Gravitational Lensing of the Cosmic Microwave Background: A New Frontier to Probe Fundamental Physics

Neelima Sehgal
Stony Brook University

KITP - May 25th, 2018

Outline

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- Lensing of the Cosmic Microwave Background

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- Neutrino Mass

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- Neutrino Mass (large-scale lensing)
- Curvature, Dark Energy (small-scale lensing)
- Gravitational Waves from Inflation (delensing)
- Dark Matter (ultra-high resolution lensing)

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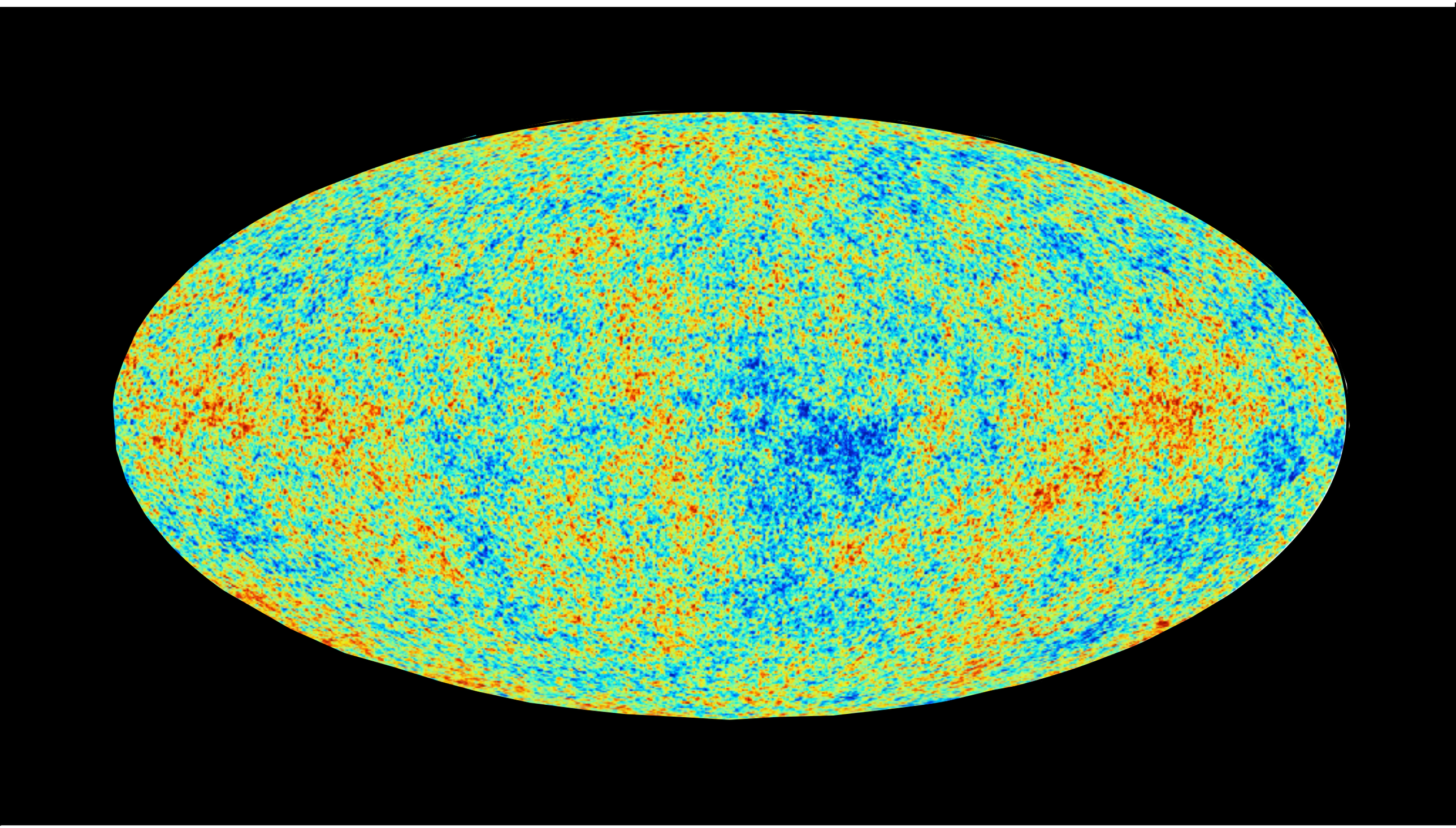
Cosmic Microwave Background



CMB Lensing

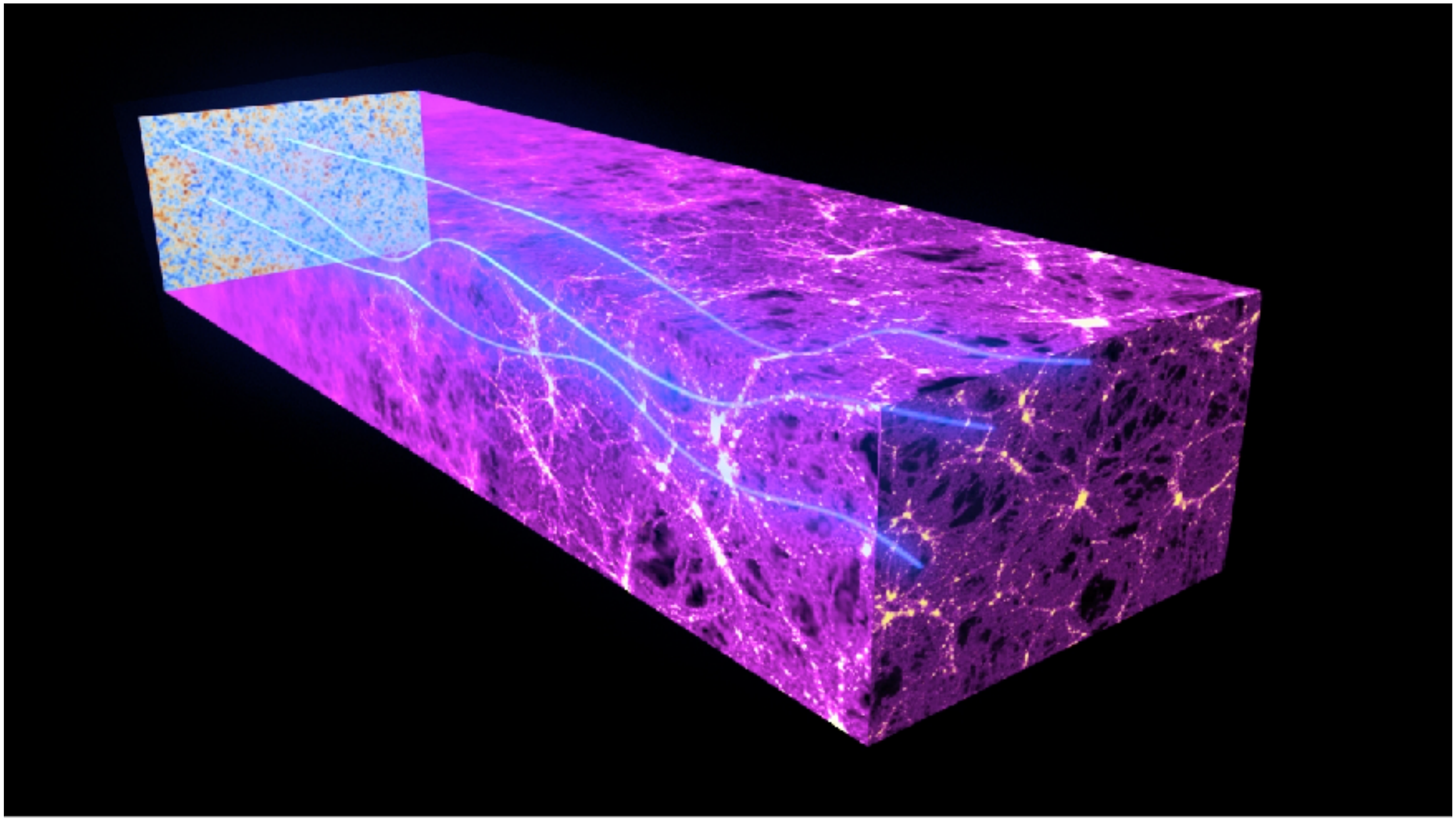
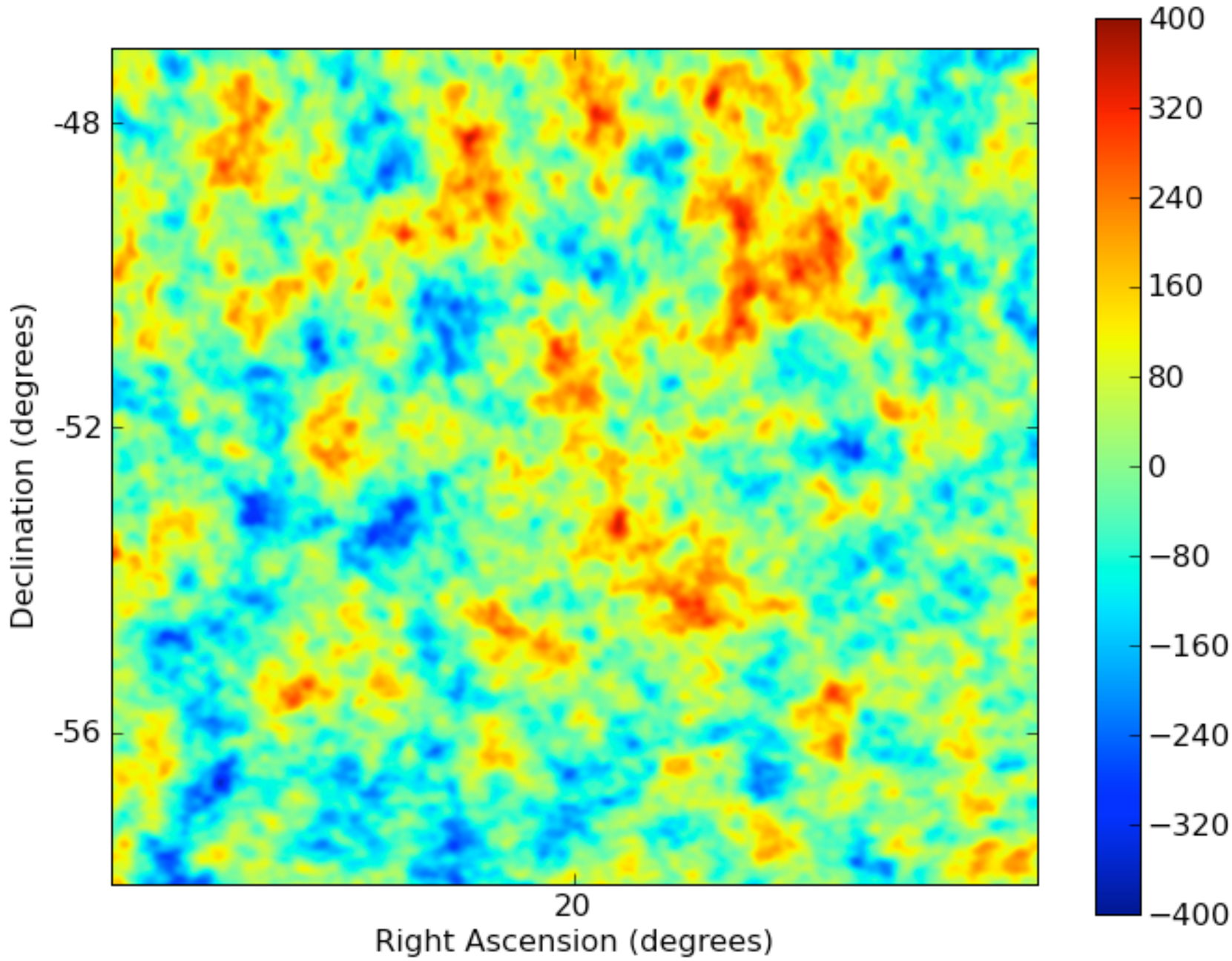


Image Credit: ESA

Unlensed CMB



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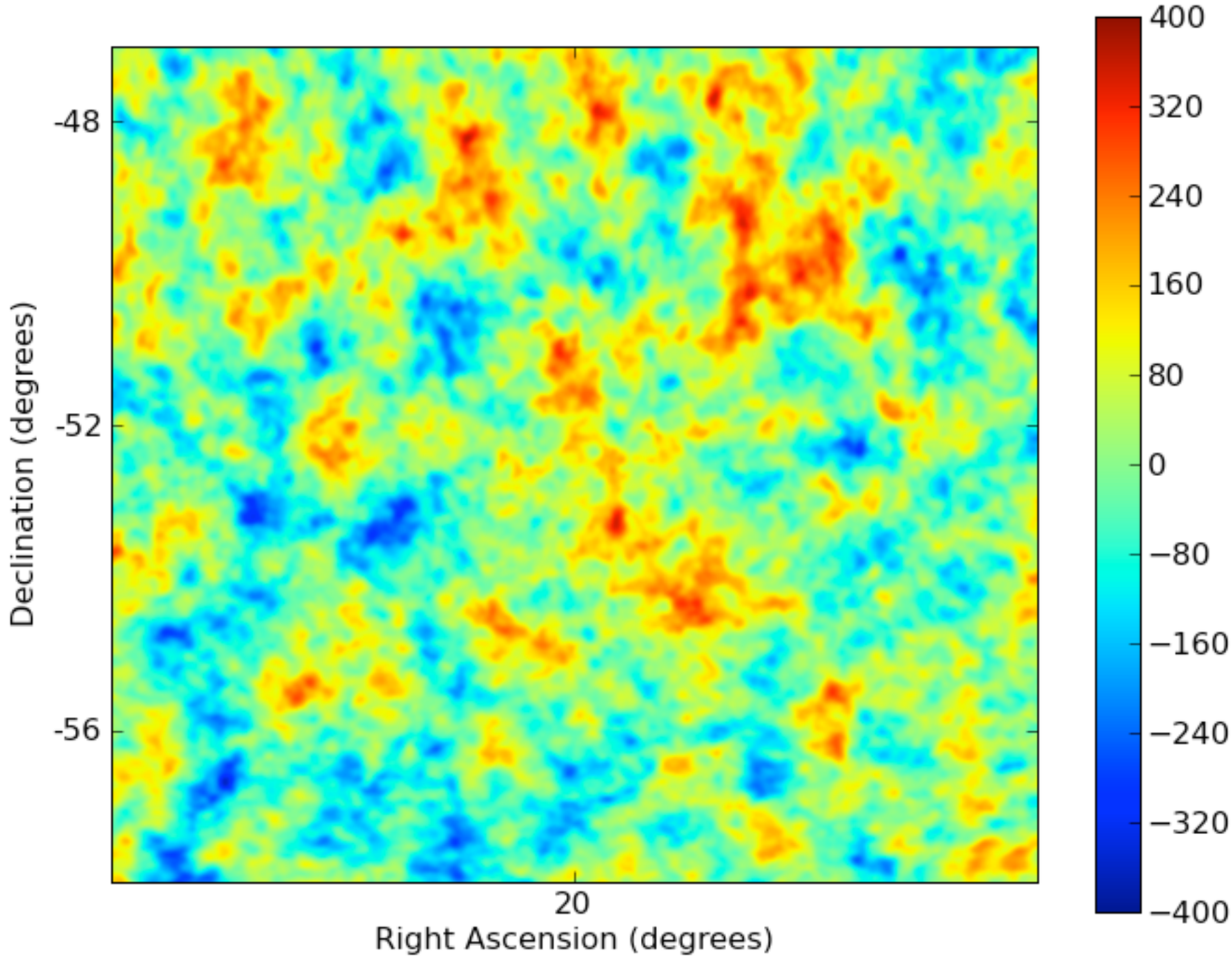
Lensed CMB



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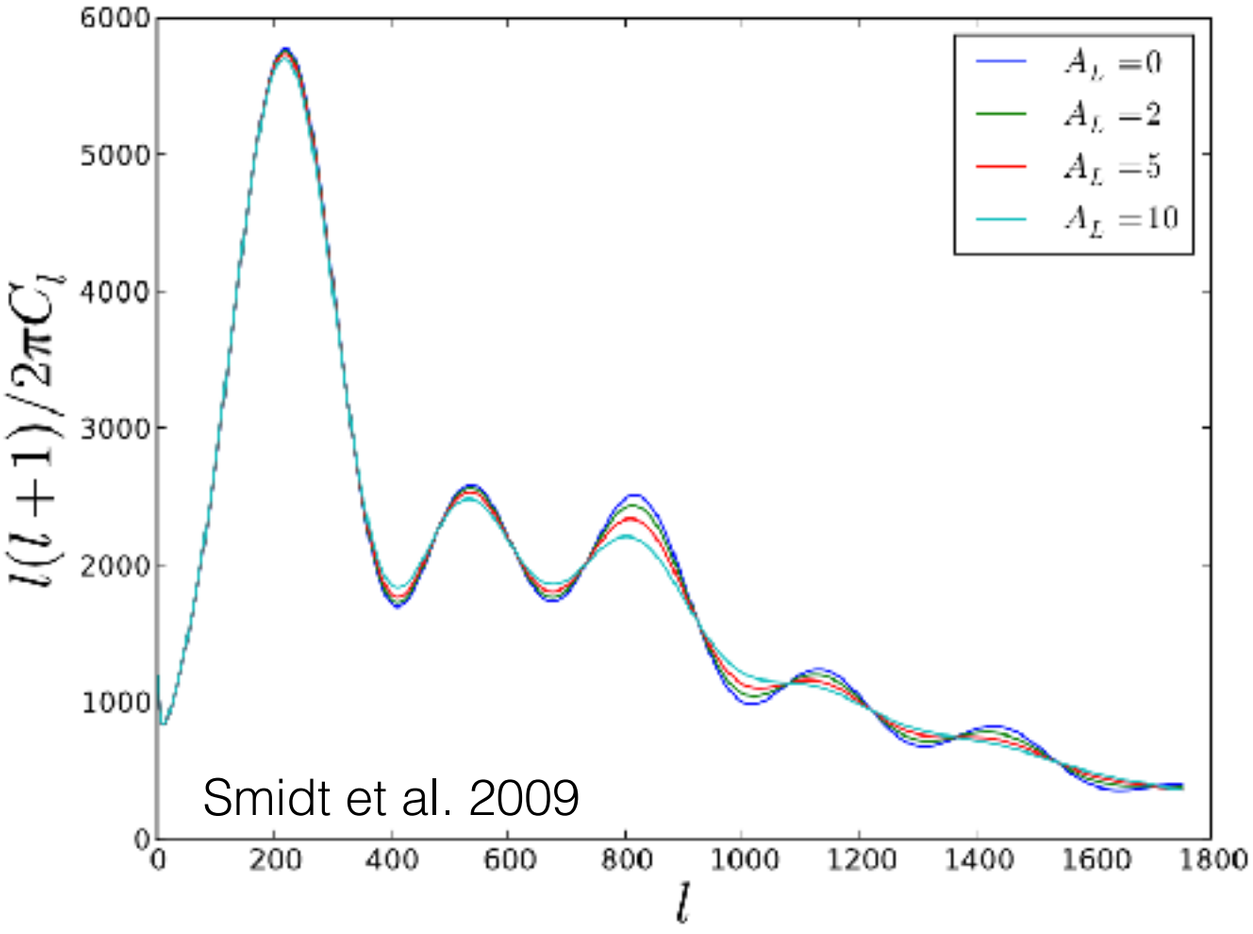
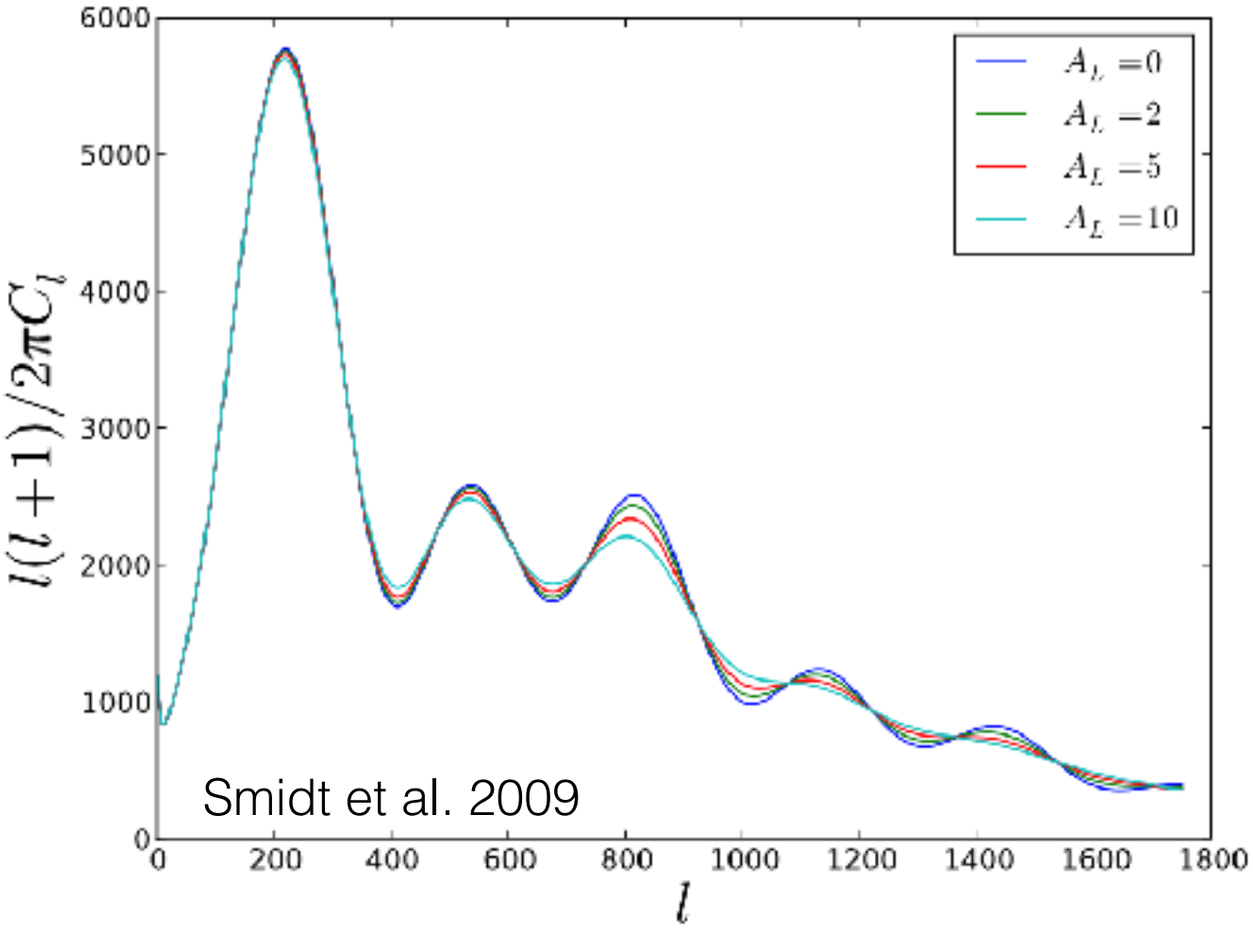
Measuring CMB Lensing



Lensing induces mode coupling

Measuring CMB Lensing



1.) Smooths CMB 2-pt function

Lensing induces mode coupling

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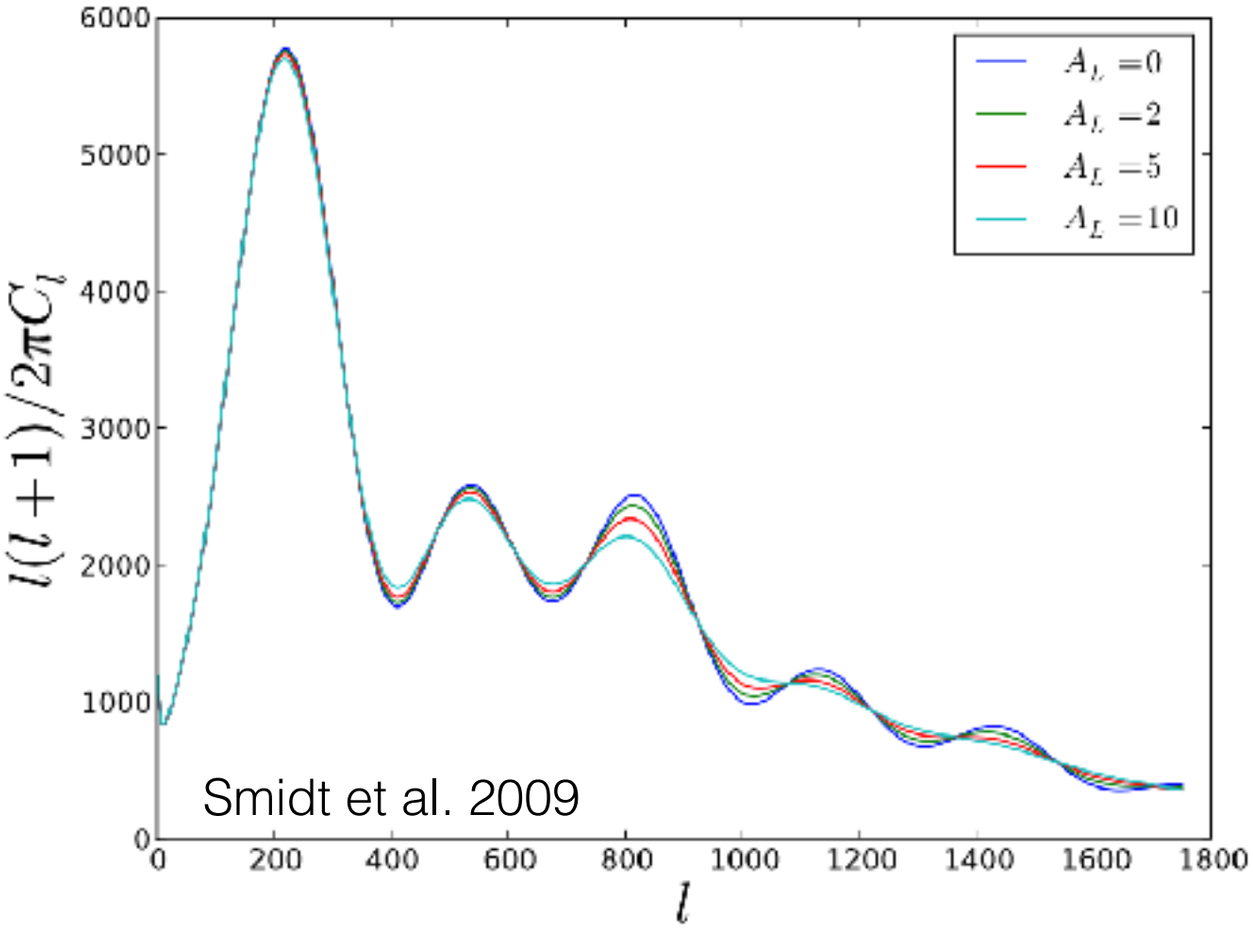

1.) Smooths CMB 2-pt function

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

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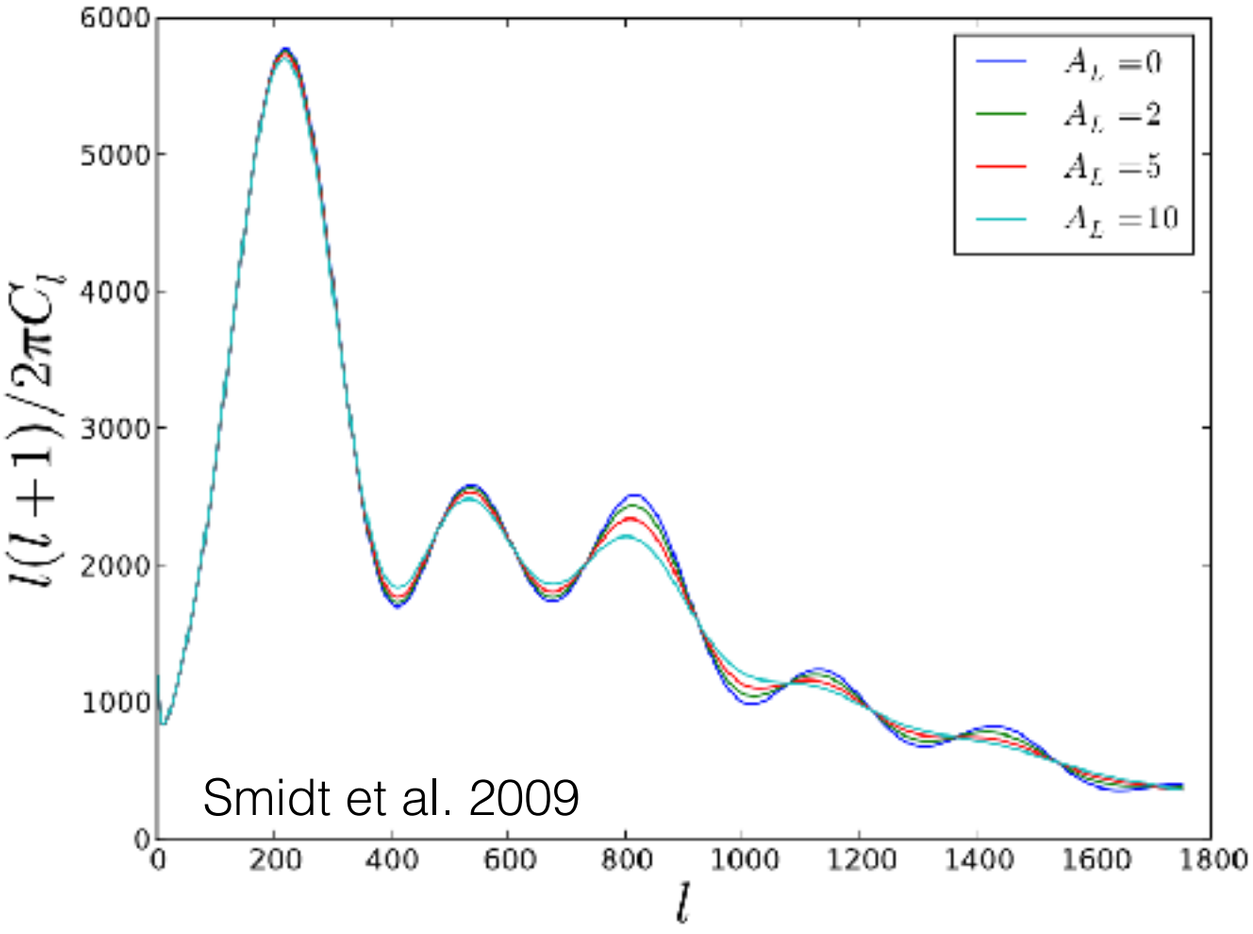

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$$\langle T(\mathbf{l}+\mathbf{L})T^*(\mathbf{l})\rangle_{\rm CMB} \propto \phi(\mathbf{L})$$

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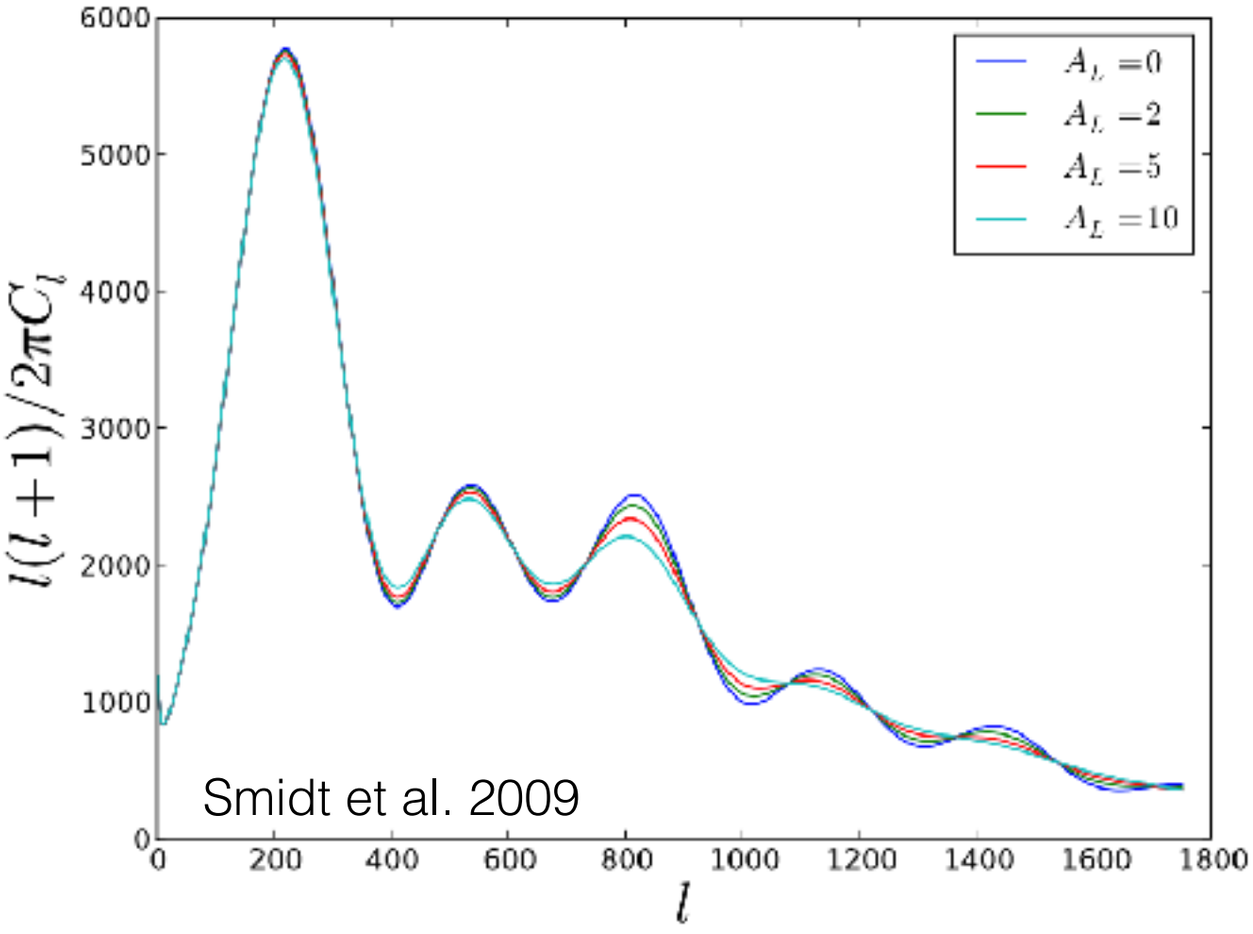

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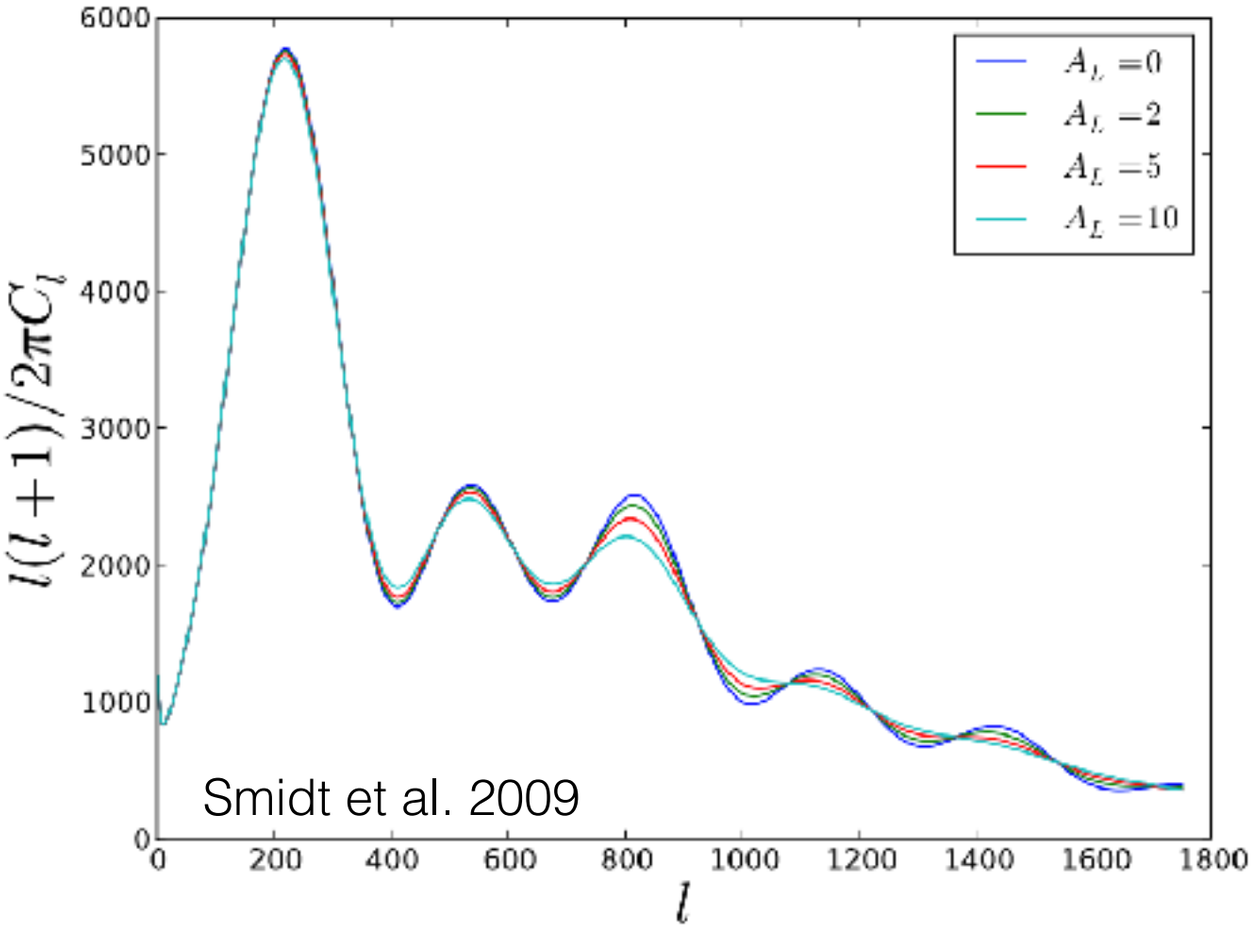

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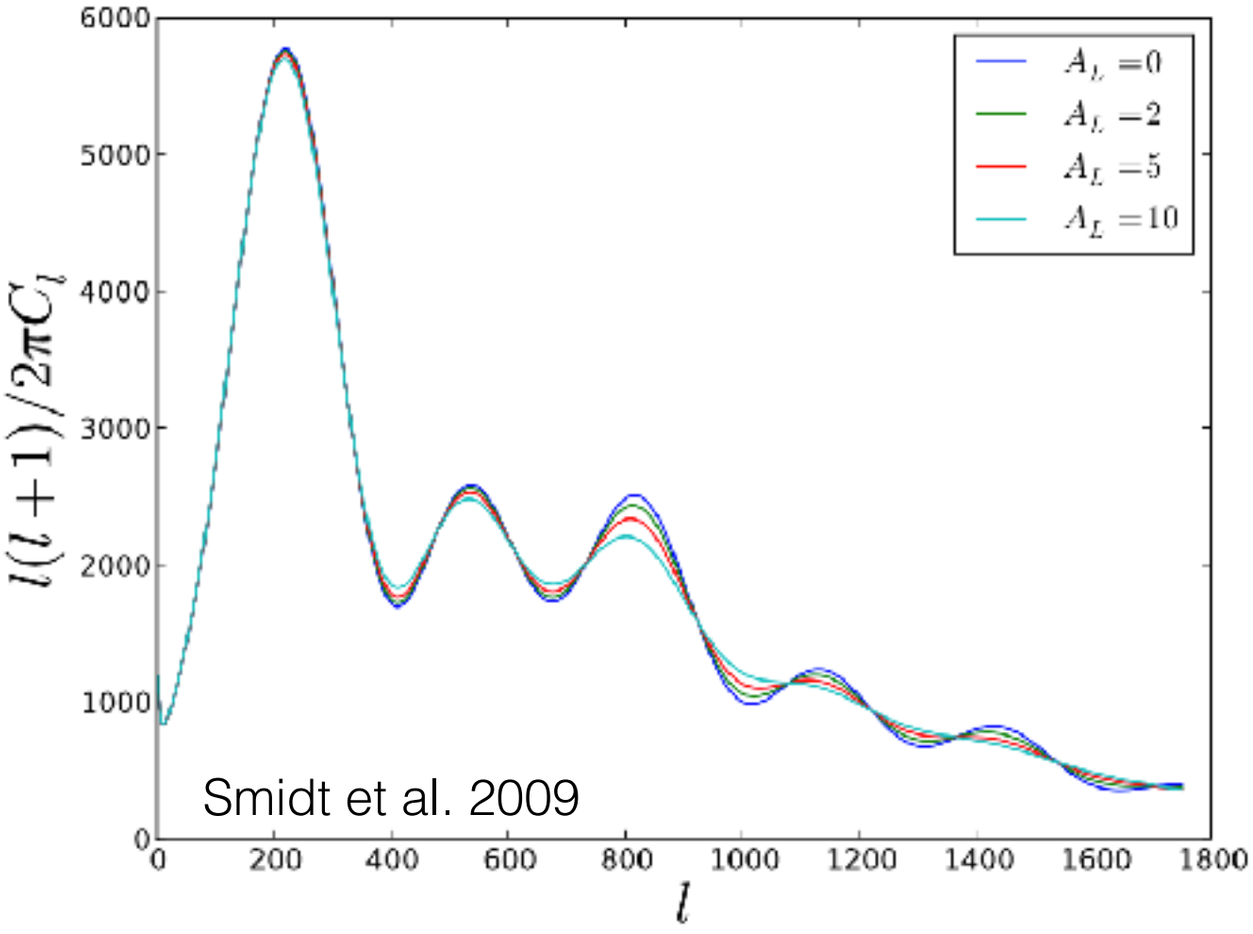
Lensing induces mode coupling

All quadrilaterals whose diagonal has length L

Measuring CMB Lensing



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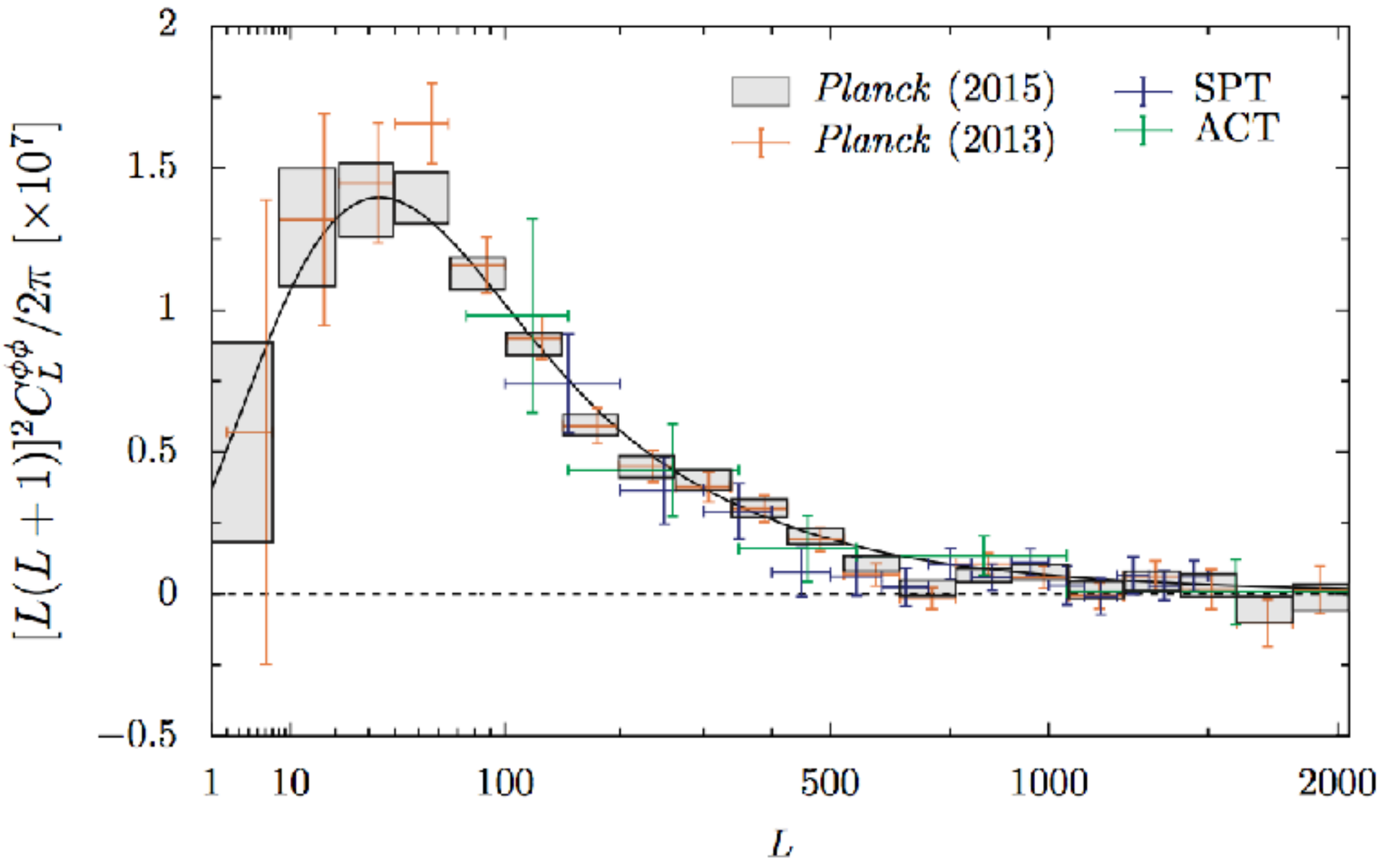
All quadrilaterals whose diagonal has length L

Lensing induces mode coupling

CMB Lensing Power Spectrum is matter power spectrum convolved with window

First Measurements of CMB Lensing



Planck Paper 15, 2015 (1502.01591)

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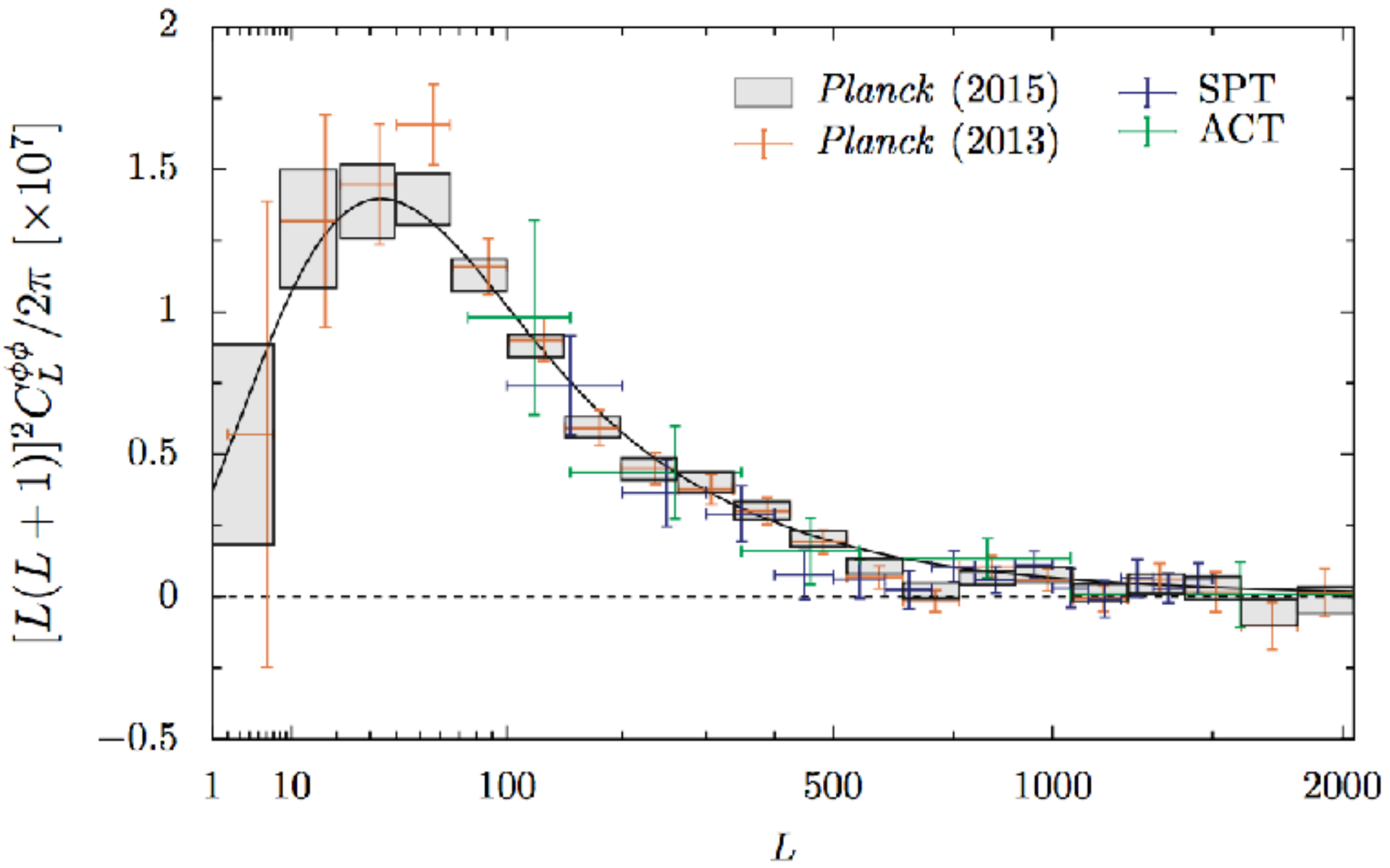

Planck Paper 15, 2015 (1502.01591)

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)

Advantage of CMB Lensing to Probe Structure

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1. Directly sensitive to matter via gravitational lensing

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Advantage of CMB Lensing to Probe Structure

1. Directly sensitive to matter via gravitational lensing
2. Source light is at well-defined redshift
3. Properties of primordial CMB are well understood
4. The CMB is behind all matter structures

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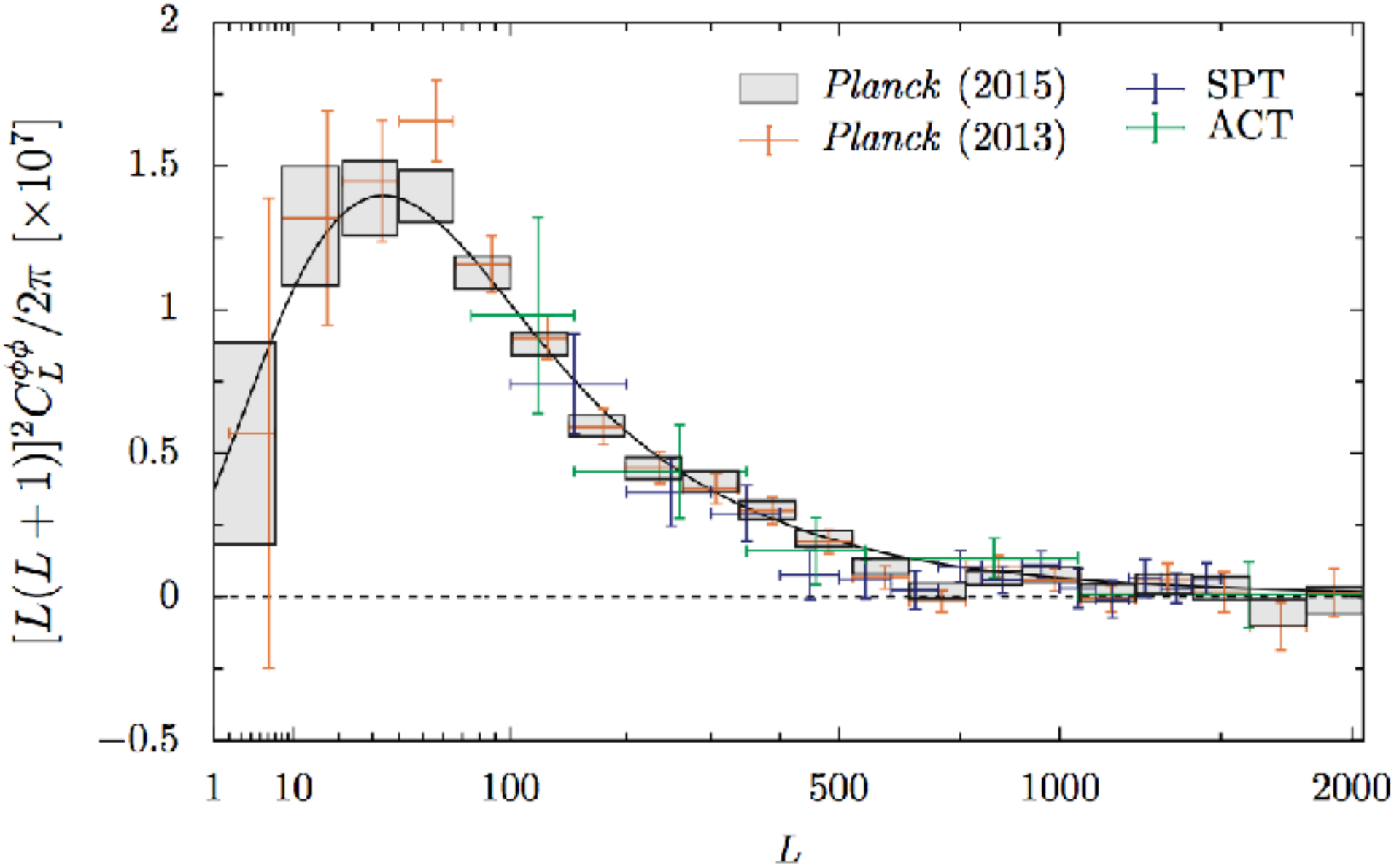

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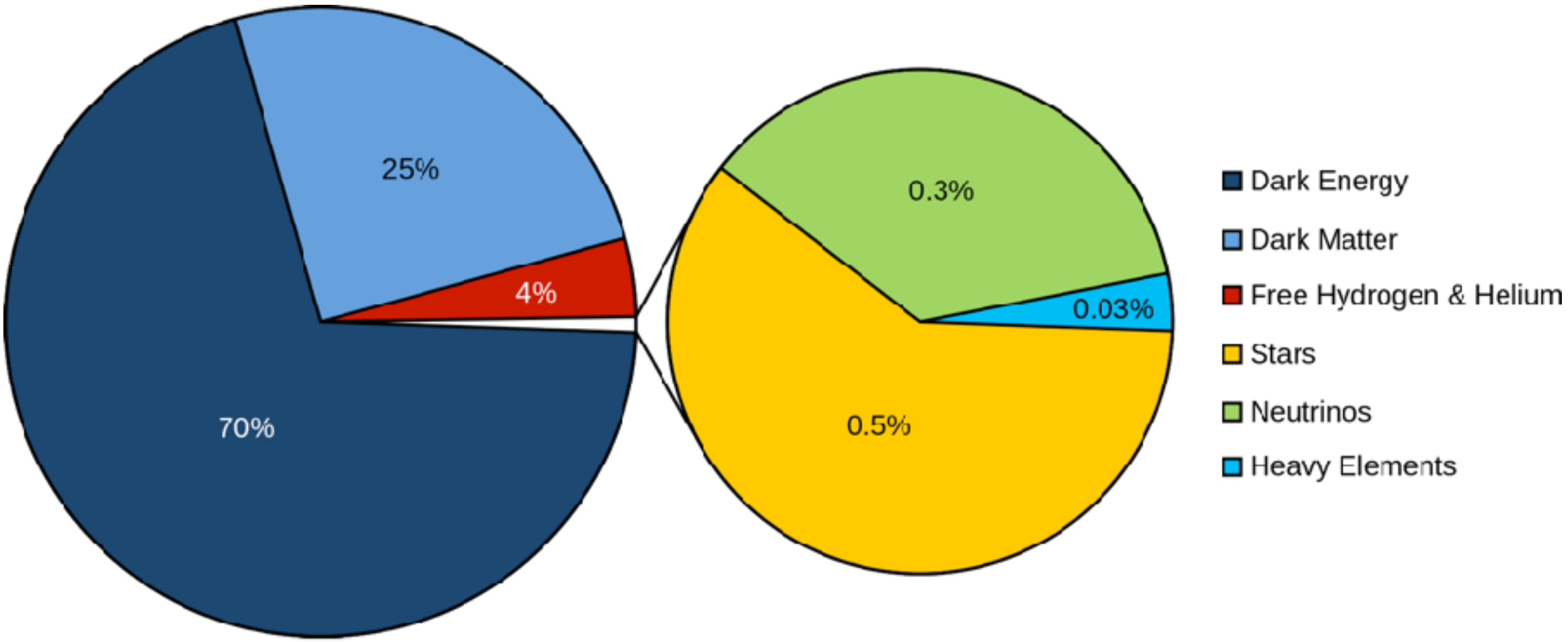
Energy Density in the Universe



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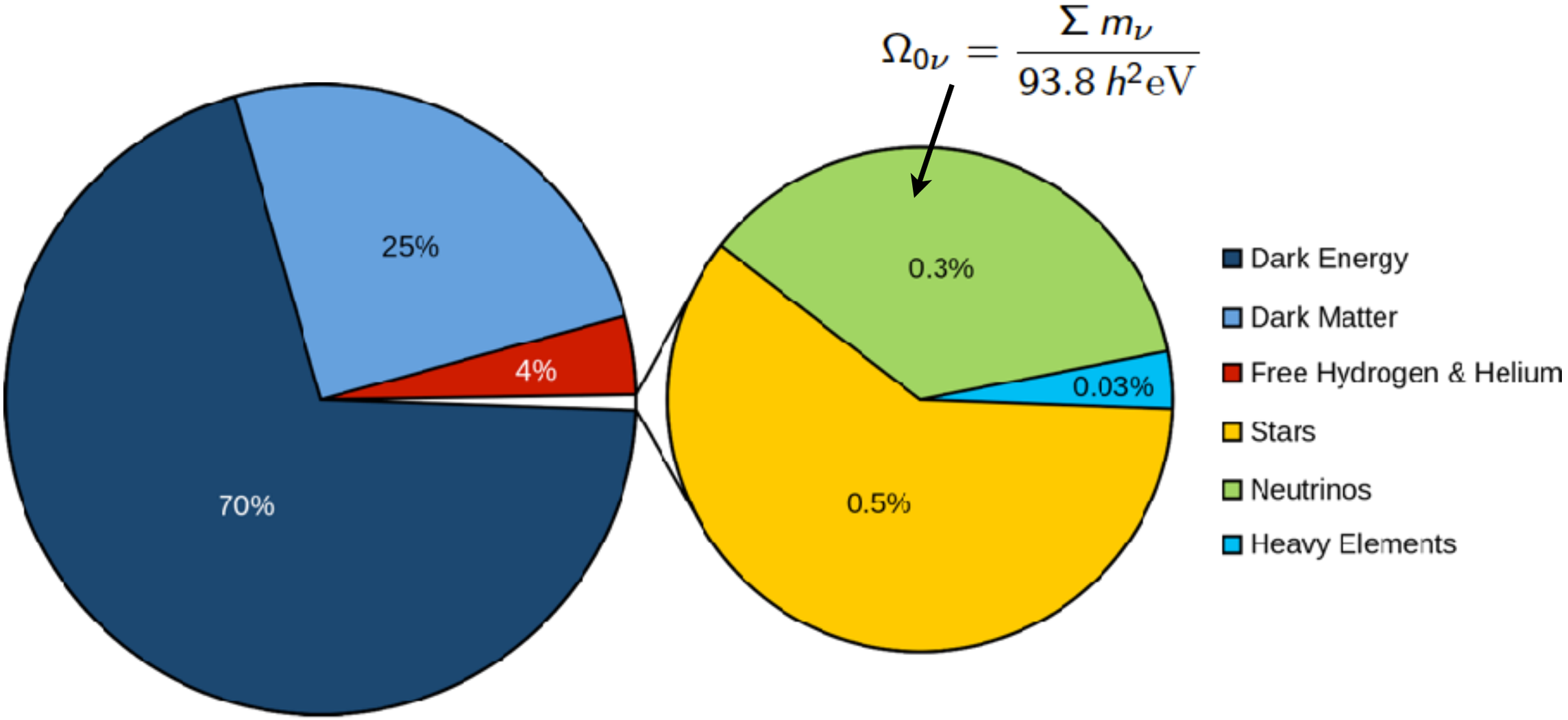

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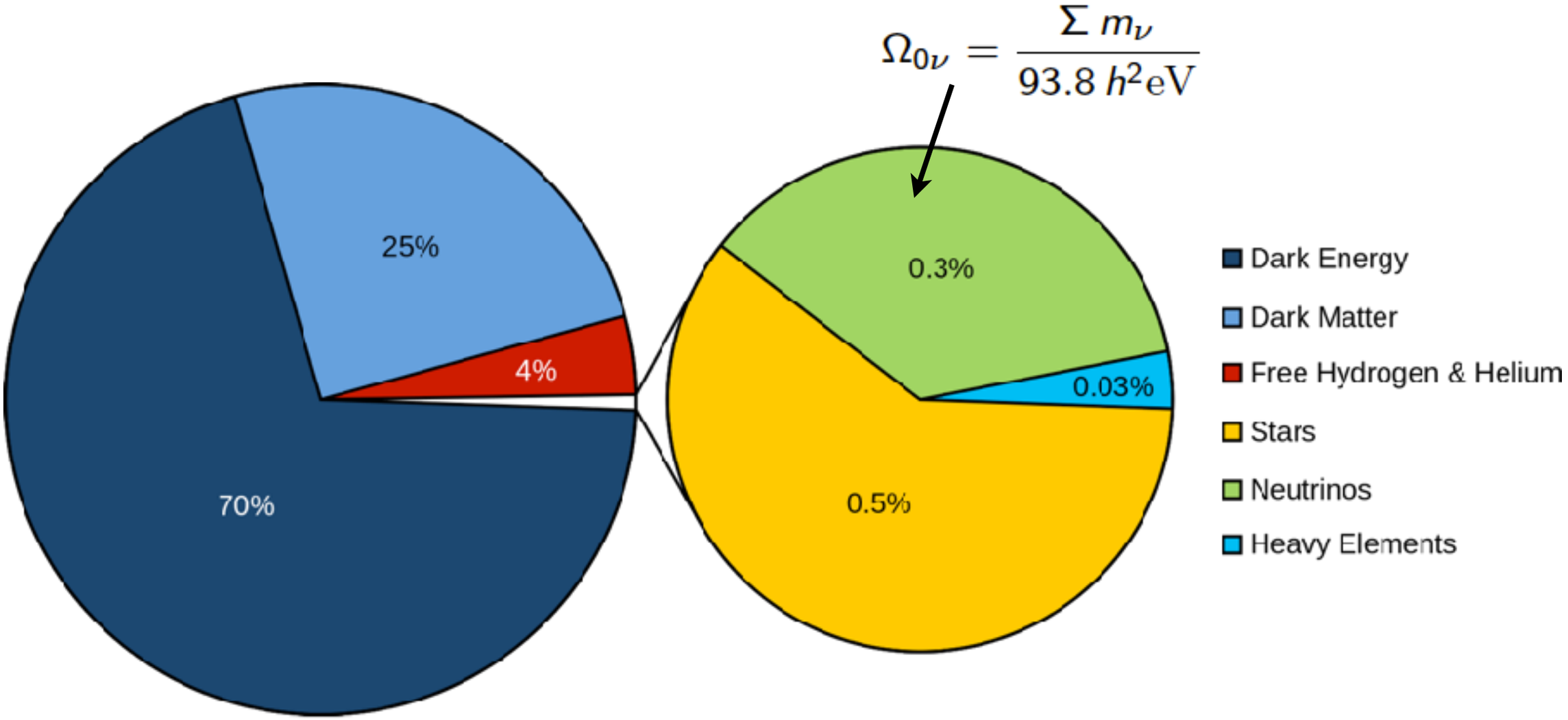

Larger neutrino mass ➡ less cold dark matter

➡ less dark matter structure

CMB Lensing Power Spectrum Sensitive to Neutrino Mass

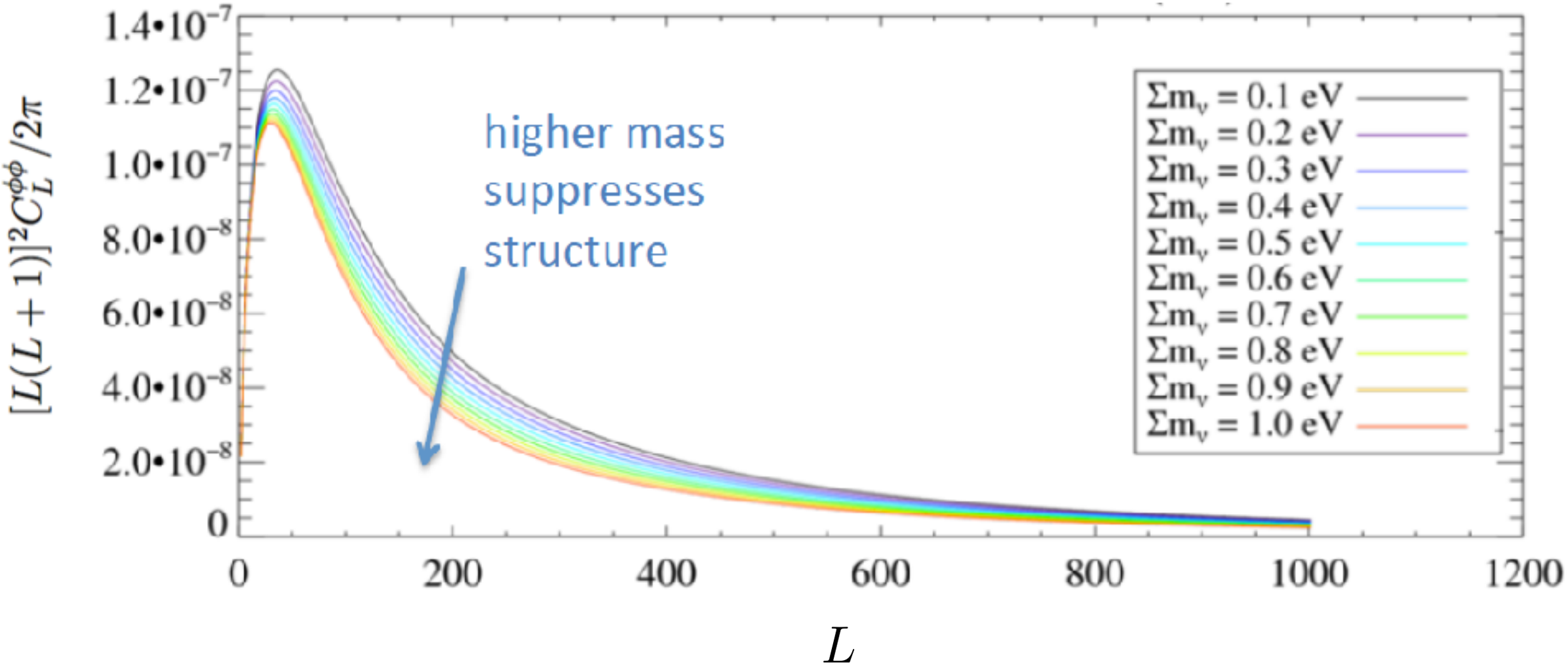

Figure credit: Alexander van Engelen (postdoc at CITA)

Suppression of Matter Power Spectrum Due to Massive Neutrinos

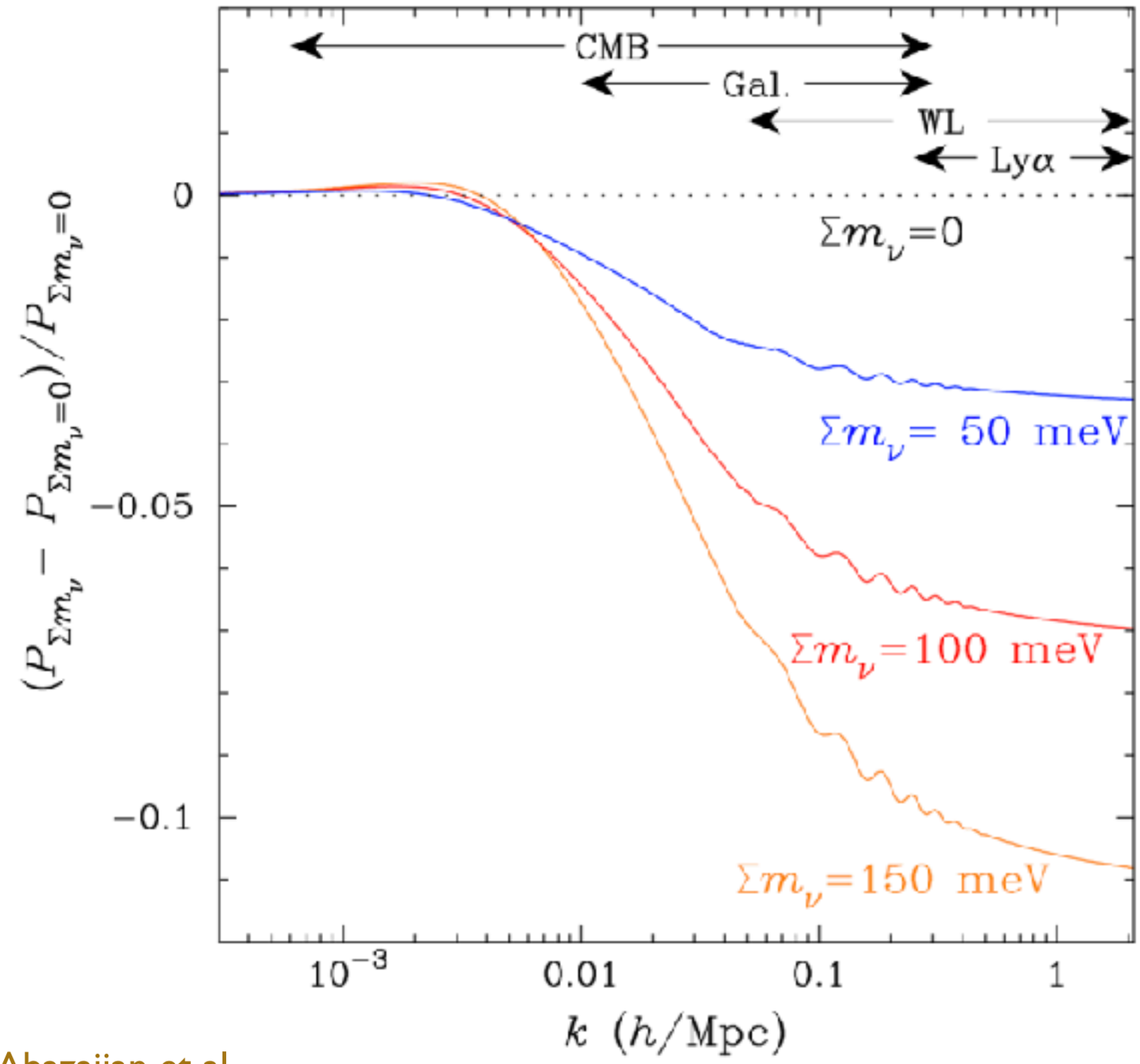

Figure credit: K. N. Abazajian et al

Neutrino Mass Detection

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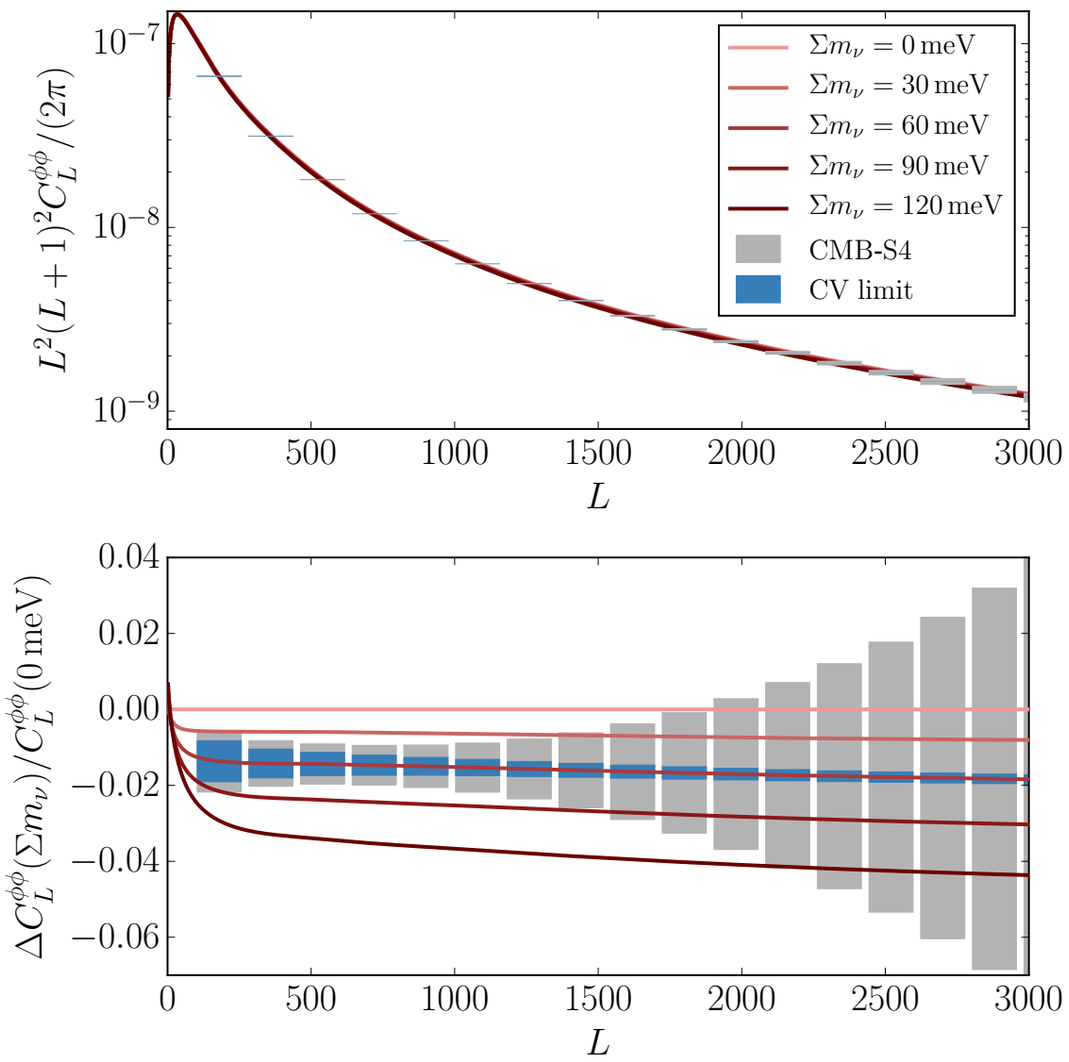

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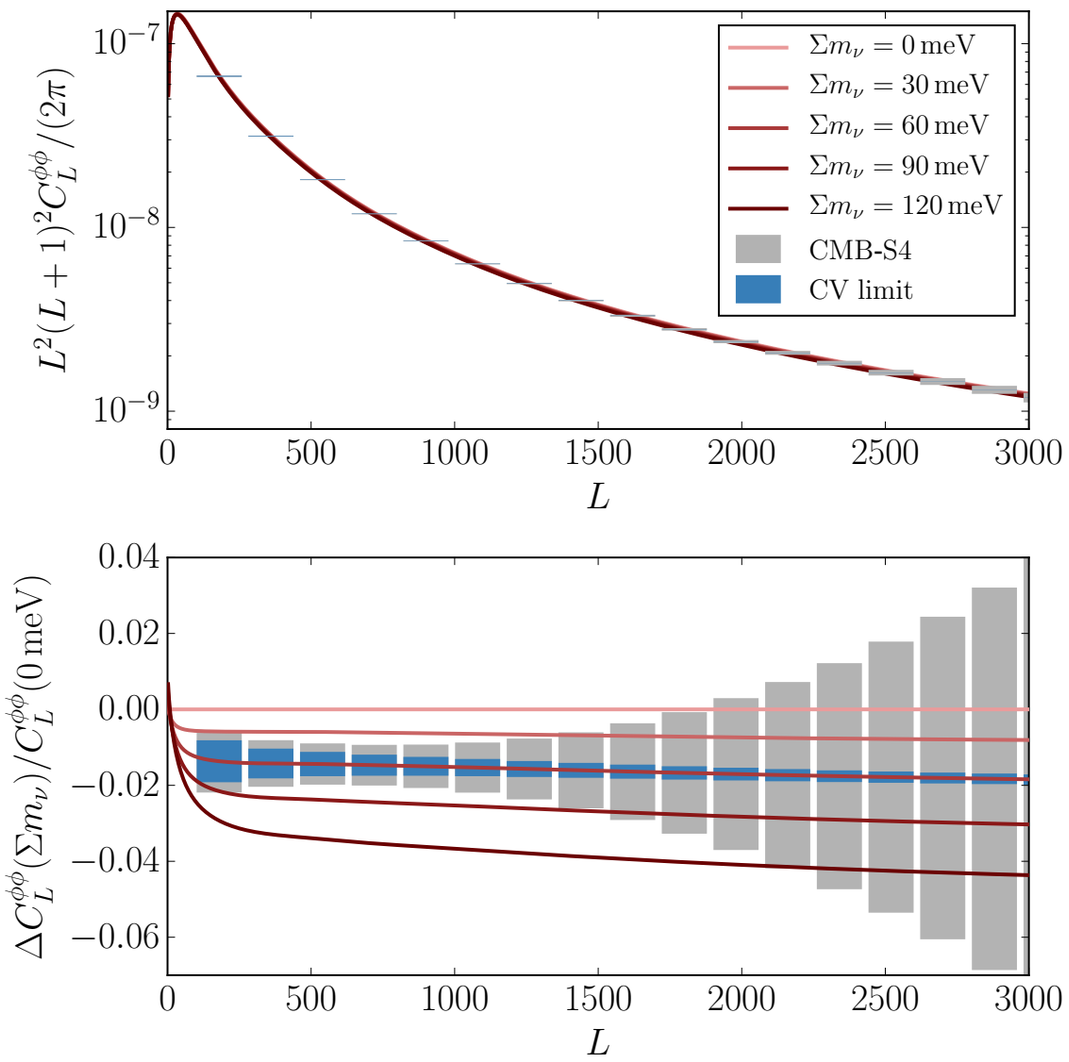

$$\sigma(\sum m_\nu) < 20 \ \ \text{meV}$$

At least 3-sigma detection with BAO and tau prior

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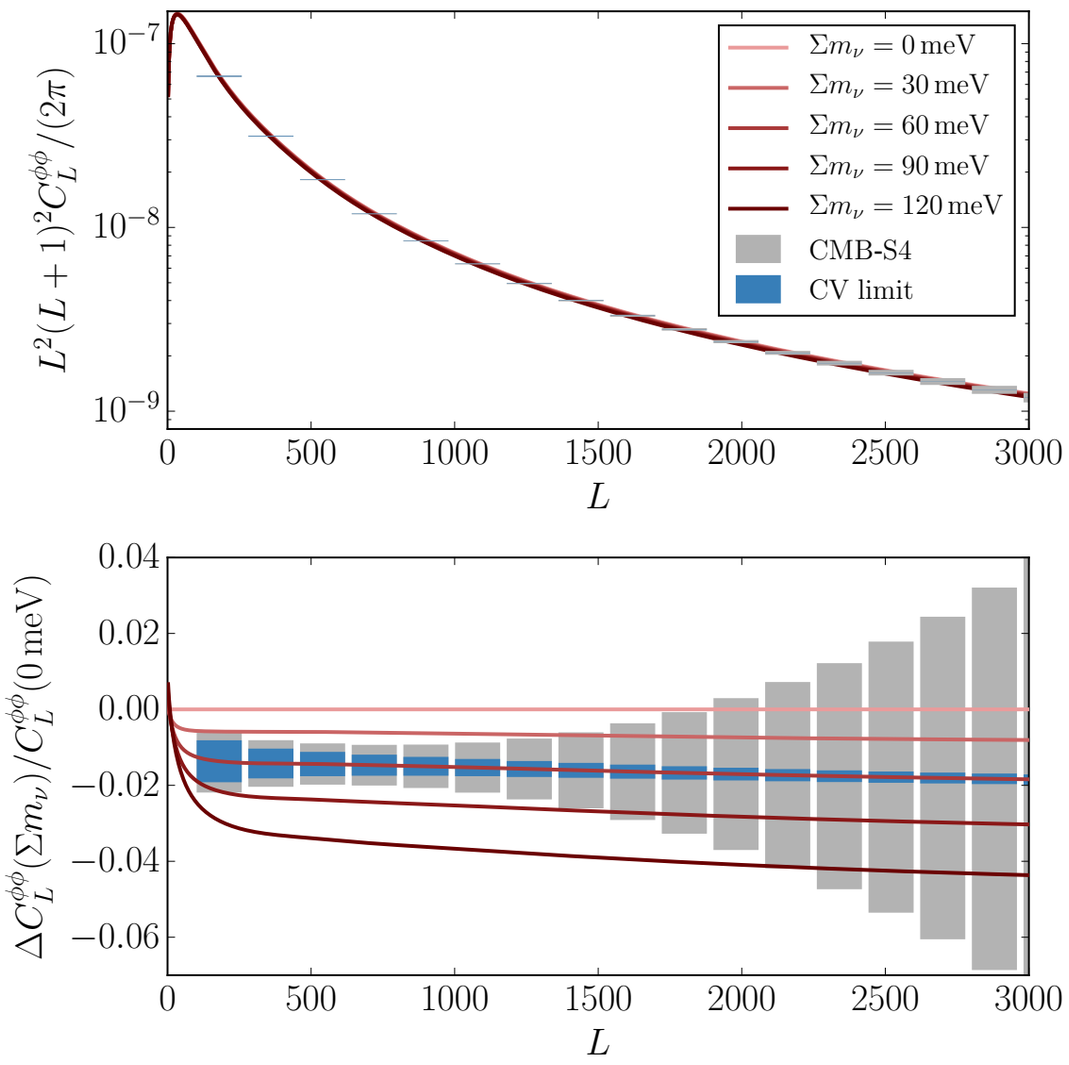
Neutrino Mass Detection



Recall:

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

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

At least 3-sigma detection with BAO and tau prior

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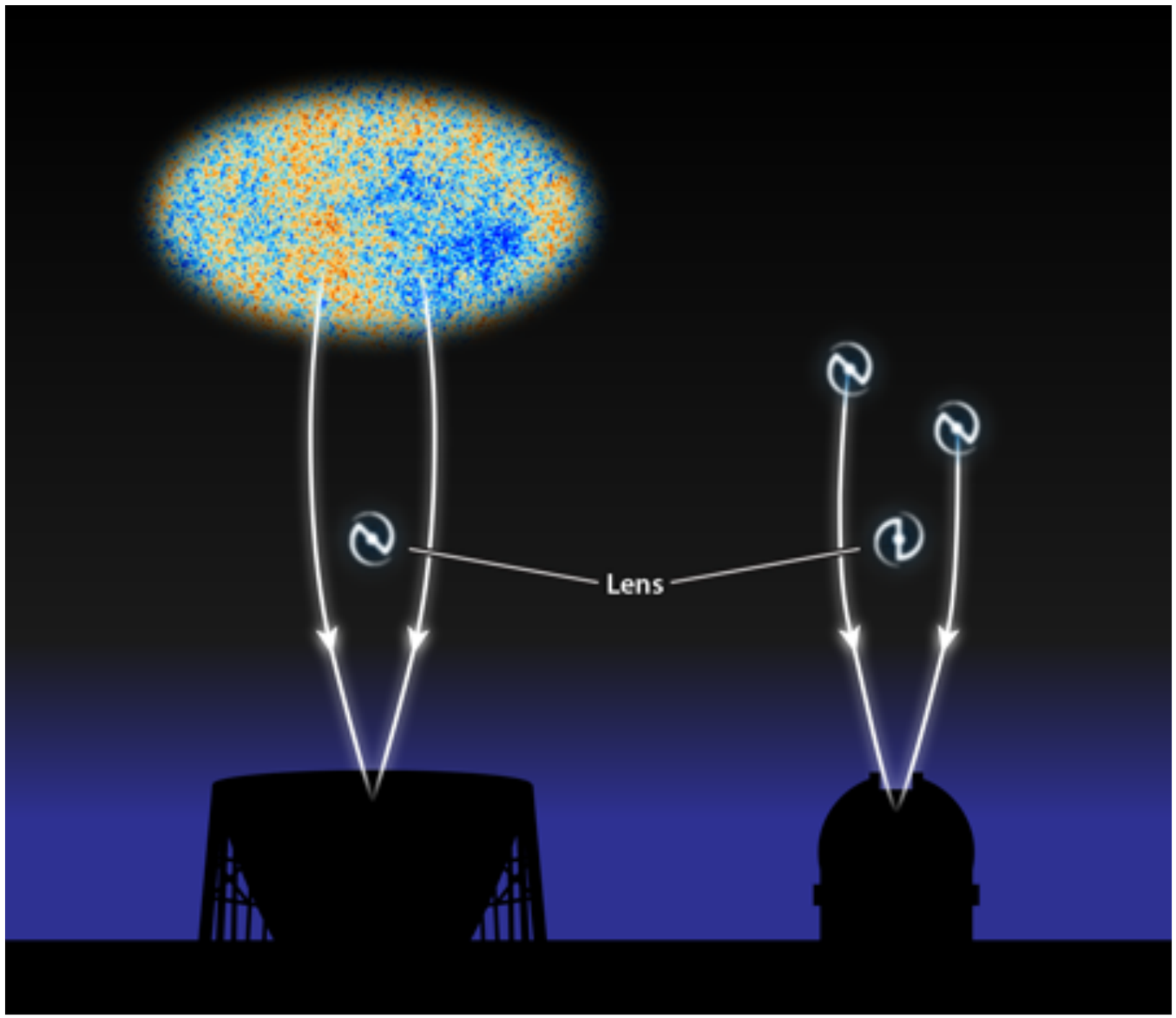
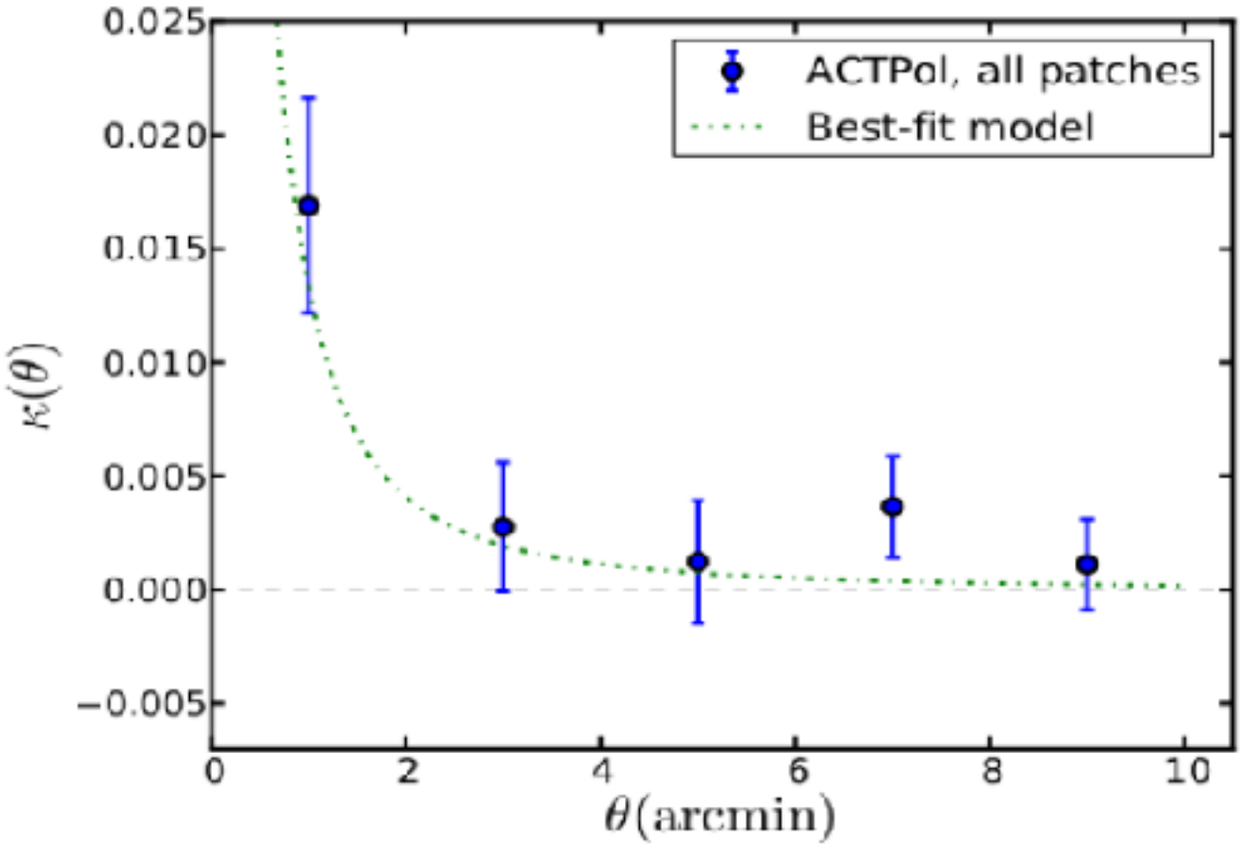
First Measurements of CMB Lensing on Small Scales

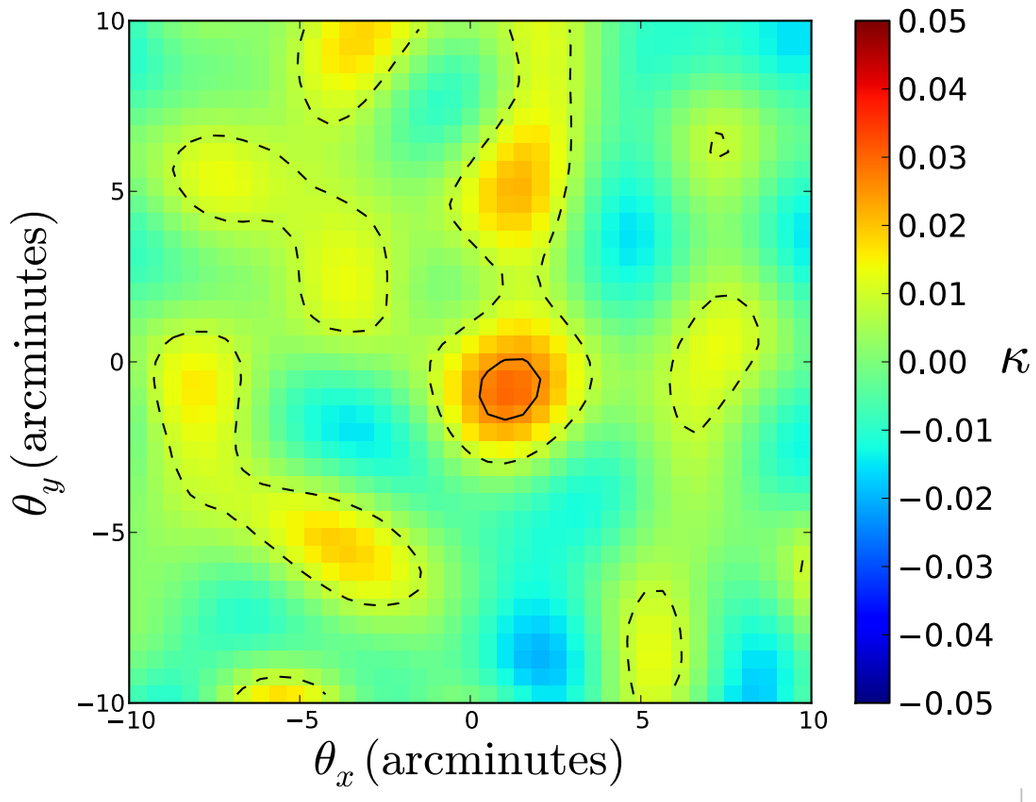


APS/**Alan Stonebraker**

First Measurements of CMB Lensing on Small Scales

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

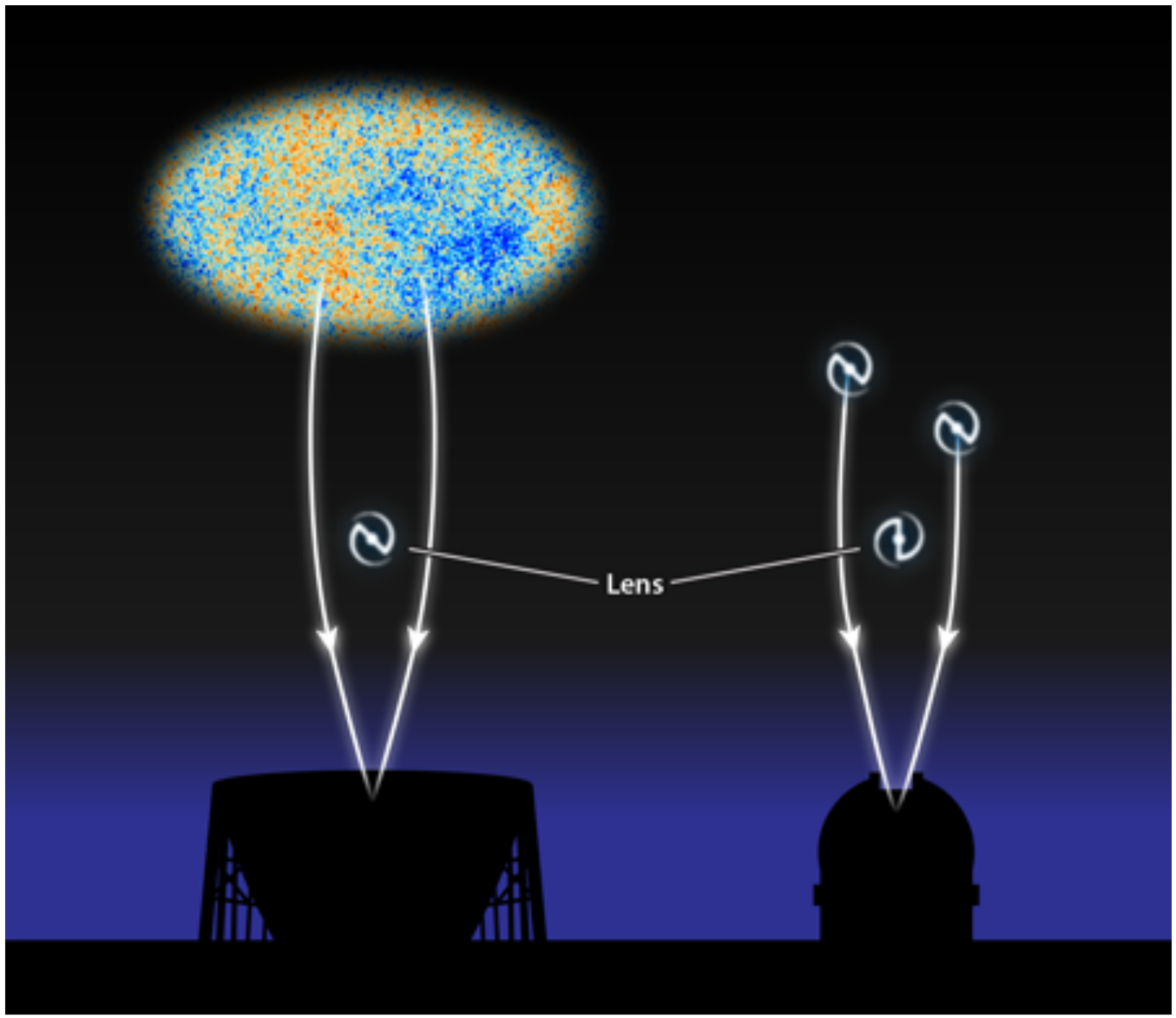




We detect halo lensing from 12,000 stacked CMASS galaxies at S/N of 3.2 sigma

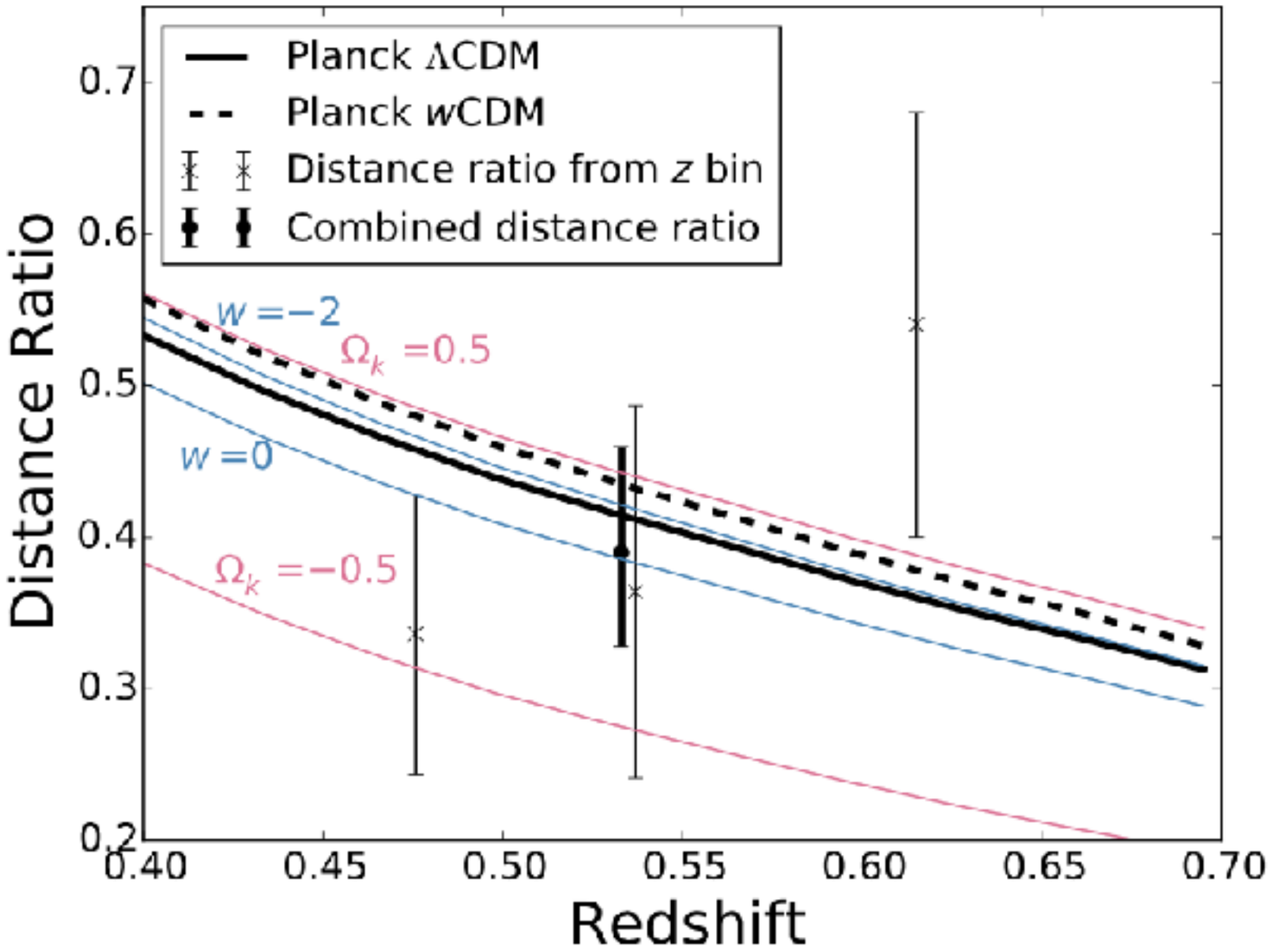
Best fit: $M_{200} = (2.0 \pm 0.7) \times 10^{13} h^{-1} M_\odot$ and $c_{200} = 5.4 \pm 0.8$

Can Take Ratio of Two Lensing Measurements



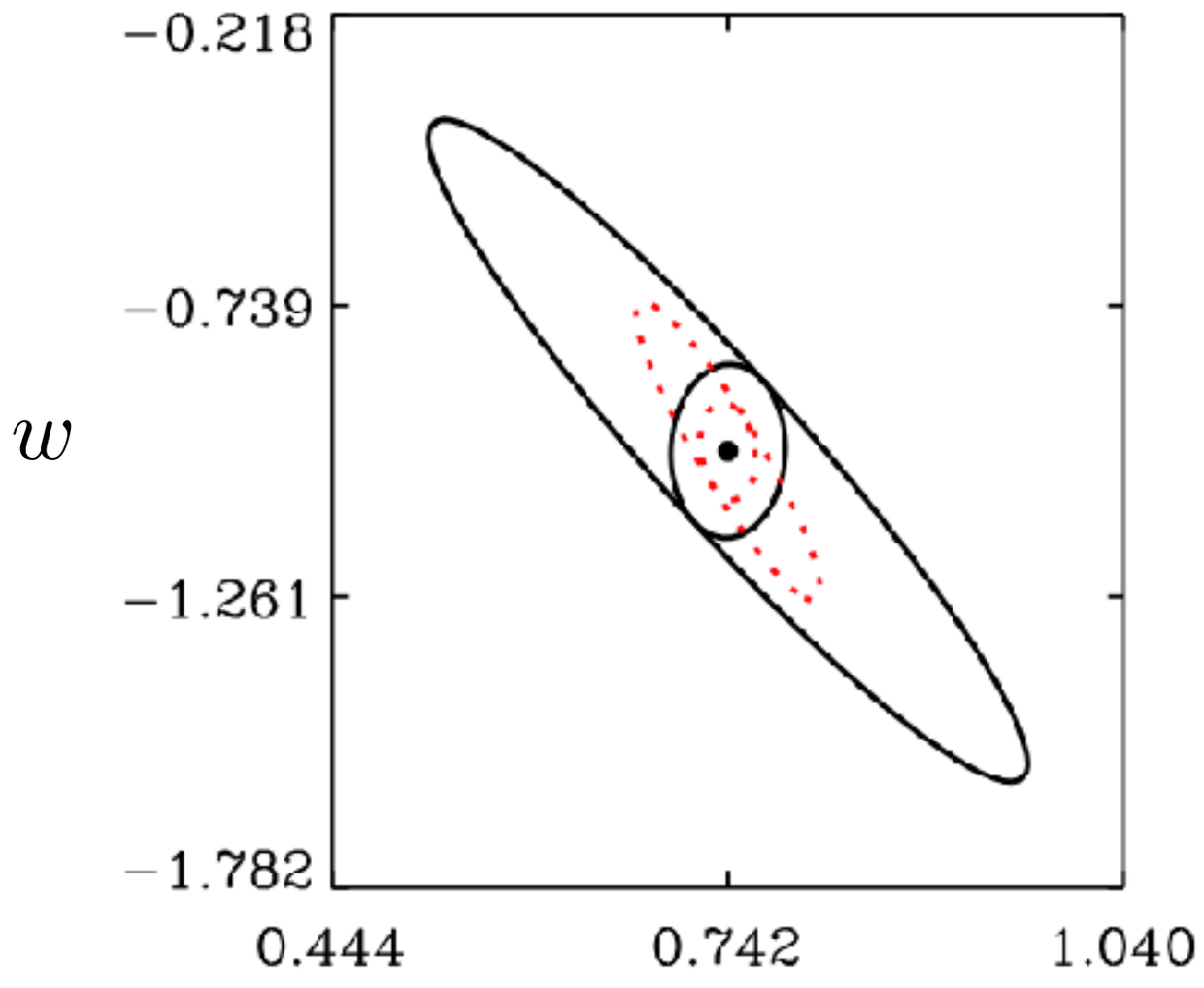
APS/**Alan Stonebraker**

First Measurement of Ratio of Optical Lensing to CMB Lensing



Miyatake, Madhavacheril, NS et al. PRL, 118, 2017

Distance Ratio Forecasts



Das and Spergel 2009

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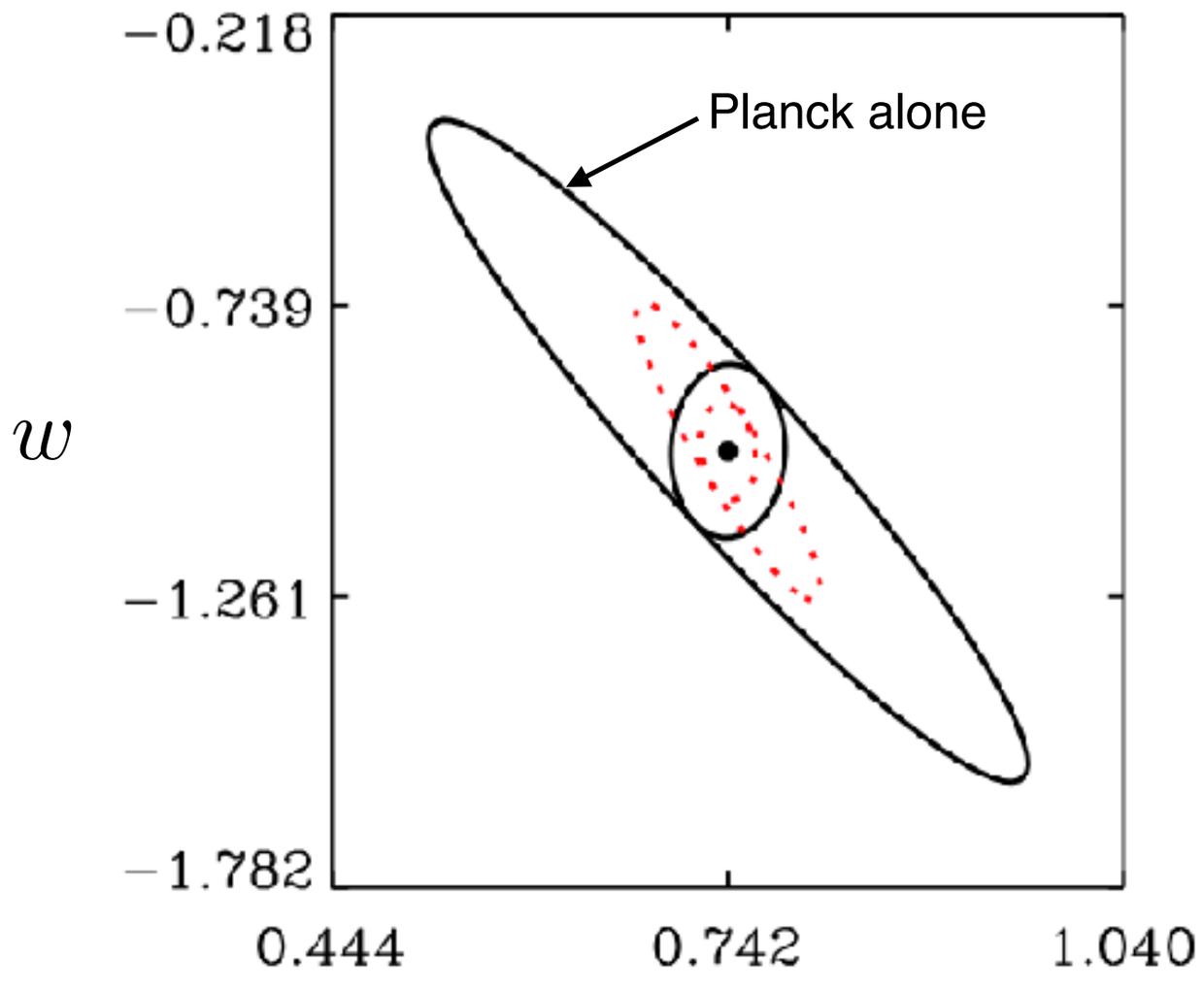

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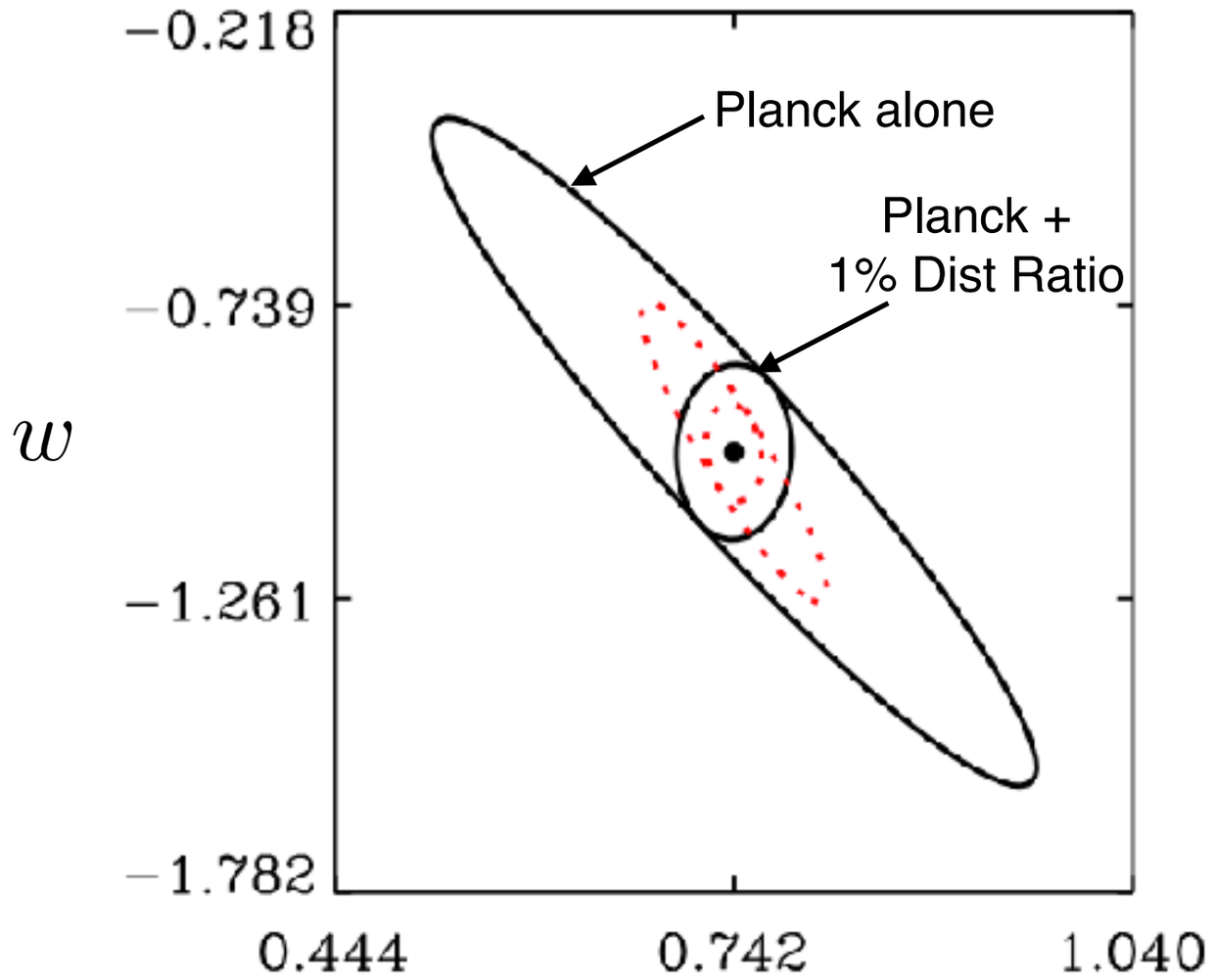

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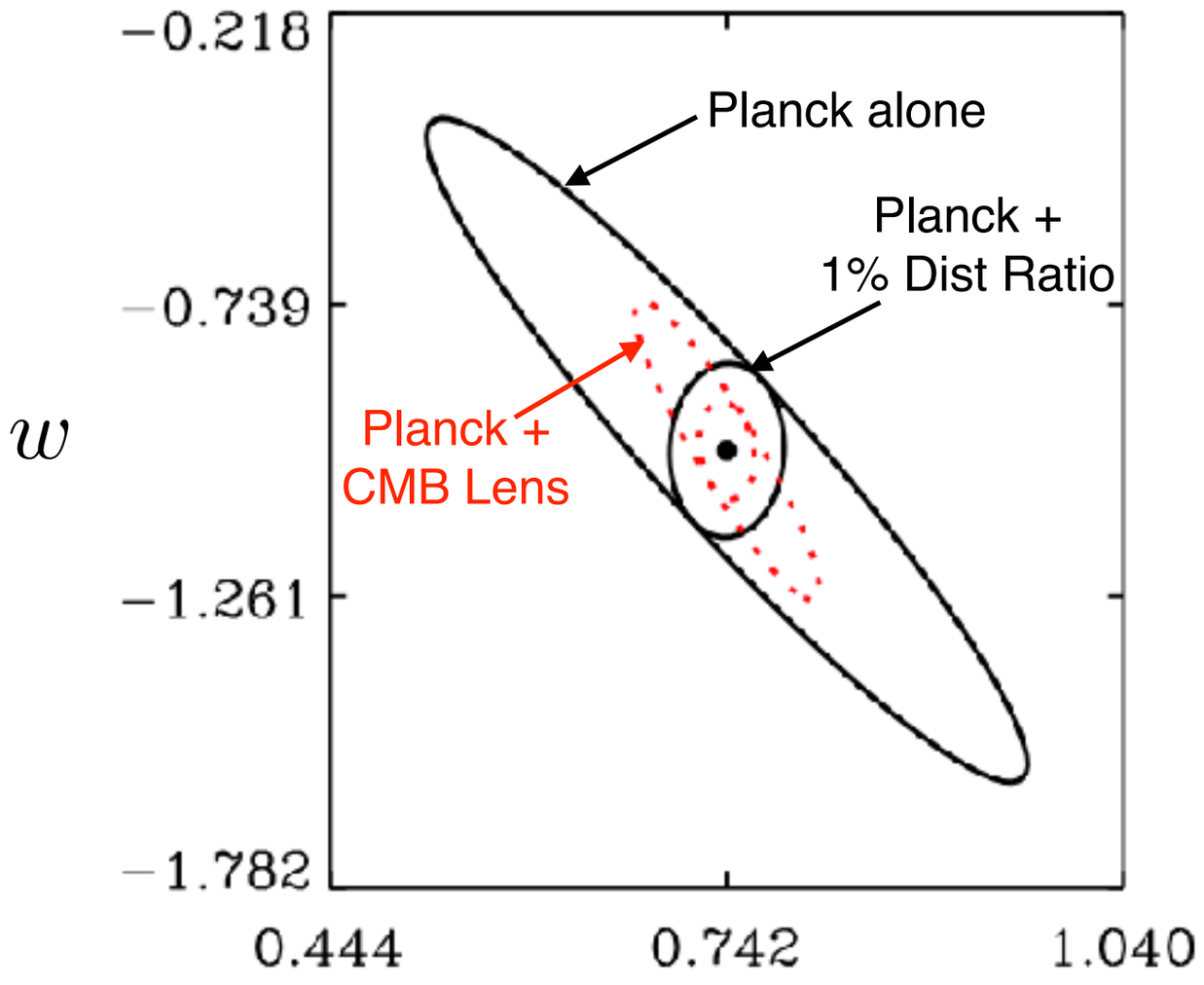

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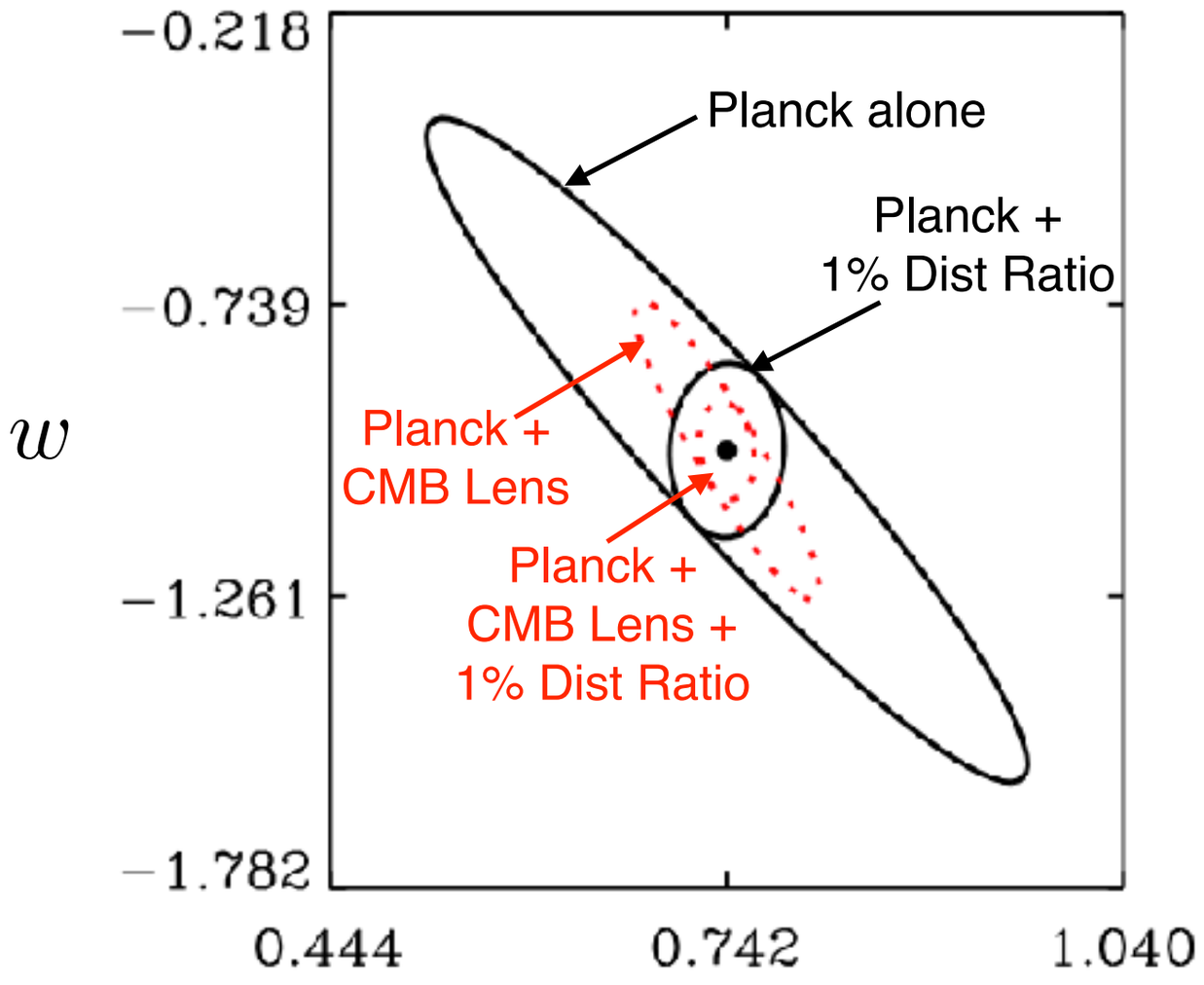

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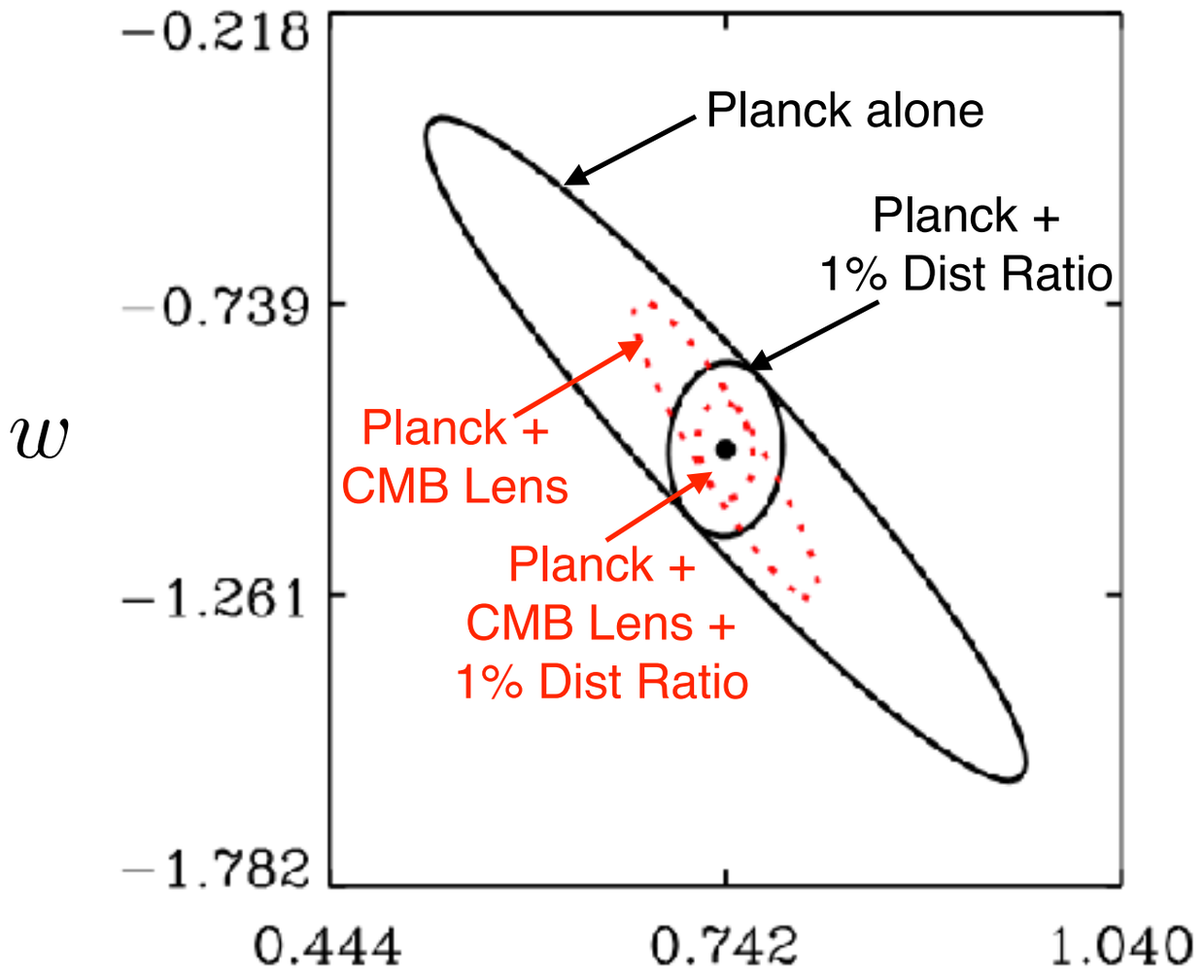

Can achieve 1% distance ratio with CMB-S4 + LSST

Das and Spergel 2009

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History of the Universe

Inflation generates gravitational waves

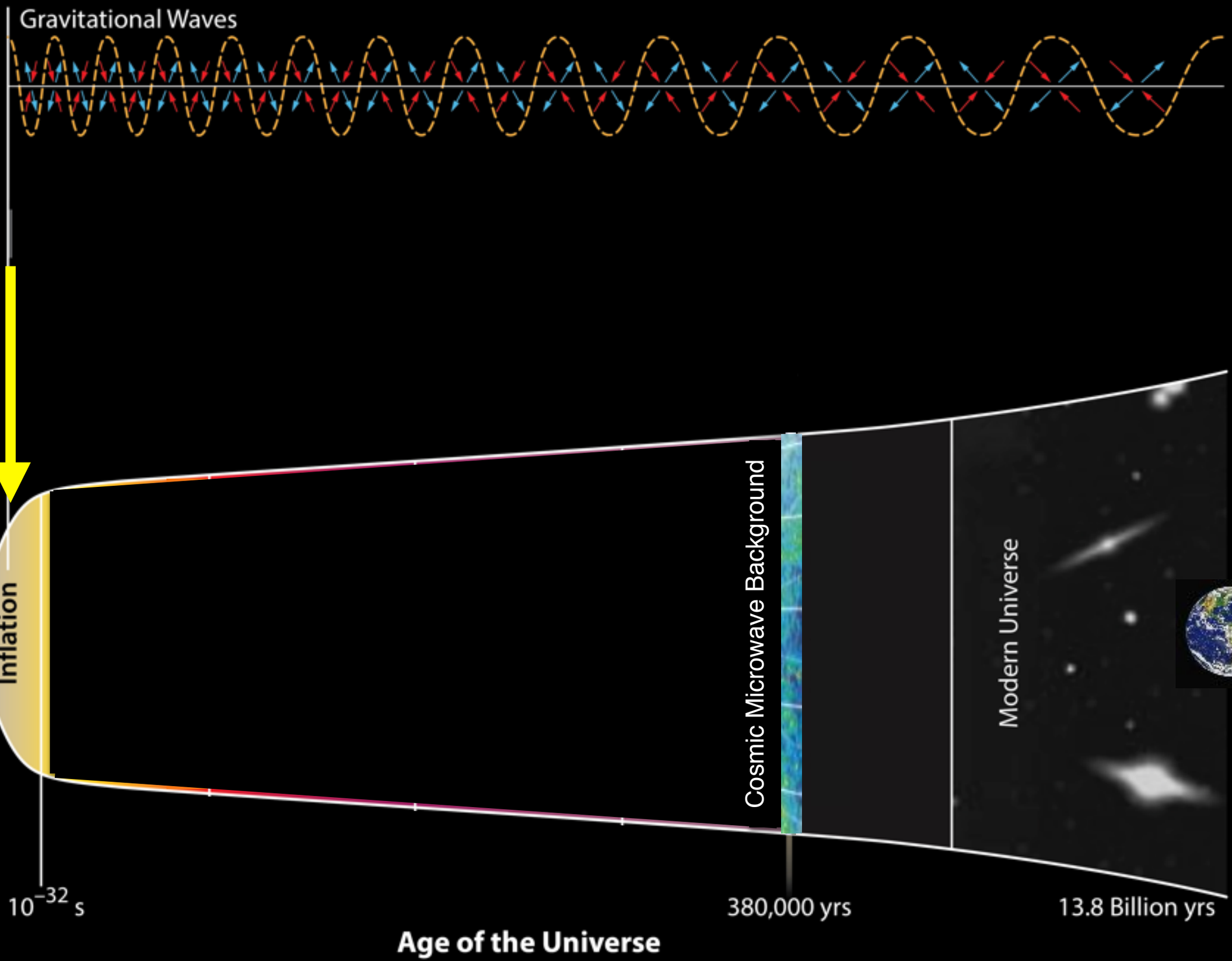

Figure Credit: BICEP2

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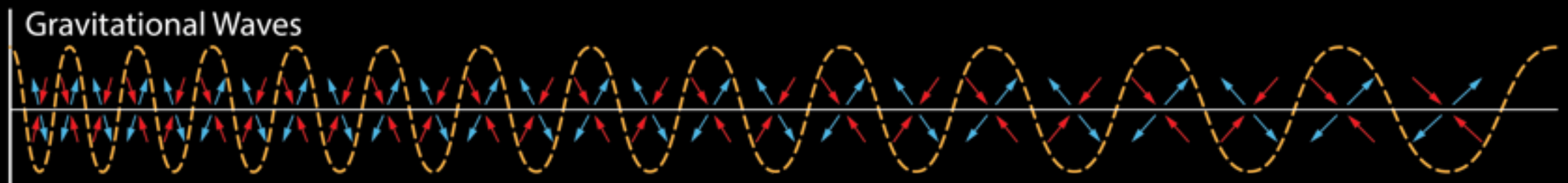
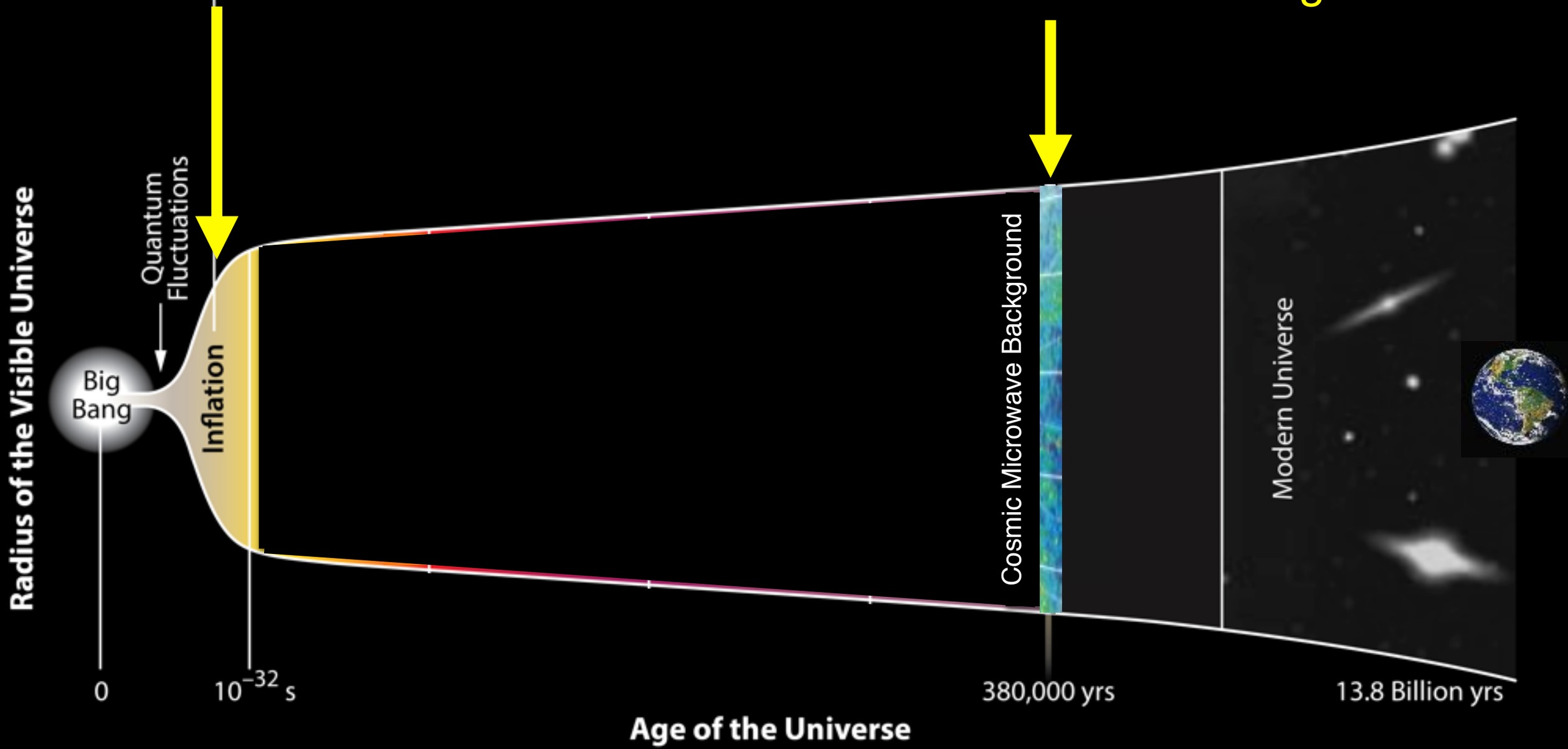


Gravitational Waves from Inflation Imprint Swirly Pattern in Cosmic Microwave Background



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History of the Universe

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Gravitational Waves

Gravitational Waves from Inflation Imprint Swirly Pattern in Cosmic Microwave Background

Radius of the Visible Universe

Quantum Fluctuations

Big Bang

Inflation

Cosmic Microwave Background

Modern Universe

0

10^{-32} s

380,000 yrs

13.8 Billion yrs

Age of the Universe

Figure Credit: BICEP2

Inflation Predicts Gravitational Waves

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Inflation Predicts Gravitational Waves

- Amplitude of gravitational waves determines energy scale when inflation happened

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- Amplitude of gravitational waves determines energy scale when inflation happened

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

Inflation Predicts Gravitational Waves

- Amplitude of gravitational waves 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 - a few orders of magnitude below the Planck scale

From Gravitational Waves to CMB Polarization

Figure Credit: S&T: Leah Tiscione

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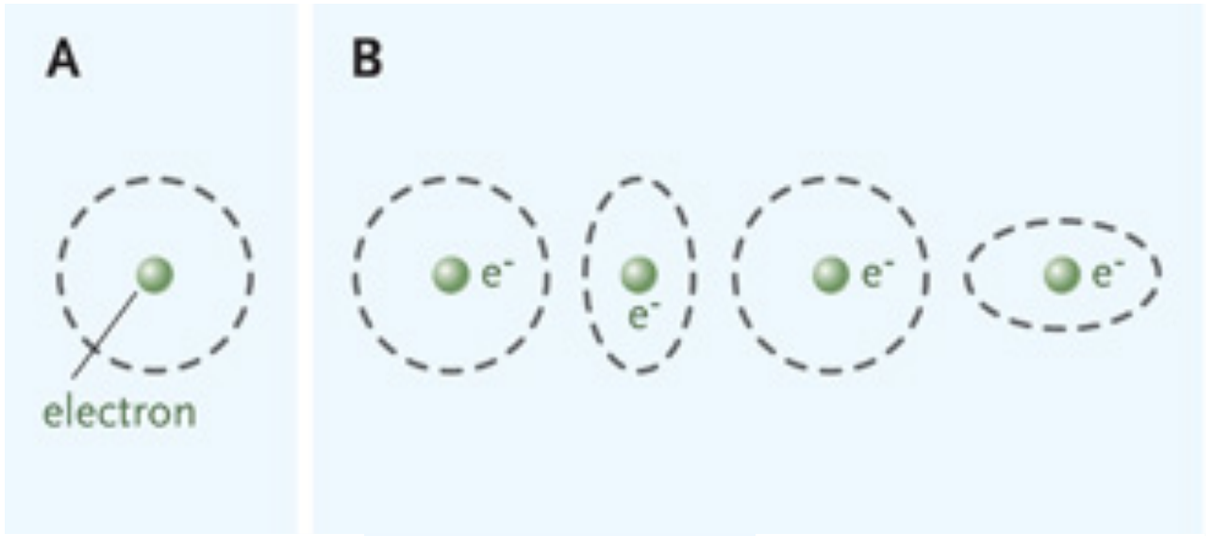

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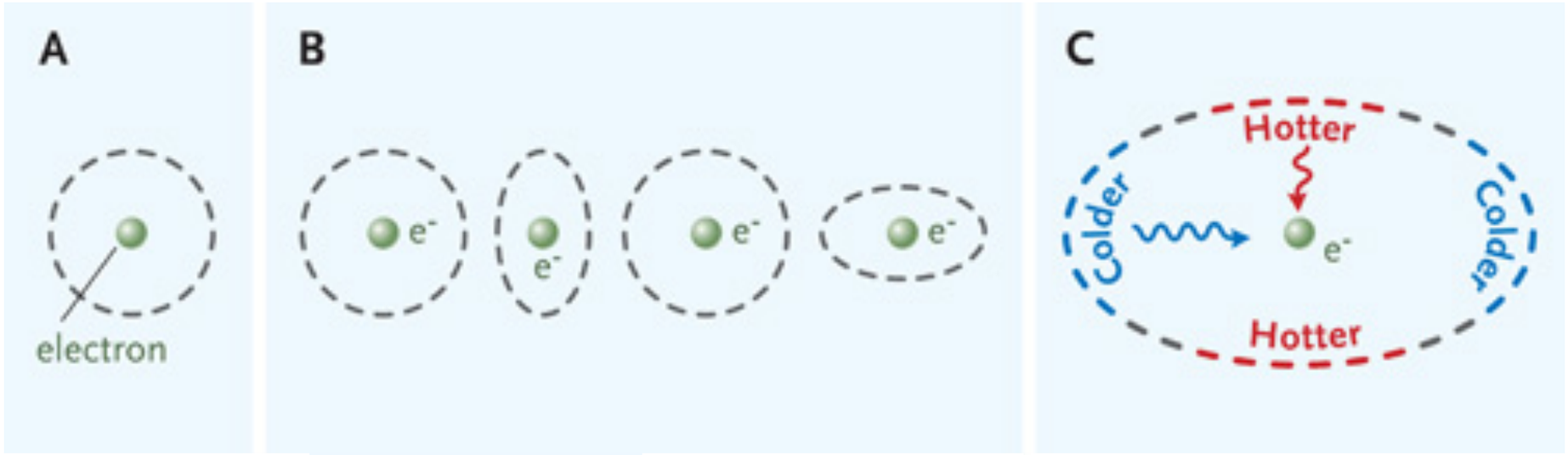

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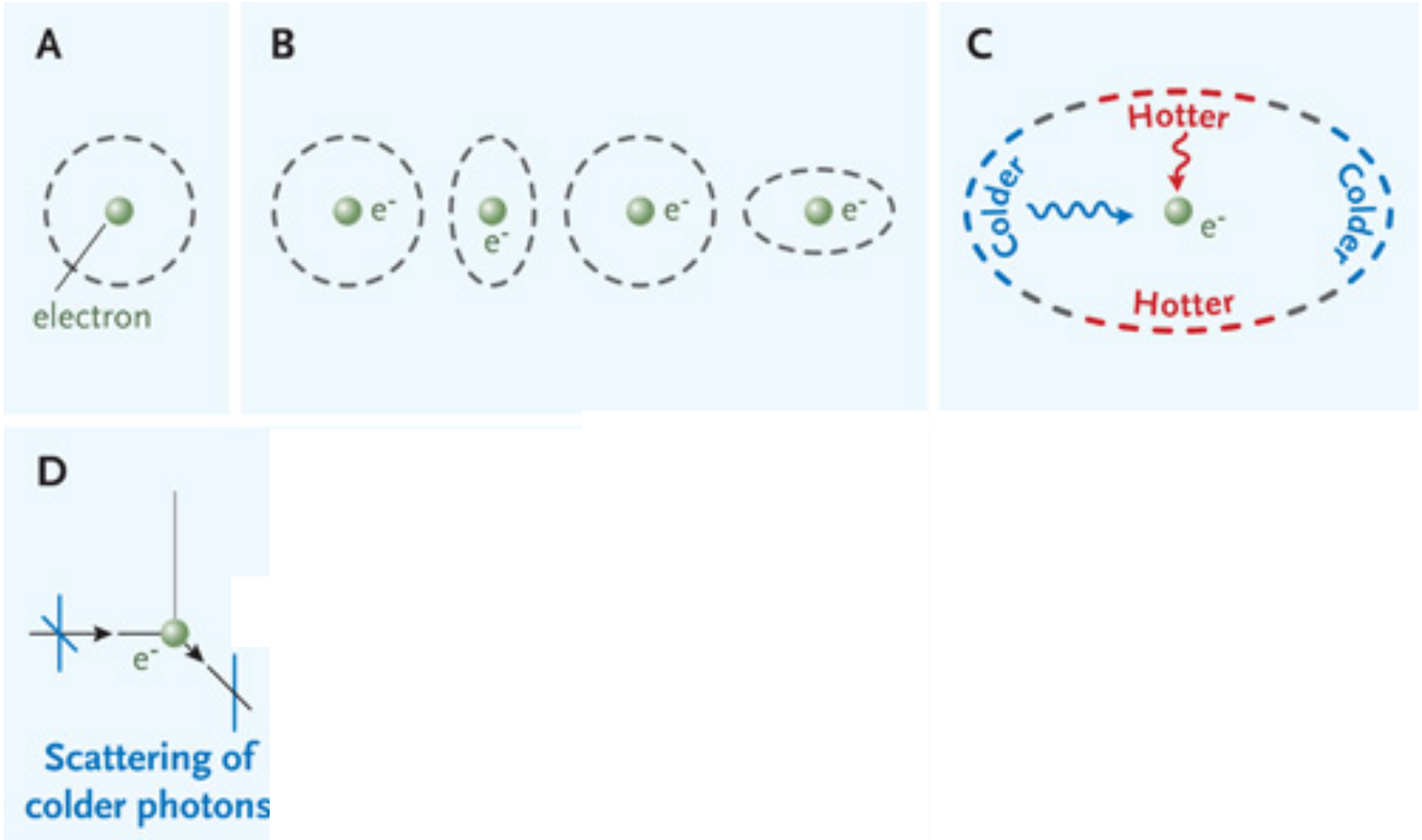

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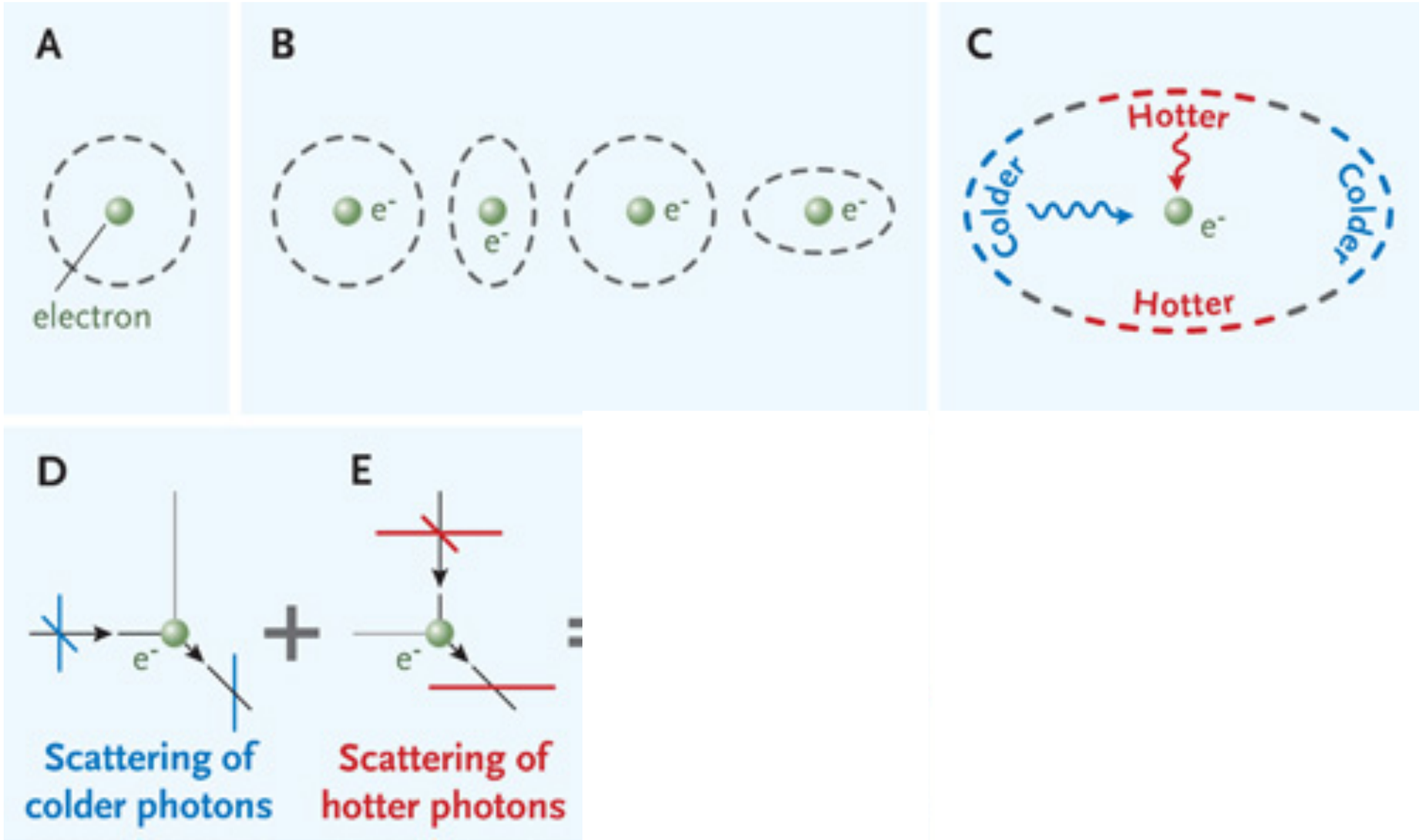

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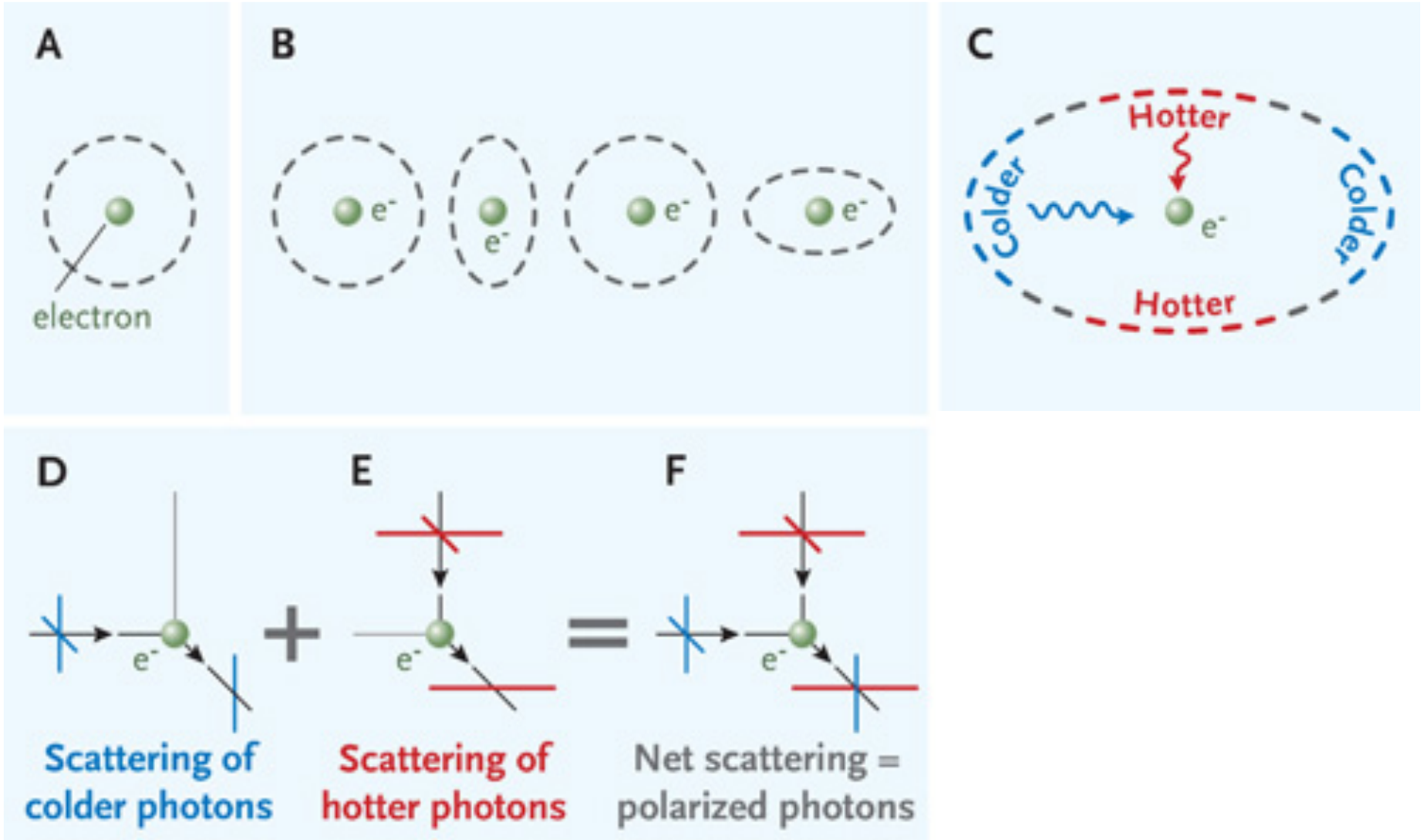


Figure Credit: S&T: Leah Tiscione

From Gravitational Waves to CMB Polarization

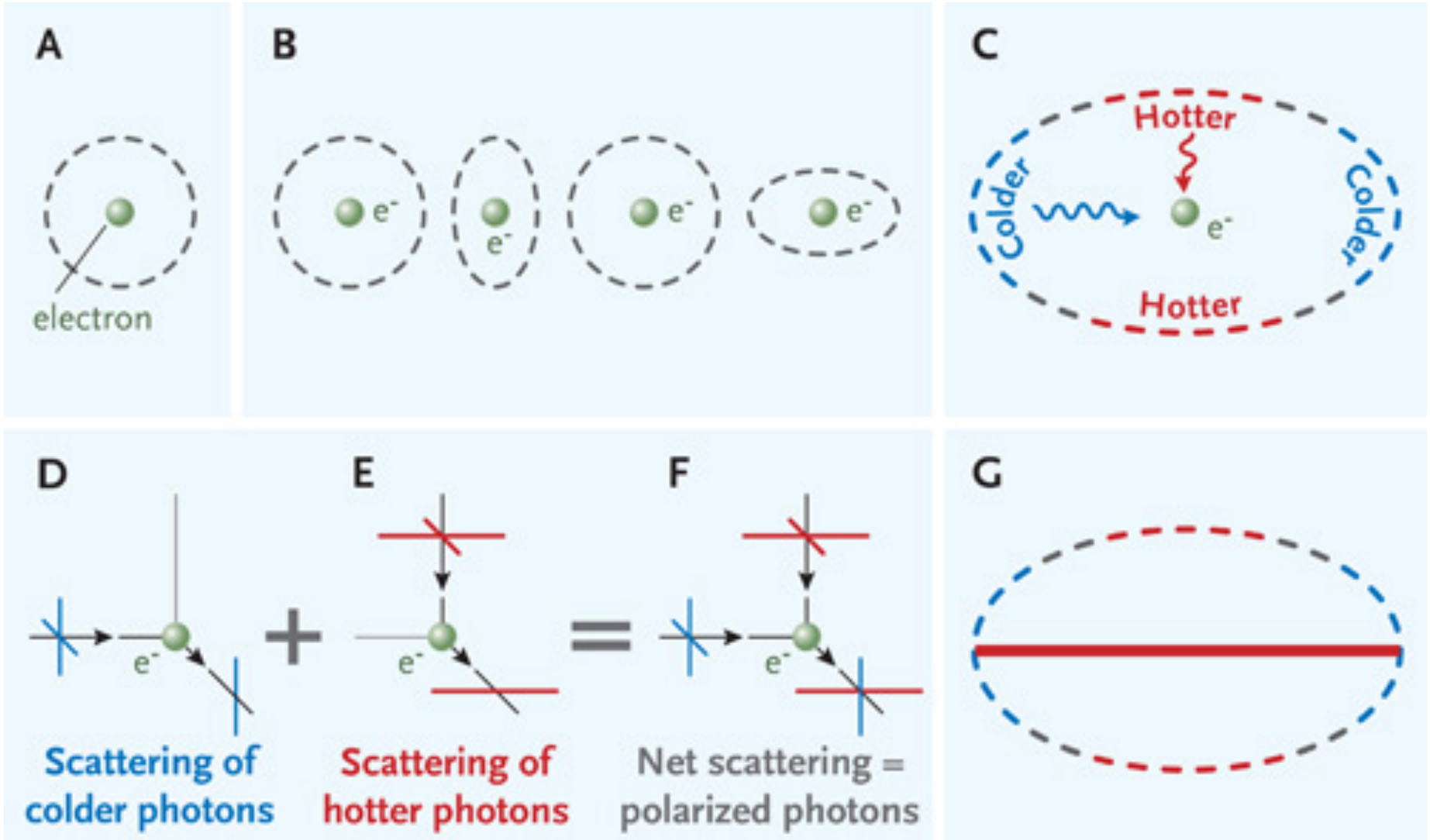
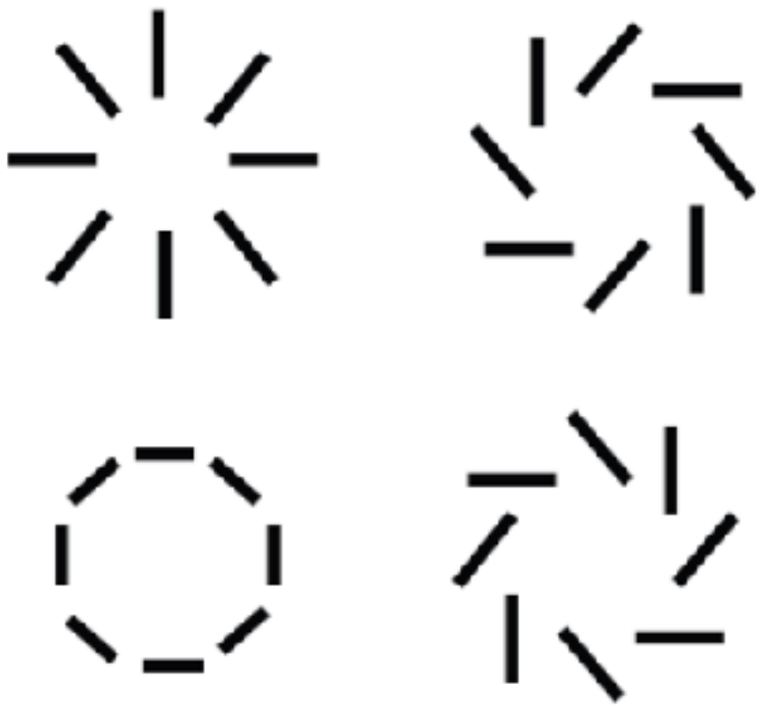


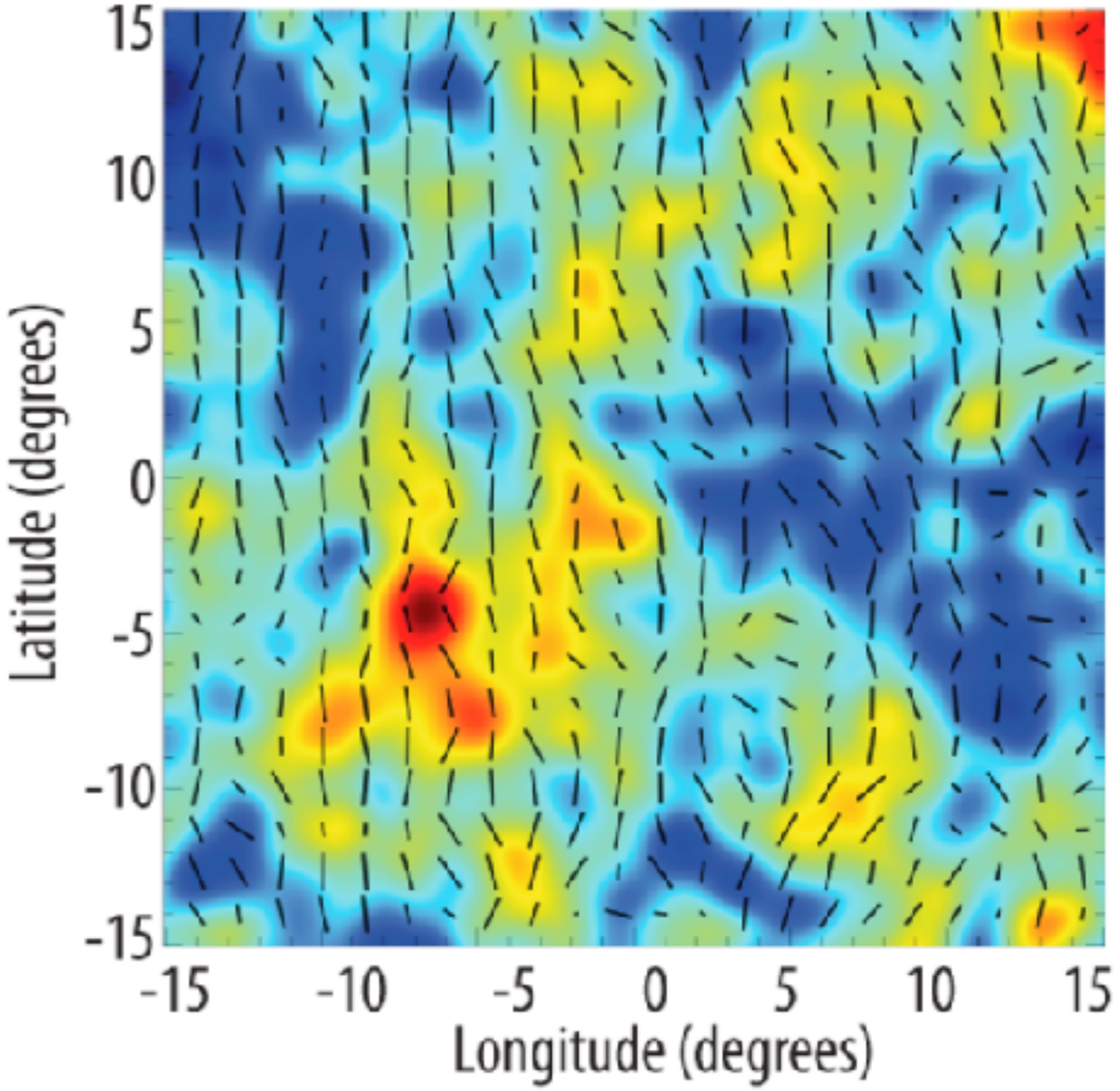
Figure Credit: S&T: Leah Tiscione

CMB Polarization

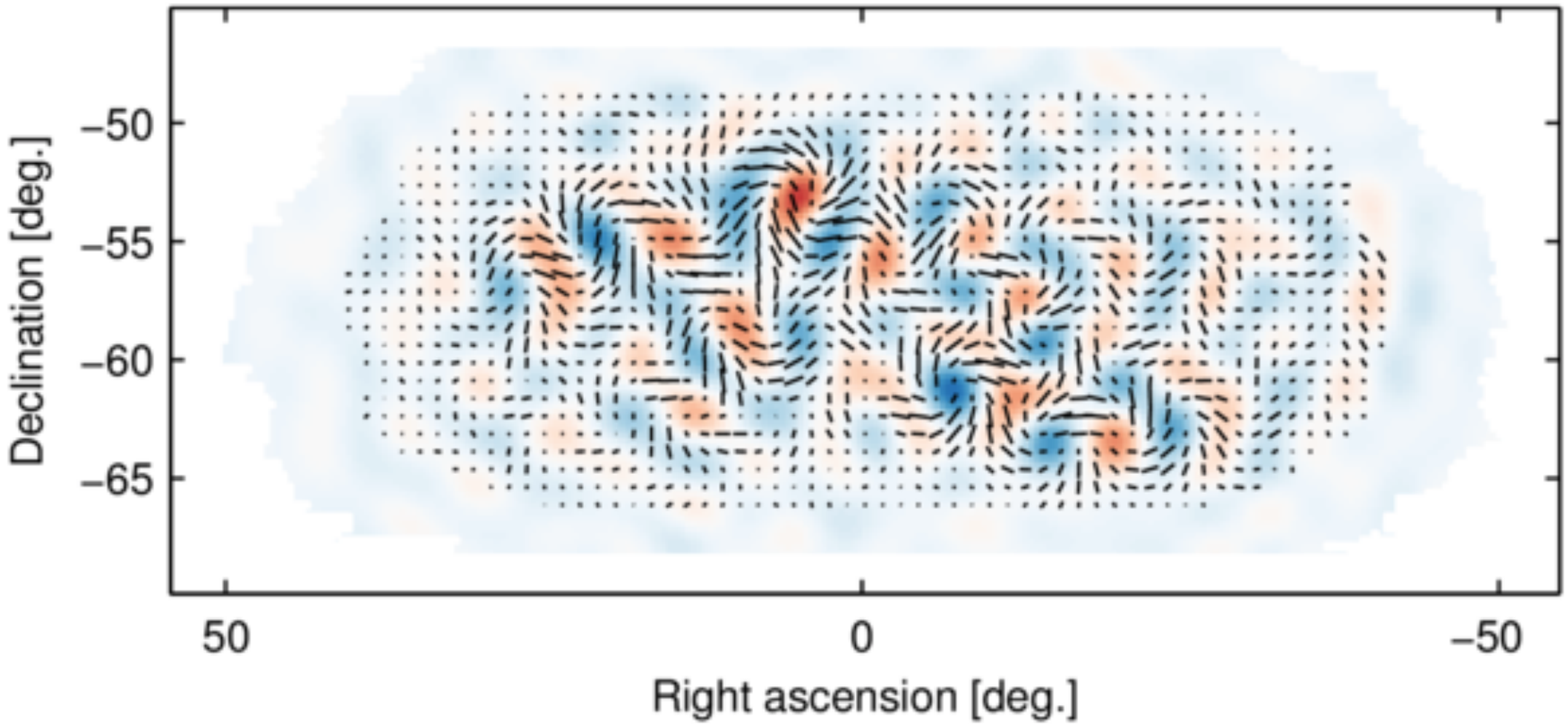


E-Modes
have no handedness

B-Modes
have handedness i.e. rotation direction



CMB Polarization from Gravitational Waves



From Lambda website

Polarization pattern from gravitational waves

Effect of Gravitational Lensing

Delensing

Neelima Sehgal, Stony Brook

Delensing

- Delensing = undo the lensing of the primordial CMB

Delensing

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$$T^L(\hat{n}) = T^U(\hat{n} + \nabla\phi(\hat{n}))$$

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Deflection angle

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Projected lensing potential

Deflection angle

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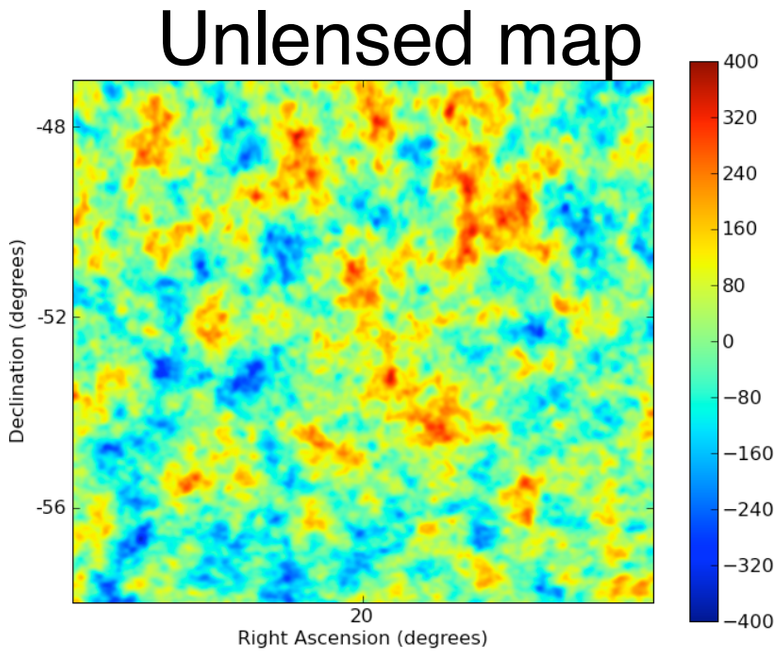

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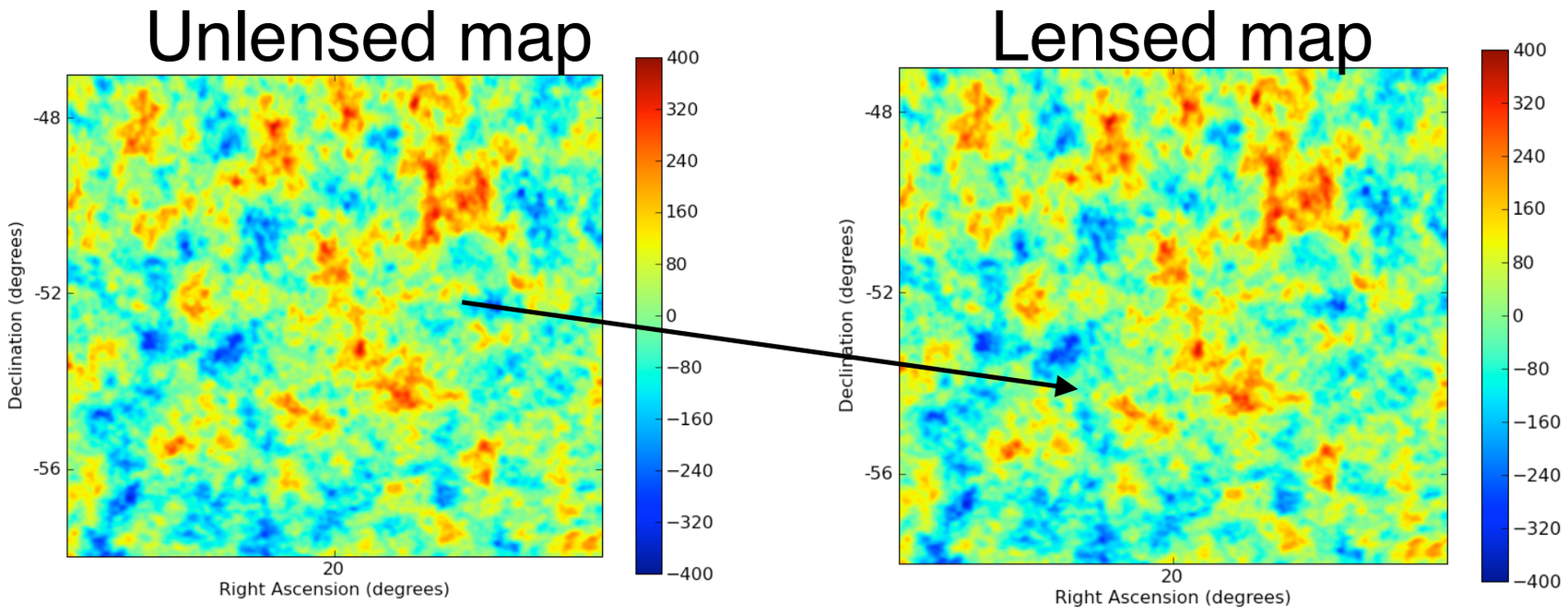

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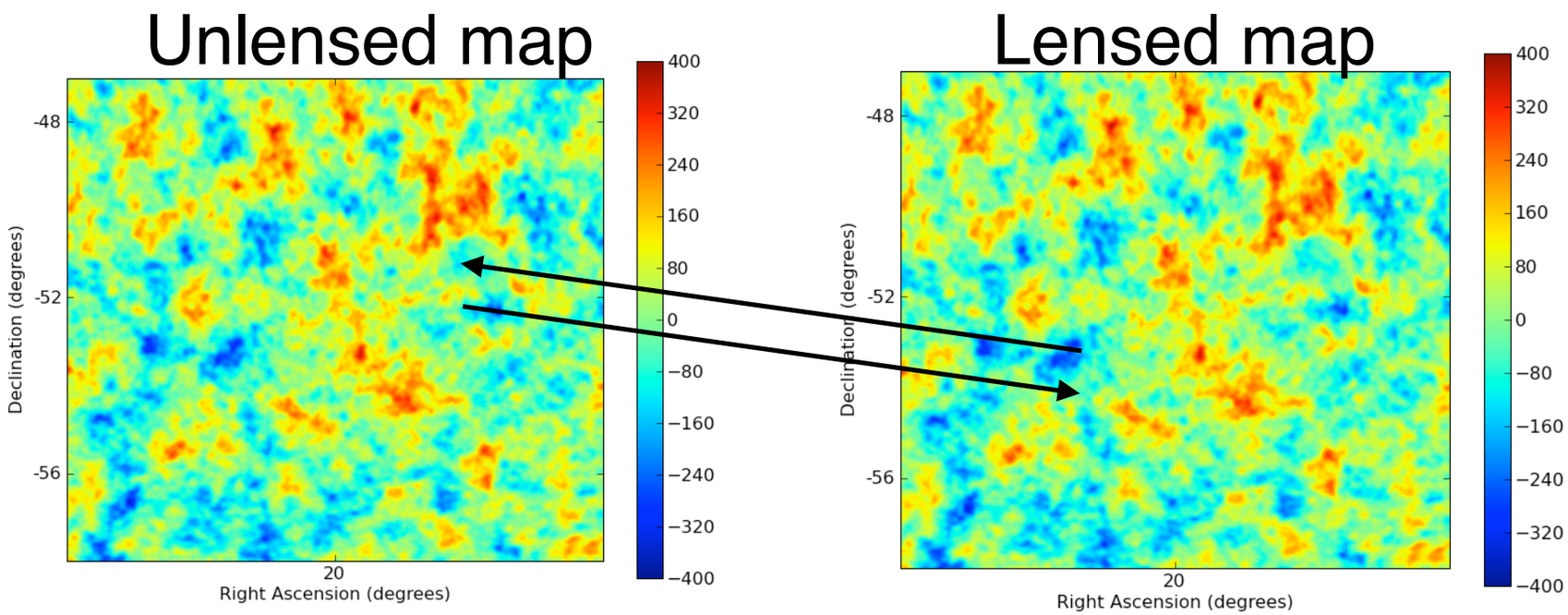


Shift pixels backward using map of projected large-scale structure to reconstruct unlensed CMB

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

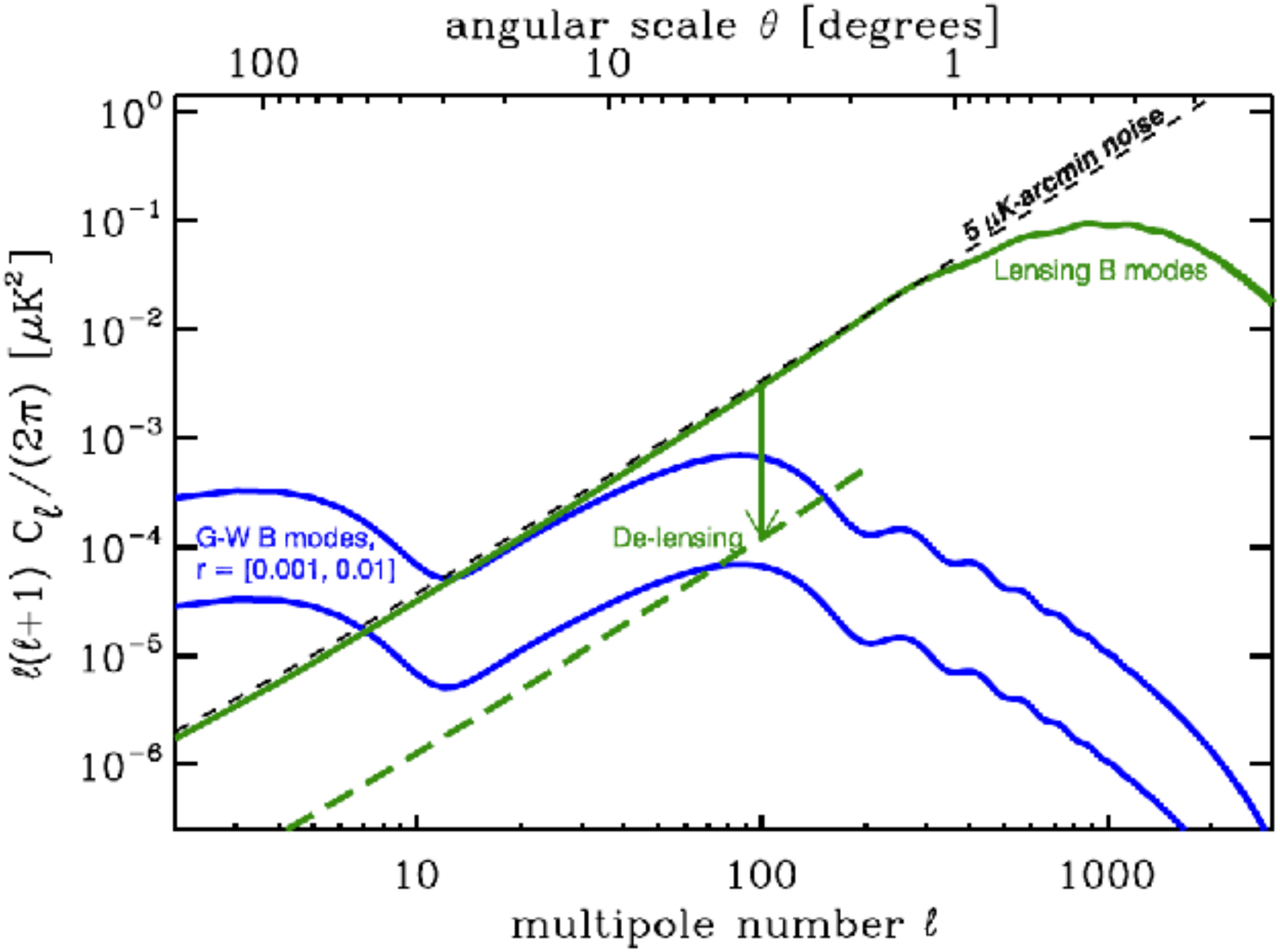
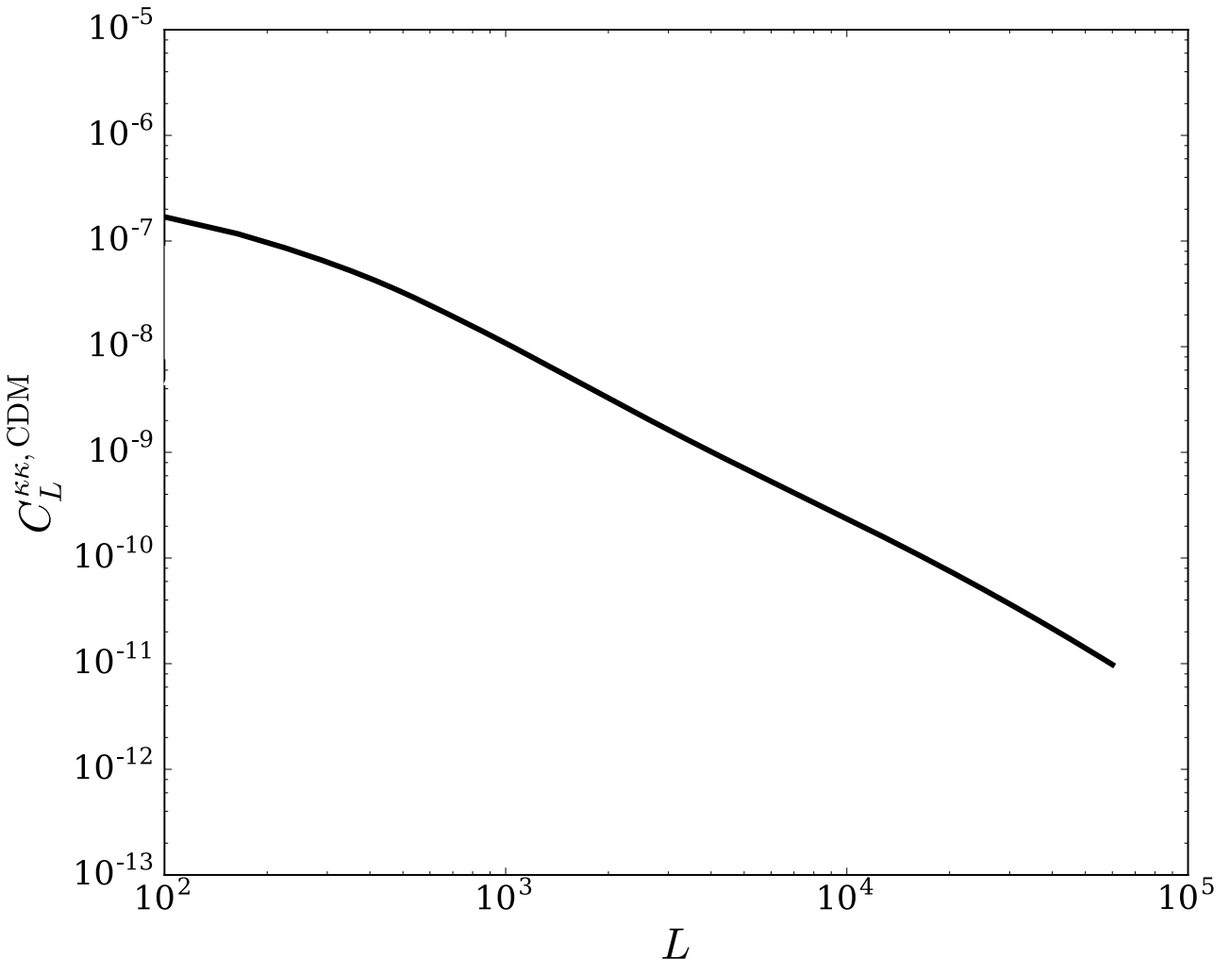


Figure credit: CMB-S4 Science Book

Outline

- Lensing of the Cosmic Microwave Background
- Neutrino Mass (large-scale lensing)
- Curvature, Dark Energy (small-scale lensing)
- Gravitational Waves from Inflation (delensing)
- Dark Matter (ultra-high resolution lensing)

Ultra-High Resolution CMB Lensing



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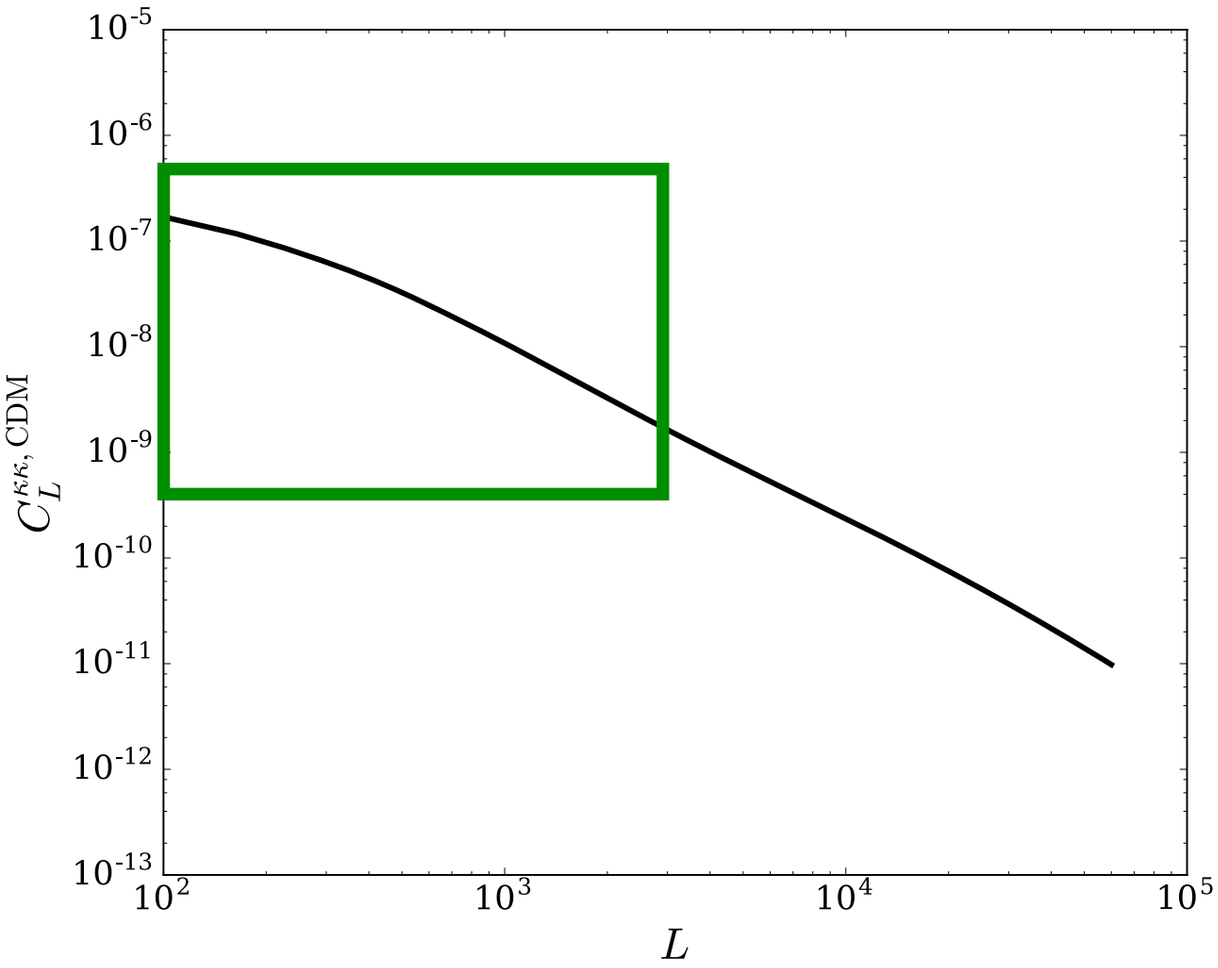

CMB Lensing Power Spectrum measured on scales L < 3000 so far (k < 1 Mpc^-1)

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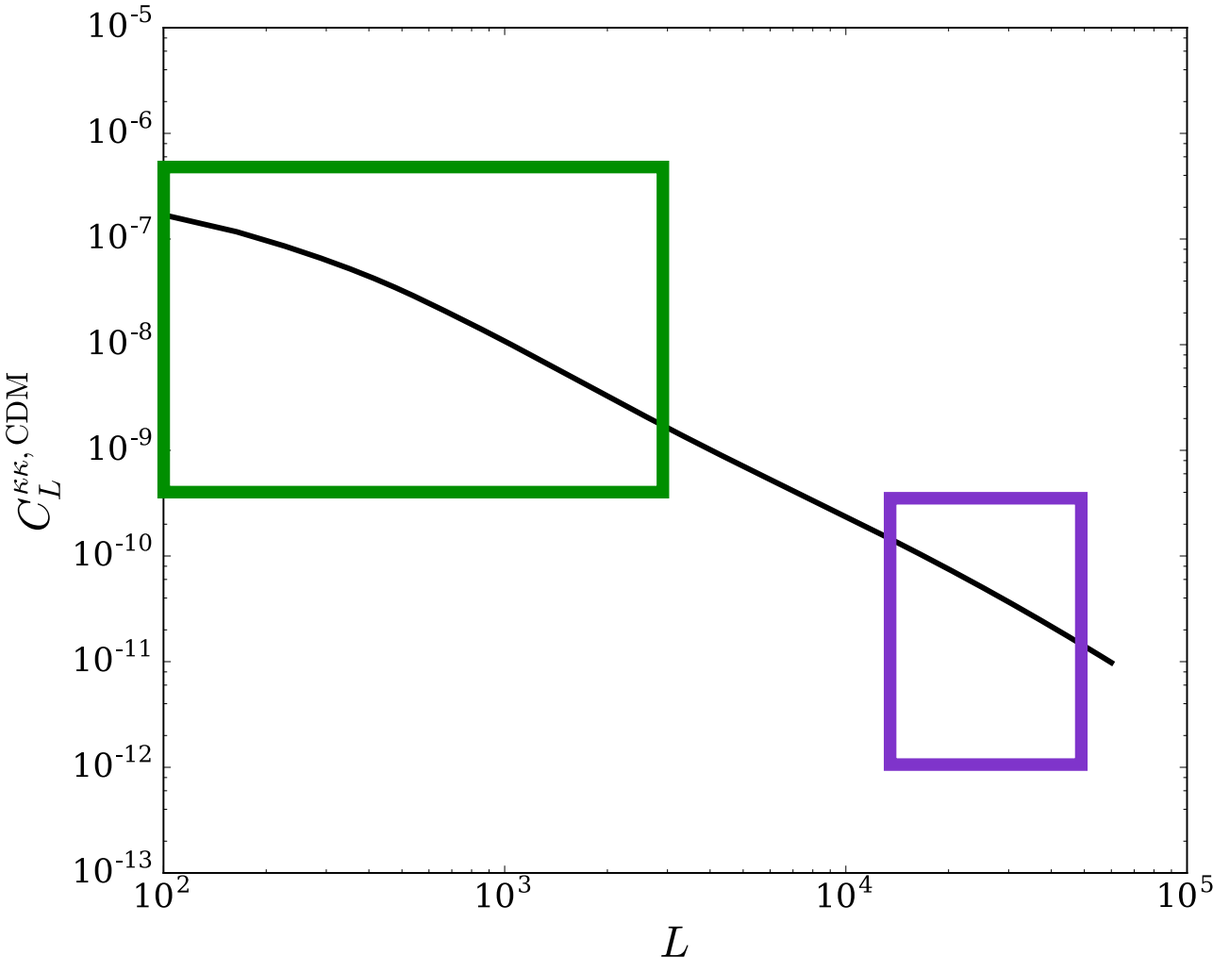

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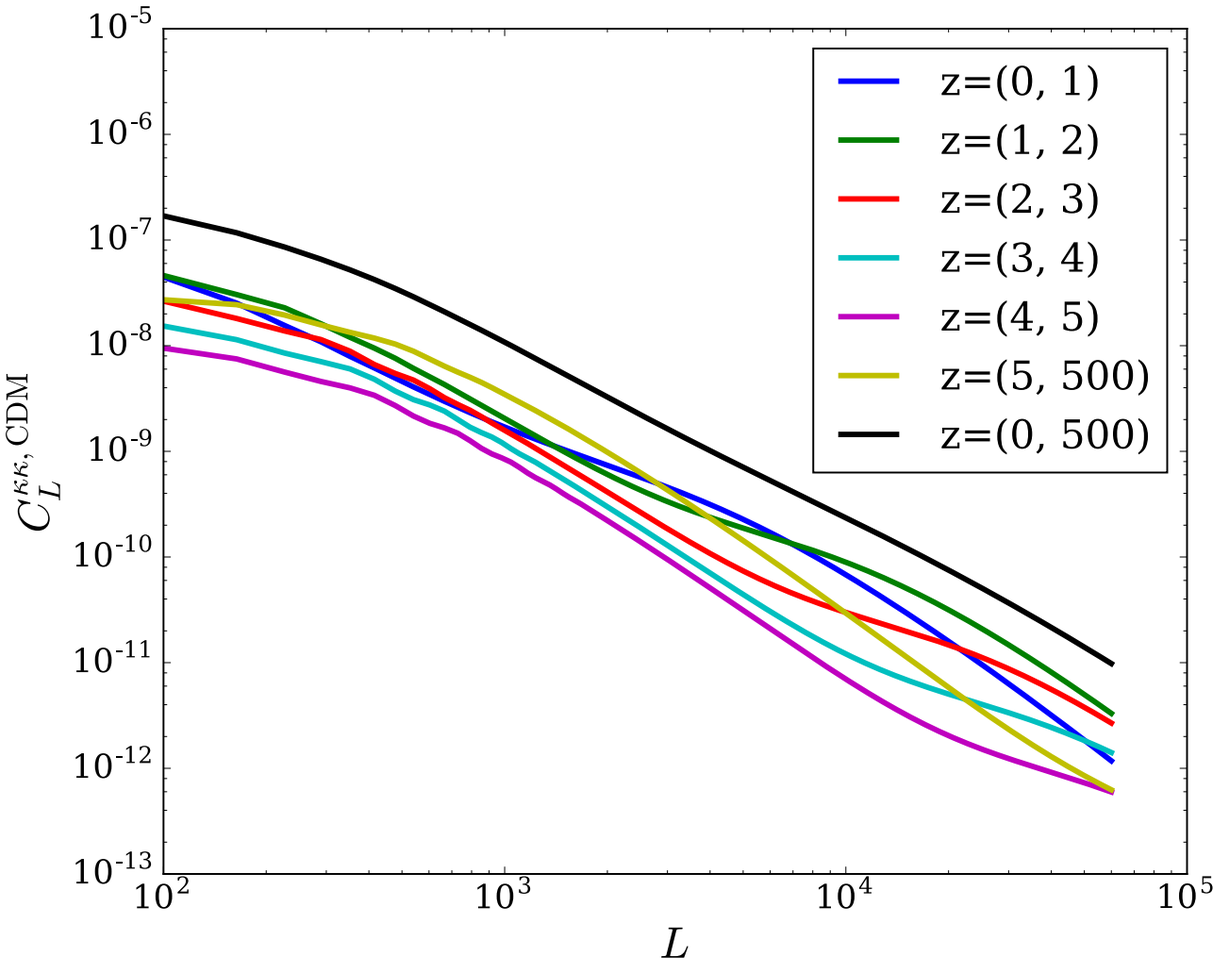

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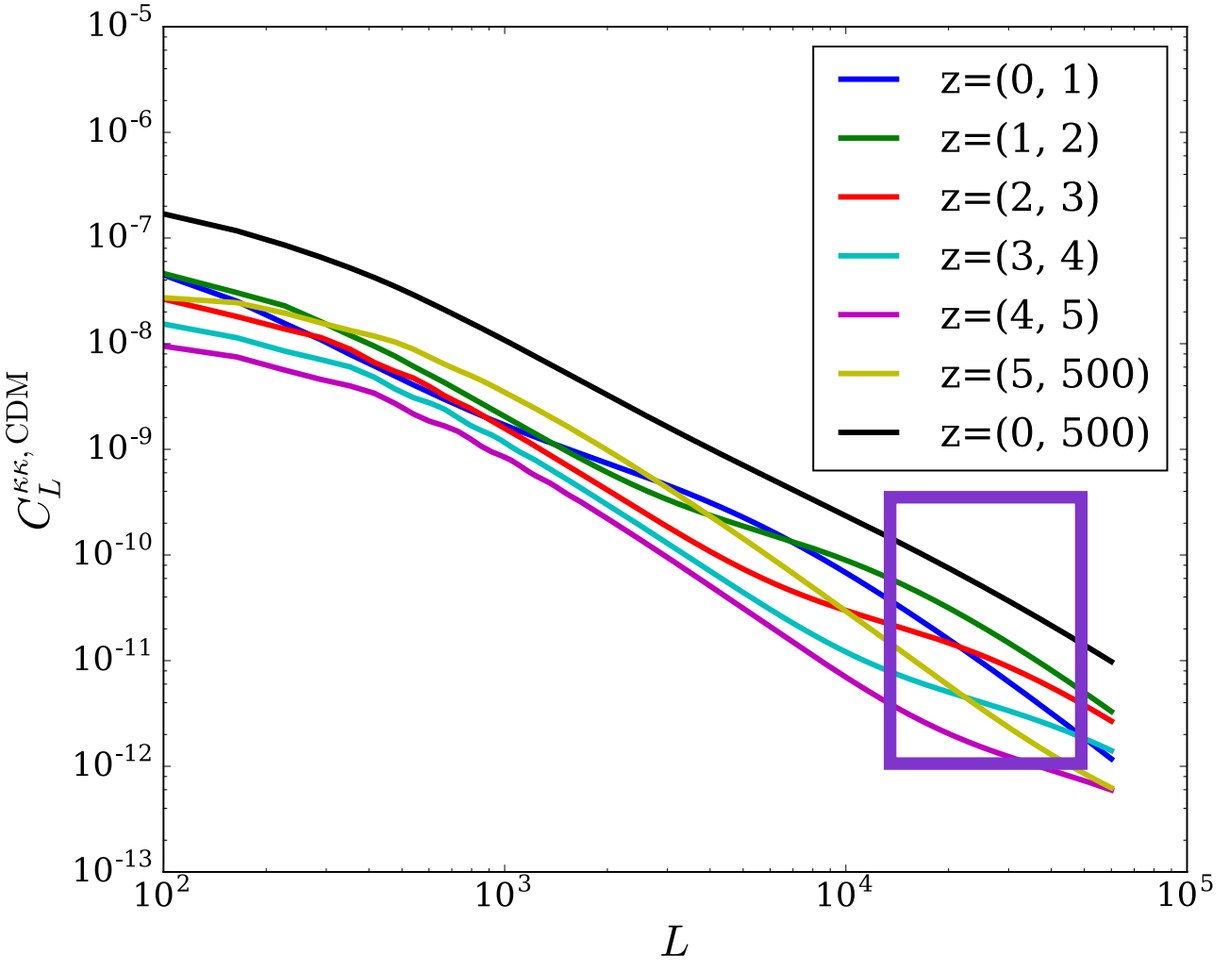

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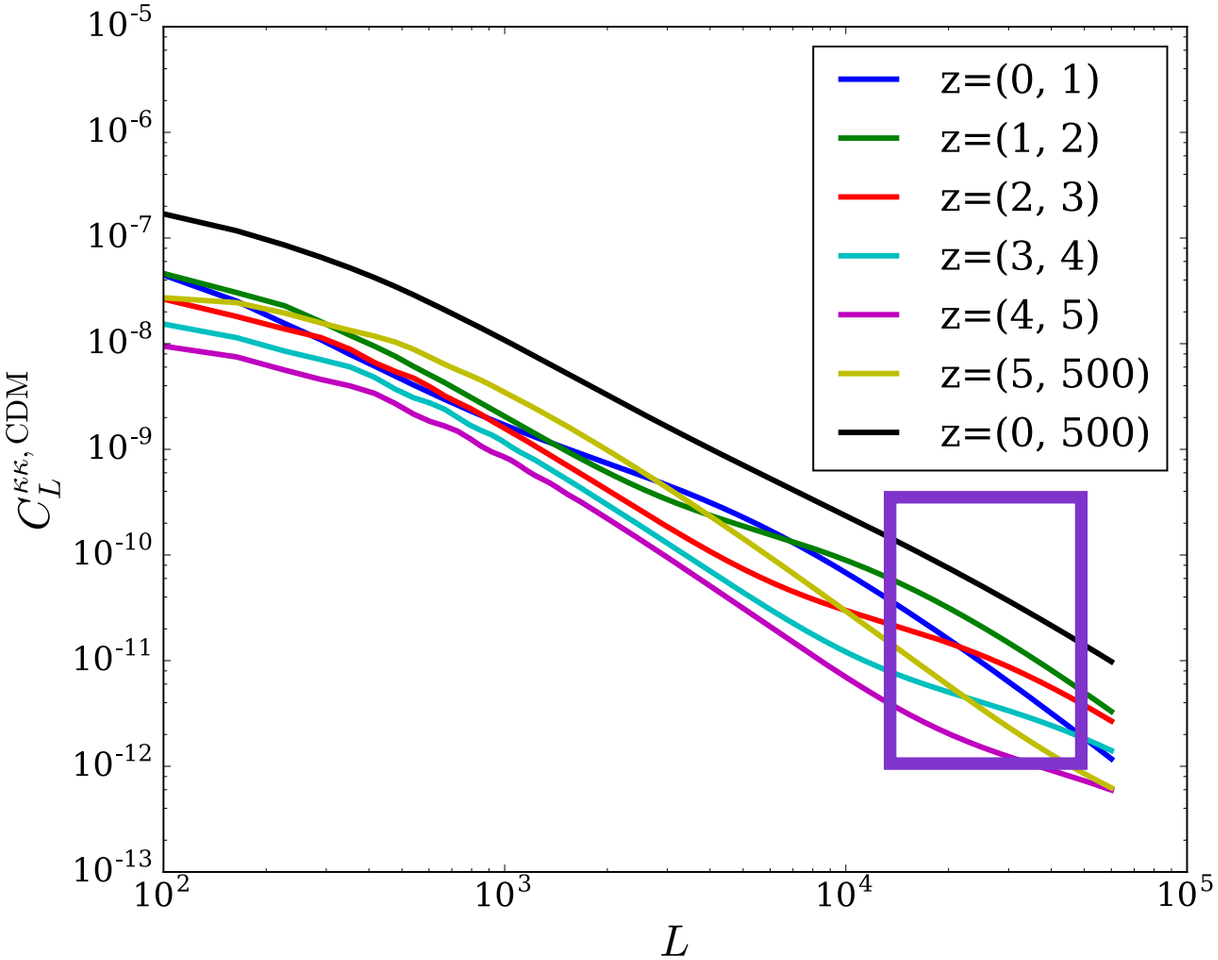

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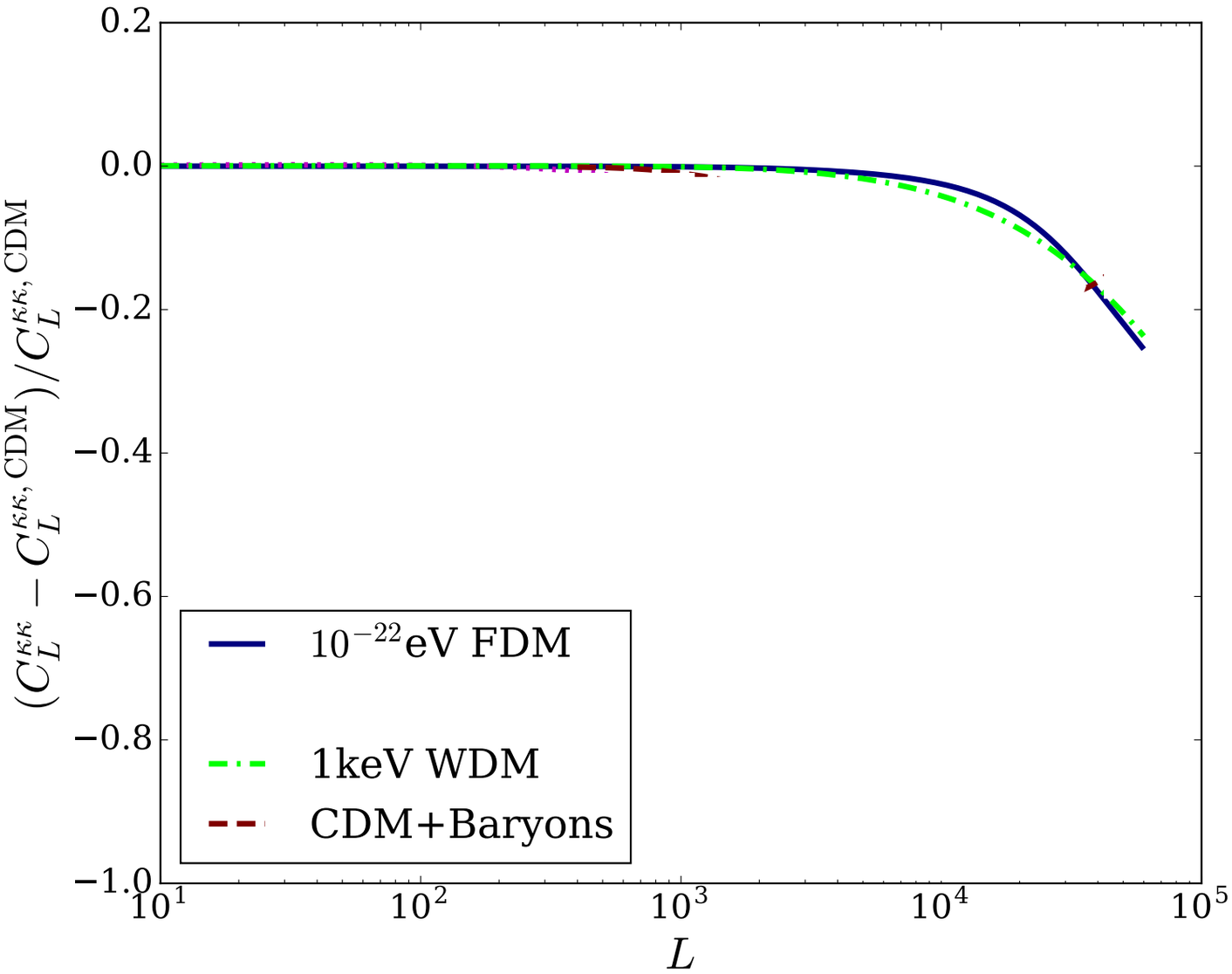
Contrast between CDM and models that wash out small-scale structure is larger at higher redshifts

CMB Lensing Power Spectrum for CDM Versus FDM/WDM



Neelima Sehgal, Stony Brook

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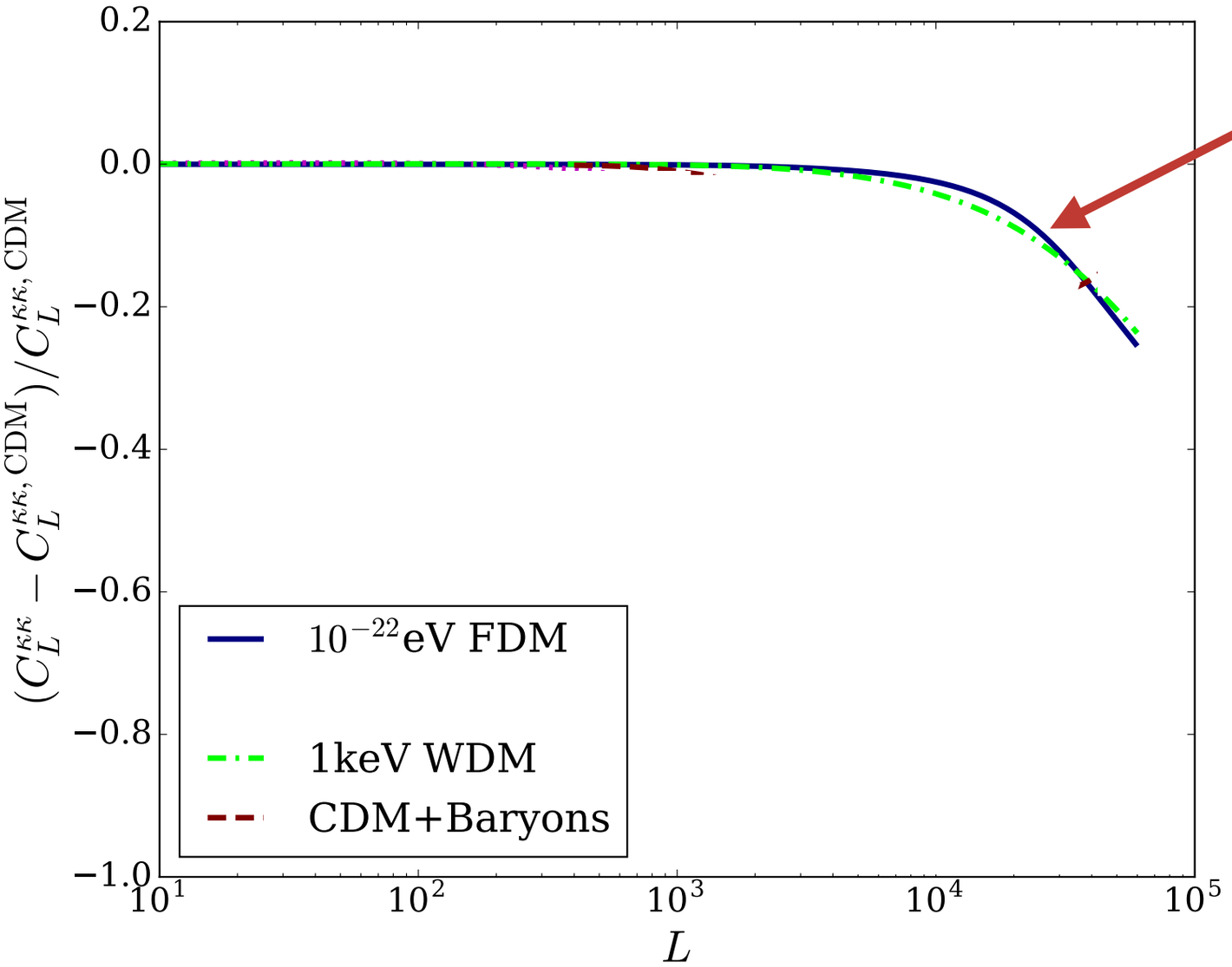

Fractional difference between FDM/WDM and CDM for the CMB lensing power spectrum

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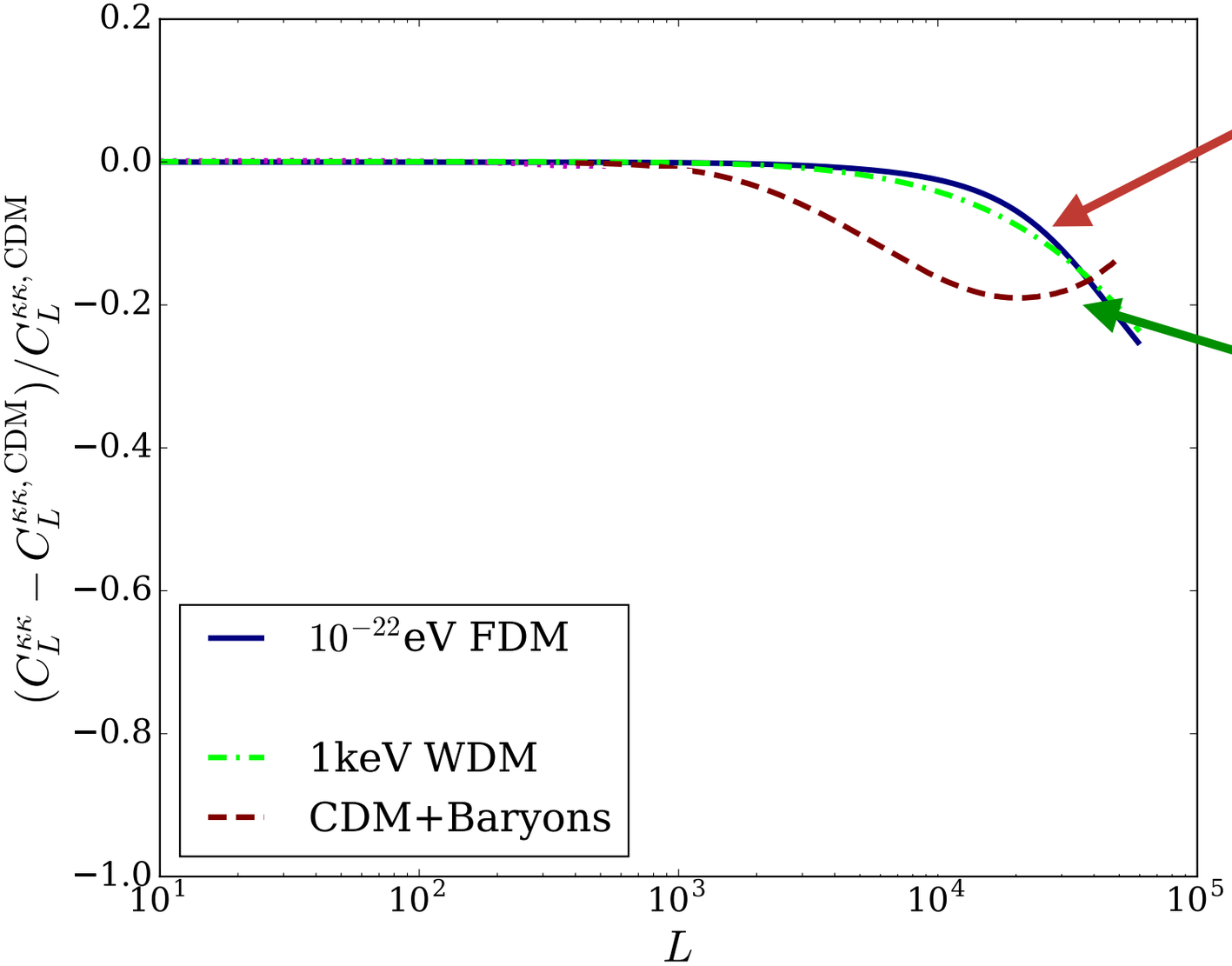

Fractional difference between FDM/WDM and CDM for the CMB lensing power spectrum

While we directly measure structure with lensing, as opposed to using a baryonic tracer, baryons may still suppress matter power

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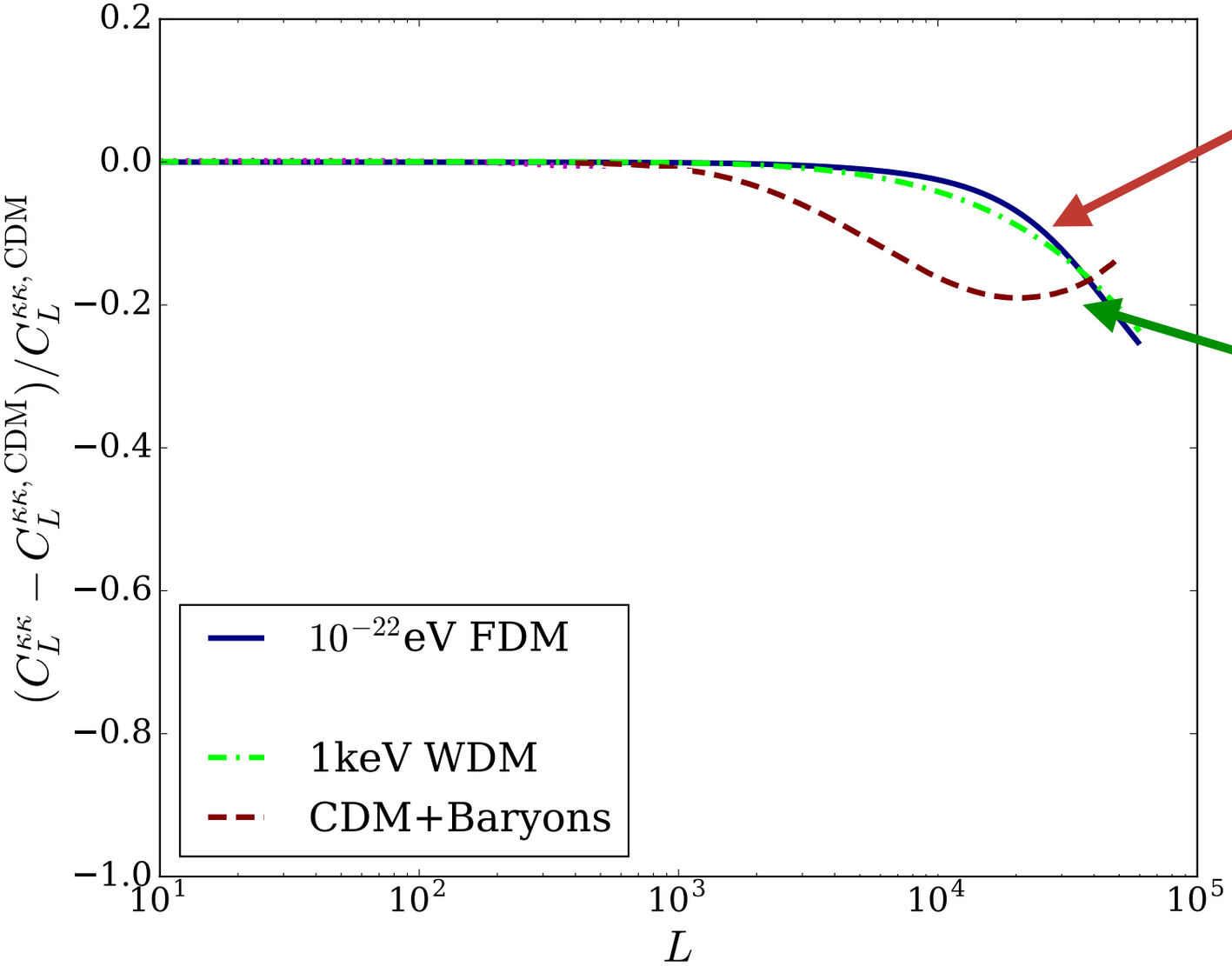

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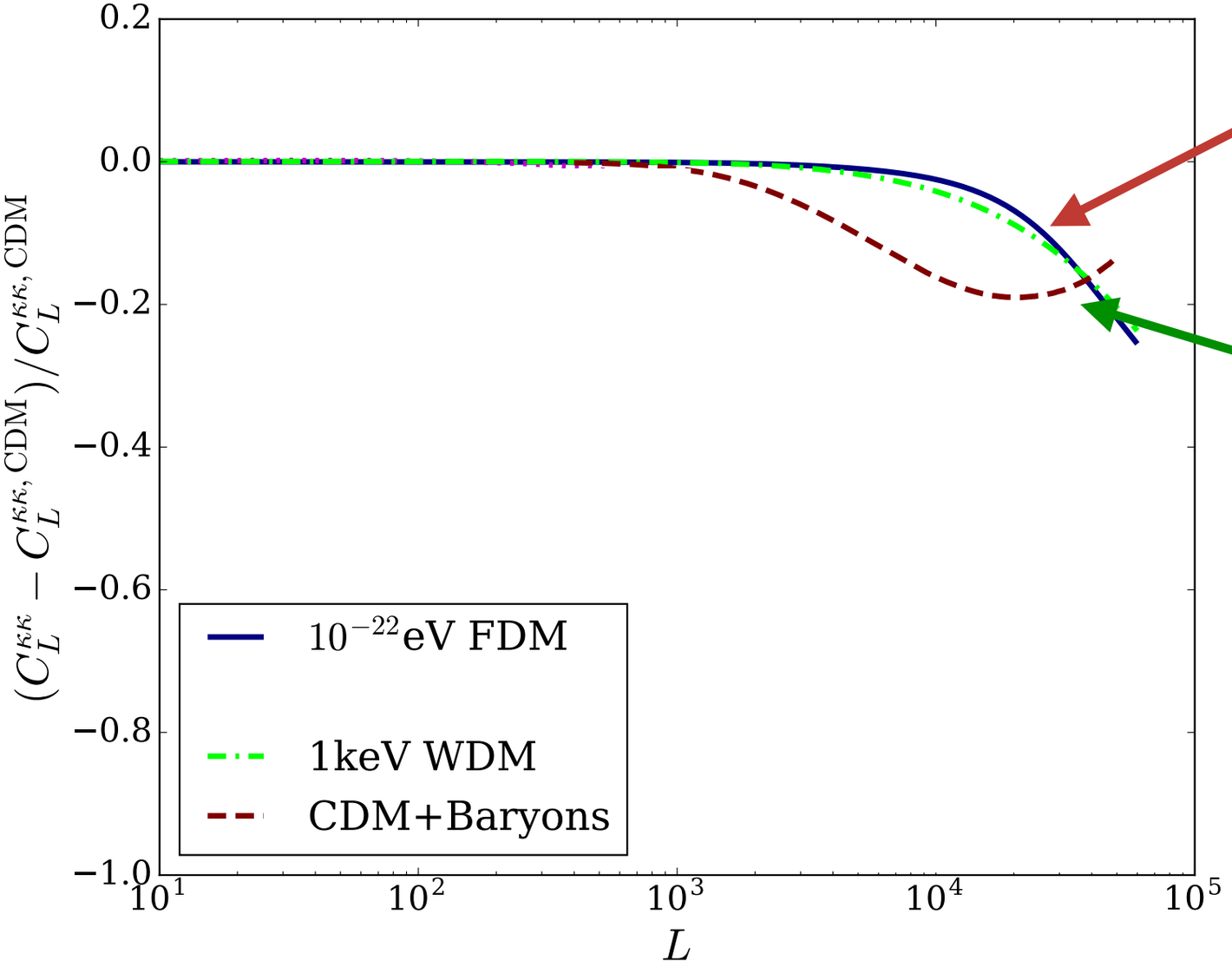

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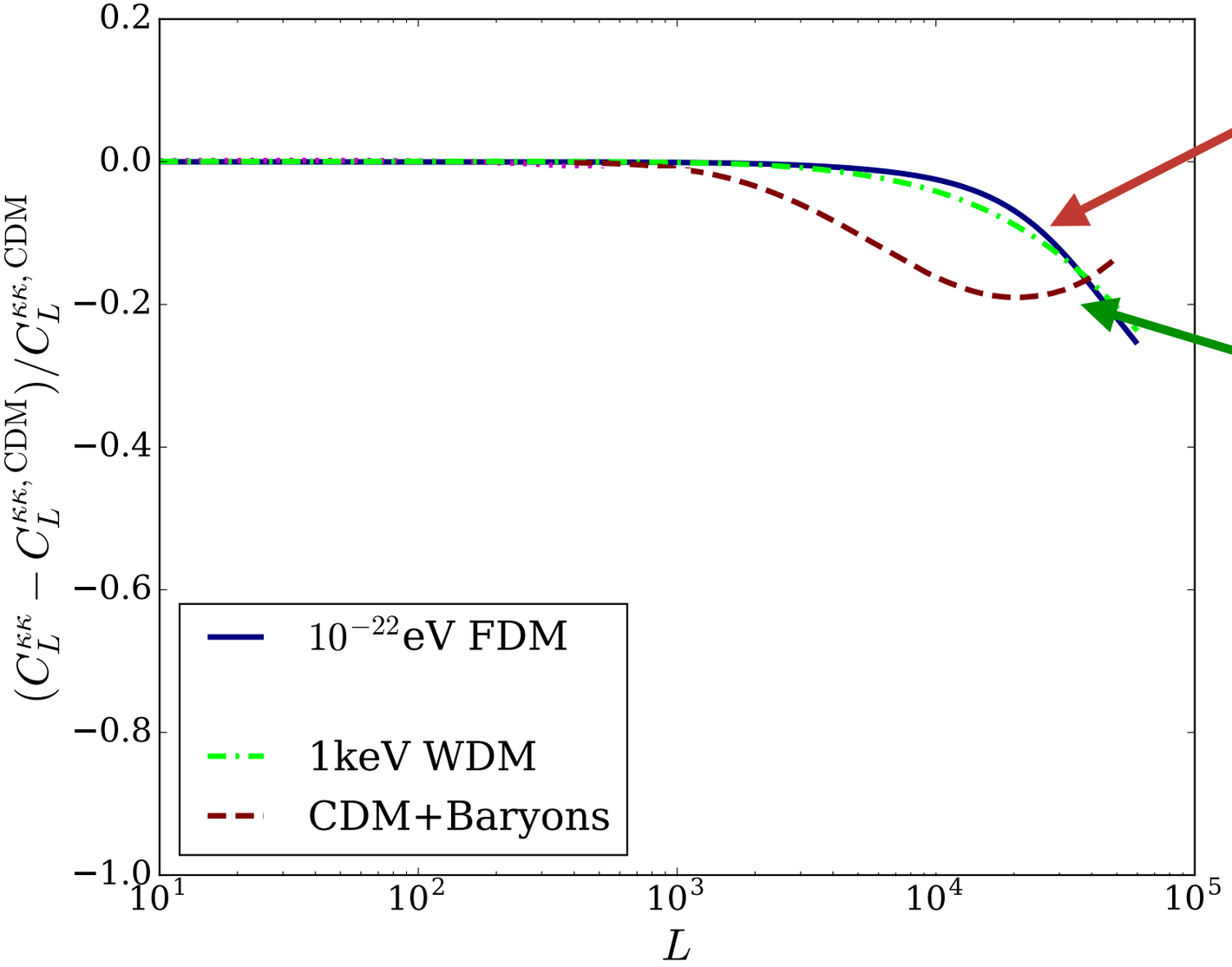

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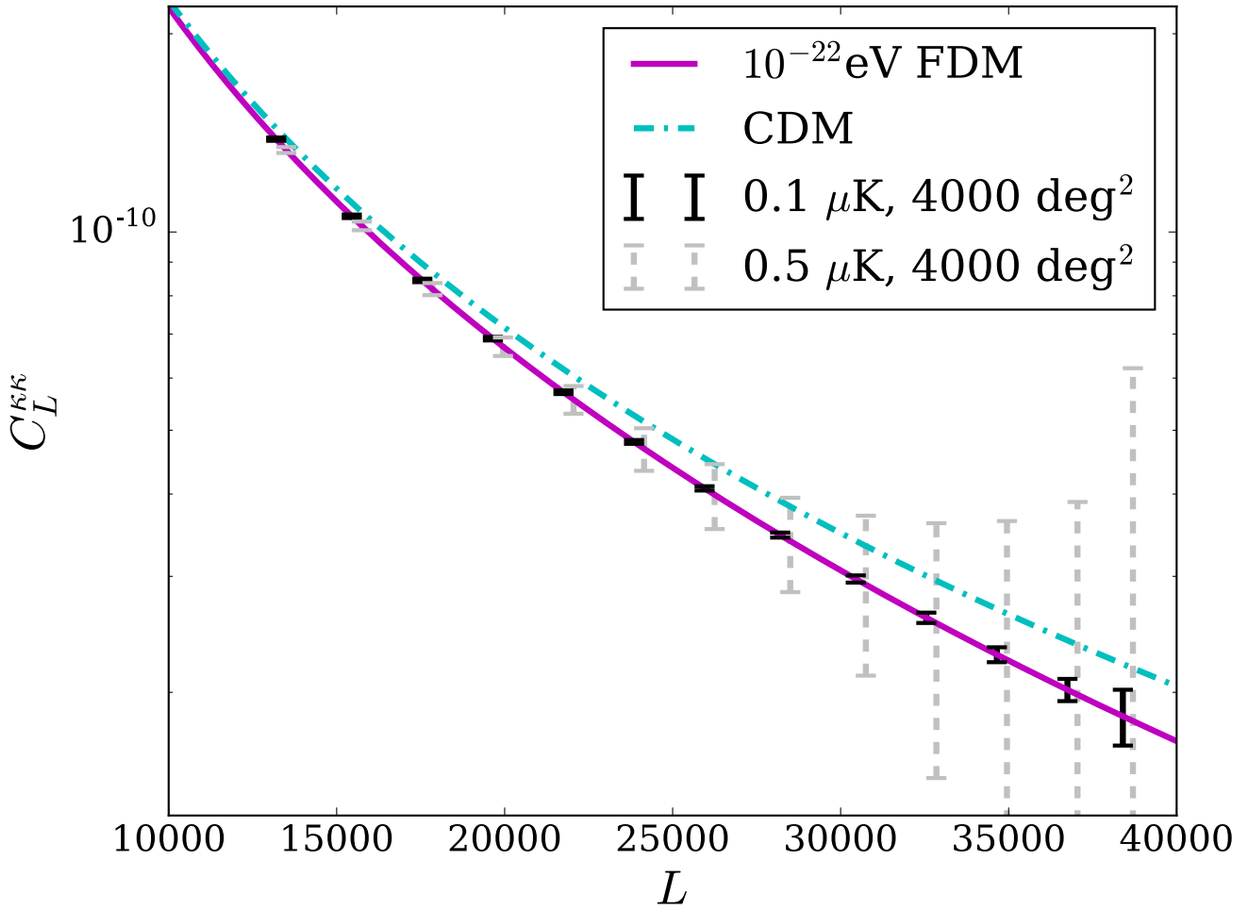
2.) If see significant deviation, then can potentially use shape of curve to determine whether it is due to baryons or alternative to CDM

Potential Ability to Distinguish Between Dark Matter Models

Ho Nam Nguyen, NS, Mathew Madhavacheril, 2017, arXiv:1710.03747



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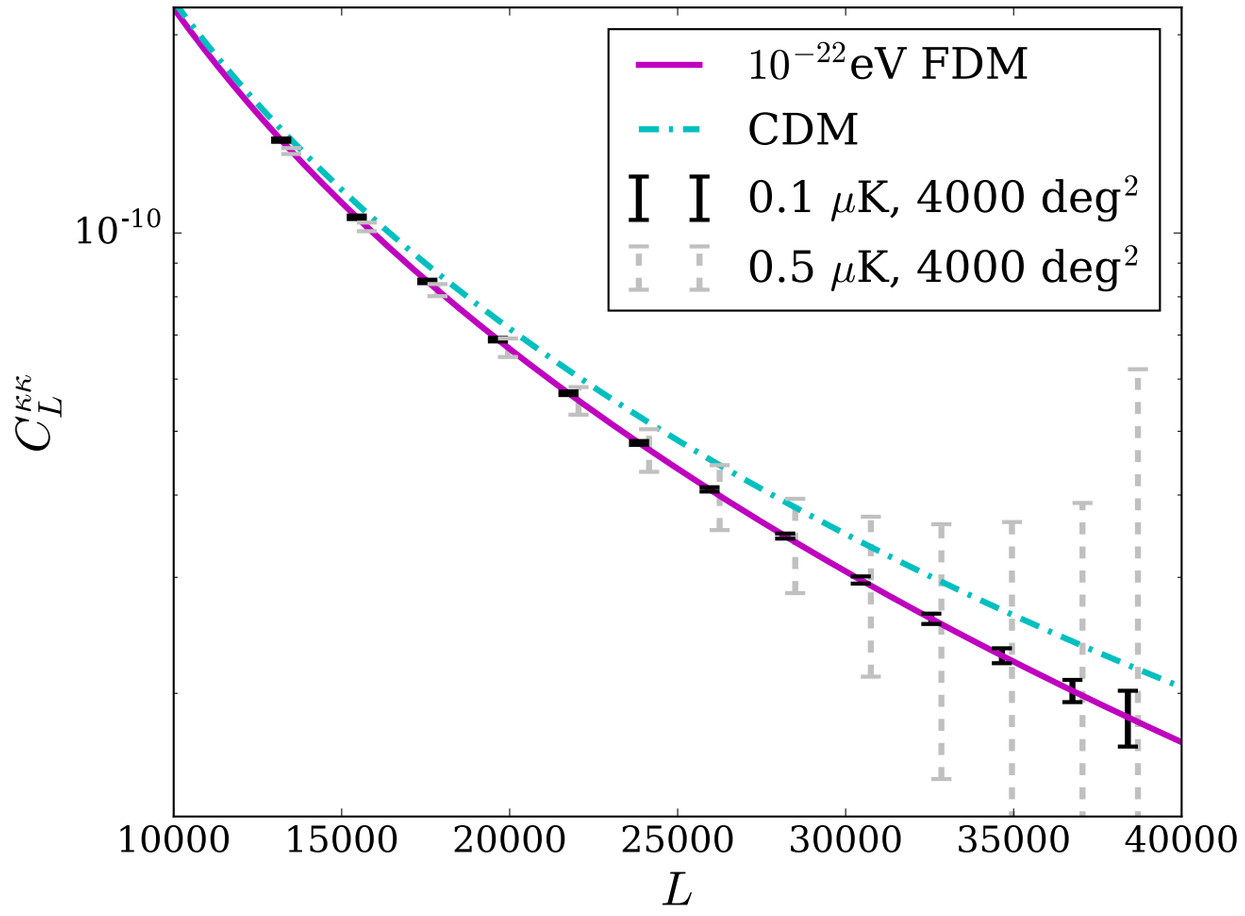

Sky fraction (f_{sky})	Noise (μK-arcmin)	Signal-to-noise ratio 18″ Resolution	Signal-to-noise ratio 9.5″ Resolution
0.1	0.5	3.9	5.2
0.025	0.1	10.1	15.9
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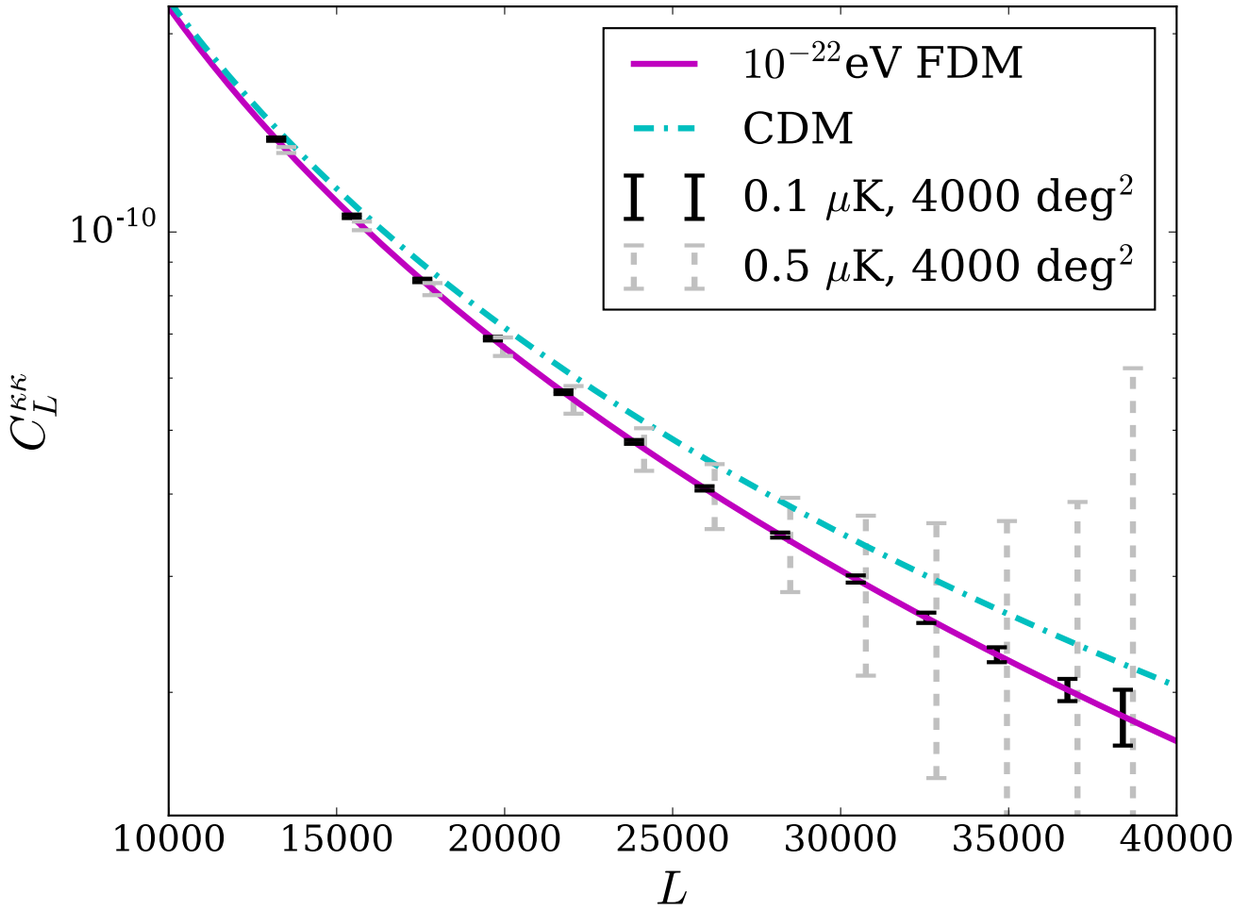

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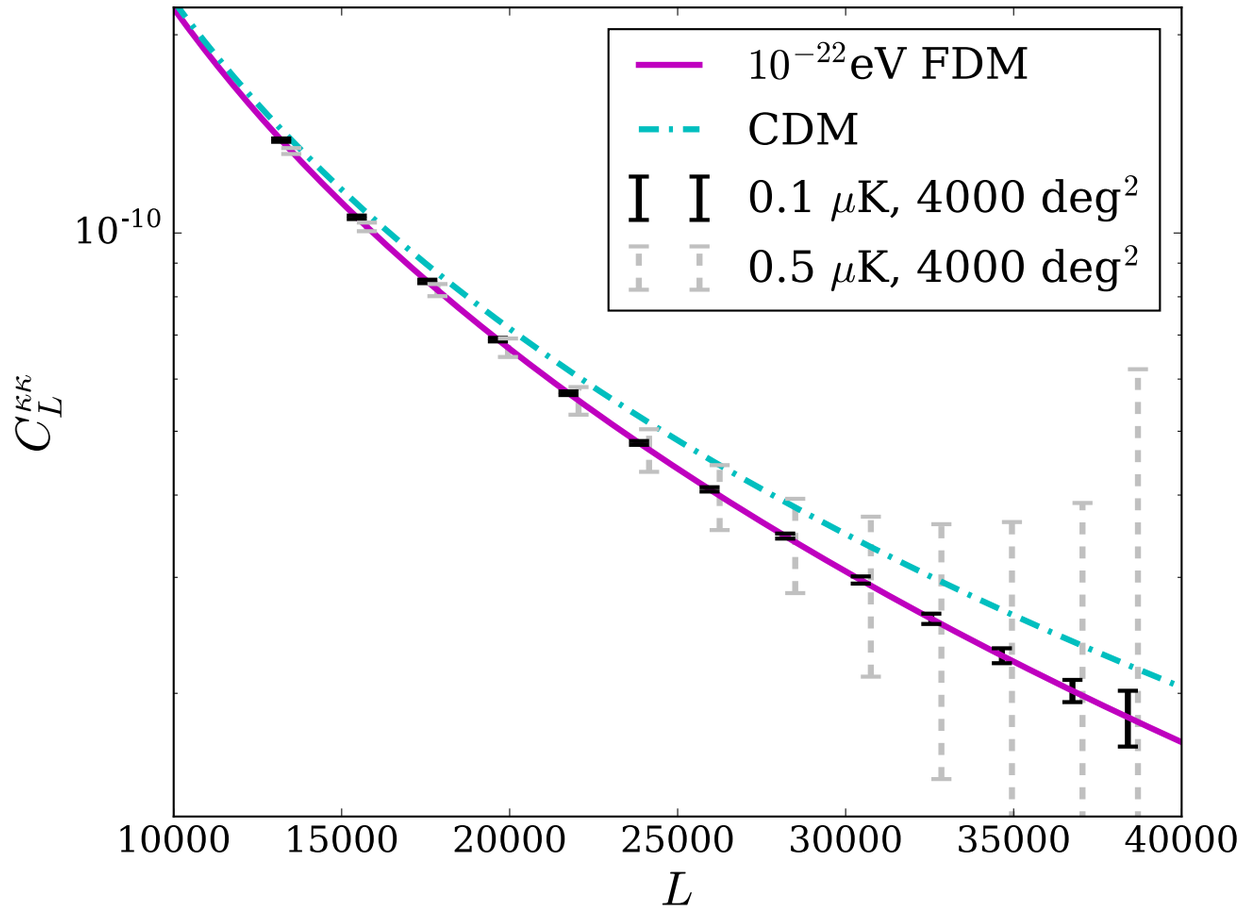

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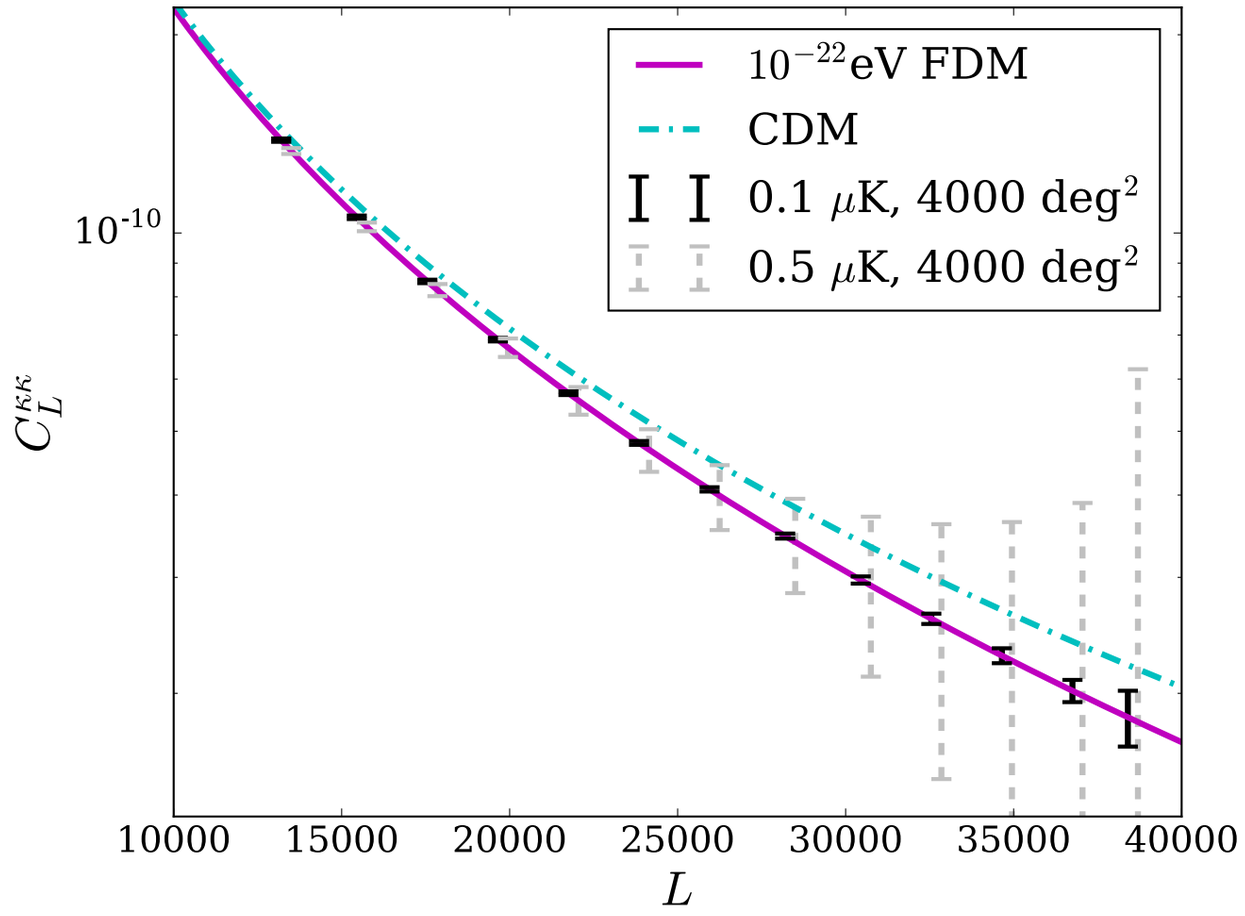

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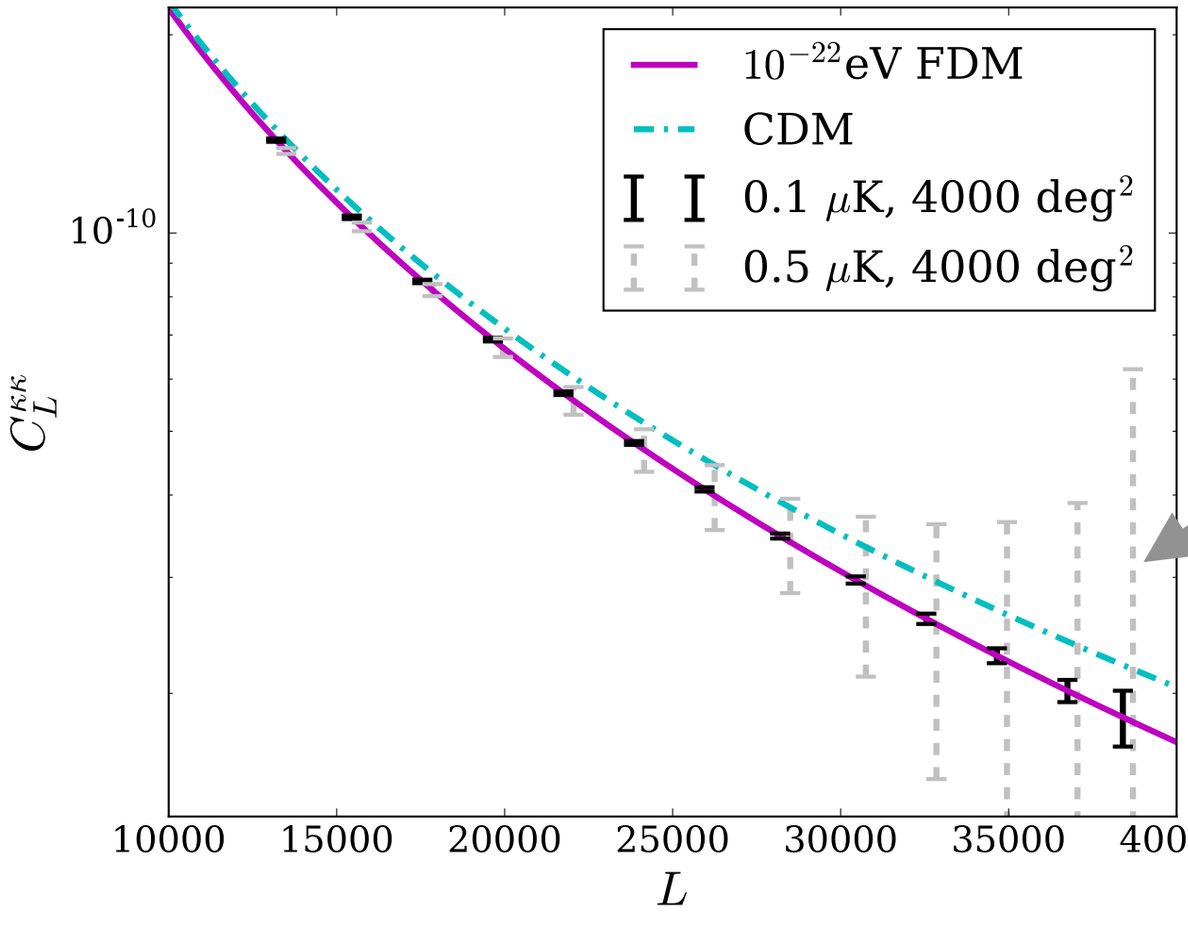

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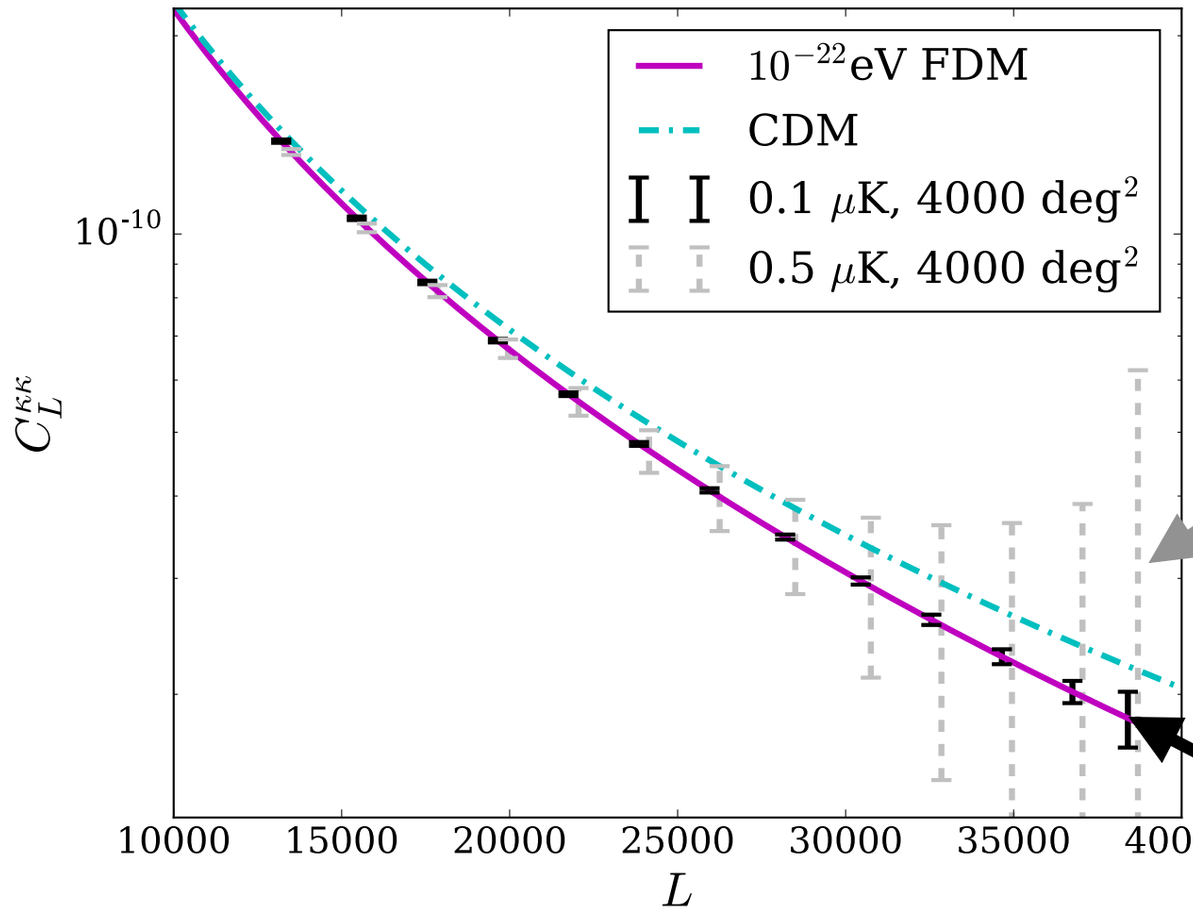

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Black: S/N ~ 30 for distinguishing between CDM and FDM/WDM

Requires: Camera few times more sensitive than CMB-S4 on existing 50-meter dish

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Neelima Sehgal, Stony Brook

Foregrounds

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Potential Paths to Make High-Res CMB Lensing Measurement

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The Large Millimeter Telescope - 50 meters (~10 arcsec resolution)

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Location of Large Millimeter Telescope

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