Measuring Gravitational Lensing of the CMB to Probe Neutrino Properties, Dark Energy, and Primordial Gravitational Waves

Neelima Sehgal

November 30, 2016
Fermilab

Outline

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- Measuring Lensing of CMB

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- Neutrino Mass from Lensing Power Spectrum

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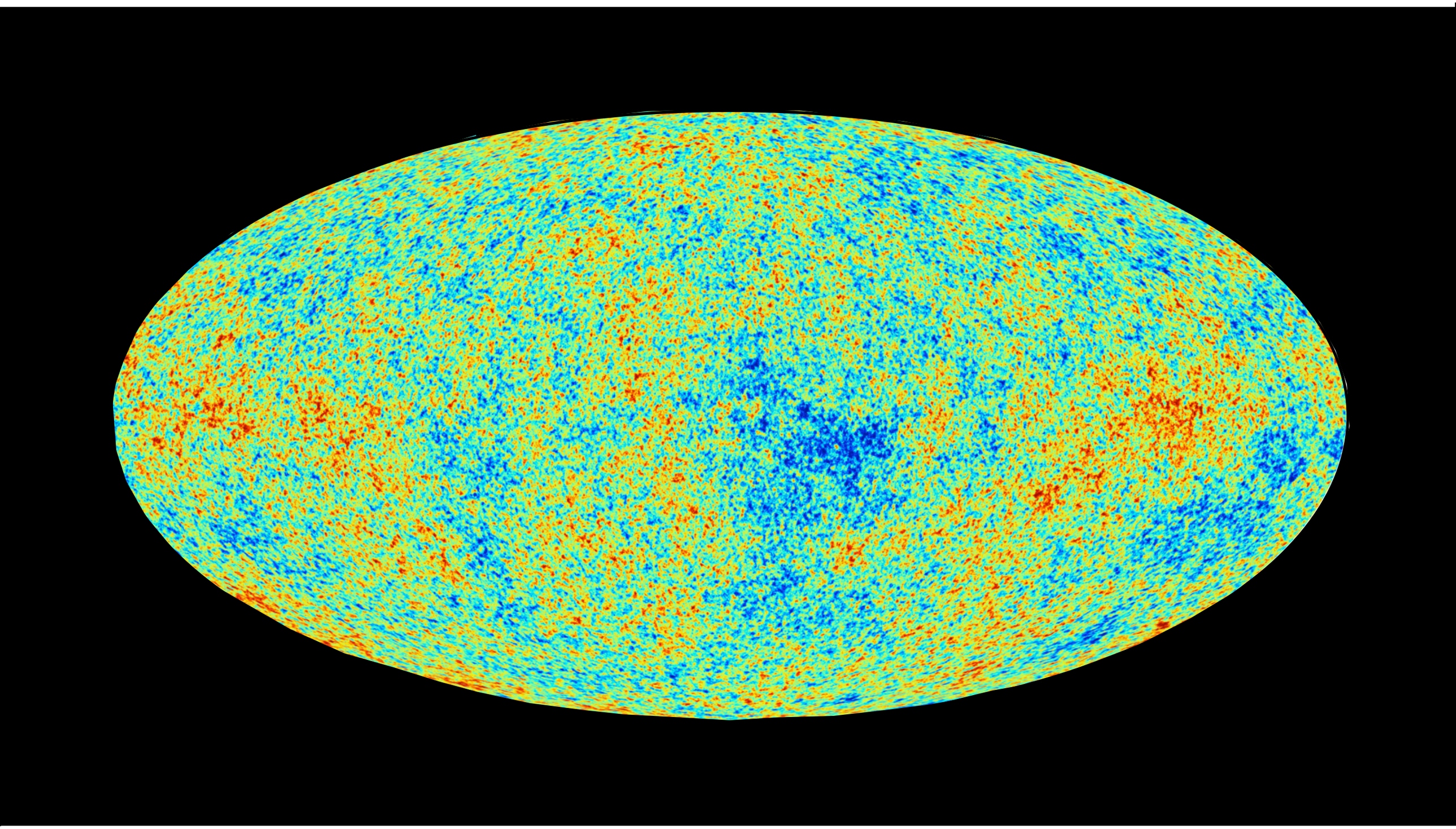
Cosmic Microwave Background



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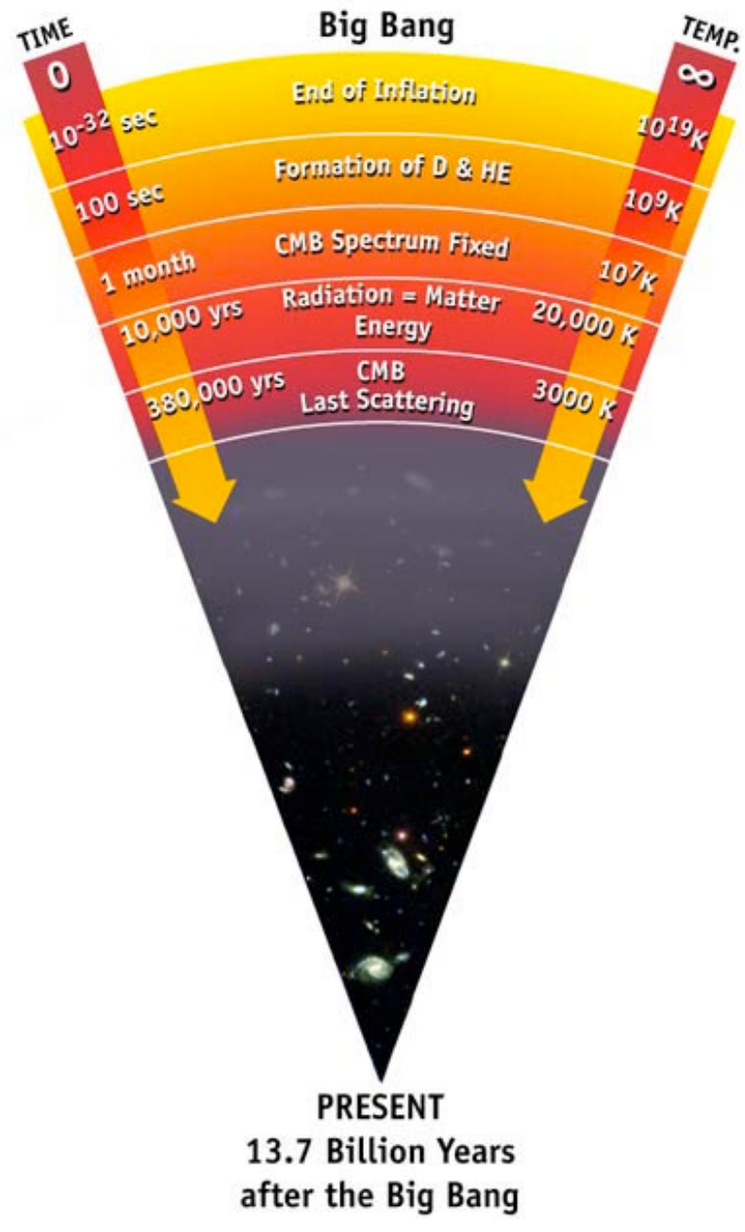
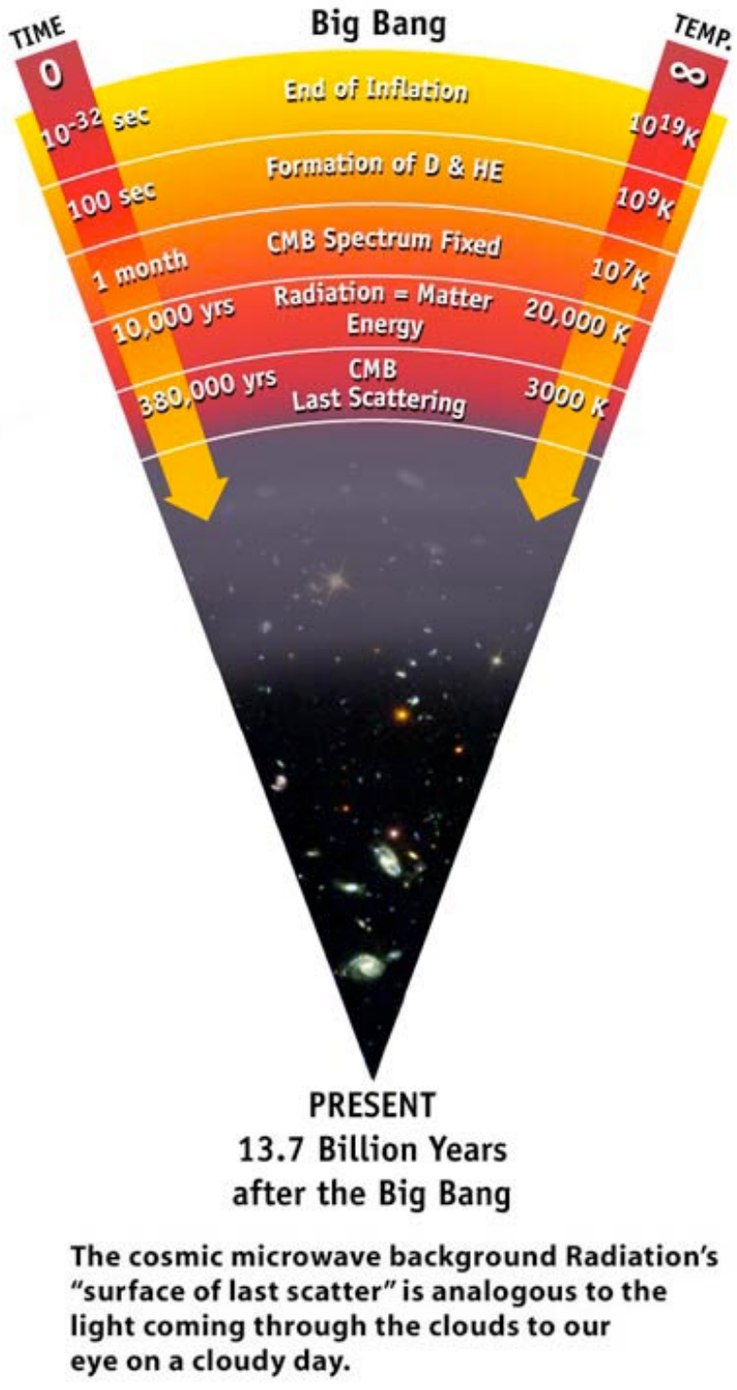
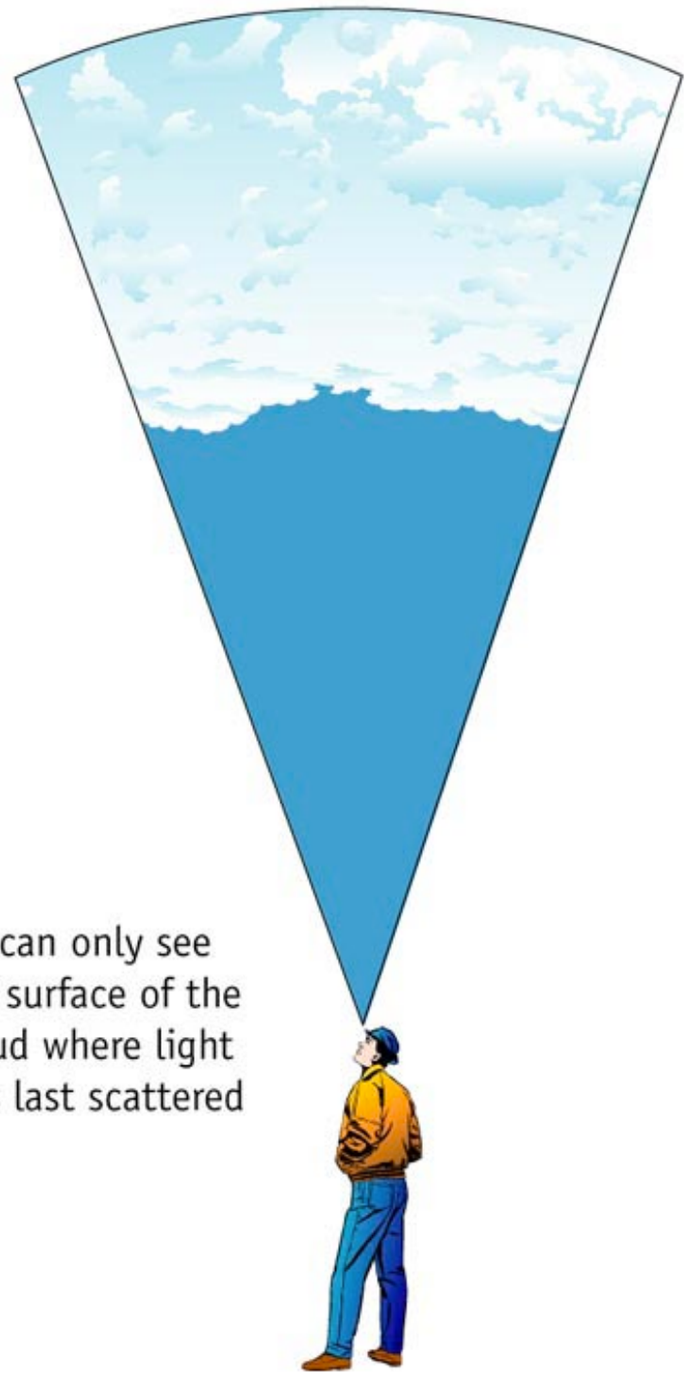


From Lambda website

Cosmic Microwave Background





From Lambda website

CMB From Last Scattering Surface

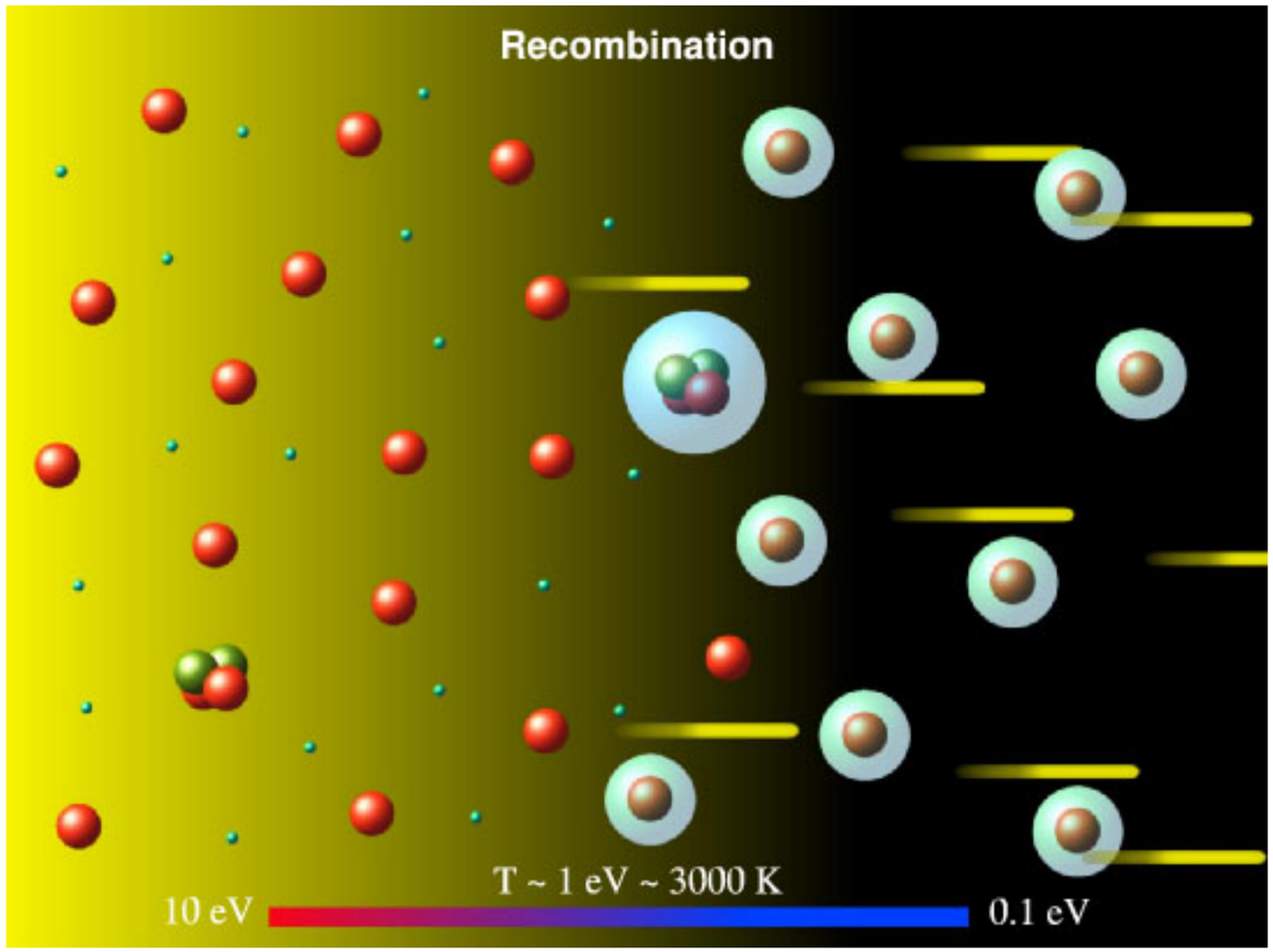


Image Credit: William Kinney

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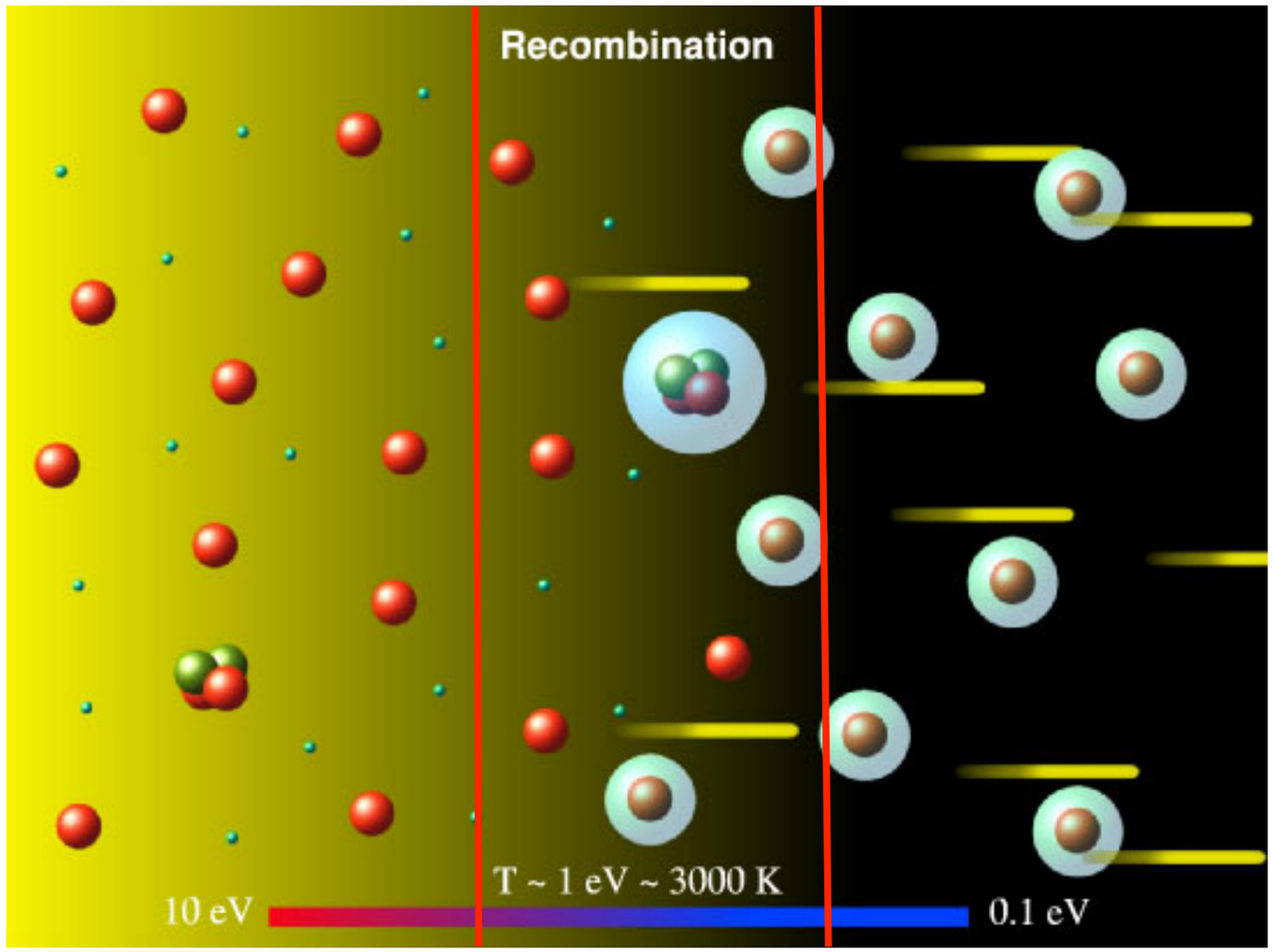
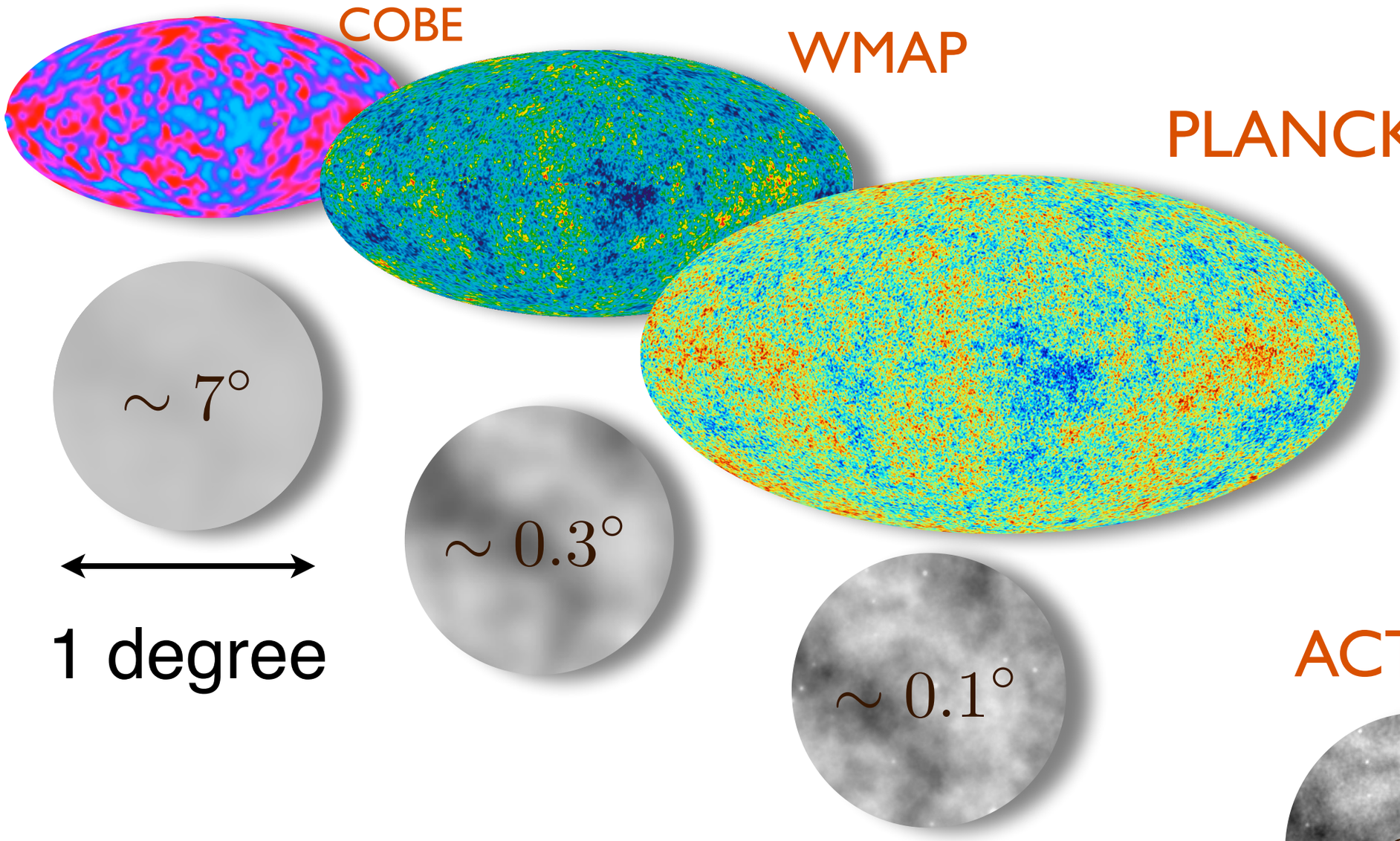


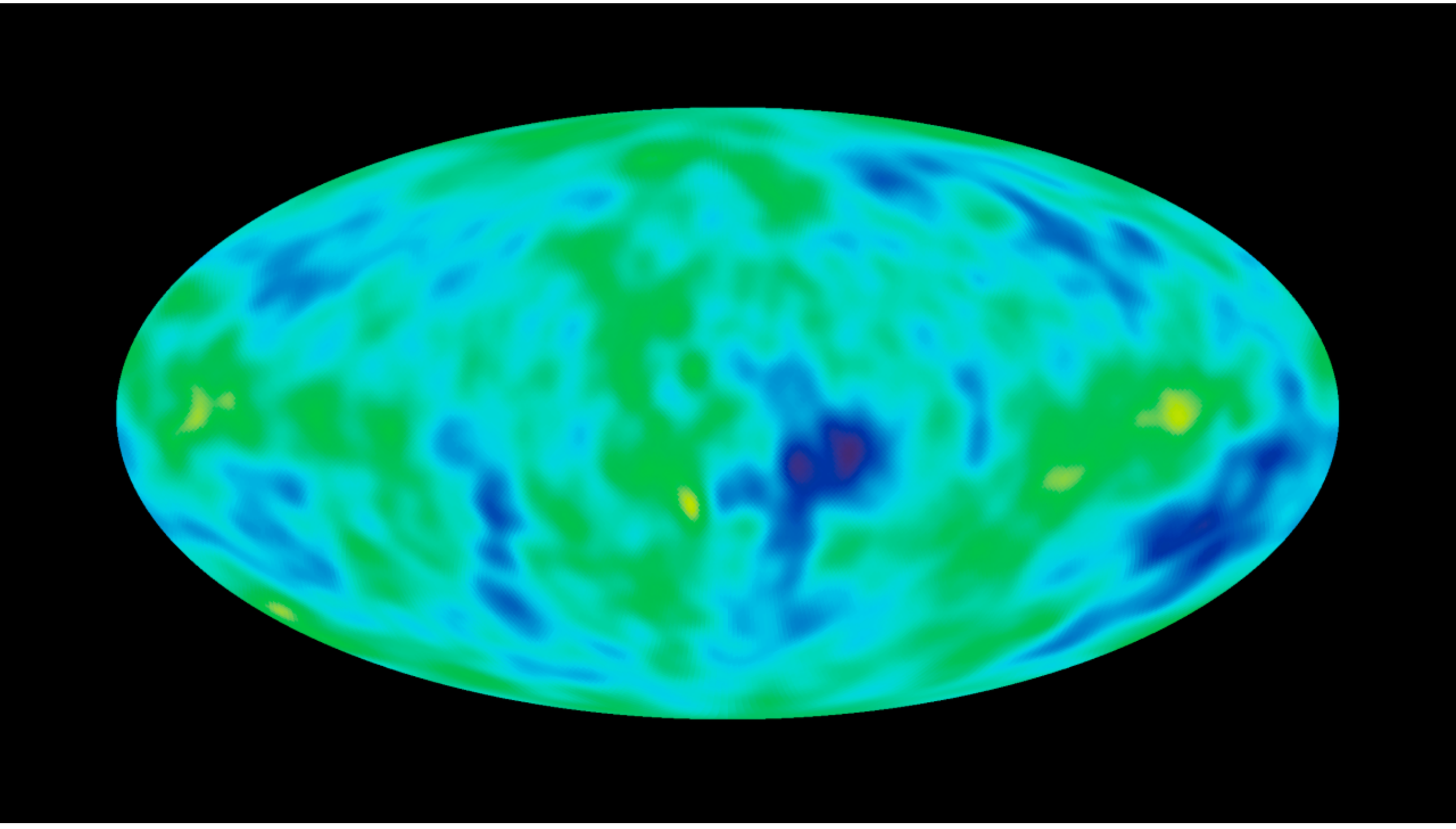
Image Credit: William Kinney

New Generation of Microwave Observations

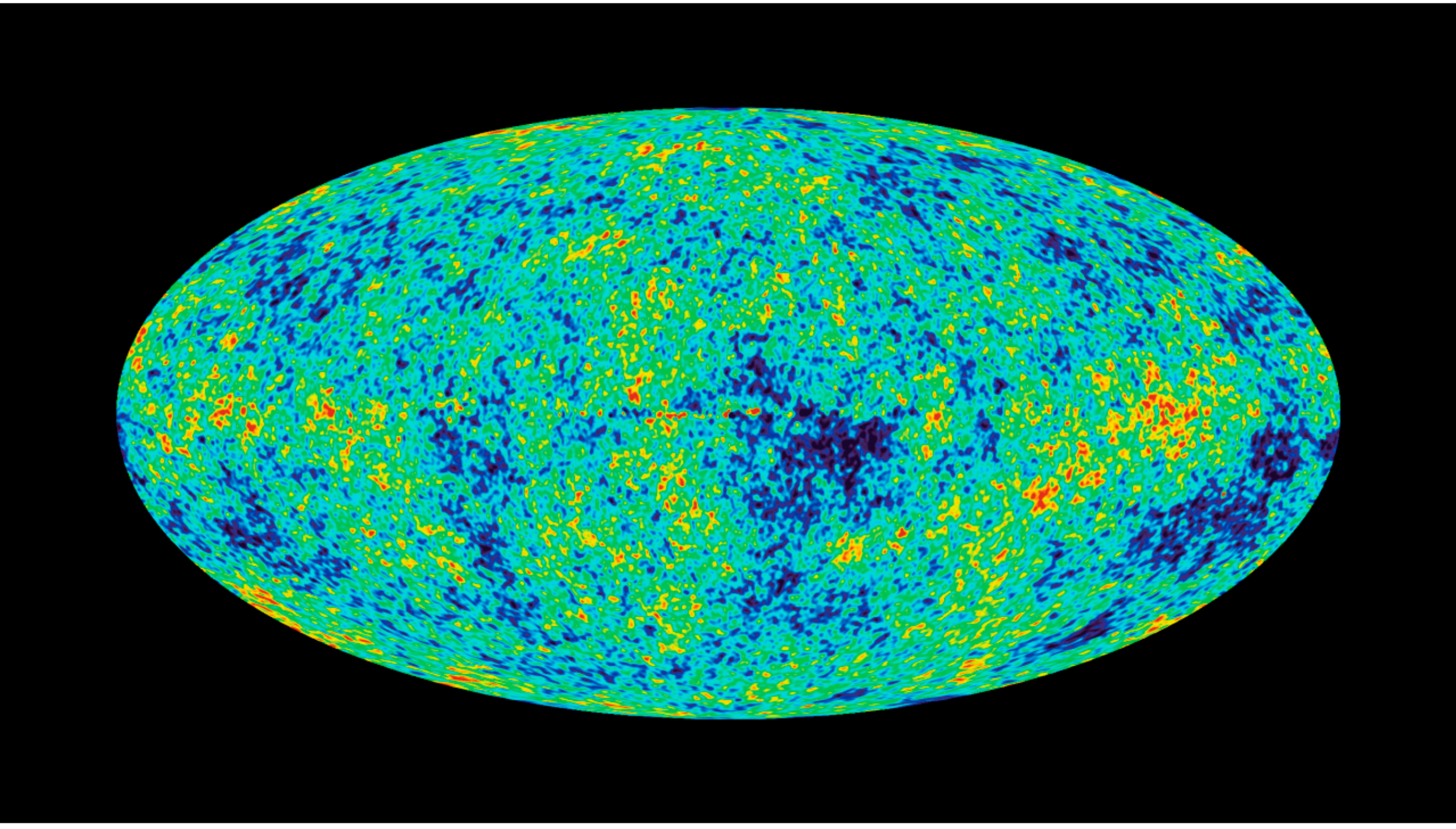


We are in a new regime in CMB physics

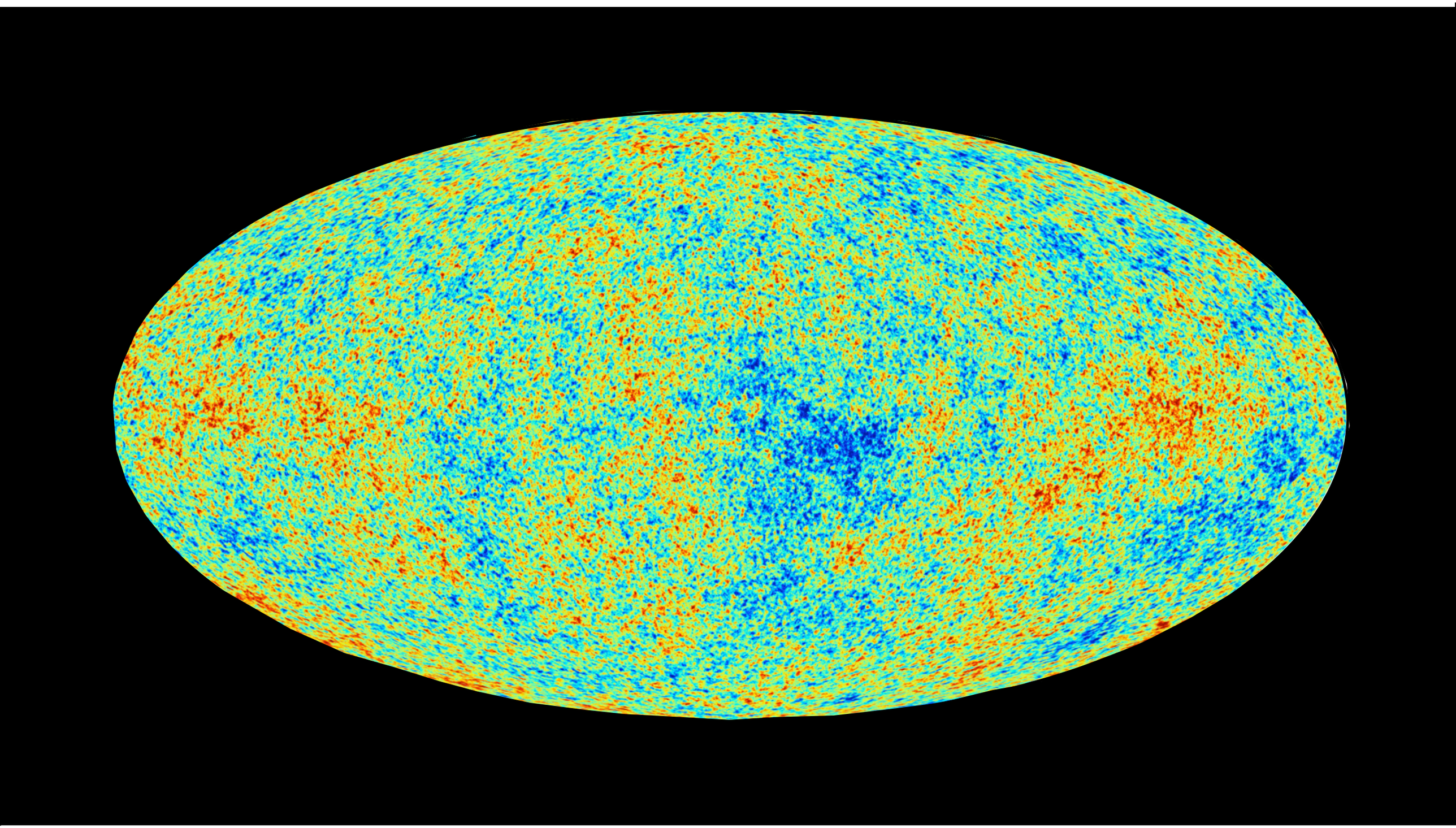
COBE Satellite 1994



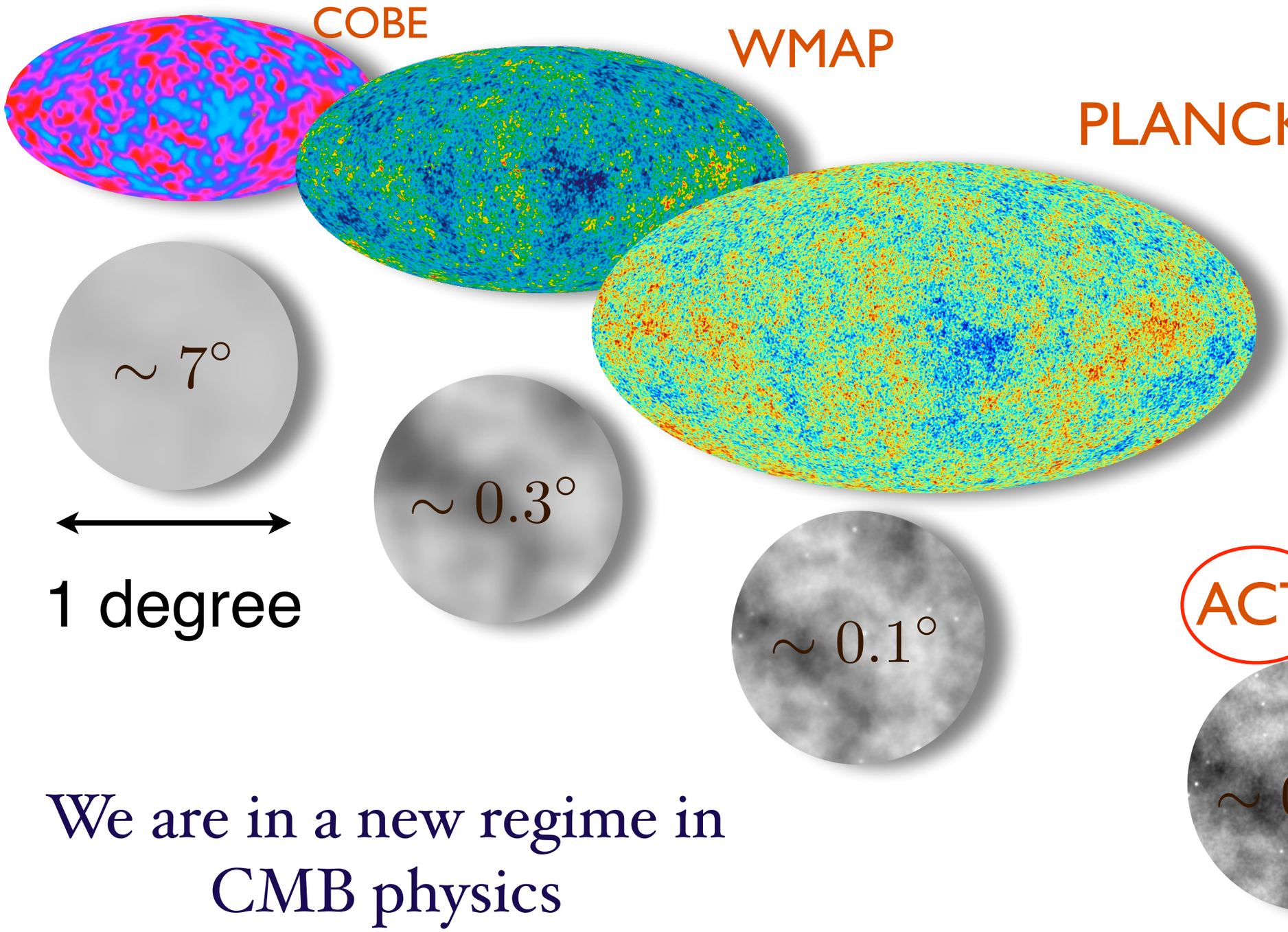
WMAP Satellite 2003



Planck Satellite 2013



New Generation of Microwave Observations



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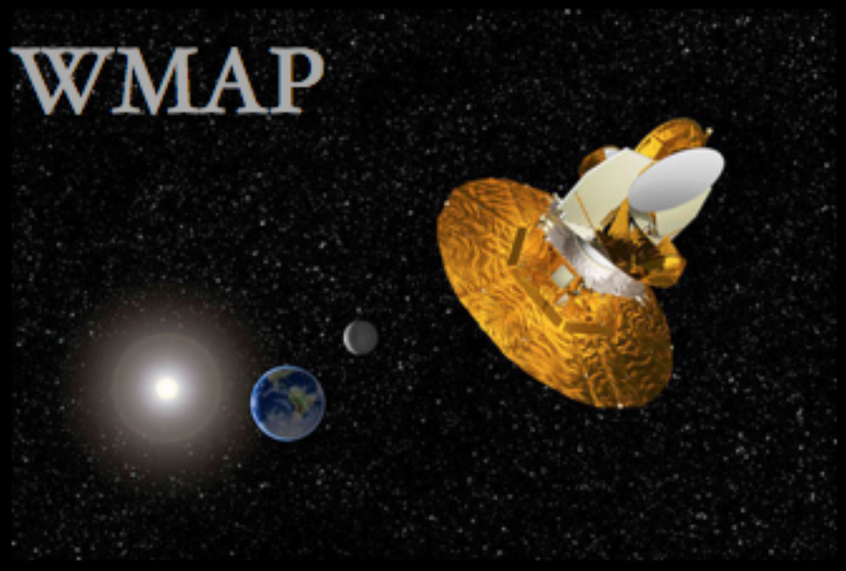
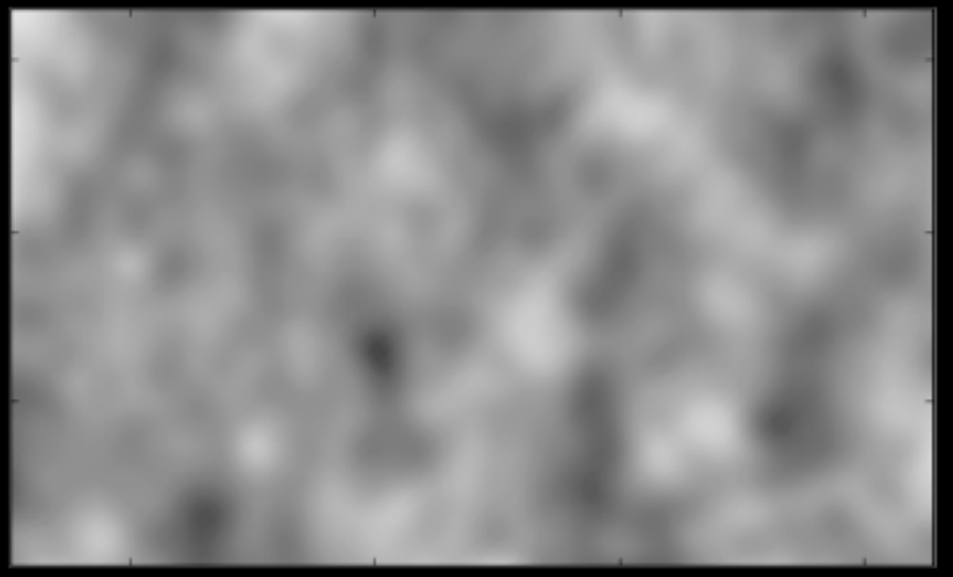
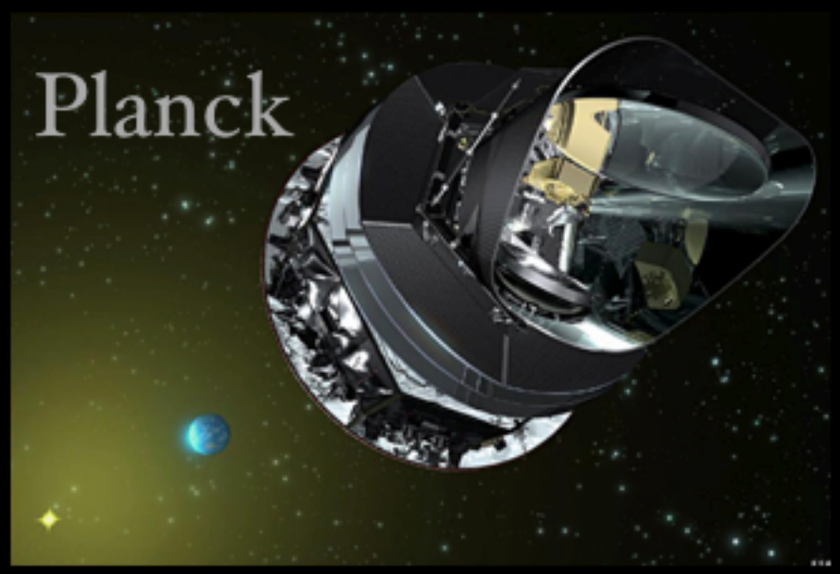
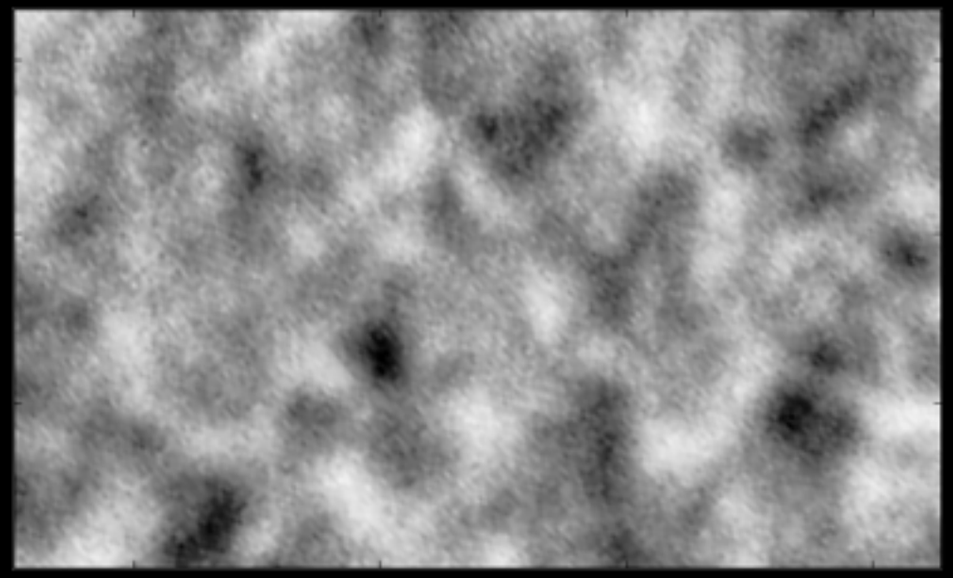
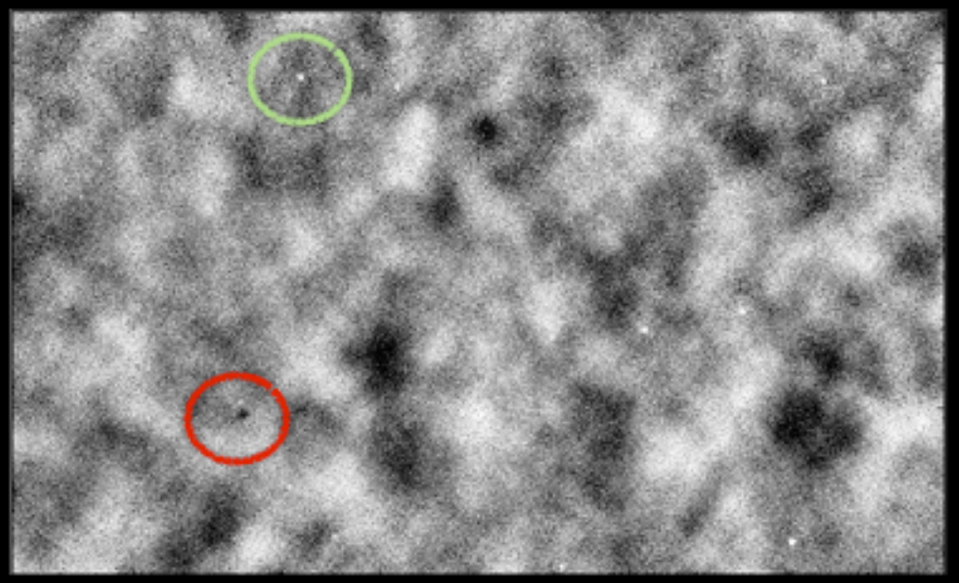




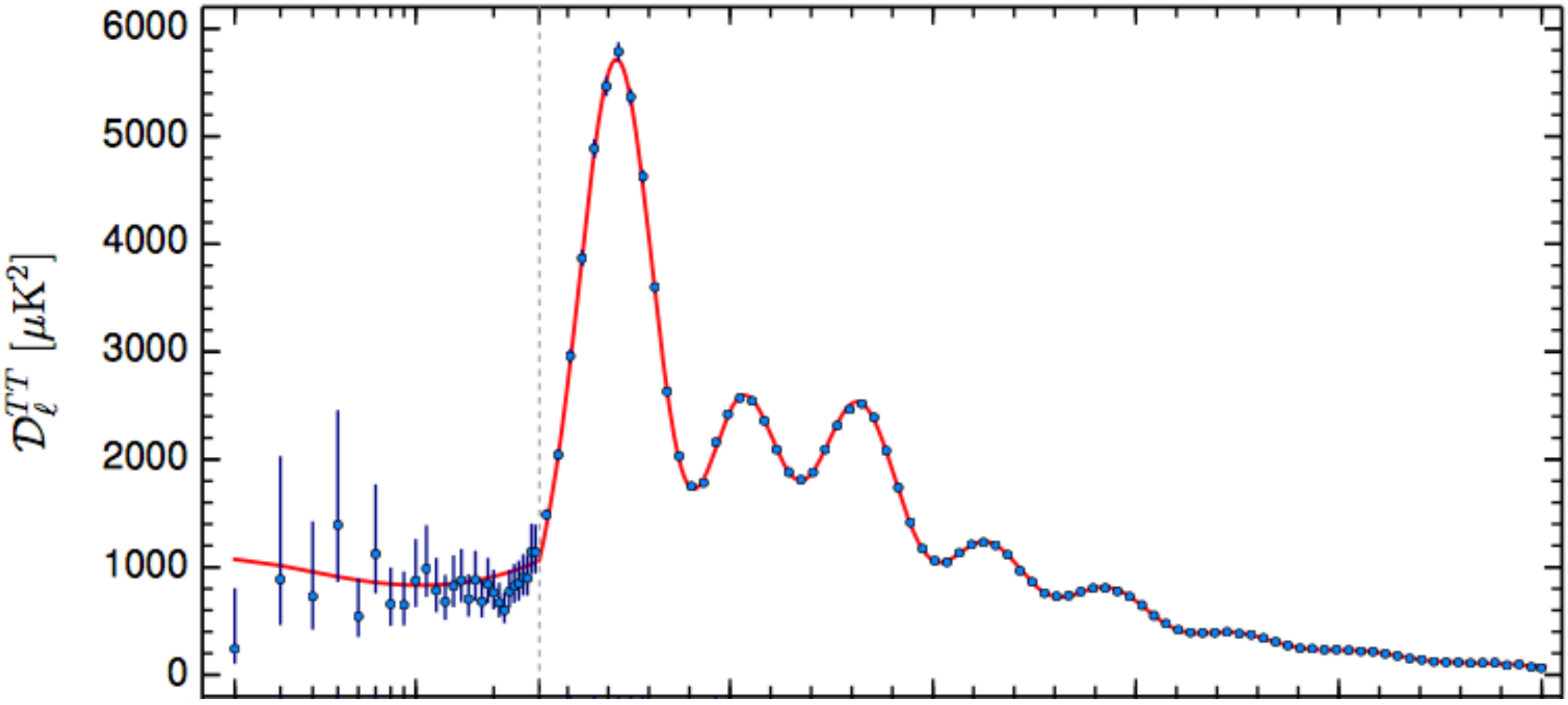




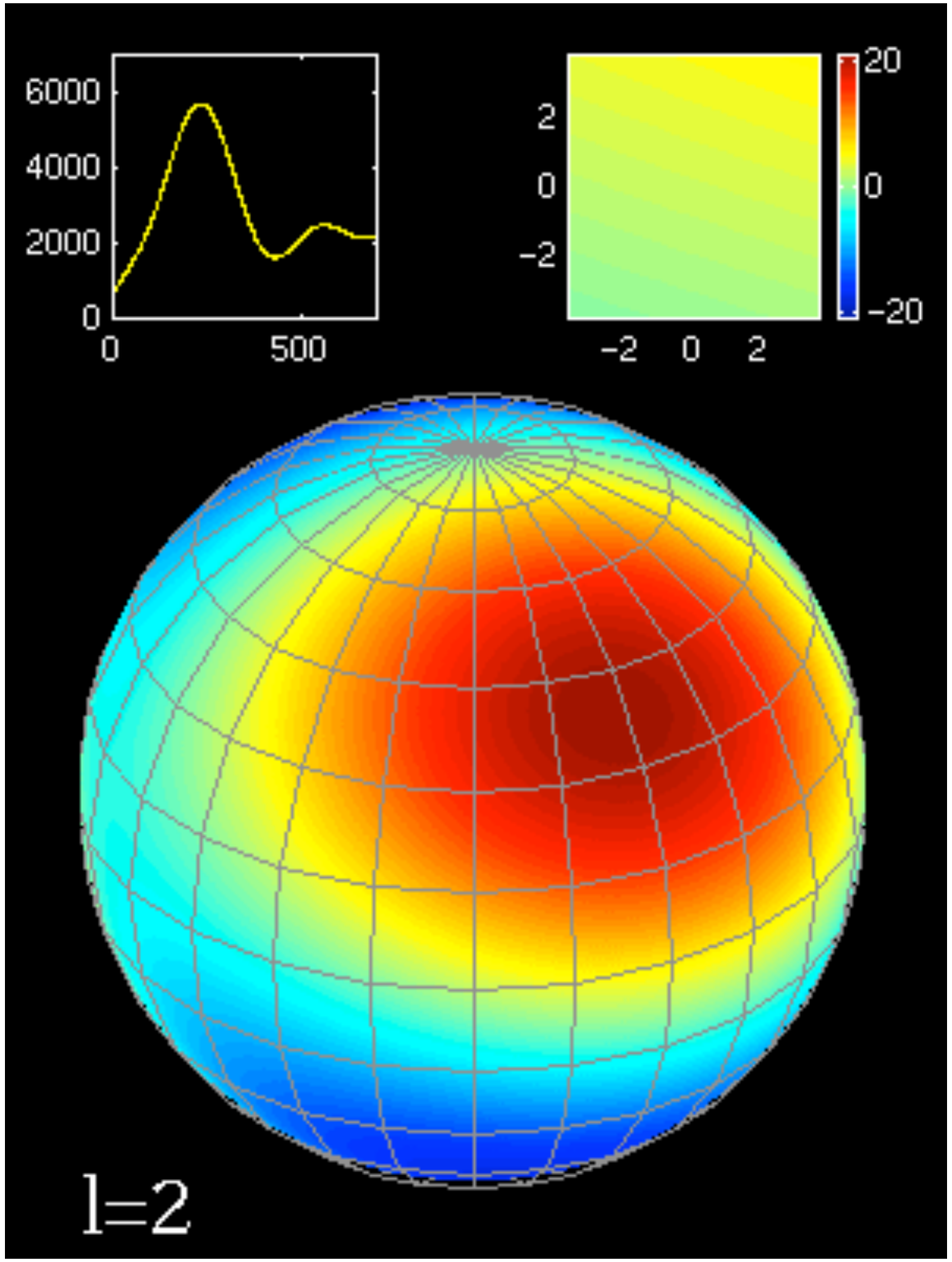


Amir Hajian for ACT

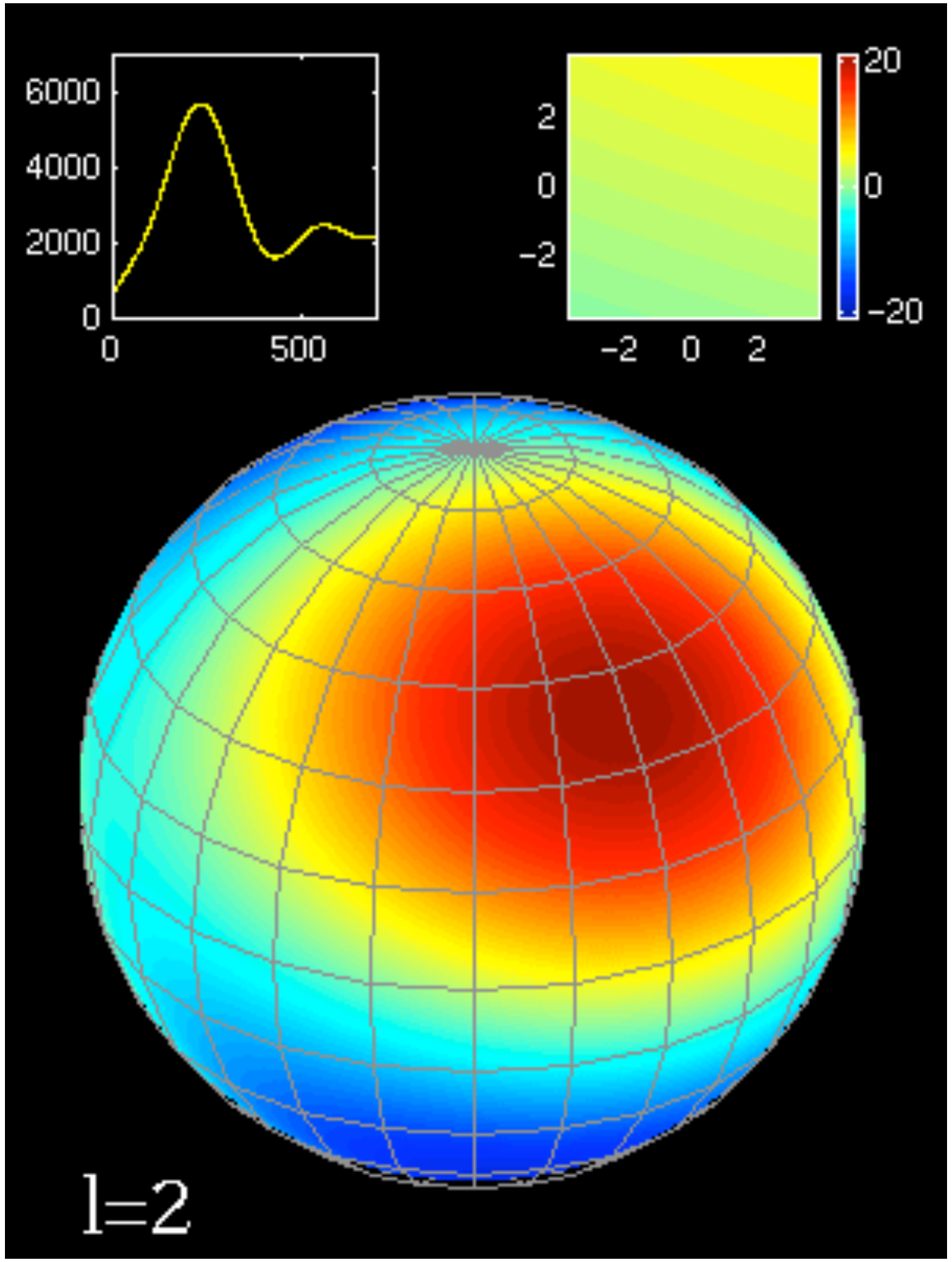
Planck CMB Power Spectrum



Planck Results 2015, Paper 13



Made by Clem Pryke



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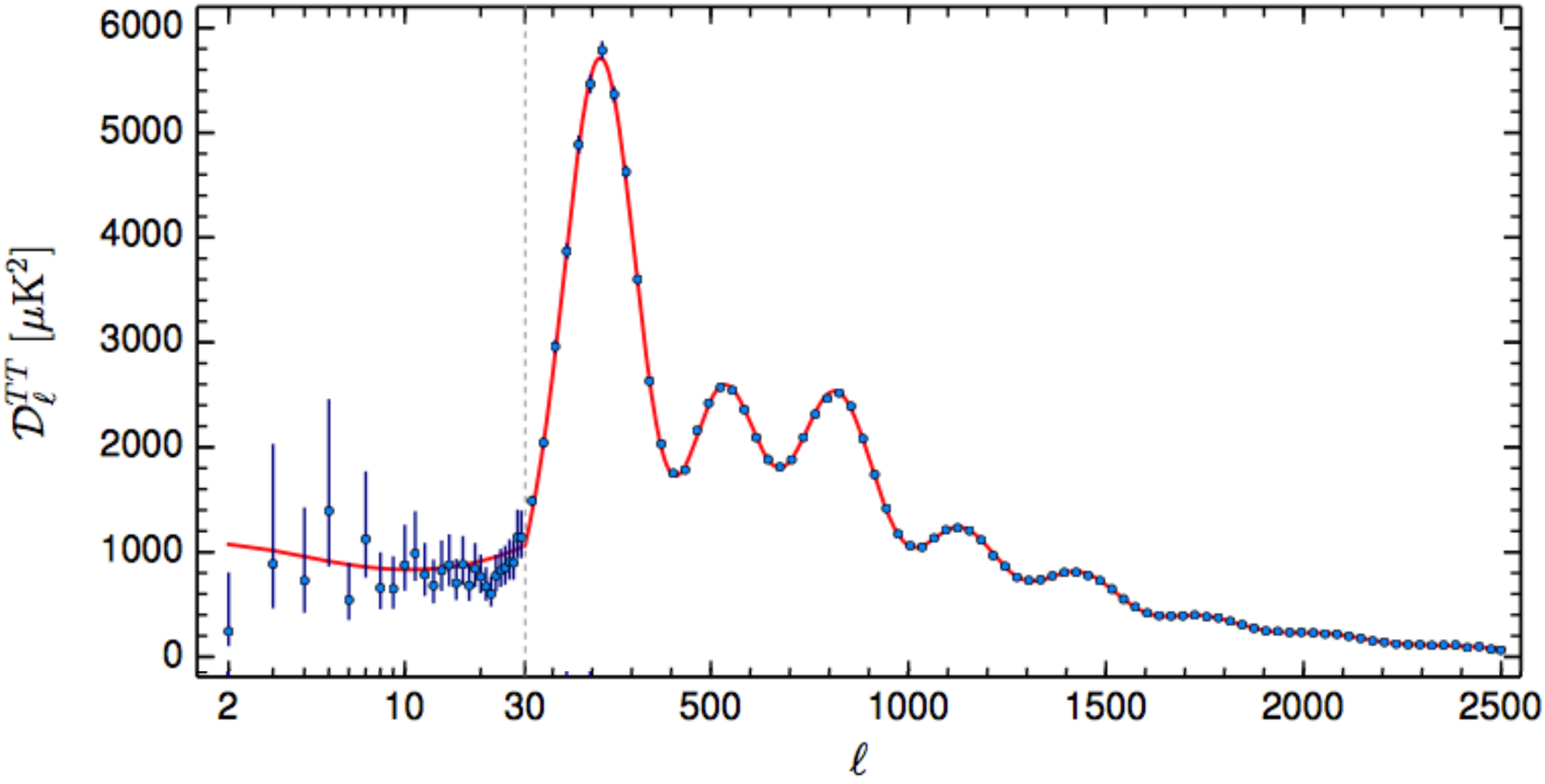
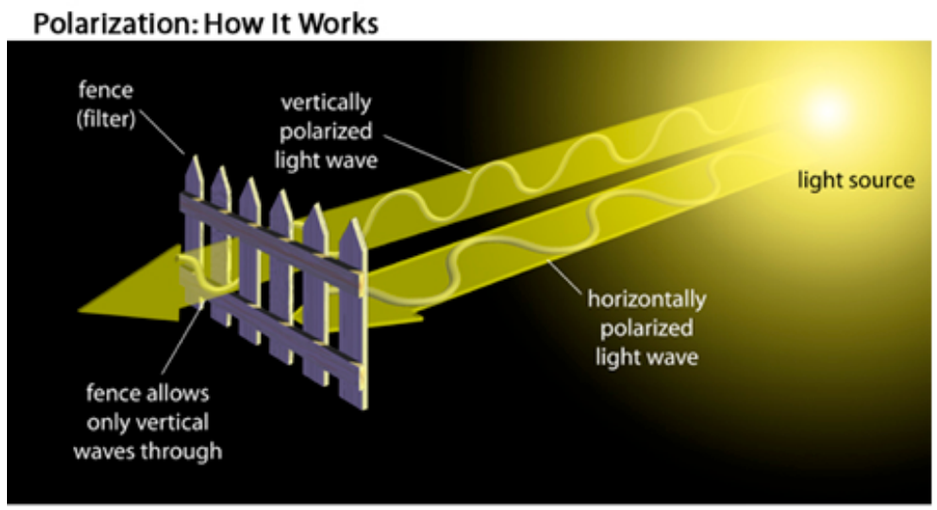
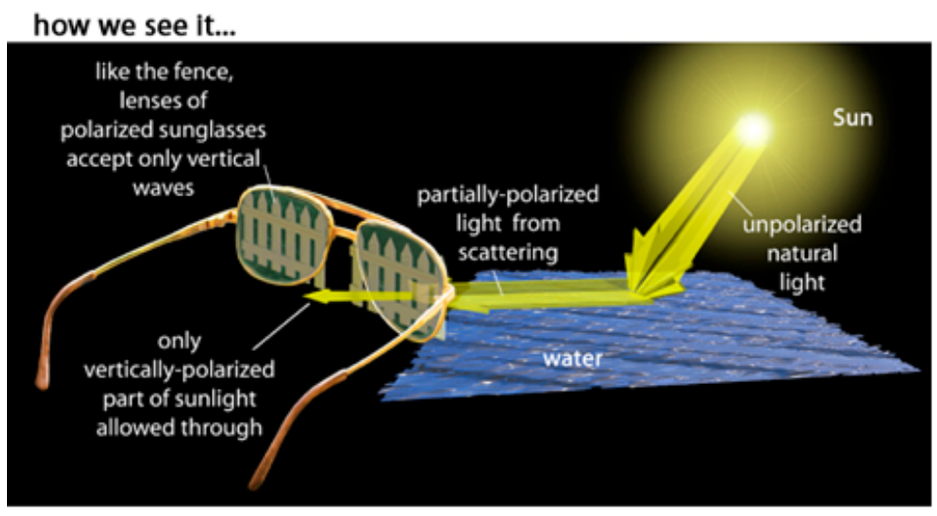
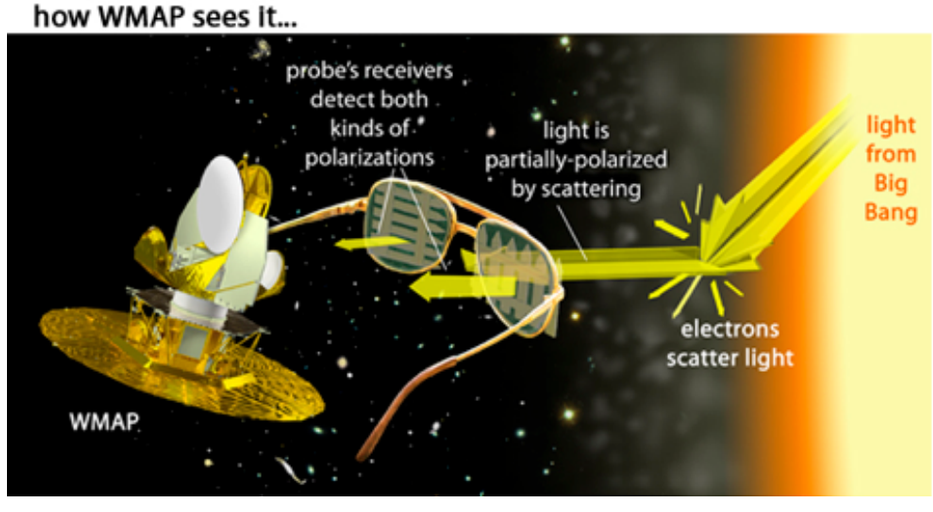


Planck Results 2015, Paper 13

CMB Polarization







From Lambda website

Neelima Sehgal, Stony Brook

CMB Polarization

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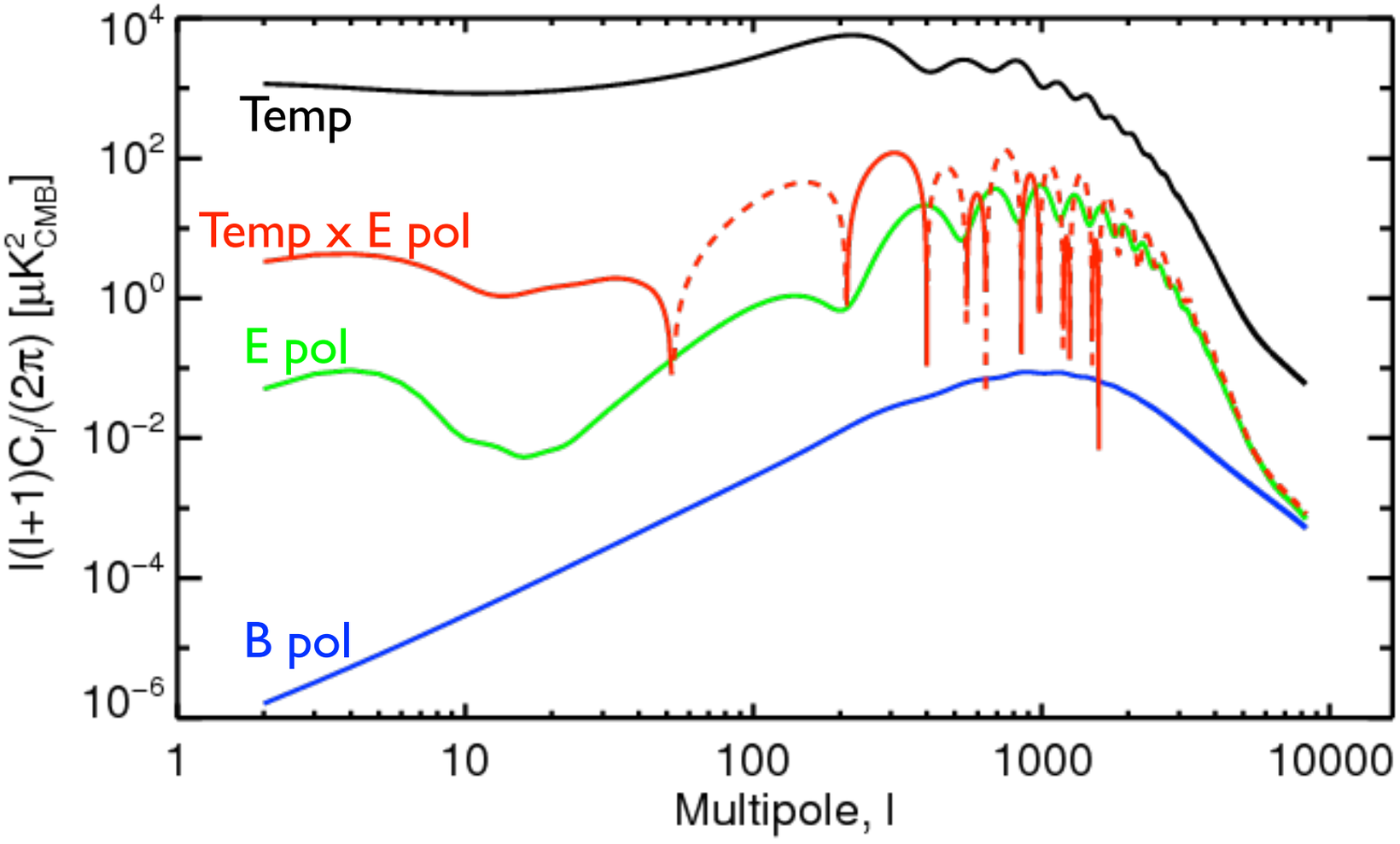
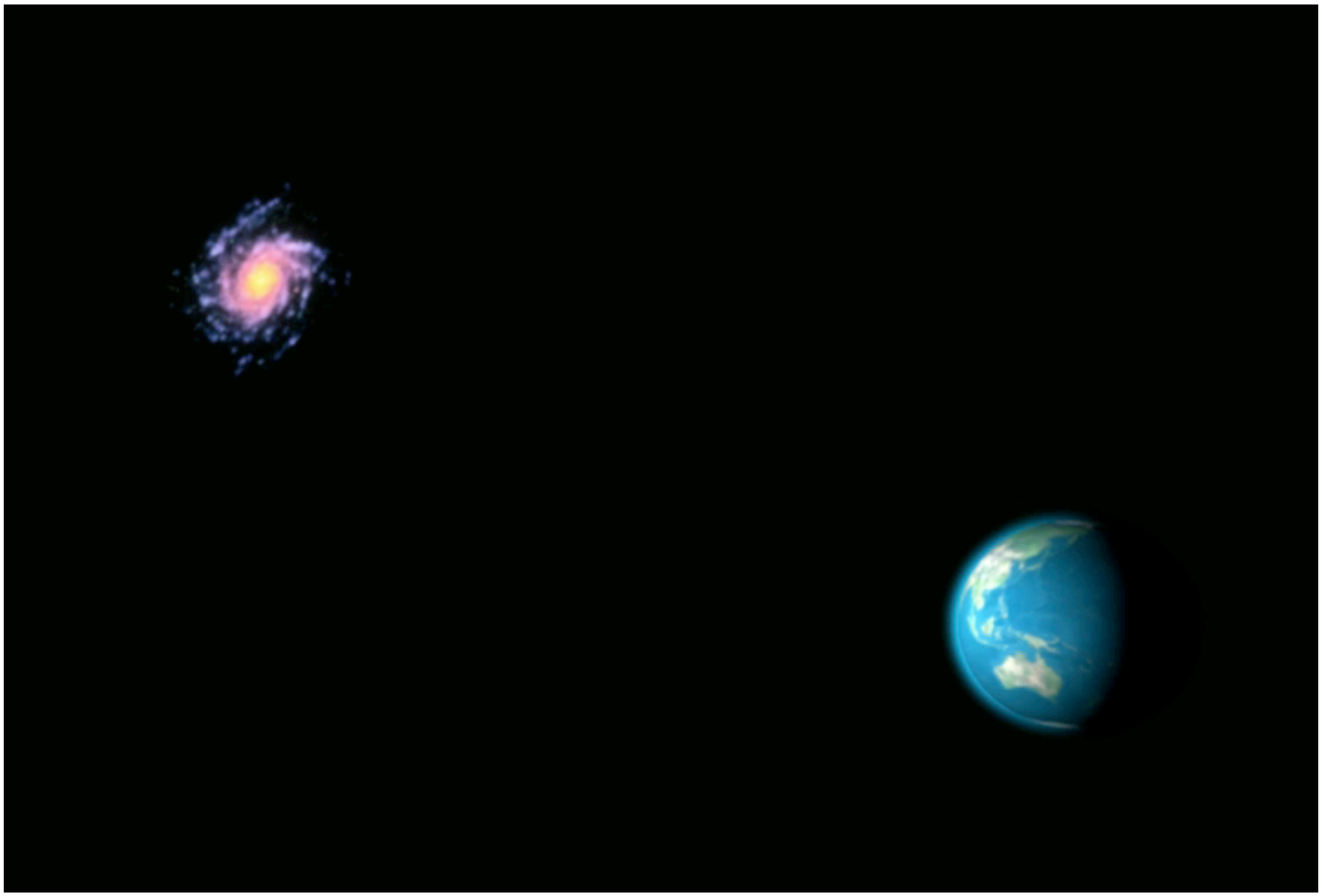
CMB Polarization



Gravitational Lensing



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

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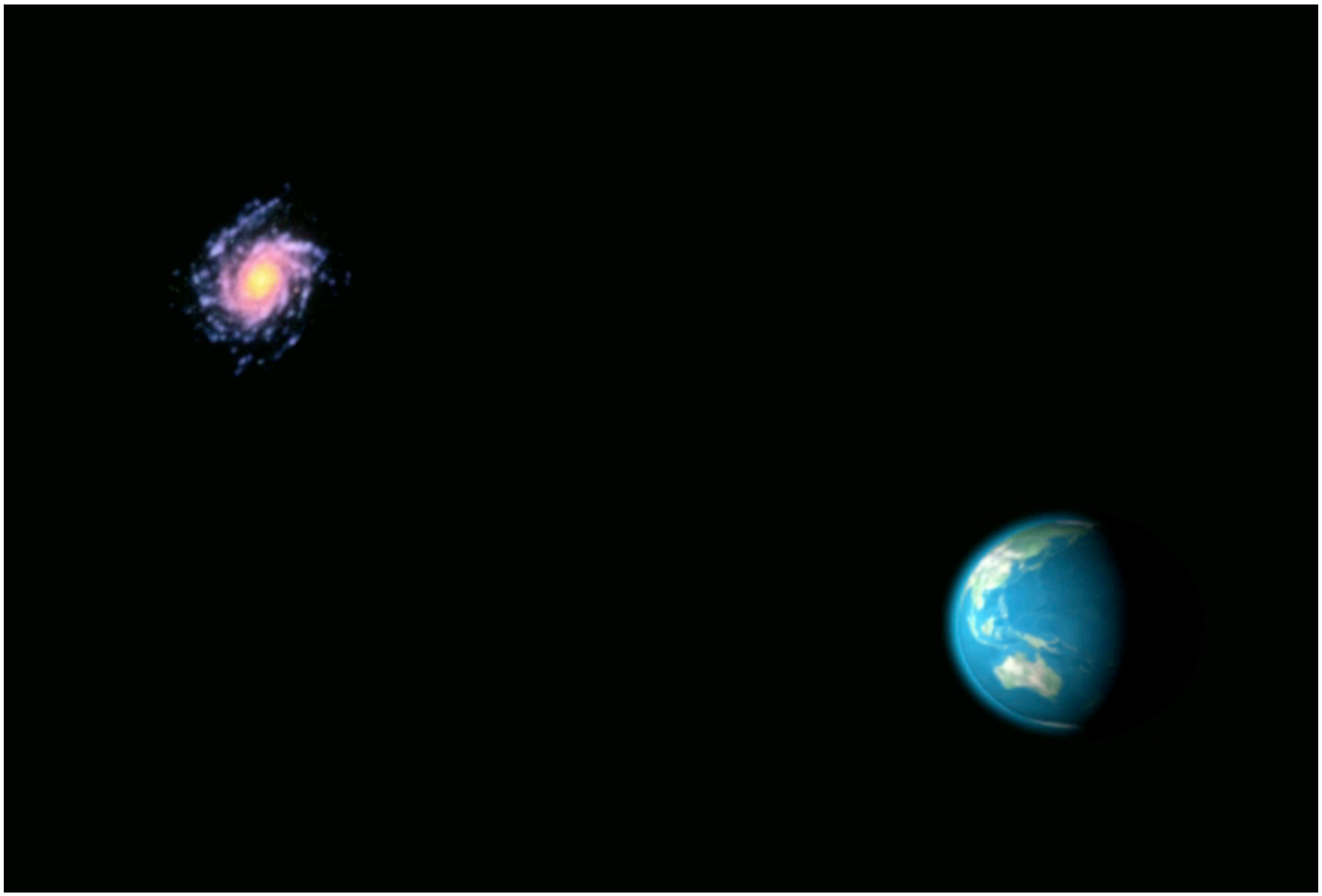

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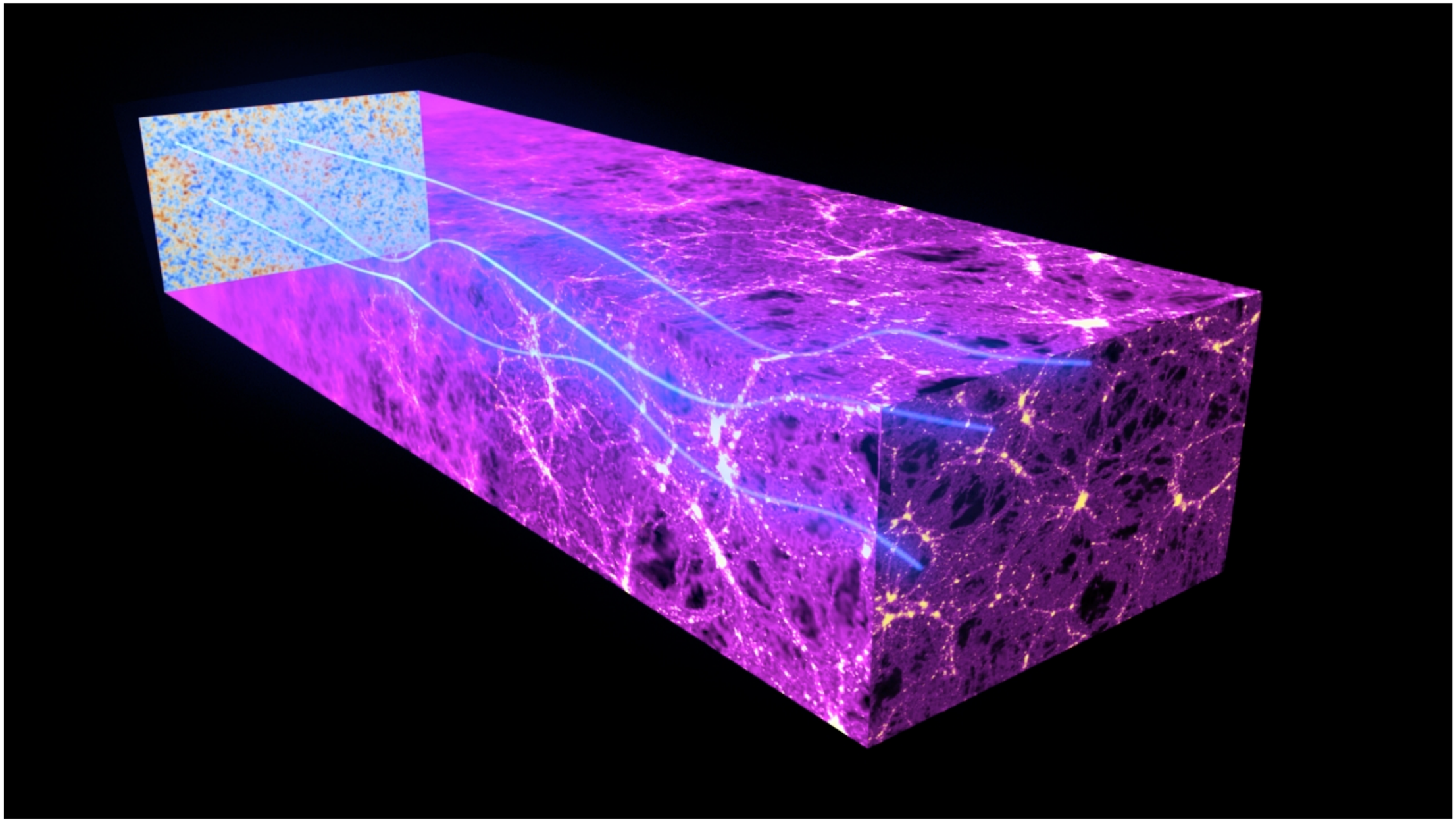
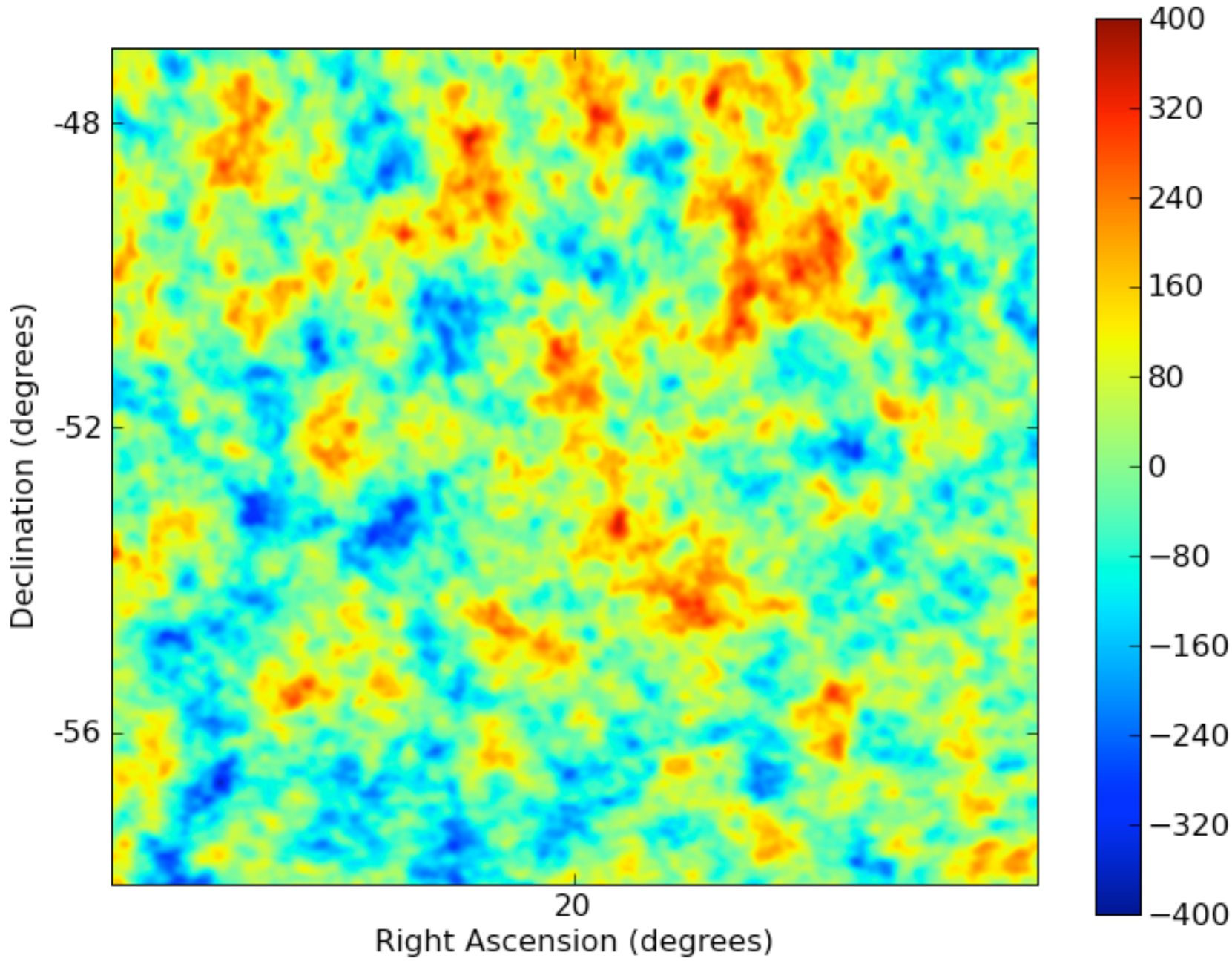


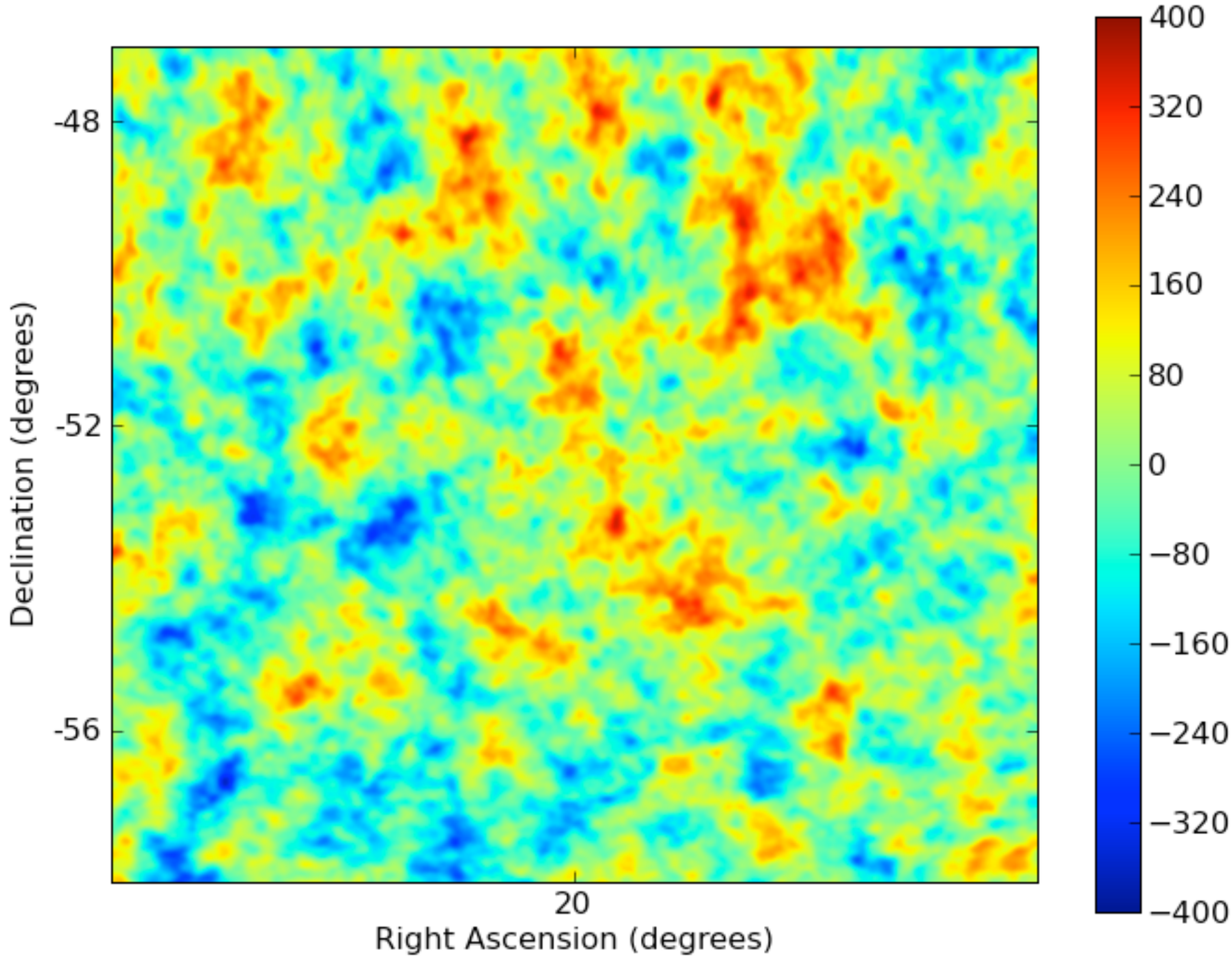
Image Credit: ESA

Unlensed CMB



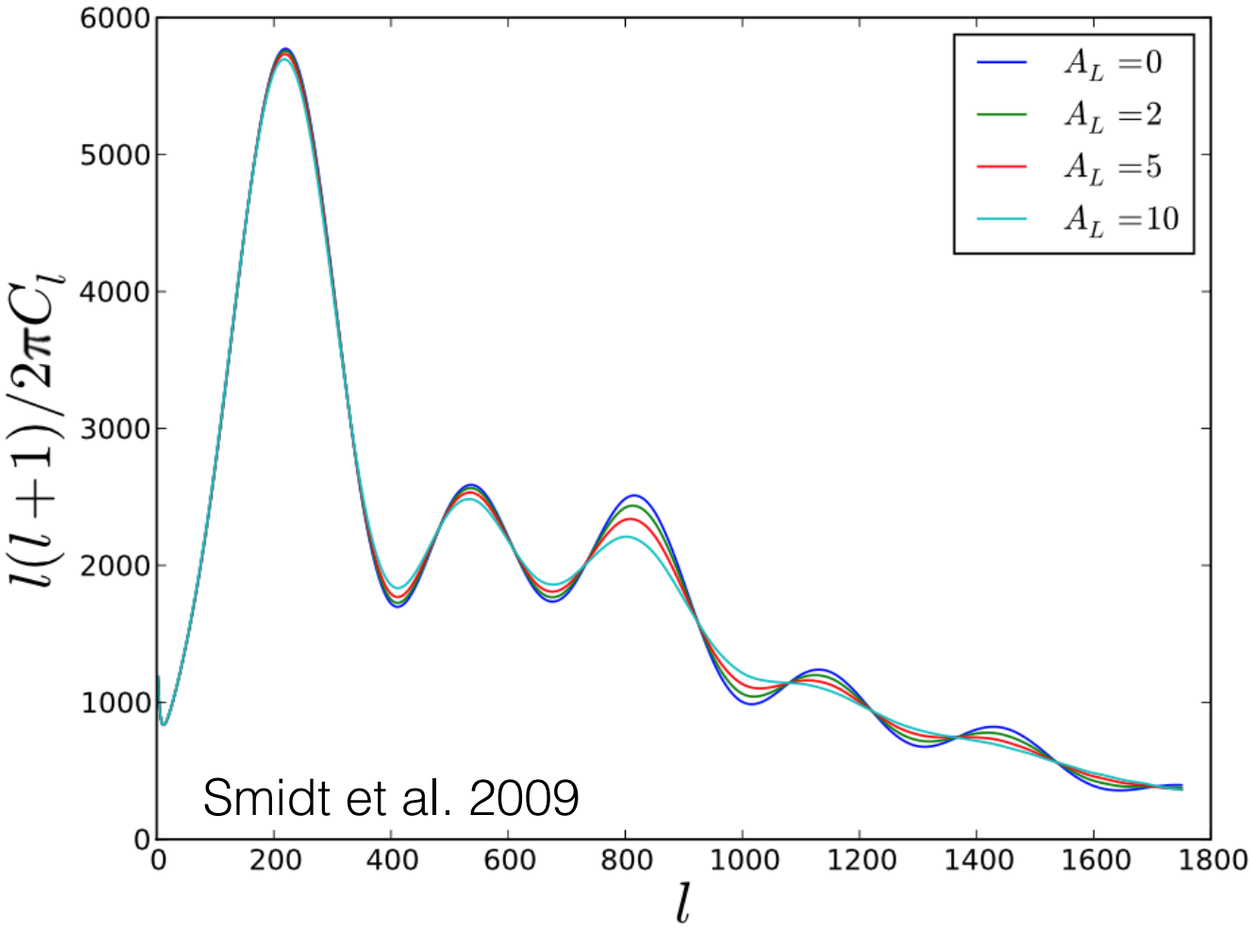
Neelima Sehgal, Stony Brook

Lensed CMB



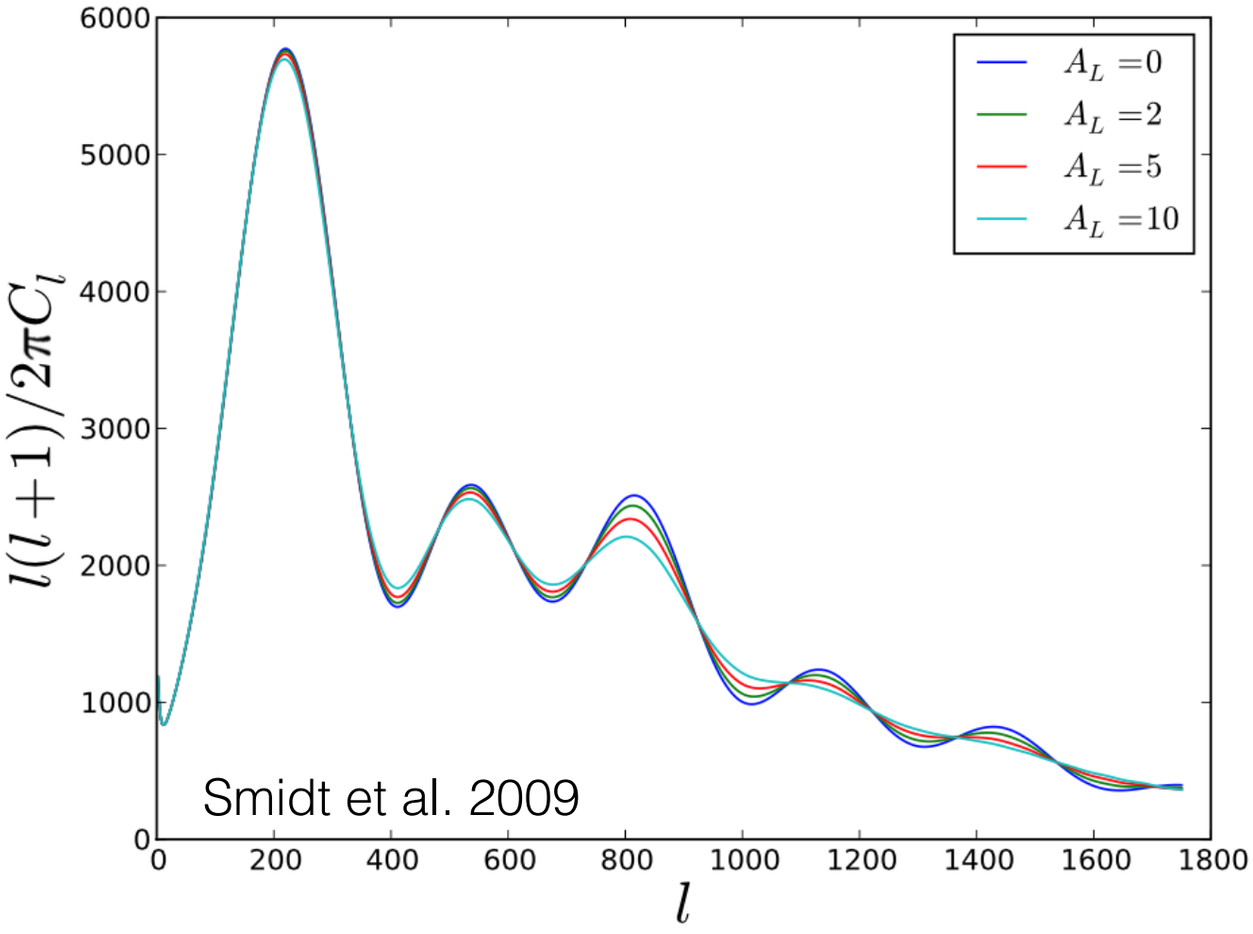
Neelima Sehgal, Stony Brook

Measuring CMB Lensing



Lensing induces mode coupling

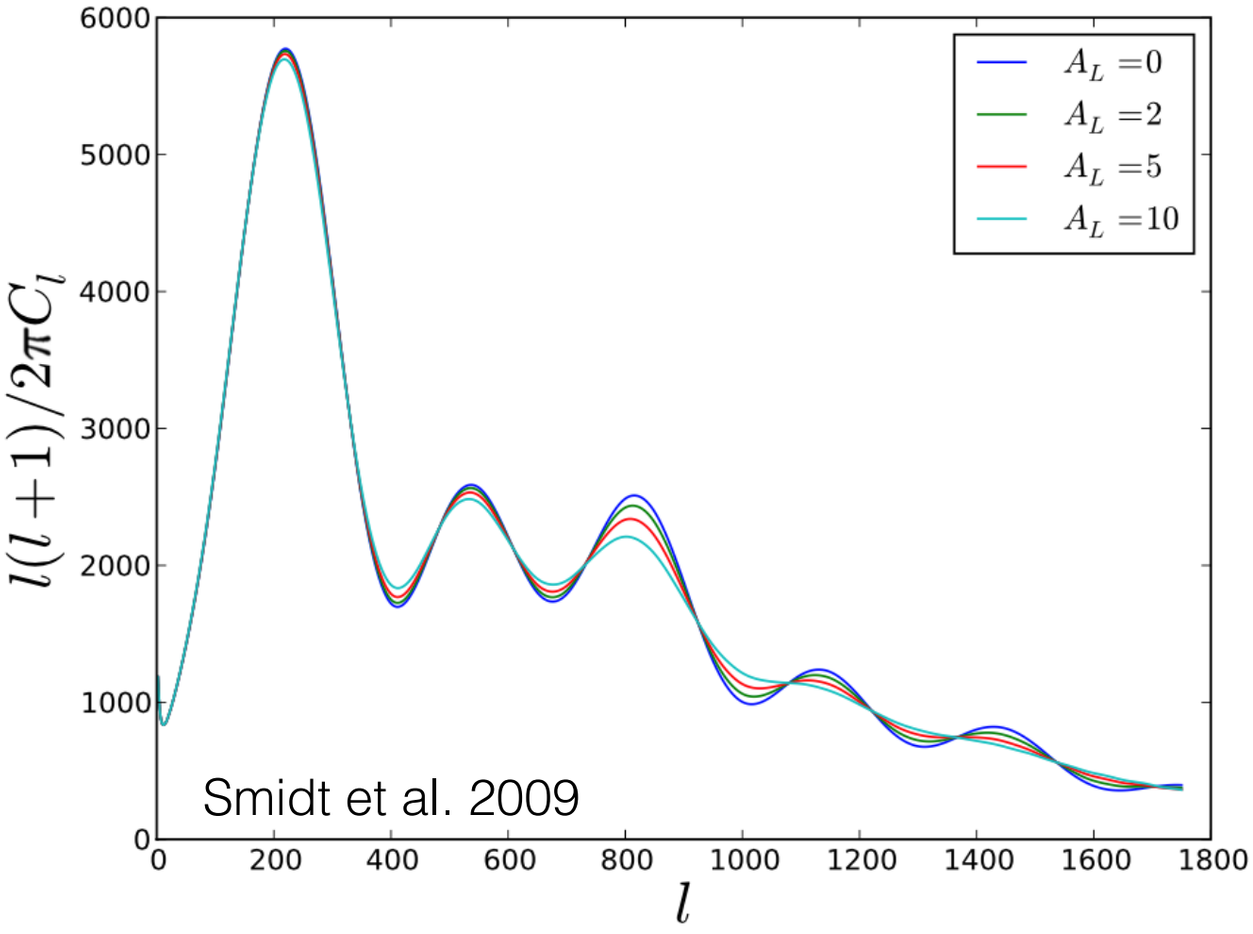
Measuring CMB Lensing



1.) Smooths CMB 2-pt function

Lensing induces mode coupling

Measuring CMB Lensing

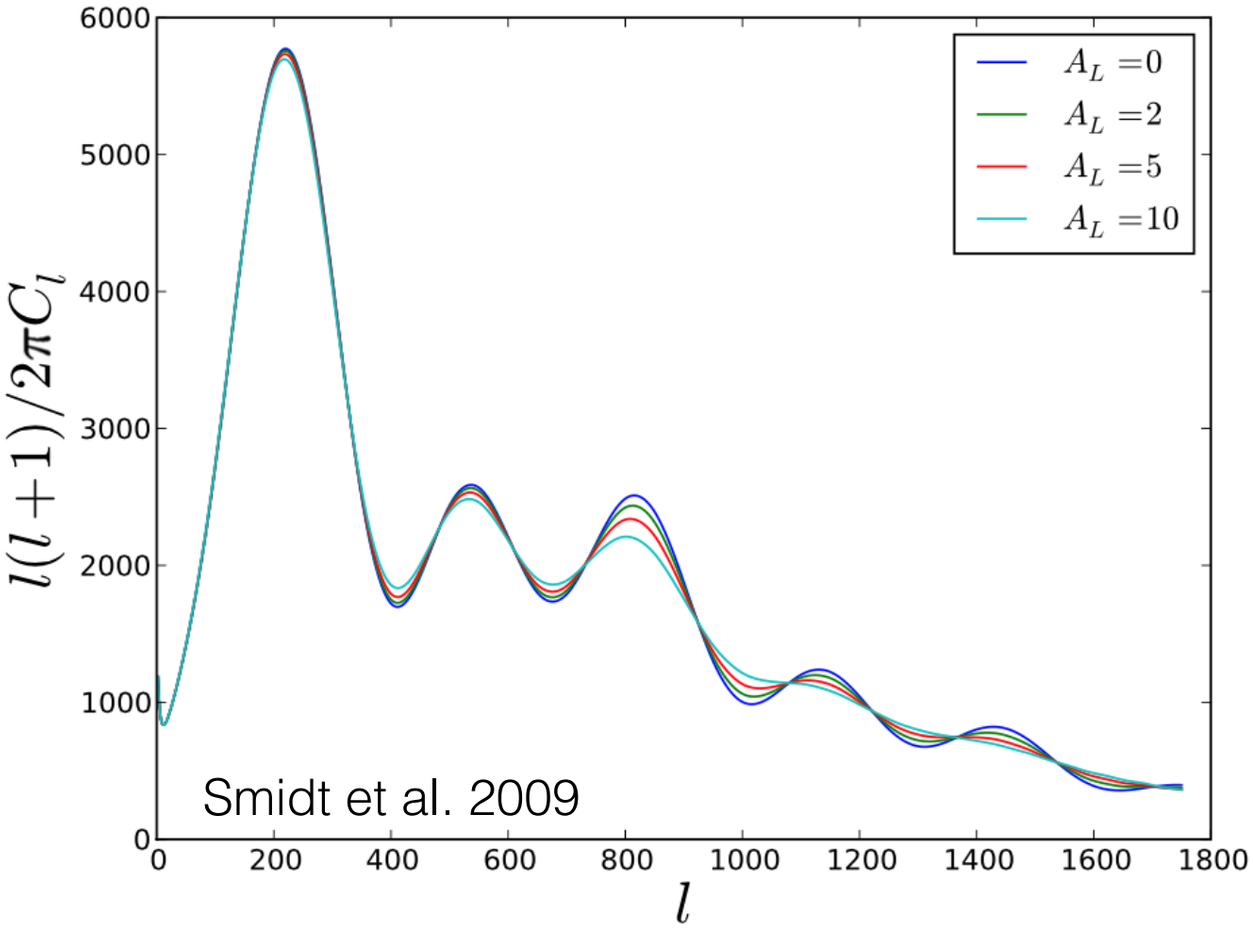


1.) Smooths CMB 2-pt function

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

Lensing induces mode coupling

Measuring CMB Lensing



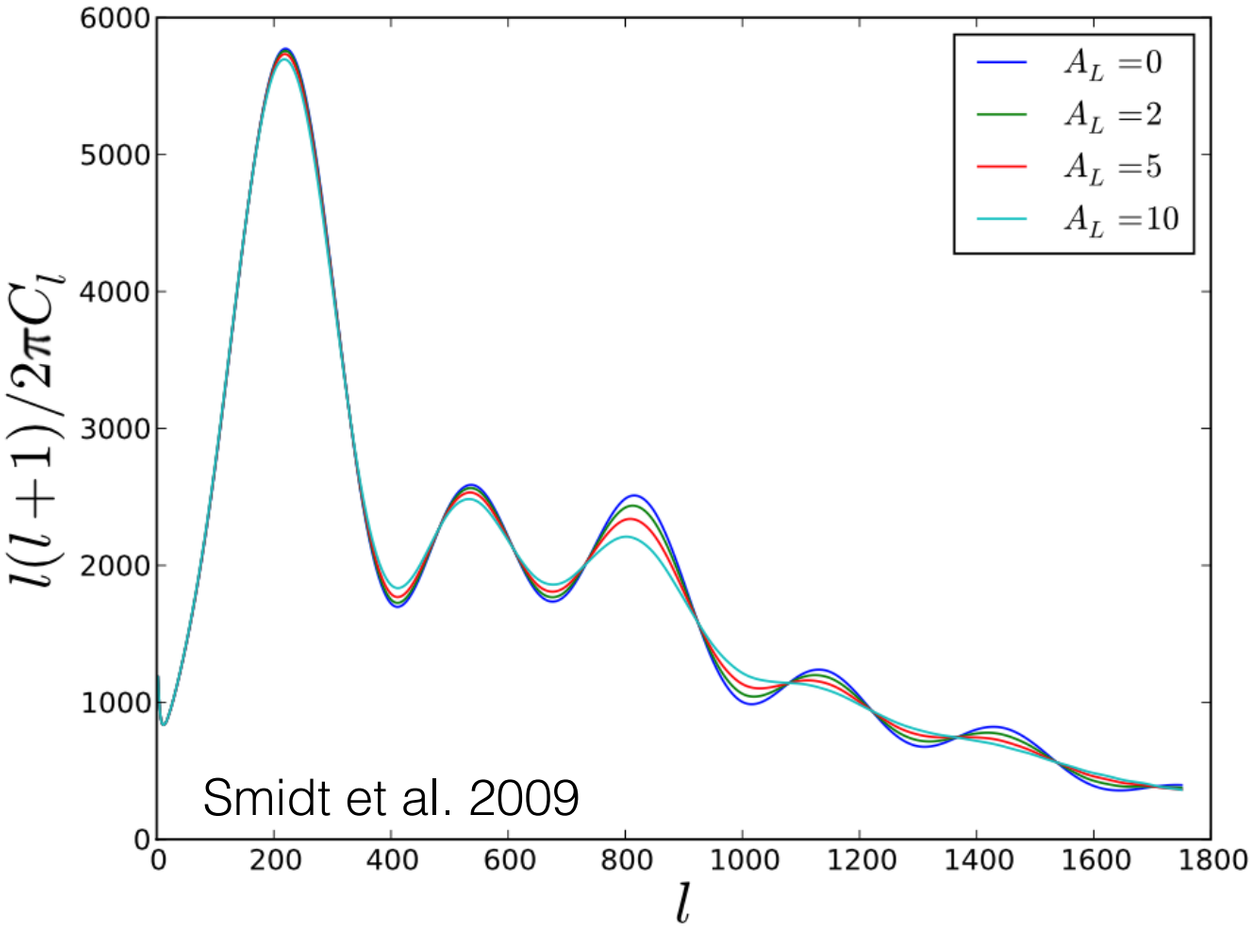
1.) Smooths CMB 2-pt function

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

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

Lensing induces mode coupling

Measuring CMB Lensing



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

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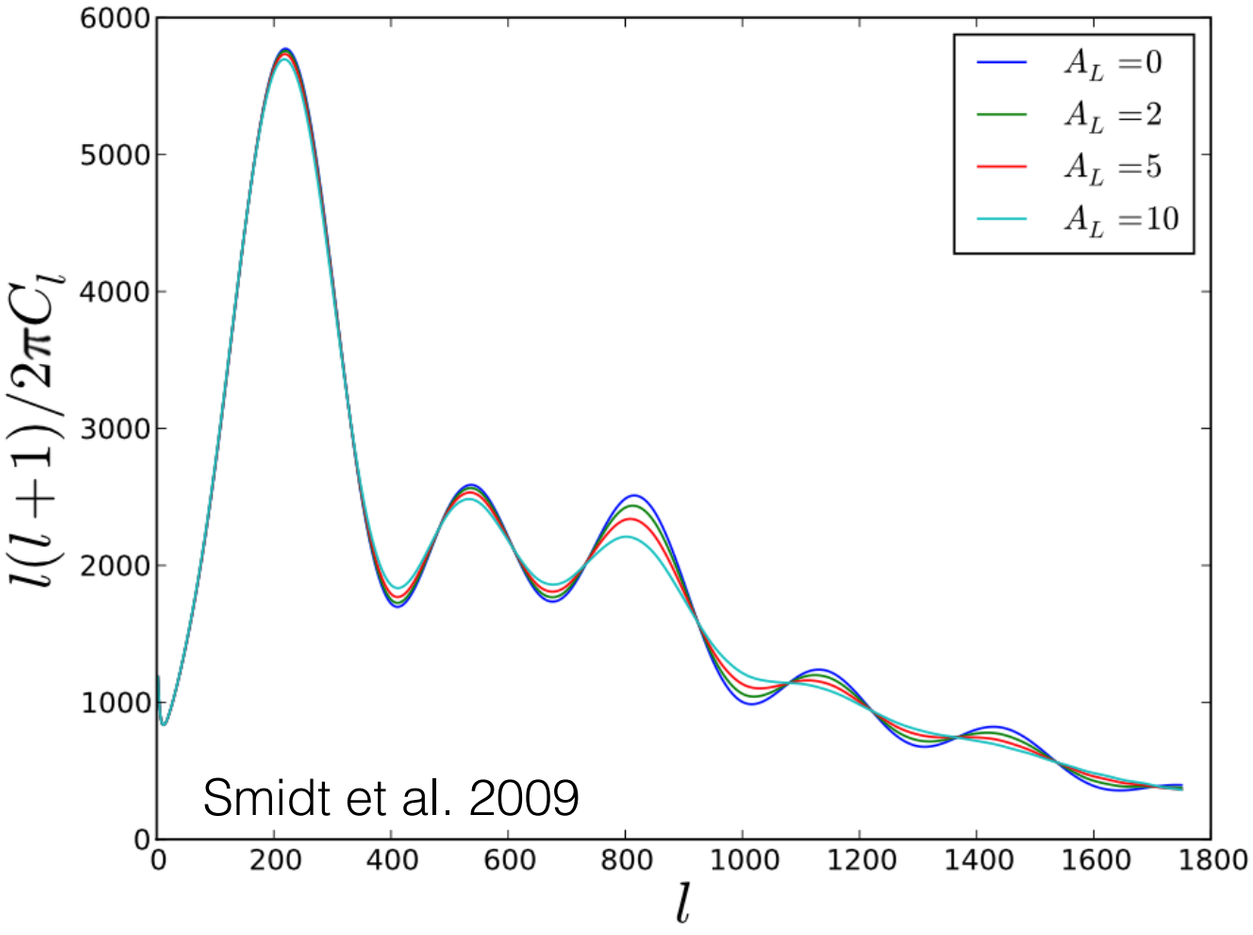
Measuring CMB Lensing



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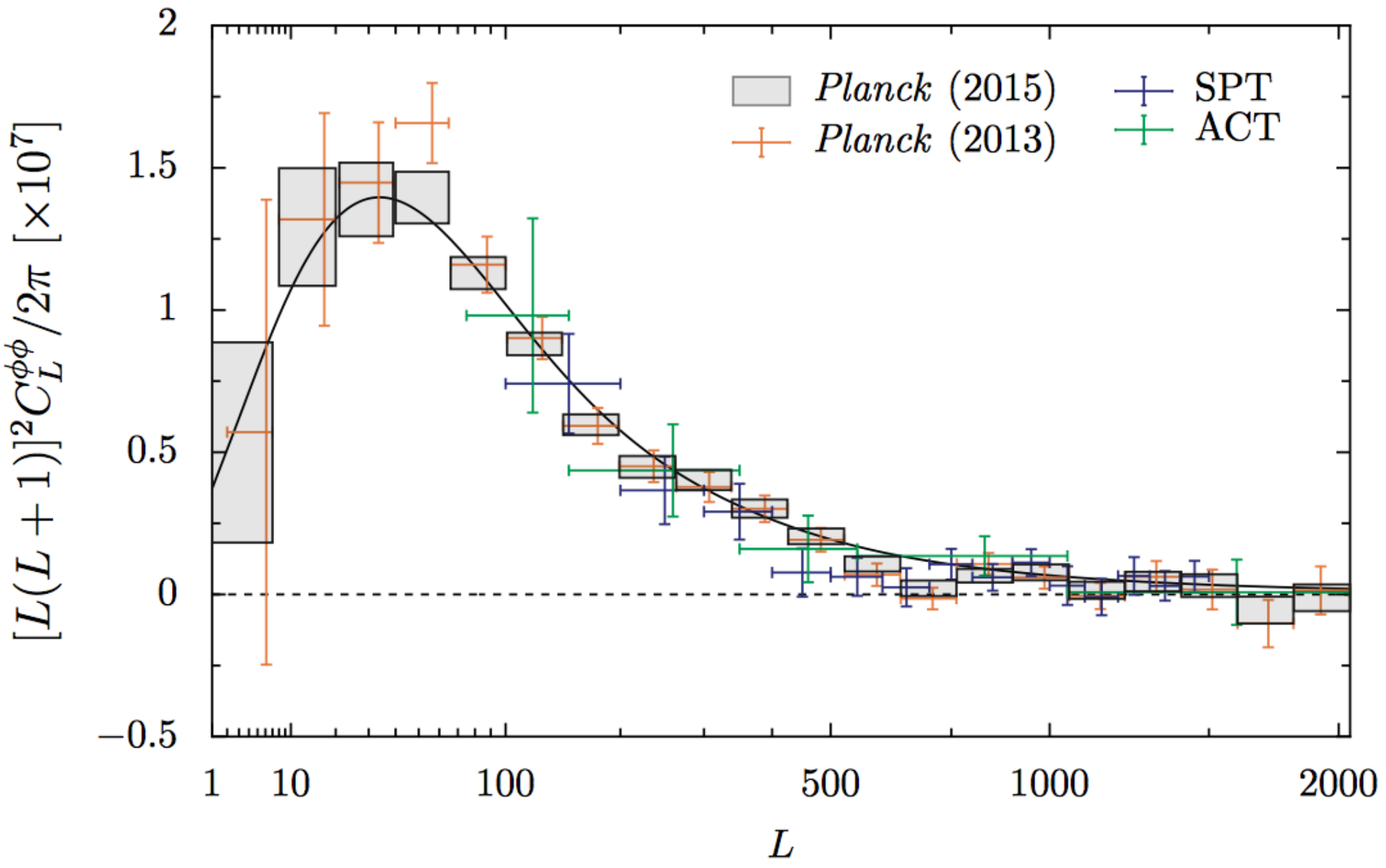
$$\hat{C}_L^{\hat{\phi}\hat{\phi}} \propto \int_{\mathbf{l},\mathbf{l}'} T(\mathbf{l})T^*(\mathbf{l}-\mathbf{L})T^*(-\mathbf{l}')T(\mathbf{L}-\mathbf{l}')$$

Lensing induces mode coupling

All quadrilaterals whose diagonal has length L

First Measurements of CMB Lensing on Large Scales



Planck Paper 15, 2015 (1502.01591)

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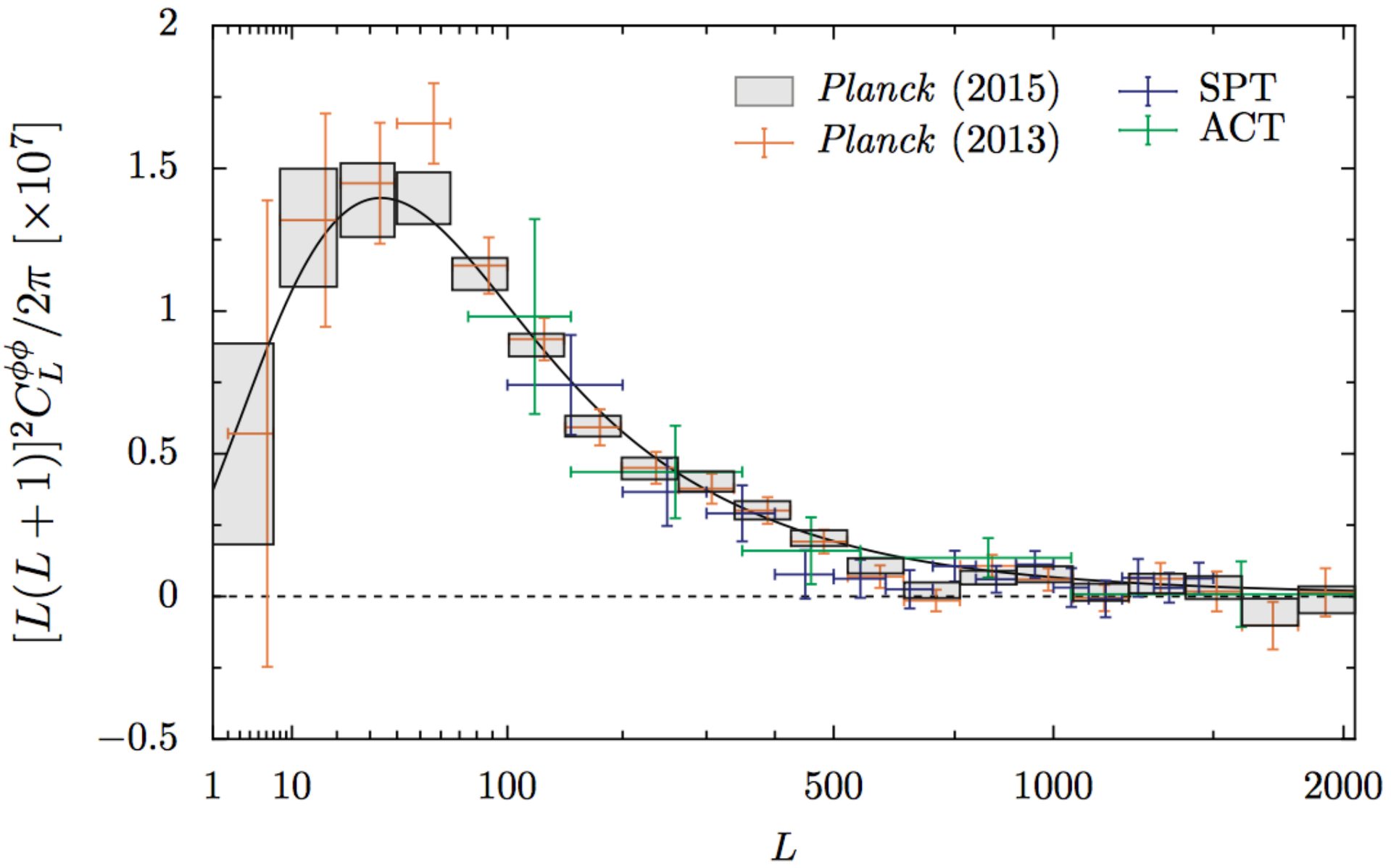

Planck Paper 15, 2015 (1502.01591)

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 2015
(detection with S/N = 40)

Atacama Cosmology Telescope Polarimeter: ACTPol

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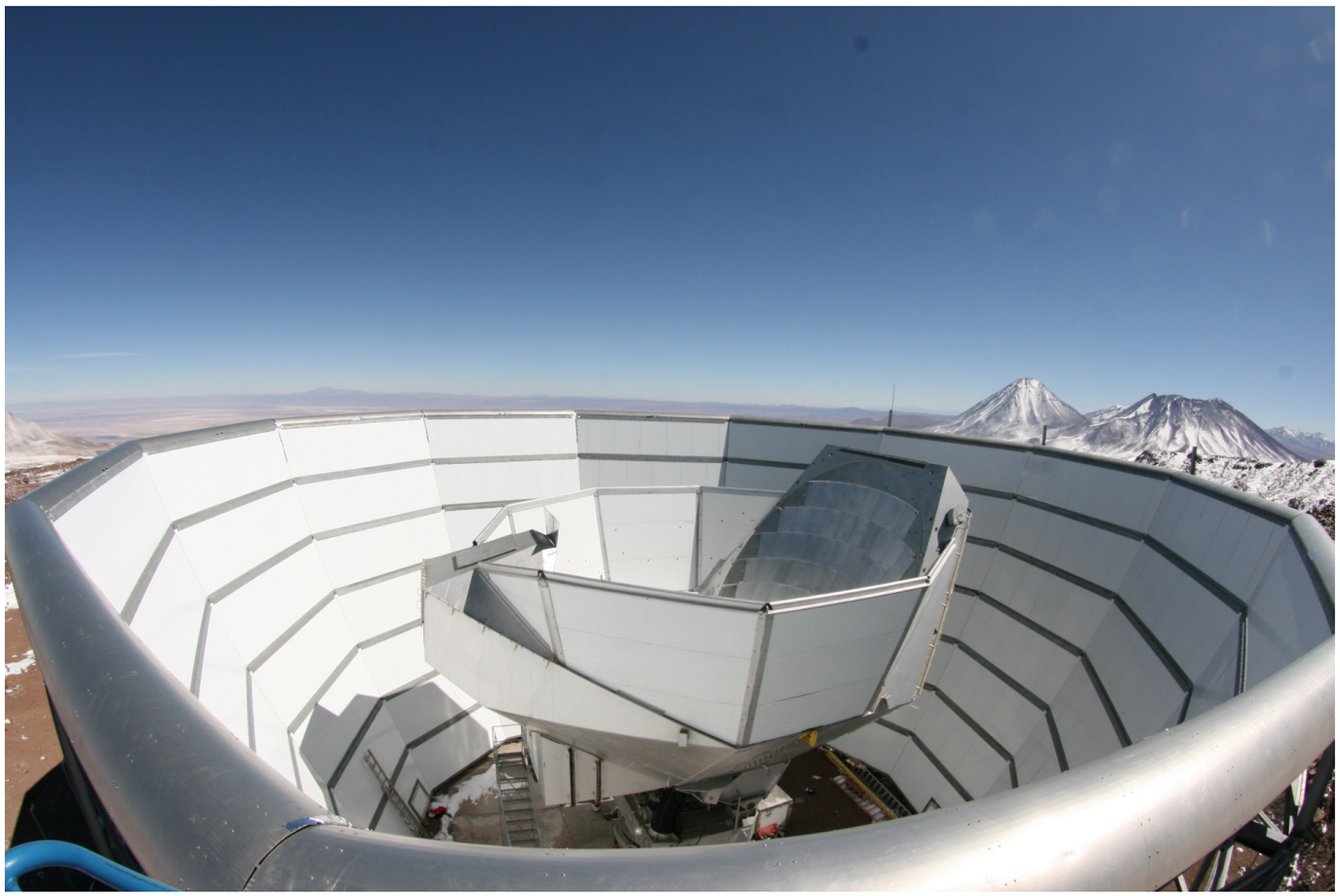
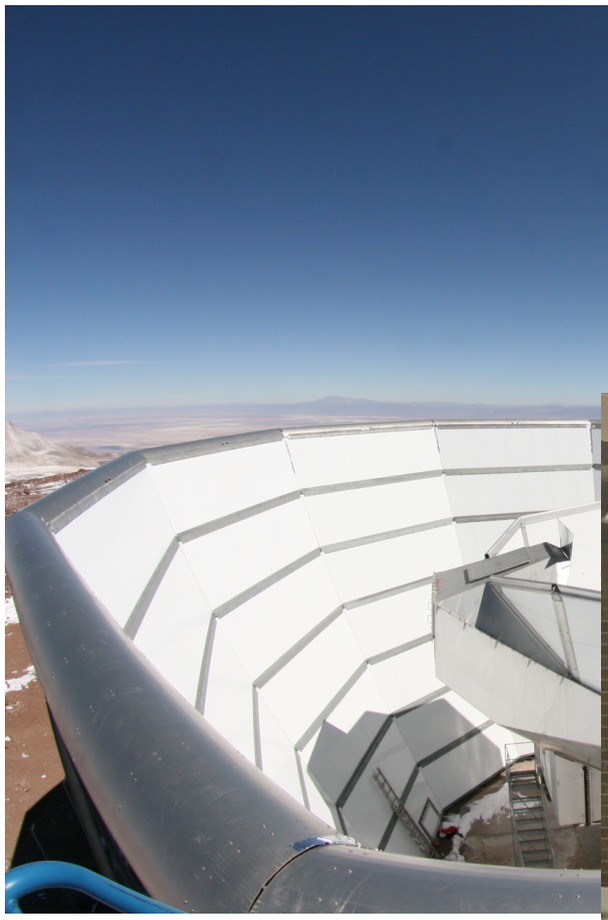


Atacama Cosmology Telescope Polarimeter: ACTPol



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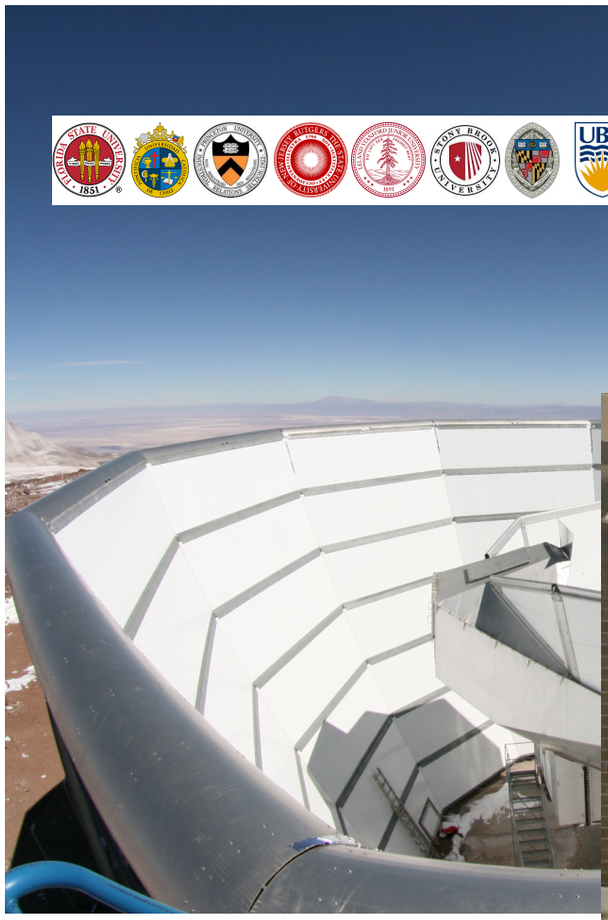
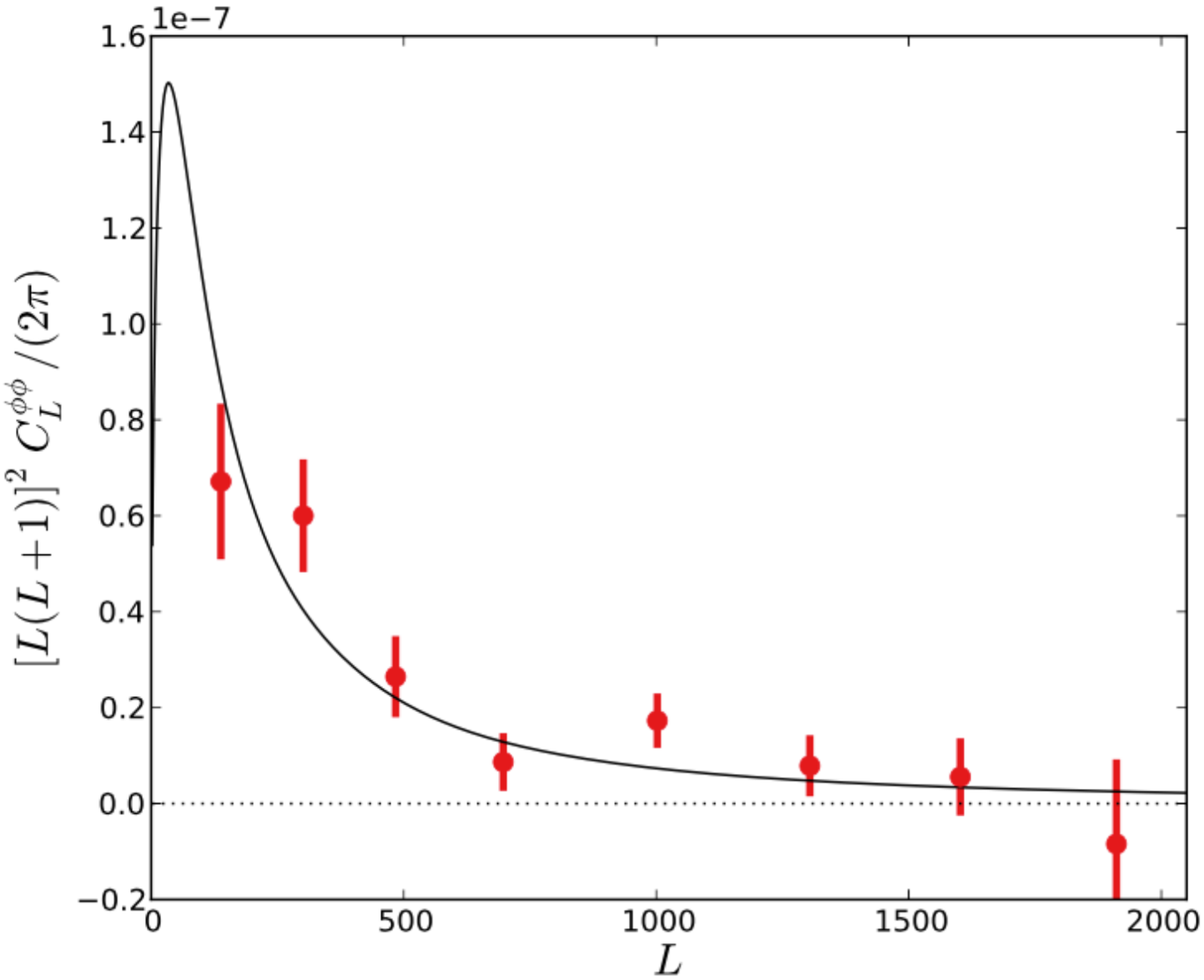
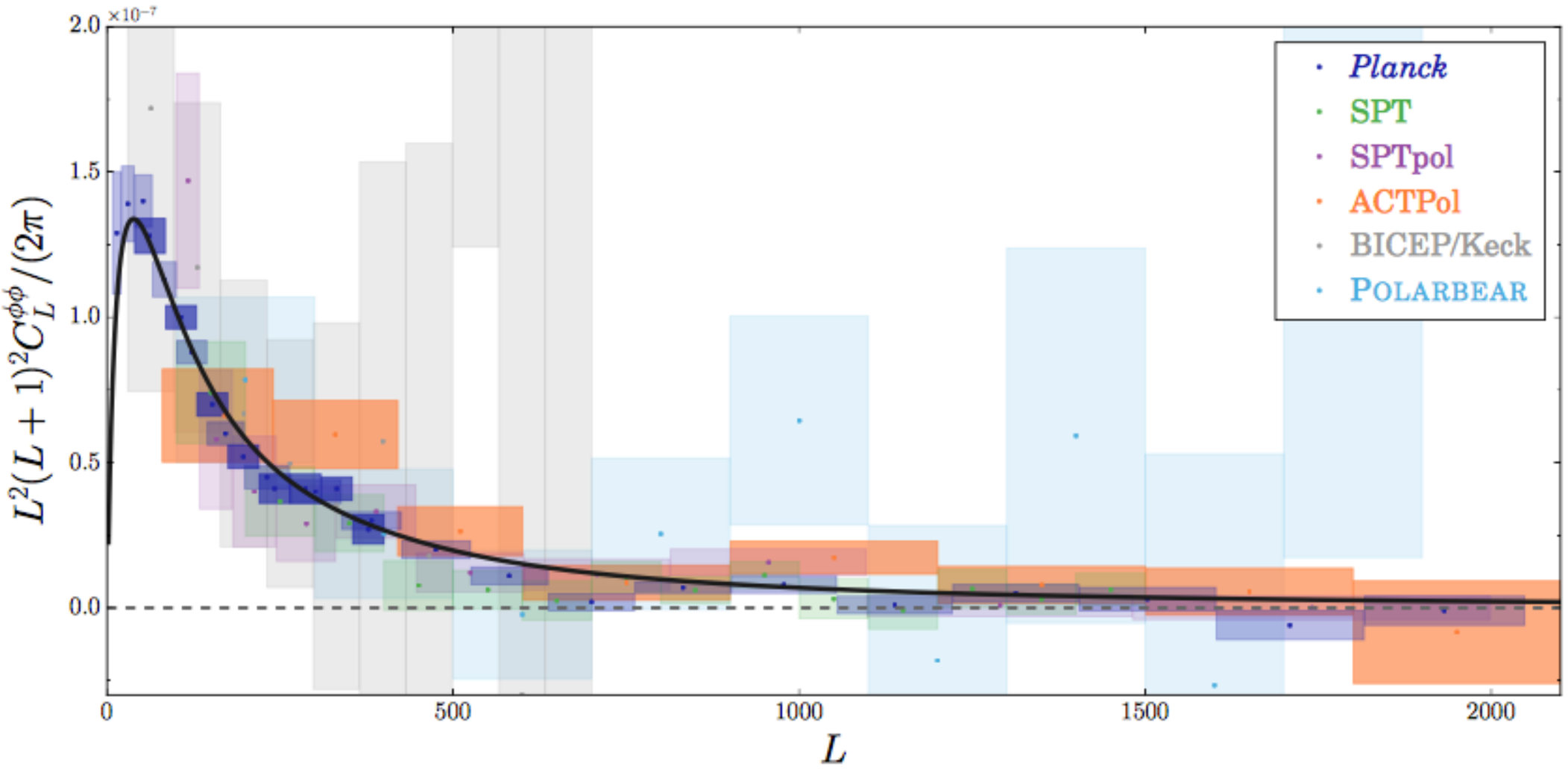


Two-Season ACTPol Lensing Power Spectrum



Blake Sherwin, Alex van Engelen, NS, Mathew Madhavacheril et al., 2016, (1611.09753)

Current Status of Lensing Power Spectrum



Blake Sherwin, Alex van Engelen, NS, Mathew Madhavacheril et al., 2016, (1611.09753)

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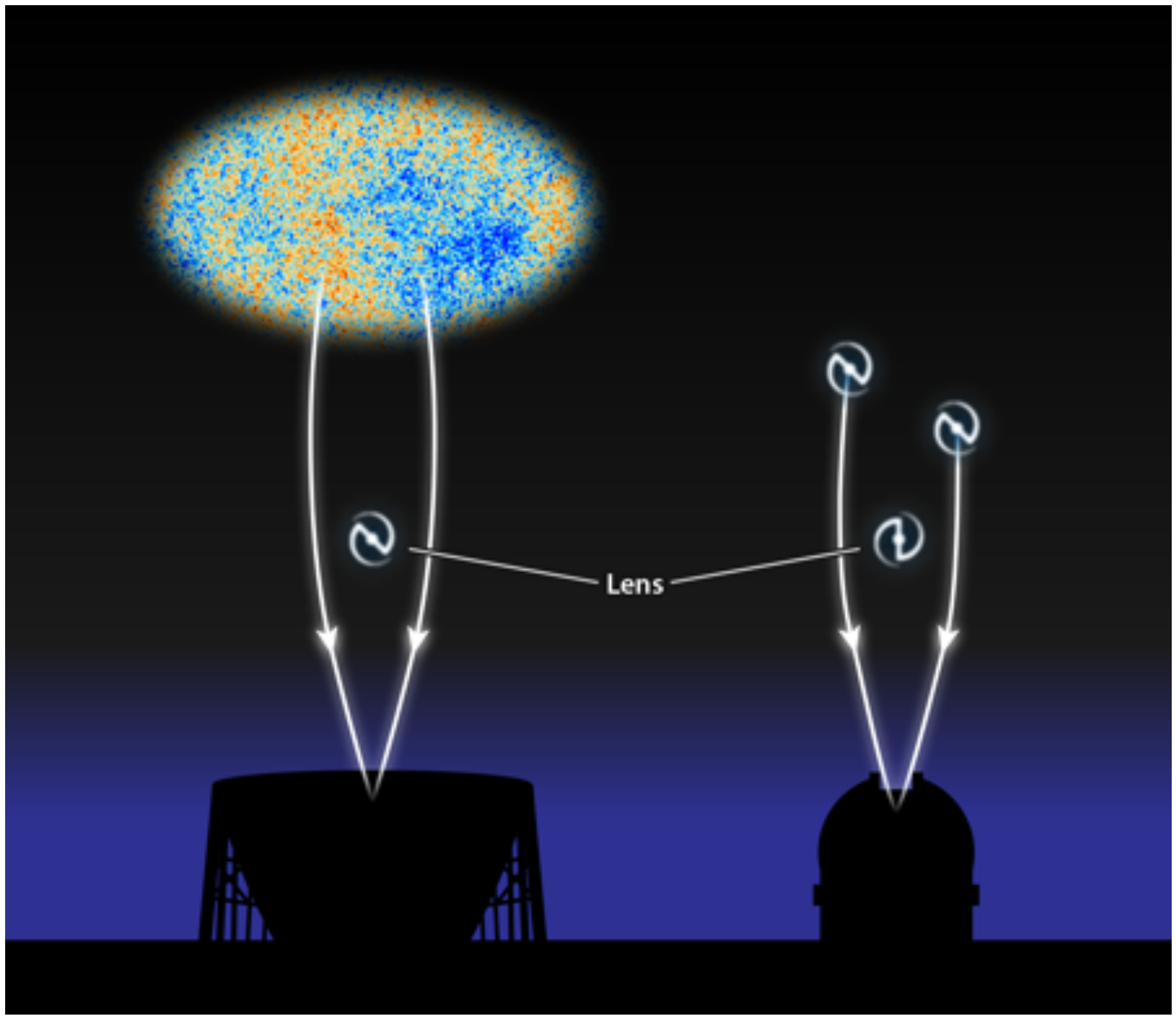
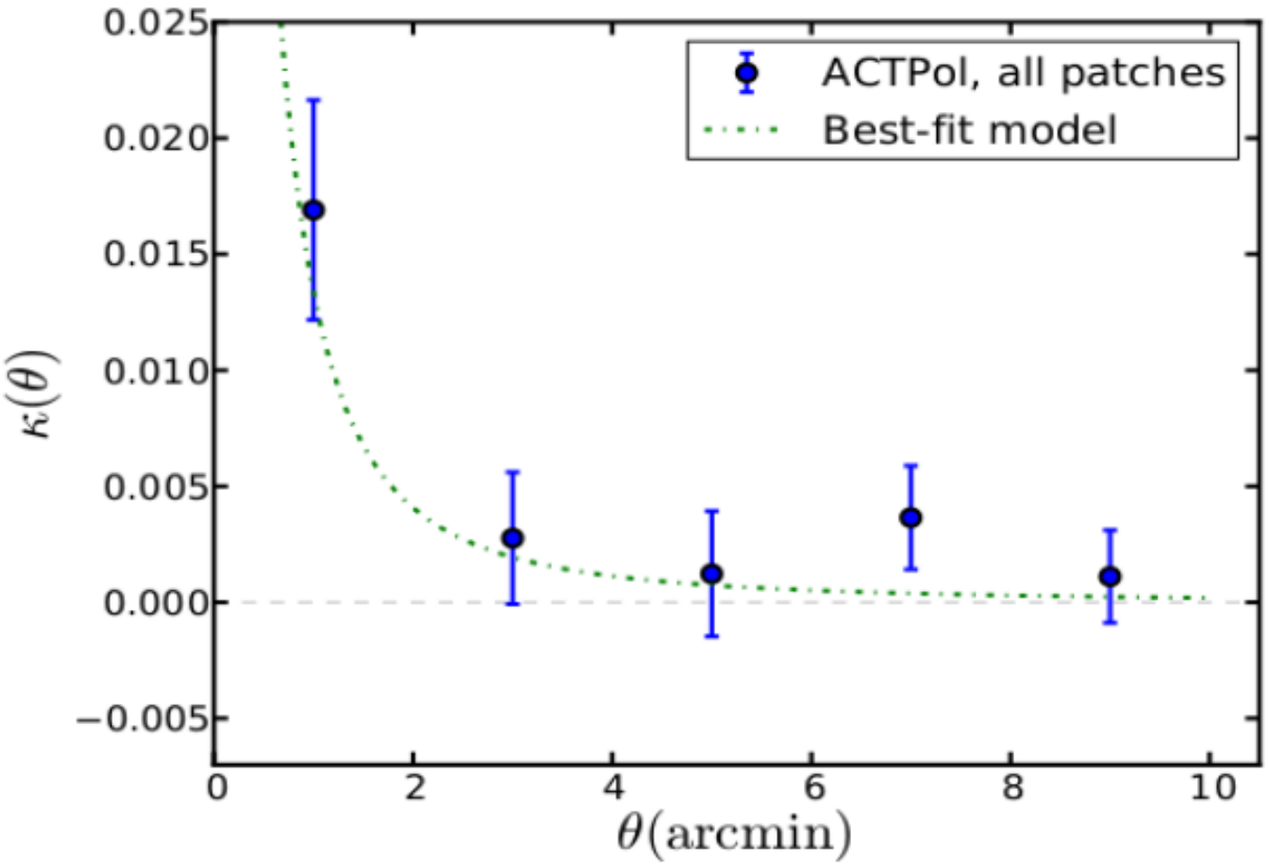
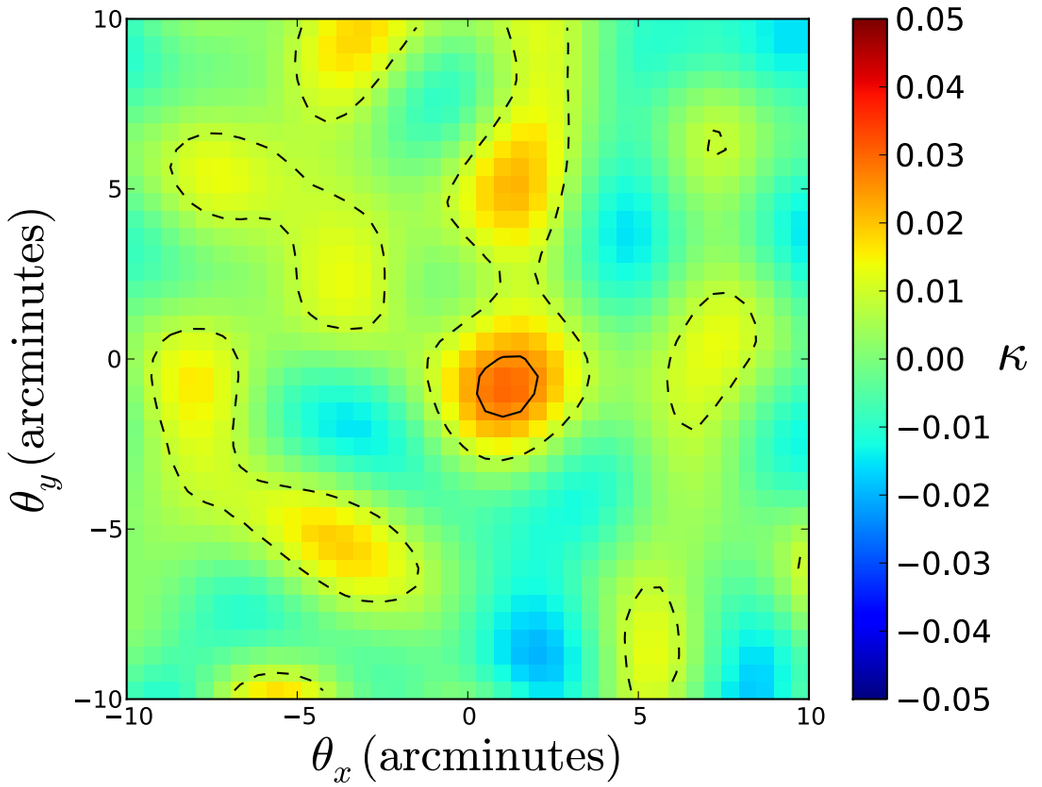


APS/**Alan Stonebraker**

First Measurements of CMB Lensing on Small Scales

Madhavacheril, Sehgal, et. al., PRL, 114, 2015





We detect halo lensing from 12,000 stacked CMASS galaxies at S/N of 3.2 sigma

Best fit: $M_{200} = (2.0 \pm 0.7) \times 10^{13} h^{-1} M_\odot$ and $c_{200} = 5.4 \pm 0.8$

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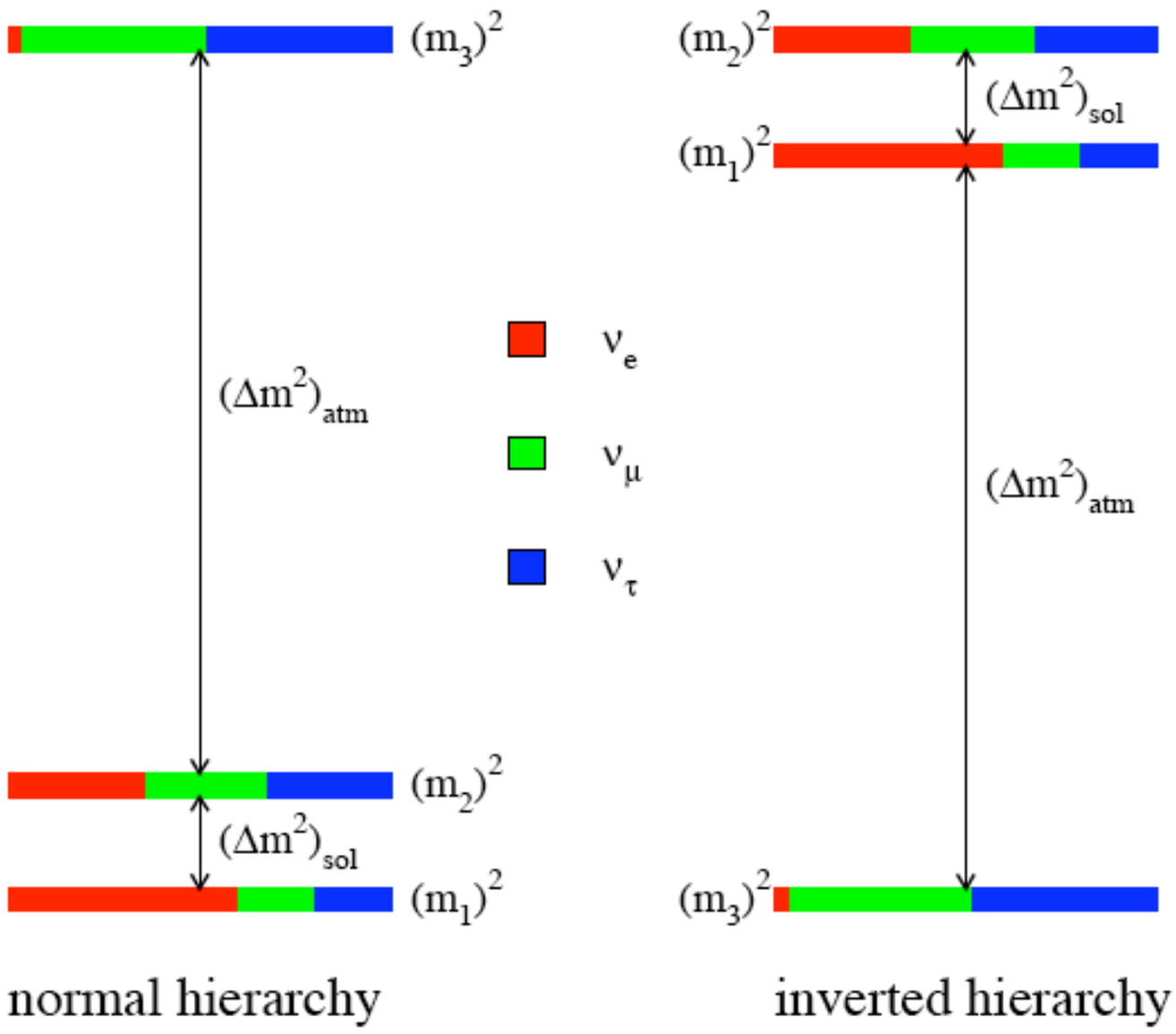
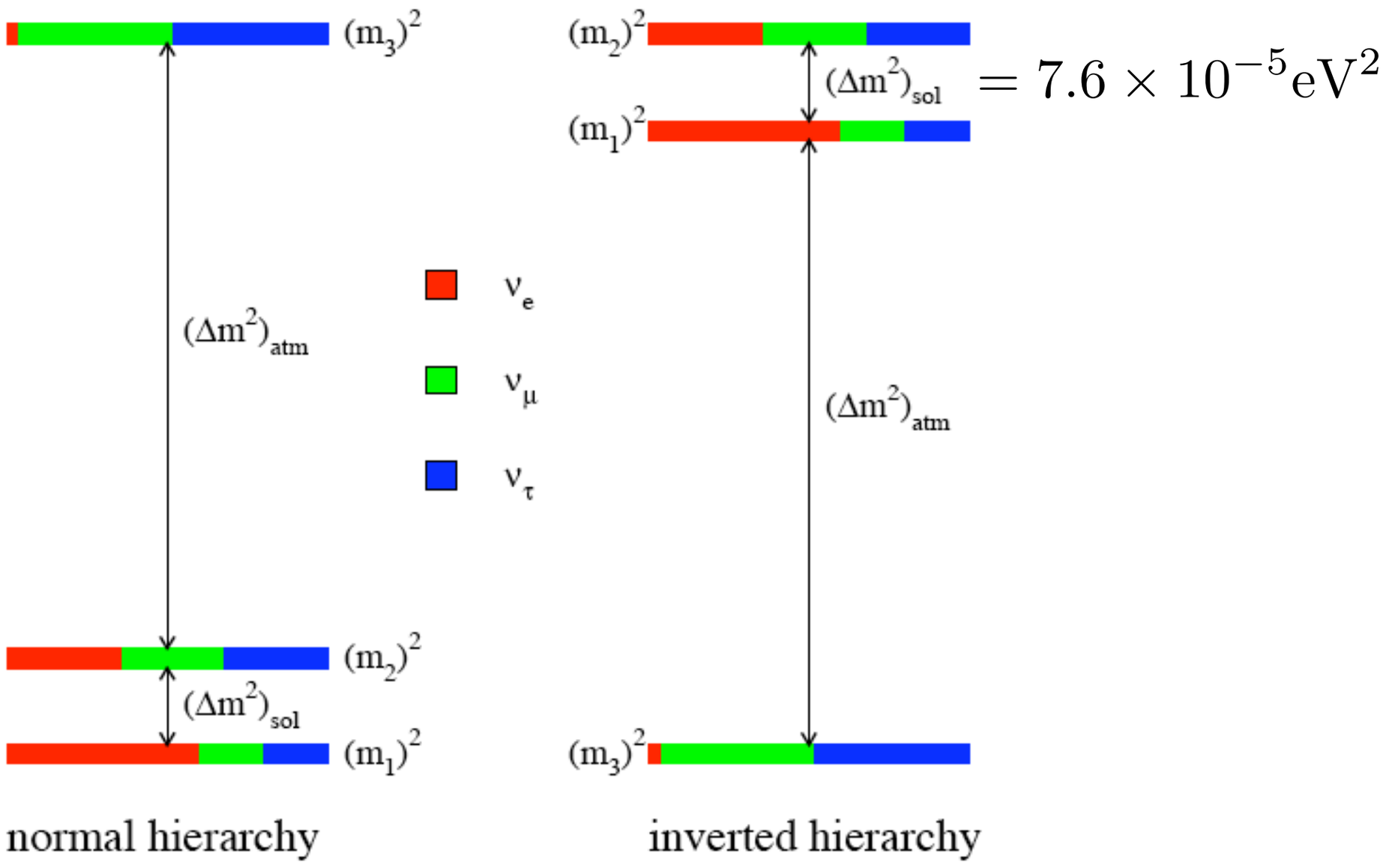
Neutrinos Have Mass



Intensity Frontier Report (1205.2671)

Neutrinos Have Mass



$= 7.6 \times 10^{-5} \mathrm{eV}^2$

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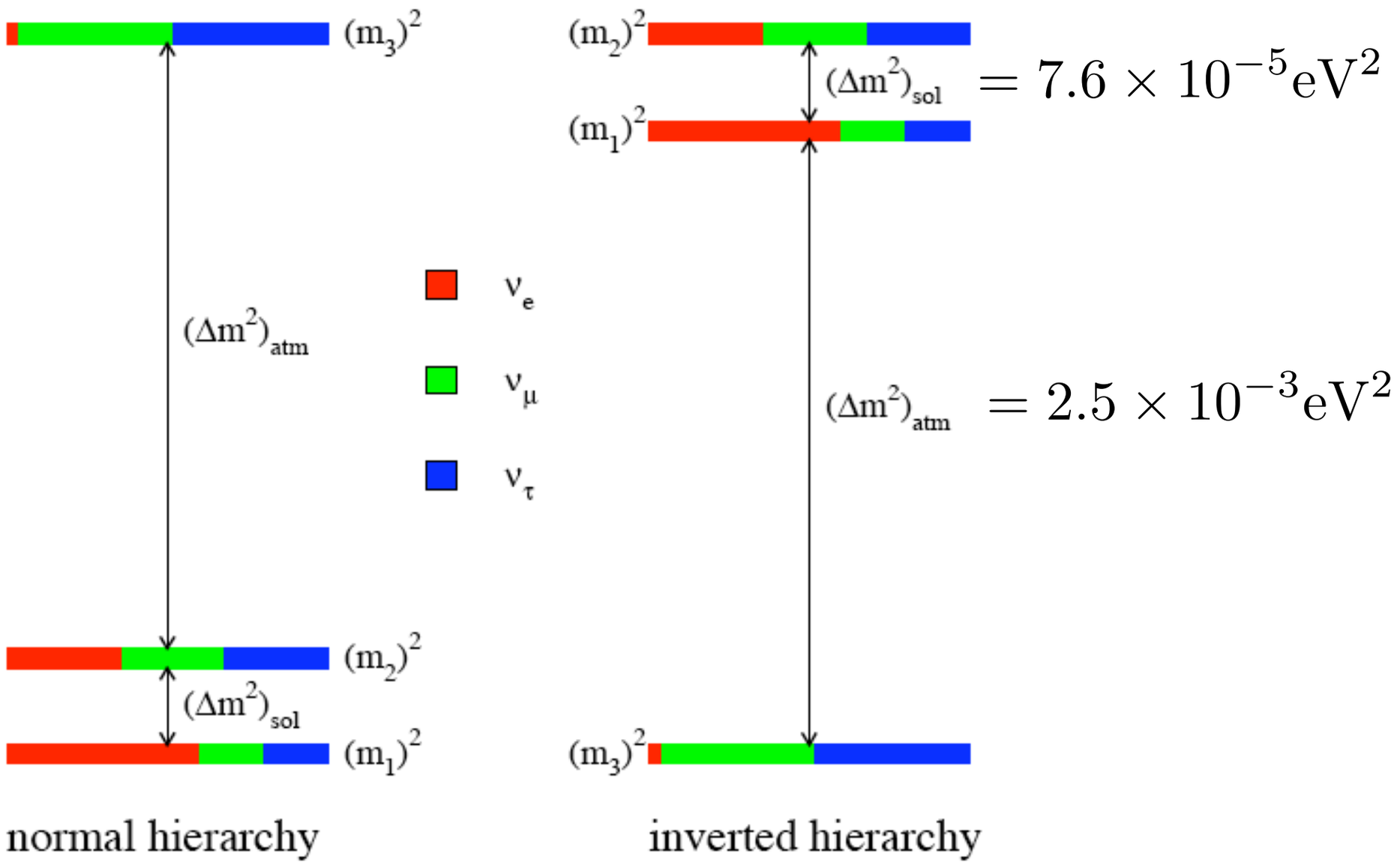

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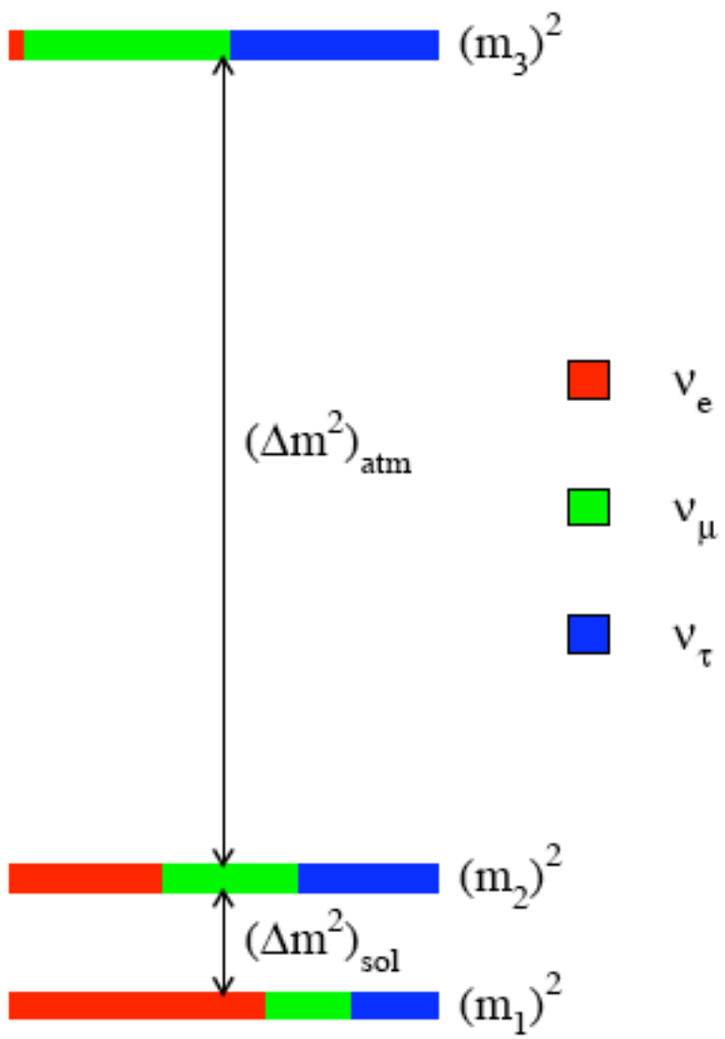
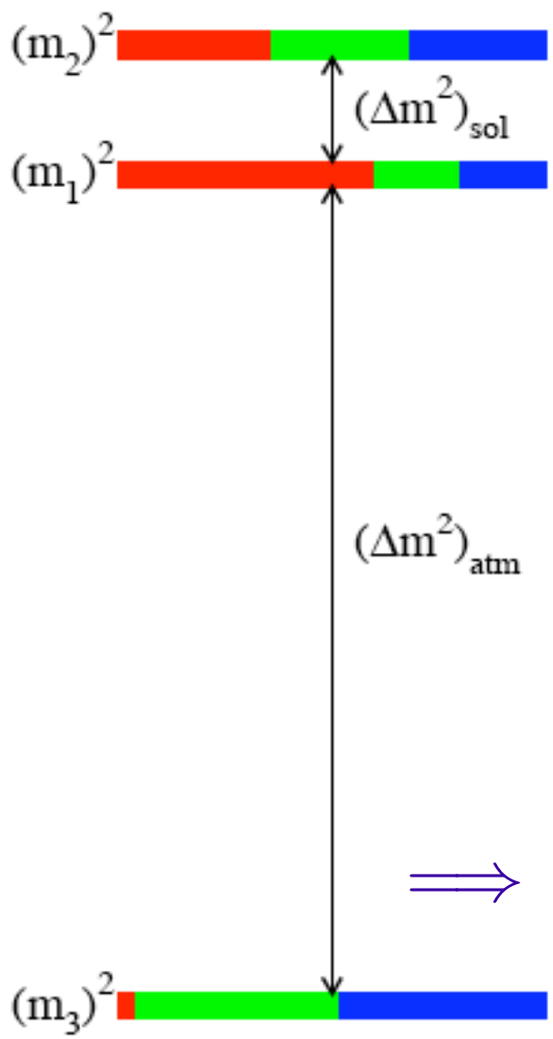


normal hierarchy



inverted hierarchy

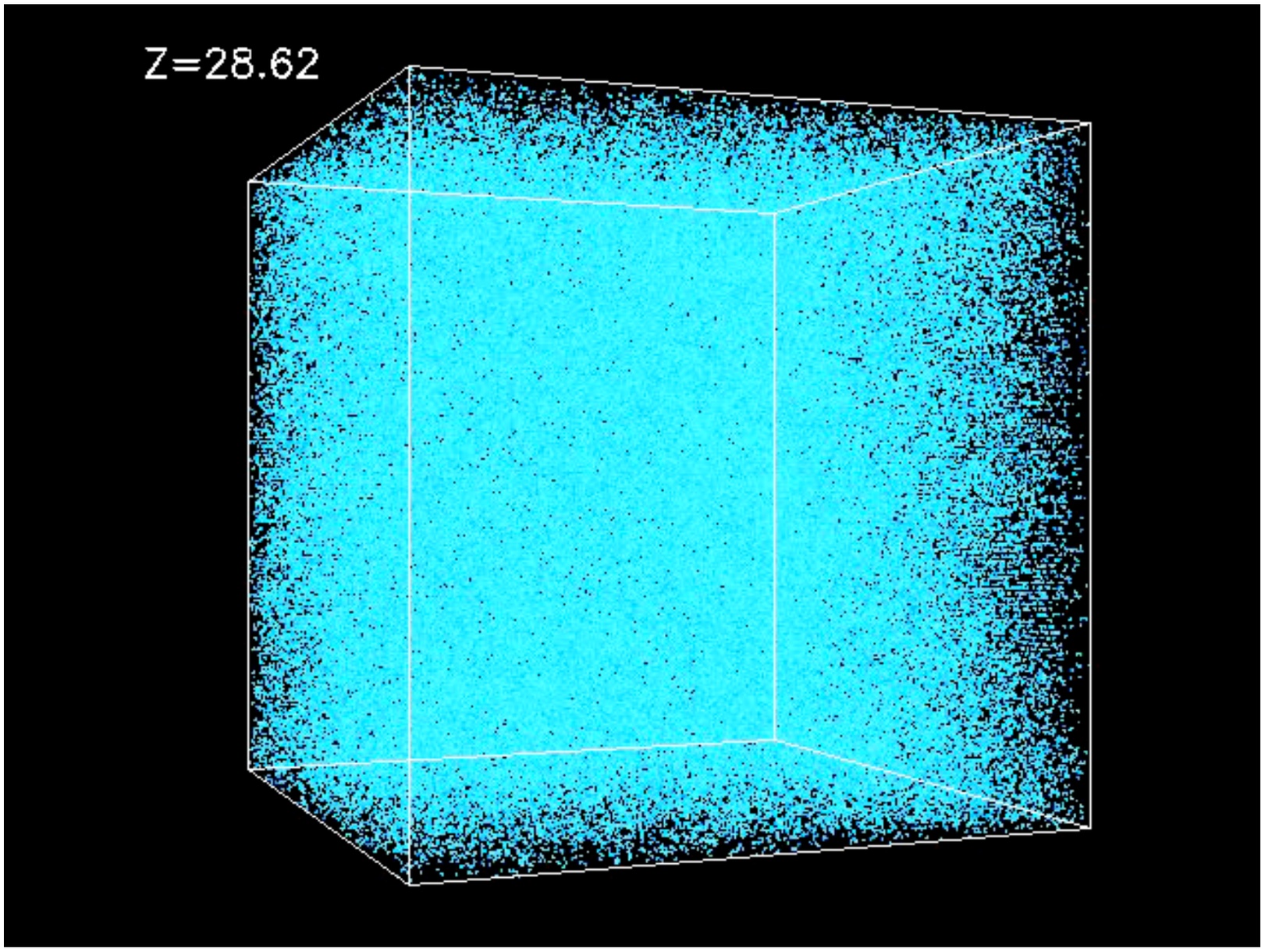
$$= 7.6 \times 10^{-5}\mathrm{eV}^2$$

$$= 2.5 \times 10^{-3}\mathrm{eV}^2$$

$$\Longrightarrow \sum m_\nu > 0.06 \text{ eV}$$

Intensity Frontier Report (1205.2671)

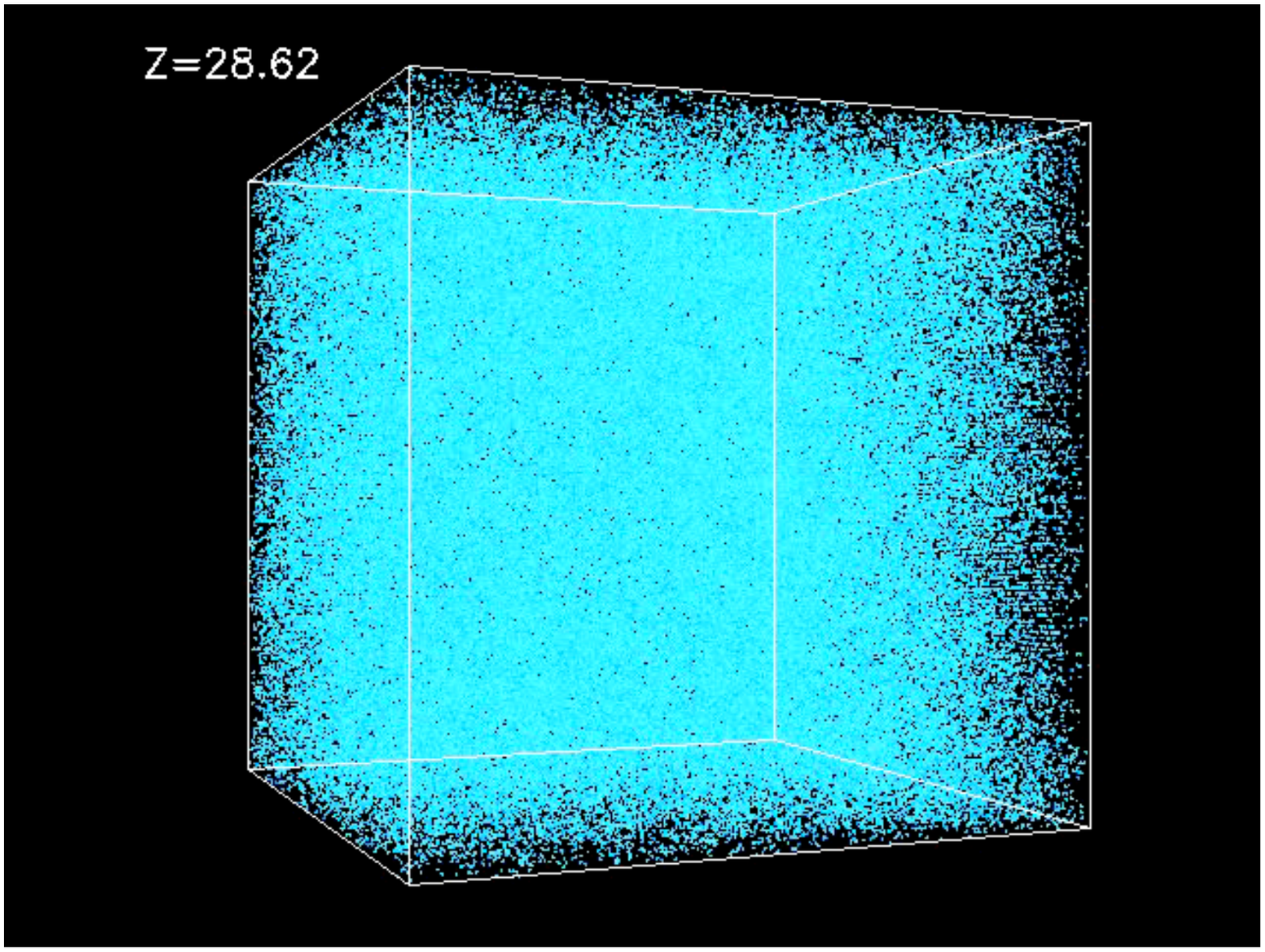
Growth of Structure



Credit: Andrey Kravtsov

Neelima Sehgal, Stony Brook

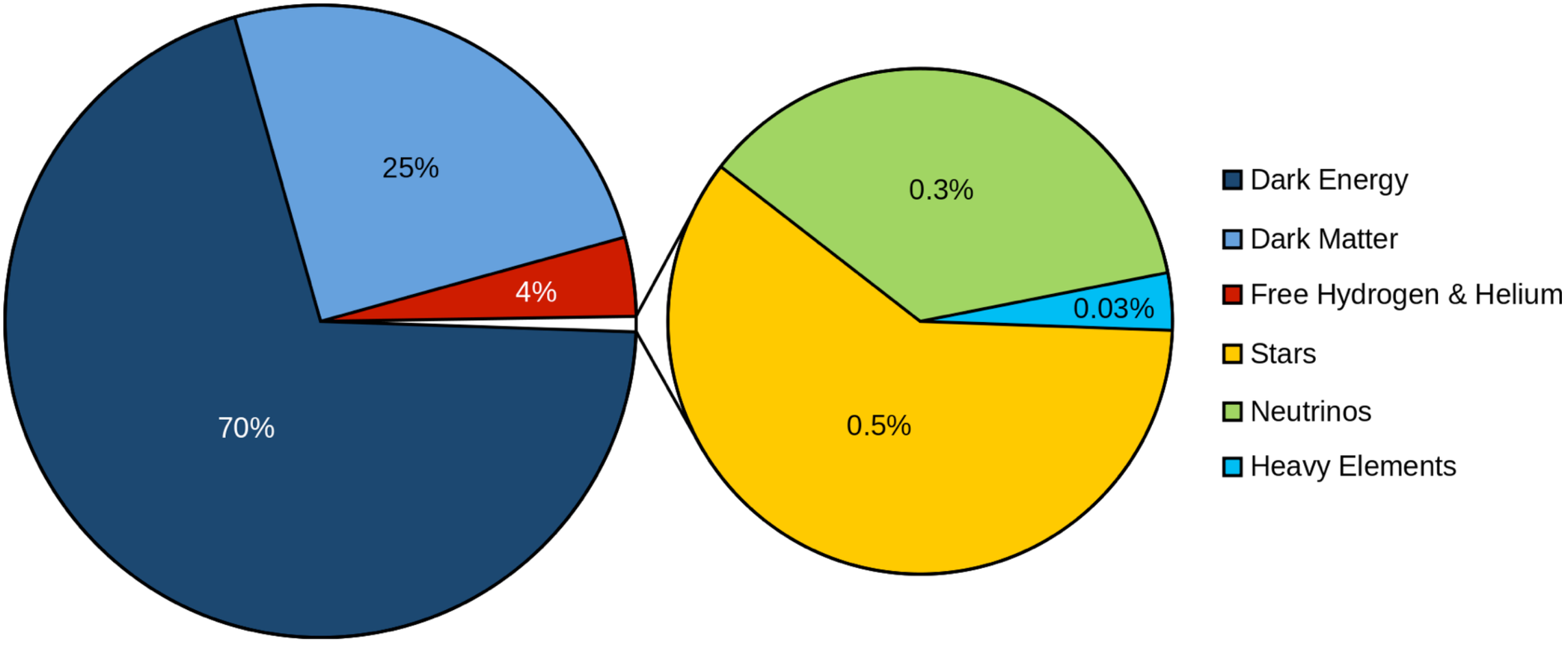
Growth of Structure



Credit: Andrey Kravtsov

Neelima Sehgal, Stony Brook

Energy Density in the Universe



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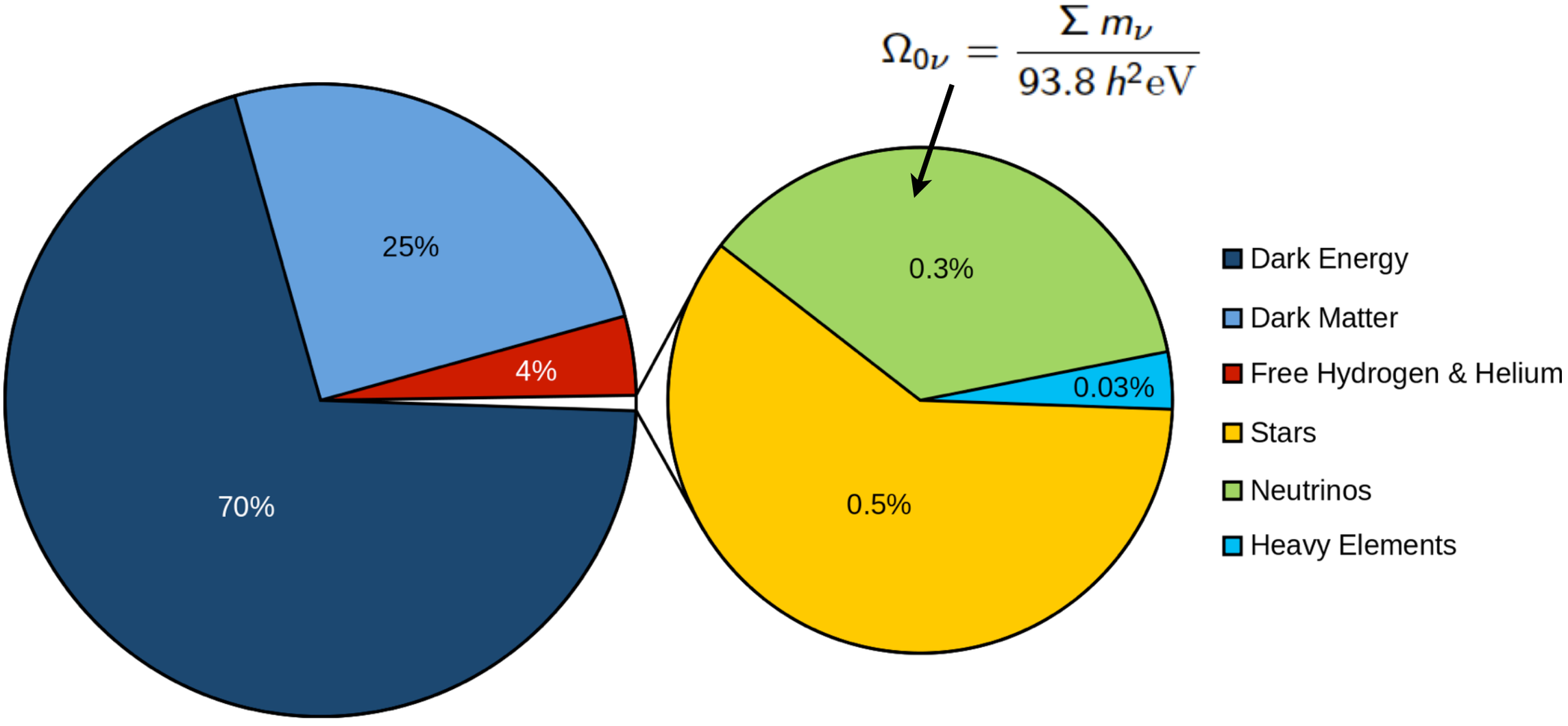

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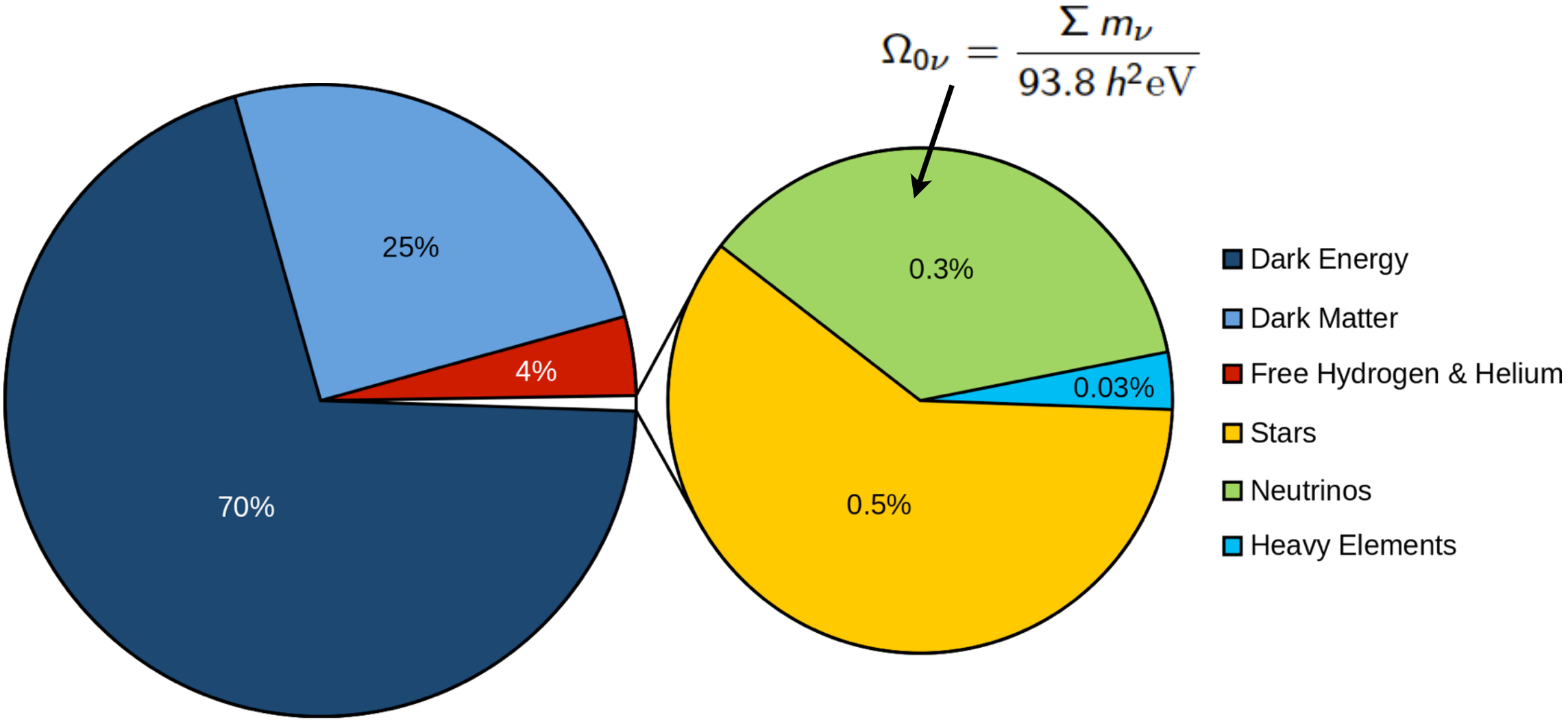


Larger neutrino mass ➡ less cold dark matter

➡ less dark matter structure

CMB Lensing Power Spectrum Sensitive to Neutrino Mass

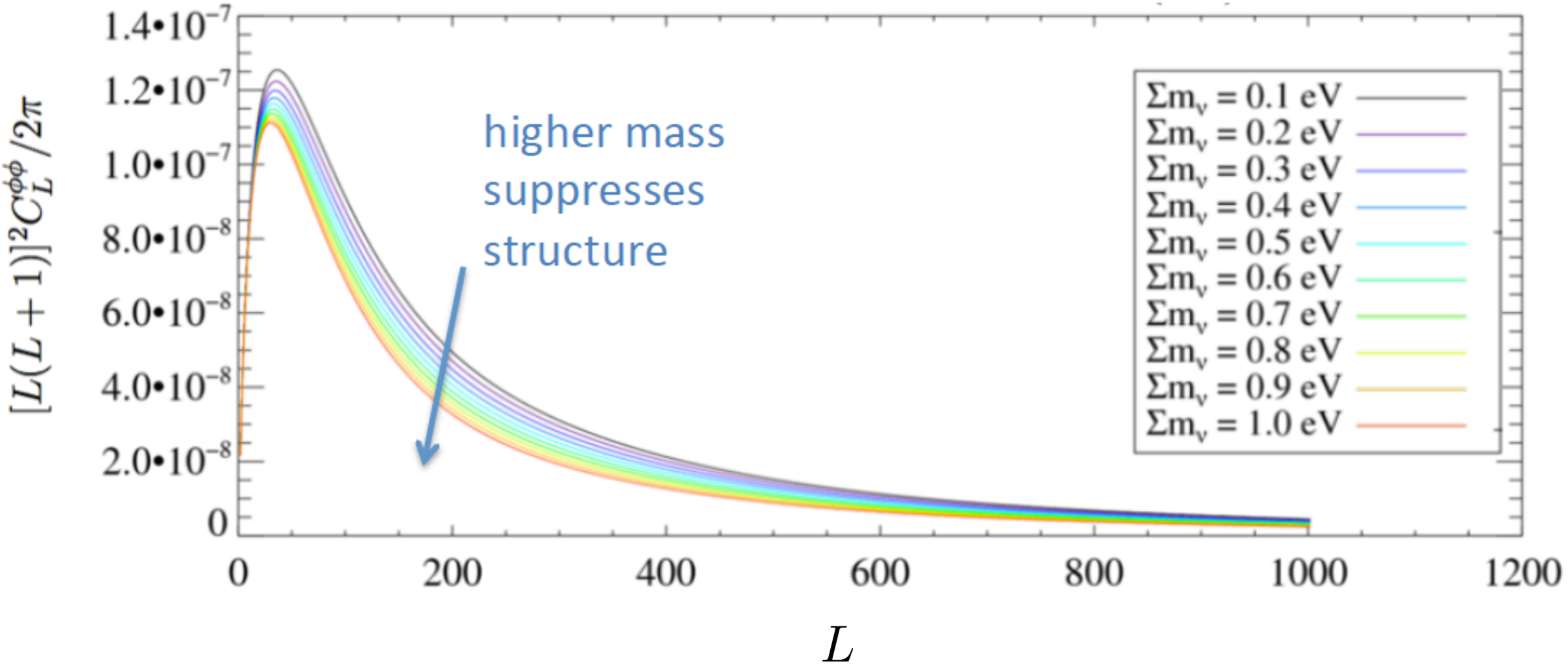
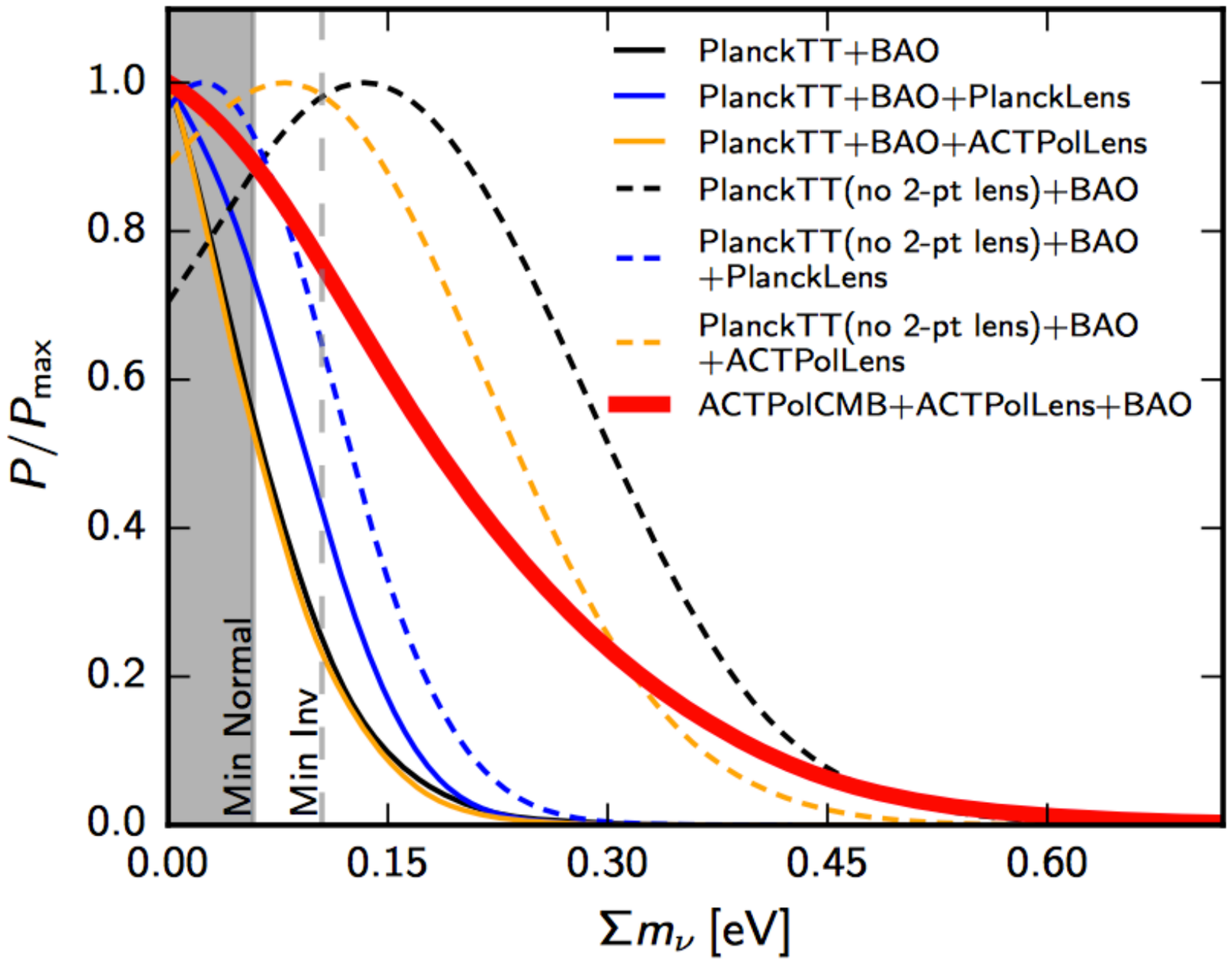


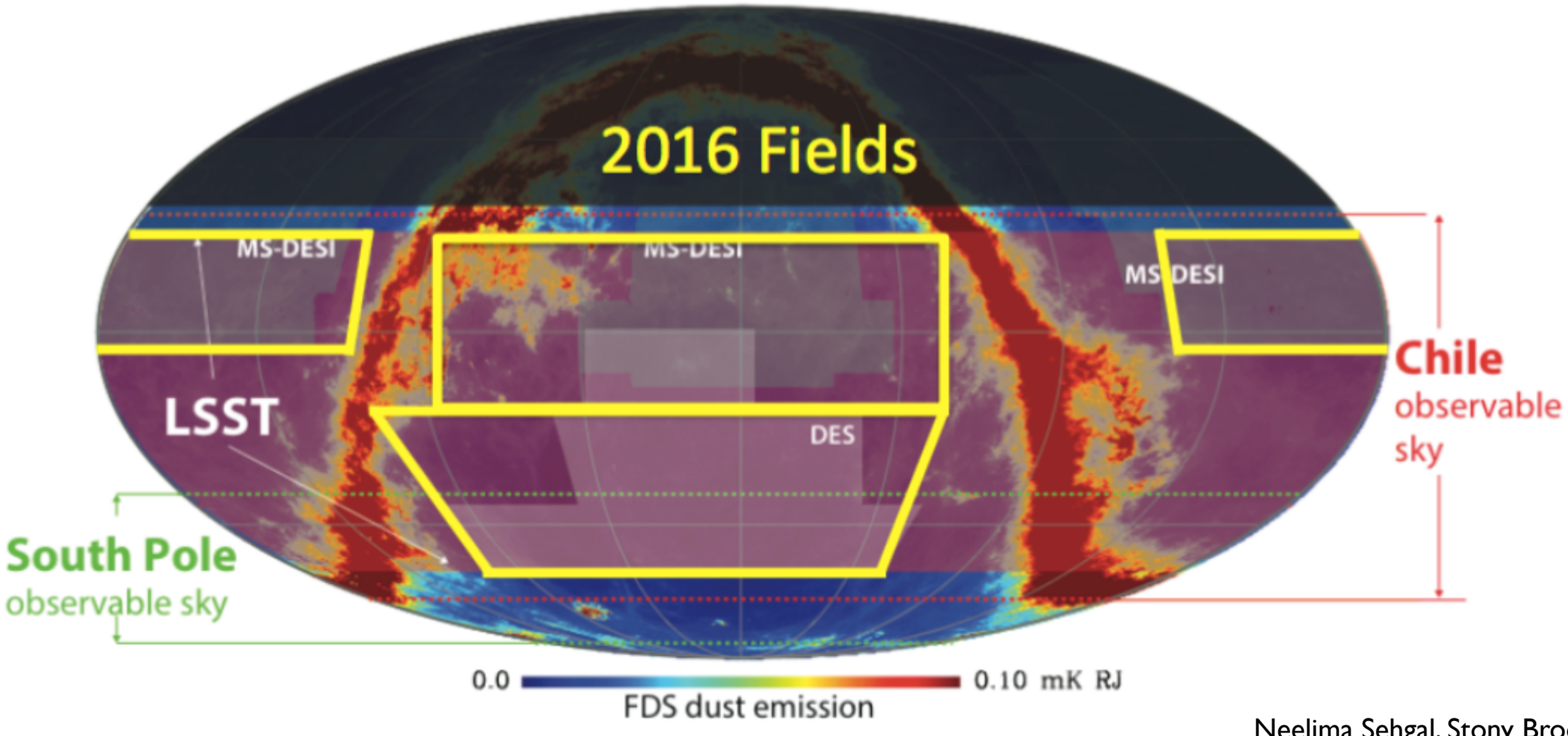
Figure credit: Alexander van Engelen

Current Neutrino Mass Constraints



Blake Sherwin, Alex van Engelen, NS, Mathew Madhavacheril et al., 2016, (1611.09753)

Stage 3 CMB: AdvACT



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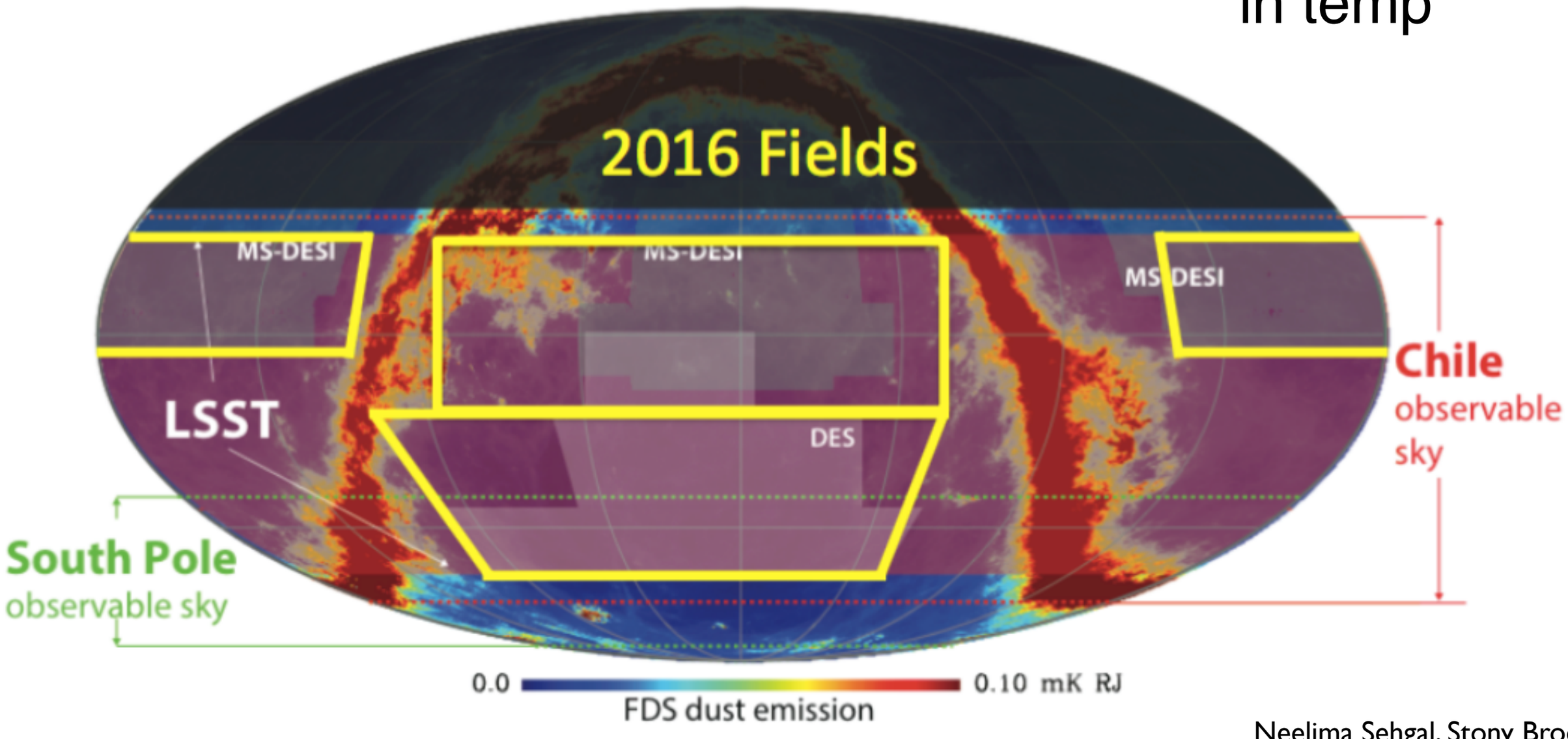
Stage 3 CMB: AdvACT

15,000 sq deg

8uK-arcmin noise in temp

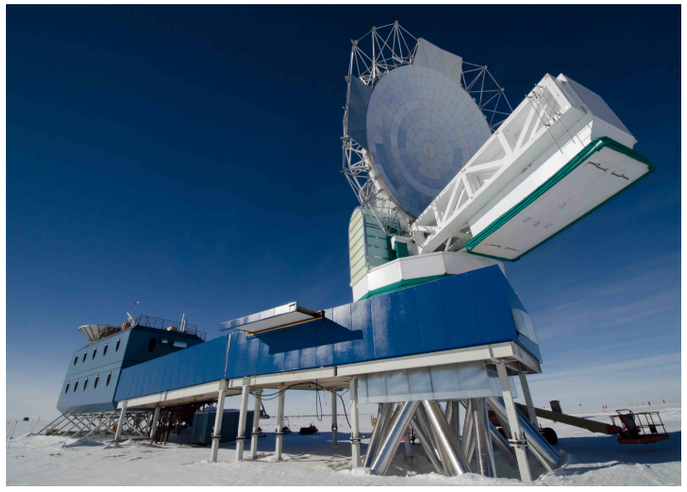


Neelima Sehgal, Stony Brook

Stage 3 CMB: SPT 3G

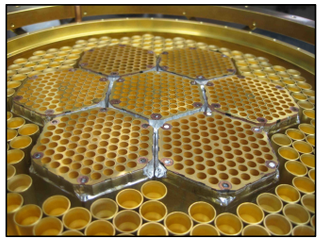
Science with the South Pole Telescope

Suman Bhattacharya, John Carlstrom, Clarence Chang, Jared Mehl,
Valentyn Novosad, Gensheng Wang, Volodymyr Yefremenko



SPT-3G

SPTpol

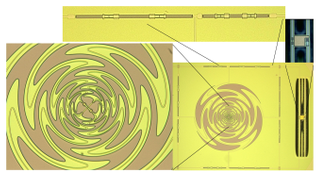


In 2012, we installed a 1600 element, polarization sensitive focal plane for the SPTpol experiment. ANL provided all the 90 GHz detectors for SPTpol.

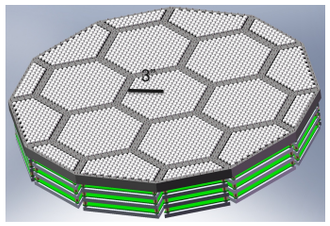
SPTpol aims to be the first experiment to detect CMB B-modes from gravitational lensing.

SPT-3G

The SPT-3G experiment will be a transformational project. It utilizes new multi-chroic detector technology to enable a focal plane with over 15,000 detectors providing an order of magnitude more sensitivity beyond the current state-of-the-art, SPTpol.



Prototype two color detector from UCB



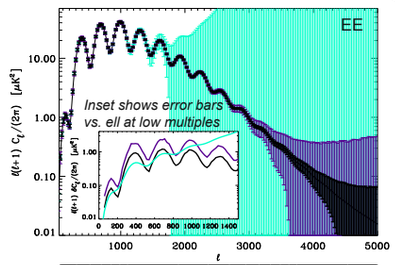
Proposed SPT-3G focal plane layout

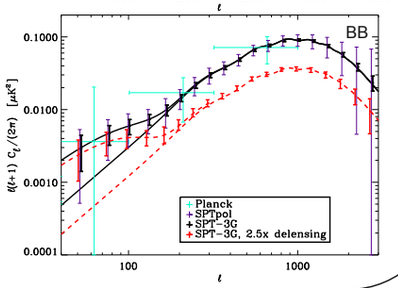
Science w/ SPTpol & SPT-3G

Dataset	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	$\sigma(r)$
Planck	0.14	117 meV	0.06
+SPTpol	0.12	96 meV	0.03
+SPT-3G	0.076	74 meV*	0.01

*60 meV including data from BOSS

Science with the SPTpol & SPT-3G experiments will include measuring the number of neutrino-like particle species (N_{eff}), measuring the neutrino mass scale (Σm_ν), and measuring the energy scale of inflation (r). Projections are in the table and projected polarization spectra (EE and BB) including uncertainties for SPTpol (purple) and SPT-3G (black) compared to Planck (cyan) are to the right.
SPT-3G will be the first experiment capable of de-lensing (red).





2500 sq deg

2uK-arcmin noise in temp

Neelima Sehgal, Stony Brook

Stage 3 CMB:
POLARBEAR, BICEP, CLASS, SPIDER

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POLARBEAR, BICEP, CLASS, SPIDER

Polarbear/
Simons Array

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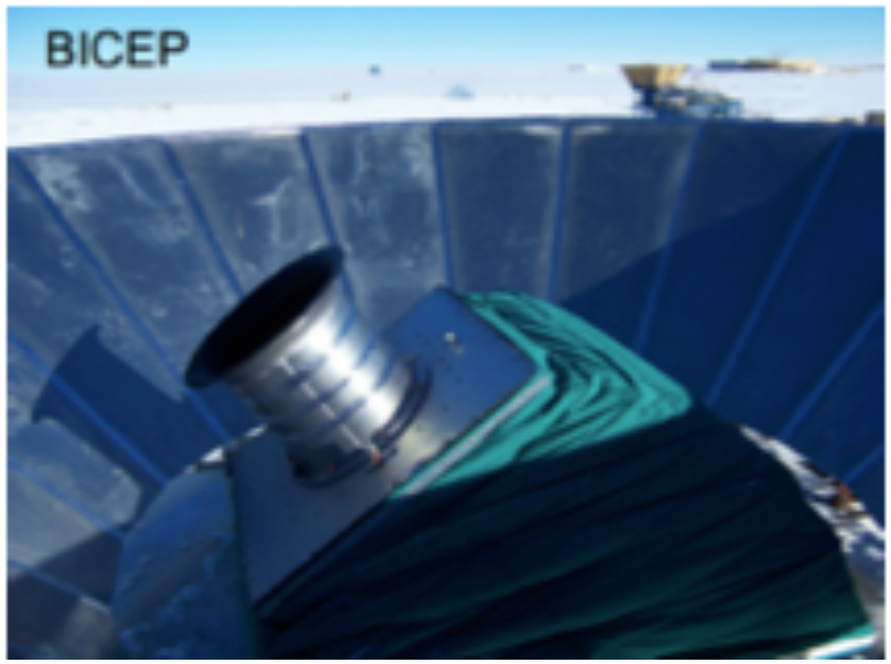

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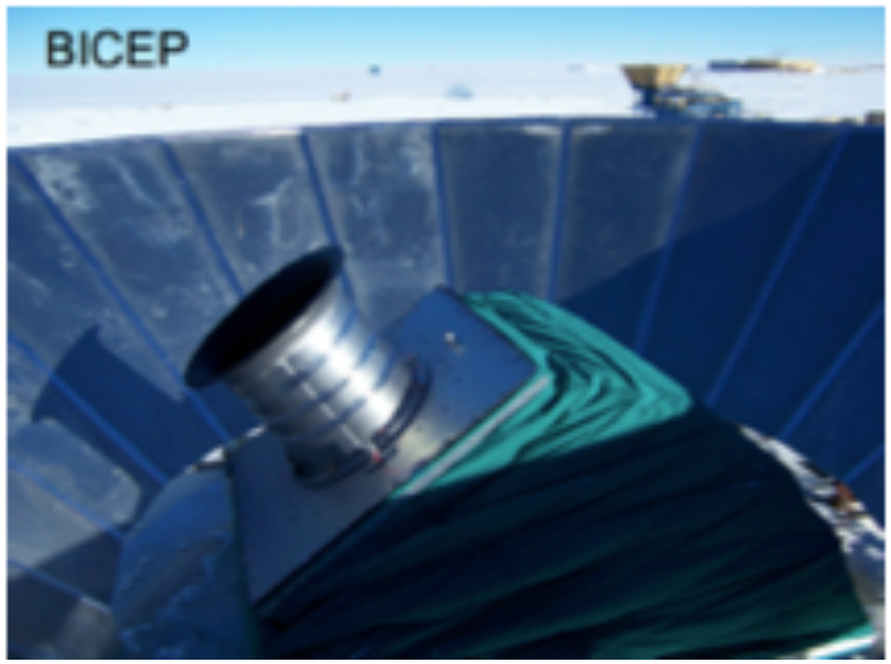
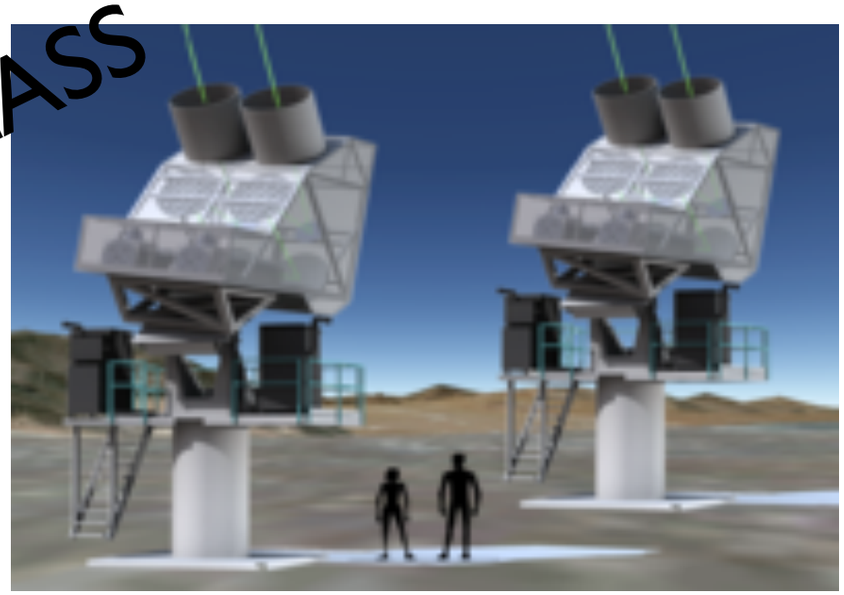


CLASS



Stage 3 CMB:
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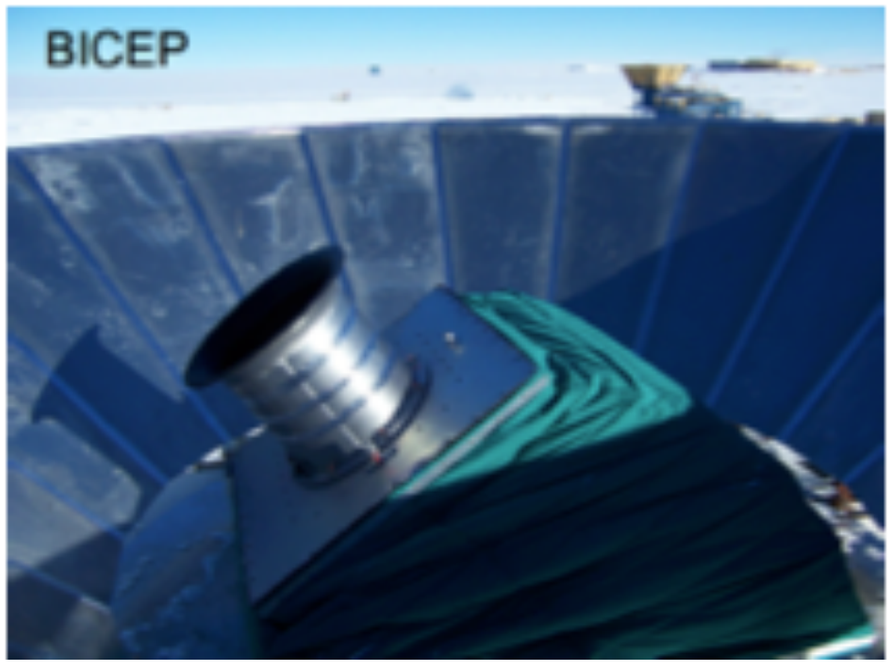

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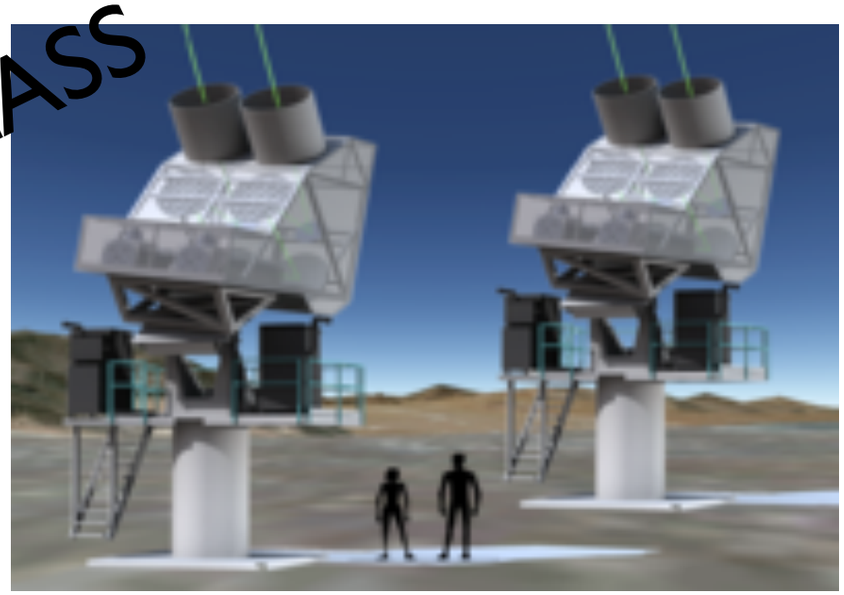
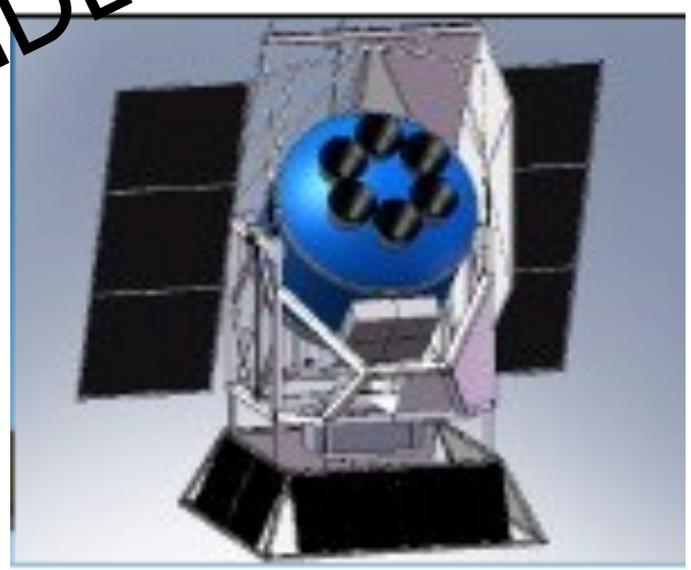


SPIDER



Near Future of CMB: SO

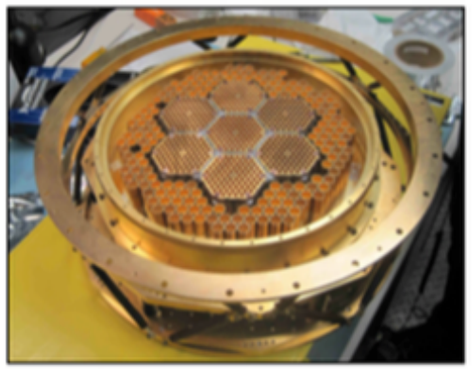
Near Future of CMB: S4

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

Stage II **ACTPol / SPTPol**

Now

~1000 detectors



Advanced ACTPol

Stage III **SPT 3G**

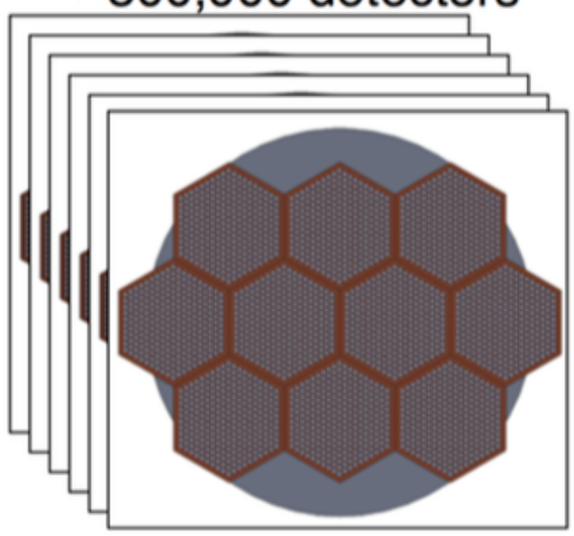
ramping up

~10,000 detectors

Stage IV

~2020 - CMB-S4

~500,000 detectors



increasing detector count

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

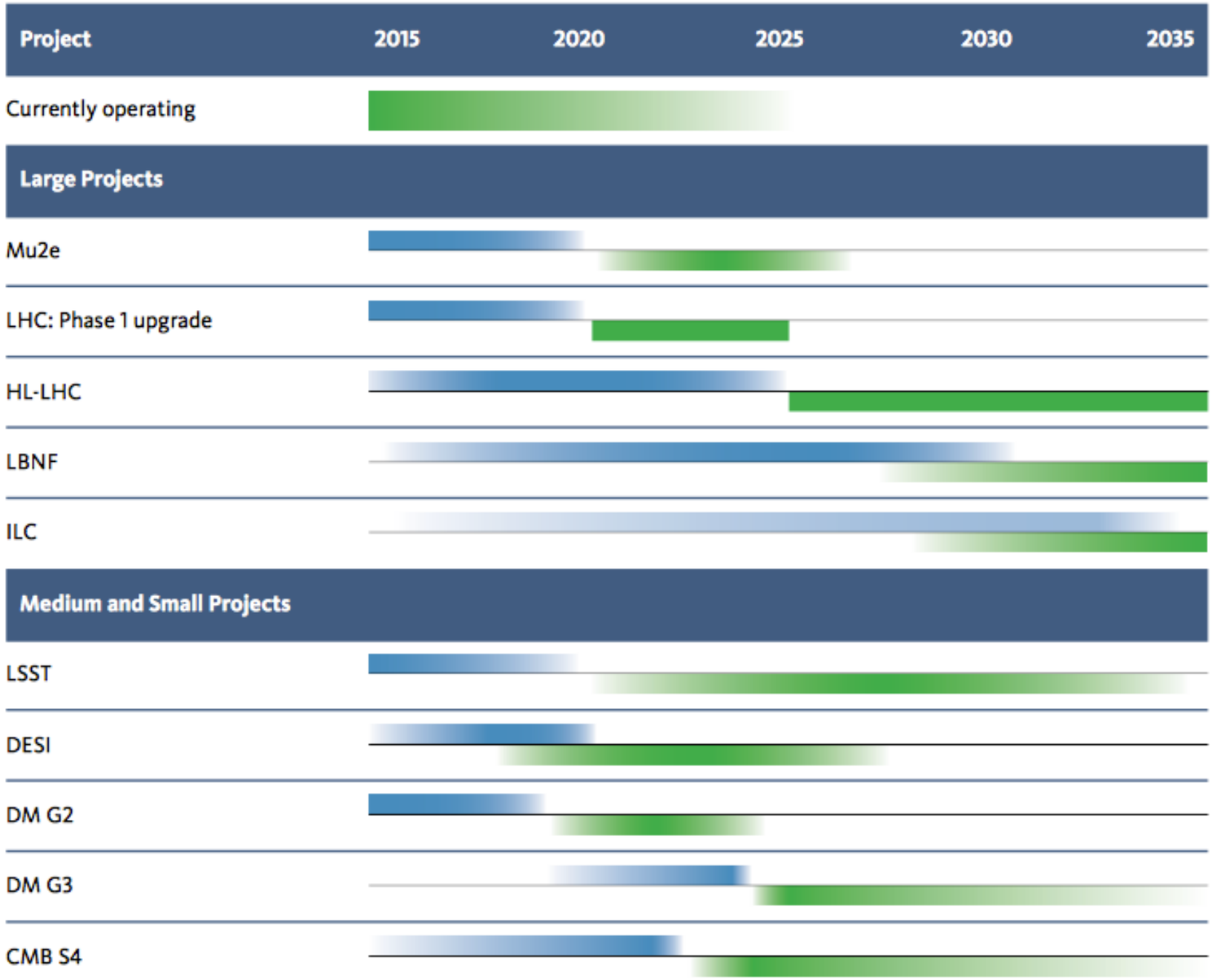
Near Future of CMB: S4

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

Executive Summary

DOE P5 Report



Near Future of CMB: S4

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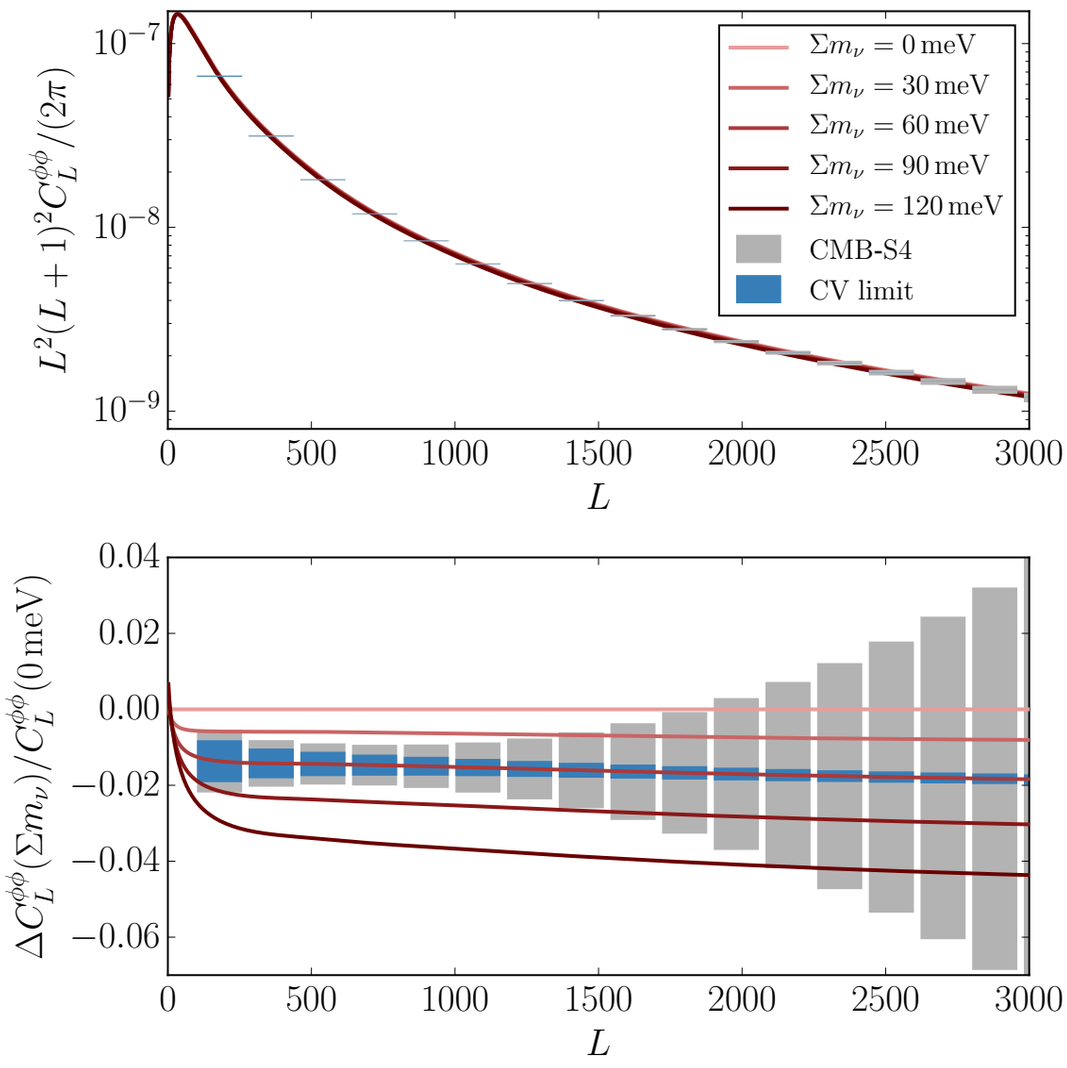
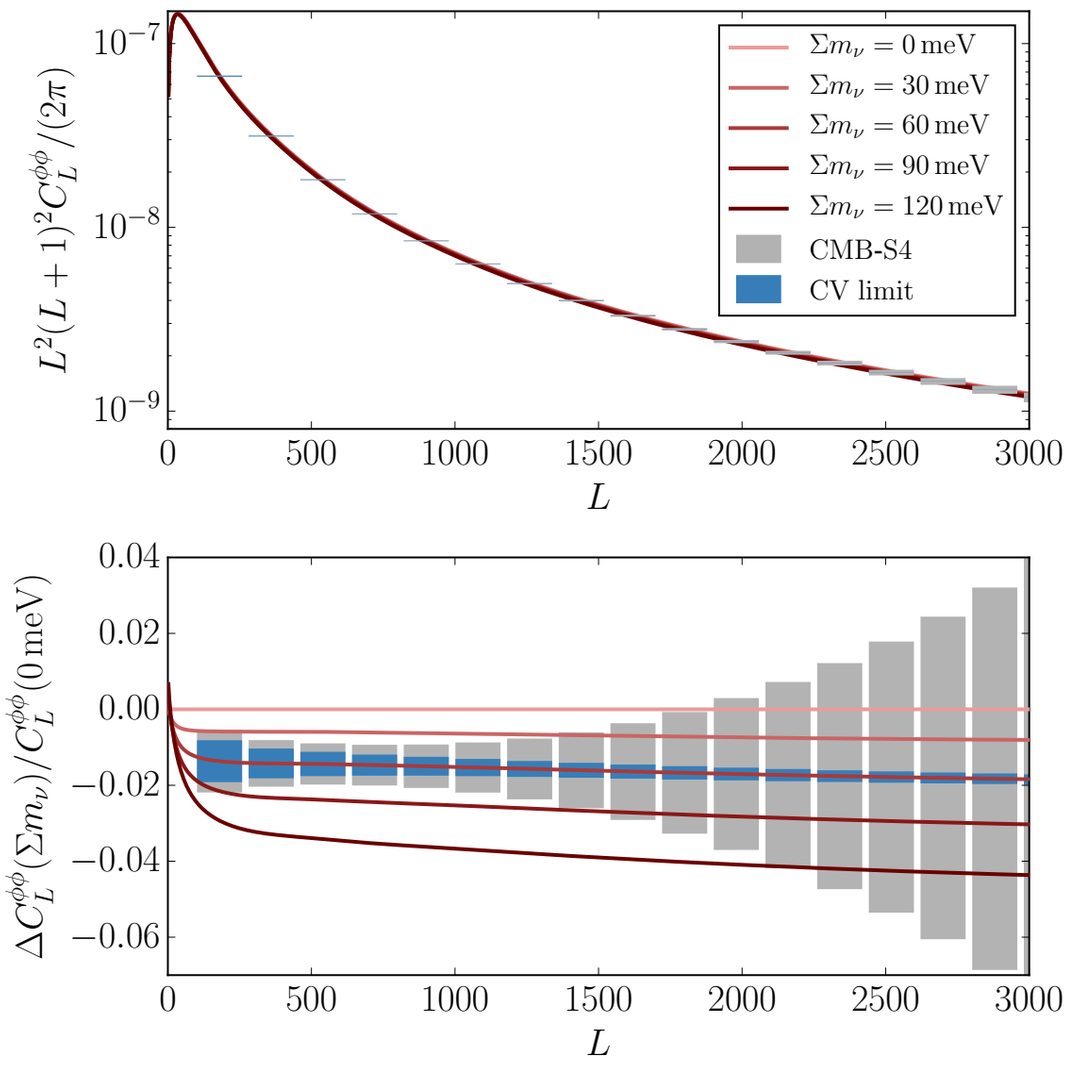
Neutrino Mass Detection

Neelima Sehgal, Stony Brook

Neutrino Mass Detection



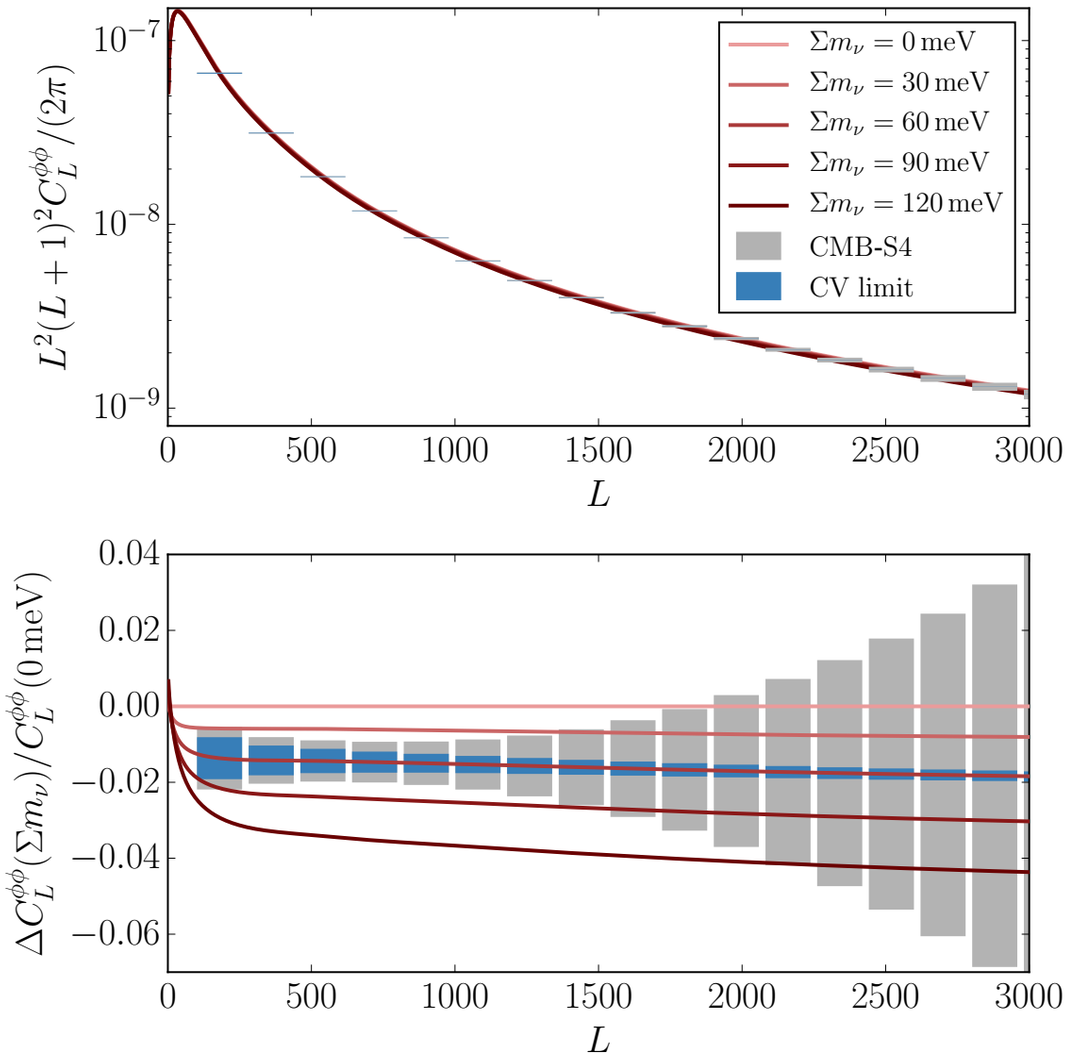
Neutrino Mass Detection



$$\sigma(\sum m_\nu) < 20 \ \ \text{meV}$$

3-sigma detection with BAO and tau prior

Neutrino Mass Detection



Next step: measure neutrino mass with AdvACT/SO/CMB-S4!

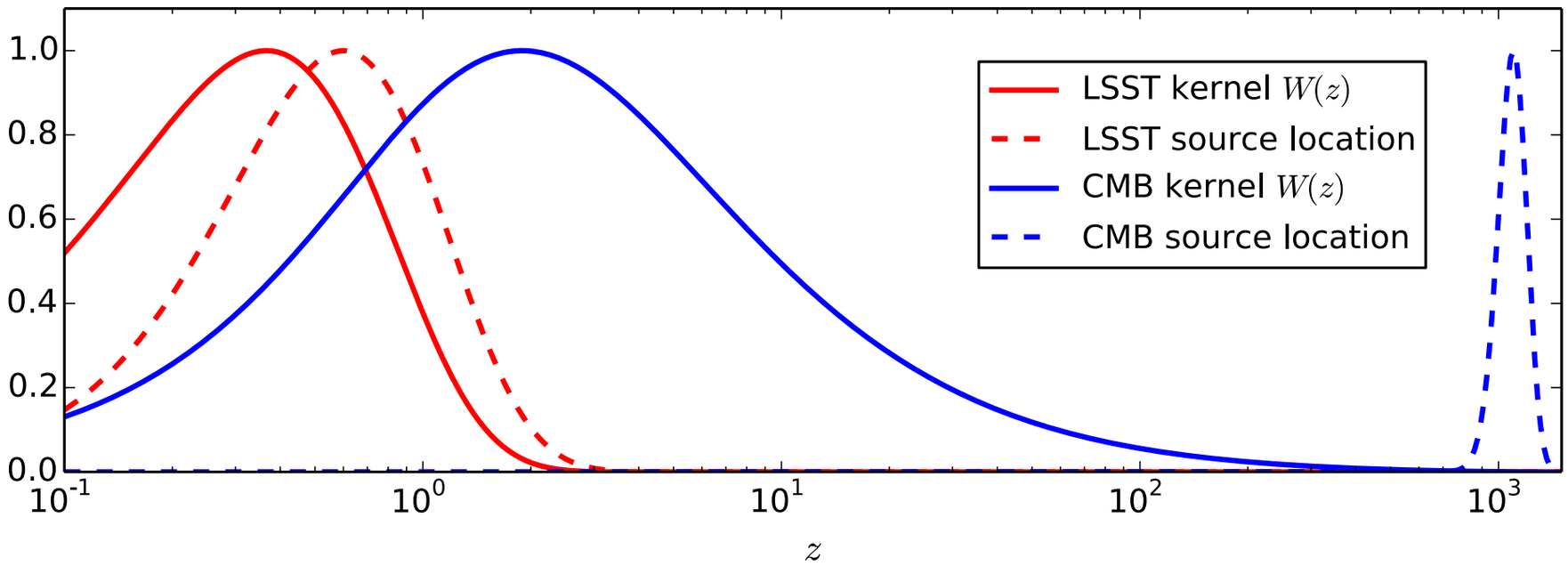
$$\sigma(\sum m_\nu) < 20 \ \ \text{meV}$$

3-sigma detection with BAO and tau prior

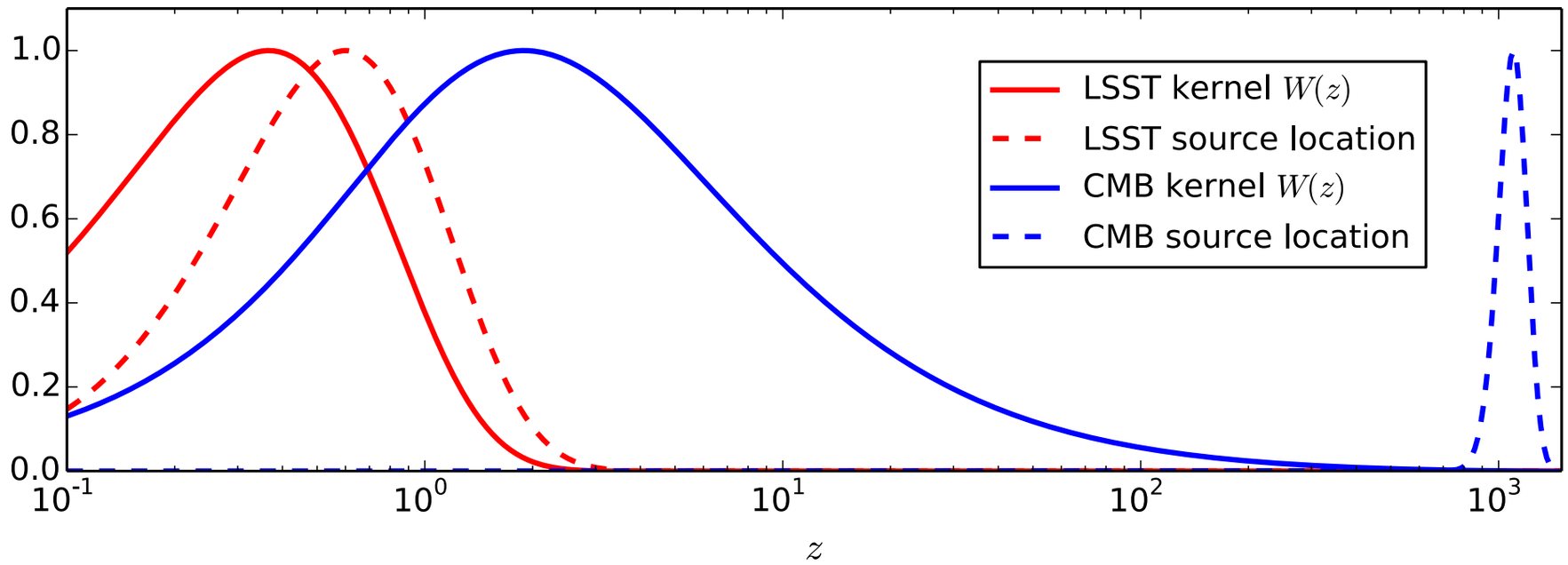
Outline

- Measuring Lensing of CMB
- Neutrino Mass from Lensing Power Spectrum
- Probing Dark Energy with Lensing Cross Correlations
- Delensing to Probe Primordial Gravity Waves

Lensing Cross Correlations

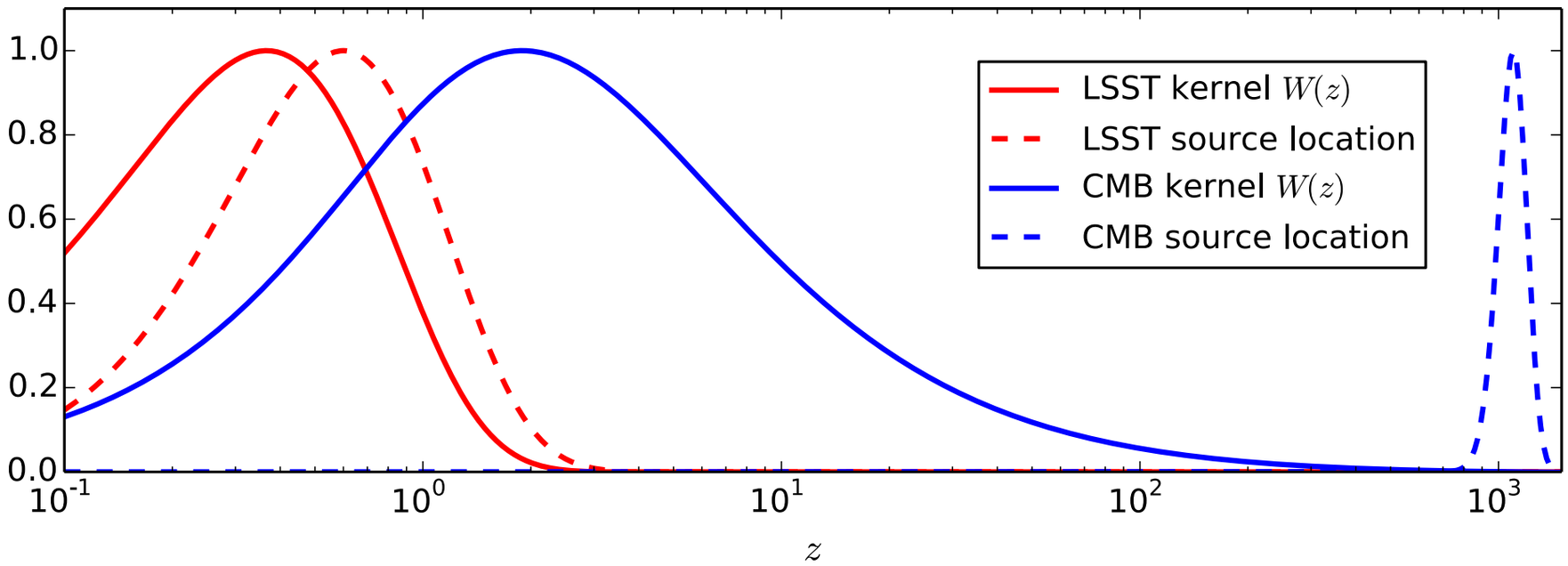


Lensing Cross Correlations



CMB provides a high-redshift anchor

Lensing Cross Correlations



CMB provides a high-redshift anchor

Dark energy dominates at z < 1

Distance Ratio

Distance Ratio

$$\kappa(\theta, z_L, z_S) = 4\pi G D_L \frac{D_{LS}}{D_S}(1+z_L)\Sigma(D_L\theta, z_L)$$

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Measured lensing signal

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Hu, Holz, Vale 2007
Das, Spergel 2009

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Purely geometric quantity

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Purely geometric quantity

Across longest possible cosmological lever arm

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Hu, Holz, Vale 2007
Das, Spergel 2009

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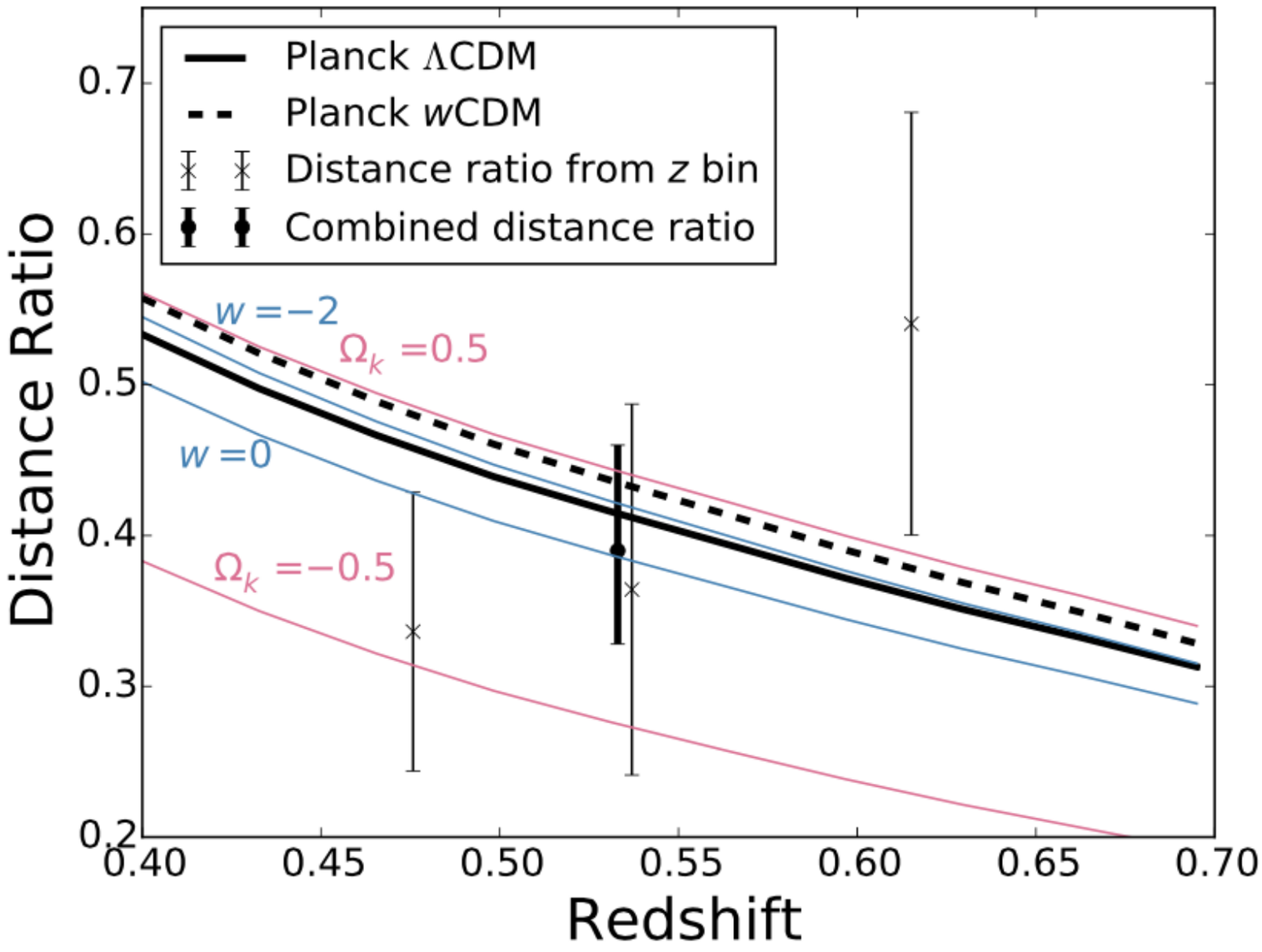
Across longest possible cosmological lever arm

Not sensitive to galaxy bias or systematics such as miscentering

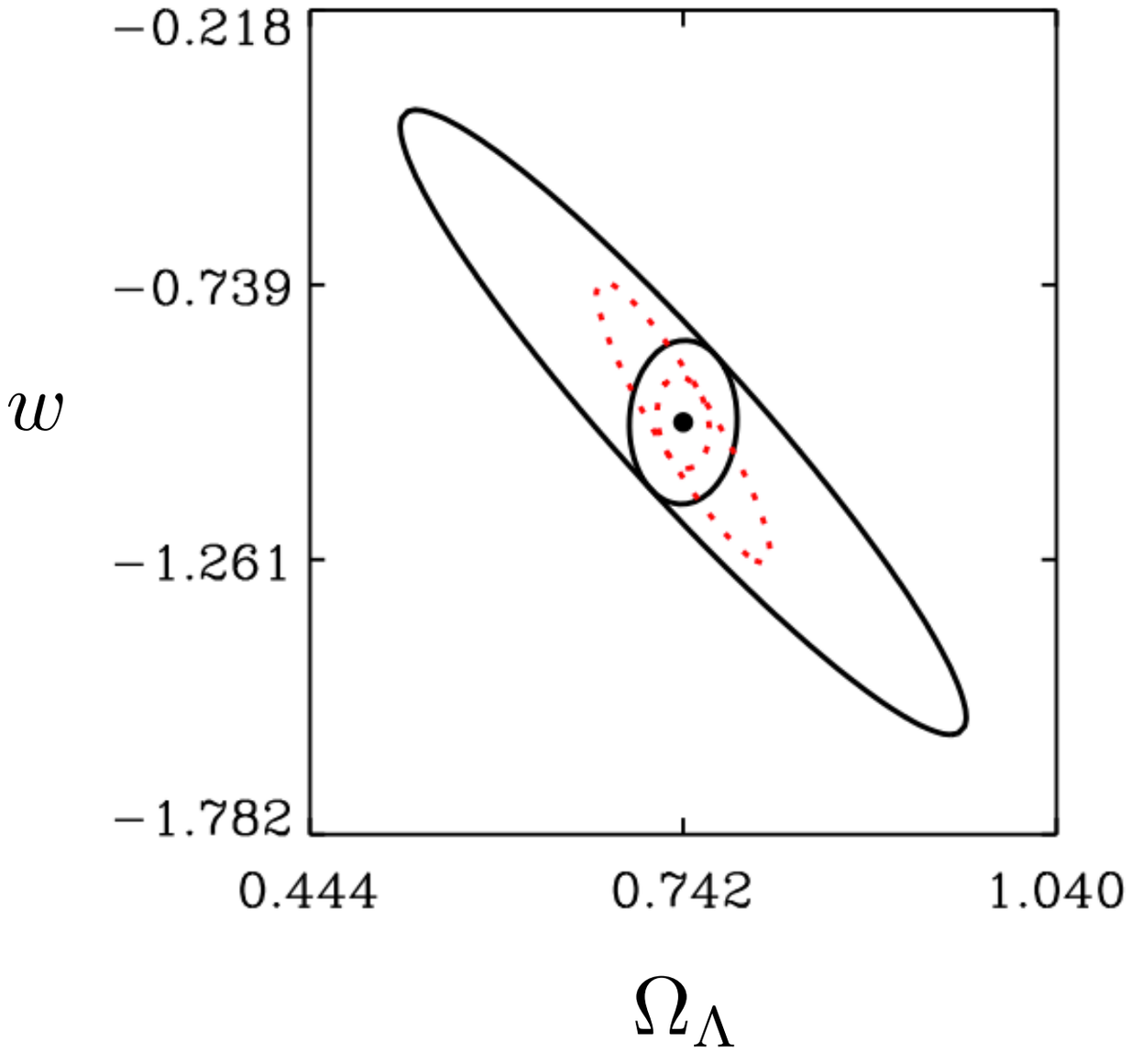
Probes dark energy equation of state, $w = \frac{p}{\rho}$

First Measurement of Distance Ratio using CMB



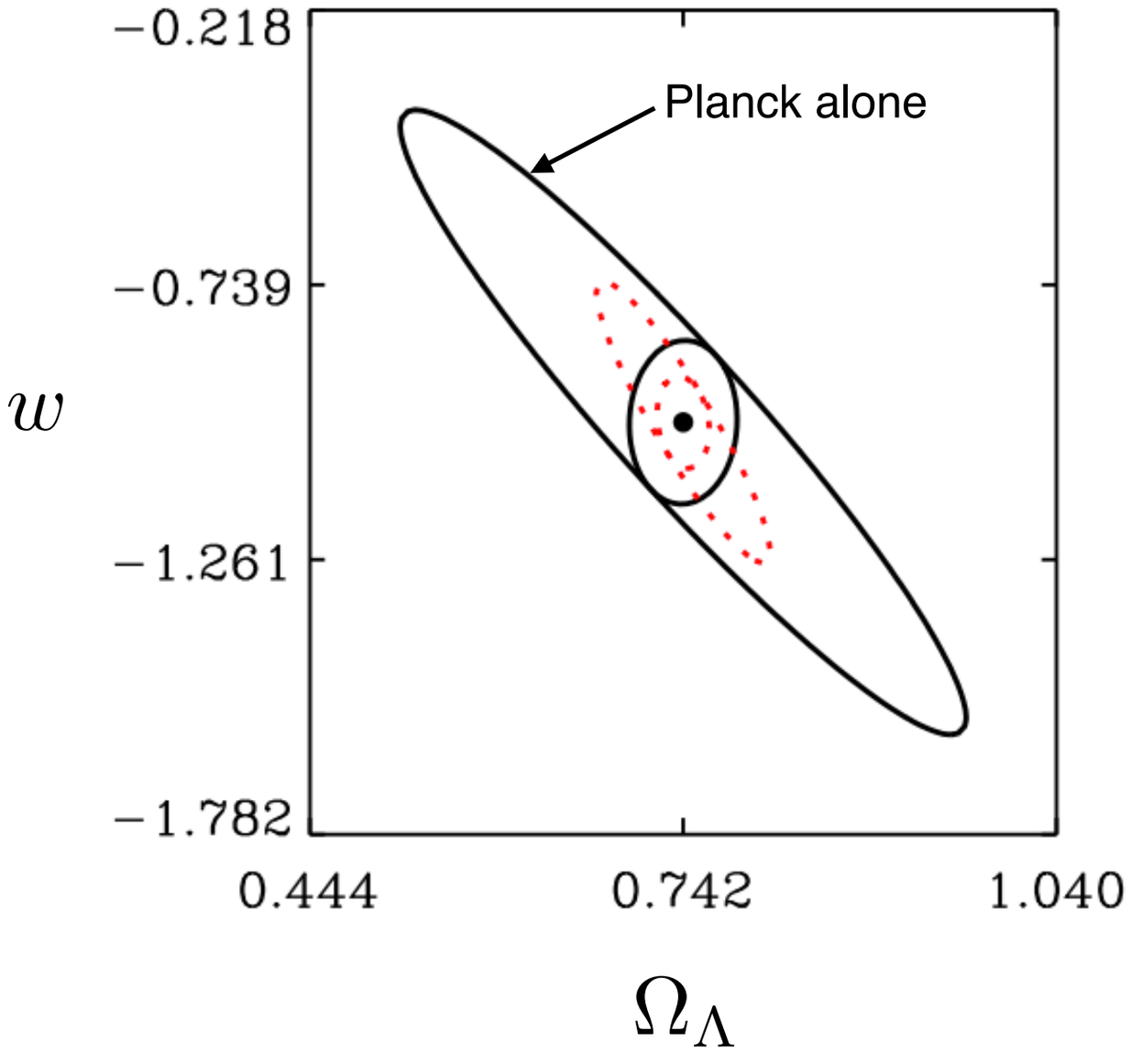
Miyatake, Madhavacheril, Sehgal et al. submitted to PRL (1605.05337)

Distance Ratio Forecasts



Das and Spergel 2009

Distance Ratio Forecasts



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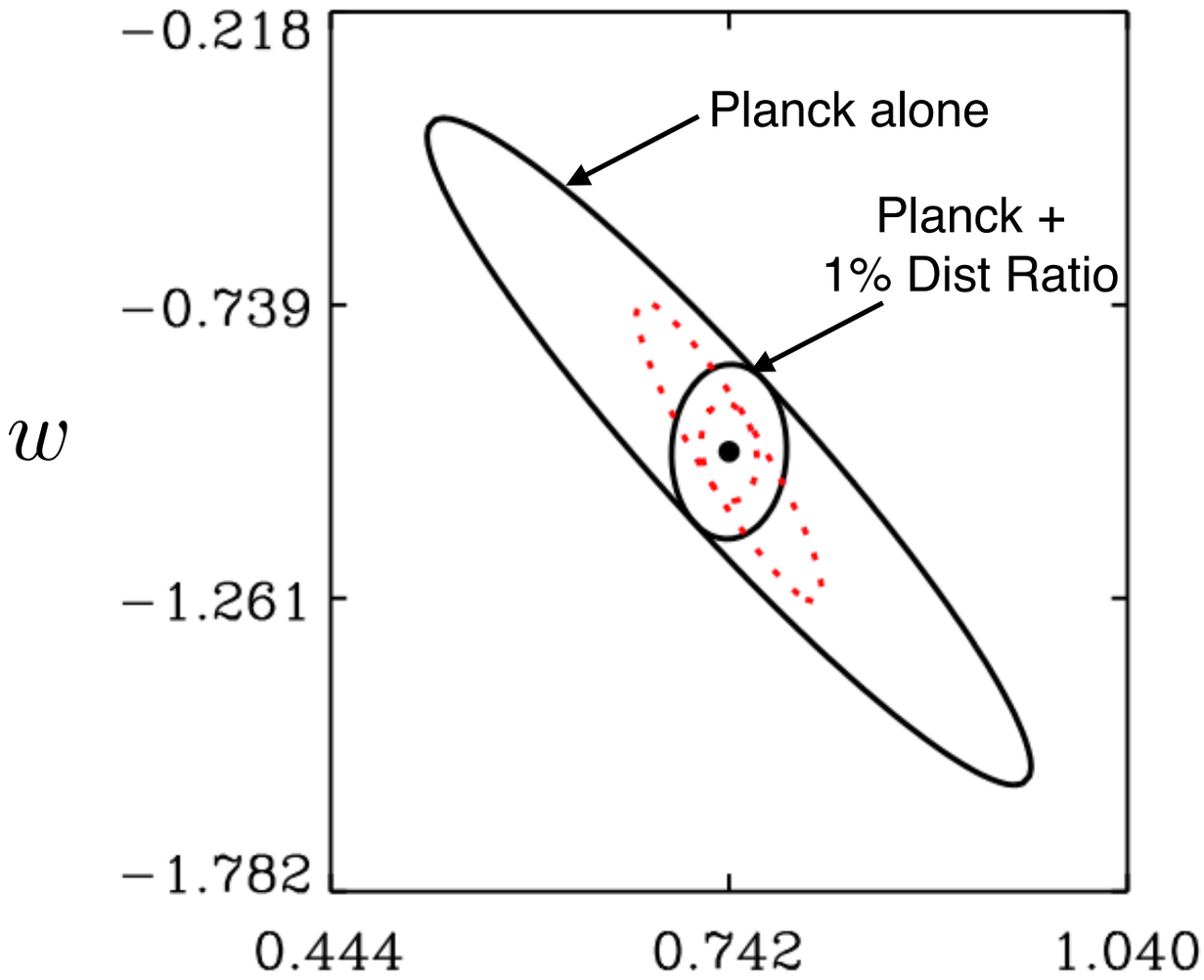

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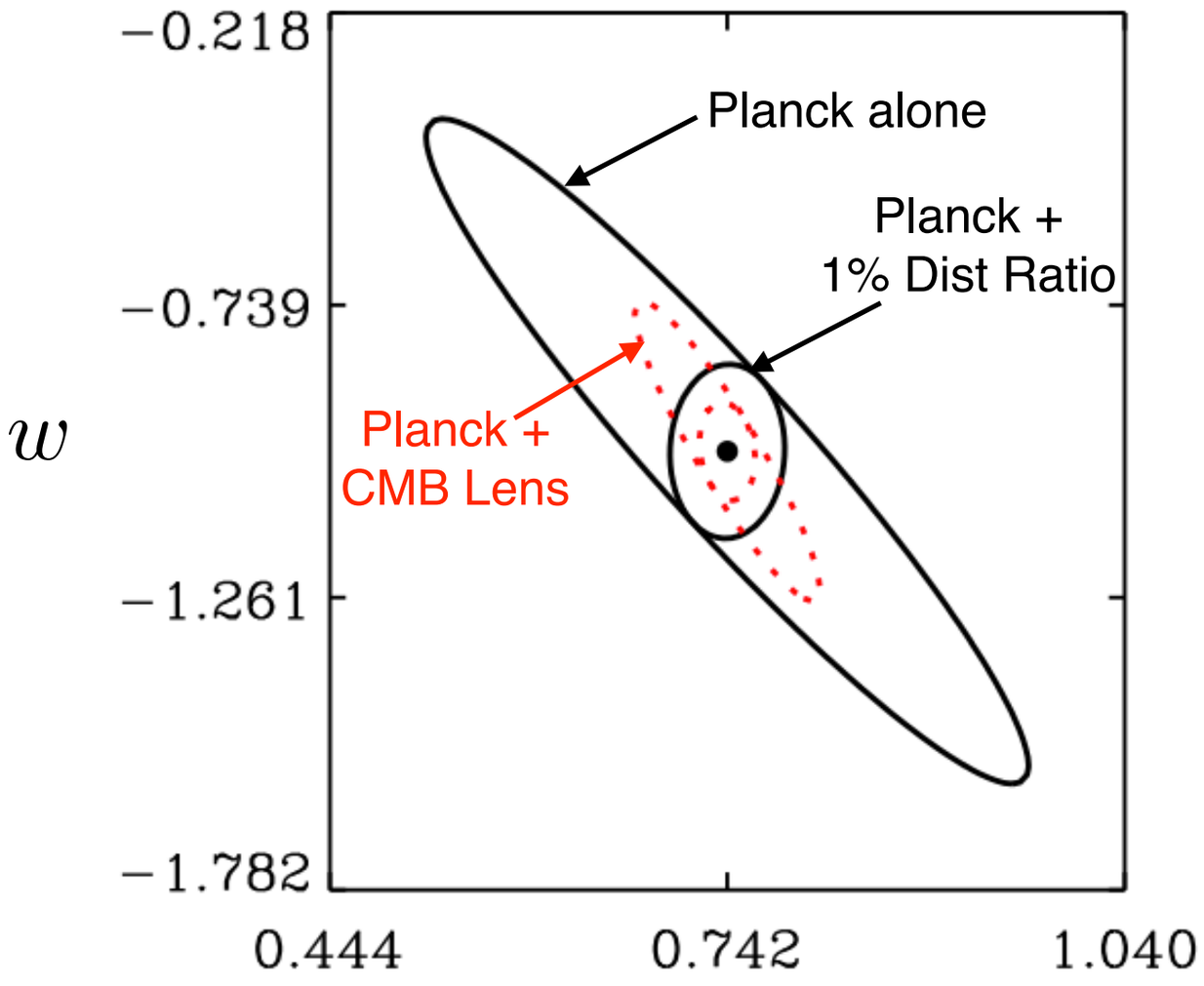

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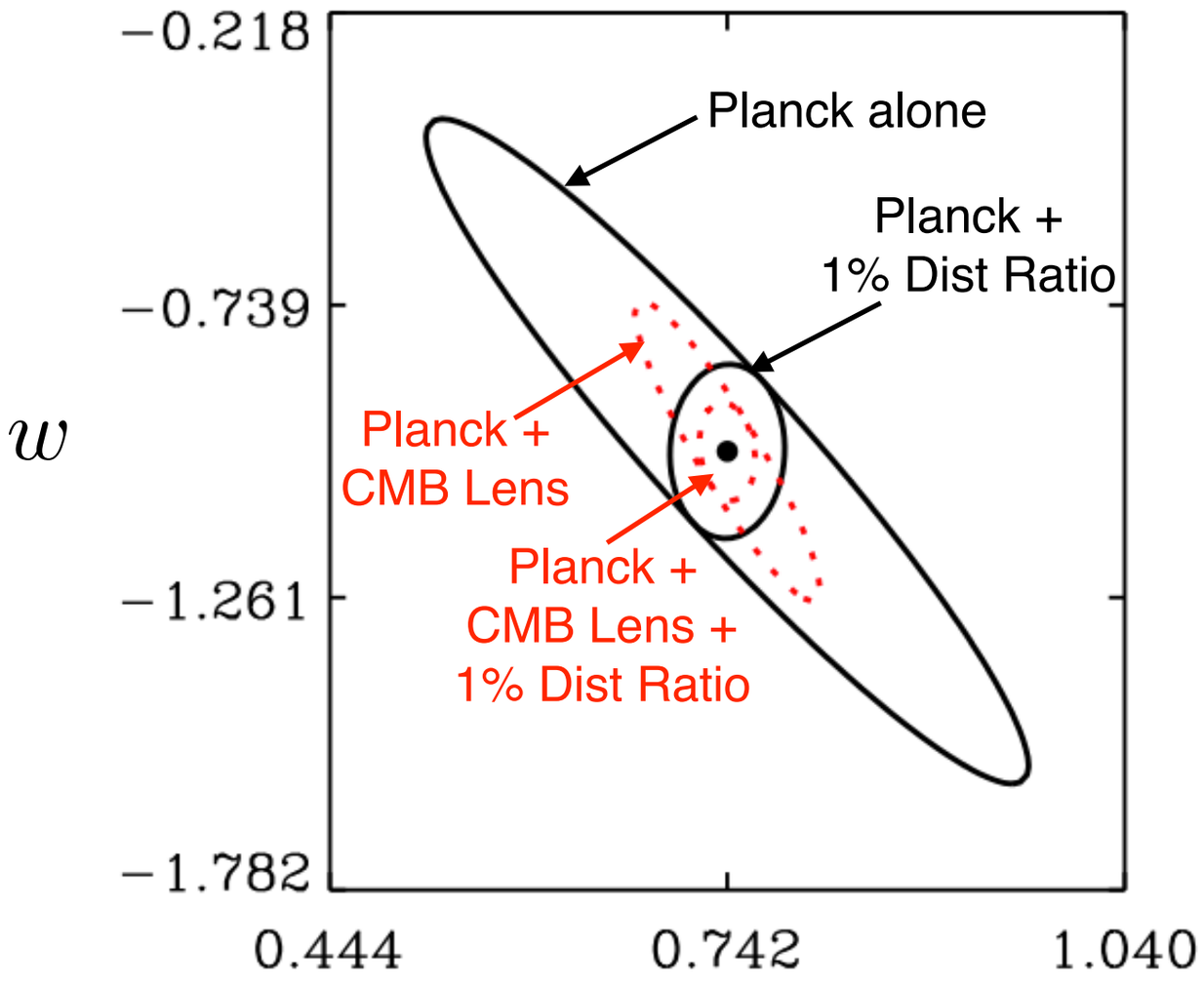

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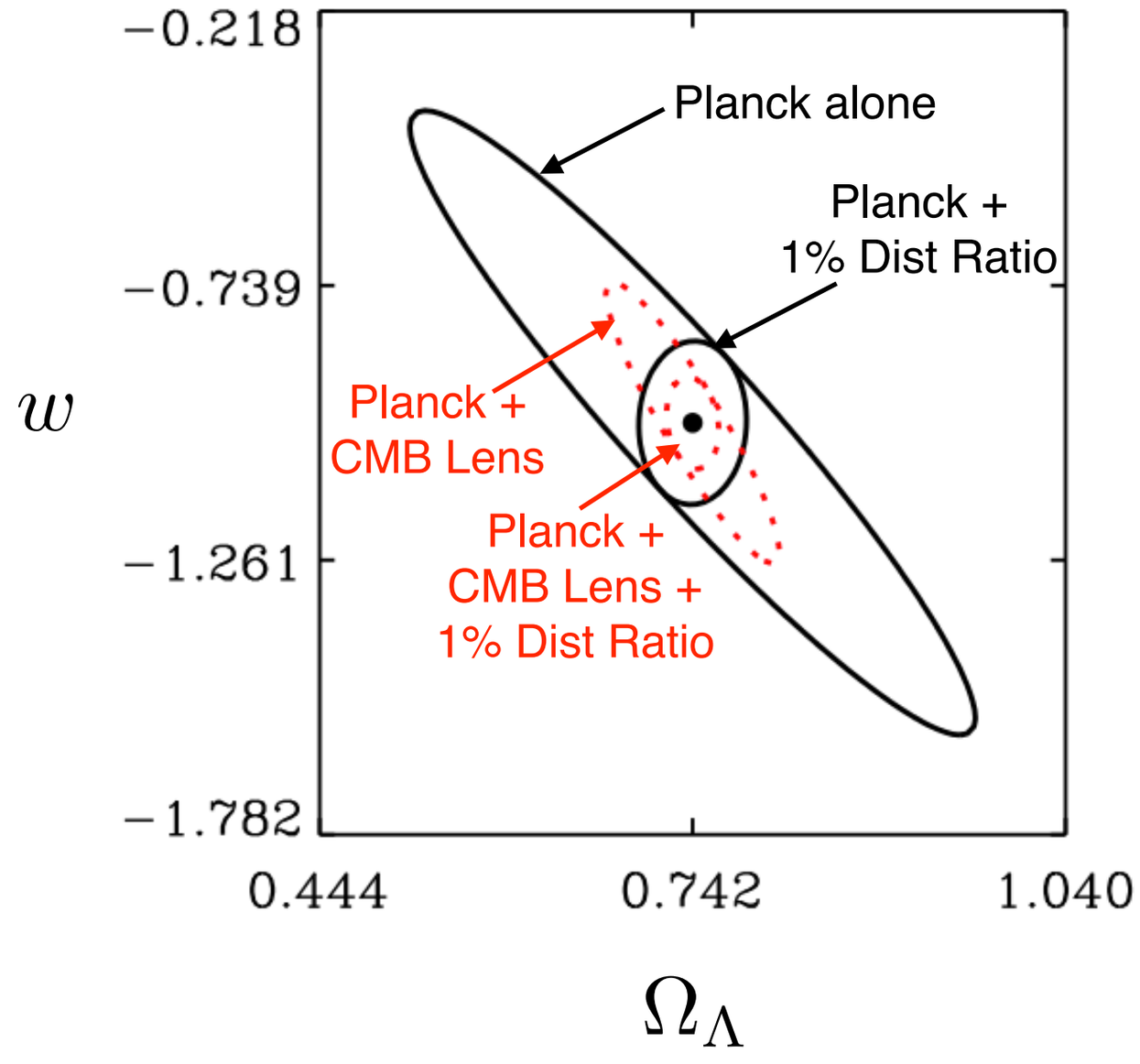

Das and Spergel 2009

Next step: measure CMB Lens x Optical Lens on imminent, higher-quality data from ACTPol, DES, HSC

Outline

- Measuring Lensing of CMB
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History of the Universe

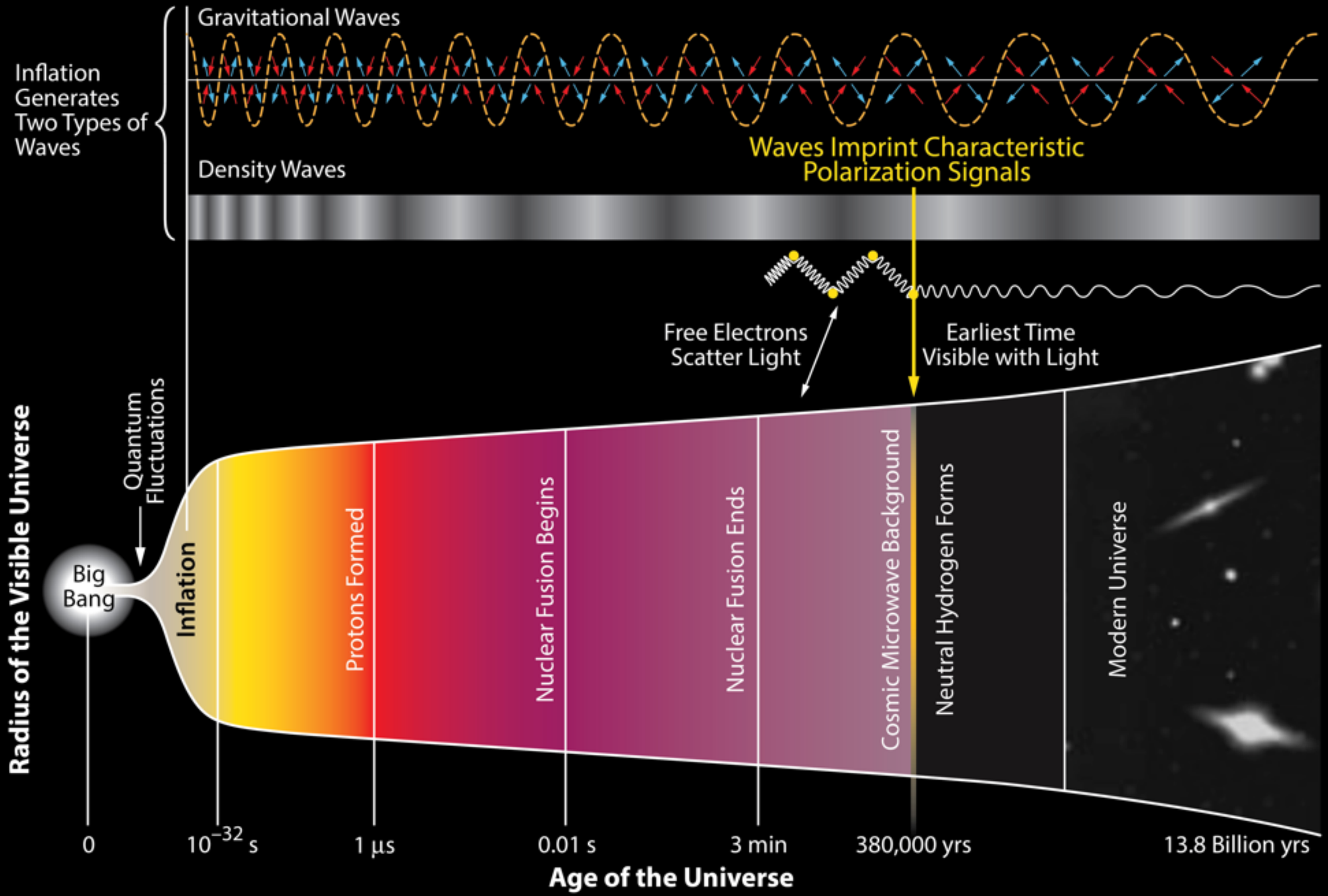

Figure Credit: BICEP2

Inflation Predicts Tensor Perturbations

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- Spectrum of primordial tensor perturbations should exist

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$$V^{1/4} \simeq 2.2 \times 10^{16}\ \mathrm{GeV} \times \left(\frac{r}{0.2}\right)^{1/4}$$

Inflation Predicts Tensor Perturbations

- Spectrum of primordial tensor perturbations should exist
- Amplitude determines energy scale when inflation happened

$$V^{1/4} \simeq 2.2 \times 10^{16}\ \mathrm{GeV} \times \left(\frac{r}{0.2}\right)^{1/4}$$

- Doorstep of quantum gravity - two orders of magnitude below the Planck scale

Measurement would give us a window on processes with energy around 10^{16} GeV

12 orders of magnitude higher than the center of mass energy of the LHC!!

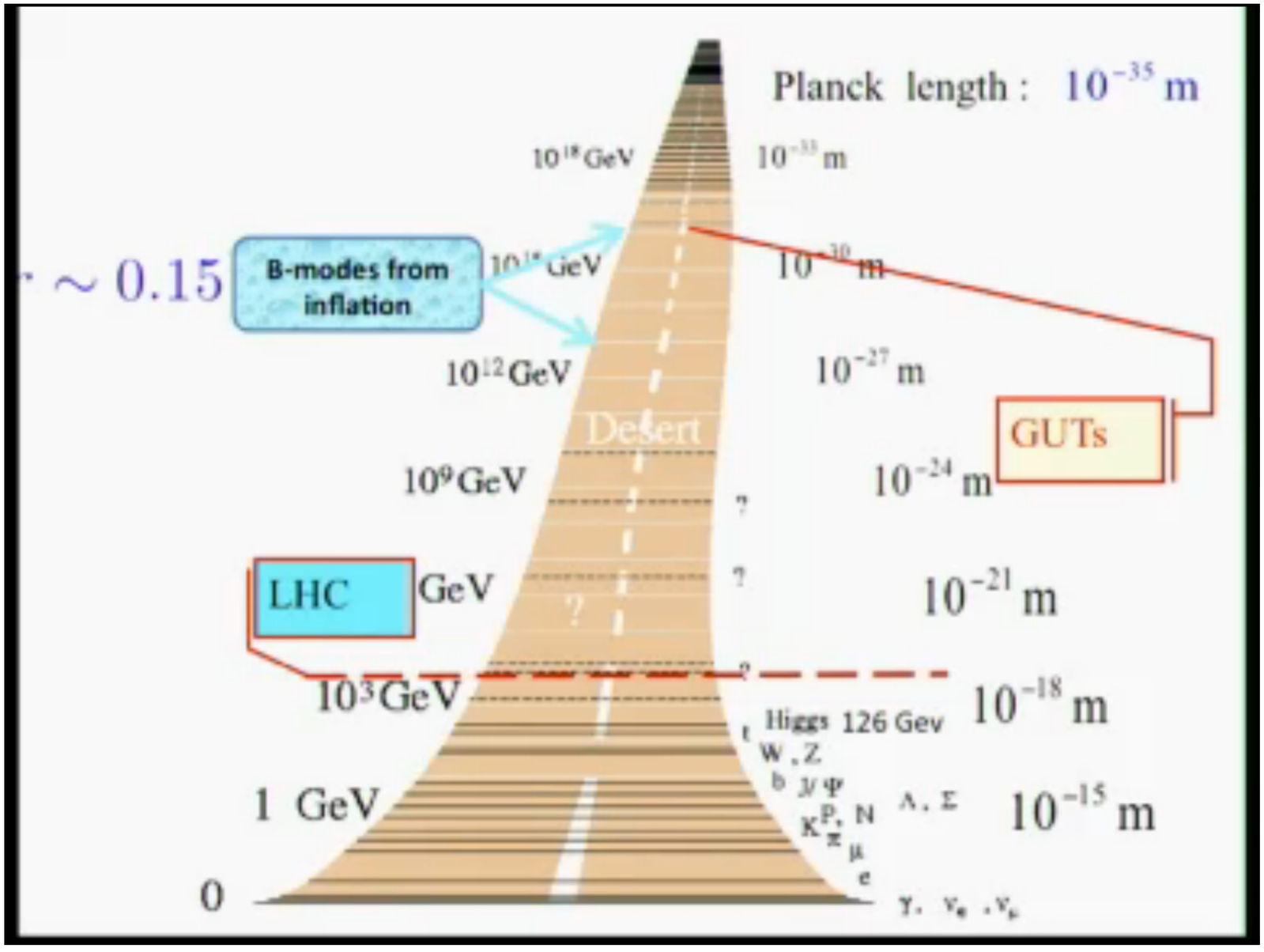

Figure Credit: Renata Kallosh

Other Implications

- First experimental evidence that gravity is quantized?

- During inflation have fluctuations of each polarization direction of gravitational wave

- Say these fluctuations are sourced by quantum fluctuations of two polarization directions of graviton

-Impose quantum commutation relations and calculate power spectrum of these fluctuations

-Measure this power spectrum in CMB

From Gravity Waves to Polarization

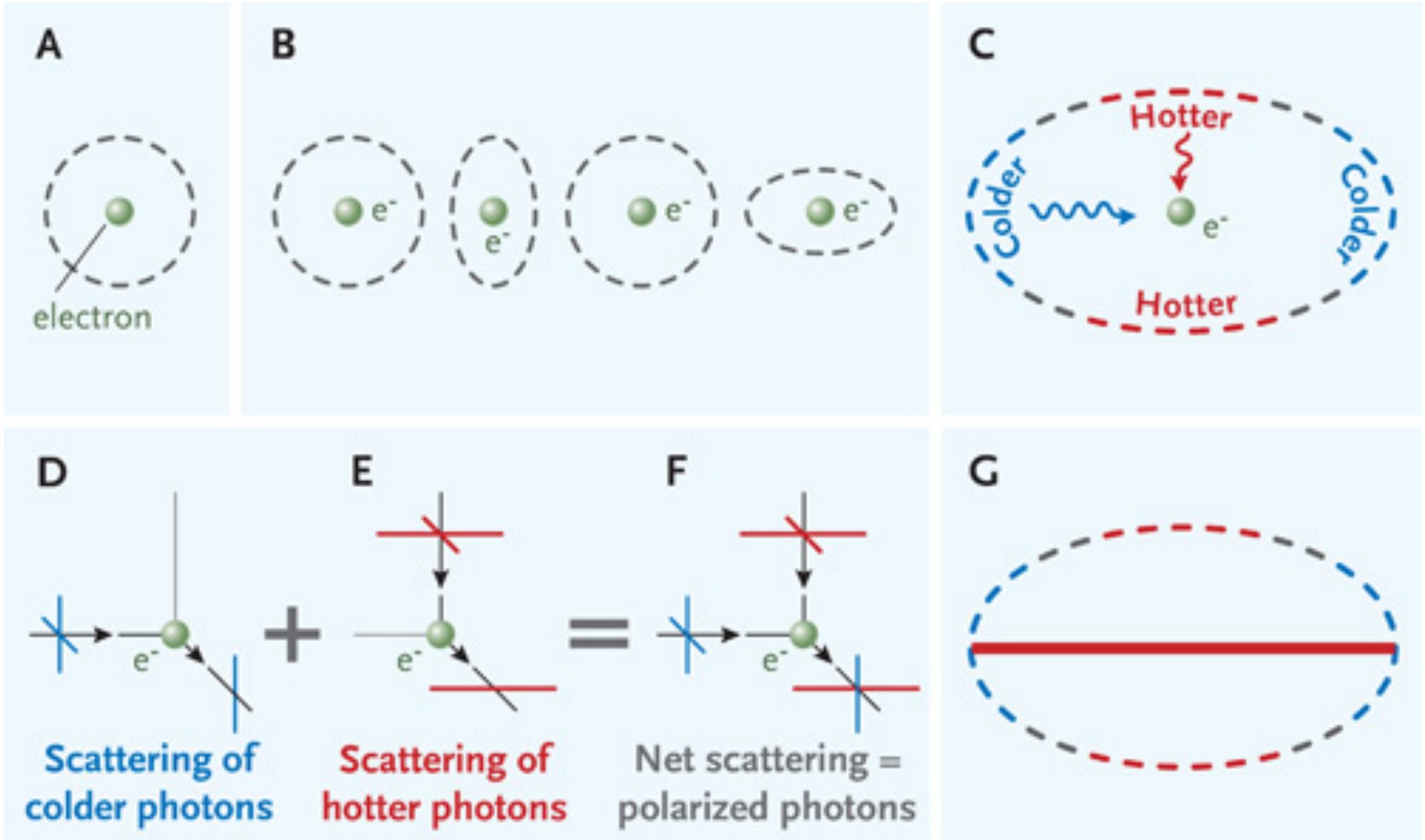

Figure Credit: S&T: Leah Tiscione

Delensing Tightens Parameter Constraints Including on tensor-to-scalar ratio, r

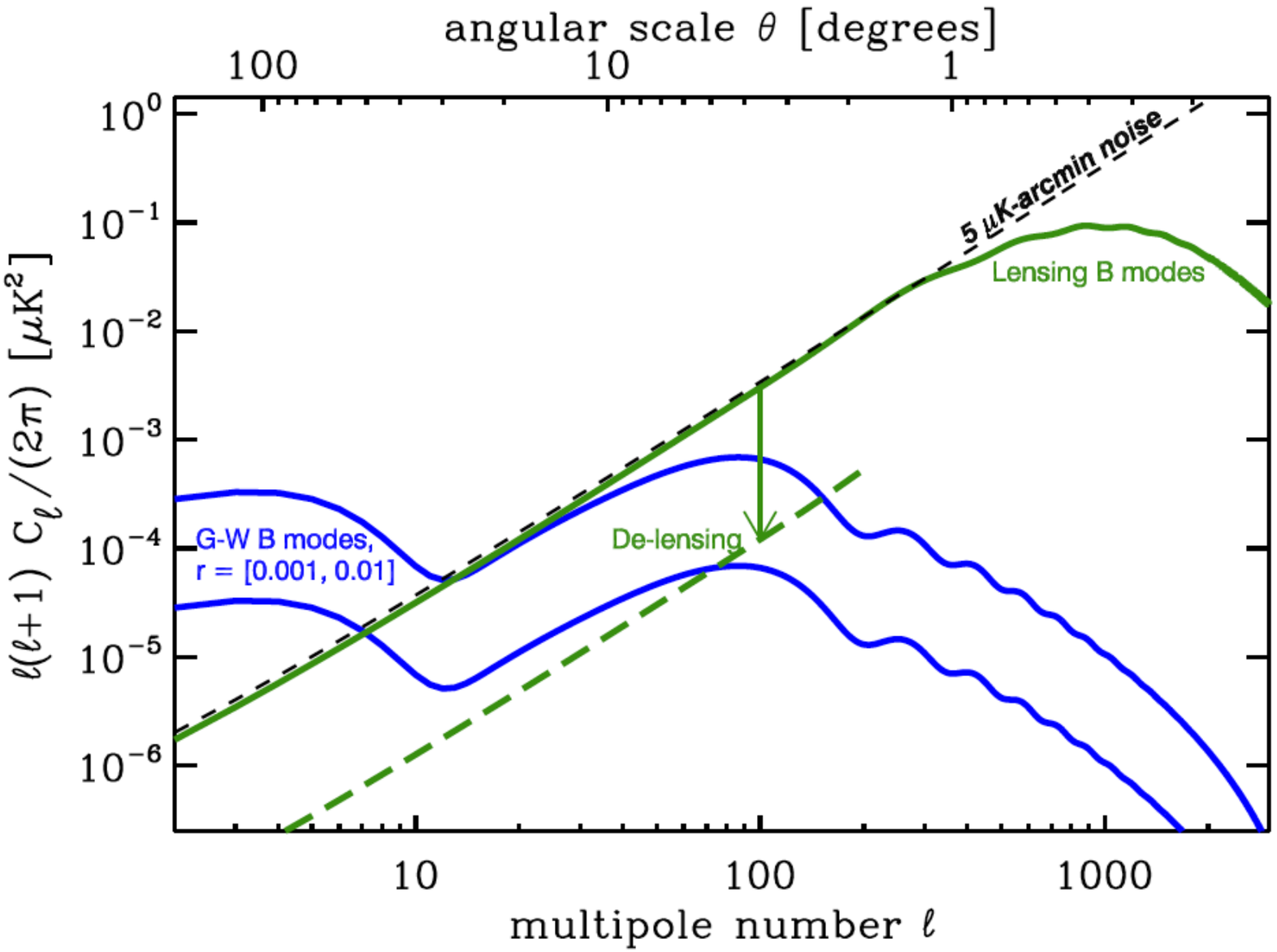

Figure credit: T. Crawford

Delensing

Neelima Sehgal, Stony Brook

Delensing

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Deflection angle

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Projected lensing potential

Deflection angle

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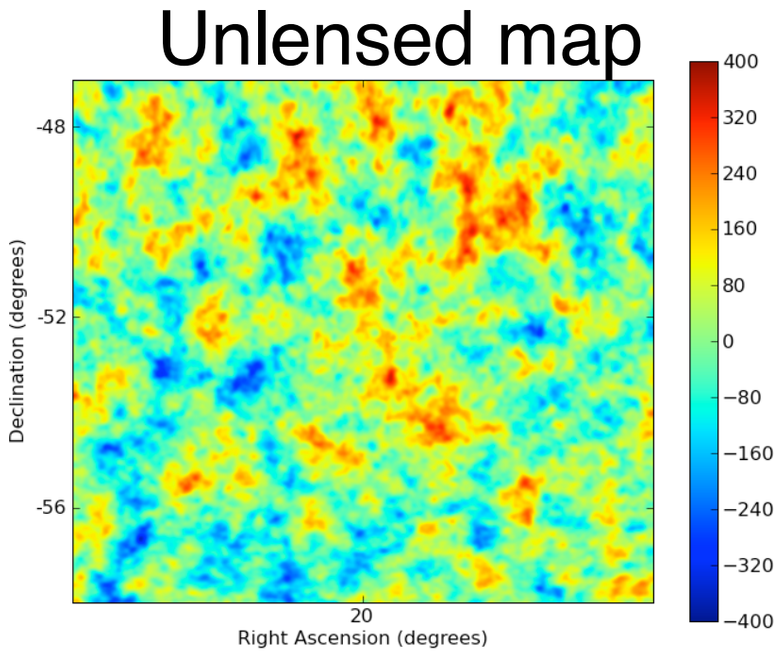

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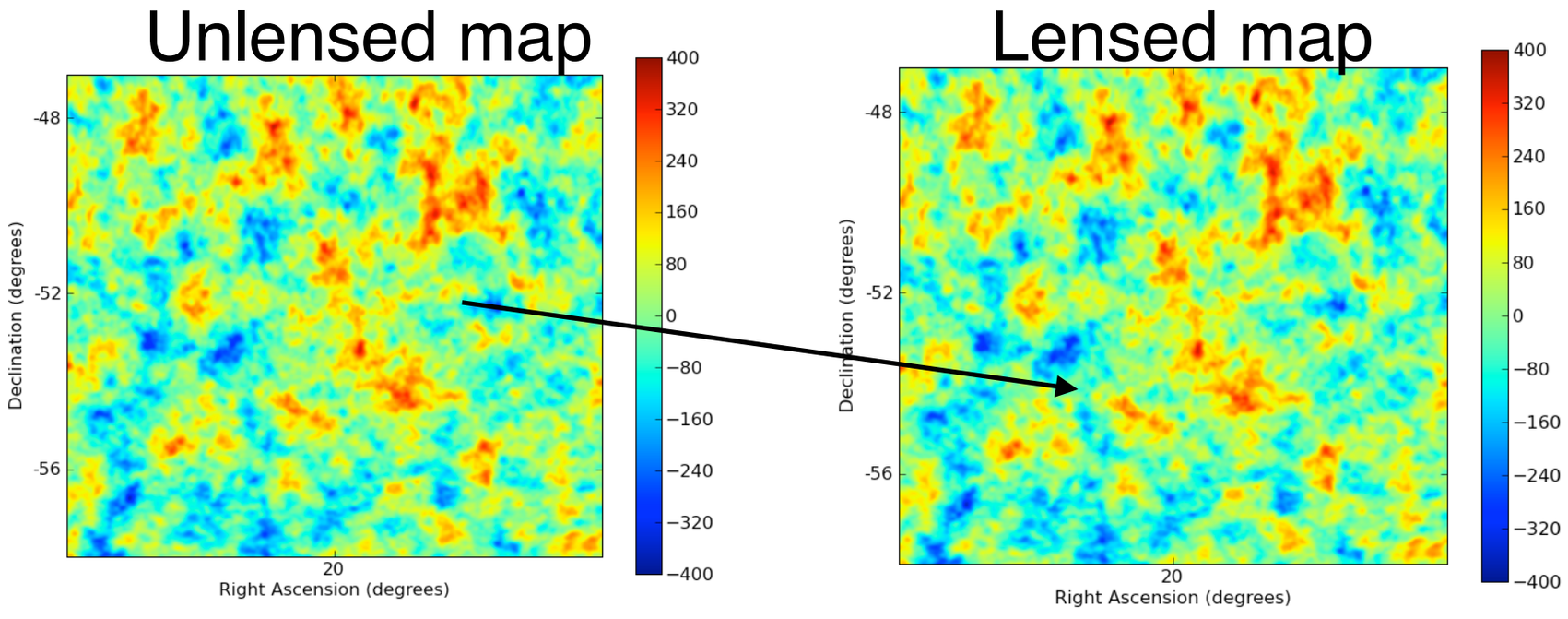

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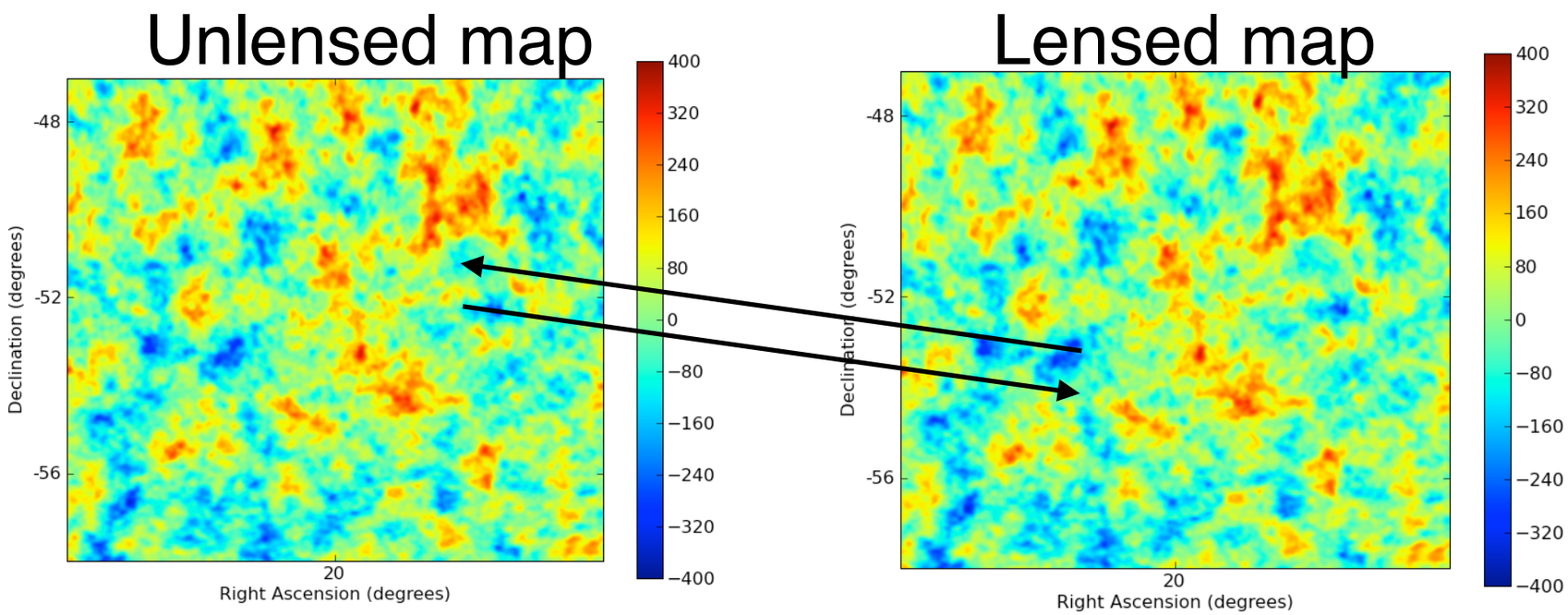
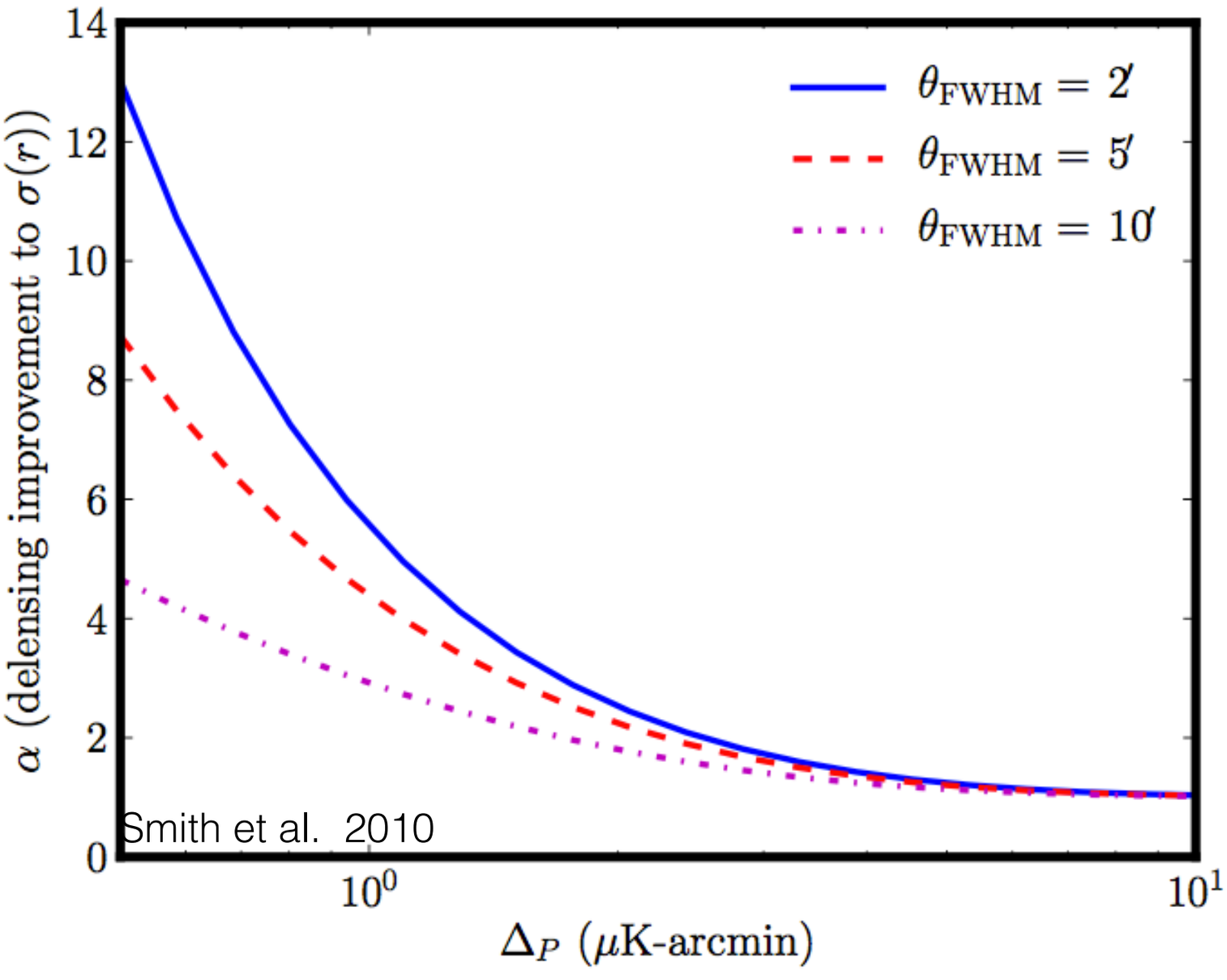


Shift pixels backward using map of projected large scale structure to reconstruct unlensed CMB

Delensing Tightens Parameter Constraints Including on tensor-to-scalar ratio, r



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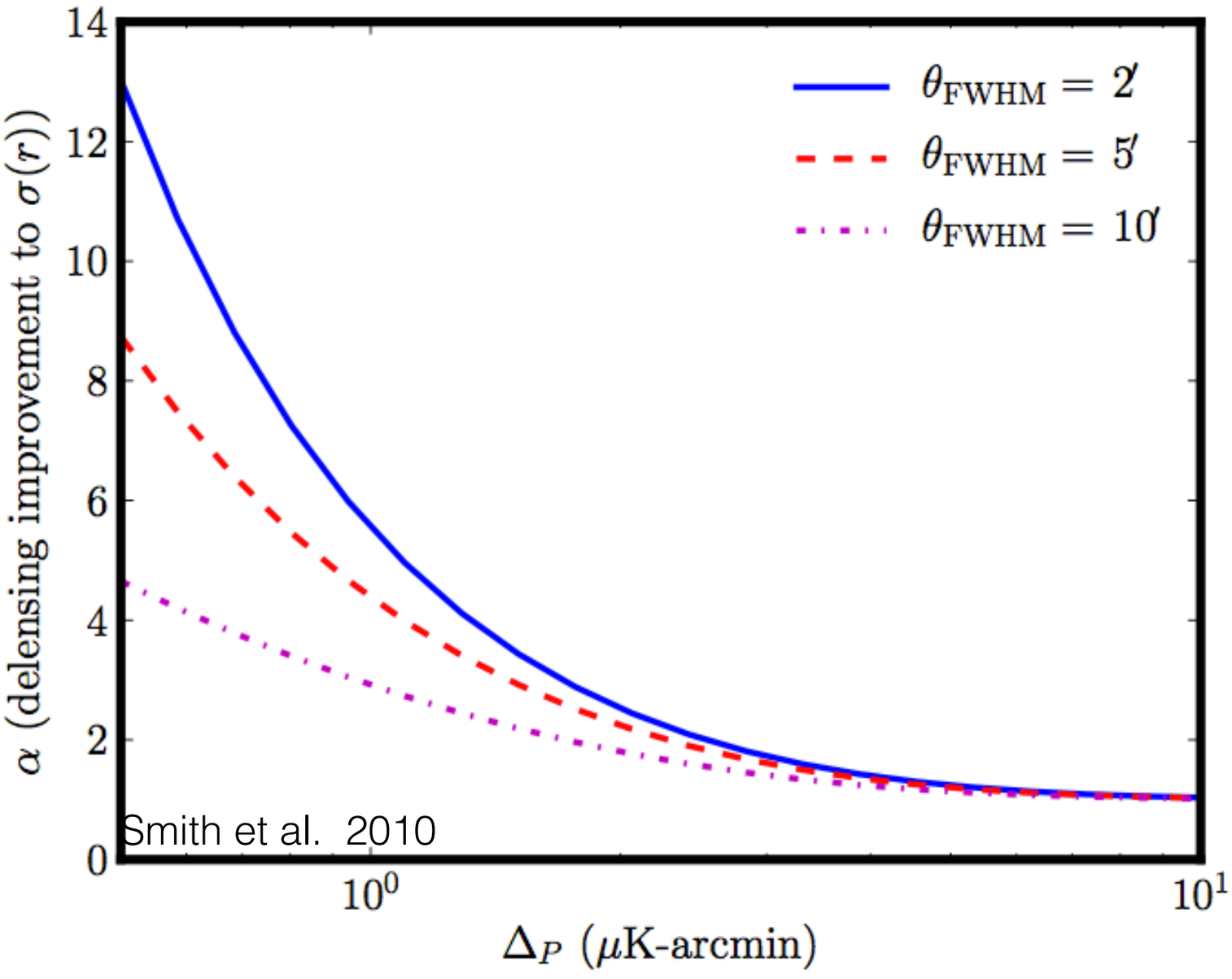

Would be nice to demonstrate we can internally delens!

Detection of Primordial Gravity Waves

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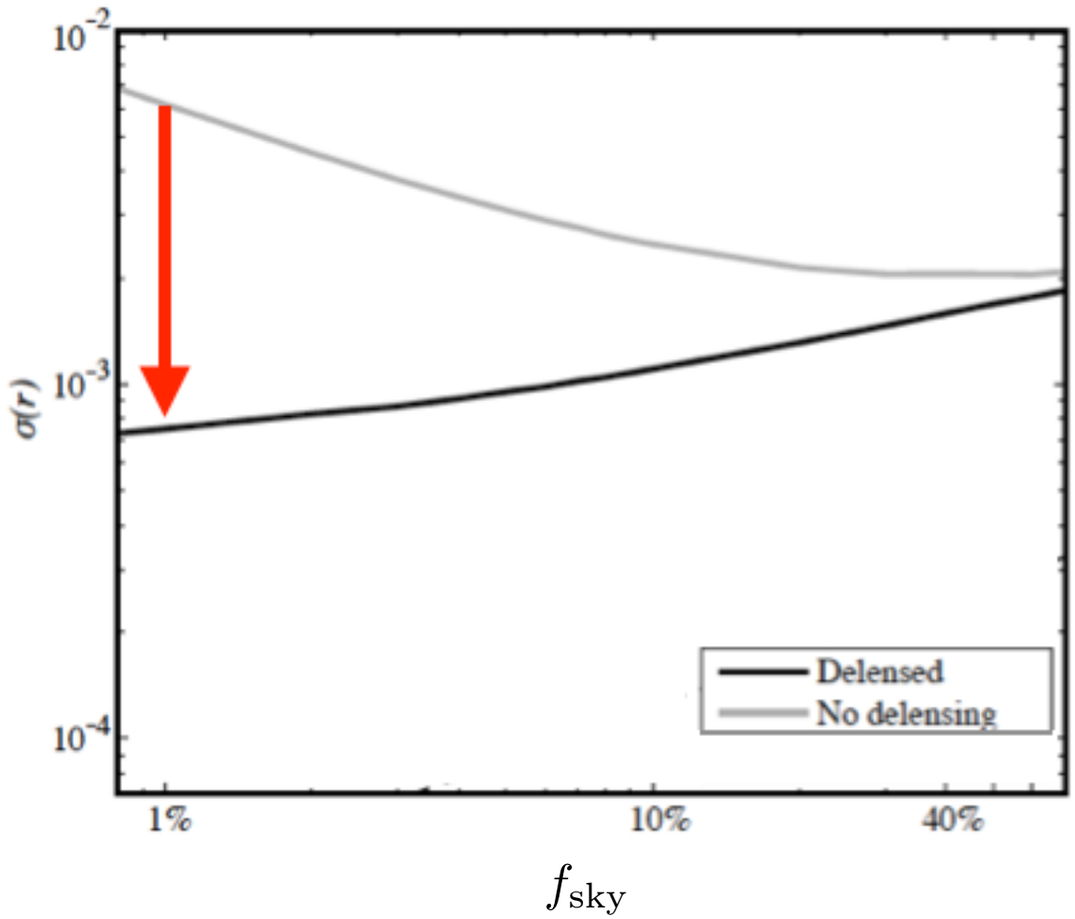

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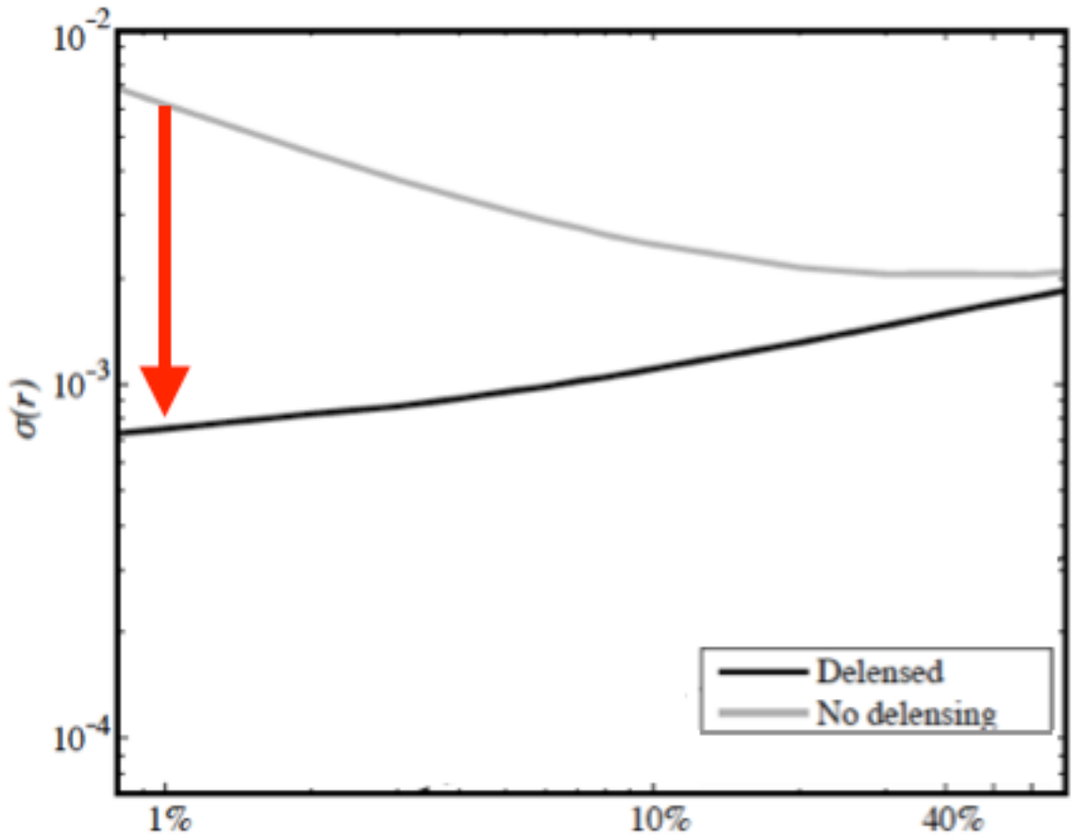

$$\sigma(r) < 10^{-3}$$

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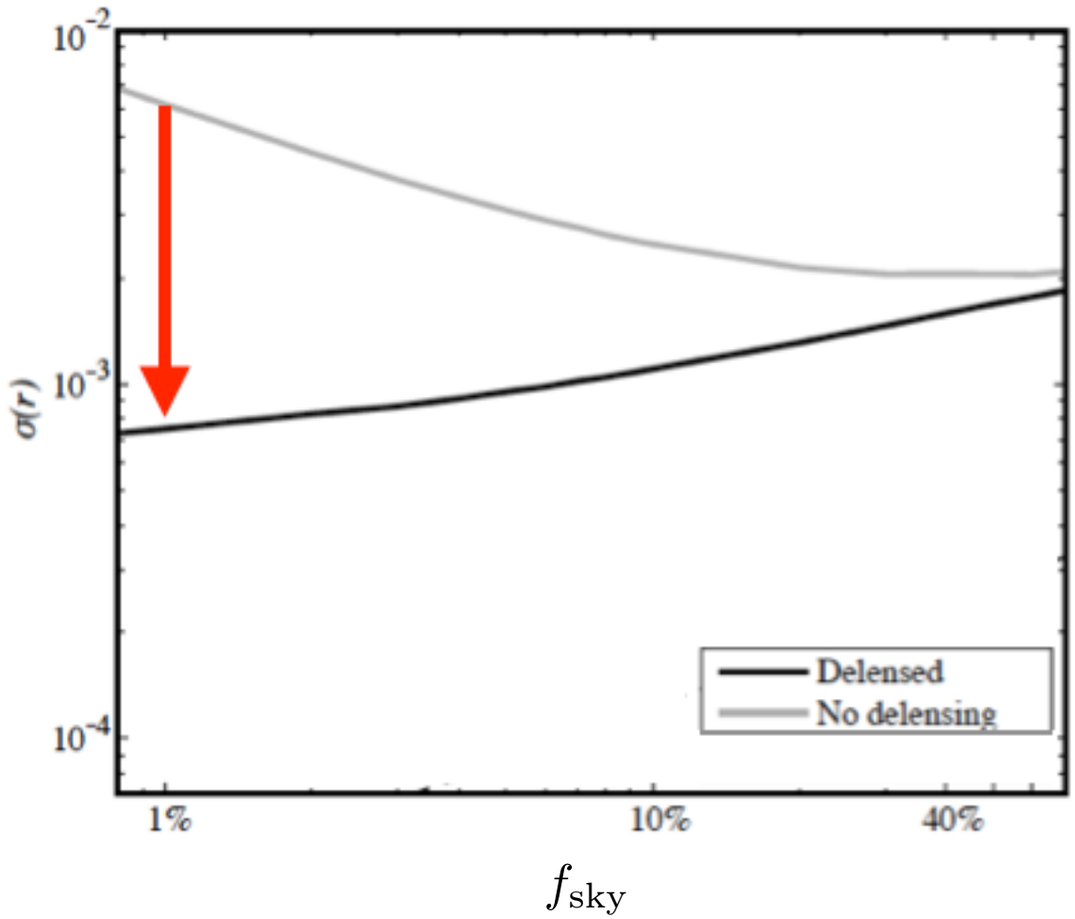

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Next step: implement delensing in practice and put bounds on r with AdvACT/SO/CMB-S4

Conclusion

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- Precisely Probe Dark Energy Equation of State with CMB Lens Cross-correlations with Optical Lens

- With Delensing Playing Integral Role, May Detect Primordial Gravity Waves with, e.g. AdvACT/SPT-3G/ SO/CMB-S4