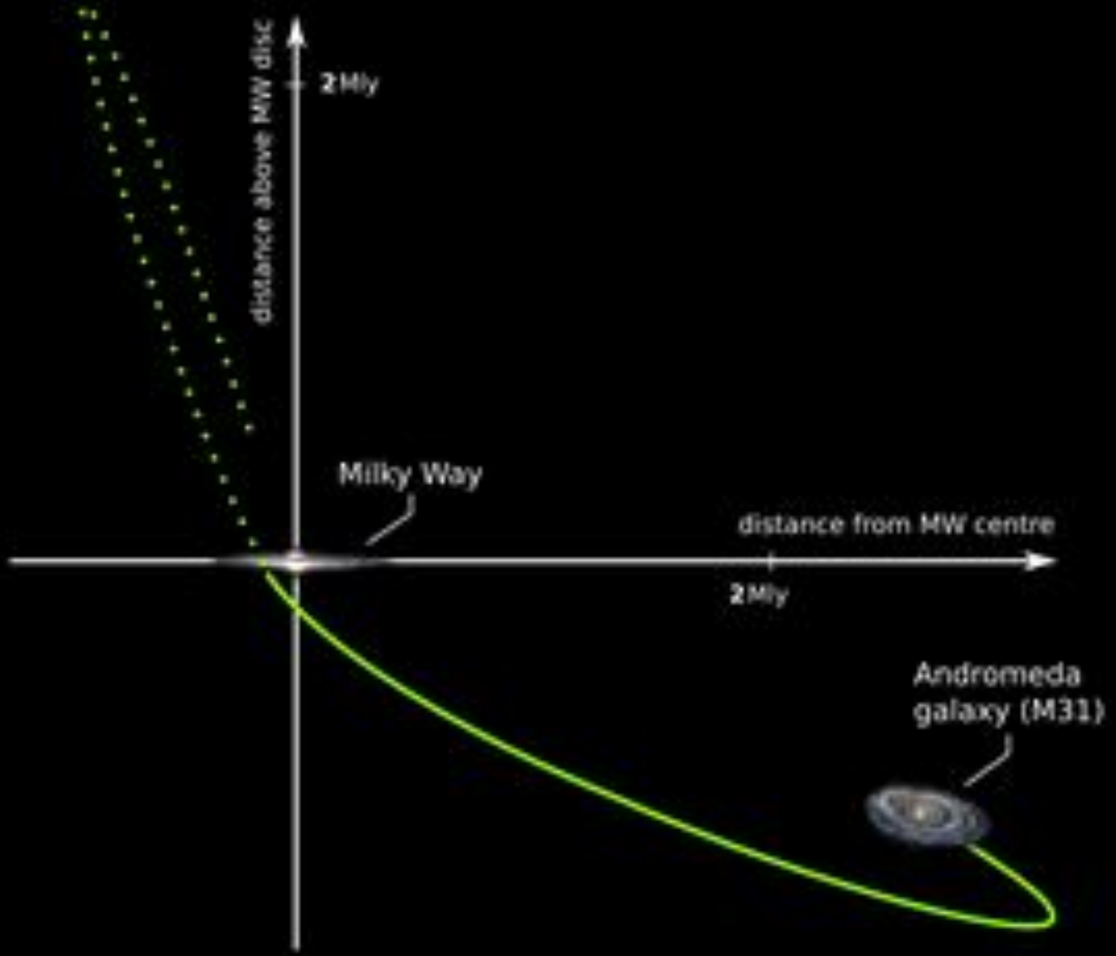
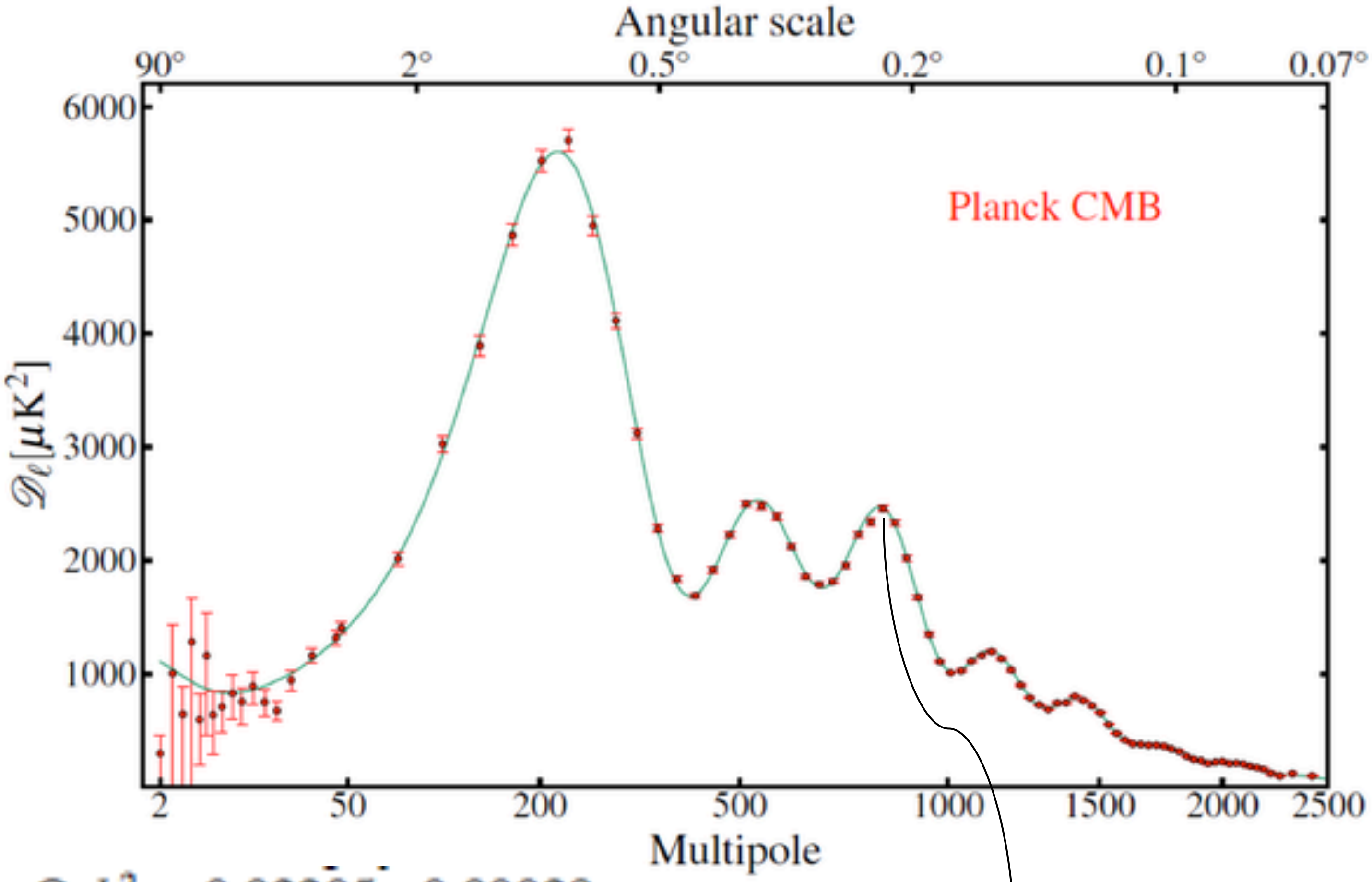
Dwarf galaxies of the Local Group as tests of gravity



B. Famaey (Observatoire Astronomique de Strasbourg)

Dark Matter



$$\Omega_b h^2 = 0.02205 \pm 0.00028$$

$$\Omega_c h^2 = 0.1199 \pm 0.0027$$

3rd peak needs net forcing term
to overcome Silk damping

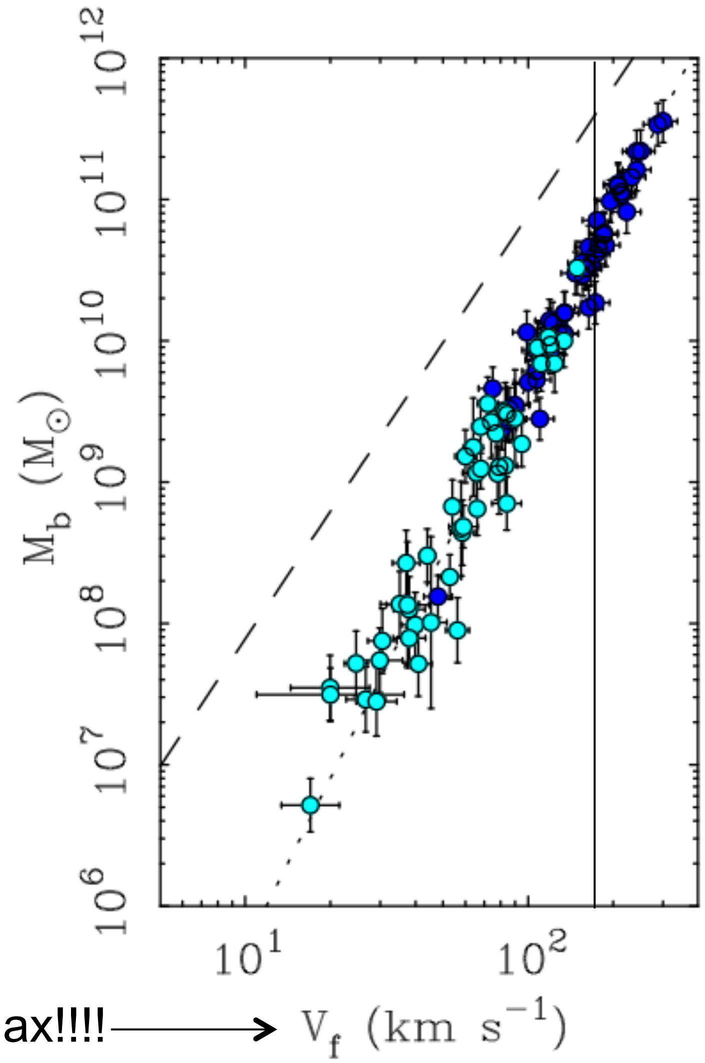
ΛCDM galaxy scale problems

« Minor » problems

- Large disks with low bulge/disk ratio
- Missing sats. Problem
- Cusp problem

Bigger problems

- Tightness of baryonic Tully-Fisher relation
- Mass Discrepancy-Surface density relation
- TBTF problem
  & sats phase-space correlation

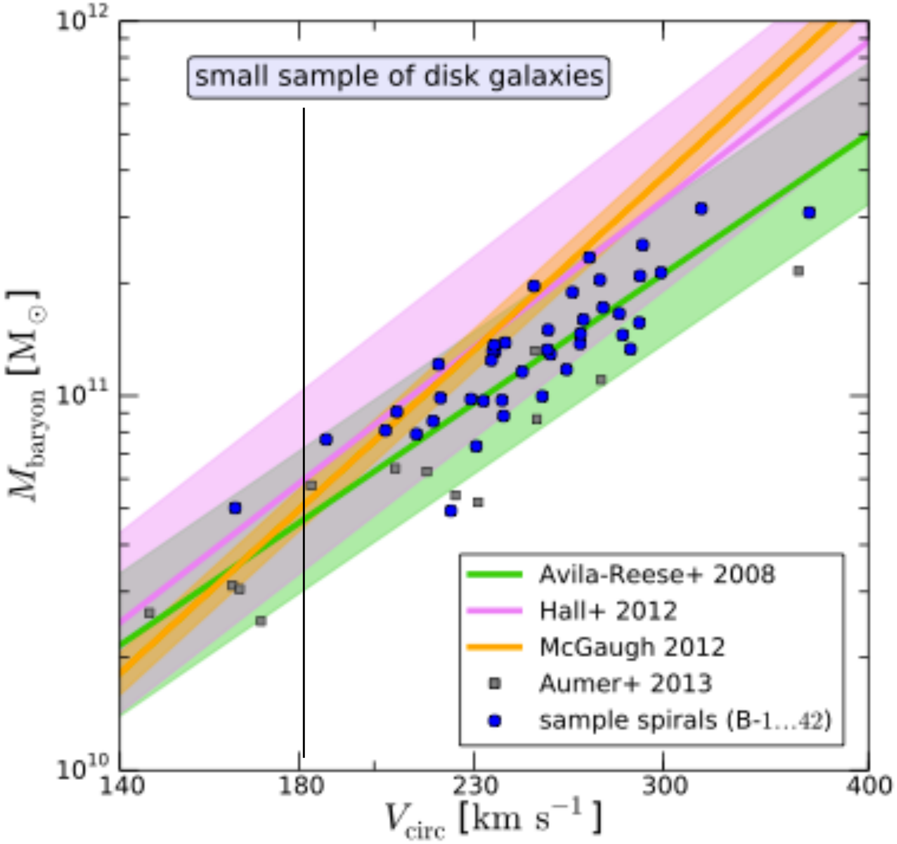


Not Vmax!!!! →

↓

Slope of 3.5 & larger scatter

McGaugh (2005, 2011)
Famaey & McGaugh (2012)



I
L
L
U
S
T
R
I
S

Baryonic Tully-Fisher relation:
$\log M_b = 4 \log V - \log \beta$

Zero-point defines an acceleration constant $a_0 \approx V^4/(GM_b) \approx 10^{-10}\ m/s^2$
Such that $\beta = G a_0$

$a_0^2 \sim \Lambda$

Effective modification of gravity by modifying DM action

$$S_{\rm DM} \equiv \int d^4x\sqrt{-g}\,[c^2(J_\mu\dot{\xi}^\mu - \rho) - W(P)],$$

Blanchet & Le Tiec 2009

$$\boxed{\begin{gathered}\frac{d\mathbf{v}}{dt} = \mathbf{g} - \mathbf{f},\\ \frac{d^2\boldsymbol{\xi}}{dt^2} = \mathbf{f} + \frac{1}{\rho}\nabla[W(P) - PW'(P)] + (\mathbf{P}\nabla)\mathbf{g},\\ -\nabla.(\mathbf{g} - 4\pi\mathbf{P}) = 4\pi G(\rho_b + \rho).\end{gathered}}$$

$$W(P) \propto \Lambda/(8\pi) + 2\pi P^2 + 16\pi^2 P^3/(3a_0) + \mathcal{O}(P^4)$$

$$g \propto -W'(P) \longrightarrow$$

MOND, i.e., $g = (g_n\, a_0)^{1/2}$
in weak field $g << a_0$

Milgrom 1983

Reproduces CMB & all ΛCDM cosmology to first order in perturbations !!

Some laws of galactic dynamics deriving from MOND

1) ~1/r acceleration → V_∞ = cst and isothermal « dark halo » to large r

2) $V^2/r = (GMa_0)^{1/2}/r$ at large r → baryonic Tully-Fisher relation

3) $V^2/r = a_0$ as a transition acceleration

4) a_0/G as critical surface density for disk stability since $\delta a/a = \delta M/2M$ instead of $\delta M/M$

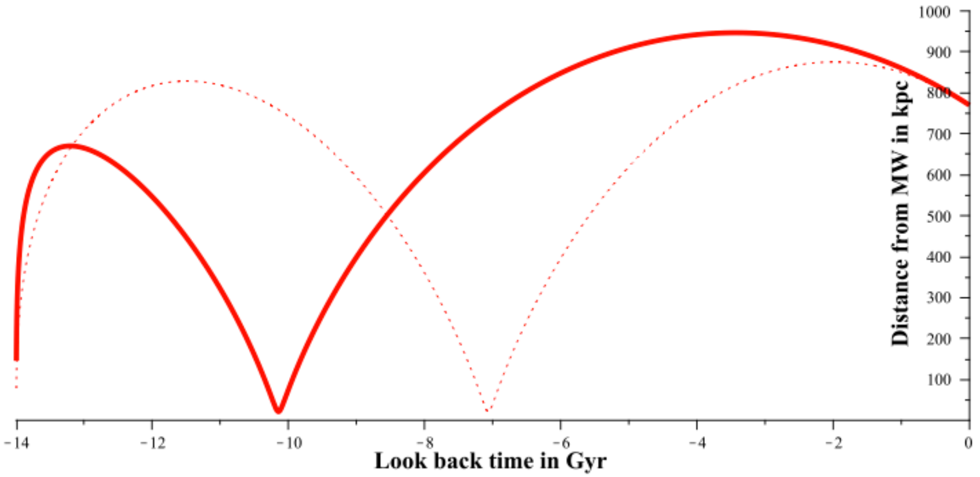
5) Correlation between the value of the average baryonic surface density and **steepness** of RC

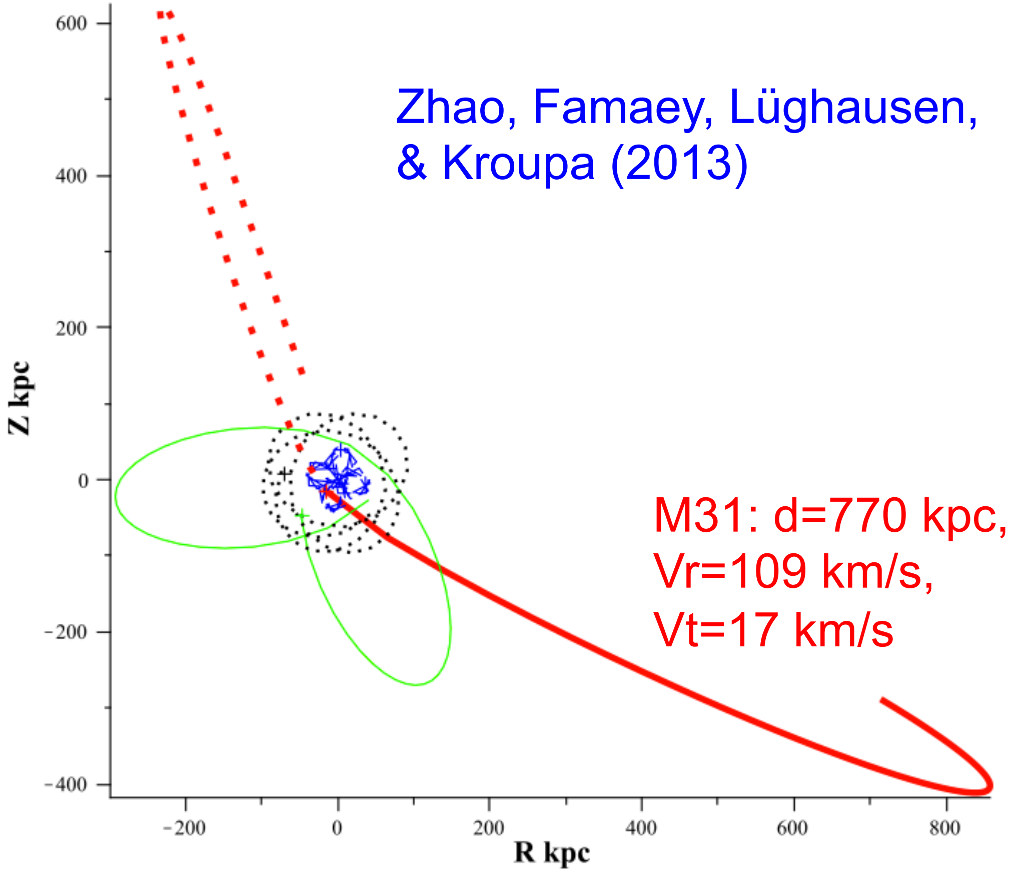
6) Features in the baryonic distribution imply features in the RC

7) **External field effects**

Local Group Orbits

$$F_{2\mathrm{body}} = \frac{2}{3}\left[(m_1+m_2)^{3/2} - m_1^{3/2} - m_2^{3/2}\right]\frac{\sqrt{Ga_0}}{r}, \quad \frac{d^2}{dt^2}\mathbf{r}_{12} = K\mathbf{r}_{12} - \frac{m_1+m_2}{m_1}\left[\frac{\mathbf{F}_{12}}{m_2}\right], \quad K \equiv \frac{\mathrm{d}^2 a}{a\mathrm{d}t^2}$$





Zhao, Famaey, Lüghausen, & Kroupa (2013)

M31: d=770 kpc,
Vr=109 km/s,
Vt=17 km/s

$$F_{12} \approx \frac{\tilde{G}m_1m_2}{r_{12}^2}, \quad \tilde{G} \equiv G\left[1+\left(y+\frac{g_{\mathrm{ext}}^2}{a_0^2}\right)^{-\alpha}\right]^{\frac{1}{2\alpha}}$$

$$y \equiv \left[\frac{\sqrt{G(m_1+m_2)a_0}}{r_{12}Qa_0}\right]^2, \quad Q \equiv \frac{2(1-q_1^{3/2}-q_2^{3/2})}{3q_1q_2} \text{ and } q_1 \equiv 1-q_2 \equiv \frac{m_1}{m_1+m_2}$$

M31 dwarfs

Deep-MOND virial relation $\sigma_{iso} \approx (\frac{4}{81} M G a_0)^{1/4}$ $\sigma_{efe} \approx (\frac{M G_{eff}}{3 r_{1/2}})^{1/2}$

In McGaugh & Milgrom (2013): 16/17 ok, only AndV problematic (too low prediction of 5 km/s w.r.t. measured 10 km/s)

A priori predictions compared to Collins et al. (2013) and Tollerud et al. (2013): correct for And XVII, **And XIX**, And XX, **And XXI**, And XXIII, **And XXV**, And XXVIII & And XIX**=>large dSph with low σ because EFE**

Further predictions: And XXX (Cass II): 3.5+- 1.5 km/s
And XXXI (Lac I): 9+-1.5 km/s
And XXXII (Cass III): 10.3+-1.7 km/s

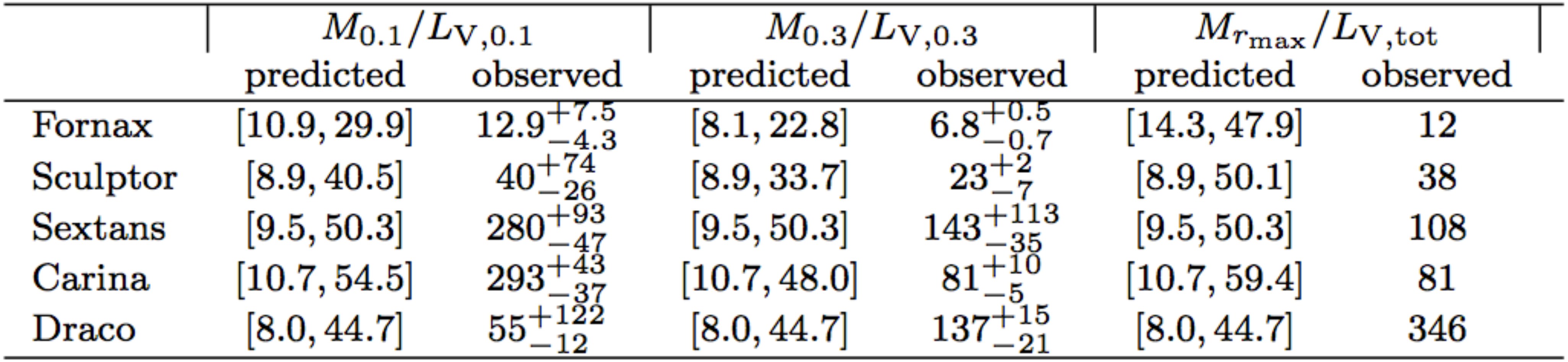
McGaugh
& Milgrom
(2013b)

For Local Group dwarfs:
Perseus I: 6.5+-1.1 km/s
Cetus: 8.2+-1.5 km/s
Tucana: 5.5+-1 km/s

Pawlowski
& McGaugh
(2014)

MW classical dwarfs

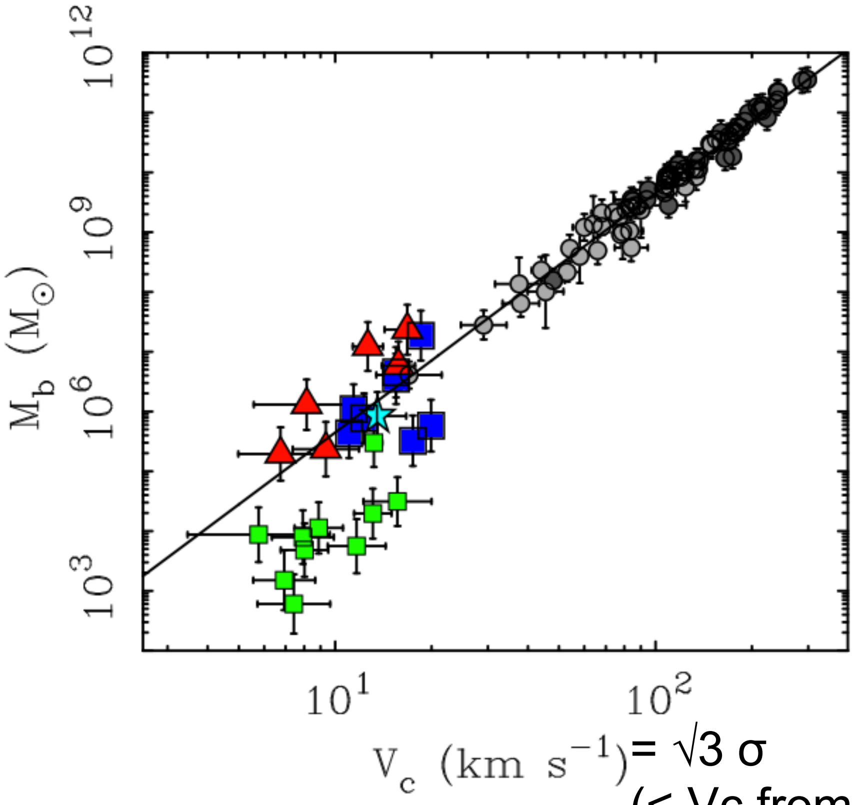
Lüghausen, Famaey & Kroupa 2014



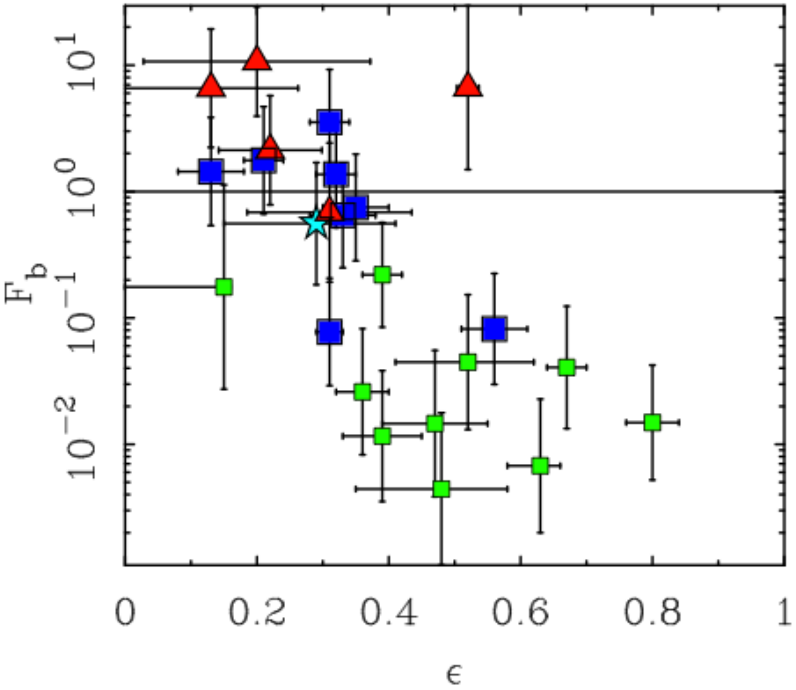
	$M_{0.1}/L_{\mathrm{V},0.1}$		$M_{0.3}/L_{\mathrm{V},0.3}$		$M_{r_{\max}}/L_{\mathrm{V},\mathrm{tot}}$	
	predicted	observed	predicted	observed	predicted	observed
Fornax	$[10.9, 29.9]$	$12.9^{+7.5}_{-4.3}$	$[8.1, 22.8]$	$6.8^{+0.5}_{-0.7}$	$[14.3, 47.9]$	12
Sculptor	$[8.9, 40.5]$	40^{+74}_{-26}	$[8.9, 33.7]$	23^{+2}_{-7}	$[8.9, 50.1]$	38
Sextans	$[9.5, 50.3]$	280^{+93}_{-47}	$[9.5, 50.3]$	143^{+113}_{-35}	$[9.5, 50.3]$	108
Carina	$[10.7, 54.5]$	293^{+43}_{-37}	$[10.7, 48.0]$	81^{+10}_{-5}	$[10.7, 59.4]$	81
Draco	$[8.0, 44.7]$	55^{+122}_{-12}	$[8.0, 44.7]$	137^{+15}_{-21}	$[8.0, 44.7]$	346

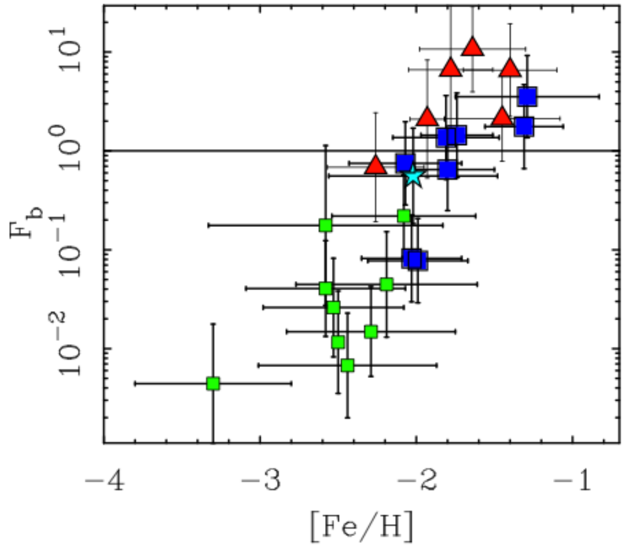
MW ultrafaints

McGaugh & Wolf 2010



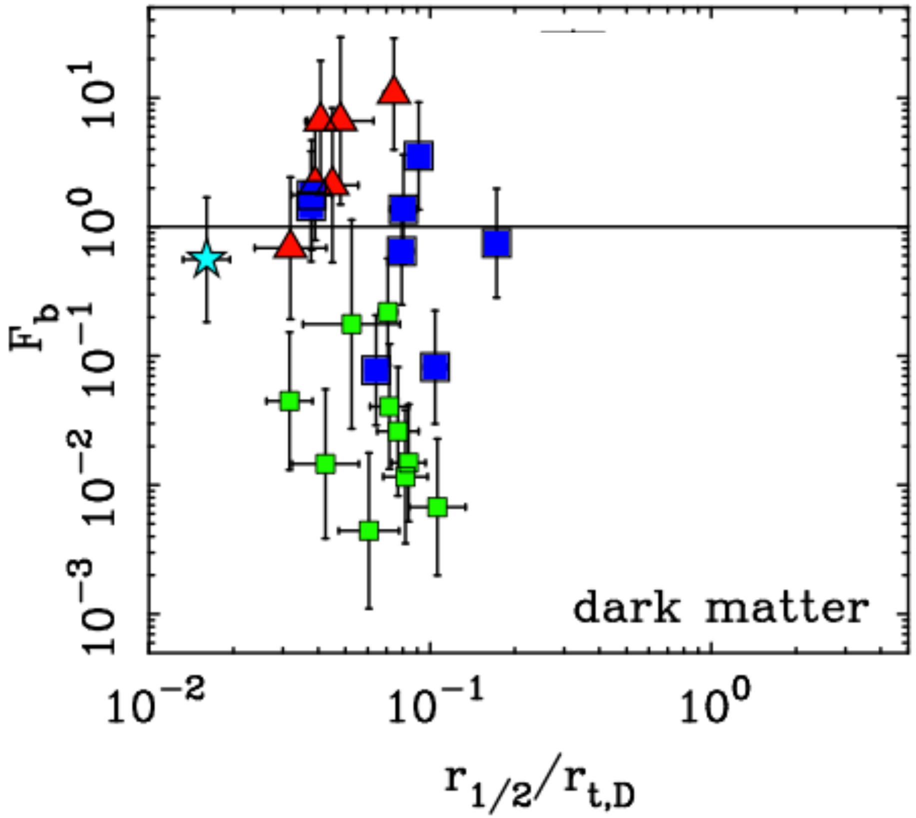
= √3 σ
(< Vc from virial relation)

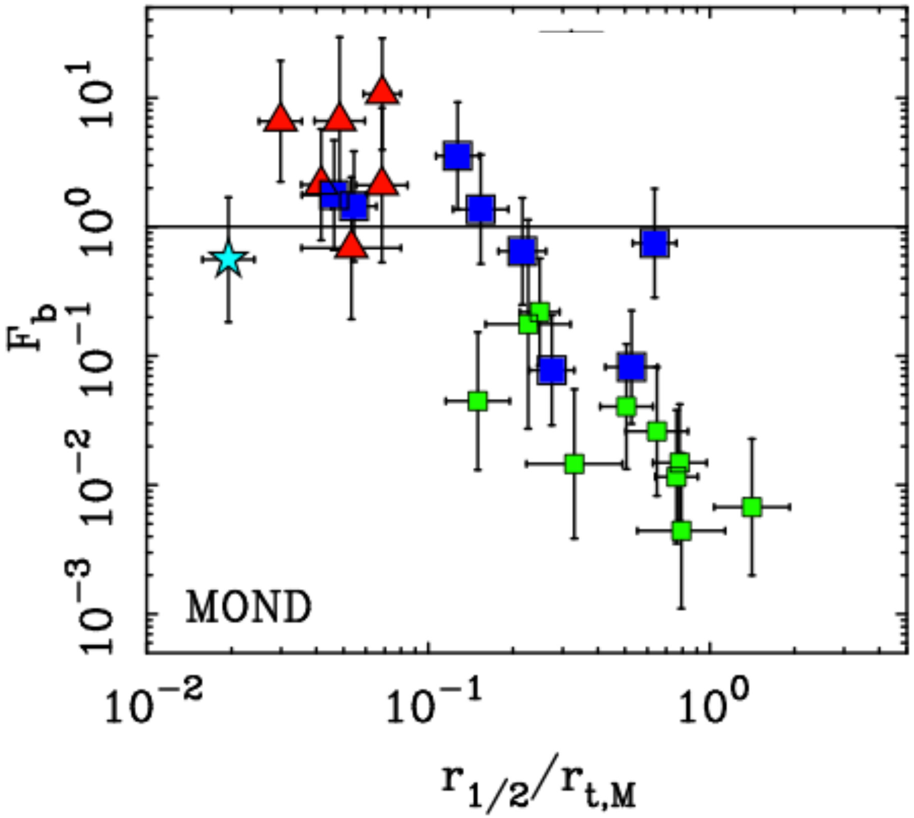




MW ultrafaints

McGaugh & Wolf 2010





$$r_{t,D} = D\left(\frac{m}{3M}\right)^{1/3}$$

$$r_{t,M} = D\left(\frac{m}{2M}\right)^{1/3}$$

Conclusion

- Independently from the theoretical framework, the MOND formula is an extremely efficient way (AND CURRENTLY THE ONLY WAY) of **predicting** the gravitational field in galaxies (hence σ of dSphs)

- MOND in the LG => past interaction between MW & M31 ~11 Gyr ago => might have triggered TDGs and observed VPOS and GPoA

- **The (very) few TDGs with RC are on the BTFR** (in NGC 5291 system)

- **M31 dwarfs & isolated LG dwarfs follow MOND predictions**

- Classical MW dwarfs ok, but Carina needs quite high stellar M/L~5, Draco needs outliers or binaries to decrease observed dispersion

-**Ultrafaints far off the MOND predictions**=>binaries + nonequilibrium dynamics? Or exclude MOND phenomenology on these scales and/or for pressure supported systems if one trusts observed σ & equilibrium