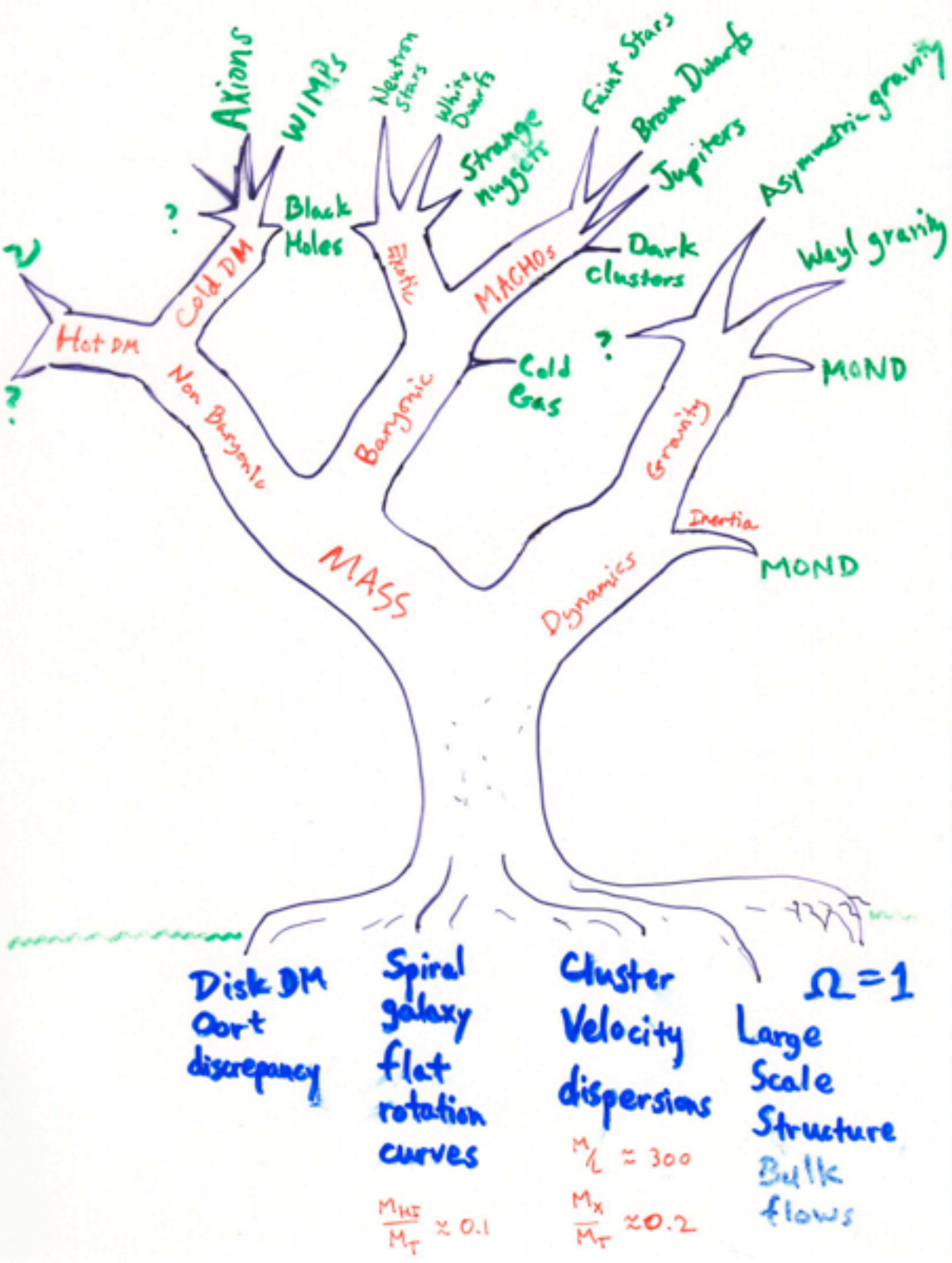
Dark Matter

ASTR 333/433
Fall 2013
MoTu 4:00-5:15pm
Sears 552

Prof. Stacy McGaugh
Sears 573
368-1808
stacy.mcgaugh@case.edu



Case Western Reserve University Est. 1826

Logistics:

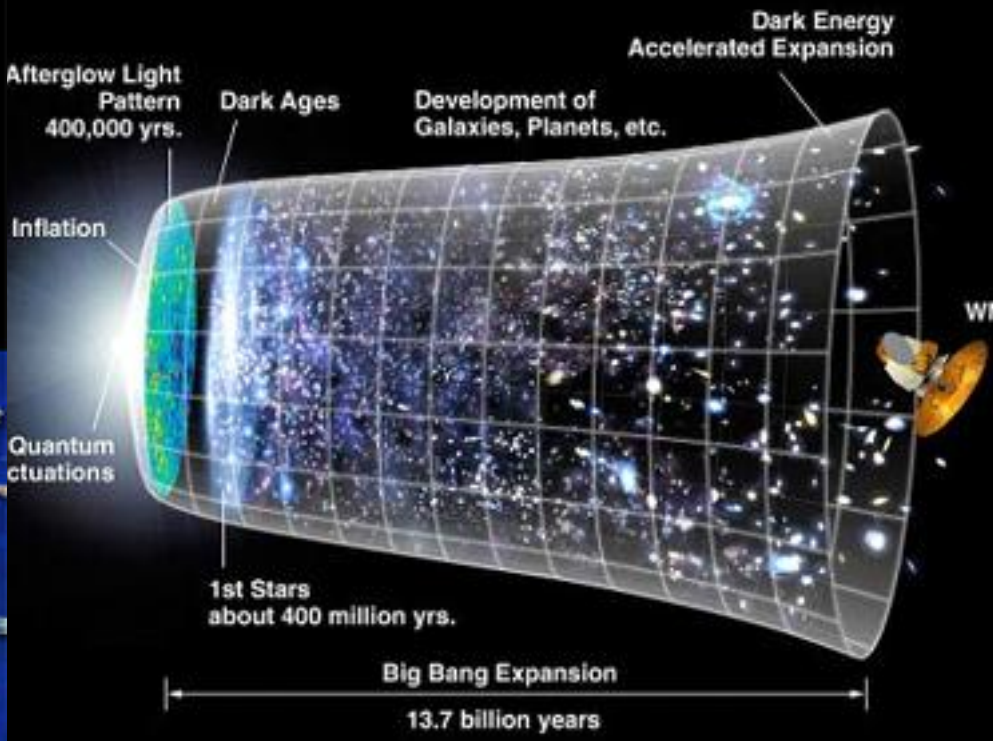
- Homework 3 return
- Abstracts for 433 talks due tomorrow
- 433 talks 12/2 & 12/3
- Homework 4 due 12/3
- Review 12/9
- Final 12/11 (9 AM)

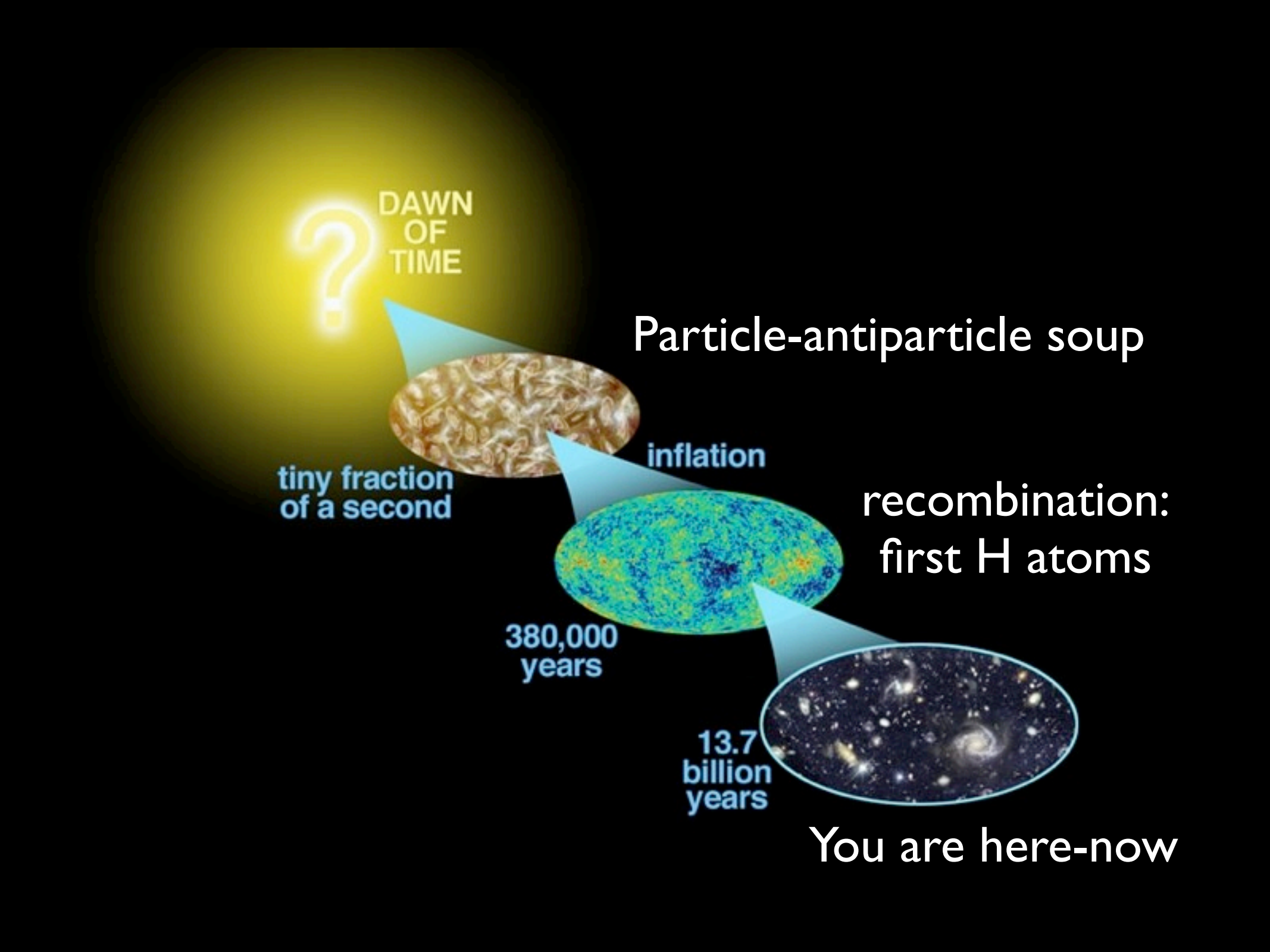
Today: **cosmology**

- measuring the mass density
- BBN
- large scale structure
- CMB

Incan cosmology

WMAP

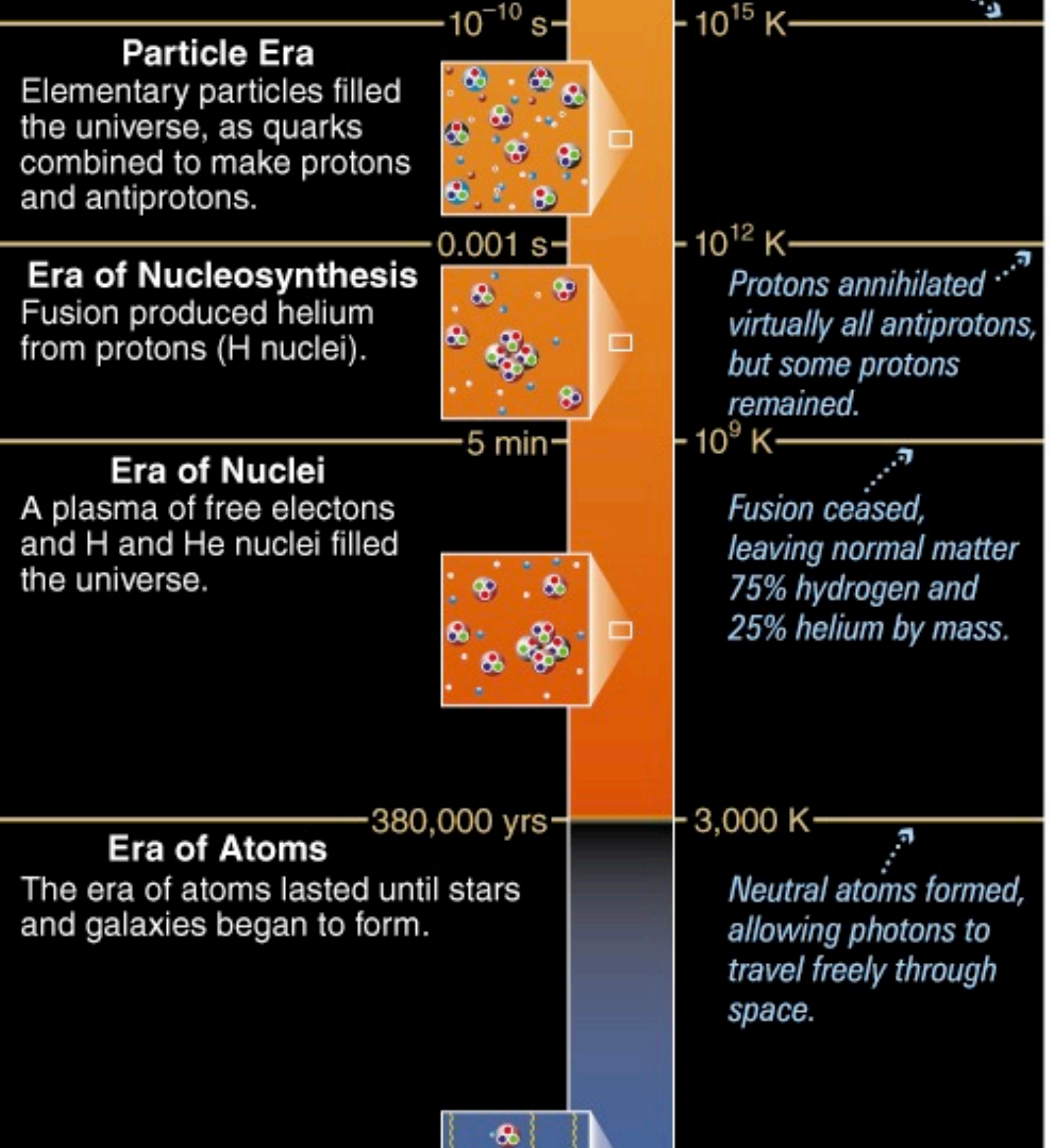




Particle-antiparticle soup

recombination:
first H atoms

You are here-now



particle soup

< millisecond

$T \sim 10^{14}$ K

nucleosynthesis

~ 3 minutes

$T \sim 10^{10}$ K

recombination

~380,000 year

$T \sim 3000$ K

emission of CMB: surface of last scattering

Basic parameters of cosmology

	H_0	Expansion rate	72 km/s/Mpc	
mass density	Ω_m		0.3	
	Ω_b		0.05	baryons
	Ω_{CDM}		0.25	not baryons
	Ω_Λ		0.7	dark energy
	σ_8	power spectrum	0.8	
	n_s	power spectrum	0.96	

Measurements of the gravitating mass density

- Cluster M/L
  - measure M/L of a cluster, combine with measured luminosity density of universe.
- Weak lensing
  - measure shear over large scales
- Peculiar Velocity Field
  - measure deviations from Hubble flow
- Power spectrum of galaxies
- CMB fits

Virgocentric infall

The Virgo cluster is the largest nearby over-density.
Its gravity distorts the Hubble flow.
We fall towards it so it appears to recede less than
it should by an amount that depends on its mass

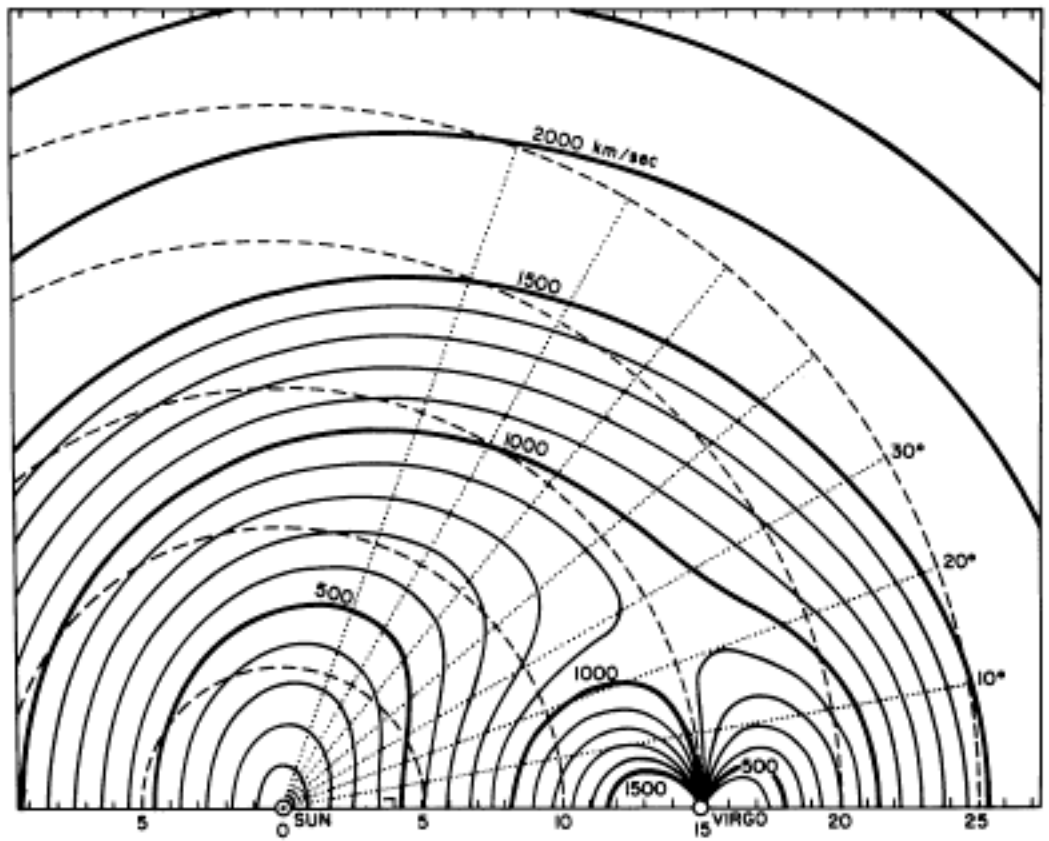


FIG. 1.—On a two-dimensional grid with the Earth and the Virgo cluster on the x axis, redshift contours are plotted for a Hubble flow perturbed by a Virgocentric flow. An infall velocity of 400 km s^{-1} at our position is assumed. A pure Hubble flow would be concentric circles.

Davis et al. (1980) found

$$\Omega_m = 0.4 \pm 0.1$$

with modern data this becomes

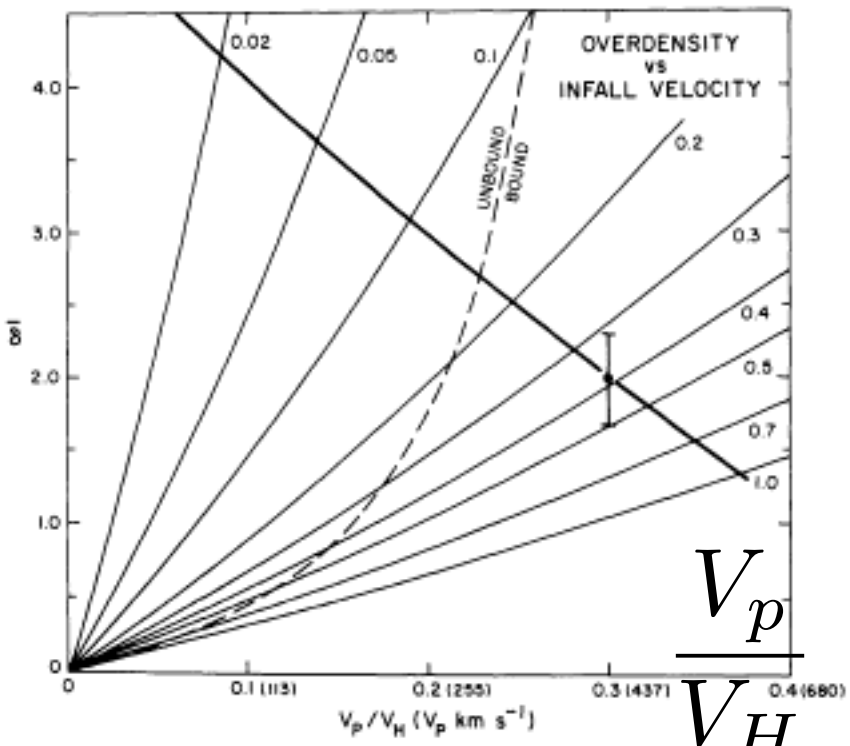
$$\Omega_m = 0.25 \pm 0.05$$

Lines are lines of constant Ω_m

ESTIMATES OF v_p

Velocity	Source
380 ± 75	Smoot and Lubin 1979
480 ± 75	Aaronson *et al.* 1980
350 ± 50	de Vaucouleurs and Bollinger 1979
290 ± 30[a]	Yahil 1980
190 ± 130	Schechter 1968

[a] Calculated with respect to the centroid at the local group as defined by Yahil *et al.* 1977.



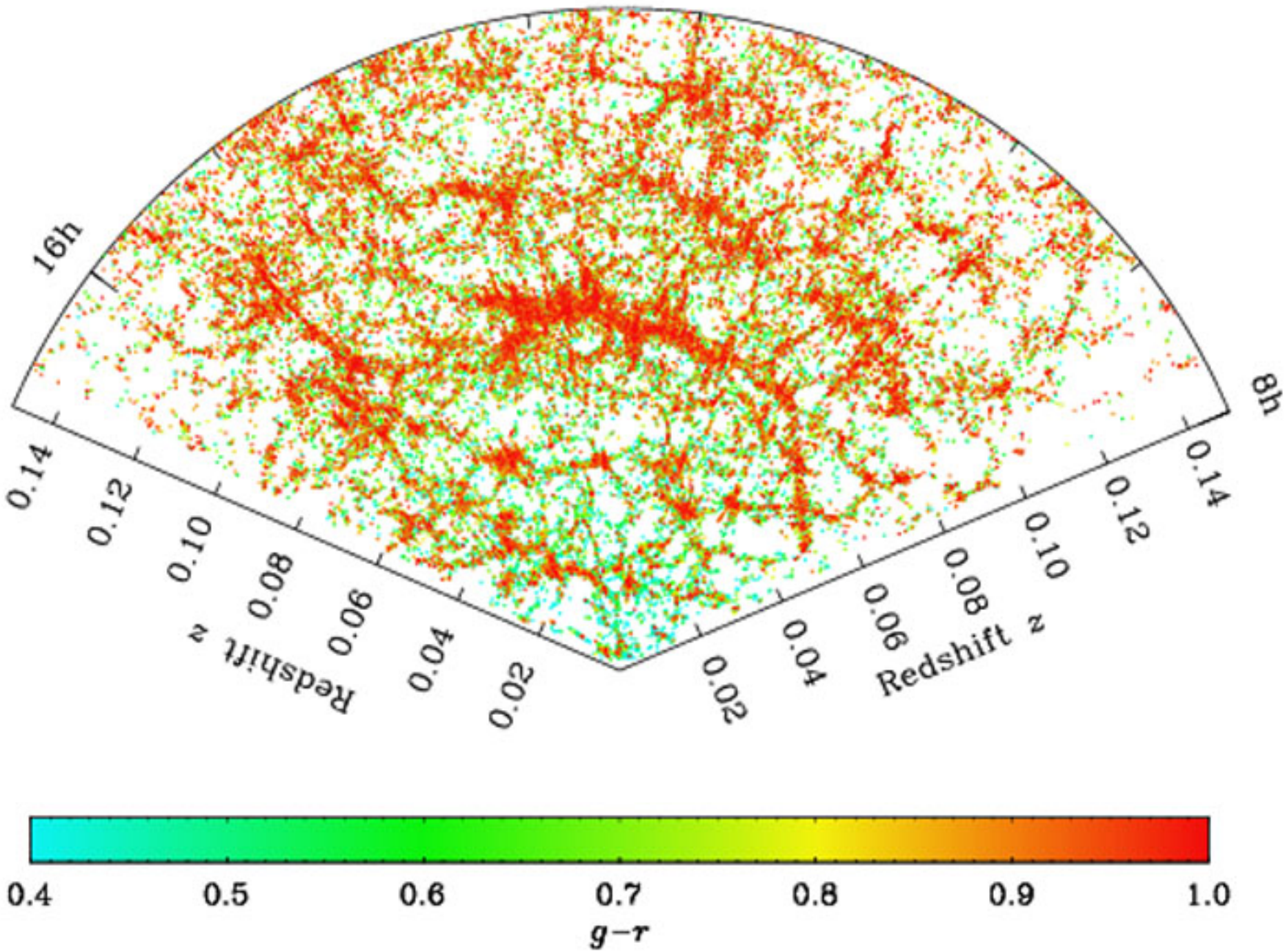
$\frac{\delta\rho}{\rho}$

$\frac{V_p}{V_H}$

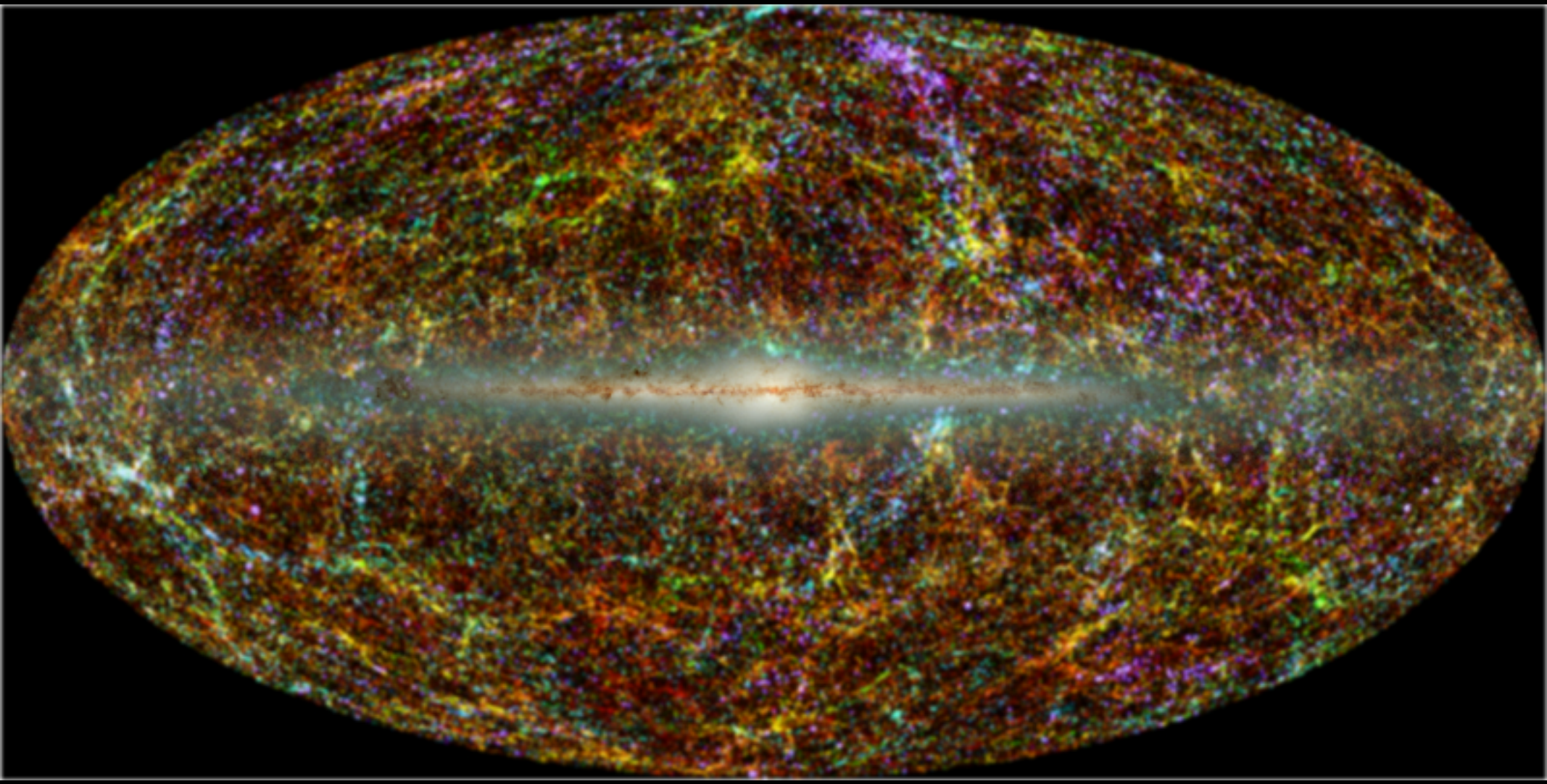
FIG. 1.—The mean overdensity of Virgo vs. v_p/v_H for various values of Ω. The x-axis is also labeled with v_p, using a recessional velocity to Virgo of 1020 km s^{-1}. The measured overdensity is prescribed by the heavy line, and is marked at the favored position as given by the anisotropy of the Hubble flow and microwave background radiation. The error bar is an estimate of the 90% confidence limit of our determination of $\bar{\delta}$. Models to the right of the dotted line are bound to Virgo.

SDSS clustering
(Zehavi et al 2011)

Red galaxies cluster more strongly than blue galaxies



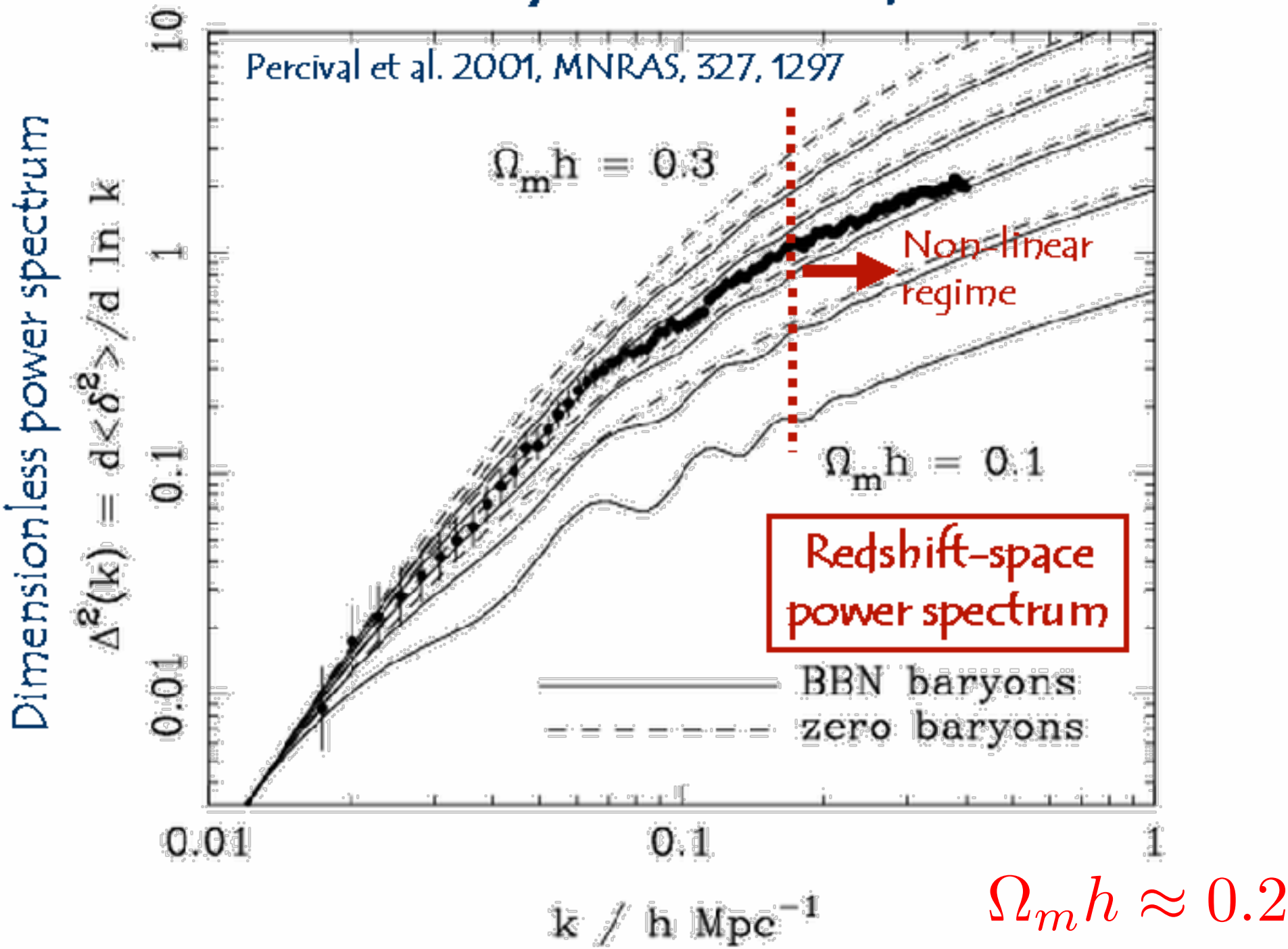
2MASS galaxy distribution on sky in Galactic coordinates



Blue points lower redshift, red points higher redshift

Jarrett et al.

The Galaxy Power Spectrum

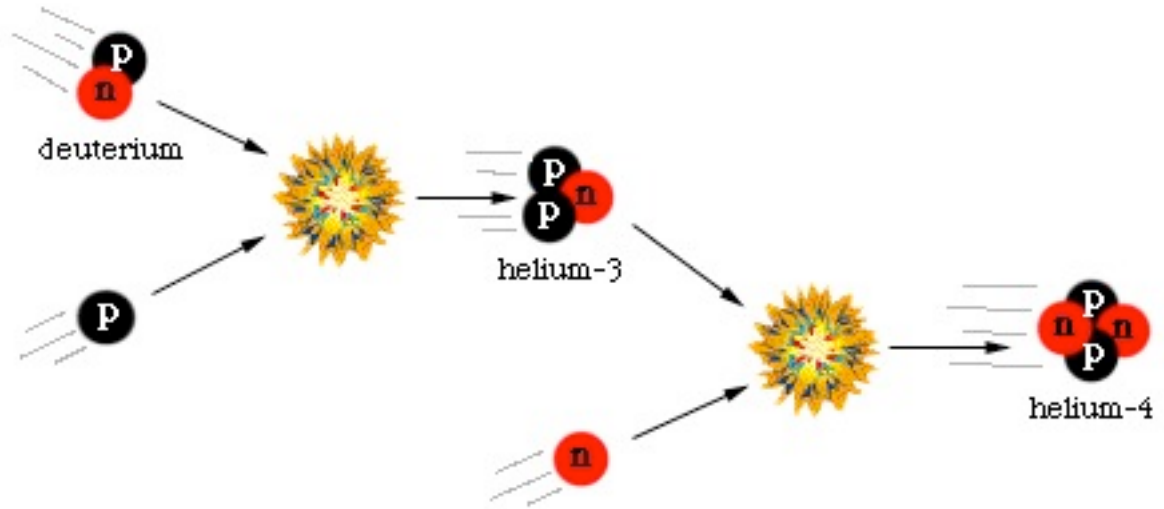


$\Omega_m h \approx 0.2$

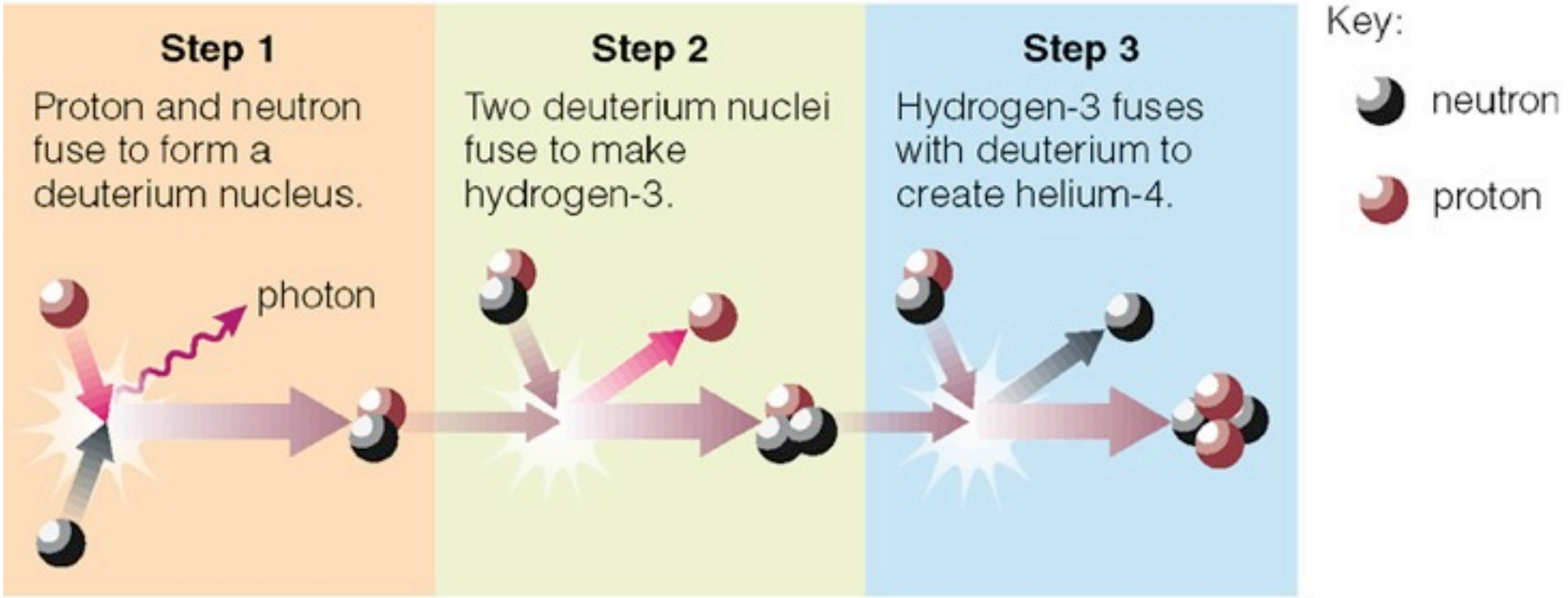
Primordial Nucleosynthesis (BBN):

Gamow

When the universe is just a few minutes old, the Temperature and Density are just right for it to be one Big Nuclear Furnace:

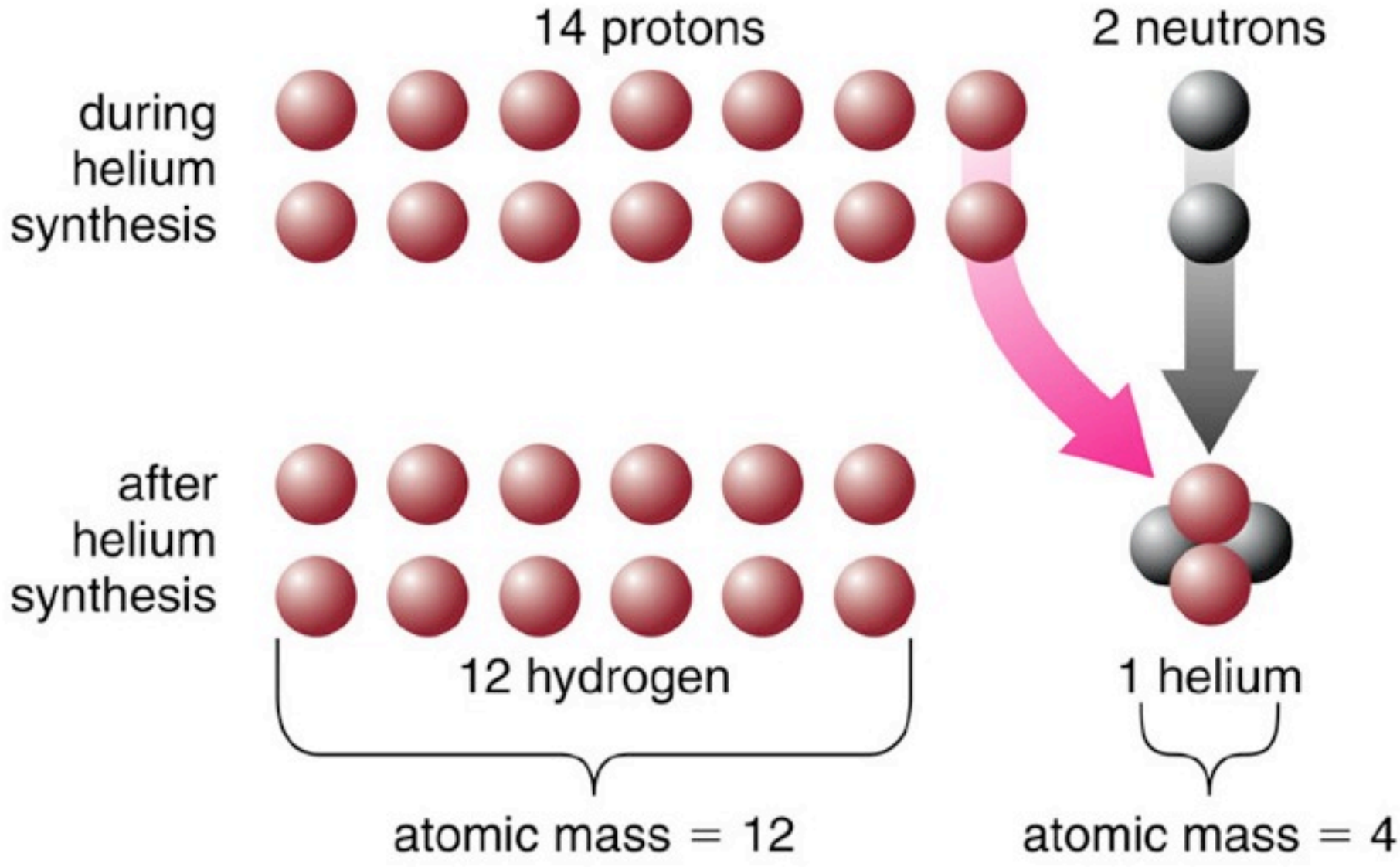


The light elements
Hydrogen, Helium, and Lithium
are made at this time.



Protons and neutrons combined to make long-lasting helium nuclei when the universe was ~3 minutes old.

The proton-proton chain was enhanced by the presence of free neutrons, making the creation of deuterium easier.



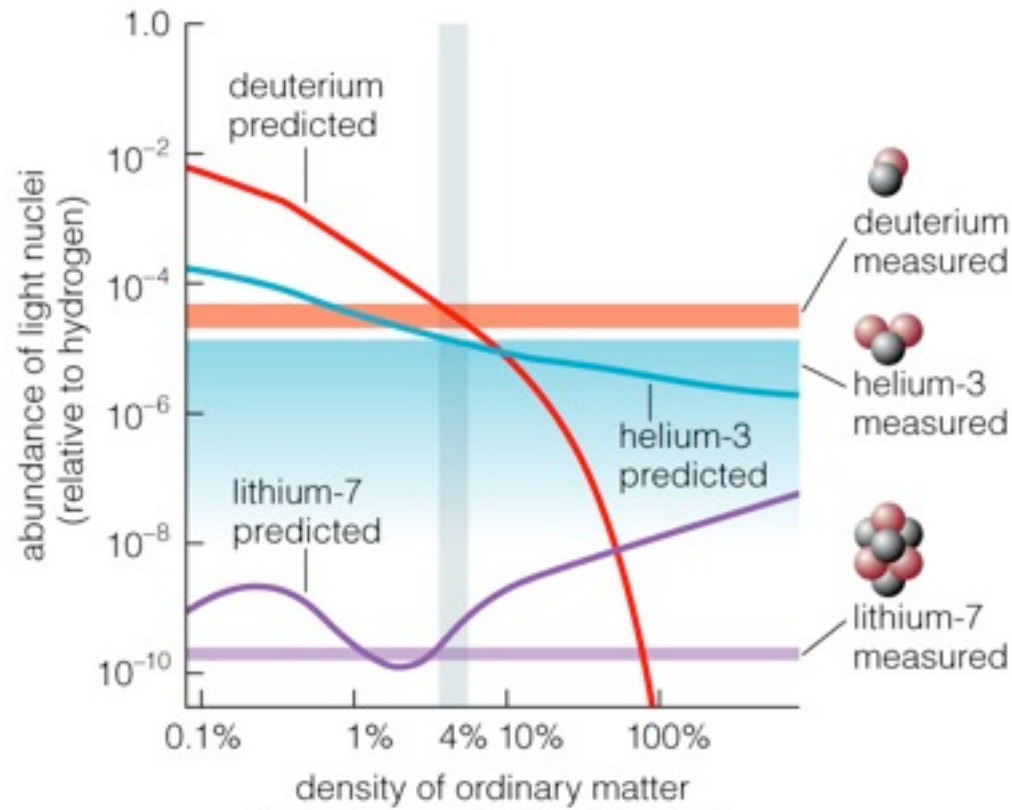
Big Bang theory prediction: 75% H, 25% He (by mass)

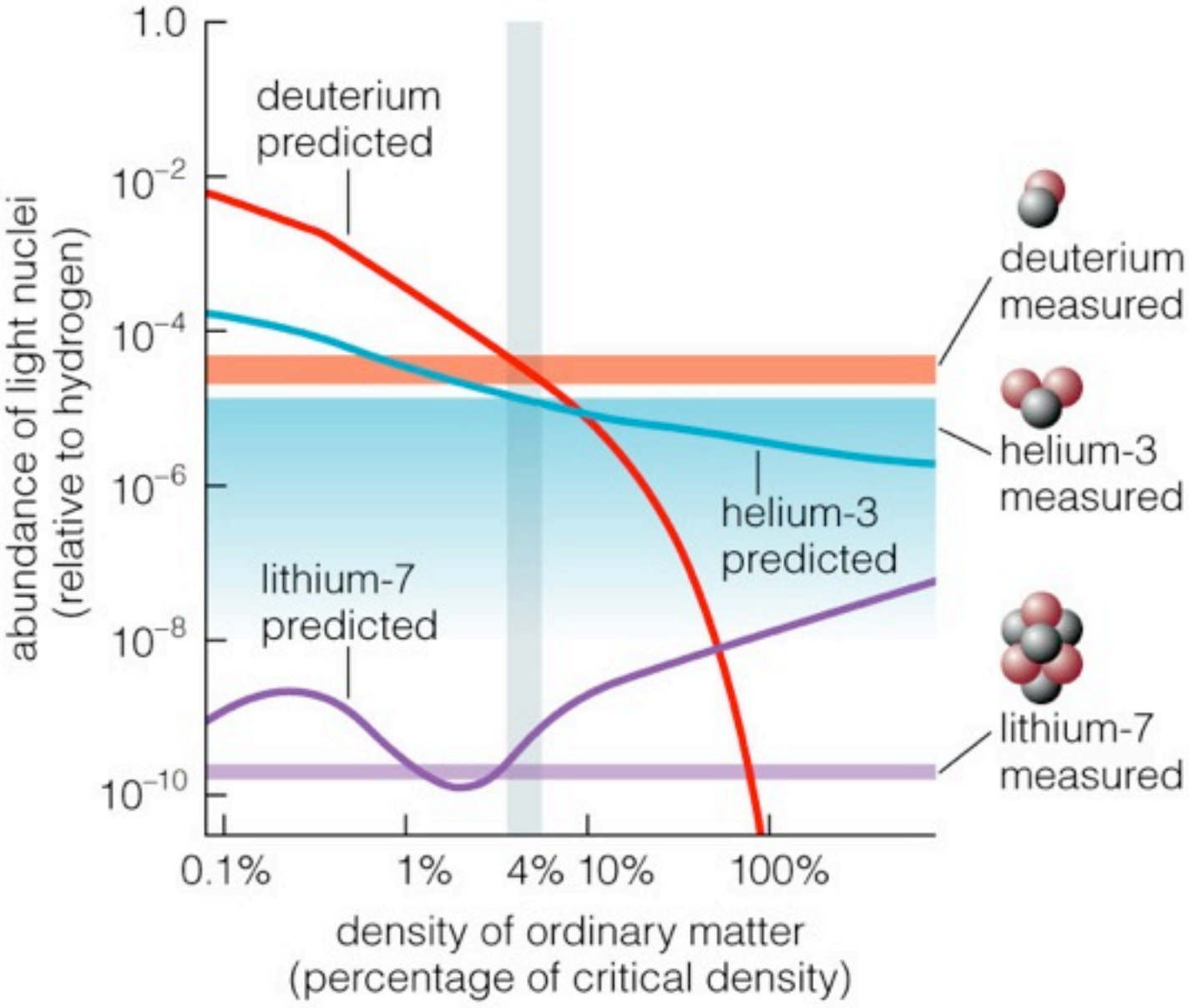
Matches observations of nearly primordial gases

BBN products:

- 3/4 Hydrogen
- 1/4 Helium
- Traces of
  - deuterium
  - tritium
  - helium 3
  - lithium
  - beryllium

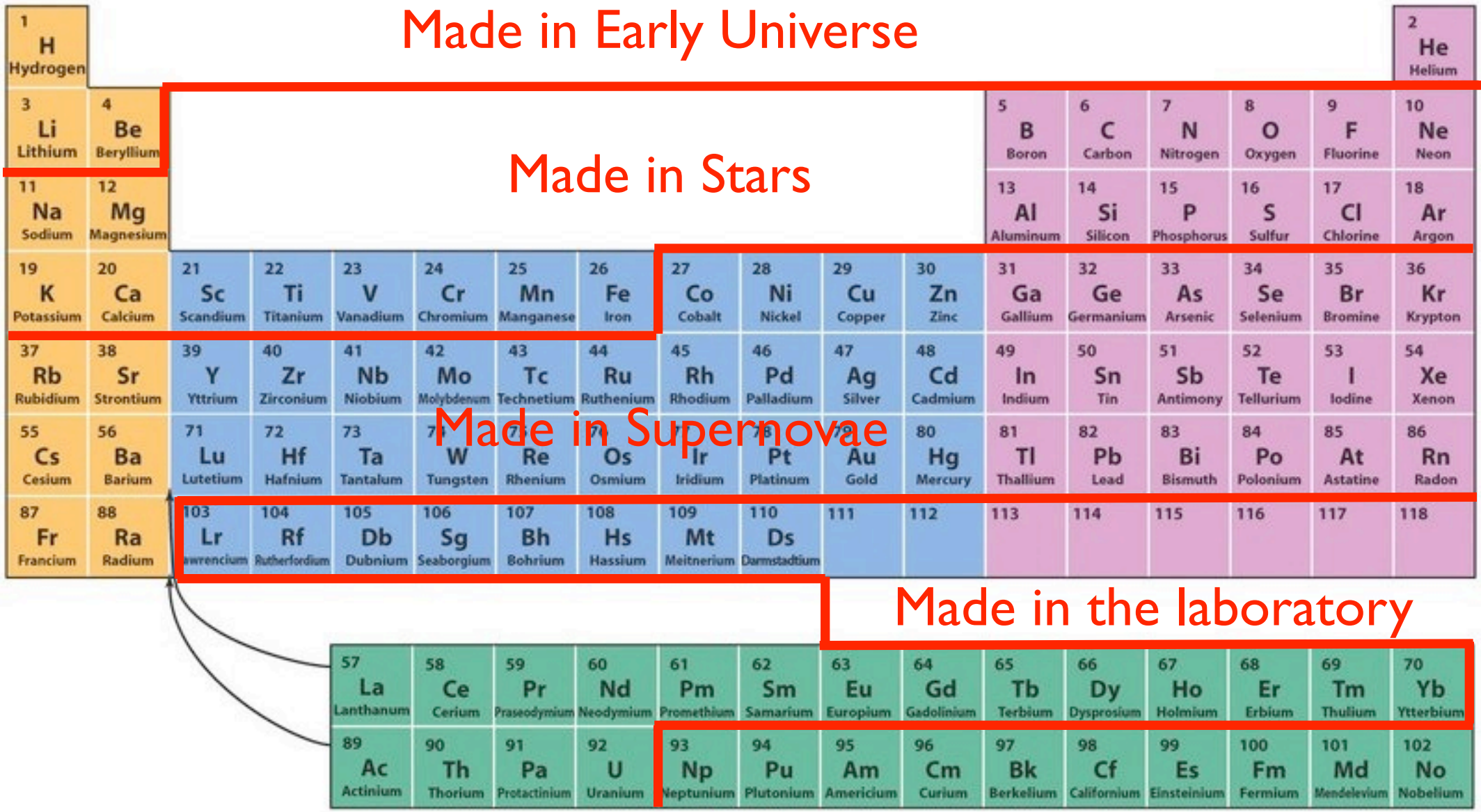
Abundances depend on the density of matter. The higher the density parameter (Ω), the more helium.



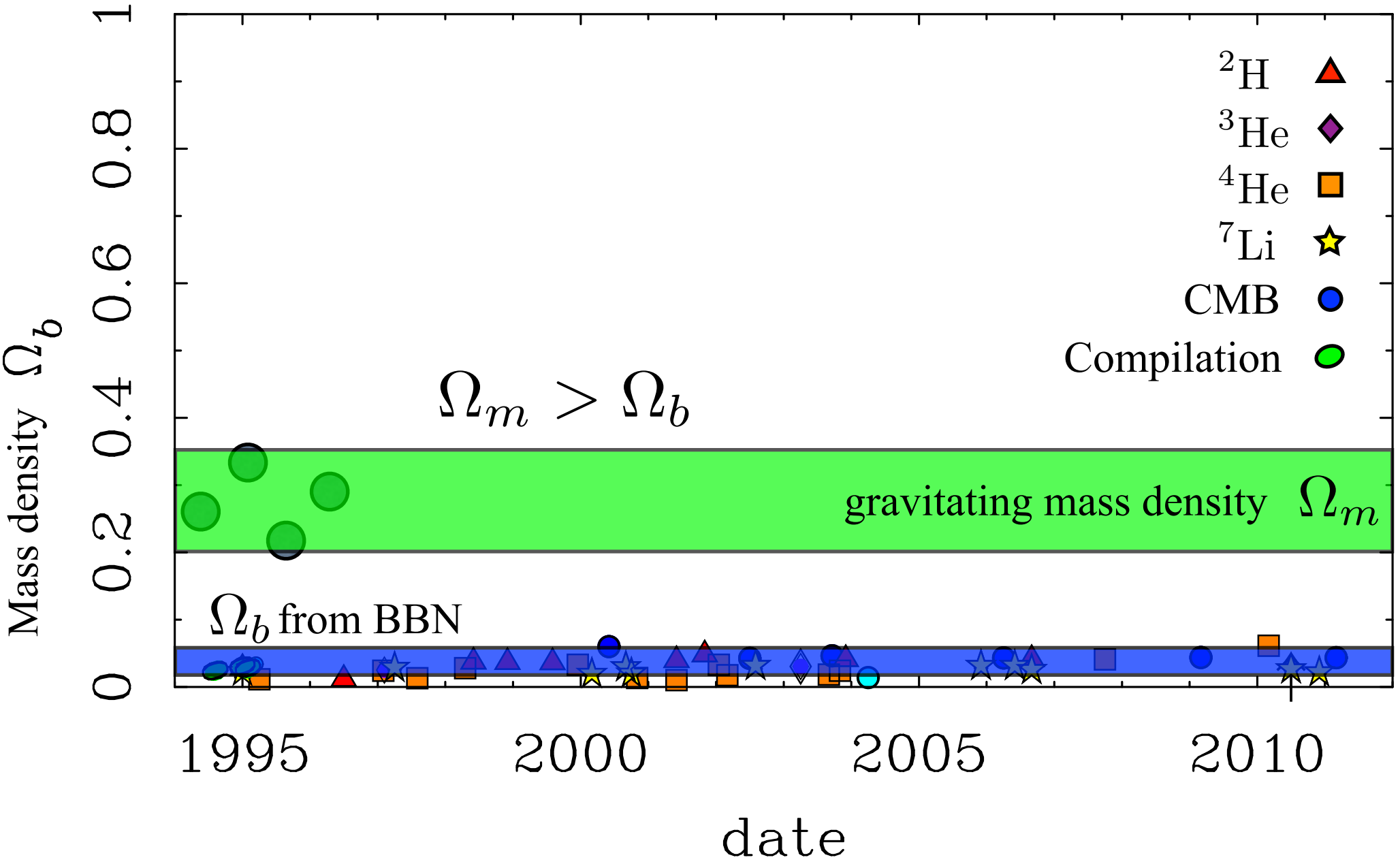


Ω

BBN gets the abundances of deuterium, helium, and lithium right if the mass density is about 4% of the critical density.


Made in Early Universe
Made in Stars
Made in Supernovae
Made in the laboratory
1 H Hydrogen
2 He Helium
3 Li Lithium
4 Be Beryllium
5 B Boron
6 C Carbon
7 N Nitrogen
8 O Oxygen
9 F Fluorine
10 Ne Neon
11 Na Sodium
12 Mg Magnesium
13 Al Aluminum
14 Si Silicon
15 P Phosphorus
16 S Sulfur
17 Cl Chlorine
18 Ar Argon
19 K Potassium
20 Ca Calcium
21 Sc Scandium
22 Ti Titanium
23 V Vanadium
24 Cr Chromium
25 Mn Manganese
26 Fe Iron
27 Co Cobalt
28 Ni Nickel
29 Cu Copper
30 Zn Zinc
31 Ga Gallium
32 Ge Germanium
33 As Arsenic
34 Se Selenium
35 Br Bromine
36 Kr Krypton
37 Rb Rubidium
38 Sr Strontium
39 Y Yttrium
40 Zr Zirconium
41 Nb Niobium
42 Mo Molybdenum
43 Tc Technetium
44 Ru Ruthenium
45 Rh Rhodium
46 Pd Palladium
47 Ag Silver
48 Cd Cadmium
49 In Indium
50 Sn Tin
51 Sb Antimony
52 Te Tellurium
53 I Iodine
54 Xe Xenon
55 Cs Cesium
56 Ba Barium
71 Lu Lutetium
72 Hf Hafnium
73 Ta Tantalum
W Tungsten
Re Rhenium
Os Osmium
Ir Iridium
Pt Platinum
Au Gold
80 Hg Mercury
81 Tl Thallium
82 Pb Lead
83 Bi Bismuth
84 Po Polonium
85 At Astatine
86 Rn Radon
87 Fr Francium
88 Ra Radium
103 Lr
104 Rf Rutherfordium
105 Db Dubnium
106 Sg Seaborgium
107 Bh Bohrium
108 Hs Hassium
109 Mt Meitnerium
110 Ds Darmstadtium
111
112
113
114
115
116
117
118
57 La Lanthanum
58 Ce Cerium
59 Pr Praseodymium
60 Nd Neodymium
61 Pm Promethium
62 Sm Samarium
63 Eu Europium
64 Gd Gadolinium
65 Tb Terbium
66 Dy Dysprosium
67 Ho Holmium
68 Er Erbium
69 Tm Thulium
70 Yb Ytterbium
89 Ac Actinium
90 Th Thorium
91 Pa Protactinium
92 U Uranium
93 Np Neptunium
94 Pu Plutonium
95 Am Americium
96 Cm Curium
97 Bk Berkelium
98 Cf Californium
99 Es Einsteinium
100 Fm Fermium
101 Md Mendelevium
102 No Nobelium

There's more mass than BBN allows in baryons



$\Omega_b \approx 0.04$ BBN baryon density

$\Omega_m \approx 0.30$ gravitating mass density

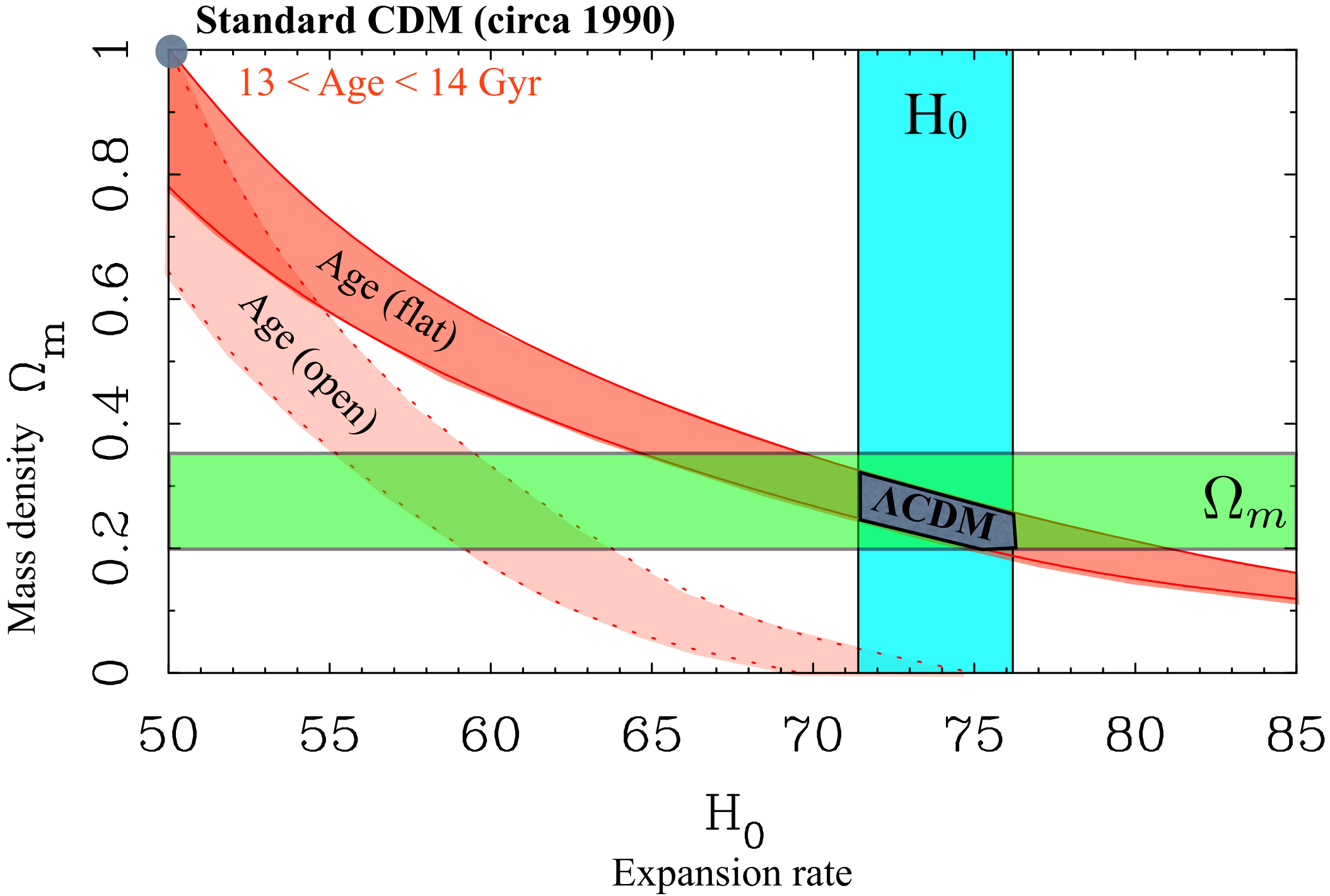
There is a hierarchy of missing mass problems

$M_b < f_b M_{200}$ halo missing baryon problem
(not enough baryons in each DM halo)

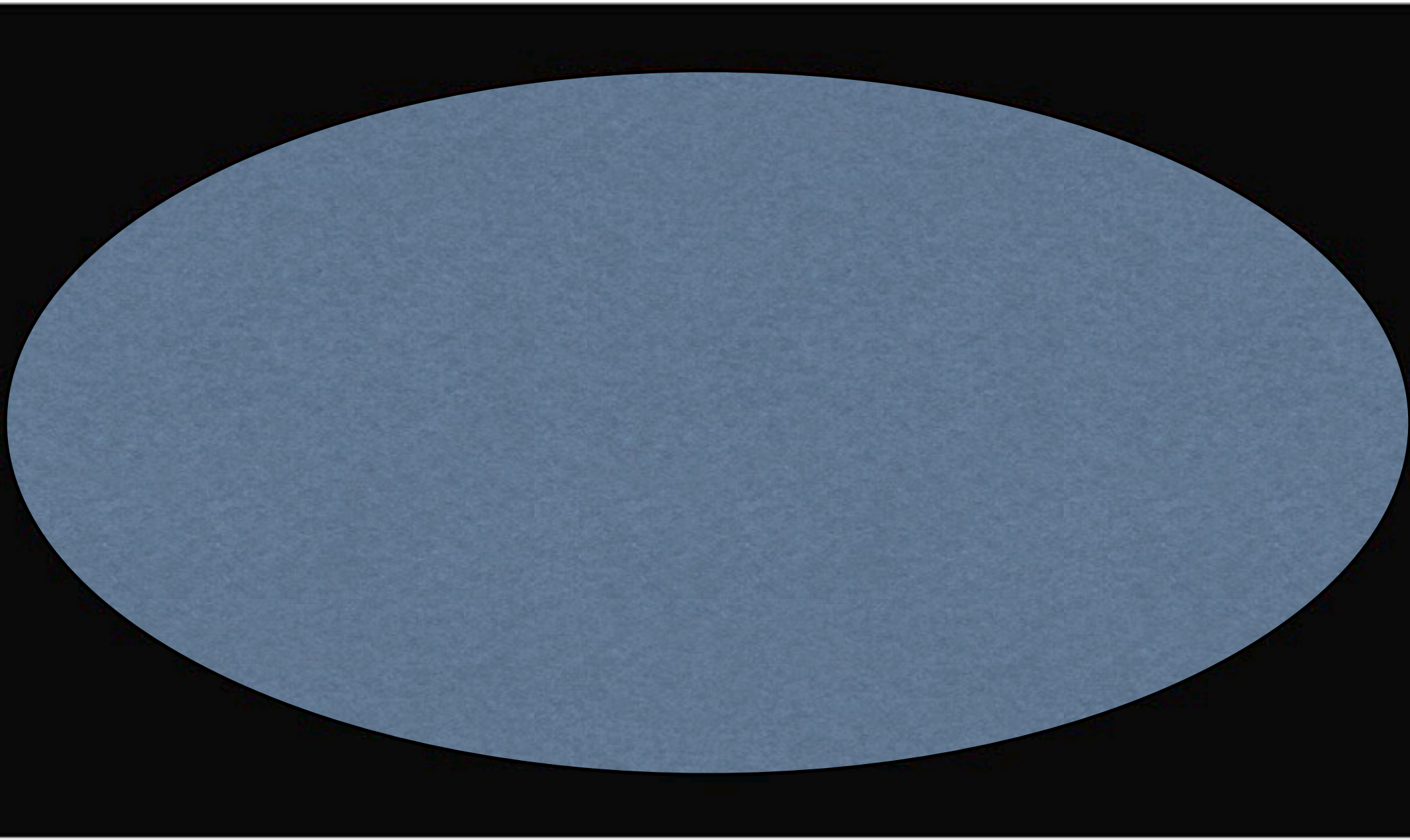
$\sum \Omega_{b,obs} < \Omega_{b,BBN}$ cosmic missing baryon problem
(not enough baryons for BBN)

$\Omega_{b,BBN} < \Omega_m$ cosmic missing mass problem
(not enough BBN baryons to explain
all the mass in the Universe)

Constraints predating SN, CMB (circa 1995)



CMB: Baby picture of the universe (380,000 years old)



Universe very uniform at z = 1000 (300,000 years old)

CMB temperature fluctuations directly related to density fluctuations

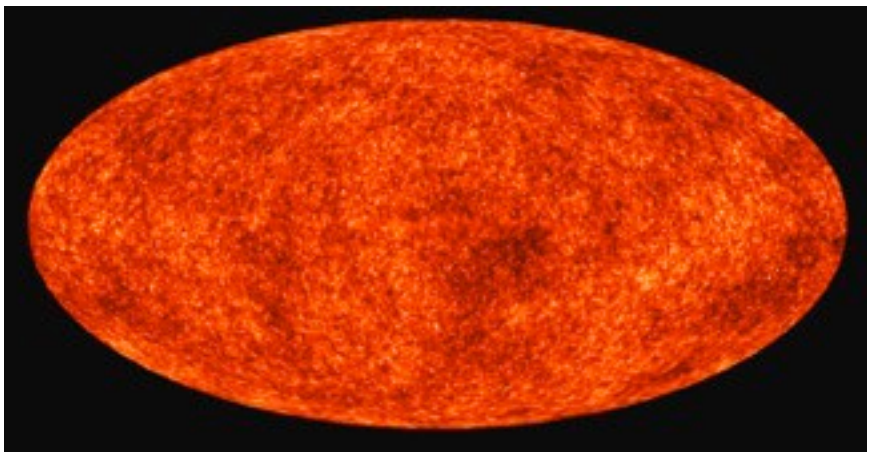
$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta \rho}{\rho}$$

Basic problem:
not enough time for structure to grow.

Gravity will grow the observed large scale structure, but it works slowly. Can't get here-now from the there-then of tiny CMB fluctuations.

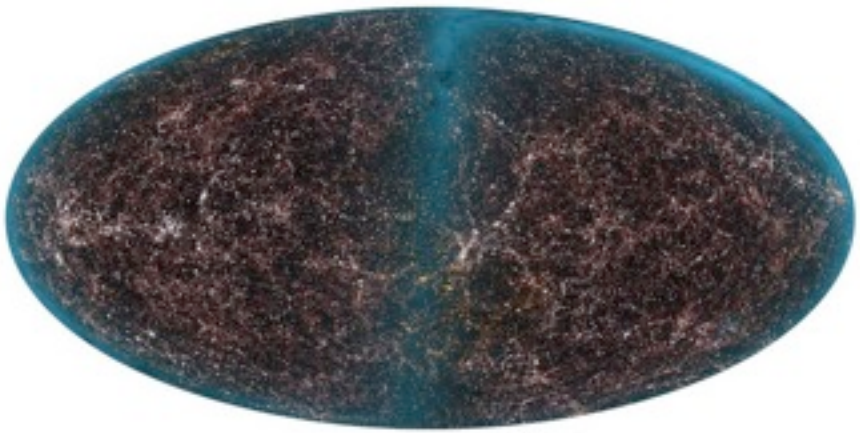
There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

$t = 3.8 \times 10^5$ yr



very smooth: $\delta\rho/\rho \sim 10^{-5}$

$t = 1.4 \times 10^{10}$ yr



very lumpy: $\delta\rho/\rho \sim 1$

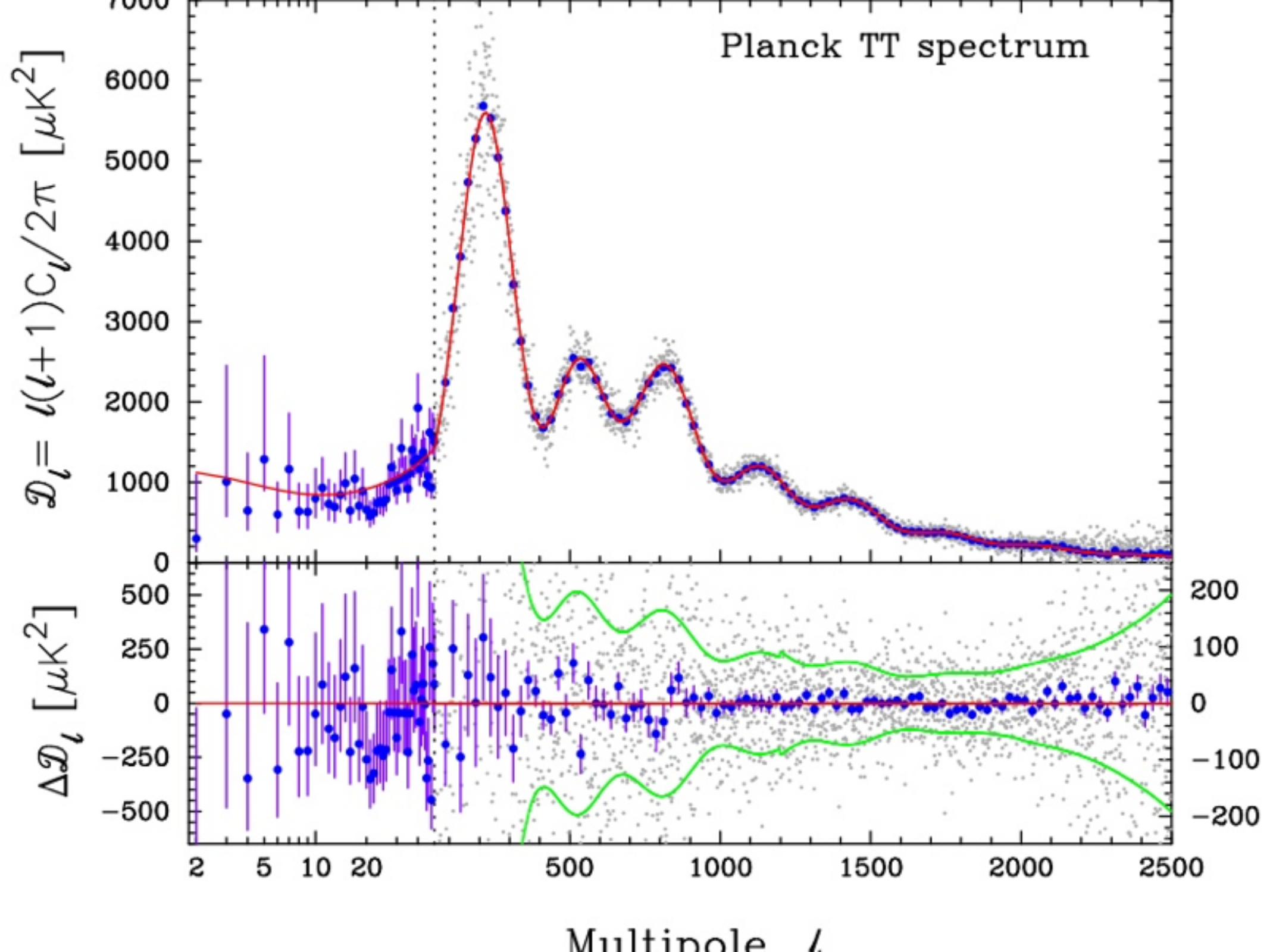
$$\delta\rho/\rho \propto t^{2/3}$$

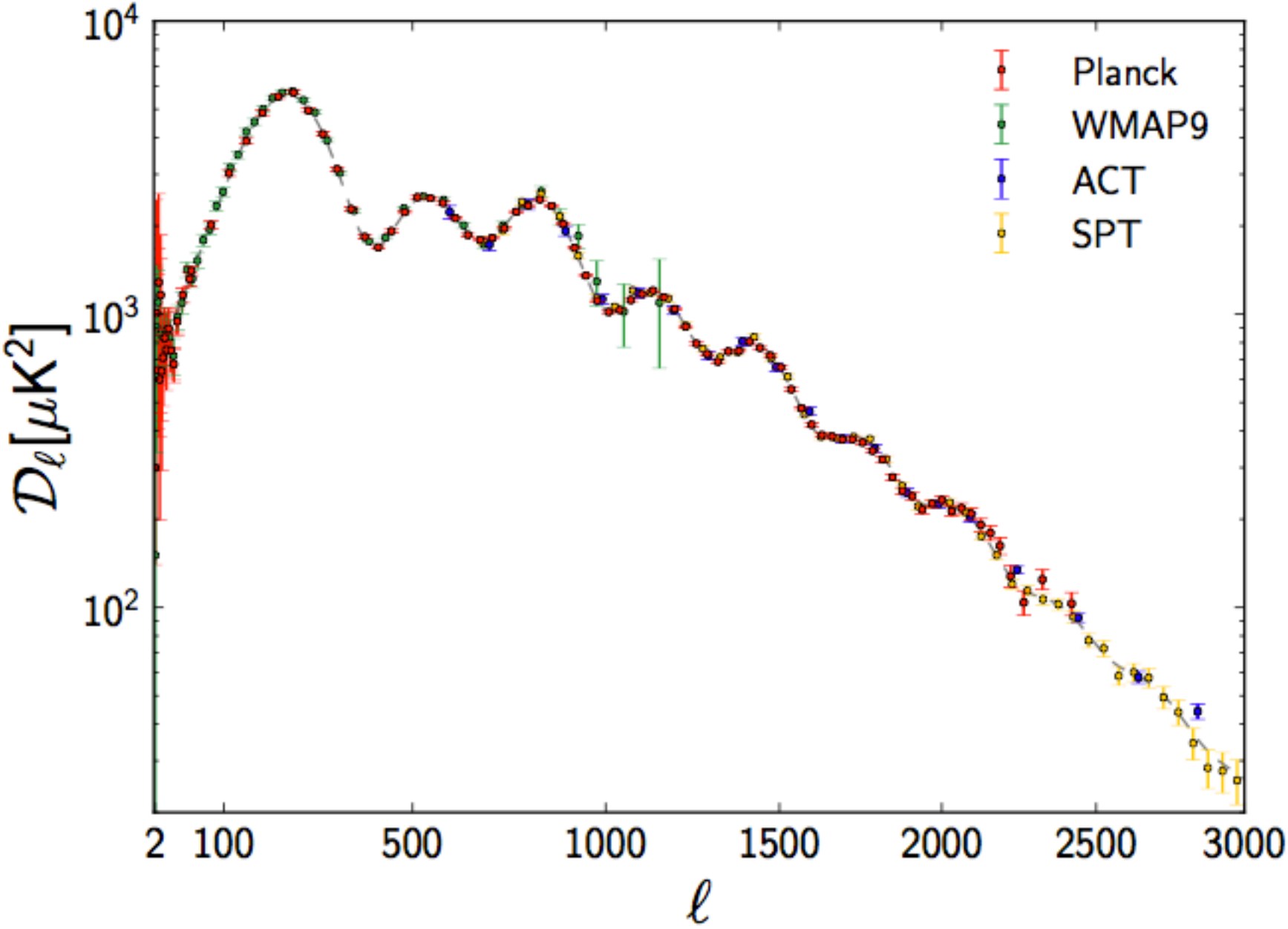
CMB temperature fluctuations directly related to density fluctuations

$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta \rho}{\rho}$$

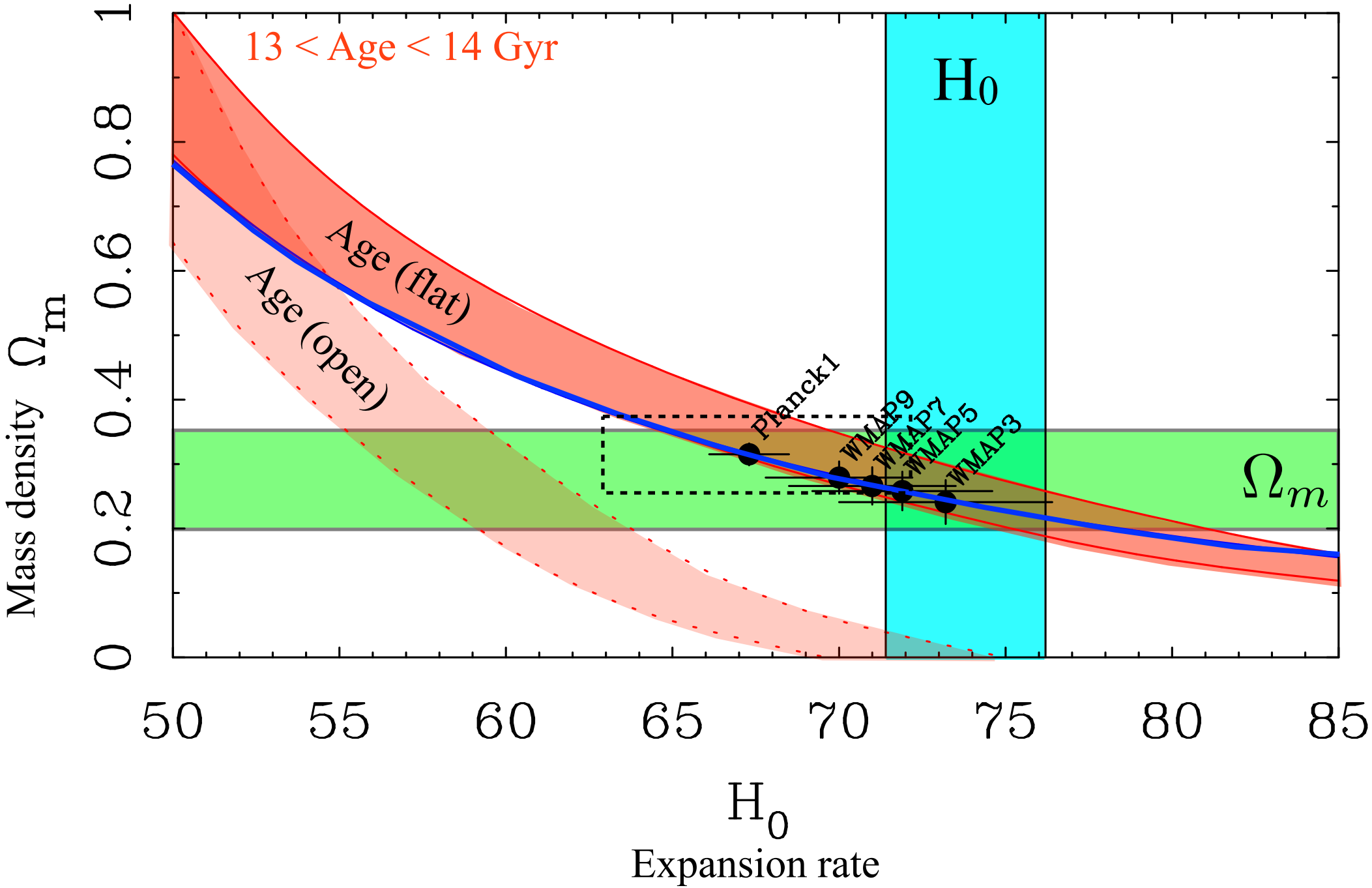
Fits to the acoustic power spectrum of the CMB strongly constrain cosmic parameters

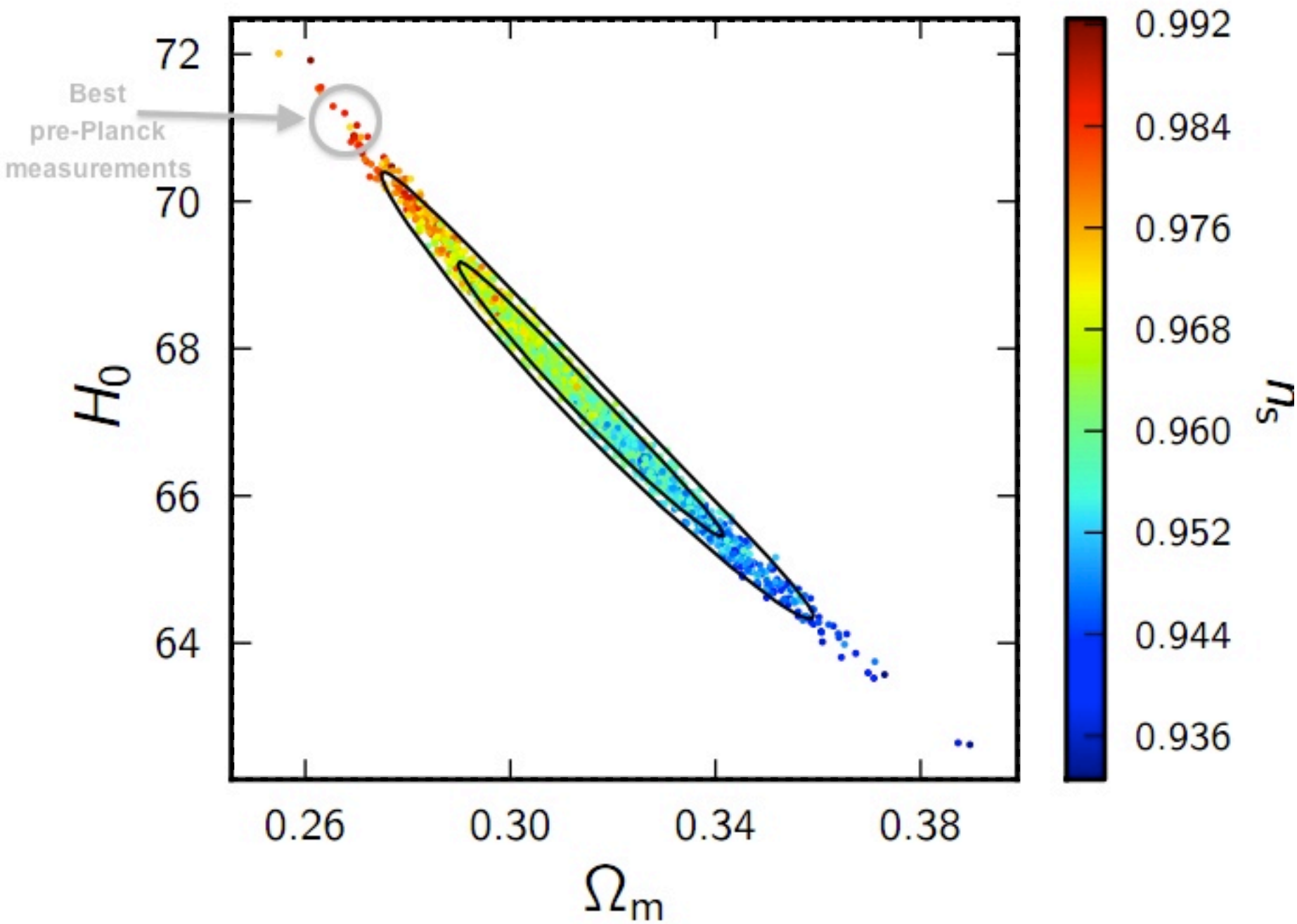
http://space.mit.edu/home/tegmark/movies.html


Planck TT spectrum
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
Multipole ℓ
0
1000
2000
3000
4000
5000
6000
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500


10^4
10^3
10^2
$\mathcal{D}_\ell[\mu K^2]$
Planck
WMAP9
ACT
SPT
2
100
500
1000
1500
2000
2500
3000
ℓ

Planck constraint: $\Omega_m h^3 = 0.0959 \pm 0.0006$




Best
pre-Planck
measurements
72
70
68
66
64
H_0
0.26
0.30
0.34
0.38
Ω_m
0.992
0.984
0.976
0.968
0.960
0.952
0.944
0.936
n_s

"Cosmologists are often wrong, but never in doubt"

- Lev Landau

Things we know for sure in cosmology:

quantity	c. 1990	WMAP5 2008	Planck 2013
Ω_m	1.00	0.258±0.027	0.315±0.017
Ω_Λ	0.00	0.742	0.685
$\Omega_b h^2$	0.0125	0.02273 ±0.00062	0.02205 ±0.00028
H_o	50	71.9±2.7	67.3±1.2
dark matter	CDM	CDM	CDM