Scale Invariance at Low Accelerations and MOND phenomenology

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MOND – synopsis

- MOND is a modified-dynamics alternative to DM that hinges on accelerations.
- Departure at small accelerations: weak-field dynamics is scale invariant.
- Works very well in predicting many properties of galaxies of all types.
- Leaves some discrepancy in galaxy clusters (isolated, bullet). Needs a small fraction of the still missing baryons.
- Not yet a coherent picture for cosmology.
- Strongly connected with cosmology in different ways.
- Several full-fledged theories (relativistic and their NR limits), but I think we do not have the final one (maybe not even close).

MOND from DM? No!!

- In the DM picture, the baryon/DM in galaxies ($\sim 0.01 - 0.02$) is much smaller than the cosmic value (~ 0.2): e.g., integrated DM of DM fits to RCs, baryonic TFR, direct evidence from weak lensing. So MOST of the baryons in galaxies were lost somewhere on the way ("feedback").

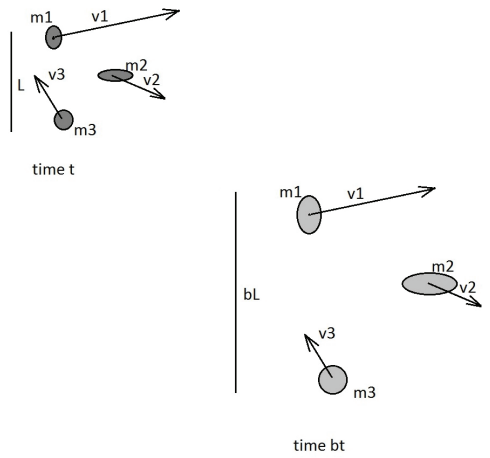
- The successes of MOND show that baryons alone account accurately for different independent aspects of dynamics, at least in galaxies. So, the small fraction of leftover baryons are supposed to do this?

- But this is inconceivable: Present day galaxies are end products of diverse, haphazard, formation/evolution processes, which, furthermore, affect DM and baryons in very different ways: mergers, accretion, feedback, collapse.

- DM is inherently incapable of making predictions for individual galaxies as MOND does: Formation history is unknowable. MOND predictions are independent of history.

The road to MOND

- Basic premise: The dynamics of systems showing large mass discrepancies (so termed DML dynamics) are space-time scale invariant.



EoMs are invariant to $(t, \mathbf{r}) \rightarrow \lambda(t, \mathbf{r})$: If $m_i,\ \mathbf{r}_i(t)$ is the solution for some initial conditions, then $m_i,\ \lambda \mathbf{r}_i(t/\lambda)$ is the solution for the scaled IC.

- G cannot appear in the DML; has to be replaced by another gravitational constant, $\mathcal{A}_0$ (apart from particle masses). It has to have dimensions $[\mathcal{A}_0] = [m]^{-\beta}[\ell]^{\gamma}[t]^{-\gamma}$ standardized to $\beta = 1$.

- The Umbrella theory satisfies the universality of free fall, and hence the constant that marks the boundary between the two limits of the theory has to be (after some standardization) $a_0 = \mathcal{A}_0/G$, which has dimensions $[a_0] = [\ell]^{\gamma-3}[t]^{-(\gamma-2)}$.

- In MOND, $\gamma = 4$, so a_0 is an acceleration, which the data point too forcibly.

$a_0 = ?$

a_0 can be derived in several independent ways:

$$a_0 \approx 1.2 \times 10^{-8} \text{ cm s}^{-2}$$

$$\bar{a}_0 \equiv 2\pi a_0 \approx cH_0 \approx c(\Lambda/3)^{1/2}$$

$$\ell_M \equiv c^2/a_0 \approx \ell_U \qquad\qquad M_M \equiv c^4/\mathcal{A}_0 \approx M_U$$

Why a critical acceleration? $a \ll a_0 \Rightarrow \ell_a \equiv c^2/a \gg \ell_M \sim \ell_U$.

No MOND black hole with $R_S \lesssim R_{Hubble}$

No MOND departure for cosmological strong lensing

No significant gravitational Cherenkov losses

MOND laws of galactic dynamics

- Essentially follow from only the basic tenets of MOND
- Are independent as phenomenological laws–e.g., if interpreted as effects of DM (just as the BB spectrum, the photo electric effect, H spectrum, superconductivity, etc. are independent in QM)
- Pertain separately to properties of the "DM" alone (e.g., asymptotic flatness, "universal" Σ), of the baryons alone (e.g., $M-\sigma$, maximum Σ), relations between the two (e.g., $M-V$)
- Revolve around a_0 in different roles

Some of the MOND laws

- Asymptotic constancy of orbital velocity: $V(r) \rightarrow V_\infty$ (H)
- Light-bending angle becomes asymptotically constant (H)
- The velocity mass relation: $V_\infty^4 = MGa_0$ (H-B)
- Discrepancy appears always at $V^2/R = a_0$ (H-B)
- Isothermal spheres have surface densities $\bar{\Sigma} \lesssim a_0/G$ (B)
- $\sigma^4 \sim MGa_0$ relation ("isothermal" spheres, virial relation) (B, H-B)
- The central surface density of "dark halos" is $\approx a_0/2\pi G$ (H)
- Disc galaxies have a disc AND a spherical "DM" components (H)
- Full rotation curves from baryon distribution alone (H-B)

Asymptotic flatness

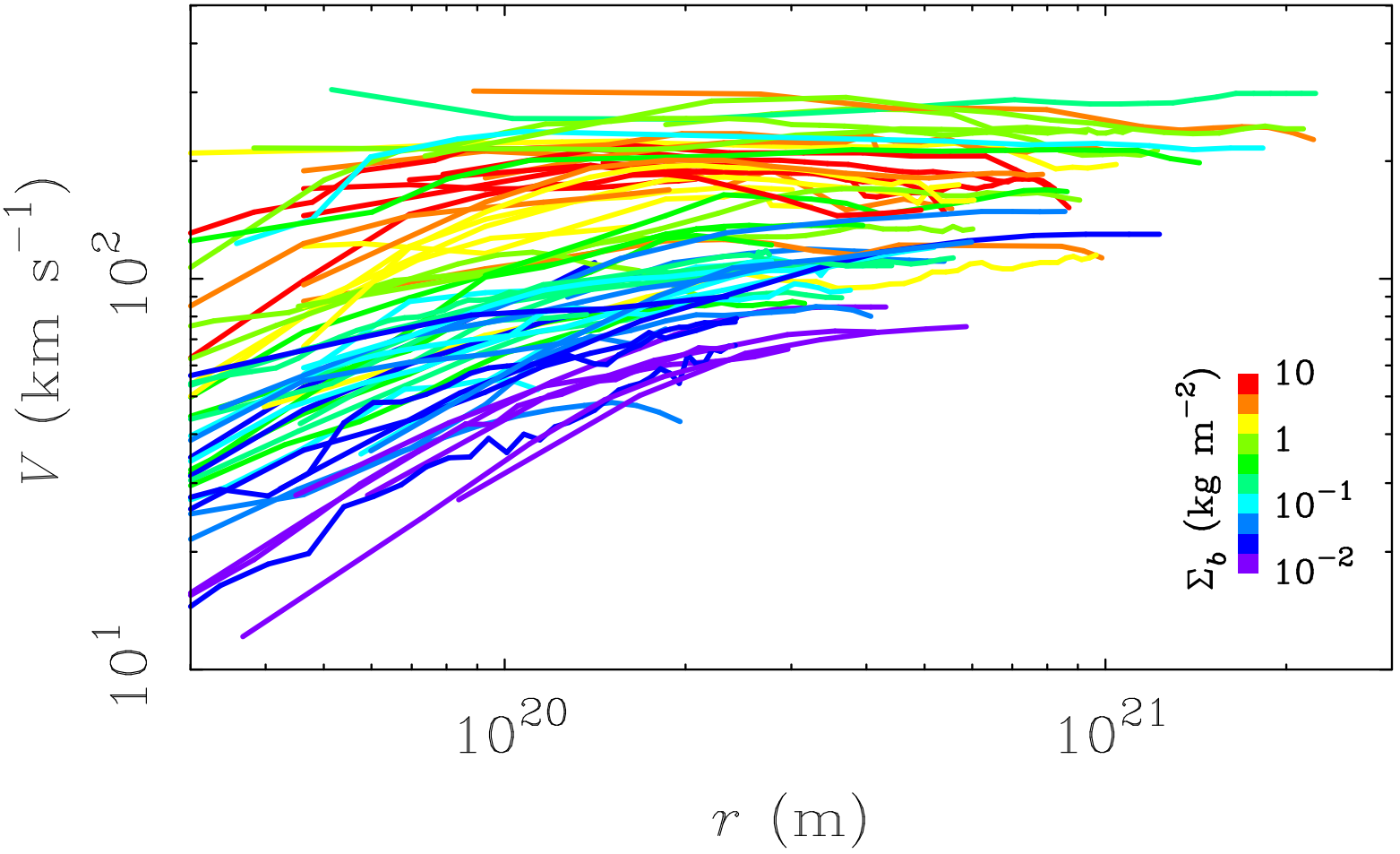
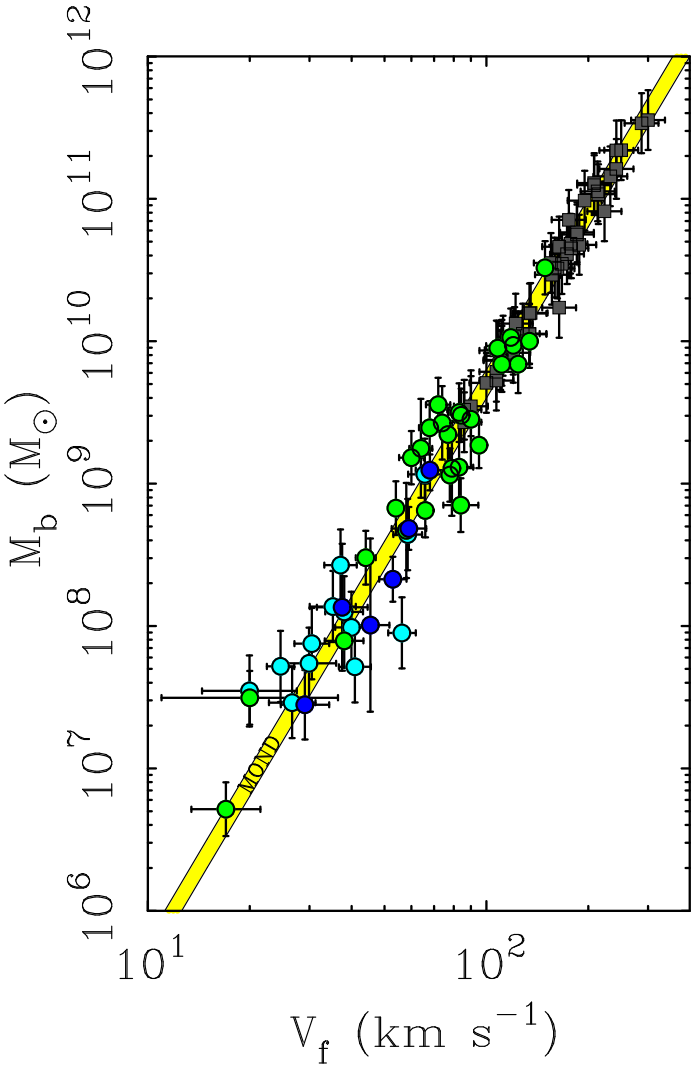
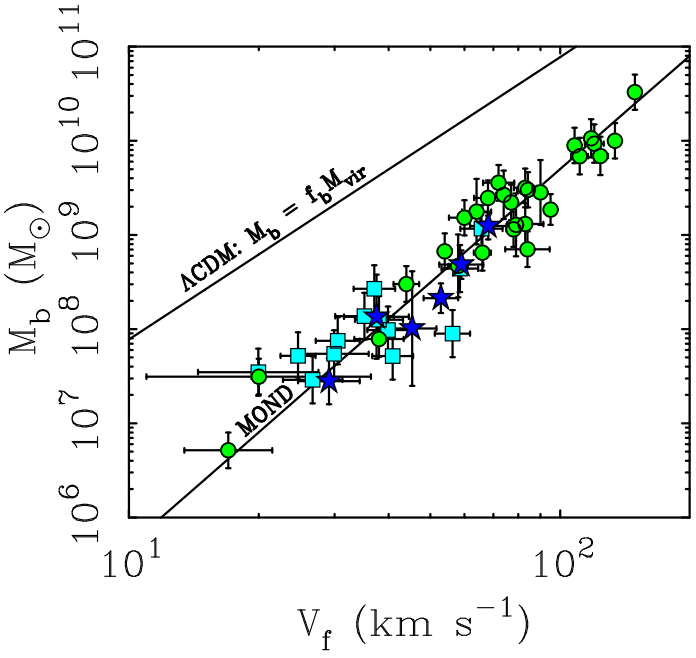
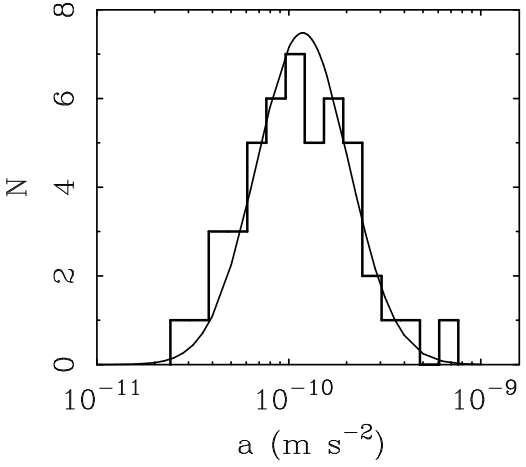


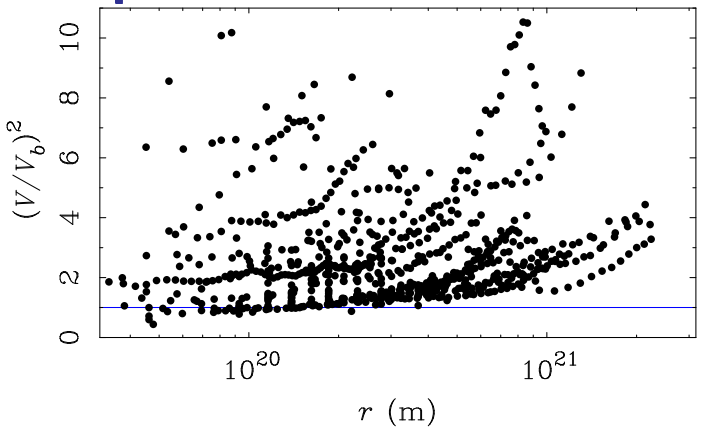
Figure 1: From Famaey and McGaugh 2012

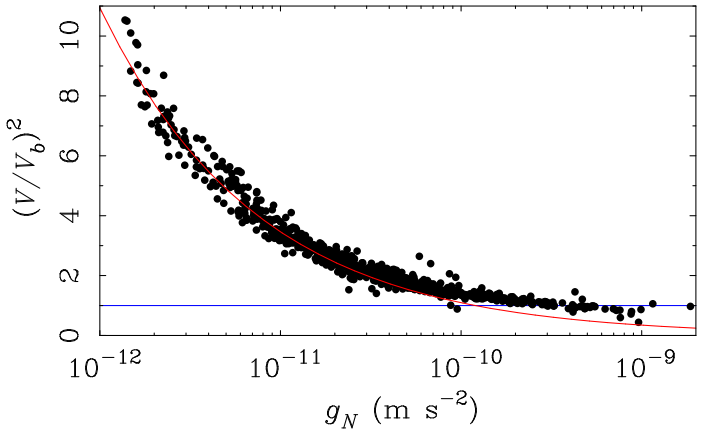

MOND
M_b ($M_\odot$)
V_f (km s^{-1})


ΛCDM: $M_b = f_b M_{vir}$
MOND
M_b ($M_\odot$)
V_f (km s^{-1})


N
a (m s^{-2})

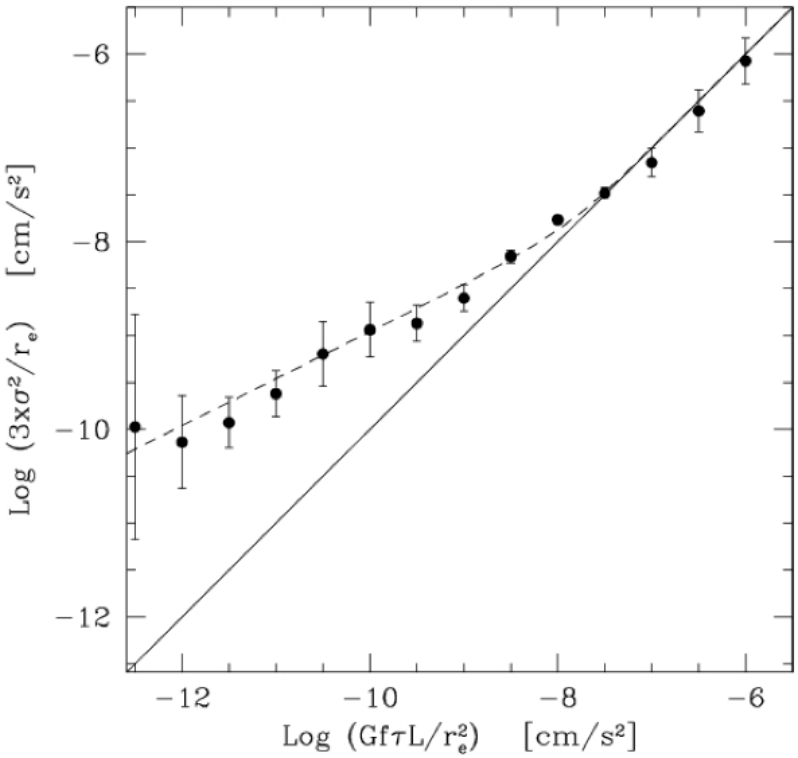
Mass discrepancies for disc galaxies





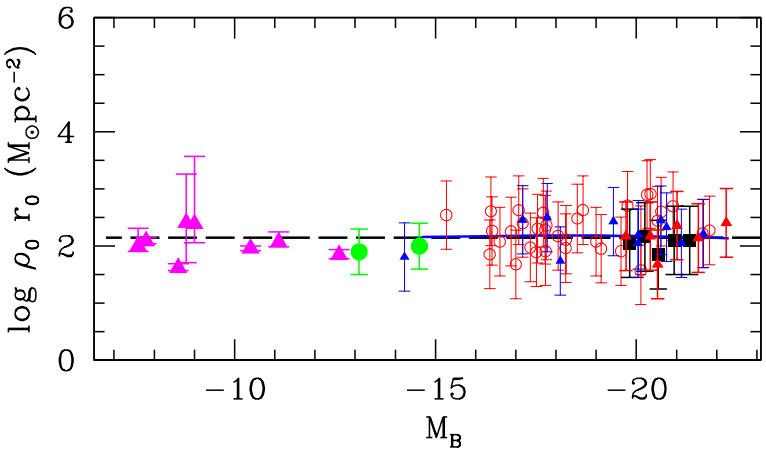
Prepared by Stacy McGaugh

Discrepancy-acceleration correlation for pressure-supported systems



From Scarpa (2006)

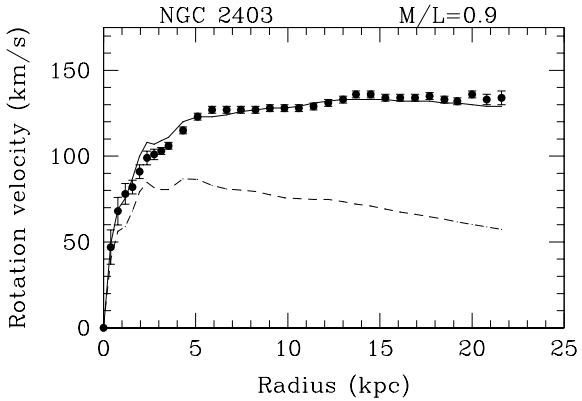
"Halo" central SD–Salucci et al. 2012

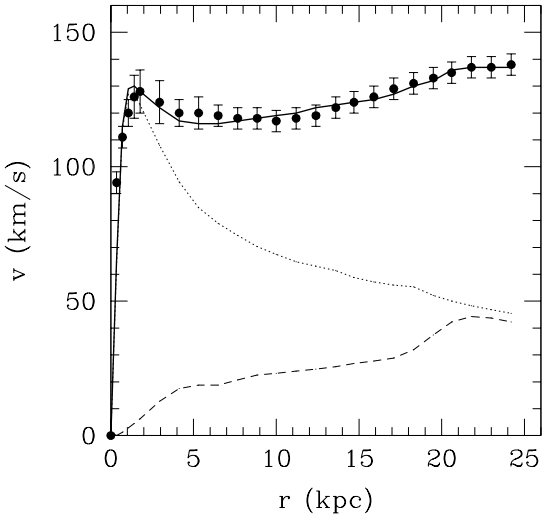


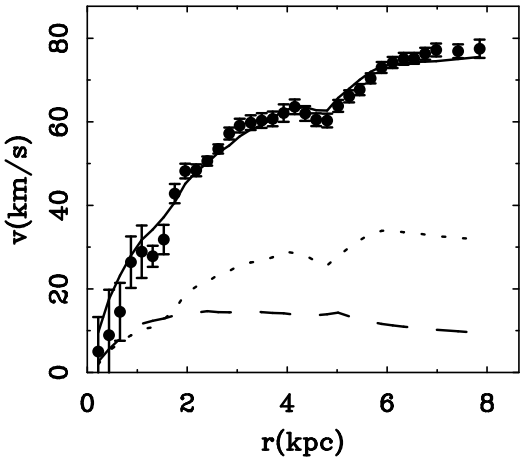
$$\nabla \cdot \mathbf{g}_h = 4\pi G \rho_h \quad \Rightarrow \quad \int_{-\infty}^{\infty} \rho_h \, dr \approx \frac{g_{max}}{2\pi G} = \frac{g_{max}}{a_0} \Sigma_M$$

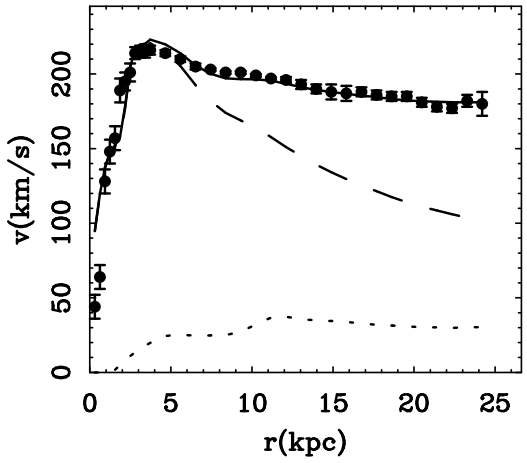
$$\Sigma_M \equiv \frac{a_0}{2\pi G} = 138 M_\odot pc^{-2}$$

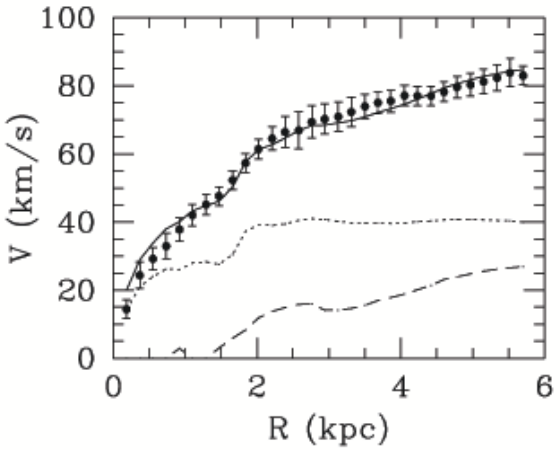
Rotation Curves of Disc Galaxies



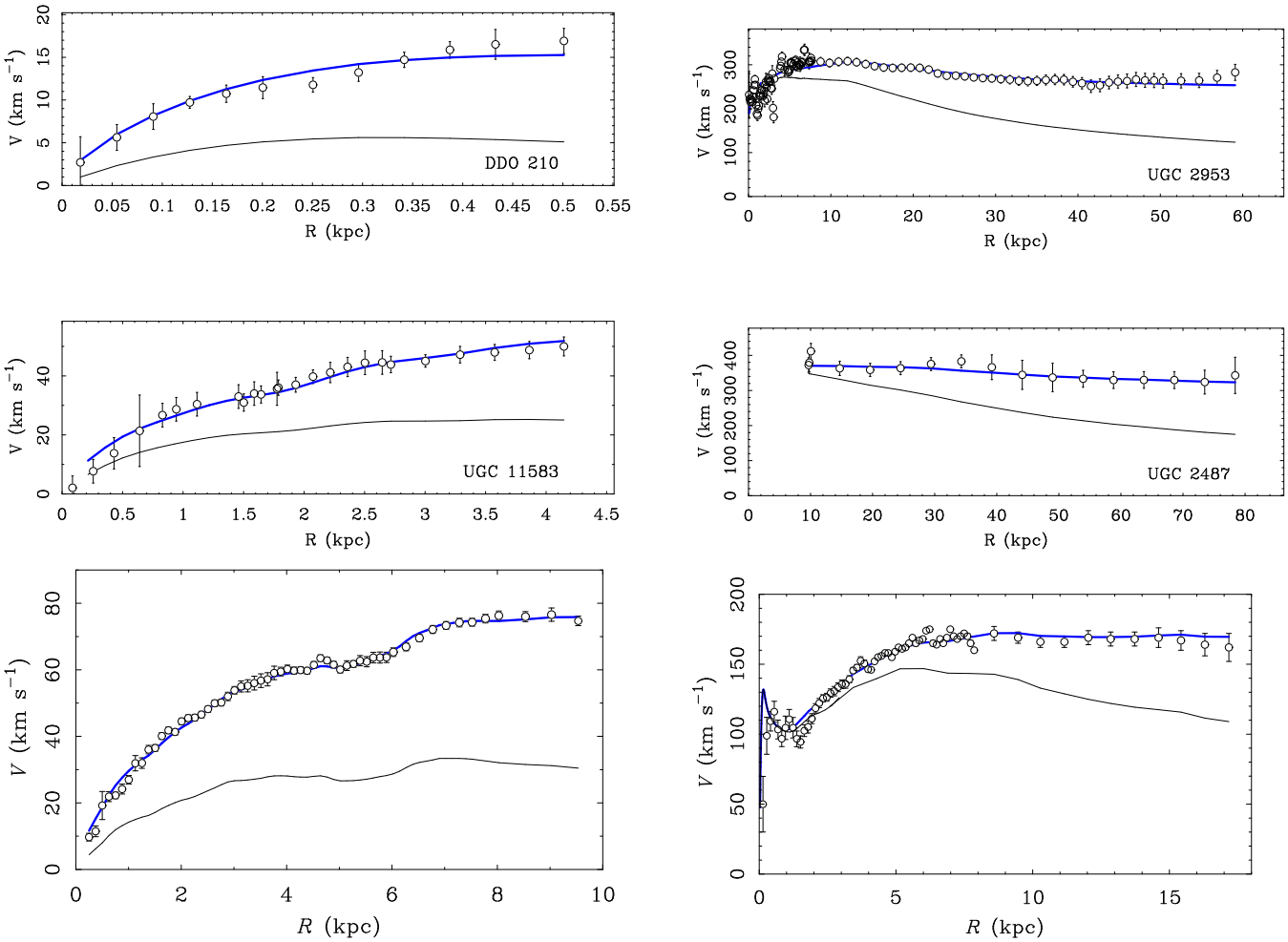




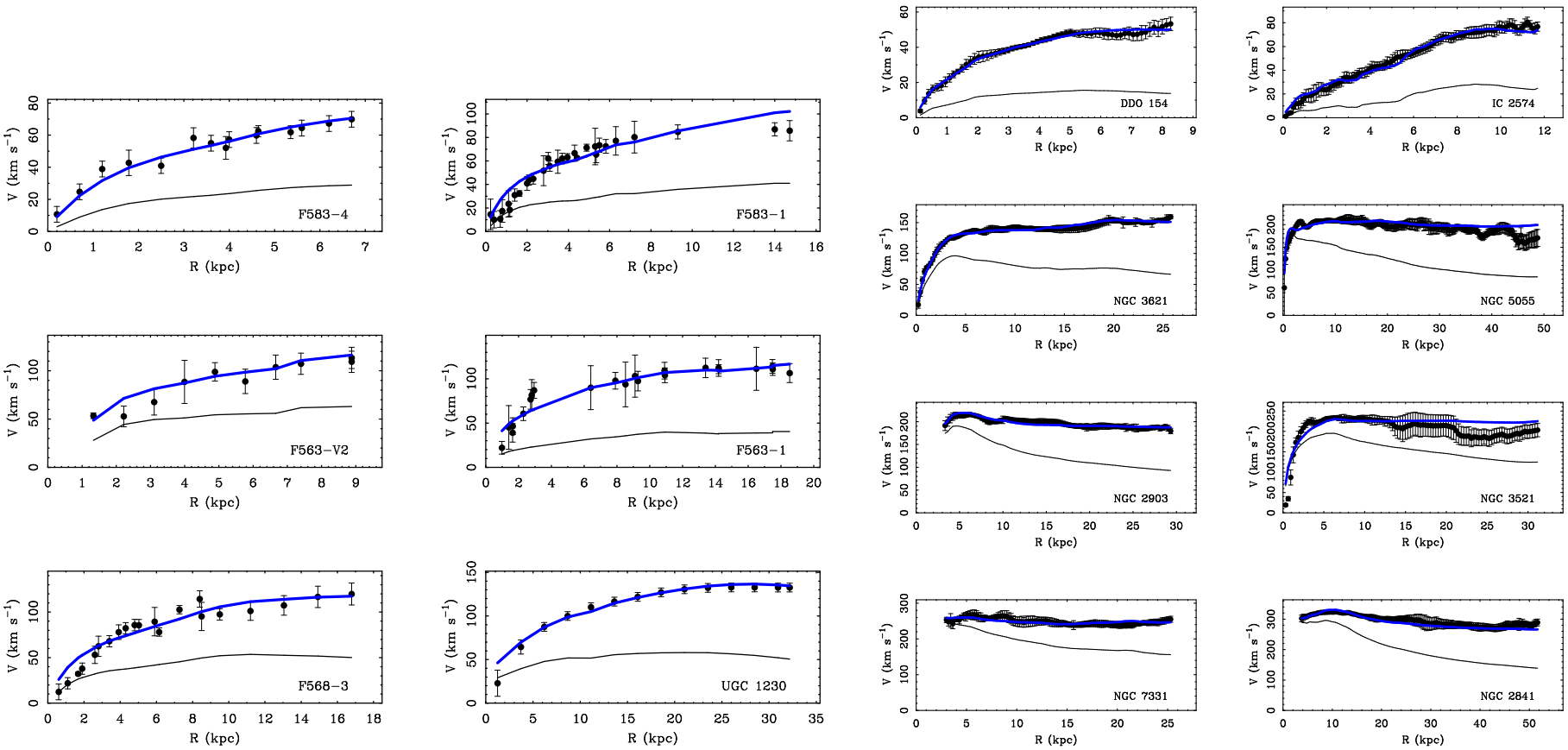




From Sanders 2005 and Sanders and McGaugh 2002



From review by Famaey and McGaugh 2012



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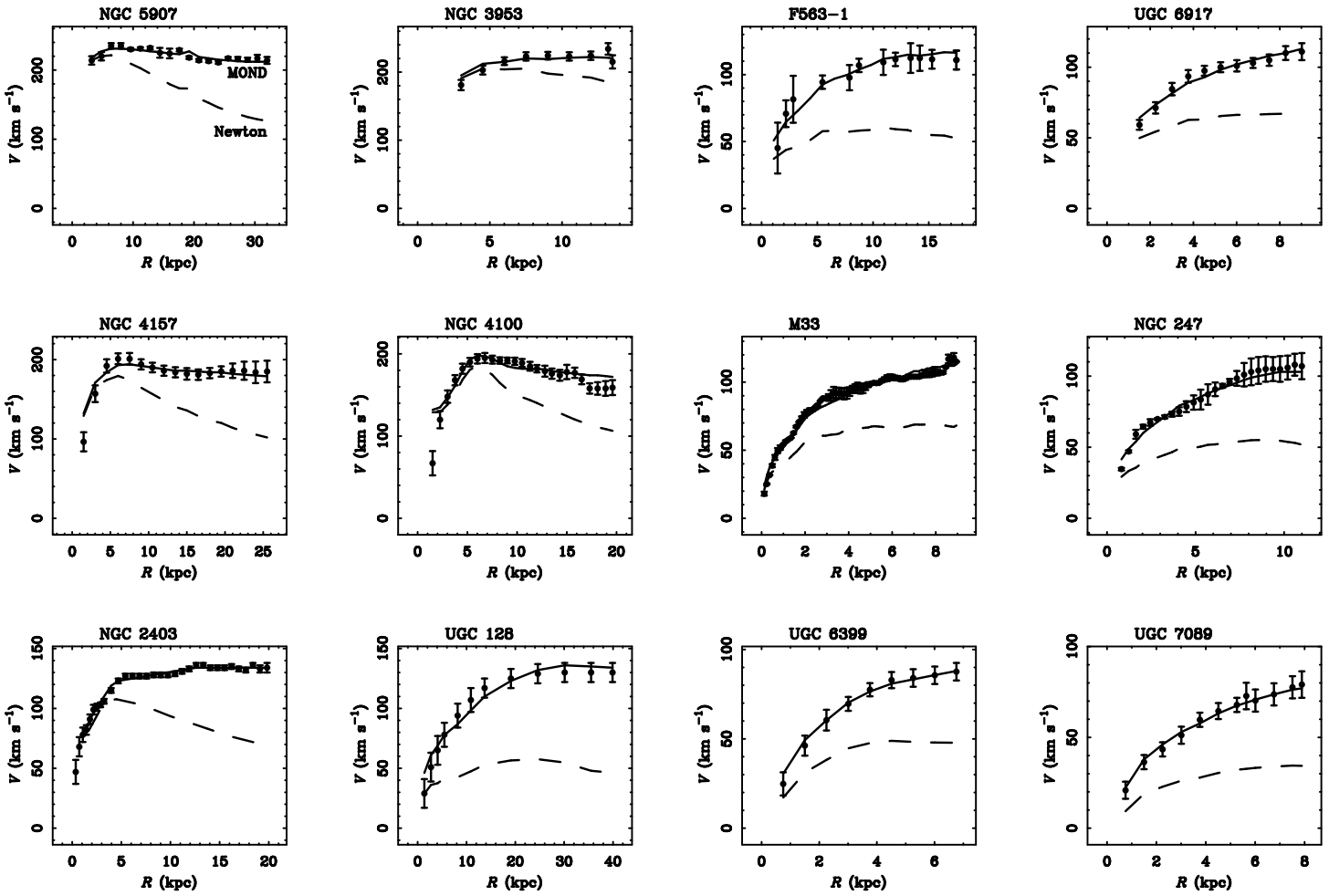
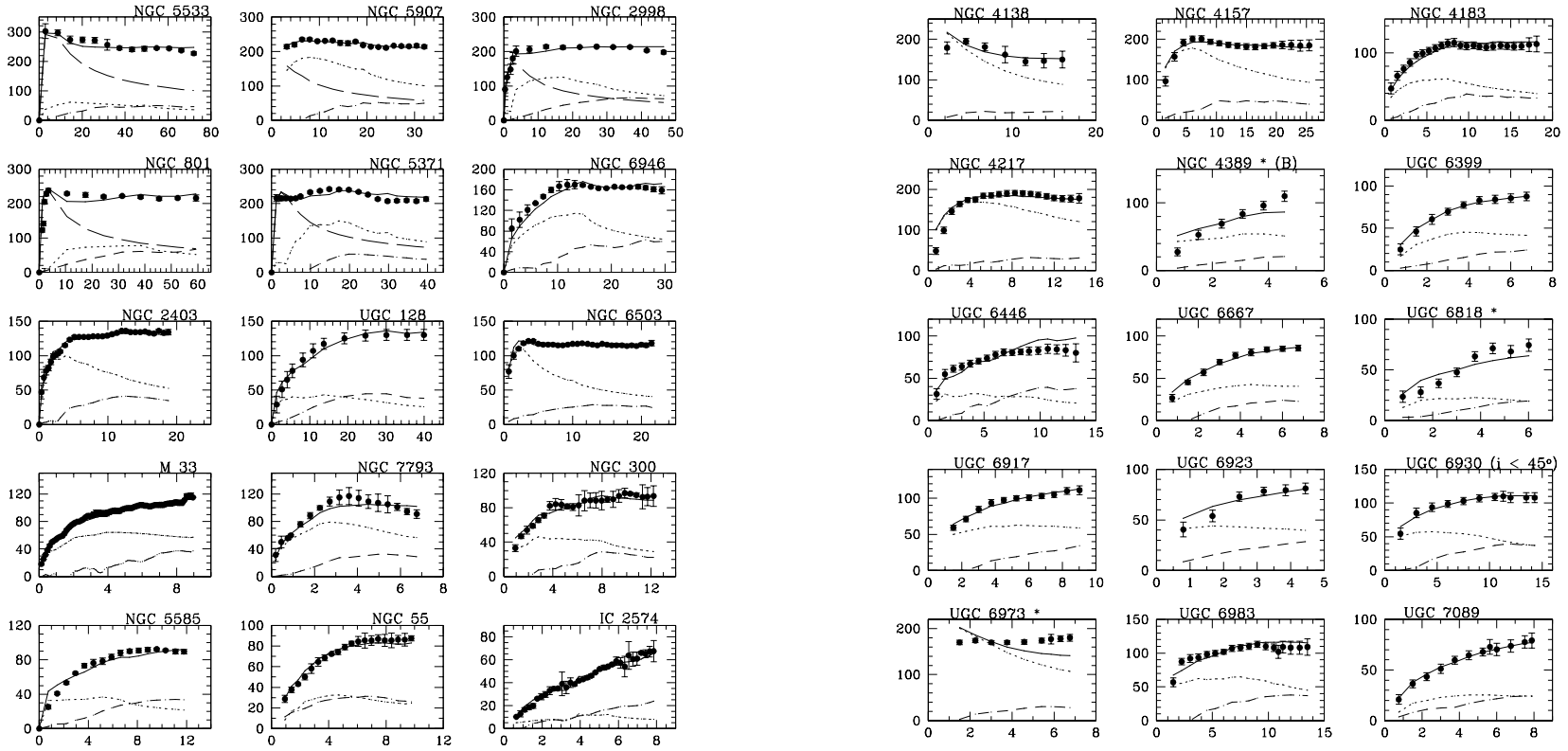
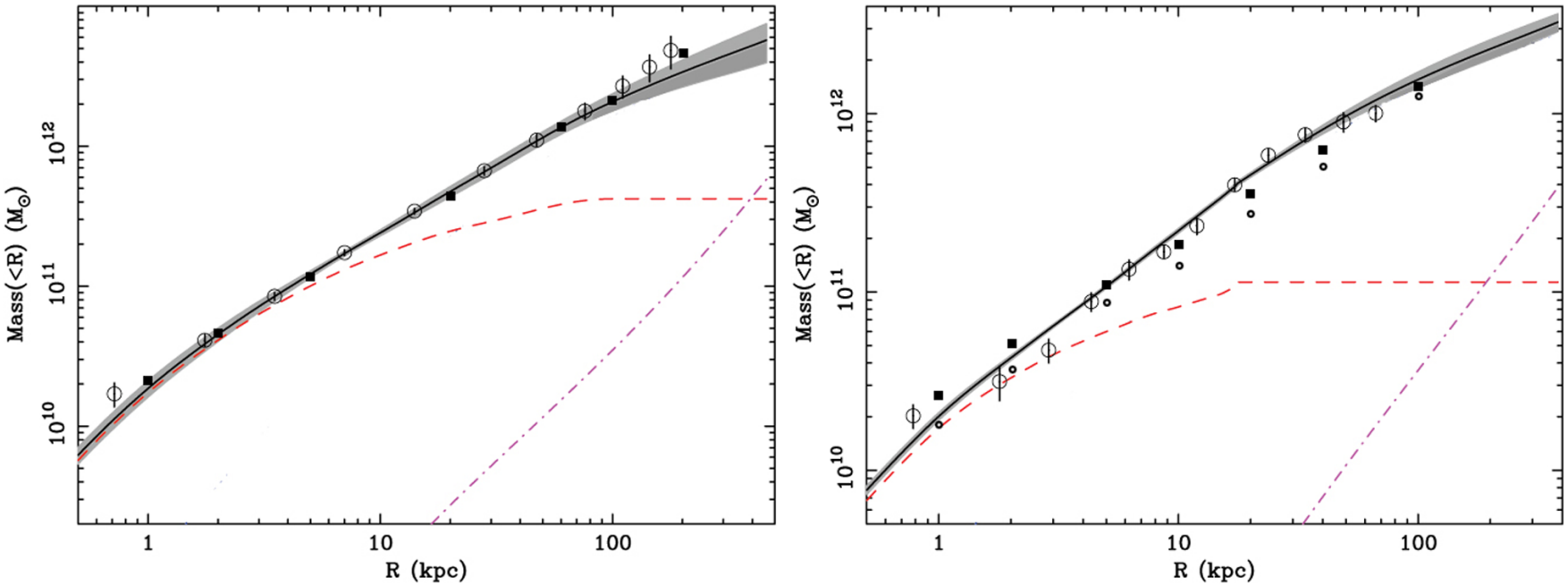

NGC 5907
MOND
Newton
NGC 3953
F563−1
UGC 6917
NGC 4157
NGC 4100
M33
NGC 247
NGC 2403
UGC 128
UGC 6399
UGC 7089
V (km s−1)
R (kpc)

McGaugh



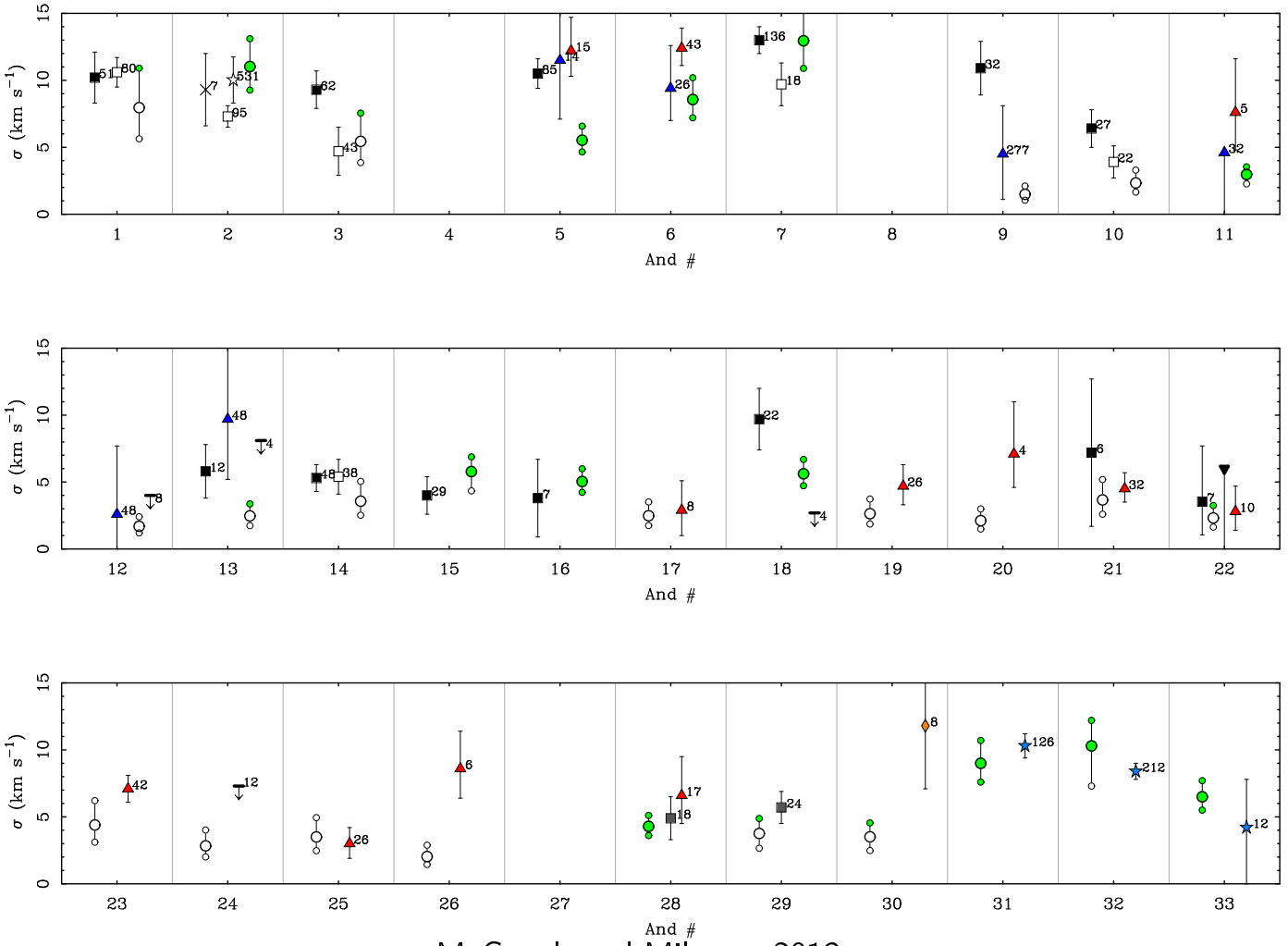
from Sanders and McGaugh 2002

x-ray Ellipticals, tested over an acceleration range $\sim 10a_0 - 0.1a_0$



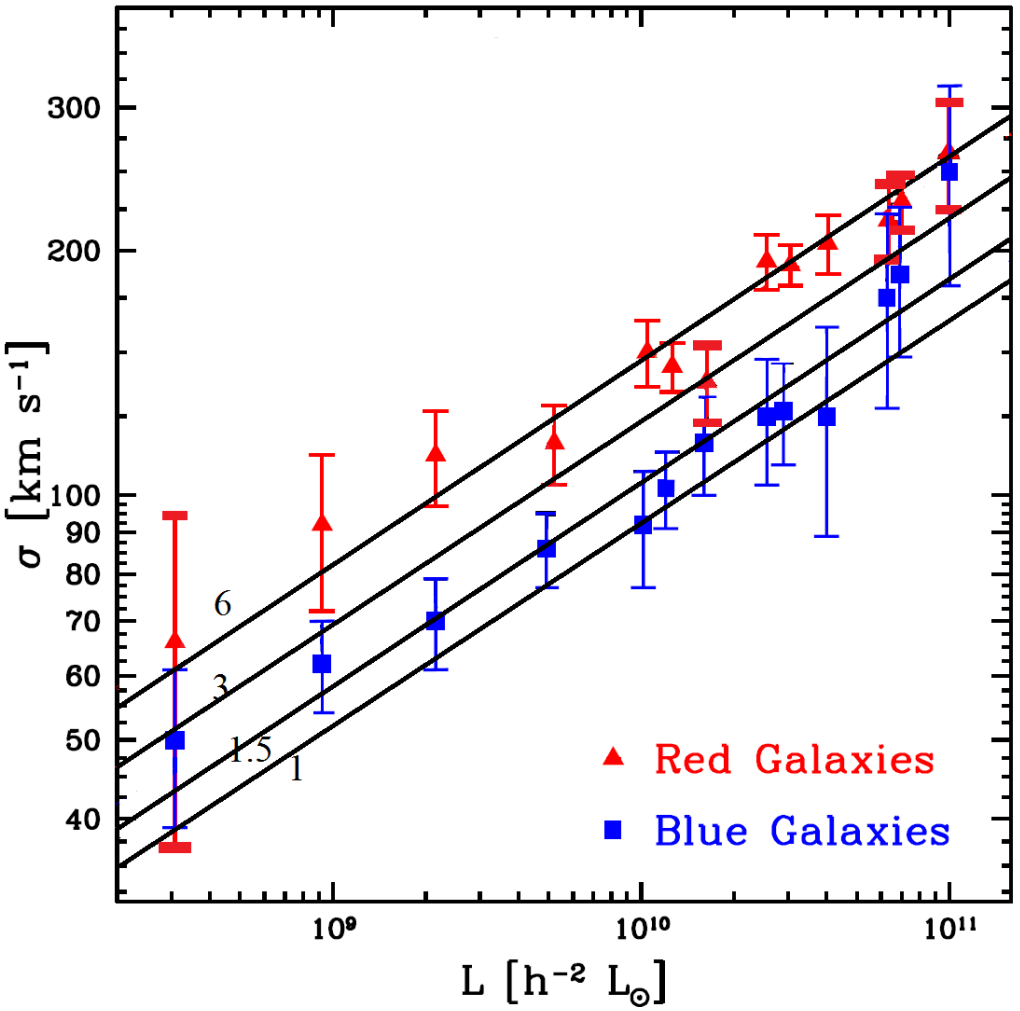
Baryon (dashed) and dynamical masses (grey band and large circles) from Humphrey et al. 2011,2012; MOND points (squares and small rings) from Milgrom 2012

Andromeda satellites–internal dynamics



McGaugh and Milgrom 2013.

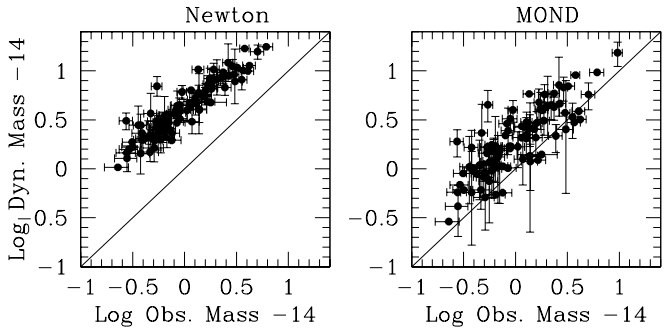
Galaxy-galaxy lensing



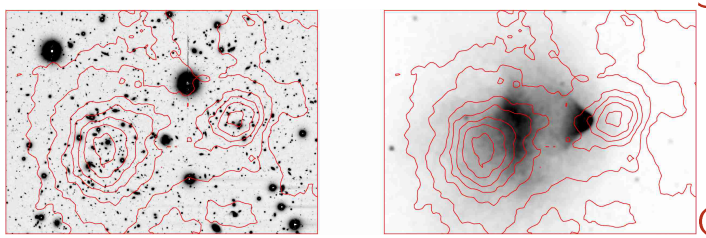
Data from Brimioulle et al. 2013, analysis from Milgrom 2013.

All is not roses

- Galaxy clusters



Sanders 1999



Clowe et al. 2006

In modified gravity, DM is NOT expected to be where the baryons are.

A small fraction ($\sim 5\ \%$) of the still missing baryons ($\sim 50 - 70\ \%$) is enough to bridge the gap.

- Cosmological DM

Summary

- MOND is a paradigm still under construction that replaces DM with new physics (or novel DM) at accelerations below $a_0 \sim cH_0 \sim c\Lambda^{1/2}$.
- Strongly anchored in symmetry (NR space-time scaling, de Sitter symmetry)
- Several theoretical directions; can differ greatly on second-rank predictions (e.g., EFE, solar system)
- There are some important things that it was not yet shown with certainty to do (e.g. replacing cosmological DM–some preliminary work).
- Still, it does a lot, and it does it extremely well.
- Rather inconceivable that MOND phenomenology can be explained as some organizing principle for CDM.