Discoveries from CMB-HD a Stage-5 CMB Facility

BNL Colloquium

Neelima Sehgal, Stony Brook

July 30th, 2024

Outline

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- Cosmic Microwave Background

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- Cosmic Microwave Background
- CMB Experiments

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- CMB-HD

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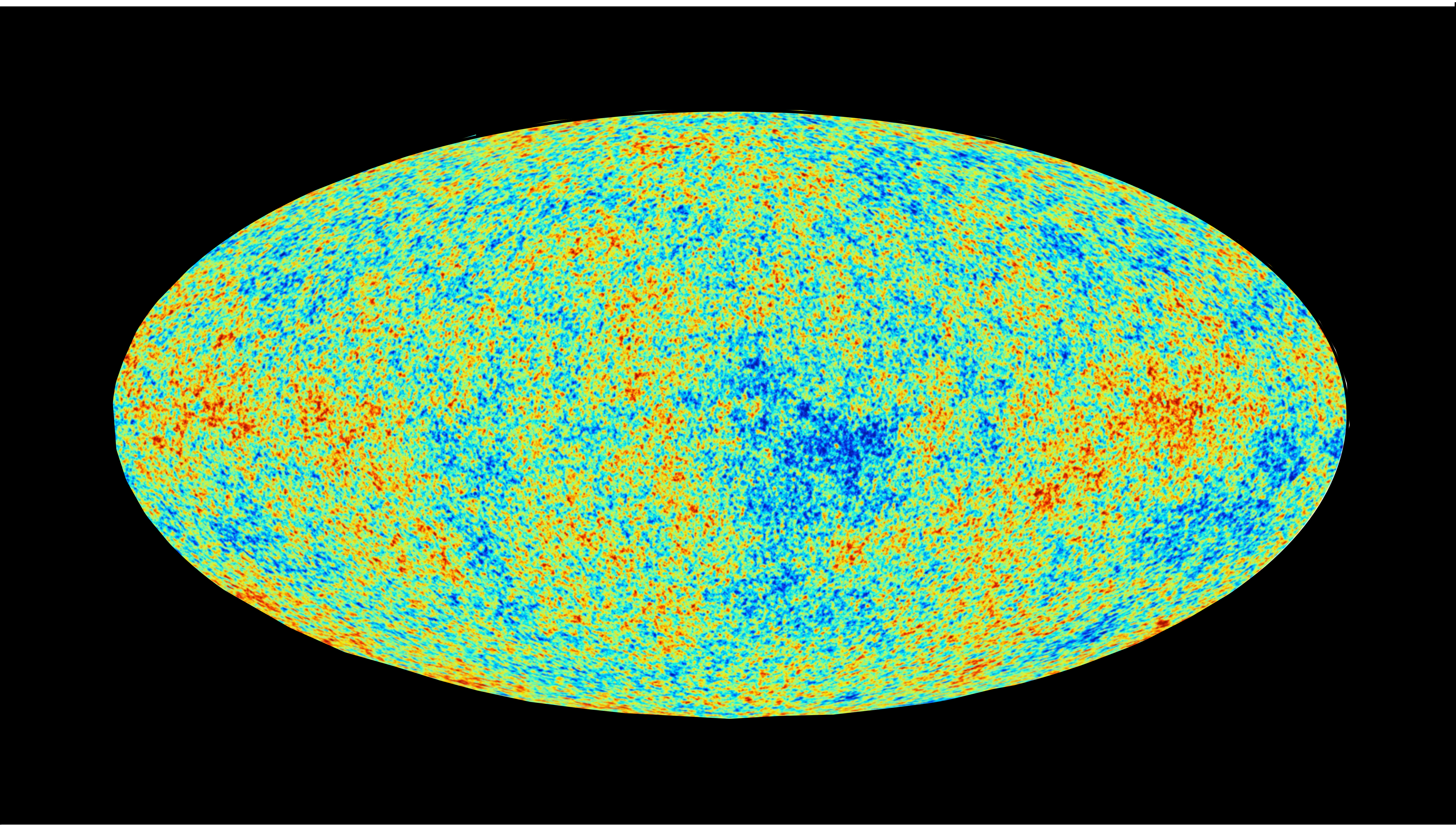
Cosmic Microwave Background



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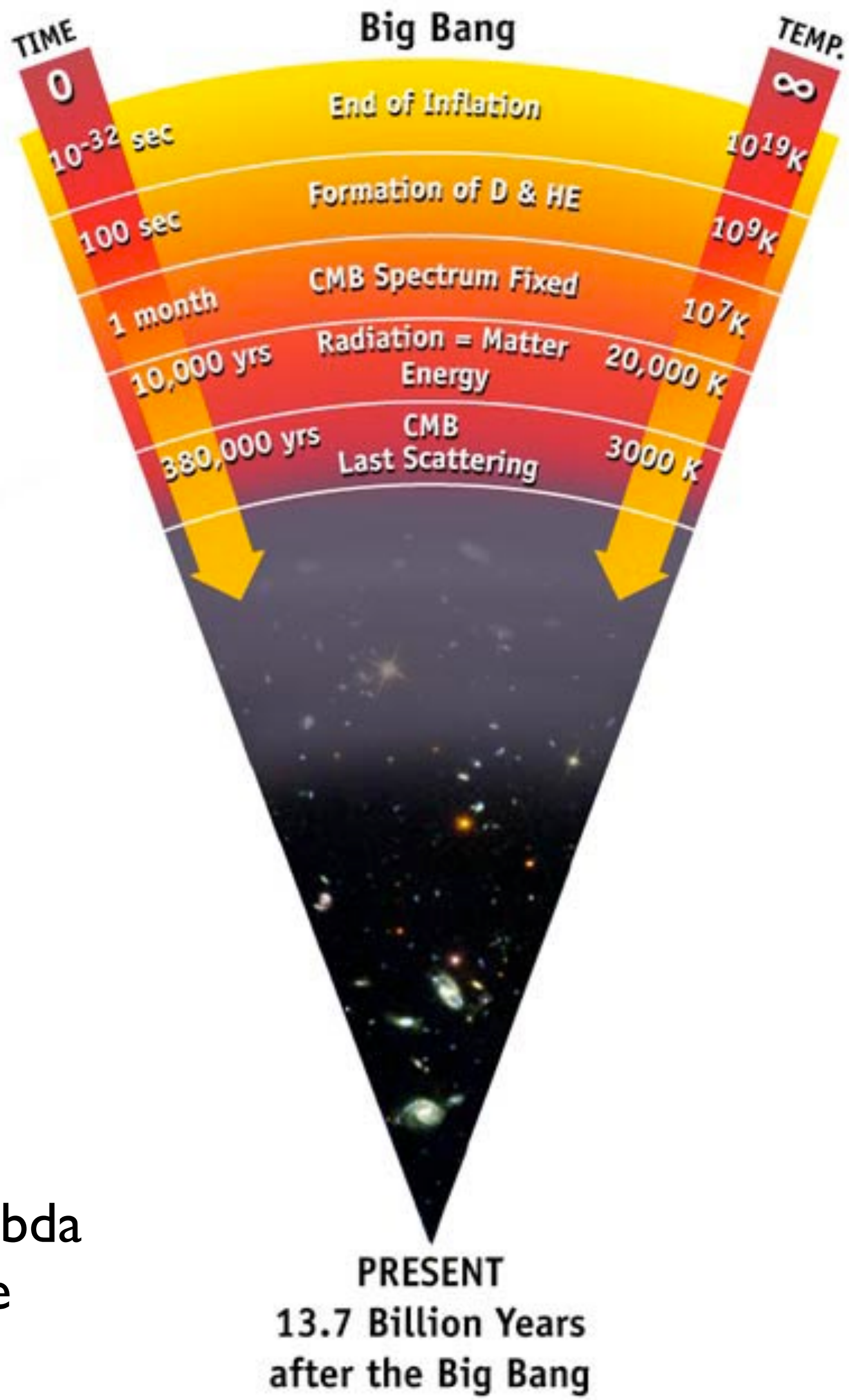
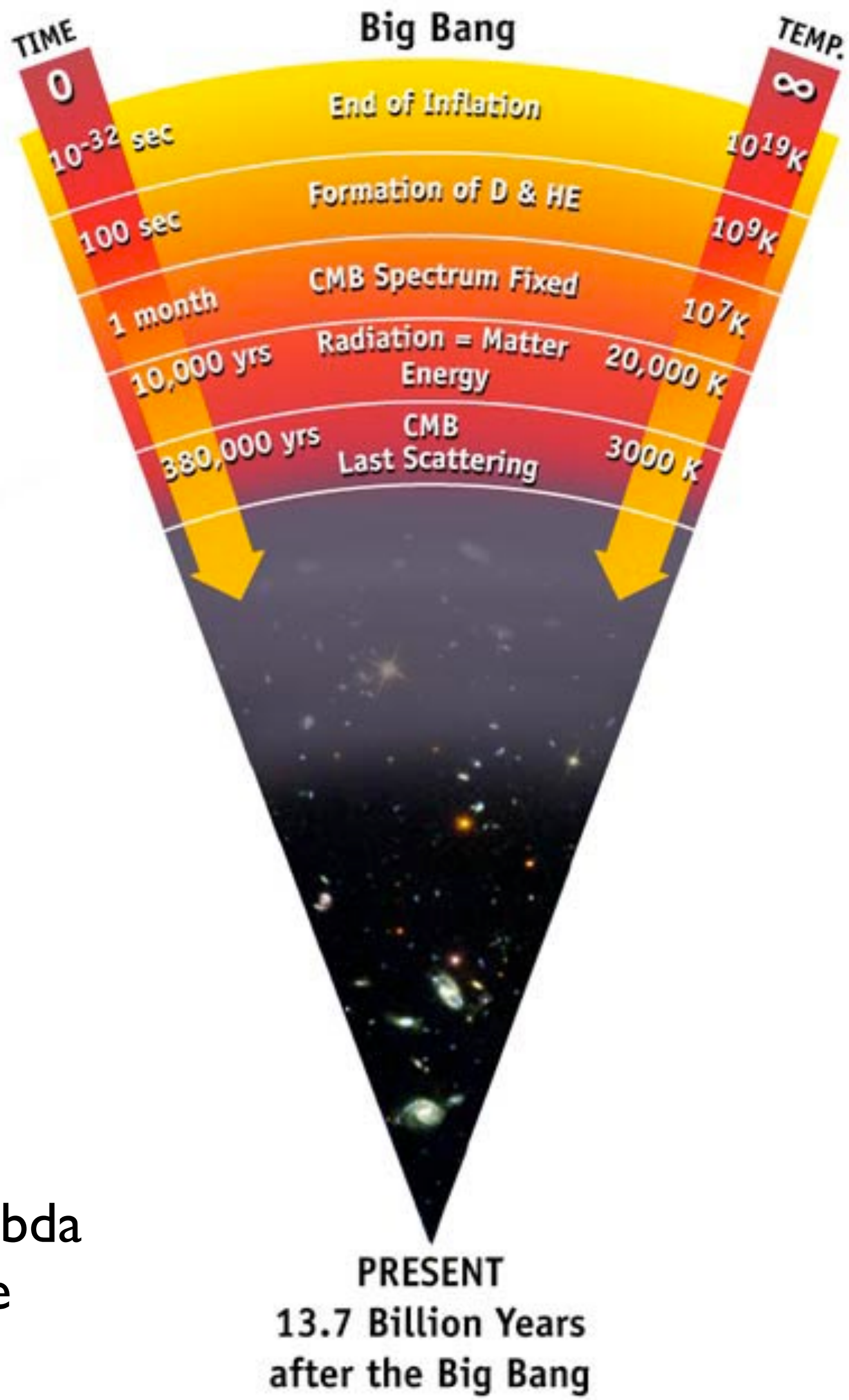
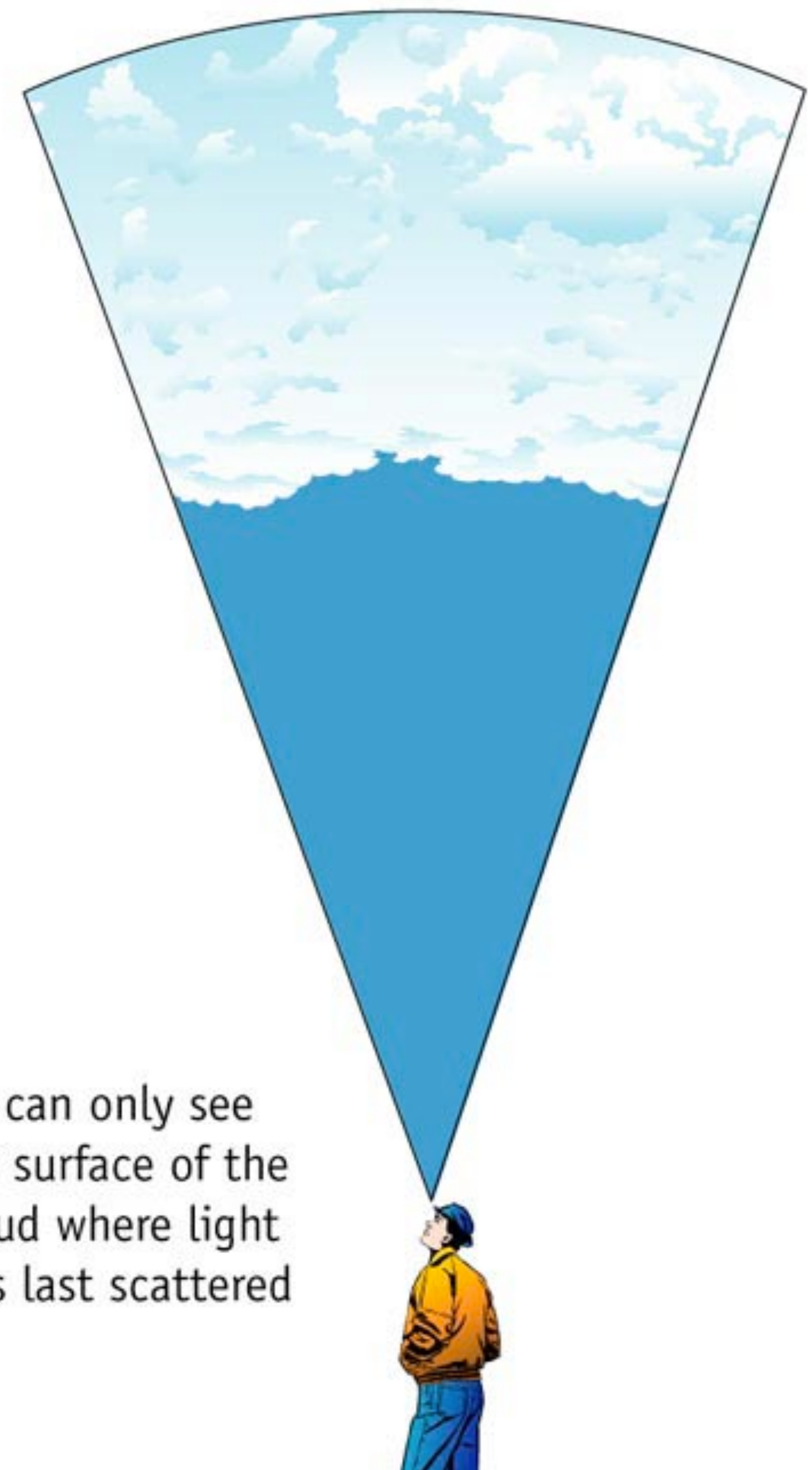


From Lambda website

Cosmic Microwave Background





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CMB From Last Scattering Surface

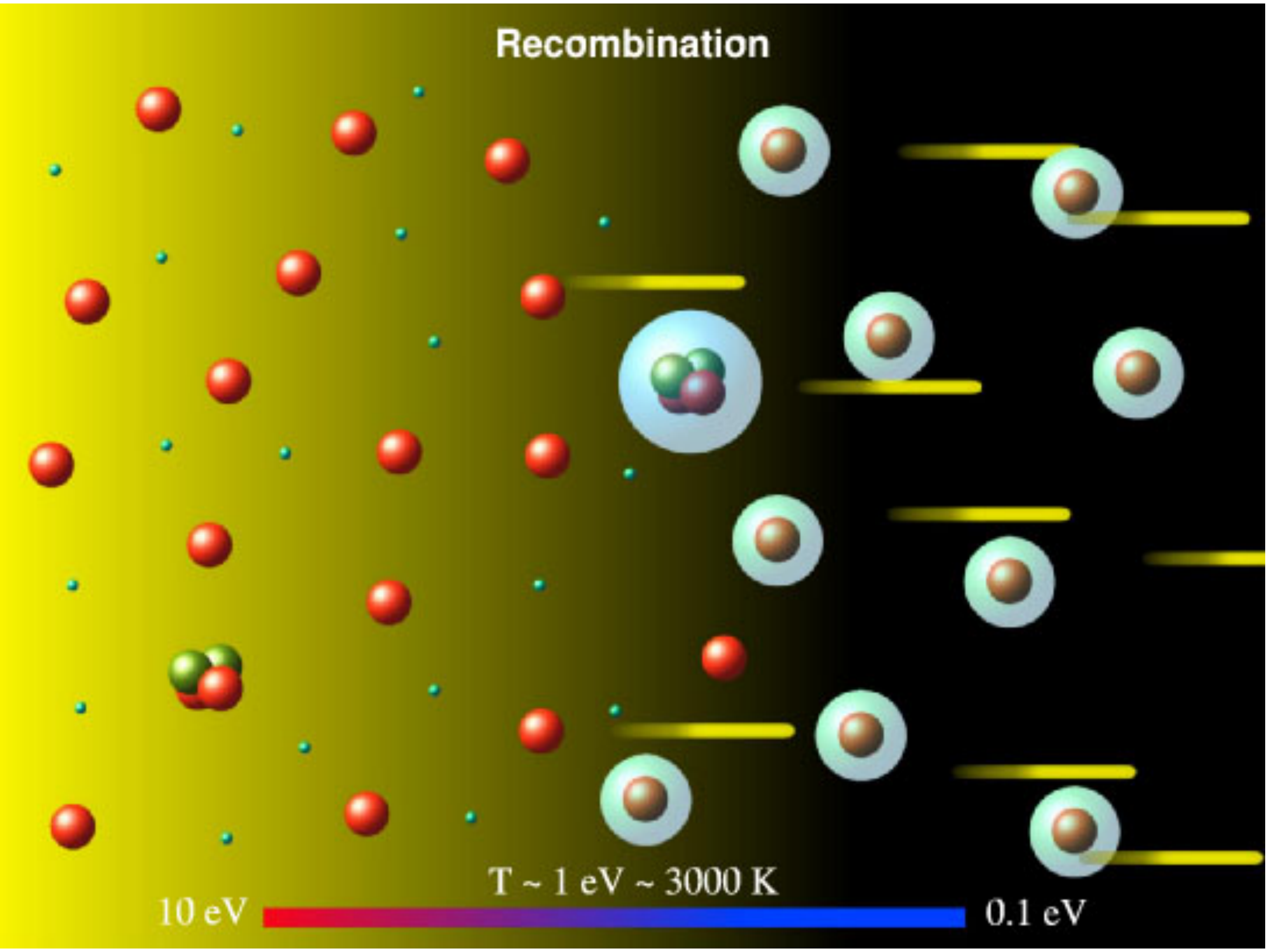

Image Credit: William Kinney

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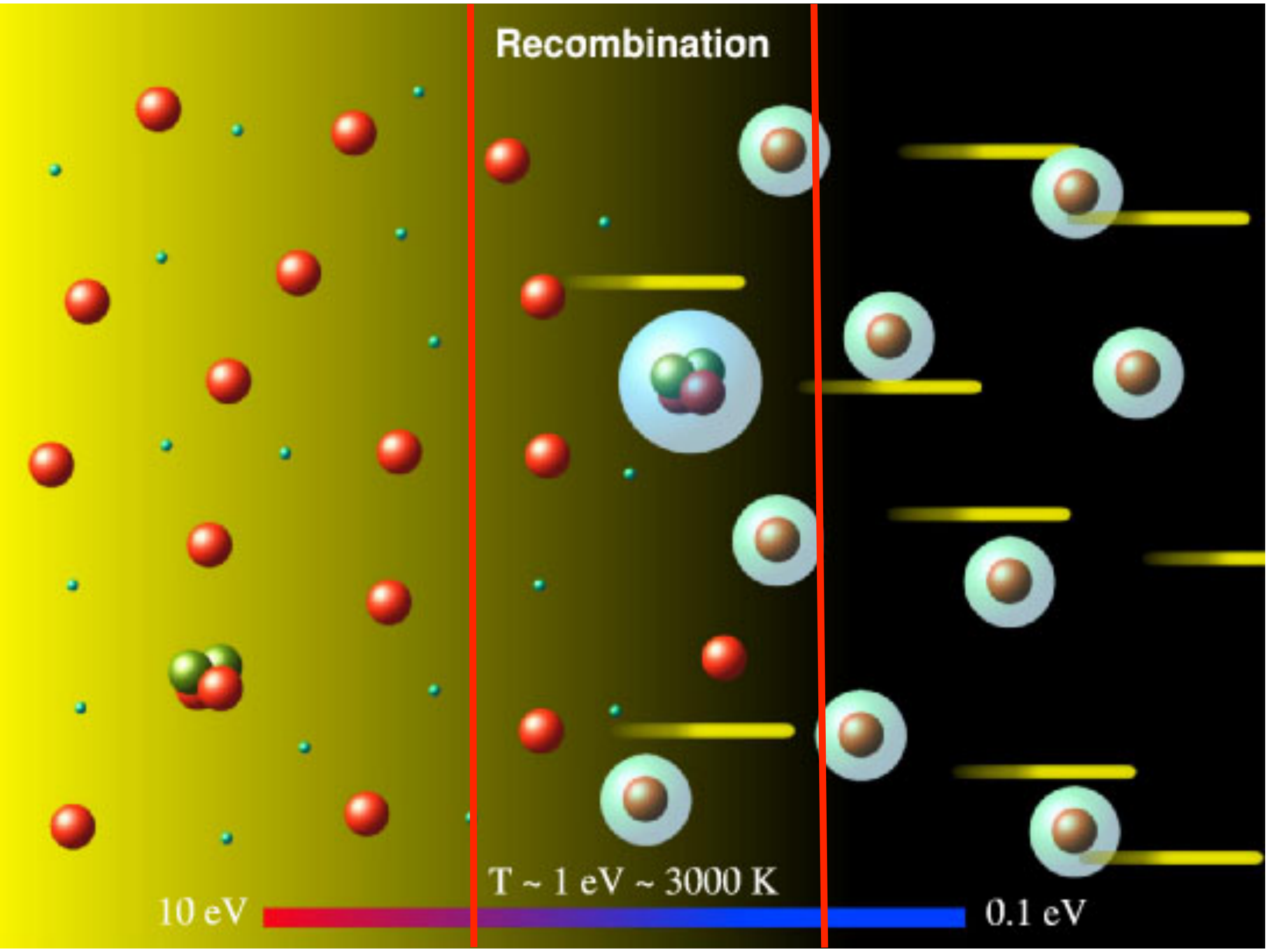

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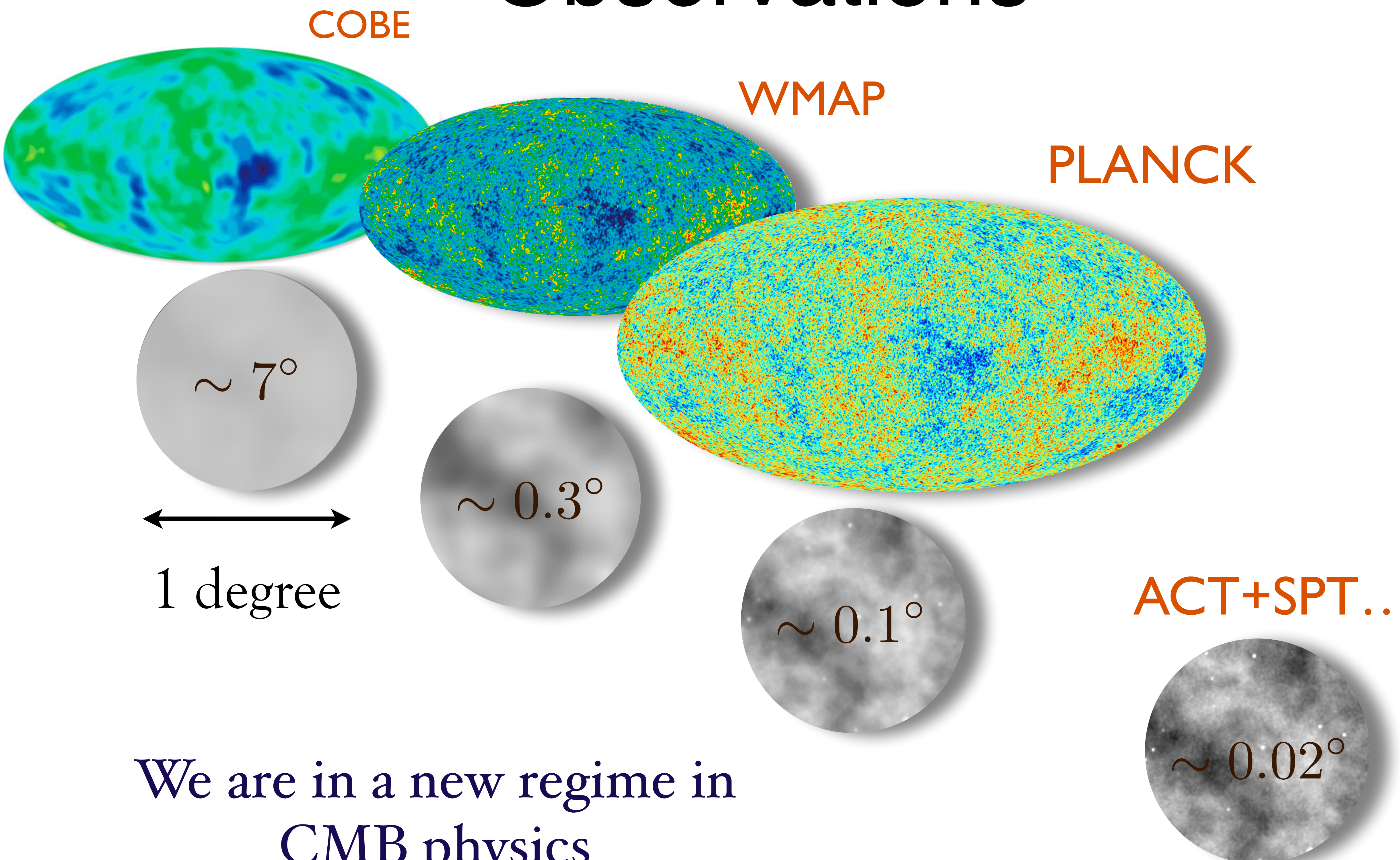
New Generation of Microwave Observations



We are in a new regime in CMB physics

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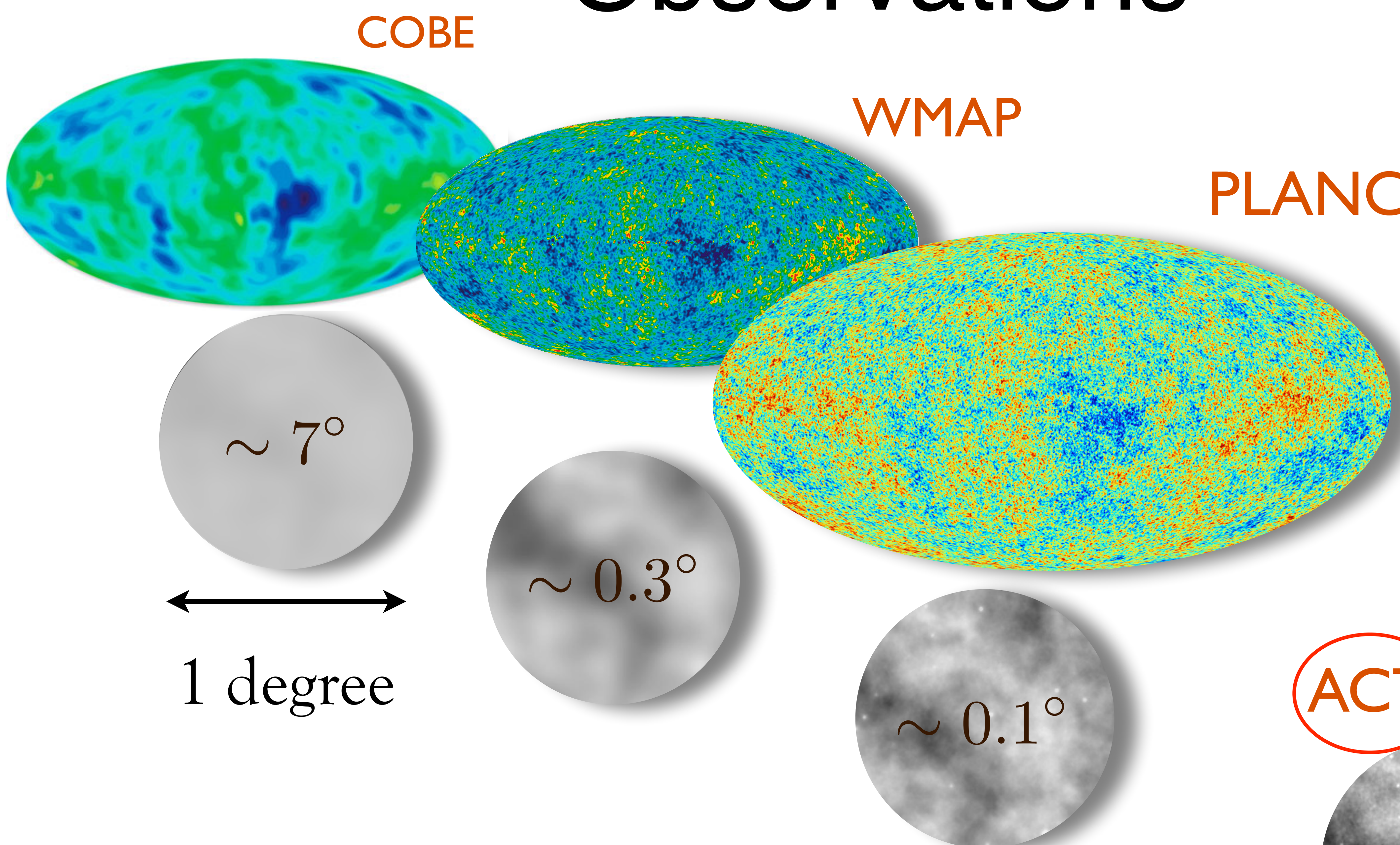

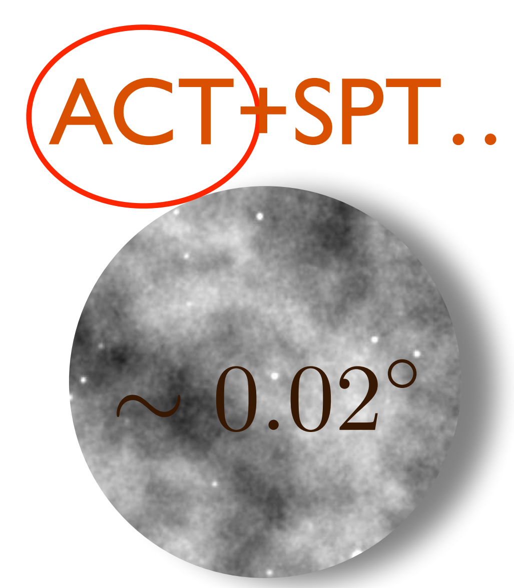

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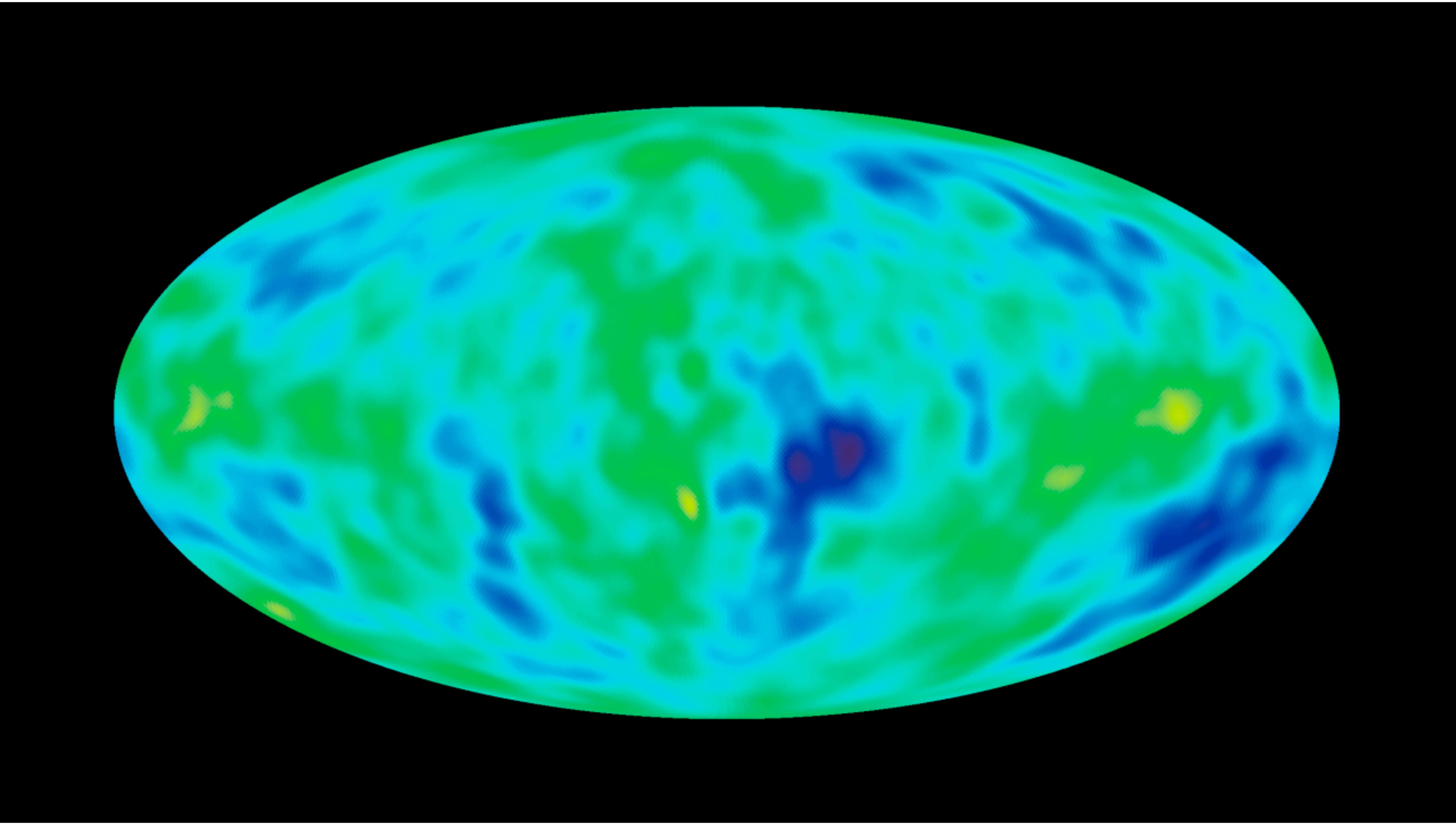
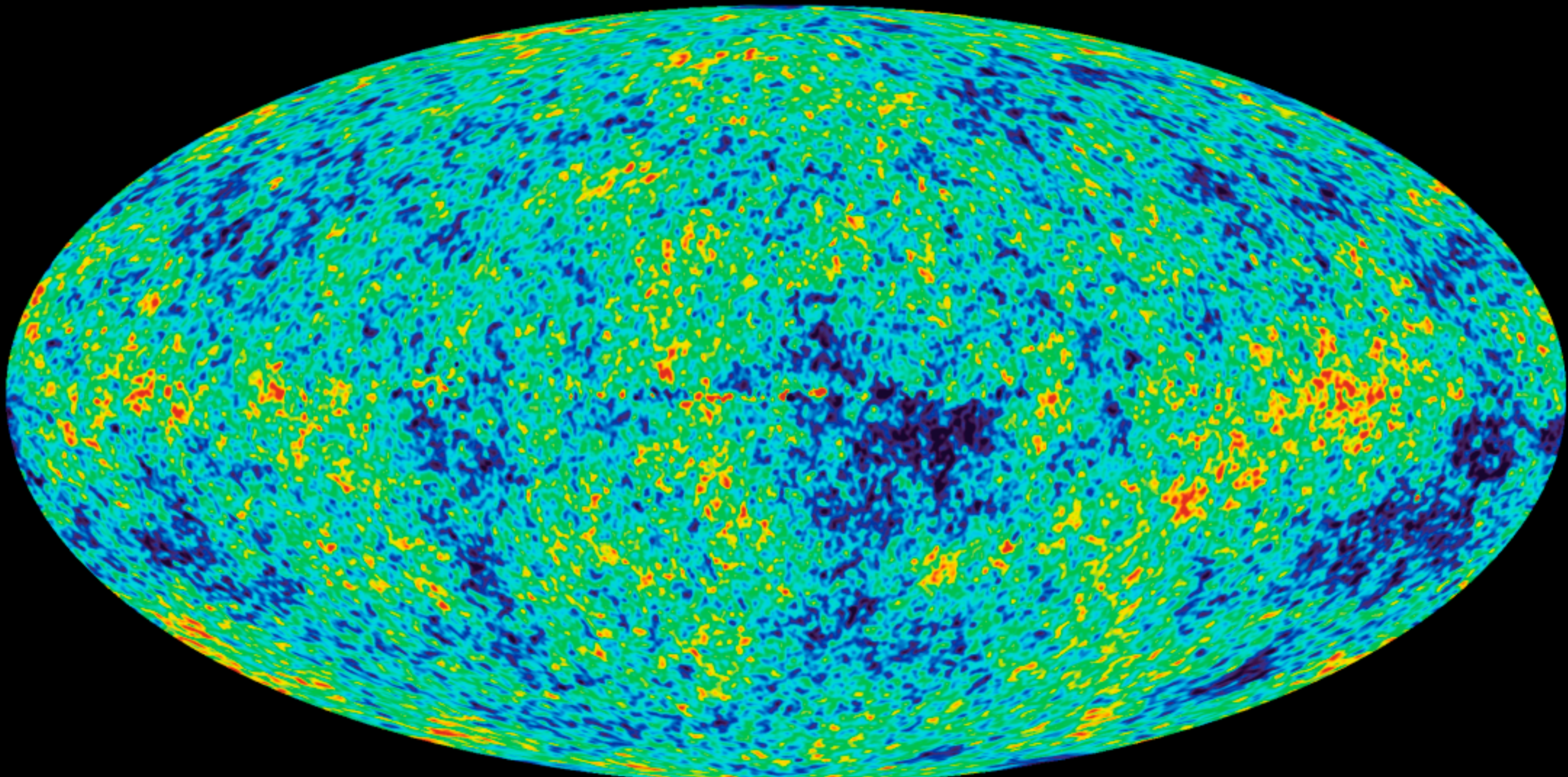
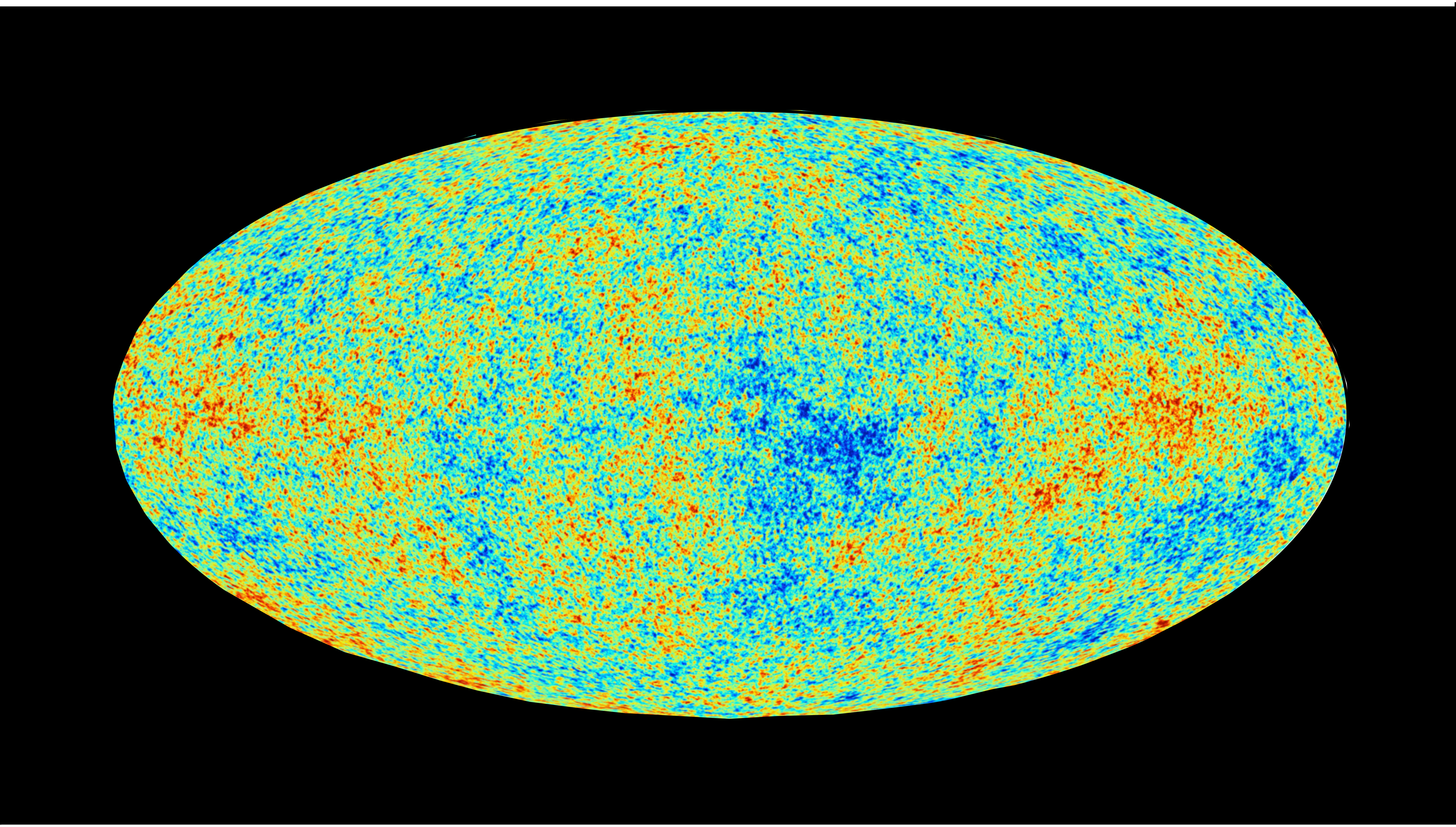
COBE Satellite 1994



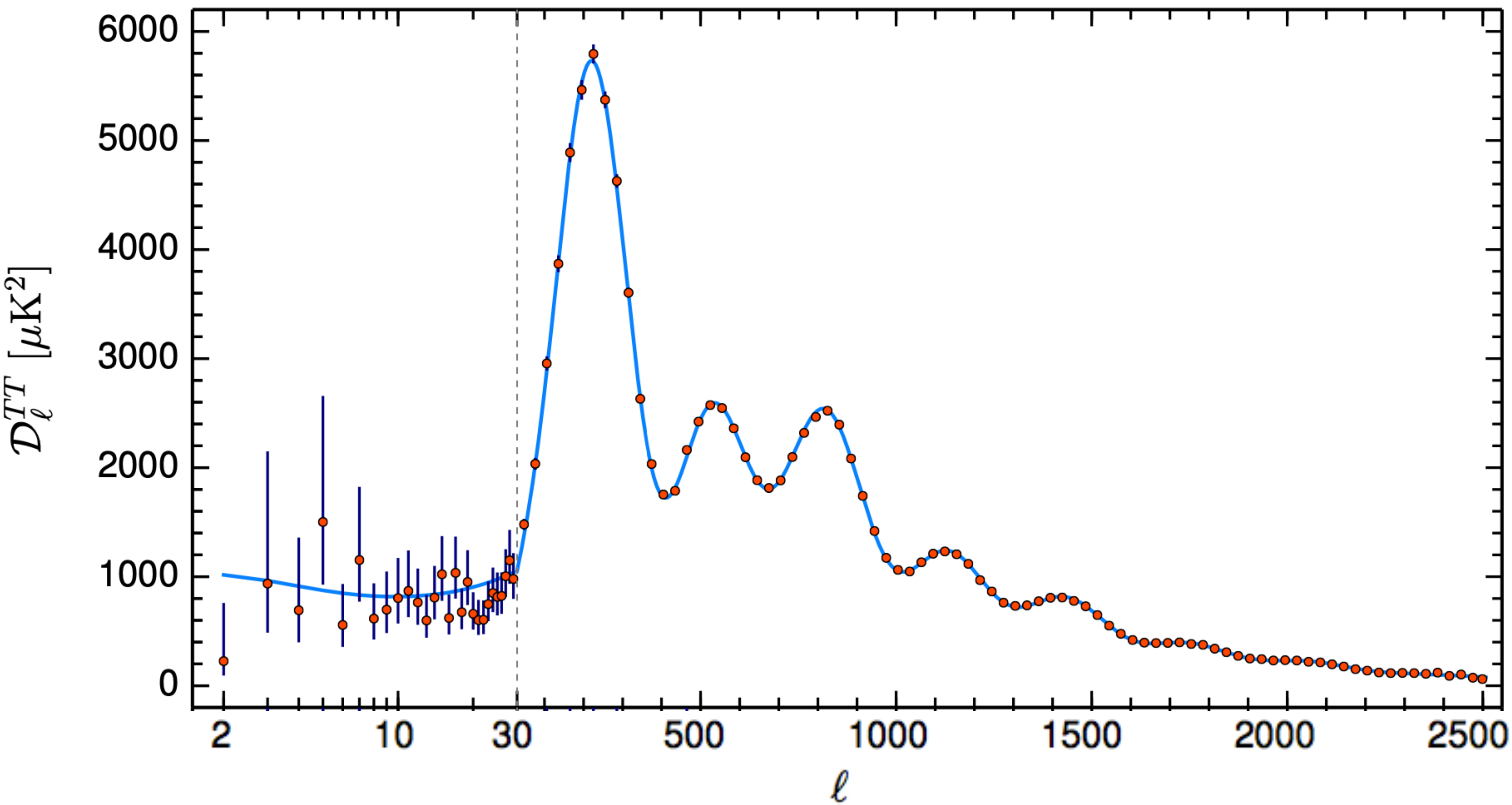
WMAP Satellite 2003



Planck Satellite 2013



Planck CMB Power Spectrum



Planck 2018 Results

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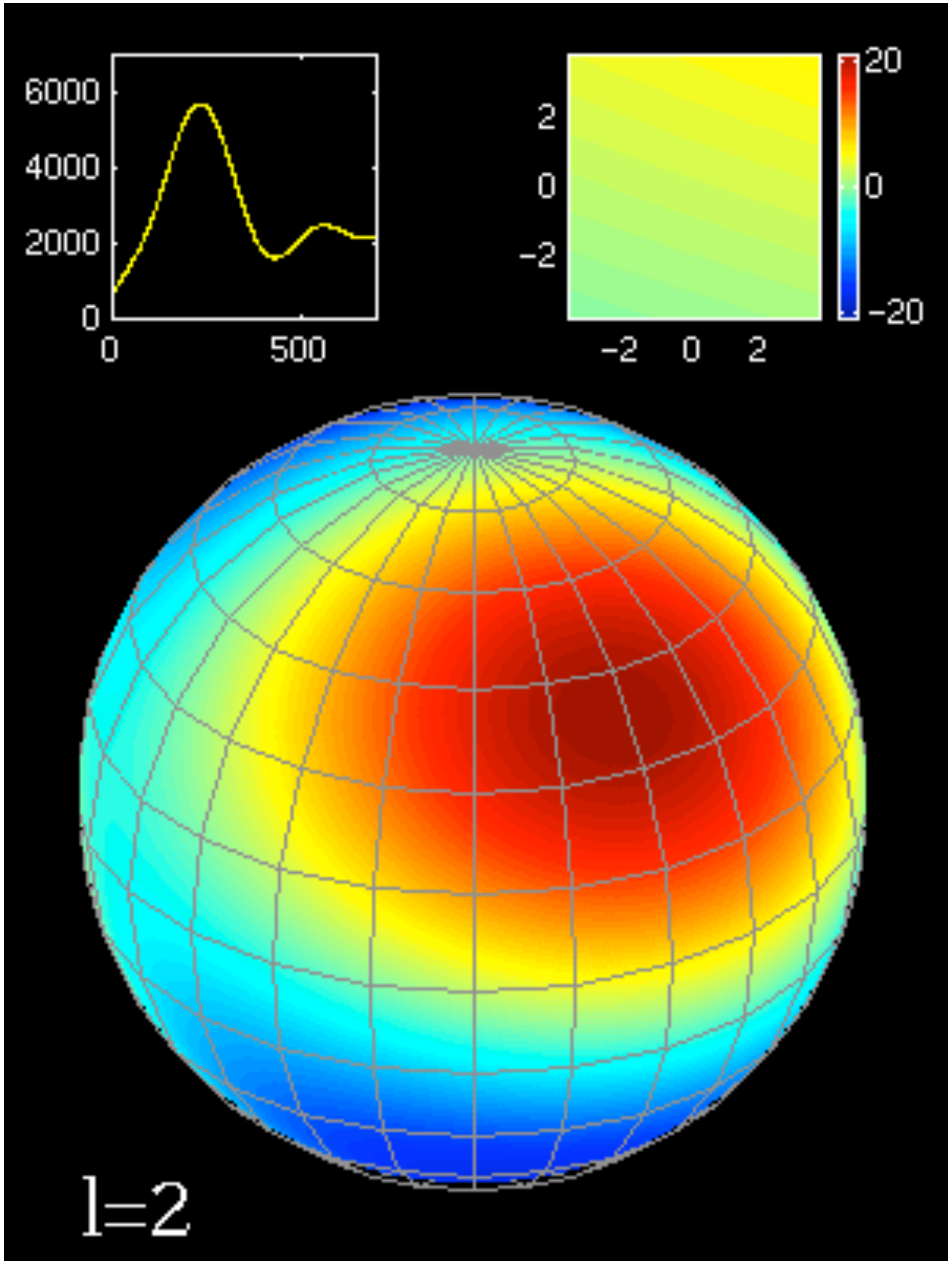
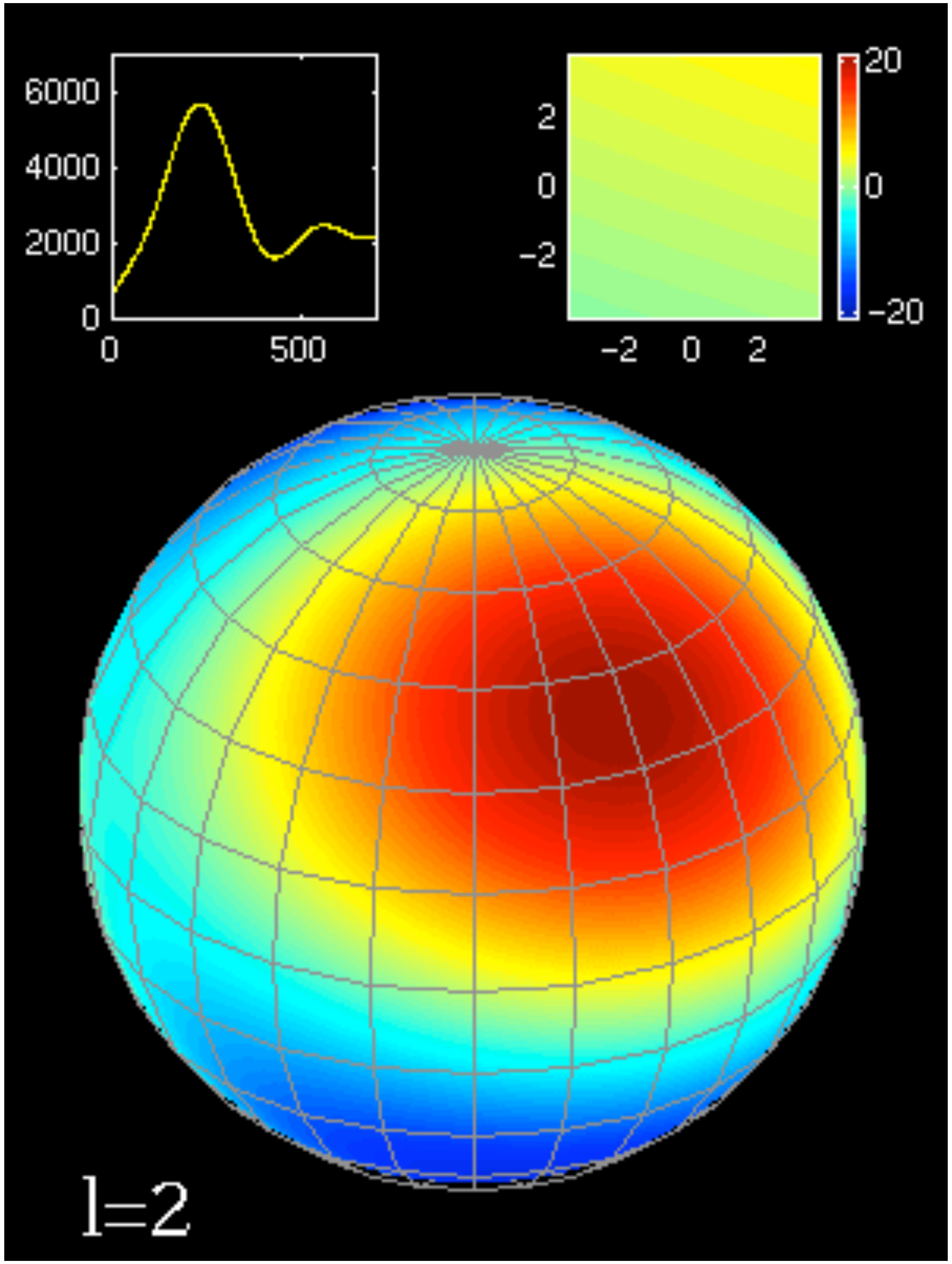


Made by Clem Pryke



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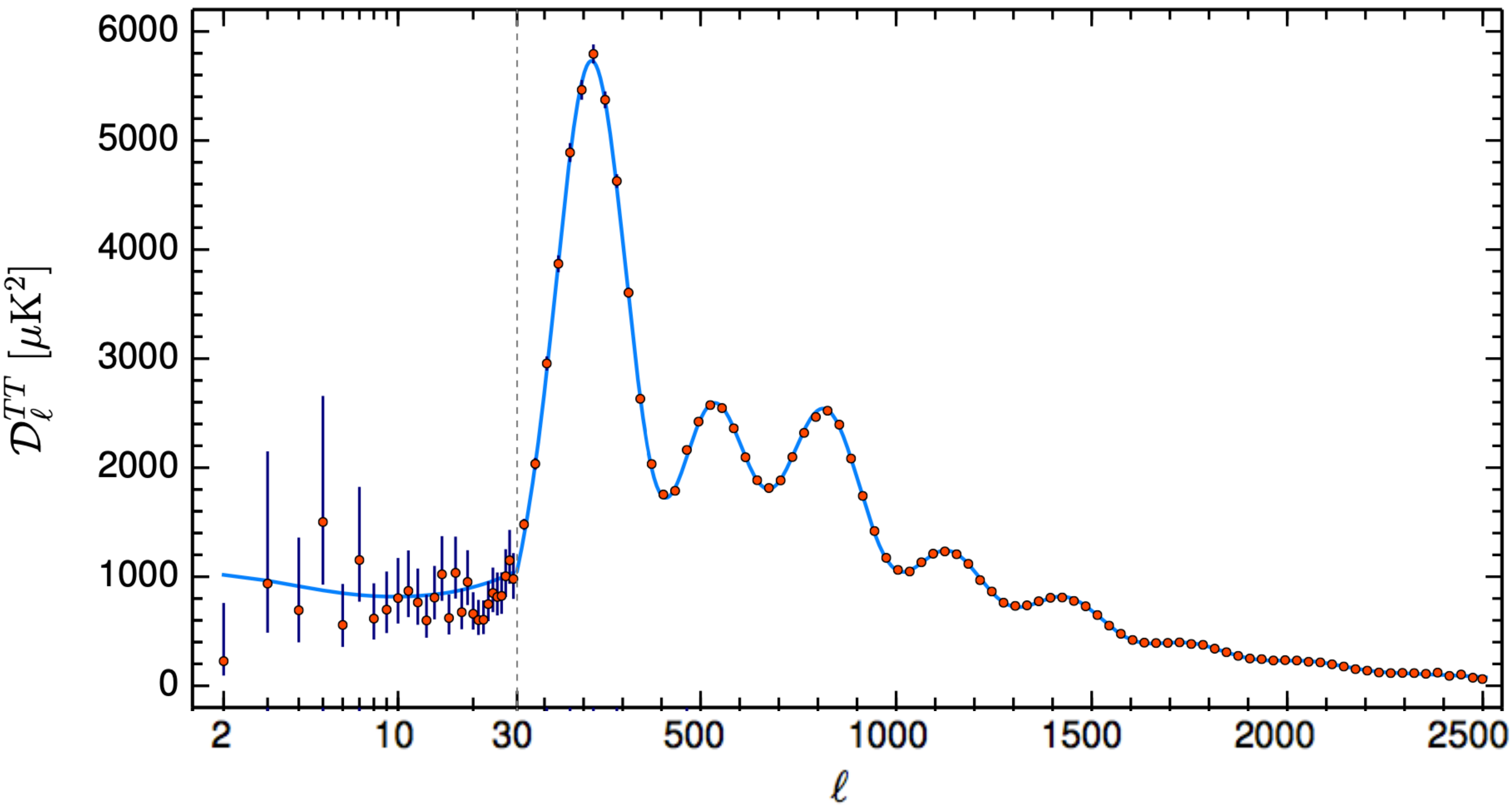

Planck 2018 Results

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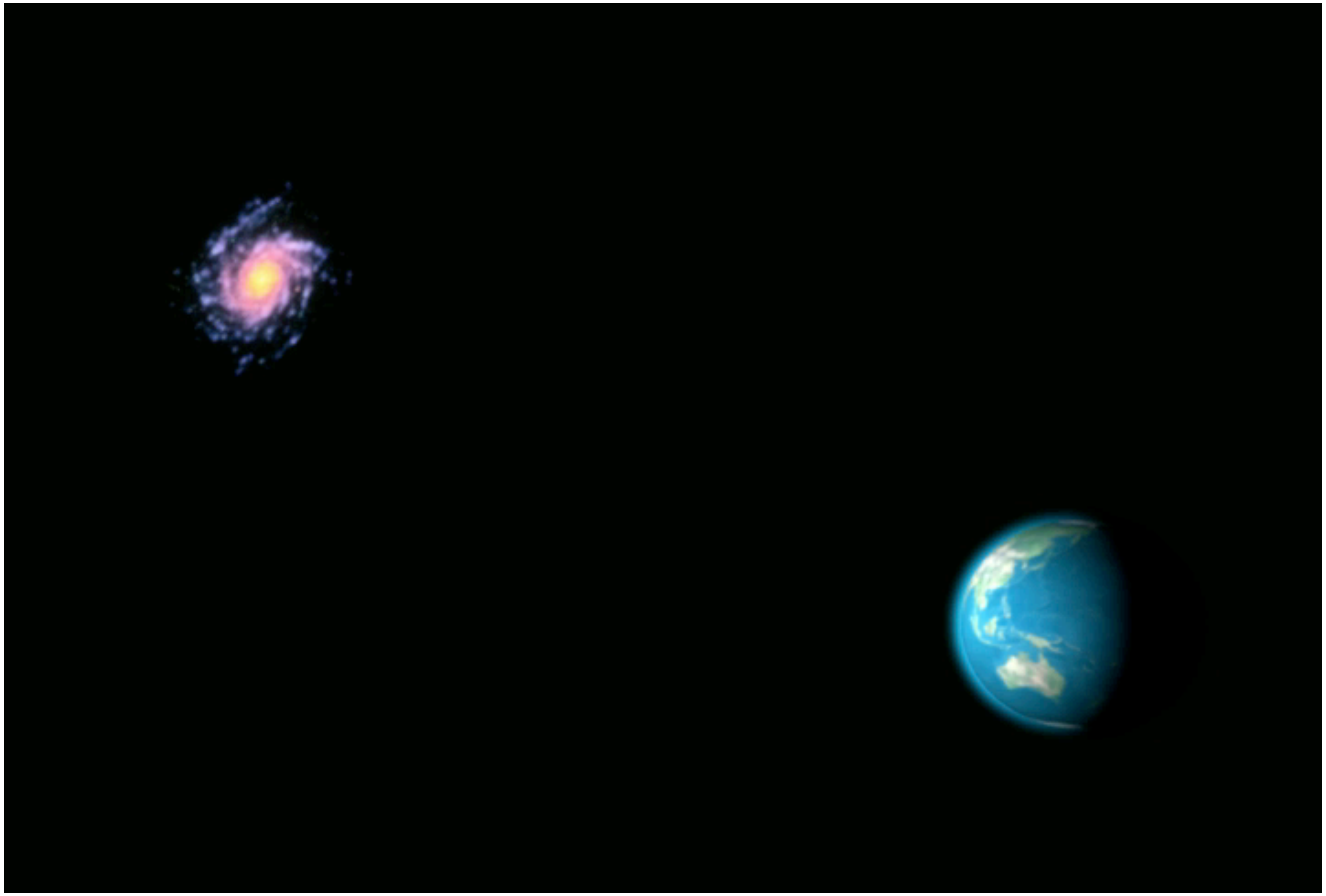
Gravitational Lensing



http://www.youtube.com/
watch?v=BkBNf_nFuhM

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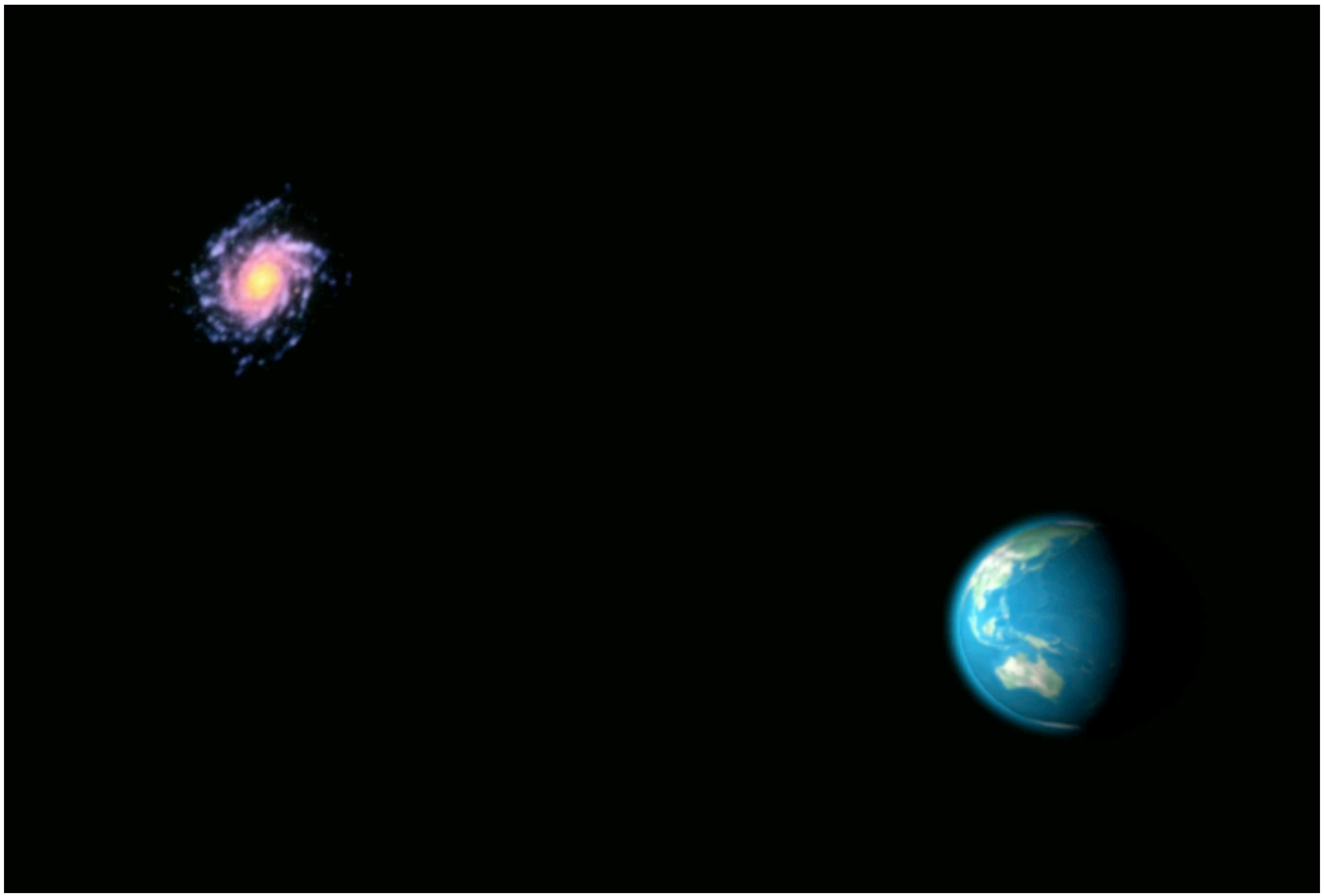

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CMB Lensing

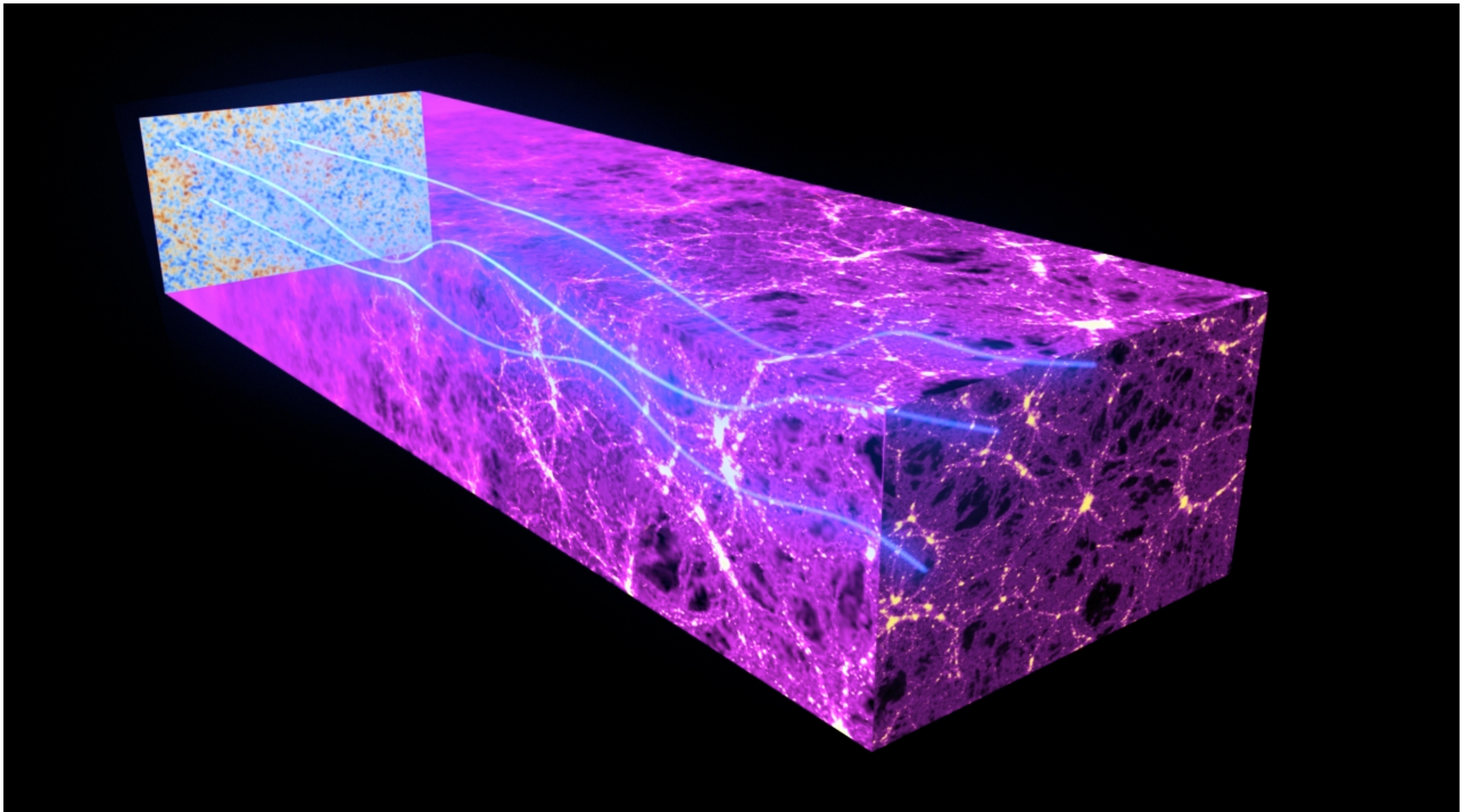

Image Credit: ESA

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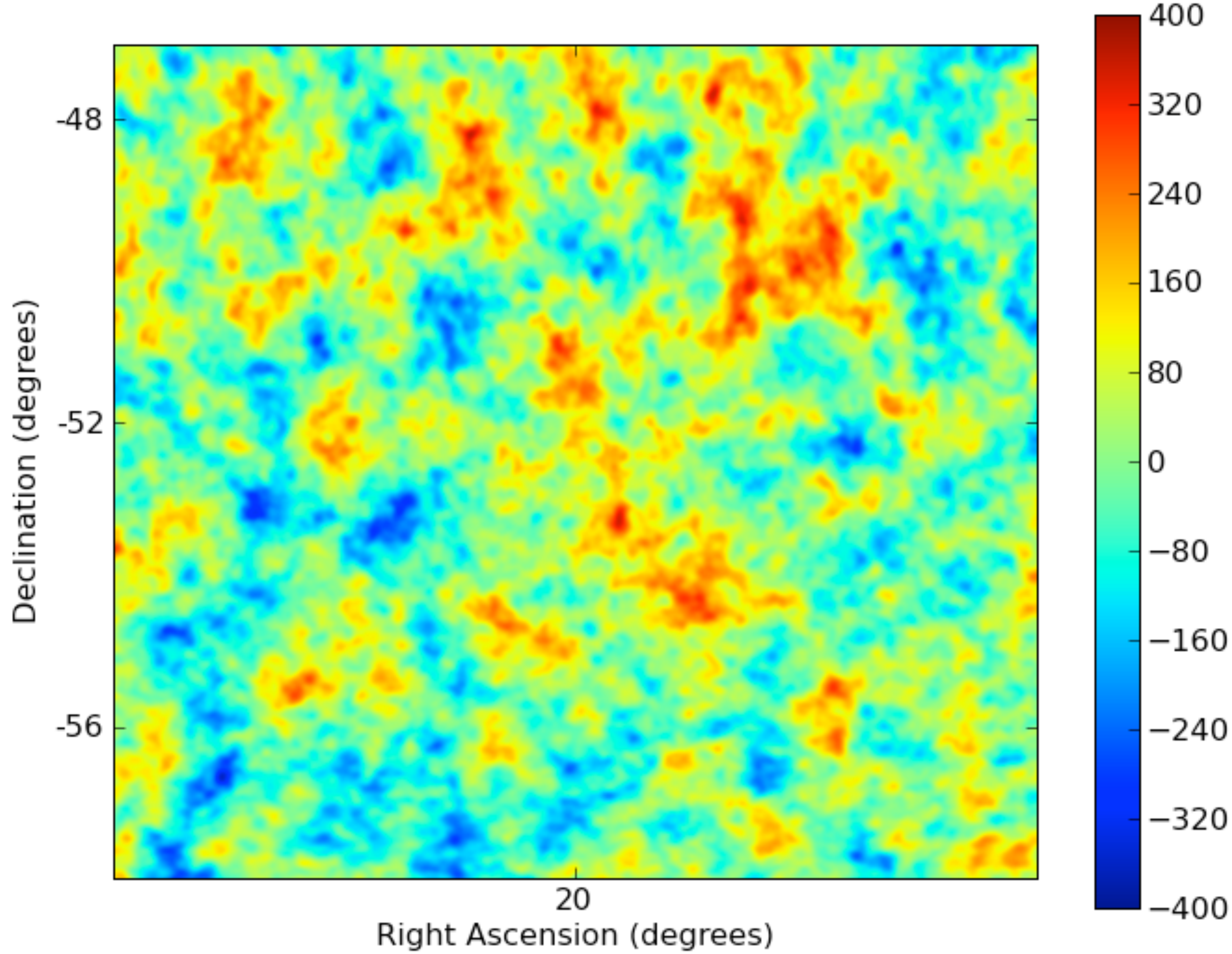
Unlensed CMB



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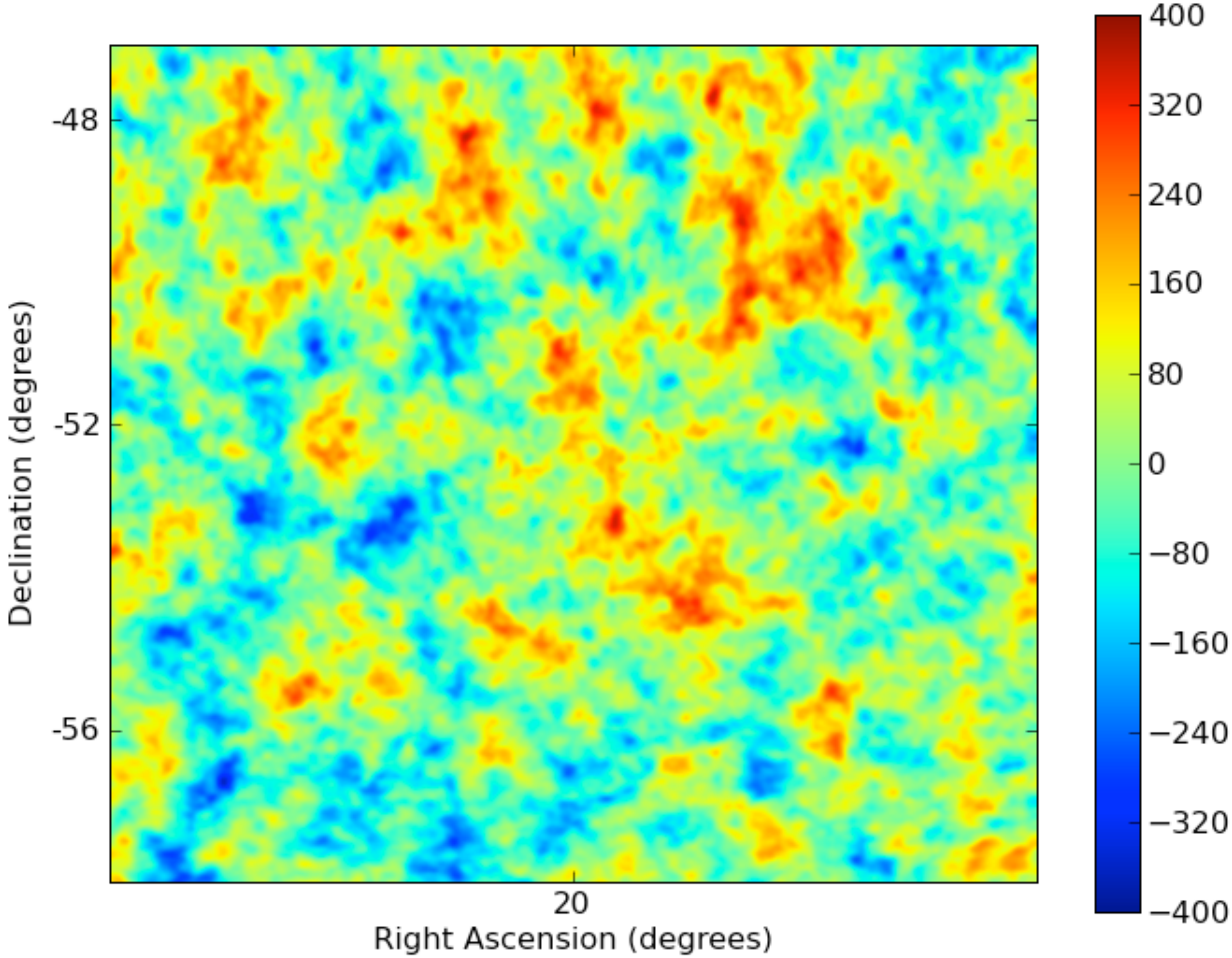
Lensed CMB



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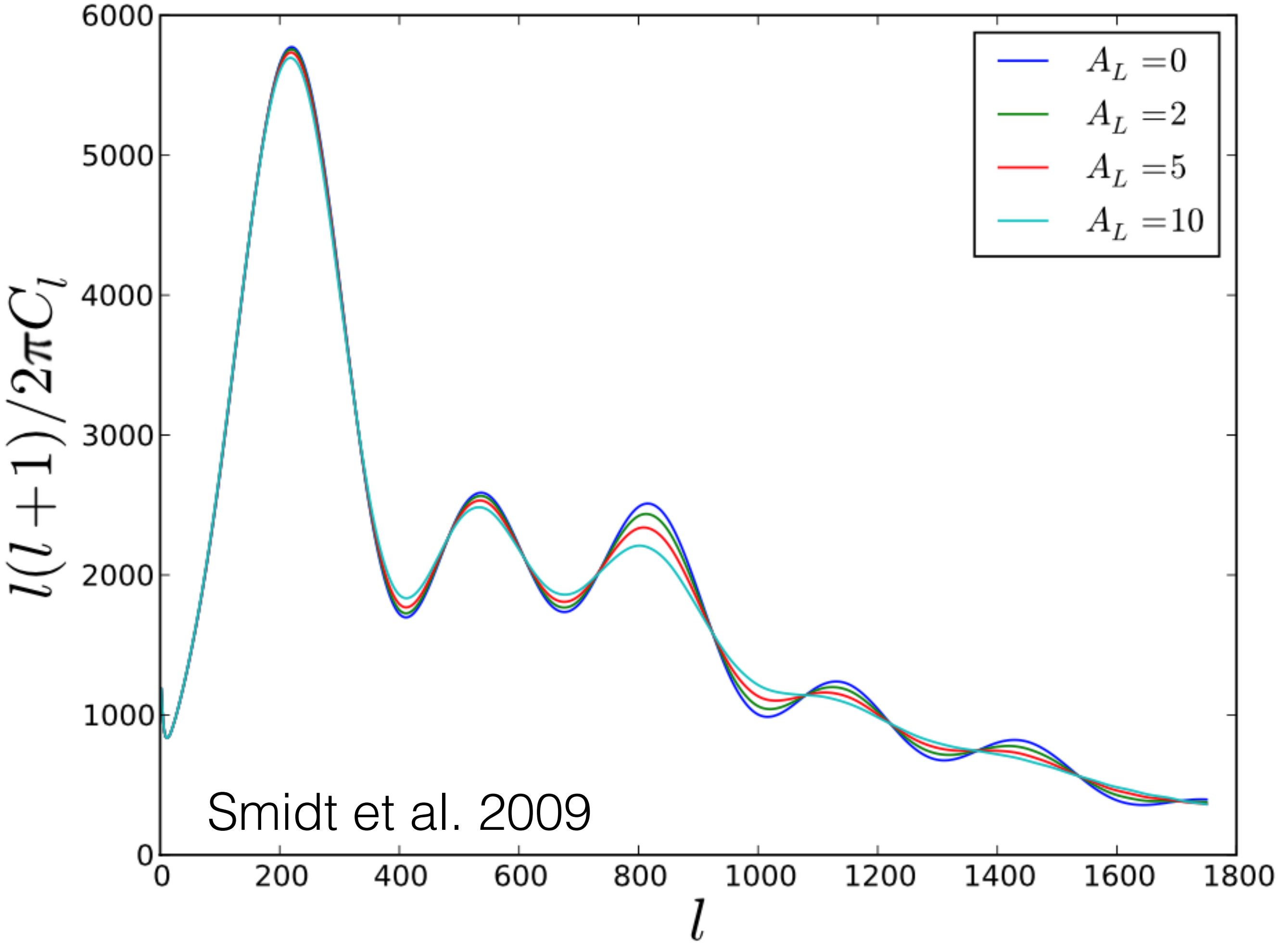
Measuring CMB Lensing



Lensing induces mode coupling

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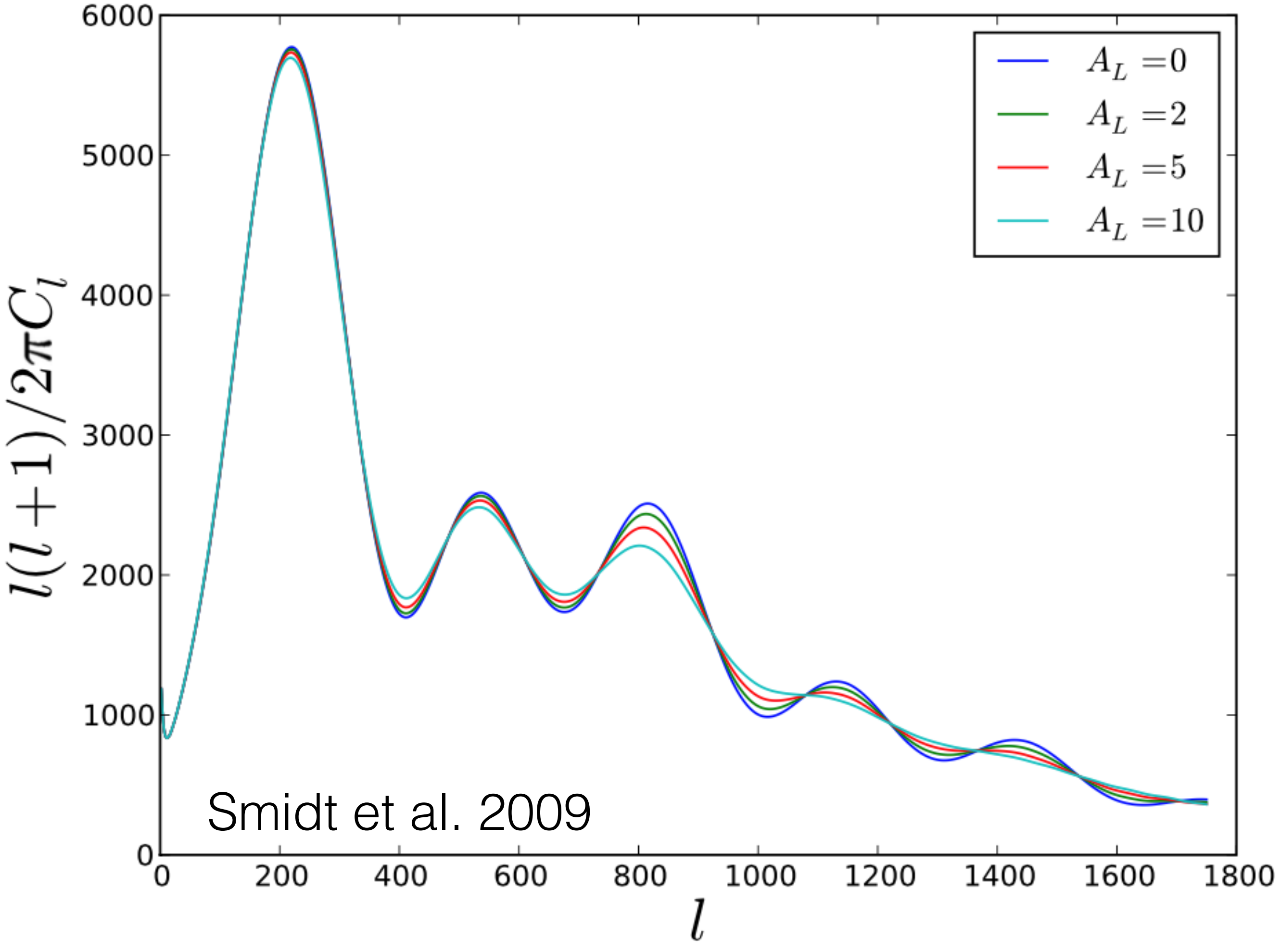
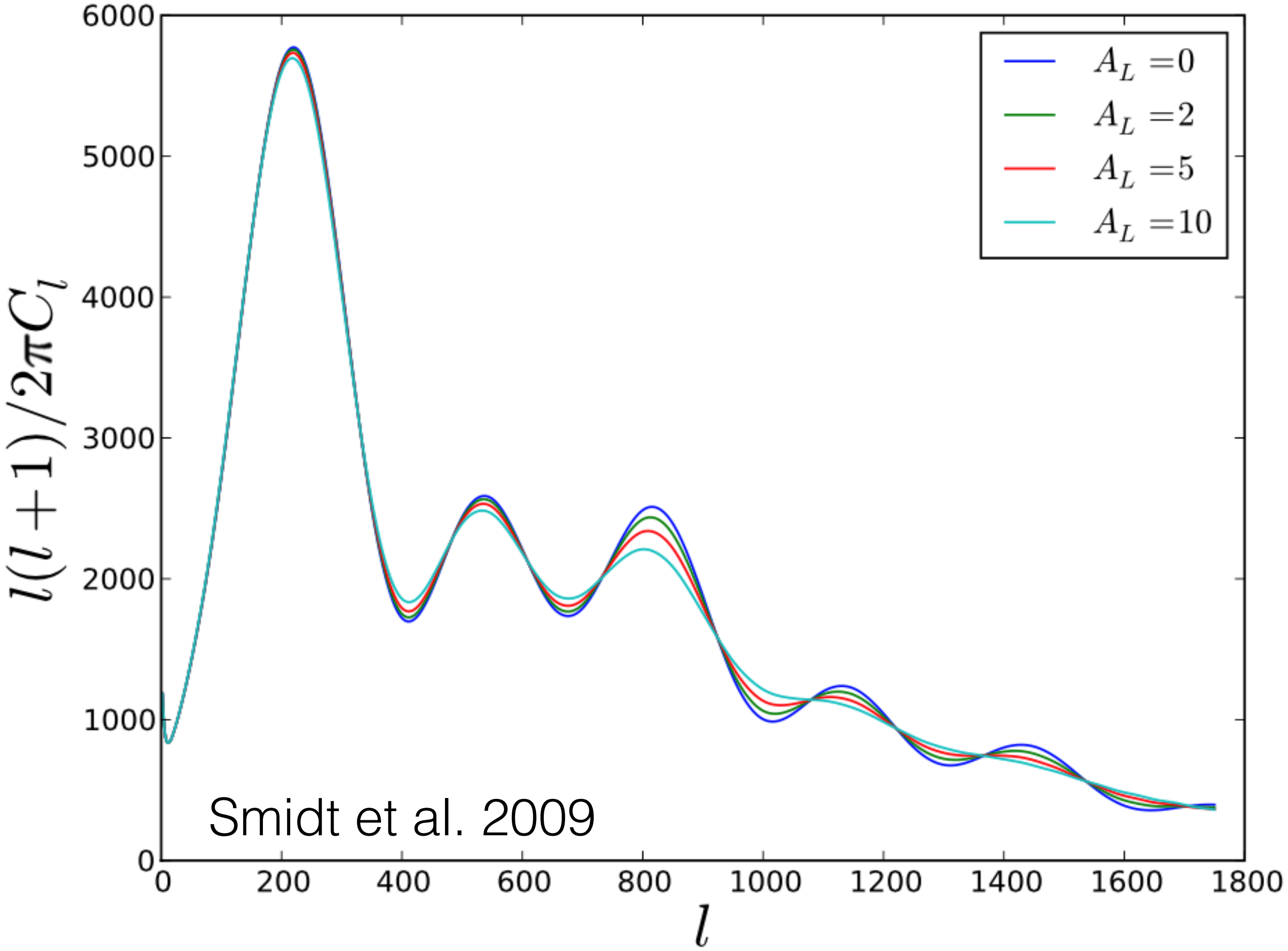


1.) Smooths CMB power spectrum

(2-pt function)

Lensing induces mode coupling

Measuring CMB Lensing



Lensing induces mode coupling

1.) Smooths CMB power spectrum

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2.) Creates non-zero CMB 4-pt function

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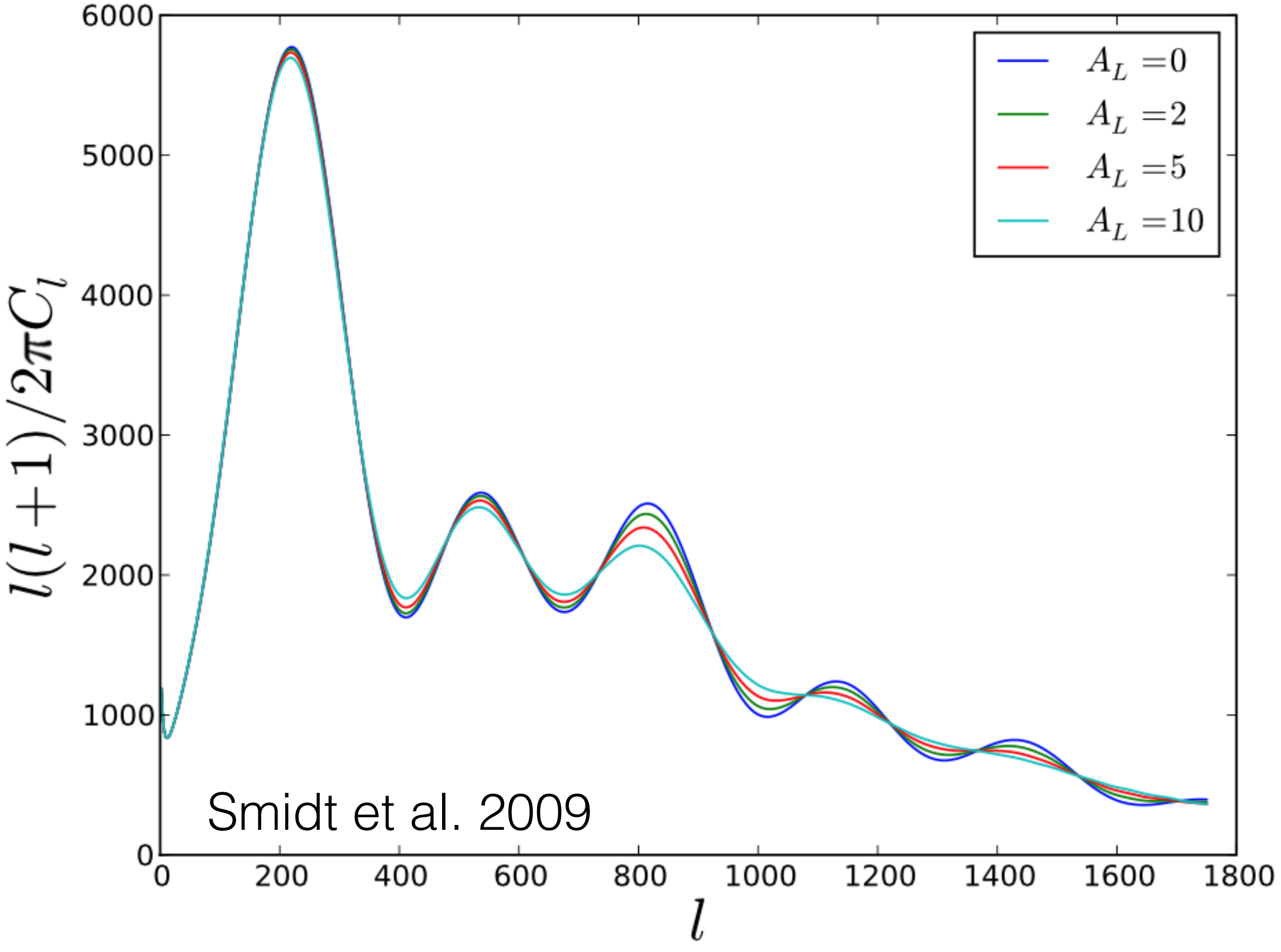
Measuring CMB Lensing



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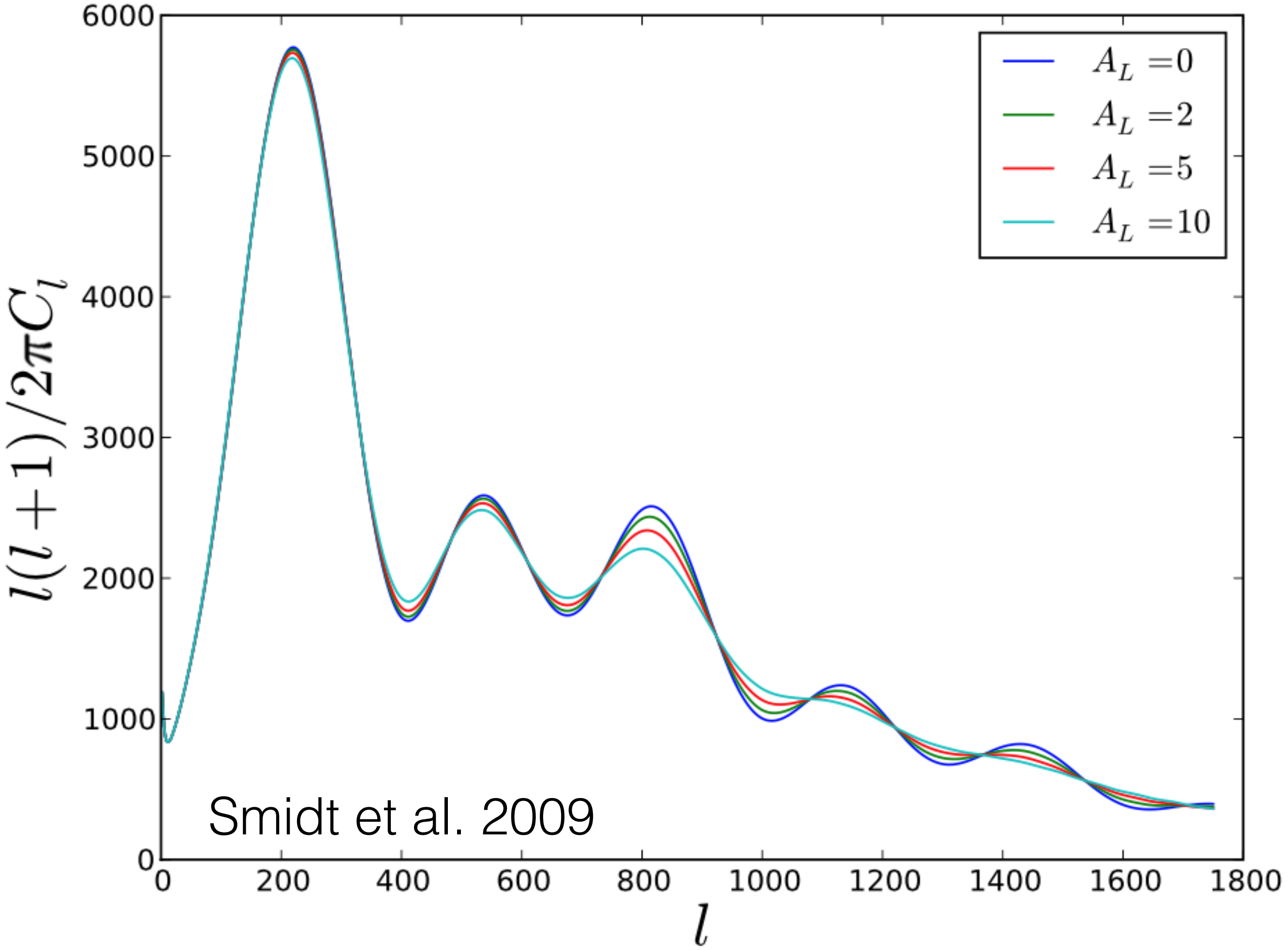
$$\langle T(\mathbf{l}+\mathbf{L})T^*(\mathbf{l})\rangle_{\rm CMB} \propto \phi(\mathbf{L})$$

Measuring CMB Lensing



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$$\hat{\phi}(\mathbf{L}) \propto \int_{\mathbf{l}} T(\mathbf{l}+\mathbf{L})T^*(\mathbf{l}) \times \mathrm{filter}$$

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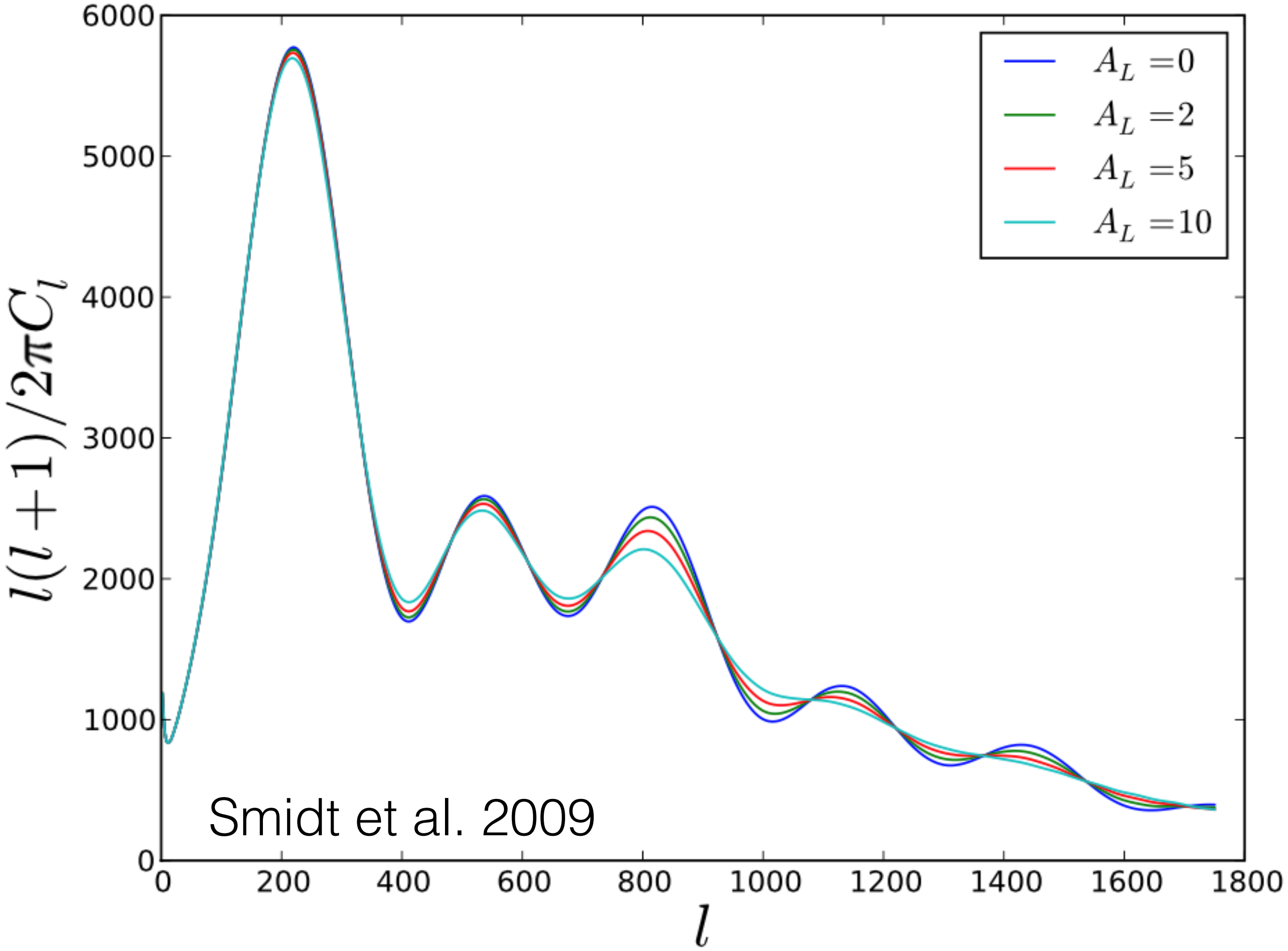
Measuring CMB Lensing



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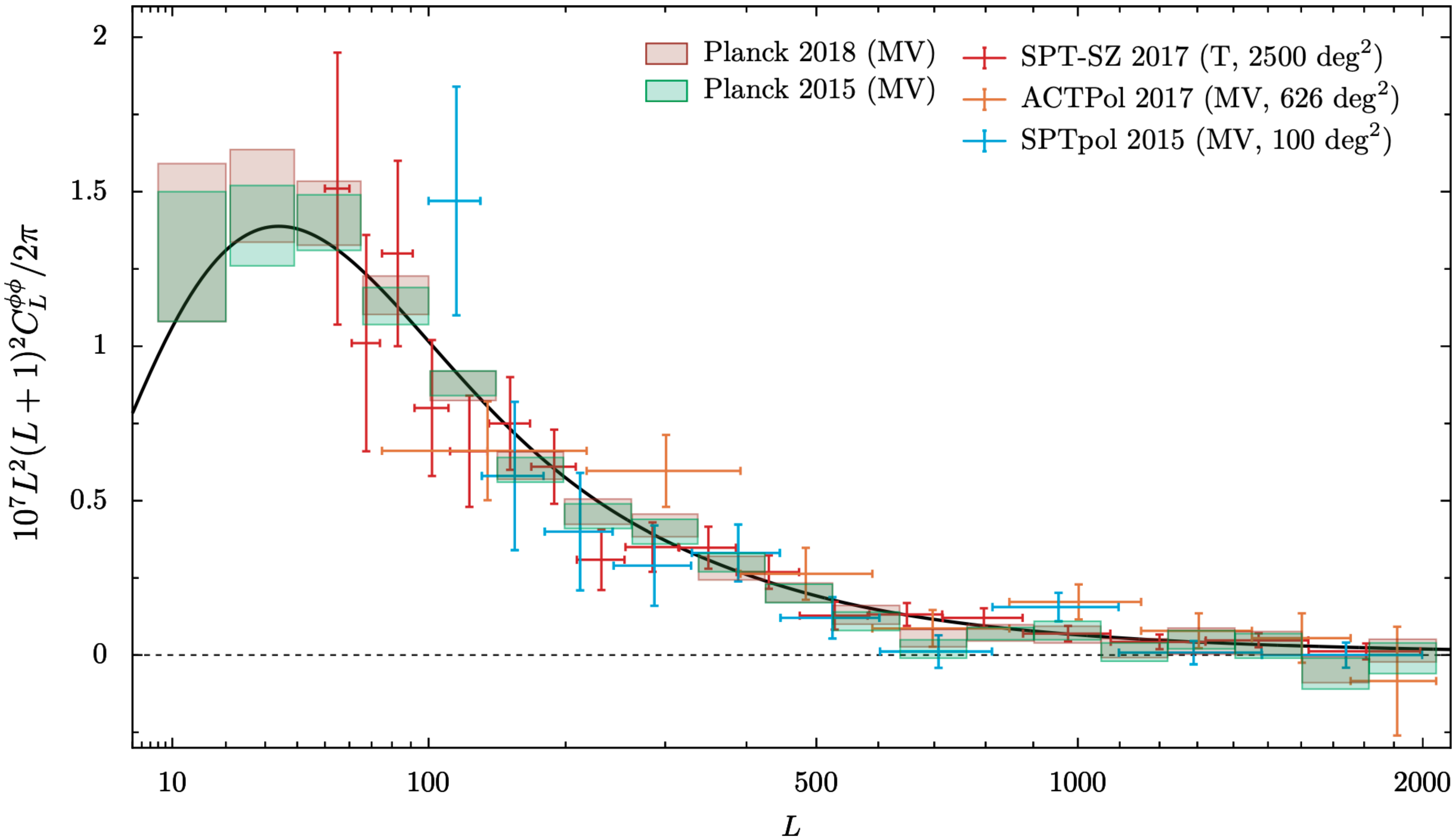
$$\hat{C}_L^{\hat{\phi}\hat{\phi}} \propto \int_{\mathbf{l},\mathbf{l}'} T(\mathbf{l})T^*(\mathbf{l}-\mathbf{L})T^*(-\mathbf{l}')T(\mathbf{L}-\mathbf{l}')$$

All quadrilaterals whose diagonal has length L

Measurements of CMB Lensing on Large Scales



Planck 2018 Results

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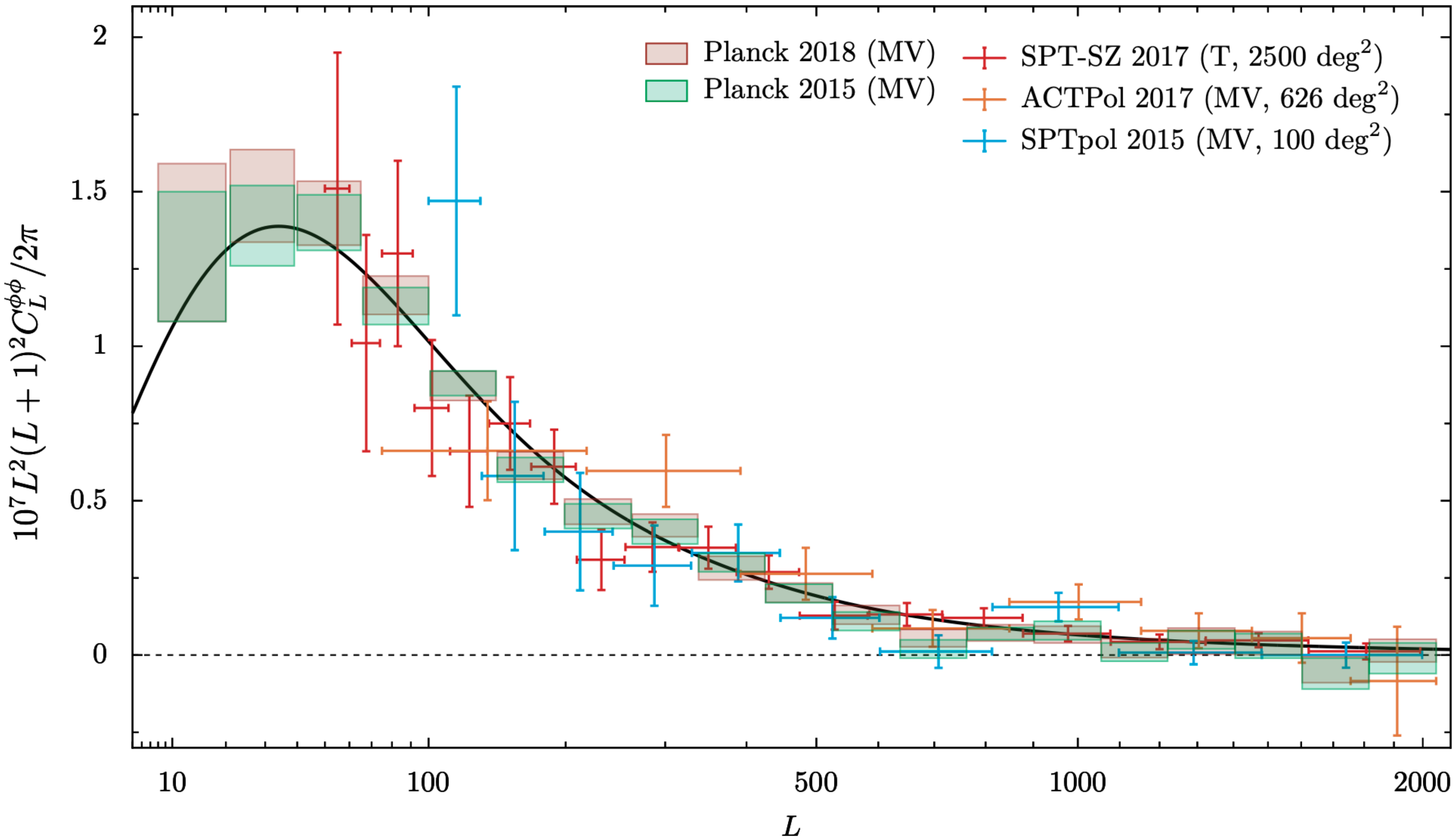
Measurements of CMB Lensing on Large Scales



Planck 2018 Results

Blanchard & Schneider 1987
(first idea of detectability)

Zaldarriaga & Seljak 1997
(first lensing estimators)

Hu 2001
Hu & Okamoto 2002
(optimal lensing estimators)

Smith, Zahn, Dore 2007
(first indirect detection)

Das et al. 2011 - ACT
(first direct detection)

van Engelen et al. 2012 - SPT
(second direct detection)

Planck Collaboration 2018
(detection with S/N = 40)

ACT Collaboration 2024
(detection with S/N = 43)

Cosmological Parameters from Planck 2018 Results

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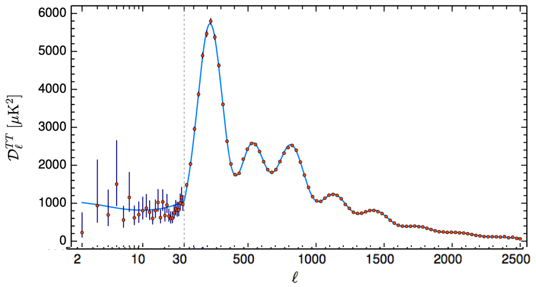

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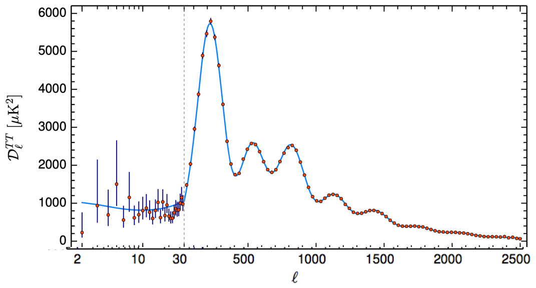

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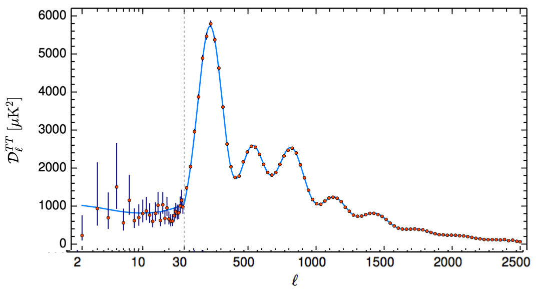

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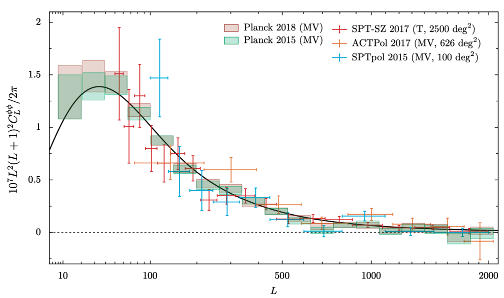

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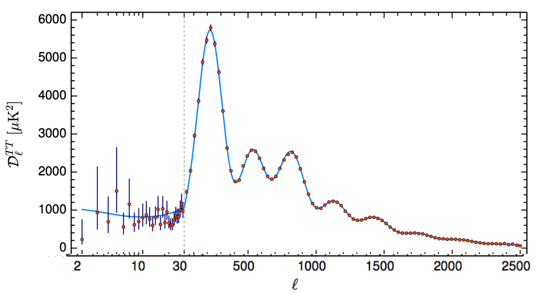

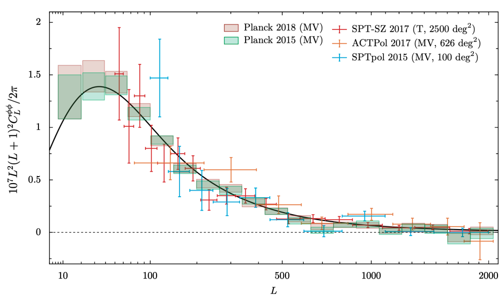

Parameter	TT,TE,EE+lowE+lensing 68% limits
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0 [km s^{-1} Mpc^{-1}] . .	67.36 ± 0.54
Ω_Λ	0.6847 ± 0.0073
Ω_m	0.3153 ± 0.0073
$\Omega_m h^2$	0.1430 ± 0.0011
$\Omega_m h^3$	0.09633 ± 0.00030
σ_8	0.8111 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$.	0.832 ± 0.013
$\sigma_8 \Omega_m^{0.25}$	0.6078 ± 0.0064
z_{re}	7.67 ± 0.73
$10^9 A_s$	2.100 ± 0.030
$10^9 A_s e^{-2\tau}$	1.883 ± 0.011
Age [Gyr]	13.797 ± 0.023
z_*	1089.92 ± 0.25
r_* [Mpc]	144.43 ± 0.26
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z_{drag}	1059.94 ± 0.30
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k_D [Mpc^{-1}]	0.14087 ± 0.00030
z_{eq}	3402 ± 26
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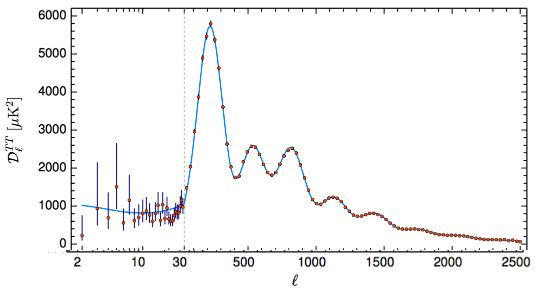
$100\theta_{s,eq}$	0.4494 ± 0.0026

Cosmological Parameters from Planck 2018 Results



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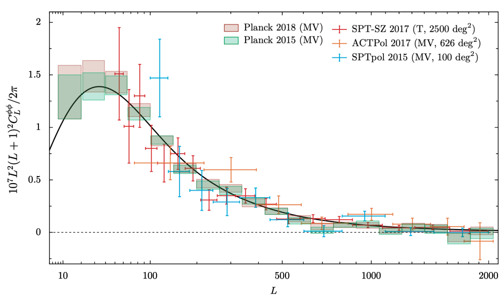

6 parameters fit to the CMB power spectra and CMB lensing spectrum

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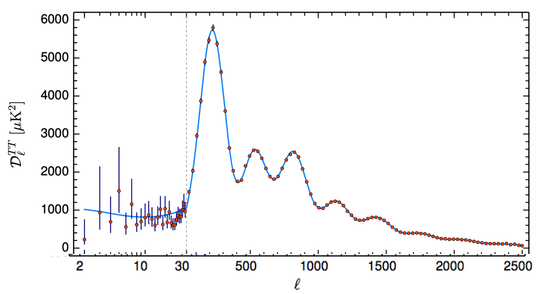

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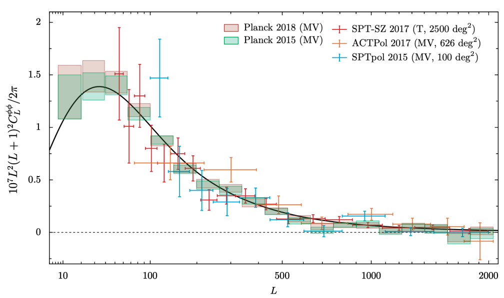

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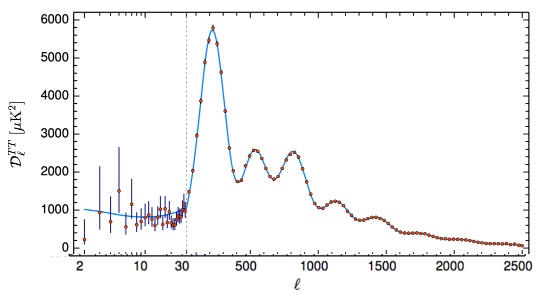
Cosmological Parameters from Planck 2018 Results



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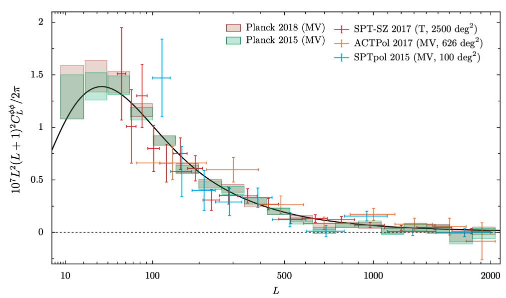

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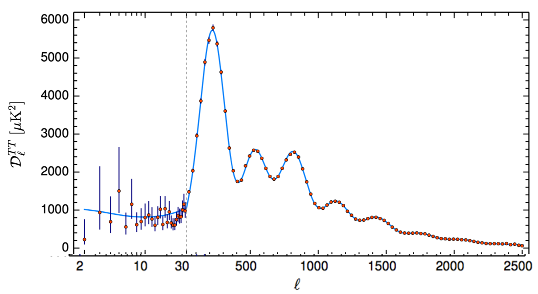

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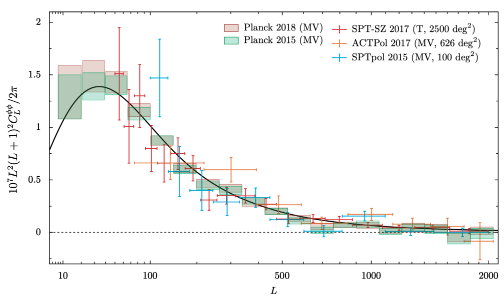

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σ_8	0.8111 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$.	0.832 ± 0.013
$\sigma_8 \Omega_m^{0.25}$	0.6078 ± 0.0064
z_{re}	7.67 ± 0.73
$10^9 A_s$	2.100 ± 0.030
$10^9 A_s e^{-2\tau}$	1.883 ± 0.011
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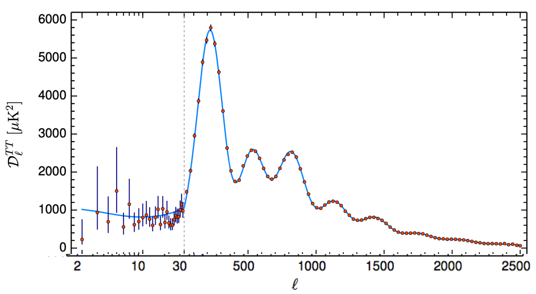
k_{eq} [Mpc^{-1}]	0.010384 ± 0.000081
$100\theta_{s,eq}$	0.4494 ± 0.0026

Cosmological Parameters from Planck 2018 Results



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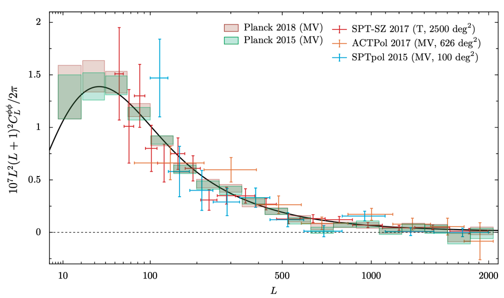

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Total Matter

Redshift when first stars turned on

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$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0 [km s^{-1} Mpc^{-1}]	67.36 ± 0.54
Ω_Λ	0.6847 ± 0.0073
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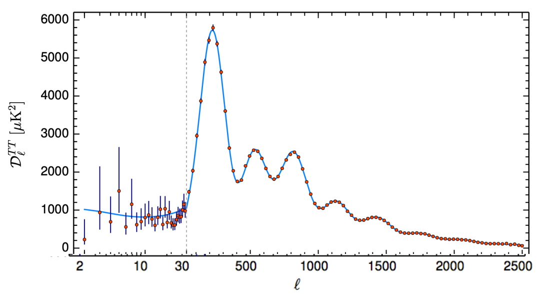

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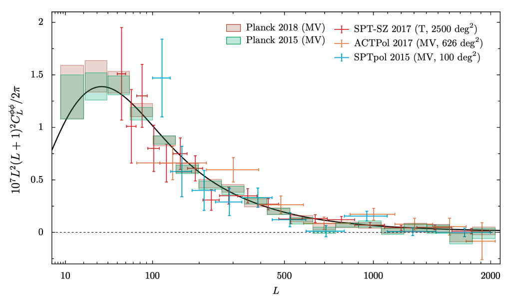

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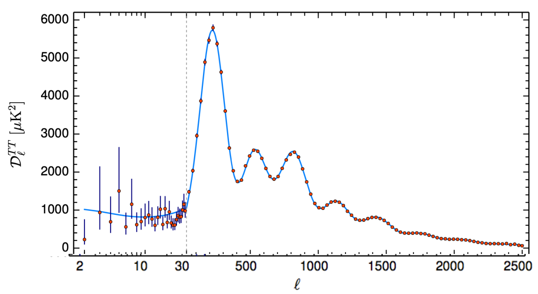

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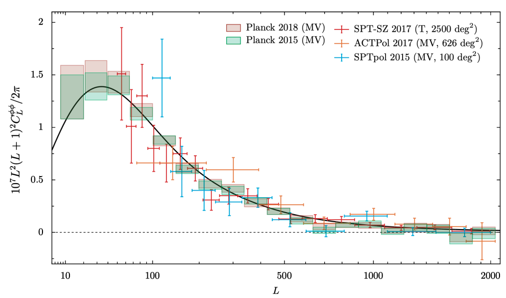

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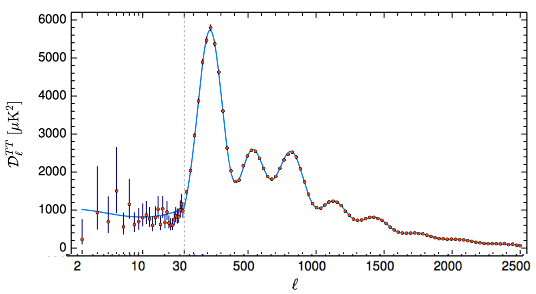

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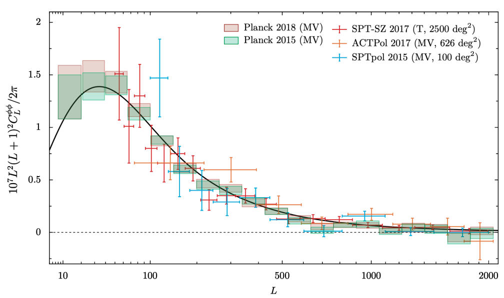

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Outline

- Cosmic Microwave Background
- CMB Experiments
- CMB-HD

Atacama Cosmology Telescope (ACT): 2006-2022

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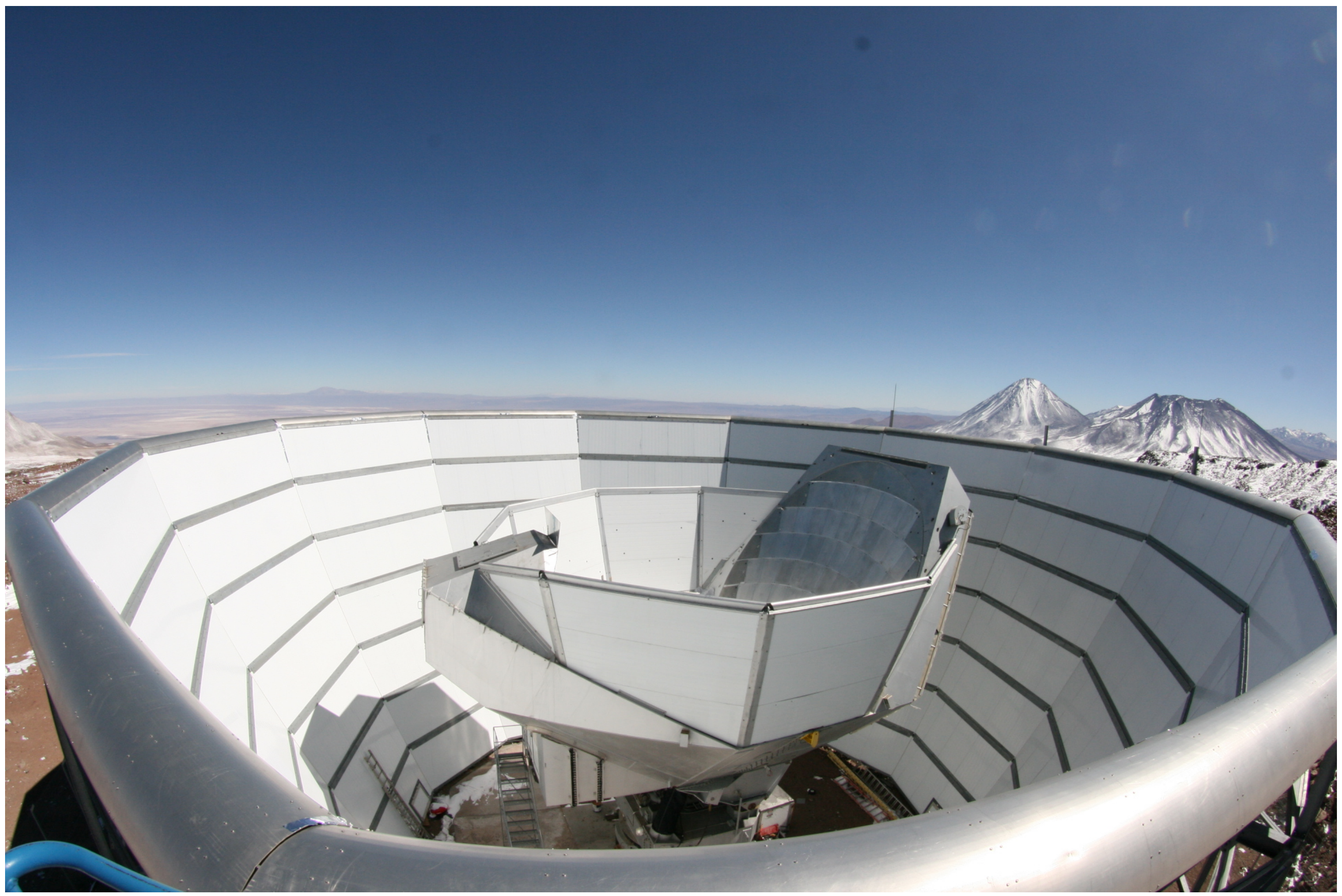

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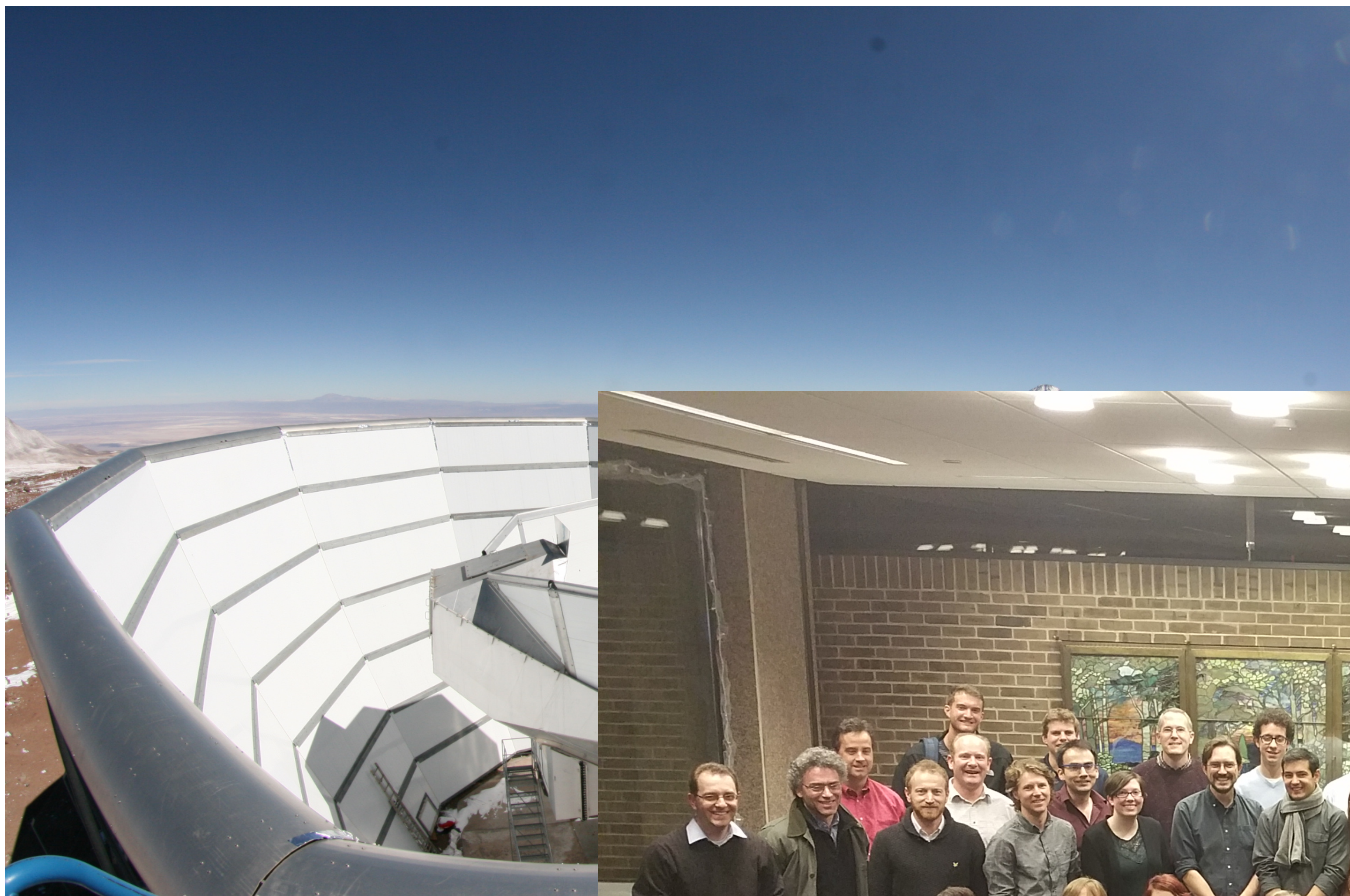

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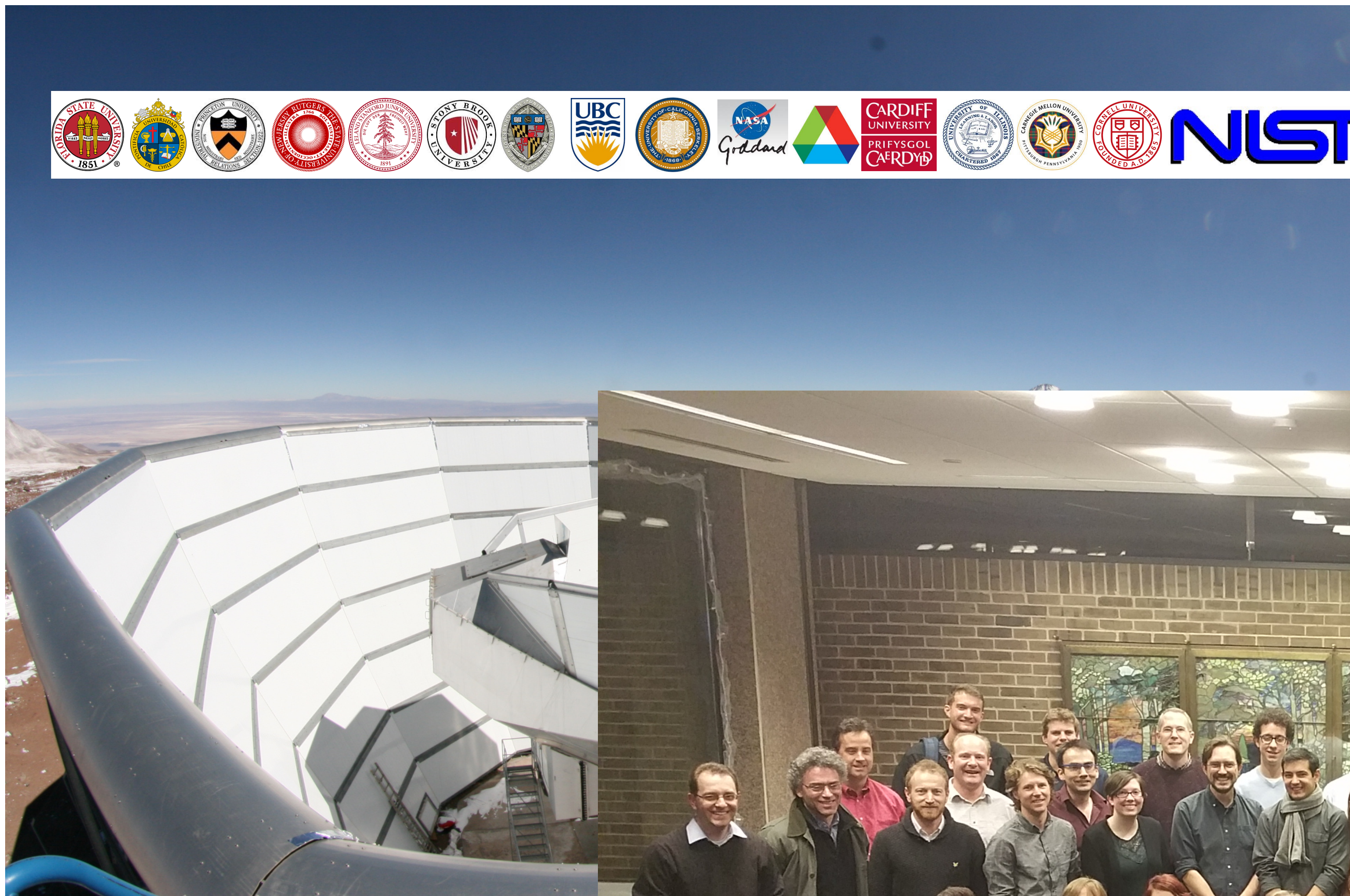

Power of CMB Lensing

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Data Release 6: S8 constraint (2024)

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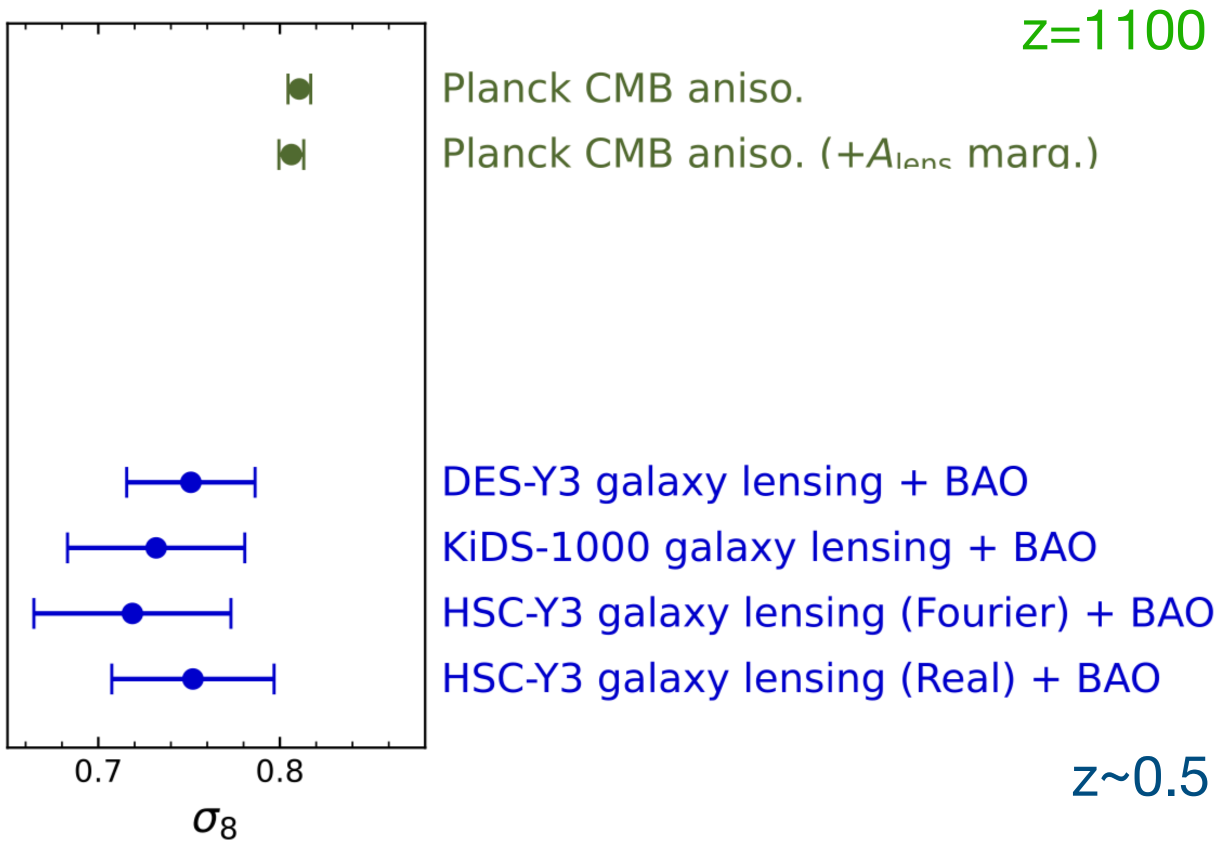

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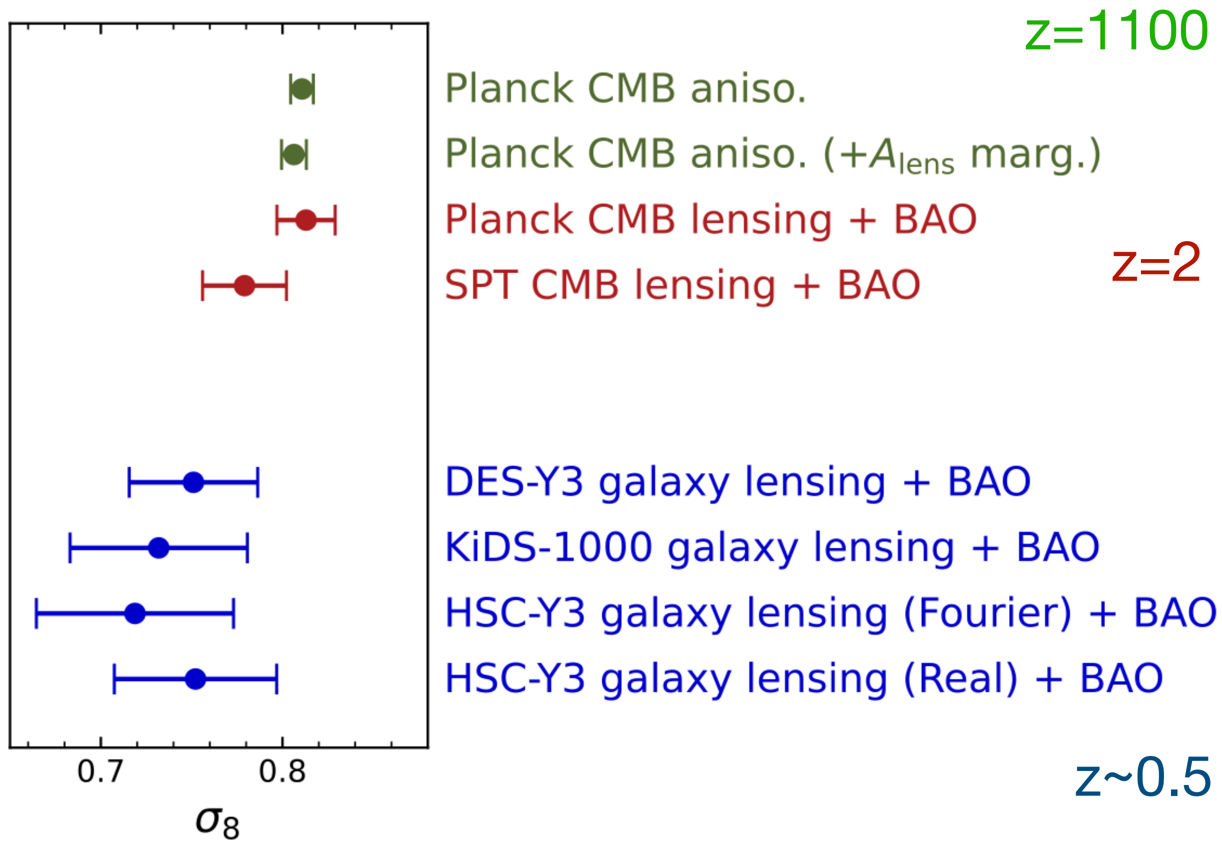

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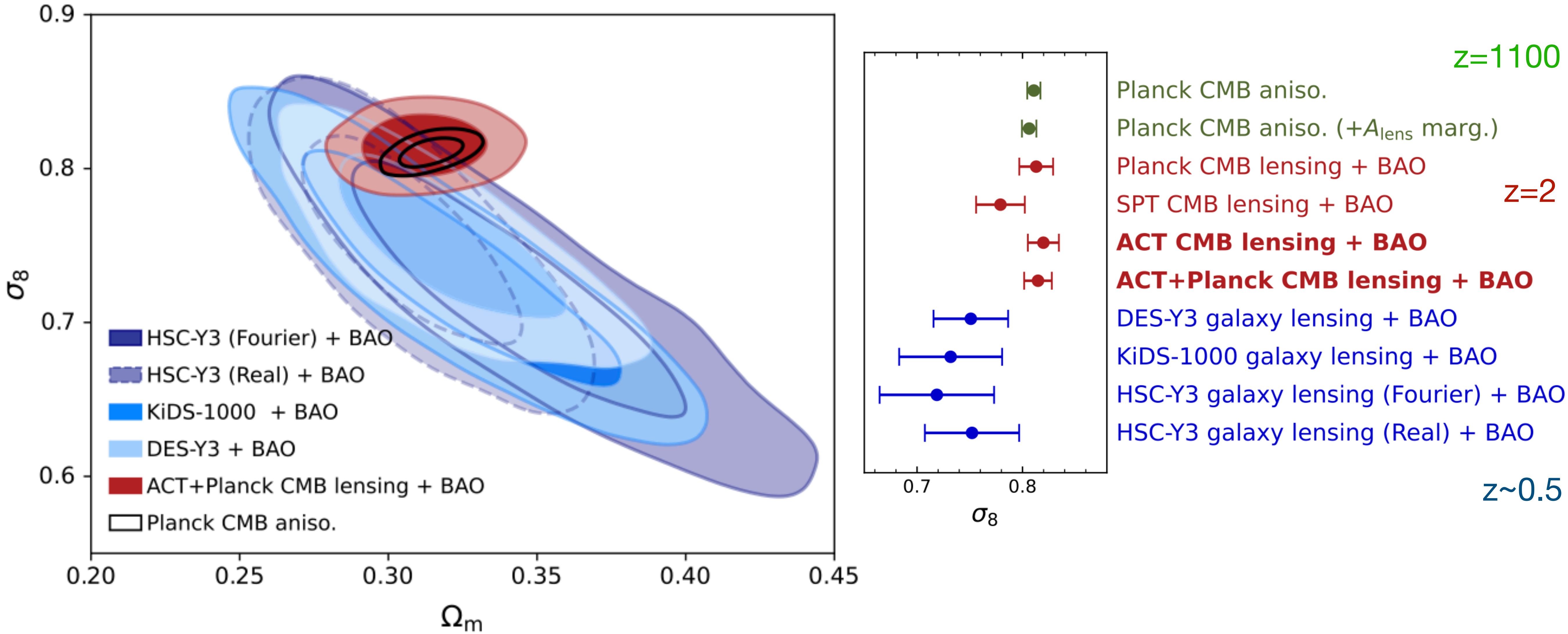

I co-lead the ACT lensing working group

Madhavacheril, Qu, Sherwin, MacCrann et al., ApJ, (2024), 2304.05203
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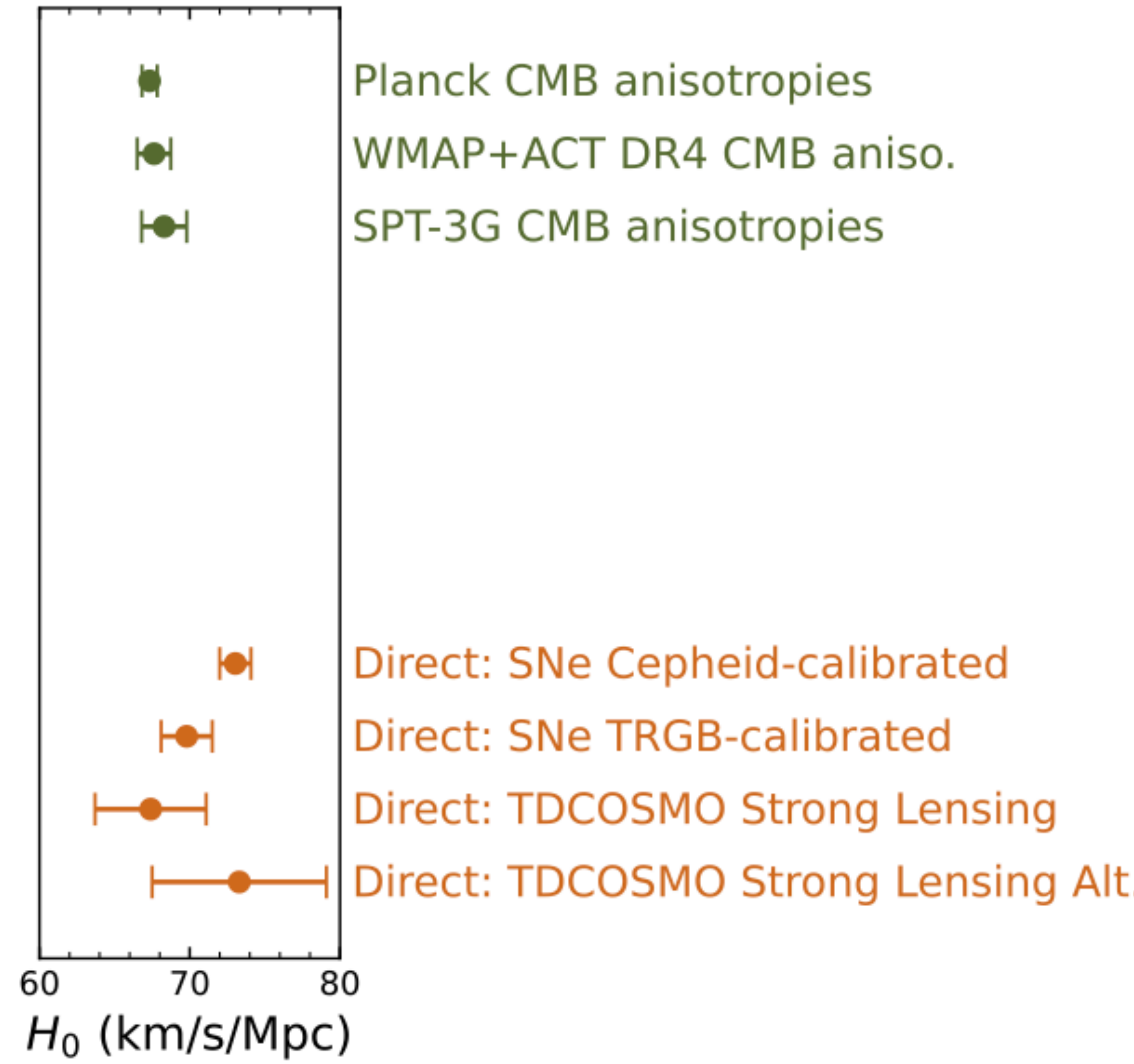

z=1100

z~0.2

Power of CMB Lensing

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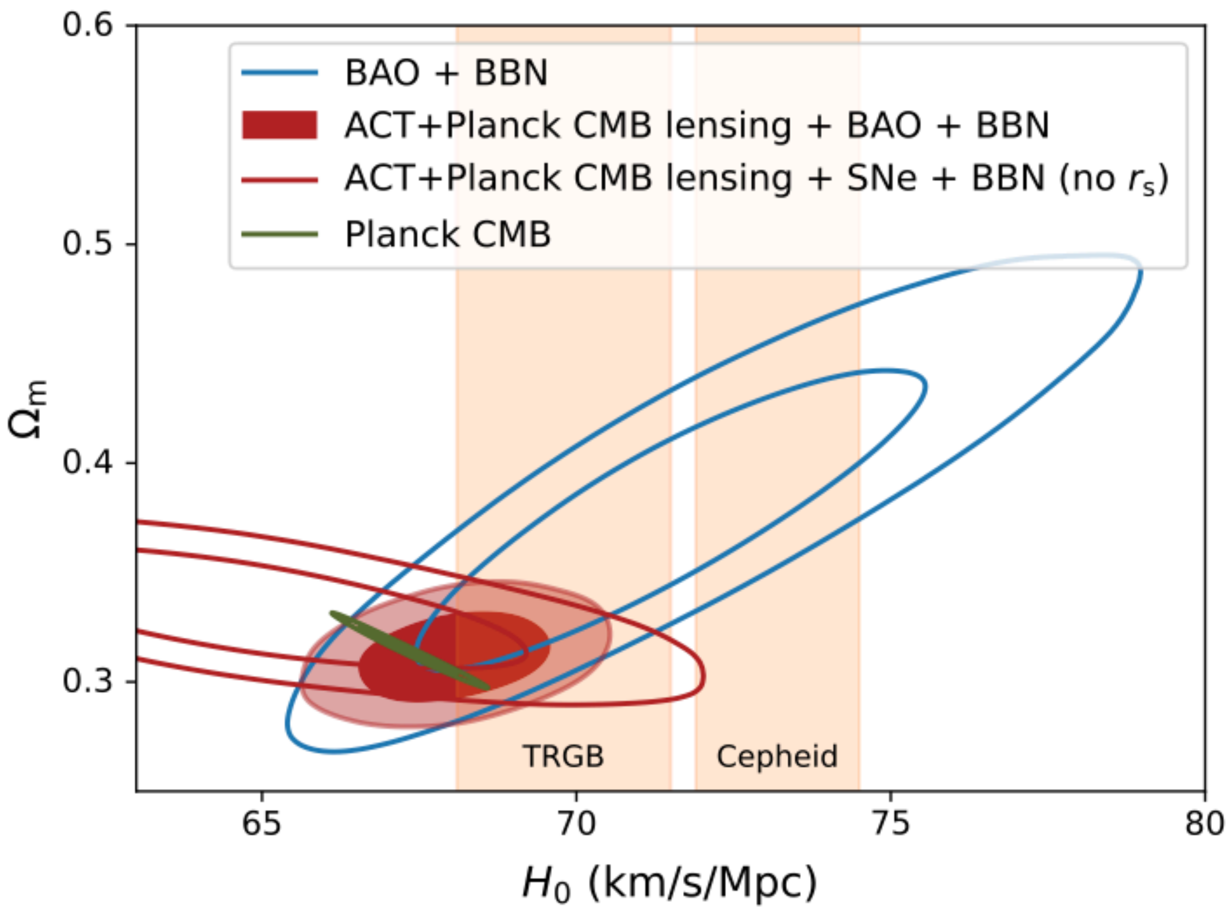

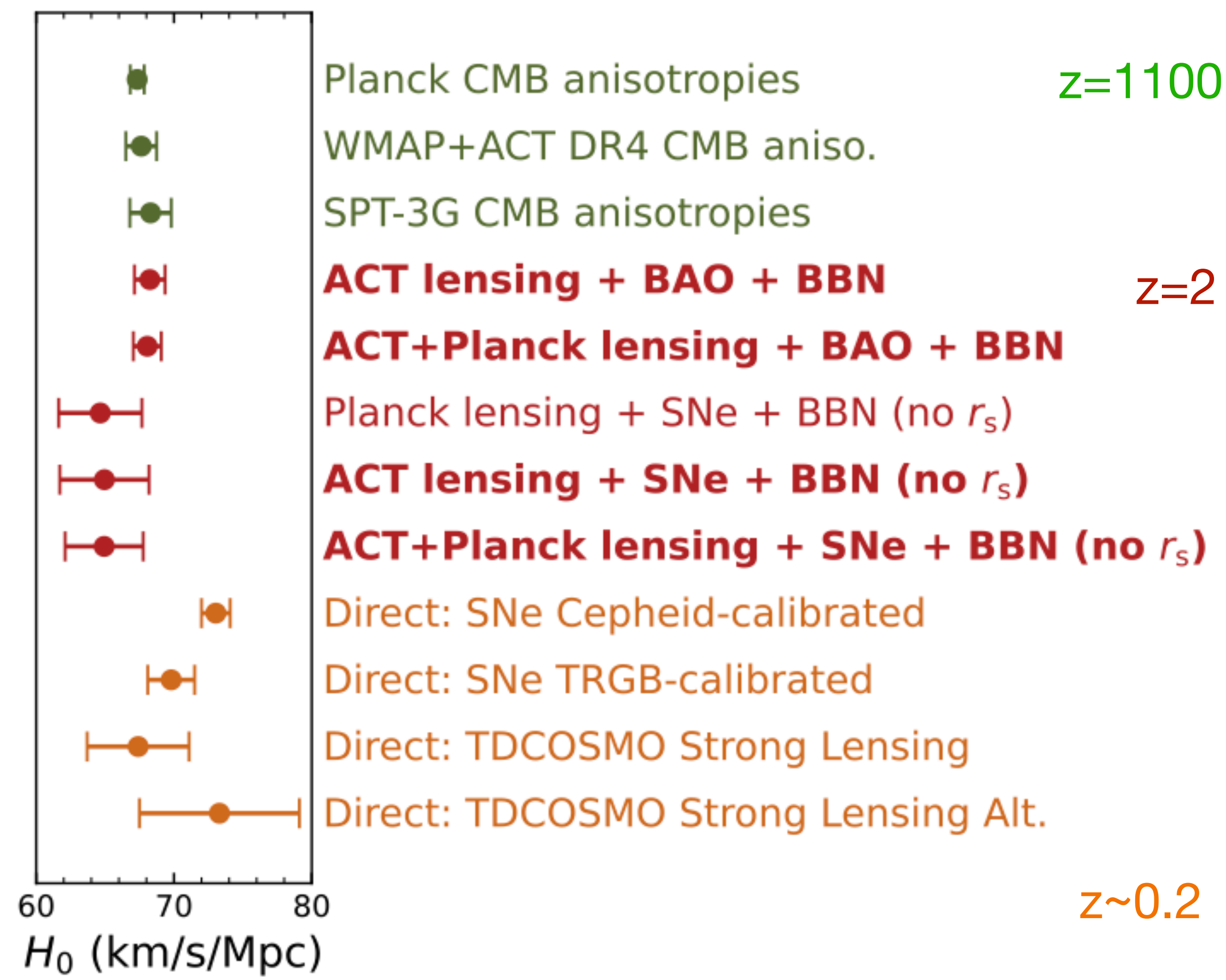

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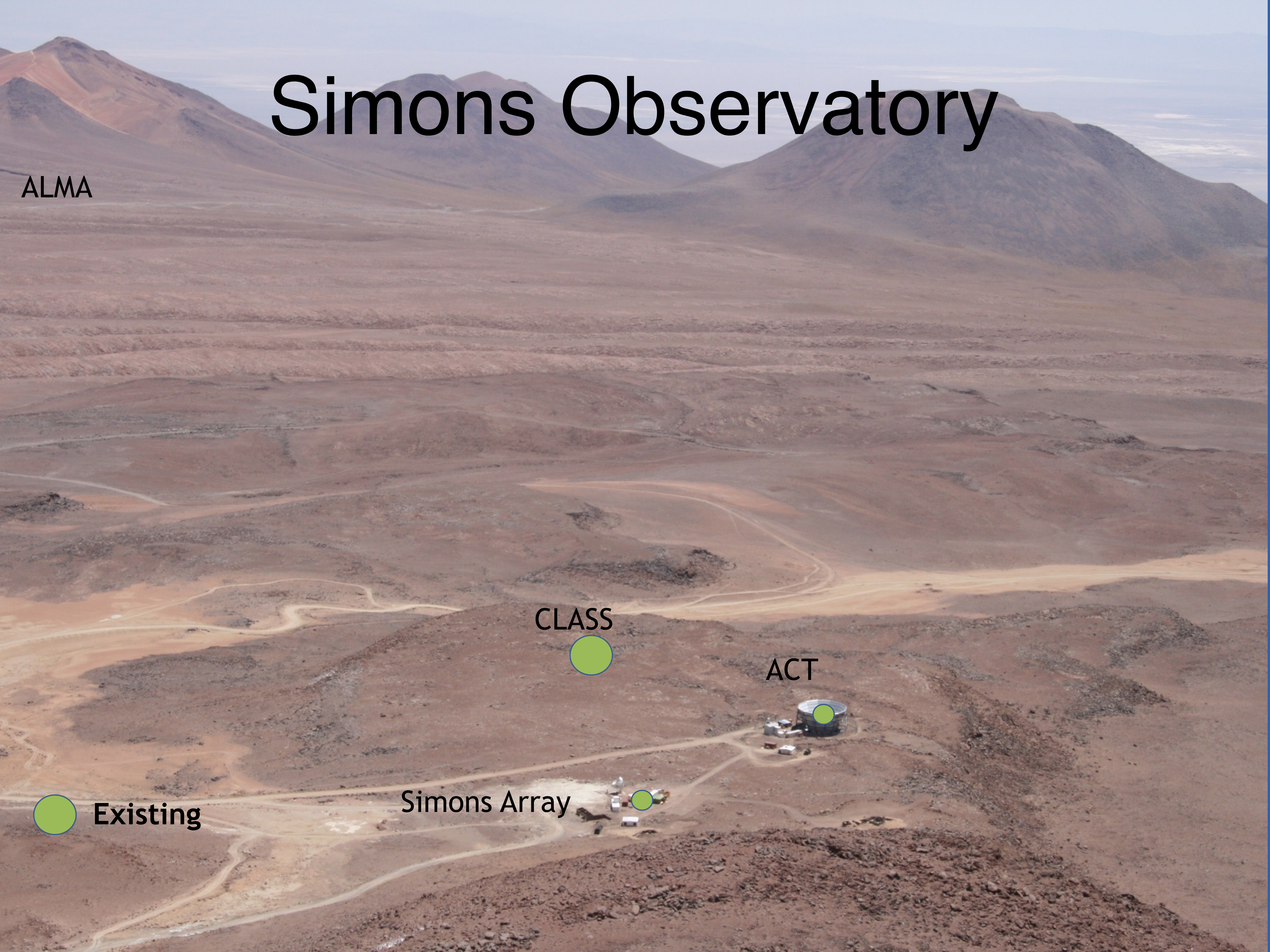
Simons Observatory



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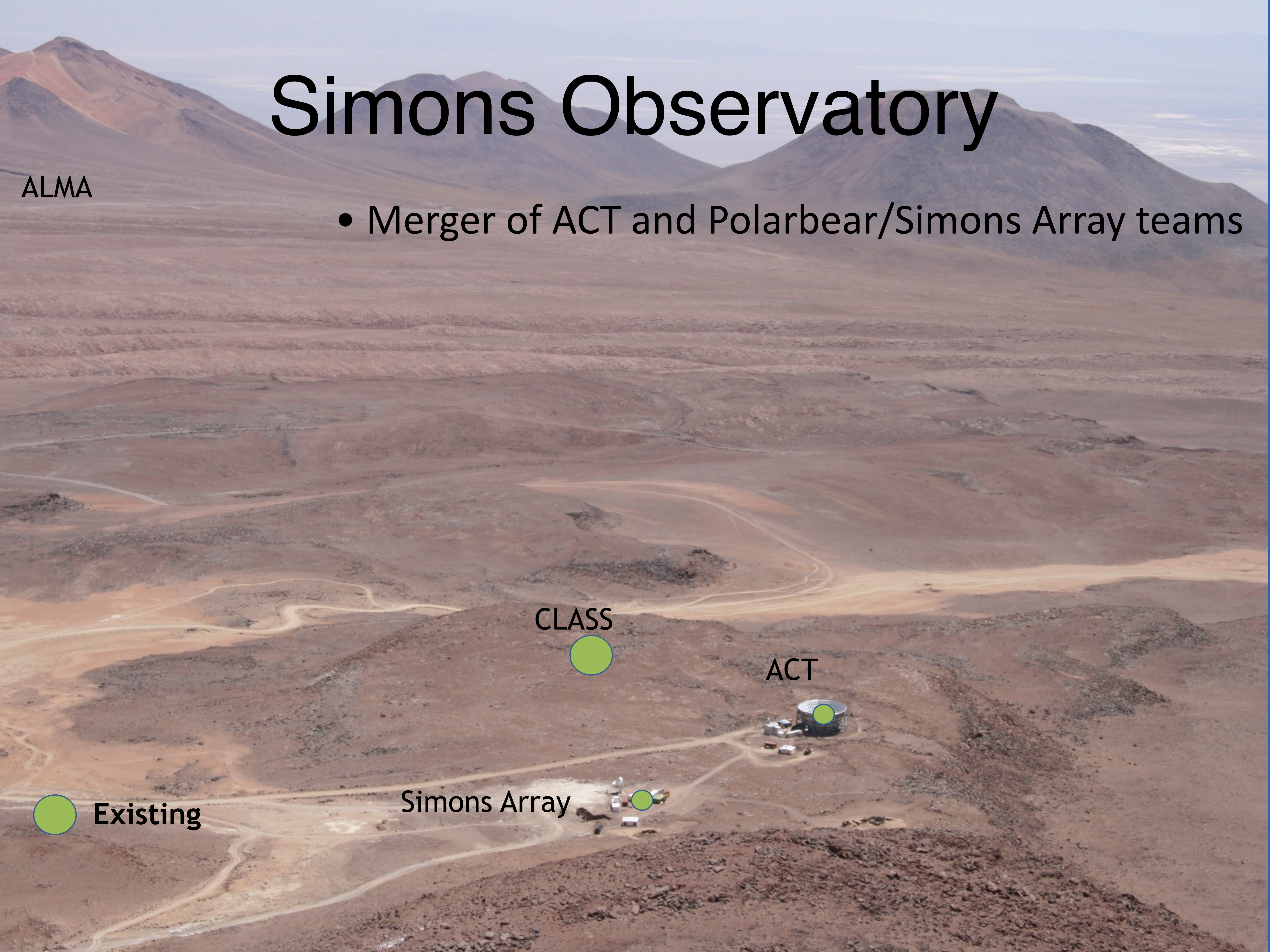

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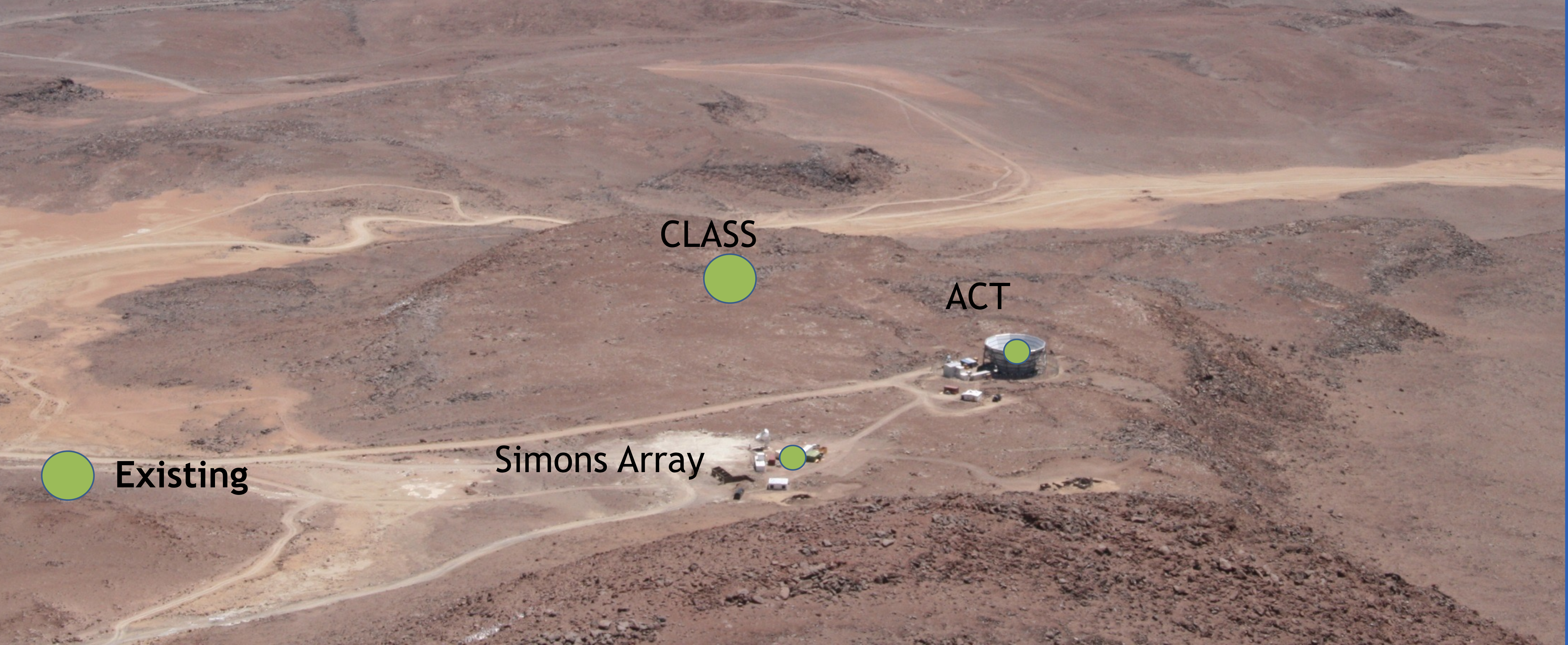

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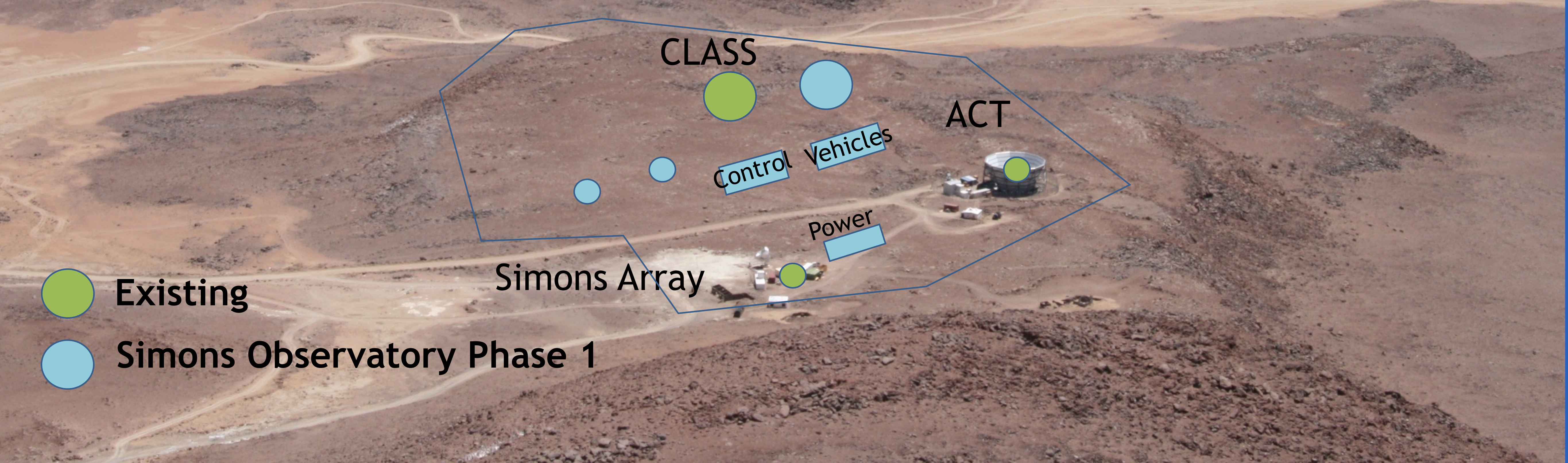

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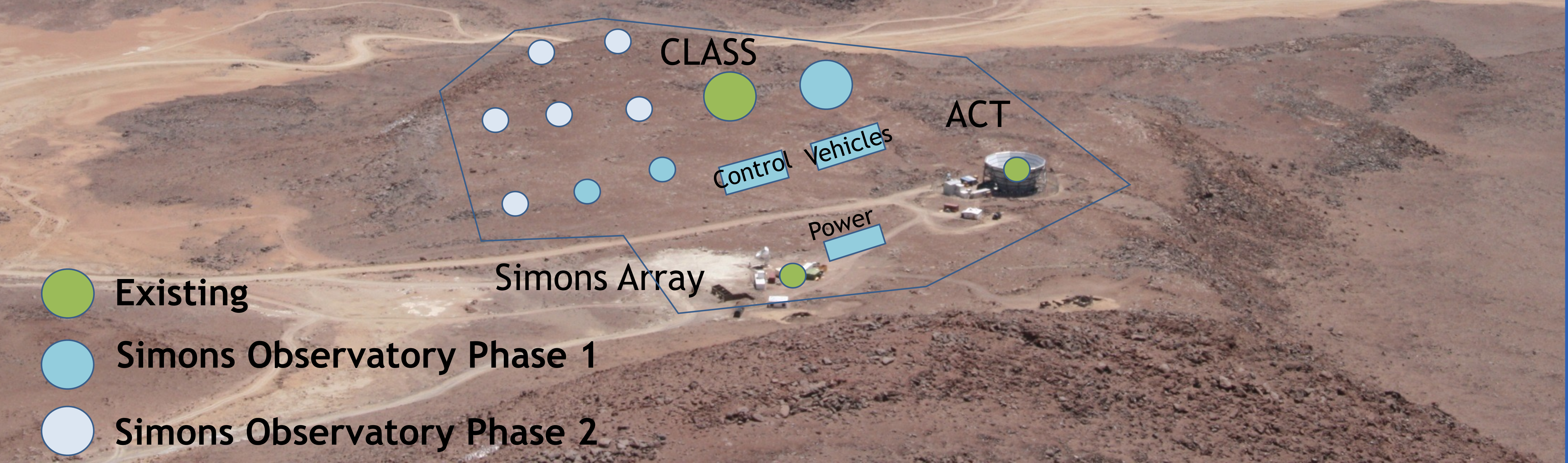

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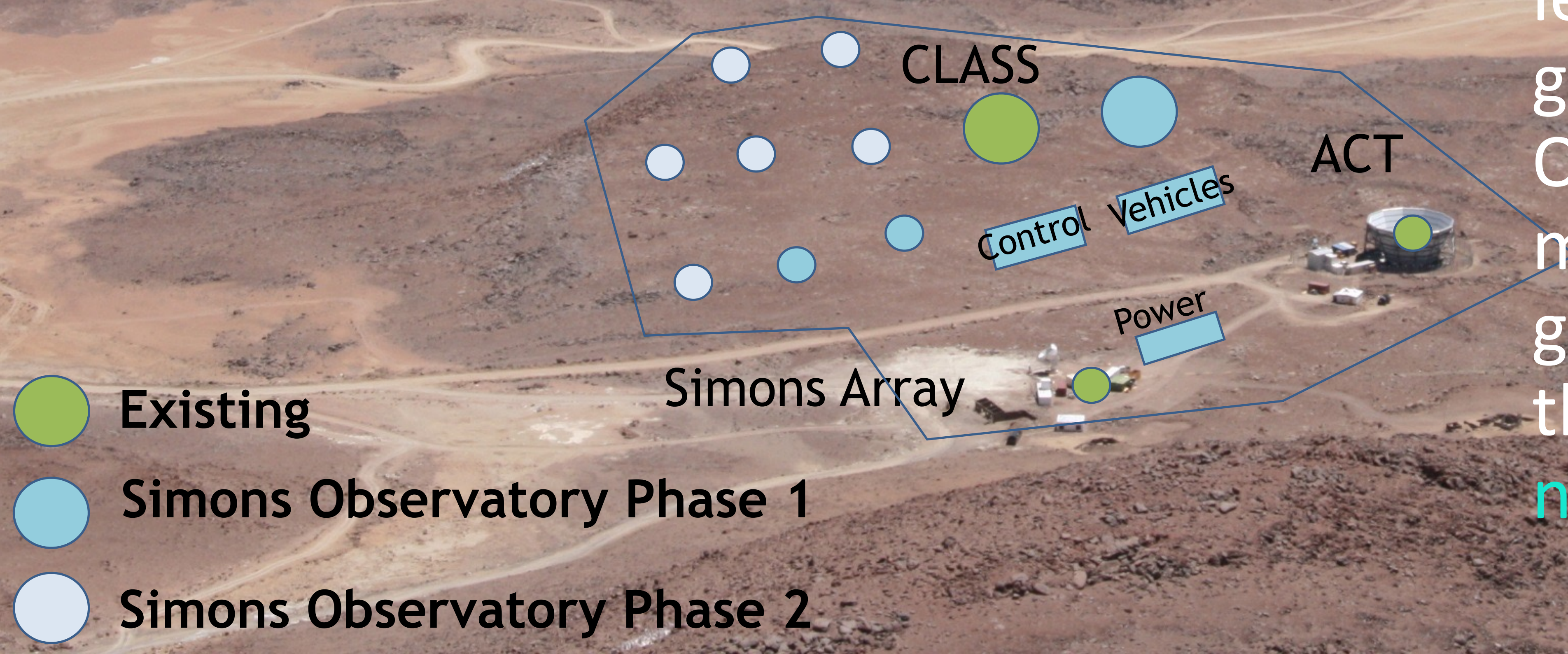
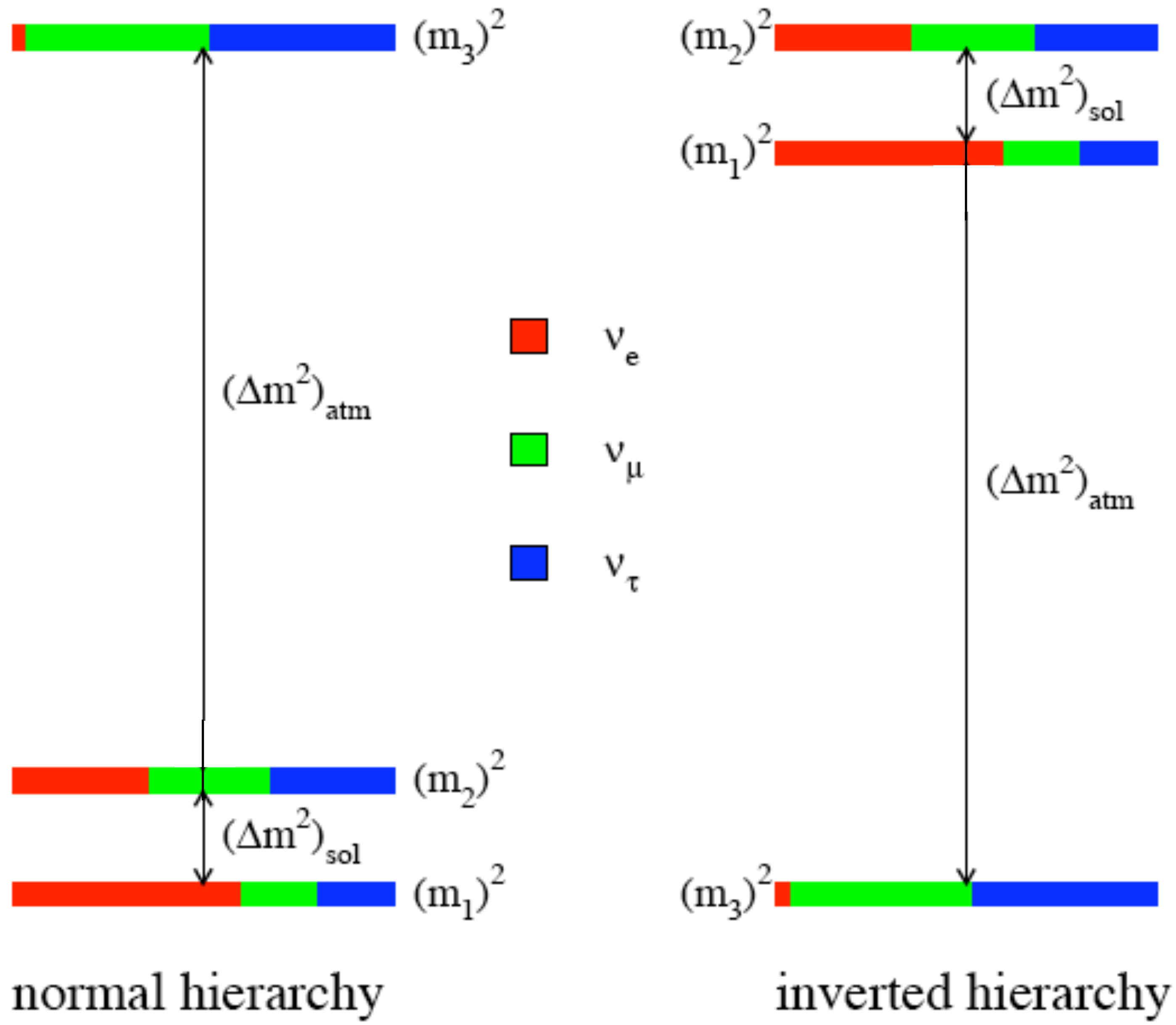


- I co-lead the CMB lensing working group for the Simons Observatory - the main science of this group is to measure the mass of the neutrinos

Neutrinos Have Mass



Intensity Frontier Report (1205.2671)

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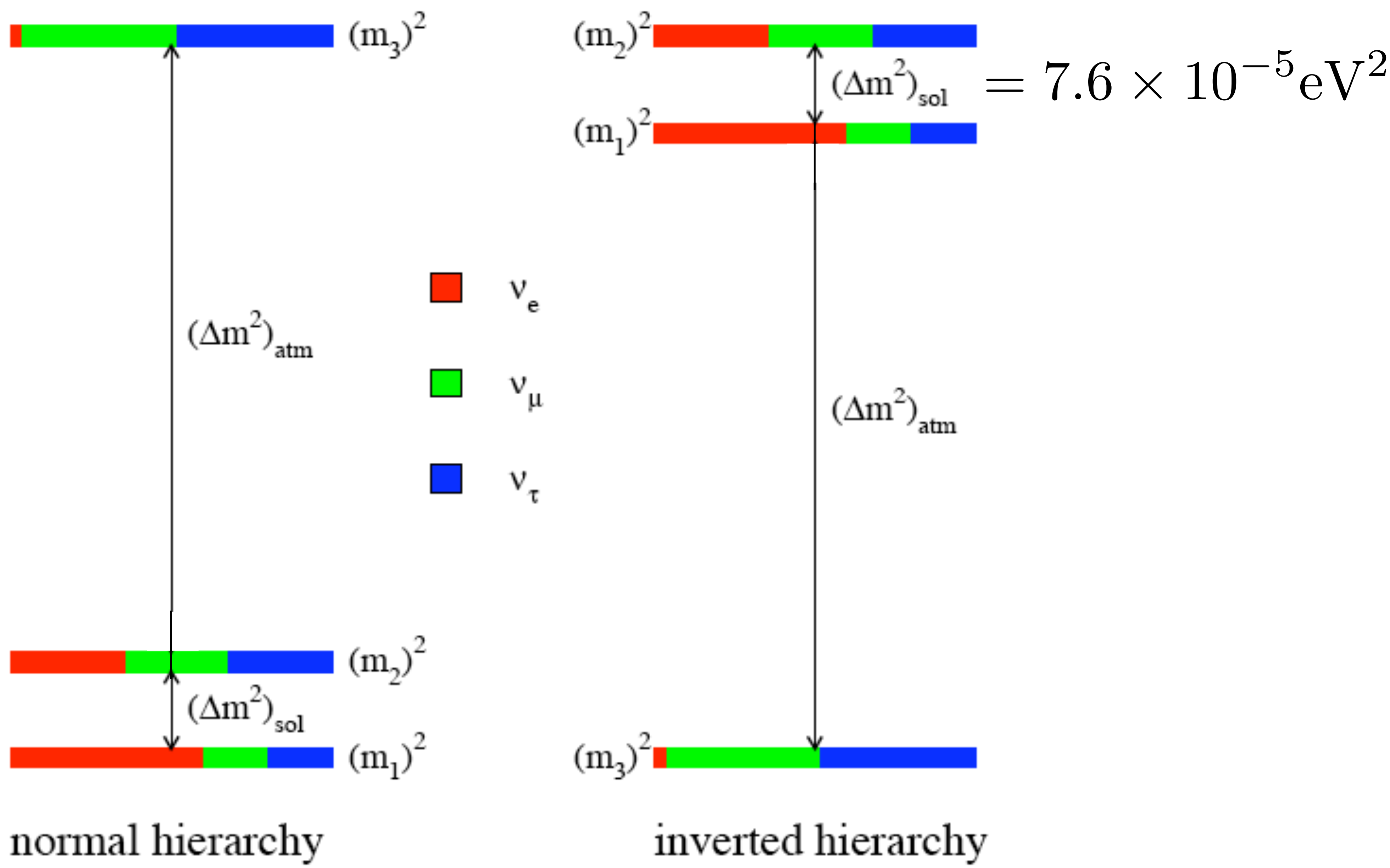

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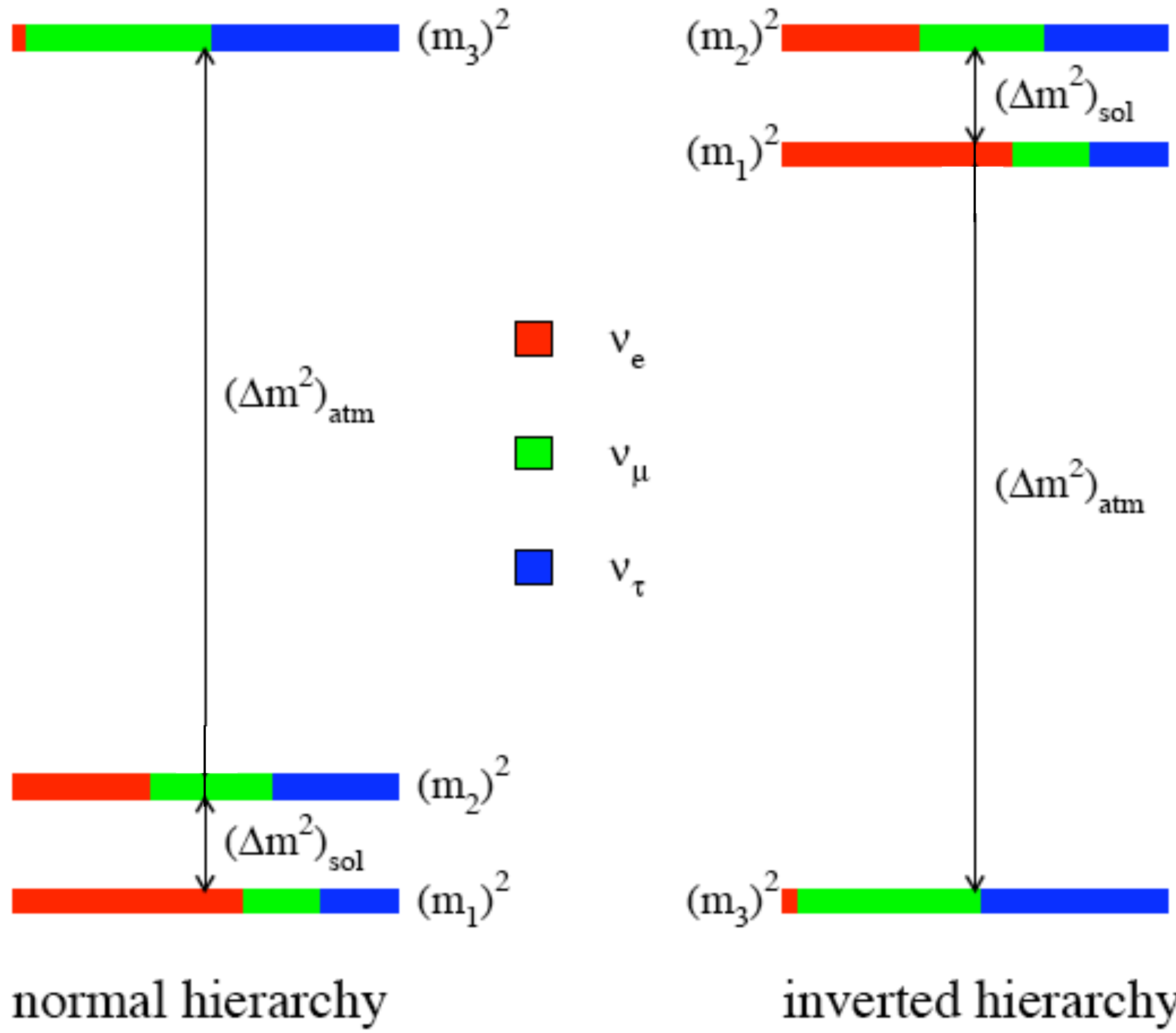

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Intensity Frontier Report (1205.2671)

Neelima Sehgal, Stony Brook

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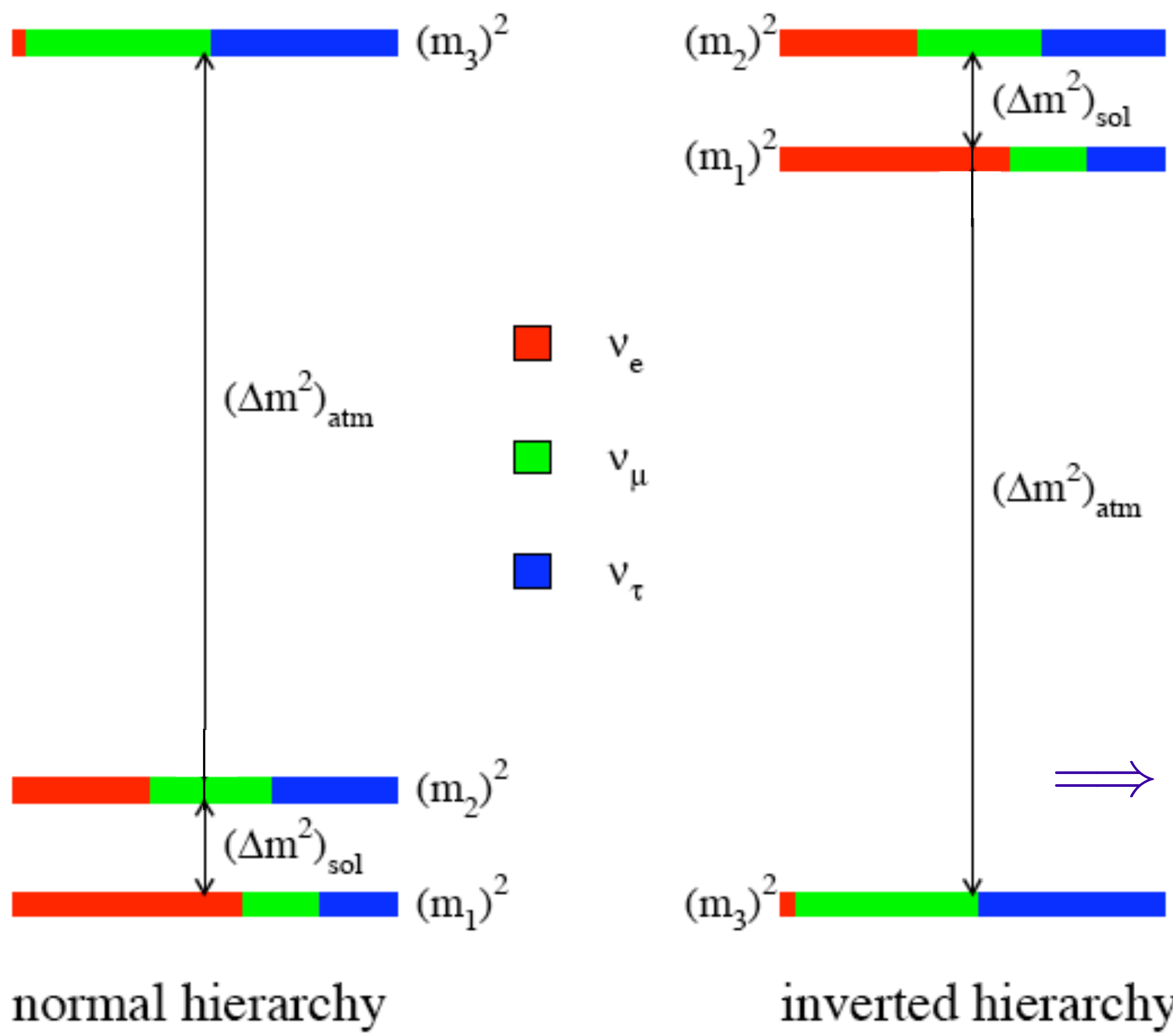

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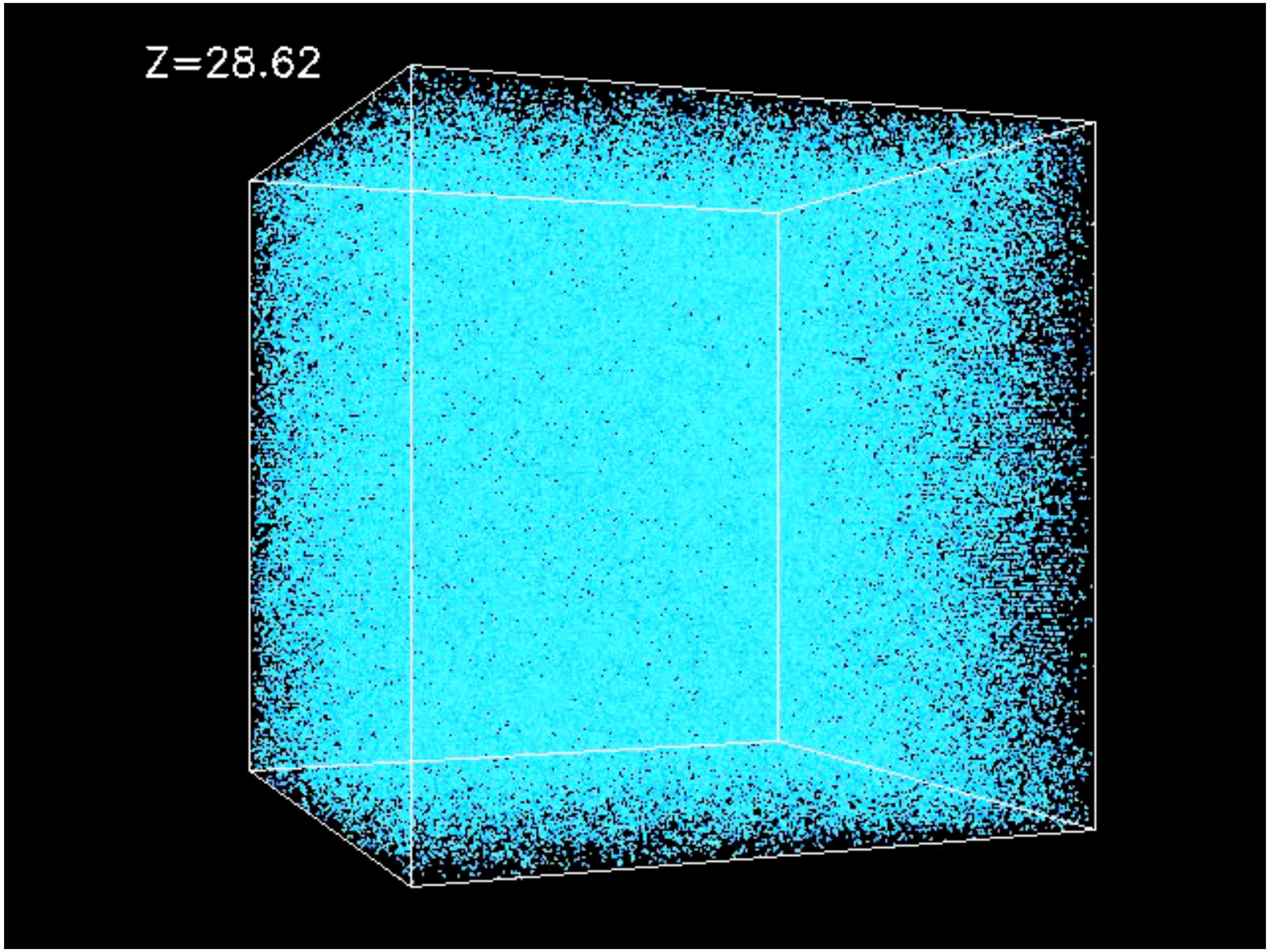
$$\Longrightarrow \sum_{\nu} m_\nu \geq 60 \text{ meV}$$

Intensity Frontier Report (1205.2671)

Neelima Sehgal, Stony Brook

Growth of Structure



Credit: Andrey Kravtsov

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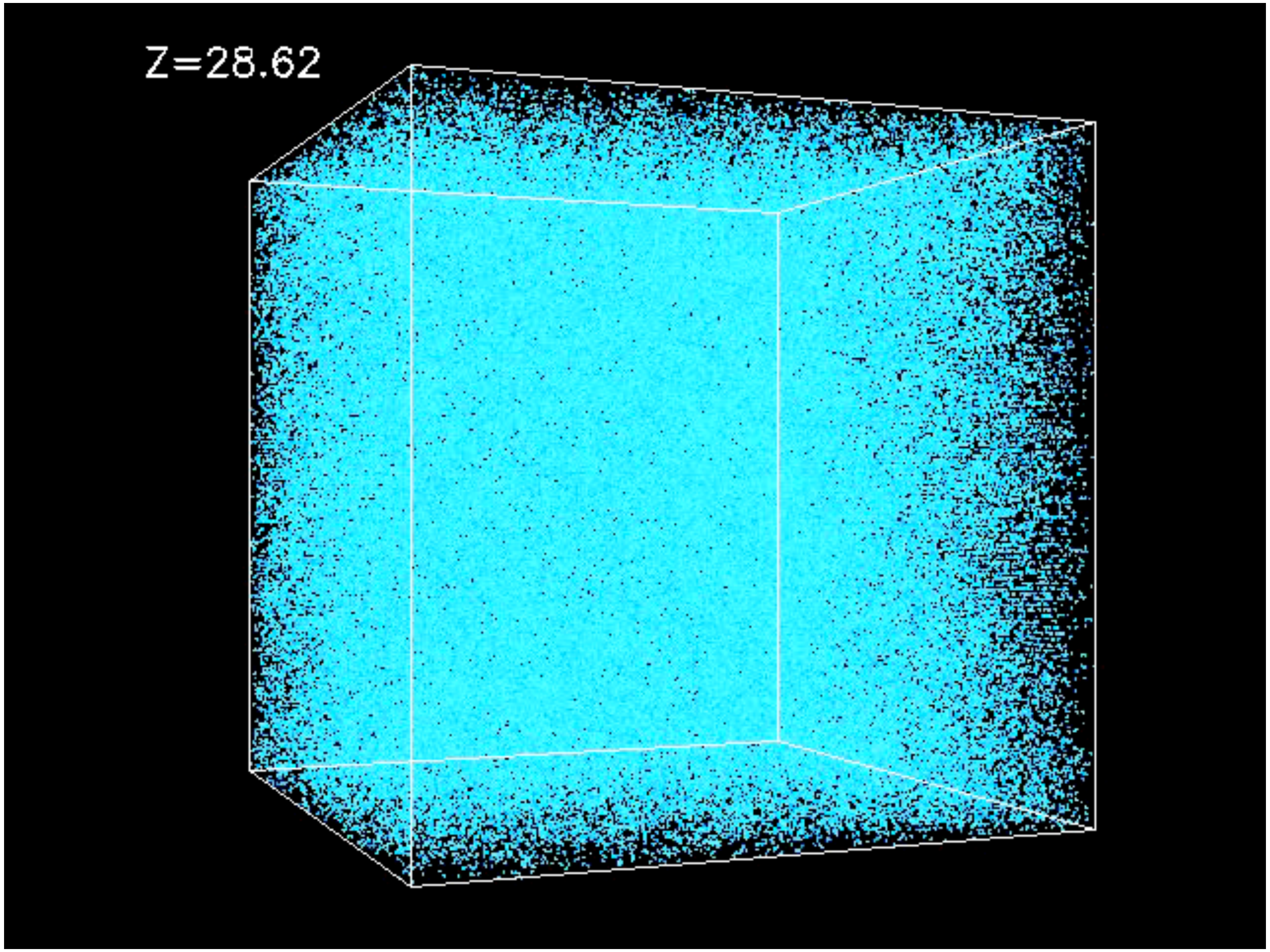

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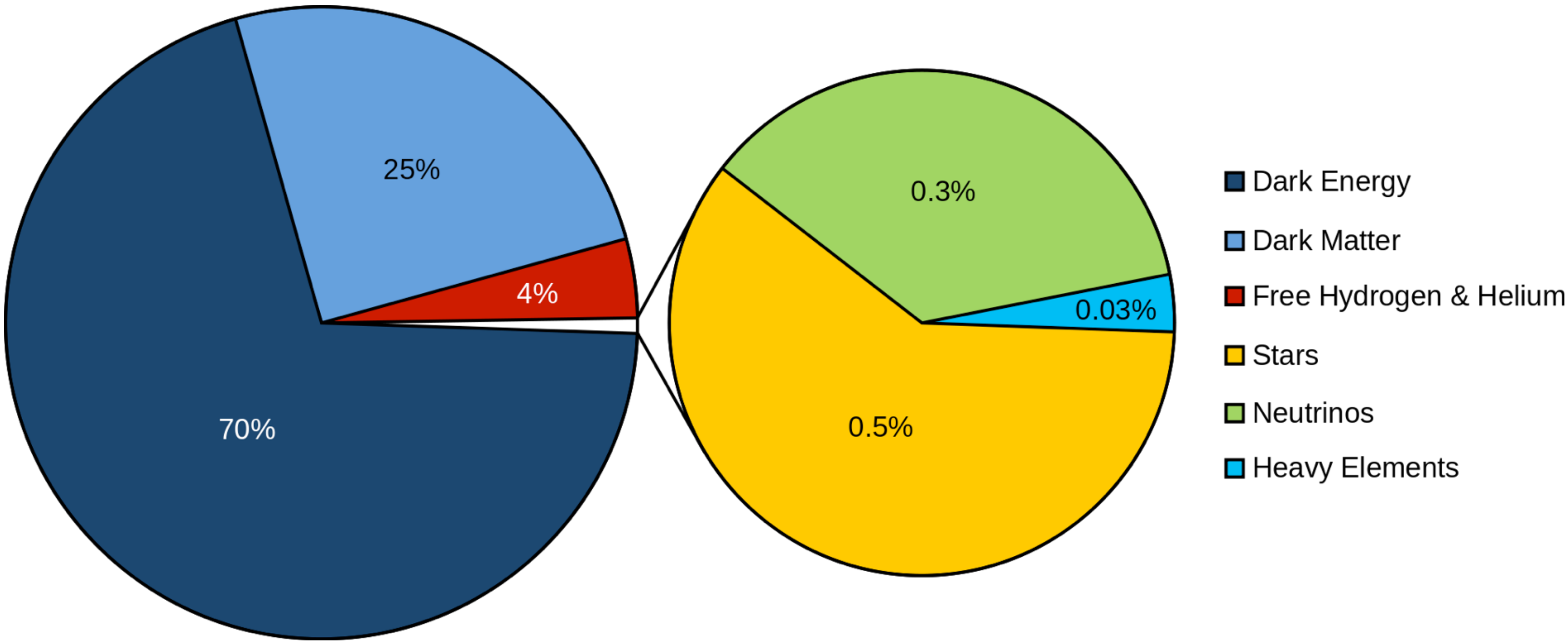
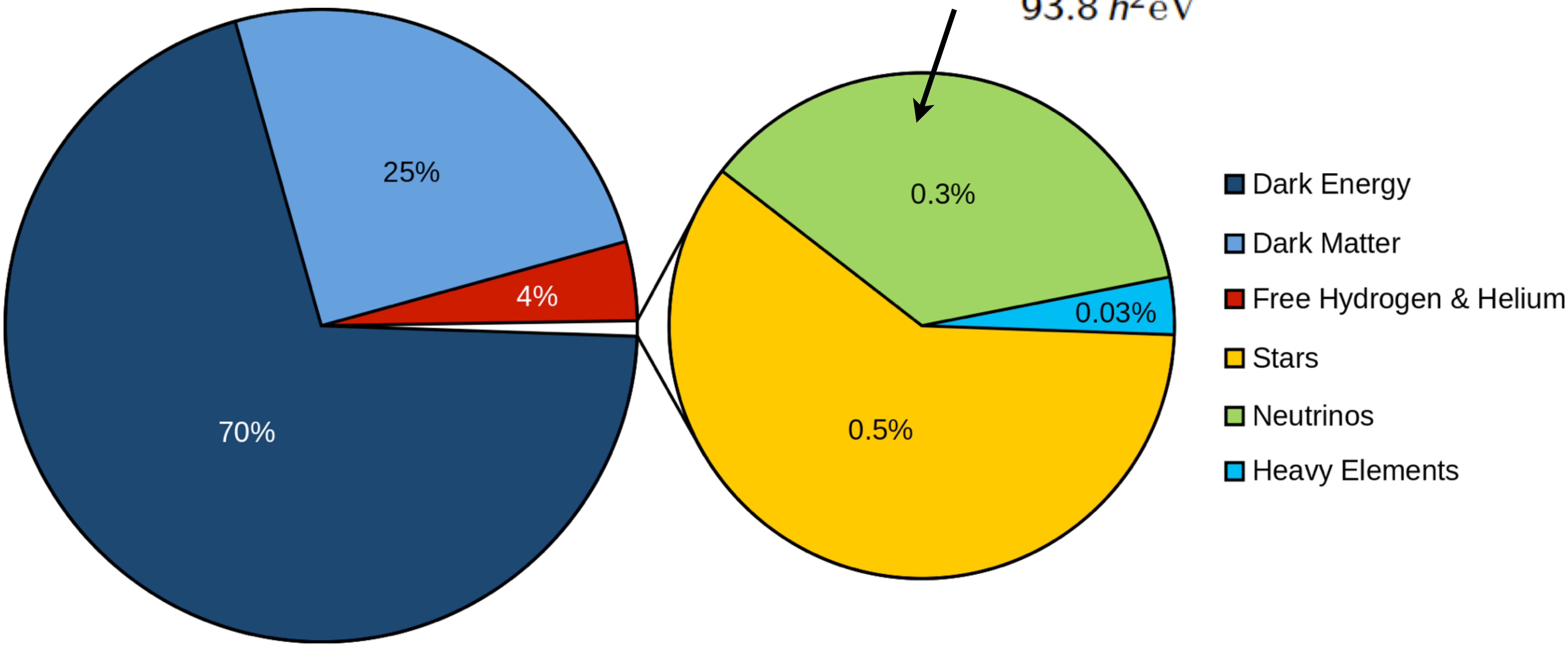
Energy Density in the Universe



Neelima Sehgal, Stony Brook

Energy Density in the Universe

$$\Omega_{0\nu} = \frac{\sum m_\nu}{93.8\, h^2 \mathrm{eV}}$$



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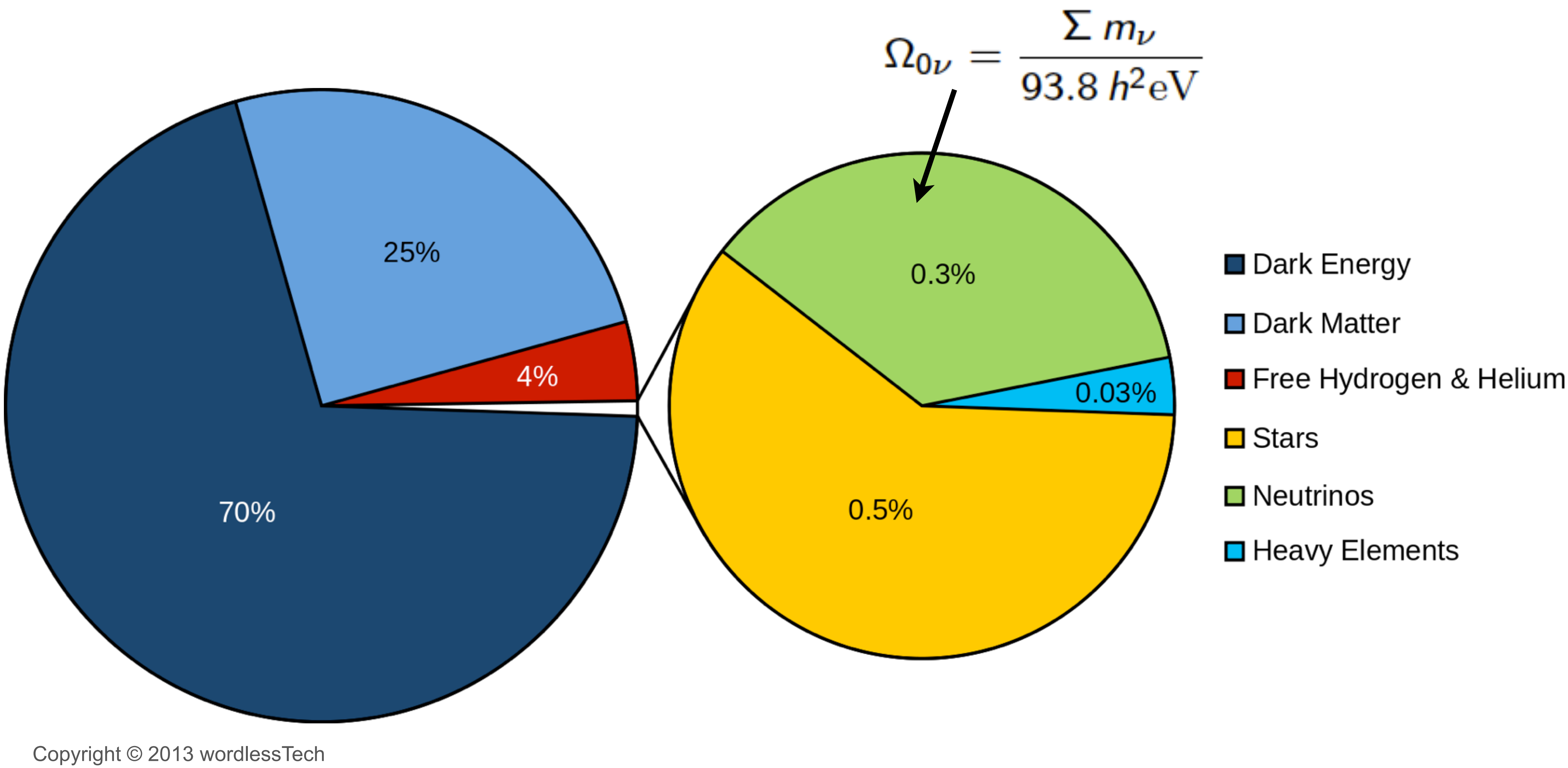


Larger neutrino mass ➡ less cold dark matter
➡ less dark matter structure

Neelima Sehgal, Stony Brook

CMB Lensing Power Spectrum Sensitive to Neutrino Mass

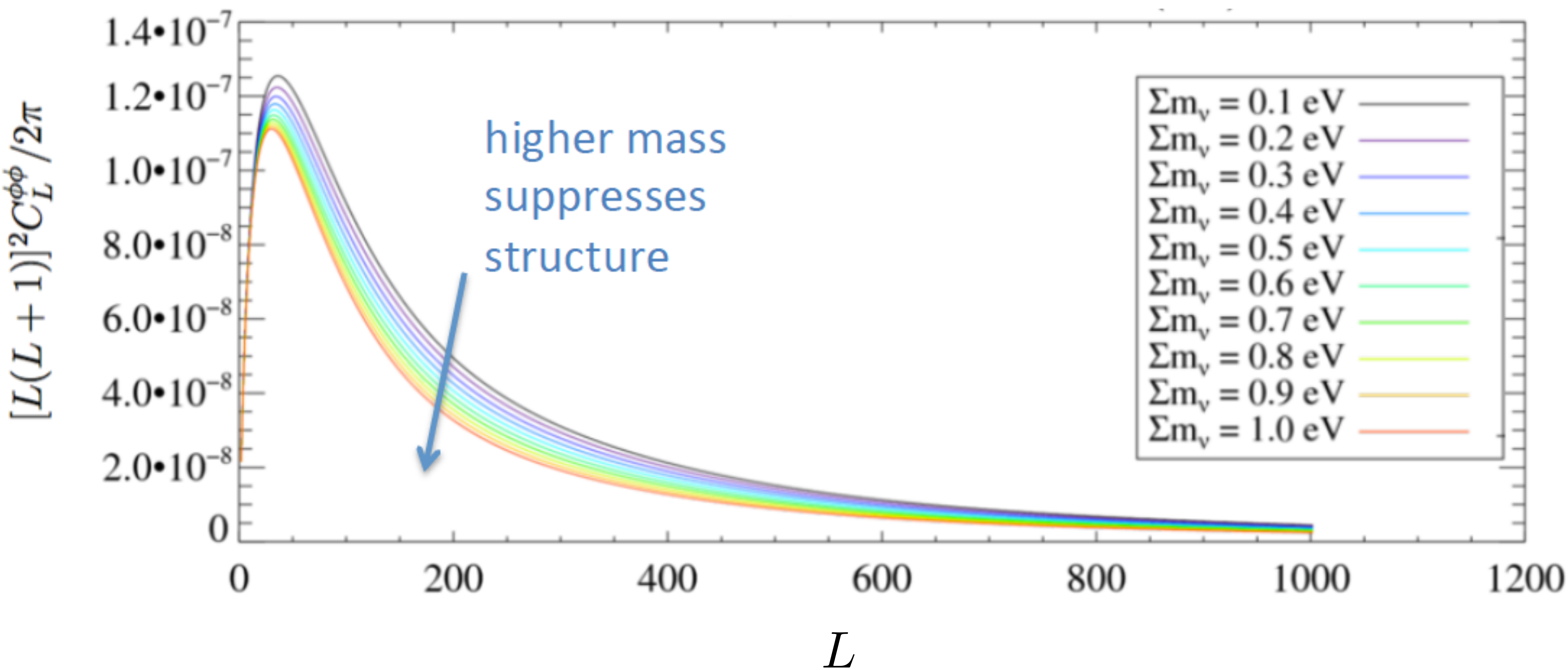
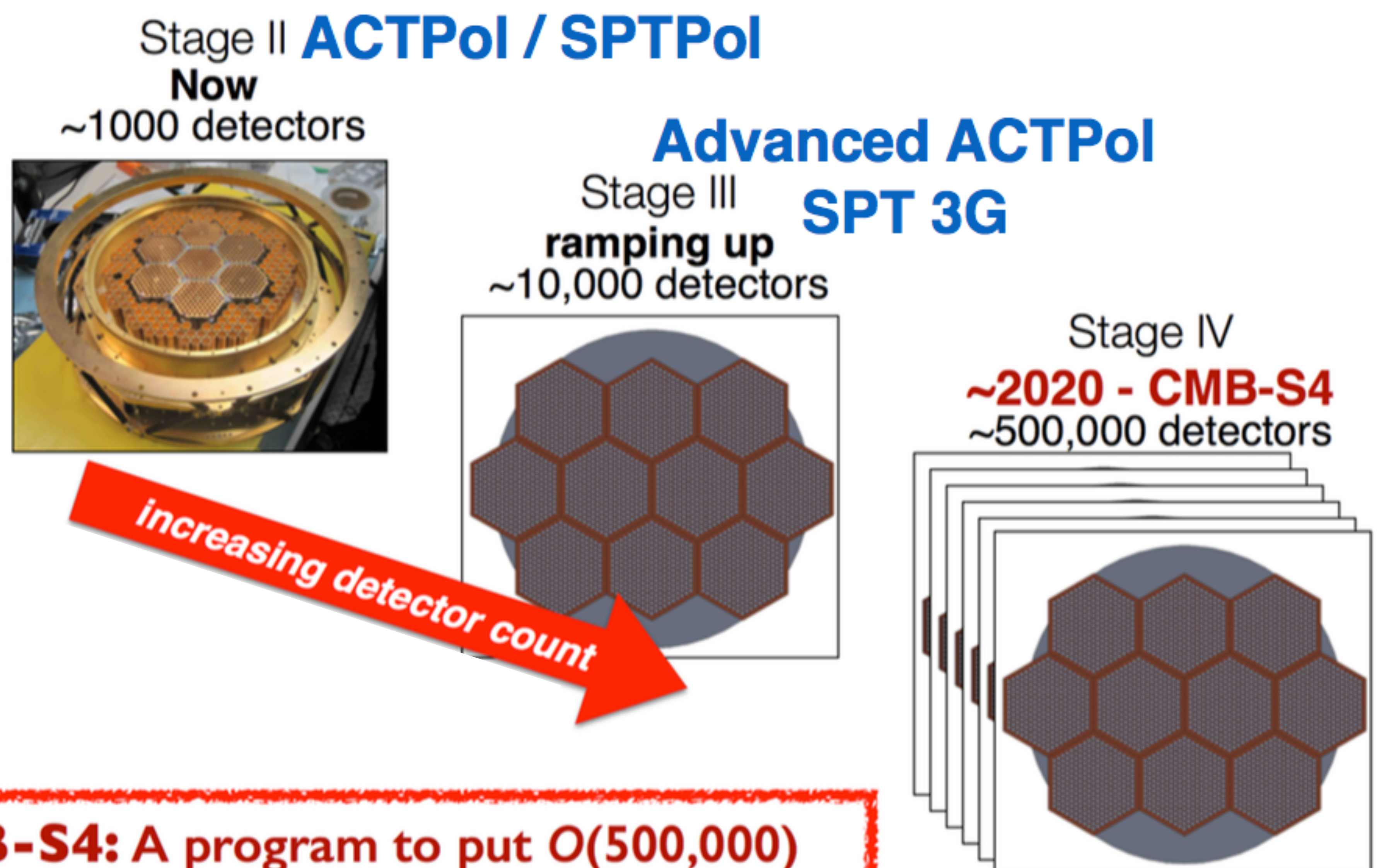


Figure credit: Alexander van Engelen

Near Future of CMB: CMB-S4

Maintaining Moore's Law: focal planes are saturated so must use parallel processing and multiple telescopes.



CMB-S4: A program to put *O*(500,000) detectors spanning 30 - 300 GHz using multiple telescopes and sites to map ≳70% of sky.

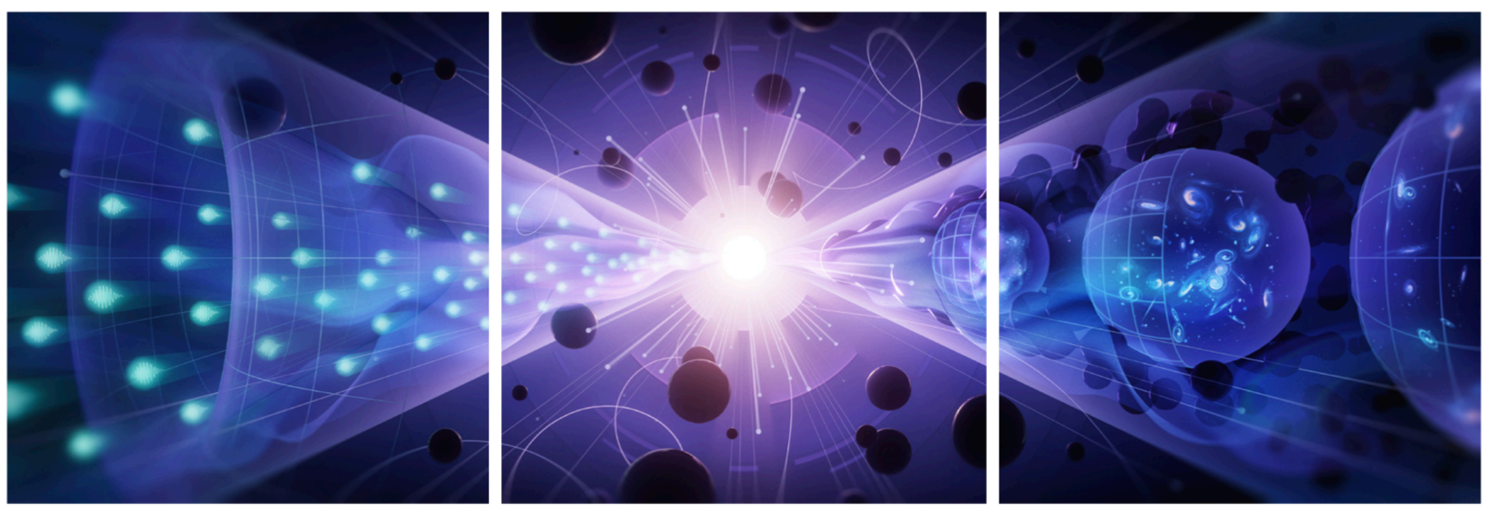
Slide credit: Jeff McMahon

P5 Report - U.S. Particle Physics Roadmap

Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

DRAFT Report of the 2023 Particle Physics Project Prioritization Panel



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

CMB is the highest P5 priority

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

These projects have the potential to transcend and transform our current paradigms. They inspire collaboration and international cooperation in advancing the frontiers of human knowledge. Plan and start the following major initiatives in order of priority from highest to lowest:

a. CMB-S4, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals (section 4.2).

b. Re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

c. An off-shore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics (section 3.2).

d. An ultimate Generation 3 (G3) dark matter direct detection experiment reaching the neutrino fog, in coordination with international partners and preferably sited in the

Timeline

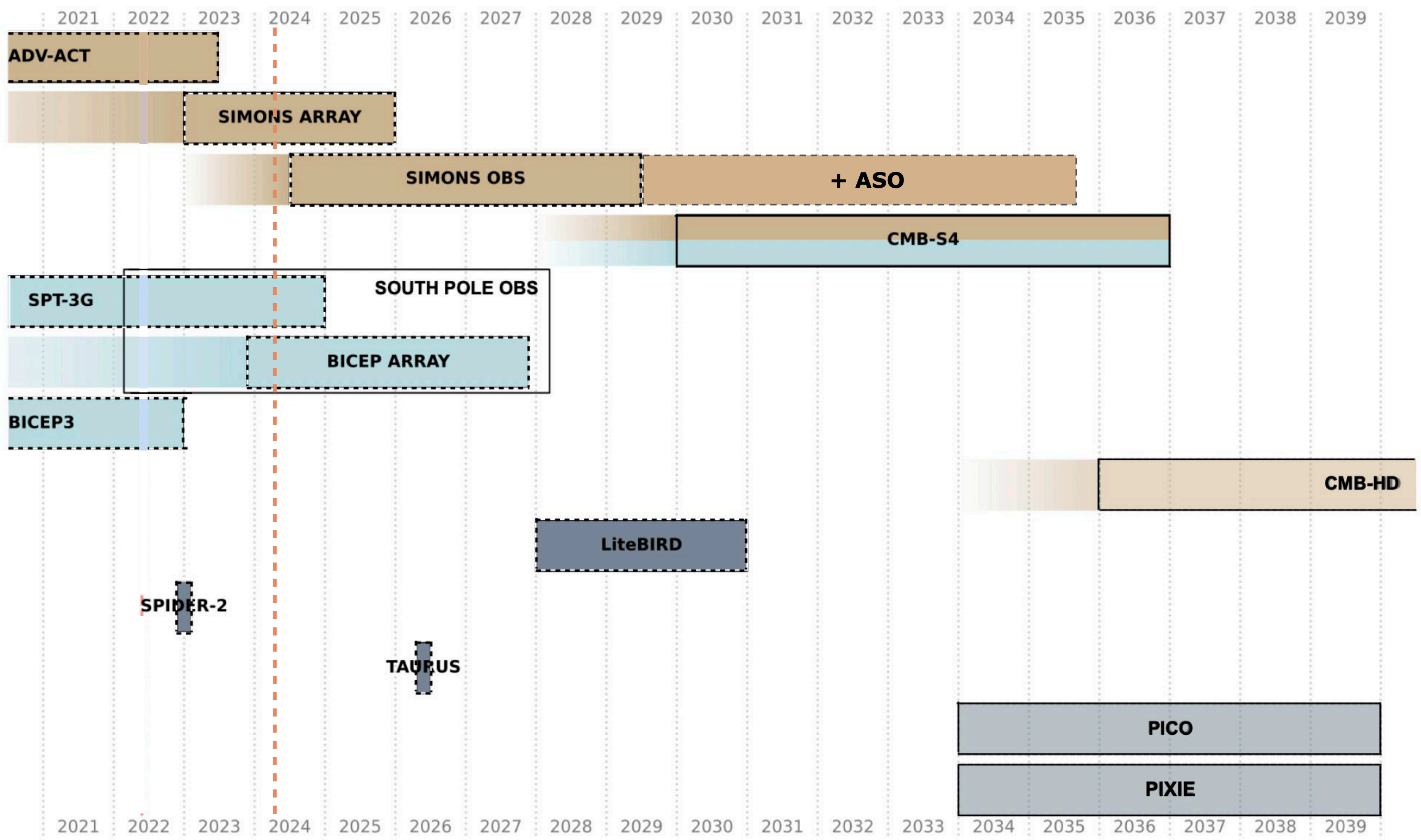


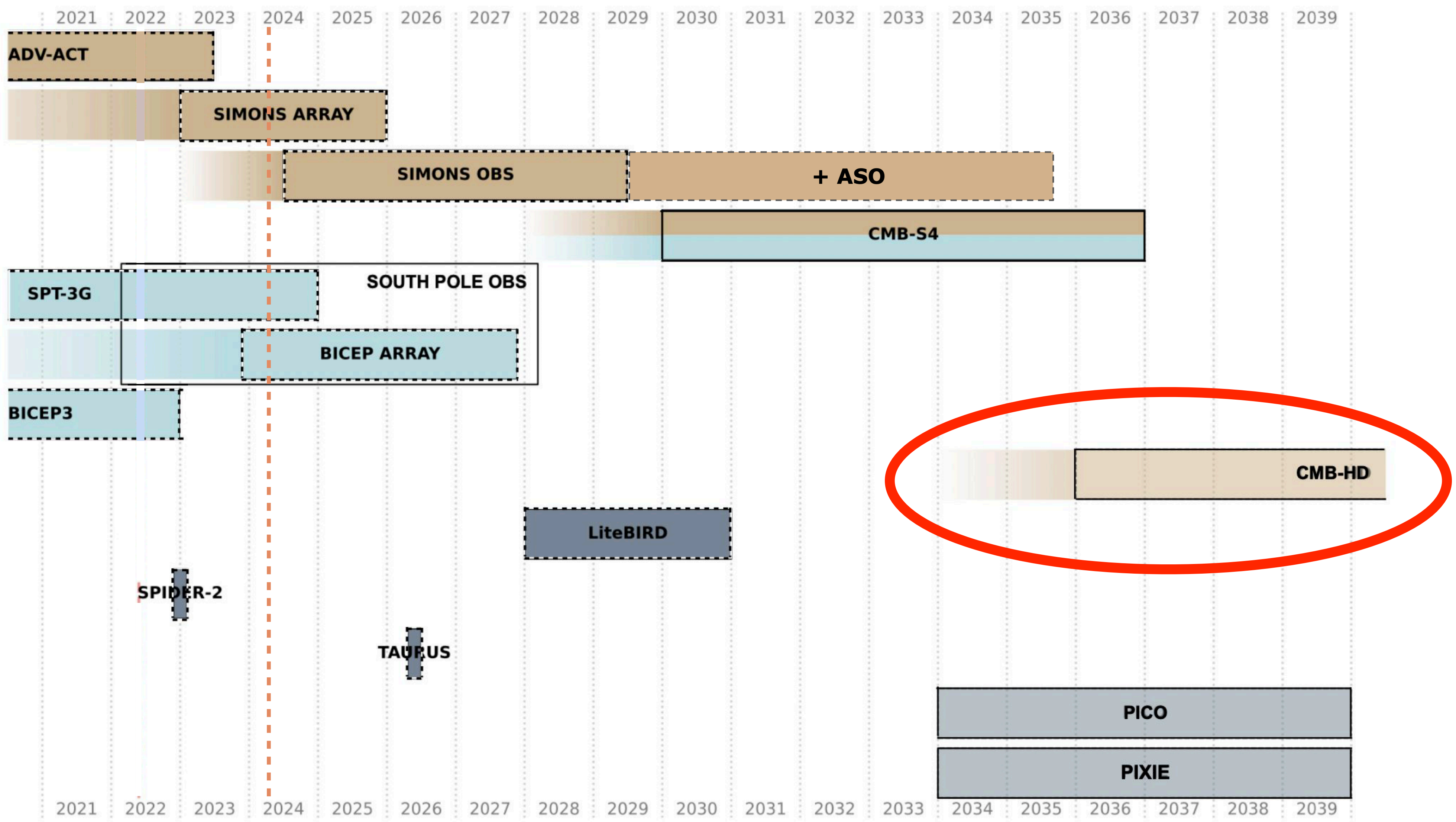
Figure 6-5. *Timeline of current and future ground-based CMB experiments. For context, the timeline also includes a few sub-orbital and satellite experiments in grey. Dashed boxes indicate fully-funded facilities. The fade-in regions indicate commissioning periods, while the boxes indicate full survey observations.*

Snowmass2021 CF6 Summary Report: 2209.08654

Neelima Sehgal, Stony Brook

Timeline

16 Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities



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P5 20-Year Vision for Cosmology

4.2.7 – 20-Year Vision

We are entering an exciting era in our study of cosmic evolution. The projects recommended by the last P5 report that are beginning operations, the project portfolio recommended by this P5 report, and the future projects for which R&D and project definition will occur in this decade, will allow for great progress in our knowledge of the entirety of our cosmic

history, from the inflationary era, through the radiation and then matter dominated eras, to the dark energy era. Together with strong theory and computational support, that progress lays the foundation for the next generation of projects.

To support the success of this portfolio of cosmic surveys at a range of wavelengths, continued work and advocacy will be important to prevent or mitigate the effects of human-produced nuisances, including light pollution, satellite constellations in low-earth orbit, and radio-frequency interference.

The knowledge gained from CMB-S4 and eventually from Spec-S5 will enlighten us about the nature of inflation at the earliest cosmic times, both in terms of the energy scale and the inflationary dynamics. We recommend pathfinding works in the next decade, specifically LIM R&D and research, that will allow us to follow up any detected primordial signal from the inflationary era. Moving forward in cosmic time to the radiation and matter eras, we will have a window to new relics during the quark-hadron transition, and lay the groundwork for future projects that can push down to the electroweak scale.

In the event of a discovery beyond the standard cosmological paradigm, LIM and high-resolution CMB experiments could be formulated to confirm and characterize the discovery. Future gravitational wave experiments could provide complementary means to probe the expansion history deeper in the matter era. And finally at late times, our recommended portfolio sets us up with multiple complementary means to rigorously test the cosmological constant hypothesis and discover the time evolution of dark energy.

The flexibility of Spec-S5 to address multiple scientific goals (inflation, late-time cosmic acceleration, dark matter) depending on the priorities that emerge from DESI, early DESI-II, and Rubin Observatory LSST results makes it a crucial part of this 20-year vision. Similarly, future survey concepts for Rubin Observatory, to be developed later this decade after early LSST science results are available, could address key questions that come to the forefront of particle physics studies of cosmic evolution in five to ten years.

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CMB-HD is the only high-resolution CMB concept that currently exists

Outline

- Cosmic Microwave Background
- CMB Experiments
- CMB-HD

CMB-HD Concept

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PI: Neelima Sehgal

Two new 30-meter mm-wave telescopes in Atacama Desert
with total sensitivity 3 times deeper than CMB-S4 wide survey == CMB-HD

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MKIDS are easier to fabricate, readout, and multiplex than traditional TES bolometers

Motivation of CMB-HD

Rich Science from CMB-HD:

Dark Matter/ Light Relics
- Dark Matter Properties from Small-Scale Matter Power Spectrum
- Number of Relativistic Species

Inflation
- Delensing for Primordial Gravitational Waves
- Primordial Non-Gausianity
- Inflationary Magnetic Fields

- Neutrino Mass
- Dark Energy

Galaxy Evolution
- Galaxy Cluster Astrophysics
- Galaxy Formation

- Reionization

Planets
- Solar and Extrasolar Planetary Studies

- Synergy with Optical Lensing Surveys

Transients
- Mapping the Transient Sky

- Novel Ideas and Searches for New Physics

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Science Motivation: Light Relics

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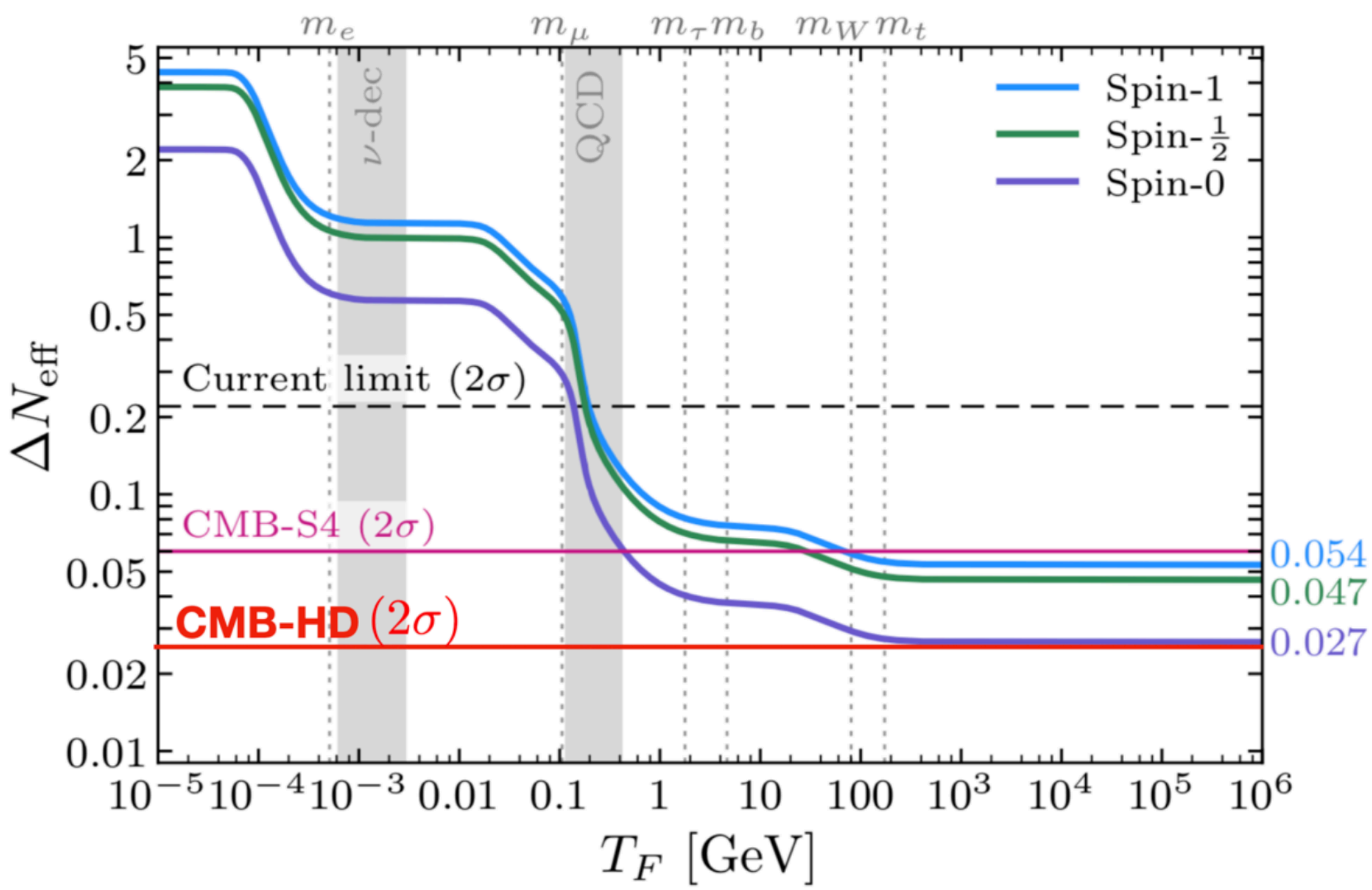
- Key light relic target: $\sigma(N_{\rm eff}) = 0.014$

Snowmass2021 CMB-HD White Paper: 2203.05728



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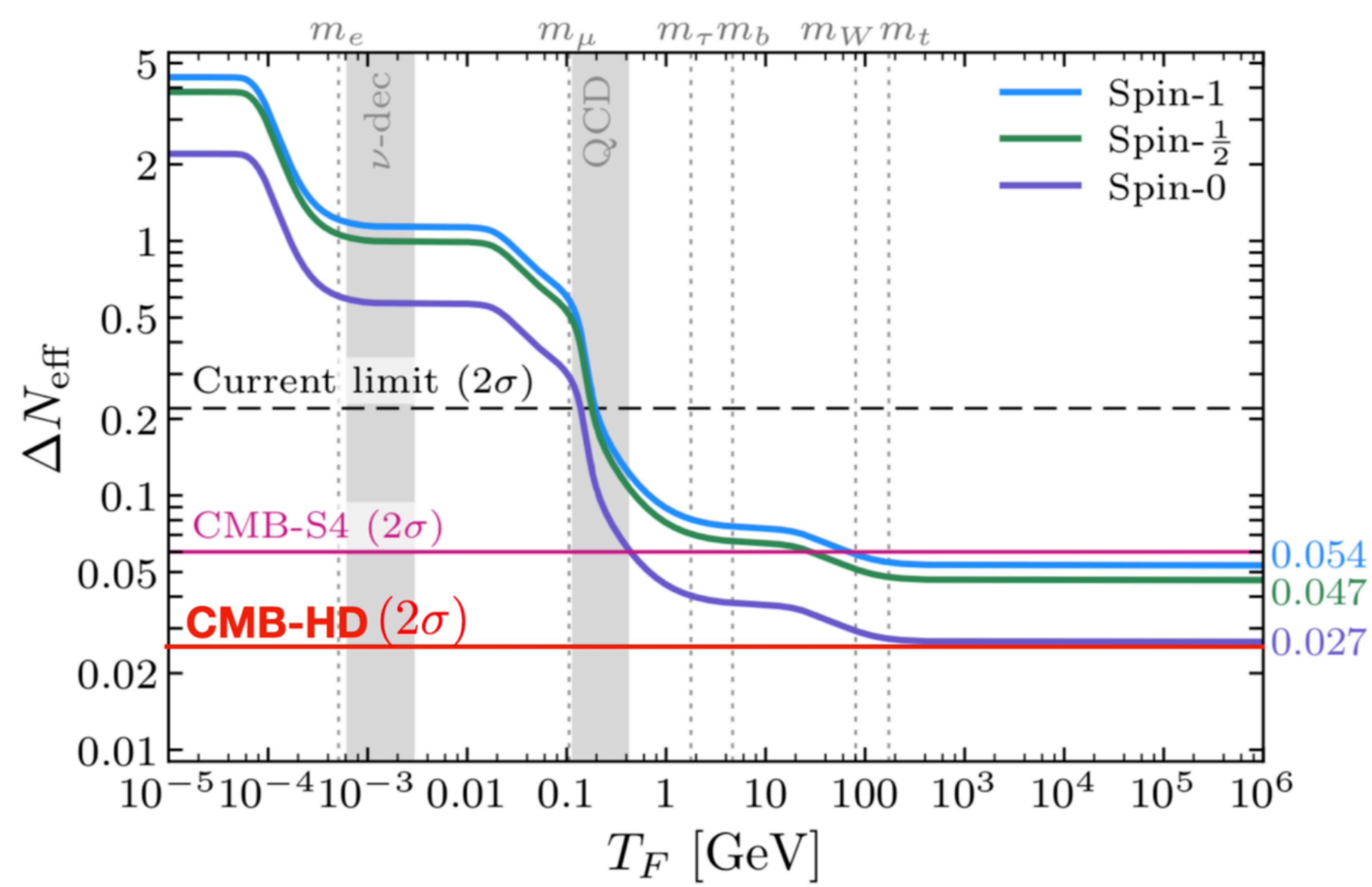

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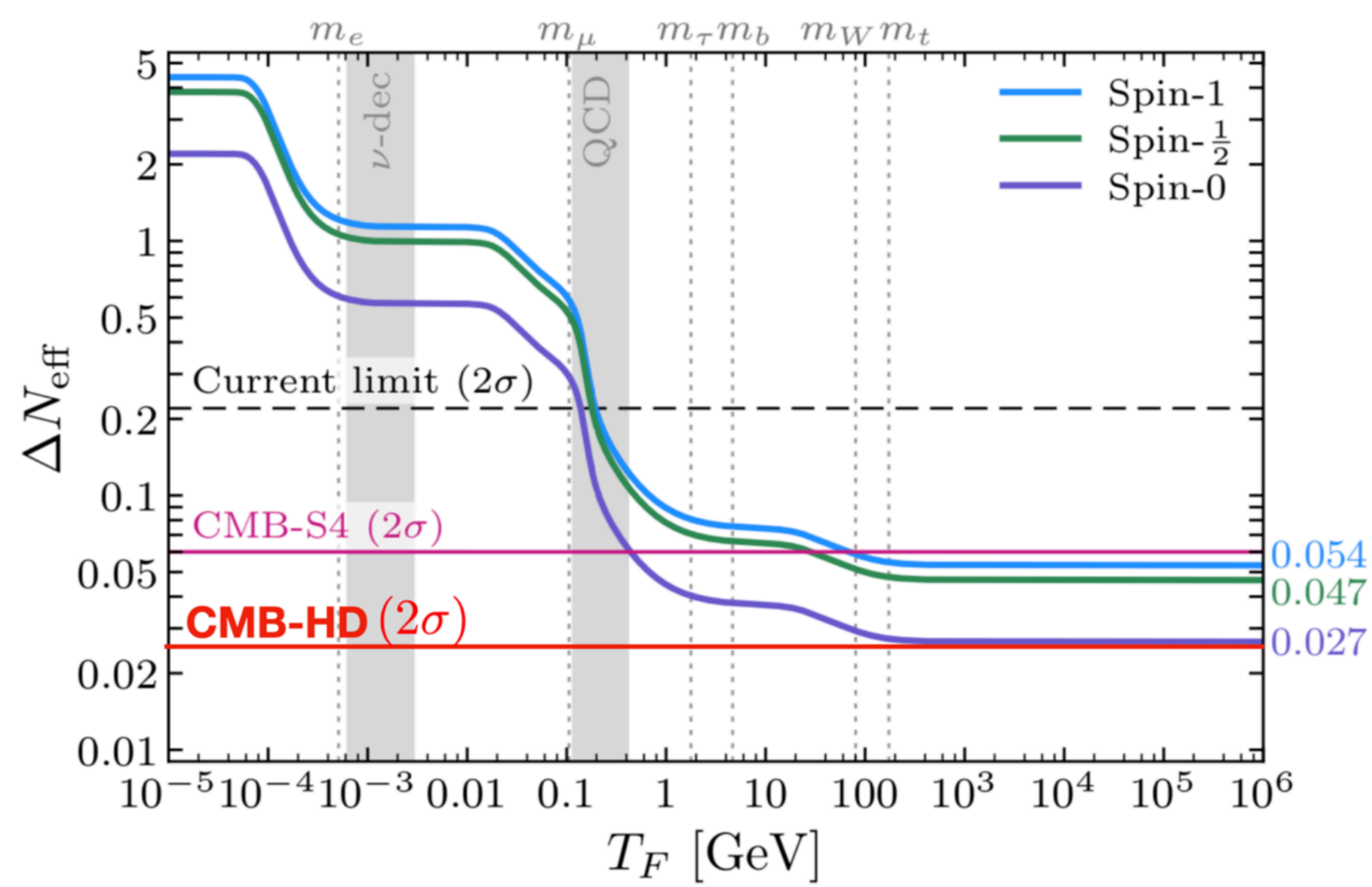

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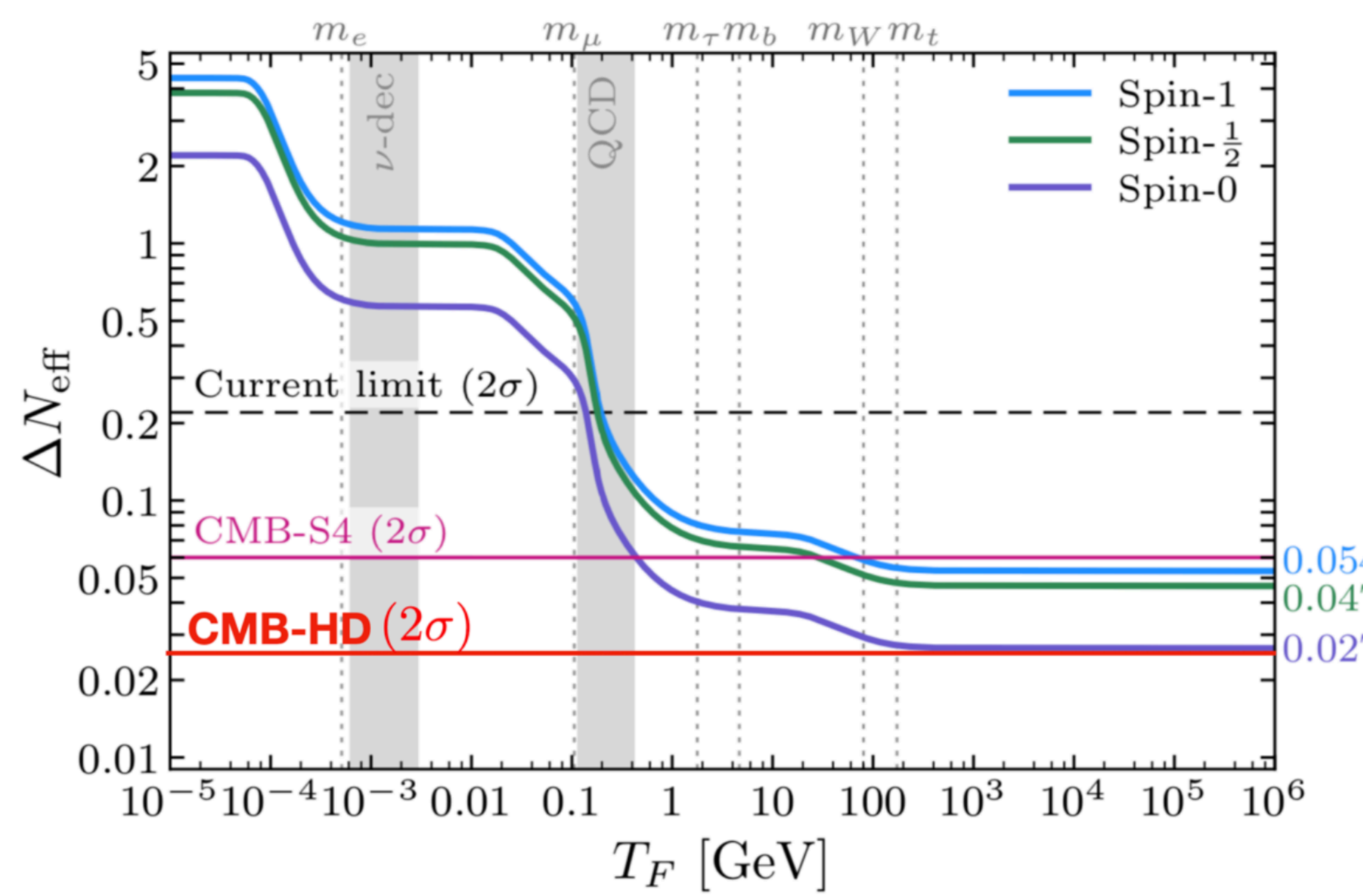

- Combining CMB-HD measurement with 3D large-scale structure probes such as Spec-S5 can yield $\sigma(N_{\rm eff}) \approx 0.01$

Science Motivation: Inflation

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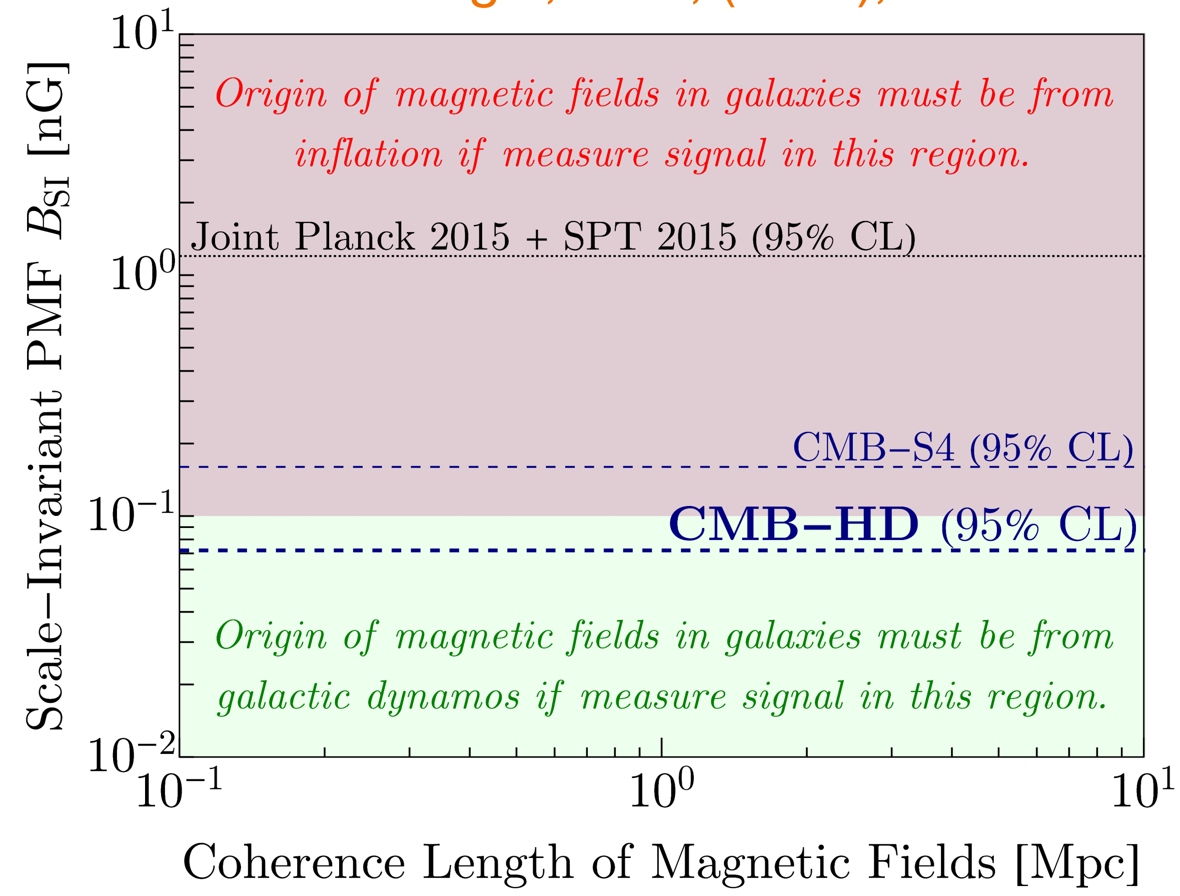
Mandal & Sehgal, PRD, (2022), 2201.02204



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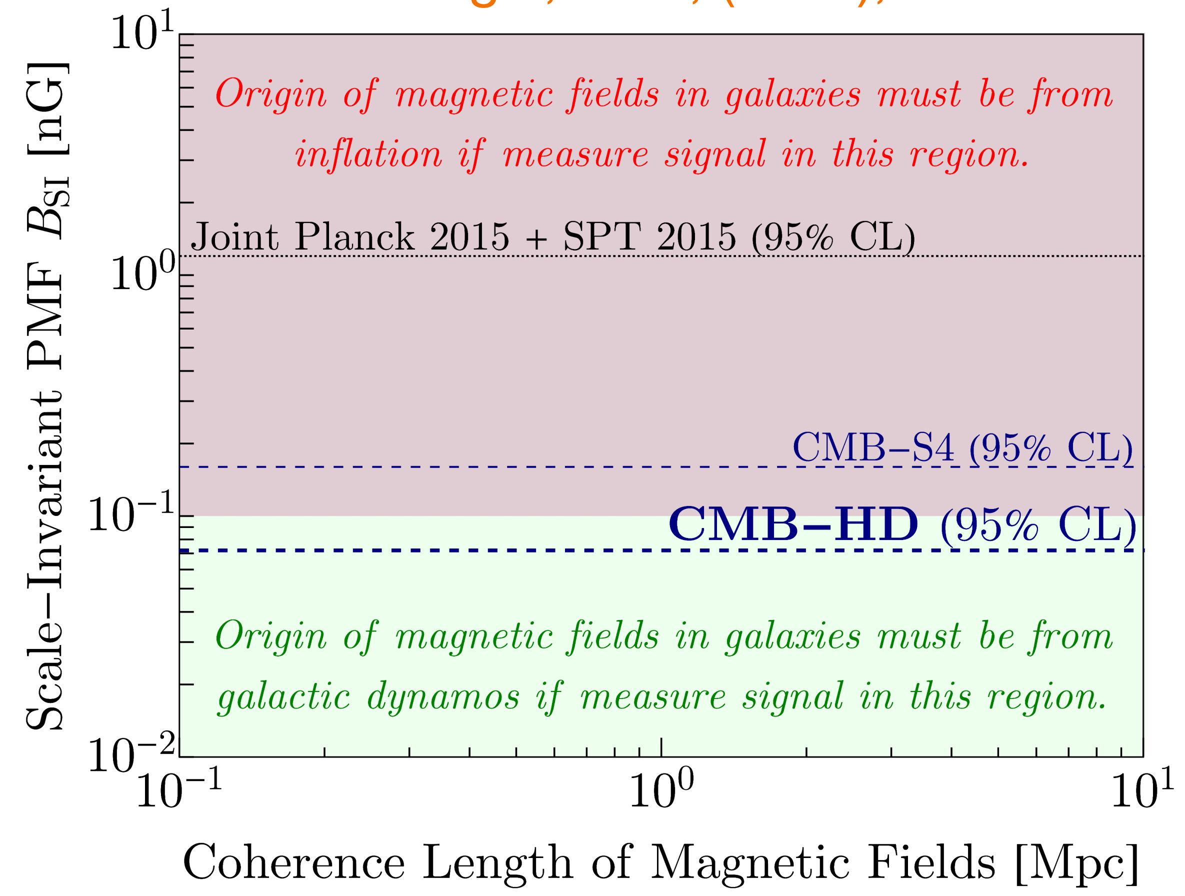

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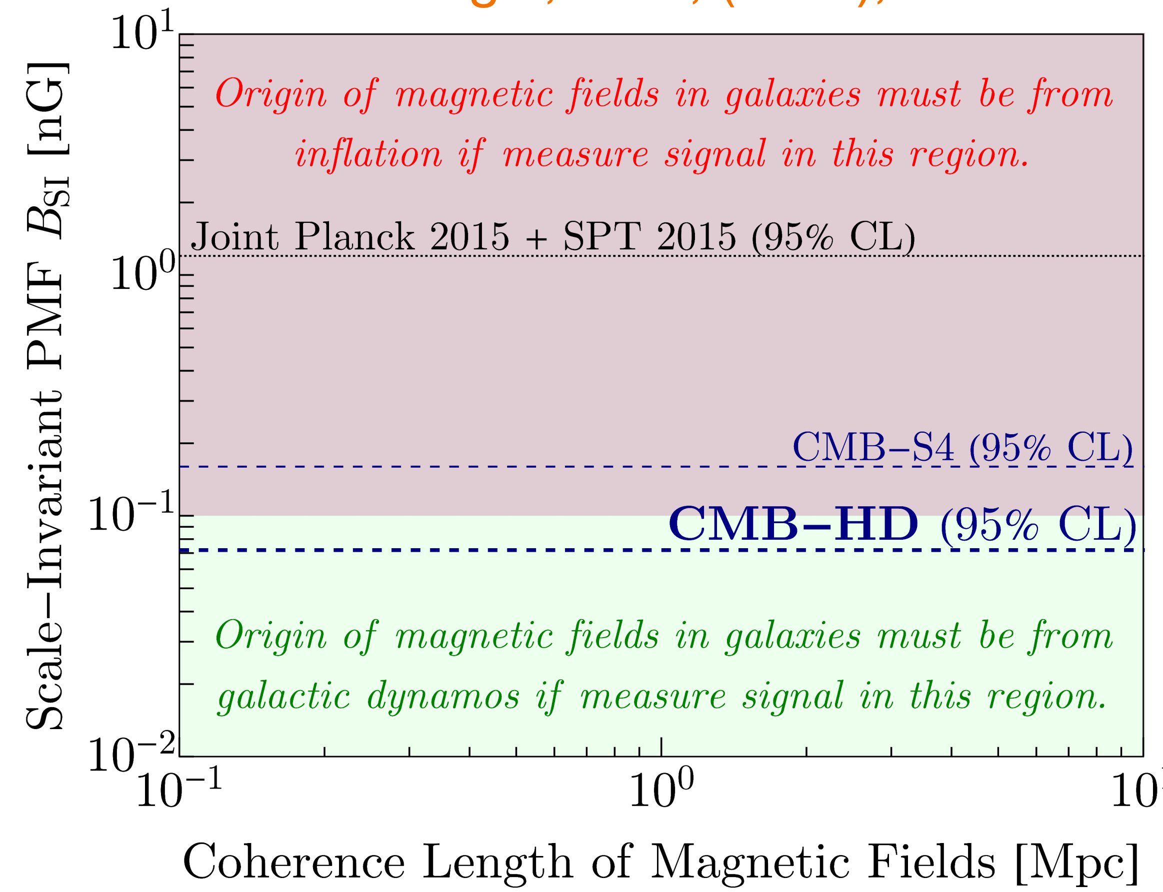

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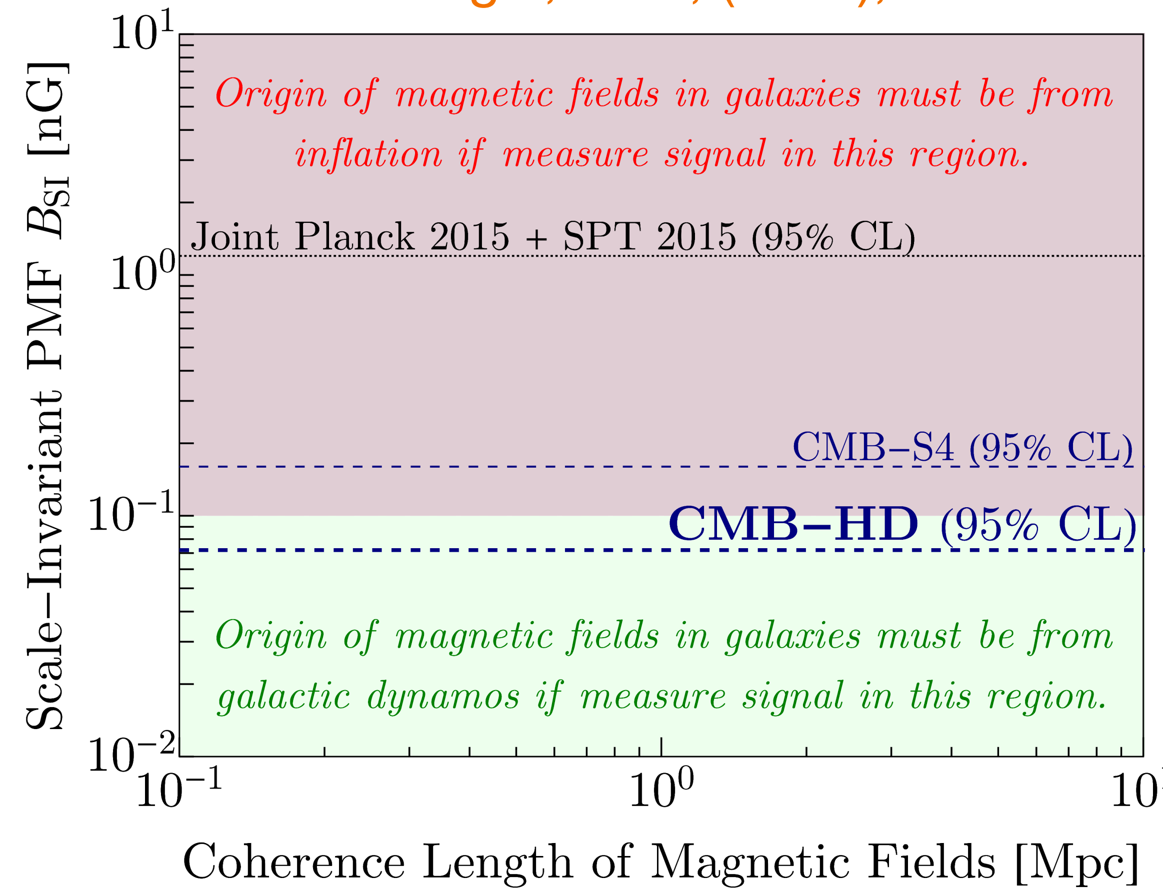

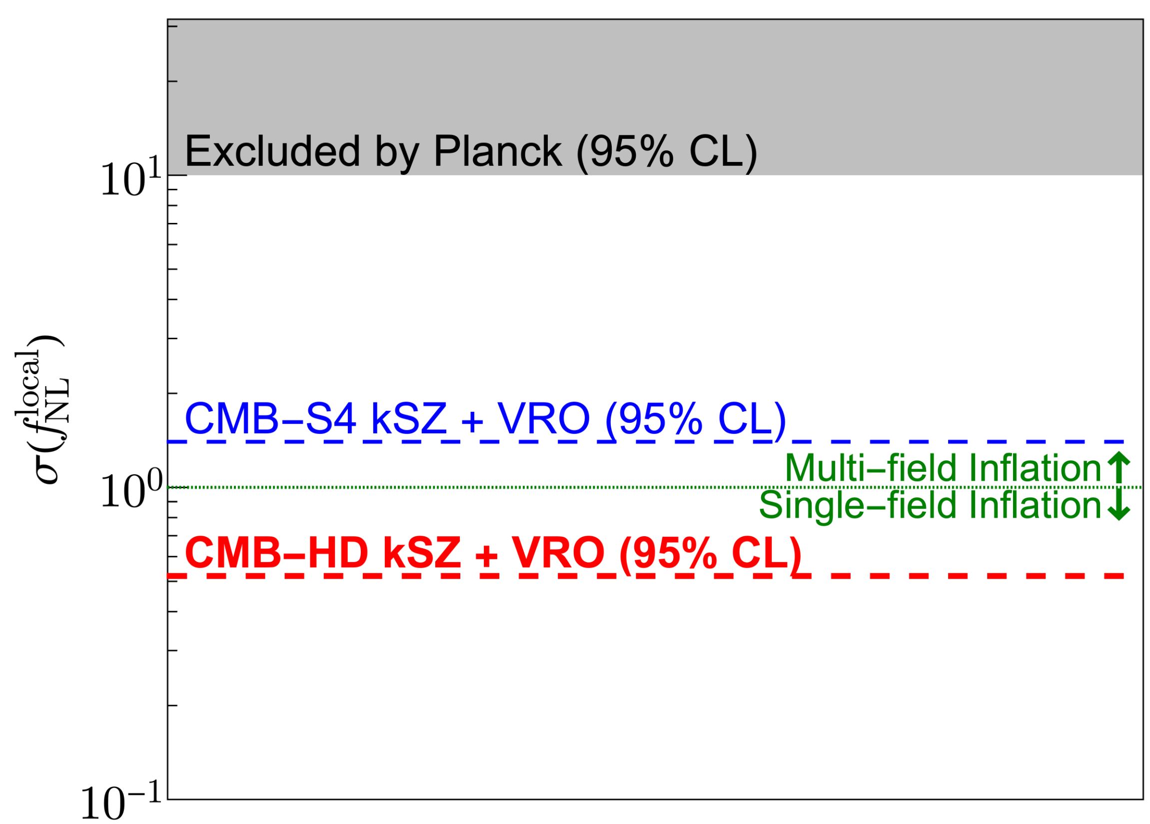

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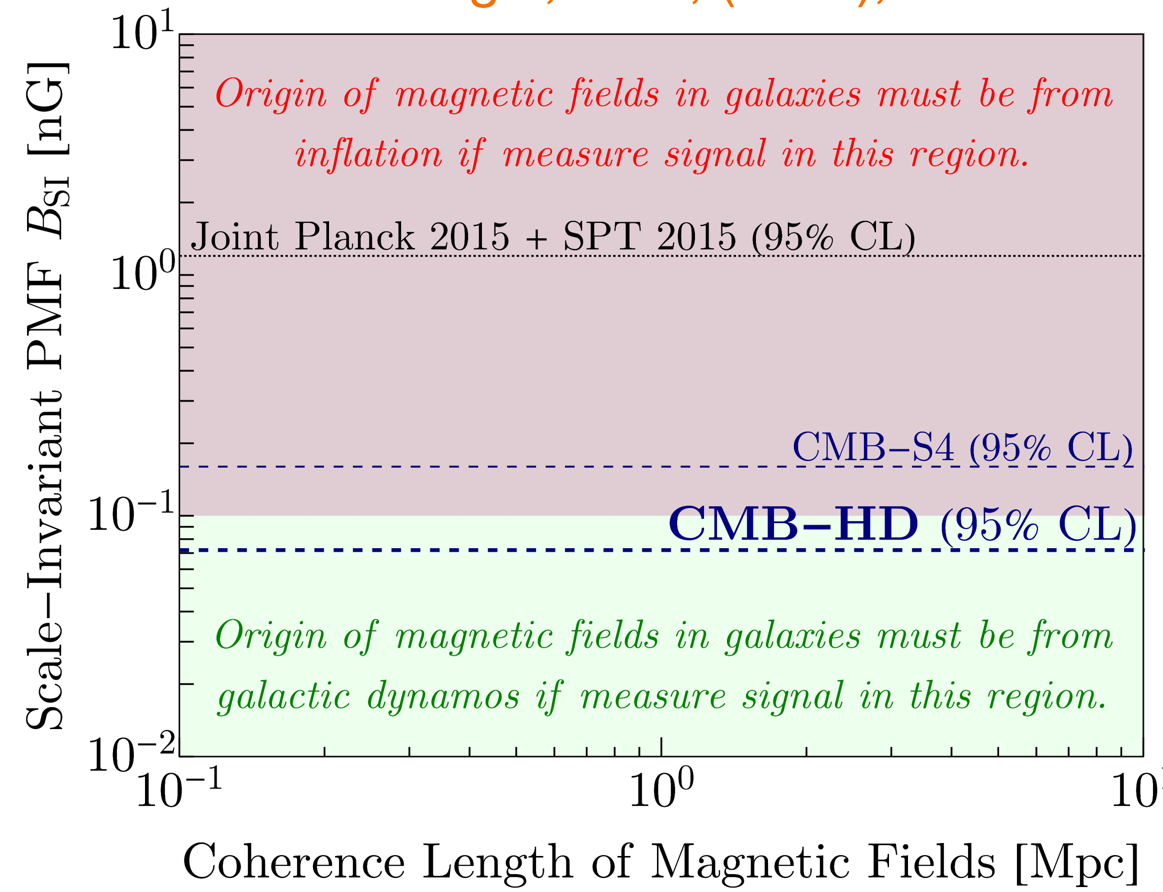

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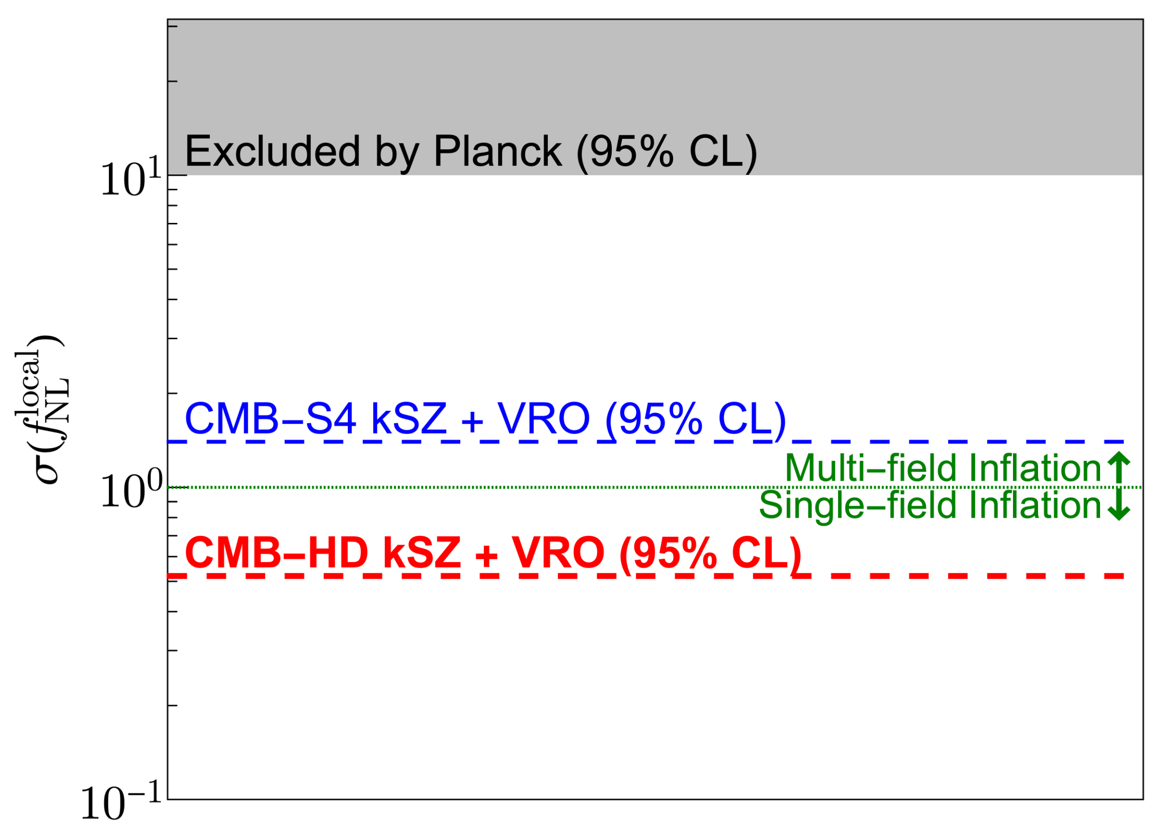

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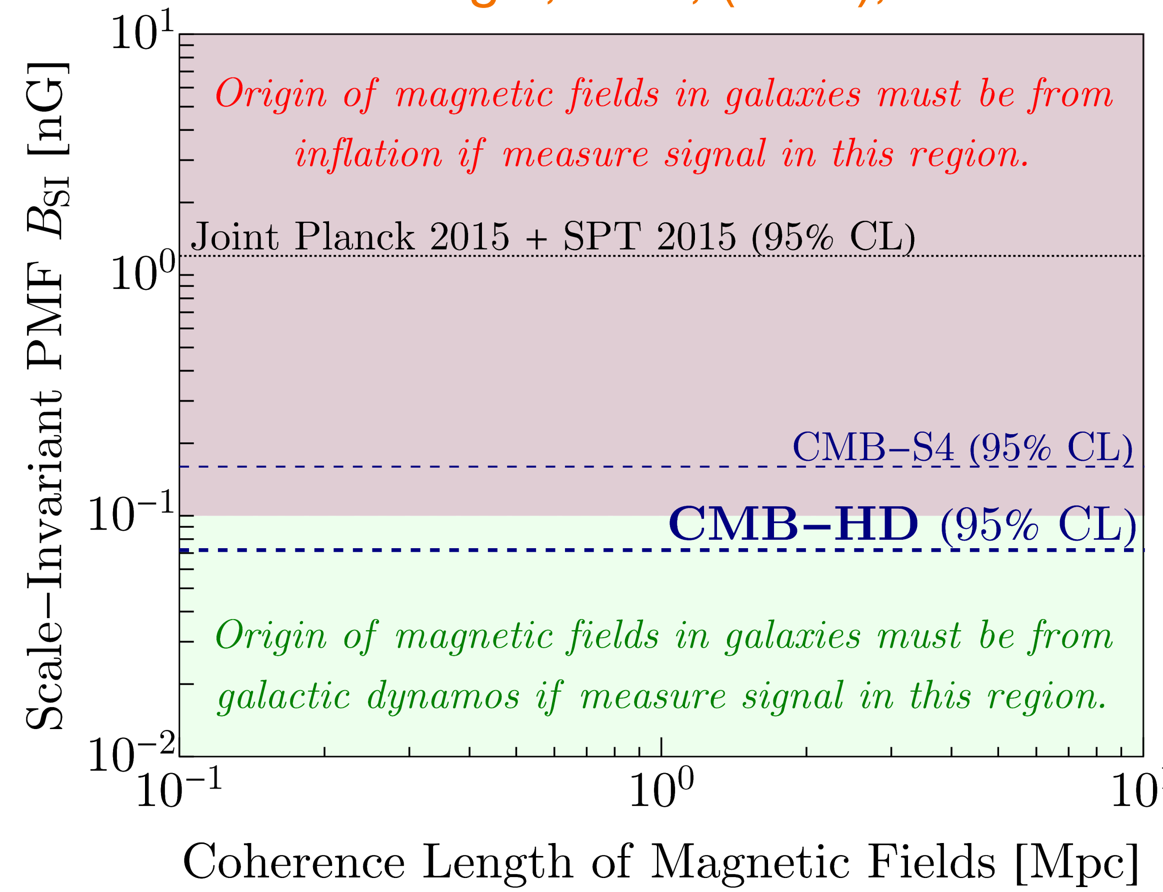

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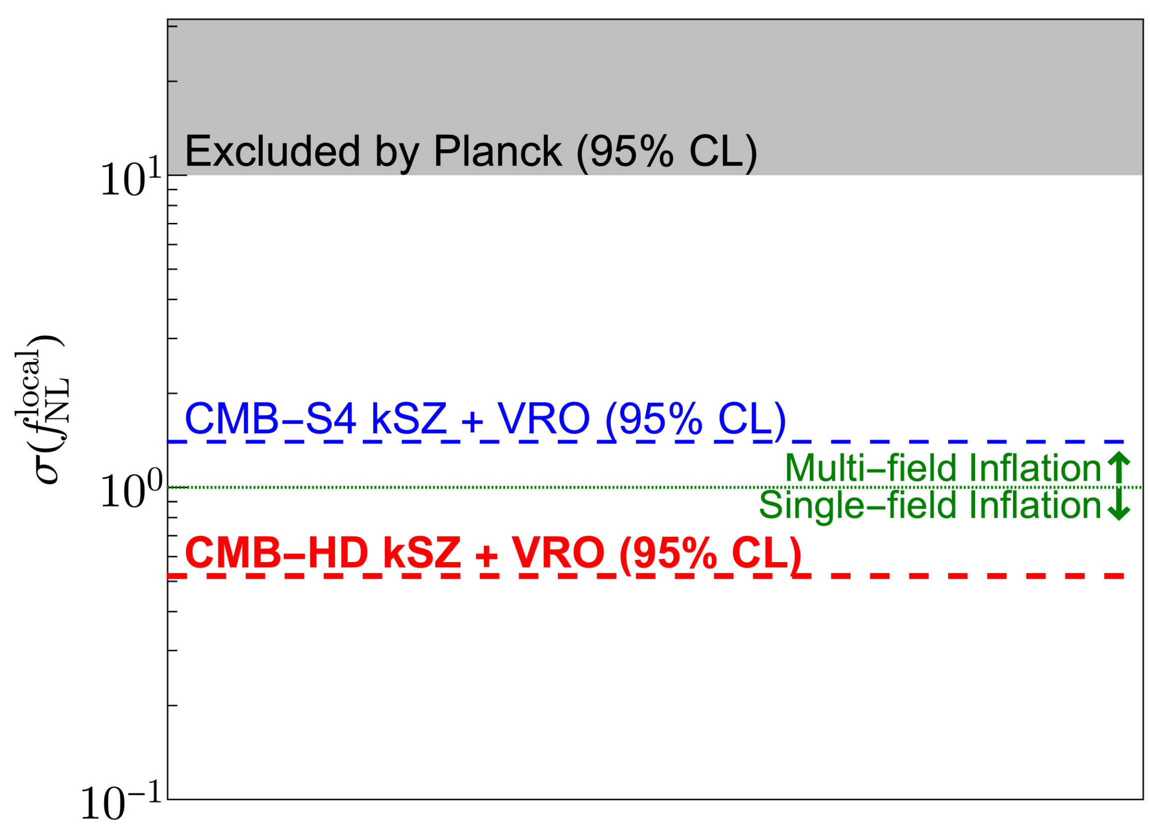
  - Achieved with combination of CMB-HD and Rubin Obs; limited by Rubin Obs, so can improve with future LSS surveys



Snowmass2021 CMB-HD White Paper: 2203.05728

Science Motivation: Dark Matter

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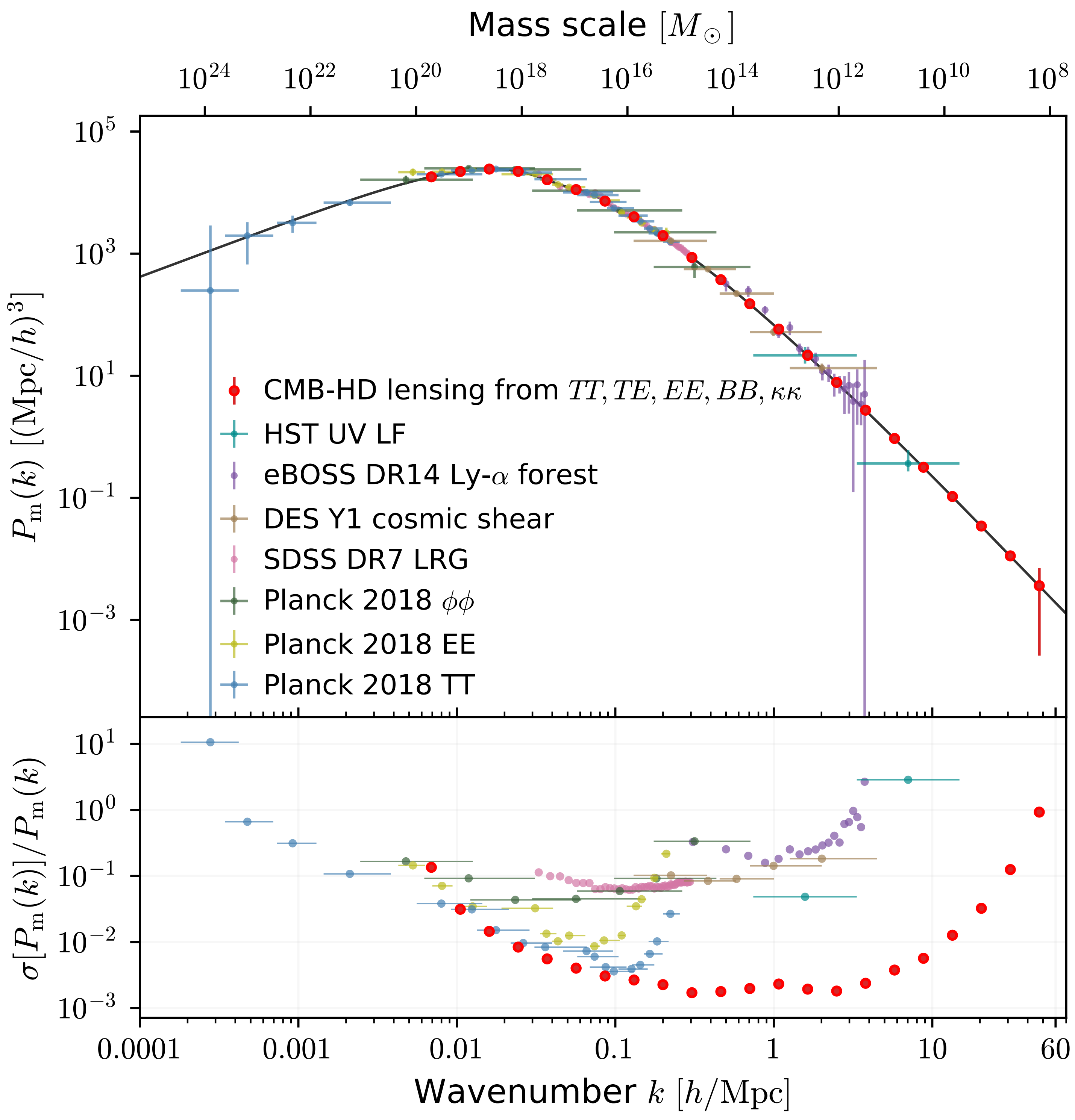
Extreme CMB lensing measurements to probe the nature of dark matter; **unique to CMB-HD**



From MacInnis & Sehgal (2024), arXiv:2405.12220

Science Motivation: Dark Energy/Neutrino Mass

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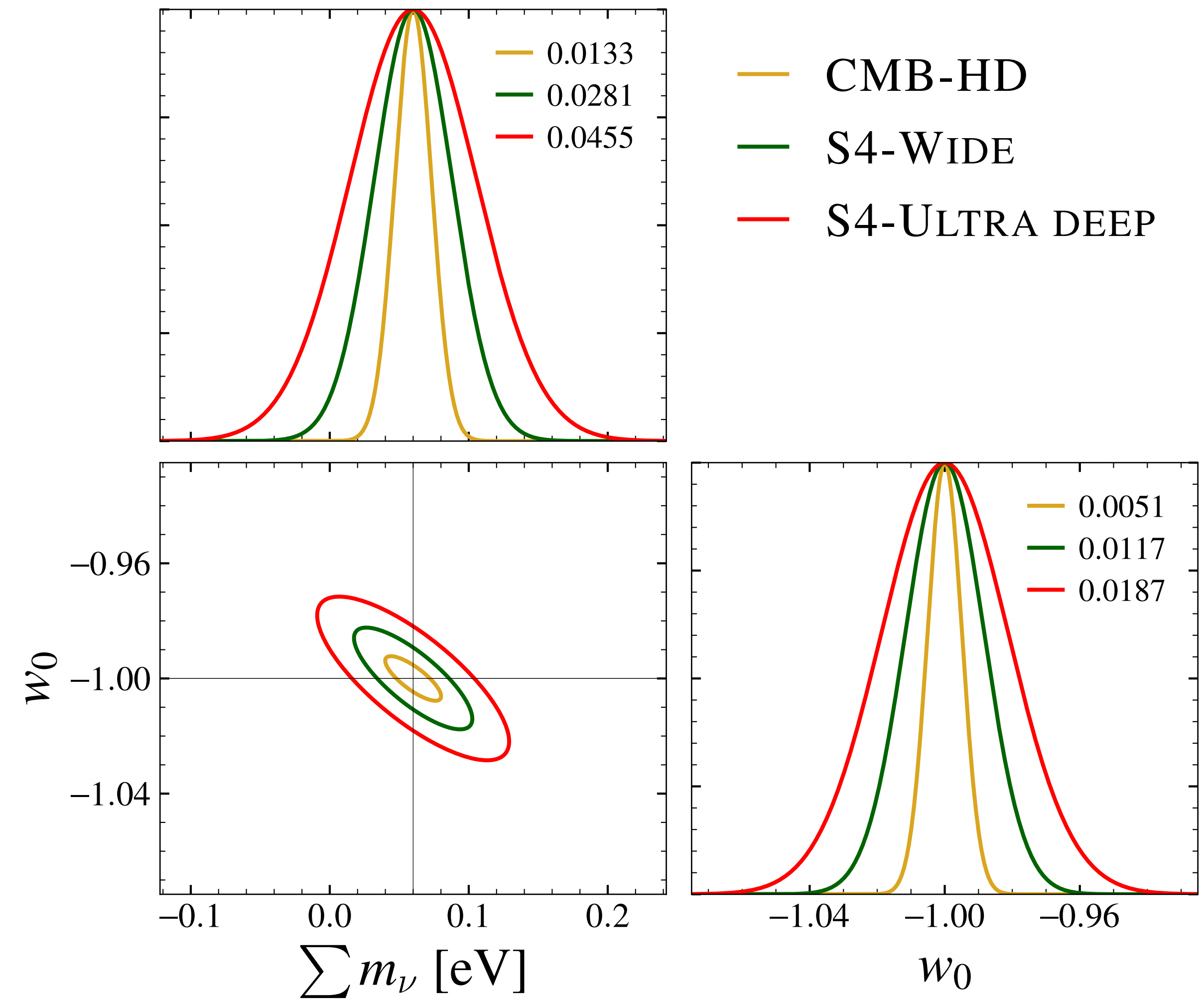

From Raghunathan et al, ApJ, (2022), 2107.10250

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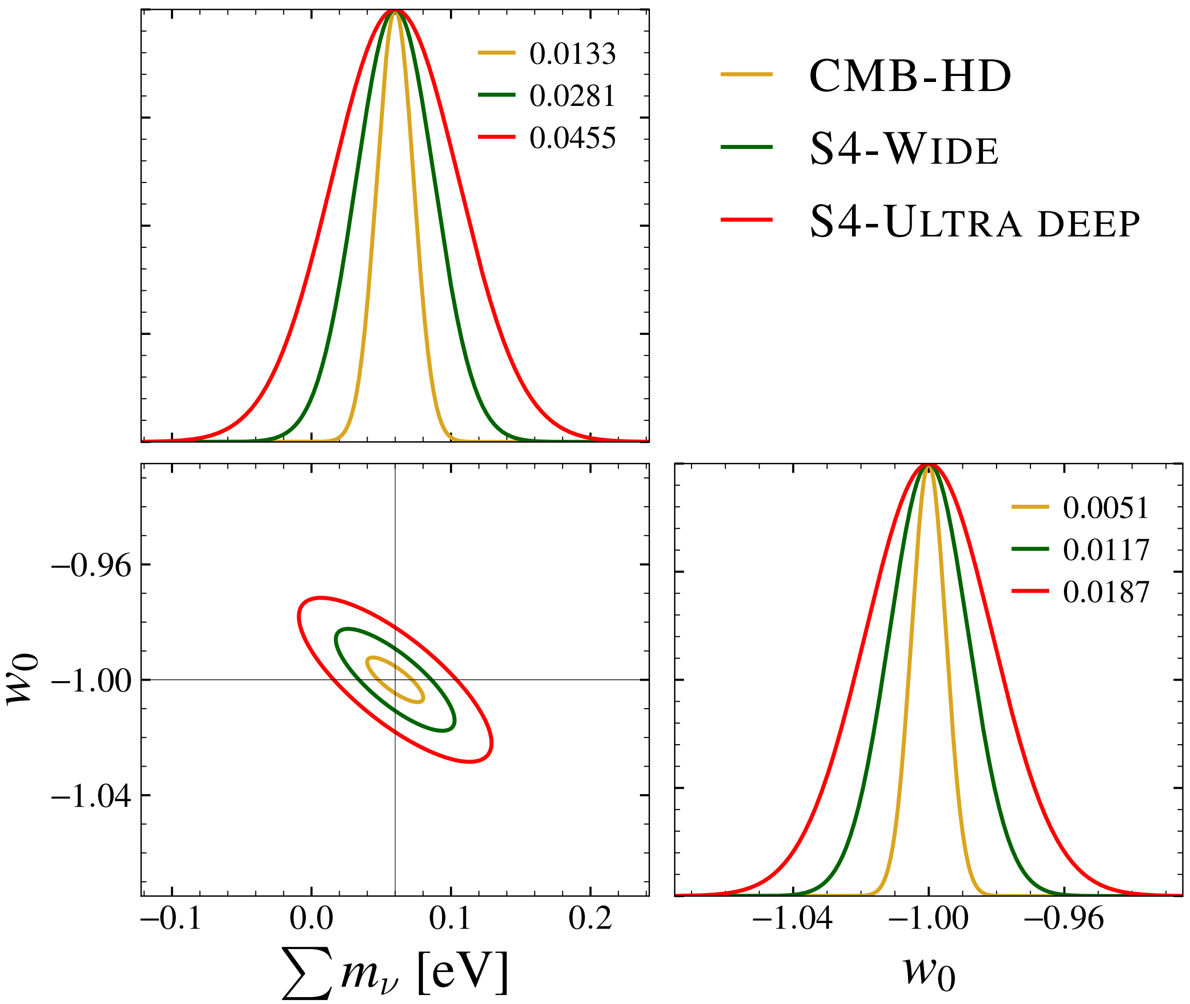

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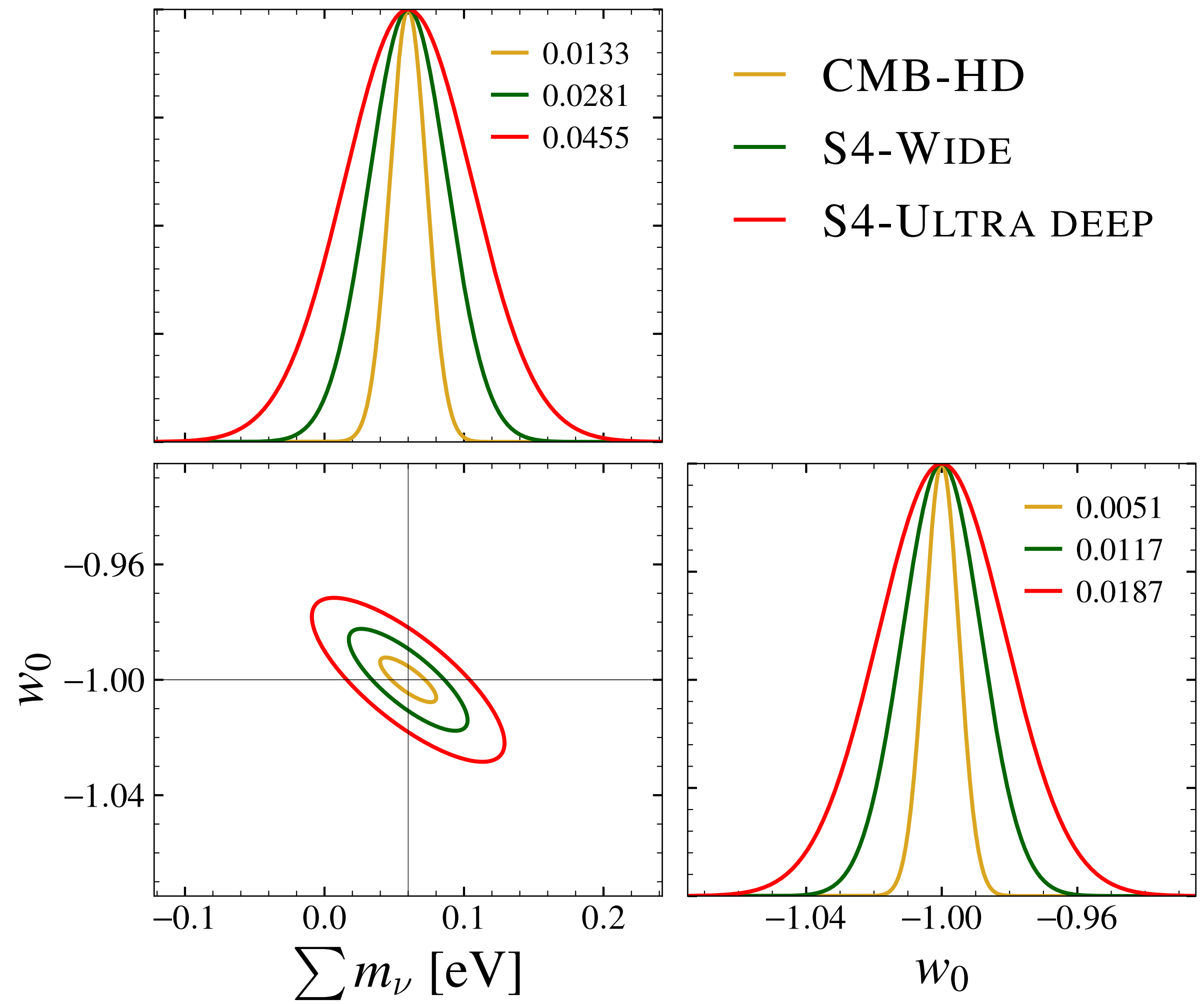

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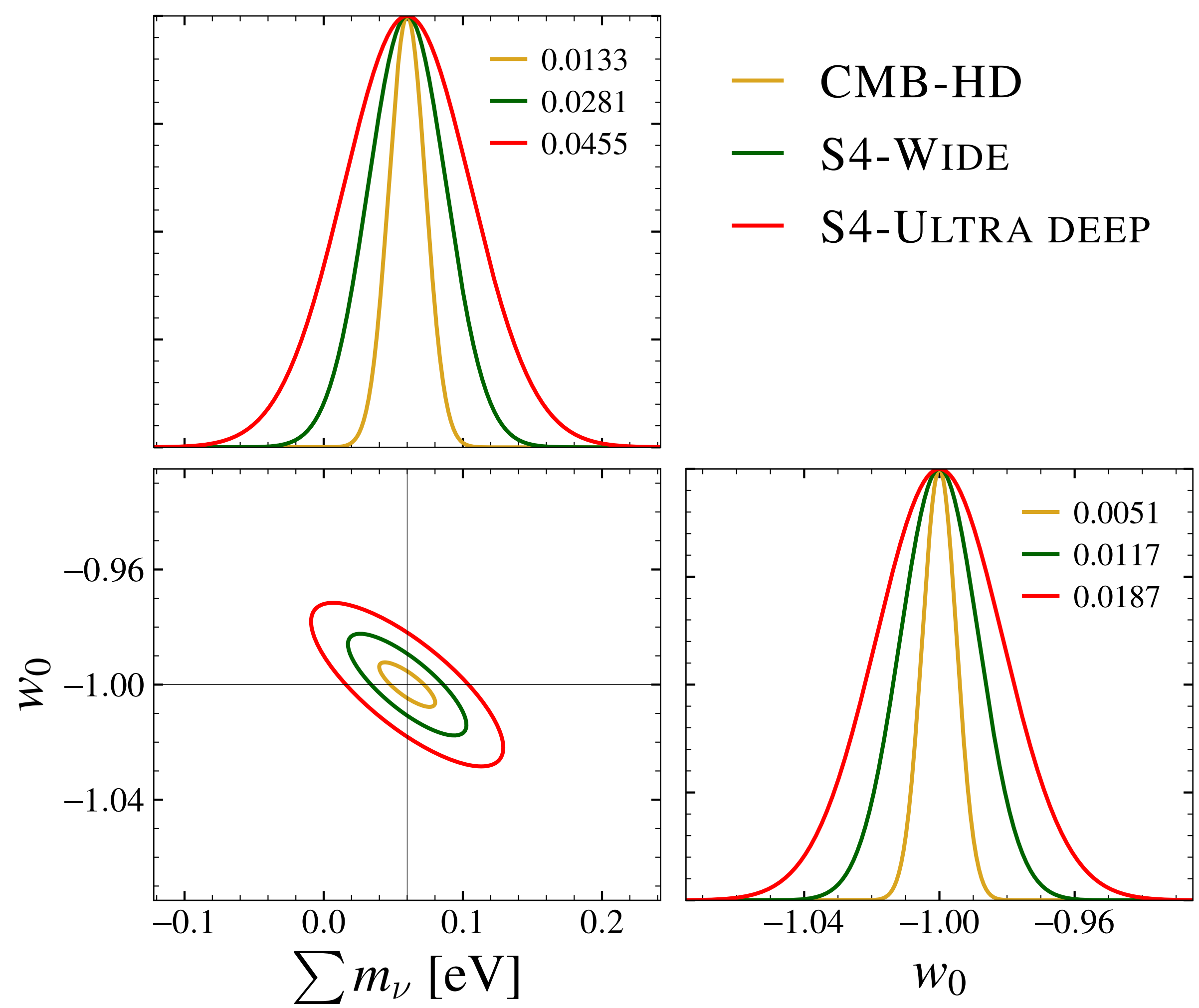
    - Almost 5σ detection of neutrino mass possible with just Planck τ prior in minimal mass case



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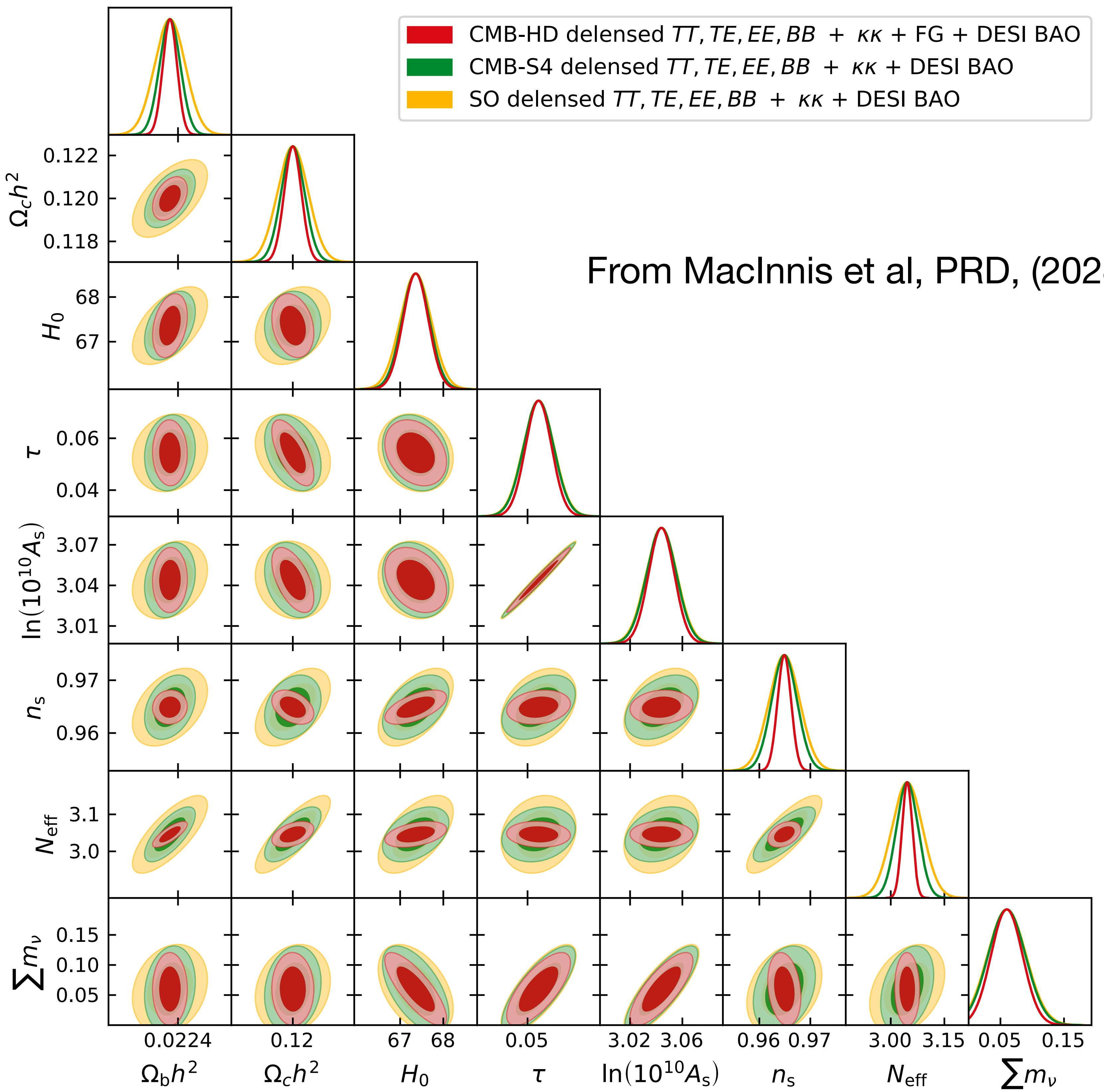
Cosmological Parameter Forecasts from a CMB-HD Survey



From MacInnis et al, PRD, (2024), 2309.03021

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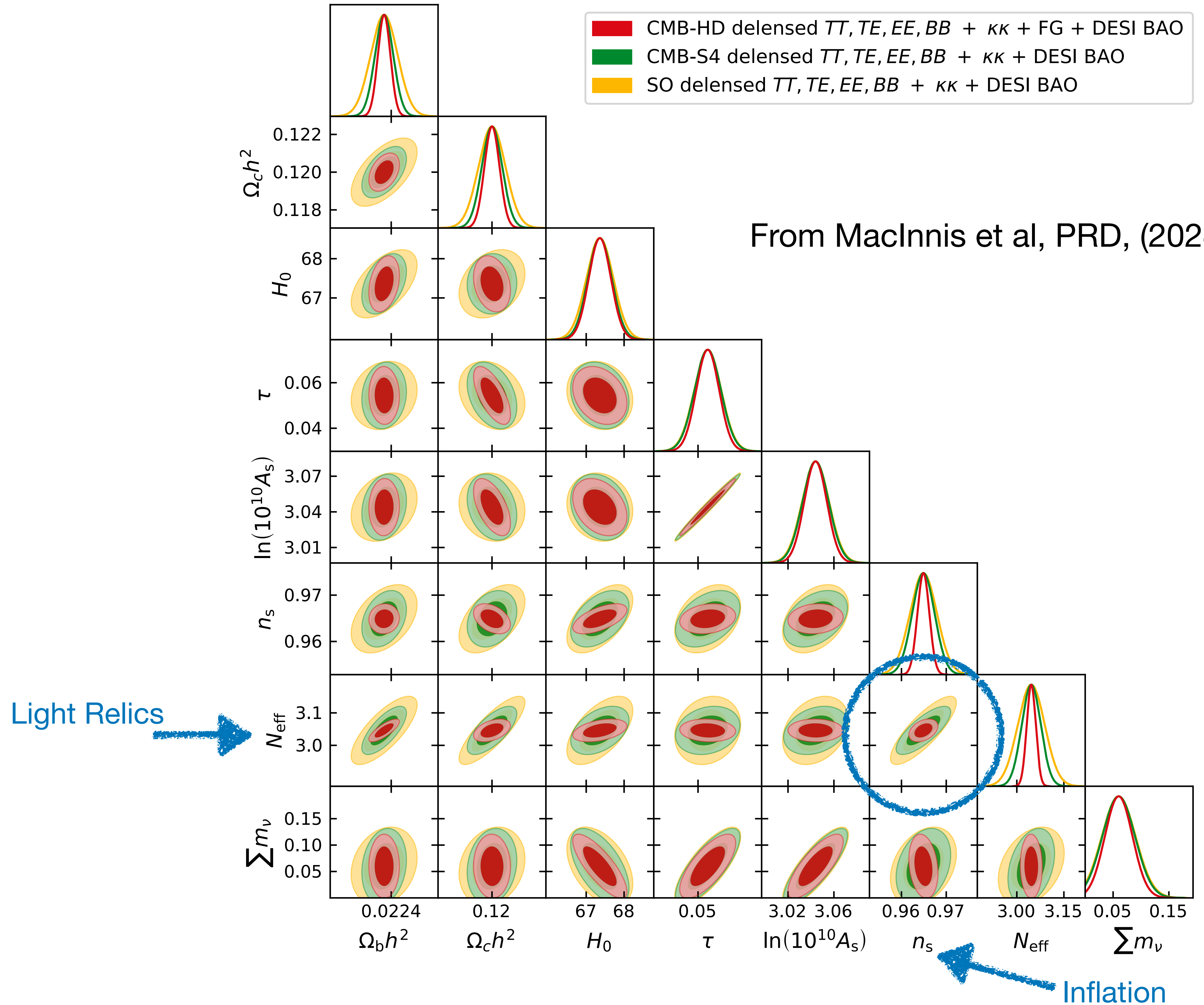

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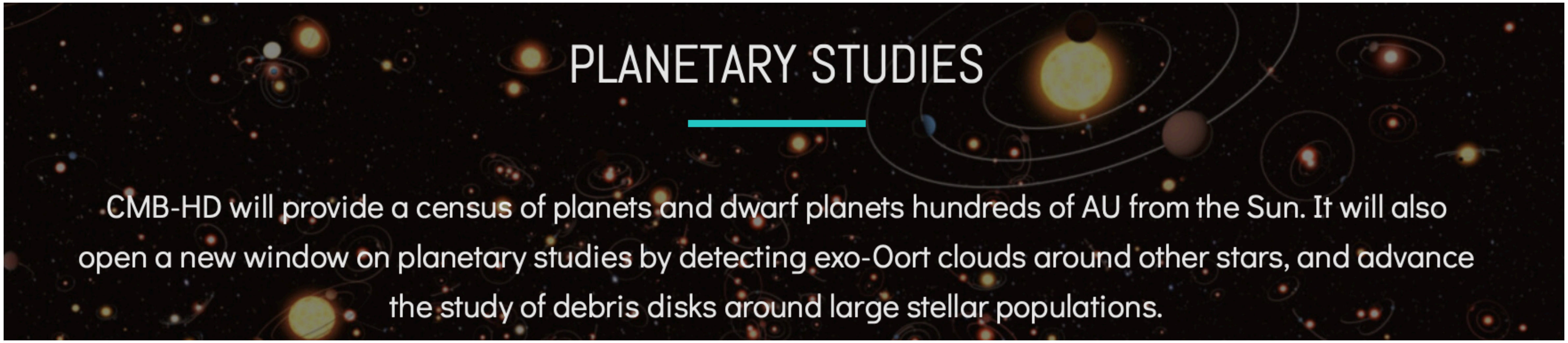

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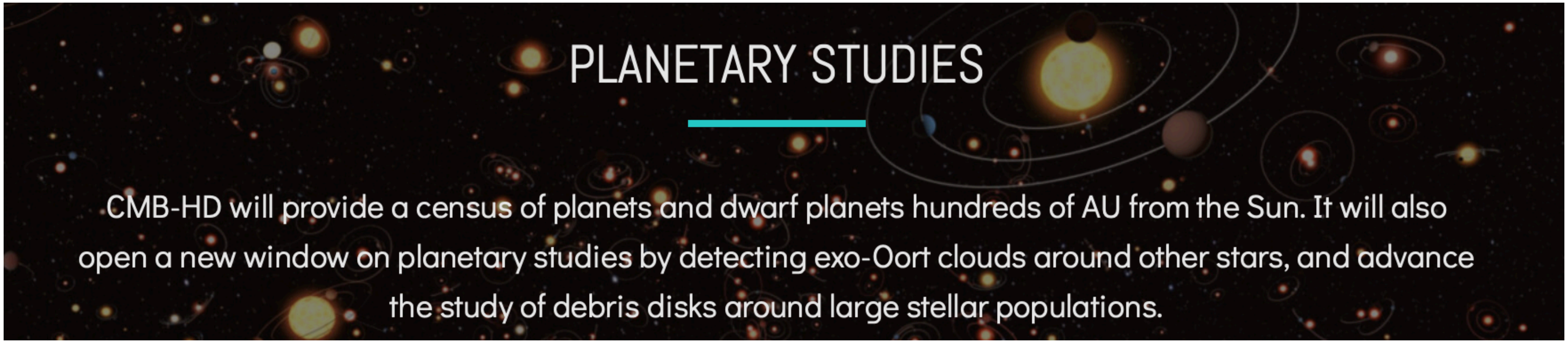

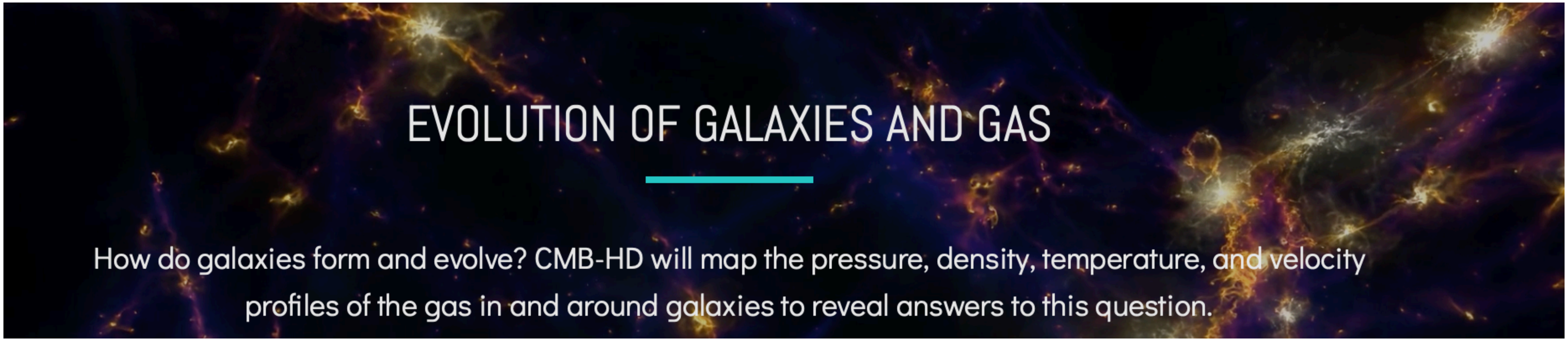

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PLANETARY STUDIES

CMB-HD will provide a census of planets and dwarf planets hundreds of AU from the Sun. It will also open a new window on planetary studies by detecting exo-Oort clouds around other stars, and advance the study of debris disks around large stellar populations.

EVOLUTION OF GALAXIES AND GAS

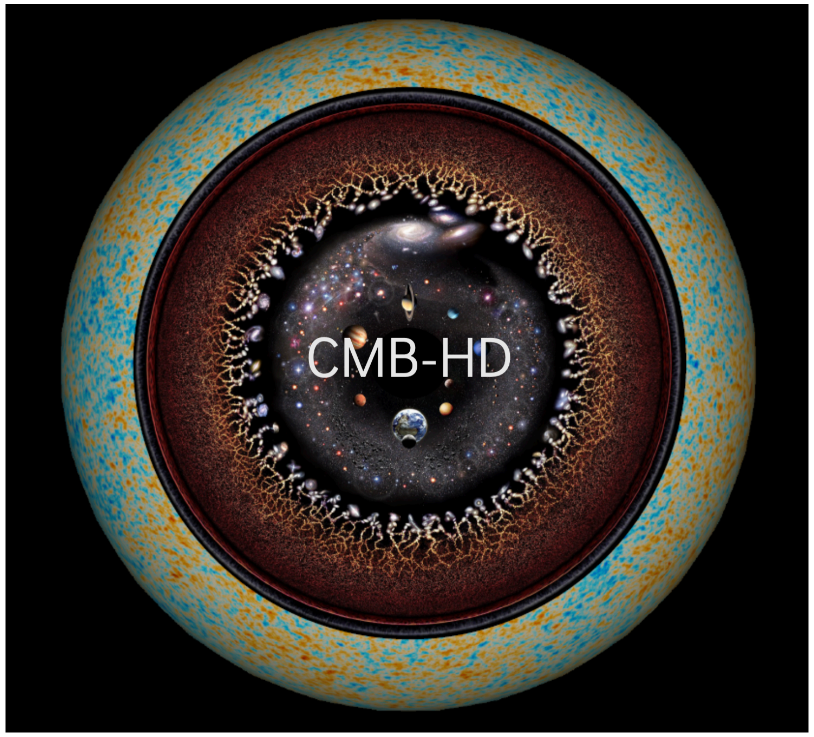
How do galaxies form and evolve? CMB-HD will map the pressure, density, temperature, and velocity profiles of the gas in and around galaxies to reveal answers to this question.

THE VARIABLE AND TRANSIENT UNIVERSE

CMB-HD will map the variable Universe by surveying half the sky every day. Weekly maps will be made public to the astronomy community.

More information

- Website: https://cmb-hd.org
  - Collaboration about 65 scientists so far (open membership)
- Snowmass2021 CMB Measurements White Paper (2203.07638)
- Snowmass2021 CMB-HD White Paper (2203.05728)
- Astro2020 CMB-HD RFI (2002.12714)
- Astro2020 CMB-HD APC (1906.10134)
- Astro2020 Science White Paper (1903.03263)



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- Hopefully on-sky in next decade