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Theoretical cosmology

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Hubble Space Telescope image of supernova 1994D in galaxy NGC 4526 (z=0.0015)

Outline of the Course

1.- Cosmological observations and FLRW models

2.- Thermodynamics in an expanding universe: decoupling and dark matter

3.- Inflation

4.- Cosmological perturbations and CMB anisotropies

Observational basis of Cosmology

Cosmology *studies the origin, evolution and structure of the universe on large scales (larger than the galaxy scale)*

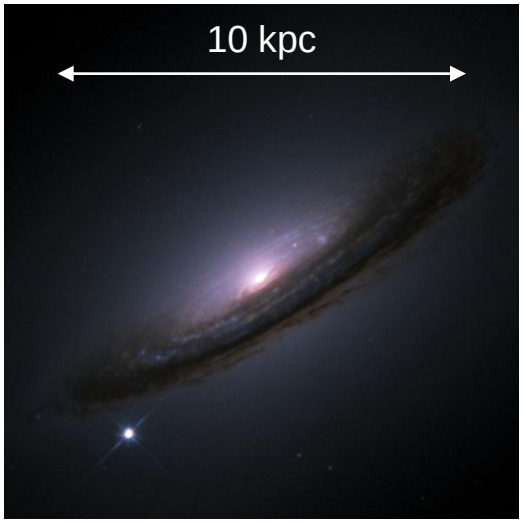
1 pc = 3.26 light years= 3.09 x 10^{16} m

Galaxy

10^{11} stars

M_{gal}= 10^{42} kg

L_{gal}= 10 kpc



On these scales ***gravitation*** *is the only relevant interaction*

Observational basis of Cosmology

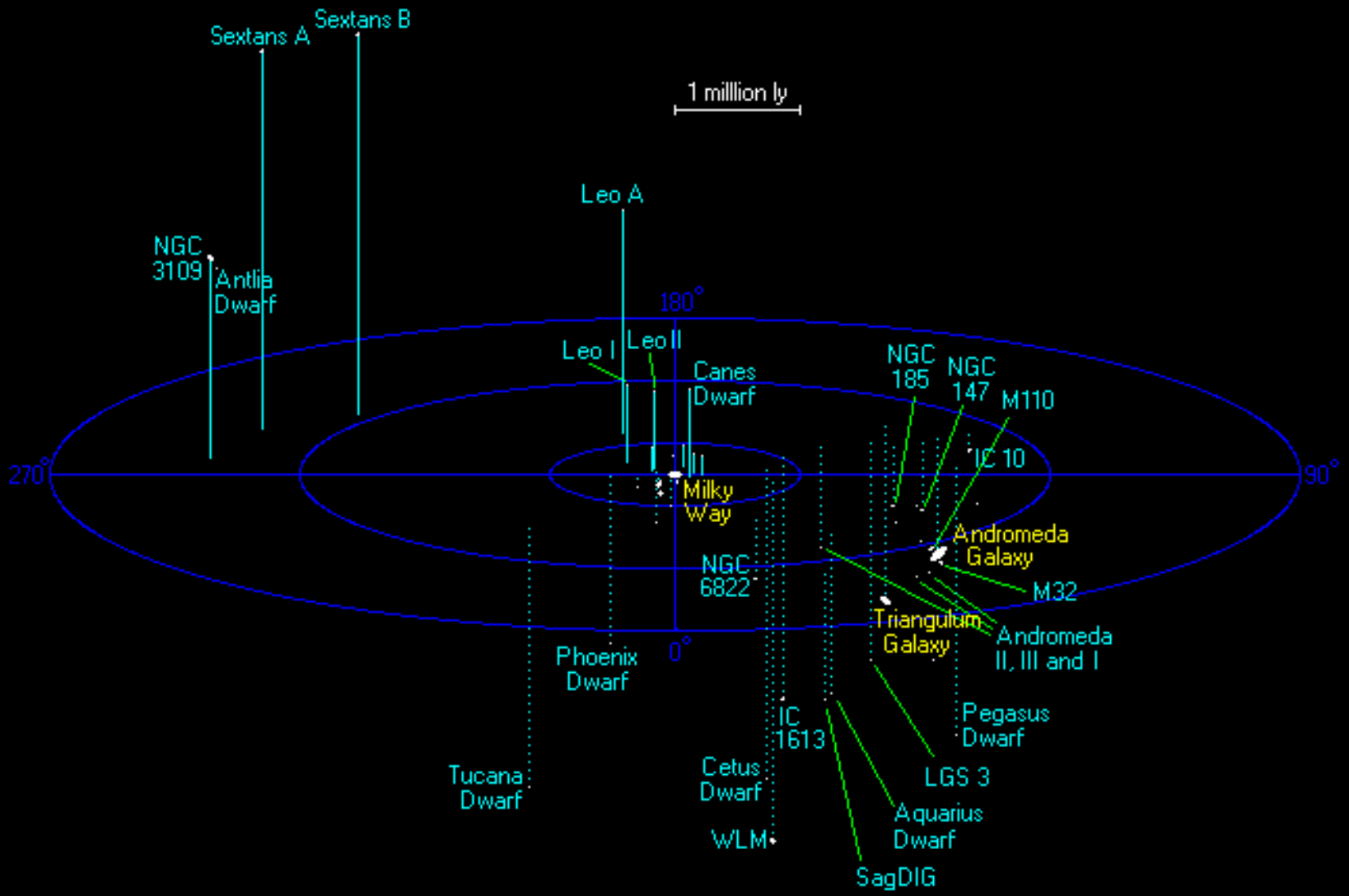
1.- Matter distribution and matter density in the universe: dark matter

2.- Universe expansion and acceleration: dark energy

3.- Light elements abundances

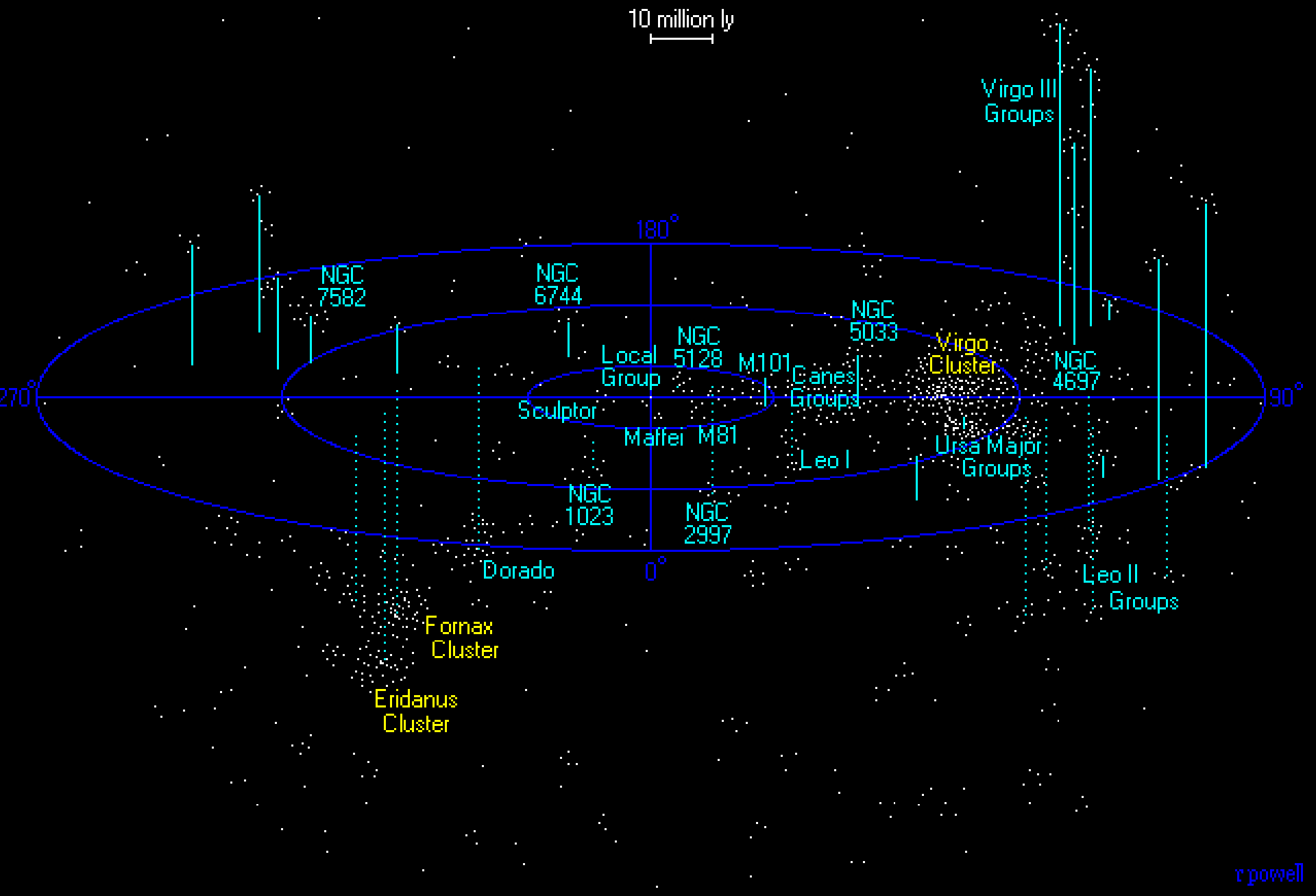
4.- Cosmic microwave background and anisotropies

1.- Matter distribution on large scales:
the universe within 1.5 Mpc: Local Group

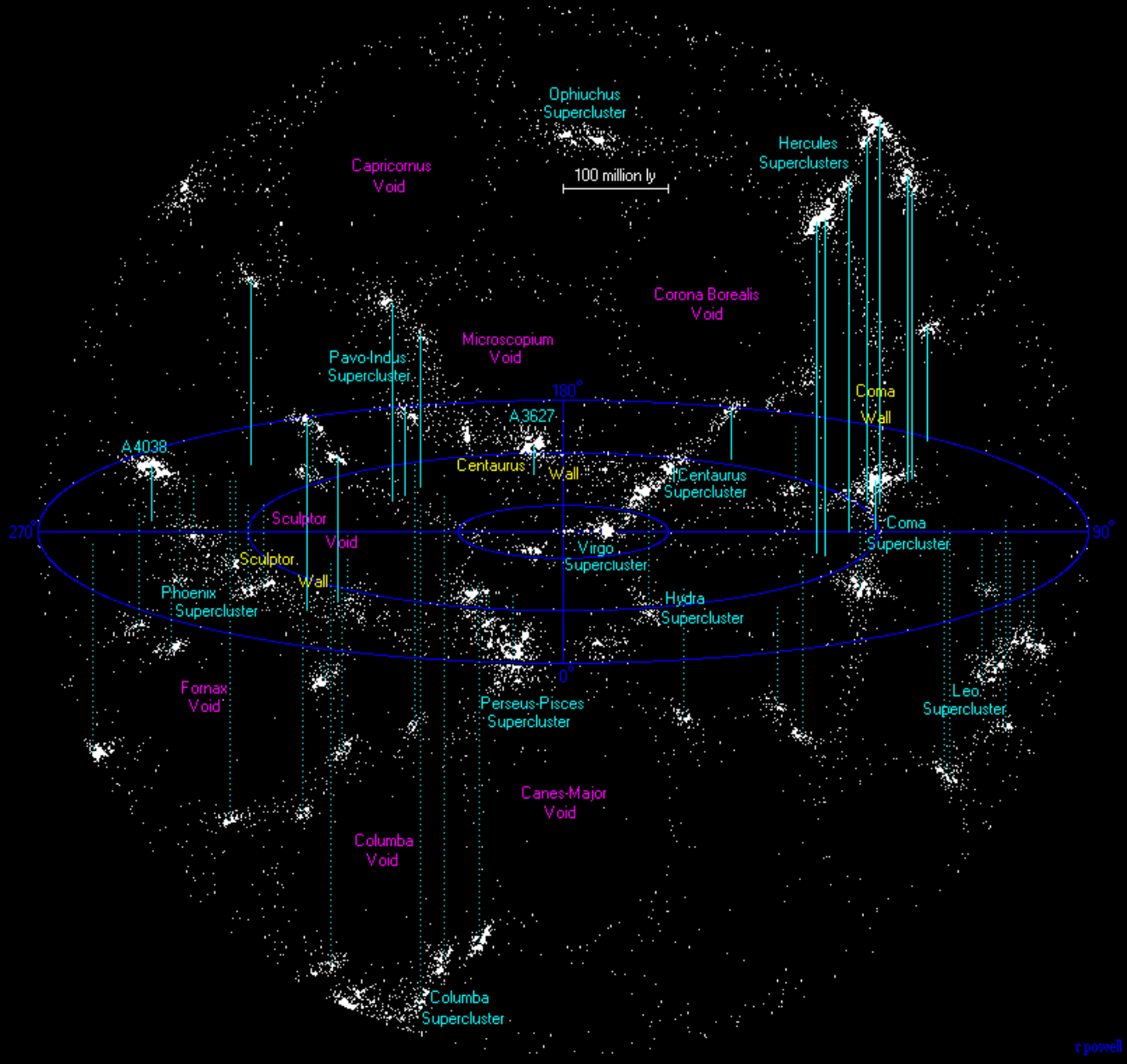


r powell

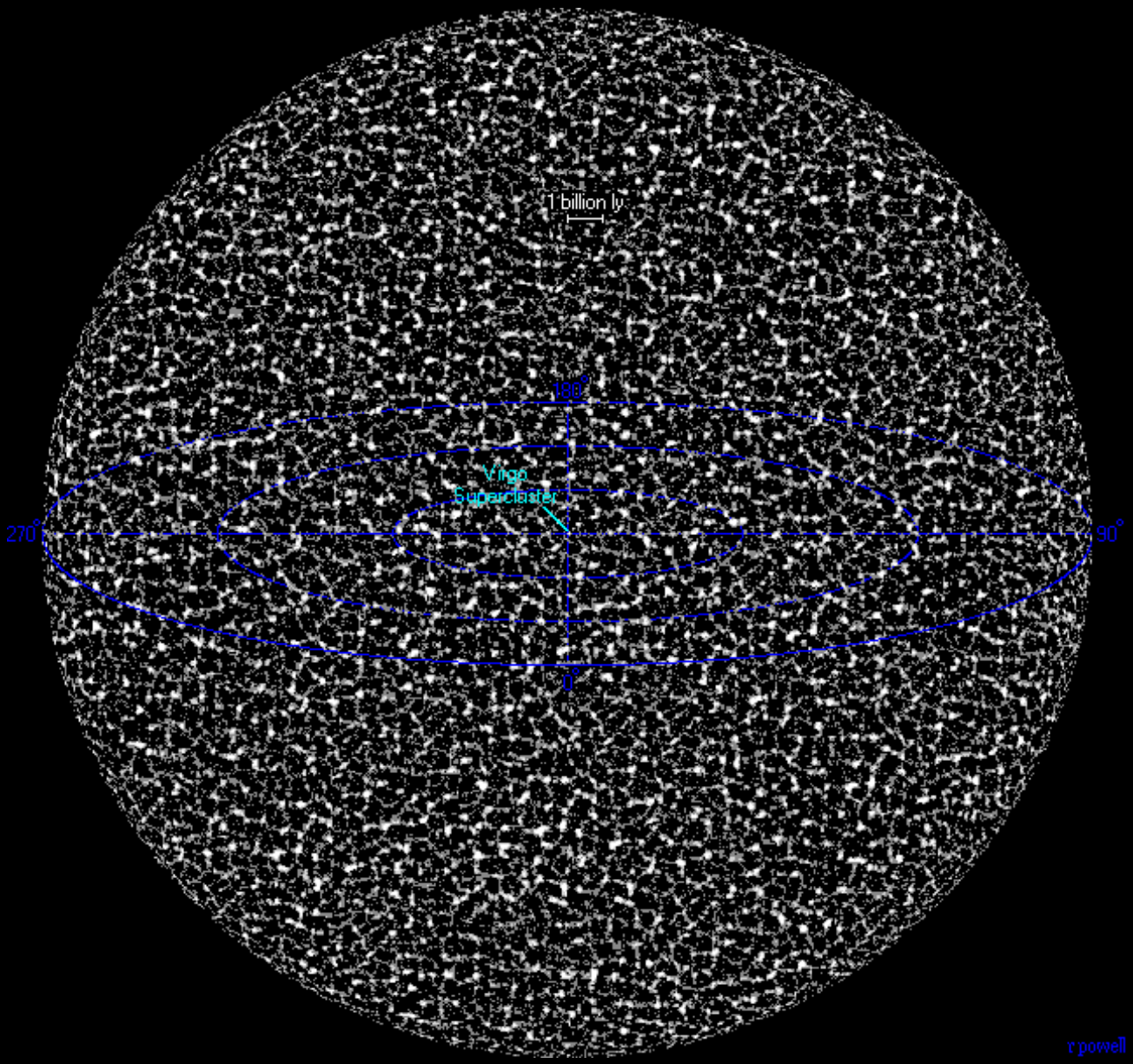
The universe within 30 Mpc: Virgo supercluster



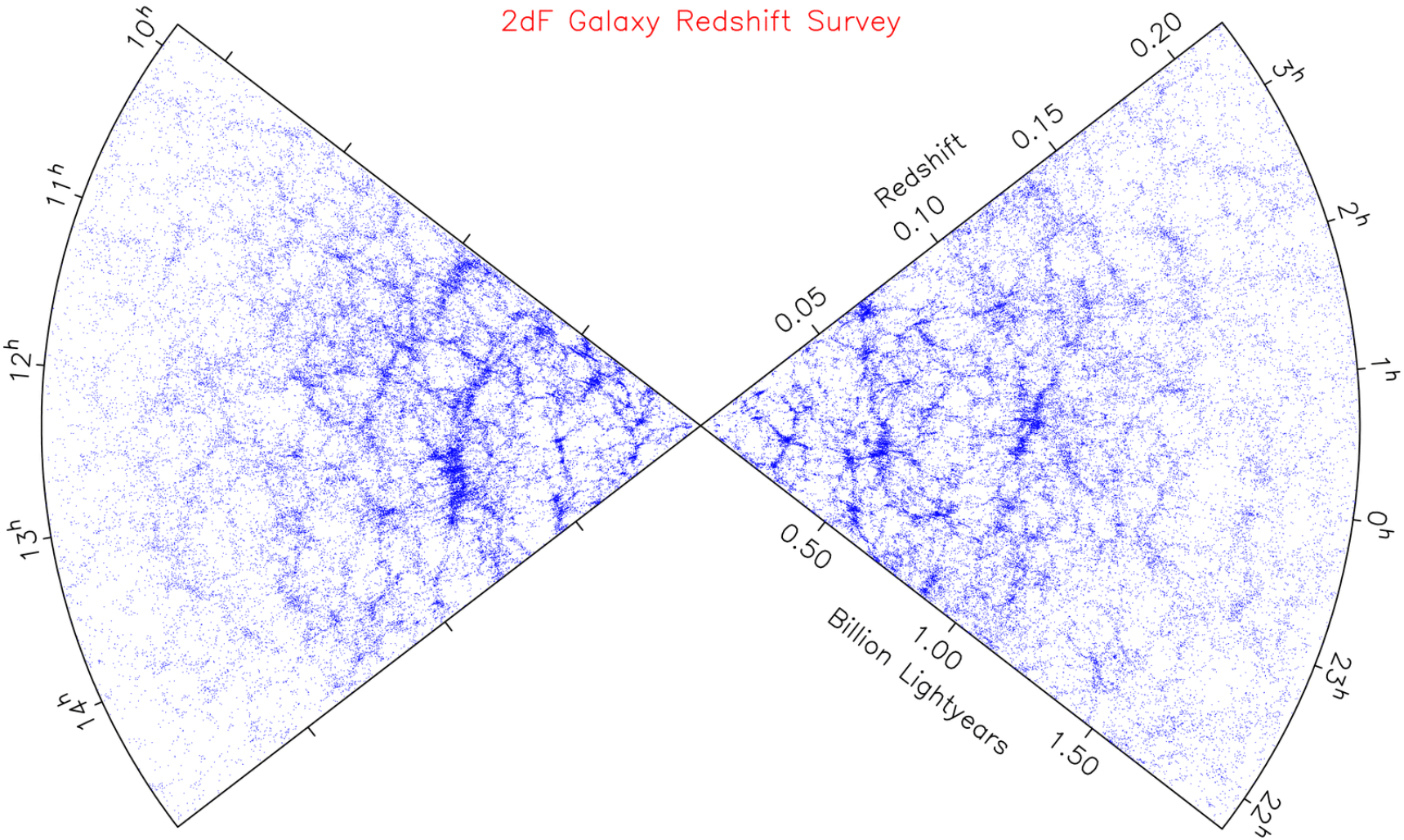
Superclusters, filaments, walls and voids within 150 Mpc

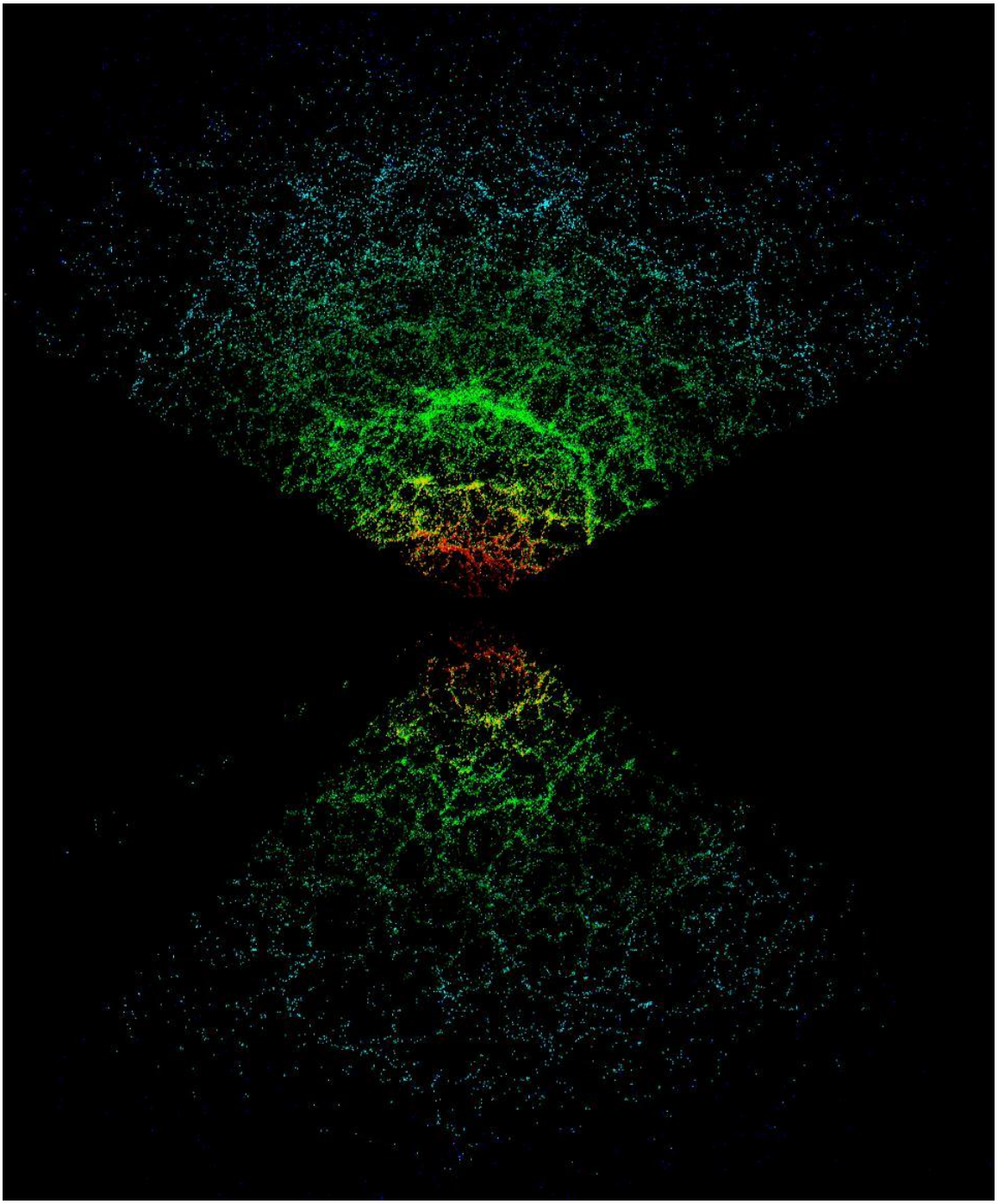


The universe within 4300 Mpc: large scale homogeneity



The Universe within 600 Mpc

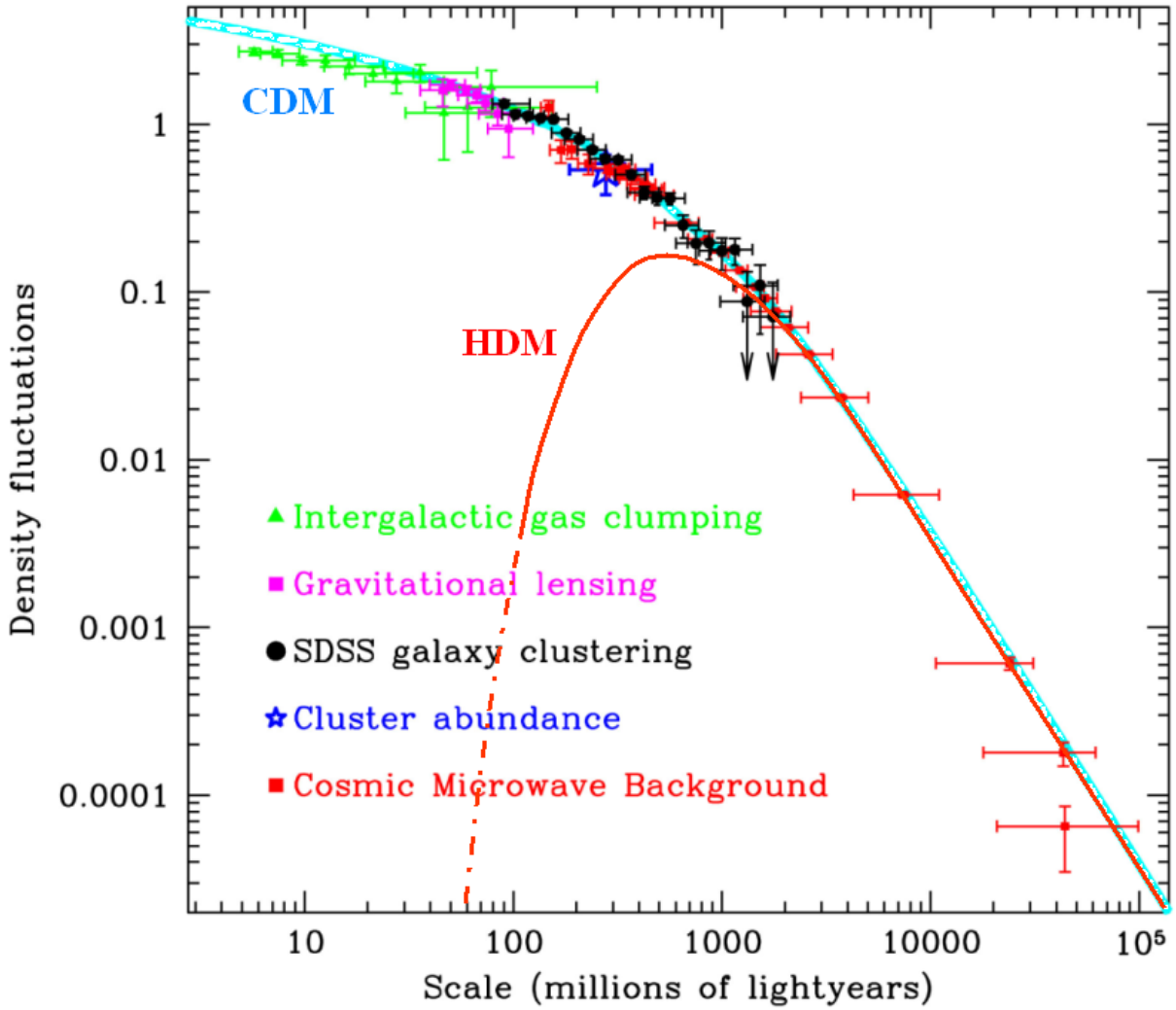




The Universe within 600 Mpc
(Sloan Digital Sky Survey)

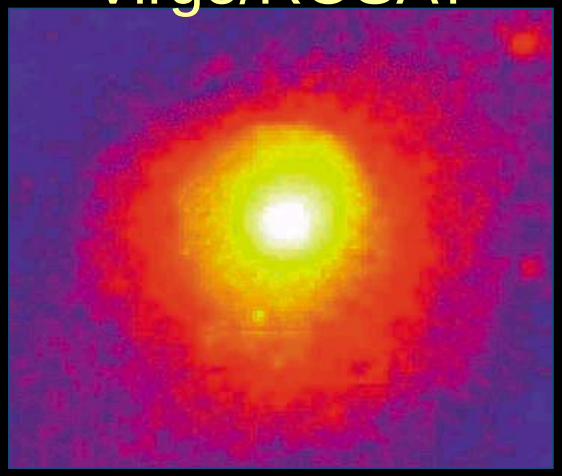
Matter density fluctuations:

Statistical homogeneity R >> 100 Mpc (**Cosmological Principle**)



Matter density of the universe:
luminous vs. dark matter

VISIBLE

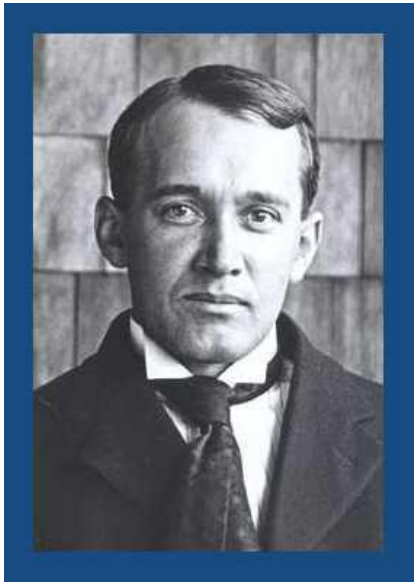


X RAY

Virial mass: M/L= 200

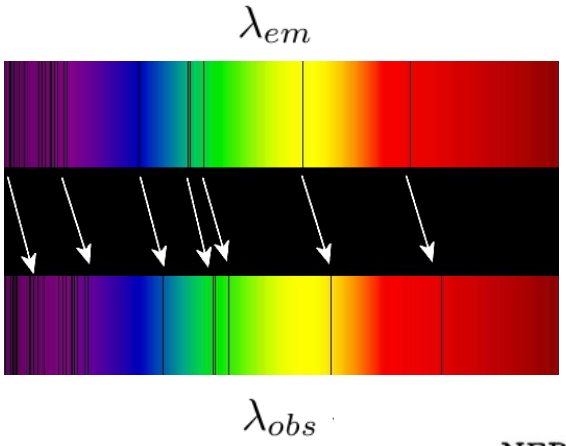
$$\rho_M = \langle\mathcal{L}\rangle M/L, \quad \langle\mathcal{L}\rangle = (2.0 \pm 0.2) \times 10^8 h L_\odot \mathrm{Mpc}^{-3}.$$
$$\Omega_M = \rho_M/\rho_c = 0.266 \pm 0.029$$
$$\Omega_{lum} = 0.005 \pm 0.002$$

2.- The expansion of the universe



Vesto M. Slipher
(1875-1969, USA),
Lowell Observatory

Discovers in 1915
the recession of galaxies



$$\frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} = z$$

$$z \simeq \frac{v}{c}, \quad v \ll c$$

z = redshift

NEBULÆ.

By V. M. SLIPHER, Ph.D.

(Read April 13, 1917.)

Radial Velocities of Twenty-five Spiral Nebulæ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580 km.
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

Distance-redshift relation: Lemaître-Hubble (1927-29)

Cepheids as standard candels

(distances up to 3 Mpc (z=0.001), or 20 Mpc with HST (z = 0.005))

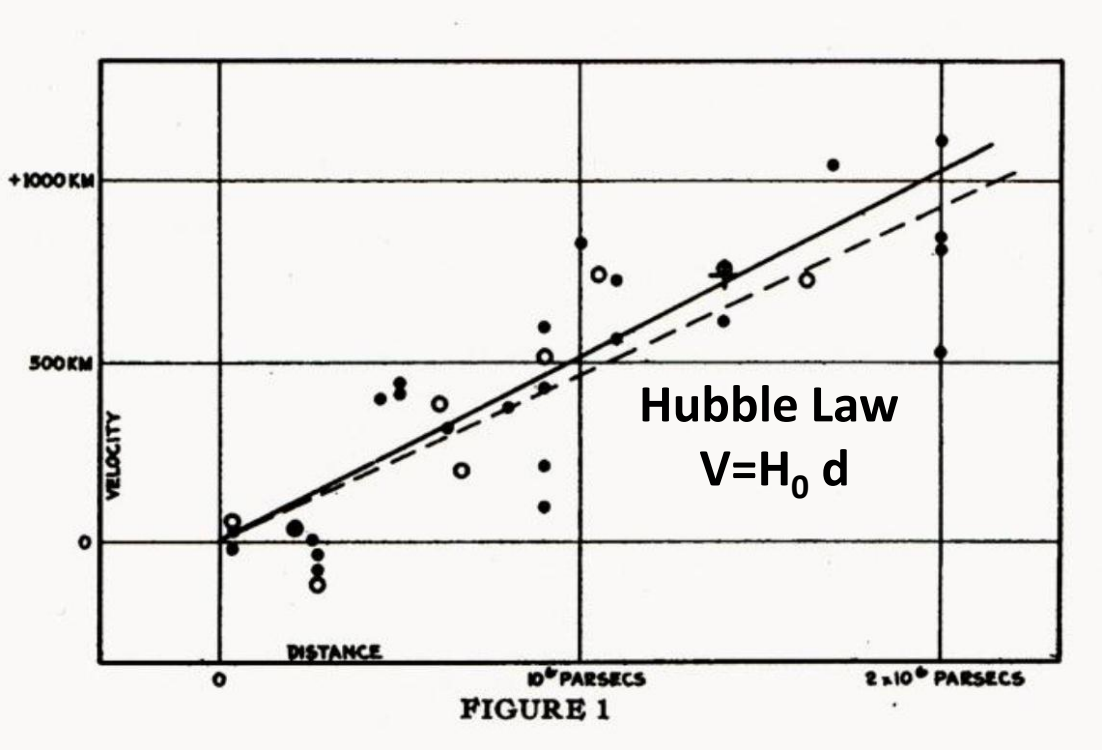


FIGURE 1

Hubble constant

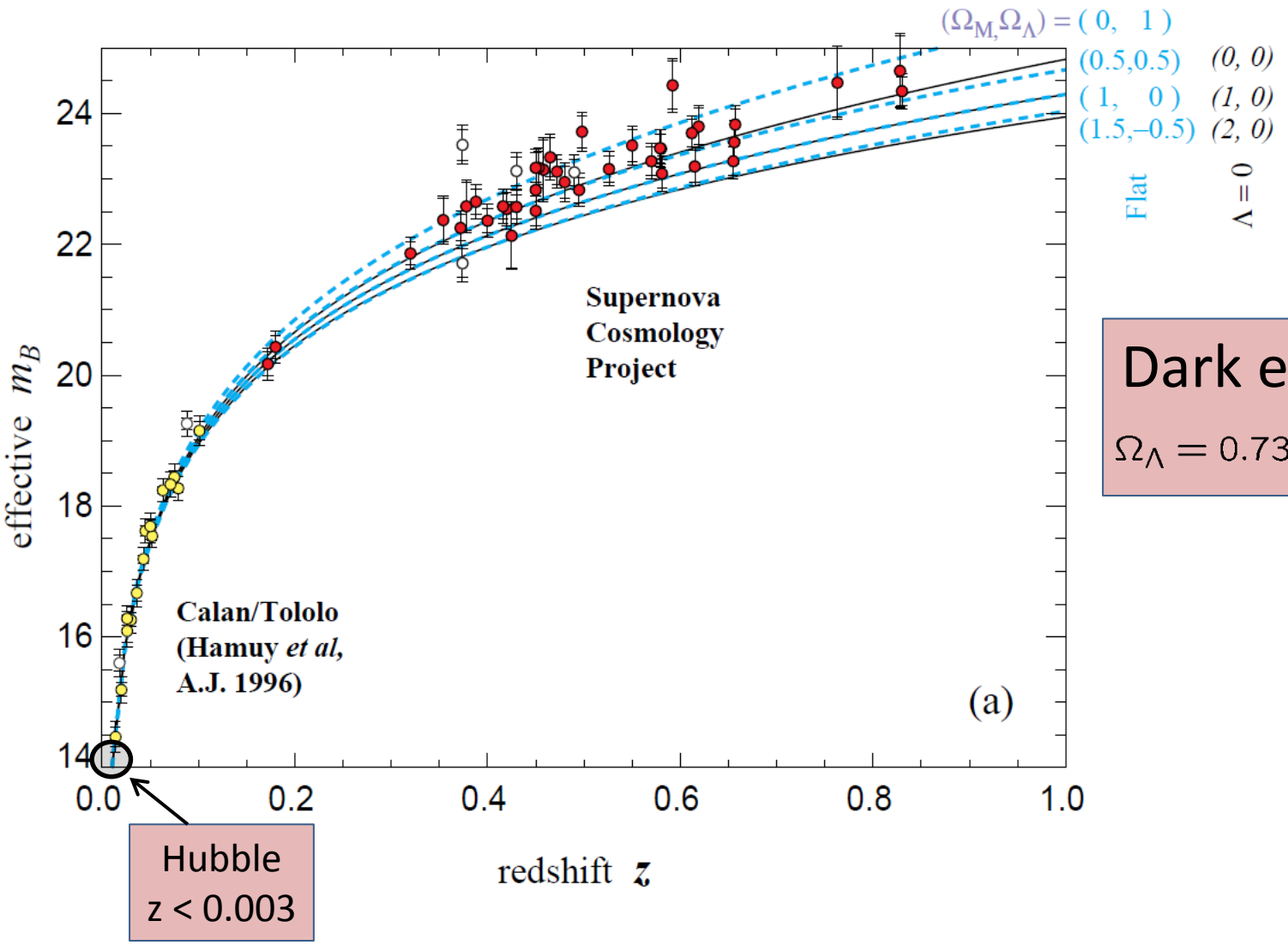
$H_0 = 73.8 \pm 2.4$ km/s/Mpc

$h = 0.738$

Age of the universe

$t_0 \simeq H_0^{-1} \simeq 13700$ Myears

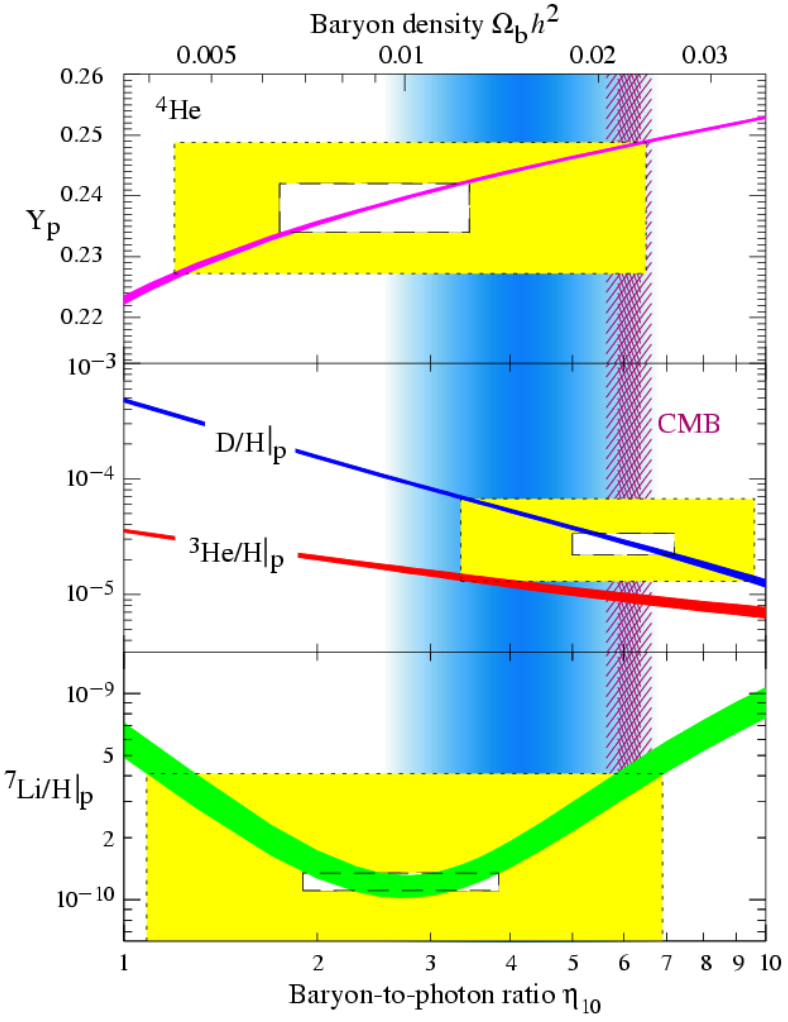
Accelerated expansion of the universe (1998)



Dark energy

$\Omega_\Lambda = 0.734 \pm 0.029$

3.- Light elements abundances



D, ^{3}He, ^{4}He, ^{7}Li

t_{BBN} = 1s - 3 min, T_{BBN}= 1 - 0.1 MeV

Baryon asymmetry

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (4.6 - 5.9) \times 10^{-10}$$

Baryon density

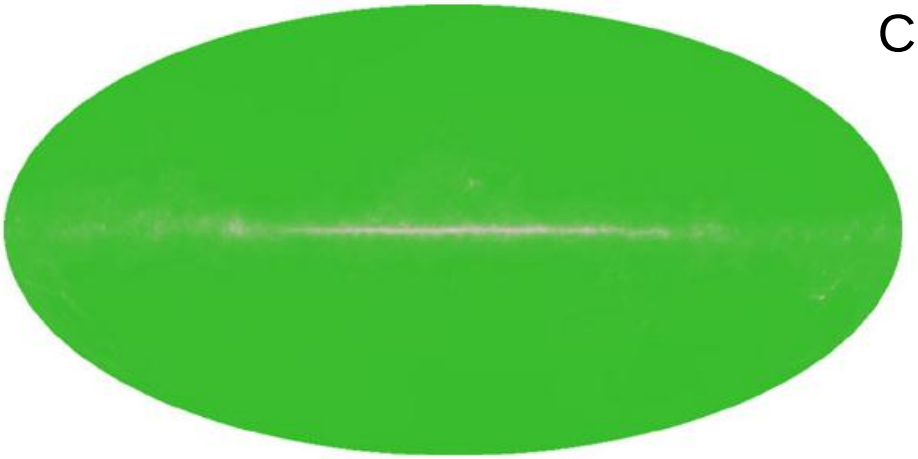
$$\Omega_B = \frac{\rho_B}{\rho_c} = 0.0449 \pm 0.0028$$

$$\Omega_M \overset{0.3}{\gg} \Omega_B \overset{0.04}{\gg} \Omega_{lum} \overset{0.005}{}$$

Non-baryonic dark matter problem

Baryonic dark matter problem

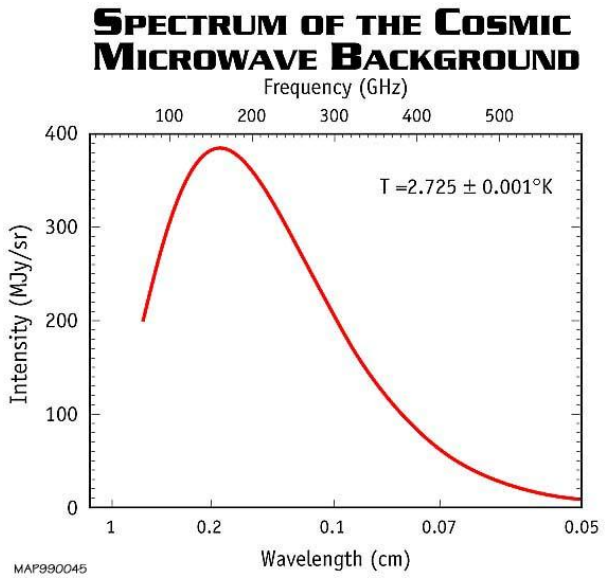
4.- Cosmic microwave background



CMB monopole

1965

Penzias and Wilson

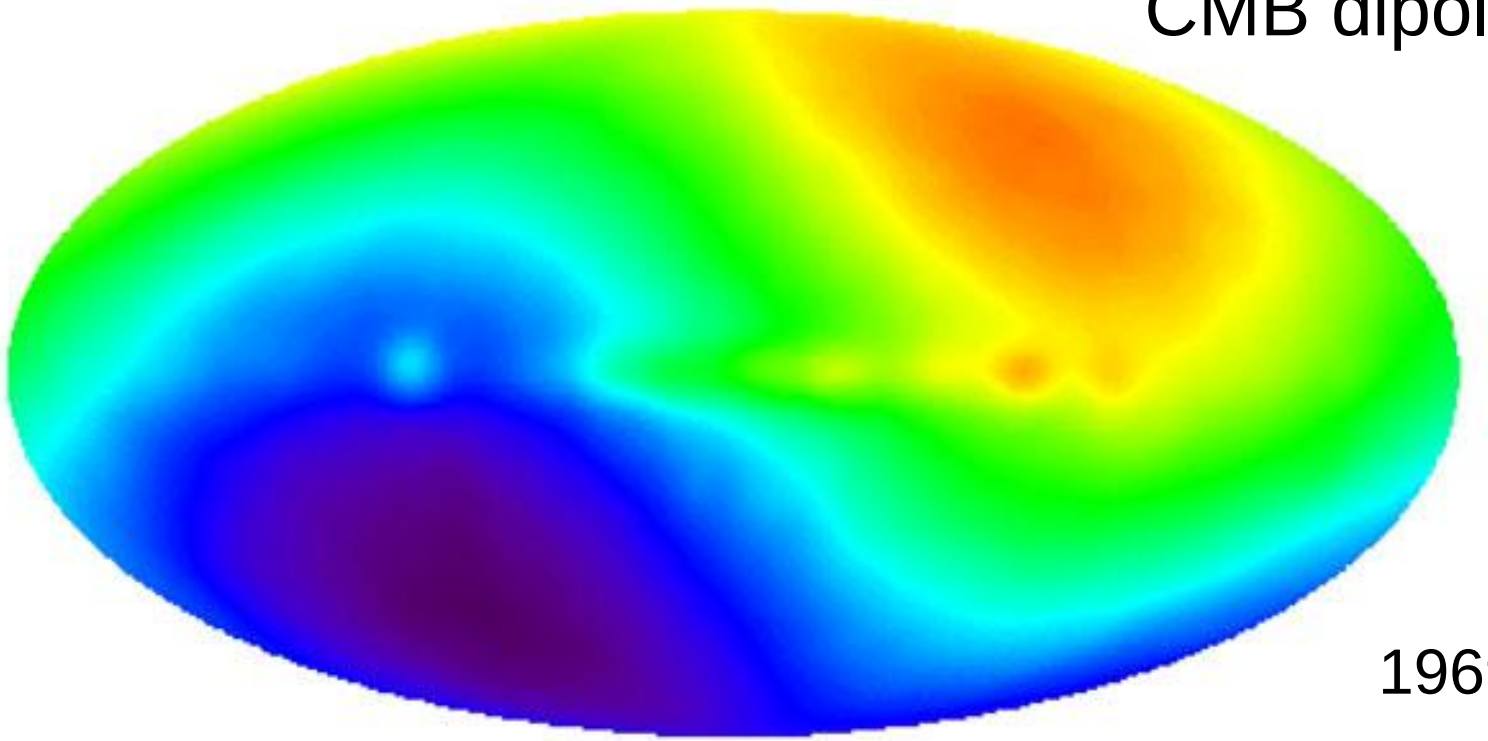


COBE-FIRAS $T_0 = 2.725 \pm 0.001$ K

$$n_\gamma(T_0) = \frac{1}{\pi^2}\int_0^\infty \frac{\omega^2 d\omega}{e^{\omega/T_0}-1} = 410\ \mathrm{cm}^{-3}$$

$$\Omega_\gamma = \frac{\rho_\gamma}{\rho_c} = 2.47 \times 10^{-5} h^{-2}$$

CMB dipole

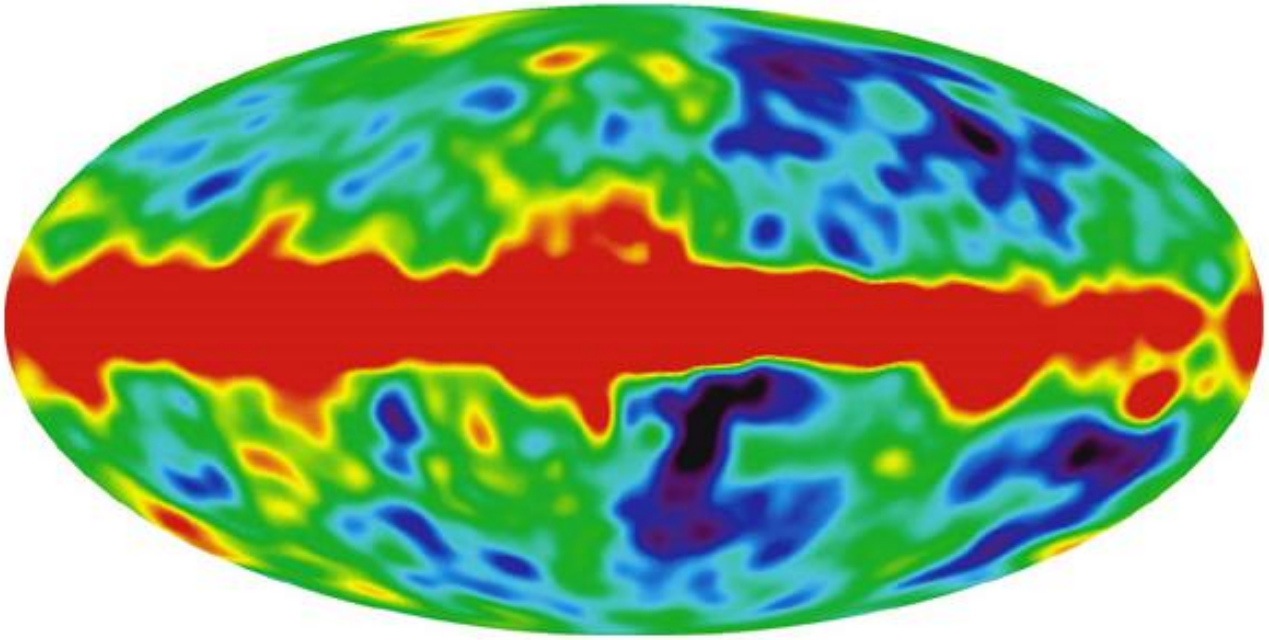


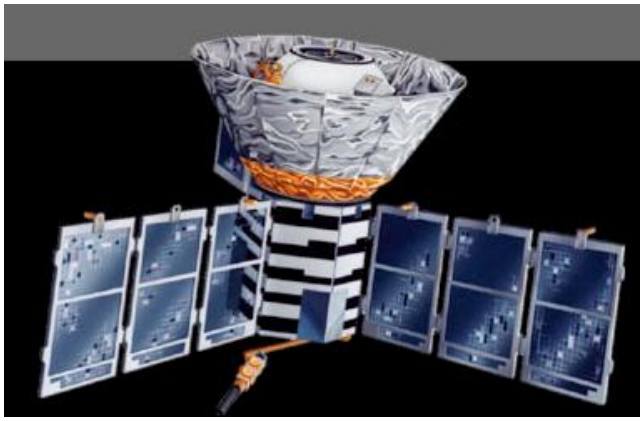
1969

E.K. Conklin
P.S. Henry

$$\frac{\delta T_1}{T_0} = 1.23 \times 10^{-3}$$

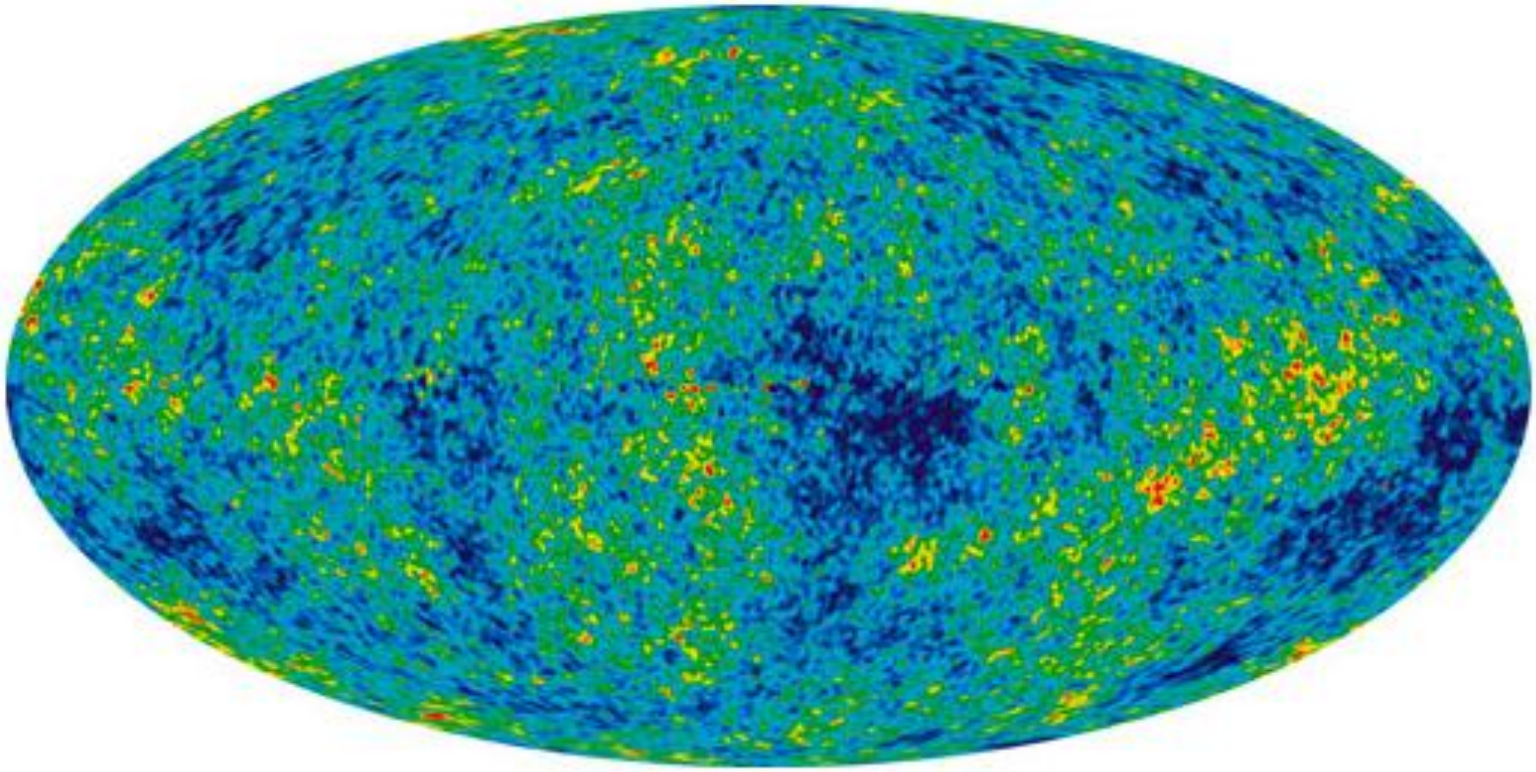
Fluctuations in the cosmic microwave background

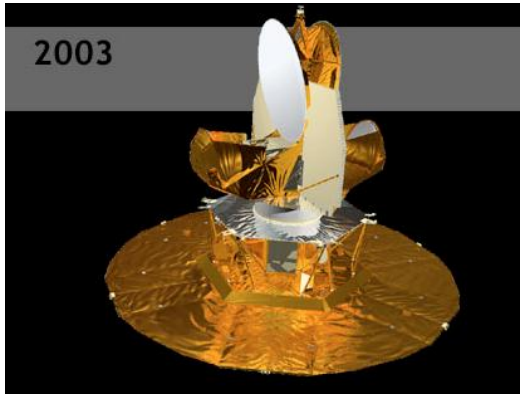




COBE DMR 1992

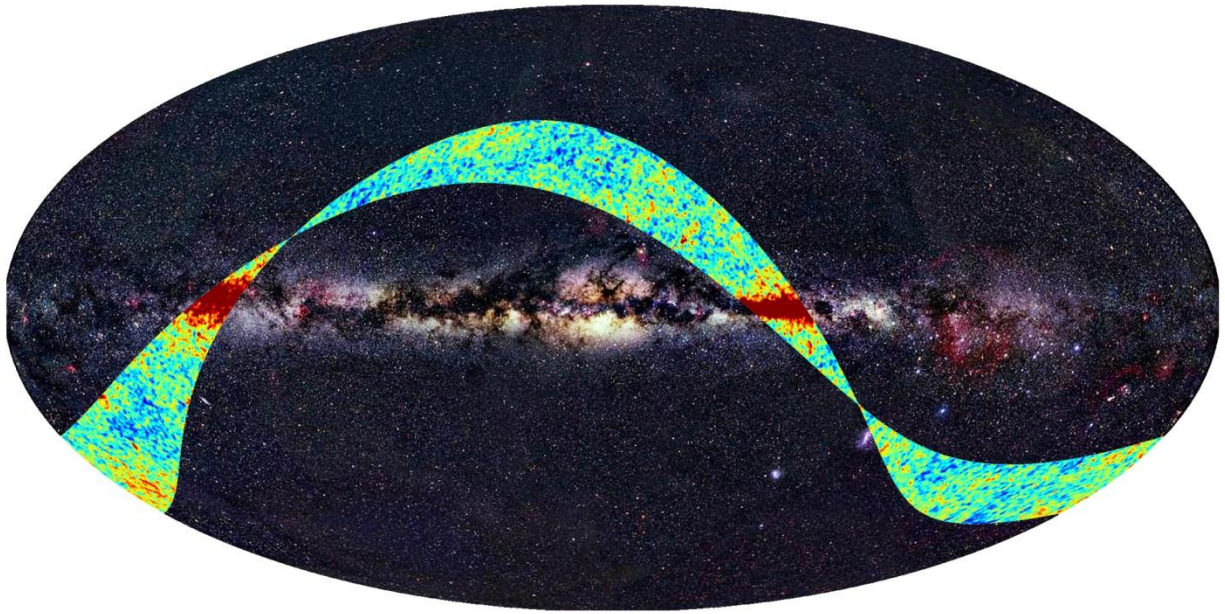
$$\frac{\delta T_2}{T_0} = 1.1 \times 10^{-5}$$

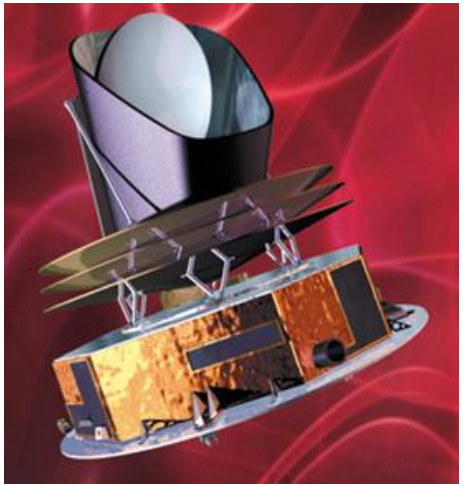




WMAP

2003



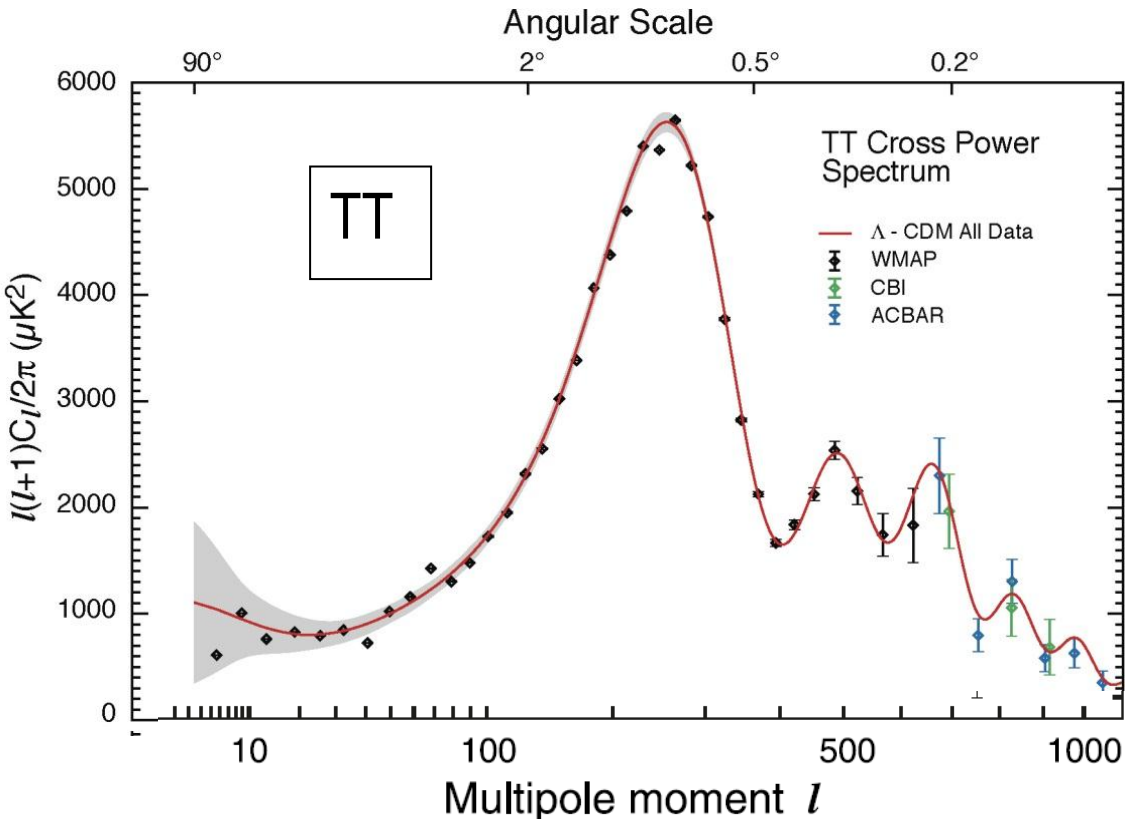


PLANCK

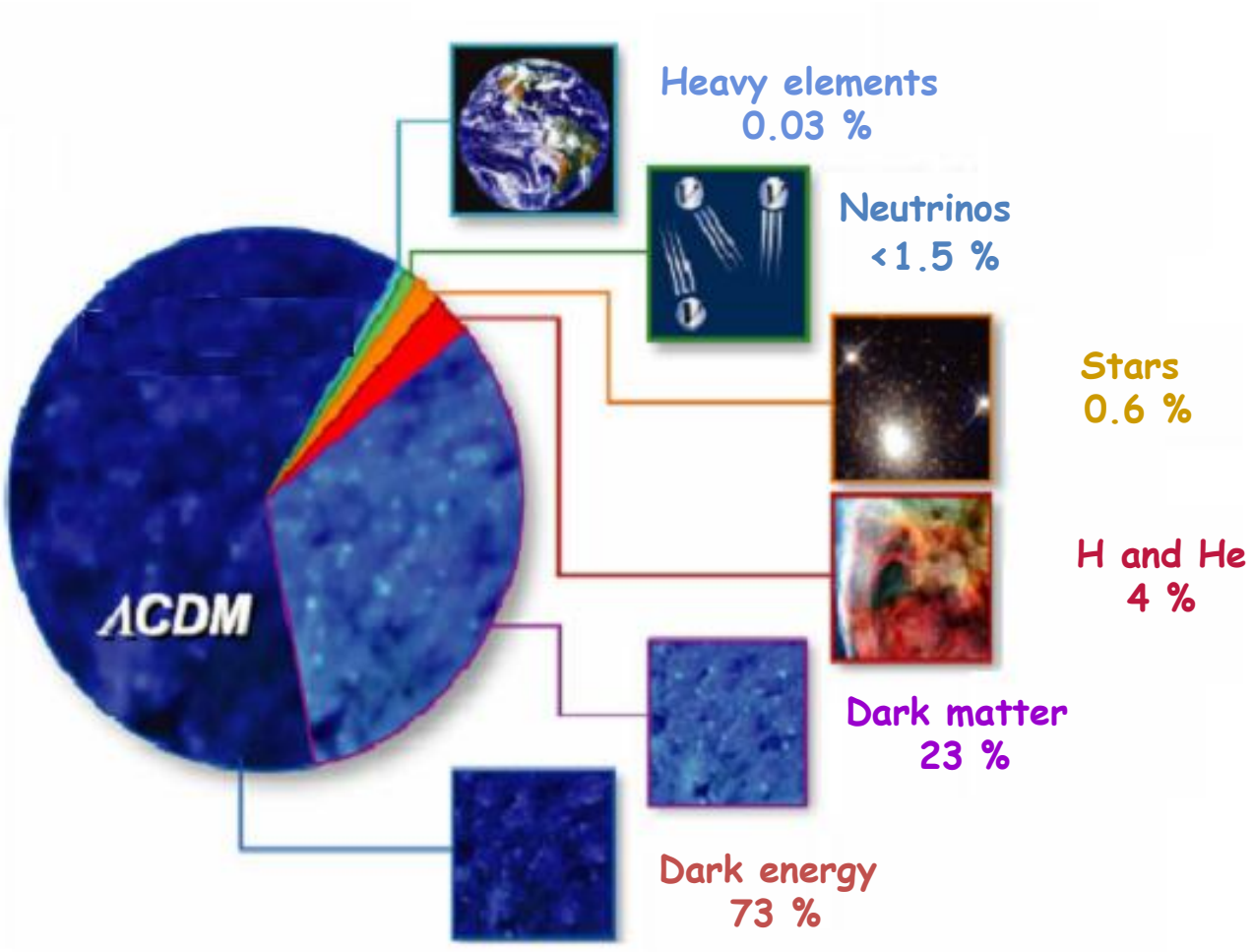
2009

(first data release in1-2 months)

WMAP temperature power spectrum



Standard Cosmology ΛCDM



Expansion of the universe in ΛCDM