Why Plasma is not 99% of the Universe anymore

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Plasma still dominates in baryons today

- The present-day universe is almost fully ionized.
- How do we know that?

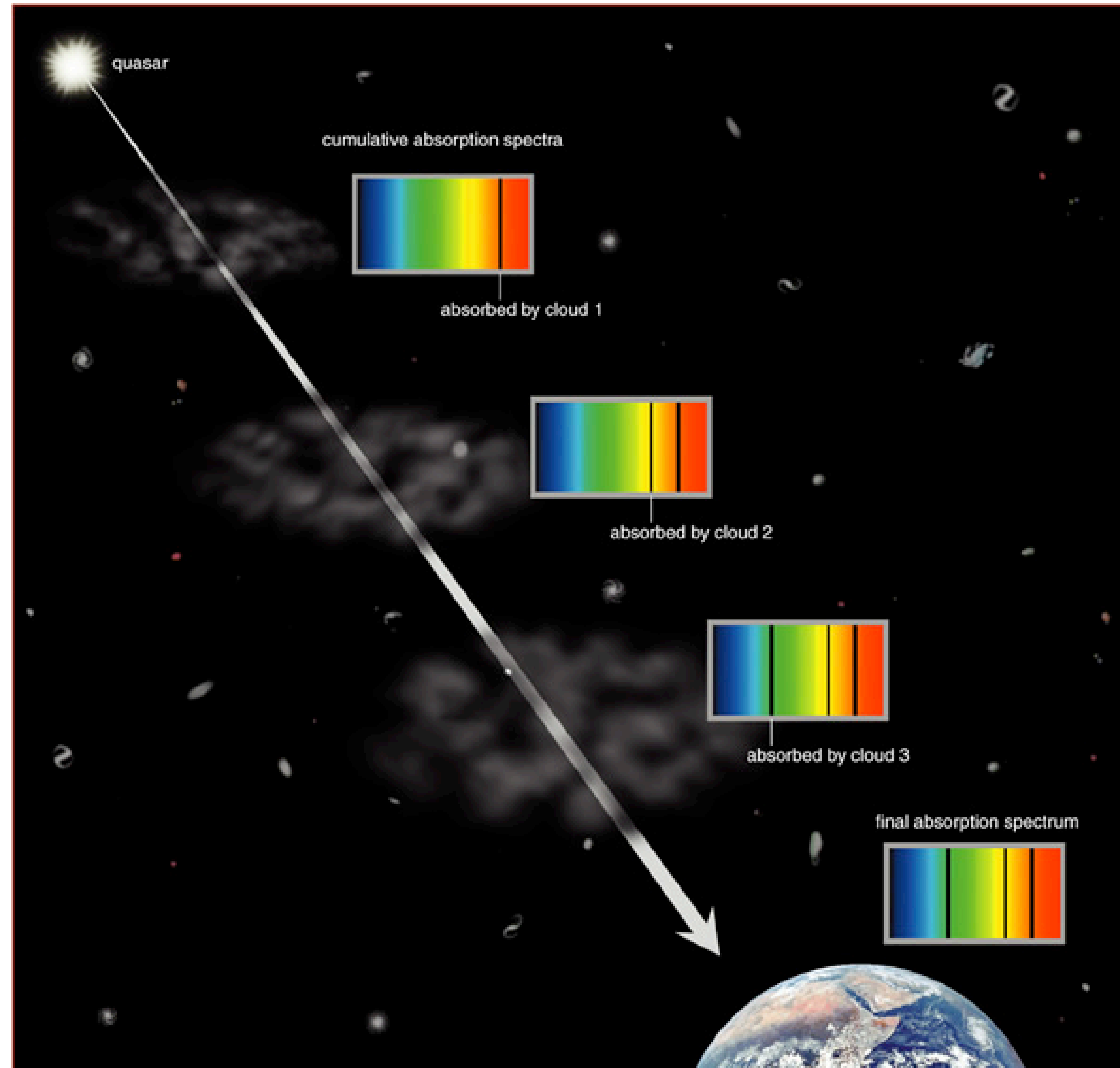
Gunn & Peterson (1965)

Gunn-Peterson Test

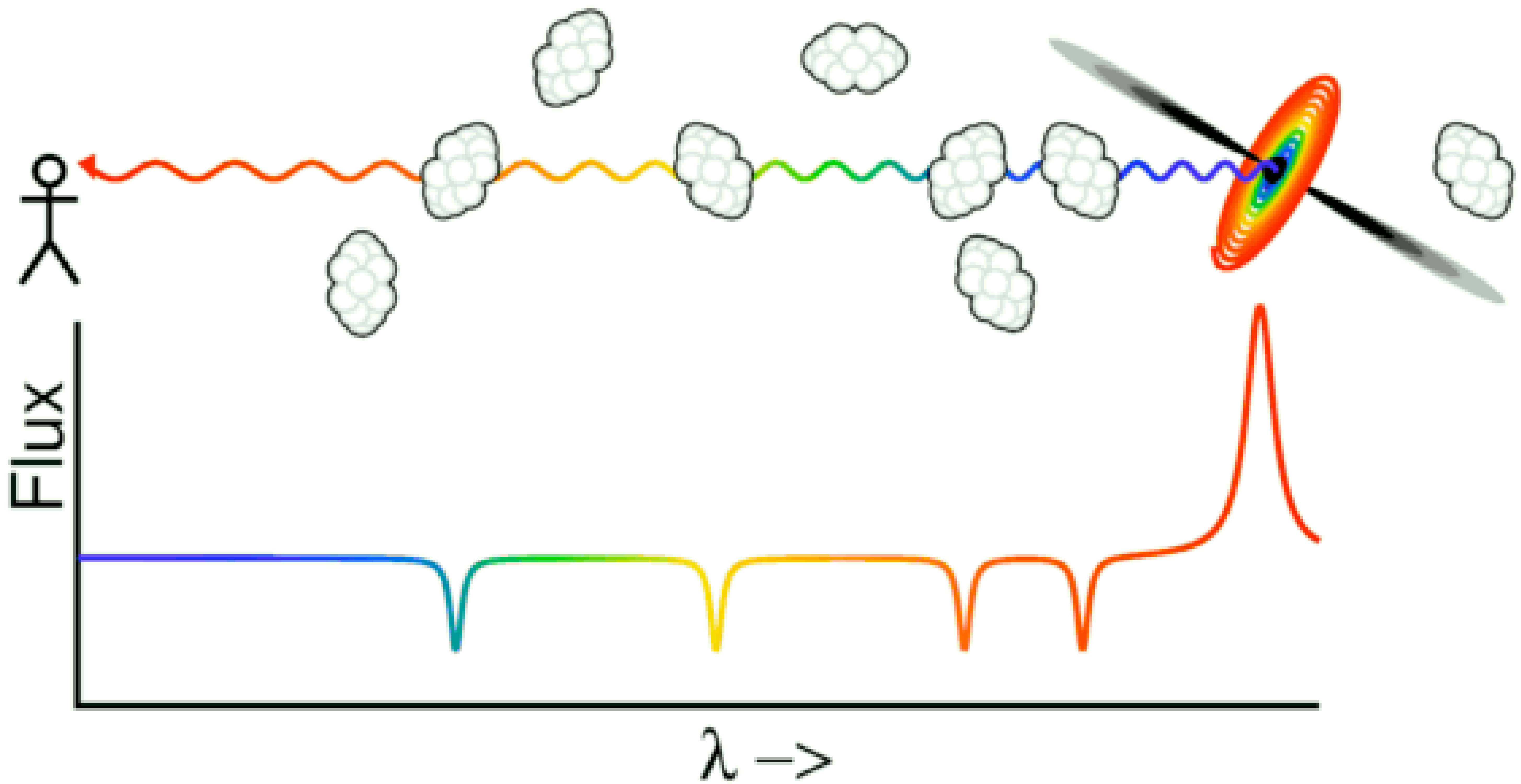
- Neutral hydrogen atoms are very good photon absorbers at the wavelength of "Lyman-alpha" line, the atomic transition from n=2 to 1 state.
  - Lyman-alpha = 1216 angstroms = 0.1216 nm
- The expansion of the Universe causes the light to be "redshifted"
  - When the size of the Universe doubles, the wavelength of the light also doubles.
  - 1+z = (observed wavelength)/(emitted wavelength)

Use Quasars as Backlight

- Neutral hydrogen clouds between the sources and Earth absorb the Lyman-alpha lines in **their rest frame**.
- We observe absorption lines at various wavelengths, depending on where (when) these photons were absorbed.



Schematic Picture

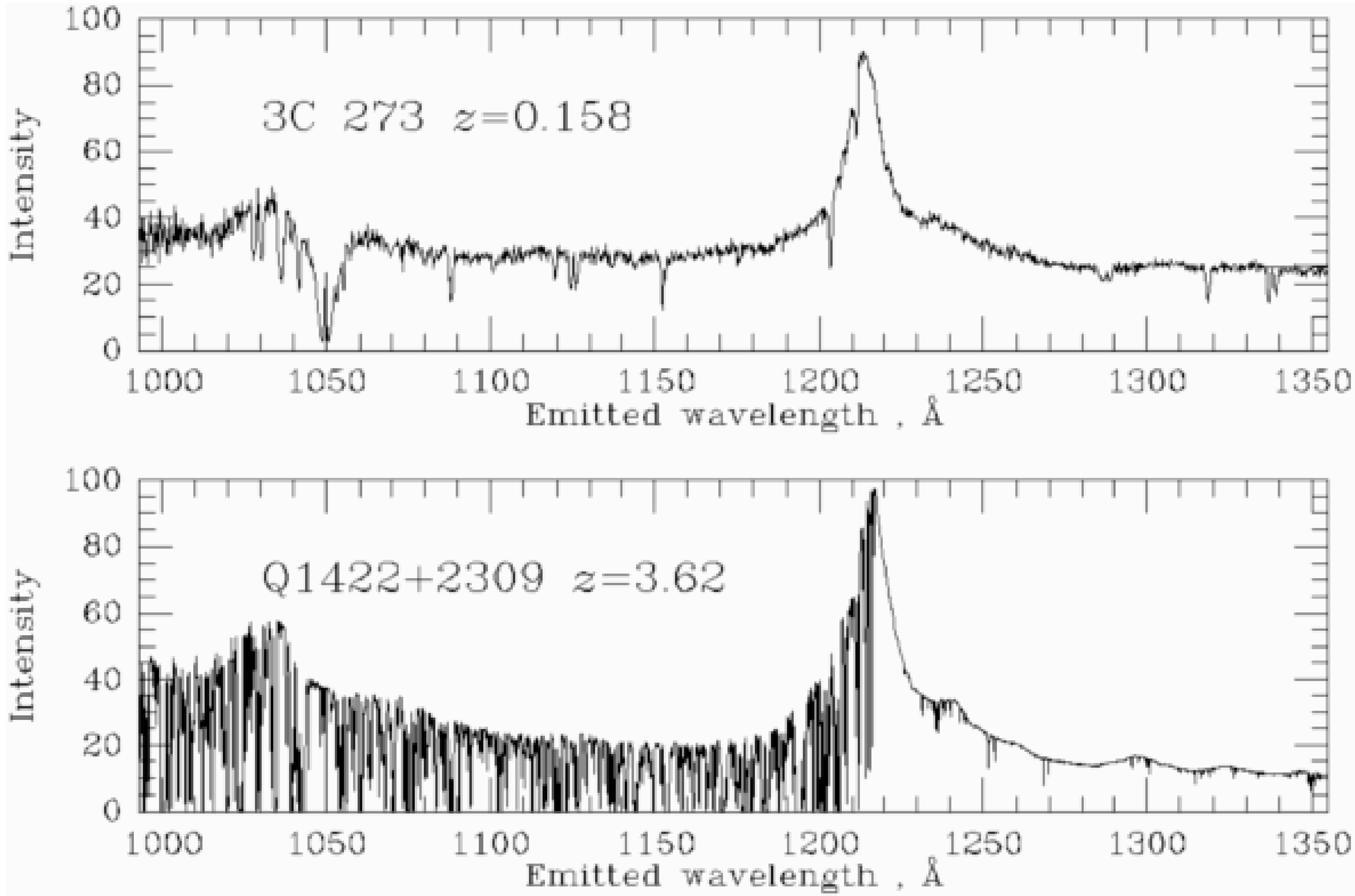


- We see absorptions at the locations of the clouds.
- If the Universe was neutral today, we should see the complete absorptions **everywhere** -- not just at the locations of clouds!

Real Data

- More distant, high-redshift quasars show more absorption lines because there are more clouds between us and them.

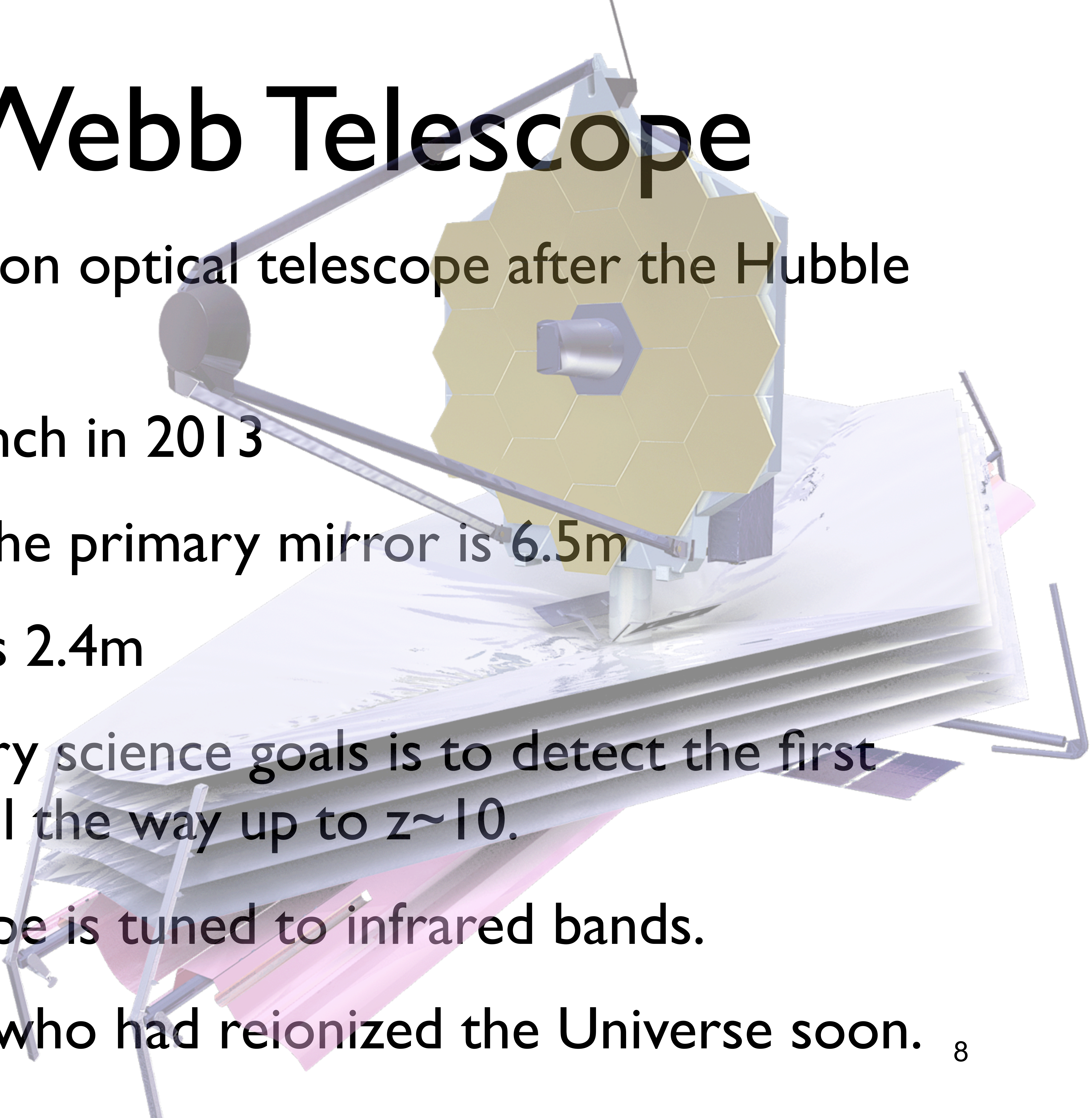
- But, the important thing is that **we don't see the complete absorption** -- significant flux still transmits between lines.



Universe Reionized

- We know that the Universe was in a plasma state when the Universe was younger than 380,000 years old (or z=1090; the size of the Universe 1/1091 of the present size; the temperature was hotter than 3000 K)
- 99.99% of atoms then turned into <u>neutral</u> hydrogen and helium atoms. (Dark Ages for plasma physicists!)
- But, we observe that the Universe is fully ionized from today (z=0) up to ~13 billion years ago (z=6)
- Somebody must have "reionized" the Universe!
  - The first generation of stars did this.

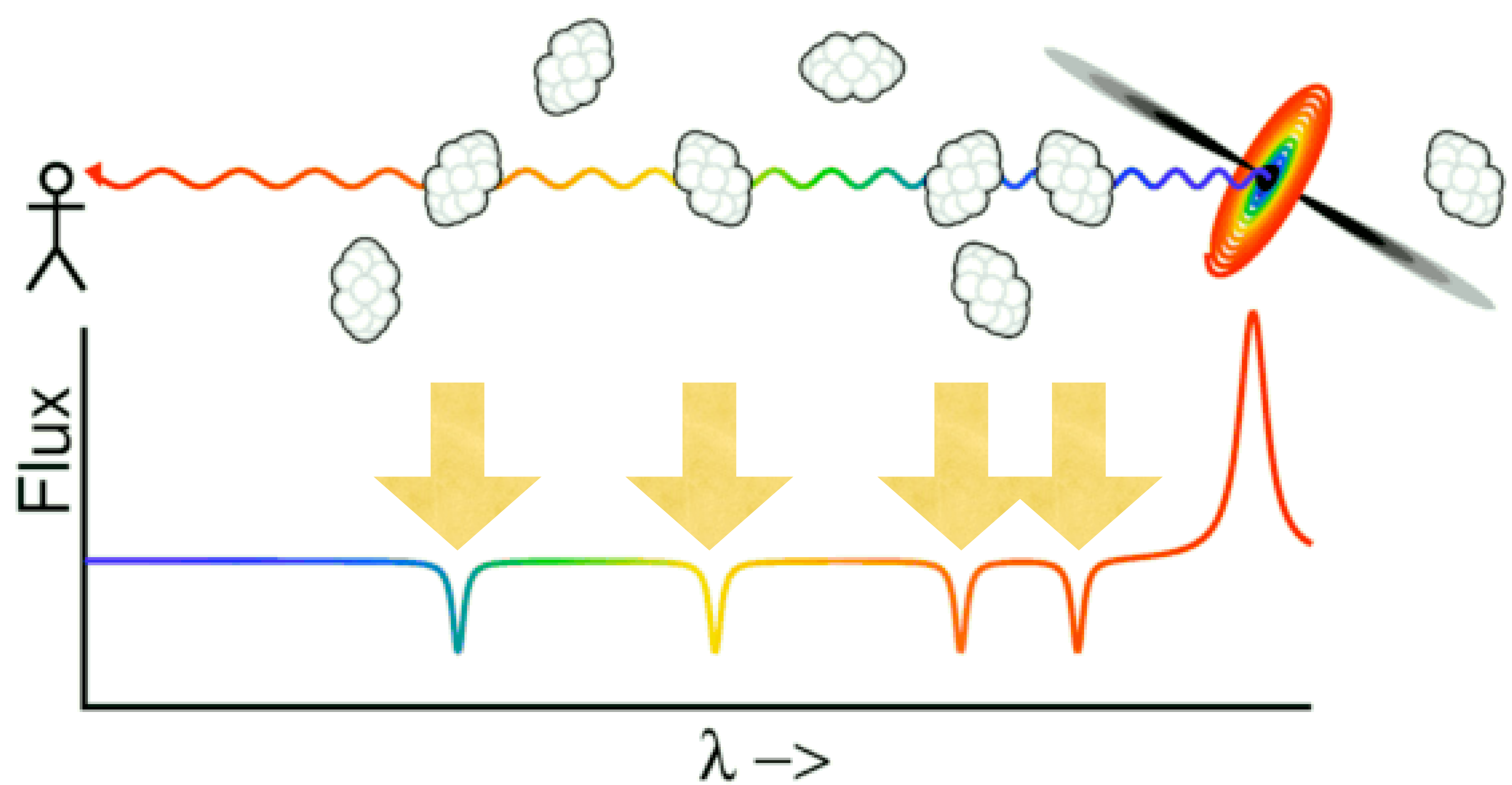
James Webb Telescope



- The next-generation optical telescope after the Hubble Space Telescope.
- Scheduled for launch in 2013
- The diameter of the primary mirror is 6.5m
  - HST's mirror is 2.4m
- One of the primary science goals is to detect the first galaxies directly, all the way up to z~10.
  - So, the telescope is tuned to infrared bands.
  - We will know who had reionized the Universe soon.

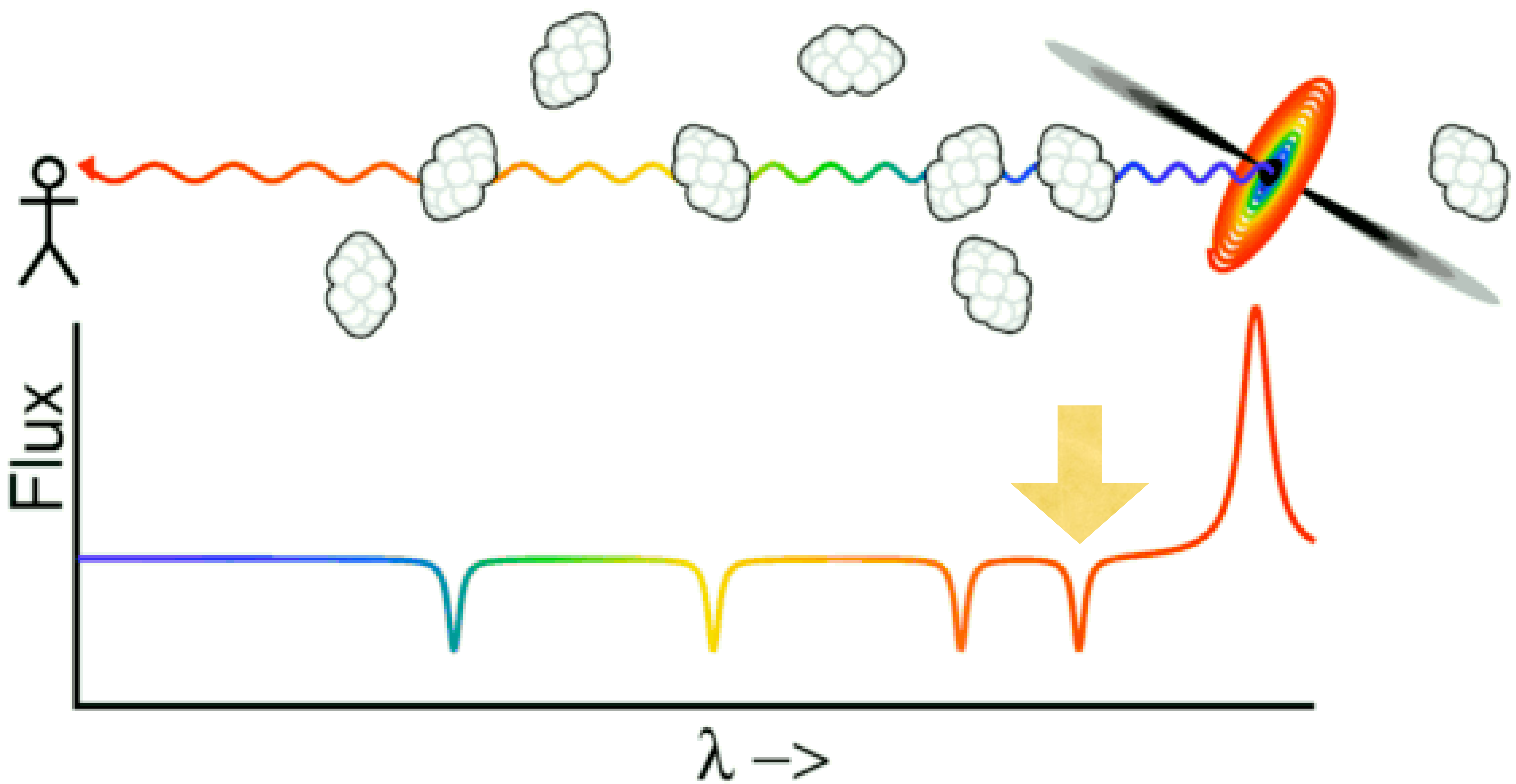
Look at the Clouds Themselves

- When you read "between the (Lyman-alpha) lines," we see that the Universe is fully ionized.
- However, what do we learn if we turn our attention to the clouds themselves?



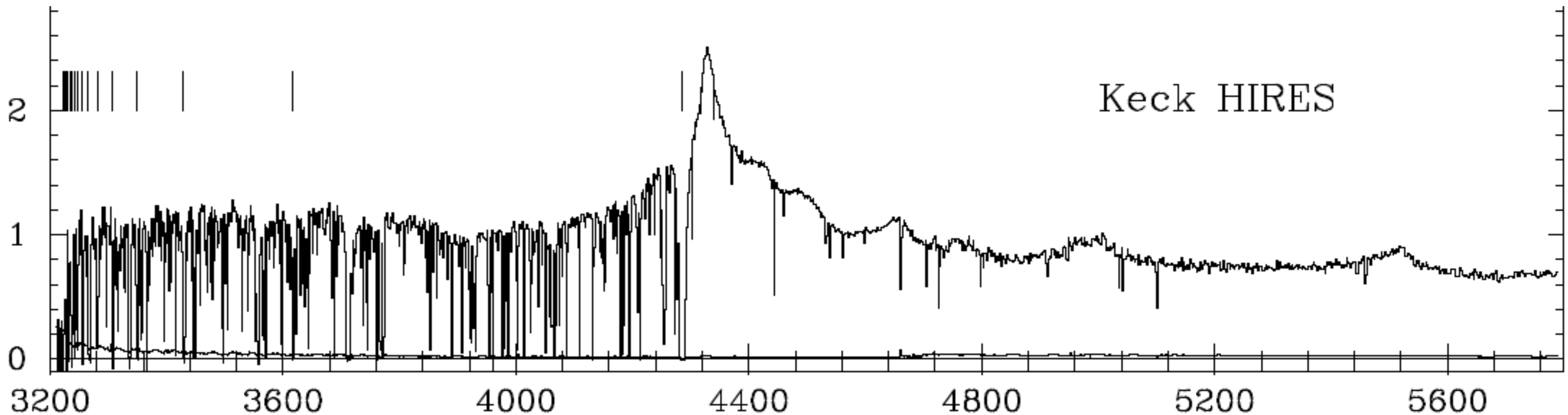
Clouds = Baryometer

- The neutral hydrogen atoms at high redshifts are excellent places to measure the primordial abundance of light elements: **hydrogen and deuterium**



Kirkman et al. (2003)

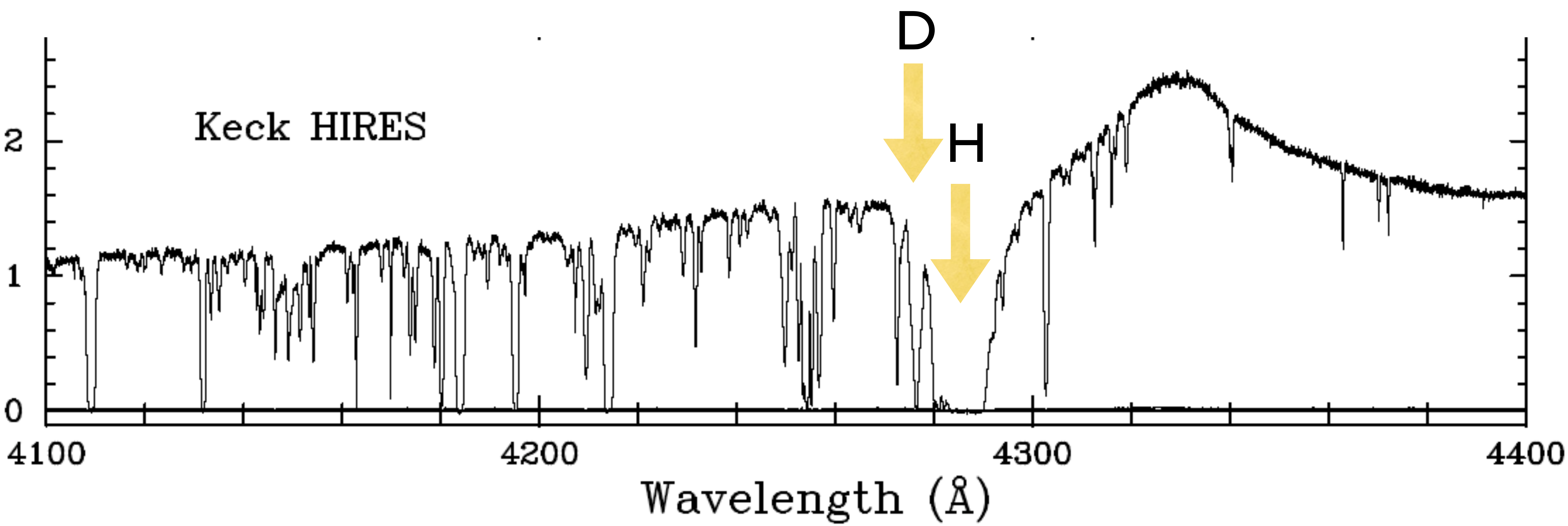
Example: QSO at z=2.526



- The vertical lines indicate the locations of the Lyman-series (Lyman-alpha, Lyman-beta, Lyman-gamma, etc.) absorption lines from one cloud that is closest to QSO z=2.526.
- Let's zoom in...

Kirkman et al. (2003)

Here is the Hydrogen Cloud

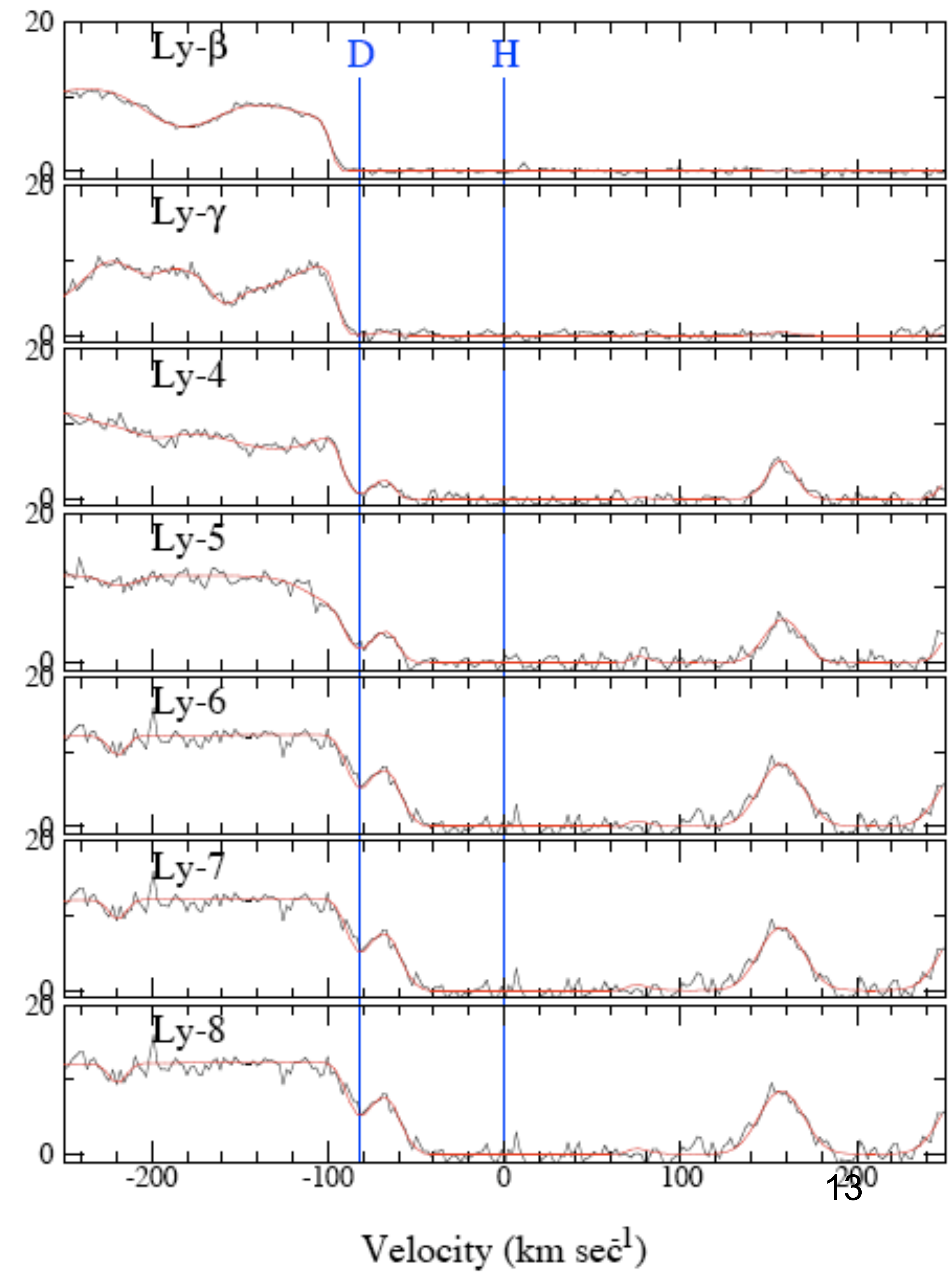


- The largest dip is the Lyman-alpha absorption due to neutral hydrogen atoms.
- But, we also see a weaker dip due to deuterium.

Kirkman et al. (2003)

Measuring D/H

- From this particular cloud, Kirkman et al. (2003) have obtained D/H~2.4×10^{-5}
- What does this measurement tell us?

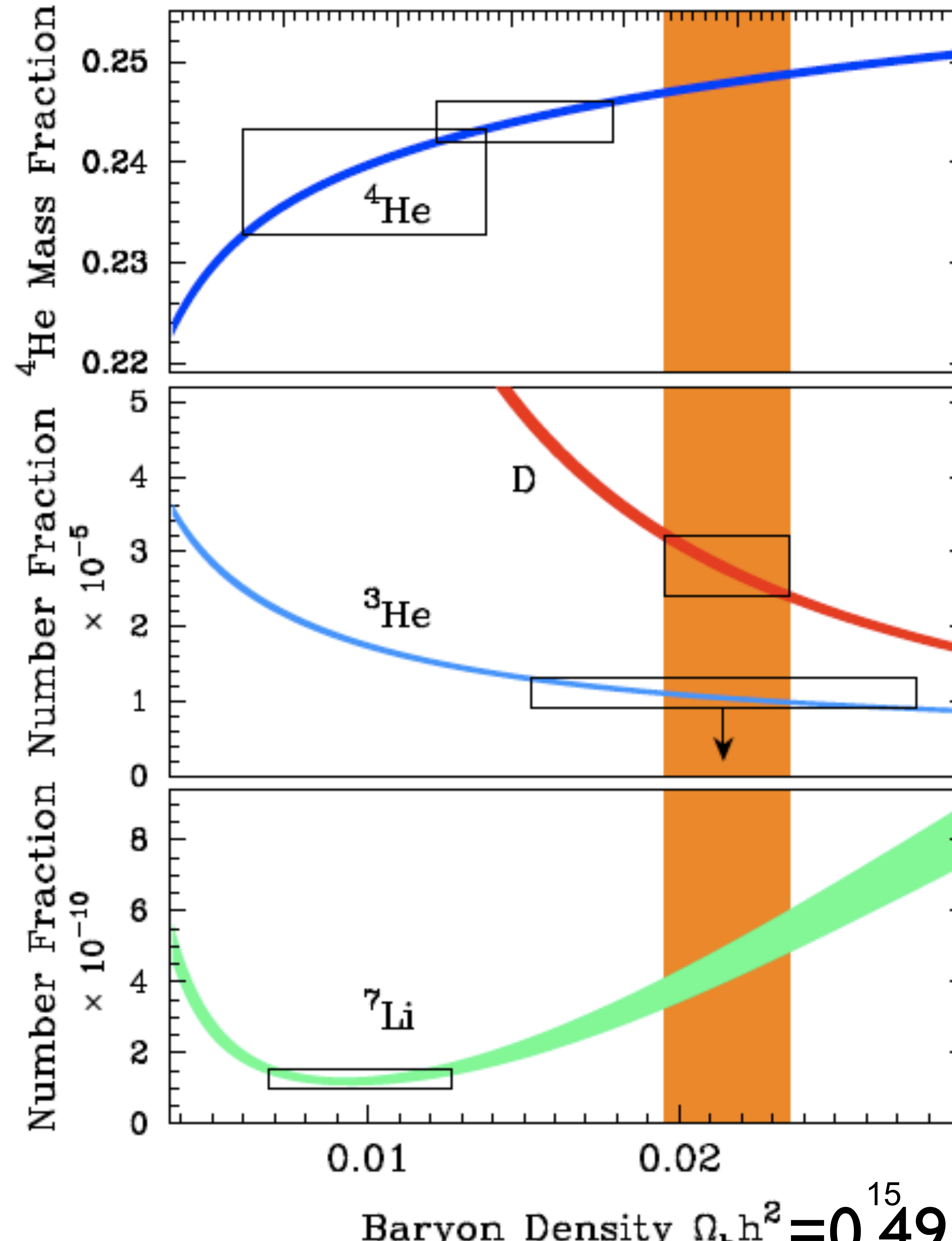


Deuterium = Ash from the Fusion in the early Universe

- When the temperature of the Universe was a billion K, deuterons formed from the fusion, **p+n->D+photon.**
- Then, the deuterons were fused into the helium-4 nuclei.
- The result: 76% of baryonic mass in H; 24% in He.
  - Deuterons = of order 10^{-5} (un-burnt ash)
  - The precise value depends upon the **baryon density in the Universe**

Baryons ~ 4%

- The deuterium is a very sensitive measure of the baryon density of the Universe.
- The measurement of D/H implies that **Ω_b~0.043**
  - Ω_b=(today's baryon density)/(today's total energy density)
- This measurement alone indicates that plasma is not 99% of the Universe anymore. It's more like 4% of the Universe!

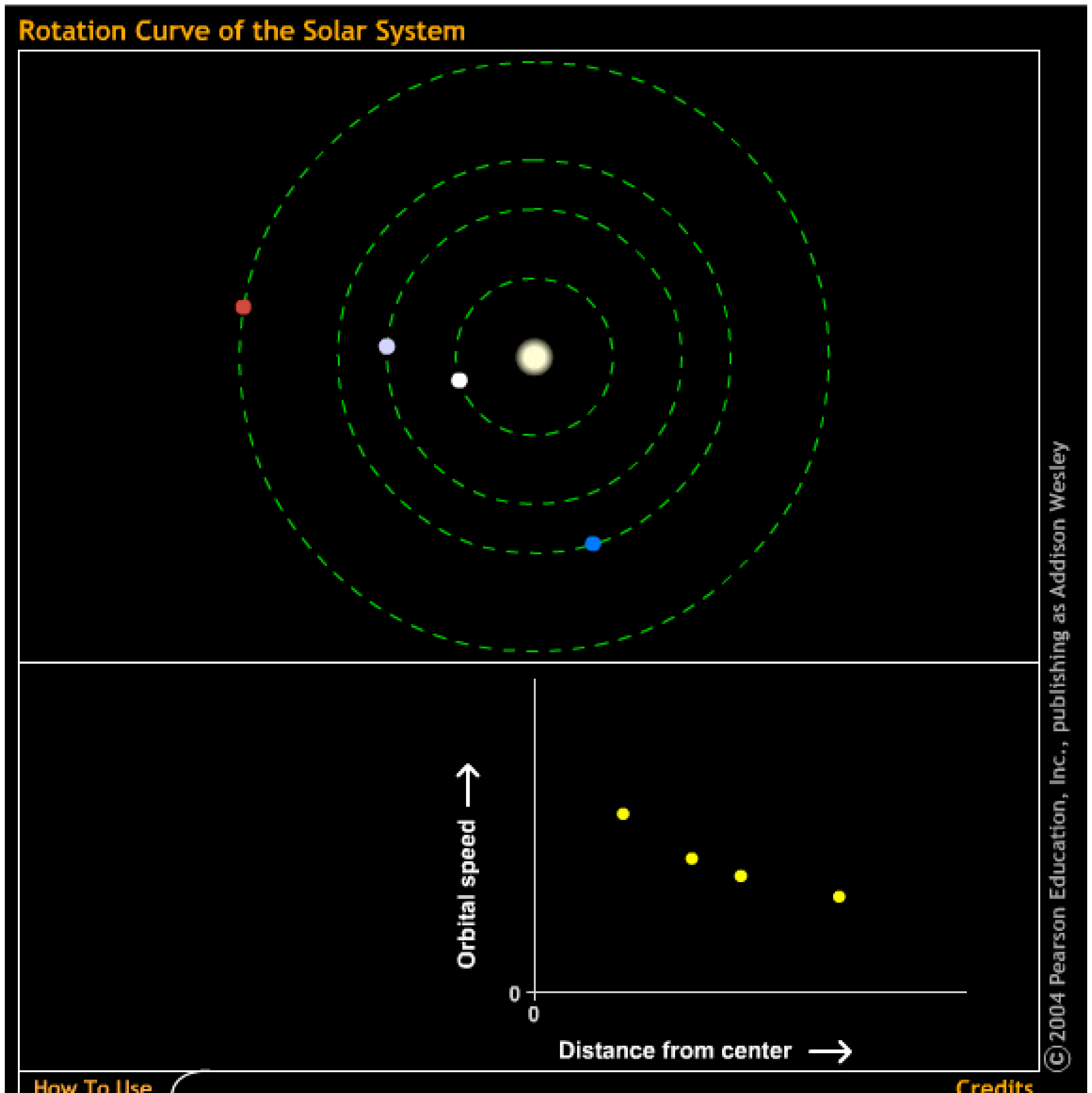


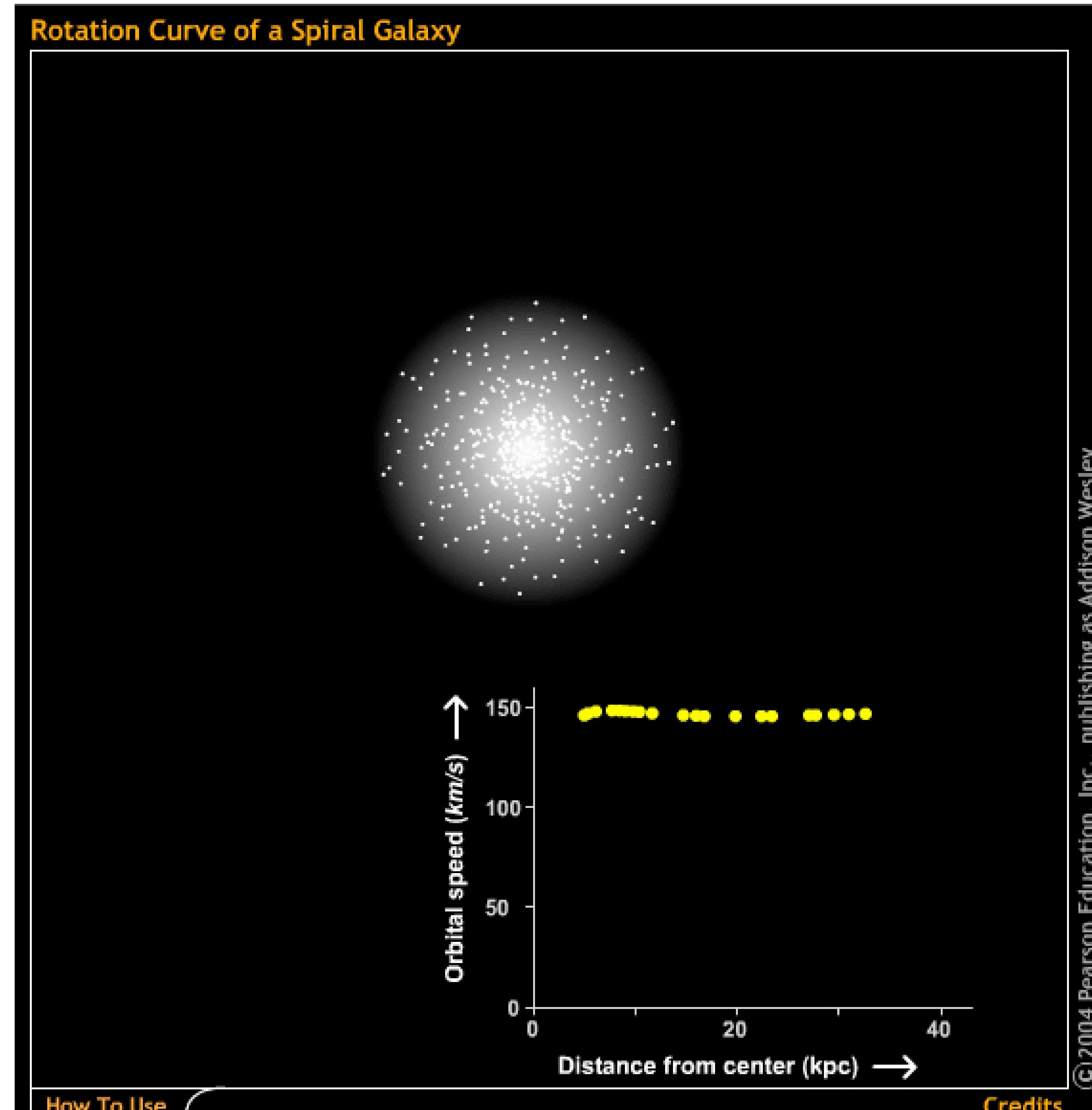
$=0.49\Omega_b$

What is the rest of the Universe made of?

- We think that 23% is in Dark Matter, and 72% is in Dark Energy.

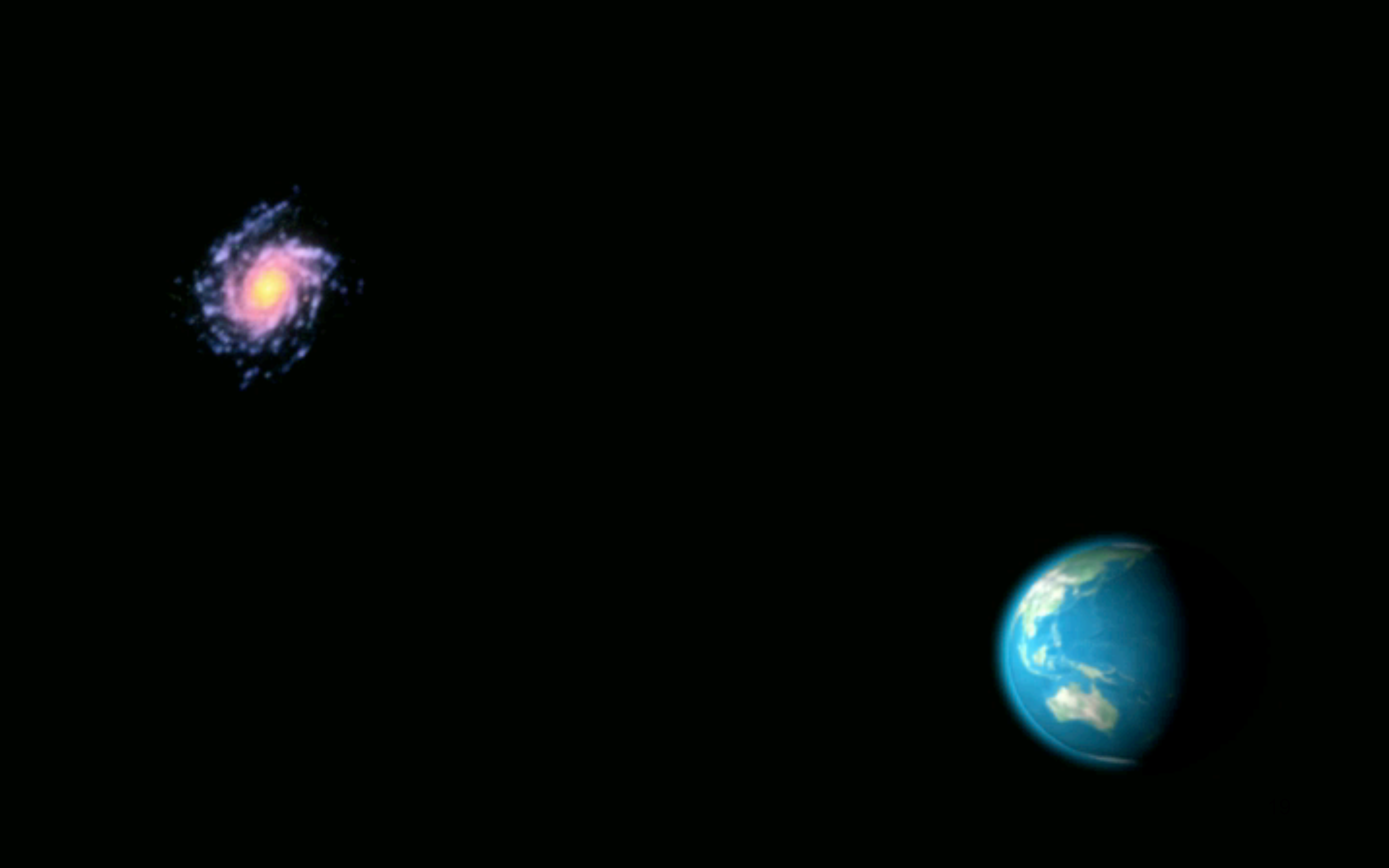
Dark Matter: Rotation Curve





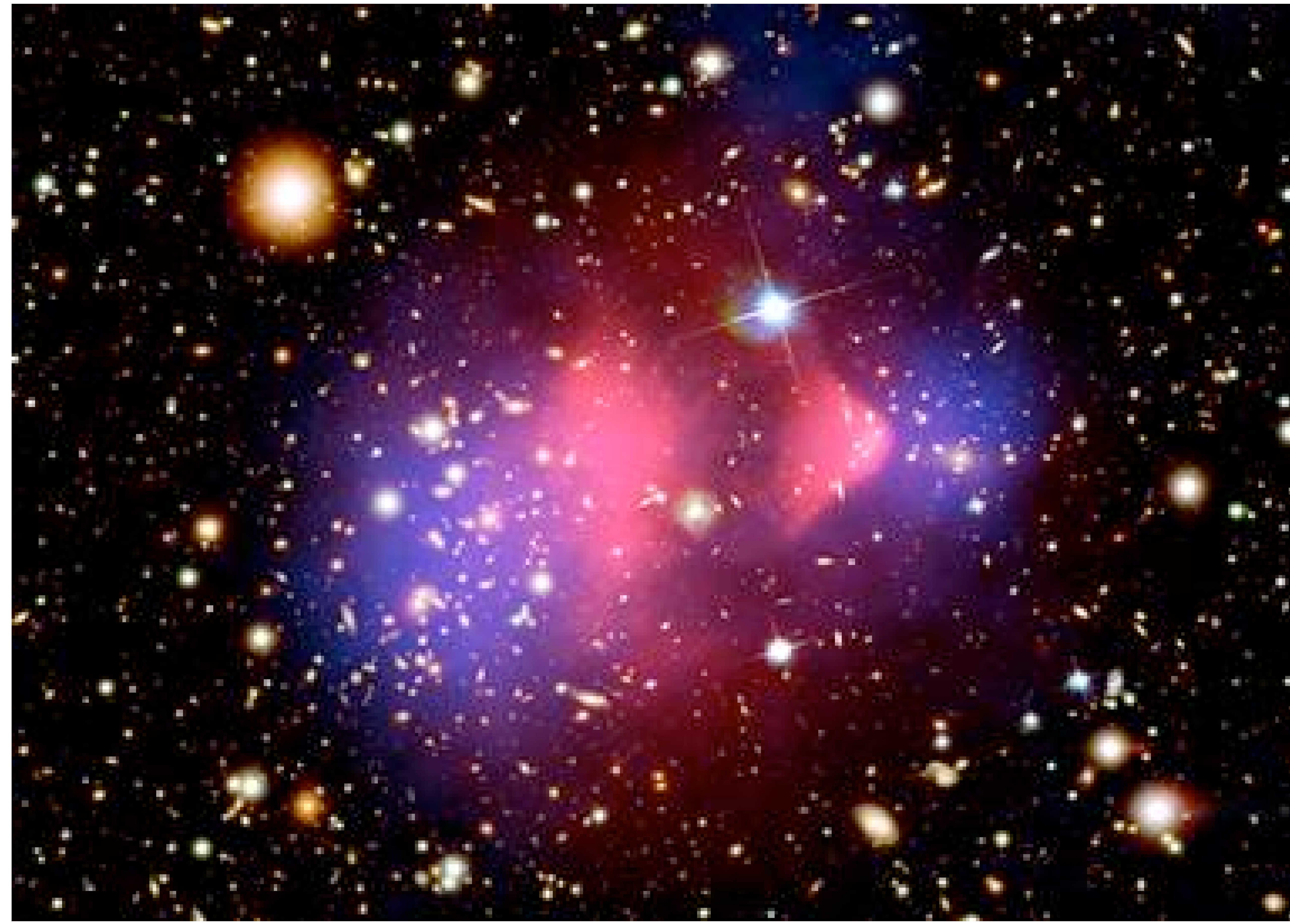
Dark Matter: Gravitational Lensing

- Invisible matter distribution can be traced by the "gravitational lensing," the bending of light by the intervening mass distribution.
- The total mass estimated from lensing is ~6 times as large as the baryonic mass.



Dark Matter is <u>not</u> Baryonic!

- High-velocity (~4500 km/s), edge-on collision of two clusters of galaxies (the co-called “bullet cluster”; Clowe et al. 2006)
- Pink: Baryonic matter, traced by X-ray emission
- Blue: Total matter, traced by gravitational lensing



Dark matter and baryons are displaced. Baryons are collisional, but dark matter particles are not.

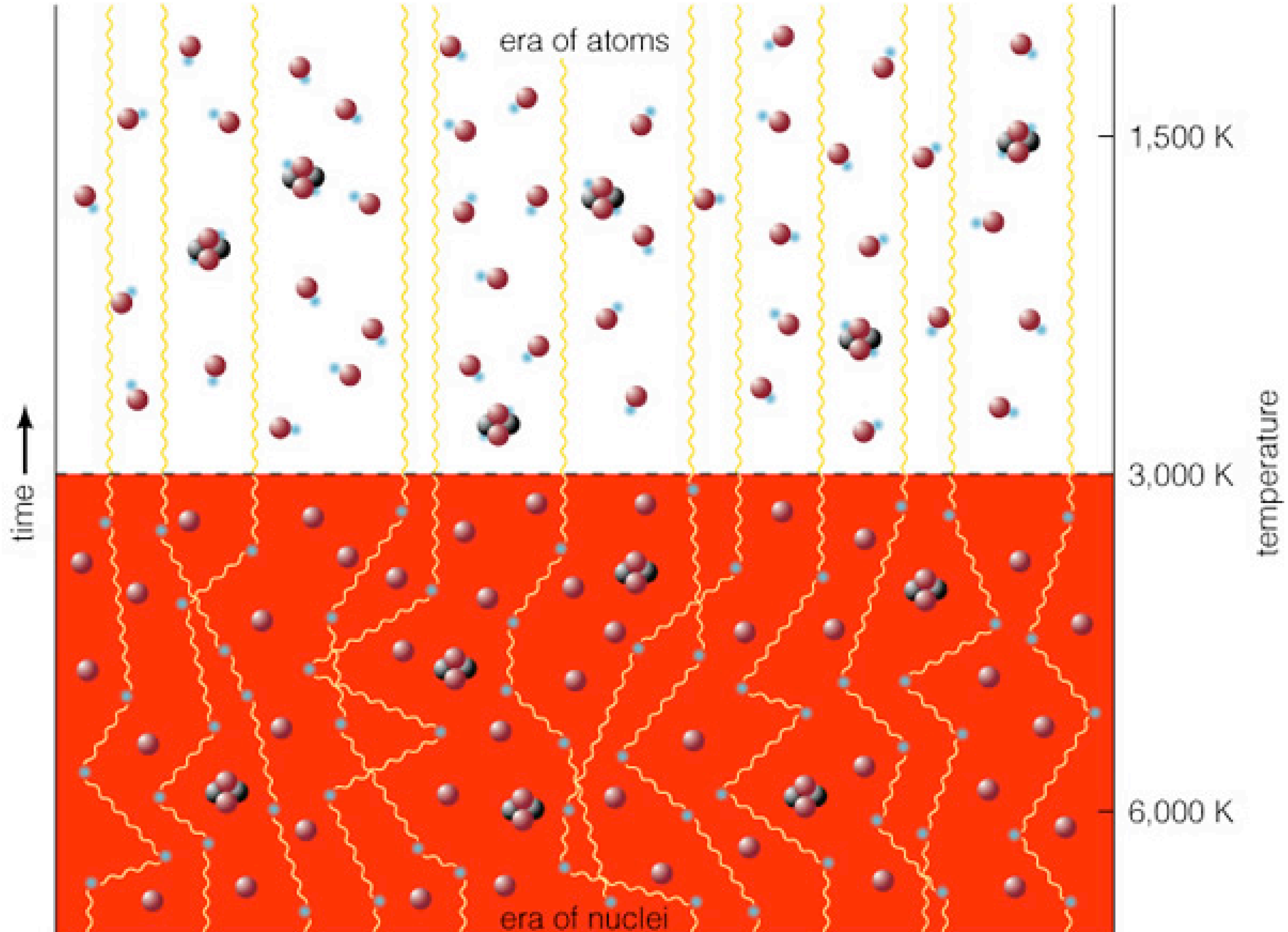
The best way to rule out baryonic dark matter

- You might say...
  - OK, hydrogen clouds suggest that there are only few baryons in the Universe. Clusters of galaxies suggest that the most of gravitational mass is invisible. But maybe, lots of baryons are hidden elsewhere, and astronomers have been looking at wrong places!
- And we say, "there is a way to rule out the baryonic dark matter completely, without worrying about baryons being hidden elsewhere."

You can't hide baryons when...

- The Universe was younger than 380,000 years old and the temperature was hotter than 3000K.
  - The Universe back then was fully ionized, and **baryons and photons were tightly coupled.**
  - The photons were released from the plasma when the temperature cooled to 3000K
  - These photons remember everything about baryons -- no baryons could hide from photons.

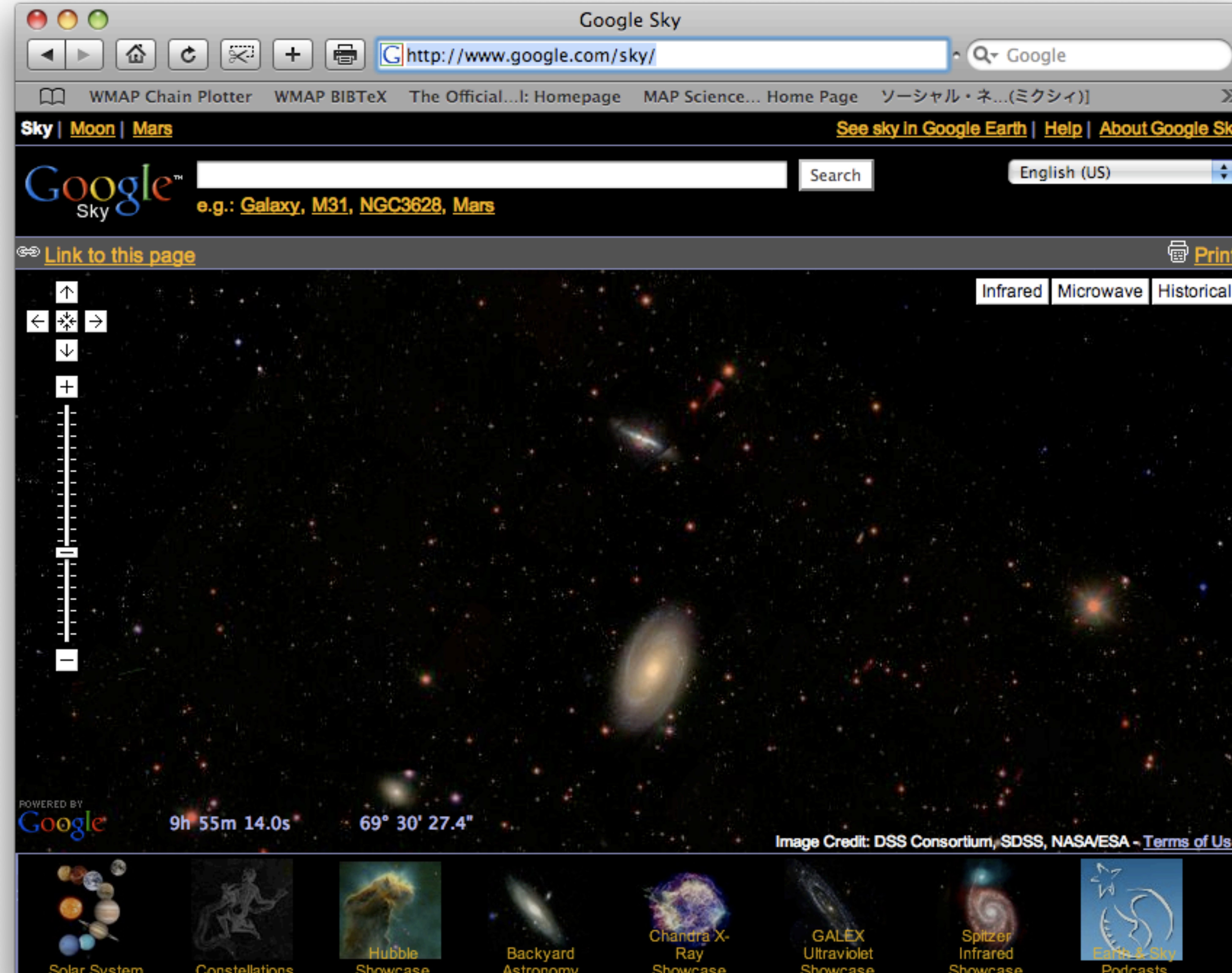
Cosmic Microwave Background



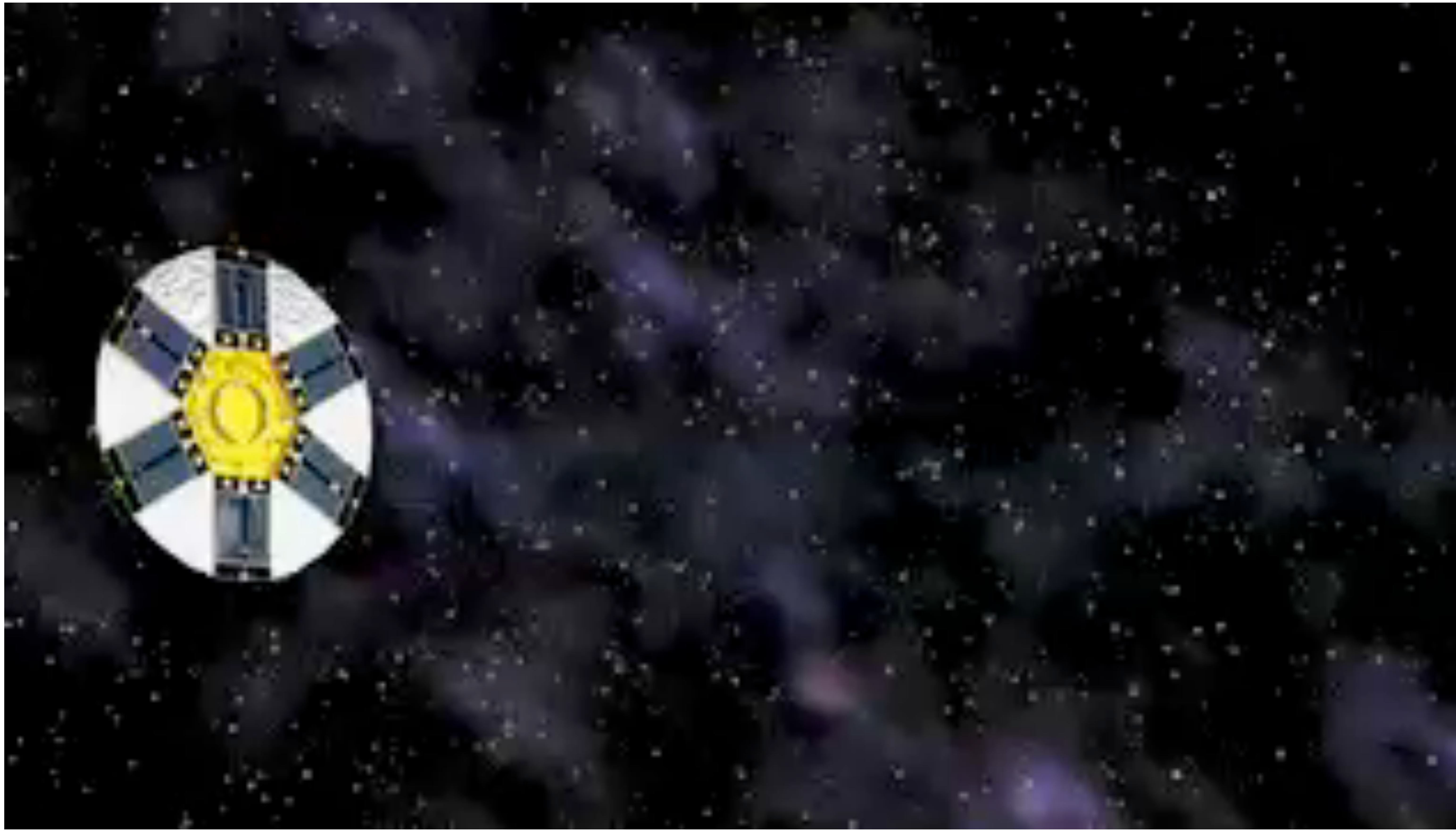
Cosmic Sound Waves

- When baryons and photons were tightly coupled, they behaved as if they were a single perfect fluid.
- Therefore, there were sound waves propagating through the cosmic plasma!
- Wave forms tell us two things:
  - Sound speed -> how much baryons in the universe
  - Gravity -> how much matter in the universe
    - Dark matter = total matter - baryonic matter

Seeing CMB on google.com/sky

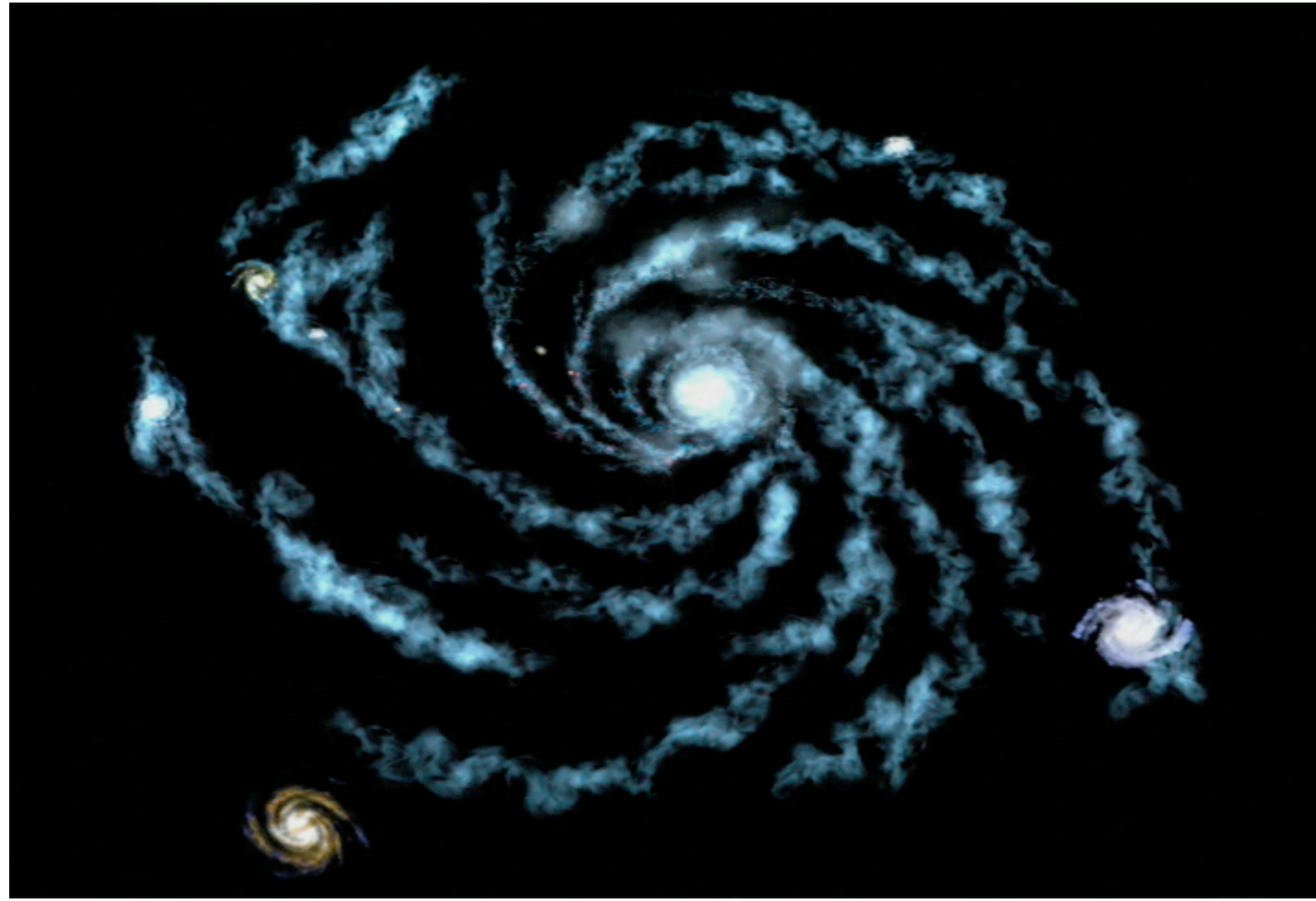


WMAP Satellite



- WMAP is a NASA's medium-size satellite measuring microwaves on the sky

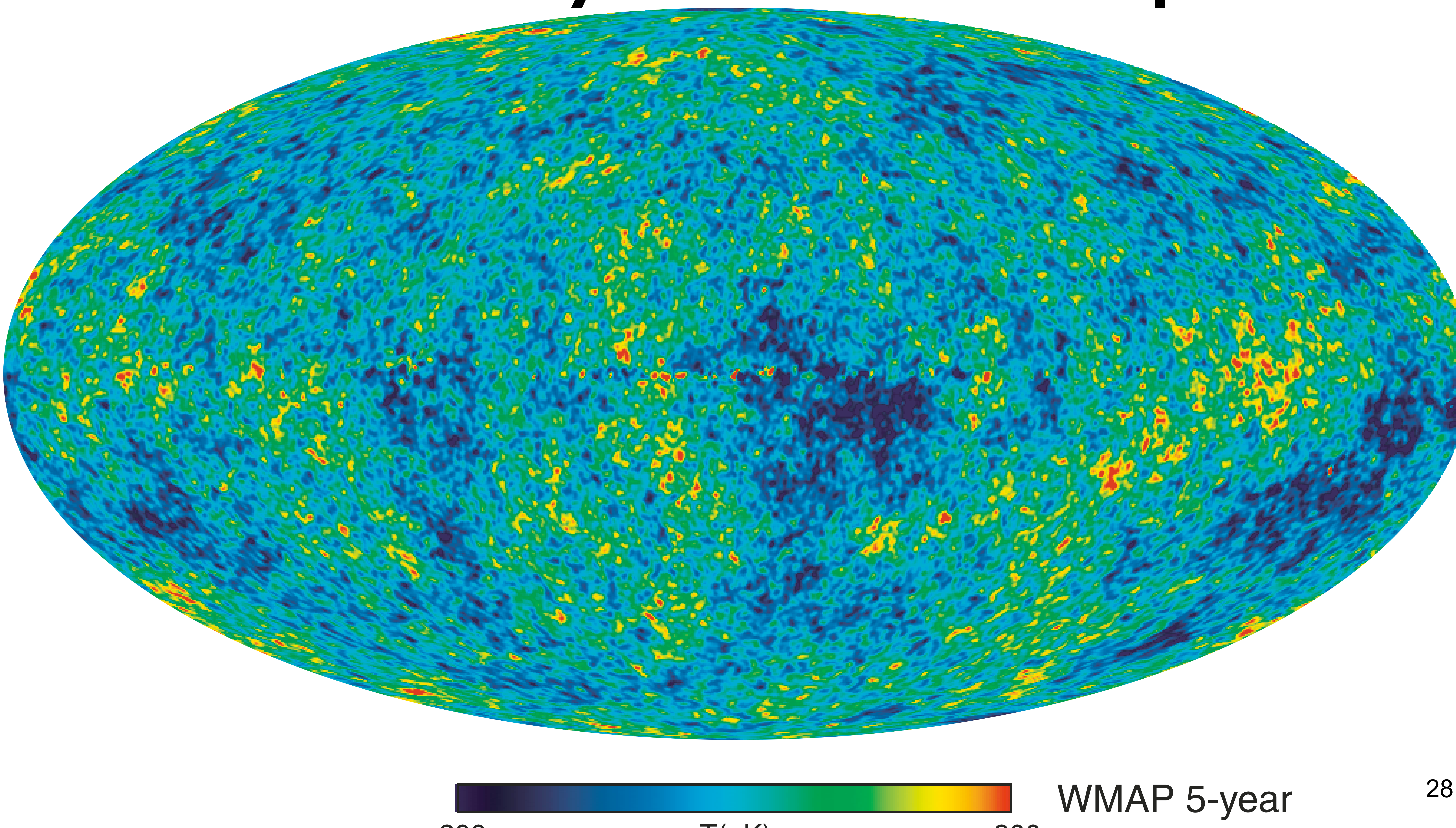
WMAP Measures Microwaves From the Universe



- The mean temperature of photons in the Universe today is 2.725 K
- WMAP is capable of measuring the temperature *contrast* down to better than one part in millionth

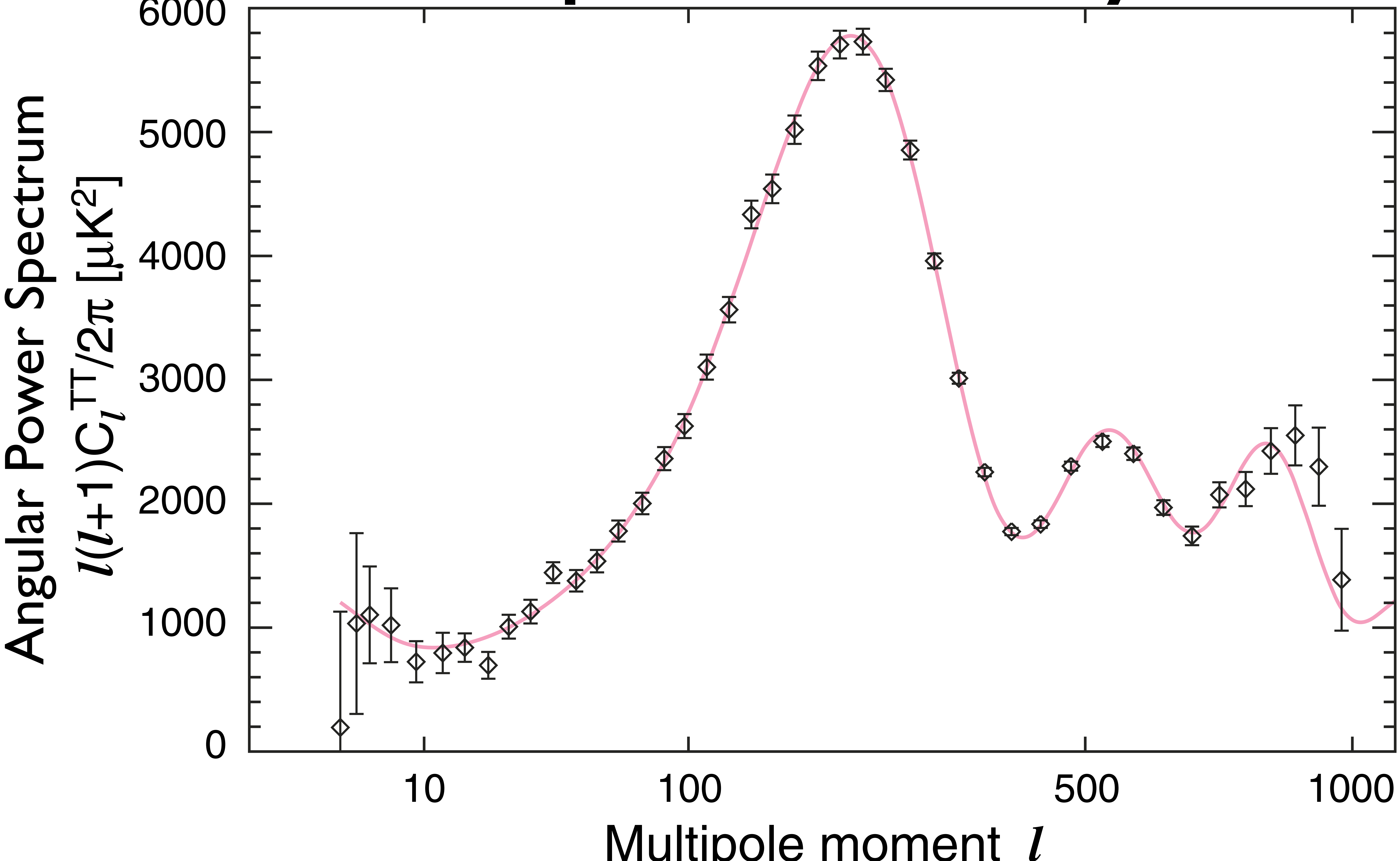
Galaxy-cleaned Map

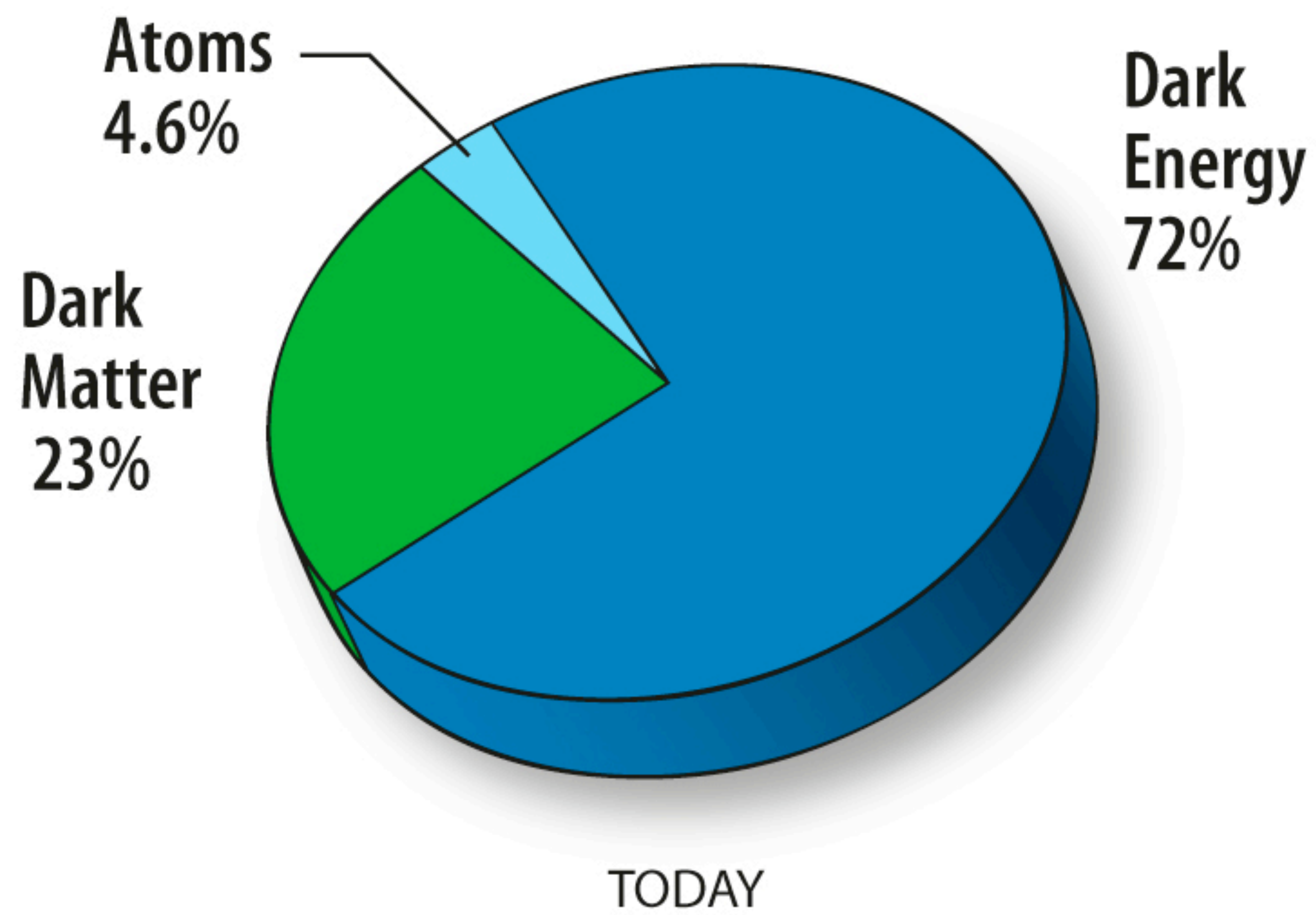
Hinshaw et al.

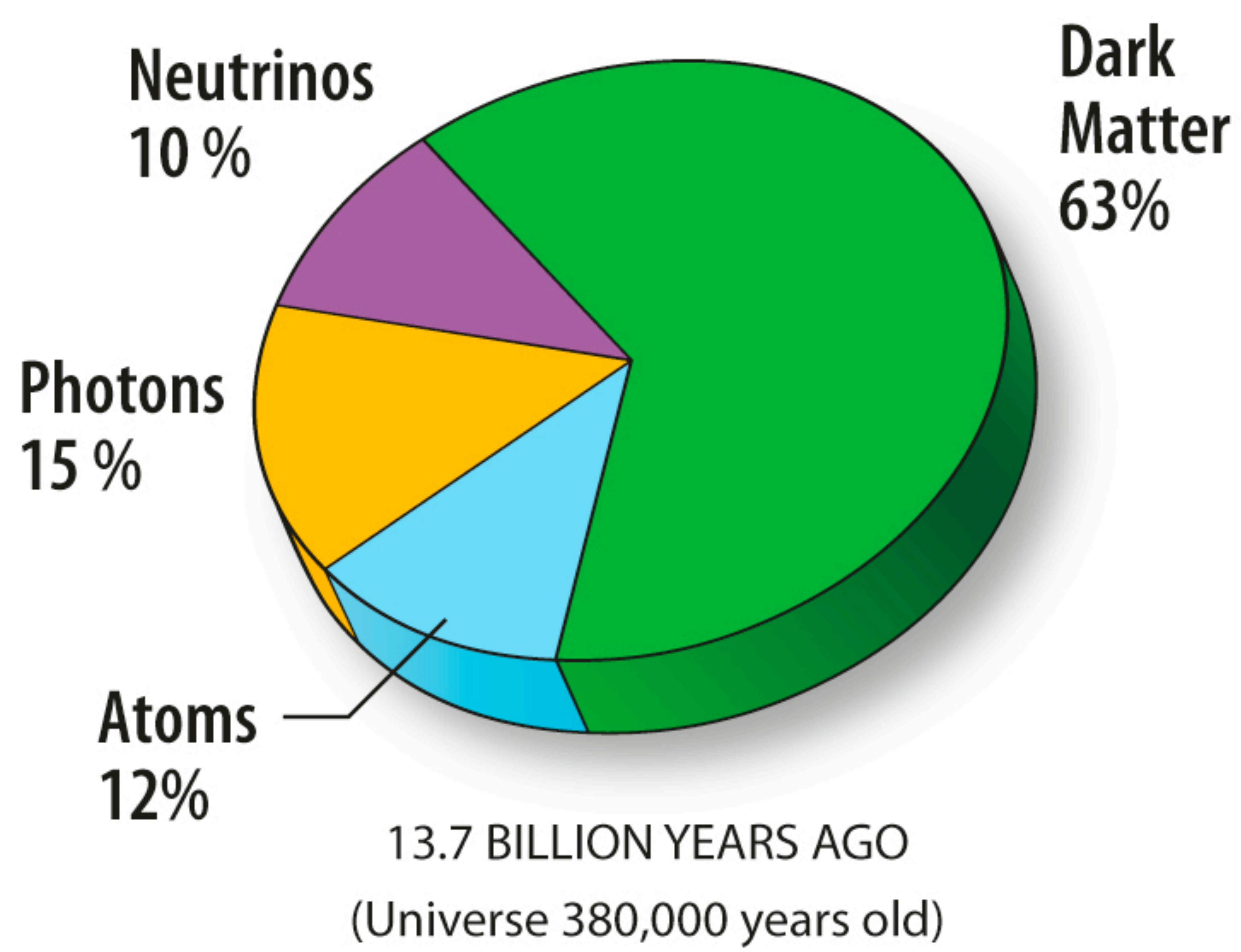


Nolta et al.

The Spectral Analysis







Komatsu et al. (2008)

Latest Cosmic Pie Chart

- <u>Universe today</u>
  - Age: **13.73 +/- 0.12** Gyr
  - Atoms: **4.62 +/- 0.15 %**
  - Dark Matter: **23.3 +/- 1.3%**
  - Vacuum Energy: **72.1 +/- 1.5%**
- <u>When CMB was released 13.7 B yrs ago</u>
  - A significant contribution from the *cosmic neutrino background*

Dark Energy

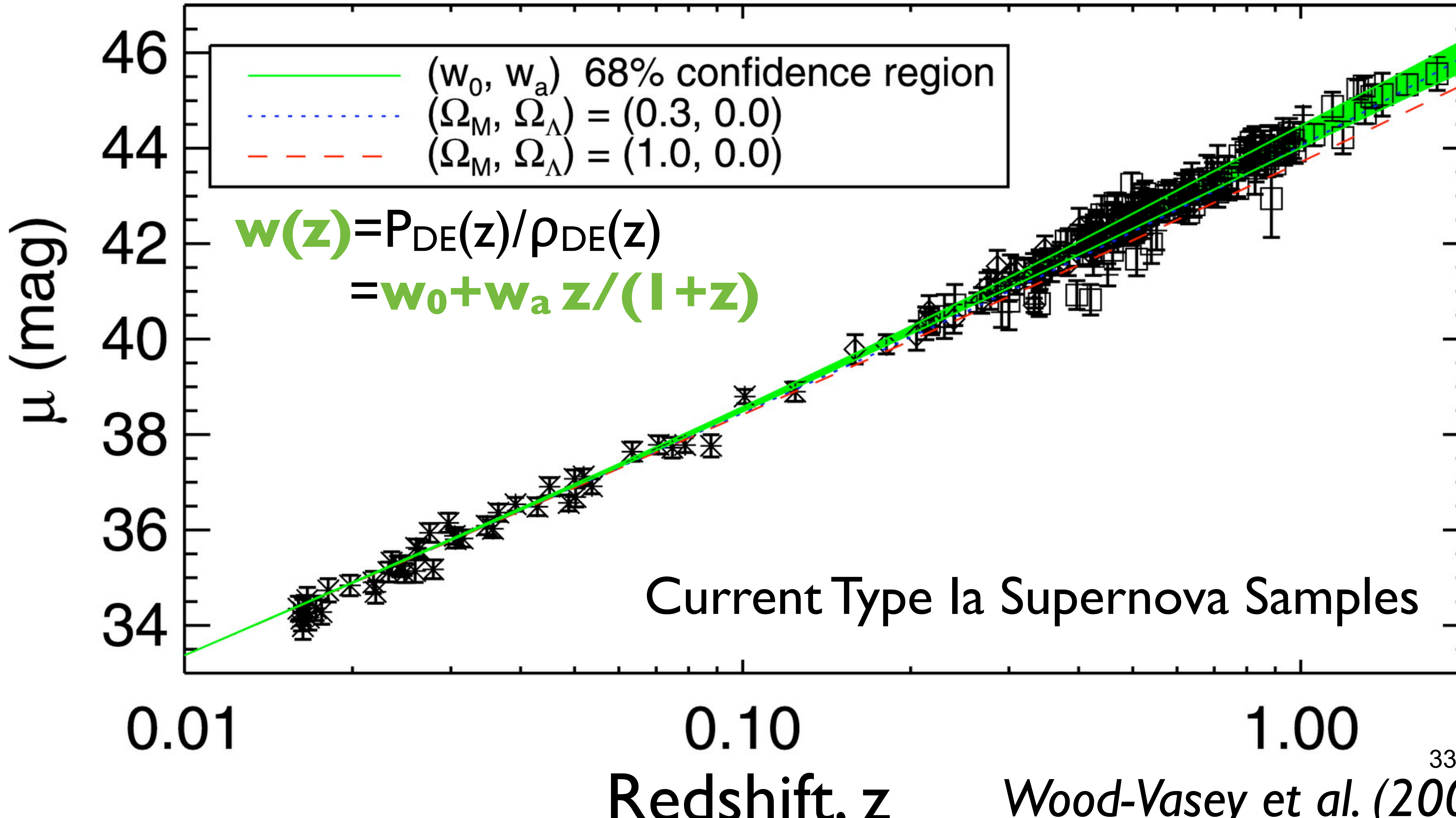
- Baryonic matter = 4.6%
- Dark matter = 23%
- **The rest is not even matter.**
  - What do we mean by that?
  - The remaining energy component appears to have a strange equation of state:
    - Pressure = **-** Energy Density
    - Significant *negative* pressure.

Riess et al. (1998); Perlmutter (1999)

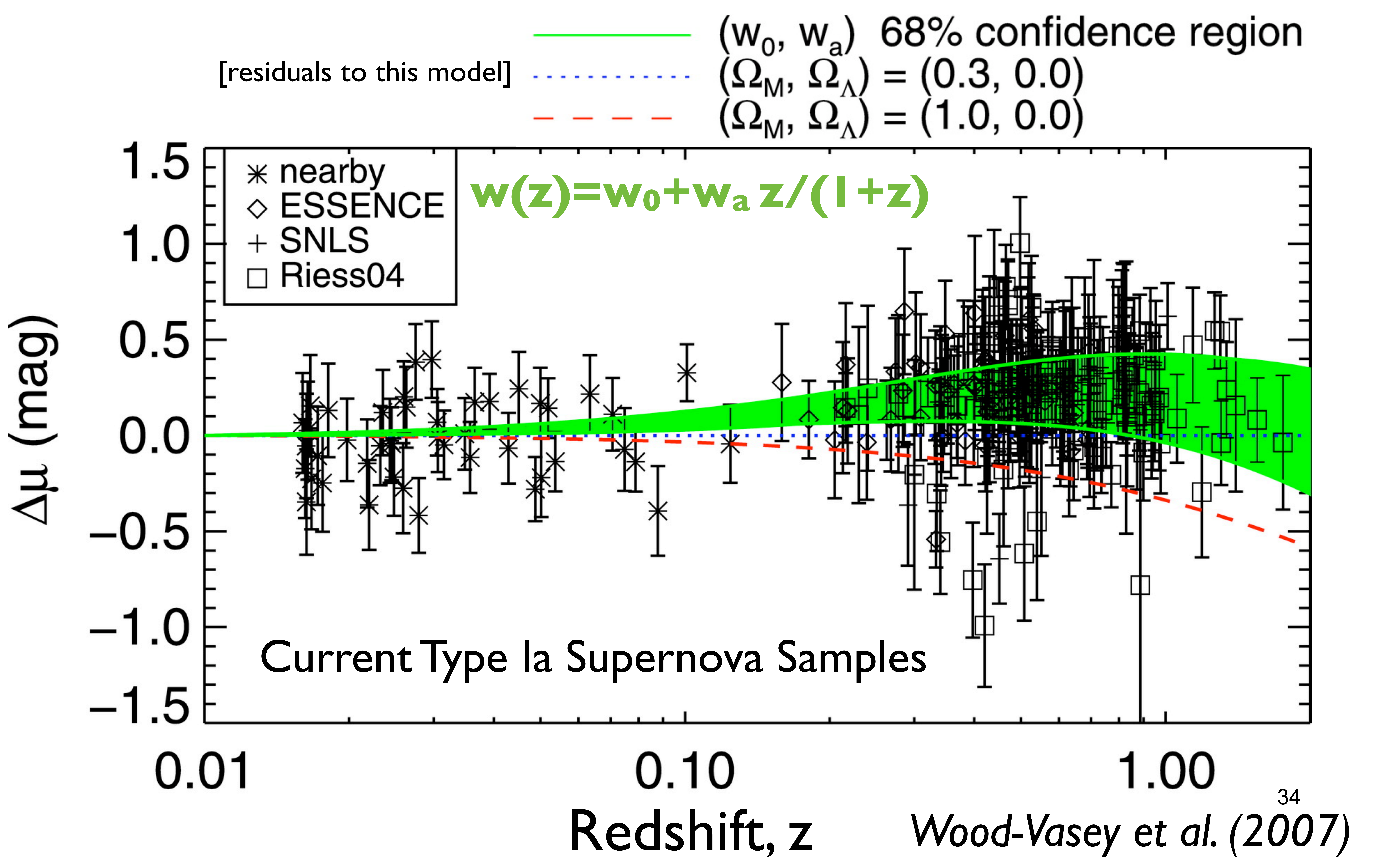
Need For Dark Energy

- The first evidence came from measurements of distances out to the luminous, "Type Ia Supernovae."
- Type Ia supernovae appeared to be dimmer (i.e., farther) than expected.
    - The most straightforward explanation is that the expansion of the Universe is accelerating today.

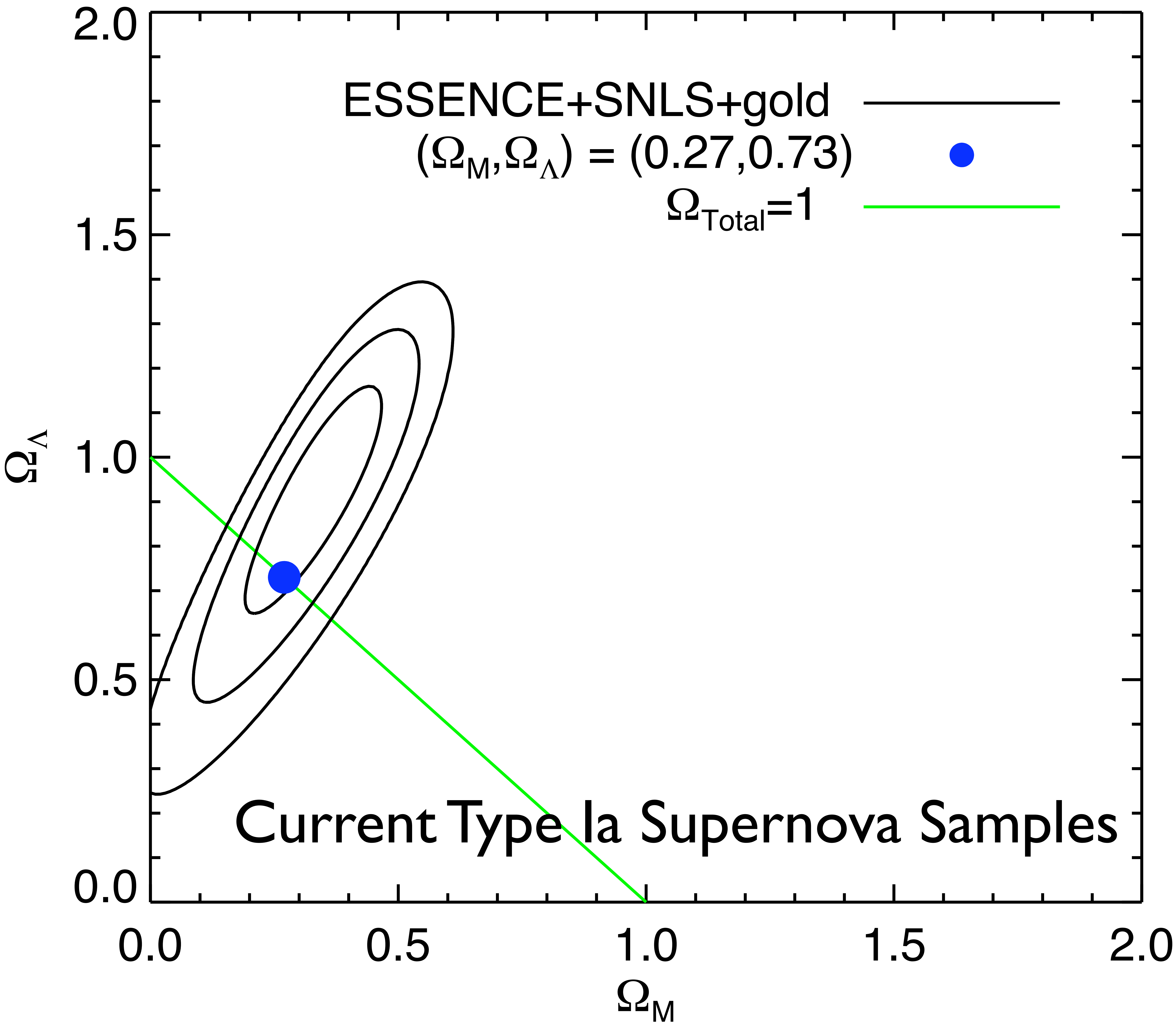
$\mu = 5\mathrm{Log}_{10}[D_L(z)/\mathrm{Mpc}] + 25$



Wood-Vasey et al. (2007)



(w_0, w_a) 68% confidence region
[residuals to this model] $(\Omega_M, \Omega_\Lambda) = (0.3, 0.0)$
$(\Omega_M, \Omega_\Lambda) = (1.0, 0.0)$
nearby
ESSENCE
SNLS
Riess04
$w(z)=w_0+w_a\,z/(1+z)$
Current Type Ia Supernova Samples
$\Delta\mu$ (mag)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.01
0.10
1.00
Redshift, z
Wood-Vasey et al. (2007)



- Within the standard framework of cosmology based on General Relativity...
- There is a clear indication that the matter density alone cannot explain the supernova data.
- Need Dark Energy.

Wood-Vasey et al. (2007)

Summary

- Plasma is 99% of the Universe anymore because...
  - Distant hydrogen clouds show that baryons occupy only ~4% of the total energy content of the Universe
  - Galaxy rotation curve, and gravitational lensing of clusters show that most of the matter is invisible
  - Cosmic microwave background shows that the missing mass is not baryonic: Dark Matter (23%)
  - Type 1a Supernovae show that the Universe is accelerating today, requiring Dark Energy (72%)
- Conclusion: **plasma is 4.5% of the Universe today.**