Set 1:
Expansion of the Universe

Ast 243: Intro to Cosmology Syllabus

Course text book: Ryden, Introduction to Cosmology, 2nd edition

- Olber's paradox, expansion of the universe: Ch 2
- Cosmic geometry, expansion rate, acceleration: Ch 3,6
- Cosmic dynamics and composition: Ch 4,5
- Dark matter and dark energy: Ch 5,7

Midterm (in class 20%)

- Hot big bang and origin of species: Ch 9
- Inflation: Ch 10
- Cosmic microwave background: Ch 8
- Gravitational instability and structure formation: Ch 11,12

Final (30%)

HW (50% grader Huanqing Chen, hqchen@uchicago.edu)

Observables

- Most cosmological inferences are based on interpreting the radiation we receive on Earth from astrophysical objects:

  stars, galaxies, clusters of galaxies, cosmic microwave background...

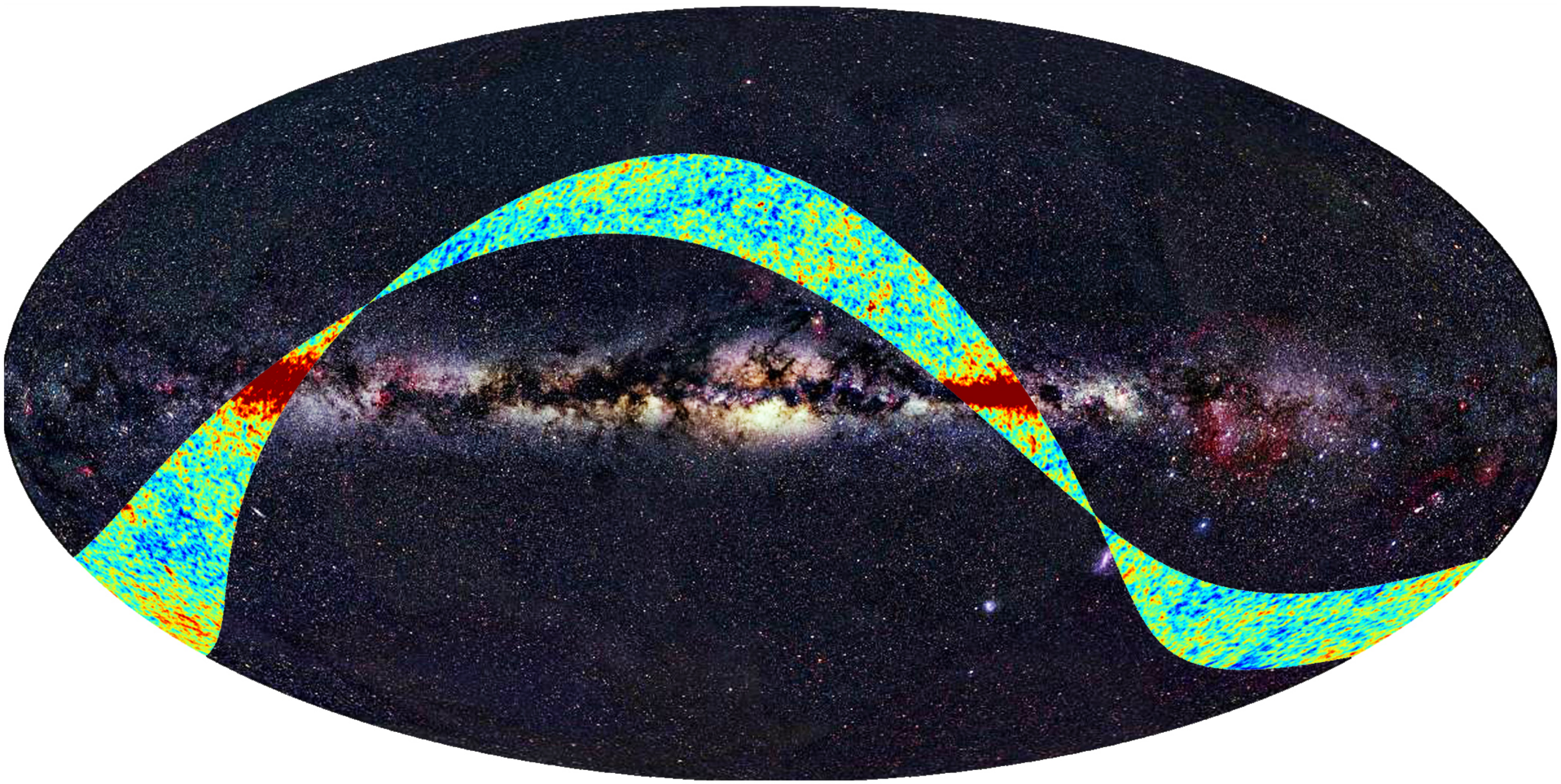
- Largely electromagnetic radiation but now also neutrinos, cosmic rays, and most recently, gravitational waves
- For light coming from a single object, e.g. a star or galaxy, let's think about the basic observable of the radiation that we measure in a detector

  flux: energy received by the detector per unit time per unit detector area

- How do we convert this basic observable into a 3D model?

Galaxy: Optical Image

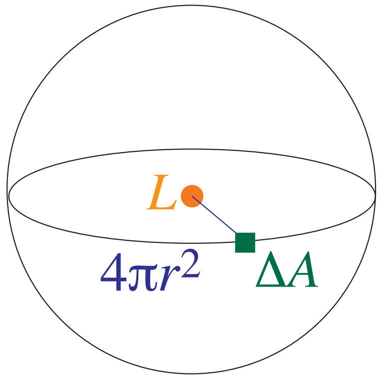
- Place nearby stars on a map of the sky and measure their flux
- Color overlay, furthest source: microwave background



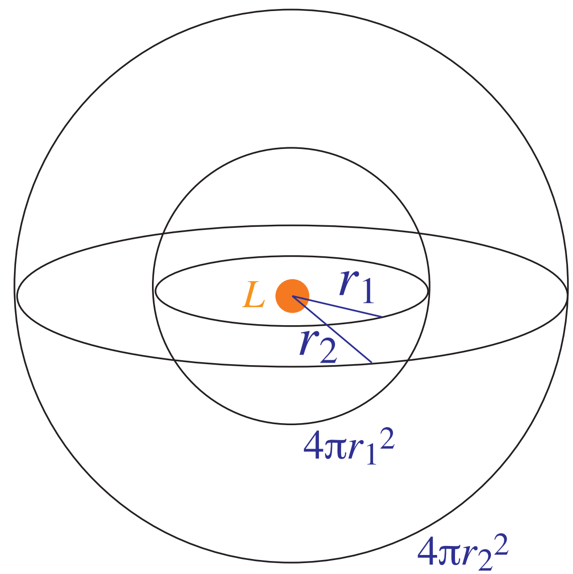
Observables

- Energy flux F given a luminosity L of the source $L = \Delta E/\Delta t$ (energy/time)

$$F = \frac{\Delta E}{\Delta t \Delta A} = \frac{L}{4\pi r^2}$$



- Astro units: often in cgs erg s^{-1} cm^{-2} (mks W m^{-2})
- Energy conservation says rate of energy passing through the shell at r_1 must be the same as r_2
- Thus flux decreases as $1/r^2$ from the source



$$F(r_1) 4\pi r_1^2 = F(r_2) 4\pi r_2^2$$

$$F \propto r^{-2}$$

From 2D to 3D

- So even without knowing the luminosity of a set of standard objects, we can judge relative distance from flux $r_2/r_1 = (F_1/F_2)^{1/2}$
- This is the idea of a standard candle, star of the same type, supernovae etc
- Aside: certain variable stars called Cepheids are excellent standard candles – pulsation period is linked to the luminosity so we can pick out objects of the same luminosity and use the measured flux to put place their relative position on a map
- 2D map becomes a 3D map and we can start to talk about the physical structure of the universe
- We can calibrate the absolute distance to the nearby ones by other methods, ultimately parallax - change in angle on the sky as earth orbits the sun at 1AU indicating distance as $d\alpha = \pm(1\mathrm{AU}/d)$

Cosmological Units

- Astro and cosmo units often look bizarre at first sight - however they are useful in that they tell you something about the observation behind the inference
- Cosmologists favorite unit is the megaparsec

$$1\text{Mpc} = 3.0856 \times 10^{24}\text{cm}$$

  because it is the typical separation between galaxies
- In other astrophysical contexts, use length scales appropriate to the system - Mpc is based on the AU - earth-sun distance
  - 1 AU subtends 1 arcsec at 1 pc – parallax to close objects allows us to convert relative distance to absolute distance
  - 1 pc: nearest stars, 1 kpc distances in the galaxy, 1 Mpc distance between galaxies, 1 Gpc distances across observable universe

Received Light: Received History

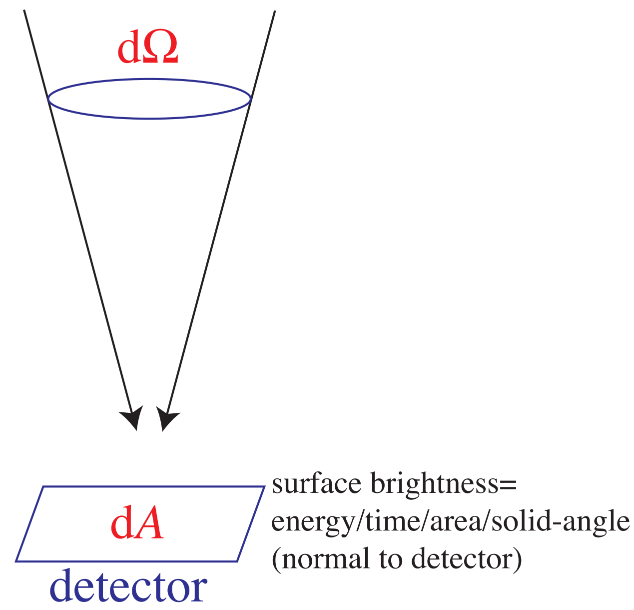
- Because of the finite light travel time, light from distant objects is emitted at earlier times so sky maps become snapshots of the history of the universe

$$\Delta t = \frac{\Delta x}{c}$$

- Speed of light can be thought of as a conversion factor between time and distance (see problem set)
- In this class we will often measure time and space in the same units, i.e. we set $c = 1$ and measure time in Mpc or distance in (light) years
- We shall see that the earliest light we can measure (from the most distant sources) comes from the cosmic microwave background, the afterglow of the big bang - many Gpc or Gyr away

Observables: Surface Brightness

- If the 2D map resolves the object in question, we can do better: measure surface brightness
- Direction: columate in an acceptance angle $d\Omega$ normal to $dA \rightarrow$ surface brightness



$$S(\Omega) = \frac{\Delta E}{\Delta t \Delta A \Delta \Omega}$$

- Units: for example in cgs, erg s^{-1} cm^{-2} sr^{-1} or mks, W m^{-2} sr^{-1}

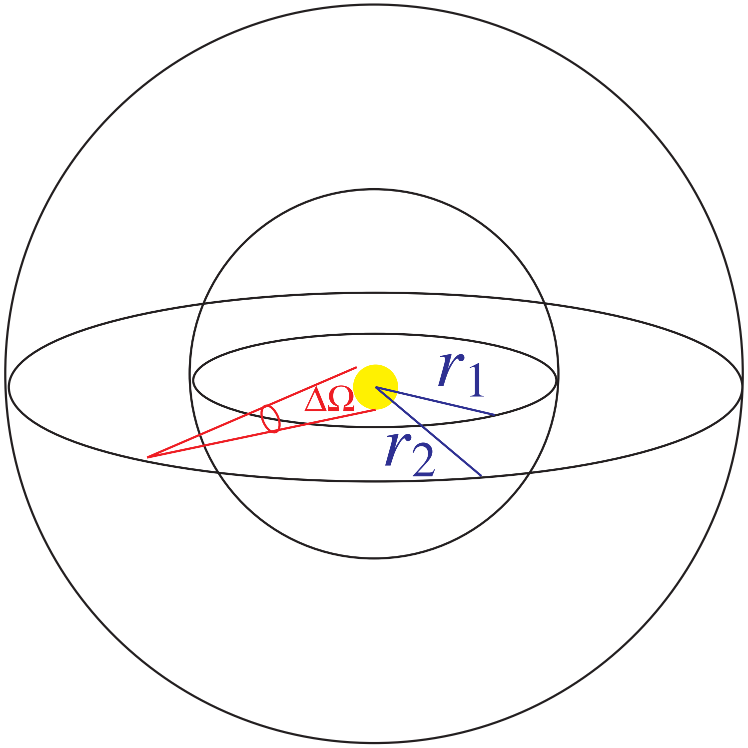
Surface Brightness Conservation

- Surface brightness $\Delta\Omega = (\lambda/d)^2$ for a region with fixed size λ

$$S = \frac{F}{\Delta\Omega} = \frac{L}{4\pi d^2}\frac{d^2}{\lambda^2}$$

- In a non-expanding geometry, these two distances cancel

$$S = \text{const.}$$



- Aside: since $S = L/4\pi\lambda^2$, astro/cosmo units for galactic scale objects are also often quoted in $L_\odot$/pc^2

Olber's Paradox

- Surface brightness of an object is independent of its distance
- So since each site line in universe full of stars will eventually end on surface of star
- Olber's Paradox: why isn't night sky as bright as sun (not infinite)
- We shall see that the resolution lies in the expansion of the universe:
  - finite "horizon" distance for the observable universe
  - and that the two distance factors don't cancel
- To understand the expansion, we need not just a map of the universe but a measurement of motion

Observables: Redshift

- We can also measure the frequency of radiation from objects
- If emission contains atomic lines with a natural rest frequency $\nu_{\rm rest}$ we can measure the redshift or velocity by the ratio of observed to rest frequency

$$1 + z = \frac{\nu_{\rm rest}}{\nu_{\rm obs}} = \frac{1 + v/c}{\sqrt{1 - v^2/c^2}}$$

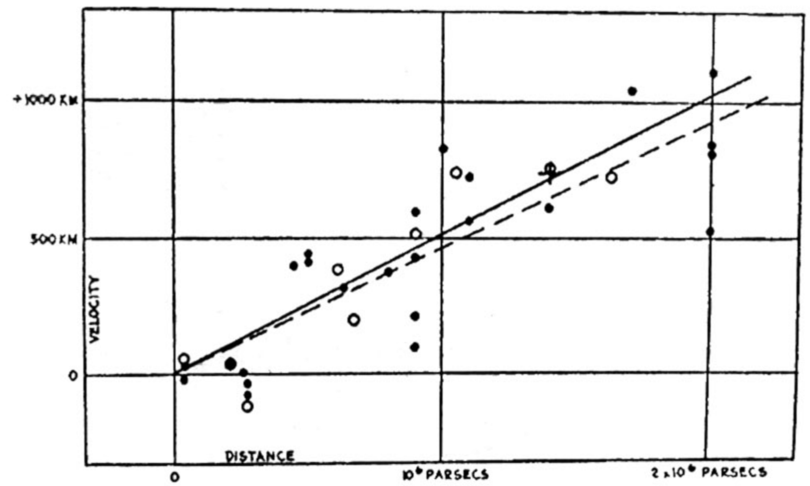
  and for $v \ll c$, $z = v/c$
- Here v is the recession velocity - i.e. light is shifted to the red if the object is receding from us
- In this class we'll often use units where $c = \hbar = 1$ which means time and length are energy are measured in the same units
- If units don't make sense add $c, \hbar$ until they do (see problem set)!

Expansion of the Universe

- Now let's put together these observational tools
- Given a standard candle with known luminosity L, we measure its distance d away from us from the measured flux $F = L/4\pi d^2$
- Given atomic line transitions, we measure the redshift z or equivalently the recession velocity v
- Hubble then plotted out recession velocity as a function of distance....

Hubble Law

- Hubble in 1929 used the Cepheid period luminosity relation to infer distances to nearby galaxies thereby discovering the expansion of the universe



- Hubble actually inferred too large a Hubble constant of $H_0 \sim 500$km/s/Mpc due to a miscalibration of the Cepheid distance scale
- H_0 now measured as 74.03 ± 1.42km/s/Mpc by combining a suite of distance measurements [arXiv:1903.07603]

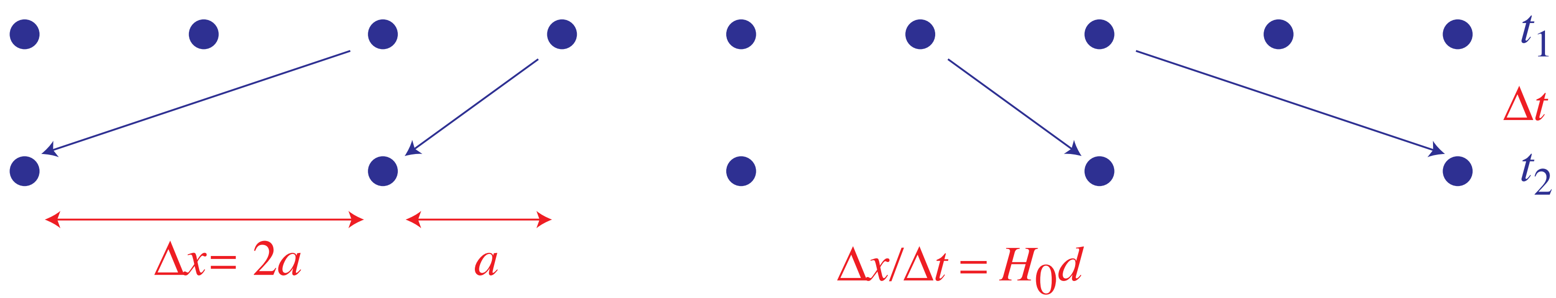
Fundamental Properties

- Hubble law: objects are receding from us at a velocity that is proportional to their distance
- Universe is highly isotropic at sufficiently large distances
- Universe is homogeneous on large scales
- Let's see why the first property, along with the implications of the second two that we are not in a special position, imply the universe is expanding

- The Hubble law sounds much like we are at the center of an explosion outwards but that would violate homogeneity and put us in a special place
- To be consistent with both, we posit space itself is expanding...

Expansion of the Universe

- Consider a 1 dimensional expansion traced out by galaxies



- From the perspective of the central galaxy the others are receding with a velocity proportional to distance
- Proportionality constant is called the *Hubble Constant* H_0
- Each observer in the expansion will see the same relative recession of galaxies

Expansion of the Universe

- Generalizes to a three dimensional expansion. Consider the observer at the origin and two galaxies at position $\mathbf{d}_A$ and $\mathbf{d}_B$
- Recession velocities according to the observer

$$\mathbf{v}_A = H_0 \mathbf{d}_A \,, \quad \mathbf{v}_B = H_0 \mathbf{d}_B$$

- According to galaxy B, the recession velocity of galaxy A is

$$\mathbf{v}_B - \mathbf{v}_A = H_0 \mathbf{d}_B - H_0 \mathbf{d}_A = H_0 \mathbf{d}_{AB}$$

  so that B will see the same expansion rate as the observer at the origin given the linearity of Hubble's law
- Hubble's law is best thought of as an expansion of space itself, with galaxies carried along the "Hubble flow"

Olber's Paradox Redux

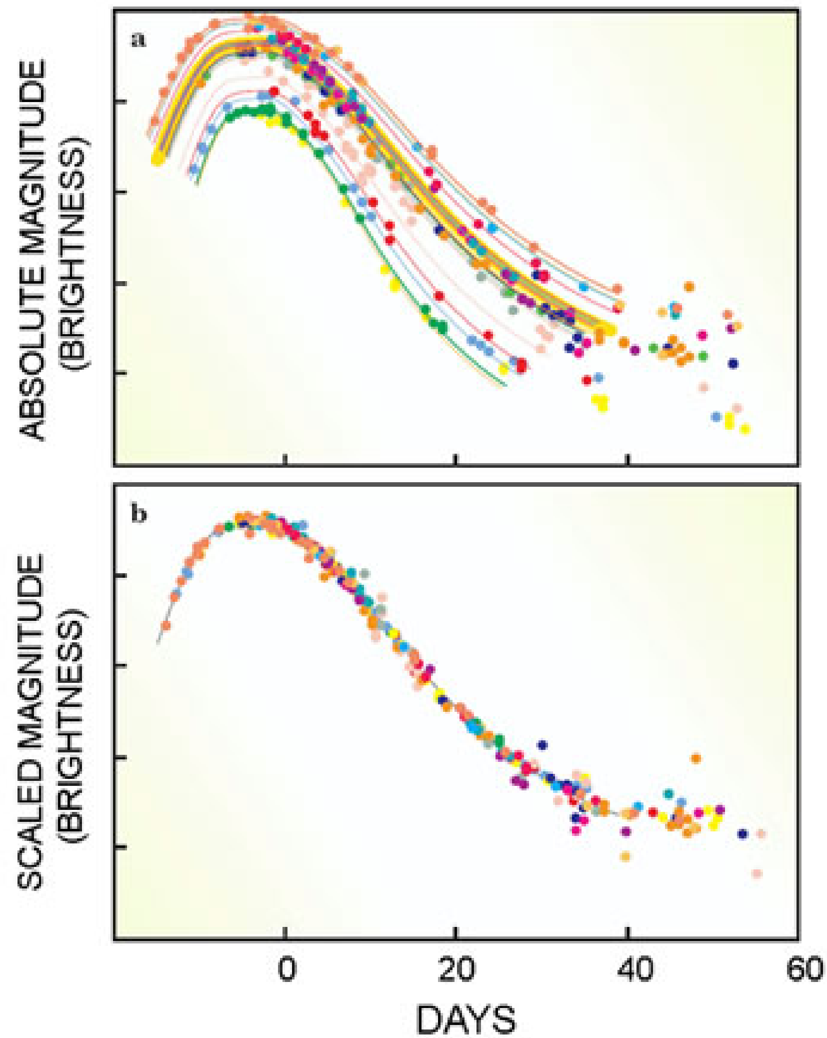
- In an expanding universe Olber's paradox is resolved
- First piece: age finite so there is a finite distance light can travel called the horizon distance - even if stars exist in the early universe, not all site lines end on stars
- But even as age goes to infinity and the number of site lines goes to 100%, surface brightness of distant objects (of fixed physical size) goes to zero
  - Angular size increases
  - Redshift of energy and arrival time

  we'll see in the next set of lectures

$$S \propto (1+z)^{-4}$$

Supernovae as Standard Candles

- Type 1A supernovae are white dwarfs that reach Chandrashekar mass where electron degeneracy pressure can no longer support the star, hence a very regular explosion
- Moreover, the scatter in luminosity (absolute magnitude) is correlated with the shape of the light curve - the rate of decline from peak light, empirical "Phillips relation"



- Higher ^{56}N, brighter SN, higher opacity, longer light curve duration

Beyond Hubble's Law

- Type 1A are therefore "standardizable" candles leading to a very low scatter $\delta m \sim 0.15$ and visible out to high redshift $z \sim 1$
- Two groups in 1999 found that SN more distant at a given redshift than expected
- Cosmic acceleration discovery won the 2011 Nobel Prize in Physics
- Requires more on cosmic geometry to understand...