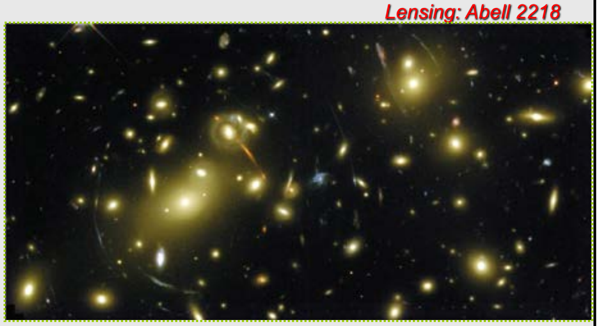
ASTR 1040: Stars & Galaxies

Lensing: Abell 2218



Prof. Juri Toomre TAs: Daniel Sega, Max Weiner

Lecture 26 Thur 16 Apr 2020

zeus.colorado.edu/astr1040-toomre

Our Schedule

- Third Mid-Term Exam next Tues April 21 on our Canvas/Quizzes site (11:00am-12:15pm)
- Review Session on Mon 4pm-6pm by Max Weiner on Zoom – will send info on Mon. Review Set #3 posted
- Homework #12 due today, new HW #13 posted

- Today examine dark matter in galaxies
- Read: 23.2 Evidence for Dark Matter
- Then turn to Cosmology: models of the universe
- Overview read: Chap 22 Birth of Universe
- Discovery of cosmic microwave background CMB implies a big-bang beginning

Now to Case for Dark Matter

- ~ 80+% of mass of universe is dark matter (invisible, missing matter)

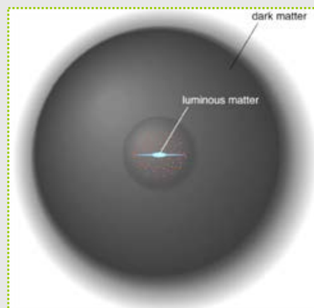
- Detectable ONLY via its gravitational forces on "light" matter (gas and stars)

- Note -- this dark matter is NOT the same as black holes, brown/black dwarfs, or dust

Individual galaxies show it

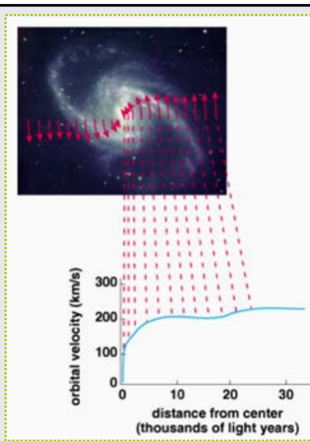
- Rotation curves: motions of stars in the galaxy

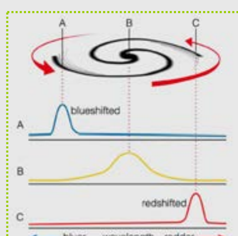
- Reveal that dark matter extends beyond visible part of the galaxy, mass is 10x stars and gas



- Flat rotation curve of galaxy

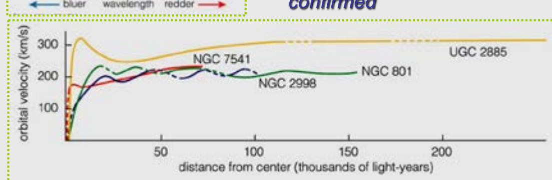
- High speeds far from luminous center: means there is dark matter in the outer regions





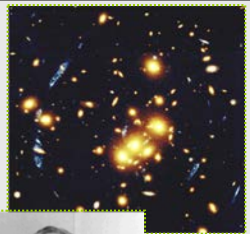
Spiral galaxy ROTATION CURVES

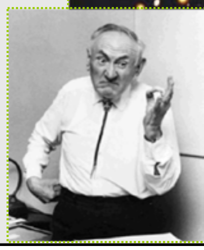
- Discovered by Vera Rubin in the 1970's
- Highly controversial until many rotation curves confirmed



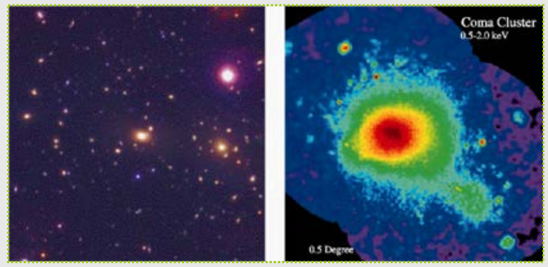
Galaxy Clusters: reveal dark matter in three ways

- **# 1**: Galaxy velocities too large to be explained by gravity of visible galaxies
- Expected ~100 km/sec for a typical cluster, found 1000 km/sec!
- Discovered in 1930's by Fritz Zwicky (they didn't believe him, either)





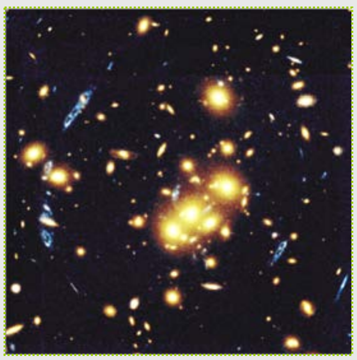
2: Hot x-ray emitting gas in cluster



- Gas between galaxies is also moving because of gravity of dark matter: gets very hot
- 1000 km/sec → 100 million K: emits x-rays!

3: Gravitational Lenses

- Dark (& visible) matter warps space → acts like a lens and distorts and magnifies the view of more distant galaxies
- Can form circular arc segments

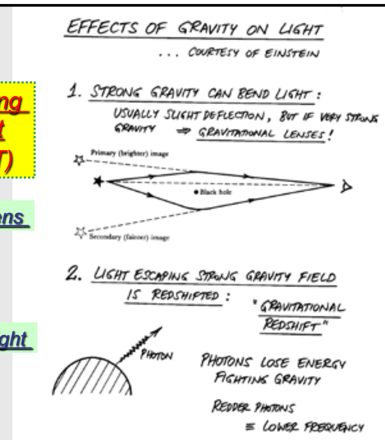


REMINDER

Effects of strong gravity on light (Einstein GRT)

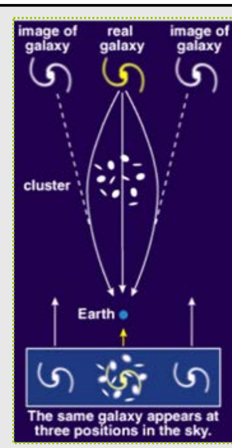
can act like lens

can redshift light

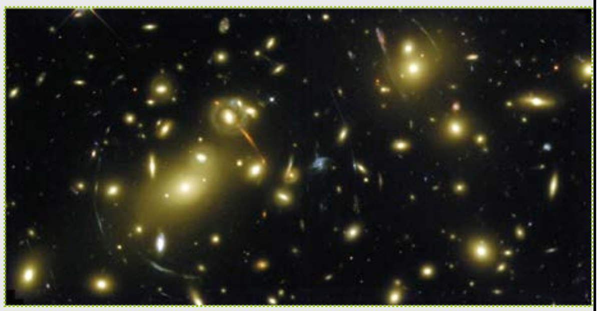


Questions or Comments

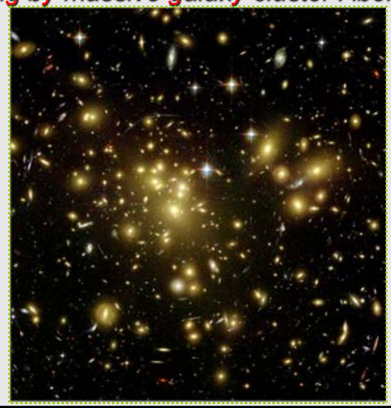
Gravitational lensing: how it works



Bending of light by cluster Abell 2218



Lensing by massive galaxy cluster Abell 1689



Quasars acting as gravitational lenses
(SDS + VLT)

Einstein Cross: gravitational lensing of (one) very distant quasar

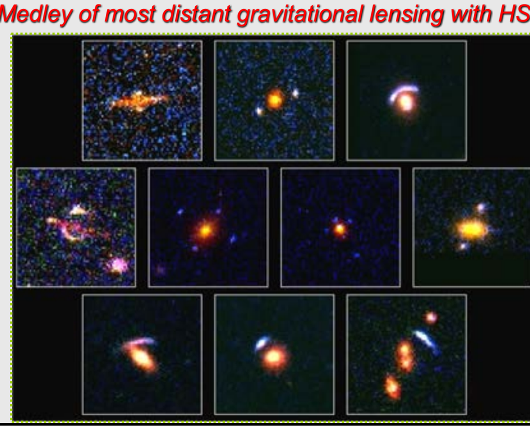
"The Beast"

4 or 5 different galaxies!

Red arc at the bottom: Z = 4.8

Erica Ellingson -- HST

Medley of most distant gravitational lensing with HST

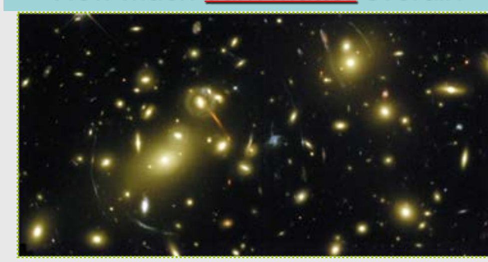


Gravitational lens drifts across your harbor view (Boston)

Effects of gravitational lensing on background galaxies

Questions or Comments

How much dark matter overall?



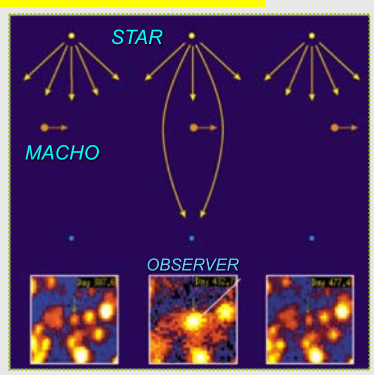
- All cluster methods generally agree
- About 5 times as much dark matter as "normal" matter overall in the universe
- Is DM measurable in our solar system?

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

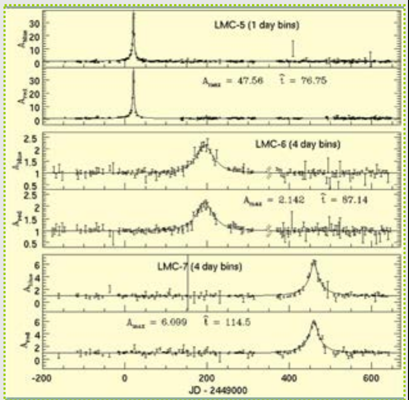
MACHO Searches

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



MACHO hunt results

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



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 underway

REVIEW

Cosmological (Big) Redshifts

(from expansion of universe)

Alternative definition of redshift :

Z = redshift
= change in wavelength/ "normal" wavelength

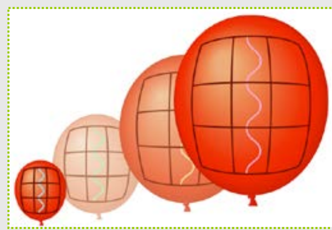
1 + Z =
observed wavelength / "normal" wavelength

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

If Z is big (~1+), use relativistic formula to get velocity v

RELATIVISTIC DOPPLER REDSHIFTS

WHEN THE RELATIVE SPEED OF RECESSION (REDSHIFT) OR APPROACH (BLUESHIFT) IS A SIGNIFICANT FRACTION OF SPEED OF LIGHT, DOPPLER EFFECT MUST BE MODIFIED,

FROM

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

($\Delta\lambda$: WAVELENGTH SHIFT; λ_0: REST WAVELENGTH; v: RADIAL VELOCITY; c: SPEED OF LIGHT)

TO

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

EXAMPLE:

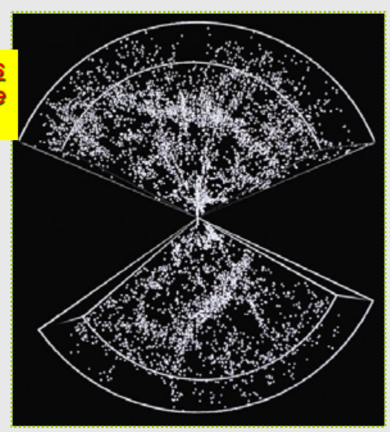
IF DOPPLER SHIFT MOVES A SPECTRAL LINE FORMED AT 3000 Å TO 9000 Å, THEN

NONRELATIVISTIC FORMULA ⇒ $\frac{v}{c} = 2$! (FASTER THAN LIGHT!)

RELATIVISTIC FORMULA ⇒ $\frac{v}{c} = 0.8$ (CORRECT)
"Z = 2"

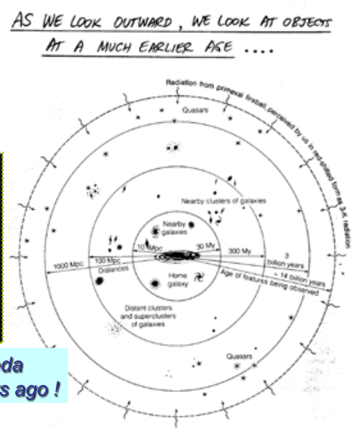
Knowing distances reveals large-scale galaxy clustering

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



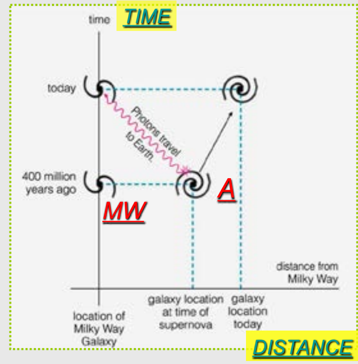
Telescopes are "lookback" time machines

Today, we see Andromeda as she was 2.54 M years ago !



Lookback time (in expanding universe)

- Say it takes 400 million years for light to get from galaxy A to us in Milky Way
- Yet during travel in spacetime, both A and MW have changed positions by expansion
- Thus "distance" is a fuzzy concept – LOOKBACK TIME is better



Poll 1: gravitational lens

- If you measure the redshifts of the yellowish and blue objects, you'll find:

A. The yellow galaxies have similar redshifts, all higher than the blue galaxies

B. The blue galaxies have the same redshift, which is higher than the yellow galaxies

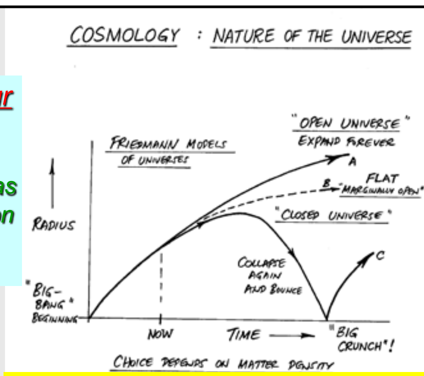
C. Yellow and blue galaxies have similar redshifts

Lensing

- **B.** The blue images are a single BACKGROUND galaxy being lensed by the foreground cluster (yellow galaxies)
- The blue galaxy (spiral) is farther from us and thus will have a higher redshift

Models of our universe

Dark matter has big influence on "open" vs "closed"



If enough mass, gravity eventually wins!

EARLY DEVELOPMENTS

Predictions of General Relativity Theory (GRT)

- Einstein in 1917 realized GRT (1915) predicted universes in motion, but preferred `steady state' – added `cosmological constant' (CC) as repulsive force in space-time to counteract attractive force of gravity
- Willem de Sitter (A, Dutch, 1917) solves GRT equations with no CC and low density of matter : showed universe must expand
- Alexander Friedmann (M, Russian, 1920) solves GRT with no CC but any density of matter : universes can expand forever, or collapse again, depending on mean matter density

More on … Predictions of GRT

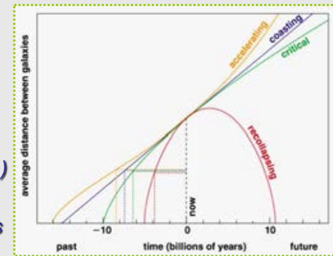
- Georges Lemaitre (P, Belgian, 1927) rediscovers Friedmann solutions, told Hubble (observing redshifts since 1924) that cosmic expansion suggests more distant galaxies should have greater redshifts (Hubble publishes $V = H_o\, d$ in 1929)
- Einstein visited Hubble in 1932, said CC "biggest blunder"

Very important diagram

"Average distance between galaxies"
= 1 / expansion factor
= 1 / (1 + Z)

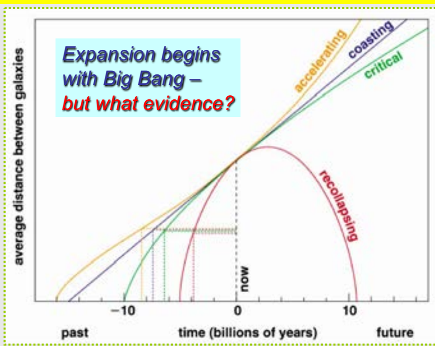
NOW is fixed in time (Z=0)

Hubble constant NOW sets slope of line = how fast universe is expanding NOW



Big Bang = when distance zero
Z = infinity

Dark Matter and Fate of the Universe



Several different models for Past and Future

Four models for fates of universe