Phenomenology of galaxy dynamics

or why is MOND still relevant?

Famaey & McGaugh 2012 (Living Reviews in Relativity)

arXiv:1112.3960

B. Famaey (Observatoire Astronomique de Strasbourg)

Particle dark matter

Definition: Particle Dark Matter is

- A collisionless and dissipationless fluid of stable elementary **particles**
- Which interact with each other and with baryons (almost) entirely **through gravity**
- **Immune** to hydrodynamical influences (does not have any other peculiar property to interact with baryons)
- **Cold or warm** to form small enough structures
- **Completely unrelated to dark energy**

Could our understanding be incomplete or wrong?

1) First hints towards (at least) incompleteness: **coincidences**

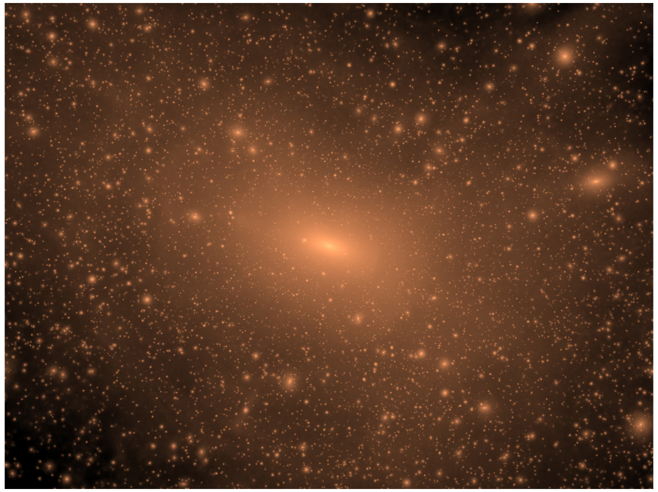
- Ω_m and Ω_Λ same order of magnitude at z=0… why?

- Ω_b and Ω_{DM} within 1 order of magnitude too, but baryon asymmetry for Ω_b and thermal freeze-out for dark matter supposedly unrelated --> ??

Suggests a possible link between the three

But only a possible hint, not a very strong argument

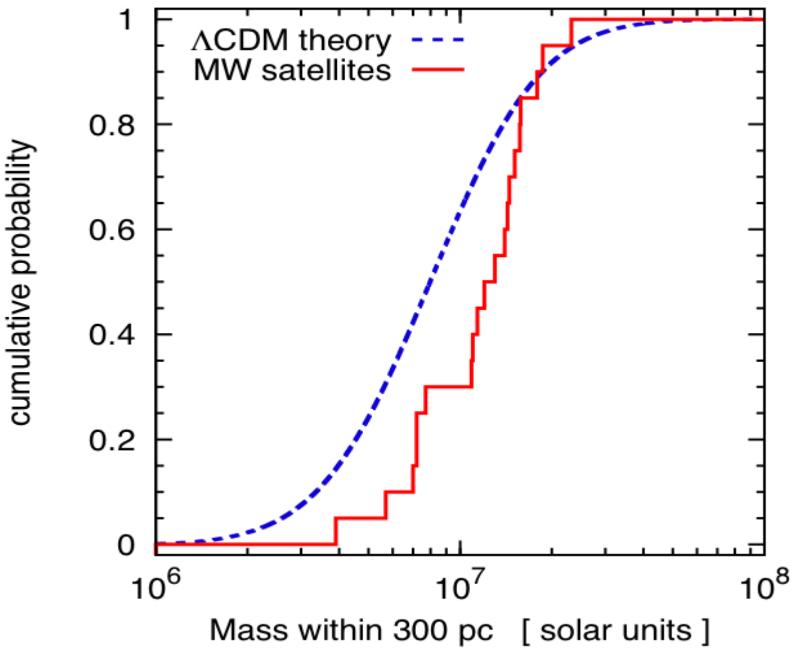
2) Second hints: **dwarf galaxies paucity and geometry**



Many new ultra-faint dwarfs have been found around the MW (Segue1, Hercules…)

-> Is the missing satellite problem solved?

No: the shape of the mass function disagrees with the expectations from CDM



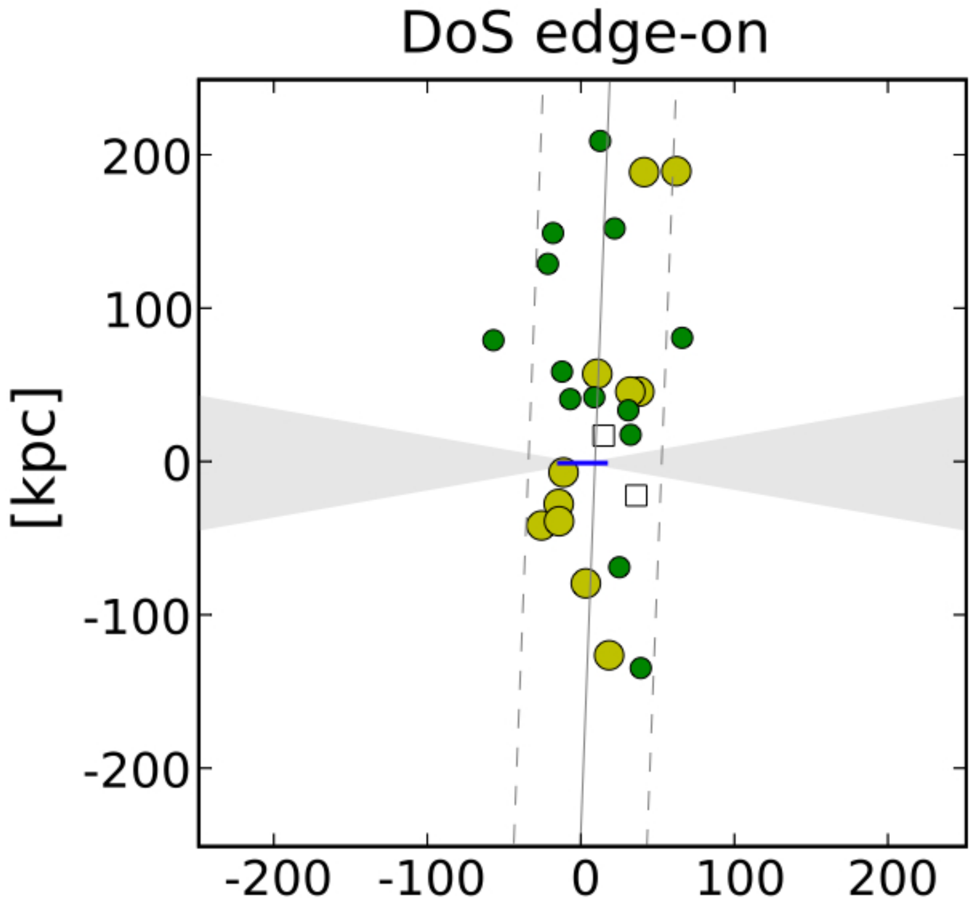
$$\xi_{\rm lum}(M_{\rm vir}) = k k_i M_{\rm vir}^{-\alpha_i},$$

with

$$\alpha_1 = 0, \quad k_1 = 1, \quad 10^7 \le \frac{M_{\rm vir}}{M_\odot} < 10^9,$$
$$\alpha_2 = 1.9, \quad k_2 = k_1\,(10^9)^{\alpha_2-\alpha_1}, \quad 10^9 \le \frac{M_{\rm vir}}{M_\odot} \le M_{\rm max},$$

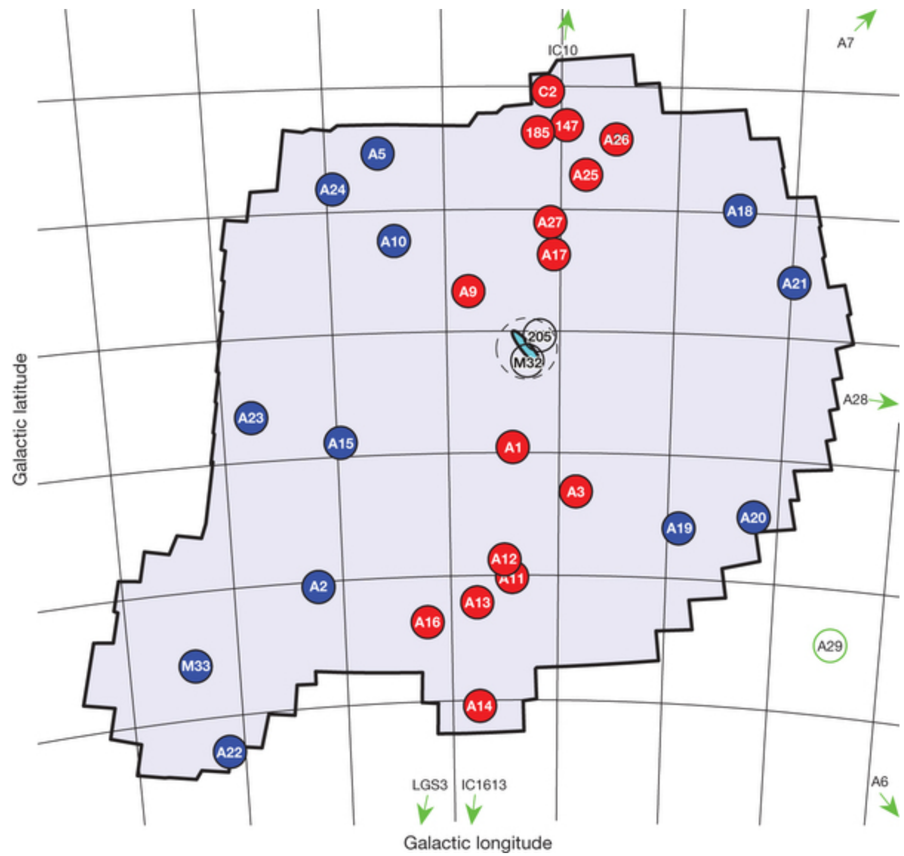
Kroupa, Famaey, et al. (2010)

Milky Way



Kroupa, Famaey, et al. (2010)

Andromeda



Ibata et al. (2013)

3) The fine-tuned **relative distribution of baryons and DM** in galaxies

Most current research concentrates on

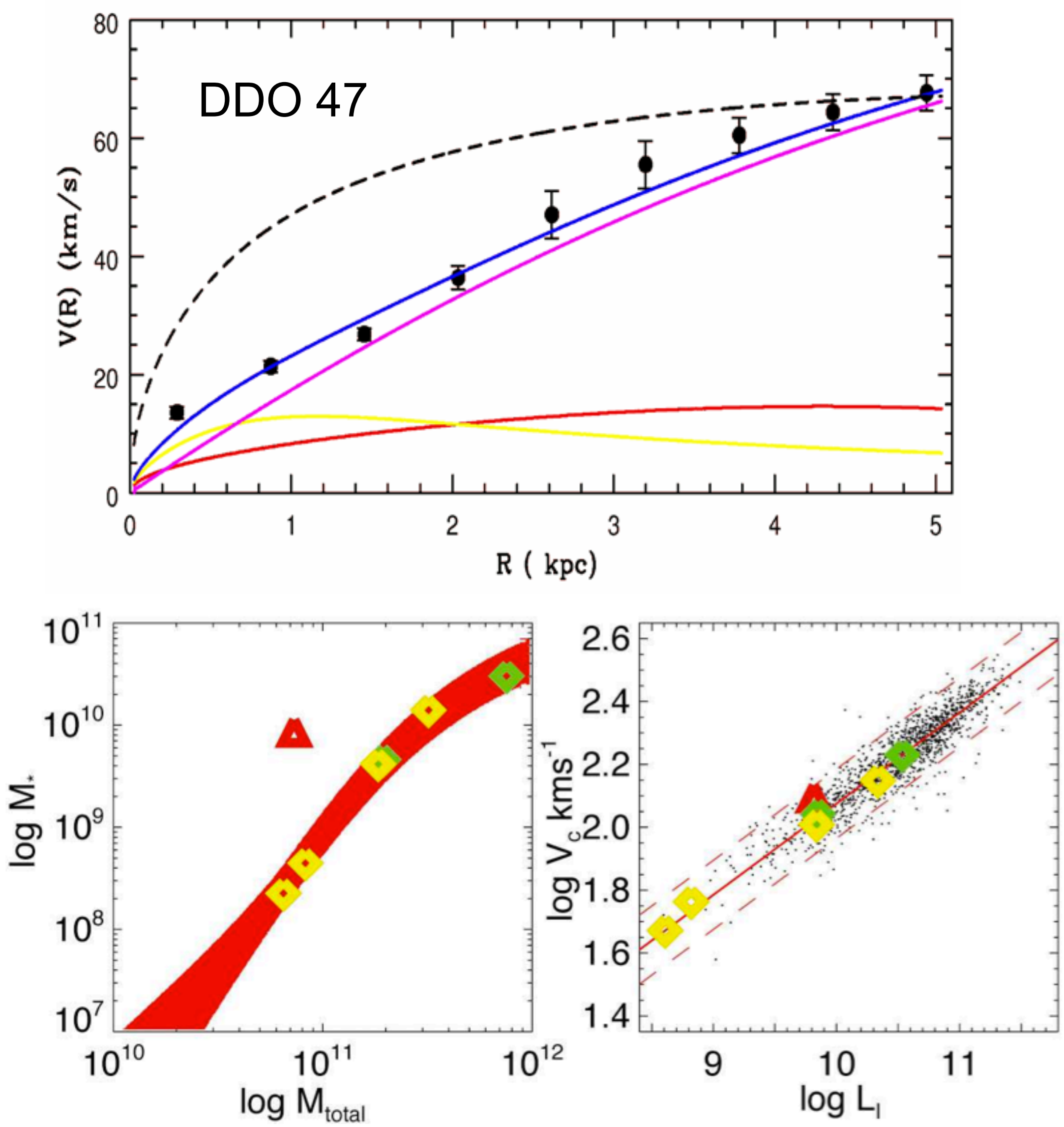
strong feedback to :

1) Erase r^{-1} DM cusps and

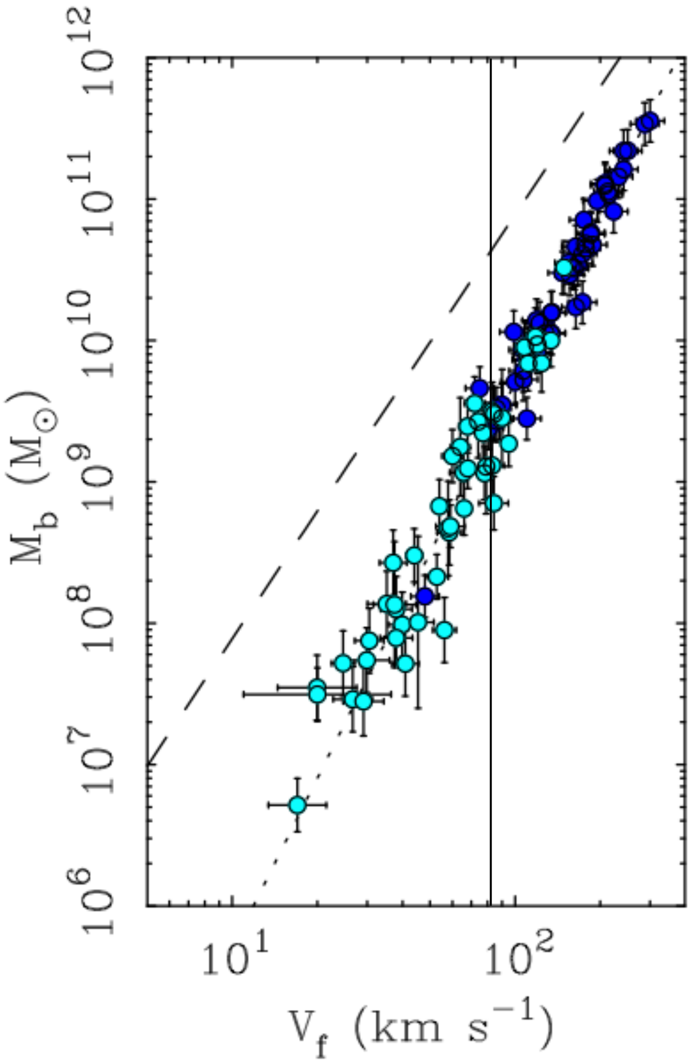
2) Create large disks with low bulge/disk ratio

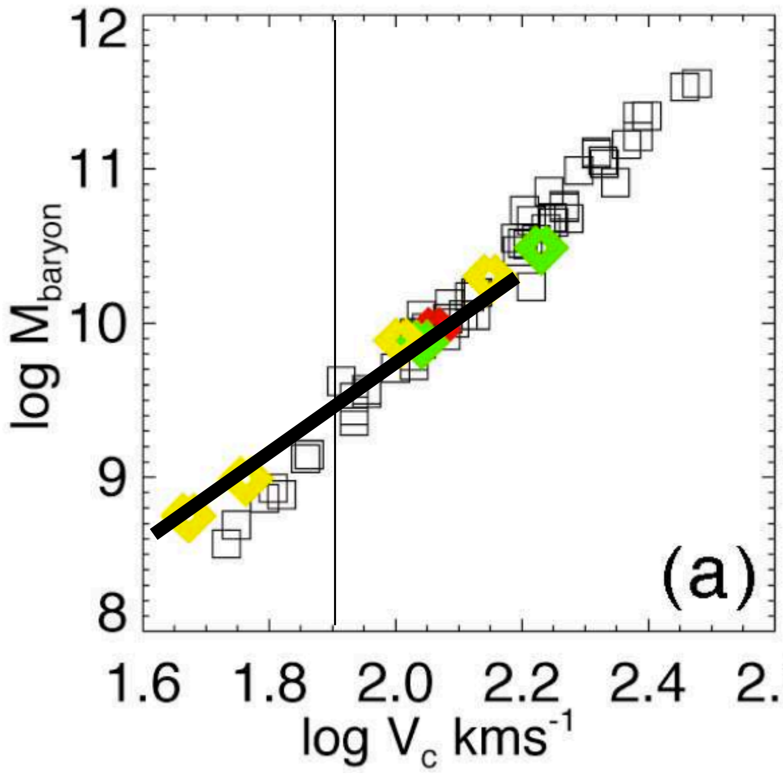
while keeping consistency with lum. function, stellar mass fraction and luminous Tully-Fisher relation

But observational situation is actually **much worse** than this…



Brook et al. (2012)





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

Baryonic Tully-Fisher relation:

$\log M_b = 4 \log V - \log \beta$

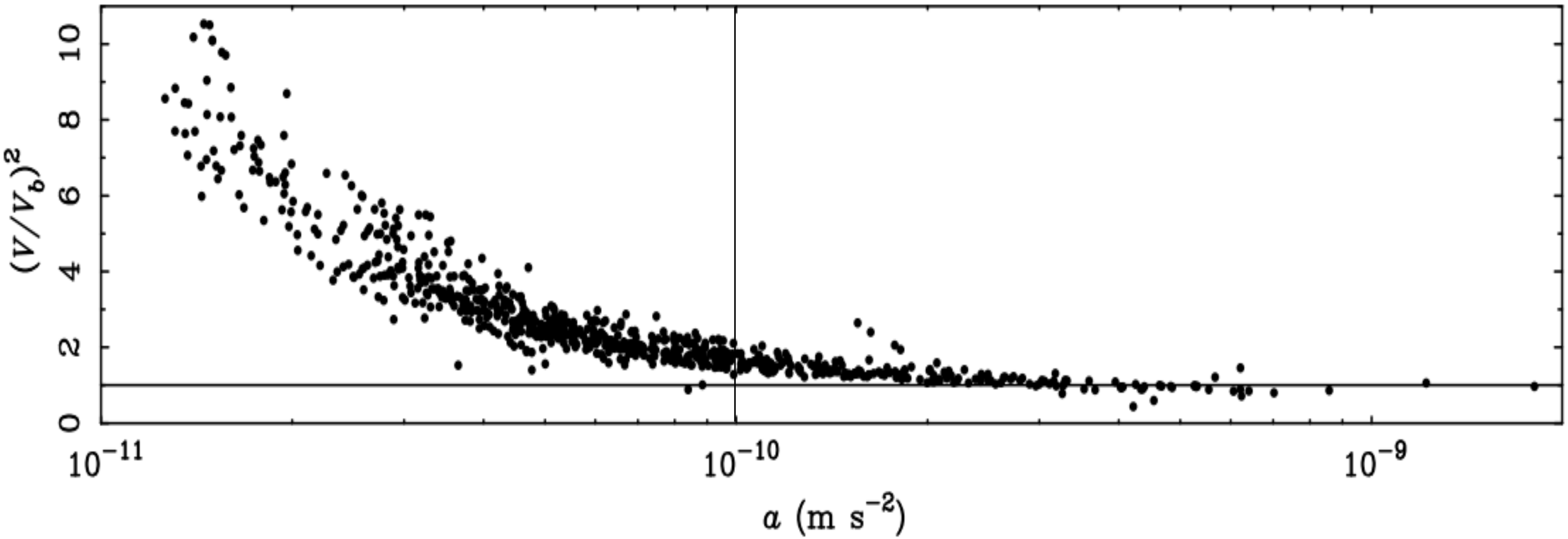
Zero-point defines an acceleration constant $a_0 \approx V^4/(GMb) \approx 10^{-10}\ m/s^2$

Such that $\beta = G a_0$

$a_0^2 \sim \Lambda$

The same acceleration constant a_0 plays the role of a **transition acceleration** where the dynamical effects of DM appears:

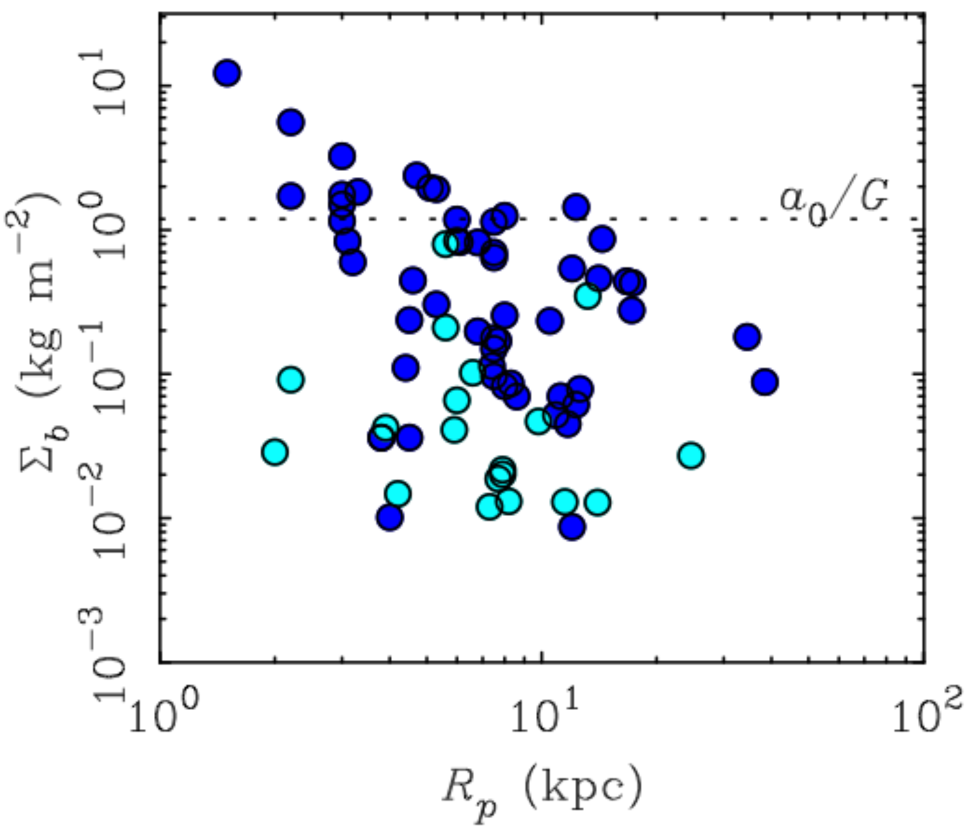
In the DM framework this is a fully **independent** role of a_0

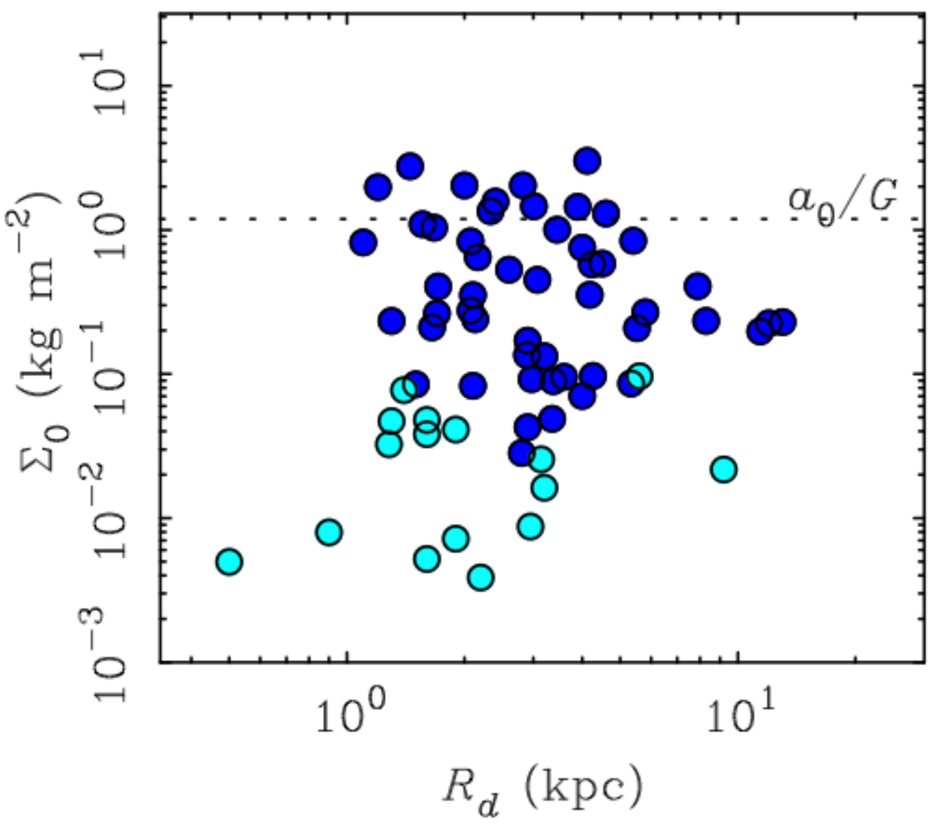


McGaugh (2004)
Famaey & McGaugh (2012)

The same acceleration constant a_0 defines a critical baryonic surface density for disk stability a_0/G

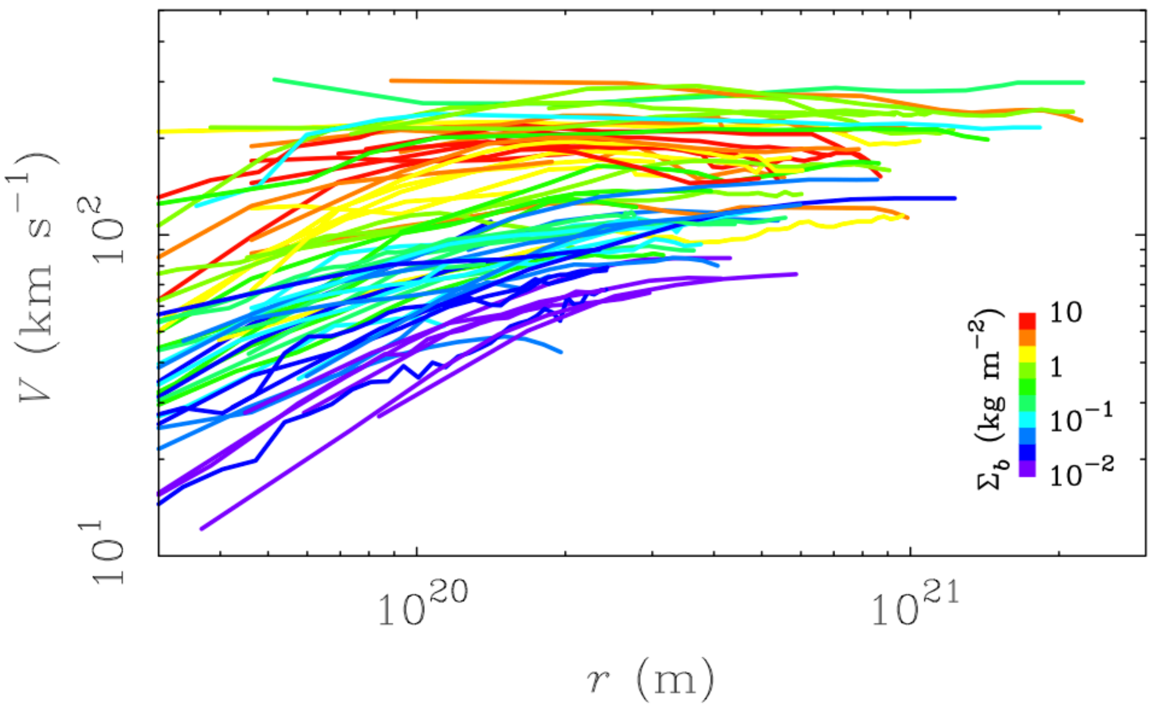
In the DM framework yet another fully **independent** role of a_0



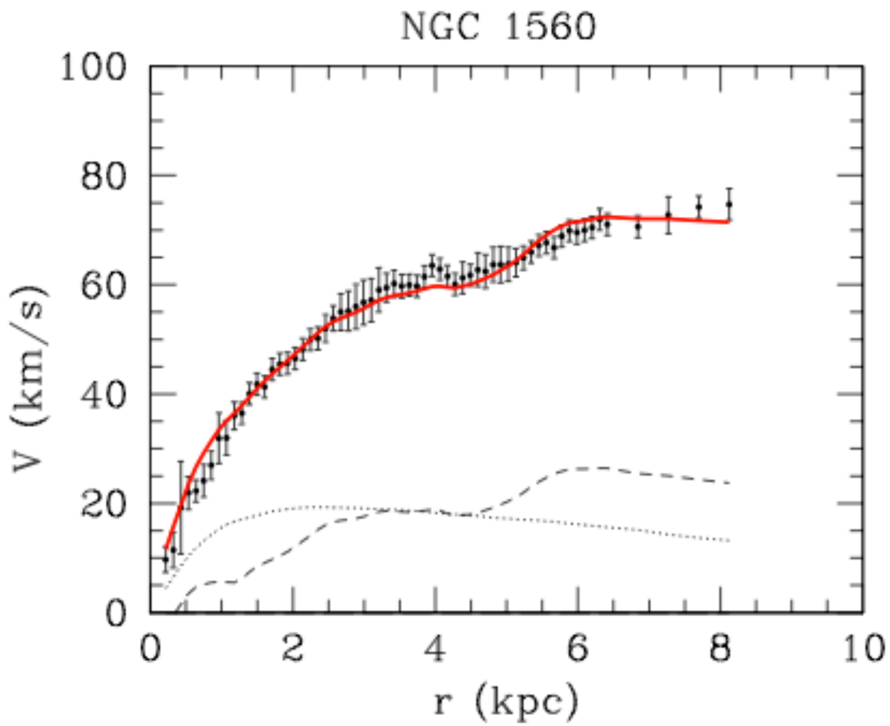


Famaey & McGaugh (2012)

The baryonic surface density (or characteristic acceleration) also determines **the shape of rotation curves:** huge fine-tuning



Famaey & McGaugh (2012)

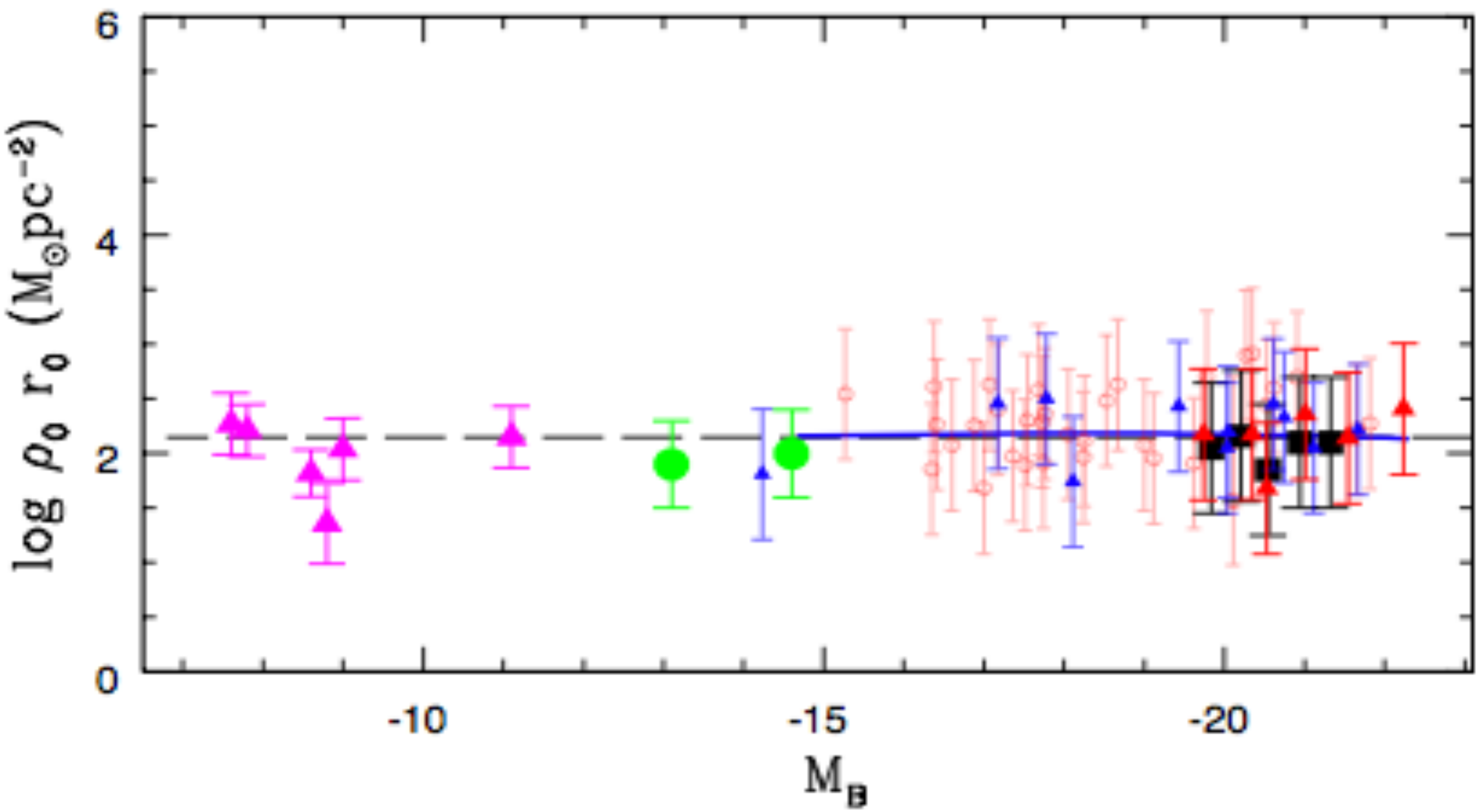


Gentile et al. (2010)

The same acceleration constant a_0 defines a typical **DM halo surface density** $\rho_0 r_0 \approx a_0/(2\pi G)$

where $\rho_{dm} = \rho_0 r_0^3/[(r + r_0)(r^2 + r_0^2)]$

In the DM framework yet another fully **independent** role of a_0



Donato et al. (2009); Gentile, Famaey, et al. (2009)

MOND

All these independent occurrences of a_0 in galaxy kinematics have been **a priori predicted** by Milgrom (1983) 30 years ago…

Milgrom's law in its simplest form:

$$\boxed{\begin{array}{ll} g = g_N & \text{if } g \gg a_0 \\ g = (g_N\, a_0)^{1/2} & \text{if } g \ll a_0 \end{array}}$$

Transition ideally determined from some deeper theory (can depend on type of orbit)

Note: formally, deep-MOND limit for $\boldsymbol{a_0 \rightarrow \infty}$ and $\boldsymbol{G \rightarrow 0}$

MOND laws of galactic dynamics

1) ~1/r acceleration → V_∞ = cst

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 $\delta a/a = \delta M/2M$

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

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

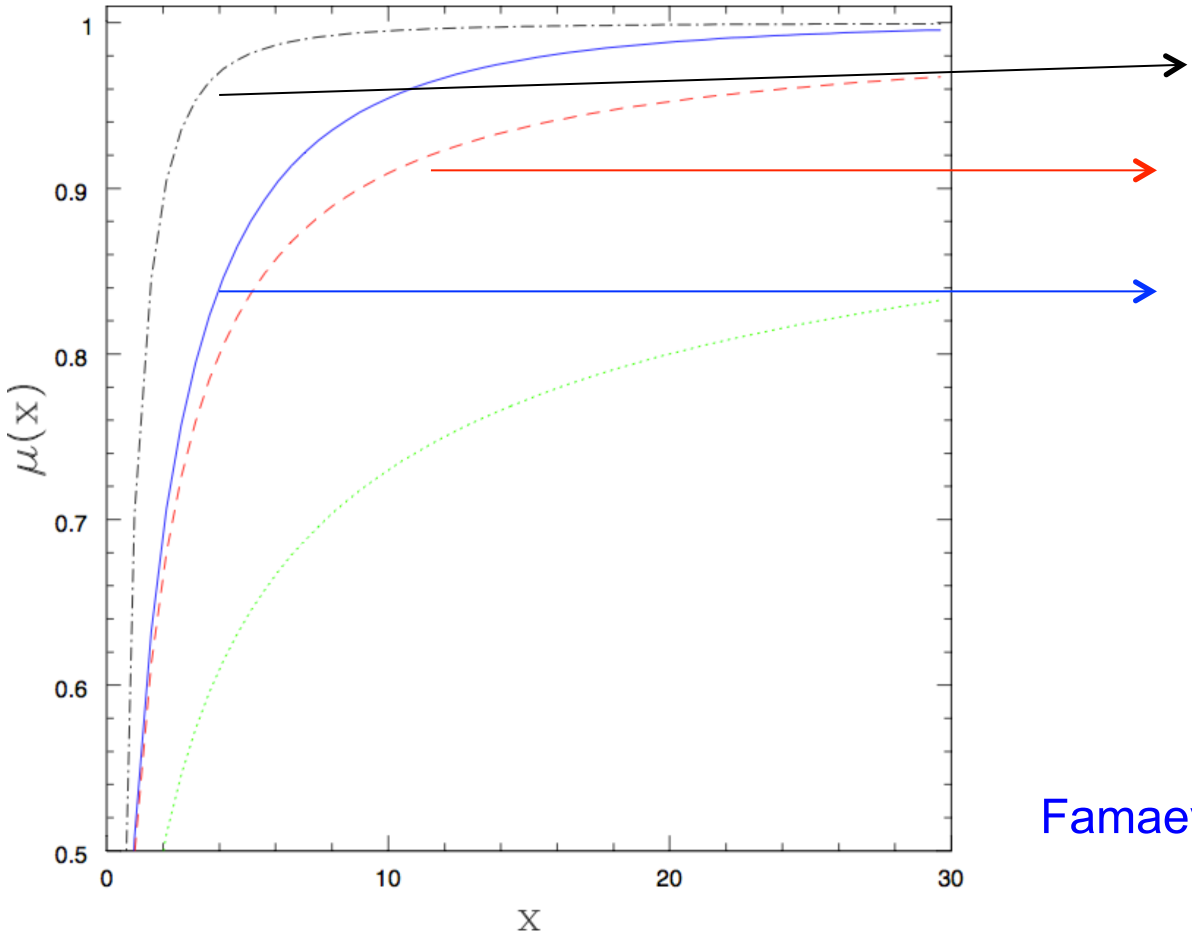
7) *$a_0/(2\pi G)$ characteristic central surface density of dark halos*

In practice

$\mu\,(g/a_0)\,g = g_{\mathrm{N\,bar}}$ or $\nu\,(g_{\mathrm{N\,bar}}/a_0)\,g_{\mathrm{N\,bar}} = g$

with $\mu(x) = x$ or $\nu\,(x) = x^{-1/2}$ for $x \ll 1$ (deep-MOND)

$\mu(x) = \nu\,(x) = 1$ for $x \gg 1$ (Newtonian)



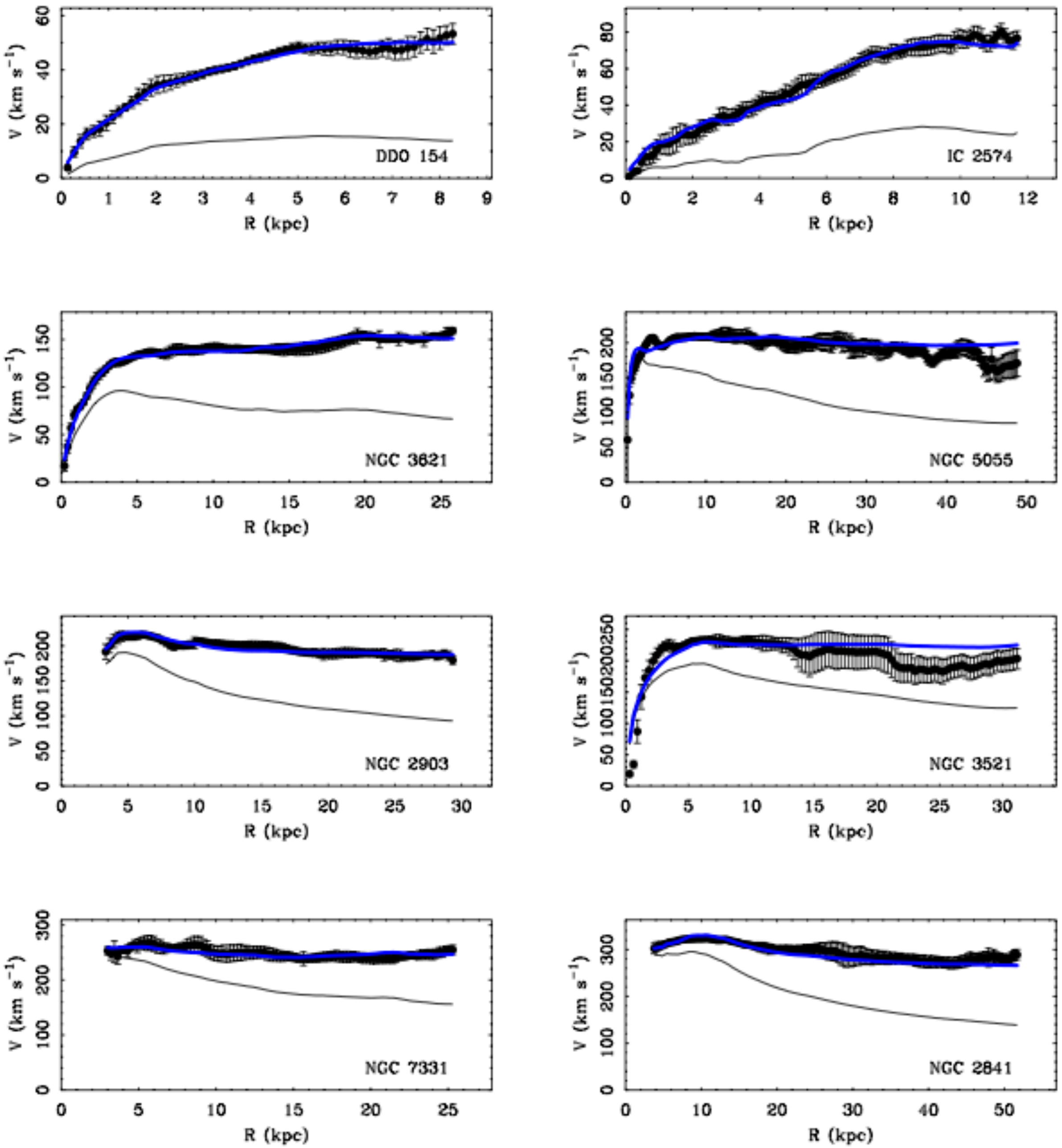
$\mu(x) = x/(1+x^2)^{1/2}$

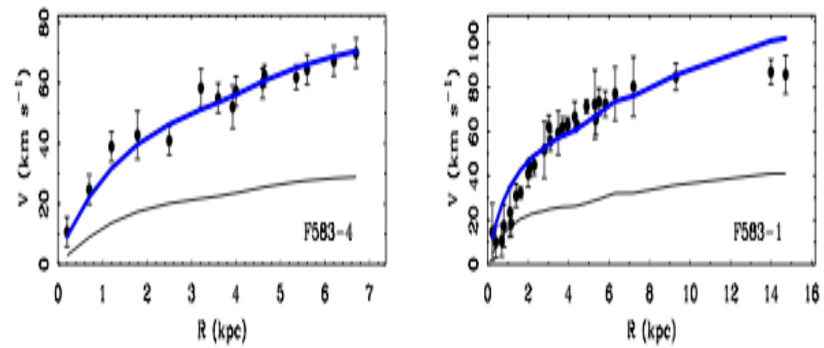
$\mu(x) = x/(1+x)$

$\nu(x) = 1/[1-\exp(-x^{1/2})]$

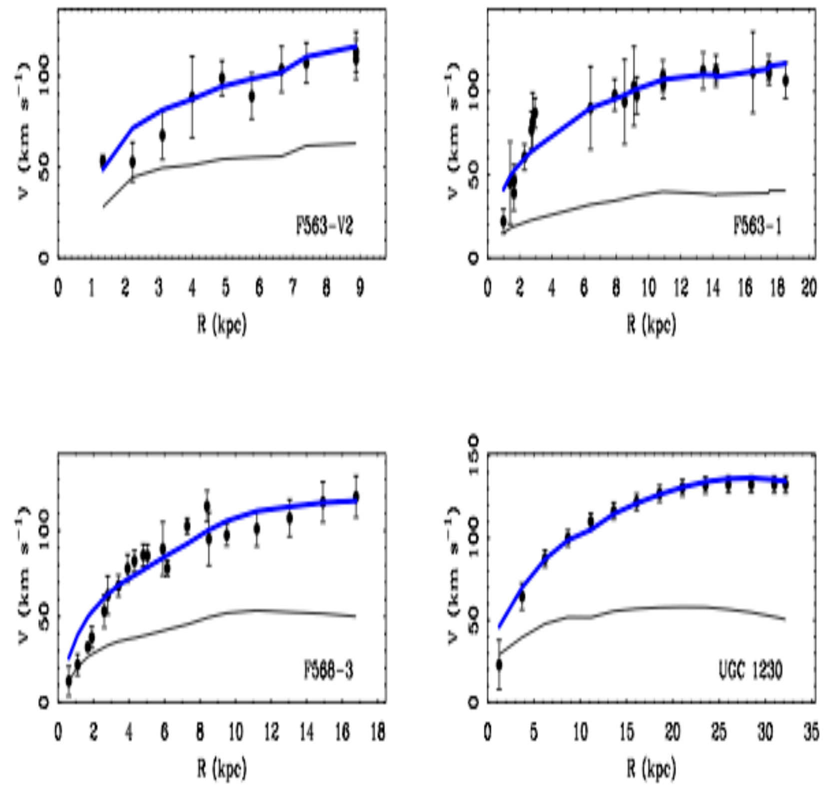
Famaey & McGaugh (2012)

Rotation curves

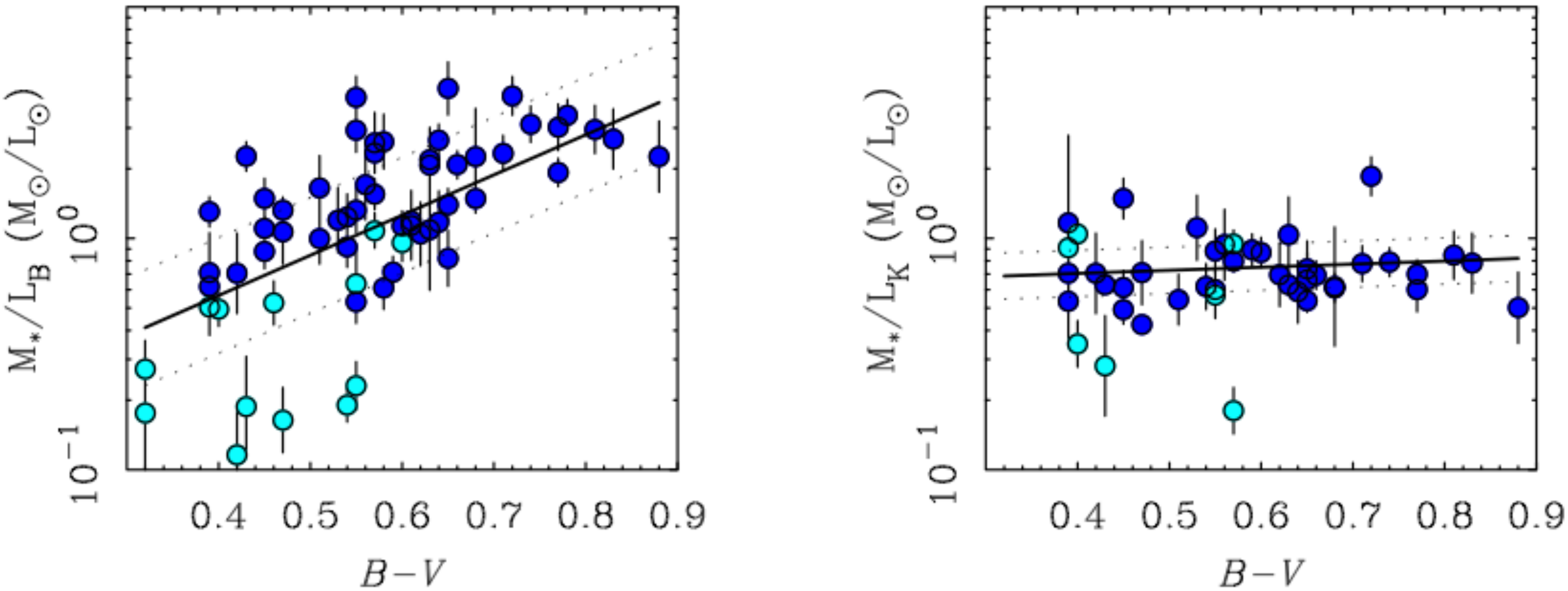




$\nu(x) = 1/[1- \exp(-x^{1/2})]$

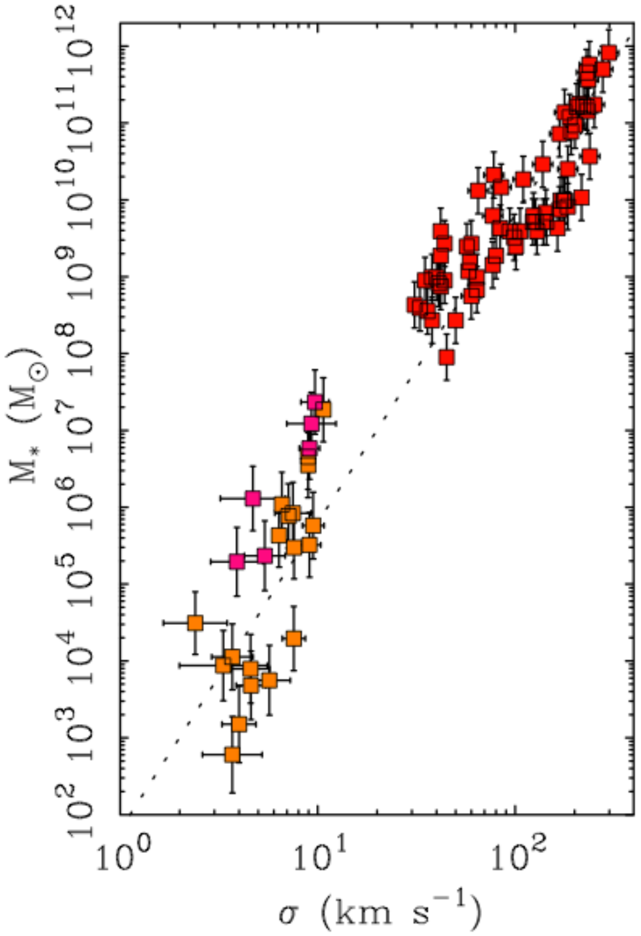


Famaey & McGaugh (2012); Gentile, Famaey & de Blok 2011

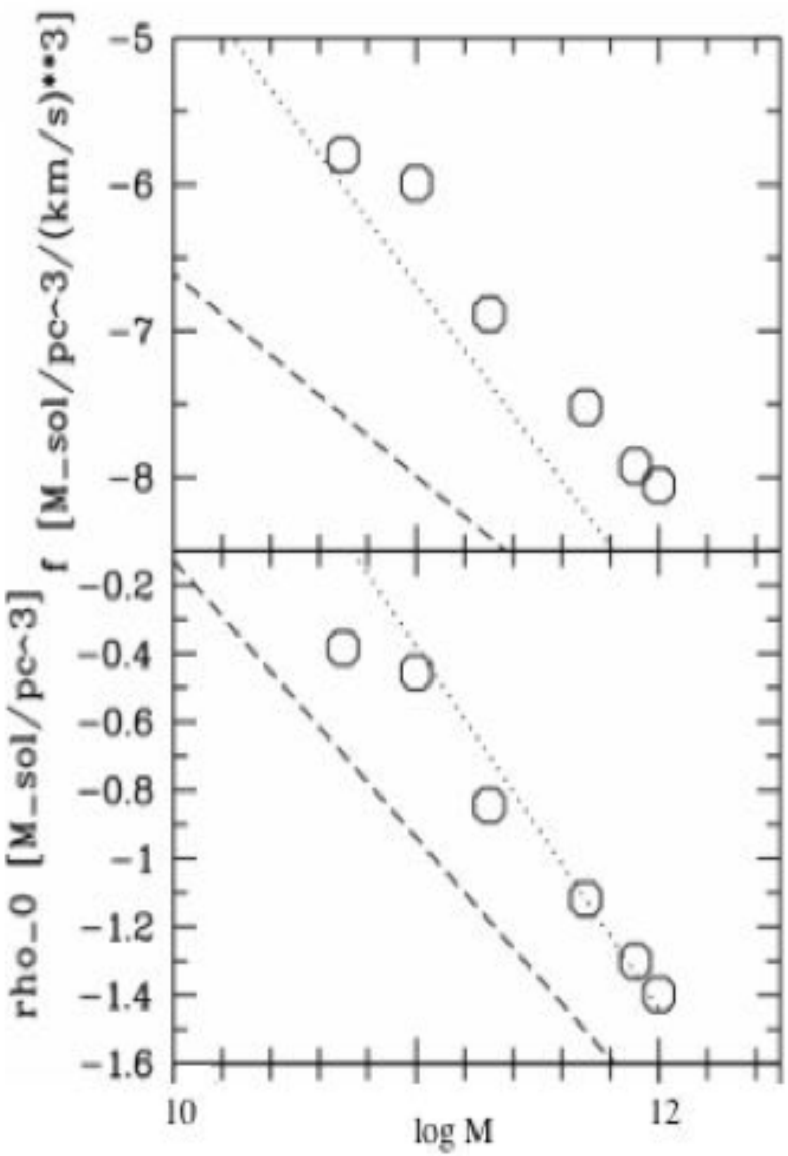


M_*/L_B ($M_\odot/L_\odot$)
10^0
10^{-1}
0.4 0.5 0.6 0.7 0.8 0.9
$B-V$
M_*/L_K ($M_\odot/L_\odot$)
10^0
10^{-1}
0.4 0.5 0.6 0.7 0.8 0.9
$B-V$

Elliptical galaxies

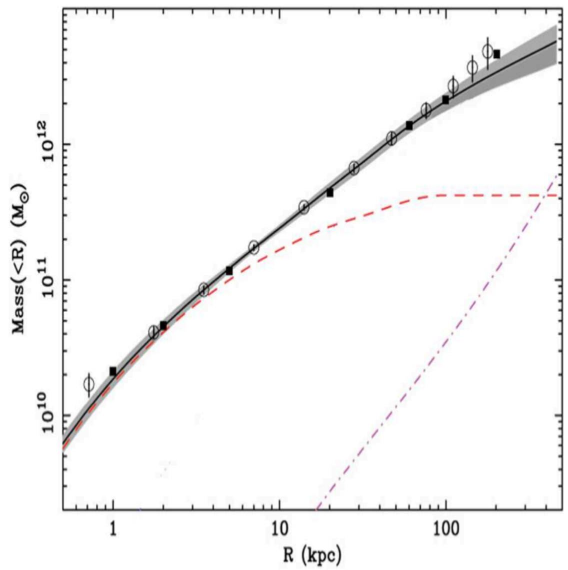


Famaey & McGaugh (2012)



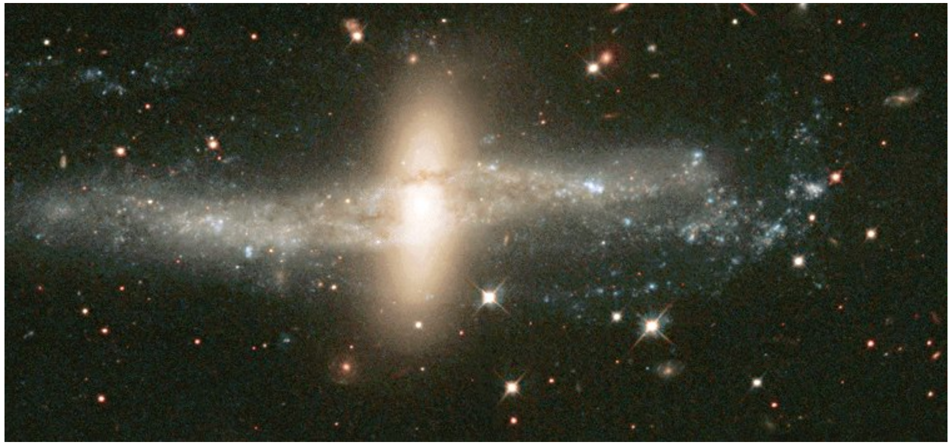
Richtler, Famaey, et al. (2011)

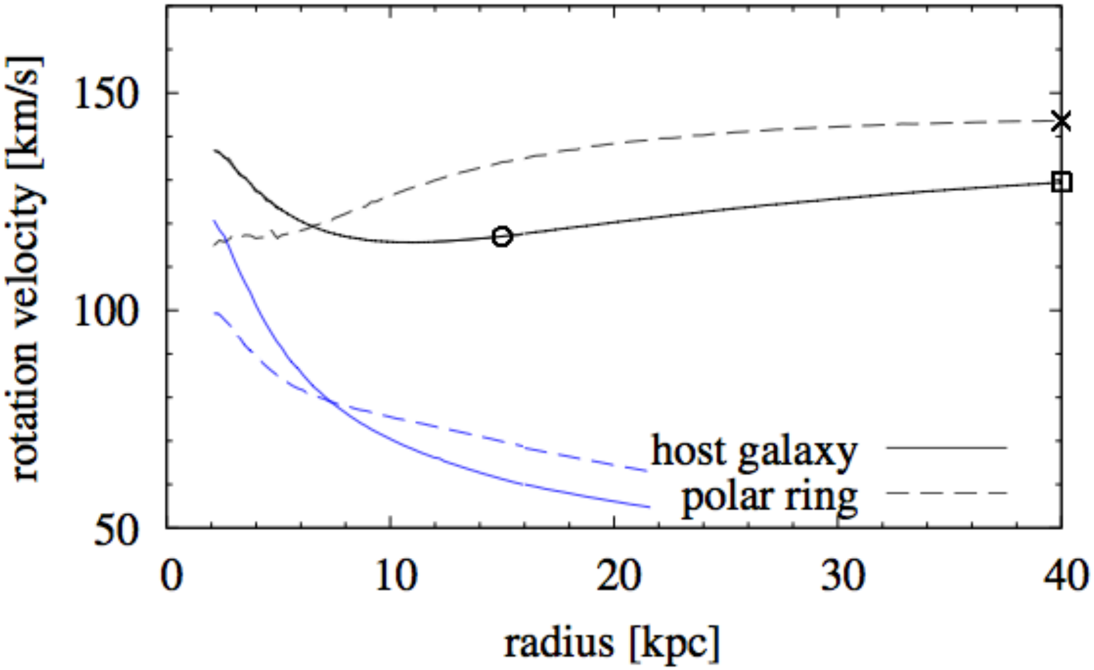
NGC 1521

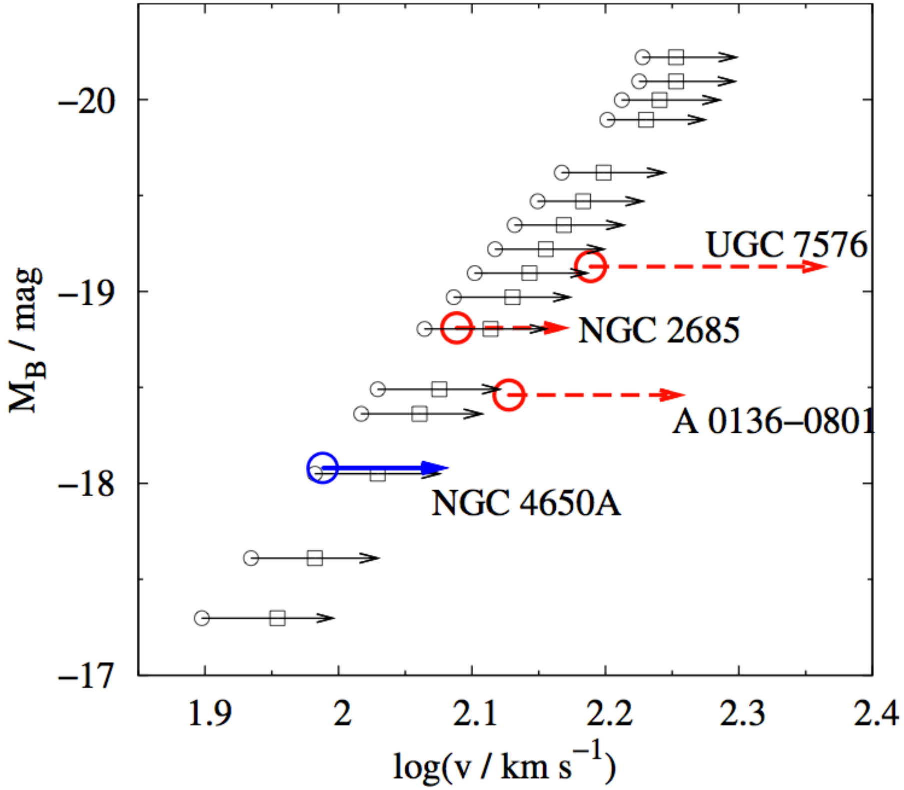


Milgrom (2012)

Polar ring galaxies



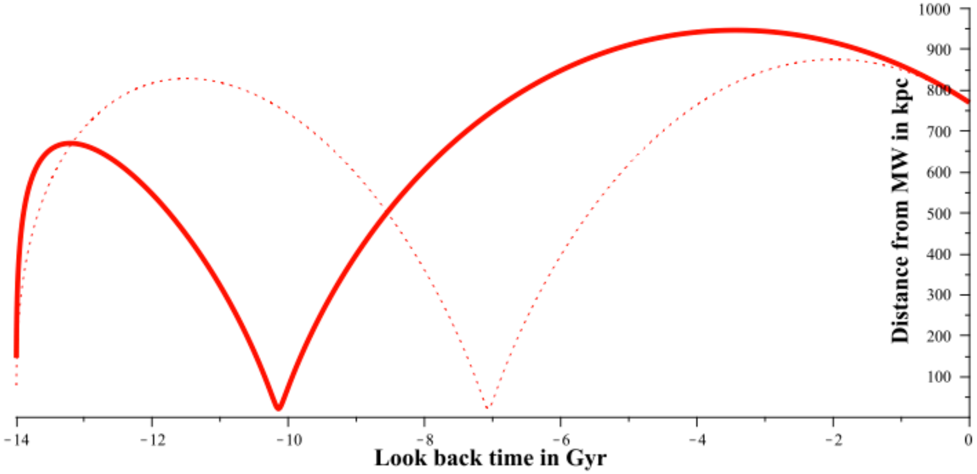


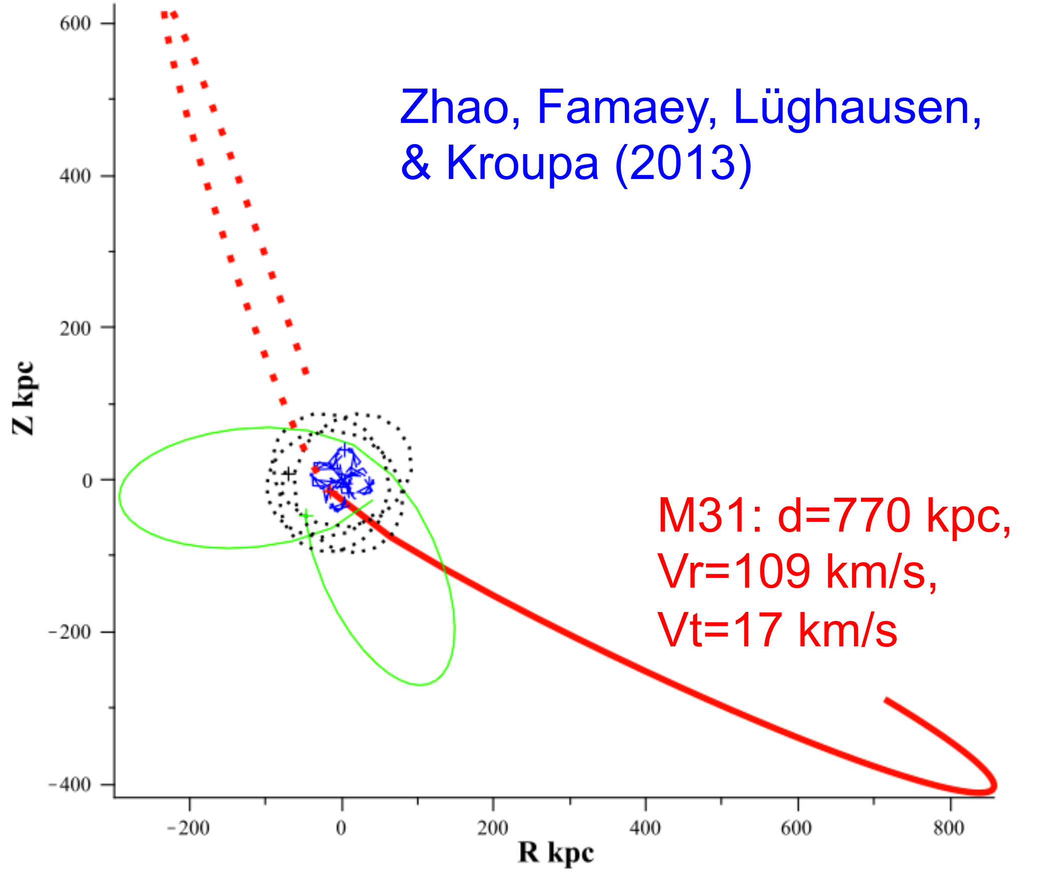


Lüghausen, Famaey, Kroupa, et al. (2013)

Local Group Timing

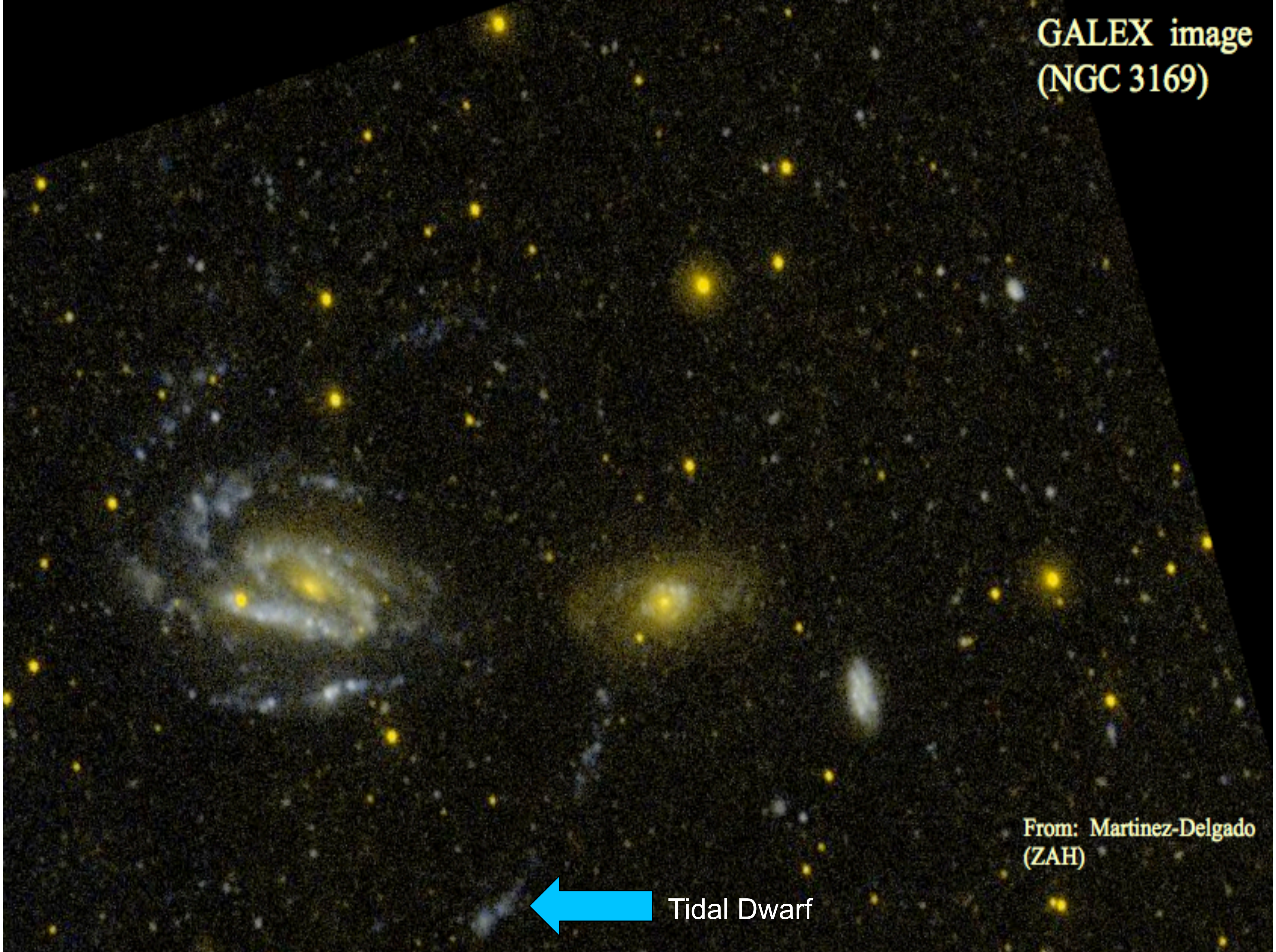
$$F_{2\text{body}} = \frac{2}{3}\left[(m_1+m_2)^{3/2} - m_1^{3/2} - m_2^{3/2}\right]\frac{\sqrt{Ga_0}}{r}, \quad \frac{d^2}{dt^2}\mathbf{r}_{12} = K\mathbf{r}_{12} - \frac{m_1+m_2}{m_1}\left[\frac{\mathbf{F}_{12}}{m_2}\right], \quad K \equiv \frac{\mathrm{d}^2 a}{a\mathrm{d}t^2}$$





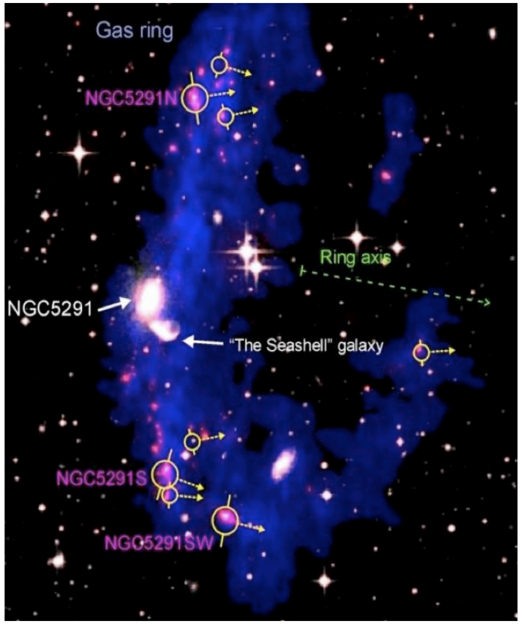
$$F_{12} \approx \frac{\tilde{G} m_1 m_2}{r_{12}^2}, \quad \tilde{G} \equiv G\left[1 + \left(y + \frac{g_{\text{ext}}^2}{a_0^2}\right)^{-\alpha}\right]^{\frac{1}{2\alpha}}$$

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


GALEX image
(NGC 3169)
From: Martinez-Delgado
(ZAH)
Tidal Dwarf

Separating baryons from particle DM

Small rotationally supported gas-dense ($> 10^{-21}$ kg/m^3)



Tidal dwarf galaxies in NGC 5291

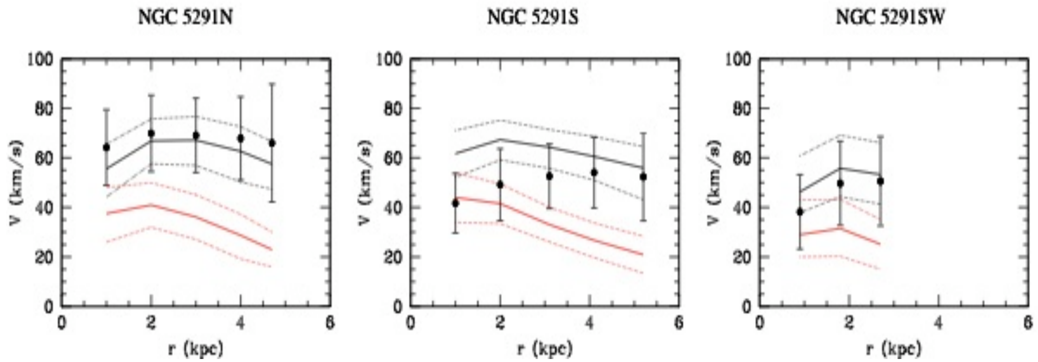
Bournaud et al. (2007)

Milgrom (2007)

Gentile, Famaey et al. (2007)

~~CDM~~

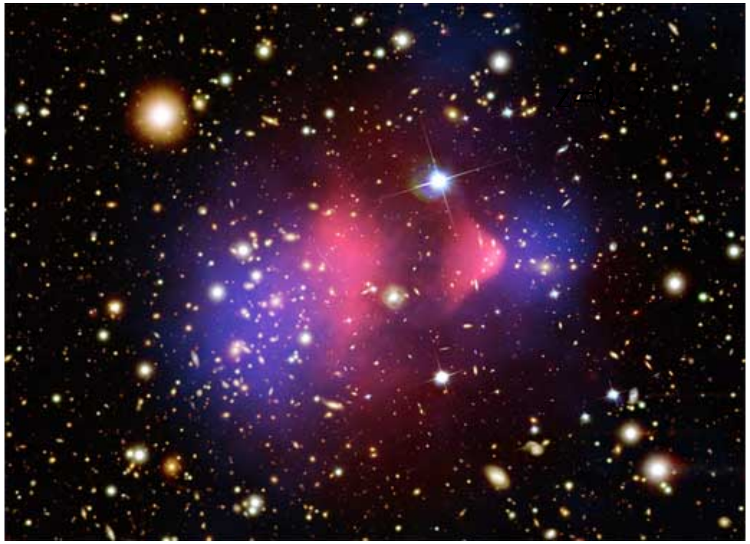
MOND



Large pressure-supported not very gas-dense

CDM

~~MOND~~

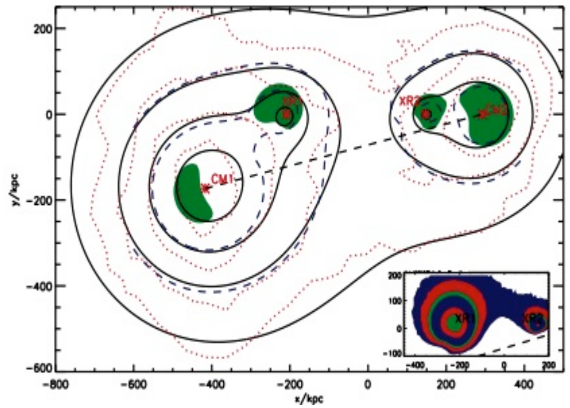


The Bullet Cluster

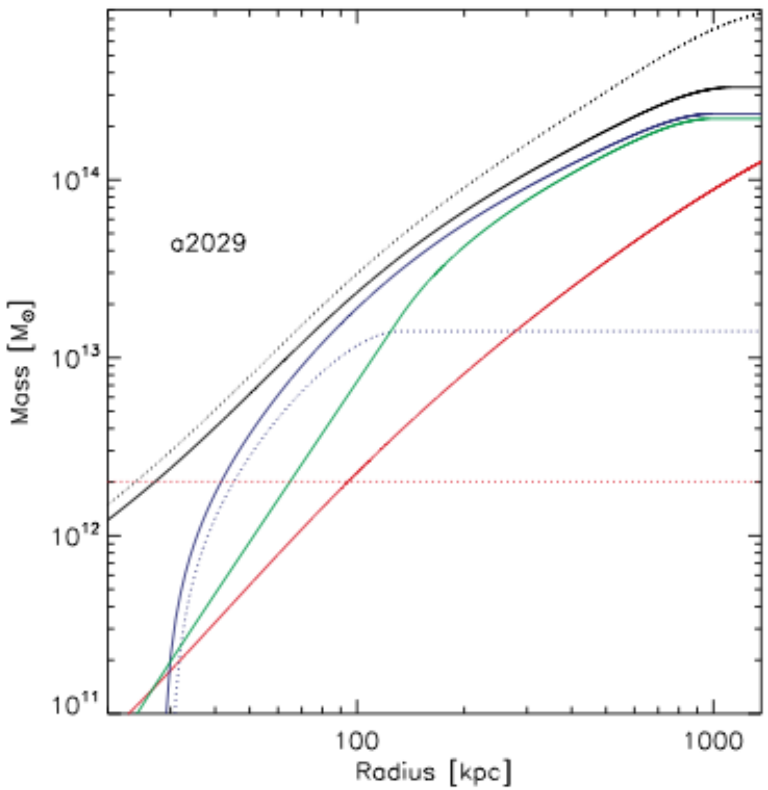
Clowe et al. (2006)

Angus, Shan, Zhao & Famaey (2007)

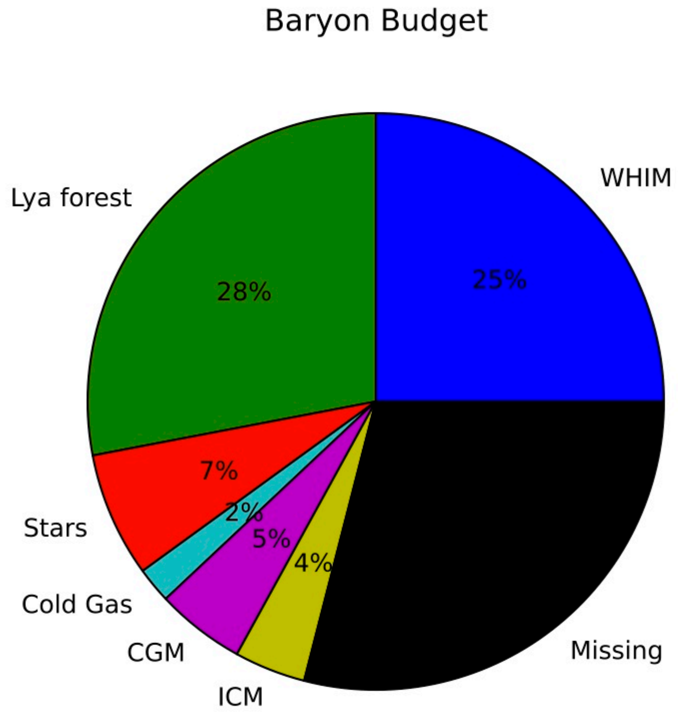
But speed 3000 km/s?



Galaxy clusters



Angus, Famaey & Buote (2008)



=> missing mass (very concentrated in the center)

- Maybe an additional fermionic dark **HDM** particle?
- Or missing cluster baryonic dark matter (**CBDM**)?
- Or new field producing MOND but behaving as DM (**DDM?**)

Conclusion

Independently from the theoretical framework, the MOND formula is an extremely efficient way of **predicting the gravitational field in galaxies**

Any galaxy formation theory should be able to ultimately reproduce the MOND formula as an **observed** relation for galaxies!

What makes it almost *impossible in the particle DM framework* is that it is history-independent!

What makes it difficult for cosmology is that we presumably need *something behaving like particle DM, at least for the CMB…*