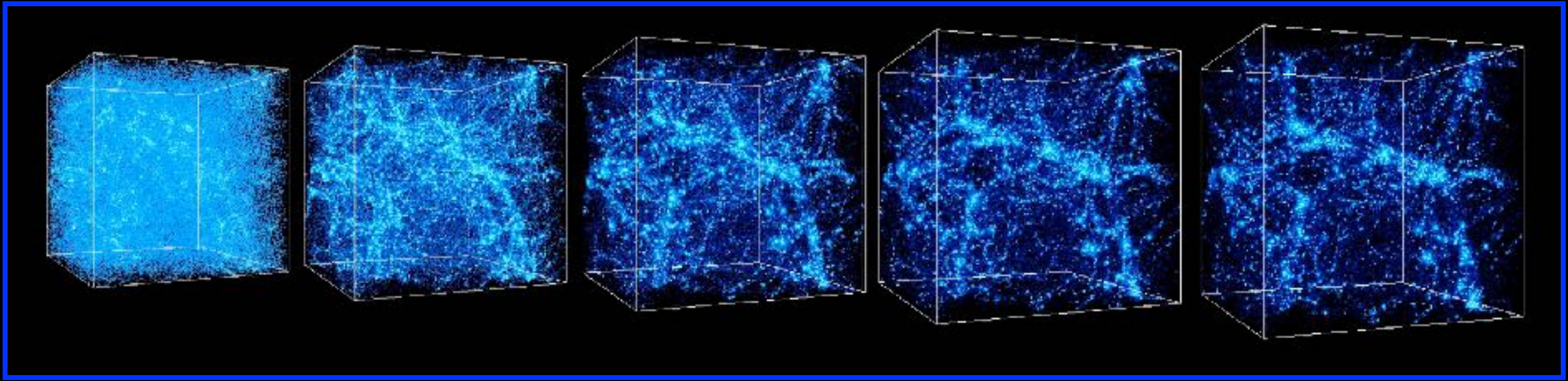


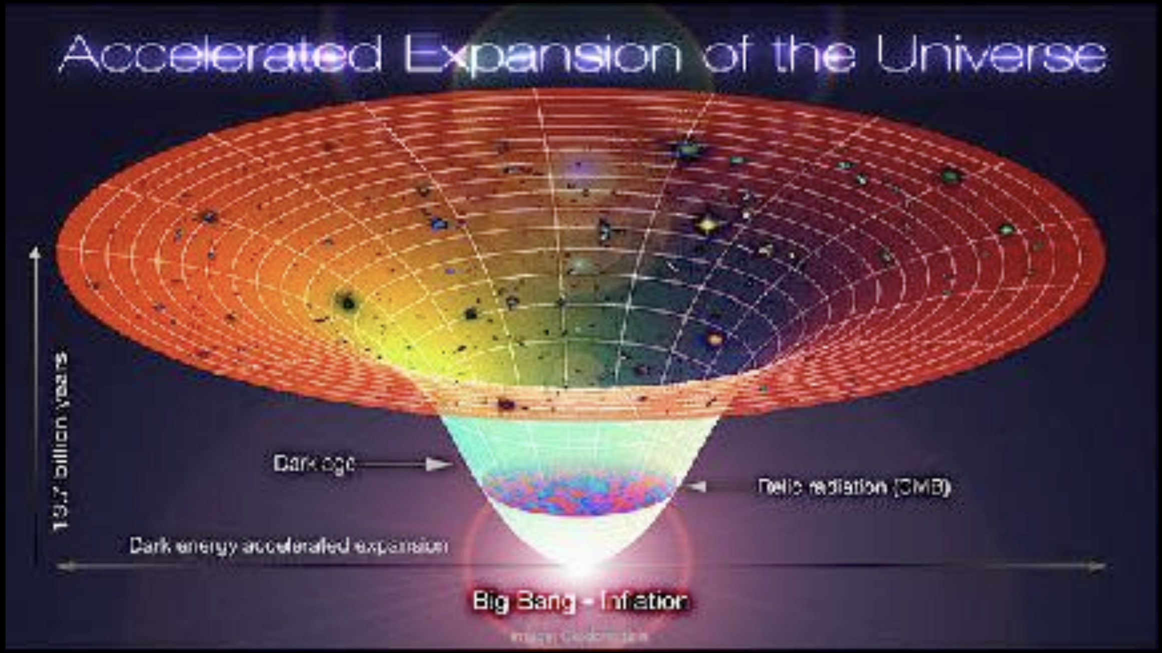
The Early Universe:

From the Big Bang to the First Galaxies

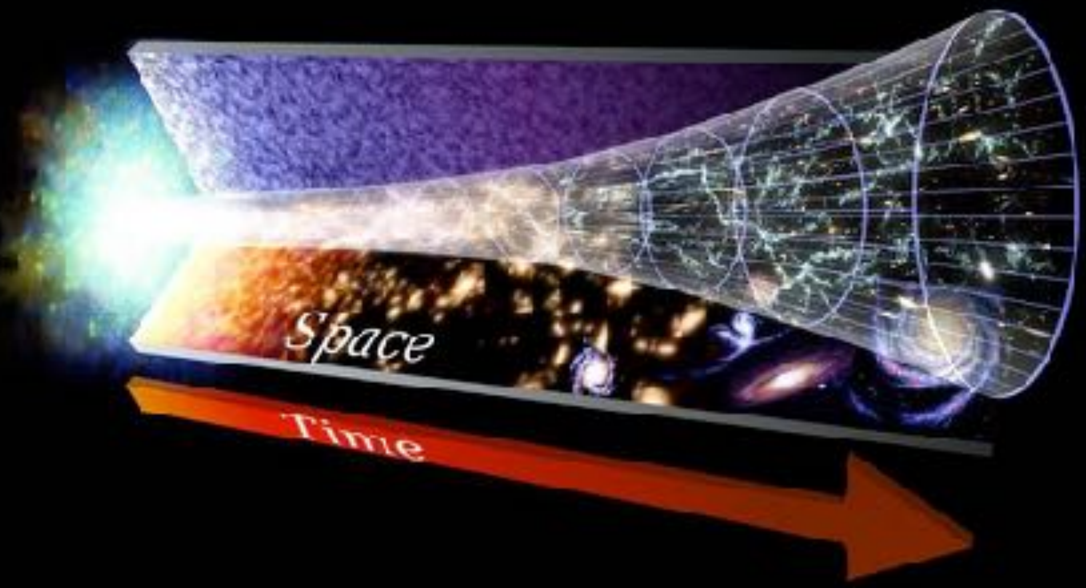
Joanna Bridge
Twitter: @bojibridge
Astronomy on Tap - Louisville
April 25, 2018

Roadmap for the evening:

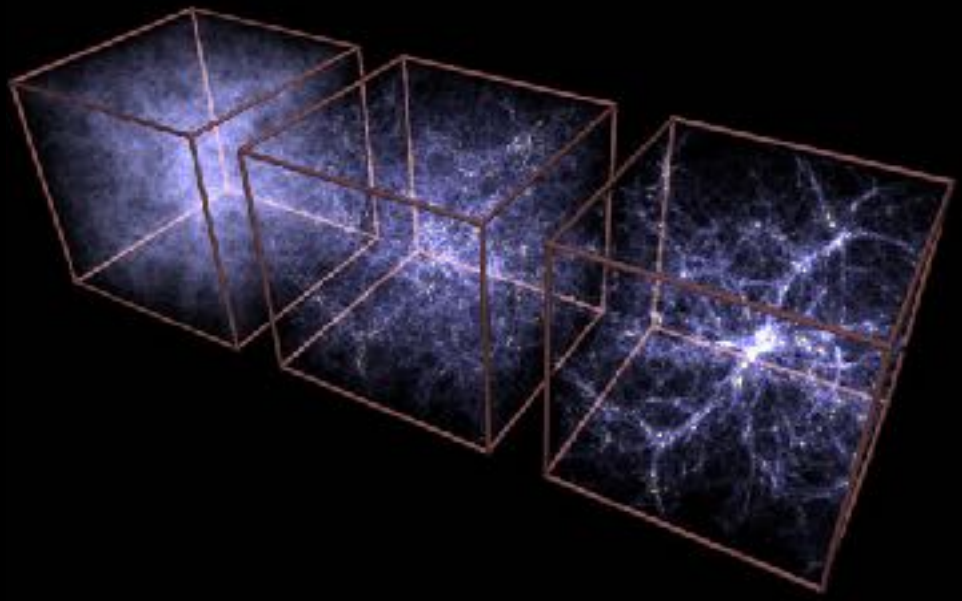
What is dark energy?



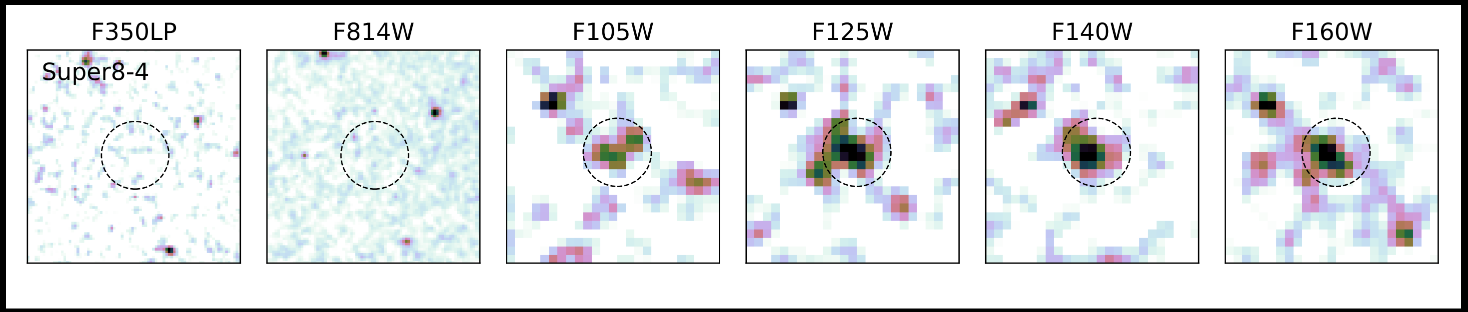
How did the Universe evolve?



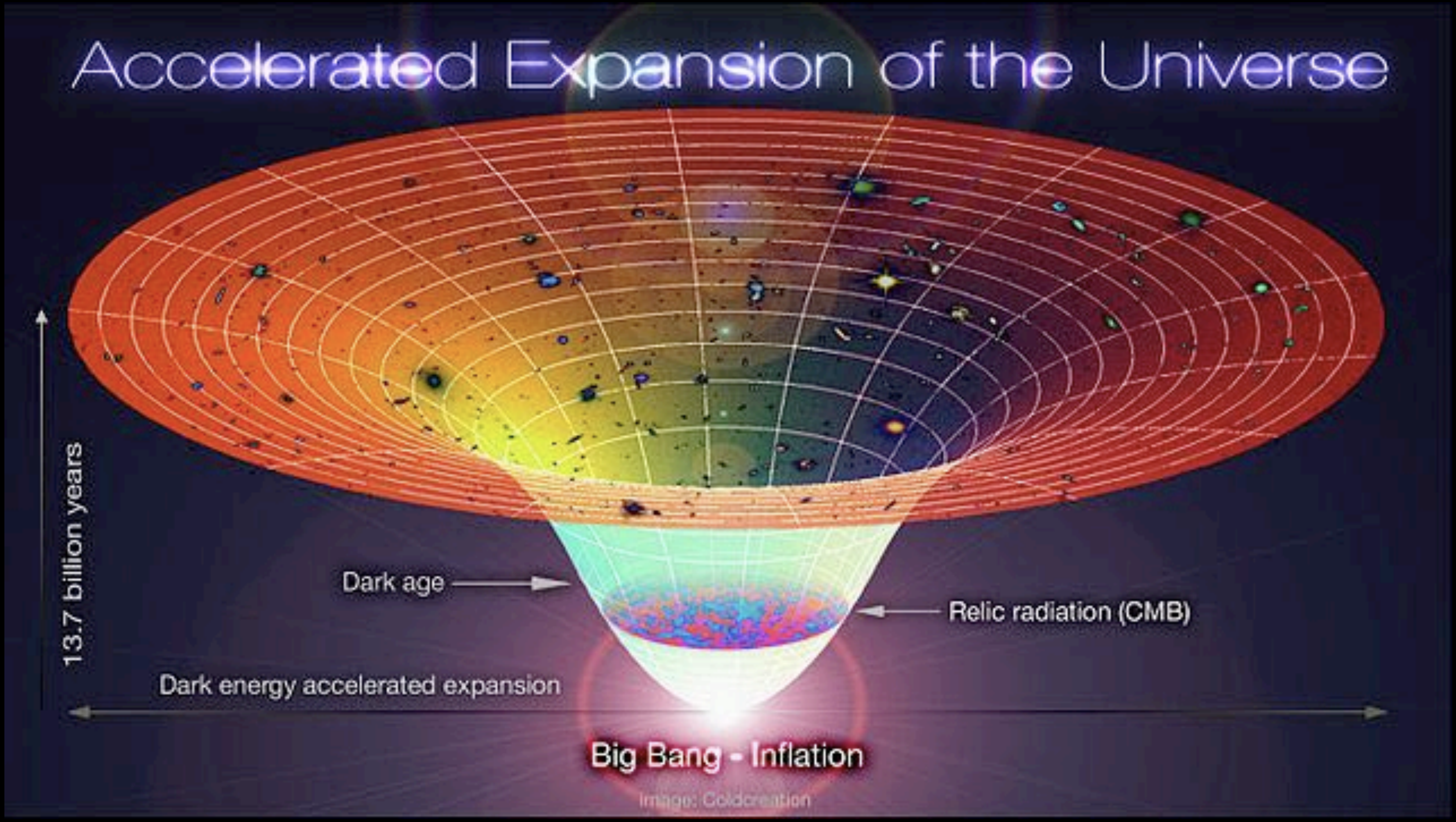
What is dark matter?



How do we study the first galaxies?



What is dark energy?



Modern cosmology began at the beginning of the 20th century

Carnegie/Huntington Library

- Edwin Hubble began work at Mt. Wilson Observatory in the 1920s
- The Great Debate: Are “nebulae” inside or outside our own Milky Way Galaxy?
- He determined that the Andromeda Galaxy is 900,000 light years away - far outside the Milky Way

(He was actually wrong - the Andromeda Galaxy is ~ 2 million light years away!)

In 1929, Hubble published what is now known as Hubble's Law

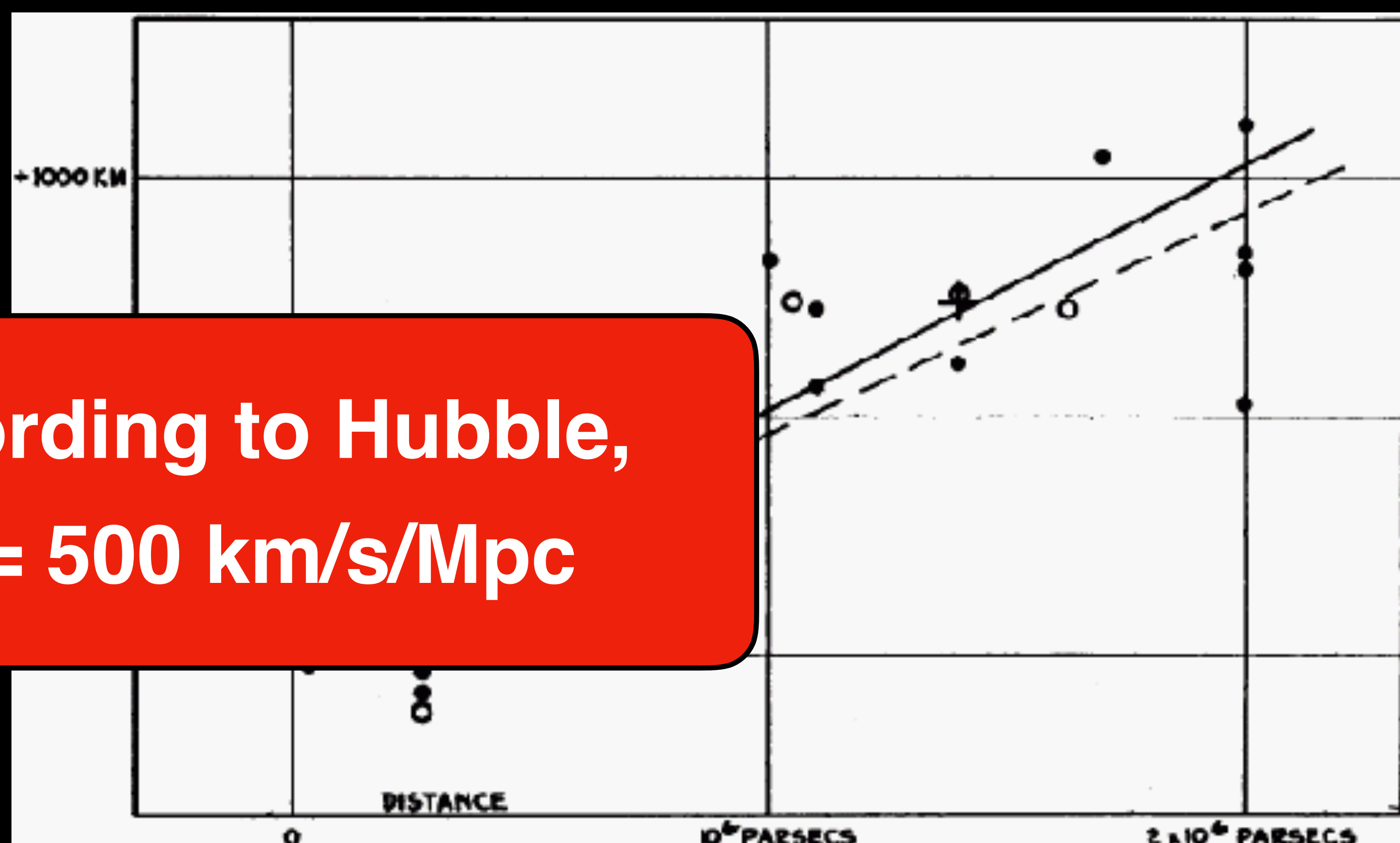


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble 1929

According to Hubble,
H_0 = 500 km/s/Mpc

g the
velocities and
many galaxies,
l that the
xpanding

aw: $v = H_0 d$

of the galaxy

s constant

d - Distance of the galaxy

The value of Hubble's constant contains what we know about the rate of the Universe's expansion

It turns out that Hubble was super wrong about the value of H_0

- Hubble originally thought that $H_0 = 500$ km/s/Mpc
- However, he incorrectly identified the distances to galaxies

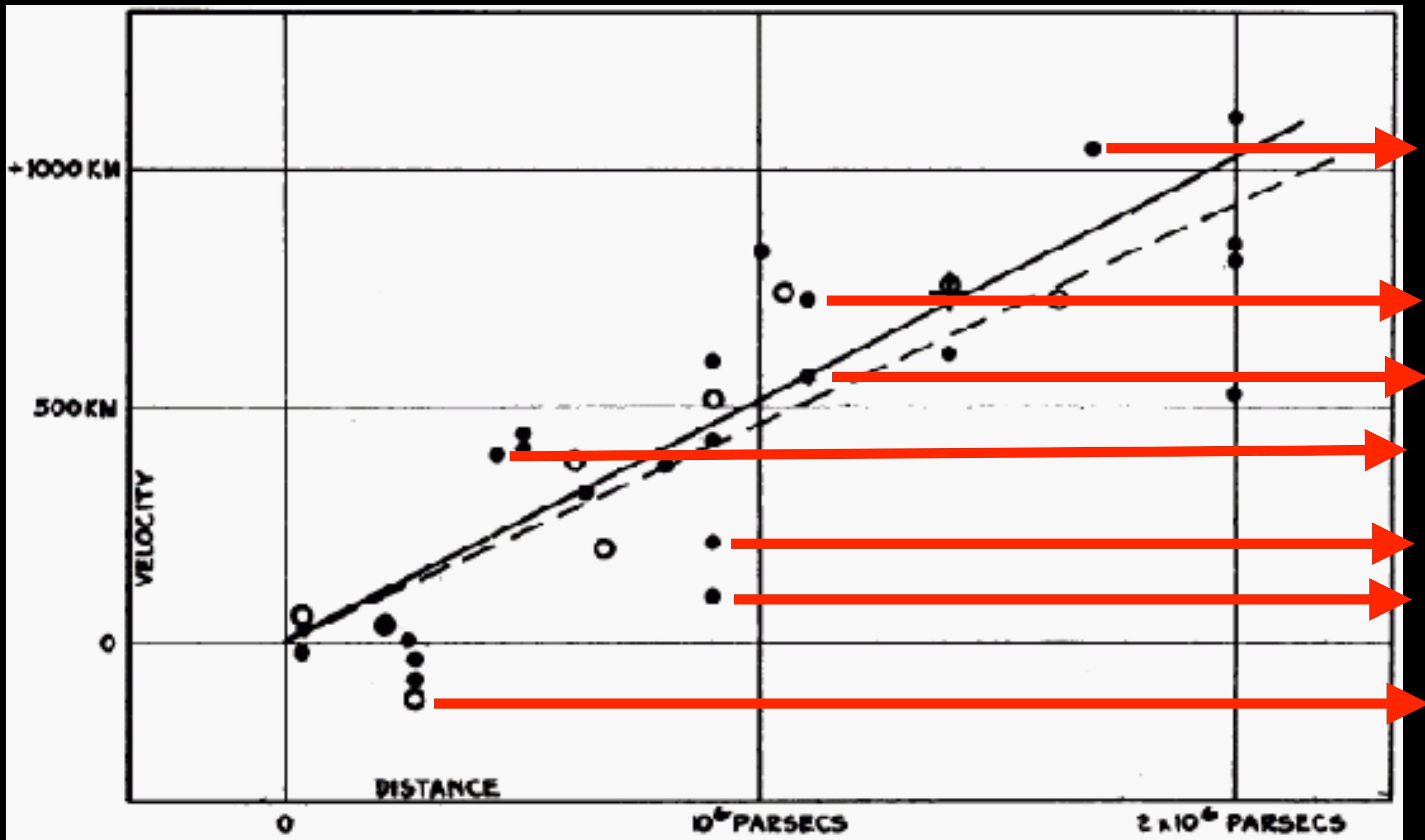
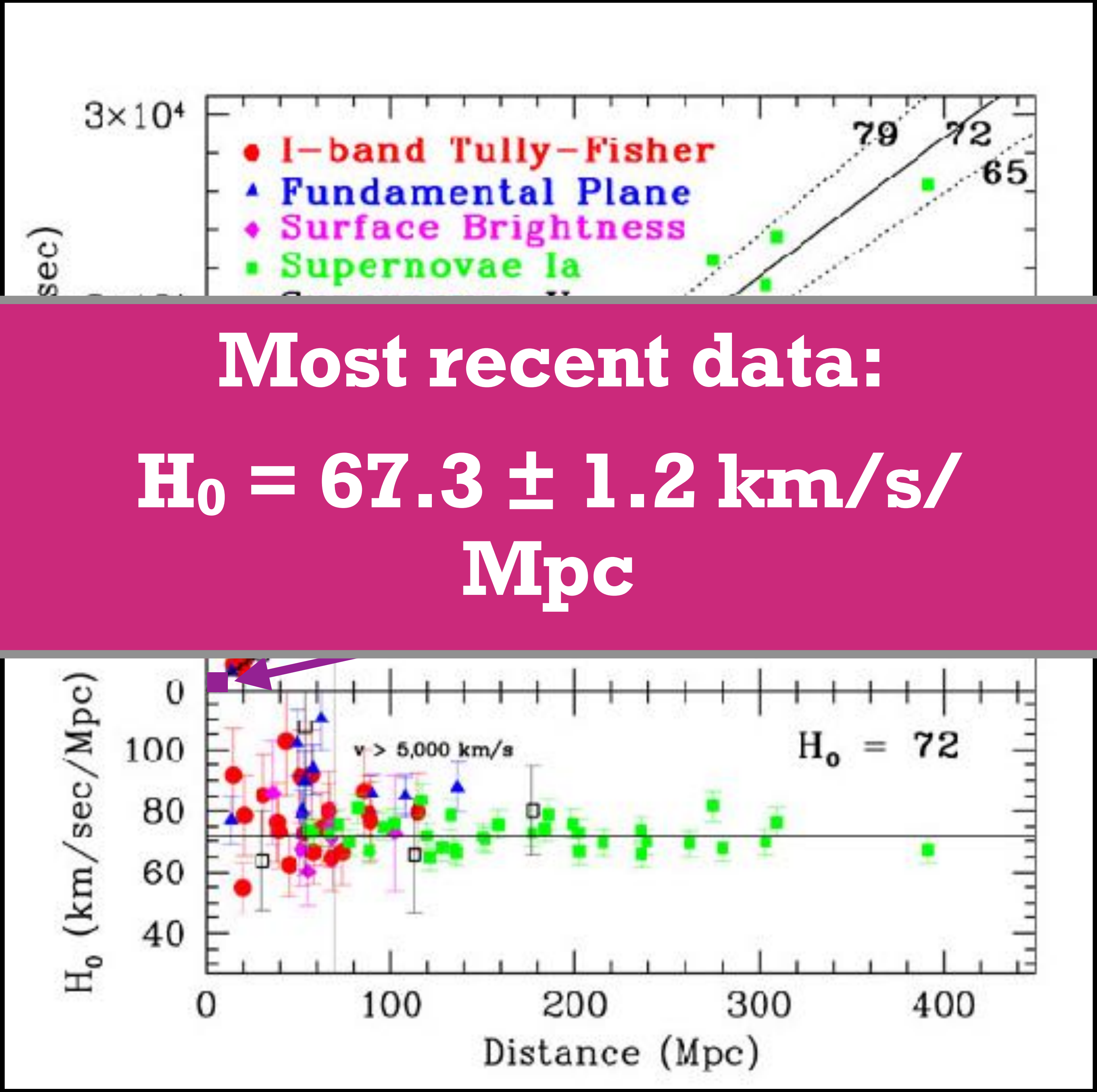


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble+1929

Today's velocity-distance relation looks very different



Most recent data:

$H_0 = 67.3 \pm 1.2$ km/s/Mpc

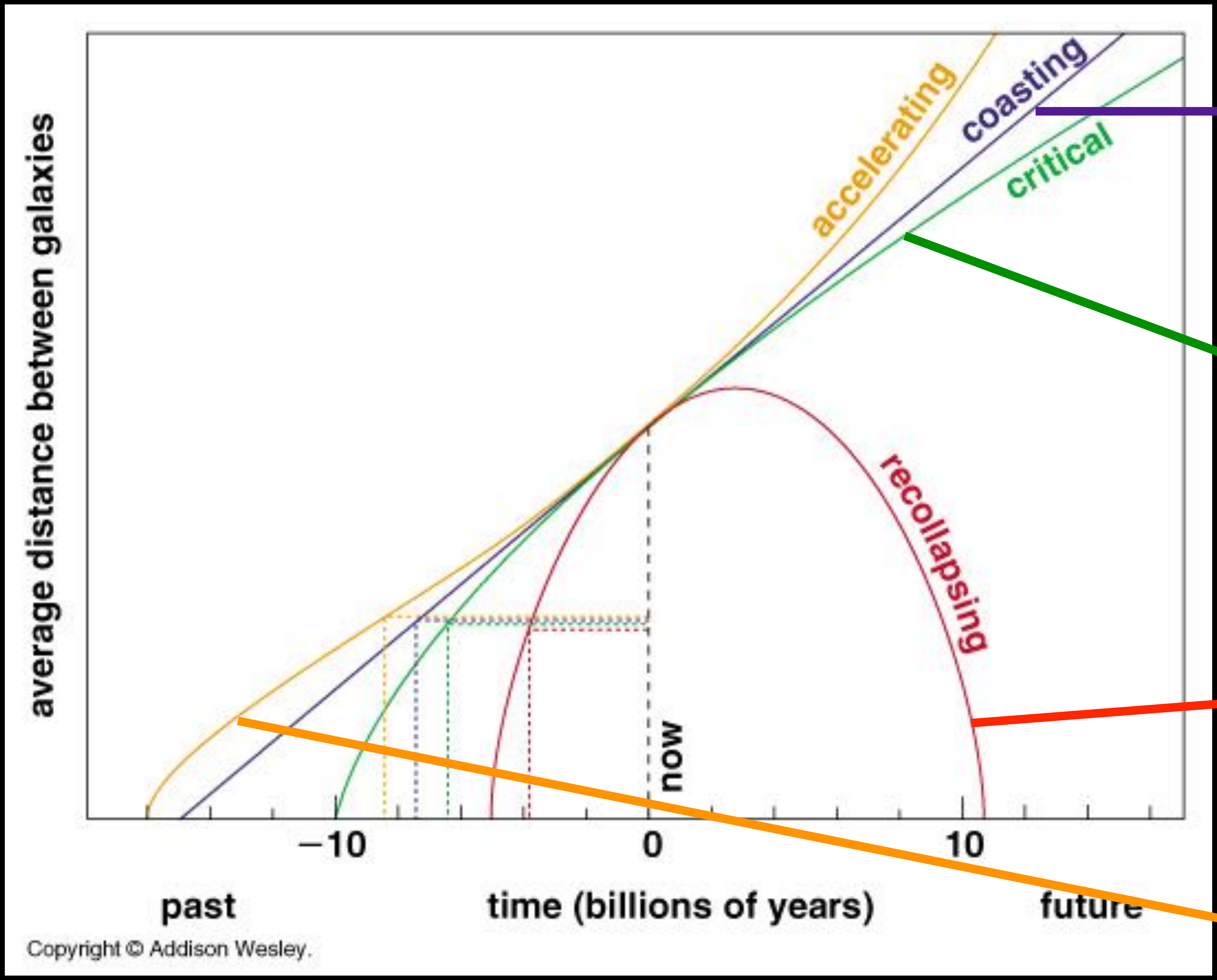
Freedman+2001

The Universe is not only expanding, but that expansion is *accelerating*

- In 1998, two teams showed that Hubble's Law has not always been constant by measuring the distances to a certain type of supernovae
  - High-z Supernova Search and the Supernova Cosmology Project
- Today, the expansion of the universe appears to be speeding up

This is weird!

There are many possible fates of the Universe



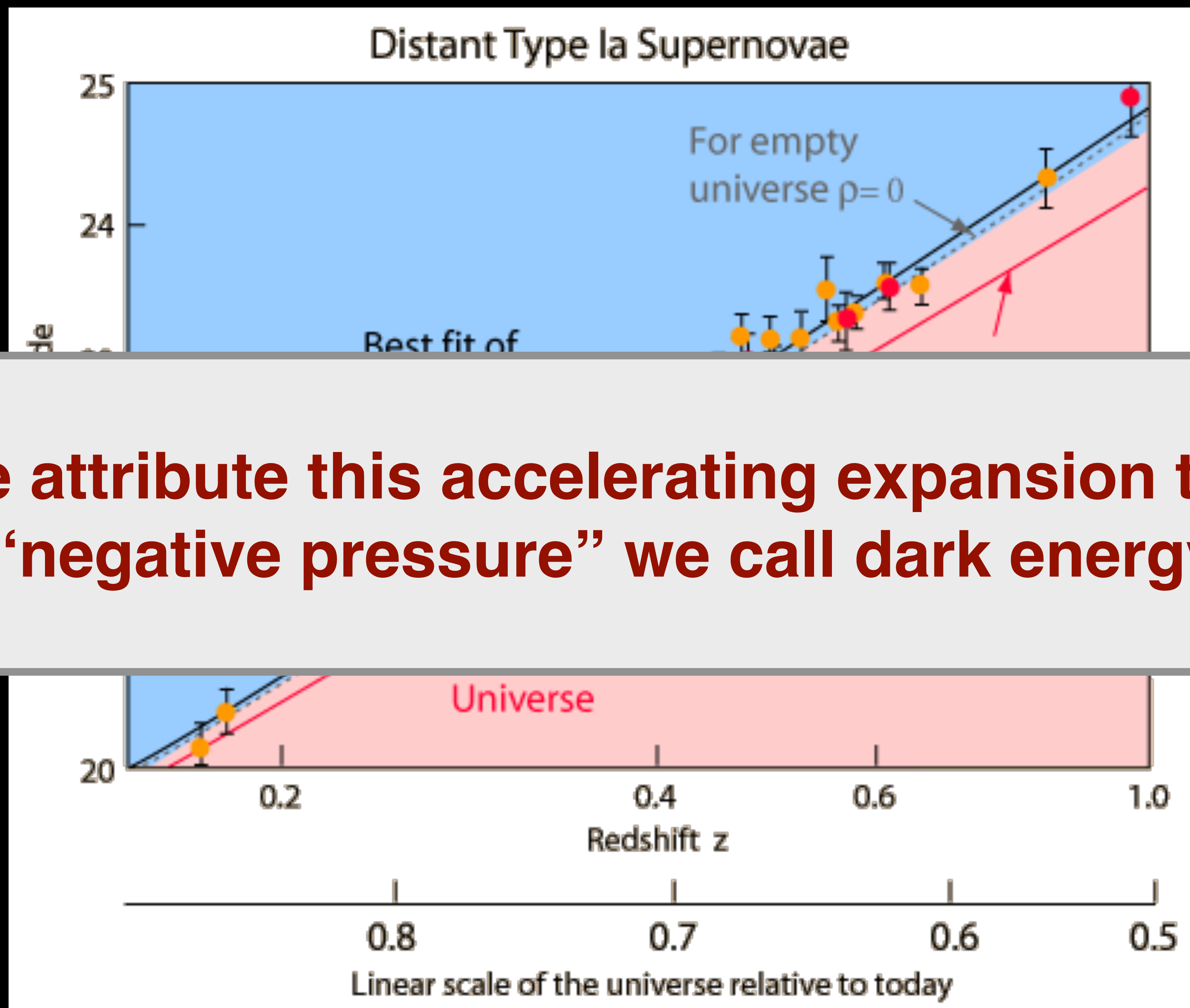
An open universe: continues to expand at a constant rate forever

A flat universe: expansion continues but slows

A closed universe: expansion reverses

An accelerating universe: expansion continues and speeds up

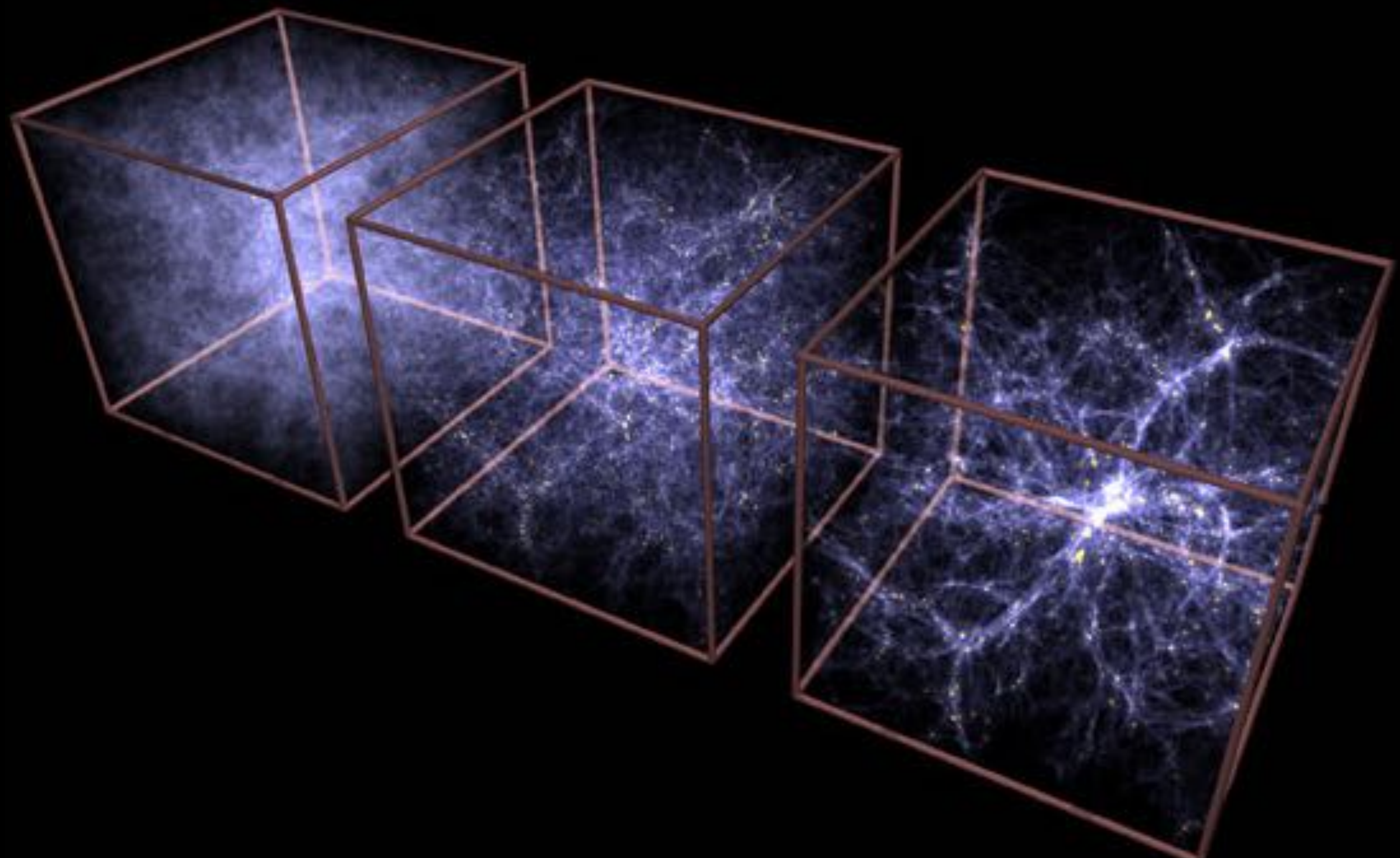
The supernovae data tell us that we live in an accelerating universe



We attribute this accelerating expansion to a “negative pressure” we call dark energy

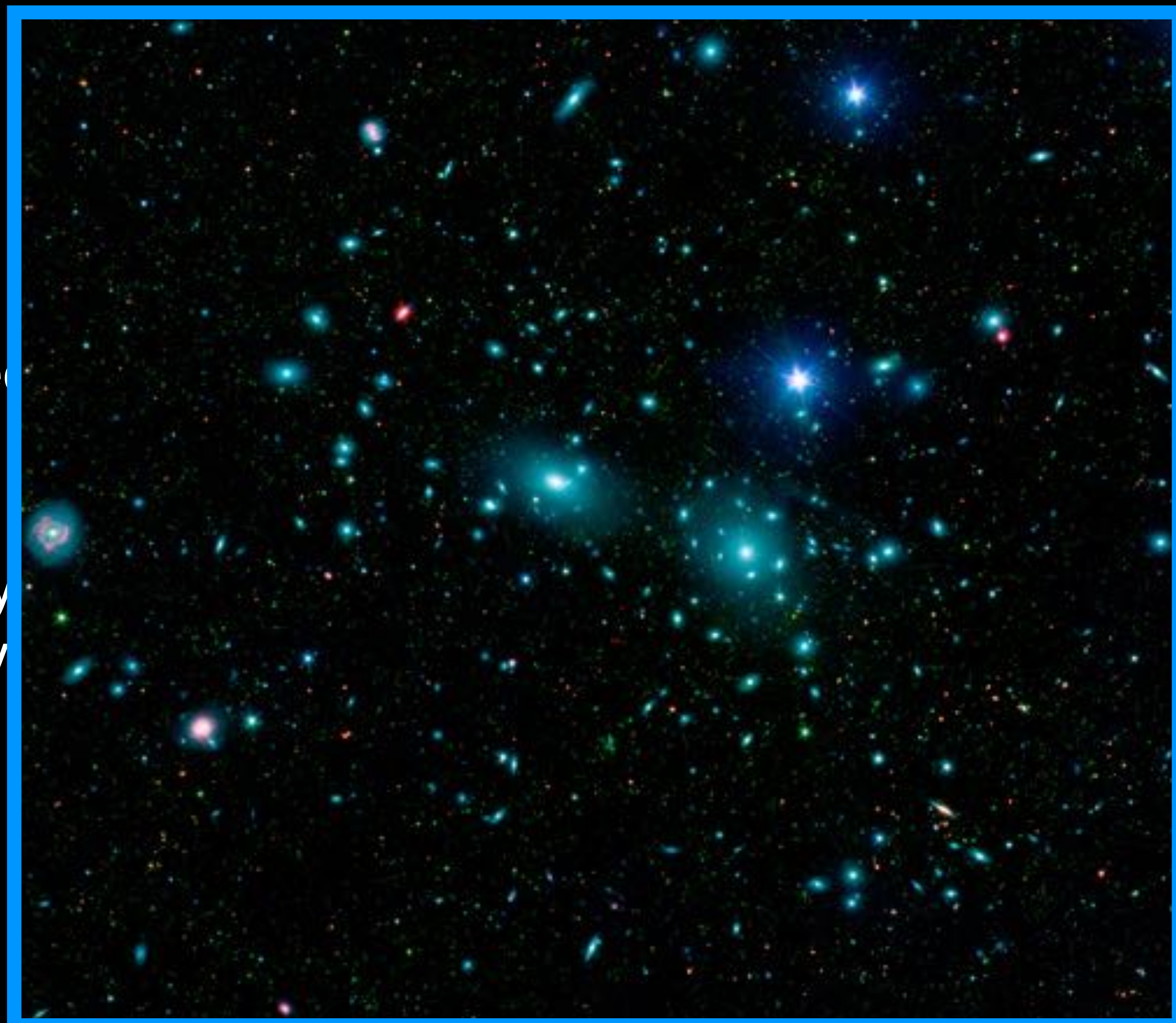
http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/univacc.html

What is dark matter?



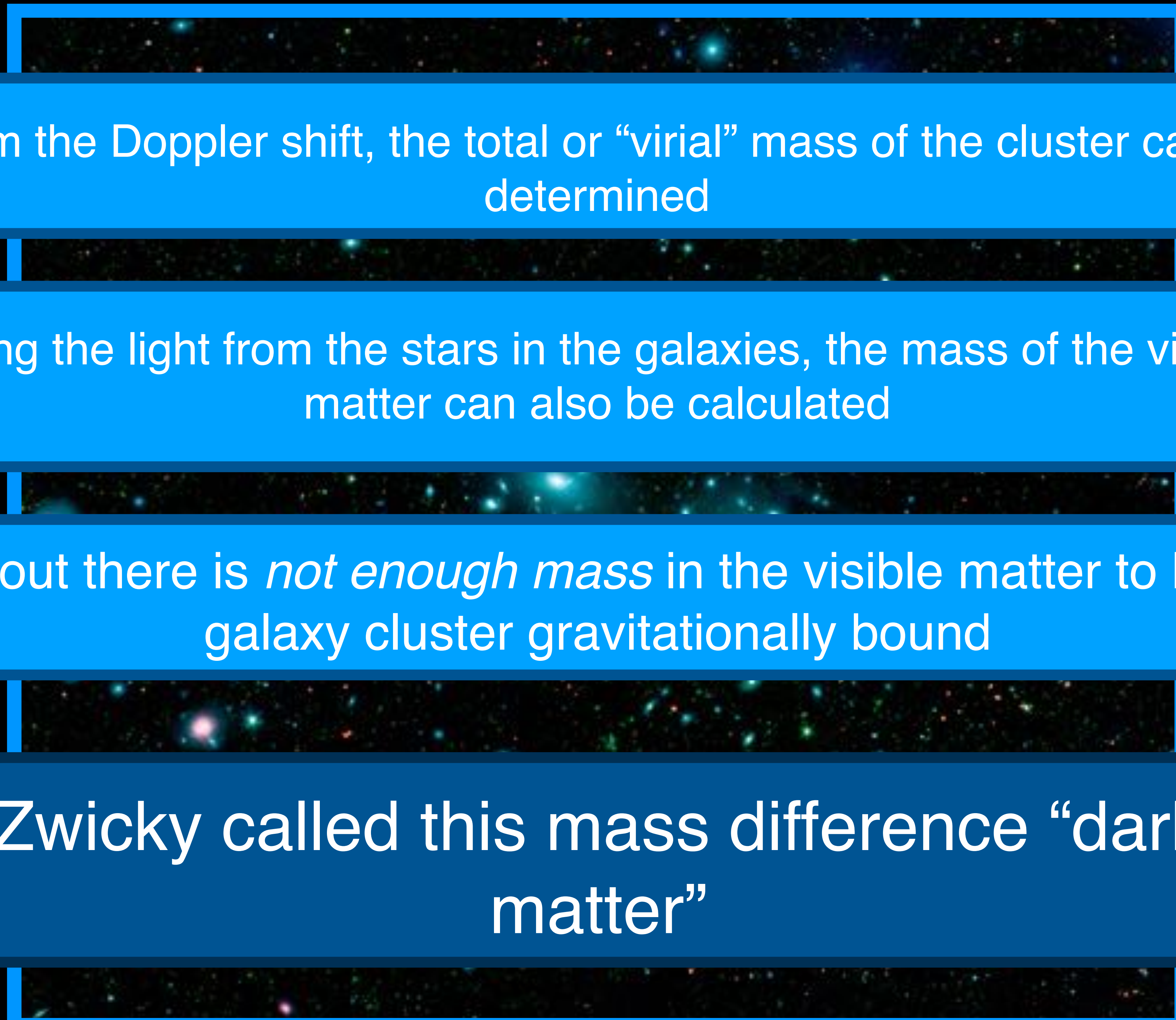
In 1933, Fritz Zwicky posited the existence of dark matter

- At Calte
  Cluster
- A galaxy
  are grav



NASA, JPL-Caltech, SDSS, Leigh Jenkins, Ann Hornschemeier (Goddard Space Flight Center)

The Coma Cluster consists of ~ 1,000 galaxies



From the Doppler shift, the total or “virial” mass of the cluster can be determined

Using the light from the stars in the galaxies, the mass of the visible matter can also be calculated

It turns out there is *not enough mass* in the visible matter to keep the galaxy cluster gravitationally bound

Zwicky called this mass difference “dark matter”

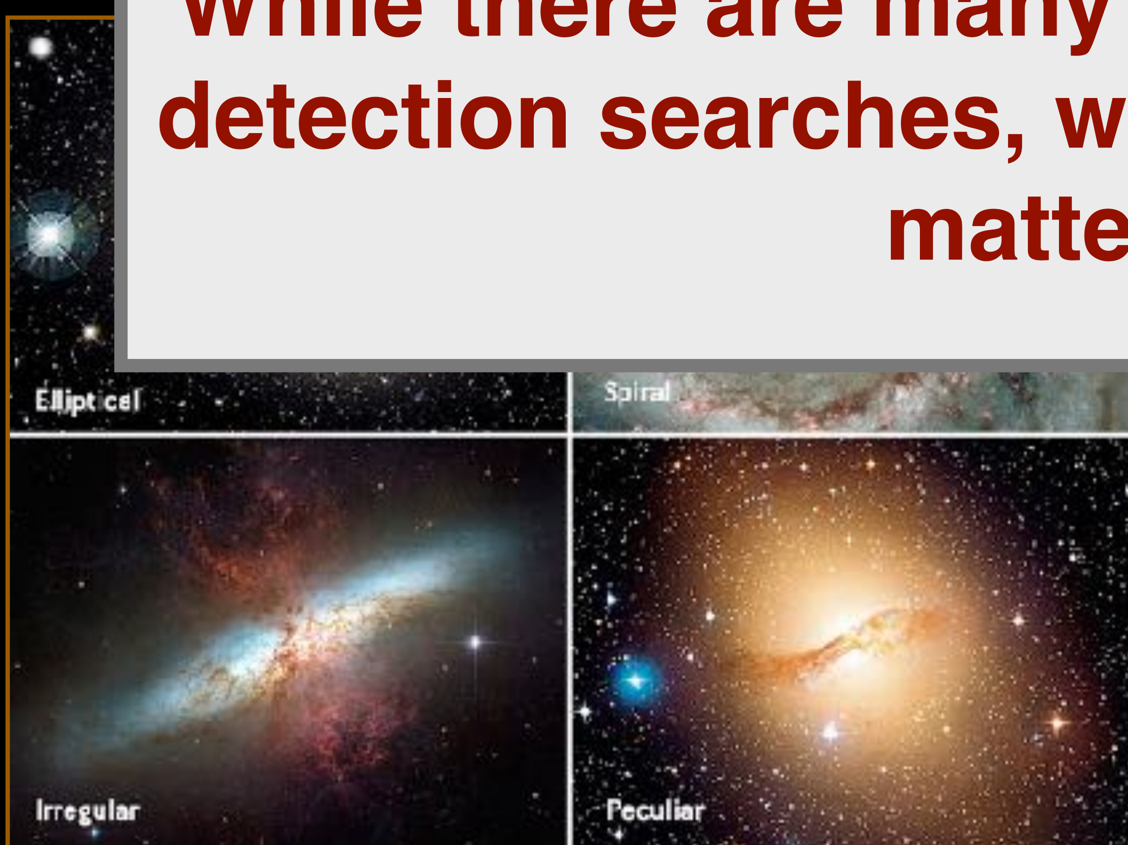
NASA, JPL-Caltech, SDSS, Leigh Jenkins, Ann Hornschemeier (Goddard Space Flight Center)

Other evidence for dark matter exists

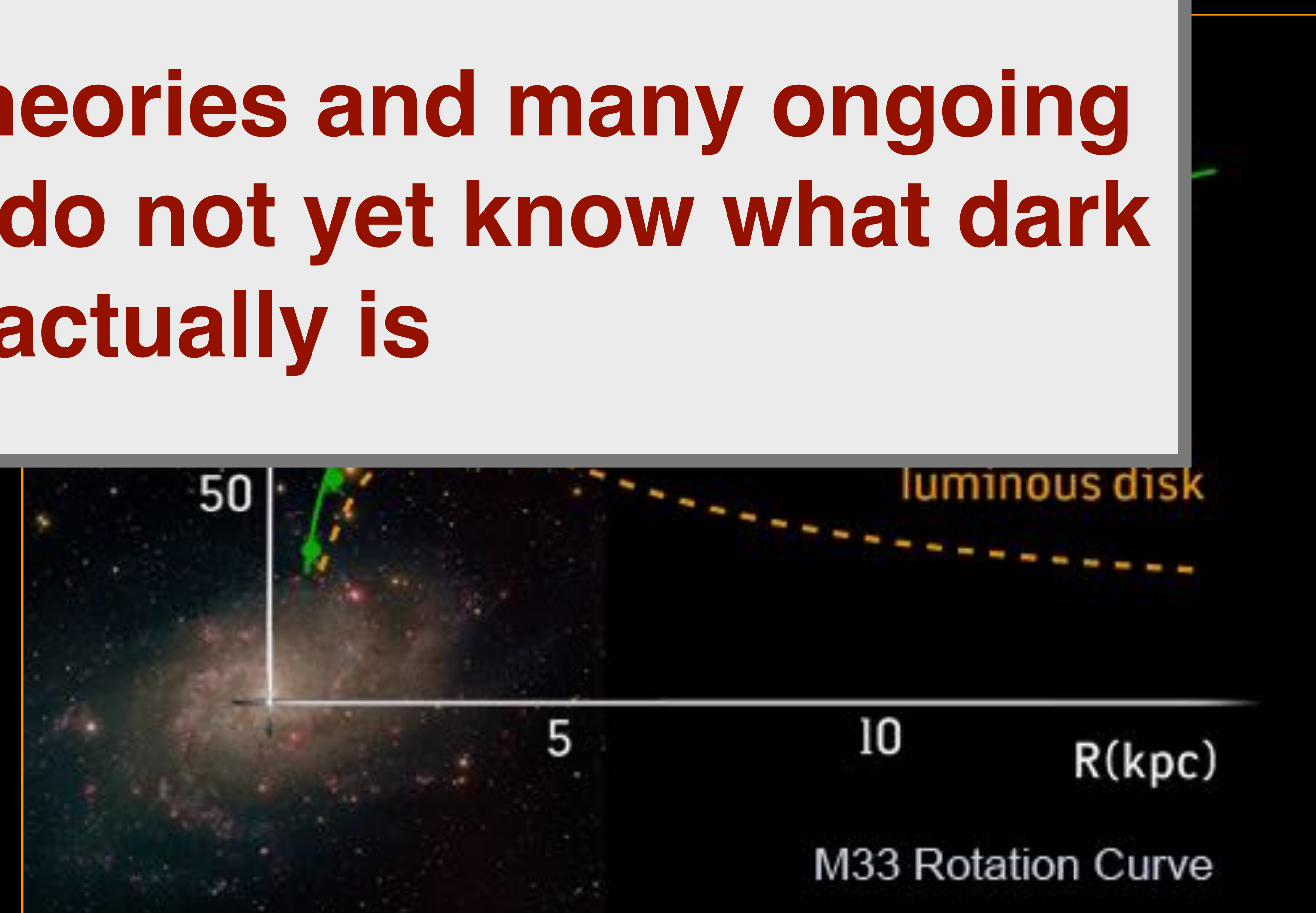
Simulations cannot replicate the shapes of galaxies we see today without a uniform distribution of mass ~ 10 times the mass of the

Galaxies rotate much faster at the edges than they would if dark matter were not present

While there are many theories and many ongoing detection searches, we do not yet know what dark matter actually is

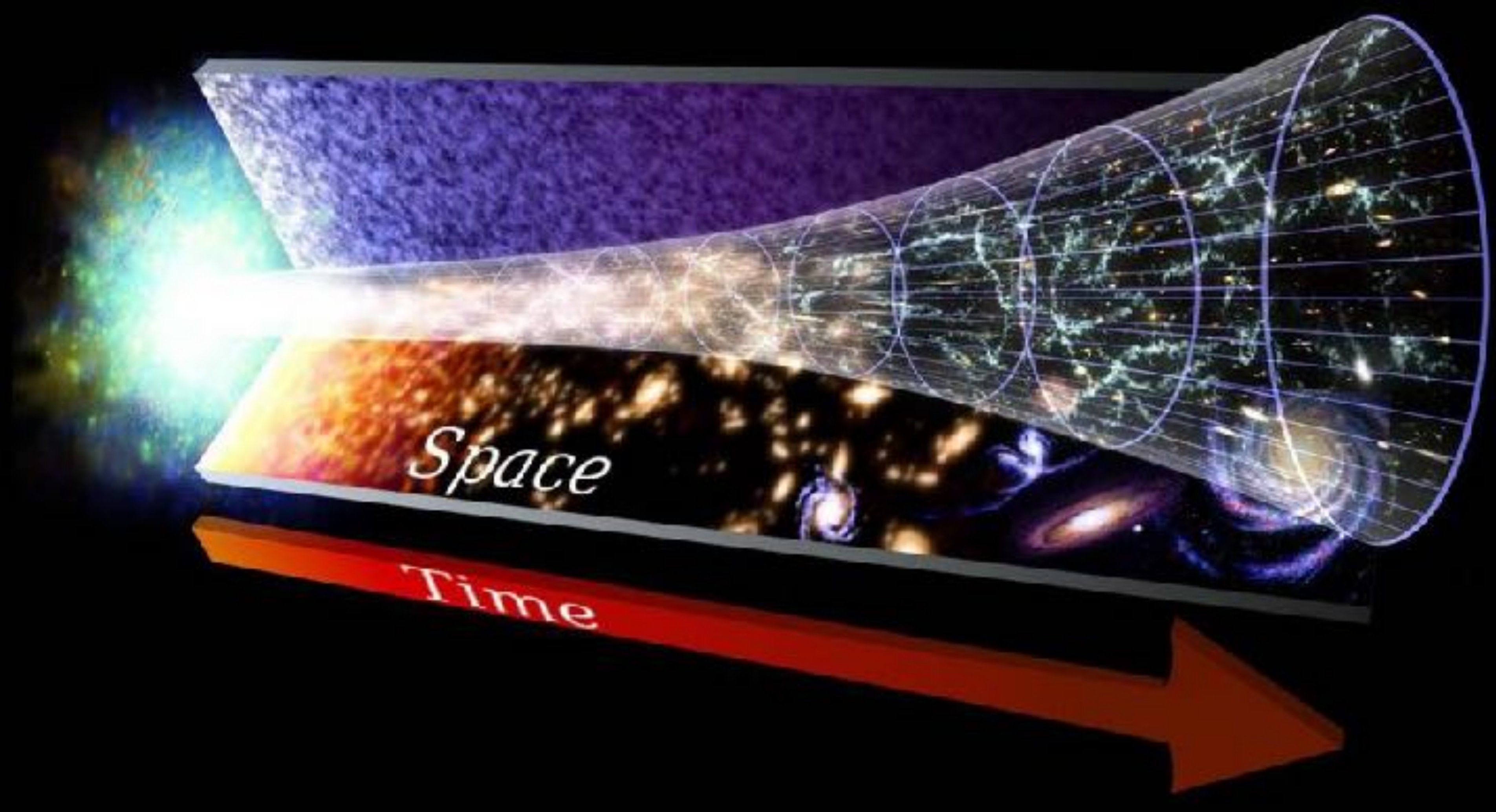


Elliptical: Canada-France-Hawaii Telescope/J.-C. Cuillandre (CFHT)/Coelum; Spiral: N. Scoville (Caltech)/T. Rector (U. Alaska, NOAO) Et Al., Hubble Heritage Team/NASA; Irregular: NASA/ESA/The Hubble Heritage Team; Peculiar: J.-C. Cuillandre (CFHT)/ Hawaii Starlight/CFHT

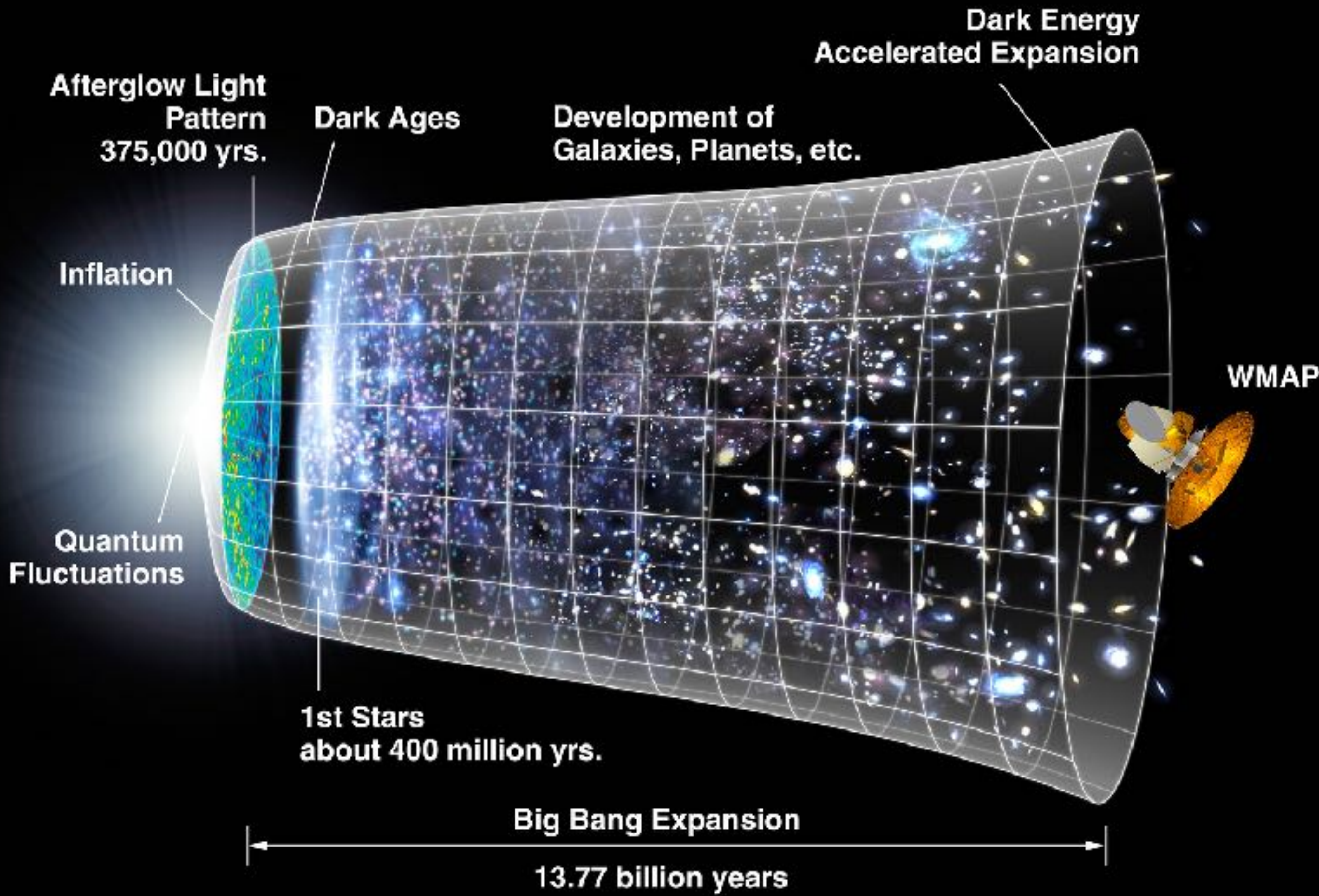


NOAO, AURA, NSF, T.A.Rector.

How did the Universe evolve?



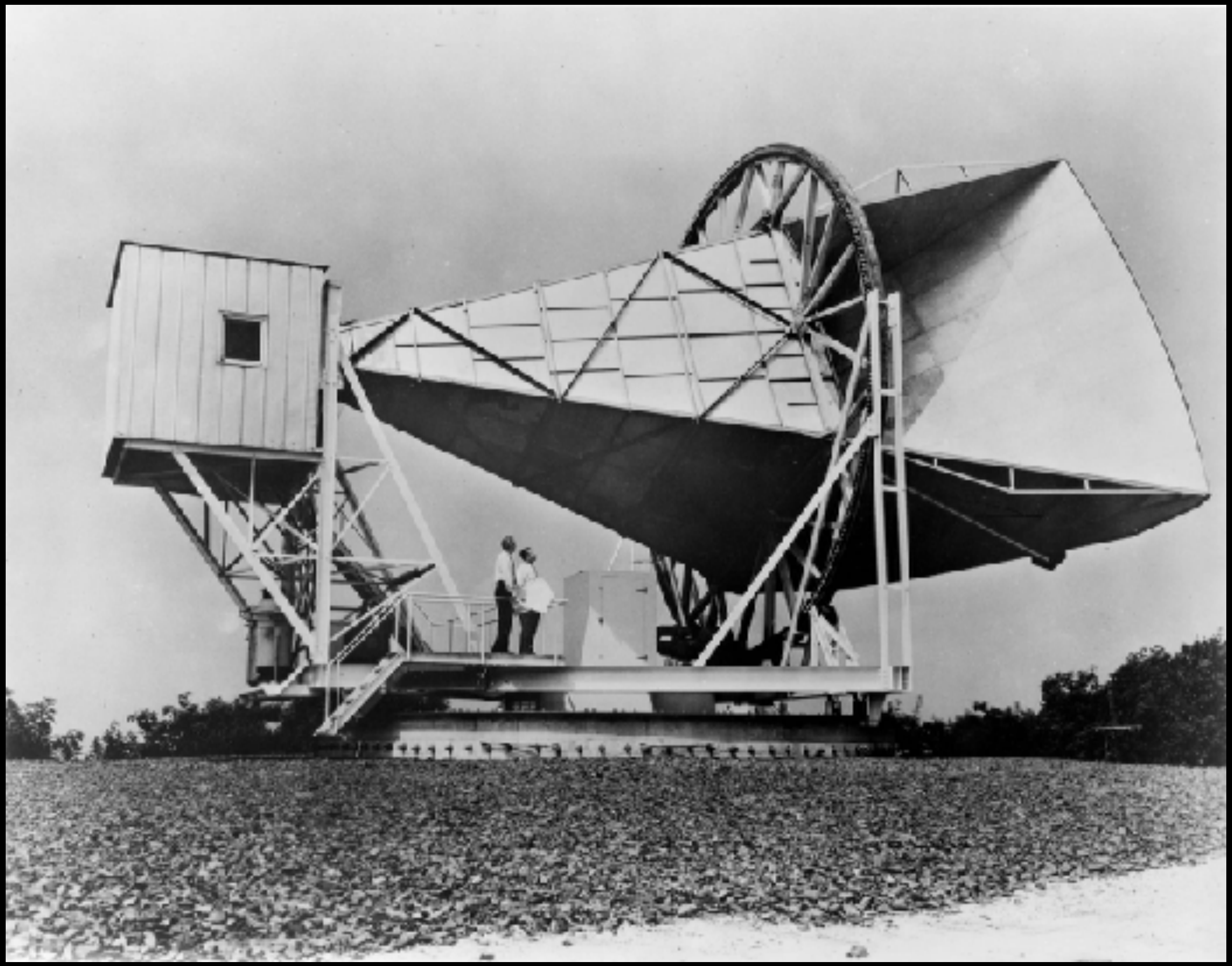
A brief history of the Universe



NASA/WMAP Science Team

The faint radiation left over from the Big Bang can be measured

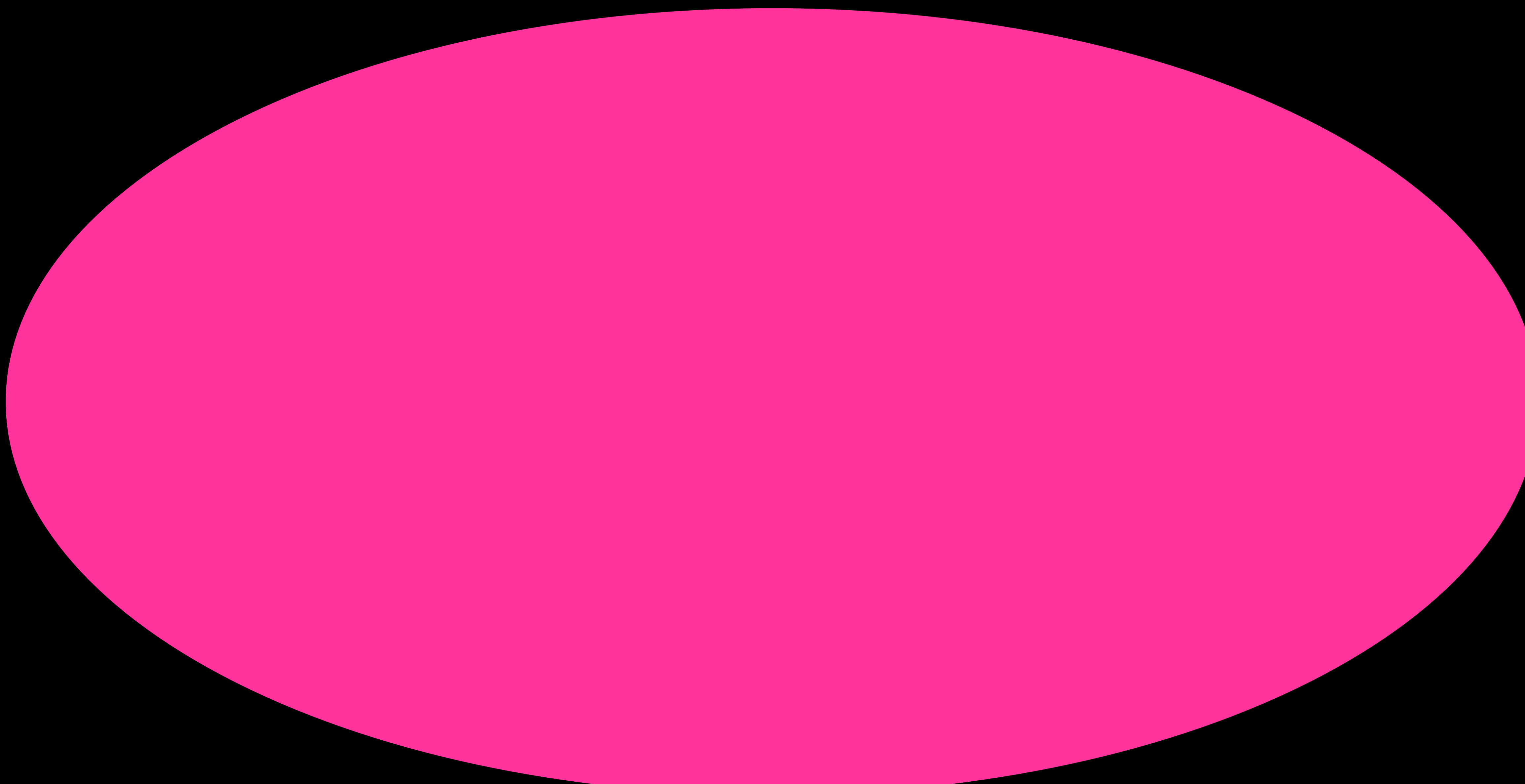
- In 1964, Arno Penzias and Robert Wilson were working on a 6-meter radio antenna at Bell Labs
- They were attempting to measure faint radio waves bounced off of satellites
- After removing all possible interference, they found a steady, low-frequency noise that persisted in the receiver



NASA Image

Much of what we know about the history of the Universe comes from light emitted 380,000 years after the Big Bang

Cosmic Microwave Background (CMB)

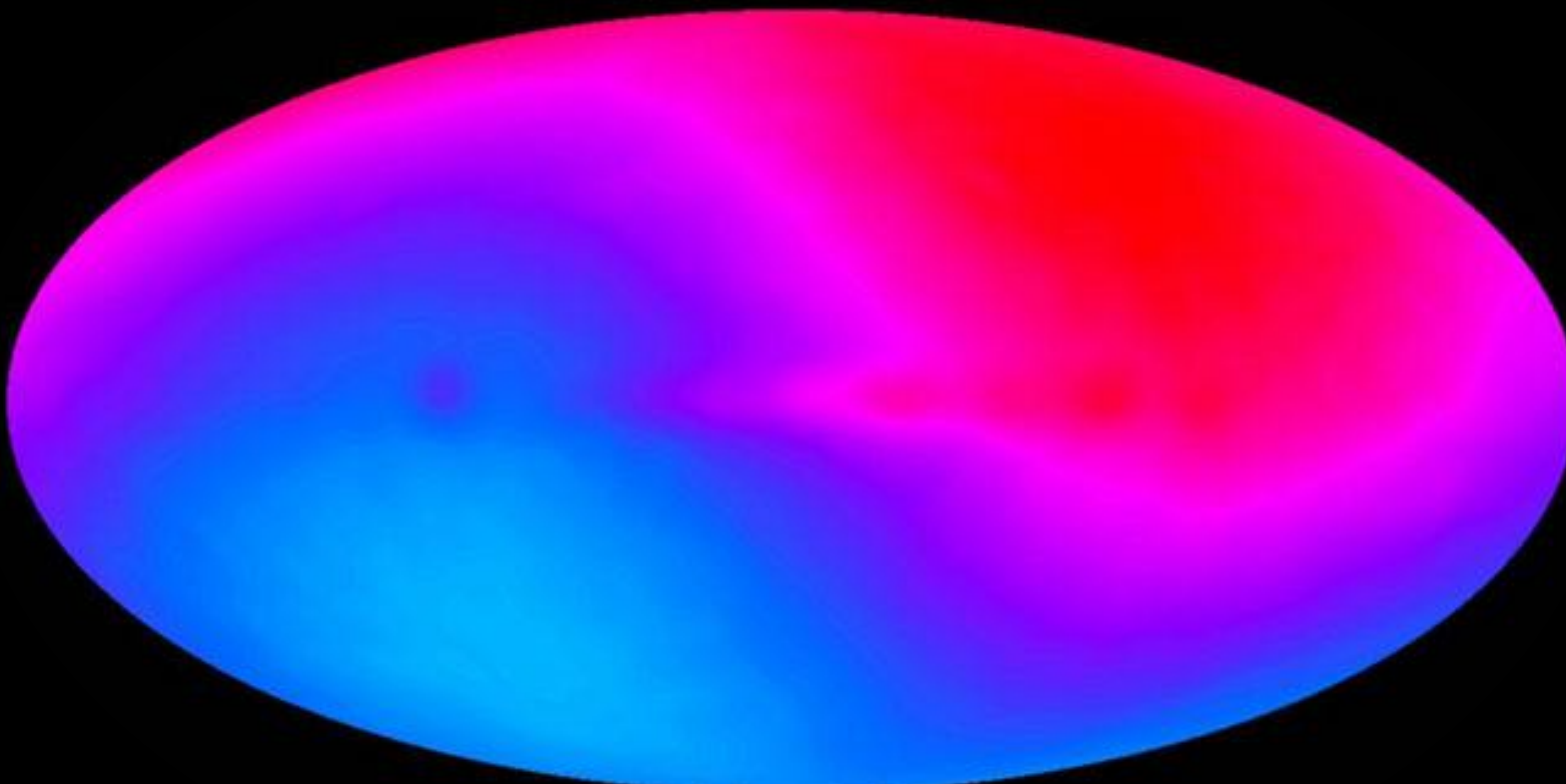


COBE

T = 2.7 K

Much of what we know about the history of the Universe comes from light emitted 380,000 years after the Big Bang

Cosmic Microwave Background (CMB)

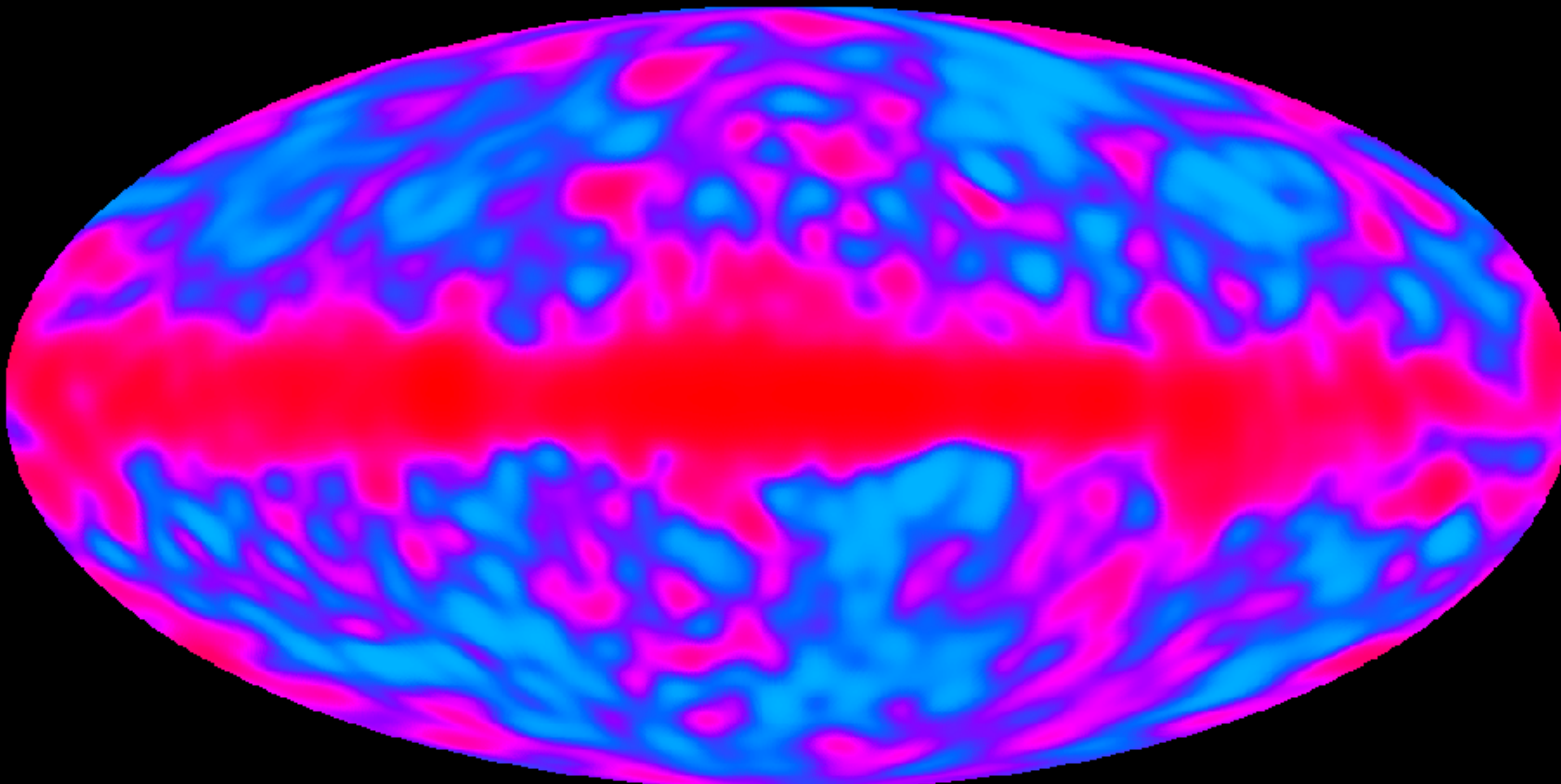


COBE

$\Delta T = 3.6$ mK

Much of what we know about the history of the Universe comes from light emitted 380,000 years after the Big Bang

Cosmic Microwave Background (CMB)

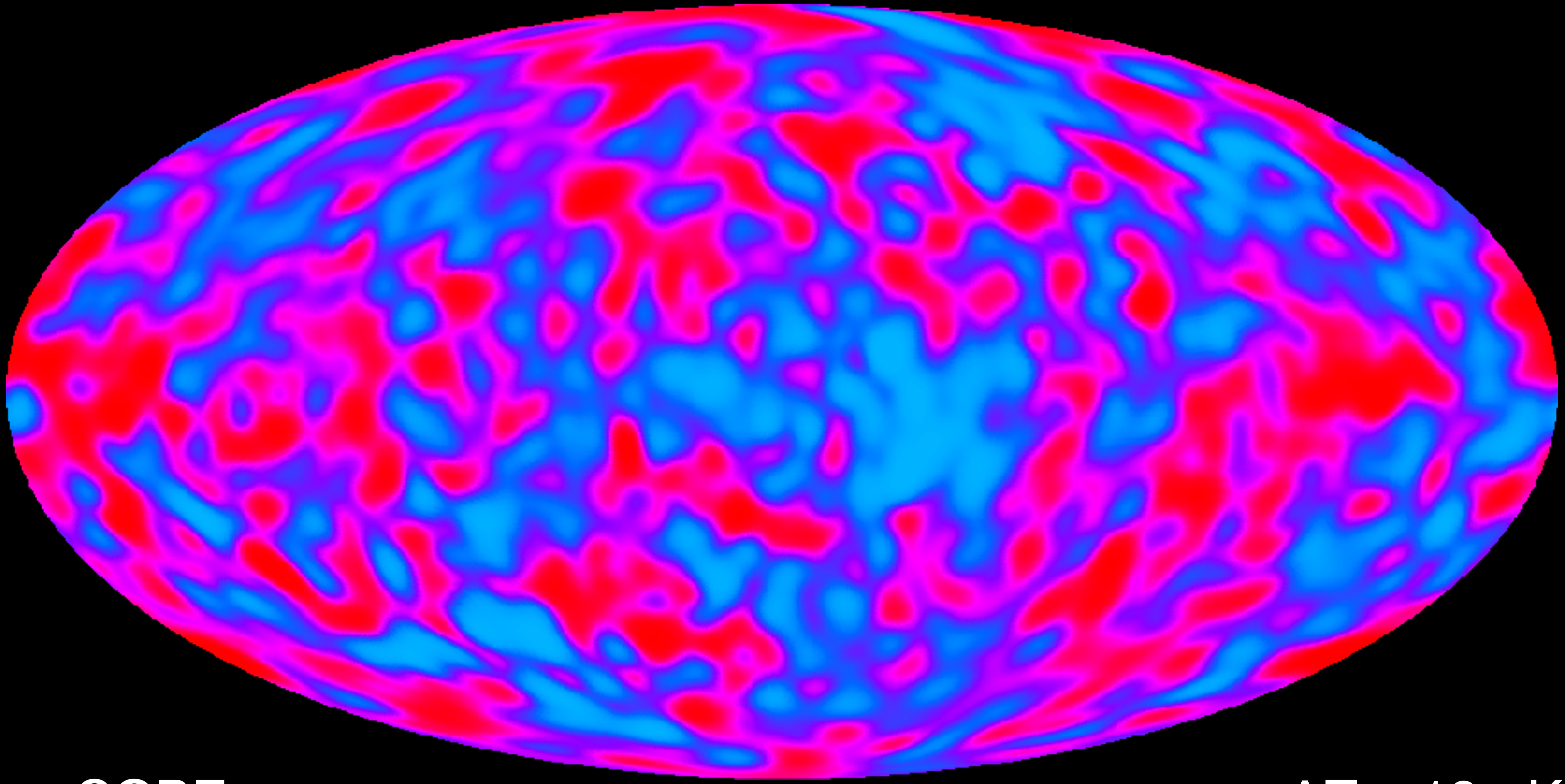


COBE

$\Delta T = 18\ \mu K$

Much of what we know about the history of the Universe comes from light emitted 380,000 years after the Big Bang

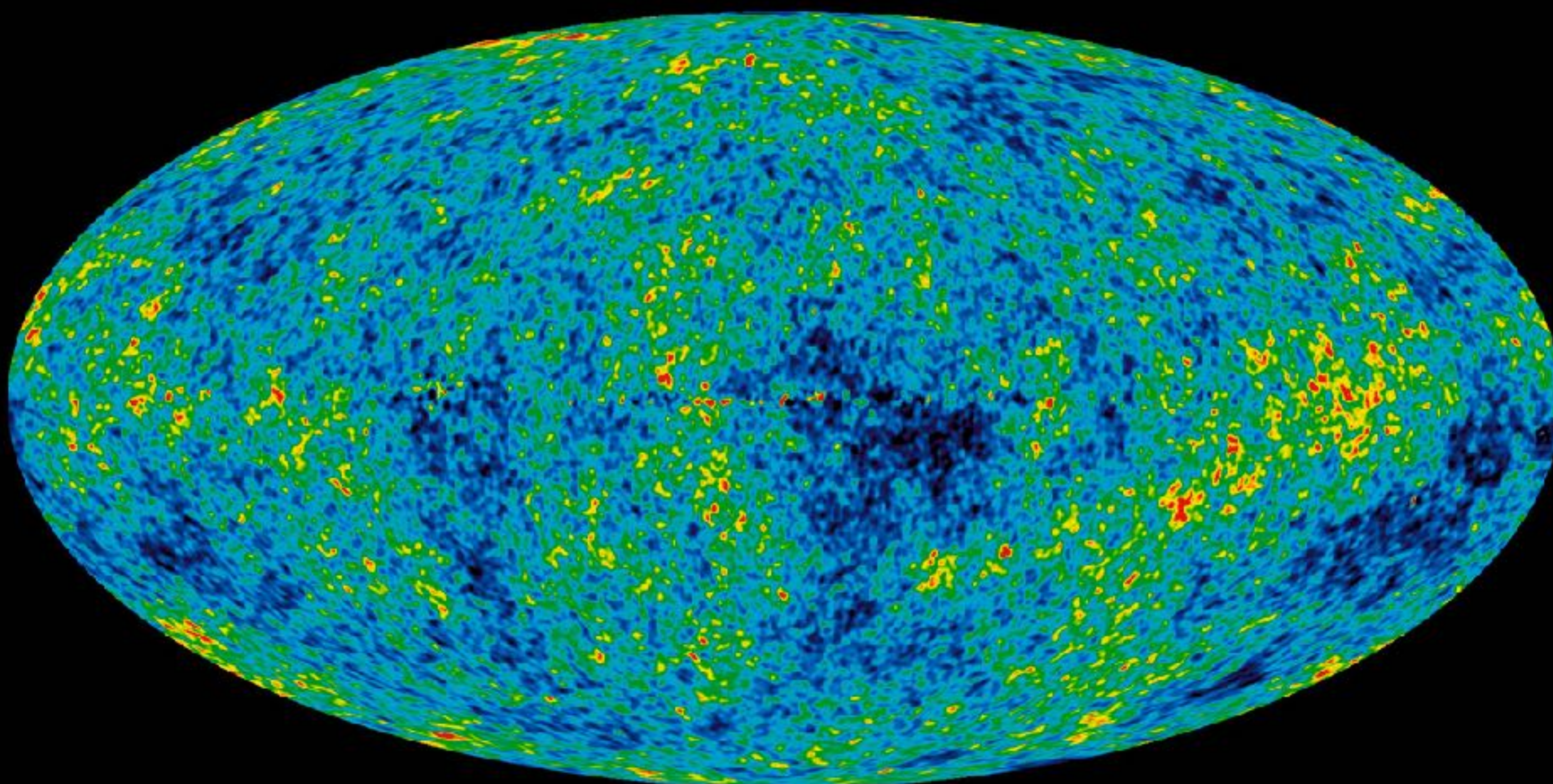
Cosmic Microwave Background (CMB)



COBE

$\Delta T = 18\ \mu K$

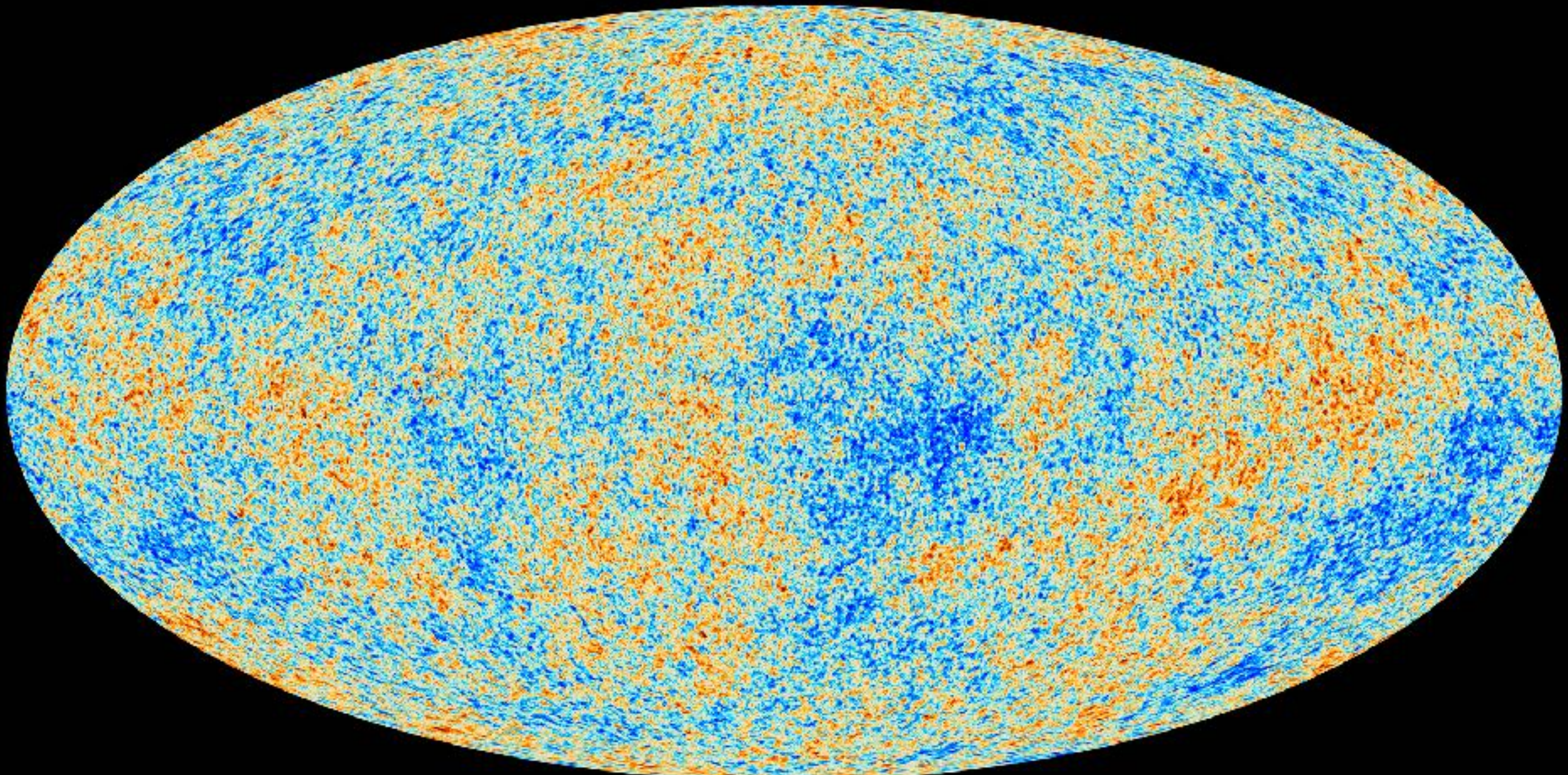
The COBE results were improved upon by the Wilkinson Microwave Anisotropy Probe



WMAP

$\Delta T = 1 \times 10^{-6}$ K

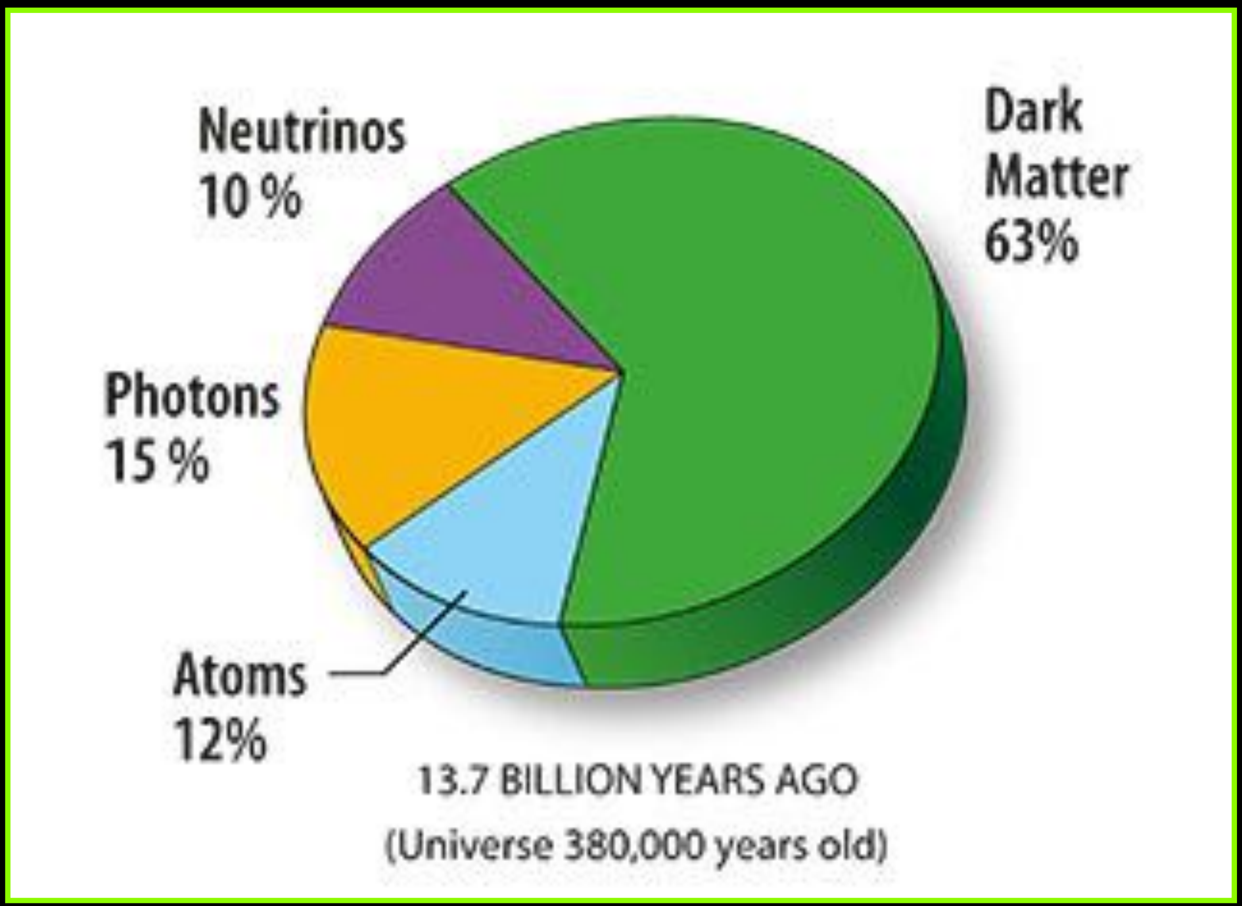
The most recent CMB probe was called Planck, a joint venture between NASA and the European Space Agency

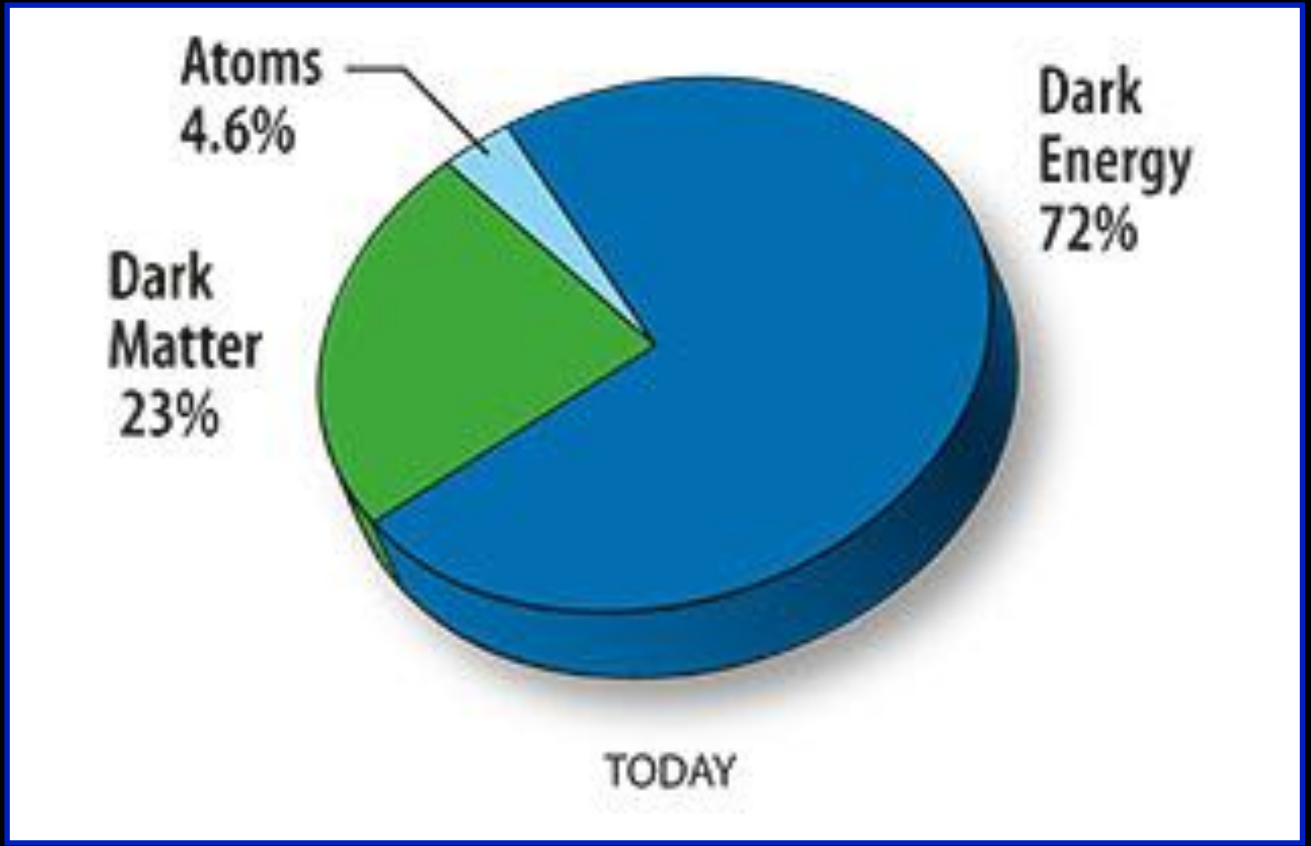


Planck

$\Delta T = 1 \times 10^{-6}$ K

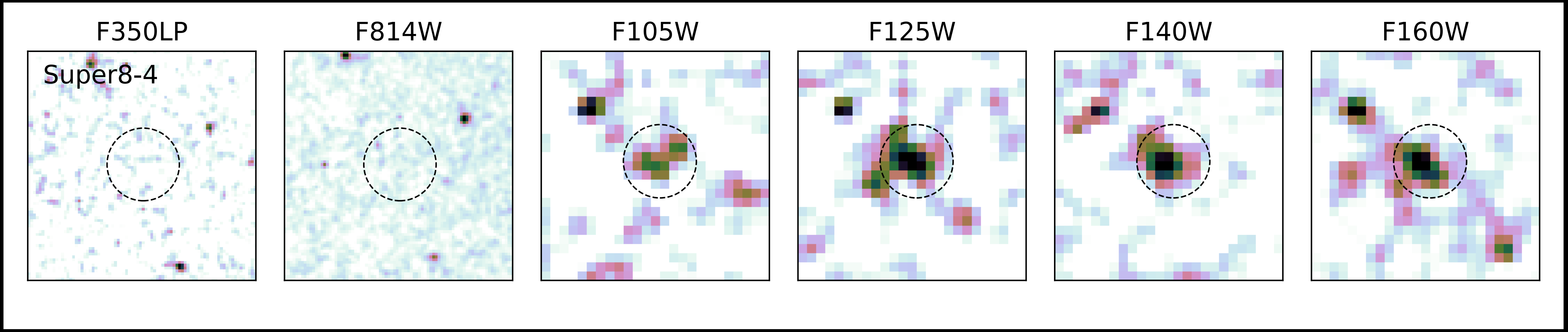
From the way the CMB is distributed, we have been able to determine a great deal about the early universe



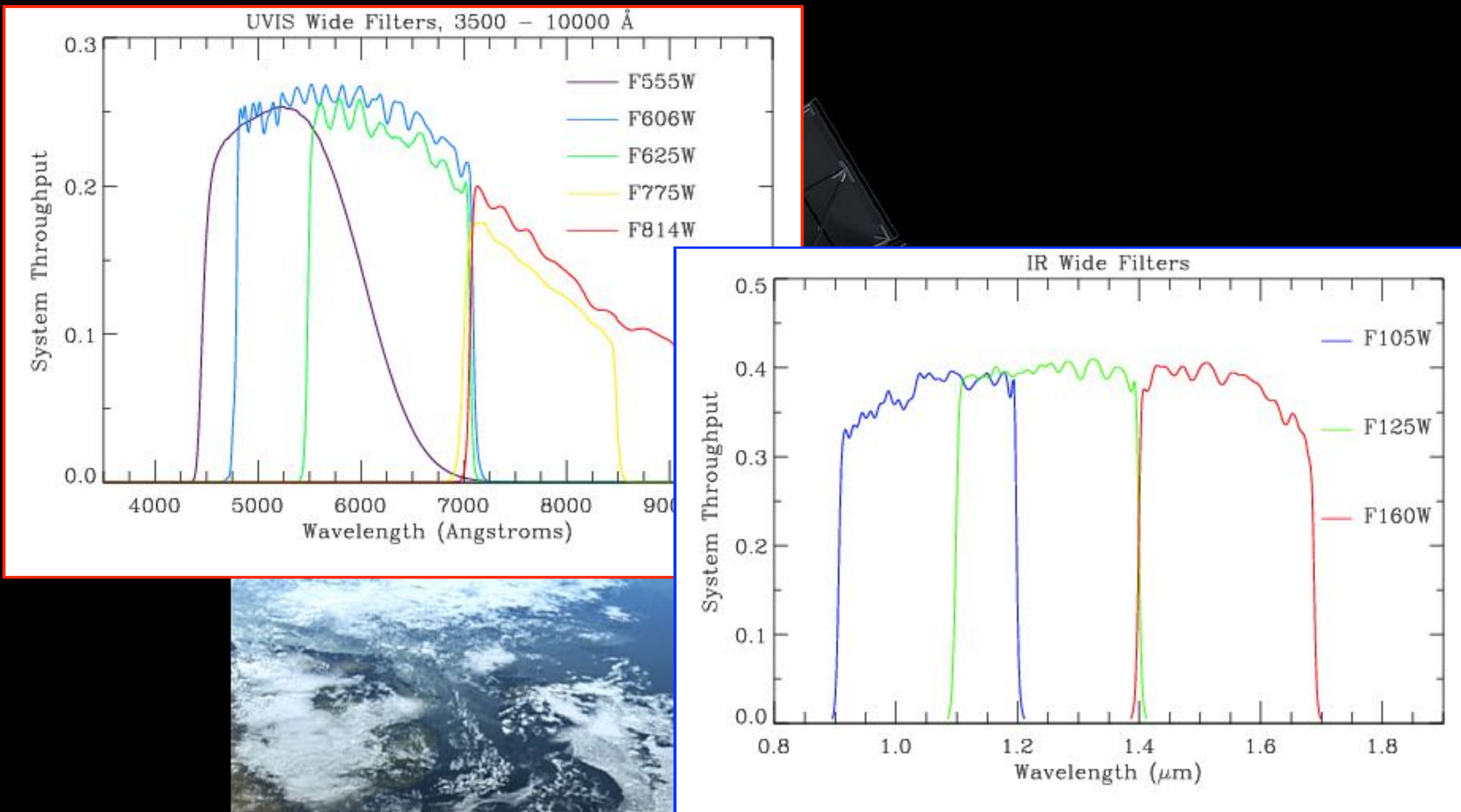


NASA/WMAP Science Team

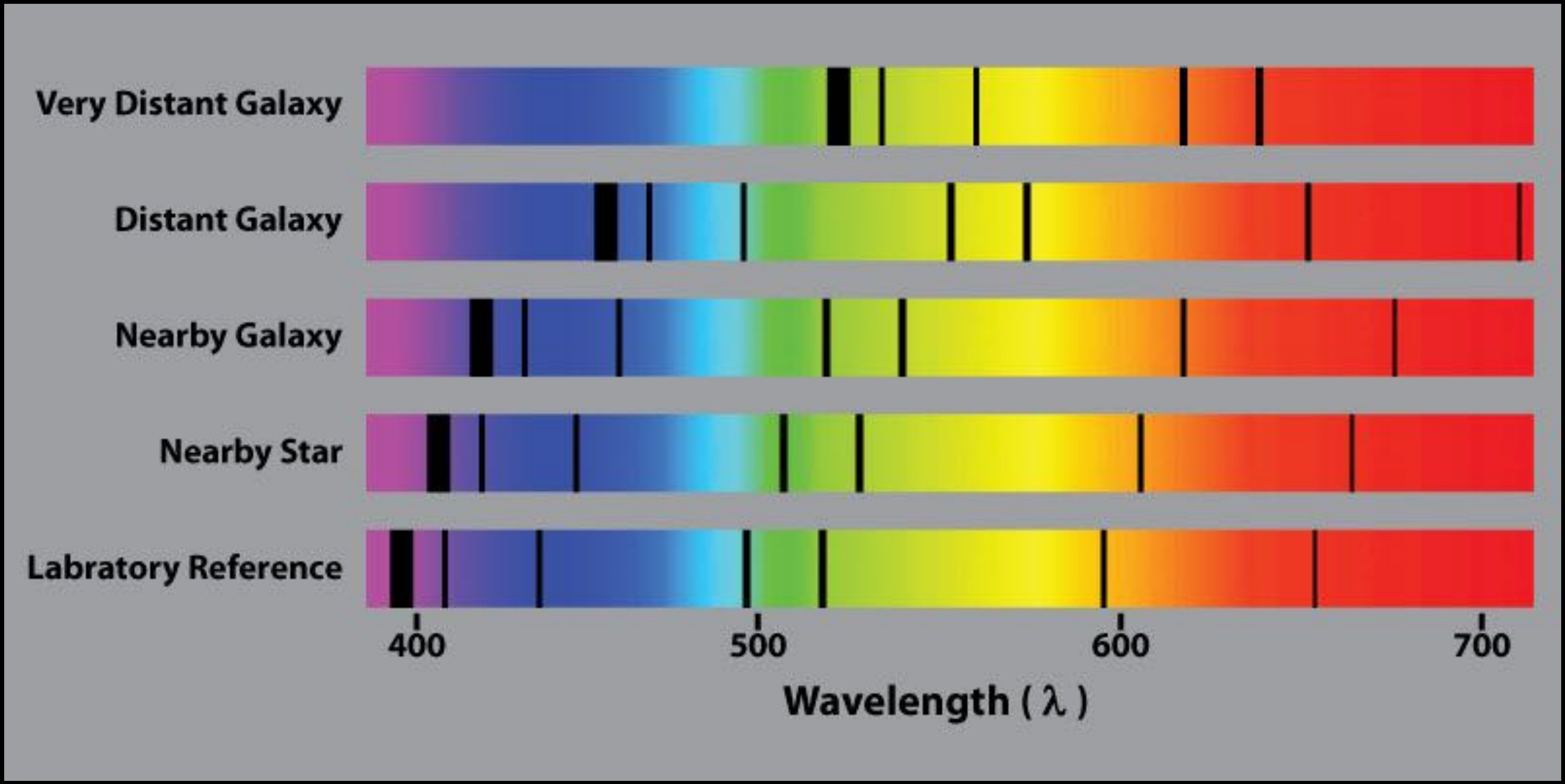
How do we study the first galaxies?



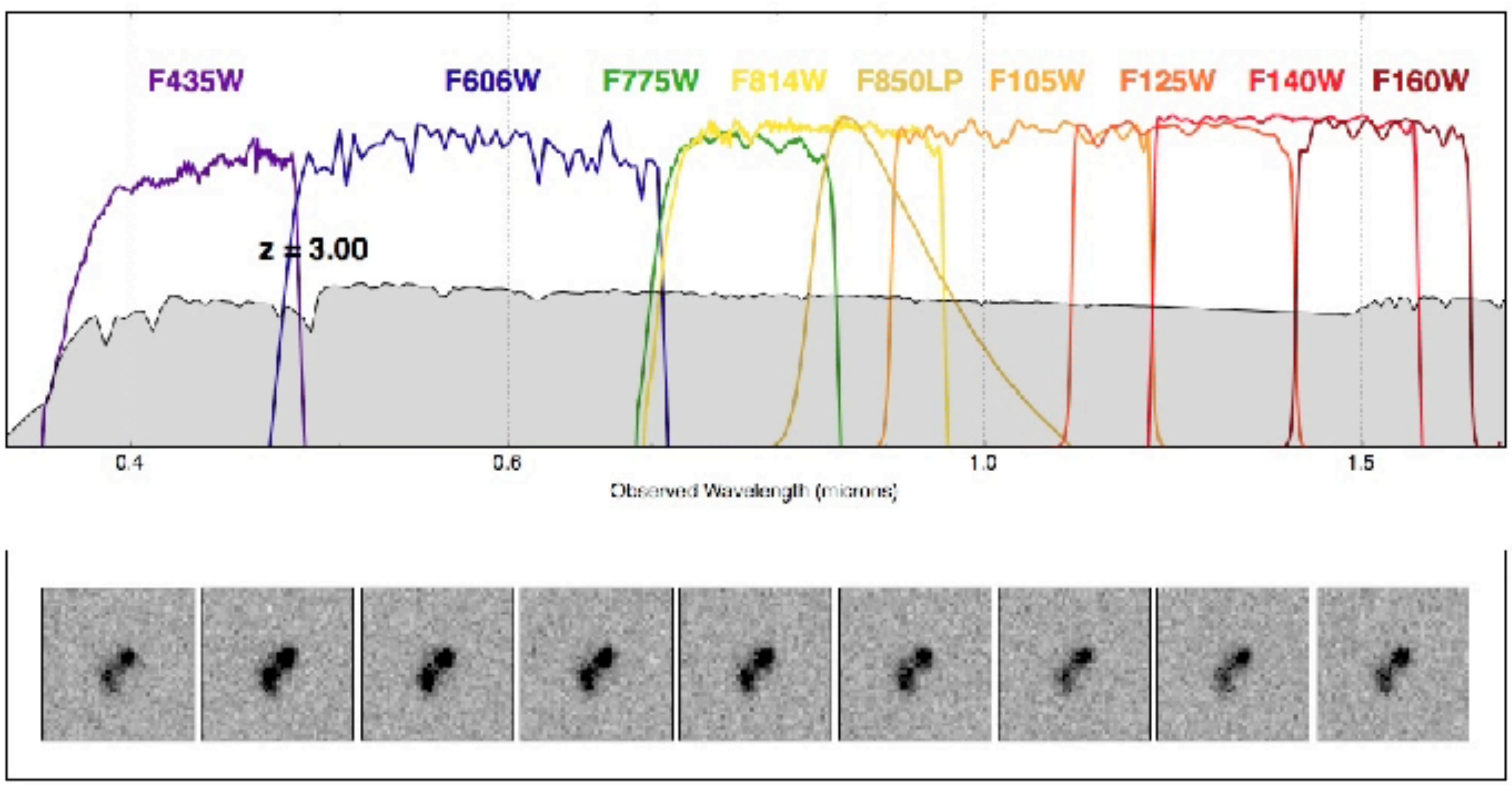
The *Hubble Space Telescope* has transformed astronomy since it's launch in 1990



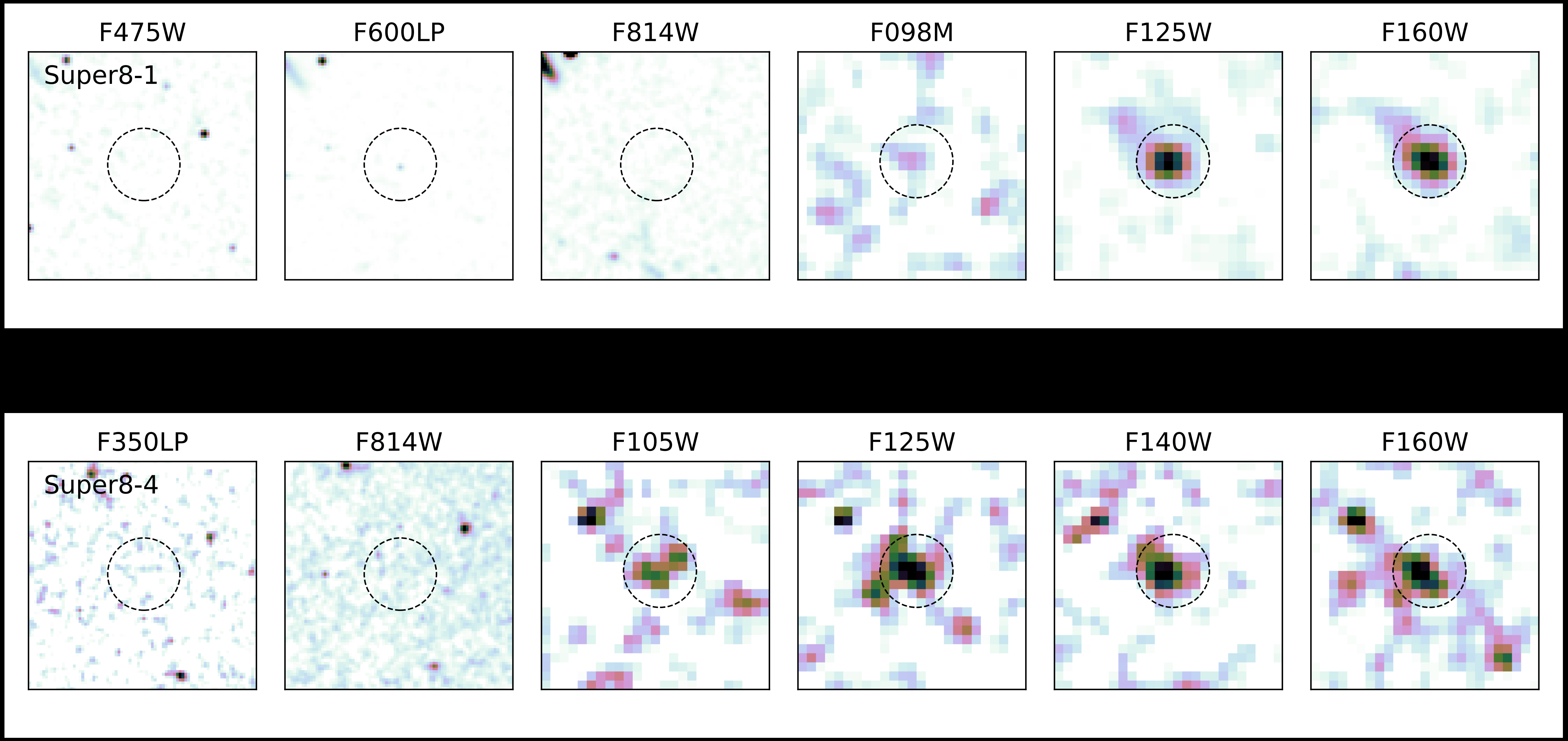
The expansion of the Universe causes light to shift to longer wavelengths



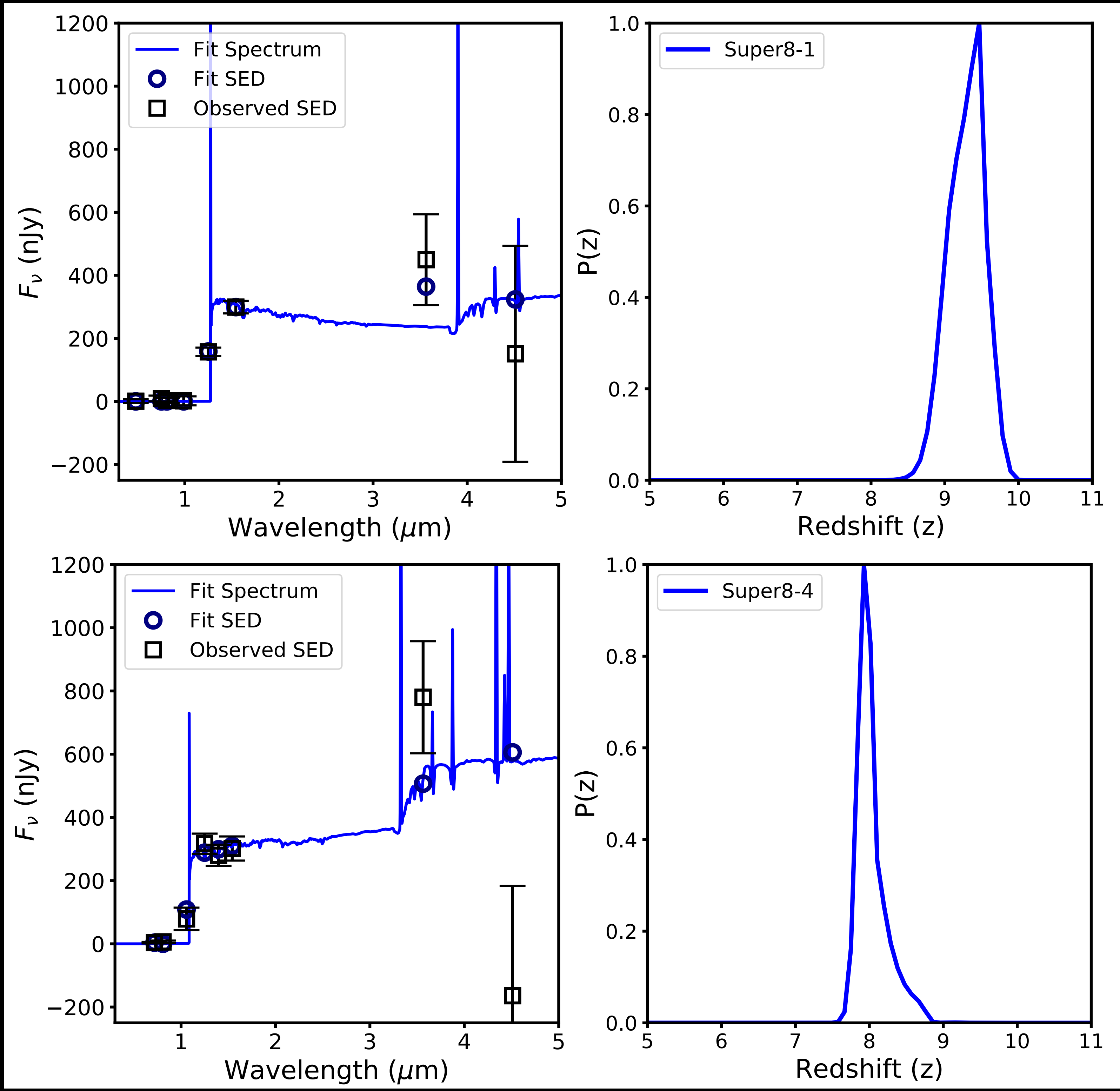
Very high redshift galaxies can be identified by what wavelengths they are visible



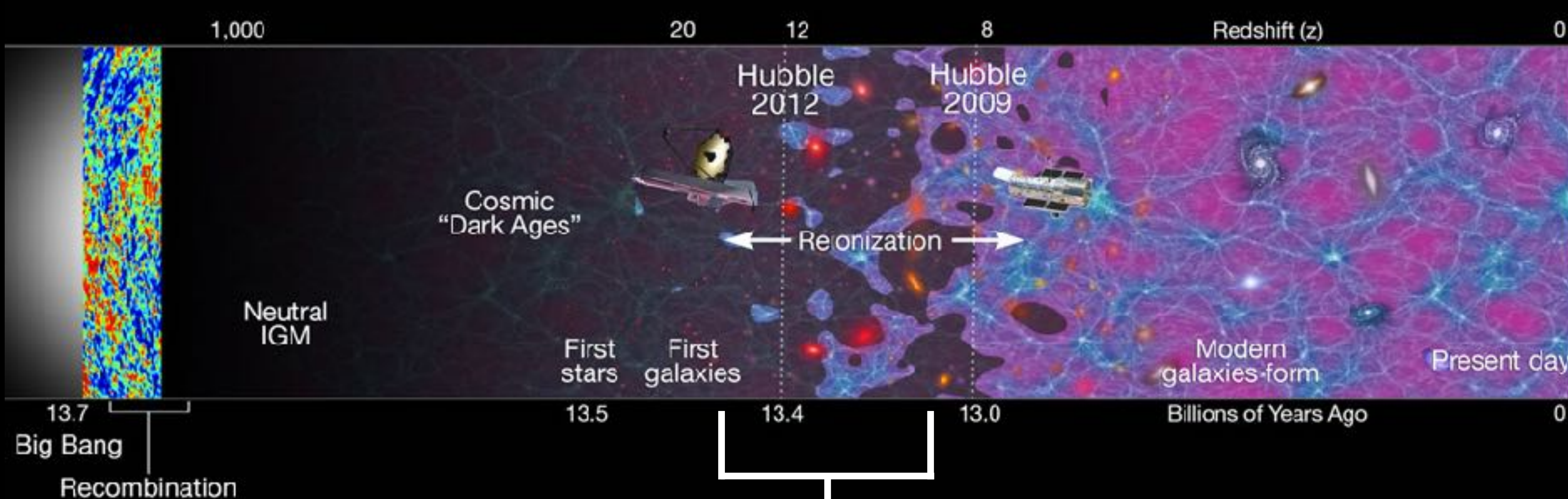
Very high redshift galaxies can be identified by what wavelengths they are visible



We can quantify the galaxies' distance based on their spectra



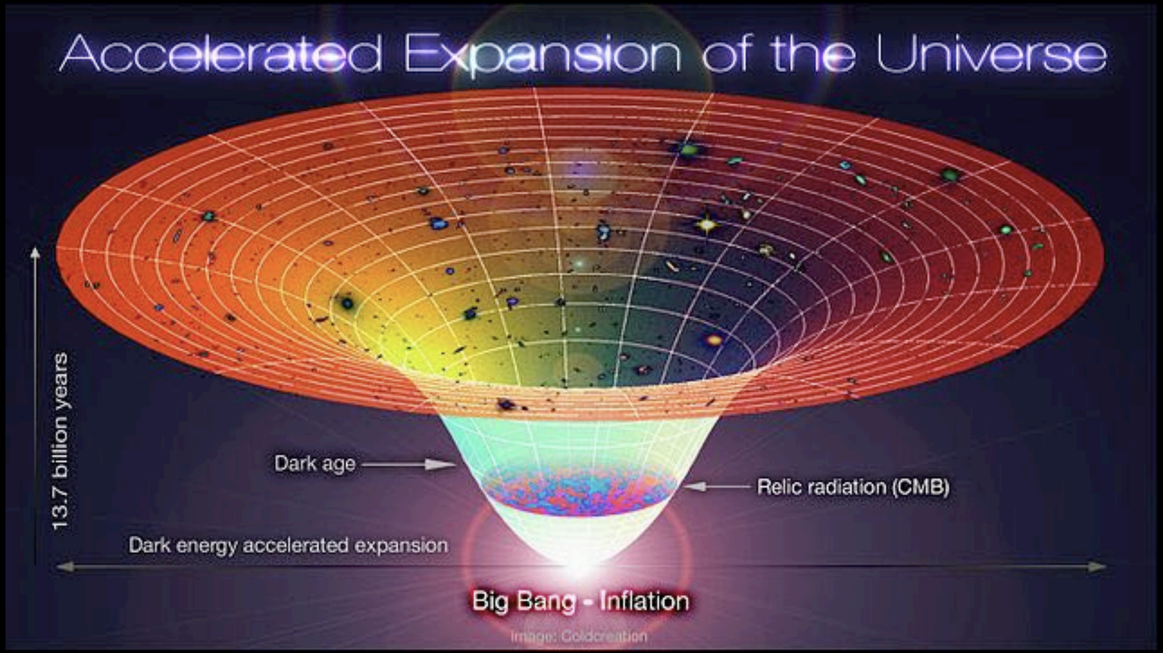
We can use these first galaxies to understand how the Universe transitioned from opaque to transparent



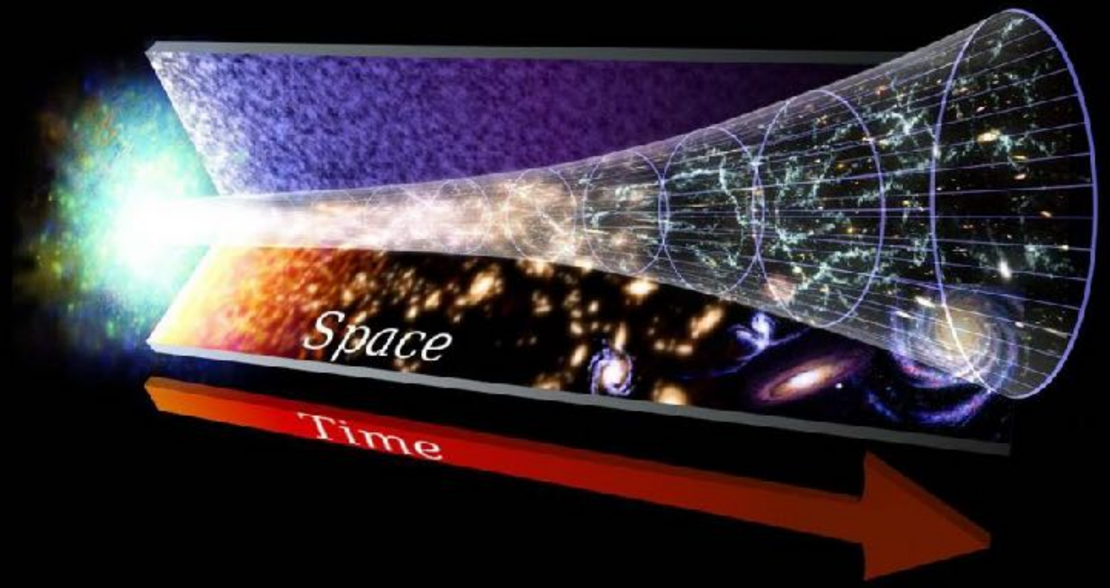
Using these early galaxies, we are able to probe the timeline of reionization

Questions we've answered:

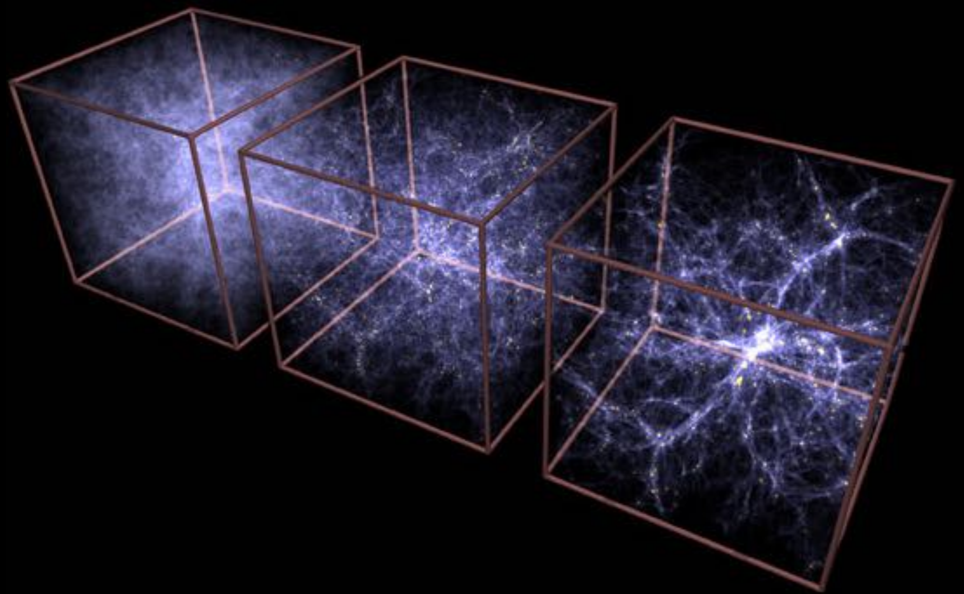
What is dark energy?



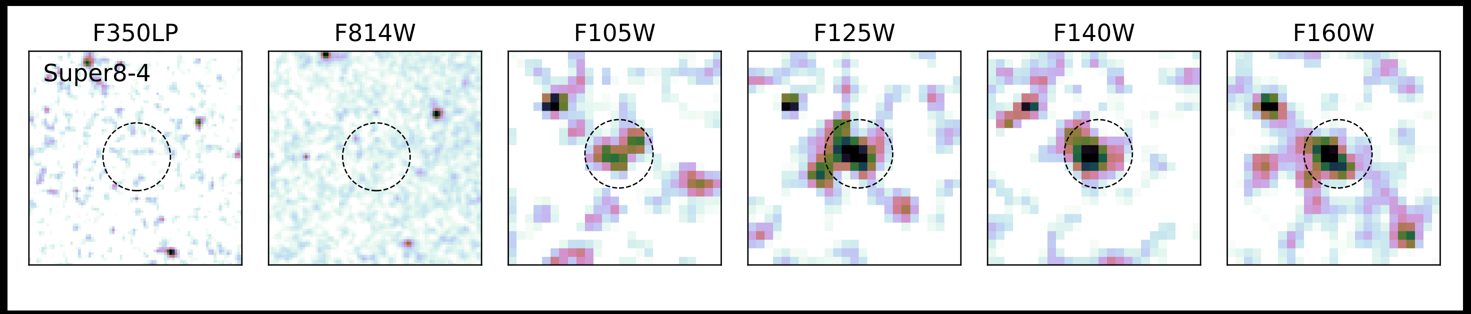
How did the Universe evolve?

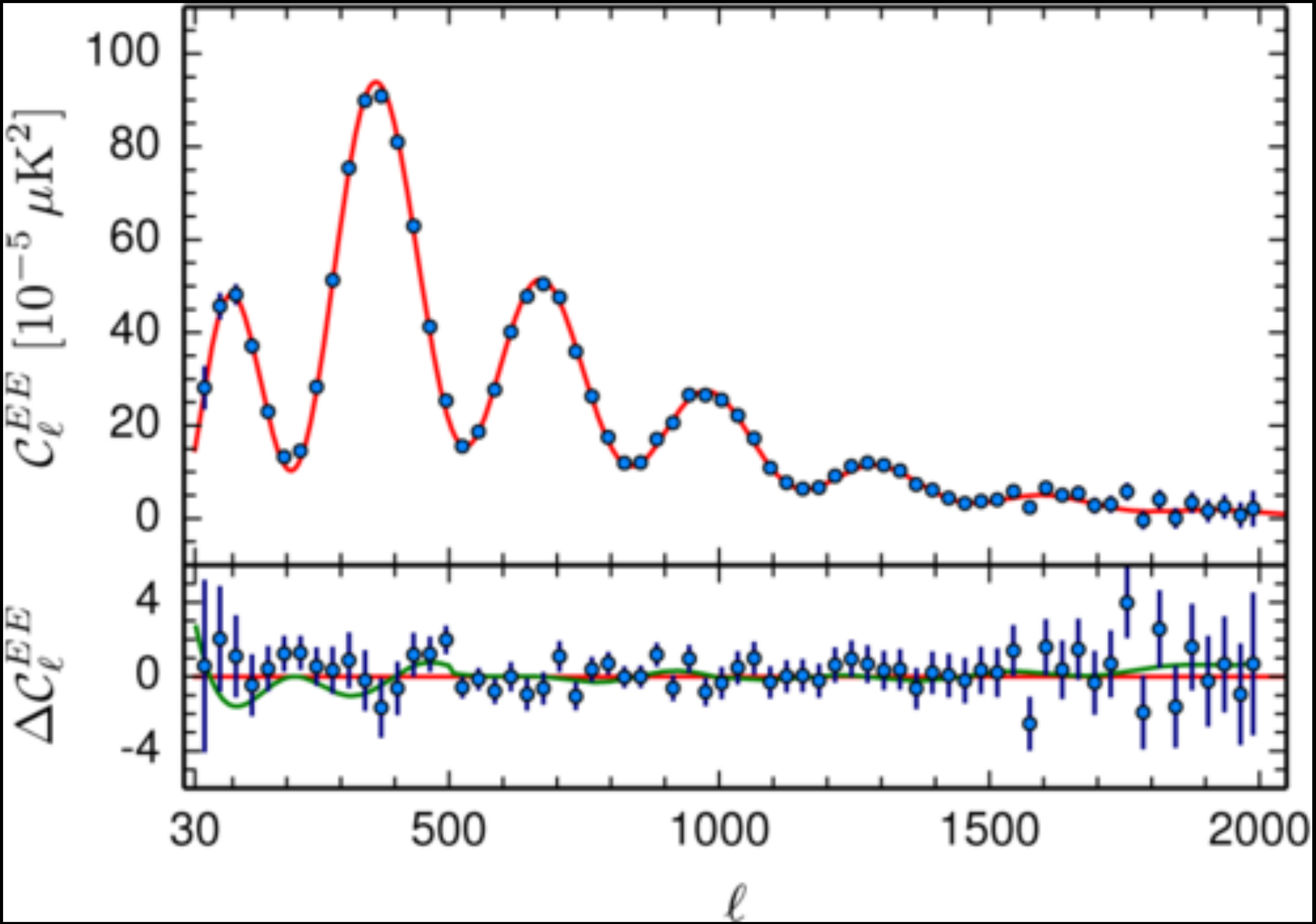


What is dark matter?

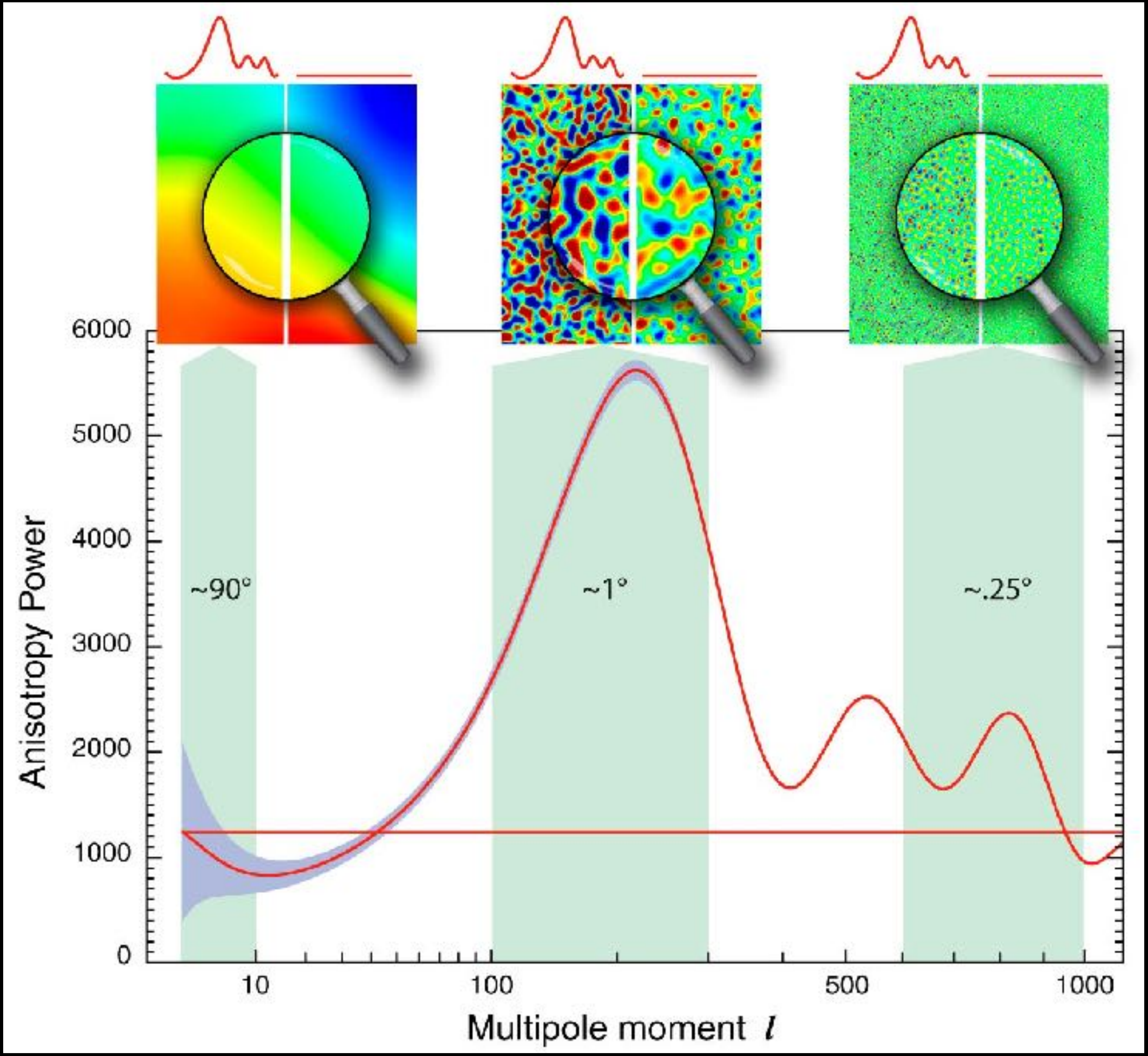


How do we study the first galaxies?

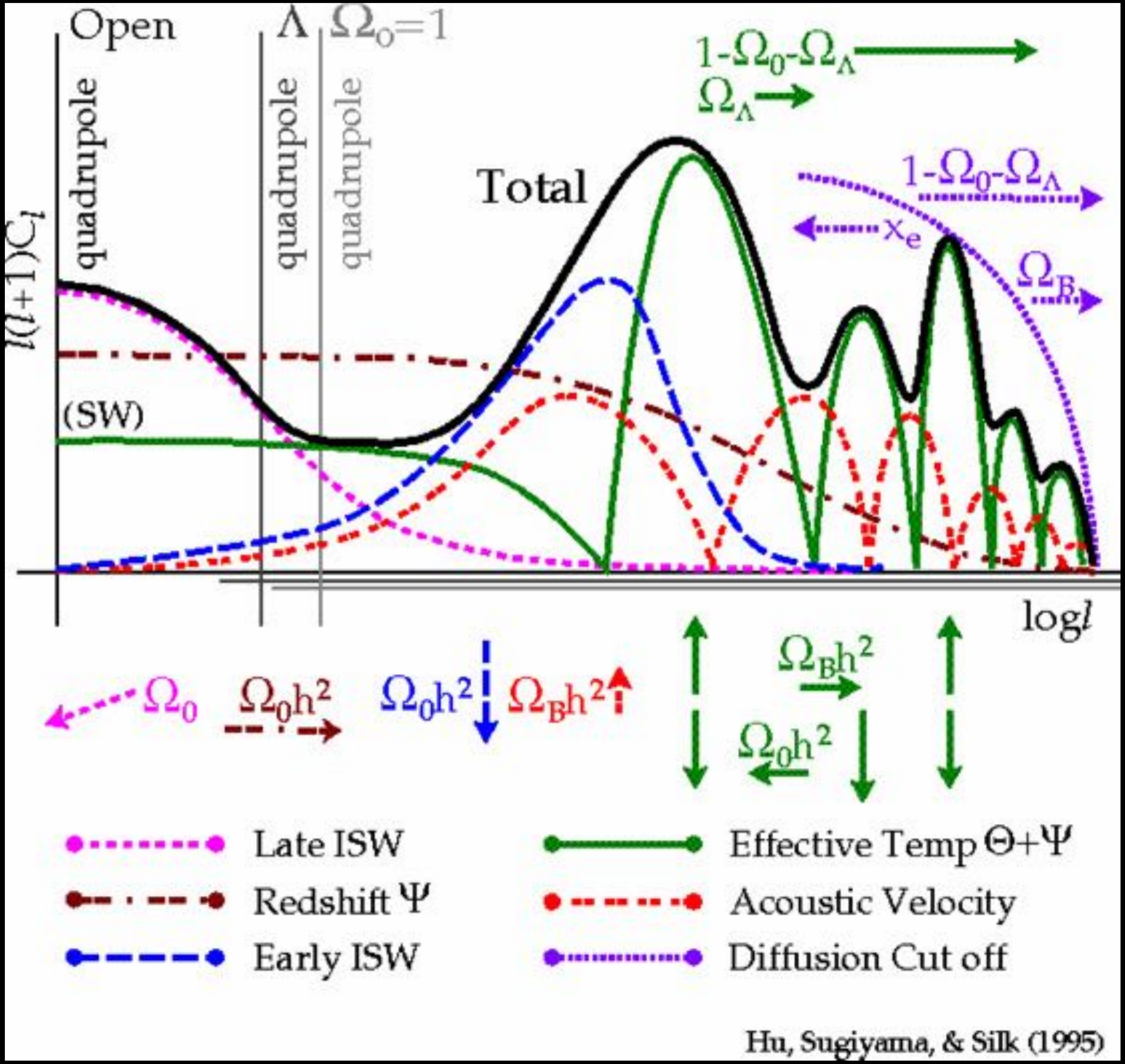




100
80
60
40
20
0
C_ℓ^{EE} [$10^{-5}\,\mu\mathrm{K}^2$]
4
0
-4
ΔC_ℓ^{EE}
30
500
1000
1500
2000
ℓ



6000
5000
4000
3000
2000
1000
0
Anisotropy Power
~90°
~1°
~.25°
10
100
500
1000
Multipole moment *l*


Open
Λ
$\Omega_0=1$
quadrupole
quadrupole
quadrupole
$l(l+1)C_l$
(SW)
Total
$1-\Omega_0-\Omega_\Lambda$
Ω_Λ
$1-\Omega_0-\Omega_\Lambda$
x_e
Ω_B
log$l$
Ω_0
Ω_0h^2
Ω_0h^2
Ω_Bh^2
Ω_Bh^2
Ω_0h^2
Late ISW
Redshift Ψ
Early ISW
Effective Temp Θ+Ψ
Acoustic Velocity
Diffusion Cut off
Hu, Sugiyama, & Silk (1995)