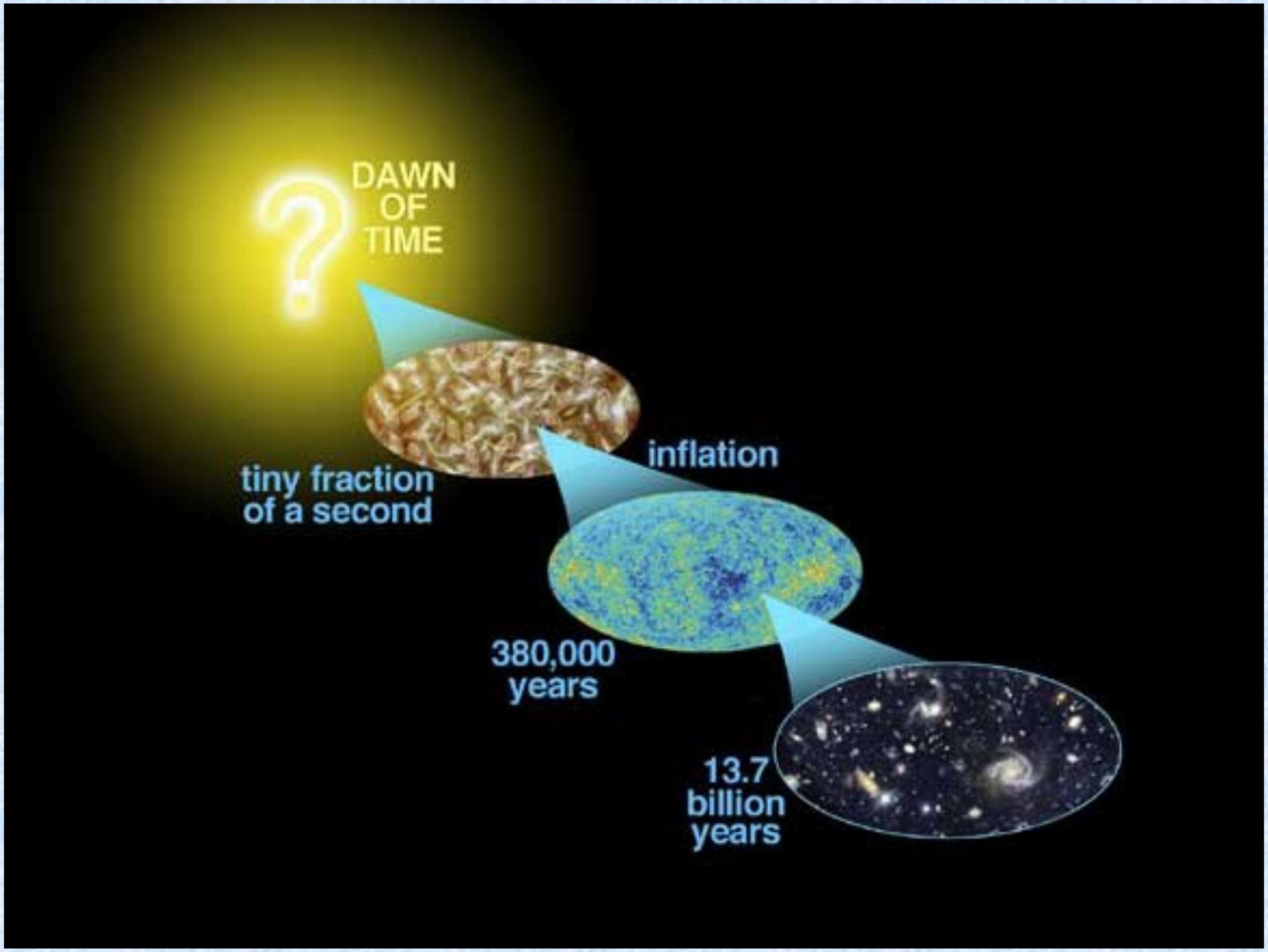
# Physics 133: Extragalactic Astronomy ad Cosmology




Lecture 4; January 15 2014

# Previously

- The dominant force on the scale of the Universe is gravity
- Gravity is accurately described by the theory of general relativity
  - Mass-energy tells spacetime how to curve and spacetime tells mass-energy how to move
- In three dimensions there are only 3 possible isotropic and homogeneous manifolds
  - Positive curvature (hyper-sphere)
  - Negative curvature (hyper-hyperboloid)
  - Zero curvature (flat Euclidean space)

# Homework #3:

- Find on the webpage at http://www.physics.ucsb.edu/~tt/PHYS133/homework.html

- **Due wednesday January 22**

# Outline:

- Geometry of the Universe:
  - The Robertson-Walker metric
    - Direct observational limits on the curvature of the Universe
  - Proper distance and redshift
- Dynamics of the Universe:
  - Friedmann Equation

# Space-time in special relativity. I

- In special relativity, space and time are united in a (flat) 4D space-time. Do you remember? How do you transform between reference frames?
- The metric of this space is?
- Minkowski's:
  - $ds^2=-c^2dt^2+dr^2+r^2d\Omega^2$

# Space-time in special relativity. II

- A photon travels along null geodesics, $ds^2=0$.
- This means photons travel along straight lines, at the speed of light.

# Space-time in general relativity. Homogeneous and isotropic universe

- If the universe is homogenous and isotropic we can separate the time part of the metric from the space part of the metric and define a cosmic time t.
- The metric can be written in one concise form, the Robertson-Walker metric. [Blackboard]

# Space-time in general relativity. Properties of RW metric

- Space component is a hyper-sphere, hyper-hyperboloid or a flat Euclidean space up to a constant scalar factor a(t) that depends on time. (k and R)
- The variable t (cosmic time) is the time measured by an observer who sees the universe expanding uniformly, i.e. at rest with the "Hubble Flow"
- The space variables are called comoving coordinates. In absence of perturbations or forces, an observer at rest would remain at a constant comoving position (this is called the Hubble Flow). Note that although observers are at rest, the distance between them increases due to a(t).
- Hubble's law is not the result of "motion" (because with respect to the comoving coordinates objects are not moving) but of the expansion of space time.

# Space-time in general relativity. The RW metric and the Universe

- The RW metric is an approximation valid only over large enough volume (100 Mpc or more).
- On large scales it describes the universe very well.
- The kinematics of the universe is described by a(t). As we will see, one can write dynamical equations for a(t) and solve them, thus reconstructing the past and future of the universe.
- We know the local derivative of a(t). What is it?
- **The Hubble constant!**

# Direct limits on the geometry of the Universe.

- We could in principle measure the curvature by drawing a big triangle and measuring the angles. This is impractical, although in some sense this is what we will be doing later on
- One thing we know is that if the universe is positively curved, the radius cannot be much smaller than the Hubble Length, otherwise photons would have had time to go around the surface in circles and we would see periodical images.

# Distances in the Universe. Not your grandmother's distance!

- What is the distance between two objects in a RW metric?
- There are several kinds of distance. E.g.:
  - Proper distance
  - Luminosity distance
  - Angular size distance
- All of them are a function of time, of course.

# Distances in the Universe. Proper distance

- The proper distance is the distance between two sets of comoving coordinates at a given cosmic time.
- This is given by the spatial part of the metric at fixed a(t)
- [Blackboard]

# Expansion factor and redshift.

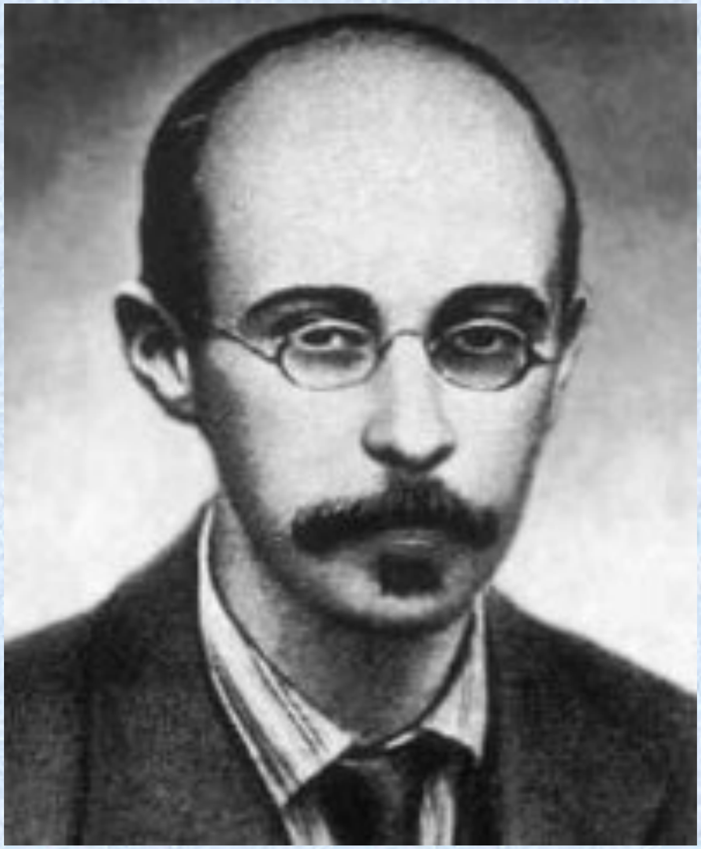
- What is the distance to the objects in the UDF?
- Given the redshift, which is easy to measure, we can infer a(t) at the time the light was emitted. This will give us the distances(s)

# Expansion factor and redshift. Propagation of light.

- Light travels along null geodesics: $c^2dt^2=a(t)^2dr^2$
- Imagine a wave of light. As time goes by, between one crest and another, the universe expands. So that the distance between wave crests appears longer to the observer.
- Light is redshifted! [Blackboard]
- **Redshift $1+z=1/a(t_e)$**

# Dynamics of the Universe. Friedmann Equation

- Now that we have the metric we need the equation of motion, i.e. the dynamics
- This is given by Friedmann Equation (1922)
- Newtonian analog [Blackboard]



1888 - 1925

# The universe is expanding. More frequently asked questions…

- Are galaxies at z=2 moving faster than the speed of light?
- No, the observed redshift is not really a Doppler effect! It's only a geometrical effect due to the expansion of the universe. As the universe gets larger wavelengths get stretched, resulting in the observed redshift.

# Theoretical foundations of the Big Bang. Summary

- The universe is a 4 dimensional manifold as in General Relativity
- The universe is homogeneous and isotropic
- This implies that space and time can be "separated" so that we can define a cosmic time t
- There are only three possible geometries for the universe. Their metric is the Robertson-Walker metric
- In a non static universe redshift is a measure of distance.
- The dynamics of the Universe is described by Friedmann Equation [TO BE CONTINUED].

# The End

See you on Wednesday!
[Monday is MLK's b-day]