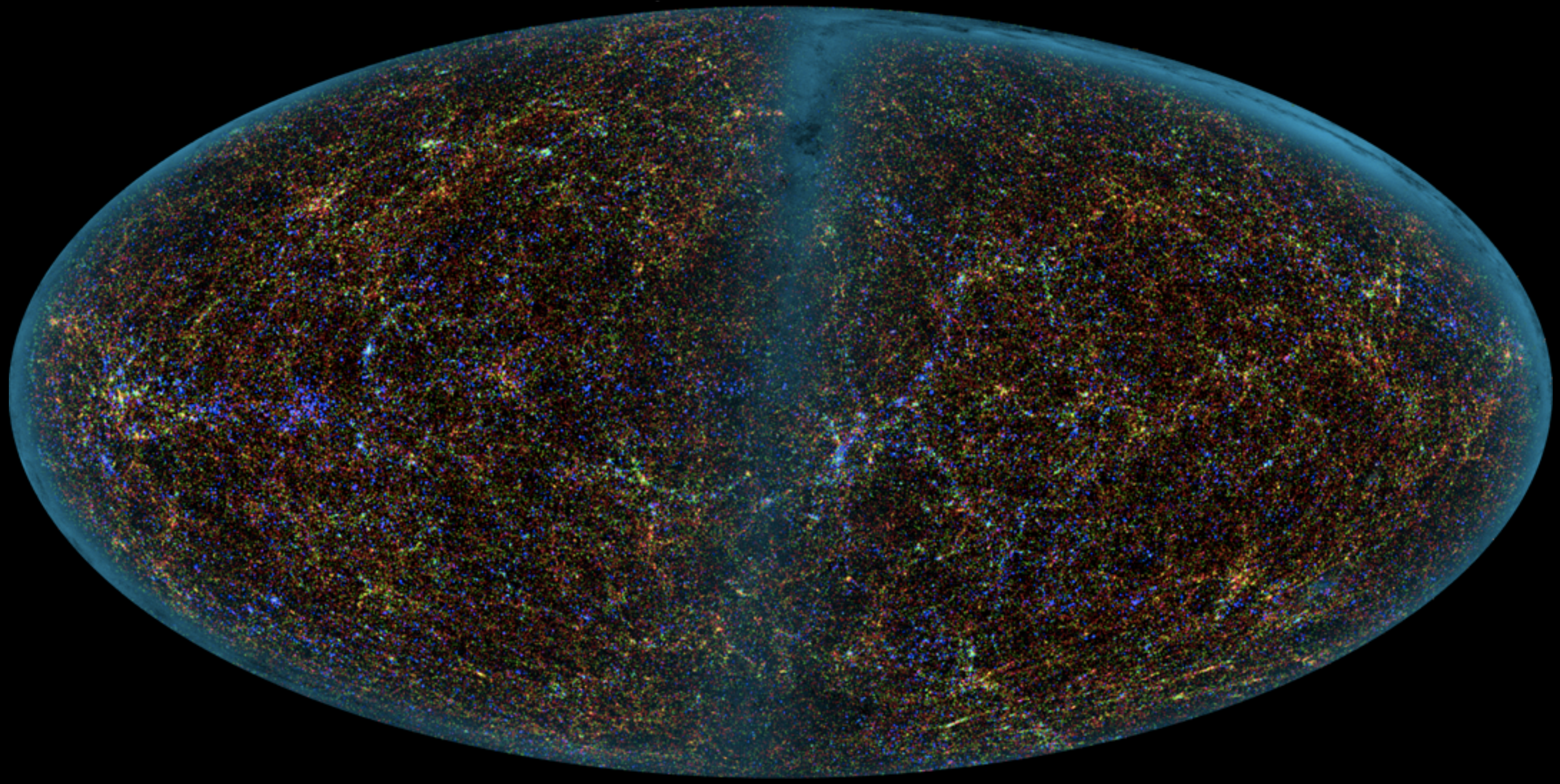
Cosmology
and Large Scale Structure

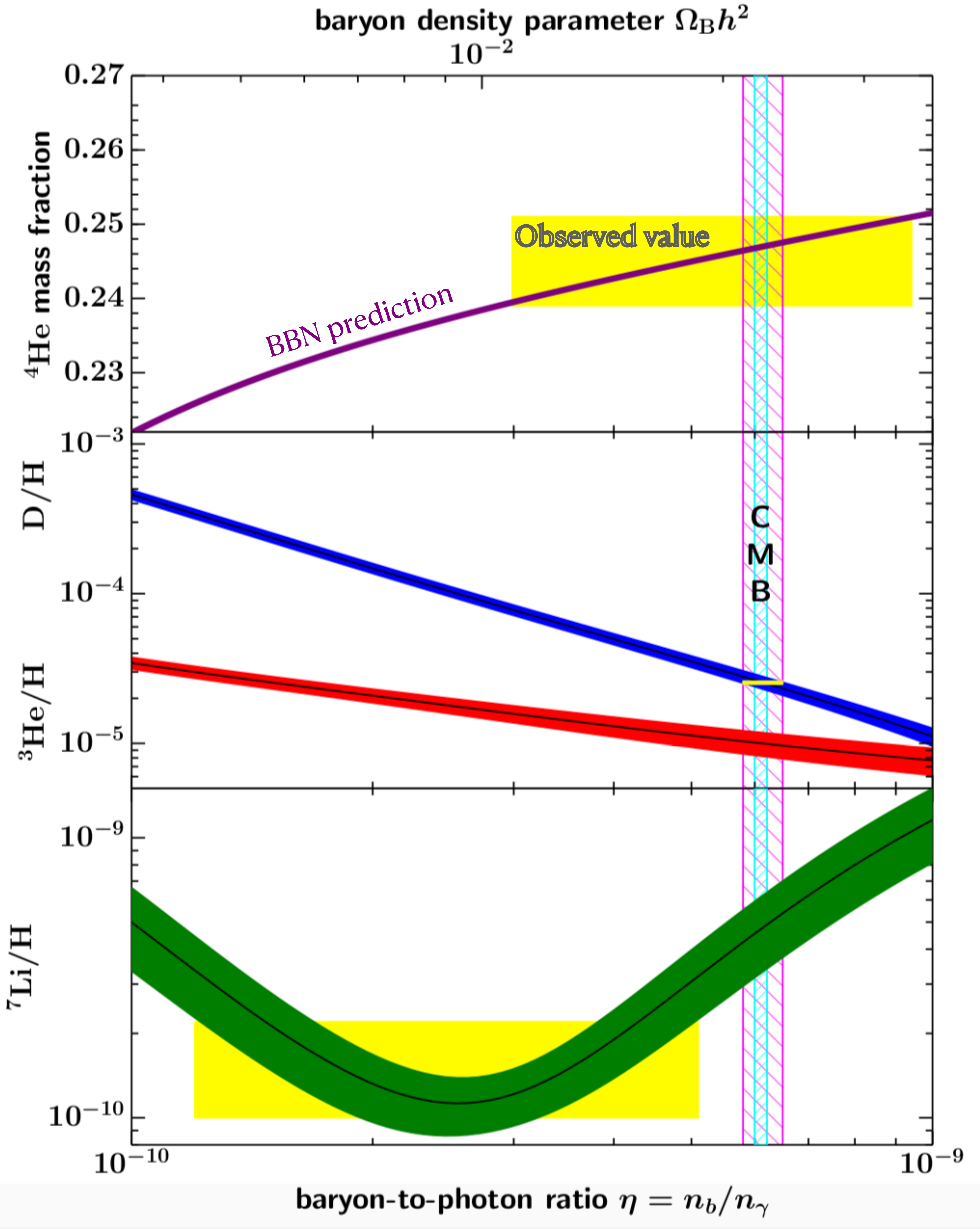


Today
Structure Formation
Cold Dark Matter

Homework 4 due

ASTR 497 is a **2 credit** course, not 3

Astroparticle seminar next time (Tuesday 11/15)
Probing the Universe's expansion and the origin of compact object binaries with multi-messenger astronomy



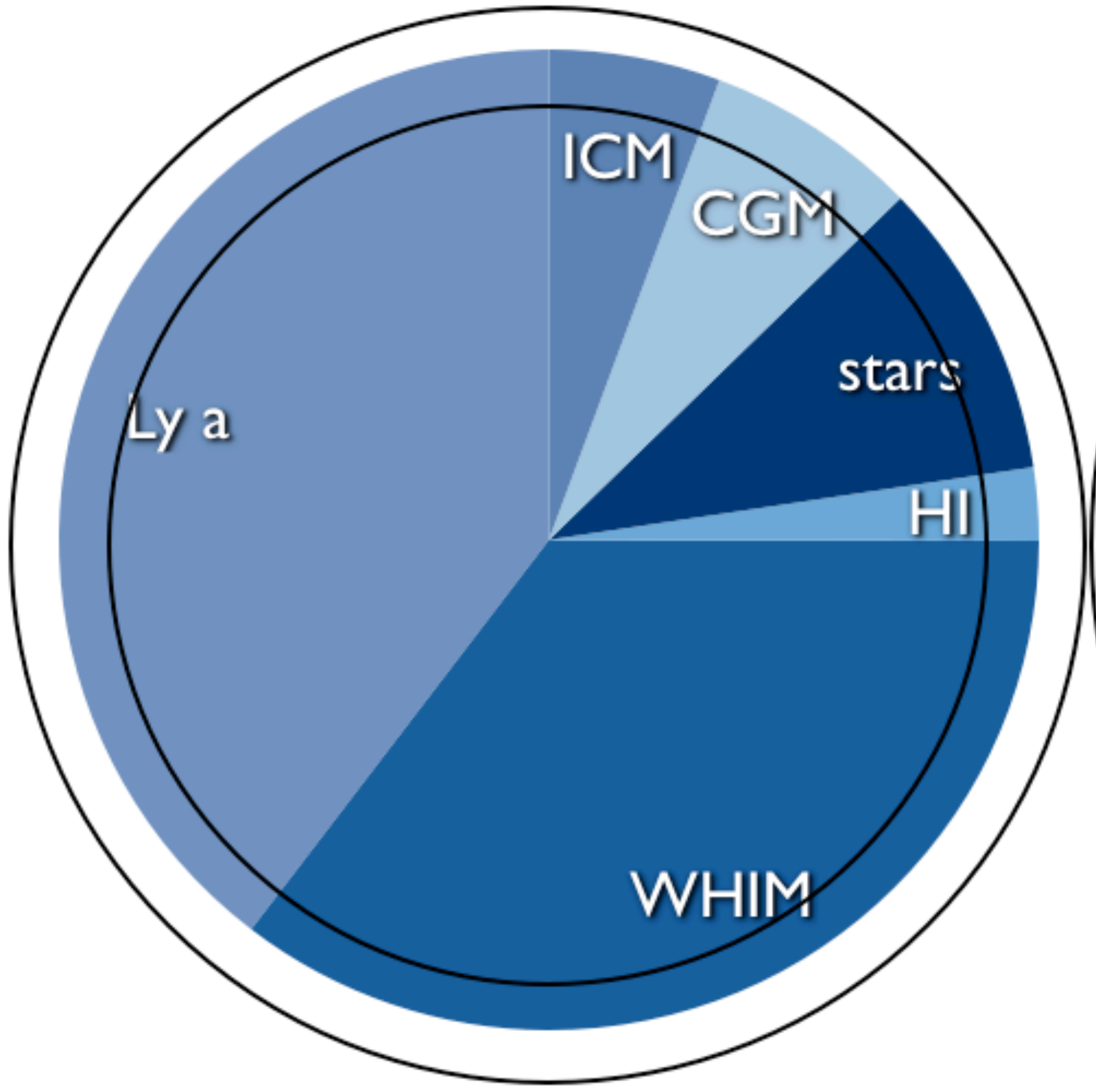
baryon density parameter $\Omega_B h^2$
10^{-2}
0.27
0.26
0.25
0.24
0.23
^{4}He mass fraction
Observed value
BBN prediction
10^{-3}
D/H
10^{-4}
^{3}He/H
10^{-5}
C
M
B
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio $\eta = n_b/n_\gamma$

Where are the baryons now? Mostly in the intergalactic medium (IGM) (Shull et al. 2012)

Ly a = Lyman alpha forest (IGM)
WHIM = Warm-Hot Intergalactic Medium
ICM = Intra Cluster Medium (hot gas in clusters)
CGM = CircumGalactic Medium (gas in galaxy halos)
stars = stars in galaxies
HI = atomic hydrogen in galaxies

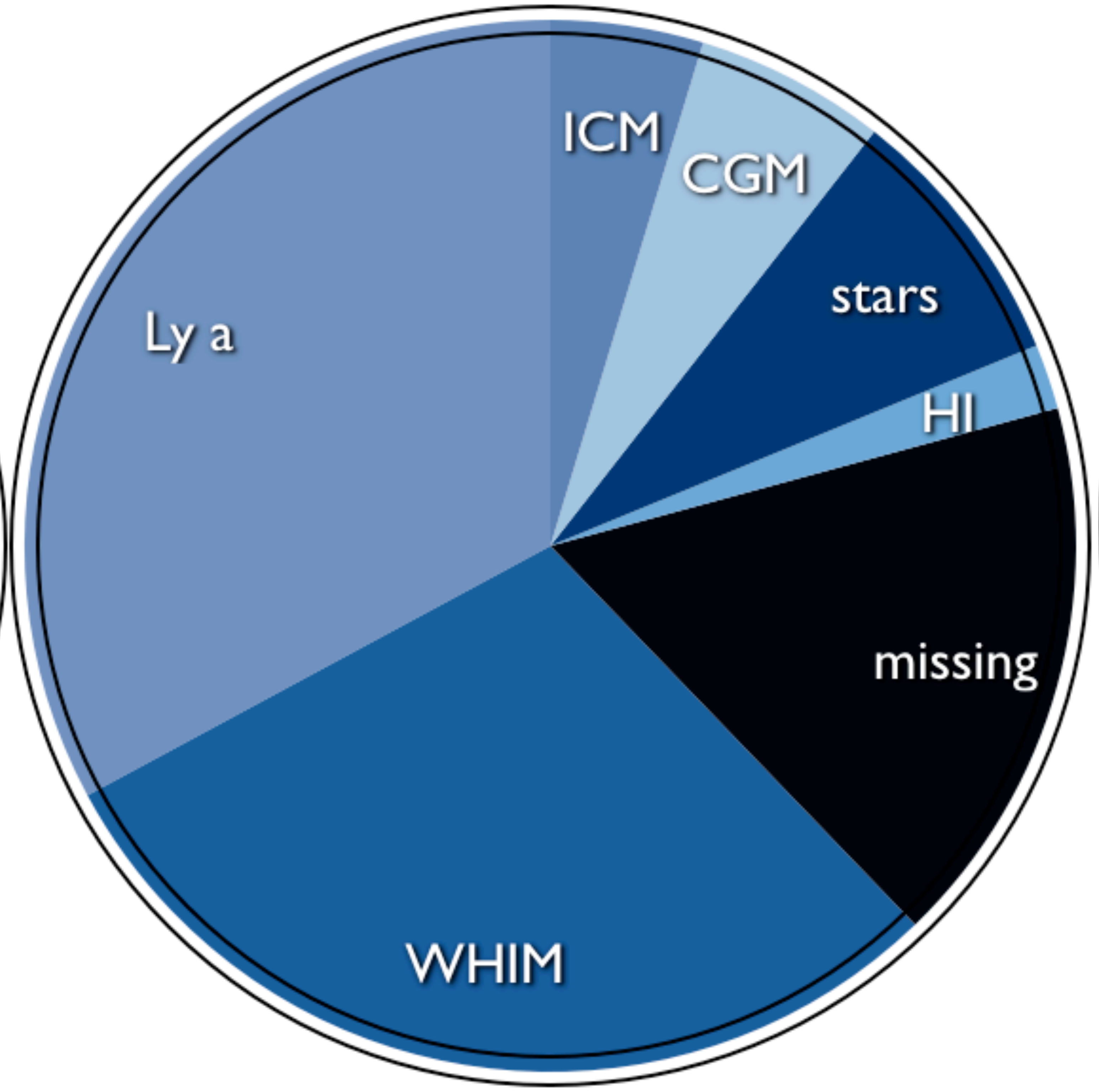
Stars only about 7% of the baryons expected from BBN - for a long time there seemed to be a missing baryon problem. Perhaps there still is, but chiefly it appeared that way because most normal matter has not condensed into stars.

BBN 1991 (Walker et al.)



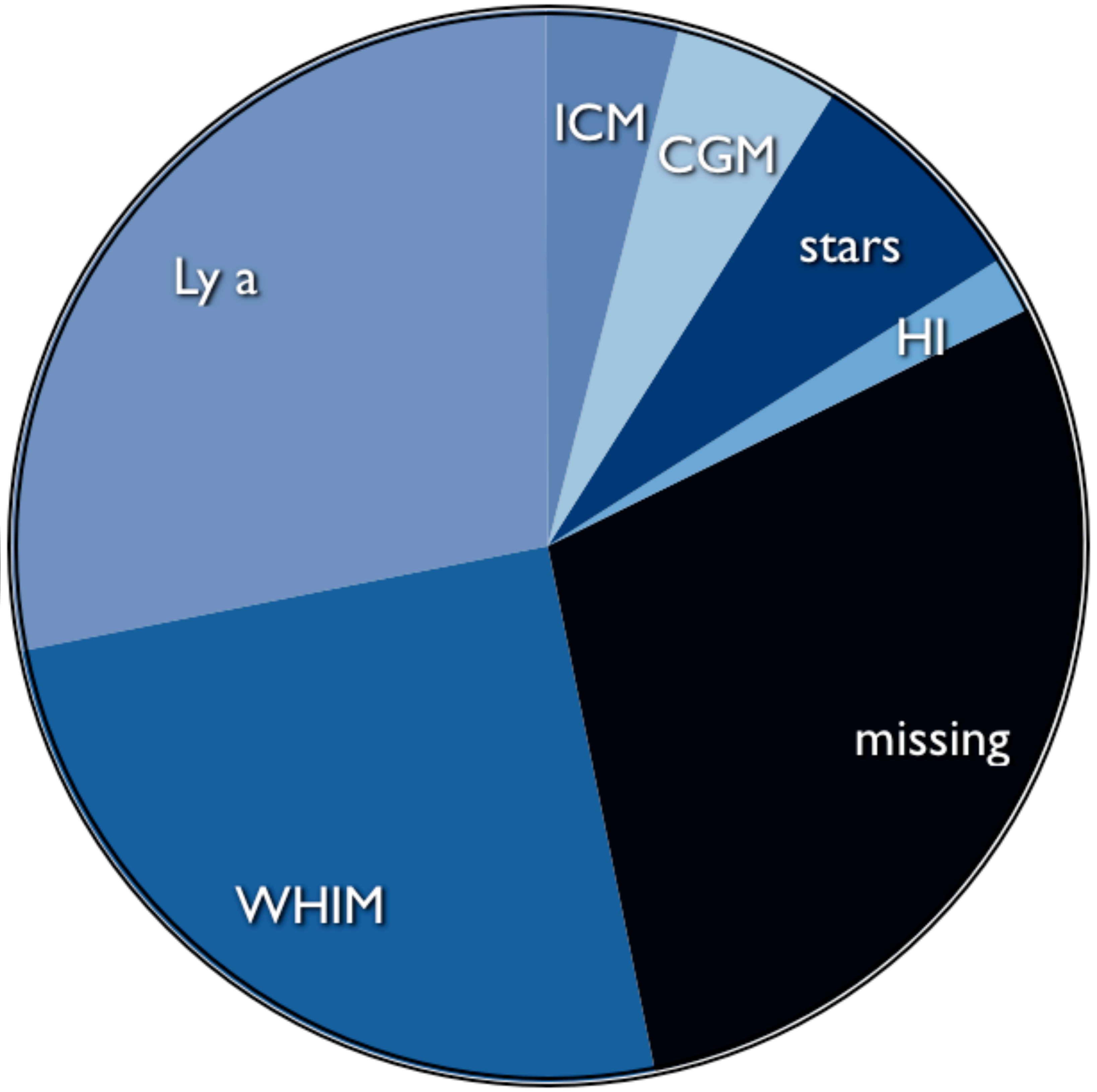
$$\Omega_b h^2 = 0.0125 \pm 0.0025$$

BBN 1999 (pre-CMB D/H)



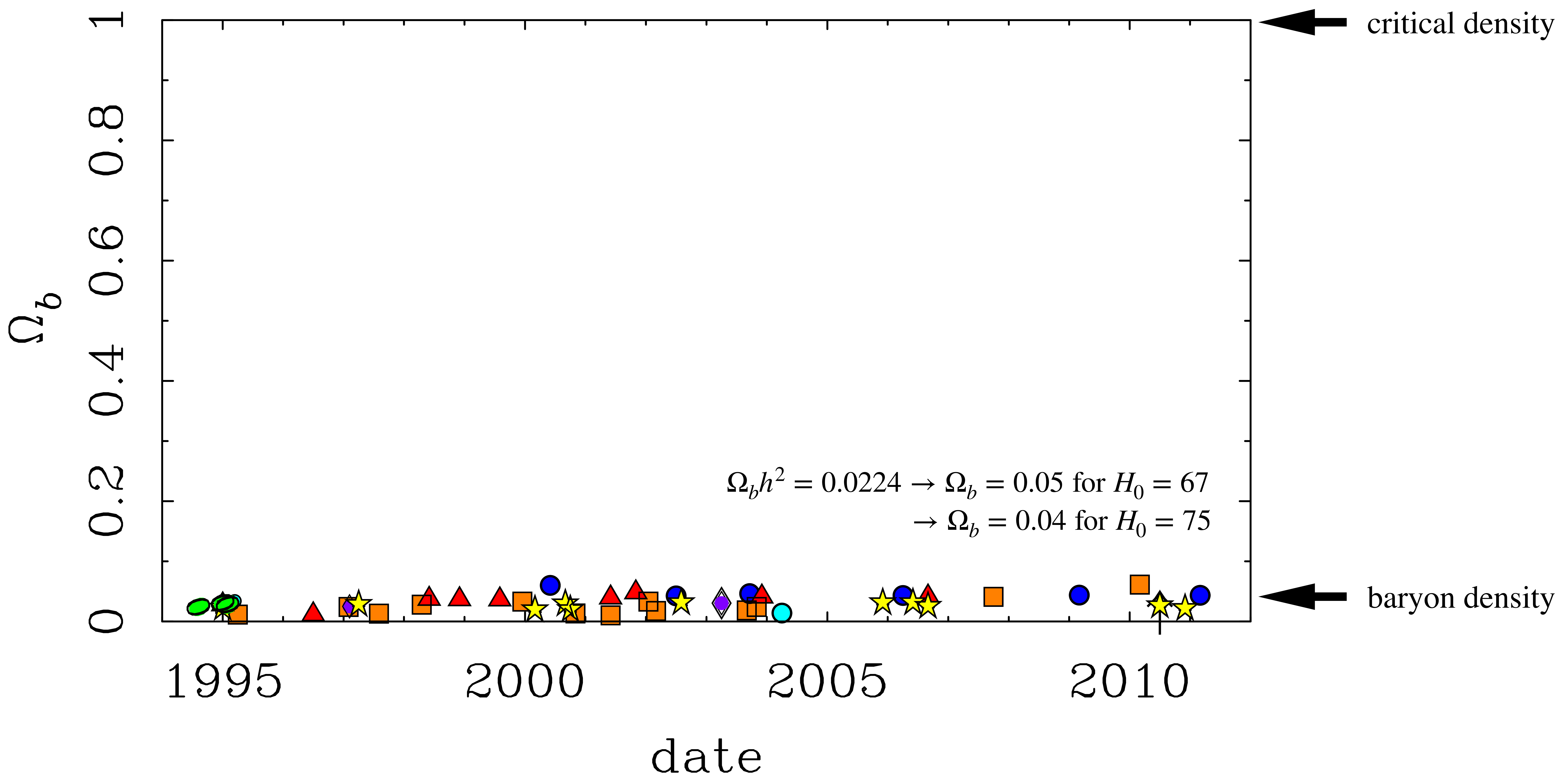
$$\Omega_b h^2 = 0.019 \pm 0.001$$

CMB 2015 (Planck)



$$\Omega_b h^2 = 0.02230 \pm 0.00023$$

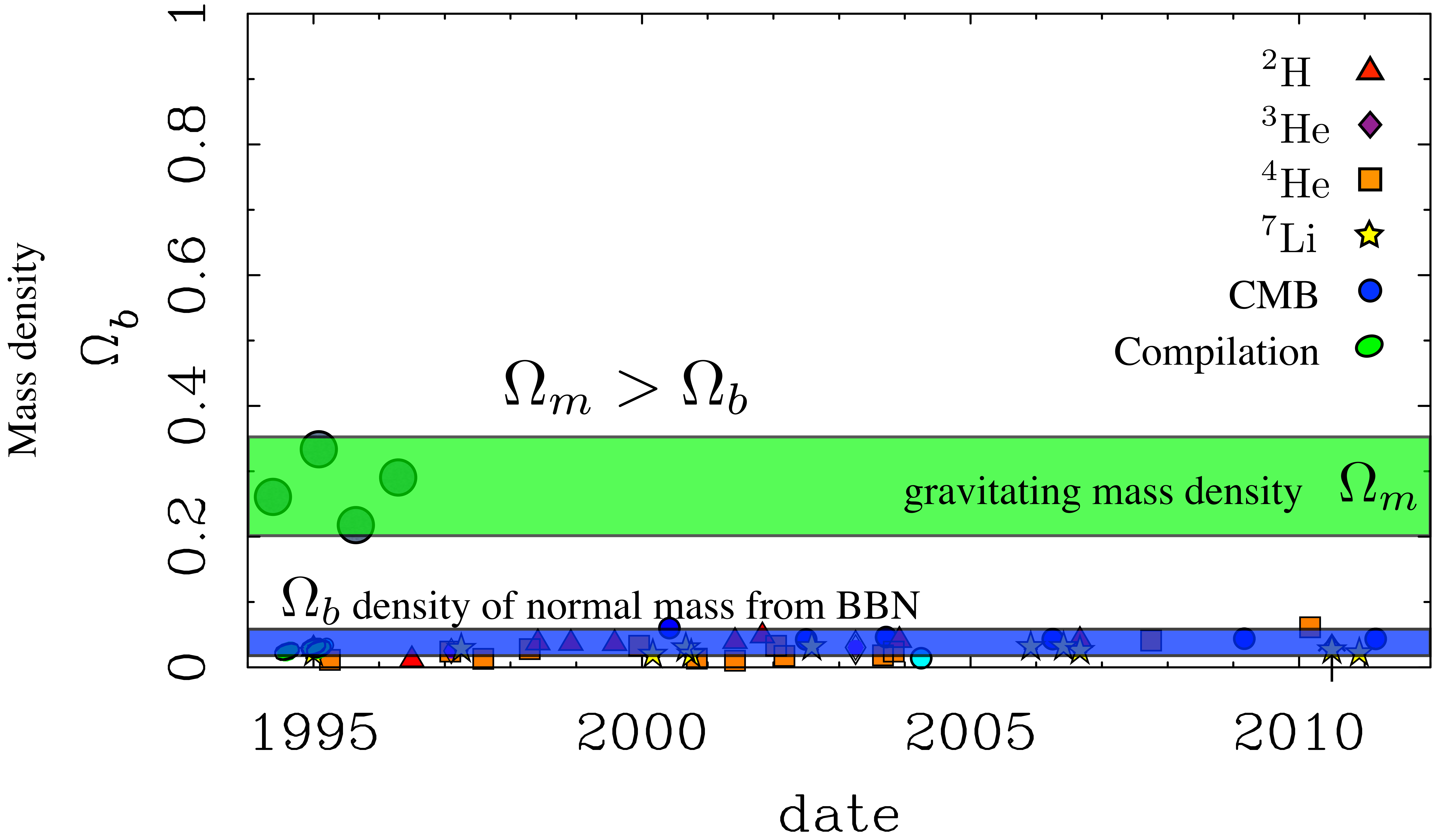
There has been more growth in the baryon density than anticipated by the uncertainties, but the basic picture is sound.



Despite tensions between independent measurements of different isotopes, the baryon density is much less than critical.

But estimates of Ω_m run higher: there's more mass than meets the eye

There is more gravitating mass than Big Bang Nucleosynthesis allows in normal matter.
Need **non-baryonic** dark matter.



Structure formation basics:

Density perturbations $\delta = \dfrac{\rho - \langle\rho\rangle}{\langle\rho\rangle}$ **(Ryden 11.58)**

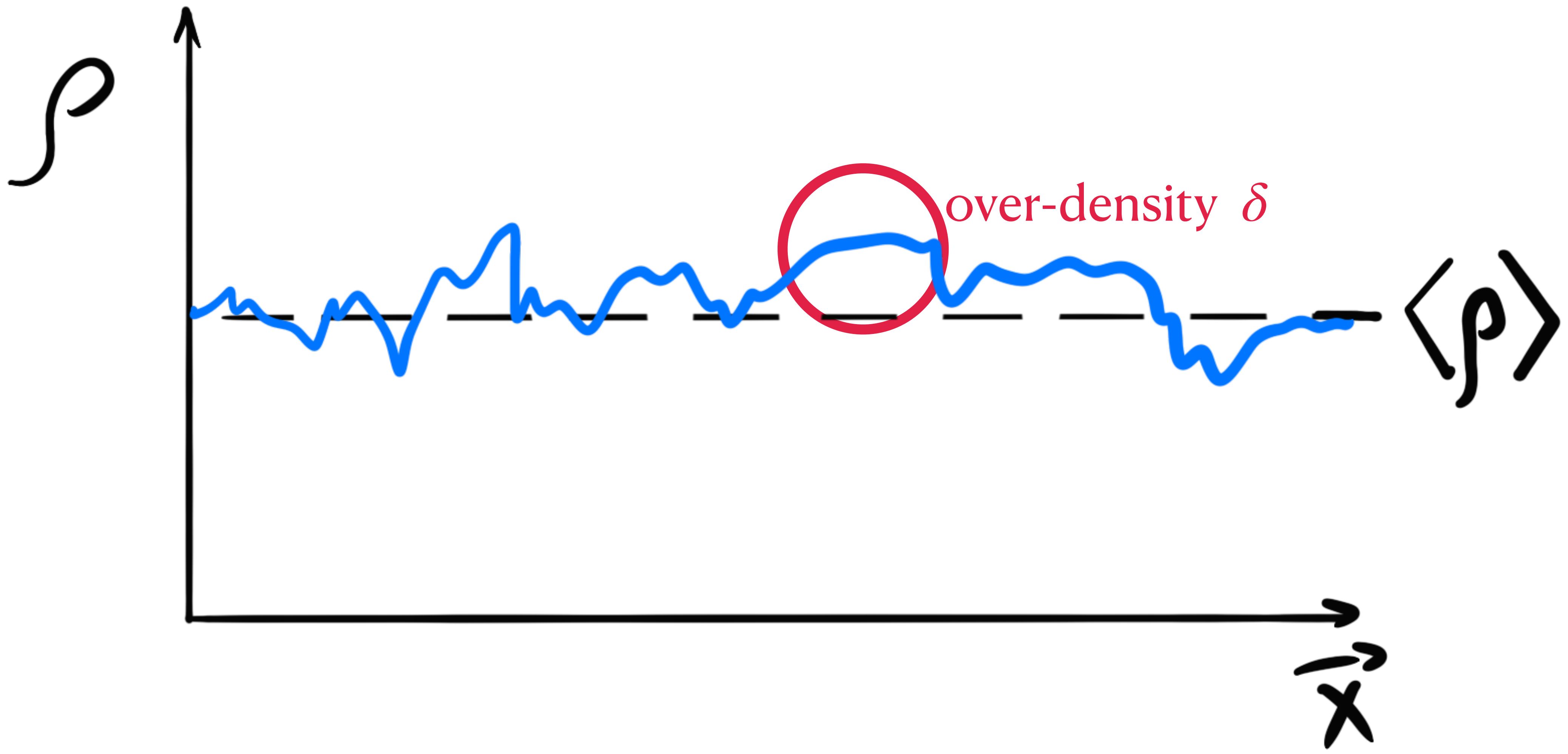
grow as $\delta(t) \sim a(t)$.

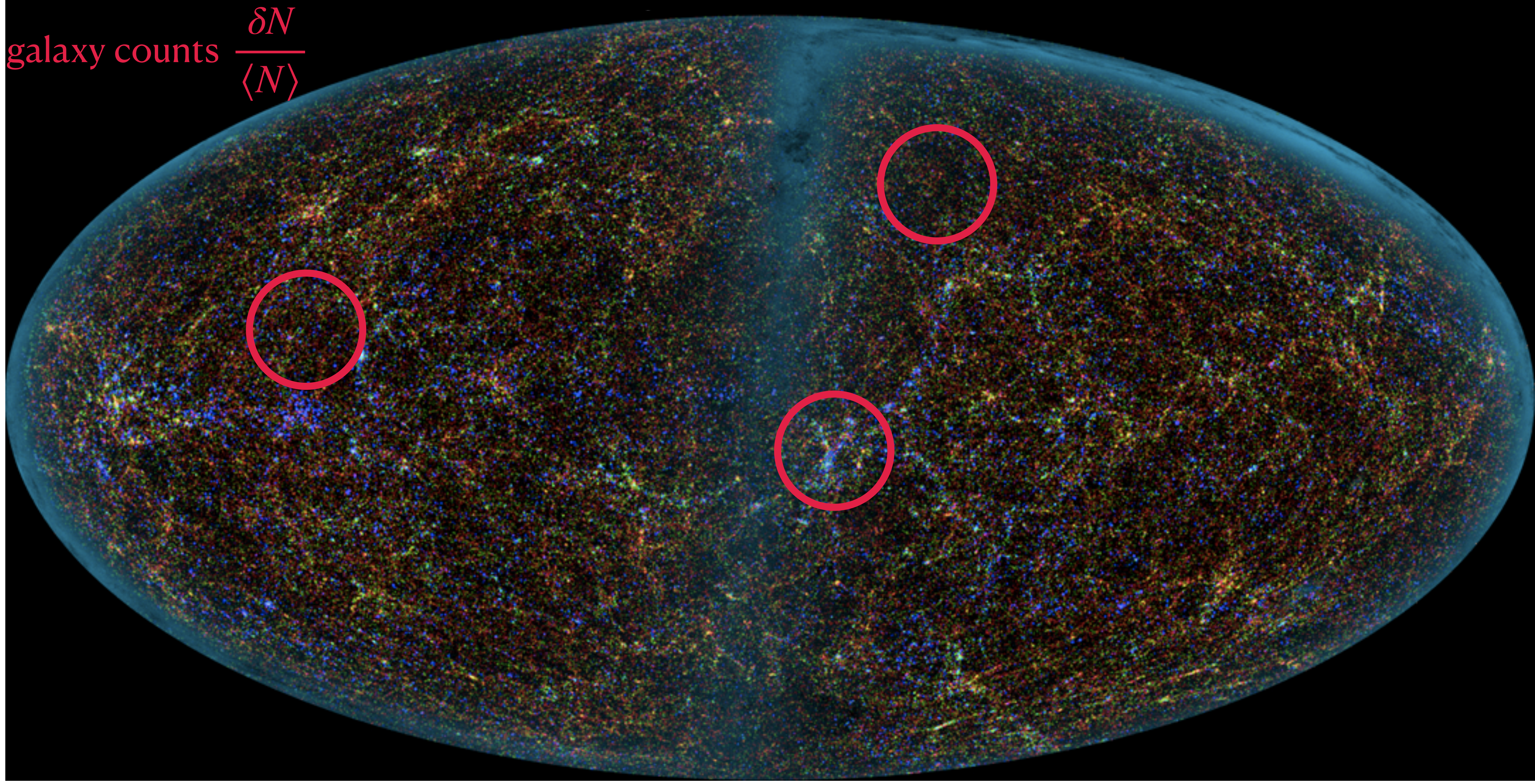
In the early universe, $\langle\rho\rangle = \rho_{\mathrm{crit}}$.

At $z = 0$, we observe $\delta \approx \dfrac{\delta N}{\langle N\rangle} \approx 1$ on scales of 8 Mpc. So if $\delta(t) \sim a(t)$, then at $z = 1000$ we expect $\delta \approx 10^{-3}$.

Instead, we observe $\delta \sim \dfrac{\Delta T}{T} \approx 10^{-5}$

— off by a factor of 100!





You can't get here from there

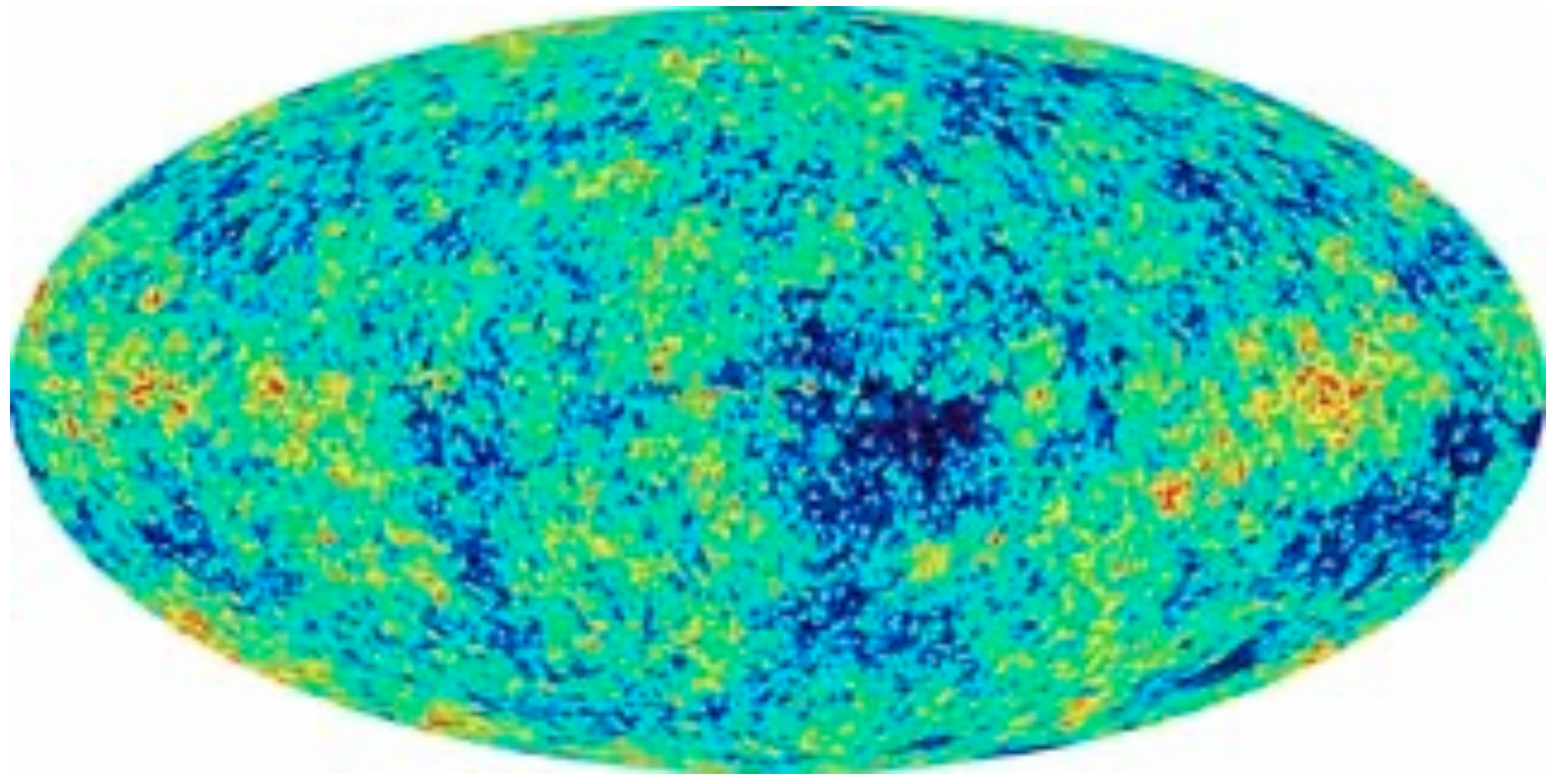
The factor of 100 offset in density and temperature fluctuations is a prime motivation for non-baryonic **cold dark matter** — a substance for which perturbations δ can grow sufficiently large while not leaving an imprint of corresponding magnitude on the CMB.

Radiation and baryon plasma tightly coupled at recombination, so a fluctuation in density is reflected by one in temperature: $\dfrac{\delta\rho}{\rho} \propto \dfrac{\Delta T}{T}$.

You can't get here from there

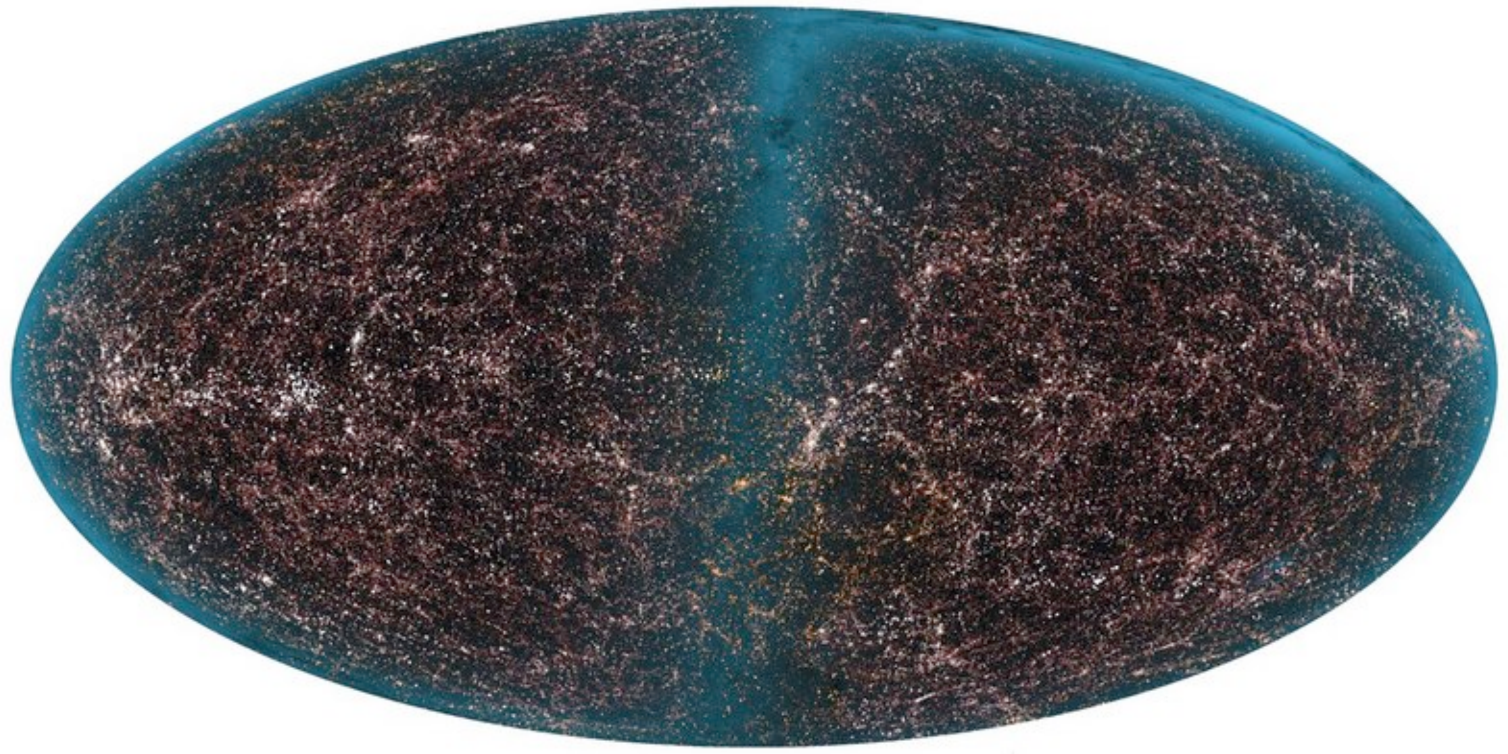
There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons (e.g., new particles with no E&M interactions).

t = 3.8 x 10^5 yr



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

t = 1.4 x 10^{10} yr



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

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

Along with BBN, the smoothness of the CMB was an important motivation for the **Cold Dark Matter** (**CDM**) paradigm.

You can't get here from there

Need something to kick-start the formation of structure. Gravity + baryons alone won't get the job done. Gravity will grow structure, but it is weak so acts slowly. The heavy baryons want to clump up via gravity, but the relativistic photons don't. This precludes structure formation before decoupling. The temperature fluctuations observed in the CMB set the starting point for the growth of large scale structure.

The conventional solution invokes non-baryonic cold dark matter - some new mass component that moves slowly ("cold" so it can clump) that doesn't interact with photons (so it can start to clump earlier).

The unconventional solution would be to modify gravity to speed the rate of growth of large scale structure.