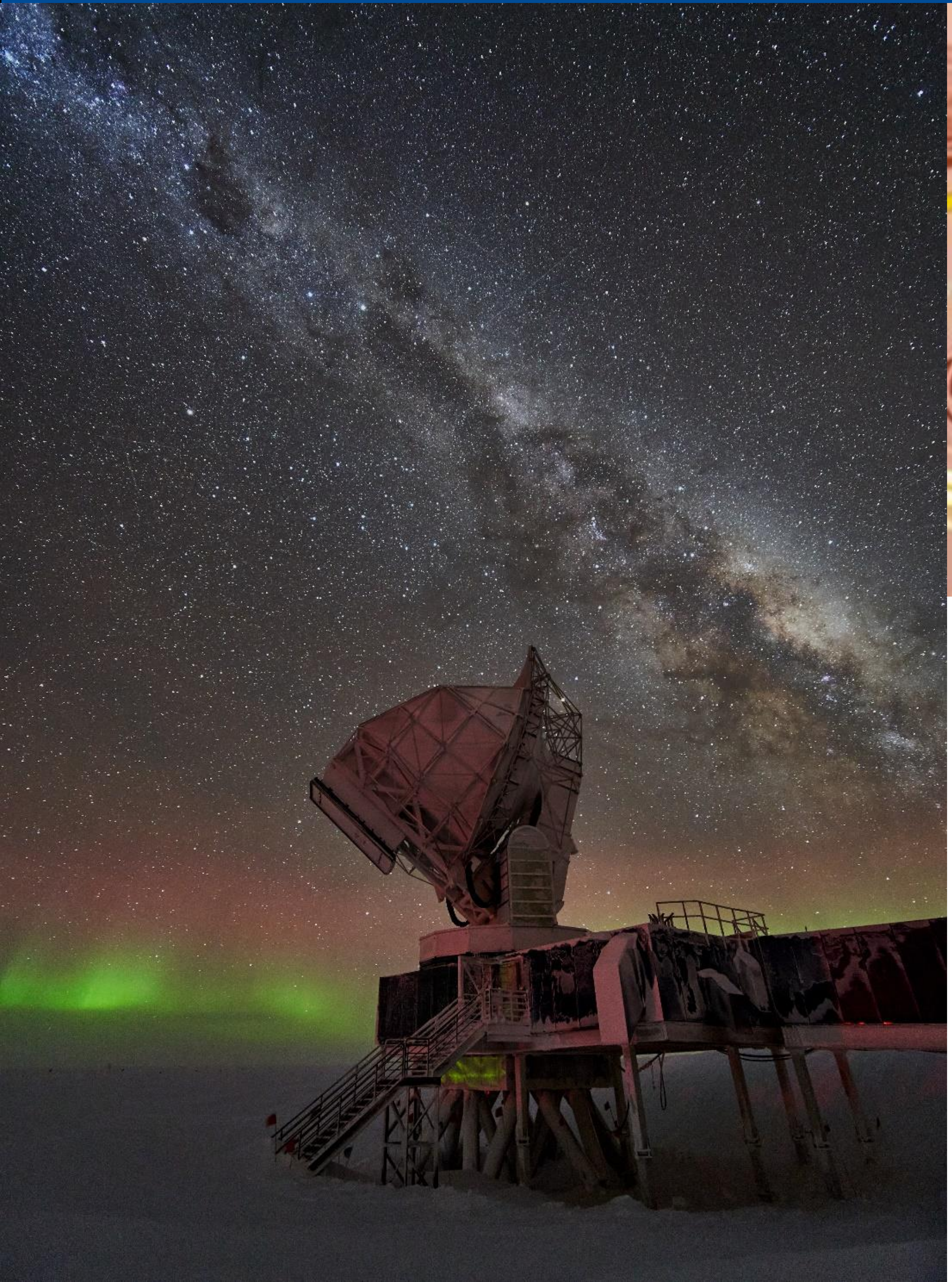
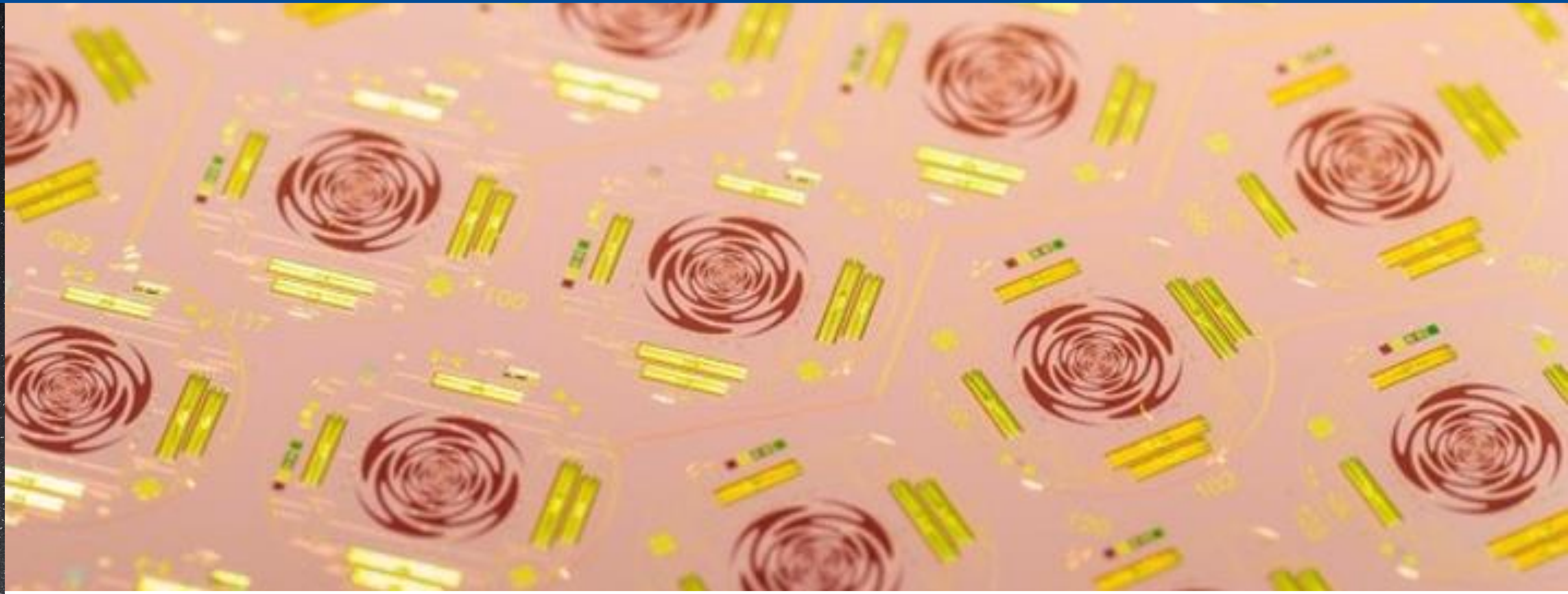




Exploring Fundamental Physics through Cosmic Microwave Background Measurements

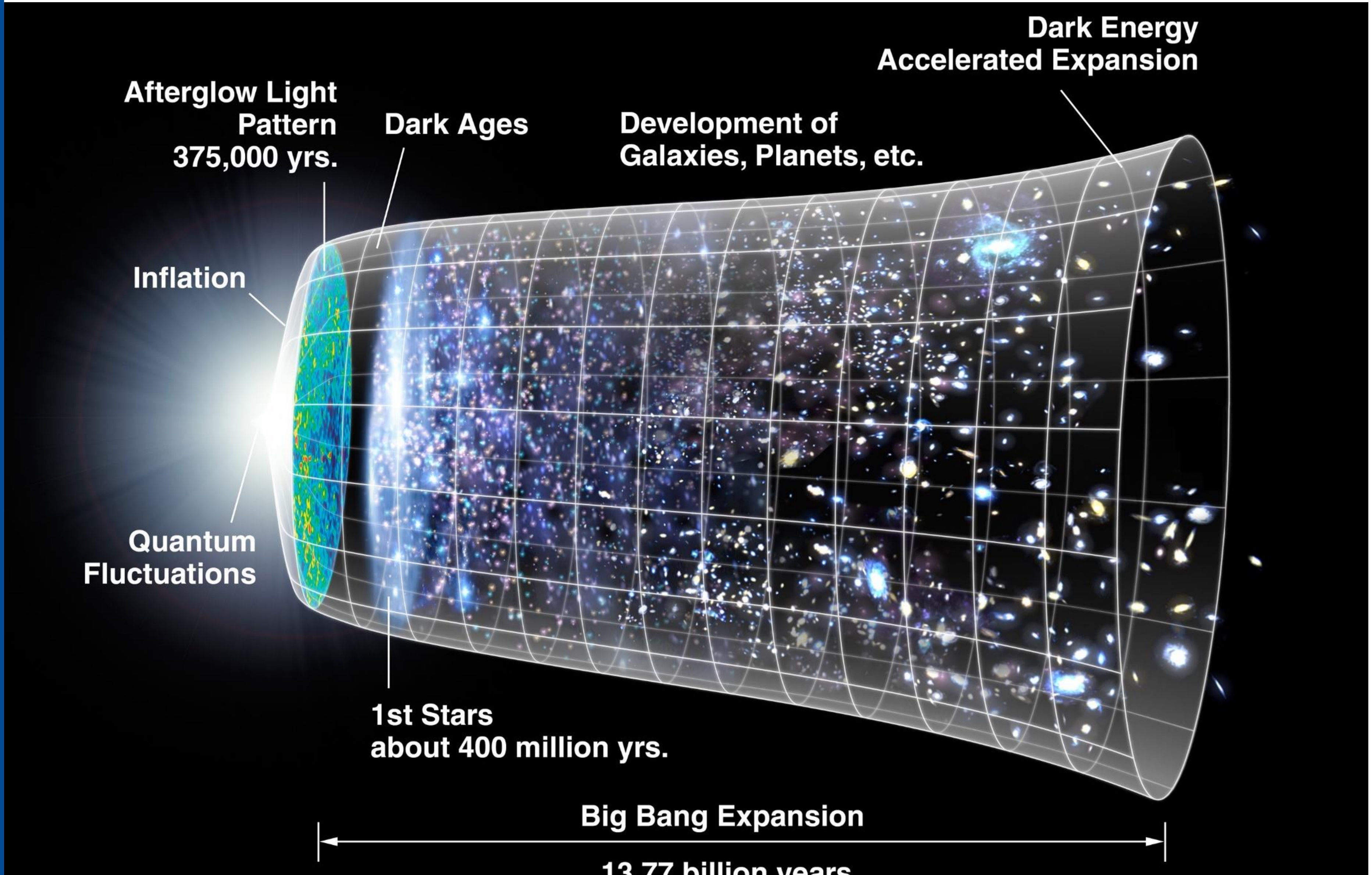
Joshua Sobrin (Fermilab, University of Chicago)

Fermilab Users Meeting 2023

June 30th, 2023

1. *Why Study the Cosmic Microwave Background?*

"The story so far…"

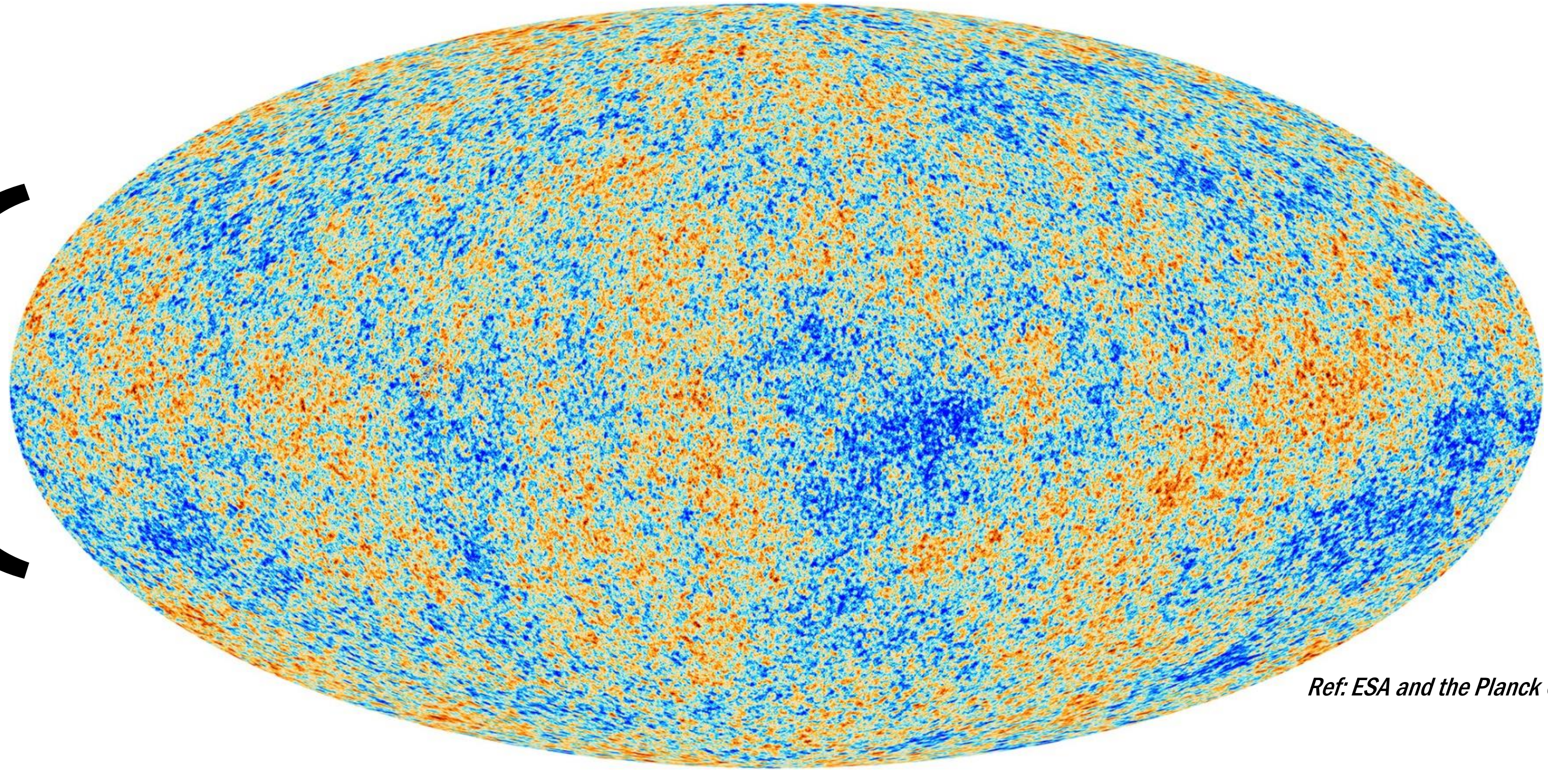


Ref: NASA/WMAP Science Team

- CMB measurements provide an early-time anchor ($z \approx 1100$) for constraining cosmological models, complementing other cosmic surveys ($z < 10$).
- The CMB encapsulates the universe's conditions prior to the first atoms forming – its features are a result of physics at the highest energy scales.

A Modern CMB Measurement

Planck Satellite All-Sky Survey (2013)

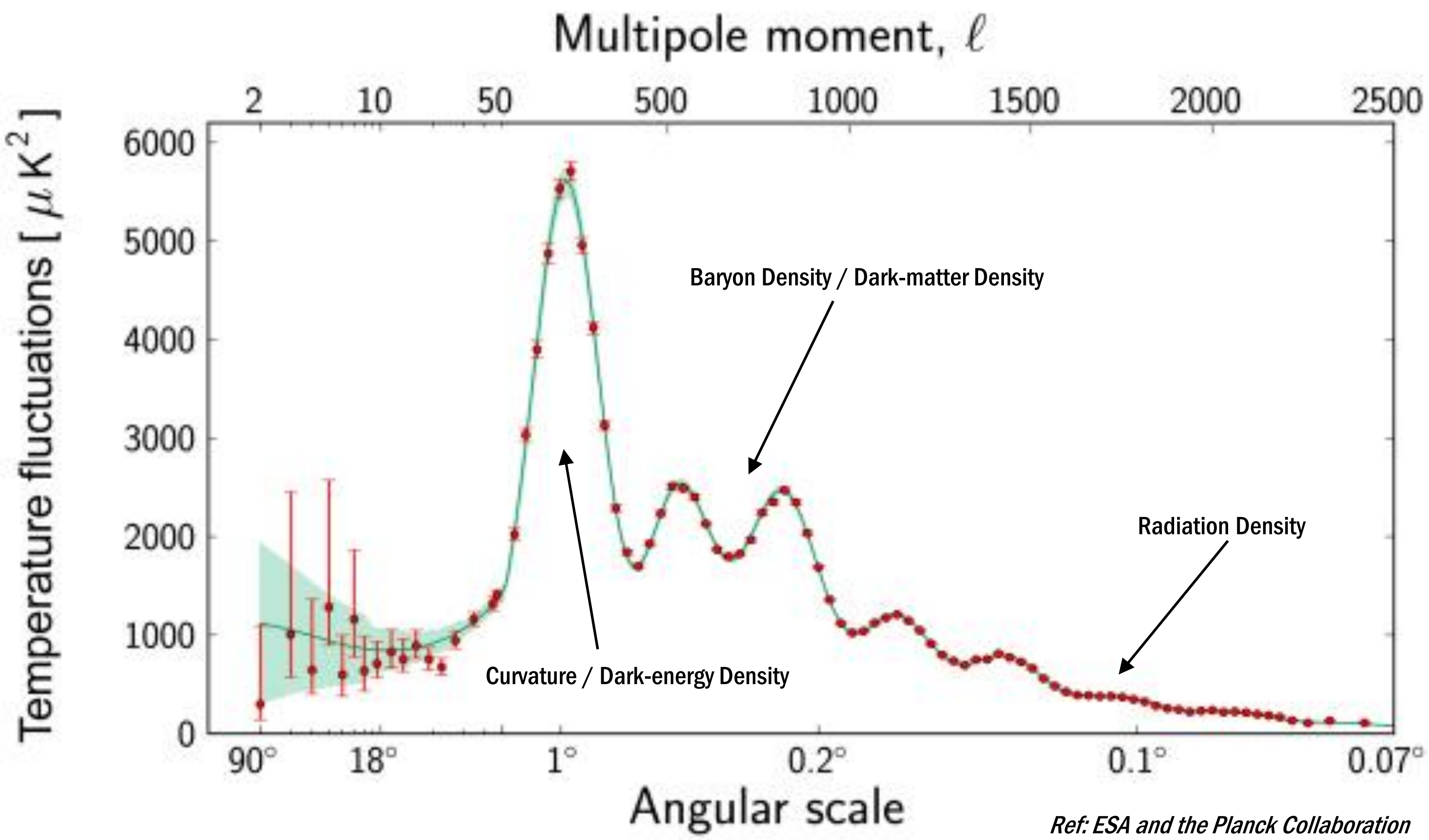
$\mathcal{F}\Big($  $\Big)$

Ref: ESA and the Planck Collaboration

30-μK RMS fluctuations about 3-K blackbody signal
(largest fluctuations on ≤1-deg scales)

CMB Power Spectra

- CMB features at different angular scales encode information about the composition and expansion history of the universe.
  - CMB power spectra measurements are in strong agreement with ΛCDM, the concordance standard model of cosmology.
- Modern experiments are largely focused on measuring the fainter polarization features of the CMB (typically decomposed into *E*- and *B*-modes).
  - Provide an independent consistency check for temperature-derived parameter constraints.
  - In addition, can probe additional physics not well constrained by temperature anisotropies alone.



Ref: ESA and the Planck Collaboration

Exploring High-Energy Physics with the CMB

- Probing physics at energy scales of grand-unified theories (GUT-scale, ~10^{16} GeV physics).
  - Searching for a remnant, unique polarization signal sourced by primordial gravitational waves during an early period of cosmic inflation.
  - Detection of this signal would provide the first evidence of quantum gravity.

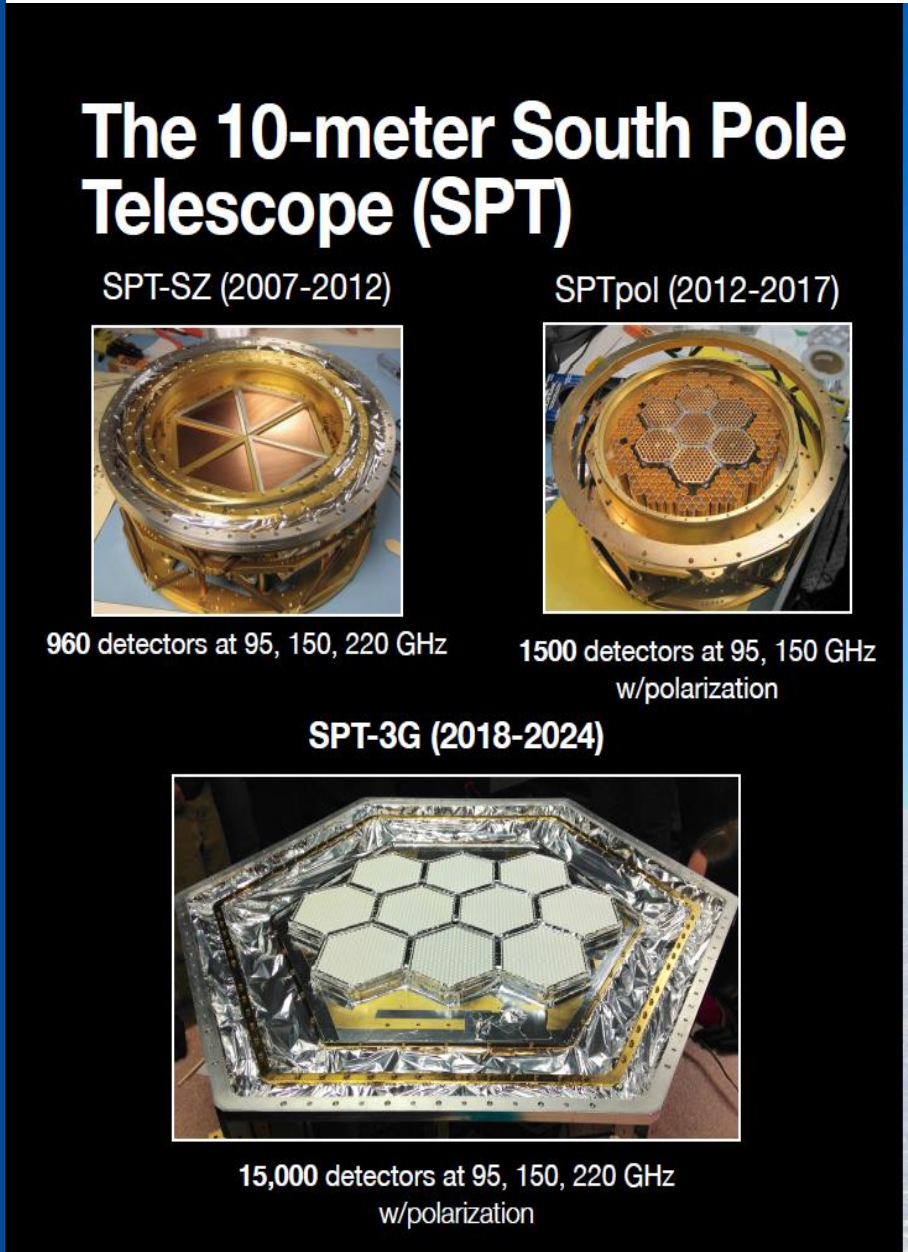
- Detecting the sum of neutrino masses.
  - A combination of CMB lensing and galaxy cluster data will detect Σm_ν, and potentially rule between a normal or inverted neutrino mass hierarchy.
  - CMB experiments complement long-baseline neutrino oscillation experiments (e.g. NOvA, DUNE), which measure the differences between neutrino masses.

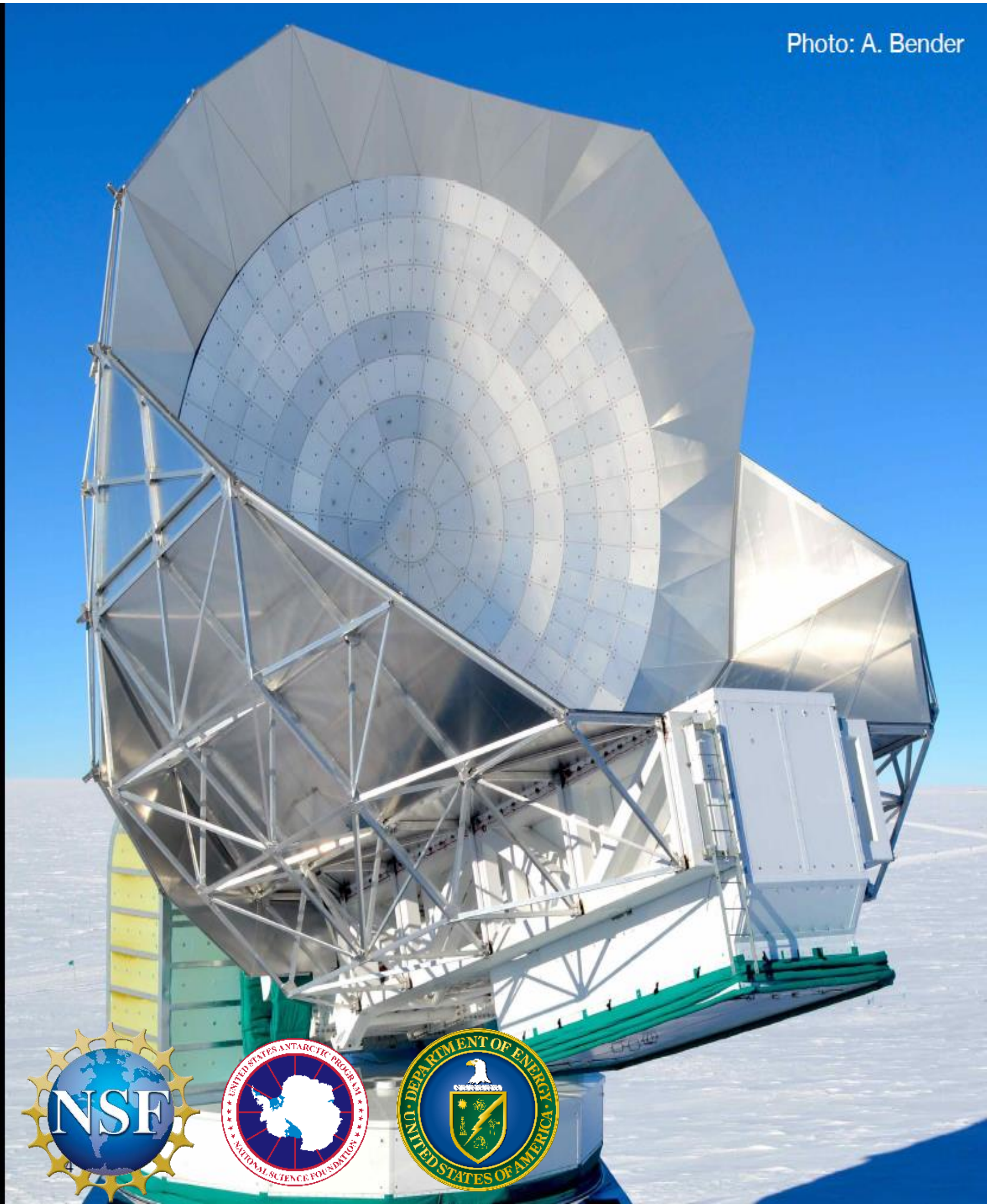
- Understanding the nature of dark energy.
  - CMB observables of large-scale structure (LSS) formation throughout our universe's history will differentiate between models involving a cosmological constant, evolving dark energy, or modified gravity.
  - Complementary datasets to other LSS probes (e.g. DES, DESI, Rubin/LSST).

- Exploring evidence for Beyond-Standard-Model (BSM) physics.
  - Improved polarization and arcminute-scale CMB data will shed new light on current tensions in ΛCDM and extension models (ΛCDM+).
  - Potentially motivate the case for new, light relic particles (N_{eff}) through a model-independent constraint on light degrees-of-freedom in the early universe.

2. *Significant Advances with SPT-3G*

The South Pole Telescope (with SPT-3G)

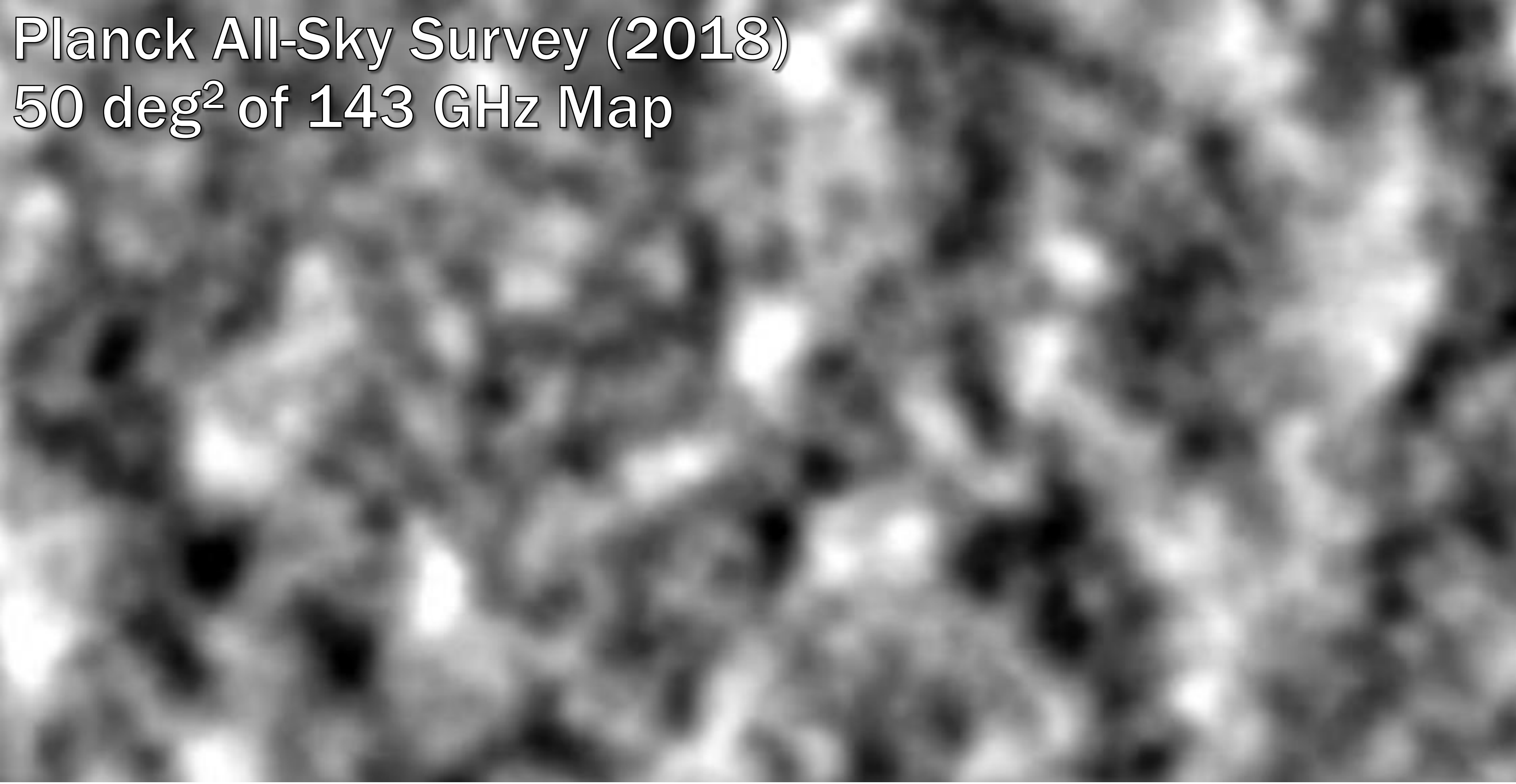




- The South Pole is the best developed place on the planet to observe the CMB:
  - Best atmospheric conditions.
  - Capability of surveying targeted fields at all times of day and year.

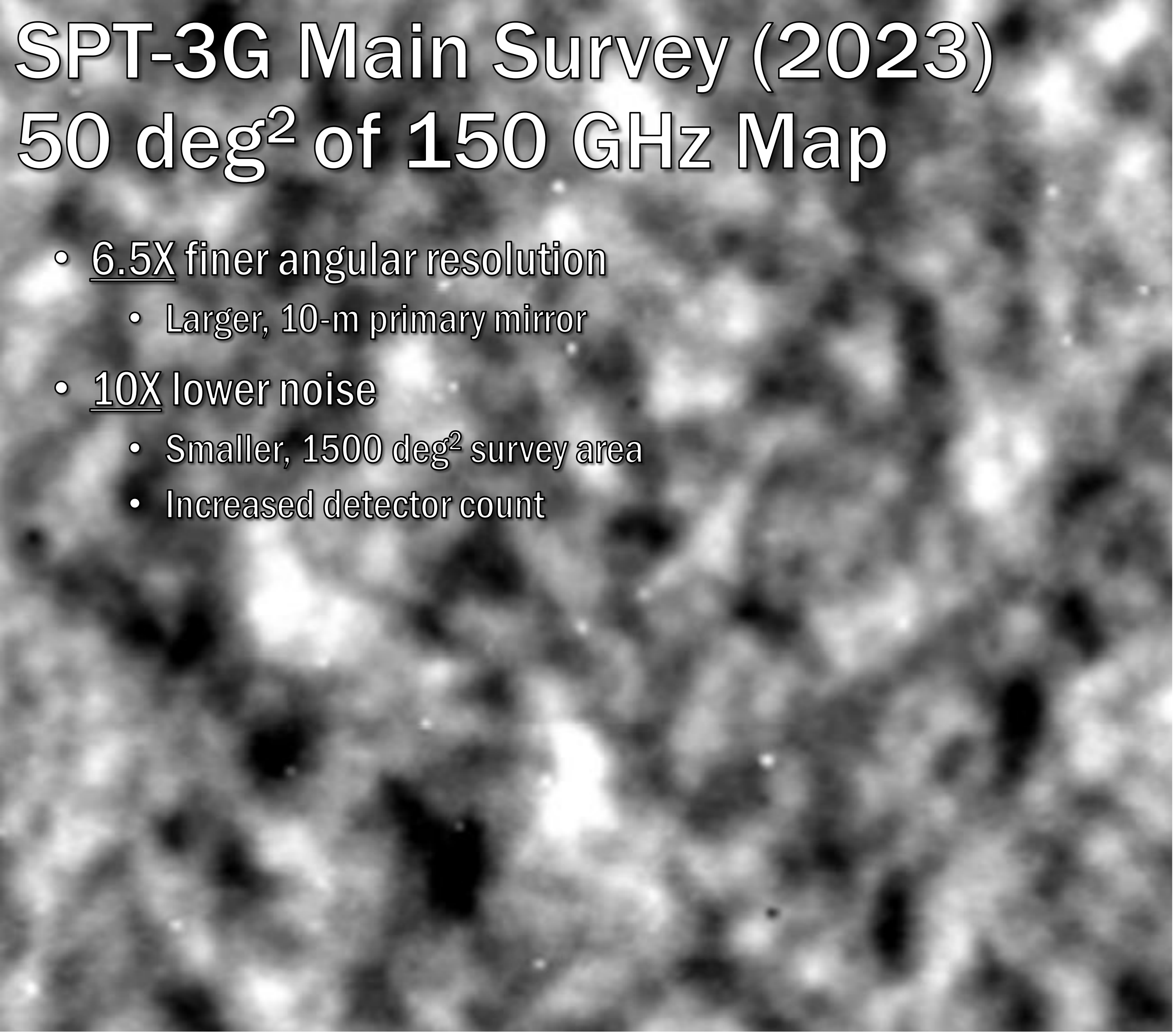
- The SPT-3G design provides low-noise, high-resolution maps of CMB temperature and polarization signals, enabling a wide variety of science goals.

Planck All-Sky Survey (2018)
50 deg^2 of 143 GHz Map

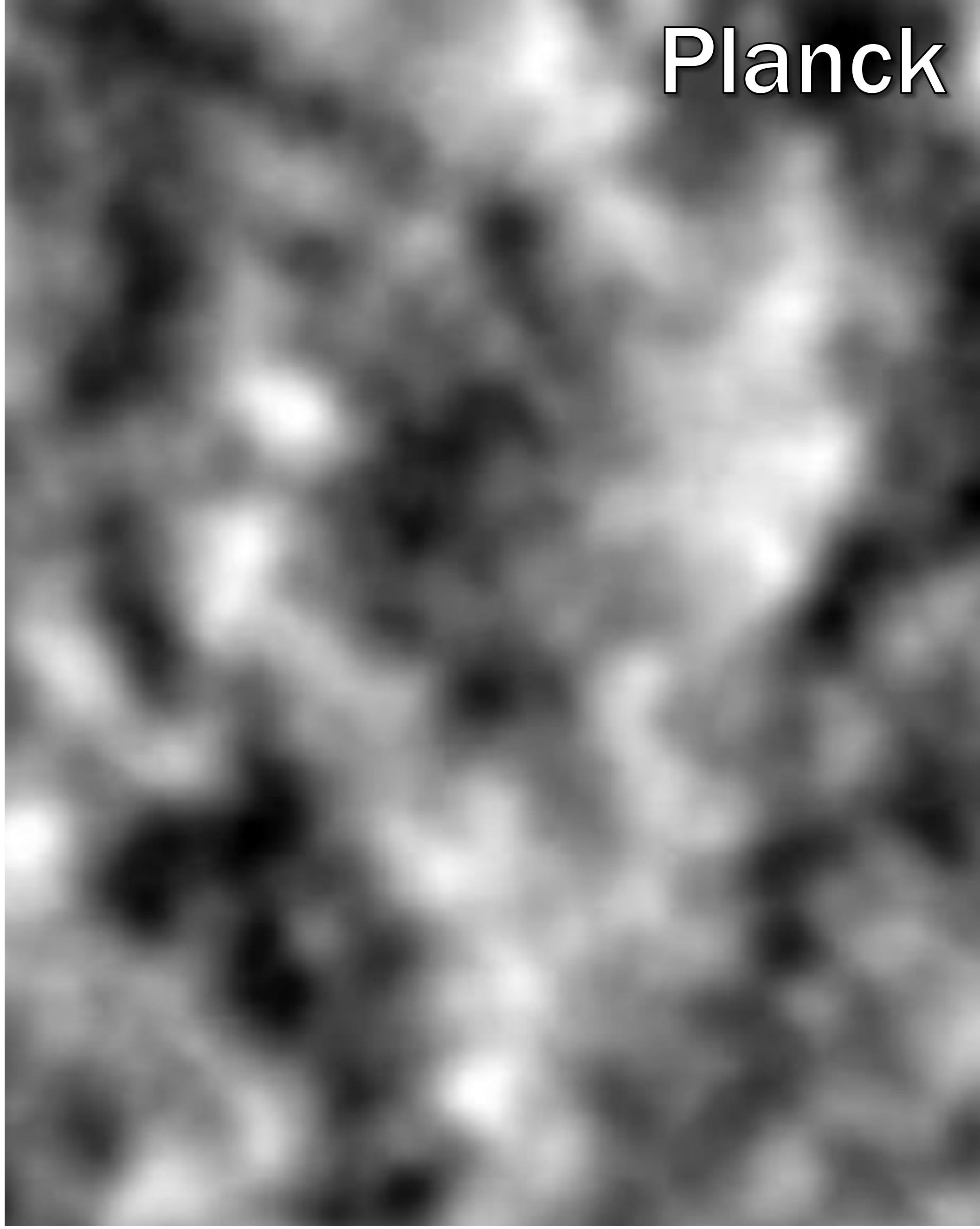


SPT-3G Main Survey (2023)
50 deg^2 of 150 GHz Map

- <u>6.5X</u> finer angular resolution
  - Larger, 10-m primary mirror
- <u>10X</u> lower noise
  - Smaller, 1500 deg^2 survey area
  - Increased detector count



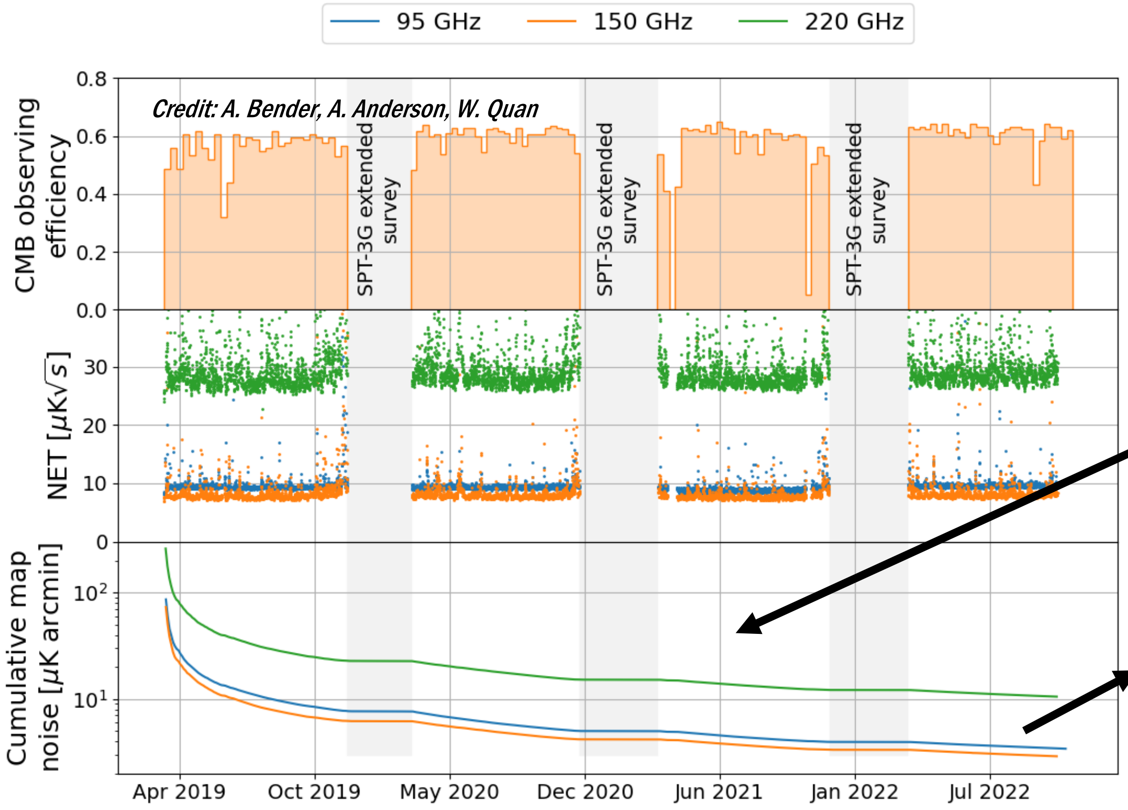
Planck



Fermilab

SPT-3G's Improved Sensitivity Over Time

SPT-3G observing efficiency, instantaneous sensitivity, and co-added map noise



Consistently high observing efficiency

+ Overall stable, low instrument noise

Fast improvement in sensitivity over time

Map Noise in μK-arcmin

	Obs. Years	Area (deg^2)	95 GHz	150 GHz	220 GHz
SPT-SZ	2007-11	2500	40	17	80
SPTpol	2012-16	500	12	5	...
SPT-3G (Main)	2019-23	1500	3.1	2.5	8.8
SPT-3G (Summer)	2019-23	2650	8.5	9.0	31

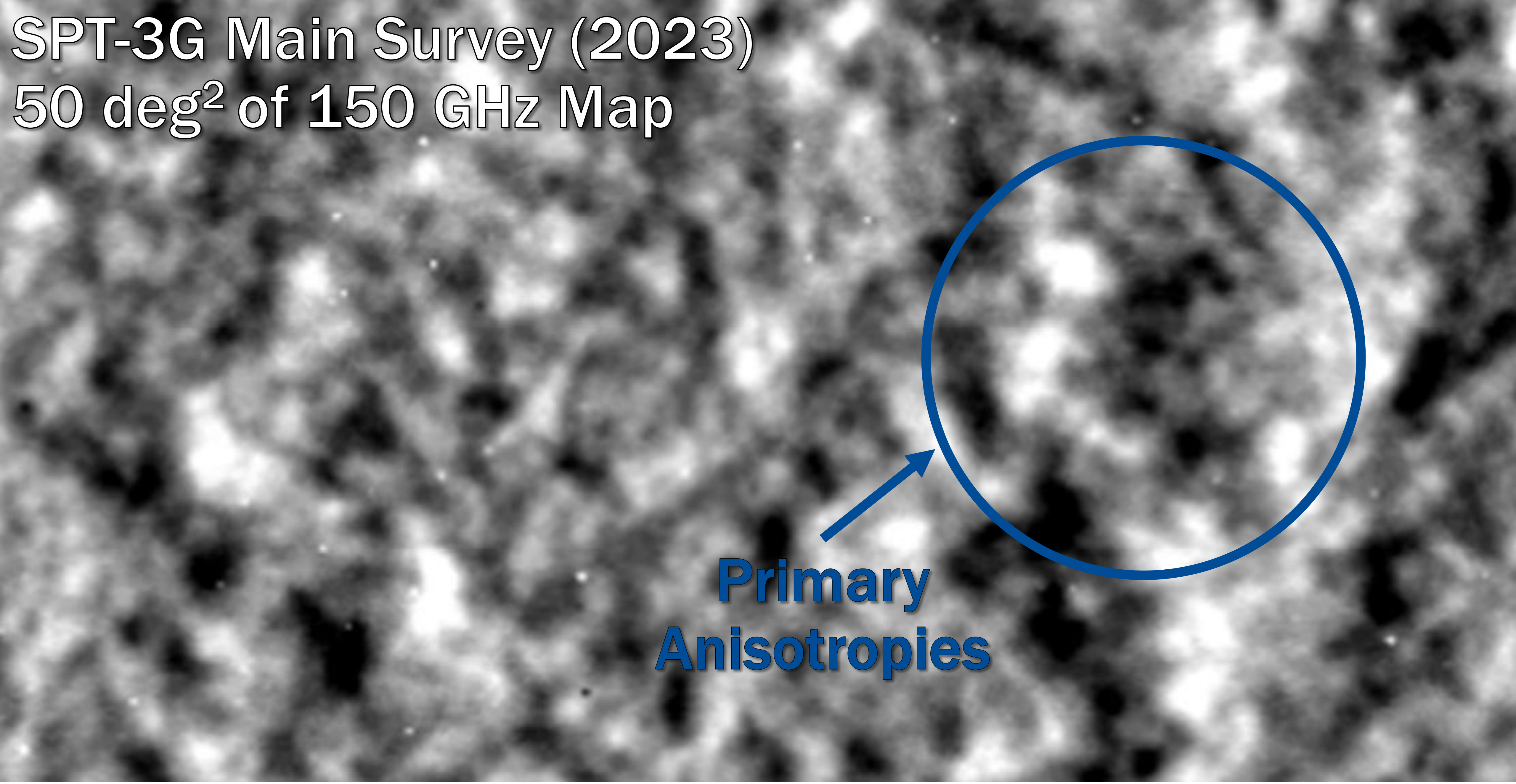
Science Results from SPT-3G

- Primary CMB temperature and polarization anisotropy measurements (J. Zebrowski)
  - arXiv: 2101.01684, 2212.05642
- Detection of galactic and extragalactic millimeter-wavelength time-varying/transient sources (A. Rahlin)
  - arXiv: 2103.06166
- Cosmological constraints from CMB power spectra measurements
  - arXiv: 2103.13618, 2212.05642
- Constraints on axion-like dark matter (A. Anderson)
  - arXiv: 2203.16567
- Measurement of pairwise kinematic Sunyaev-Zeldovich effect
  - arXiv: 2207.11937
- Catalog of Galaxy Clusters selected via the Sunyaev-Zeldovich effect (J. Sobrin, B. Benson)
  - *Coming soon…*

Key analysis contributions by Fermilab scientists!

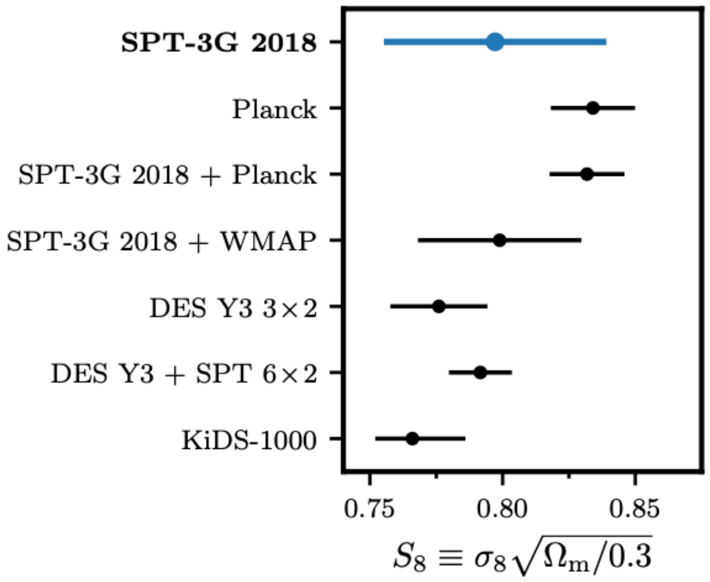
Many more analyses with current data underway!

SPT-3G Main Survey (2023)
50 deg^2 of 150 GHz Map



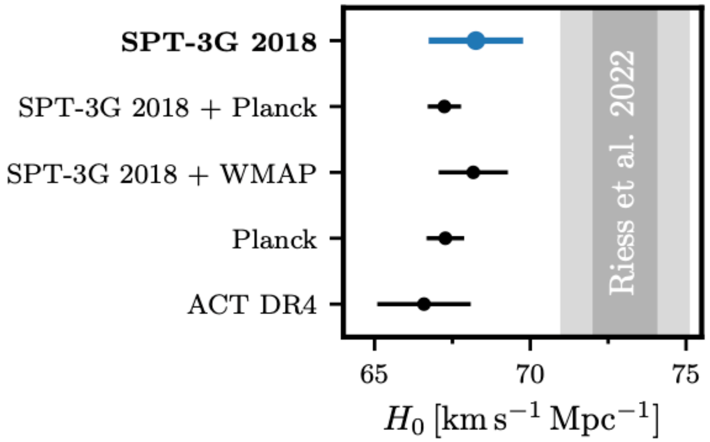
Cosmology with SPT-3G Power Spectra Data

- Constraints for both the expansion rate (H_0) and amplitude of matter fluctuations on large scales (S_8) derived from CMB data ($z \approx 1100$) and local-universe surveys ($z < 10$) are in disagreement.
  - True discrepancies could motivate the need for BSM or ΛCDM+ physics to resolve tensions.
- **4 months** of SPT-3G primary temperature and polarization power spectra data were used to constrain ΛCDM cosmology.
  - Parameter constraints were in good agreement with Planck and best current ground-based measurements (ACT DR4).
  - Constraints were not as strong as Planck **yet**, but provided a crucial consistency check by utilizing SPT-3G's improved arcminute-scale and polarization-sensitive data to derive constraints.
- 20X more data now on disk, and upcoming 2019-2020 SPT-3G data release will either compare-to or surpass Planck's constraining power.
  - Ground-based CMB experiments have a strong future in ruling between new, proposed physics models.

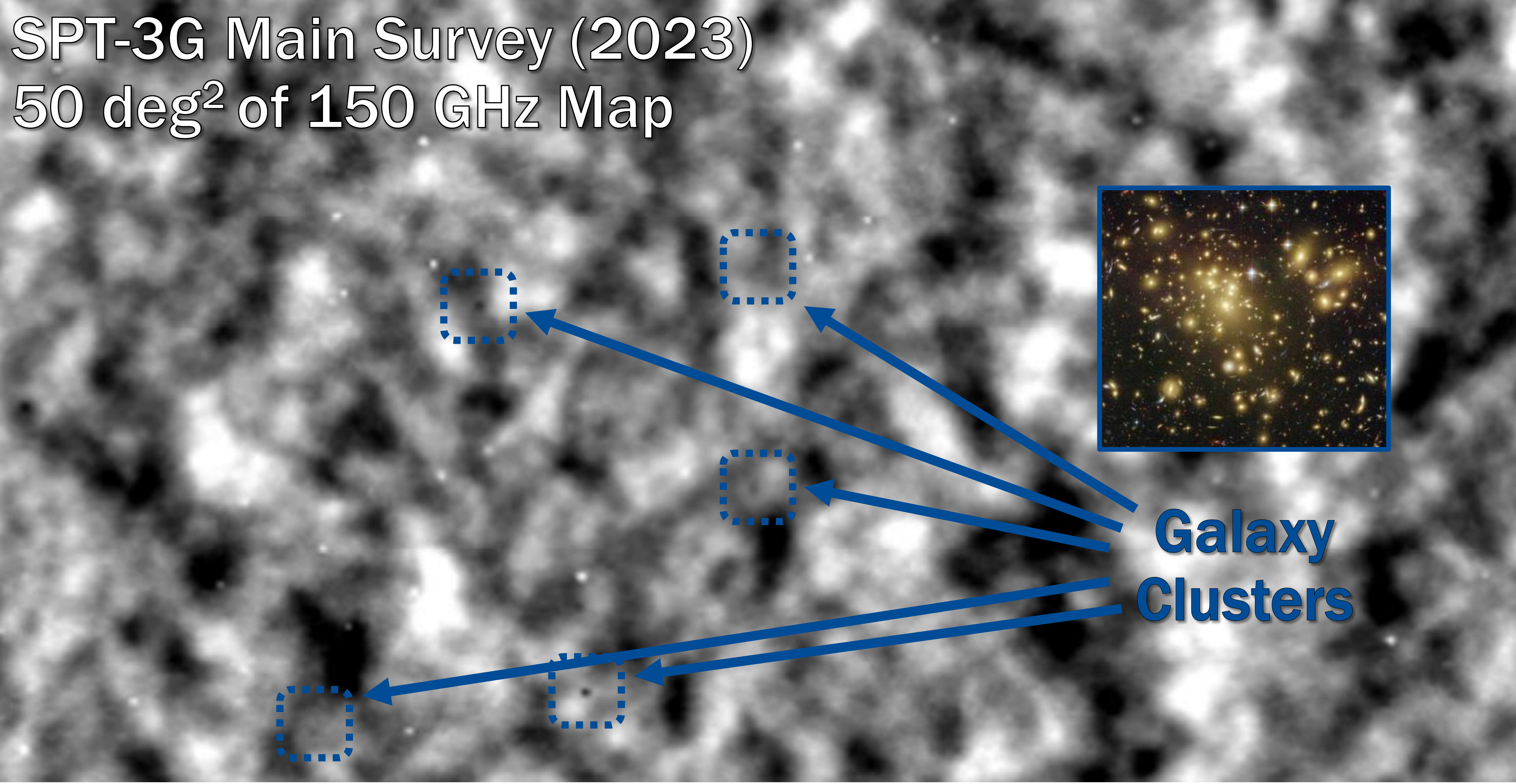


Balkenhol et al. 2022
(Accepted by PRD)

Compilations of H_0 and S_8 constraints from several CMB and local-universe surveys.



SPT-3G Main Survey (2023)
50 deg^2 of 150 GHz Map

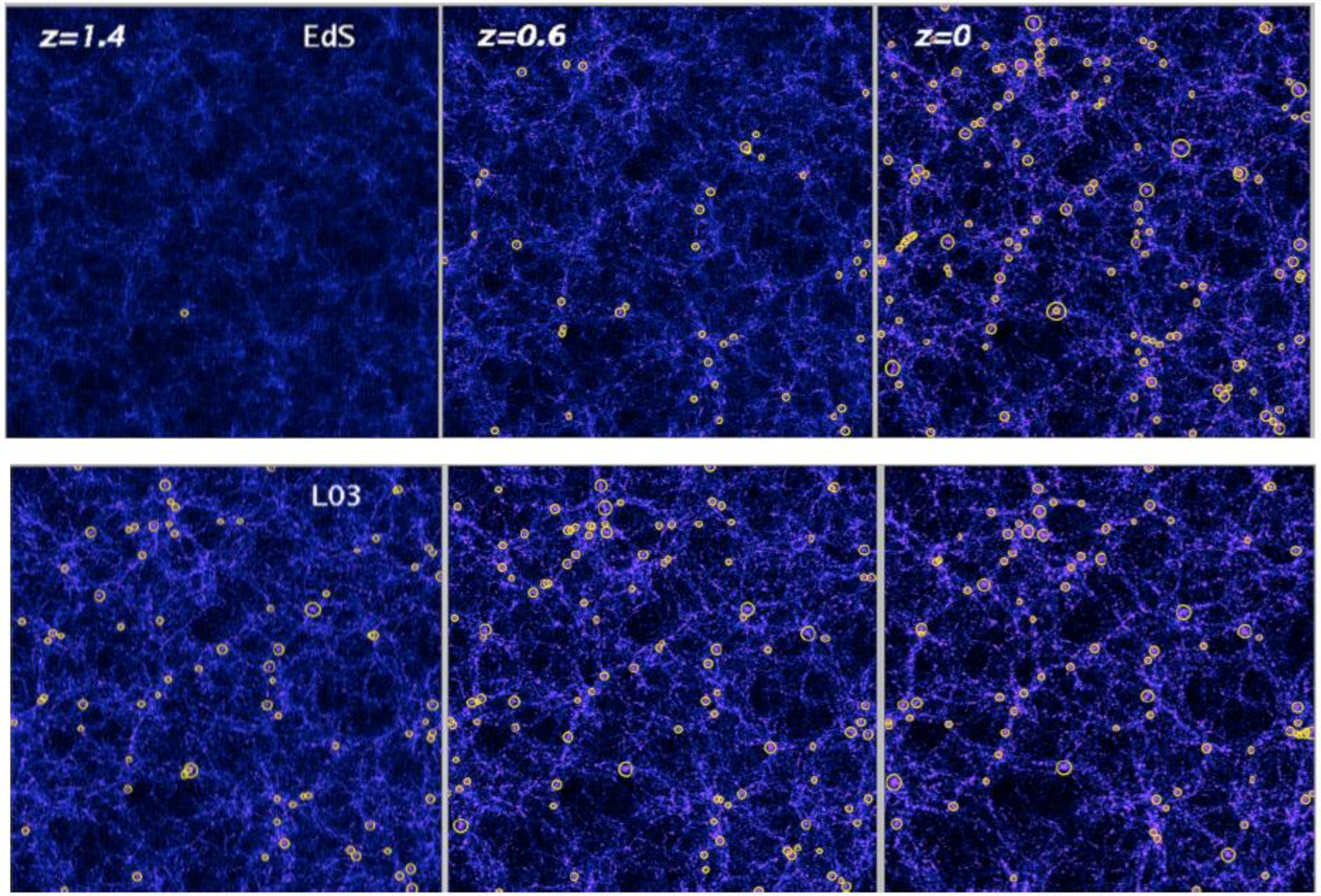


Galaxy Clusters as Tracers of Structure Formation

Ref: Borgani and Guzzo (2001)

Matter-dominated universe with no dark energy

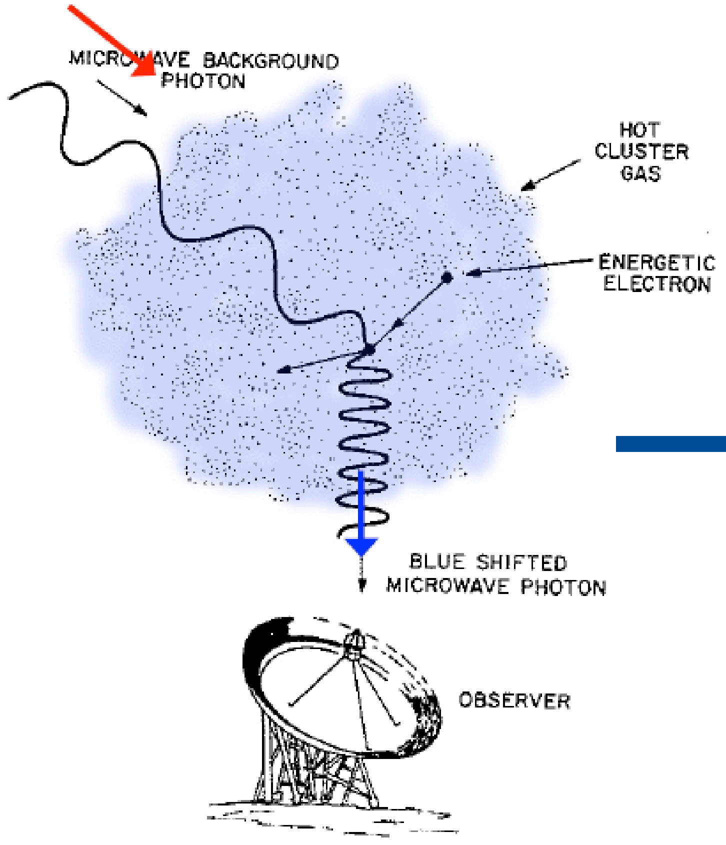
Universe with 70% dark energy and 30% matter



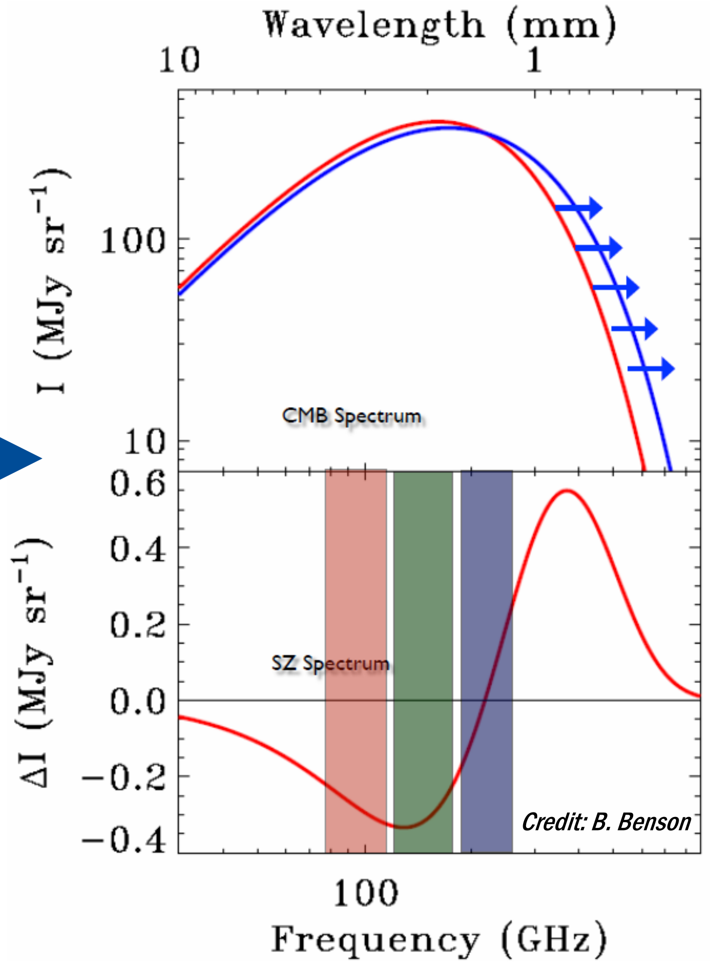
Time

- Galaxy-cluster formation history has been strongly dependent on the universe's physical conditions through cosmic time.
  - Potentially one of the strongest cosmological probes of dark energy and neutrino mass.
- Measuring the **abundance** and **masses** of clusters across redshift space provides a promising way to constrain physical cosmology with independent systematics.
  - However, cluster selection functions and mass calibrations are not well characterized at high redshift ($z > 1$) by surveys measuring cluster emission.

The Sunyaev-Zeldovich (SZ) effect



Credit: L. Van Speybroeck

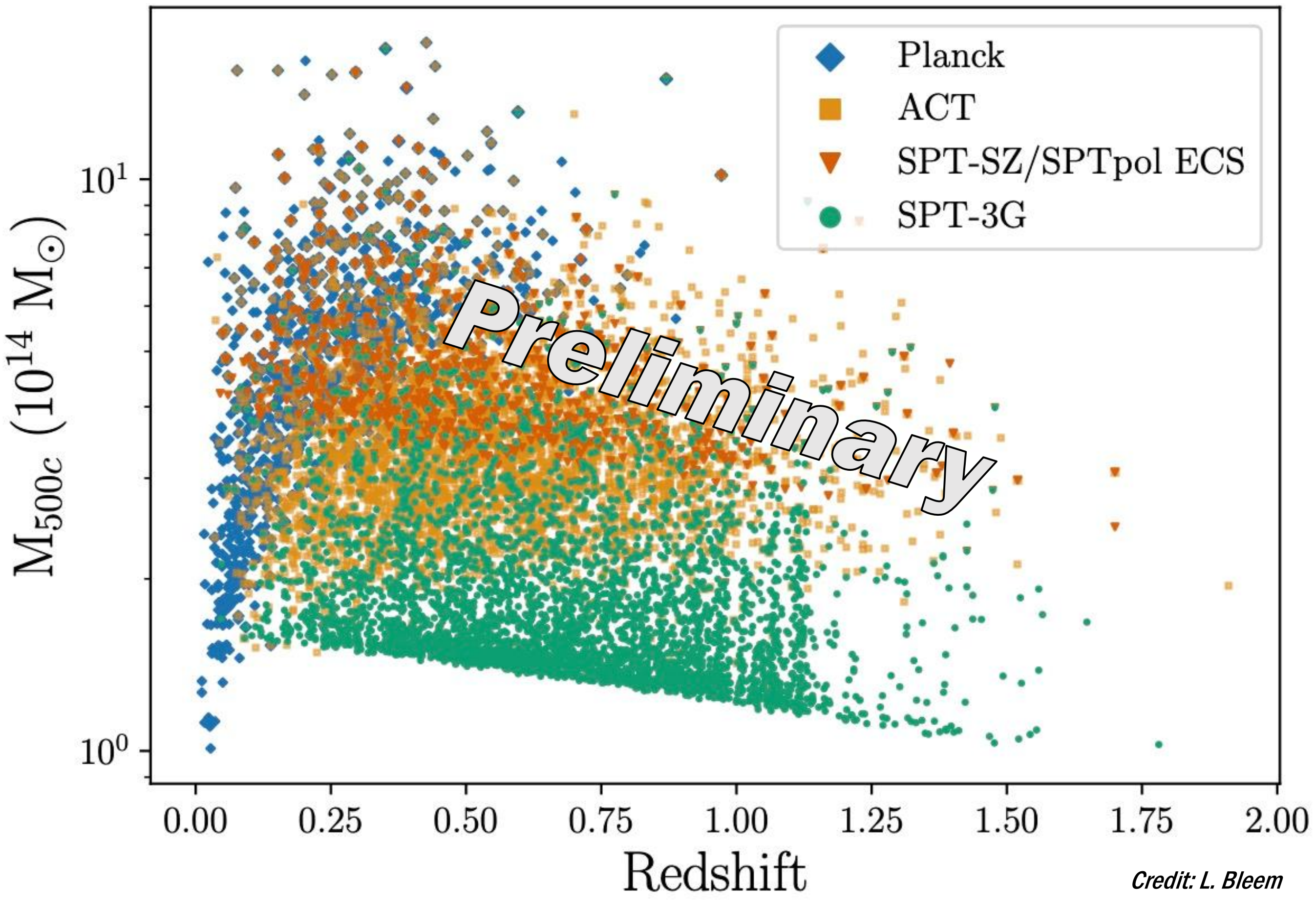


Credit: B. Benson

- When passing through a galaxy cluster, a portion of CMB photons inverse-Compton scatter off relativistic, ionized particles present in the intra-cluster medium.
- This process results in arcminute-scale intensity distortions in the CMB, which can be detected to identify and characterize galaxy clusters.
- Very importantly, this scattering effect is both redshift-independent and cluster-mass sensitive.
    - CMB SZ surveys provide an excellent complement to X-ray, optical, and infrared emission surveys.

SPT-3G 2019-2020 Main-field Cluster Catalog

- 5891 candidates detected with SNR > 3.85 over 1500 deg^2, using 2 years of SPT-3G data.
  - 2457 candidates SNR > 5 (more than 99% purity).
  - Candidates cross-matched with DES to validate low-redshift clusters (z < 1). Additional promising candidates being followed-up with targeted Magellan FourStar NIR imaging (follow-up ongoing).
- Detection density is many factors higher than best previous SZ-effect cluster surveys.
- This forthcoming, partial cluster sample already demonstrates SPT-3G's significantly improved ability to discover and characterize the lowest-mass, highest-redshift clusters.



Credit: L. Bleem

3. *The Future of CMB at Fermilab: CMB-S4*

New Physics or Not?

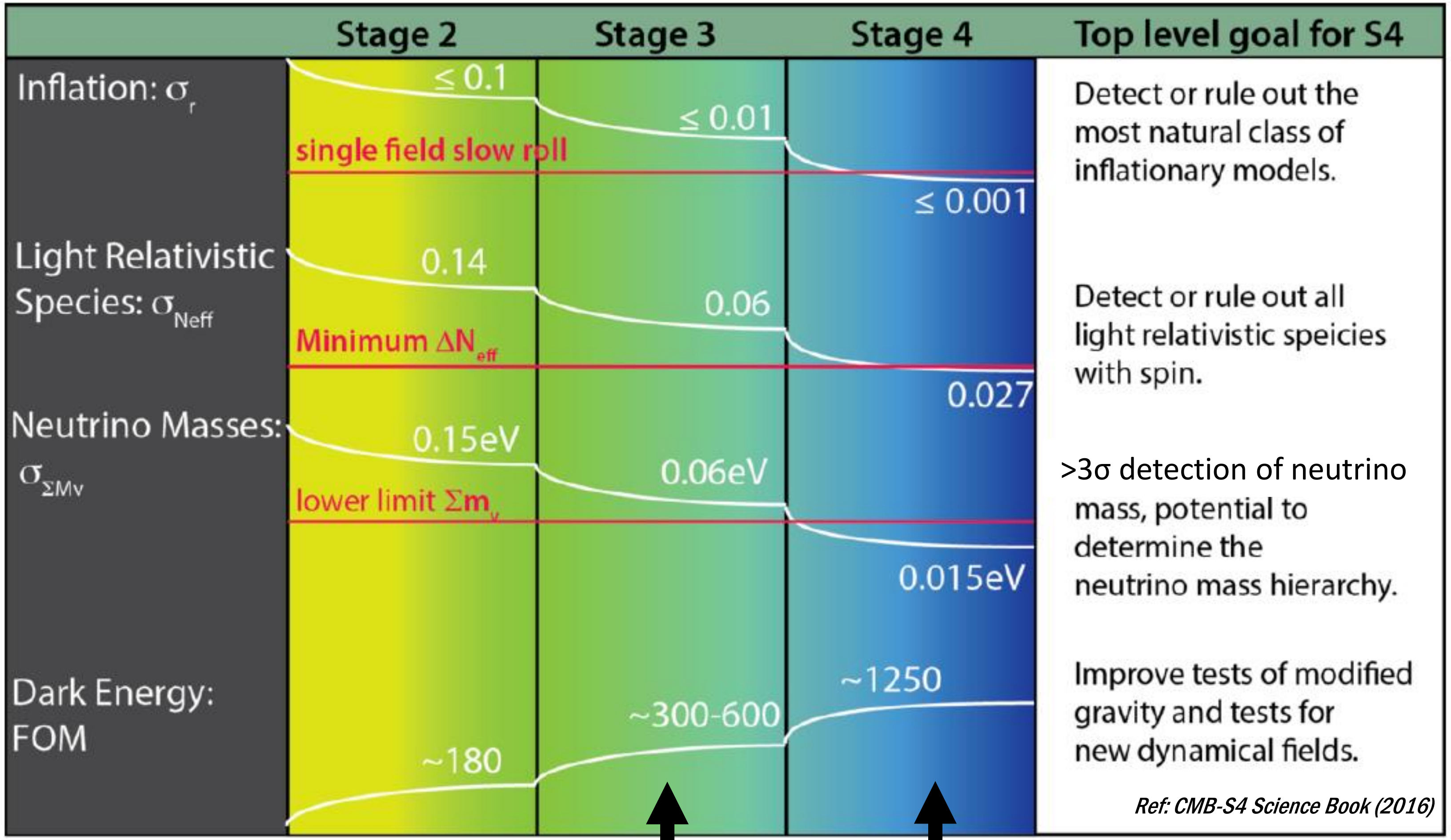
- For modern photon-noise dominated CMB experiments:

  Sensitivity = $\sqrt{\text{N(Detectors) x Time}}$.

- While current experiments will either detect or set upper limits on BSM and LCDM+ physics, it is unlikely they will reach the necessary sensitivities to conclusively rule out new physics.

- A dramatic increase in experiment scale and improvement in systematics handling is necessary to answer questions about new physics decisively.

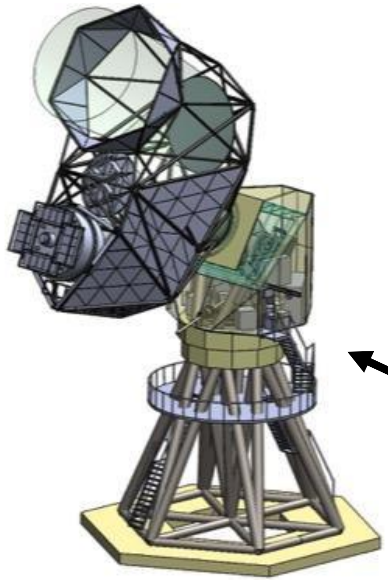
Parameter Thresholds for Ruling Out New Physics



~10K detectors ~500K detectors

CMB-S4 Experimental Plan

- A combination of large-aperture (LAT) and small-aperture (SAT) telescopes across two sites will optimally map degree- to arcminute-scale CMB temperature and polarization modes with <u>480,000</u> photon-noise limited detectors:

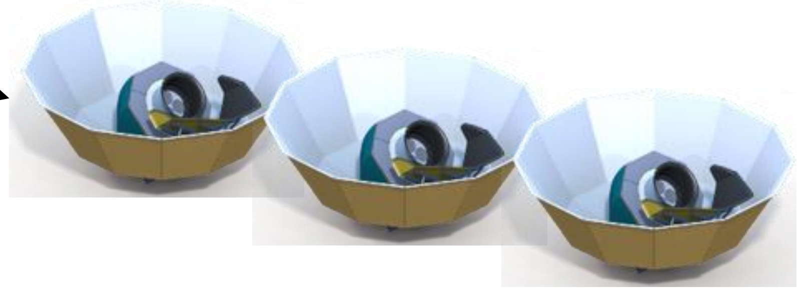


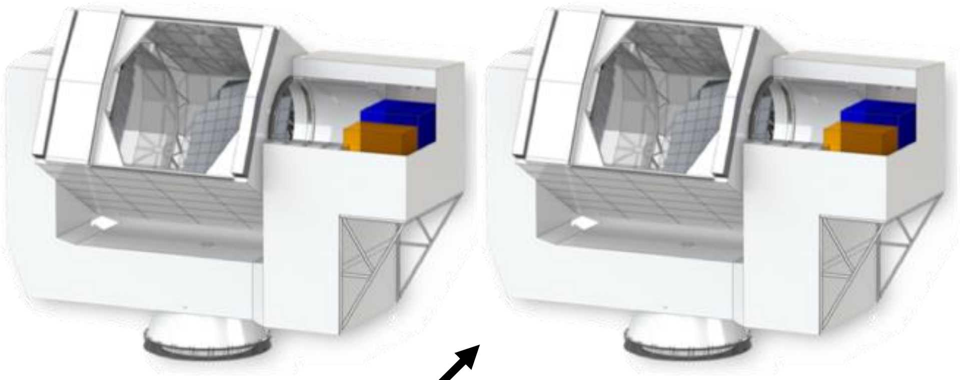
<u>South Pole:</u>

- Deep survey of 3% of the sky to meet inflation science goals.

One 5m three-mirror anastigmat (TMA): <u>130K</u> detectors

Nine 0.5m refracting telescopes: <u>80K</u> detectors





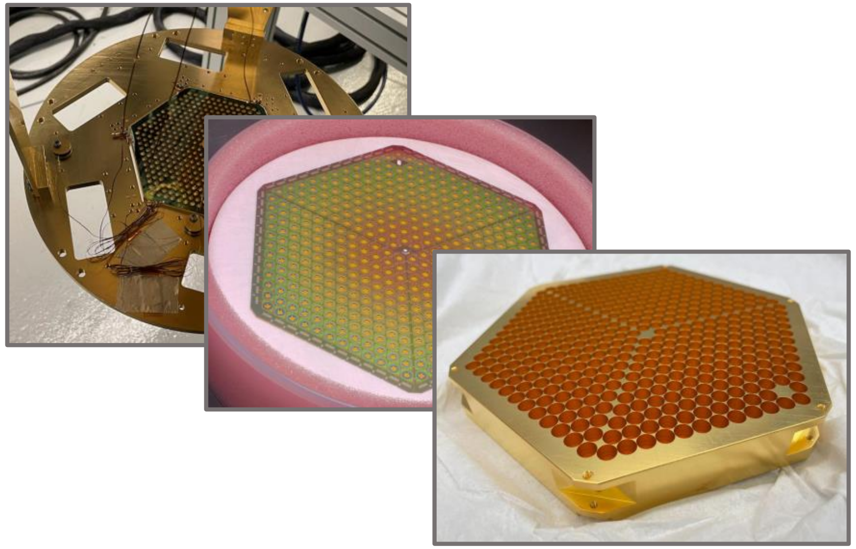
Two 6m crossed-Dragone telescopes: <u>270K</u> detectors

<u>Chile:</u>

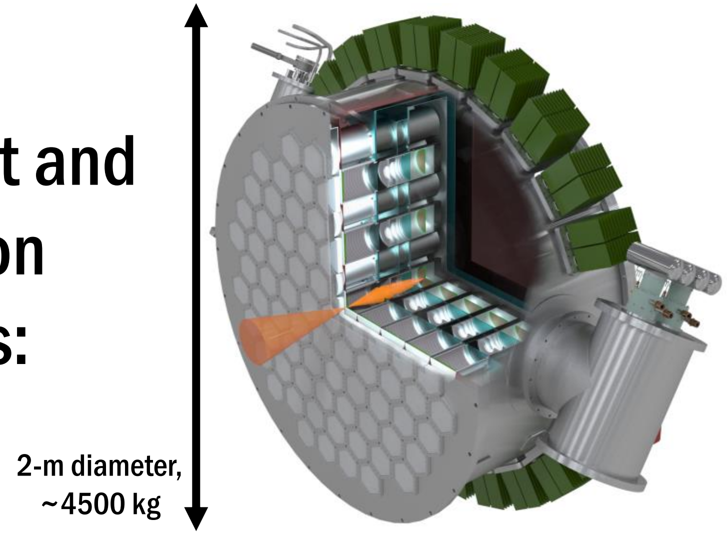
- Wide survey of 40% of the sky to meet light relic and transient-science science goals.

Fermilab's Leading Contributions to CMB-S4

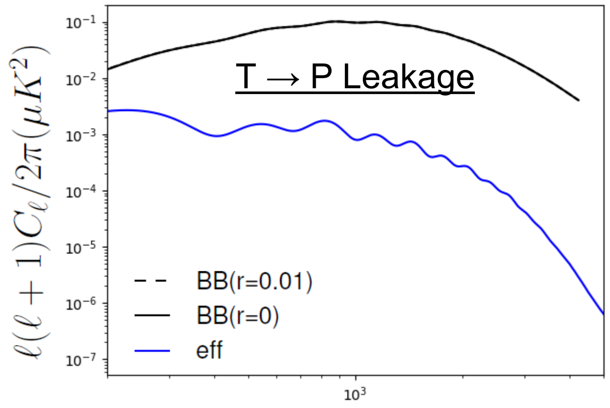
Module Design, Assembly, and Testing:



LAT Receiver Development and Anti-reflection Technologies:



Modeling Instrument Systematics:



Leveraging Fermilab's strong history in silicon-detector and cryogenic-receiver development!

Thank You.