The Universe Caught Speeding: Dark Energy 2 Decades After

Dragan Huterer

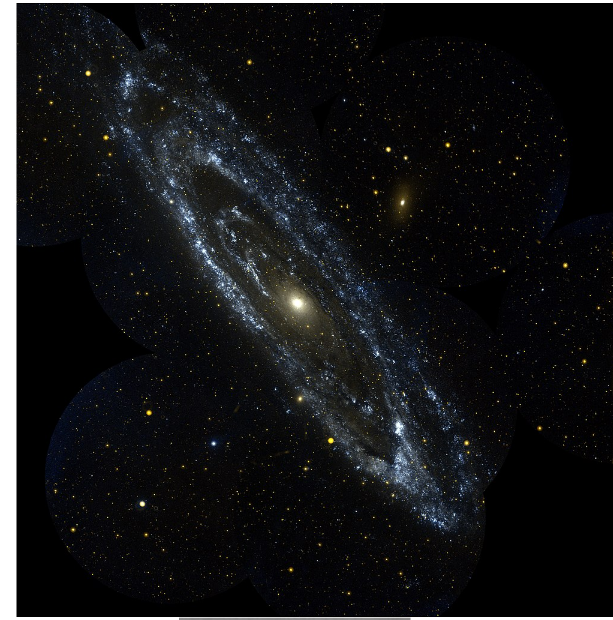
Department of Physics
University of Michigan

What are these objects?

Hubble Ultra Deep Field

Shapley-Curtis debate

(Washington DC, 1920)



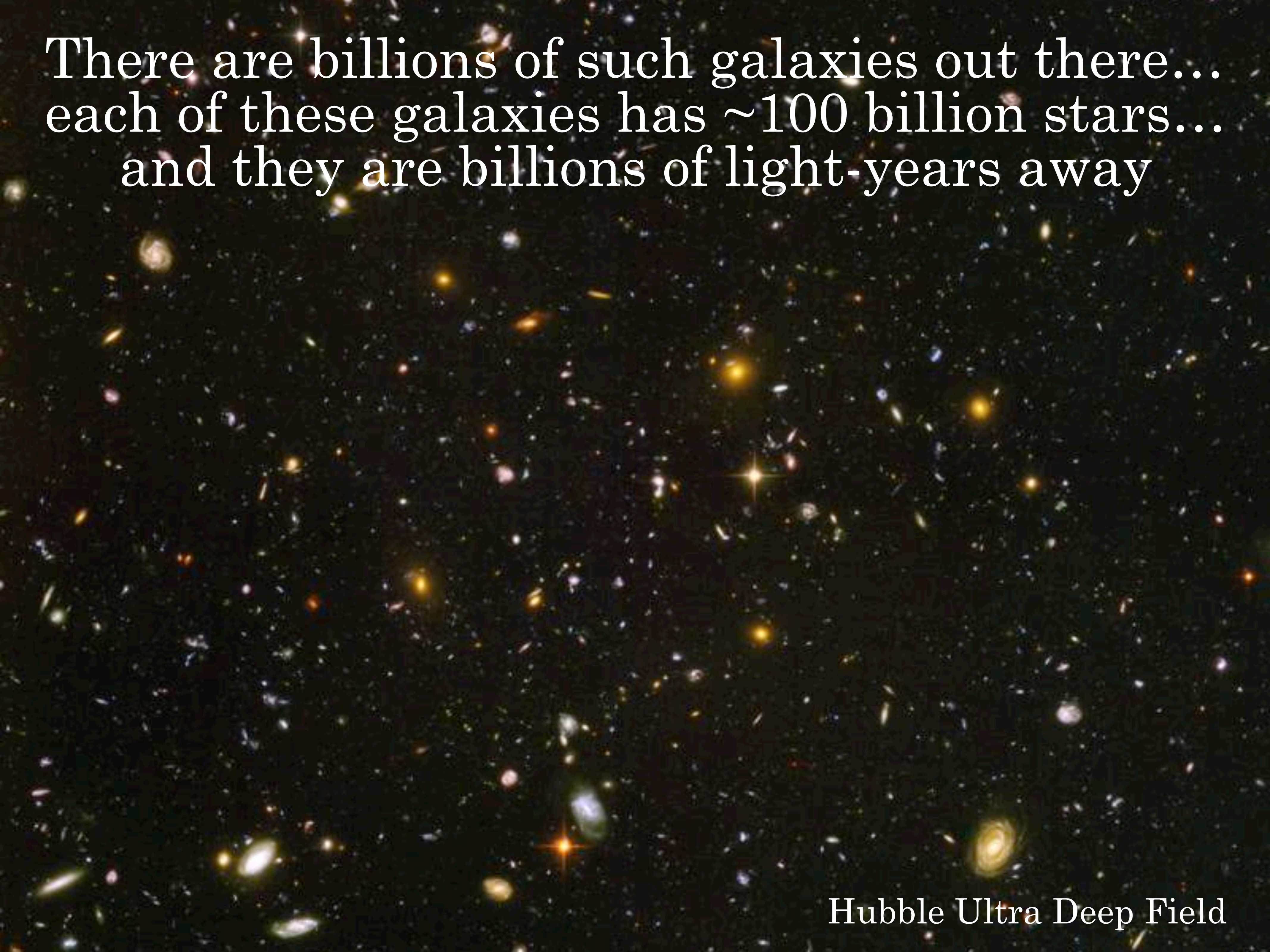
What is the nature of
"spiral nebulae"
(today called galaxies)
such as Andromeda?

- Shapley: they are all part of **our** Galaxy, the Milky Way

- Curtis: they are **separate** "island universes" (i.e. galaxies)

Curtis was correct!

There are billions of such galaxies out there…
each of these galaxies has ~100 billion stars…
and they are billions of light-years away



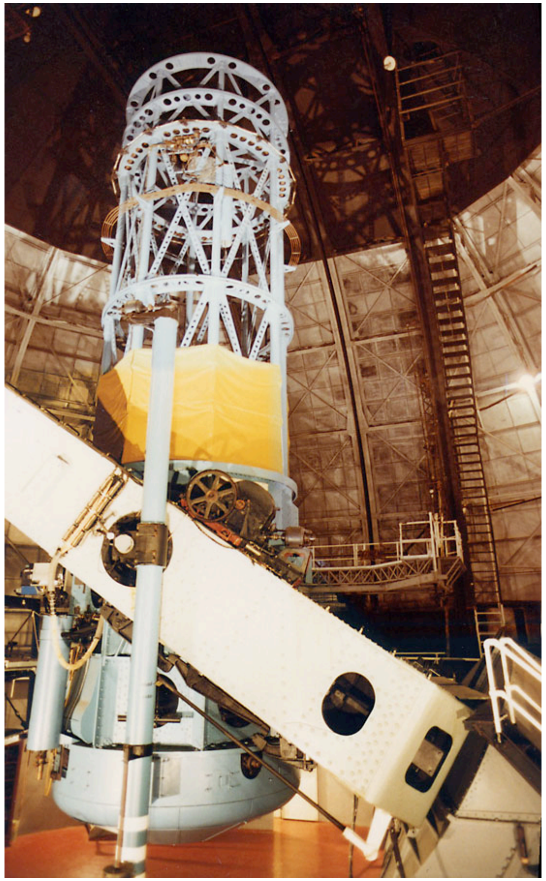
Hubble Ultra Deep Field

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

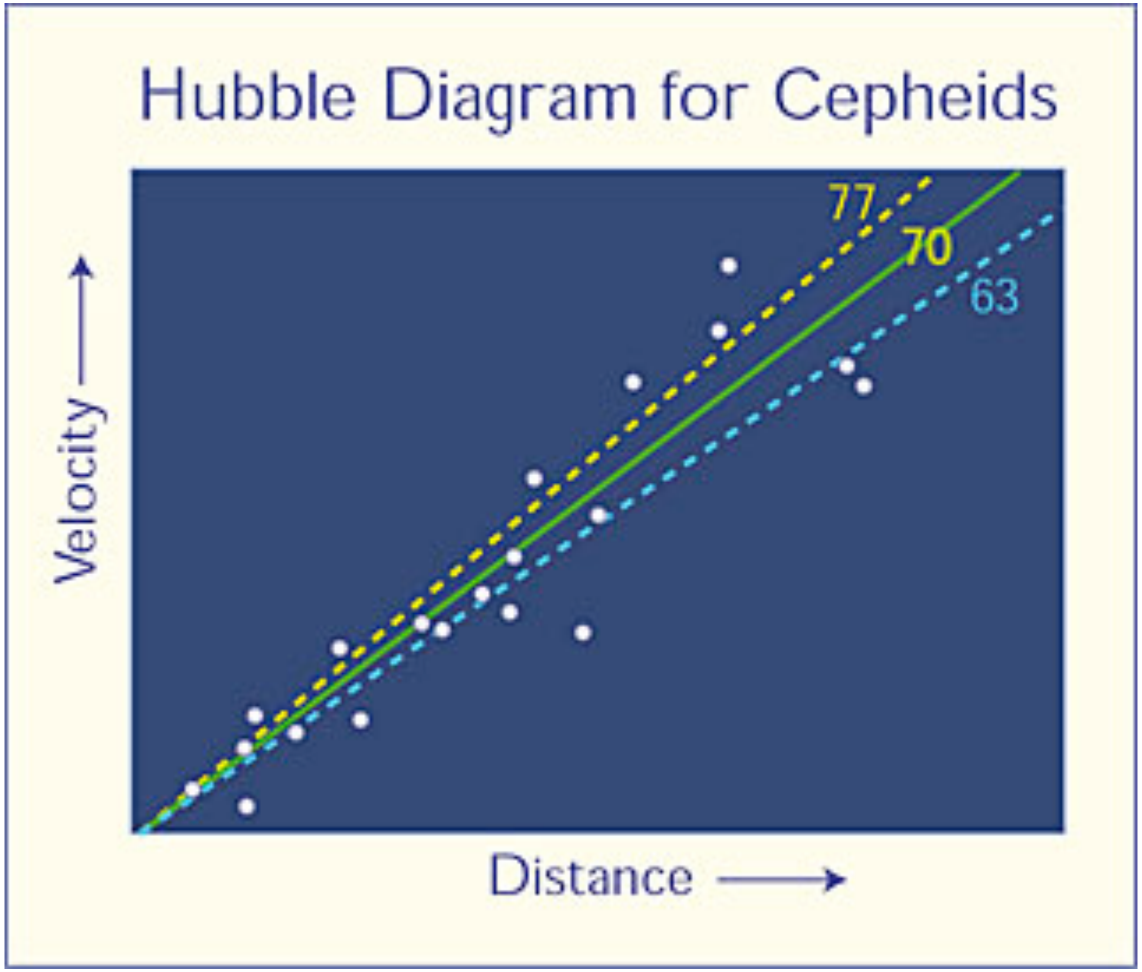
$\Rightarrow$

The Universe is Expanding!

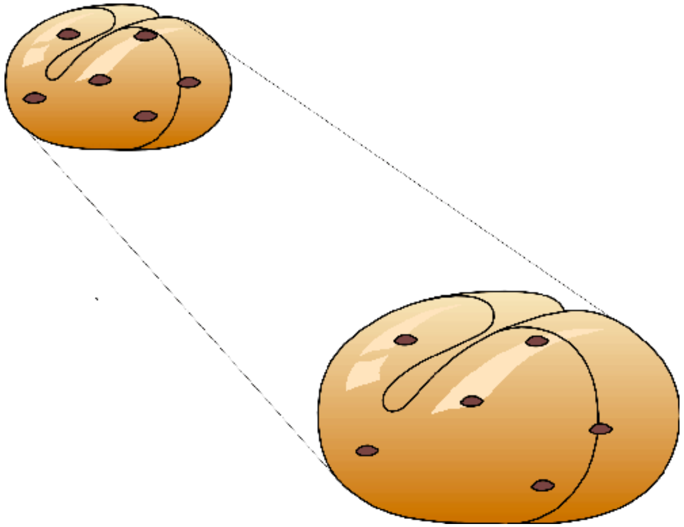


100 inch Hooker telescope
(Mt Wilson, CA)

Expanding spaces: bread & universe

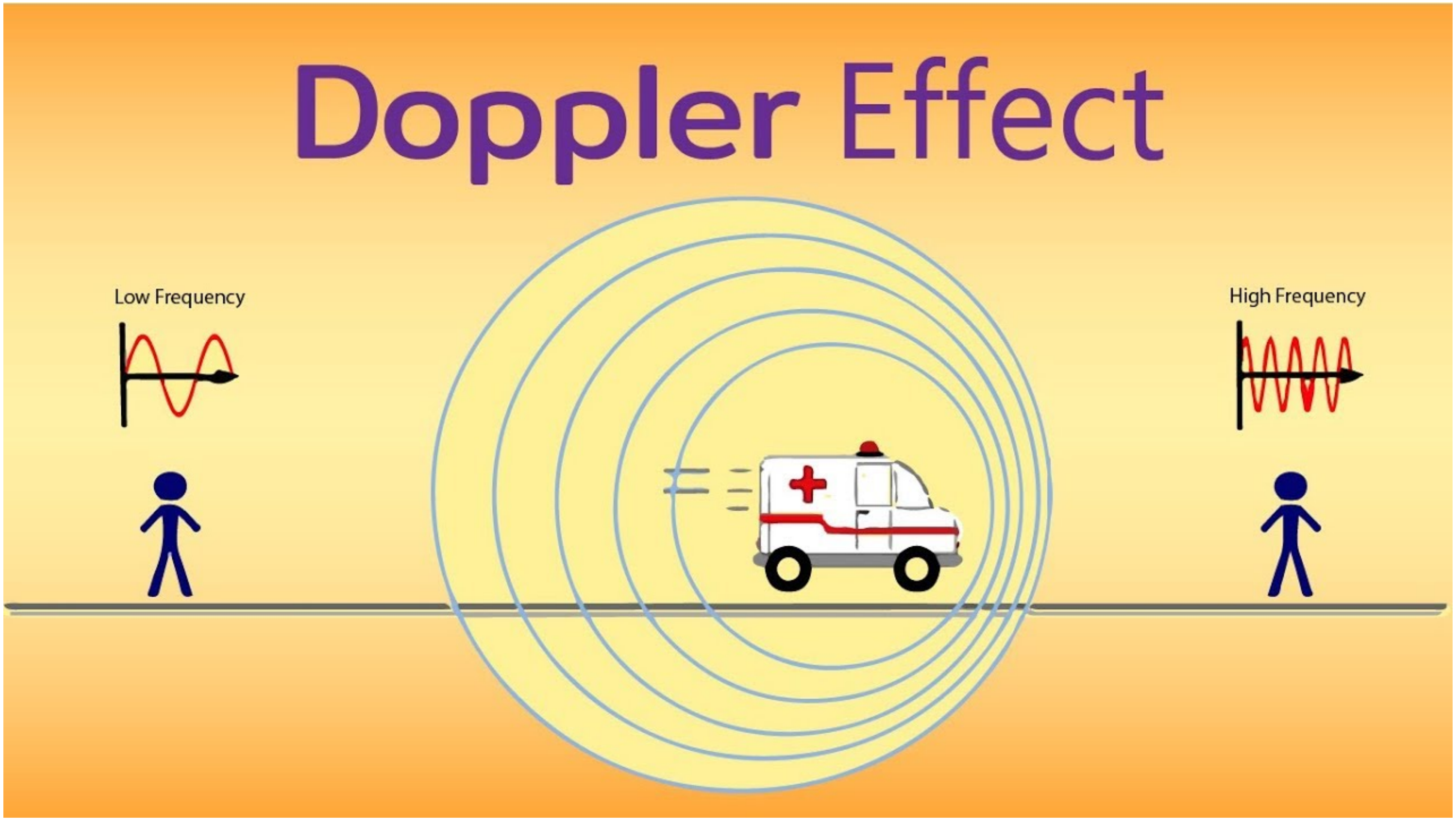


Baking the raisin bread: the **farther** two raisins are, the **faster** they are receding



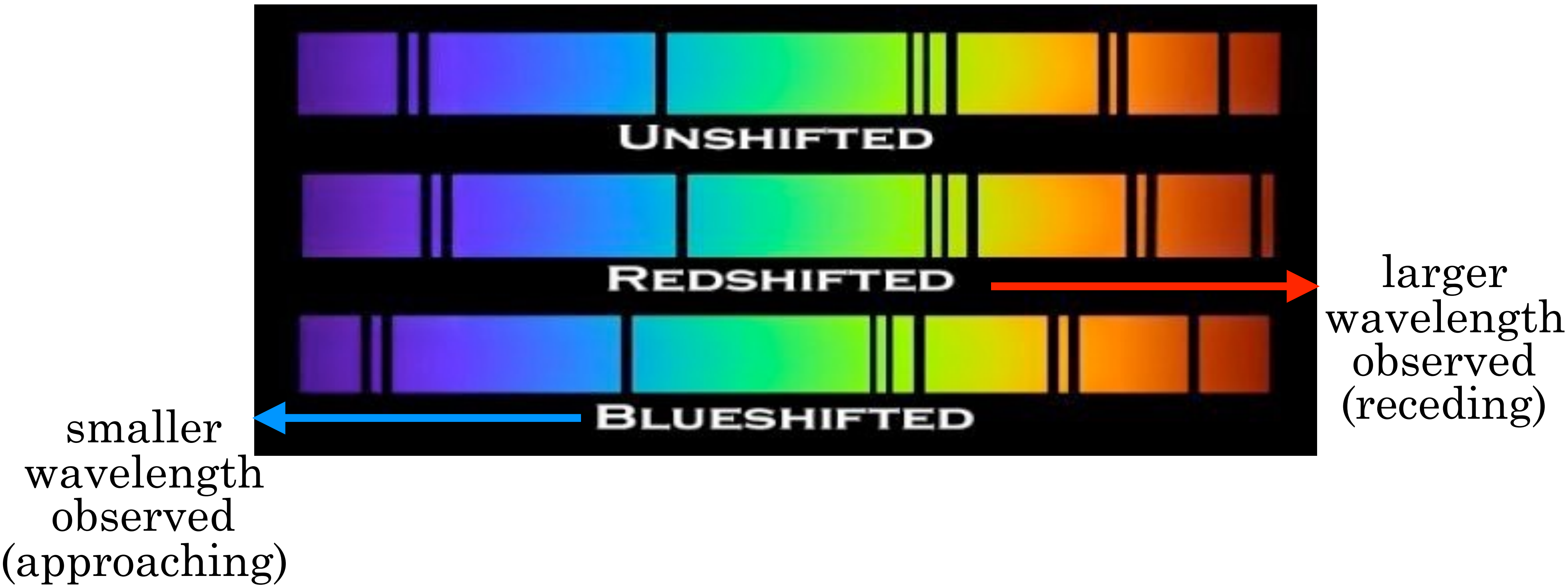
- Velocity is easy: from the Doppler recession of galaxy spectra
  (first done by astronomer Vesto Slipher, whom Hubble never credited)
- Distance is hard: from Cepheid variable stars

How do you get galaxy velocity (with respect to us)?



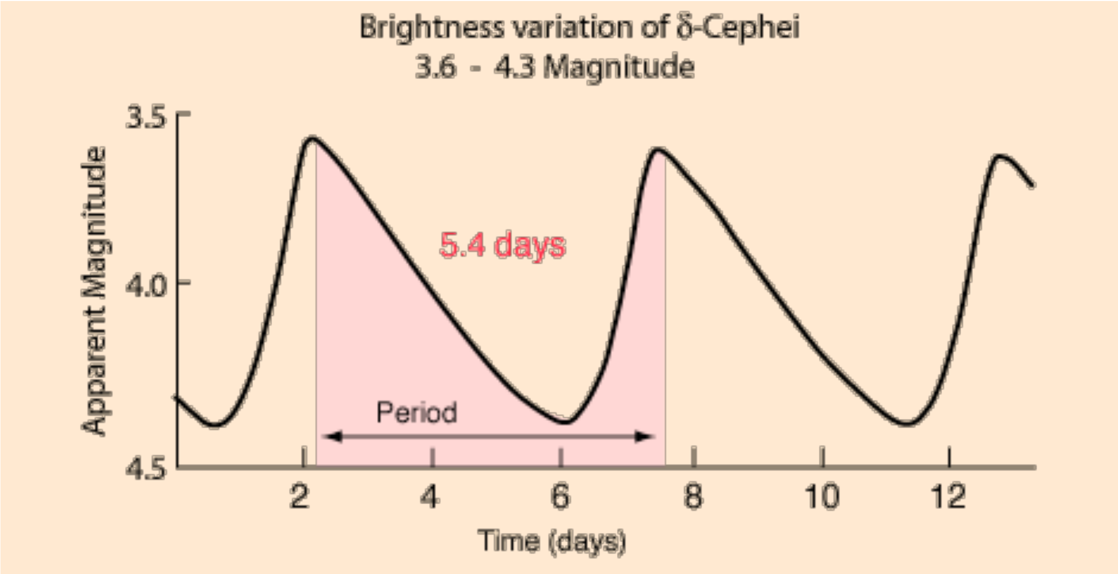
Demo: Doppler whistle

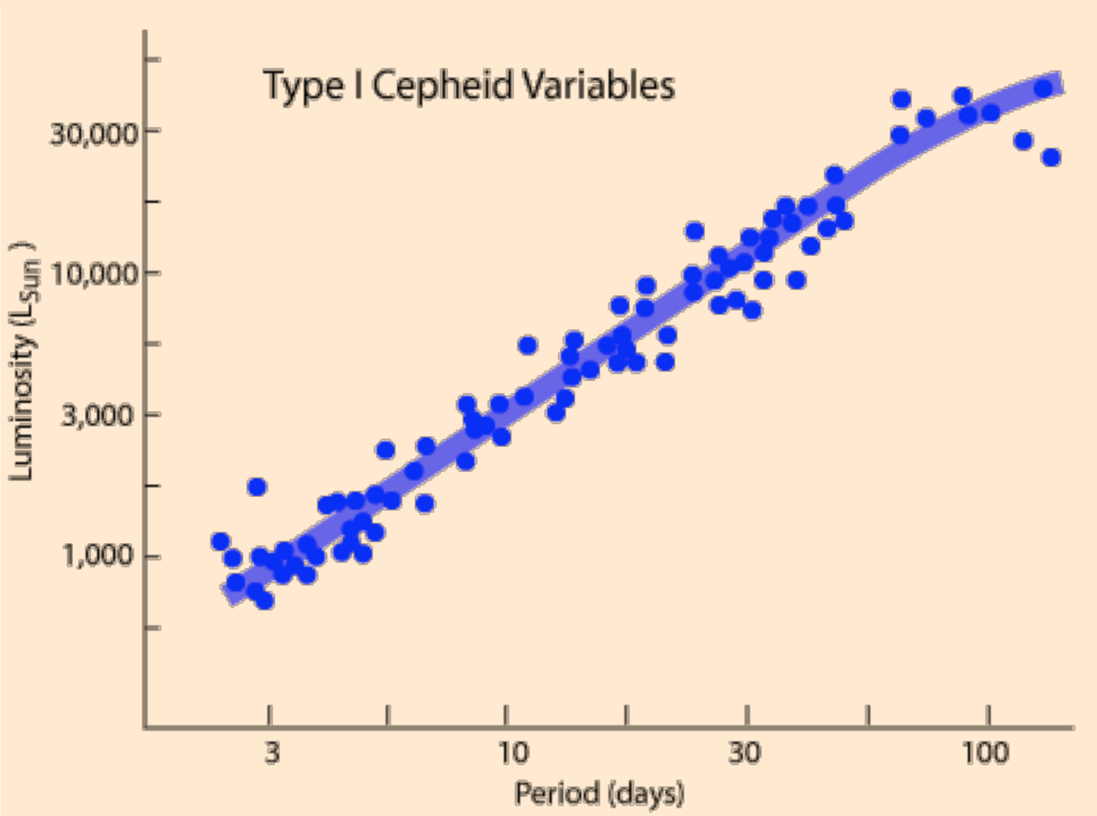
Redshift: shift of galaxy light wavelength
(due to galaxy’s motion relative to us)



Light from almost all galaxies is redshifted (and not blueshifted)
- **the galaxies are receding away from us**!

How do you get distances to galaxies?





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

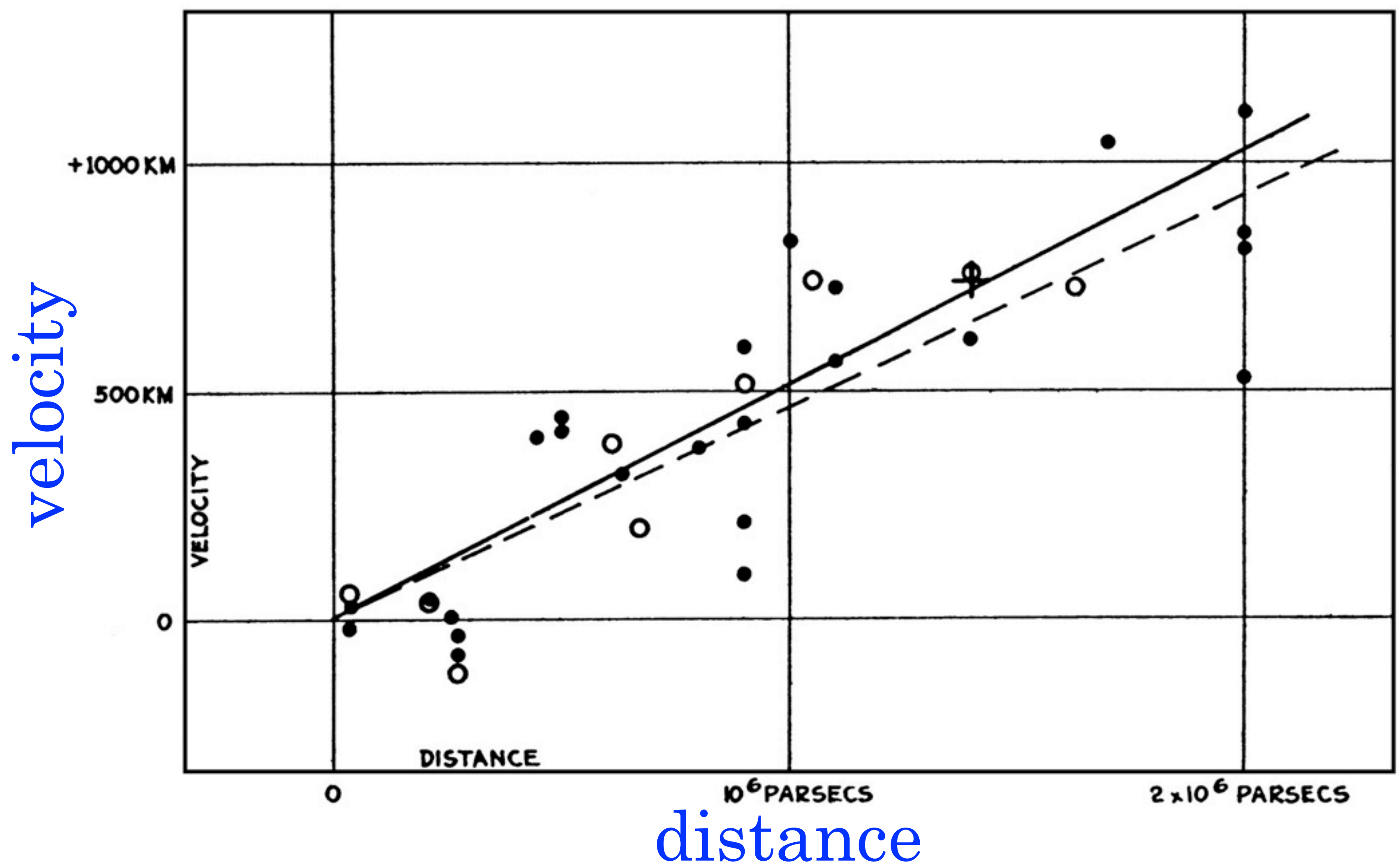
Cepheids (variable stars)

- 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 (1929)

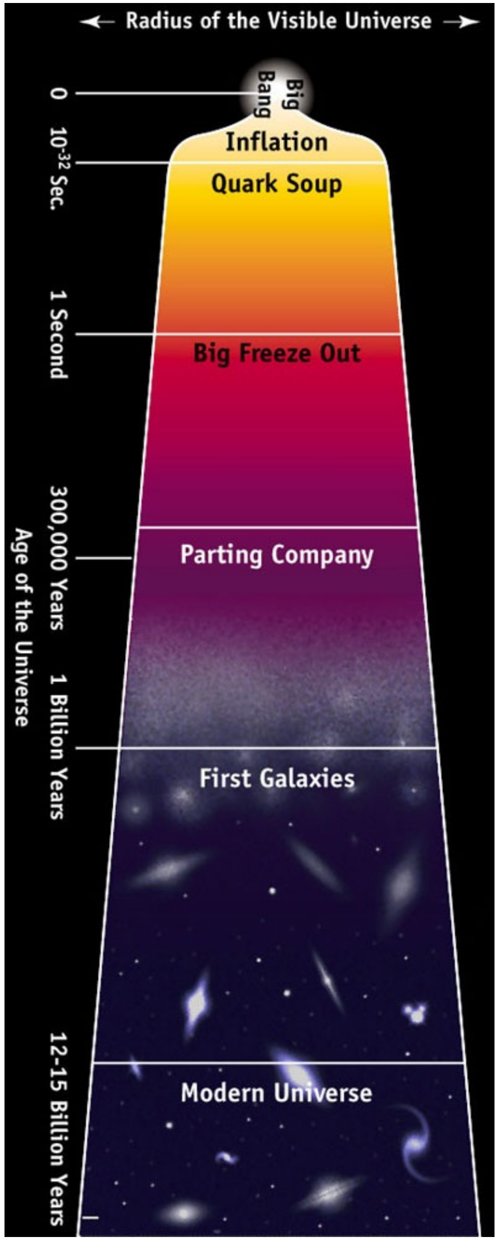


Slope of this relation (velocity vs. distance) is called the Hubble constant H_0.

Modern value:

$H_0 \approx 70$ km/sec/megaparsec (will return to H_0 later!)

History of the universe from t=0 to t=13.8 Gyr

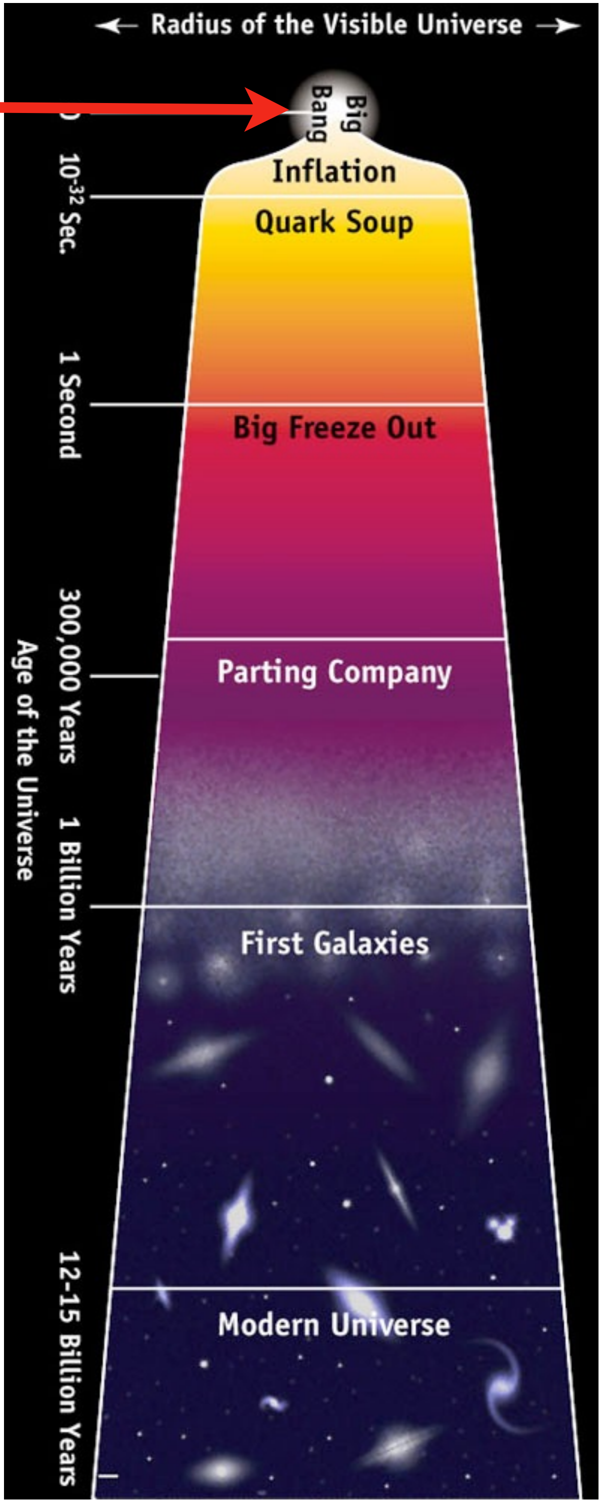


A Brief Overview...

Big Bang (t=0)

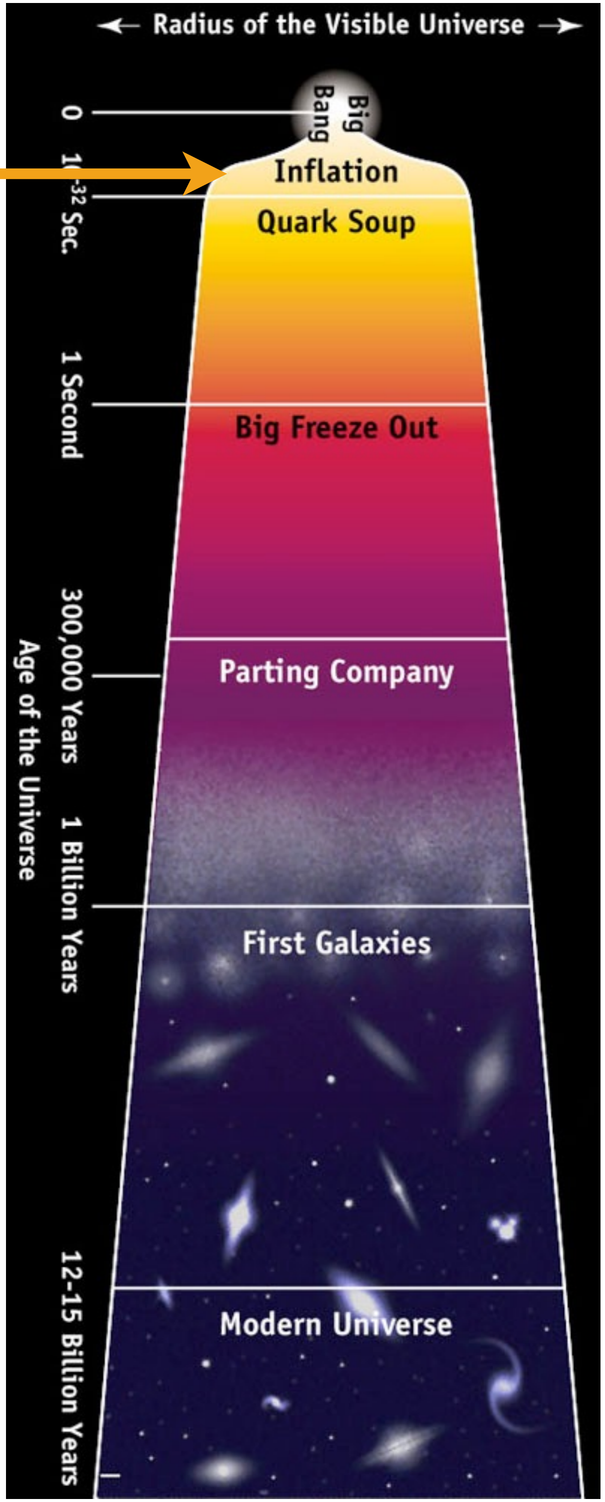
- Expansion starts
- Happened "everywhere"
- Details not well known
- Currently beyond reach of any cosmological probe

- Please don't ask "what happened before the big bang?"



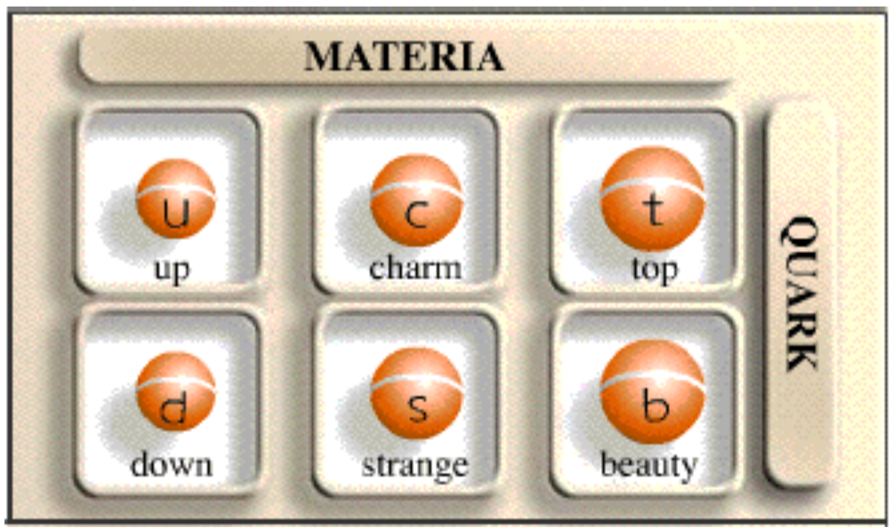
Very early Universe
(t=tiny moments after BB)

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

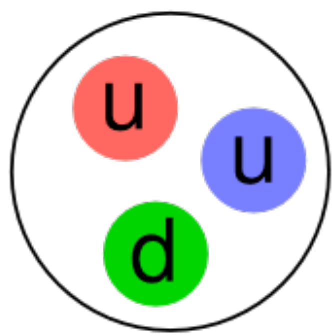


Quark Soup
(t<1 sec)

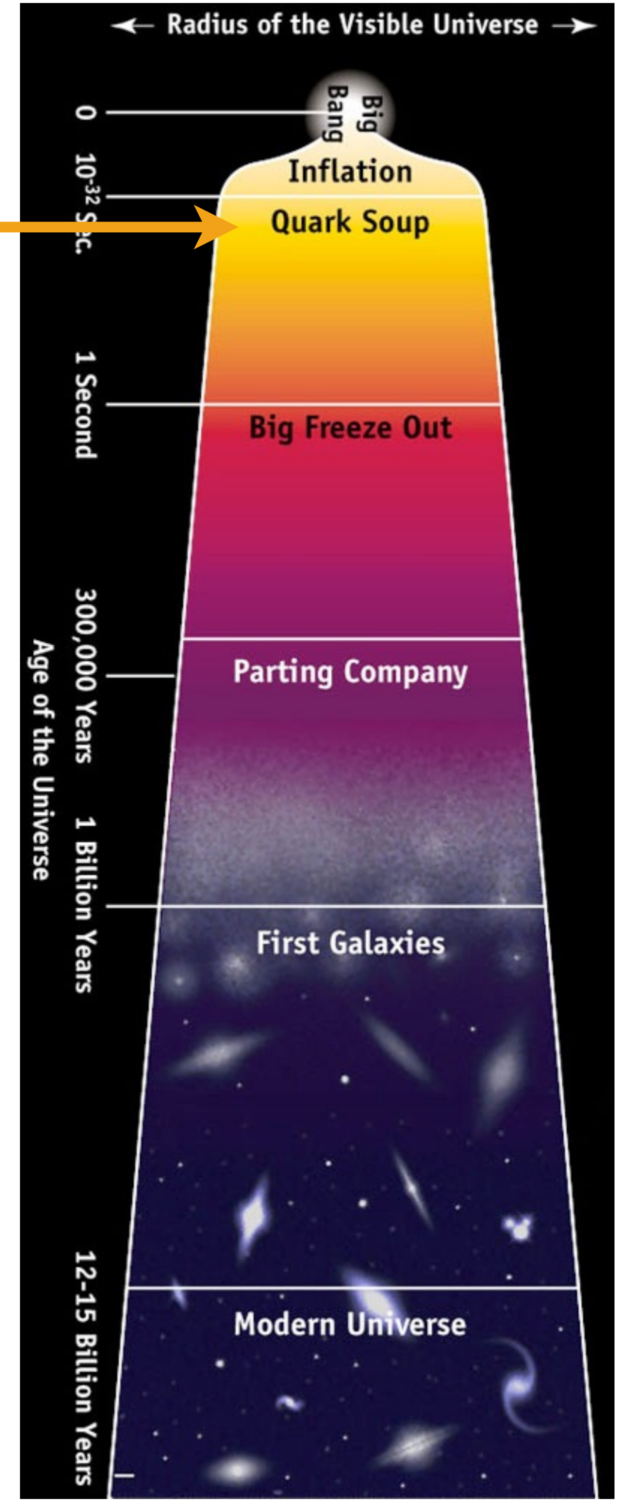
Quarks are free, floating around



Later, they are bound

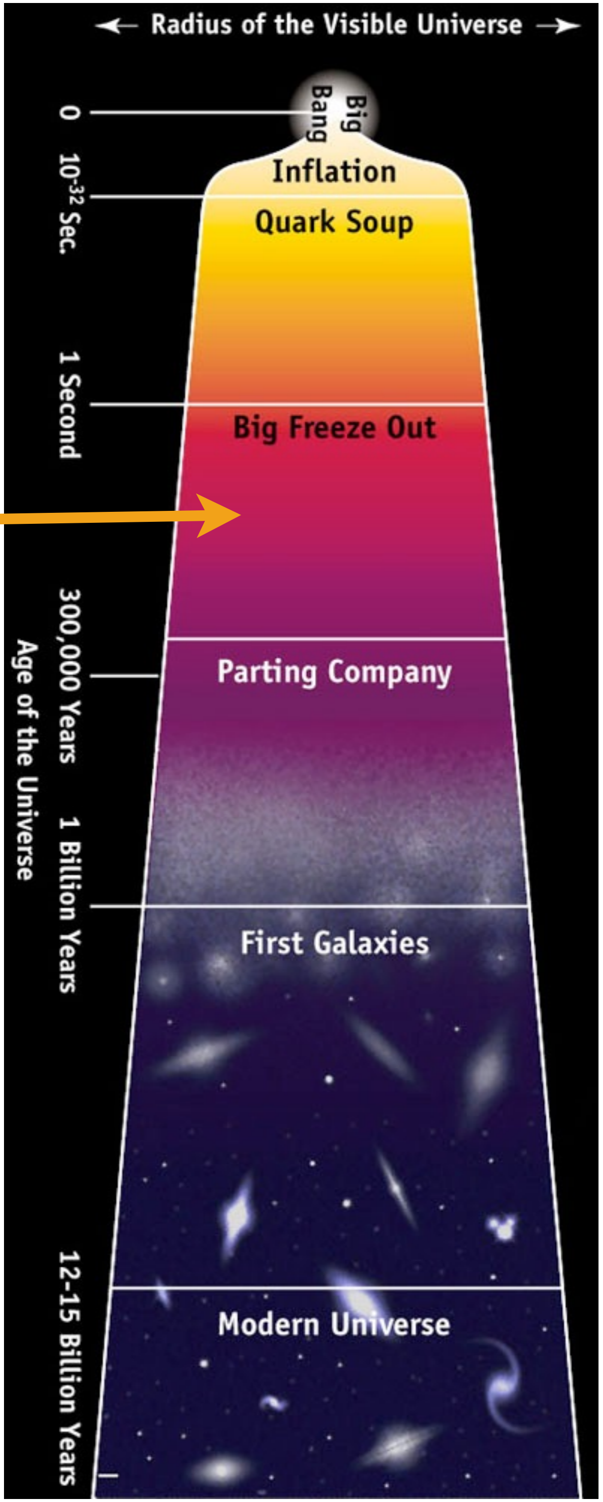


PROTON



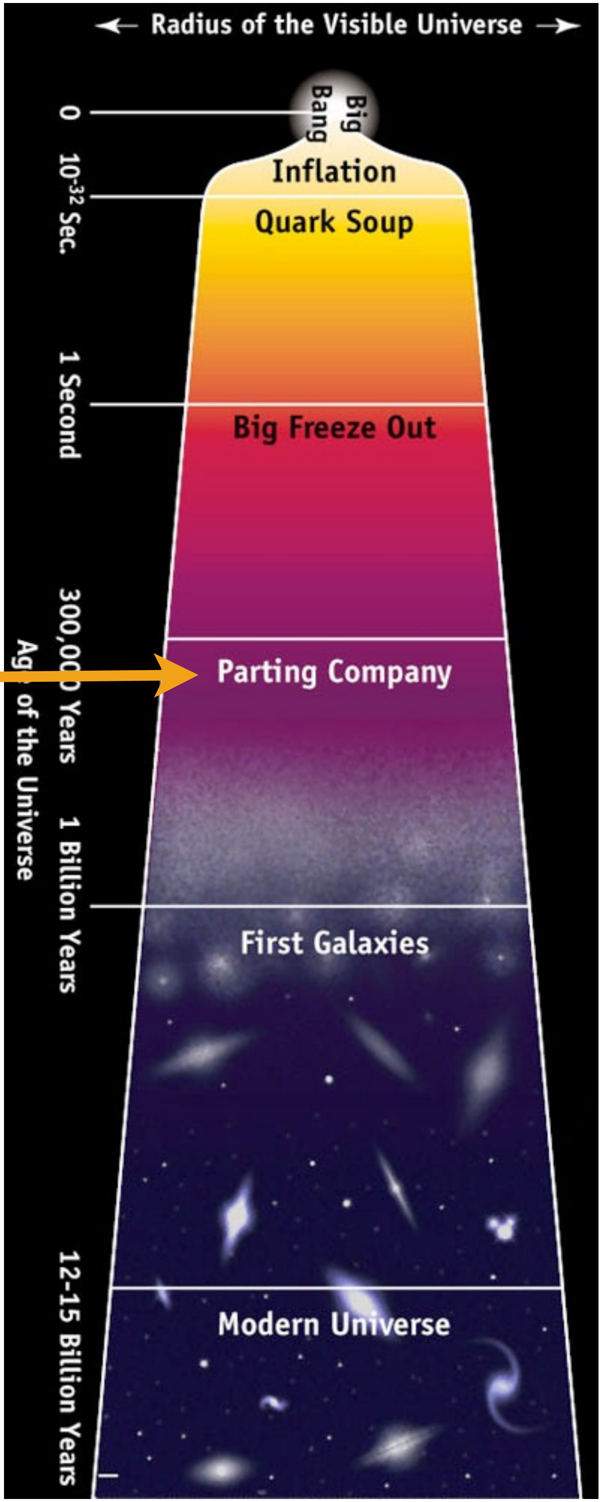
Nucleosynthesis (t=3 minutes)

- Nuclei form!
- ...out of neutrons, protons
- Hydrogen, Helium, small quantities of a few other light elements
- Universe is dominated by radiation (photons)
- Universe is still opaque - photons do not propagate far



Universe becomes transparent (t=300,000 yrs)

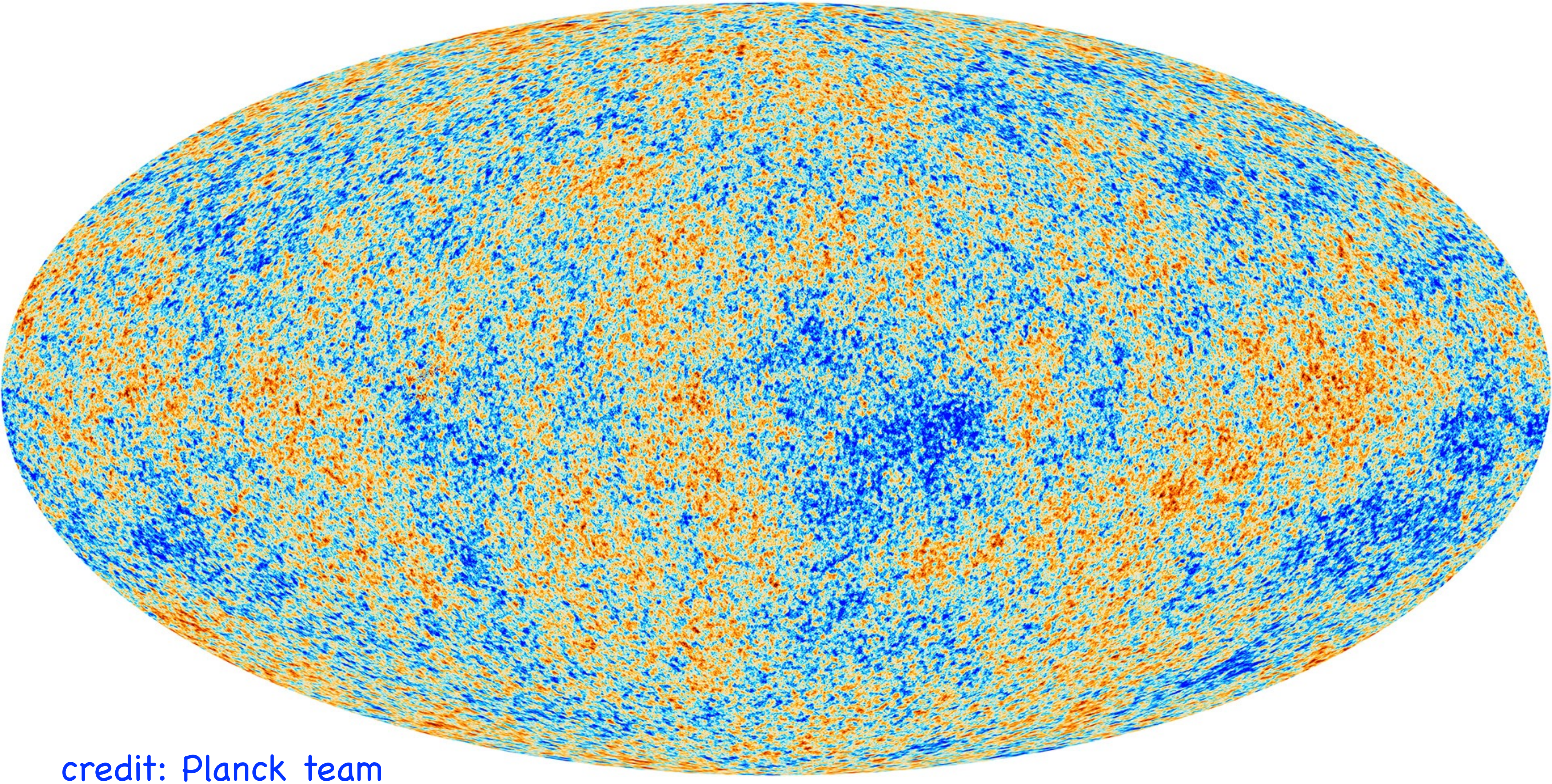
- Atoms form!
- ... electrons and nuclei combine
- Photons finally free to propagate - universe has rarified enough
- The Cosmic Microwave Background radiation we observe has been released at this time; Temperature today=2.725 Kelvin
- Uniform to one part in 100,000



T=2.726 Kelvin

Penzias & Wilson, 1965
Camden Hill, NJ
(Nobel Prize 1978)

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

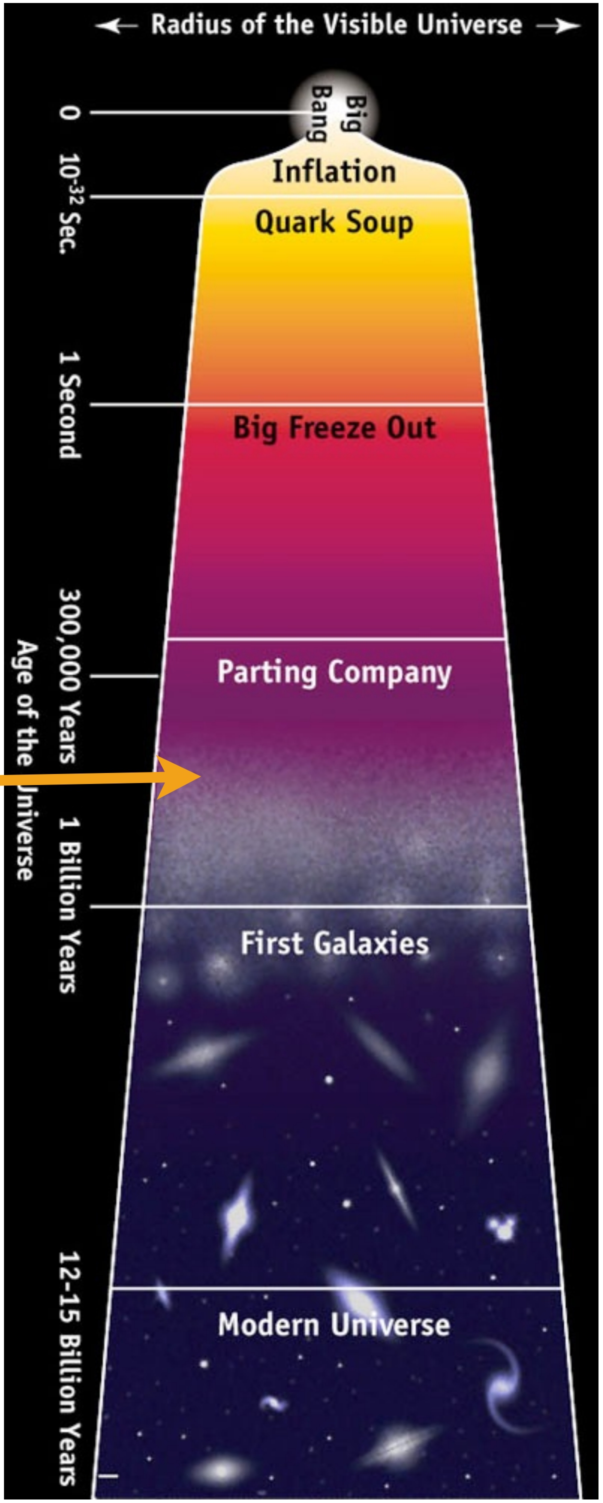


credit: Planck team

(Nobel Prize for discovery of fluctuations (in 1992): to COBE team members, in 2006)

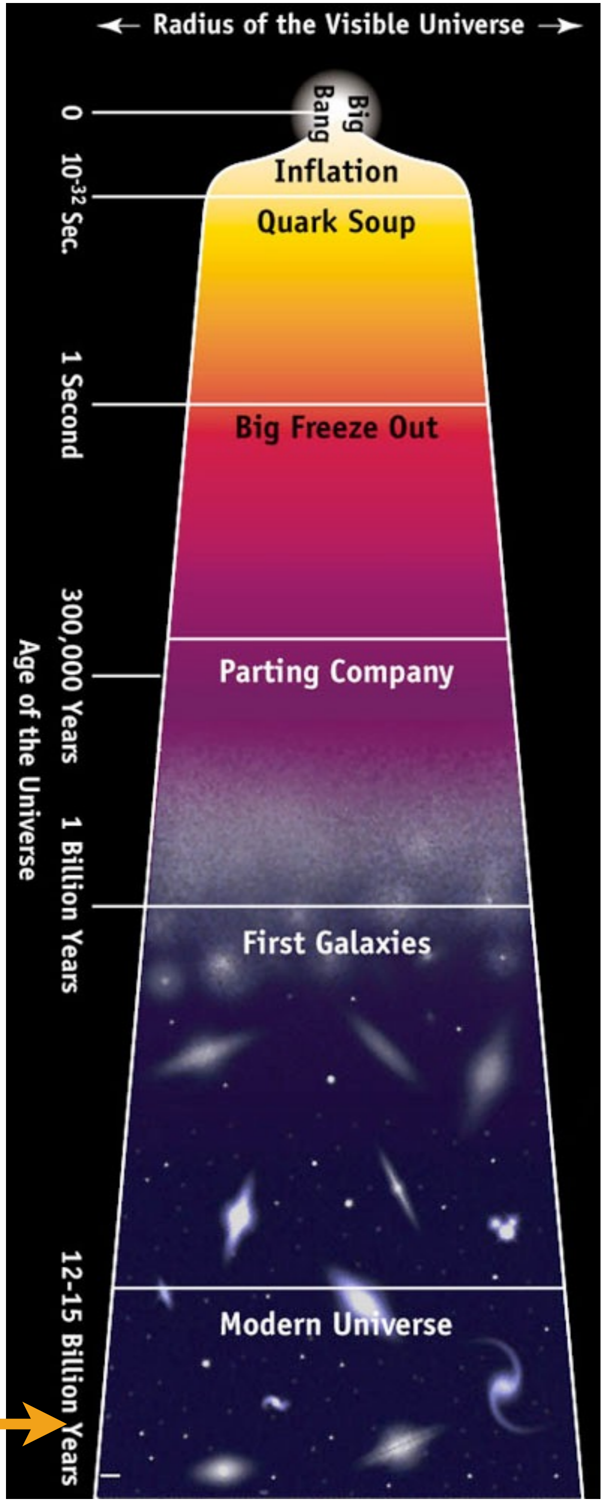
The dark ages
(t< 1 billion yrs)

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

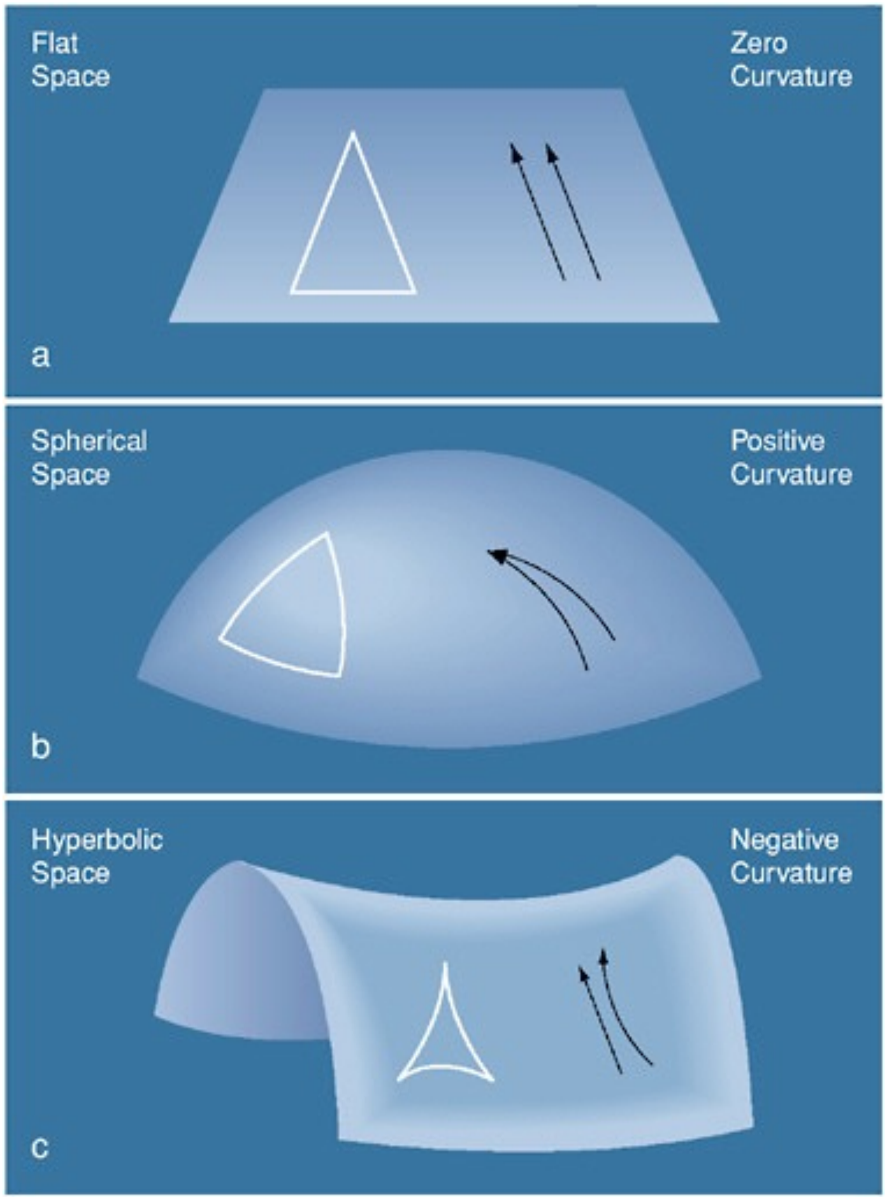


Modern Universe (t< 13.8 billion yrs)

- Stars, Galaxies, Clusters of galaxies everywhere
- Even more Dark Matter than we cannot directly see
- Universe is still matter dominated - or so we thought!
- A big surprise is in store!!



What is the geometry of space?

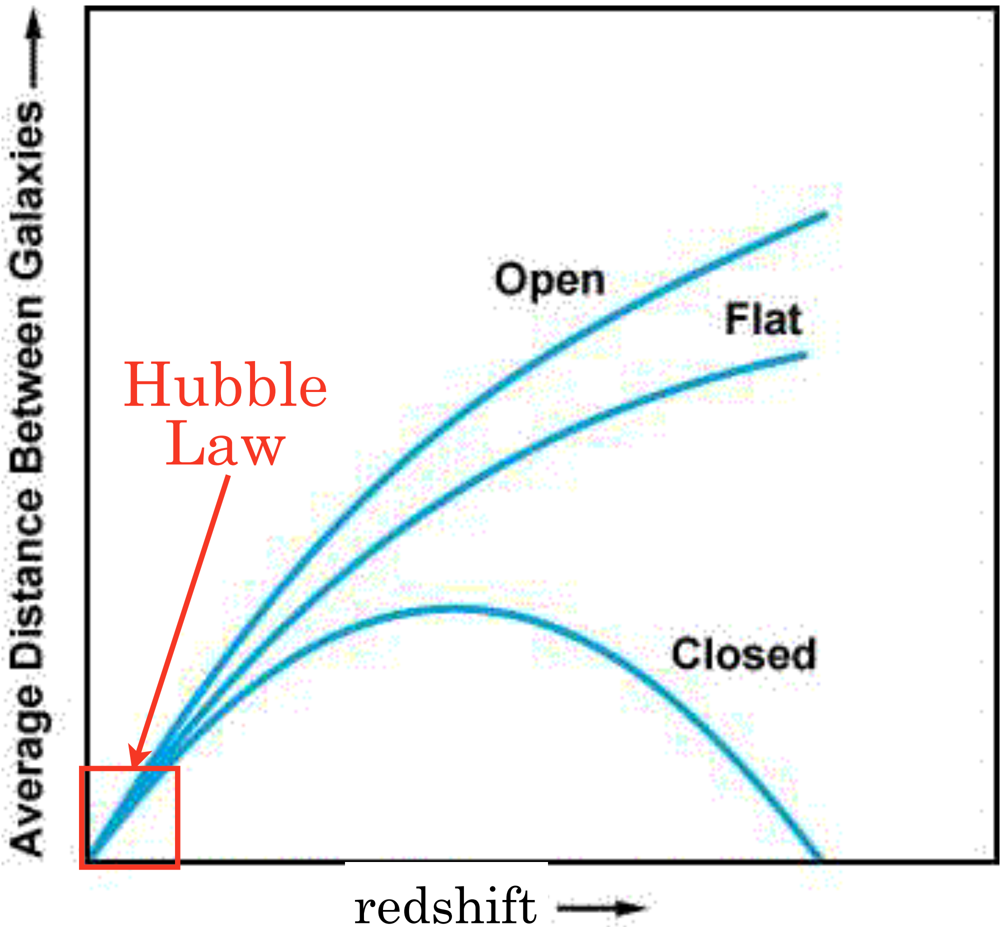


Flat (zero curvature)

Positively curved
("closed")

Negatively curved
("open")

By measuring distances in the universe, you can determine its **geometry**



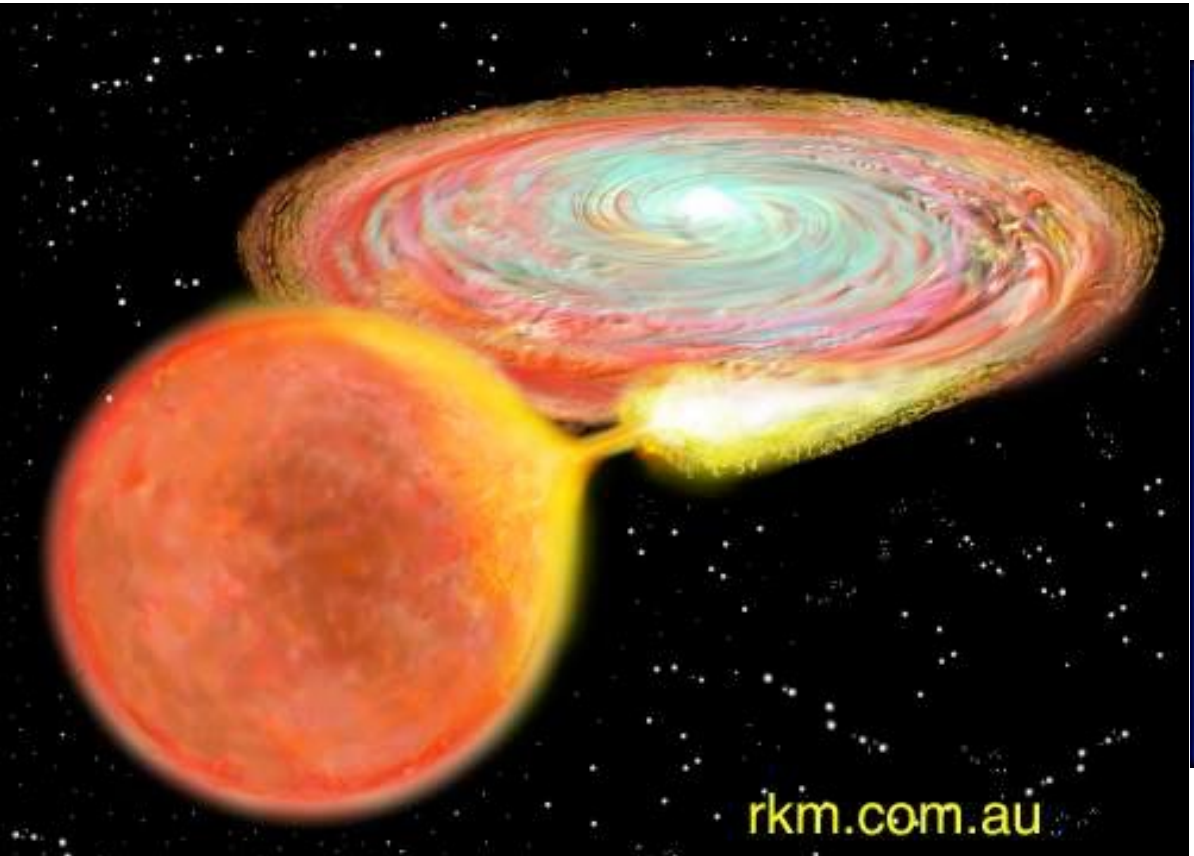
Problem:
distances in astronomy
are notoriously
hard to measure

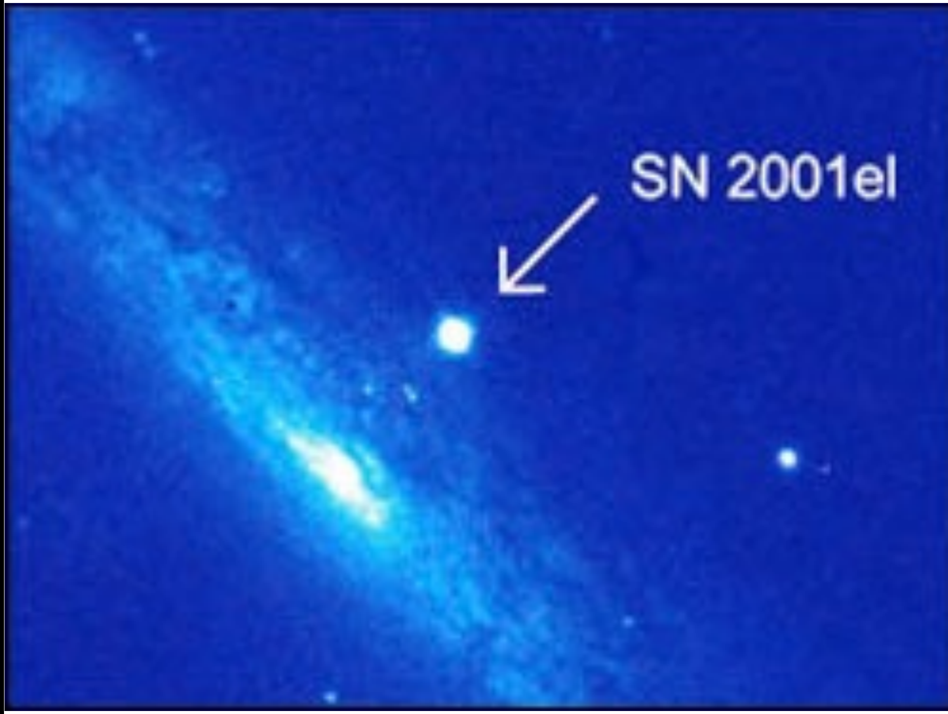
Type Ia Supernovae!

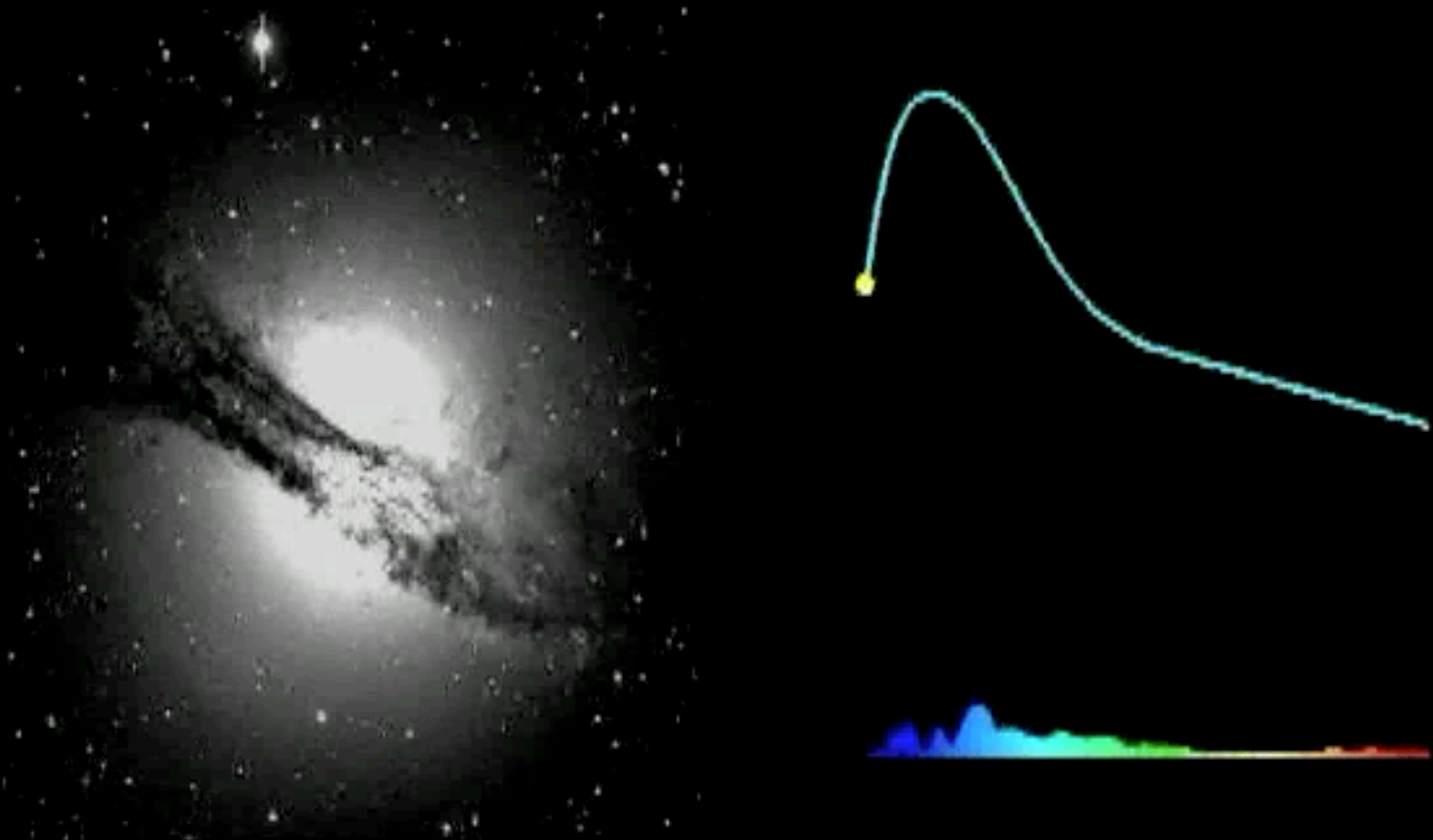
A white dwarf accretes matter from a companion.

Once the WD star's mass reaches a certain limit,
the star explodes

Each explosion yields (about) the same amount of energy/light
$\Longrightarrow$ **standard candle**







credit: Supernova Cosmology Project

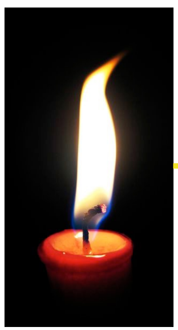
A “Standard Candle” analogy: Headlights of a Car

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

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

(f = flux
L = luminosity
d = distance)

Key property of SNe Ia:
Their intrinsic luminosity is (nearly) constant
$\Longrightarrow$ They are **standard candles**



flux ~ 1/distance^2

So, by measuring the flux, you can determine distance to supernova

And by measuring the shift of spectral lines, you can determine redshift of supernova

But how do you find SNe?

Rate: 1 SN per galaxy per 500 yrs!

Solution:

- use world's large telescopes,
- schedule them to find, then "follow-up" SNe
- heroic hard work by two teams of researchers

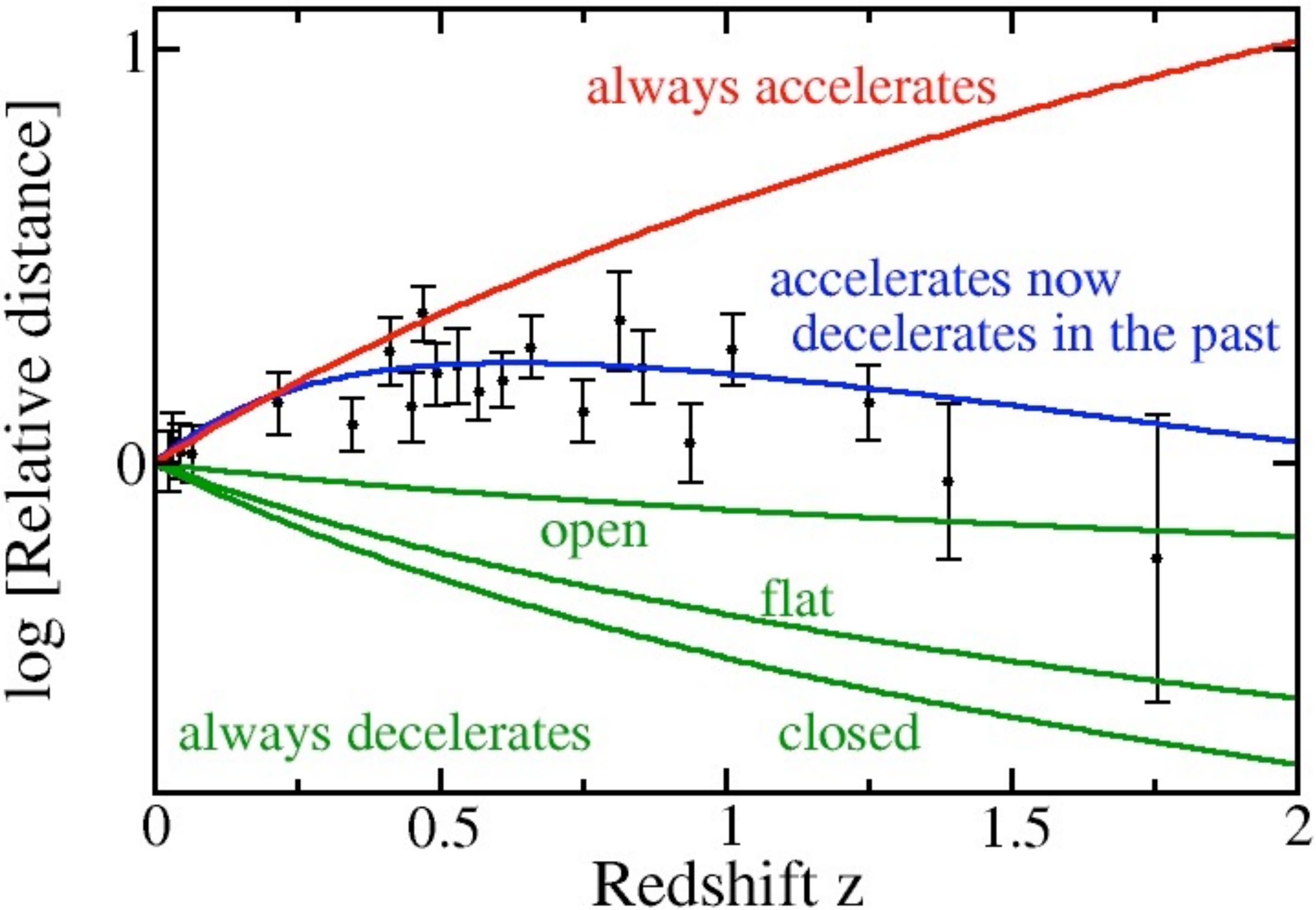
Nobel Prize in Physics 2011

Adam Riess
Johns Hopkins University

Saul Perlmutter,
Lawrence Berkeley Lab

Brian Schmidt,
Australian National Univ.

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



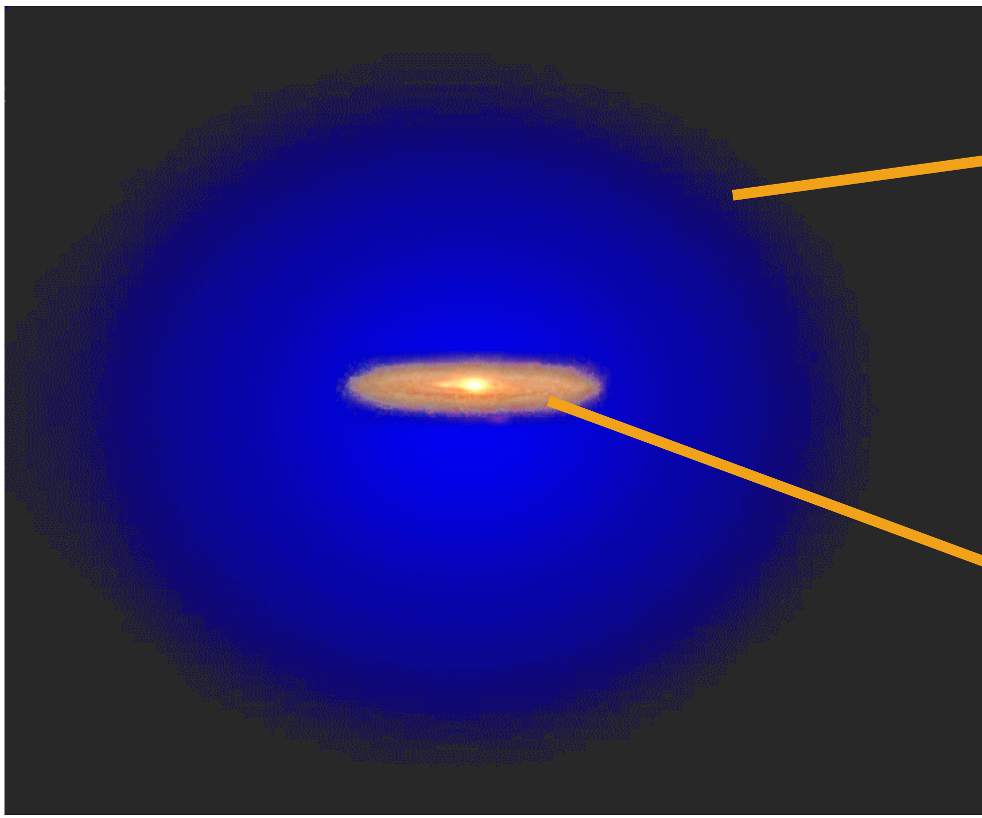
Matter only cases

Dr. Michael Turner
University of Chicago

Dark Energy

- Universe is dominated by something other than dark matter
- This new component - “dark energy” - makes the universe expand faster and faster (i.e. slower as we look in the past)
- This new component is 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

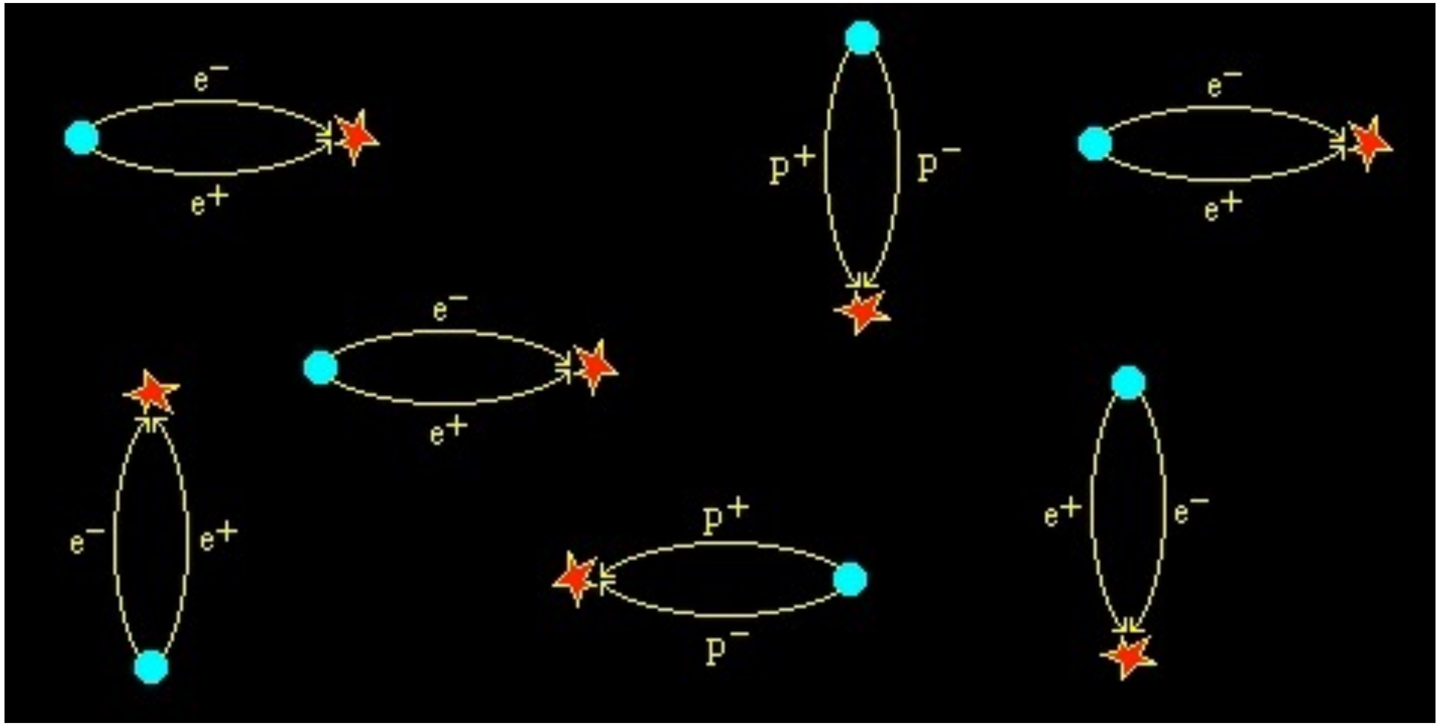
Dark Matter ≠ Dark Energy

Facts about DE

- DE is smooth
- DE pushes things (galaxies) apart
- DE energy *density* approximately constant - double the volume, double the energy (for matter, double the volume, energy stays the same)
- $\Rightarrow$ Verifying whether this is true is at forefront of measurements in cosmology
- DE is only noticeable at recent times (ie. low redshifts), and completely subdominant in early univ.
- DE slows down the growth of structure

A Candidate: Vacuum Energy

Quantum Physics says:
"empty space" is filled with particles and antiparticles getting created and annihilated



Mystery #1

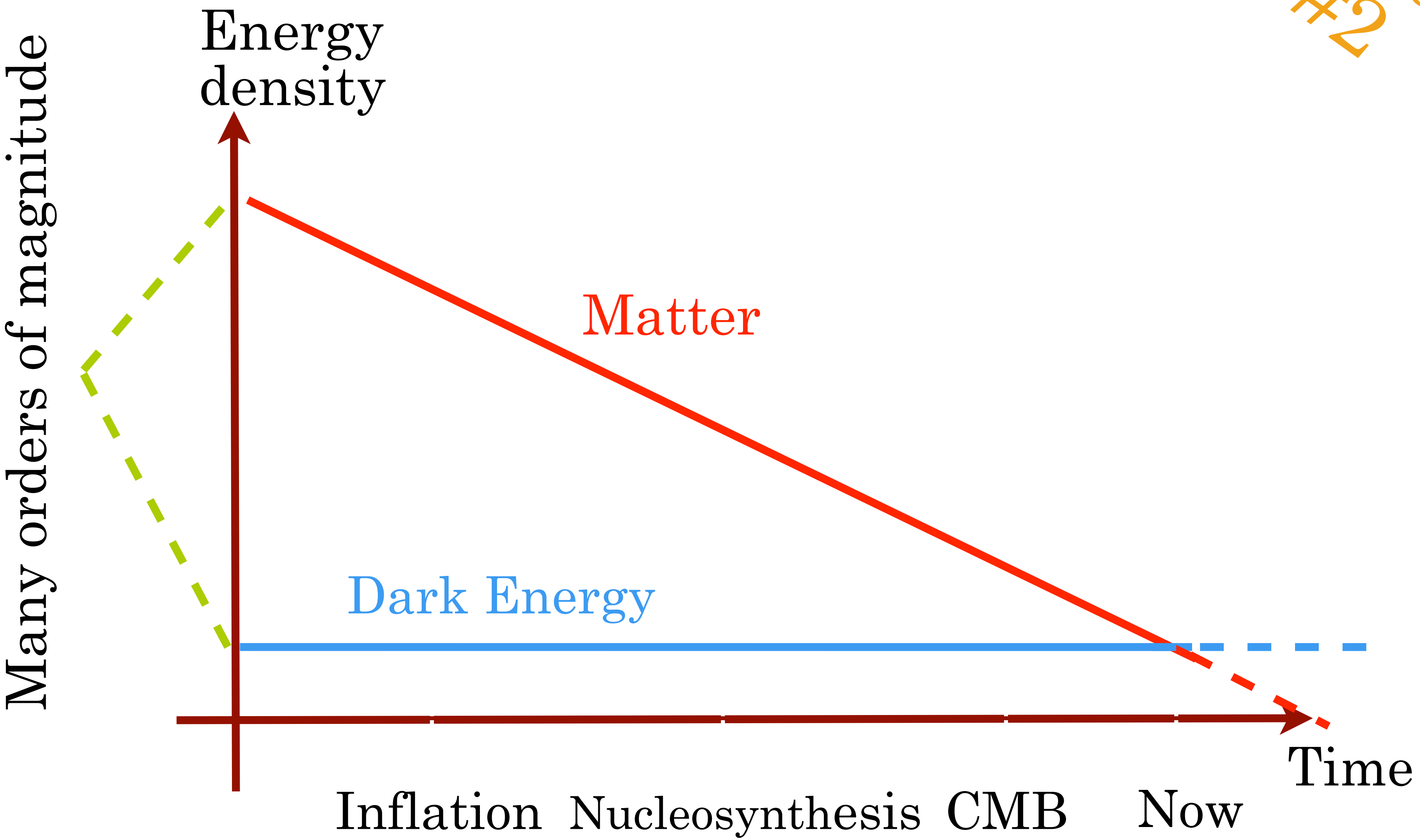
Theoretical prediction for vacuum energy

A straightforward calculation using quantum mechanics gives
100,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000
(or 10^{120}) times more than the observed amount

This is known as the
COSMOLOGICAL CONSTANT PROBLEM

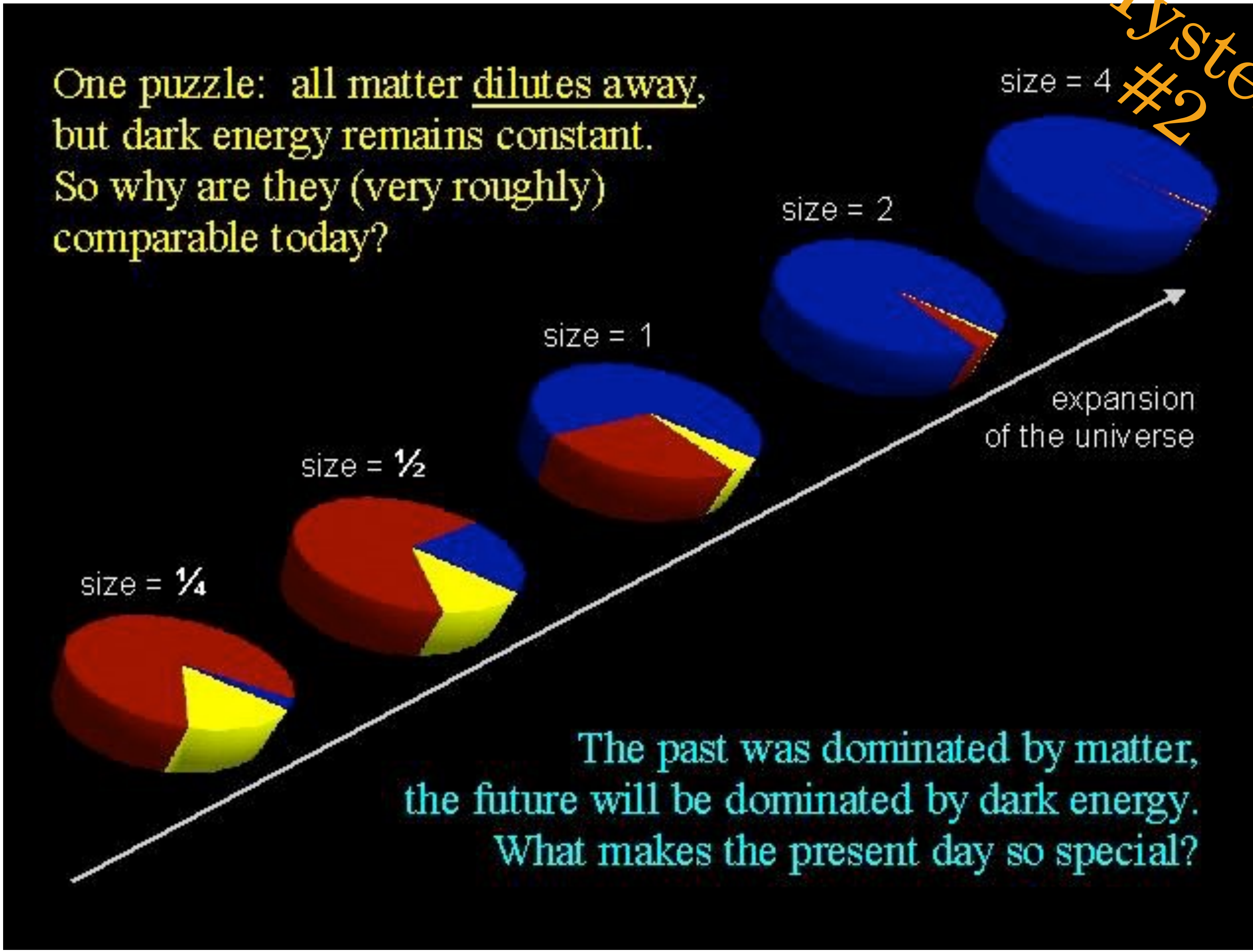
“Why Now!?”

Mystery #2



This is known as the COINCIDENCE PROBLEM

Mystery #2



credit: Sean Carroll

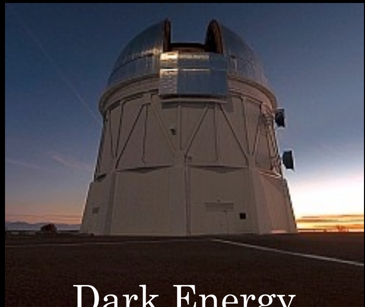
What is dark energy?

- Is it vacuum energy?
- Is it modification of Einstein's theory of gravity?
- Is it a (funny) fluid that fills up universe?
- Or is it something else - completely, utterly unexpected?

(Bizarre) Consequences of DE

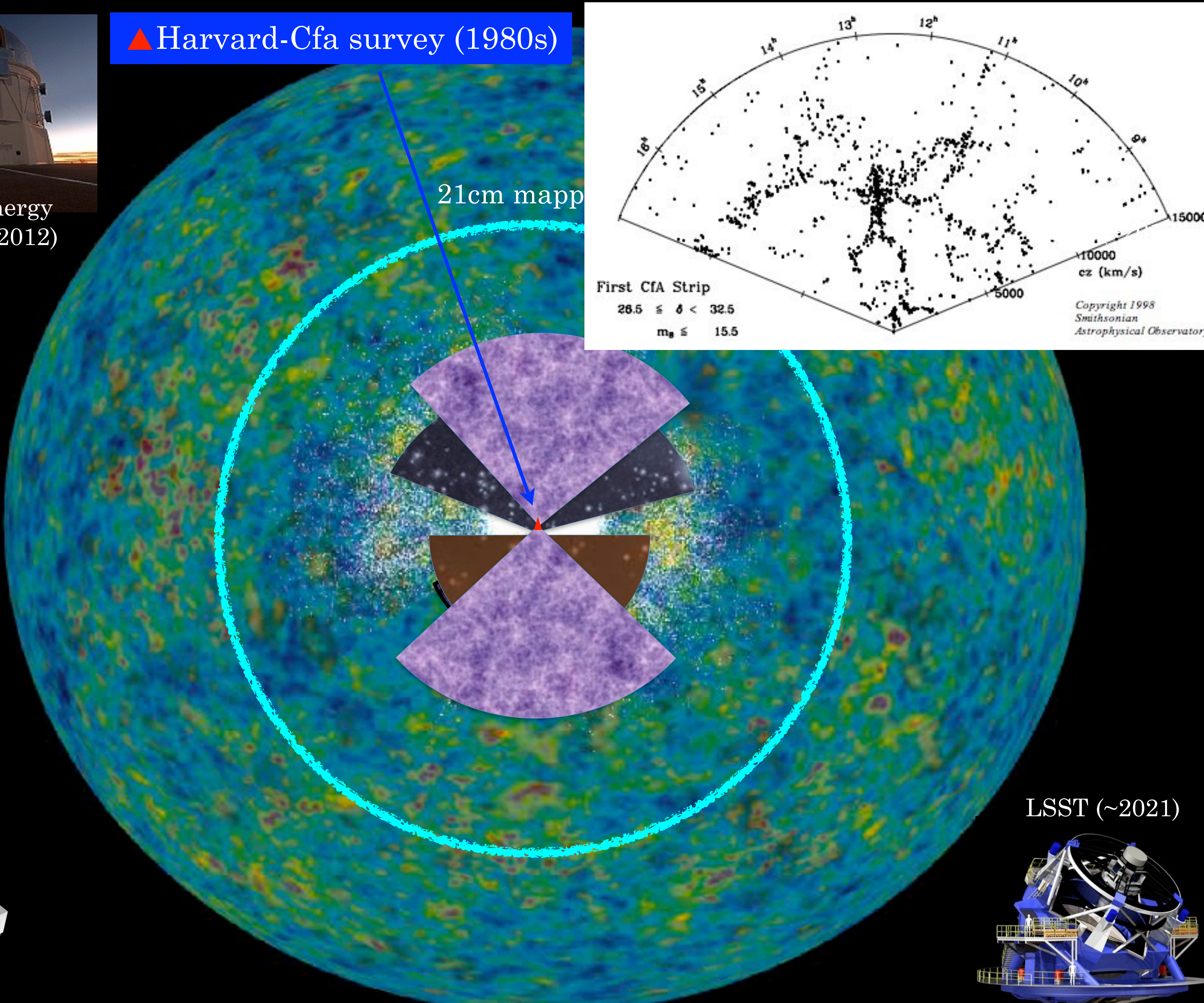
- In the accelerating universe, galaxies are leaving our observable patch $\Longrightarrow$ the sky will be empty in 100 billion years!

- In particular, under certain circumstances we will have a Big Rip - galaxies, stars, planets, our houses, atoms, and then the fabric of space itself will rip apart!

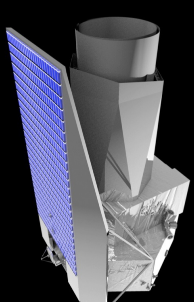


Dark Energy Survey (2012)

Harvard-Cfa survey (1980s)



Euclid and WFIRST (~2027)



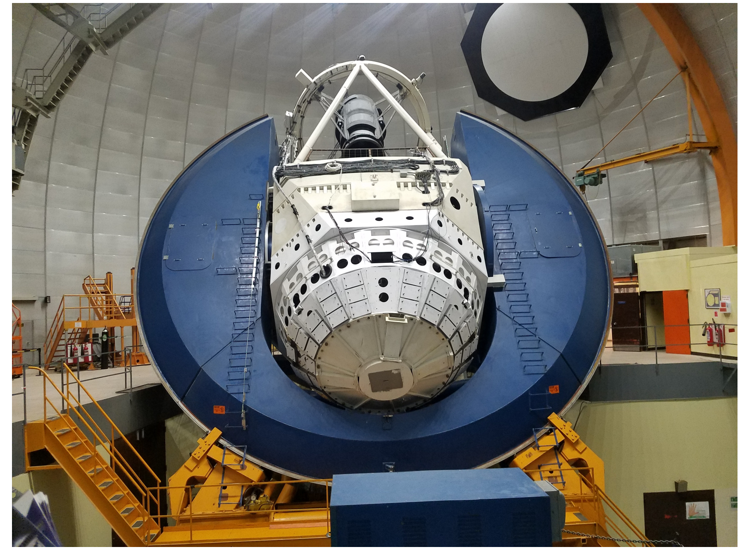
LSST (~2021)

Dark Energy Survey

- New camera on 4m telescope in Chile
- Observations 2013-2019
- ~700 scientists worldwide
- Analyses in progress (first major results Aug 2017)

Dark Energy Survey (DES)

Cerro Tololo, Chile



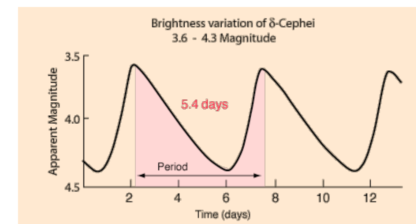
Blanco Telescope

Breaking news:

Hubble tension!

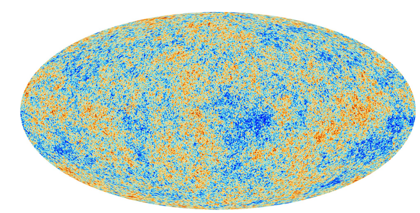
Type Ia supernovae + Cepheid distances give

$$H_0 = 74.0 \qquad \text{(km/s/Mpc)}$$



Cosmic Microwave Anisotropies give

$$H_0 = 67.0 \qquad \text{(km/s/Mpc)}$$



These two measurements are about five standard deviations (quoted errors) apart

$\Longrightarrow$ discrepant at 99.99997% confidence

The hottest topic in cosmology in past couple of years:

Is Hubble tension due to new physics?
[e.g. unusual, new behavior of dark energy]

Dark matter and dark energy are here to stay, but this may be evidence for e.g. unusual, new behavior of dark energy

There is worldwide effort by

- cosmology **theorists** to better understand the sources of this tension and
- cosmology **experimentalists** to better measure H_0 using a variety of methods

Conclusions

1. Universe is expanding $\Longrightarrow$ it was smaller in the past, it started with a Big Bang

2. Dark Energy $\Longrightarrow$ universe is accelerating, worldwide effort to understand/measure better

3. Hubble tension $\Longrightarrow$ discrepancy in measurements of H0 by two trusted methods, may indicate a major new discovery!

Talk available at
http://www-personal.umich.edu/~huterer/activities.html