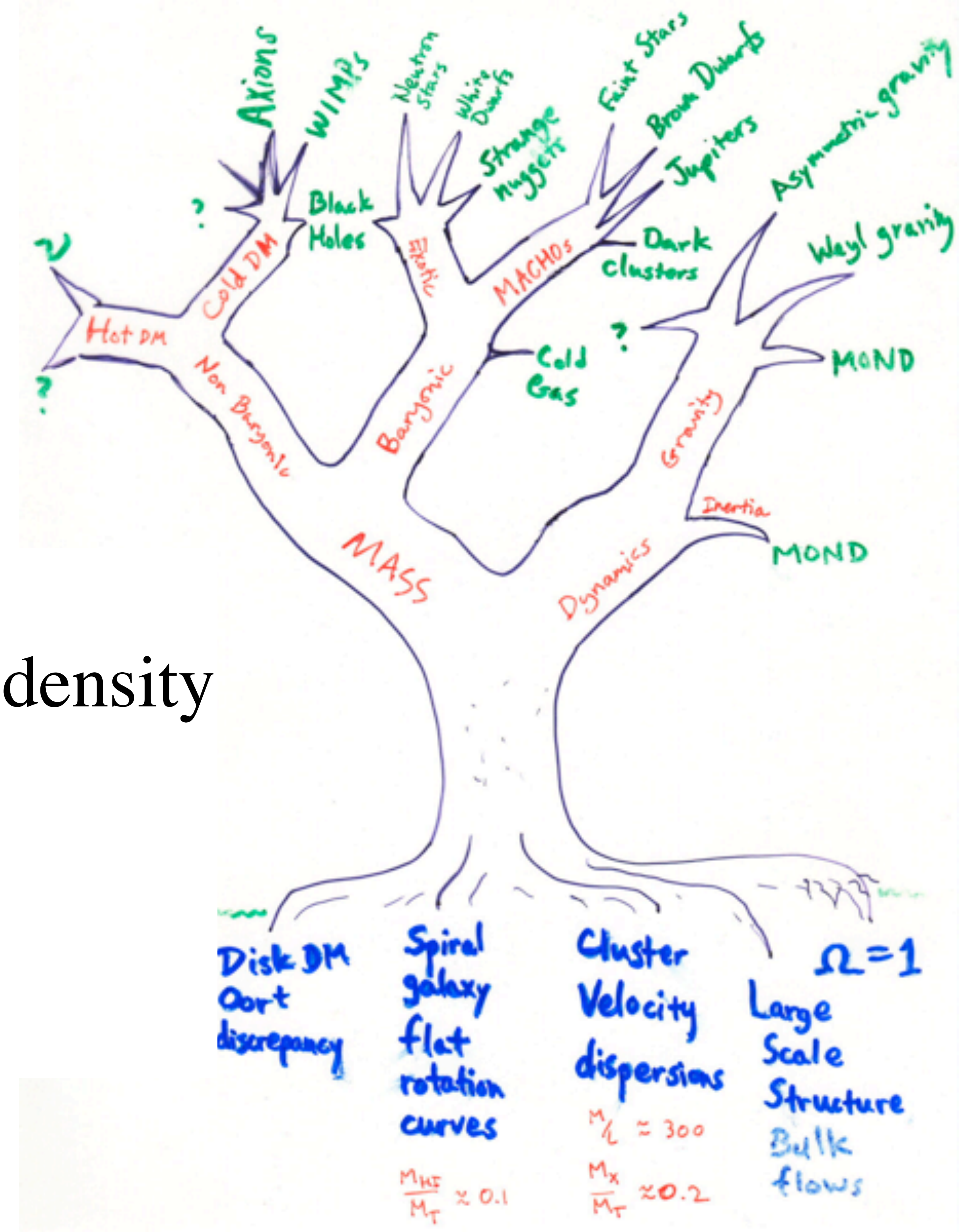


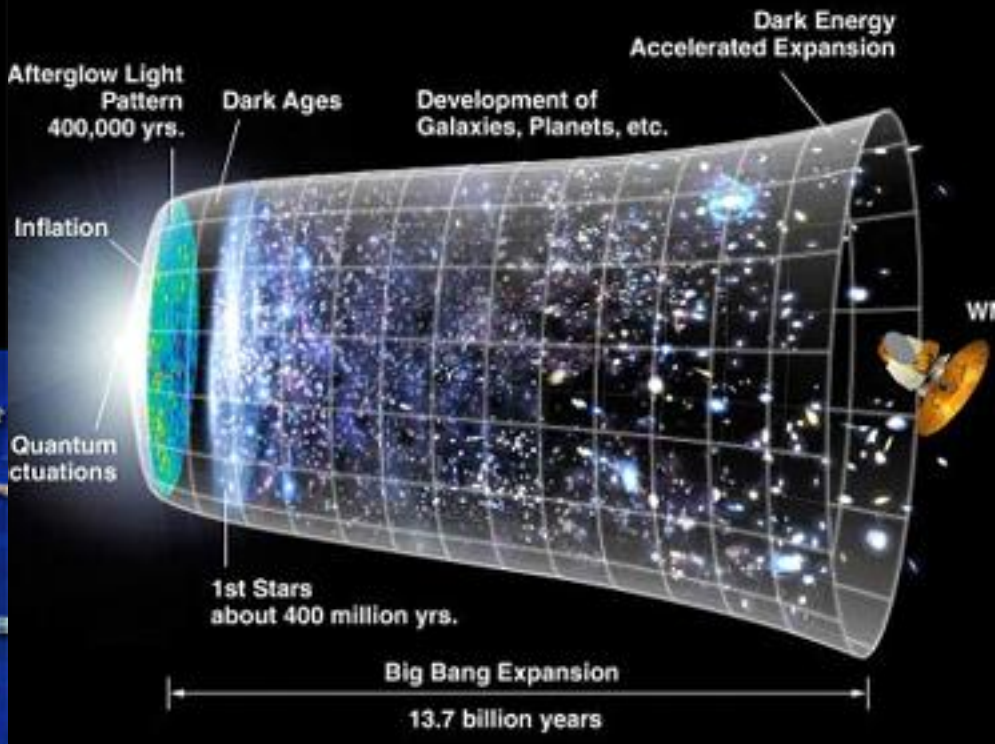
Today: **cosmology**

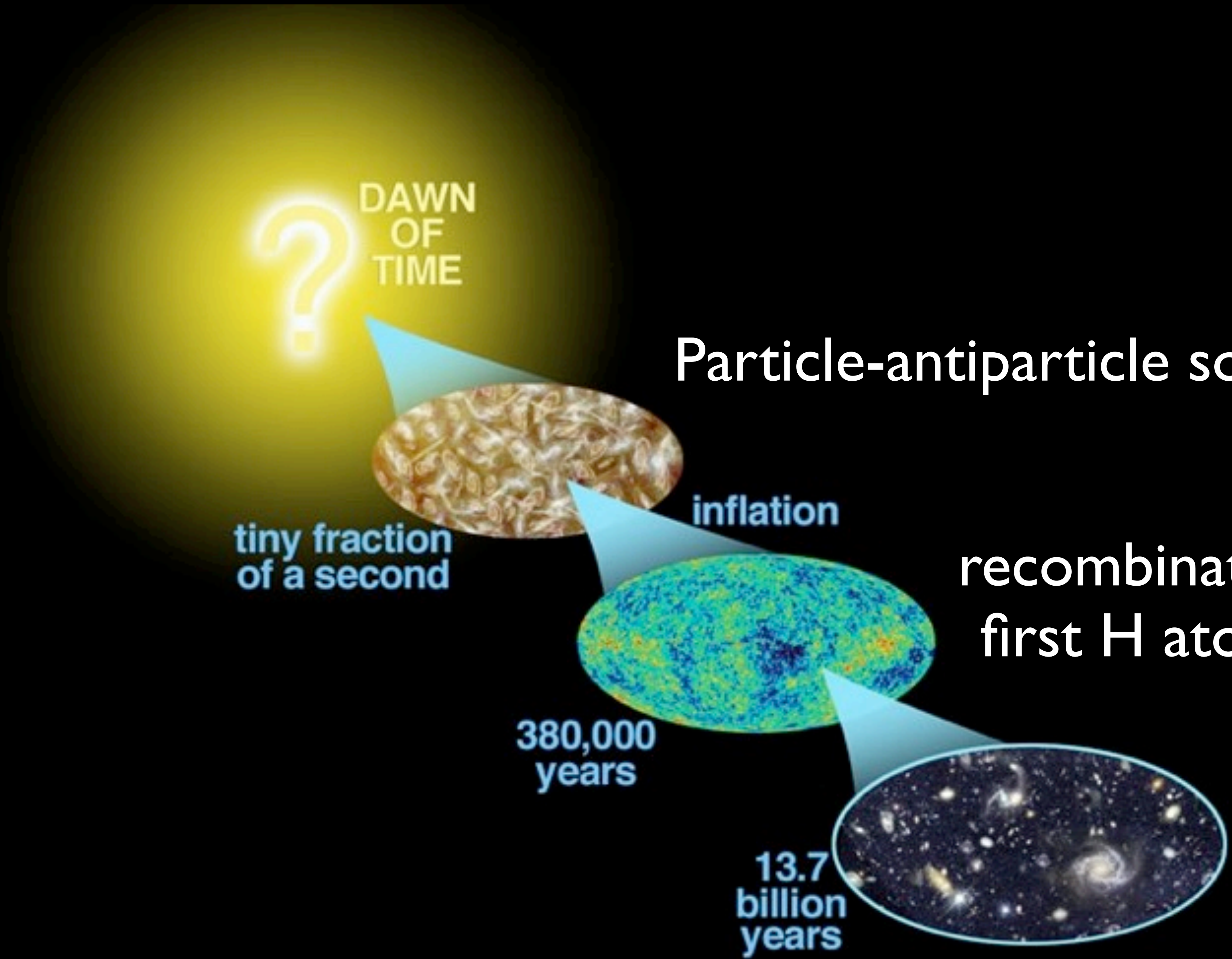
- measuring the mass density
- BBN
- large scale structure
- CMB

Incan cosmology

Inca Cosmos
based on March 1990
National Geographic
"Ancient Skywatchers"
Art revised for web by
http://www.edwardtbabinski.us/

WMAP

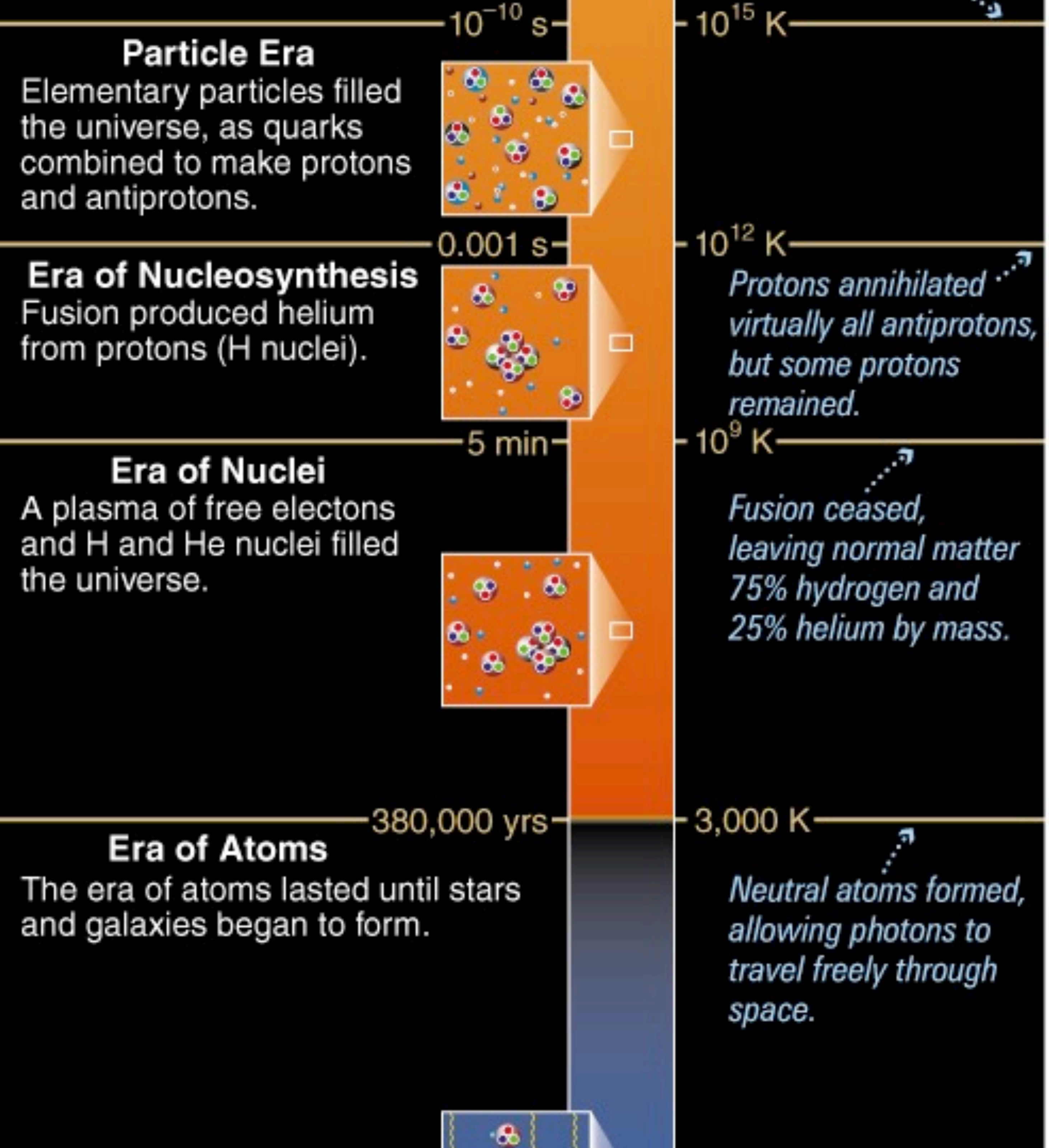




Particle-antiparticle soup

recombination:
first H atoms

You are here-now



10^{-10} s — 10^{15} K

Particle Era
Elementary particles filled the universe, as quarks combined to make protons and antiprotons.

0.001 s — 10^{12} K

Protons annihilated virtually all antiprotons, but some protons remained.

Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).

5 min — 10^{9} K

Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.

Era of Nuclei
A plasma of free electons and H and He nuclei filled the universe.

380,000 yrs — 3,000 K

Neutral atoms formed, allowing photons to travel freely through space.

Era of Atoms
The era of atoms lasted until stars and galaxies began to form.

particle soup

< millisecond

T ~ 10^{14} K

nucleosynthesis

~ 3 minutes

T ~ 10^{10} K

recombination

~380,000 year

T ~ 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			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

682 TONRY AND DAVIS (1981)

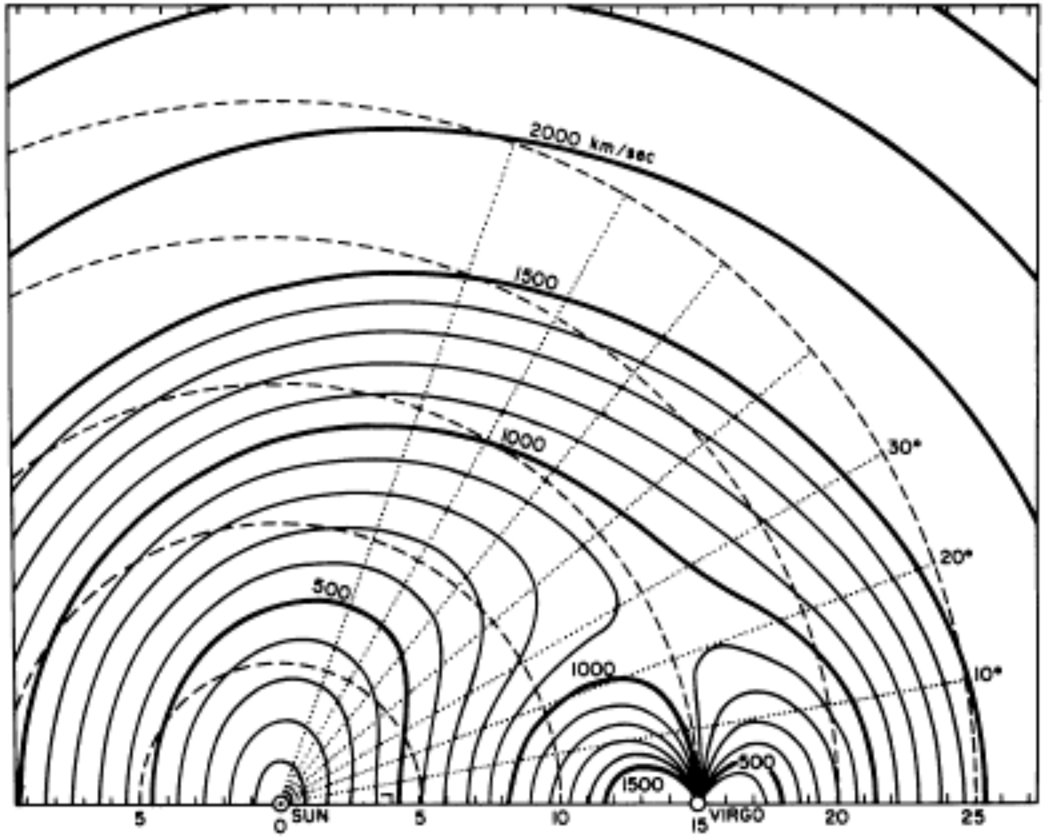


FIG. 1.—On a two-dimensional grid with the Earth and the Virgo cluster on the x axis, redshift contours are plotted for a Hubble flow perturbed by a Virgocentric flow. An infall velocity of 400 km s^{-1} at our position is assumed. A pure Hubble flow would be concentric circles.

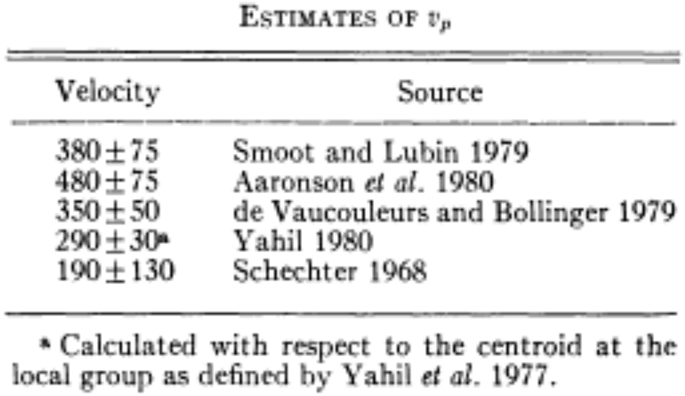
Davis et al. (1980) found

$$\Omega_m = 0.4 \pm 0.1$$

with modern distances this becomes

$$\Omega_m = 0.25 \pm 0.05$$

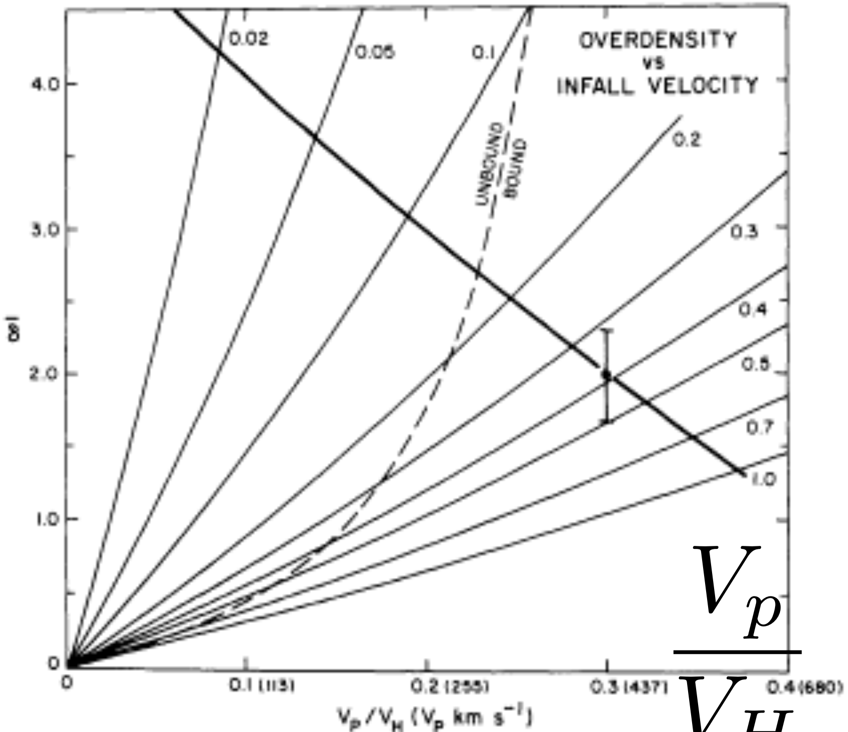
Lines are lines of constant Ω_m



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.



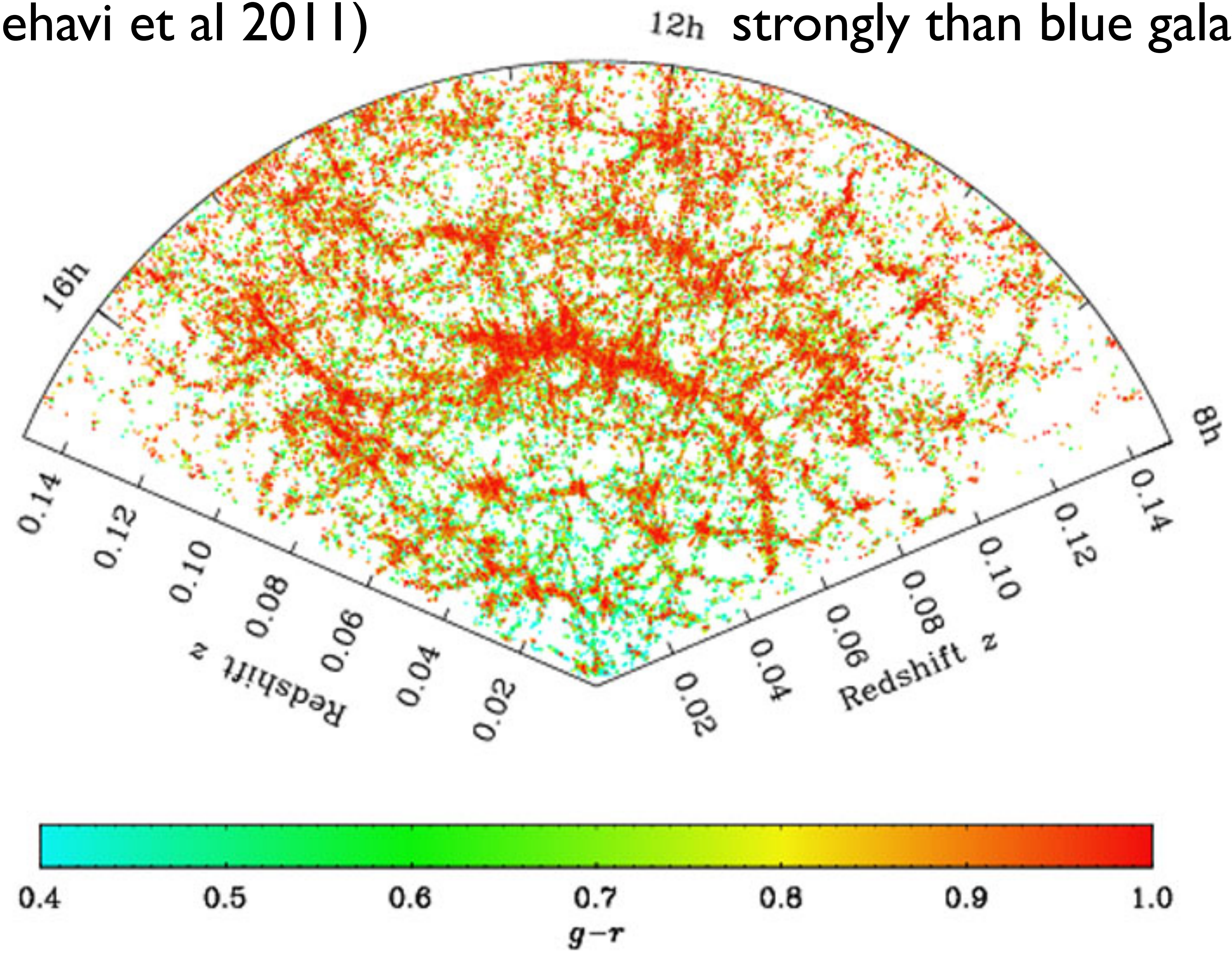
$$\frac{\delta\rho}{\rho}$$

$$\frac{V_p}{V_H}$$

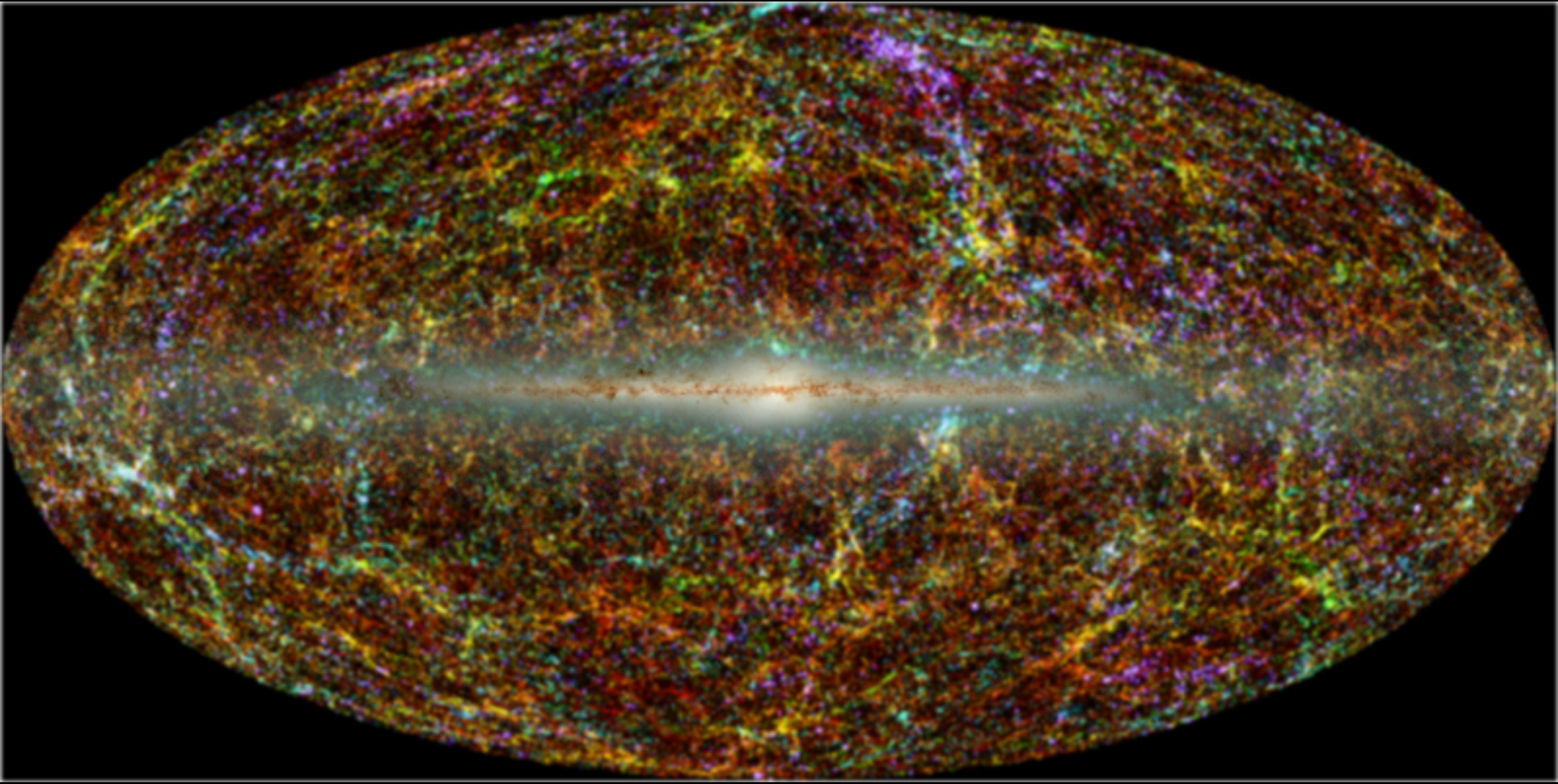
FIG. 1.—The mean overdensity of Virgo vs. v_p/v_H for various values of Ω. The x-axis is also labeled with v_p, using a recessional velocity to Virgo of 1020 km s^{-1}. The measured overdensity is prescribed by the heavy line, and is marked at the favored position as given by the anisotropy of the Hubble 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



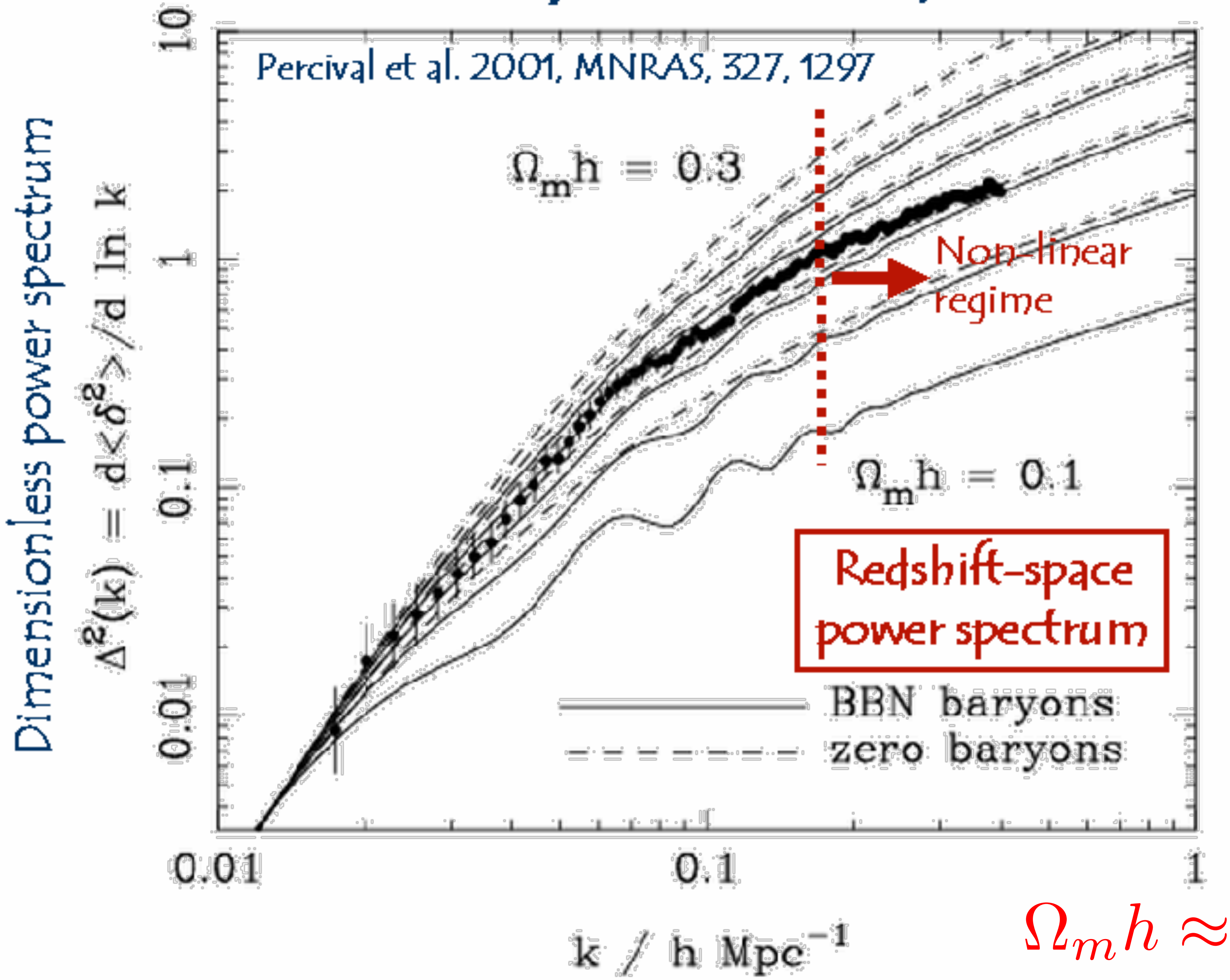
2MASS galaxy distribution on sky in Galactic coordinates



Blue points lower redshift, red points higher redshift

Jarrett et al.

The Galaxy Power Spectrum



$\Omega_m h \approx 0.2$

Basically all data suggest a gravitating mass density

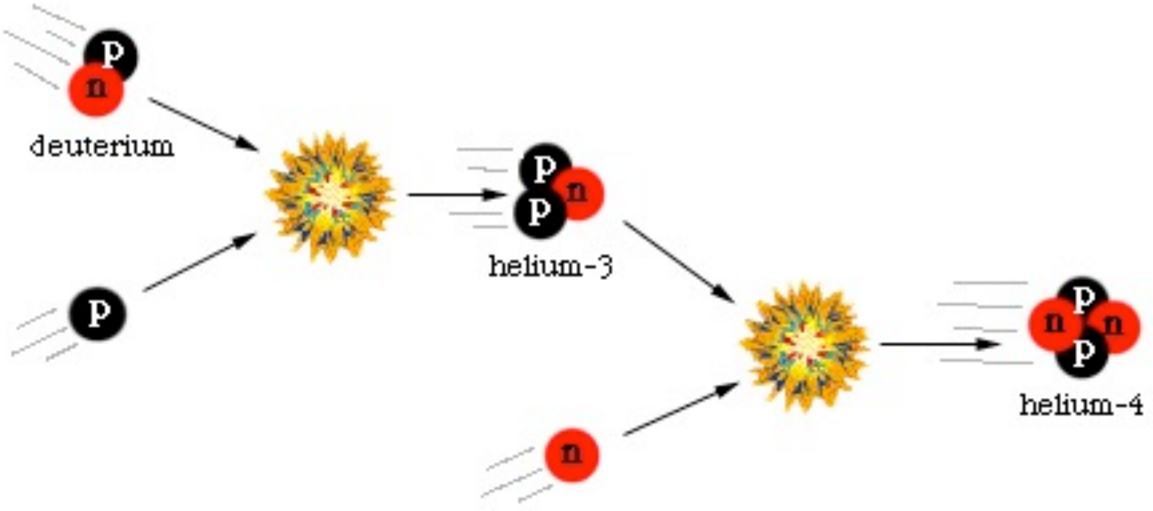
$$\frac{1}{4} < \Omega_m < \frac{1}{3}$$

What about baryons?

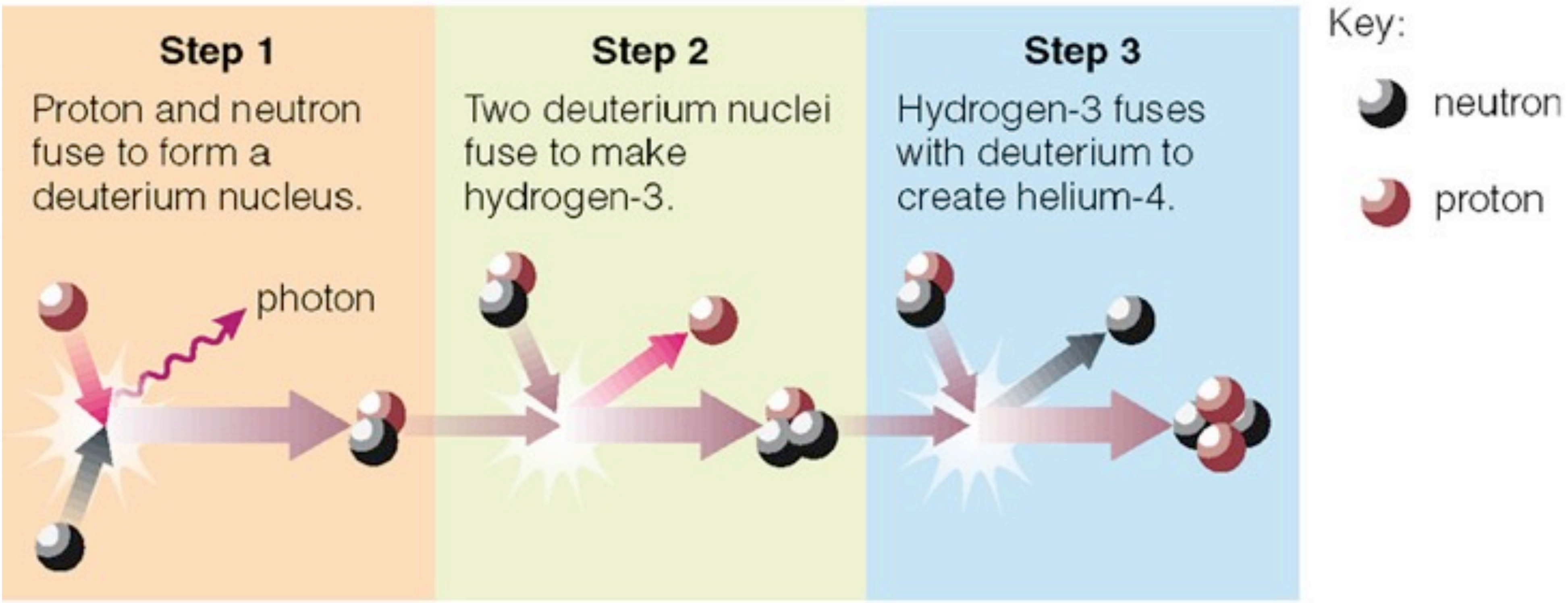
Primordial Nucleosynthesis (BBN):

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.



Step 1

Proton and neutron fuse to form a deuterium nucleus.

Step 2

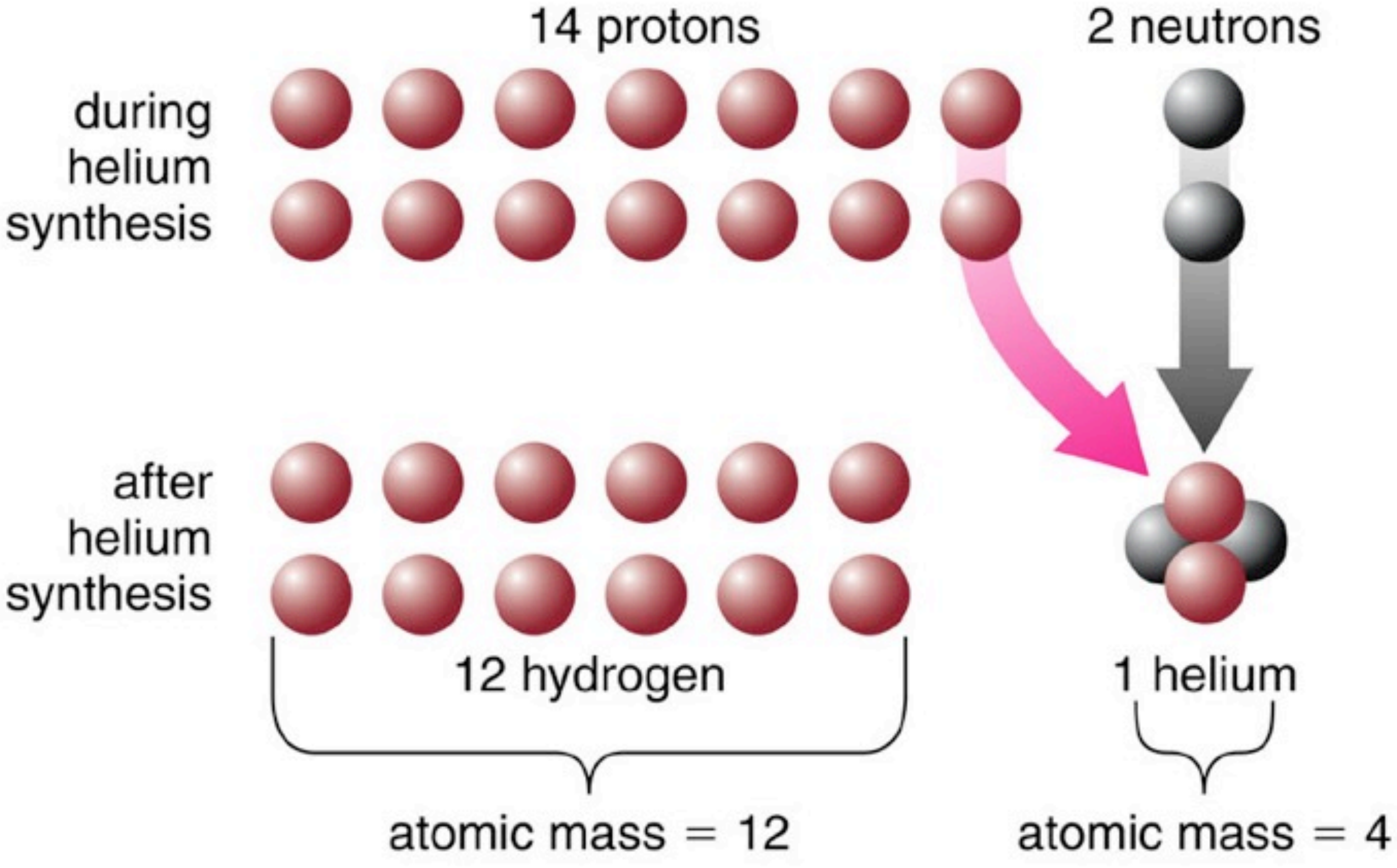
Two deuterium nuclei fuse to make hydrogen-3.

Step 3

Hydrogen-3 fuses with deuterium to create helium-4.

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.



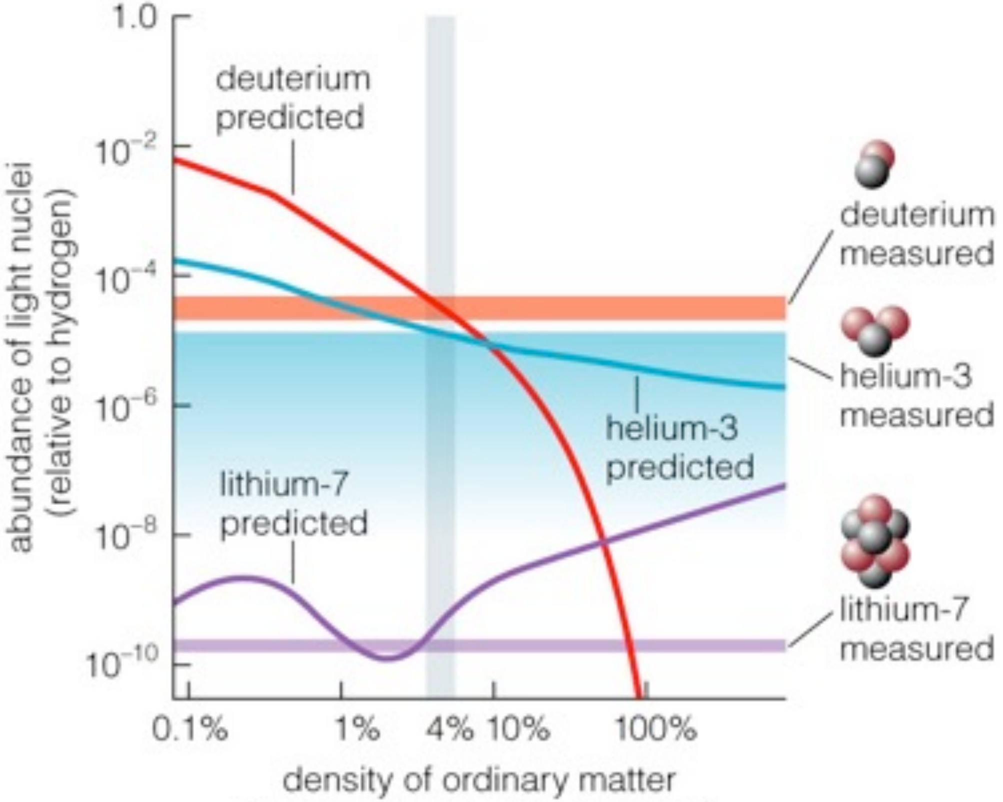
Big Bang theory prediction: 75% H, 25% He (by mass)

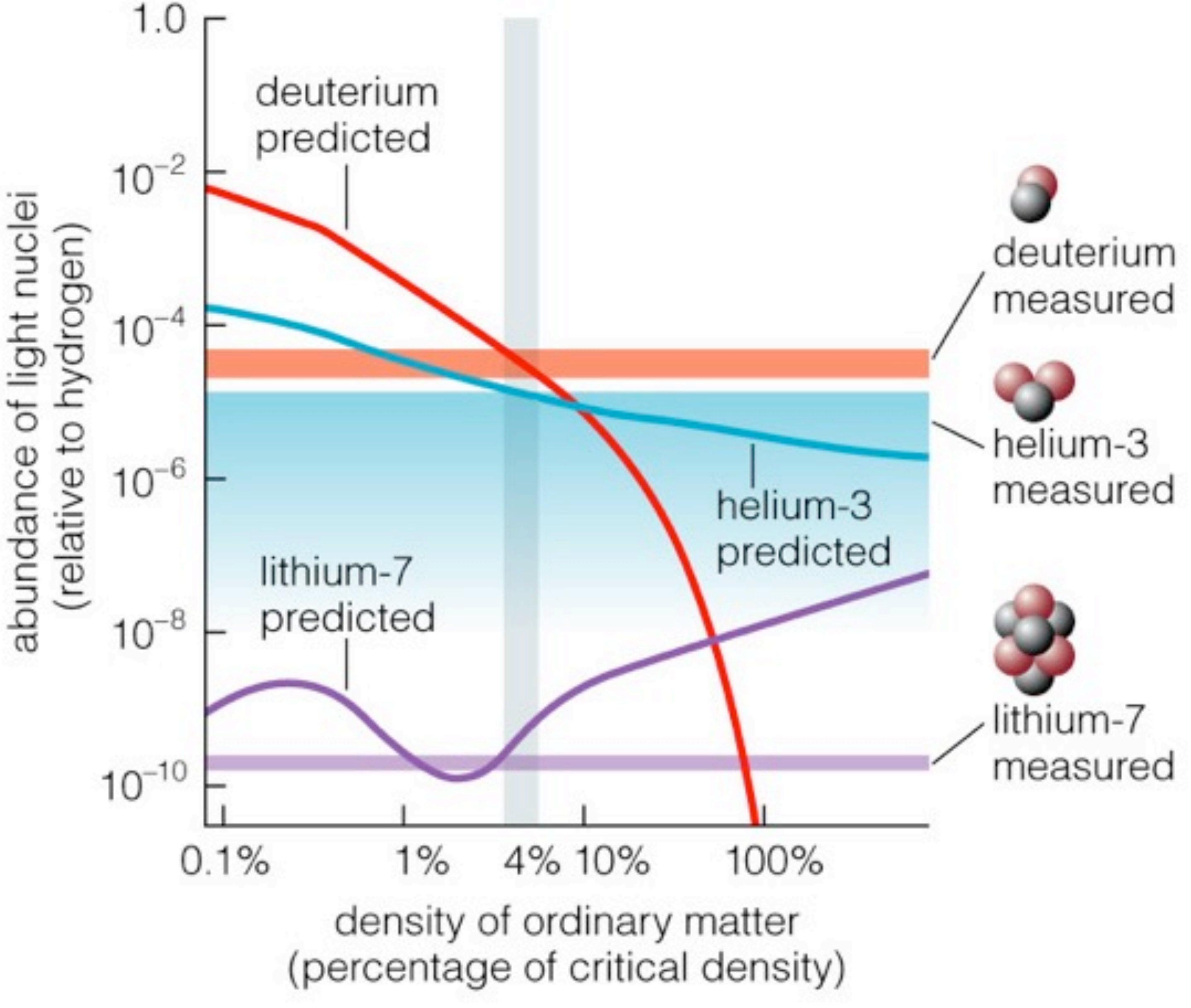
Matches observations of nearly primordial gases

BBN products:

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

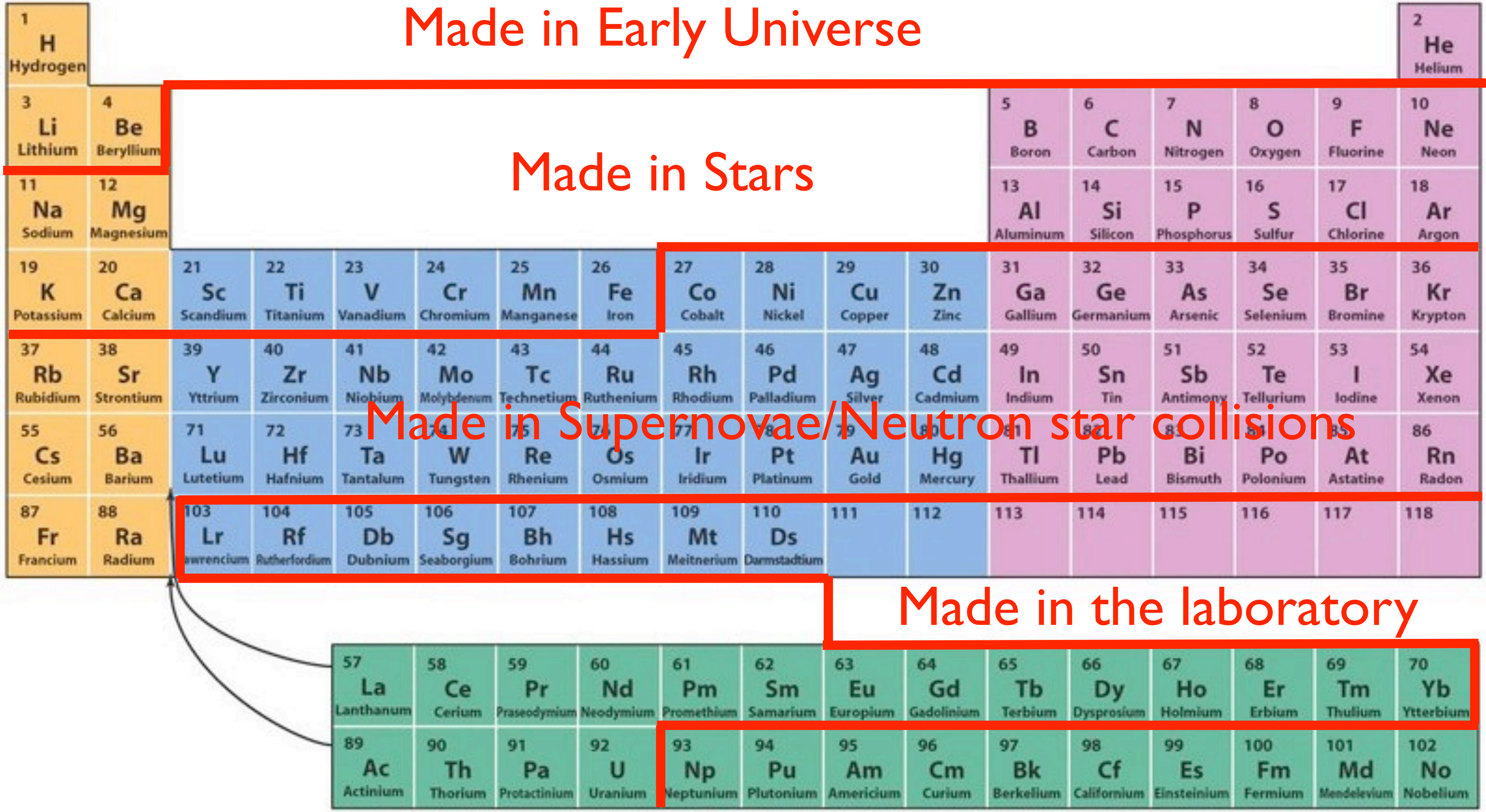
Abundances depend on the density of matter. The higher the density parameter (Ω), the more helium.





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

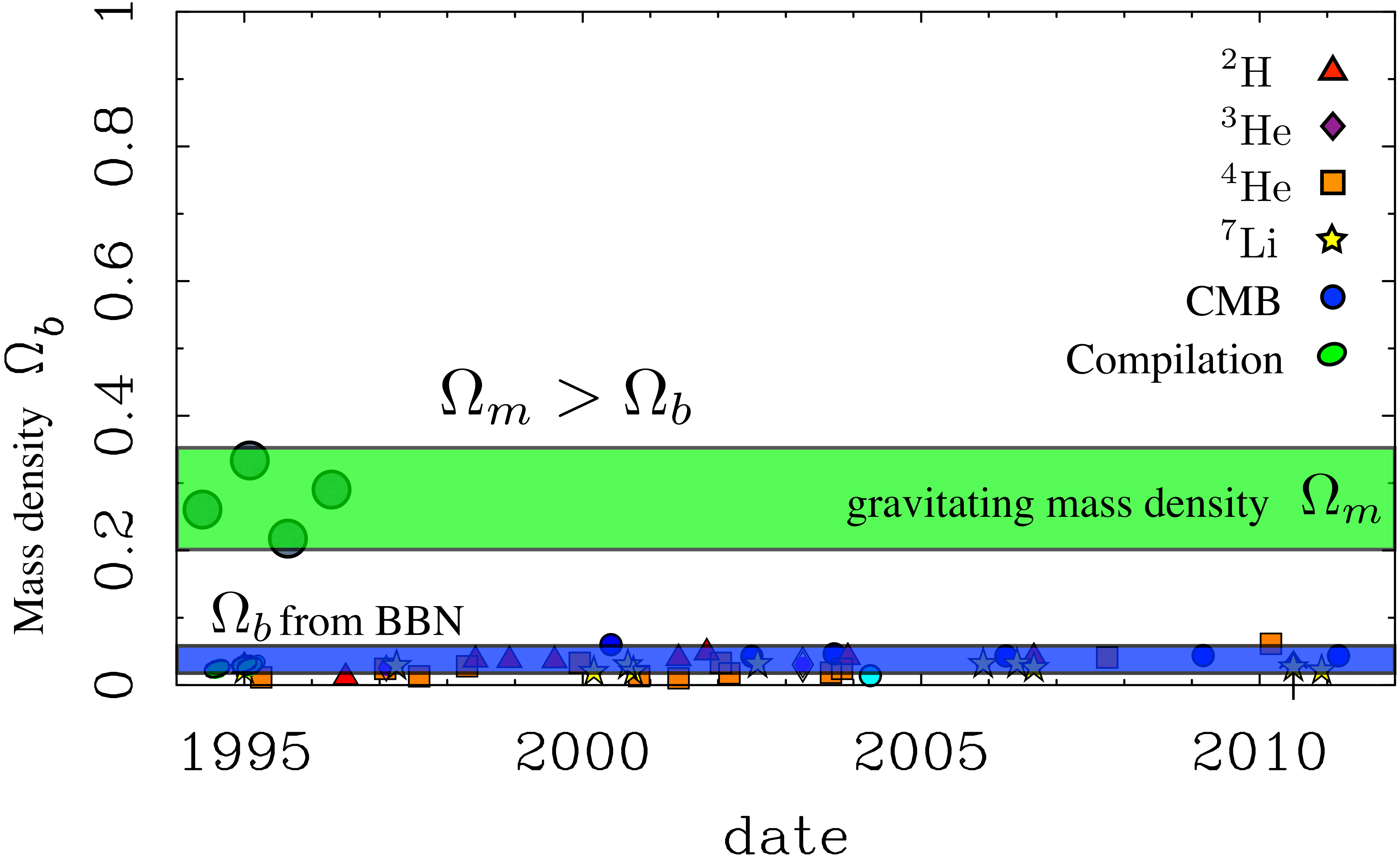
Made in Stars

Made in Supernovae/Neutron star collisions

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	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 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 awrencium	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

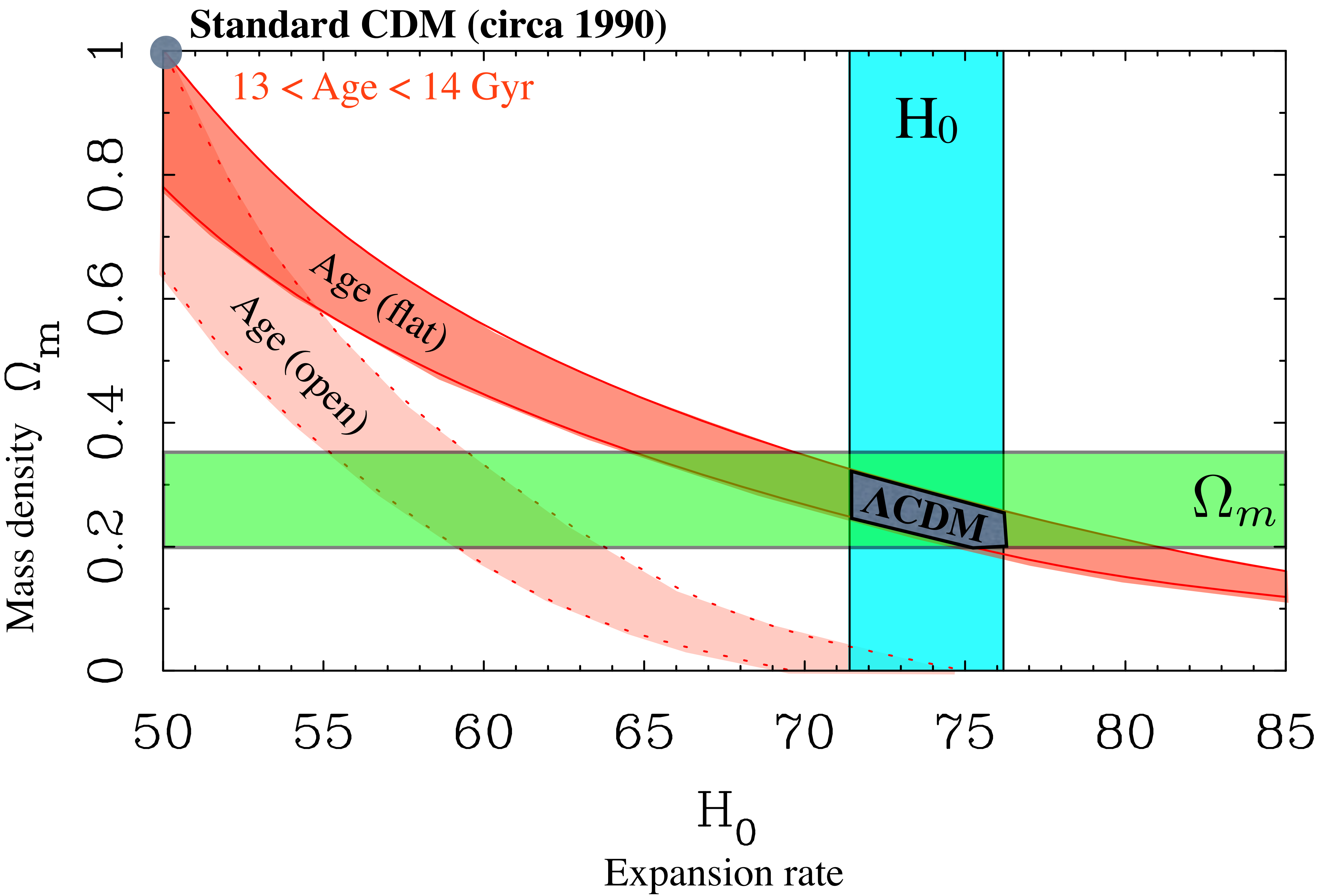
There is a hierarchy of missing mass problems

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

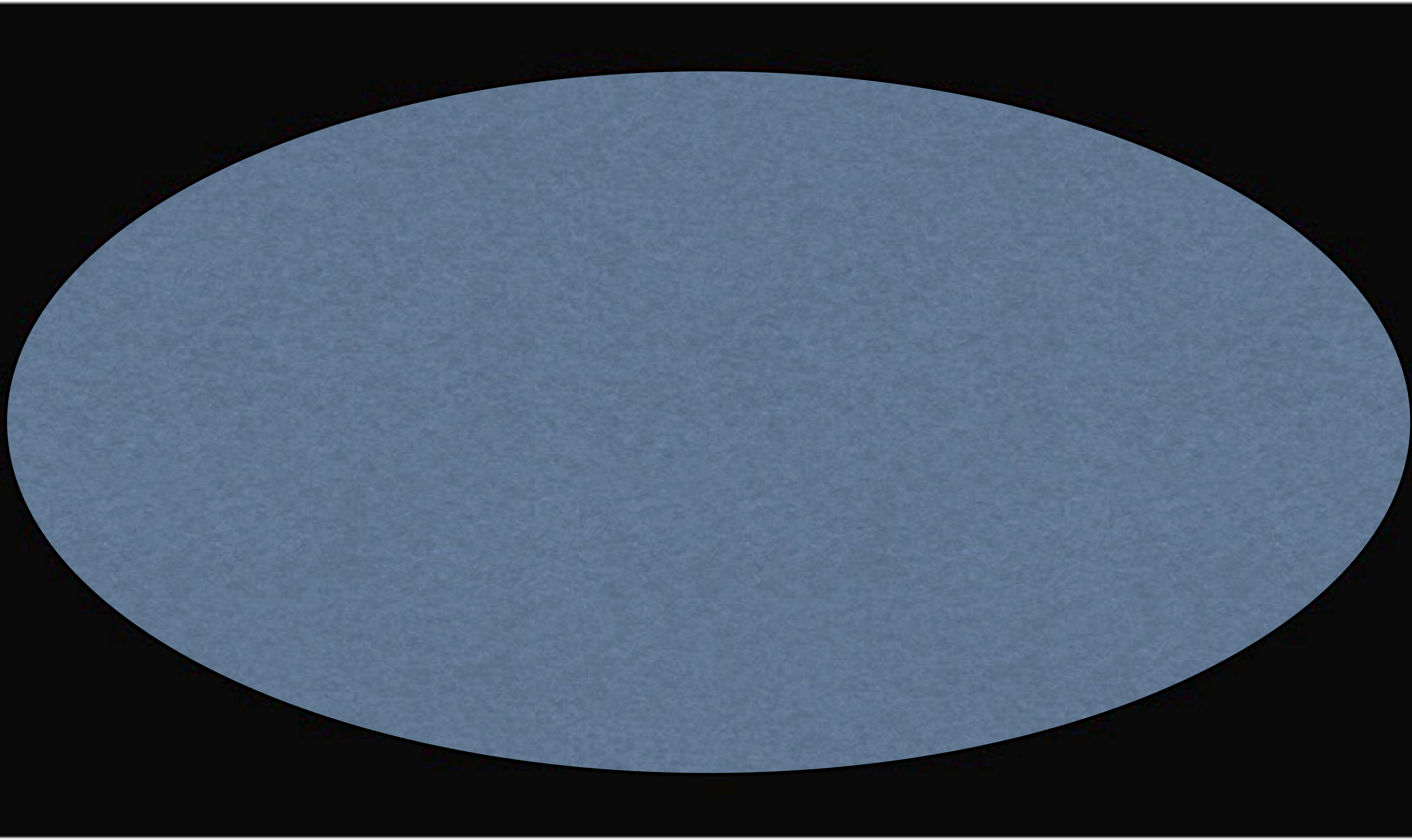
$\sum \Omega_{b,obs} < \Omega_{b,BBN}$ cosmic missing baryon problem
(not enough baryons for BBN)

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

Cosmic 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

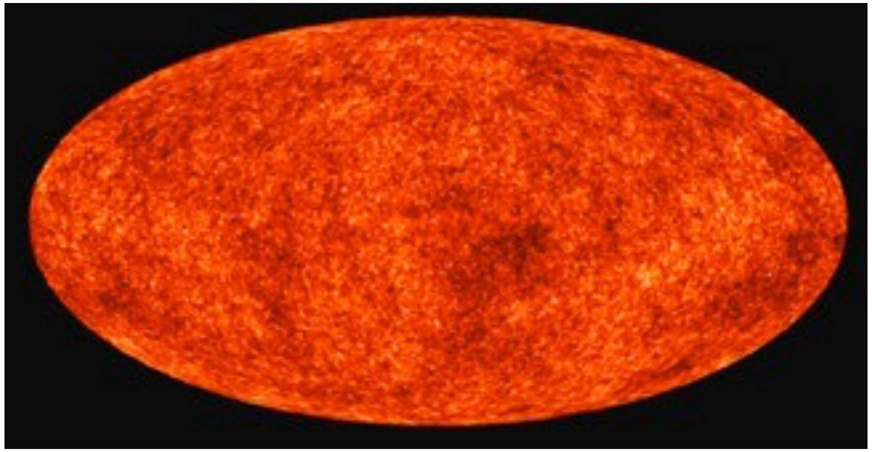
$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta \rho}{\rho}$$

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