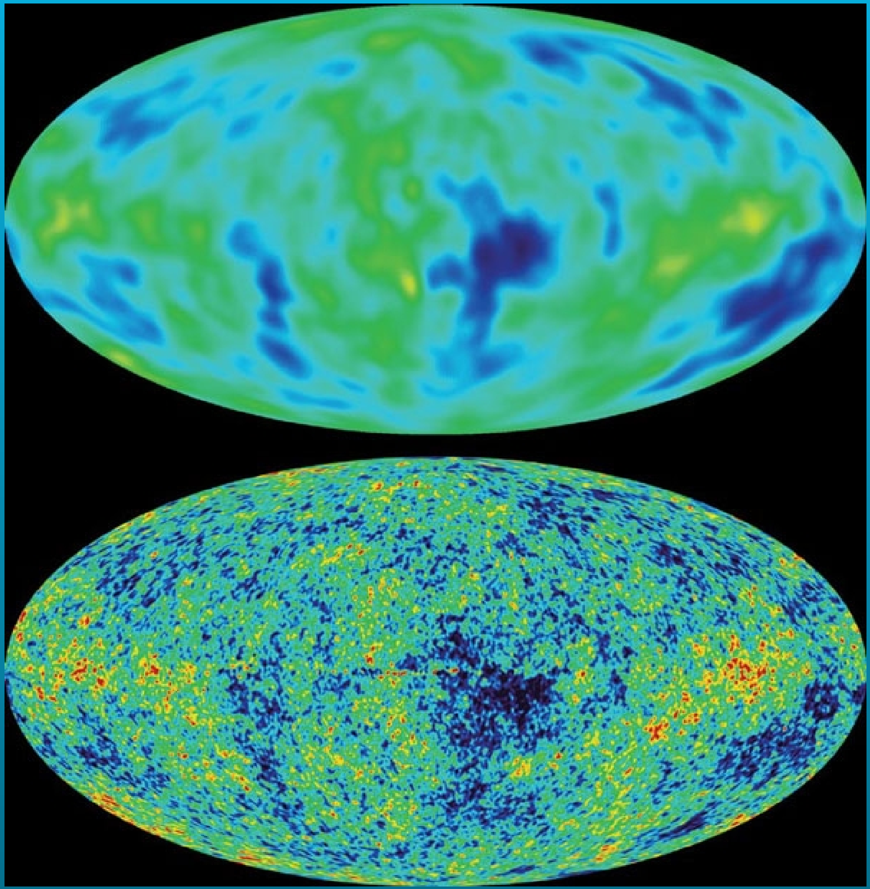
The Cosmic Microwave Background



NASA

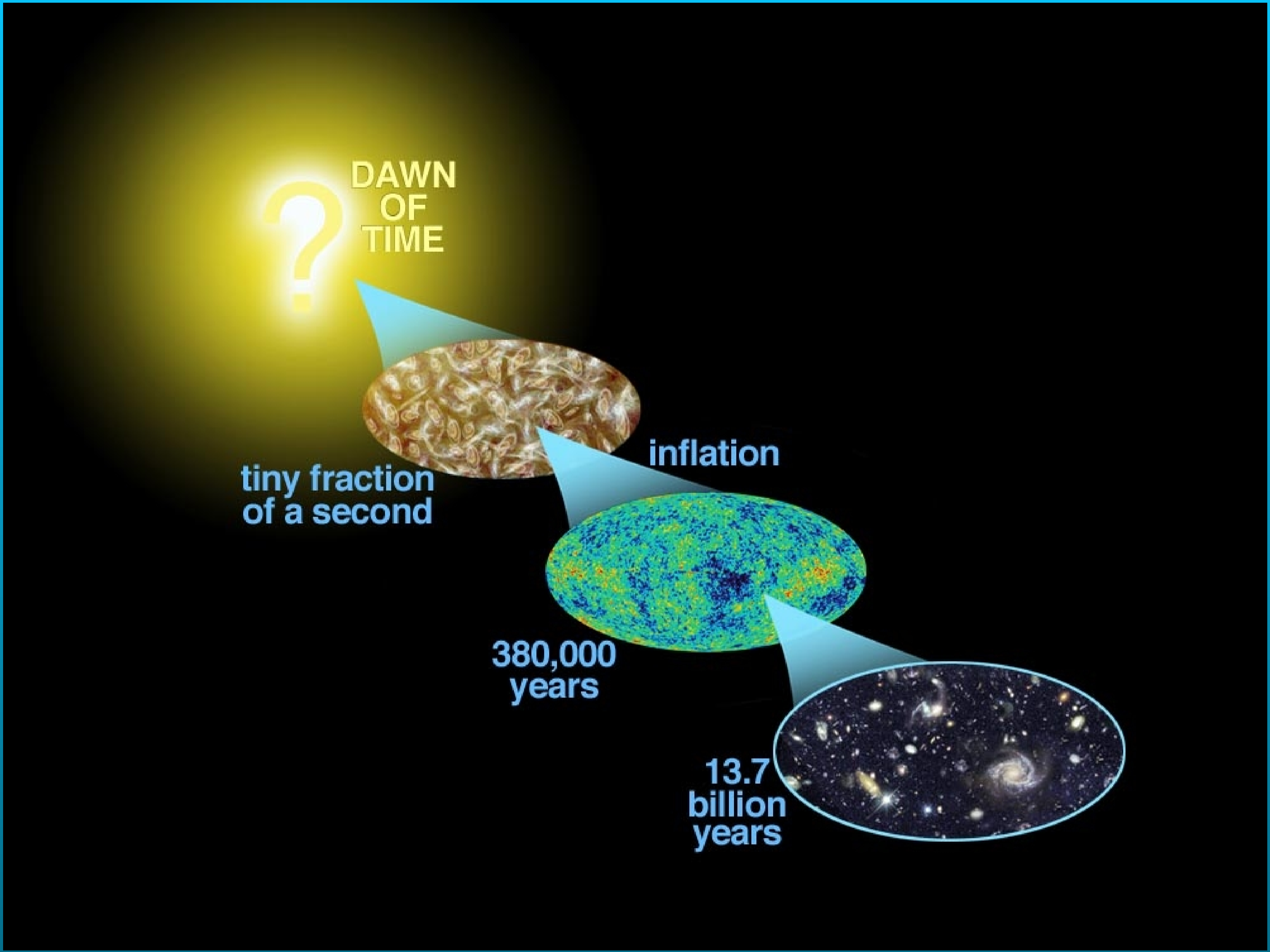
Compilation of extracts from:

A. Wetzel (Berkeley),

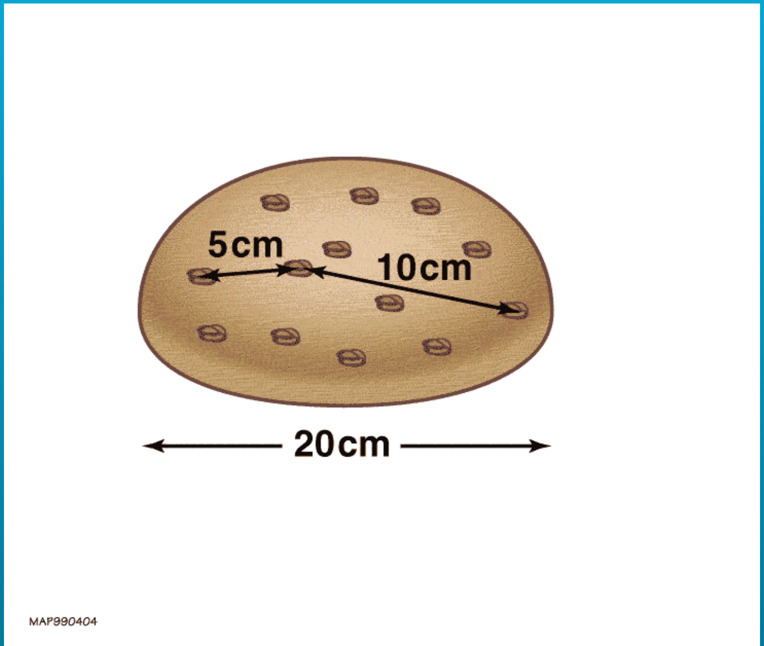
R. Bustos (UDEC),

D. Spergel (Princeton),

T. Richtler (UDEC)


DAWN OF TIME
inflation
tiny fraction of a second
380,000 years
13.7 billion years

NASA


5cm
10cm
20cm
MAP990404

Cosmological Parameters

Parameter	Symbol	Value
Hubble parameter	h	0.73 ± 0.03
Total matter density	$\Omega_{\rm m}$	$\Omega_{\rm m} h^2 = 0.134 \pm 0.006$
Baryon density	$\Omega_{\rm b}$	$\Omega_{\rm b} h^2 = 0.023 \pm 0.001$
Cosmological constant	Ω_Λ	See Ref. 7
Radiation density	$\Omega_{\rm r}$	$\Omega_{\rm r} h^2 = 2.47 \times 10^{-5}$
Neutrino density	Ω_ν	See Sec. 1.1.2
Density perturbation amplitude	$\Delta^2_{\mathcal{R}}(k_*)$	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. $\Omega_{tot} \sim 1$)

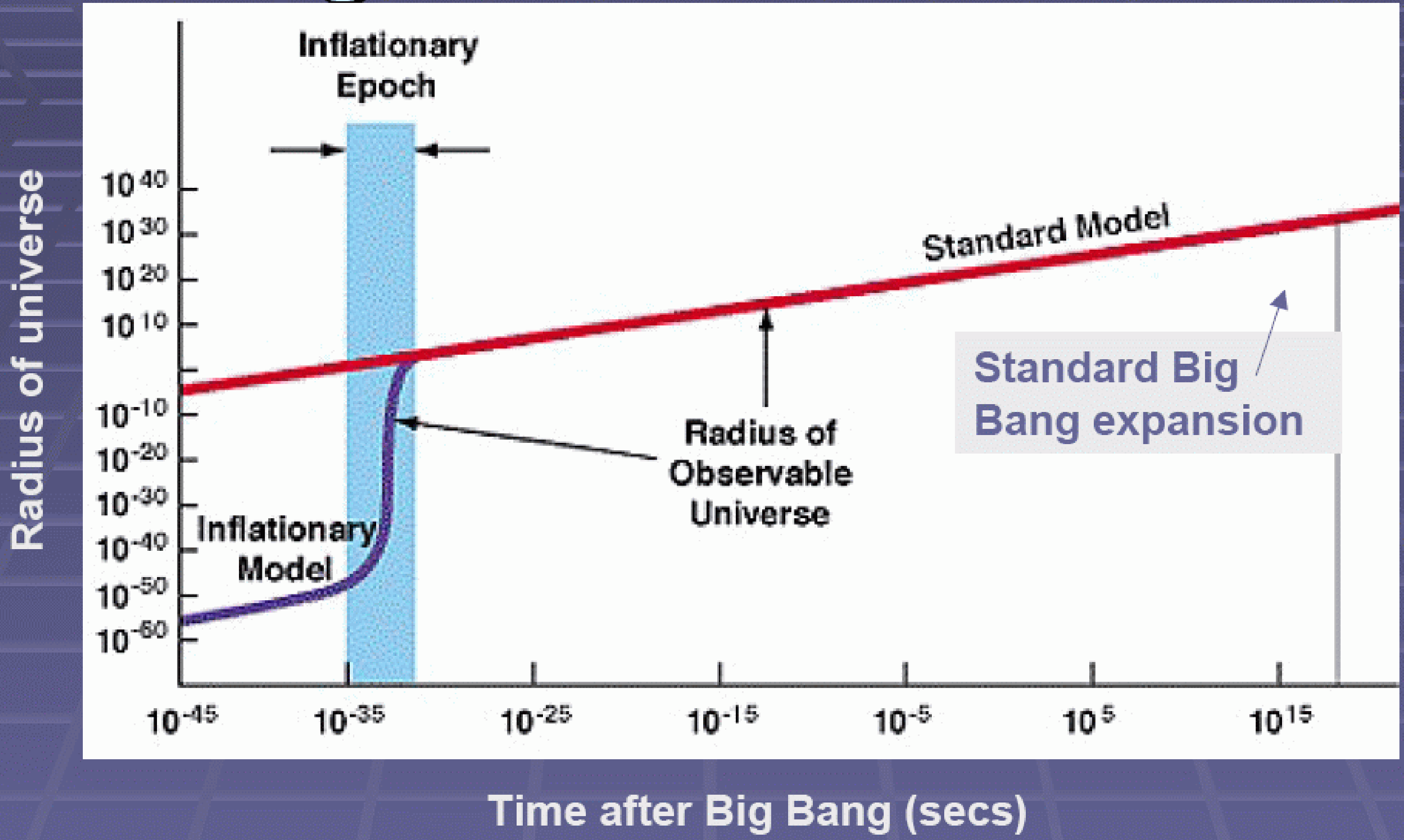
τ : because CMB photons can be scattered, altering anisotropies

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

Density pertubation amplitude: often expressed as σ_8

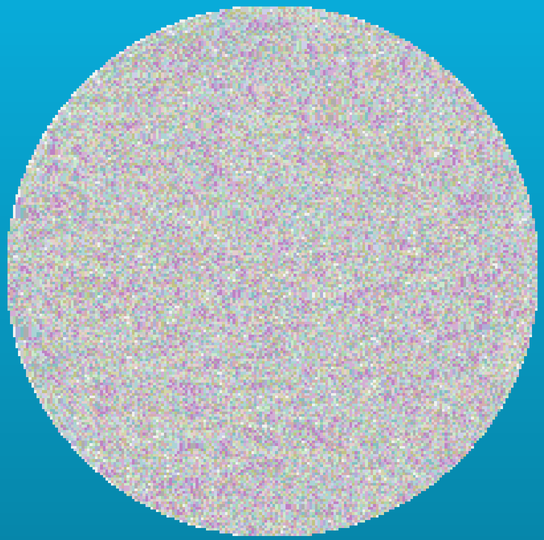
Bias: between galaxy distribution and dark matter distribution

Solving the Horizon Problem

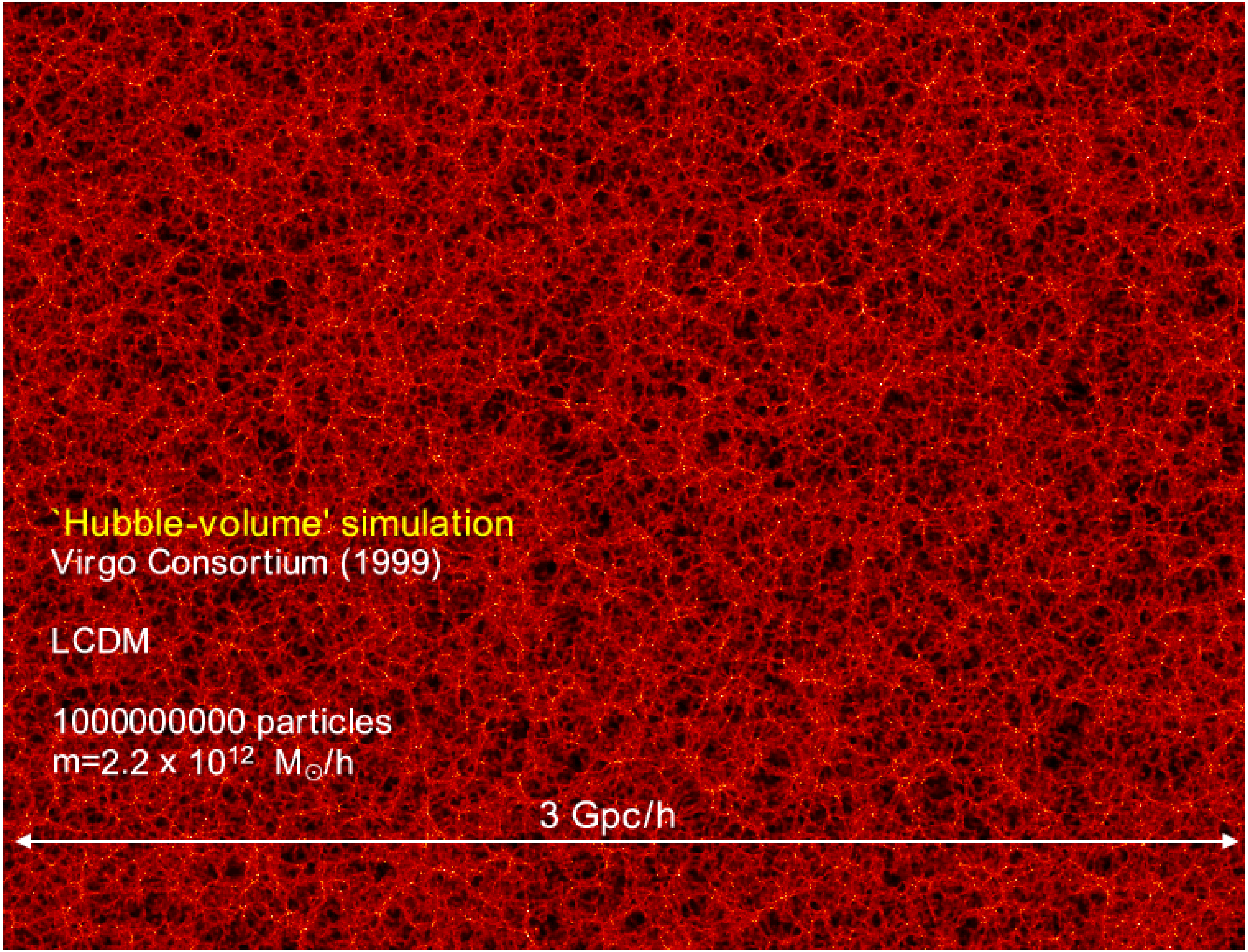


If super-expansion lasts long enough, CMB patches on opposite sides of the sky would have been close enough to communicate in the primordial times.

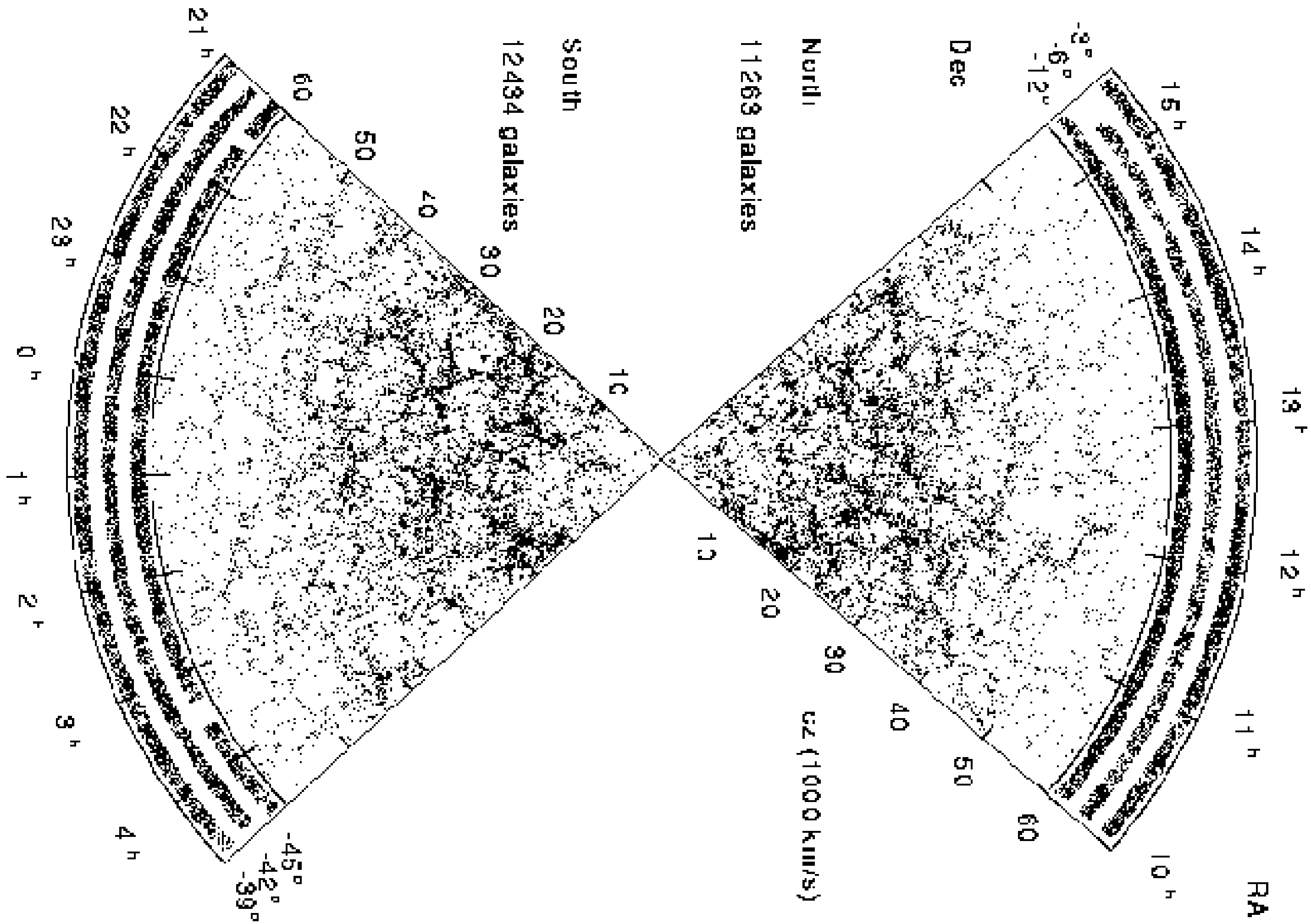
Quantum Fluctuations in the early universe

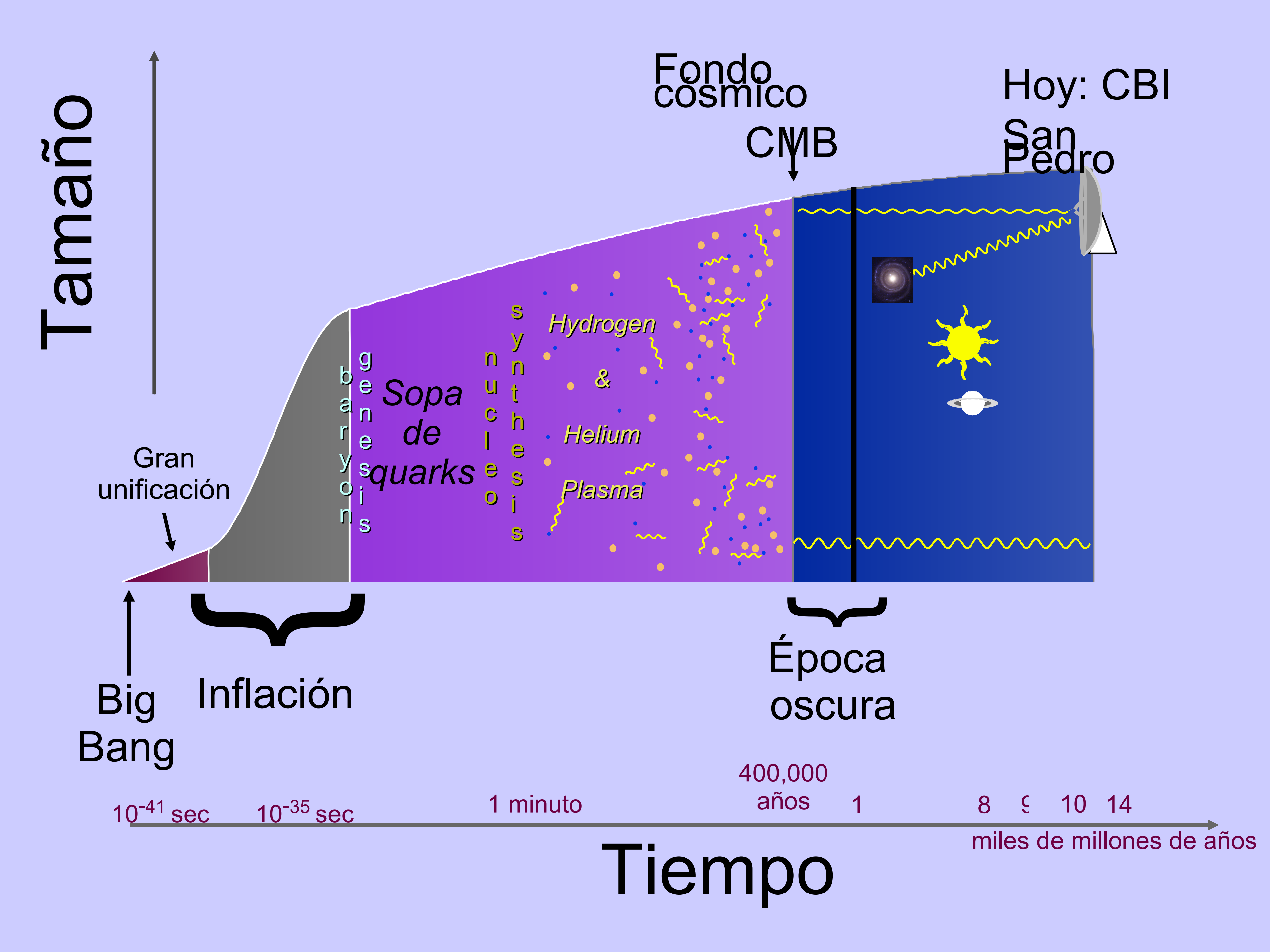


The state of the art …

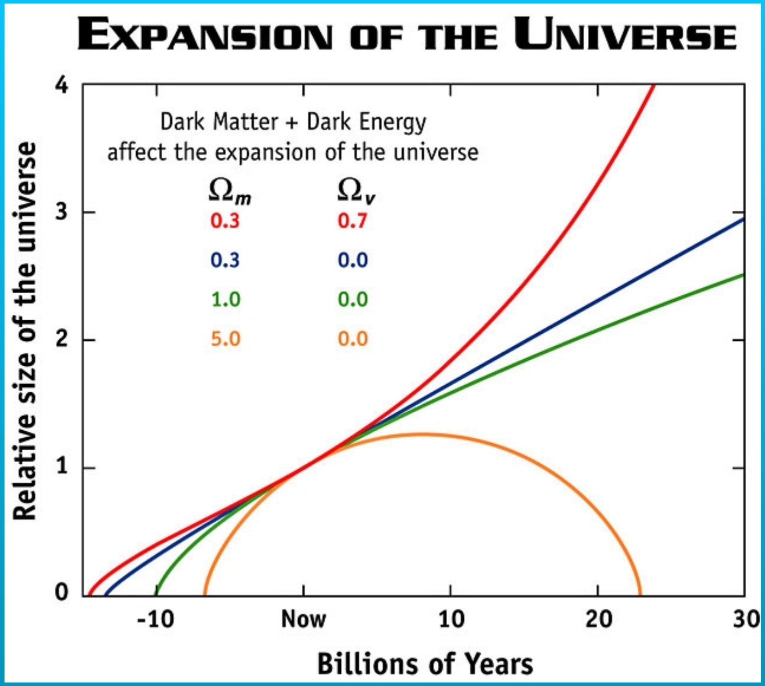


Large-scale structure in the distribution of galaxies





Tamaño
Fondo cósmico
CMB
Hoy: CBI
San Pedro
Gran unificación
baryon genesis
Sopa de quarks
nucleo synthesis
Hydrogen
&
Helium
Plasma
Big Bang
Inflación
Época oscura
10^{-41} sec
10^{-35} sec
1 minuto
400,000 años
1
8
9
10
14
miles de millones de años
Tiempo



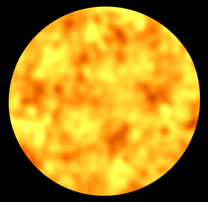
Expansion of the Universe
Dark Matter + Dark Energy
affect the expansion of the universe
Ω_m
Ω_v
0.3 0.7
0.3 0.0
1.0 0.0
5.0 0.0
Relative size of the universe
0
1
2
3
4
-10
Now
10
20
30
Billions of Years

Consecuencias de los resultados del WMAP/CBI etc.:

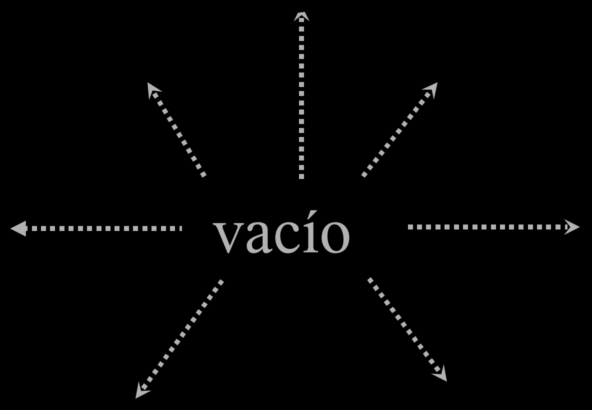
Una revolución en la física fundamental

Ω_b 4 % materia normal

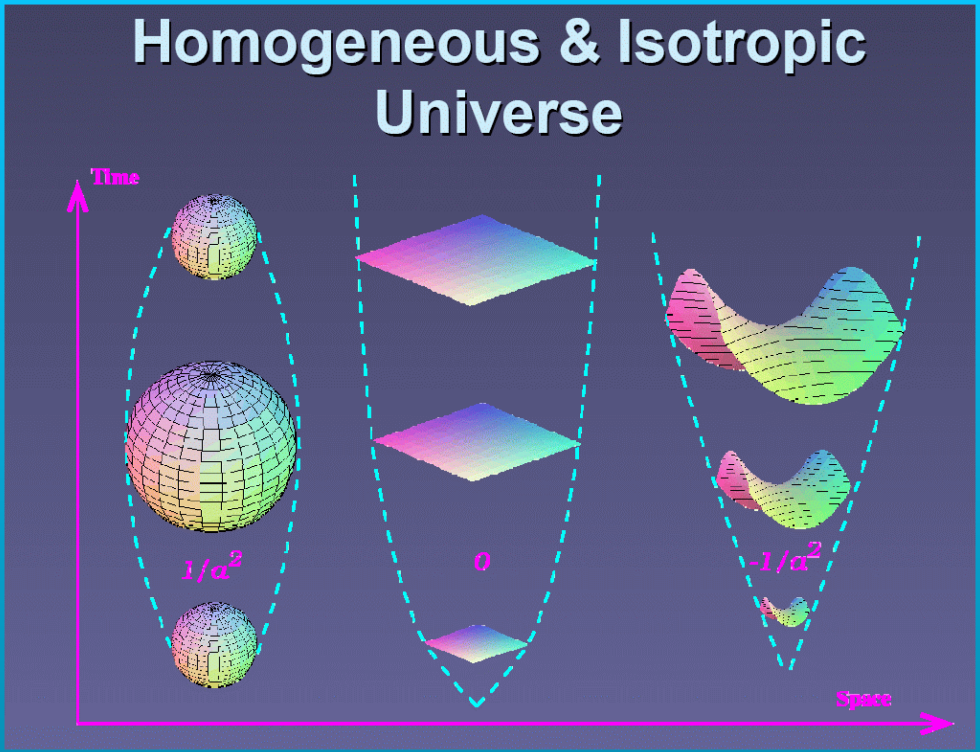
Ω_{nb} 21 % materia oscura



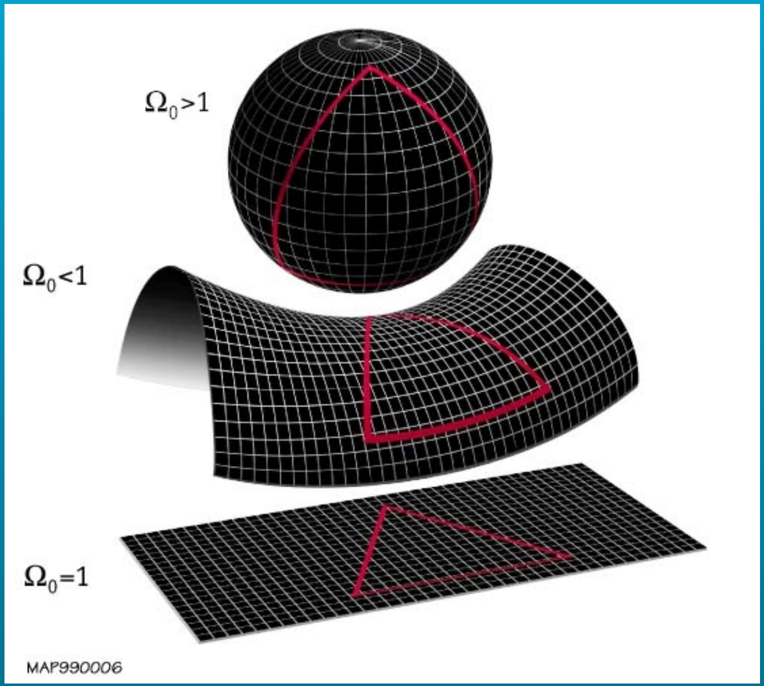
Ω_Λ 75 % energía oscura

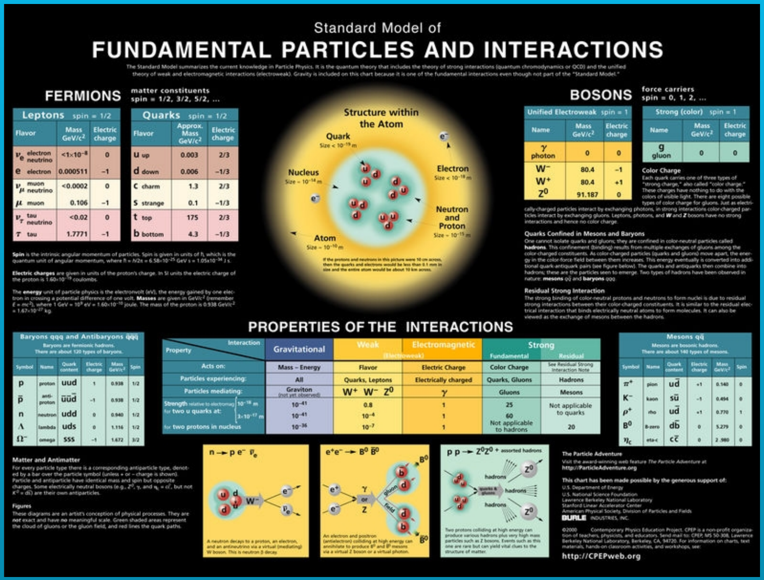


Edad del Universo: 13.5 mil millones de años

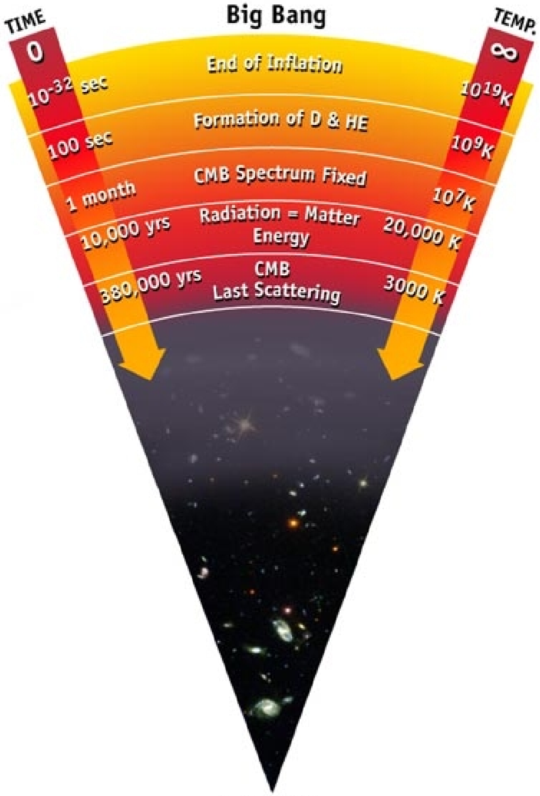


Universe is flat (WMAP)



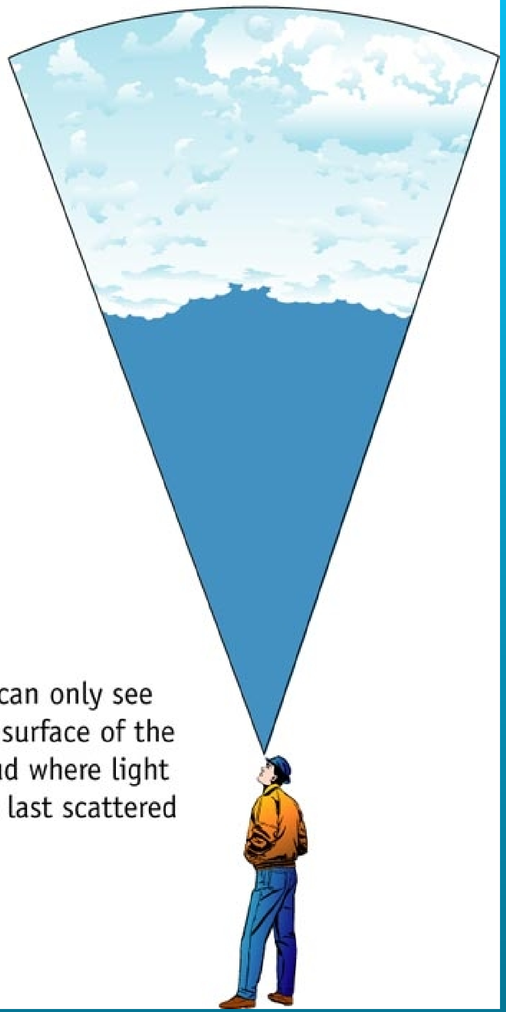


Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
FERMIONS
matter constituents spin = 1/2, 3/2, 5/2, ...
Leptons spin = 1/2
Quarks spin = 1/2
Structure within the Atom
Quark
Nucleus
Electron
Neutron and Proton
Atom
BOSONS
force carriers spin = 0, 1, 2, ...
Unified Electroweak spin = 1
Strong (color) spin = 1
PROPERTIES OF THE INTERACTIONS
Gravitational
Weak
Electromagnetic
Strong
Baryons qqq and Antibaryons q̄q̄q̄
Mesons qq̄
http://CPEPweb.org



PRESENT
13.7 Billion Years
after the Big Bang

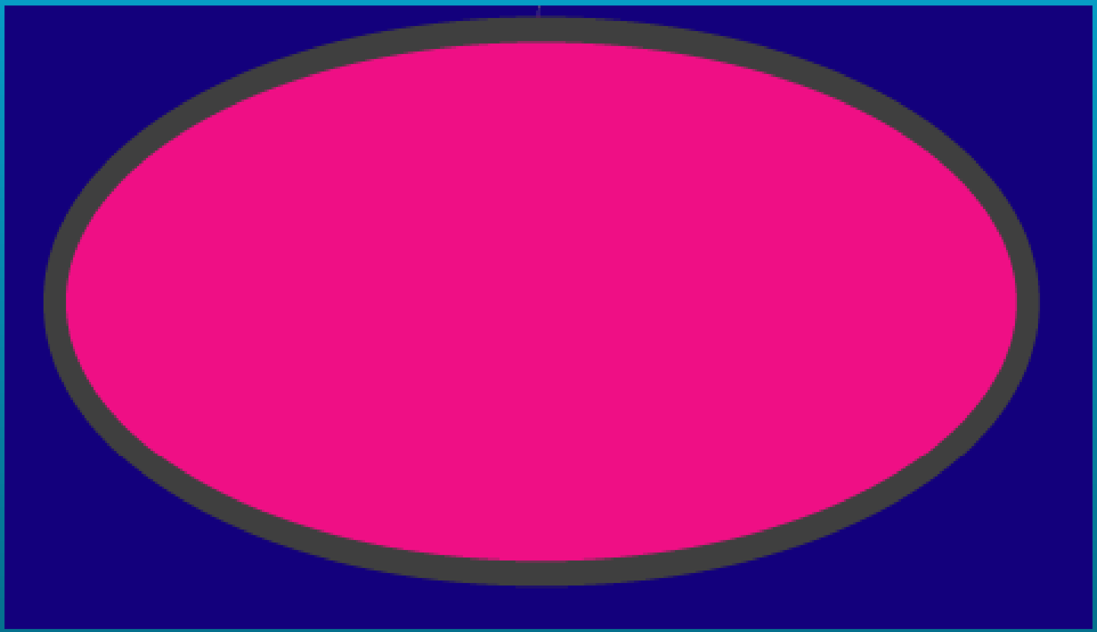
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



We can only see the surface of the cloud where light was last scattered

Measuring the CMB Anisotropies

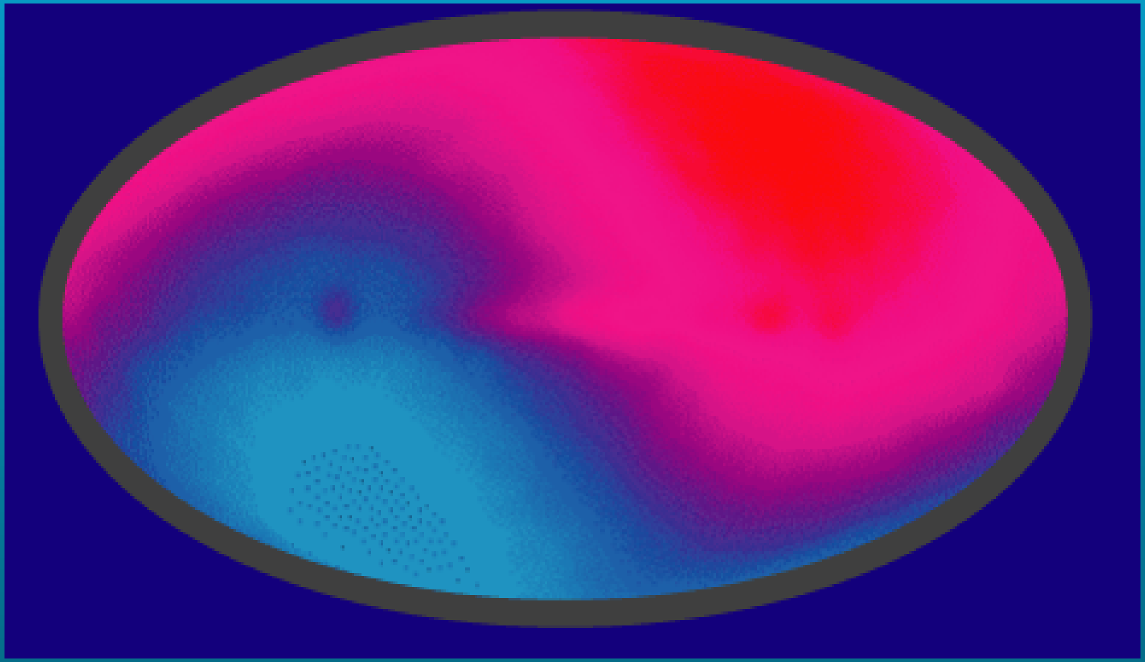
- First COBE image
- No variation on the scale 1 part in 1000



Wayne Hu

Measuring the CMB Anisotropies

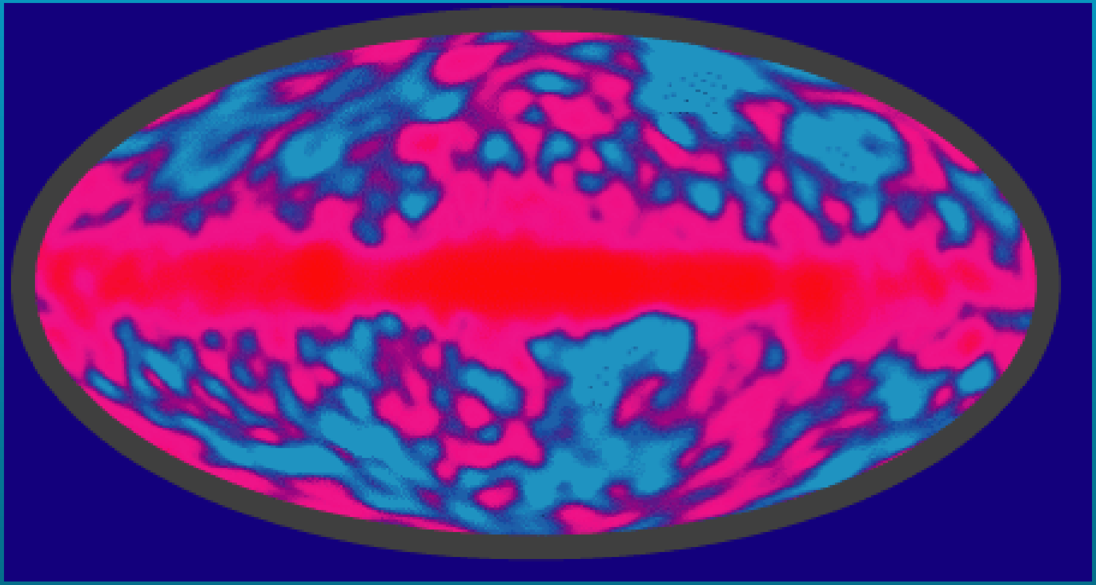
- Turn up resolution slightly
- Dipole - redshift from our motion



Wayne Hu

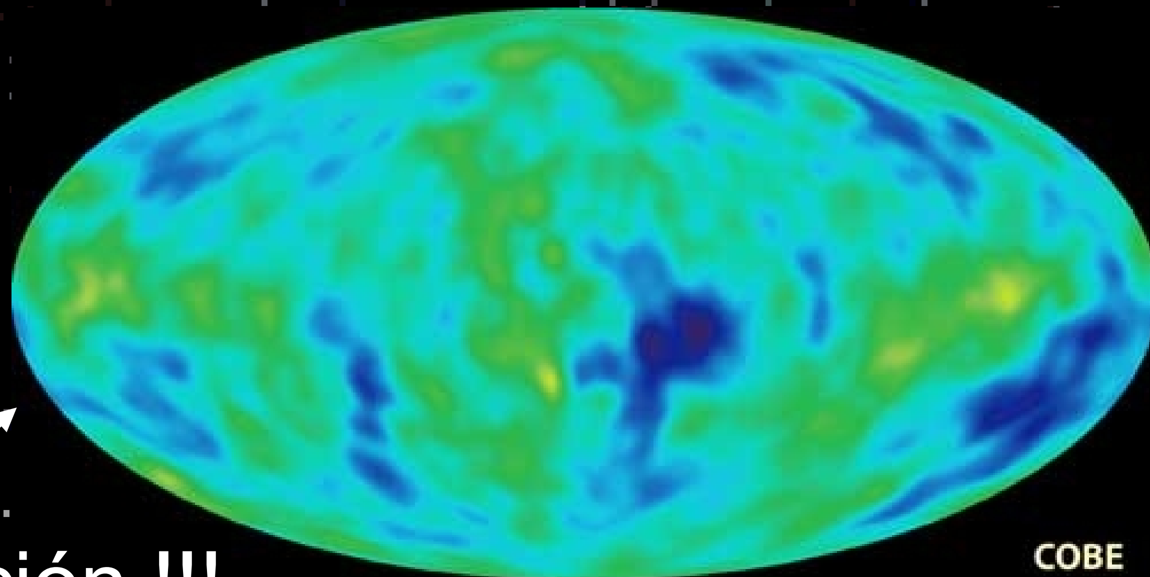
Measuring the CMB Anisotropies

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



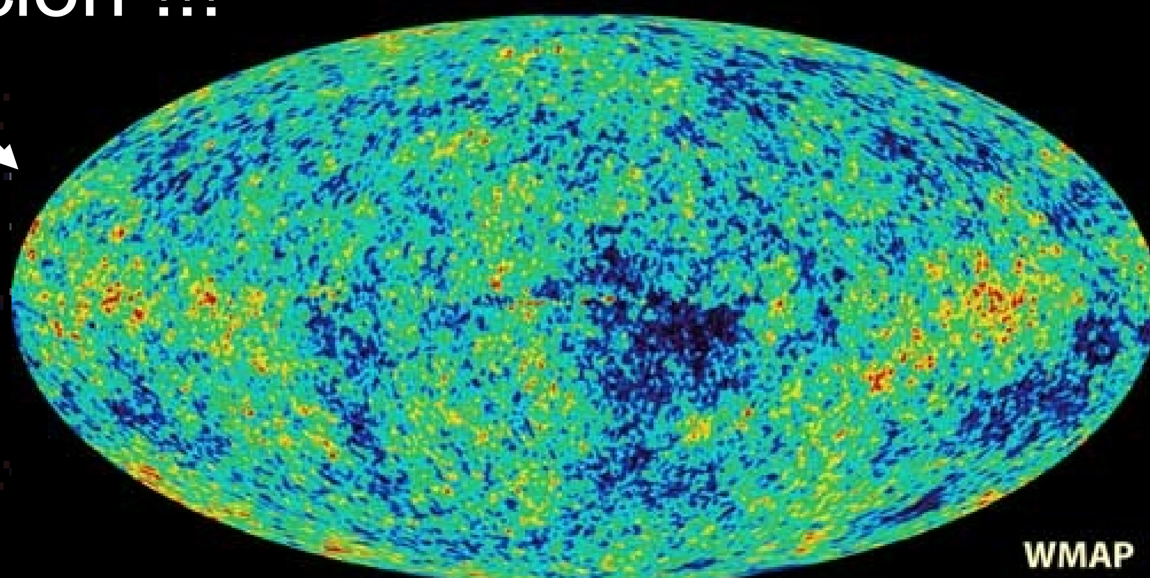
Wayne Hu

Imágenes totales del cielo de las anisotropías del CMB.
2.725 K +/- ~ 30 μK rms



1992

Resolución !!!



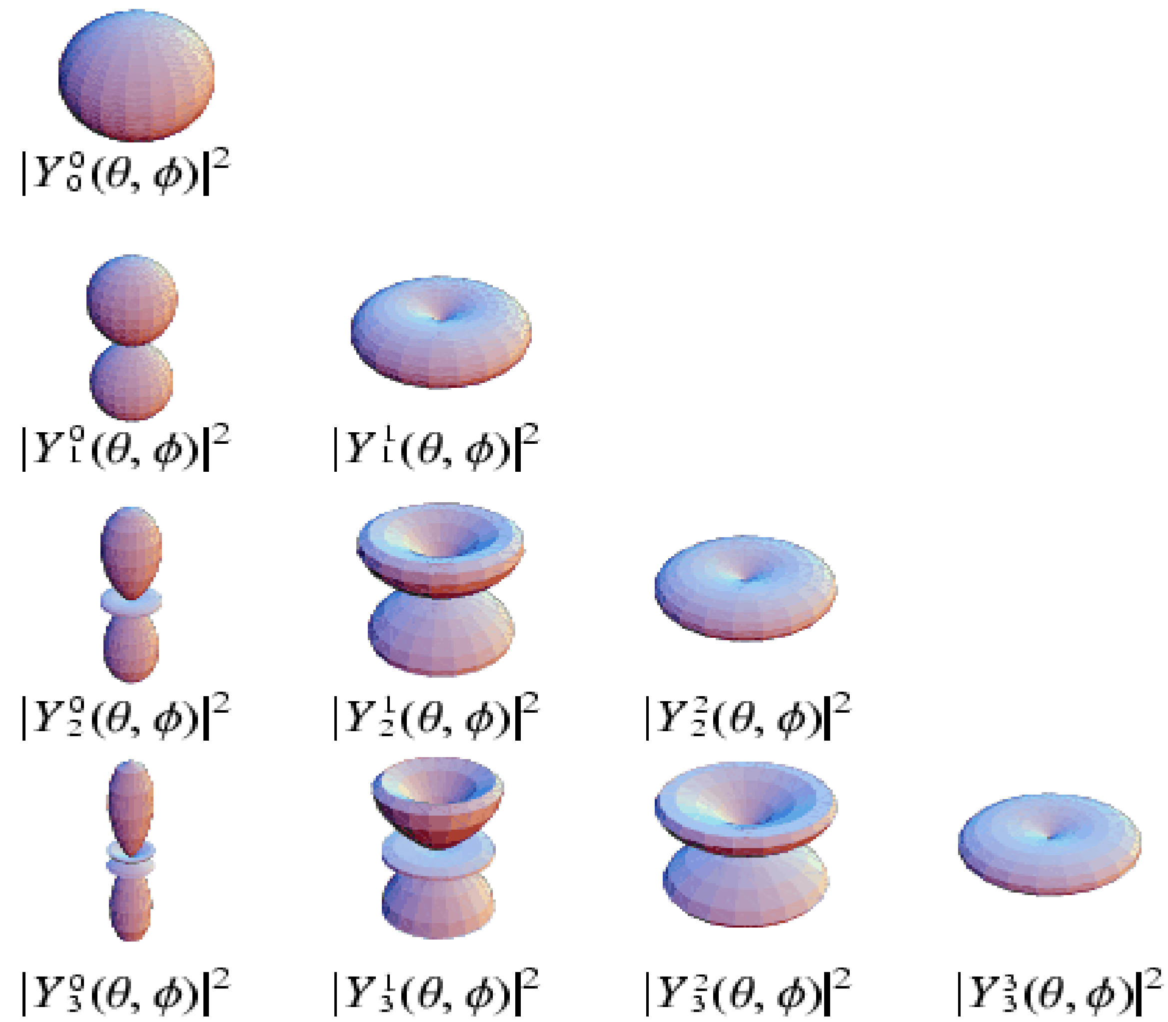
2003

CMB Power Spectrum

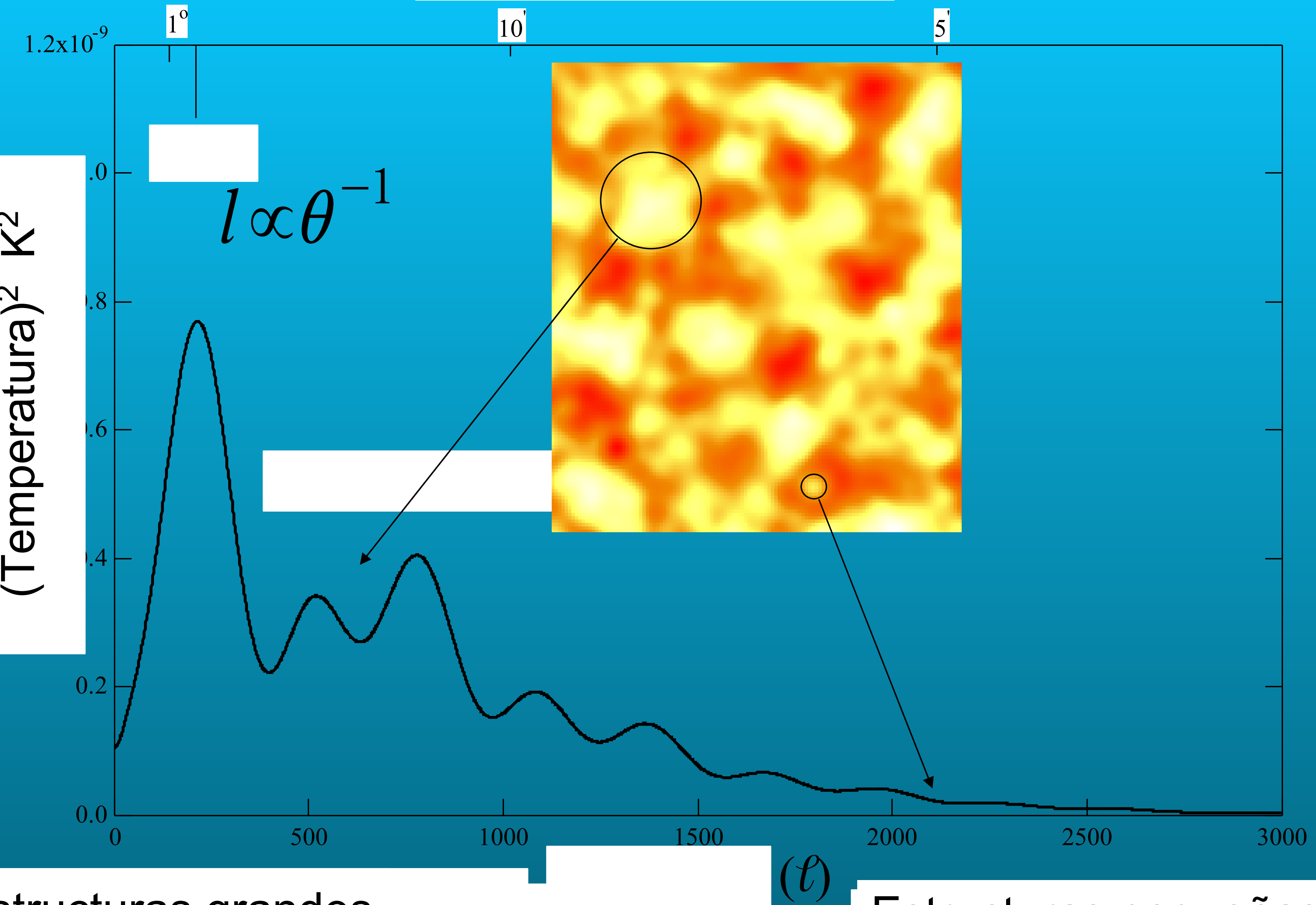
- Measure the angular coherence of the temperature fluctuations
- We are familiar with decomposing signals in Fourier space with *k* modes
- Since CMB fluctuations are on the 2-D sky, we need angular decomposition in multipole space to study the amplitude

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

Spherical Harmonics



Escala angular en el cielo



Estructuras grandes

Estructuras pequeñas

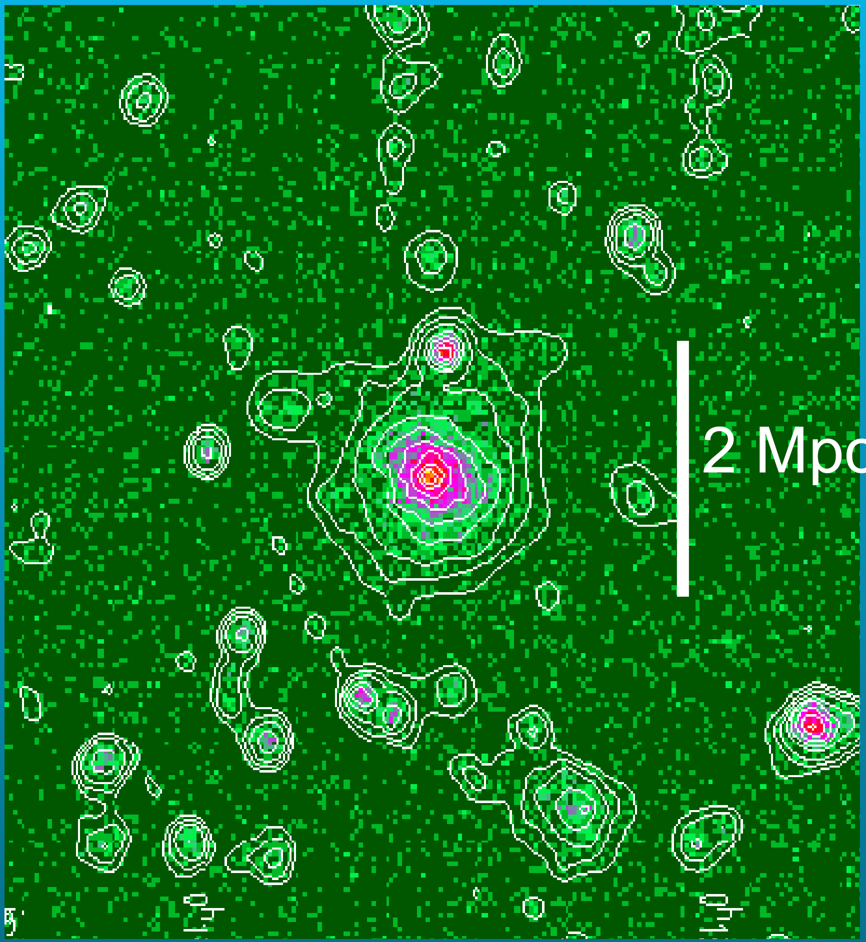
Systematic sources of error since recombination

(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



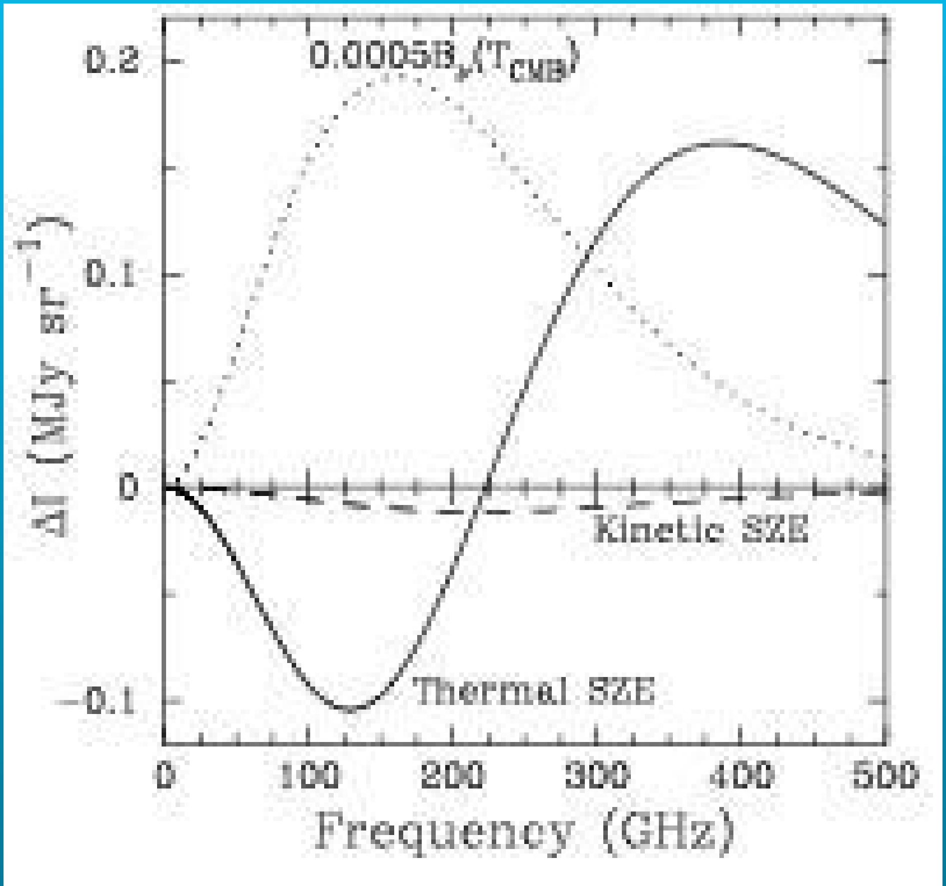
$T_e \approx 6$ keV

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

$L \approx 1$ Mpc

What is it?: Inverse Compton

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

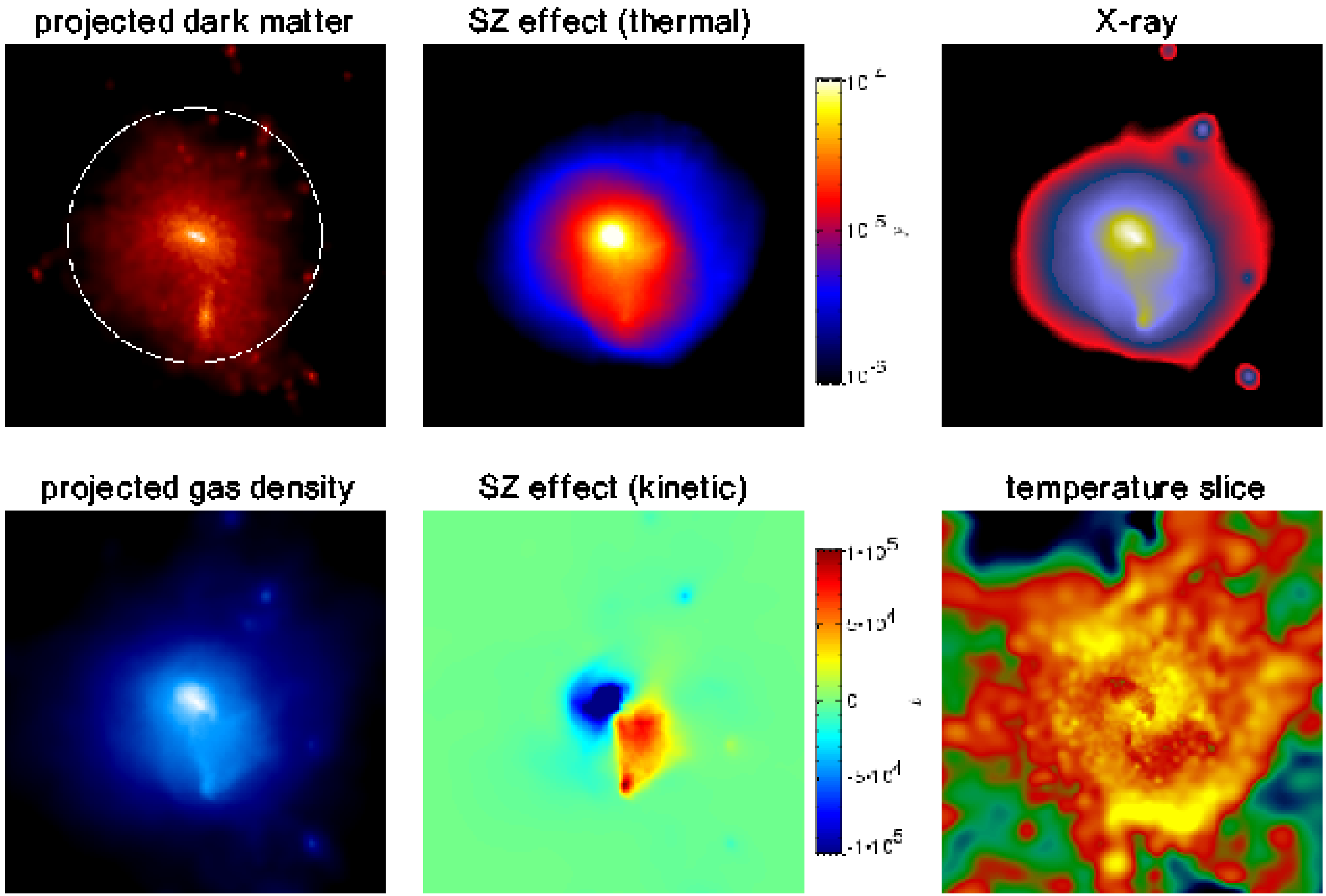


[3]

Carlstrom, Holder, Reese, "Cosmology with the Sunyaev-Zel'dovich Effect," 2002, astro-ph/0208192.

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

A CLUSTER SEEN IN DIFFERENT WAYS



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

$$\Omega_b = 0.047 \pm 0.006$$
$$\Omega_m = 0.29 \pm 0.07$$
$$t_0 = 13.4 \pm 0.3\,Gyr$$

Combine WMAP, CBI, ACBAR, 2dFGRS, Lyα Forest Data

$$\Omega_b h^2 = 0.0224 \pm 0.0009$$
$$\Omega_m h^2 = 0.135 \pm 0.009$$
$$h = 0.71 \pm 0.04$$

$$\Omega_b = 0.044 \pm 0.004$$
$$\Omega_m = 0.27 \pm 0.04$$
$$t_0 = 13.7 \pm 0.2\,Gyr$$

Cosmological Parameters

Parameter	Symbol	Value
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Total matter density	Ω_{m}	$\Omega_{\mathrm{m}} h^2 = 0.134 \pm 0.006$
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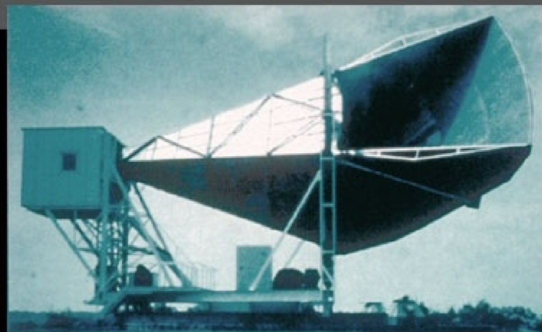
Density pertubation amplitude: often expressed as σ_8

Bias: between galaxy distribution and dark matter distribution

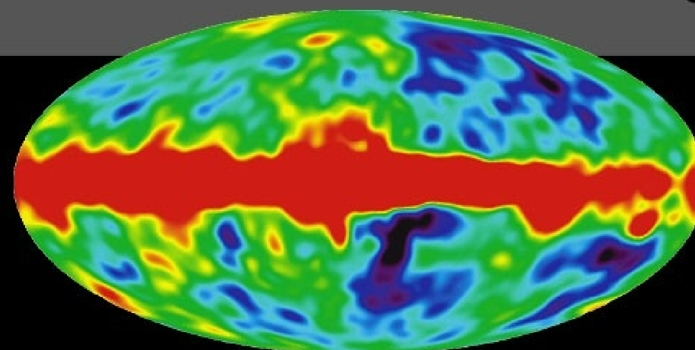
1965

Penzias and Wilson



1992

COBE



2003

WMAP