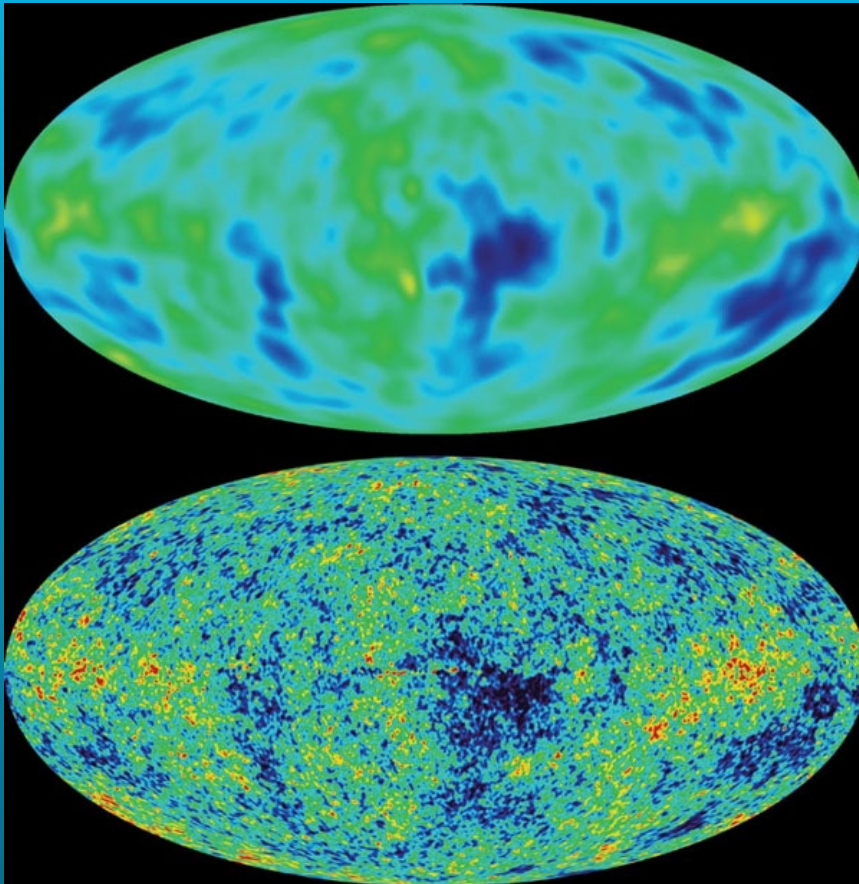


The Cosmic Microwave Background

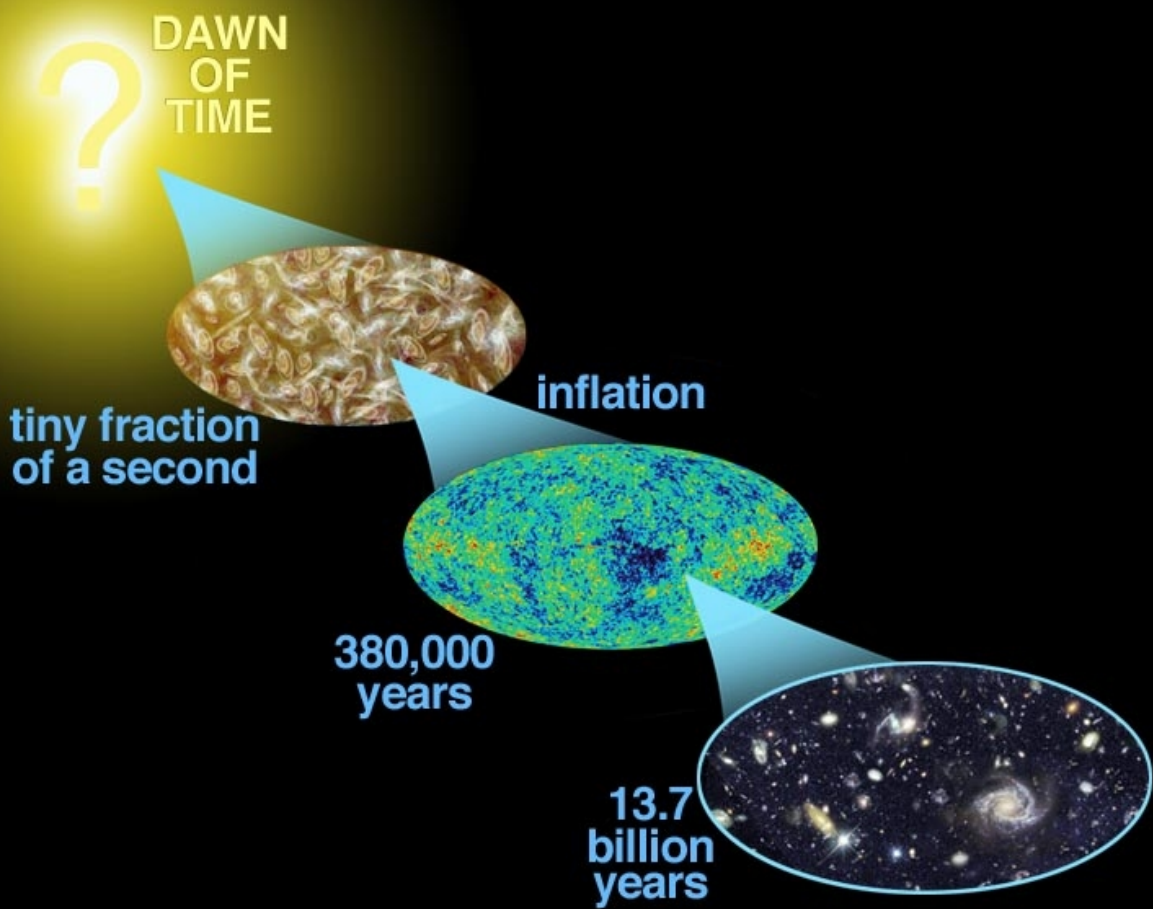


NASA

Compilation of extracts
from:

A. Wetzel (Berkeley),
R. Bustos (UDEEC),
D. Spergel (Princeton),
T. Richtler (UDEEC)

**DAWN
OF
TIME**

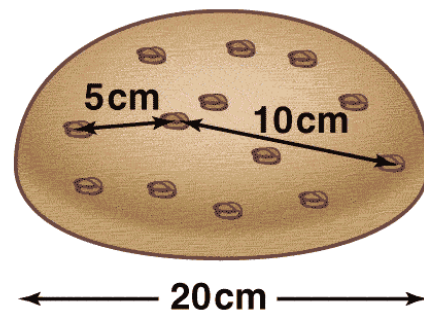


**tiny fraction
of a second**

inflation

**380,000
years**

**13.7
billion
years**



Cosmological Parameters

Parameter	Symbol	Value
Hubble parameter	h	0.73 ± 0.03
Total matter density	Ω_{m}	$\Omega_{\text{m}} h^2 = 0.134 \pm 0.006$
Baryon density	Ω_{b}	$\Omega_{\text{b}} h^2 = 0.023 \pm 0.001$
Cosmological constant	Ω_{Λ}	See Ref. 7
Radiation density	Ω_{r}	$\Omega_{\text{r}} h^2 = 2.47 \times 10^{-5}$
Neutrino density	Ω_{ν}	See Sec. 1.1.2
Density perturbation amplitude	$\Delta_{\mathcal{R}}^2(k_*)$	See Ref. 7
Density perturbation spectral index	n	$n = 0.97 \pm 0.03$
Tensor to scalar ratio	r	$r < 0.53$ (95% conf)
Ionization optical depth	τ	$\tau = 0.15 \pm 0.07$
Bias parameter	b	See Sec. 1.3.4

$k = 0$ (because the universe is flat, i.e. $\Omega_{\text{tot}} \sim 1$)

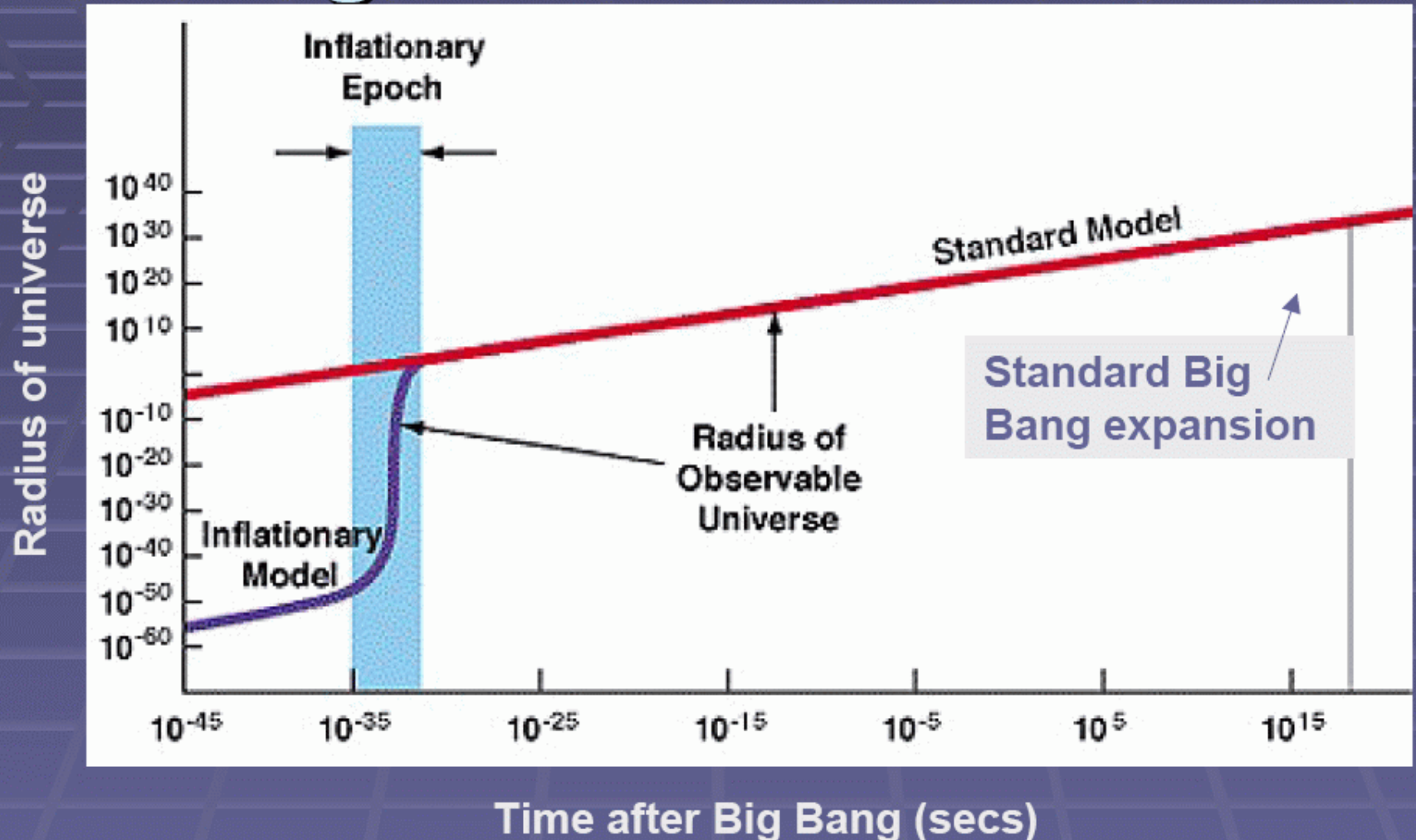
τ : because CMB photons can be scattered, altering anisotropies

r : set to 0? since there is no evidence of tensor perturbations

Density perturbation amplitude: often expressed as σ_8

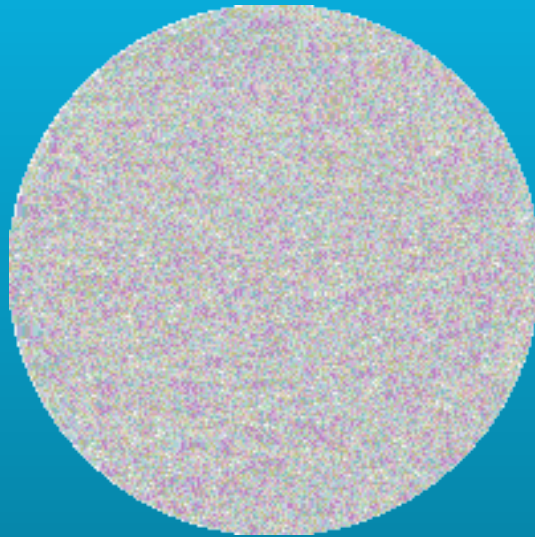
Bias: between galaxy distribution and dark matter distribution

Solving the Horizon Problem

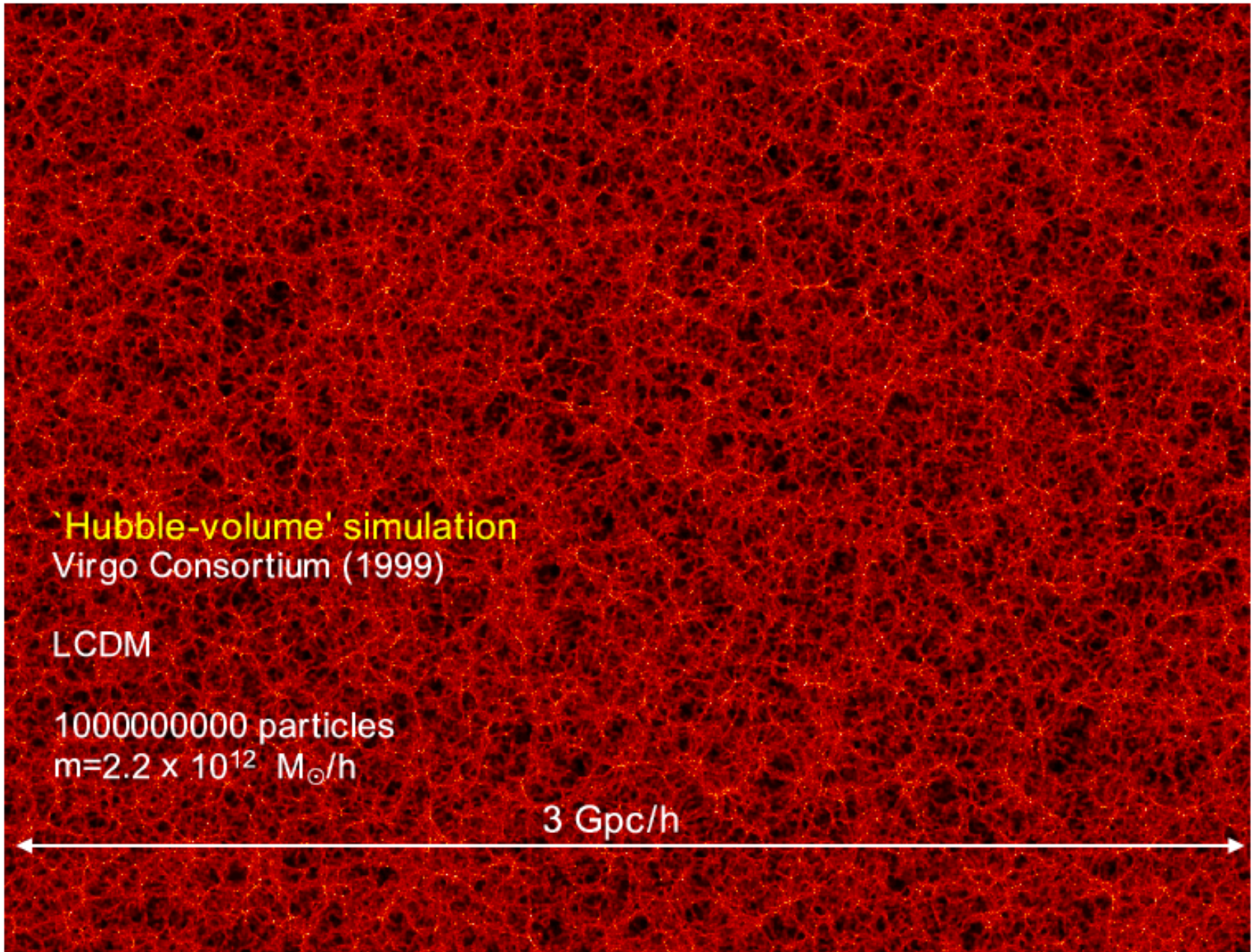


If super-expansion lasts long enough, CMB patches on opposite sides of the sky would have been close enough to communicate in the primordial times.

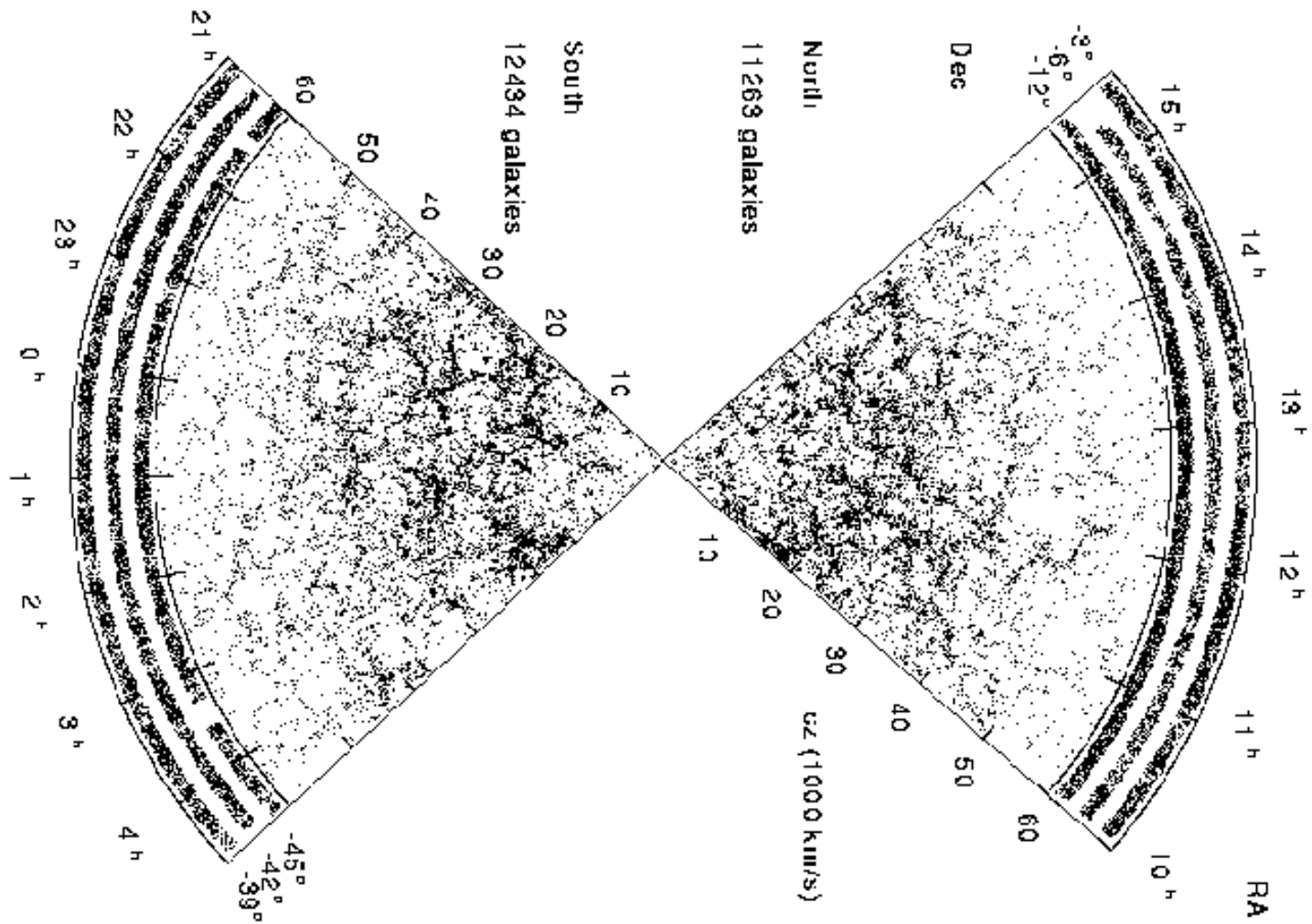
Quantum Fluctuations in the early universe



The state of the art ...



Large-scale structure in the distribution of galaxies



Tamaño

Fondo
cósmico

CMB

Hoy: CBI

San
Pedro

Gran
unificación

g
a
r
a
n
u
n
i
f
i
c
a
c
i
o
n
e
s

Sopa
de
quarks

s
y
n
t
h
e
s
i
s

Hydrogen

&

Helium

Plasma

Época
oscura

Big
Bang

Inflación

10^{-41} sec

10^{-35} sec

1 minuto

400,000

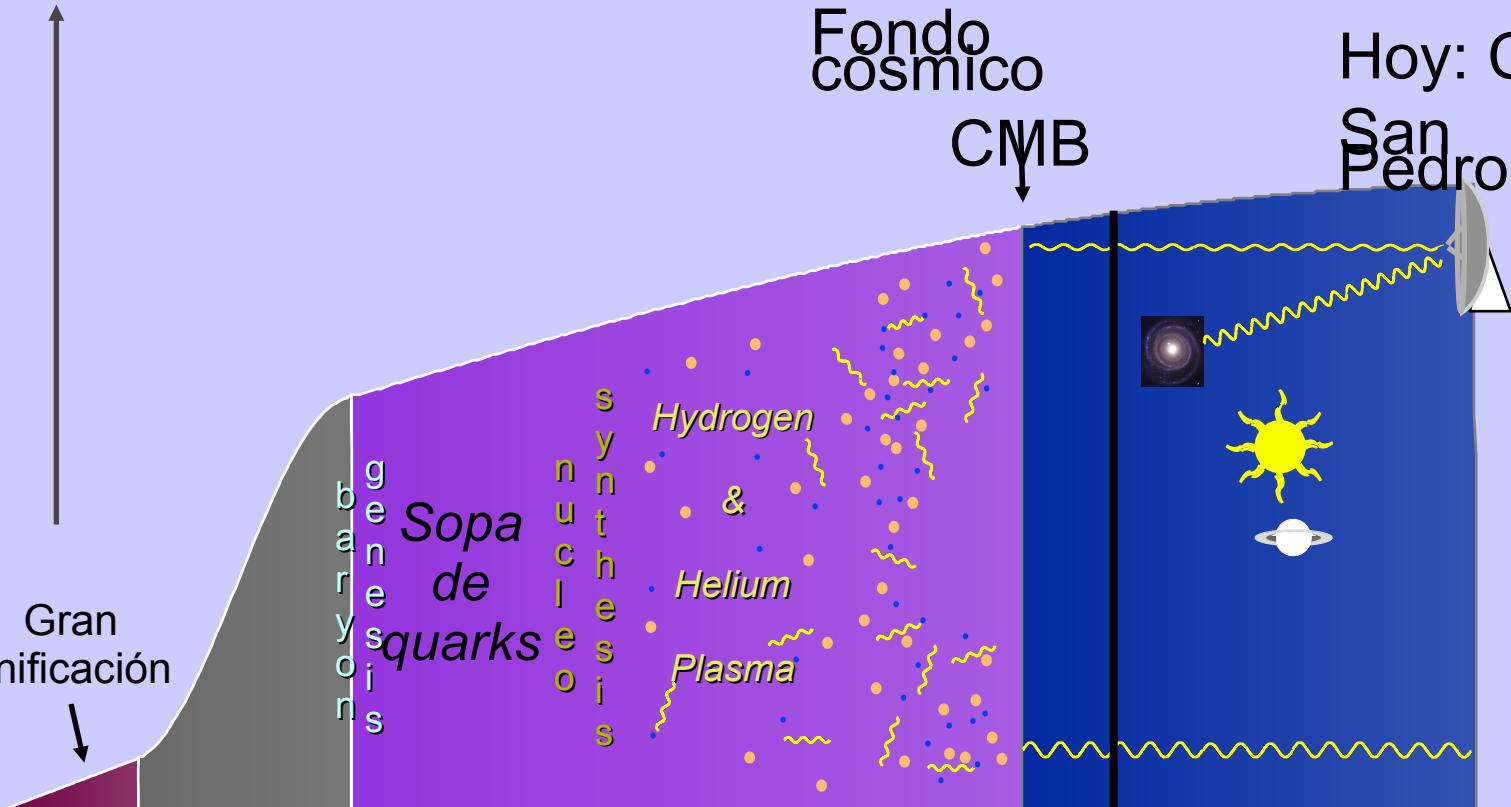
años

1

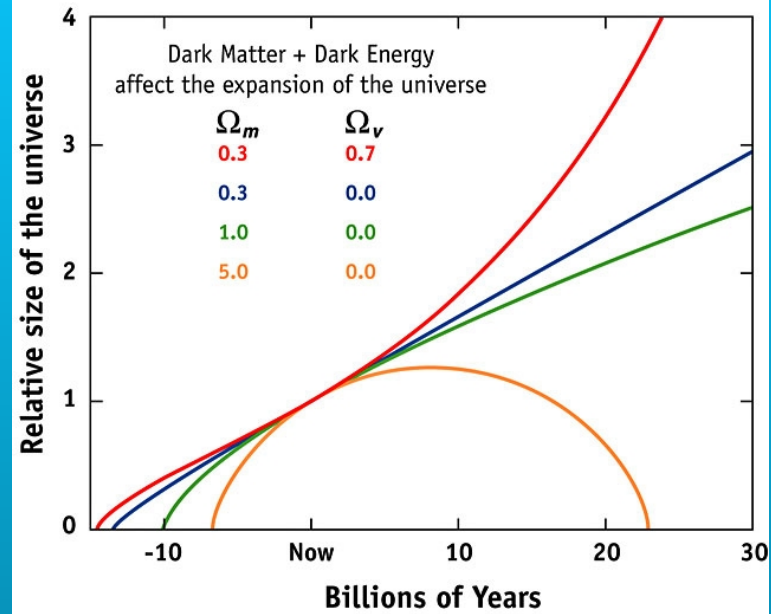
8 9 10 14

miles de millones de años

Tiempo



EXPANSION OF THE UNIVERSE



Consecuencias de los resultados del WMAP/CBI etc.:

Una revolución en la física fundamental

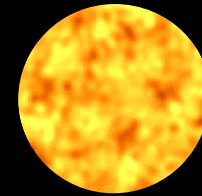
Ω_b

4 % materia normal



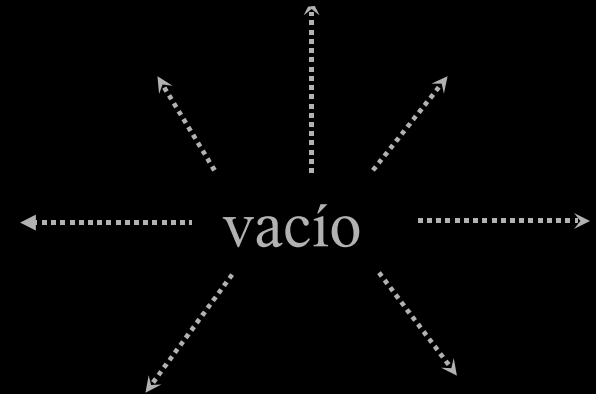
Ω_{nb}

21 % materia oscura



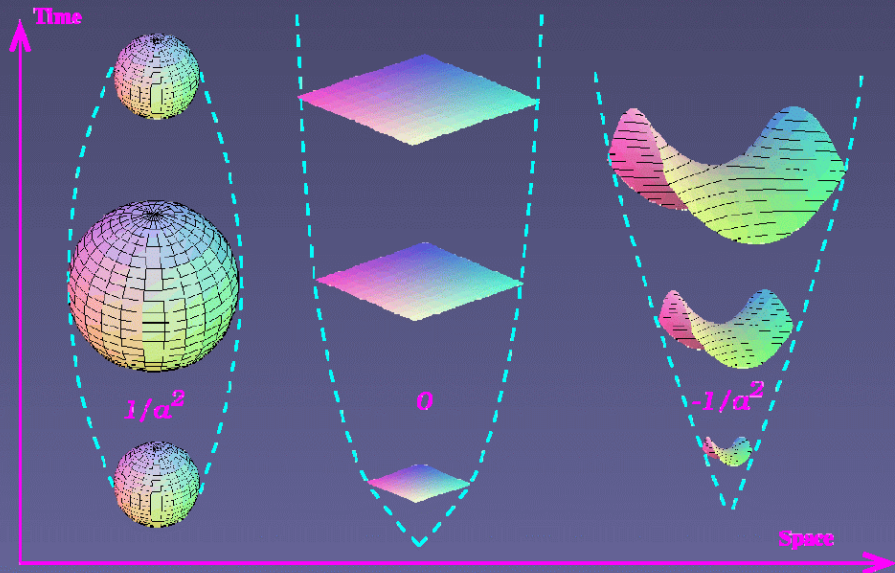
Ω_Λ

75 % energía oscura

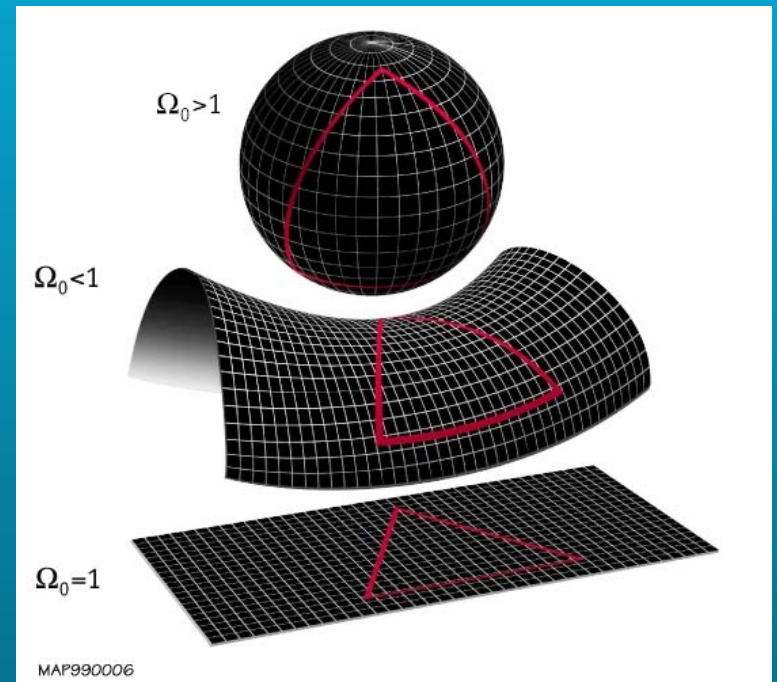


Edad del Universo: 13.5 mil millones de años

Homogeneous & Isotropic Universe



Universe is flat (WMAP)



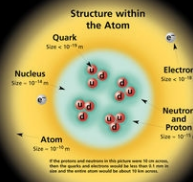
The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

matter constituents 50331

matter constituents
spin = 1/2, 3/2, 5/2,

Leptons $\text{spin} = 1/2$			Quarks $\text{spin} = 1/2$		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1.1 \times 10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	-1	d down	0.006	-1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	-1	s strange	0.1	-1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	-1	b bottom	4.3	-1/3

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c² (remember $E = mc^2$), where 1 GeV = 10⁹ eV = 1.60 × 10⁻¹⁰ joule. The mass of the proton is 0.938 GeV/c² = 1.67 × 10⁻²⁷ kg.

Baryons $\bar{q}q\bar{q}$ and Antibaryons $q\bar{q}q$ 

BOSONS

Unified Electroweak $\text{spin} = 1$			Strong (color) $\text{spin} = 1$		
Name	Mass GeV/c^2	Electric charge	Name	Mass GeV/c^2	Electric charge
γ photon	0	0	g gluon	0	0
W^-	80.4	-1	Color Charge Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with color.		
W^+	80.4	+1			
Z^0	91.1876	0			

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the

Residual Strong Interaction

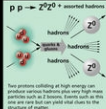
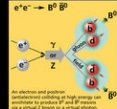
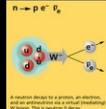
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color charged constituents. It is similar to the residual interactions in neutral atoms that lead to the formation of molecules.

PROPERTIES OF THE INTERACTIONS

Karyons qqq and Antikaryons qqq				Mesons qq or qqq				Mesons qq			
There are about 100 types of baryons.				There are about 100 types of mesons.				There are about 100 types of mesons.			
		Property	Interaction	Gravitational	Weak	Electromagnetic	Strong				
								Fundamental	Residual		
		Act on		Mass - Energy	Flavor	Electric Charge	Color Charge	via Residual Strong			
		Particles experiencing	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons				
		Particles mediating	Gravitational	W^+ W^- Z^0	γ	Gluons	Mesons				
p	proton	uud	+	1.6726	1	2/3	1	1	1	+	1.007
n	neutron	udd	0	1.6749	1	1/3	1	1	1	0	1.008
p	antiproton	u $\bar{u}\bar{d}$	-	1.6726	1	-2/3	1	1	1	-	1.007
n	antineutron	u $\bar{d}\bar{d}$	0	1.6749	1	-1/3	1	1	1	0	1.008
e	electron	lepton	-	0.0005	1	-1	0	0	0	-	0.0005
e	positron	lepton	+	0.0005	1	1	0	0	0	+	0.0005
μ^-	muon	lepton	-	0.1056	1	-1	0	0	0	-	0.1056
μ^+	antimuon	lepton	+	0.1056	1	1	0	0	0	+	0.1056
τ^-	tauon	lepton	-	1.7768	1	-1	0	0	0	-	1.7768
τ^+	antitauon	lepton	+	1.7768	1	1	0	0	0	+	1.7768

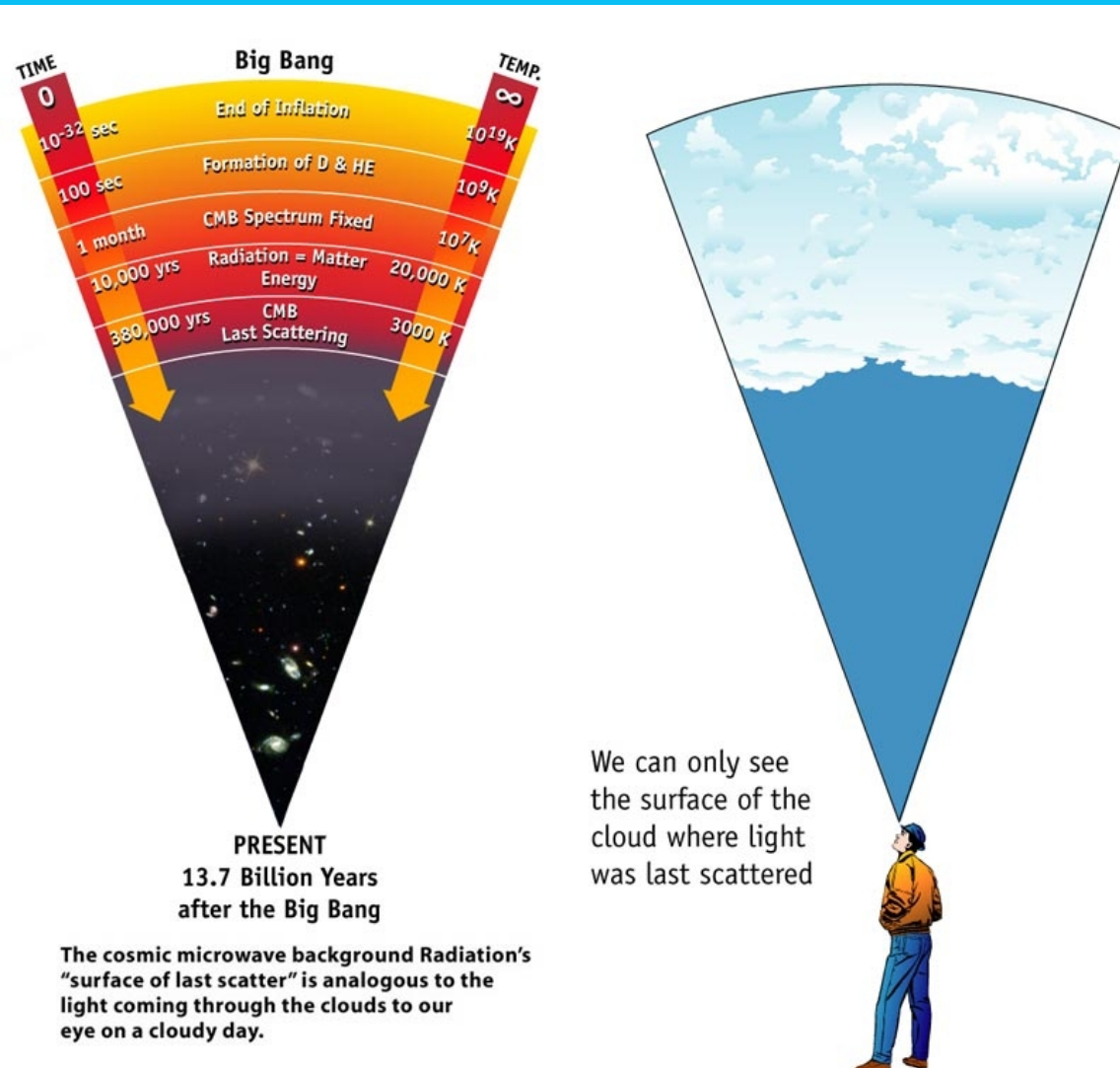
For every particle type there is a bar over the particle

Figures
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



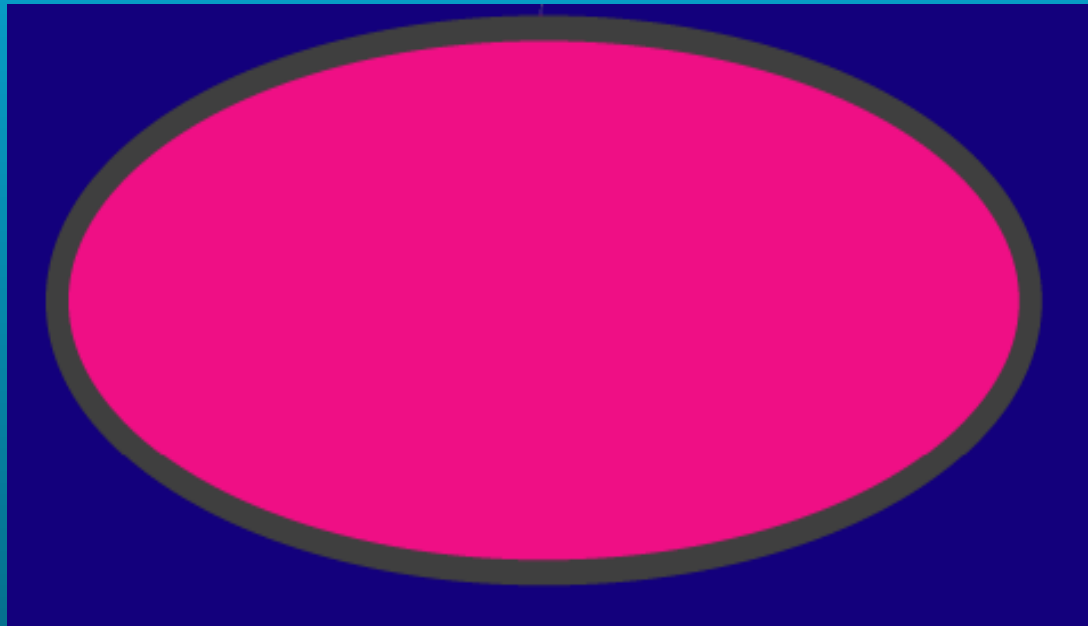
This chart has been made possible by the generous support of:
 U.S. Department of Energy
 U.S. National Science Foundation
 Lawrence Berkeley National Laboratory
 Stanford Linear Accelerator Center

http://CPEPweb.org



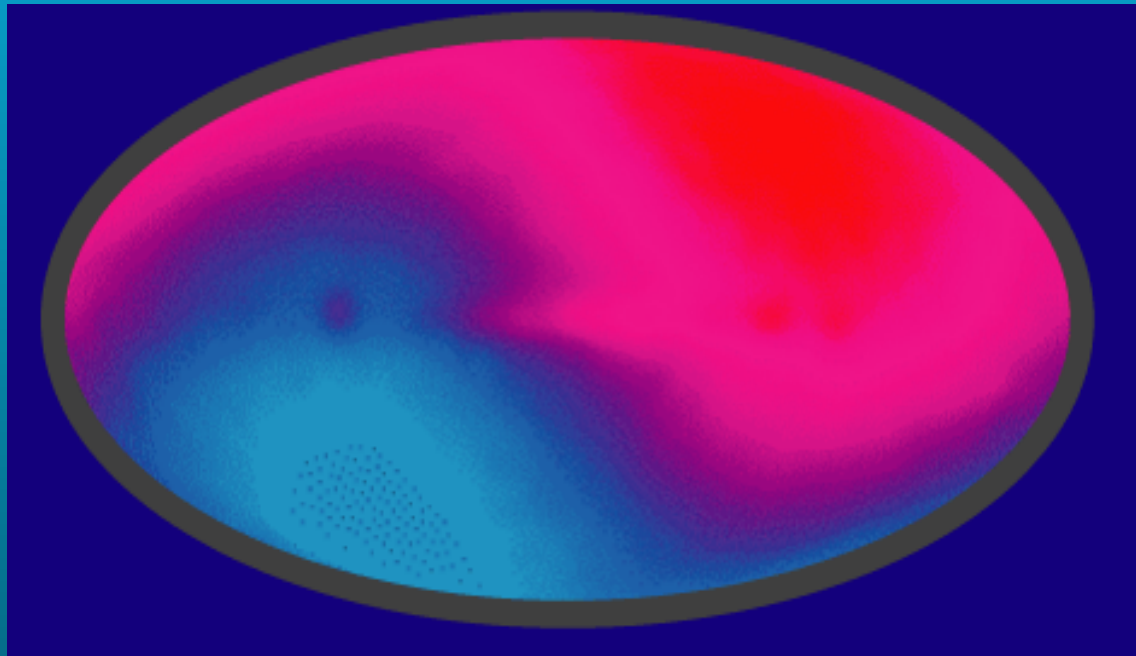
Measuring the CMB Anisotropies

- First COBE image
- No variation on the scale 1 part in 1000



Measuring the CMB Anisotropies

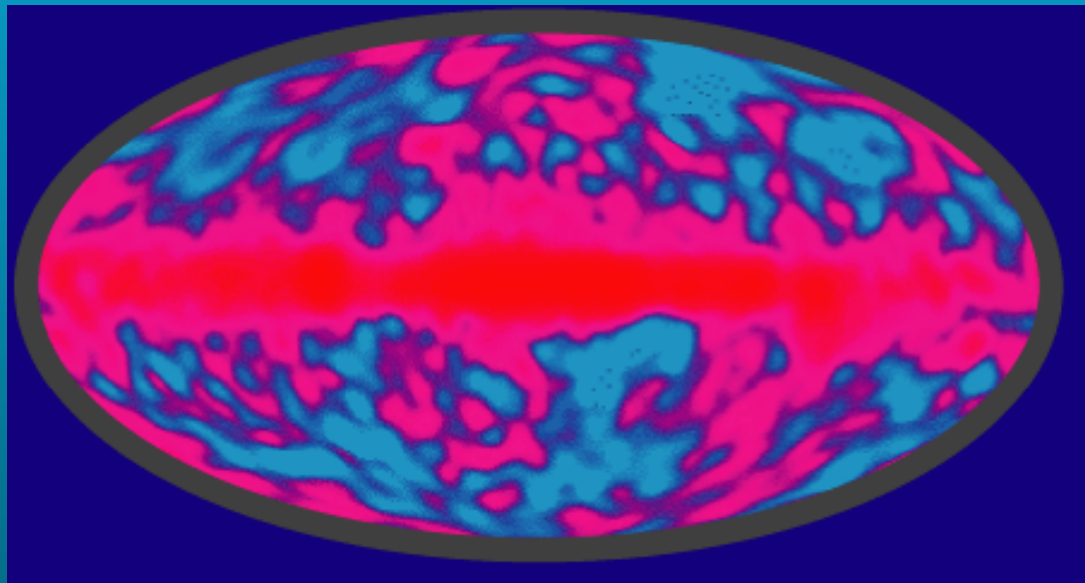
- Turn up resolution slightly
- Dipole - redshift from our motion



Wayne Hu

Measuring the CMB Anisotropies

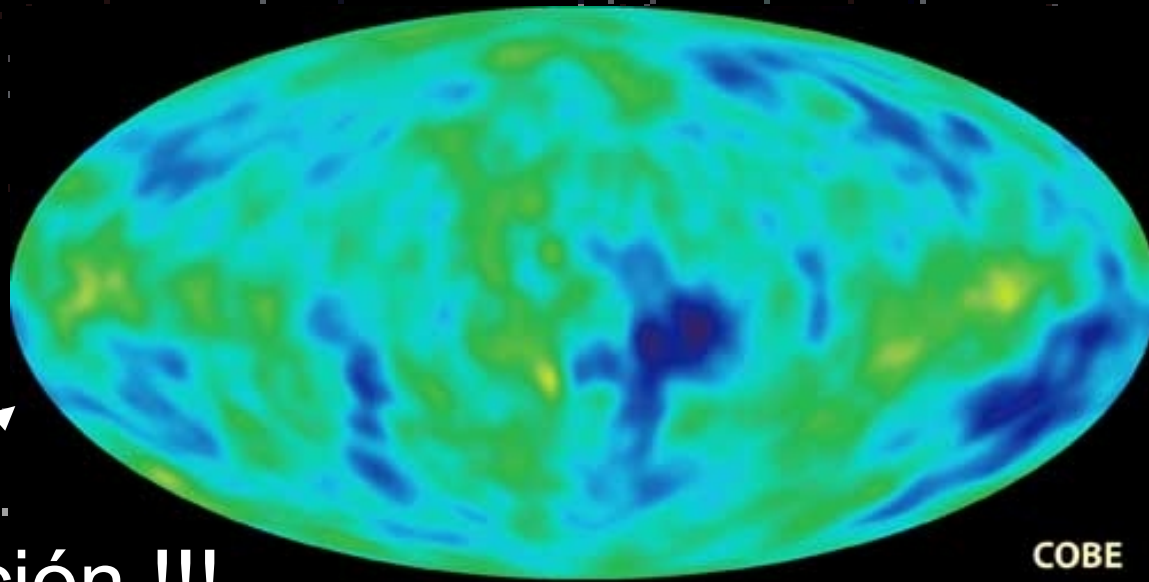
- Approach microKelvin precision
- We see the early perturbations that give rise to the structure of today



Wayne Hu

Imágenes totales del cielo de las anisotropías del CMB.

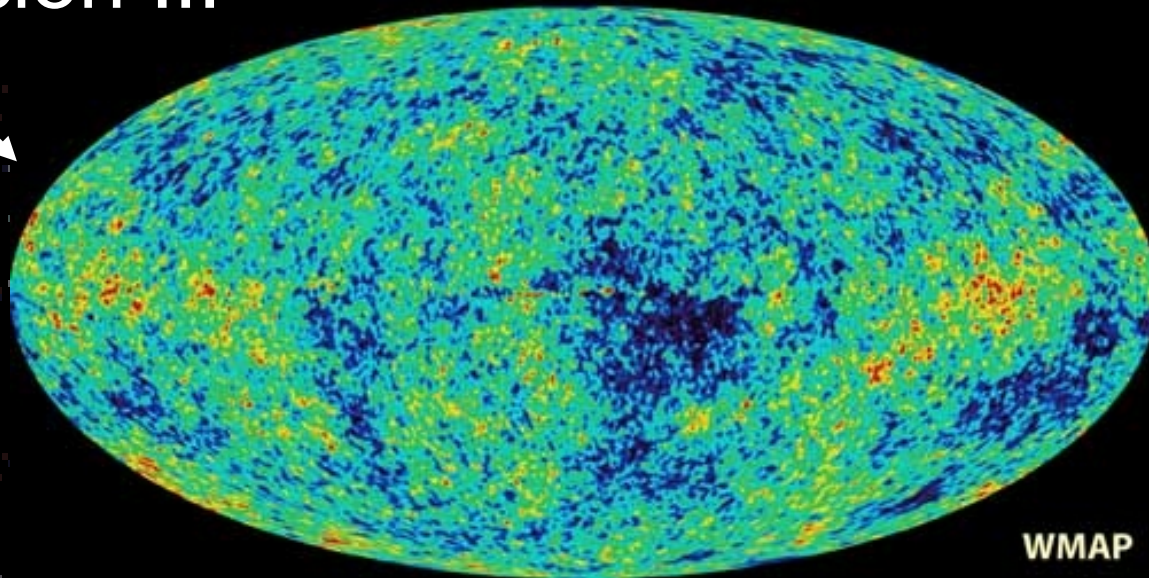
$2.725\text{ K} \pm \sim 30\text{ }\mu\text{K rms}$



1992

COBE

Resolución !!!



2003

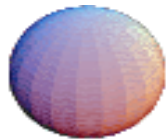
WMAP

CMB Power Spectrum

- Measure the angular coherence of the temperature fluctuations
- We are familiar with decomposing signals in Fourier space with k modes
- Since CMB fluctuations are on the 2-D sky, we need angular decomposition in multipole space to study the amplitude

$$\frac{\Delta T(\theta, \phi)}{T} = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

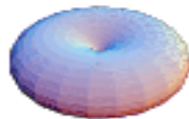
Spherical Harmonics



$$|Y_0^0(\theta, \phi)|^2$$



$$|Y_1^0(\theta, \phi)|^2$$



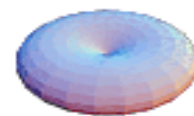
$$|Y_1^1(\theta, \phi)|^2$$



$$|Y_2^0(\theta, \phi)|^2$$



$$|Y_2^1(\theta, \phi)|^2$$



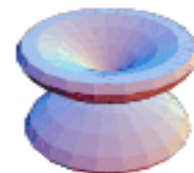
$$|Y_2^2(\theta, \phi)|^2$$



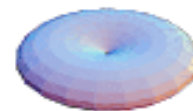
$$|Y_3^0(\theta, \phi)|^2$$



$$|Y_3^1(\theta, \phi)|^2$$

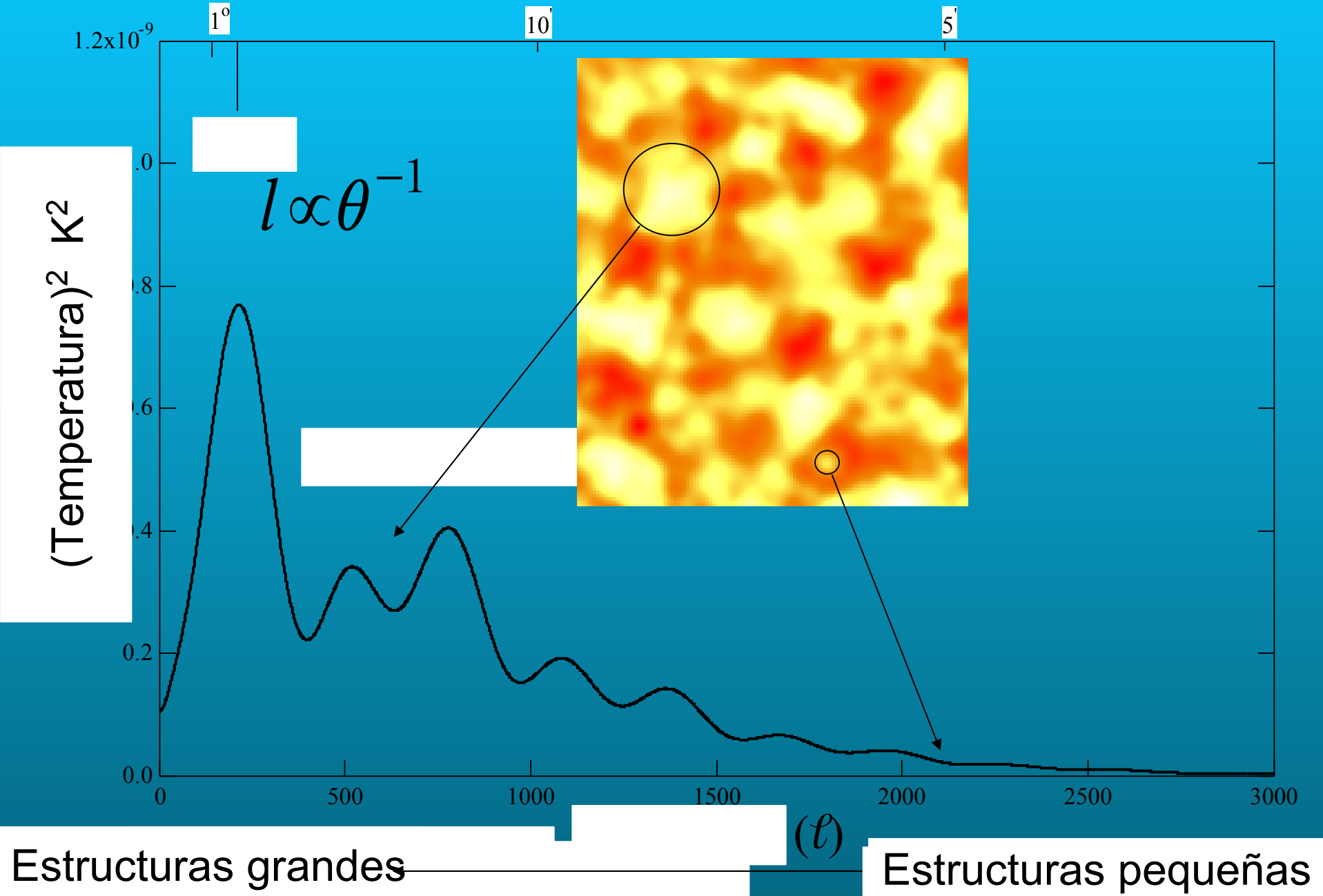


$$|Y_3^2(\theta, \phi)|^2$$



$$|Y_3^3(\theta, \phi)|^2$$

Escala angular en el cielo



Systematic sources of error since recombination

(affect primarily small scale power)

- Gravitational waves
 - Affect polarizations
- Integrated Sachs Wolf effect
 - Depth of potential well changes photon frequency as universe expands
- Reionization
 - Eliminates anisotropies
- Lensing effects
- Sunyaev Zeldovich effect

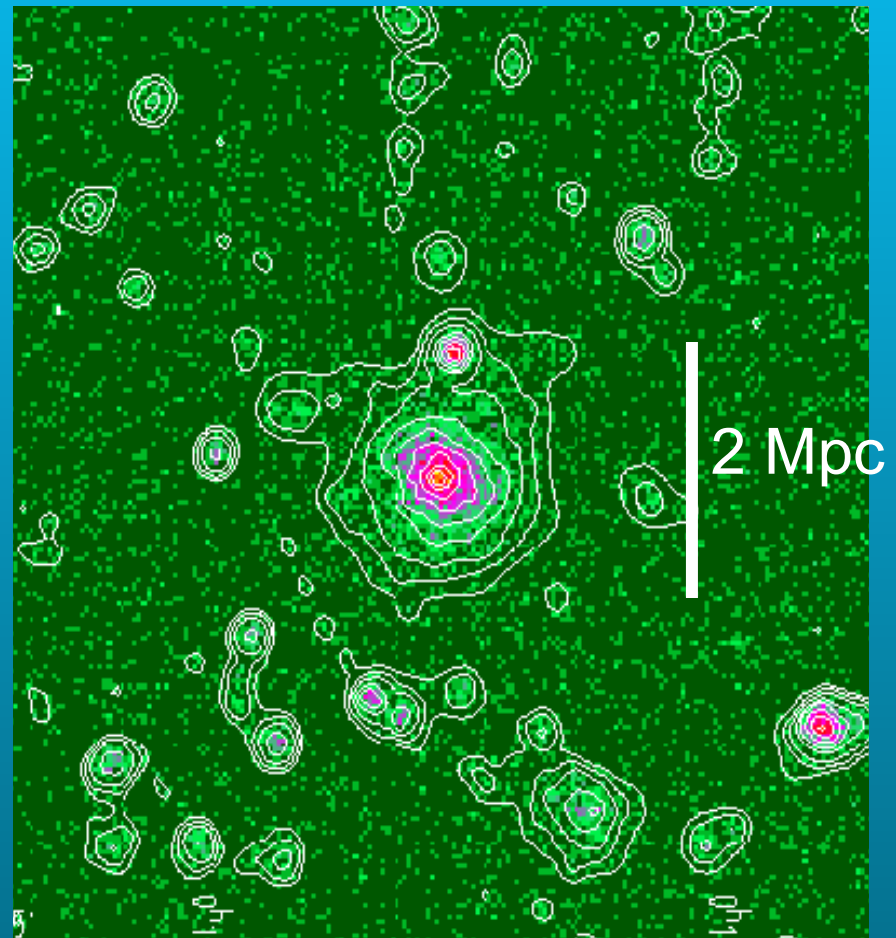
2. The origin of the SZ effect

Clusters of galaxies contain extensive hot atmospheres

$$T_e \approx 6 \text{ keV}$$

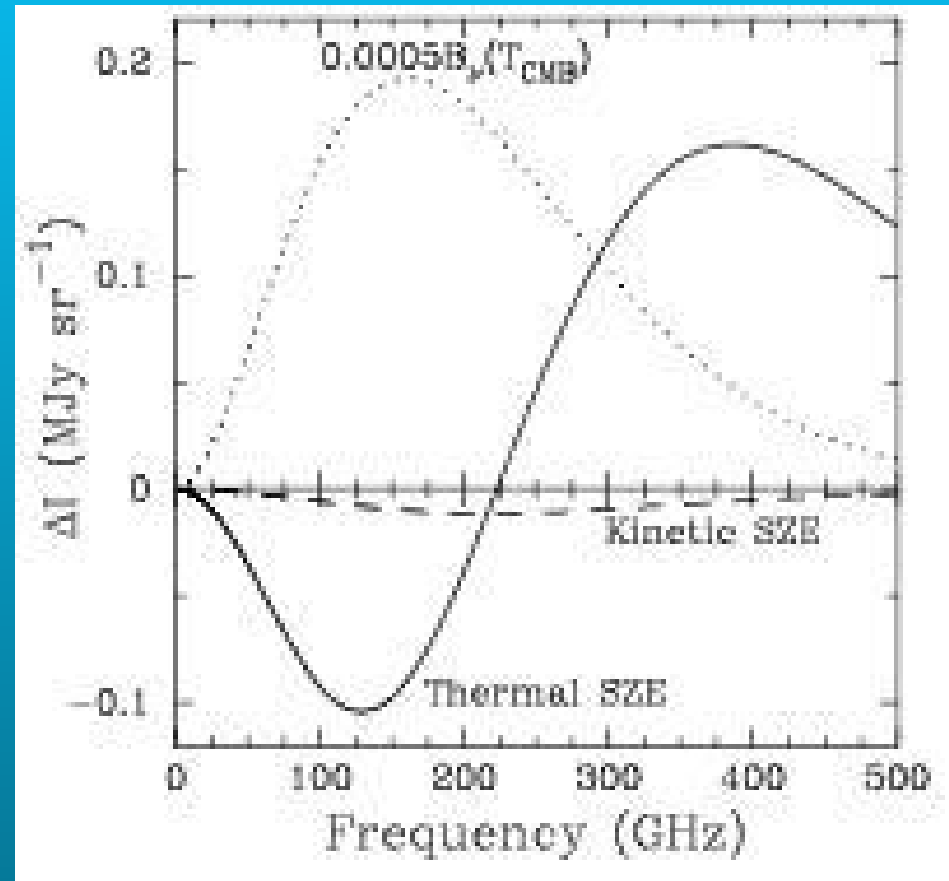
$$n_p \approx 10^3 \text{ protons m}^{-3}$$

$$L \approx 1 \text{ Mpc}$$



What is it?: Inverse Compton

- Photon scatters off of *moving* e^-
 - Gains energy from e^-
 - $\Delta I \quad 0 \rightarrow$ increases
- Decrement in Rayleigh-Jeans
- Increment in Wein

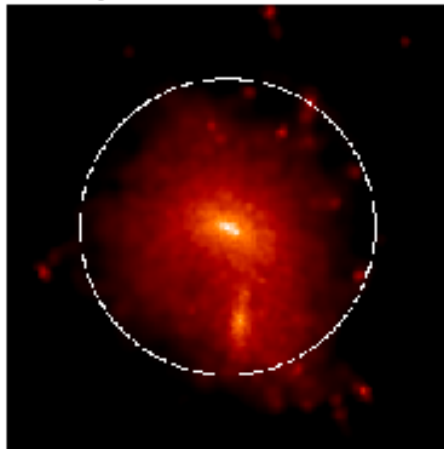


[3]

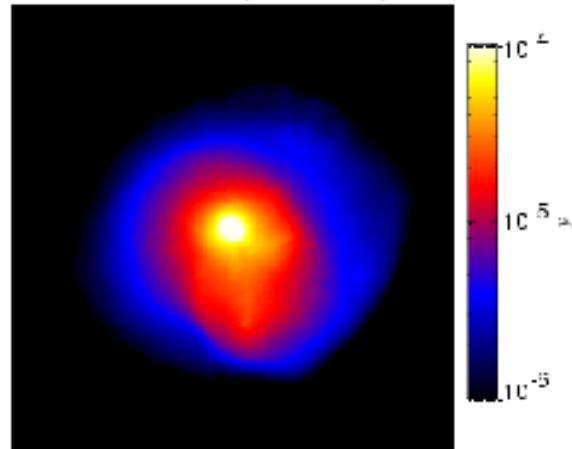
Combined measurements of X-ray, and thermal & kinetic SZ are powerful tools to study the structure of clusters

A CLUSTER SEEN IN DIFFERENT WAYS

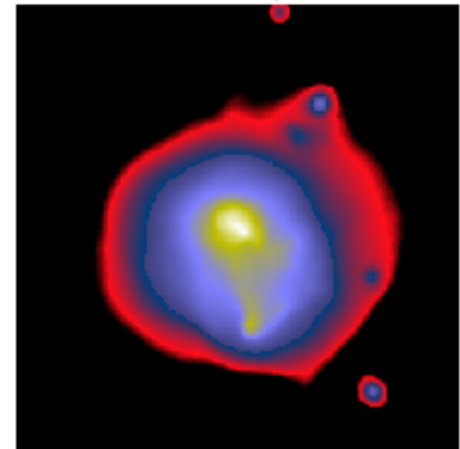
projected dark matter



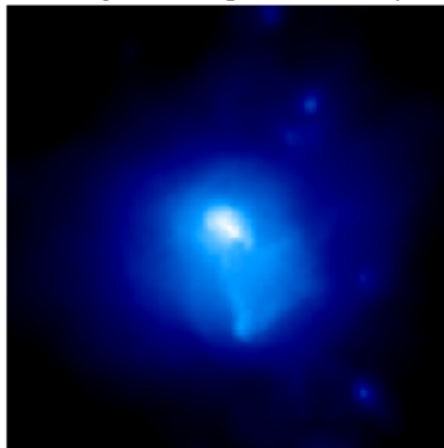
SZ effect (thermal)



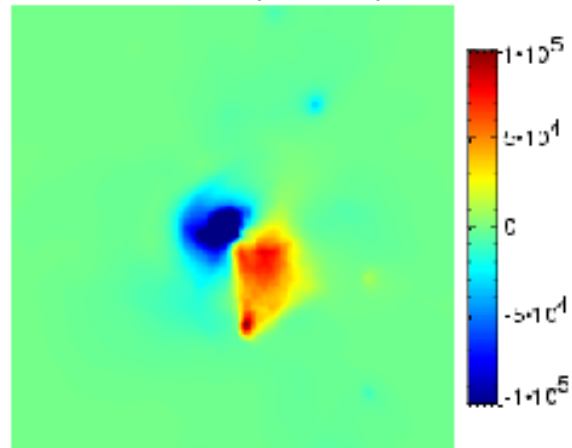
X-ray



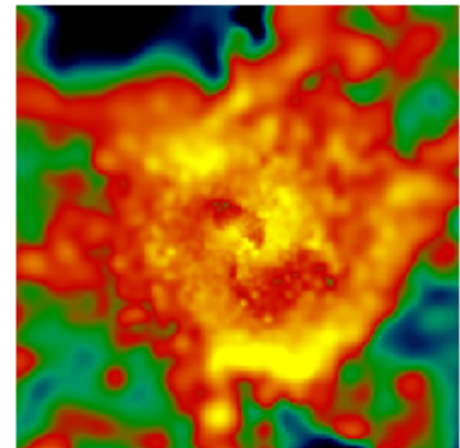
projected gas density



SZ effect (kinetic)



temperature slice



Parameter Estimation

- Need to assume value and error of some parameters a priori to fit other cosmological parameters to CMB power spectrum

Initial Fit to WMAP - 6 parameters

Fit

$$\Omega_b h^2 = 0.024 \pm 0.001$$

$$\Omega_m h^2 = 0.14 \pm 0.02$$

$$h = 0.72 \pm 0.05$$

Derived

$$\Omega_b = 0.047 \pm 0.006$$

$$\Omega_m = 0.29 \pm 0.07$$

$$t_0 = 13.4 \pm 0.3 \text{ Gyr}$$

Combine WMAP, CBI, ACBAR, 2dFGRS,
Ly α Forest Data

$$\Omega_b h^2 = 0.0224 \pm 0.0009$$

$$\Omega_m h^2 = 0.135 \pm 0.009$$

$$h = 0.71 \pm 0.04$$

$$\Omega_b = 0.044 \pm 0.004$$

$$\Omega_m = 0.27 \pm 0.04$$

$$t_0 = 13.7 \pm 0.2 \text{ Gyr}$$

Cosmological Parameters

Parameter	Symbol	Value
Hubble parameter	h	0.73 ± 0.03
Total matter density	Ω_{m}	$\Omega_{\text{m}}h^2 = 0.134 \pm 0.006$
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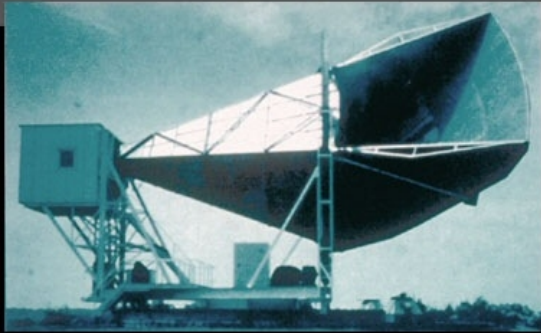
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r : set to 0? since there is no evidence of tensor perturbations

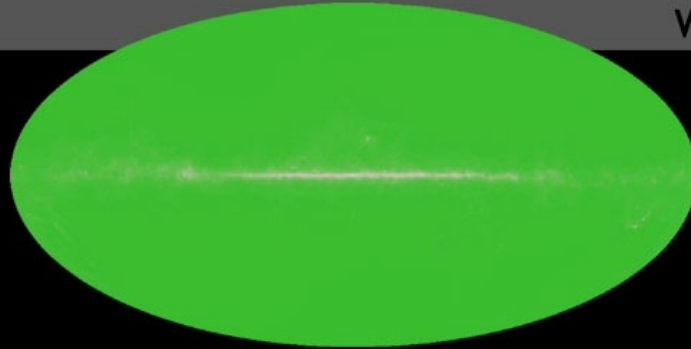
Density perturbation amplitude: often expressed as σ_8

Bias: between galaxy distribution and dark matter distribution

1965



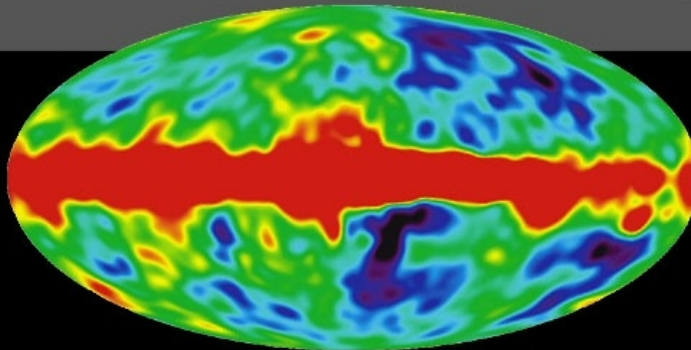
Penzias and
Wilson



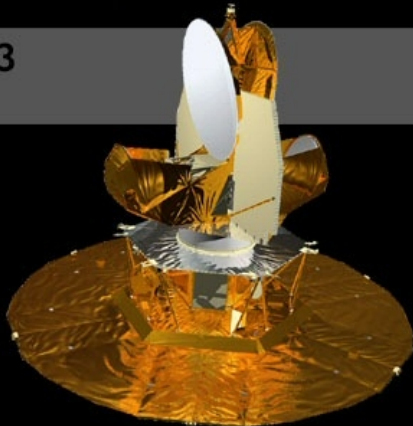
1992



COBE



2003



WMAP

