Big Bang Theory: The Three Pillars

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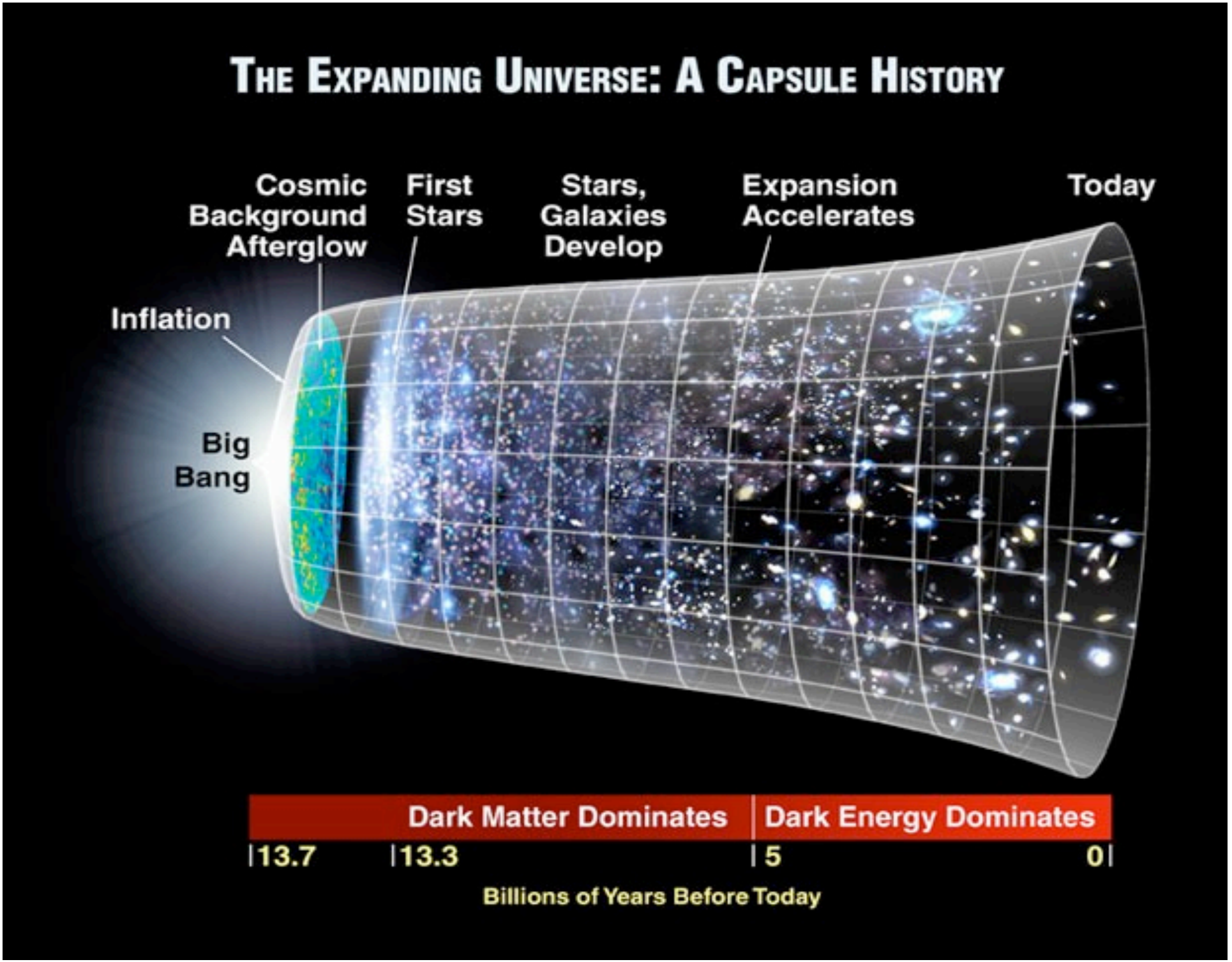
Hubble Ultra Deep Field



http://hetdex.org/dark_energy/

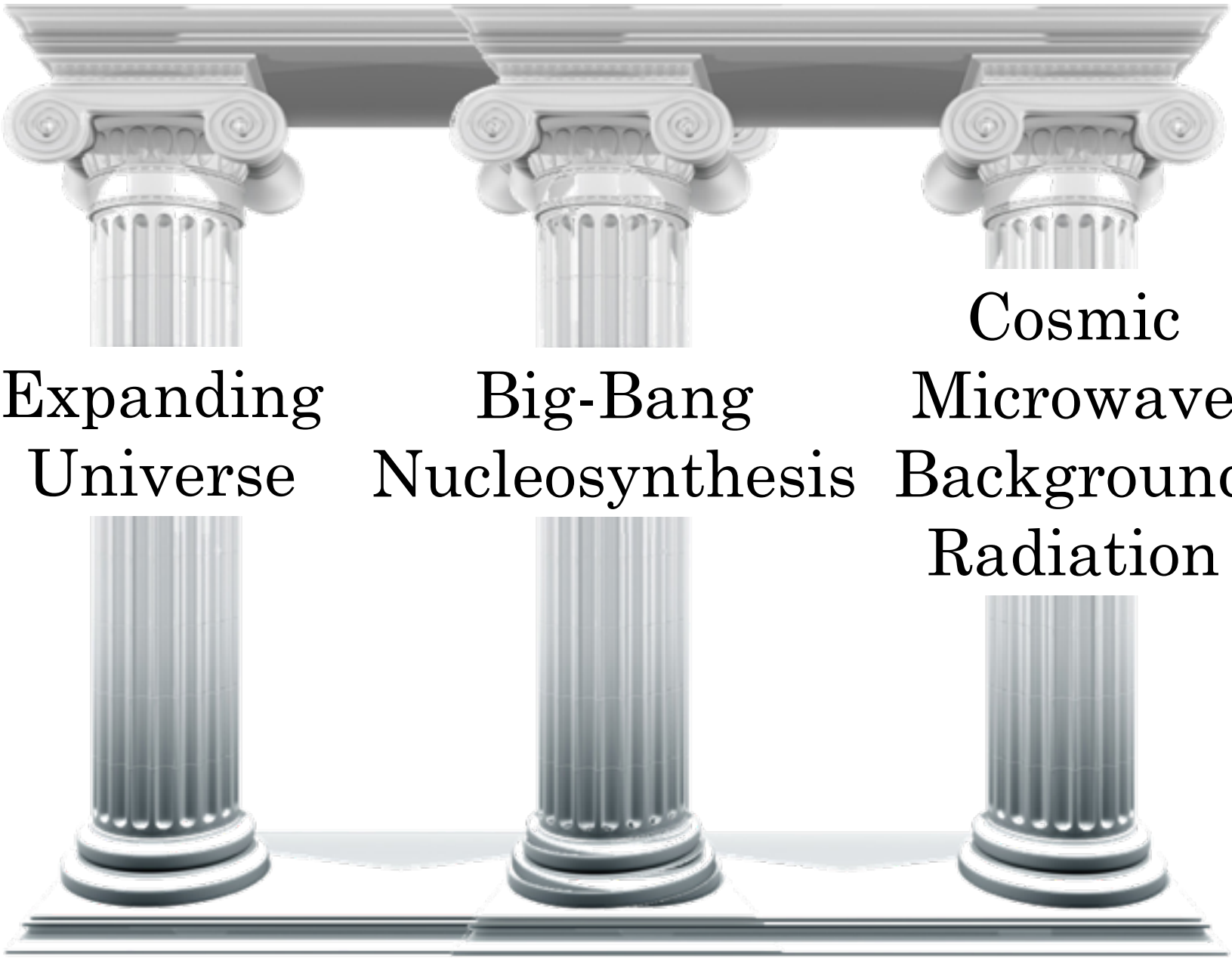
The Hot Big Bang model of the universe

- In the past, the Universe was smaller and hotter
- About 13.7 billion years ago, its size was zero, and temperature was infinity
- The universe has been expanding ever since the Big Bang

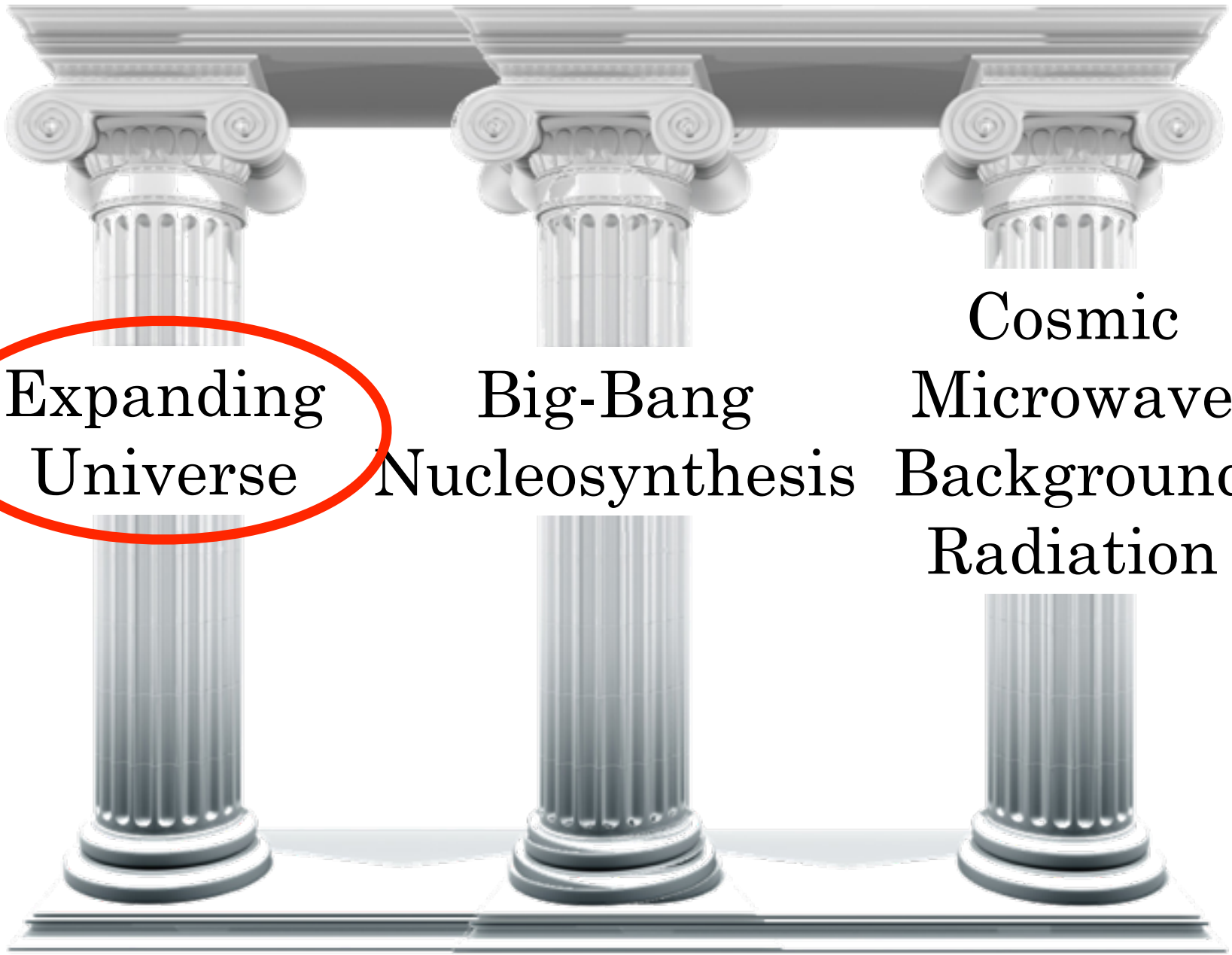
Main Competitor was (1920s - 1960s, RIP): the Steady-State theory

- The universe is infinitely old and big
- The universe is, on average, unchanging

Three pillars of the Big Bang model



Three pillars of the Big Bang model

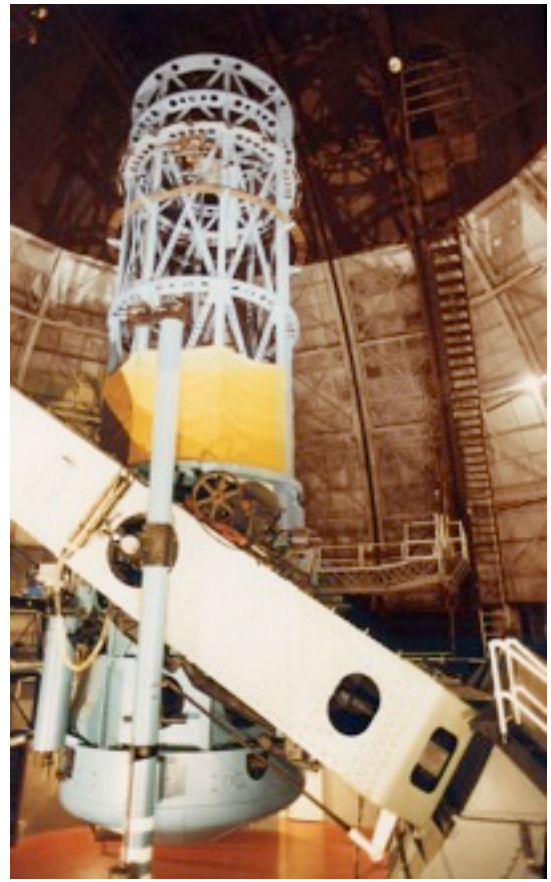


Edwin Hubble and the Expansion of the Universe (1929)

In 1929 Hubble measured the red shift (or, redshift) of nearby galaxies and found that they nearly all move away from us

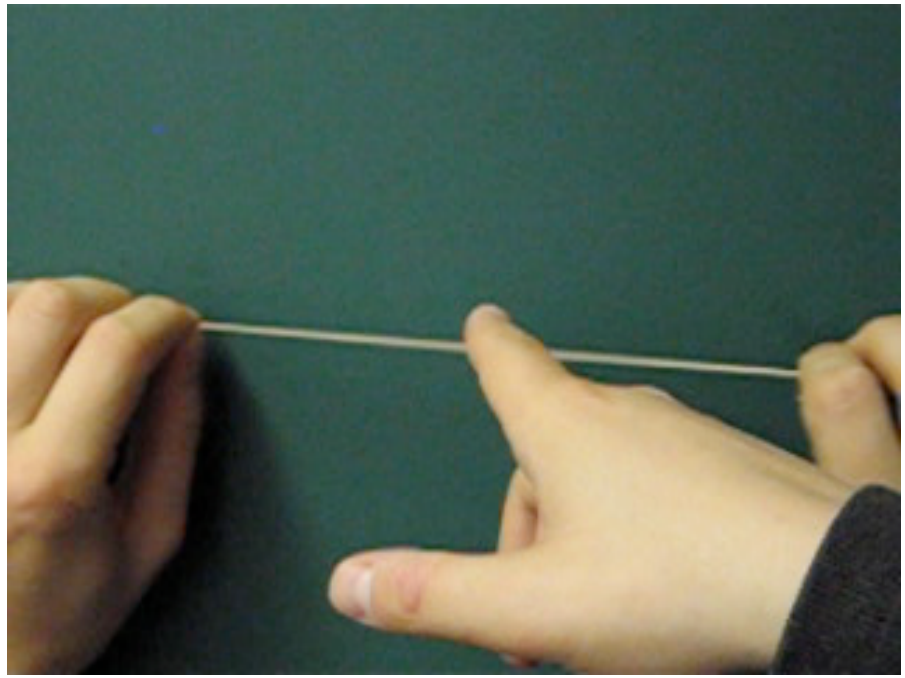
$\Rightarrow$

The Universe is Expanding!



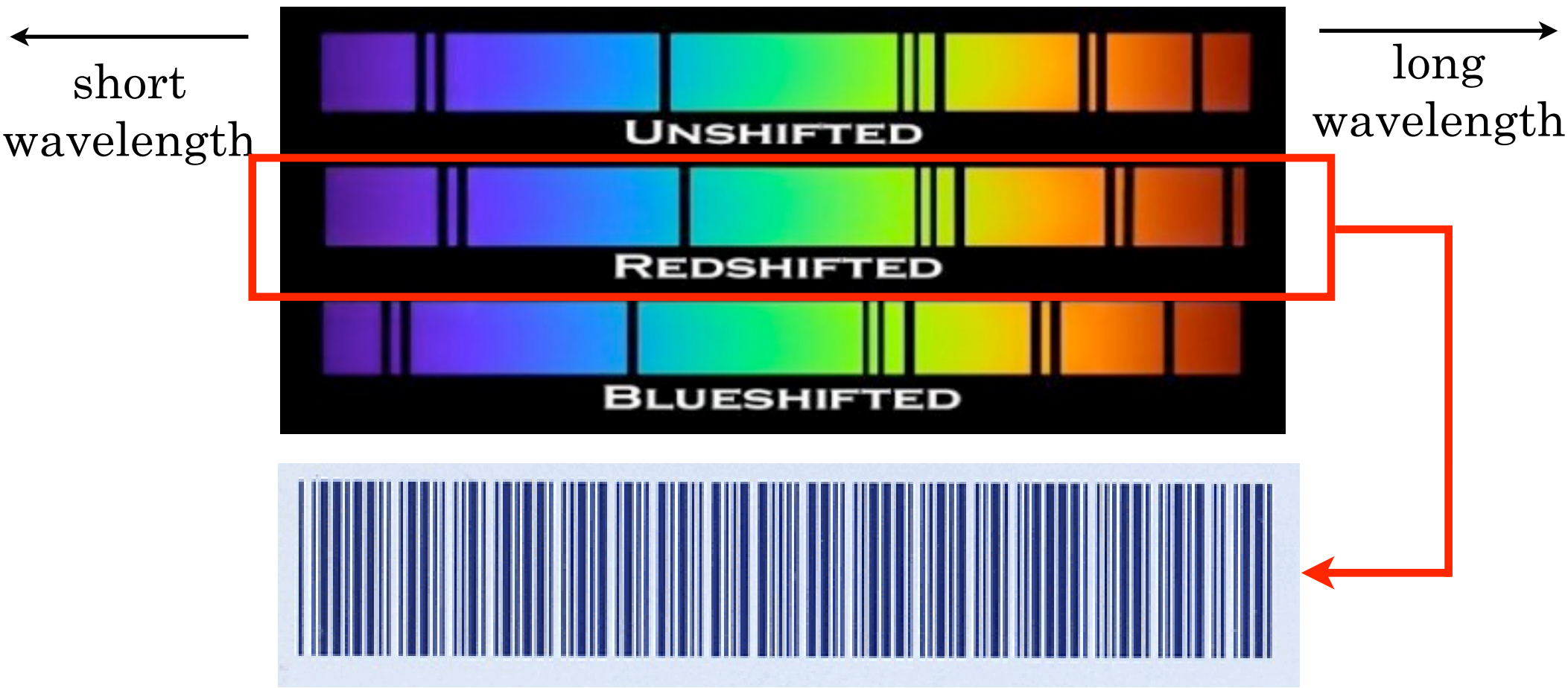
100 inch Hooker telescope
(Mt Wilson, CA)

Space expands ⇒ Photons (light) stretch - and thus lose energy

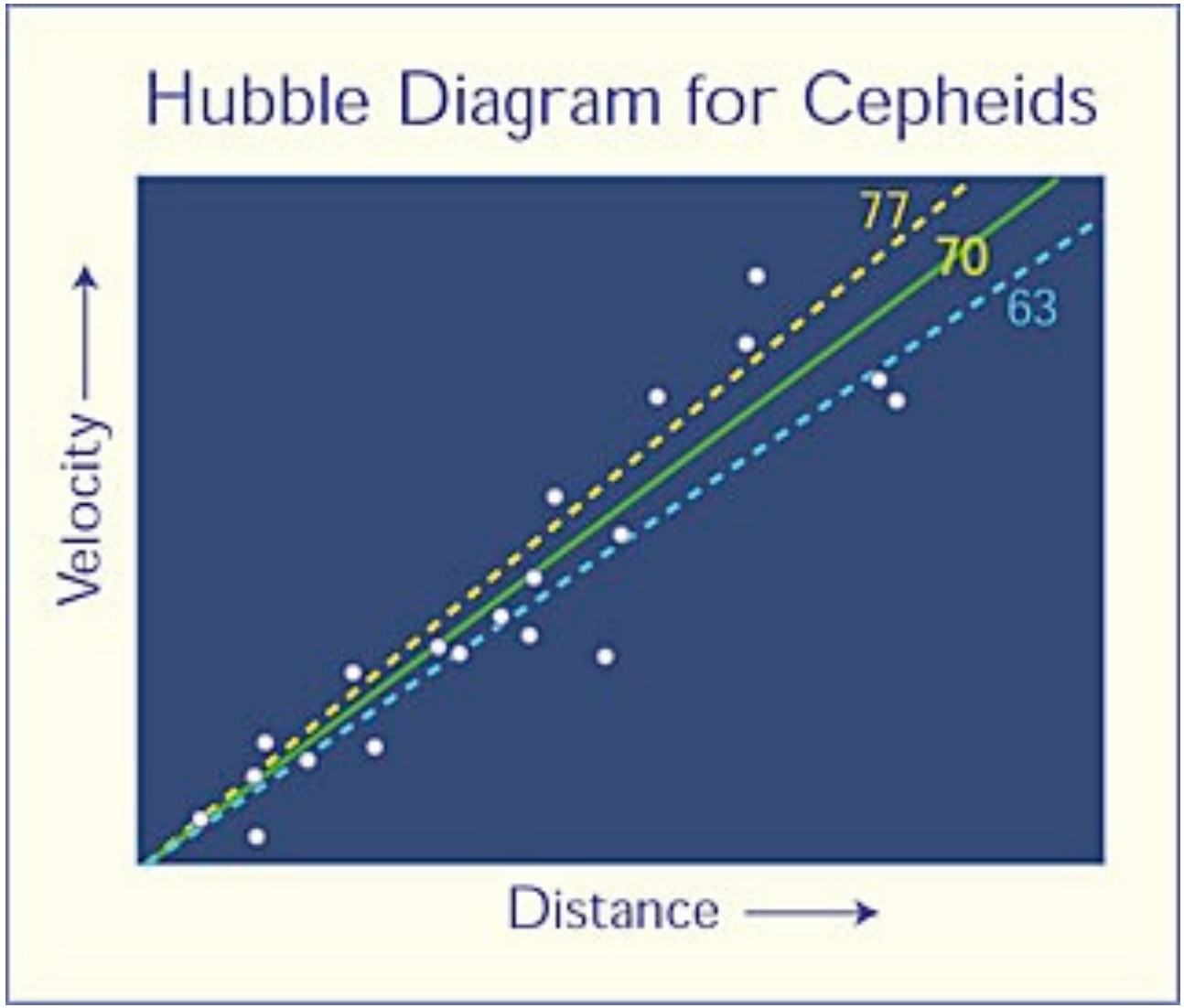


- Wavelengths Expand As Space Expands
- Good Analogy: A Rubber Band Stretched Between Your Hands!

The Cosmological Redshift

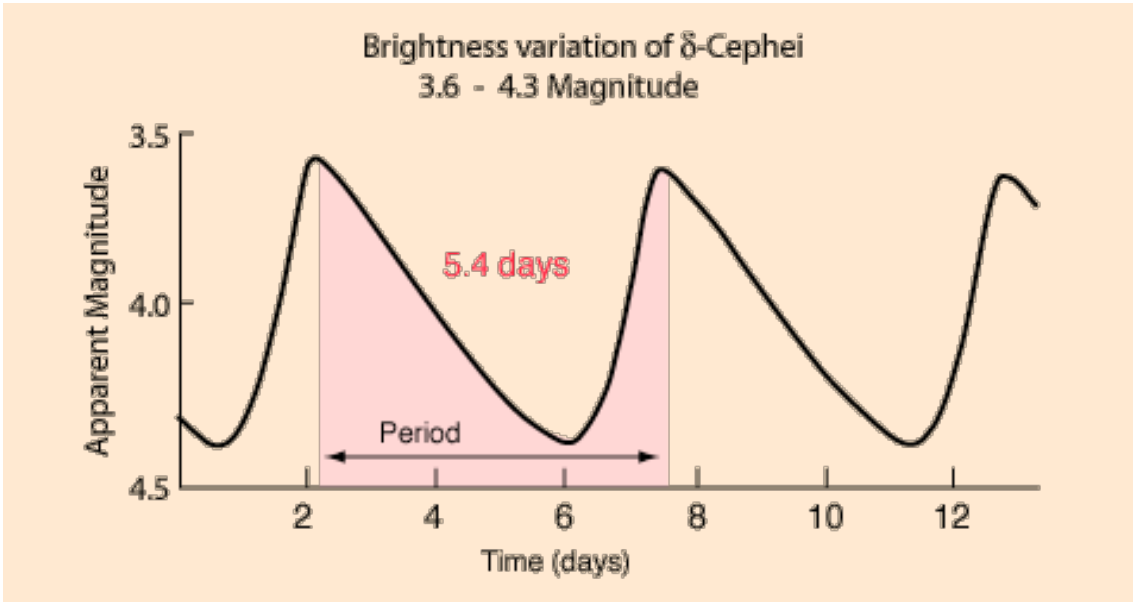


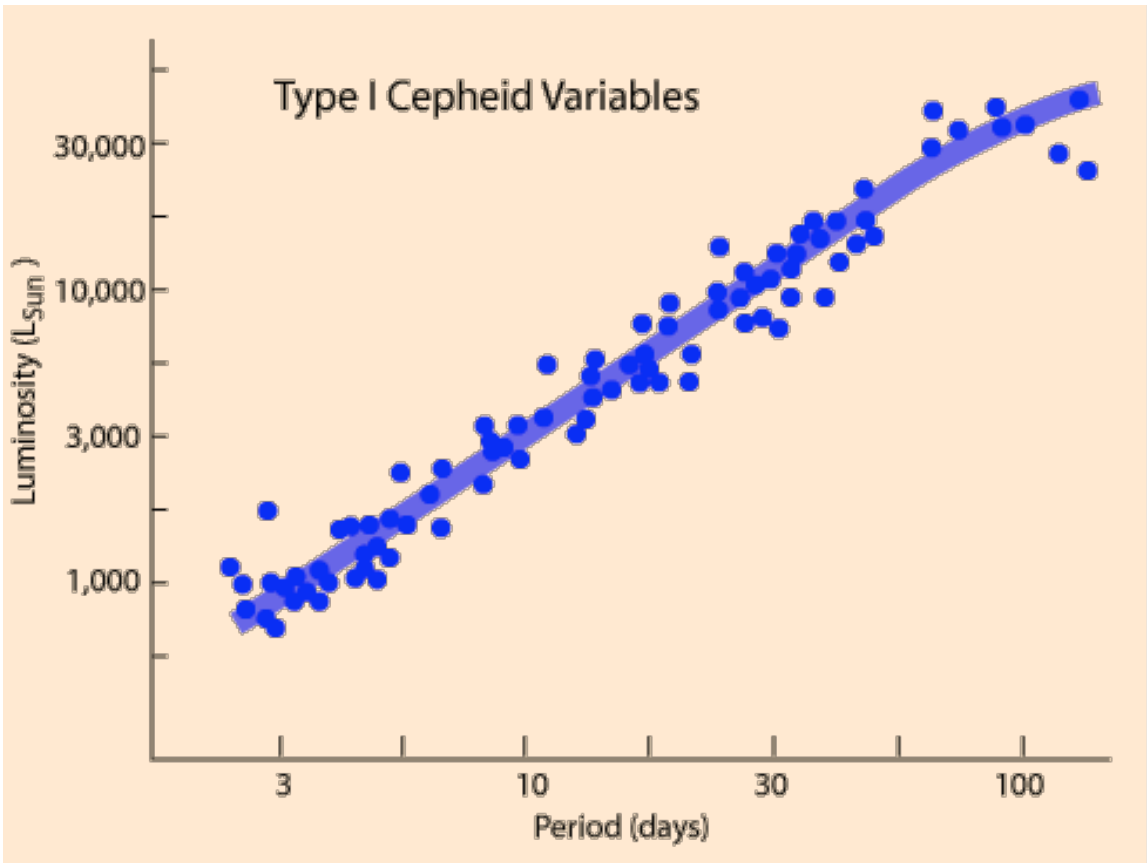
- Like a barcode, spectral lines give the amount of wavelength expansion, or REDSHIFT



- Velocity is easy: from the Doppler recession of galaxy spectra
  (first done by astronomer Vesto Slipher, whom Hubble never credited)
- Distance is hard: from Cepheid variable stars

Cepheids (variable stars)





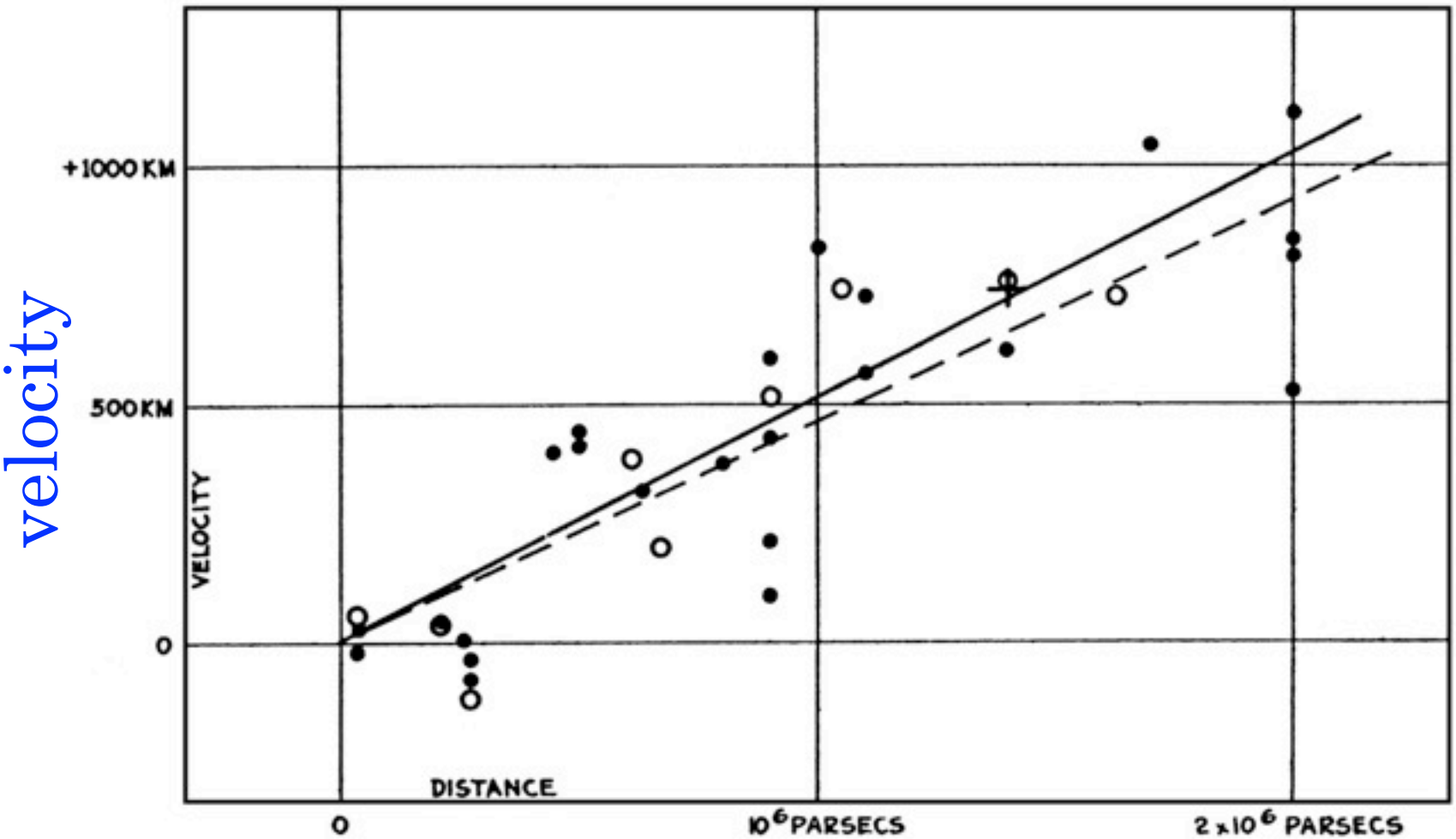
http://hyperphysics.phy-astr.gsu.edu/

- Empirical finding: Cepheids' period of pulsation is proportional to intrinsic luminosity
- Measure period
- Measure apparent luminosity (or, flux)
- Then, can get **distance**:

$$f = L / (4\pi d^2)$$

(f = flux
L = luminosity)

The original Hubble diagram



velocity

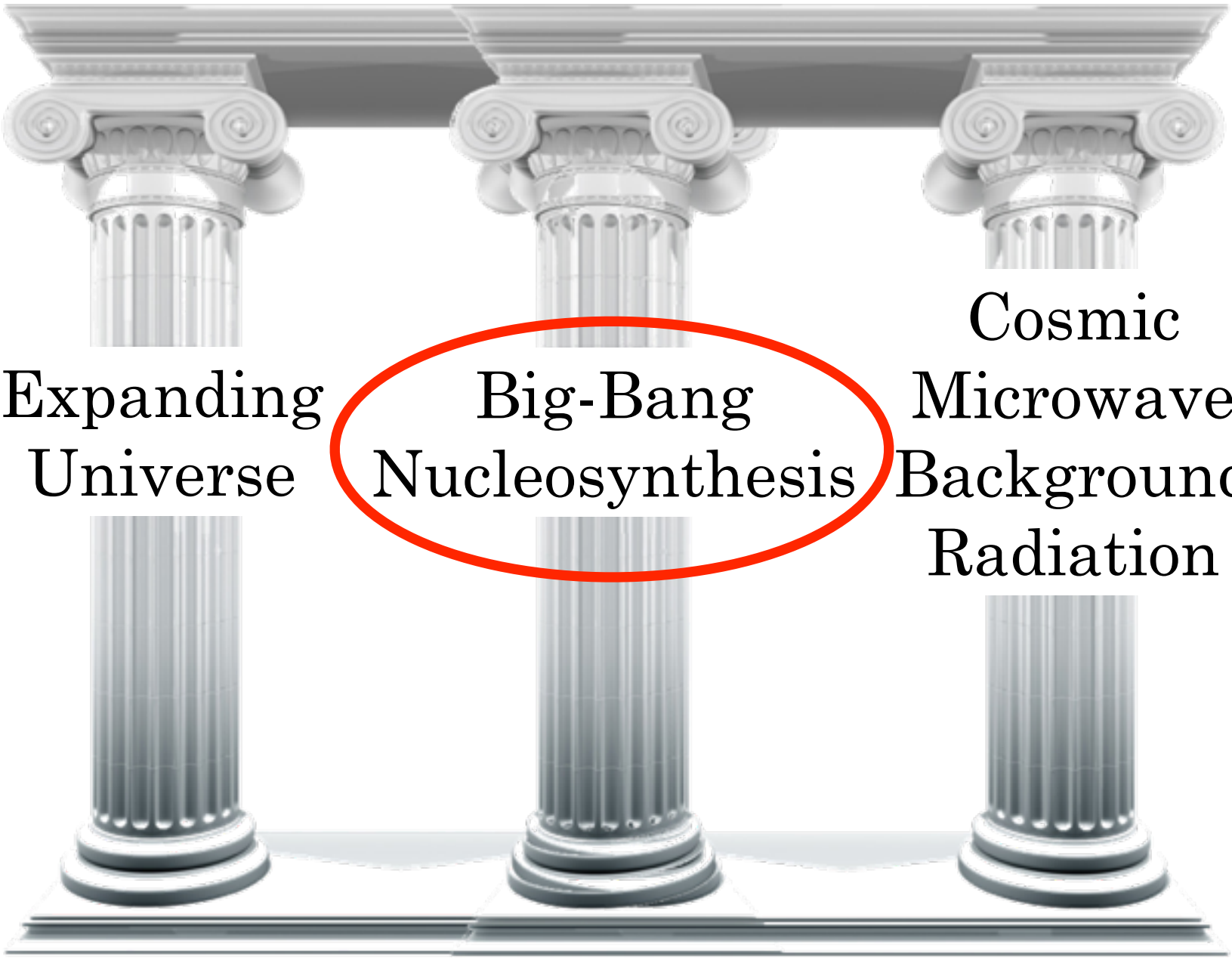
distance

Slope of this relation (velocity vs. distance) is called the Hubble constant H_0.

Modern value:

$$H_0 \approx (72 \pm 3) \text{ km/sec/megaparsec}$$

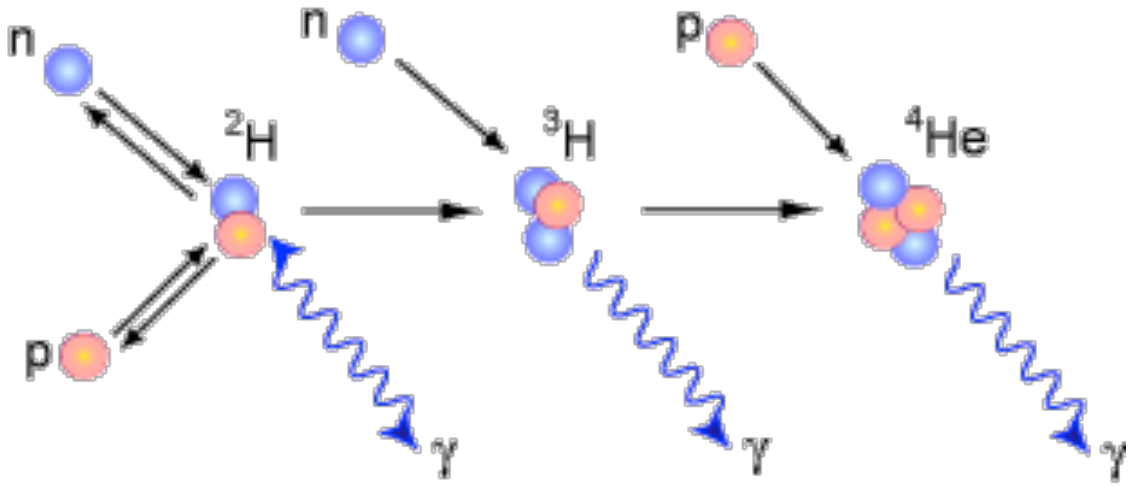
Three pillars of the Big Bang model

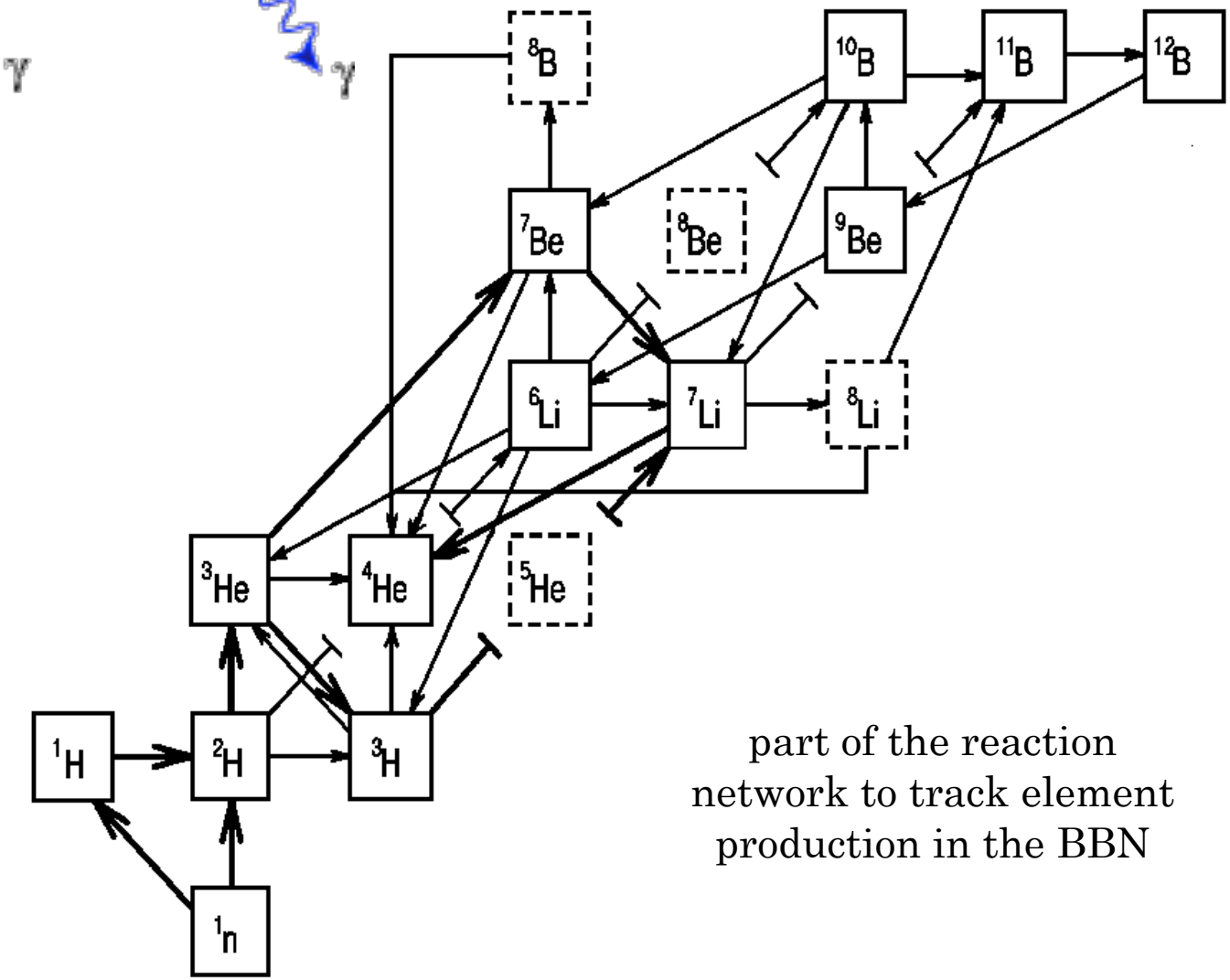


Big Bang Nucleosynthesis (BBN)

- Occurs from **t=1 sec to t=3 mins after Big Bang**
- A variety of nuclear reactions. E.g. proton can add a neutron or another proton.
- **Lightest elements** (Hydrogen, Helium, a few others) are created in the BBN...
- ...while heavier elements (Carbon, Oxygen, Iron...) are created much later, in stars
- While complicated, these reactions are basically well known
- **The abundances of light elements predicted by the BBN agree with observations**

Big Bang Nucleosynthesis

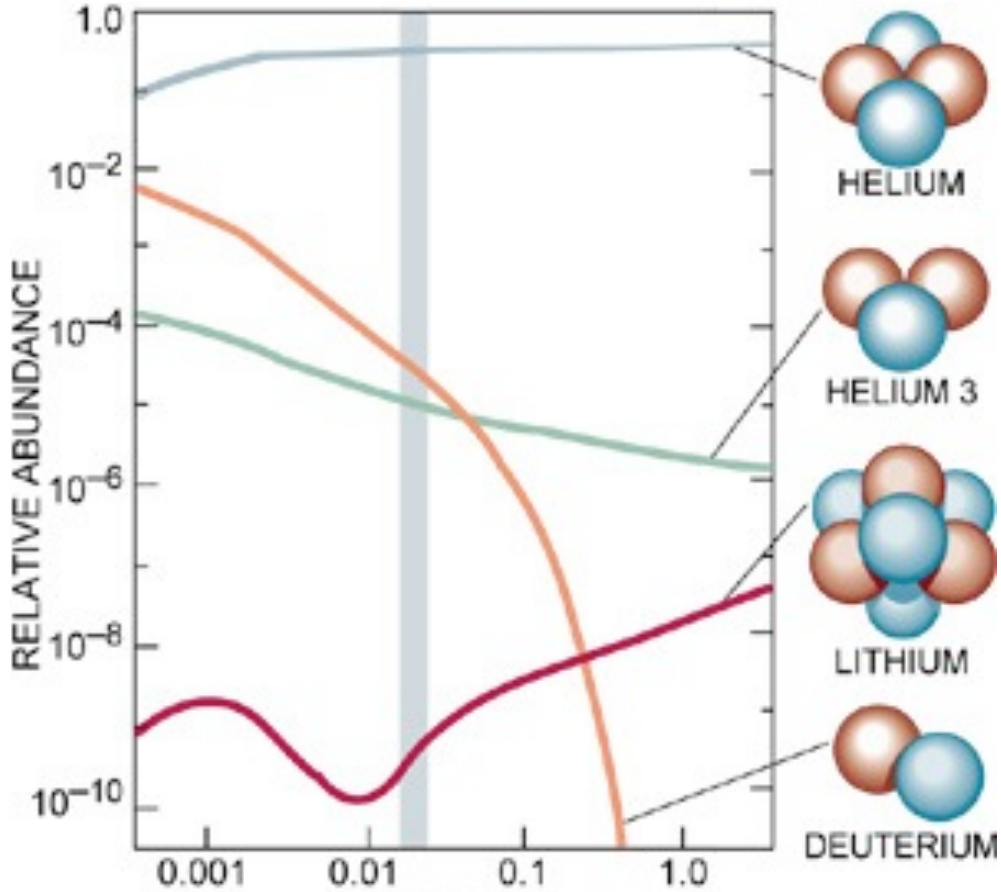




part of the reaction network to track element production in the BBN

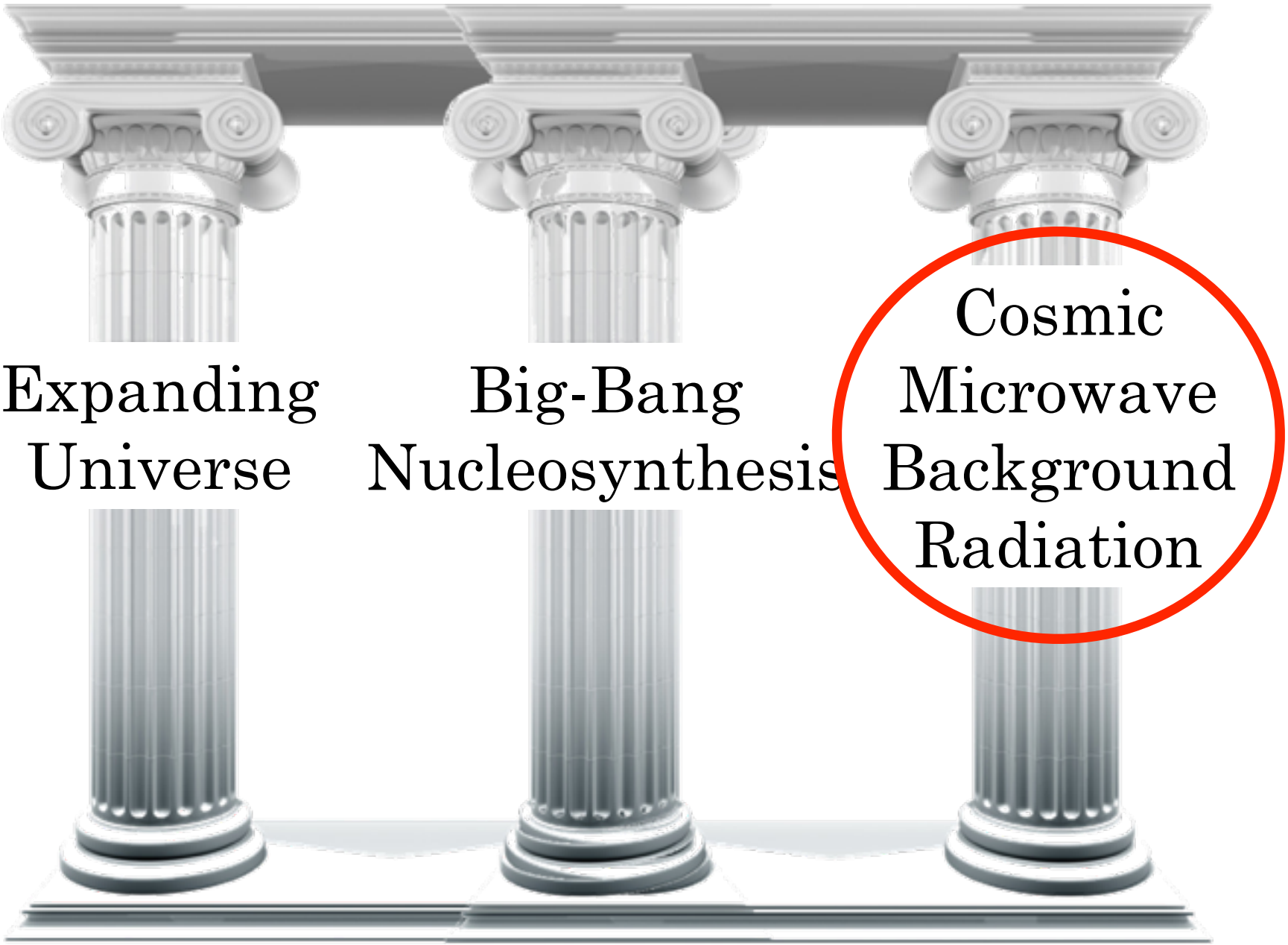
Predictions of elemental abundances

- Using computer codes to track the whole network of reactions in time
- First done: late 1960s
- Nuclear reactions are experimentally measured
- Elemental abundances today: by mass, 75% hydrogen, 25% Helium, and trace amounts of a few more elements are produced during the BBN
- Heaver elements are created later - in stars!



Density of baryons (protons, neutrons...)

Three pillars of the Big Bang model



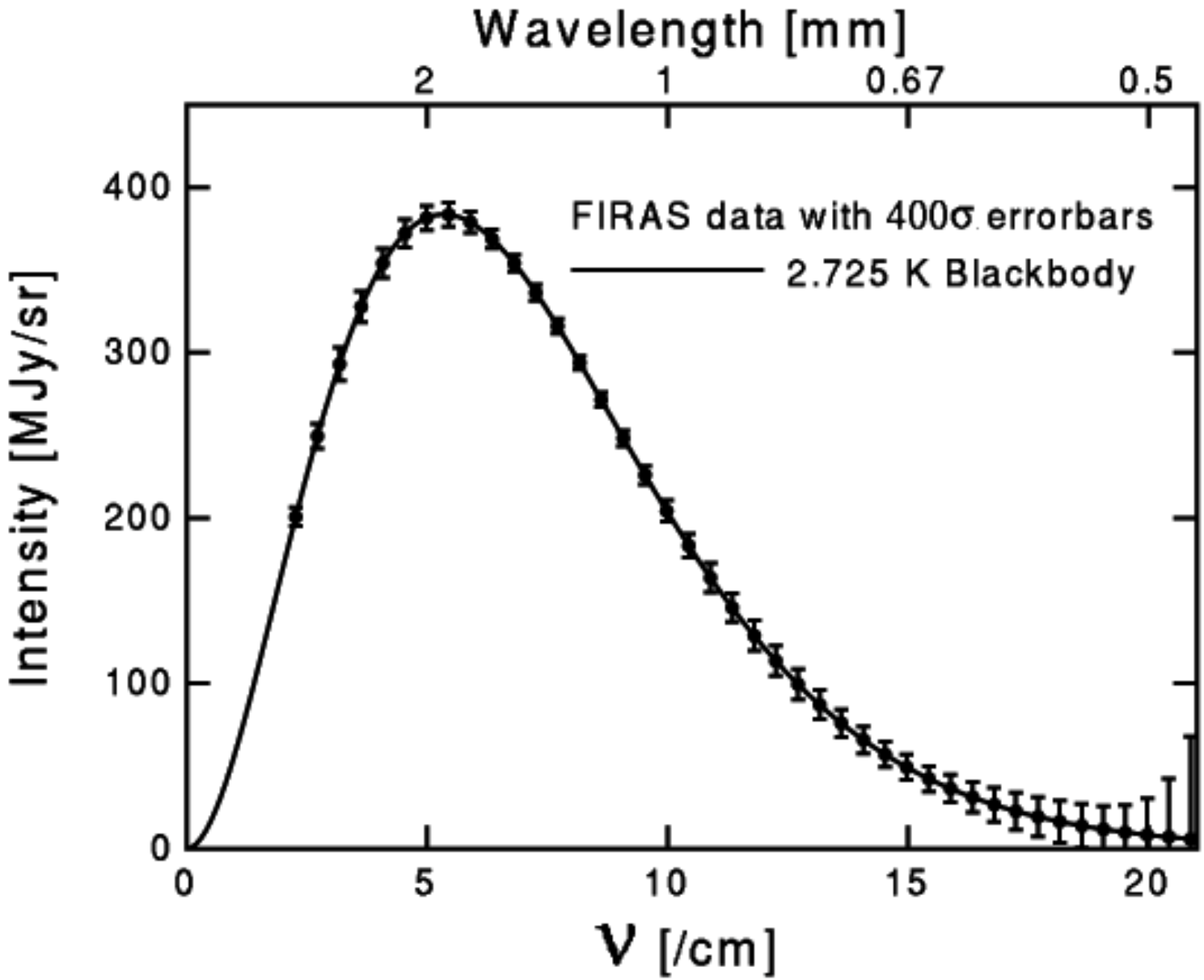
Cosmic Microwave Background: radiation left over from Big Bang

- George Gamow, Ralph Alpher and Robert Herman (1940s): in the Big-Bang model of the universe, there should be left-over radiation from the "primeval fireball" of temperature ~5-50 Kelvin
- This prediction is mostly ignored and forgotten
- Then, in 1965, two Bell Labs engineers, Arno Penzias and Robert Wilson, made a great accidental discovery of excess noise in an antenna they were installing
- 1% of "snow" on your TV is the CMB!

Discovery of the CMB (1965)

- While installing their antenna, Penzias and Wilson note that there is an excess noise corresponding to 3 degrees above absolute zero
- Persists even after removing "white dielectric material"
- They tell their cosmologist friend, and he tells them that they may have made a big discovery
- Nobel Prize 1978

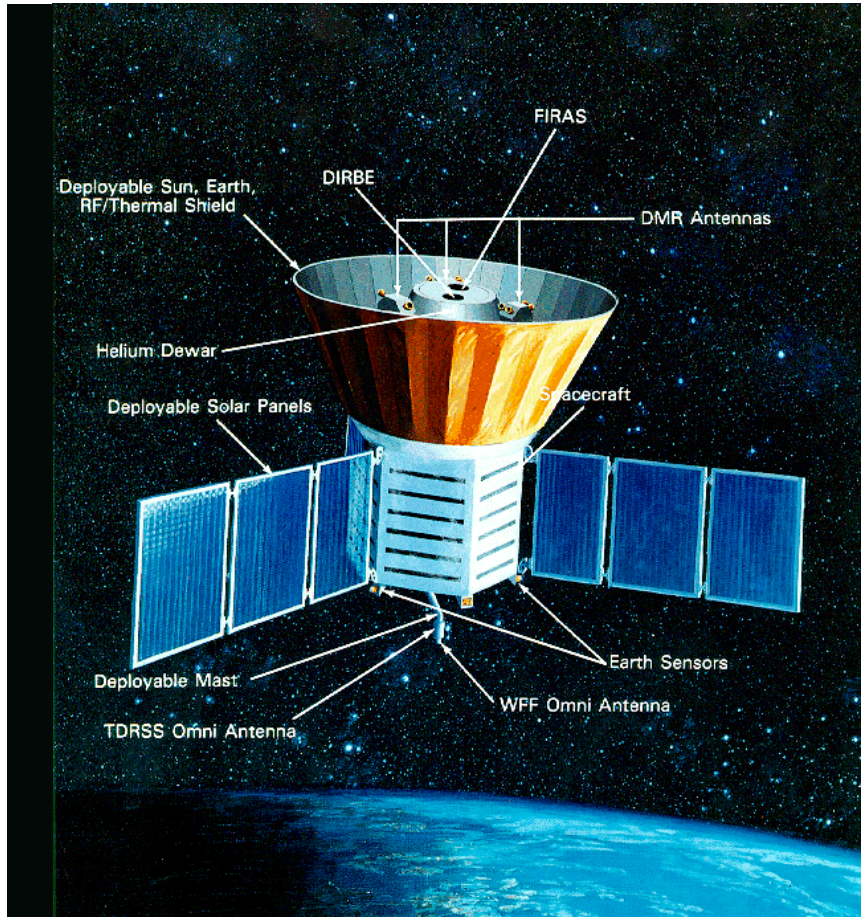
CMB is a perfect 'blackbody'



(frequency of radiation)

CMB anisotropies (1992)

- Holy Grail of cosmology in 1980s: find the seeds of structure in the CMB - the CMB anisotropies (temperature fluctuations)
- COBE (launched 1989) instruments:
  - FIRAS (Far Infrared Absolute Spectrophotometer) to compare temperature spectrum to Bbody
  - DMR (Differential Microwave Radiometer) to look for anisotropies
- 1992: COBE discovers anisotropies, $\delta T/T \approx 10^{-5}$
- Nobel Prize 2006: George Smoot, John Mather

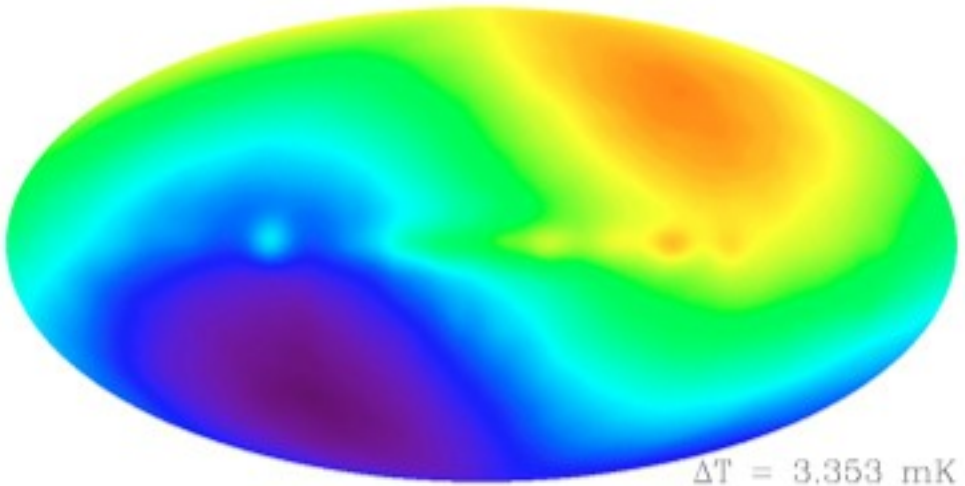


Cosmic Background Explorer (COBE)

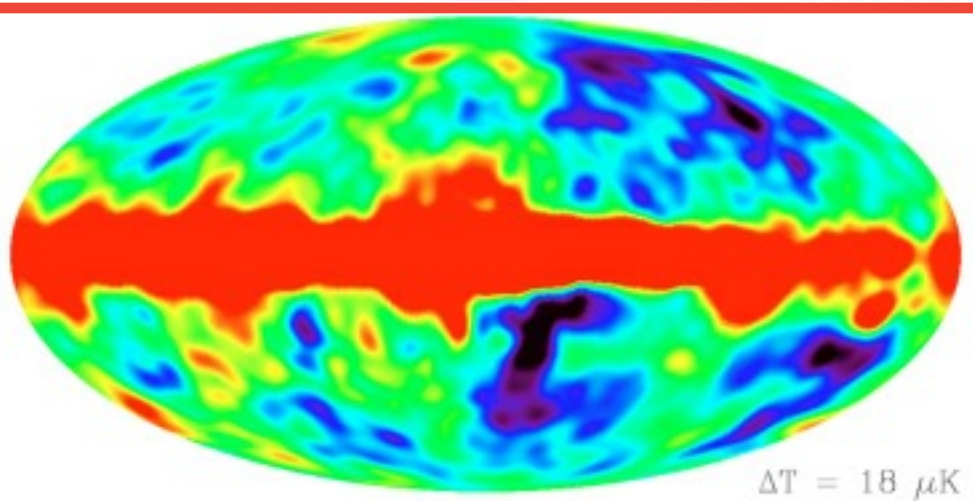
T=2.726 Kelvin

CMB monopole
(i.e. average)
T=2.725 K

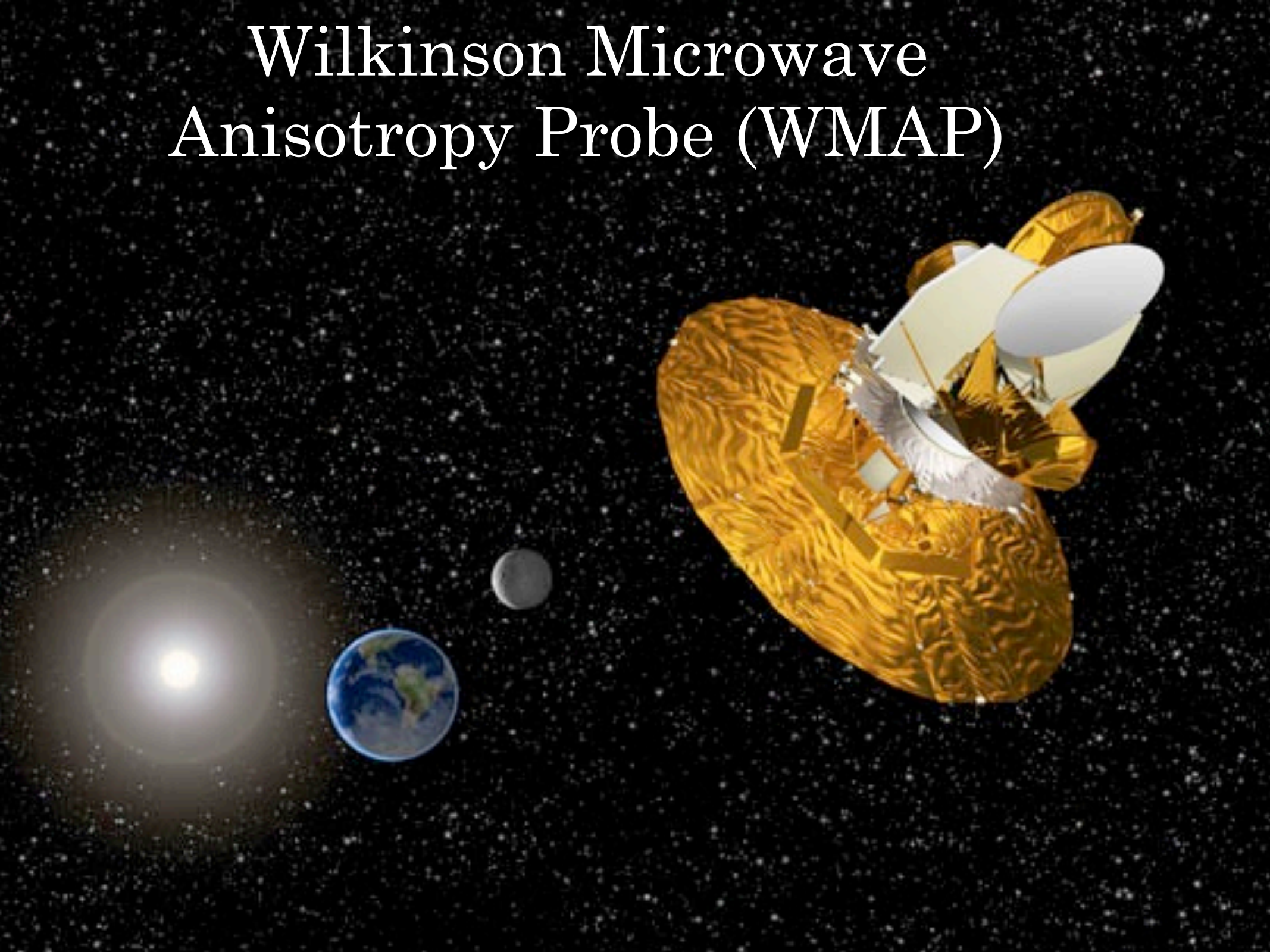
CMB dipole
(due to our motion)
T=3.353 mK
(so blue = 2.721K, red = 2.729 K)



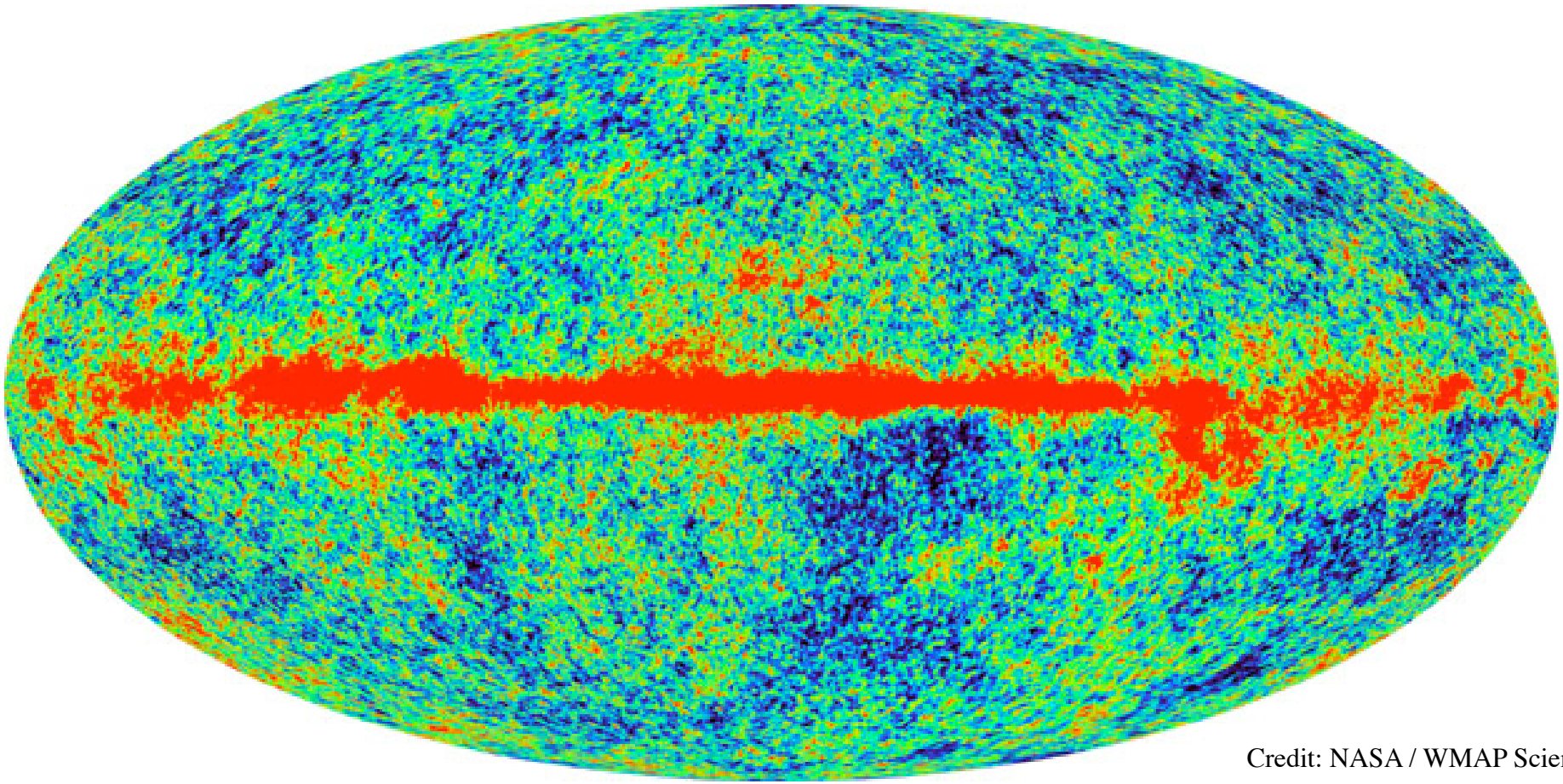
CMB higher anisotropies
(at COBE's 8° res.)
T≈10 μK



Wilkinson Microwave Anisotropy Probe (WMAP)



Fluctuations 1 part in 100,000 (of 2.726 Kelvin)

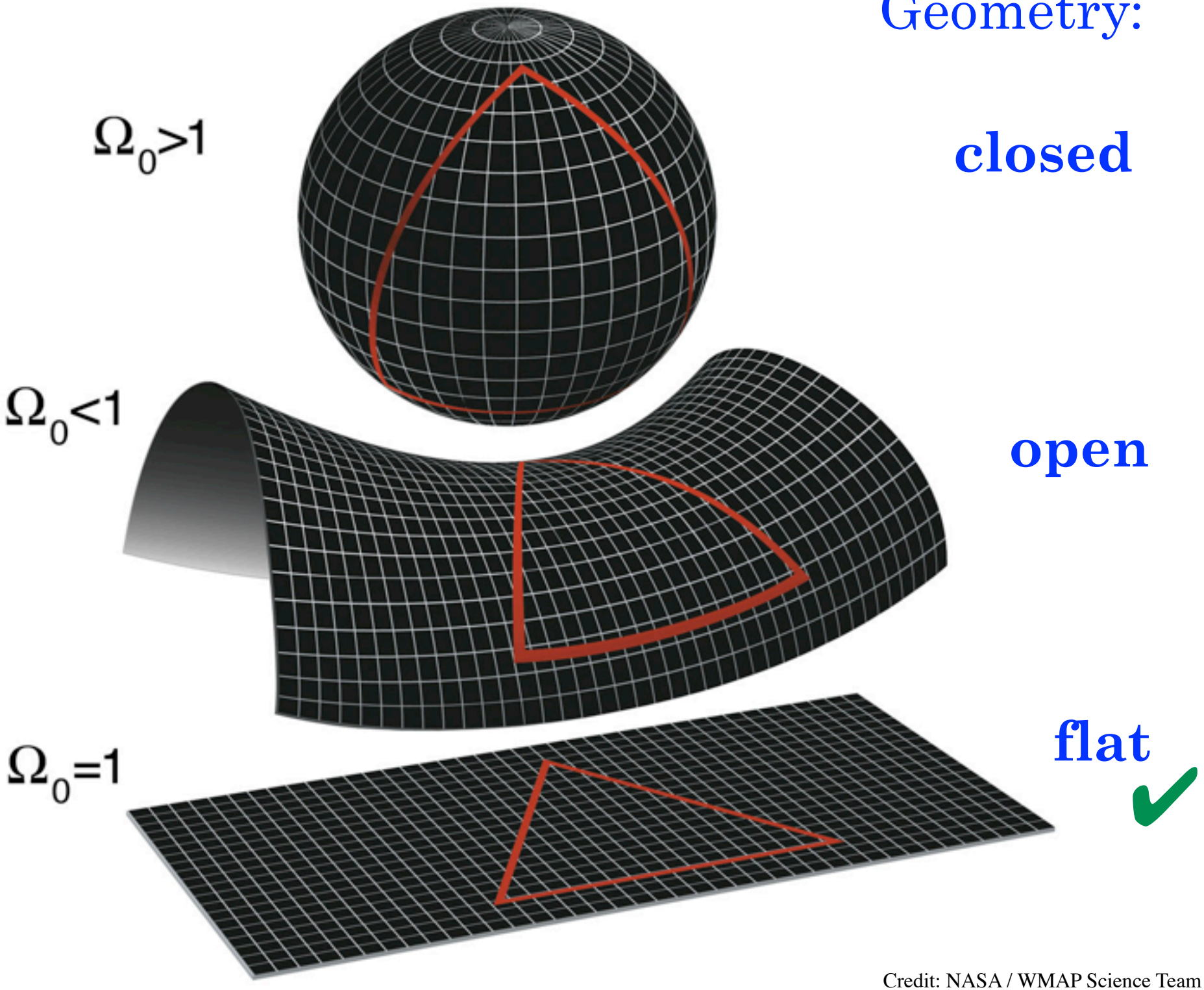


Credit: NASA / WMAP Science Team

Provides excellent measurements of:

- geometry of the universe
- age of the universe
- many other interesting things

Geometry:



closed

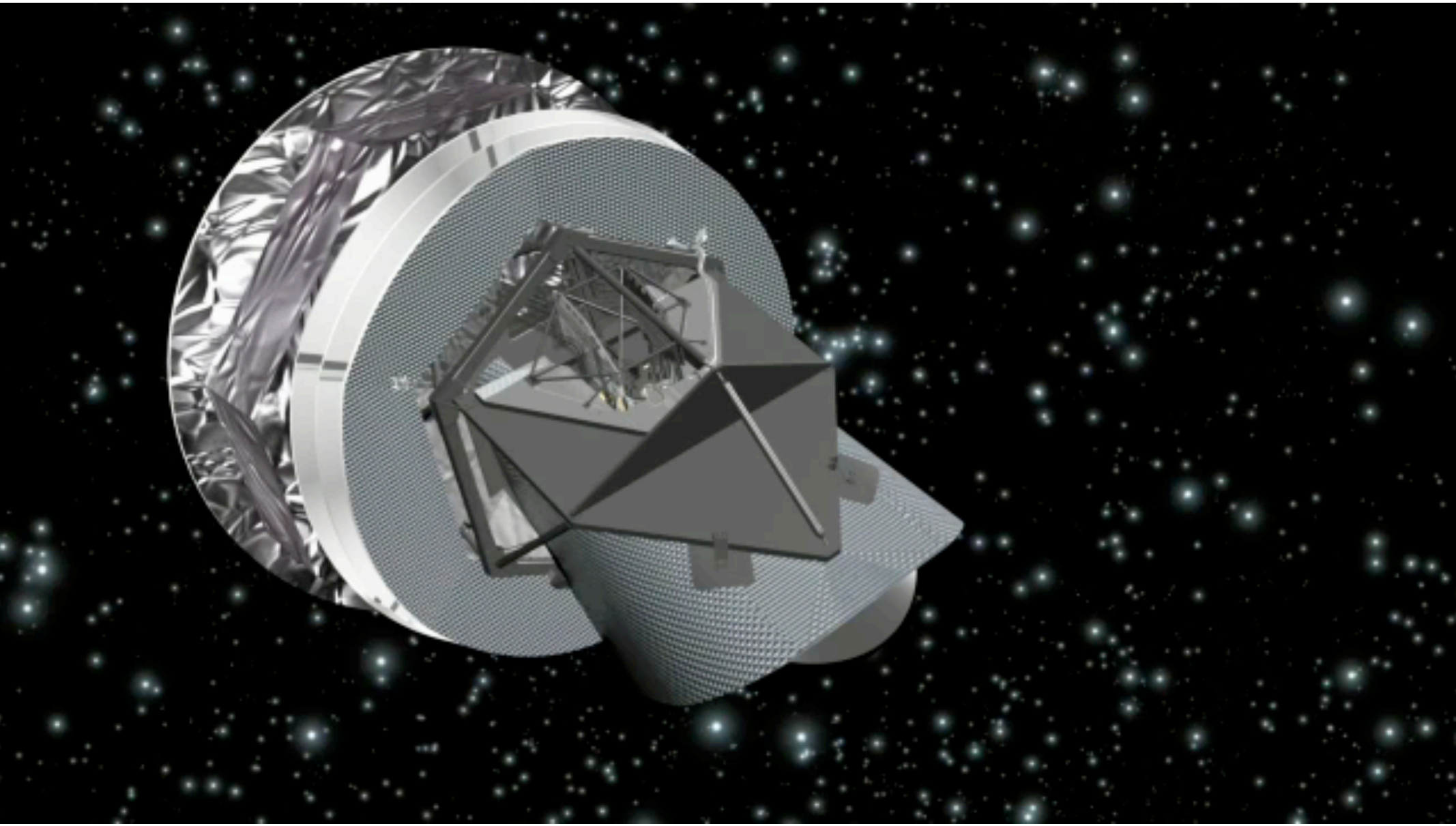
open

flat ✔

Credit: NASA / WMAP Science Team

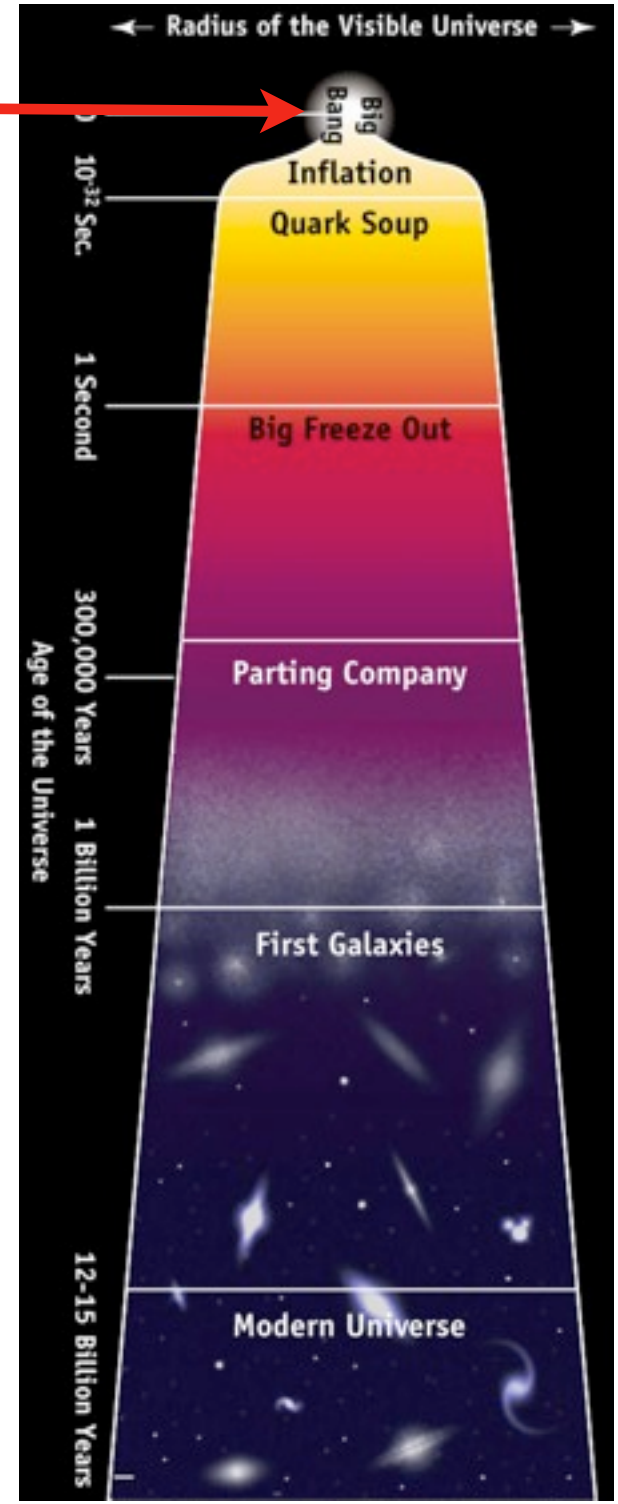
Credit: NASA / WMAP Science Team

Planck experiment



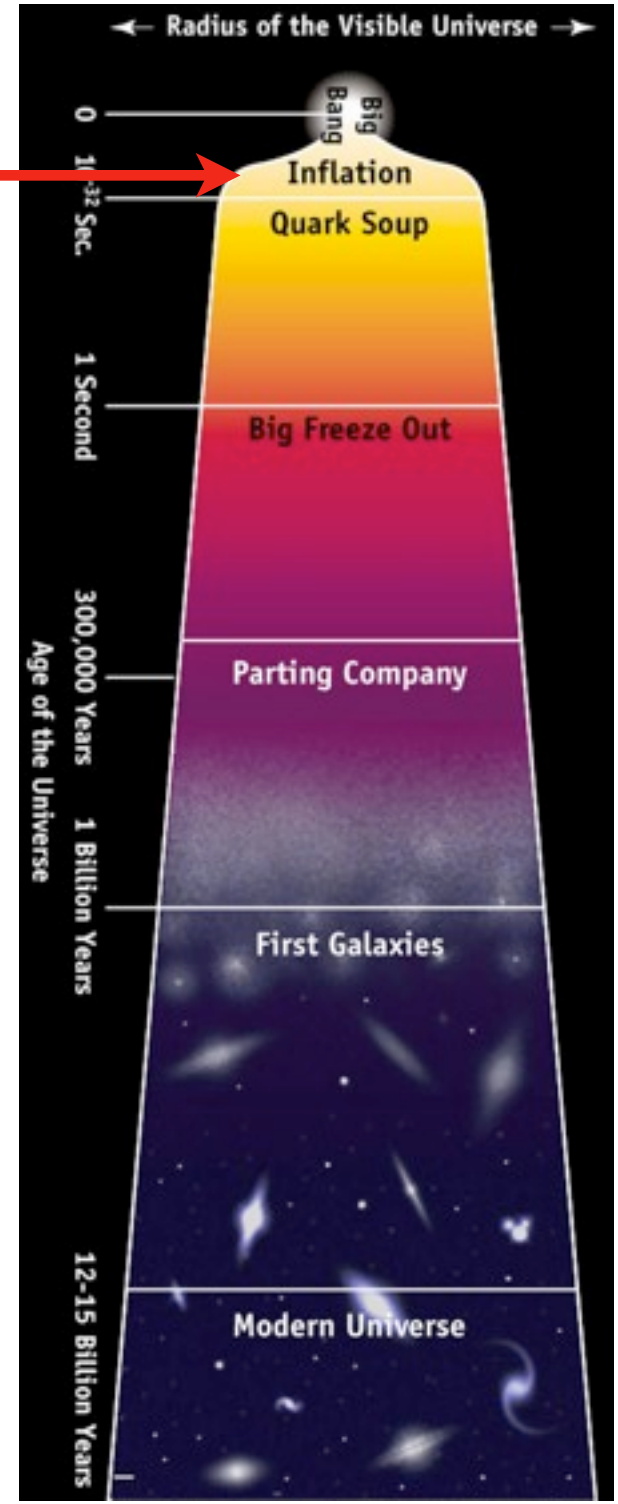
Big Bang (t=0)

- Expansion starts
- Happened “everywhere”
- Details not well known
- Currently beyond reach of any cosmological probe



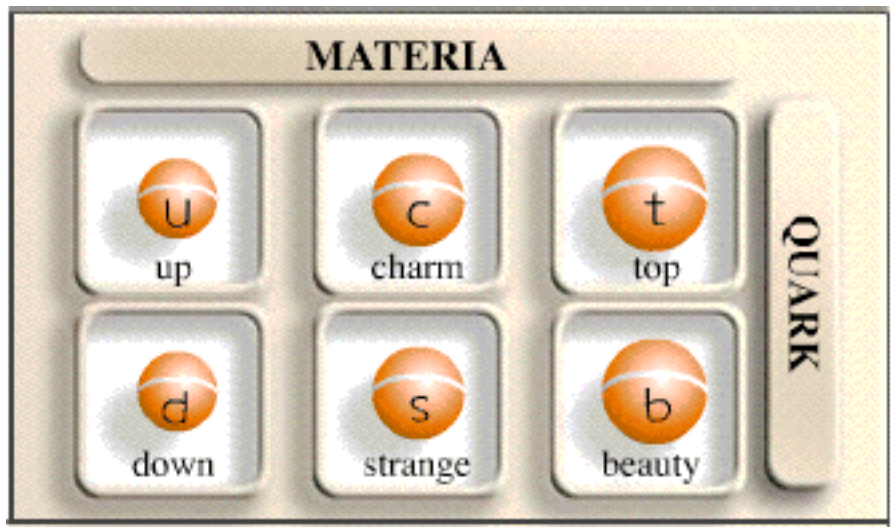
Very early Universe (t=tiny moments after BB)

- High energies
- Exotic physics
- Grand Unified Theory? (all forces united)
- Inflation - a period of rapid expansion
- Density fluctuations laid out!

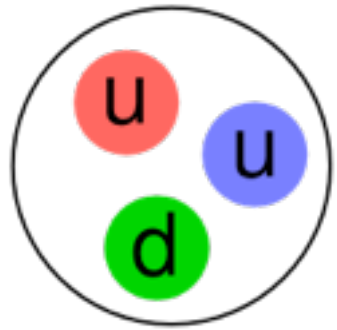


Quark Soup (t<1 sec)

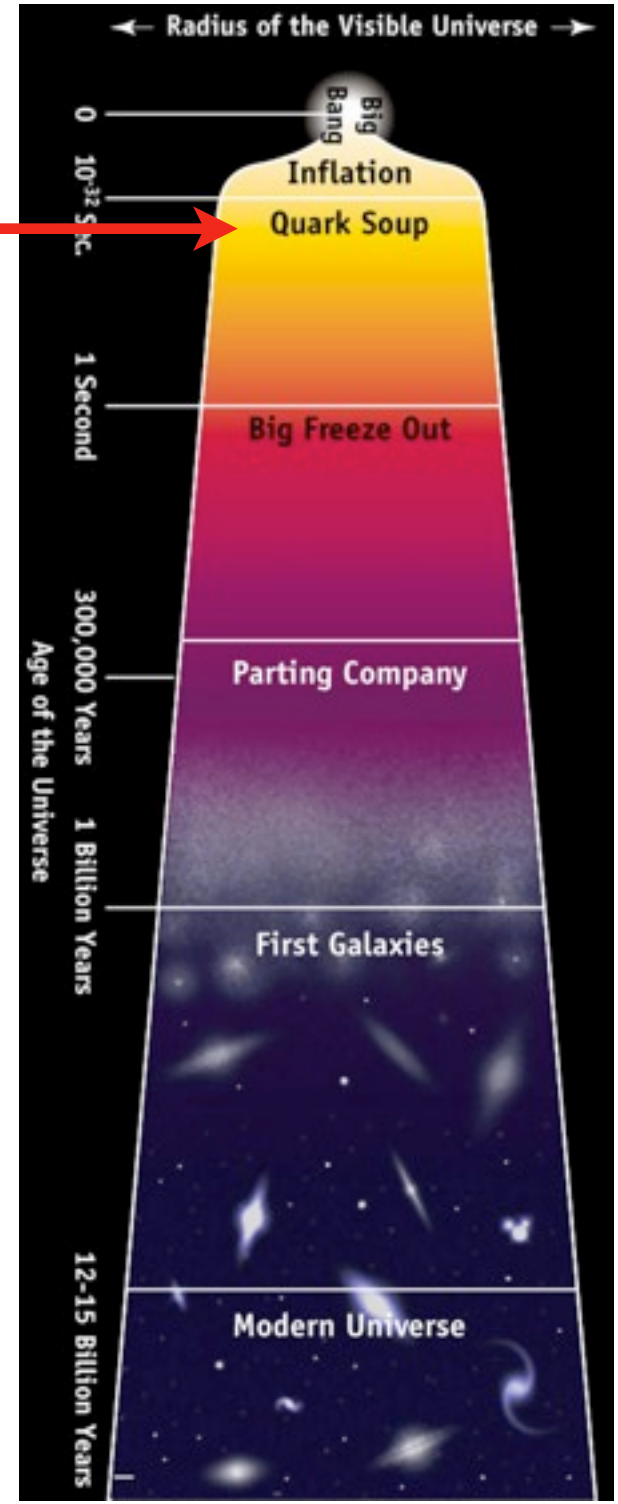
Quarks are free, floating around



Later, they are bound

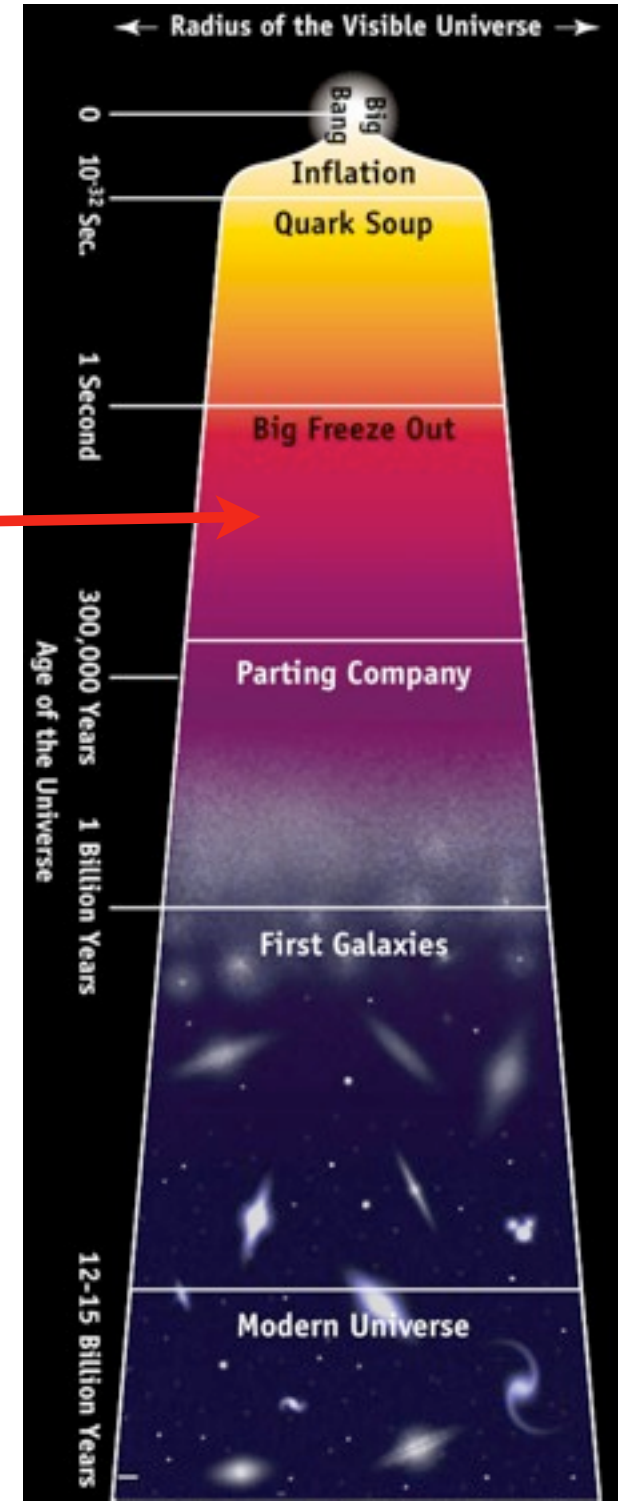


PROTON



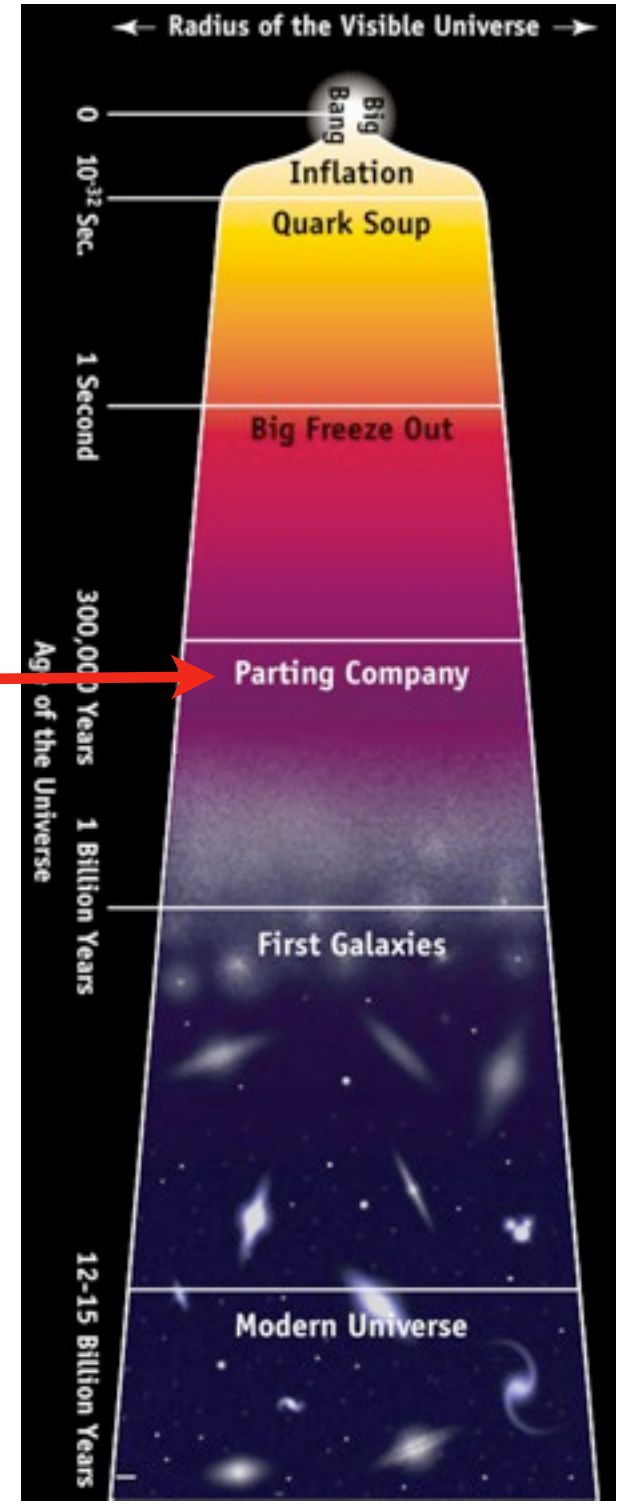
Big Bang Nucleosynthesis (t=1 minute)

- (Lightest) nuclei form
- Hydrogen, Helium, small quantities of other elements
- Universe is still dominated by radiation (photons)
- Universe is still opaque - photons do not propagate far



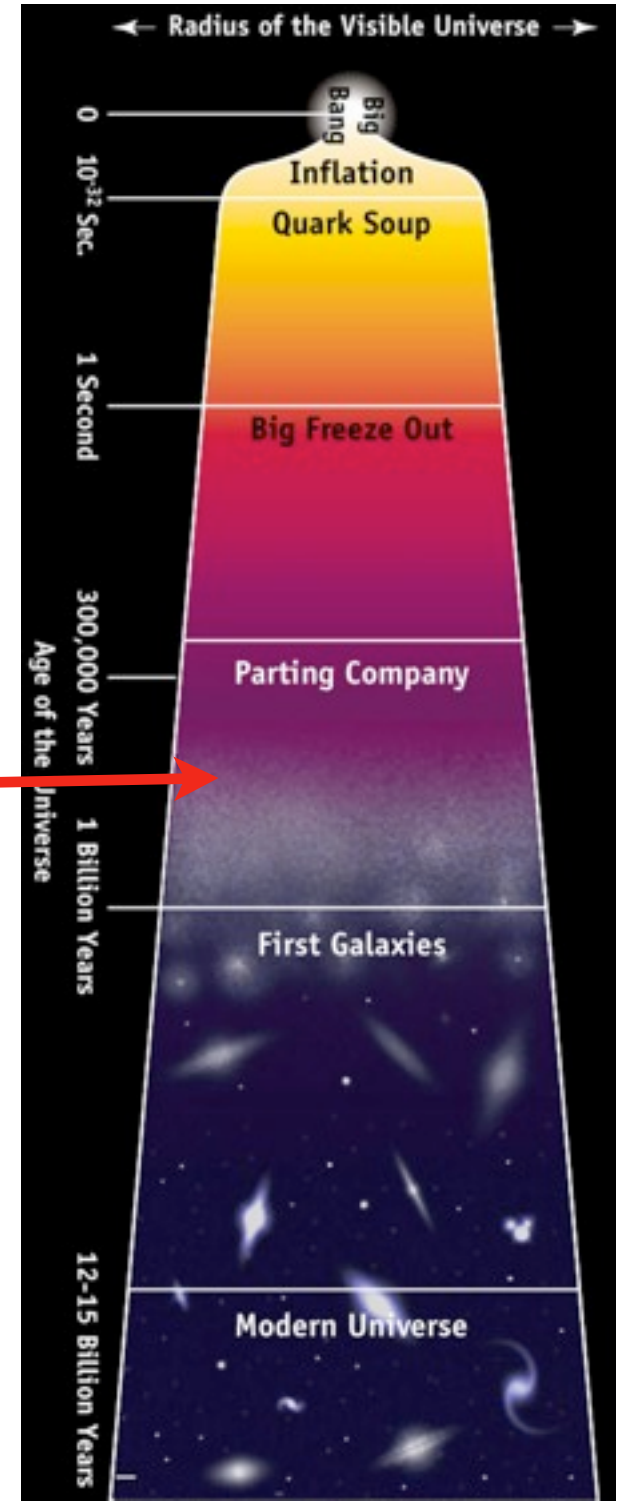
Universe becomes transparent (t=300,000 yrs)

- Atoms form (electrons and nuclei combine)
- Radiation finally free to propagate
- The Cosmic Microwave Background radiation we observe has been released
- Temp ≈3000 Kelvin
- Uniform to one part in 100,000



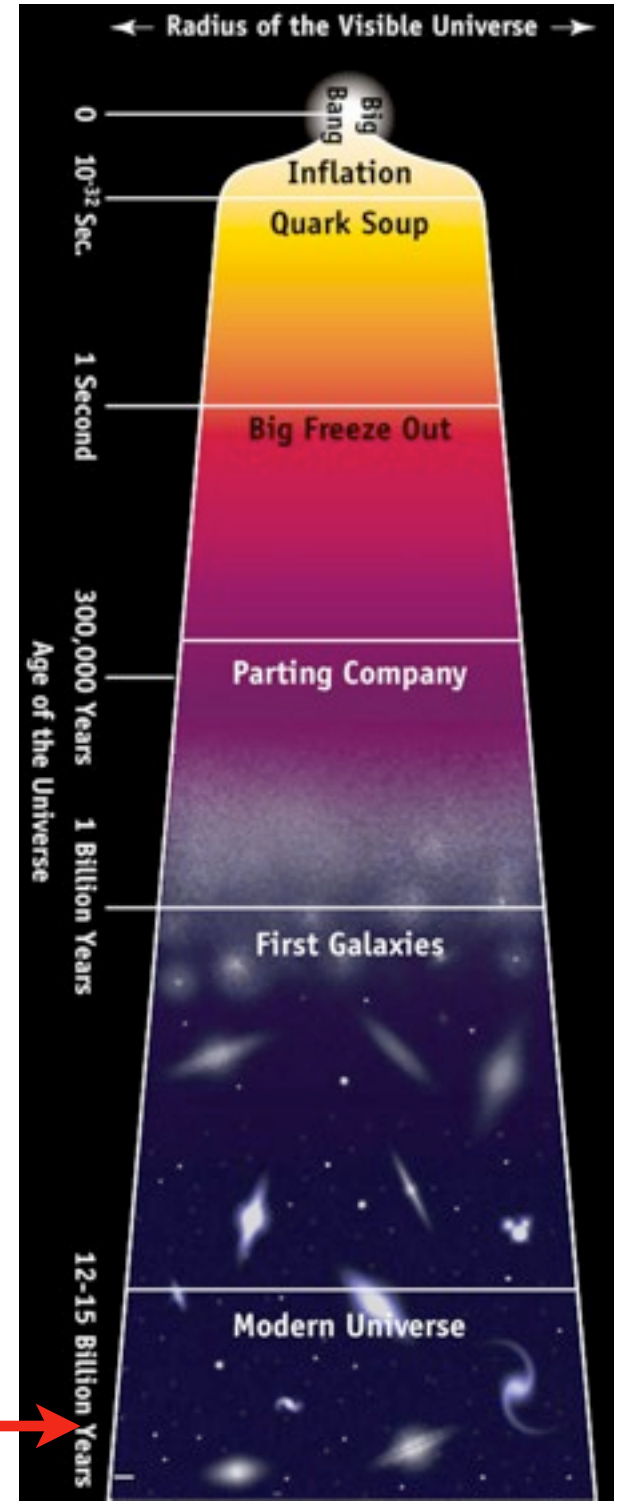
The dark ages (t< 1 billion yrs)

- Universe is dark, slowly becomes matter dominated
- First stars ionize the hydrogen atoms
- First stars and first galaxies eventually form



Modern Universe (t< 13.7 billion yrs)

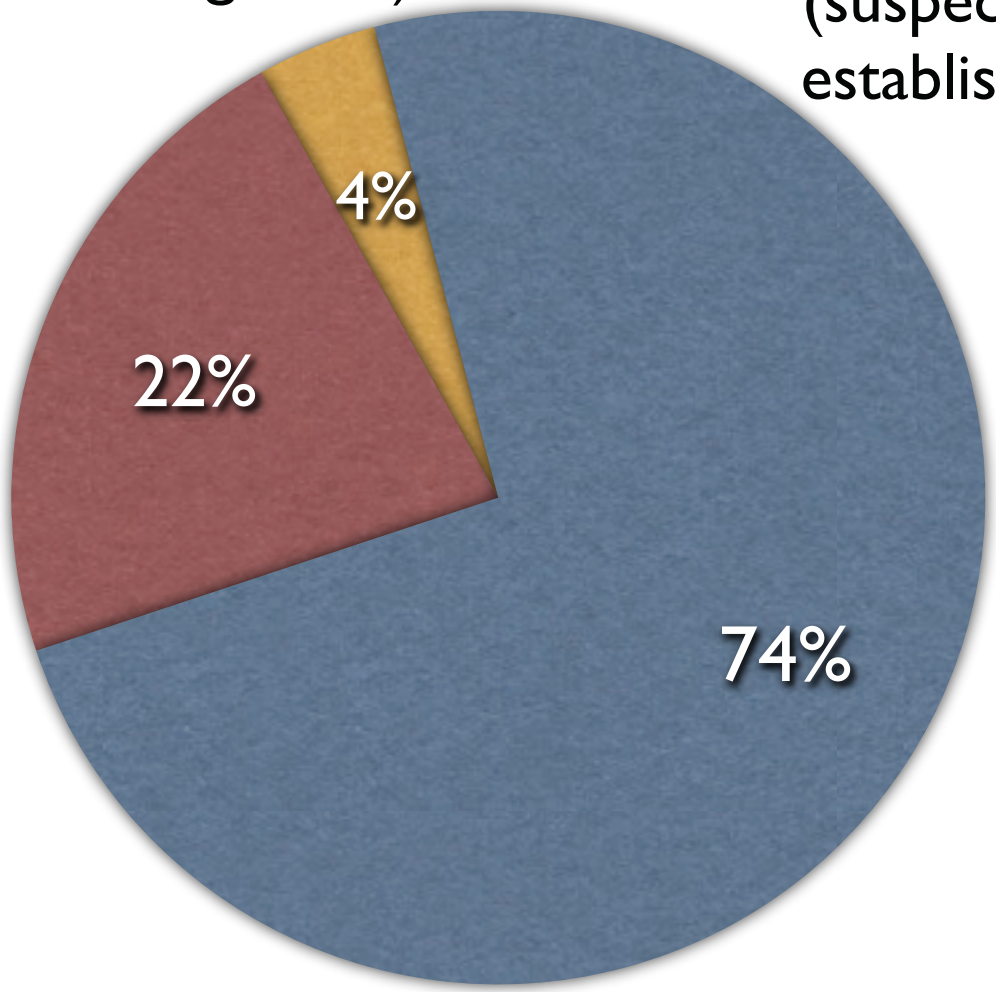
- Stars, Galaxies, Clusters of galaxies everywhere
- Even more **Dark Matter** than we cannot directly see
- Universe is **Dark Energy** dominated!



Makeup of universe today

Baryonic ("visible") Matter
(stars 0.4%, gas 4%)

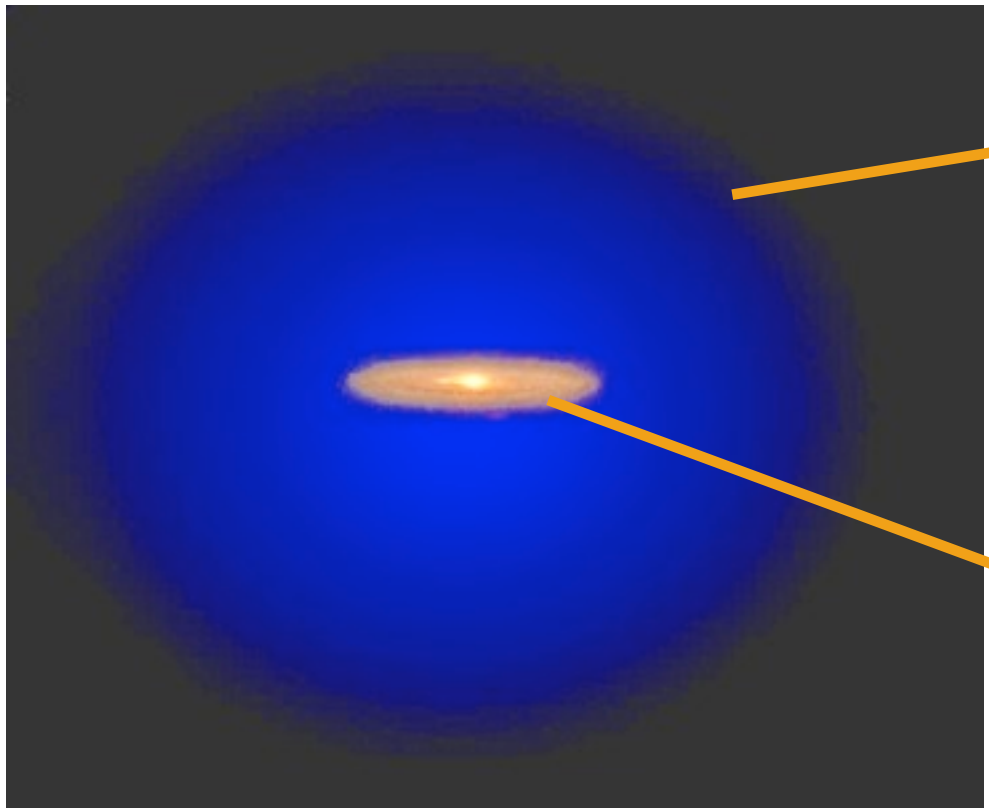
Dark Energy
(suspected since 1980s
established since 1998)



Dark Matter
(suspected since 1930s
established since 1970s)

Also:
radiation (0.01%)

Dark Matter is in "halos" around galaxies



(invisible)
Dark Matter halo

(visible) light
from galaxy

Simulation by Heidi Wu
Formation of 10^{15} M_{sun} cluster

Dark Energy

Michael Turner
University of Chicago

- Universe is dominated by something other than dark matter
- This new component - “dark energy” - makes the universe undergo accelerated expansion
- Other than that, we don’t know much!
- The discoverers shared the 2011 Nobel Prize in Physics
- Subject of next lecture in this series!!

Big-Bang cosmology: Common misconceptions

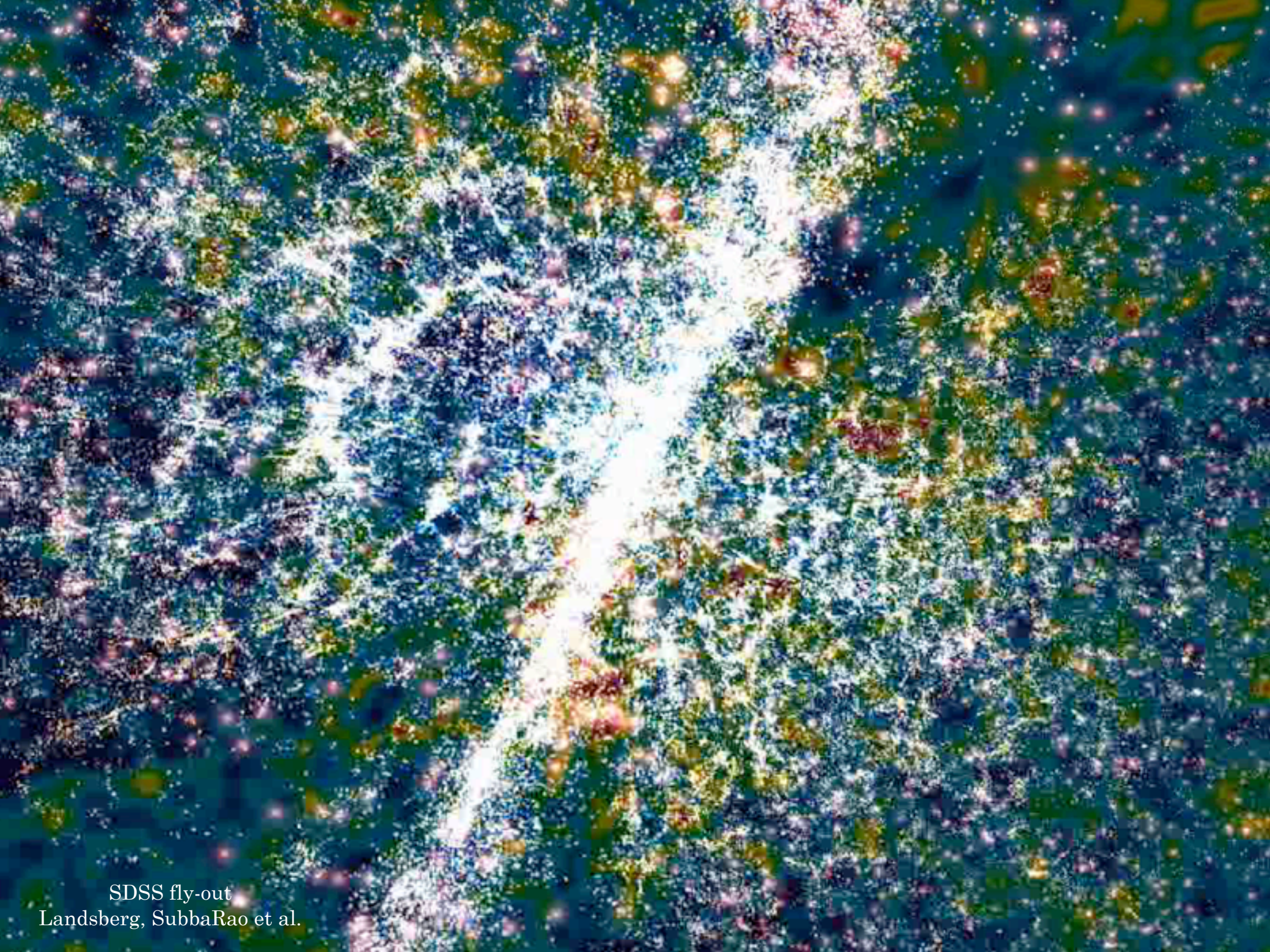
- Big Bang was a giant explosion
  - No. Big Bang was the beginning of the expansion
- There was a center to the Big Bang.
  - Nope. "The Big Bang happened everywhere".
- The universe and everything in it is expanding.
  - The universe is expanding, and space between galaxies too. But things that are bound by gravity or electromagnetic force are not: you, I, this building, Earth, Solar System, our (or any) Galaxy.

Big-Bang cosmology: Common misconceptions

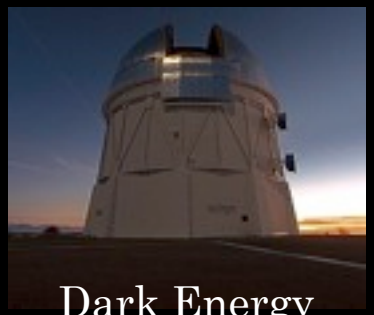
- Galaxies can't recede faster than the speed of light.
  - Wrong. Space between us and galaxies expands. And the "speed" of stretching of space can be >c.

- Cosmic redshift happens because galaxies are moving through space and their light is Doppler-shifted.
  - No, it happens because space itself is stretching.

- The radius of the observable Universe is 13.7 billion light years, since the Universe is 13.7 billion years old.
  - The radius is actually closer to 50 Bly - remember that the Universe was smaller early on. In other words, a patch crossed by light early on has stretched in the meantime

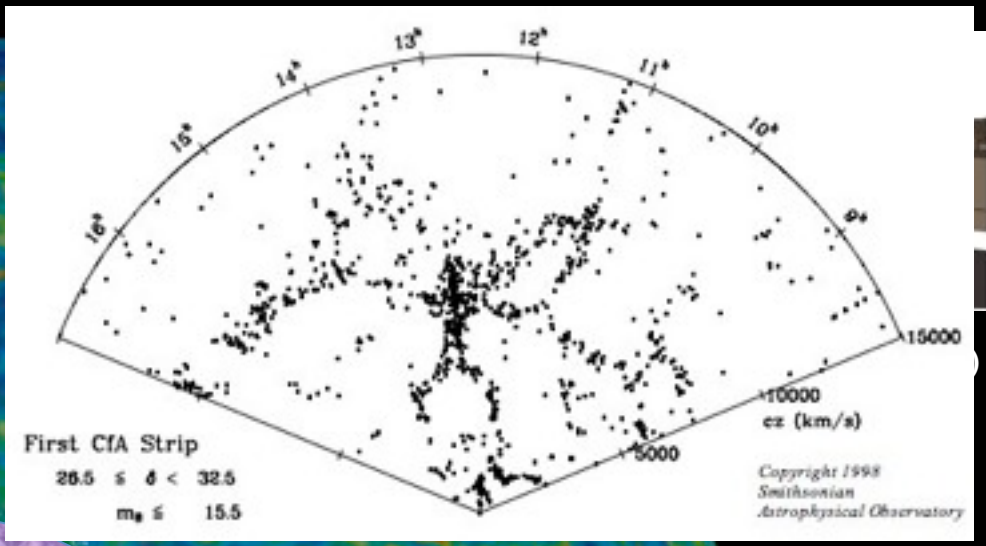


SDSS fly-out
Landsberg, SubbaRao et al.

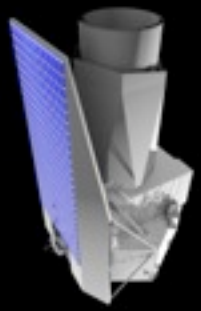


Dark Energy Survey (2012)

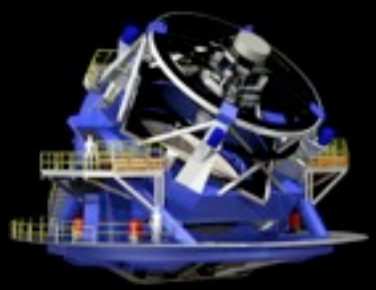
Harvard-Cfa survey (1980s)



Euclid or WFIRST (~202X)



LSST (~2018)



Hobby-Eberly Telescope
(McDonald observatory, Texas)

Conclusions - evidence for Big Bang cosmology

1. Universe is expanding $\Longrightarrow$ it was smaller in the past

2. Big Bang Nucleosynthesis $\Longrightarrow$ light elements needed the 'right conditions'

3. CMB radiation $\Longrightarrow$ the universe was hotter in the past

Further reading - popular articles:

"The Once and Future Cosmos", Scientific American special issue, December 2002 ($7.95 online, $10.95 hardcopy)

EXTRA SLIDES

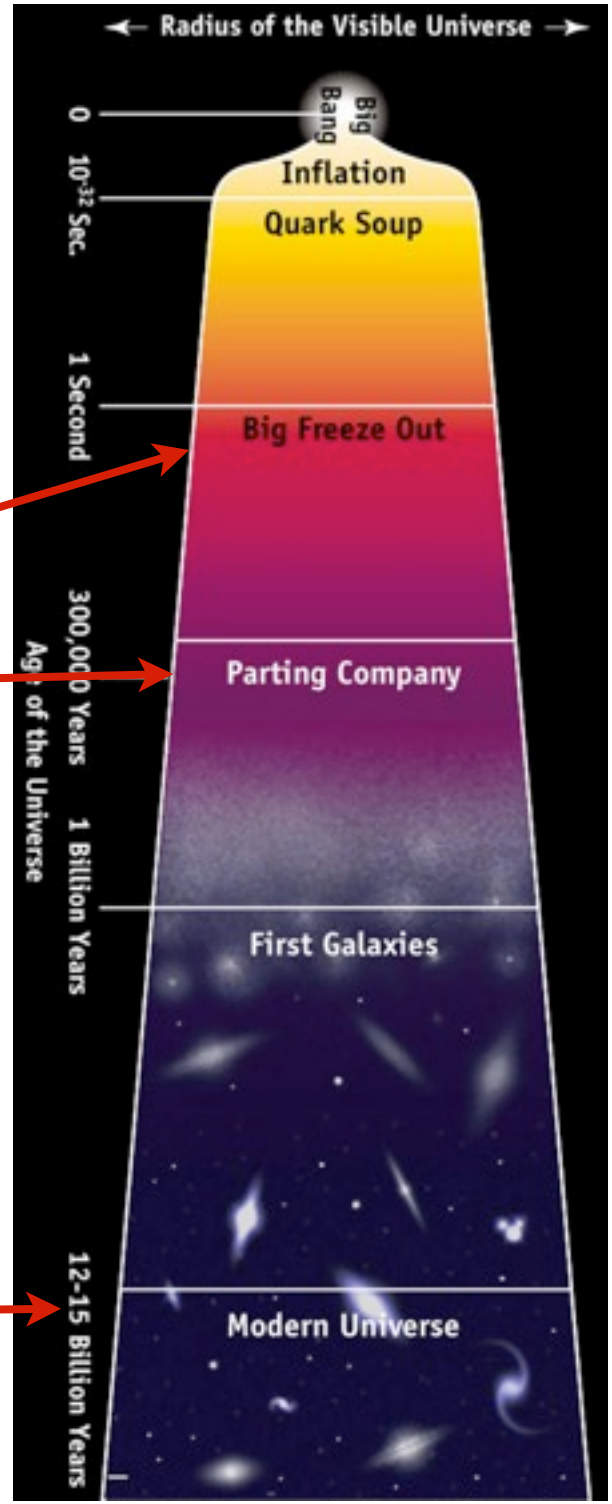
Dark Energy Survey (DES)

- Camera specifically built to make cosmological measurements to study Dark Energy
- On 4-meter telescope on Cerro Blanco, Chile

Some of the early history of the Universe is actually understood better!

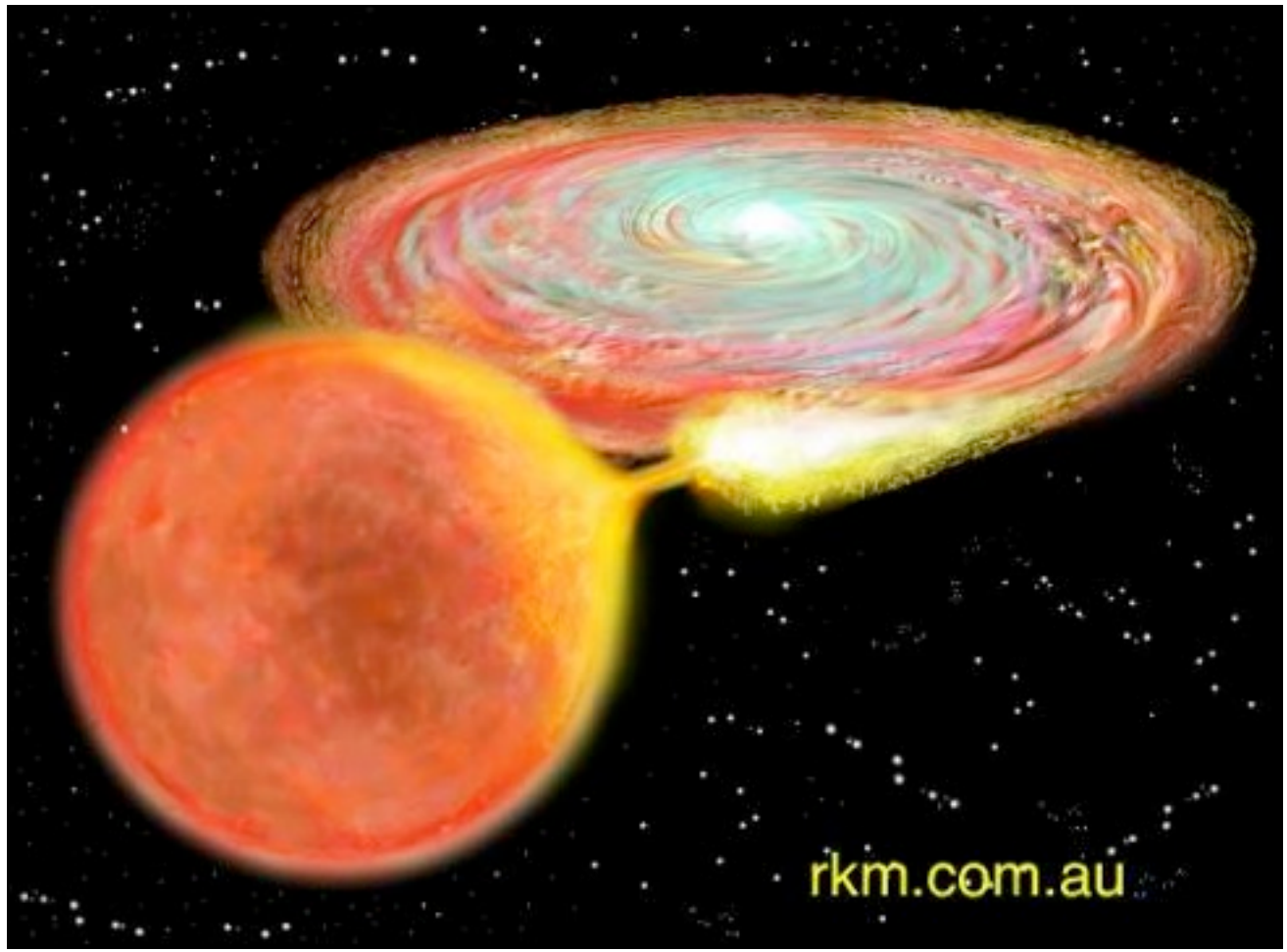
Physics quite well understood

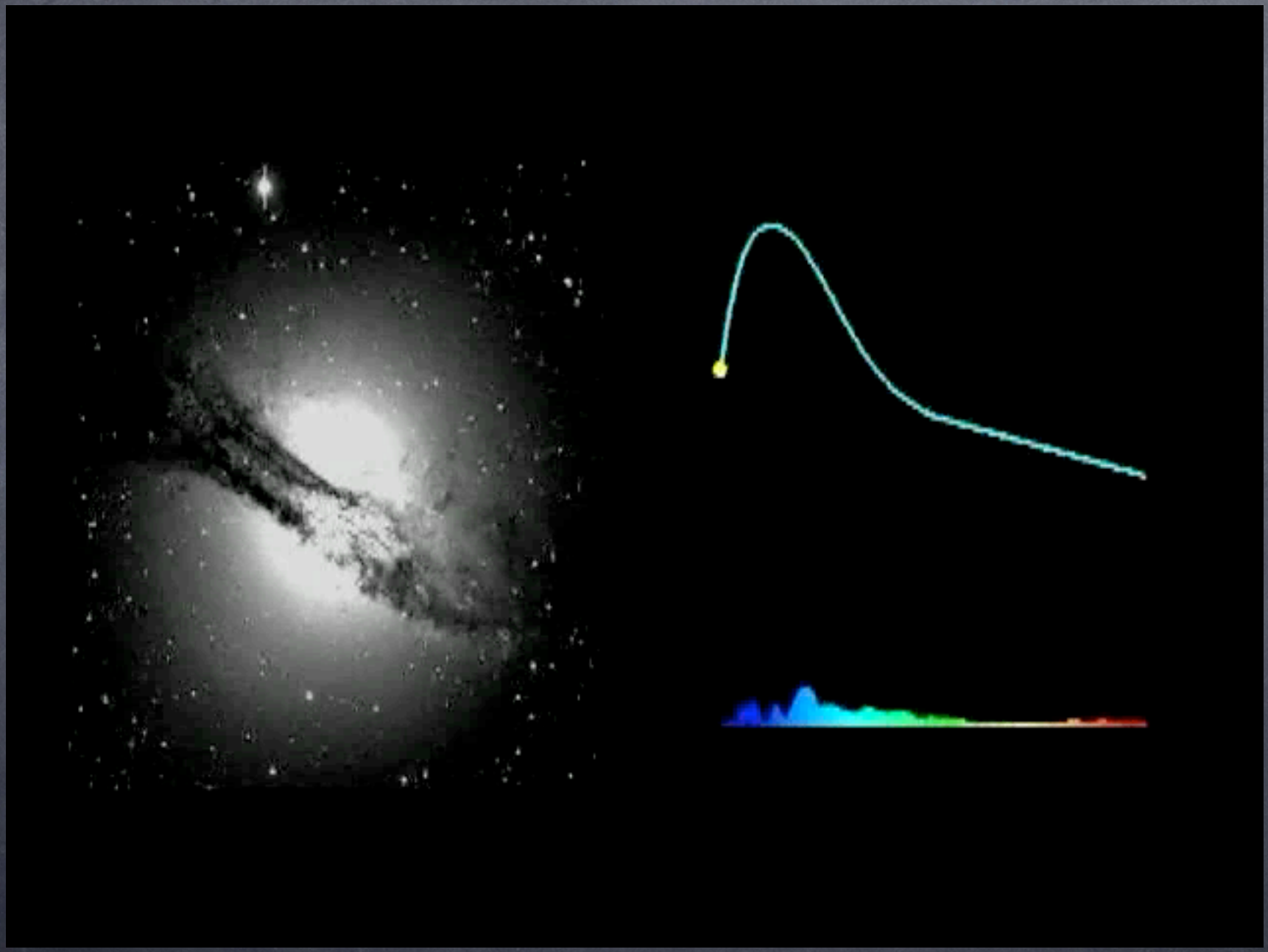
95% of mass/energy only phenomenologically described



Type Ia Supernovae

A white dwarf accretes matter from a companion.





credit: Supernova Cosmology Project

SNe Ia are "Standard Candles"

(car headlights example)

If you know the intrinsic brightness of the headlights, you can estimate how far away the car is

A way to measure (relative) distances to objects far away

But how do you find SNe?

Rate: 1 SN per galaxy per 500 yrs!

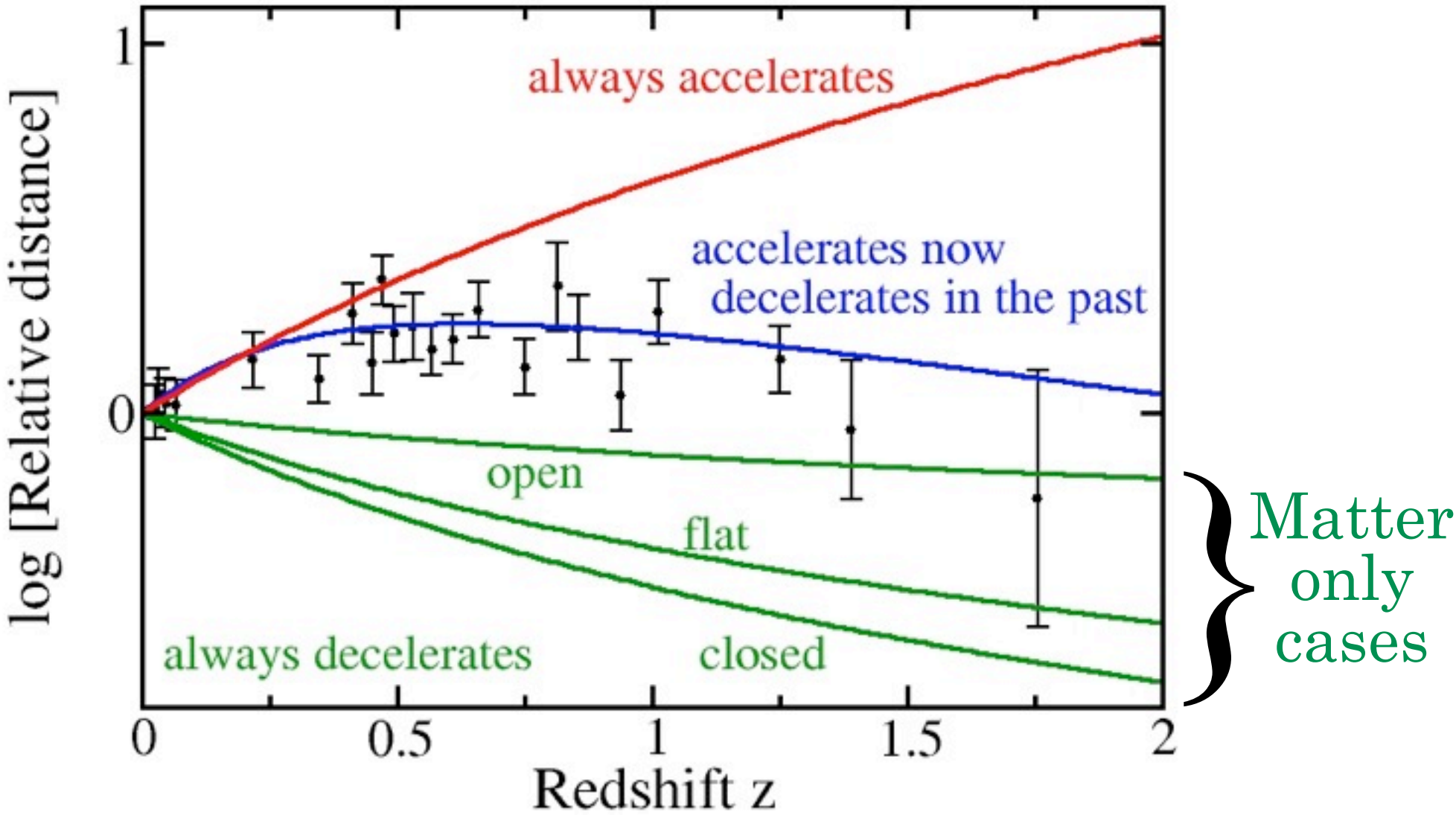
Solution:

1. use world's large telescopes,
2. schedule them to find, then "follow-up" SNe
3. put in heroic hard work

Motivation: to measure geometry of the universe

Supernova Hubble diagram

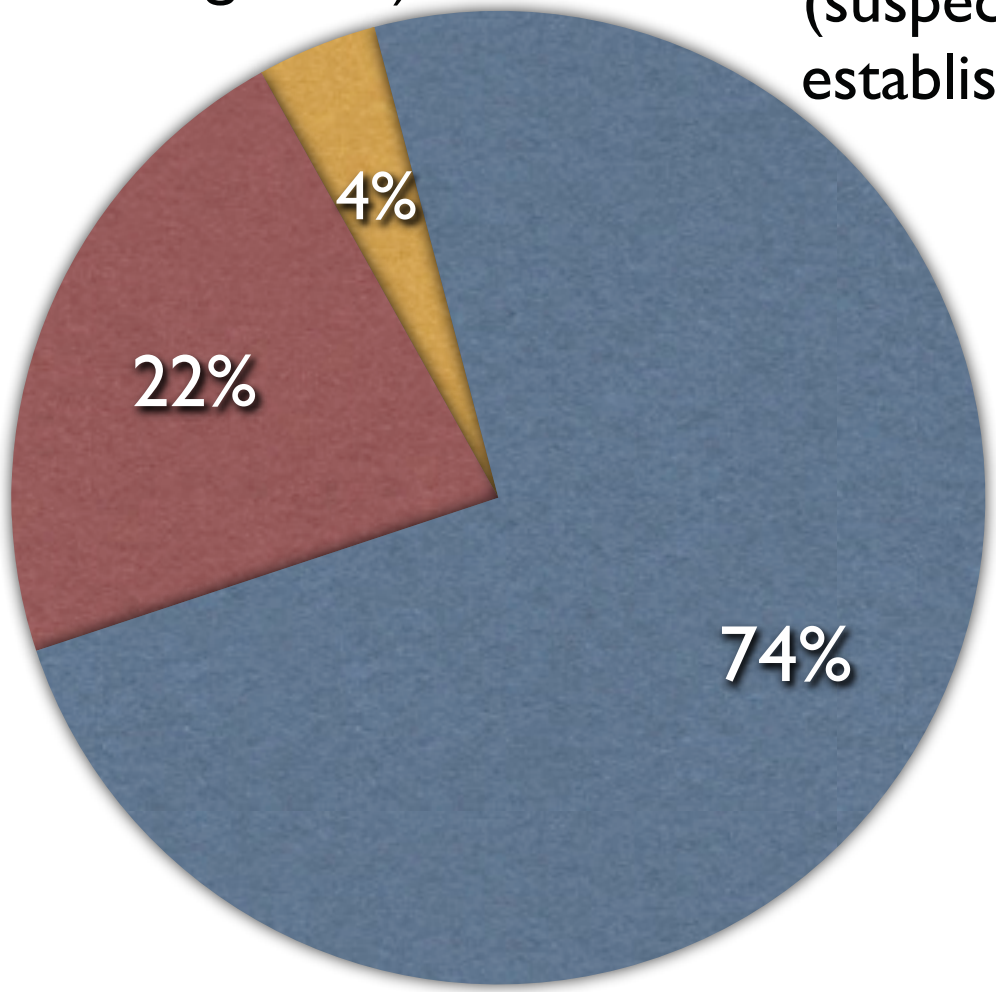
(actual data; each error bar denotes ~20 SN)



Makeup of universe today

Baryonic ("visible") Matter
(stars 0.4%, gas 4%)

Dark Energy
(suspected since 1980s
established since 1998)



Dark Matter
(suspected since 1930s
established since 1970s)

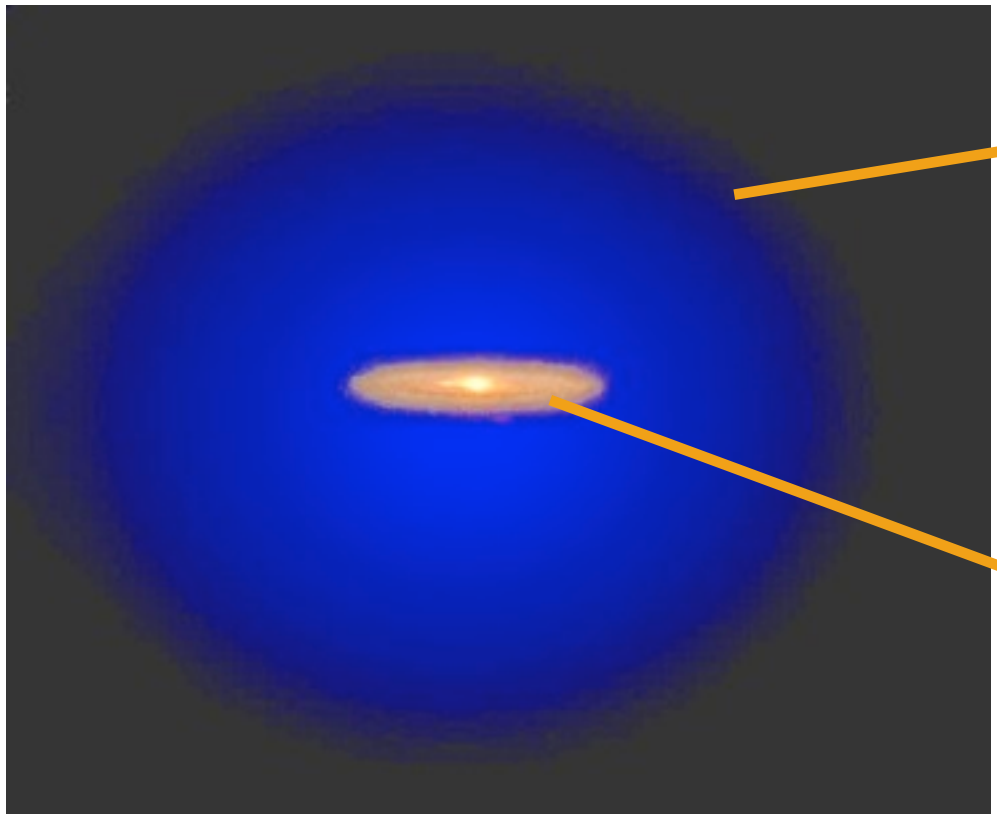
Also:
radiation (0.01%)

Michael Turner
University of Chicago

Dark Energy

- Universe is dominated by something other than dark matter
- This new component - "dark energy" - makes the universe undergo accelerated expansion
- This new component is largely smooth
- Other than that, we don't know much!

Recall: Dark Matter is in "halos" around galaxies

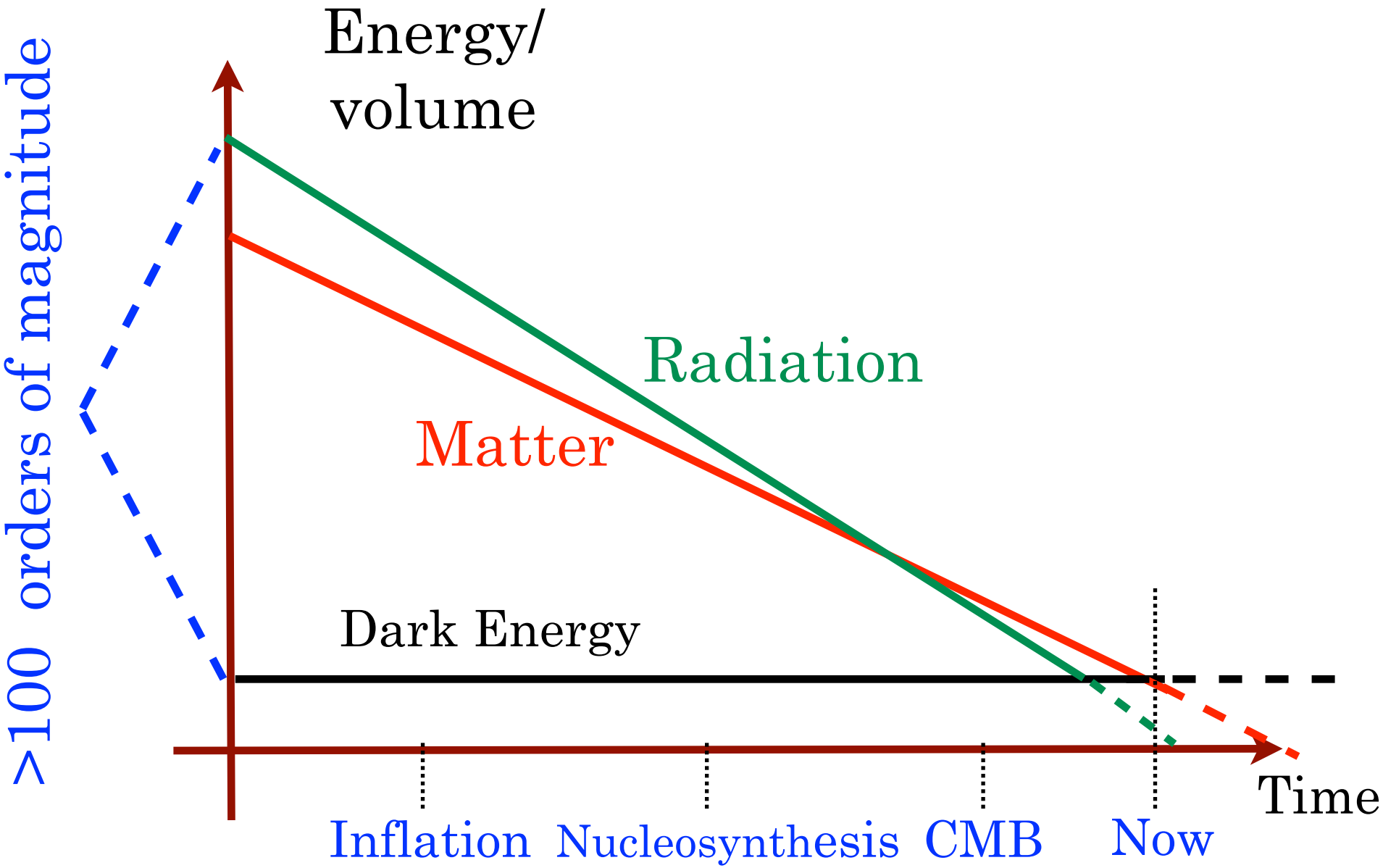


(invisible)
Dark Matter halo

(visible) light
from galaxy

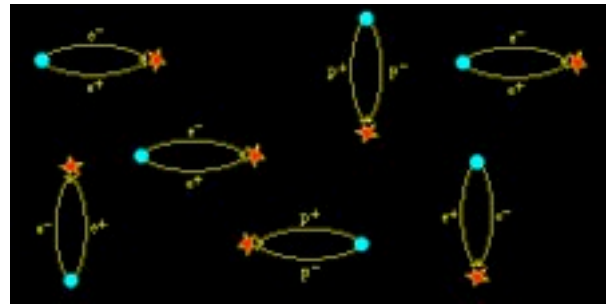
Dark Matter ≠ Dark Energy

Mystery #1: Coincidence problem



Mystery #2:
Theory prediction for how much DE

Quantum mechanics predicts
vacuum energy to be



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(or 10^{120}) **times more** than the observed amount

This is known as
the COSMOLOGICAL CONSTANT PROBLEM

(Bizarre) Consequences of DE

- Geometry is not destiny any more! Fate of the universe (accelerates forever vs. recollapses etc) depends on the future behavior of DE
- In the accelerating universe, galaxies are leaving our observable patch -> the sky will be empty in 100 billion years
- Under certain conditions we will have a Big Rip - galaxies, stars, planets, our houses, atoms, and then the fabric of space itself will rip apart!

Steven Weinberg:

``Right now, not only for cosmology but for elementary particle theory, this is the bone in our throat"

Frank Wilczek:

``... maybe the most fundamentally mysterious thing in all of basic science"

Ed Witten:

``... would be the number 1 on my list of things to figure out"

Michael Turner:

"... the biggest embarrassment in theoretical physics"