Precision Cosmology with the Cosmic Microwave Background

Photo courtesy of Jon Ward

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Fermilab

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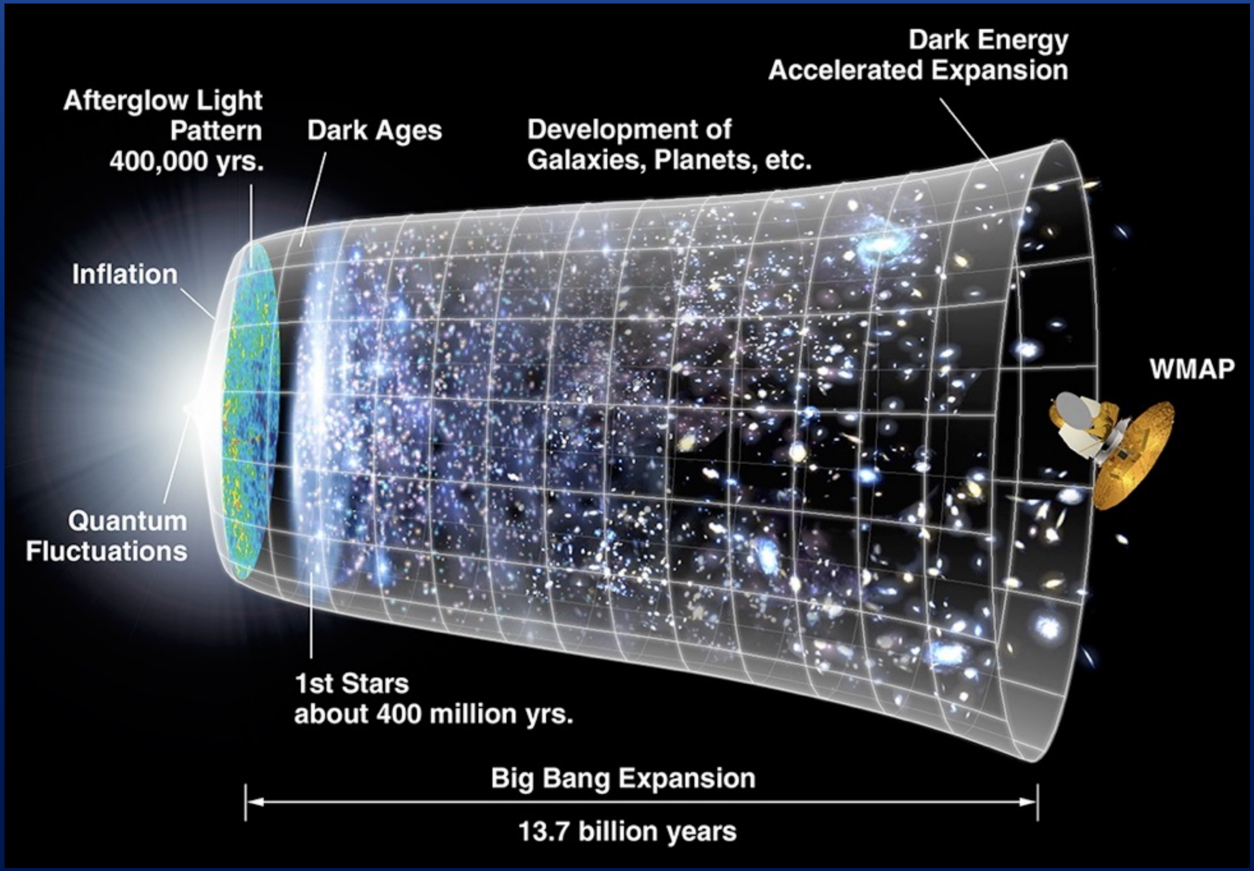
ΛCDM Cosmology

- Expanding, flat universe that began in a hot, dense state
- Dominated by dark energy and dark matter



NASA WMAP Science Team

- ΛCDM model describes our universe incredibly well… BUT it leaves many fundamental questions unanswered

The Cosmic Microwave Background (CMB) is the afterglow of the Big Bang

- Formed ~400,000 years after the Big Bang→ oldest light in the universe

1. Snapshot of the early universe
   - Picture of the earliest moments in the universe
   - ~10 trillion times the energies of particle accelerators

2. Backlight to the formation and evolution of structure in the universe (galaxies, galaxy clusters, etc.)
   - Information about dark matter, dark energy, information about particles and their interactions, astrophysics

The CMB answers fundamental questions

- CMB can measure the energy scale of inflation (*r*)
  - One of the few ways to probe early universe ~10^{-36} s after its beginning

Inflation is currently the leading theory of the early universe

- Universe underwent exponential expansion shortly after its beginning

- Offers explanations for several unexplained phenomena
  - Flatness and uniformity of the universe
  - Source of structure in the universe

- If inflation occurred, it would have left a signature pattern in the CMB polarization
  - “B-mode” polarization
  - Size of this signal would directly measure the energy scale of inflation
  - One of the few ways to probe early universe ~10^{-36} s after its beginning

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  - Constrain/probe theories that predict new light particles

Particles Beyond the Standard Model

- Relativistic particles contribute to the radiation density of the universe
- Changes in radiation density change the expansion rate and primordial oscillations → change characteristics of the temperature and polarization of the CMB
- Standard Model: $N_{eff} = 3.046$

$\Delta N_{eff} \geq 0.047$ Spin $\frac{1}{2}$, 1, $\frac{3}{2}$

$\Delta N_{eff} \geq 0.027$ Spin 0

Planck (current): $\sigma(N_{eff}) \sim 0.2$

Simons Observatory: $\sigma(N_{eff}) \sim 0.07$

CMB-S4: $\sigma(N_{eff}) \sim 0.027$

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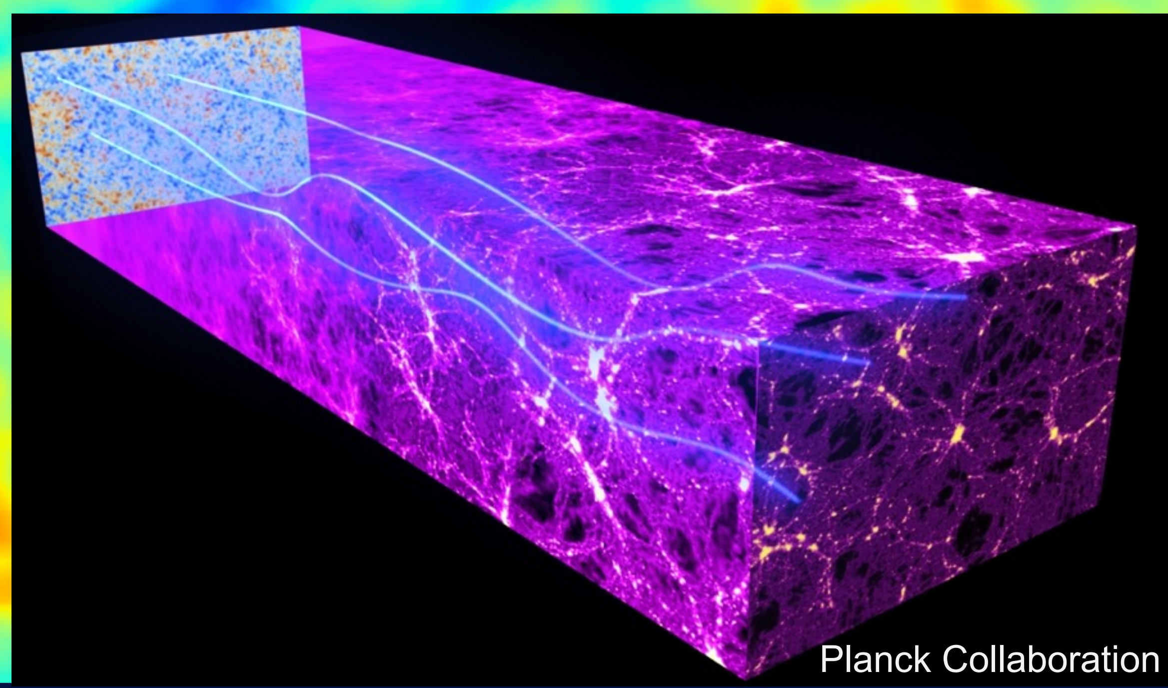
- CMB measures the sum of the neutrino masses ($\sum m_v$)
  - Compliment to neutrino oscillation experiments that measure Δm_{ij}^2
- CMB constrains dark matter and dark energy through the growth of structure (σ_8), the expansion rate (H_0), and the amounts of dark matter and dark energy
  - Extremely accurate probe of these mysterious dark components
  - Highly complementary to supernovae and large-scale structure studies

CMB as a Backlight

- Photons from the CMB are gravitationally deflected by structure
- Can reconstruct maps of the dark matter distribution
- Lensing probes the growth of structure → dark energy, $\sum m_\nu$
- Need improved temperature + polarization measurements on small angular scales across large areas of the sky



Planck Collaboration

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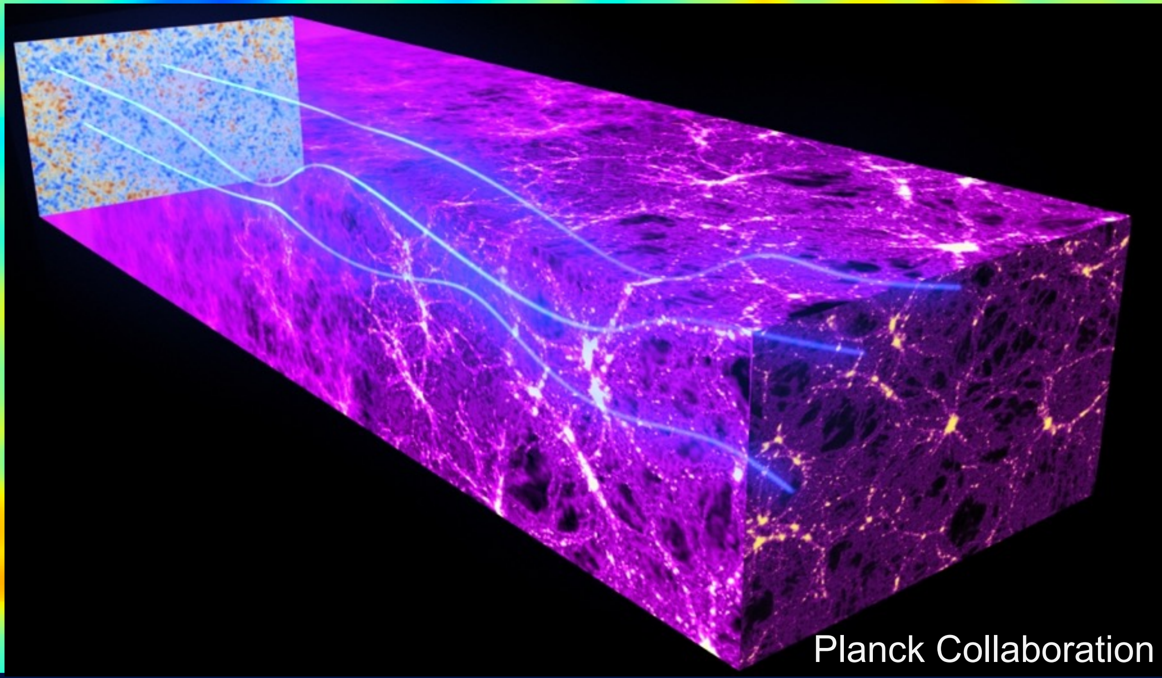
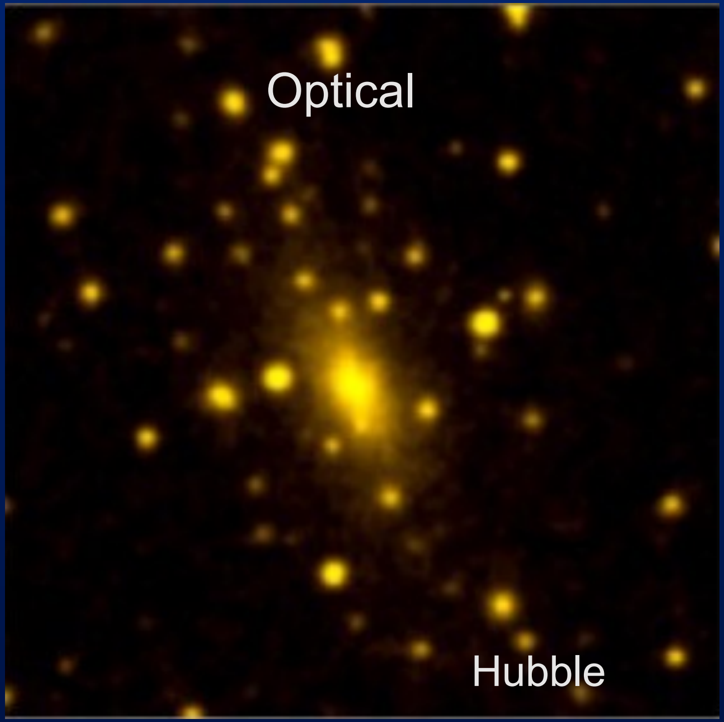


Planck Collaboration

Galaxy Clusters

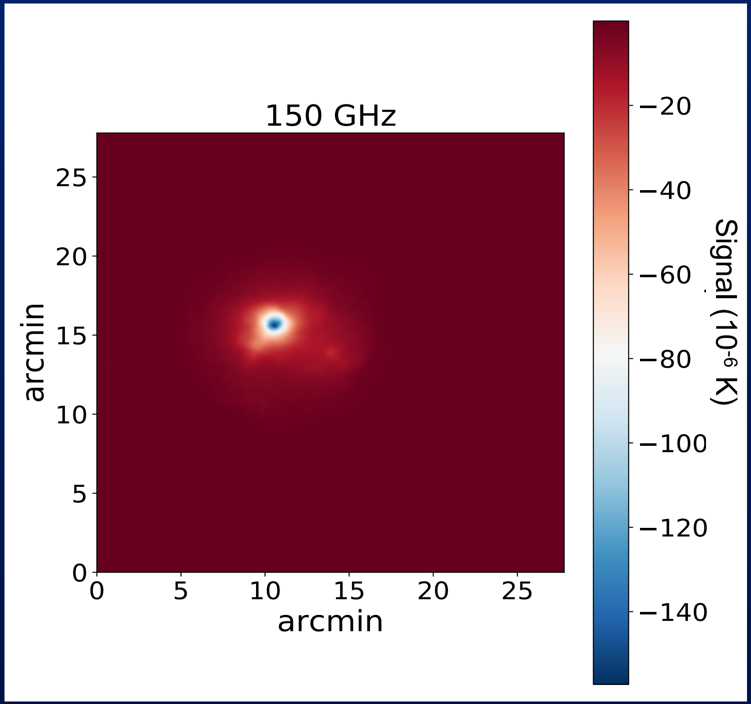
- Galaxy clusters are largest structures in the universe → formation is highly sensitive to effects of dark matter and dark energy

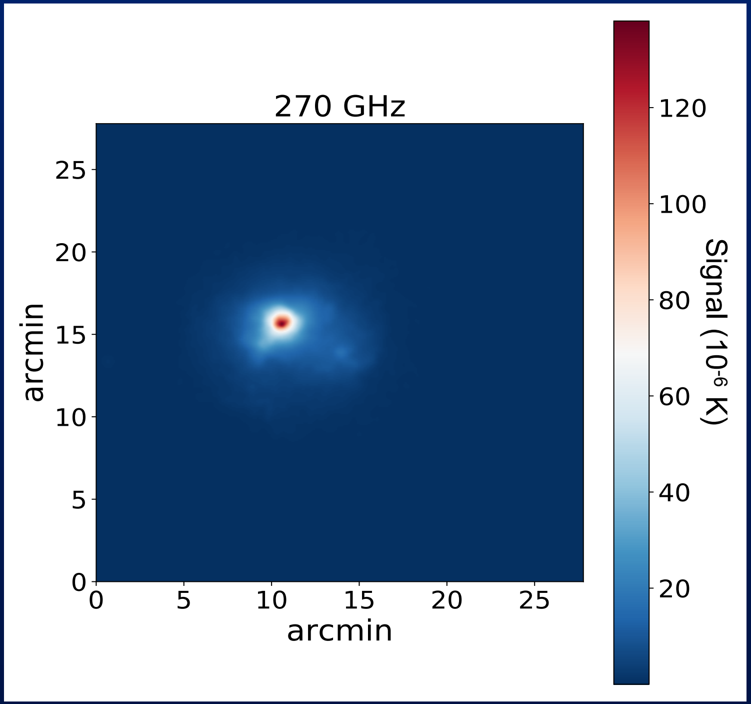


CMB as a backlight to galaxy clusters

- CMB photons collide with high energy gas in galaxy clusters→ Boosts their energy (increases their frequency)

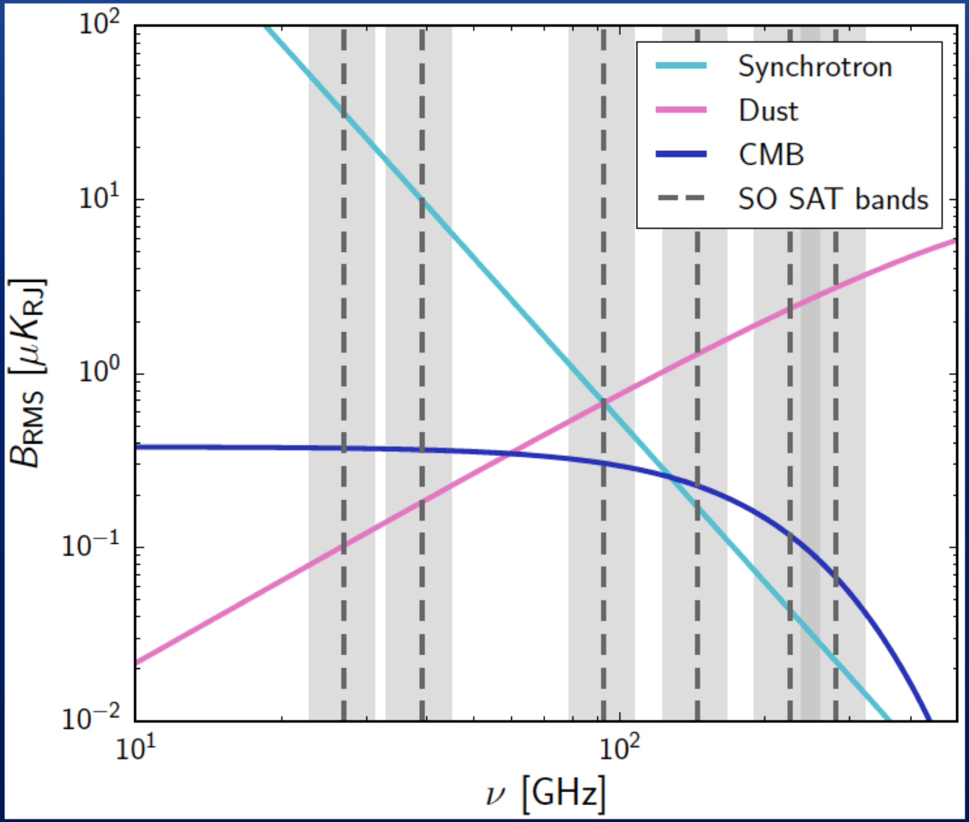
- Signal does not dim with distance → picture of evolution





Measurement Challenges

- The amplitude of the inflationary signal is small → Need high sensitivity
- Polarized foreground contamination from synchrotron and dust emission → Need wide frequency coverage
- Fluctuations in the unpolarized atmosphere, especially on large angular scales (ground-based) → Need to lower atmospheric noise



The Simons Observatory Collaboration, 2018

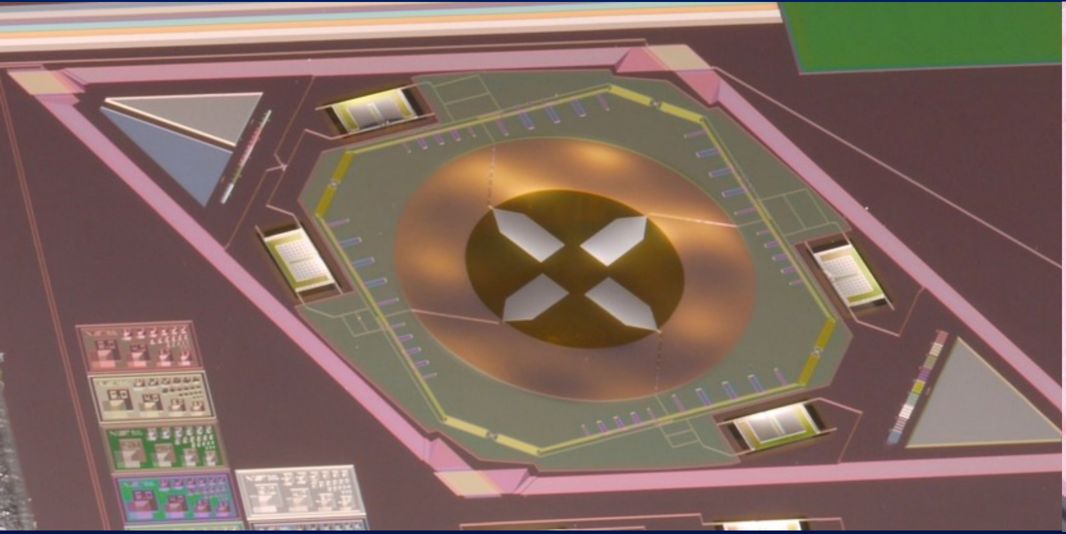
Future Progress in CMB Science

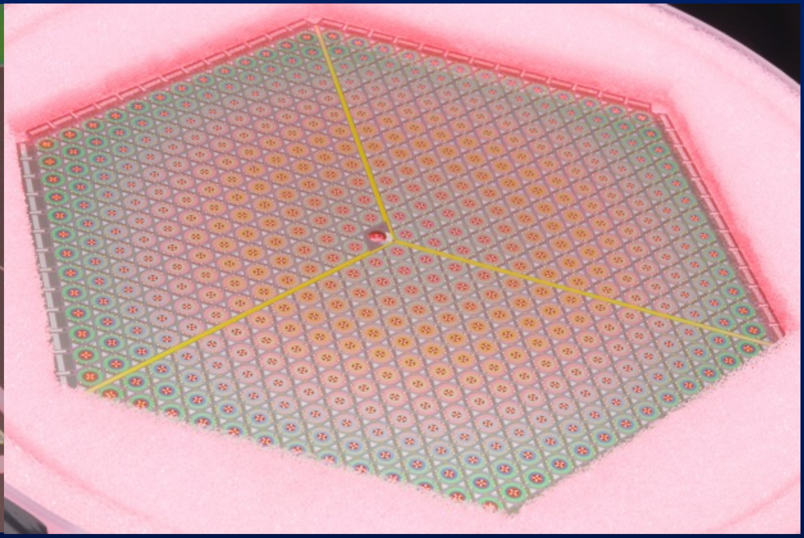
- **Progress is now driven by instrumental advancements**

- Multichroic pixels → increased sensitivity and frequency coverage

- Polarization modulators → lower atmospheric noise

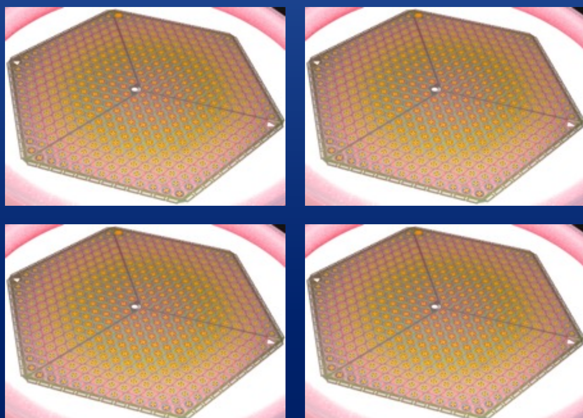
- Increased detector count → increased sensitivity
  - Increased number of detectors/array
  - Increased number of arrays





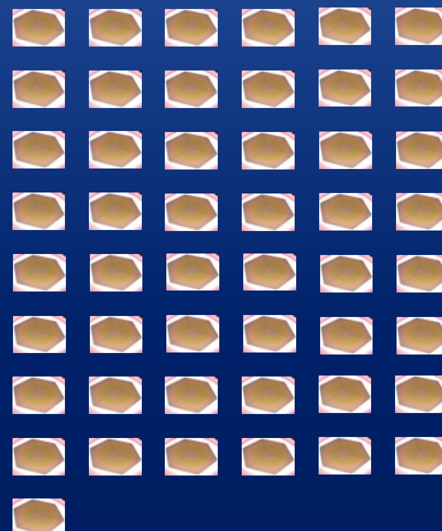
Next Decade: More Detectors = More Sensitivity

AdvACT (Current)

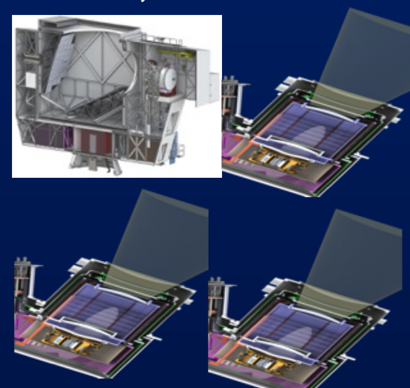


~5000 detectors

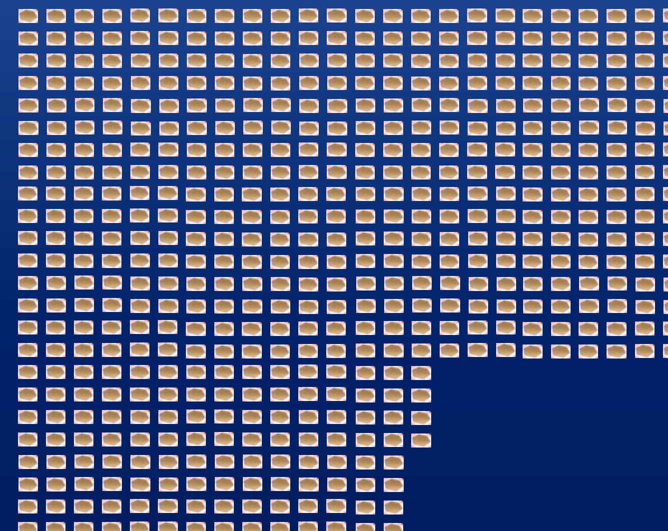
Simons Observatory (~2023)



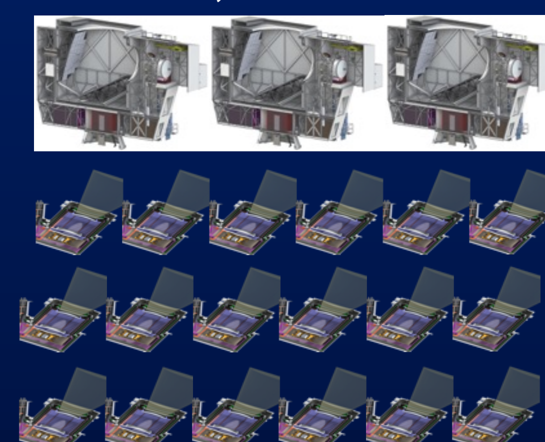
~50,000 detectors



CMB-S4 (~2030)



~500,000 detectors



Science Forecasts

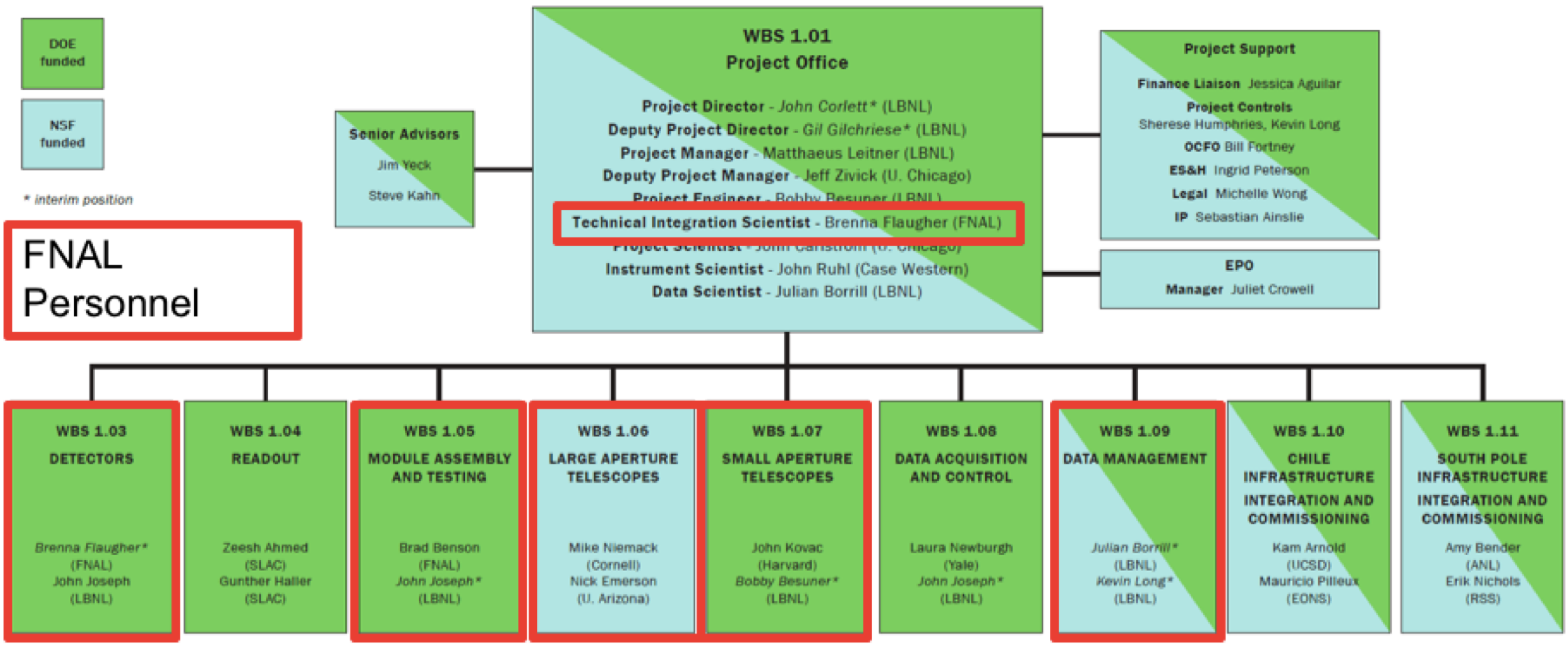
Parameter	Current Best	SO Baseline	CMB-S4 Baseline	Method
$\sigma(r)$	0.03	0.003	0.0005	BB + ext delens
$\sigma(N_{eff})$	0.2	0.07	0.027	TT/TE/EE + $\kappa\kappa$
$\sigma(\sum m_\nu)$	0.1 eV	0.04 eV	0.015 eV	$\kappa\kappa$ + DESI-BAO
$\sigma(H_0)$	0.5	0.4	0.24	TT/TE/EE + $\kappa\kappa$
$\sigma(\sigma_8)$ (%)	7%	2%	0.1%	$\kappa\kappa$ + LSST-LSS + DESI-BAO

The Simons Observatory Collaboration, 2018
The CMB-S4 Collaboration, 2016

Plus:
SO: 20,000+ galaxy clusters
CMB-S4: 100,000+ galaxy clusters

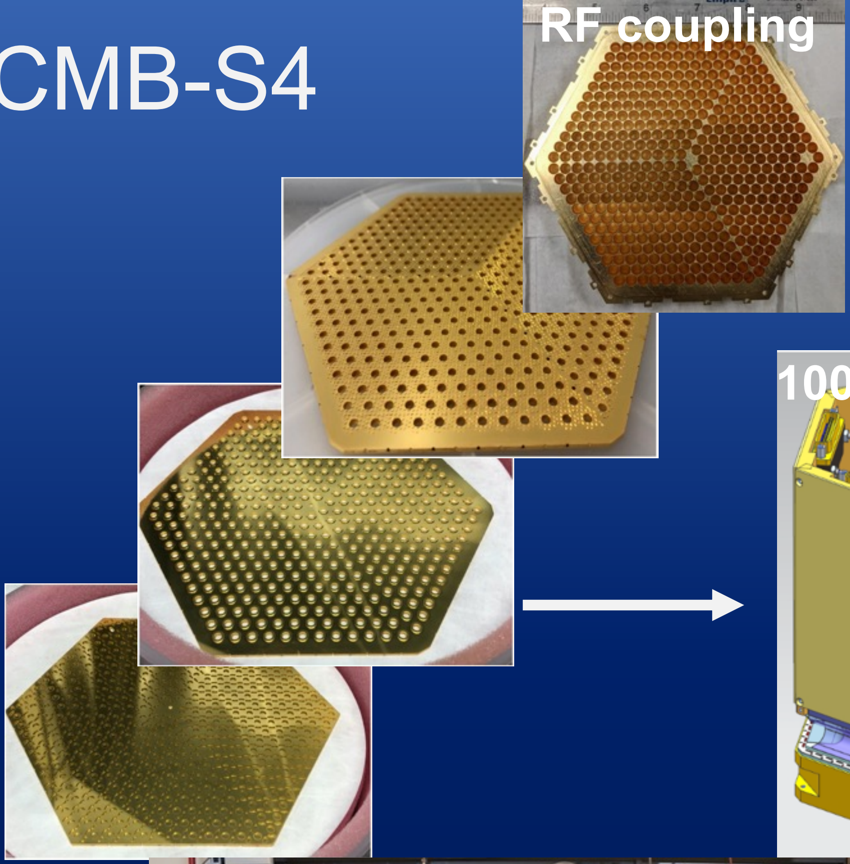
CMB-S4

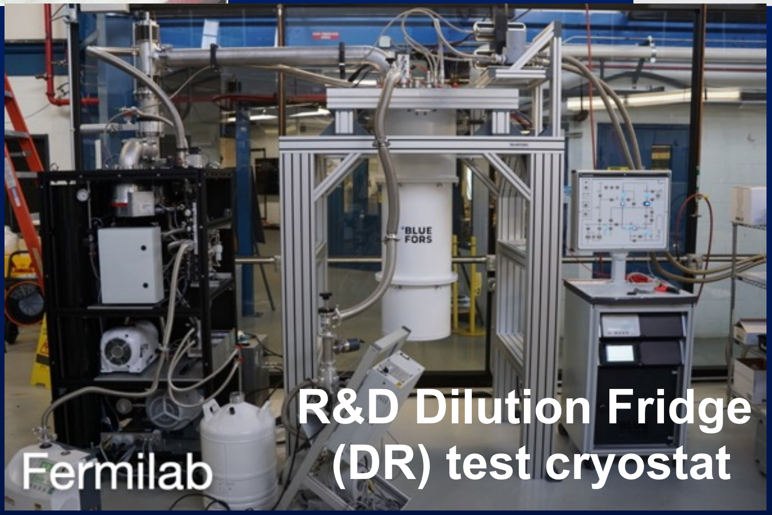
- CMB-S4 is a joint project between the DOE and NSF
- CMB-S4 Collaboration has 317+ members from 96 institutions (universities + national labs); 16 countries



Fermilab Roles on CMB-S4

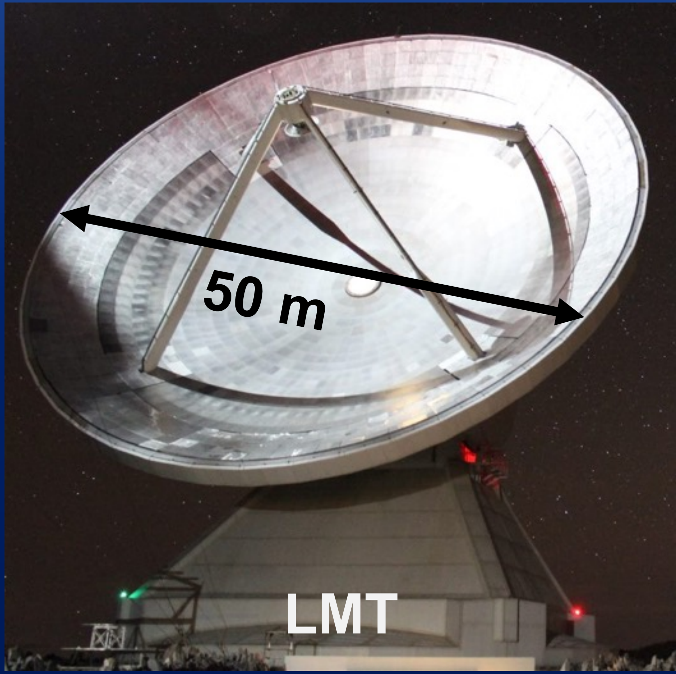
- 100 mK Detector Module Assembly and Testing
  - Microwave coupling
  - Module design and assembly
  - Module characterization
  - >2024: Mass production and testing of modules
- Detector group leadership and project leadership
- Data simulation + Site computing infrastructure
- Cryostat design and commissioning receiver for high resolution telescopes
- Calibration for inflationary signal telescopes





Beyond CMB-S4

- CMB-S4 will nominally operate until ~2037
  - Data analysis will be rich→ inform new directions
  - Many opportunities for combining with surveys at other wavelengths
- Large millimeter surveys of the sky → much like optical (LSST)
  - More sensitivity → time + detectors
  - Opportunities for combining data sets + multi-messenger astronomy (especially with transient sources)
- Higher resolution: ~arcminute to ~few arcsec (e.g. TolTEC, CMB-HD)
  - Improved measurements and constraints of core CMB science
  - Detailed galaxy cluster measurements→ resolve substructure
  - Higher resolution transient detections



Summary

- The next generation of CMB observations are poised to make tremendous discoveries
  - r : Observe gravity operating on quantum scales
  - N_{eff} : Probe for particles beyond the standard model
  - $\sum m_{\nu}$: Constrain the masses of neutrinos
  - New insights into dark energy, dark matter, structure formation

- CMB-S4 will be on the forefront of these next-generation observations