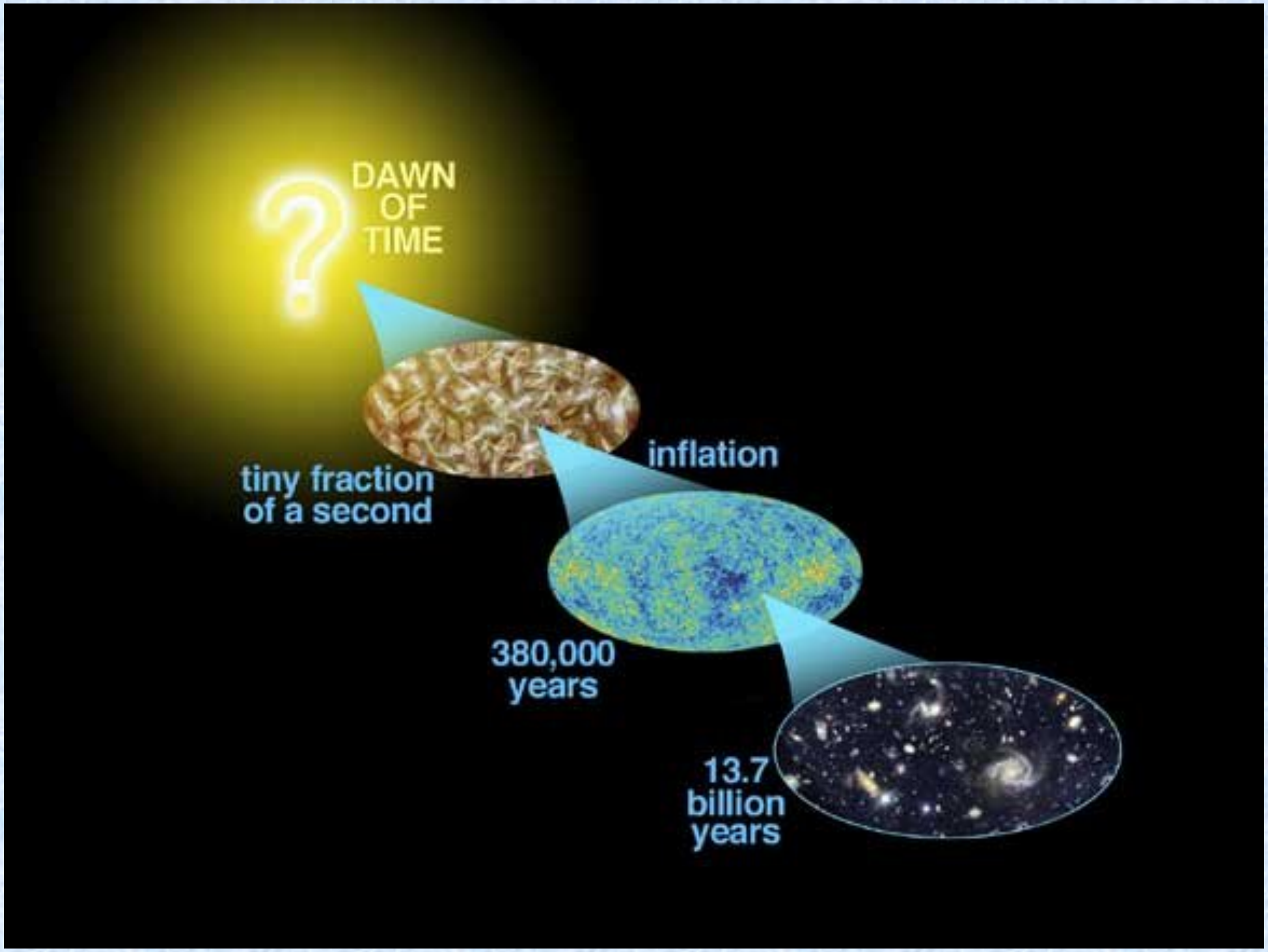
Astro-2: History of the Universe



Lecture 10; May 14 2013

Previously… on astro-2

- 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

Previously… on astro-2

- 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 because, e.g., they predict an age for the universe that is in conflict with the ages of globular clusters

Previously… on astro-2

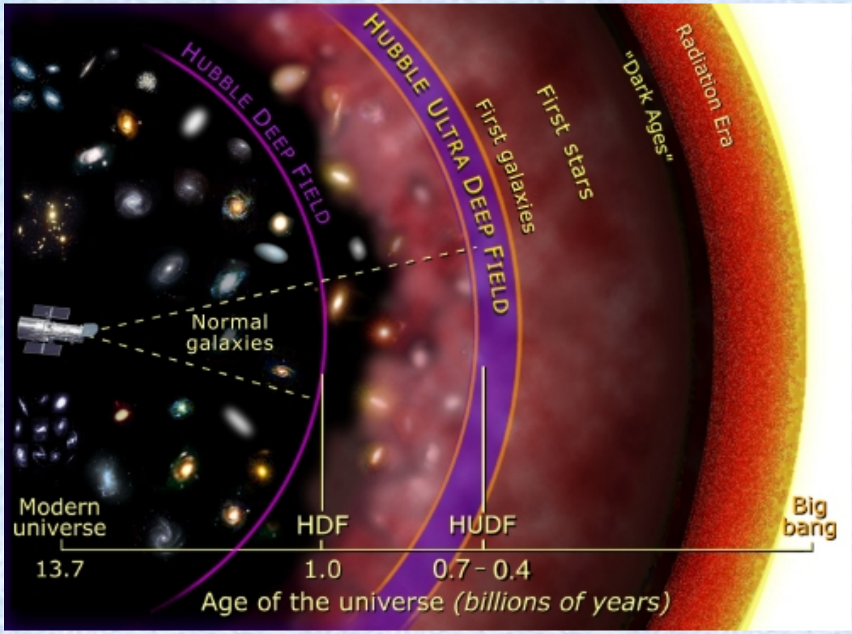
- The cosmological constant was initially introduced by Einstein to find a static solution for the universe (but it's unstable!!)
- When the universe was shown to expand the idea was abandoned
- The cosmological constant was brought back by MEASUREMENTS less than a decade ago
- Most people prefer to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

Today.. On Astro-2.

1. Cosmography. How do we measure the cosmological parameters?
   1. Standard rods and standard candles
   2. Volume based tests and cluster based tests
   3. Cosmic Background Radiation
2. The era of concordance cosmology. Happy campers?
3. Acceleration and horizons. Big rip?

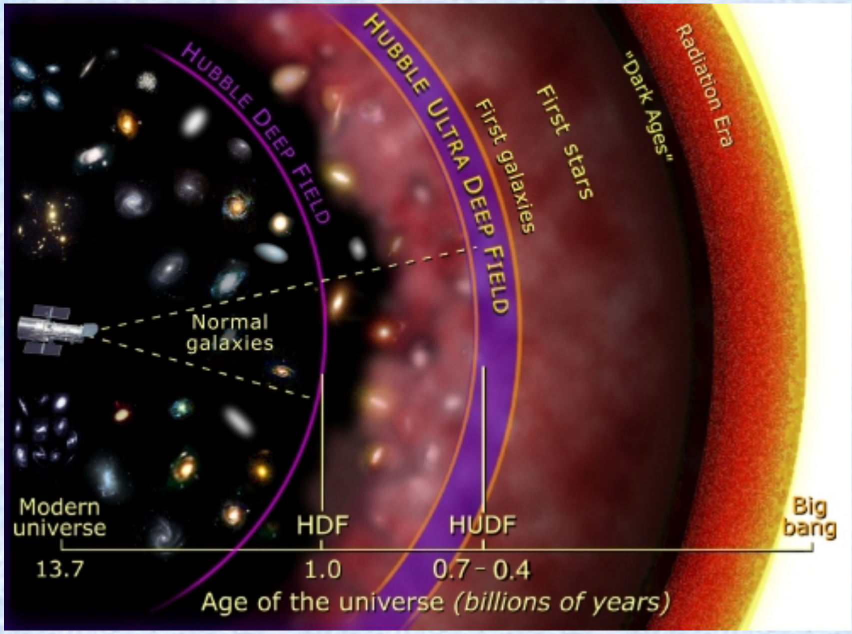
Cosmography and distances

- In a normal euclidean space how does observed flux F scale with distance R?
- $F=L/4\pi R^2$
- How about angular sizes?
- $\theta=D/R$
- What happens in the universe in the classic big bang picture?



Cosmography and distances

- In an expanding universe, even if it is flat, things are a bit trickier because the universe changes as light travels across it.
- In practice there is no unique definition of distance
- By analogy with the Euclidean static space people define a luminosity distance as
- $F=L/4\pi R_L^2$
- And an angular size distance
- $\theta=D/R_A$
- These are NOT the same.



Cosmography and distances

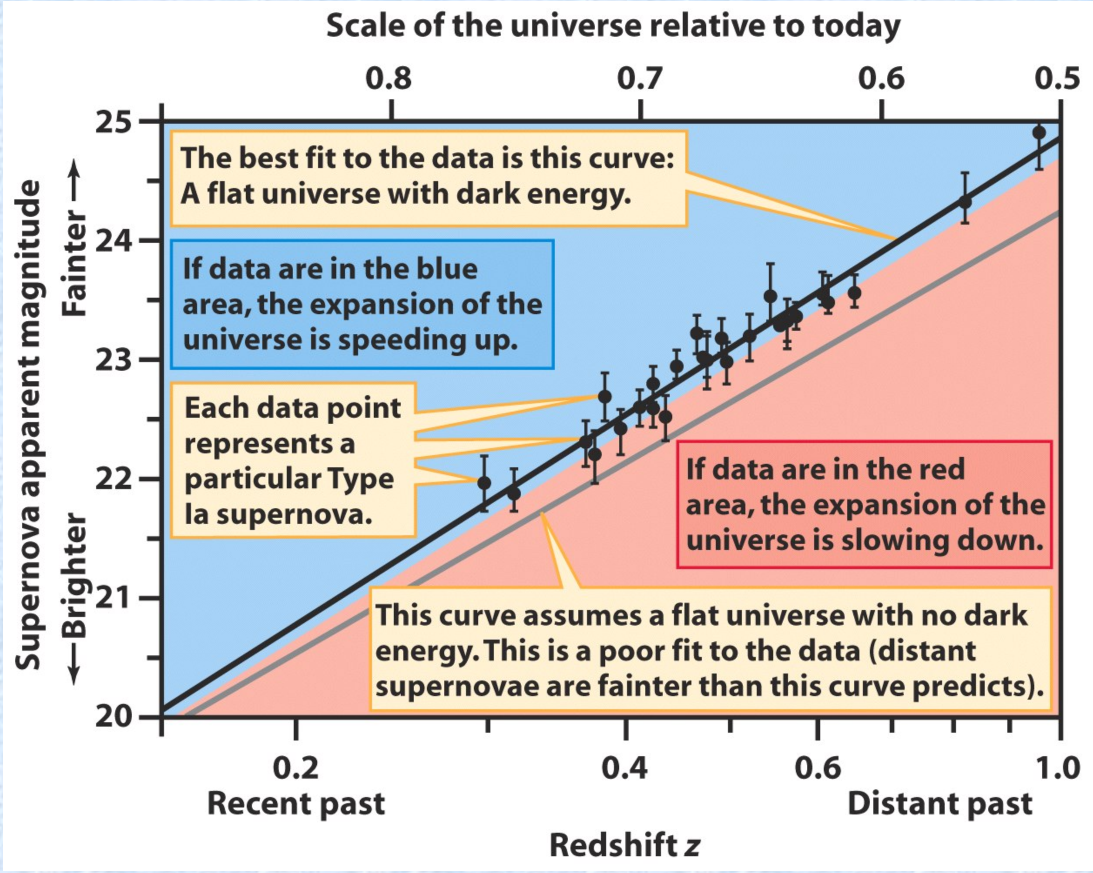
- The relationship between distance and redshift depends on the cosmological parameters.
- For example?
- Hubble's Law: $zc \sim H_0 R$ for low z
- At higher z this depends also on all the other cosmological parameters
- So what do we need?

Cosmography and distances

- We need some object of known luminosity (or size)
- Standard candle (or rod).
- Then we measure its redshift and its flux (or angular size) and we infer the cosmological parameters
- What is a good standard candle?
- SN Ia

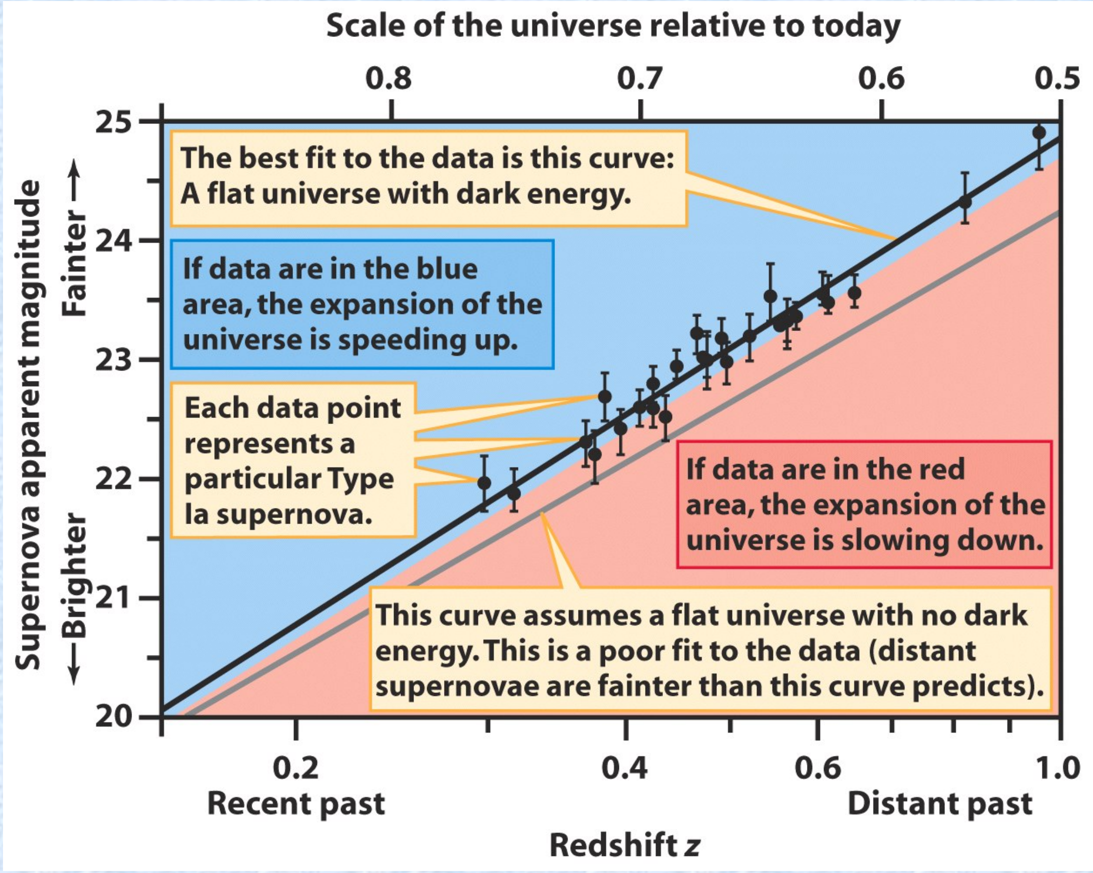
Cosmography and distances. Sn Ia

- Supernovae Ia are believed to be standard candles.
- That is, when they explode they always produce a very similar amount of light



Cosmography and distances. Sn Ia

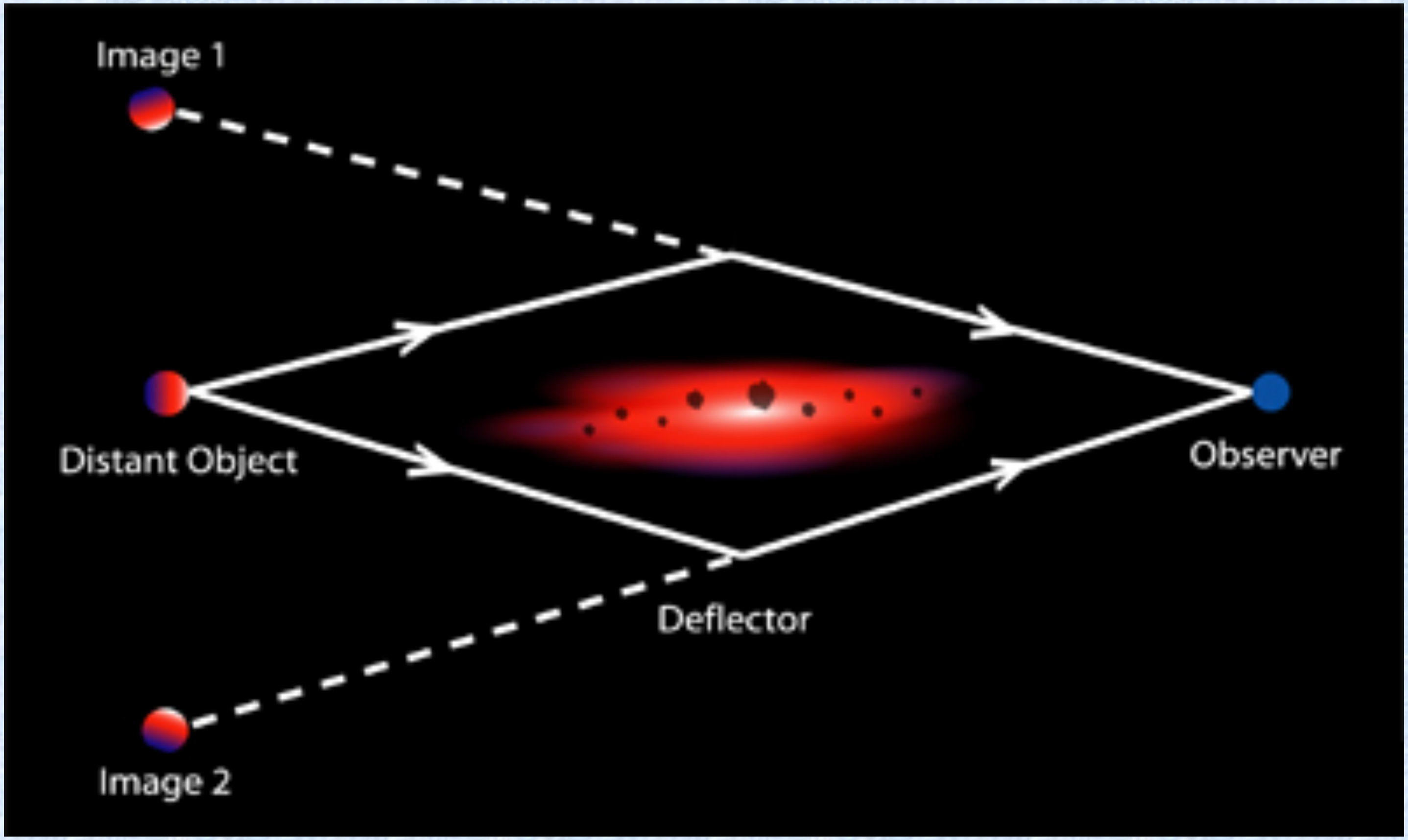
- The fact that supernovae at high-z appear fainter that we expect for a "normal" expanding universe is interpreted by many as evidence that the expansion is accelerating.
- Any other interpretation?



Cosmography and distances. Sn Ia and systematics

- Evolution of the progenitors
- Dust screen

Cosmography and distances. Future: gravitational time delays?

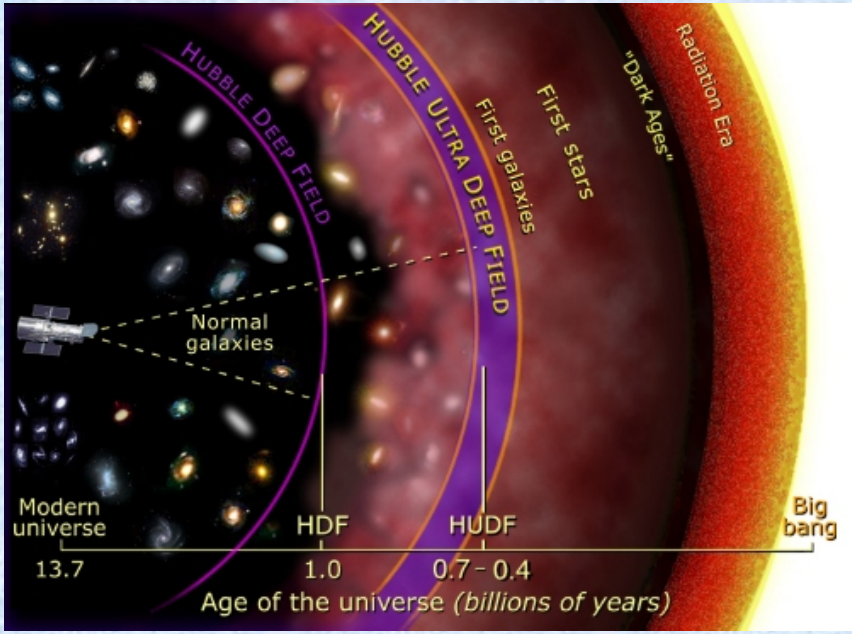


Cosmography and distances. Summary

- In an expanding universe the relationship between redshift and distance depends on the cosmological parameters (i.e. the geometry and expansion of the universe).
- Every reliable standard candle or rod can provide you with an answer.
- The most popular at the moment are Supernovae Ia. They look dimmer than expected in the past indicating that the universe is accelerating
- This is the so called "Cosmic jerk"

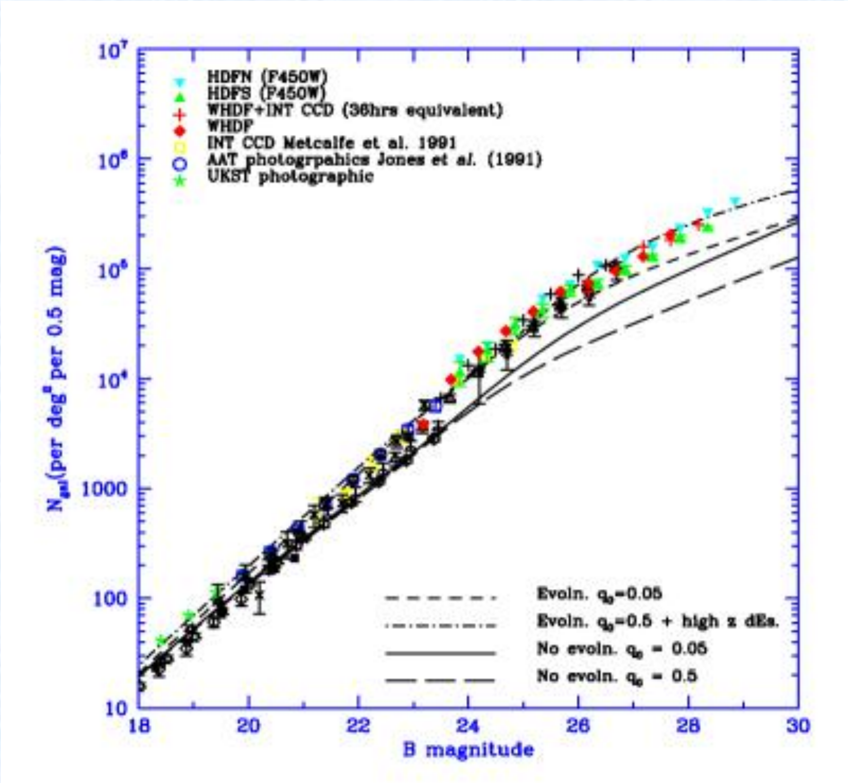
Cosmography, volume, and the growth of structures

- In a normal euclidean space how does the volume within a distance R scale with R?
- $V \sim R^3$
- In an expanding Universe things get a bit "tricky". As you look further away the universe was smaller… so volumes scale with redshift in a more complicated way.
- This depends on?



Cosmography, volume, and the growth of structures

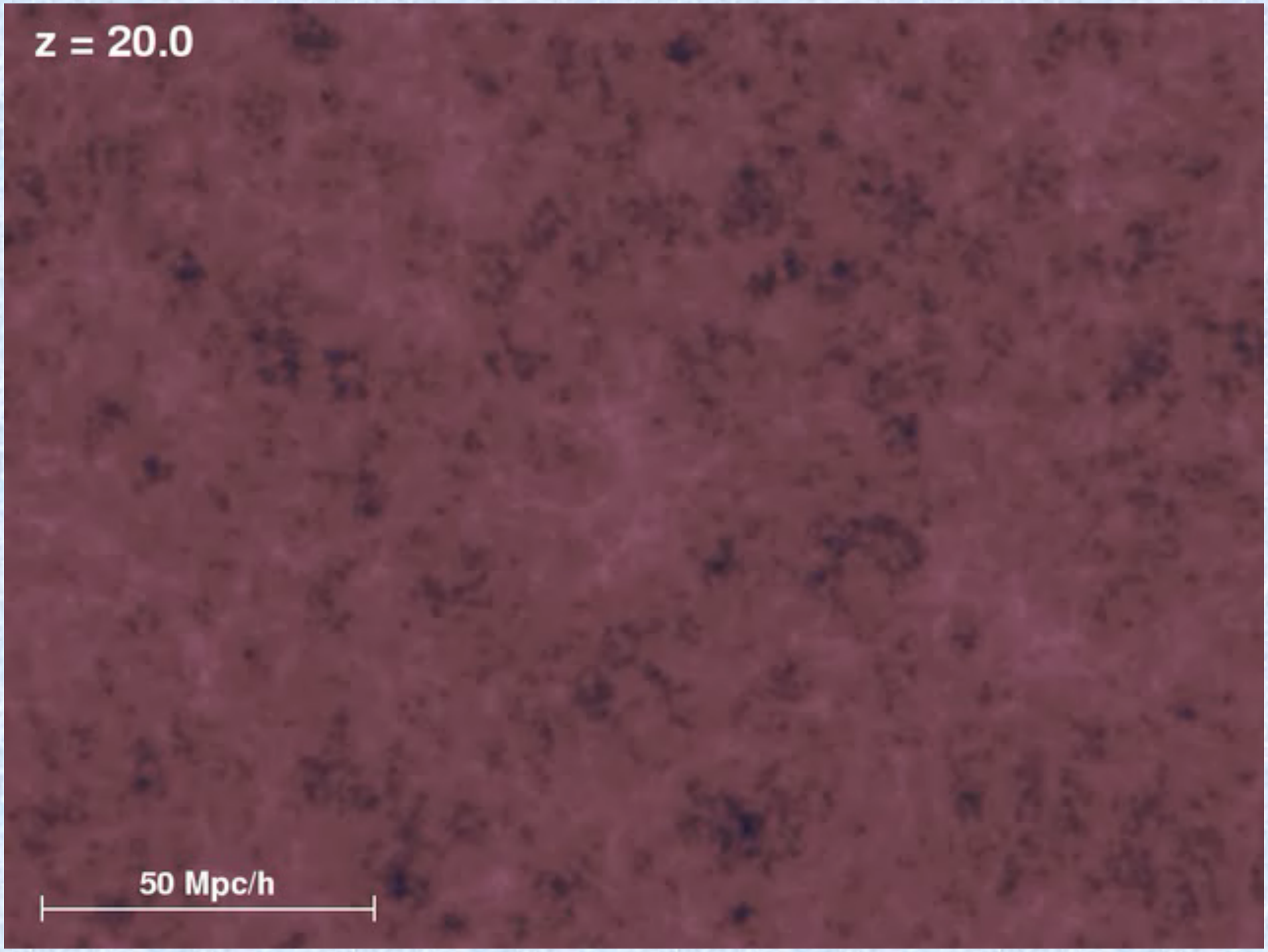
- So if you have a uniform population of objects of known luminosity and you look fainter and fainter you should see more of them because you are looking at a larger volume.
- This is attempted with galaxies for example.
- But there is a problem. What?



Cosmography, volume, and the growth of structures

- The problem is evolution, there is no uniform population of galaxies! So this does not work very well.
- However, we can use evolution to do cosmography
- In fact, large scale structures evolve due to gravity.
- The more mass the faster the evolution.
- Therefore the abundance of structure as a function of cosmic time can be used to measure the matter density of the universe

Cosmography, volume, and the growth of structures



Cosmography, volume, and the growth of structures

42 *S. Cole et al.*

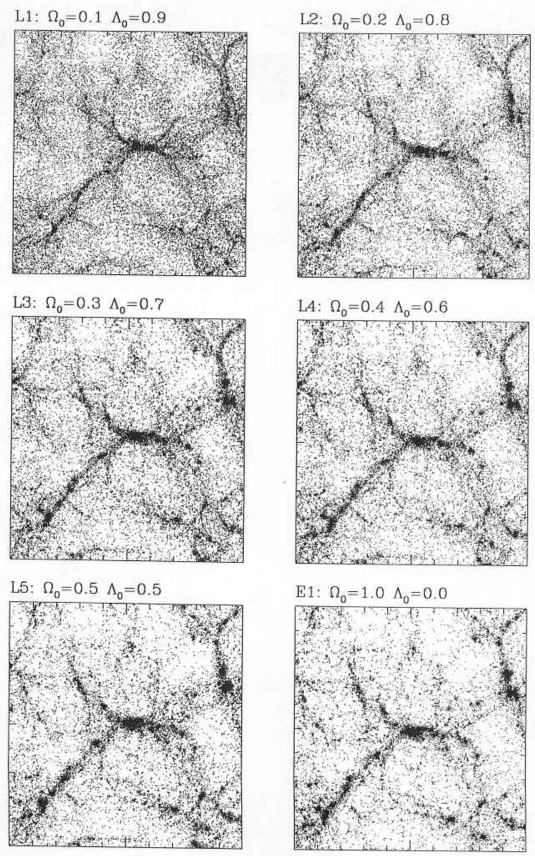
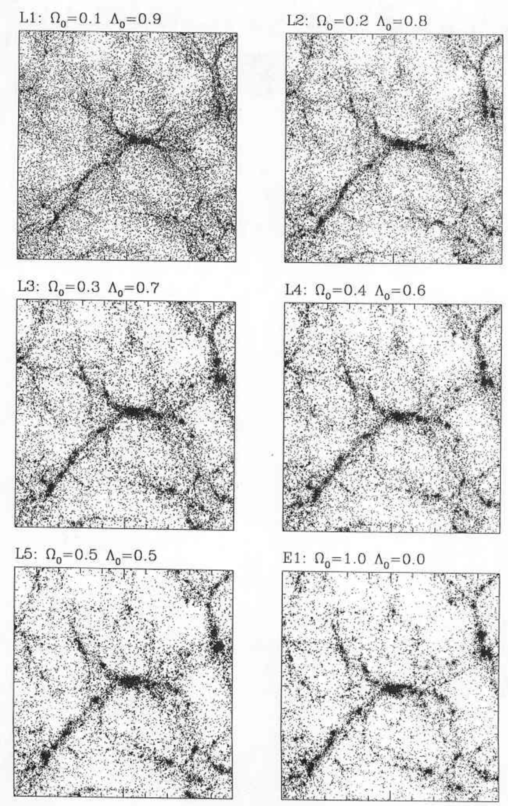


Figure 2. Evolved particle distributions from the six DMR-normalized, flat universe models. The slices are $20\,h^{-1}$ Mpc thick and $100\,h^{-1}$ Mpc on a side, and they show the same portion of the simulation volume that is shown in the lower left panel of Fig. 1.

Cosmography, volume, and the growth of structures

- Cosmography can be done by measuring (e.g.):
  - statistical properties of large scale structures
  - Cluster abundance and its redshift evolution
- Each method of course has limitations so it is important to apply more than one!

42 S. Cole et al.



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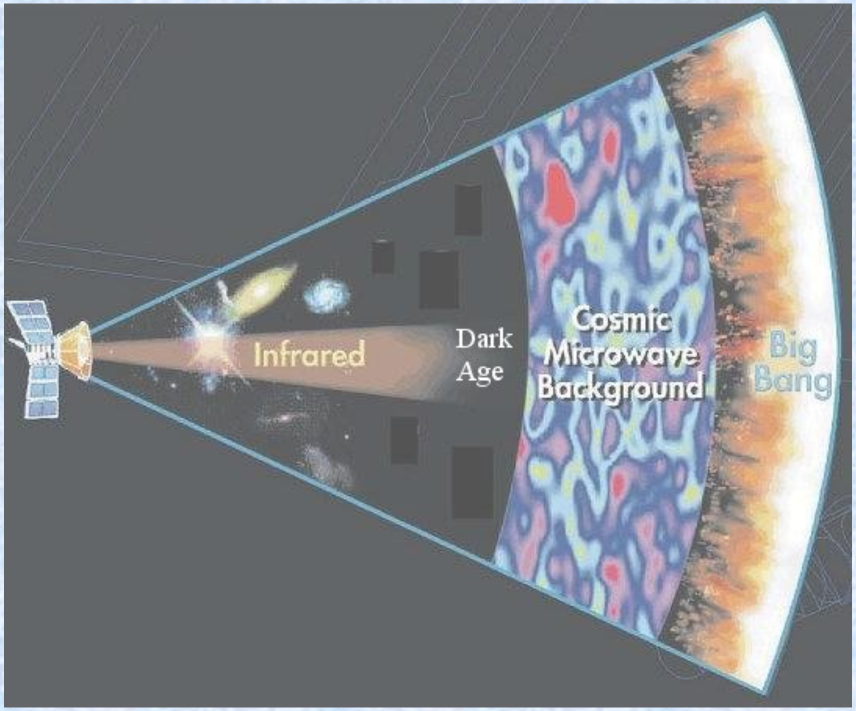
Cosmography, volume, and the growth of structures. Summary

- The volume of the universe as a function of redshift depends on the cosmological parameters, so can be used to do cosmography.
- Another approach is to measure the properties of the large scale structure of the universe and the abundance and evolution of density peaks (clusters). This is a sensitive measure of the matter density of the universe. (And the laws of gravity!)
- These two approaches are useful but difficult to do in practice. It is important to have more than one method.

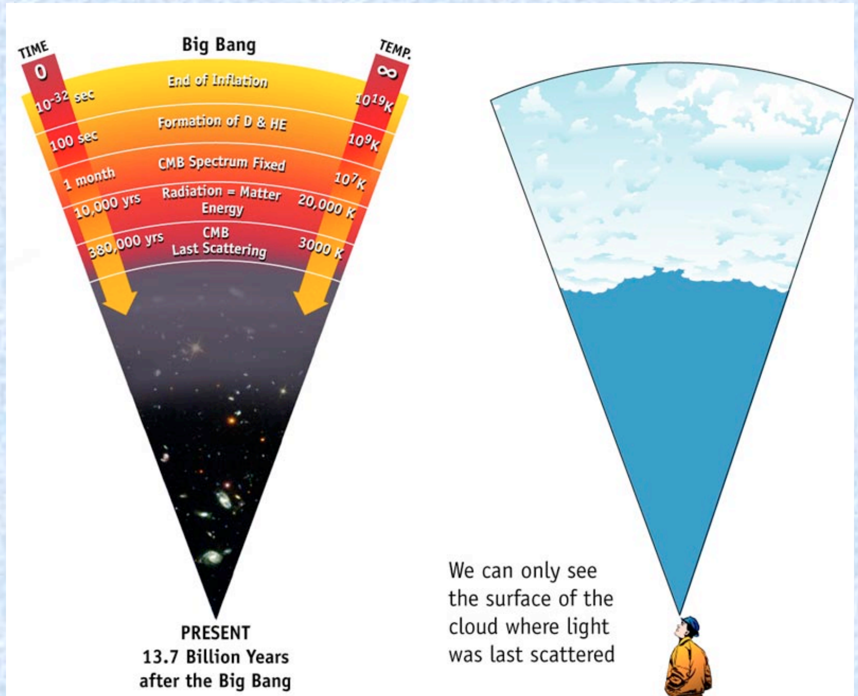
Cosmic Microwave Background as a cosmic "yardstick"

- As we have seen earlier the universe is filled with a homogeneous and isotropic radiation field (blackbody at T~3K) the CMB.
- The anisotropy of the CMB contains an incredible amount of information about the history of the early universe, its content and geometry.
- To understand how this is possible, we need to understand what exactly is the CMB.



CMB: recombination and last scattering surface

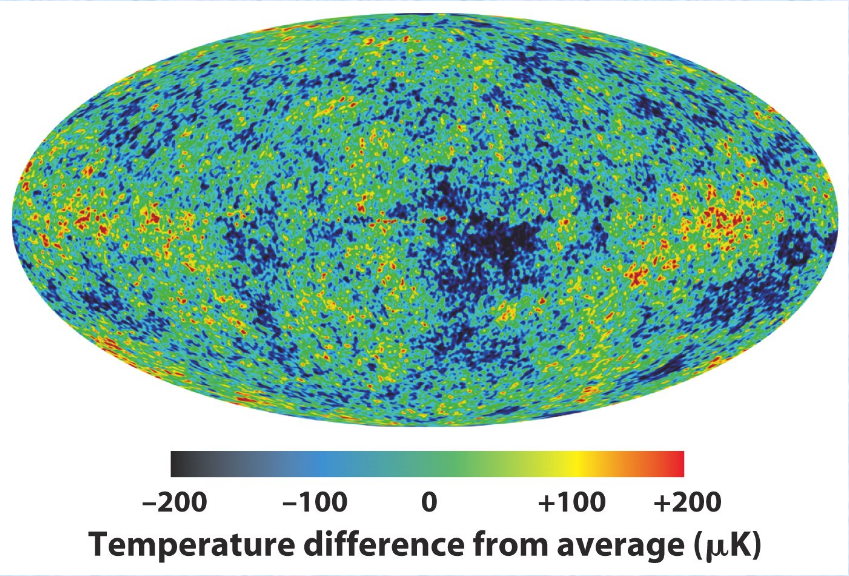
- The CMB anisotropies are a "Snapshot" of the universe taken at the epoch of recombination (z~1000), the so called last scattering surface.



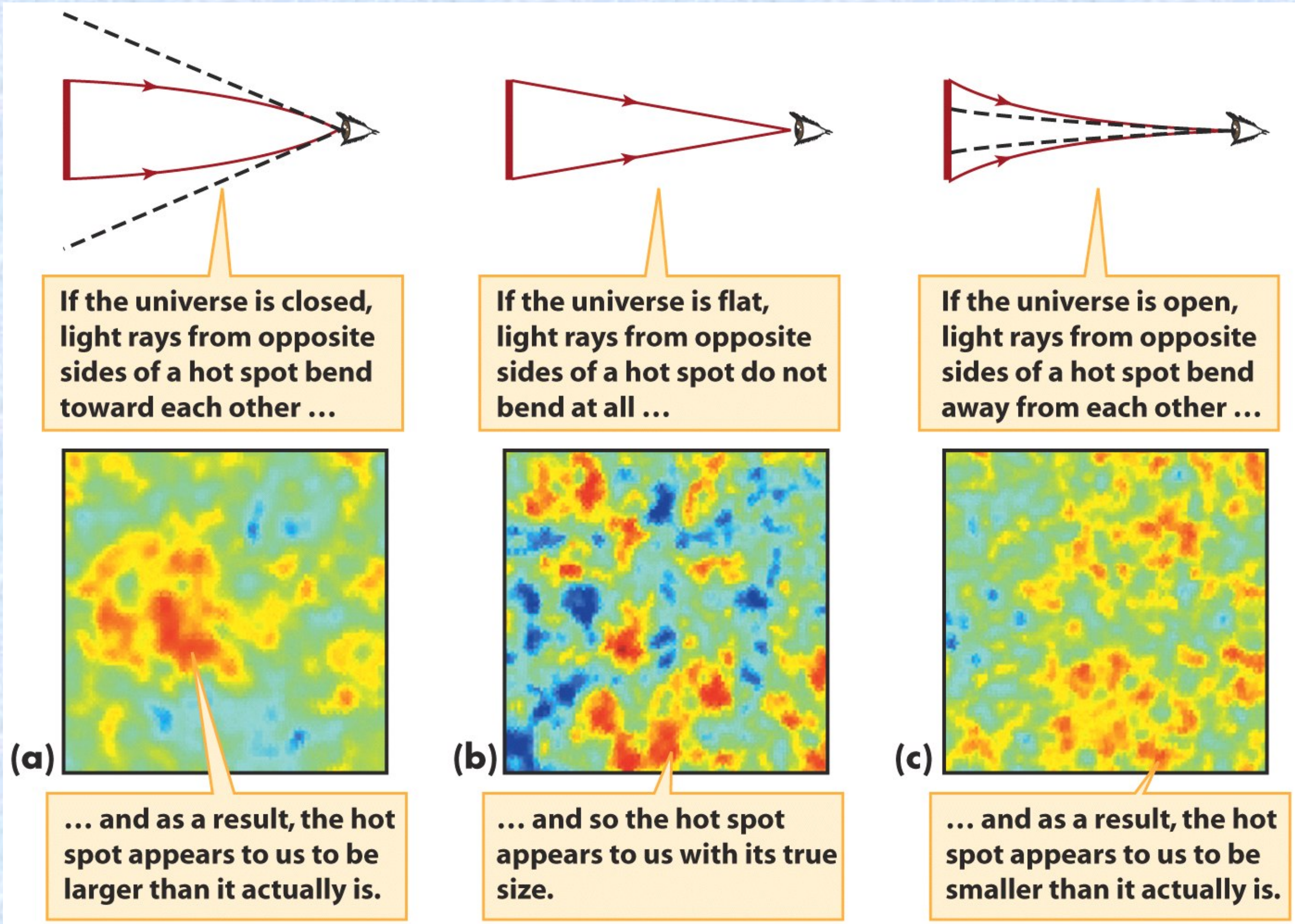
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

CMB anisotropies and cosmography.

- CMB anisotropies are useful for cosmography in two ways.
  - Peaks and valleys in Temperature correspond to valleys and peaks in the gravitational field at the time of recombination
  - The pattern is modified as it travel through space time to get to us, recording the geometry of the Universe.



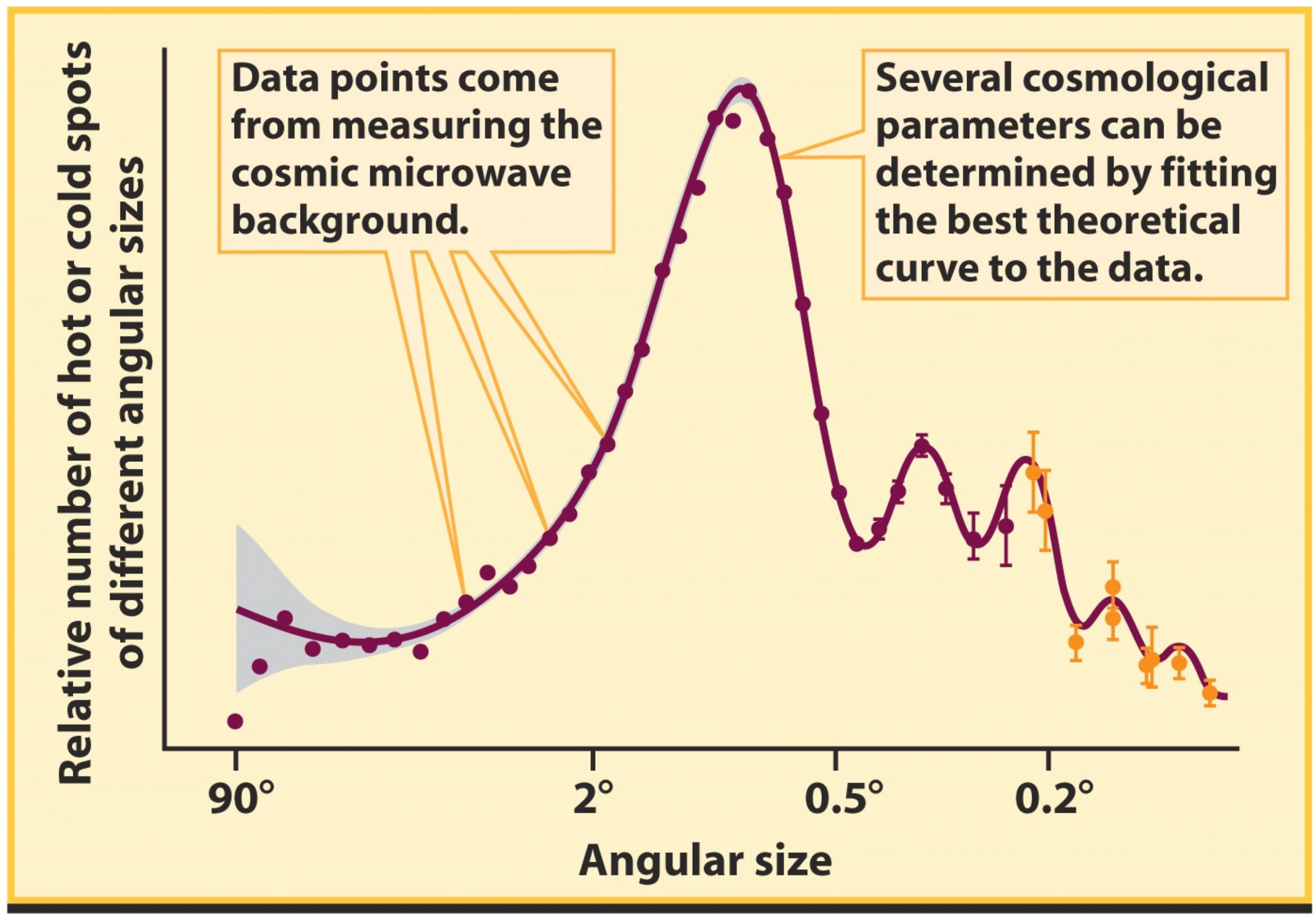
CMB anisotropies and cosmography. Light propagation



Credit NASA and the WMAP team; MOVIE (39)!

CMB anisotropies and cosmography. Light propagation

CMB anisotropies and cosmography. Acoustic peaks



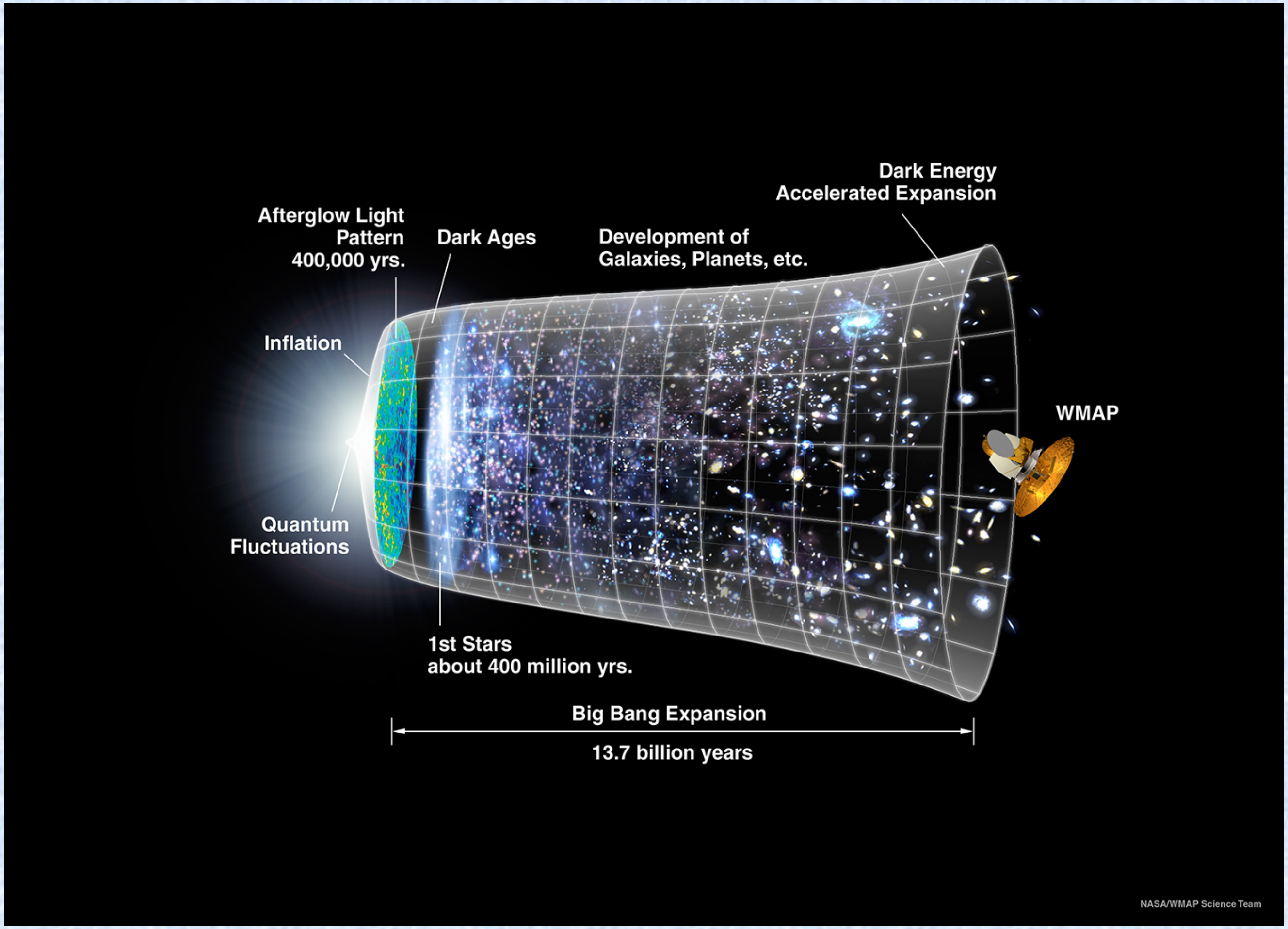
CMB anisotropies and cosmography. Results

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, Ω_0	Combined mass density of all forms of matter *and* energy in the universe, divided by the critical density	1.02 ± 0.02
Matter density parameter, Ω_m	Combined mass density of all forms of matter in the universe, divided by the critical density	0.27 ± 0.04
Density parameter for ordinary matter, Ω_b	Mass density of ordinary atomic matter in the universe, divided by the critical density	0.044 ± 0.004
Dark energy density parameter, Ω_Λ	Mass density of dark energy in the universe, divided by the critical density	0.73 ± 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 ± 1

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

CMB anisotropies and cosmography. Results

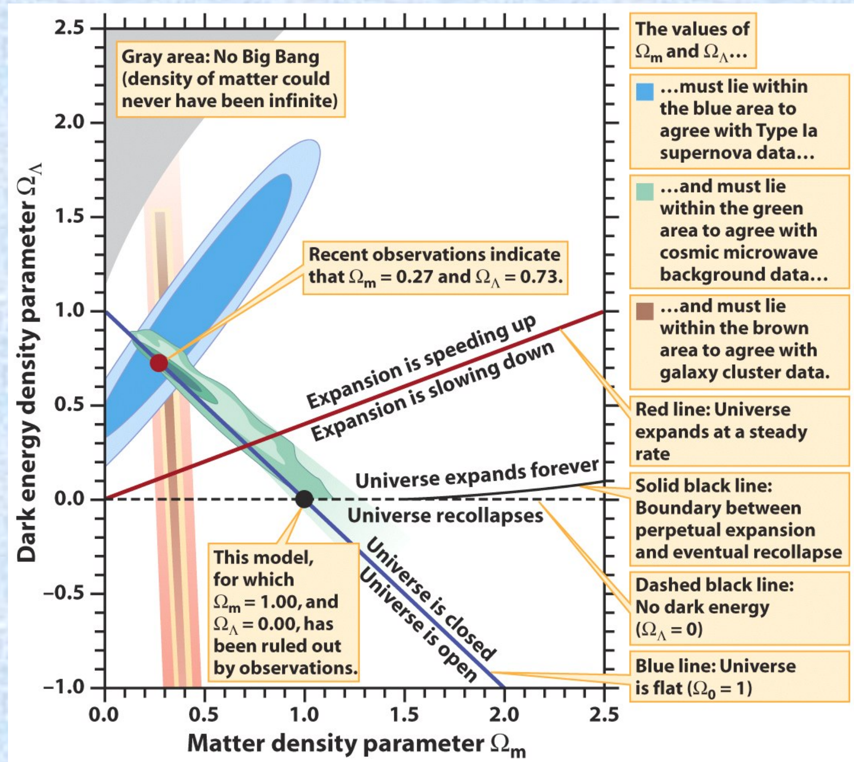


CMB cosmography. Summary

- CMB anisotropies are a snapshot of the universe at the last scattering surface at z~1000, when the universe was about 380,000 years old
- They convey information about the content and geometry of the universe so that many parameters are known to a 10% or better.

Concordance cosmology. Happy campers?

- Do the various methods agree?
- They do!
- This is called "concordance cosmology"



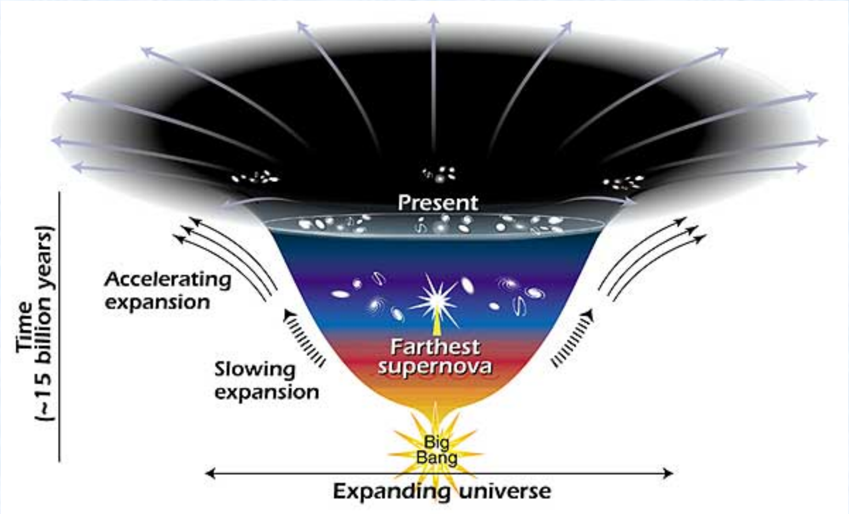
Concordance cosmology.
Happy campers?

Acceleration and Horizons

"SOME THINGS THAT USED TO BE UNOBSERVABLE ARE NOW OBSERVABLE — BUT SURPRISINGLY ENOUGH, SOME THINGS THAT USED TO BE OBSERVABLE ARE NOW UNOBSERVABLE."

Acceleration and Horizons

- The universe is expanding and accelerating
- So the portion of the universe inside our visible horizon does not grow as fast as for a static universe
- Depending on the properties of dark energy some objects may never be in our horizon, or even objects that are now in our horizon will not be in the future
- Acceleration may even increase so much that the universe will be ripped apart “Big Rip” [movie]



The End

Thursday is midterm!