Cosmology
Lecture 10

The Cosmic Microwave Background Part 2: Fluctuations in the CMB

Lectures

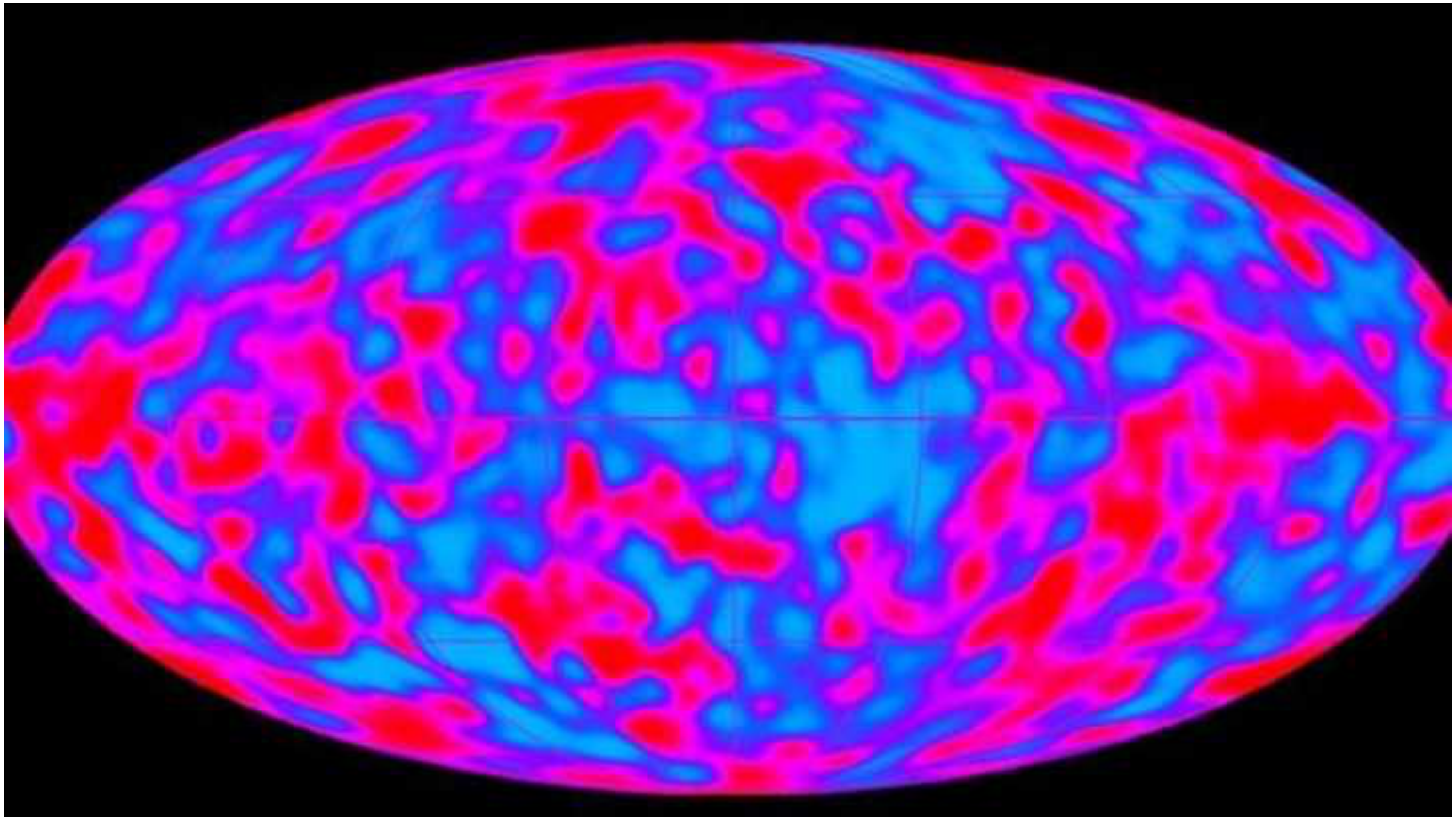
01: Fundamental Observations
02: Shape of universe and cosmological distances
03: The Friedmann Equation
04: Solving the Friedmann Equation I
05: Solving the Friedmann Equation II
06: Model universes
07: The Benchmark Model and measurable distances
08: The Dark Universe
09: The Cosmic Microwave Background I
<u>10: The Cosmic Microwave Background II</u>
11: Nucleosynthesis I
12: Nucleosynthesis II
13: Inflation
14: Structure Formation I
15: Structure Formation II
16: Baryons & Photons I
17: Baryons & Photons II

Learning Objectives

- The cause of the anisotropies (aka “speckles”) in the Cosmic Microwave Background.
- How we determine the physical sizes of the anisotropies.
- How we measure the statistical properties of the anisotropies.
- Understand what is meant by the CMB Power Spectrum and how it is measured.
- The causes of the various peaks in the CMB Power Spectrum, and how they provide Cosmological Parameters.

Cosmological anisotropies

The COBE mission in the early 1990's was the first to discover small-scale anisotropies once the large-scale dipole anisotropies were subtracted:



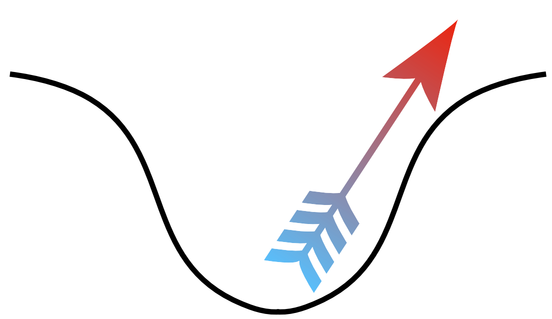
These anisotropies are at the level of around 30 microKelvin, or one part in 10^5 of the average CMB temperature (i.e., 2.755K)

What causes cosmological anisotropies?
The short version:

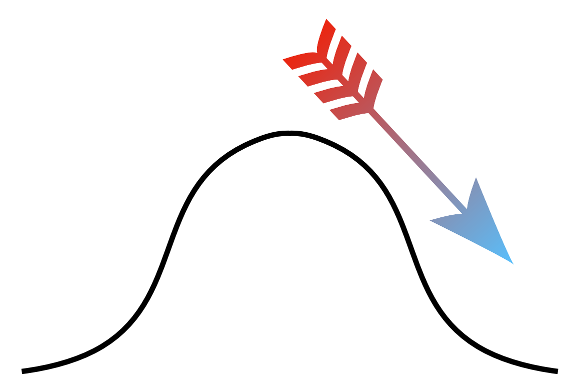
The small-scale CMB anisotropies had been predicted since the early 1970s.

Since the CMB is due to the interaction of photons with matter, if matter is not distributed perfectly smoothly, then there will be fluctuations in the CMB:

Gravitational potential



A photon in a region of high density at decoupling gets redshifted

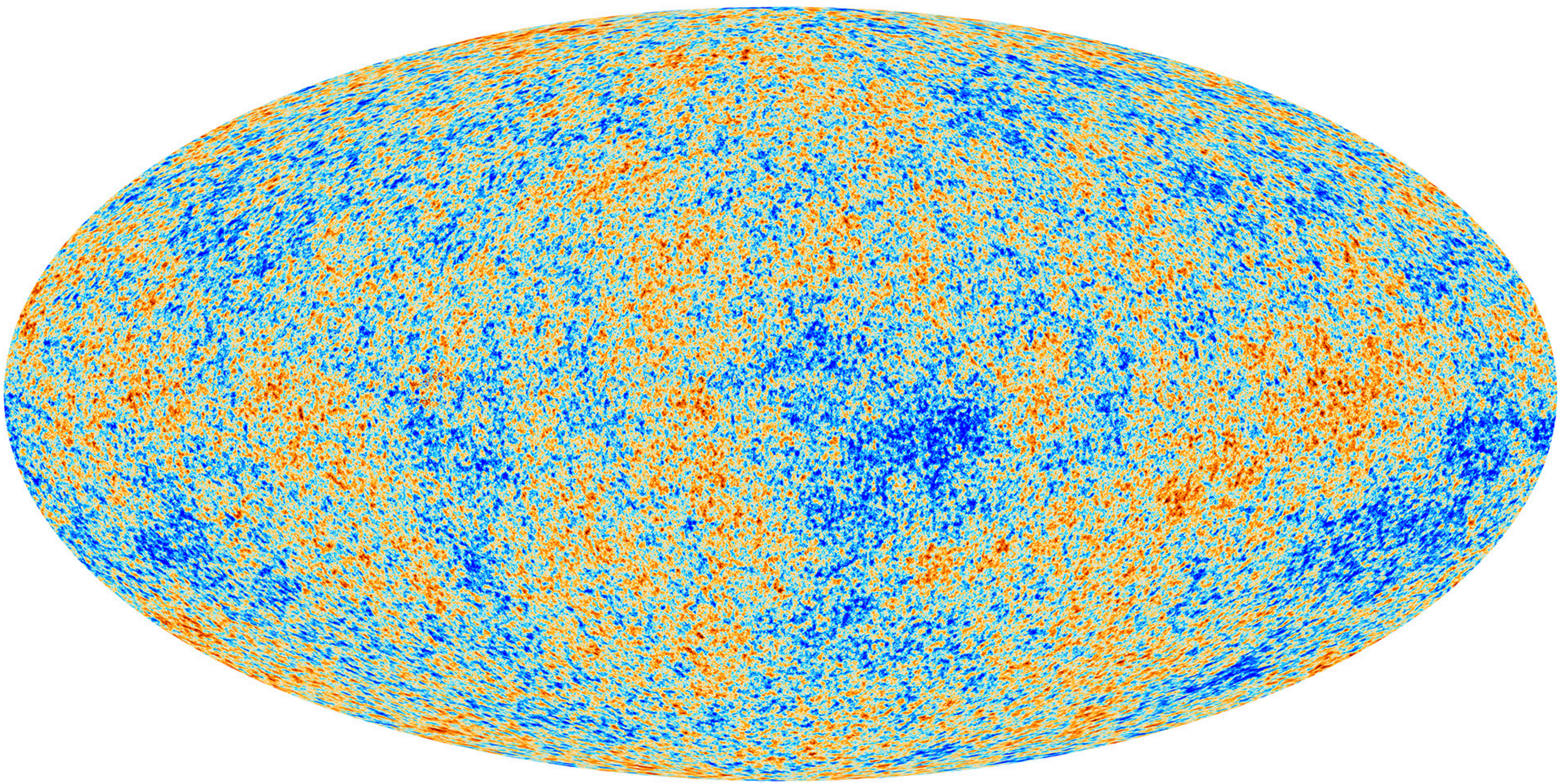


A photon in a region of low density at decoupling gets blueshifted

CMB anisotropies in detail: angular size

A key feature of the anisotropies is their angular size.

What sets this size?



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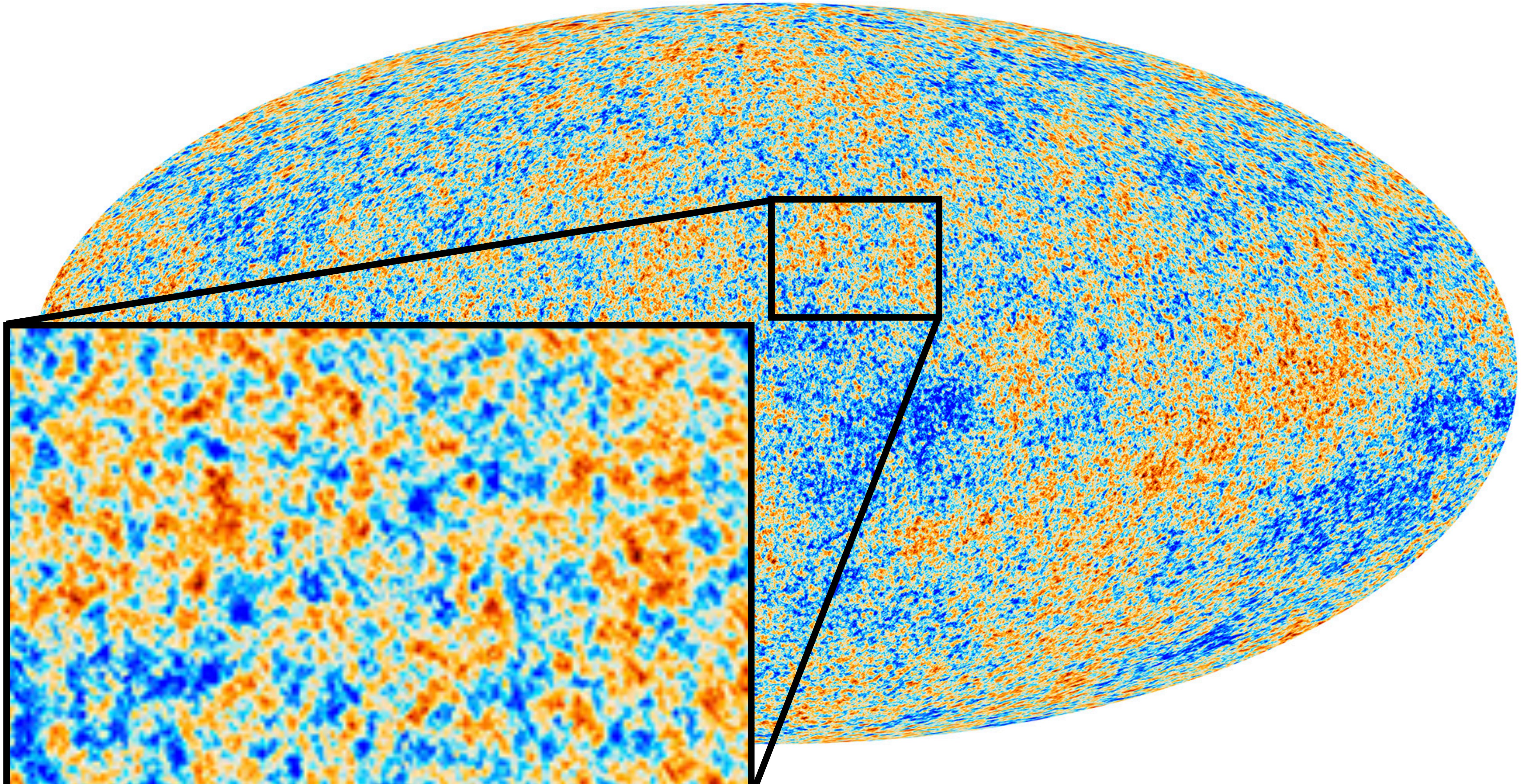

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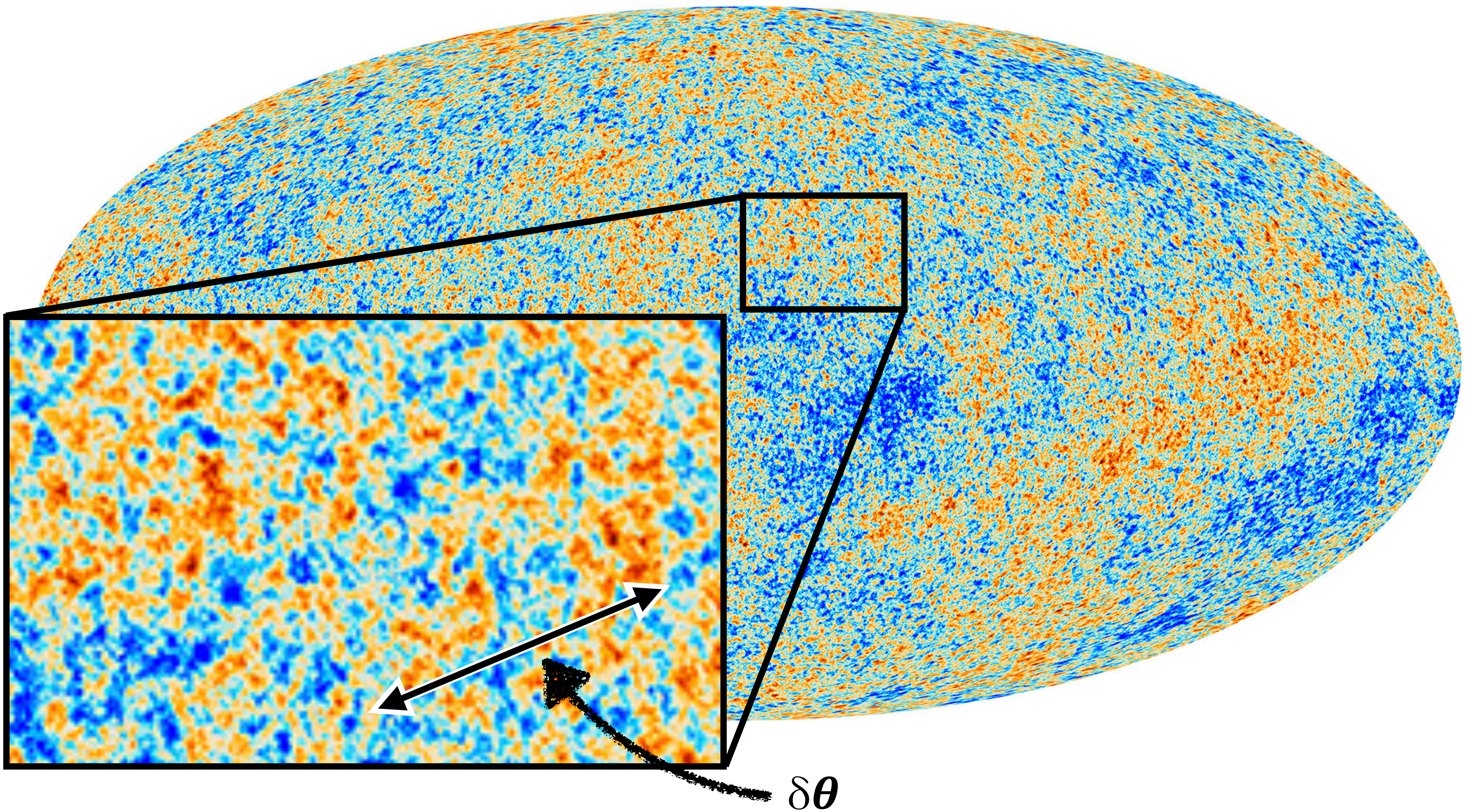

CMB anisotropies in detail: physical size

How do we convert angular sizes to physical sizes?

Remember, $d_A = d_p(t_0)/(1+z)$ = 14,000 Mpc/1090 = 12.8 Mpc

Meaning two points on the CMB that are separated on-sky by 1 radian were physically separated by 12.8 Mpc at the time the CMB was produced.

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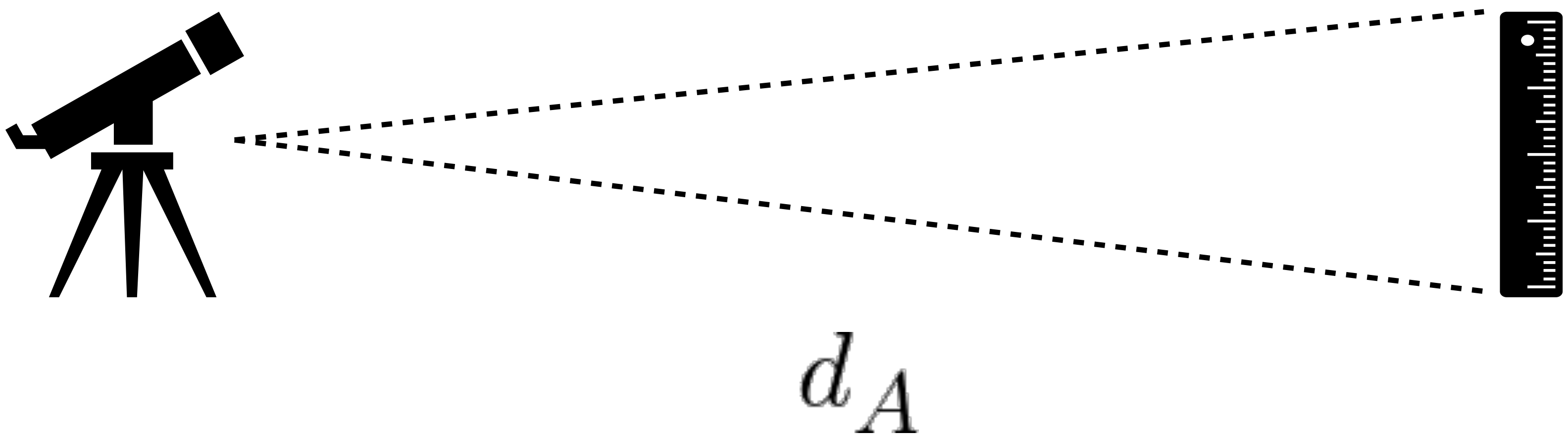

$$l = \theta d_A$$

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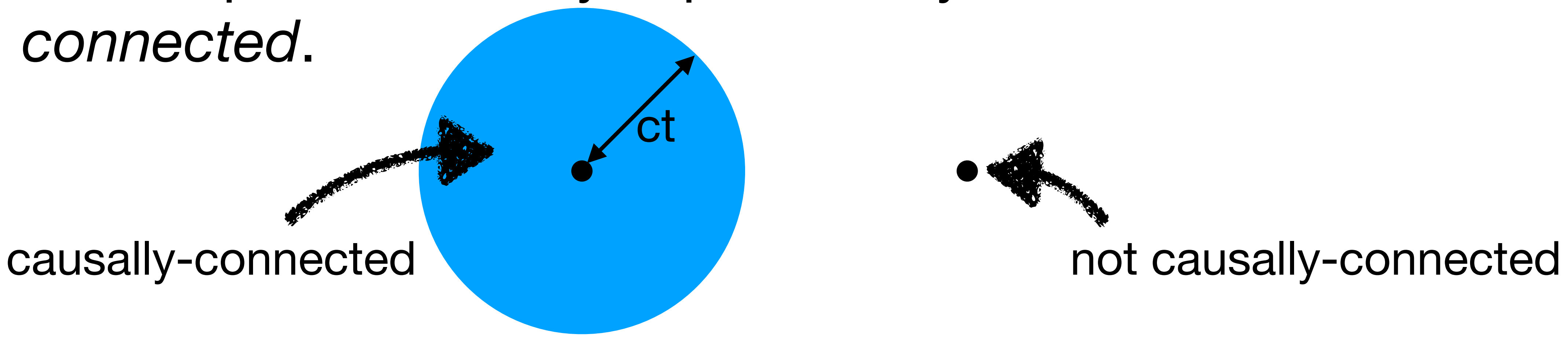
CMB anisotropies in detail: the horizon distance

Two points on the CMB that are separated on-sky by 1 radian were physically separated by 12.8 Mpc at the time the CMB was produced.

However, at that time, the Universe was only ~370,000 years old - light hadn't had time to travel 12.8 Mpc (~41.7 Mly).

So two patches of sky separated by 1 radian were not *causally connected*.



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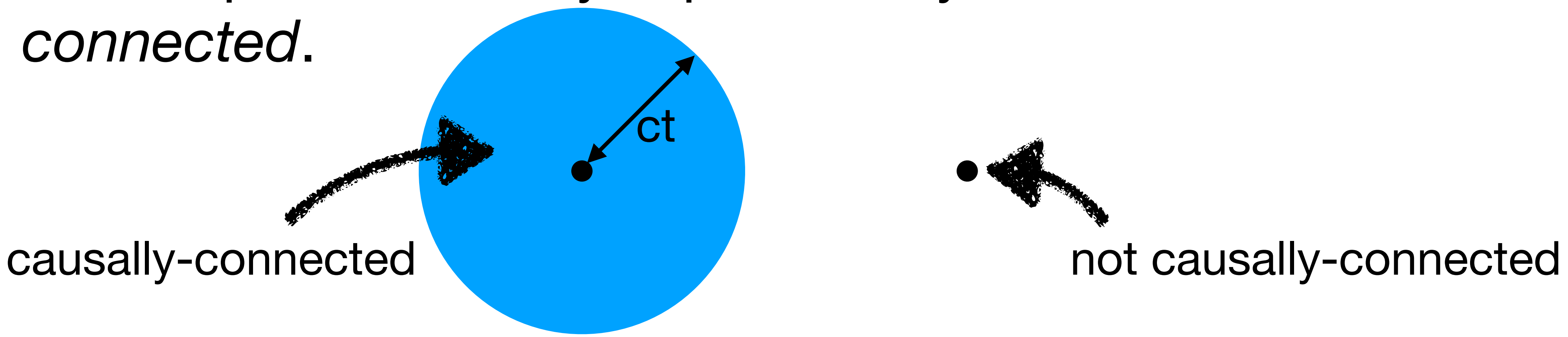


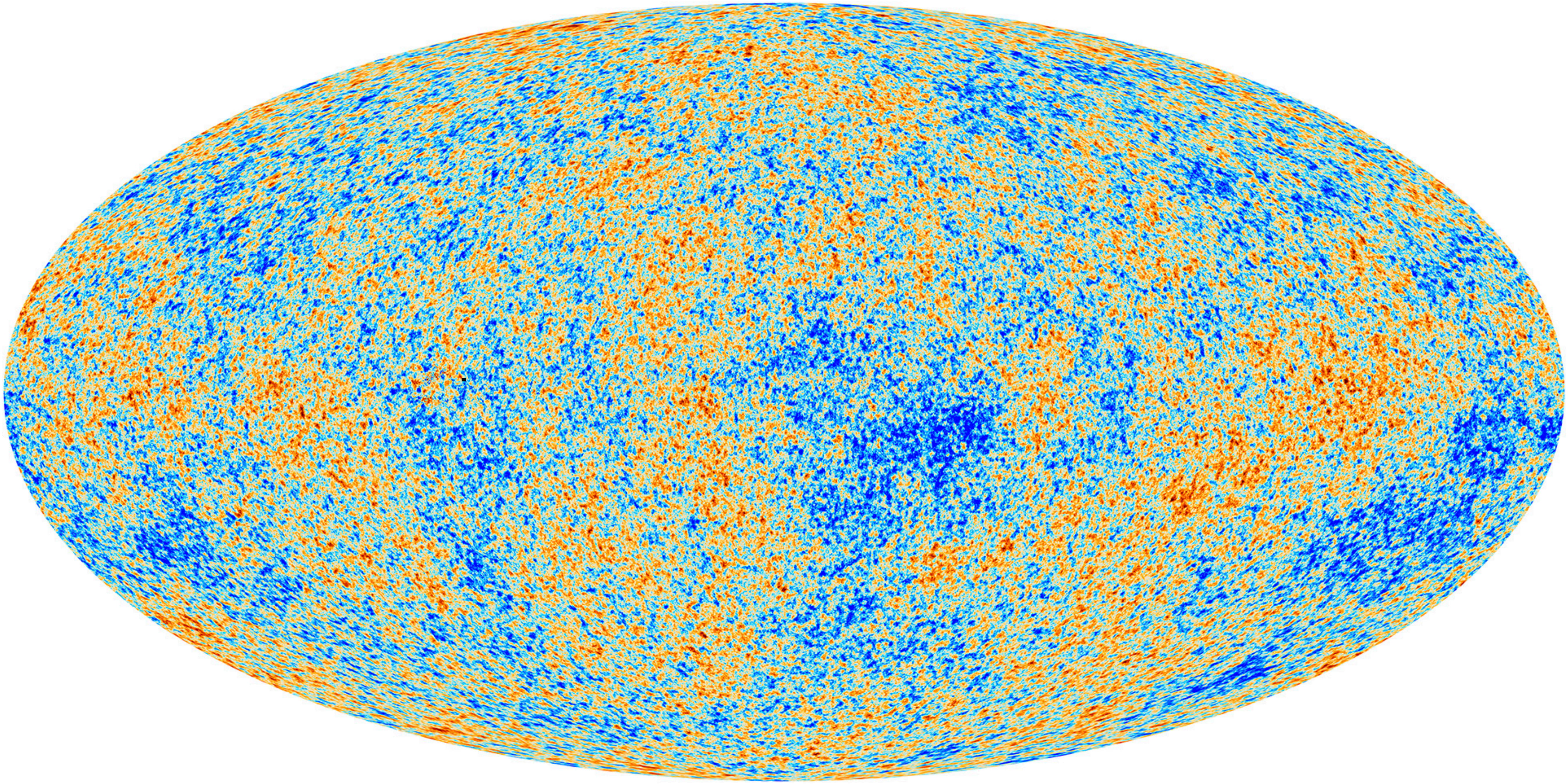
Using the Benchmark Model, we can calculate the maximum separation that was causally connected when the CMB was produced. This is known as the *Horizon distance:*

$$d_{\mathrm{hor}}(t_{\mathrm{cmb}}) = a(t_{\mathrm{cmb}})c\int_0^{t_{\mathrm{cmb}}} \frac{dt}{a(t)} = 2.24ct_{\mathrm{cmb}} = 0.251\ \mathrm{Mpc}$$

CMB anisotropies in detail: the horizon angle

Using the angular distance, we can calculate the angular size of the horizon distance:

$$\theta_{\rm hor} = \frac{d_{\rm hor}(t_{\rm cmb})}{d_A} = \frac{0.251\ {\rm Mpc}}{12.8\ {\rm Mpc}} = 0.020\ {\rm rad} = 1.1^\circ$$



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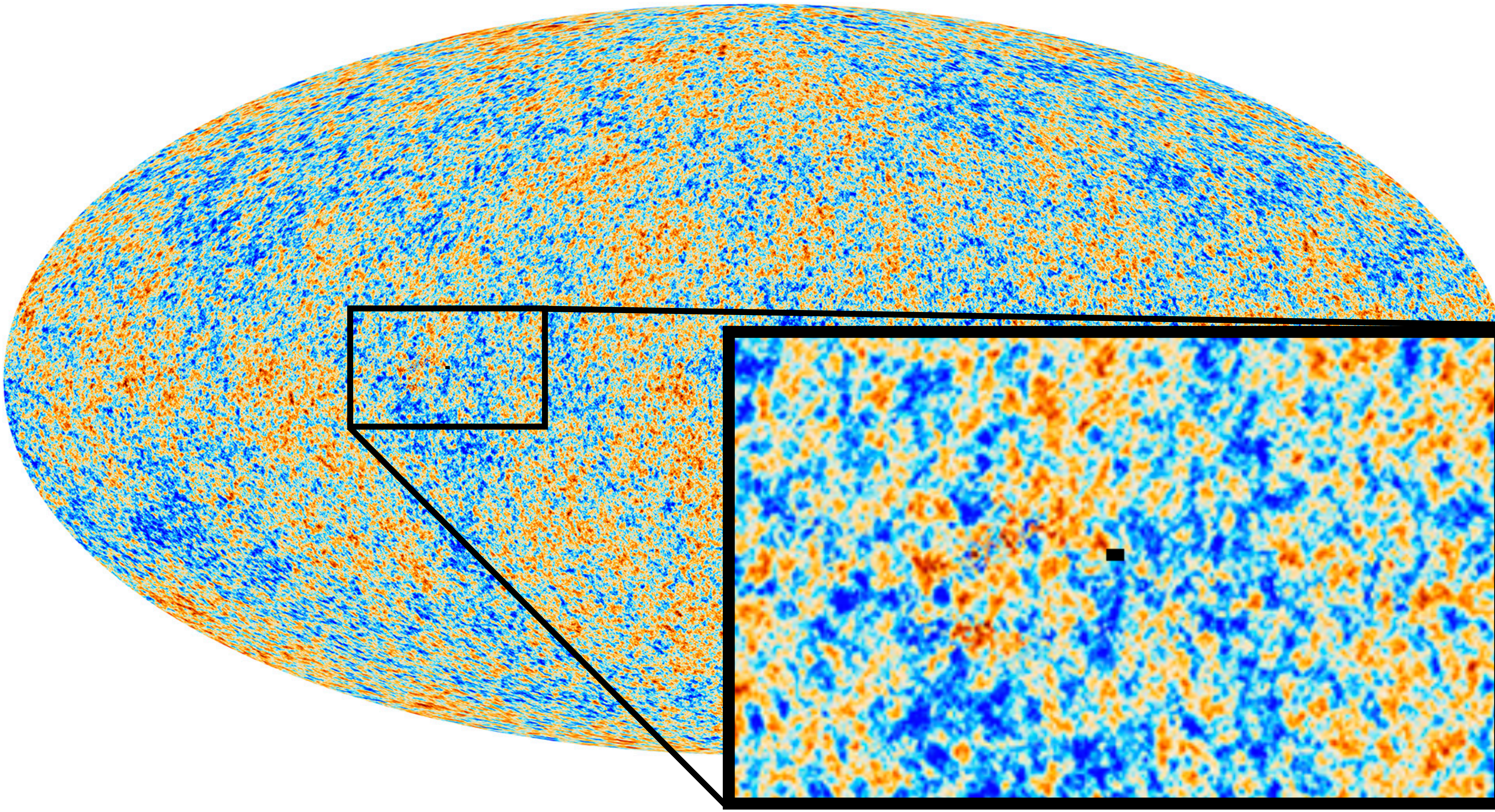

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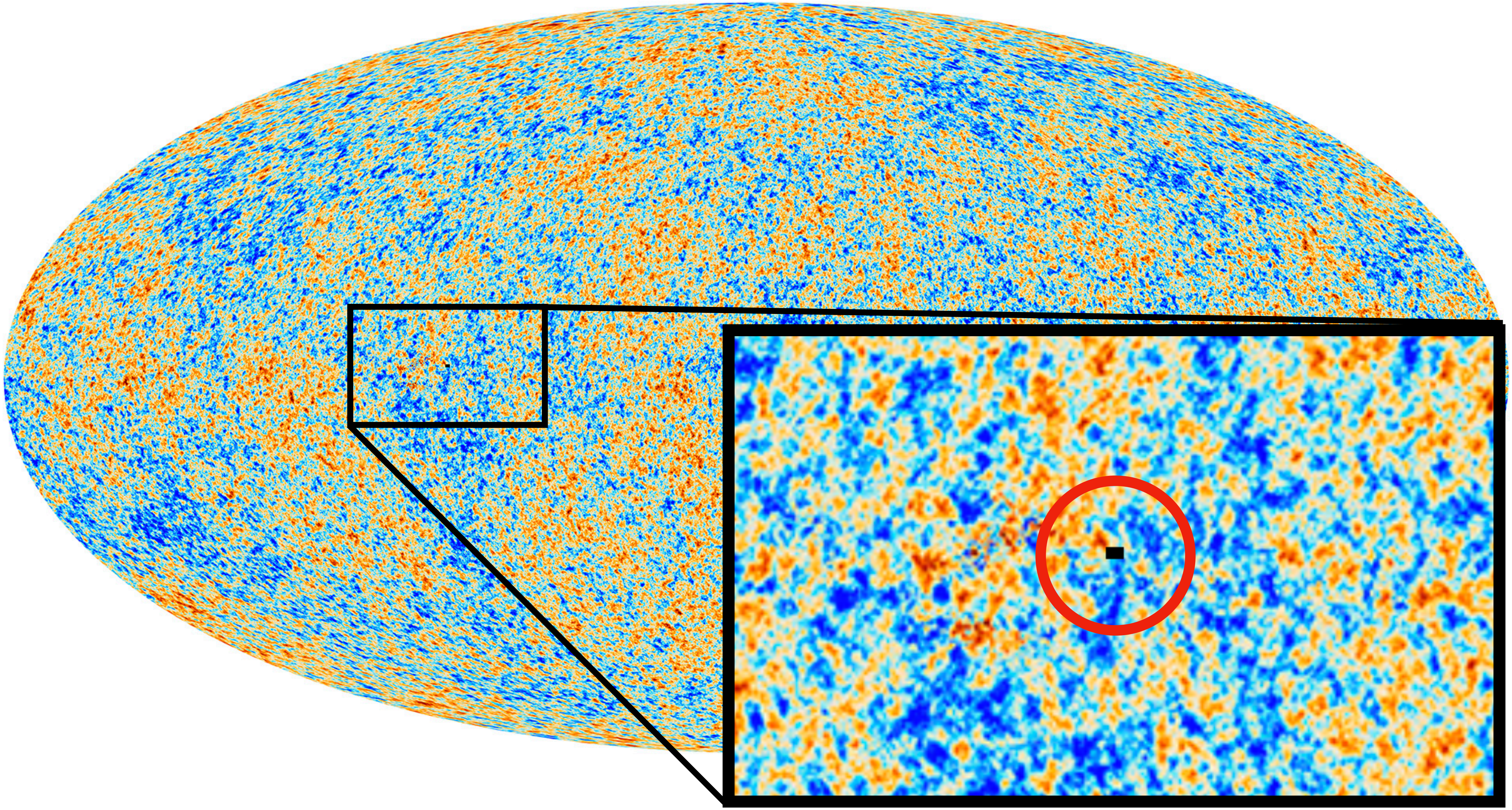
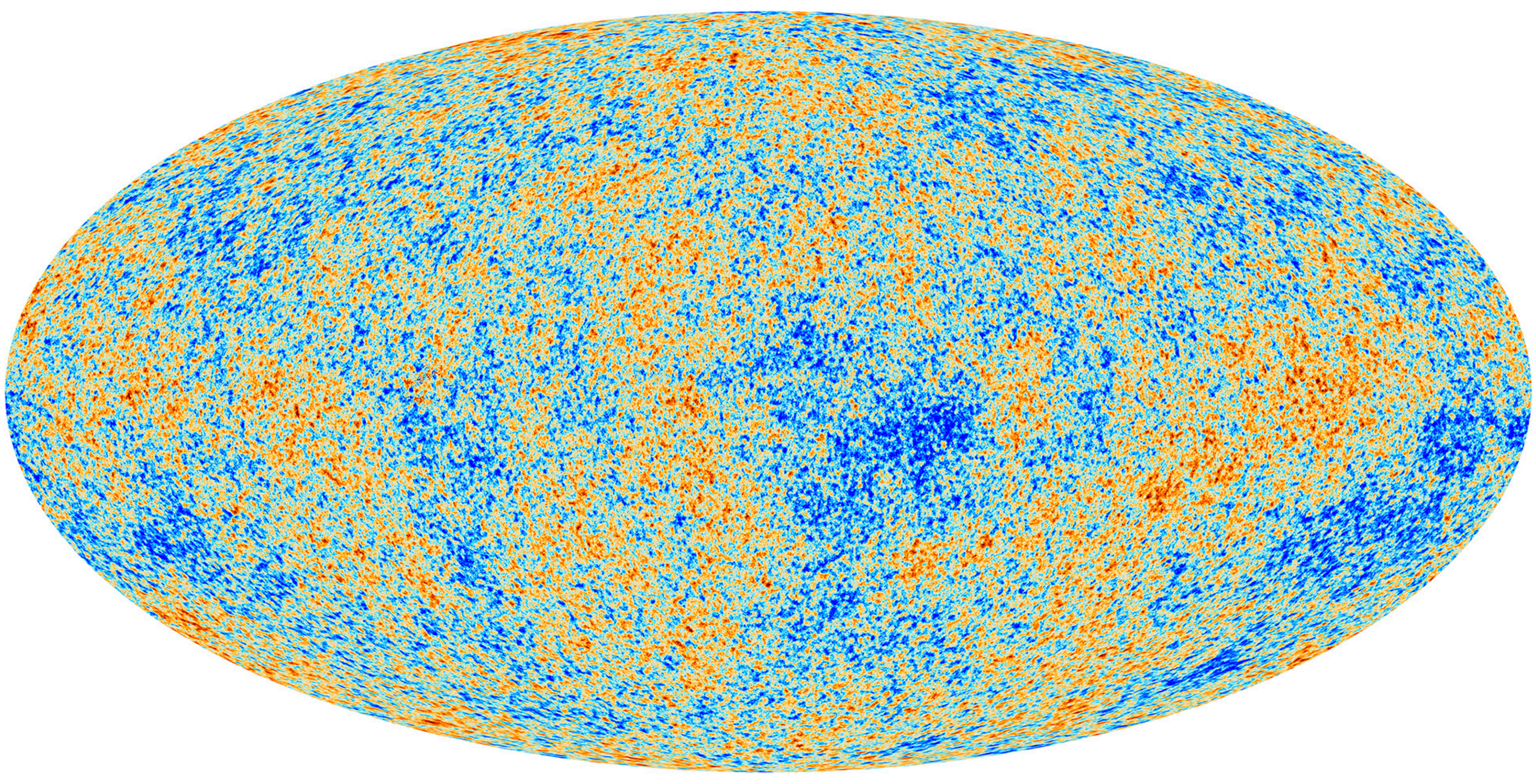


Precision CMB cosmology

Cosmologists are most interested in the statistical properties of the CMB.

Most notably how different parts of the CMB *correlate* with each other on different scales.

This tells cosmologists how different regions of the Universe related to one another at the time when the CMB was produced.



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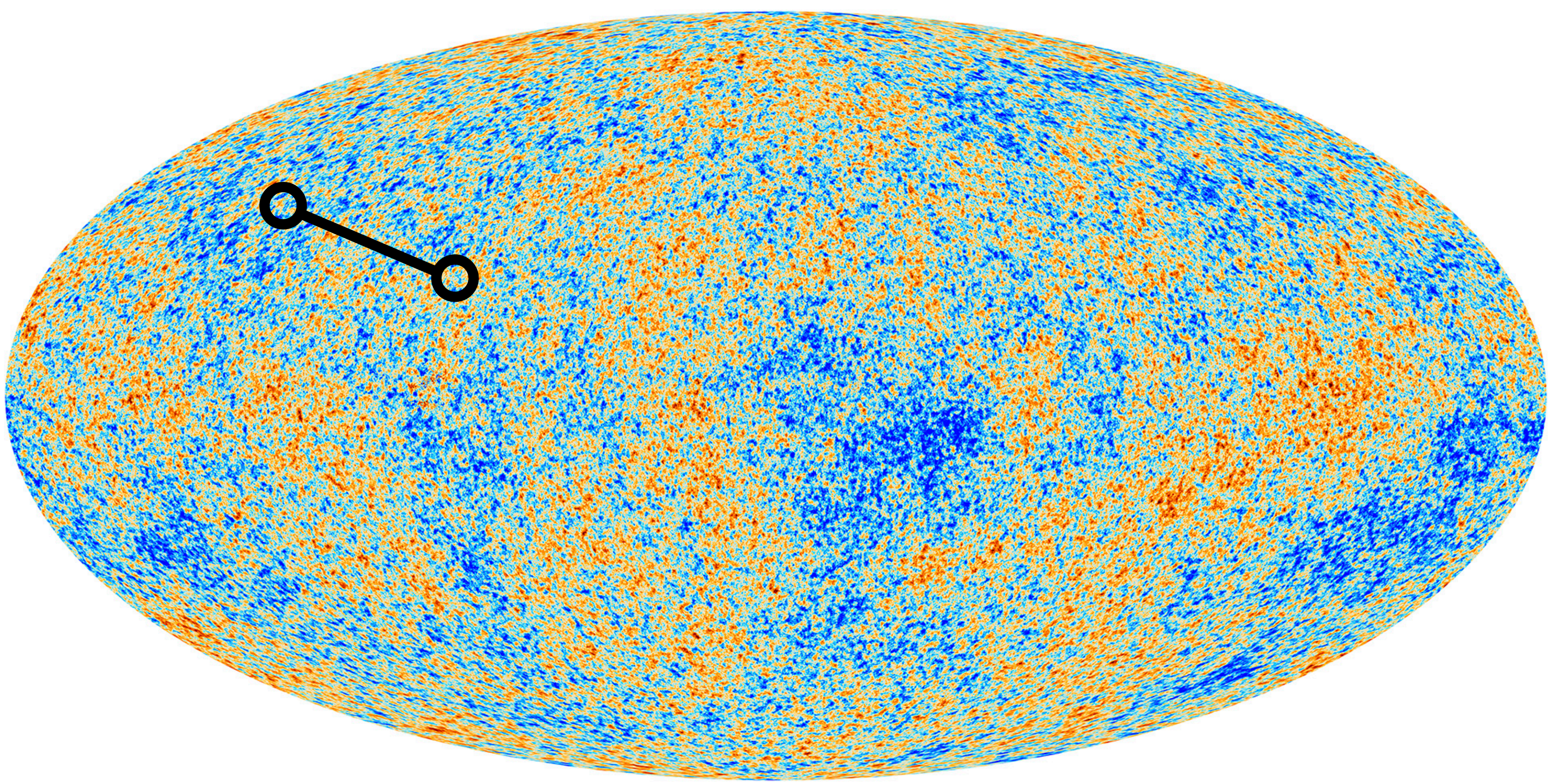

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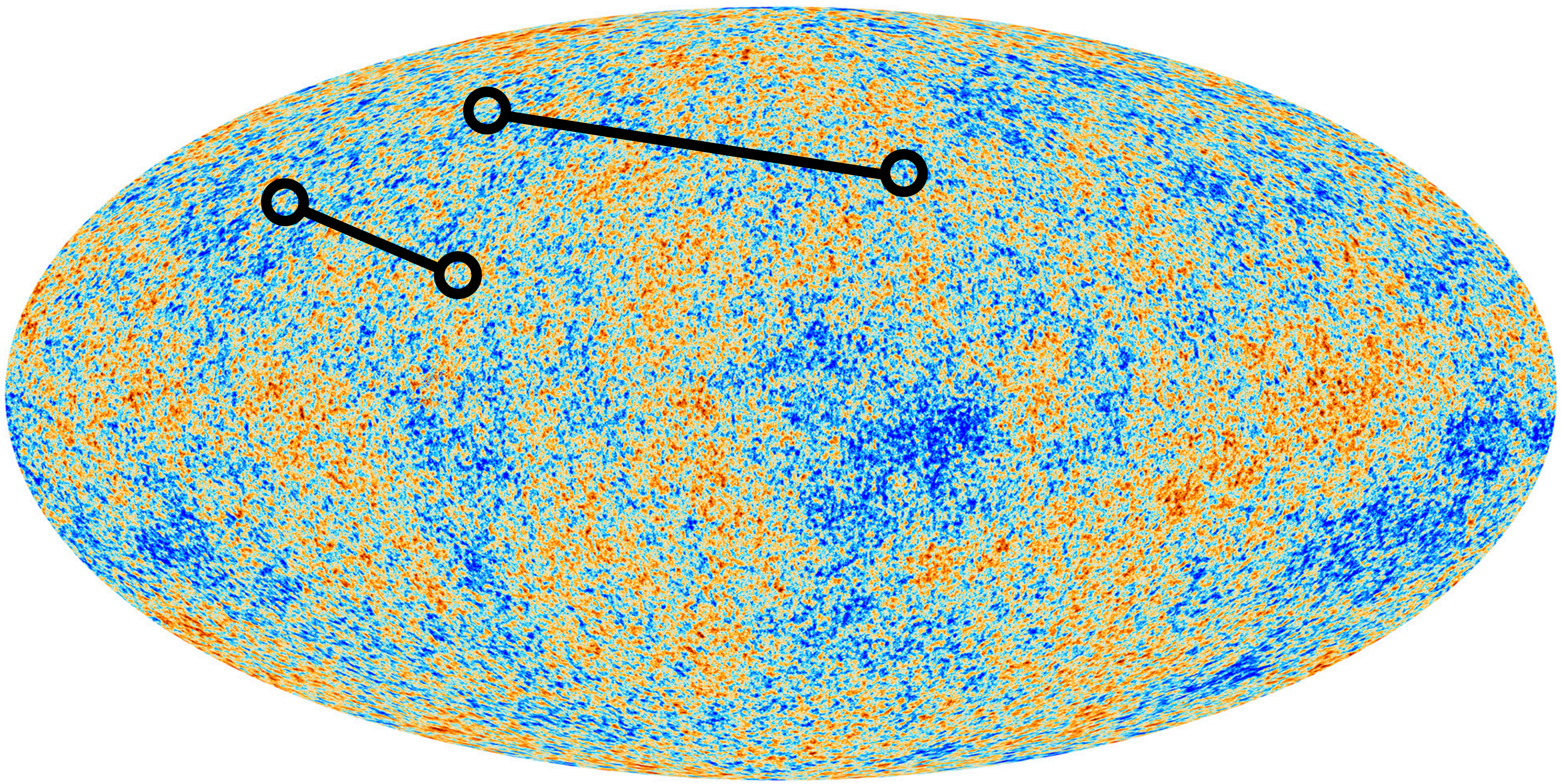

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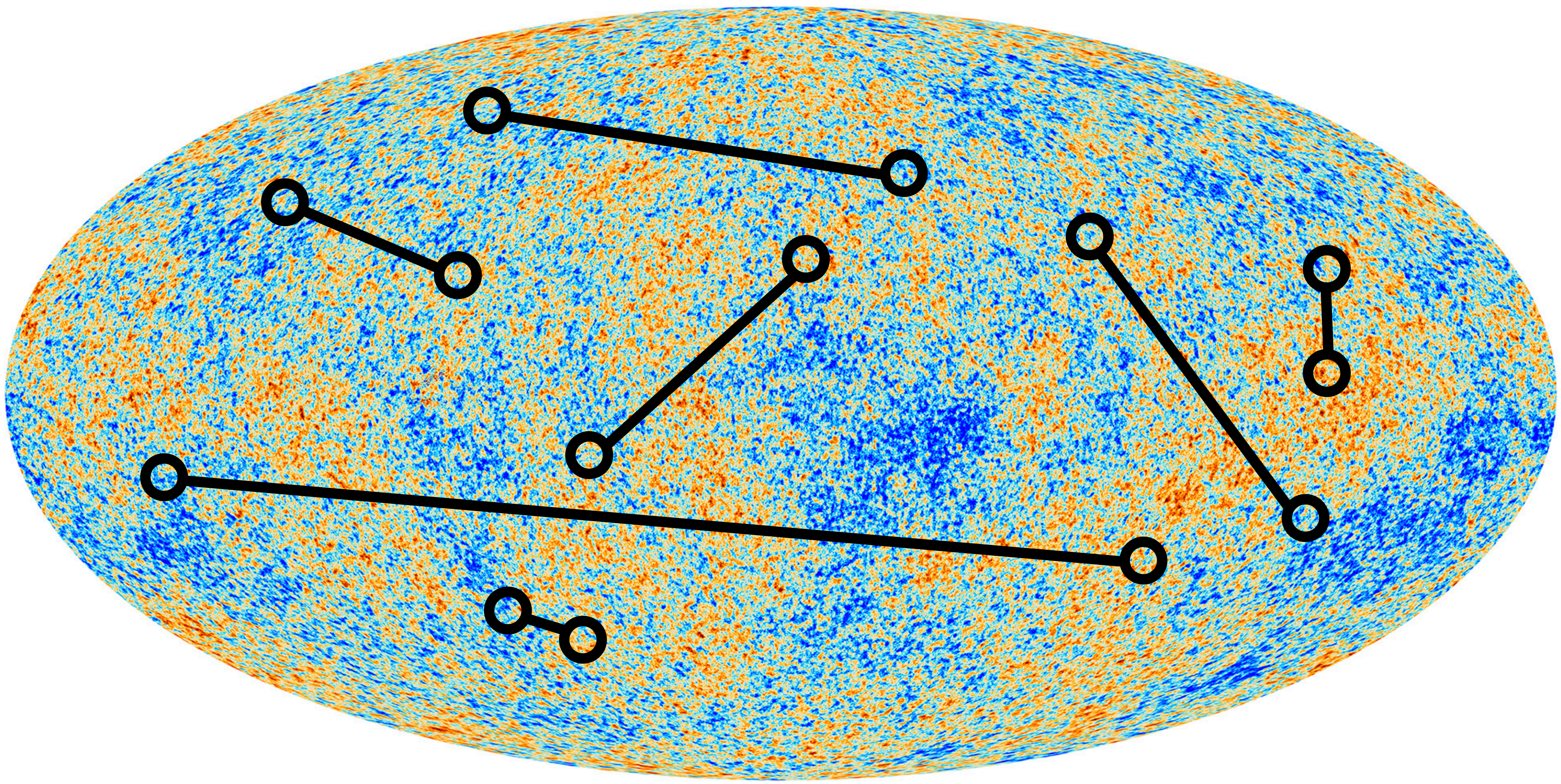

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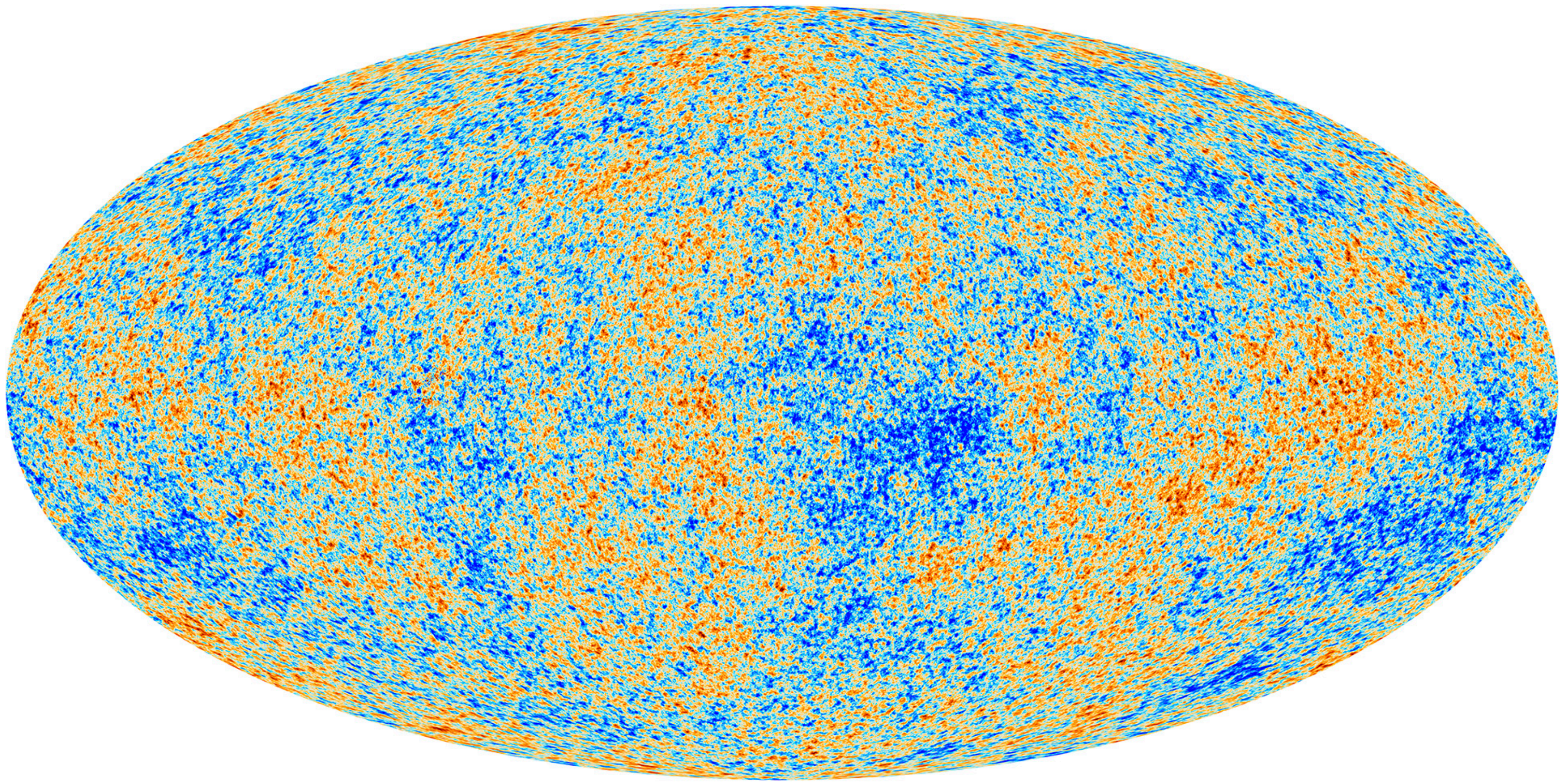

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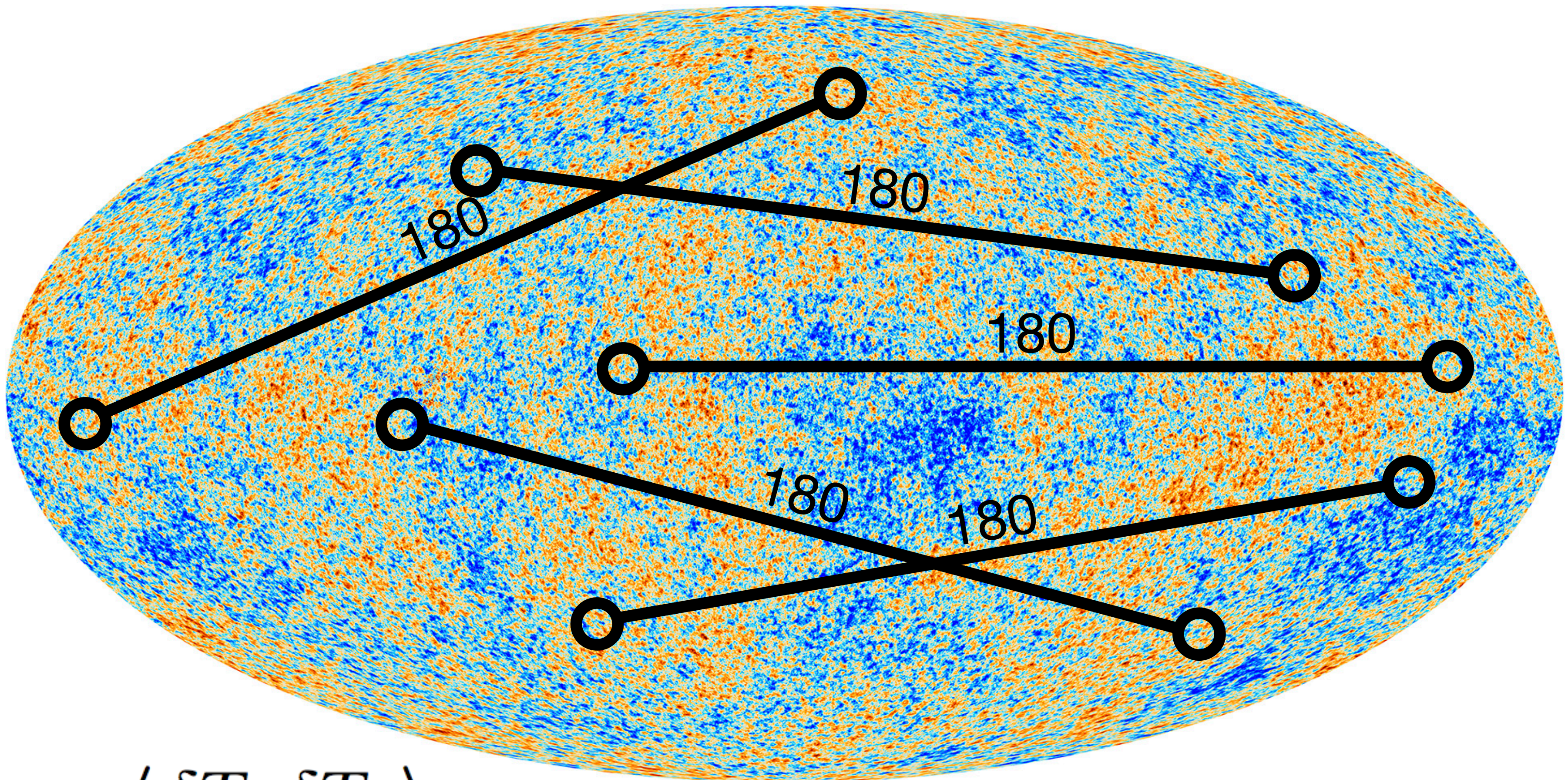

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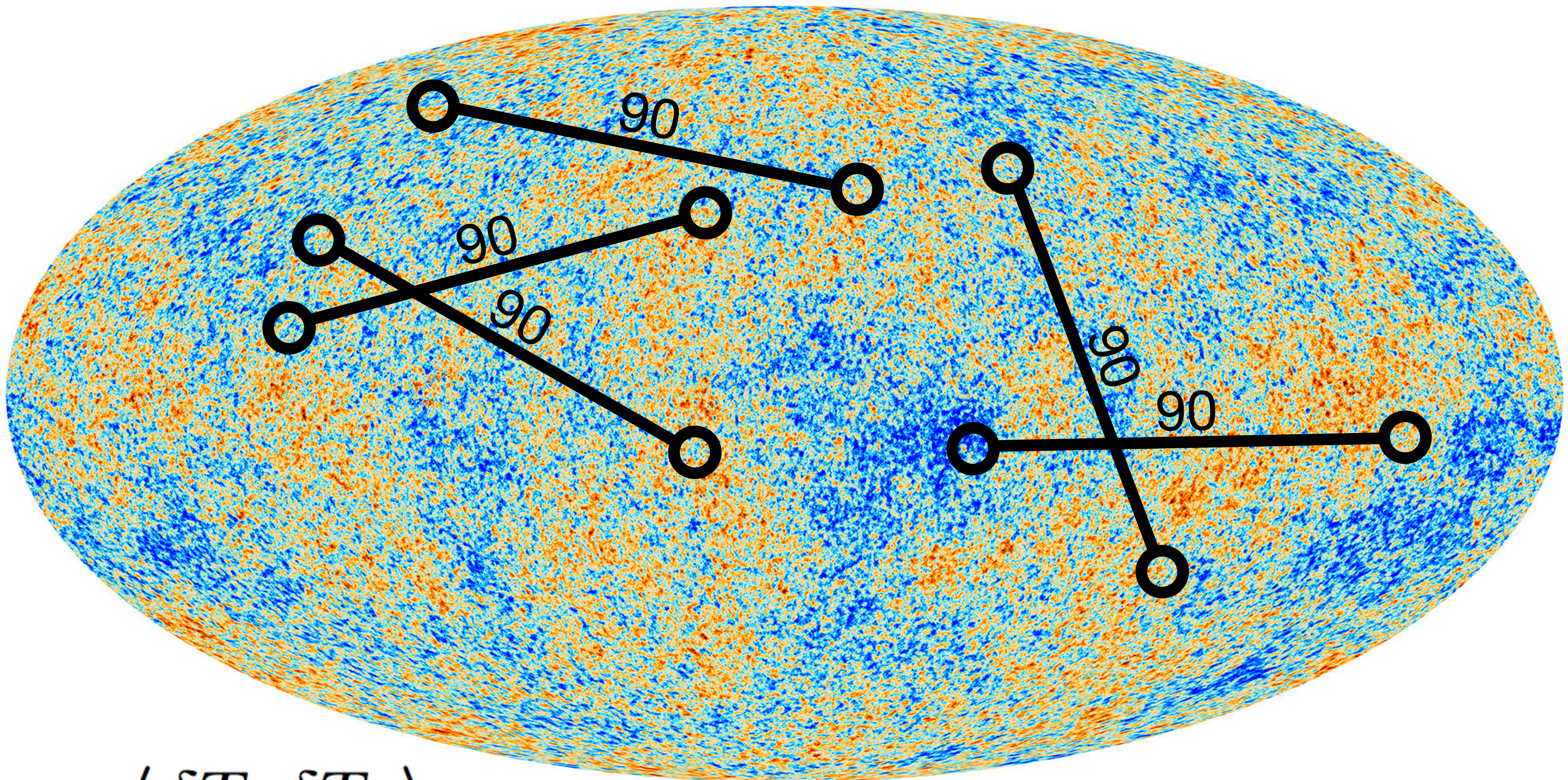

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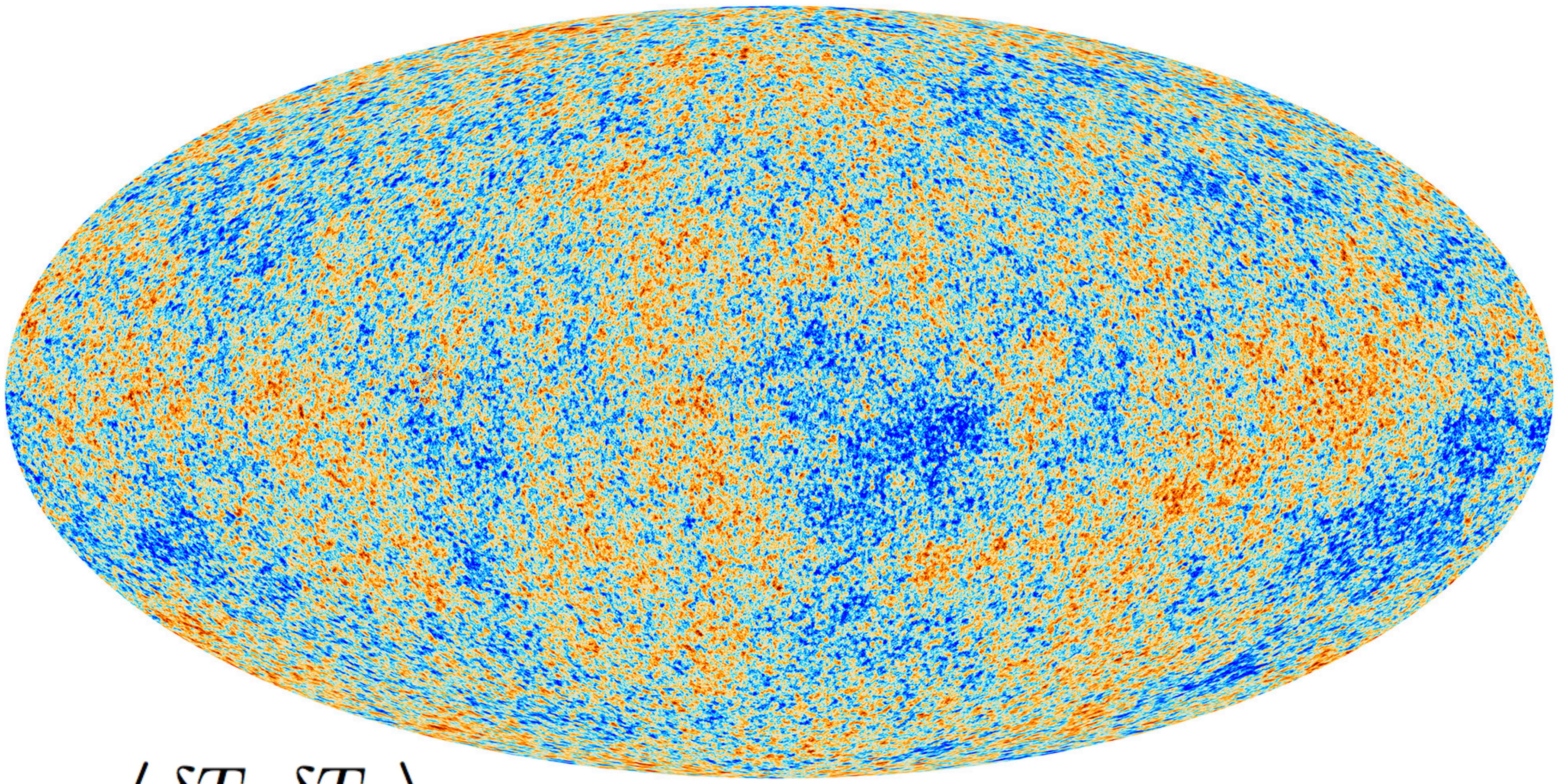

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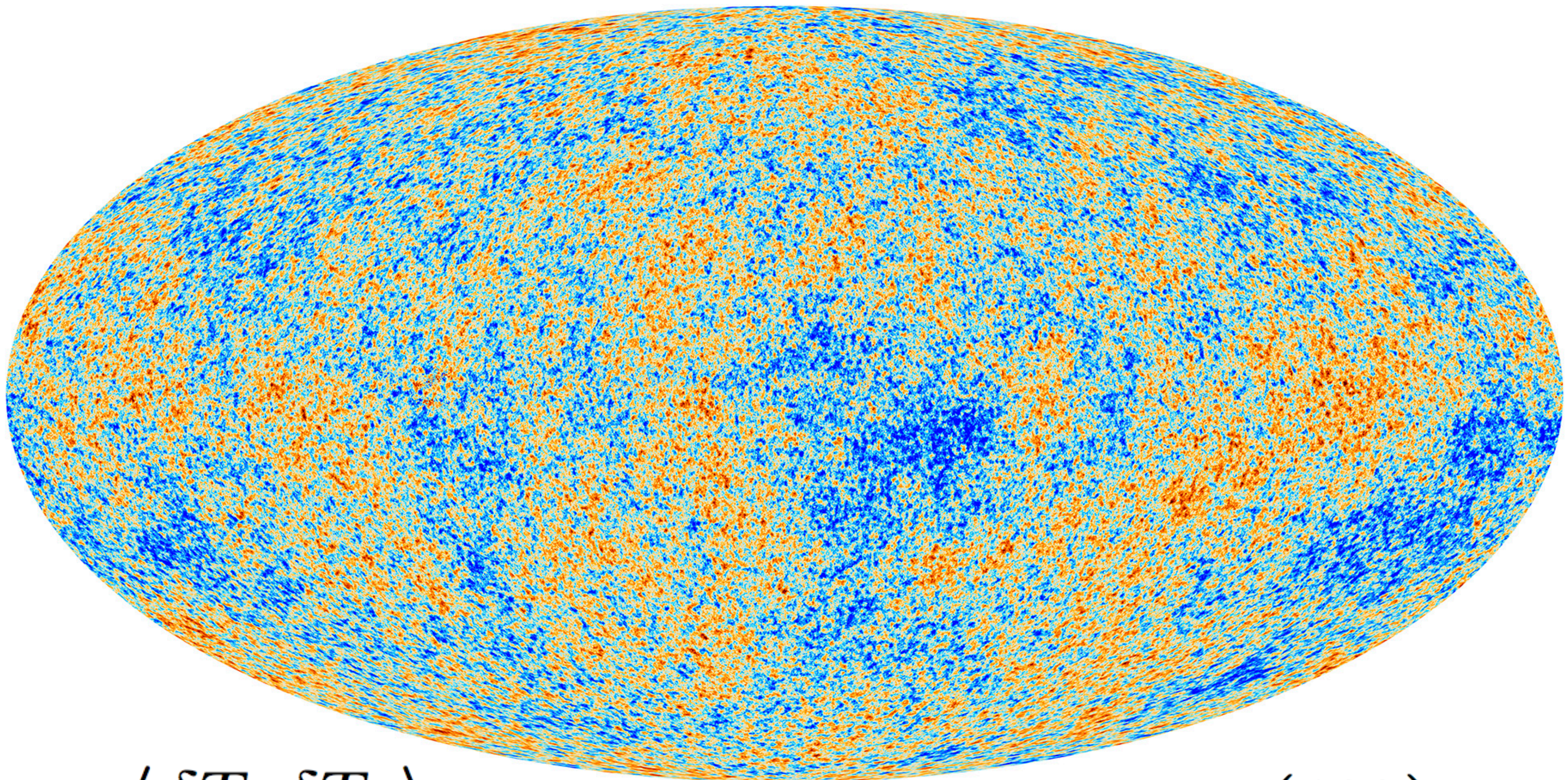

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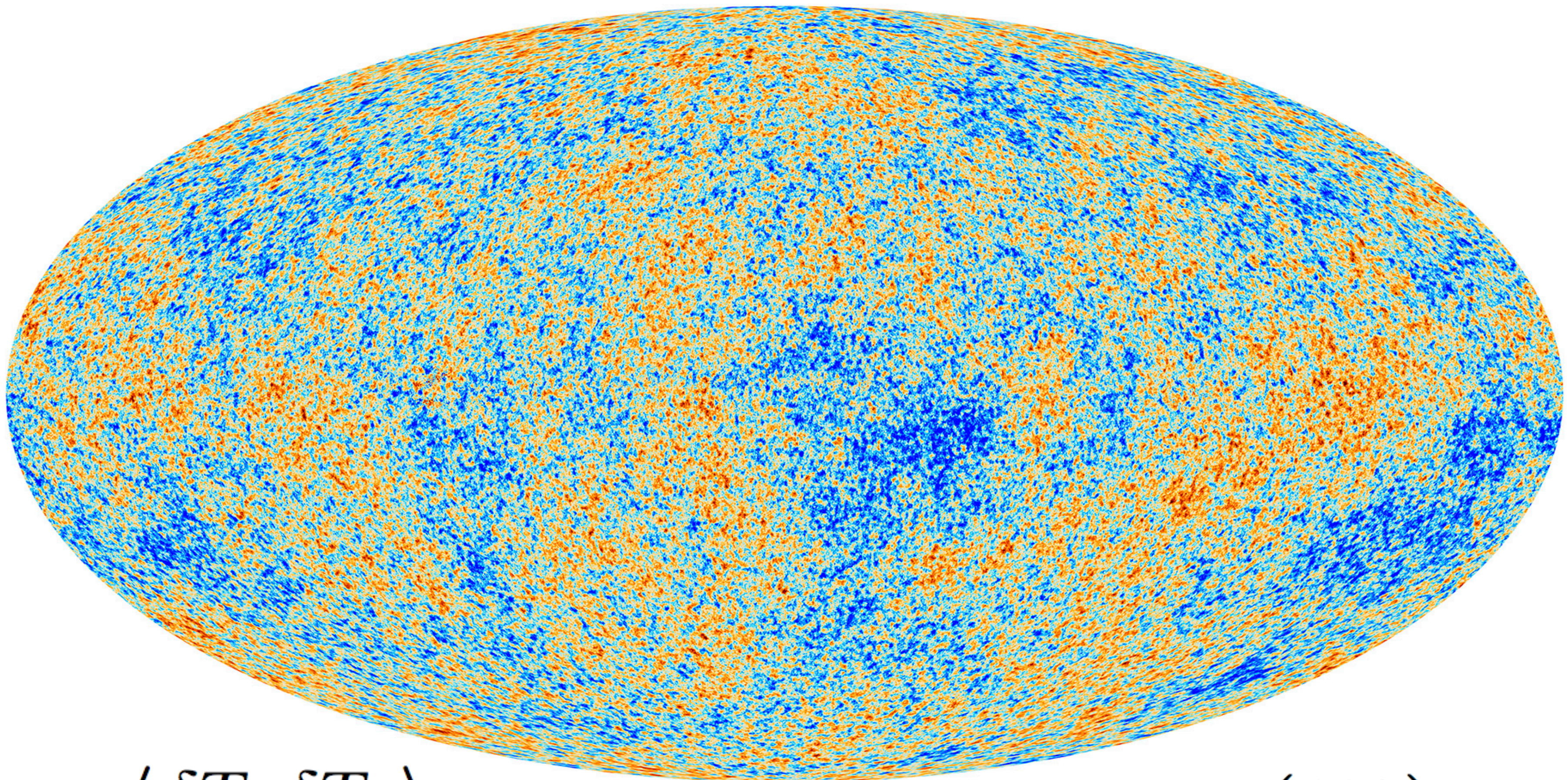

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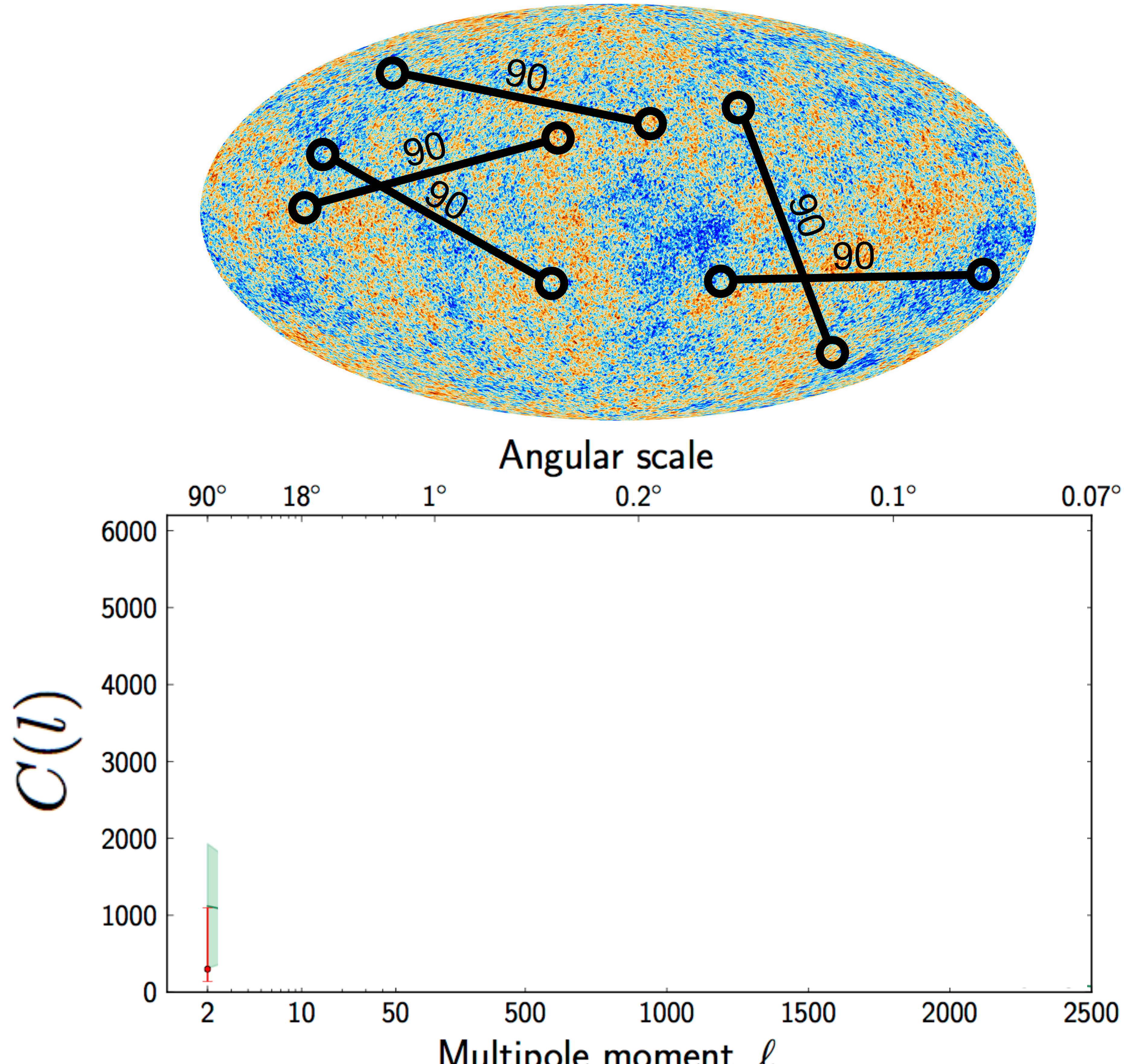
The CMB Power Spectrum



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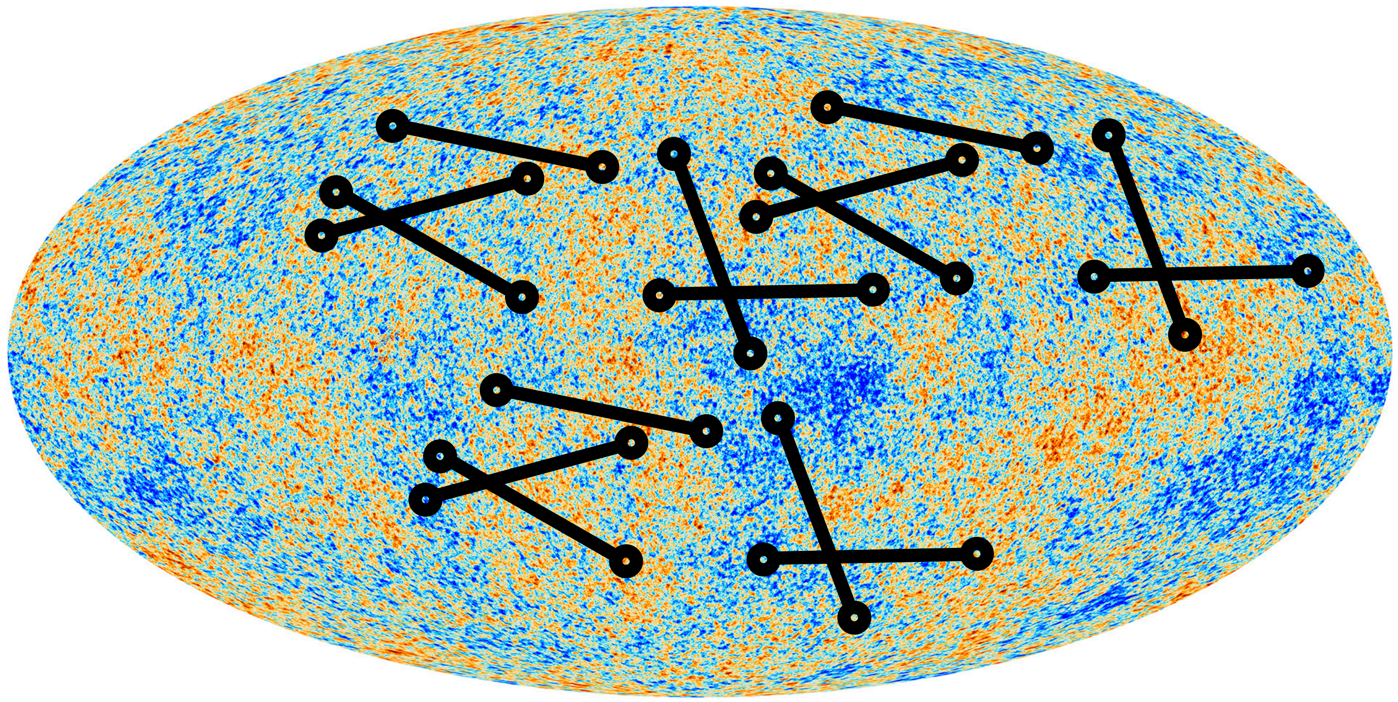

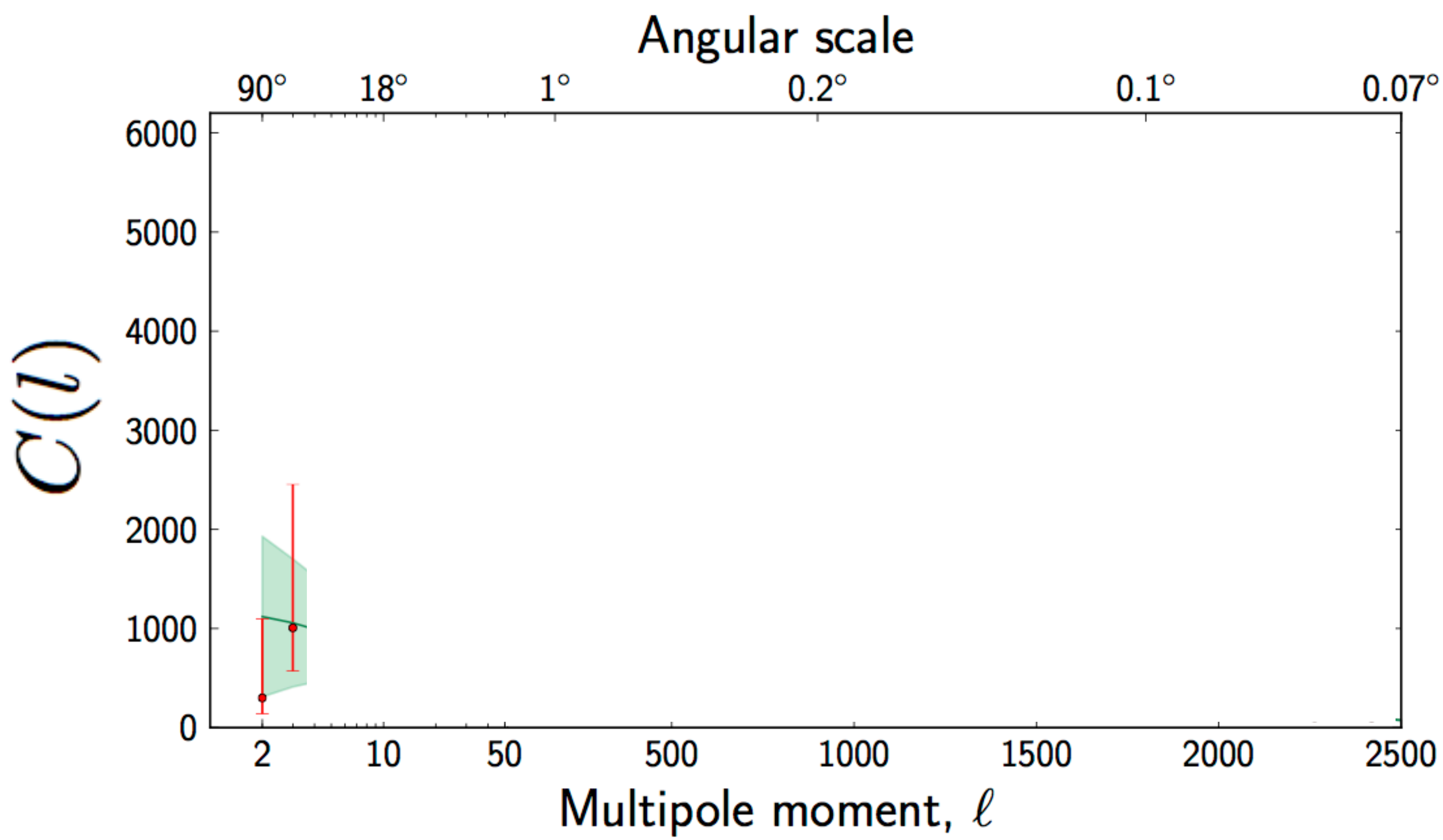

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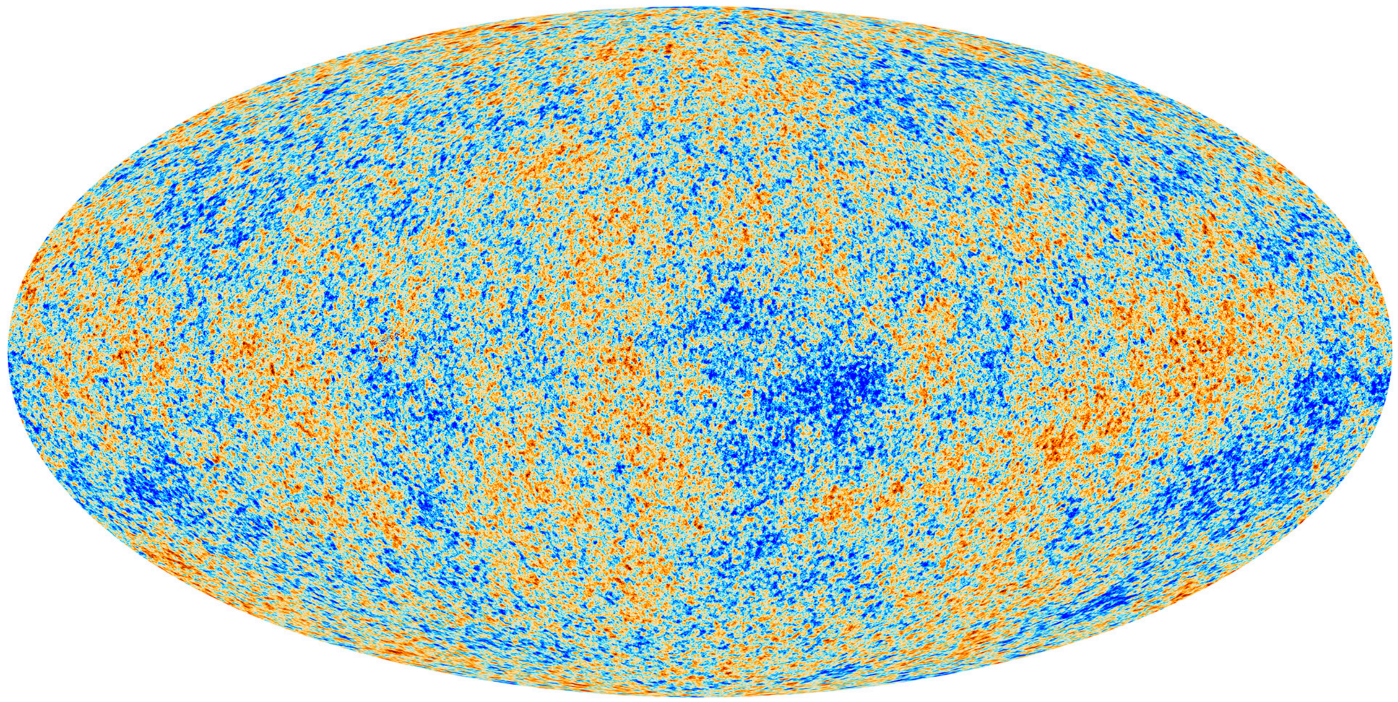

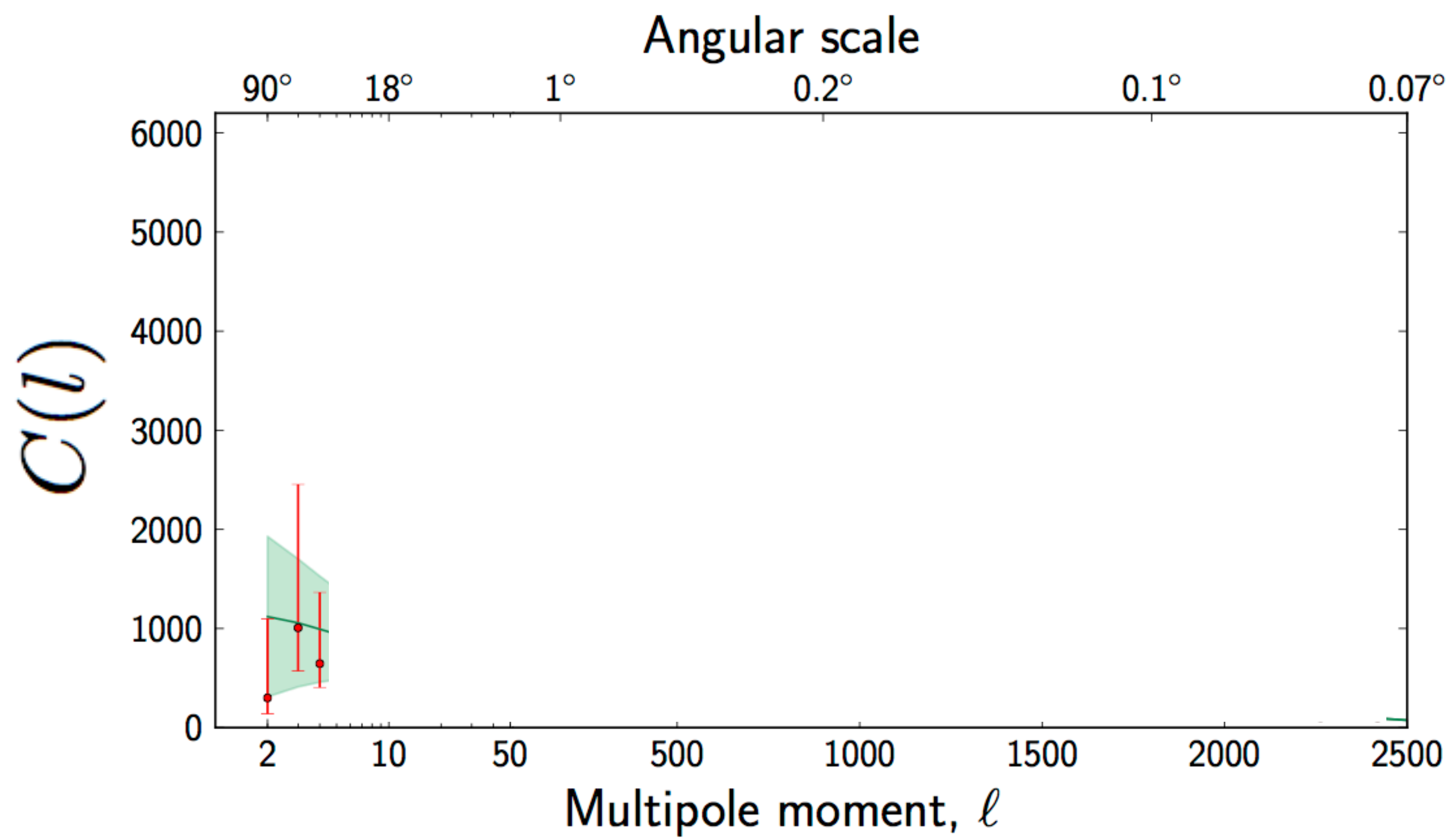

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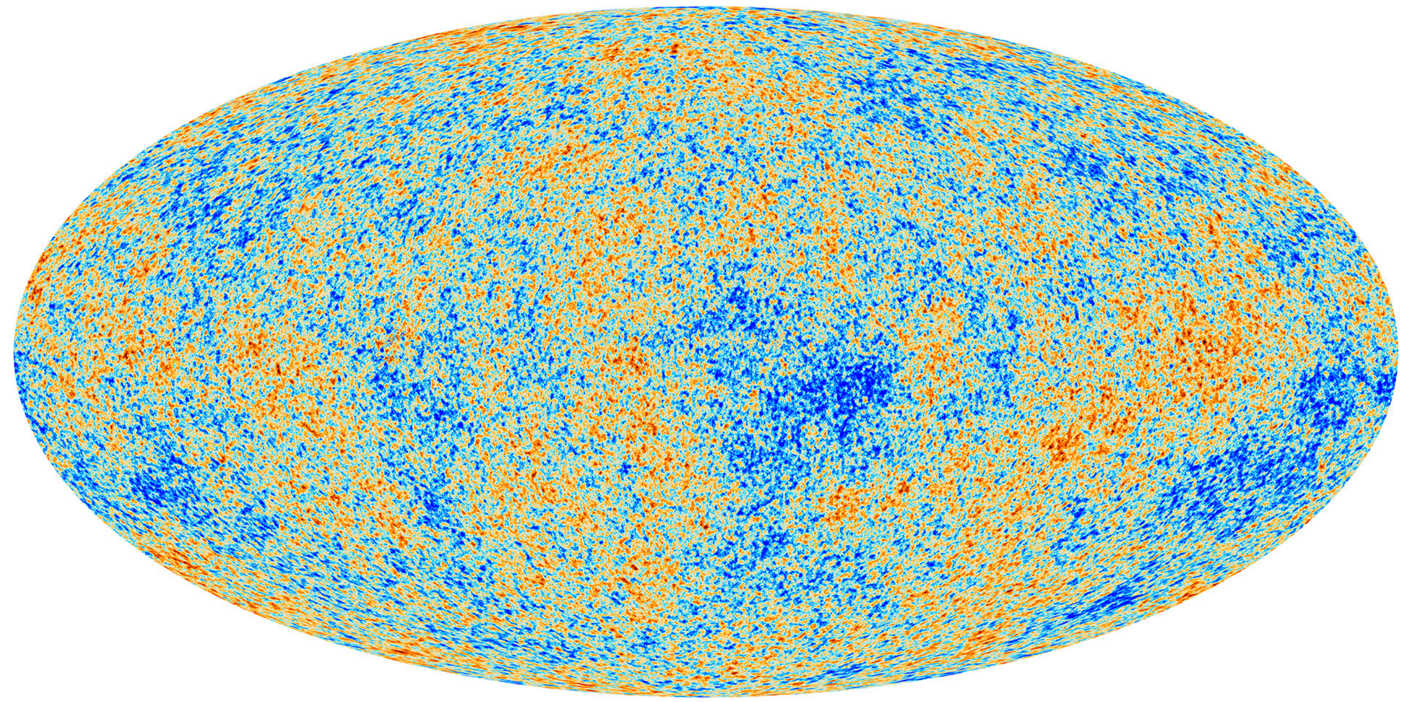

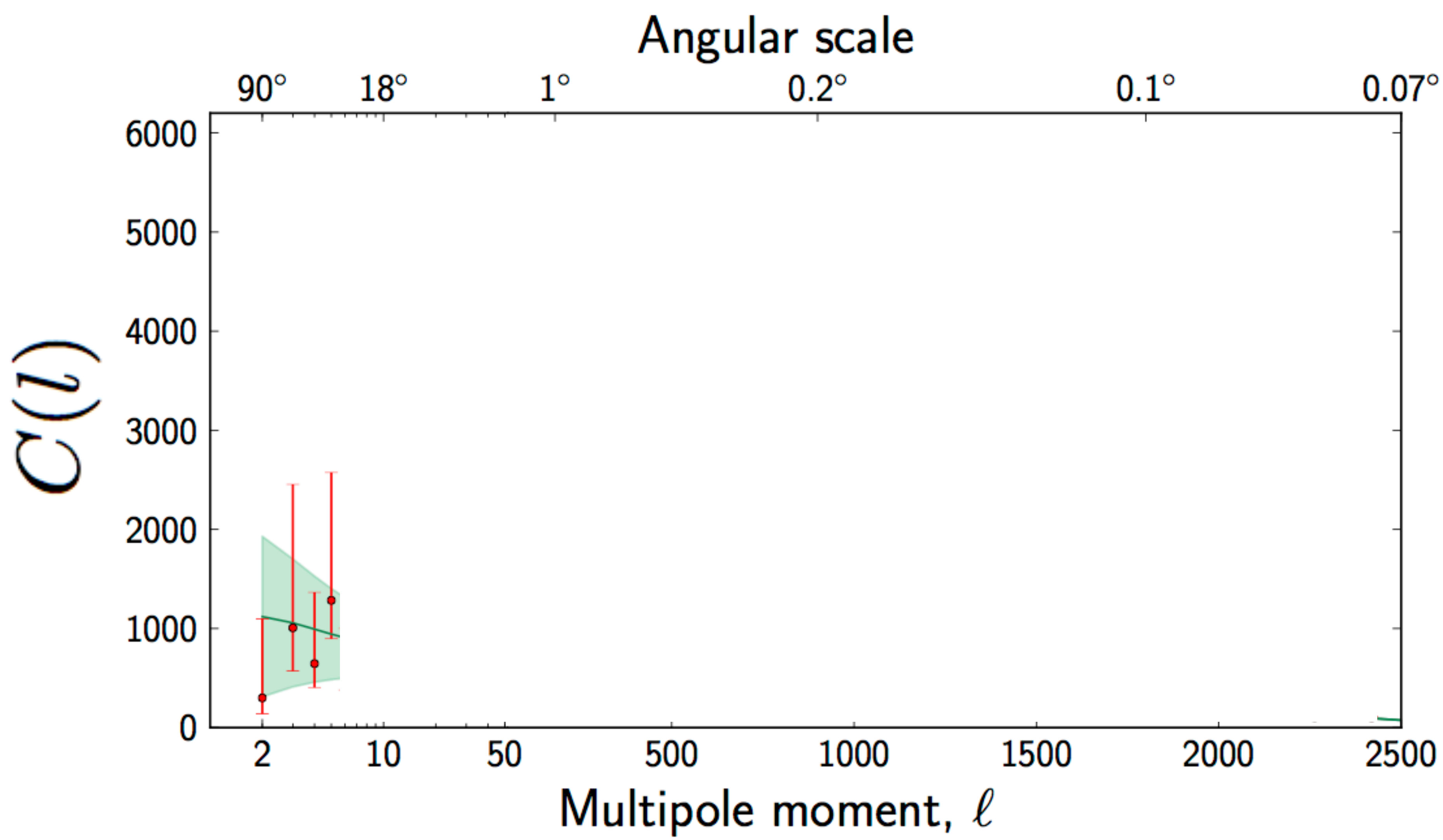

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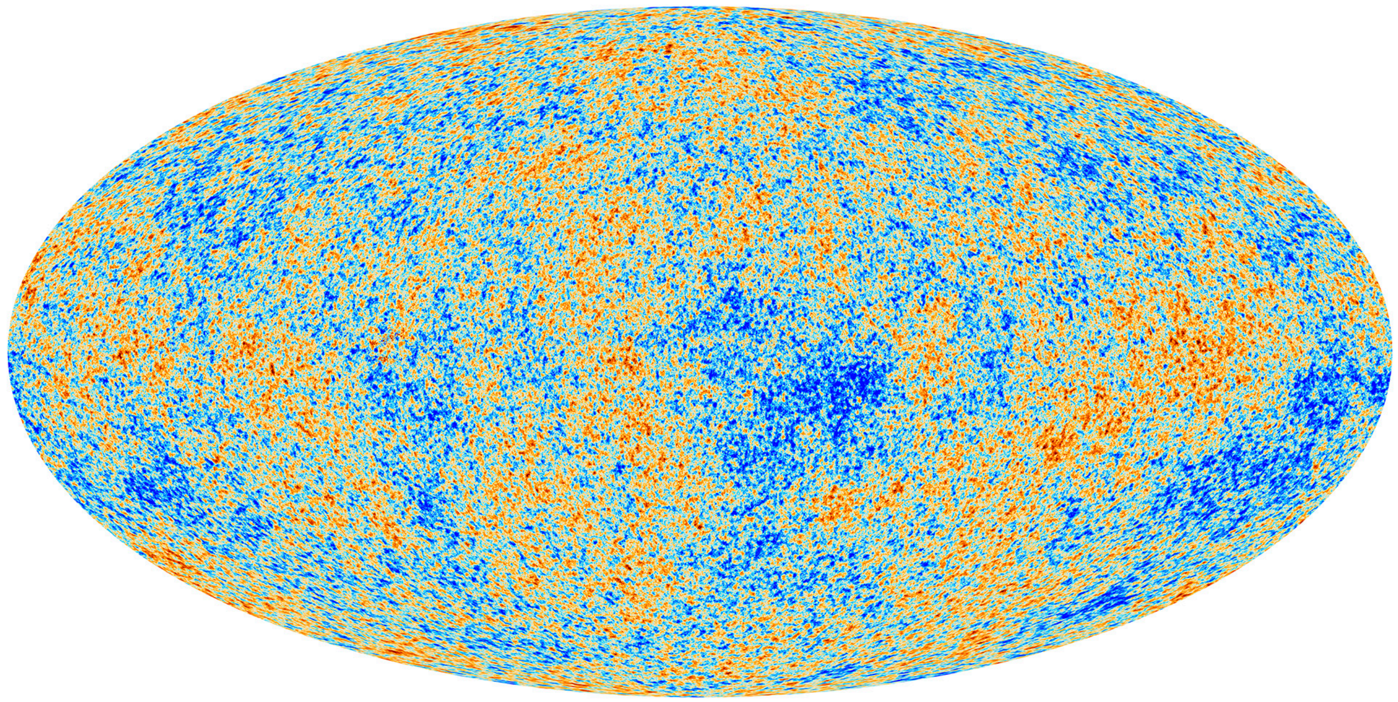
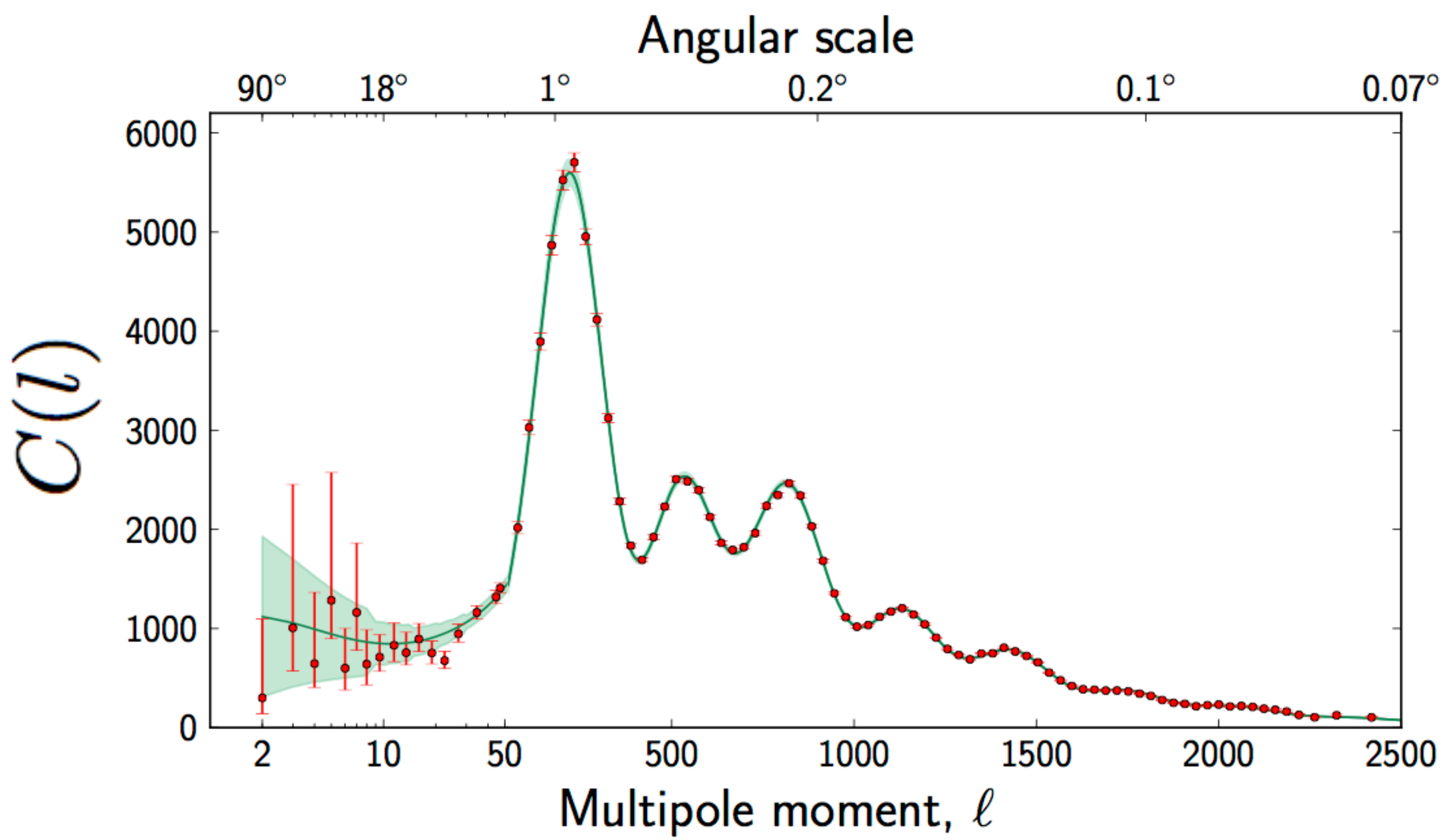
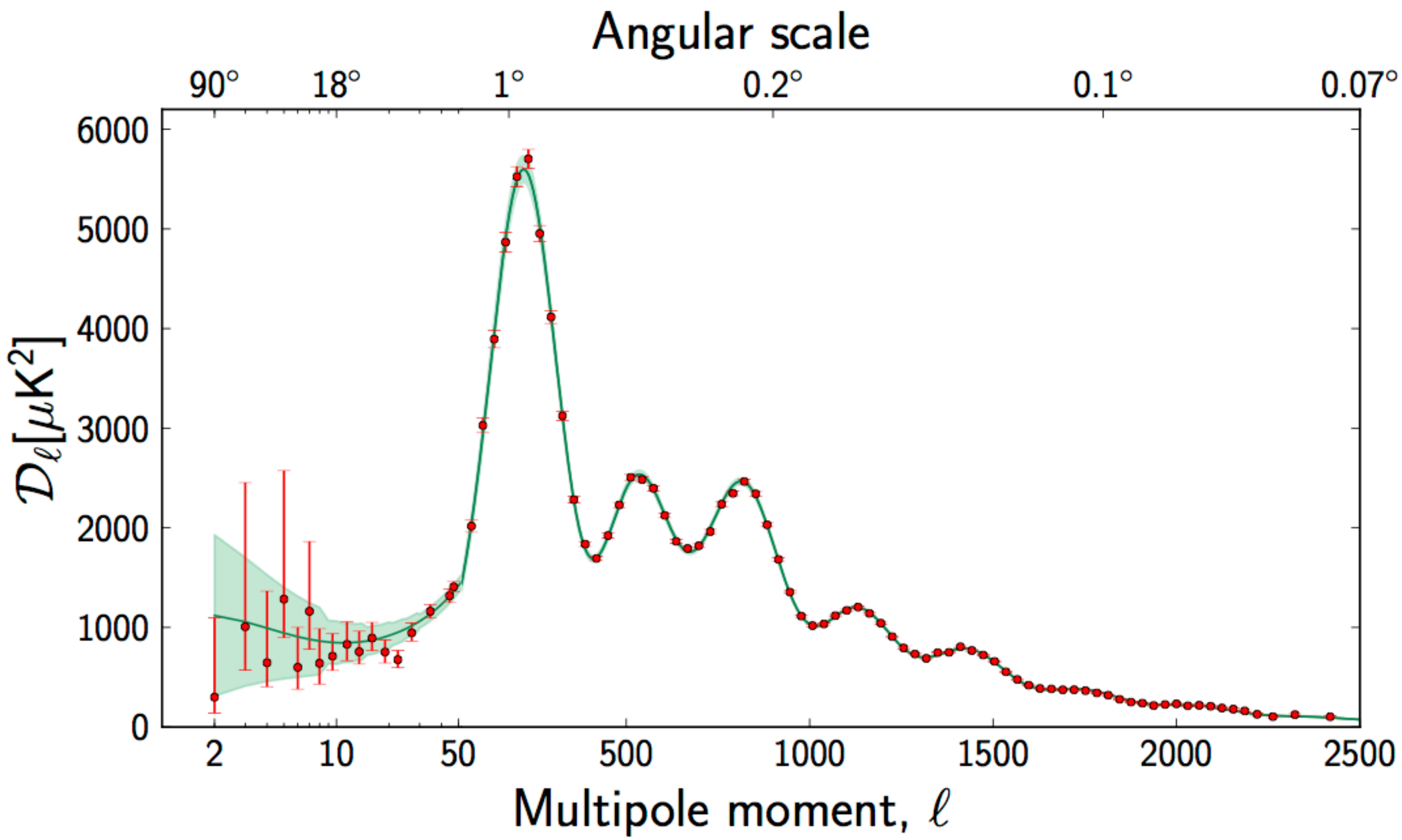




What causes the wiggles?



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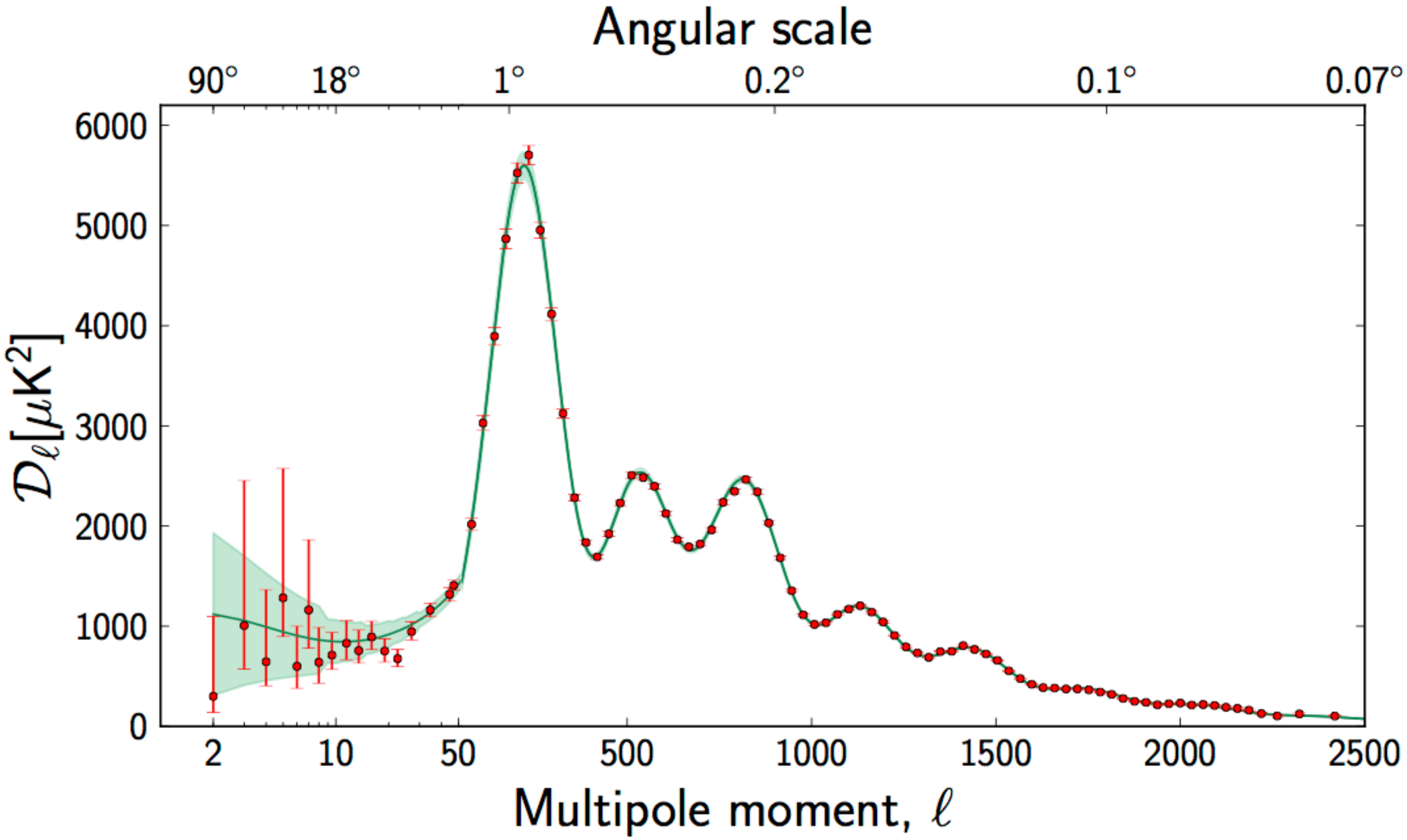

The strength of correlation at the different scales have different causes.

First, consider the horizon distance at the time of last scattering — the distance that light has had time to travel since the Big Bang:

$$d_{\mathrm{hor}} = a(t_{\mathrm{ls}})c\int_0^{t_{\mathrm{ls}}} \frac{dt}{a(t)} = 2.24t_{\mathrm{ls}} = 0.251\ \mathrm{Mpc}$$

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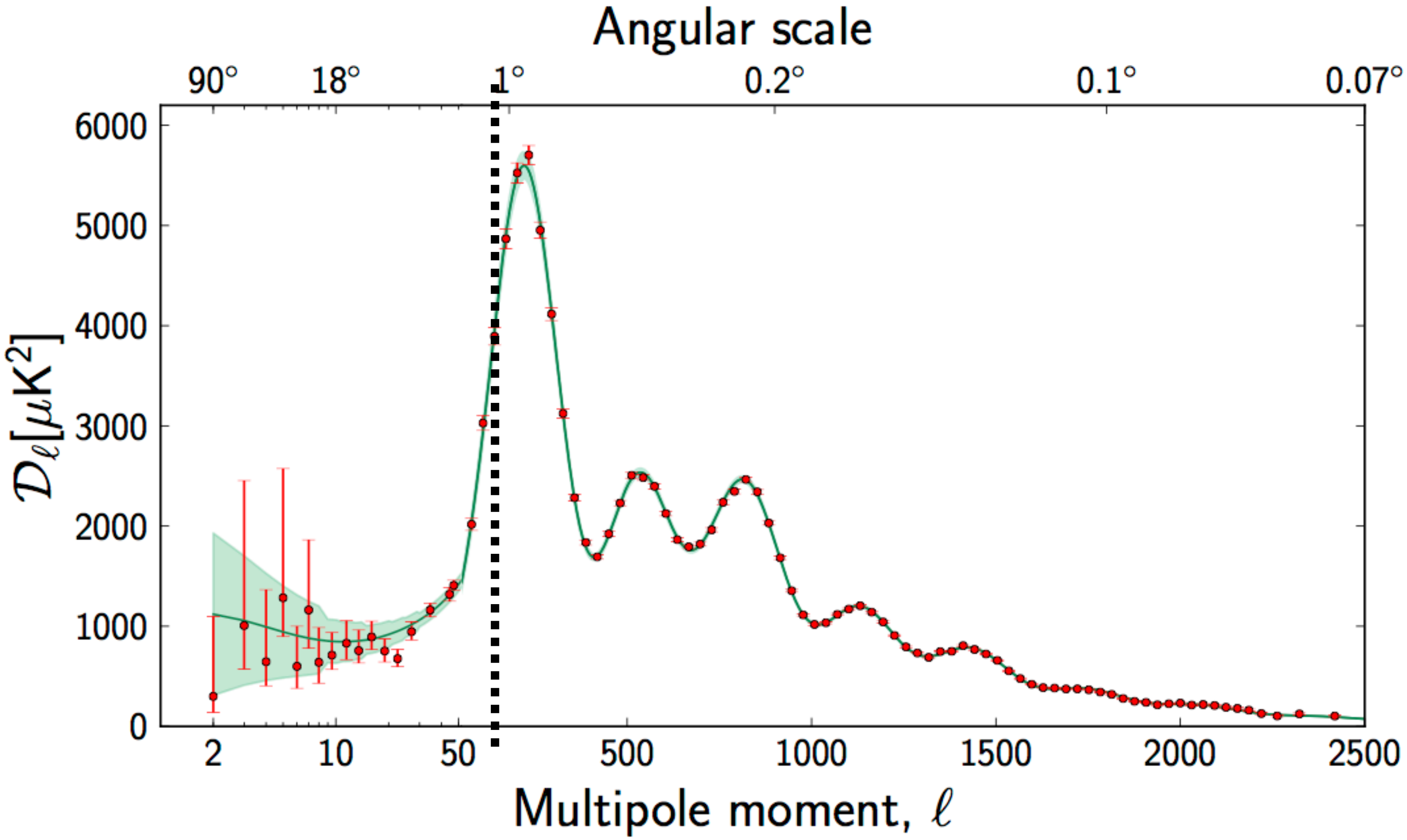

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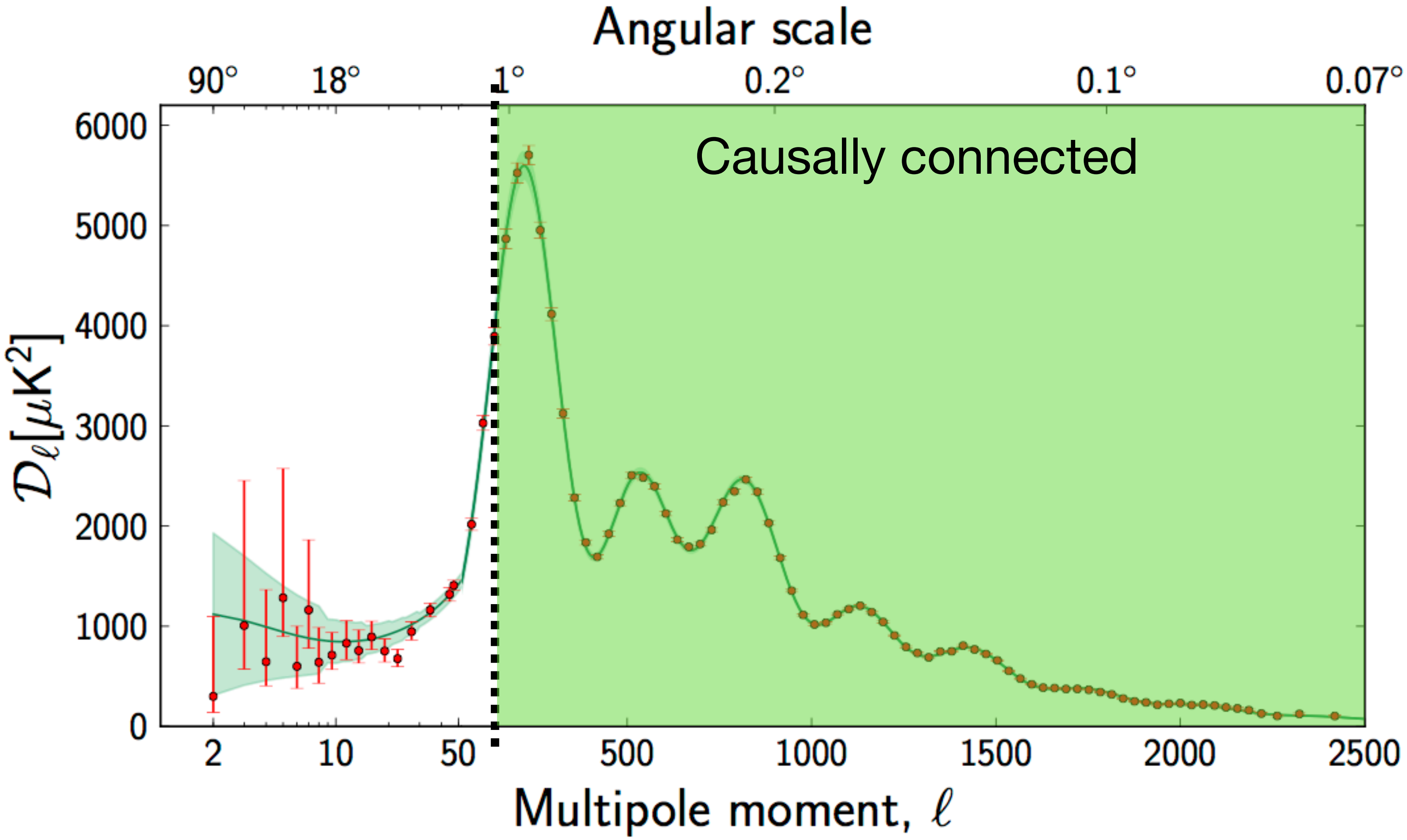

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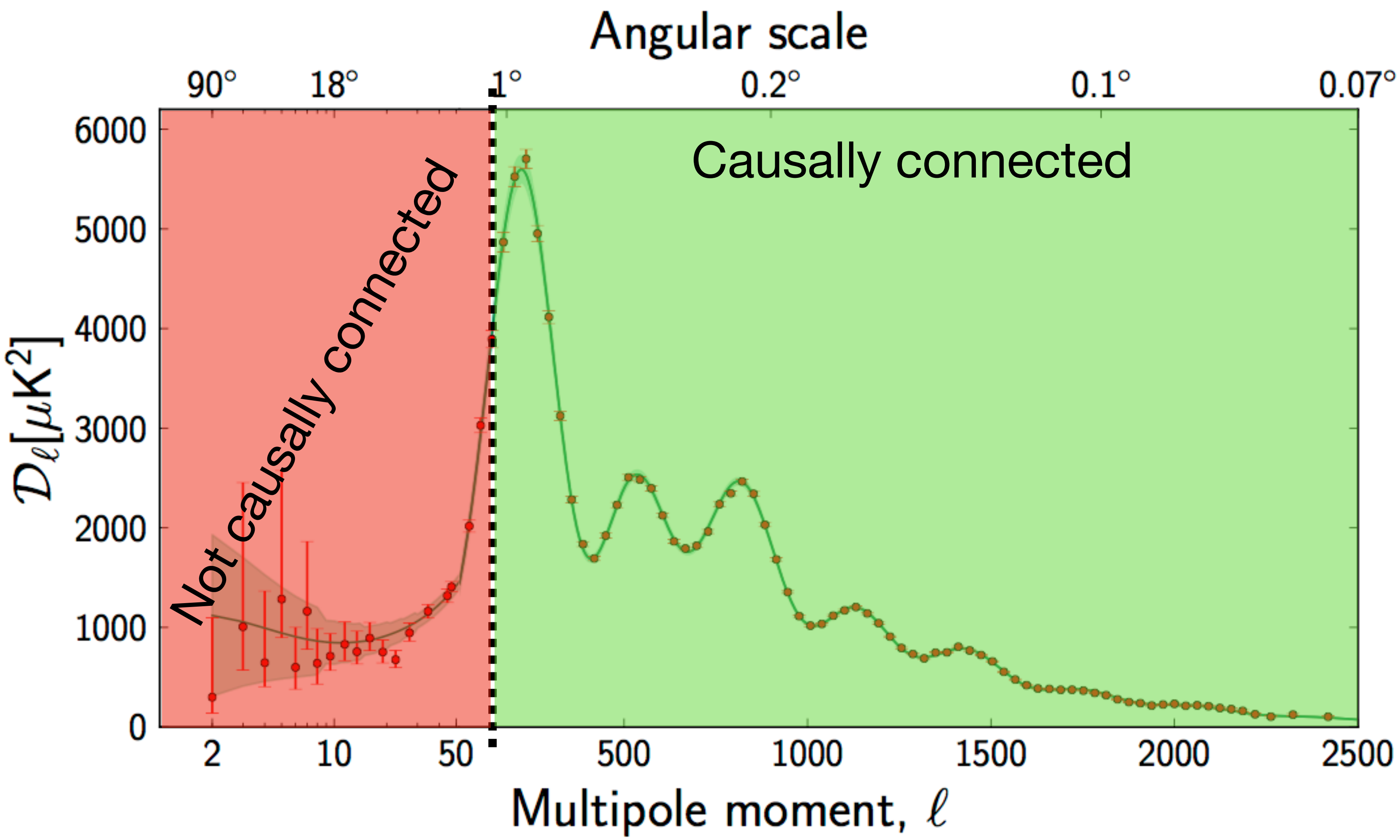

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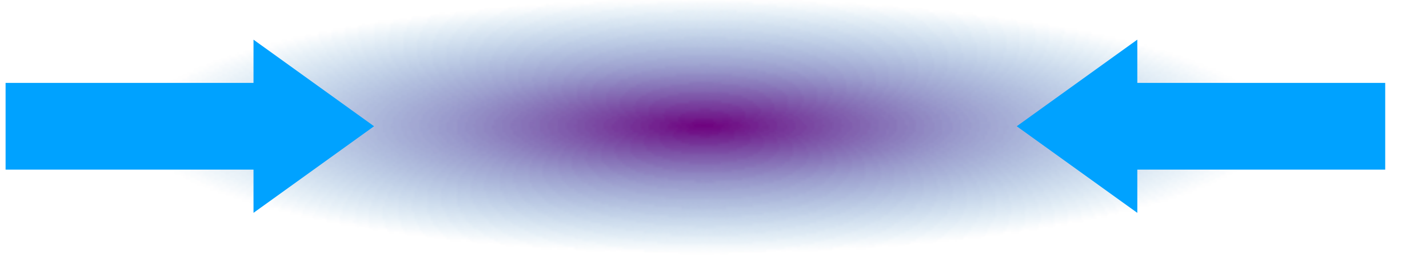
The cause of the first peak

Prior to the time of last scattering, photons and baryons were coupled, forming a photon-baryon fluid.

But, dark matter dominated the gravitational potential, so the fluid moved under the influence of gravity from dark matter.

As the fluid flows to regions of high dark matter density, the density of the fluid increases.



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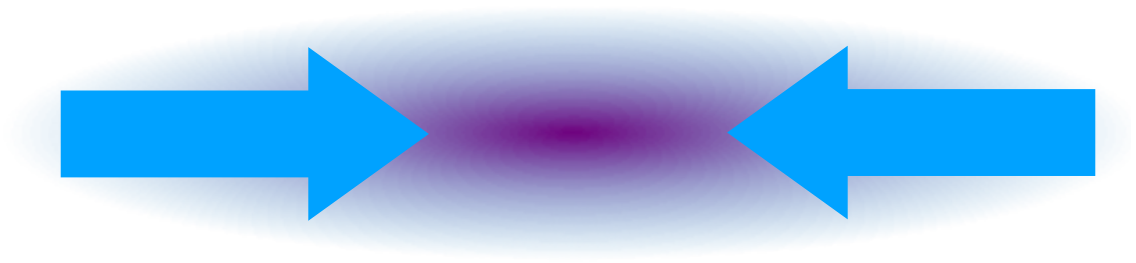

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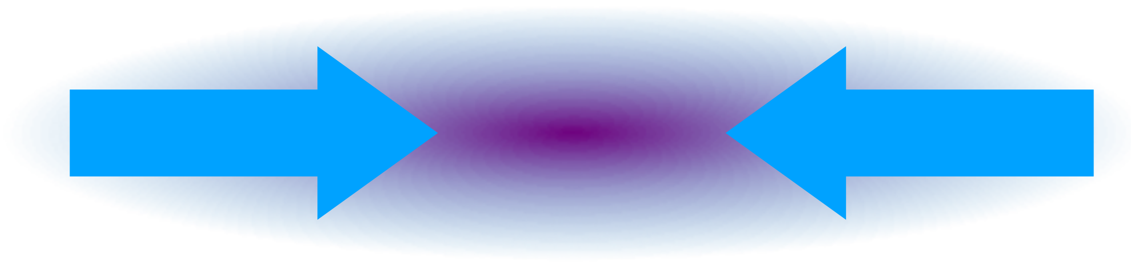

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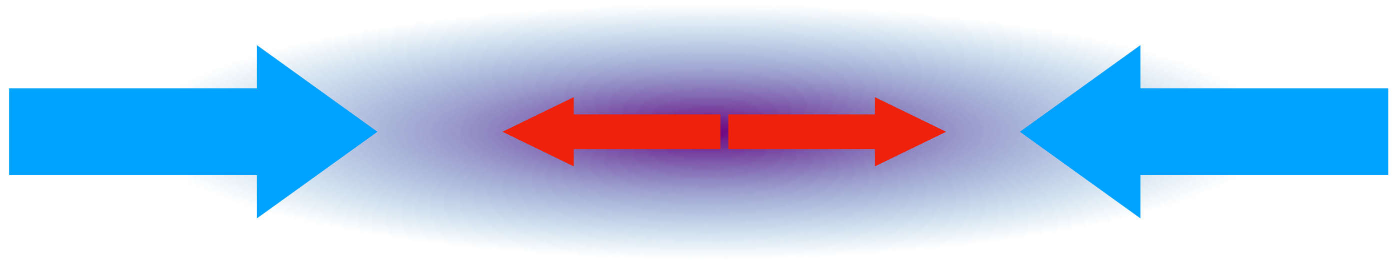

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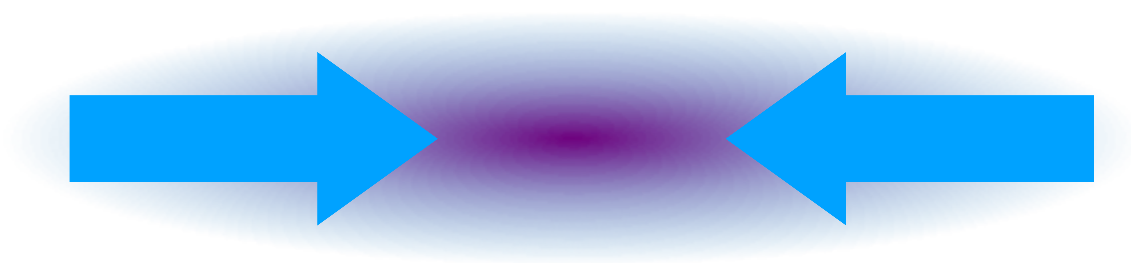

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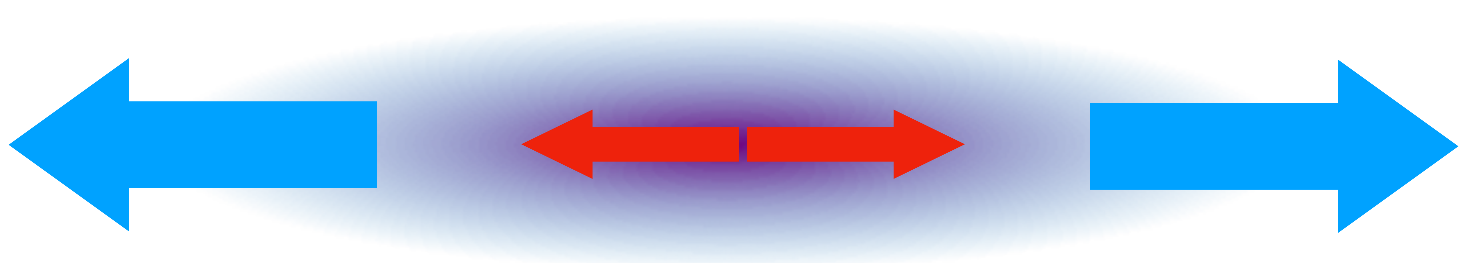

The cause of the first peak

We therefore have a attracting force (gravity) and a restoring force that is proportional to the compression of the fluid.

As 3rd-year physics students, you should be familiar with this situation.

It is also known as…

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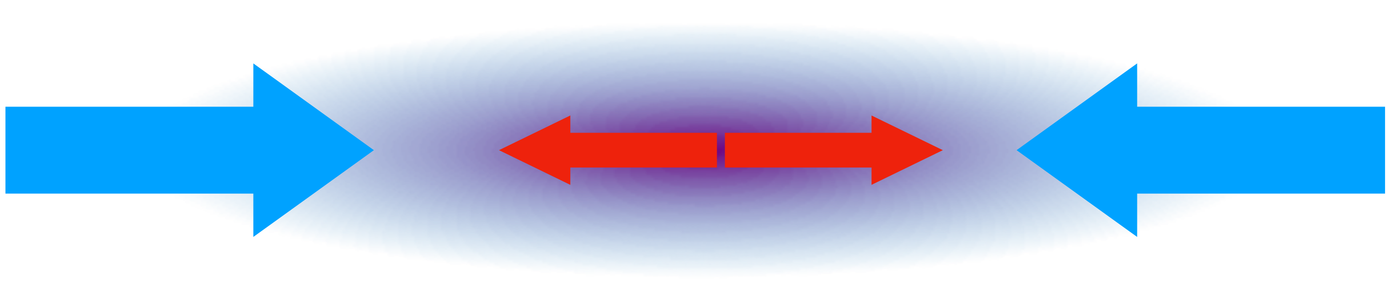
A Simple Harmonic Oscillator

And a SHO embedded in a dense fluid creates…



The cause of the first peak

We therefore have a attracting force (gravity) and a restoring force that is proportional to the compression of the fluid.

As 3rd-year physics students, you should be familiar with this situation.

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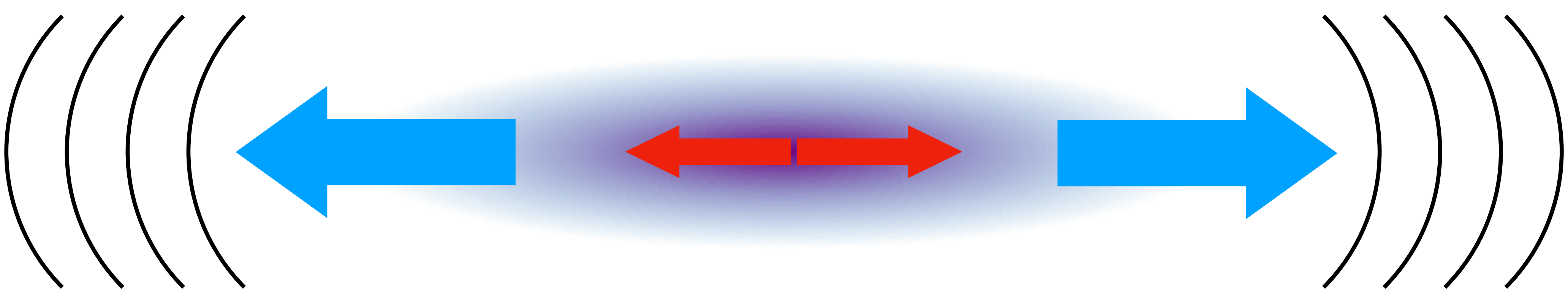

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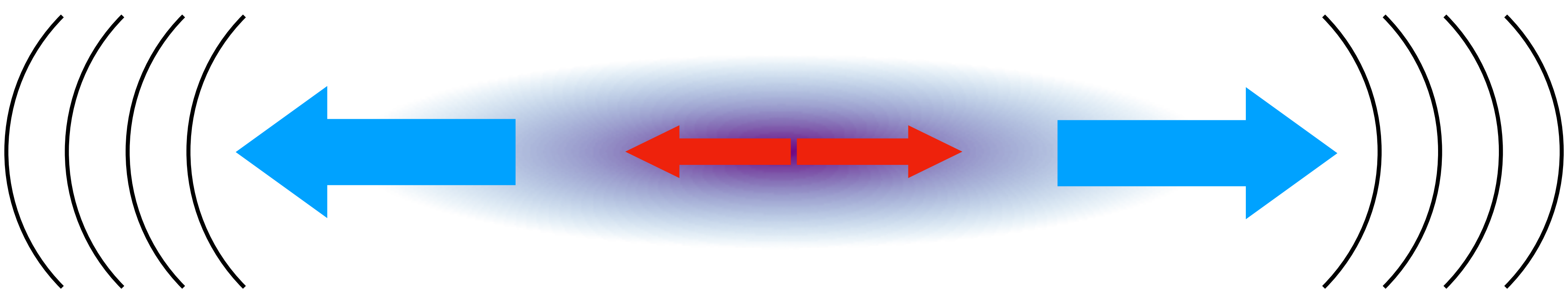

Sound waves

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By the time the photons decouple from the baryons at the time of recombination, this sound wave has travelled a distance:

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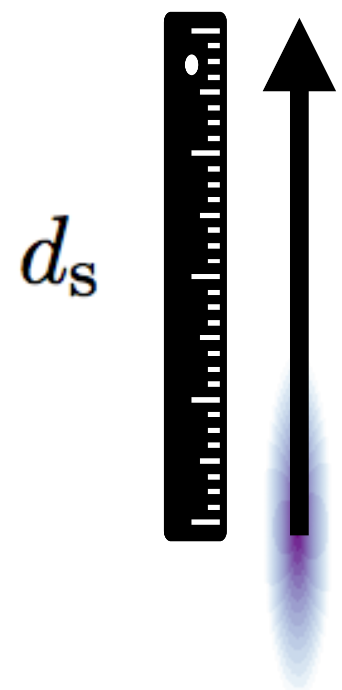

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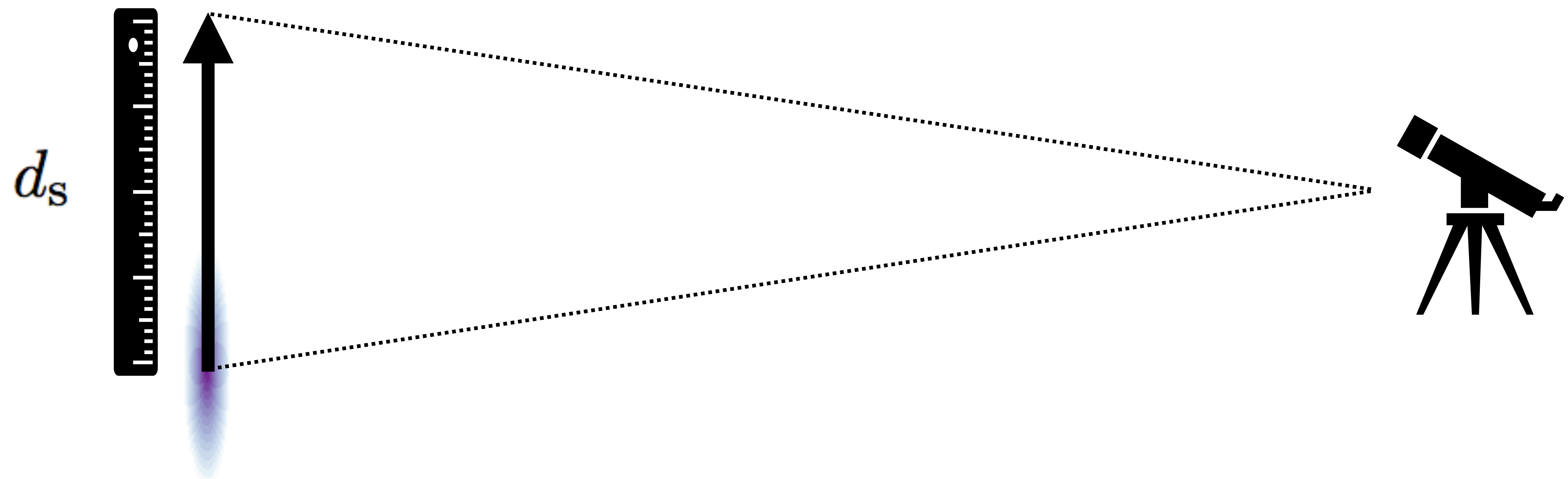

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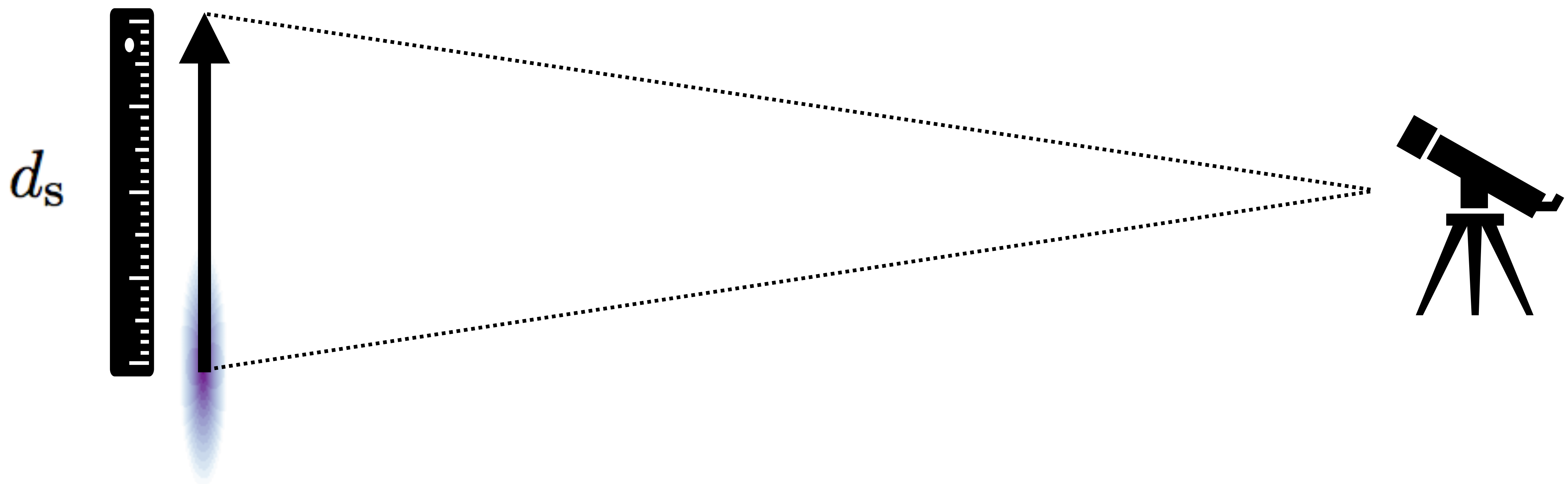

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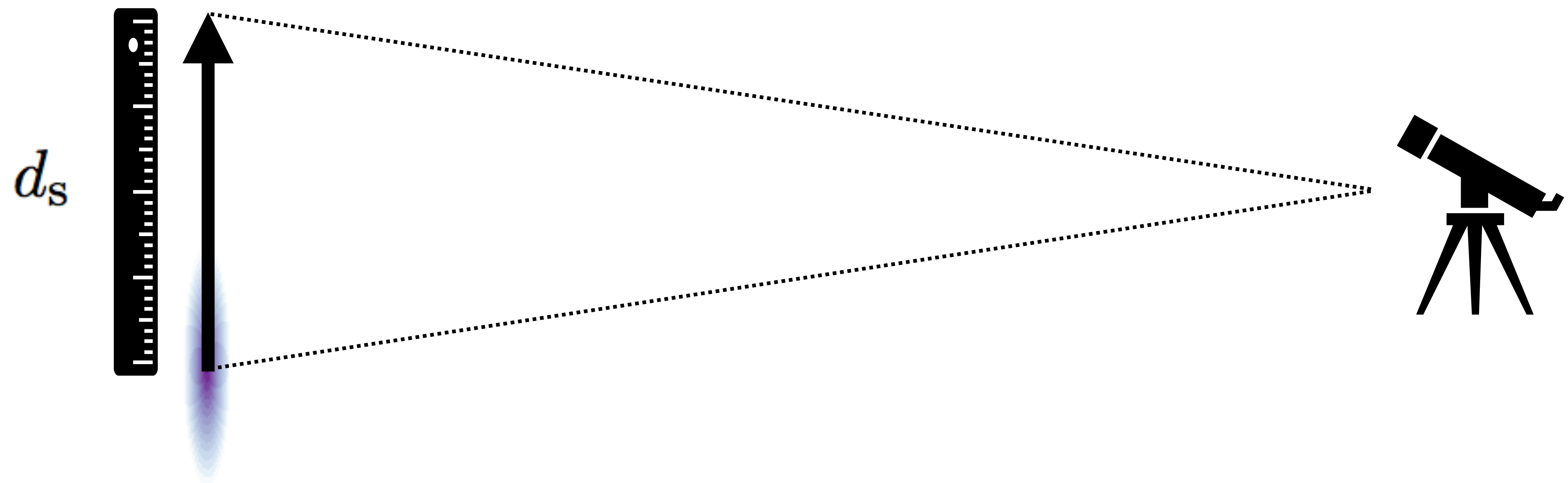

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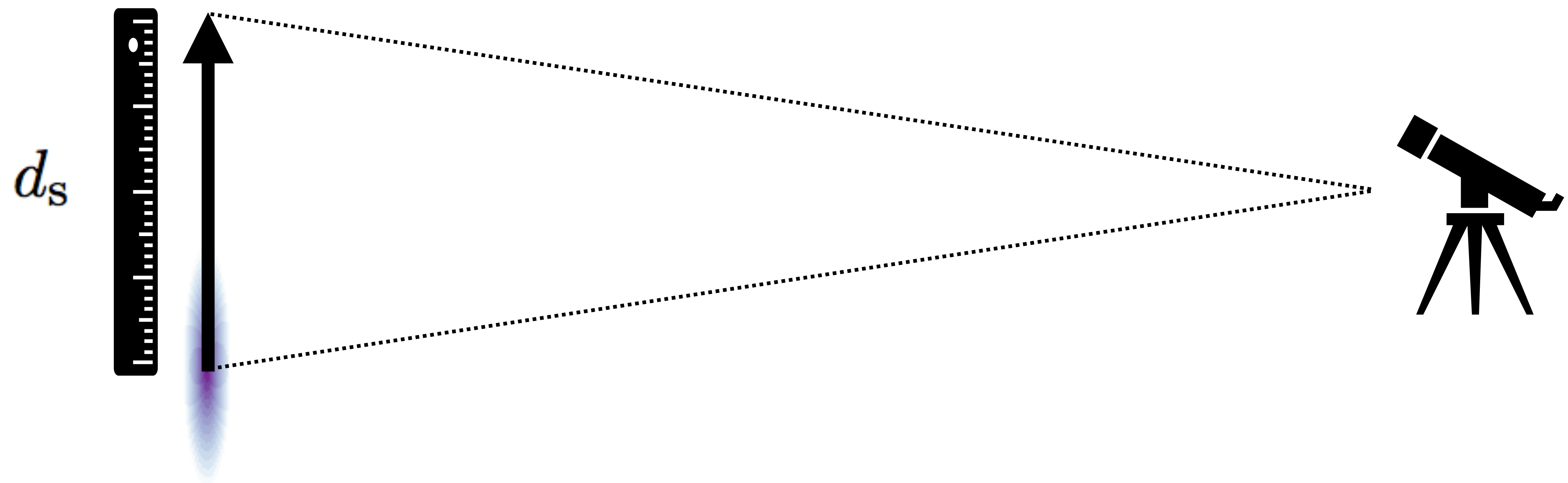

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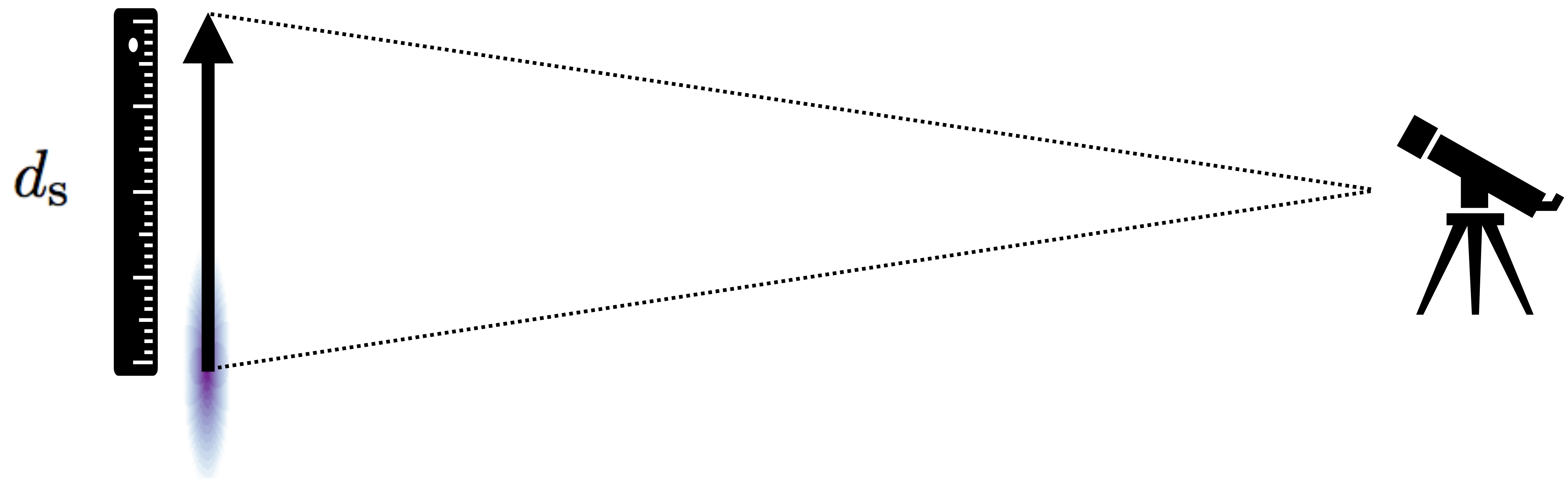

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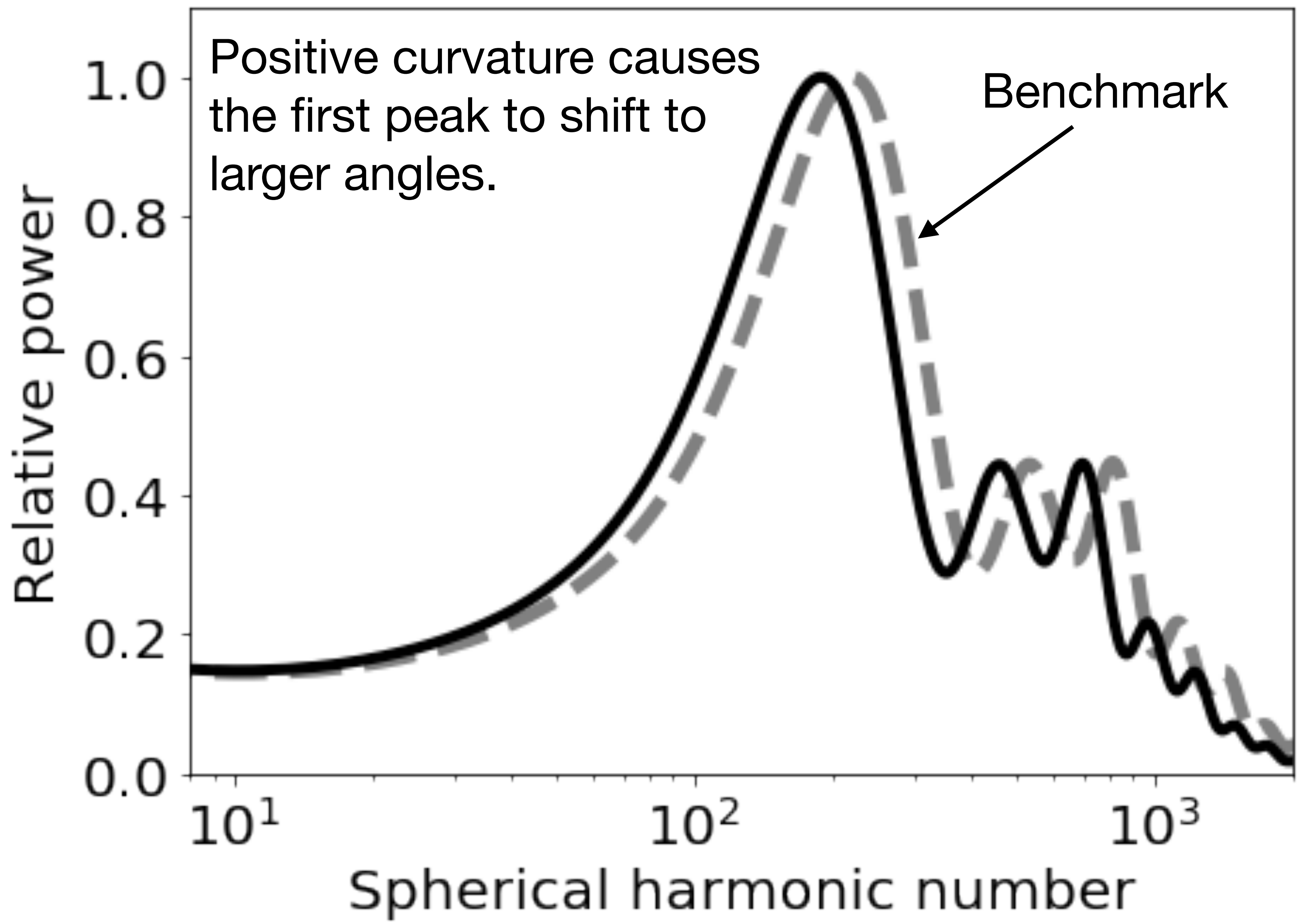
The location of the first peak tells us about the curvature of the Universe. If we also know the matter and photon densities, it then tells us about the density of D.E.

The position of the first peak



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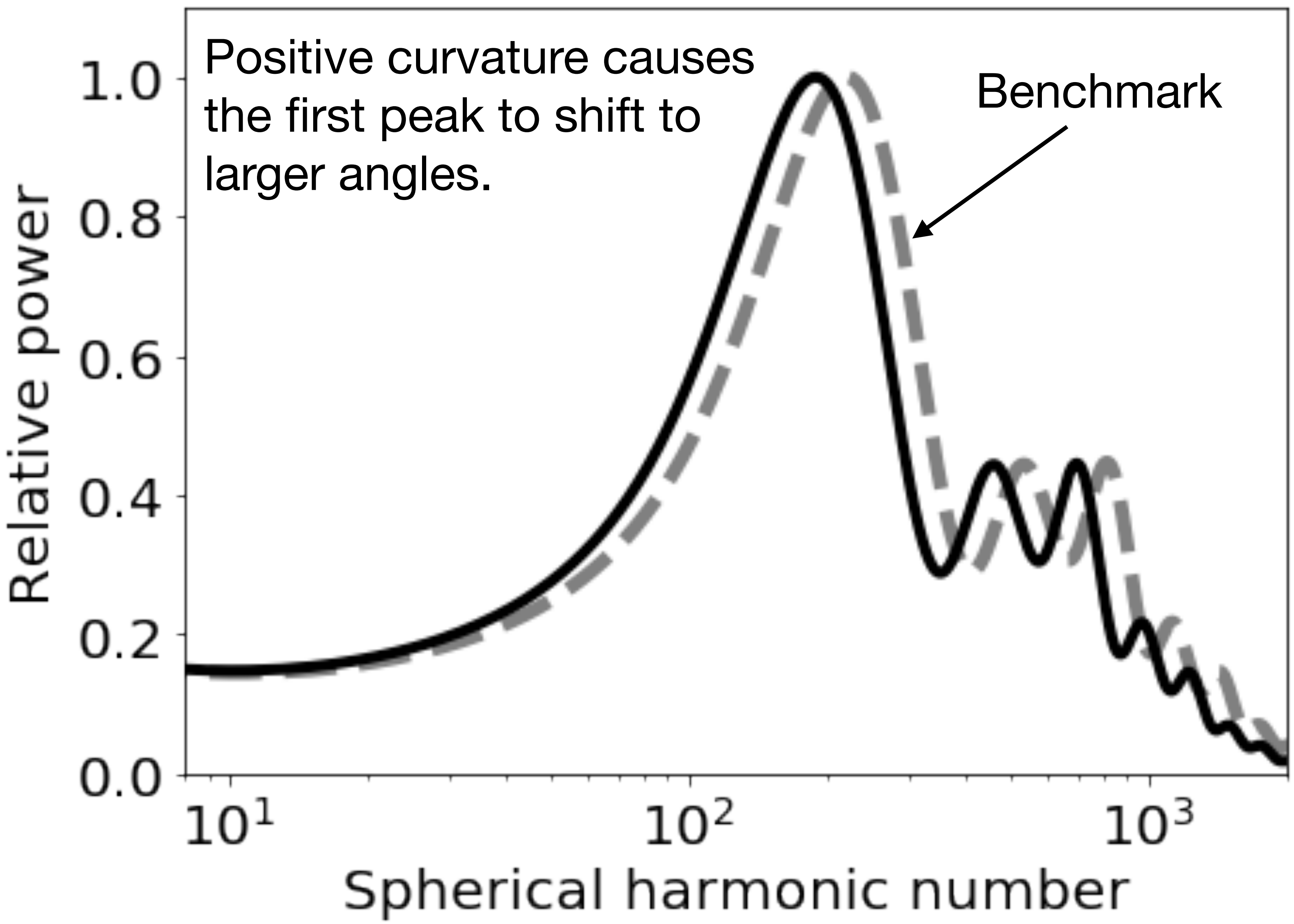
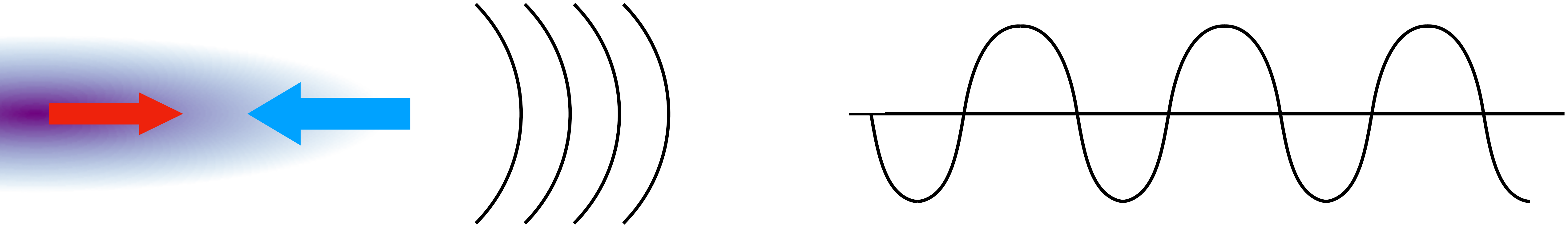


The location of the first peak tells us about the curvature of the Universe. If we also know the matter and photon densities, it then tells us about the density of D.E.

The cause of the second peak

The amplitude of the second peak relative to the first is sensitive to the density of baryons relative to photons at the time of recombination.



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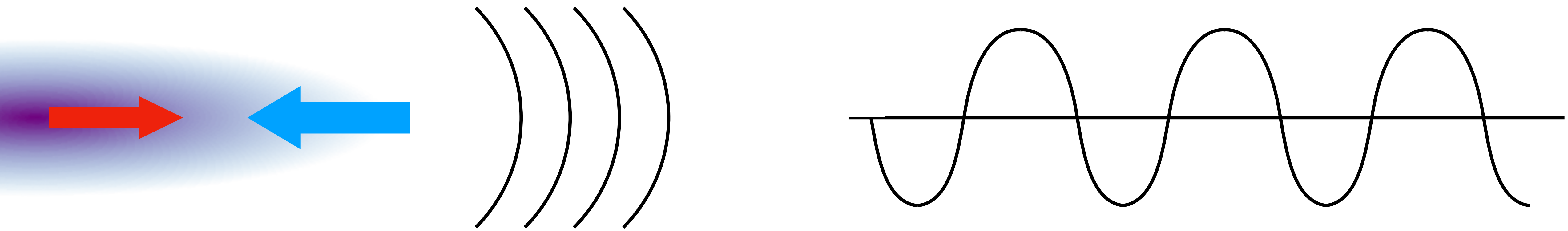
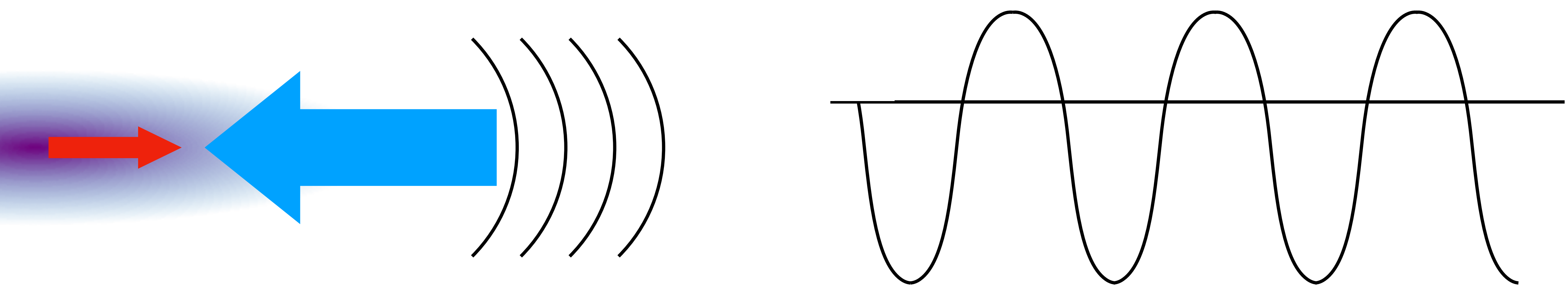
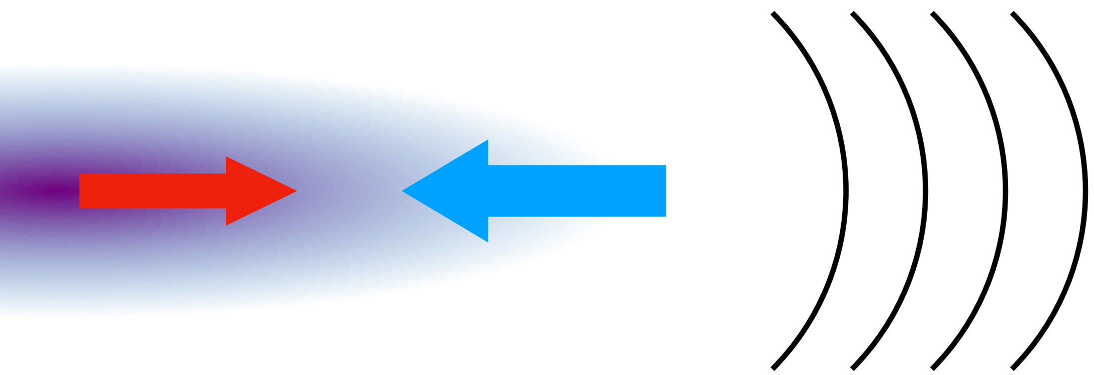


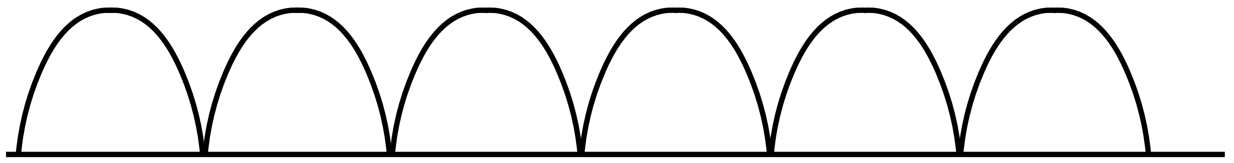
With an increased baryon density, the depths of the troughs of the sound wave increase relative to the heights of the peaks:



The cause of the second peak

But, because a power spectrum is always positive, the troughs are represented as the odd (1st, 3rd, 5th, etc) peaks in the CMB power spectrum:





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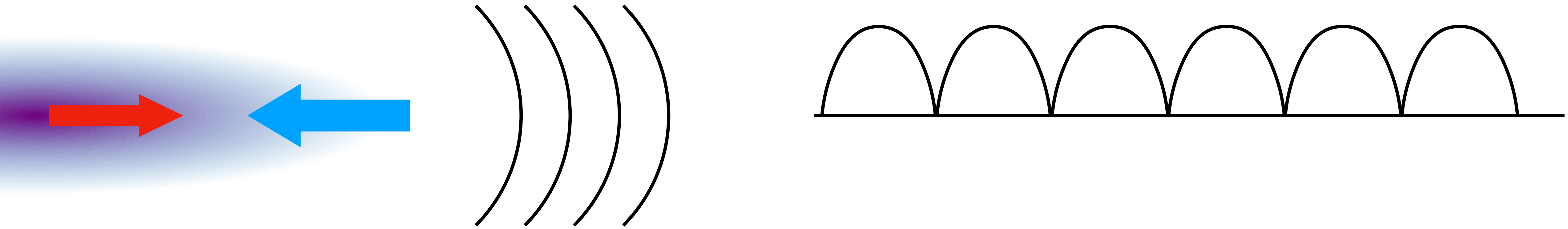
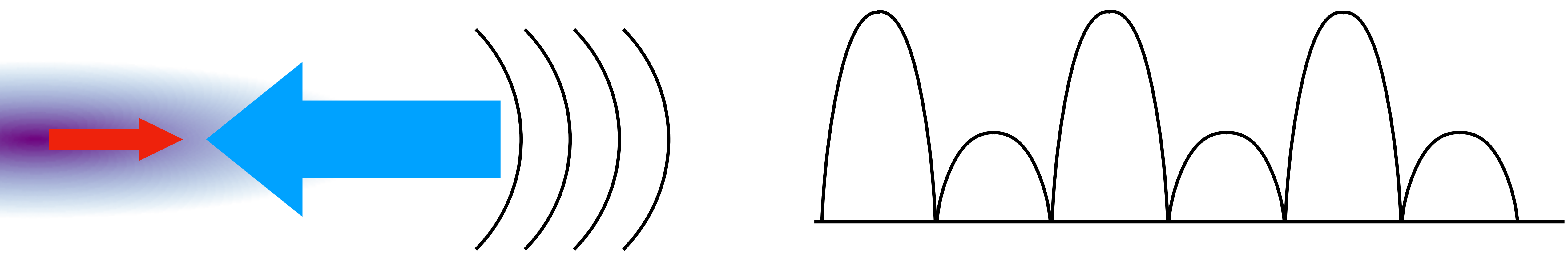


Therefore, with an increased baryon density, the *heights* of the odd (1st, 3rd, 5th, etc) peaks are *increased* relative to the even peaks.



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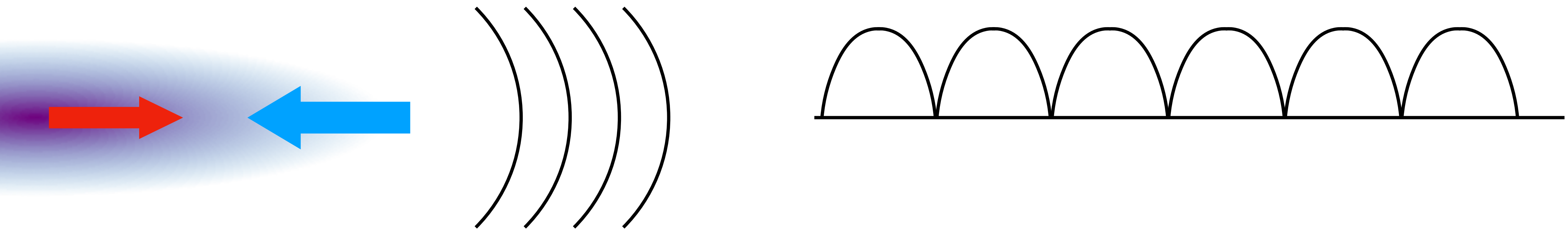

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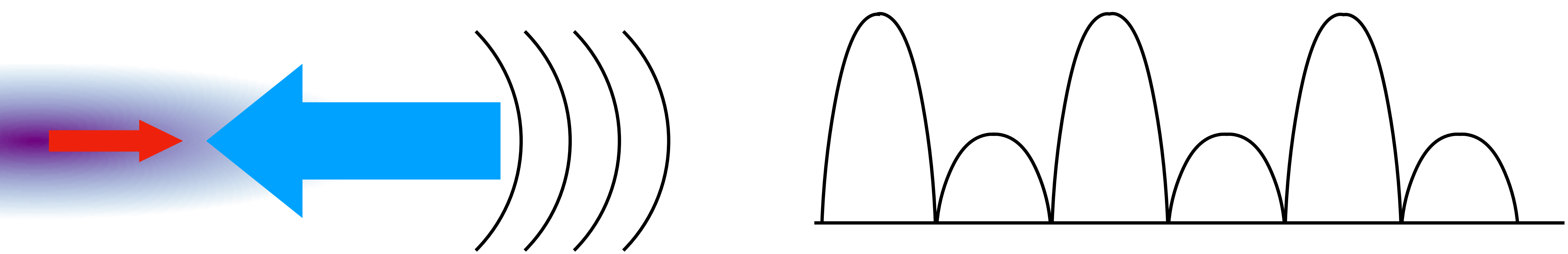
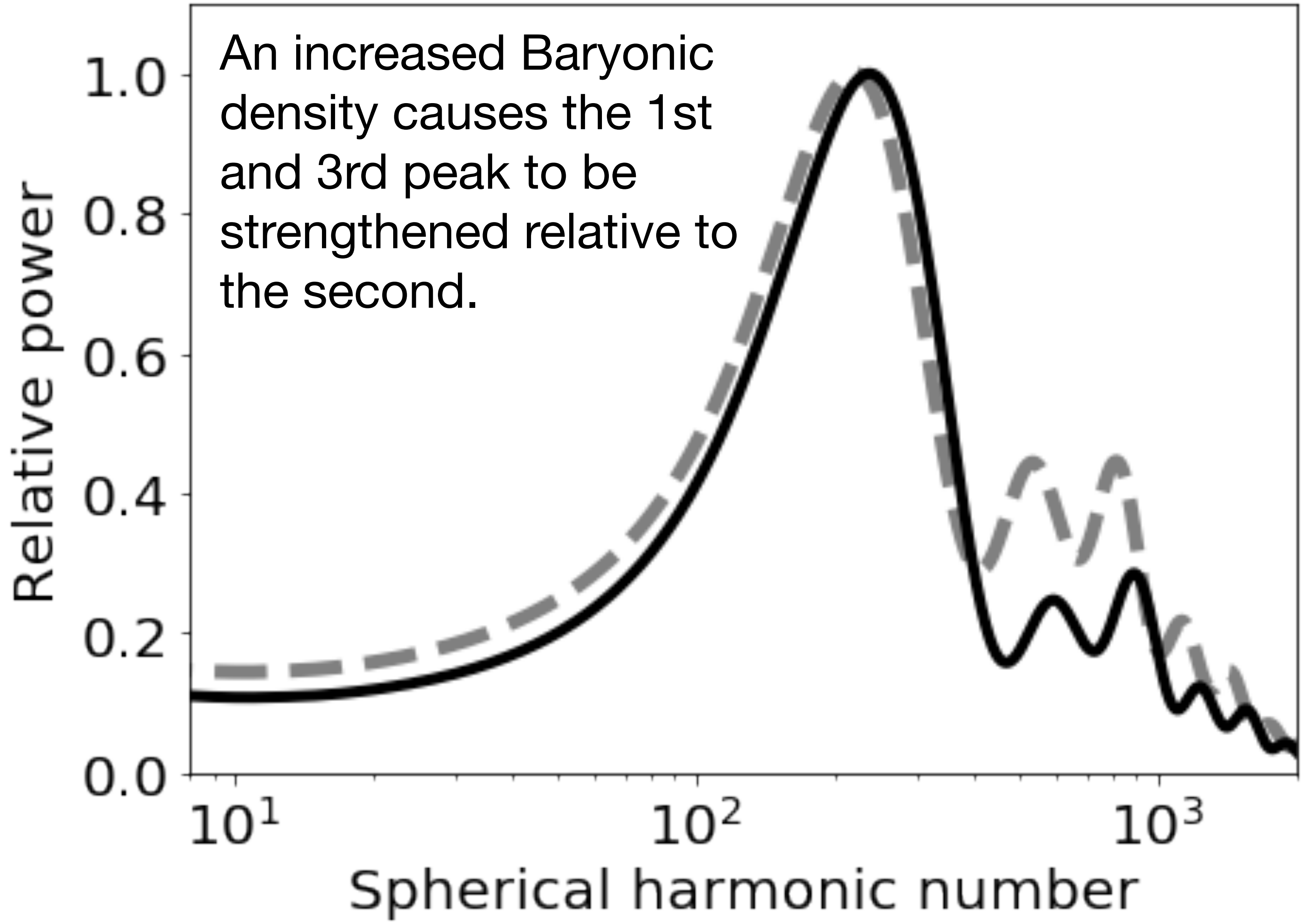


The amplitude of the second peak relative to the amplitude of the first peak tells us about the relative densities of photons and baryonic matter in the Universe.

The strength of the second peak



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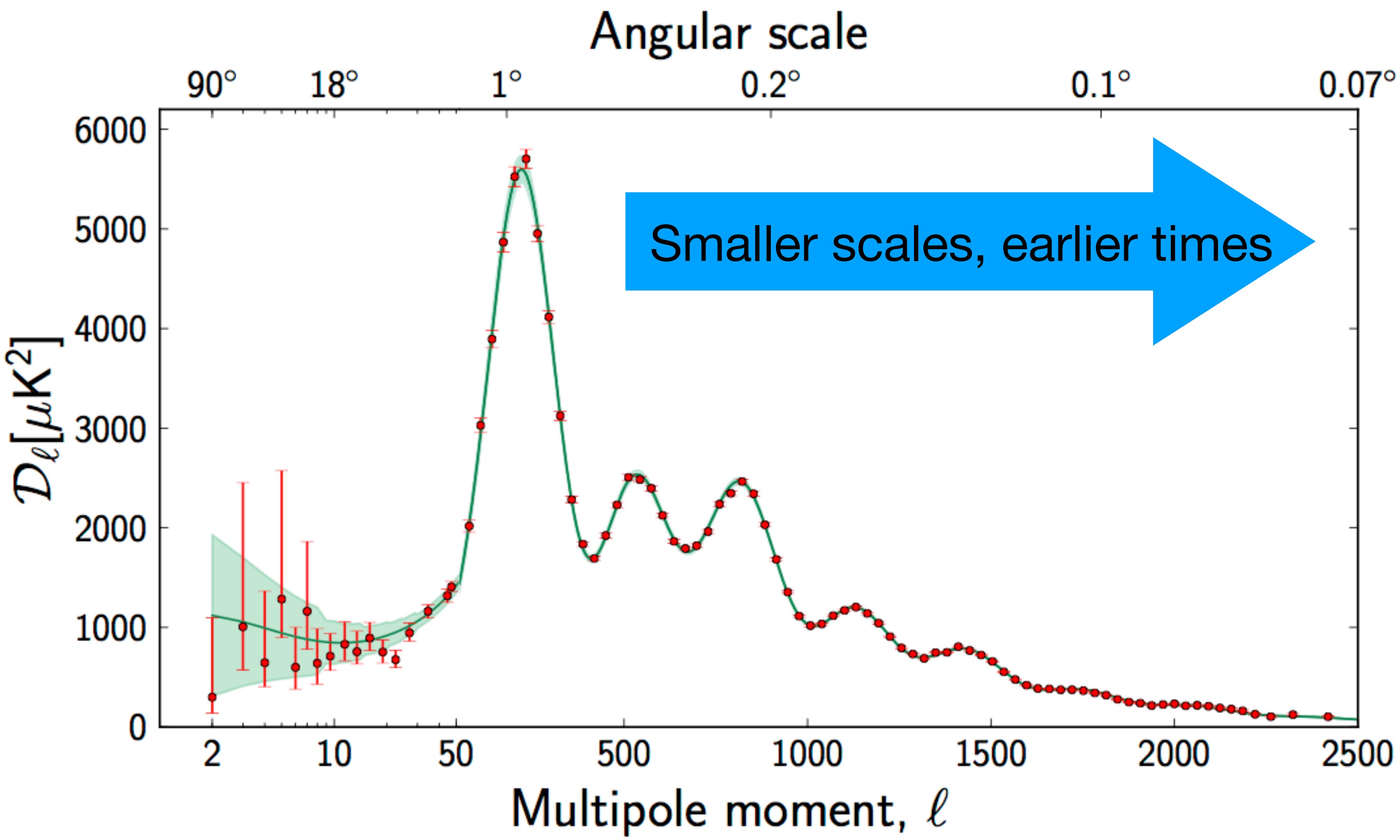
Higher-order peaks



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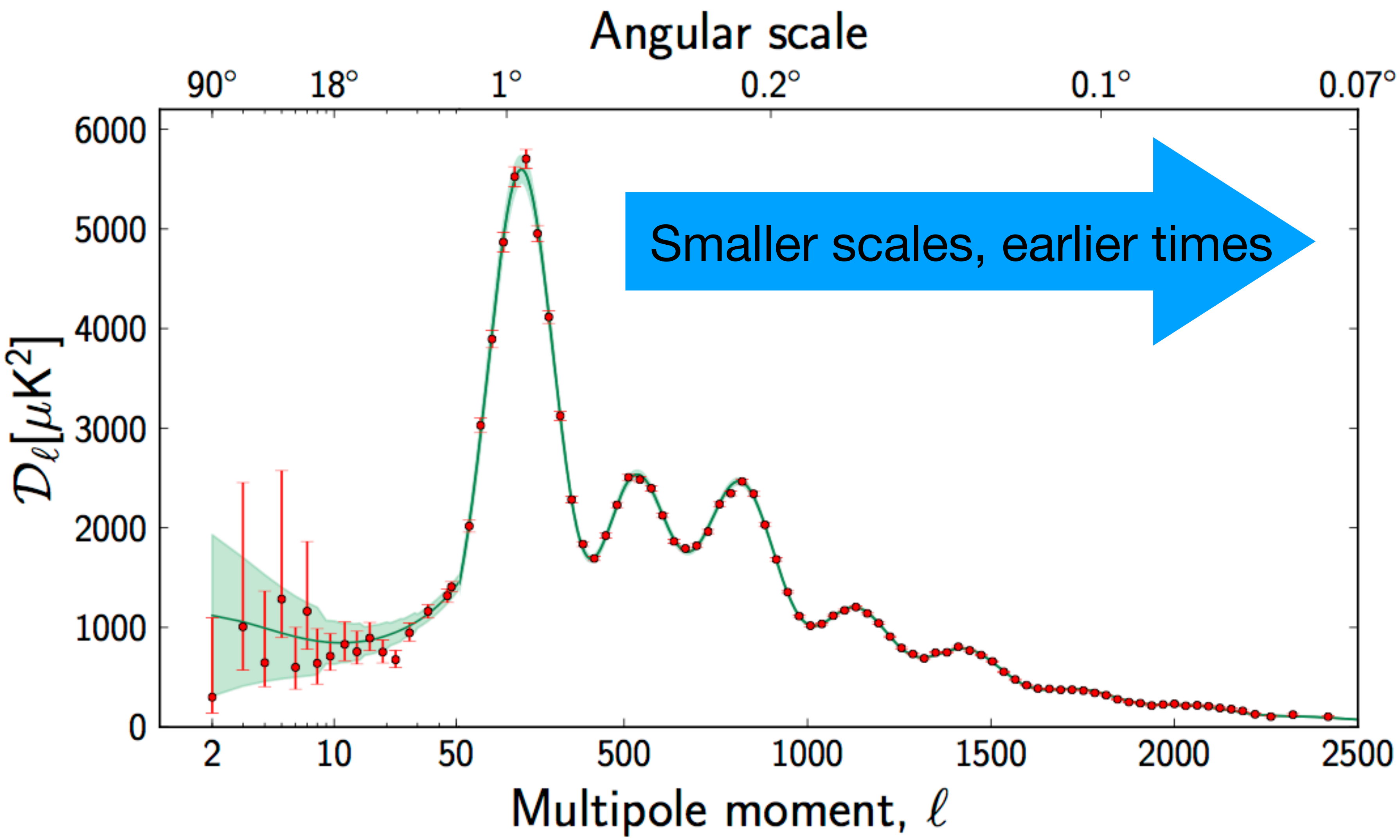

- The higher-order peaks correspond to smaller scales that started oscillating at earlier and earlier times.

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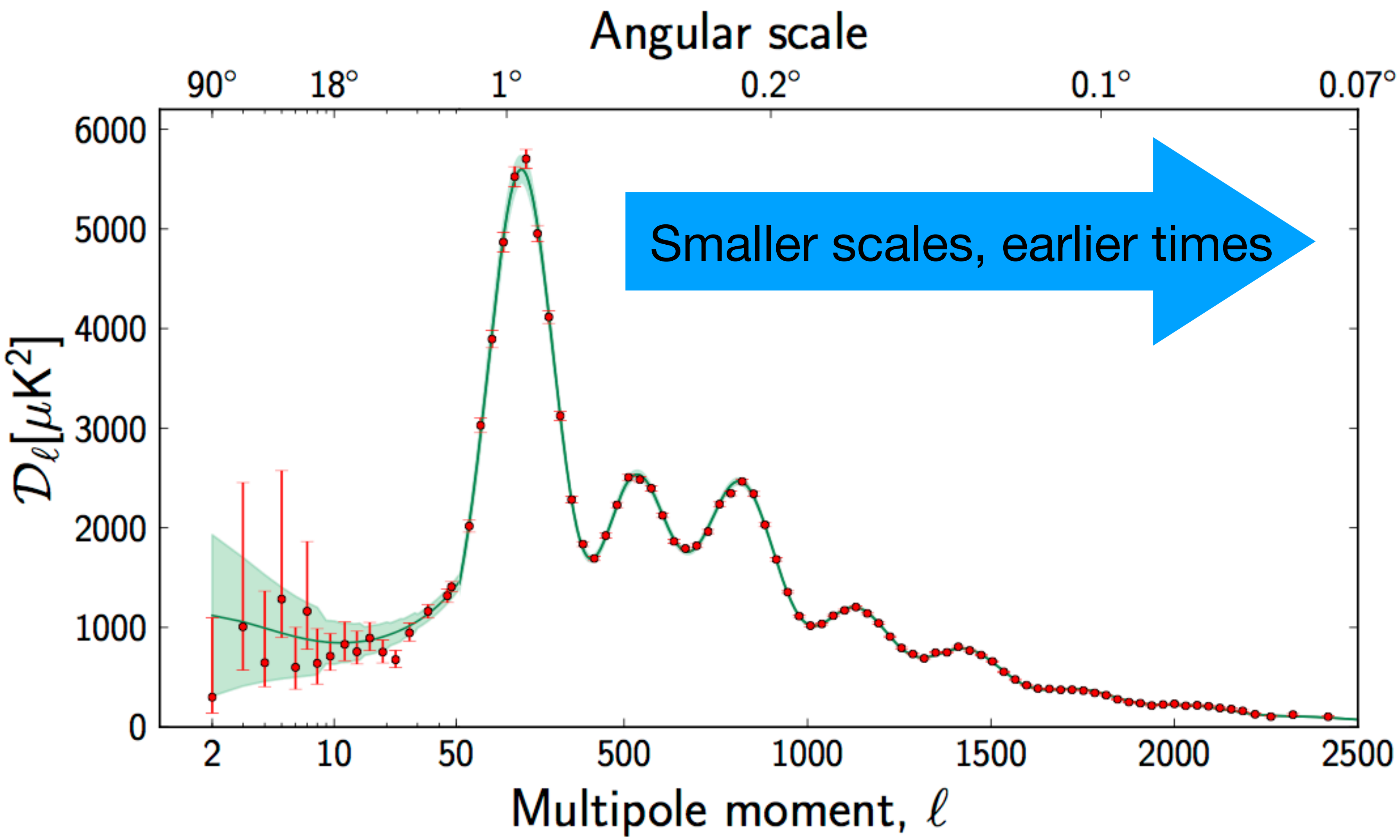

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- At earlier times, the photon energy density was increased relative to the matter energy density (due to photon's a^{-4} scaling compared to the a^{-3} scaling of matter).

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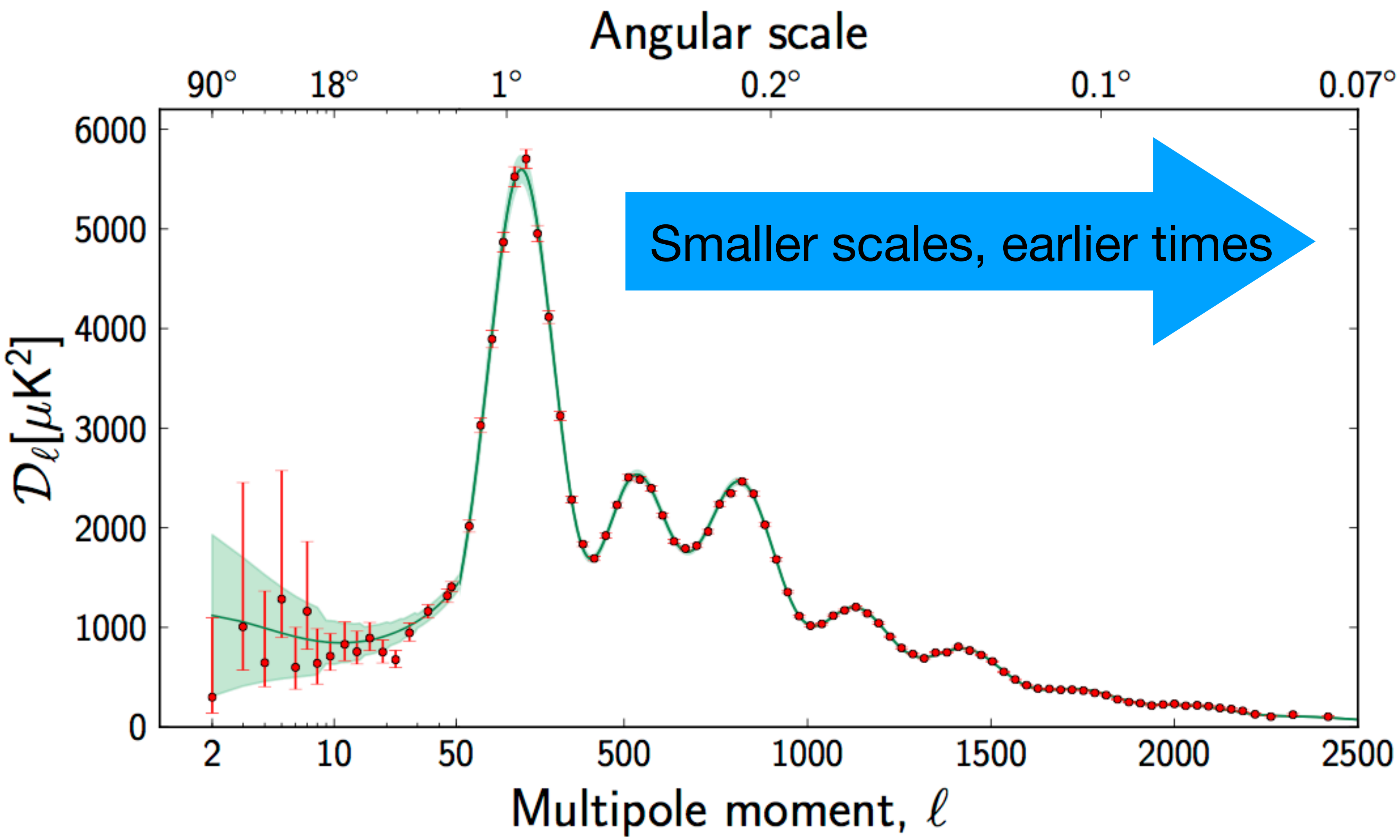
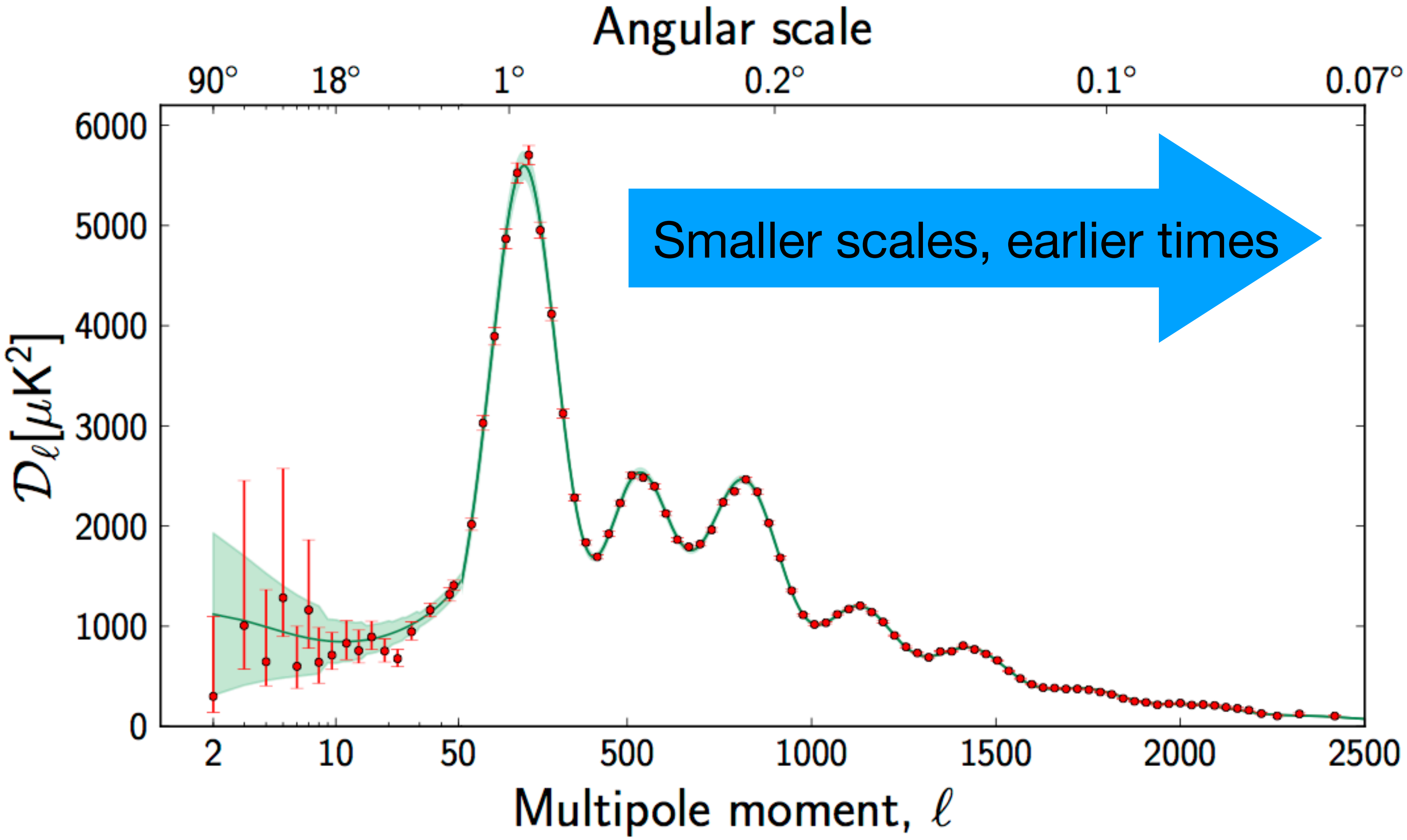


- The higher-order peaks correspond to smaller scales that started oscillating at earlier and earlier times.
- At earlier times, the photon energy density was increased relative to the matter energy density (due to photon's a^{-4} scaling compared to the a^{-3} scaling of matter).
- Because we need matter (both dark and baryonic) to produce the oscillations, this means that the higher-order peaks — corresponding to earlier times — are suppressed relative to the lower-order peaks.

Higher-order peaks



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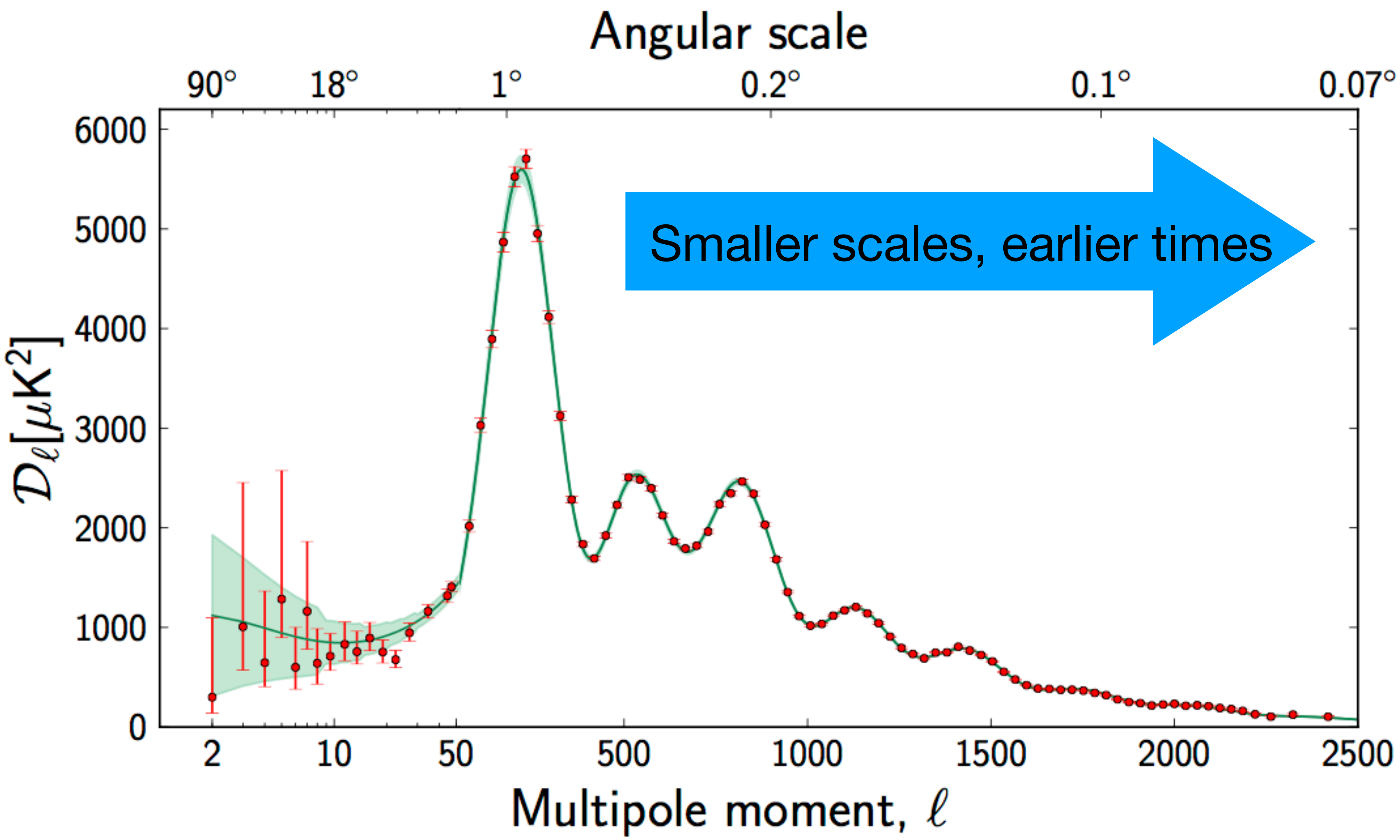

- The scale at which the higher-order oscillations become suppressed is sensitive to the relative matter and photon densities.

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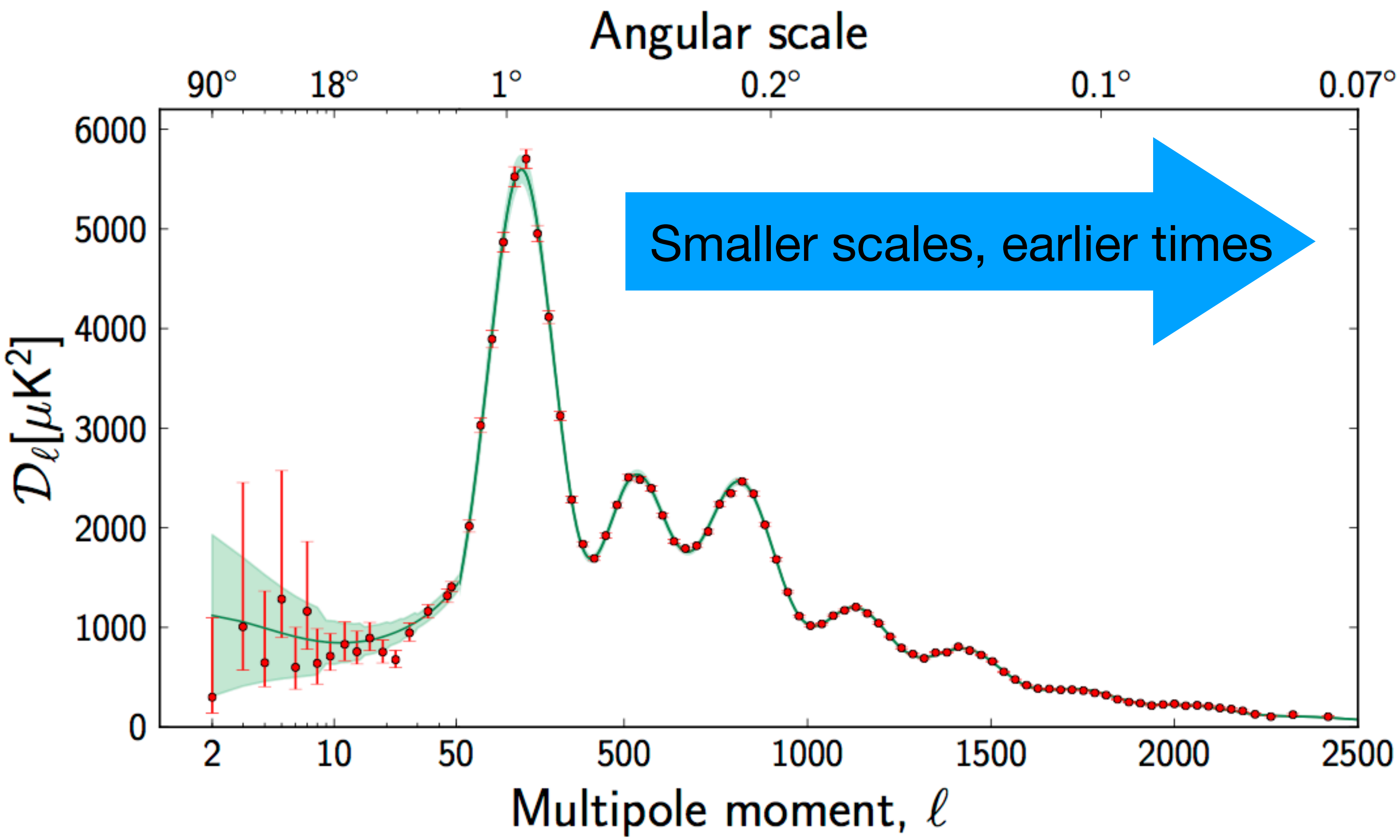

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- With higher matter densities, we have to look to smaller scales to probe when the Universe was radiation-dominated.

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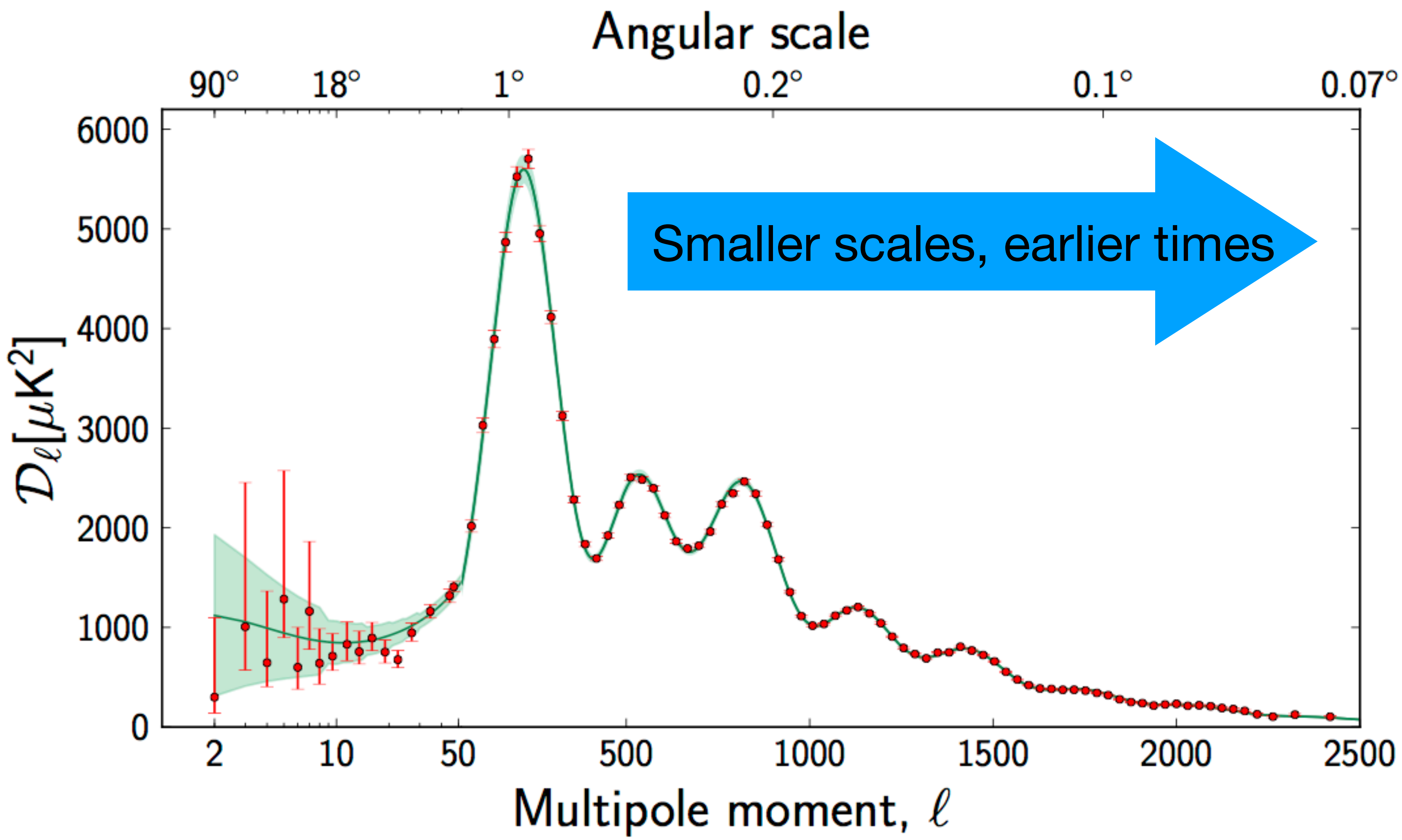

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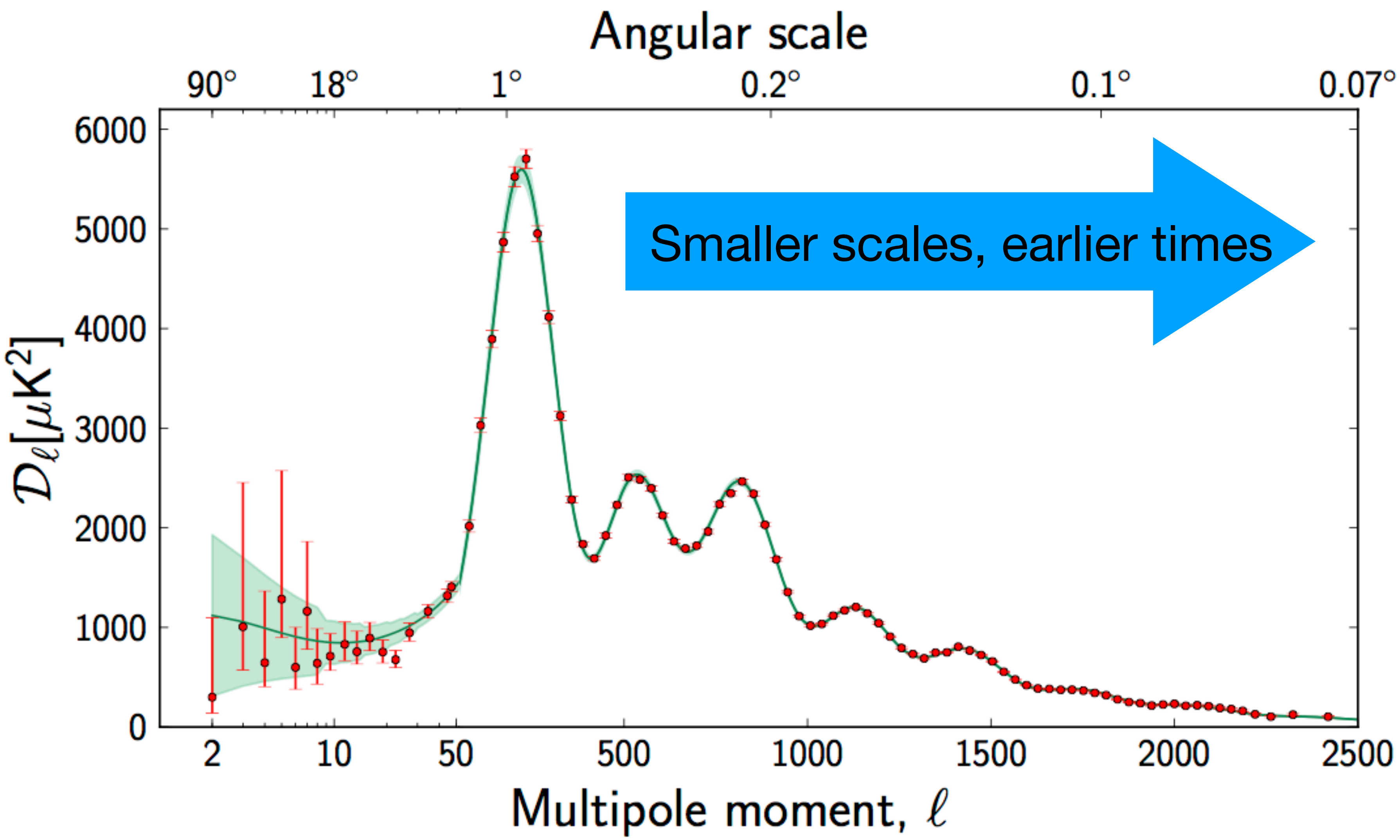

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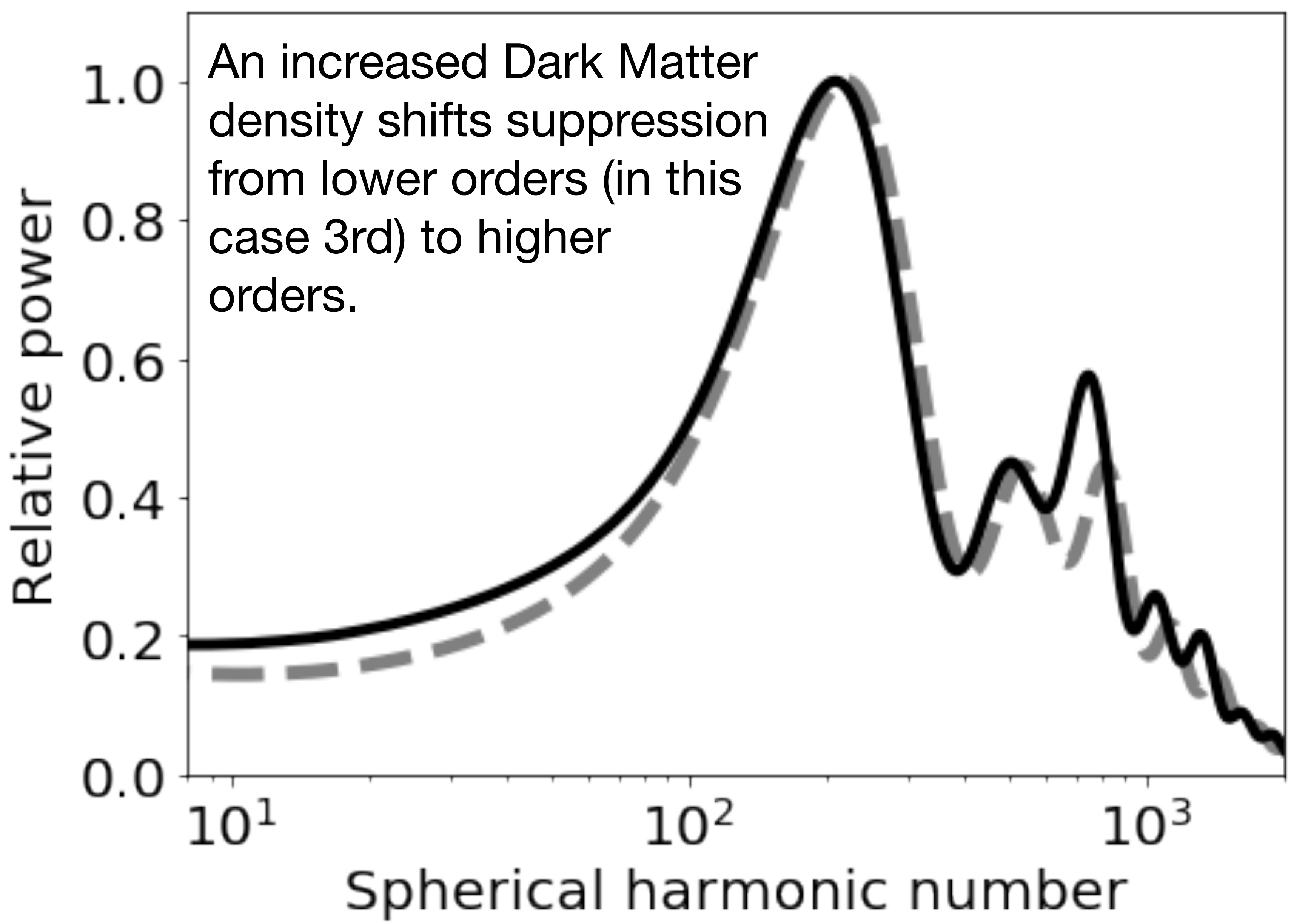

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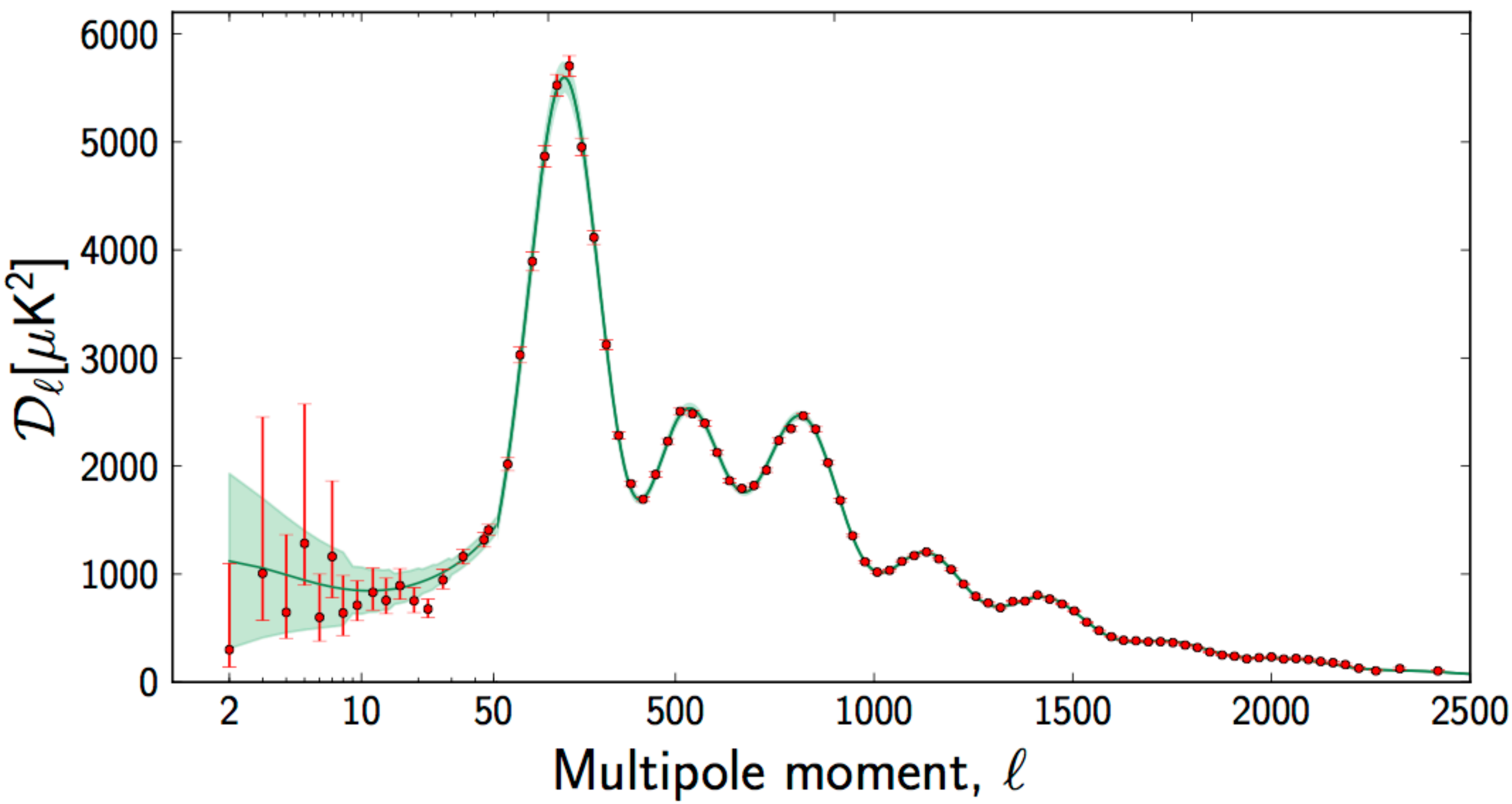
Summary of what the CMB power spectrum tells us



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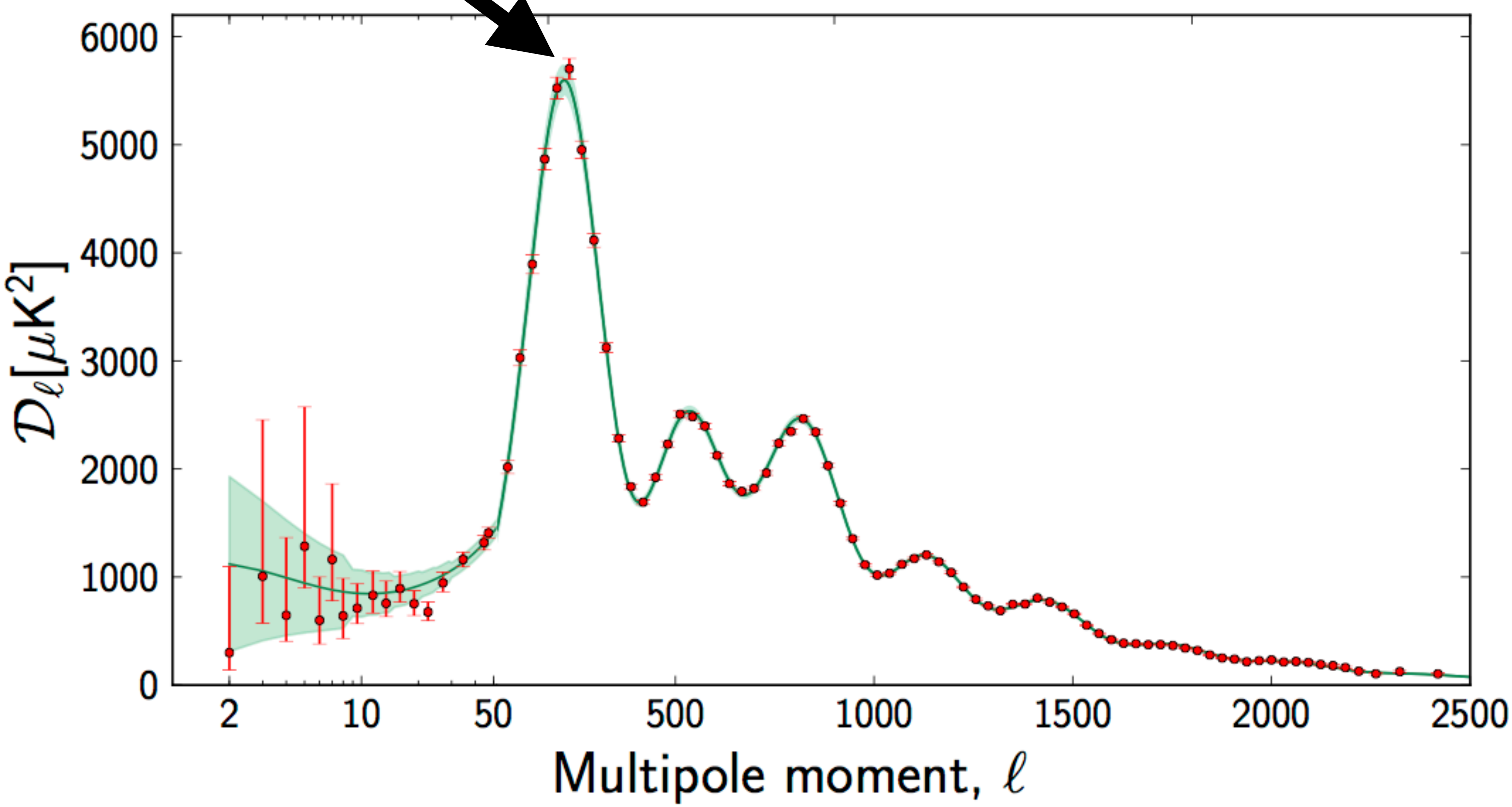

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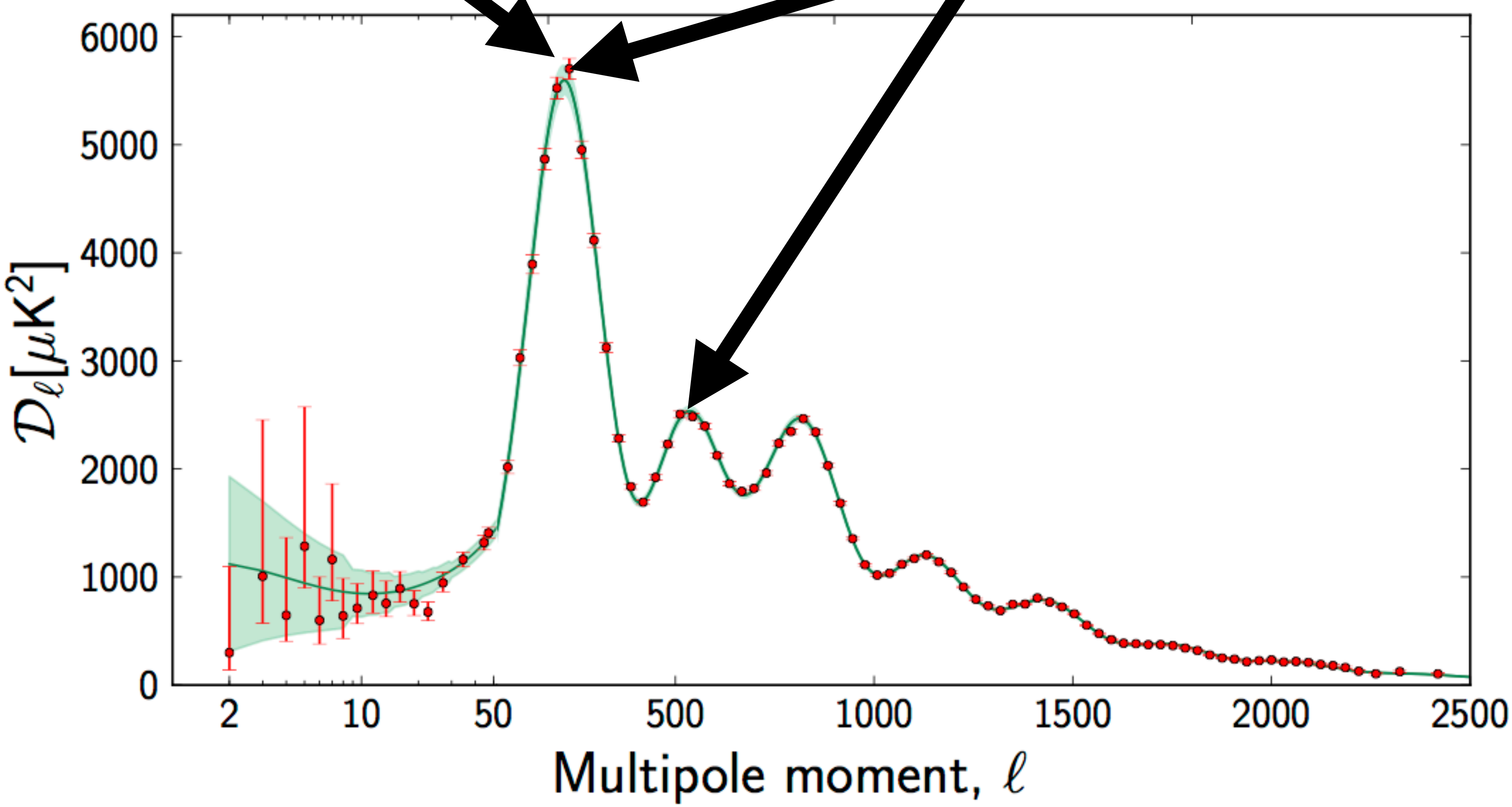
The relative amplitudes of the 1st and 2nd peaks tell us about the baryon to photon energy density ratio.



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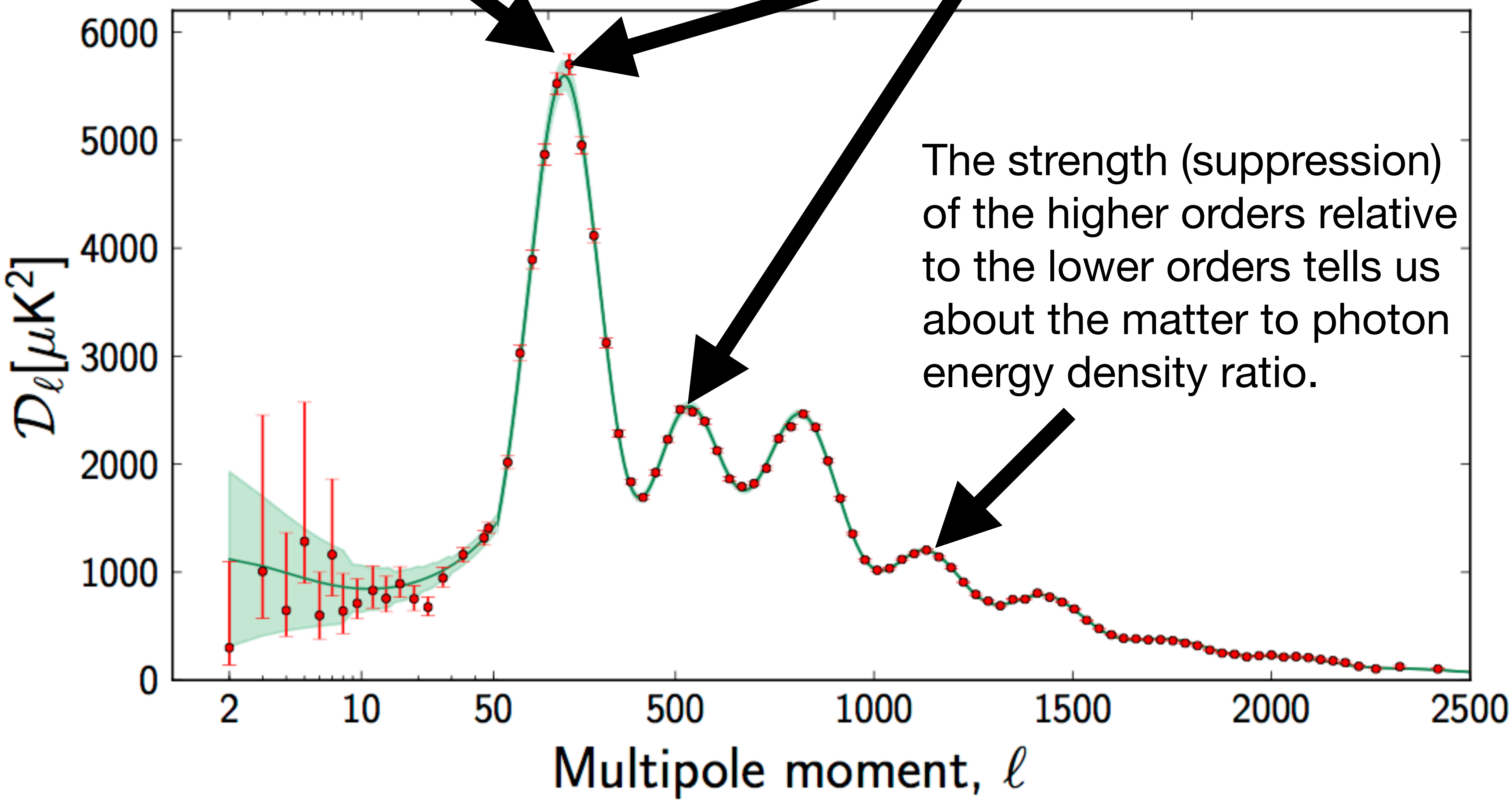

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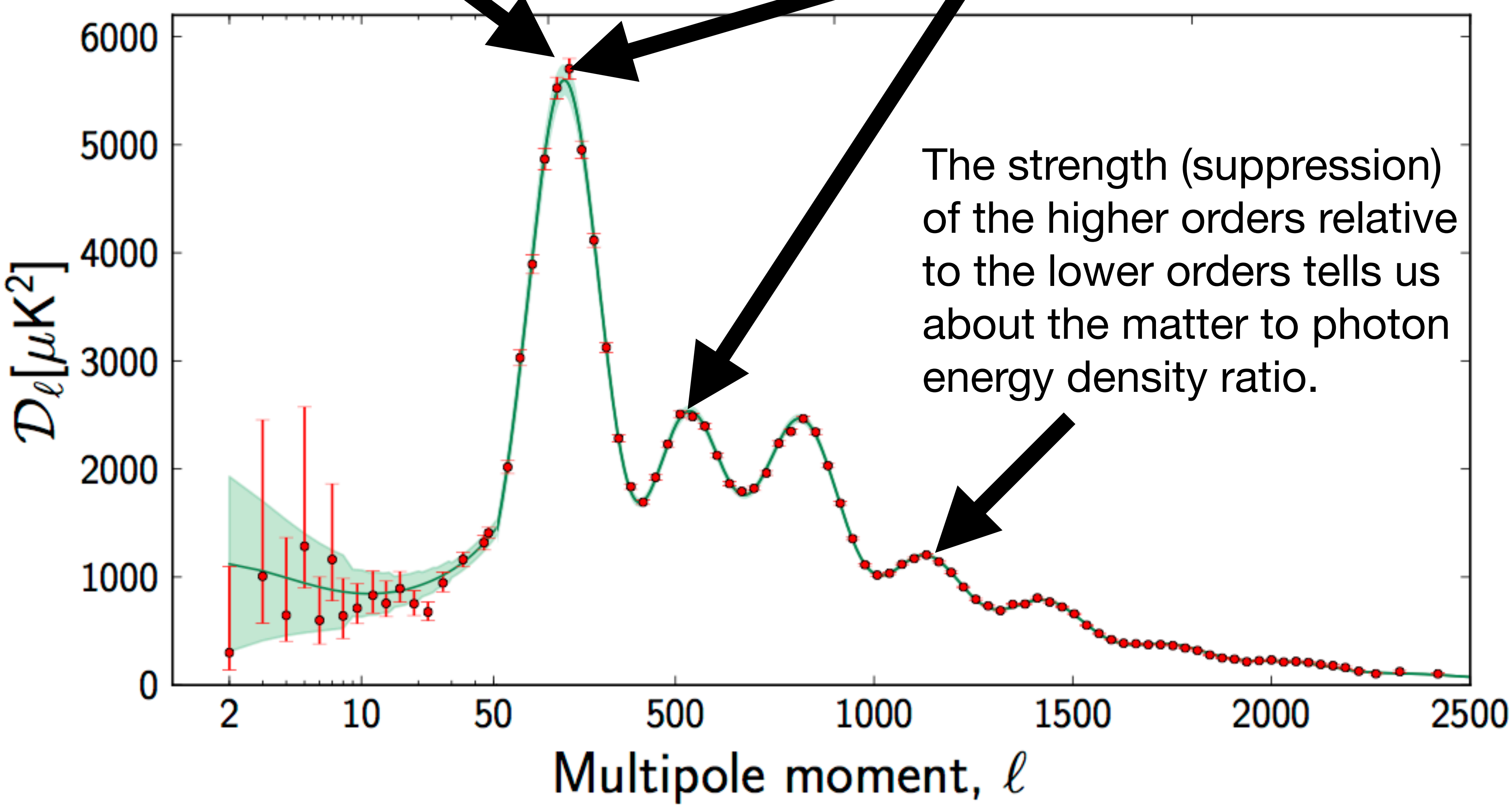

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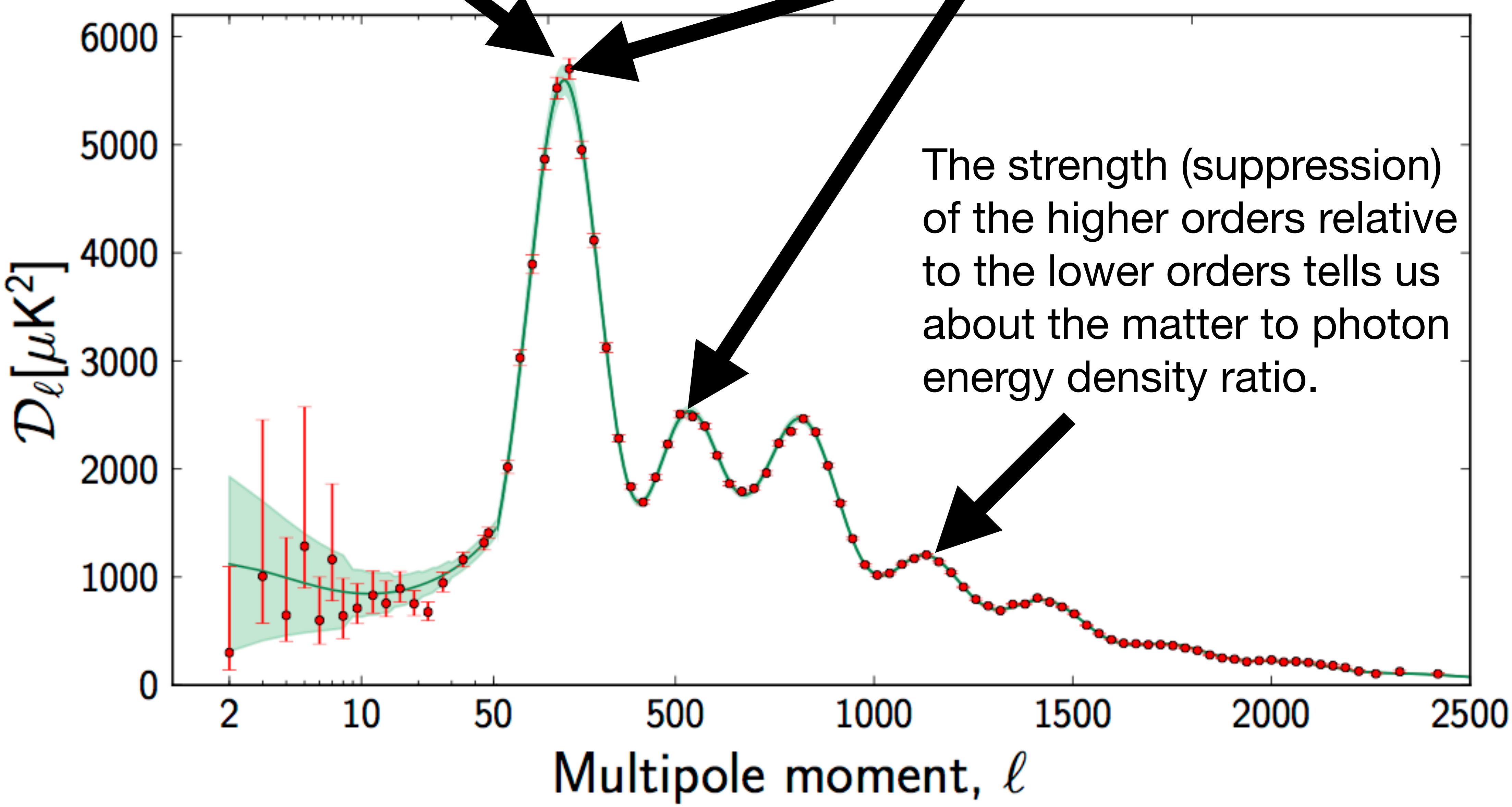

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The CMB power spectrum provides measurements of all the energy densities.

Getting the feel of it…

Analysis of the CMB provides us with a *huge* amount of information about the Universe.

The CMB dipole tells us about our motion in space relative to the CMB.

Temperature fluctuations in the CMB tell us about how matter was distributed at early times in the Universe, before any stars or galaxies formed.

While at first glance these fluctuations look random there exists, in fact, strong correlations at different scales.

These correlations provide us with precise measurements of all the density parameters.