‘It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't’.

Mark Twain


GALAXIES
DARK MATTER
-vs-
MOND
Competing Paradigms

It is widely accepted that the Universe is saturated by an exotic and invisible substance - Cold Dark Matter. ΛCDM is considered to gravitationally dominate normal baryonic matter. $\Omega_{dm} \gg \Omega_b$

But increasingly attention has been paid to an alternative to CDM – the idea that nature can be better explained by a modification of Newton's Laws.

In 1930s Dutch astronomer Jan Oort deduced the mass density of the Milky Way from the motion of stars.

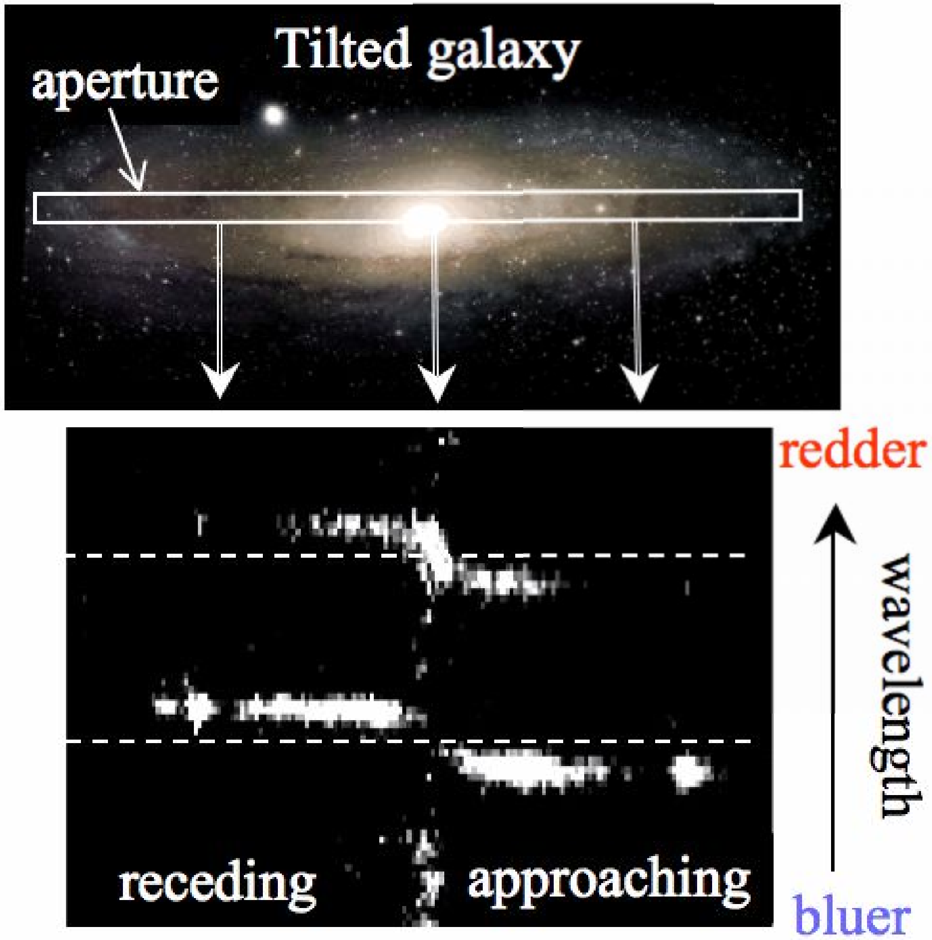
At about the same time Fritz Zwicky, studying the Coma Cluster, concluded that a great deal of mass was missing.

Fifty years later Vera Rubin WK. Ford and N. Thonnard published their 1980 paper which discussed the optically determined rotation curves of 21 bright spiral galaxies.

Spectral gas emission measurements were taken along the (apparent) major axis of bright spiral galaxies.

The objective was to obtain a two dimensional 'rotation curve' for each object.

Vera Rubin measuring galaxy rotation curves (~1970)



Resulting spectrum of light within aperture

Rotation Curves:

The orbital speed of an object (e.g. planet or asteroid) describing a circular path at radius ‘r’ about a central mass (such as the Sun) falls with distance from the mass according to $1/\sqrt{r}$.

$$V_c = \sqrt{\frac{GM}{r}}$$

'M' is the mass enclosed within the orbit and for all practical purposes the mass about which the Earth orbits is constant because it is the mass of the Sun.

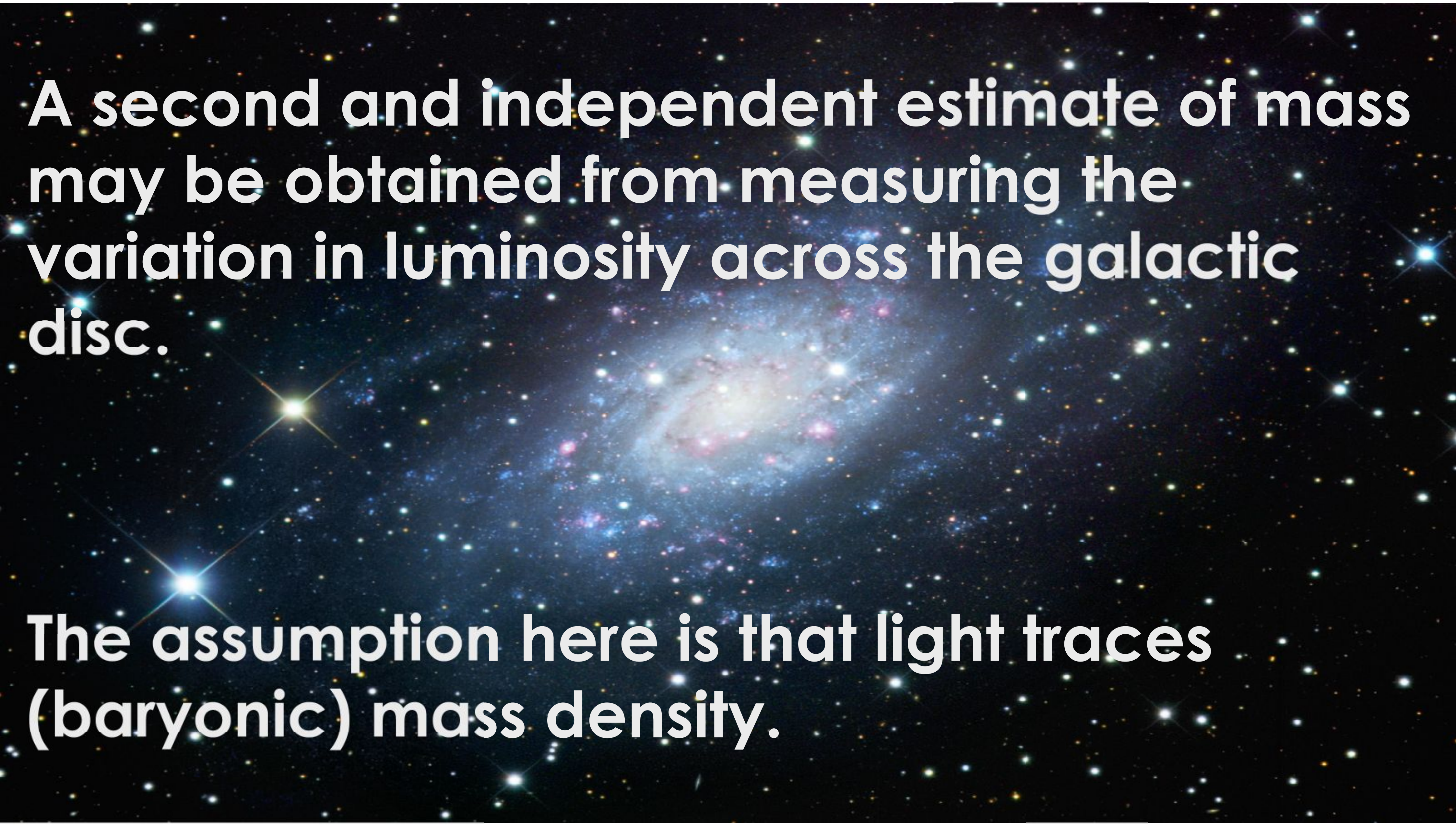
Gravitational constant $G = 6.67 \times 10^{-11}\ m^2/(kg\ s^2)$.

A massive black hole probably resides at the centre of every galaxy.

Weighing in at about $4.5 \times 10^6\ M_{o}$, the central black hole of the Milky Way is still not large enough to dominate the collective mass of the many millions of stars in the disc.

The previous expression may be transposed to estimate the enclosed mass:

$$M = \frac{rV_c^2}{G}$$


A second and independent estimate of mass may be obtained from measuring the variation in luminosity across the galactic disc.
The assumption here is that light traces (baryonic) mass density.

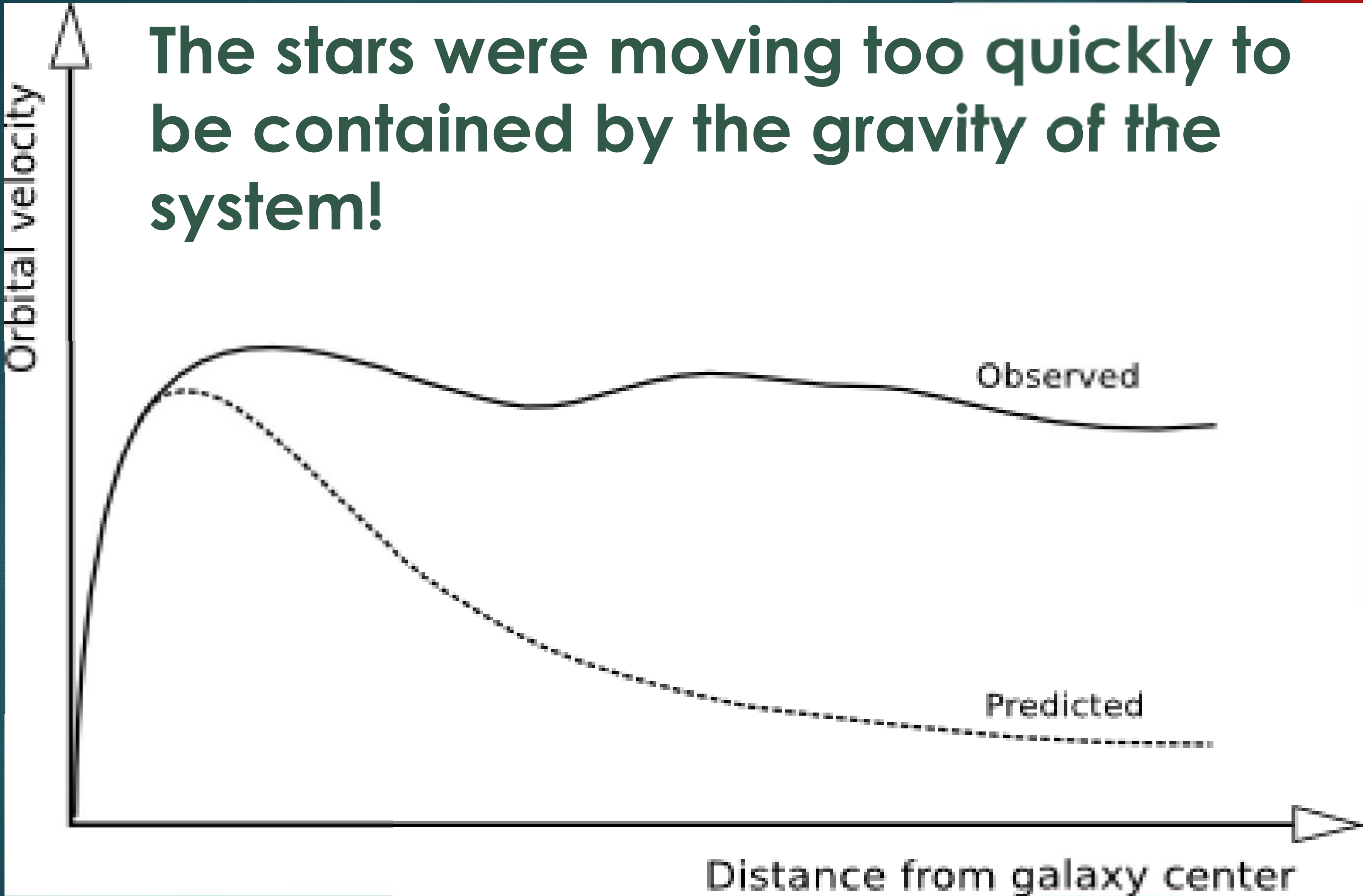
If the Sun is a representative average star the absolute luminosity of a galaxy expressed in terms of solar luminance L_o is an estimate of the number of stars (and therefore mass) within a galaxy.

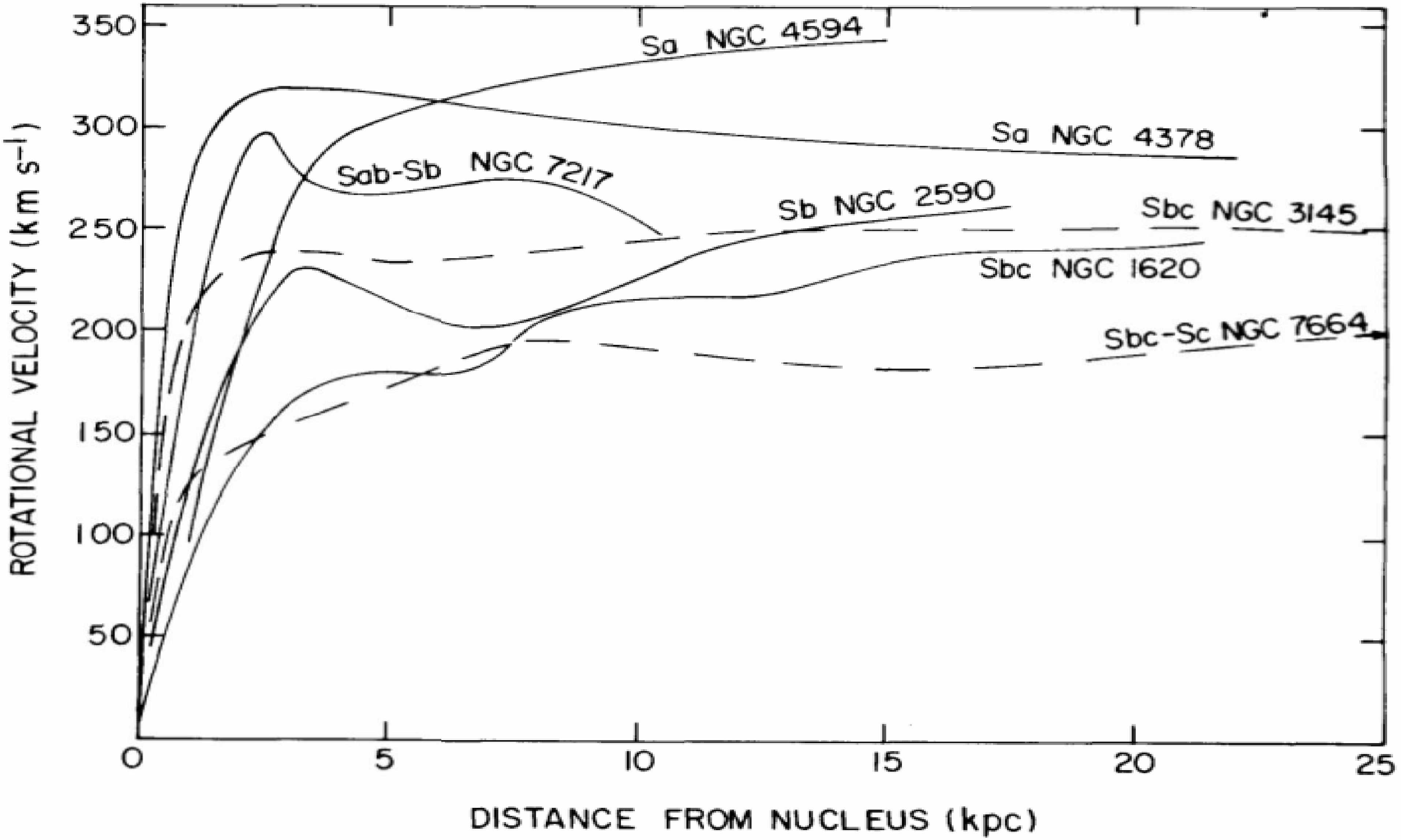
If the absolute brightness of a galaxy is measured as for example 10^{11} L_o then it will have a mass equivalent to about 10^{11} Suns.

Spiral galaxy are considered to have a $M/L \approx 1$

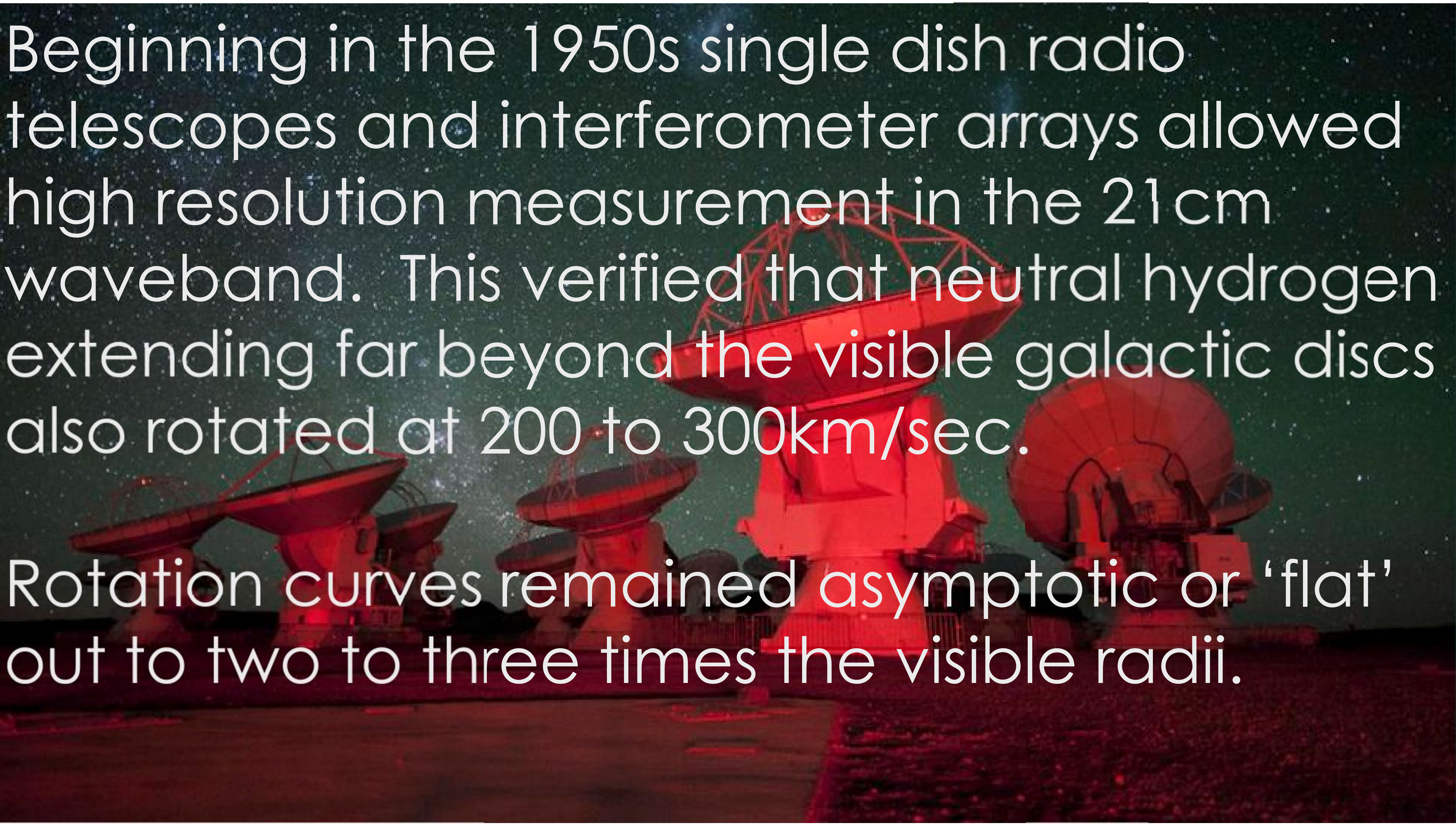
The mass inferred from light distribution enabled Rubin to estimate the expected or predicted speed of stars orbiting at any galactic radius. When 'predicted' rotation curves were compared to 'measured' velocity curves there was a surprising difference.

The stars were moving too quickly to be contained by the gravity of the system!





Sa NGC 4594
Sa NGC 4378
Sab-Sb NGC 7217
Sb NGC 2590
Sbc NGC 3145
Sbc NGC 1620
Sbc-Sc NGC 7664
ROTATIONAL VELOCITY (km s⁻¹)
DISTANCE FROM NUCLEUS (kpc)
350
300
250
200
150
100
50
0
5
10
15
20
25



Beginning in the 1950s single dish radio telescopes and interferometer arrays allowed high resolution measurement in the 21cm waveband. This verified that neutral hydrogen extending far beyond the visible galactic discs also rotated at 200 to 300km/sec.

Rotation curves remained asymptotic or ‘flat’ out to two to three times the visible radii.

By the mid-1980s it was clear from optical and radio observation that there was a major difference between the observed baryonic mass Ω_b and the total mass Ω_n implied by application of Newtonian mechanics.

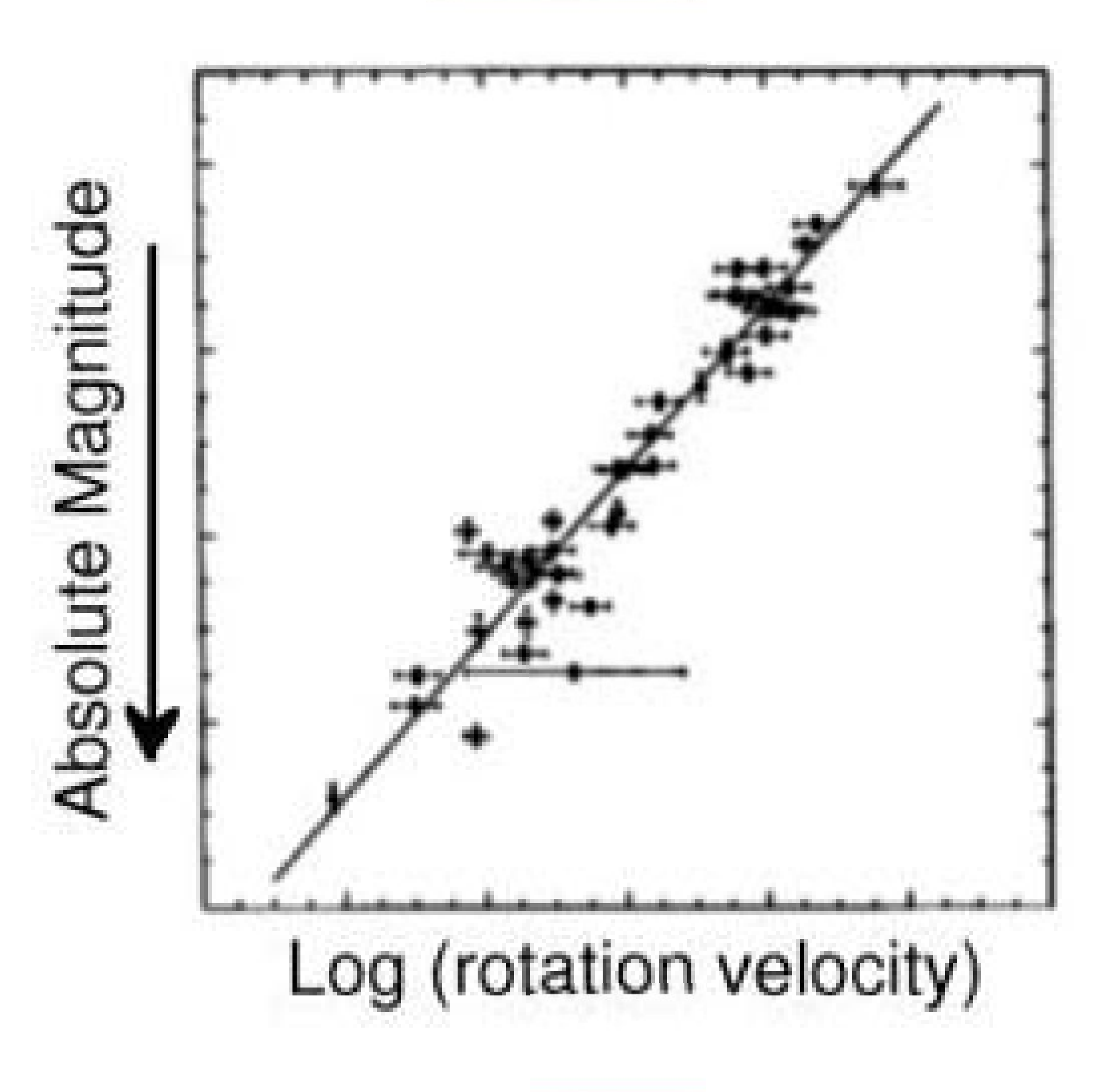
For spiral galaxies the unexpectedly high velocity of 200-300km/sec of stars and gas clouds measured in all parts of optical and radio discs beyond the core was not consistent with the luminosity of the galaxies – there was a substantial **mass discrepancy!**

Radio telescopes showed the mass discrepancy was greatest within the region of tenuous neutral hydrogen clouds rotating beyond the visible galactic discs.

Here the apparent mass-to-light ratio (M/L) was extreme.

1977 - Tully & Fisher compare radio and optical observations of nearby galaxies.

They discover a close relationship between absolute magnitude (visible mass) and rotation velocity.

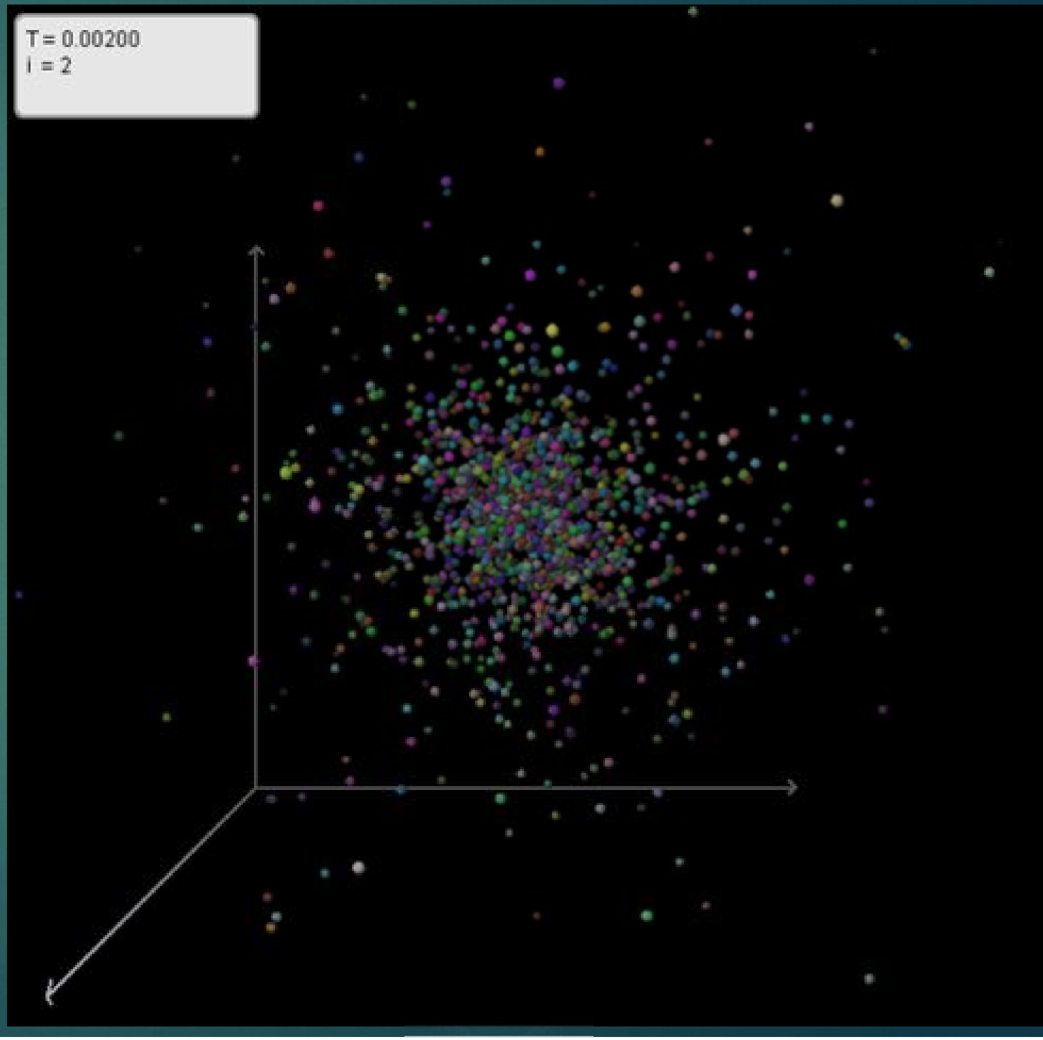


Optical magnitude depends on the mass of the visible stellar disc.

But rotation velocity depends upon ‘CDM’.

Why should optical magnitude and CDM be systematically related in this way?

THEORETICAL FACTORS: In the 1960s advancing computing power opened the way to mathematical modelling of galaxies and solution of the Newtonian 'N-body problem'.



To be meaningful ‘N’ needed to be large

By the late 60s calculations involving 100,000 or more ‘bodies’ were possible.

The components of a massive rotating disc will experience a gravitational attraction.

If the structure is dynamically stable gravity will provide the centripetal acceleration needed to ensure each discrete body (star) continues on a near circular path about the centre of the simulated galaxy.

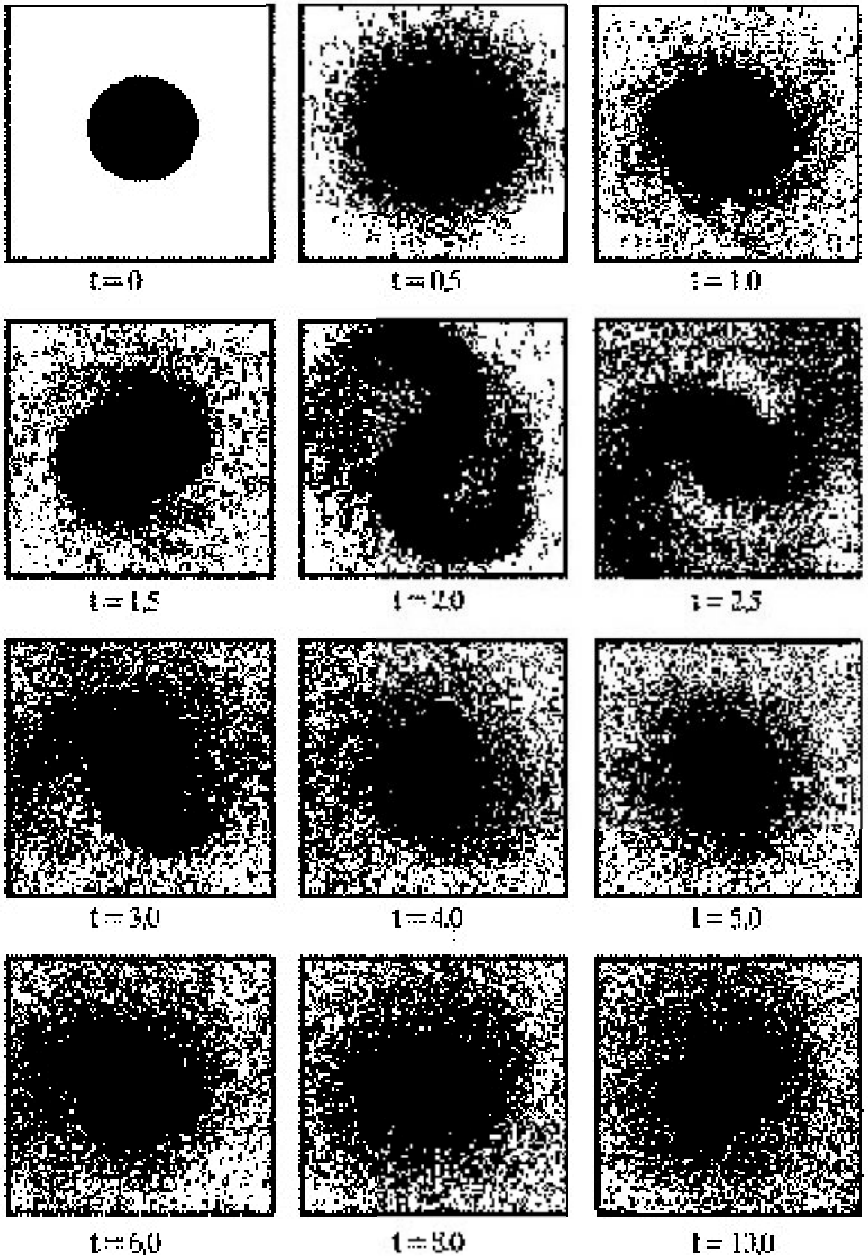
But this is not how the N-body 'experiments' behaved:

● After one or two rotations the discs evolved spiral arms and became elongated - with shapes distinctly similar to barred spiral galaxies.

● Within a few disc revolutions the barred galaxies morphed to less structured forms similar to elliptical galaxies.

Simulated N-body galaxy development.

Frank Hohl - 1971



DARK HALOS

The Milky Way and other galaxies possess kinetic energy because of their overall general rotation at about 200-300km/sec about a central axis.

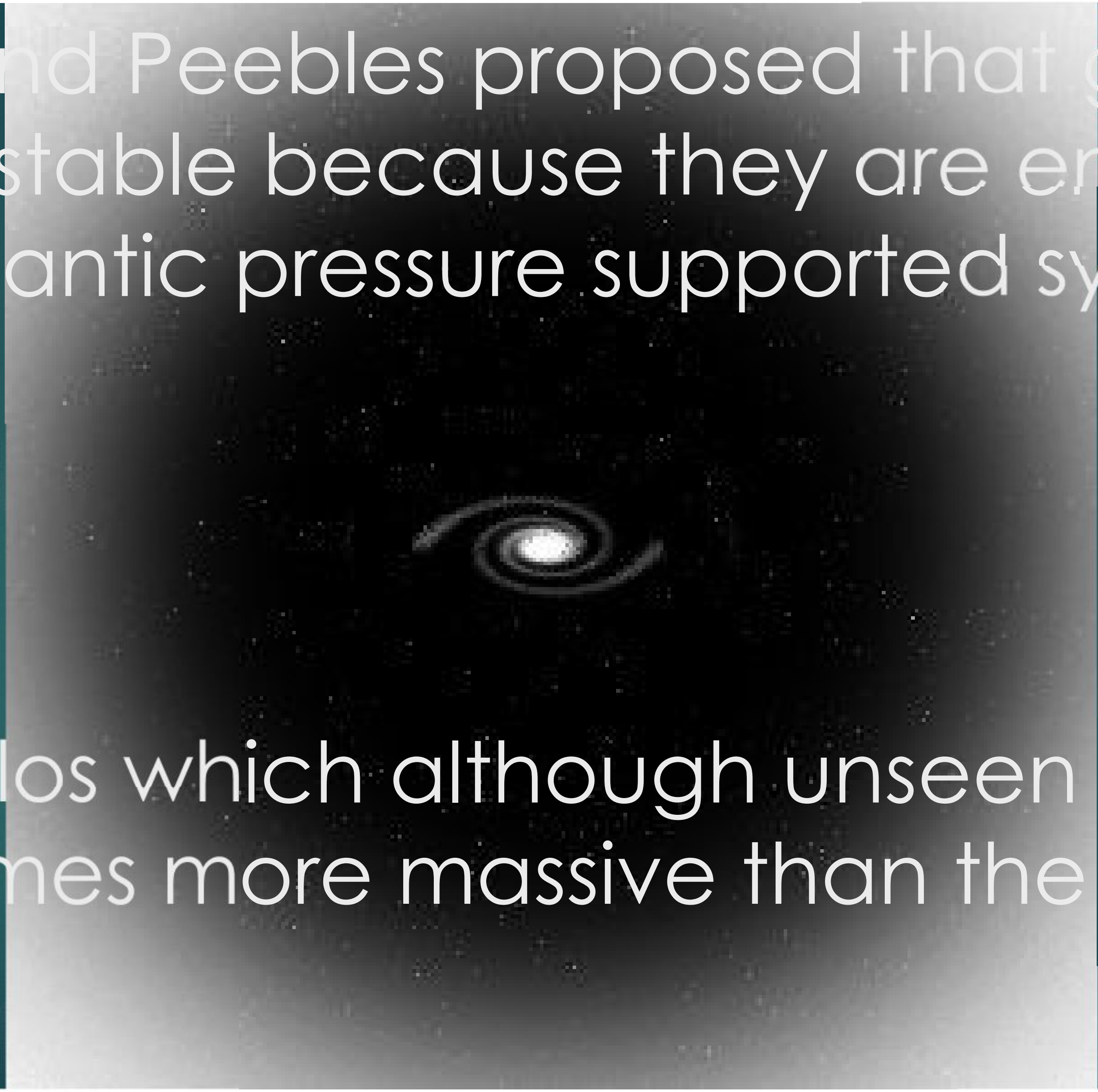
The stars also have a random velocity in the order of 40km/sec.

- In 1971 Jerry Ostriker and James Peebles of Princeton worked on N-body analysis of disc galaxies.

- From previous work Ostriker new that rotating discs and spheres would be unstable if more than 28% of the total kinetic energy was present as rotational energy about the central axis.

- Study of the Milky Way revealed that the rotational energy was about 49%. The Milky Way should be unstable – but it clearly is not.

Ostriker and Peebles proposed that galactic discs are stable because they are embedded within gigantic pressure supported systems



– dark halos which although unseen are several times more massive than the visible material.

Modelling a halo twice as massive as the disc demonstrated that Newtonian rotationally supported systems would be stable over time.

But in the 70s the suggestion that every galaxy was immersed in an extensive cocoon of unseen and undetectable ‘dark matter’ was greatly resisted.

To this day, after more than forty years of searching the cosmos and much theorising and experiment on Earth no CDM has been detected. The evidence for it remains indirect by way of an <u>apparent</u> observational mass discrepancy and theoretical mathematical studies based on Newtonian models.

MOND

Modified Newtonian Dynamics

Israeli physicist Mordehai (Moti) Milgrom proposed an alternative explanation to the mass discrepancy problem. He reasoned that if galaxies do not behave as theory predicts a rational explanation may be that the theory is not quite correct.

Milgrom was impressed by the flat rotation curves and by the relationship discovered by Tully-Fisher:

$$L \propto V^{\alpha}$$

He realised that both could be explained by a modification to Newton's laws of gravity.

Although Newton works exceptionally well in all tested situations Milgrom proposed that in circumstances of exceedingly low acceleration the appropriate force/inertia law is not the familiar *F=ma* but:

$$F = ma(a / a_o) \qquad \alpha \prec \alpha_0 \simeq 10^{-10} m / Sec^2$$

A value for a_o of $1.2x10^{-10}\, m/s^2$ was derived from the observed Tully-Fisher data. This low acceleration pertains at galactic and larger scales but is very much lower than anything relating to objects within the Solar System.

The revised law is more formally stated as:

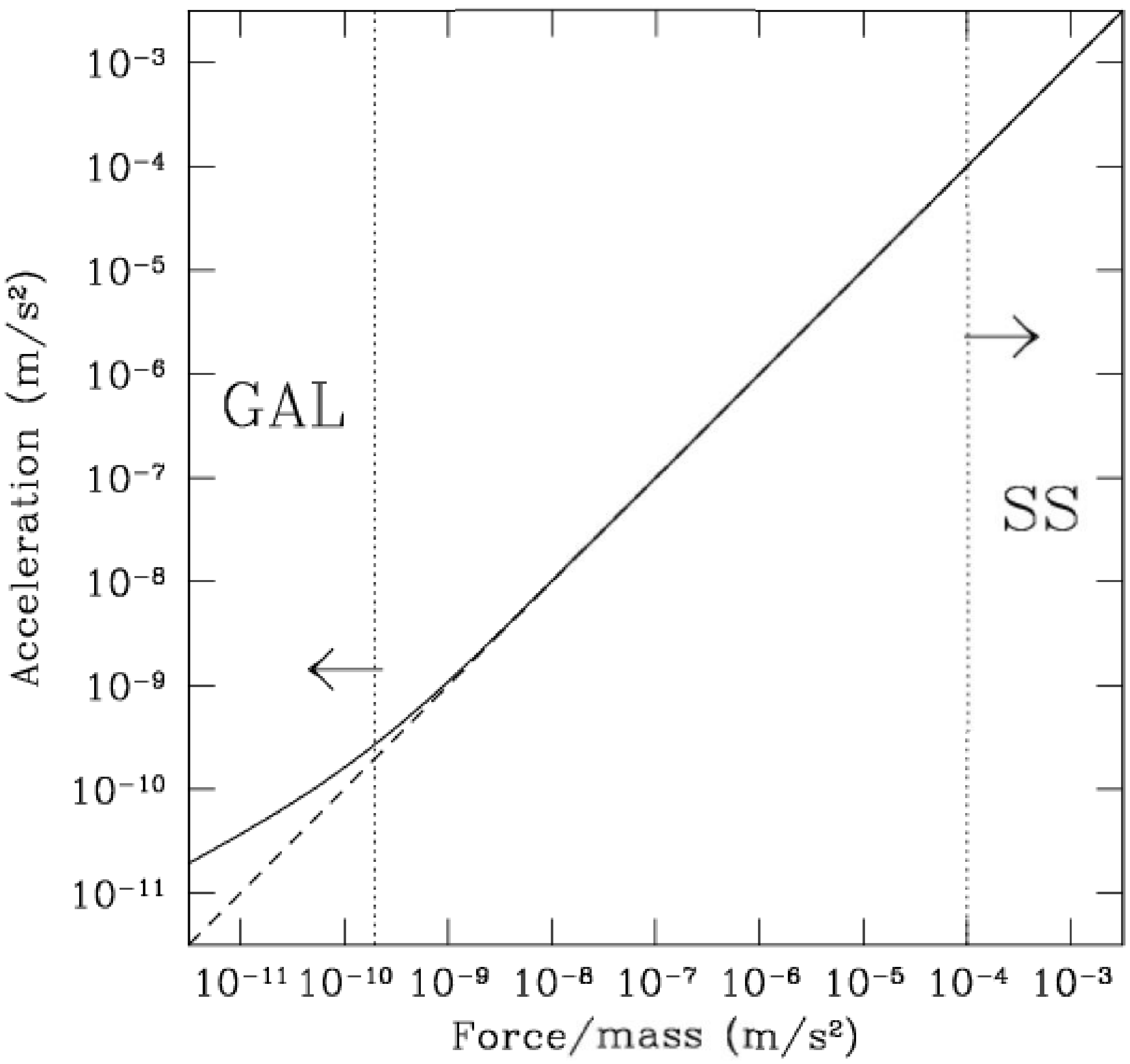
$$F = ma\mu(a / a_o)$$

μ is an interpolation function.

When a>> $\mu(a/a_o) = 1$

When a ≤ a_o $\mu(a/a_o) = (a/a_o)$

Divergence of MOND and Newtonian Dynamics – noticeable at a< $10^{-10} m/s^2$



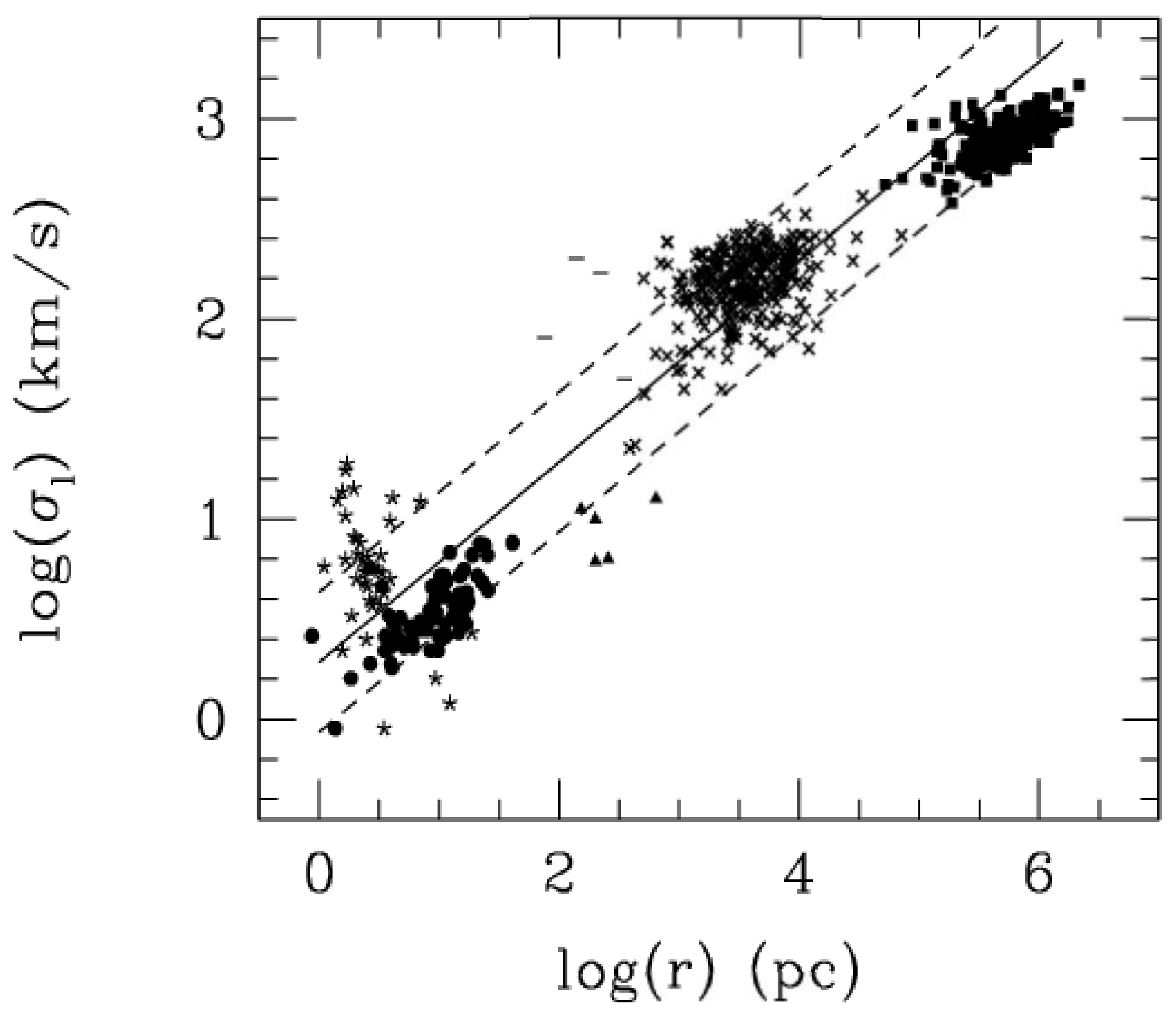
For more than 25 years MOND has proved to be robust. Applied to spiral galaxies it provides results consistent with flat rotation curves and also with Tully-Fisher.

MOND also explains the Faber-Jackson relationship:

$$M \propto \sigma^4$$

Isothermal objects: globular clusters, elliptical galaxies, galaxy clusters.

MOND isothermal sphere is finite.



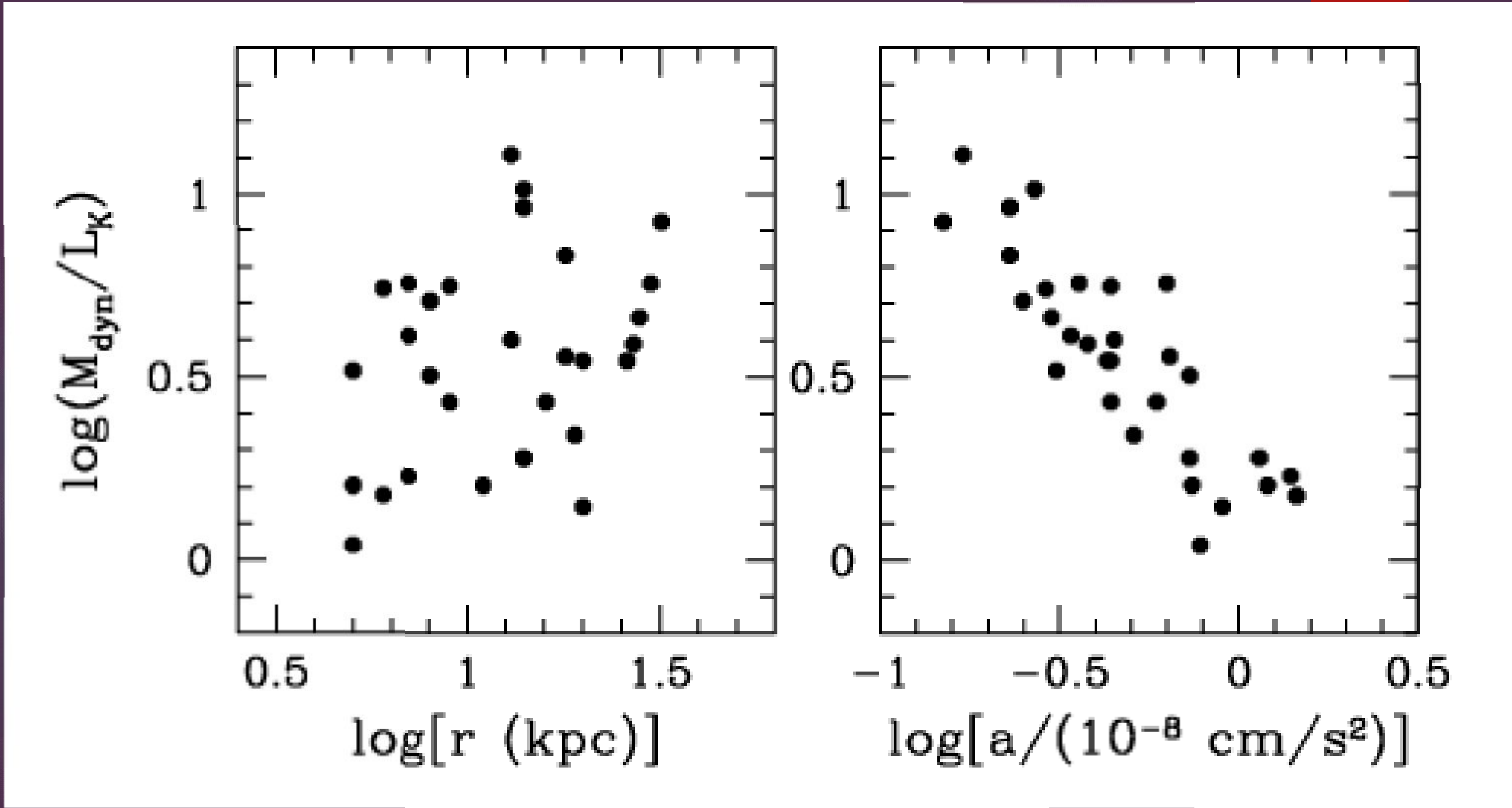
Milgrom predicted the apparent mass discrepancy of astronomical objects would be related to absolute luminosity and would be greatest for low luminosity objects.
It was reasoned that low luminosity objects would have low mass surface density (Σ < 200Mo/PC^2) and therefore low accelerations.

Freeman limit

About 15 years after Milgrom conceived MOND Sanders and McGaugh plotted rotation curve data for spiral galaxies lying in Ursa Major.

They compared absolute luminosity (M/L) with galaxy size and with acceleration at the edge of the observed region.

Comparison of Ursa Major Galaxies



There was no relationship between galaxy size and luminosity (i.e. apparent mass). But, there was a clear relation between apparent galactic mass and asymptotic acceleration. In the light of Newtonian mechanics the lower the acceleration the greater the mass discrepancy – i.e. there was (apparently) more CDM.

If the CDM paradigm is valid for galaxies – the observation that rotation velocity and acceleration are directly related to brightness and the mass of baryonic matter means the putative visible but low mass content of a galaxy is in control – i.e. the ‘tail wags the dog’.

If MOND expresses natural law what was discovered for the Ursa Major galaxies must be absolute - there can be no exceptions. Flat rotation curves and the Tully-Fisher relation $L \propto V^{\alpha}$ must always apply.

MOND predicts:

● When galaxy surface density is less than about 200 solar masses/square parsec rotation will be in the MOND domain.

● With density greater than this Newtonian mechanics will apply.

● Bright galaxies will need no hypothecated CDM but dim galaxies will need substantial CDM to explain their rotation.

This is what has been found by observation. Dim and hard to locate LSB galaxies 'need' a high proportion of CDM. HSB galaxies of high absolute magnitude and baryonic surface density need no addition of CDM to explain their motion.

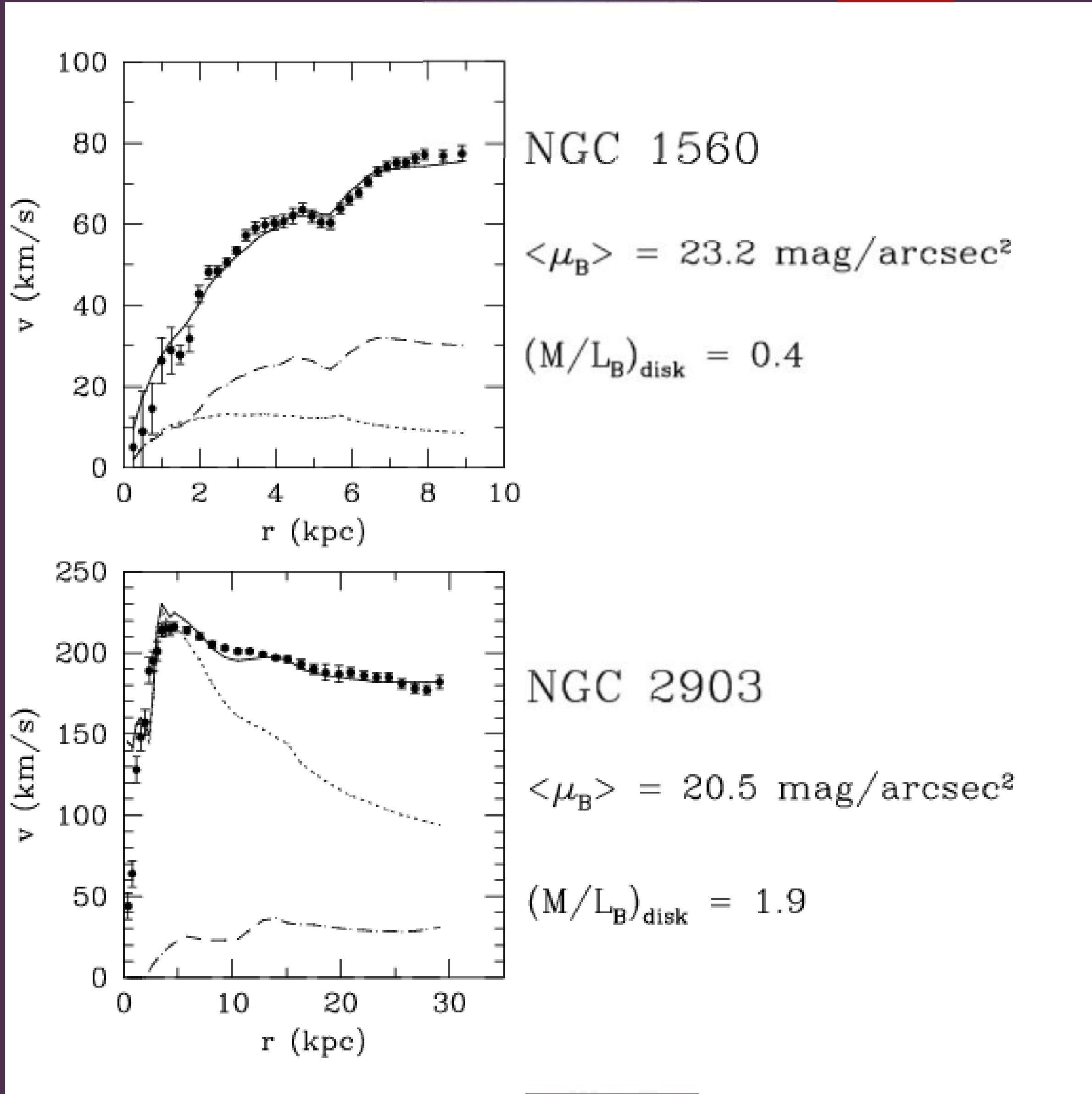
This clear prediction <u>does not</u> arise from the CDM paradigm.

In the context of MOND LSB galaxies are deep inside the MOND domain. HSB galaxies are Newtonian within the inner optical disc but MOND in the outer regions.

Milgrom used MOND to predict different rotation curves for these two classes of galaxy.

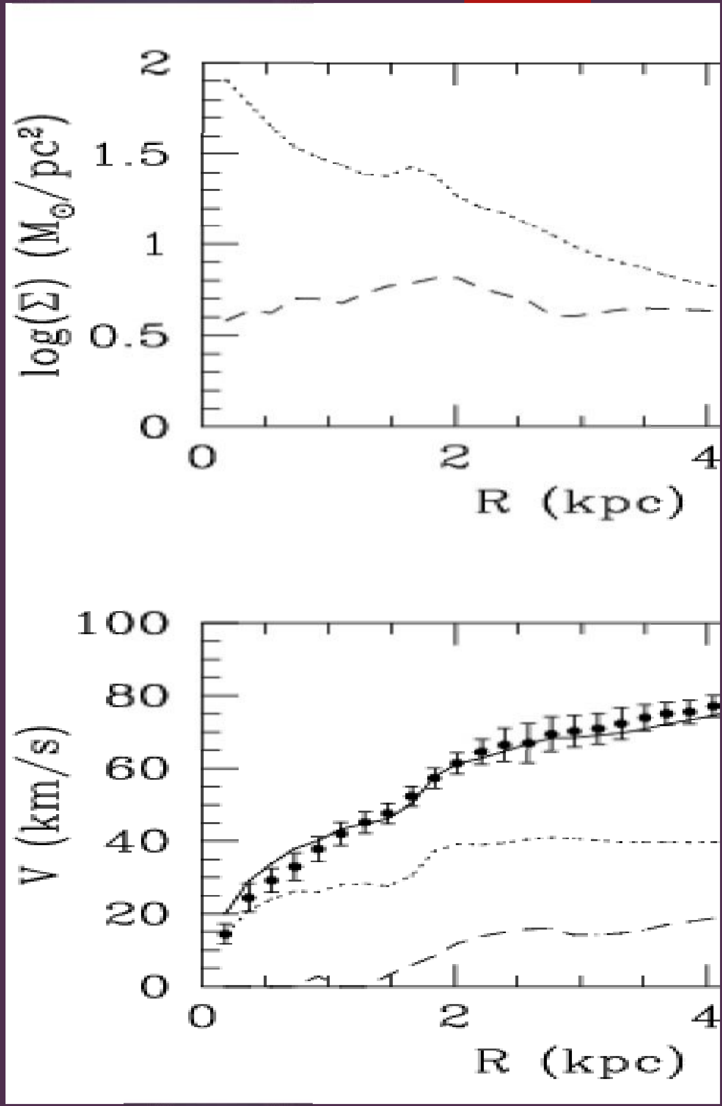
LSB – slow rise to asymptotic rotation.

HSB – rapid rise to asymptotic velocity.

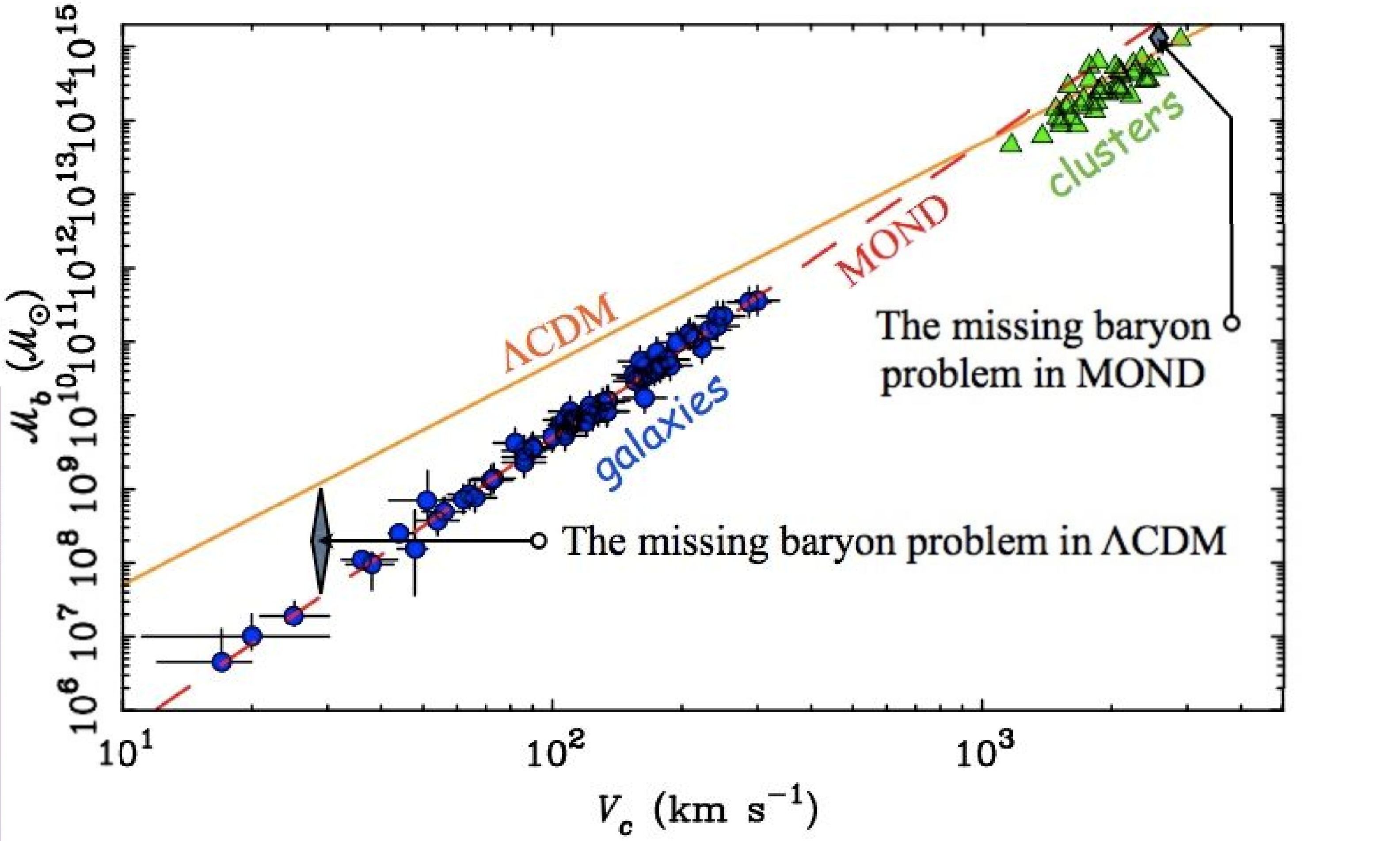


MOND mass is consistent with observations.

E.g. UGC 7524 – baryonic mass density (no assumed CDM) matches observed rotation curve.



MOND and galaxy clusters?



MOND suffers a missing baryon problem in clusters of galaxies.
ΛCDM suffers a similar, even larger discrepancy in galaxies.
In both theories, some of the normal matter has to be dark.

MOND and the Cosmos:

A thought provoking feature of MOND is that it may be related to deep cosmological parameters:

$$a_o \approx \frac{cH_o}{2\pi} = 1.15 \bullet 10^{-10} (m/s^2)$$

Travelling for the *Hubble Time* a body subject to acceleration *a*o would just reach the speed of light.

MOND is falsifiable. This is an important attribute of a scientific theory. Discovery of CDM would probably put an end to MOND.

CDM is not falsifiable. When observations do not fit the paradigm the problem may be solved by assuming more or less CDM.

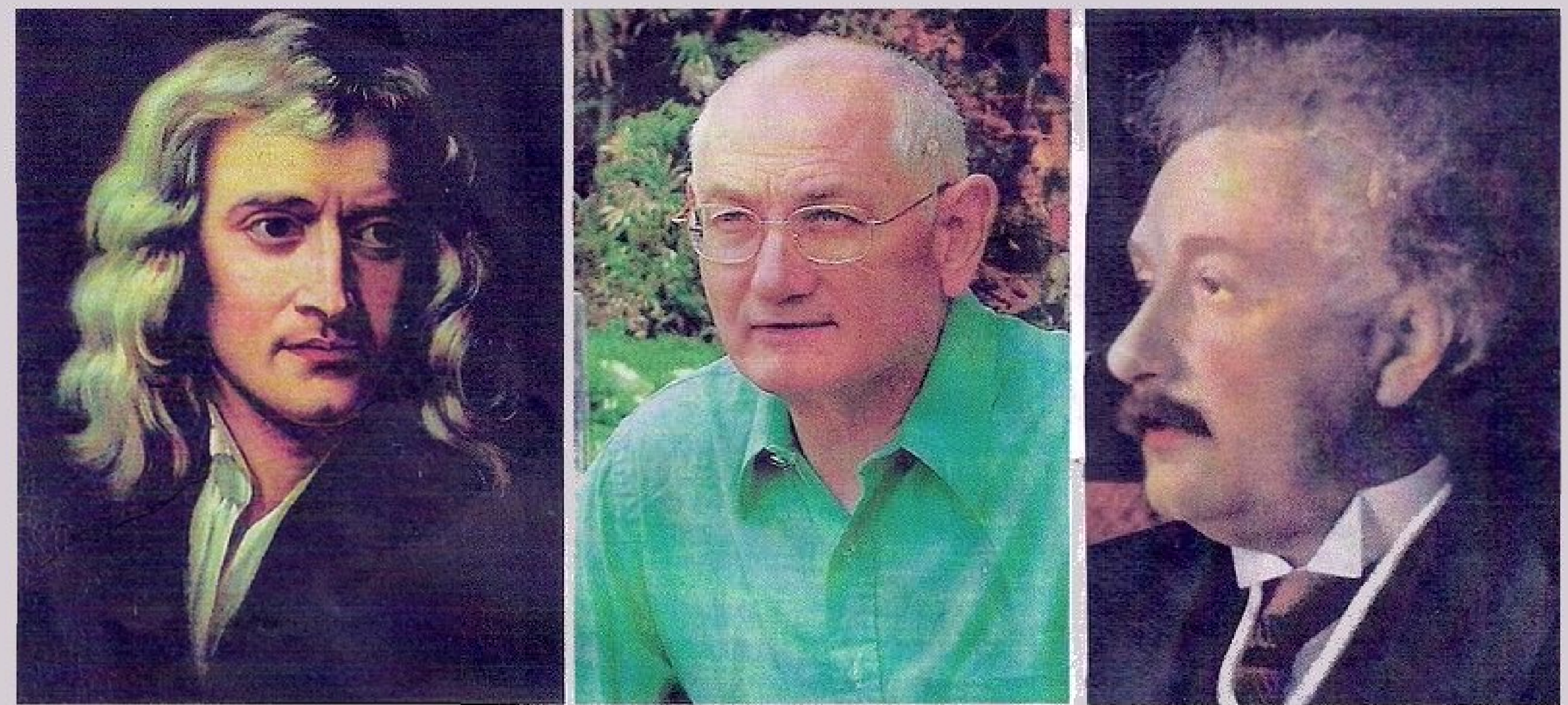
Newton's laws have never been physically tested at scales beyond the orbit of Pluto – acceleration $3.7 \bullet 10^{-6} m/s^2$

But the Pioneer anomaly may represent such a test.

The story does not end here:

Theoretical work is now underway in several locations to reconcile MOND with General Relativity and provide a deeper theoretical basis for what has been demonstrated to be a workable model of galaxy dynamics.

An modern pantheon of gravity?



Images of Isaac Newton (left) and Albert Einstein (far right) flank Mordehai Milgrom, a physicist who has boldly updated Newtonian motion and, in doing so, has reconceived Einsteinian gravity.

‘Keep in mind that new ideas are commonplace, and almost always wrong.’

EO Wilson – ‘*Consilience*’