

- Our Schedule**
- **Course evaluations (FCQ) online next week, separately for lecture and recitations**
  - **Third Mid-Term Exam** in class last 50 min
  - **New HW #13 passed out, HW #12 due**
  - **Focus on 22.2 Evidence for Big Bang**
  - **Complete overview read Chap 23: Dark Matter, Dark Energy, Fate of Universe**

**How much dark matter overall?**

- All cluster methods generally agree
- About **5+ times as much dark matter as "normal" matter overall in the universe**
- **Is DM measurable in our solar system?**

- Big Puzzle: What is Dark Matter?**
- Two possible flavors for Dark Matter:
  - **Possibility 1. MACHOs**
  - Massive Compact Halo Objects
  - Very faint, actual things; baryonic matter
  - Brown dwarfs, black holes, black dwarfs ... etc.
  - May be floating through the galaxy halo unnoticed

**MACHO Searches**

- Use gravitational lensing
- When a MACHO floats in front of a star, the star **suddenly brightens**
- Focusing effect of compact massive object

STAR

MACHO

OBSERVER

**MACHO hunt results**

- MACHOs are detected by brightenings
- But not enough to explain all dark matter

LMC-5 (1 day bins)

$\lambda_{max} = 47.56$   $\tau = 70.75$

LMC-6 (4 day bins)

$\lambda_{max} = 2.142$   $\tau = 87.14$

LMC-7 (4 day bins)

$\lambda_{max} = 6.099$   $\tau = 114.5$

JD - 2449000

## Possibility 2. WIMPs

- Weakly Interacting Massive Particles
- Non-baryonic → subatomic particle (possibly made in Big Bang?)
- Neutrinos? probably not... they move too fast and cannot be collected into stable galaxy halos
- Slower (unknown) particles: **"Cold Dark Matter"** ... **BIG SEARCHES** (and thinking) underway

### Cosmology: Big scales of our Universe

**DISTANCE ESTIMATE 5**

Use Hubble's Law itself to estimate vast distances  $D$


- Measure velocity, then:  $D = v / H_0$

**REMINDER**

- Example: using  $H_0 = 70 \text{ km/sec/Mpc}$ , and finding that  $v = 700 \text{ km/sec}$   
 $D = 700 \text{ km/sec} / 70 \text{ km/sec/Mpc} = 10 \text{ Mpc}$   
 $= 32 \text{ million light years}$

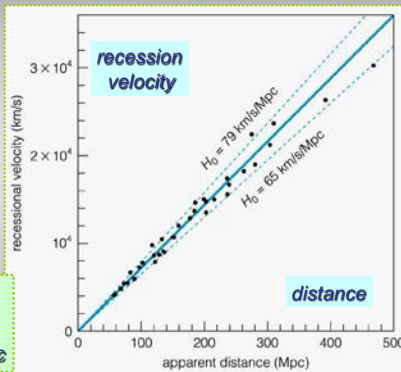
**VELOCITY =  $H_0 \times \text{DISTANCE}$**

**REVIEW**



**"HUBBLE CONSTANT"**

$H_0 = 71 \pm 4 \text{ km/sec/Mpc}$



**REVIEW**

### Cosmological (Big) Redshifts

(from expansion of universe)

Alternative definition of **redshift** :

$Z = \text{redshift}$   
 $= \text{change in wavelength} / \text{"normal" wavelength}$

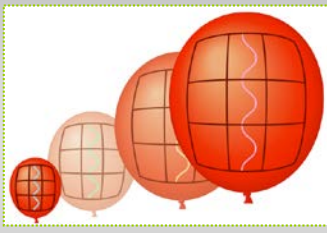
$1 + Z = \text{observed wavelength} / \text{"normal" wavelength}$

redshifts always have  $Z > 0$   
 (redder light has larger wavelengths)

### Redshift is "expansion factor"

$1 + Z$  also measures how much universe has expanded

and wavelength of light is effectively stretched



$1 + Z = \frac{\text{distance between galaxies now}}{\text{distance between galaxies then}}$

**REVIEW**

### Relativistic redshifts

**RELATIVISTIC DOPPLER REDSHIFTS**

WHEN THE RELATIVE SPEED OF RECESION (REDSHIFT) OR APPROACH (BLUESHIFT) IS A SIGNIFICANT FRACTION OF SPEED OF LIGHT, SIMILAR EFFECT

MUST BE MODIFIED,  $\lambda_0$  REST WAVELENGTH,  $\lambda$  OBSERVED WAVELENGTH,  $c$  SPEED OF LIGHT,  $v$  RELATIVE VELOCITY

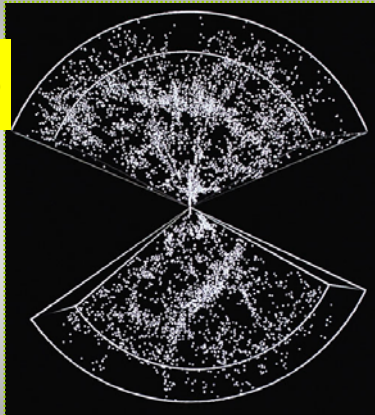
FROM  $Z = \frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$  (NON-RELATIVISTIC)

TO  $Z = \frac{\Delta\lambda}{\lambda} = \sqrt{\frac{1 + (v/c)}{1 - (v/c)}} - 1$  (RELATIVISTIC)

EXAMPLE: IF DOPPLER SHIFT MOVES A SPECTRAL LINE FROM 4000 Å TO 5000 Å, THEN NON-RELATIVISTIC FORMULA  $\Rightarrow \frac{v}{c} = Z = 2.5$  ! (IMPOSSIBLE) RELATIVISTIC FORMULA  $\Rightarrow \frac{v}{c} = 0.8$  (CORRECT) "Z = 2"

Knowing distances reveals large-scale galaxy clustering

Find clusters + super-clusters : sheets and voids like 'bubble bath'



### Third Mid-Term Exam

