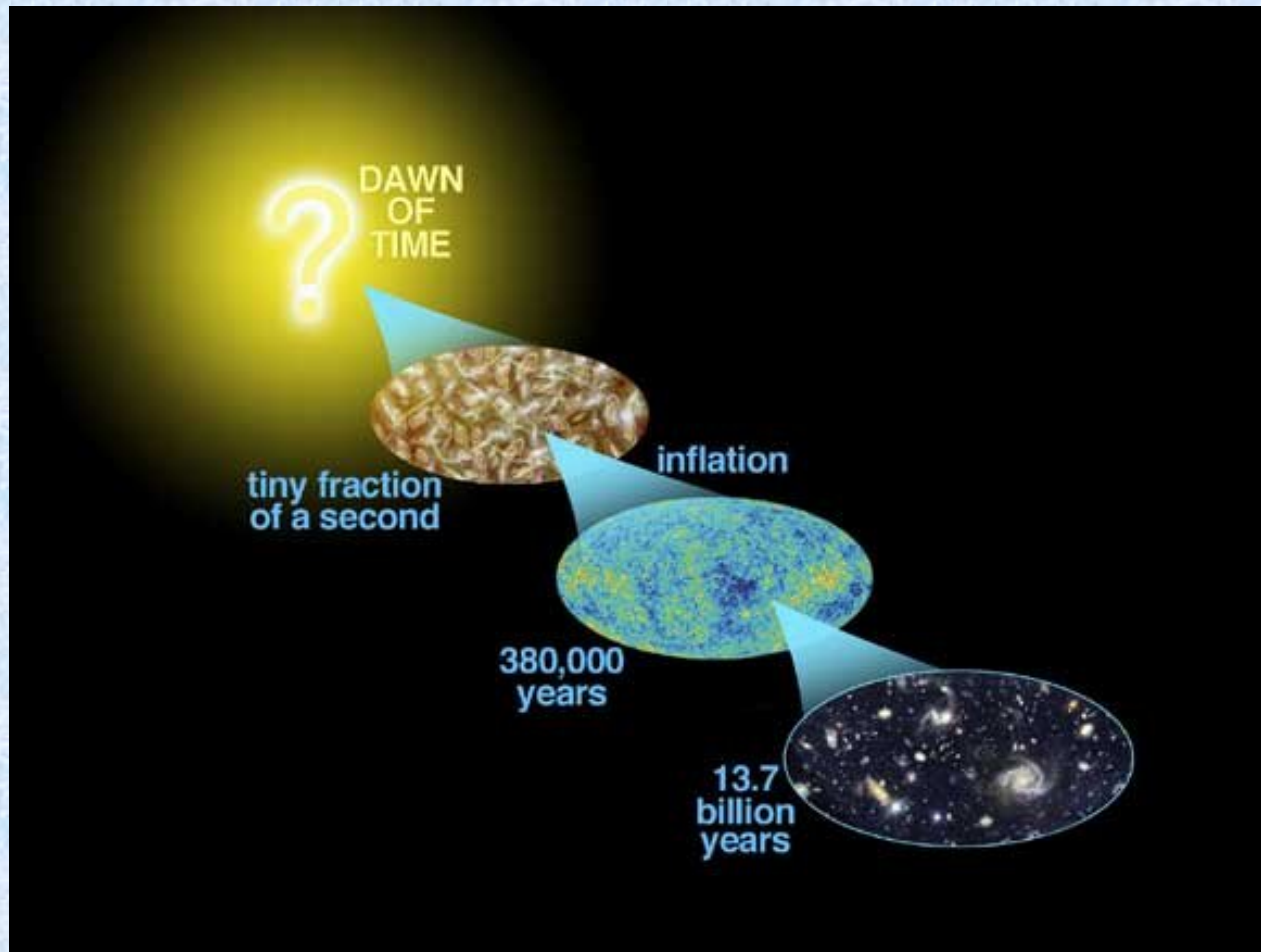


# Astro-2: History of the Universe

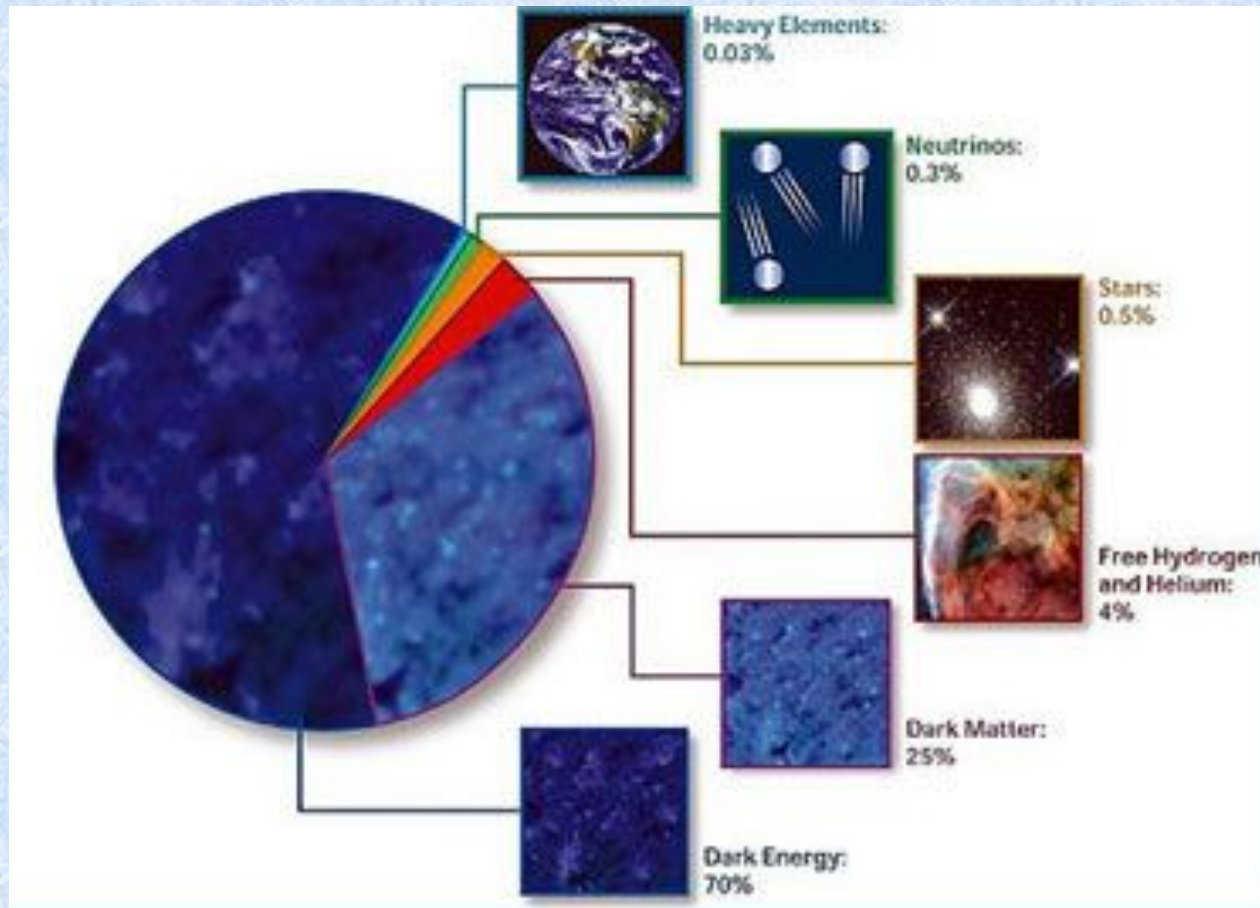


Lecture 9; May 9 2013

## Previously... on Astro-2. Helium abundance.

- Helium is too abundant and too homogeneous to have formed through fusion in stars
- The Big Bang theory explains He abundance with primordial nucleosynthesis when the Universe was hot enough
- $T$  scales as  $(1+z)$ , so that He was formed up to until  $z \sim 100,000,000$

# Previously on Astro-2. Matter density of the Universe.



# Previously... on Astro-2.

## A brief history of the universe.

- Mass/energy density in various components scales with redshift as:
  1.  $\Omega_{\Lambda} = \Omega_{\Lambda,0}$  [Dark energy/Cosmological Constant]
  2.  $\Omega_m = \Omega_{m,0} (1+z)^3$  [Massive particles, i.e. baryons and dark matter]
  3.  $\Omega_{\text{rad}} = \Omega_{\text{rad},0} (1+z)^4$  [Radiation]
- At very high redshift ( $>5,000$ ) radiation dominates (radiation dominated era)
- Then matter dominates until very recently ( $z \sim 0.4$ ) when dark energy starts to dominate

# Today... on Astro-2.

1. Big Bang models
2. Friedman Equation. Geometry and mass
3. Cosmological Constant

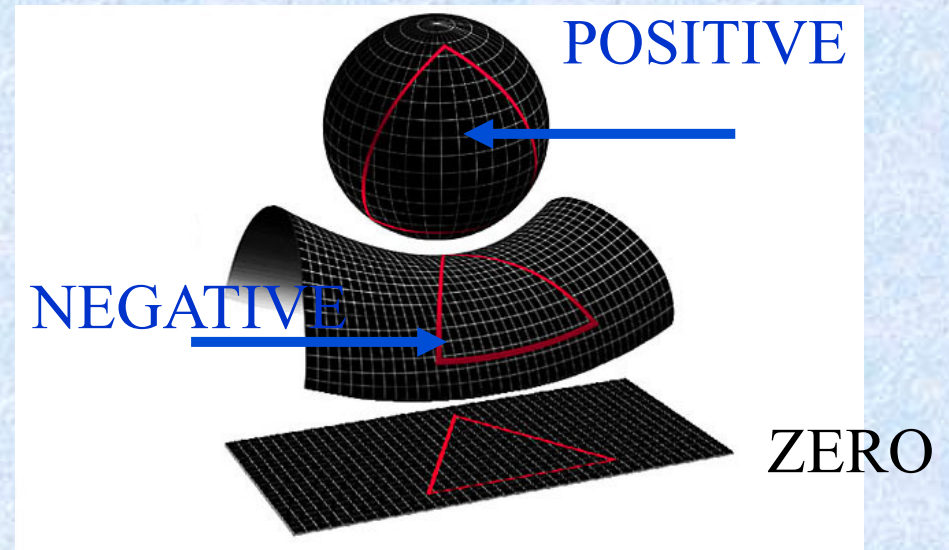
# Big Bang Models. Geometry

- Ingredients:
  - The universe is homogeneous and isotropic
  - The universe is a 4 dimensional space time as in General Relativity
  - The dynamics of the Universe are described by General Relativity

# Big Bang Models. Geometry

- Given the ingredients there are very general results for possible world models:
  1. Space and time can be “separated” so that we can define a cosmic time
  2. At any given time the universe is 3D space with a global curvature, which can be positive/zero/negative
- The three geometries are referred to as closed/flat/open Universes

## 2D ANALOGS



# Big Bang Models.

## Closed Universe

- For a closed Universe we can draw from our experience as creatures living on Earth to understand some of the basic principles.
  1. There is no “edge” to the Earth surface, yet the surface is finite
  2. We can travel around the globe and get back to where we started moving always in the same direction
  3. Meridians cross at the poles, so straight divergent lines cross at some point
  4. The sum of the angles of a triangle is more than 180 degrees
  5. There is no CENTER on the surface of the Earth.

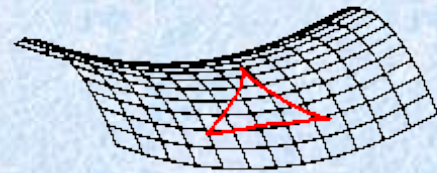




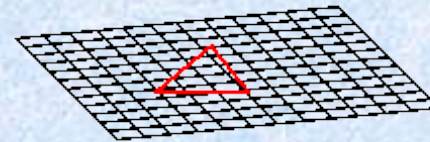
# Big Bang Models.

## Open Universe

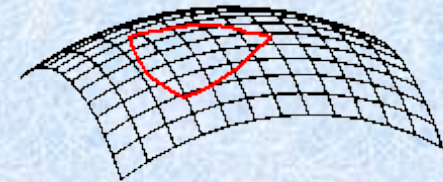
- Open universes are more difficult to relate to everyday experience. It's like an infinite saddle:
  1. The surface is infinite so there is no edge
  2. The sum of the angles of a triangle is less than 180 degrees
  3. There is no CENTER because the surface is infinite



Open universe :  
looks like a  
horse saddle



Flat universe

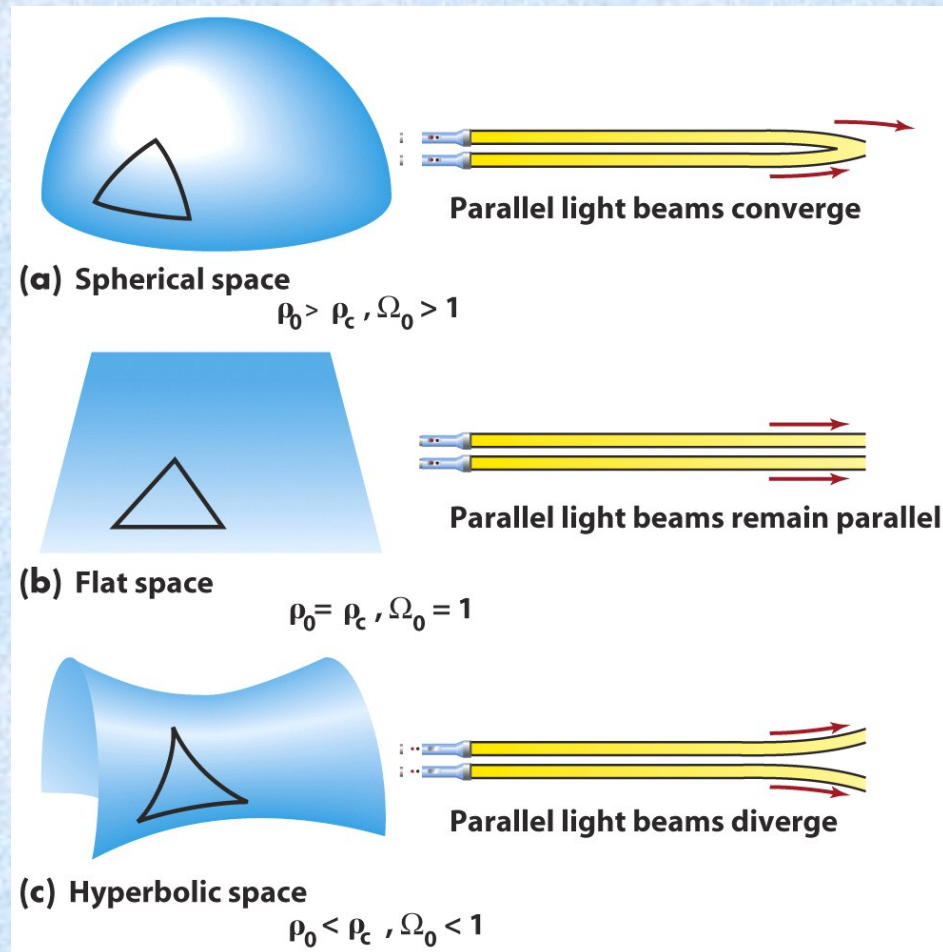


Closed universe :  
looks like the  
surface of a sphere

numiano

# Big Bang Models.

## Parallel lines



# Big Bang Models. Geometry.

## Summary

- If the universe is homogenous and isotropic and correctly described by General Relativity:
  1. At any given time the universe is a 3D space
  2. It could be open/close/flat
  3. If it is close, its volume is finite. If it is open or flat its volume is infinite.
  4. In any case **THERE IS NO CENTER AND THERE ARE NO EDGES**

# The geometry of the universe.

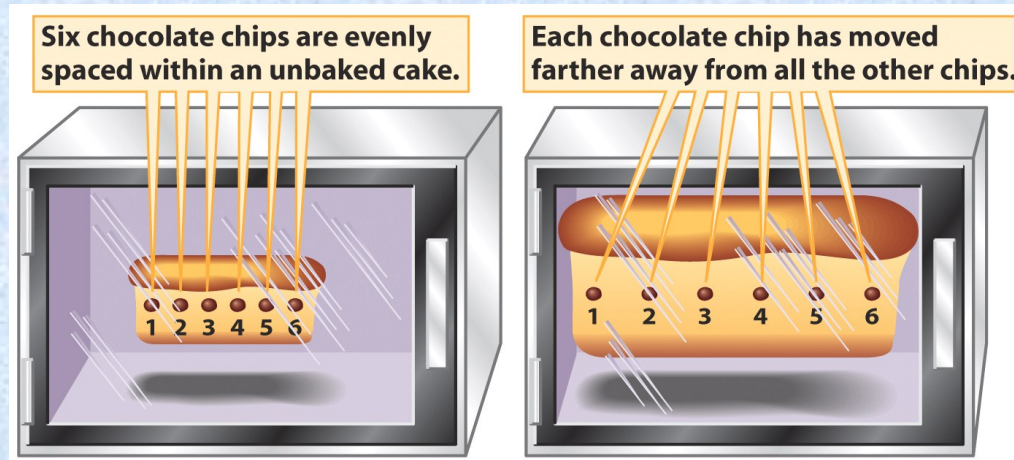
## Discussion

- “There is a single general space, a single vast immensity which we may freely call void: in it are innumerable globes like this on which we live and grow; this space we declare to be infinite, since neither reason, convenience, sense-perception nor nature assign to it a limit.” (Giordano Bruno)
- “It is fairly certain that our space is finite though unbounded. Infinite space is simply a scandal to human thought” (Bishop Barnes)

# Geometry and dynamics of the Universe

- In general relativity geometry and mass are closely related.
- The mass content of the universe determines its geometry AND its dynamics
- In general, the dynamical evolution of the universe is determined by a single function that describes the evolution of distances as a function of time, called  $a(t)$
- Consider two points at a time  $t_1$  and  $t_2$ . The ratio of the distances between the two points is  $a(t_1)/a(t_2)$
- Once we have a model of the universe we can compute  $a(t)$  and compare it with the observations

# What does Hubble's Law mean in this context?



- Take us and a cluster at a distance of 1 Gpc now ( $t_1$ ). Hubble's law says that the distance is increasing with time ("moving away").
- In billion years ( $t_2$ ) the cluster will be more distant
- This means that  $a(t_2) > a(t_1)$
- This is true for any two points. Every two points are "moving away from each other" at this time.

# Expansion and mass/geometry

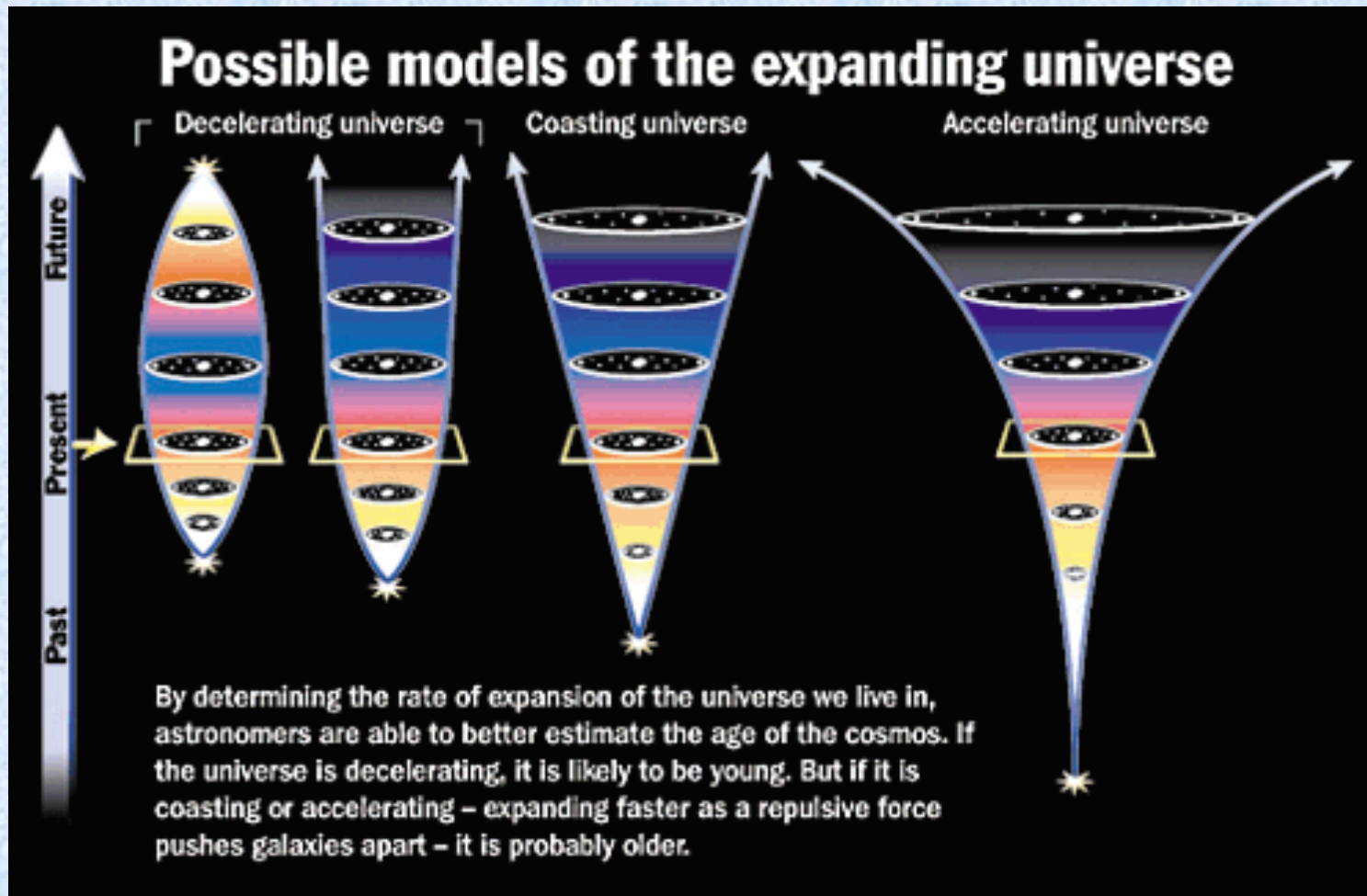
- The expansion rate, i.e. the ratio between velocity and distance (the generalization of the Hubble constant) can change with time.
- This is exactly what we want to know!
- Friedman's Equation connects the Hubble parameter with the mass geometry of the Universe:
- $H^2 = H_0^2 [\Omega_{\text{rad},0}(1+z)^4 + \Omega_{\text{m},0}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda]$
- $\Omega_k$  is related to the overall geometry of time, being zero for a "flat" universe, negative for a closed universe and positive for an open universe
- At early times  $(1+z)^4$  so when the universe is radiation dominated the other terms do not matter.

# Expansion and geometry. Past and future of the Universe

- By measuring the parameters we can determine the past and future of the Universe, as well as its overall geometry [Note that all  $\Omega$  add up to 1 so that we can infer the geometry by measuring the other parameters]
- For example, those parameters fix the current age of the universe and whether it will expand forever or recollapse, etc.



# Past and future of the Universe

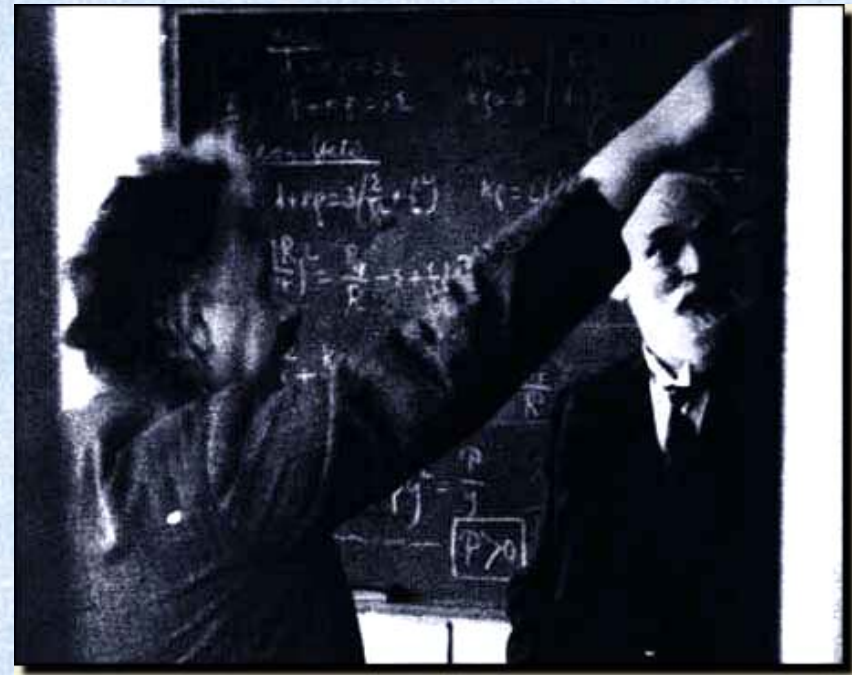


# We need hypothesis and measurements...



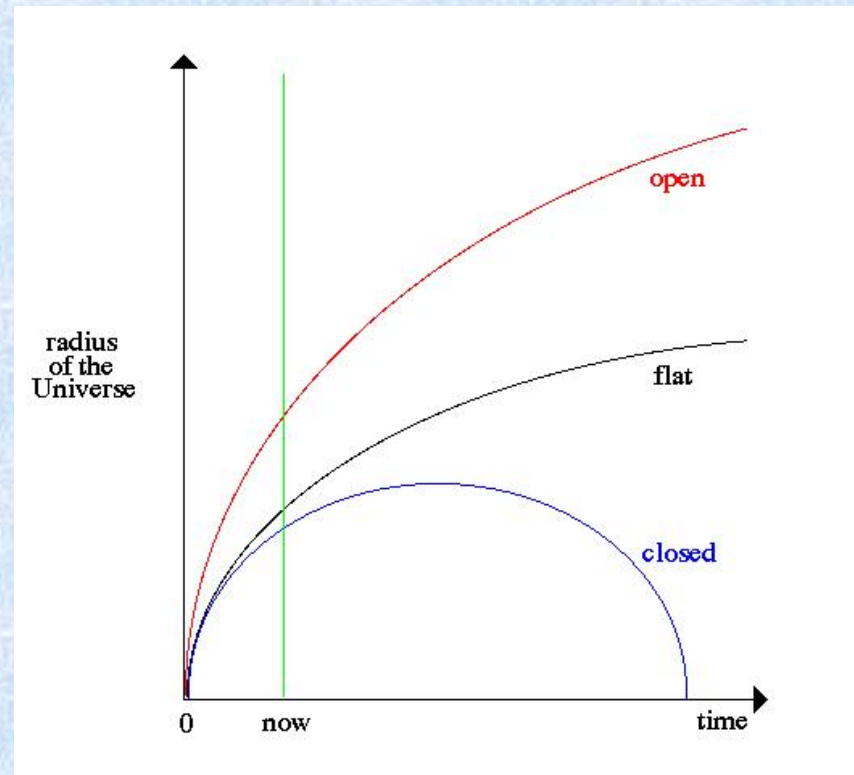
# The Einstein-de Sitter Model

- Einstein and de Sitter conjectured that only quantities known to be non-zero should be considered, everything else should be set to 0.
- So they only kept mass... assuming no cosmological constant and flat space...
- In this model the age of the universe is  $2/3 (1/H_0)$ .
- Does this work?



# Geometry and mass

- In a model with mass and curvature, you get a behavior like this, depending on the geometry of the universe.
- Note that the critical mass density is the mass density required to have a flat universe in this model. If the density is supercritical the universe recollapses in a finite amount of time (the “big crunch”)

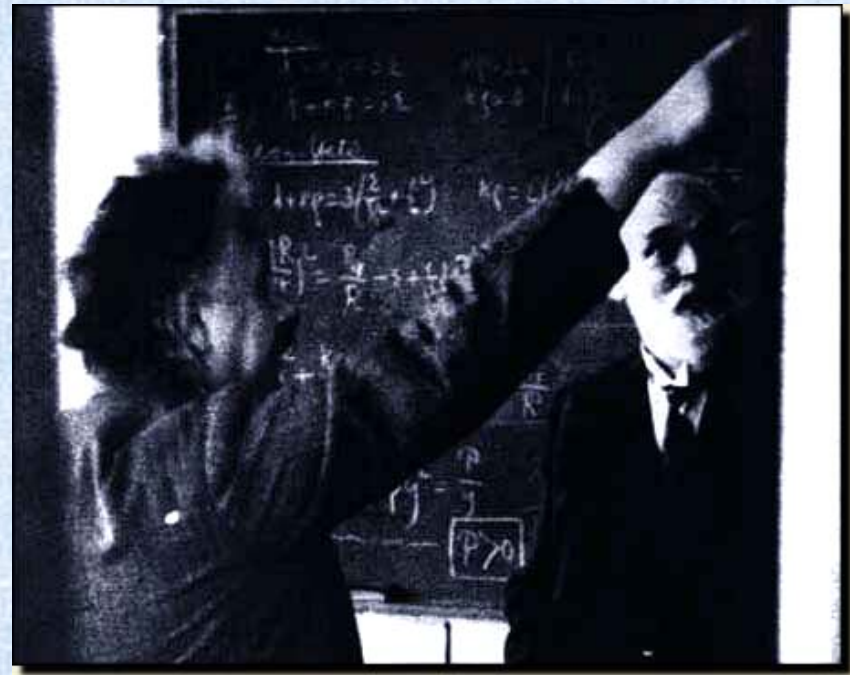


# Friedmann equation. Summary

- In the Big Bang model the “size” of the universe evolves according to the Friedmann equation.
- Knowing the current value of the cosmological parameters (cosmography) we can calculate the past history of the Universe and predict its future.
- The simplest models (e.g. Einstein-de Sitter) don't work.

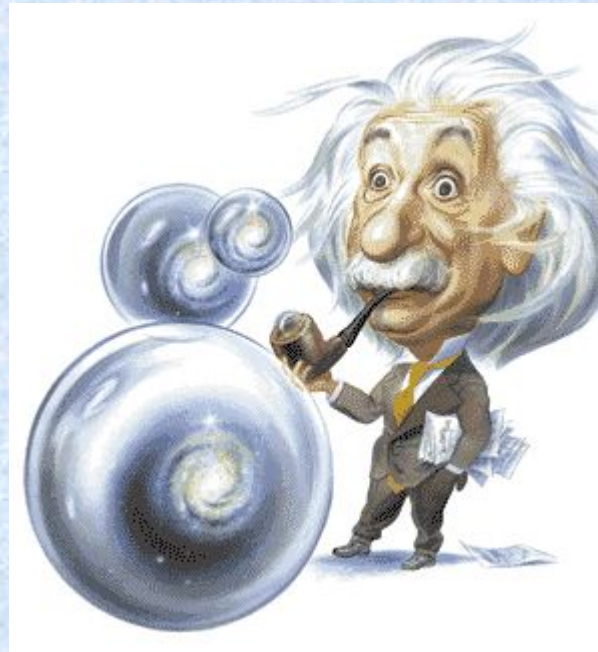
# The cosmological constant

- Soon after the completion of general relativity (1916) people used it to describe the universe.
- However, with only matter there was no way to obtain a static solution, which at that time was the prejudice.
- Einstein added the cosmological constant to his equations to find a static solution...



# The cosmological constant

- Unfortunately the static solution is unstable
- And, when Hubble announced his discovery of the expansion, unnecessary
- So the cosmological constant remained on the outskirts of cosmology for a long time...



# The cosmological constant is back!

table 28-2   Some Key Properties of the Universe		
Quantity	Significance	Value*
Hubble constant, $H_0$	Present-day expansion rate of the universe	$71^{+4}_{-3}$ km/s/Mpc
Density parameter, $\Omega_0$	Combined mass density of all forms of matter <i>and</i> energy in the universe, divided by the critical density	$1.02 \pm 0.02$
Matter density parameter, $\Omega_m$	Combined mass density of all forms of matter in the universe, divided by the critical density	$0.27 \pm 0.04$
Density parameter for ordinary matter, $\Omega_b$	Mass density of ordinary atomic matter in the universe, divided by the critical density	$0.044 \pm 0.004$
Dark energy density parameter, $\Omega_\Lambda$	Mass density of dark energy in the universe, divided by the critical density	$0.73 \pm 0.04$
Age of the universe, $T_0$	Elapsed time from the Big Bang to the present day	$(1.37 \pm 0.02) \times 10^{10}$ years
Age of the universe at the time of recombination	Elapsed time from the Big Bang to when the universe became transparent, releasing the cosmic background radiation	$(3.79^{+0.08}_{-0.07}) \times 10^5$ years
Redshift $z$ at the time of recombination	Since the cosmic background radiation was released, the universe has expanded by a factor $1 + z$	$1089 \pm 1$

\*Values are from the first year of WMAP data. (NASA/WMAP Science Team)

And... by the way... the Universe is close to flat (more in lecture 12)



# Cosmological constant or dark energy?

- Nowadays people prefer to talk in terms of dark energy, instead of cosmological constant.
- The classic cosmological constant point of view is a modification of Einstein's equation adding an extra term
- In the dark energy approach the extra component is interpreted as something with negative pressure filling space and people try to understand is a some sort of vacuum energy or some concept related to particle physics.
- But we really don't know...



# The cosmological constant.

## Summary

- The cosmological constant was initially introduced by Einstein to find a static solution for the universe (but it's unstable!!)
- When the universe was shown to expand the idea was abandoned
- The cosmological constant was brought back by MEASUREMENTS (next lecture) a decade ago
- Most people prefer to interpret the cosmological constant as dark energy and to give it a “particle physics” interpretation rather than a geometric one

# Frequently asked questions...just checking...

- What is the universe expanding into?
- Nothing, the universe is all there is, space is expanding itself
- Where is the center of the expansion? Where is the center of the universe
- Nowhere, there is no center, the universe is homogenous and isotropic
- Is the universe infinite/finite?
- We do not know for sure but we think it's infinite
- Does it matter?
- Not really because our horizon is finite

**The End**

See you on tuesday!