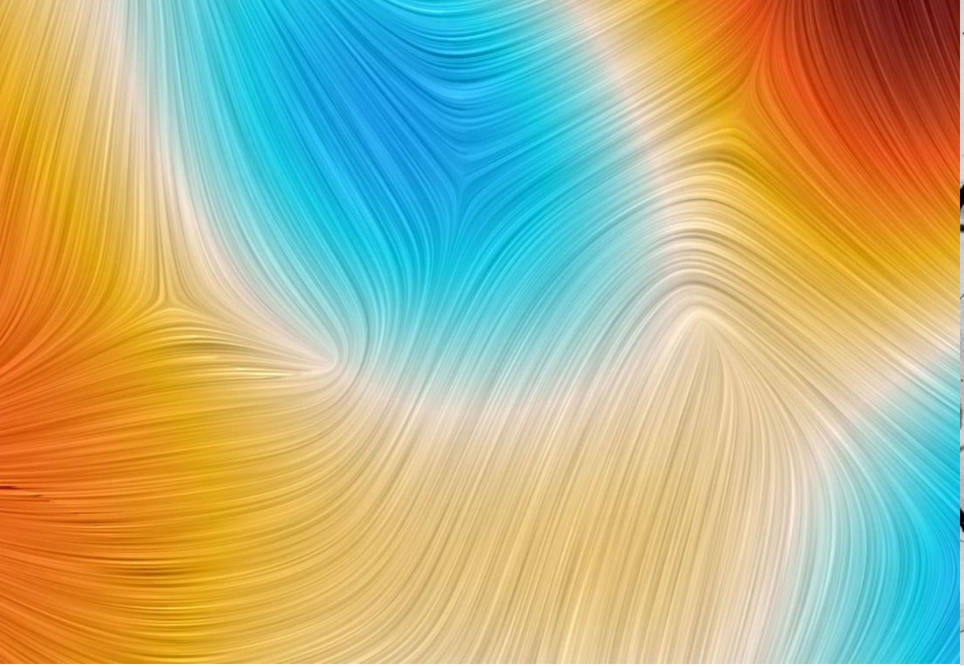
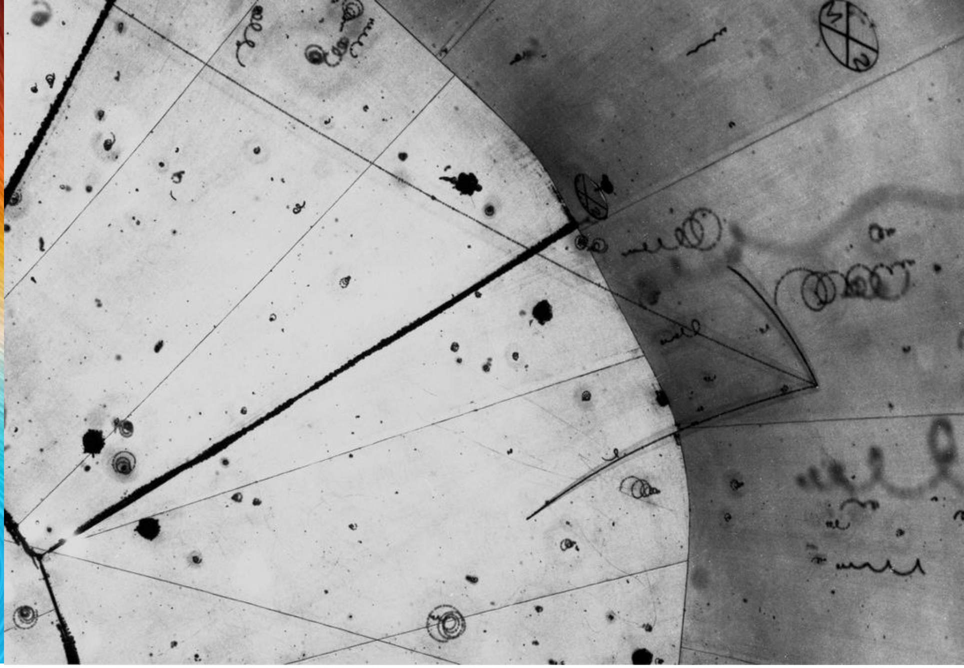




Cosmological Probes of Fundamental Physics

Joel Meyers

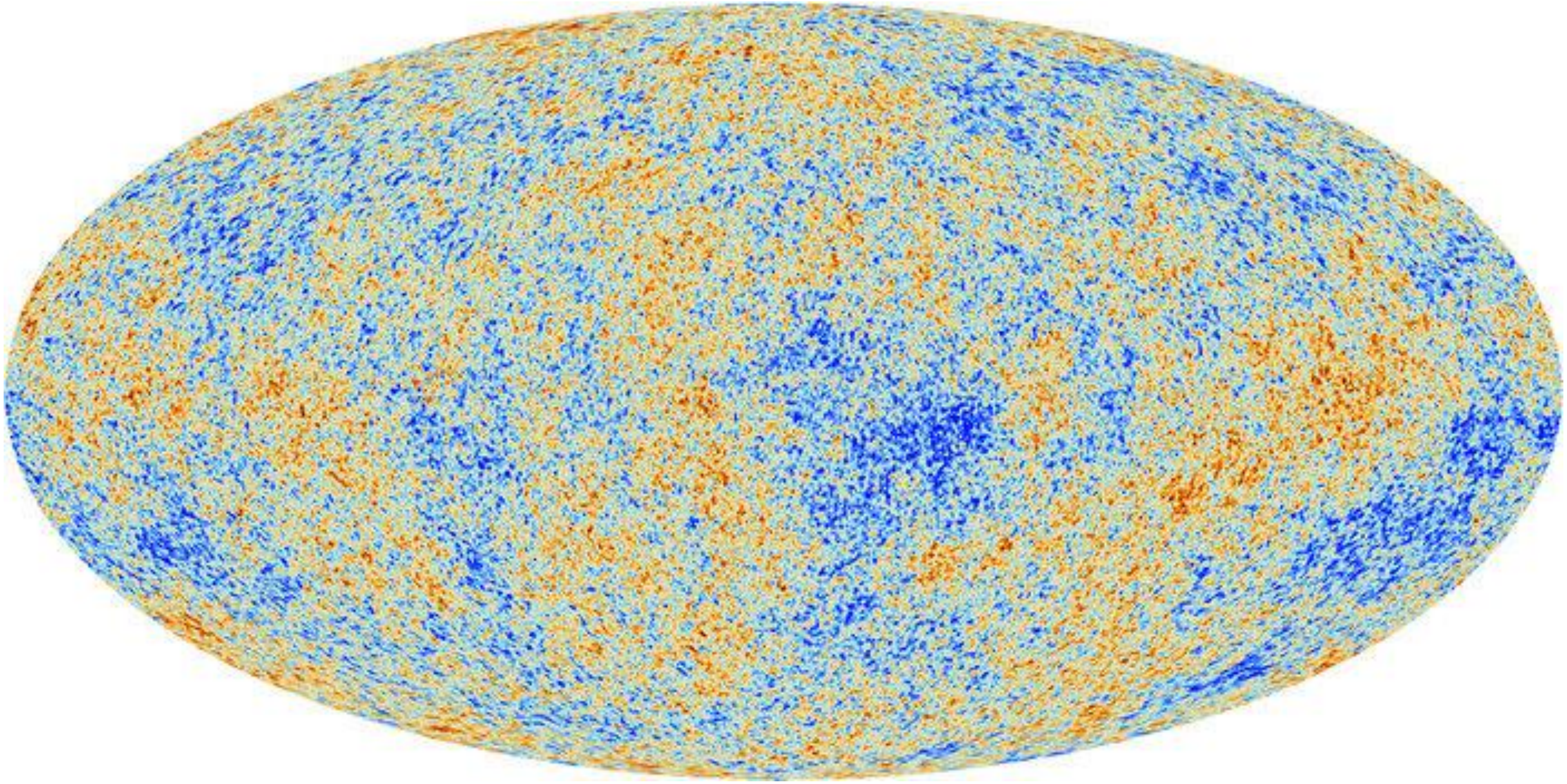
Canadian Institute for Theoretical Astrophysics

SMU Physics Colloquium

February 5, 2018

Image Credits: Planck, ANL

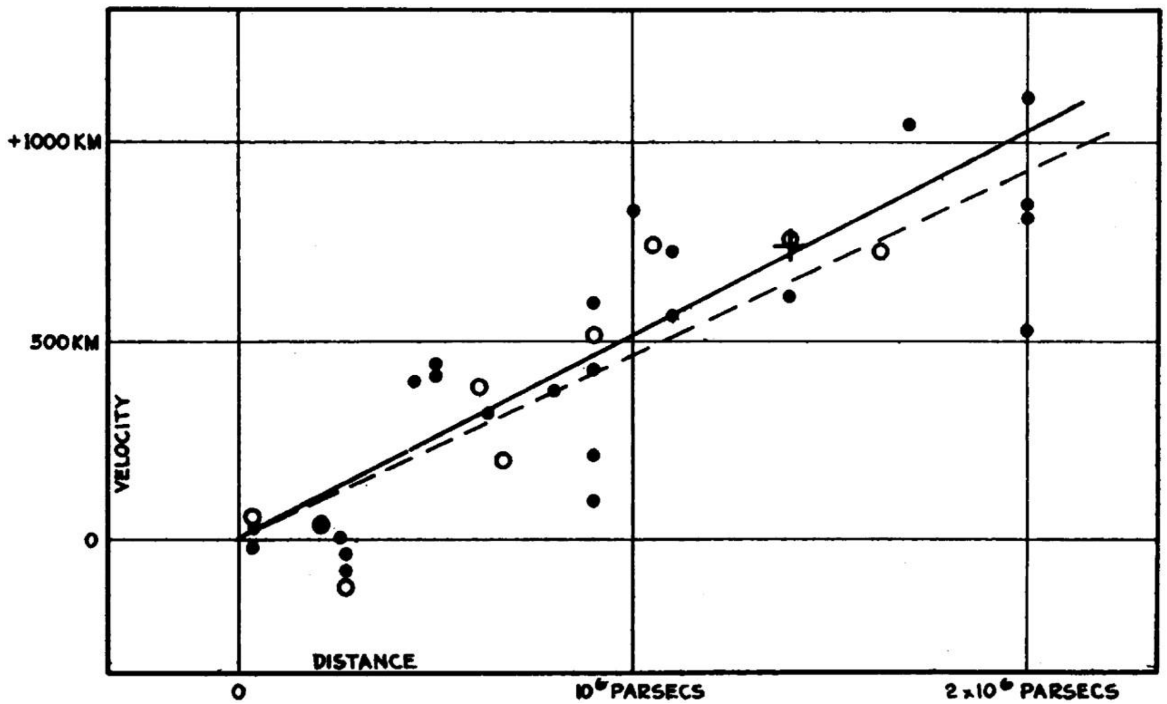
The Cosmic Microwave Background

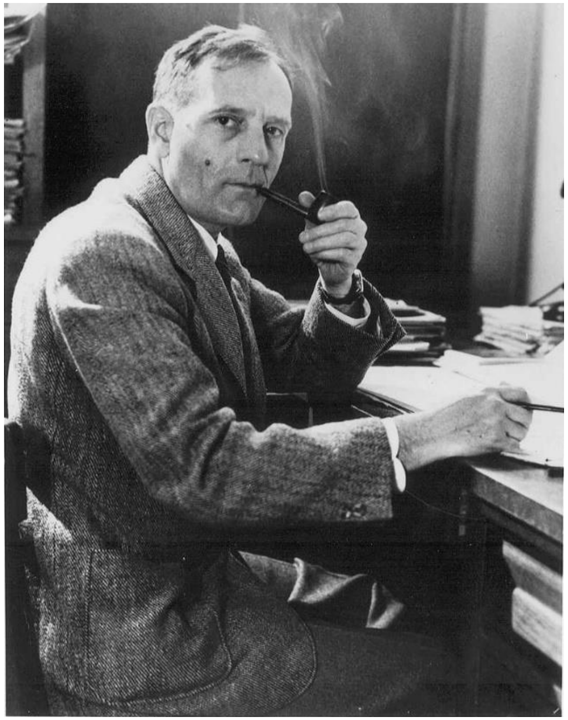


Planck (2013)

Distance – Redshift Relation

The Expanding Universe - 1929



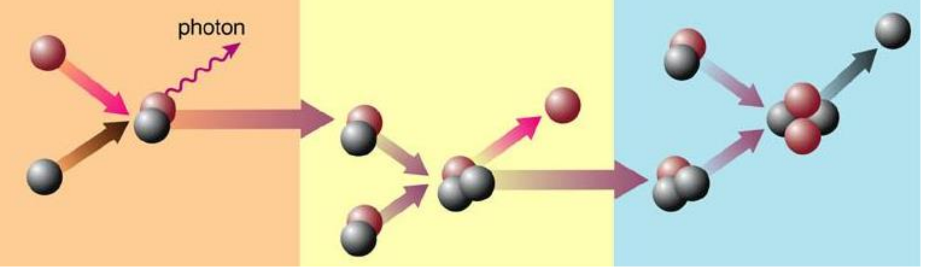


Hubble (1929)

Image Credit: Observatories of the Carnegie Institute of Washington

Big Bang Cosmology

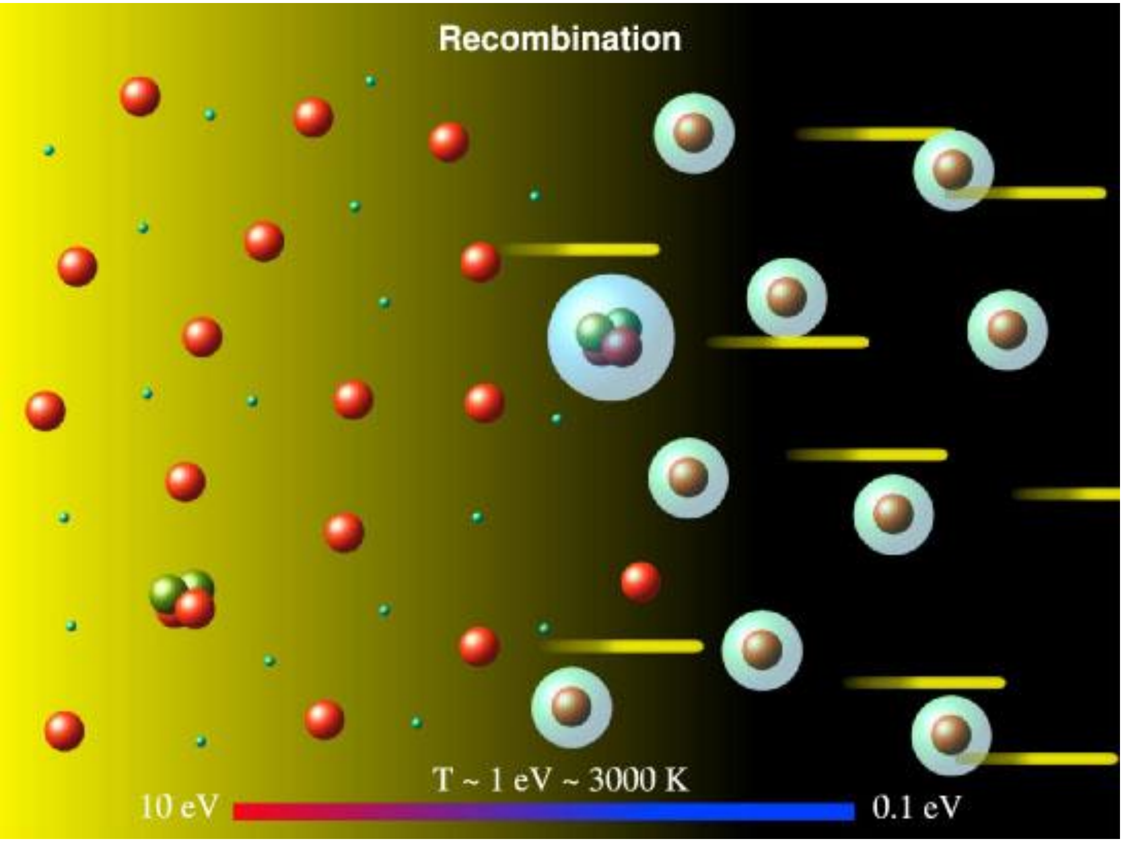
Primordial Nucleosynthesis - 1948



Alpher, Bethe, Gamow (1948); Alpher, Herman (1948); Gamow (1948)
Image Credits: American Scientist; Pearson Education

Big Bang Cosmology

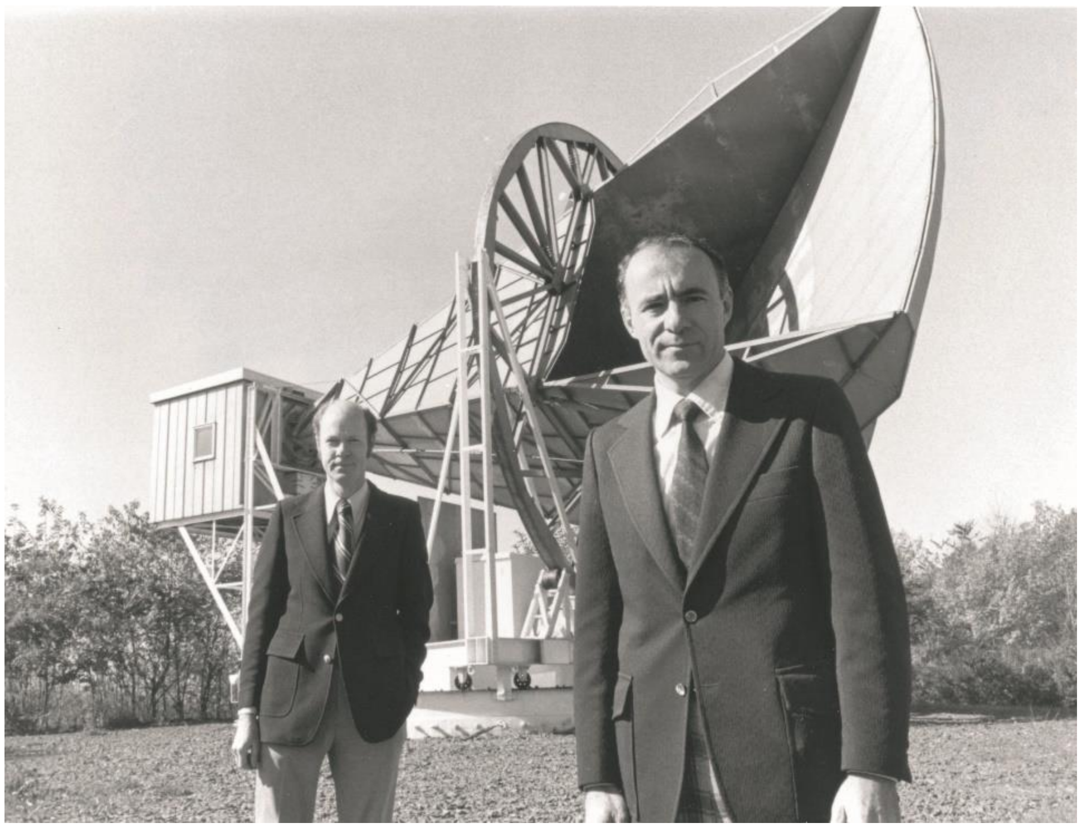
Prediction of Cosmic Microwave Background - 1948



Alpher, Bethe, Gamow (1948); Alpher, Herman (1948); Gamow (1948)
Image Credit: William Kinney

Observations Begin

First Detection of the Cosmic Microwave Background (CMB) - 1964



Penzias, Wilson (1965); Dicke, Peebles, Roll, Wilkinson (1965)
Image Credit: Bell Labs

Precision Measurement

First CMB Satellite - COBE - 1989-1996

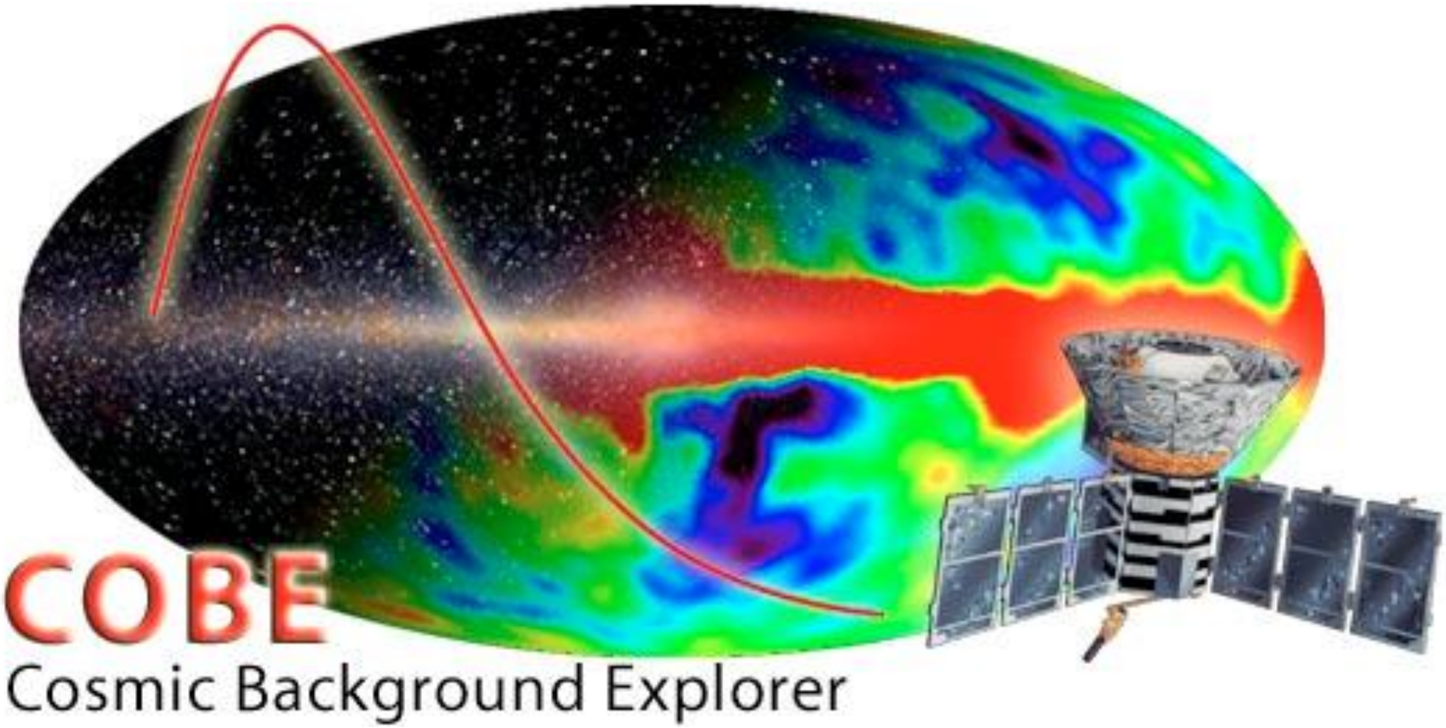
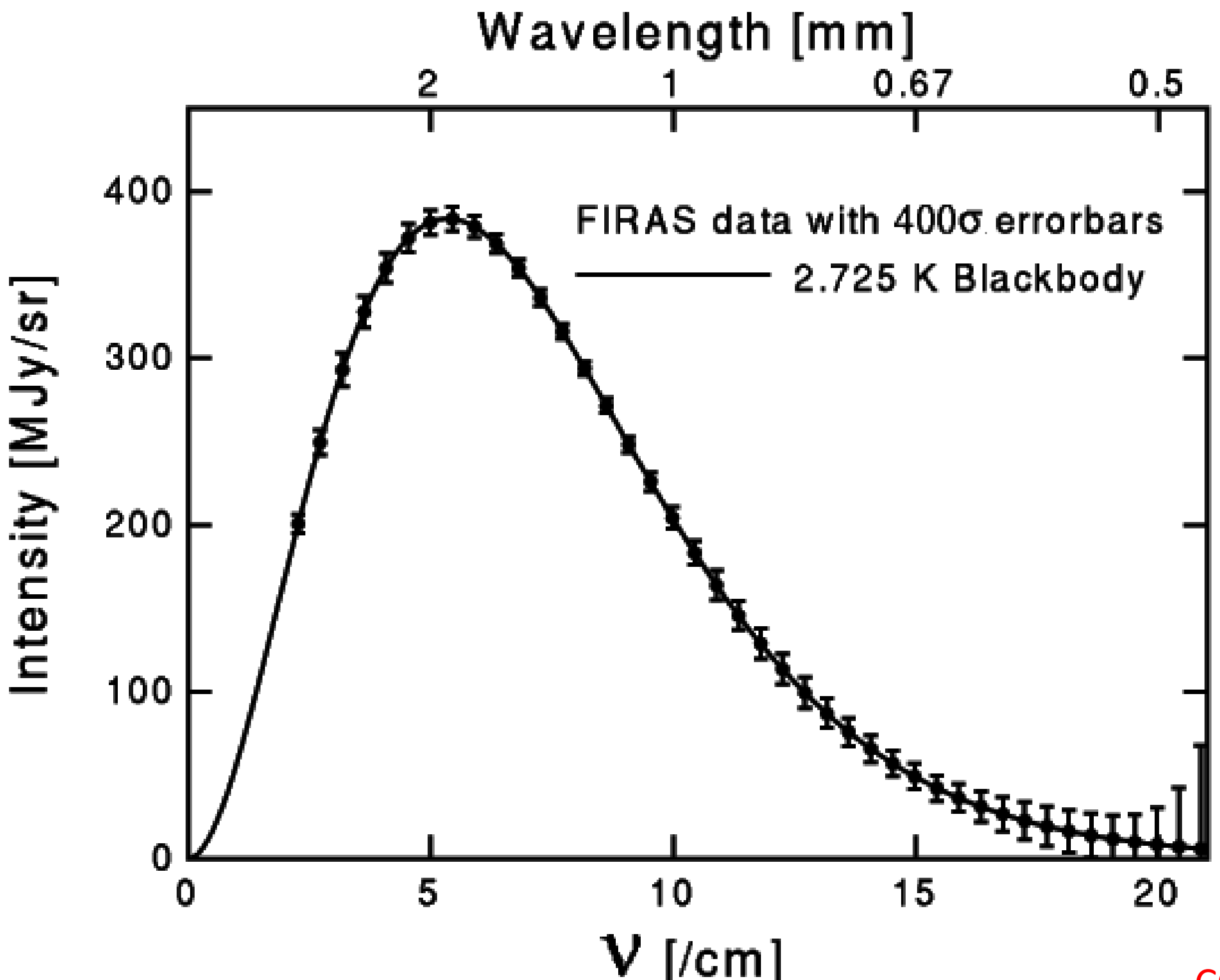


Image Credit: NASA

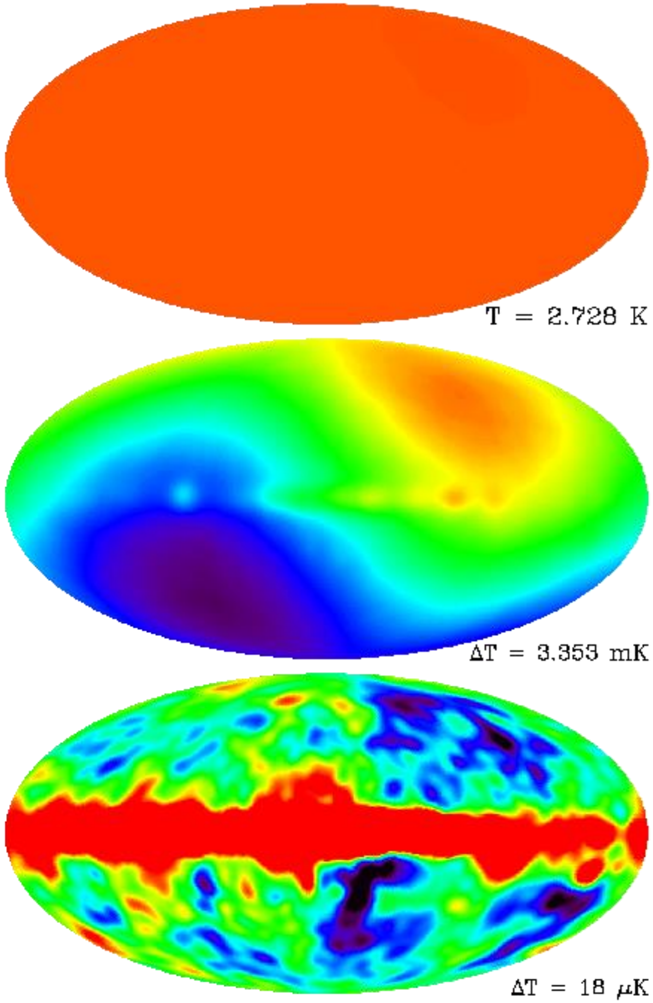
Thermal Spectrum

Confirmation of Hot Big Bang Cosmology - 1994



COBE FIRAS (1997)

Temperature Anisotropies



Nearly Isotropic

Motion-Induced Dipole

Small Primary Anisotropies

COBE DMR (1992)

Fluctuation Focus

Mapping Anisotropies - WMAP - 2001-2010

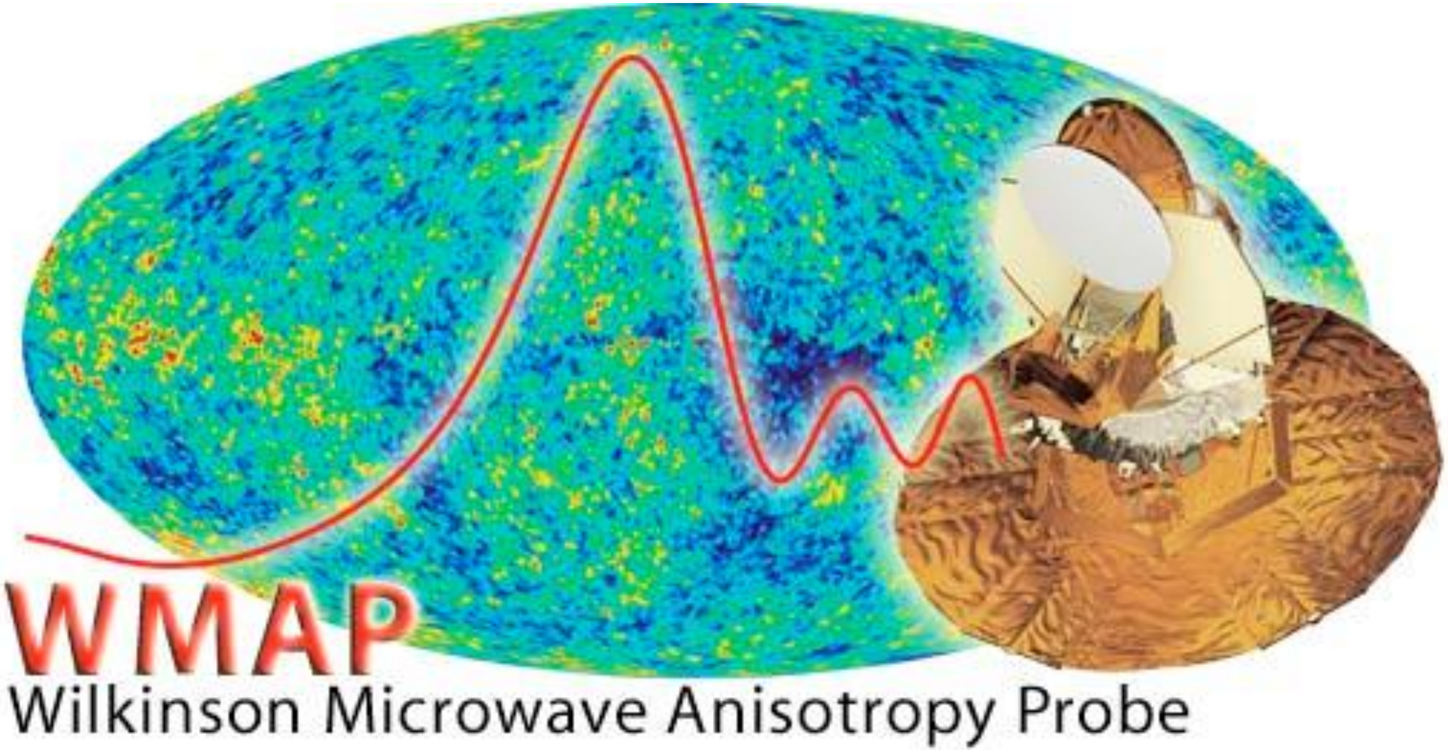
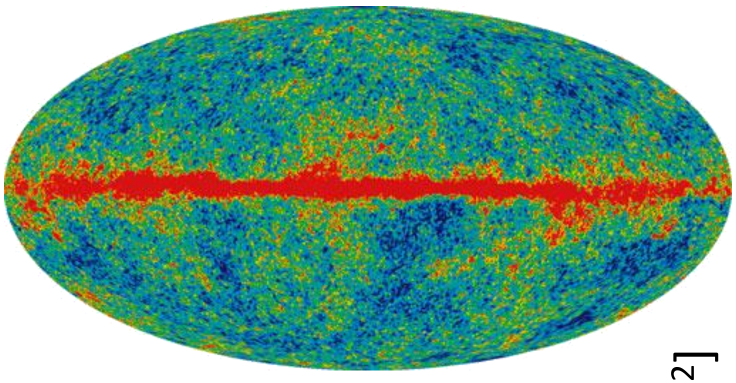


Image Credit: NASA

CMB Angular Power Spectrum



Harmonic Transform of Two-Point Correlation Function

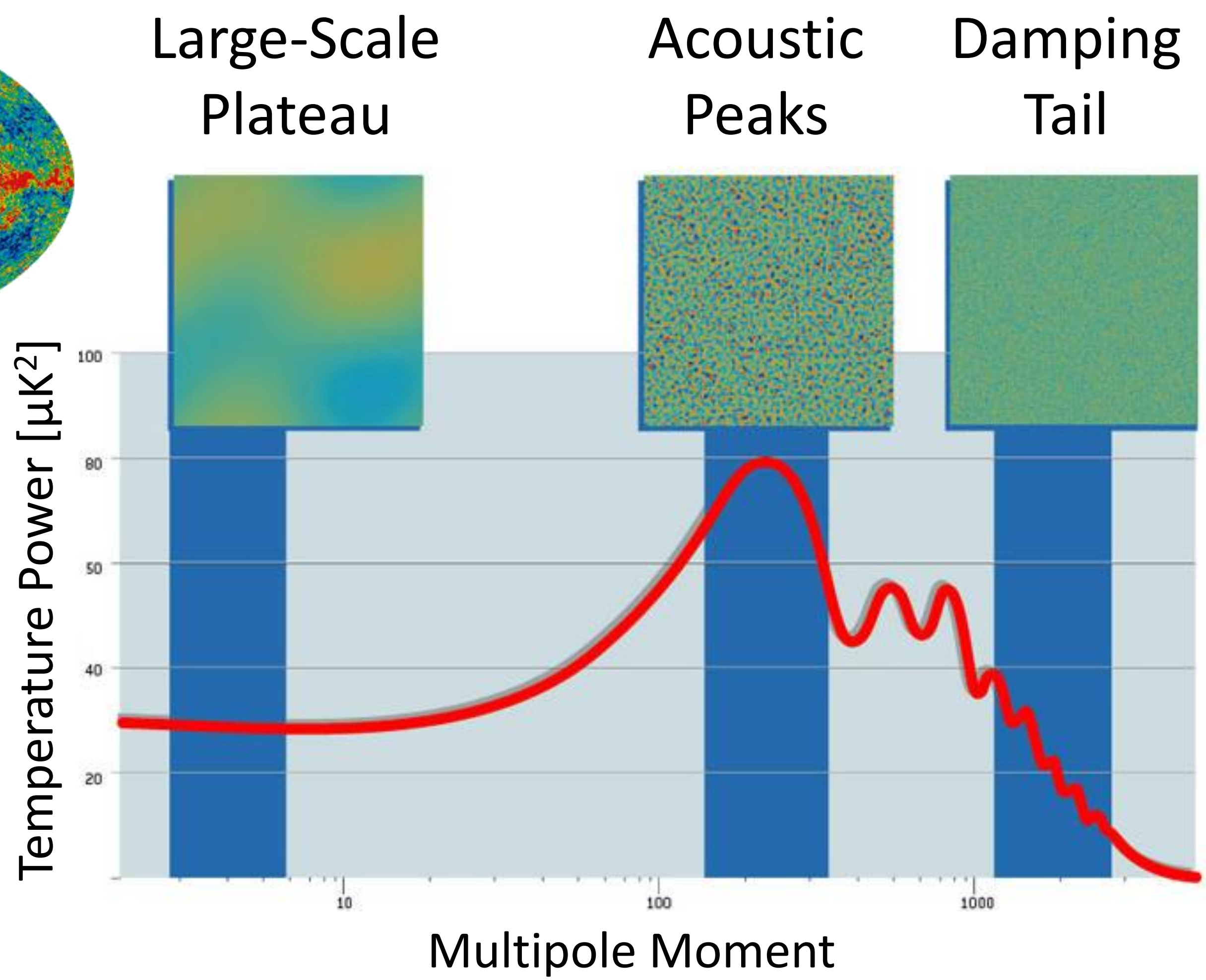
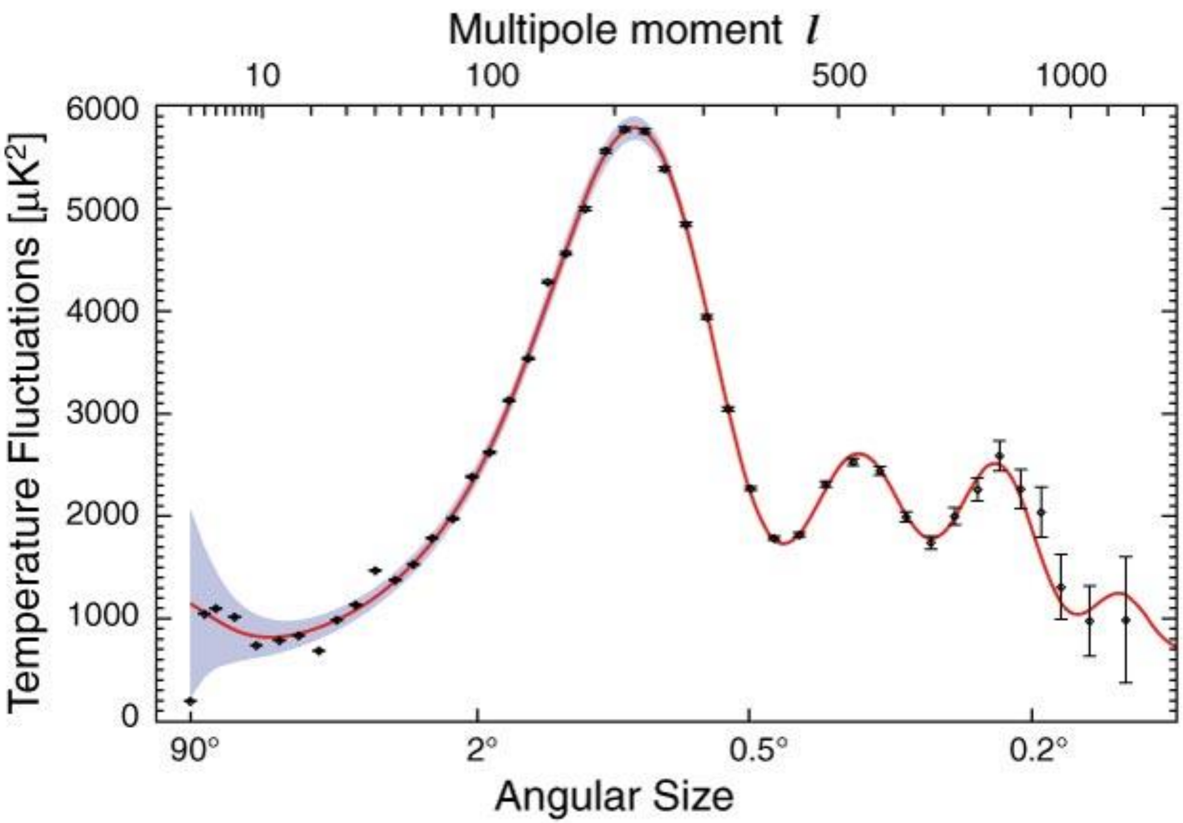


Image Credits: NASA/WMAP, Hu/Scientific American

Standard Model of Cosmology

Flat ΛCDM Universe



Primordial Fluctuations

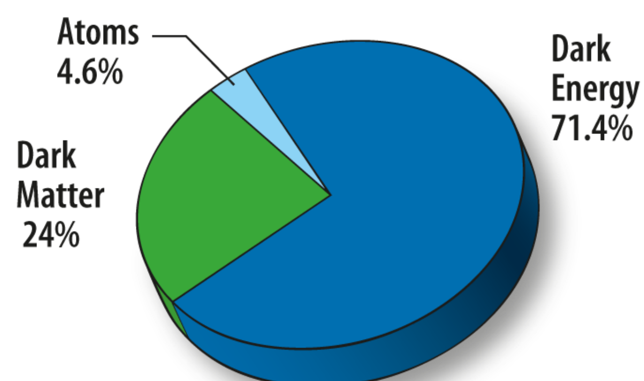
$A_s \quad n_s$

Contents

$\omega_b \quad \omega_c \quad \theta_s$

Rescattering

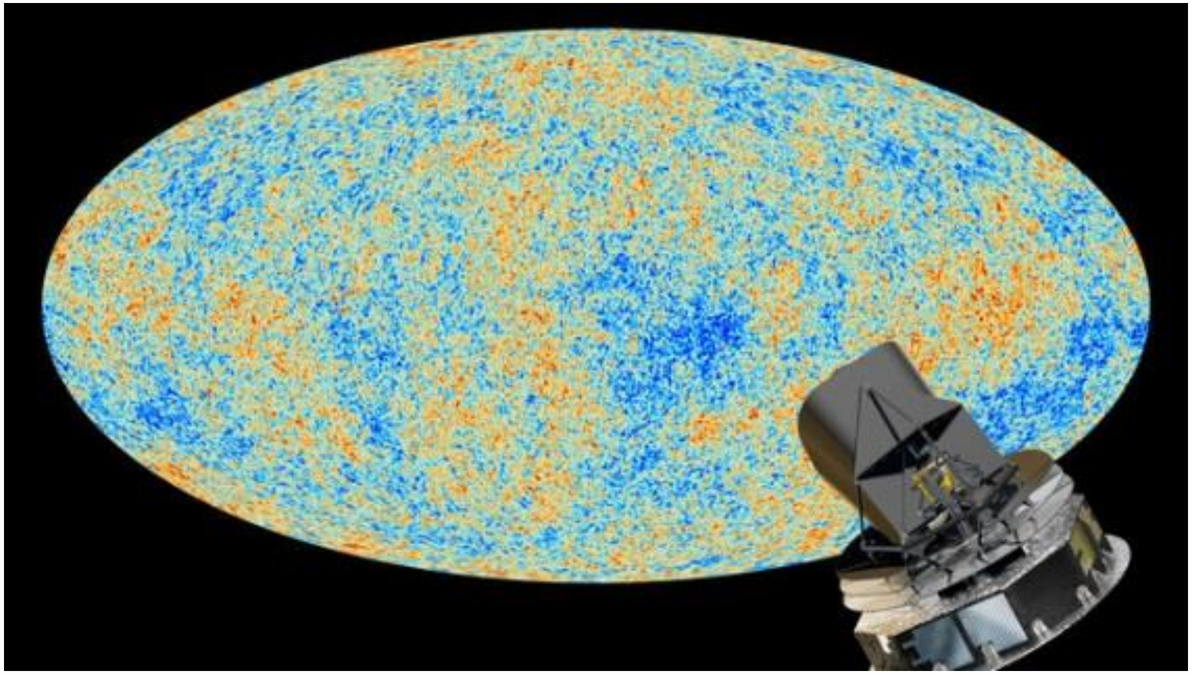
τ



WMAP (2008)

Digging Deeper

Beyond the Power Spectrum - Planck - 2009-2013



planck

Image Credit: ESA

Gravitational Lensing

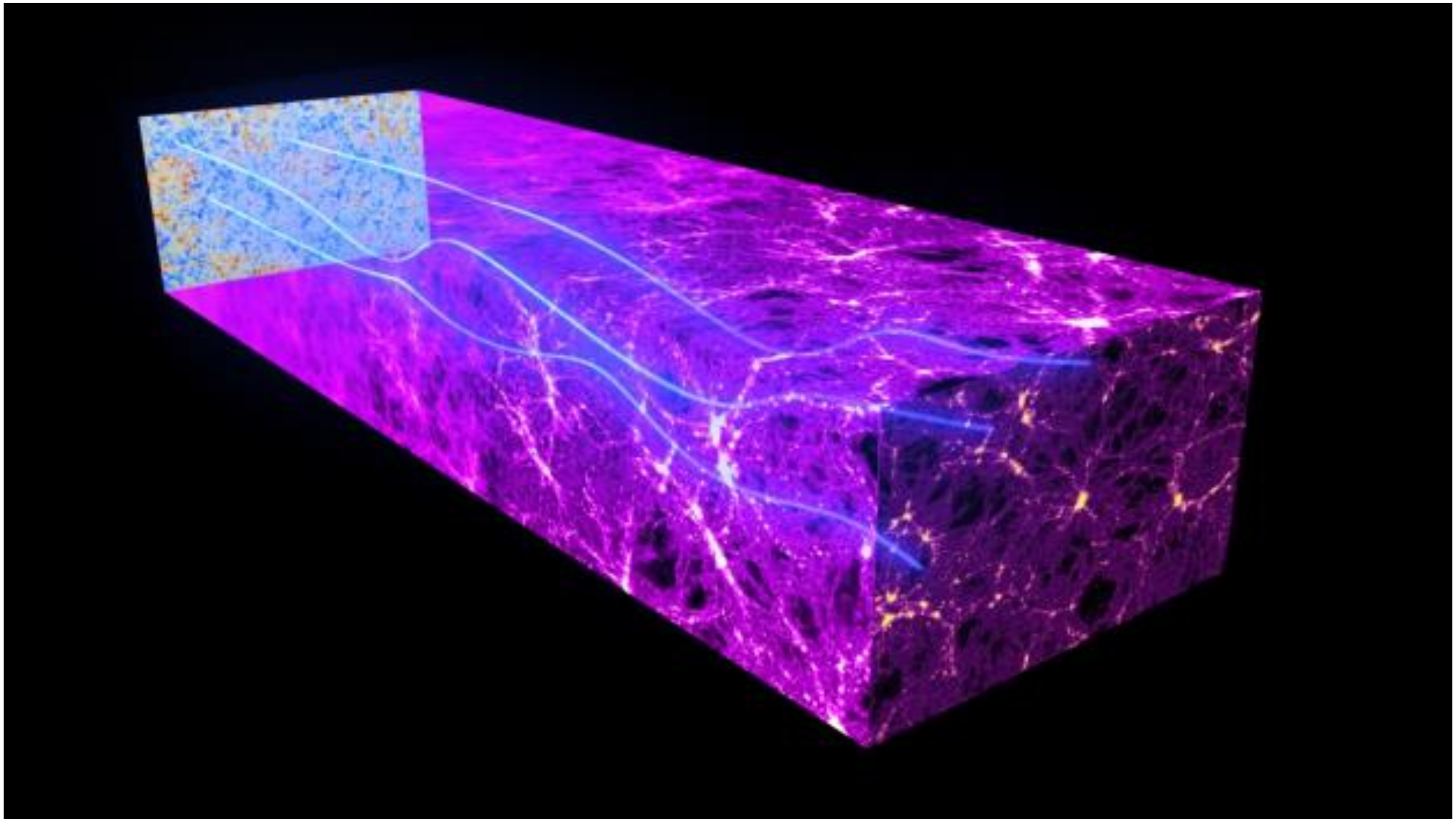
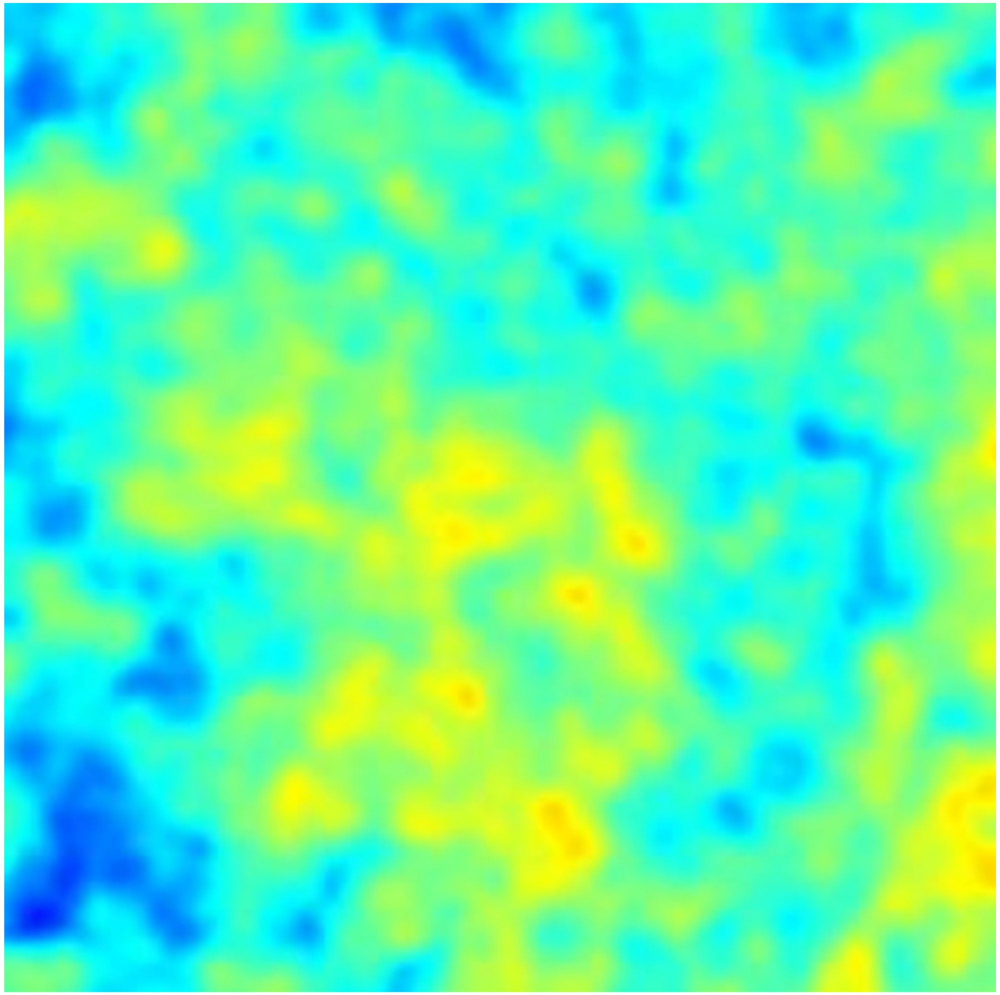


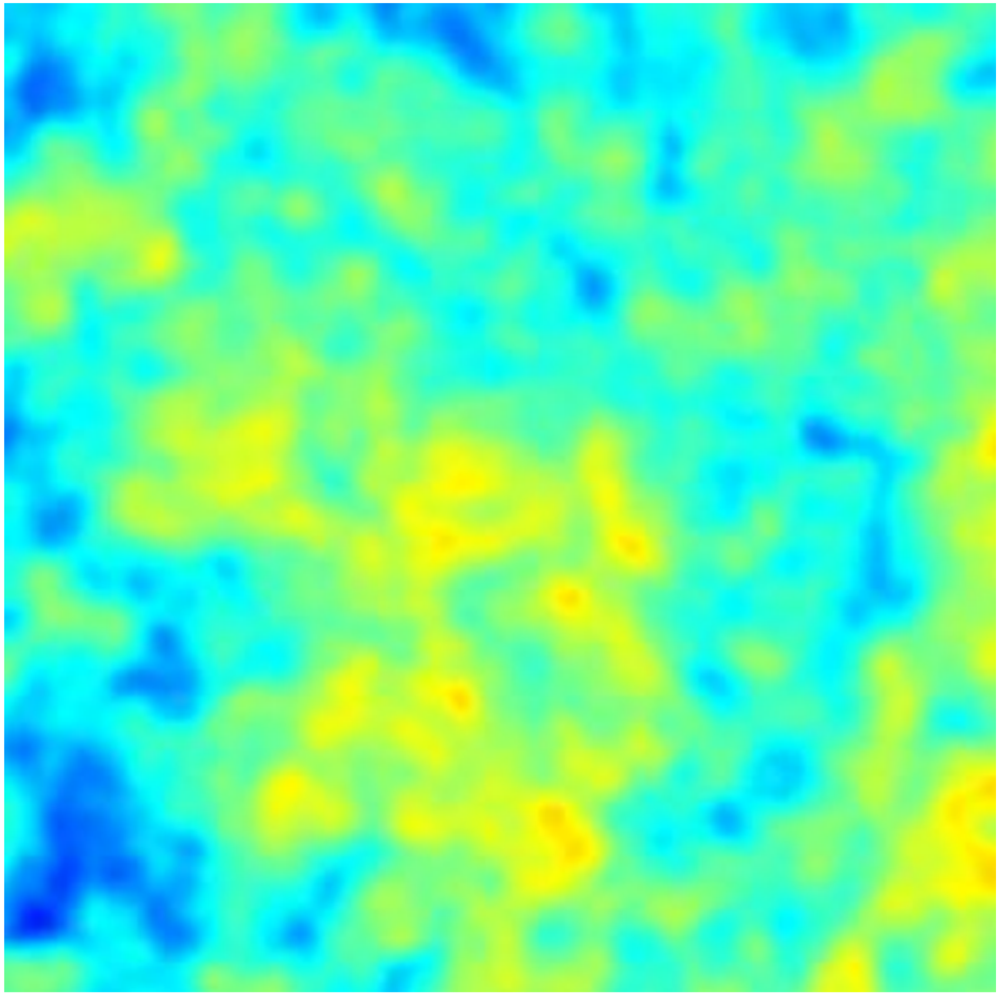
Image Credit: ESA

CMB Lensing



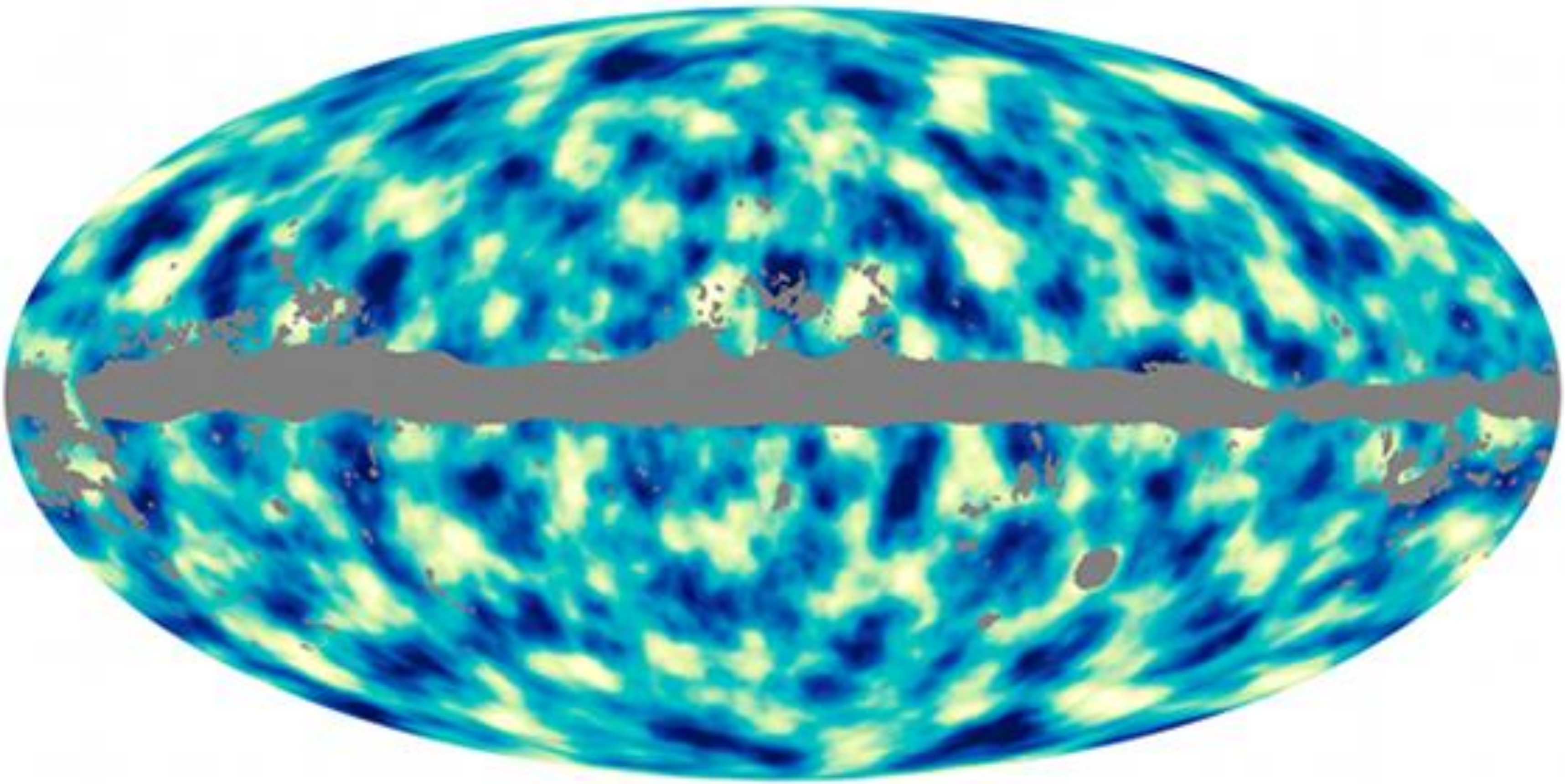
Hu and Okamoto (2002); Image Credit: Sigurd Naess

CMB Lensing



Hu and Okamoto (2002); Image Credit: Sigurd Naess

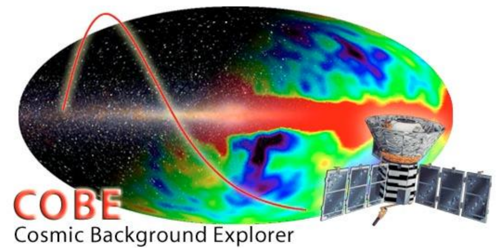
Illuminating Dark Matter

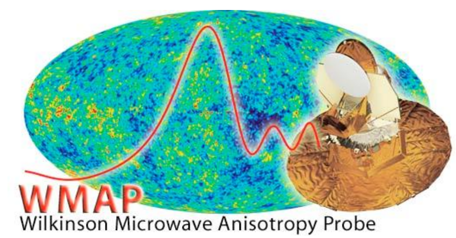


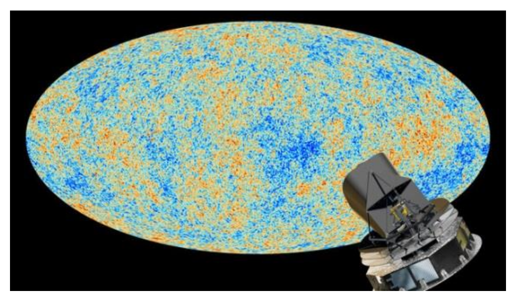
Planck (2013)

CMB Timeline

- 1948 – Theoretical Prediction
- 1964 – First Detection
- 1992 – Spectrum and Anisotropies
- 2003 – ΛCDM Cosmology
- 2013 – Beyond the Power Spectrum
- 2018+ – Beyond the Standard Model







SIMONSOBSERVATORY

Next Generation CMB Experiments

SIMONSOBSERVATORY

CMB-S4
Next Generation CMB Experiment

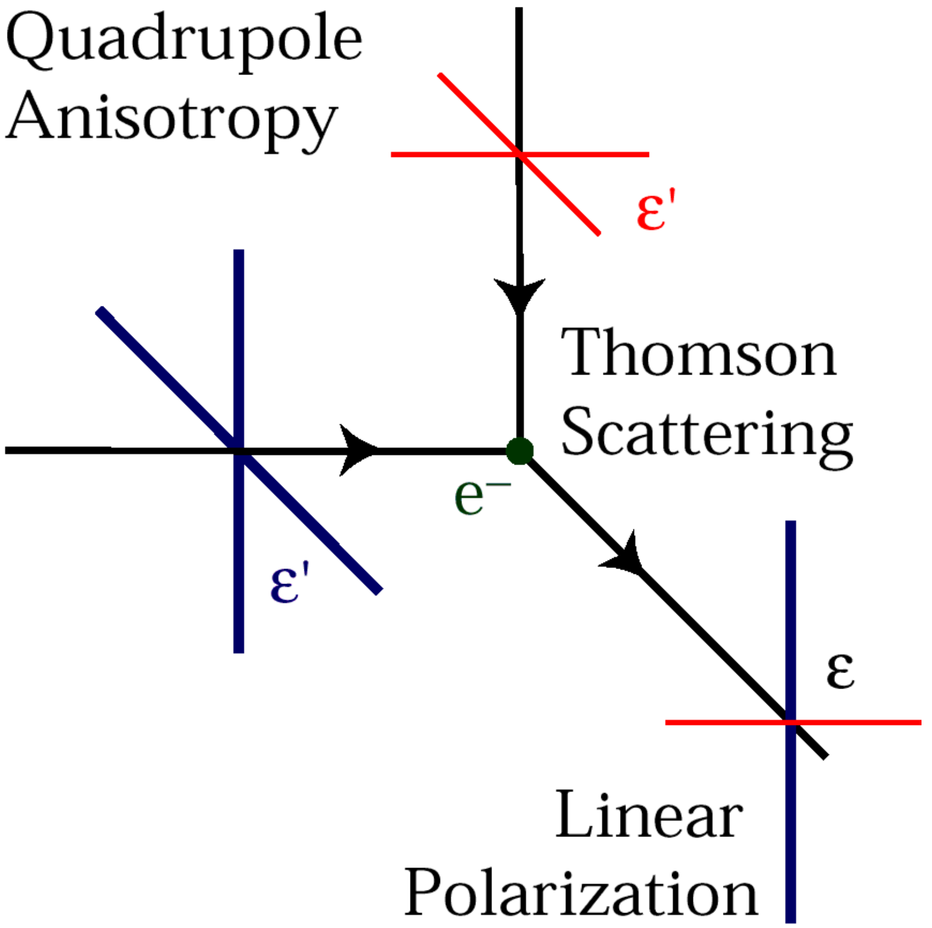
- Observing 2021-2022
- Telescope array in Atacama Desert in Chile

- Observing mid-2020s
- Multiple telescopes in Atacama Desert and at South Pole

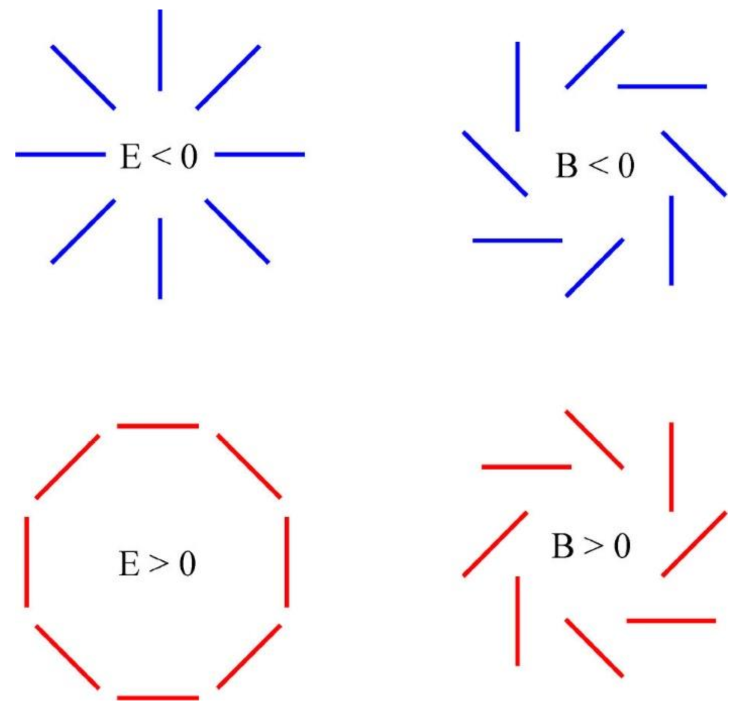
Science Goals:

- **Fundamental Physics:** Primordial Gravitational Waves, Neutrino Properties, Light Relics
- **Astrophysics:** Mass Maps, Clusters, Cross-Correlations

CMB Polarization

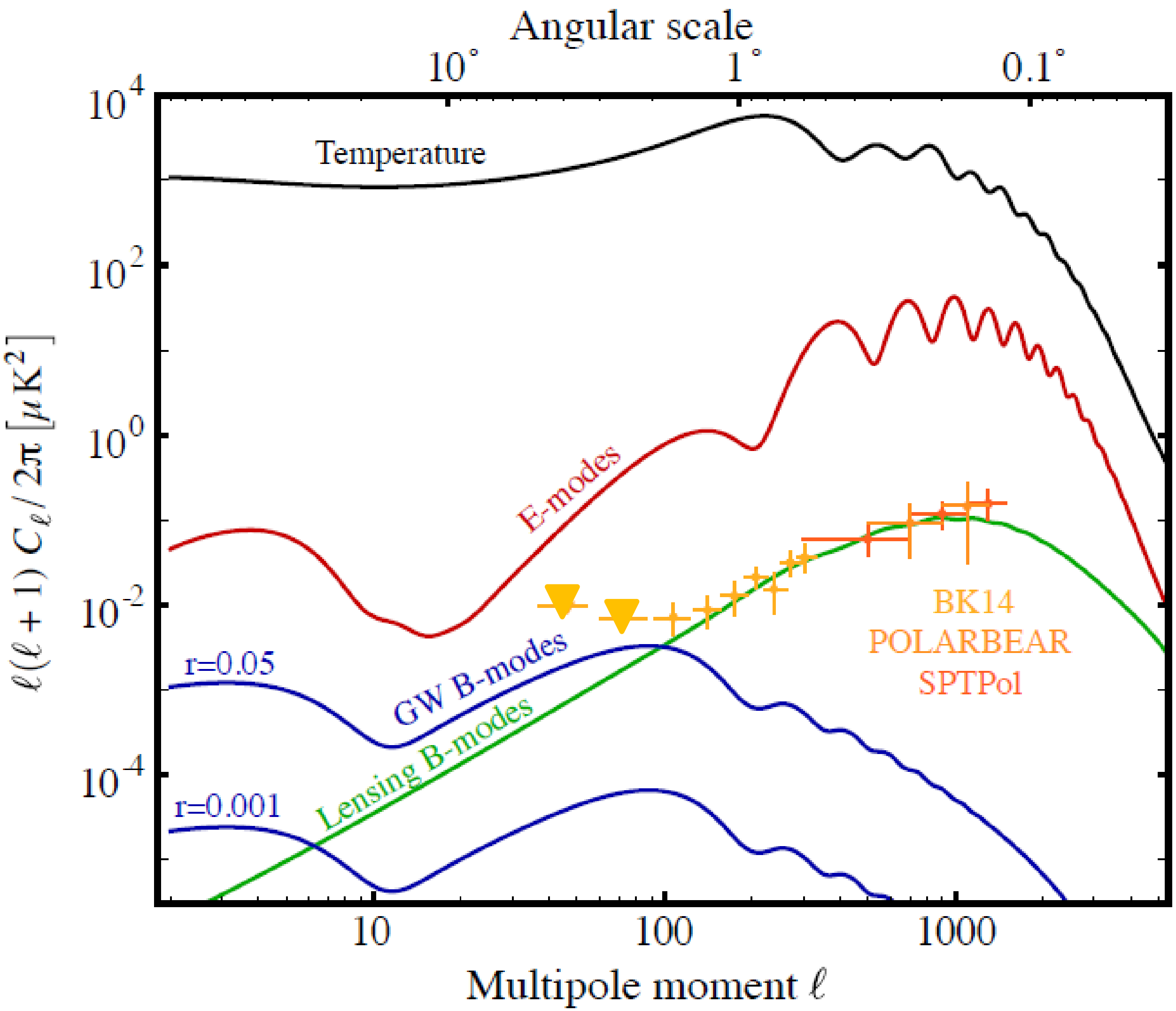


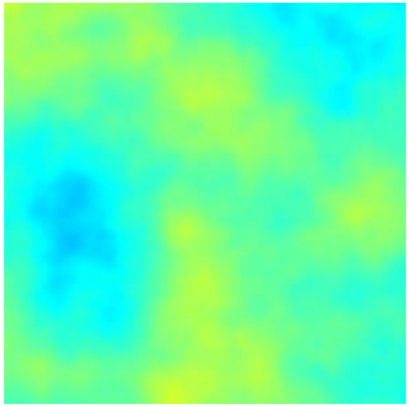
Density Perturbations → T, E
Gravitational Waves → T, E, B



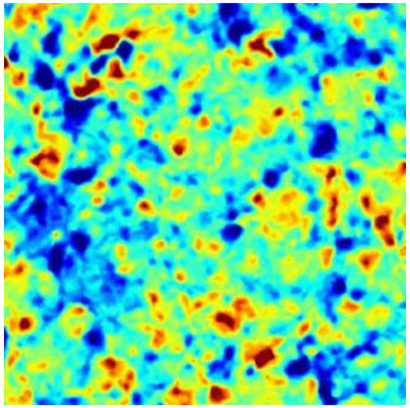
Kamionkowski, Kosowsky, Stebbins (1997); Seljak, Zaldarriaga (1997)
Image Credit: Hu

Primordial Gravitational Waves





Unlensed
B Modes

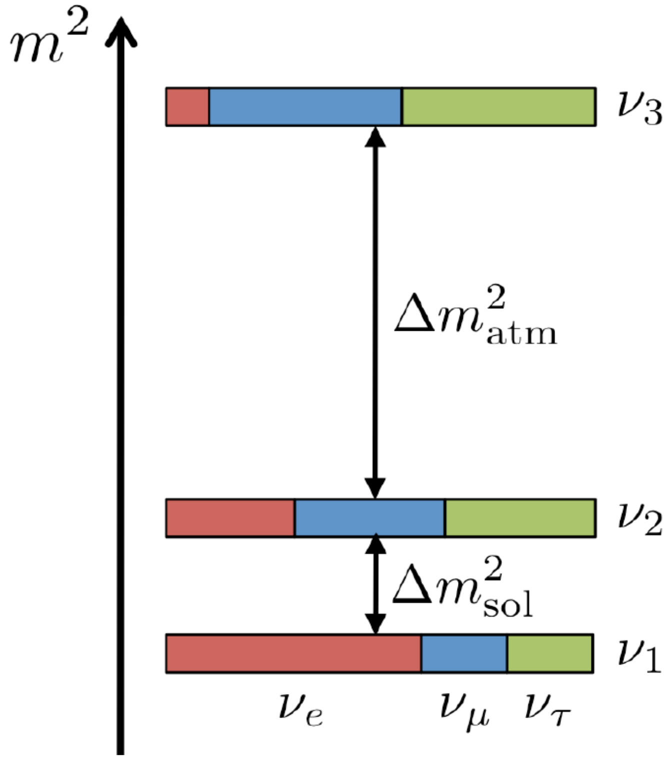


Lensed
B Modes

Zaldarriaga, Seljak (1998); Kesden, Cooray, Kamionkowski (2002); Lyth (1997) ; CMB-S4 Science Book (including JM) (2016)

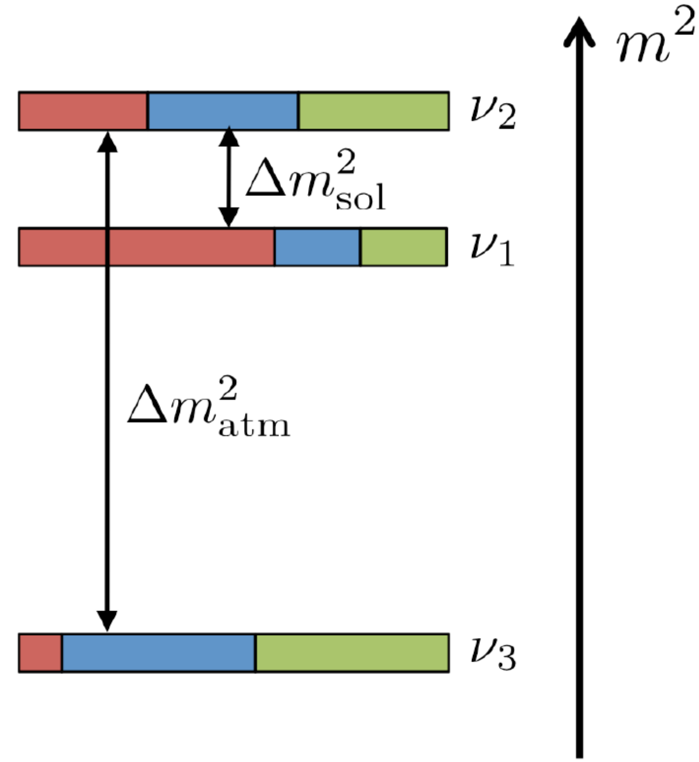
Neutrino Mass

normal hierarchy (NH)



$$\sum m_\nu \gtrsim 58 \text{ meV}$$

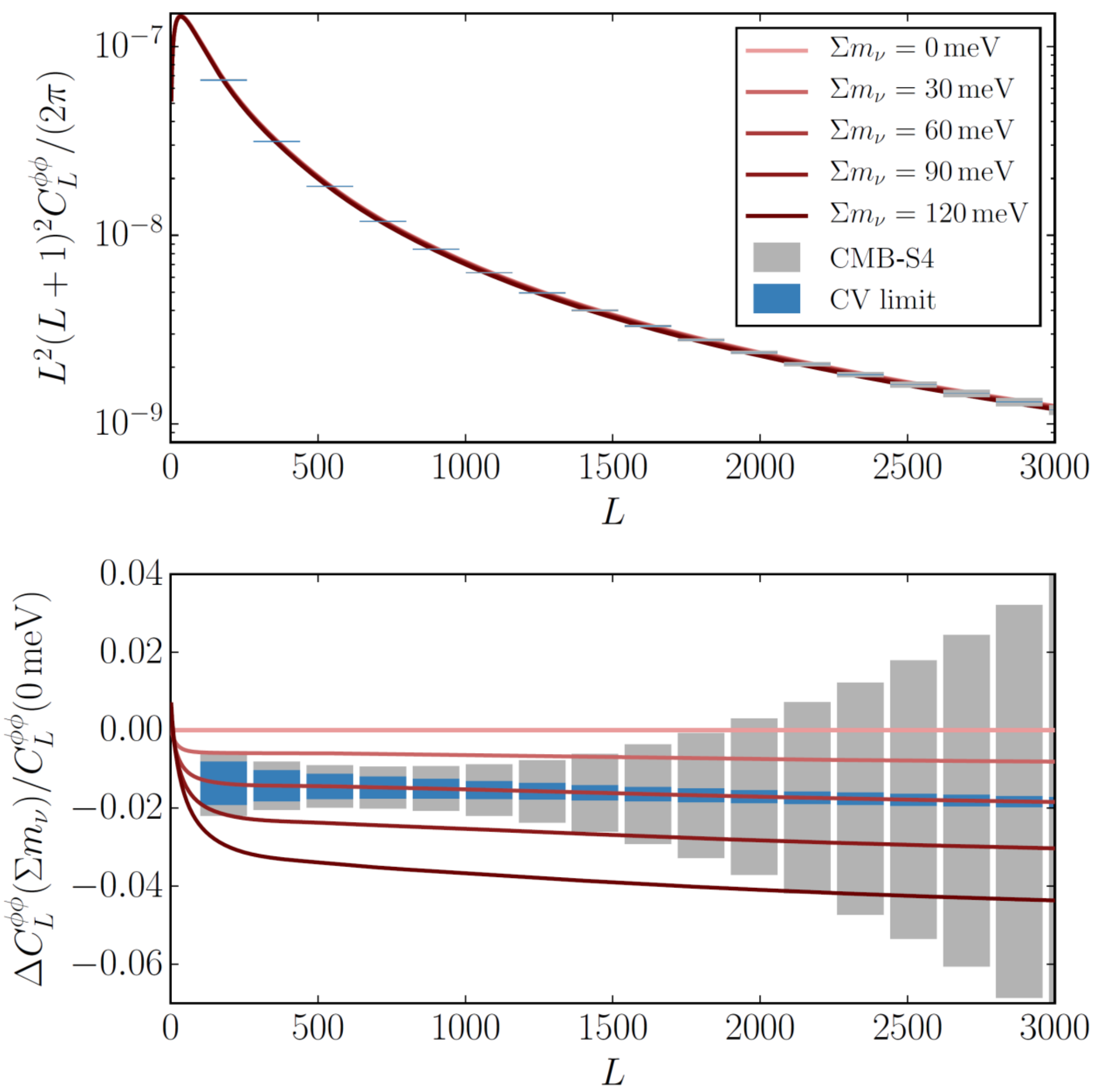
inverted hierarchy (IH)



$$\sum m_\nu \gtrsim 105 \, \text{meV}$$

Super-Kamiokande (1999); Sudbury Neutrino Observatory (2001);
CMB-S4 Science Book (including JM) (2016)

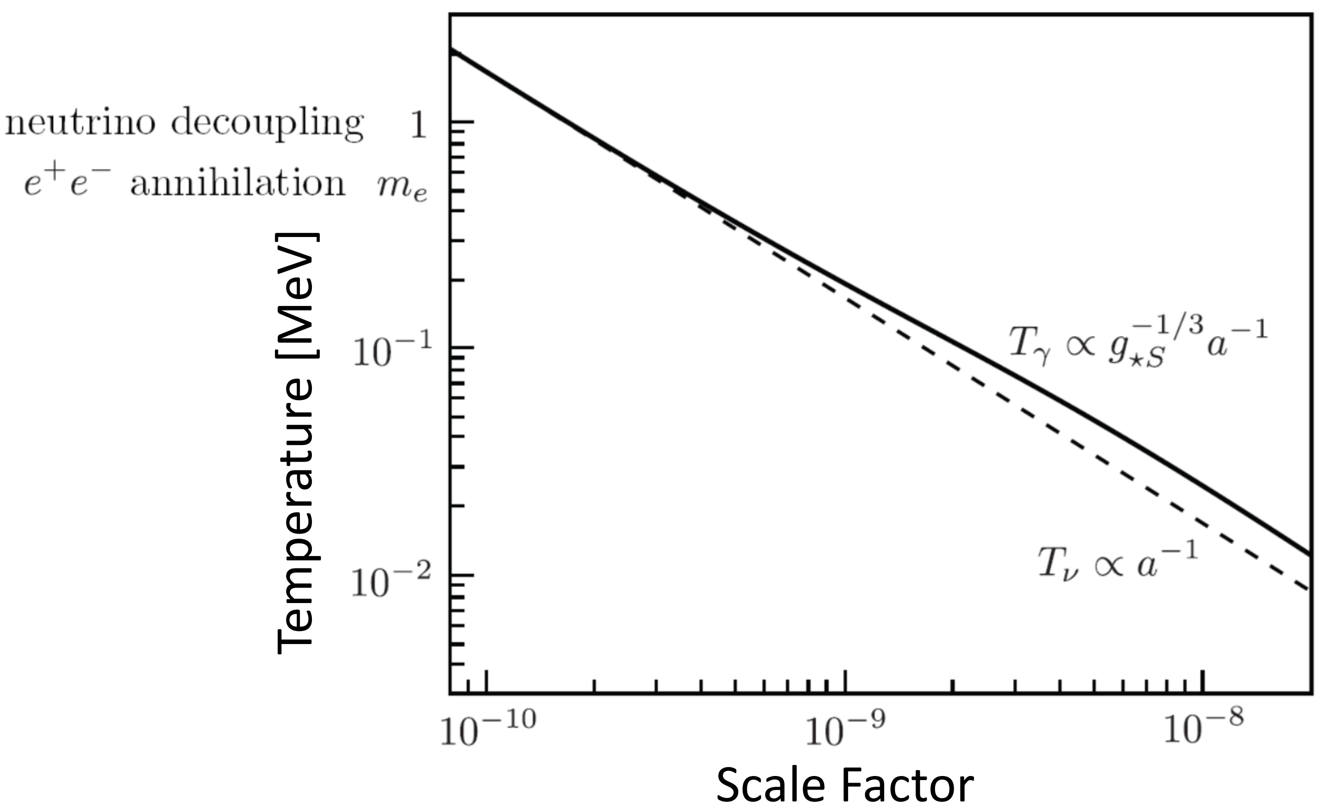
Effect of Neutrino Mass



Eisenstein, Hu (1997); Kaplinghat, Knox, Song (2003); CMB-S4 Science Book (including JM) (2016)

Light Relics

$$\rho_{\rm r} = \rho_\gamma \left(1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\rm eff} \right)$$



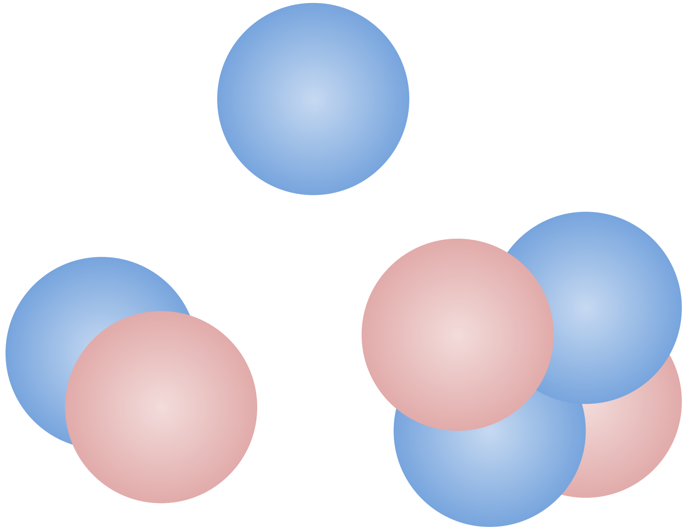
$$N_{\rm eff}^{\rm SM} = 3.046$$

PDG (2013); Mangano, et al. (2005); de Salas, Pastor (2016)

Observing Light Relics

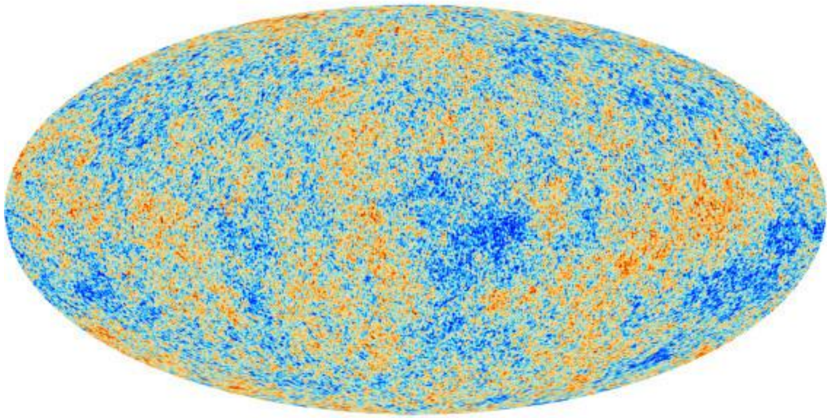
Primordial Abundances

$$N_{\rm eff}^{\rm BBN} = 3.28 \pm 0.28$$



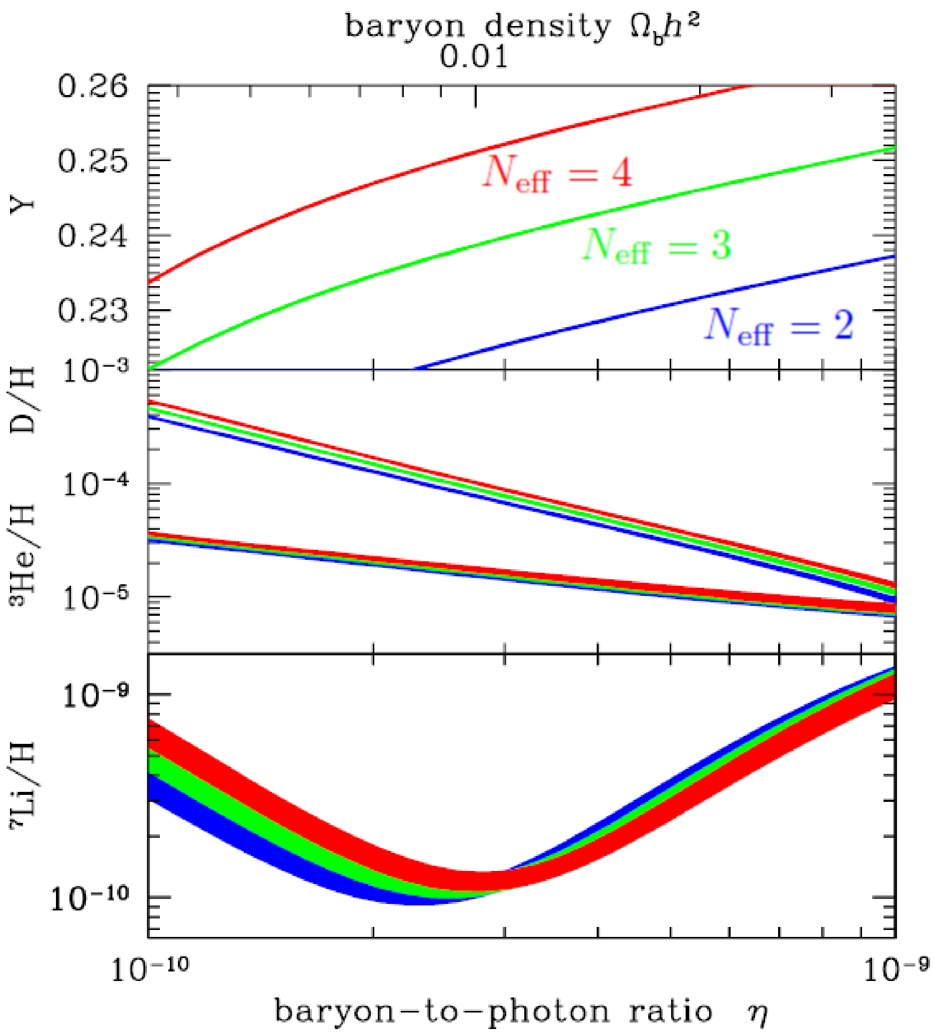
CMB Measurements

$$N_{\rm eff}^{\rm CMB} = 3.04 \pm 0.18$$



Cooke, et al. (2014); Cyburt, et al. (2015), Planck (2015); Fischler, JM (2010); Millea, Knox, Fields (2015)

Big Bang Nucleosynthesis



$$N_{\rm eff}^{\rm BBN} = 3.28 \pm 0.28$$

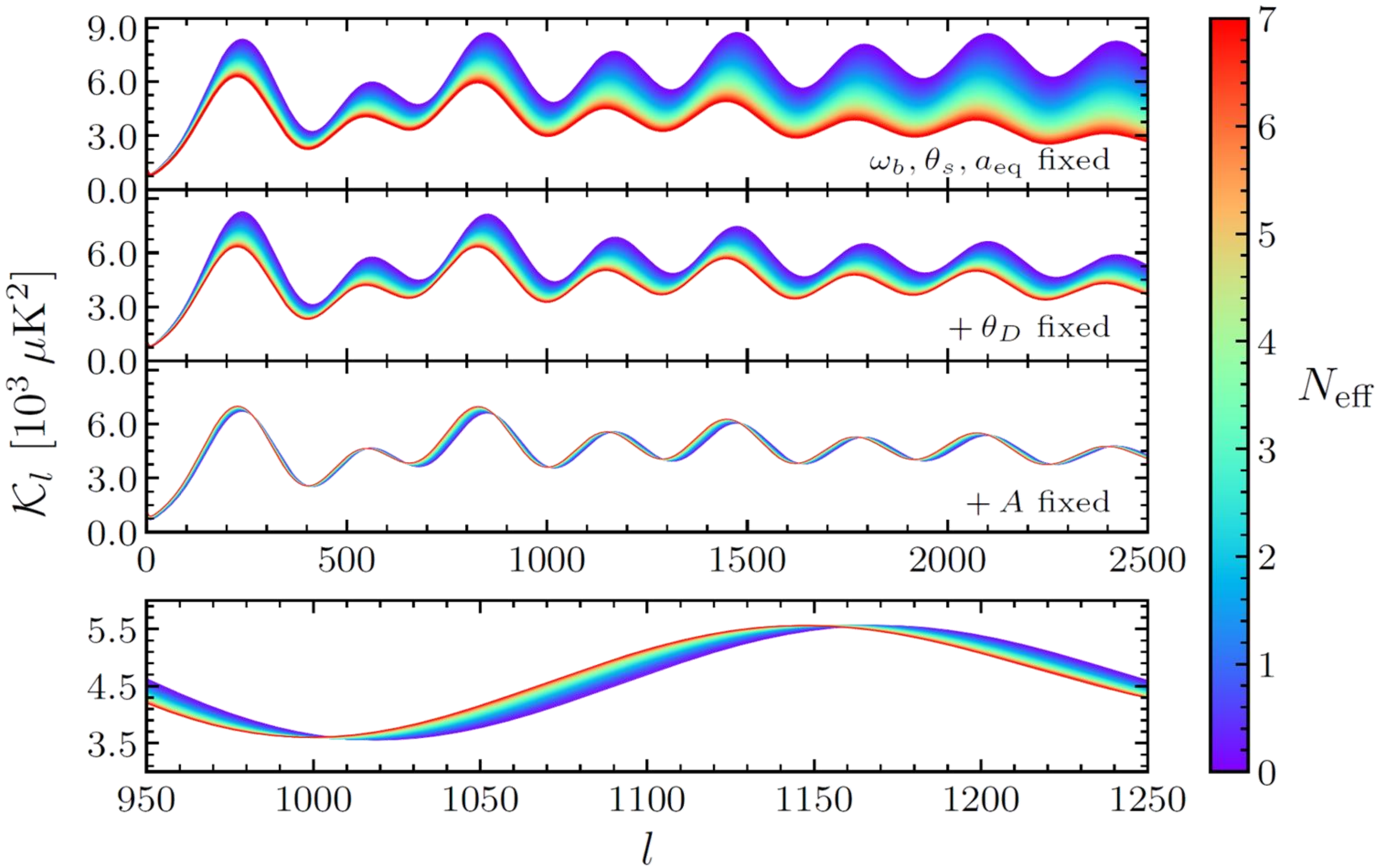
Increased N_{eff} leads to:

- Increased Expansion Rate
- Decreased Time for Free Neutron Decay
- More Neutrons Available for Deuterium Formation
- Increased Helium-4 Density

PDG (2013); Cooke, et al. (2014); Cyburt, et al. (2015); Bond, Fuller, Grohs, JM, Wilson (In prep.)

Effects of Light Relics on the CMB

$$N_{\rm eff}^{\rm CMB} = 3.04 \pm 0.18$$



Damping

Amplitude Shift

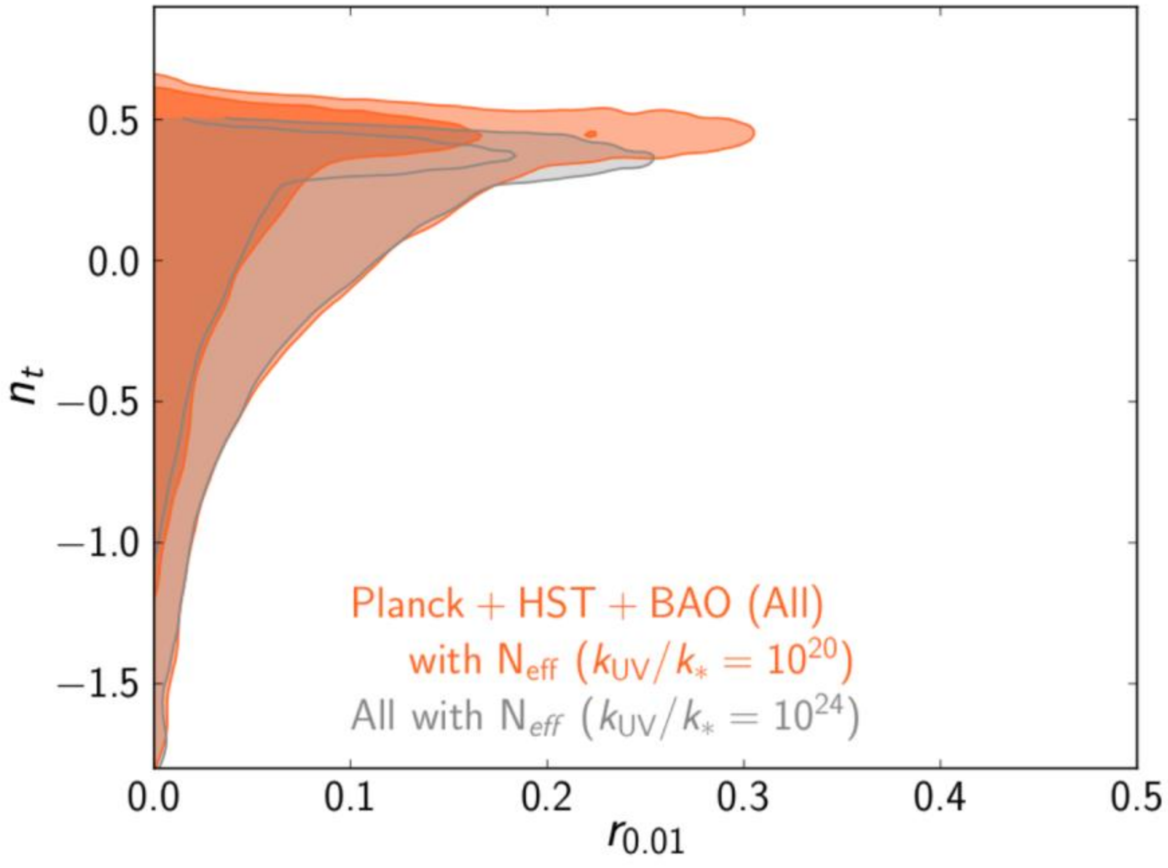
Phase Shift

Bashinsky, Seljak (2004); Hou, Keisler, Knox, Millea, Reichardt (2012); Follin, Knox, Millea, Pan (2015); Baumann, Green, JM, Wallisch (2015); Baumann, Green, Wallisch (2018)

Dark Radiation

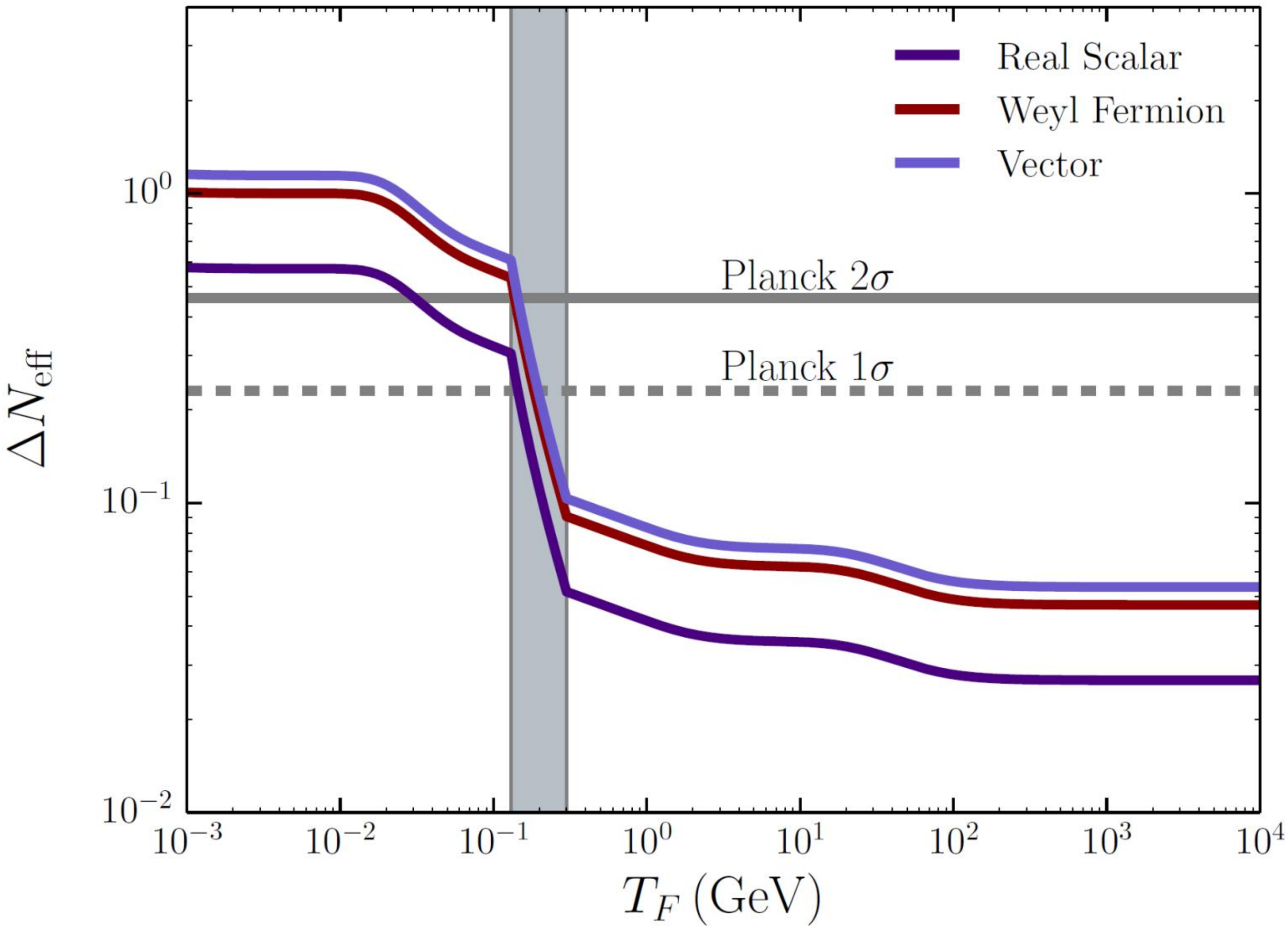
- Axions
- Sterile neutrinos
- Dark photons
- Gravitinos
- Gravitational waves

Gravitational Wave Constraints with N_{eff}



Chu, Cirelli (2006); Boyle, Buonanno (2007); Ackerman, et al. (2008); Steigman (2012); Meerburg, Hadzhiyska, Hlozek, JM (2015) …

Thermal Relics and N_{eff}



Fermions

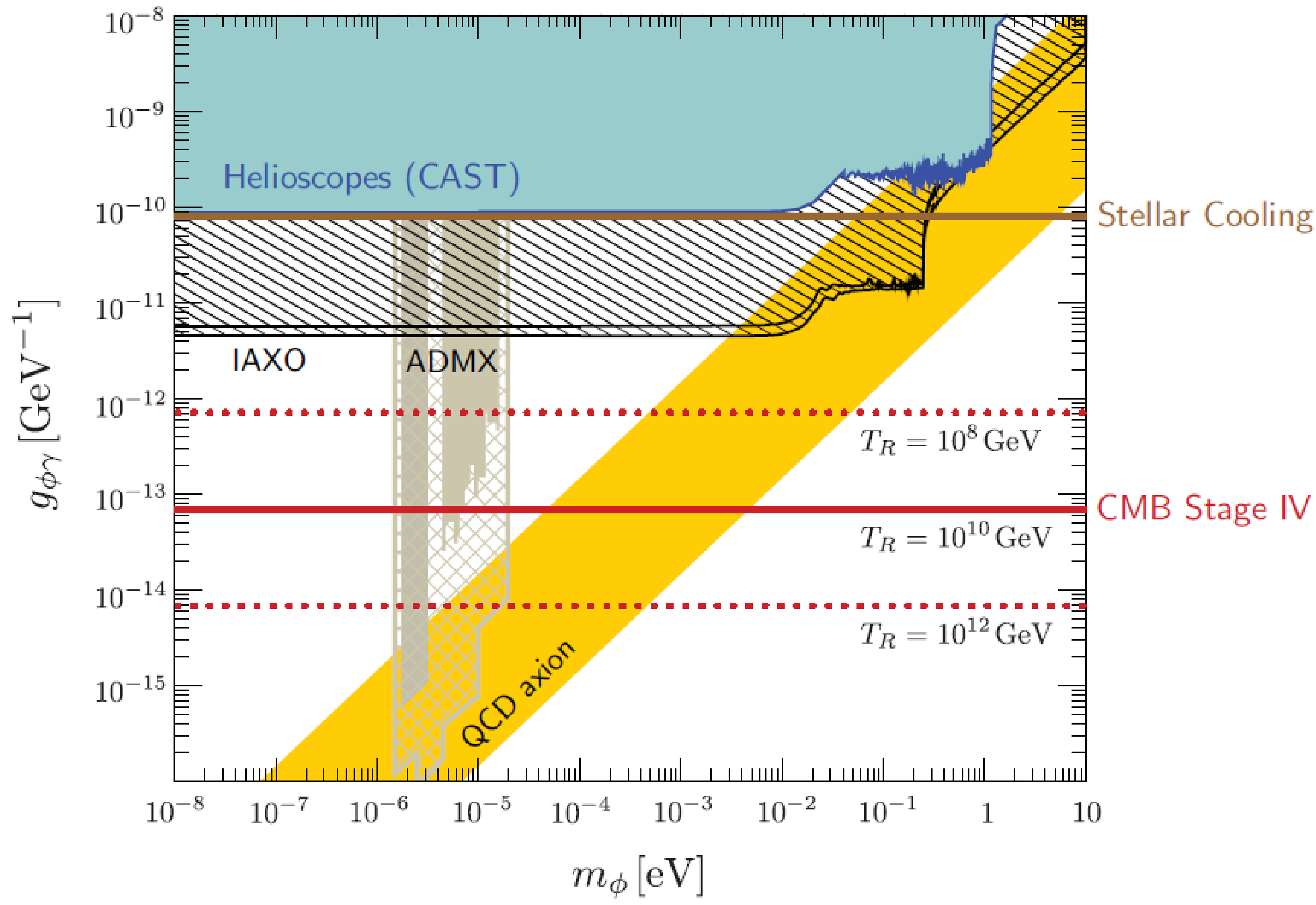
$$\Delta N_{\text{eff}} \geq 0.047$$

Scalars

$$\Delta N_{\text{eff}} \geq 0.027$$

Brust, Kaplan, Walters (2013); Chacko, Cui, Hong, Okui (2015);
Adshead, Cui, Shelton (2016); CMB-S4 Science Book (including JM) (2016)

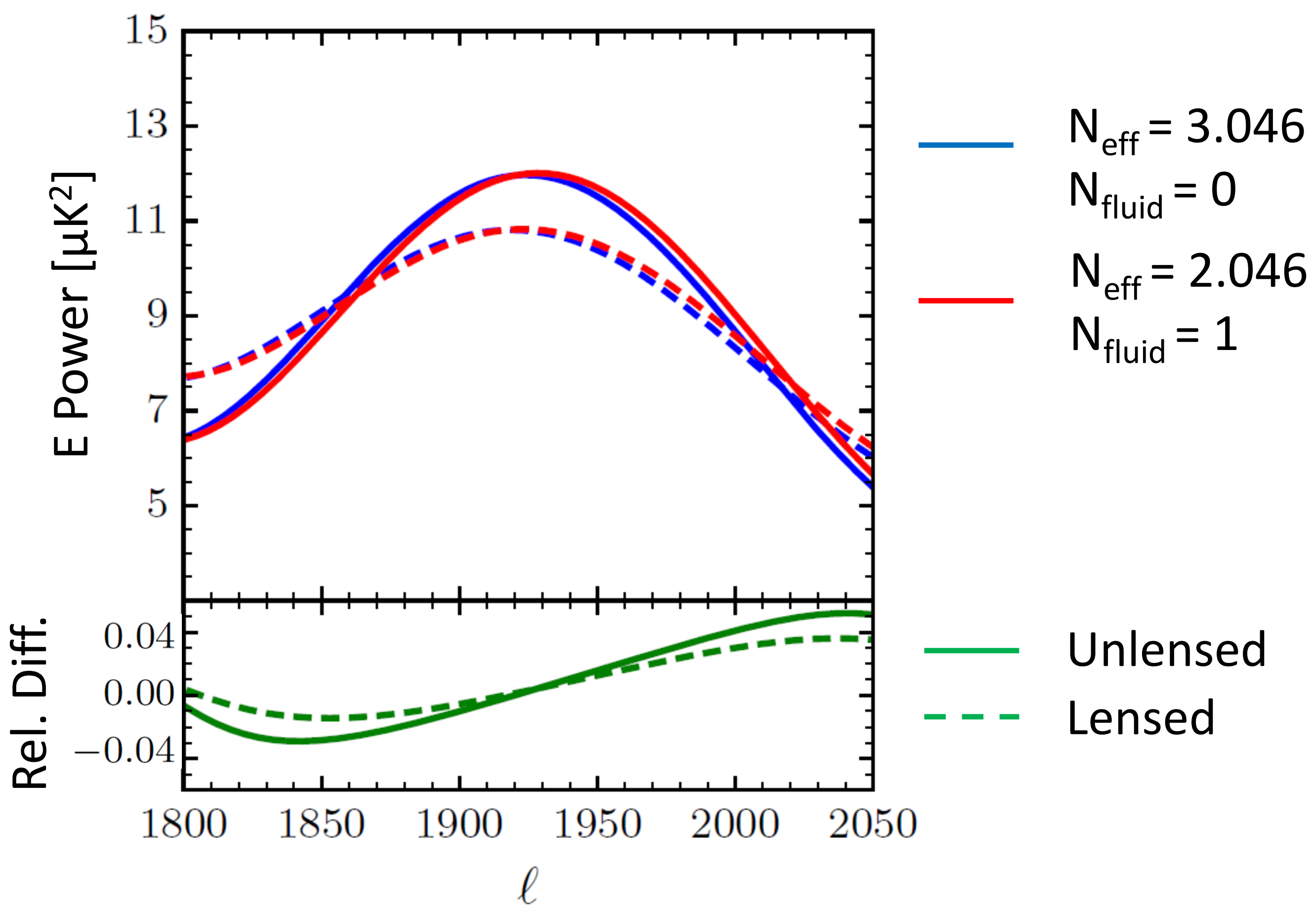
Axion Constraints



Baumann, Green, Wallisch (2016)

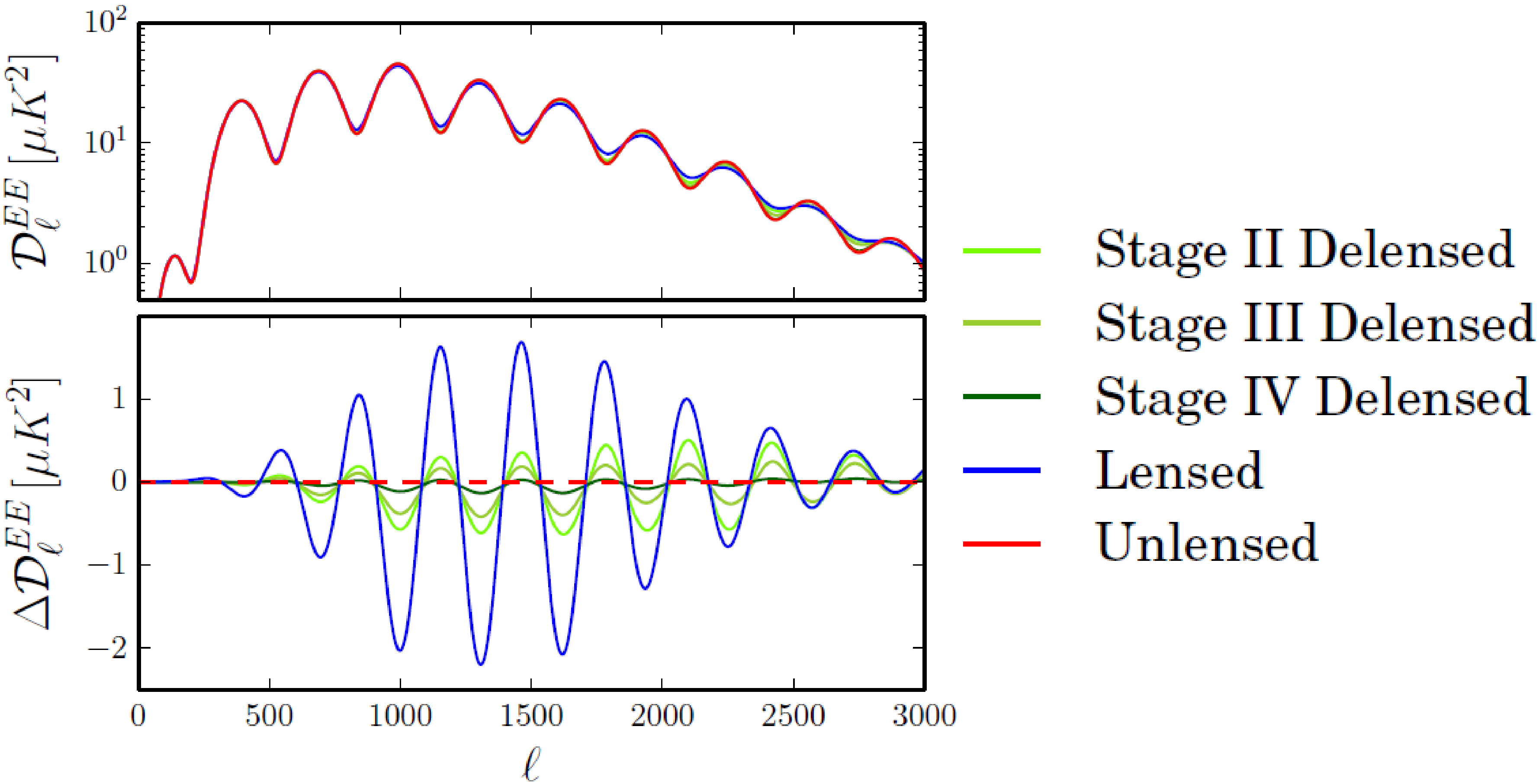
The Special Role of the Phase Shift

- Unique
- Robust
- Constraining



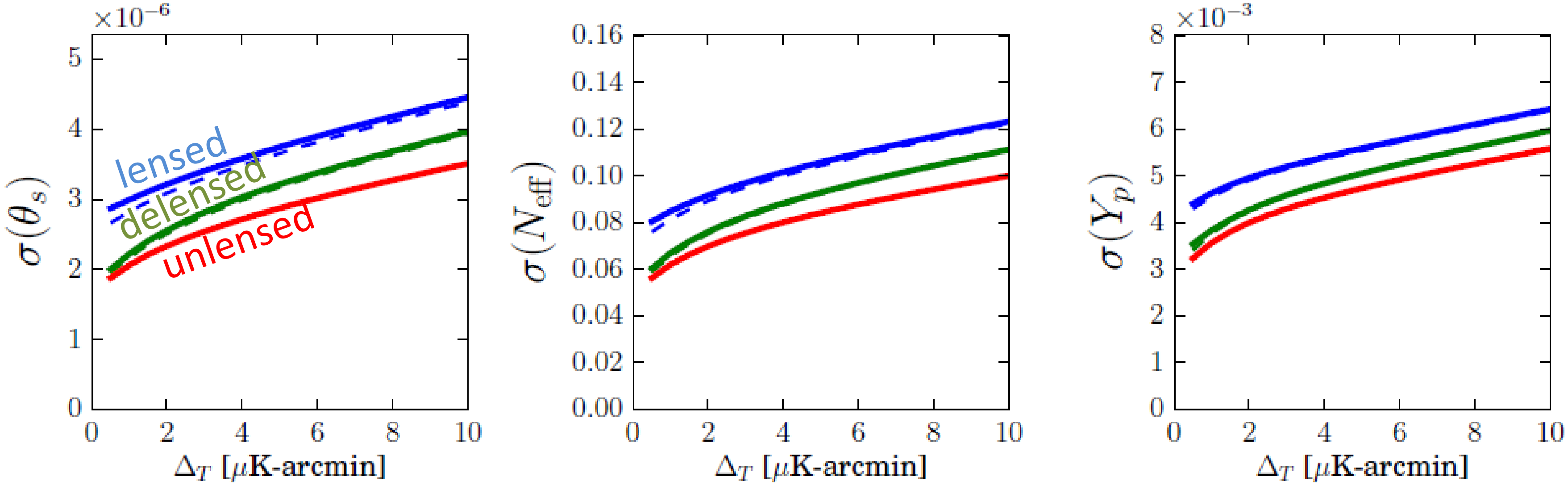
Bashinsky, Seljak (2004); Baumann, Green, JM, Wallisch (2015)

Delensing the CMB



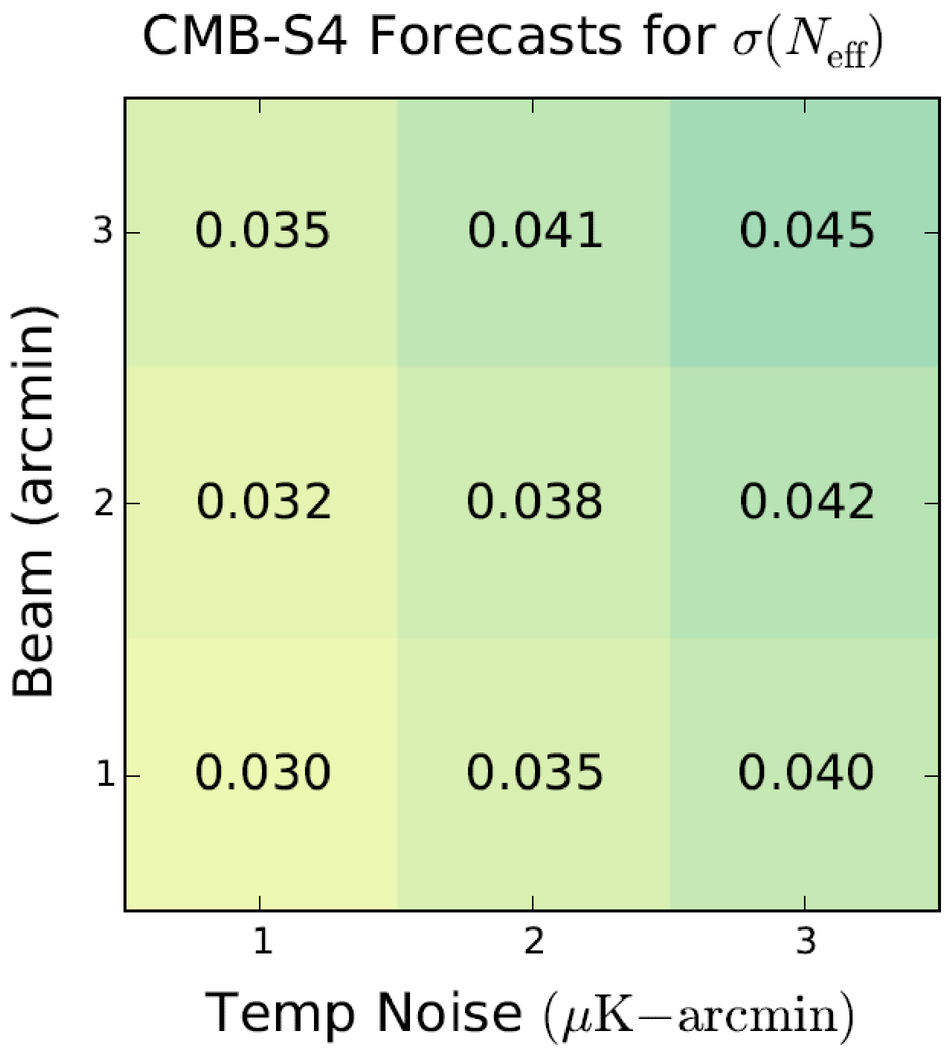
Green, JM, van Engelen (2016)

Benefits of Delensing



Green, JM, van Engelen (2016)

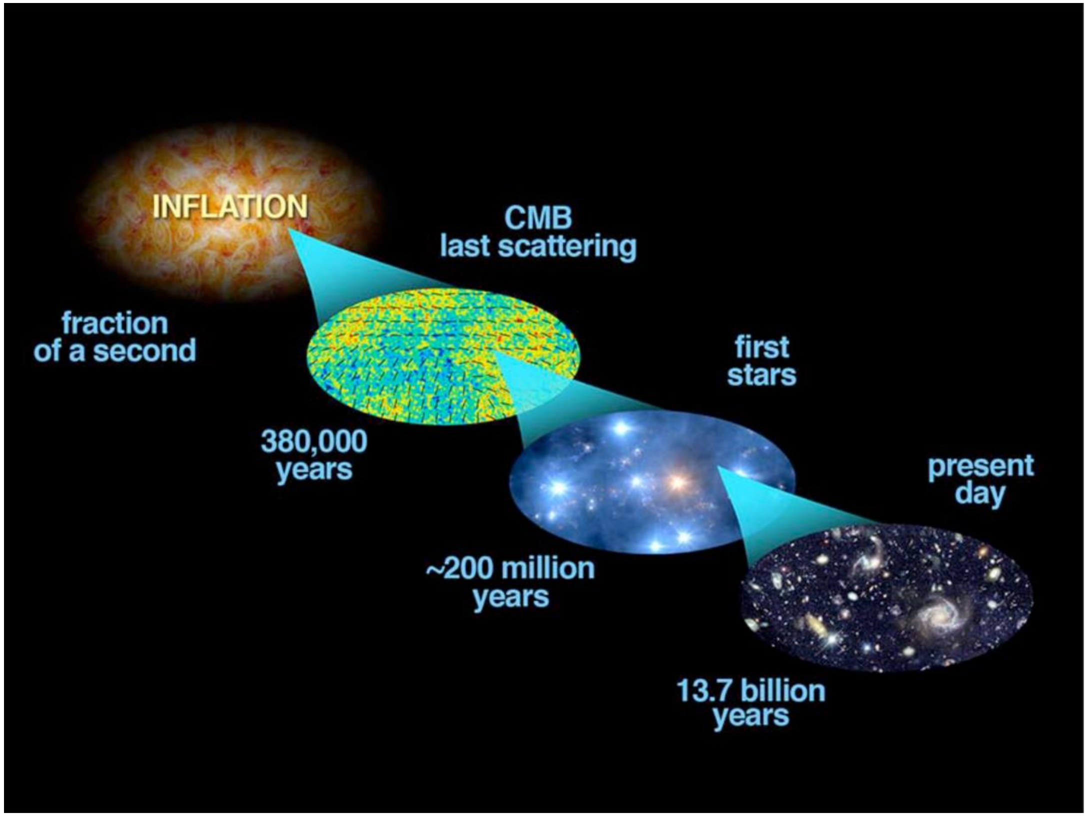
CMB-S4 N_{eff} Forecasts



CMB-S4 Science Book (including JM) (2016)

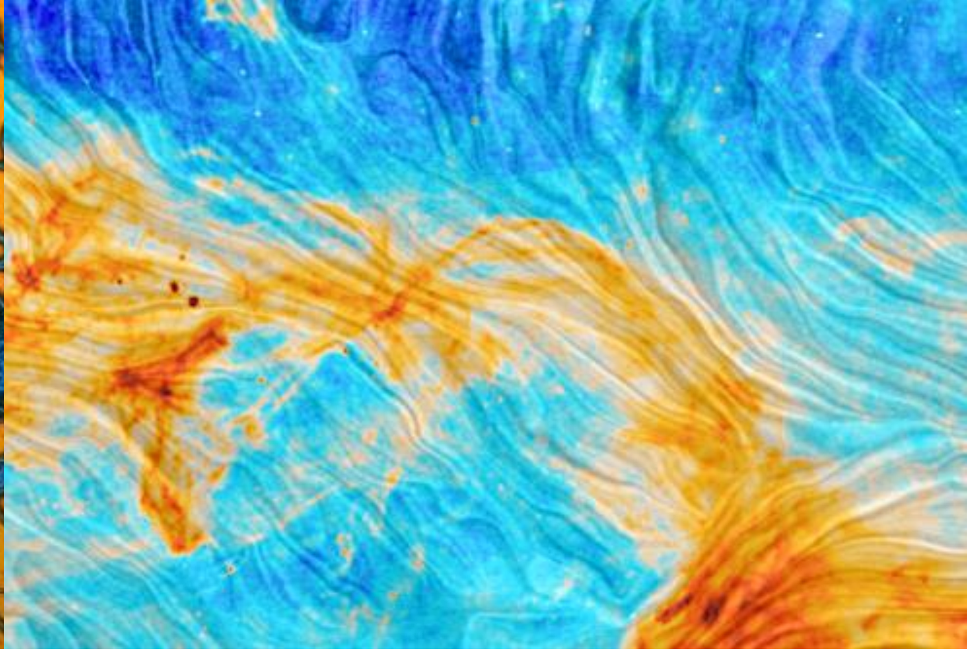
Other CMB Targets

Cosmic Inflation



Astrophysics and Cross-Correlations

Image Credit: Bock, et al (2006)

Thank You!

Image Credits: BEBC/CERN and Planck/ESA