

# Dark Energy and the Accelerating Universe

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The universe today presents us  
with a grand puzzle:

What is 95% of it made of?

Shockingly, we still don't know.

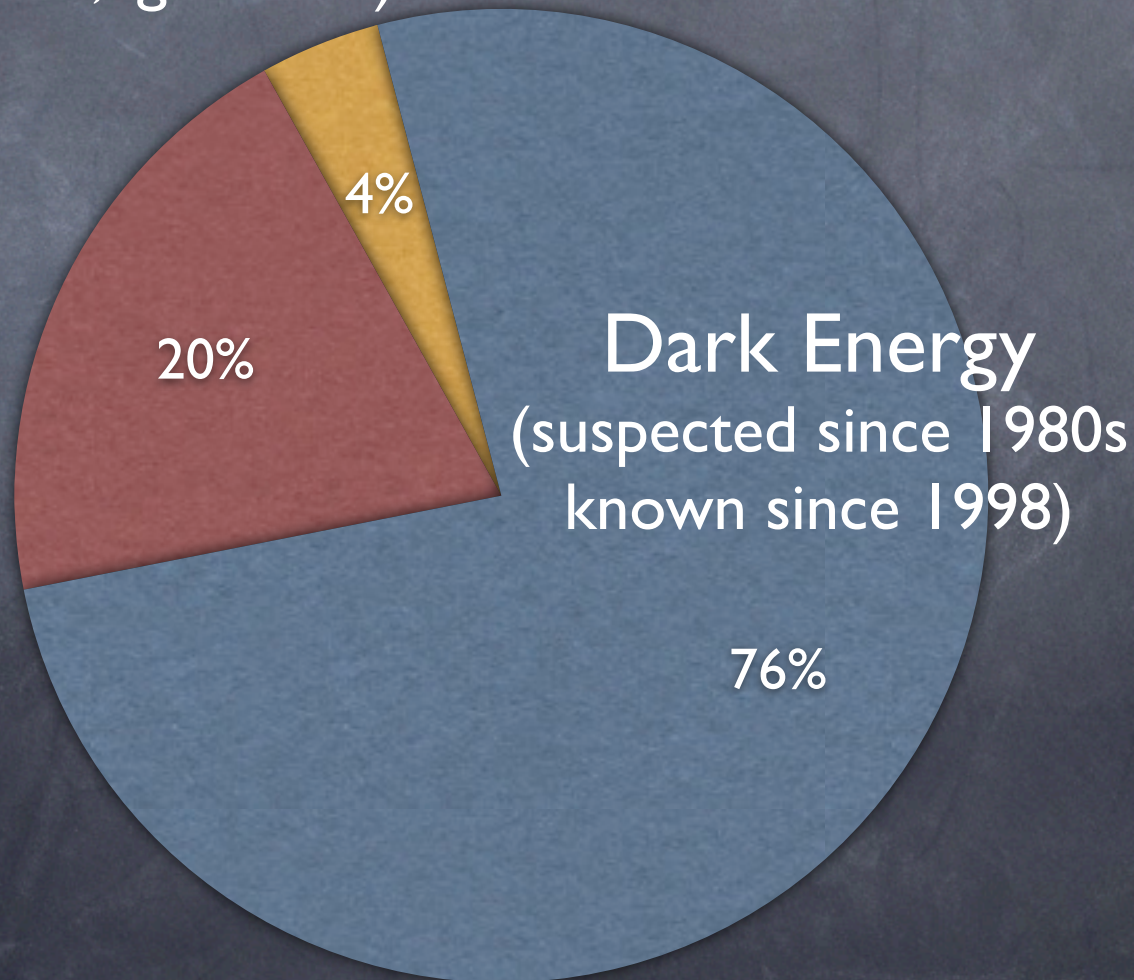
But we are getting closer to the  
answer.

# Makeup of universe today

Visible Matter  
(stars 0.4%, gas 3.6%)

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

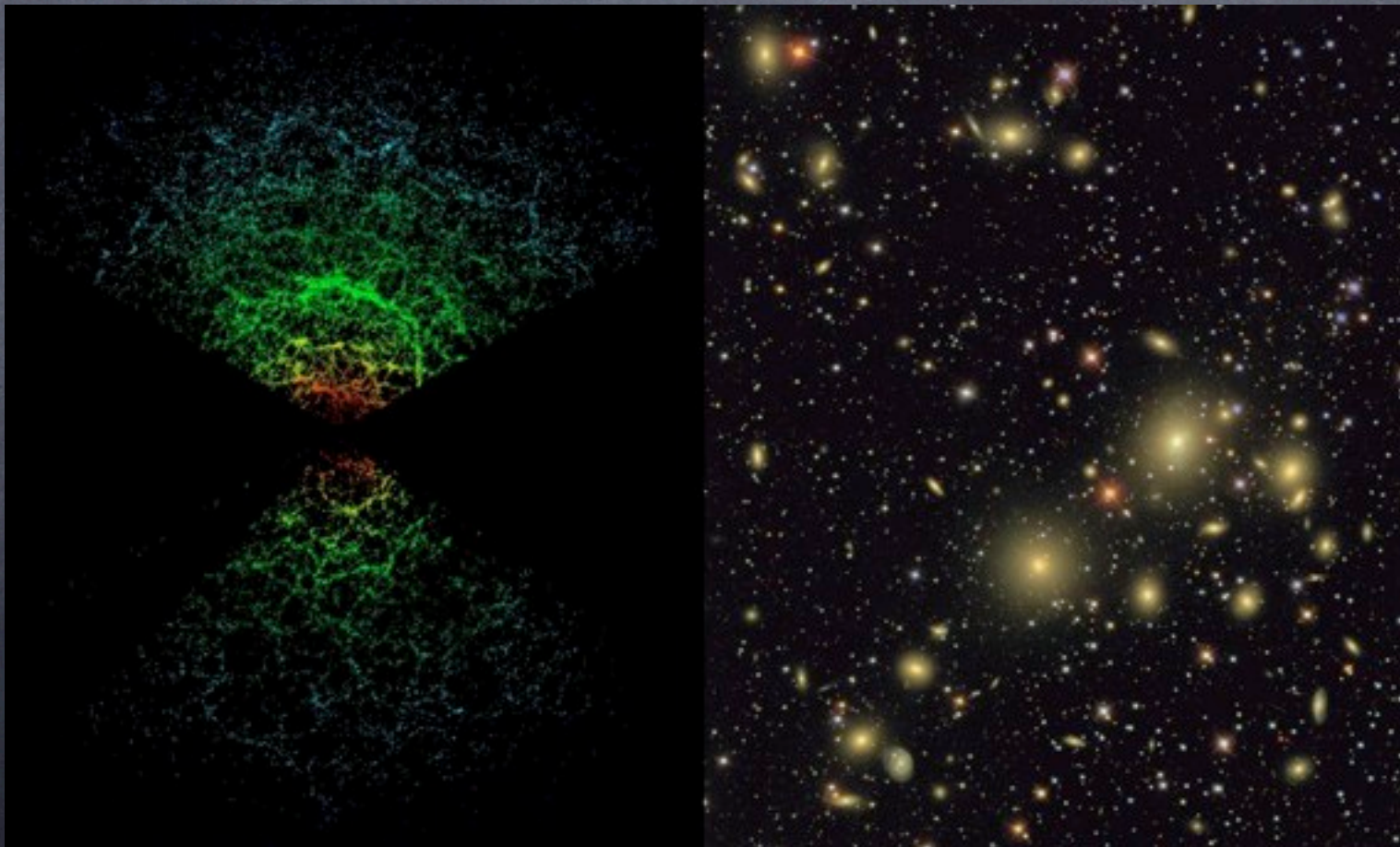
Also:  
radiation (0.01%)



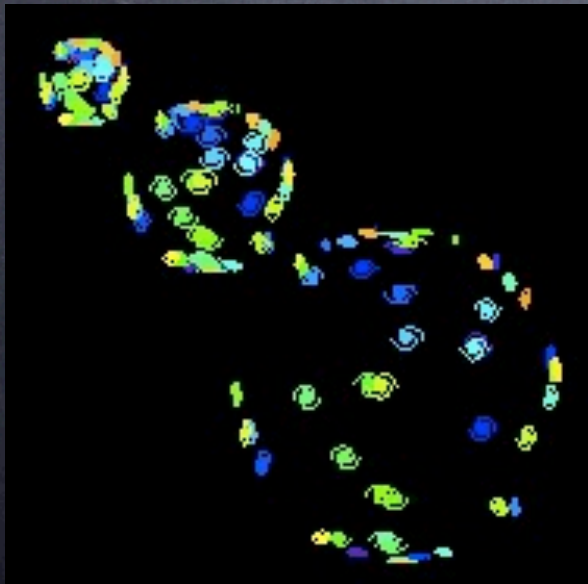
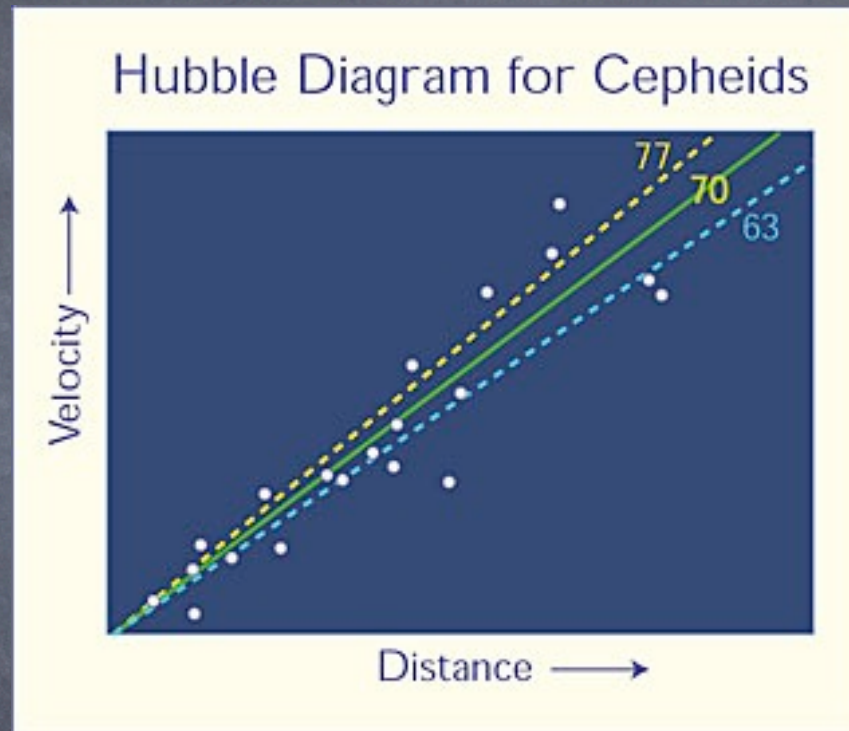
Dark Energy  
(suspected since 1980s  
known since 1998)

# The universe is homogeneous and isotropic

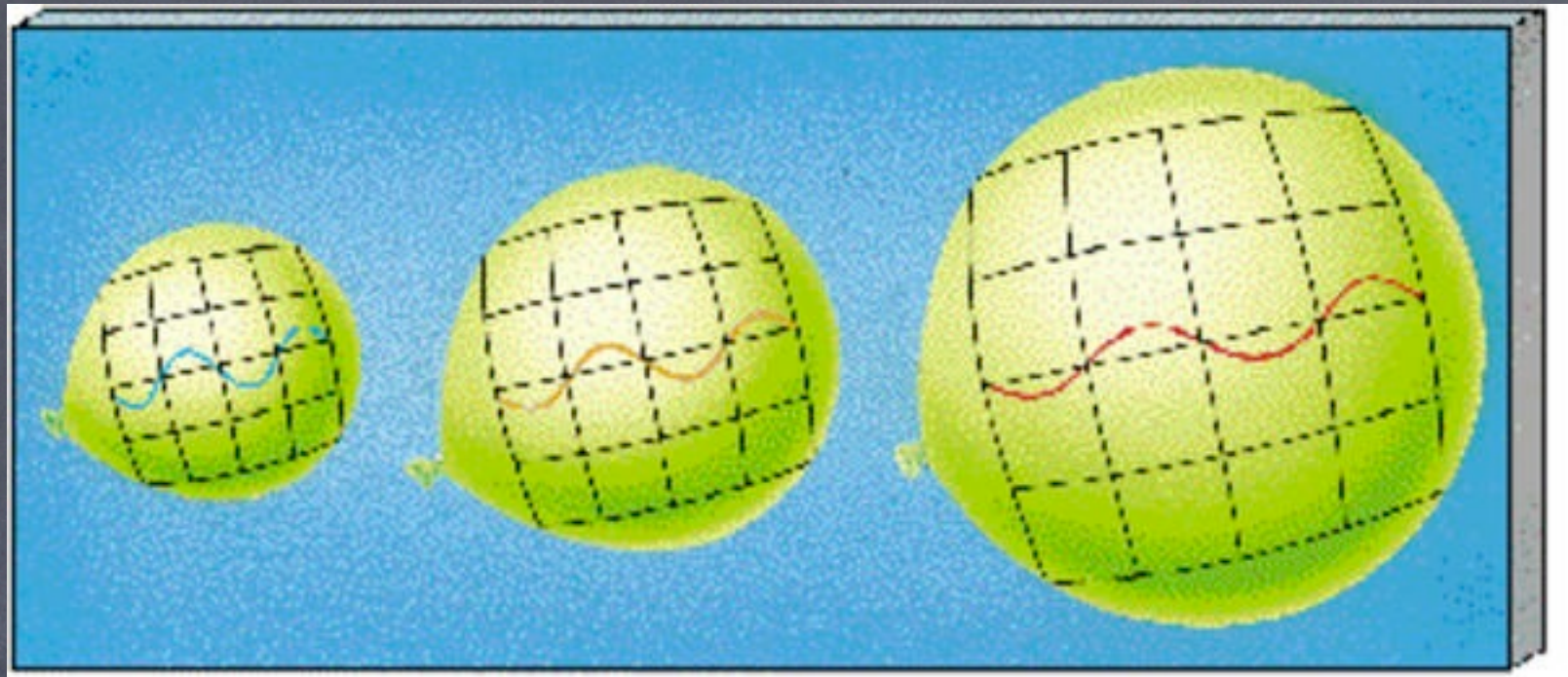
- **Homogeneous**: appears the same everywhere in space
- **Isotropic**: appears the same in every direction



# 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



$1 + \text{redshift} = \frac{\text{size of universe now}}{\text{size of universe when light was emitted}}$

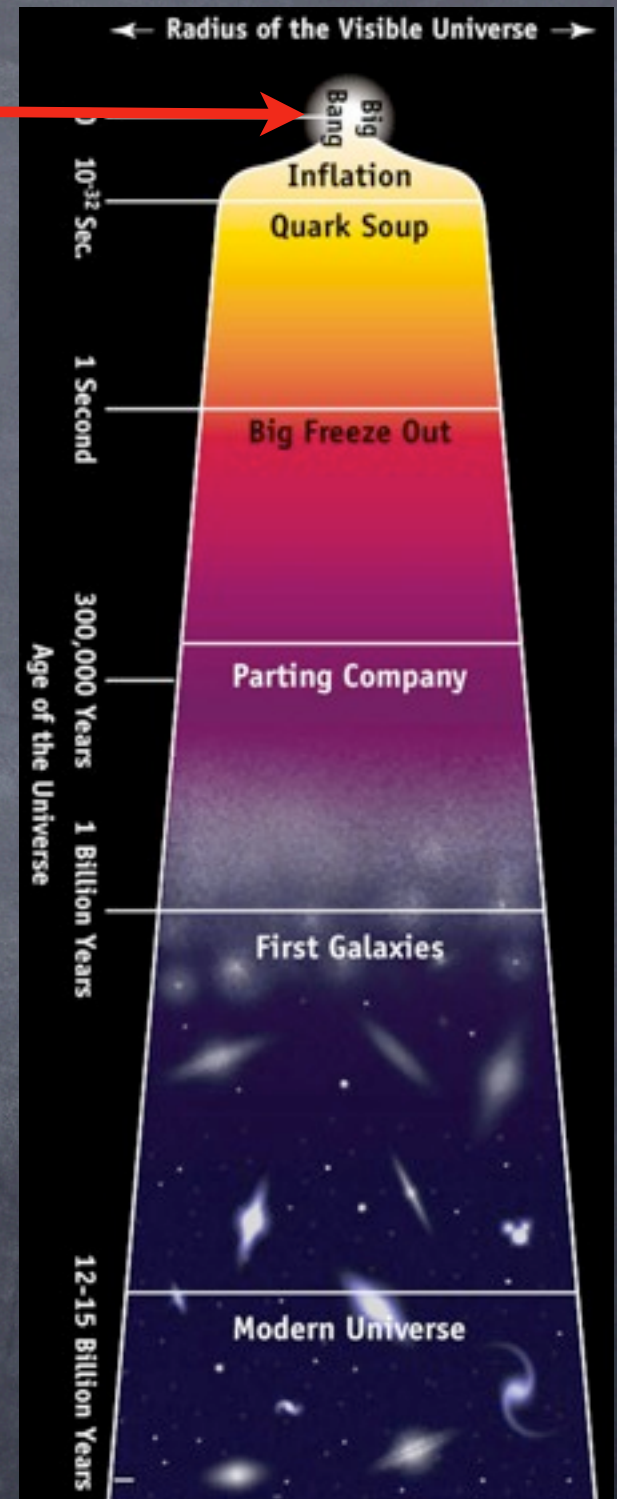
# History of the universe from $t=0$ to $t=13.7$ Gyr

A Brief Overview...



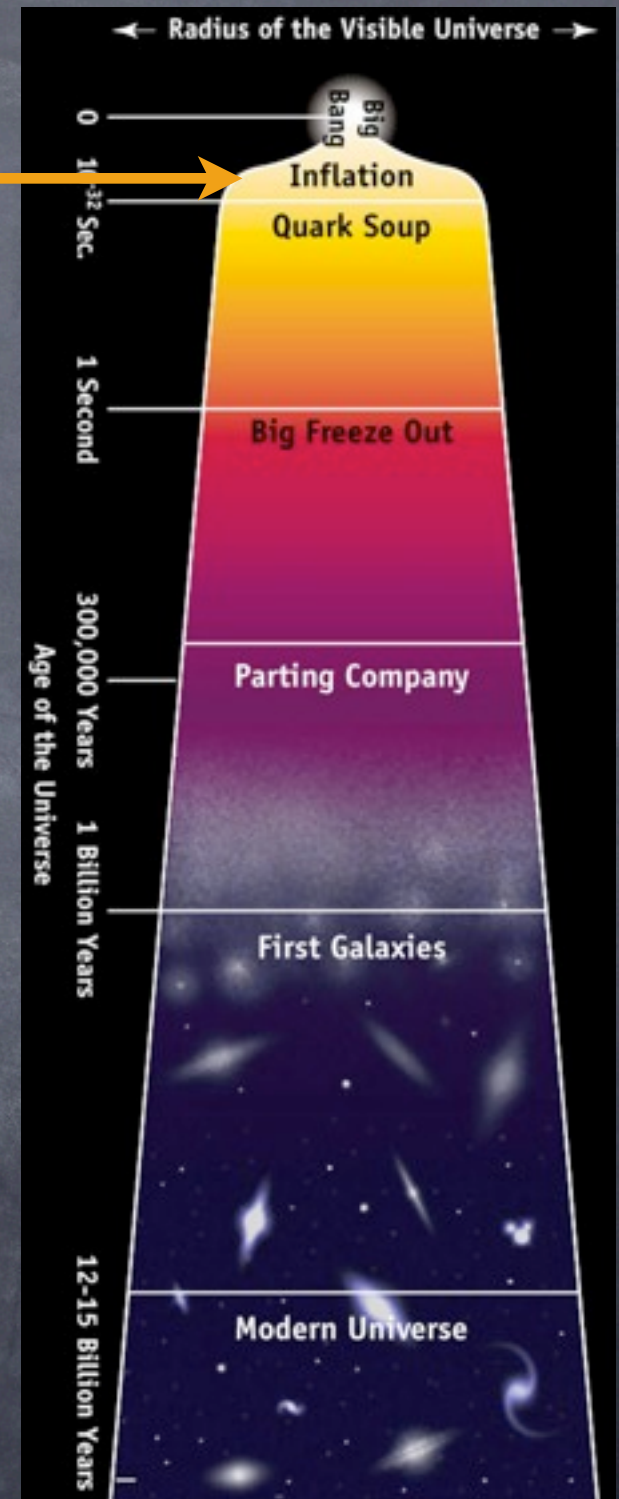
# Big Bang ( $t=0$ )

- 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?”



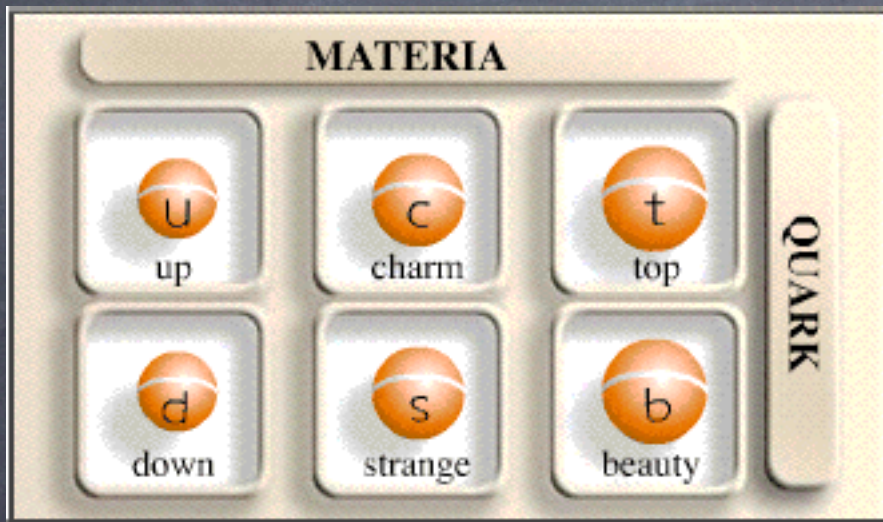
# Very early Universe ( $t$ =tiny moments after BB)

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

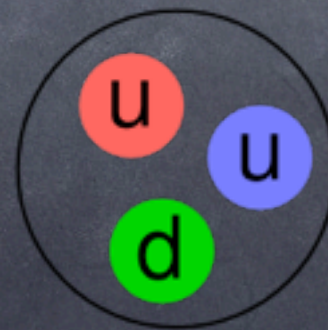


# Quark Soup ( $t < 1$ sec)

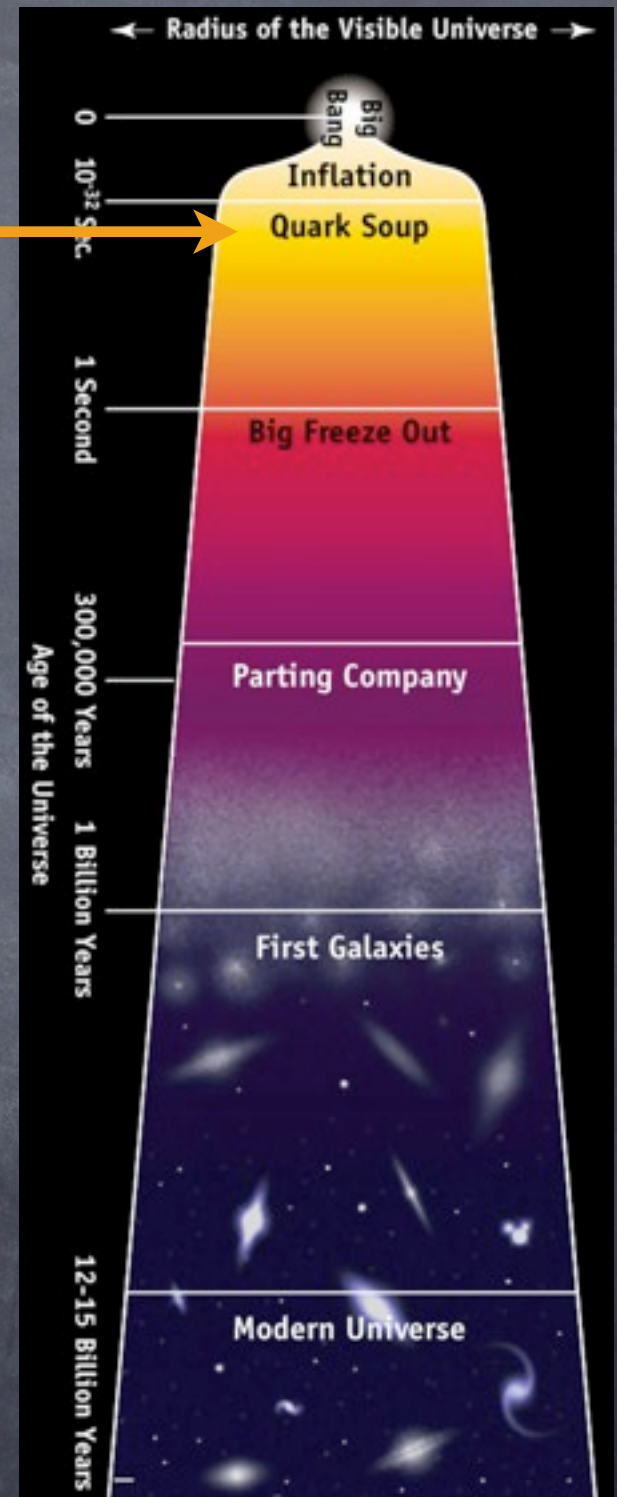
Quarks are free, floating around



Later, they are bound

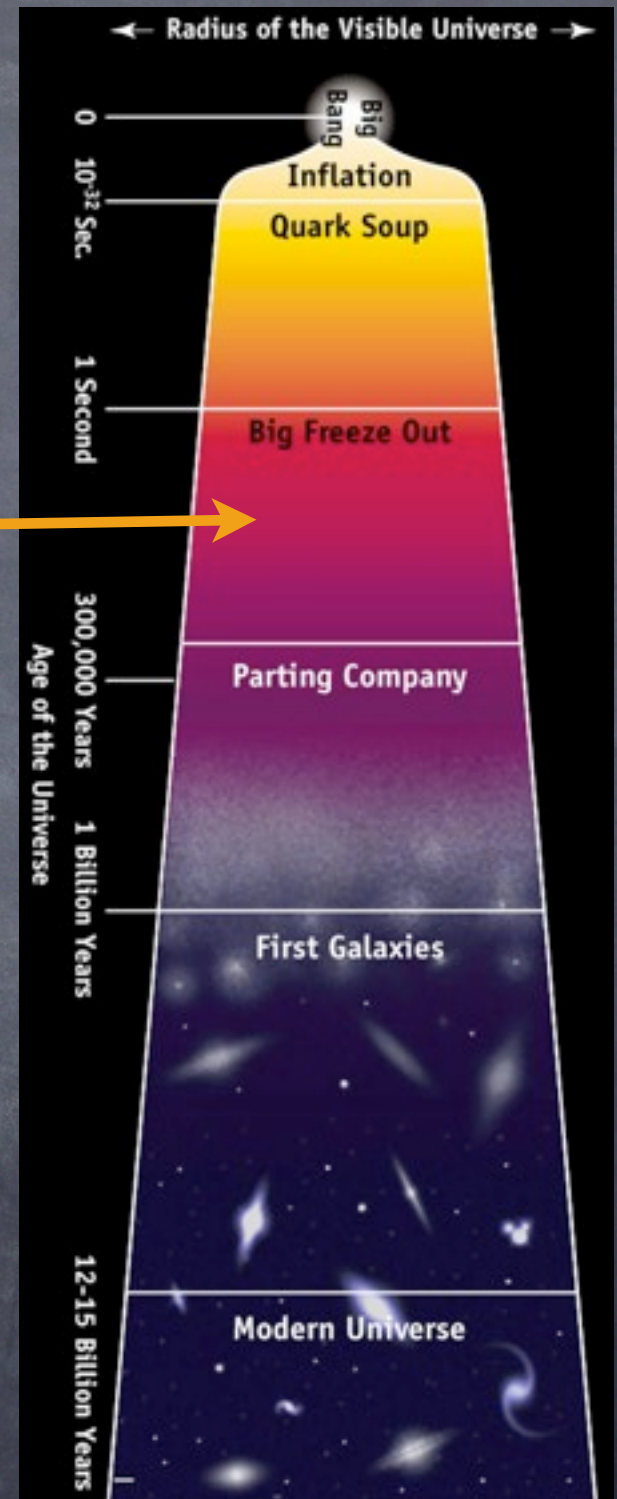


PROTON



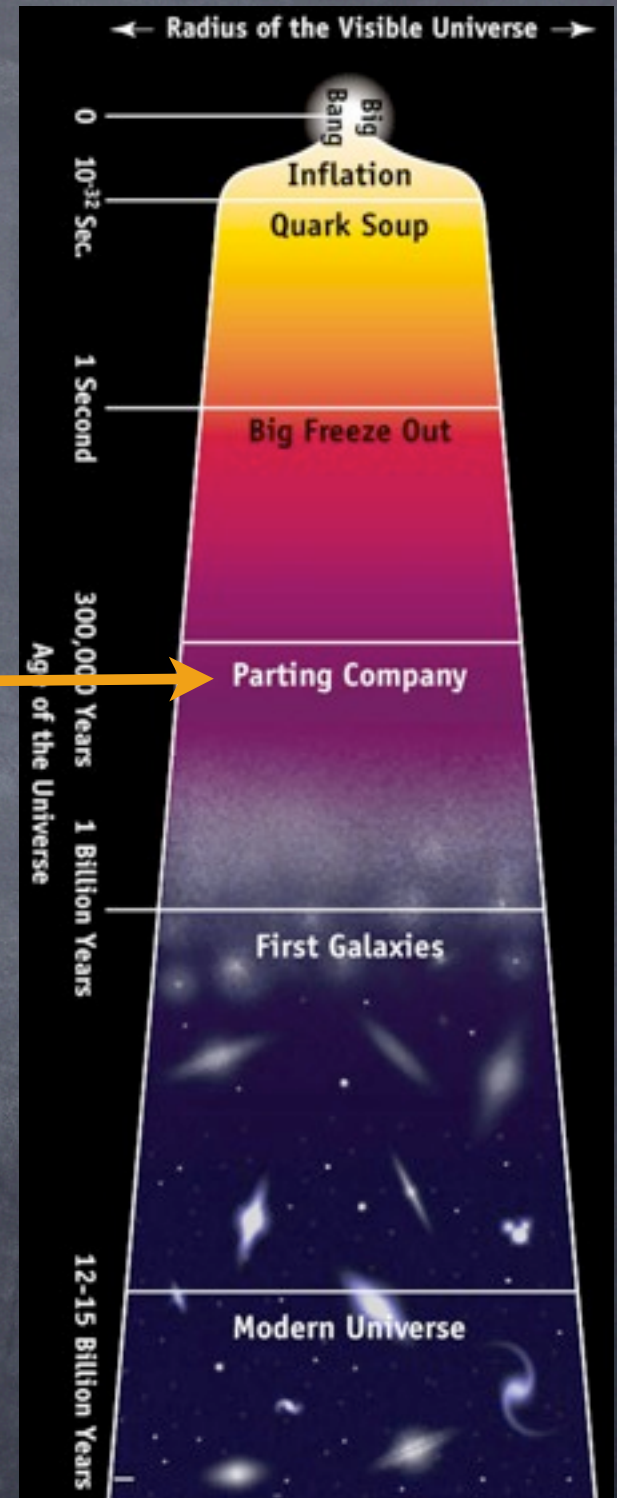
# Nucleosynthesis ( $t=3$ minutes)

- 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



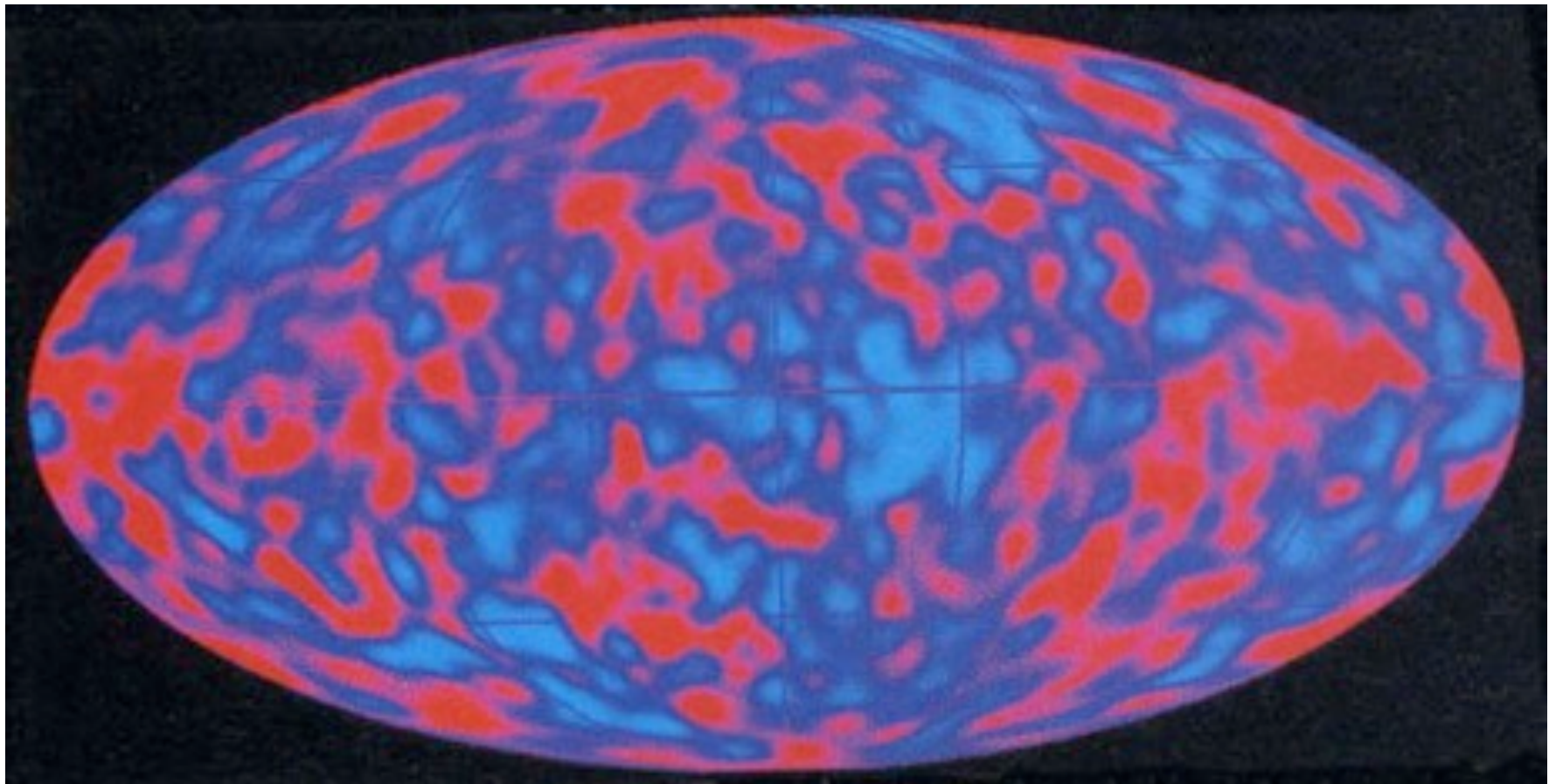
T=2.726 Kelvin



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

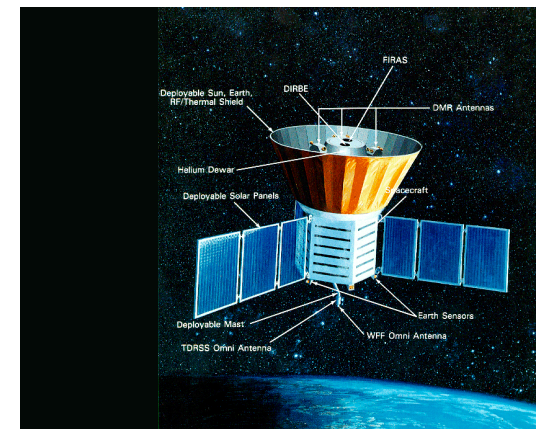


# Fluctuations 1 part in 100,000 (of 2.726 Kelvin)

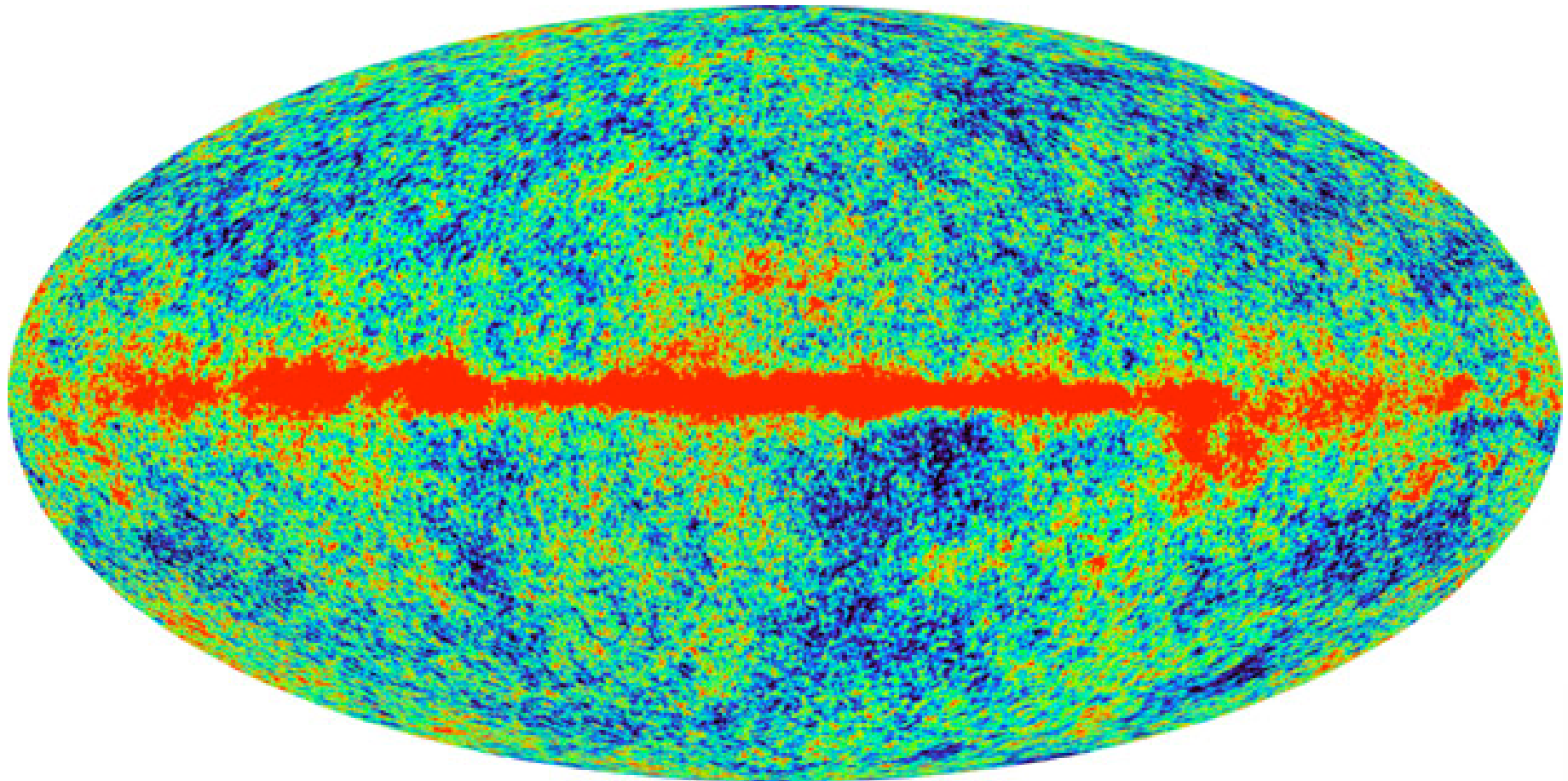


credit: COBE team

COBE satellite, 1992  
(Nobel Prize 2006)

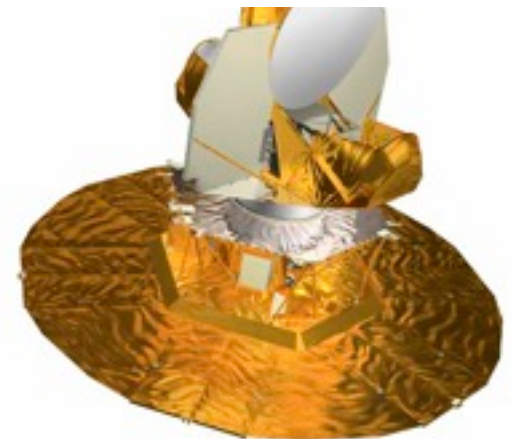


# Fluctuations 1 part in 100,000 (of 2.726 Kelvin)



credit: WMAP team

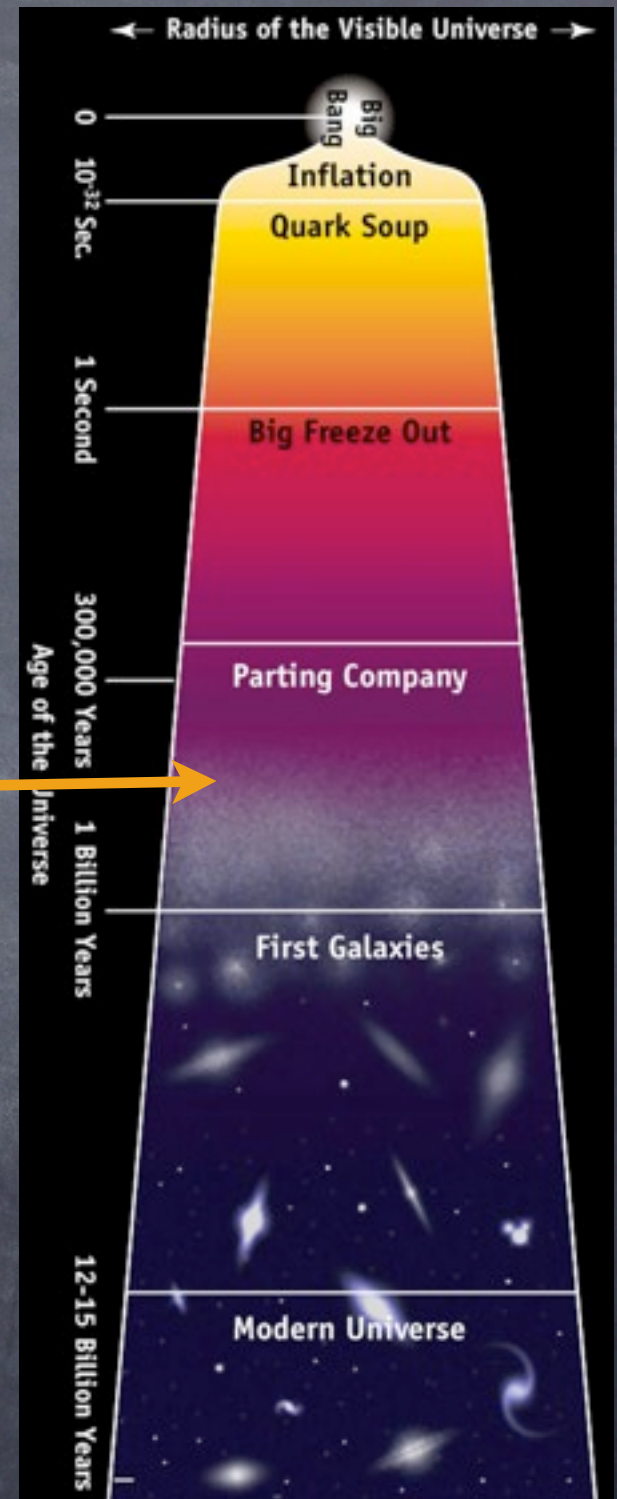
WMAP satellite, 2003





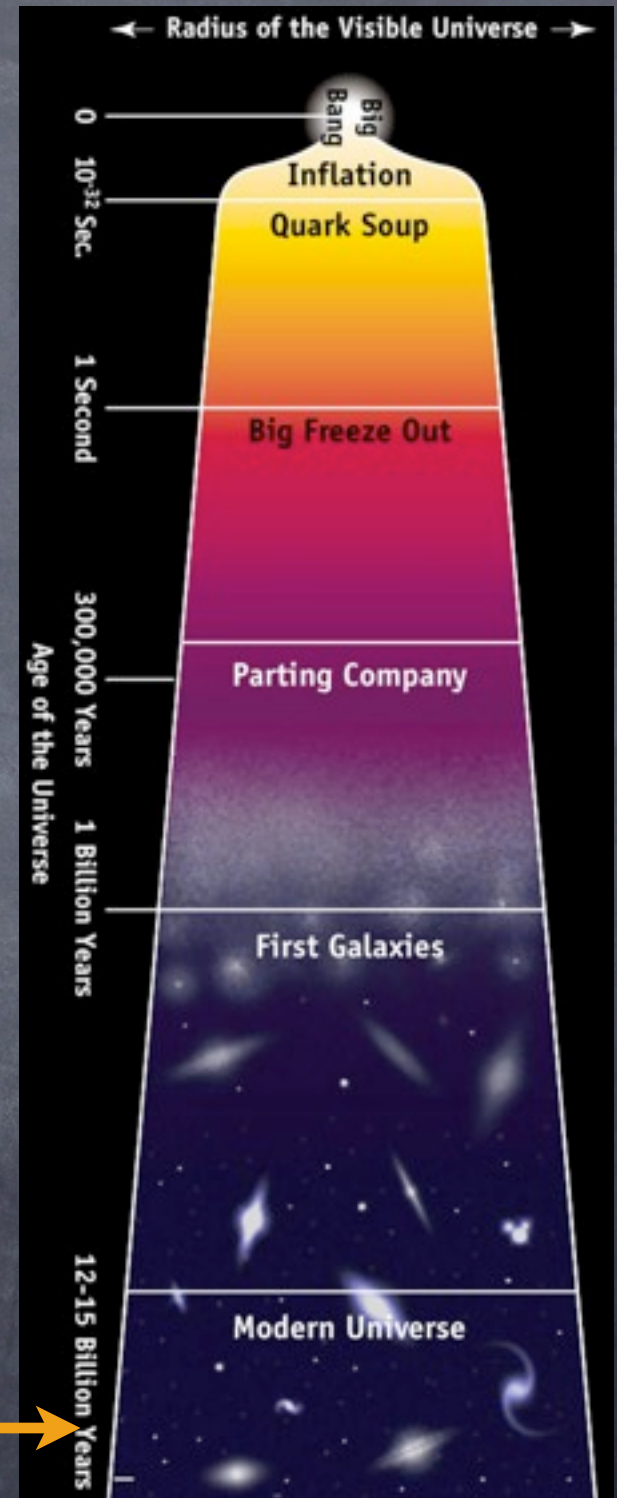
# The dark ages ( $t < 1$ billion yrs)

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

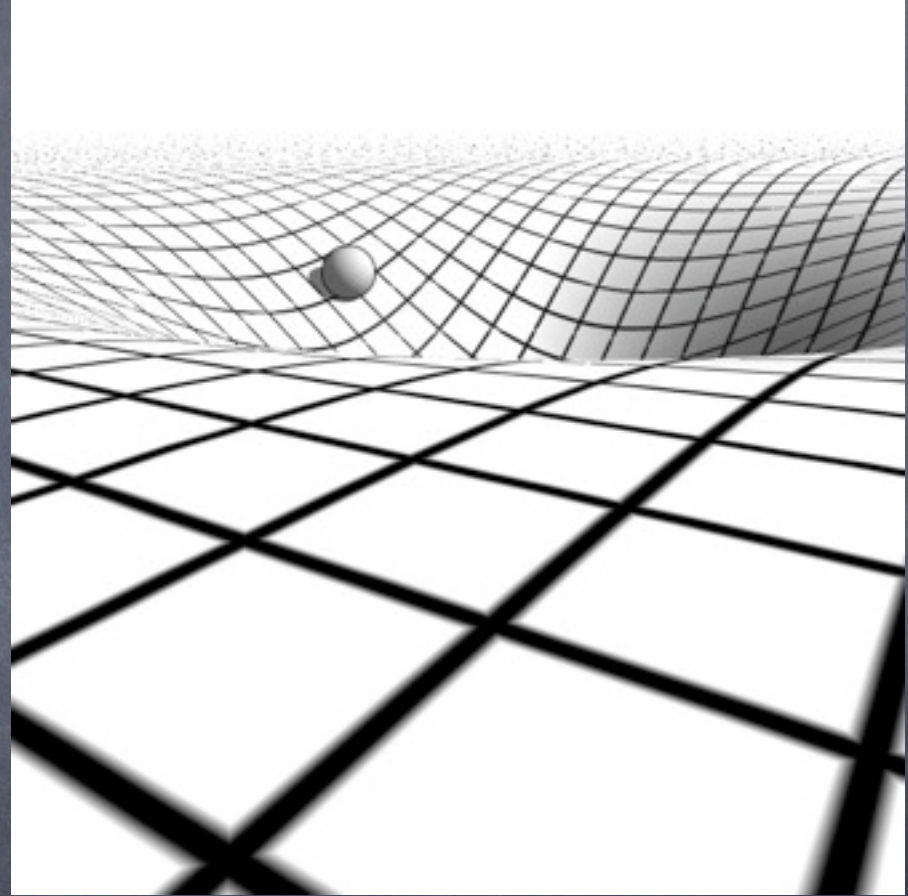
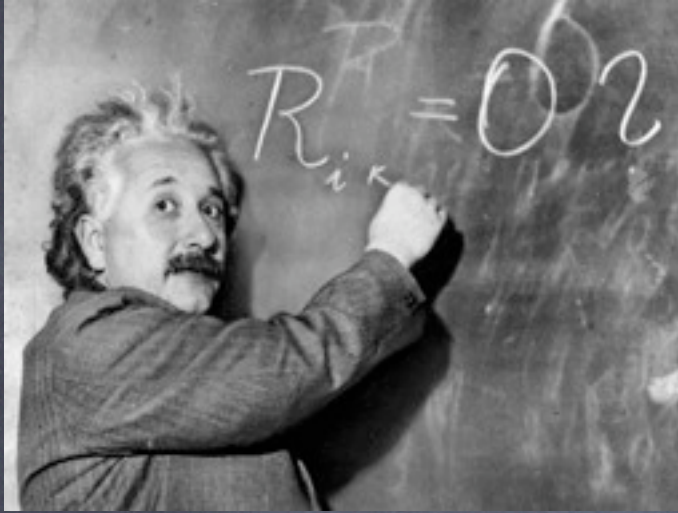


# Modern Universe ( $t < 13.7$ billion yrs)

- 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!!



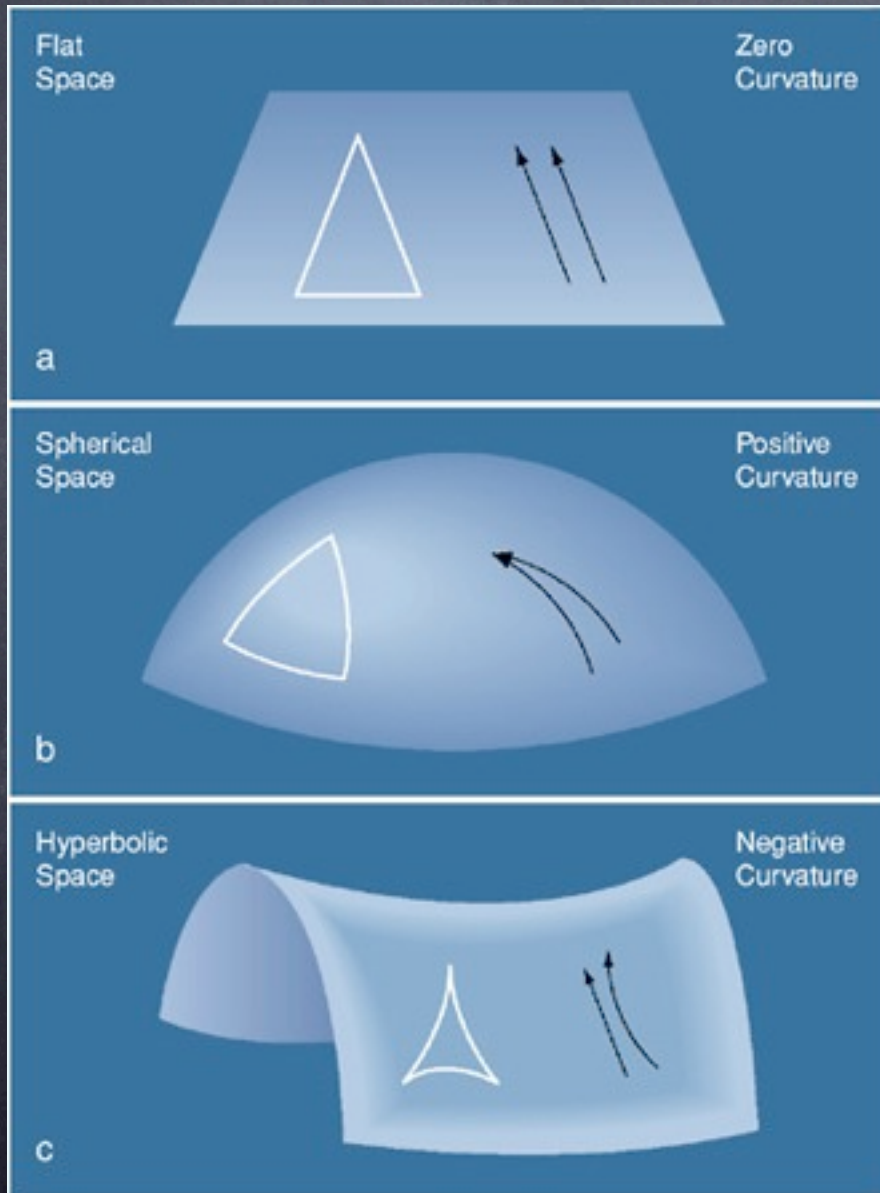
# Einstein's theory of gravity



“Matter tells space how to curve  
Space tells matter how to move”

# One implication of gravity: geometry is destiny\*

\*In a matter-dominated Universe!



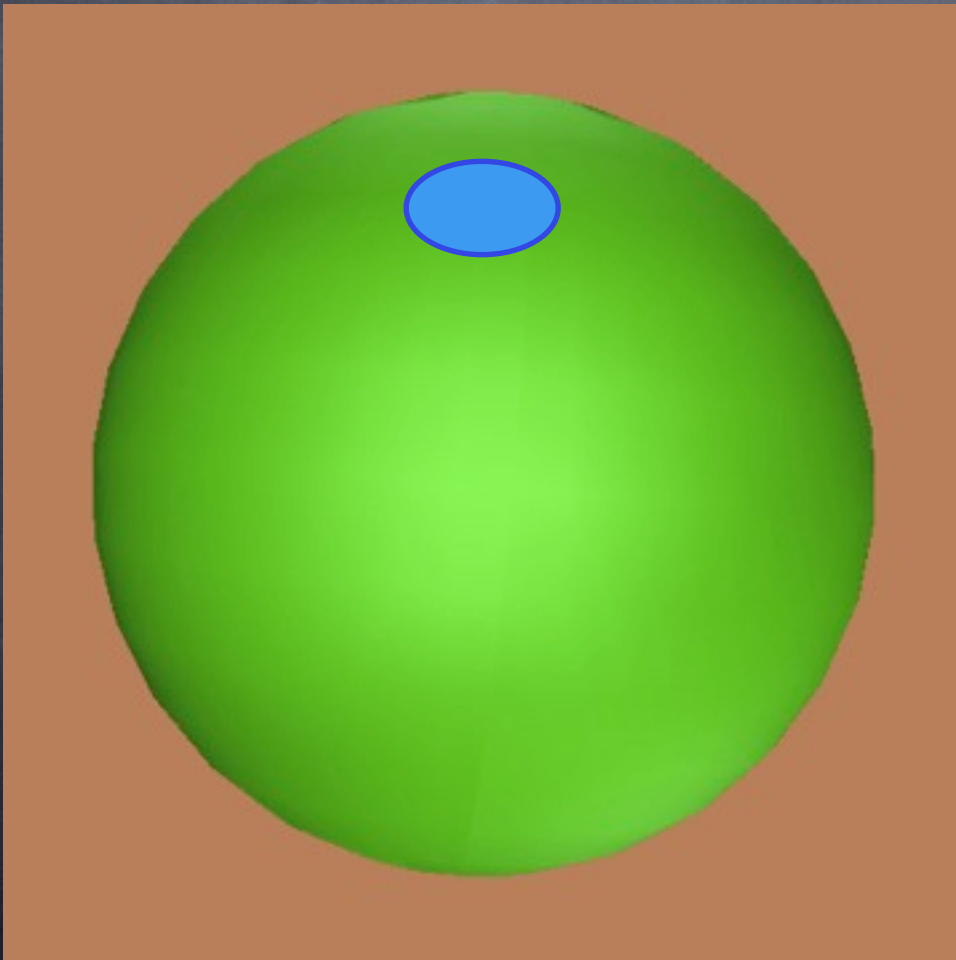
Expands forever  
(but barely)

Recollapses eventually  
(Big Crunch)

Expands forever

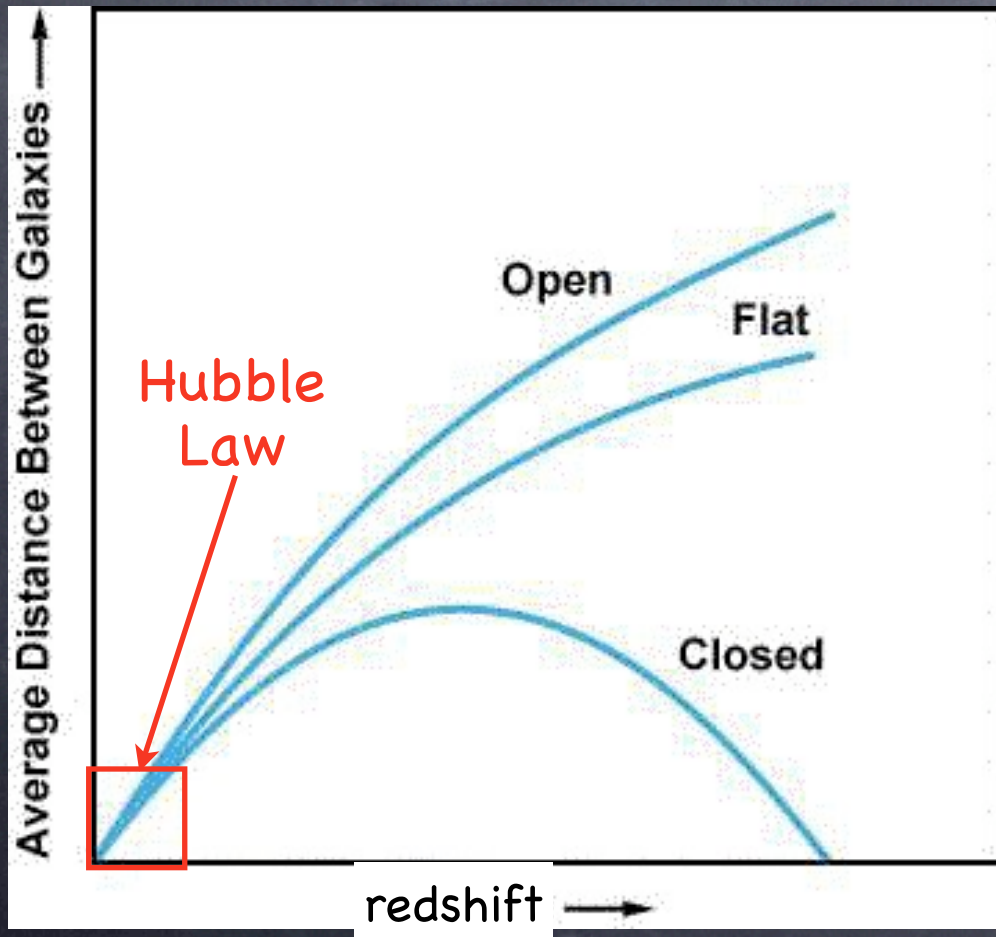
If inflation is correct,  
universe is expected to be flat

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

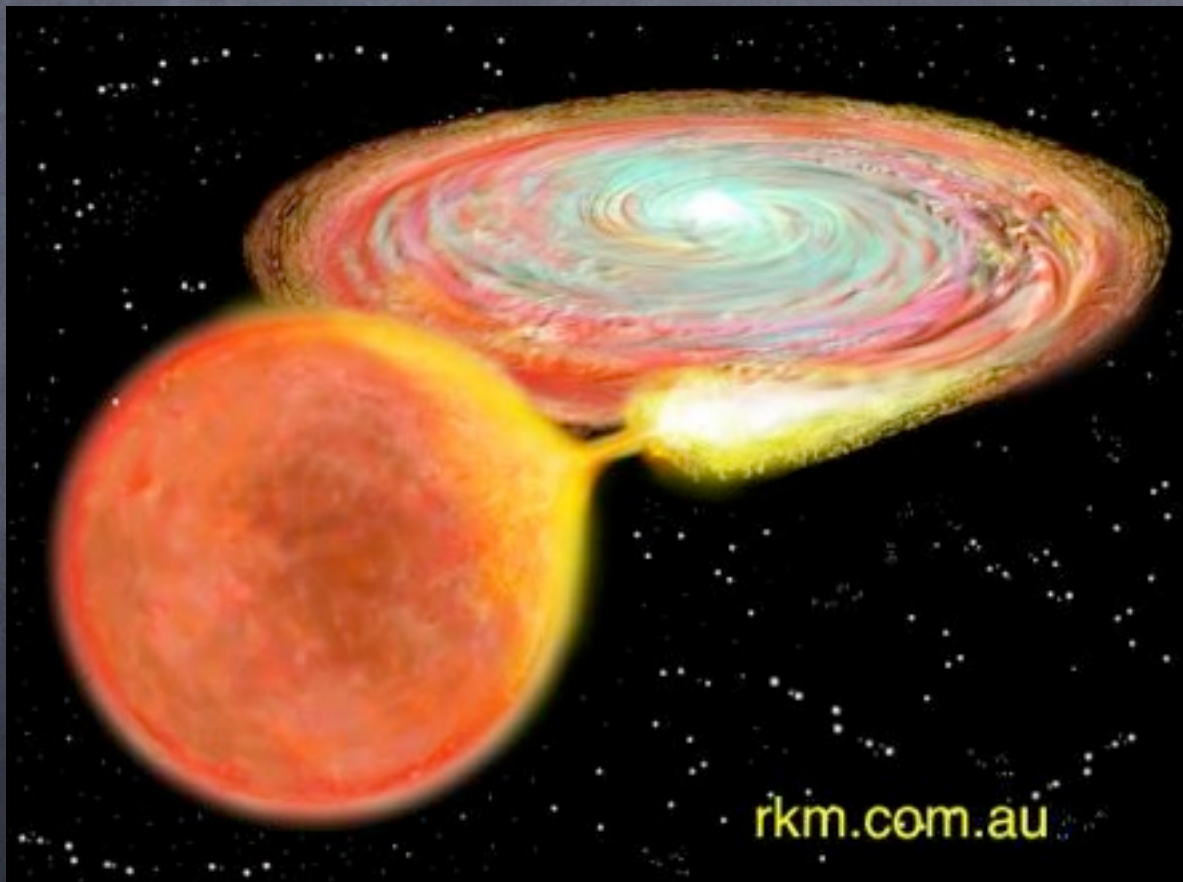
By measuring **distances** in the universe, you can determine its curvature



Problem:  
distances in astronomy  
are notoriously  
**hard to measure**

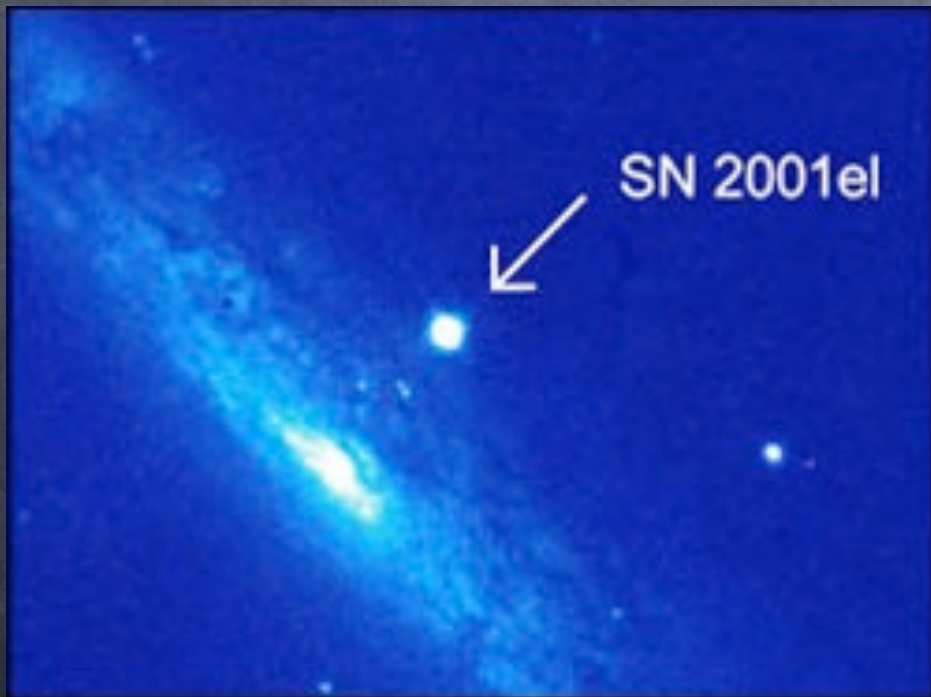
# Type Ia Supernovae!

A white dwarf accretes matter from a companion.

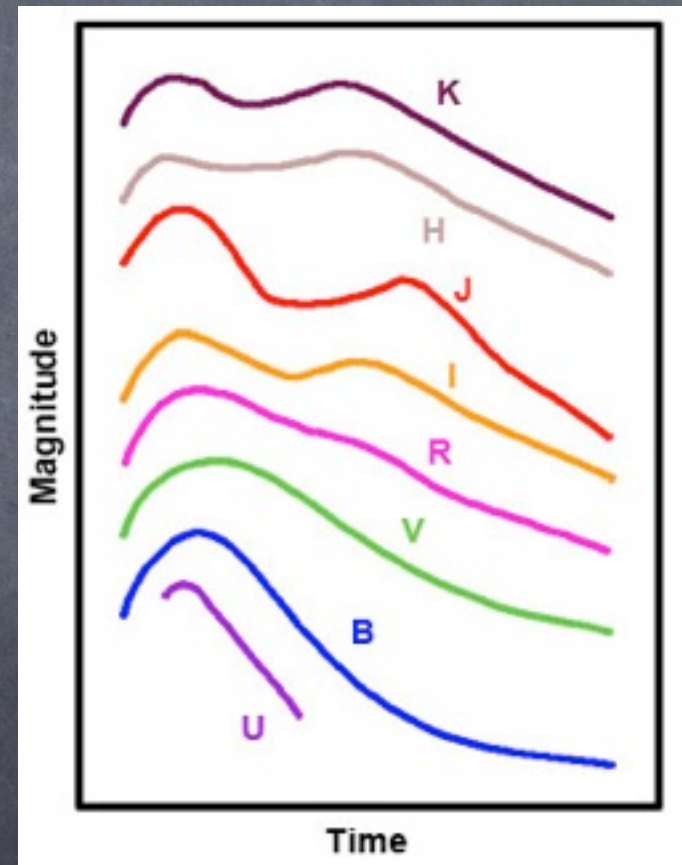


# Type Ia Supernovae

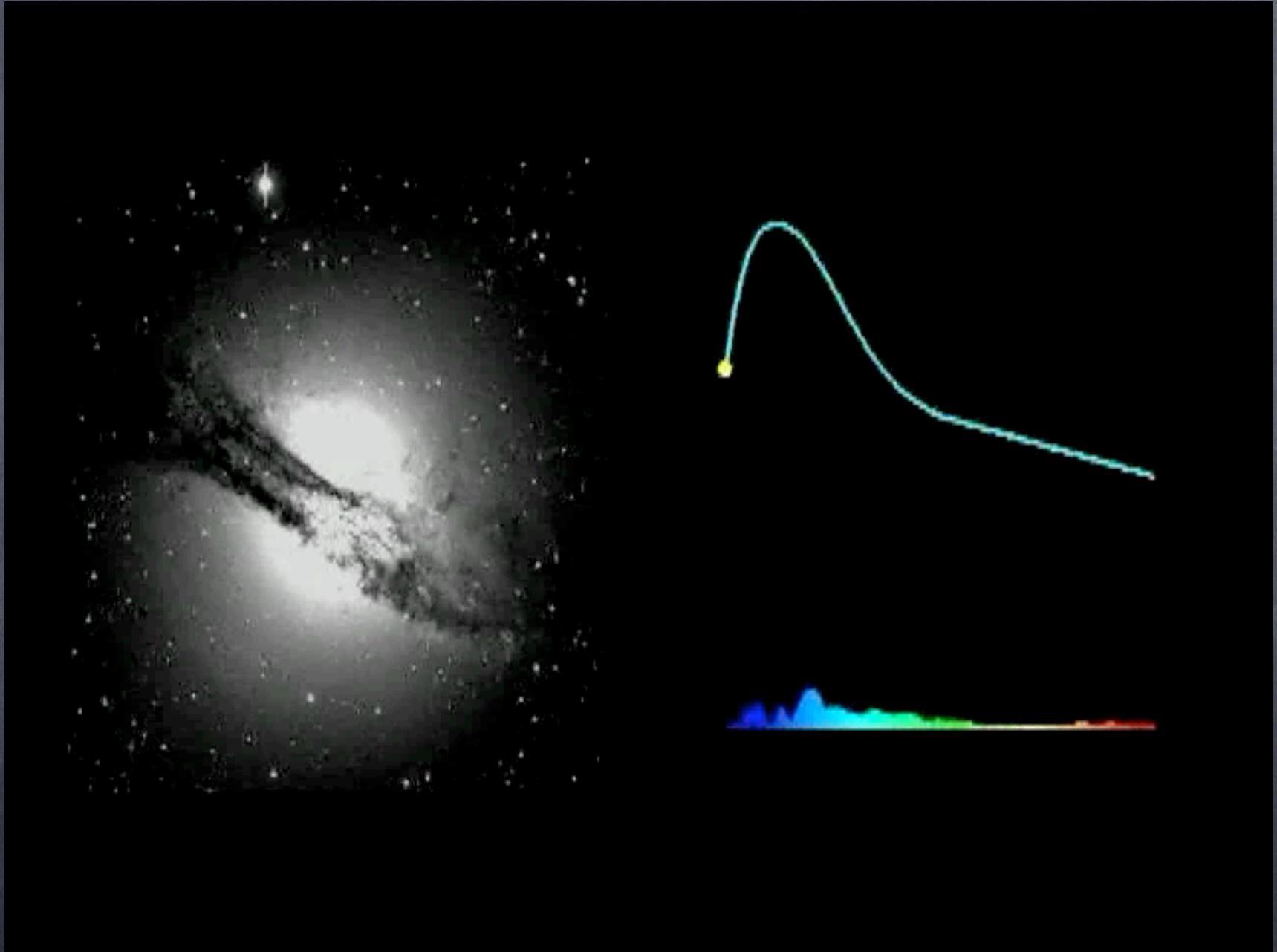
If the star's mass is greater than a certain amount, it **explodes**



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  $\rightarrow 1/\text{distance}^2$



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

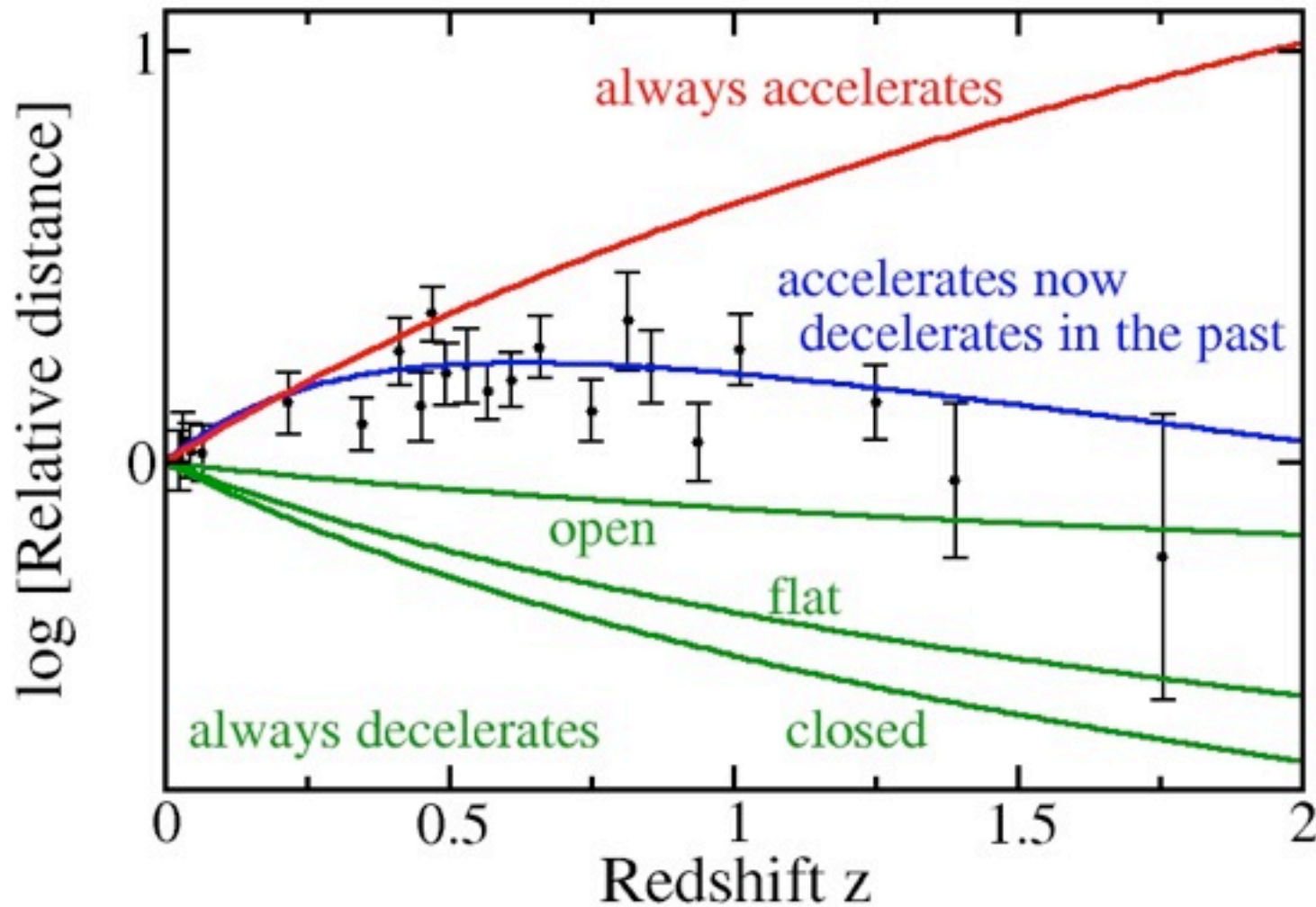
Dr. Saul Perlmutter,  
Supernova Cosmology Project



Dr. Brian Schmidt,  
High-redshift Supernova Team



So, starting in the mid-1990s...



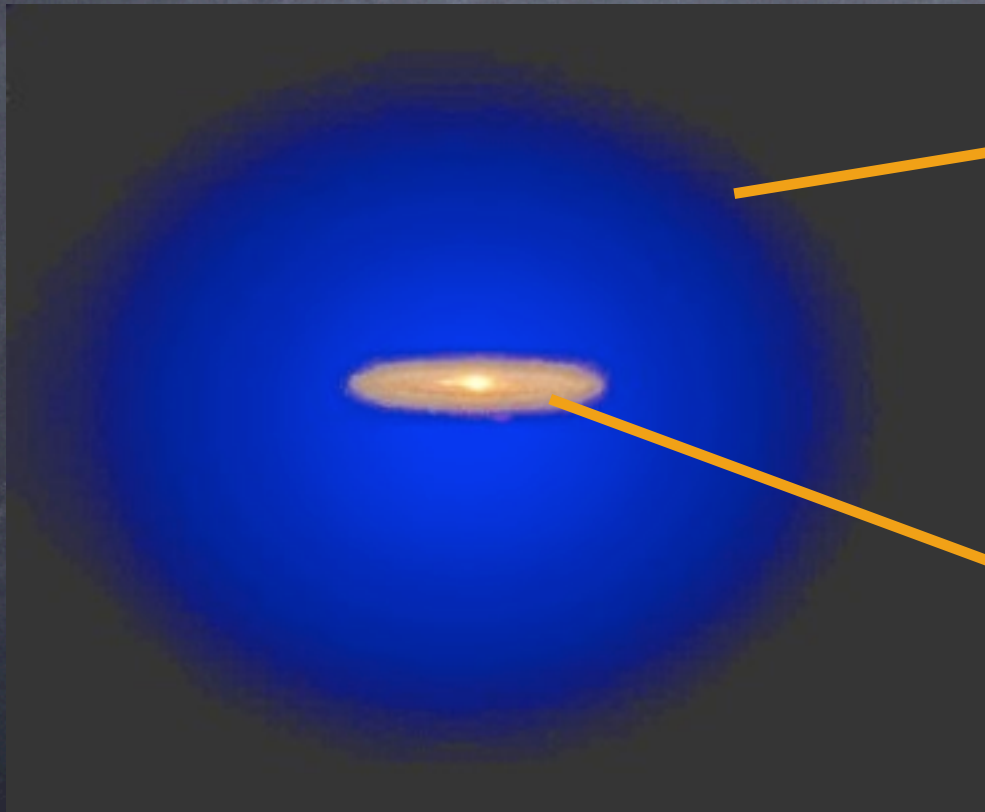
# Dark Energy



- 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

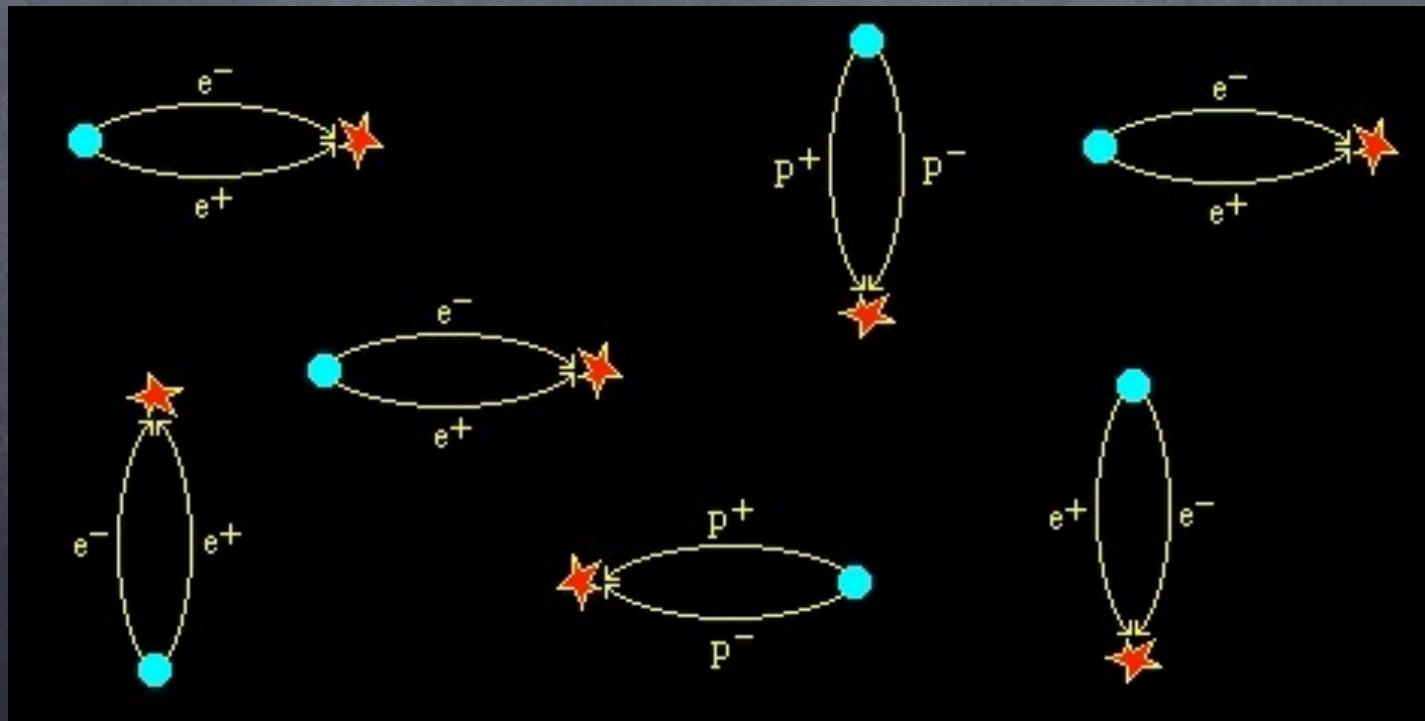
# Consequences of DE

- 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 last 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

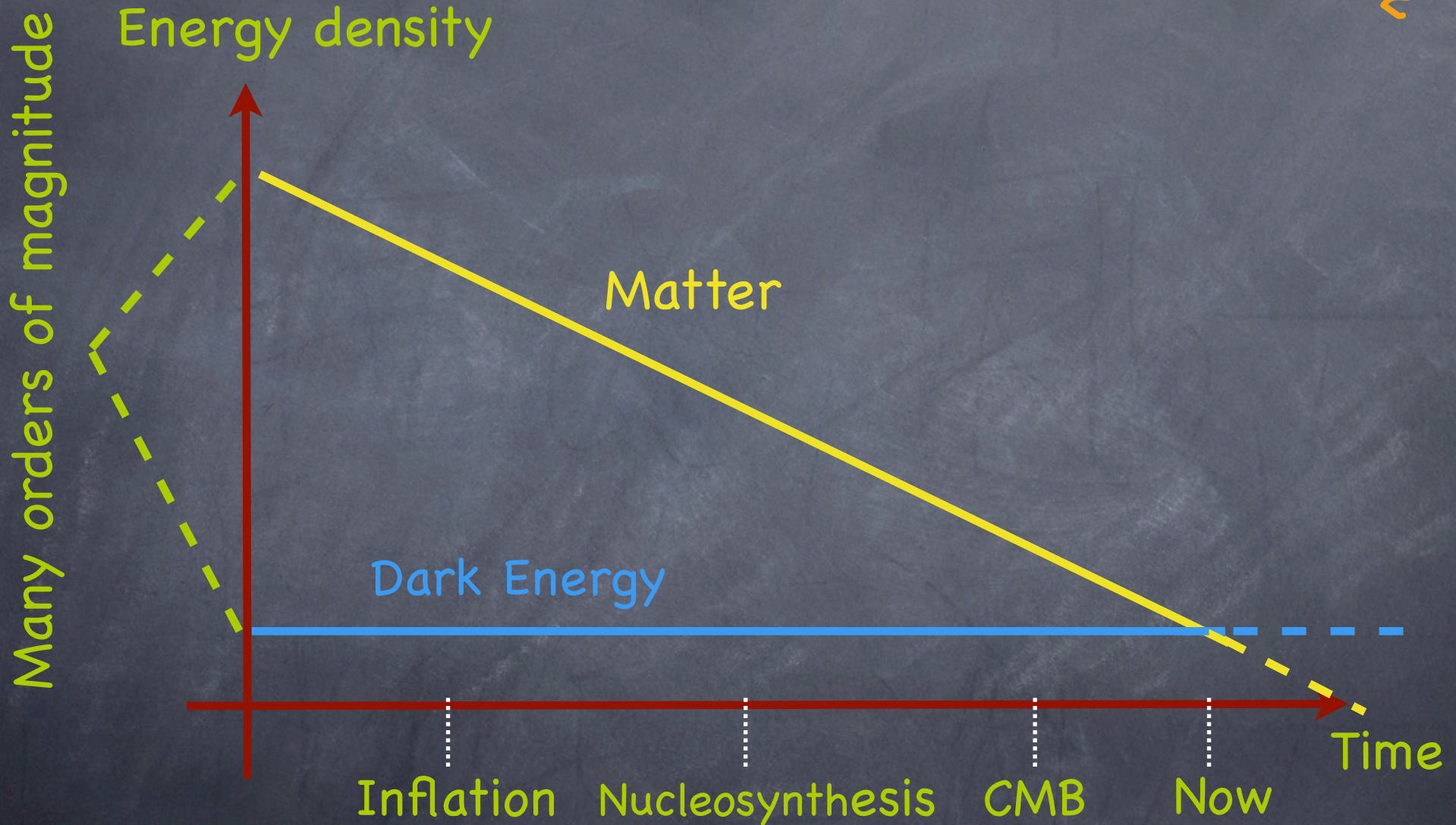
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(or  $10^{120}$ ) times more than the observed amount

This is known as  
the **COSMOLOGICAL CONSTANT PROBLEM**

# "Why Now!?"

Mystery  
#2



This is known as the **COINCIDENCE PROBLEM**

One puzzle: all matter dilutes away,  
but dark energy remains constant.  
So why are they (very roughly)  
comparable today?



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

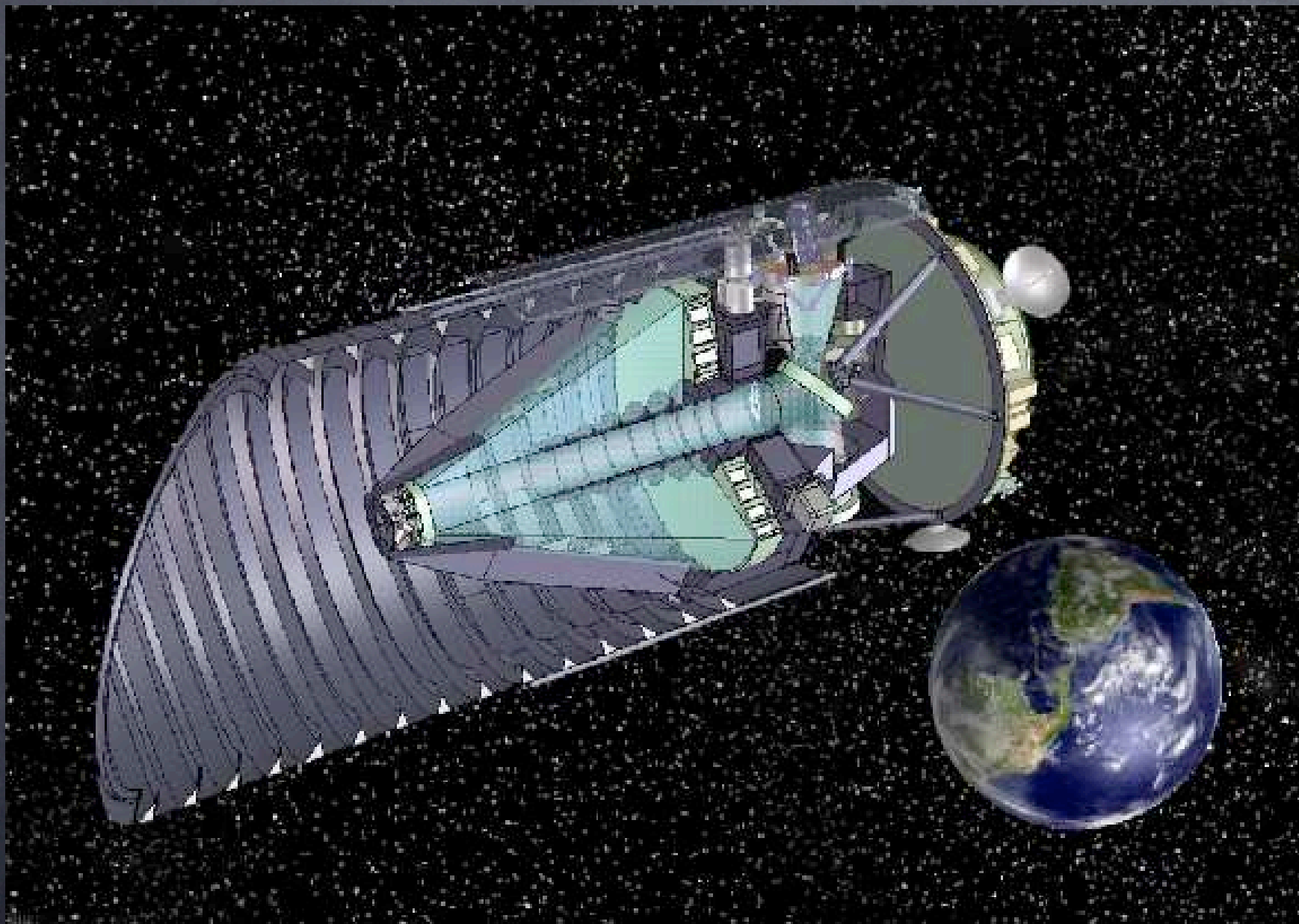
# How do we find out more about Dark Energy?

- 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](http://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>