

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.

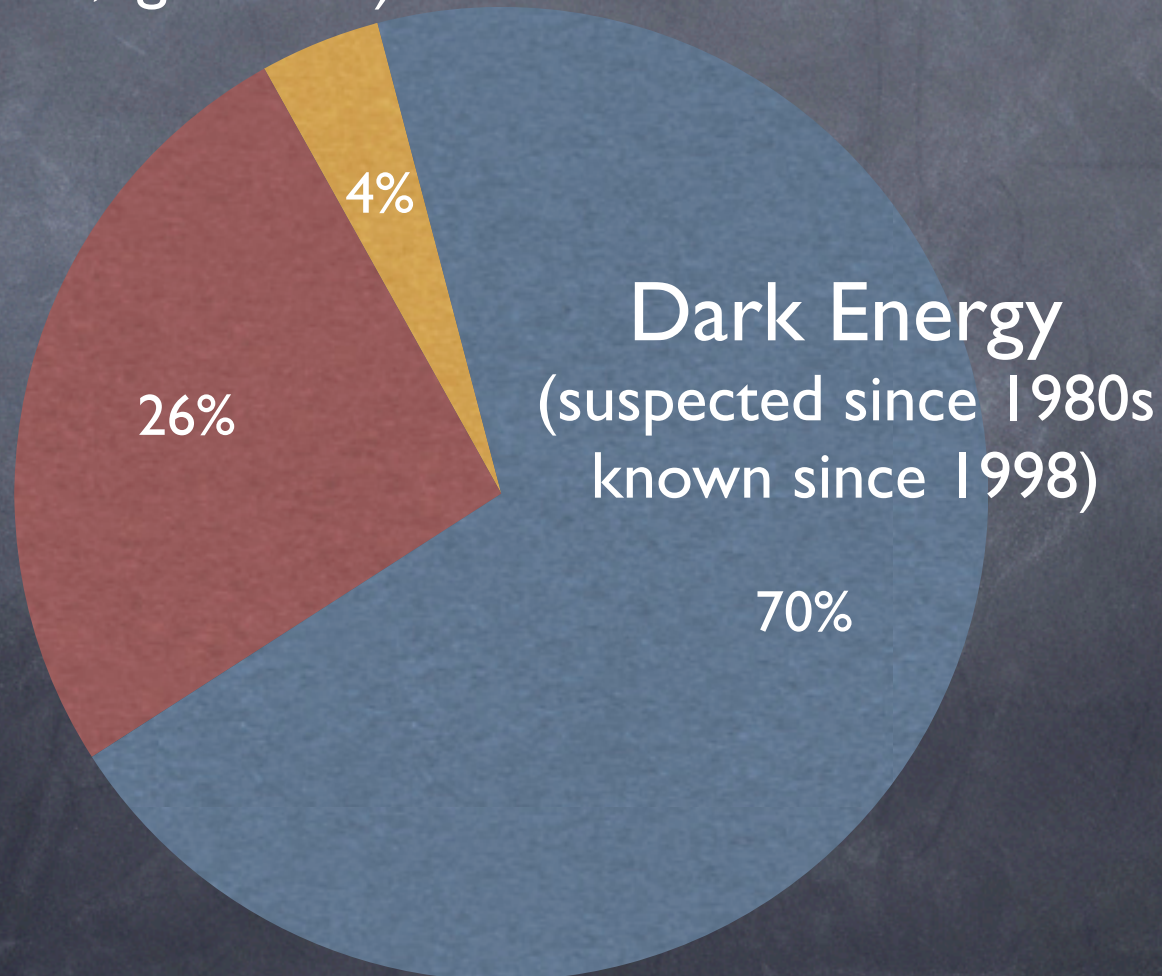
But we are getting closer to the
answer.

Makeup of universe today

Visible Matter
(stars 0.4%, gas 3.6%)

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

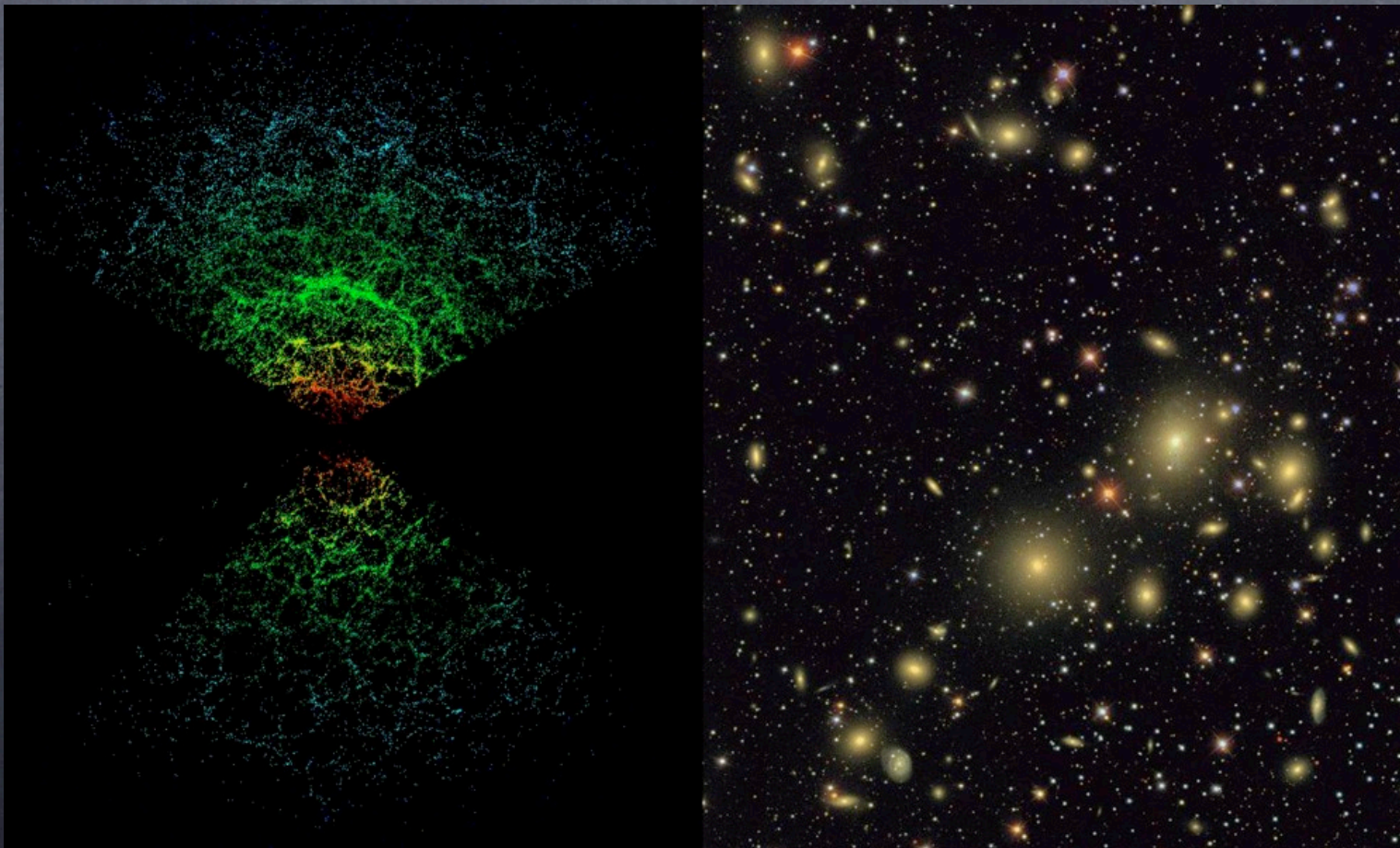
Also:
radiation (0.01%)



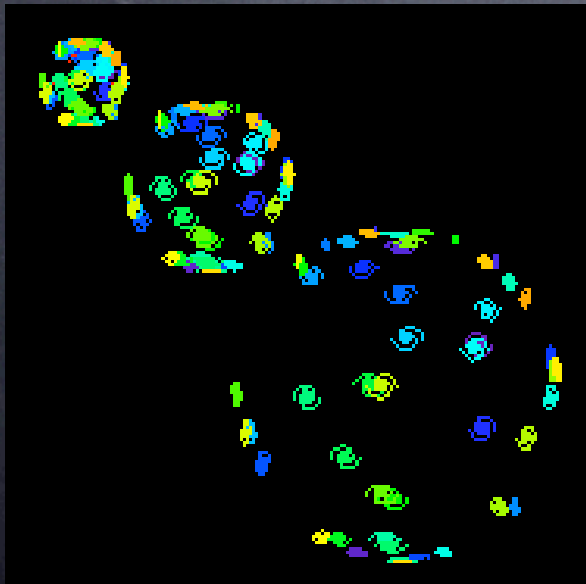
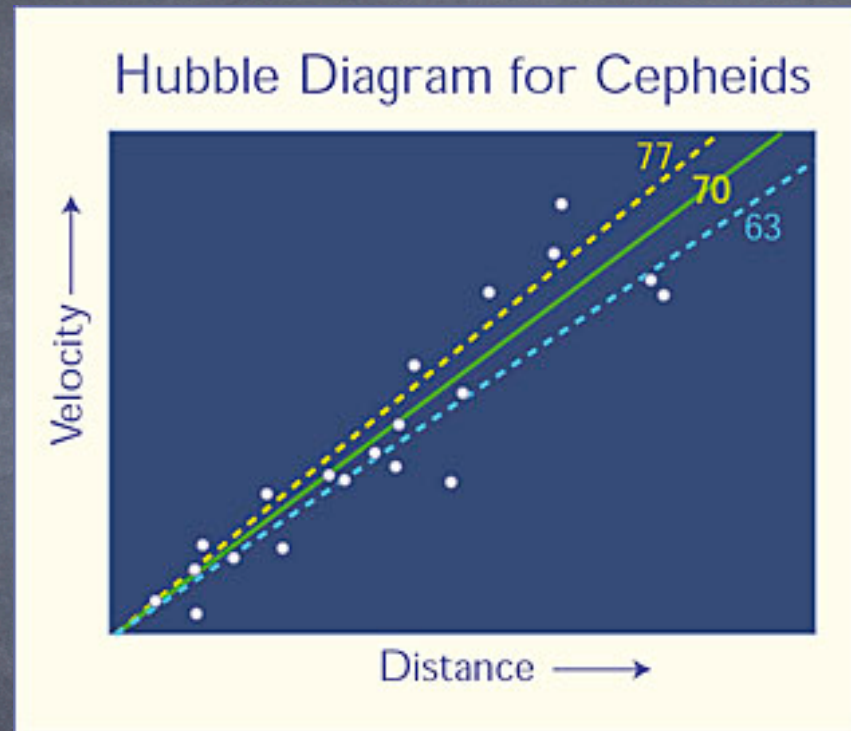
Dark Energy
(suspected since 1980s
known since 1998)

The universe is homogeneous and isotropic

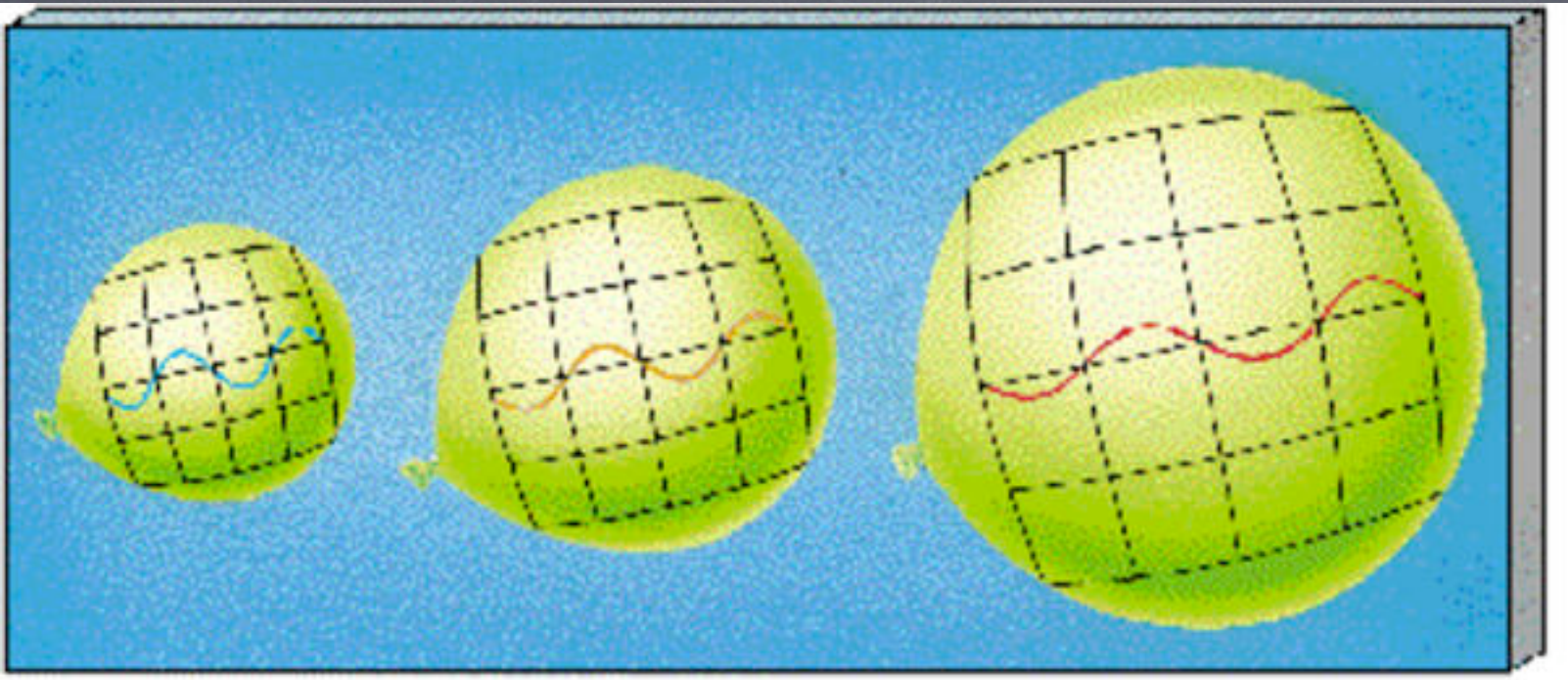
- 👁 **Homogeneous**: appears the same everywhere in space
- 👁 **Isotropic**: appears the same in every direction



The universe is expanding!

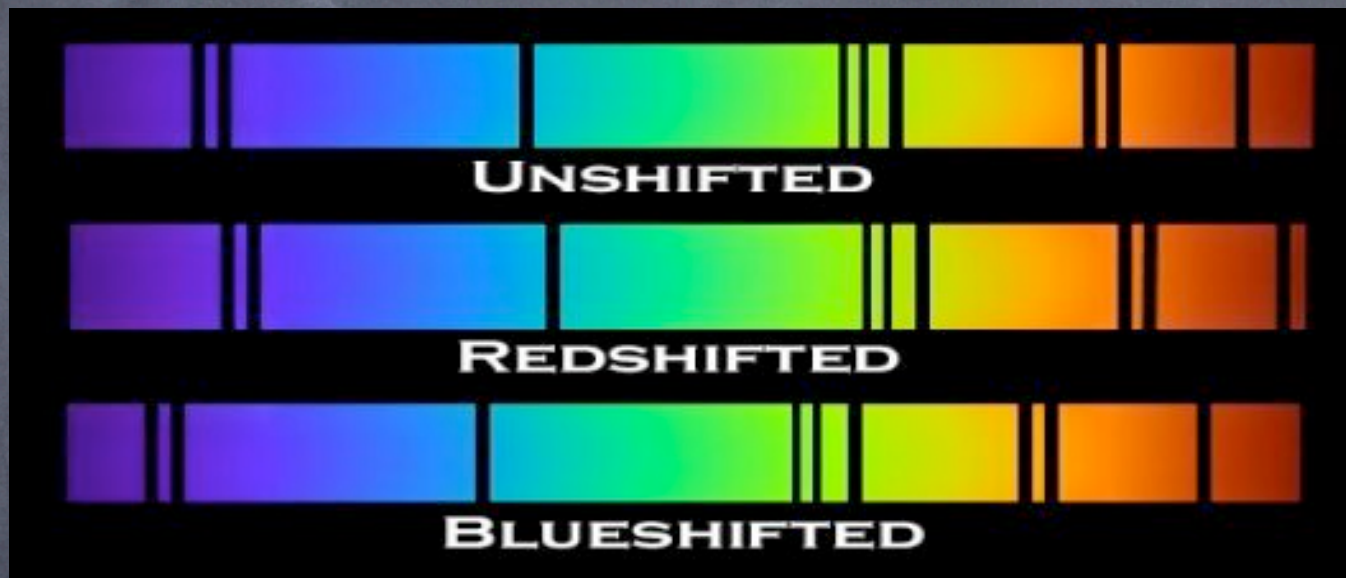


Edwin Hubble



- Expansions dilutes the matter particles
- Expansion stretches wavelength of radiation (what is another name for this stretching?)

Redshift



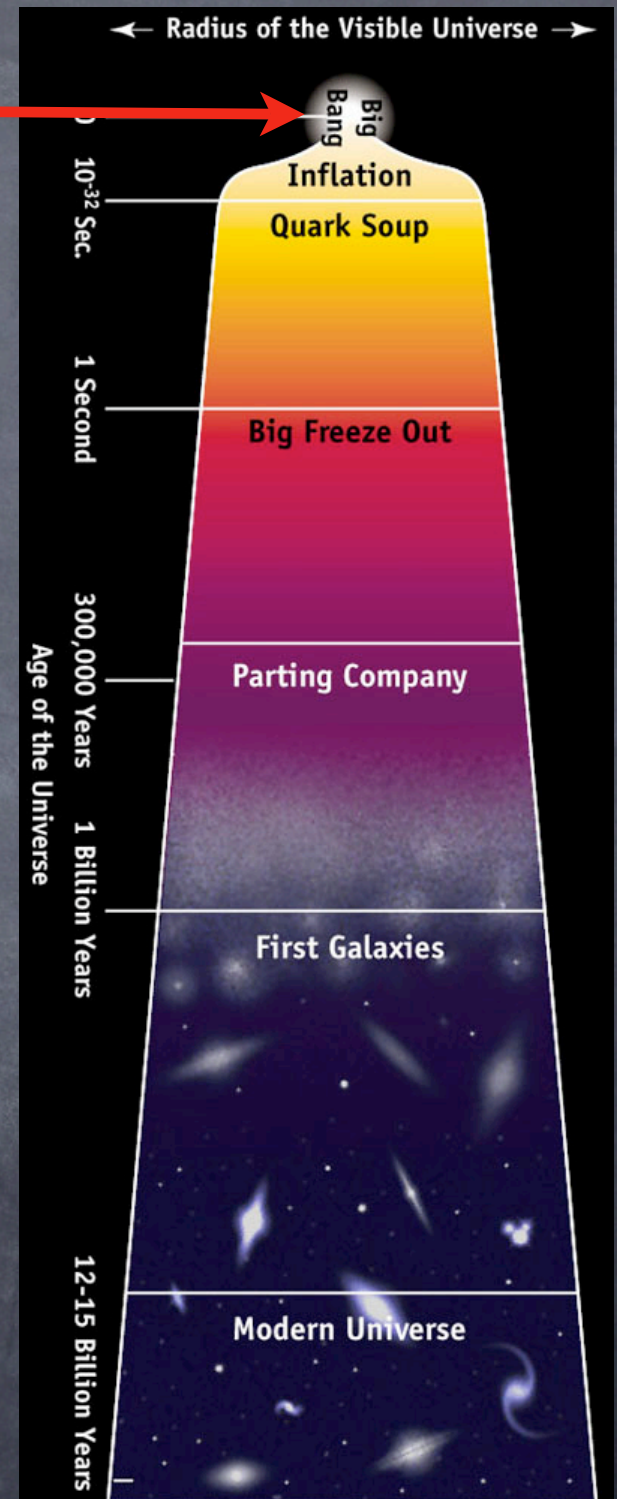
$$1 + \text{redshift} = \frac{\text{size of universe now}}{\text{size of universe when light was emitted}}$$

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

An Overview...

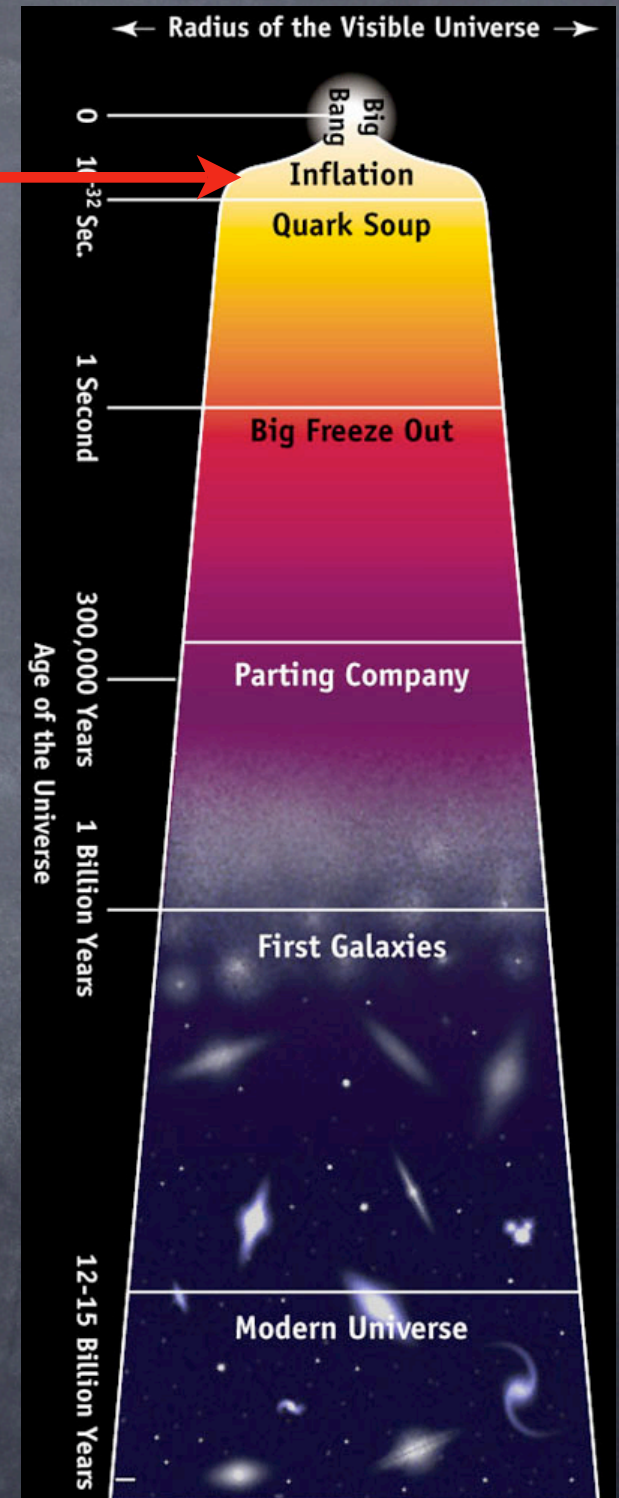
Big Bang ($t=0$)

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



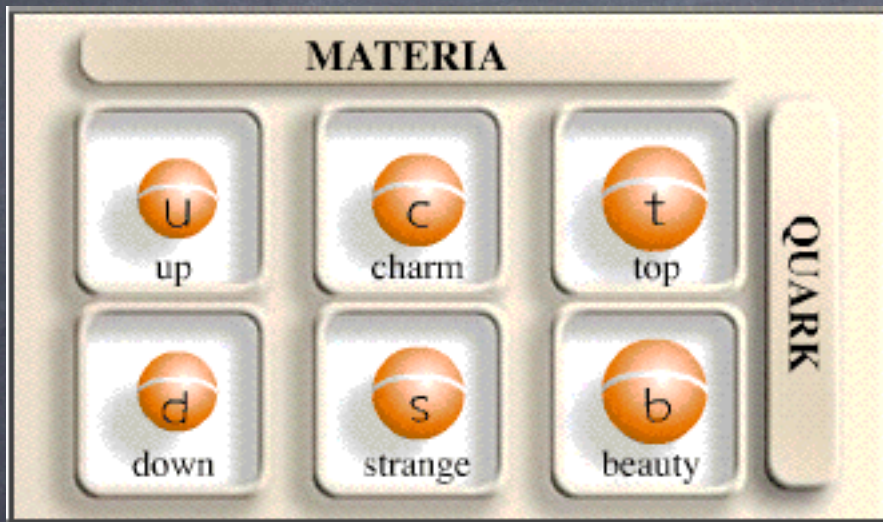
Very early Universe (t =tiny moments after BB)

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

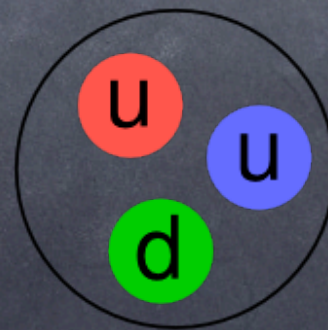


Quark Soup ($t < 1$ sec)

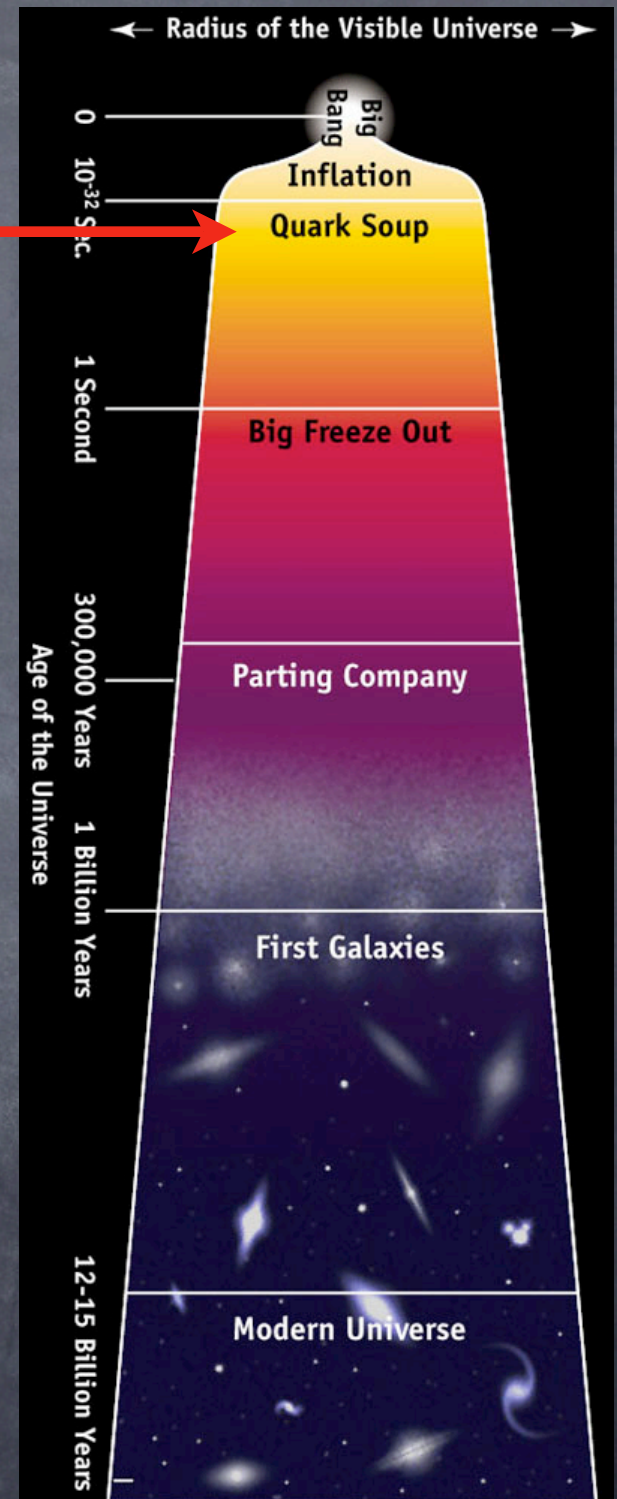
Quarks are free, floating around



Later, they are bound

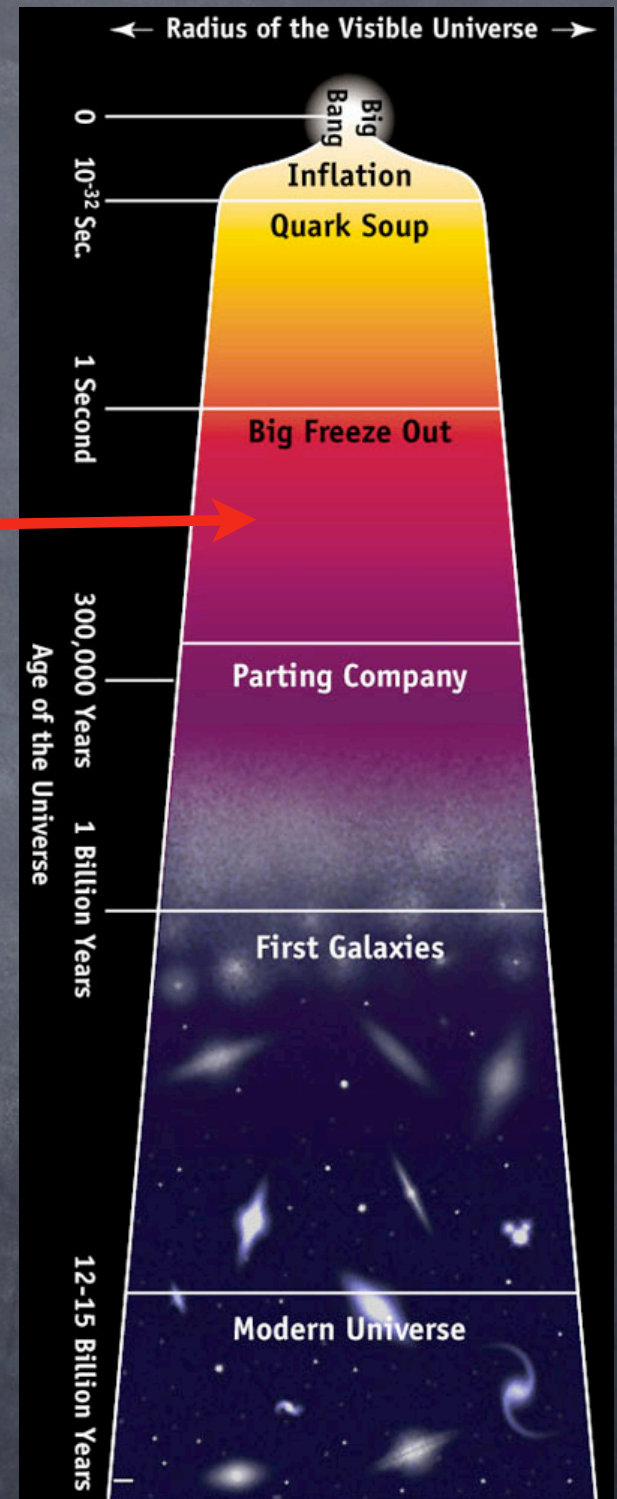


PROTON



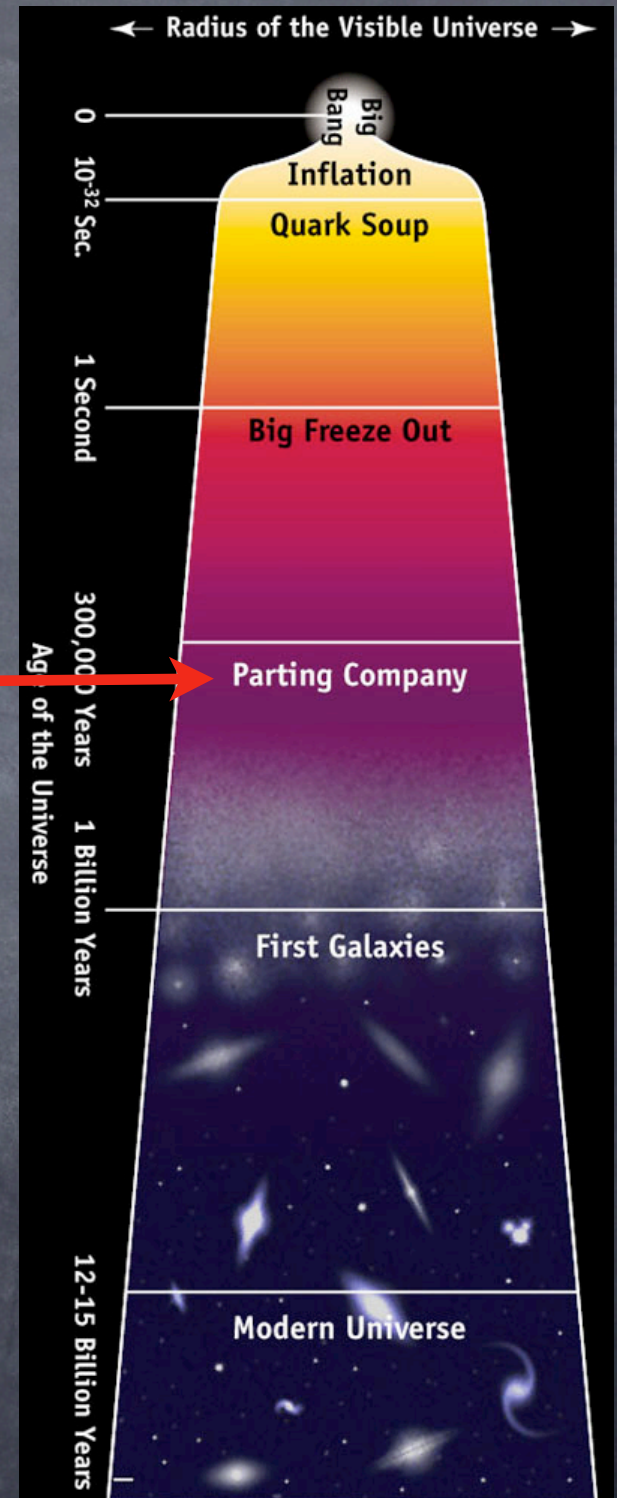
Nucleosynthesis ($t=3$ minutes)

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



Universe becomes transparent ($t=300,000$ yrs)

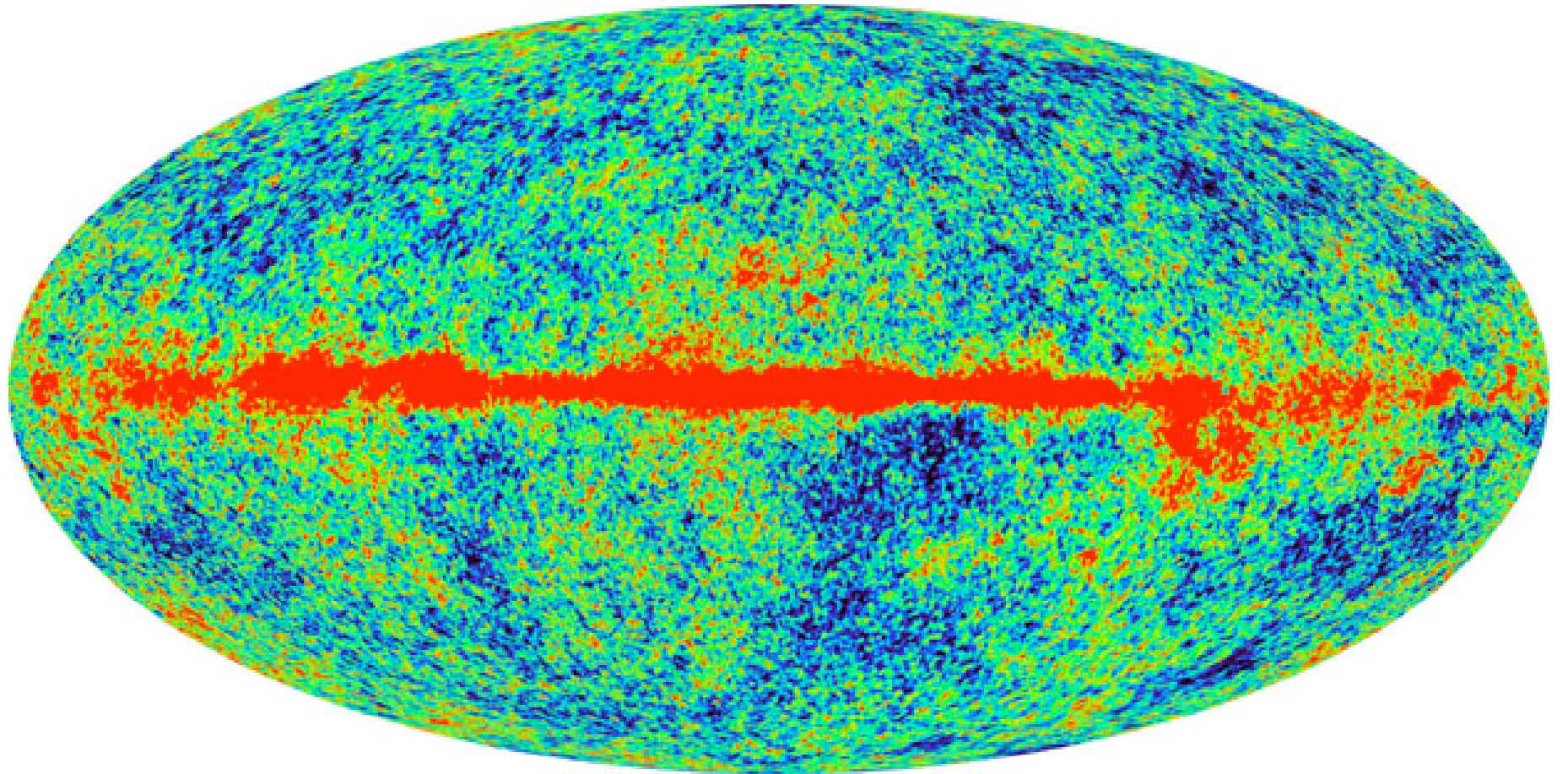
- Radiation finally free to propagate - universe has rarified enough
- The **Cosmic Microwave Background** radiation we observe has been released at this time (S. Meyer talk)
- Temp= 2.725 Kelvin
- Uniform to one part in $100,000$



T=2.726 Kelvin

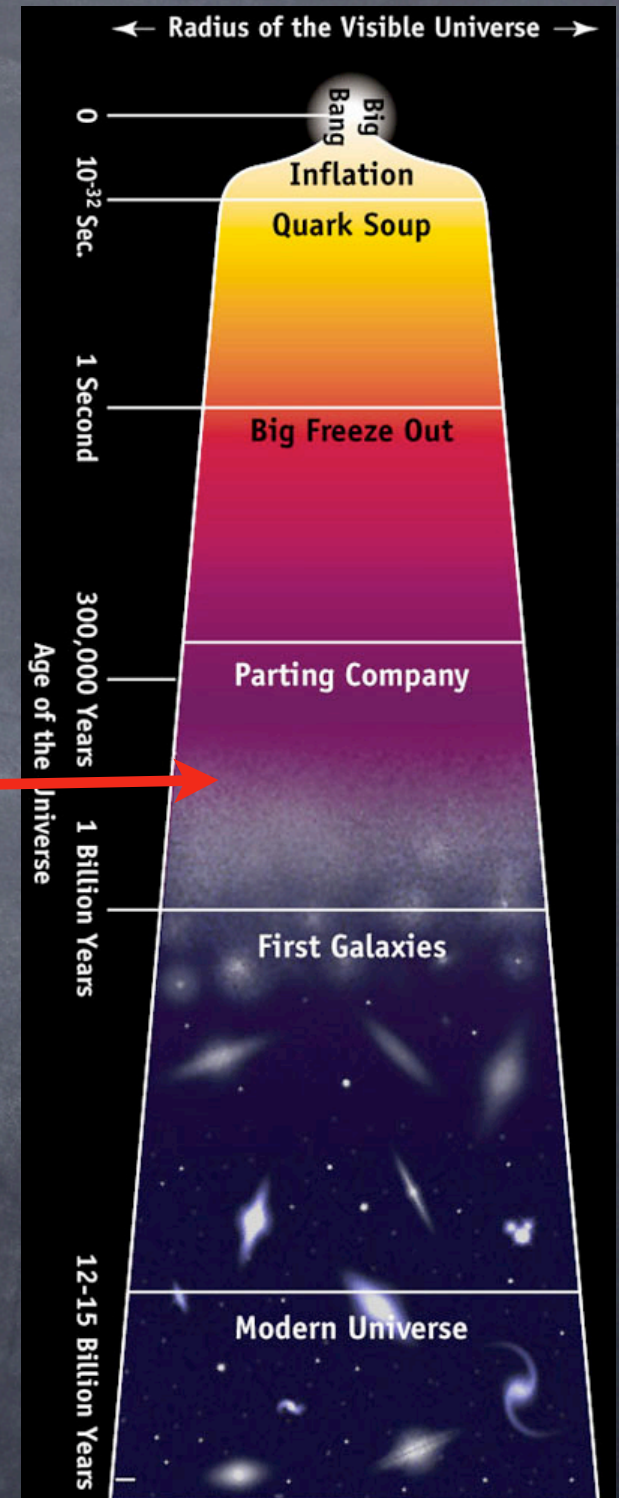


Fluctuations 1 part in 100,000 (of 2.726 Kelvin)



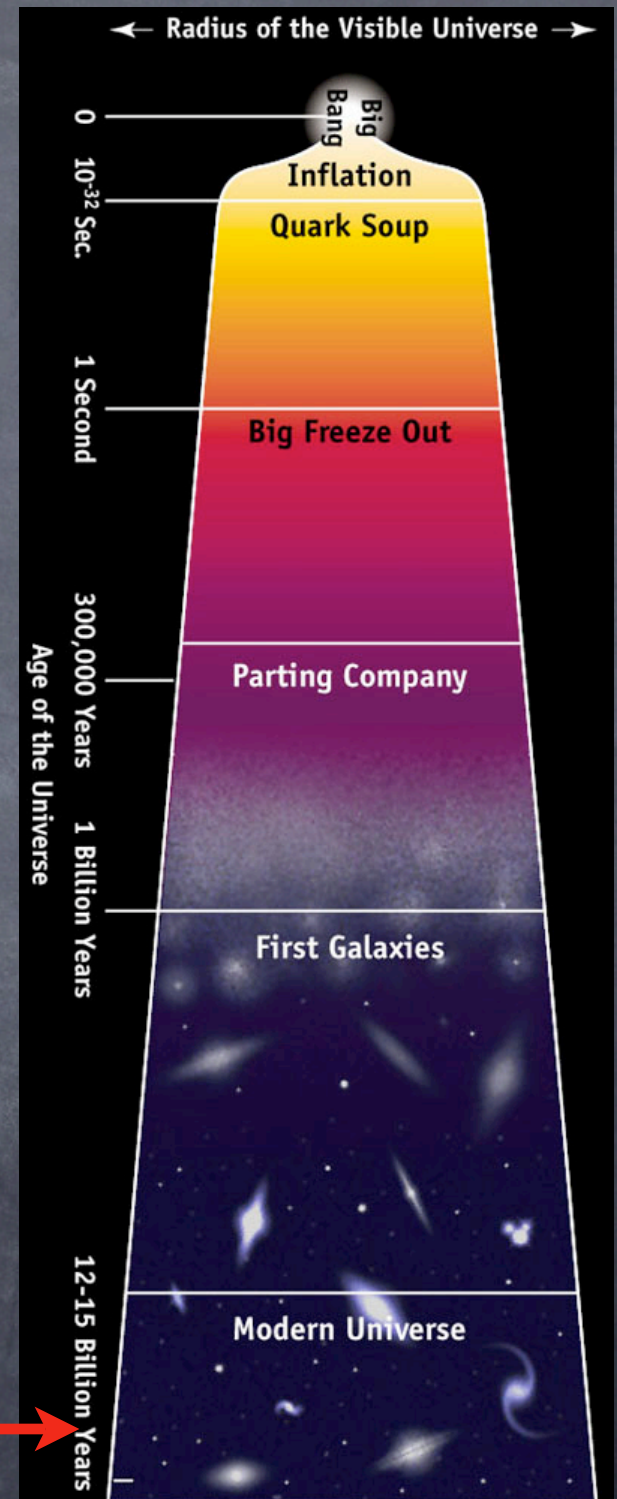
The dark ages ($t < 1$ billion yrs)

- Universe is dark, slowly becomes matter dominated
- First stars ionize the hydrogen atoms (N. Gnedin talk)
- First stars and first galaxies eventually form

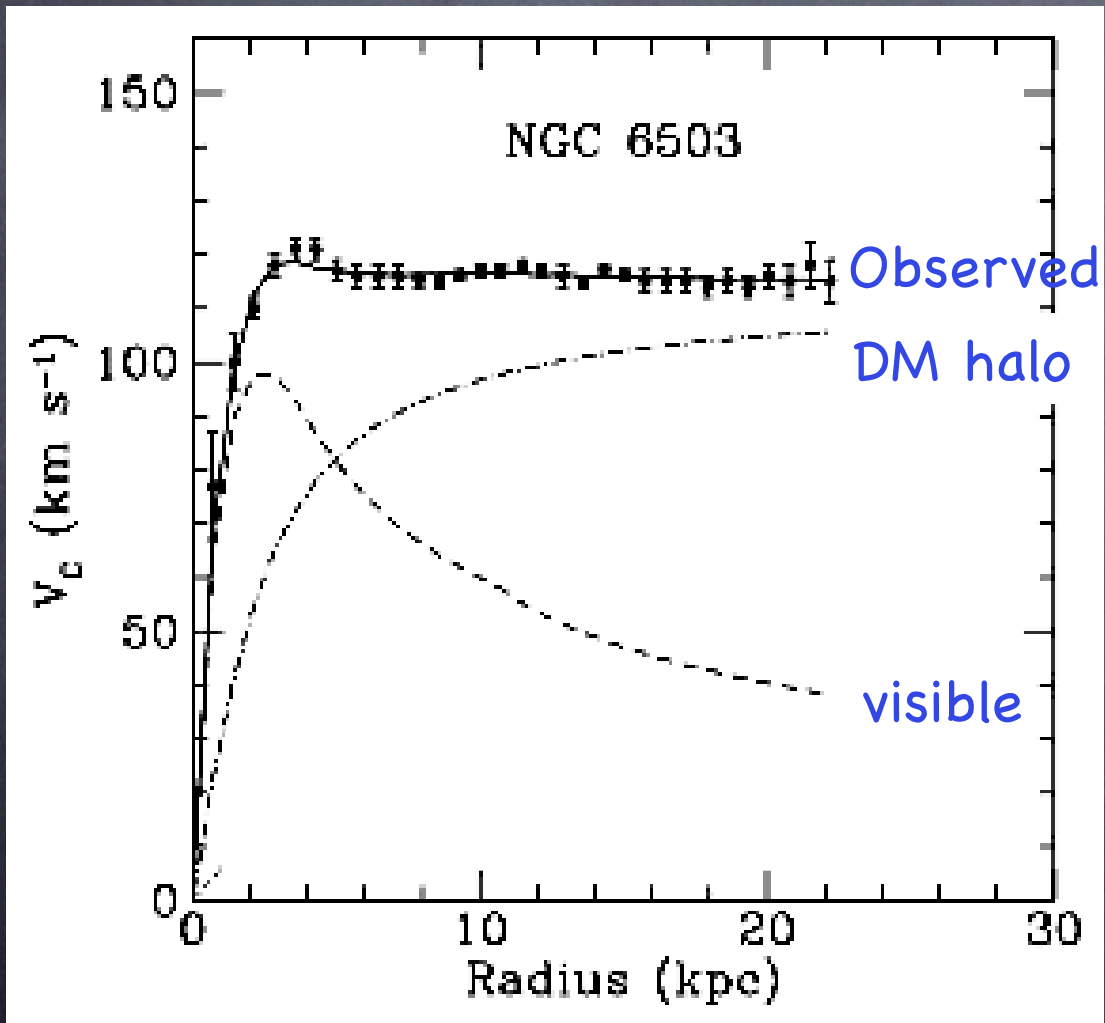


Modern Universe ($t < 13.7$ billion yrs)

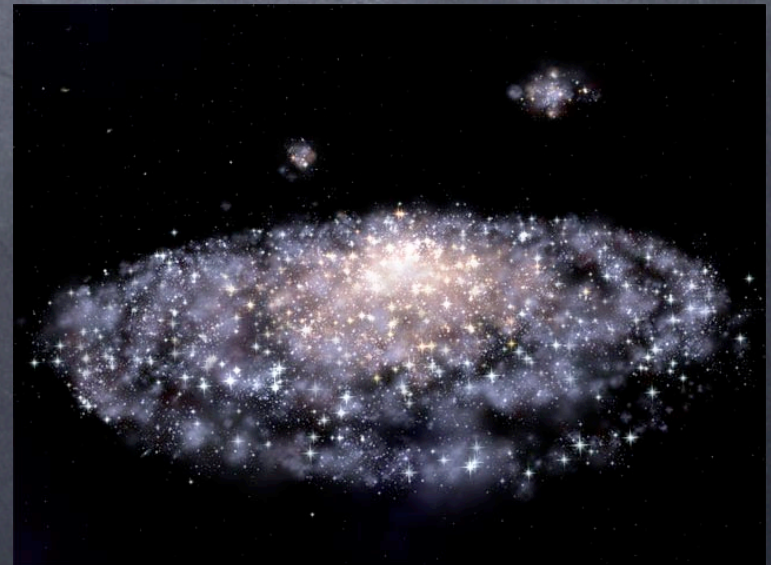
- Stars, Galaxies, Clusters of galaxies everywhere
- Even more Dark Matter than we cannot directly see
- Subject of this talk
- Universe is matter dominated – or so we thought!
- A big surprise is in store!!



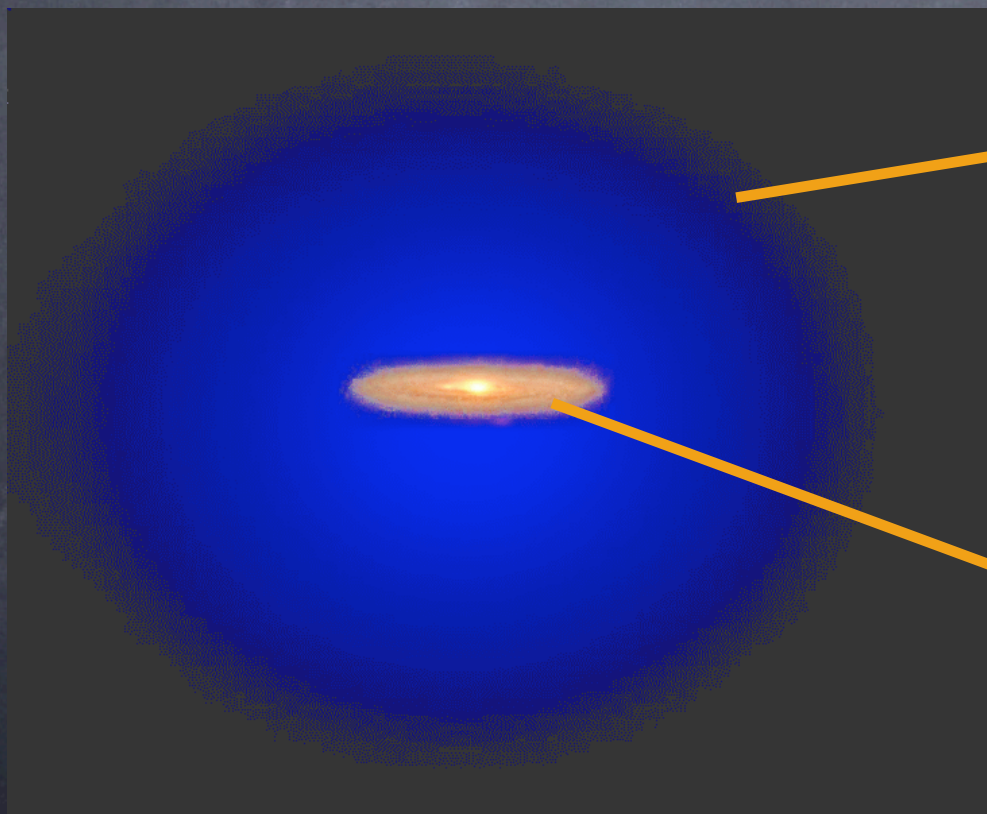
Aside: a quick overview of **Dark Matter**



Historically the first
evidence for DM:
“flat rotation curves”
(1970s)



Dark Matter is in "halos" around galaxies

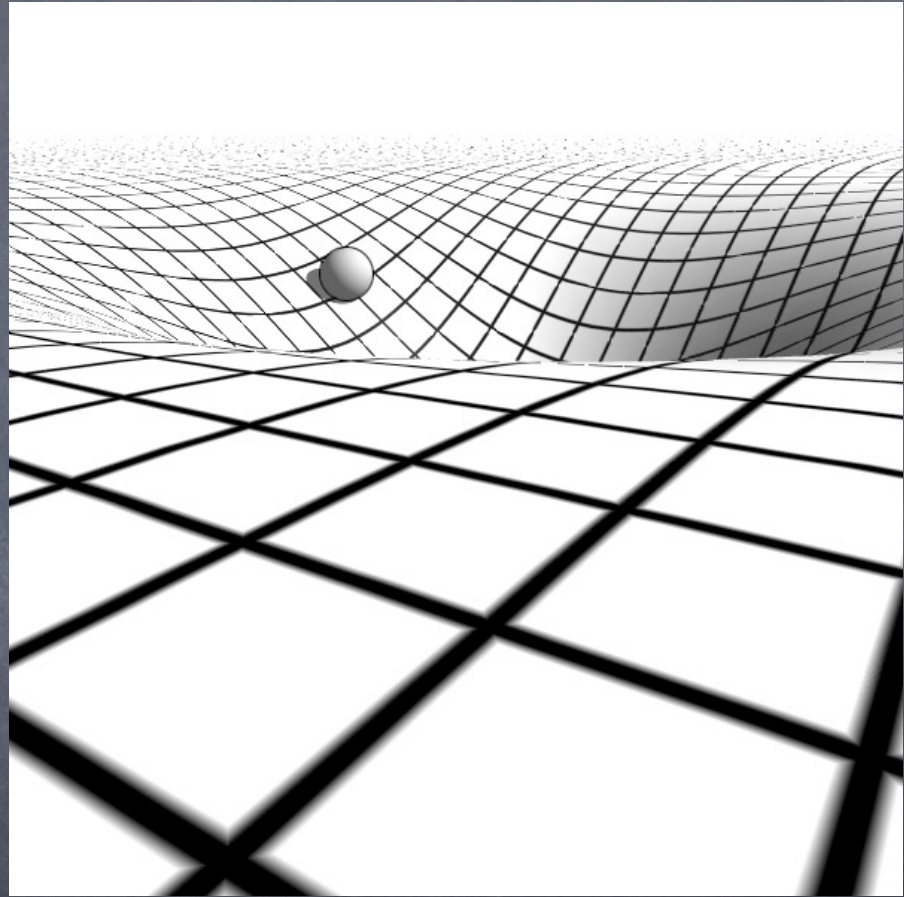
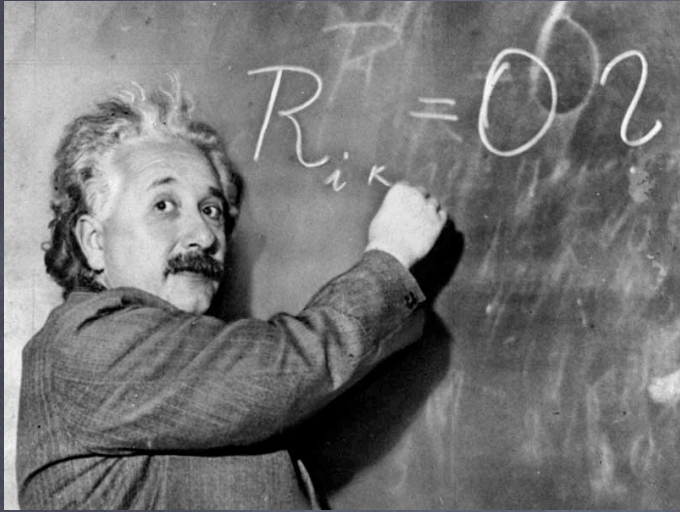


(invisible)

Dark Matter halo

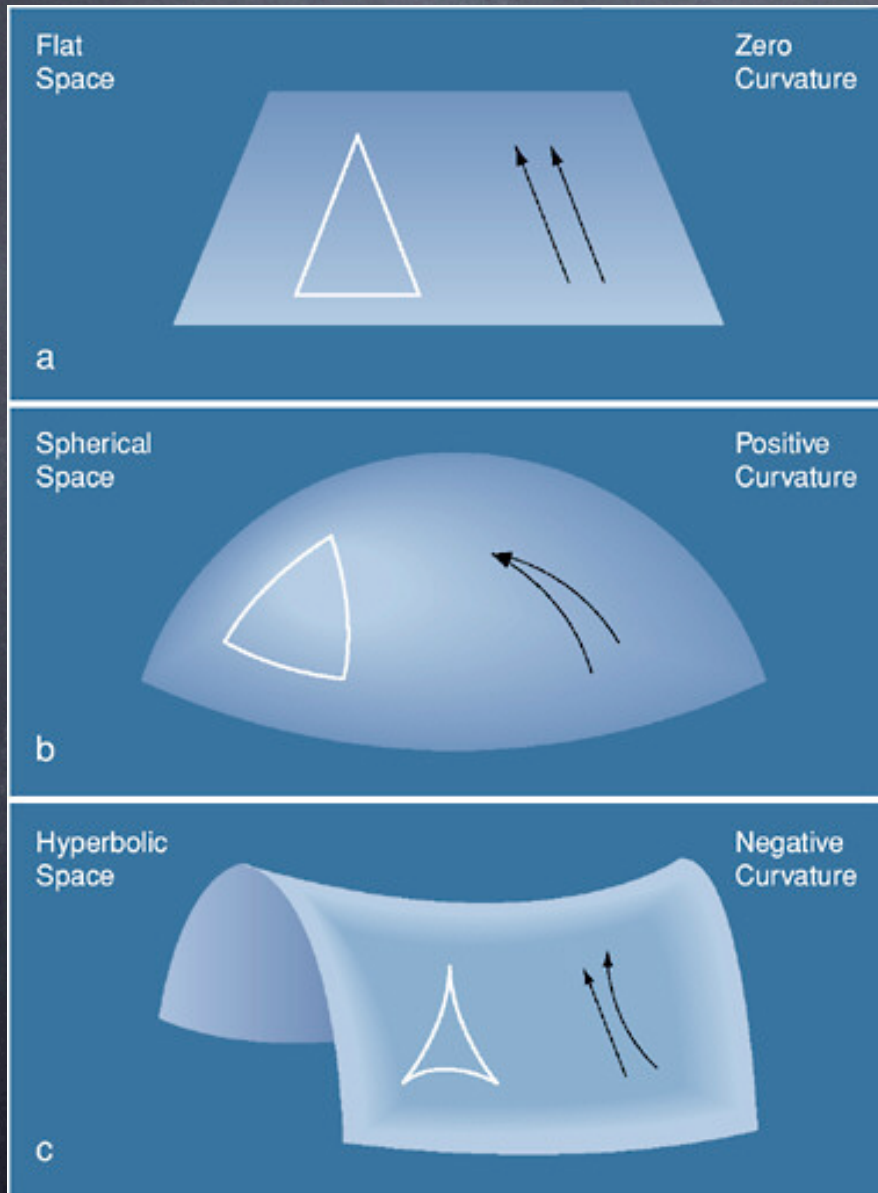
(visible) light
from galaxy

Einstein's theory of gravity



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

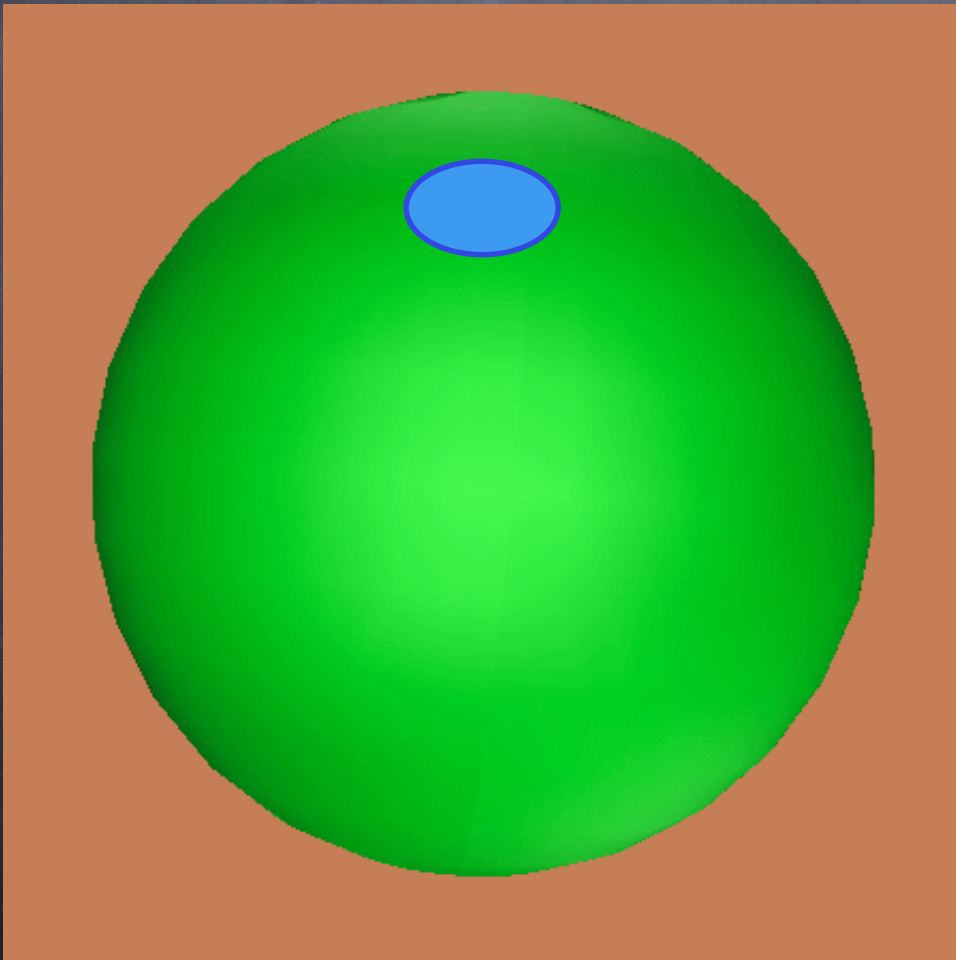
One implication of gravity:



Curvature of the universe is determined by the amount of "stuff" in it.

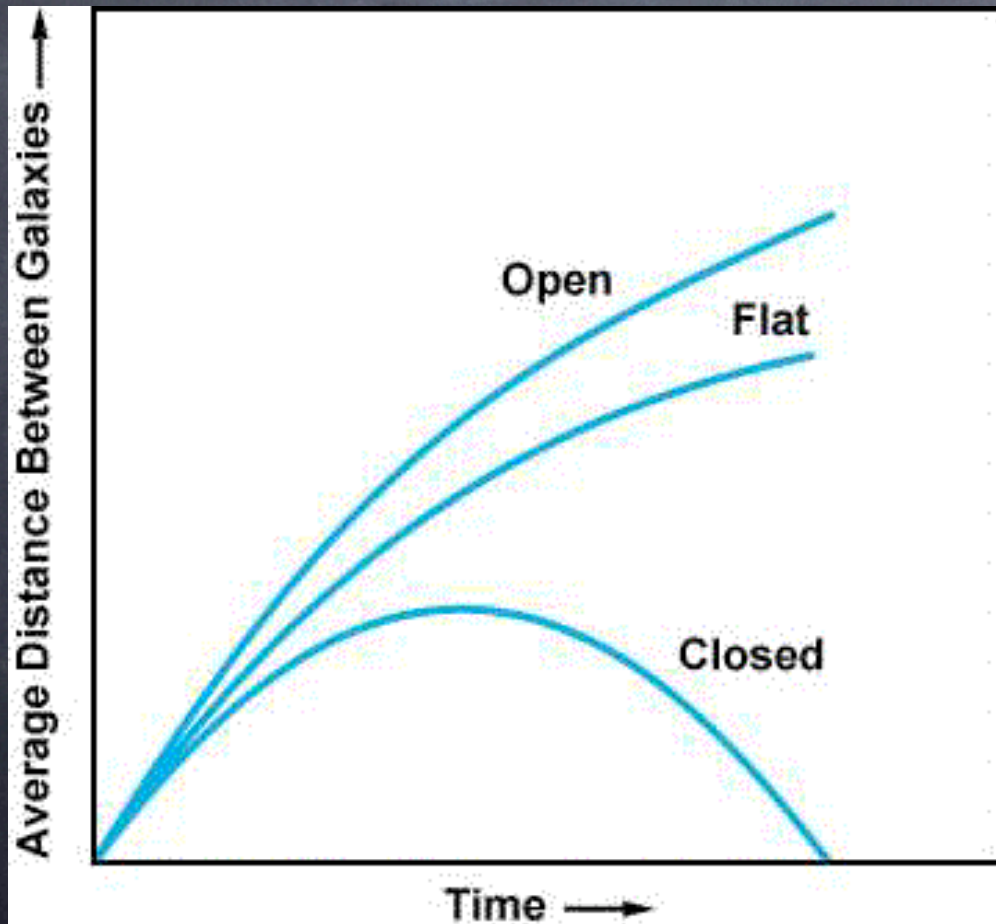
If inflation is correct,
universe is expected to be **flat**!

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

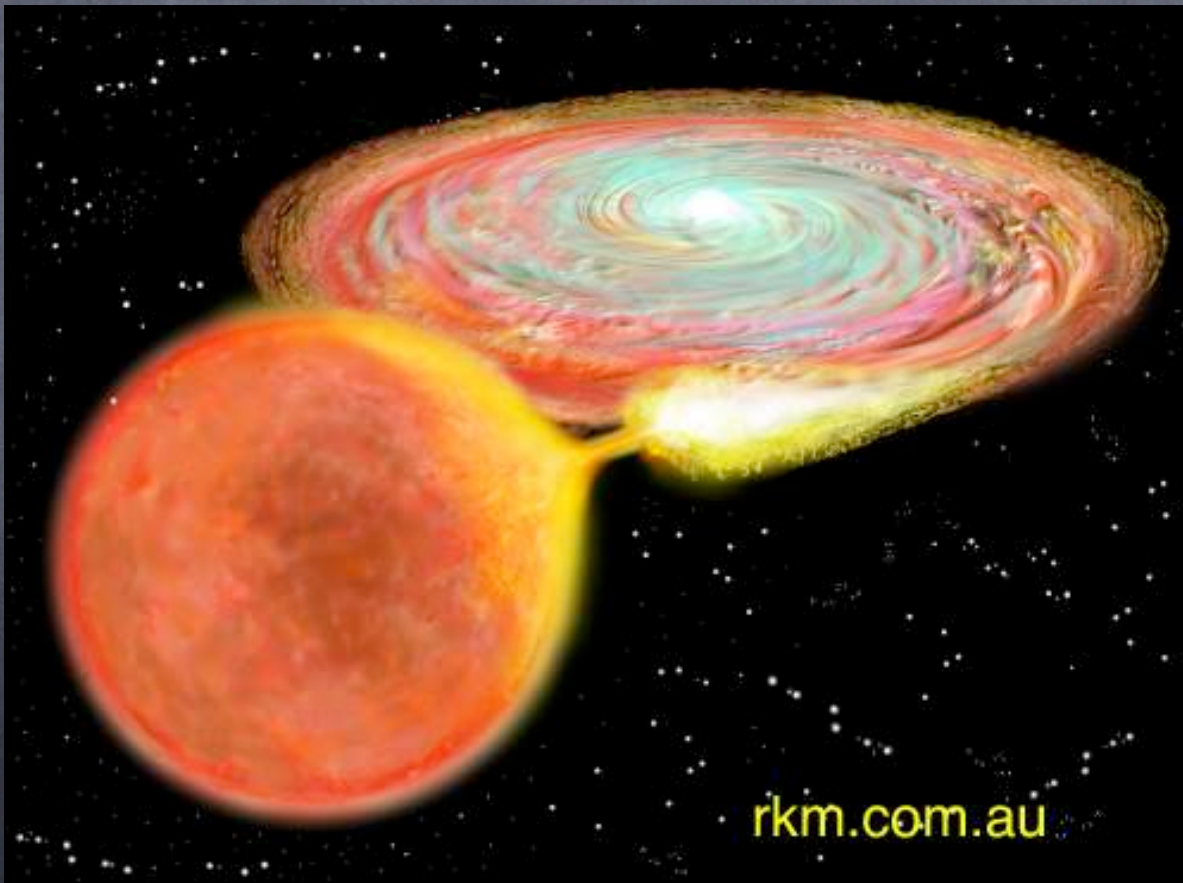


(or redshift)

Problem:
distances in astronomy
are notoriously
hard to measure

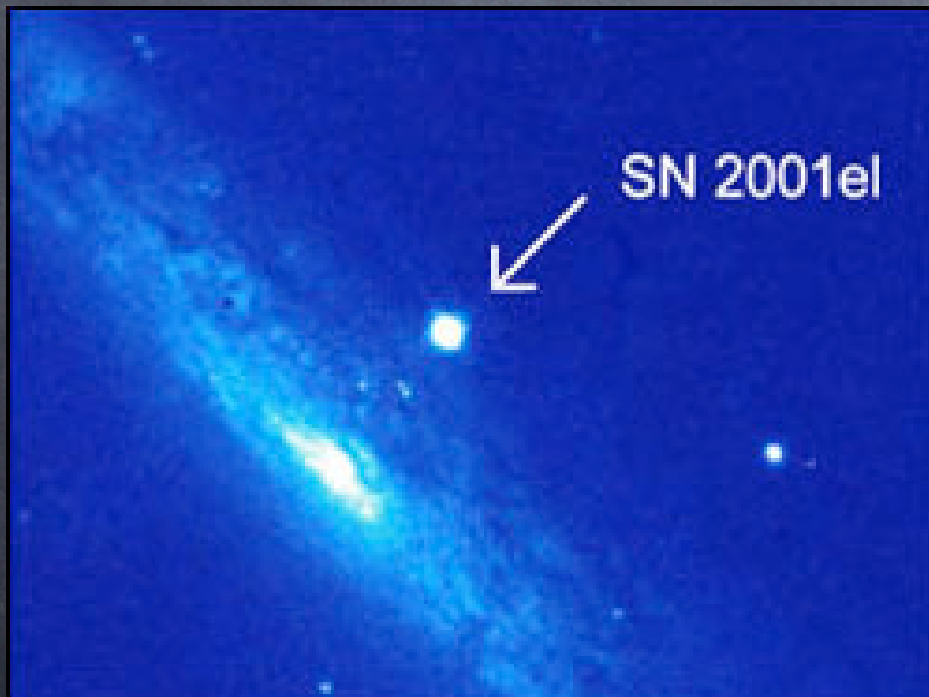
Type Ia Supernovae

A white dwarf accretes matter from a companion.

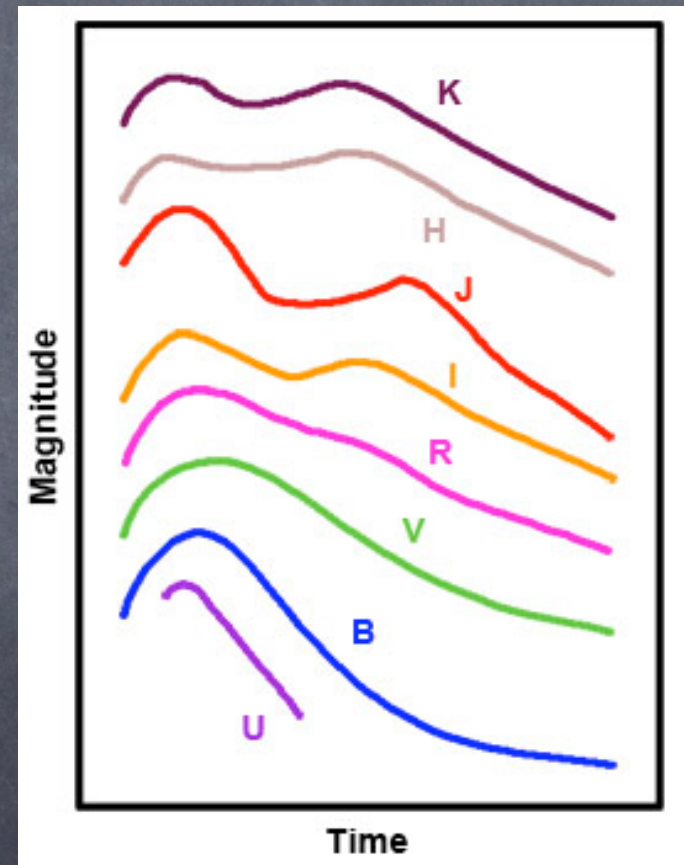


Type Ia Supernovae

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



As bright as the whole galaxy!



Show movie...

Key property of SNe Ia:

Their intrinsic luminosity is (nearly) constant

=> They are **standard candles**



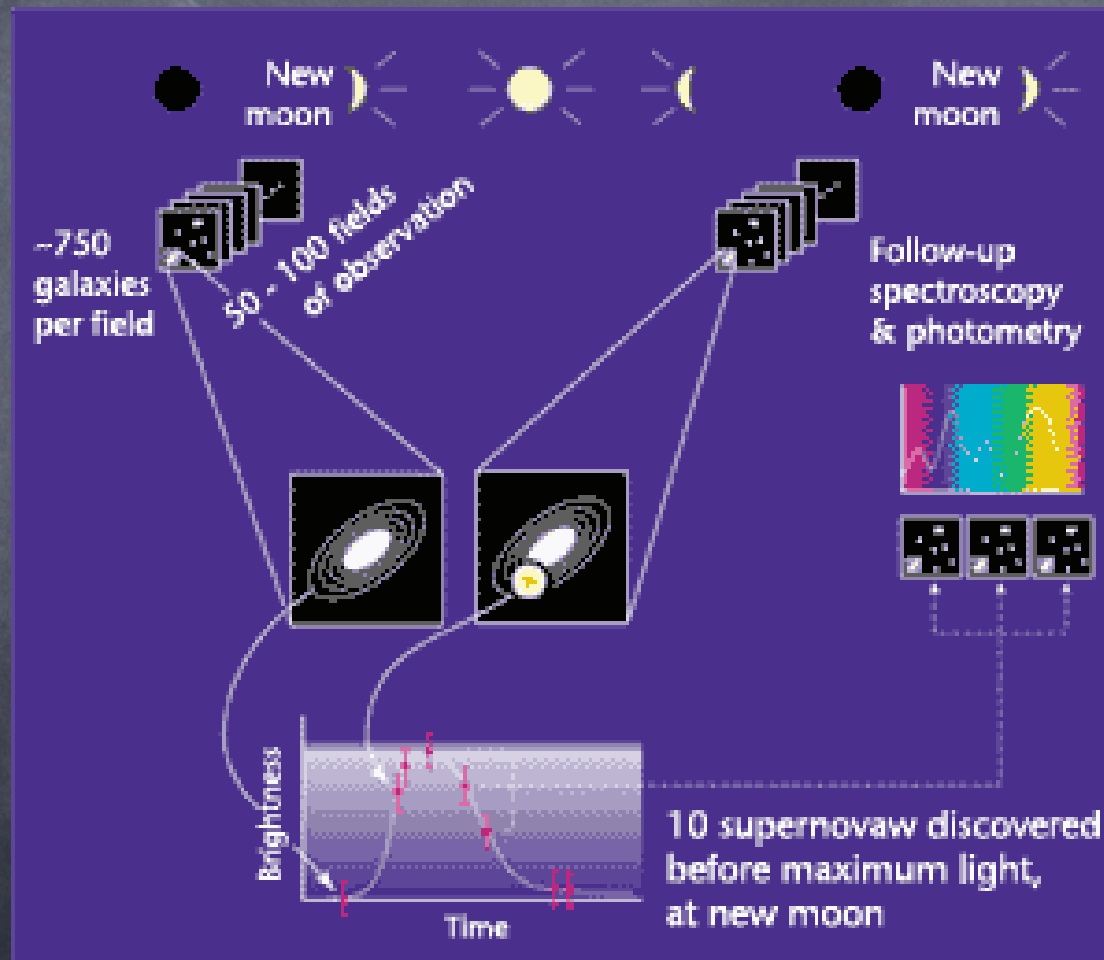
flux $\rightarrow 1/\text{distance}^2$



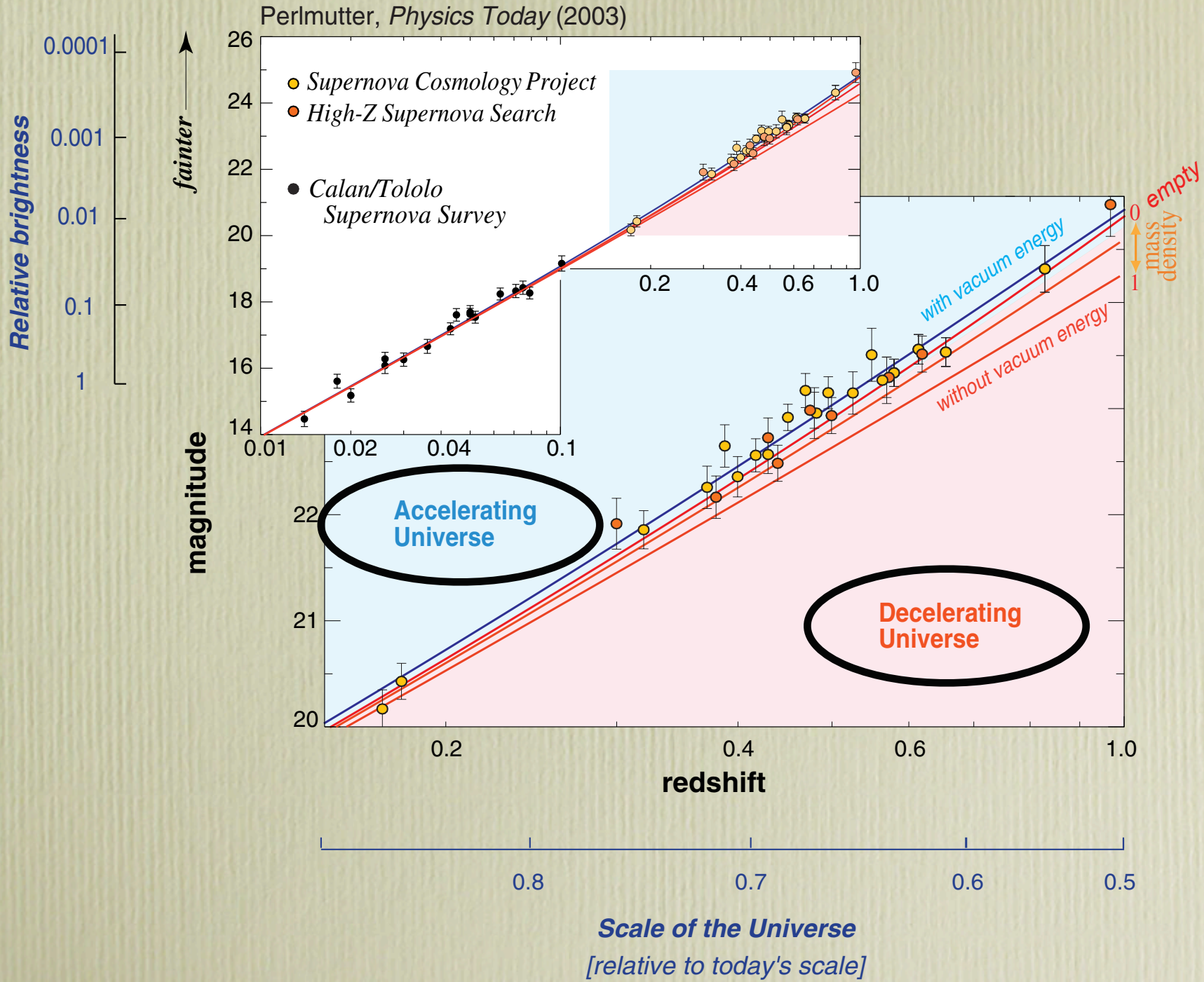
By measuring the flux, you can
determine the **distance**

But how do you find SNe?

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



Type Ia Supernovae



Dark Energy



- Universe is dominated by something other than dark matter
- This new component 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!

Actual photo of dark energy

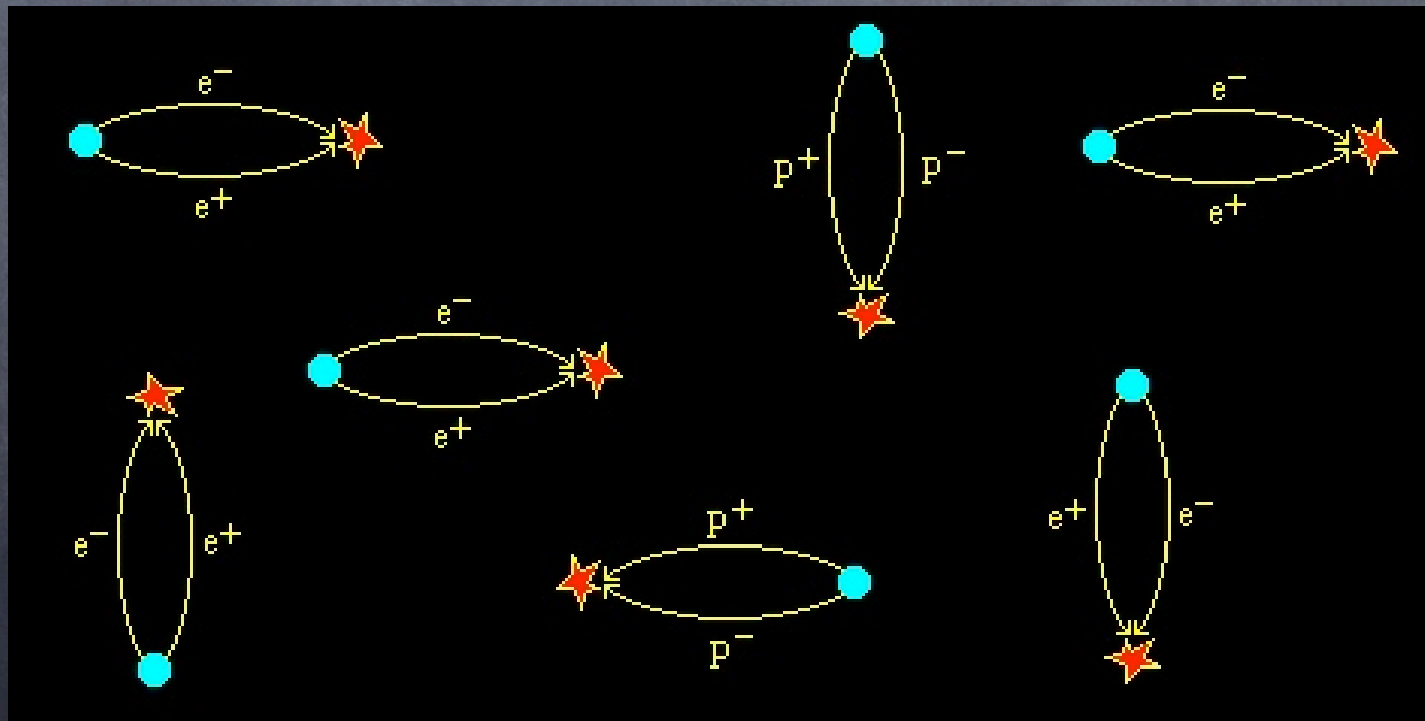
Consequences

- Excellent fit to SNa and 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.

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

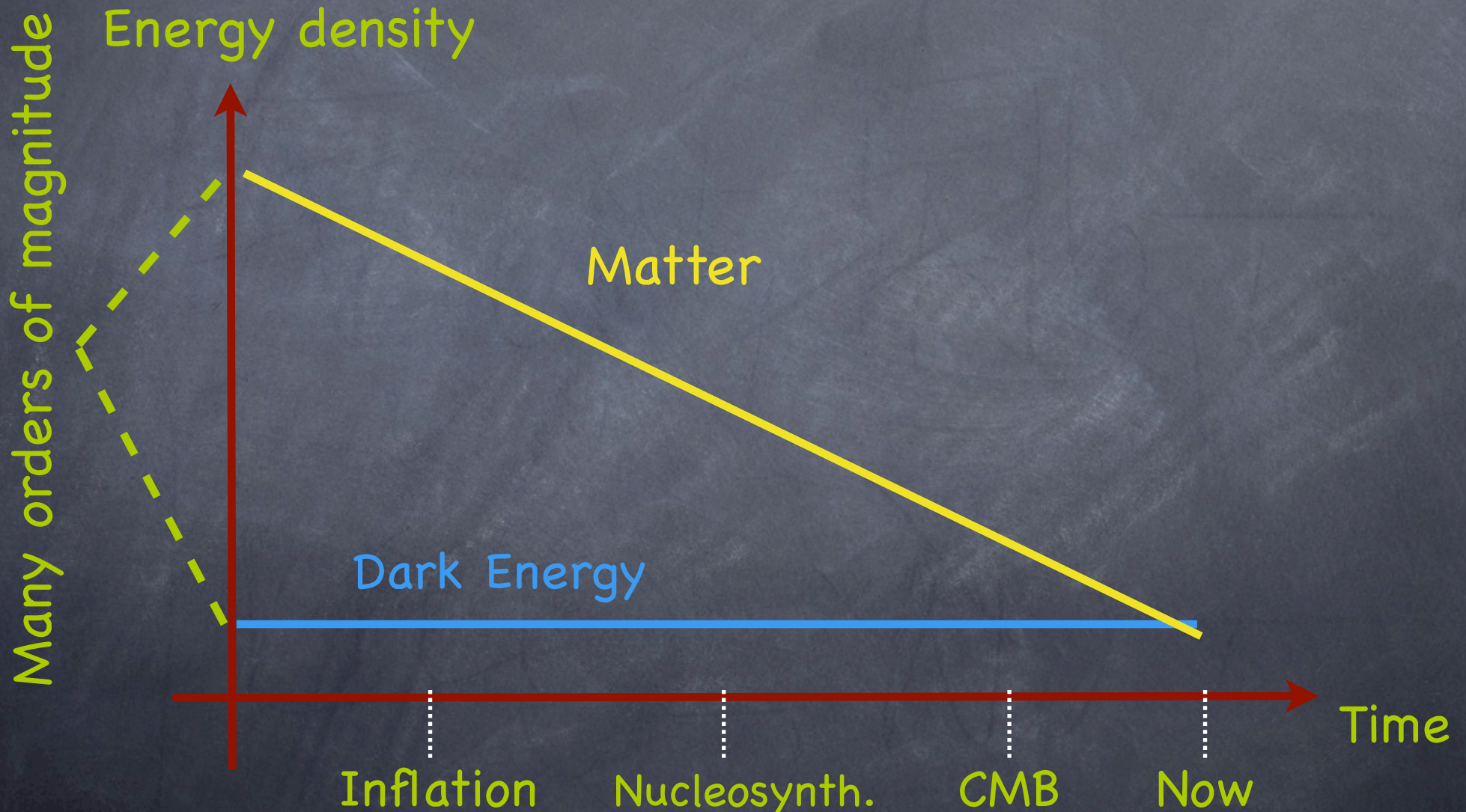
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times more than the observed amount

The cosmological constant problem

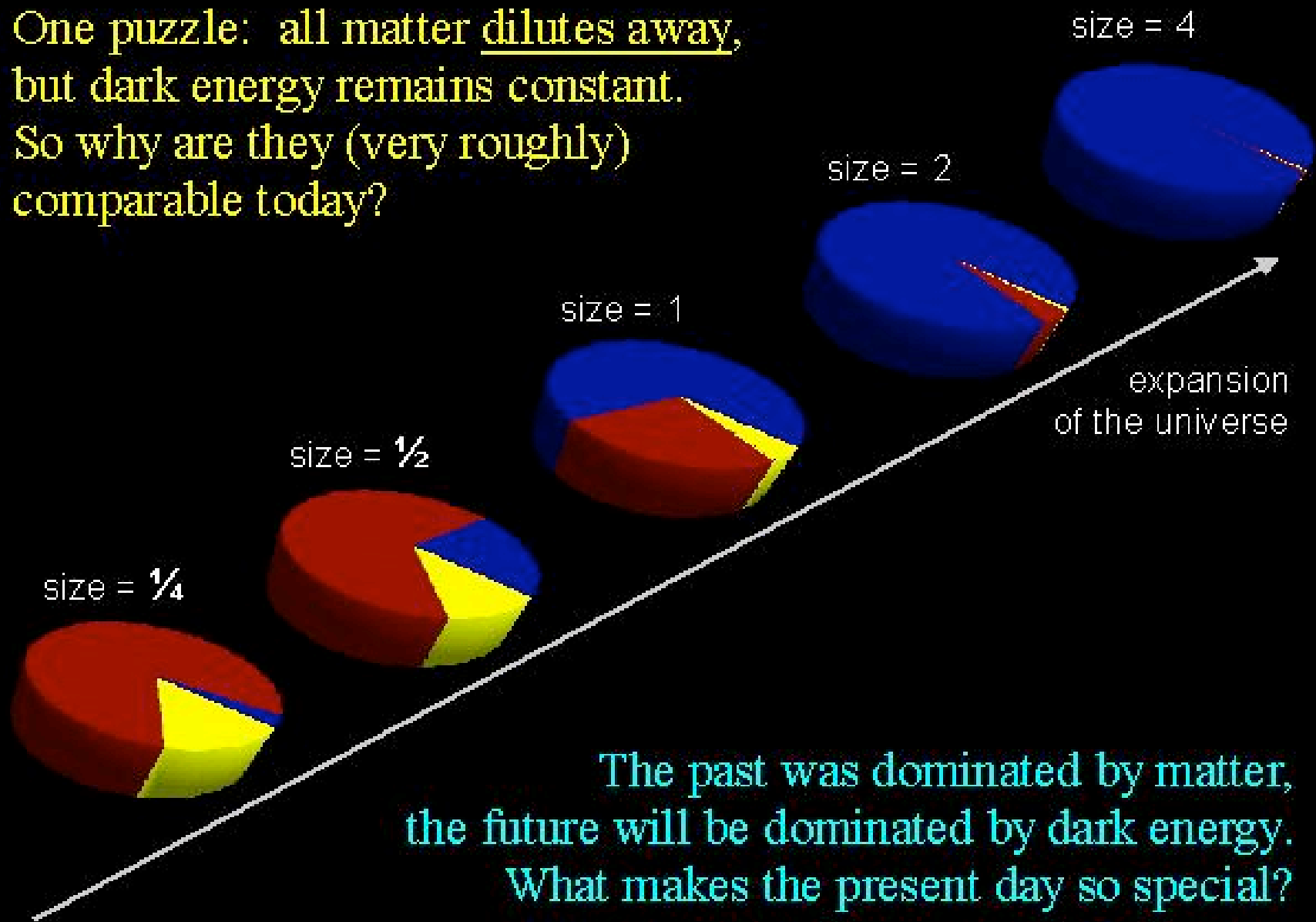
"Why Now!?"

Mystery #2



The coincidence problem

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



The past was dominated by matter,
the future will be dominated by dark energy.
What makes the present day so special?

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?

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



Skeptic:

"This is too weird to be true.

There are errors in astronomical measurements.

Dark energy is simply a **collection of a few simple blunders.**"



Skeptic:

"This is too weird to be true.

There are errors in astronomical measurements.

Dark energy is simply a **collection of a few simple blunders.**"

Cosmologist:

"This is not the case because

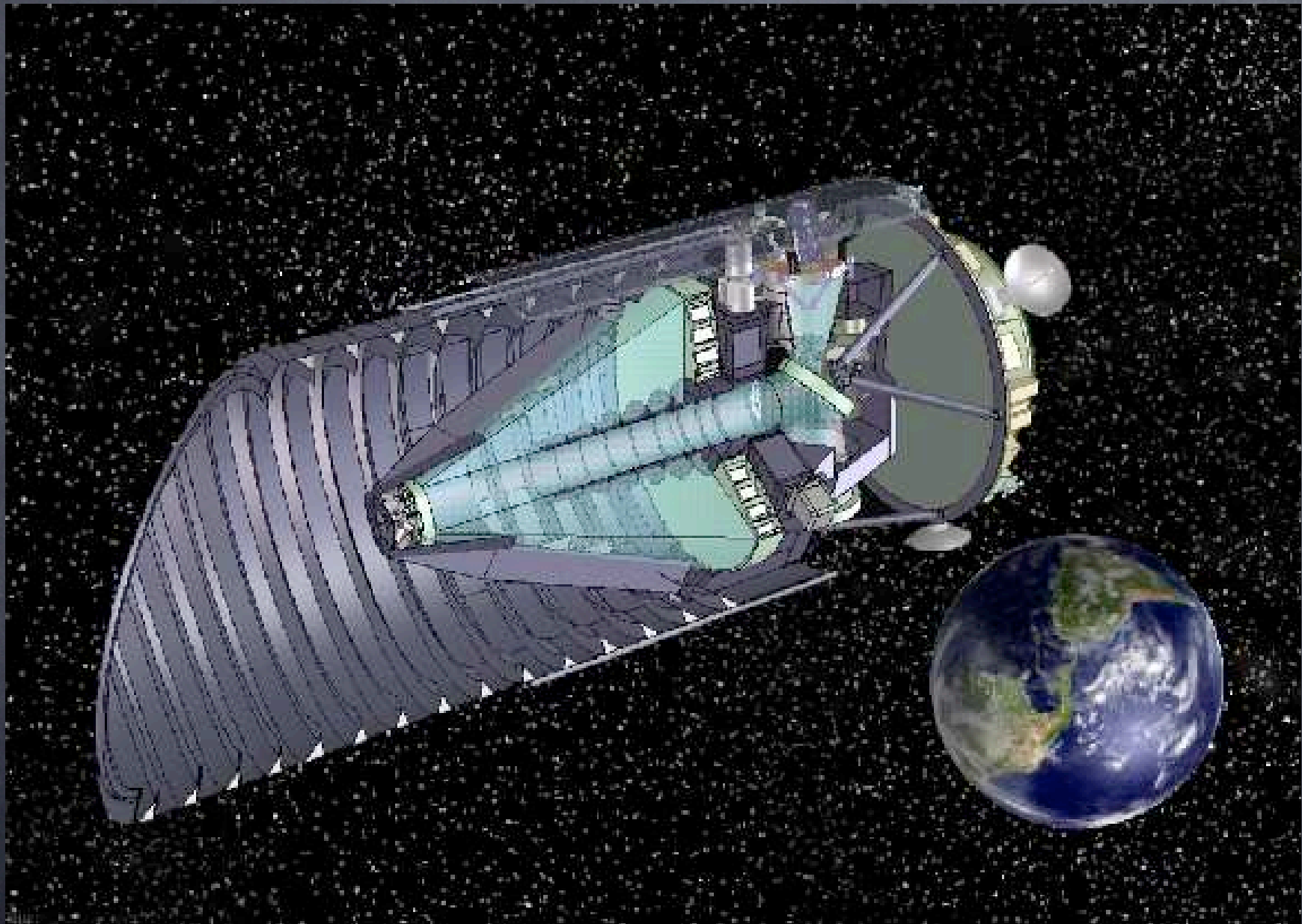
- There are now **multiple, independent lines of evidence** for DE
- All cosmological measurements now **require DE, and disagree with matter only universe**"



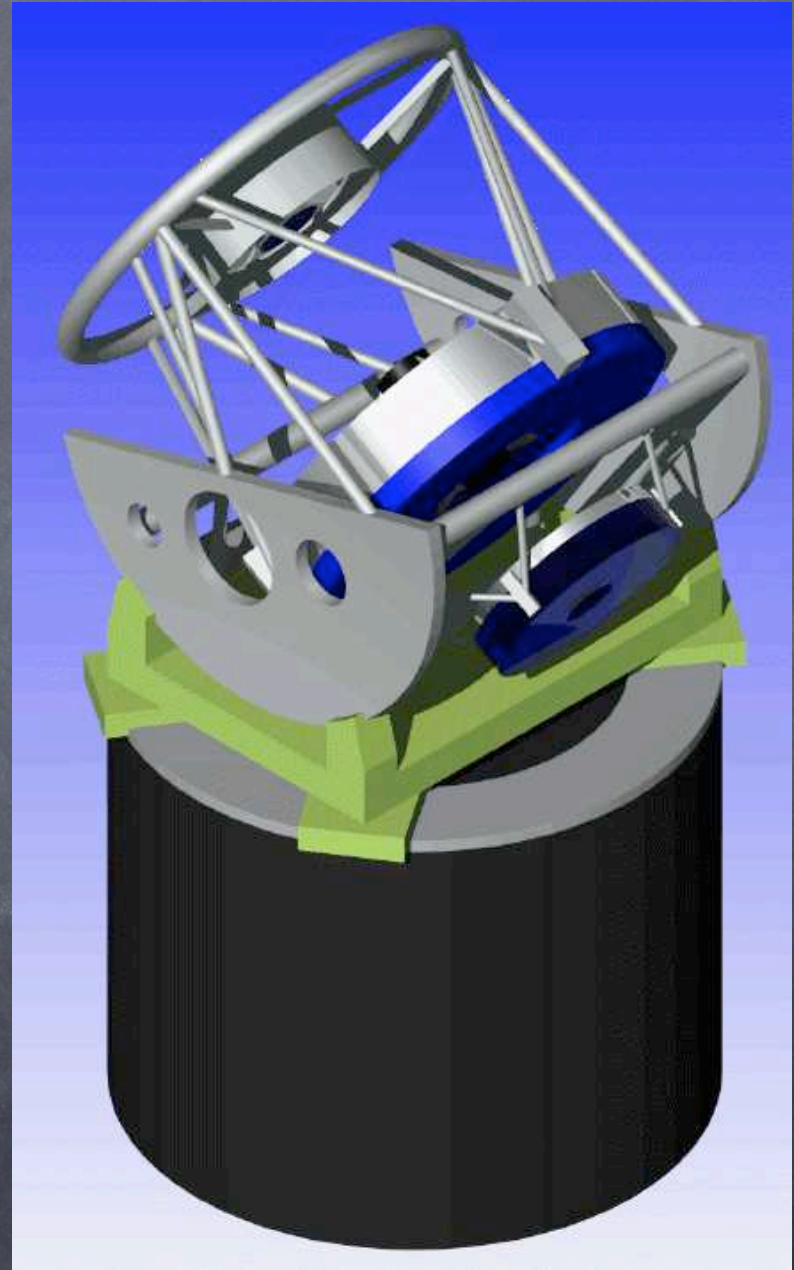
How do we find out about Dark Energy?

- 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**

SuperNova/Acceleration Probe (SNAP)

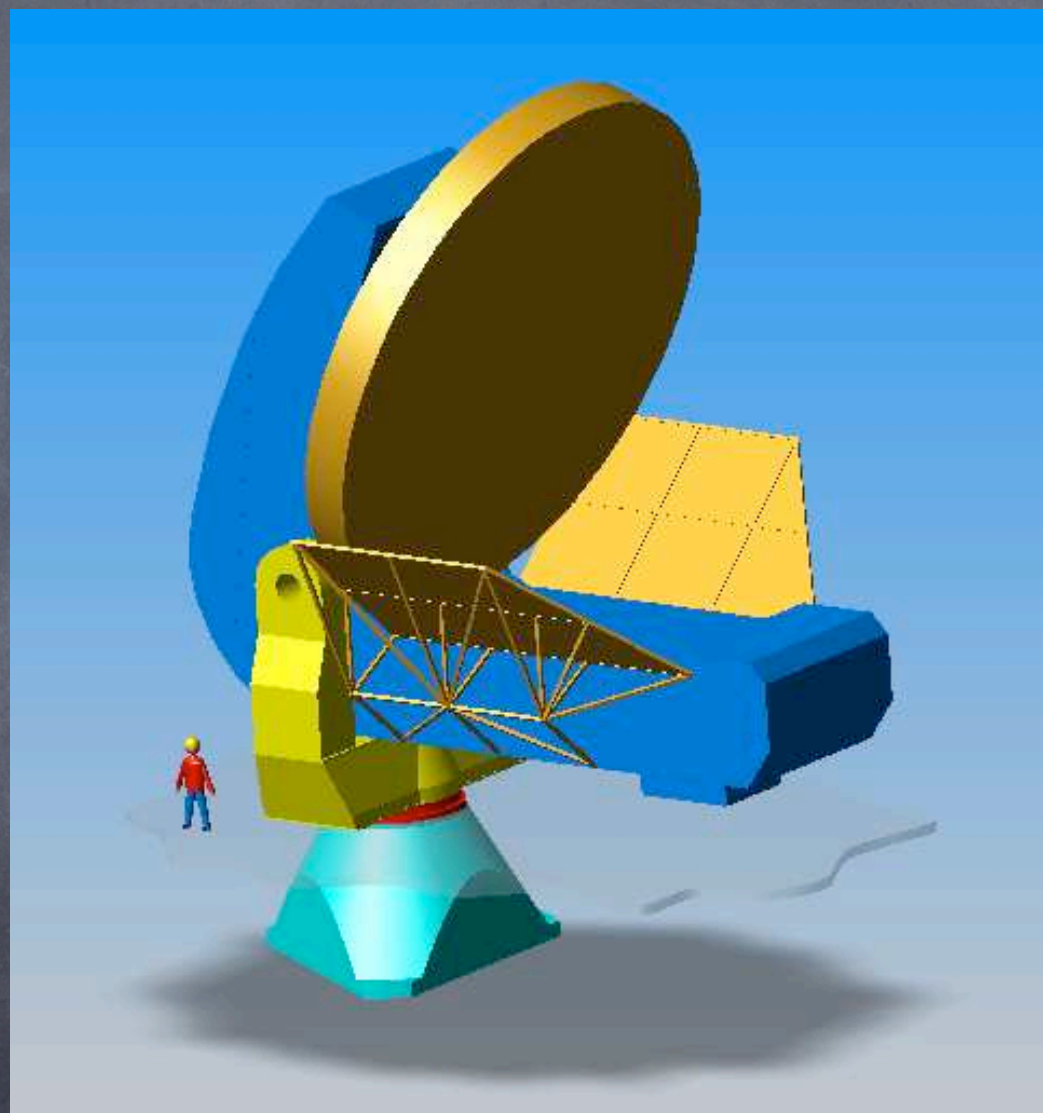


Large Synoptic Survey Telescope (LSST)



South Pole Telescope (SPT)

Galaxy cluster



Conclusions

- Dark Energy was directly discovered around 1998
- Its origin and nature are very mysterious
- It makes up about 70% 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://kicp.uchicago.edu/~dhuterer/EPO/adler.pdf>