MOND versus Dark Matter Update

GLAST for Lunch

SLAC March 16, 2006

(Version 2: 3/23/2006 Errors fixed + Neutrino Additions)

Gary Godfrey
godfrey@slac.stanford.edu

Introduction

1) Many spectacular regularities are seen from 10^6 to 10^{14} solar mass systems.

Tully-Fisher	Faber-Jackson
Rot curves of spirals	Bulge-BH Mass Correl

2) Are these due to:

(Einstein's Field Eqns)
A modification of Newtonian Gravity ? or Various amounts of Dark Matter ?

3) Newtonian Gravity is not well tested for accelerations below what is seen in our Solar System.

$$a_{Pluto} = (GM_{Sun}/r^2_{Pluto\ Orbit}) = 3.9 \times 10^{-4}\ \mathrm{cm/sec}^2 \gg a_0$$

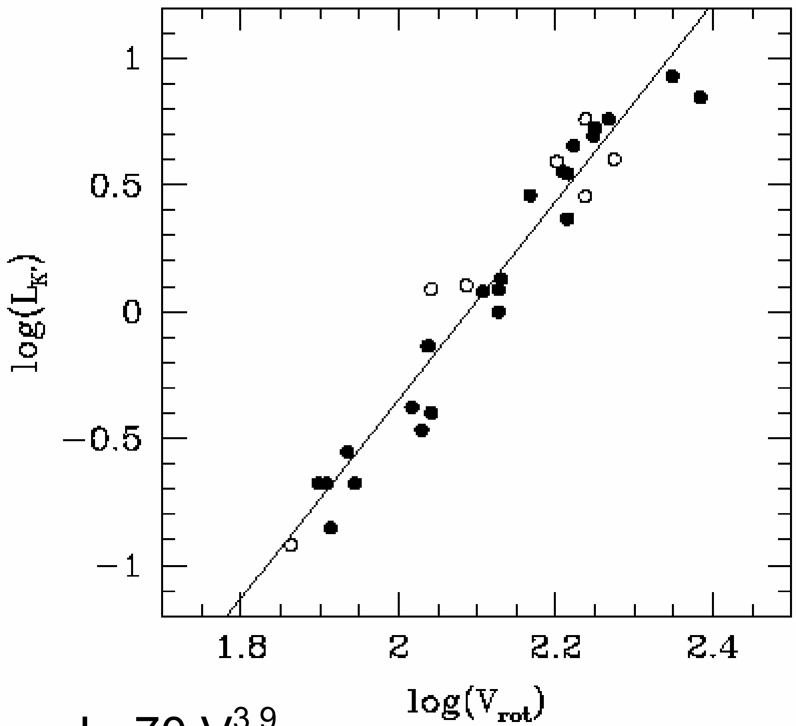
4) The MOND ("Modified Orbital Newtonian Dynamics") prescription:
(Milgrom, 1983 ApJ 270)

$a\,u(a/a_0) = a_{Newton}$ where $u(x)=x$ $x \ll 1$ $a_0 \sim 1.2 \times 10^{-8}\ \mathrm{cm/sec}^2$
$=1$ $x \gg 1$
$u(x)=x / \mathrm{sqrt}(1+x^2)$ is an often used function with these limits

Therefore: $a = \mathrm{sqrt}(a_0 * GM/r^2)$ when $a \ll a_0$

= Geometric Mean (a_0 * Newton)

Tully-Fisher



$L=70\ V^{3.9}_{\text{rot asymptotic}}$

1) All these galaxies are at about the same distance (15.5 Mpc). Thus, $1/r^2$ decrease in flux is the same for all these galaxies.

2) Tully – Fisher

$L \sim V^{4}_{\text{rot asymptotic}}$

MOND

$V^2_{\text{rot asymptotic}}/r = \text{sqrt}(a_0 * GM/r^2)$

$V^4_{\text{rot asymptotic}} = a_0 * GM$

$=(a_0 G)(M/L)\ L$

$\sim(\text{Const})\ L$ = Tully Fisher

Newton

Add Dark Matter to make TF work

Figure 2: The near-infrared Tully-Fisher relation of Ursa Major spirals ((Sanders & Verheijen 1998)). The rotation velocity is the asymptotically constant value. The velocity is in units of kilometers/second and luminosity in $10^{10}\ L_{\odot}$. The unshaded points are galaxies with disturbed kinematics. The line is a least-square fit to the data and has a slope of 3.9 ± 0.2

Sanders & McGaugh; astro-ph/0204521 Apr 2002.

Baryonic Tully-Fisher

Baryonic Tully-Fisher

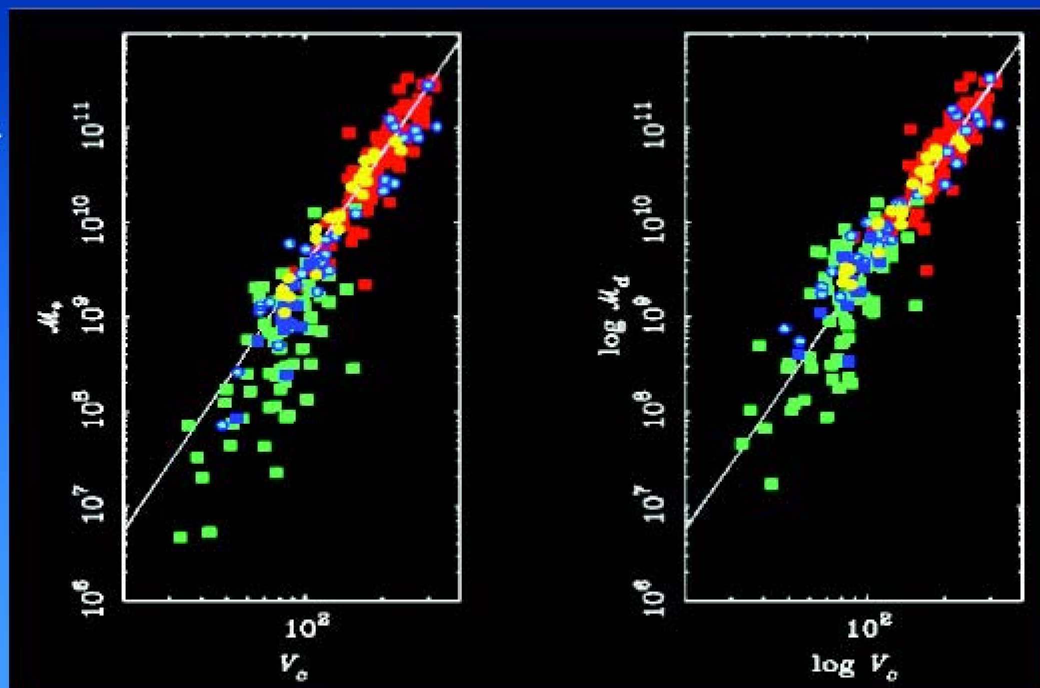
McGaugh et al. 2000
ApJL, 533, 99

$M/L)_{Stars}=1$

Left:
"Luminous mass" vs. rotational Velocity. Galaxies with v<90 km/s fall below the relation.

Right:
Including gas the relation is restored.

The solid line has slope 4

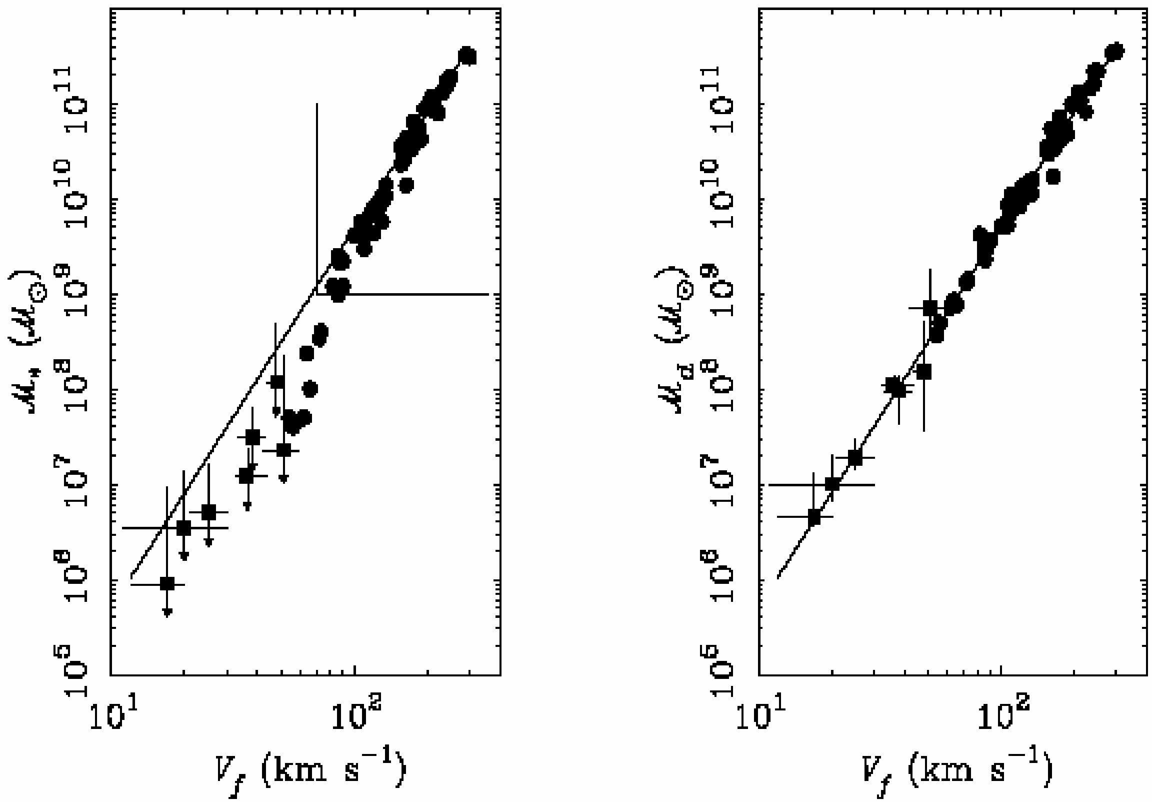


The T-F is a relation between MASS and Velocity, as indeed predicted by MOND

Baryonic Tully-Fisher

(Total Baryonic Mass works better than Lum)

$M = 40\ V_f^4$ [V_f=km/sec]



M/L)$_{Stars}$=
MOND fit to
rot curves

FIG. 6.— The stellar mass (left) and baryonic (right) Tully-Fisher relations, including the data for the extreme dwarf galaxies listed in Table 5. The horizontal lines through these objects are the maximum plausible range for V_f: these are much larger than 1σ error bars. The vertical lines show the full range of possible stellar masses, from zero to maximum disk. The extrapolation of the BTF fit to the more massive galaxies from Table 1 is in good agreement with these extreme dwarfs. The importance of this check is illustrated by the thin lines inset in the left panel. These show the limits of samples that suggest shallower slopes (e.g., Bell & de Jong 2001; Courteau et al. 2003).

McGaugh; astro-ph/0506750 Aug 2005

Faber-Jackson Relation – for Ellipticals

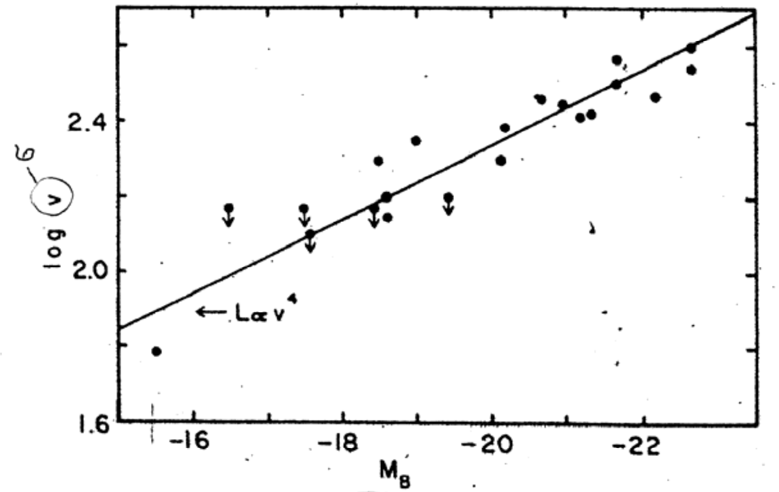


FIG. 16.—Line-of-sight velocity dispersions versus absolute magnitude from Table 1. The point with smallest velocity corresponds to M32, for which the velocity dispersion (60 km s⁻¹) was taken from Richstone and Sargent (1972).

Ref: Faber+Jackson, ApJ 204, 668-683 (1976)

Newton

Add DM to make it work.

MOND

Choose radius to enclose the entire mass of the elliptical

$$v^2 = \sqrt{GMa_0}$$

$$v^4 \propto M$$

$$v^4 \propto L \quad for \quad \frac{M}{L} \sim 1$$

σ ~ v

Critical Mass Surface Density

Consider the Newtonian acceleration "a" at the outer edge of a ball of matter "M" of radius "r". To an observer this ball appears as a disk with surface density "Σ":

$a = G(M/r^2) = G\pi\,(M / \pi r^2)$
$= G\pi\Sigma < a_0$ for MOND behavior

When $a < a_0$ (ie: $\Sigma < a_0/G\pi$), the outer parts of the ball enter the MOND regime.

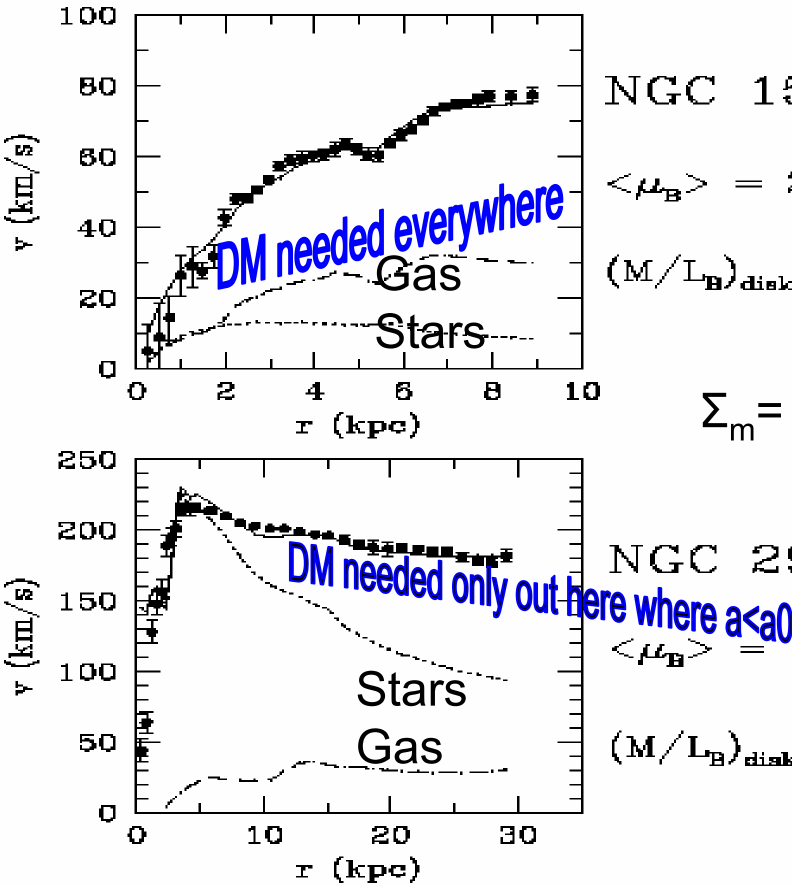
Thus there exits a critical surface density $\Sigma_m \sim a_0/G\pi = 140\ M_{sun}/pc^2$ (=22 mag/arcsec^2 for M/L~2)

If $\Sigma > \Sigma_m$ "HSB" High Surface Brightness
This galaxy is Newtonian. The rot curve peaks and then falls outside the baryonic matter until it enters the $a<a_0$ MOND regime and approaches its asymptote.

$< \Sigma_m$ "LSB" Low Surface Brightness
This galaxy is Mondian everywhere. The rot curve rises to the asymptote. These galaxies are interpreted to have lots of DM

Rotation Curves of Spirals – Two Types

$V^2_{Meas} = V^2_{Stars} + V^2_{Gas} + V^2_{DM}$ if Newton



NGC 1560

$\langle\mu_B\rangle = 23.2$ mag/arcsec²

$(M/L_B)_{disk} = 0.4$

LSB

$\Sigma_m =$ 22 mag/arcsec²

MOND fits the data with one parameter M/L of the visable component

NGC 2903

$\langle\mu_B\rangle = 20.5$ mag/arcsec²

$(M/L_B)_{disk} = 1.9$

HSB

Figure 3: The points show the observed 21 cm line rotation curves of a low surface brightness galaxy, NGC 1650 (Broeils 1992) and a high surface brightness galaxy, NGC 2903 (Begeman 1987). The dotted and dashed lines are the Newtonian rotation curves of the visible and gaseous components of the disk and the solid line is the MOND rotation curve with $a_o = 1.2 \times 10^{-8}$ cm/s² – the value derived from the rotation curves of 10 nearby galaxies (Begeman et al. 1991). The only free parameter is the mass-to-light ratio of the visible component.

Rotation Curves of Spirals

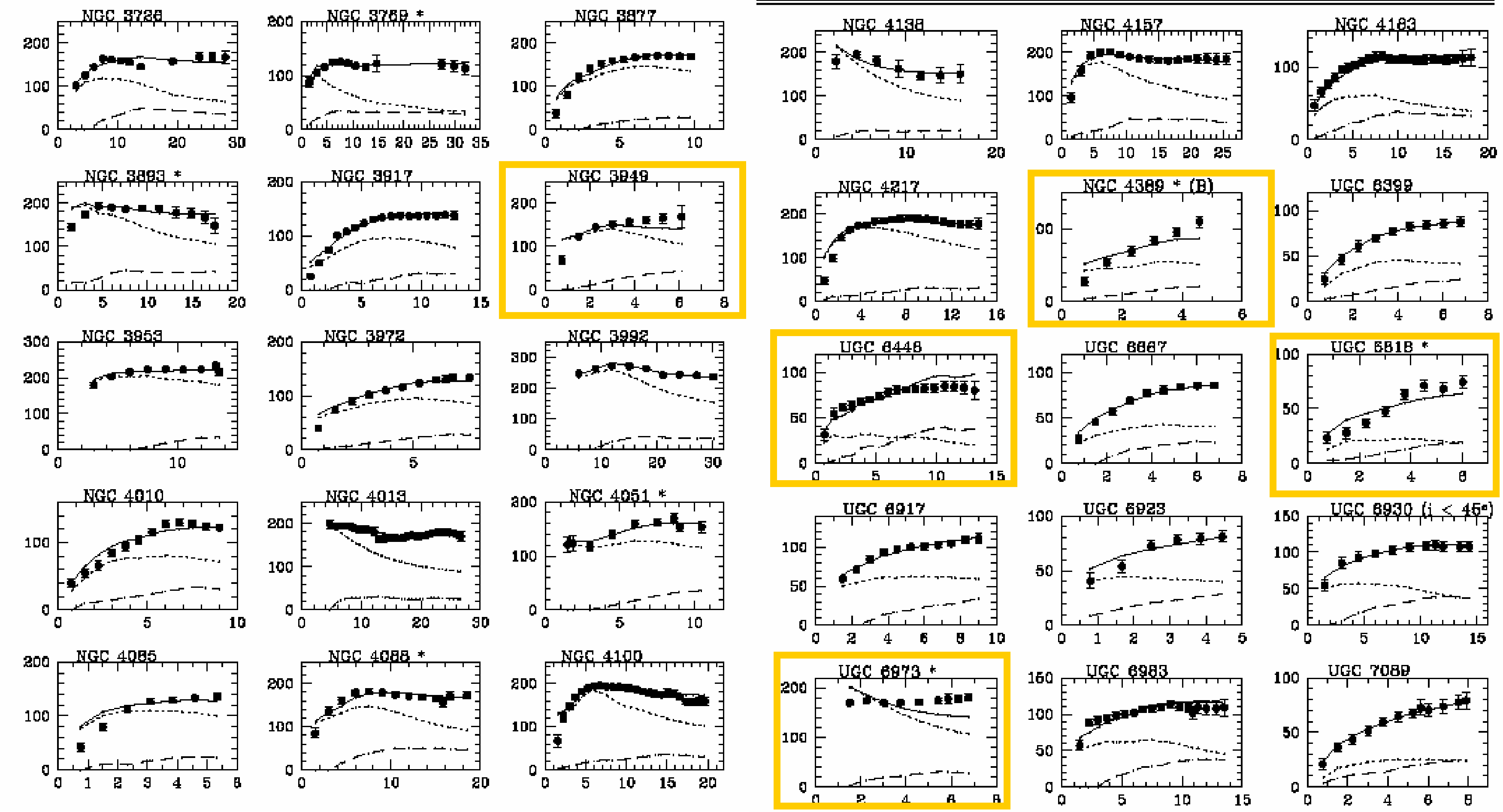
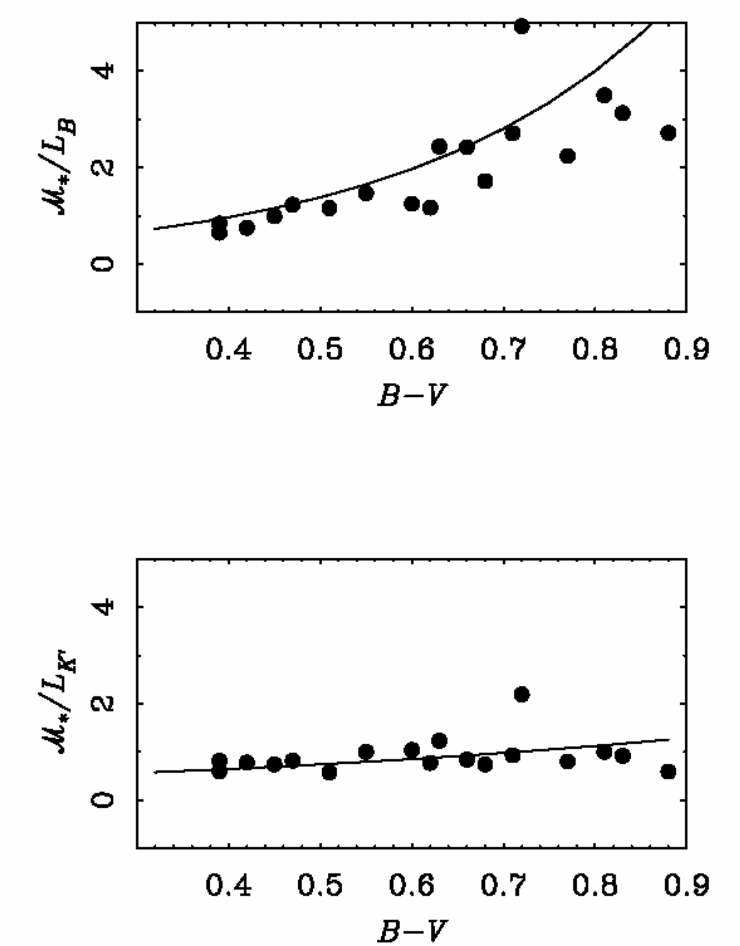


Figure 4: MOND fits to the rotation curves of the Ursa Major galaxies (Sanders & Verheijen1998). The radius (horizontal axis) is given in kiloparsecs and in all cases the rotation velocity is in kilometers/second. The points and curves have the same meaning as in Fig.3. The distance to all galaxies is assumed to be 15.5 Mpc and ao is the Begeman et al.(1991) value of 1.2×10^{-8} cm/s2. The free parameter of the fitted curve is the mass of the stellar disk. If the distance to UMa is taken to be 18.6 Mpc, as suggested by the Cepheid-based re-calibration of the Tully-Fisher relation (Sakai et al. 2000), then ao must be reduced to 10^{-8} cm/s2.

Look at extra slide at end of talk for reasons fits may have failed on these 5 galaxies.

M/L)$_{\text{Stars in K-band}}$~1 for MOND



MOND fit M/L ratios for the UMa spirals (Sanders & Verheijen) in the

B-band (top)
K'-band (bottom)

plotted against B-V (blue minus visual) color index.

The solid lines show predictions from populations synthesis models by Bell and de Jong (2001).

If K band (near infrared) luminosities were used, then an M/L)$_{\text{Stars}}$=1 would fit the rotation curves of all 18 Ursa Major spirals with <u>no</u> free parameters (since a_0=1.2 x 10^{-8} was fixed by other galaxies) !!

Rotation Curves of Spirals

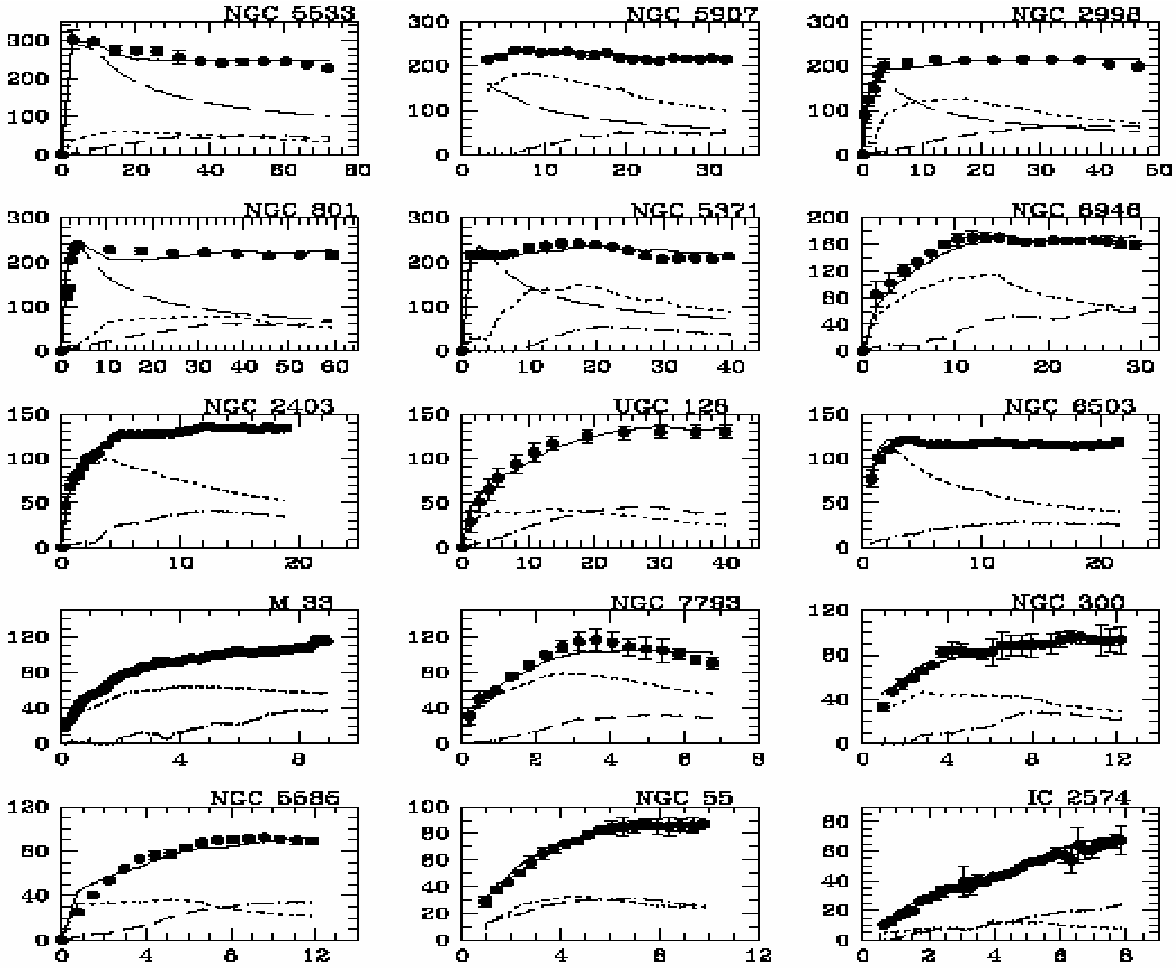


Figure 5: MOND fits to the rotation curves of spiral galaxies with published data, from Sanders (1996) and de Blok & McGaugh (1998). The symbols and curves are as in Fig. 4.

Relation Between Dark and Baryonic Mass

Perhaps MOND is just a lucky ansatz that has managed to fit all spiral rotation curves with just one parameter $M_{Lum}/L \sim 1$ when it is given the Baryonic mass distribution. But the ansatz is still useful because now the Baryonic mass distribution fixes the Dark Matter distribution !! Consider Ursa Major spirals for which M/L =1 for all of them. There is no need to measure $V^2(r)$.

$$\text{MOND} + M_{Baryonic}(r) \longrightarrow V^2(r) \longrightarrow \text{Newton} + M_{DM}(r)$$

$$a(r) = V^2(r)/r = V^2_{Stars}(r)/r + V^2_{Gas}(r)/r + V^2_{DM}(r)/r \qquad \text{Newton}$$

$$= u^{-1}(x)\,[a_{\text{Newton Stars}} + a_{\text{Newton Gas}}] \qquad \text{MOND}$$

$$= u^{-1}(x)\,[V^2_{Stars}(r)/r + V^2_{Gas}(r)/r]$$

Then:

$$V^2_{DM}(r) = [u^{-1}(x)-1]\,[V^2_{Stars}(r) + V^2_{Gas}(r)]$$

where: $a_0 = 1.2 \times 10^{-8}$ cm/sec^2
$x(r) = a(r)/a_0$
$u(x) = x / \text{sqrt}(1+x^2)$

Relation Between Dark and Baryonic Mass

by Lum, 21 cm, xray intensities

So:

1) Use measured $M_{Stars}(r)$ and $M_{Gas}(r)$ with Newton to calc $V^2_{Stars}(r)$ and $V^2_{Gas}(r)$.
2) Use $V^2_{Stars}(r)$, $V^2_{Gas}(r)$, and MOND u(x) to calculate $V^2_{DM}(r)$.
3) Use $V^2_{DM}(r)$ and Newton to calculate $M_{DM}(r)$.

This is a wonderful convenience that $M_{Stars}(r)$ and $M_{Gas}(r)$ imply $M_{DM}(r)$! You don't have to measure the rotation curve to get $M_{DM}(r)$….just use $M_{Stars}(r)$ and $M_{Gas}(r)$.

Now it remains to be theoretically explained :

How does Baryonic and non-interacting Dark Matter remain so tightly coupled that one distribution exactly predicts the other ?

Will a stochastic formation history accomplish this wonder ?

Non-existing Hybrid Spiral Galaxy

MOND fails to fit the rotation curve of this fake galaxy. (Good !!)

DM fits the rotation curve of the fake just fine.

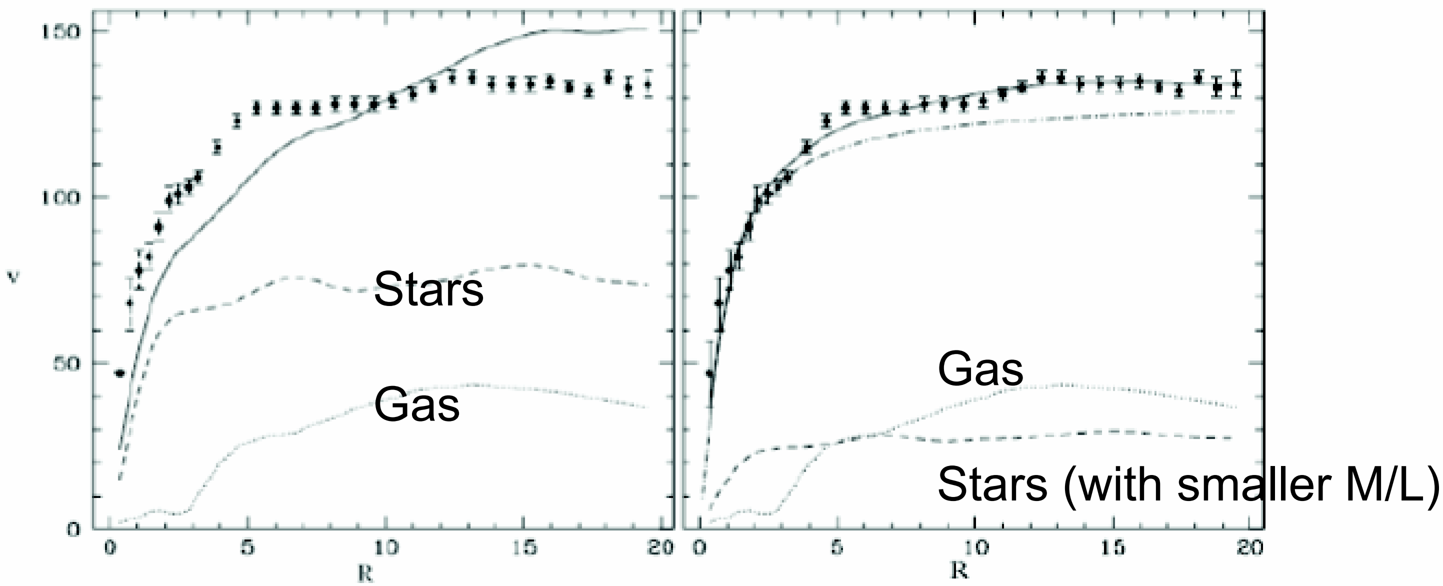


FIGURE 3. Fit of the rotation curves of an hybrid galaxy, obtained using the velocity information for one galaxy (NGC2403) and the photometry – used to compute masses – from another (UGC 128) (data from [15]). MOND (left panel) fails to fit this fake galaxy, which is good. On the other hand, a fit of an isothermal dark-matter halo (right panel) allows so much freedom that an acceptable fit can be found, which is bad. The curves relative to the gas component (dotted line) and stellar disk (dashed line) are also shown. Velocities in km/s, and radius in kpc.

Scarpa; http://xxx.lanl.gov/pdf/astro-ph/0601478

Globular Clusters of Stars

Shows flattening of rotation curves with a_0=1.4 – 2.1 x 10^{-8} cm/sec^2 (with errors ~consistent with 1.2). Are there DM halos around Globular clusters too?

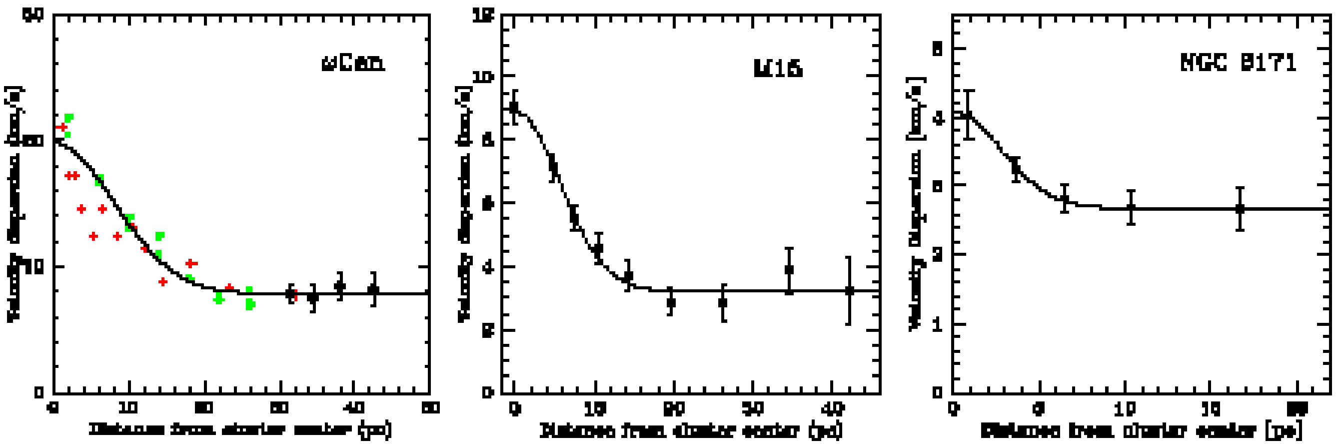


Figure 1: Left: The velocity dispersion profile of ω Centauri (as presented in [6]) flattens out at R= 27±3 pc, where $a = 2.1 \pm 0.5 \times 10^{-8}$ cm s^{-2}. Center: Dispersion profile for M15 as derived from data by [11]. The flattening occurs at R= 18 ± 3 pc, equivalent to $a = 1.7 \pm 0.6 \times 10^{-8}$ cm s^{-2}. Right: Velocity dispersion profile for NGC 6171 as derived combining our VLT data with data from [10]. The profile remains flat within uncertainties outward of 8 ± 1.5 pc, where $a = 1.4^{+0.7}_{-0.4} \times 10^{-8}$ cm s^{-2}. In all panels, the solid line is a fit obtained using a Gaussian plus a constant, meant to better show the flattening of the profile.

Scarpa, etal, http://arxiv.org/pdf/astro-ph/0601581

Pressure Supported Systems

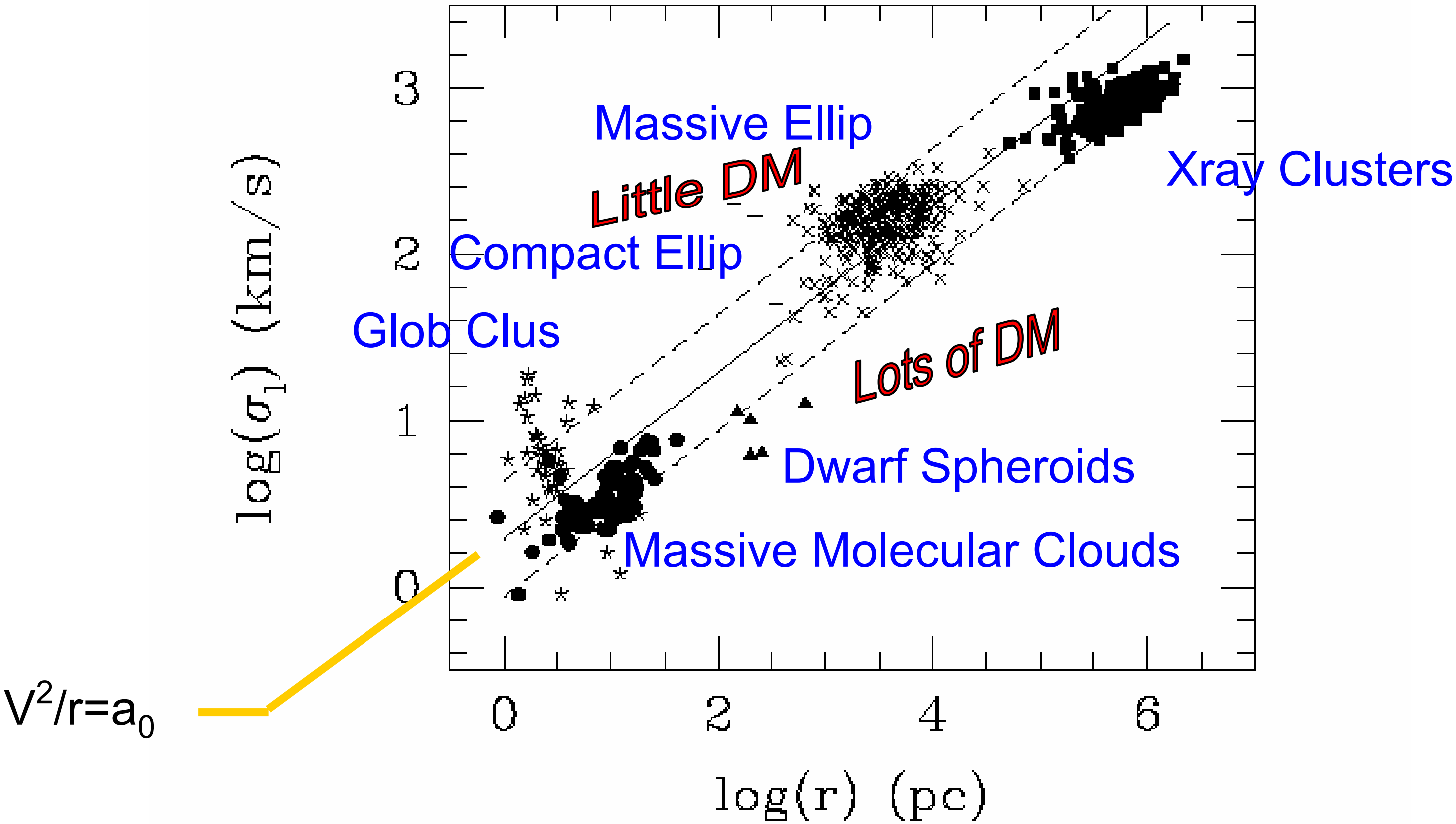


Figure 7: The line-of-sight velocity dispersion vs. characteristic radius for pressure supported astronomical systems. The star-shaped points are globular clusters (Pryor & Meylen 1993, Trager et al. 1993), the points are massive molecular clouds in the Galaxy (Solomon et al. 1987), the triangles are the dwarf spheroidal satellites of the Galaxy (Mateo1998), the dashes are compact elliptical galaxies (Bender et al. 1992), the crosses are massive elliptical galaxies (Jørgensen et al. 1995a,b, Jørgensen 1999), and the squares are X-ray emitting clusters of galaxies (White, et al. 1997). The solid line is shows the relation $\sigma^2/r = a_0$ and the dashed lines a factor of 5 variation about this relation.

Bulge – Central Black Hole Mass Correlation

Using MOND the explanation is simple:

The Bulge always puts ~.004 of its mass into the Black Hole

Baryon Tully Fisher

M_{BH}=.07 σ^4_{Bulge}=.07 (1/40) M_{Bulge}=.002 M_{Bulge}

M/L~2

M_{BH}=.01 L_{Bulge}=.005 M_{Bulge}

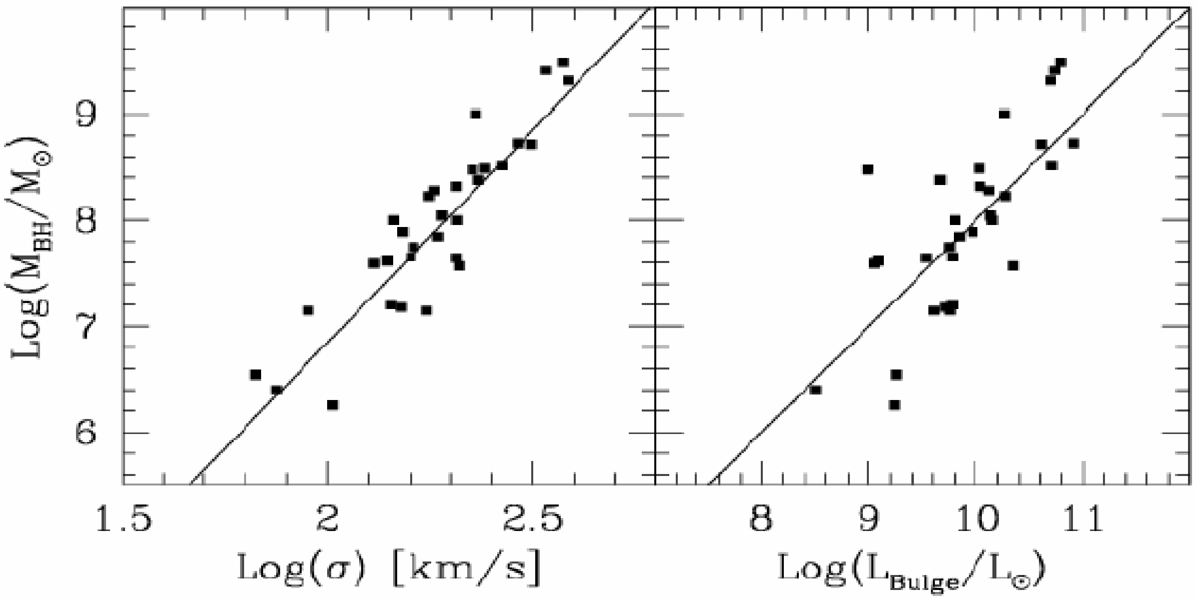


FIGURE 11. **(Left)** The black hole mass – bulge central velocity dispersion relation is well described by the relation $M_{BH}/M_\odot$=0.07σ^4 (solid line, σ in km/s). **(Right)** The bulge luminosity – black hole mass relation is consistent with the linear relation $M_{BH}/M_\odot$=0.01$L_B/L_\odot$. Both relations are well understood in absence of dark matter. Data are from the compilation of [42].

Scarpa, etal, http://arxiv.org/pdf/astro-ph/0601478

Cluster Masses from X-rays

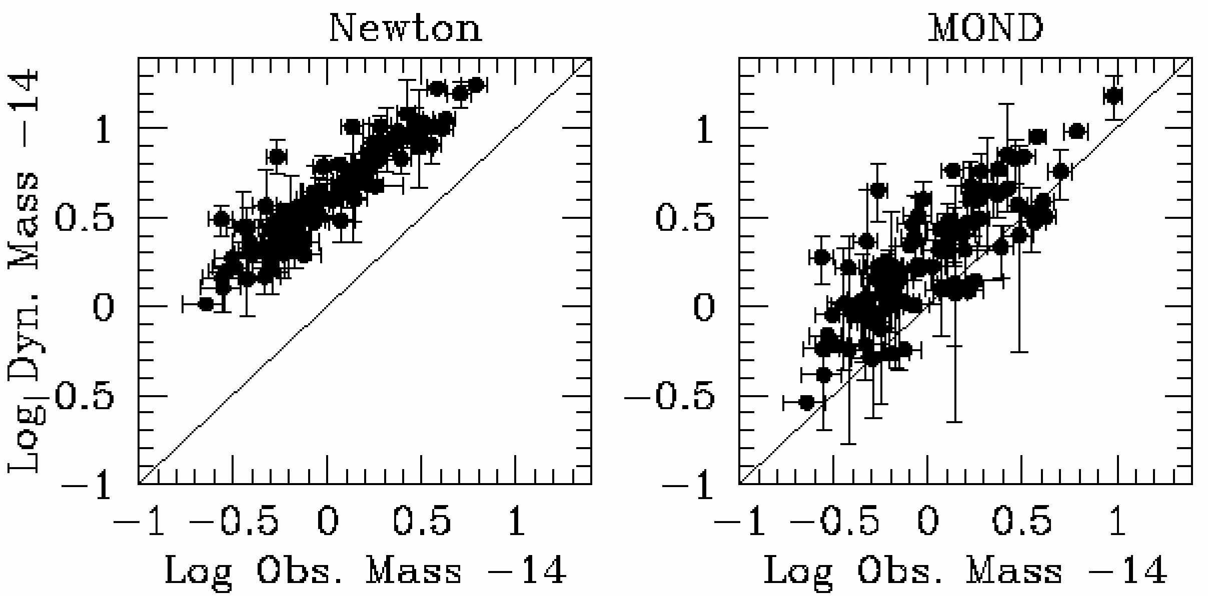


Figure 10: (*Left*) the Newtonian dynamical mass of clusters of galaxies within an observed cutoff radius (r_{out}) vs. the total observable mass in 93 X-ray emitting clusters of galaxies (White et al. 1997). The solid line corresponds to $M_{dyn} = M_{obs}$ (no discrepancy). (*Right*) the MOND dynamical mass within r_{out} vs. the total observable mass for the same X-ray emitting clusters. From Sanders (1999).

MOND says from velocity dispersion M_{Total} ~ 2 x M_{Gas}.
Thus, need ~1 M_{Gas} of DM (2 eV neutrinos?) in clusters of galaxies.

Sanders & McGaugh: http://cul.arxiv.org/pdf/astro-ph/0204521

Cluster Masses from X-rays

Clusters seemed to need DM even before the definitive Bullet Cluster result:

Gas temperature in Galactic Clusters is ~flat with radius. MOND then says all the mass must be at the center of the cluster, which the visible mass clearly is not. Aguirre, etal., astro-ph/0105184

Thus MOND needs some non-baryonic DM in clusters of galaxies.

Neutrino velocity:

$(4/11)^{1/3}$ x (2.7 °K) x (10^{-4} ev/°K) = 1/2 (2 eV) $(v/c)^2$

v = 3900 km/sec

Would the cold Maxwell tail of these neutrinos be captured in the cluster's typical 1000 km/sec escape velocity ?

Neutrino Energy Density – Fermi Level

Since neutrinos are fermi particles, each must occupy a different "particle in a box of side L" energy level. Add up all the (rest mass + kinetic) energies up to the kinetic energy of the maximum bound velocity in the cluster for m_v= 2 eV:

$g := 2 \cdot 2 \cdot 3$ [ ] Number of fermi distributions (2 part/anti x 2 spins x 3 gen)

$m\nu := 2.0$ [eV]

$vmax = 1.00 \cdot 10^{6}$ [m/sec] Max neutrino velocity

$TkinMax := \frac{1}{2} \cdot m\nu \cdot \left(\frac{vmax}{c}\right)^2$

$TkinMax = 1.11 \cdot 10^{-5}$ [eV] Max neutrino kinetic energy

$N\nu := g \cdot \frac{2 \cdot \pi \cdot (2 \cdot m\nu)^{\frac{3}{2}}}{hc^3} \cdot \left(\frac{2}{3} \cdot TkinMax^{\frac{3}{2}}\right)$

$N\nu = 7.85 \cdot 10^{12}$ [# / m^3] Number density of neutrinos

$\rho\nu := g \cdot \frac{2 \cdot \pi \cdot (2 \cdot m\nu)^{\frac{3}{2}}}{hc^3} \cdot \left(m\nu \cdot \frac{2}{3} \cdot TkinMax^{\frac{3}{2}} + \frac{2}{5} \cdot TkinMax^{\frac{5}{2}}\right)$

$\rho\nu = 1.57 \cdot 10^{13}$ [eV/m^3] Neutrino energy density

Neutrinos (if 2 ev mass) ~equal the average cluster baryonic mass density !

$\rho Baryons := \frac{10^{13} \cdot Msun}{\left(10^{6} \cdot \pi \cdot 10^{7} \cdot c\right)^3}$

$\rho Baryons = 1.34 \cdot 10^{13}$ [eV/m^3] Baryonic energy dens of Clus

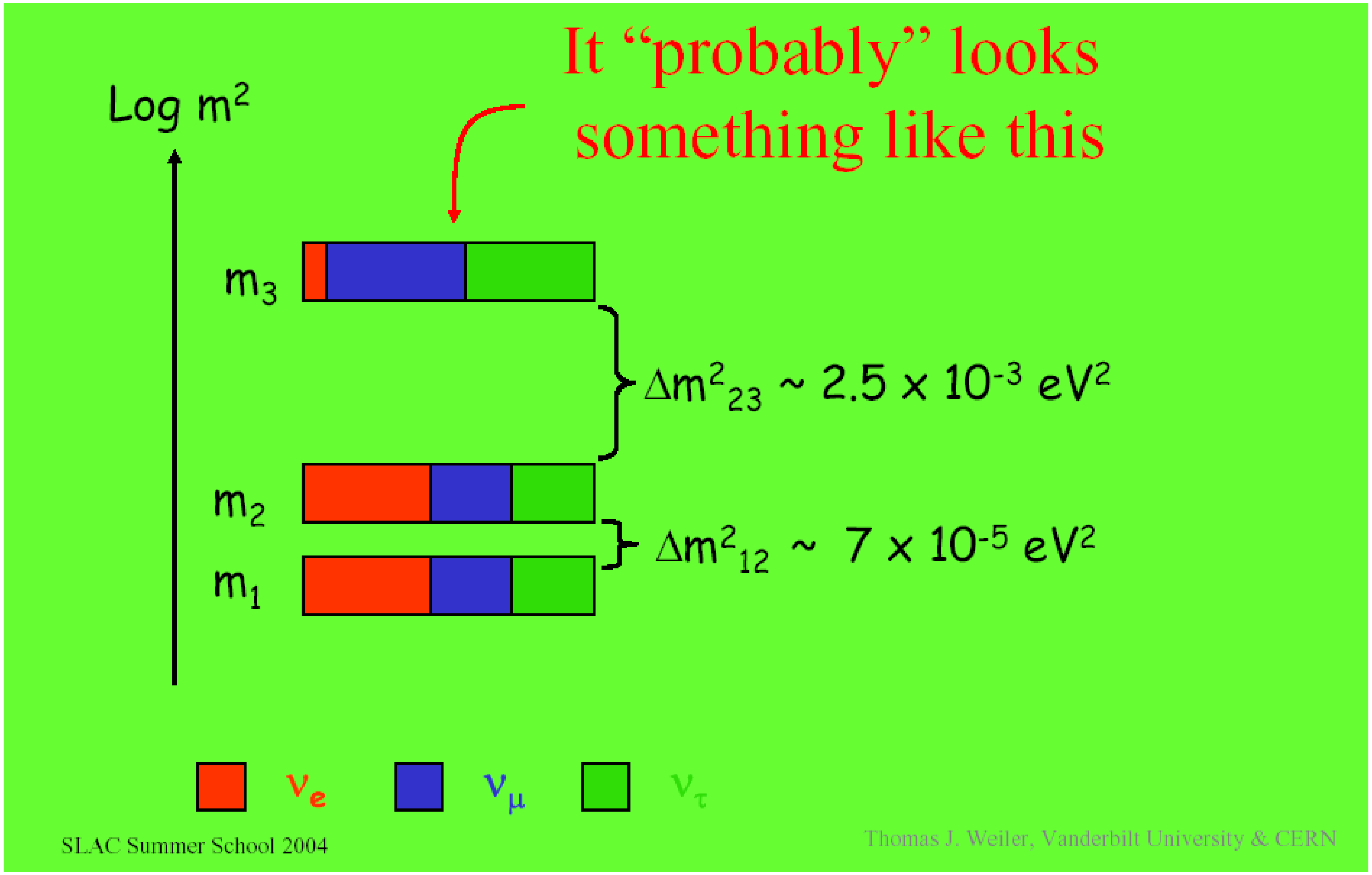
Neutrinos are a negligible fraction a galaxy's average baryonic mass density !

$\rho Galaxy := \frac{10^{11} \cdot Msun}{\left(10^{4} \cdot \pi \cdot 10^{7} \cdot c\right)^3}$

$\rho Galaxy = 1.34 \cdot 10^{17}$ [eV/m^3] Baryonic energy dens of Gal

($\rho_{critical} = 5 \times 10^{9}$ eV/m^3)

Neutrino Oscillation Mass Difference Limits



If one generation is 2 eV, all generations are ~2 eV.

Neutrino Mass Limits

$M_{\nu e} <$ 2.2 eV — Tritium decay endpoint measurements (But much better will come from KATRIN ~2007). A much lower mass limit would rule out neutrinos being a significant DM mass in galactic clusters.

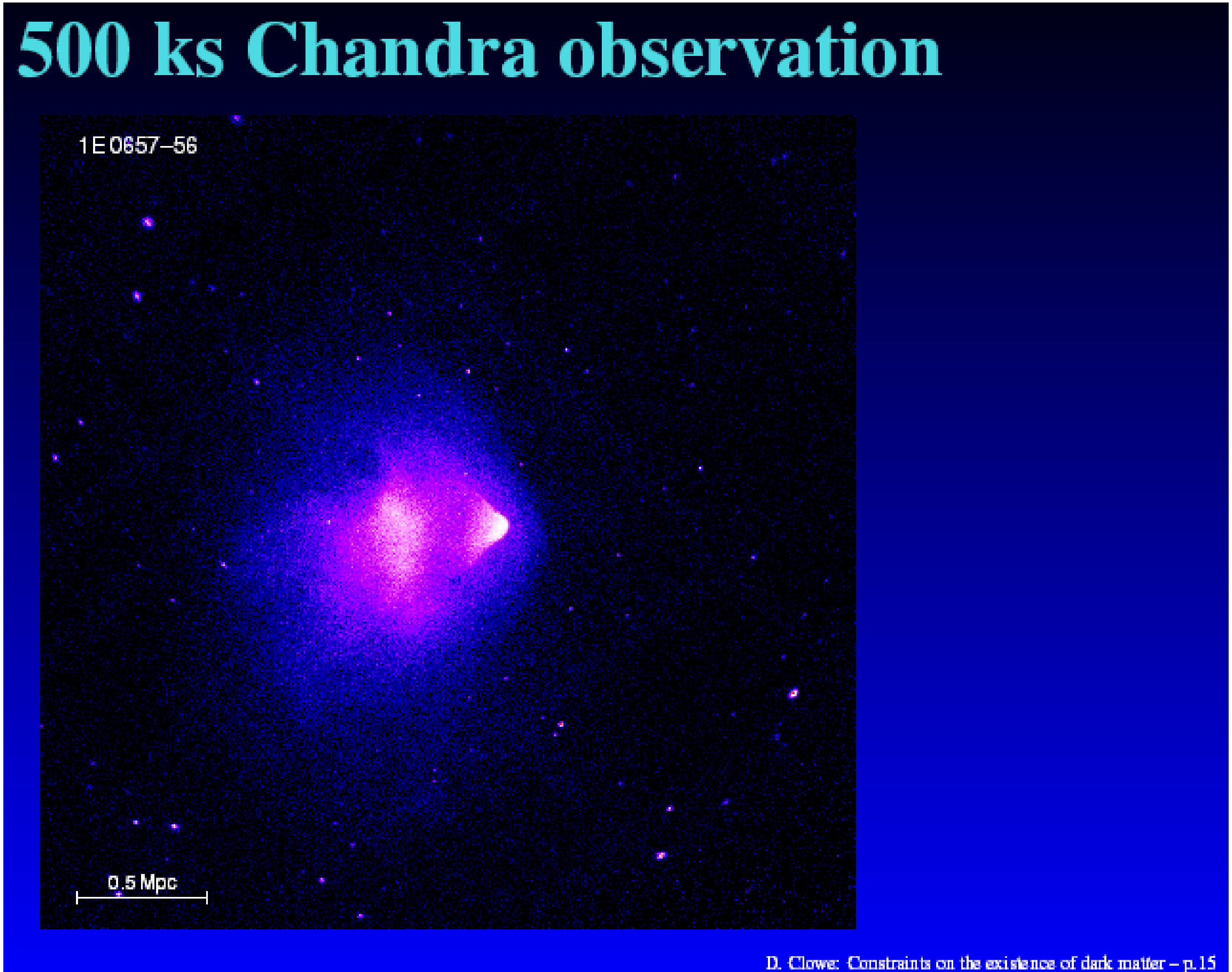
$M_{\nu\mu} <$ 170 KeV — $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$M_{\nu\tau} <$ 18 MeV — $\tau^- \rightarrow 2\pi^- + \pi^+ + \nu_\tau$

$(M_{\nu e} + M_{\nu\mu} + M_{\nu\tau}) < .68$ eV — WMAP (March 2006 results for 3 years of data), but uses Einstein's Field Eqn. for structure formation (ie: Newton, which is not the MOND force law).

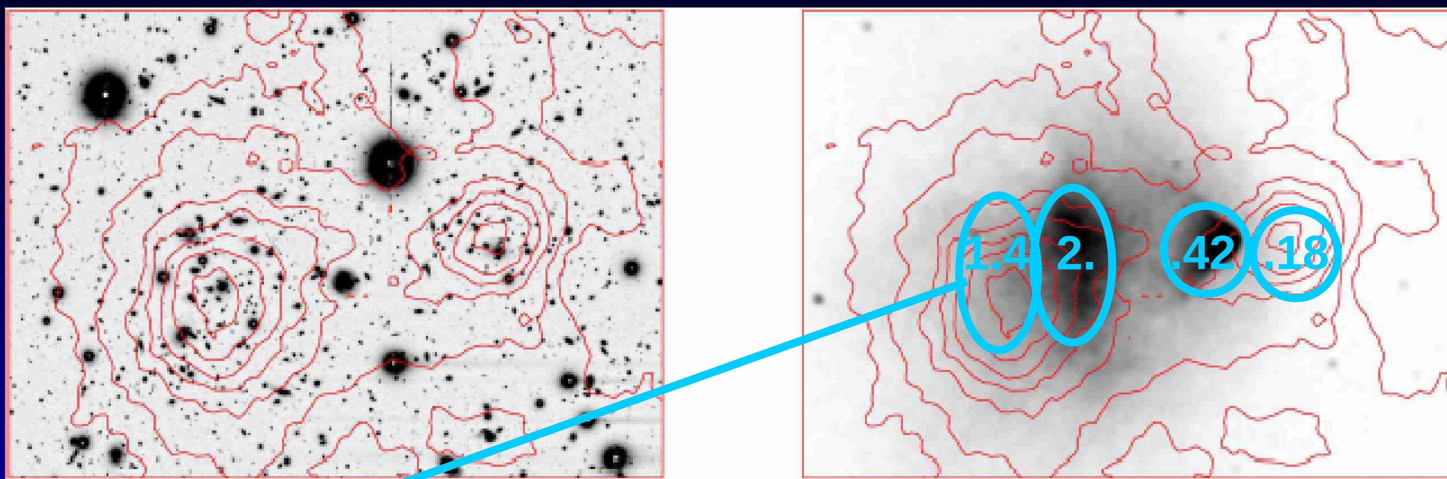
Maybe MOND + the galactic cluster results are the first measurement that the typical neutrino mass is ~2 eV !

1E0657-56 Colliding “Bullet Clusters”



1E0657-56 Colliding “Bullet Clusters”

Weak lensing reconstruction



Very approximate from a private communication

Clowe,etal; Dark Matter 2006 Conference, Marina del Rey

Eagerly waiting for preprint to appear in astro-ph !

D. Clowe: Constraints on the existence of dark matter – p.17

Bekenstein Tensor-Vector-Scaler Theory (TeVeS)

Three dynamical gravitational fields:

  Tensor   (metric)
+ Scaler   (needed for a~1/r at large distances)
+ 4-vector (timelike vector needed for covarience)

Reduces to GR in a limit where a couple of constants go to zero.

Bekenstein: http://cul.arxiv.org/pdf/astro-ph/0403694

Pioneer 10 and 11 Anomaly

arXiv:gr-qc/9808081 v2 1 Oct 1998

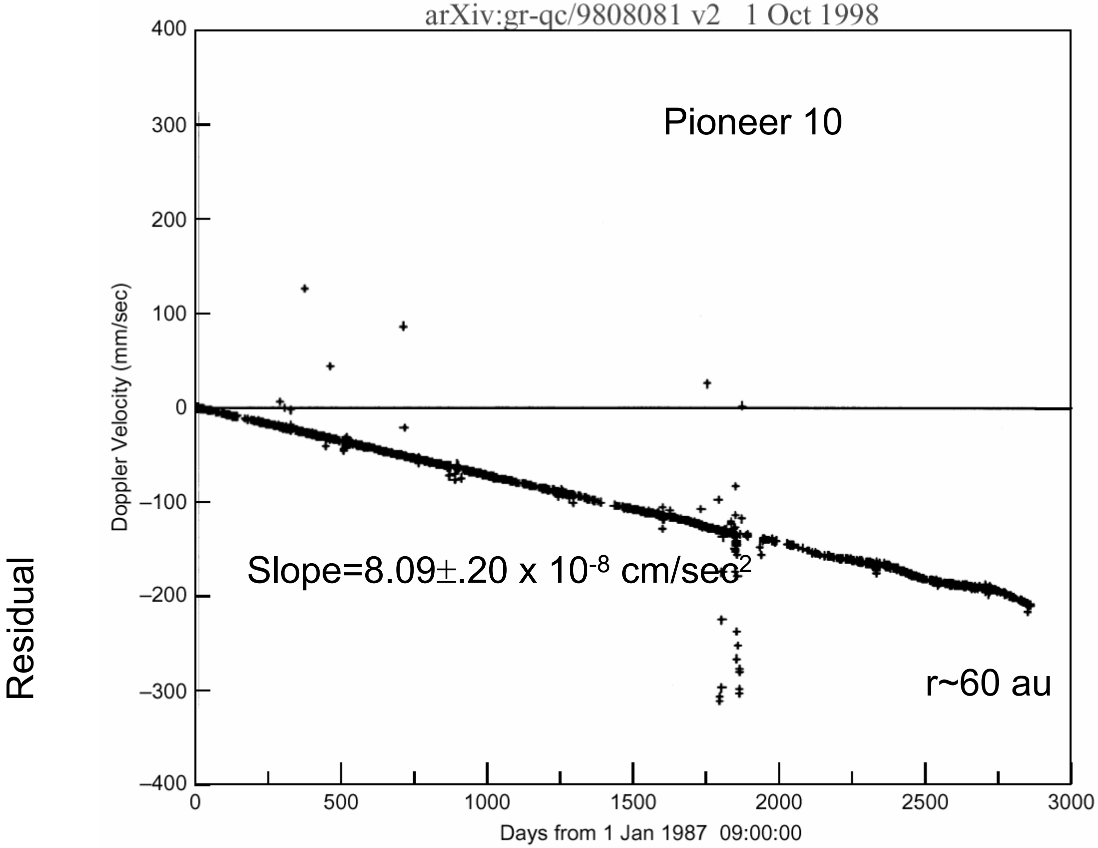


FIG. 1. Two-way Doppler residuals (observed Doppler velocity minus model Doppler velocity) for Pioneer 10 in mm/s vs. time. Solar system gravity is represented by the Sun and the planetary systems [17]. [If one adds one more parameter to the model (a constant radial acceleration) the residuals are distributed about zero Doppler velocity with a systematic variation ~ 3.0 mm s^{-1} on a time scale ~ 3 months.] The outliers on the plot were rejected from the fit.

Non-MOND regime.
Acceleration is ~10^4 a_0 at 60 au.

$$a_{Newton} = \frac{GM_{Sun}}{r^2} = \frac{GM_{Sun}}{c^2}\frac{c^2}{r^2} = 1.5\,km\,\left(\frac{1}{60 \times 500\,\sec}\right)^2 = 1.7 \times 10^{-4}\,cm/\sec^2 >> a_0$$

$a_{Pioneer\ 10}$ = $8.09 \pm .20 \times 10^{-8}$ cm/sec^2

$a_{Pioneer\ 11}$ = $8.56 \pm .15 \times 10^{-8}$ cm/sec^2

$a_{Ulysses}$ = $12 \pm 3 \times 10^{-8}$ cm/sec^2

Toward the Sun

Conclusion

1) It is seems inescapable that the Bullet Cluster measurements show Dark Matter is doing the weak lensing and not baryonic matter. Is the cluster DM ~2 eV neutrinos or new cold DM ?

2) The wide ranging phenomenological success of the simple MOND ansaz is a clue that must be explained by the correct theory (even if it's cold DM+GR).

   a) If DM is non-interacting, then why is $M_{DM}(r)$ exactly predictable from $M_{Stars}(r)+M_{Gas}(r)$ in all spirals?

   b) Pressure supported systems from molecular clouds to clusters of galaxies are characterized by the same internal acceleration a_0.

   c) Tight baryonic $M \sim V^4$ or $L \sim V^4$ for spirals (Tully-Fisher law).

   d) Luminosity-velocity dispersion relation for ellipticals (Faber-Jackson law)

   e) Why is $a_0 = 1.2 \times 10^{-8}$ cm/sec^2 ~ $cH_0 = 7 \times 10^{-8}$ cm/sec^2

Conclusion

3) Presently, there are lots of “Angels” (eg: Dark Matter, Dark Energy, Inflation) in physics to make our old ideas keep working. A historic branch point in physics is occurring:

- There really is cold Dark Matter, possibly already in the fertile zoo of particle theories.

OR

- $R^{uv} - 1/2\, R\, g^{uv} = T^{uv}$ needs modification / replacement and MOND is an experimental clue.

Experiments will decide.

Extra Slides

Ursa Major Problematic Rotation Curves

These are the Ursa Major spirals which MOND did not give good fits to their rotation curves.

NGC 3949: Verheijen (1997) notes that this rotation curve has a considerable side-to-side asymmetry: it rises more steeply on the receding side than on the approaching side, and there is a faint companion 1.5 arc min to the north which may be interacting with this galaxy.

NGC 4389: This system is strongly barred, and the neutral hydrogen is not extended but contiguous with the optical image of the galaxy. Verheijen (1997) points out that the velocity field cannot be interpreted in terms of circular motion and that the overall kinematics is dominated by the bar.

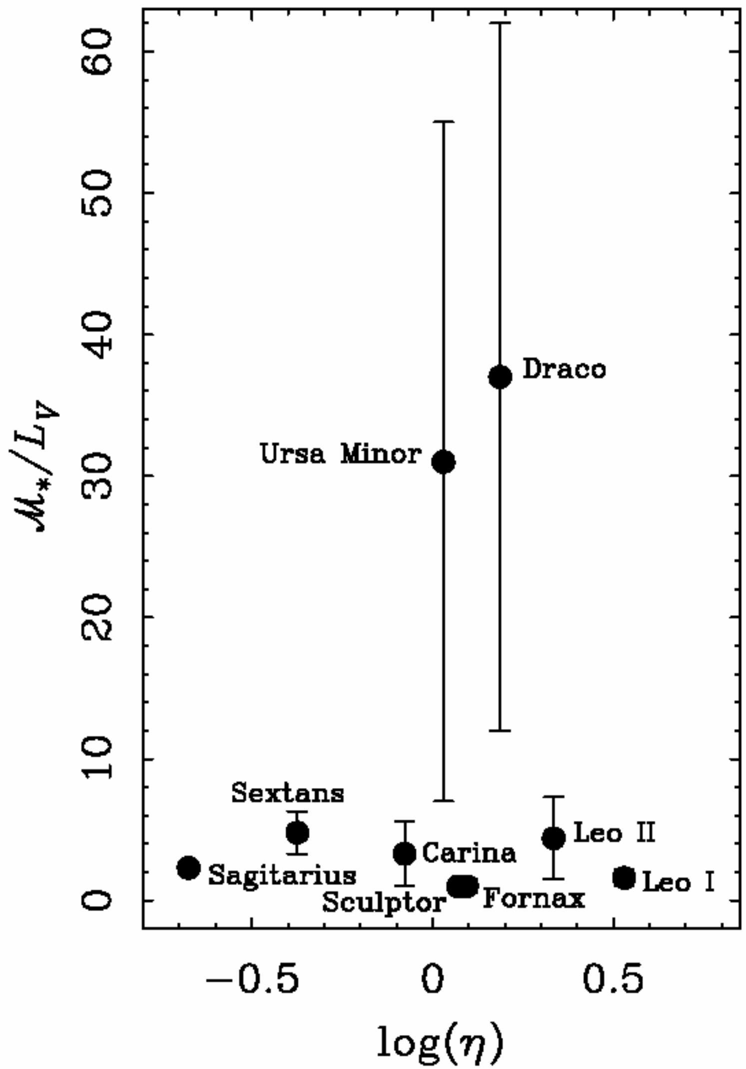
UGC 6446: This low surface-brightness, gas-rich galaxy has an asymmetric rotation curve in the inner regions; on the receding side it rises more steeply than on the approaching side. The MOND fit is much improved if the distance to this galaxy is only 8 or 9 Mpc instead of the adopted 15.5 Mpc. Such a possibility is consistent with the fact that this galaxy has the lowest systemic velocity in the sample: 730 km/s which is 1.5 sigma below the mean of 950 km/s.

UGC 6818: This is a dwarf galaxy which is probably interacting with a faint companion on its western edge (Verheijen 1997)

UGC 6973: Verheijen (1997) notes that this galaxy is interacting with UGC 6962 to the northwest and that the HI disk is warped. Moreover, there is considerable evidence for vigorous star formation in the inner region which is bright red and dusty. In the central regions this is the reddest galaxy in the sample; in terms of central surface brightness $\mu_o^{B} - \mu_o^{K'} = 6.47$ (Tully et al. 1996). This suggests that the K′ band may be contaminated by dust emission and not be a true tracer of the distribution of the old stellar population. The resulting calculated Newtonian rotation curve would be unrealistically declining as a result.

Sanders & Verheijen: arXiv:astro-ph/9802240 v2 27 Mar 1998

MOND M/L for Dwarf Satellites of the Milky Way



The MOND M/L ratio for dwarf spheroidal satellites of the Galaxy as a function of , the ratio of the internal to external acceleration.

This is the parameter that quantifies the influence of the Galactic acceleration field (the external field effect); when η< 1 the object is dominated by the external field.

$$\eta = \frac{3\sigma^2/2r_c}{V_\infty{}^2/R} \approx \frac{g_i}{g_e}$$

where r_c is the core radius, V_∞ is the asymptotic rotation velocity of the Galaxy ~200 km/s) and R is the galactocentric distance of the dwarf.

Sanders & McGaugh: http://cul.arxiv.org/pdf/astro-ph/0204521

Strong Gravitational Lensing

1) Strong Lensing occurs for a surface mass density > $\Sigma_{critical}$

$\Sigma_{critical} = (1/4\pi)\ (cH_0/G)\ F$ where F~10 depends on lens and source redshifts

MOND applies for $\Sigma < a_0/G \sim \Sigma_{critical}/5$

Therefore: Strong Lensing never occurs in the MOND regime.

Weak Gravitational Lensing

Deflection of light at a large impact parameter “r” from a point mass “M” in MOND is independent of the impact parameter !

$$\theta \sim 2 \quad x \quad (r/c) \quad x \quad sqrt(GMa_0/r^2)$$

GR is 2 x Newton. Time accel is applied. MOND acceleration.

Isothermal DM density ~$1/r^2$ also predicts a constant deflection angle at large r.

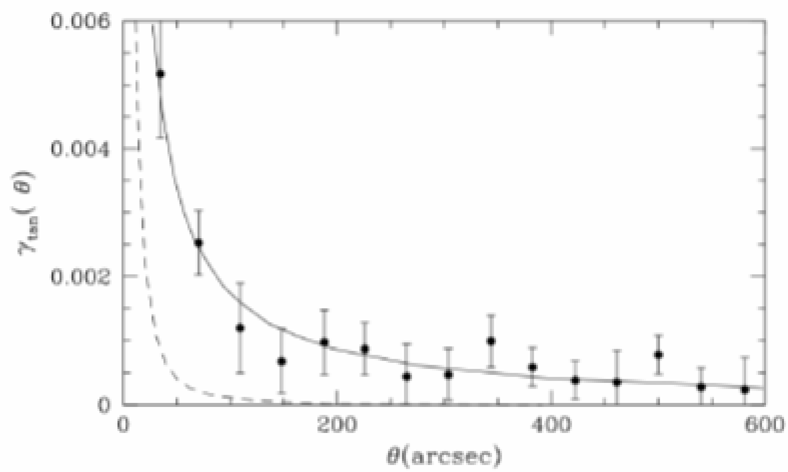


FIGURE 10. The mean cosmic shear γ around foreground galaxies compared to Newtonian and MOND prediction. The original data [37] in the g’, r’, and i’ photometric bands have been averaged, excluding the first and third g’ points that clearly deviated from the values found in the other two bands The models shown are the one presented in [38] and refers to the MOND prediction (solid line), and the Newtonian result if there is no dark matter (dashed line).

Scarpa, etal, http://arxiv.org/pdf/astro-ph/0601581

Can Dark Matter Explain MOND ?

Turner & Kaplinghat have calculated a characteristic acceleration "a_{DM}" at which the acceleration due to DM would begin to dominate over that from Baryonic matter.

Einstein-deSitter model
Scale-free seed density perturbations
Baryonic dissipation (so they become more concentrated in structures than DM)
Numerical coincidence

$a_{DM}=O(1)\ cH_0\ (L/L_0)^{0.2}$ where L=size of region that collapsed (at the time it did)
L_0~10 Mpc= Scale of nonlinearity today from COBE

$a_{DM} \sim a_0$ MOND

Unfortunately, no discussion of how the total acceleration becomes the MOND ansatz = sqrt($a_{Baryons}$*a_{DM}).

Turner & Kaplinghat: http://cul.arxiv.org/pdf/astro-ph/0107284

Tully-Fisher and Newton

Newtonian dynamics and T-F

$$\begin{cases} \dfrac{v^2}{r} = \dfrac{GM}{r^2} \\ L = \pi r^2 \Sigma \end{cases} \quad \begin{cases} v^4 = \dfrac{(GM)^2}{r^2} \\ r^2 = \dfrac{L}{\pi\Sigma} \end{cases} \Rightarrow v^4 \propto \frac{M^2\Sigma}{L^2} L = \tau^2 \Sigma L$$

T-F requires $\tau^2\Sigma = \text{const.}$

- But M/L=τ depends on stellar population, basically the same in all galaxies
- Surface brightness Σ varies significantly going from HSB to LSB galaxies and has nothing to do with M/L.
- Therefore Newton implies a link of two very unrelated quantities and predicts LSB and HSB galaxies to follow different T-F relations.

Scarpa: http://www.sc.eso.org/santiago/science/seminars/Sep2005/Scarpa.pdf