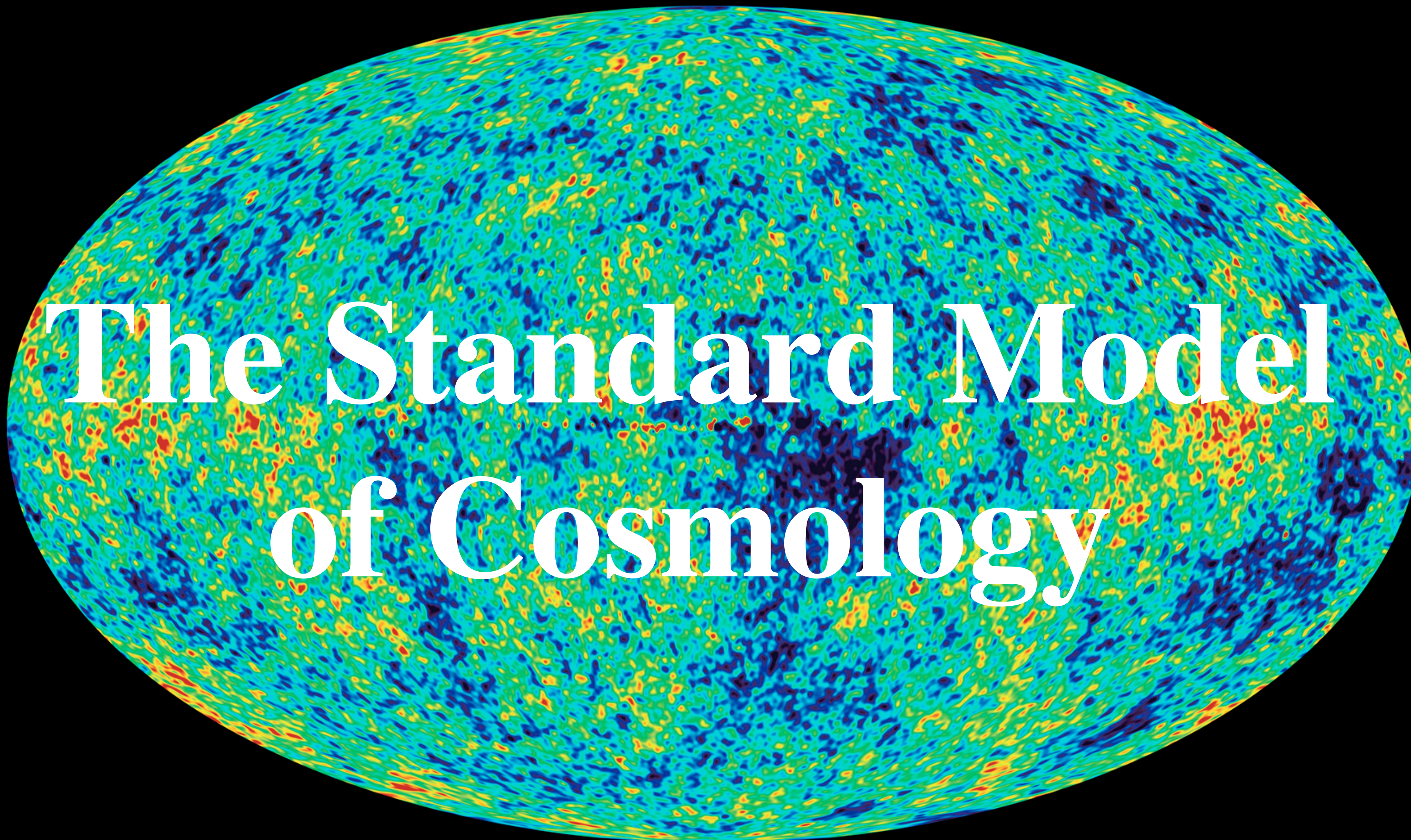
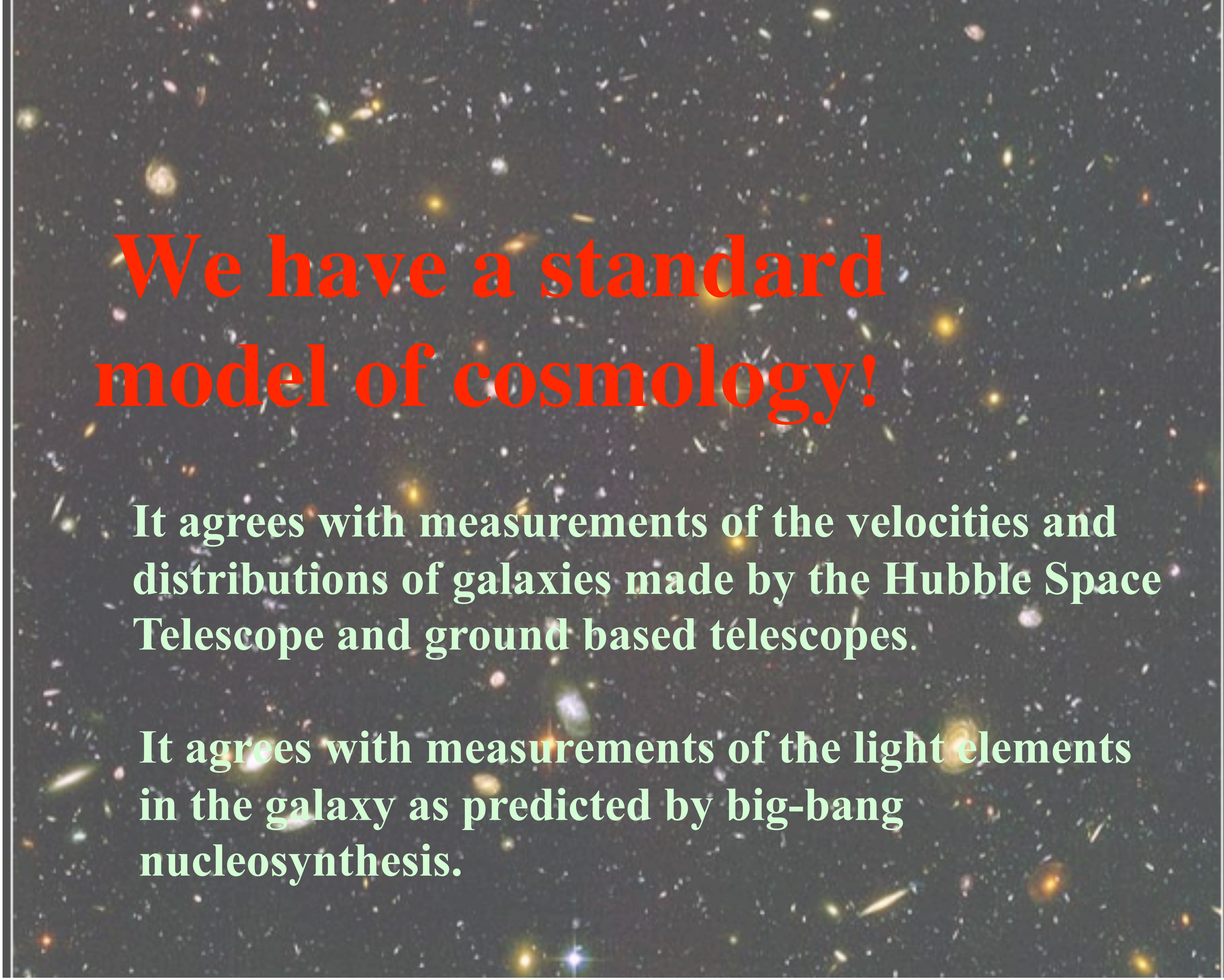
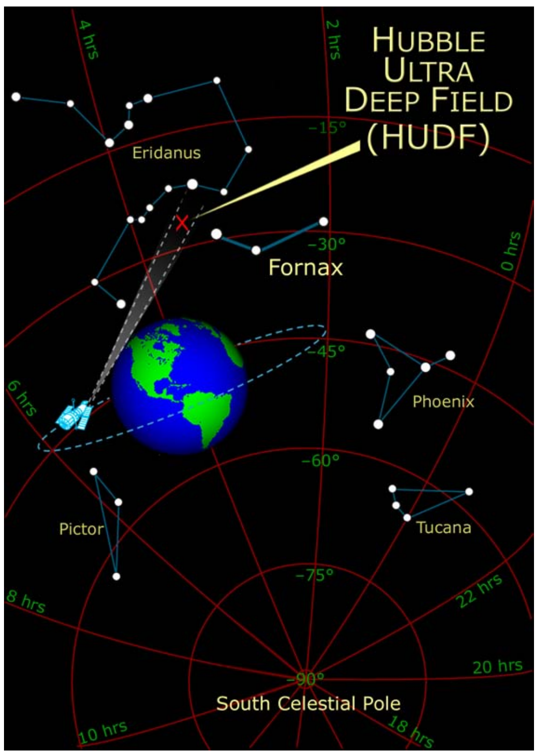
The Standard Model of Cosmology



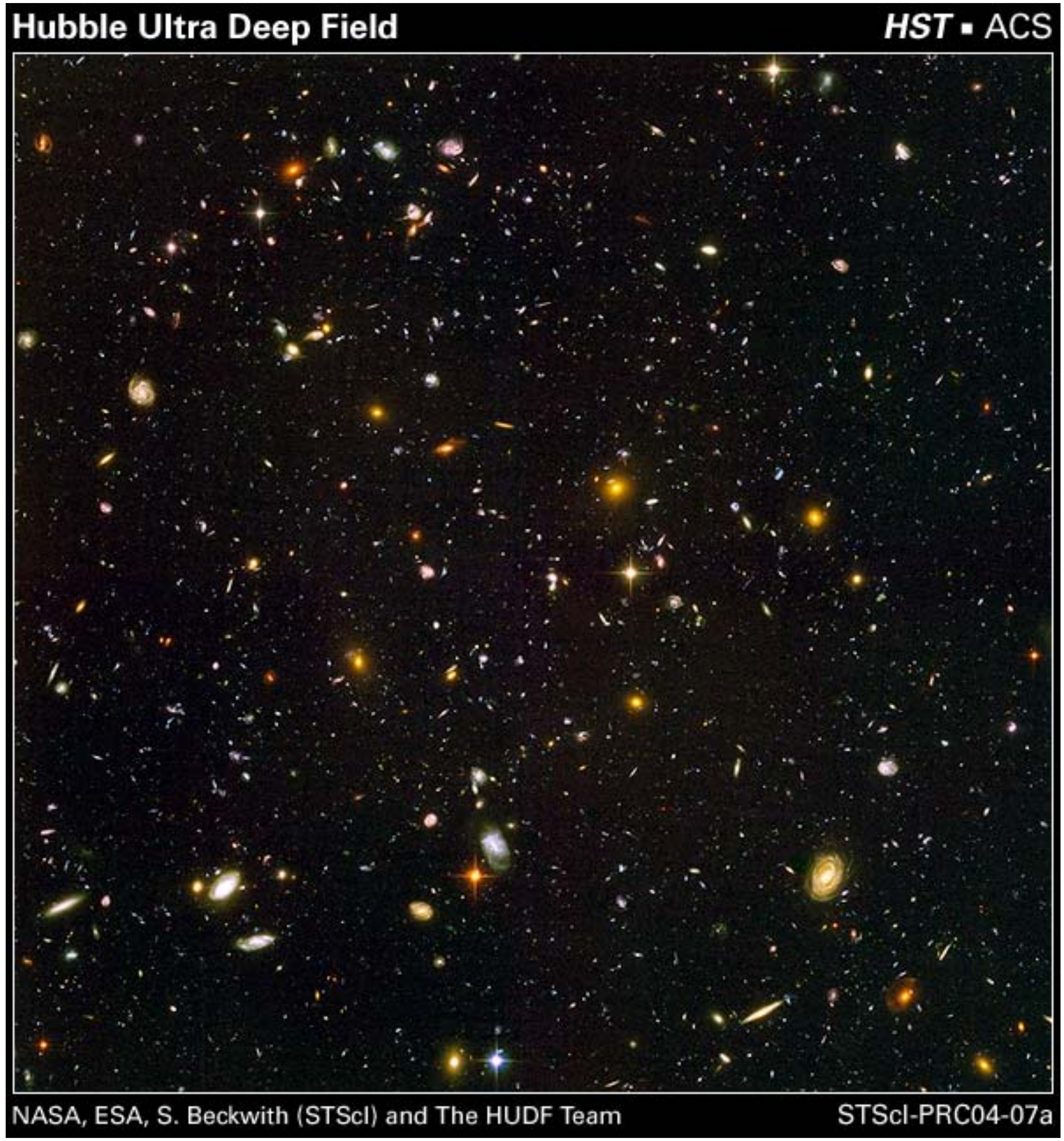
L. Page, Tata Institute of Fundamental Research, April 2010


We have a standard model of cosmology!
It agrees with measurements of the velocities and distributions of galaxies made by the Hubble Space Telescope and ground based telescopes.
It agrees with measurements of the light elements in the galaxy as predicted by big-bang nucleosynthesis.

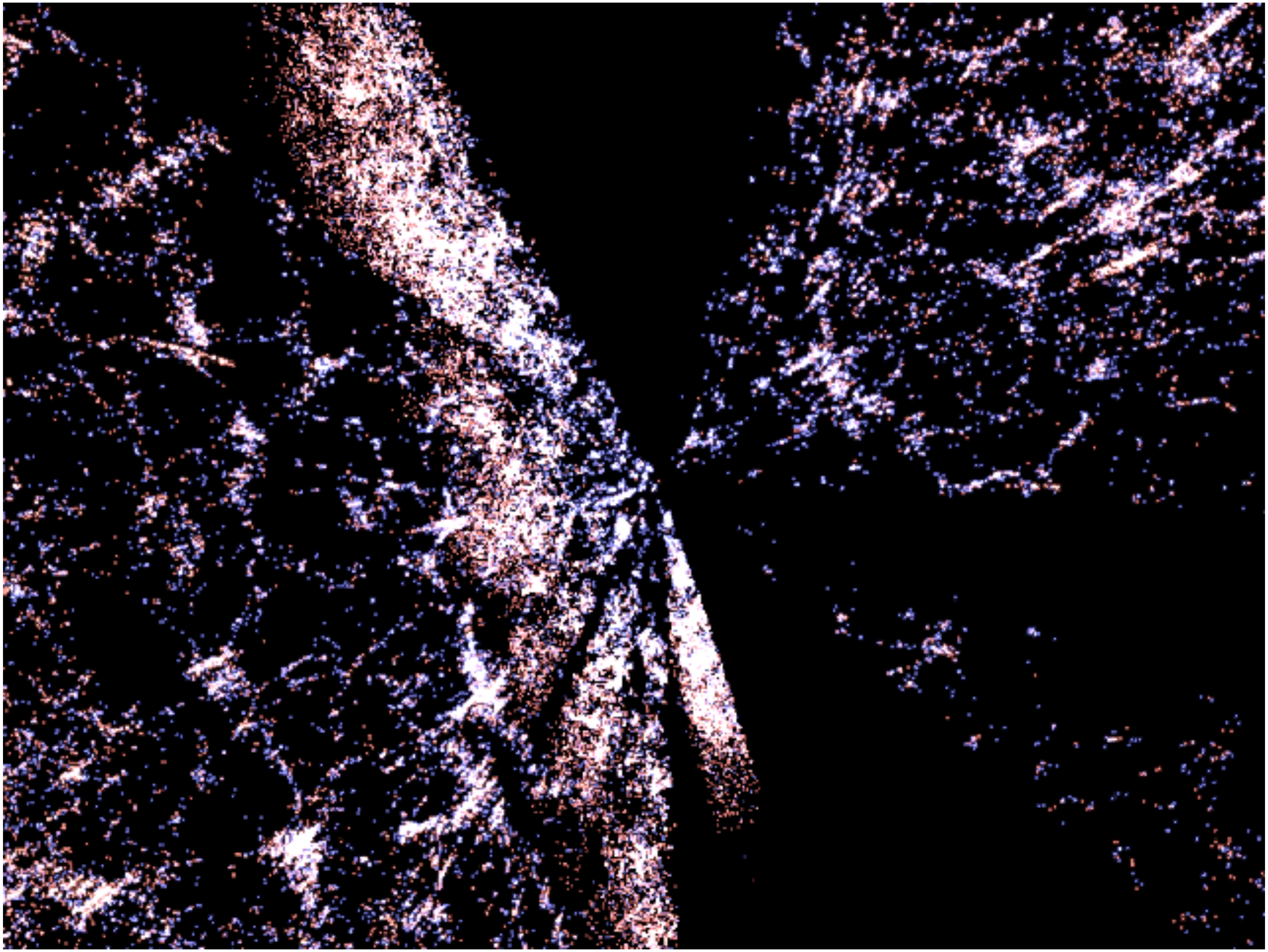
From Hubble



STScI/NASA Field & Levay



10^{11} Galaxies in Observable Universe

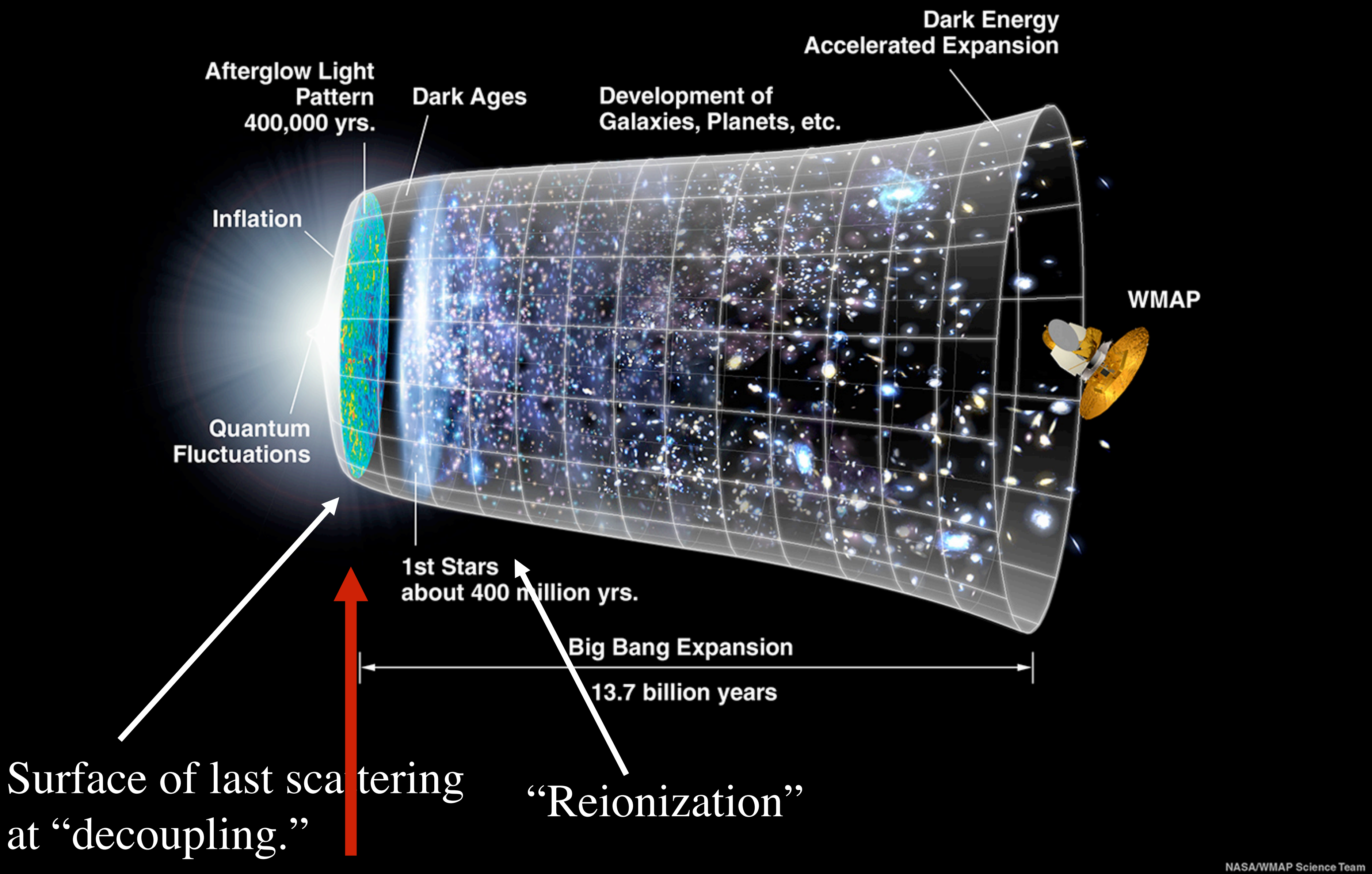


Mark Subbarao & SDSS Collaboration

Some Questions

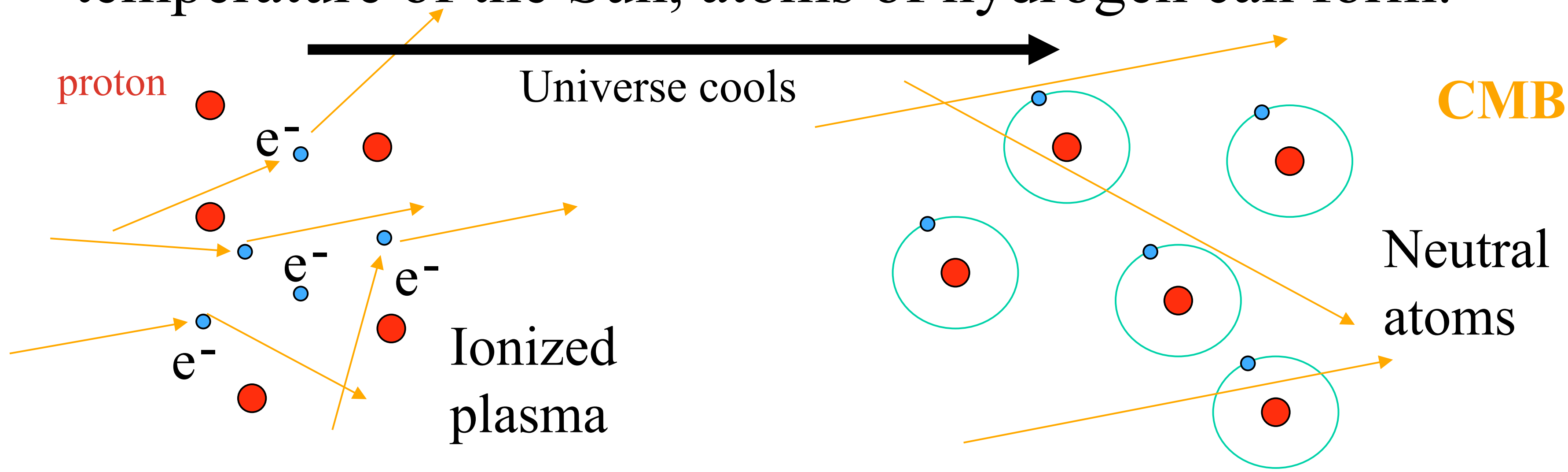
- Why are there galaxies, what seeded them?
- How is it that galaxies are rushing away from us?
- What is the geometry of the Universe? How big is it?
- What is the age of the Universe?

The Standard Model of Cosmology



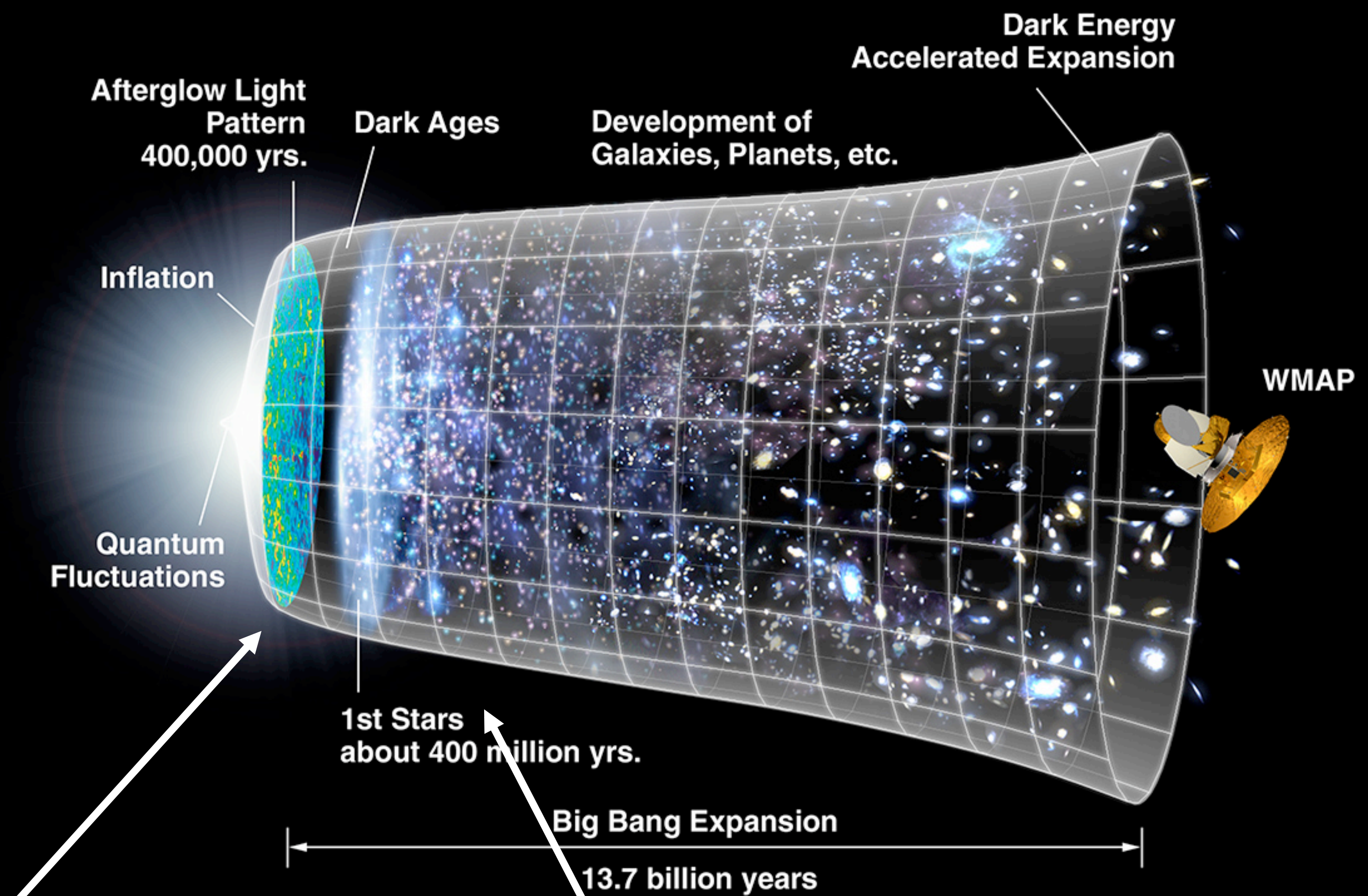
Decoupling of the CMB

- The universe expands and cools from its fiery beginning.
- When the temperature of the Universe is roughly half the temperature of the Sun, atoms of hydrogen can form.



This is called the **epoch of decoupling** and it occurred 379,000 years after the Big Bang.

The Standard Model of Cosmology



Surface of last scattering
at “decoupling.”

“Reionization”

NASA/WMAP Science Team

The Model

What seeded the galaxies? Quantum fluctuations arising from processes in the very very early universe.

How is it that galaxies are rushing away? Space is expanding, galaxies are markers.

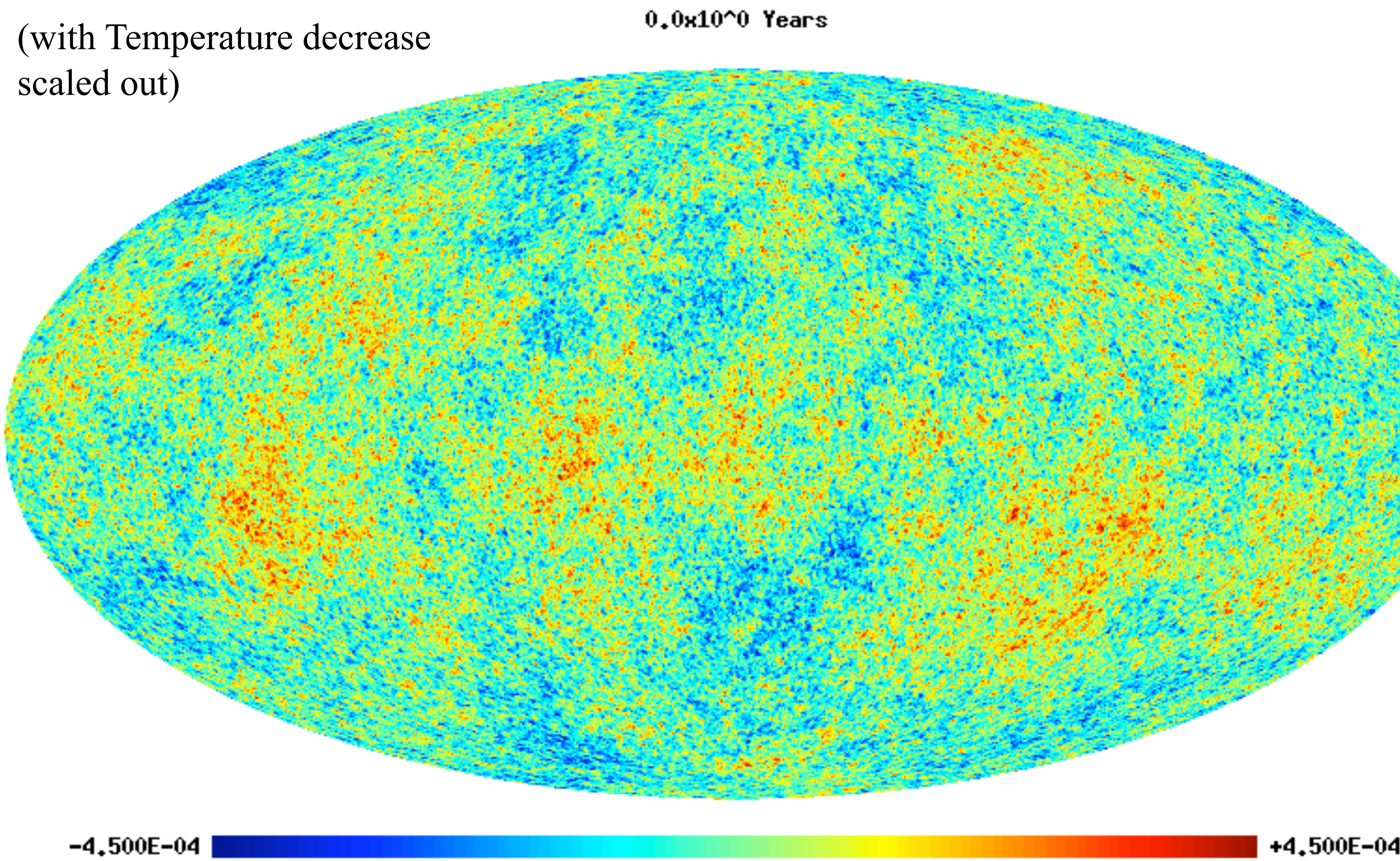
What is the geometry of the Universe? Flat—just as you might think. We model it as infinite.

What is the age of the Universe?....

These are all addressed with measurements of the cosmic microwave background (CMB).

Expanding CMB Photosphere

(with Temperature decrease scaled out)



How Do We Measure the CMB?

With the expansion of the universe, the CMB has cooled to -270 ^{o}C, or 2.725 ^{o}C above absolute zero.

The CMB is about 1000 times cooler than the Sun and so “shines” in the microwave regime.

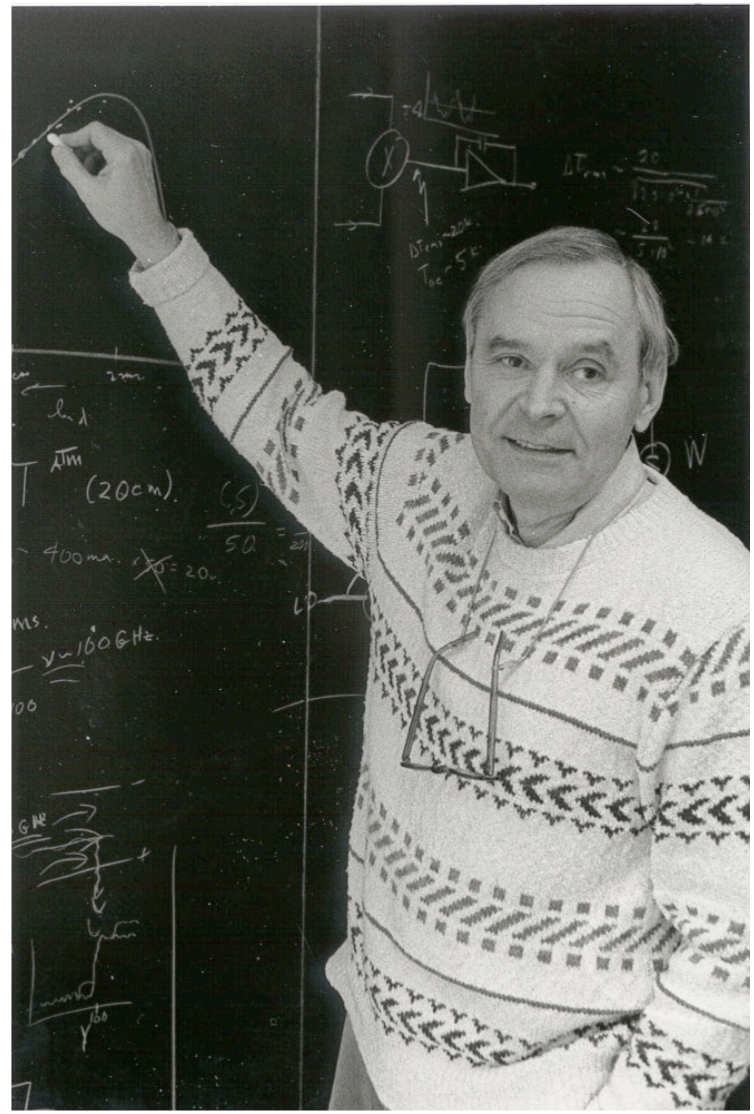
You’ve all detected the CMB!

TV Channel 69 broadcasts at 800 MHz

CMB approx 1% of TV noise!

Wilkinson Microwave Anisotropy Probe

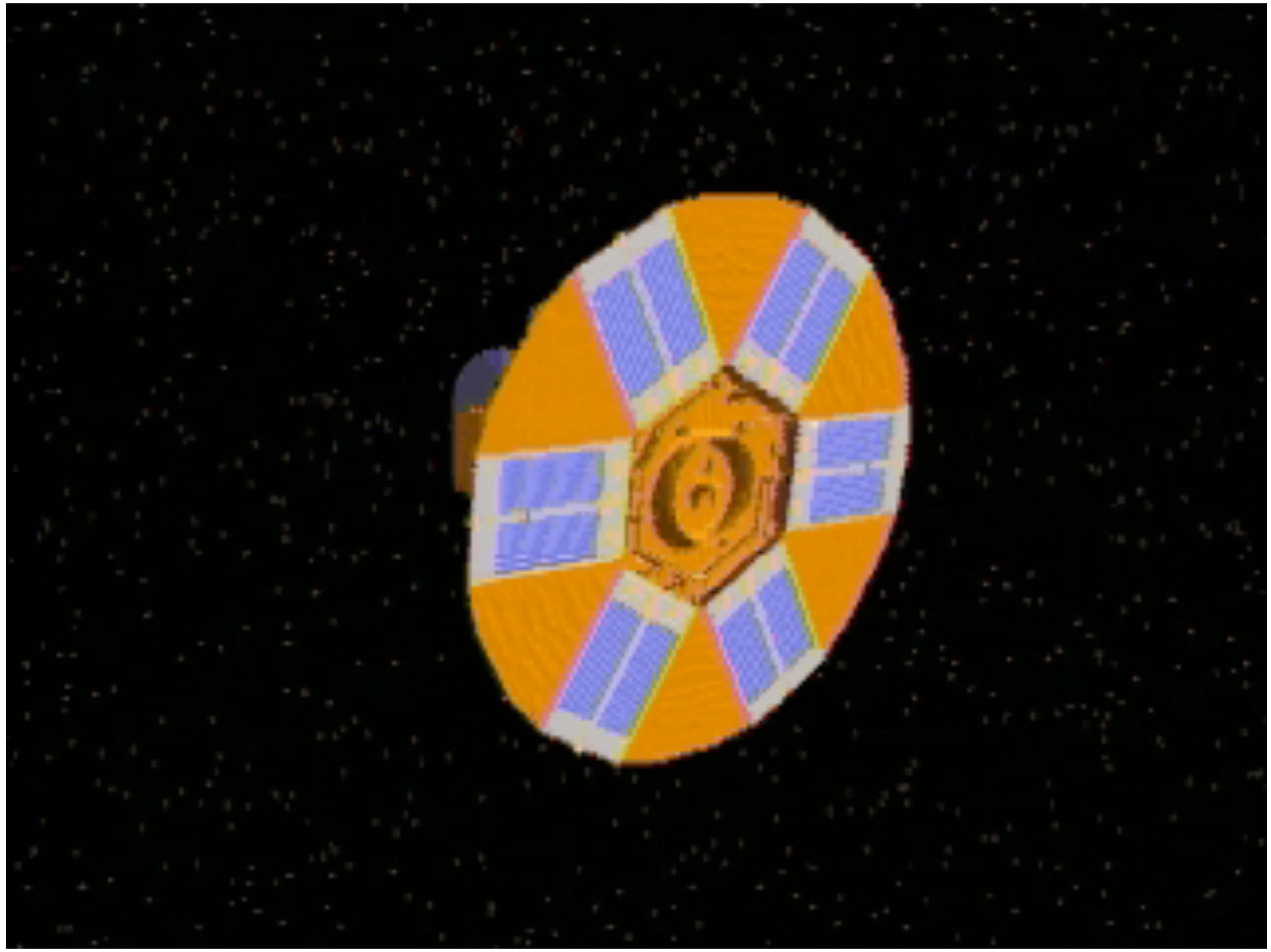
(WMAP).



Dave Wilkinson

WMAP

A partnership between NASA/GSFC and Princeton



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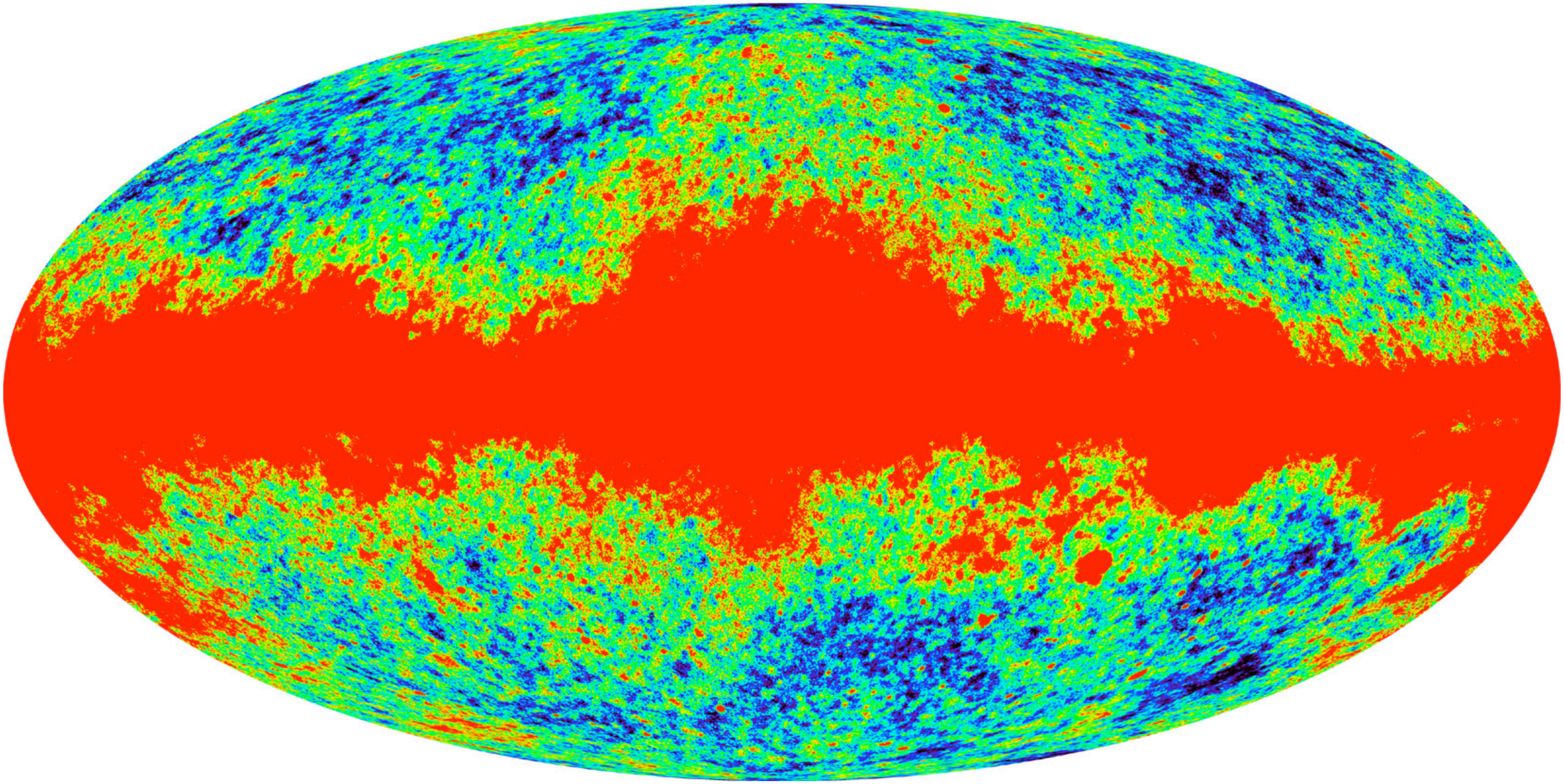
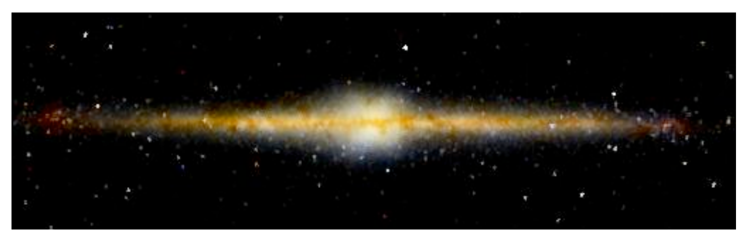
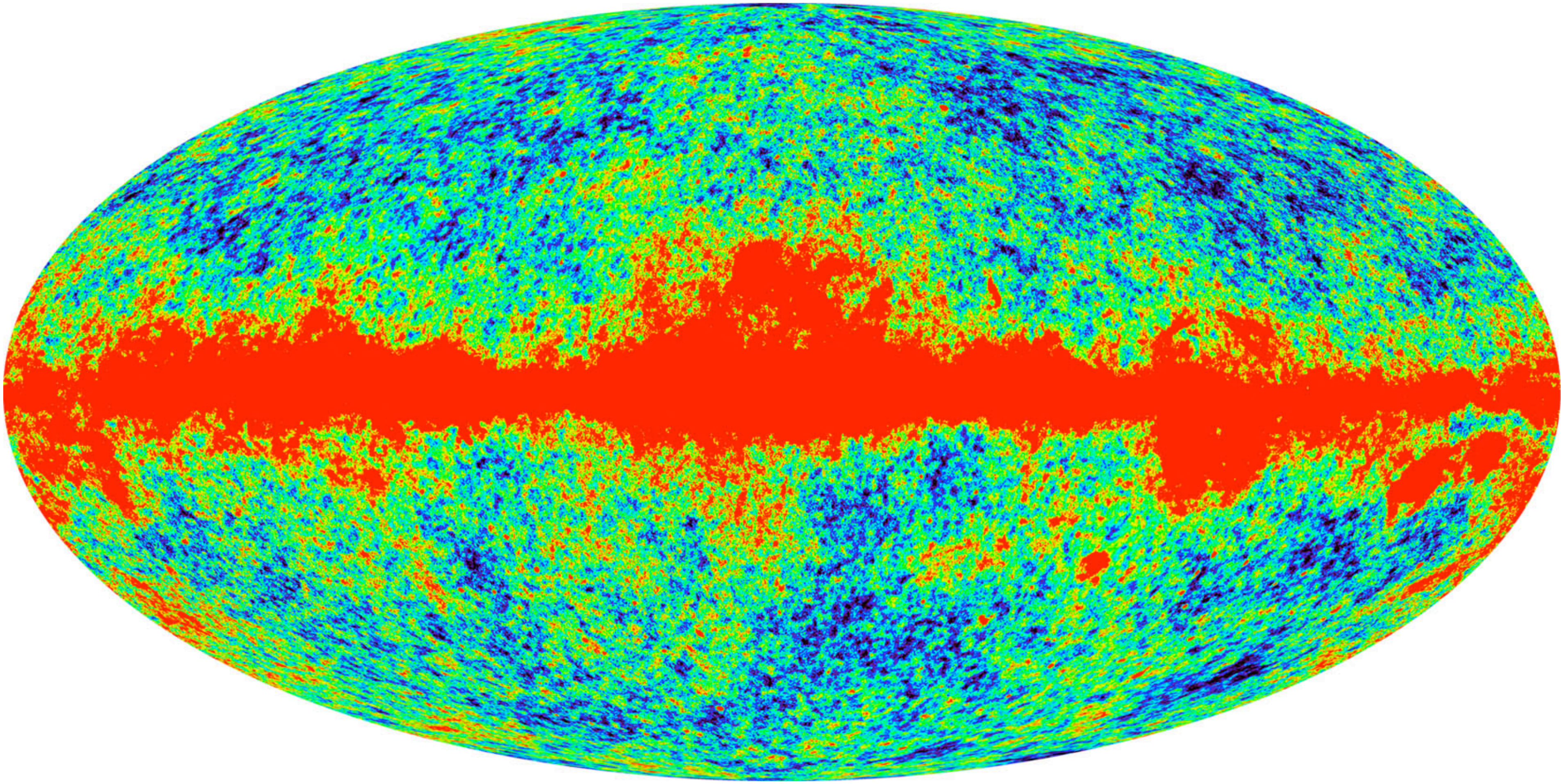
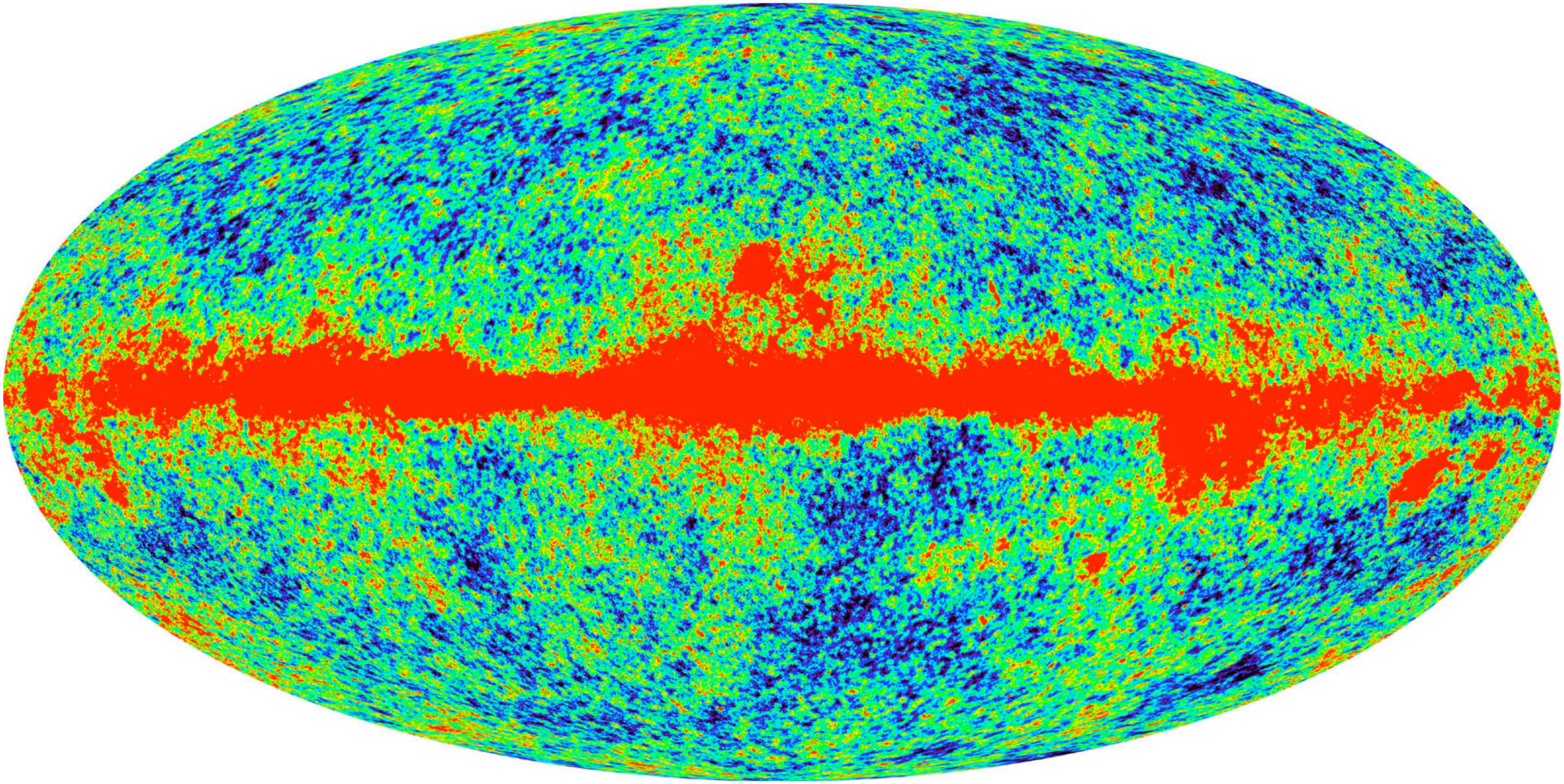


K Band, 22 GHz, 1.4 cm

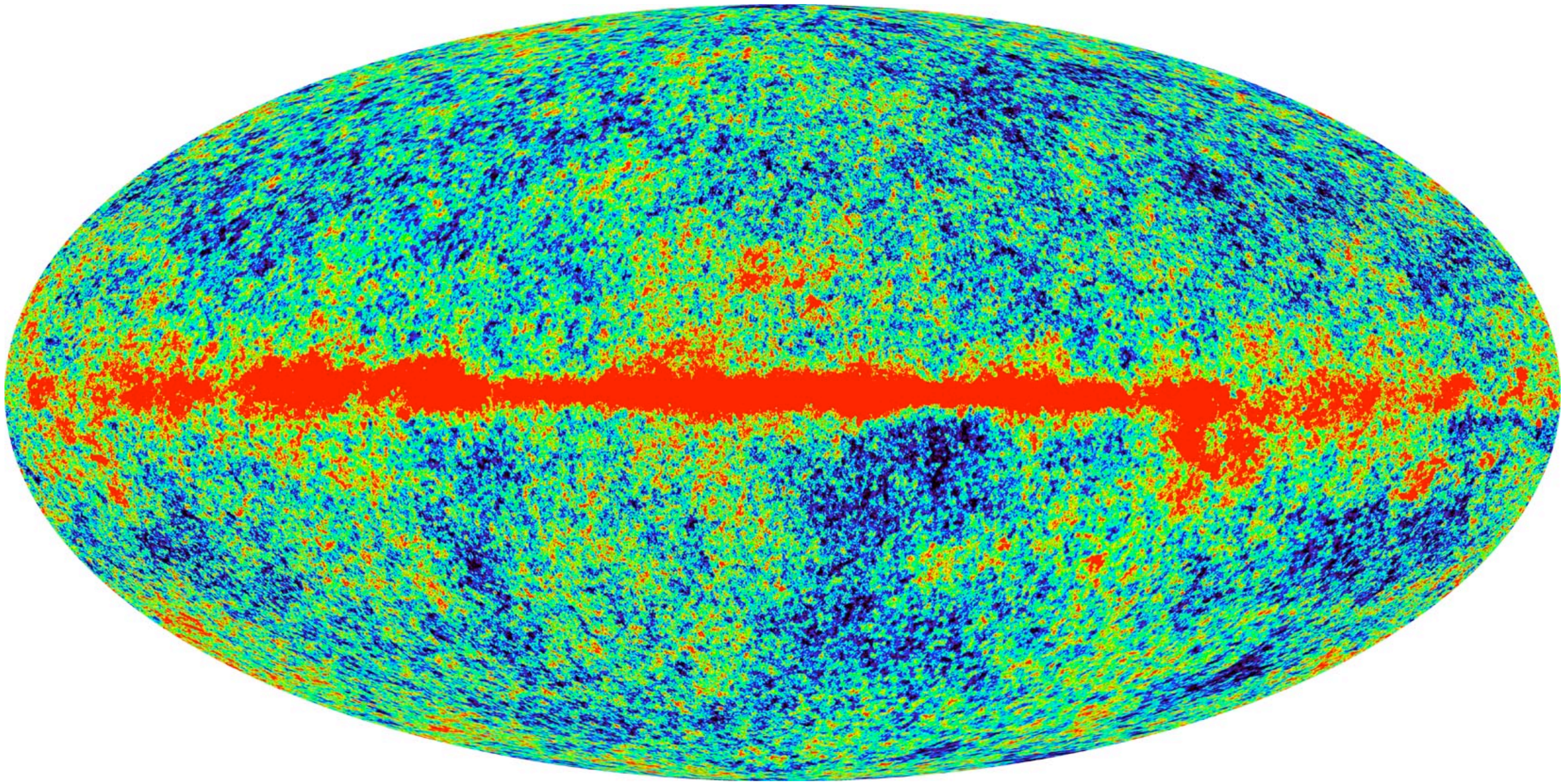




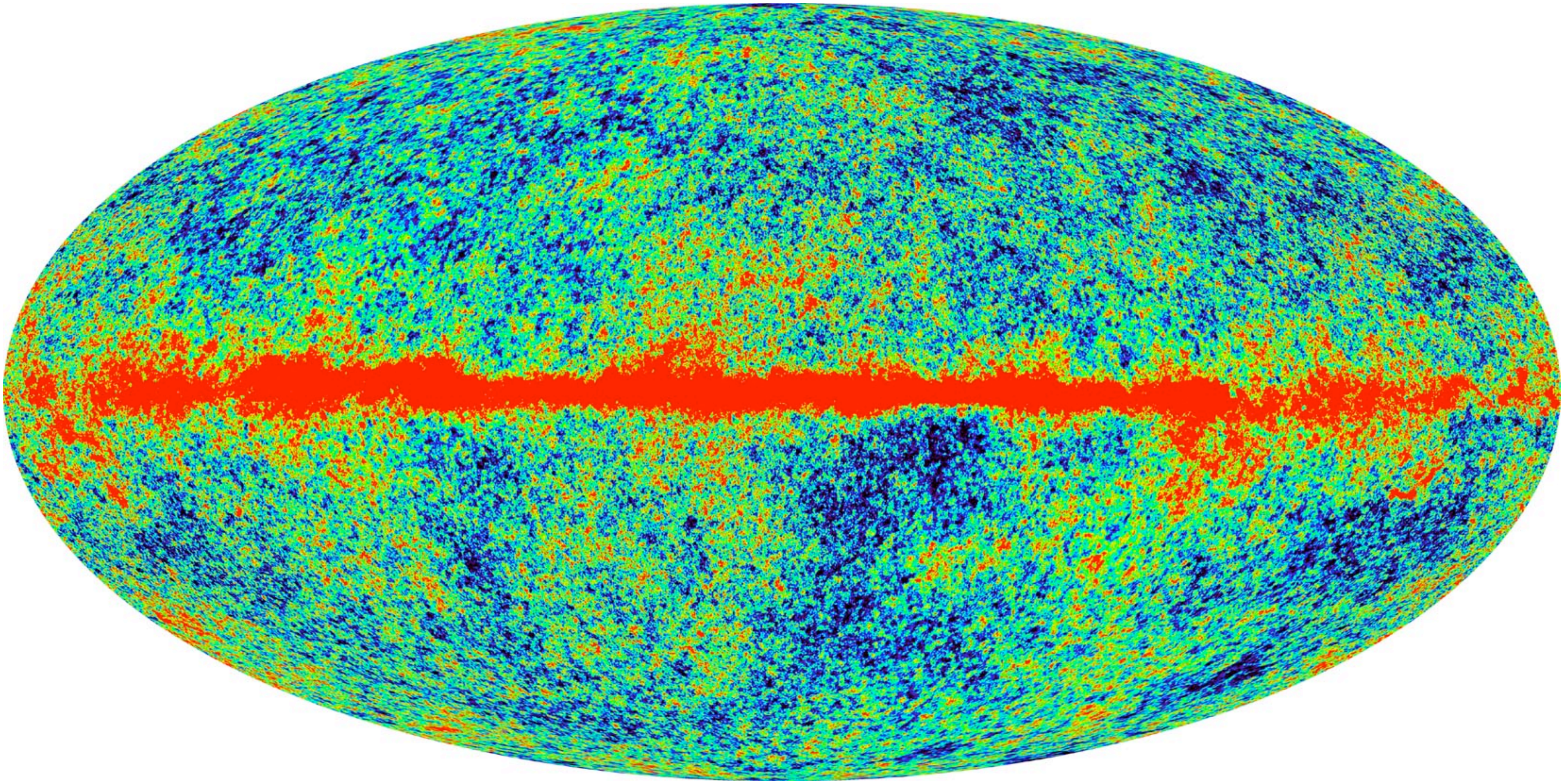
Ka Band, 33 GHz, 1 cm



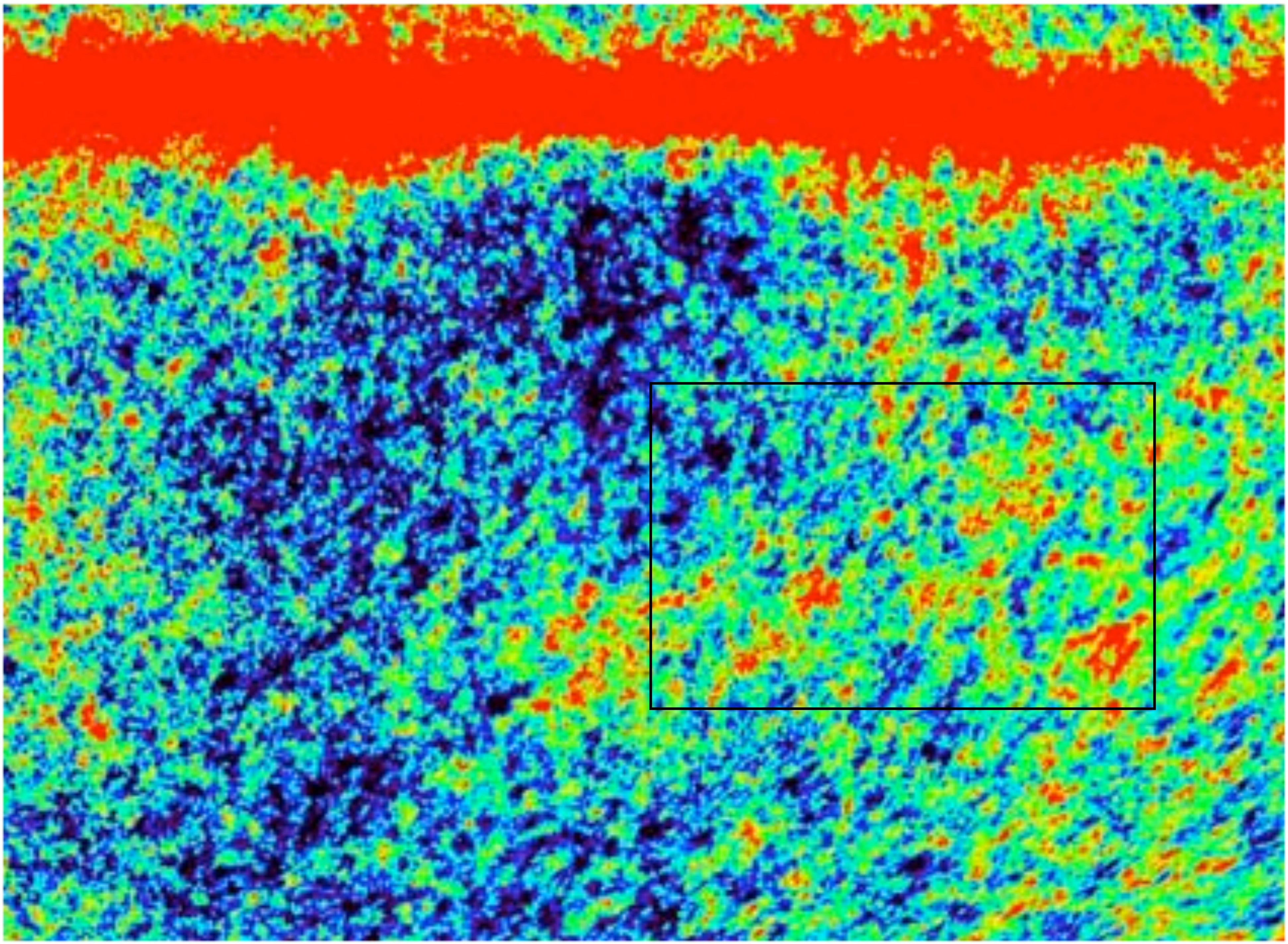
Q Band, 41 GHz, 0.7 cm

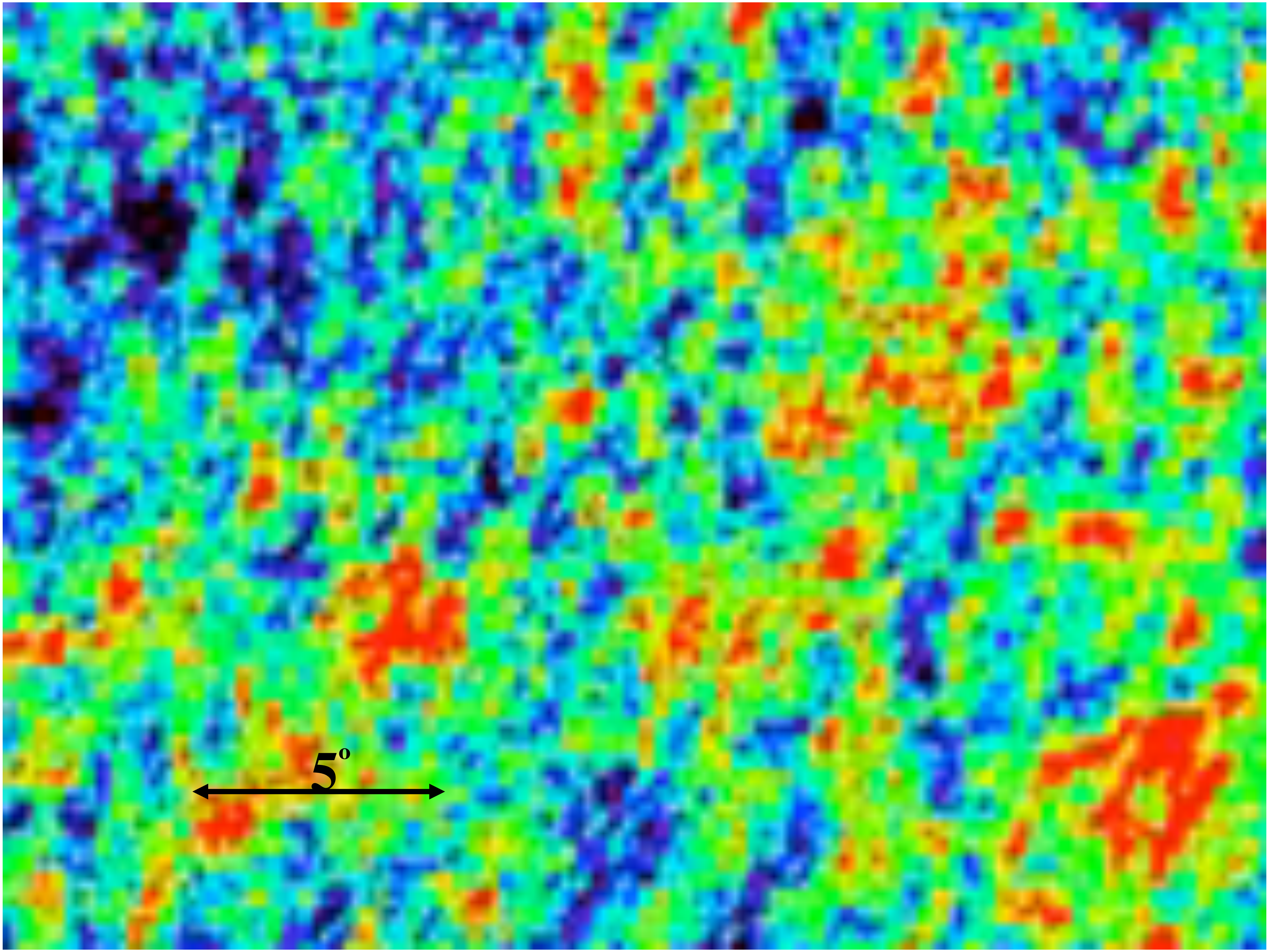


V Band, 61 GHz, 0.5 cm

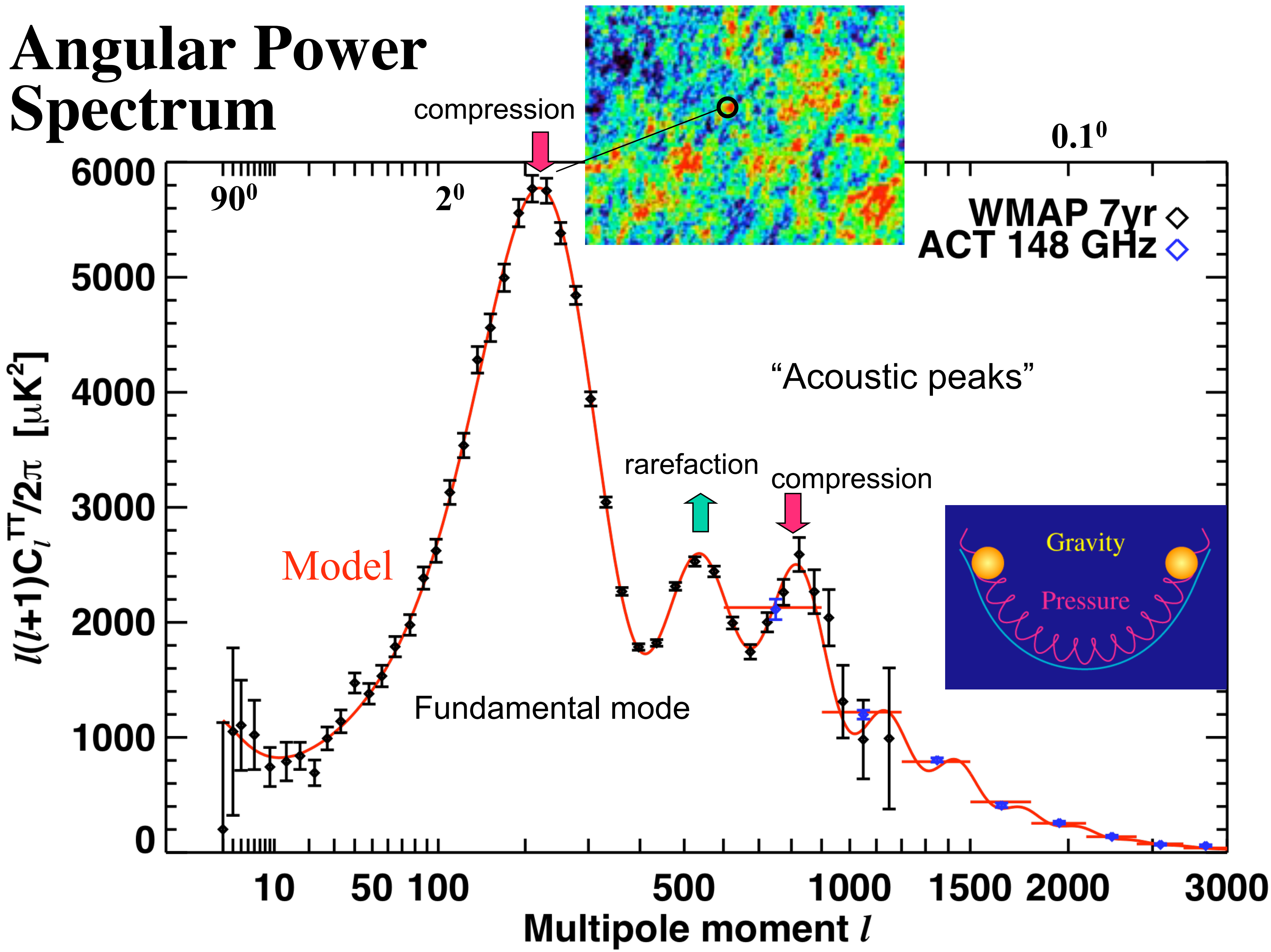


W Band, 94 GHz, 0.3 cm



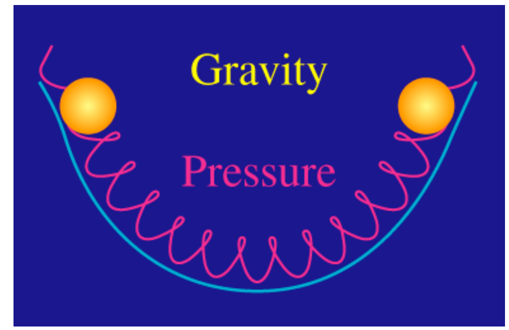

5°

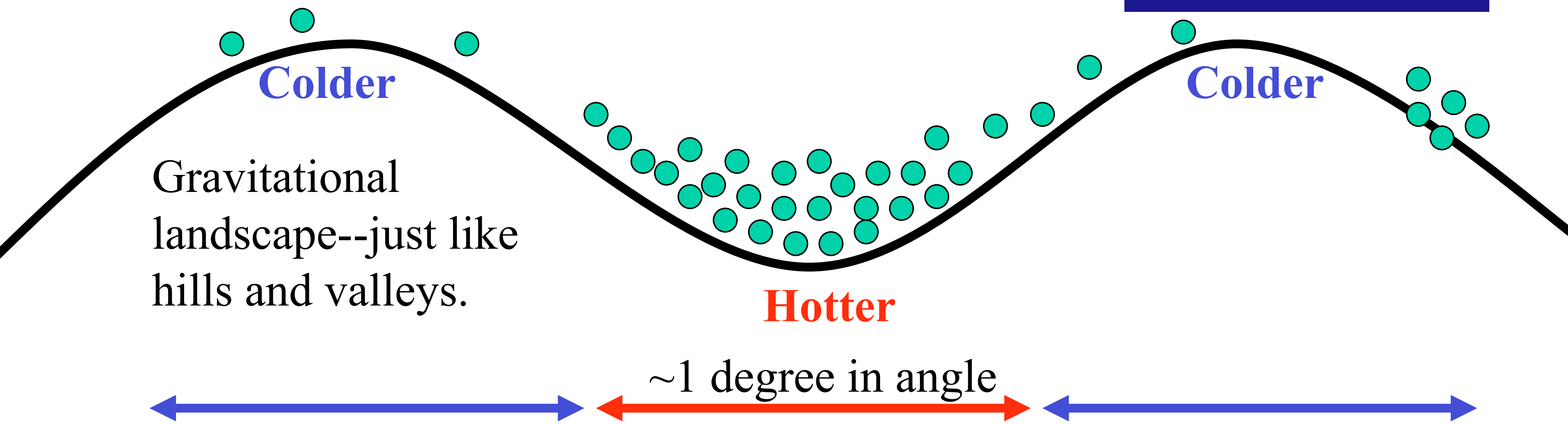
Angular Power Spectrum



How do we get hot and cold patches?

W. Hu

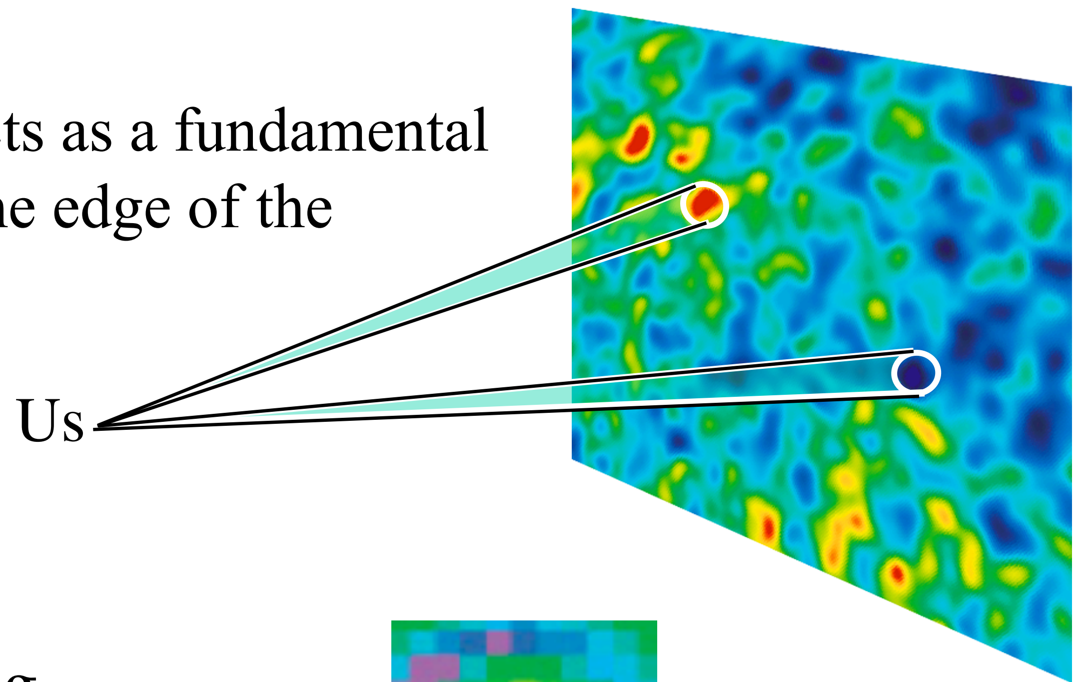




Spot size = [speed plasma (●) travels]x[age of universe at decoupling]

Cosmic Paleontology

The "fundamental mode" acts as a fundamental "footprint" or yardstick at the edge of the observable universe.



Θ=0.595 +/− 0.0015 deg

(12,000 stacked hot spots.)

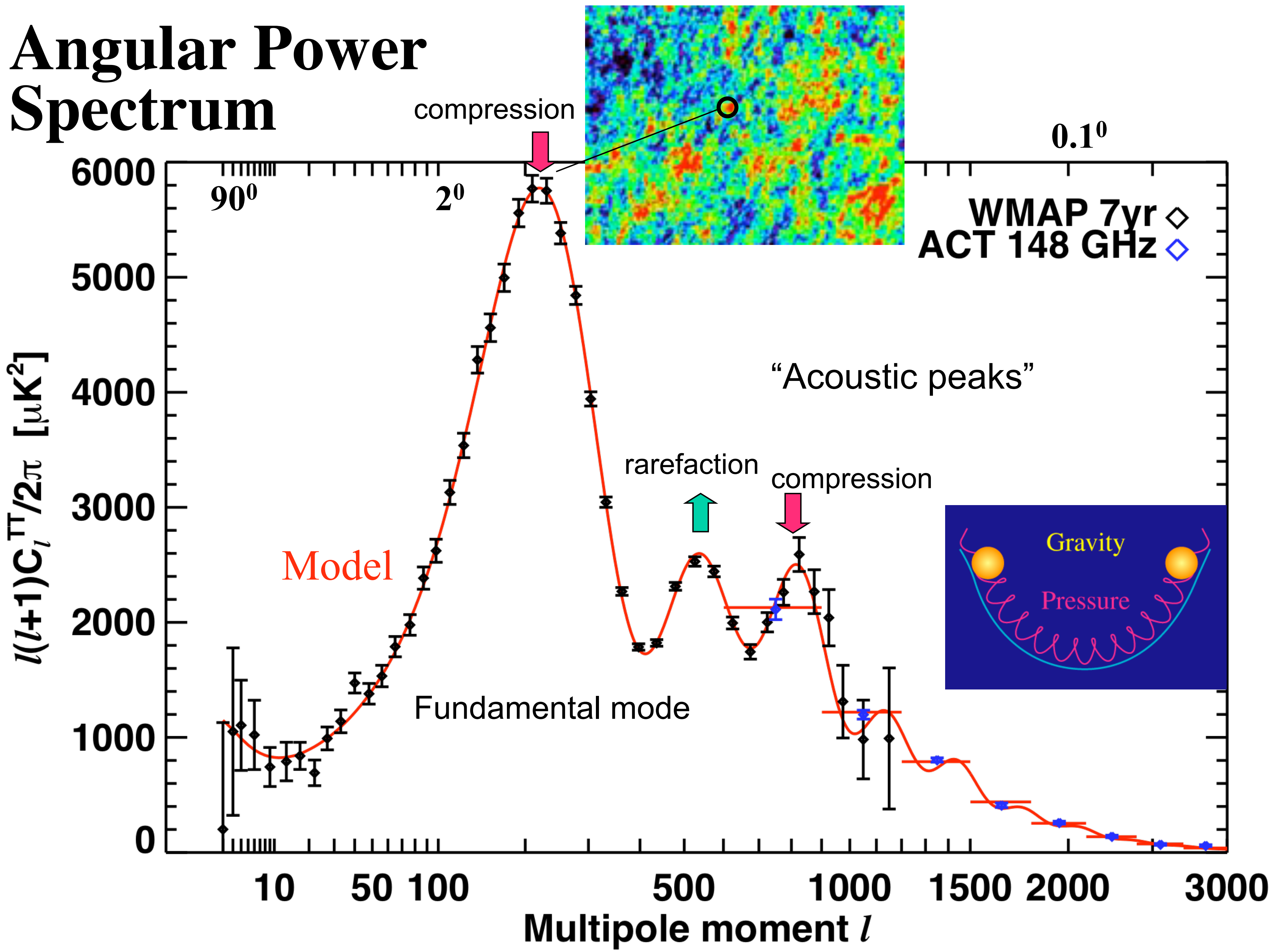
This allows us to determine the size of the observable universe.

From the standard yardstick, we can deduce the distance to the edge of the universe.

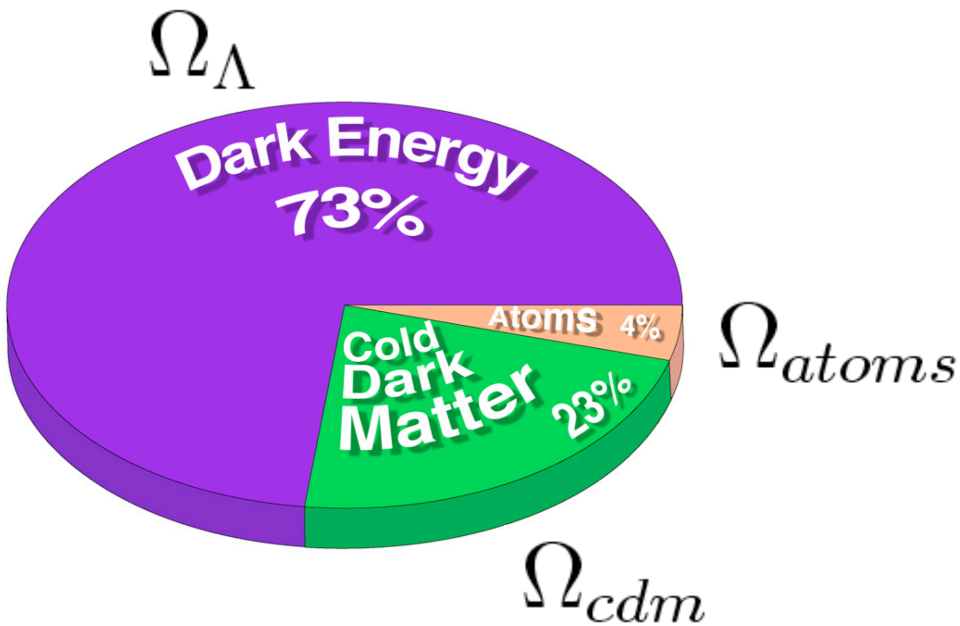
Knowing this distance, and the speed of light, we deduce that the age of the universe is:

$$\mathbf{t_U = 13.75 +/- 0.13\ Gyr}$$

Angular Power Spectrum



Parameters of the Model



Basic model (with only six parameters) agrees with virtually all cosmological measurements.

$$\Omega_{cdm} + \Omega_\Lambda + \Omega_{atoms} = 1$$

22.6% 72.8% 4.6%

95.5% of the Universe is new to us!

- The "dark energy" (73%) has no foundation in any fundamental theory of nature. It is as though the vacuum has an energy associated with it that drives the universe apart, like antigravity.

  Most feel that "dark energy" represents a missing piece of theory as opposed to a substance.

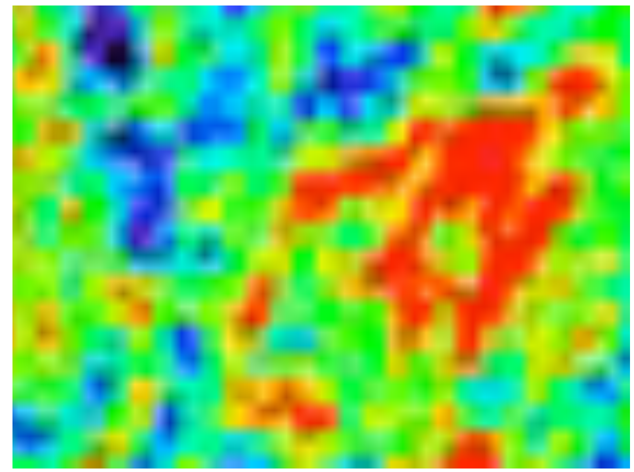
- The "dark matter" (23%) is likely a new particle or particles that will be directly detected soon.

Abbreviated

The Standard Cosmological Model

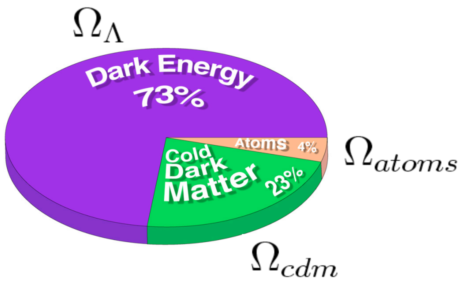
- At a very early time a “quantum field” impressed on the universe a gravitational landscape. We measure characteristics of this field.

This is a picture of a quantum field from the birth of the universe.



- Matter fell into the valleys to form eventually “structure.” But only 1/6 of this matter is familiar to us.

- The dynamics of the universe is now driven not so much by the matter but by an apparent Dark Energy



The Latest CMB Science

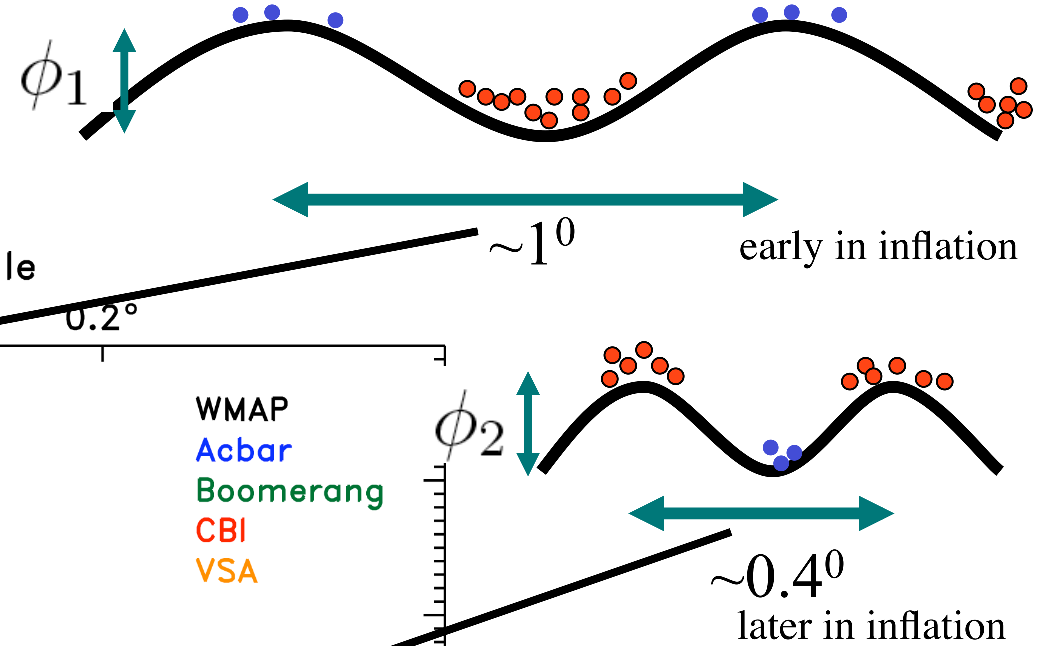
Ω_{cdm} & Ω_Λ are parameterized phenomenologically. We don't know why they are what we observe.

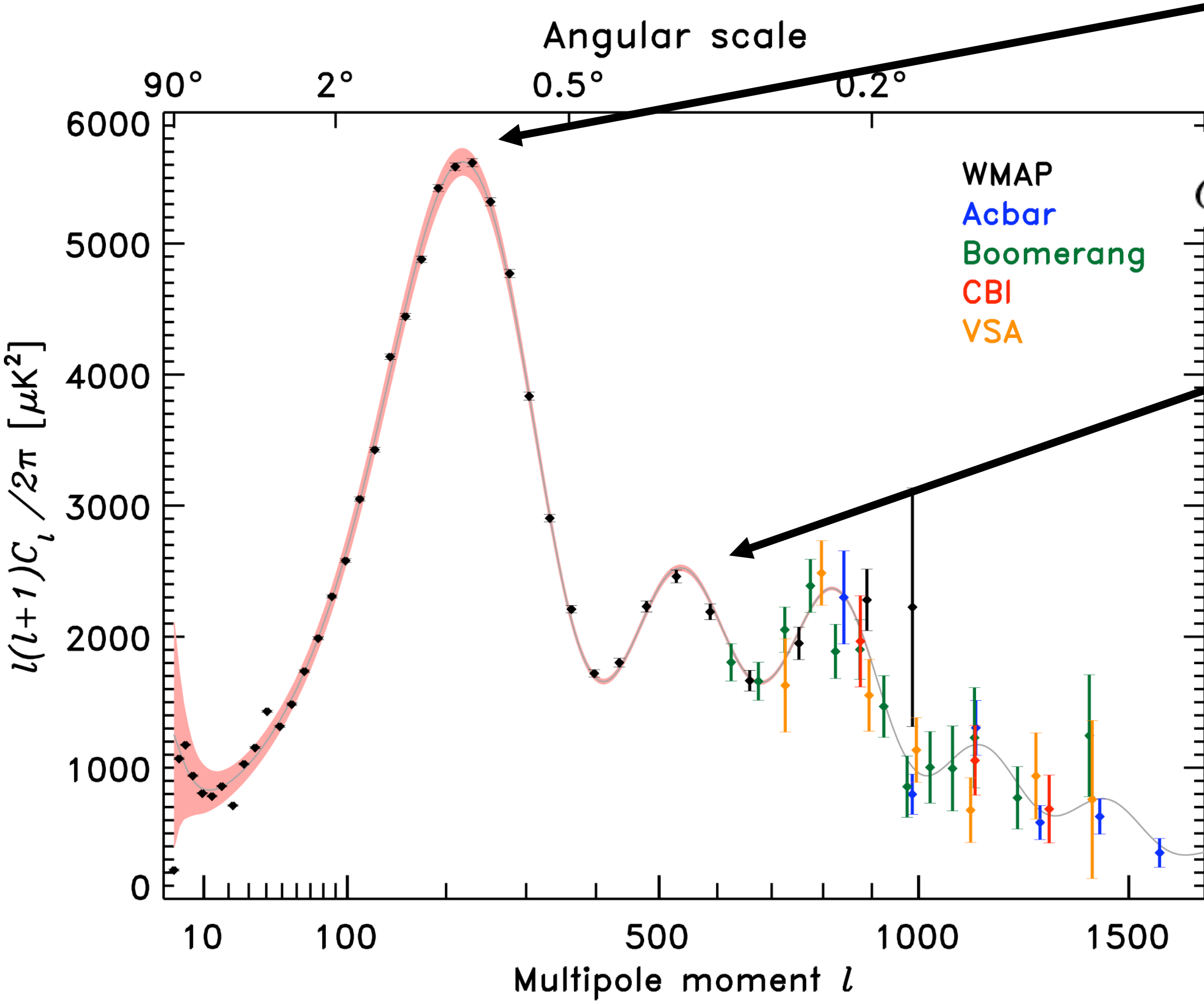
However:

Theories of the $t<10^{-20}$s Universe predict the gravitational landscape to which the contents respond to high accuracy. We can measure the CMB so well we can differentiate between different models.

Angular Power Spectrum.

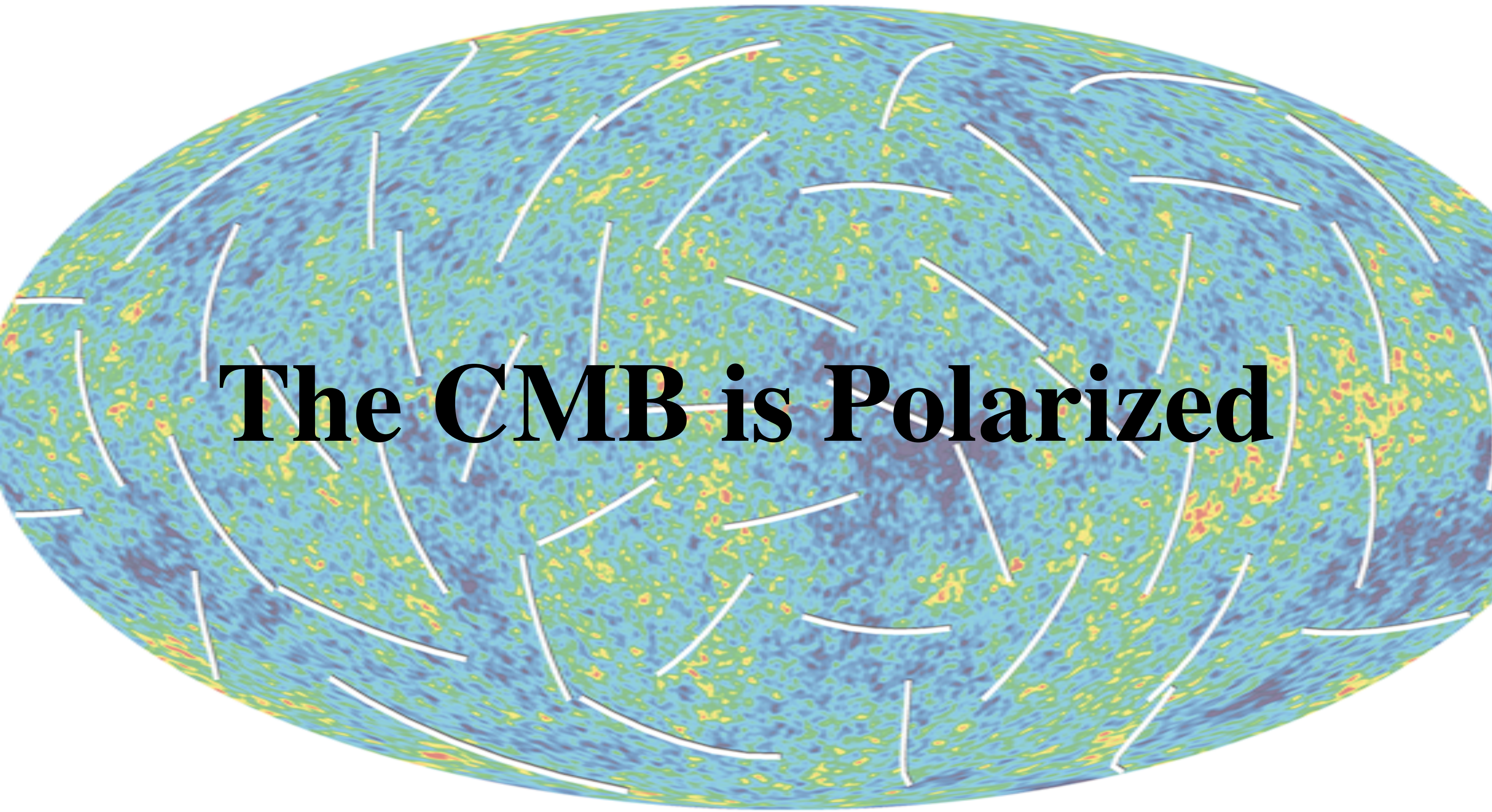
Physical size = plasma speed X age of universe at decoupling





The overall slope of this spectrum is the new handle on inflation.

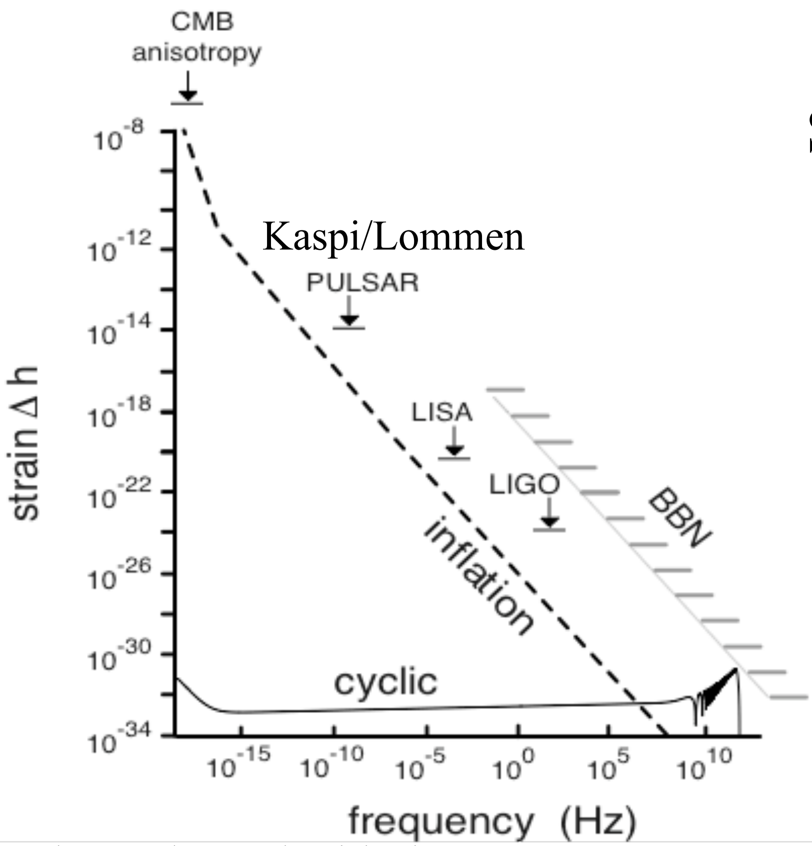
The CMB is Polarized



Primordial Gravitational Waves

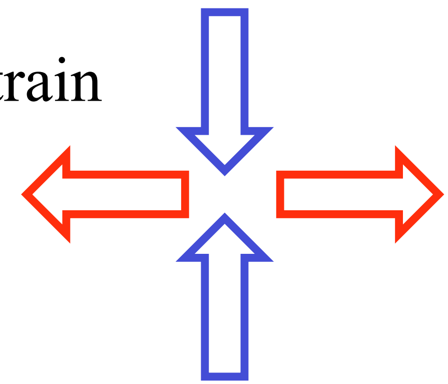
We have just discussed scalar perturbations or $\delta\phi/\phi \sim \delta\rho/\rho$.

Many models of the early universe also predict tensor perturbations or δh where h is strain.



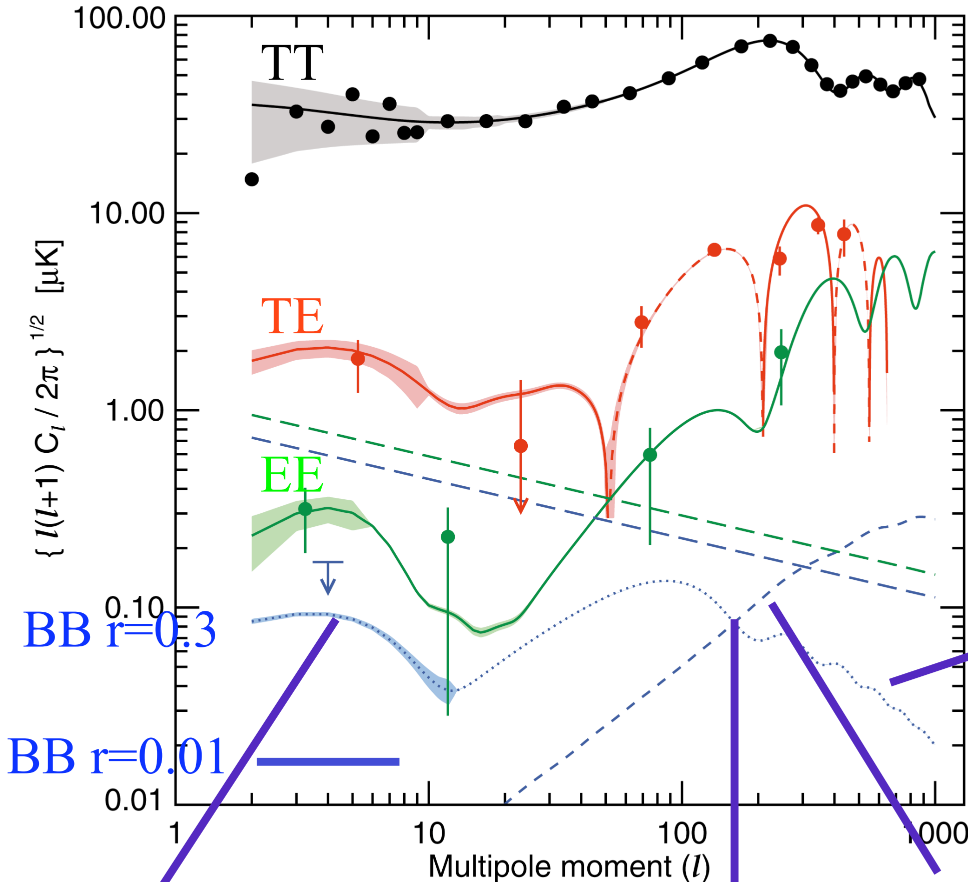
From Latham Boyle & Paul Steinhardt

Strain



Over the expanse of universe, one side is displaced ~1000 ly with respect to the other.

Polarization Landscape



EE from decoupling

EE from reionization

Approx EE/BB foreground averaged over 75% of the sky.

BB from GWs

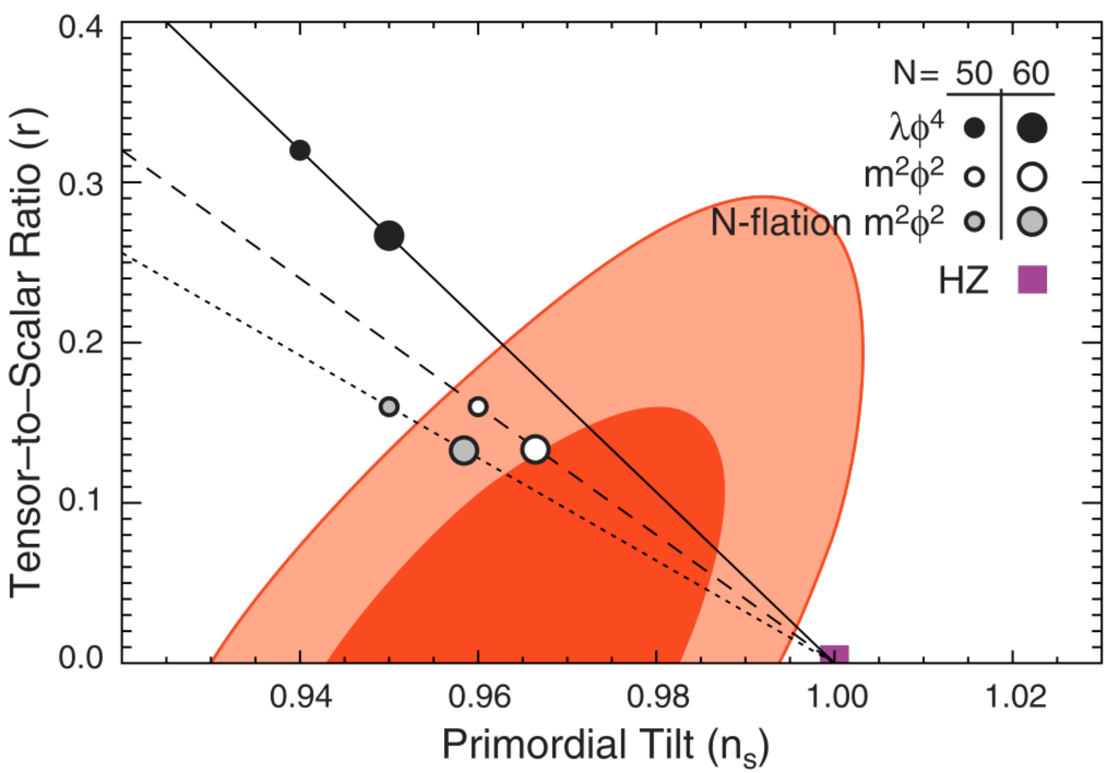
G-waves decay once inside the horizon.

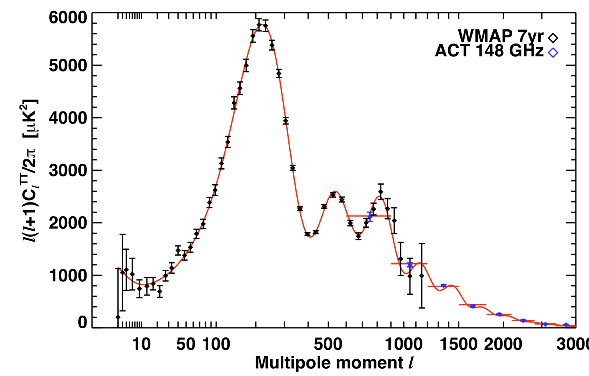
BB from lensing of E-modes (not primordial)

Reionization peak (z_r=10)

Horizon size at decoupling ($\theta_H \sim 1.2^0$)

The early Universe: r & n_s





Tensors add here.

WMAP $+H_0$+BAO r<0.24 (95% cl.)

BiCEP r<0.72 (95% cl., B-modes)

For r=0:

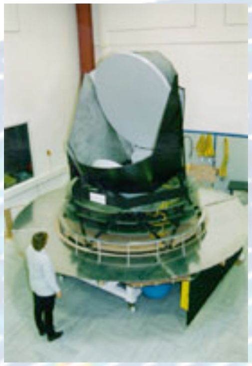
n_s=0.963 +/-0.014 WMAP

n_s=0.963 +/-0.012 All

n_s= +/-0.005 Planck

What's Next in Polarization ?

Planck



(50 bolometers)

BiCEP 2

ACTPol
(1920 feeds)
Chile

PIPER

BRAIN

SPIDER

2011 2012 2013 2014

QUIET

ABS

HTT/Polarbear-I
(640 feeds)
California

POLARBEAR

SPTPol
(~1000 feeds)
South Pole

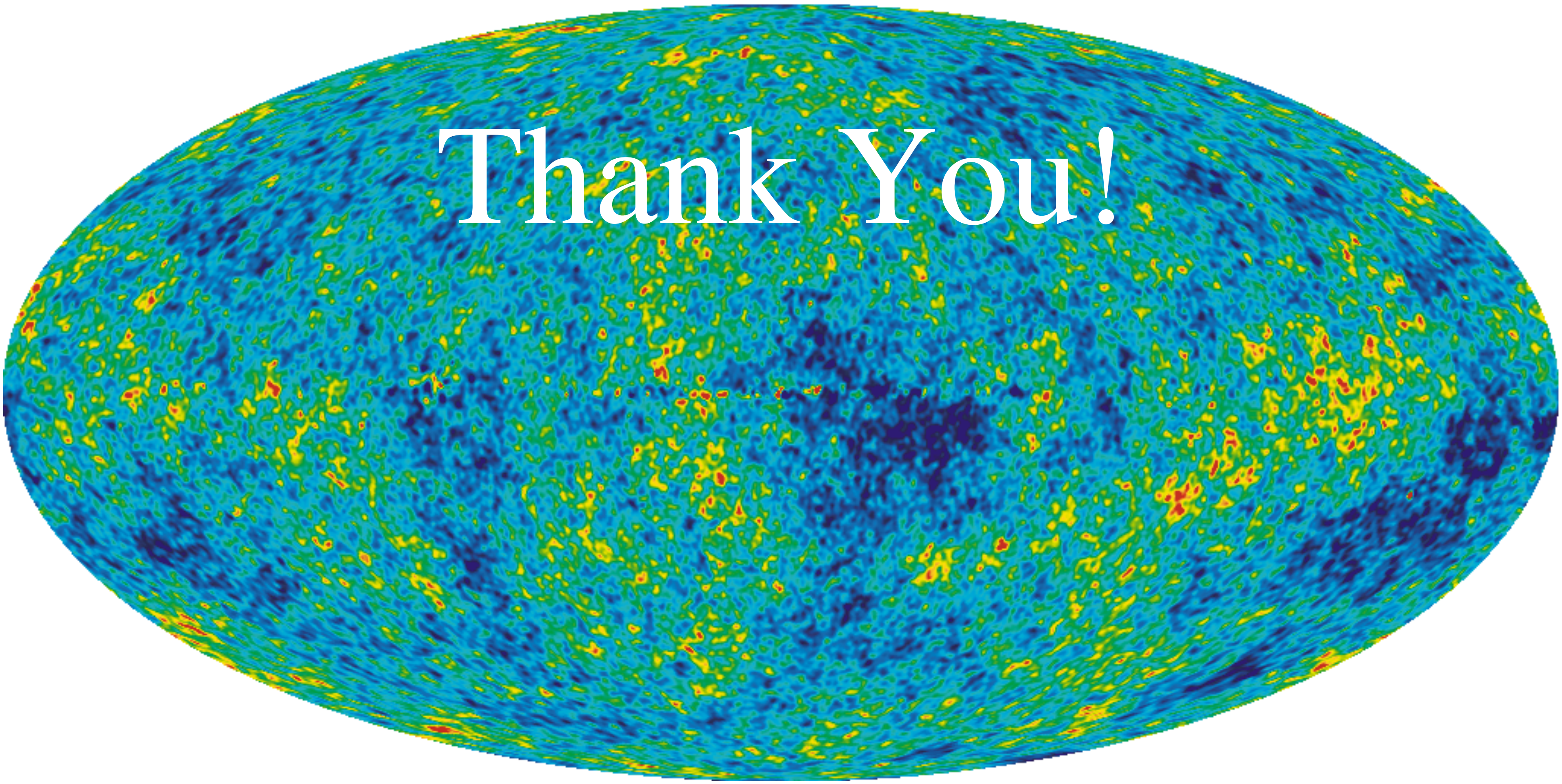
EBEX

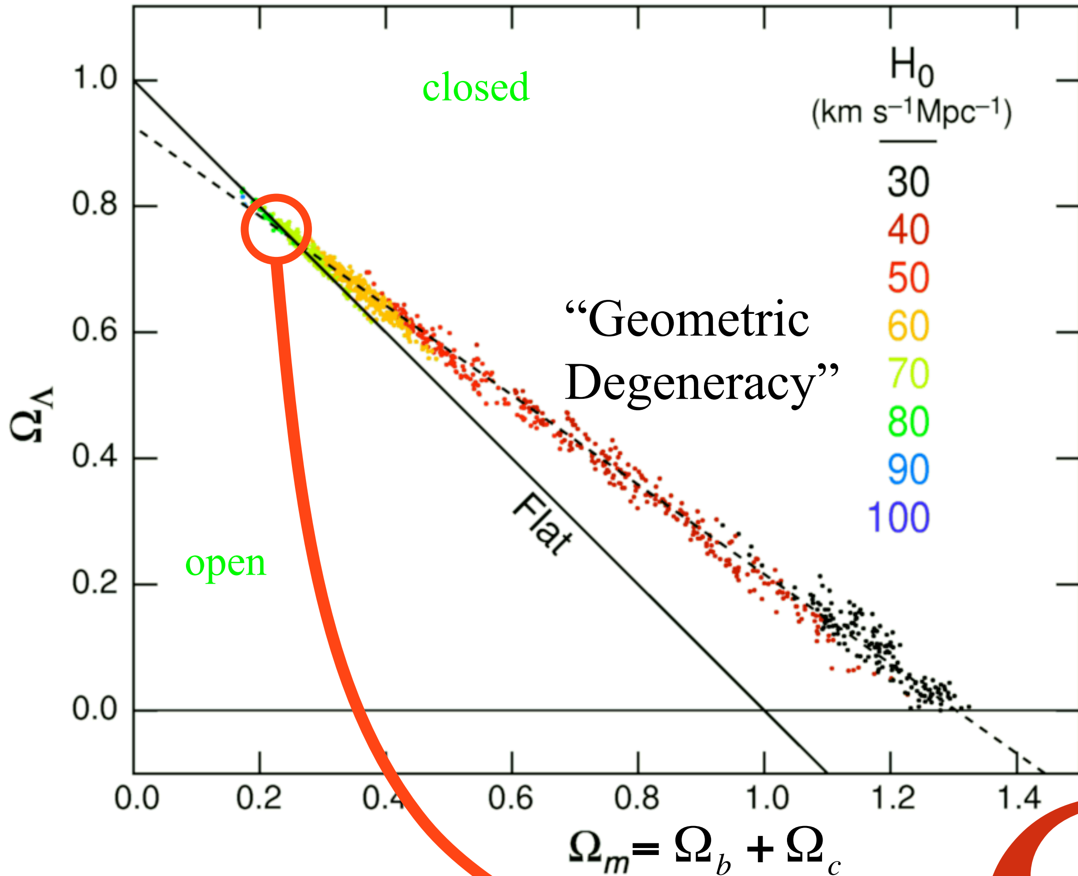
POLAR-1

POINCARE

CLASS

K ba


Thank You!



CMB alone tells us we are on the "geometric degeneracy" line

Assume flatness

WMAP7 only best fit LCDM

$\Omega_b h^2 = 0.0226$ +/- 0.00057

$\Omega_c h^2 = 0.1109$ +/- 0.0056

h = 0.710 +/- 0.025

σ_8 = 0.801 +/- 0.030

τ = 0.088 +/- 0.015

n_s = 0.963 +/- 0.014