• Evidence for/constraints on dark matter in galaxies and clusters

• HW#9 is due; please hand in your summaries; then you get to talk (I have slides of the different facilities/telescopes.

• HW#10 is now assigned. More work on your projects!
  • Final presentations, 10 mins (incl questions), Mon Nov 30th
  • Final written paper (formal style), Thurs Dec 10 @4:30 (electronic submission as PDF).

• Next Monday: 30 minute quiz
  • Similar in form to the last one
  • Emphasis on lectures since Oct 1 and starting HW#6&7
  • Review class slides, portfolio handouts, homeworks, readings
History of dark matter

1933: like many things in astronomy, dark matter was first postulated by Fritz Zwicky.
- Apply virial theorem to indiv. galaxies in the Coma cluster → $M_{\text{galaxy}}$
- Apply virial theorem to cluster as a whole → $M_{\text{cluster}}$
  Zwicky found $M/L_{\text{cluster}} \sim 200 \leftrightarrow ?? → M/L_{\text{galaxy}} \sim 8$

~1970: Vera Rubin, Mort Roberts, Ken Freeman and others explore rotation curves and (re-)find the need for dark matter (formerly called missing).

Actual diagnosis: gravity acts stronger than expected on the basis of the identified mass (= sources of gravity)

“The Case of the Missing Mass”
Burbidge, G. & Sargent, 1969, CoASP, 1, 220
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\[ \Rightarrow M_{\text{cluster}} \gg N \times M_{\text{galaxy}} \]

"If this [overdensity] is confirmed we would arrive at the astonishing conclusion that dark matter is present [in Coma] with a much greater density than luminous matter." He continues: "From these considerations it follows that the large velocity dispersion in Coma (and in other clusters of galaxies) represents an unsolved problem."

- Zwicky 1933 (in German)
- See: van den Bergh (1999)
Early evidence of dark matter

1939: Babcock -- 1st rotation curve of M31

mass-to-light ratio or (2) strong dust absorption. Babcock wrote: "[T]he great
range in the calculated ratio of mass to luminosity in proceeding outward from the
nucleus suggests that absorption plays a very important rôle in the outer portions
of the spiral, or, perhaps, that new dynamical considerations are required, which
will permit of a smaller relative mass in the outer parts". Subsequently Babcock’s

• => must be dim stars in the outer parts of M31

1959: Woltjer and Kahn:
  – M31 is approaching (returning after initial expansion on elongated
    orbit).
  – What mass is needed for $t_{\text{orbit}} < t_{\text{universe}}$? $M > 1.8 \times 10^{12} \, M_{\odot}$ !!
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History of dark matter

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“...the rotational velocity is essentially constant over the outer 10 kpc, i.e., from 20 to 30 kpc radius. The latter implies a mass that increases linearly with R over this range and a mass-to-luminosity ratio of $\geq 200$ for this outer region”

Evidence for Dark Matter

- Disk galaxy rotation curves
- Masses of ellipticals and clusters derived from velocity distribution
- X-ray observations of clusters of galaxies
- Masses of galaxies and clusters derived from gravitational lensing

- Where is the dark matter?
- What is the dark matter?
Possible Dark-Matter Candidates

Baryonic Dark Matter Candidates

- neutron stars
- black holes
- black dwarf stars
- brown dwarf stars
- planets
- rocks

Non-Baryonic Dark Matter Candidates

- massive neutrino
- Weakly Interacting Massive Particles (WIMPS)
- cosmic strings
- modified gravity

\[ a \ll a_0 \]
Dark matter candidates

Non-Baryonic Dark Matter Candidates

- **massive neutrino**: they exist, but very low mass
- **Weakly Interacting Massive Particles (WIMPS)**: little to no evidence of their existence
- **cosmic strings**: little to no evidence of their existence
- **modified gravity**: little to no evidence of their existence
Dark Matter Evidence: “Rotation Curves”

- e.g. NGC3198: Begeman 1989
  - HI more extended than stars => measure 21cm line
  - flat rotation curve -- found in (nearly) all spiral (=gas rich) galaxies!

\[ V_c = \text{const} \quad M \sim r \quad \text{or} \quad \rho \sim r^{-2} \]

- The vast majority of spiral rotation curves are flat (or even still rising) in the outermost points
The Draco dwarf galaxy

Sky image of Draco

$D_{\text{sun}} \approx 70 \text{ kpc}$

Odenkirchen+ 2001, AJ 122, 2538
Lokas+ 2005, MNRAS 363, 918
The Draco dwarf galaxy

\[ D_{\text{sun}} \approx 70 \text{ kpc} \]

\[ \text{Draco is a bound system in equilibrium} \]
The Draco dwarf galaxy

Stellar density contours of Draco from SDSS
Odenkirchen et al 2001

$D_{\text{sun}} \approx 70$ kpc

→ Draco is a bound system in equilibrium
Mass Modelling of Draco

Expected $(M/L)_* \sim 2$

$\rightarrow$ Draco is dark matter dominated

More recent observations of the ultra faint dwarfs in the Local Group suggest they are all dark-matter dominated!

- 159 stars in Draco w/ $\sim 2$ km/s precision
- Try models with different DM profiles
  $\rightarrow M (<10')$ well constrained

Dark Matter in Galaxy Clusters

In galaxy clusters the masses can be measured three ways:

- Galaxy clusters contain hot gas (bound by dark matter?)
- Galaxy velocity dispersion
- Gravitational lensing

\[ T = 10^6 \text{ K} \rightarrow \text{X-ray emission} \]
X-Ray Gas in Hydrostatic Exquilibrium

\[
\frac{dP}{dr} = -\frac{GM(<r)}{r^2} \rho
\]

\[
M(<r) = -\frac{kT}{\mu m_H g} \left( \frac{d\ln g}{d\ln r} + \frac{d\ln T}{d\ln r} \right)
\]

\[M_{\text{stars}} \sim M_{\text{gas}} \sim 3 \times 10^{13} M_{\odot}\]

but estimates from the velocity dispersion (Virial Theorem) give

\[M_{\text{tot, cluster}}(R_{\text{virial}}) \sim 10^{15} M_{\odot}\]
Gravitational lenses
The lens phenomenon exists because gravity bends the paths of light rays.

In general relativity, gravity acts by producing curvature in space-time.

The paths of all objects, whether or not they have mass, are curved if they pass near a massive body.

Prediction of bending confirmed for starlight passing near the Sun in the 1919 solar eclipse.
Masses from gravitational lensing
Masses from gravitational lensing
Geometry, geometry, geometry

Lensing by cosmic strings would be important and different!
3 Classes of Gravitational Lenses

- **Strong lensing** - easily visible distortions
  - Einstein rings, arcs, and multiple images
- **Weak lensing** - distortions are much smaller
  - Detected by analyzing large numbers of objects to find distortions of only a few percent.
  - The lensing shows up statistically as a preferred stretching of the background objects perpendicular to the direction to the center of the lens
- **Microlensing** - no distortion in shape can be seen but the amount of light received from a background object changes with time
  - Microlensing occurs with stars and extrasolar planets
Gravitational Microlensing

- Star observed to brighten and then return to normal
- Variation in brightness is symmetric from rise to fall
- Monochromatic (no wavelength dependence of brightness change.)
Fig. 4. Schematic view of the wavefronts in the presence of a cluster perturbation. The lens produces two effects. First, it deflects the light rays, and second it induces a pure gravitational time delay. Hence a deflected light ray which intersects the observer will arrive with a pure geometrical delay and a pure gravitational delay. Depending on the lens configuration, the observer will see multiple and strongly distorted images (arcs), single distorted images with elliptical shape (arclets), or weakly distorted images (weak shear regime) with individual elongation almost invisible. But each lensing regime has its own interest: strong lensing is rare but gives strong local constraints on the potential. Weak lensing is often
Lensing geometry

Fig. 3.34. As a reminder, another sketch of the lens geometry
Masses from gravitational lensing

What shape is your lens?

Aligned spherical mass distribution: Einstein Ring

Spherical lens gives an Einstein ring
Masses from gravitational lensing

What shape is your lens?

Elongated lens gives multiple images – Einstein Cross

Elongated mass distribution
Gravitational lensing: calculating the mass

\( \theta_E = \frac{\text{Radius of Einstein Ring (in radians)}}{4 G M} \)

\[ \theta_E = \sqrt{\frac{4 G M d_{LS}}{c^2 d_L X d_S}} \]

\( M = \frac{\theta_E c^2 d_L X d_S}{2 G d_{LS}} \)

For an Einstein Ring Lens:
1. Measure the redshifts of the lensing and lensed objects
2. Measure the size of the ring

\( \Rightarrow \) Calculate the mass!
Distortion by weak lensing

The radial profile of the weak lensing shear strength allows to calculate the cluster mass profile at larger radii.

Fort et al. (1994) ARAA, 5, 239

Fig. 5. Distortion field generated by a lens. The left panel shows the grid of randomly distributed background galaxies by a cluster lens. The right panel shows the same observation once they are distorted by a foreground (invisible) circular cluster with a typical velocity dispersion of 1000 km s$^{-1}$. The geometrical signature of the cluster is clearly visible. The potential can be calculated using the formalism defined in part 4. In this simulation, the sources are at $z = 1.3$, and the lens at $z = 0.4$. 
Masses from gravitational lensing

**Weak Lensing... Correlated Distortions**

Map variance

\[(e_t, e_r)\]

Top hat shear variance:

\[\langle e^2 \rangle \sim \gamma^2\]

Shear correlation functions:

\[\langle \gamma_t \gamma_t \rangle > 0\]
\[\langle \gamma_t \gamma_r \rangle < 0\]
\[\langle \gamma_r \gamma_r \rangle > 0\]

Look for correlations in galaxy orientations in small region of image

Image Credit: Y. Mellier
Unlike optical lenses, gravitational lenses produce multiple images

- In an optical lens, maximum bending occurs furthest from the central axis
- In a gravitational lens, maximum bending occurs closest to the central axis
- A gravitational lens has no single focal point
- If the source, the lens, and the observer lie in a straight line, the source will appear as a ring around the lens
- If the lens is off-center, multiple images will appear. The lensed image will always be distorted
Cluster of Galaxies Cl0024+16

- The reddish objects are galaxies in the lensing cluster at $z=0.39$
- The bluish objects are multiple images of a distant galaxy at $z=1.63$ lensed by the cluster
- The distant galaxy has been reconstructed from models of the individual pieces of the arc

Gravitational lenses act like telescopes!
Simulating Gravitational Lenses

- **HST MDS WFPC2 HST Gravitational Lens Simulation**
  (mds.phys.cmu.edu/ego_cgi.html)

- A galaxy having a mass of over 100 billion solar masses will produce multiple images separated by only a few arcseconds.

- Galaxy clusters can produce separations of several arcminutes.
Dark Matter in Galaxy Clusters

- Gravitational lensing
The Bullet Cluster

- Given what we know about gravitational lensing (tracing the total mass in blue), hot X-ray gas in (the dominant baryonic mass, red), we can show that dark matter exists in at least one system:

Images from Clowe et al. 2006 and the Chandra press release
The Bullet Cluster

- Lensing of background galaxies seen in the optical images lets the mass distribution be mapped.

- The X-rays trace the hot gas, the dominant source of baryons in this cluster merger.

- They don’t line up! Why? Dark Matter seems to not interact with itself the way diffuse gas does during a cluster collision.
See this animation of the Bullet Cluster collision

https://archive.org/details/CHAN-687
Summary: Dark Matter Evidence

- A wide range of dynamical phenomena cannot be explained through the known (baryonic) mass content of the universe alone.

- All (well, almost all) these problems can be solved if we make one radical assumption:
  85% of all matter with rest mass ($\Omega_M \approx 0.25$) is in a form (dark matter) that was
  - initially distributed as ordinary matter
  - interacts with the rest (almost) only through gravity
  - acts like a collisionless “fluid”
  - is cold, i.e. consists of non-relativistic particles

- Stars, gas are now more concentrated/clumped than DM
  - galaxies sit at the center of much larger DM halos
  - Note: $r_{\text{baryon}} \sim 8 \times r_{\text{stars}}$

- We also need a “cosmological” constant (vacuum energy), i.e. a long-distance ‘repulsive’ force
**MOND: Modified Newtonian Dynamics**


- based on Newtonian, non-relativistic gravitational theory
- Let \( F \propto a^2 \) (not \( a \))

\[
F = m \cdot a \cdot \mu \left( \frac{a}{a_0} \right)
\]

\[
\mu(x) = \begin{cases} 
  x & \text{if} \quad 0 < x << 1 \\
  1 & \text{if} \quad x >> 1 
\end{cases}
\]

\[
g_N = g \cdot \mu \left( \frac{g}{a_0} \right)
\]

**Modification of inertia**

\[
F = m \cdot \frac{a^2}{a_0} \quad \text{if} \quad a << a_0
\]

**Modification of gravity**

\[
g = \sqrt{g_N a_0} \quad \text{if} \quad g << a_0
\]

**New fundamental constant:**

\[
a_0 \approx 1 \cdot 10^{-10} \frac{m}{s^2}
\]

This value is empirical.

\[
a_0 \approx \frac{cH_0}{2\pi} = 1.1 \cdot 10^{-10} \frac{m}{s^2}
\]

Might be a coincidence.
Alternatives to Dark Matter

• **MOND**: Modified Newtonian Dynamics (Milgrom 1983)

for accelerations $a$ less than $a_0$, gravity behaves as $a(a/a_0) = GM/r^2$

$\rightarrow$ as $a(r) \sim 1/r$ of $a < a_0$:

$=>$ flat rotation curves

Note:

• $a < a_0$ untested in the lab

• single value of $a_0$ works for all rotation curves

But:

• No relativistic version of MOND

• MOND has trouble explaining DM in clusters and far out in halos