Cosmic Microwave Background

Jessica Avva

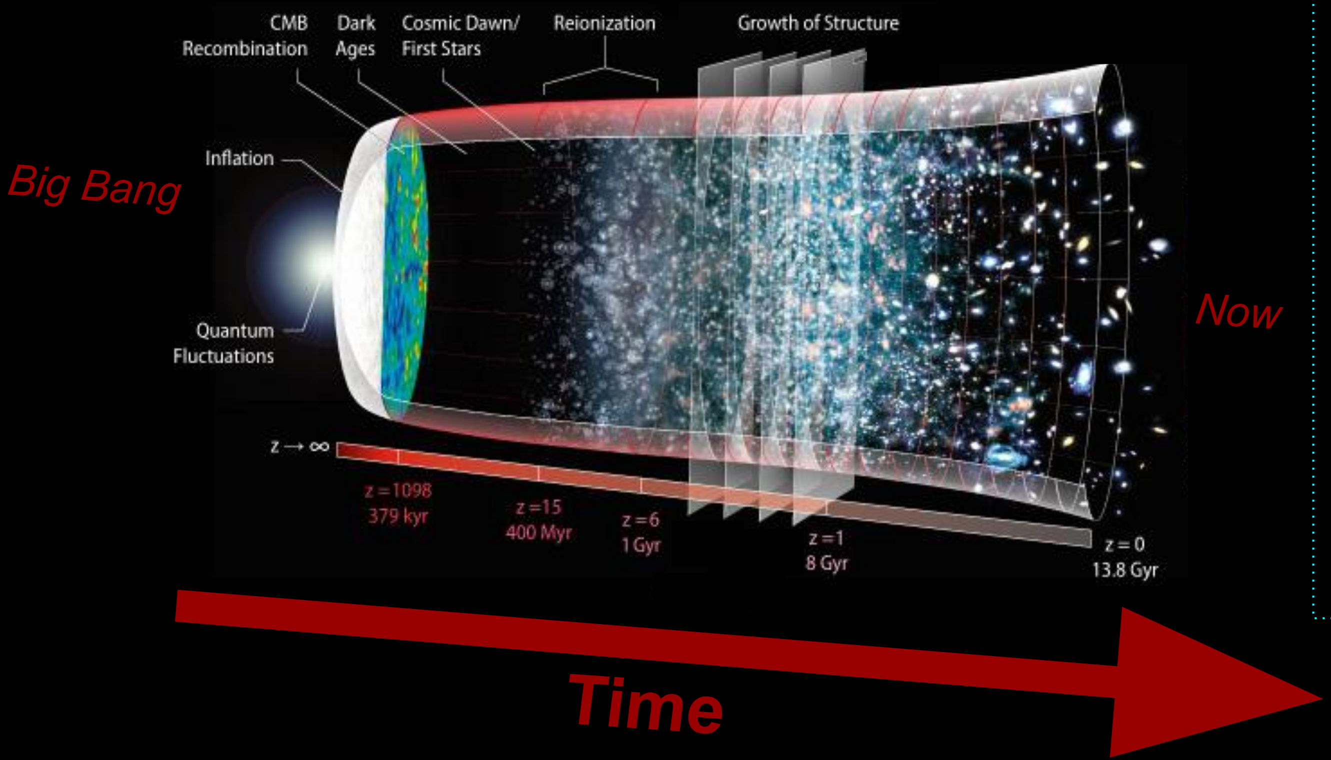
FNAL 55th Annual Users Meeting

June 14th, 2022

Outline

- CMB Science Overview
- Setting field-leading constraints on cosmology at FNAL with SPT-3G
- The future of CMB: FNAL's role in CMB-S4

The Observable Universe



Unsolved Mysteries

What mechanism drove inflation?

Can we use observations of the universe to learn about particle physics?

What is dark energy?

Image Credit: NASA / LAMBDA Archive Team

The Observable Universe - Fermilab Collaborations

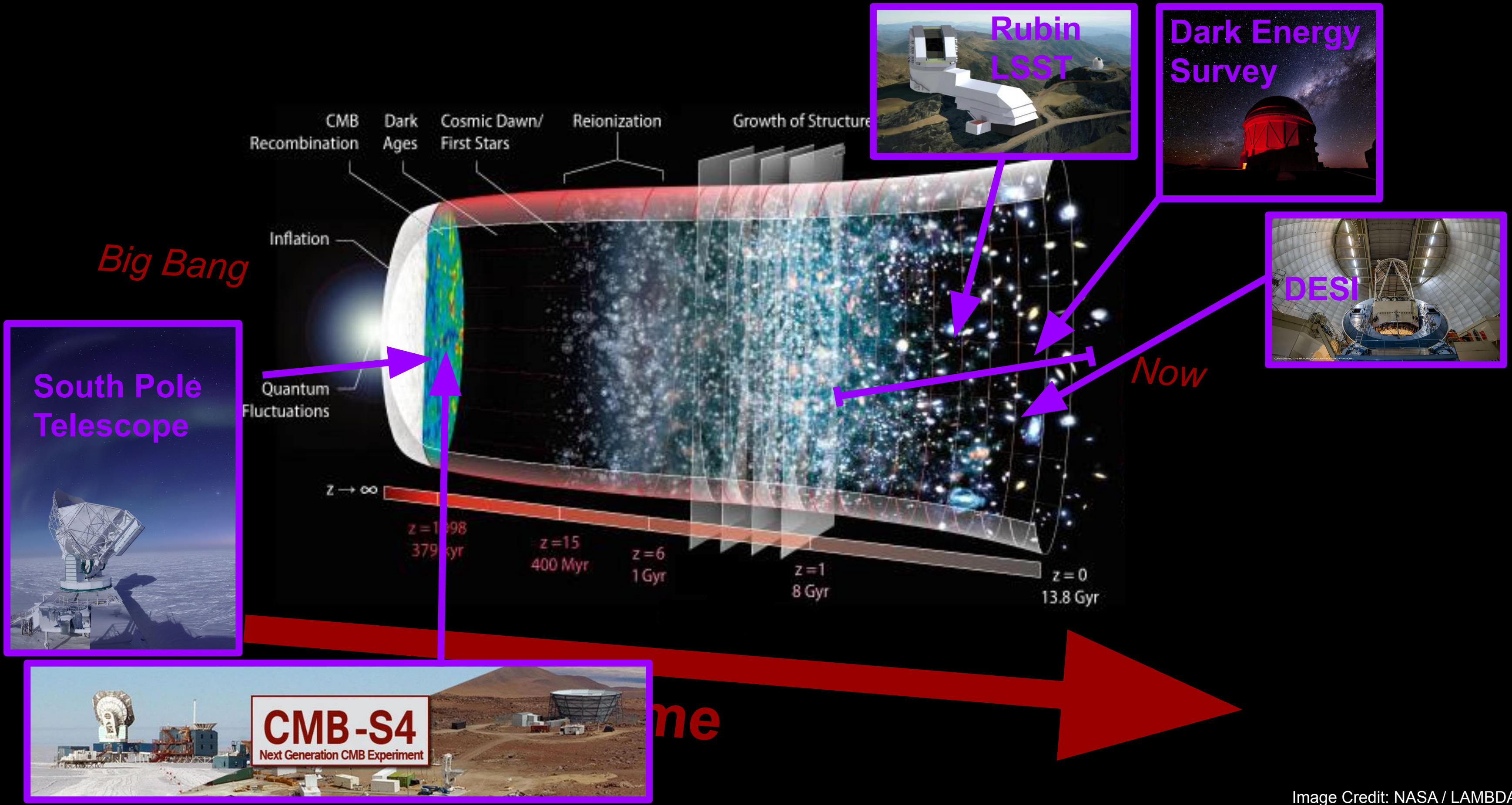


Image Credit: NASA / LAMBDA Archive Team

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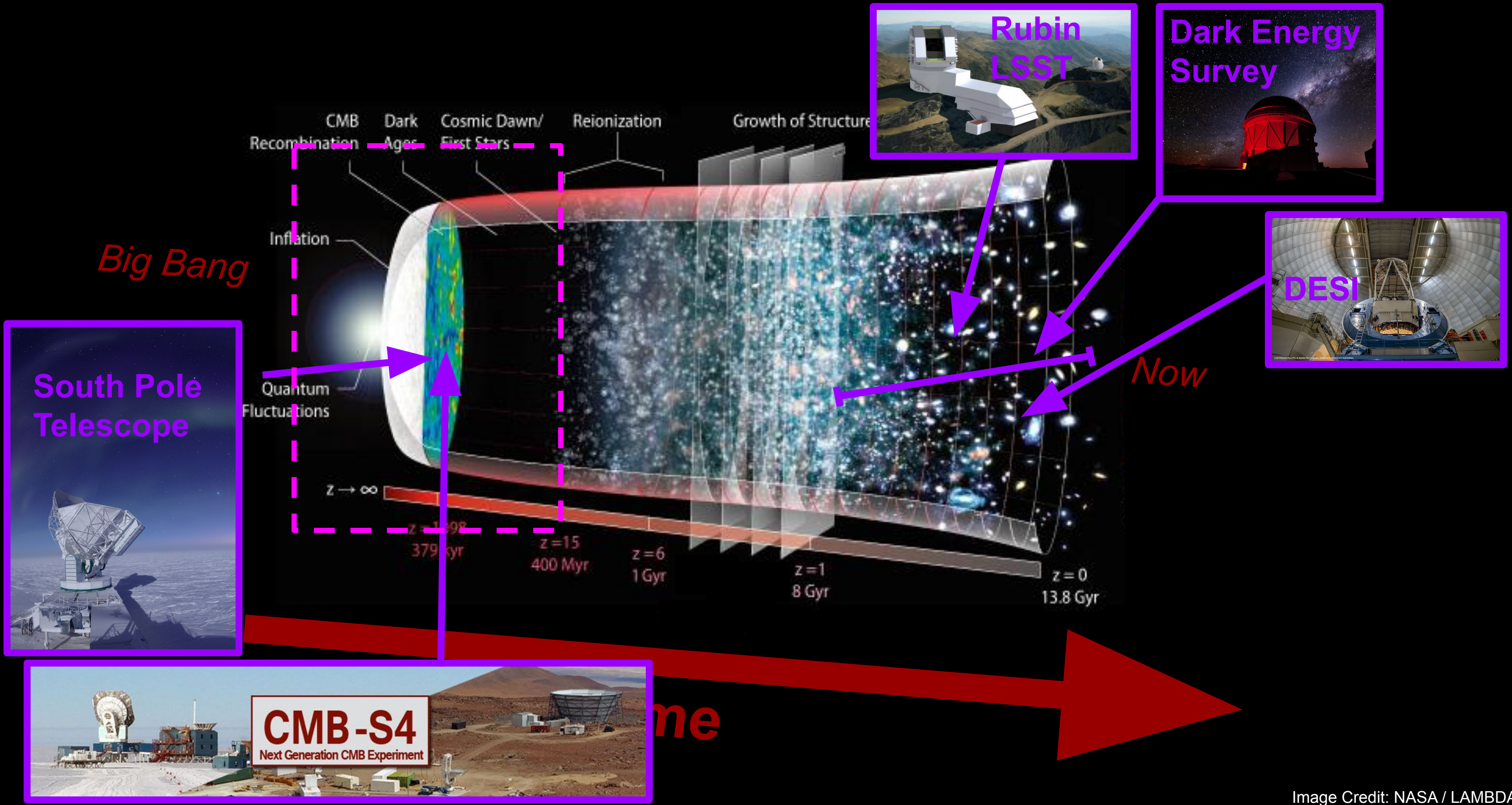
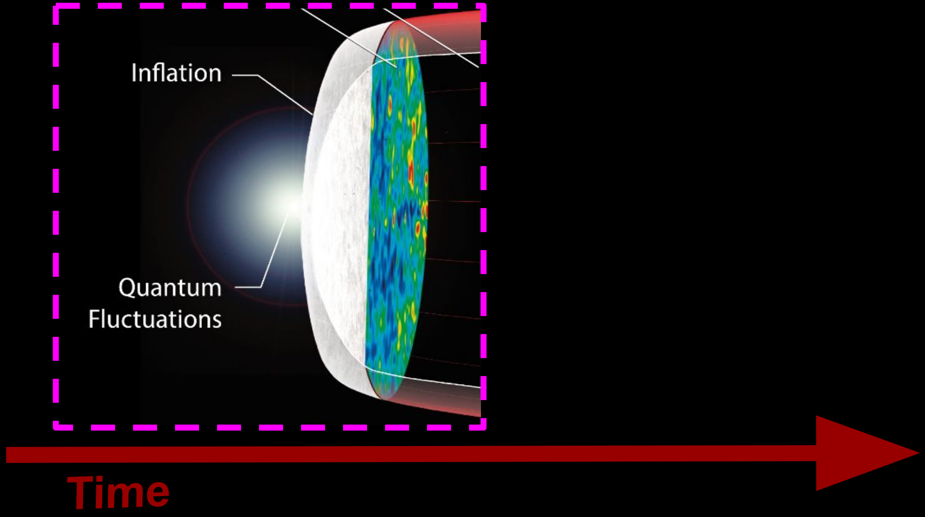


Image Credit: NASA / LAMBDA Archive Team

Formation of the Cosmic Microwave Background



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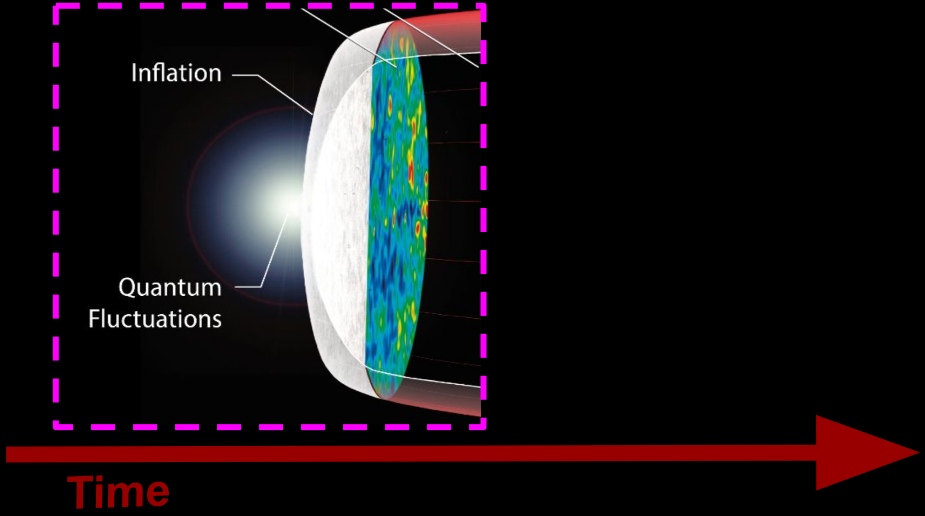
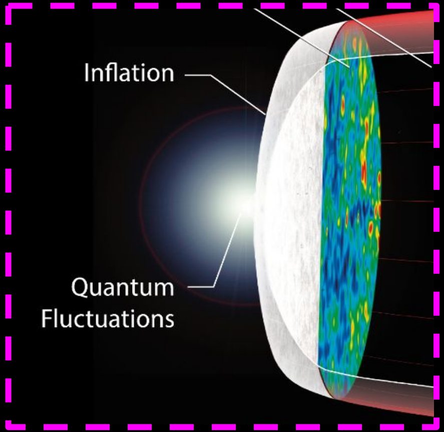


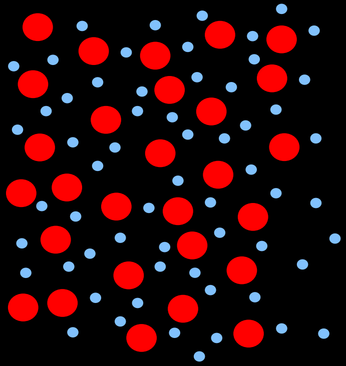
Inflation: exponential superluminal expansion of the early universe

- Explains the level of large-scale structure (such as galaxies) we see today
- Energy scale of ~ 10^{16} GeV

Formation of the Cosmic Microwave Background



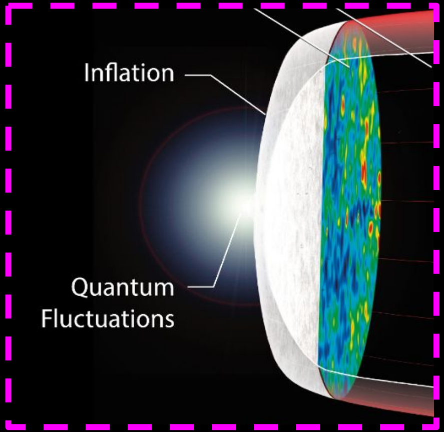
Time



6,000 K

3,000 K

Formation of the Cosmic Microwave Background



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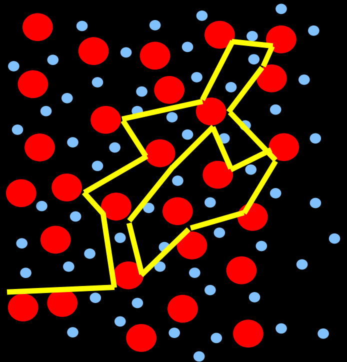

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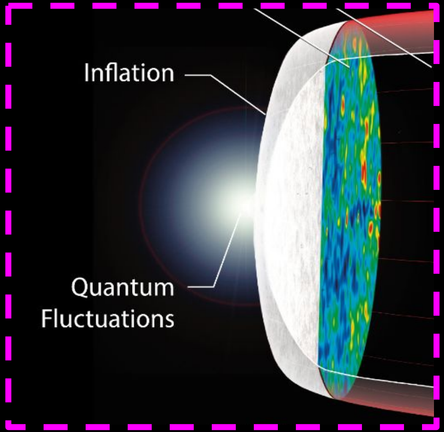

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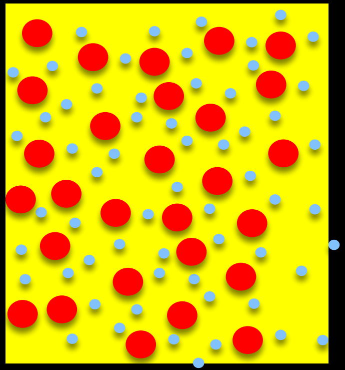

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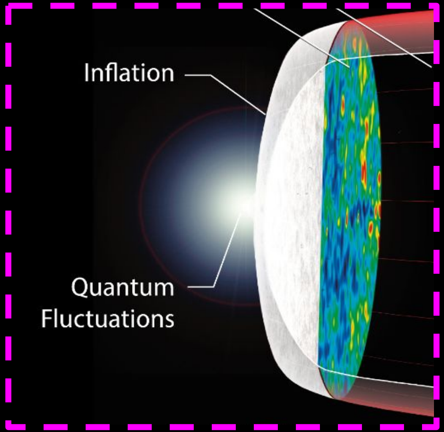

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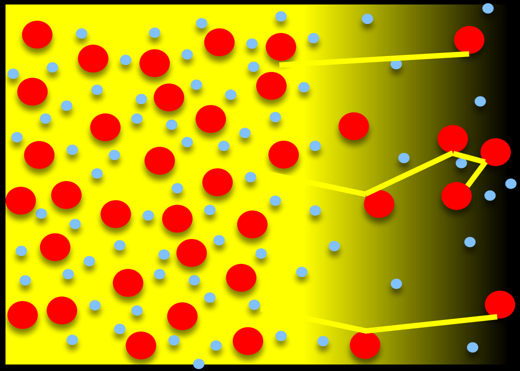

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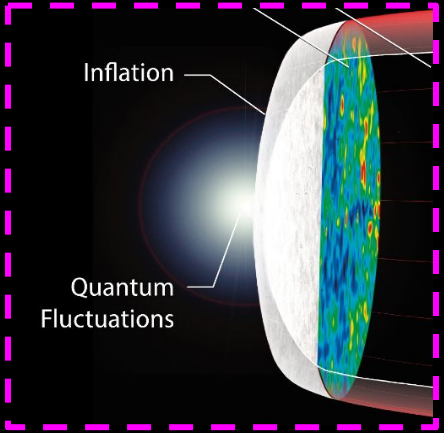

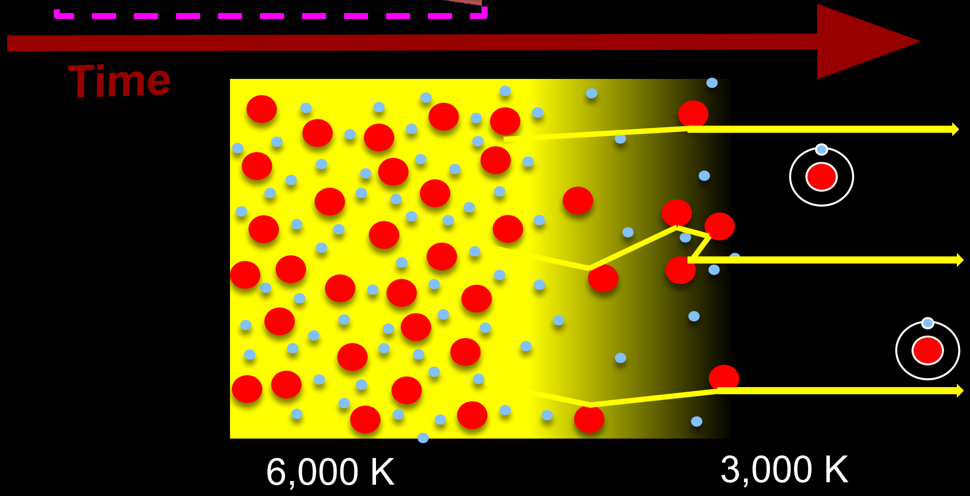

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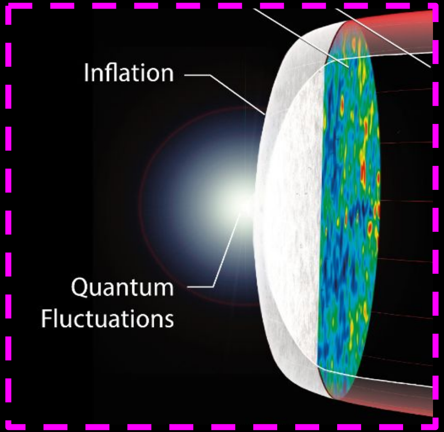
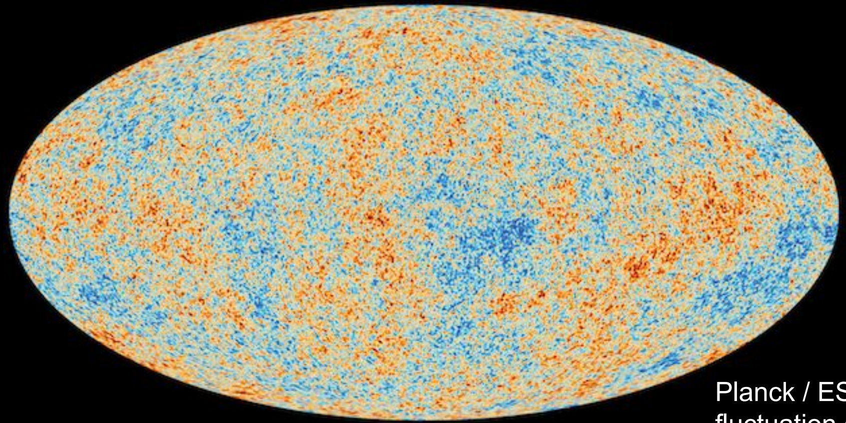
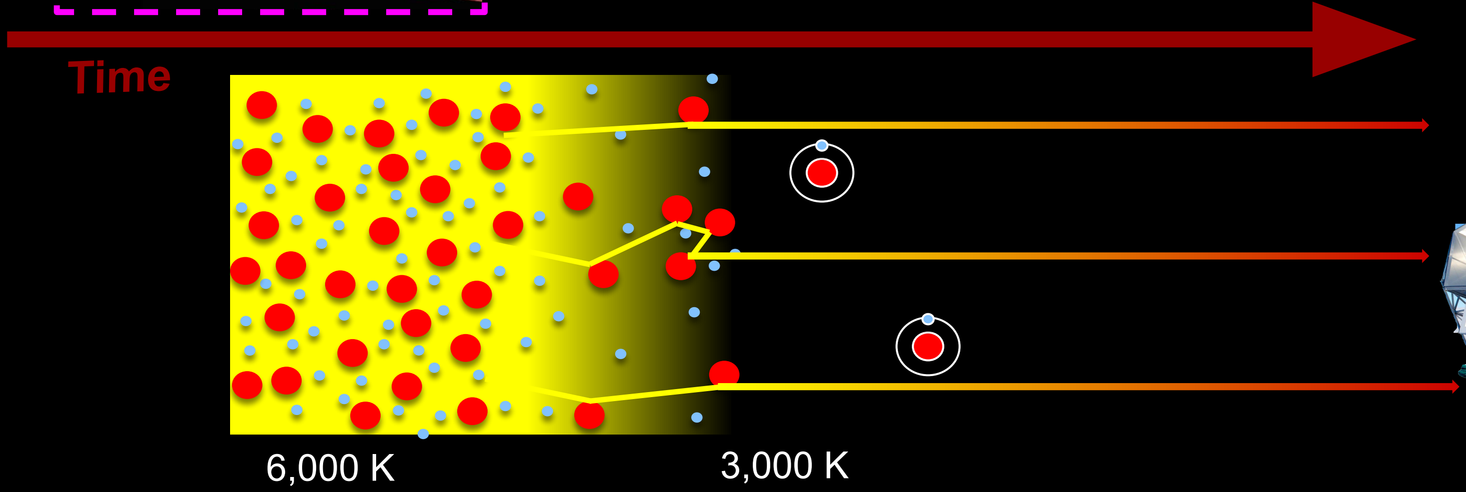
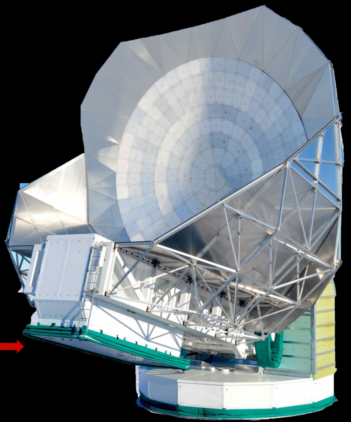




Planck / ESA, 30μK rms fluctuation on a 3K blackbody





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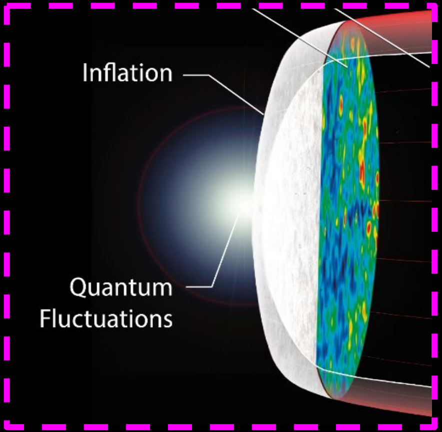

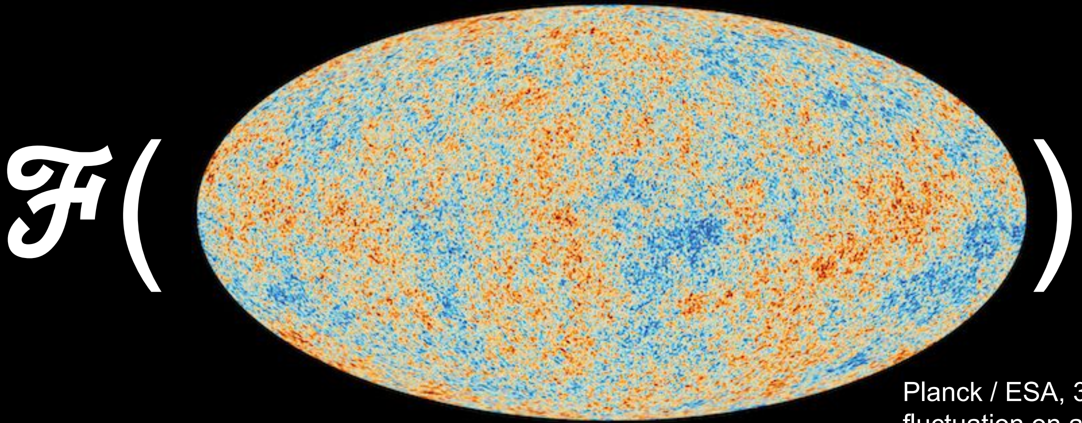

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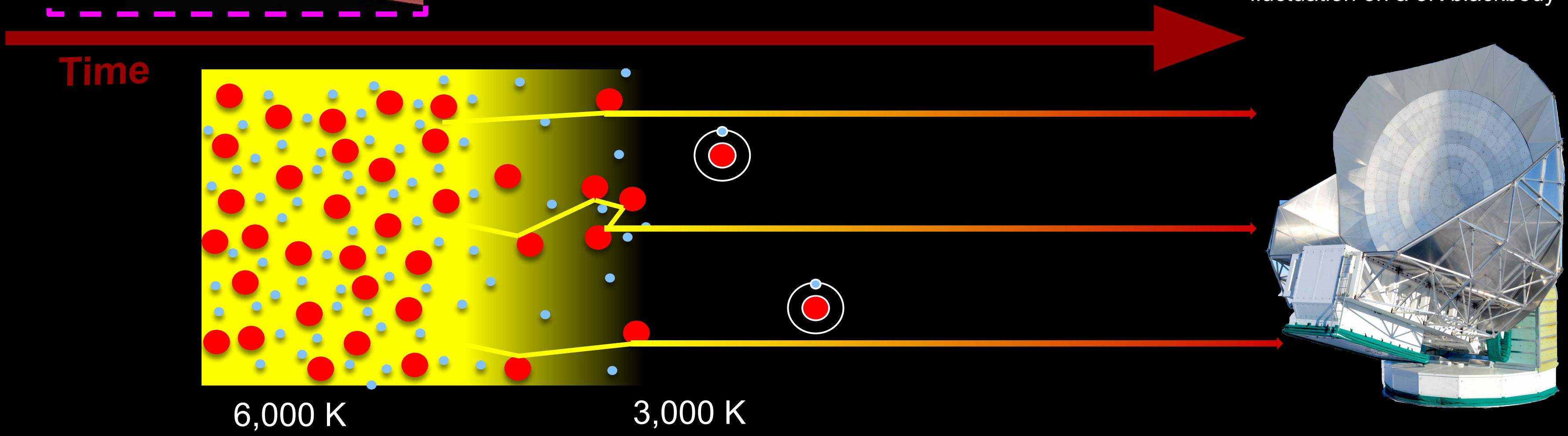
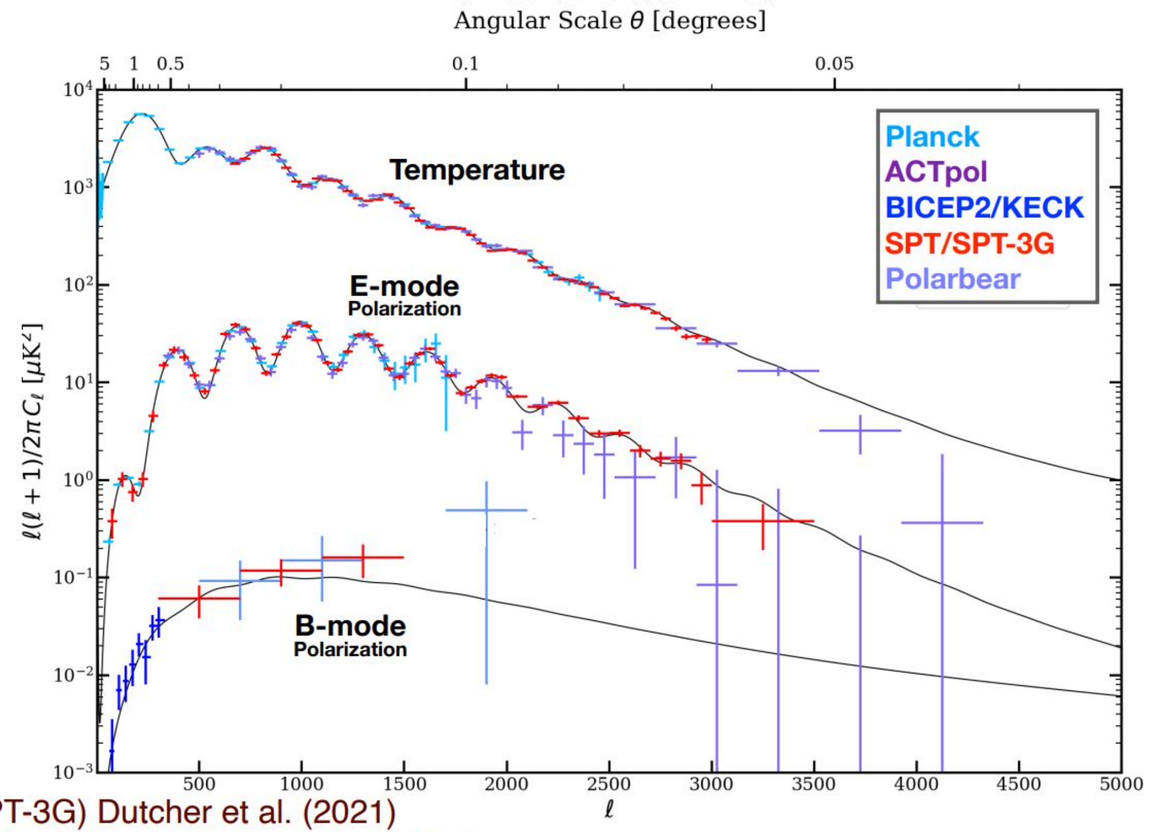
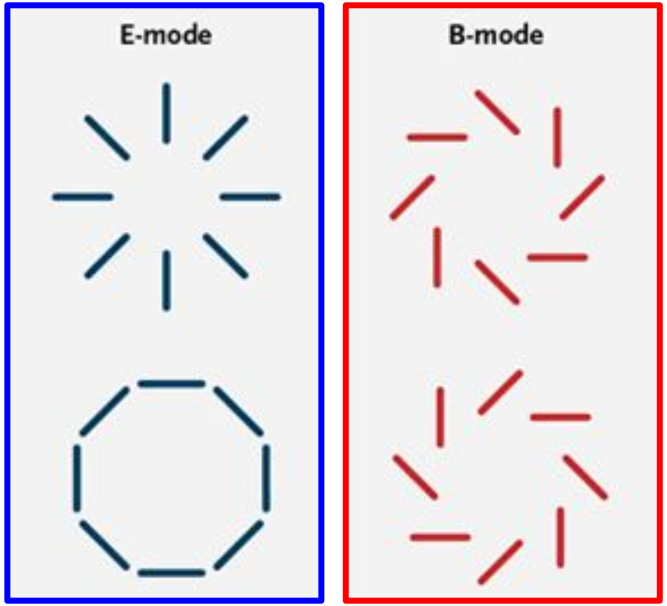


CMB Power Spectra



(SPT-3G) Dutcher et al. (2021)
(SPTpol) Henning et al. (2018), ApJ

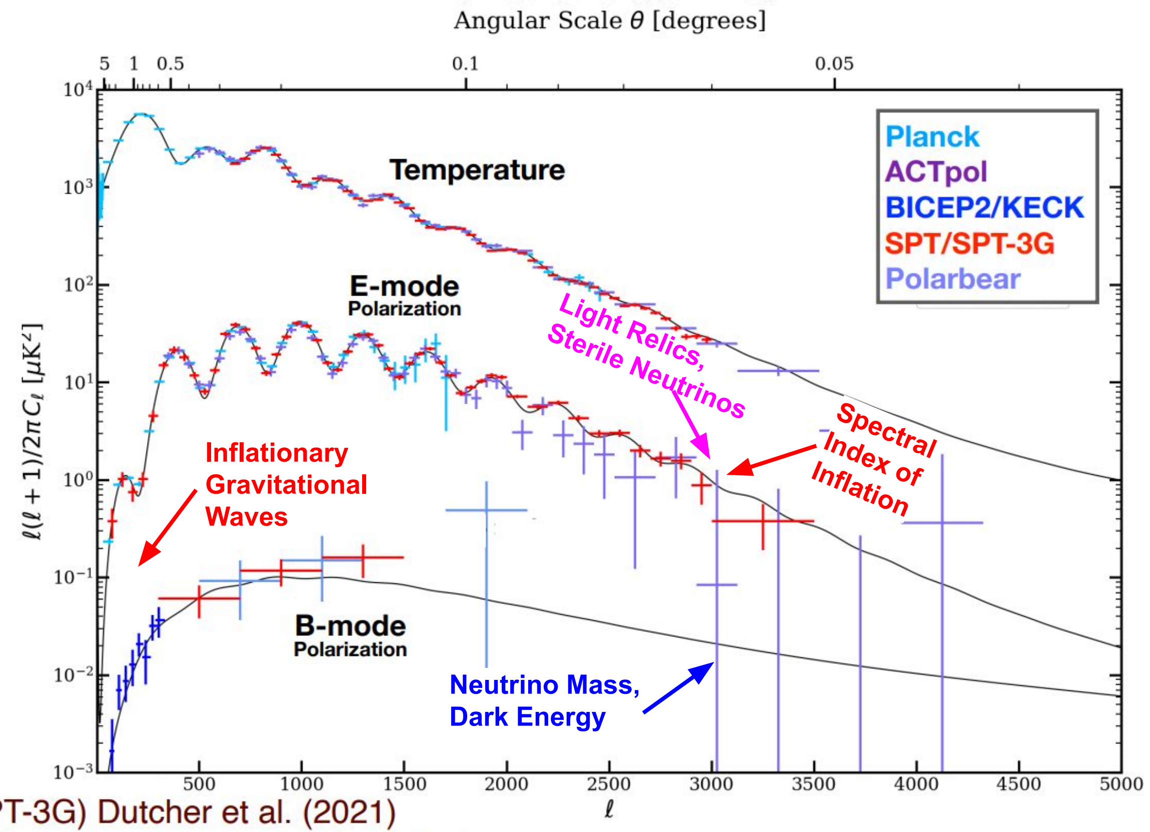
CMB Polarization



- Even parity
- Temperature anisotropy

- Odd parity
- Gravitational Waves
- Gravitational Lensing

CMB Power Spectra



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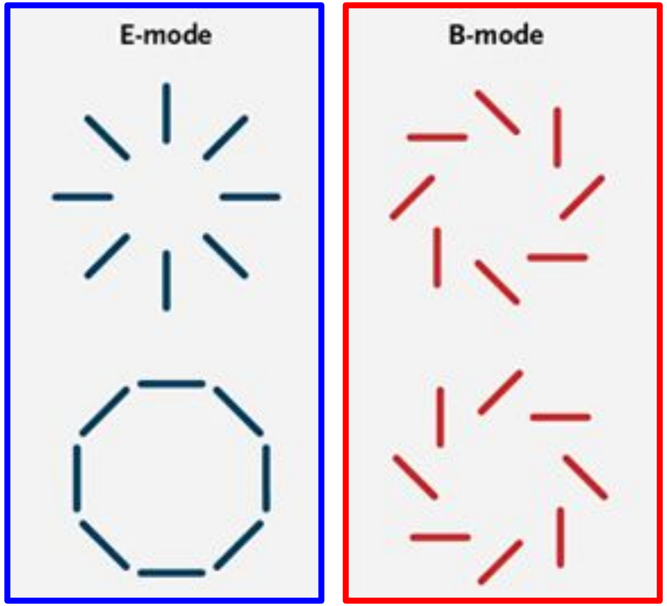

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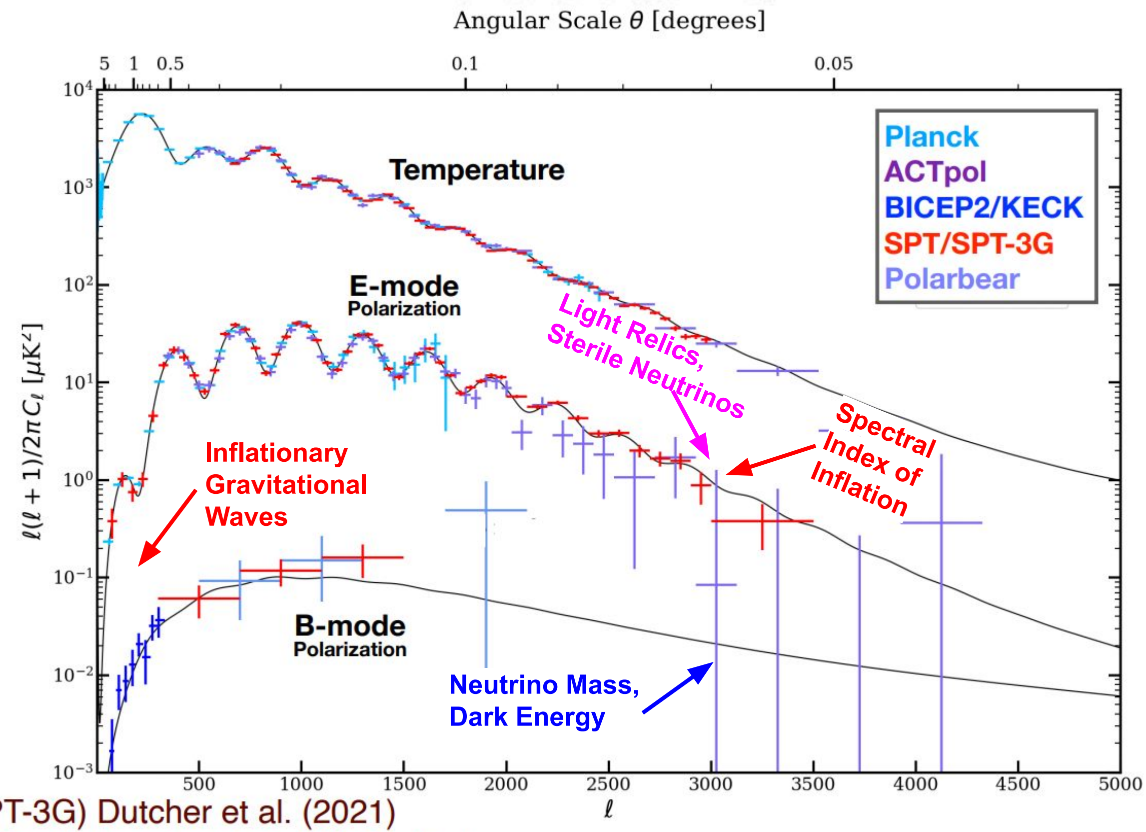

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Light Relic and Sterile Neutrino CMB constraints complementary to:

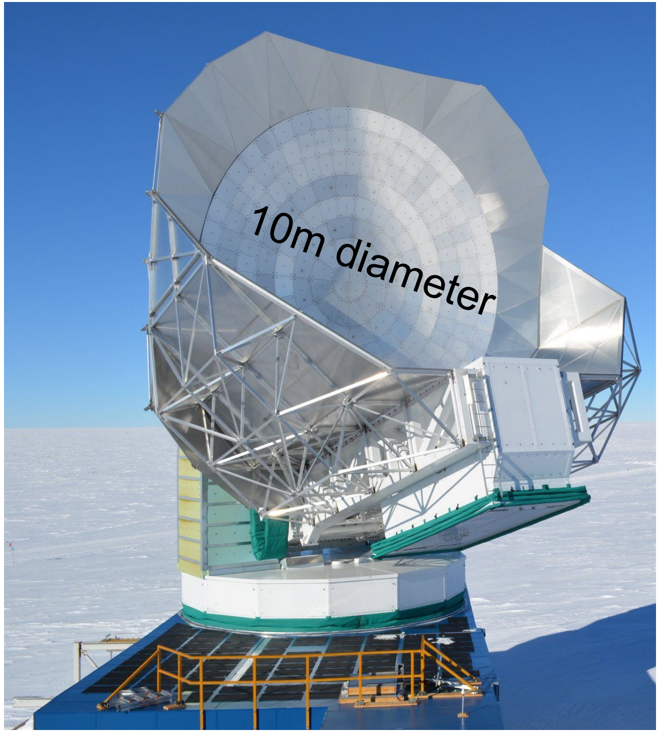
Short Baseline Neutrino Program

Neutrino Mass CMB Constraints complementary to:

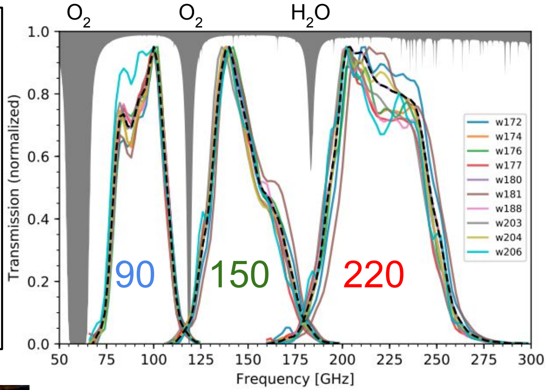
DUNE

NOvA

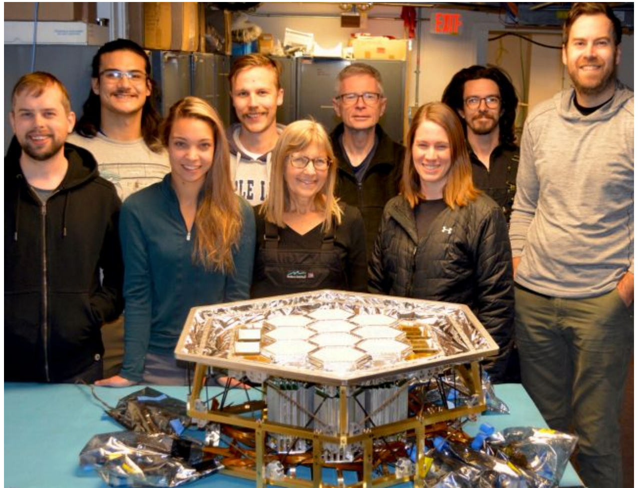
The SPT-3G camera on The South Pole Telescope

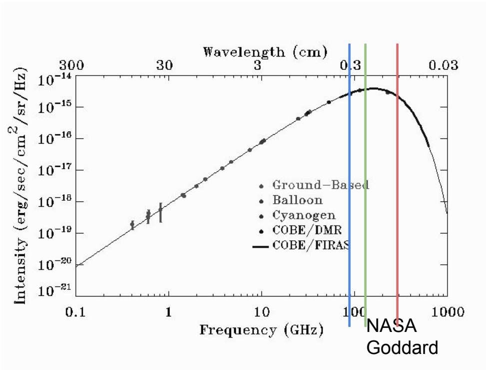


- 16,000 TES bolometers
- 90, 150, and 220 GHz
- Polarization
- 1.6, 1.2, 1.0 arcmin beams
- Observing 1500 deg^2 patch
- 2017-2023

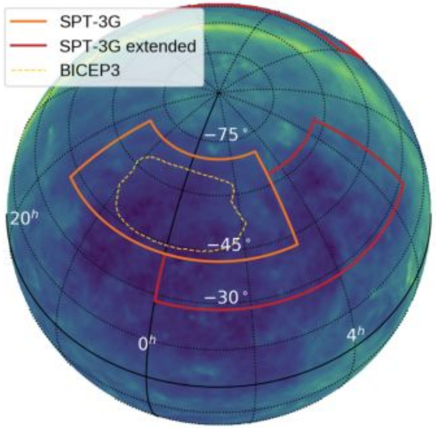


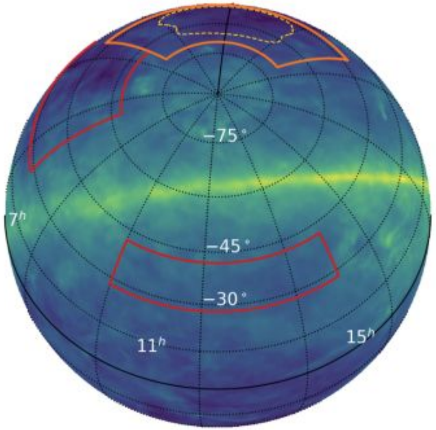
Sobrin 2106.11202





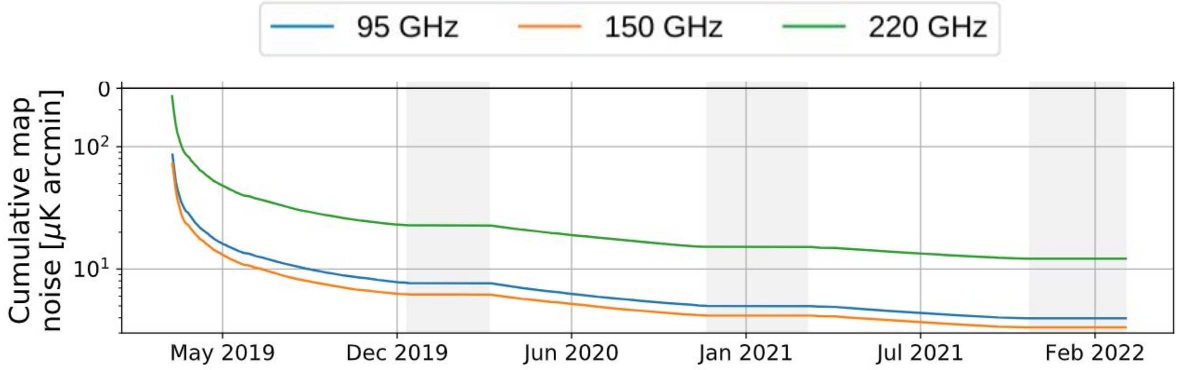
Survey Performance of SPT-3G





Full Survey Map Depths for SPT-3G

	95 GHz	150 GHz	220 GHz
Temperature	3.0 µK-arcmin	2.2 µK-arcmin	8.8 µK-arcmin
Polarization	4.2 µK-arcmin	3.1 µK-arcmin	12.4 µK-arcmin



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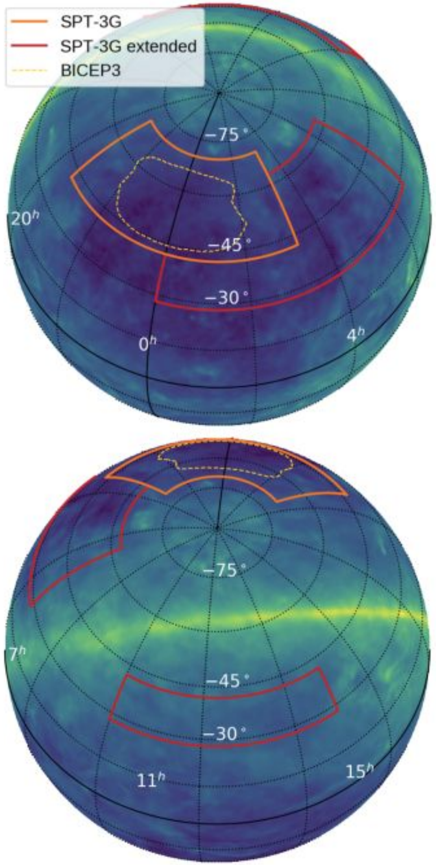

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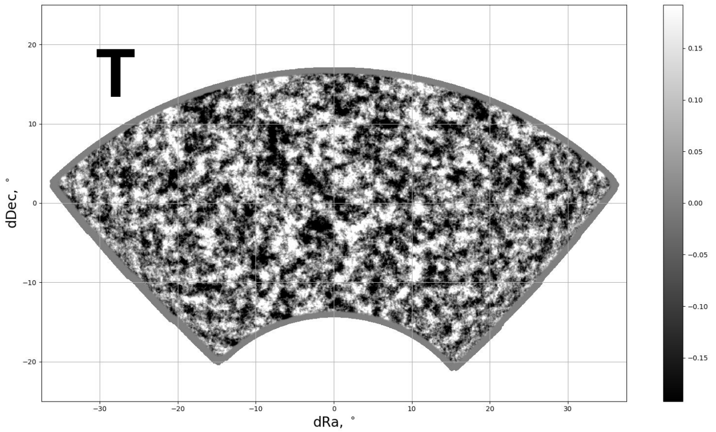
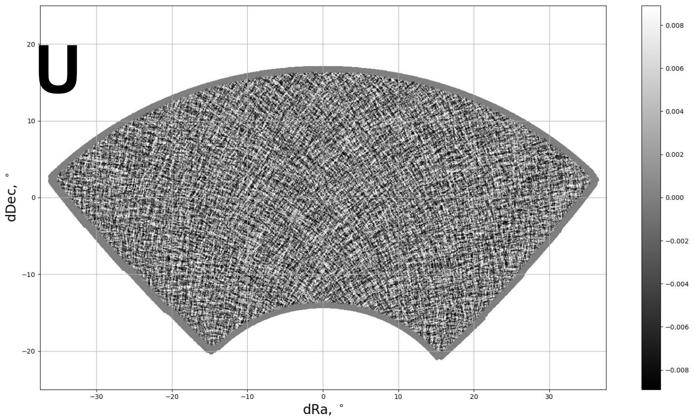
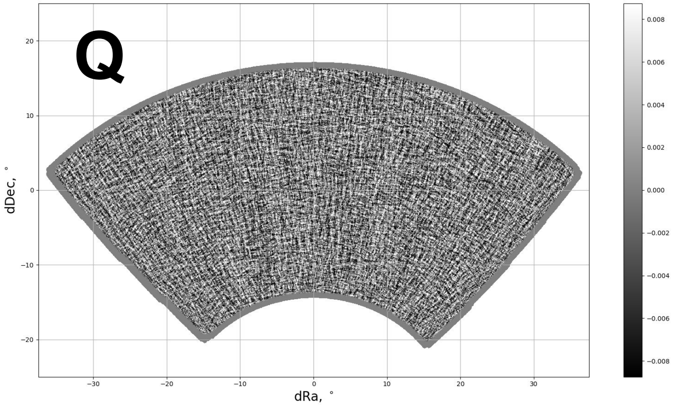
			T (μK-arcmin)	Sky Fraction
operating →	SPO *Moncelsi 2012.04047*	**LAT (150 GHz)**	2.2	4%
		SAT (150 GHz)	1.8	4%
next-gen →	Simons Observatory *Ade 1808.07445 Baseline*	LAT (145 GHz)	10	40%
		SAT (145 GHz)	3.3	10%
future →	CMB-S4 *Preliminary Baseline Design (PBDR)*	LAT (150 GHz)	2.0	60%
		SAT (145 GHz)	0.65	3%

SPT-3G 2019 and 2020 Maps

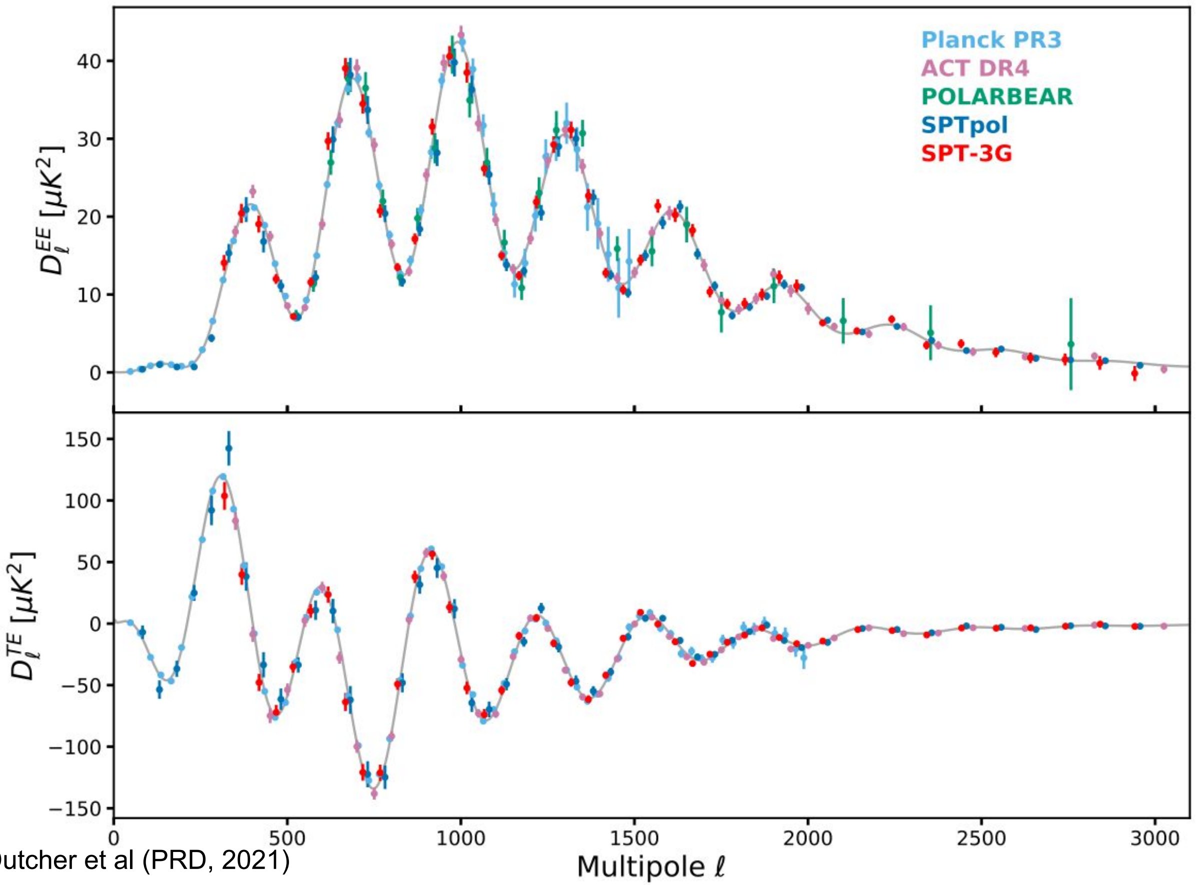




polarization



SPT-3G Science Results: 2018 Power Spectra

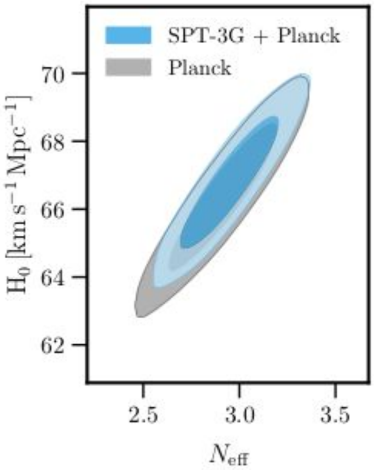


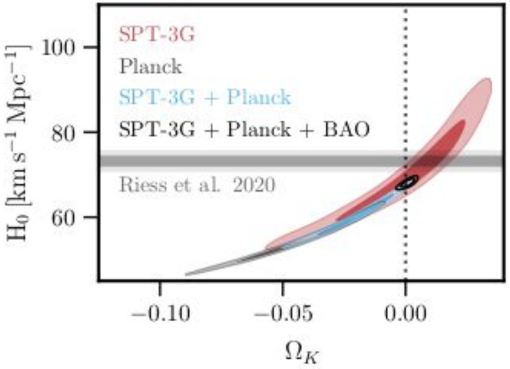
Dutcher et al (PRD, 2021)

- First SPT-3G power spectra!
- Constraints comparable to or exceed leading measurements at intermediate scales
- In agreement with ΛCDM model of cosmology

SPT-3G Science Results: 2018 ΛCDM Extensions

- Probe extensions to ΛCDM / the standard model
  - N_{eff}
  - H_0
  - Σm_ν
  - Y_p
  - Ω_κ

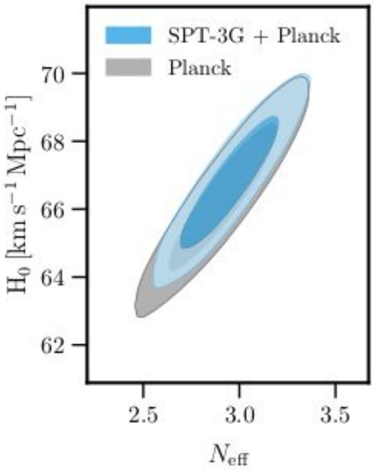


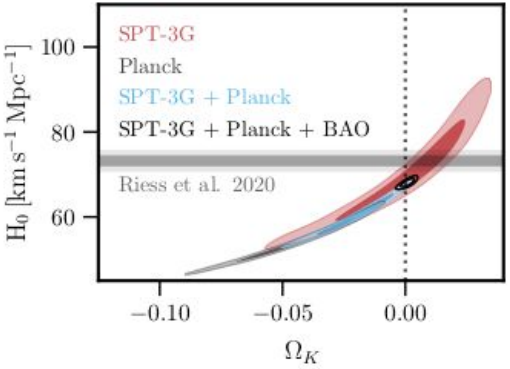


Balkenhol et al (PRD, 2021)

SPT-3G Science Results: 2018 ΛCDM Extensions

- Probe extensions to ΛCDM / the standard model
    - N_{eff}
        - corresponds to number of relativistic species in early universe - sensitive to number of neutrinos, sterile neutrinos, light dark matter, axions, etc
        - *Standard Model prediction for 3 neutrinos = 3.046*
        - N_{eff} = 2.95 ± 0.17 (SPT3G + Planck)
    - H_0
    - Σm_ν
    - Y_p
    - Ω_κ

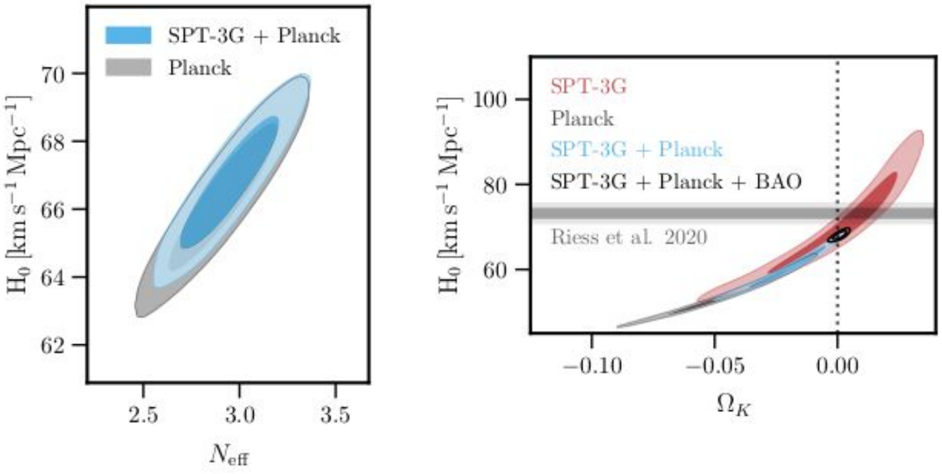




Balkenhol et al (PRD, 2021)

SPT-3G Science Results: 2018 ΛCDM Extensions

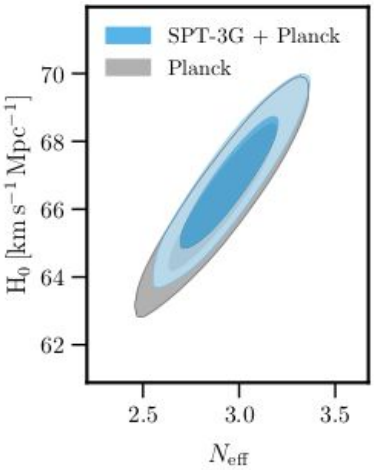
- Probe extensions to ΛCDM / the standard model
  - N_{eff}
  - H_0
    - corresponds to expansion rate of the universe
    - constraints from the CMB and from distance-ladder measurements using Cepheids and supernovae
    - 5σ tension with (Riess et al 2022)!
    - H_0 = 67.49 ± 0.53 km s−1 Mpc−1 (SPT3G + Planck + ACT DR4) *tightest constraint on H_0 to date !*
  - Σm_ν
  - Y_p
  - Ω

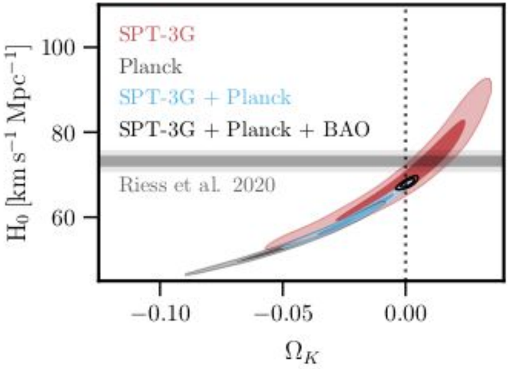


Balkenhol et al (PRD, 2021)

SPT-3G Science Results: 2018 ΛCDM Extensions

- Probe extensions to ΛCDM / the standard model
  - N_{eff}
  - H_0
  - Σm_ν
    - The CMB is sensitive to the sum of neutrino masses from their impact on the growth of structure when neutrinos transition from being hot dark matter to cold dark matter as the universe expands and cools
    - $\Sigma m_\nu < 0.13$ eV (95% CL) (Planck + SPT3G + BAO)
  - Y_p
  - Ω_κ





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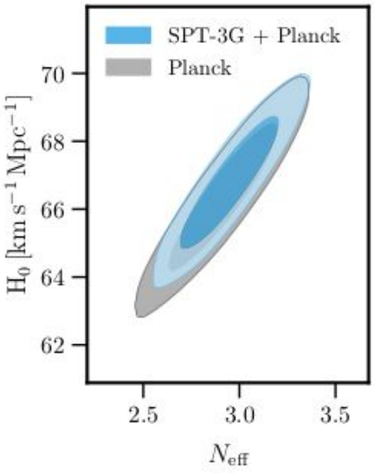
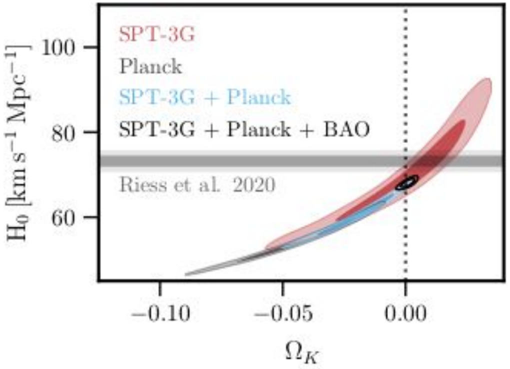
SPT-3G Science Results: 2018 ΛCDM Extensions

- Probe extensions to ΛCDM / the standard model
  - N_{eff}
  - H_0
  - Σm_ν
  - Y_p
    - the fraction of the primordial helium in the total mass of baryonic matter
    - Strong prediction (0.2454) from nuclear physics - this value deviating from expectation would point to new physics!
    - $Y_P = 0.234 \pm 0.012$ (SPT3G + Planck)
  - Ω_κ





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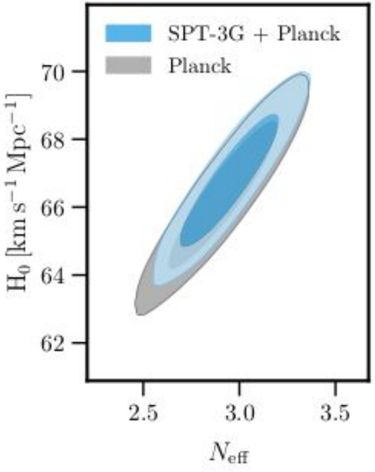
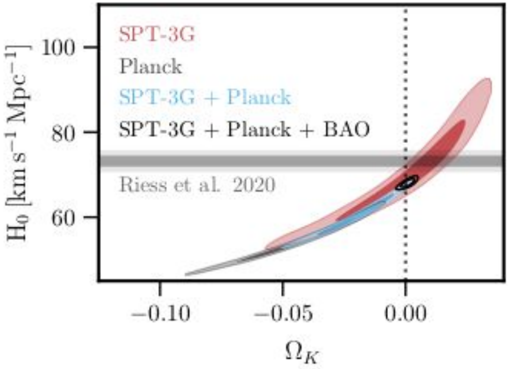
SPT-3G Science Results: 2018 ΛCDM Extensions

- Probe extensions to ΛCDM / the standard model
  - N_{eff}
  - H_0
  - Σm_ν
  - Y_p
  - Ω_κ
    - Flatness of the universe, predicted to be 0
    - $\Omega_\kappa = 0.0009 \pm 0.0018$ (SPT3G + Planck + BAO)



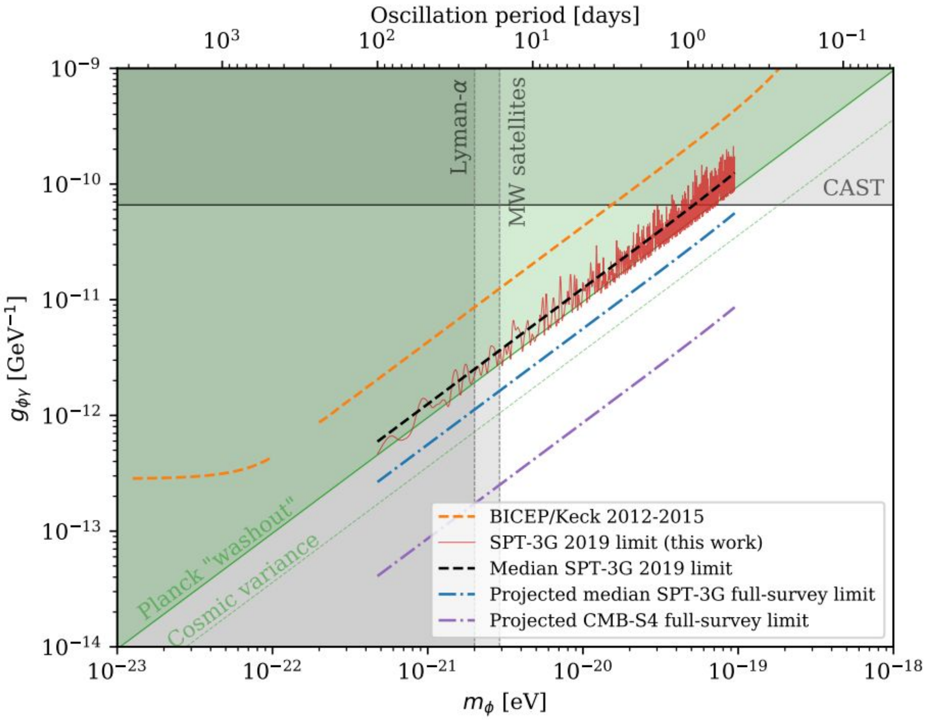


Balkenhol et al (PRD, 2021)

SPT-3G Science Results: Axion Dark Matter Constraints

- Oscillation of an axion field induces a polarization rotation in linearly polarized line-of-sight photons
- Look for time-dependent polarization rotation in CMB photons, frequency of oscillation corresponds to the particle mass
- SPT's observing cadence allows for limits on

$$10^{-22}\text{eV} \lesssim m_\phi \lesssim 10^{-19}\text{eV}$$



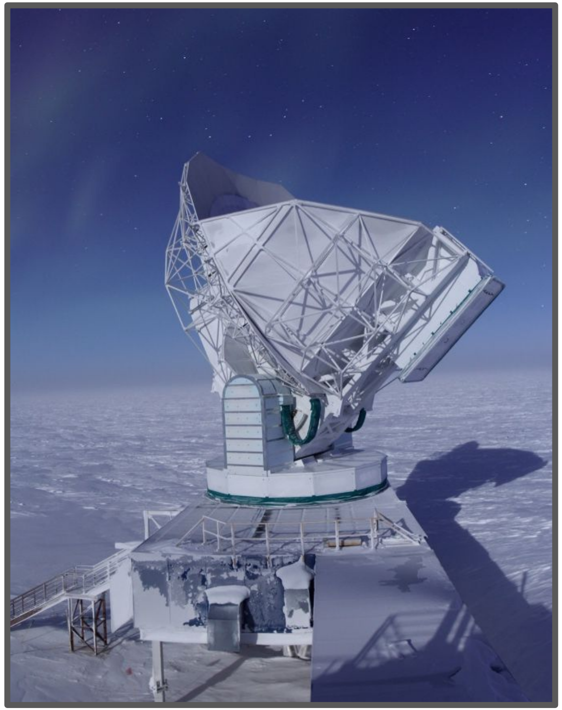
Ferguson et al (2022)

Great science to come from SPT-3G!

CMB
B-Modes
(inflationary
constraints)

CMB lensing

Event
Horizon
Telescope



Time-variable
mm-wave sky
(blazars, AGN,
GRB
afterglows)

Galaxy
Cluster
physics

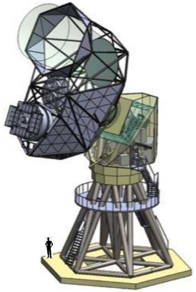
Evolution of
early
galaxies

The Future of CMB: CMB-S4

- Next generation ground-based program to pursue inflation, neutrino properties, dark radiation, dark energy, and new discoveries!
- >10x sensitivity of combined Stage 3 experiments
- ***Endorsed by 2014 P5 report and Astro2020 Decadal Survey!***

Chile : **2 x 6m telescopes** targeting 60% of sky with **269,184 detectors**.

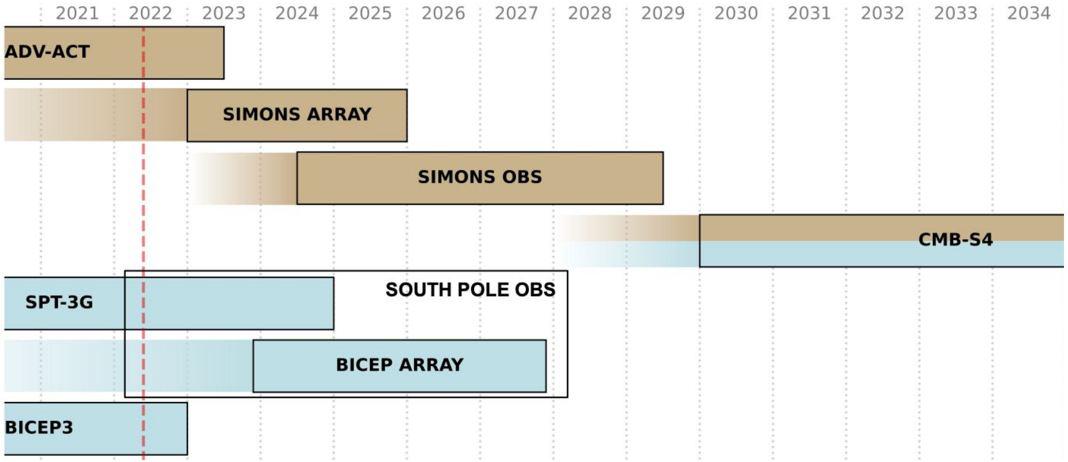
South Pole: **18 x 0.5m small refractor telescopes** targeting ≥ 3% of sky with **154,560 detectors** and a dedicated **5m telescope** with **126,360 detectors**



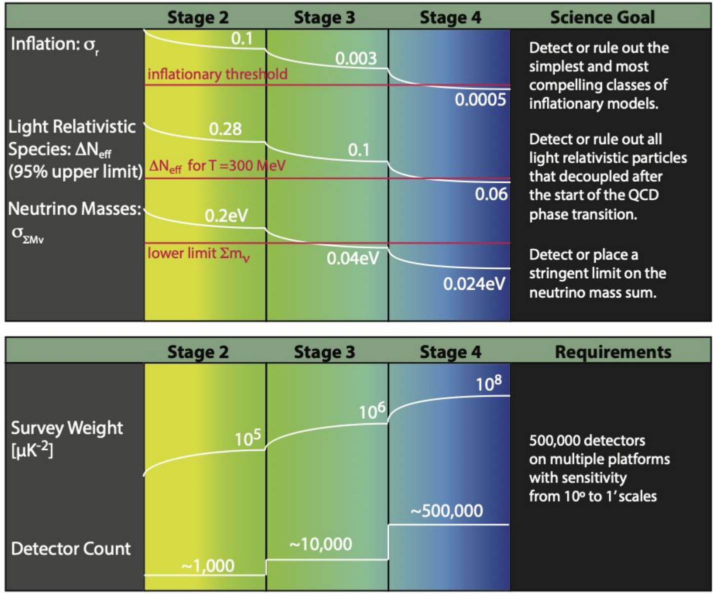
Greatest technical challenge : Scaling up to deploying ~500,000 TES detectors

- ***FNAL Leading detector module packaging and 100 mK testing!***

Timeline for CMB at FNAL : SPT-3G and CMB-S4



Chang et al. 2022, Snowmass CF5 arxiv: 2203.07638



- Ongoing “Stage-3” experiments like SPT-3G and BICEP Array, and the upcoming Simons Observatory, promise a steady flow of results over next several years.
- Earlier experiments lay the groundwork for CMB-S4, providing (e.g.) intermediate science results, developing analysis tools and instrumentation, and providing representative data for systematics and instrument modelling.

Summary

- The CMB is a powerful probe of inflation, neutrino properties, dark radiation, dark energy, and new discoveries
- Setting field-leading cosmology and particle physics constraints with SPT-3G at FNAL
- Expertise and experience from Stage-3 experiments will allow FNAL to lead crucial parts of CMB-S4, and enable critical science thresholds to be crossed