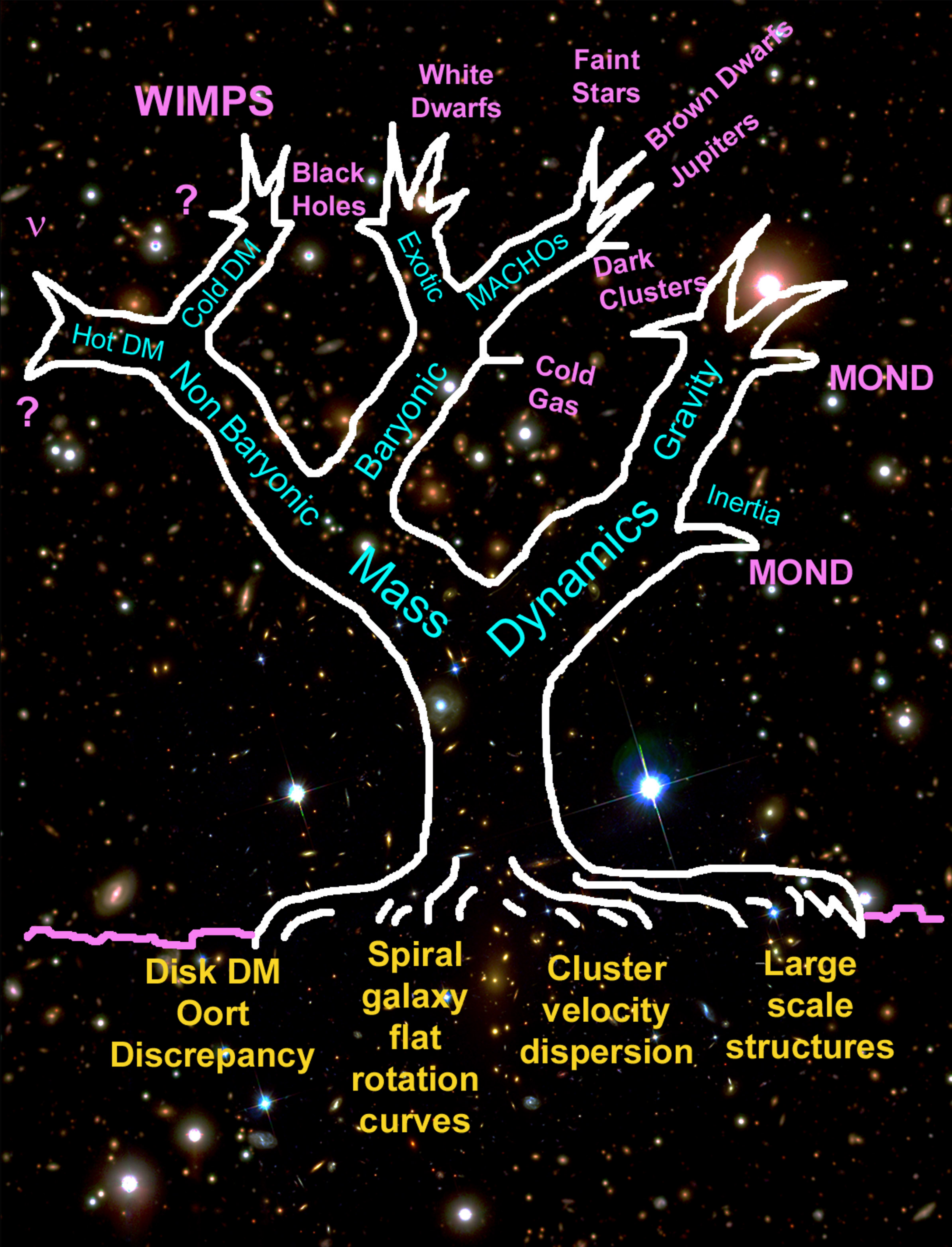
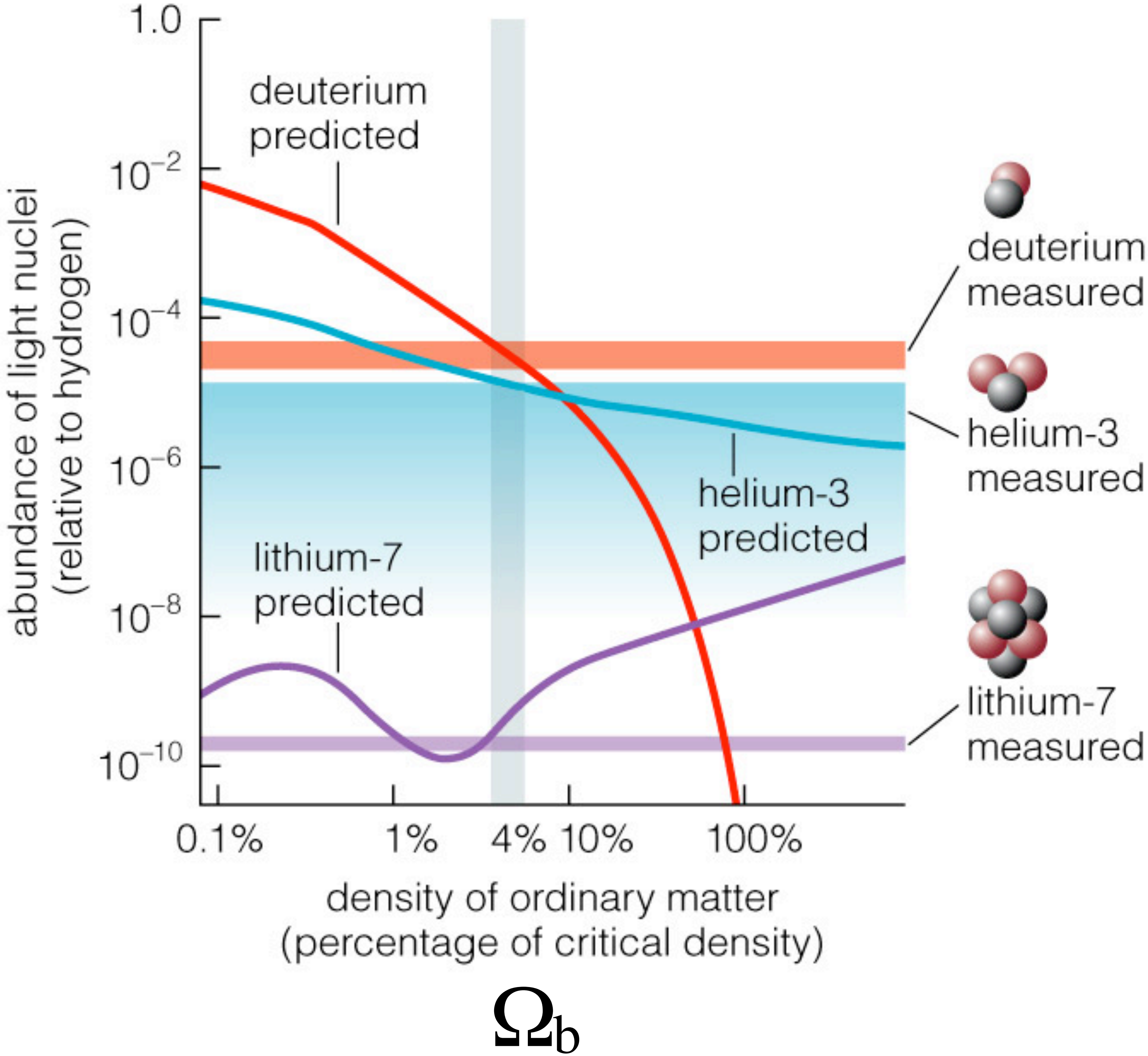
Dark Matter

ASTR 333/433

TODAY

Missing Baryons

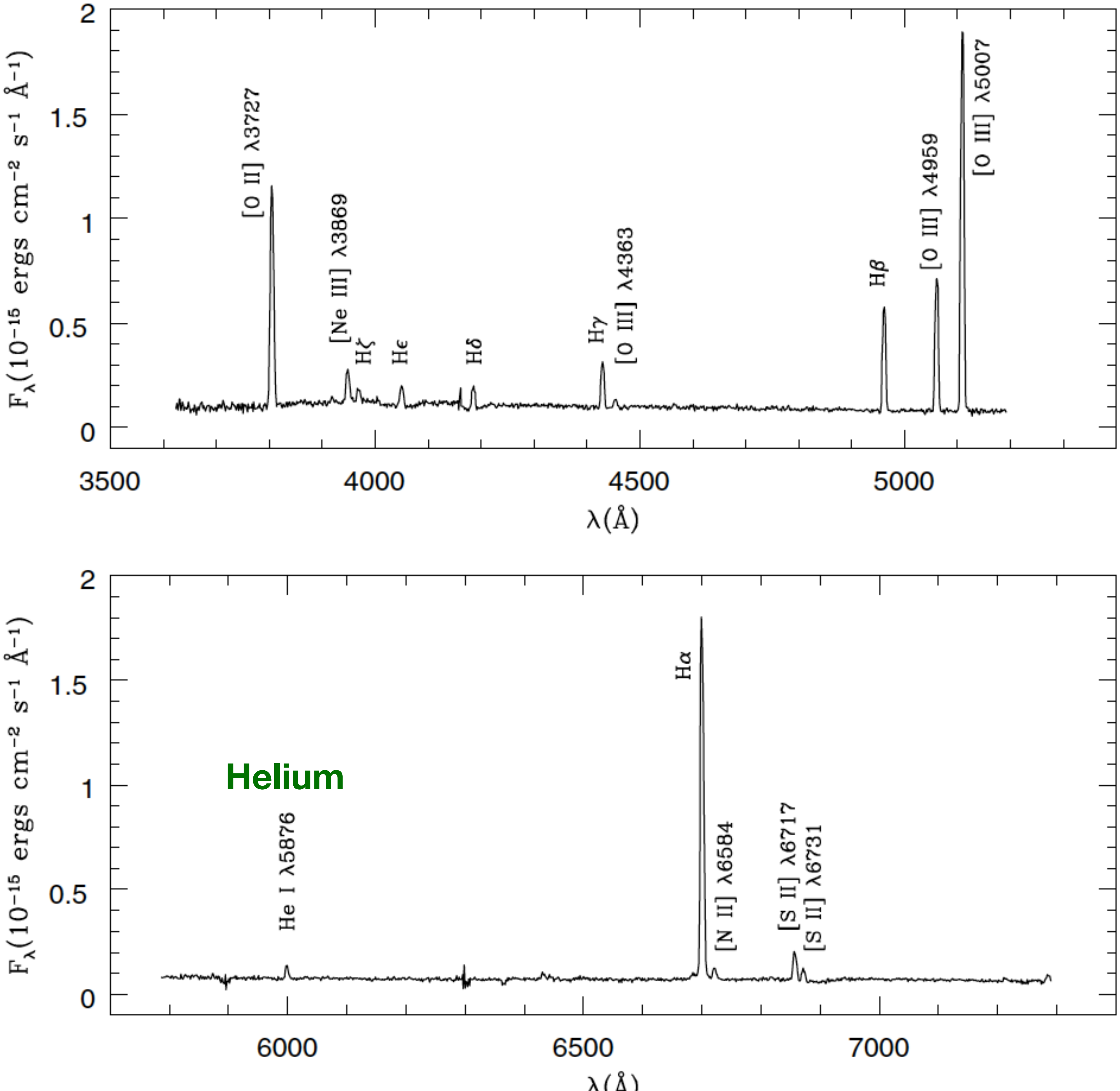




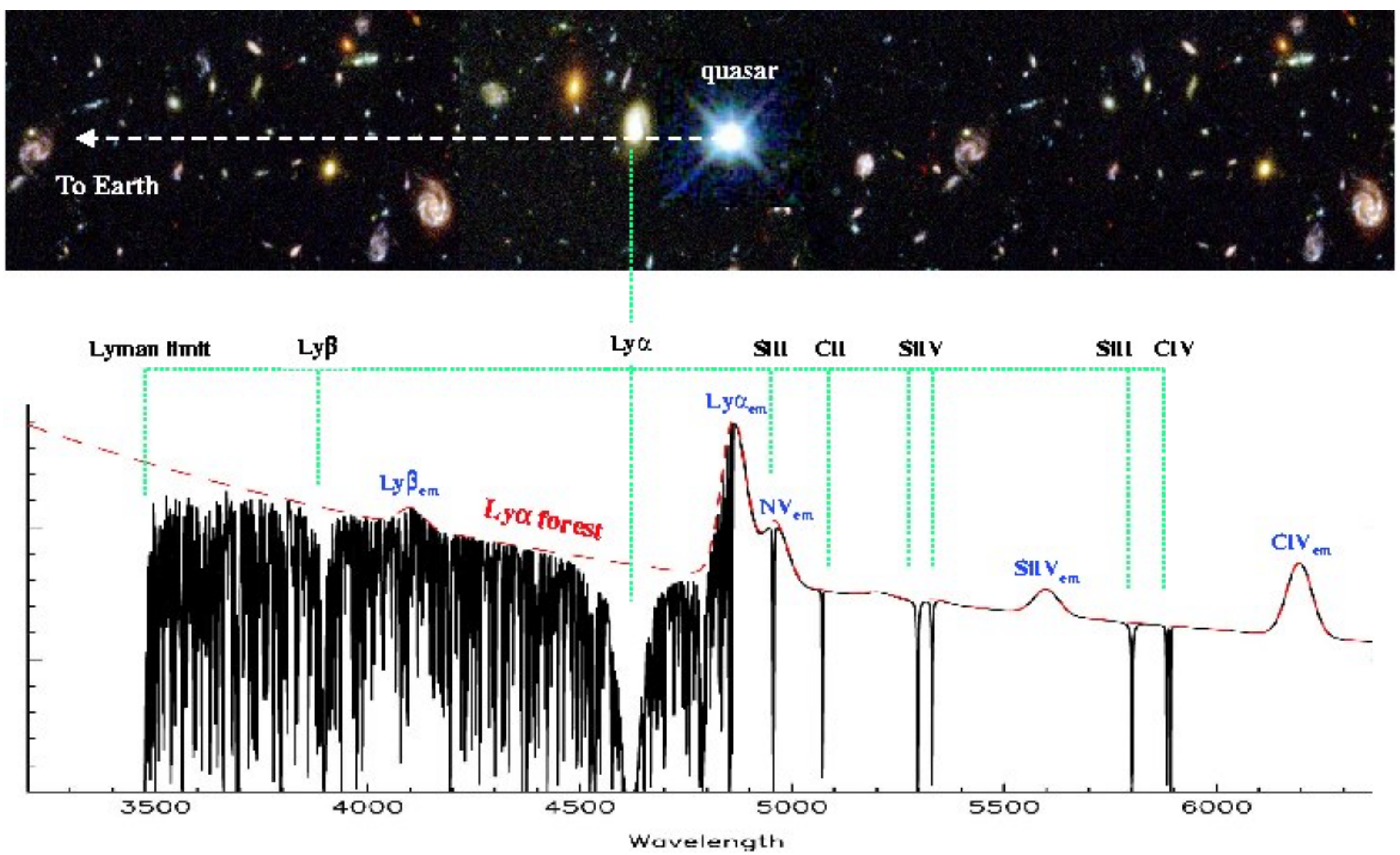
BBN gets the abundances of deuterium, helium, and lithium right if the mass density is about 4% of the critical density.

UGC 12695

Spectrum of
HII region S1(2)



D/H in absorption along the line of sight to high redshift QSOs



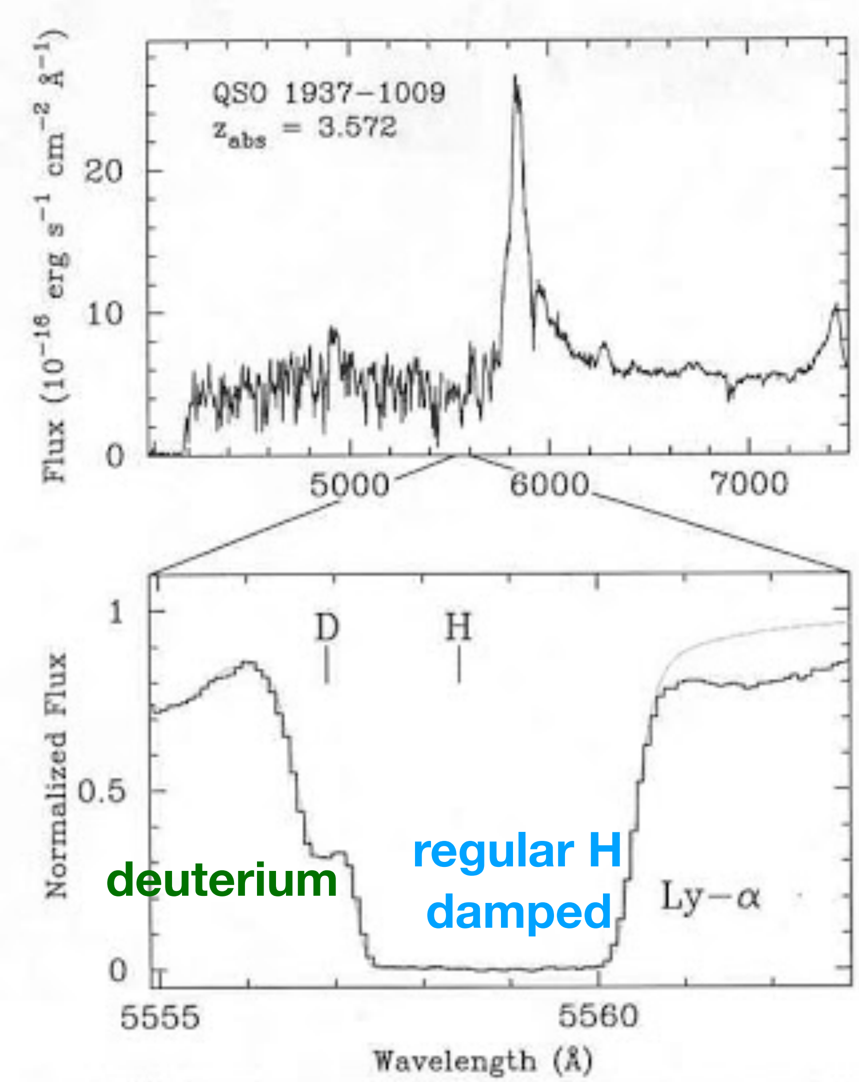
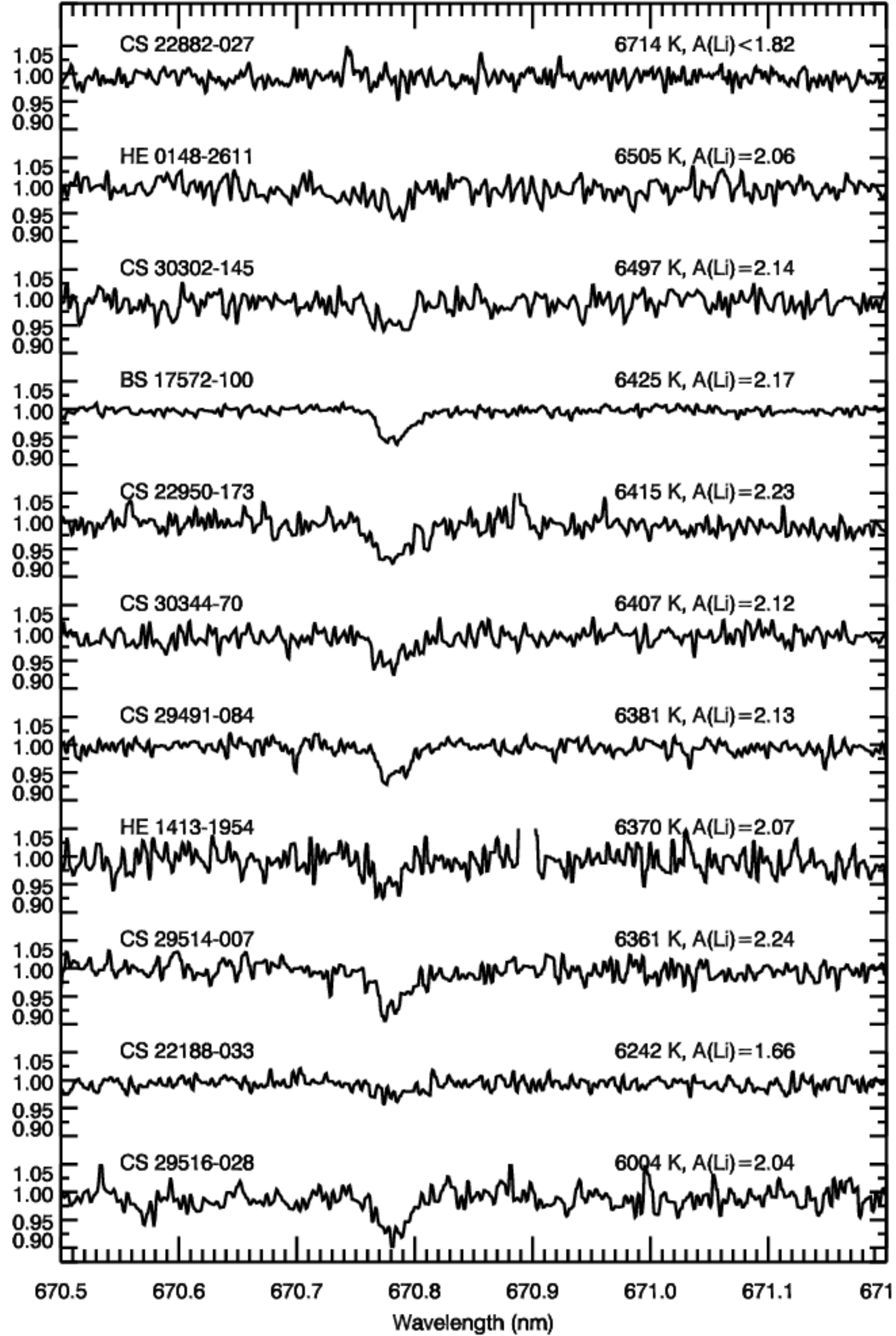


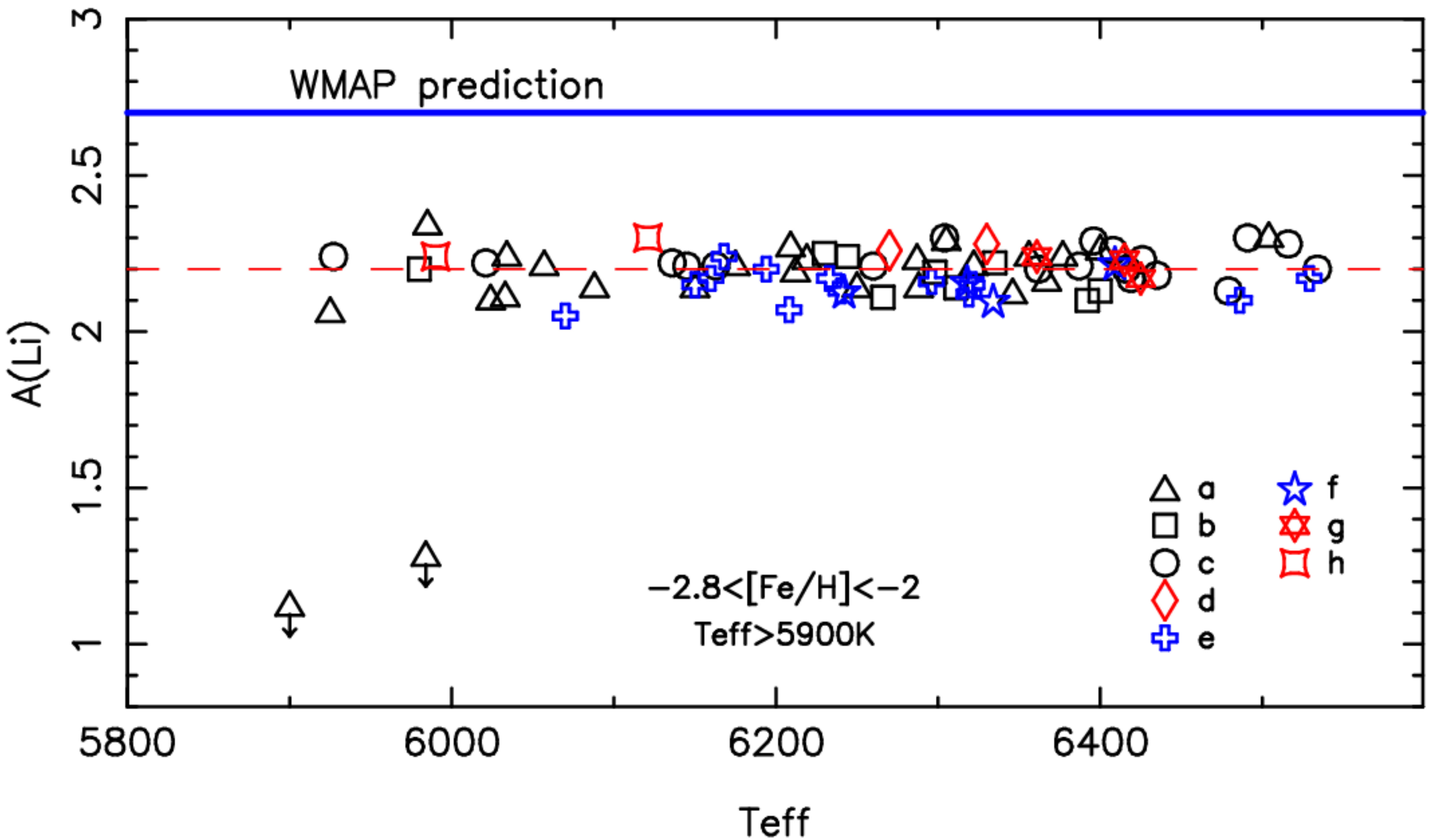
FIG. 3. Spectrum of Q1937-1009; blueward of the characteristic Lyman-α emission line of the quasar is the "forest" of Lyman-α absorption due to the hundreds of intervening gas clouds. The lower panel shows a blowup of the region around the deuterium detection, a cloud at redshift $z = 3.572$, and the model fit.

Stellar spectra
showing Lithium absorption

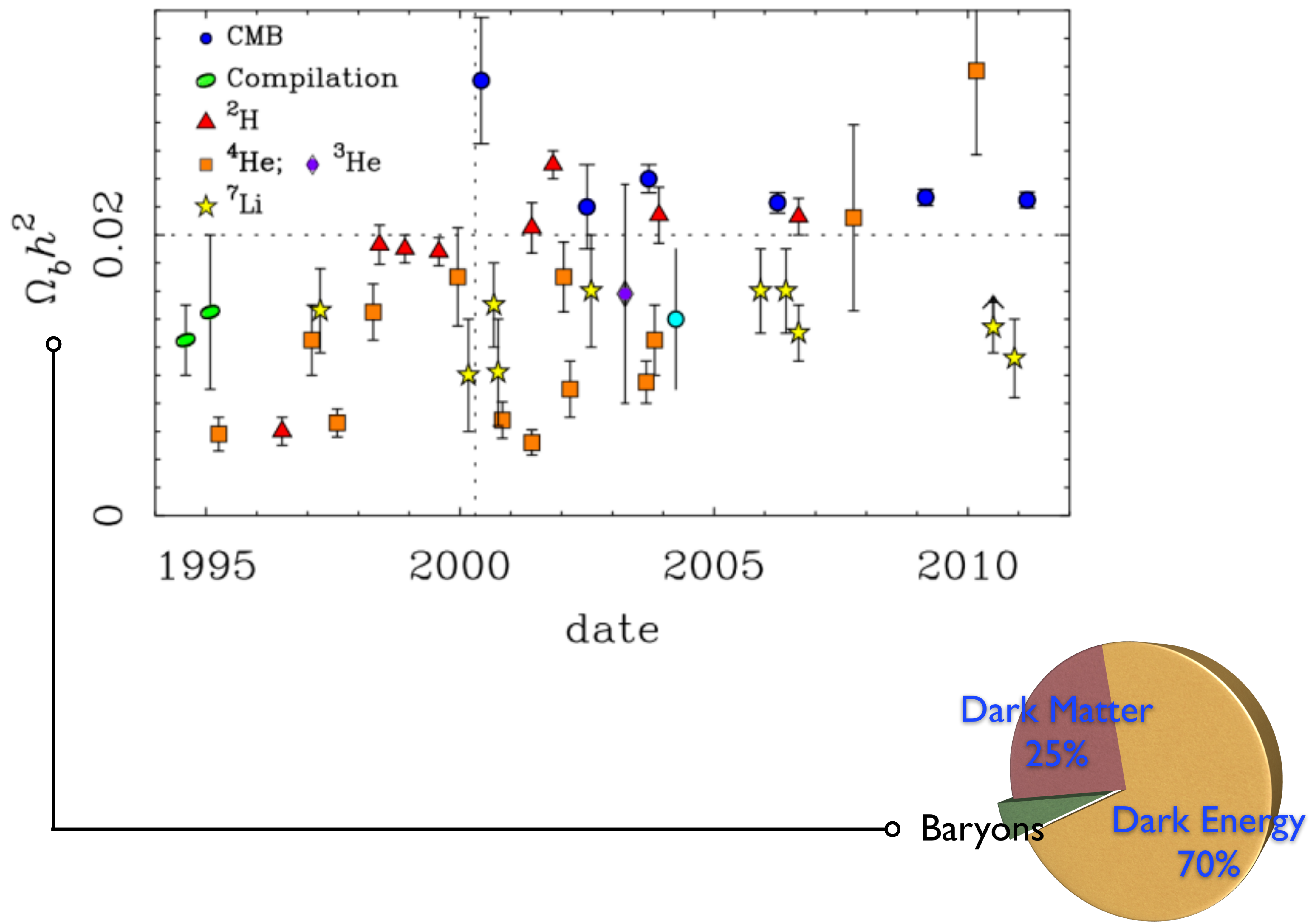


Lithium abundance in old, metal poor stars

the Spite plateau



Abundance observations translated into BBN baryon density



$\Omega_b \approx 0.04$ BBN baryon density

$\Omega_m \approx 0.30$ gravitating mass density

There is a hierarchy of missing mass problems

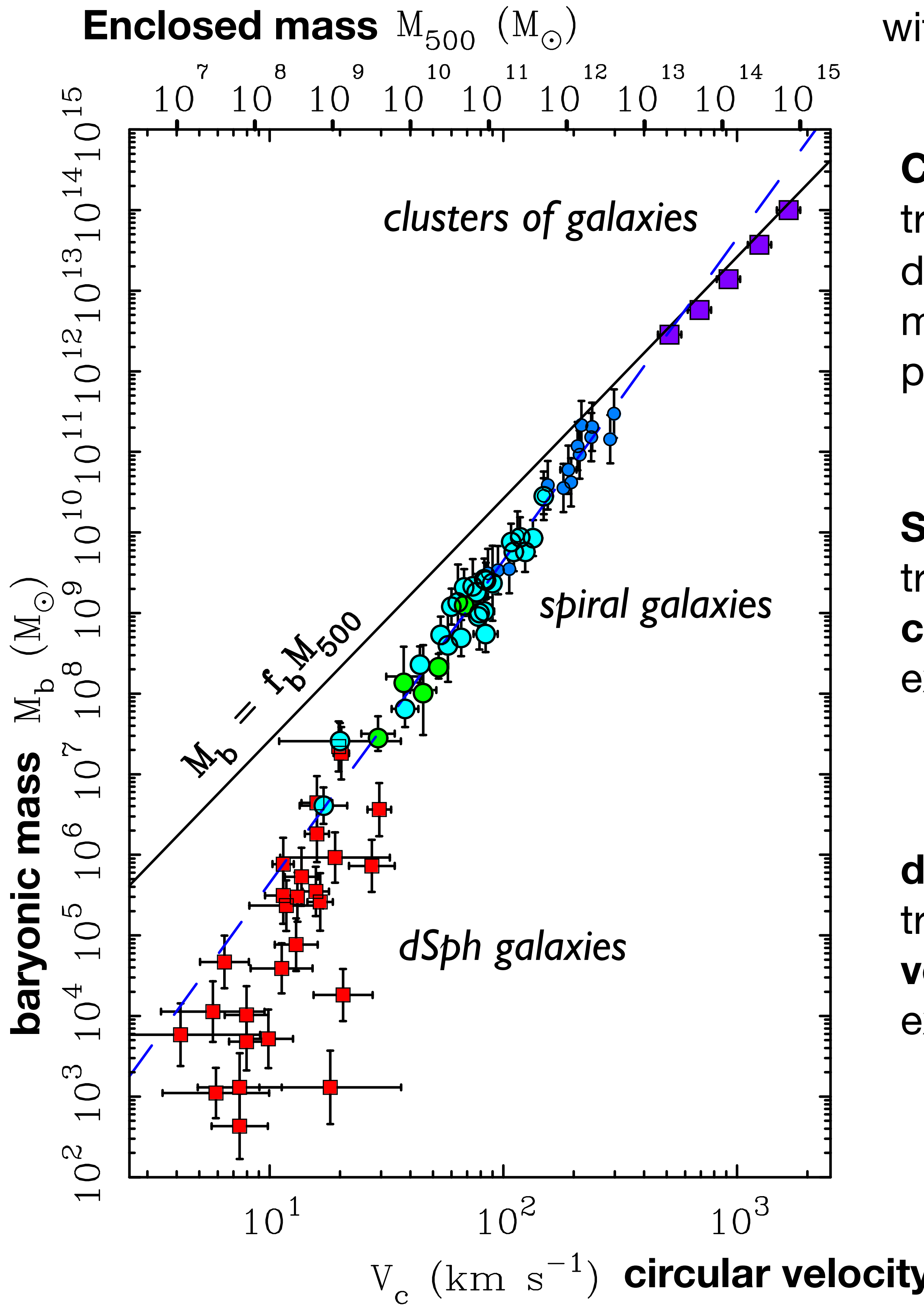
$M_b < f_b M_{200}$ halo missing baryon problem
(not enough baryons in each DM halo)

$\sum \Omega_{b,obs} < \Omega_{b,BBN}$ 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)

Mass budget

Basically an accounting exercise: for every object, how much normal matter is there? How much total mass?



within an over-density $\Delta = 500$

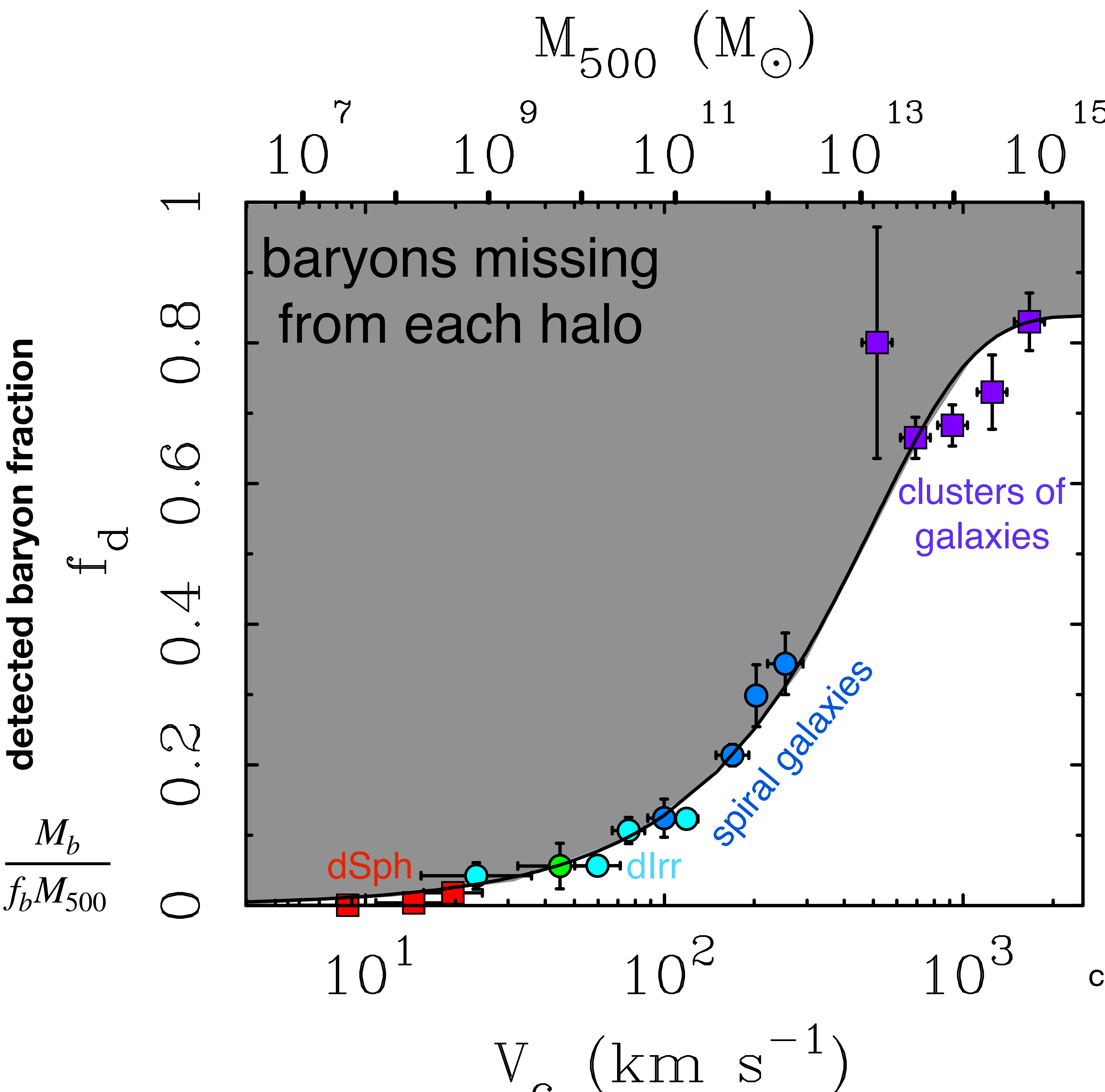
Clusters
traced by **X-rays**
data are binned: many clusters per point; hides scatter

Spirals
traced by **circular velocity** extrapolated to R_{500}

dwarf Spheroidals
traced by **velocity dispersion** extrapolated to R_{500}

McGaugh et al (2010)

Expect each halo to contain its fair share of baryons, but it don't:

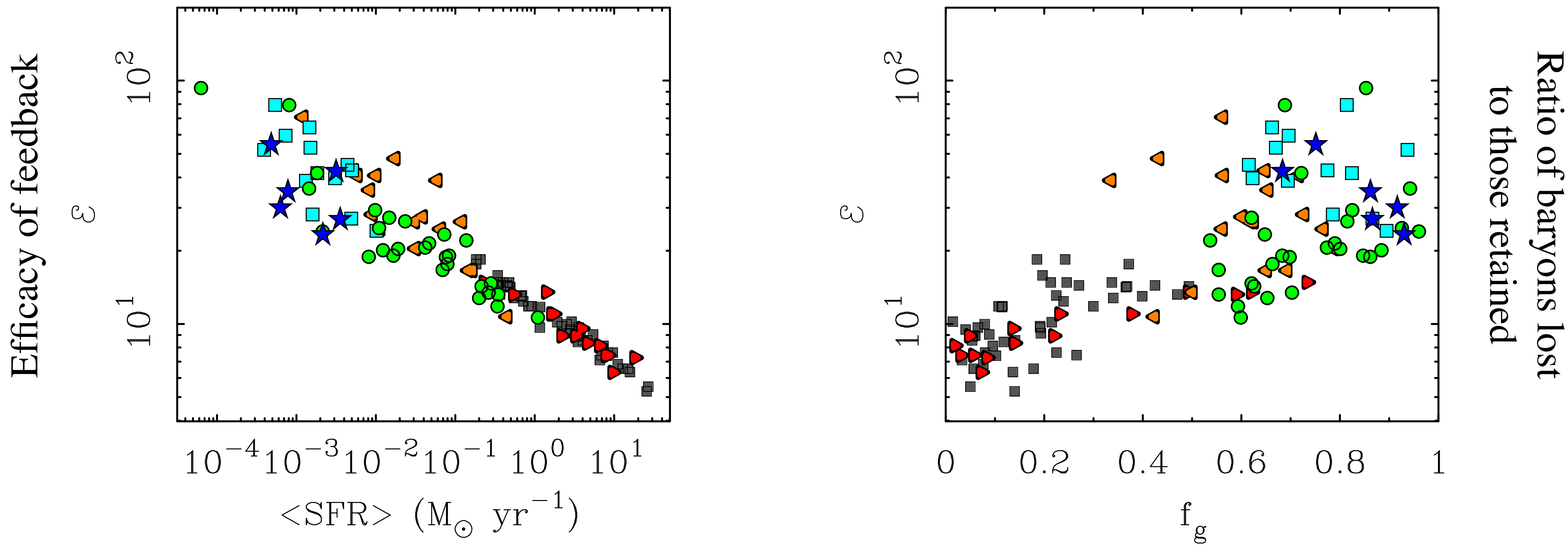


$$f_d = \frac{M_b}{f_b M_{500}}$$

cosmic baryon fraction
$f_b = 0.17$

Feedback

Invoked here to explain the over-cooling problem:
why aren't the baryons visible?



The answer is unclear, but it is widely thought that either
(i) supernova feedback blows the excess baryons out of halos, or
(ii) feedback heats baryons so they don't dissipate into the disk

SN feedback is thought to be most effective in low mass galaxies with small potential wells that can't retain material that explodes outwards.

You might expect these processes to be more effective when there is more star formation (more SN, more heating) but the opposite is observed. There is also more gas left over in galaxies that have suffered the most feedback, so it can't blow out 100% of the gas.

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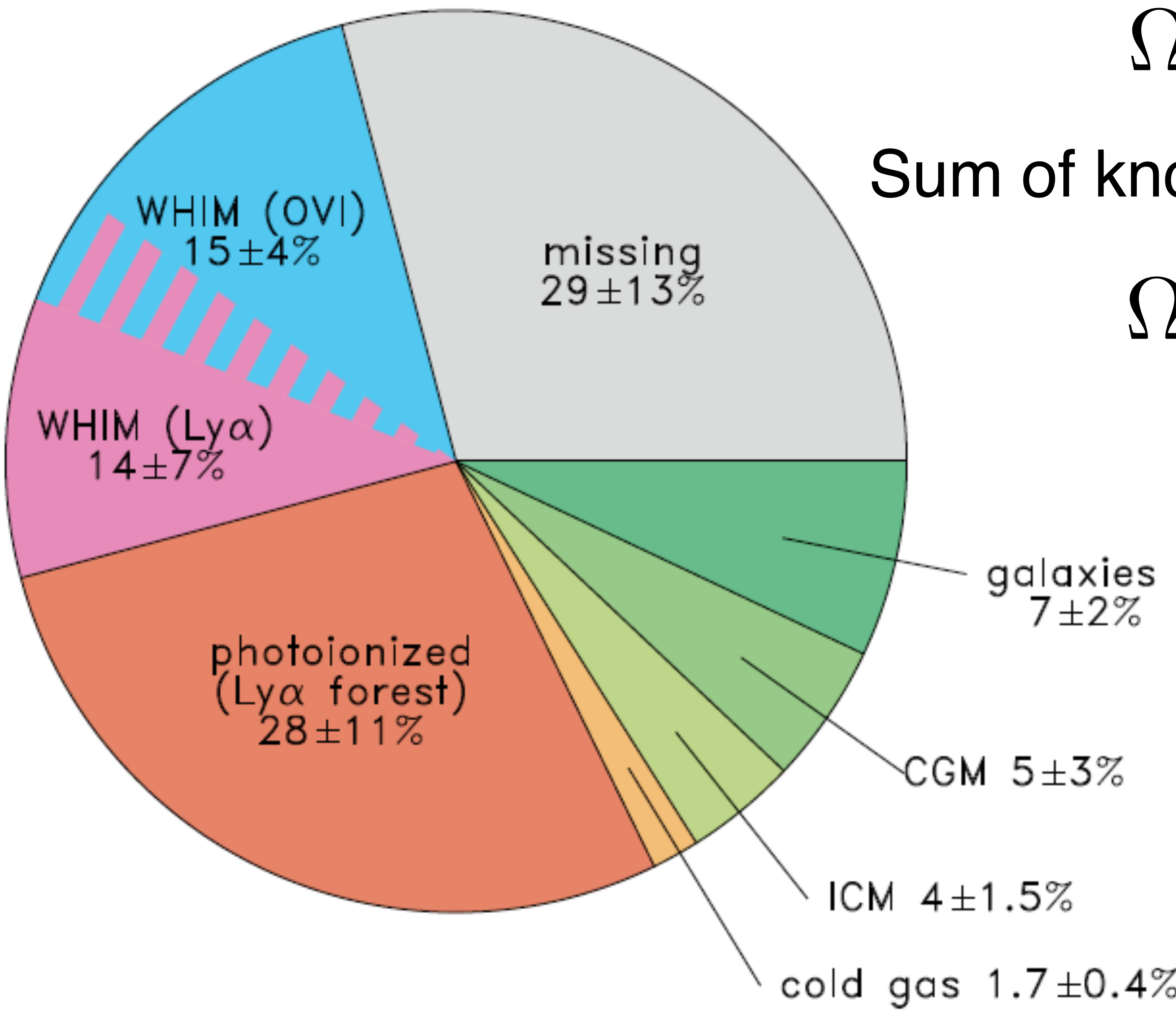
The global missing baryon problem

Cosmic baryon budget

(Shull et al arXiv:1112.2706)

$@ z = 0$



Big Bang Nucleosynthesis
CMB fits give

$$\Omega_b h^2 = 0.022$$

Sum of known baryons only

$$\Omega_b h^2 \approx 0.017$$

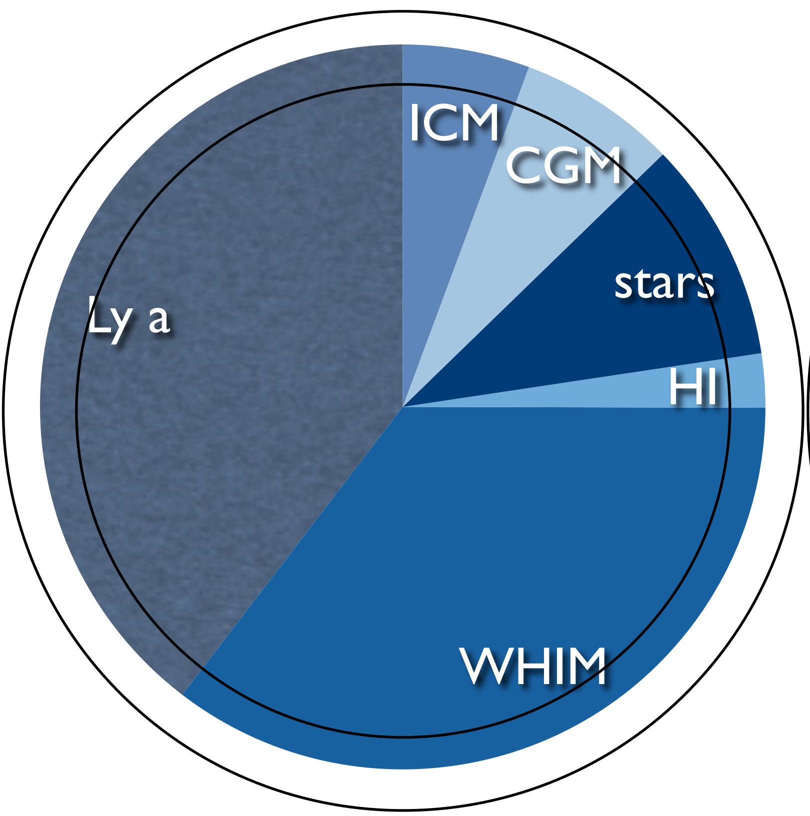
Baryon reservoirs

- Galaxies
  - Stars 7% → integrate luminosity function; estimate M*/L
  - cold gas 2% → integrate HI mass function; estimate molecular gas fraction
  - circumgalactic medium (CGM) 5% → absorption of highly ionized gas along sight lines; estimate ionization fraction and covering factor
- Clusters
  - intracluster gas (ICM) 4% → integrate X-ray cluster luminosity function
- Intergalactic Medium (IGM)
  - Warm-Hot IGM 29% → absorption of highly ionized gas along sight lines; estimate ionization fraction
  - Lyman α forest 28% → Lyα absorption lines in QSO spectra

% uncertainties are large

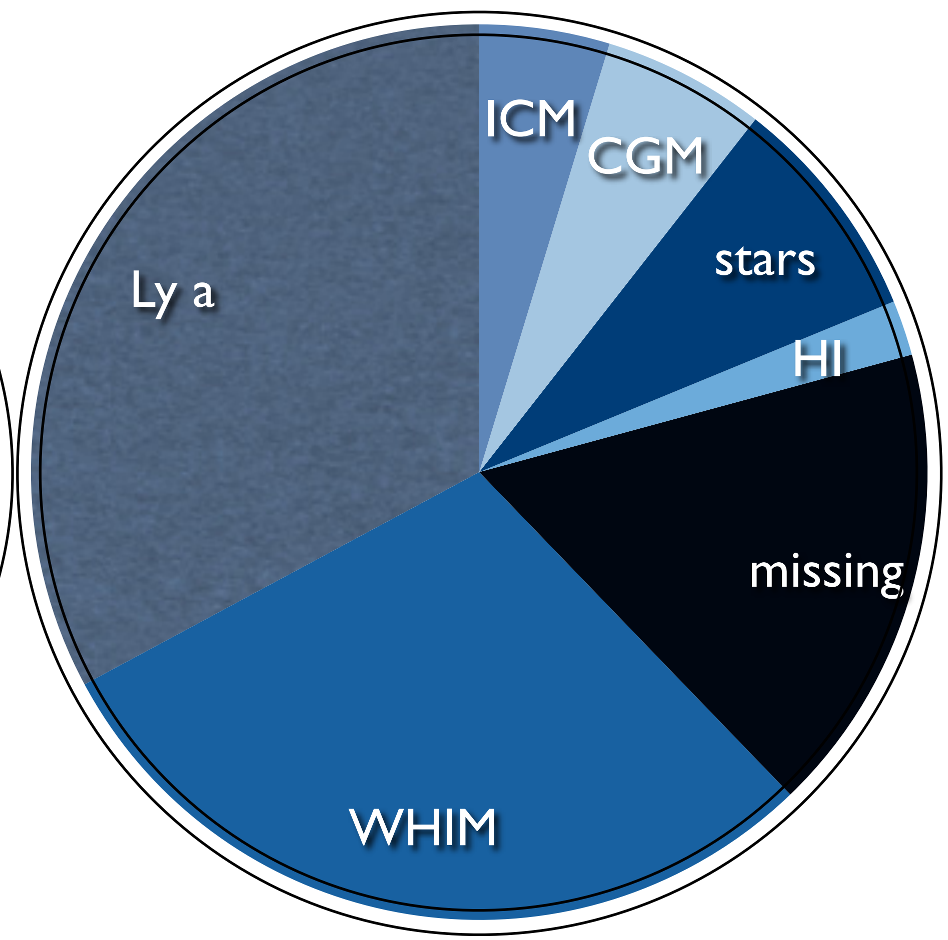
How many baryons are missing depends on how many BBN predicts

BBN 1991 (Walker et al.)



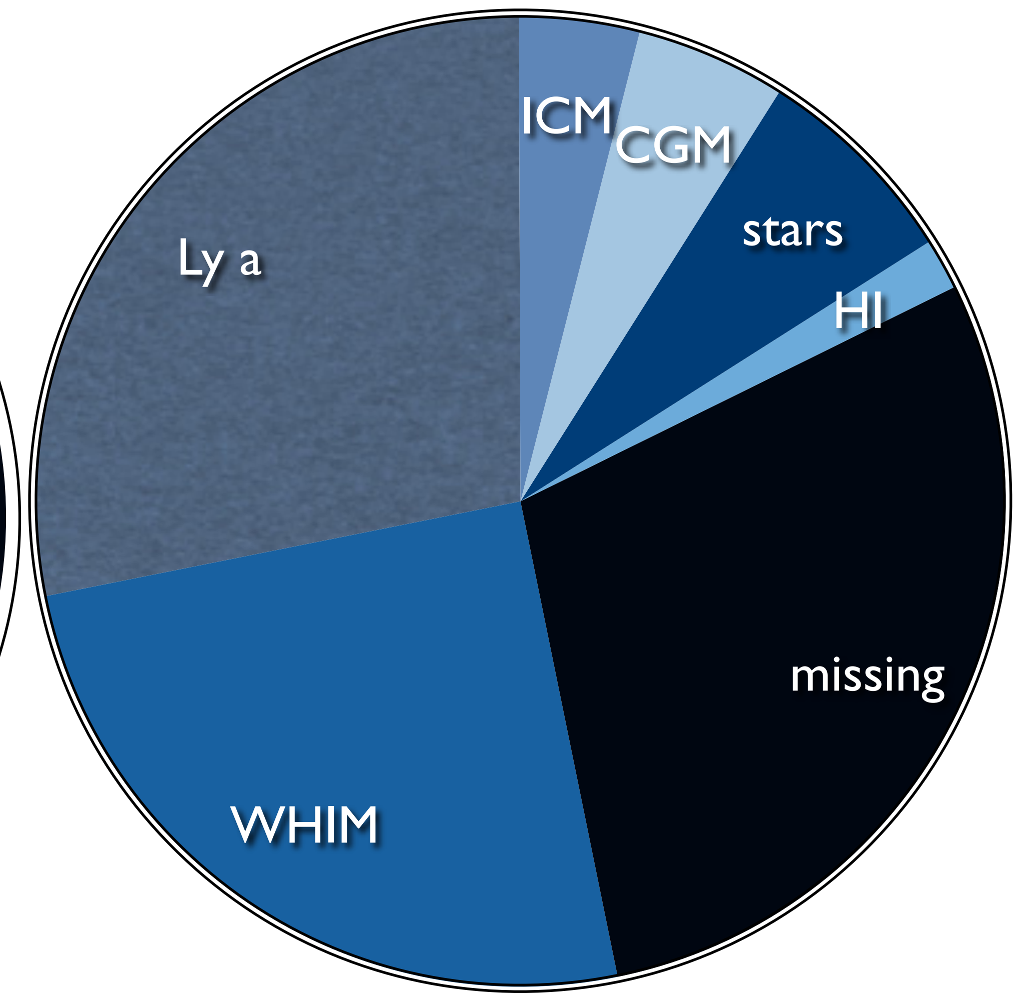
$\Omega_b h^2 = 0.0125 \pm 0.0025$

BBN 1999 (pre-CMB D/H)



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

CMB 2015 (Planck)



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

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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)

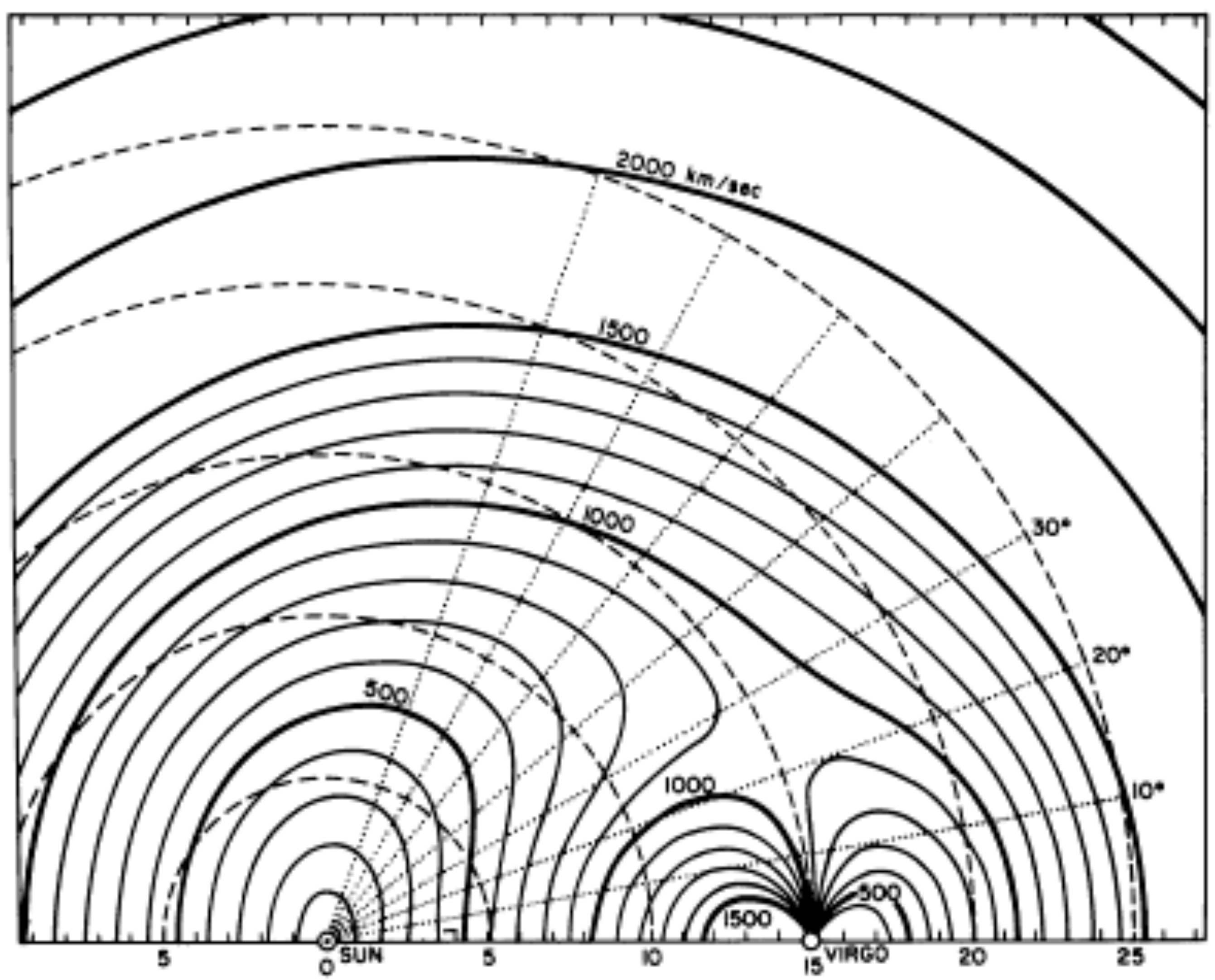

FIG. 1.—On a two-dimensional grid with the Earth and the Virgo cluster on the x axis, redshift contours are plotted for a Hubble flow perturbed by a Virgocentric flow. An infall velocity of 400 km s^{-1} at our position is assumed. A pure Hubble flow would be concentric circles.

Davis et al. (1980) found

$$\Omega_m = 0.4 \pm 0.1$$

with modern distances this becomes

$$\Omega_m = 0.25 \pm 0.05$$

basically unchanged for nearly 40 years

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.

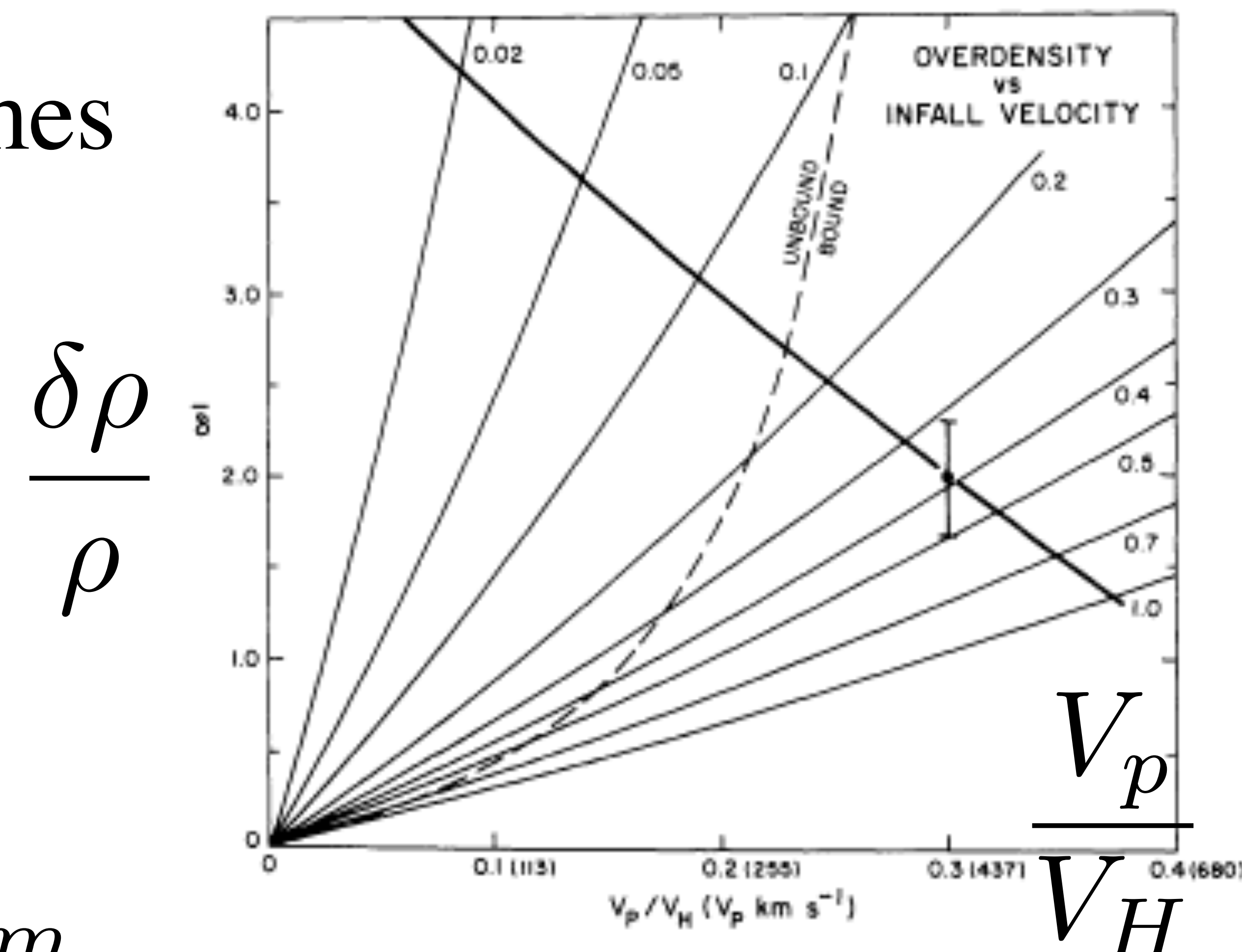

FIG. 1.—The mean overdensity of Virgo vs. v_p/v_H for various values of Ω. The x-axis is also labeled with v_p, using a recessional velocity to Virgo of 1020 km s^{-1}. The measured overdensity is prescribed by the heavy line, and is marked at the favored position as given by the anisotropy of the Hubble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

There's more gravitating mass than BBN allows in baryons

Hence the need for non-baryonic dark matter