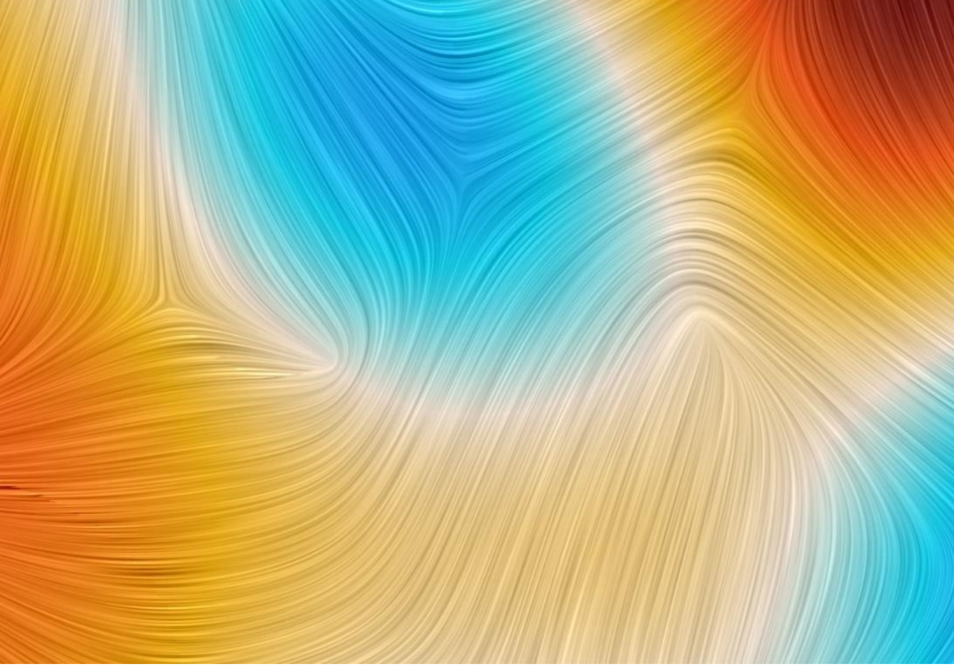
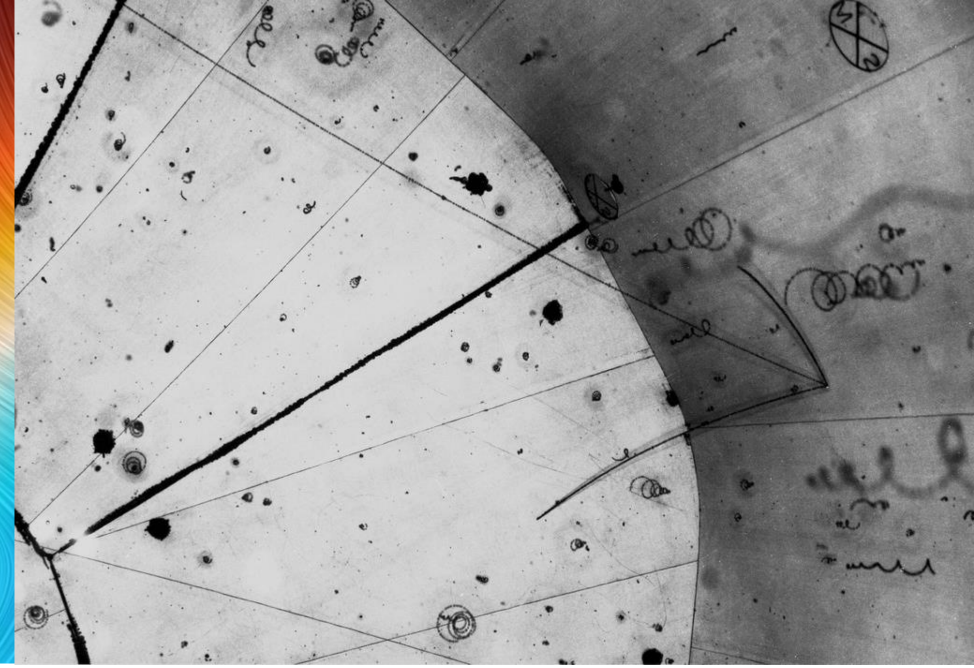




Neutrinos in the CMB

Joel Meyers

SMU

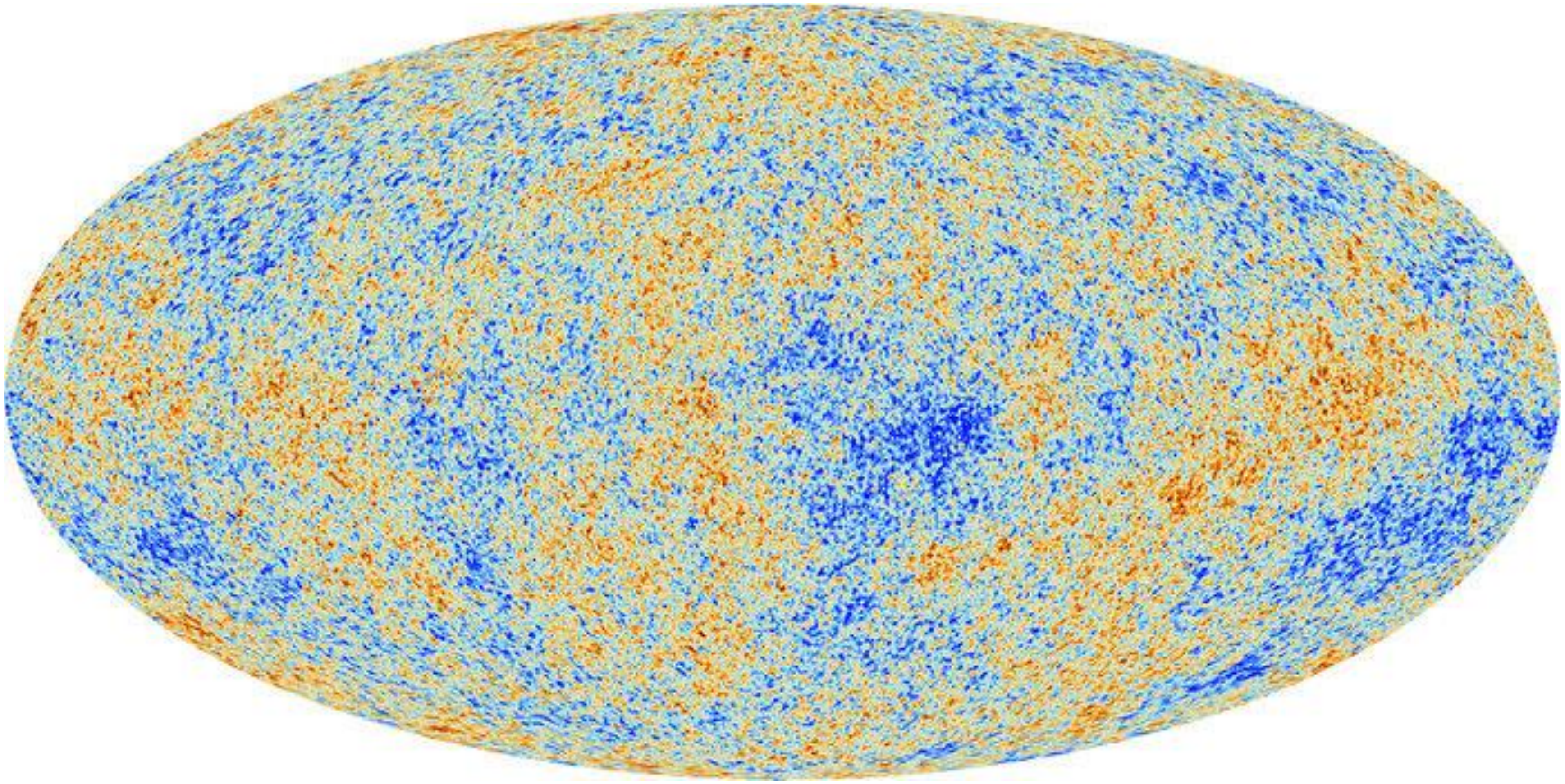
Topics in Cosmic Neutrino Physics

Fermilab

October 9, 2019

Image Credits: Planck, ANL

Cosmic Microwave Background (CMB)



Planck (2013)

Next Generation CMB Experiments

SIMONS OBSERVATORY

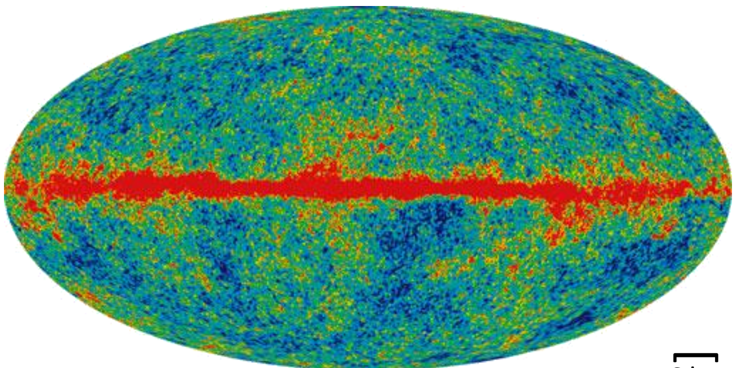
CCAT-prime

CMB-S4
Next Generation CMB Experiment

LiteBIRD

PICO
PROBE OF INFLATION AND COSMIC ORIGINS

CMB Angular Power Spectrum



Harmonic Transform of Two-Point Correlation Function

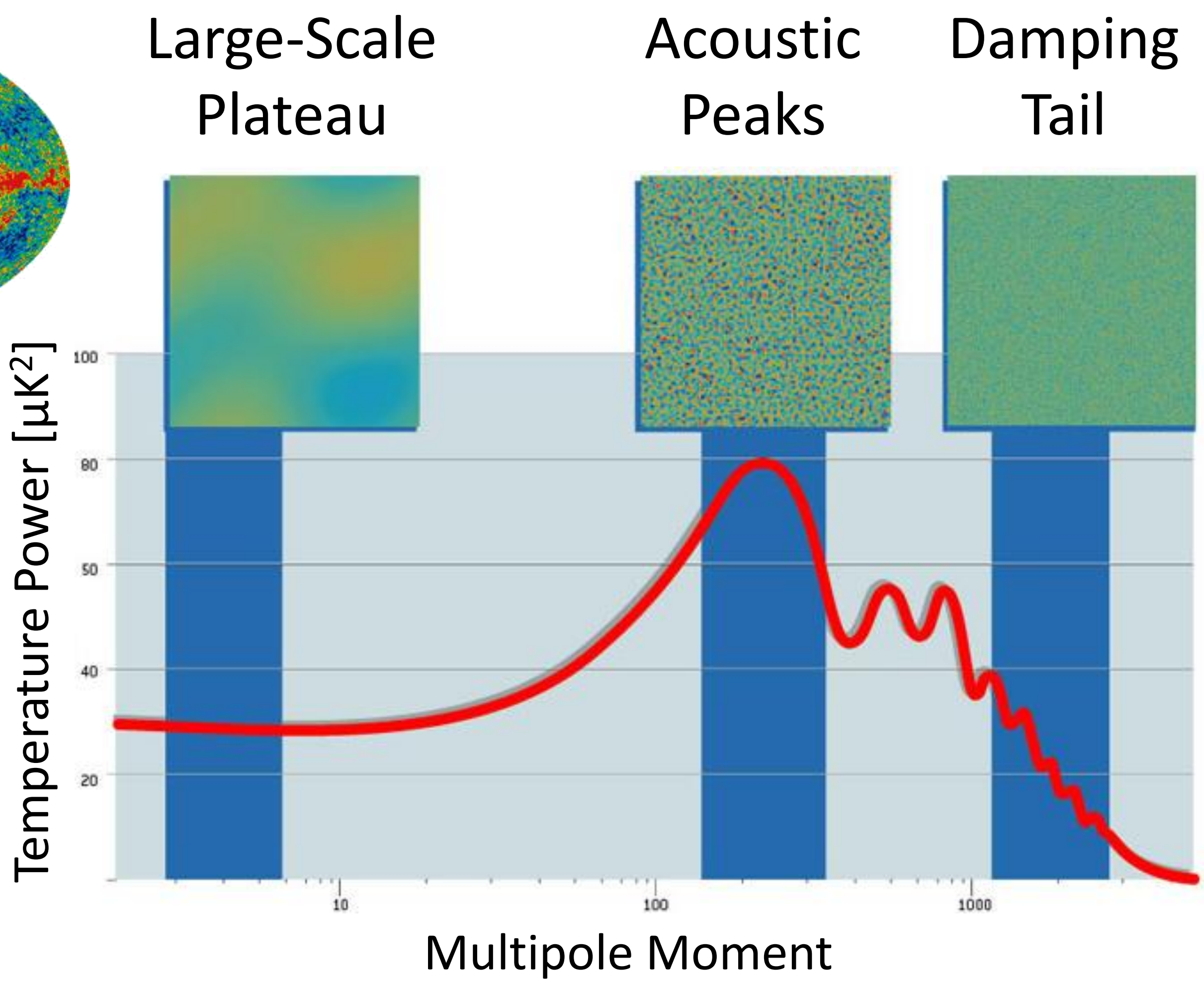
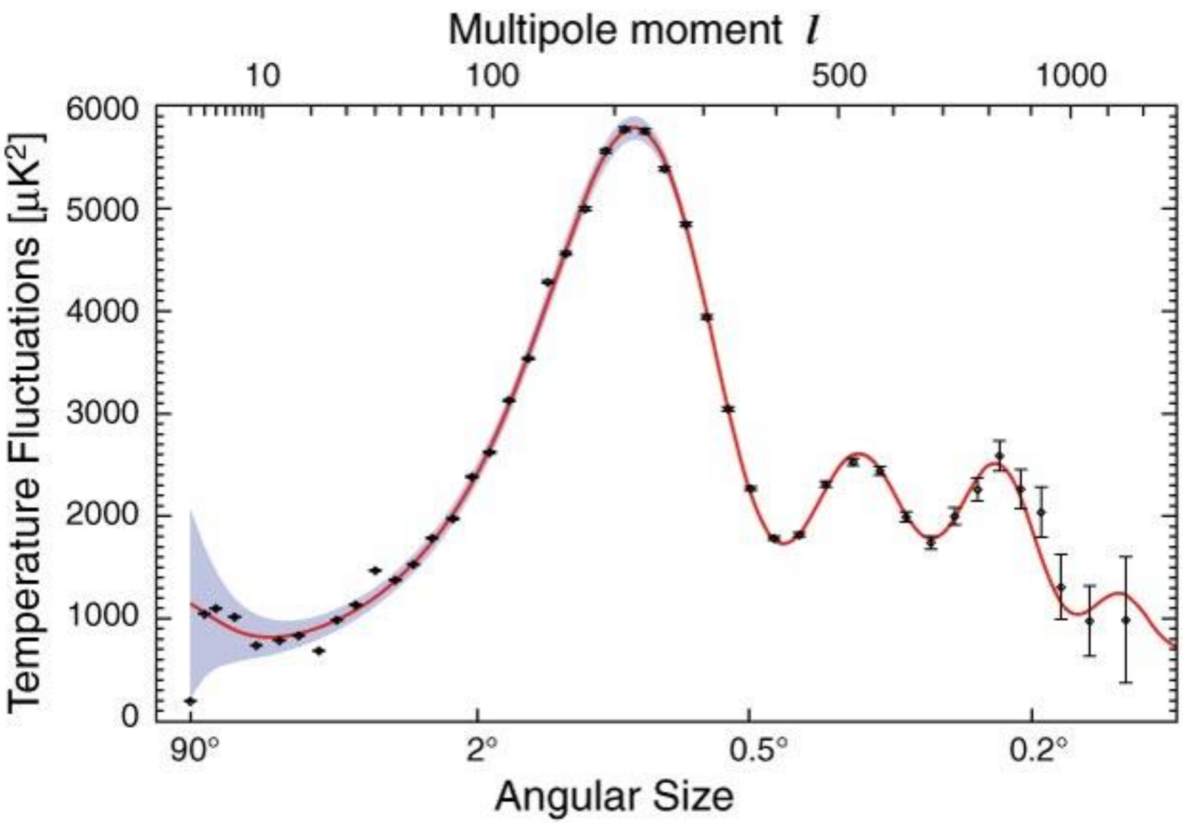


Image Credits: NASA/WMAP, Hu/Scientific American

Standard Model of Cosmology

Flat ΛCDM Universe



Primordial Fluctuations

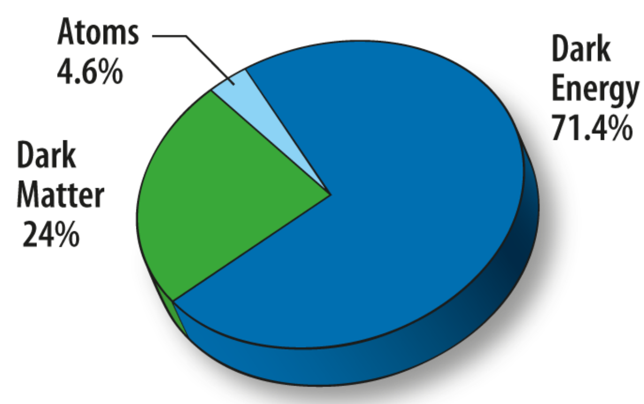
A_s n_s

Contents

ω_b ω_c θ_s

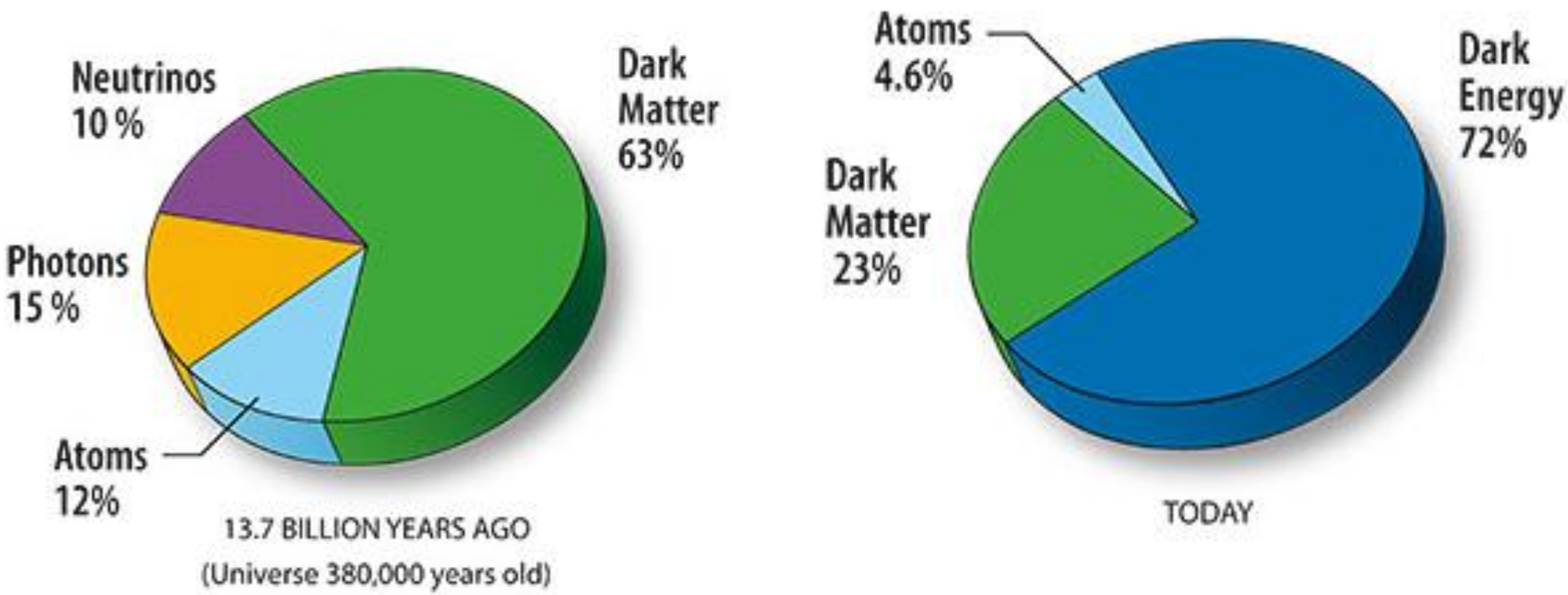
Rescattering

τ



WMAP (2008)

Cosmic Neutrinos in the Early and Present Universe



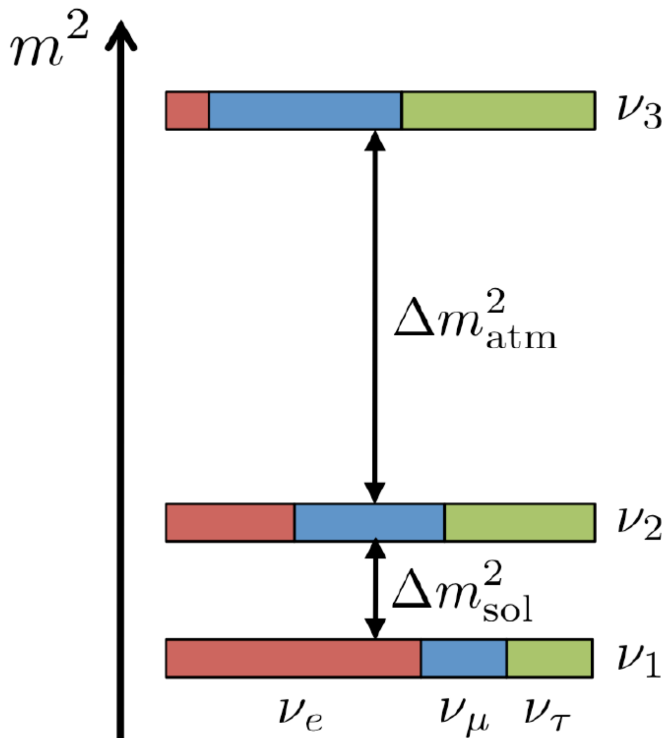
$$n_{\nu_i,0} = 112\,\mathrm{cm}^{-3}$$

$$T_{\nu,0} = 1.95\,\mathrm{K} = 1.68 \times 10^{-4}\,\mathrm{eV}$$

Image Credit: NASA/WMAP

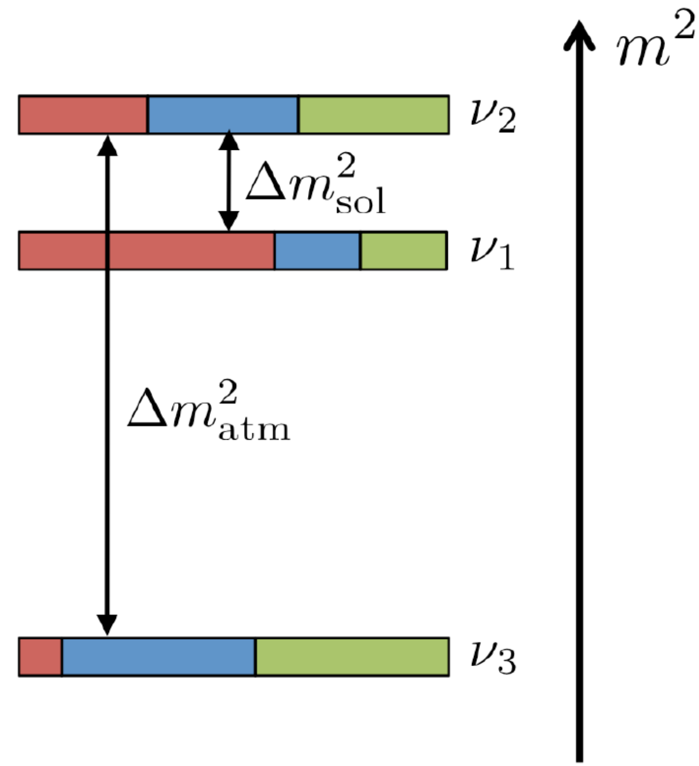
Neutrino Mass

normal hierarchy (NH)



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

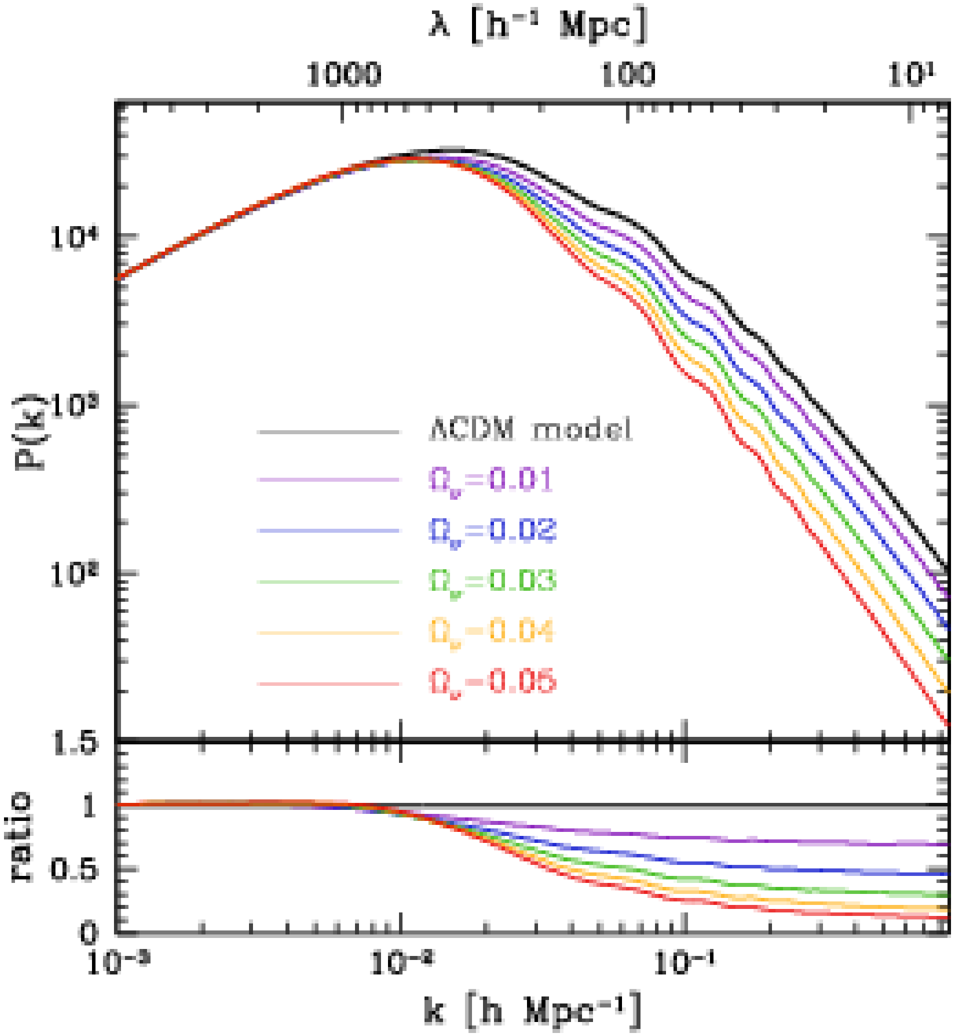
inverted hierarchy (IH)



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

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

Neutrino Mass Suppresses Matter Power Spectrum



$$\frac{P_m(k \gg k_{\rm fs})}{P_m(k \gg k_{\rm fs}|m_\nu = 0)} = 1 - 8f_\nu$$

$$f_\nu \equiv \frac{\Omega_\nu}{\Omega_m} \simeq 0.0045 \left(\frac{\sum m_\nu}{60\,\mathrm{meV}}\right)\left(\frac{\Omega_m}{0.316}\right)^{-1}$$

Eisenstein, Hu (1997); Kaplinghat, Knox, Song (2003); Park, et al. (2016); CMB-S4 Science Book (2016)

Gravitational Lensing

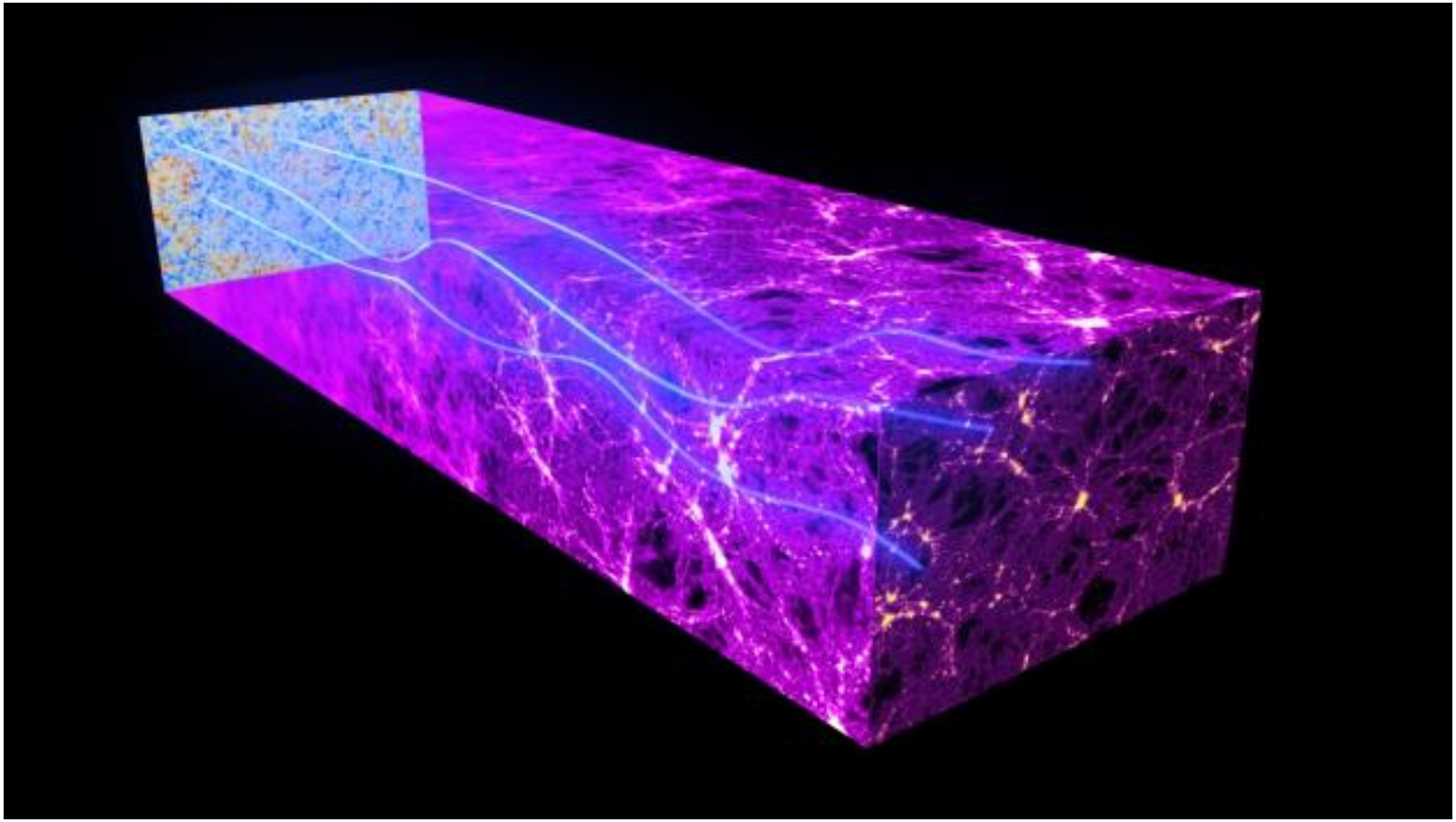
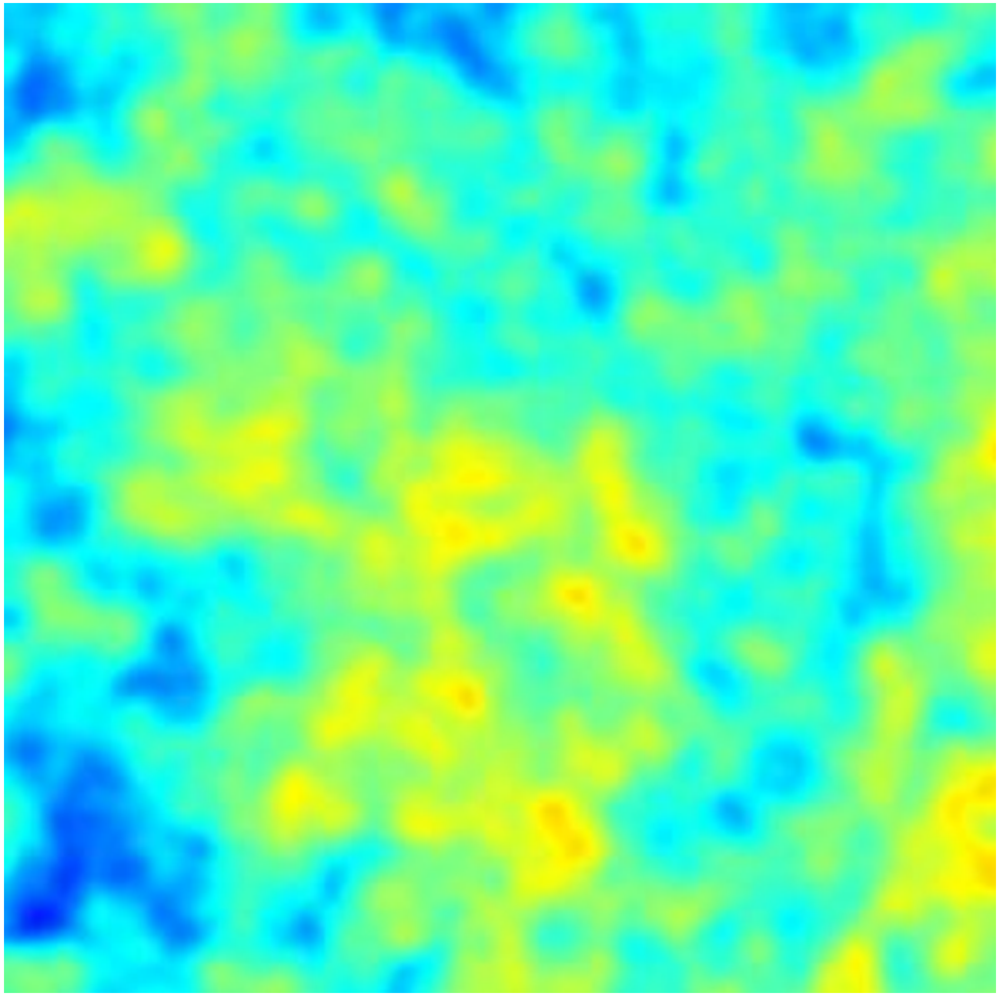


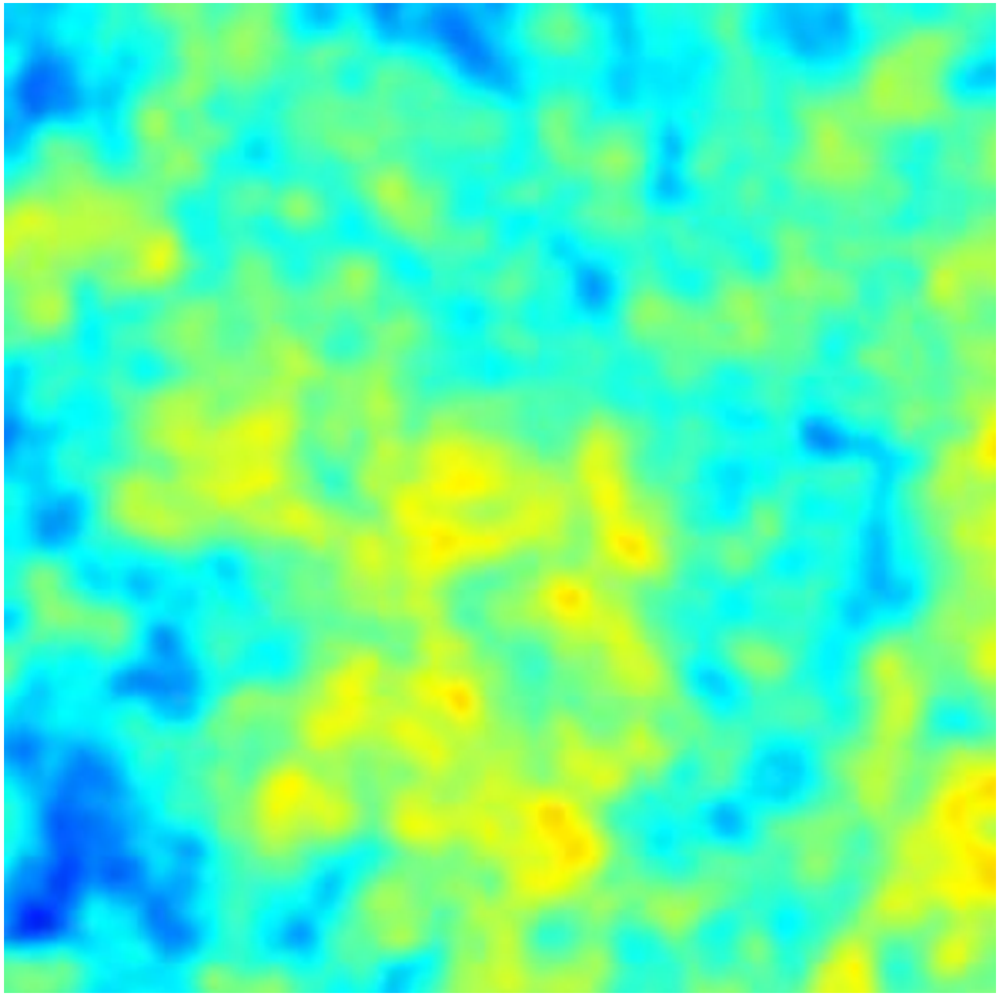
Image Credit: ESA

CMB Lensing



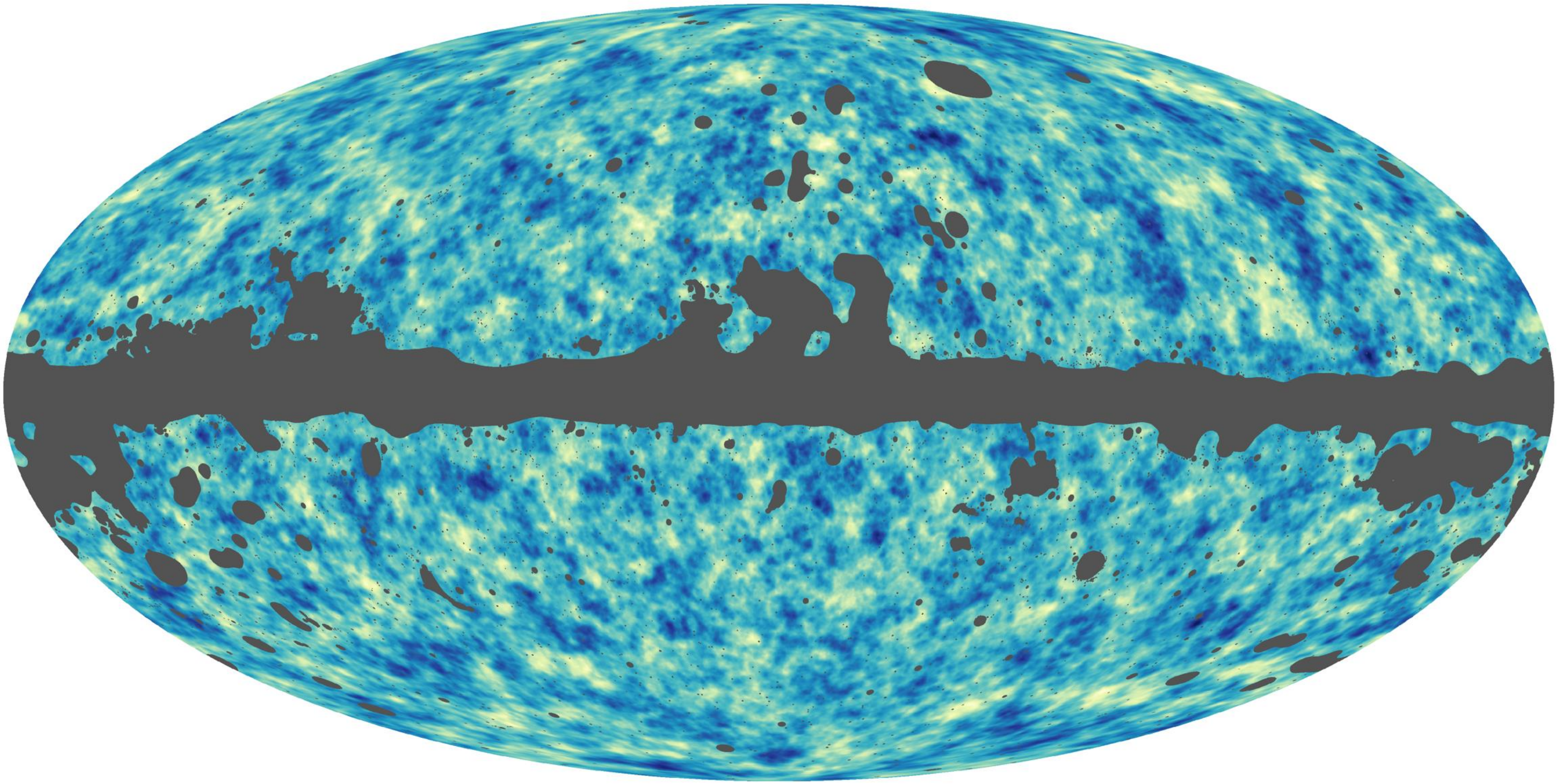
Hu and Okamoto (2002); Image Credit: Sigurd Naess

CMB Lensing



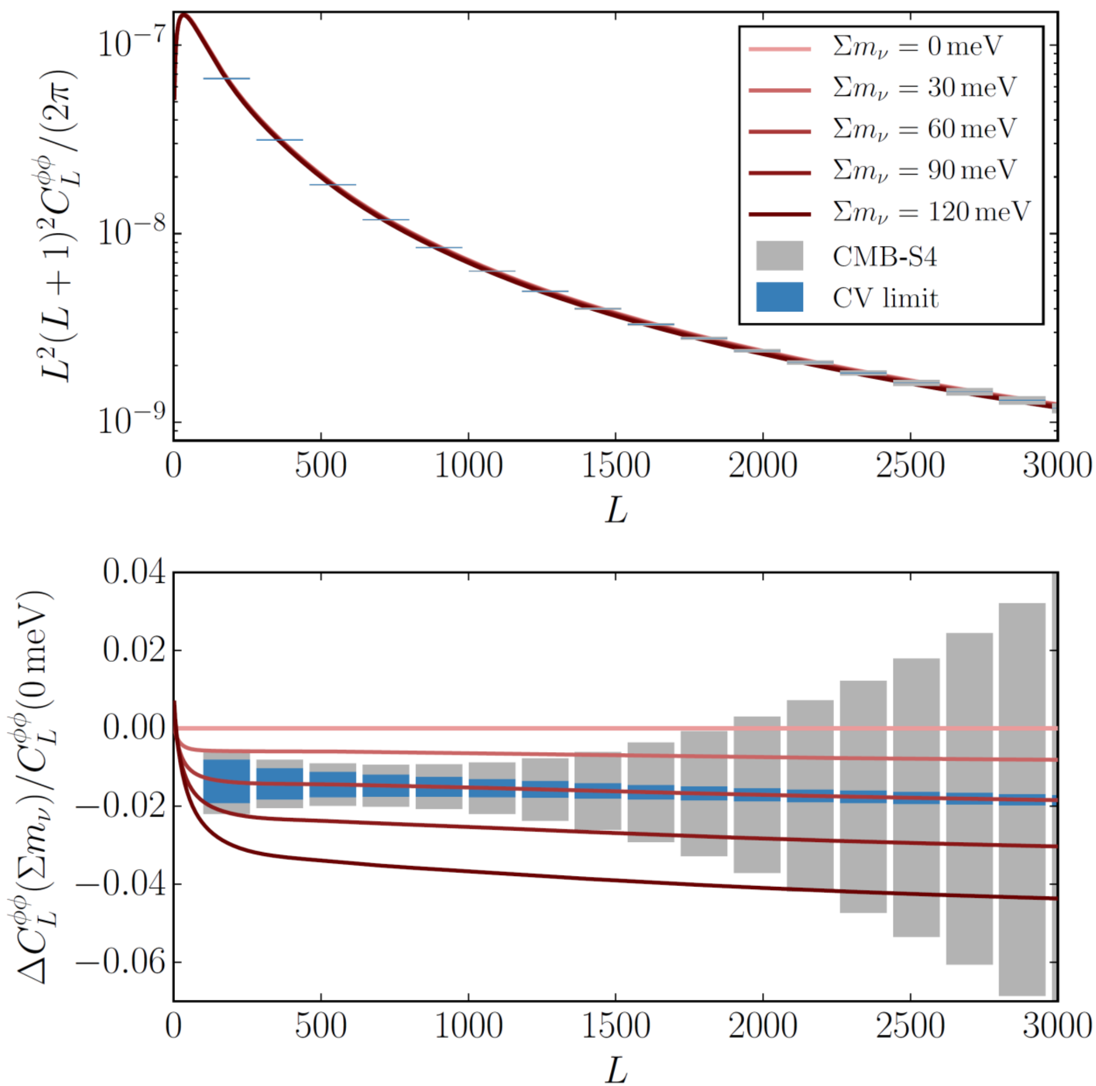
Hu and Okamoto (2002); Image Credit: Sigurd Naess

Gravitational Lensing Map



Planck (2018)

Effect of Neutrino Mass on Lensing

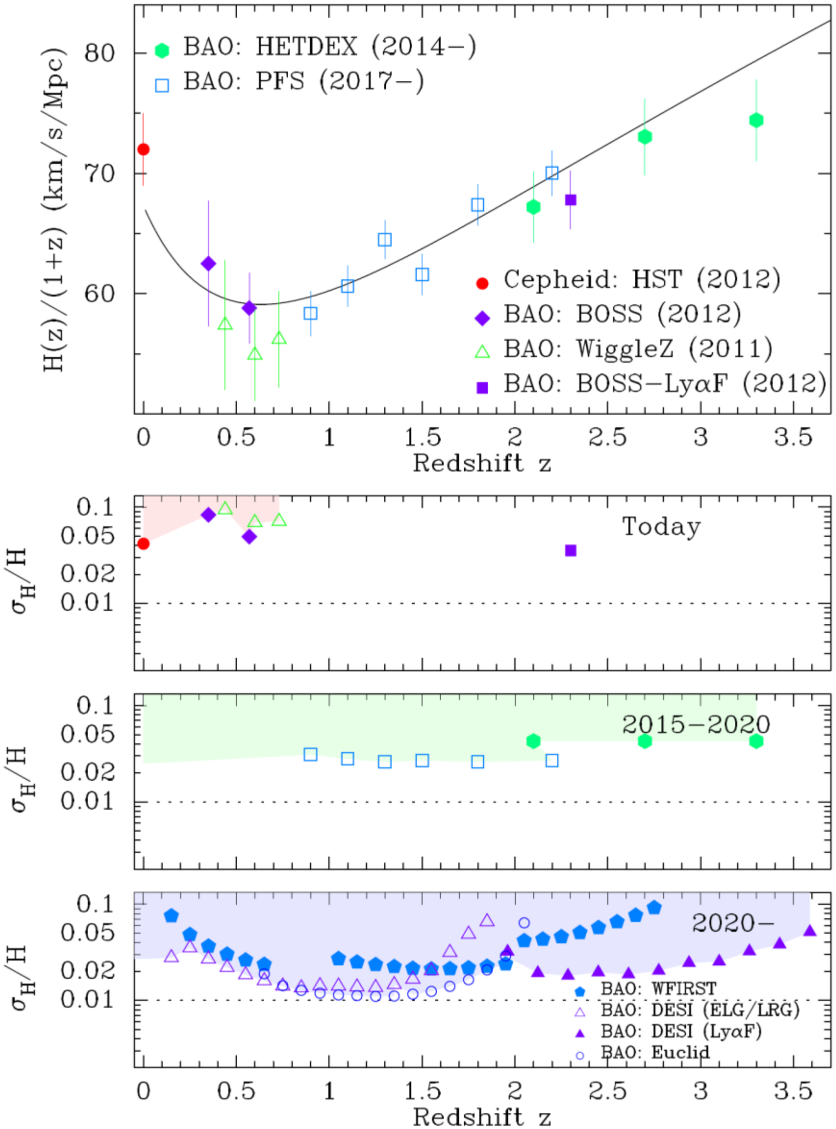


Two important degeneracies:

1. Matter Density
2. Optical Depth

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

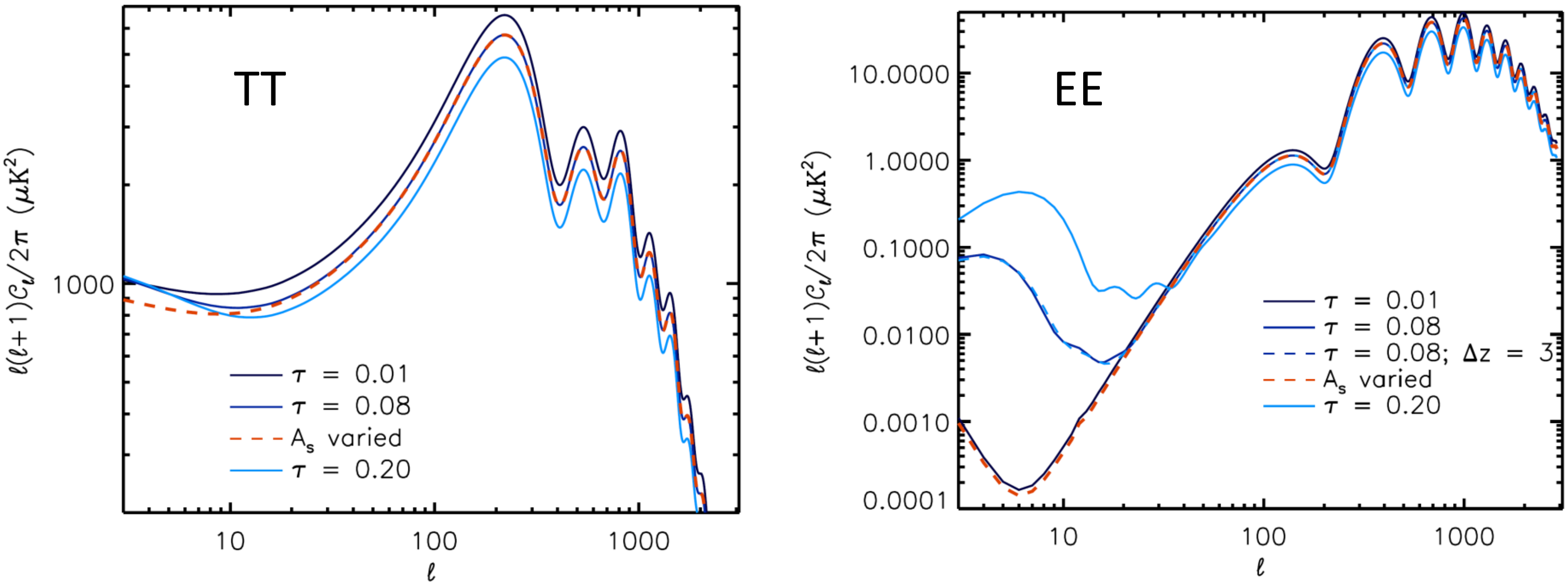
Baryon Acoustic Oscillations



BAO measurements, such as from DESI, will tightly constrain expansion history and thus matter density

Snowmass-Dark Energy (2013)

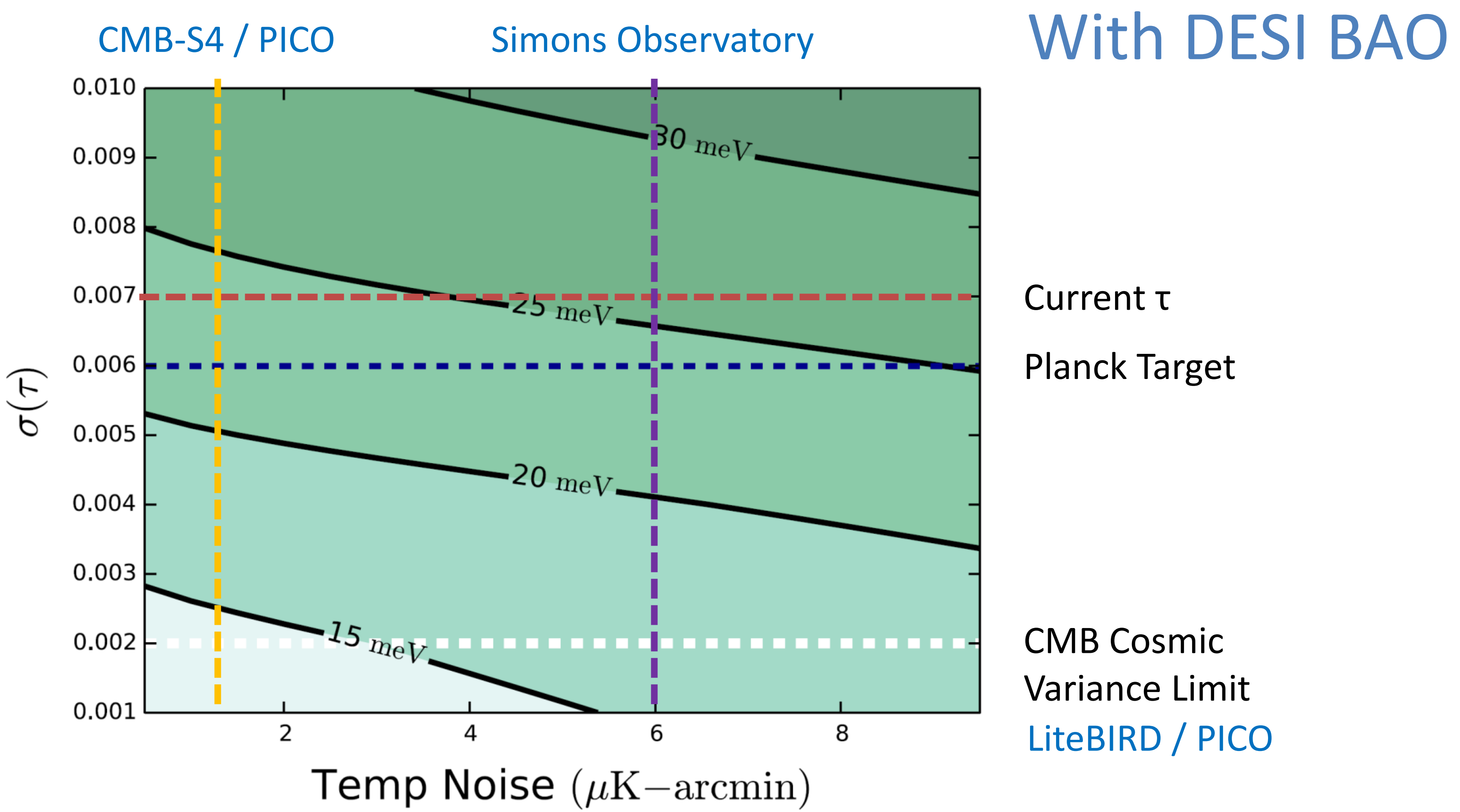
Optical Depth to Reionization and the Primordial Amplitude



CMB polarization measurements on large scales (from space) will significantly improve optical depth and primordial amplitude measurement

Figure credit: Reichardt (2015)

Optical Depth and Neutrino Mass

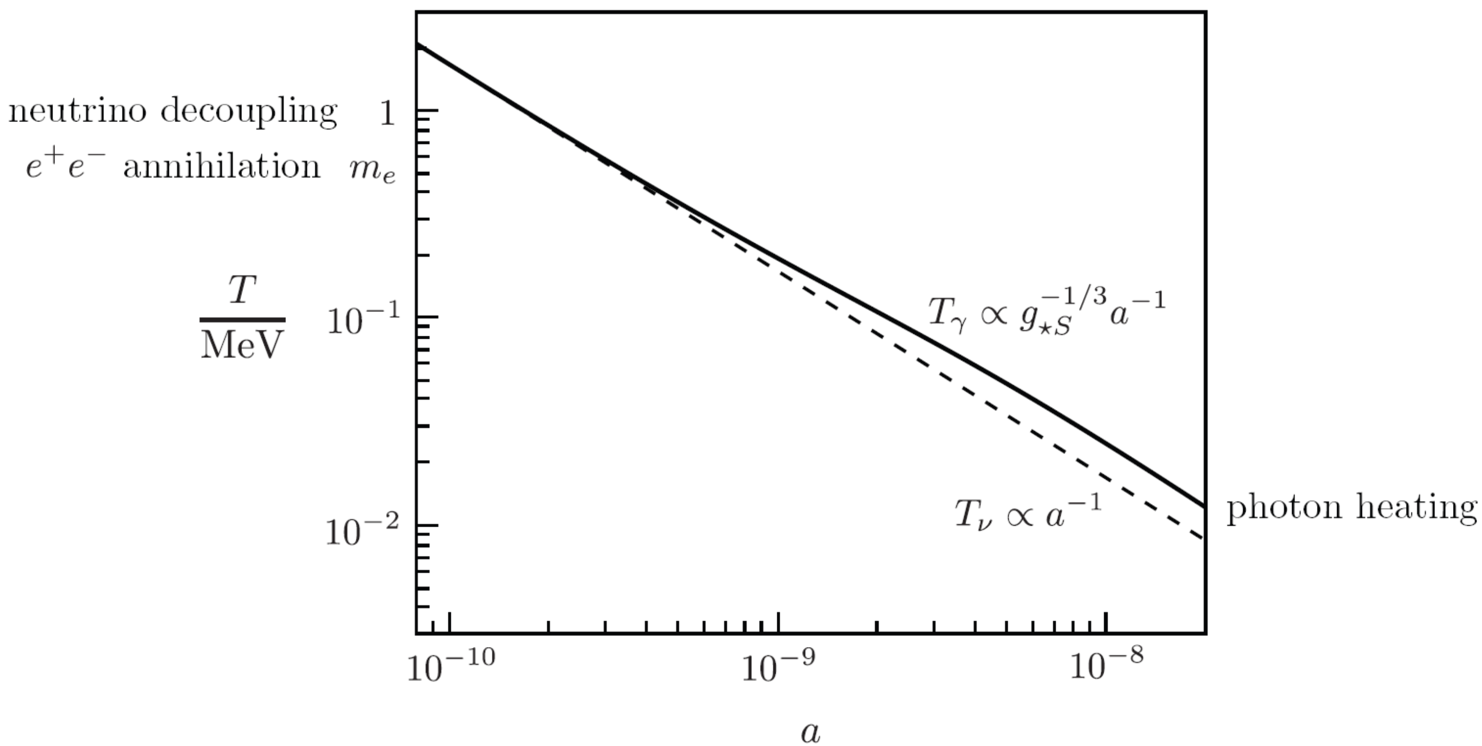


CMB-S4 Science Book (2016)

Light Relics

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

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

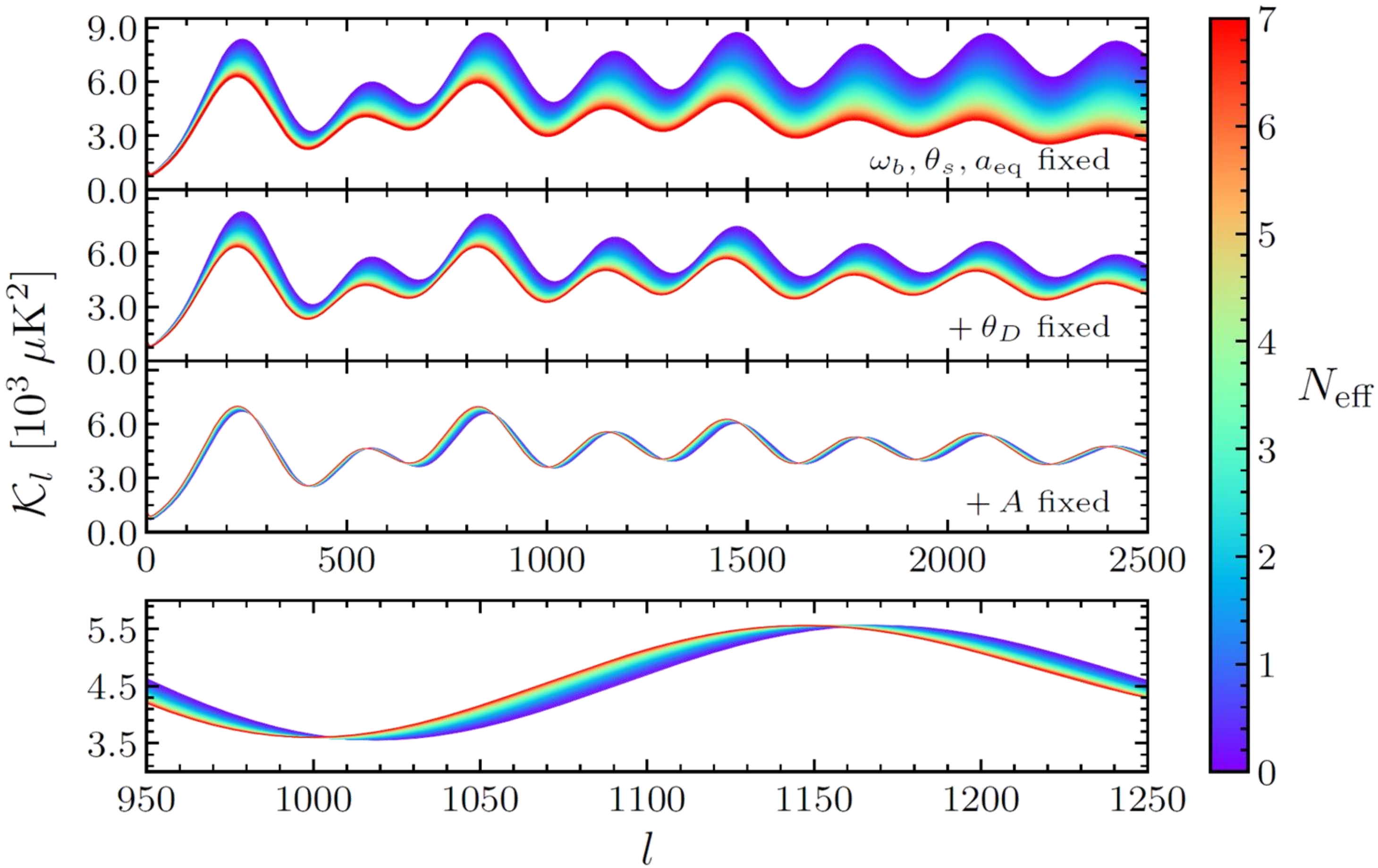


PDG (2013); Mangano, et al. (2005); de Salas, Pastor (2016); Grohs, et al. (2016)

Figure Credit: Daniel Baumann

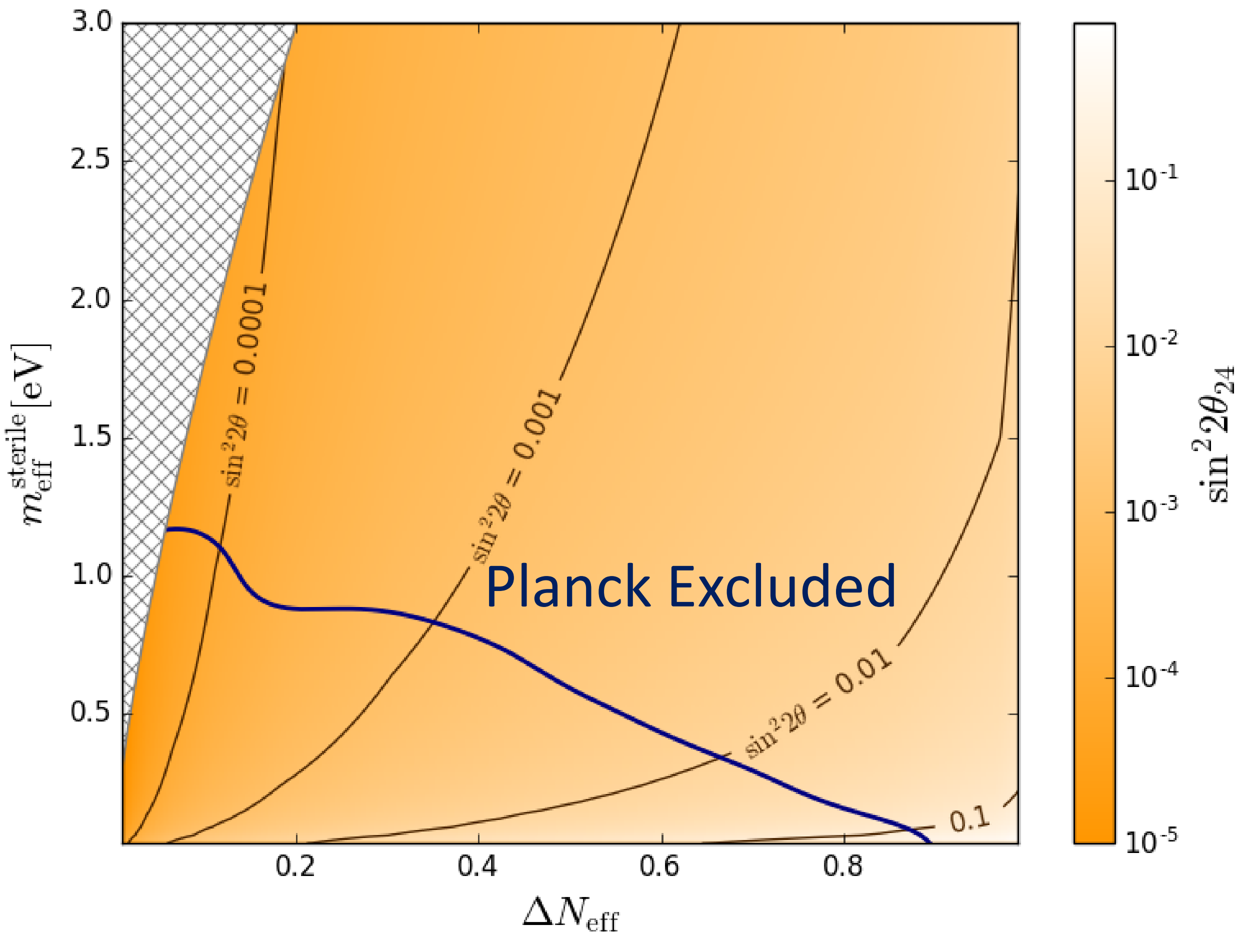
Effects of Light Relics on the CMB

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



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

Sterile Neutrino Constraints



Boyarsky (2009); Abazajian (2017)
Figure Credit: :Bridle, et al. (2016)

Thermal Relics and N_{eff}

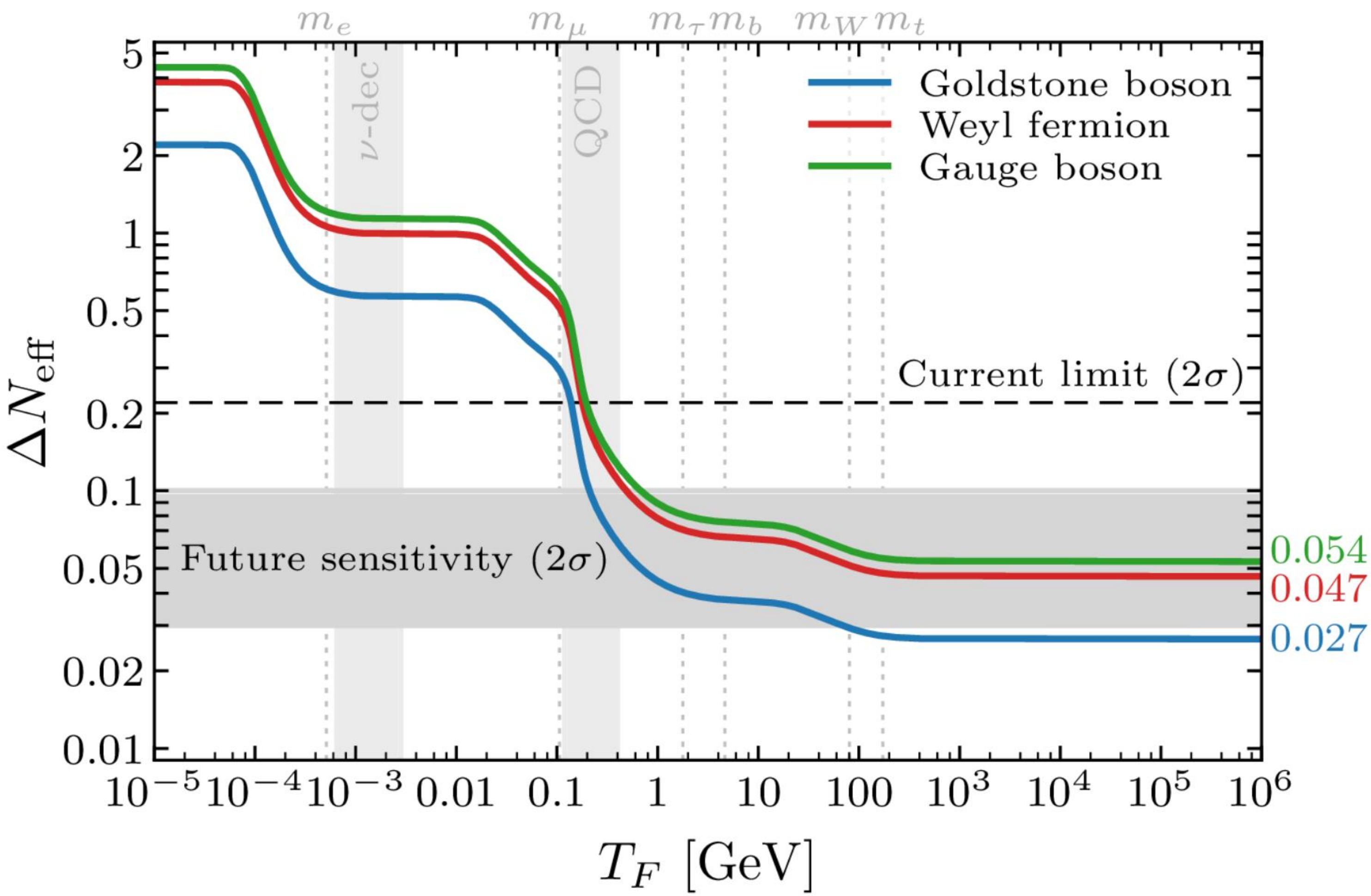
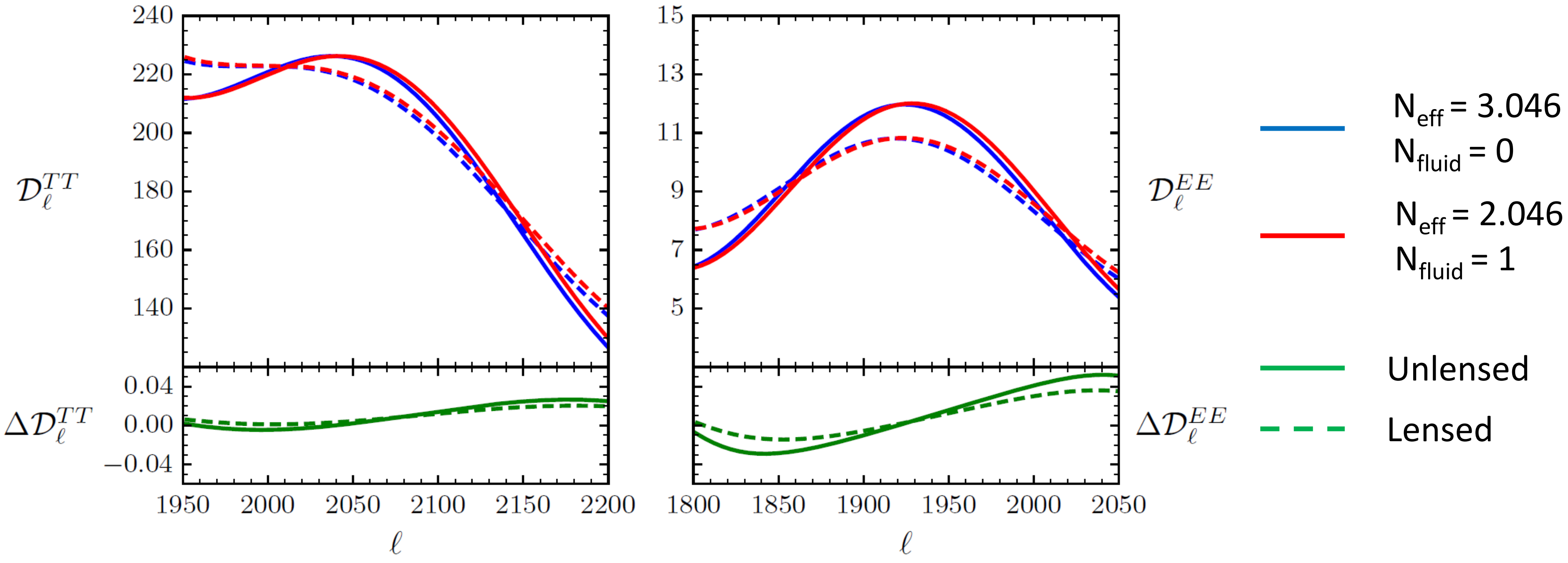


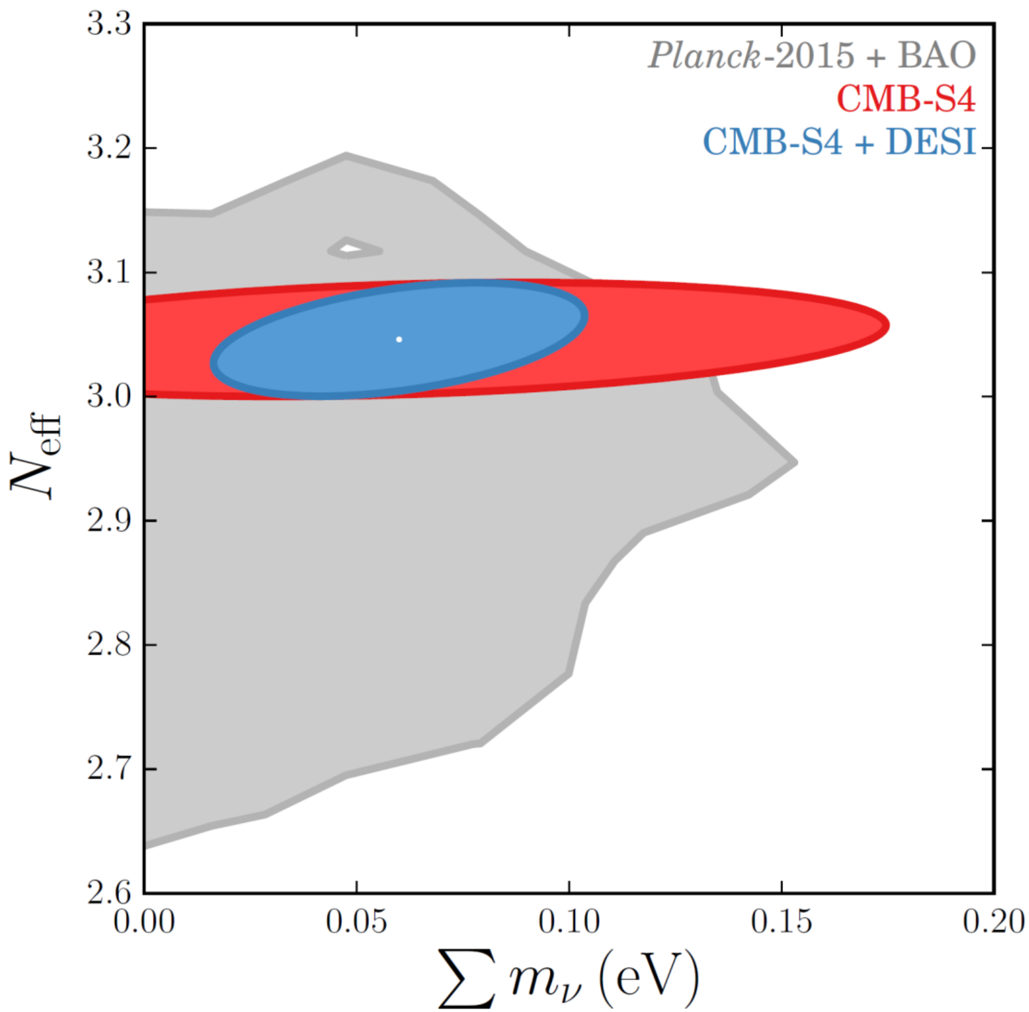
Figure Credit: Benjamin Wallisch; Wallisch (2018); Green, et al (2019); CMB-S4 Science Book (2016); Simons Observatory White Paper (2018); PICO White Paper (2019)

Free Streaming and the Phase Shift



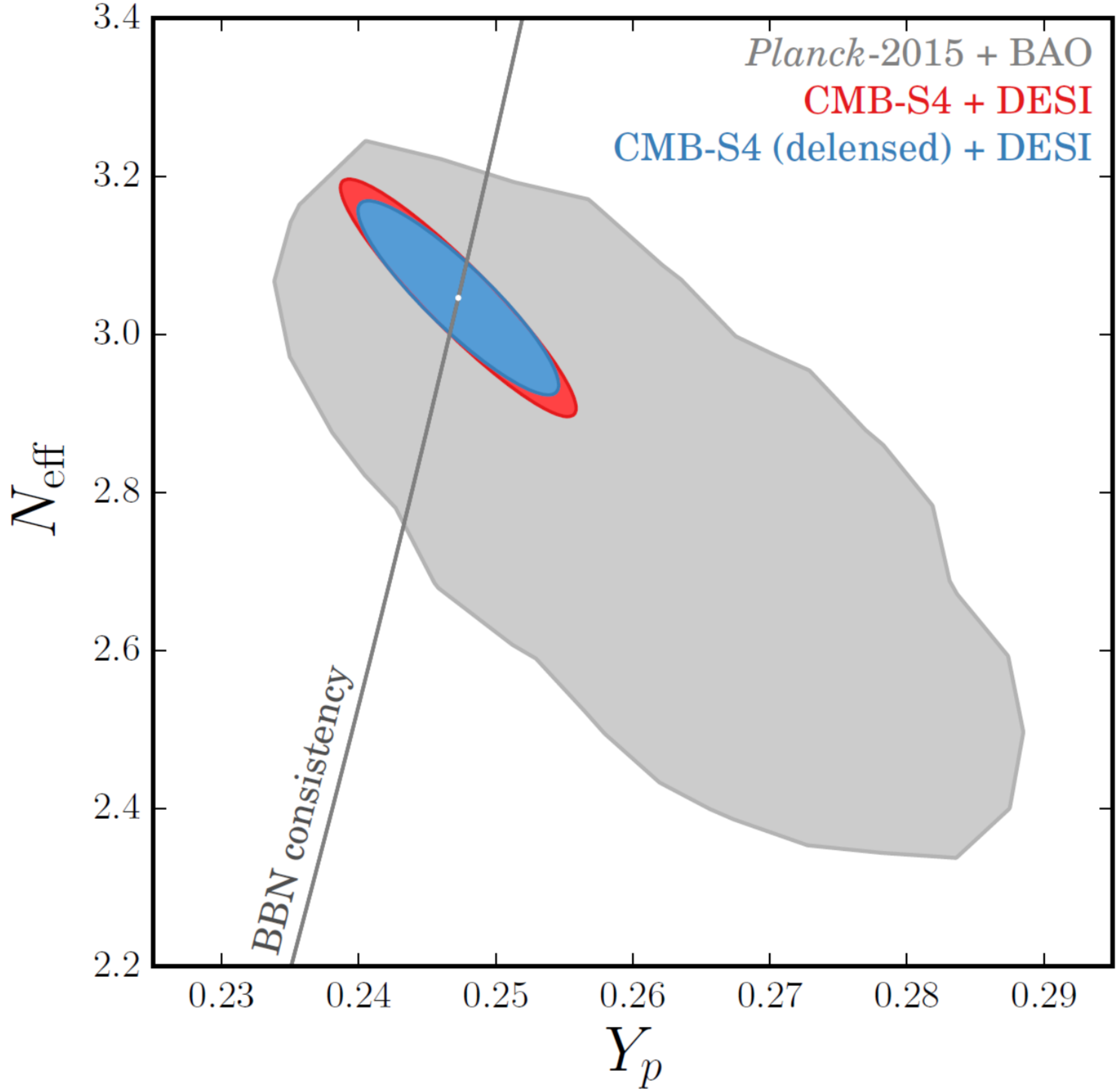
Bashinsky, Seljak (2004); Follin, Knox, Millea, Pan (2015);
Baumann, Green, JM, Wallisch (2015); Baumann, Green, Wallisch (2018)

Sterile and Exotic Neutrinos

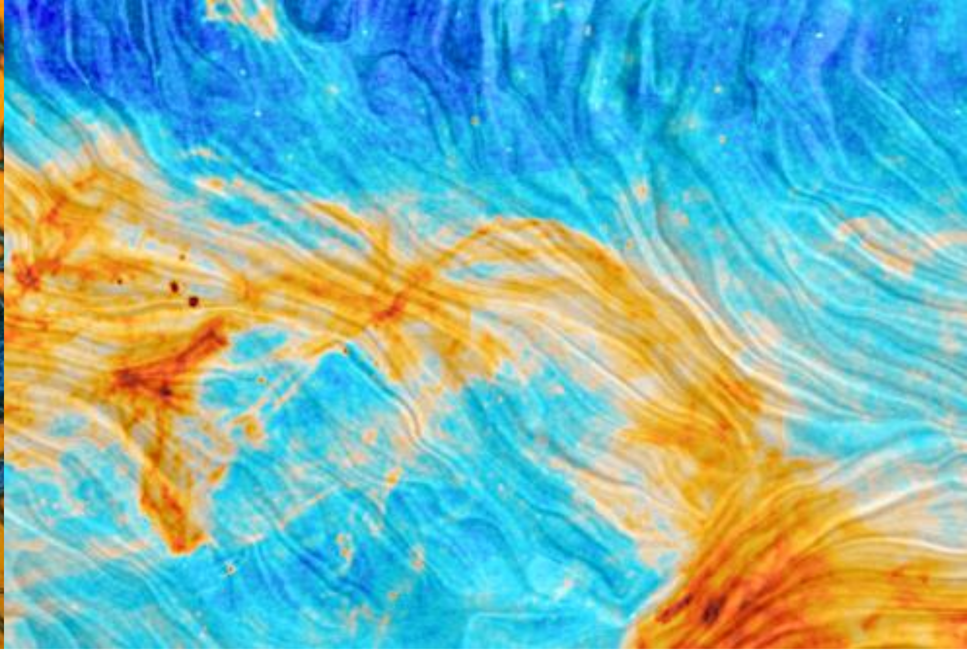


CMB-S4 Science Book (2016)

Testing BBN with the CMB



Green, JM, van Engelen (2016); CMB-S4 Science Book (2016)



Thank You!

Image Credits: BEBC/CERN and Planck/ESA