

ASTR 1040: Stars & Galaxies
Lensing: Abell 2218



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 Lecture 26 Thur 19 Apr 2018
 zeus.colorado.edu/astr1040-toomre

Our Schedule & Next Topics

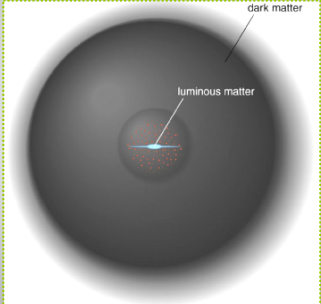
- **Third Mid-Term Exam** in class today (last 50 minutes)
- New Homework #13 out, HW #12 due
- **Observatory Night** next Tues (Apr 26)
- **Cosmology: models of the universe**
- Discovery of **cosmic microwave background** implies a big-bang beginning
- Focus on **22.2 Evidence for Big Bang**
- Complete overview read **Chap 23: Dark Matter, Dark Energy, Fate of Universe**

Now to Case for Dark Matter

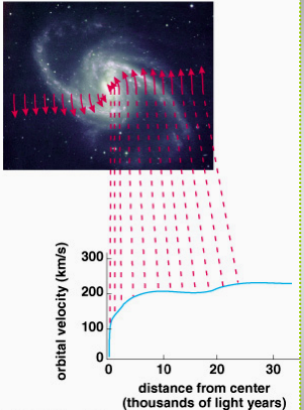
- ~ 80+% of **mass of universe** is **dark matter** (invisible, missing matter)
- Detectable **ONLY** via its gravitational forces on "light" matter (gas and stars)
- **Note** -- this dark matter is **NOT** the same as black holes, brown/black dwarfs, or dust

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**

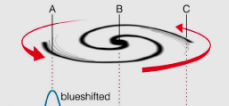


- **Flat rotation curve** of galaxy
- **High speeds far from luminous center:** means there is dark matter in the outer regions



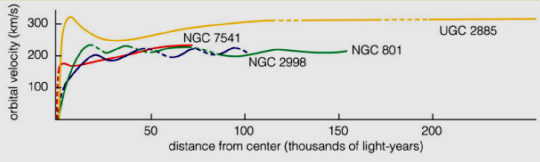
The graph shows orbital velocity (km/s) on the y-axis (0 to 300) and distance from center (thousands of light years) on the x-axis (0 to 30). The velocity rises sharply from the center and then levels off to a constant value of approximately 200 km/s for distances greater than 10 thousand light years.

Spiral galaxy ROTATION CURVES



• Discovered by **Vera Rubin** in the 1970's

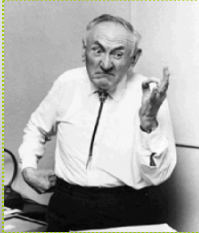
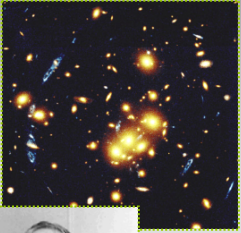
• **Highly controversial until many rotation curves confirmed**



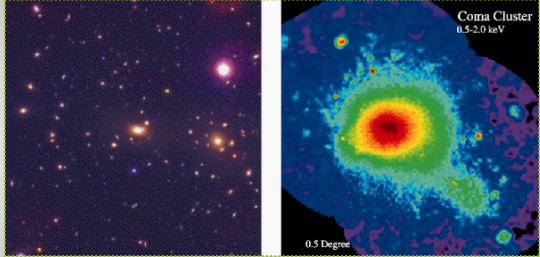
The graph shows orbital velocity (km/s) on the y-axis (0 to 300) and distance from center (thousands of light-years) on the x-axis (0 to 200). Several curves are shown for different galaxies: NGC 7541, NGC 2998, NGC 801, and UGC 2885. All curves show a flat rotation curve at large distances.

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

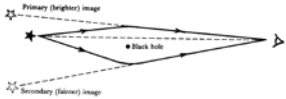
Effects of strong gravity on light (Einstein GRT)

can act like lens

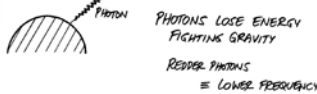
can redshift light

EFFECTS OF GRAVITY ON LIGHT
... COURTESY OF EINSTEIN

- STRONG GRAVITY CAN BEND LIGHT:**
USUALLY SLIGHT DEFLECTION, BUT IF VERY STRONG GRAVITY ⇒ **GRAVITATIONAL LENSES!**

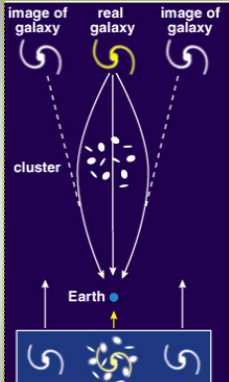


- LIGHT ESCAPING STRONG GRAVITY FIELD IS REDSHIFTED:** "GRAVITATIONAL REDSHIFT"



PHOTONS LOSE ENERGY FIGHTING GRAVITY
REDDER PHOTONS ⇒ LOWER FREQUENCY

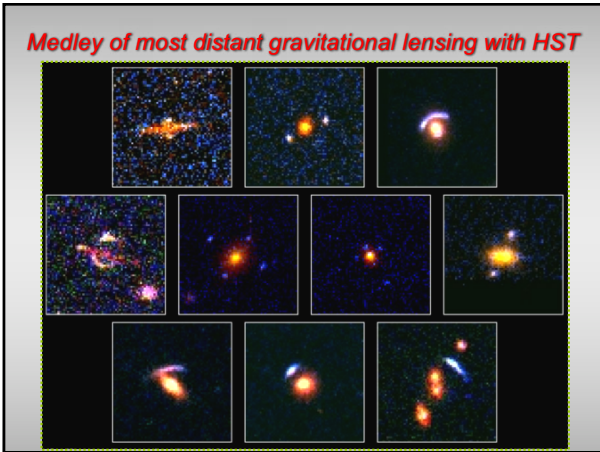
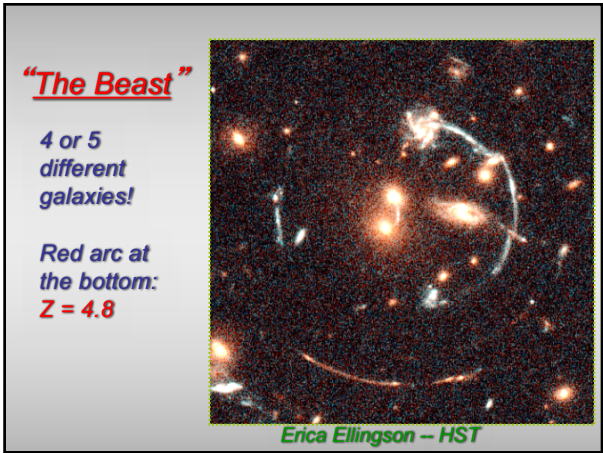
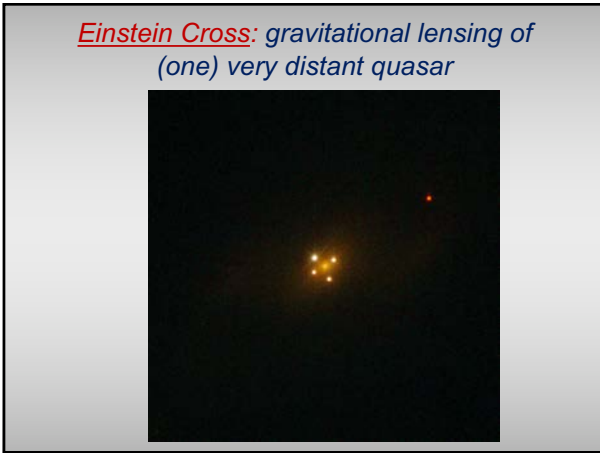
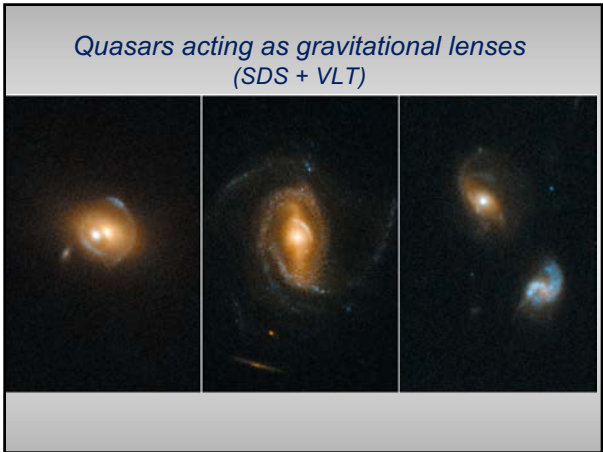
Gravitational lensing: how it works



The same galaxy appears at three positions in the sky.

Bending of light by cluster Abell 2218





Effects of gravitational lensing on background galaxies



Third Mid-Term Exam

