Dark Energy and the Accelerating Universe

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University of Michigan

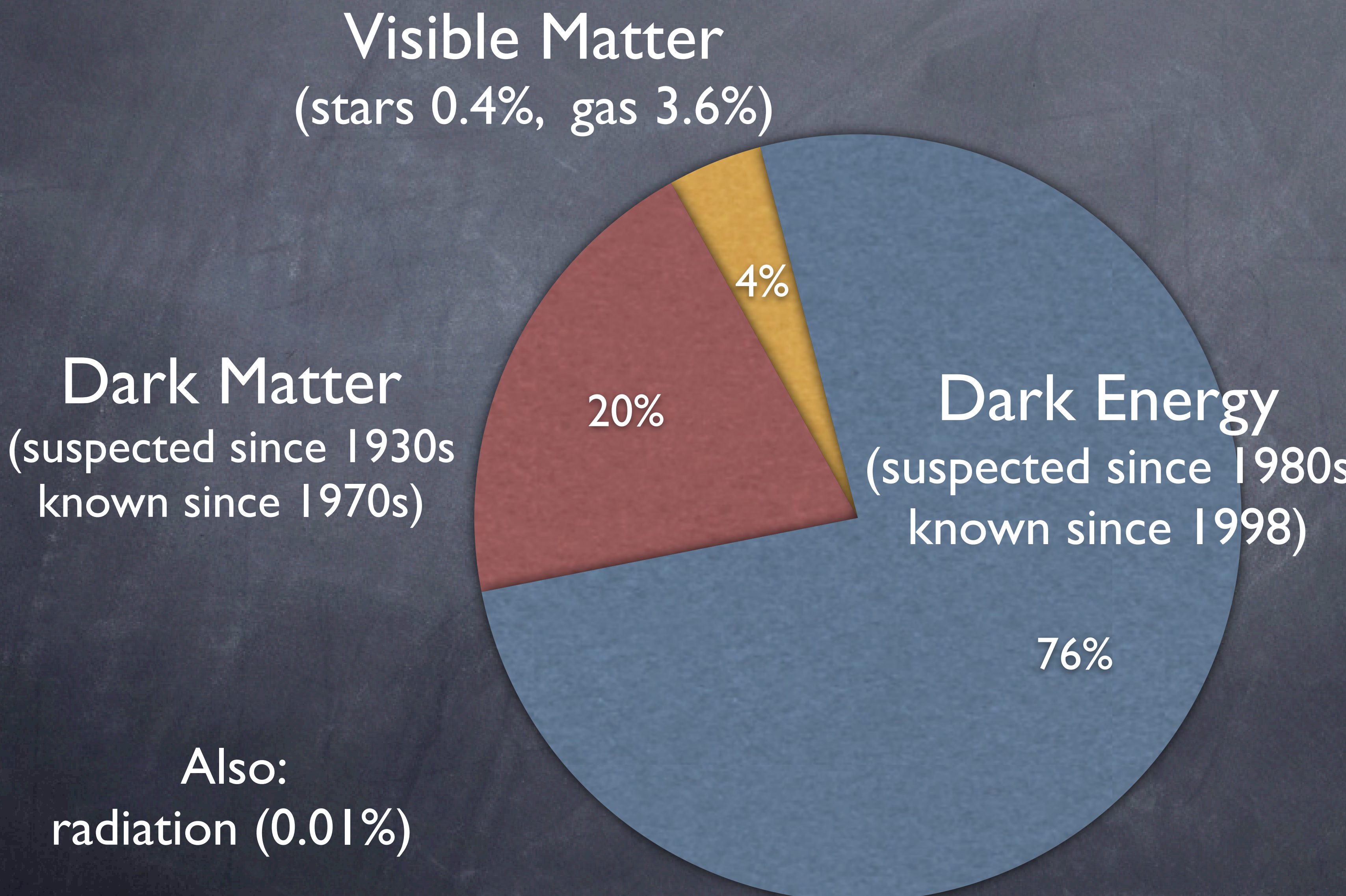
The universe today presents us with a grand puzzle:

What is 95% of it made of?

Shockingly, we still don't know.

But we are getting closer to the answer.

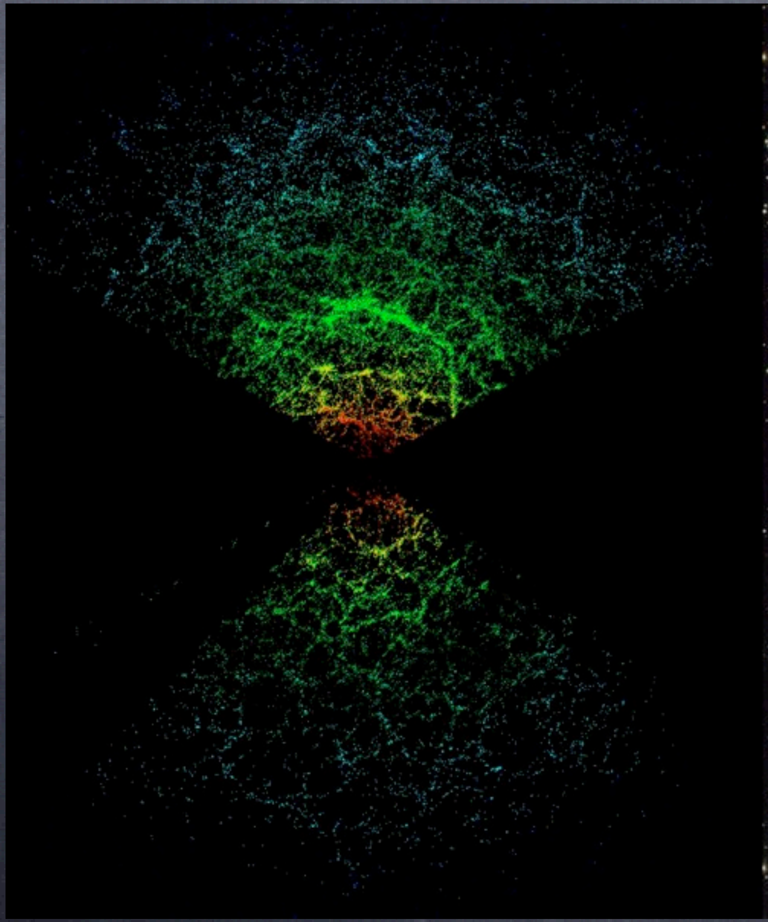
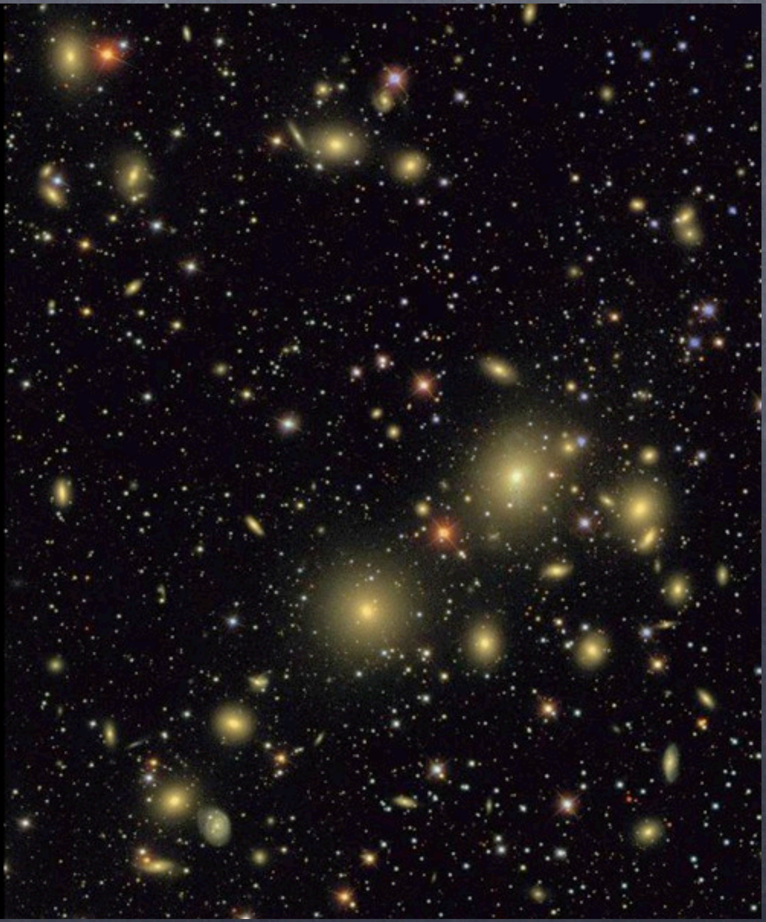
Makeup of universe today



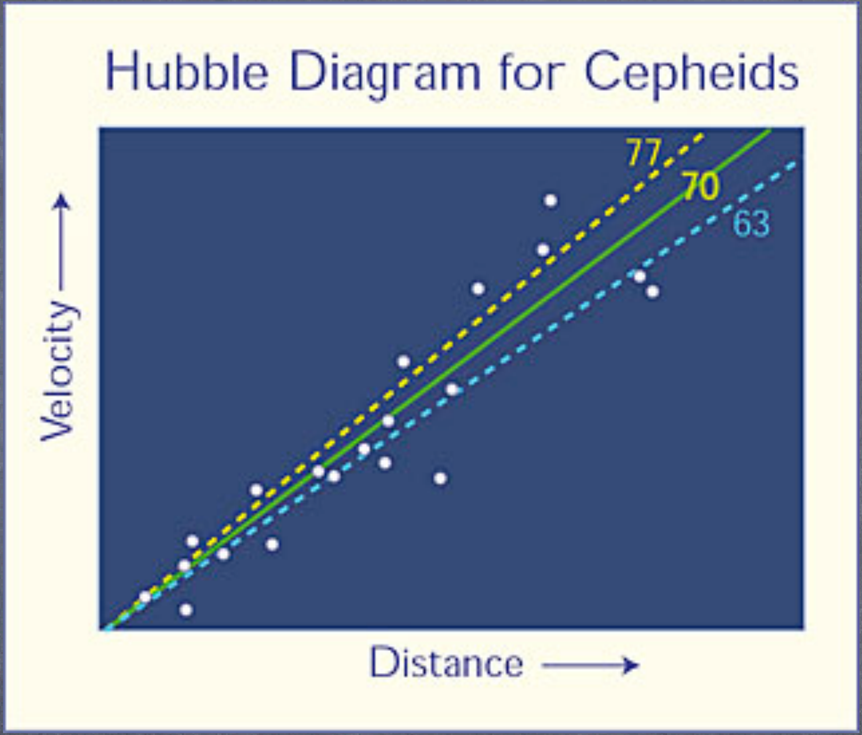
Also:
radiation (0.01%)

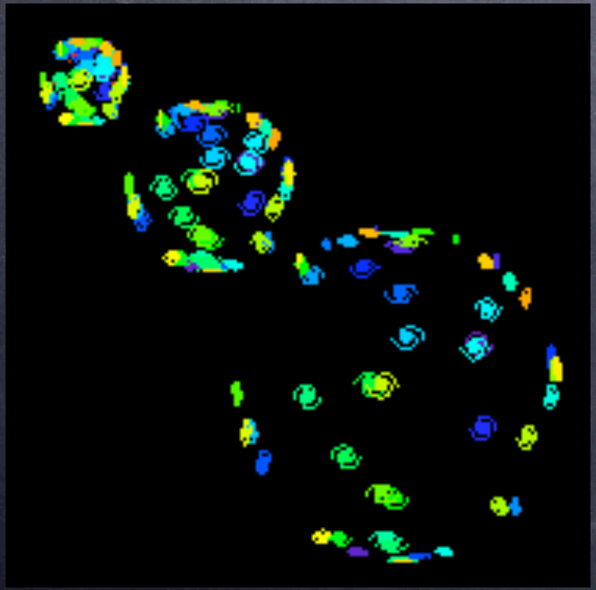
The universe is homogeneous and isotropic

- Homogeneous: appears the same everywhere in space
- Isotropic: appears the same in every direction

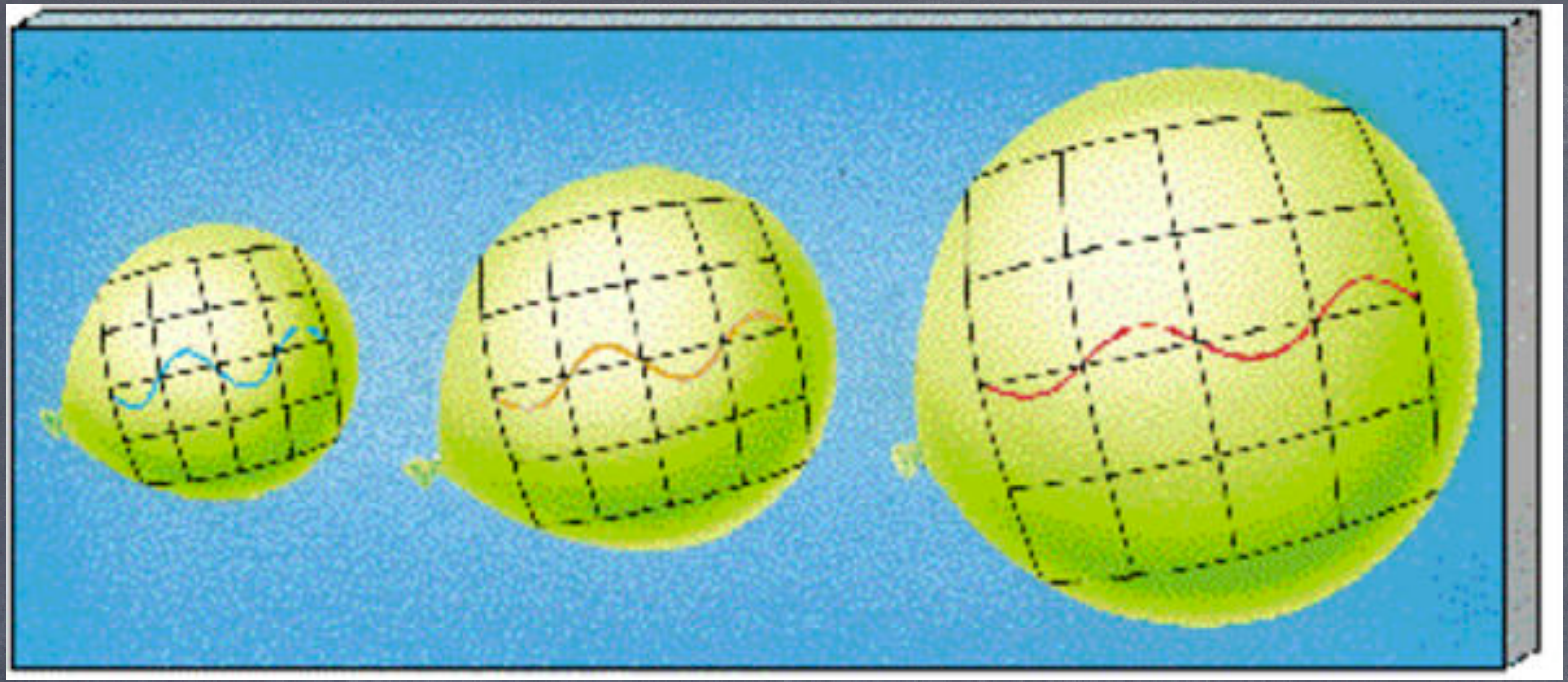



The universe is expanding!



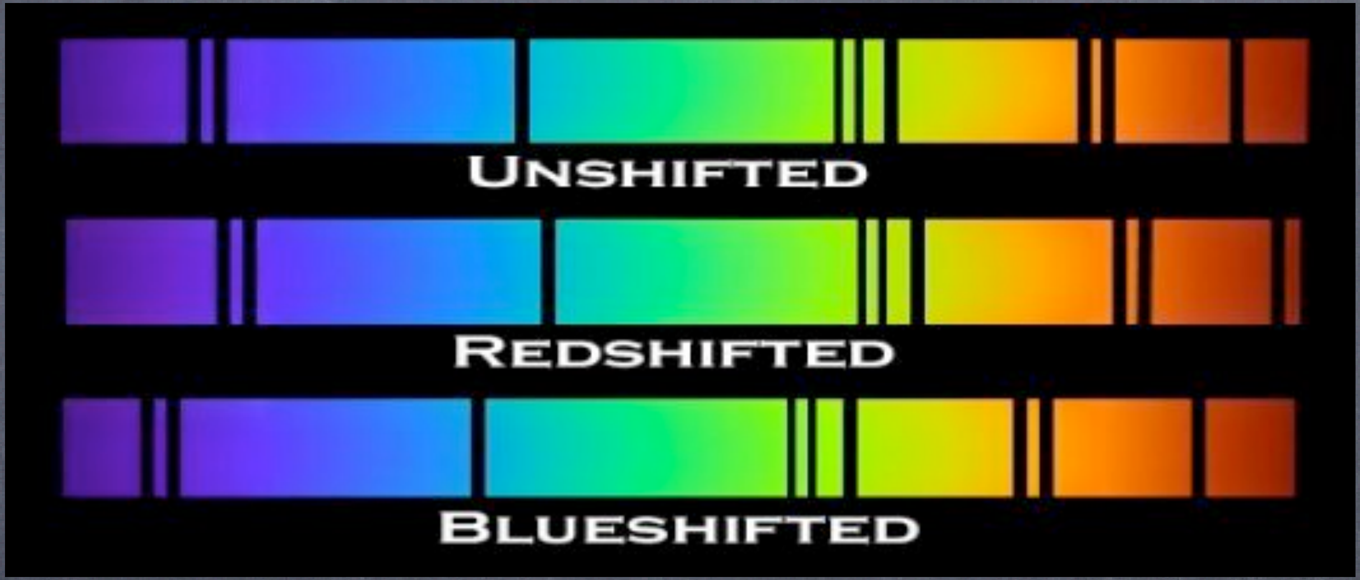


Edwin Hubble



- Expansions dilutes the matter particles; double the volume, halve the matter density
- Expansion stretches wavelength of radiation -> the radiation "redshifts"

Redshift



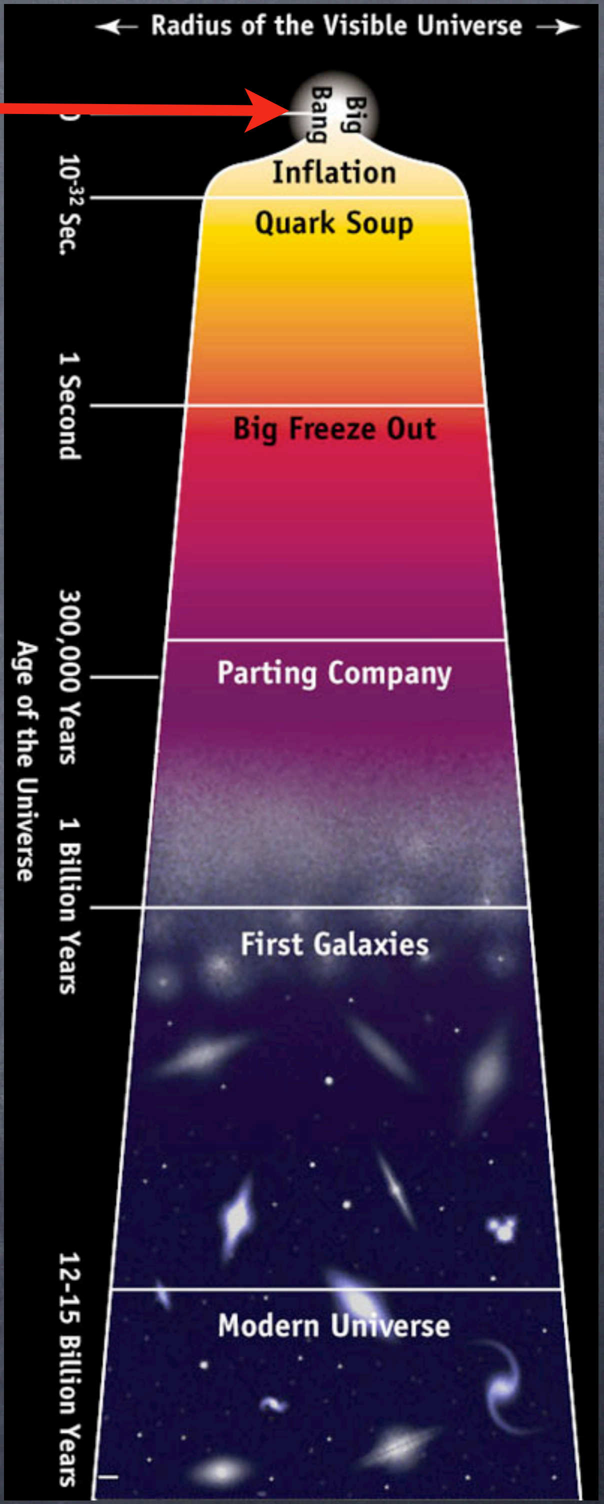
1+redshift = (size of universe now) / (size of universe when light was emitted)

History of the universe from t=0 to t=13.7 Gyr

A Brief Overview...

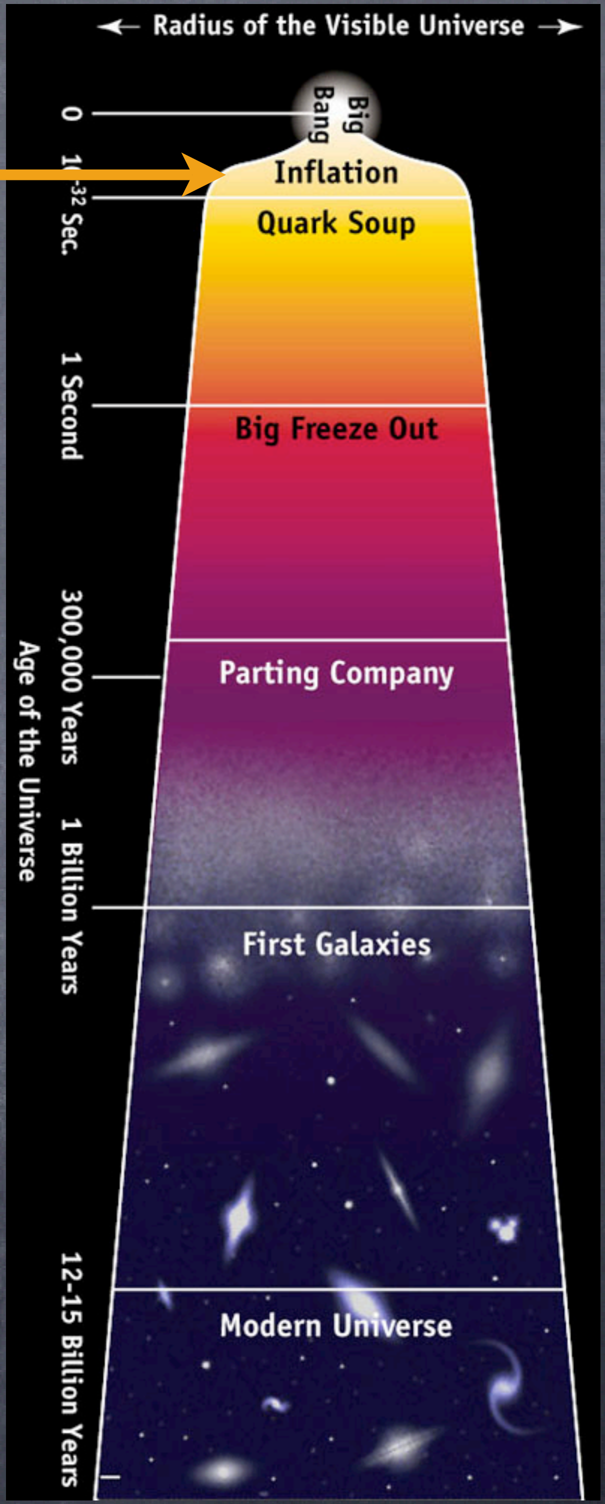
Big Bang (t=0)

- 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?"



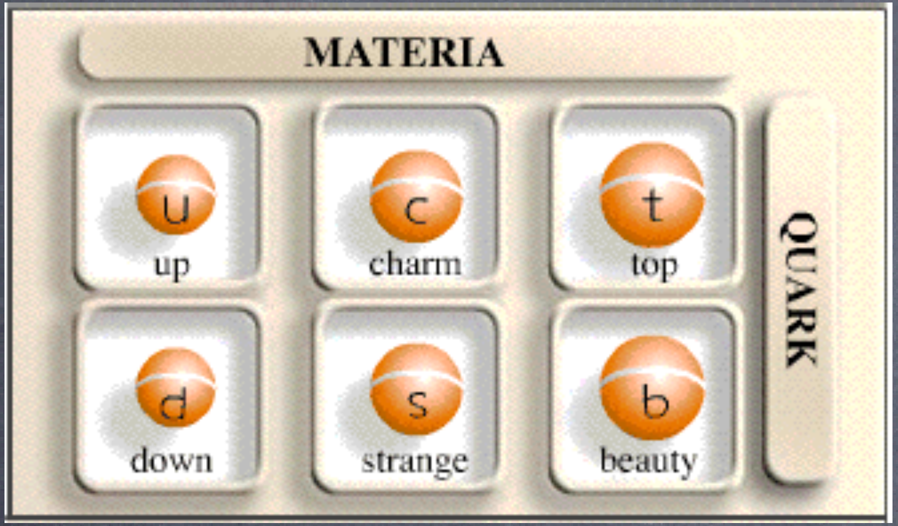
Very early Universe
(t=tiny moments after BB)

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

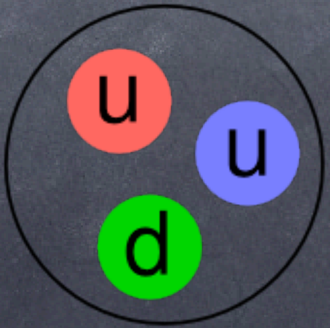


Quark Soup
(t<1 sec)

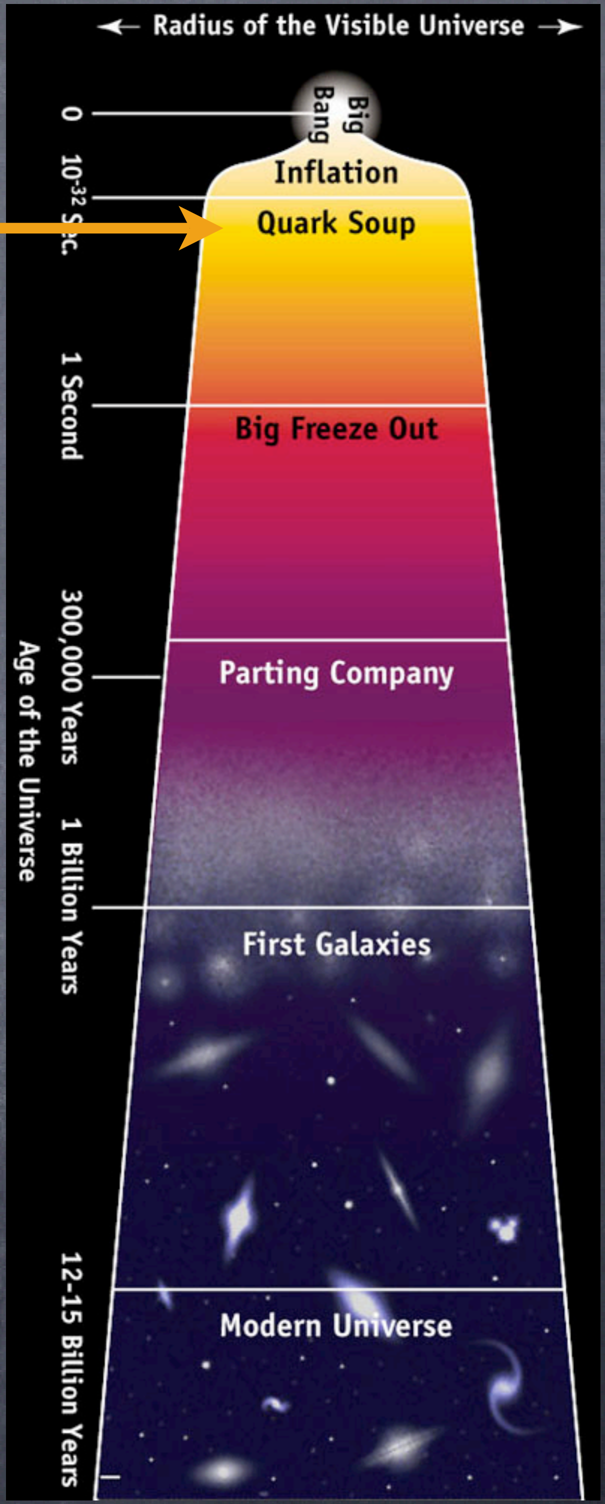
Quarks are free, floating around



Later, they are bound

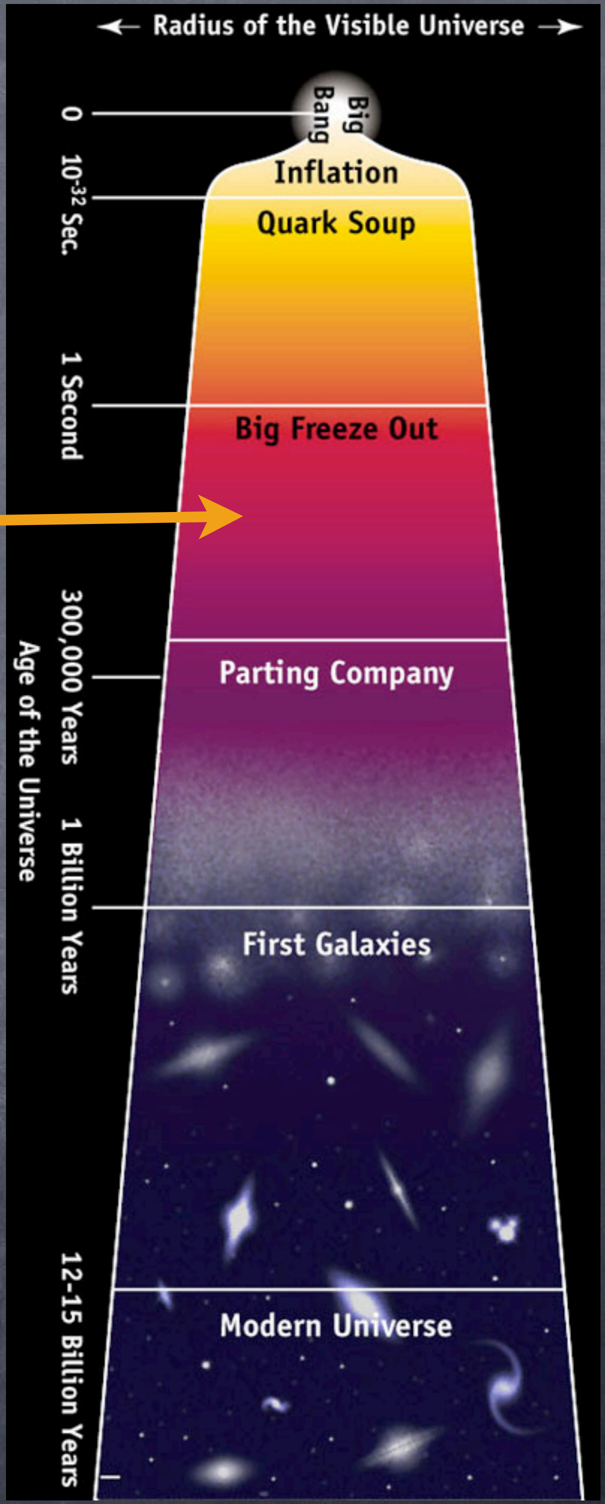


PROTON



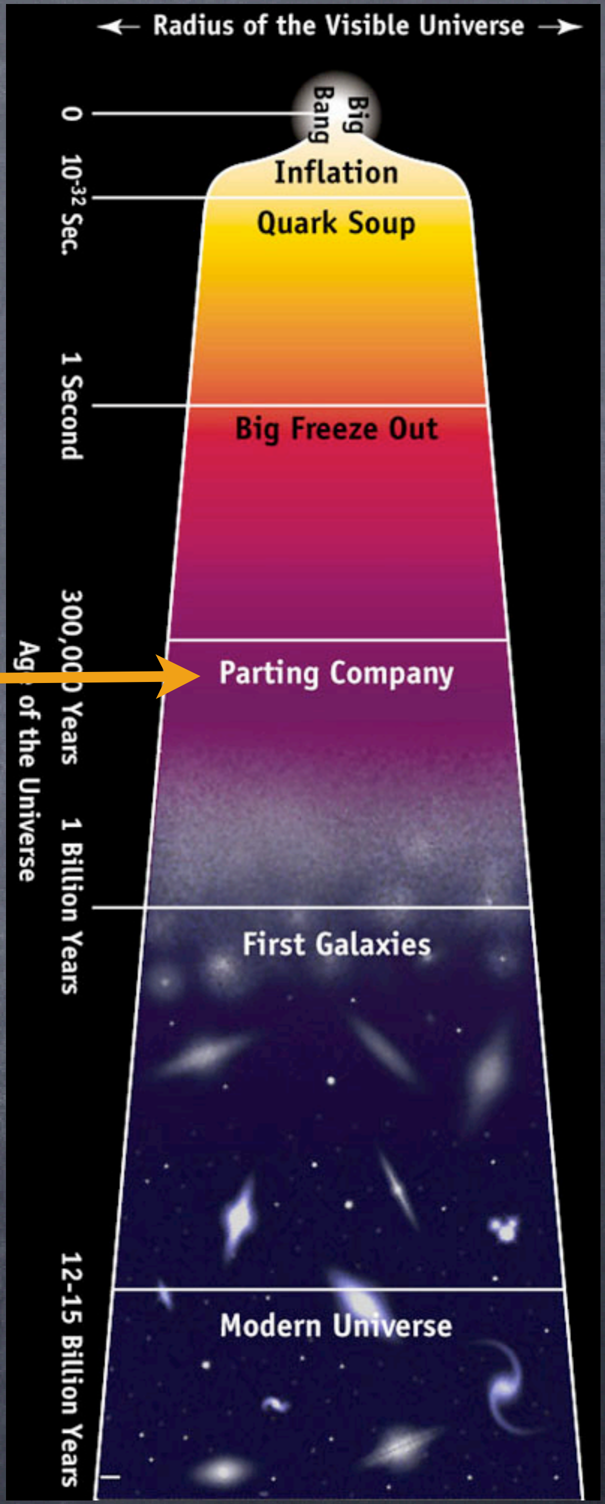
Nucleosynthesis (t=3 minutes)

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



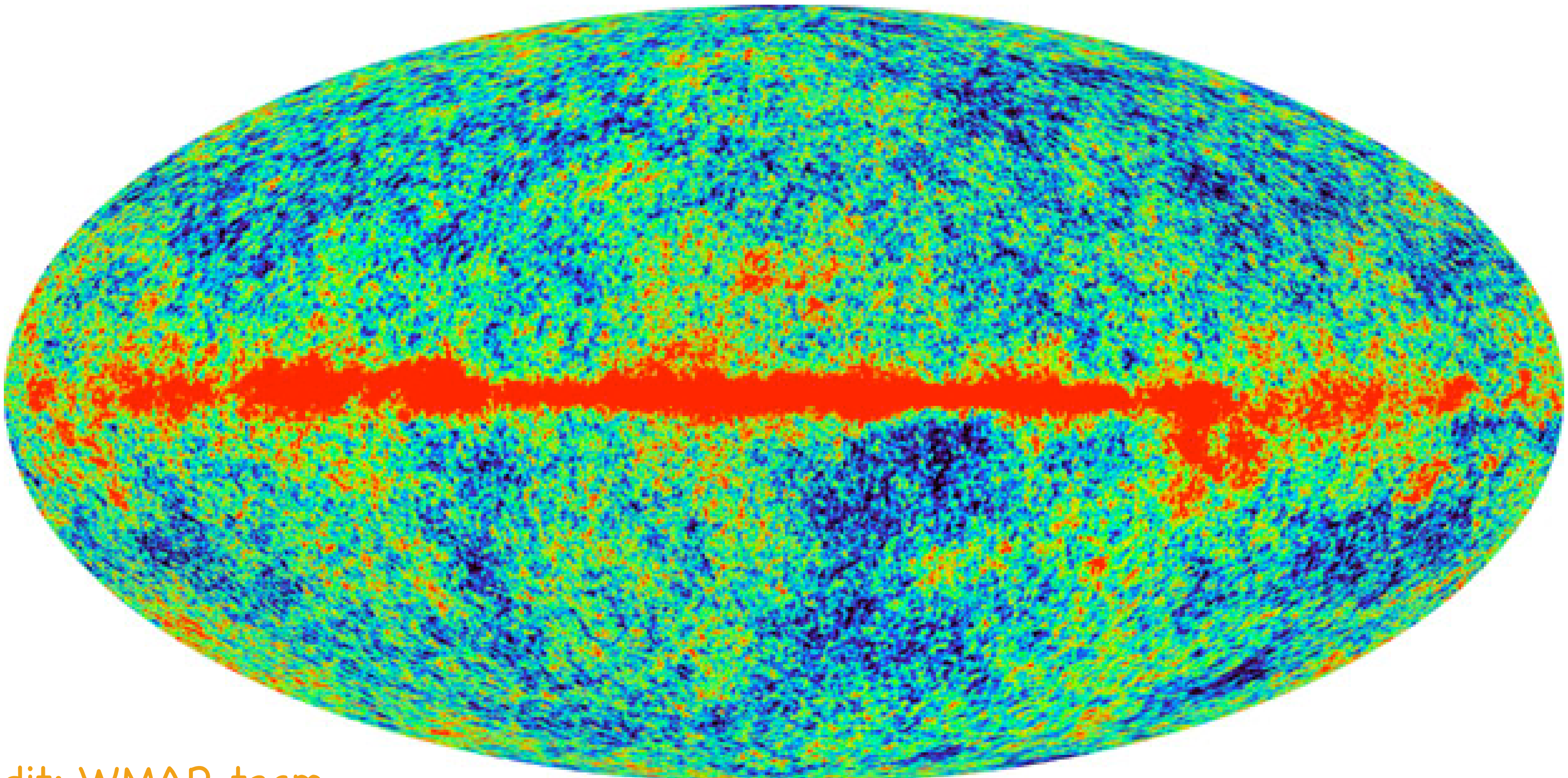
Universe becomes transparent (t=300,000 yrs)

- Universe is now matter dominated
- Radiation finally free to propagate - universe has rarified enough
- The Cosmic Microwave Background radiation we observe has been released at this time; Temp=2.725 Kelvin
- Uniform to one part in 100,000



T=2.726 Kelvin

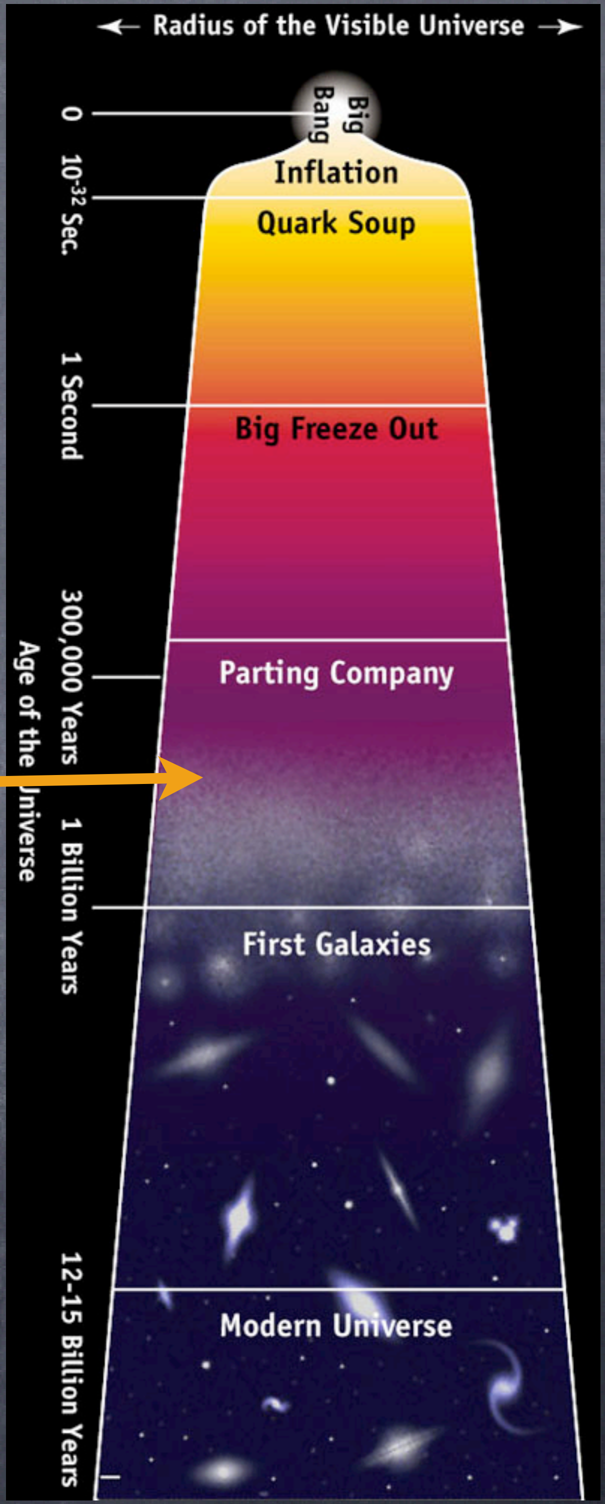
Fluctuations 1 part in 100,000 (of 2.726 Kelvin)



credit: WMAP team

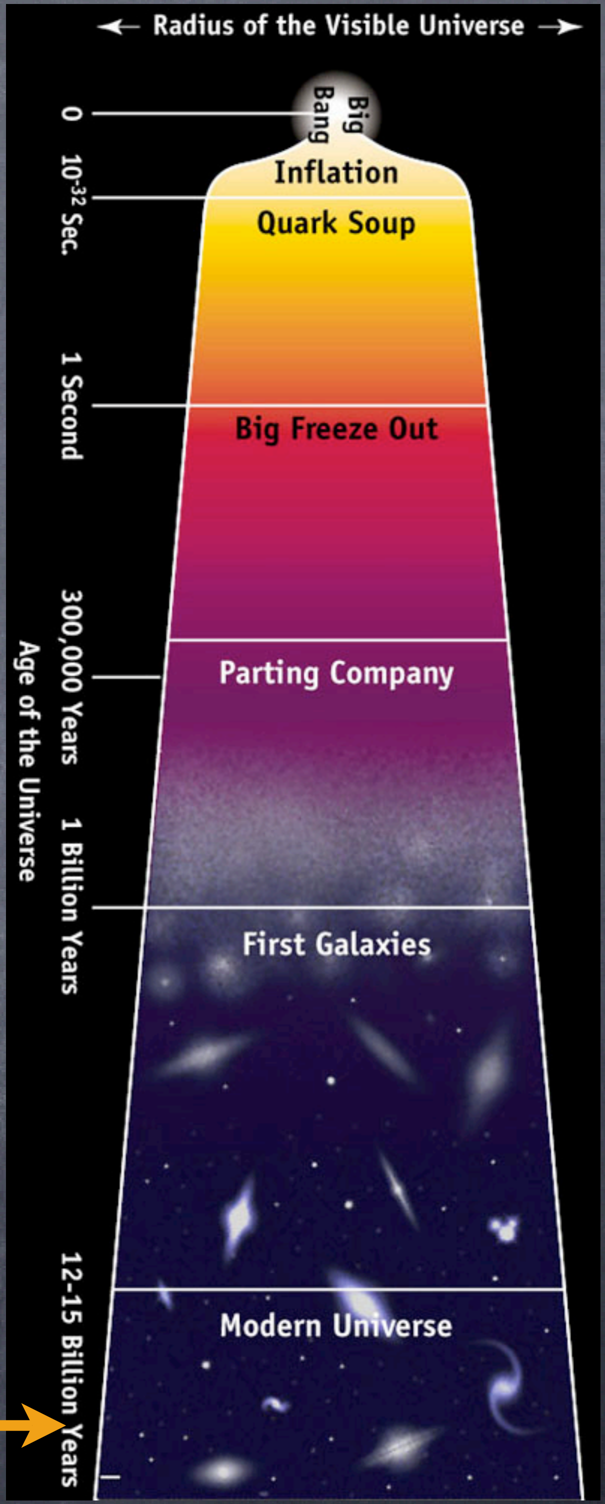
The dark ages (t< 1 billion yrs)

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

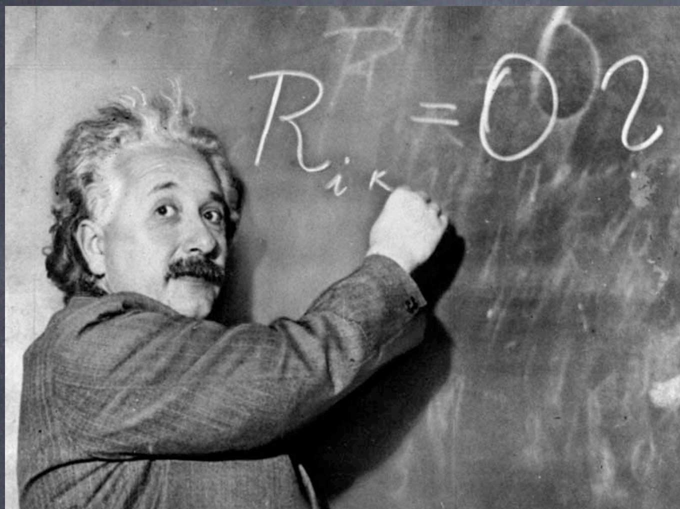


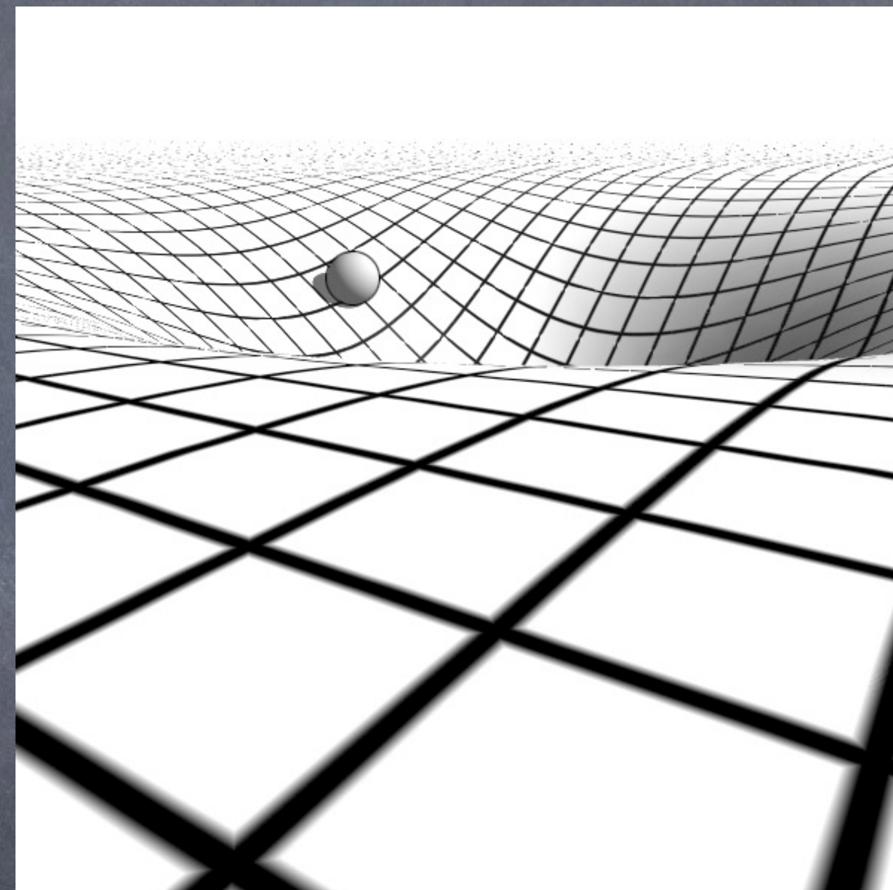
Modern Universe (t< 13.7 billion yrs)

- 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!!



Einstein's theory of gravity

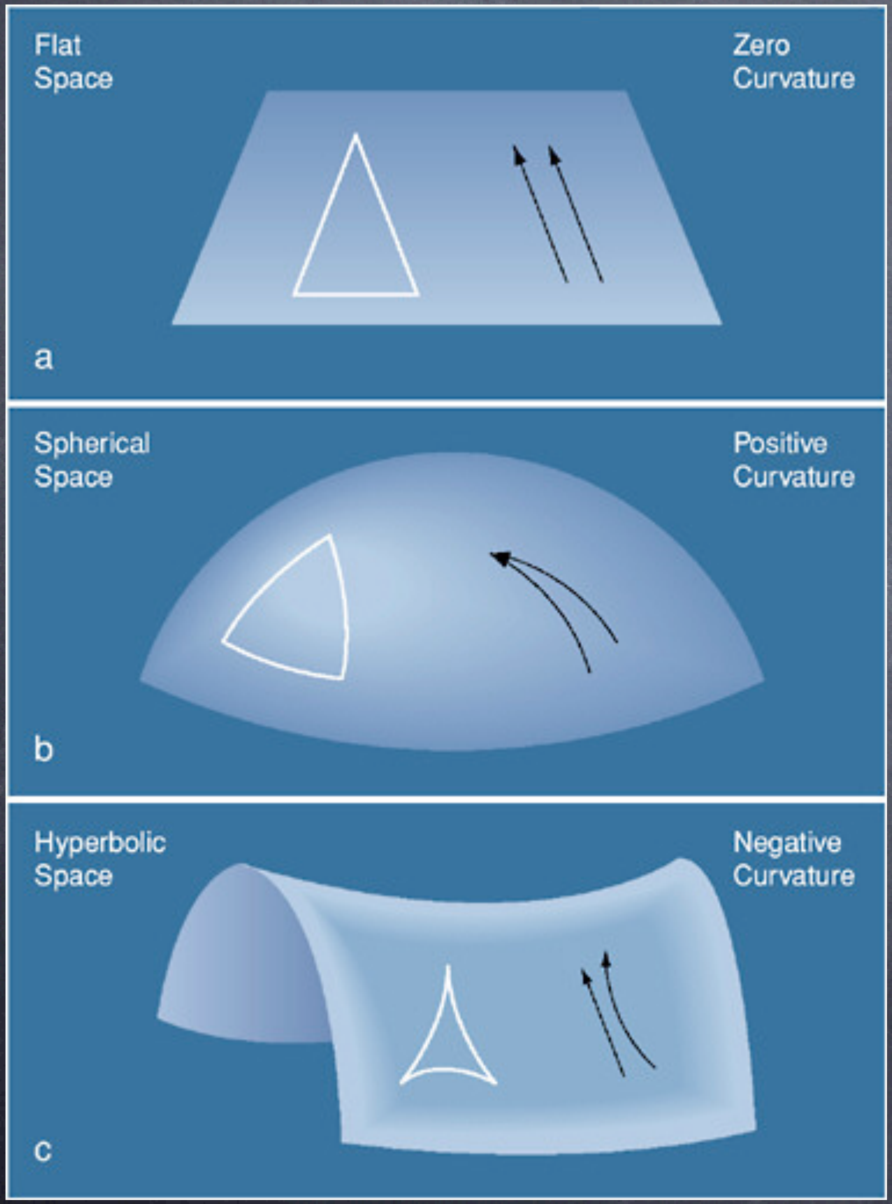




"Matter tells space how to curve
Space tells matter how to move"

One implication of gravity: geometry is destiny*

*In a matter-dominated Universe!



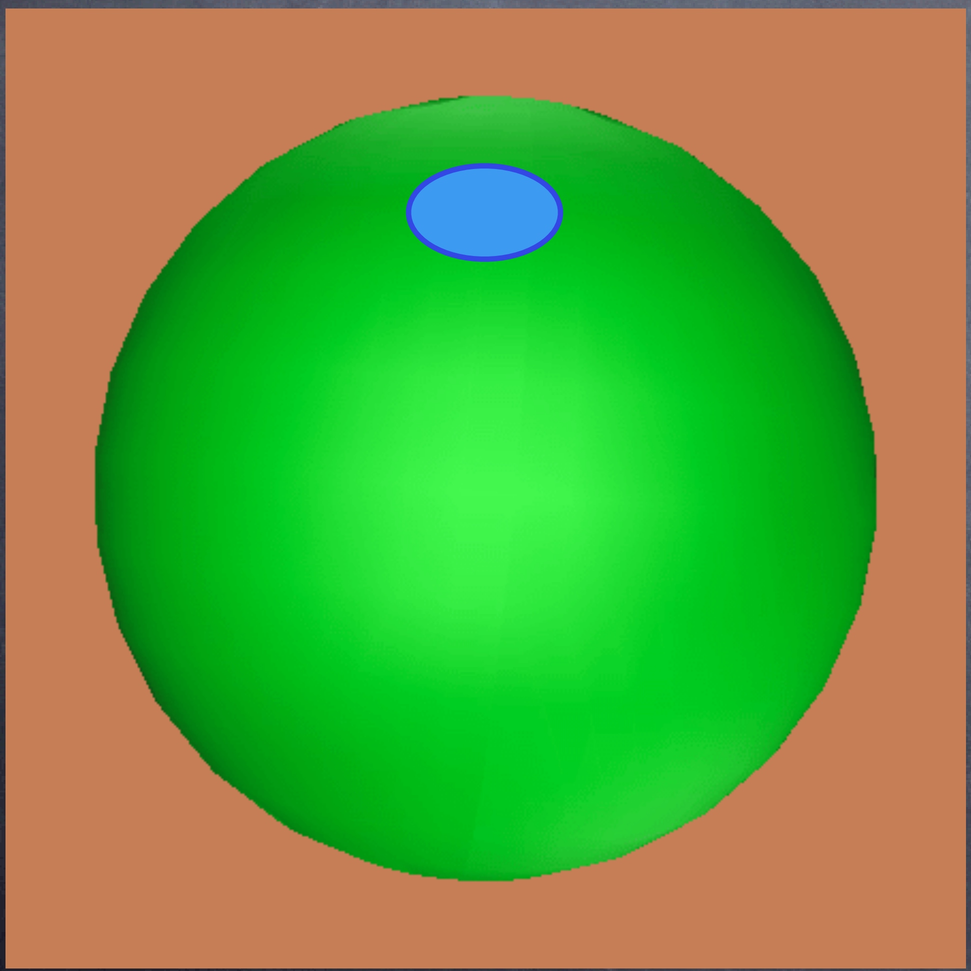
Expands forever
(but barely)

Recollapses eventually
(Big Crunch)

Expands forever

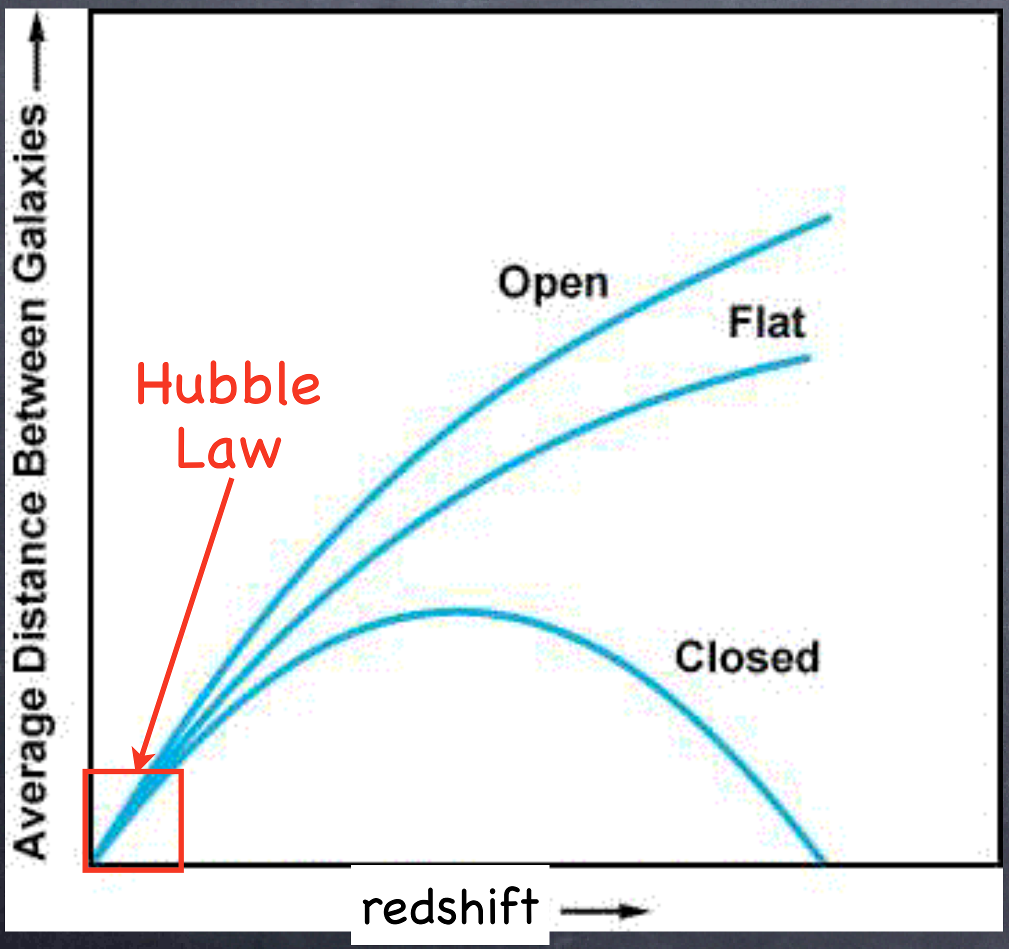
If inflation is correct, universe is expected to be flat

Imagine a colony of ants living on surface of a balloon



If the whole universe has been "blown up" early on (by inflation) then our observable universe appears flat to us

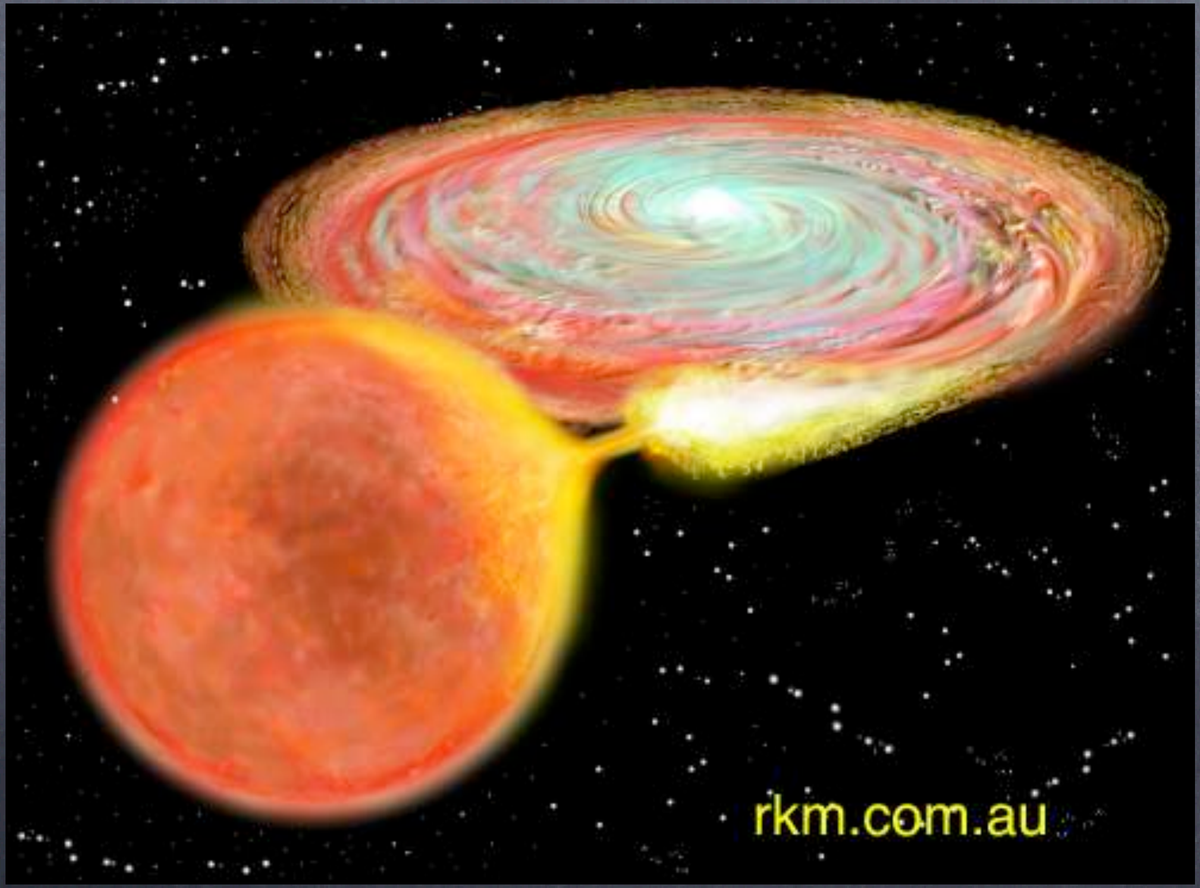
By measuring distances in the universe, you can determine its curvature



Problem:
distances in astronomy are notoriously hard to measure

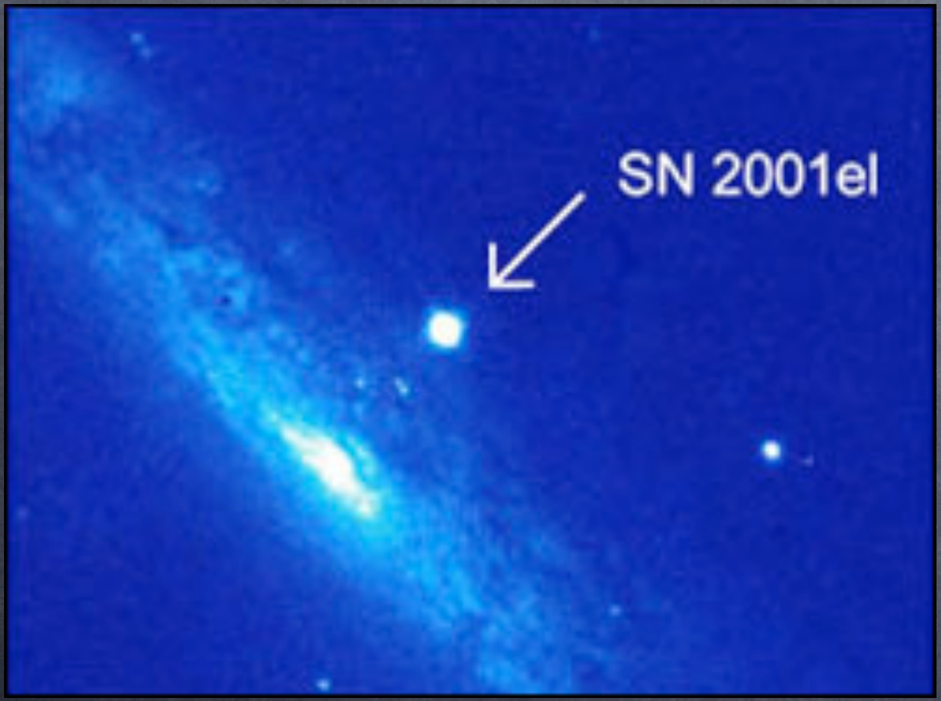
Type Ia Supernovae!

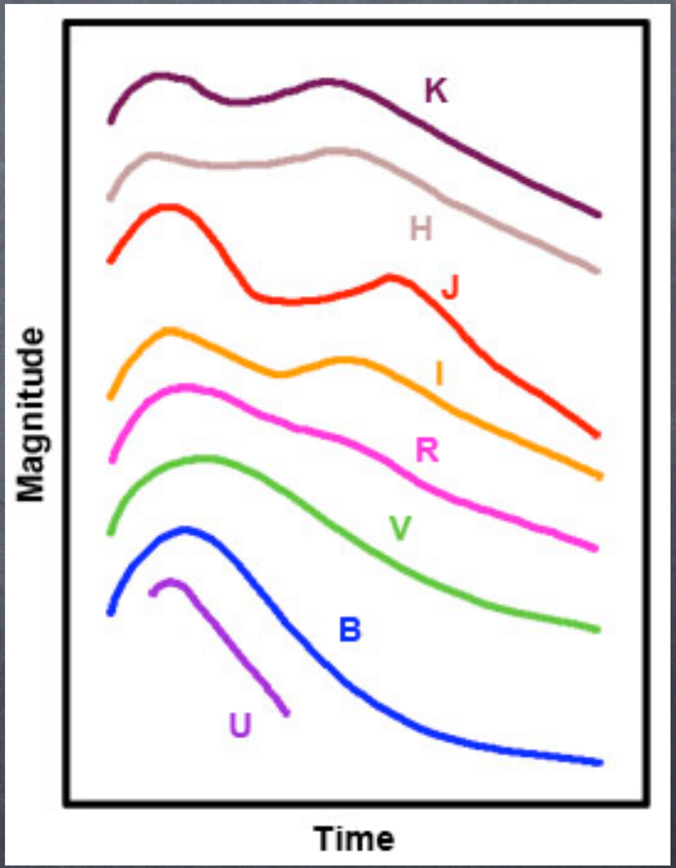
A white dwarf accretes matter from a companion.



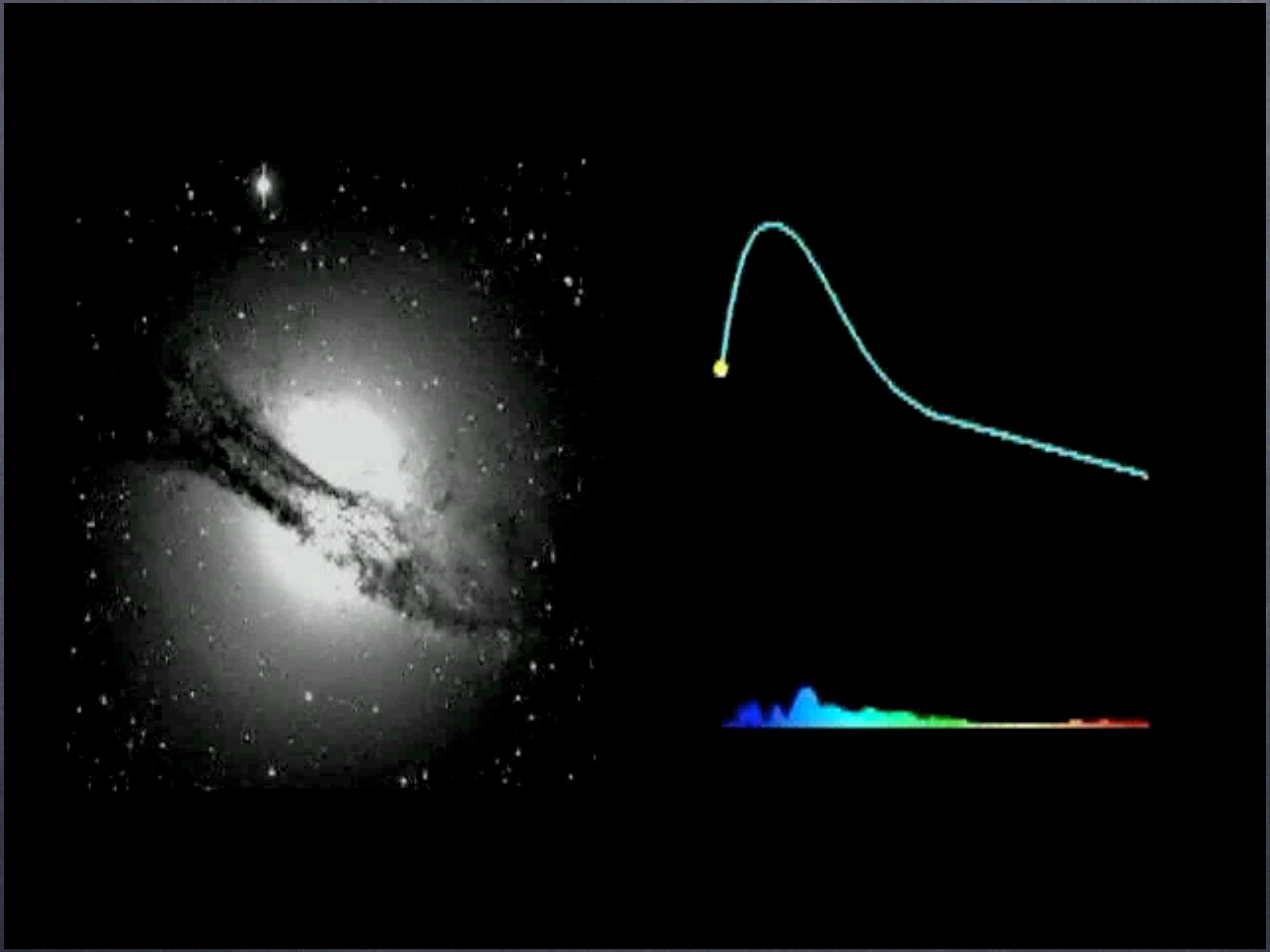
Type Ia Supernovae

If the star's mass is greater than a certain amount, it explodes





As bright as the whole galaxy!



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

Key property of SNe Ia:

Their intrinsic luminosity is (nearly) constant

=> 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?

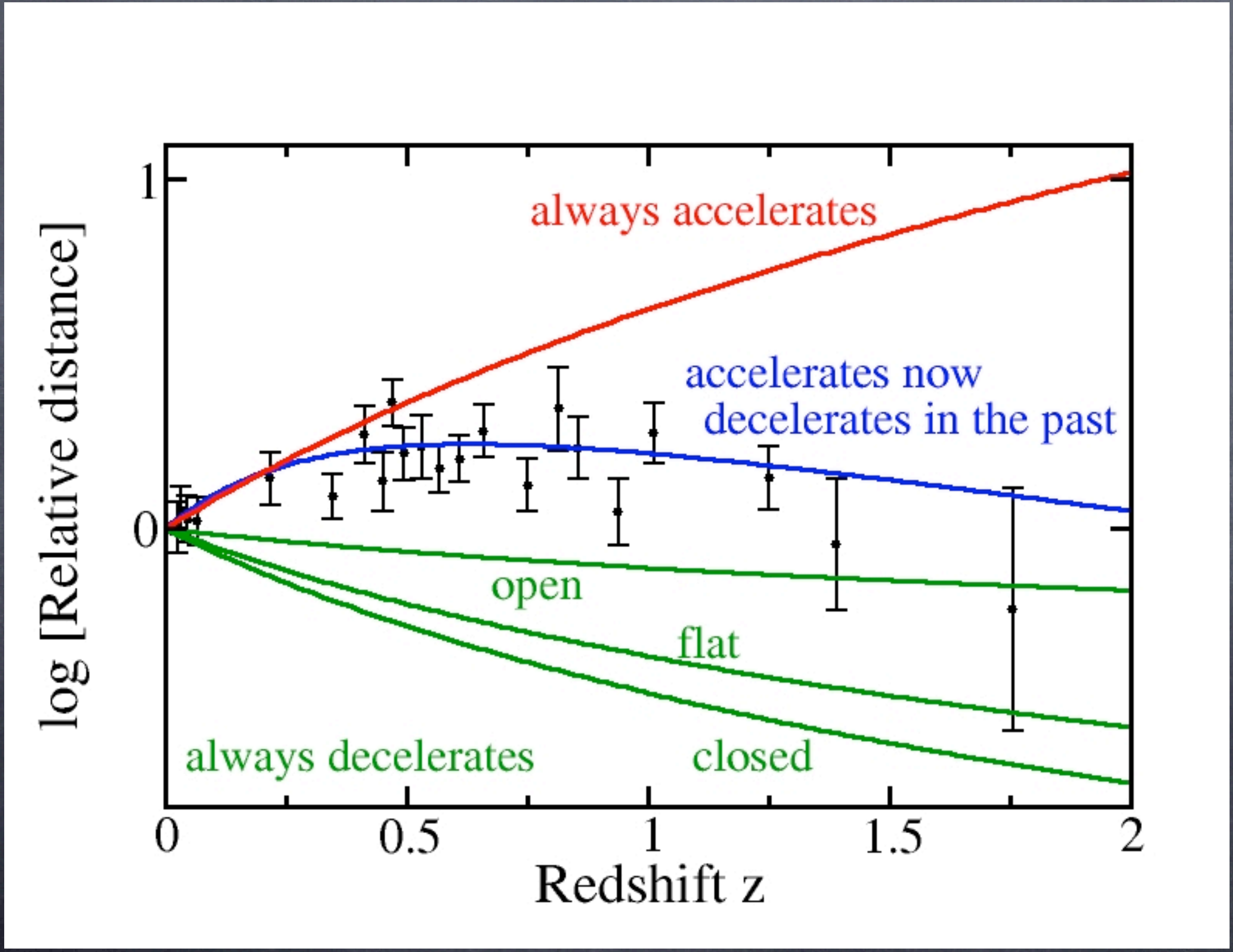
Rate: 1 SN per galaxy per 5,000 yrs!

Solution:
a combination of using world's large telescopes, scheduling them to find, then "follow-up" SNe and heroic hard work by two teams of researchers

Dr. Saul Perlmutter,
Supernova Cosmology Project

Dr. Brian Schmidt,
High-redshift Supernova Team

So, in the mid-1990s...

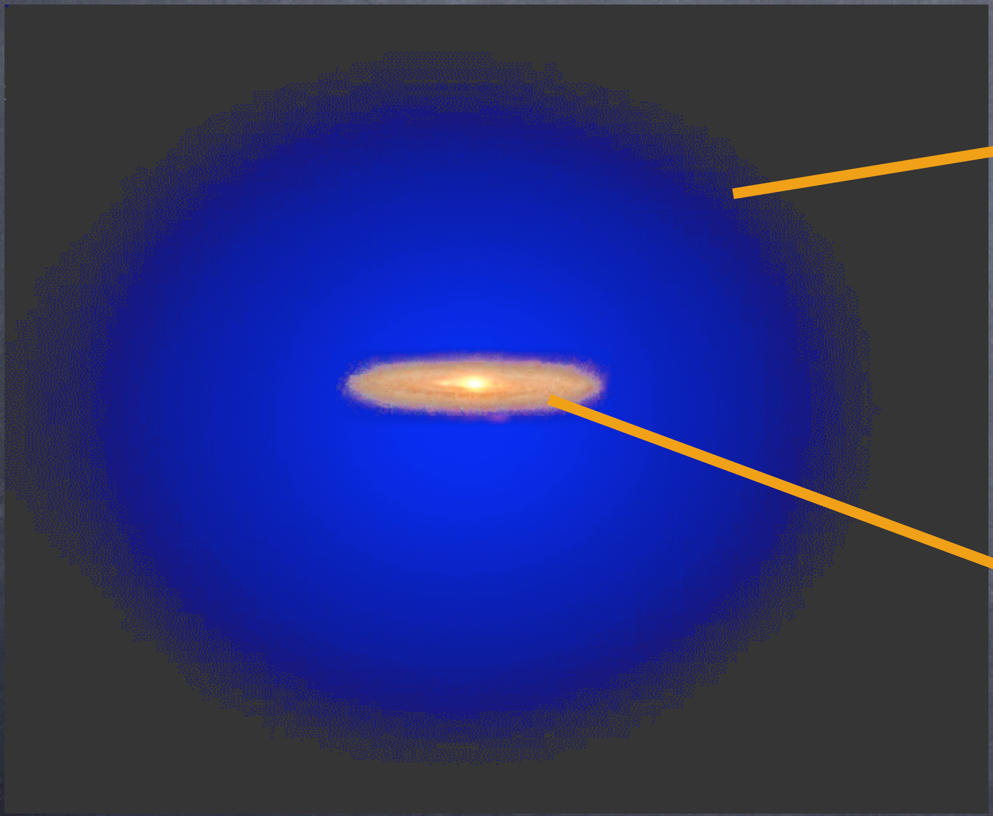


Dr. Michael Turner
University of Chicago

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

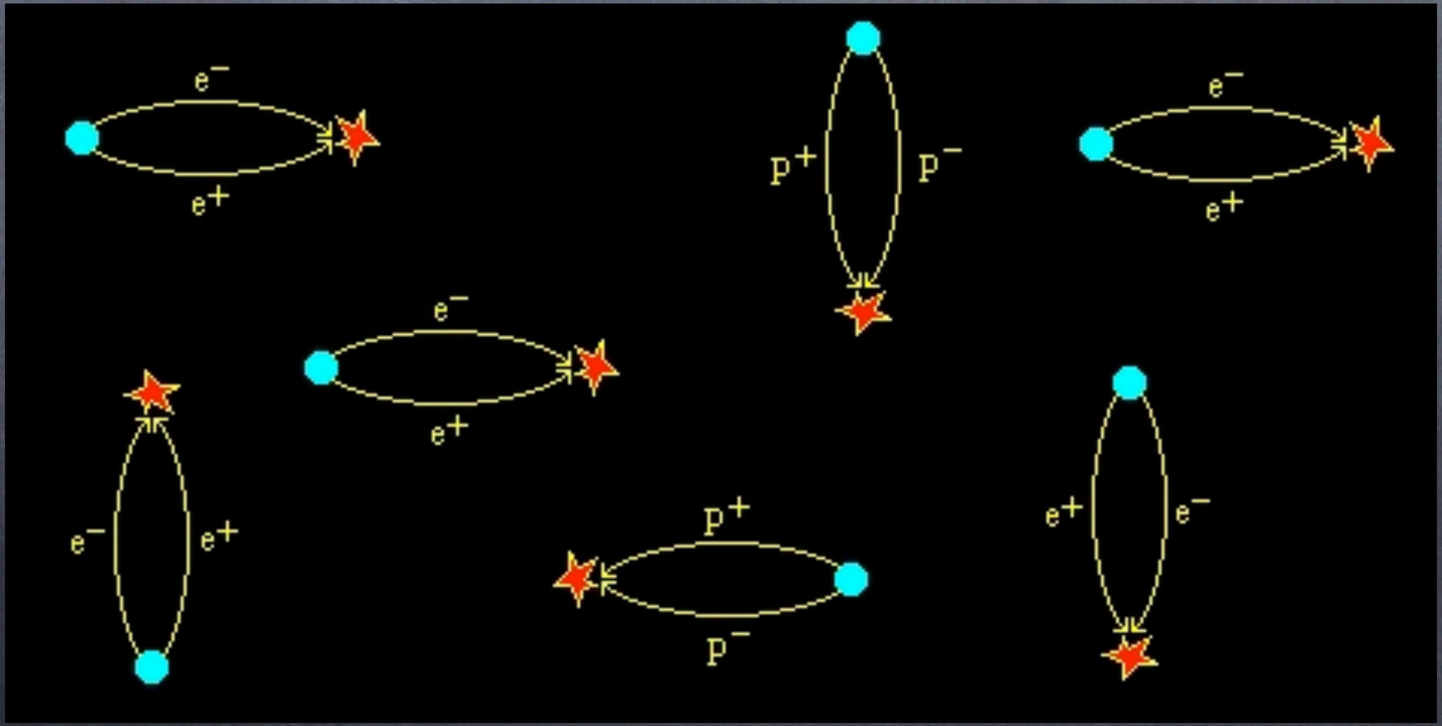
Actual photo of dark energy

Consequences of DE

- Implied by SNe and variety of other data
- Makes the universe older (without DE, it's apparently younger than some objects in it!)
- Pushes things apart at large distances
- Its discovery is revolutionary (1998; 10-year anniversary this year!)

A Candidate: Vacuum Energy

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



Theoretical prediction for vacuum energy

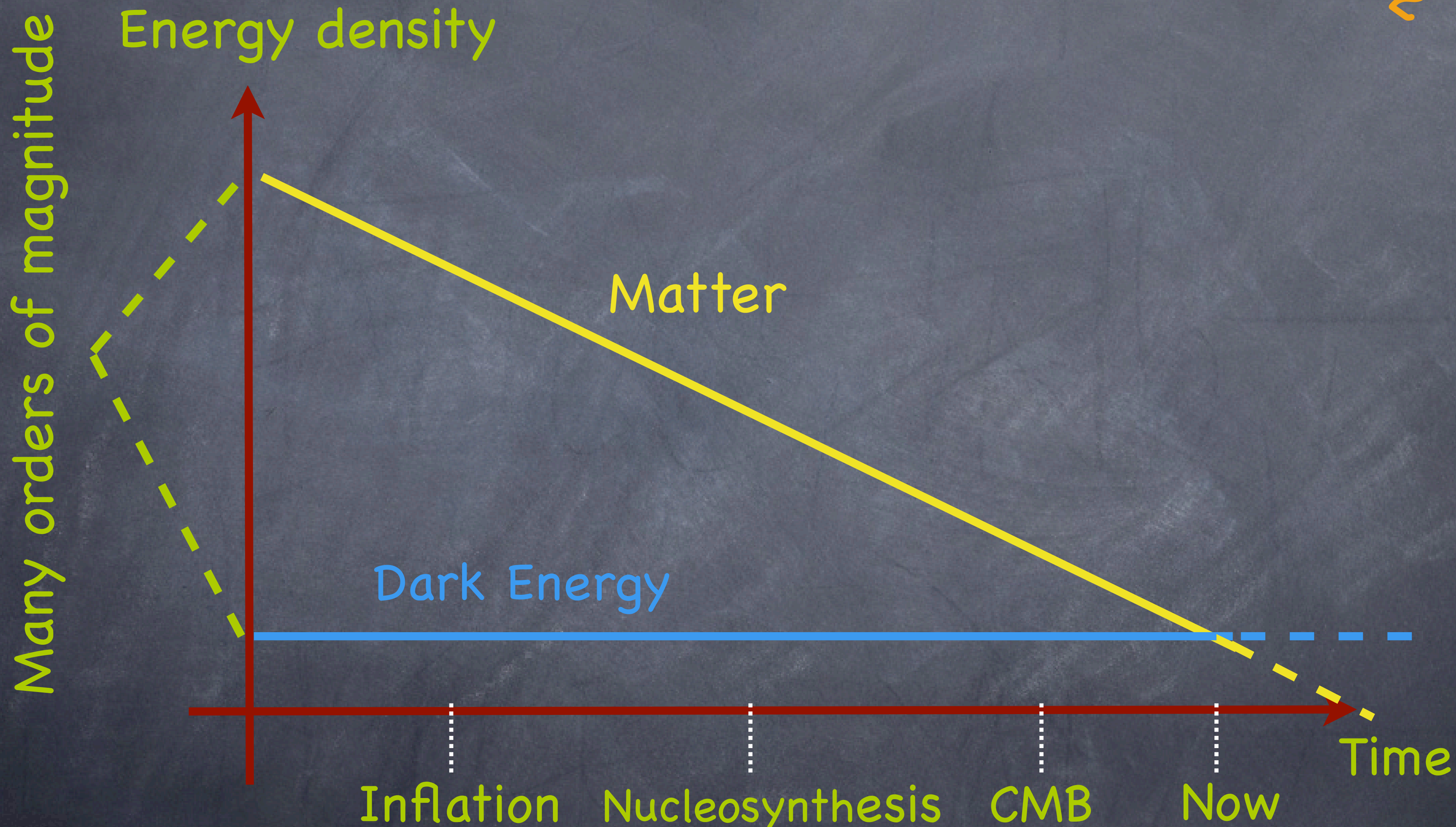
Mystery #1

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,
000,000,000,000,000,000,000,000,000,000
(or 10^{120}) times more than the observed amount

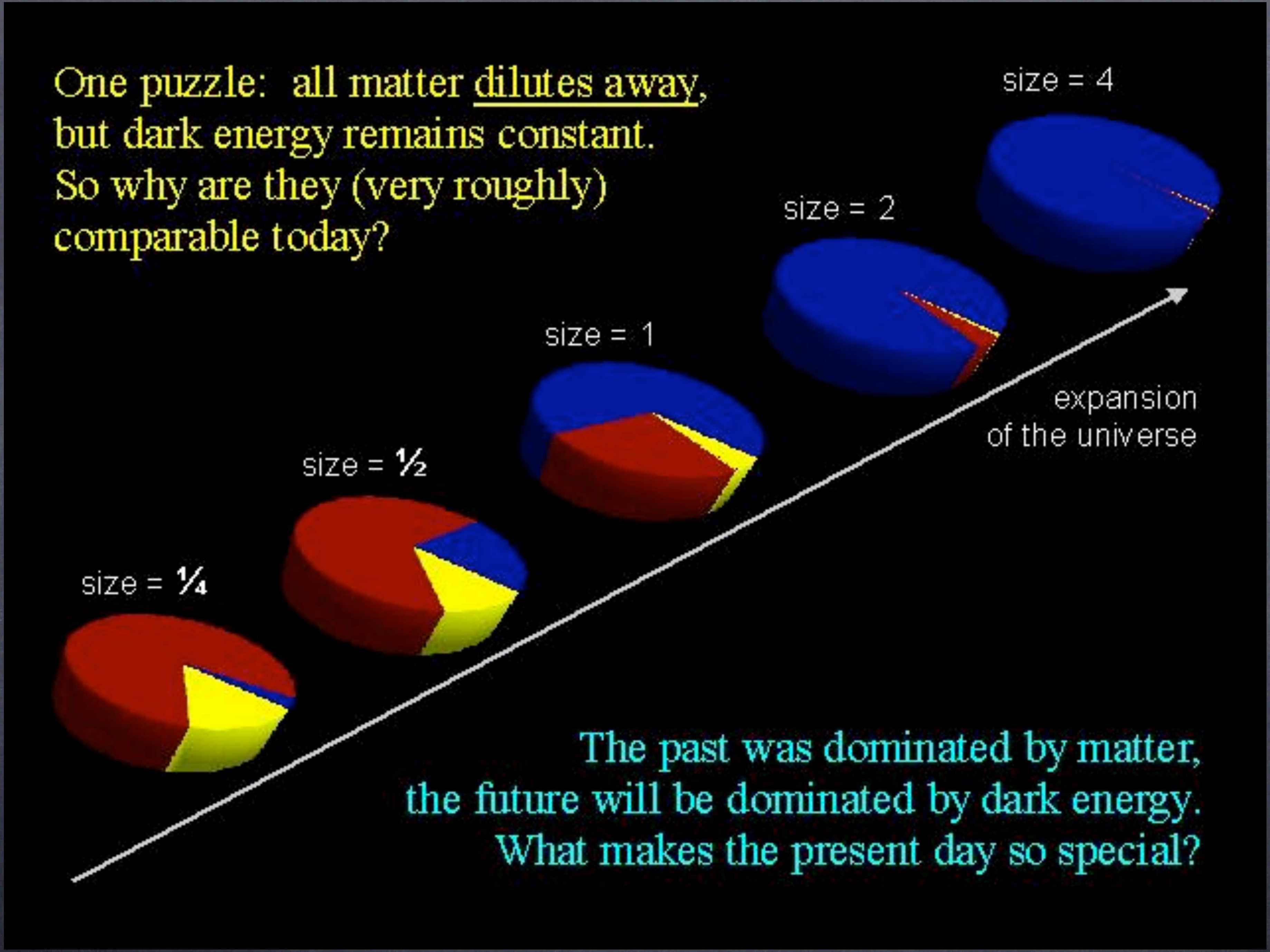
This is known as
the COSMOLOGICAL CONSTANT PROBLEM

"Why Now!?"

Mystery #2



This is known as the COINCIDENCE PROBLEM



credit: Sean Carroll

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"

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

- Geometry is not destiny any more! Fate of the universe (accelerates forever vs. recollapses etc) depends on the future behavior of DE
- 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!
- In the accelerating universe, galaxies are leaving our observable patch -> the sky will be empty in 100 billion years!

Test

Is Dark Energy very similar to Dark Matter?

A) Yes
B) No
C) In the distant past only

Test

Is Dark Energy very similar to Dark Matter?

A) Yes
B) No
C) In the distant past only

- Dark matter is attractive, DE is repulsive
- Dark Matter is clumped, DE is smooth

How do we find out more about Dark Energy?

- A comprehensive program of cosmological observations
- All of them indirectly sensitive to DE (e.g. measuring distances to SNe)
- Right now, we don't know how to look for it in the lab
- Near-term goal: find out its global properties (how much of it there is, if it clusters at all)
- Ultimate goal: understand its nature and origin

Current areas of research

- In addition to SNe, these methods are sensitive to DE:
  - Distribution of galaxies on the sky
  - Gravitational lensing
  - Cosmic Microwave Background
  - Abundance of Galaxy Clusters
- Theoretical work - searching for an explanation from particle theory, string theory, gravity theory...
- Right now, we don't know how to look for DE in the lab

SuperNova/Acceleration Probe (SNAP)

snap.lbl.gov

Movie follows...

Conclusions

- Dark Energy was directly discovered around 1998
- Its origin and nature are very mysterious
- It makes up about 75% of energy density; its energy is (roughly) unchanging with time
- It makes the universe's expansion speed up
- "Why now? Why so small?"
- One of the biggest mysteries in science today

Talk available at
http://huterer8.physics.lsa.umich.edu/~huterer/activities.html