Phenomenology of the MOND alternative to dark matter

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IPMU, October 2014

MOND – synopsis

MOND hinges on accelerations: These are many orders of magnitude in galactic systems and the universe at large (e.g., cH0) compared with lab and SS ones.

- Departure at small accelerations.
- Works very well in predicting many properties of galaxies of all types.
- Leaves some discrepancy in galaxy cluster. 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).

Basic tenets

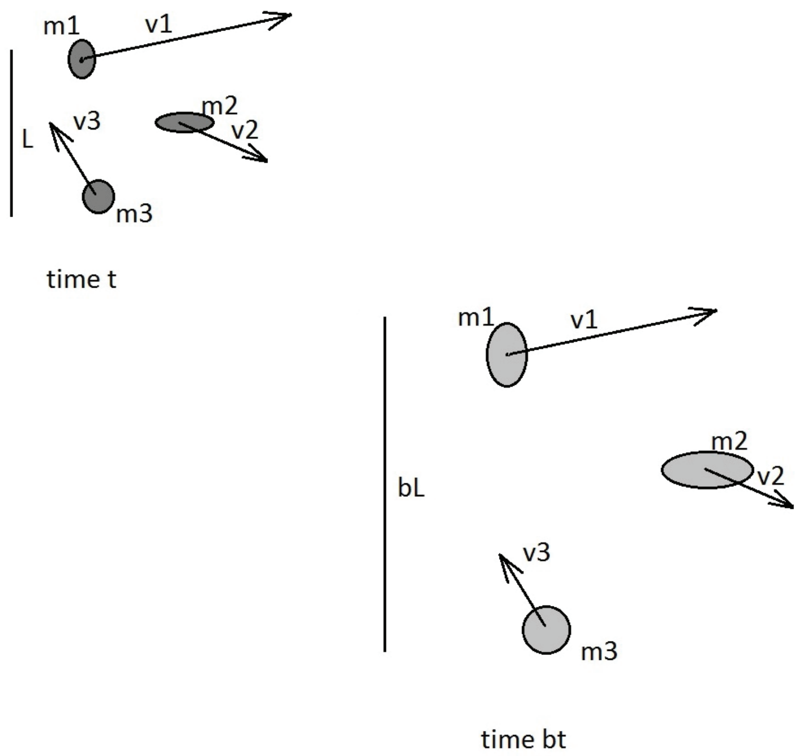
A theory of dynamics (gravity/inertia) involving a new constant a_0 (beside G, ...)

$\text{Standard limit } (a_0 \to 0)$: The Newtonian limit

$\text{MOND limit}: \; a_0 \to \infty, \;\; G \to 0, \;\; \mathcal{A}_0 \equiv G a_0 \; fixed$:

Scale invariance: $(t, \mathbf{r}) \to \lambda(t, \mathbf{r})$

Scale invariance



X $\quad m\mathbf{a} = \mathbf{F}, \qquad F = mMG/r^2$

V $\quad ma^2/a_0 = F, \qquad F = mMG/r^2,$

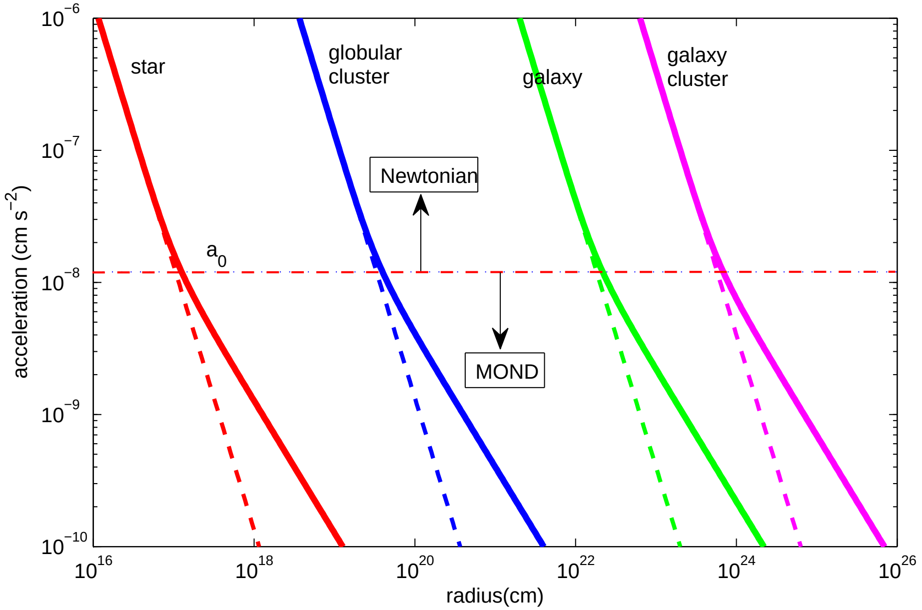
or $\quad ma = F, \qquad F \propto m(M\mathcal{A}_0)^{1/2}/r$

In analogy to c in the relativity/classical, or $\hbar$ in QM/classical context: a_0 marks the boundary between the two regimes, and also appear in many phenomena in the deep-MOND regime, where it can only appear as $\mathcal{A}_0$.

Example:

Point-like central mass: $a = \frac{MG}{R^2} f\left(\frac{MG}{R^2 a_0}\right)$

$$a \approx \begin{cases} MG/R^2 & : \quad a \gg a_0 \\ (M\mathcal{A}_0)^{1/2}/R & : \quad a \ll a_0 \end{cases}$$



$a_0 =?$

a_0 can be derived in several independent ways:

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

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

Why a critical acceleration? MOND length, MOND mass.

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

No MOND departure for cosmological strong lensing

No significant gravitational Cherenkov losses

Nonrelativistic theories

Nonlinear Poisson equation:

$$I = -\frac{a_0^2}{8\pi G}\int \mathcal{F}\left[\frac{(\vec{\nabla}\phi)^2}{a_0^2}\right] d^3r - \int \rho\phi \, d^3r$$

$$\vec{\nabla}\cdot[\mu(|\vec{\nabla}\phi|/a_0)\vec{\nabla}\phi] = 4\pi G\rho \qquad \mu(x) \equiv \mathcal{F}'(x^2) \qquad (\mathbf{a} = -\vec{\nabla}\phi)$$

The deep-MOND limit: Scaling $\mathcal{F}(y) \propto y^{3/2}$, $\quad \mu(x \ll 1) = x$:

$$\Delta_3\phi \equiv \vec{\nabla}\cdot[|\vec{\nabla}\phi|\vec{\nabla}\phi] = 4\pi\mathcal{A}_0\rho$$

conformally invariant

Quaslinear MOND (QUMOND)

$$I = -\frac{1}{8\pi G}\int\{2\vec{\nabla}\phi\cdot\vec{\nabla}\phi_N - a_0^2\mathcal{Q}\left[\left(\frac{\vec{\nabla}\phi_N}{a_0}\right)^2\right]\}d^3r - \int\rho\phi\, d^3r$$

$$\Delta\phi_N = 4\pi G\rho, \qquad \Delta\phi = \vec{\nabla}\cdot[\nu(|\vec{\nabla}\phi_N|)\vec{\nabla}\phi_N]$$

The deep-MOND limit: Scaling $\mathcal{Q}(y) \propto y^{3/4}$, $\quad \nu(y \ll 1) = y^{-1/2}$:

Relativistic theories

- Tensor-Vector-Scalar Gravity (TeVeS–Bekenstein 2004, after Sanders 1997) Gravity is described by $g_{\alpha\beta}$, $\mathcal{U}_\alpha$, ϕ: $\tilde{g}_{\alpha\beta} = e^{-2\phi}(g_{\alpha\beta} + \mathcal{U}_\alpha \mathcal{U}_\beta) - e^{2\phi}\mathcal{U}_\alpha \mathcal{U}_\beta$

  Reproduces NR modified gravity on galactic scales ($a_0 \propto k\hat{k}^{-1/2}$). Lensing: Similar to the GR result with modified potential Cosmology and structure formation: preliminary work (Dodelson and Liguori, Skordis et al.) CMB: preliminary work: has potential to mimic aspects of cosmological DM (Skordis et al.).

- MOND adaptations of Aether theories (Zlosnik, Ferreira, & Starkman 2007)

$$\mathcal{L}(A, g) = \frac{a_0^2}{16\pi G}\mathcal{F}(\mathcal{K}) + \lambda(A^\mu A_\mu + 1), \quad (1)$$

where

$$\mathcal{K} = a_0^{-2}\mathcal{K}^{\alpha\beta}_{\gamma\sigma} A^\gamma{}_{;\alpha} A^\sigma{}_{;\beta}. \quad (2)$$

$$\mathcal{K}^{\alpha\beta}_{\gamma\sigma} = c_1 g^{\alpha\beta} g_{\gamma\sigma} + c_2 \delta^\alpha_\gamma \delta^\beta_\sigma + c_3 \delta^\alpha_\sigma \delta^\beta_\gamma + c_4 A^\alpha A^\beta g_{\gamma\sigma},$$

- Galileon k-mouflage MOND adaptation (Babichev, Deffayet, & Esposito-Farese 2011)

  Also a tensor-vector-scalar theory. Said to improve on TeVeS in various regards (e.g., small enough departures from GR in high-acceleration environments)

- Nonlocal metric MOND theories (Soussa & Woodard 2003; Deffayet, Esposito-Farese, & Woodard 2011) Pure metric, but highly nonlocal in that they involve $F(\Box)$.

BIMOND

$$I = I_{EH} + I_M + \hat{I}_{EH} + \hat{I}_M + I_{Int}$$

$$I = -\frac{1}{16\pi G}\int [g^{1/2}R + \hat{g}^{1/2}\hat{R} - 2(g\hat{g})^{1/4}a_0^2\mathcal{M}]d^4x + I_M(g_{\mu\nu}, \psi_i) + \hat{I}_M(\hat{g}_{\mu\nu}, \chi_i)$$

$\mathcal{M}$ a dimensionless scalar a function of (quadratic) scalars of

$$a_0^{-1}C^{\alpha}_{\beta\gamma}, \qquad C^{\alpha}_{\beta\gamma} = \Gamma^{\alpha}_{\beta\gamma} - \hat{\Gamma}^{\alpha}_{\beta\gamma}$$

$$\Upsilon_{\mu\nu} = C^{\gamma}_{\mu\lambda}C^{\lambda}_{\nu\gamma} - C^{\gamma}_{\mu\nu}C^{\lambda}_{\lambda\gamma}$$

$$\Upsilon = g^{\mu\nu}\Upsilon_{\mu\nu}, \quad \hat{\Upsilon} = g^{\hat{\mu}\nu}\Upsilon_{\mu\nu}$$

“Microscopic” approaches

- DM with novel, unexpected properties, that may behave as dictated by MOND:
  - ▷ Polarized dark medium (Blanchet 2007, Blanchet & Le Tiec 2009)
  - ▷ Novel baryon-DM interactions (Bruneton & al. 2008)
  - ▷ Dark Fluid (Zhao 2008)

- Entropic effect (Verlinde): (Klinkhamer & Kopp 2011, Pikhitsa Ho & al. 2010, Li & Chang 2010), others

- Vacuum effects (Milgrom 1999)

- Membranes with gravitational DoF extra coordinates (Milgrom 2002)

- Horava gravity (Romero & al. 2010), Sanders (2011), Blanchet & Marsat (2011)

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)

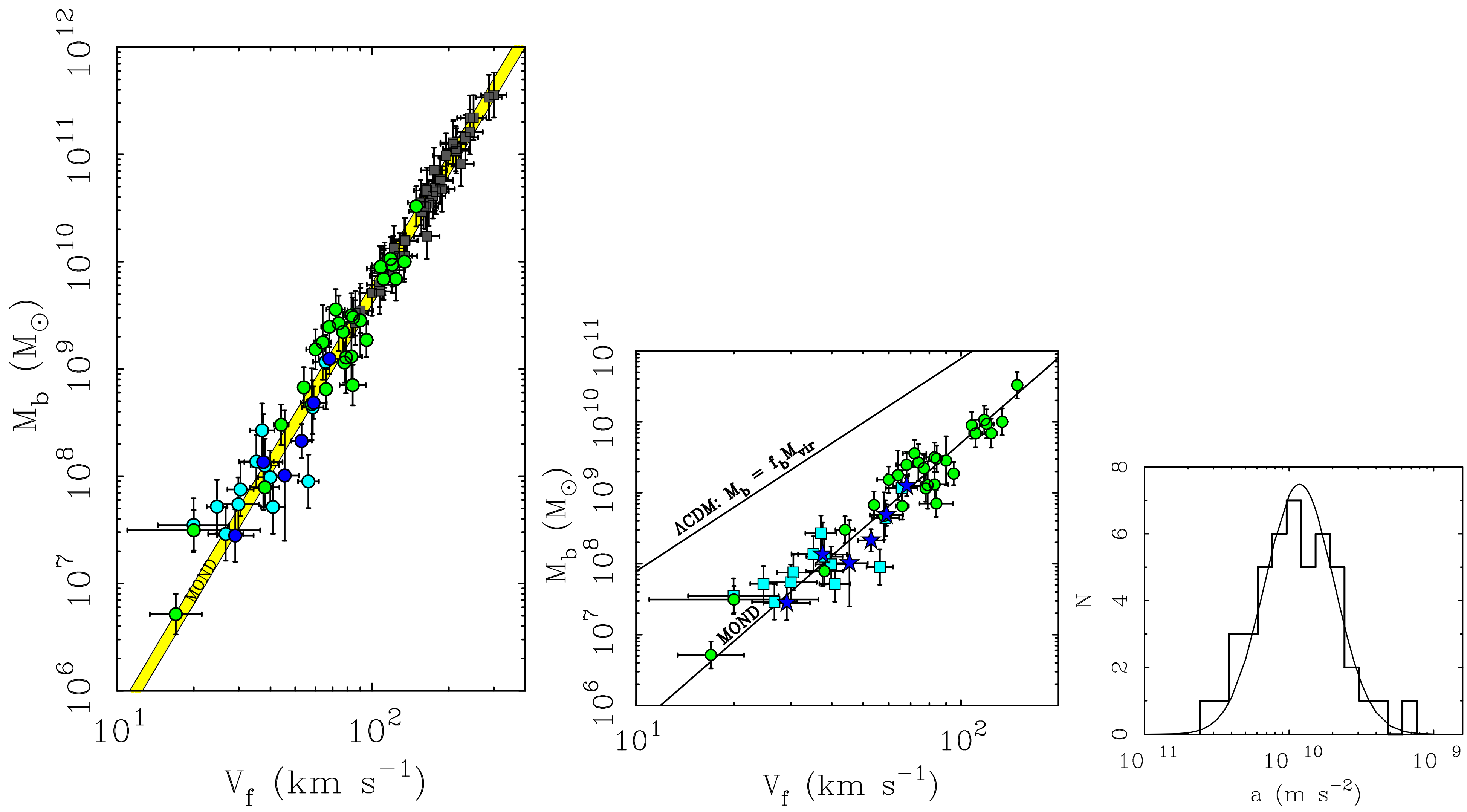
- Pertain separately to properties of the "DM" alone (e.g., asymptotic flatness, "universal" Σ), of the baryons alone (e.g., $M-\sigma$, maximum Σ), relations between the two (e.g., $M-V$)

- Revolve around a_0 in different roles

Some of the MOND laws

- Asymptotic constancy of orbital velocity: $V(r) \to V_\infty$ (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)

Mass-asymptotic-speed relation–McGaugh 2011

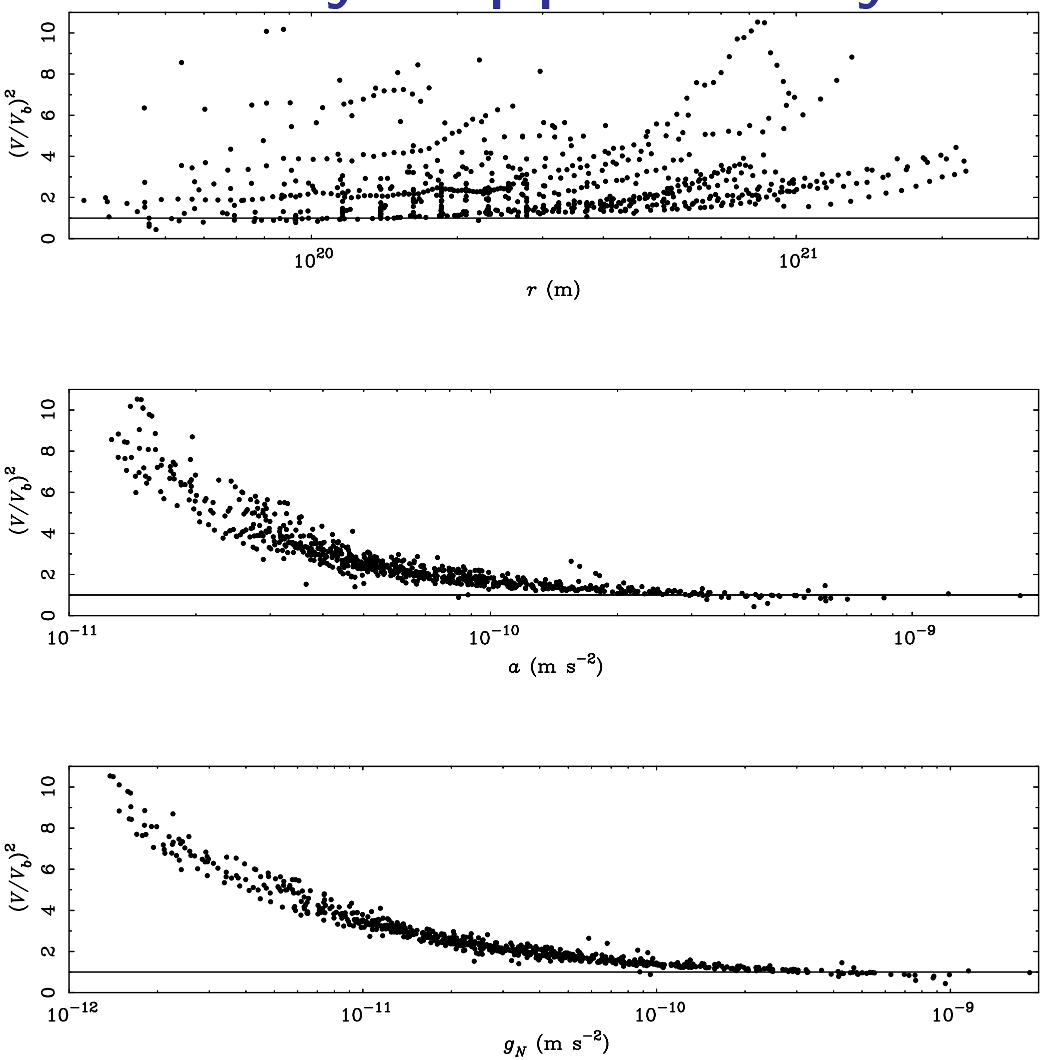


Discrepancy-acceleration correlation

$$g = f(g_N) \to g = g_N \nu(g_N/a_0)$$

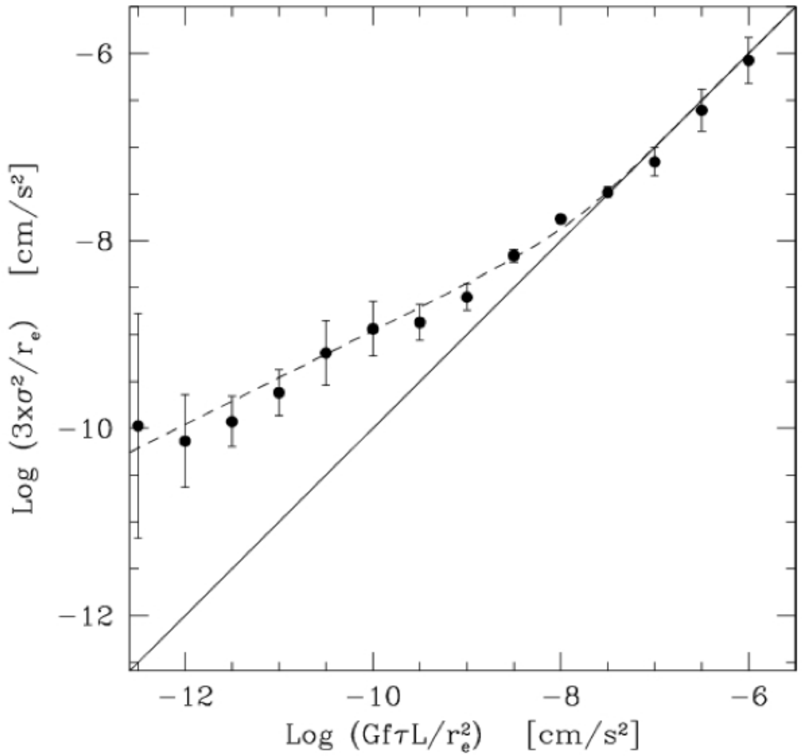
$$\nu(y \to \infty) \to 1, \qquad \nu(y \ll 1) \approx y^{-1/2}$$

Discrepancy-acceleration correlation for rotationally-supported systems



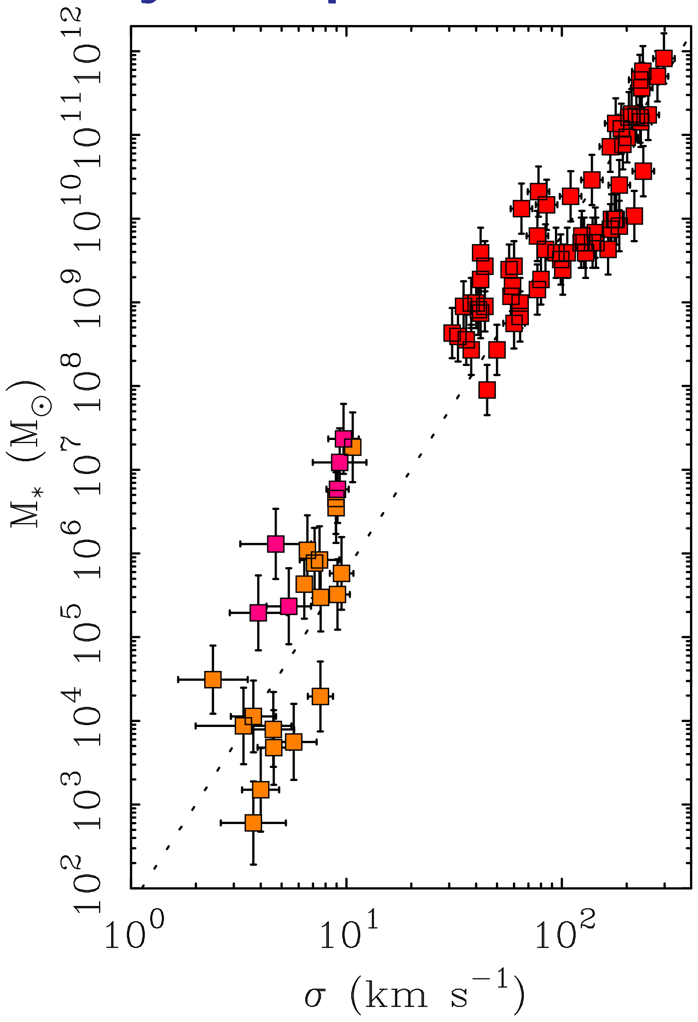
From review by Famaey and McGaugh 2012

Discrepancy-acceleration correlation for pressure-supported systems



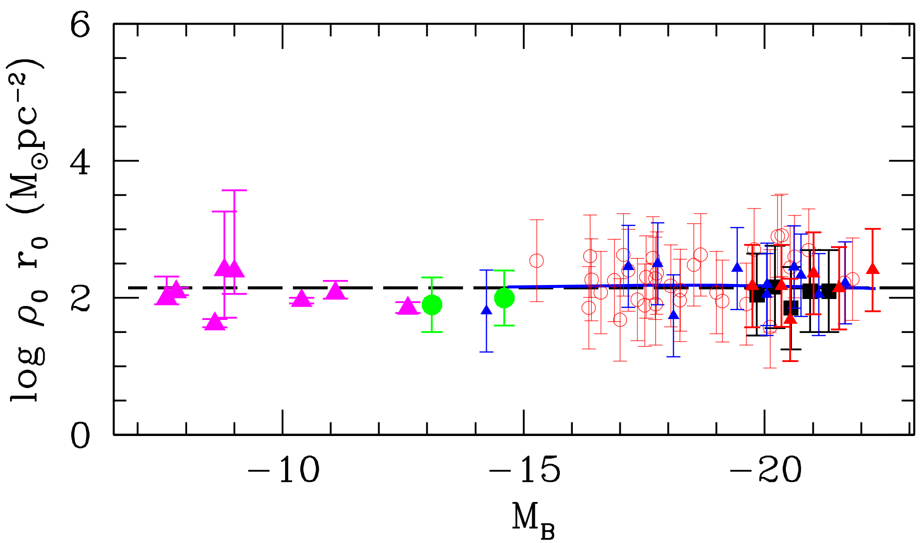
From Scarpa (2006)

Mass-velocity-dispersion-correlation



From review by Famaey and McGaugh 2012

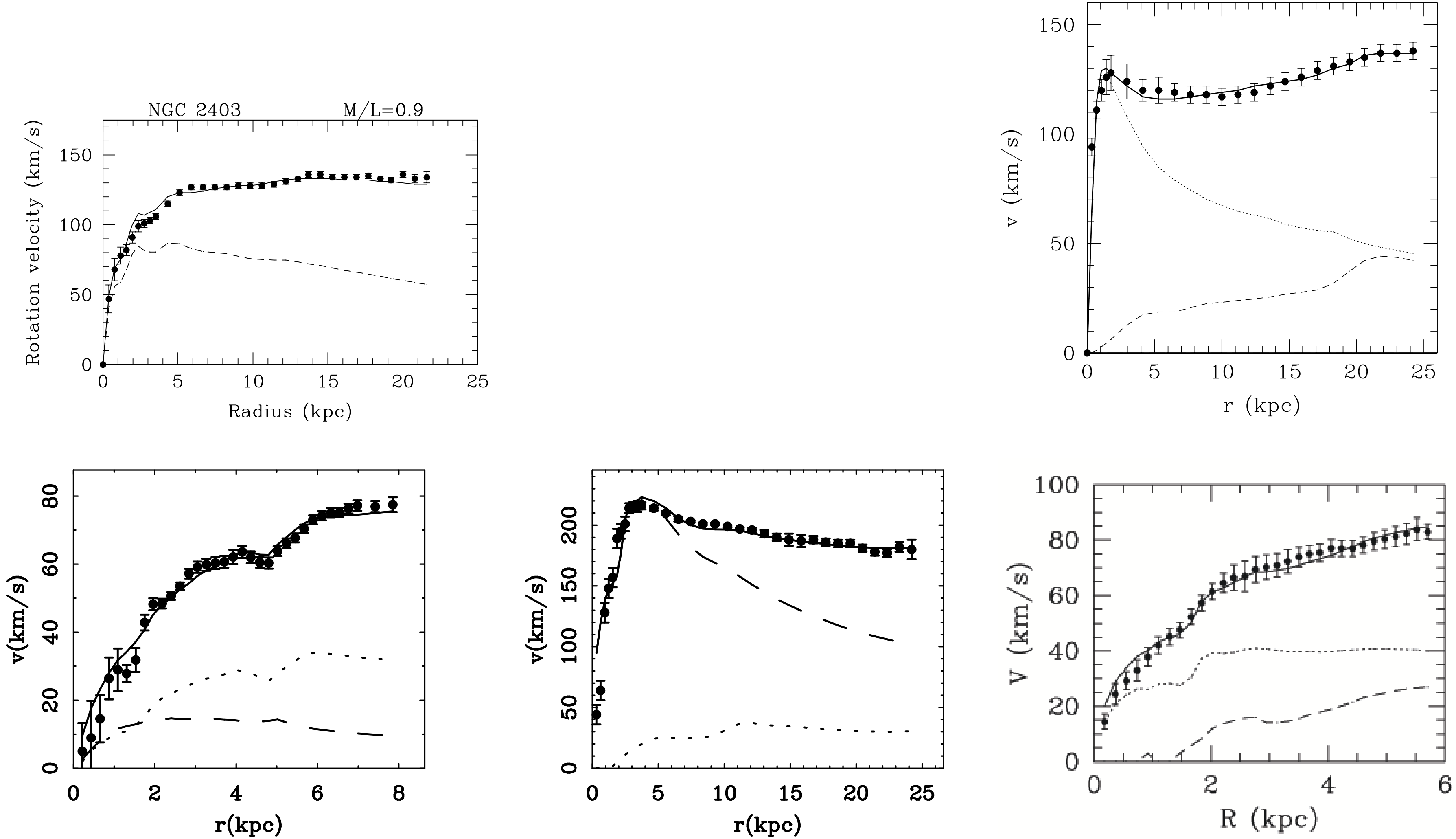
"Halo" central SD–Salucci et al. 2012



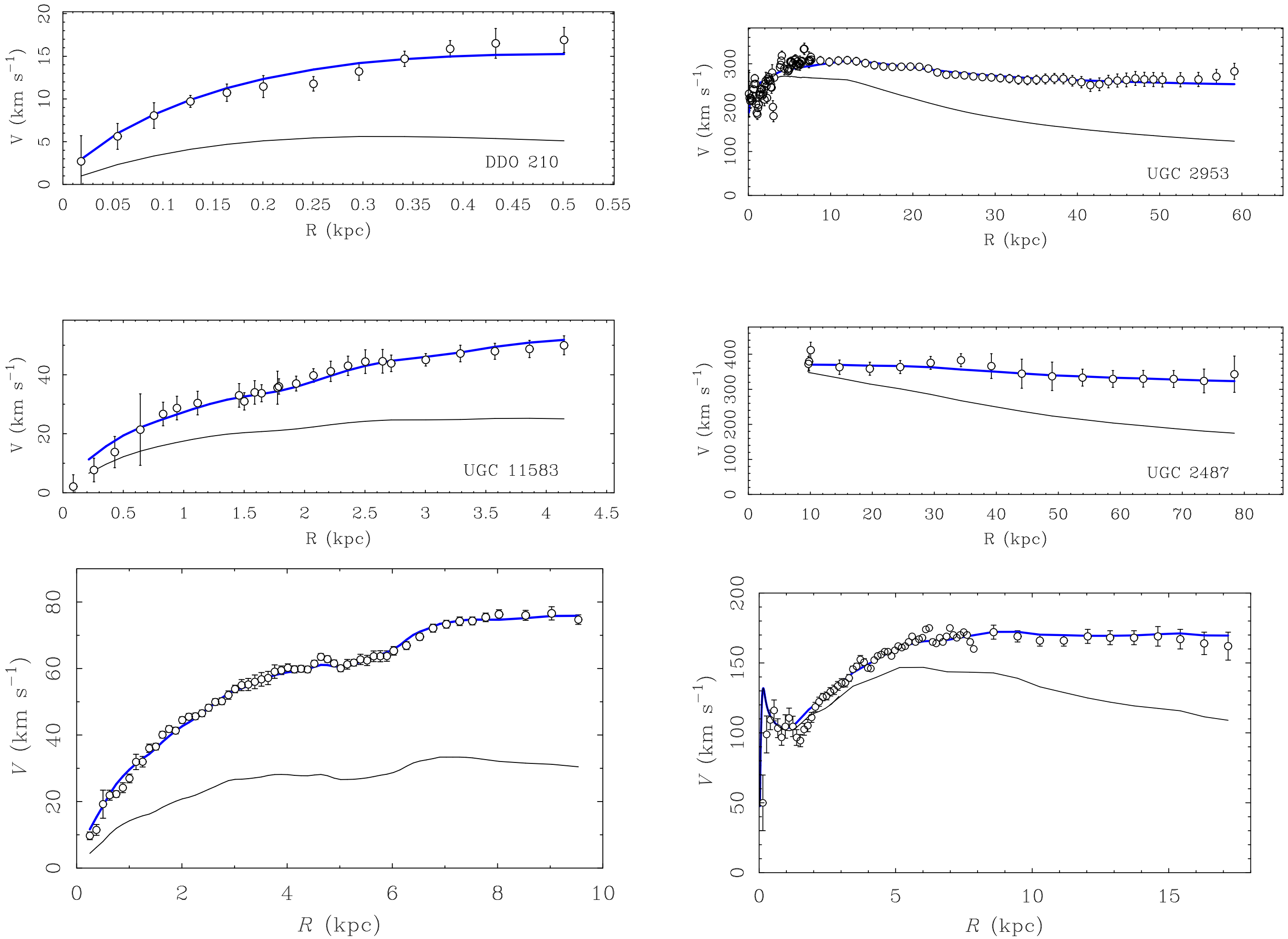
$$a_0/2\pi G = 138 M_\odot pc^{-2}$$

$$[log(a_0/2\pi G) = 2.14]$$

Rotation Curves of Disc Galaxies



From Sanders 2005 and Sanders and McGaugh 2002



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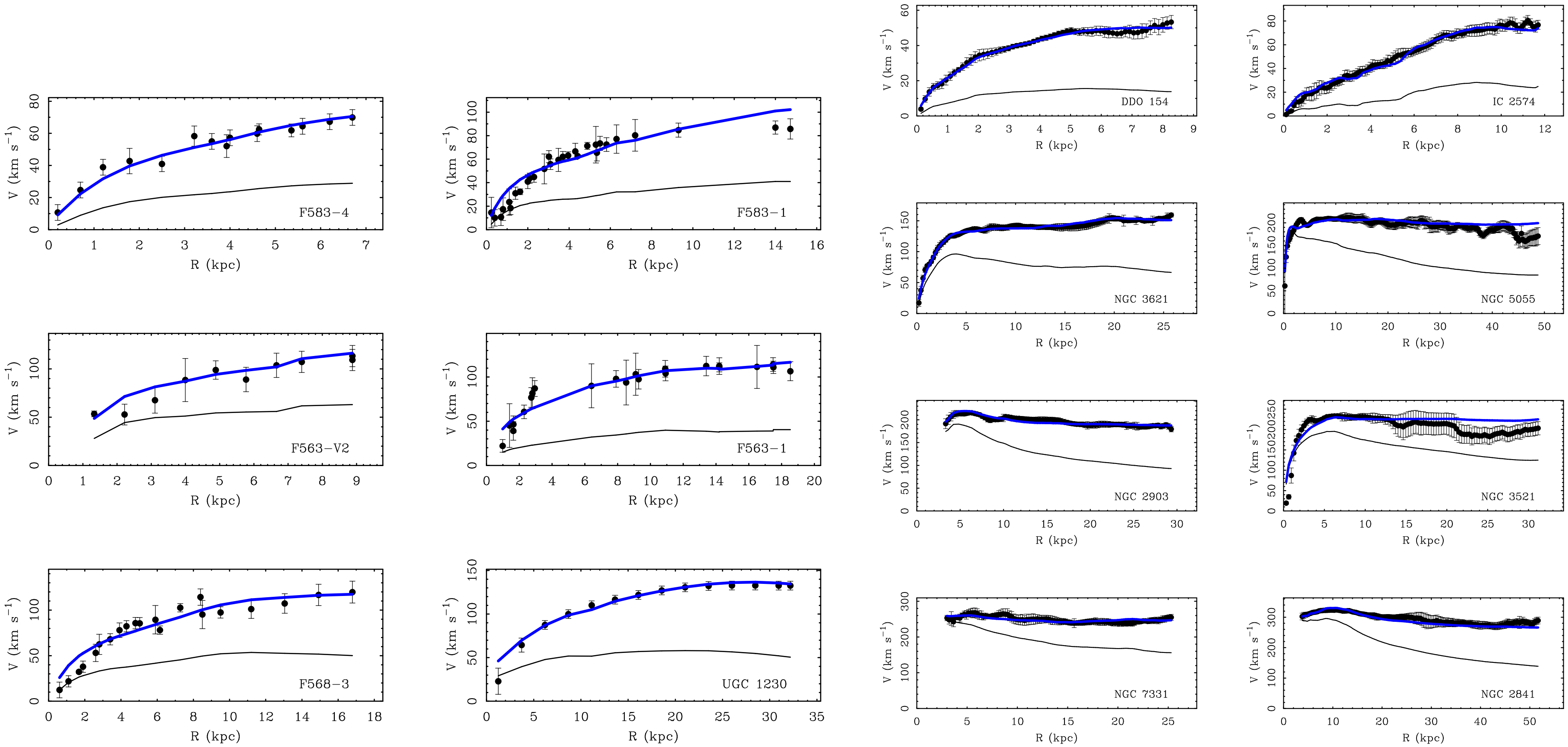

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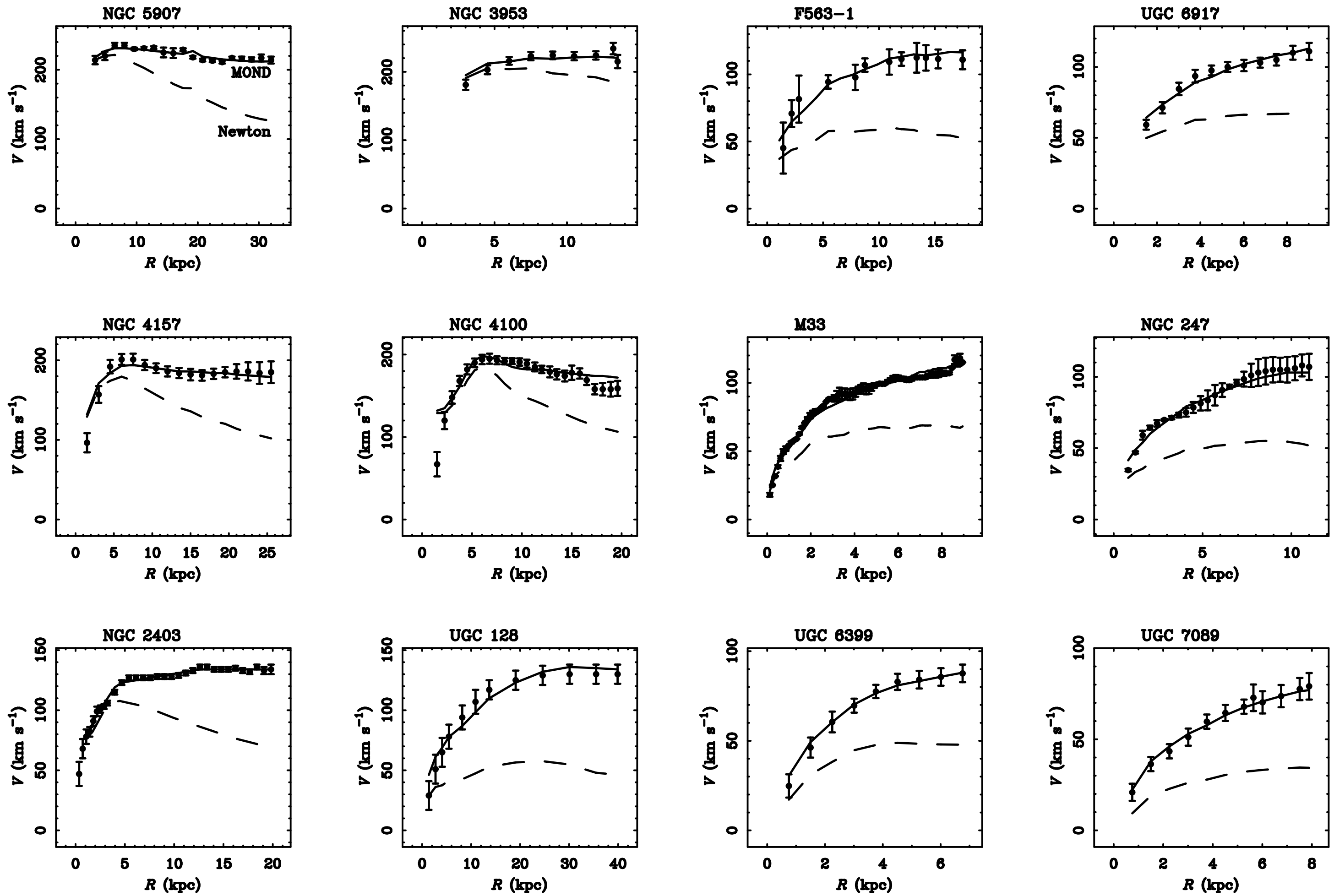
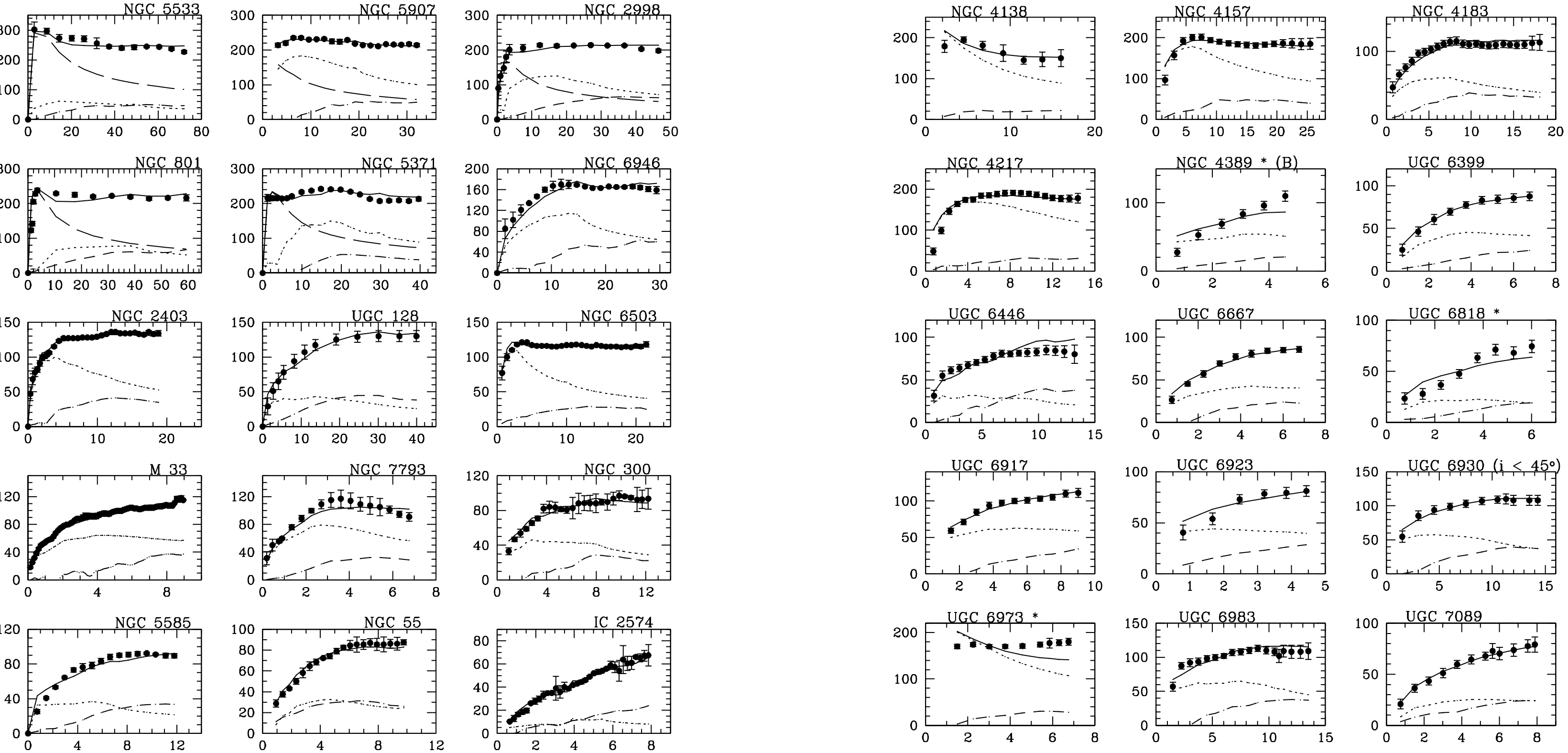
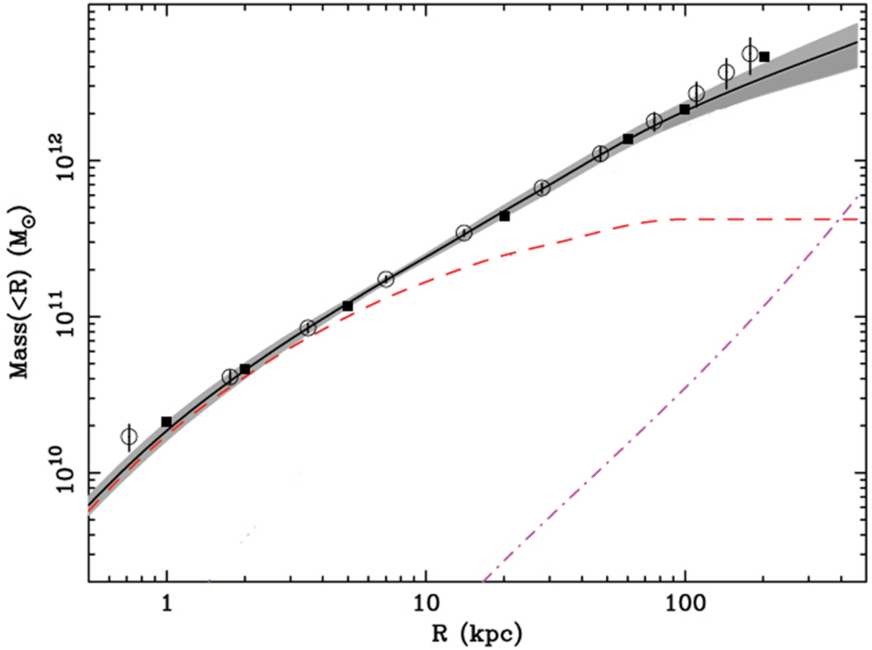

NGC 5907
NGC 3953
F563-1
UGC 6917
NGC 4157
NGC 4100
M33
NGC 247
NGC 2403
UGC 128
UGC 6399
UGC 7089
MOND
Newton
V (km s^{-1})
R (kpc)

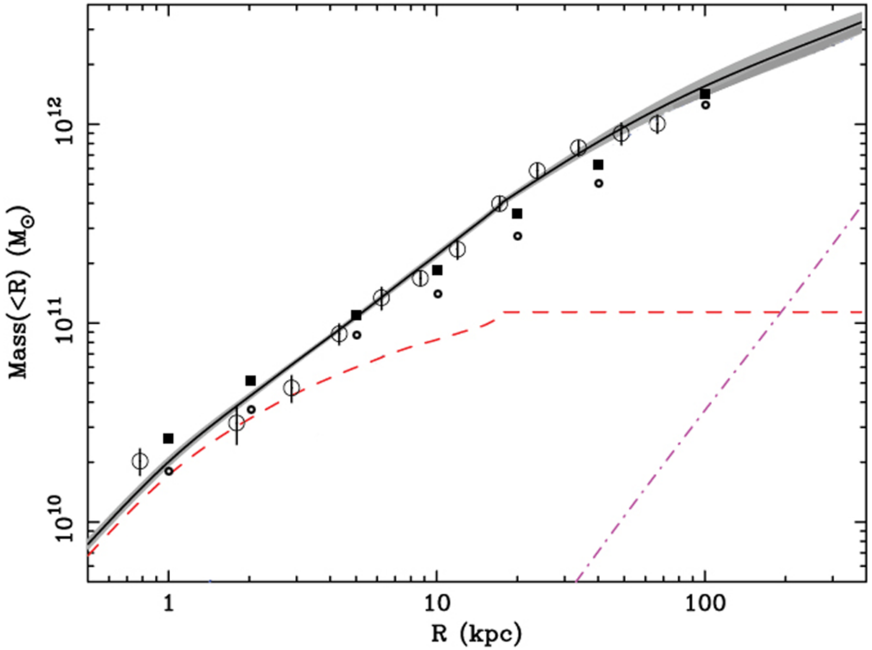
McGaugh



from Sanders and McGaugh 2002

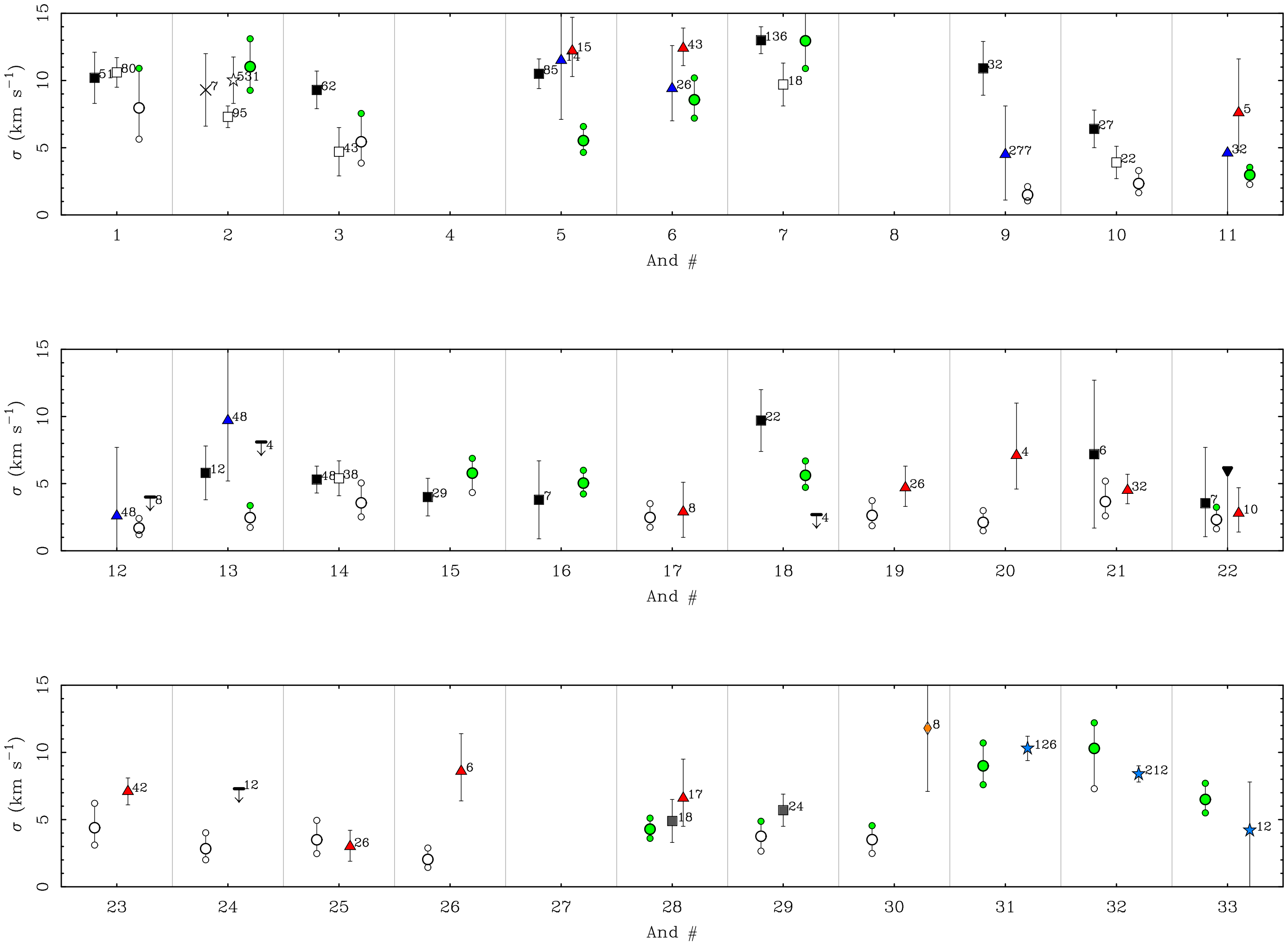
x-ray Ellipticals, tested over an acceleration range $\sim 10a_0 - 0.1a_0$





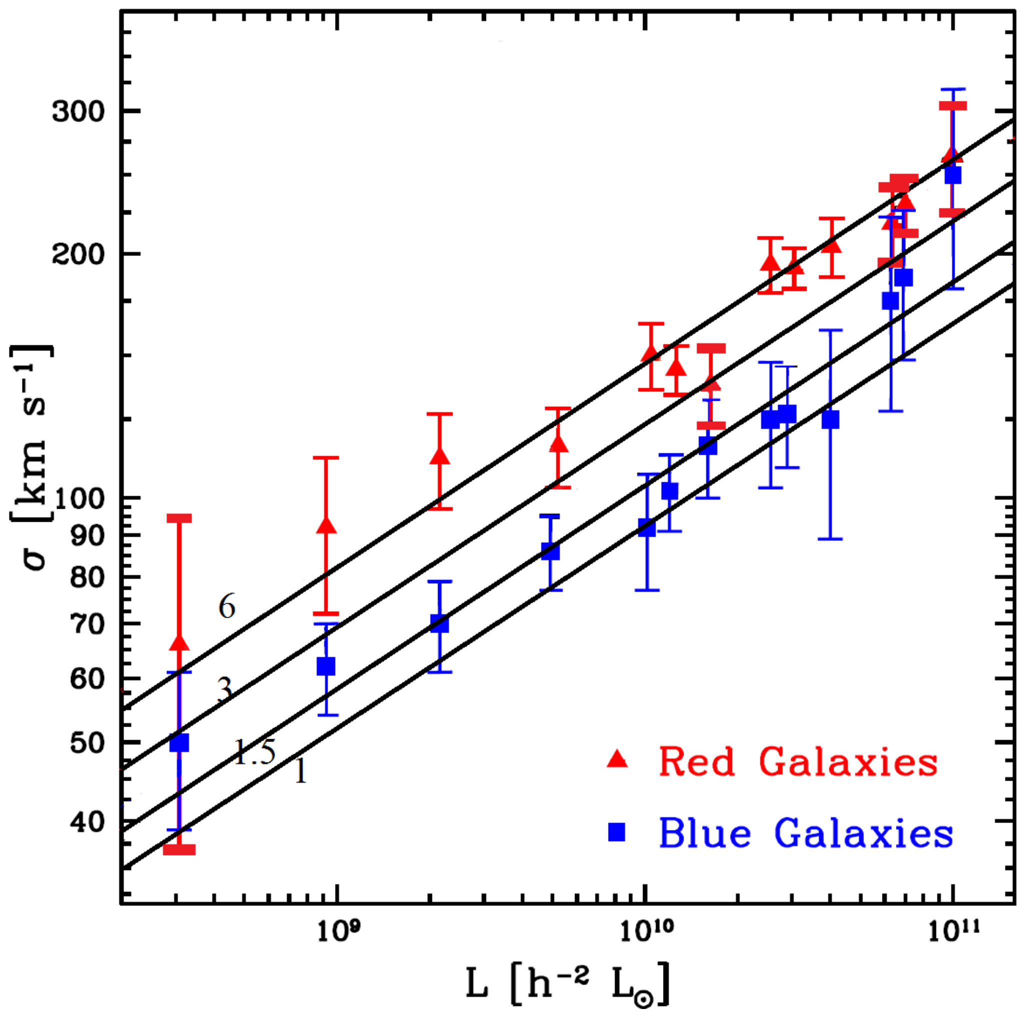
Baryon (dashed) and dynamical masses (grey band and large circles) from Humphrey et al. 2011,2012; MOND points (squares and small rings) from Milgrom 2012

Andromeda satellites–internal dynamics



McGaugh and Milgrom 2013.

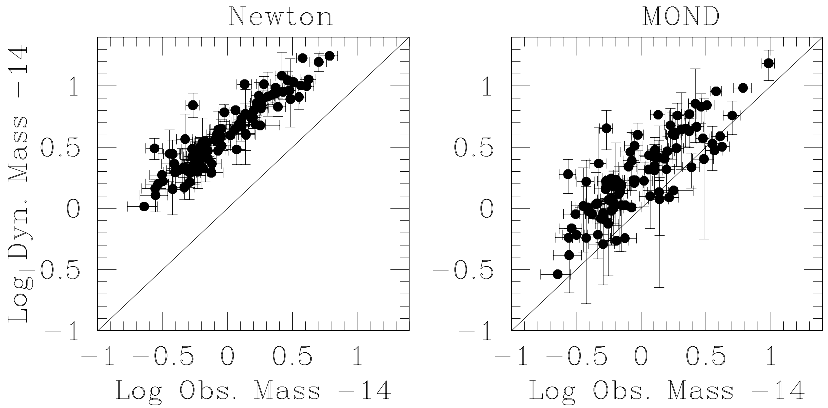
Galaxy-galaxy lensing



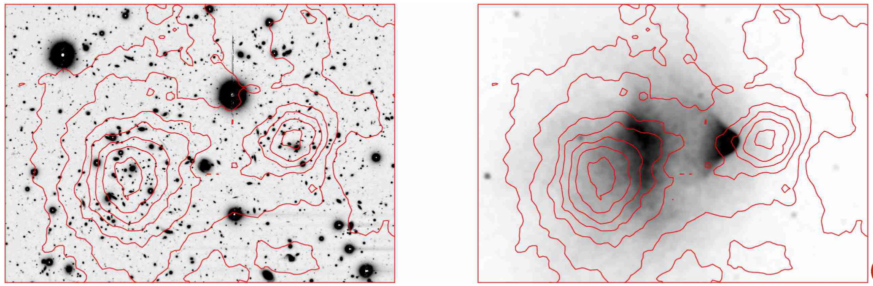
Data from Brimioulle et al. 2013, analysis from Milgrom 2013.

All is not roses

- Galaxy clusters



Sanders 1999



Clowe et al. 2006

- 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.