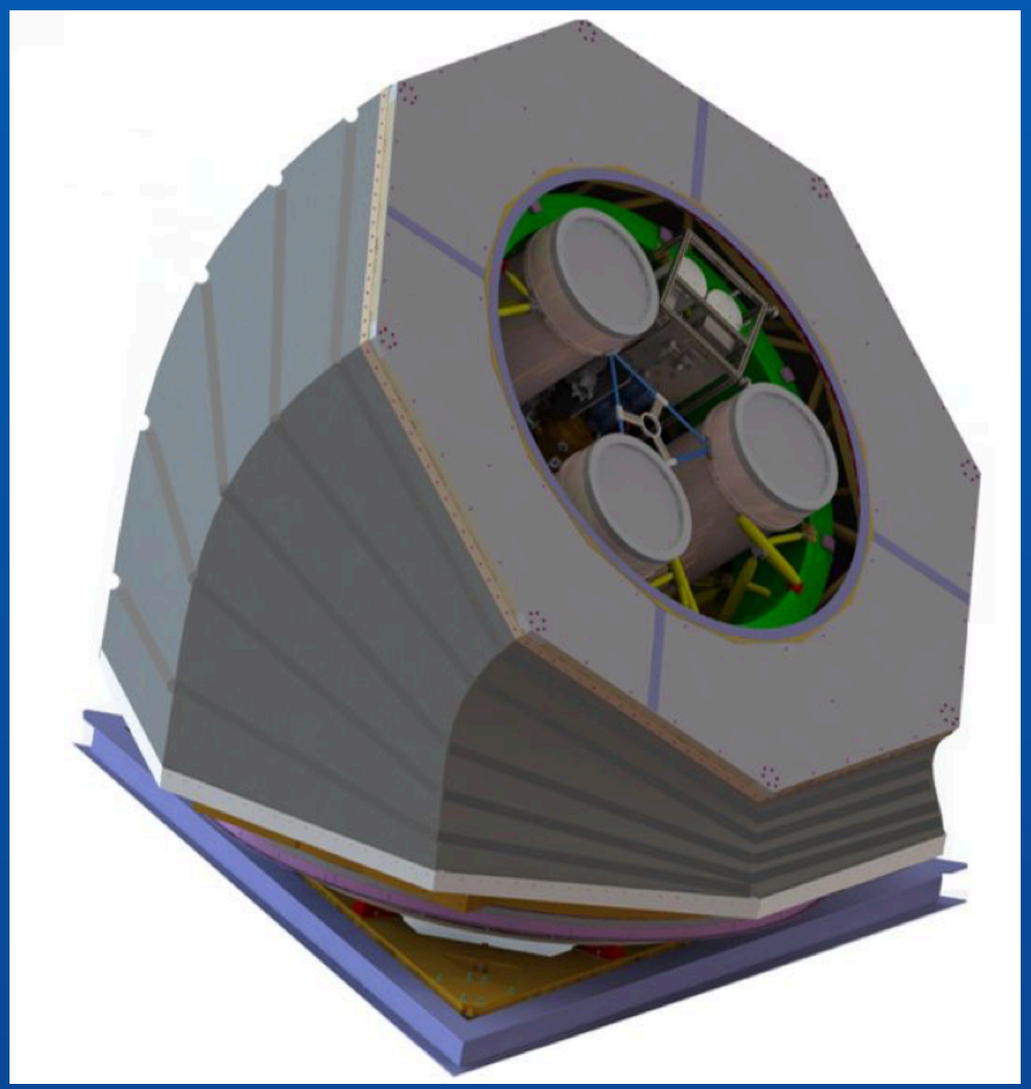
CMB-S4

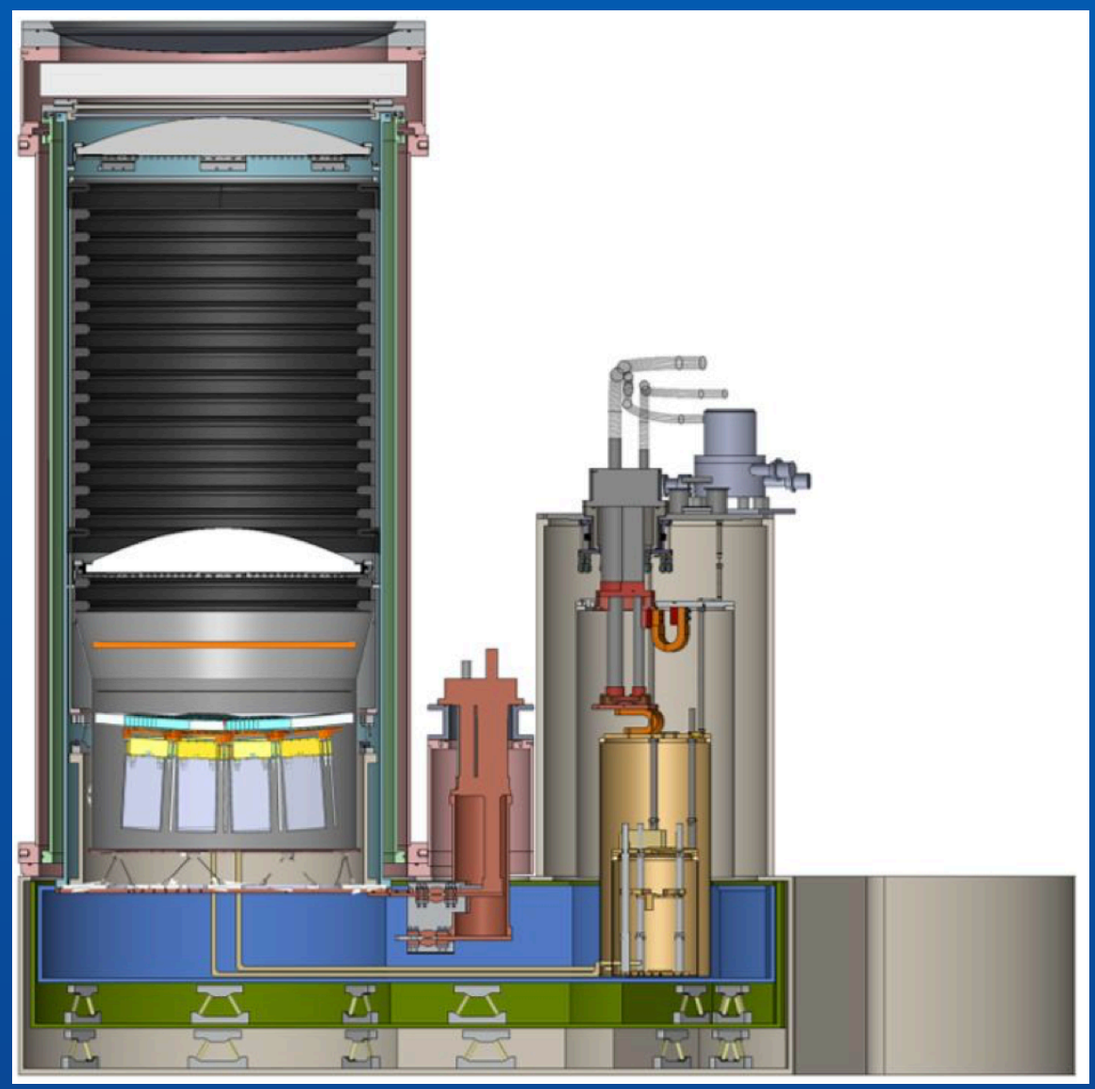
Goal	1. Constrain Inflation	2. Investigate the "Dark" Universe	3. Map the matter distribution through lensing	4. Investigate millimeter-wave transients
Experiment Requirements	• Large Survey Area • Extremely Deep Survey • Low Angular Resolution • Sensitive at Large Angular Scales	• Large Survey Area • Extremely Deep Survey • High Angular Resolution	• Large Survey Area • Extremely Deep Survey • High Angular Resolution	• Largest Survey Area Possible • Extremely Deep Survey • High Angular Resolution • High Cadence Scans
Instrument Solution	Small Aperture Telescopes at the South Pole	Large Aperture Telescopes at the Atacama and the South Pole		Large Aperture Telescope in Atacama

CMB-S4 Instruments

Instrument Solution

Small Aperture Telescopes



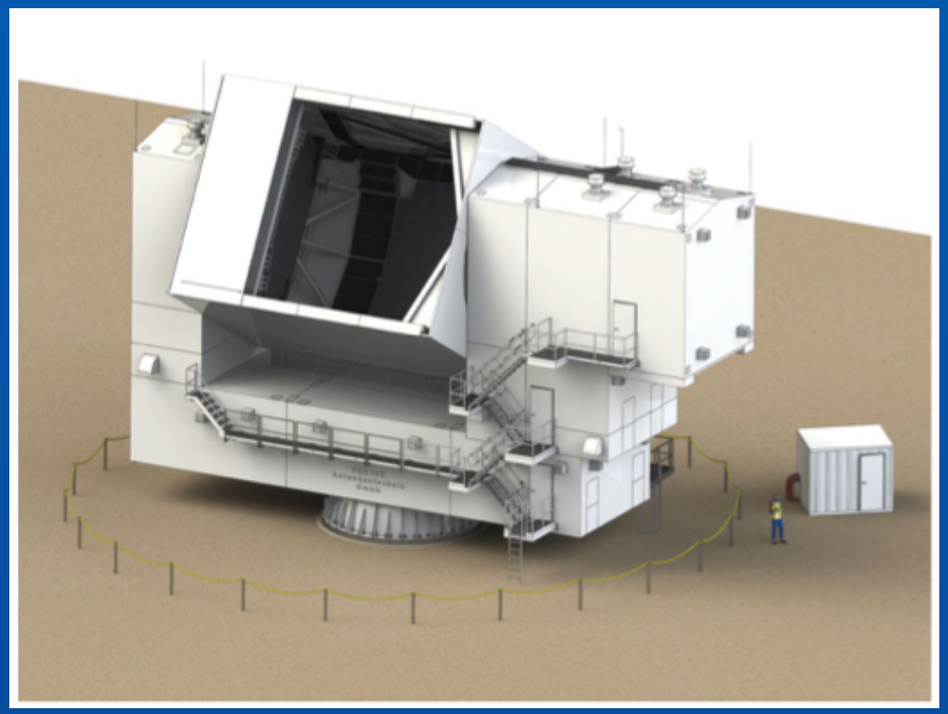


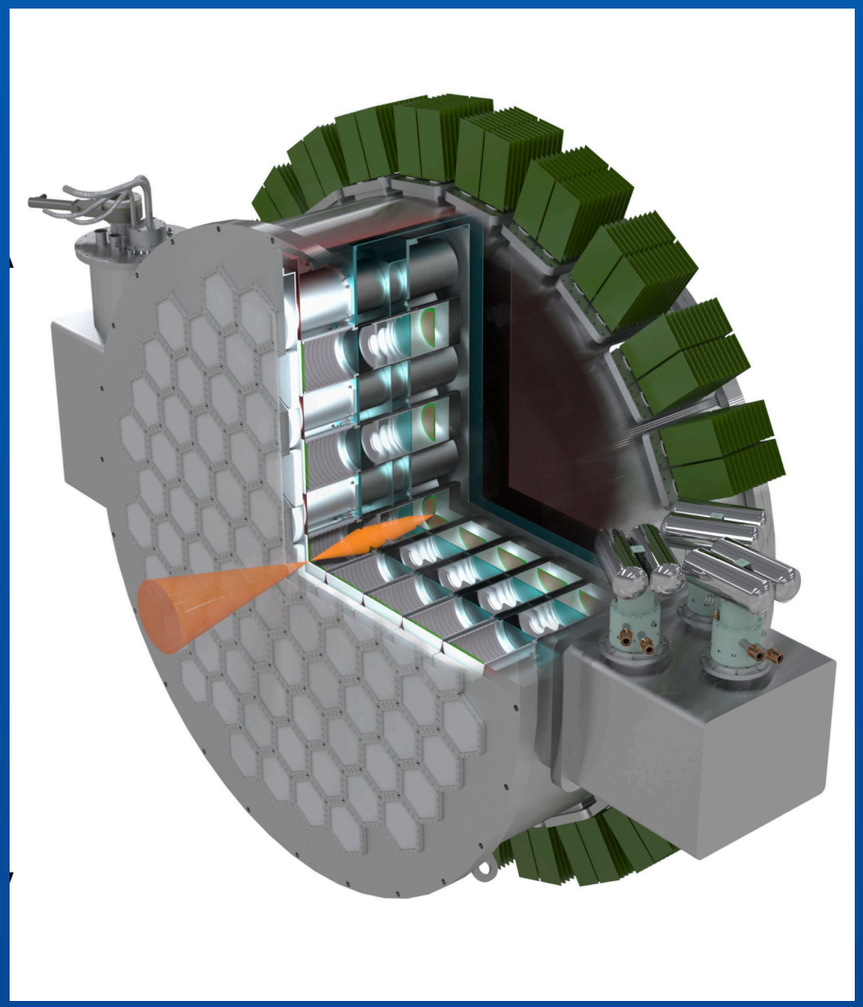
Both images from CMB-S4 Spring 2021 Workshop (J. Kovac)

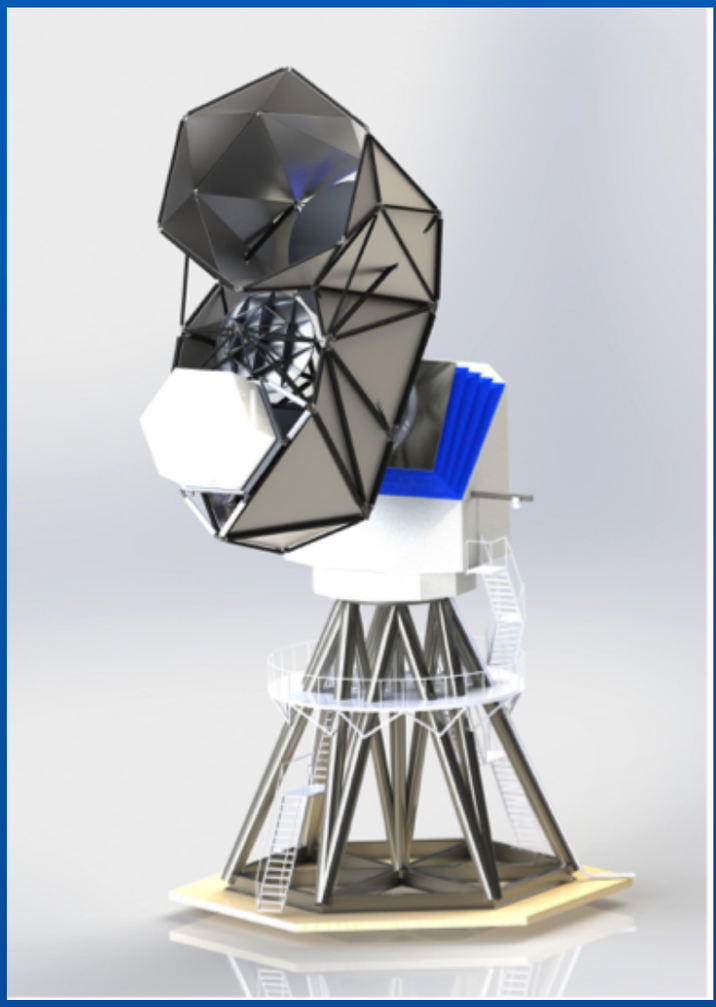
CMB-S4 Instruments

Instrument Solution

Large Aperture Telescopes







Images from CMB-S4 Spring 2021 Workshop (M. Niemack)

Optical Requirements

- CMB-S4 will require hundreds of optical elements for all of its instruments

- Highly transparent optics are required to collect more photons and mitigate instrument systematics

- S4 will require >100 alumina filters alone

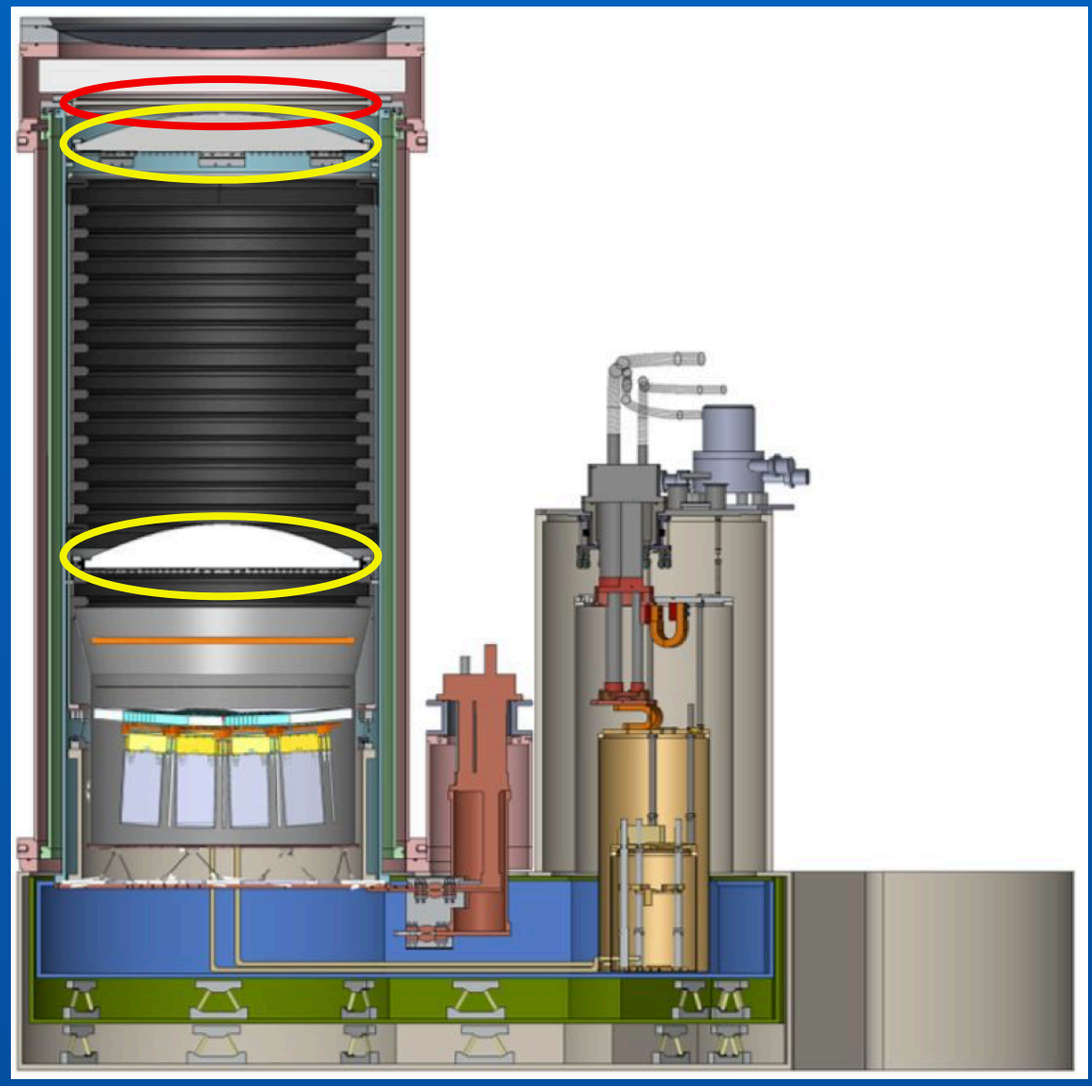


Image from CMB-S4 Spring 2021 Workshop (J. Kovac)

x18

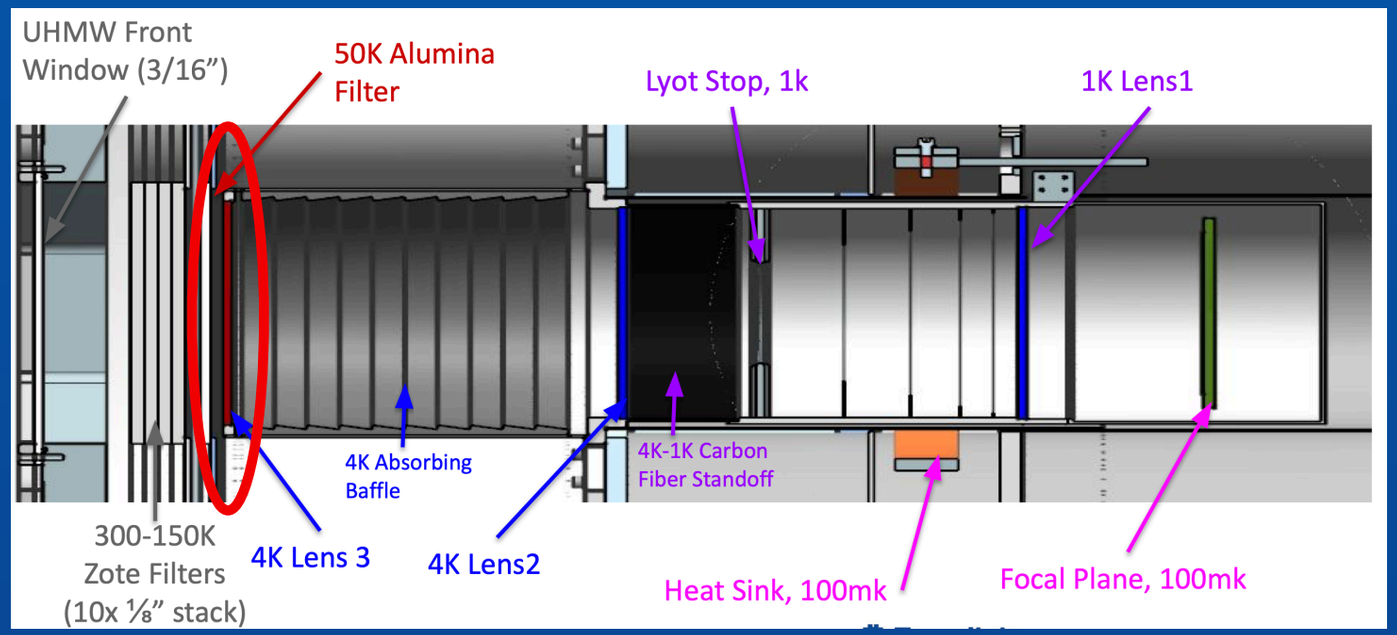


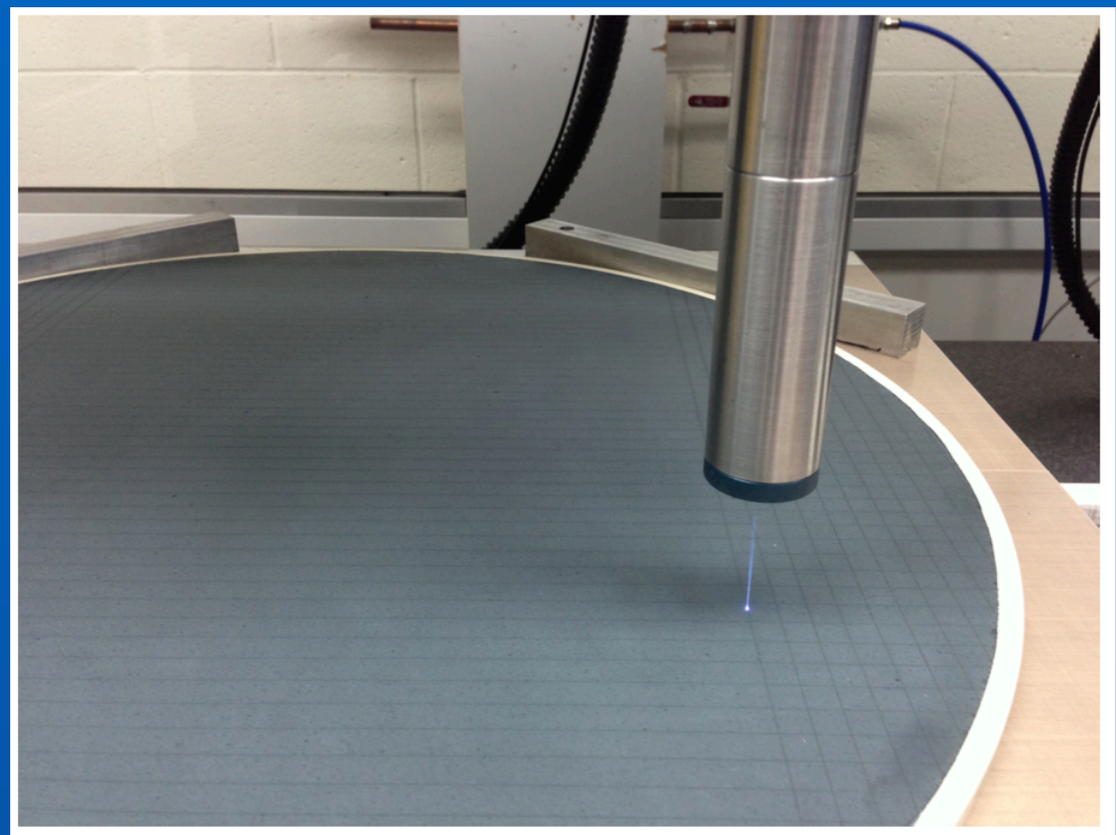
Image from CMB-S4 Spring 2021 Workshop (D. Mitchell)

x85

Alumina Optics

- Alumina has great optical properties at millimeter wavelengths
- Low transmission at IR frequencies makes alumina a good filter
- Current experiments like SPT-3G and BICEP3 use alumina lenses
- Existing AR coating methods are lossy and can suffer from cryomechanical failures

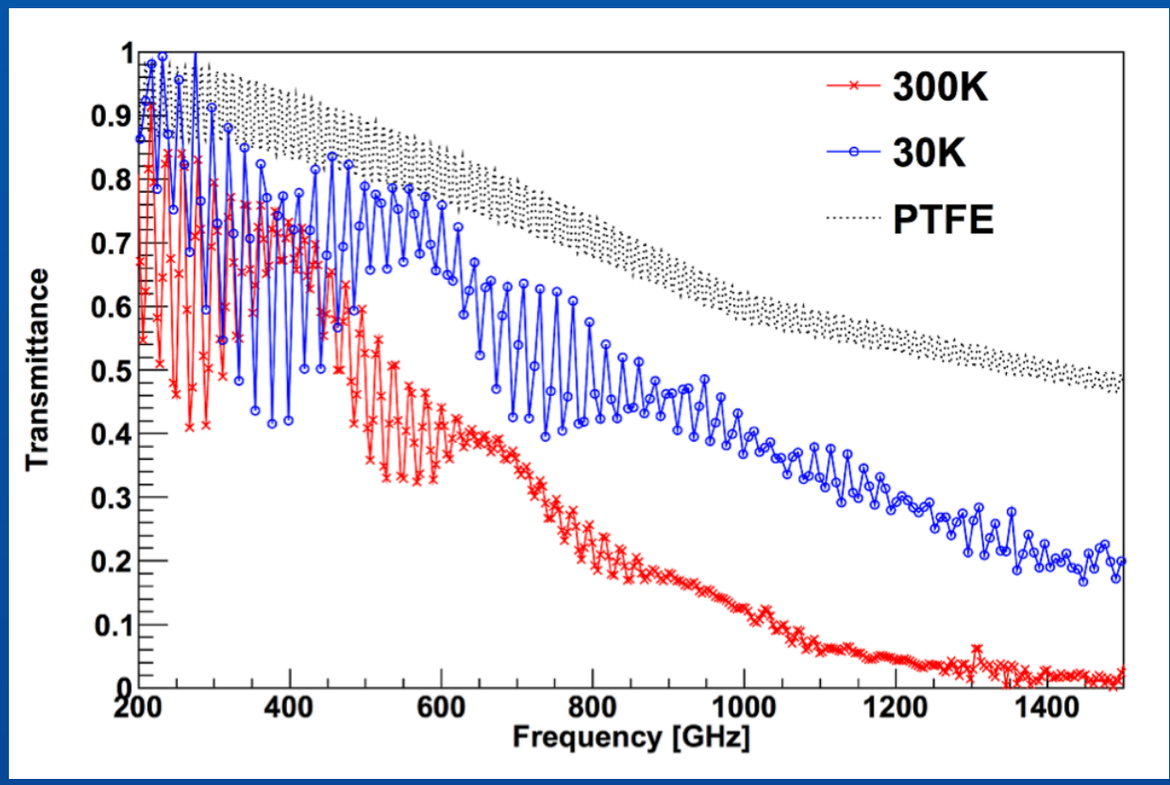
BICEP3 Filter



SPT-3G Lens

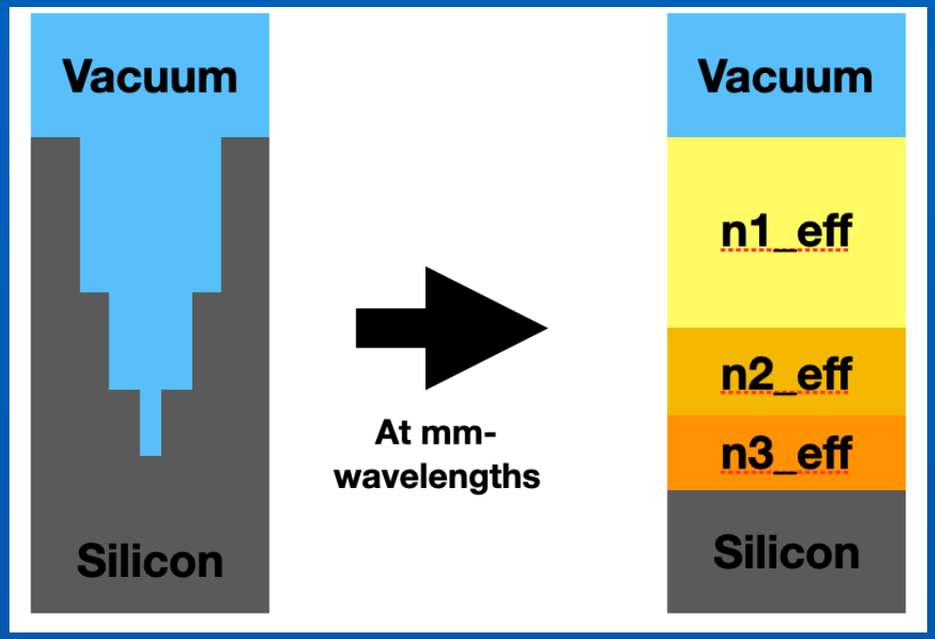
A. Nadolski et al. (2018)

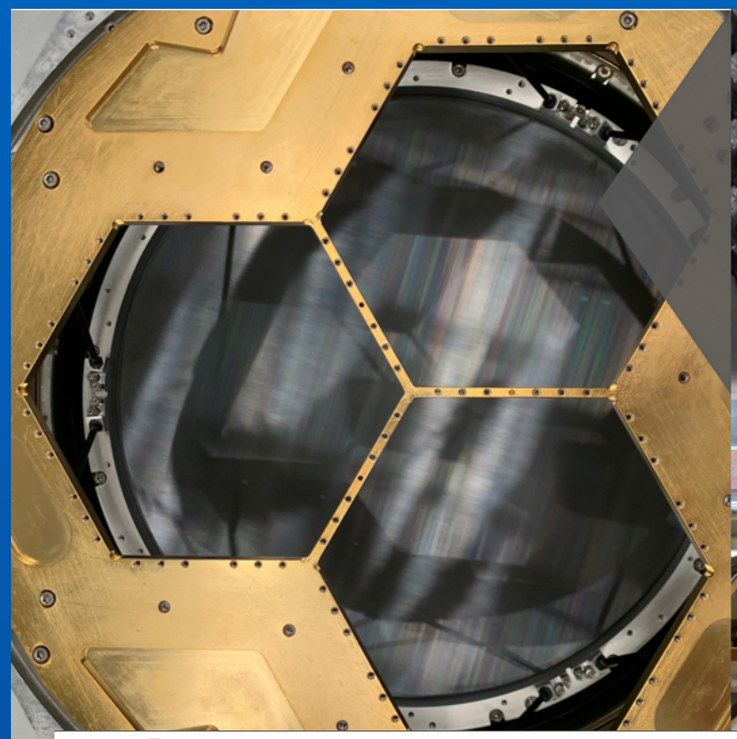
Z. Ahmed et al. (2014)

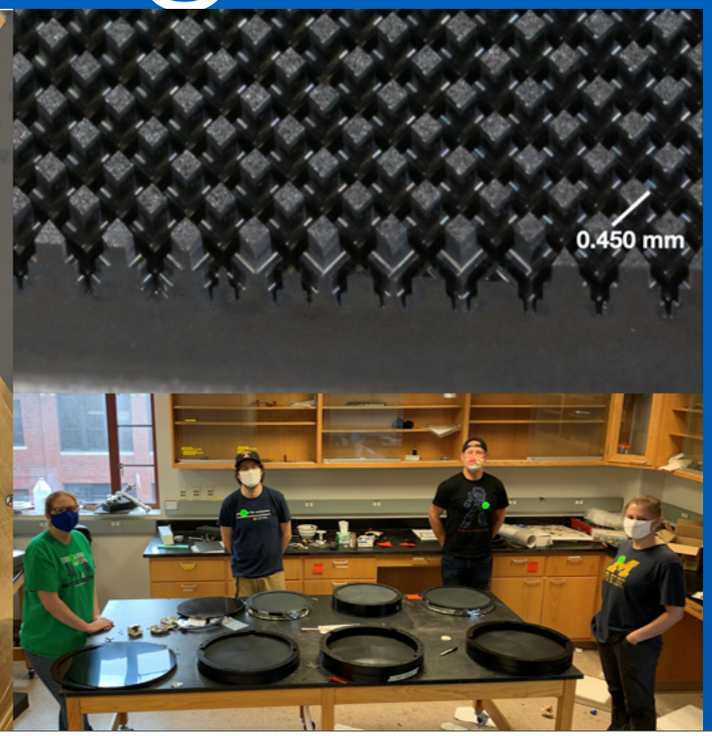


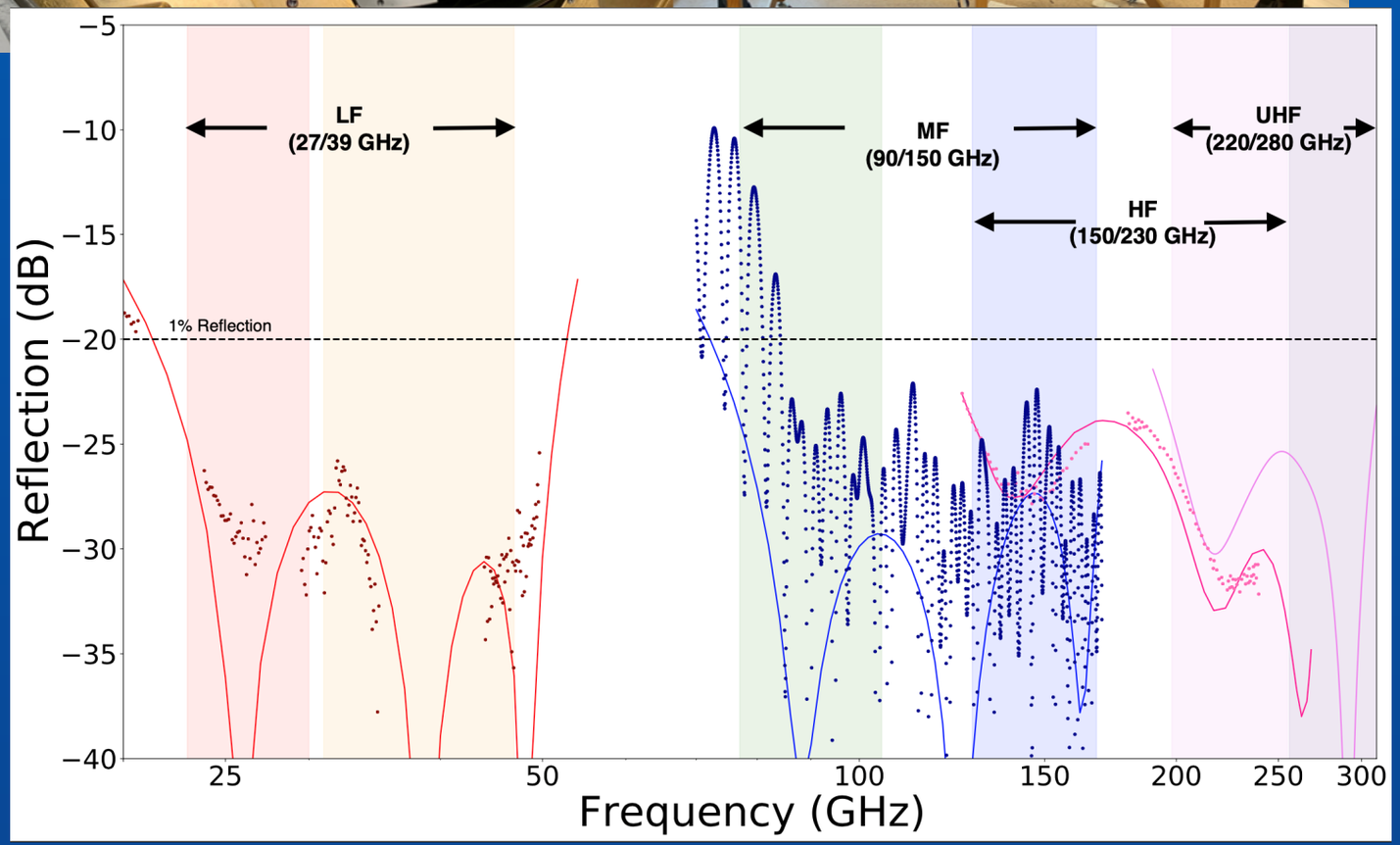
CMB-S4 Technology Book

Metamaterial AR Coatings





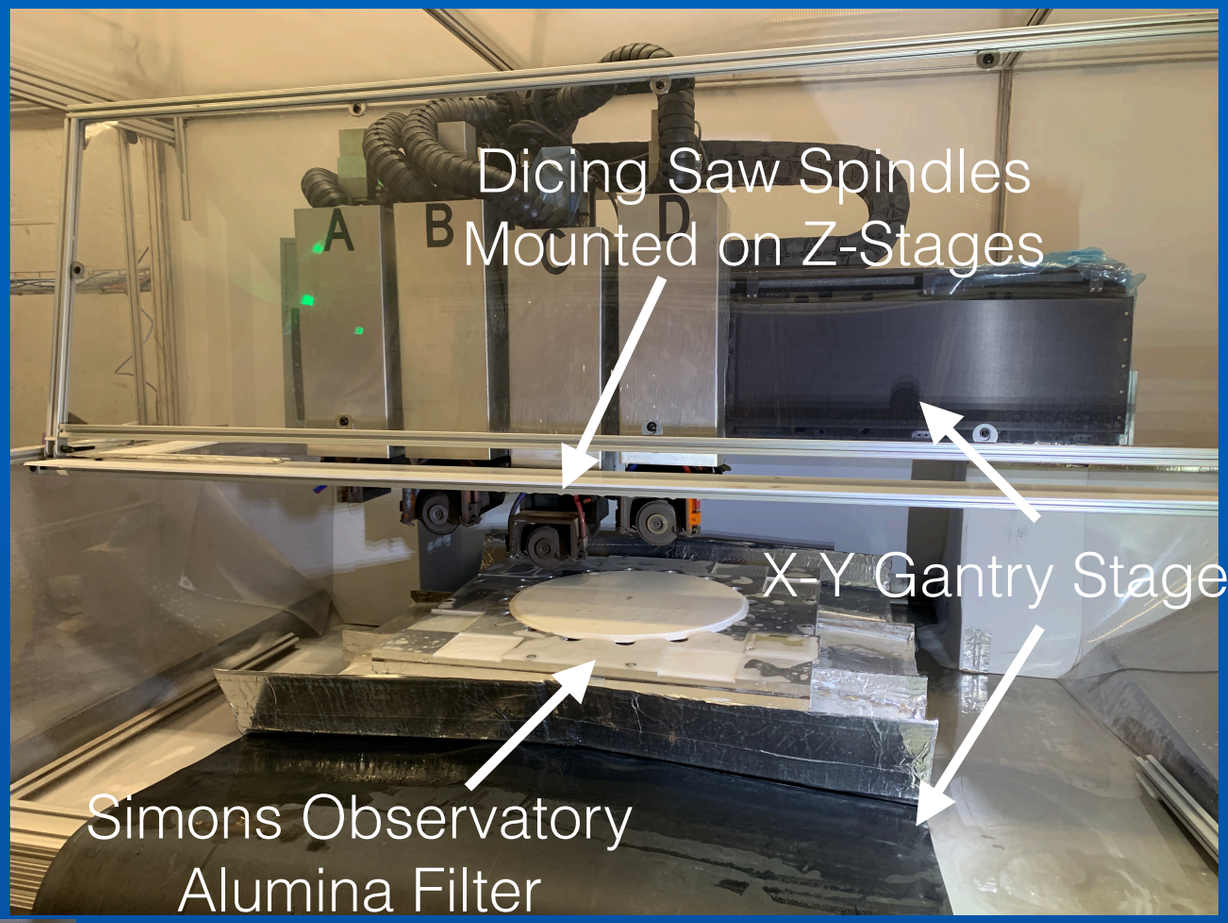


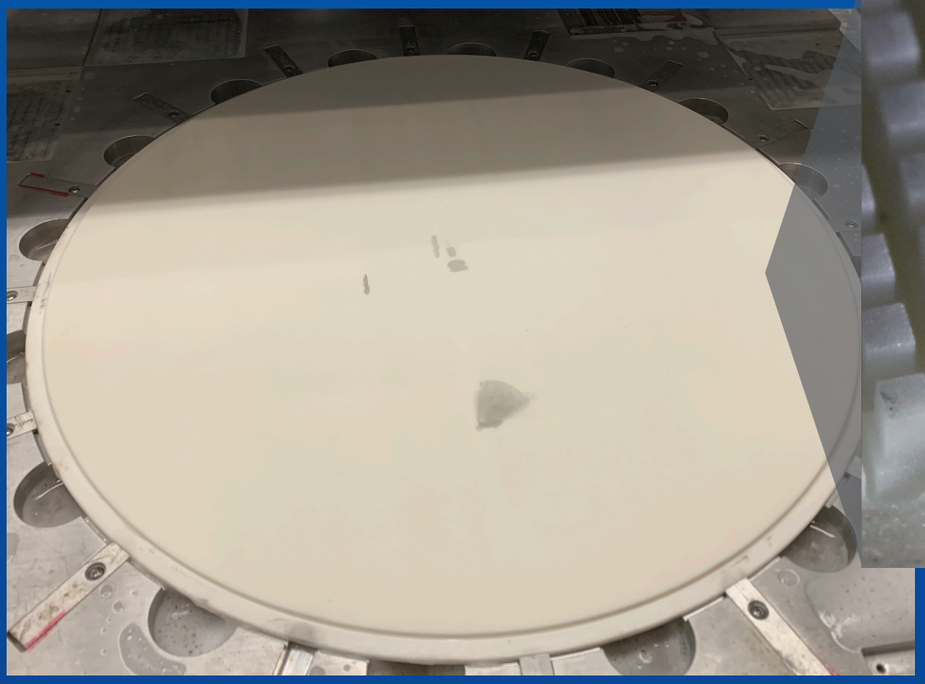


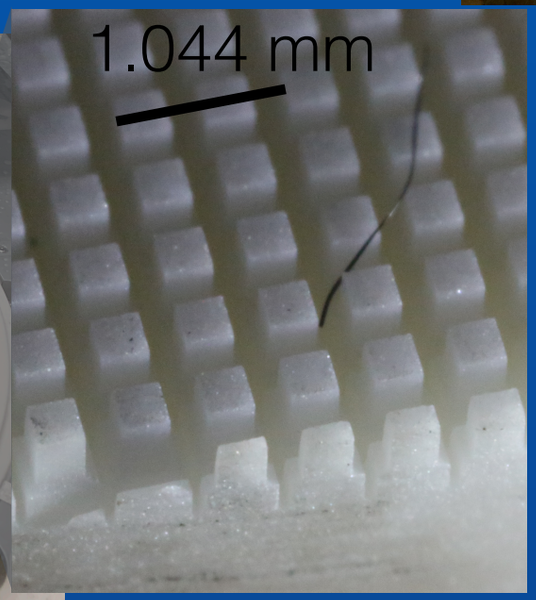
- Experiments like AdvACTPol and Simons Observatory use metamaterial AR coated silicon lenses
- Features are fabricated with a dicing saw
- Metamaterial AR coatings have low reflection across large bandwidths
- Alumina is a much harder material than silicon so applying this technology to alumina filters is difficult

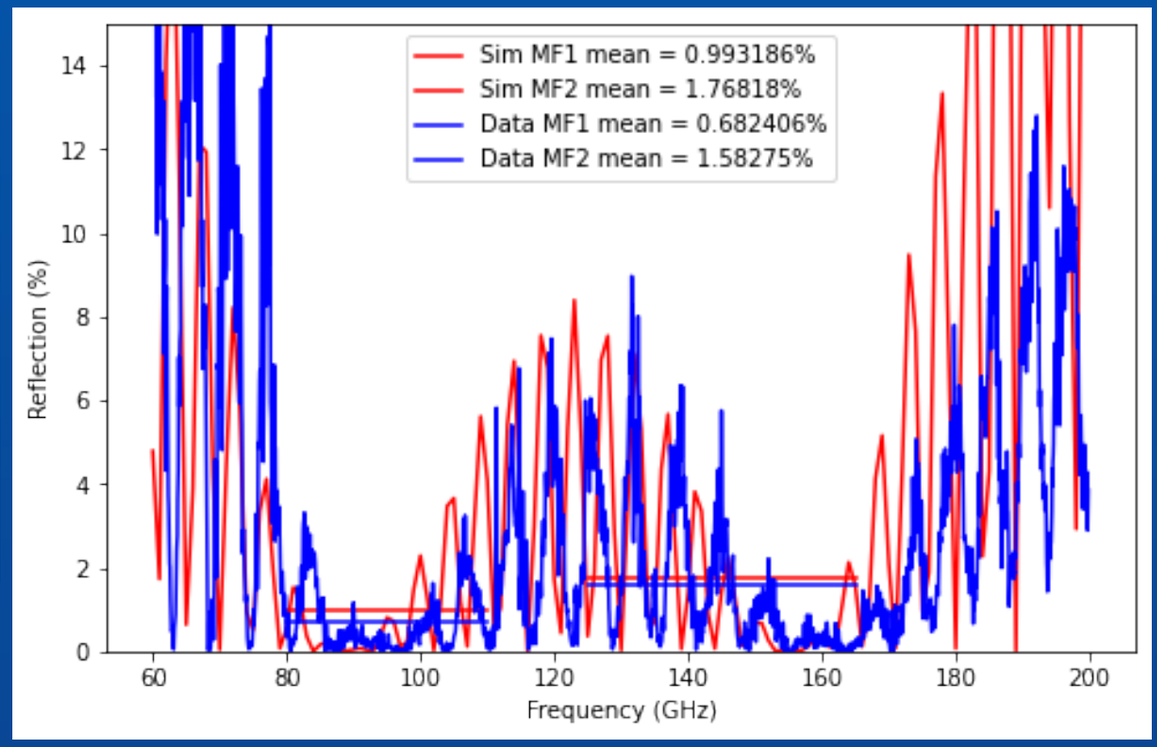
Alumina Metamaterial AR Coatings

- Alumina filters are diced at Fermilab using a custom dicing saw in the D0 building
- Prototypes were made to constrain blade wear
- The first full scale metamaterial AR coated filter was finished in early July and measured to have low reflections in observing band



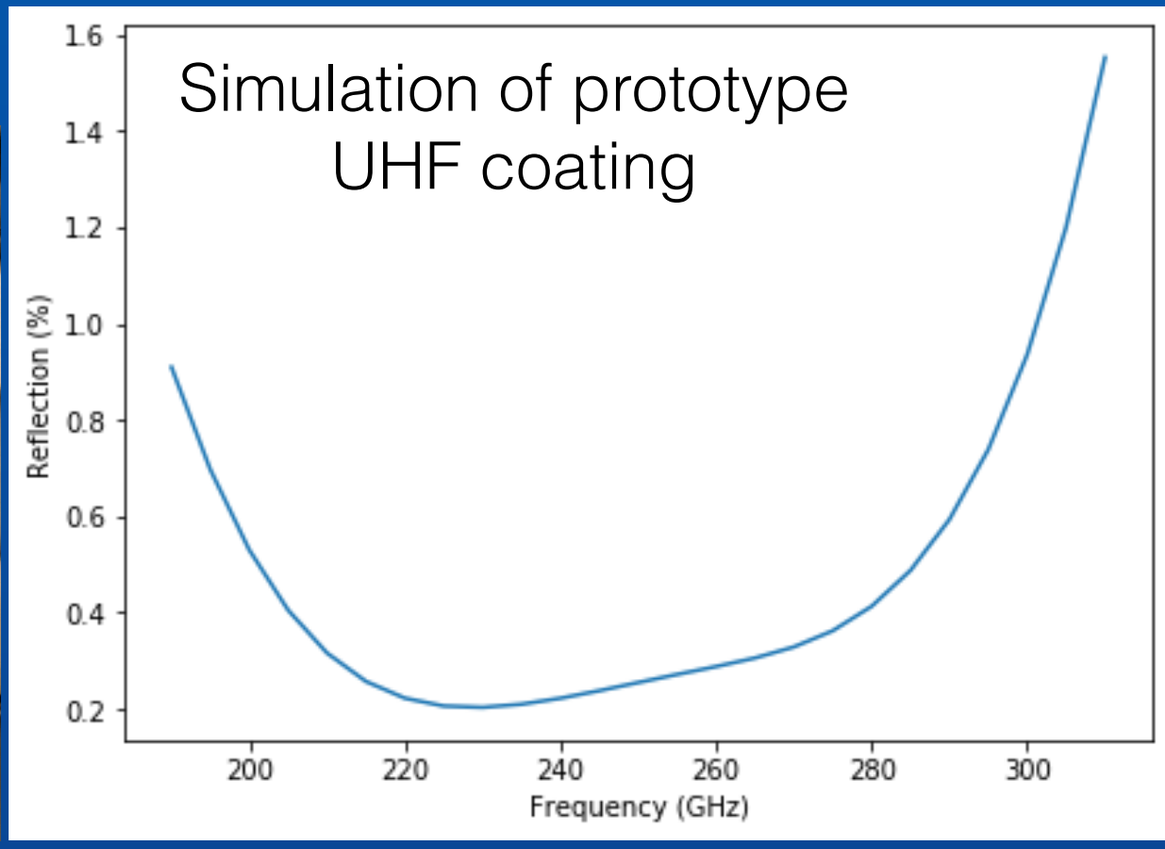






Future Steps

- CMB-S4 has three observing bands. Development of AR coatings effective in the other two bands is a priority
- To accommodate the large number of optics needed for CMB-S4, we need to increase our production rate
- Building another saw system will allow us to parallelize production



Conclusion

- The ΛCDM model is incredibly accurate at describing our universe, but there is still much we do not know
- Precision measurement of the CMB reveals a tremendous amount about the universe
- CMB-S4 will be the most sensitive CMB instruments ever deployed and highly transparent optics are needed to ensure that sensitivity
- Metamaterial AR coatings for alumina optics solves reflection problems for critical optical elements
- Expanding metamaterial AR coating technologies in alumina to other frequency bands and increasing AR coating throughput will be essential for CMB-S4

Acknowledgements

- This work was partially supported by a NASA Space Technology Research Fellowship

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