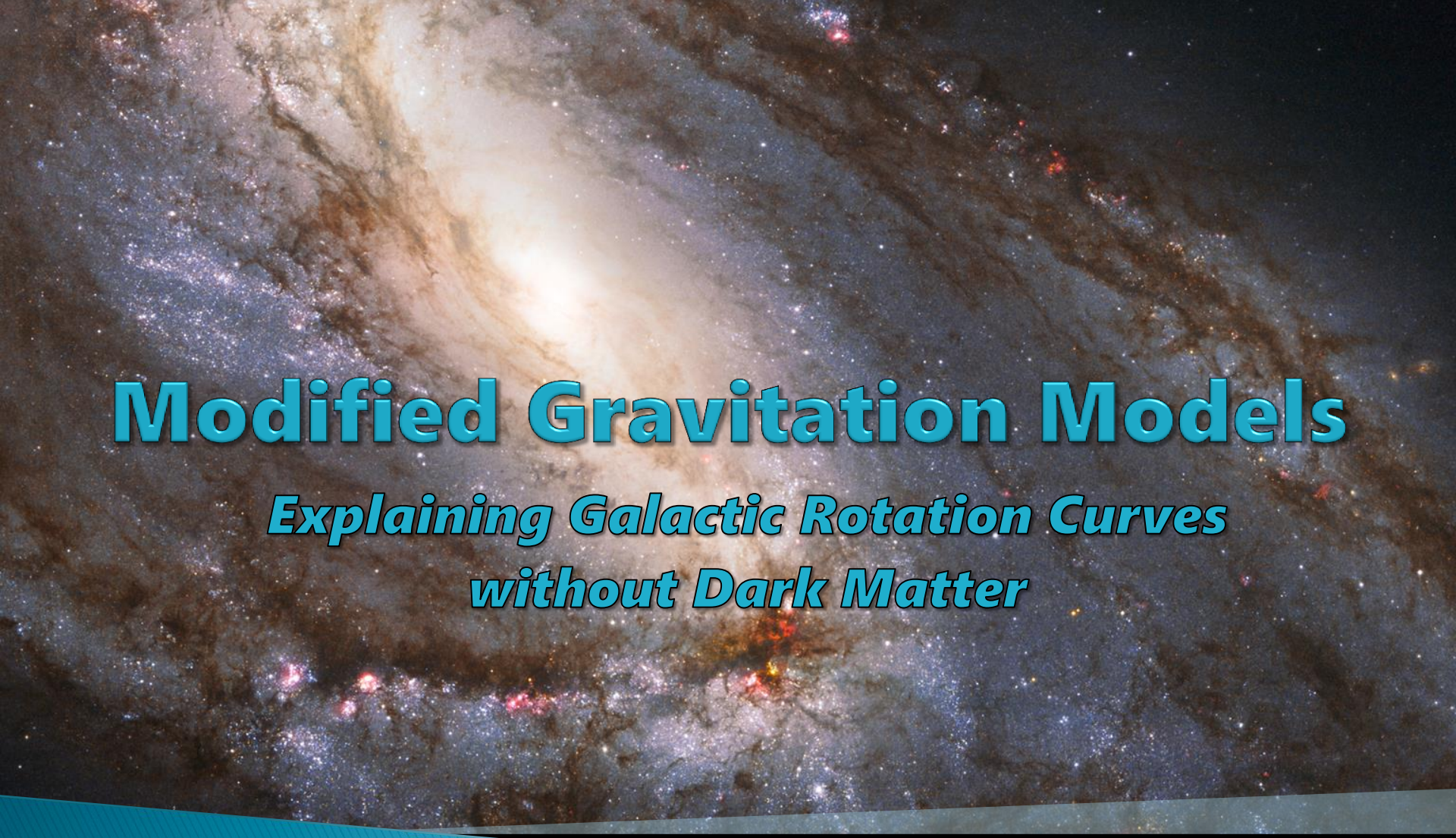
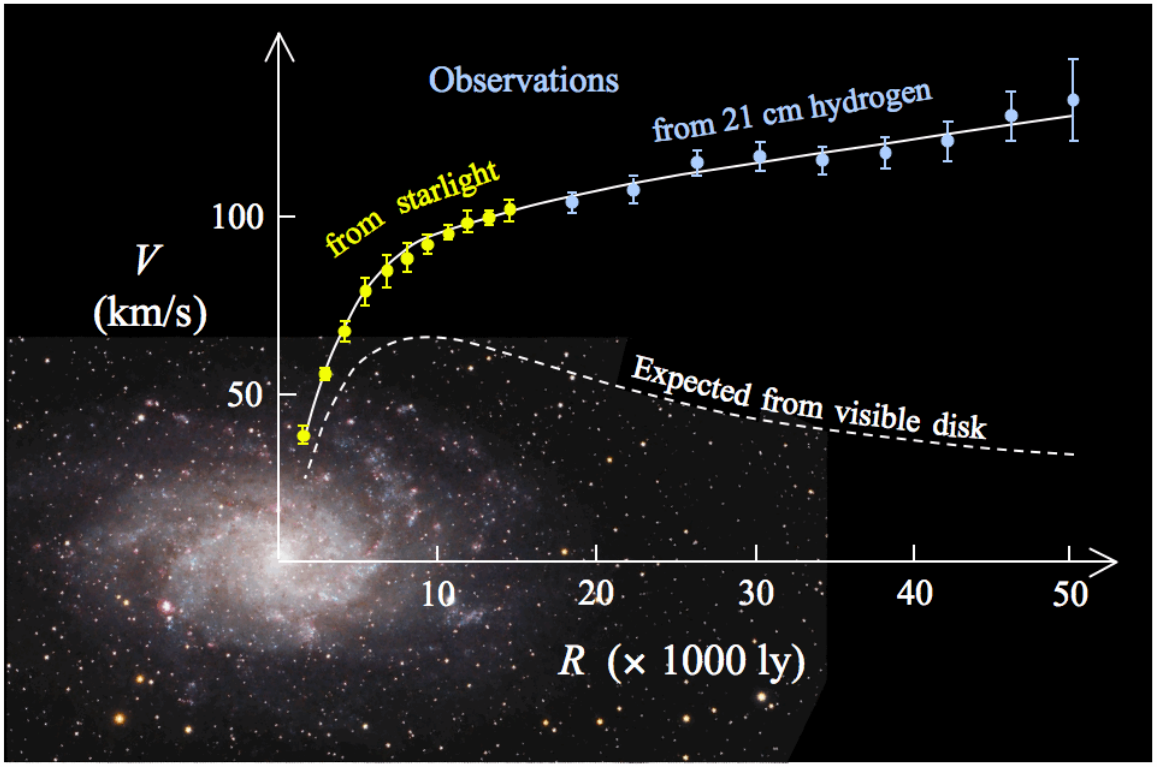


Modified Gravitation Models

Explaining Galactic Rotation Curves without Dark Matter

Alexander Warren

Galactic Rotation Curve Problem



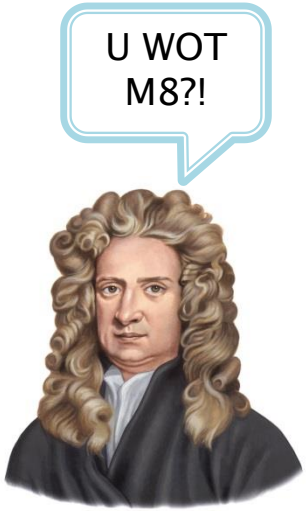
- Rotational velocity of galaxies ≠ predictions.
- Matter rotating too fast for their orbits to be stable.
- Explained by "dark matter" or modified gravity laws.

Dilemma! – We must either:

1) Invent a new type of matter that has never been seen before but nevertheless completely dominates over normal matter in the universe, or
2) Modify Newton's Universal Law of Gravity (and GR).

Modified Newtonian Dynamics (MOND)

- $\vec{F}_{Gravity} = -G\frac{m_1 m_2}{r^2}\hat{r} = m\mu(a_o, a)\vec{a}$
- $\mu(a_o, a)$ modifies acceleration, variants include $\left(1+\frac{a_o}{a}\right)^{-1}$ and $\left(1+\left(\frac{a_o}{a}\right)^2\right)^{-1/2}$
- Physical constant $a_o = 1.2 \times 10^{-10} ms^{-2}$ introduced. Oddly $a_o \approx \frac{cH_o}{2\pi} \approx c^2\sqrt{\Lambda/_3}$ and $\frac{c^2}{a_o} \approx 10^{26} m$, the current Hubble diameter.
- 2nd Law & Equivalence Principle **Violated** (*scandalous!*)



Crazy Idea? Maybe Not!

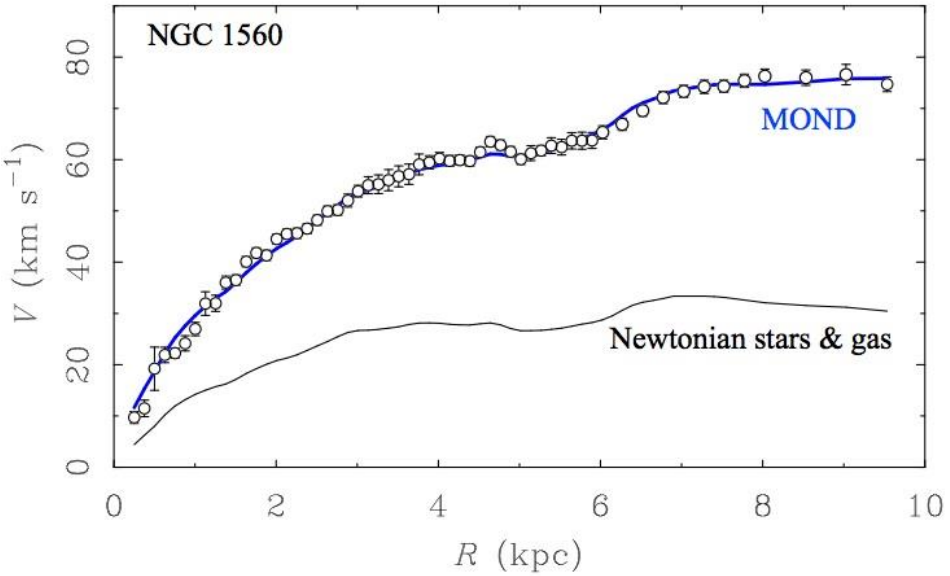


Fig. 1: NGC 1560
Comparison of the observed rotational velocities of material in galaxy NGC 1560 (white data points) with the Newtonian and MOND predictions.

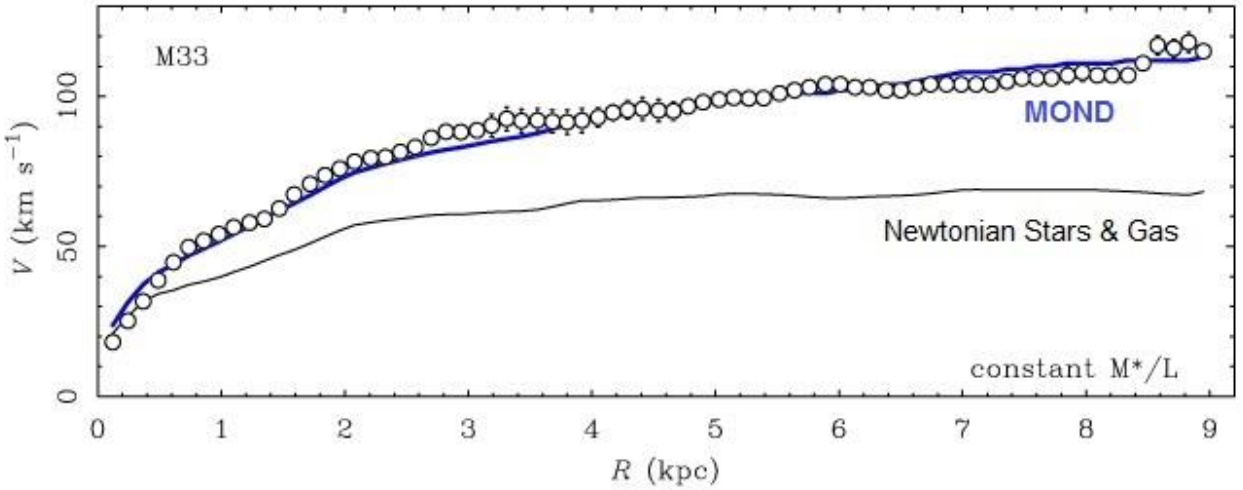


Fig. 2: M33
Same comparison for galaxy M33.

Approach

- Simulate M33, populate initial lattice with particles according to mass distribution model:

$$M(r)M_{\odot} = \begin{cases} 460e^{\left(-\frac{r}{1.56kpc}\right)}, & r \leq 6kpc \\ 9.33e^{\left(+\frac{r}{125kpc}\right)}, & r > 6kpc \end{cases}$$

- Calculate initial velocities for each particle to maintain circular orbits in Newtonian gravity and MOND with both variants of $\mu(a_o, a)$.
- Time evolve each system with velocity Verlet.
- Calculating acceleration will require root finding each time step i.e. $\frac{F}{m} = a\left(1 + \frac{a_o}{a}\right)^{-1}$, solve for a.

Goals

1. Implement a 2D lattice of particles that replicates the distribution of baryonic matter throughout galaxy M33.
2. Calculate the initial velocities needed for the particles to maintain circular orbits in this configuration under:
   i. Classical Newtonian gravitation
   ii. MOND with $\mu(a_o, a) = \left(1 + \frac{a_o}{a}\right)^{-1}$
   iii. MOND with $\mu(a_o, a) = \left(1 + \left(\frac{a_o}{a}\right)^2\right)^{-1/2}$.
3. Implement velocity Verlet loop to simulate the evolution of each system over time.
4. Plot the velocity for a particle at a given radius from the core for each system at different time steps, compare against observational. Is the behavior stable?
5. Measure average kinetic and potential energy for each system over time.