Cosmological redshift tells us age of Universe when light left the galaxy

Observed redshift \( z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{rest}}} - 1 \) = function (Cosmological \( z_{\text{cos}} \), Doppler \( z_{\text{dop}} \))

\[1 + z_{\text{cos}} = \frac{\text{Size of Universe today}}{\text{Size of Univ when light left galaxy}} = f \left( \text{expansion rate of Universe, age of Universe} \right)\]

For distant galaxies can set \( z = z_{\text{cos}} \) and related \( z \) to age of Universe.

\( \rightarrow \) age = 5.8 Gyr
\( \rightarrow \) lookback = 13.7 – age = 7.9 Gyr

Relationship between angular & physical scale of 1” varies with redshift

1” corresponds to

~ 7000 pc at redshift \( z=1 \)
~ 200 pc at redshift \( z=0.01 \)

What angular resolution (or point spread function) do you need to resolve the bulge of a typical spiral galaxy at \( z=1 \)? Assume the bulge has a radius of 1 kpc

Current and Next-Generation Multi-wavelength Facilities: why do we need them?
Assembling a galaxy (made of gas, stars, dark matter) is a complex process involving gas accretion, mergers of galaxies and dark matter halo, and formation of new stars from cold gas. To understand that process we need high resolution, multi-wavelength observations of many galaxies at different epochs.

**Technical capabilities**

(angular resolution, sensitivity, speed, etc.)

Optical/IR telescopes: angular resolution and signal-to-noise

\[ \theta = \frac{1.22 \lambda}{D} \]

Diffraction-limited angular resolution \( \theta_{\text{diff}} \) of a single dish telescope

\[ \theta = \frac{2.1 \times 10^3 \lambda}{D} \] arcseconds

Radio Telescopes: Angular resolution of single dish radio telescope vs radio interferometer

\[ \theta = \frac{1.22 \lambda}{D} \]

Diffraction-limited angular resolution of a single dish telescope

\[ \theta = \frac{2.1 \times 10^3 \lambda}{D} \] arcseconds

Example of diffraction limited angular resolution for a single dish radio telescope of 100 m diameter

**See in-class notes for discussion of points below**

1) Angular resolution or PSF \( \theta = \) = function of \( \theta_{\text{atm}}, \theta_{\text{pix}}, \theta_{\text{electron}}, \theta_{\text{tel}} \) = function of atmosphere + telescope-instrument specs

2) Comparison of PSF for current and future facilities
   - ground facilities, e.g., VLT, Keck, HET vs GMT
   - space facilities, e.g., HST/ACS, HST/NIC3 vs JWST

3) Signal to noise in CCD images
   = function of (time \( t \), source counts, photon noises, sky noise, detector noise, readout noise)
Radio Telescopes: Angular resolution of single dish radio telescope vs radio interferometer

\[ \theta = \frac{1.22 \lambda}{B} \]

\( B \) = Baseline i.e. telescope separation

For 2 telescopes separated by 30 km
\[ \implies \text{Ang. res.} \approx 1 \text{ arcsecond} - \text{MUCH BETTER!} \]

Wave-fronts from distant source perfectly in phase

Radio Observations: A few useful equations

Converting Units

In radio astronomy, one often converting between different units of measurement and computing the required integration time for varying spectral resolutions. Here we provide a few important reference equations. (For further details, see "Tools of Radio Astronomy" by Robson and V. S.

To convert frequency to wavelength, a handy rule of thumb is to remember that the wavelength is \( \approx 1 \text{ mm} \) to three decimal places when the frequency is 1000 GHz. Thus, to convert frequency (in GHz) to wavelength (in mm),

\[ \lambda \approx \left( \frac{300 \text{ GHz}}{c} \right) \]

Spectral or velocity resolution

To achieve a particular velocity resolution \( \Delta v \) at a given observing frequency \( \nu \), requires a frequency resolution \( \Delta \nu \) of

\[ \Delta \nu = \left( \frac{c}{\lambda} \right) \Delta v \]

For example, a 1 km/s resolution at 300 GHz would require a frequency resolution of 1 MHz. Conversely, a channel spacing of 0.1 MHz (correlator mode 12; see table page 9, page 9) would correspond to a velocity spacing of 0.1 km/s at 90 GHz, or 0.05 km/s at 180 GHz.

Radio Observations: A few useful equations

Flux density and Brightness Temperature

The conversion from brightness temperature \( T \) to flux \( S \) with synthesized beam solid angle \( \Omega_b \) is

\[ S = 2 \times 3.7 \times 10^5 \frac{T}{\Omega_b} \]

An alternate formula for is often useful as

\[ \left( \frac{S}{B} \right) = \left( \frac{1}{\text{by km}^{-1}} \right) \left( \frac{1 \text{ GHz}}{\nu} \right)^2 \left( \frac{8 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}}{B} \right) \]

Noise in radio observations

Finally, the noise \( \Delta S_p \) in an integration time \( M \) varies with system temperature \( T_{sys} \), frequency resolution \( \Delta \nu \), number of antennas used \( N \), diameter of the antennas \( D \), and number of polarization measurements obtained \( b_p \), in the following manner:

\[ \Delta S_p = \frac{T_{sys}}{D^2 \nu b_p N (N - 1) \Delta \nu} \Delta S_p^2 \text{ W m}^{-2} \text{ Hz}^{-1} \]

Redshift-dependent systematic effects to consider when observing galaxies at high redshift
Redshift-dependent systematic effects

When observing galaxies at high redshift, need to consider redshift-dependent systematic effects, such as:

1) Bandpass shift
2) Loss in spatial resolution (in pc) at a given angular resolution (aka ‘blurring’)
3) Cosmological surface brightness dimming

Bandpass shift: a given filter traces light at different rest-frame wavelength in galaxies at different redshift

- A given filter (e.g., F606W filter with observed wavelength $\lambda_{\text{obs}}$ of 5915 Å) will trace light at different rest-frame wavelengths ($\lambda_{\text{rest}}$) in galaxies at different redshifts $z$. This effect is called bandpass shift.

Example

F606W filter image of a galaxy at redshift $z$ traces rest-frame wavelength

$$\lambda_{\text{rest}} = \frac{\lambda_{\text{obs}}}{1+z} = \frac{5915 \text{ Å}}{1+z}$$

- trace rest-frame optical ($\lambda < 4000$ Å) light if redshift $z < 0.5$
- trace rest-frame ultraviolet ($\lambda < 3000$ Å) if redshift $z > 0.5$

→ Hence even if the 2 galaxies at different redshifts are identical, their F606W images can look very different as they are tracing light at different rest-frame wavelengths, which are dominated by stars of different temperature (Wien’s law), mass and age. See figure on next page

Another Example of Bandpass Shift

Another example of bandpass shift is that a given galaxy at a given redshift $z$ will look different when imaged with different filters, such as F06W and F850LP

Same galaxy at $z=0.8$ observed in F606W (left) and in F850 LP (right)

F606W $\lambda_{\text{rest}} = \frac{5915 \text{ Å}}{1+0.8} = 3268$ Å = UV wavelengths
F850LP $\lambda_{\text{rest}} = \frac{9103 \text{ Å}}{1+0.8} = 5057$ Å = optical wavelengths
1' corresponds to 
~ 7000 pc at redshift z=1  
~ 200 pc at redshift z=0.01  

What angular resolution (or point spread function) do you need to resolve the bulge of a typical spiral galaxy at z=1? Assume the bulge has a radius of 1 kpc.

Cosmological surface brightness dimming

- See in class notes showing the bolometric SB of an object fall with redshift at rate of $(1+z)^{-4}$. This effect is a purely geometrical effect and is called cosmological SB dimming.
- Hence when interpreting images of galaxies at high redshift, have to ask:
  Is the lack of low surface brightness features in the observed image of a galaxy due to the fact that these features are really absent in the galaxy OR is it due to the fact that geometrical cosmological effects dim the features out?

Examples of Cosmological SB dimming + loss of spatial resolution

Artificially redshift local mergers out to z=0.5 and 0.8 and 'observe' with ACS. Courtesy: Jogee and Weinzirl (use FERENGI software by Barden et al. 2008)

Examples of Cosmological SB dimming + loss of spatial resolution

Artificial redshift local mergers out to z=0.5 and 0.8 and 'observe' with ACS. Courtesy: Jogee and Weinzirl (use FERENGI software by Barden et al. 2008)
Example of some large and deep optical surveys done with HST Advanced Camera for Surveys (ACS) from 2004-2009

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Why do we need the Hubble Space Telescope (HST)?

- Launched in 1990
- Mirror diameter= 2.5 m
- Orbits 600 km above Earth
- Powered by solar batteries
- Instruments on board: uv, optical, infrared

Advantage of HST vs. a ground-based telescope: BYPASS THE ATMOSPHERE
1) No blurring by Earth’s atmosphere → image has high spatial resolution
2) Can observe UV photons without absorption by Earth’s atmosphere
3) Can observe infrared emission without high background (glare) from sky

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Optical Images from HST are sharper than ground image by a factor of over 30

HST vs Ground-based data for moderately distant galaxies in the Coma cluster

Courtesy: Z. Levay (STScI) NASA, ESA, Coma ACS Treasury Team
Note the huge improvement in spatial resolution in going from the ground-based Combo-17 image (1.5") to space-based Hubble ACS image (0.1").

Galaxy Surveys with the Advanced Camera for Surveys (ACS) on Hubble Space Telescope as of 2003

SM3: Installing new gyroscopes and ACS aboard HST
Servicing Mission 3 (SM3) split into two parts:
- SM3A in Dec 1999 via shuttle Discovery: replace all 6 gyroscopes on HST
- SM3B in Mar 2002 via shuttle Columbia: replace solar panels, install powerful ACS

Galaxy Surveys with ACS on Hubble
Early galaxy surveys, including the famous Hubble Deep Field (HDF) in 1996, used the old WFPC2 camera aboard HST. WFPC2 had a very small field of view.

The Advanced Camera for Surveys (ACS), installed in 2002, is 10 times more powerful than WFPC2:
- has a larger field of view (60 times larger)
- more sensitive
- higher angular resolution

It has allowed several state-of-the-art surveys of galaxy evolution in 2004:
- the GEMS survey: large area (30'x30'), moderate depth out to z=1
- the COSMOS survey: large area (2 sq degree), moderate depth out to z=1
- the GOODS survey: small area, large depth out to z=6
- the HST Ultra Deep Field (HUDF): very small area, very deep out to z=6
The GEMS Survey: Example of a shallow large-area survey of galaxies with HST

GEMS surveys galaxies out to lookback times of 8 Gyr, when the Universe was 5.7 Gyr old.

HUDF surveys galaxies out to lookback times of 13 Gyr, when the Universe was 0.7 Gyr old.

GEMS is the largest-area imaging survey conducted using 2 filters on the ACS camera aboard HST.

GEMS survey area:
- 77 ACS pointings patched together
- 30'x30' size of full moon on sky
- 120 x area of Hubble Deep Field (HDF) containing with UDF in 1995
- 72 x area of Hubble Ultra Deep Field (HUDF)

GEMS also has galaxy spectra which provide accurate redshifts for ~9000 galaxies. The redshifts are used to derive the lookback times, which lie in the range 2 to 9 Gyr.

Example of normal 'non-merging' galaxies over $z=0.7-1.0$ ($T_{lookout}=6-8$ Gyr).
Example of interacting/merging galaxies at lookback = 3 to 8 Gyr


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**Galaxy and Cosmic Explorer Tool (GCET)**

See in-class demo  =  http://www.as.utexas.edu/gcet/

Surf the GEMS survey with your browser!

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**The Hubble Ultra Deep Field (HUDF) Survey: Example of a deep small-area survey of galaxies with HST**
The Hubble Ultra Deep Field (HUDF) is the deepest visible-light image of the Universe. It consists of a million s exposure taken with the ACS camera aboard HST in 2004 by the HUDF team. It probes lookback times of 13 Gyr, when Univ was a mere 0.7 Gyr old.

1) Galaxy surveys show early epochs of proto-galaxy evolution at z~6-7
At z~6-7 (when age of Universe~0.9 to 0.7 Gyr or 5% of its present age, corresponding to lookback times of 12.8 to 13.0 Gyr)
  → we see young proto-galaxies, made of (dark matter, gas, some stars)
  → the masses of these proto-galaxies are found to be similar to dwarf galaxies (mass~ 10^7-10^8 Msun) and much less massive than present-day spirals or E.

2) Probing Early Cosmic Epochs with GEMS and HUDF
GEMS surveys galaxies out to lookback times of ~8 Gyr, when Univ was 5.7 Gyr old.
HUDF surveys galaxies out to lookback times of 13 Gyr, when Univ was 0.7 Gyr old.
Chaotic period ~ 13.0 Gyr ago where first proto-galactic disks structures form and merge. The Universe is dominated by violent major mergers at early times.

Over last 10 Gyr, from z=2 to 0: Today, mature galaxies on the Hubble sequence are in place. The mass and structures (disks, bars, bulges) of galaxies grow via accretion, secular evolution and mergers. It appears that major mergers may not have played such a key role!

13.7 (100%) 4.7 (35%) 0.7 (5%) 0 (0%)

Lookback Time in Gyr
Age of Universe in Gyr and %

0.0 13.0 13.7 13.9

Mass of the universe (matter of stars)