ROE, Edinburgh, 20 April 2006

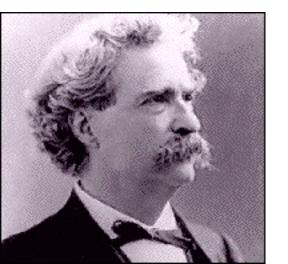
Observational Constraints on the Acceleration Discrepancy Problem

> Stacy McGaugh University of Maryland

What gets us into trouble is not what we don't know.

It's what we know for sure that just aint so.

- Mark Twain



i.e., we shouldn't be overly confident that the universe is filled with some new form of invisible, non-baryonic mass (such as WIMPs) until we actually detect the stuff directly in the laboratory. Current cosmology (ACDM) invokes not one but two aethers (dark matter and dark energy); let us be careful not to fall into the same conceptual trap that led classical physicists to infer that Maxwell's theory *required* aether. It is at least conceivable that there could be a theory which captures the successes of cosmology without the excess baggage. The Dark Matter Tree:

The roots represent the empirical roots of the problem; the branches the various proposed solutions. Hot DM

Vor Brenowin Dark matter solutions are represented on the left branch; modifications of dynamical laws are represented on the right branch.

MASS This review focusses on the phenomenology of the mass discrepancy, which appears at a particular acceleration scale. By request, I focus on rotation curves, but will also touch on other data.

Time restrictions limit discussion of theories to the specific case of MOND.

> Disk DM curves

> > M- 2 0.1

Cort

Black Holer

8 mains

Gas

Dira

Scale Structure flows

Dark Clusters

Gran

Inertia

MSTG

TeVeS

BSTV

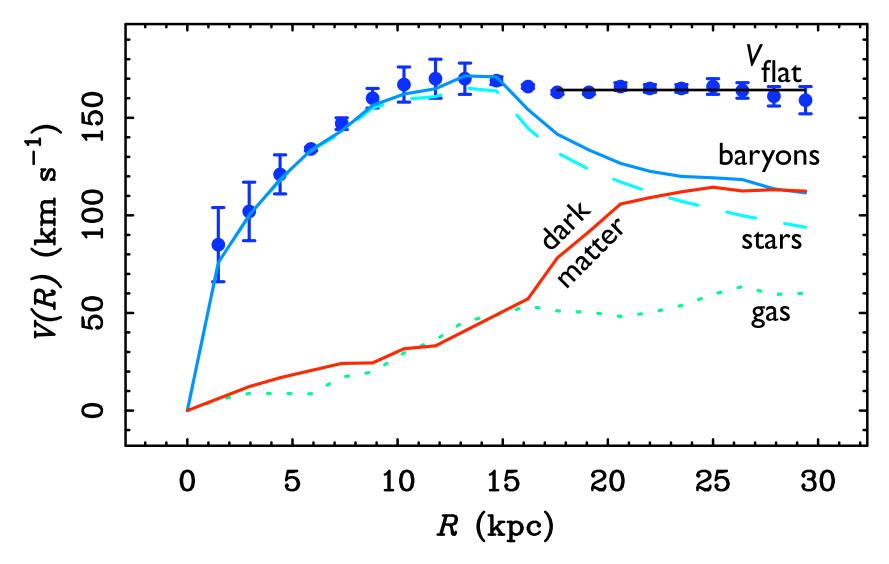
MOND

a=1

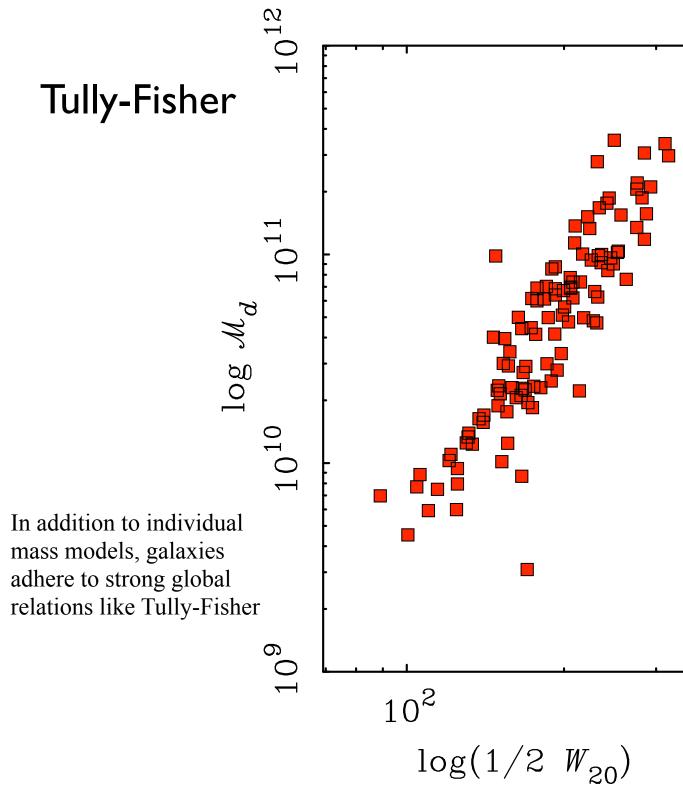
MOND

٧G

NGC 6946:
$$\mathcal{M}_*/L_B = 1.1 \ \mathcal{M}_{\odot}/L_{\odot}$$



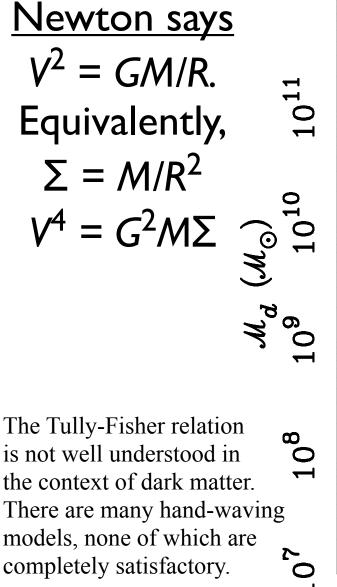
The rotation curve and mass model of NGC 6946 (pictured on the first slide). The baryons are the sum of stars and gas computed from the observed mass distribution for the case of maximum disk. Dark matter is whatever is left over.

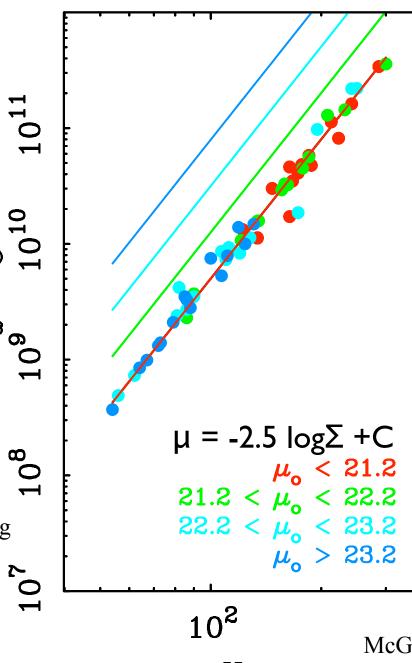


relation between luminosity/mass and rotation speed

> Bothun et al. (1985) *H*-band

TF Relation



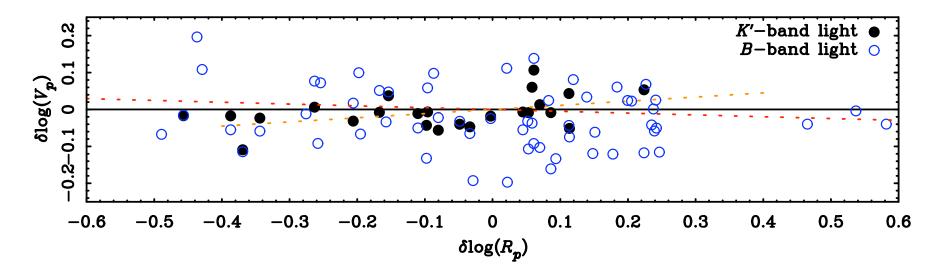


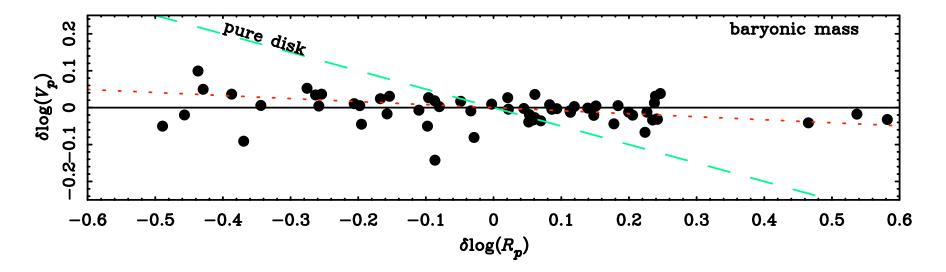
V flat <u>Therefore</u> Different Σ should mean different TF normalization.

One expects, from basic physics, that variations in the distribution of baryonic mass should have an impact on the Tully-Fisher relation (lines). They do not (data). See discussions in

McGaugh & de Blok 1998, ApJ, 499, 41 Courteau & Rix 1999, ApJ, 513, 561

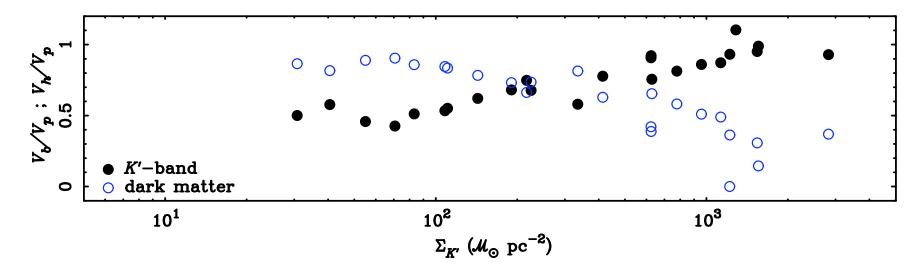
No Residuals from TF rel'n

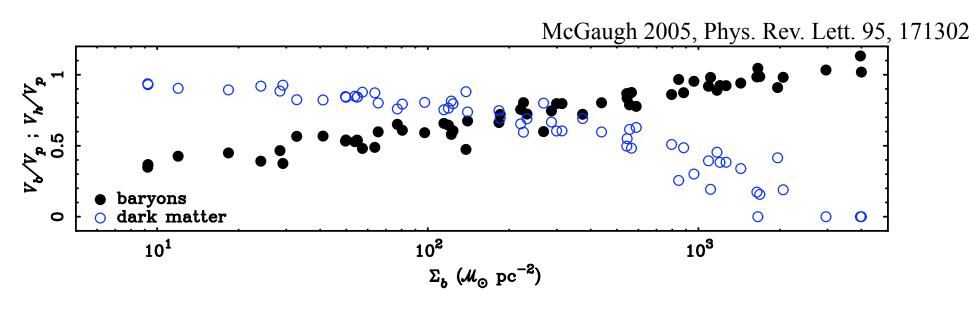




Indeed, the residuals from Tully-Fisher are nearly to totally imperceptible, depending weakly on the choice of circular velocity measured. This causes a fine-tuning problem which is generic to any flavor of dark matter...

Requires fine balance between dark & baryonic mass





The contribution of the baryonic (filled points) and dark matter (open points) to any given point along the rotation curve must be finely balanced, like a see-saw. As the baryonic contribution increases with baryonic surface density, the dark matter contribution decreases. The two components know intimately about each other...

Renzo's Rule:

"When you see a feature in the light, you see a corresponding feature in the rotation curve."

(Sancisi 1995, private communication)

(See also Sancisi 2004, IAU 220, 233)

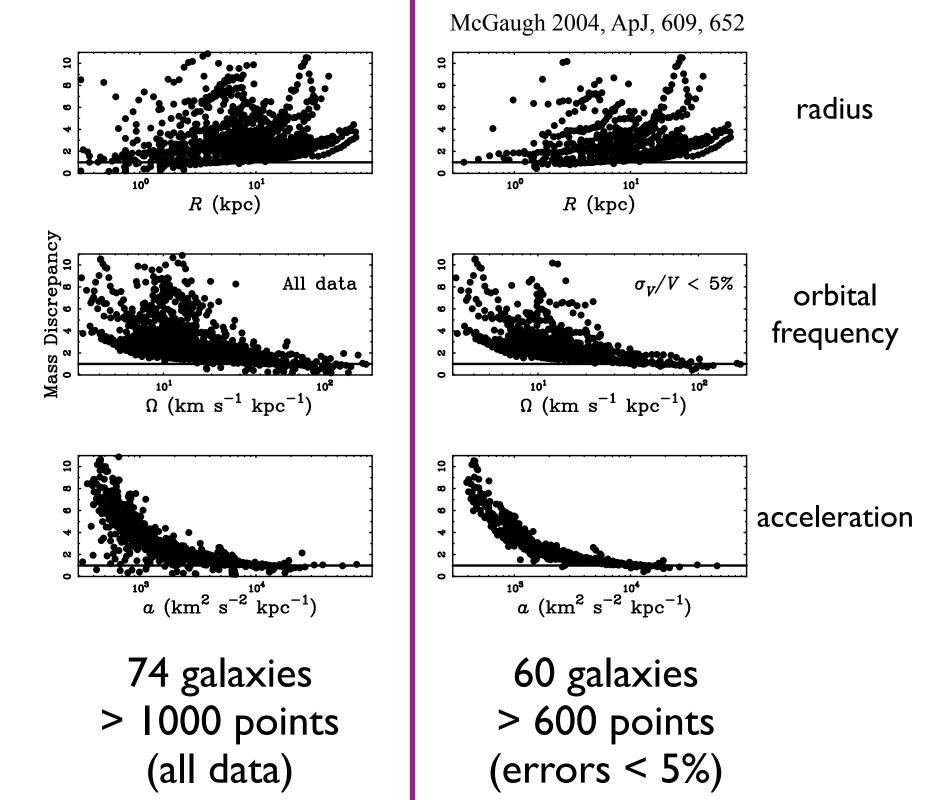
The distribution of mass is coupled to the distribution of light.

Quantify by defining the Mass Discrepancy:

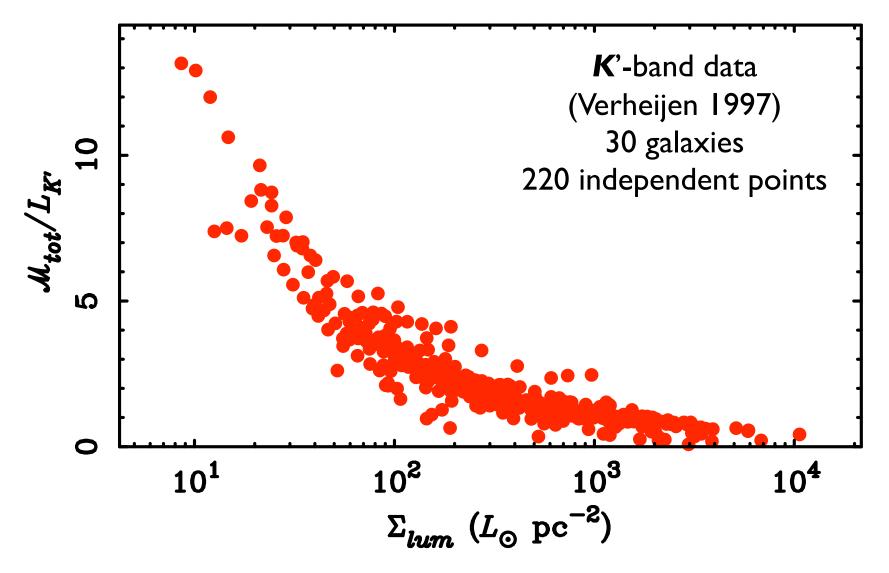
$$\mathcal{D} = \frac{V^2}{V_b^2} = \frac{V^2}{\Upsilon_\star v_\star^2 + V_g^2}$$

This is essentially the ratio of total to baryonic mass. It depends on the stellar mass-to-light ratio, Υ_{\star} , for which we can explore many possibilities.

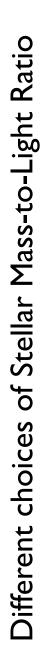


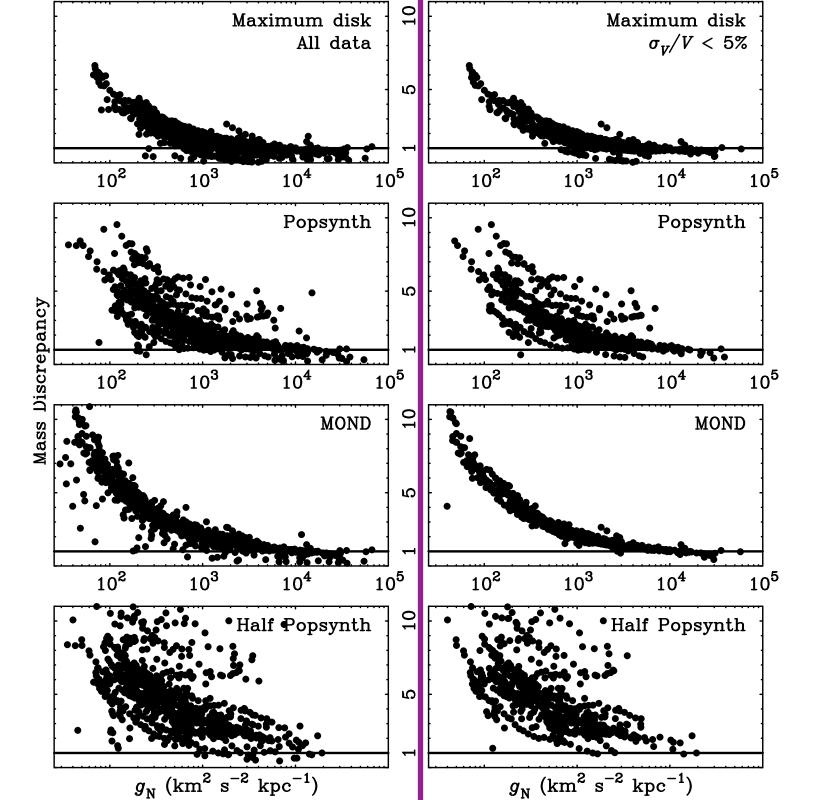


Before we explore the choice of stellar mass-to-light ratio, note that the basic phenomenology is already present in the data, without any free parameters.



The K'-band dynamical mass-to-light ratio correlates with surface brightness. Note that acceleration relates to surface density: $g_N = G\Sigma$





McGaugh 2004, ApJ, 609, 652





MOdified Newtonian Dynamics introduced by Moti Milgrom in 1983

instead of dark matter, suppose the force law changes such that

for
$$a >> a_o, a \Rightarrow g_N$$

for $a << a_o, a \Rightarrow \sqrt{(g_N a_o)}$

where
$$g_N = GM/R^2$$

is the usual Newtonain acceleration. More generally, these limits are connected by a smooth interpolation fcn $\mu(a/a_0)$ so that

 $\mu(a/a_o) \ a = g_N.$ MOND can be interpreted as a modification of either inertia (F = ma) or gravity (the Poisson eqn).

ApJ, 270, 381

Milgrom 1983

MODIFICATION OF NEWTONIAN DYNAMICS

No. 2, 1983

A major step in understanding ellipticals can be made if we can identify them, at least approximately, with idealized structures such as the FRCL spheres discussed above. I have also studied isotropic and nonisotropic isothermal spheres, in the modified dynamics, as such possible structures. I found that they have properties which very much resemble those of ellipticals and galactic bulges. I describe these in Milgrom (1983c).

VIII. PREDICTIONS

The main predictions concerning galaxies are as follow's.

Velocity curves calculated with the modified dynamics on the basis of the observed mass in galaxies should agree with the observed curves. Elliptical and SO galaxies may be the best for this purpose since (a)practically no uncertainty due to obscuration is involved and (b) there is not much uncertainty due to the possible presence of molecular hydrogen.

2. The relation between the asymptotic velocity (V_{r}) and the mass of the galaxy (M) $(V_{\infty}^4 = MGa_0)$ is an absolute one.

3. Analysis of the z-dynamics in disk galaxies using the modified dynamics should vield surface densities which agree with the observed ones. Accordingly, the same analysis using the conventional dynamics should yield a discrepancy which increases with radius in a predictable manner.

4. Effects of the modified dynamics are predicted to be particularly strong in dwarf elliptical galaxies (for review of properties see. e.g., Hodge 1971 and Zinn 1980). For example, those dwarfs believed to be bound to our Galaxy would have internal accelerations typically of order $a_{in} \sim a_0/30$. Their (modified) acceleration, g, in the field of the Galaxy is larger than the internal ones but still much smaller than $a_0, g \approx (8$ kpc/d) a_0 , based on a value of $V_{\infty} = 220$ km s⁻¹ for the Galaxy, and where d is the distance from the dwarf galaxy to the center of the Milky Way (d - 70-220)kpc). Whichever way the external acceleration turns out to affect the internal dynamics (see the discussion at the end of § II, the section on small groups in Paper III, and Paper I), we predict that when velocity dispersion data is available for the dwarfs, a large mass discrepancy will result when the conventional dynamics is used to determine the masses. The dynamically determined mass is predicted to be larger by a factor of order 10 or more than that which can be accounted for by stars. In case the internal dynamics is determined by the external acceleration, we predict this factor to increase with d

and be of order (d/8 kpc) (as long as $a_{in} \ll g$, $h_{50} = 1$). Prediction 1 is a very general one. It is worthwhile listing some of its consequences as separate predictions, numbered 5-7 below (note that, in fact, even prediction 2 is already contained in prediction 1).

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5. Measuring local M/L values in disk galaxies (assuming conventional dynamics) should give the following results: In regions of the galaxy where $V^2/r \gg a_0$ the local M/L values should show no indication of hidden mass. At a certain transition radius, local M/Lshould start to increase rapidly. The transition radius should occur where $V^2/r \approx a_0$. This test has the following advantages: (a) It does not require an absolute calibration of M/L as we are concerned only with variations of this quantity; (b) Effects of the modified dynamics manifest themselves more clearly in local mass determination than in the integrated masses: and (c) In many cases this test requires information on local behavior in the disk only while the spheroid can be neglected. This makes the determination of mass from velocity more certain.

6. Disk galaxies with low surface brightness provide particularly strong tests (a study of a sample of such galaxies is described by Strom 1982 and by Romanishin et al. 1982). As low surface brightness means small accelerations, the effects of the modification should be more noticeable in such galaxies. We predict, for example, that the proportionality factor in the $M \propto V_{\perp}^4$ relation for these galaxies is the same as for the high surface density galaxies. In contrast, if one wants to obtain a correlation $M \propto V_{\infty}^4$ in the conventional dynamics (with additional assumptions), one is led to the relation $M \propto$ $\Sigma^{-1}V_{\infty}^{4}$ (see, for example, Aaronson, Huchra, and Mould 1979), where Σ is the average surface brightness. This implies that low surface density galaxies, of a given velocity, have a mass higher than predicted by the M-Vrelation derived for normal surface density galaxies.

We also predict that the lower the average surface density of a galaxy is, the smaller is the transition radius, defined in prediction 5, in units of the galaxy's scale length. In fact, if the average surface density is very small we may have a galaxy in which $V^2/r < a_0$ everywhere, and analysis with conventional dynamics should yield local M/L values starting to increase from very small radii.

7. As the study of model rotation curves shows, we predict a correlation between the value of the average surface density (or brightness) of a galaxy and the steepness with which the rotational velocity rises to its asymptotic value (as measured, for example, by the radius at which $V = V_{\infty}/2$ in units of the scale length of the disk). Small surface densities imply slow rise of V

IX. DISCUSSION

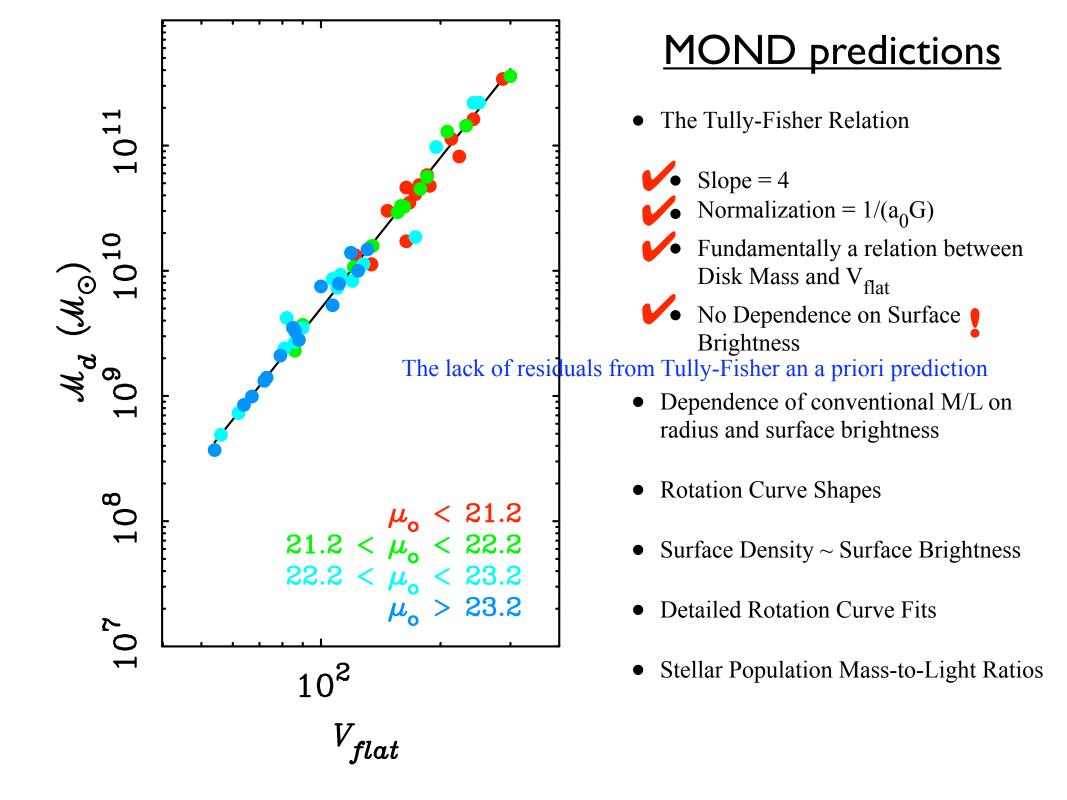
the statement that the modified dynamics eliminates the need to assume hidden mass in galaxies. The effects in galaxies which I have considered, and which are commonly attributed to such hidden mass, are readily explained by the modification. More specifically:

MOND predictions

The Tully-Fisher Relation

- Slope = 4
- Normalization = $1/(a_0G)$
- Fundamentally a relation between Disk Mass and V_{flat}
- No Dependence on Surface Brightness
- Dependence of conventional M/L on radius and surface brightness
- Rotation Curve Shapes
- Surface Density ~ Surface Brightness
- Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios

The main results of this paper can be summarized by "Disk Galaxies with low surface brightness provide particularly strong tests" None of the following data existed in 1983. At that time, LSB galaxies were widely thought not to exist.



Test TF slope by extrapolation to very low velocities:

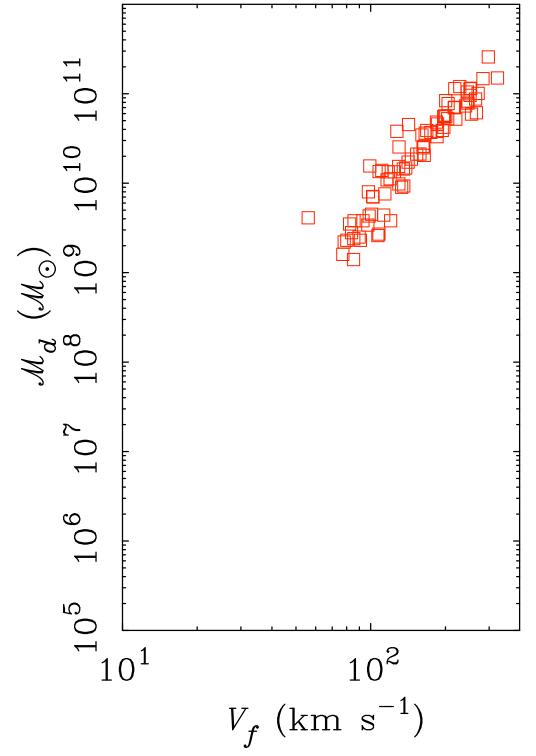
(McGaugh 2005)

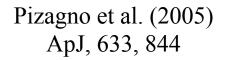
Extreme Dwarf Galaxy Data				
Galaxy	V_f (km s ⁻¹)	${\cal M}_{\star}$ (10 ⁶ ${\cal M}_{\odot}$)	${\cal M}_g$ (10 ⁶ ${\cal M}_{\odot}$)	References
ESO215-G?009	51^{+8}_{-9} 48^{+3}_{-4} 44^{+4}_{-2} 38^{+5}_{-5} 36^{+8}_{-4} 25^{+5}_{-4} 20^{+10}_{-13} 17^{+3}_{-5}	23	714	1
UGC 11583 ^a	48^{+3}_{-4}	119	36	2, 3
NGC 3741	44^{+4}_{-2}	25	224	4
WLM	38^{+5}_{-5}	31	65	5
KK98 251	36^{+8}_{-4}	12	98	3
GR 8	25^{+5}_{-4}	5	14	6
Cam B	20^{+10}_{-13}	3.5	6.6	7
DDO 210	17^{+3}_{-5}	0.9	3.6	8

TABLE 5 Extreme Dwarf Galaxy Data

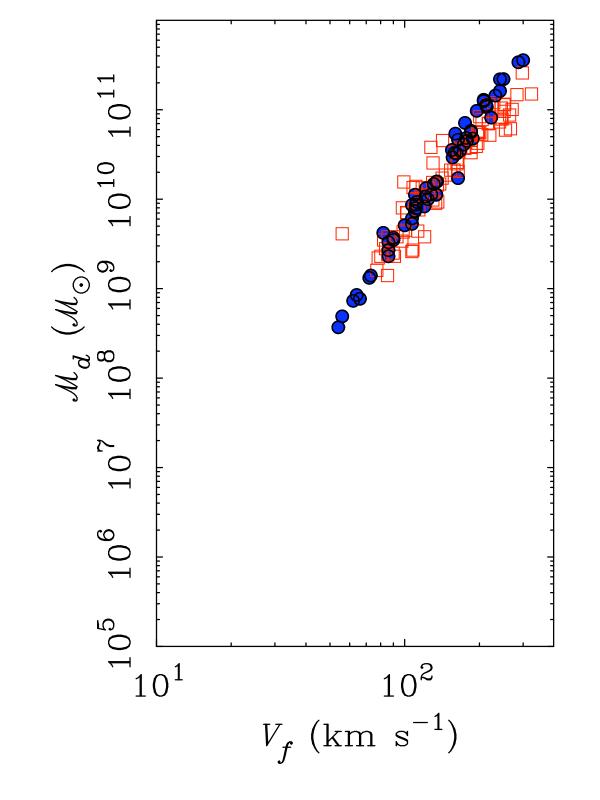
^a UGC 11583 is KK98 250.

REFERENCES.—(1) Warren et al. 2004; (2) McGaugh et al. 2001; (3) Begum & Chengalur 2004a; (4) Begum et al. 2005; (5) Jackson et al. 2004; (6) Begum & Chengalur 2003; (7) Begum et al. 2003; (8) Begum & Chengalur 2004b.

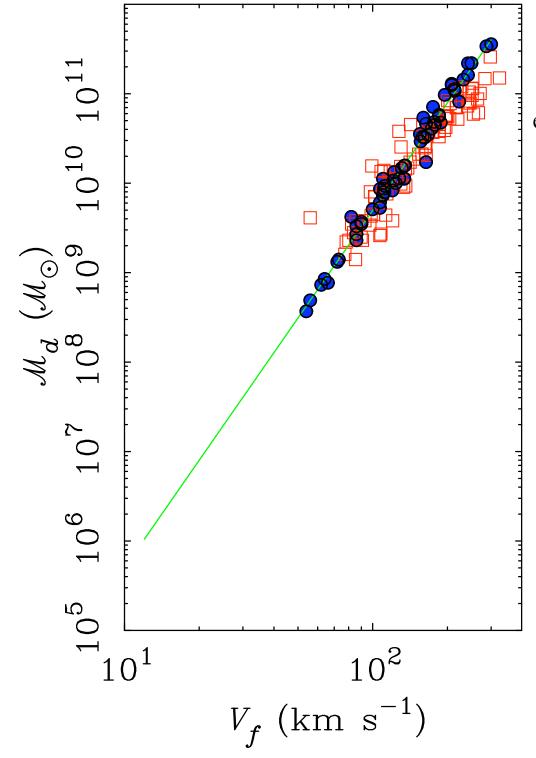




This is typical of the range covered by most Tully-Fisher studies.



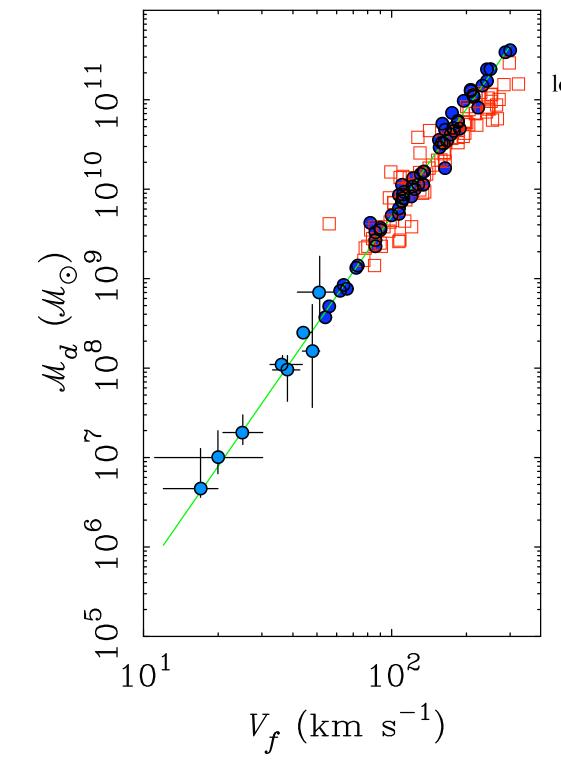
McGaugh (2005) ApJ, 632, 859



green line: best fit for mass-to-light ratio estimator with minimum scatter:

$$\mathcal{M}_d = 50V^4$$

 $(\mathcal{M}_\odot) \quad (\mathrm{km} \ \mathrm{s}^{-1})$



The green line is a good predictor of the location of the extreme dwarfs.

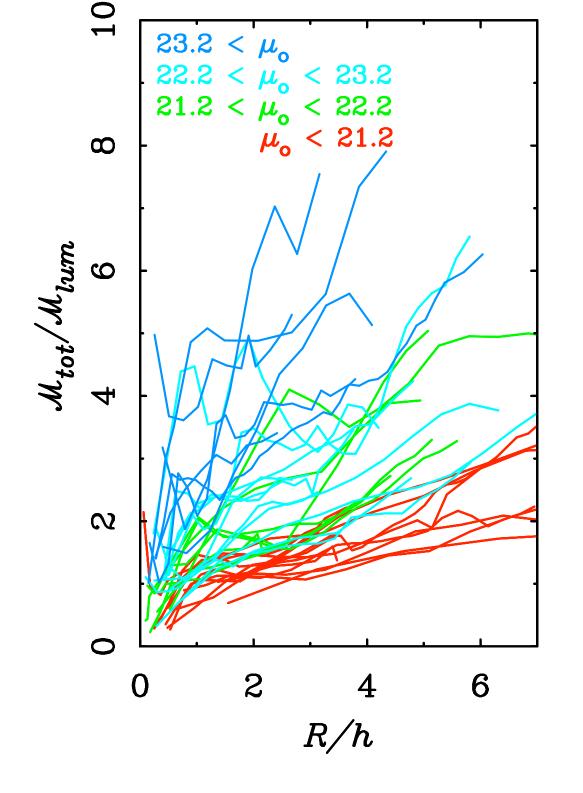
The slope is steep (4; the nominal prediction of CDM is 3)

Mass estimates adopted from the original authors (table).

Vertical error bars represent the range from minimum to maximum disk.

Horizontal error bars include random uncertainties plus the range of the asymmetric drift correction.

These more accurate, independent data confirm the steep slope found by McGaugh et al. (2000) ApJ, 533, L99

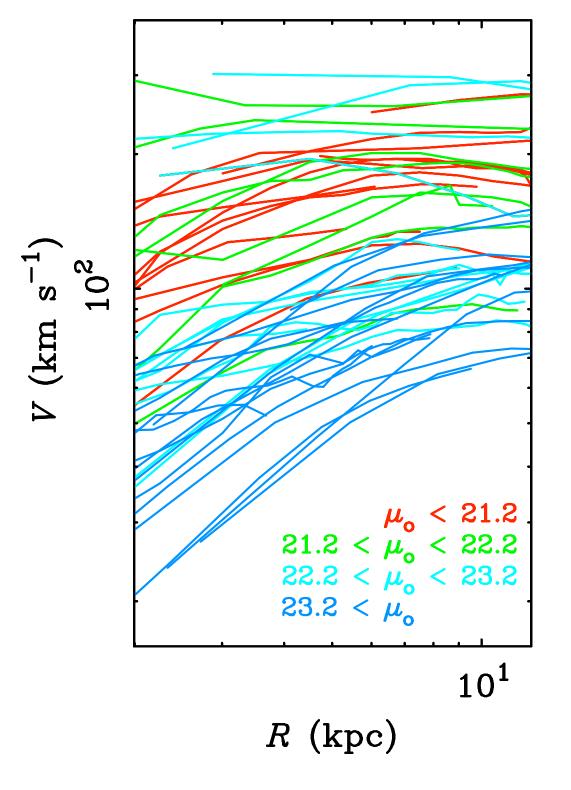


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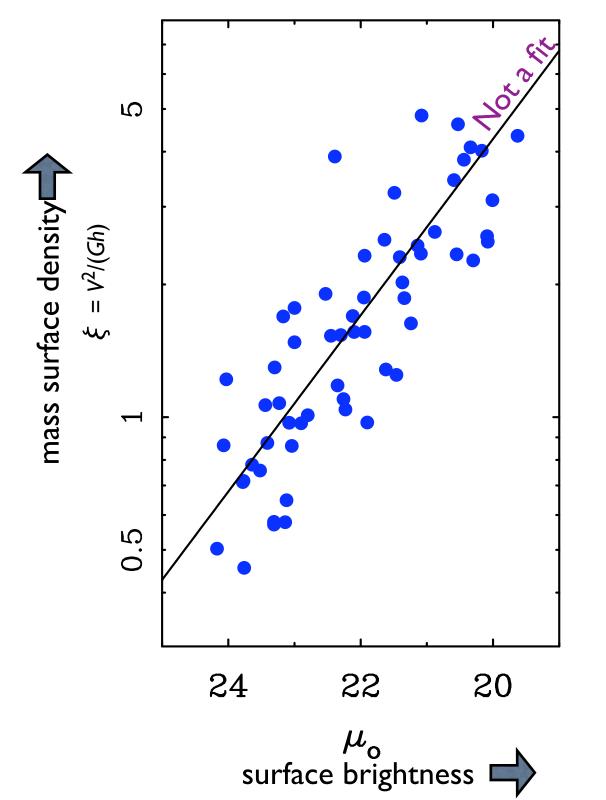
Other a priori MOND predictions

- Dependence of conventional M/L on radius and surface brightness
 - Rotation Curve Shapes
 - Surface Density ~ Surface Brightness
 - Detailed Rotation Curve Fits
 - Stellar Population Mass-to-Light Ratios



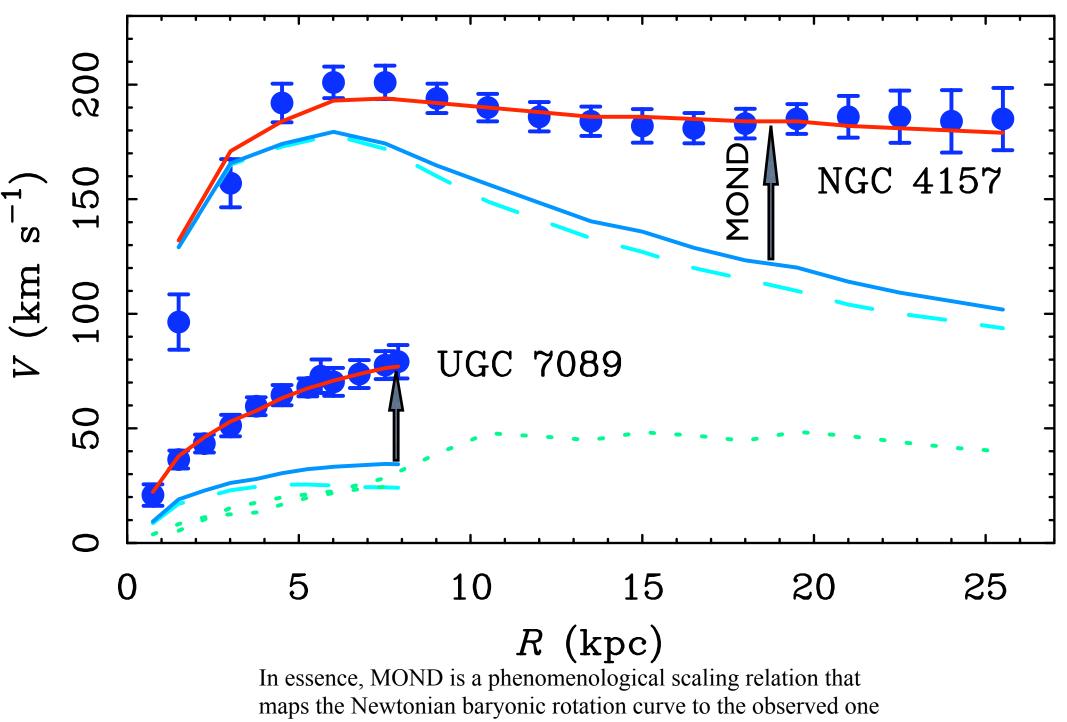
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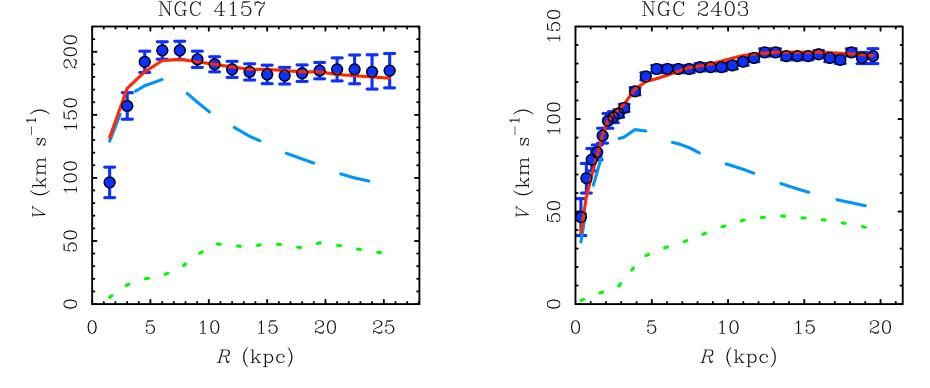


MOND predictions

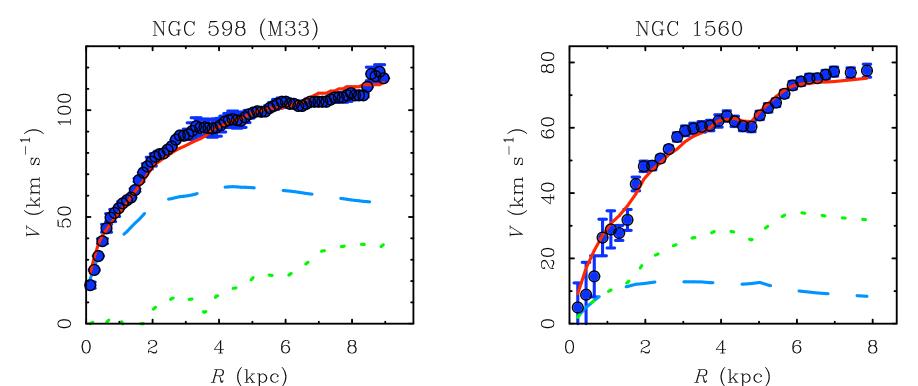
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- Rotation Curve Shapes
- Surface Density ~ Surface Brightness No dark matter, so these better correlate
 - Detailed Rotation Curve Fits
 - Stellar Population Mass-to-Light Ratios



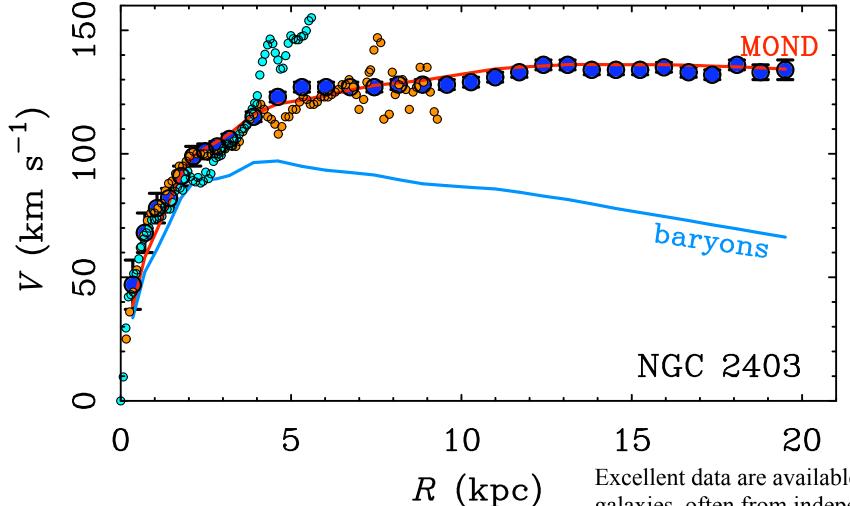
with only a single free parameter, the stellar mass-to-light ratio.



A detailed look at four galaxies.



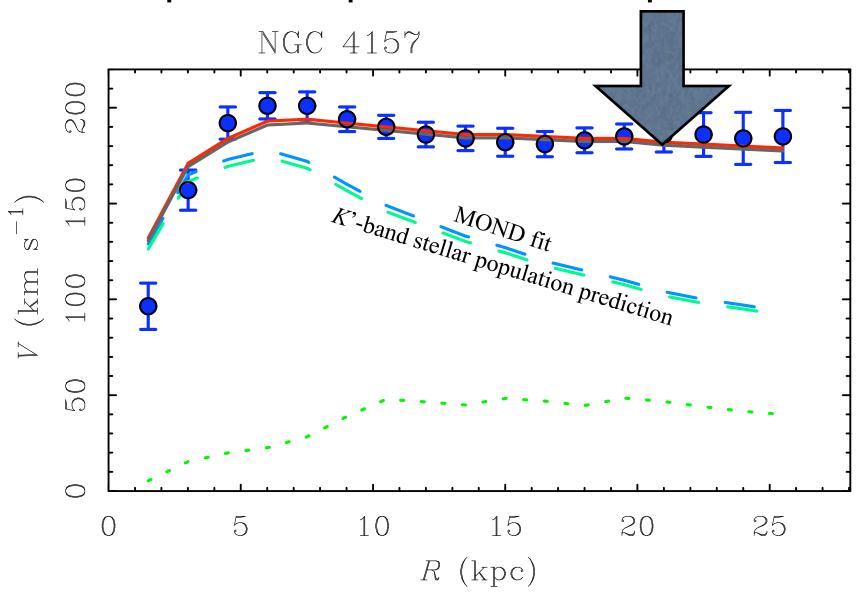
Begeman, Broeils, & Sanders (1991)



- Begeman (1987): HI data
- Blais-Ouellette et al. (2004) H α Fabry-Perot
- Daigle et al. (2006) Hα Fabry-Perot

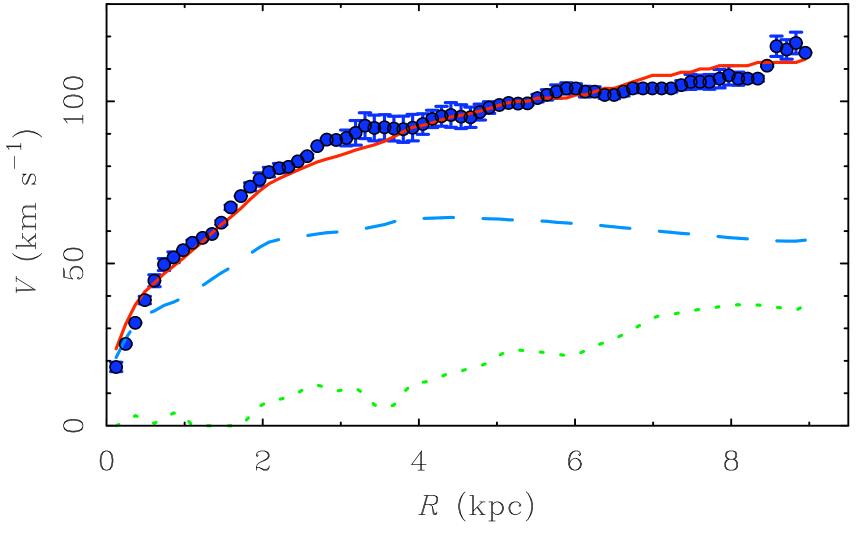
Excellent data are available for some galaxies, often from independent data sets. The HI generally traces further out; H α generally has better resolution. In this case, H α goes silly when only one side traces the rotation. All three data sets trace the kink at 3 kpc, which is reflected in the photometry: recall Renzo's rule.

predictive power: zero free parameters



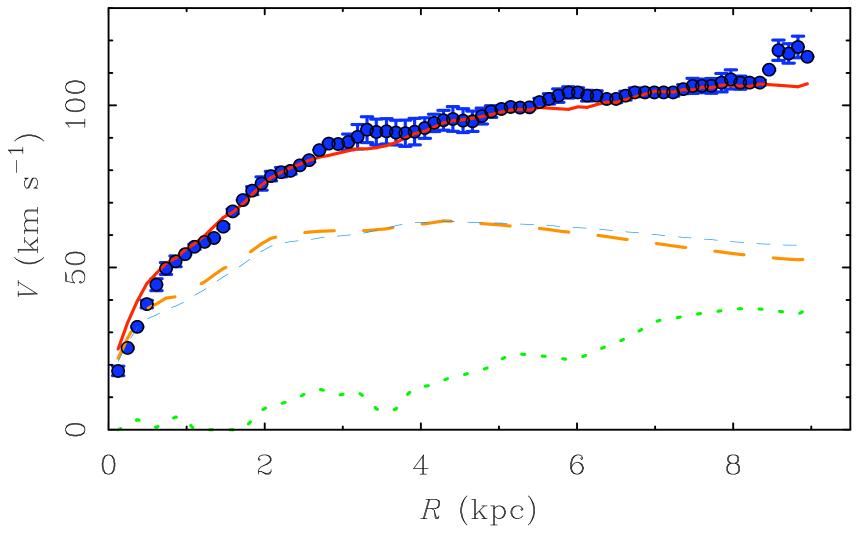
The K'-band is perhaps the best tracer of stellar mass available. One can use stellar population synthesis models (e.g., Bell et al. 2003) to predict the mass-to-light ratio. This does a good job of predicting the mass-to-light ratio needed in MOND fits. In effect, one can predict the rotation curve completely from the photometry.

M33



Color gradients should correspond to gradients in the mass-to-light ratio.

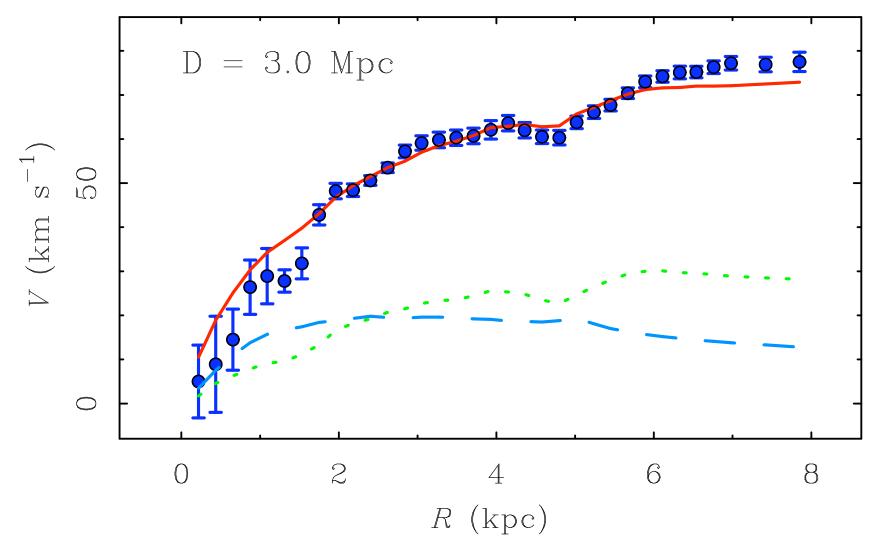
M33 color gradient corrected



This example shows the effect of correcting for the observed gradient.

Begeman, Broeils, & Sanders (1991)

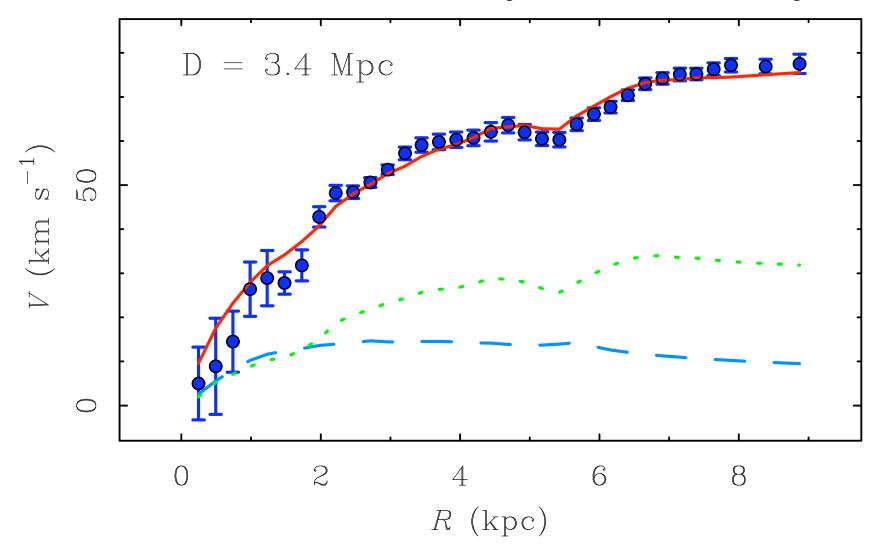
NGC 1560 This case is interesting for the prominent kink at large radii, where the quasi-spherical dark matter halo should dominate. (Recall Renzo's rule.)



 $\Upsilon_* = 0.97$

Begeman, Broeils, & Sanders (1991)

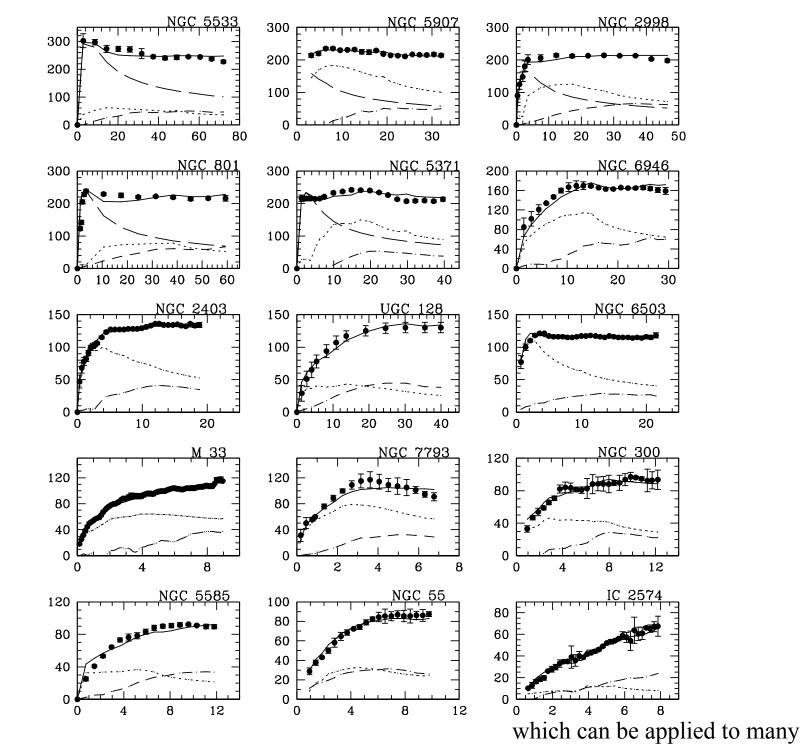
NGC 1560 Begeman et al. found a better fit if they increased the distance from the value of 3.0 Mpc estimated in 1991 to 3.4 Mpc.



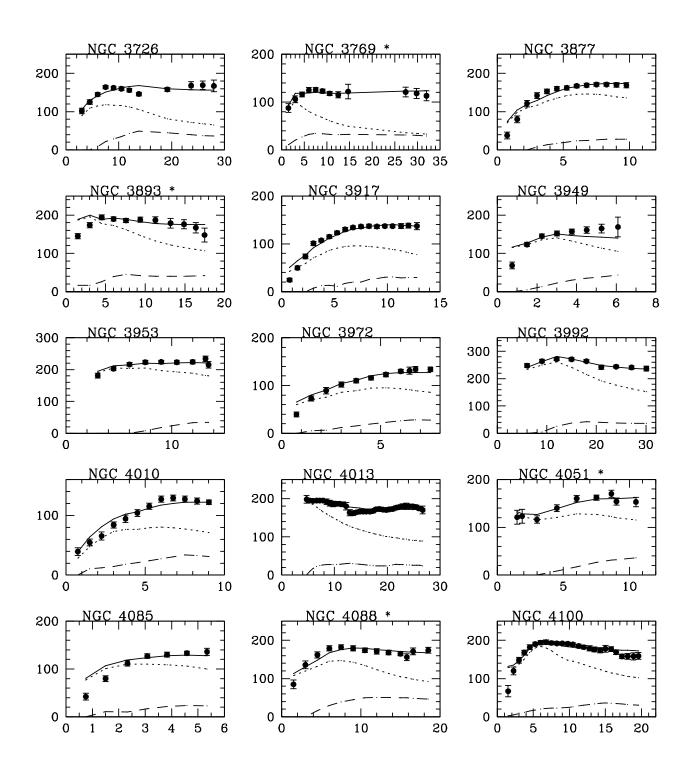
The modern D = 3.45 Mpc, as measured by the Tip of the Red Giant Branch method (Karachentsev *et al.* 2004)

 $\Upsilon_{*} = 0.44$

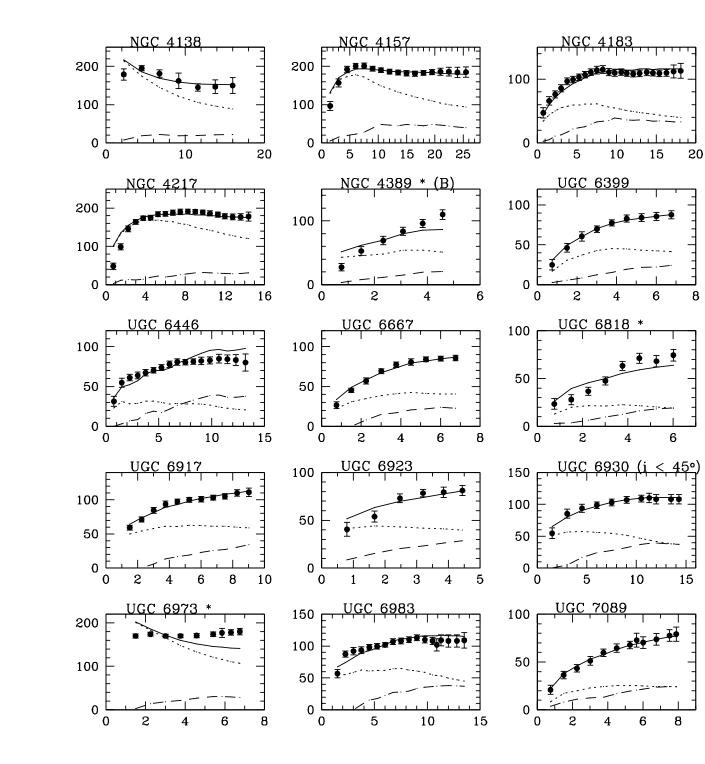
Every rotation curve provides a strong test of MOND





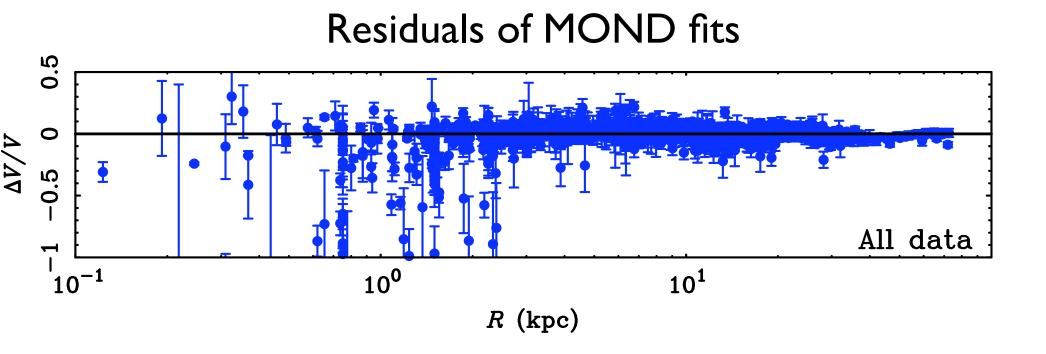


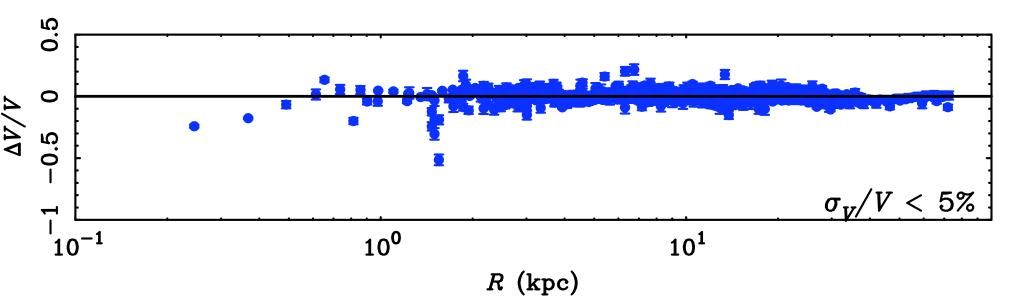
many



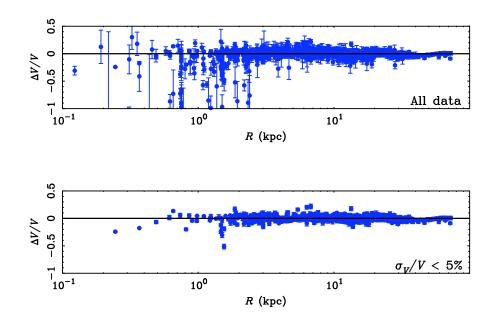
many cases.

8





Taken together, the fits are pretty good. There is a slight hint of non-circular motion at small radii, though this is considerably less than commonly invoked for cuspy halos.

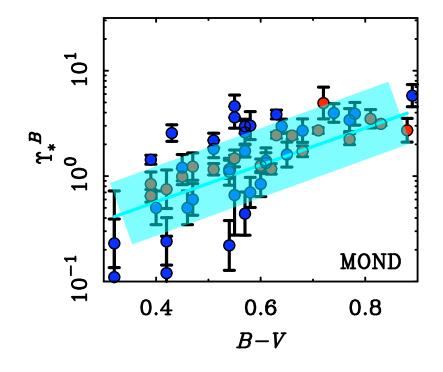


The success of detailed rotation curve fits is highly non-trivial. Once the form of the force law is specified, the dynamics must follow from the observed baryon distribution.

This procedure is much, much, much more strongly constrained than fits with an invisible dark matter component, which can be arranged however needed. Such fits have a minimum of three free parameters, resulting in enormous freedom and numerous degeneracies.

MOND predictions

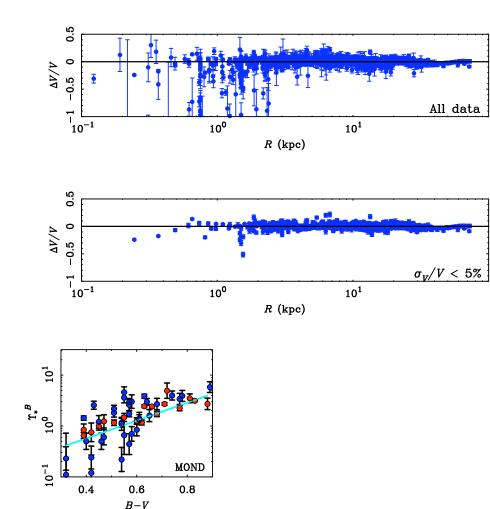
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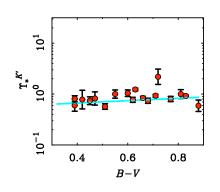


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The single free parameter of a MOND fit is the stellar mass-to-light ratio. This is subject to an independent check against the expectations of stellar population synthesis models.

These compare favorably (lines from Bell et al. 2003). MOND fit mass-to-light ratios reproduce not only the mean expected value, but also the trend expected with color and the smaller scatter expected in redder bands.

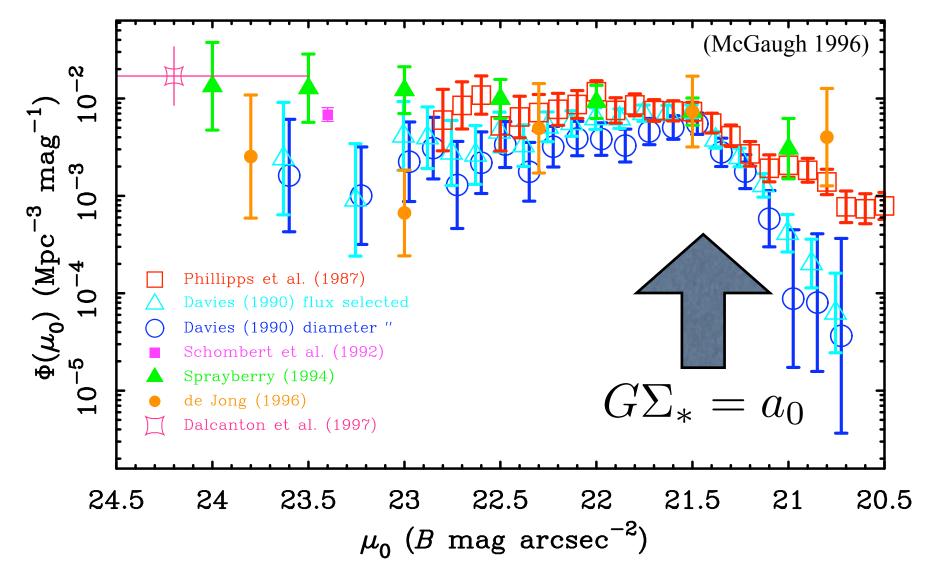




MOND predictions

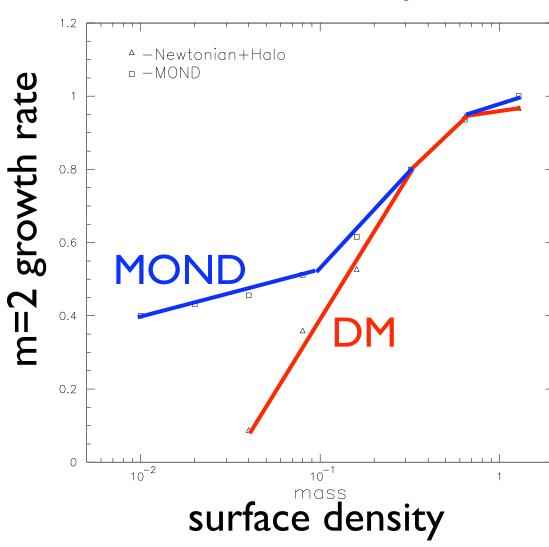
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What are we suppose to conclude from this? That MOND is wrong?



For example, the disk stability limit (Milgrom 1989). This provides a natural explanation for the maximum in the surface brightness distribution (e.g., Freeman's Limit). Disks below the critical surface density are stabilized by MOND; those above are in the Newtonian regime and subject to the usual instabilities. This scale has to be inserted by hand into dark matter models (e.g., Dalcanton et al. 1997). The same scale has been found in SDSS dividing disks and ellipticals (e.g., Kauffmann et al. 2004).

disk stability



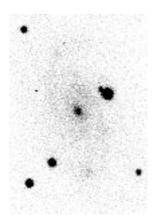
The stability properties of high surface density disks are indistinguishable in dark matter and MOND. However, the two diverge as one goes to low surface density galaxies deep in the MOND regime. The large SCQ dark-to-luminous mass ratios in these systems tend to over-stabilize the disks 0 $\stackrel{\circ}{\leq}$ (see also Mihos et al. 1997). Familiar features like bars \bigcirc and spiral arms are readily

and spiral arms are readily understood as disk dynamical features, provided the disk selfgravity is important. The presence of such features in LSB galaxies provides another clue...

Figure 11: The growth rate, in units of the dynamical time, for the m=2 mode as a function of the total mass of the disk. \square MOND, \triangle Newtonian + Halo.

Figure from Brada's Ph.D. thesis (1996). See also Brada & Milgrom (1998).

ſ	m	Q	time step	Growth rate		halo mass
			scaling	MOND	Newt+DM	at R=1



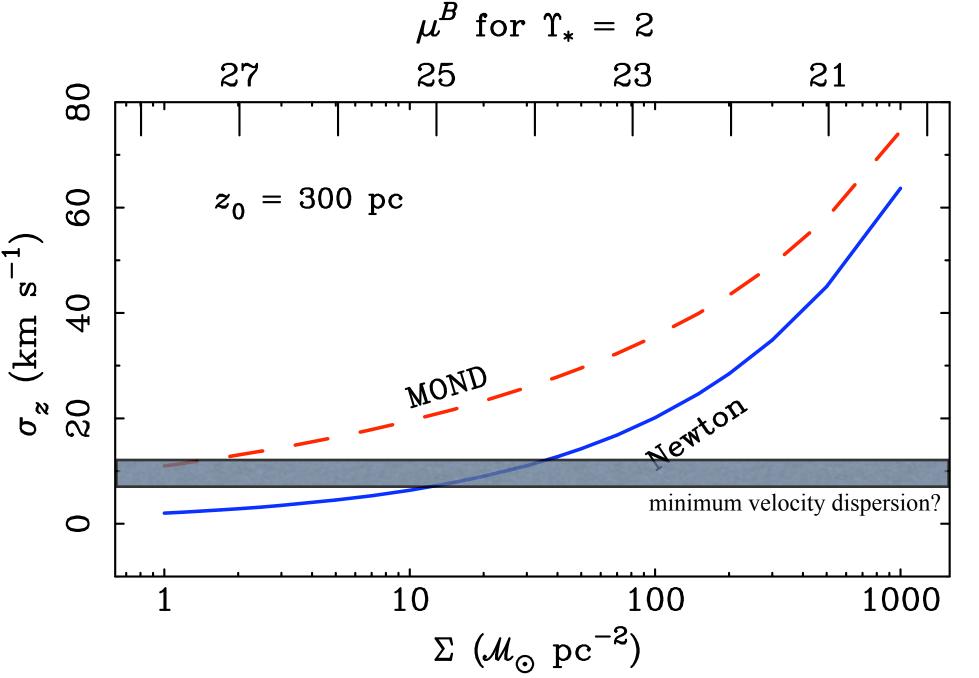
LSB galaxies got spiral arms!

McGaugh & de Blok (1998) predicted that, if conventional density wave analysis were applied to constrain the massto-light ratios of LSB disks, one would infer very high mass-to-light ratios. This follows from the need for disk self gravity to drive spiral features. Subsequent analyses (e.g., Fuchs 2002) found exactly this.

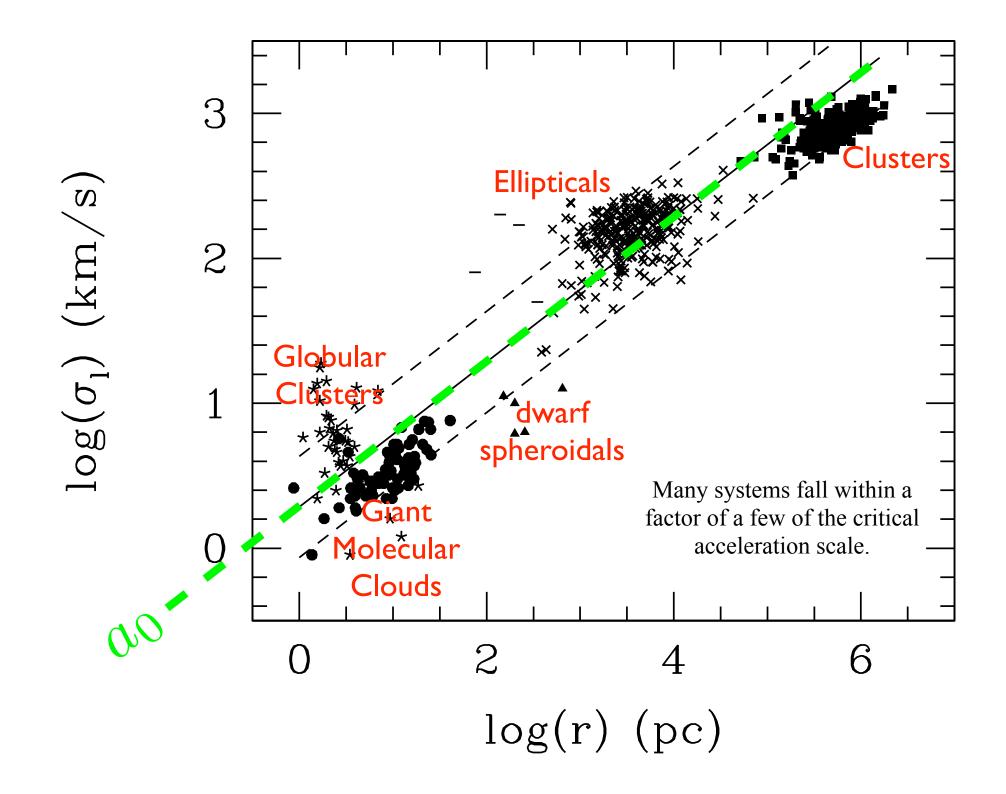
Disk Masses from Density Waves

Galaxy	(M/L) _*		
F568-1	14		
F568-3	7		S.*
F568-6	П		
F568-VI	16		S
UGC 128	4		Big (M/L)*'s
UGC 1230	6		B
UGC 6614	8		
ESO 14-40	4	not LSBs I am familiar	
ESO 206-140	4		
ESO 302-120	1.7		with
ESO 425-180	2.4		

from B. Fuchs, astro-ph/0209157



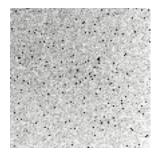
For a disk of a given thickness, MOND can support a higher vertical velocity dispersion than a Newtonian disk plus quasi-spherical dark matter halo. This difference is small at high surface brightness, but becomes pronounced as one goes to low surface densities. MOND provides a natural explanation for the minimum \sim 7 km/s velocity dispersion frequently measured and for very thin LSB disks seen edge-on.



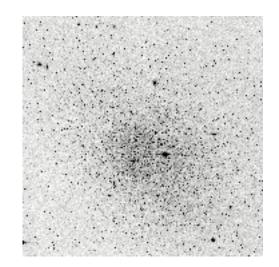
dwarf spheroidal satellites of the Milky Way



Carina

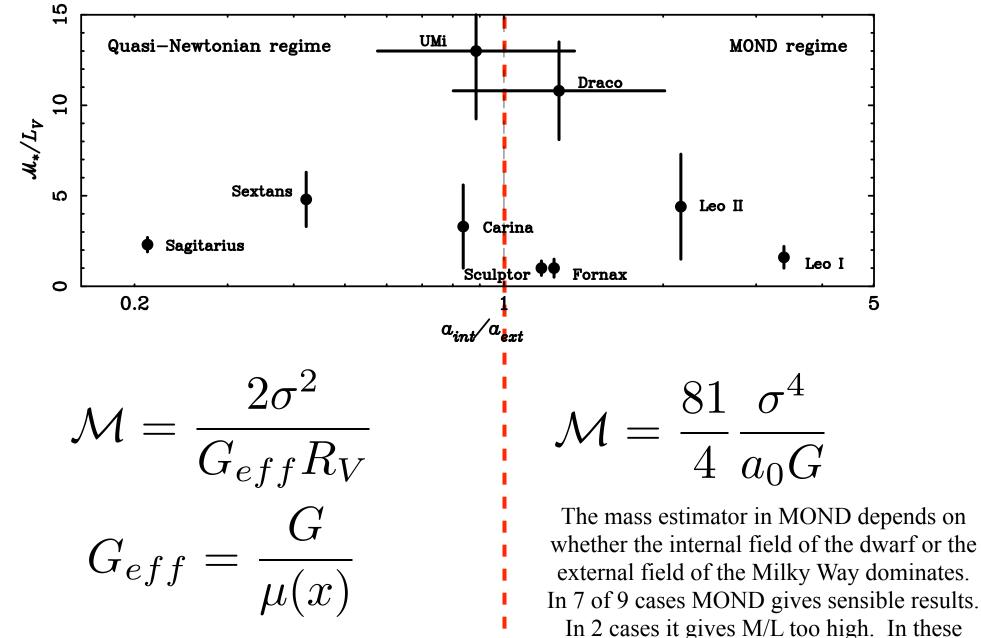


Draco

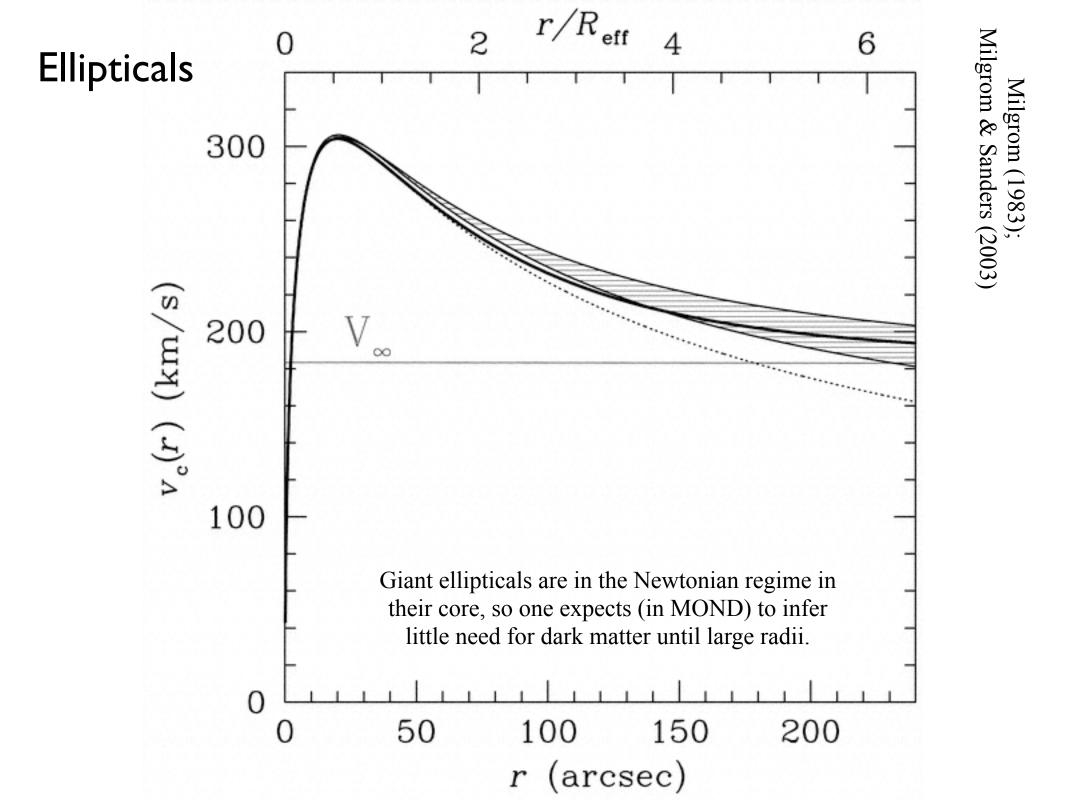


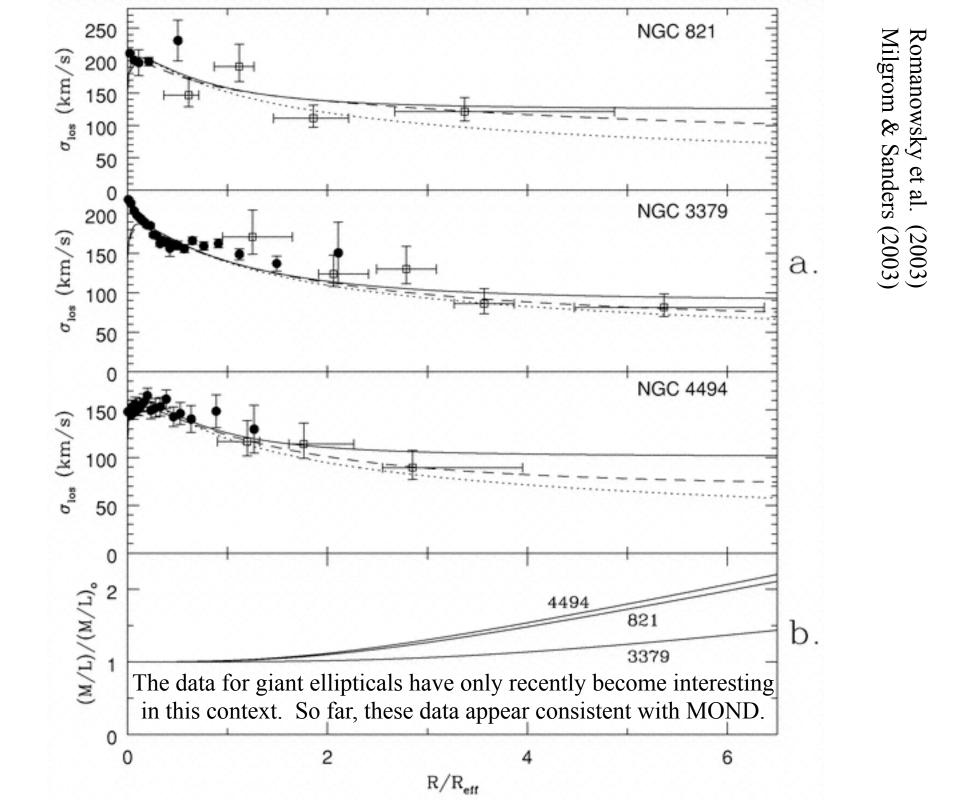
Fornax

The dwarf spheroidal satellites of the Milky Way are among the lowest acceleration systems known. As you can see, some of these systems are so low surface density that they are hardly even there!

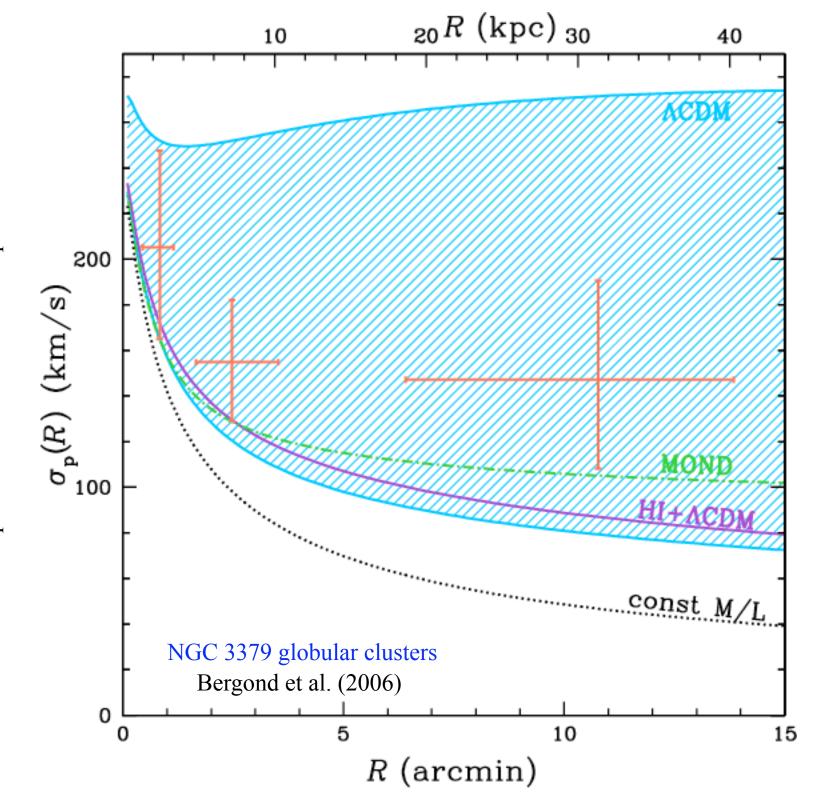


cases, it is not clear (at 1 sigma) which estimator should be employed. One can spin the interpretation either way here... which is the forest and which are the trees?

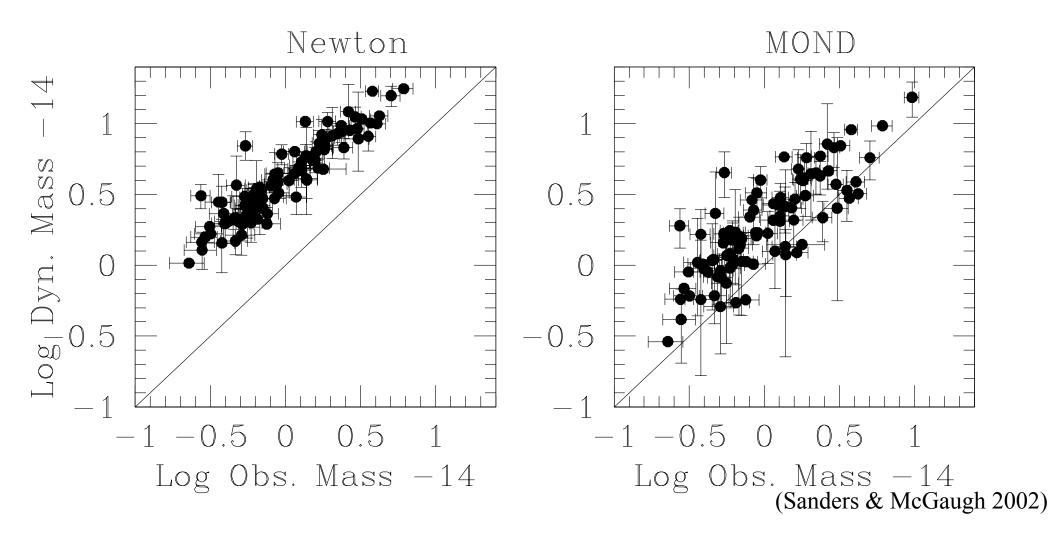




More generally, one wonders why one continues to see the mass discrepancy appear at a particular acceleration scale when ACDM predicts such a vast swath of possibilities.

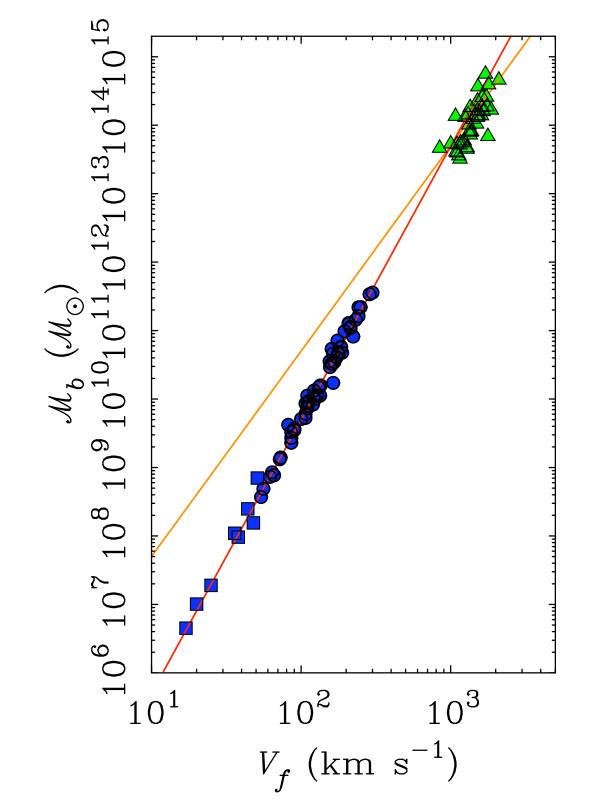


Clusters of Galaxies

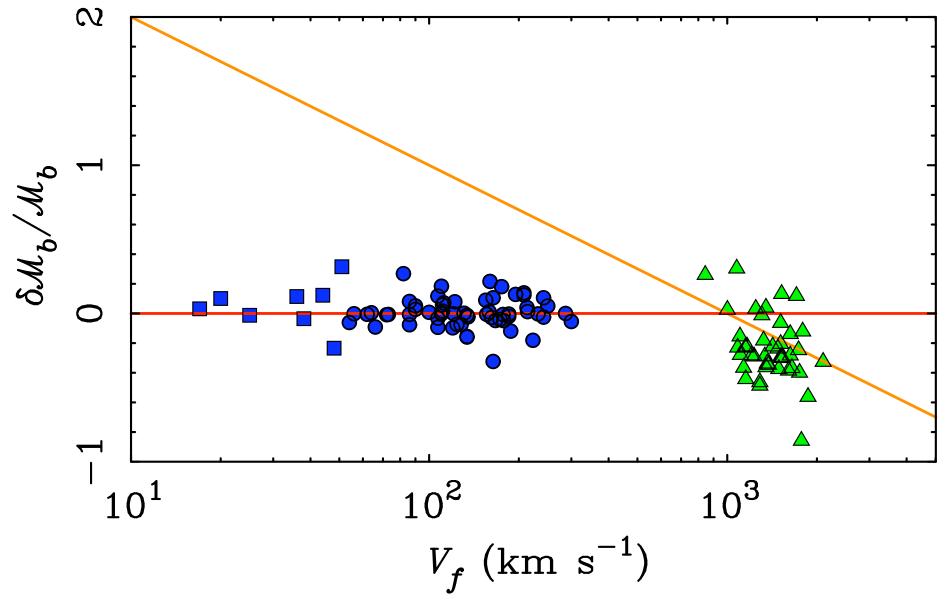


On the scale of individual galaxies, MOND clearly performs better than CDM. The opposite is true in rich clusters of galaxies, where MOND does not suffice to explain the entire mass discrepancy - one needs more mass (neutrinos?).

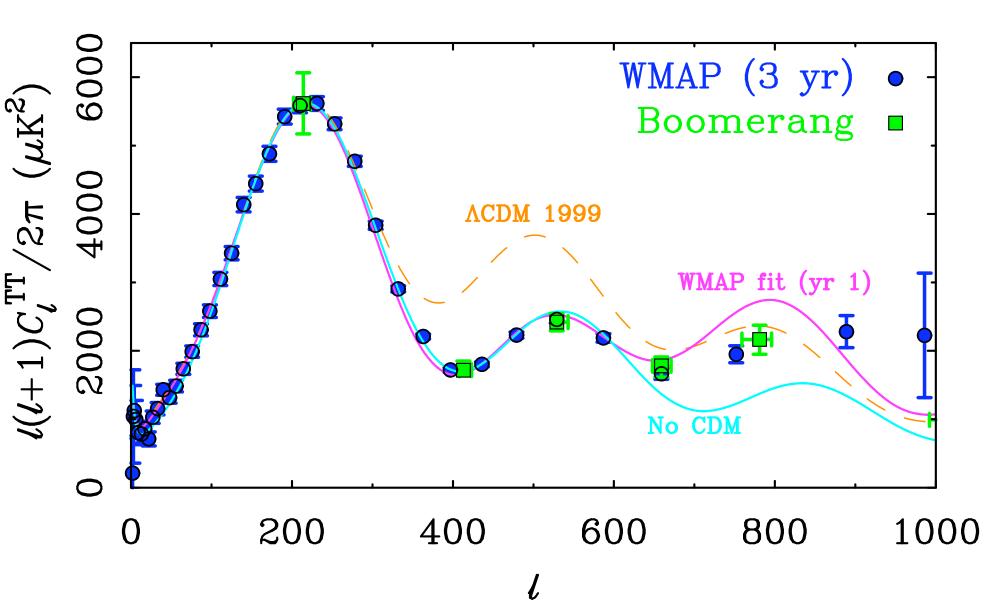




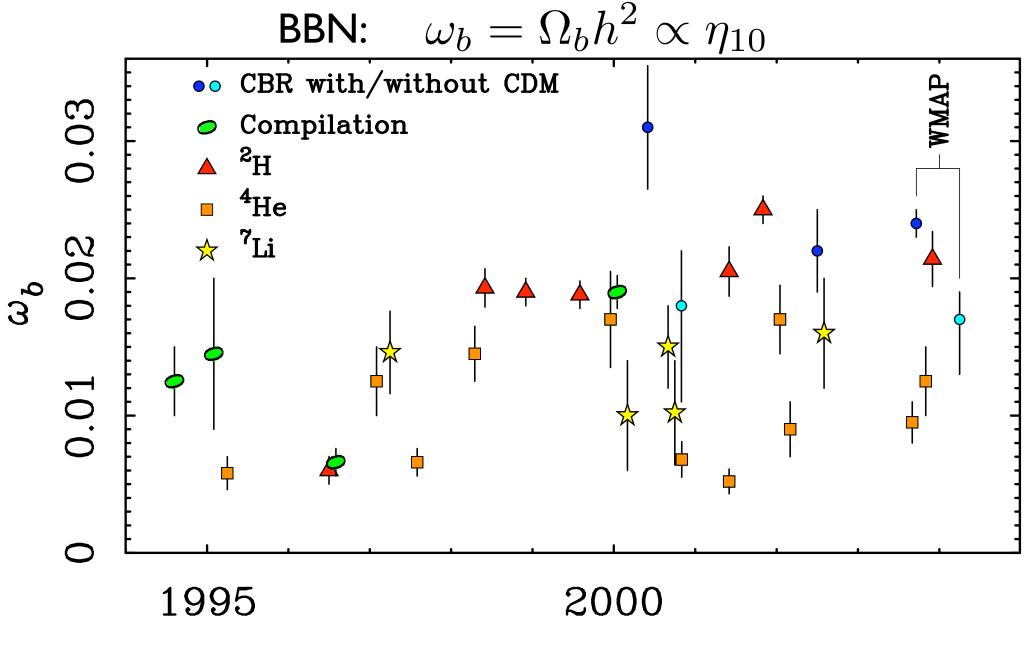
Sanders (2003) Reiprich (2001)



This is the same as the preceding plot but with a slope of 4 taken out. The difference between the red line and the green triangles is the residual mass discrepancy for clusters in MOND. The orange (Λ CDM) line is more consistent with these data. It does rather worse for galaxies. More generally, ~1000 km/s seems to be a break point in the phenomenology. Above this scale, the universe looks like Λ CDM. Below this scale, it looks like MOND.

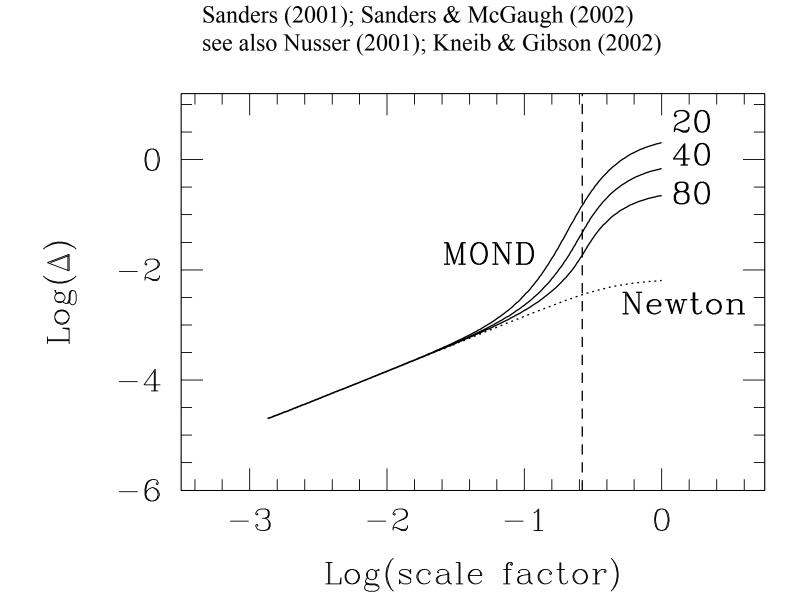


The 3rd year WMAP data compared to various predictions: pre-Boomerang ACDM, the fit to the first year WMAP data sans tilt, and no-CDM (McGaugh 1999; 2004). WMAP3 clearly shows power in excess of the low third peak predicted by no-CDM. I thought this would prove fatal to modified gravity theories, but at this conference Skordis & Ferreira showed that I was wrong to think so.



date

Measurements of BBN abundances (compiled by McGaugh 2004). The WMAP data without CDM favor a lower baryon density which is more consistent with the bulk of independent data than is the fit with CDM.



A common misconception is that non-baryonic cold dark matter is required to grow structure. This is only true in the context of GR. If we consider more general theories, the growth rate can be more rapid, potentially achieving the effect usually attributed to dark matter.

Other MOND tests

- Disk Stability
 - Freeman limit in surface brightness distribution
 - thin disks
 - velocity dispersions
 - LSB disks not over-stabilized
- Dwarf Spheroidals ?
- Giant Ellipticals
- X• Clusters of Galaxies
- **?•** Structure Formation
 - Microwave background
 - 1st:2nd peak amplitude; BBN
 - early reionization
 - enhanced ISW effect
 - 3rd peak ? see Skorids et al. 2005

MOND does well in a variety of tests, not just those with rotation curves. It certainly has problems (e.g., rich clusters; how do galaxies merge?) but it is not obvious that they are worse than those faced by Λ CDM (e.g., not just one but two invisible components; heinous fine-tuning problems to reproduce rotation curve phenomenology). What we need are rigorous predictions that subject theories to falsification. I am most suspicious of theories that claim to fit everything all the time. We should take especial care not to be too credulous of claims that happen to support our most favored theory.