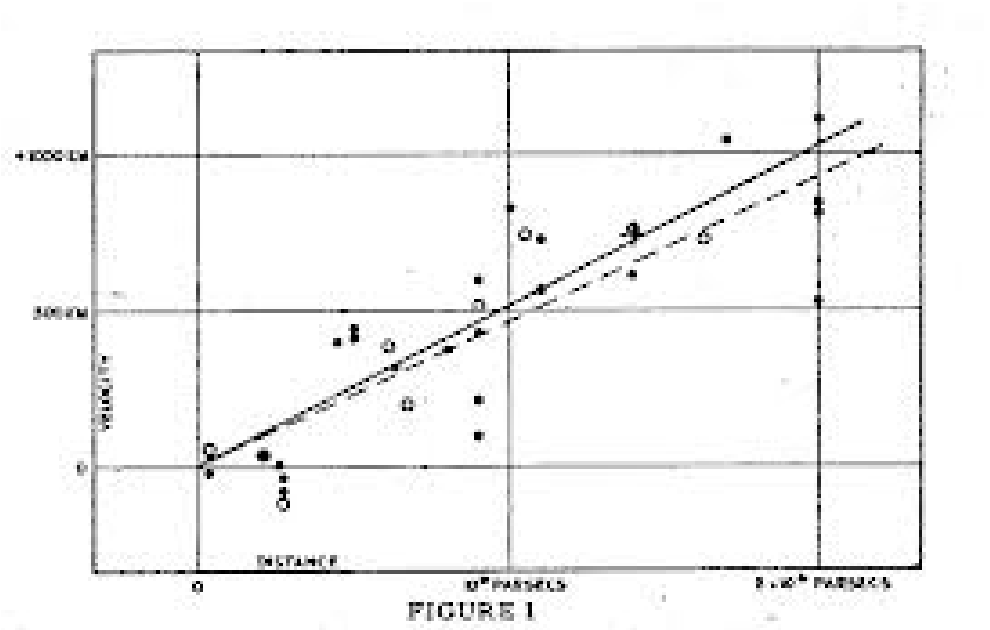
The Role of the CMB in Modern Cosmology

Bruce Partridge
For the Planck Collaboration
(Address: Haverford College, Haverford PA 19041 USA)
bpartrid@haverford.edu

The Emergence of Modern Cosmology

Edwin Hubble (1920s) discovers the Universe is expanding: distant galaxies move away from us



From Hubble's *The Realm of the Nebulae* (1936)

The Emergence of Modern Cosmology

Penzias and Wilson (1964) discover the cosmic microwave background (CMB)

The Power of the CMB

CMB makes the early universe ***simple***

-- and ***accessible***

CMB measurements provide ***precision*** in cosmology

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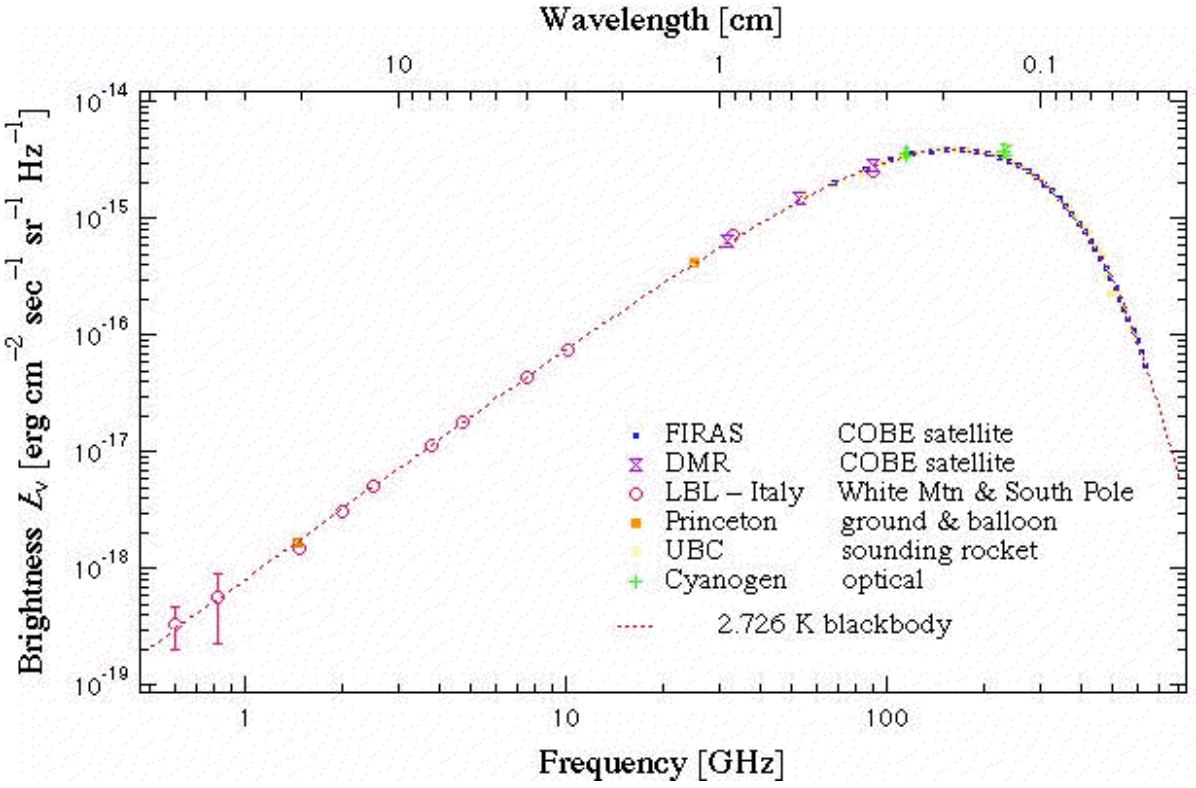
Two key properties of the CMB if it is truly cosmic

If it Is from a Hot Big Bang, the CMB Should Have…

A particular spectrum: blackbody or Planckian



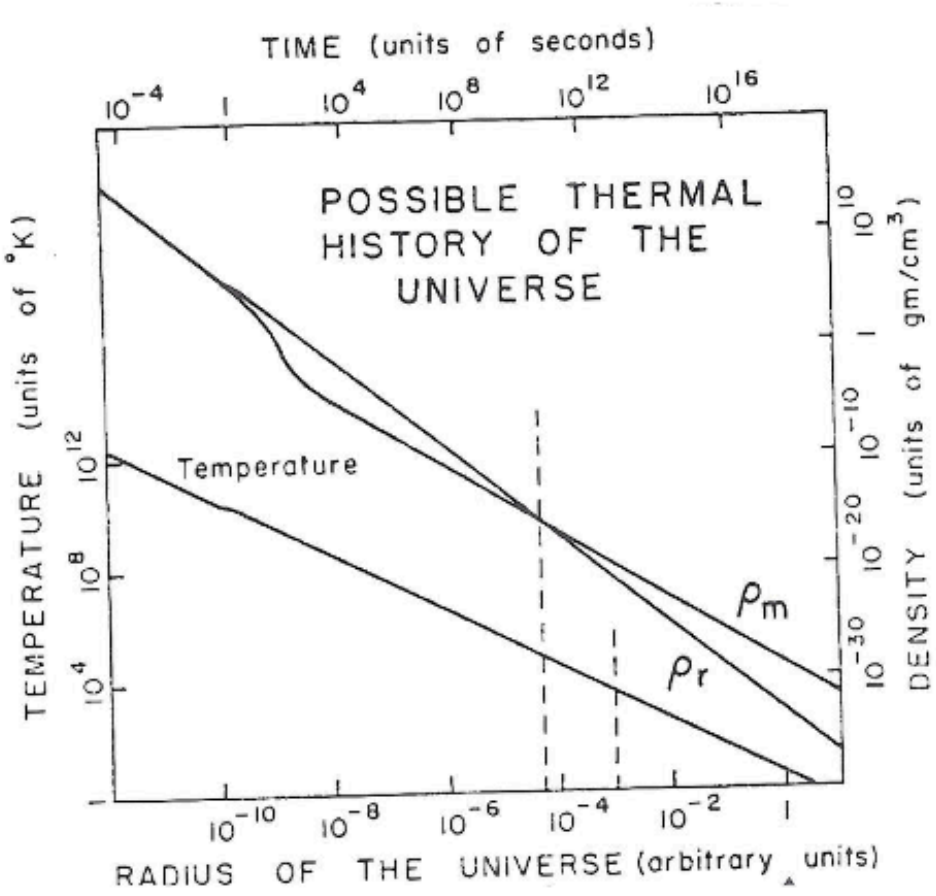
The observations agree: points are measurements; dashed line the expected spectrum

The Universe Had a Hot Big Bang Origin— And Has Been Cooling Since

As the Universe expands, it grows cooler and less dense *in predictable ways*

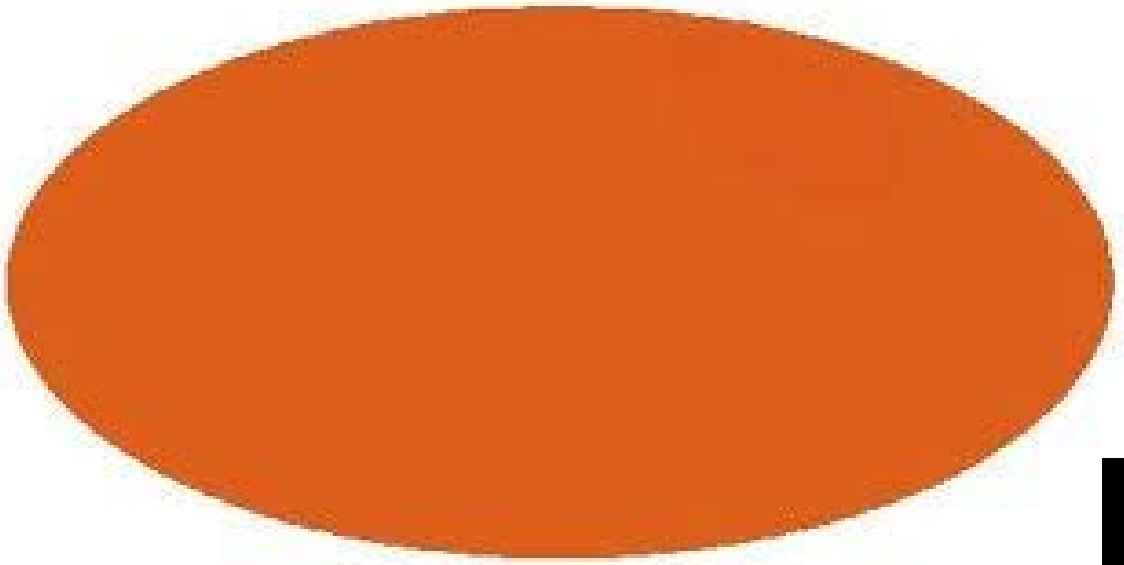
From Dicke, Peebles, Roll and Wilkinson, explaining the CMB (early 1965)

Moving back to earlier times, radiation density grew faster



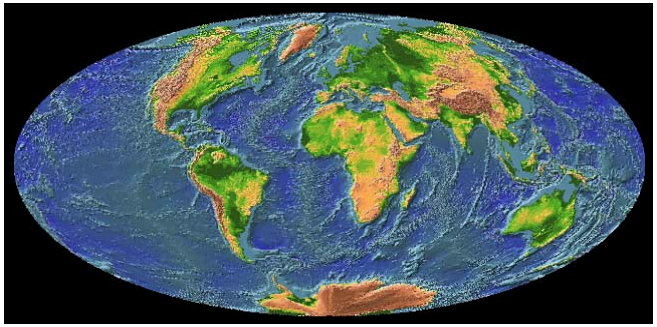
If it Is from the Big Bang , the CMB Should Be…

Almost the *same in all directions* – the beginning of the Universe is all around us



A microwave map of the whole sky

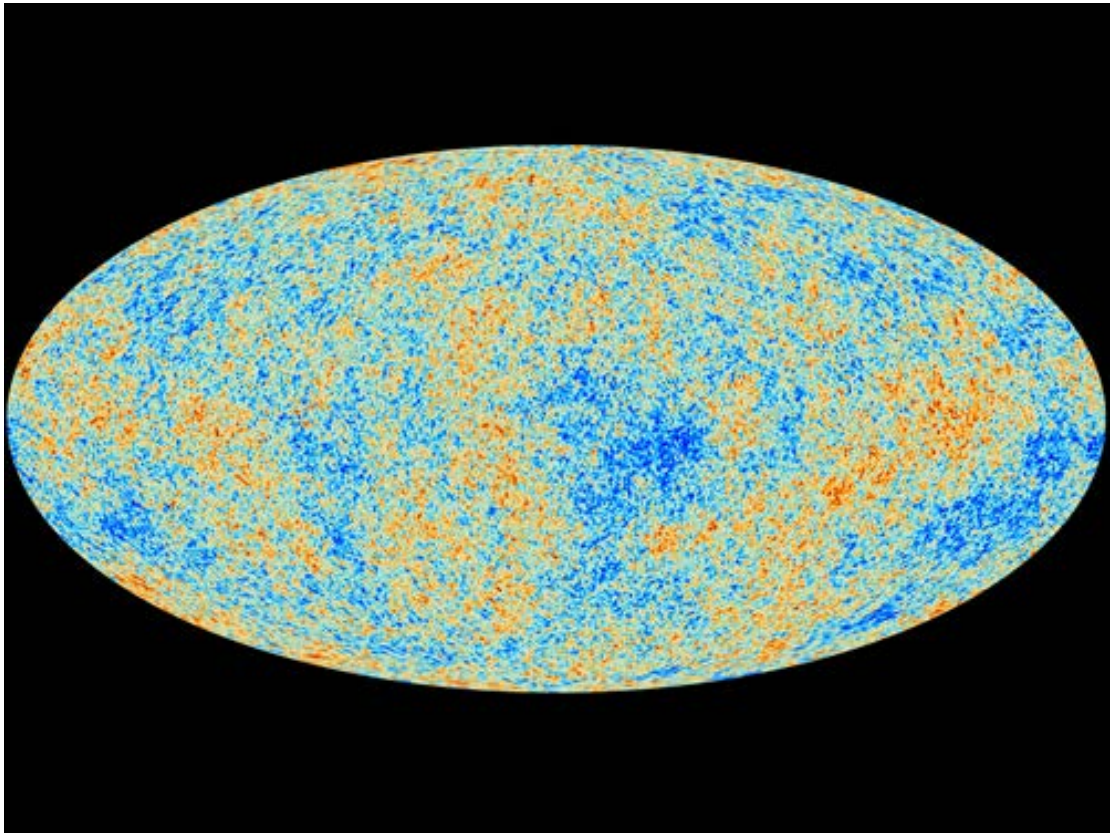
(stretched out like this map →



CMB is (almost) the same in all directions: T = 2.275 K everywhere

If it Is Cosmic, the CMB Should Be…

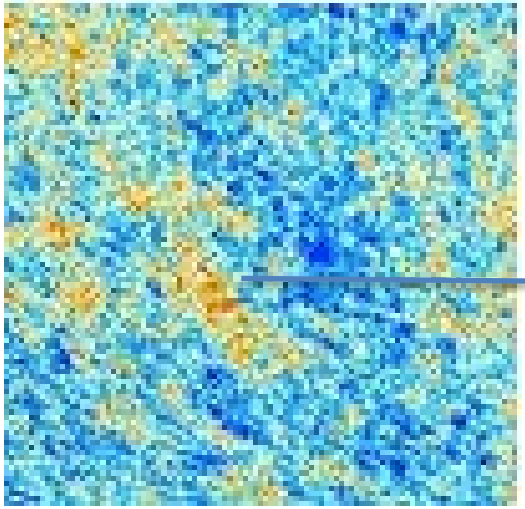
Almost the same in all directions, but *not* exactly



There need to be small temperature differences; and there are.
Orange regions are a bit hotter, blue regions a bit cooler.

Hot and Cold Spots Show Where Matter Was Denser or Less Dense

Dense parts grew into galaxies and clusters of galaxies



gravity

Size and Amplitude of Hot and Cold Spots Encode Cosmological Information

Amplitude of peaks and troughs tells us Universe must contain Dark Matter

Detailed study of spots tells us:

- The density of ordinary matter (protons, neutrons and electrons) in the Universe
- When the first stars heated up the Universe
- That a period of super-rapid expansion called inflation happened in the first ~10^{-30} sec

Size of characteristic spots tells us that geometry of space is flat

Detailed studies also tell us about fundamental physics:

- Physical constants are constant
- The number of neutrinos is 3, and the sum of their masses is < 0.2 eV

AND MUCH MORE!

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Detailed study of hot and cold spots tells us:

- The density of ordinary matter (protons, neutrons and electrons) in the Universe
- When the first stars heated up the Universe
- That a BRIEF period of super-rapid expansion called inflation happened in the first ~10^{-30} sec

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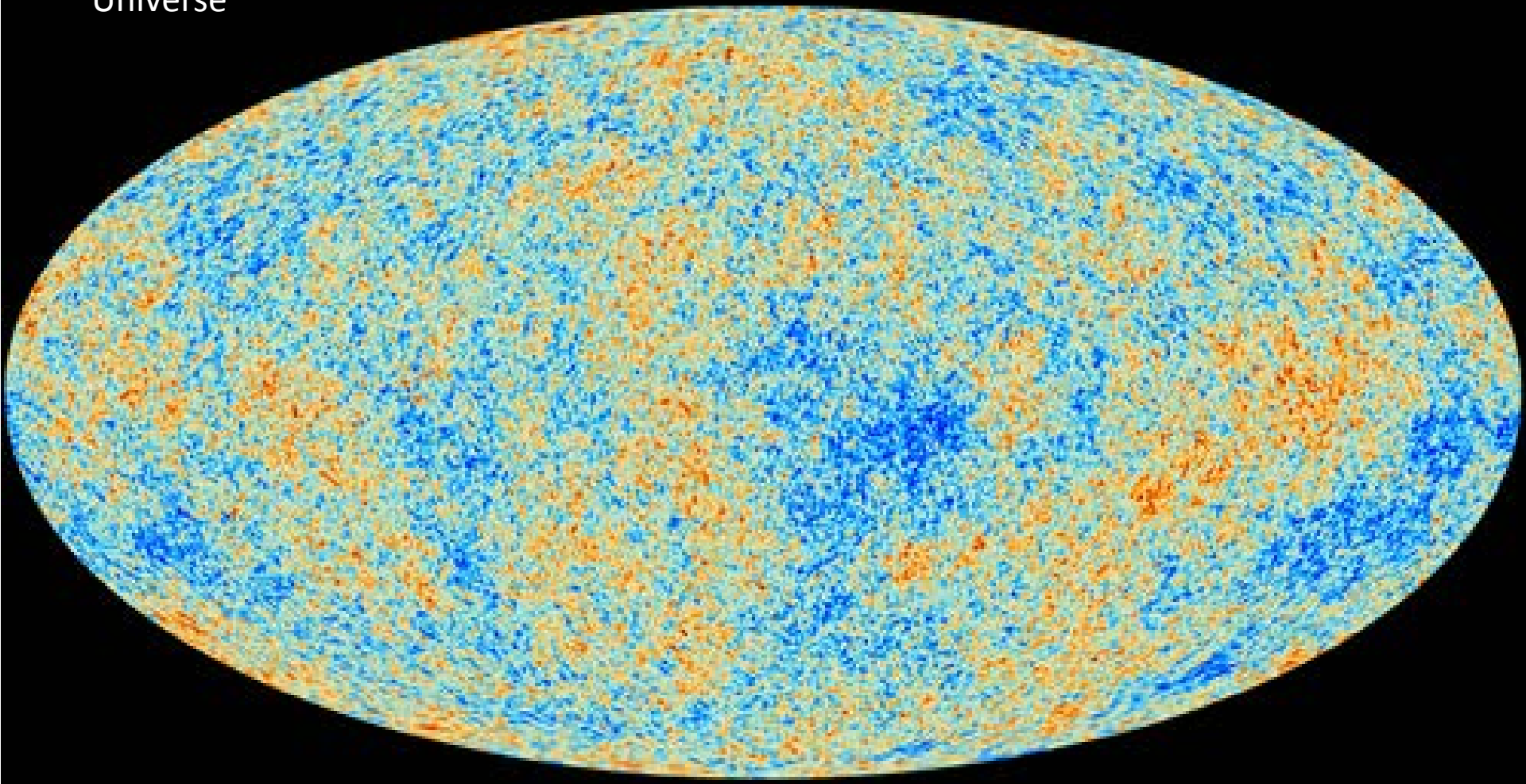
AND MUCH MORE! – details in next talk

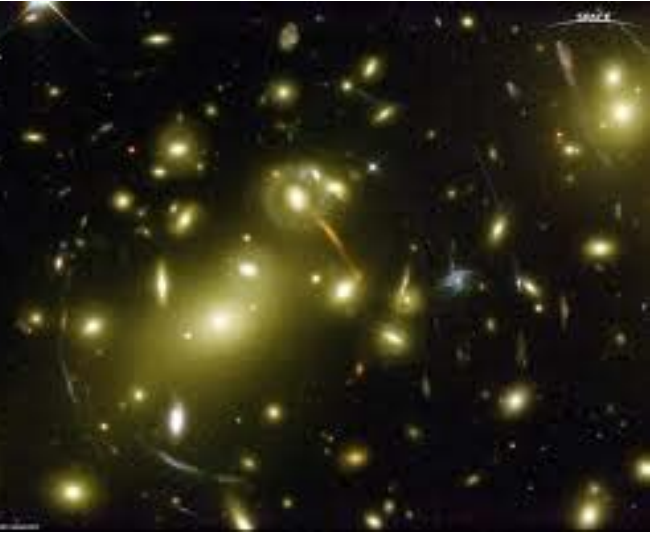
Planck's high-resolution baby picture of the Universe



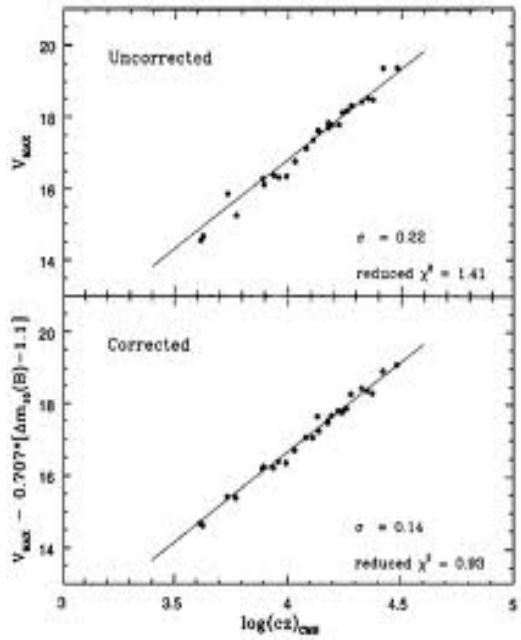
Other Astronomical Evidence…

Exploding stars

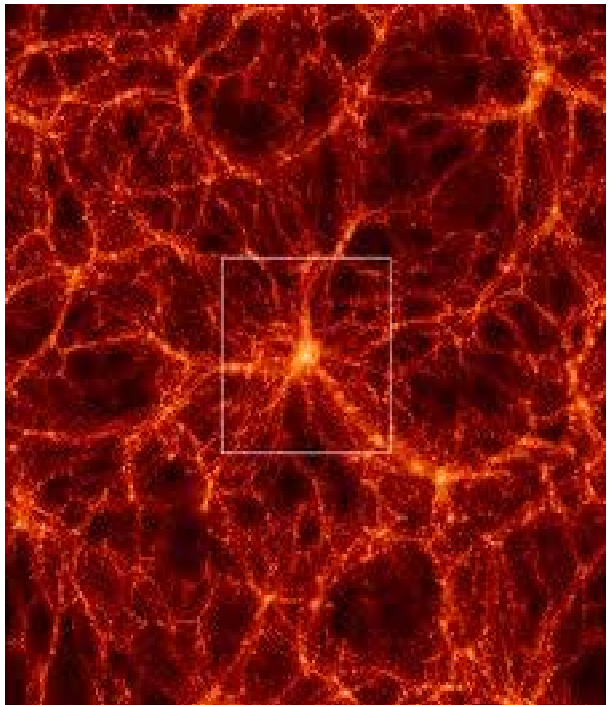
(supernovae)

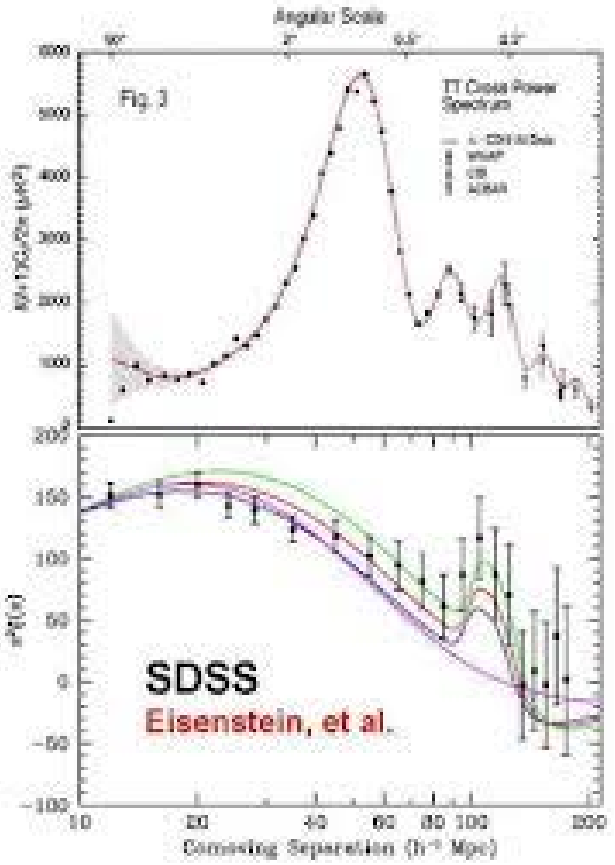


Gravitational lensing



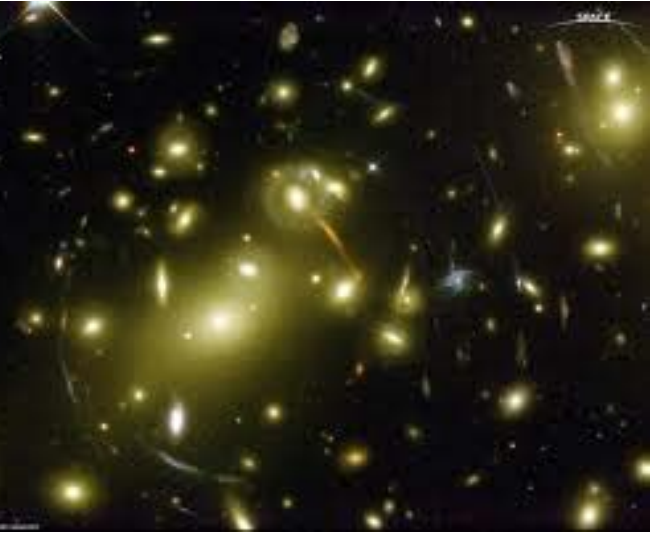
Expansion rate of local Universe

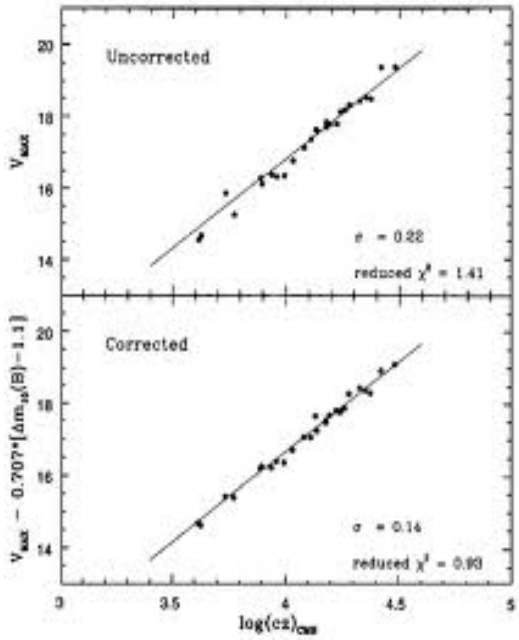


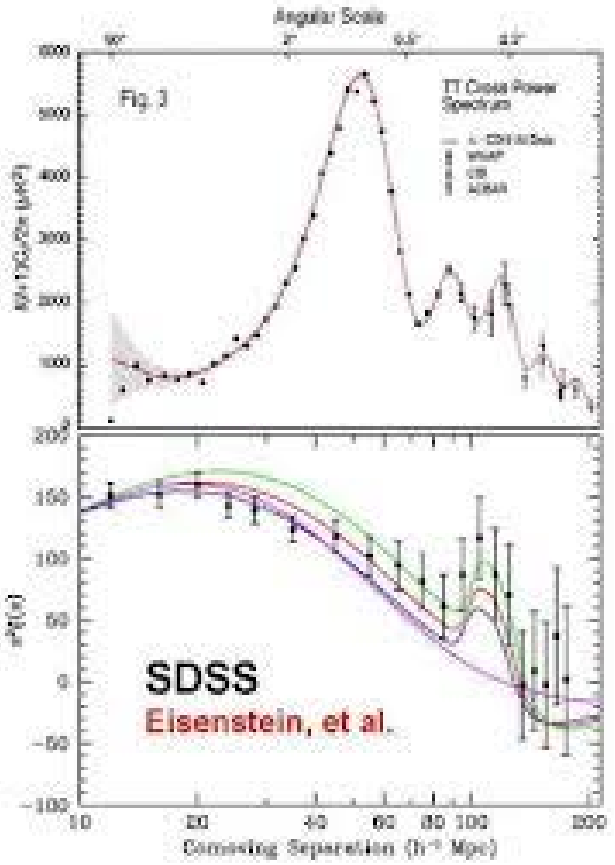


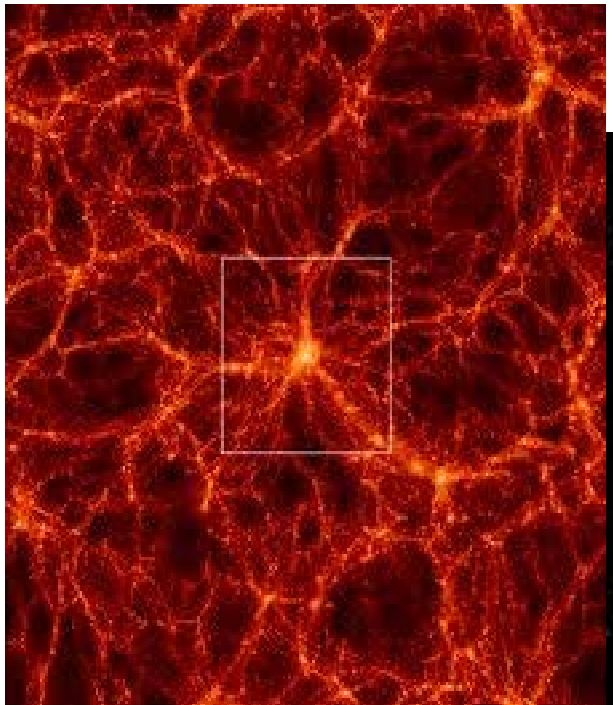
Large scale structure

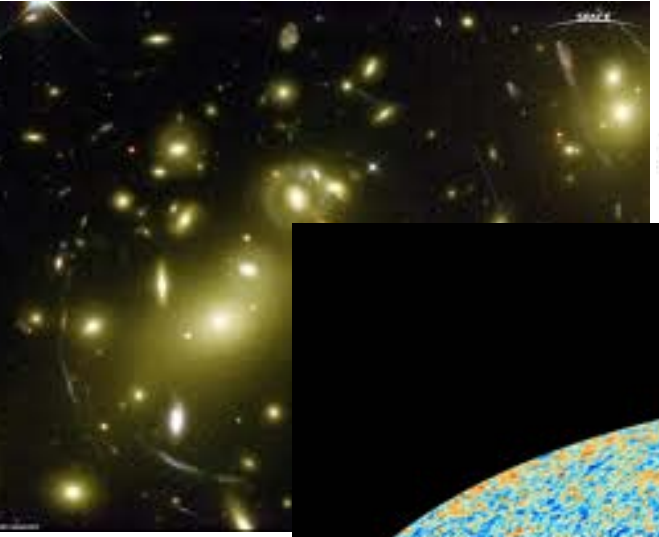
Masses of clusters of galaxies

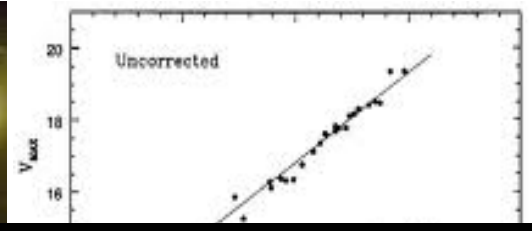


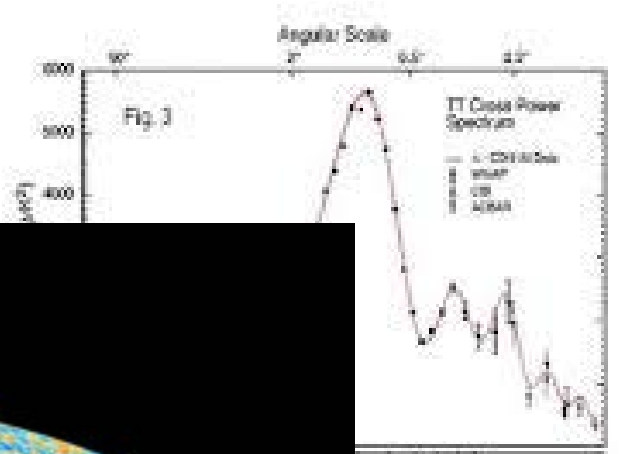

Uncorrected
σ = 0.22
reduced χ^2 = 1.41
Corrected
σ = 0.14
reduced χ^2 = 0.93
V_{max}
$V_{max} - 0.707*[\Delta m_{15}(B) - 1.1]$
$\log(cz)_{CMB}$

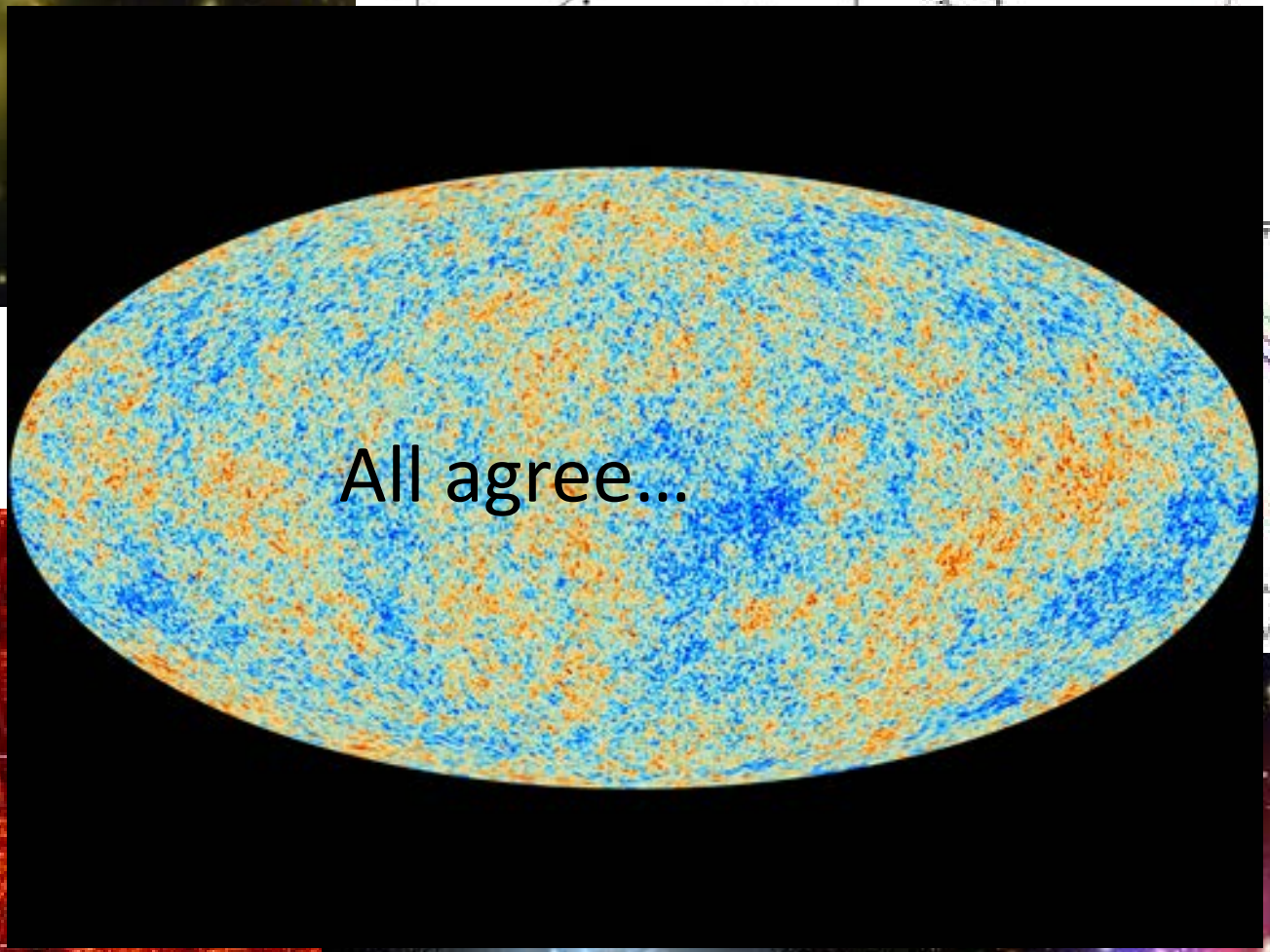

Angular Scale
Fig. 3
TT Cross Power Spectrum
SDSS
Eisenstein, et al.
Comoving Separation (h^{-1} Mpc)



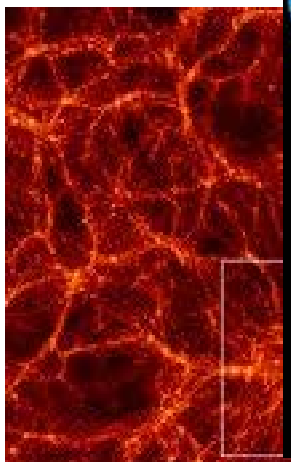


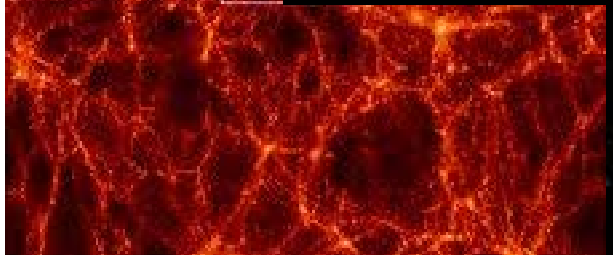

Uncorrected


Angular Scale
Fig. 3
TT Cross Power Spectrum

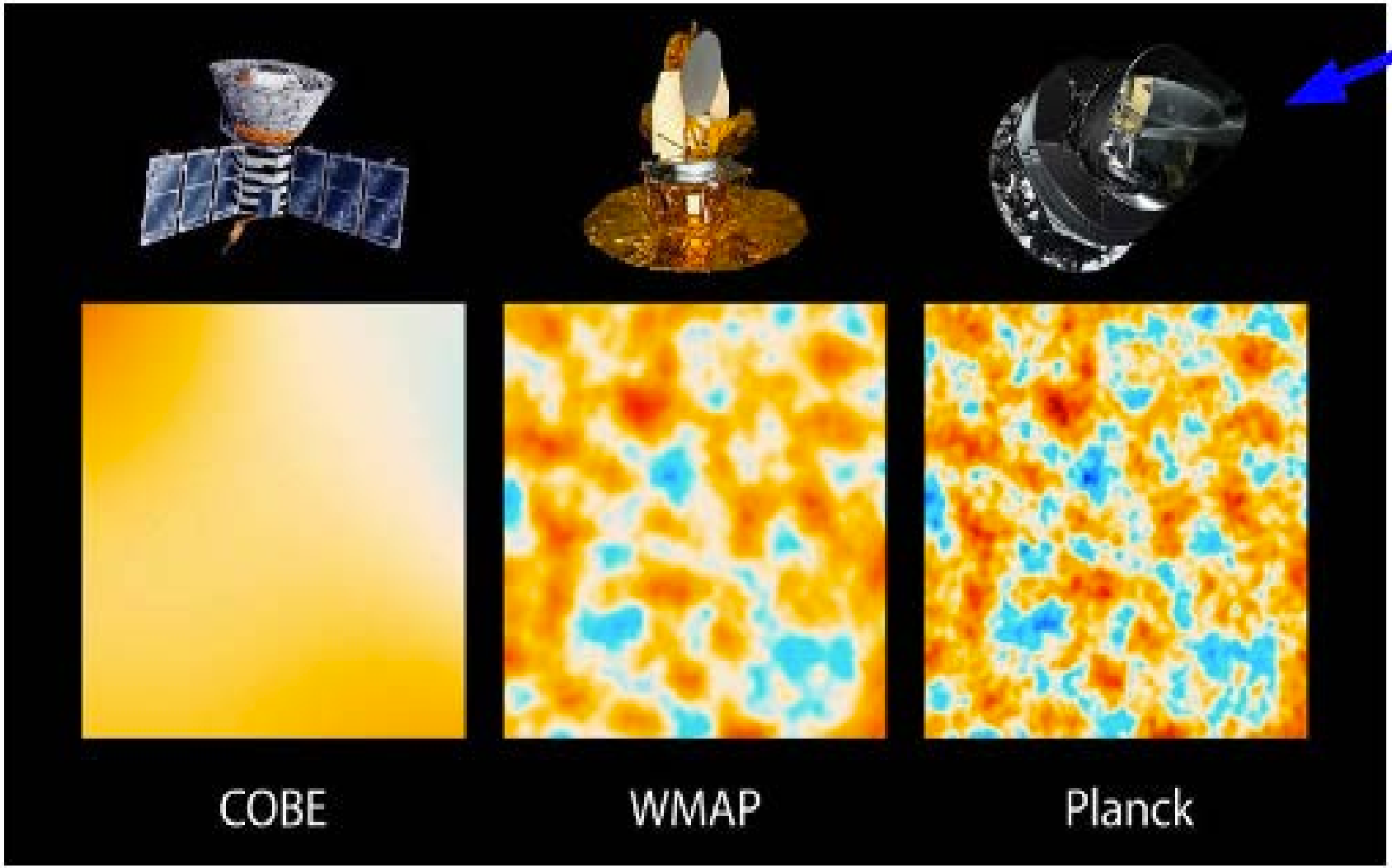

All agree…


al.
60
80
100
200

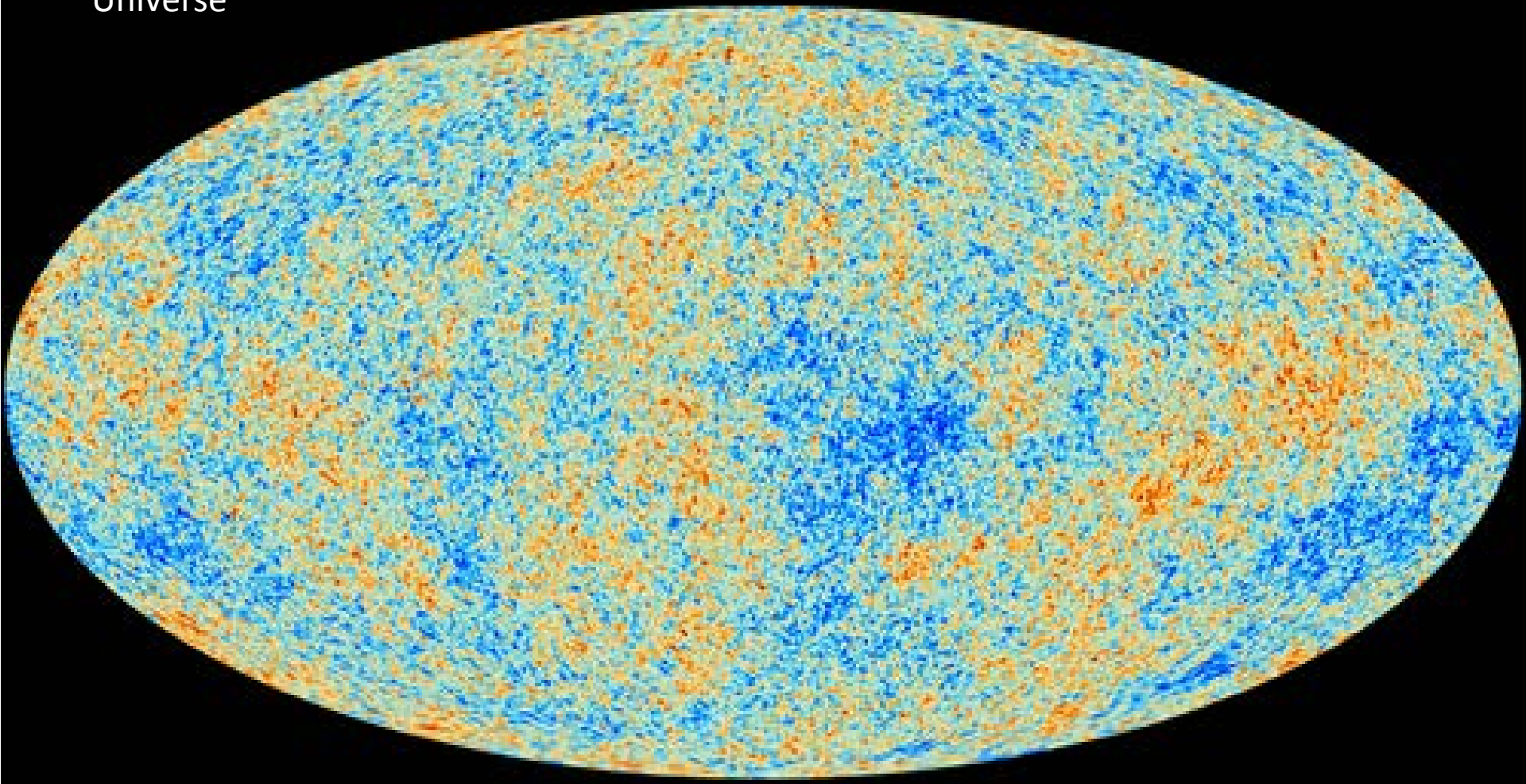




Better, Sharper Baby Pictures



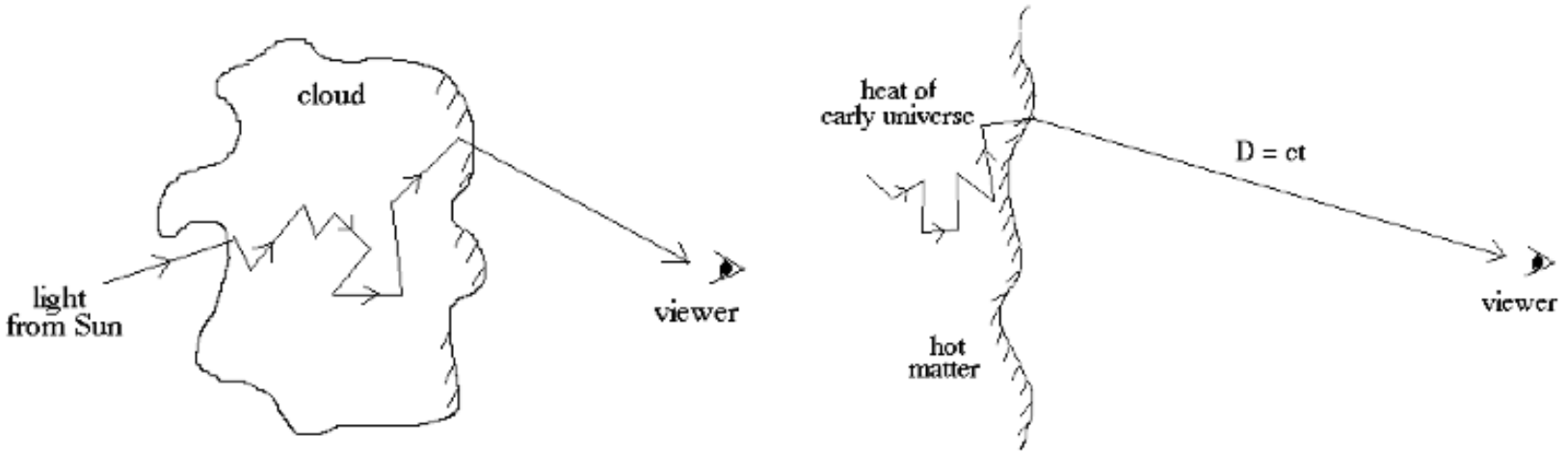
Planck's high-resolution baby picture of the Universe



Dank u wel, Thank you, Merci, Grazie, Gracias, Obrigado, Danke, Takk, etc.

What is this a Picture Of?

We “see” back to a time when the the CMB last interacted with matter, just as we see the *surface* of a cloud



For the cosmos, this is when it is 370,000 years old (corresponding to the first day in the life of a 70 year old)