Dark Matter and MOND

Famaey & McGaugh 2012 (Living Reviews in Relativity)

arXiv:1112.3960

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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**

Challenges for the standard picture

1) Possible hint 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) « Minor » problems:

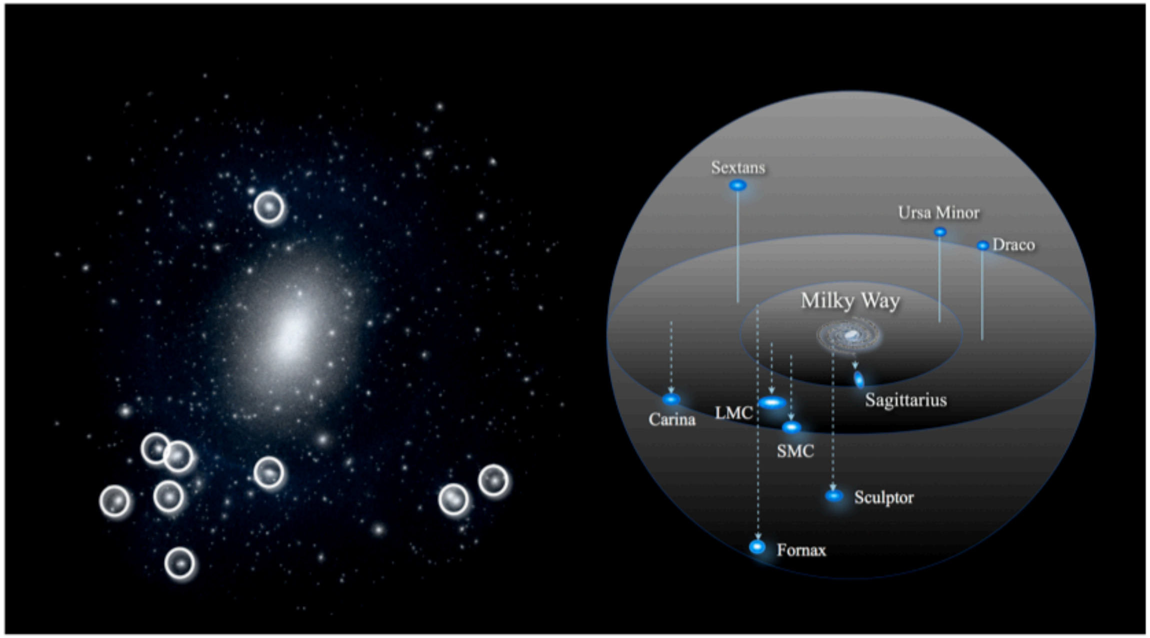
- **Cusp problem**: solved through baryon feedback for most massive ones, but still problematic if remains in faintest galaxies

The Milky Way halo is **NOT** cusped (Bissantz et al. 2003, Famaey & Binney 2005)

- **Create large disks with low bulge/disk ratio** while keeping consistency with luminosity function and stellar mass fraction

- **Missing satellites and « too big to fail »**

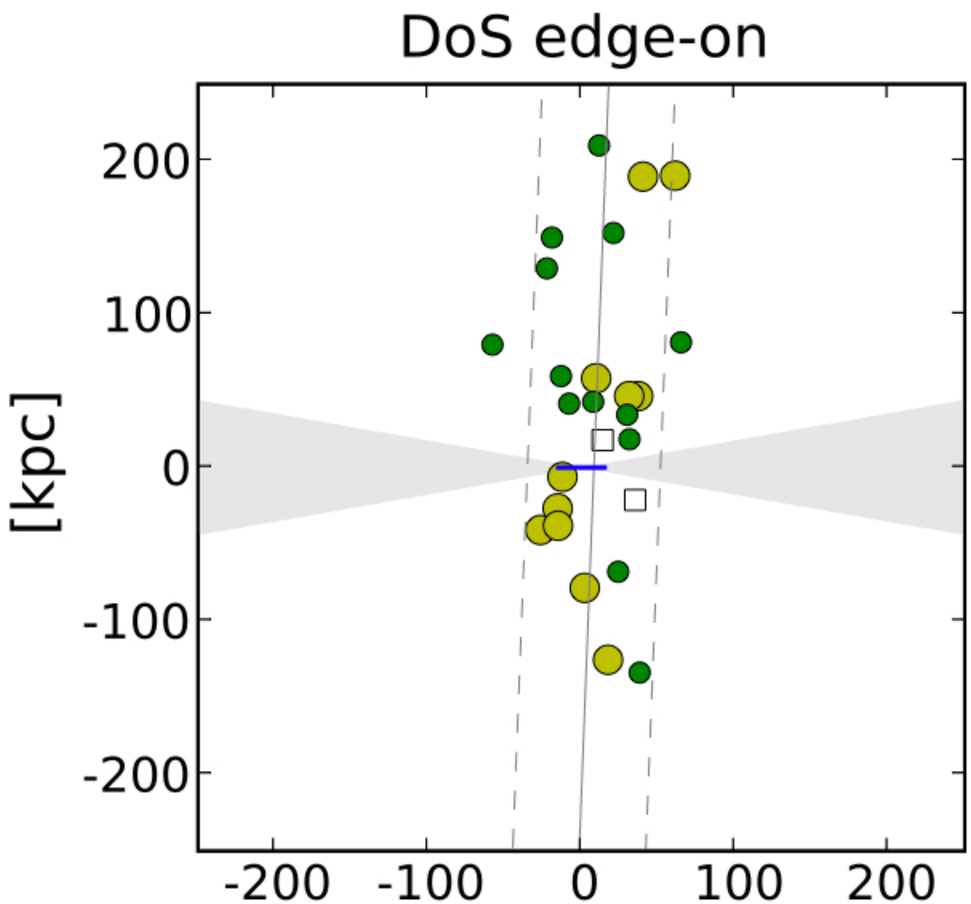
Many new ultra-faint dwarfs have been found around the MW (Segue1, Hercules…)



Bullock & Boylan-Kolchin

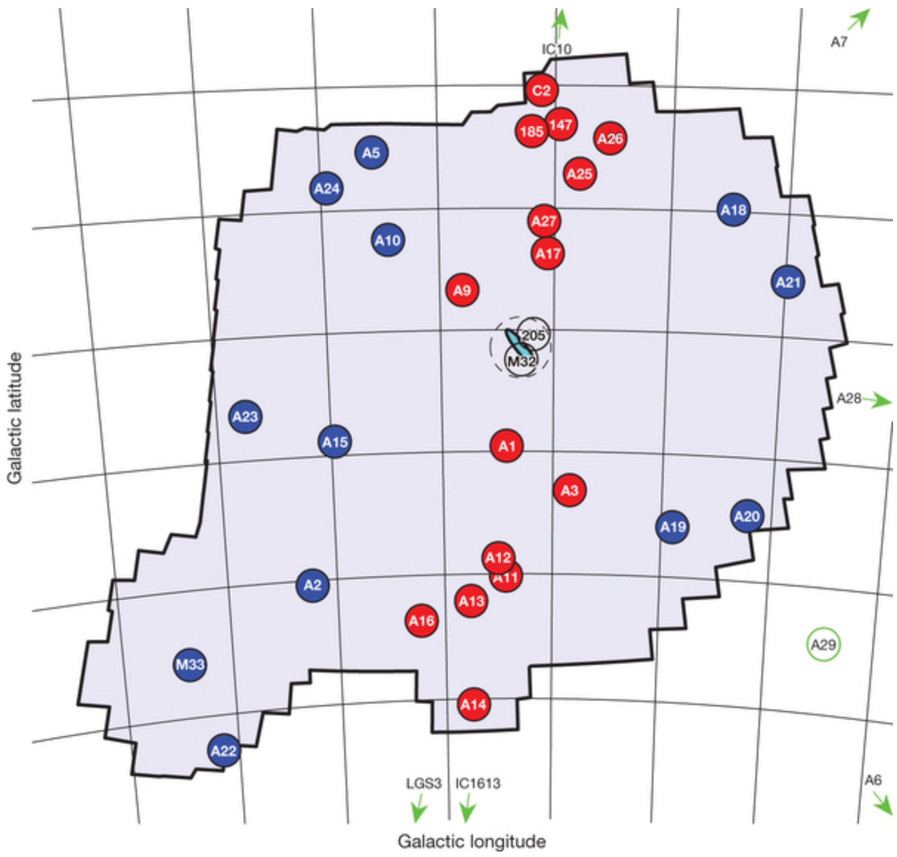
3) Major problem: **dwarf satellites geometry** , i.e. phase-space correlation (rotating disks of satellites)

Milky Way



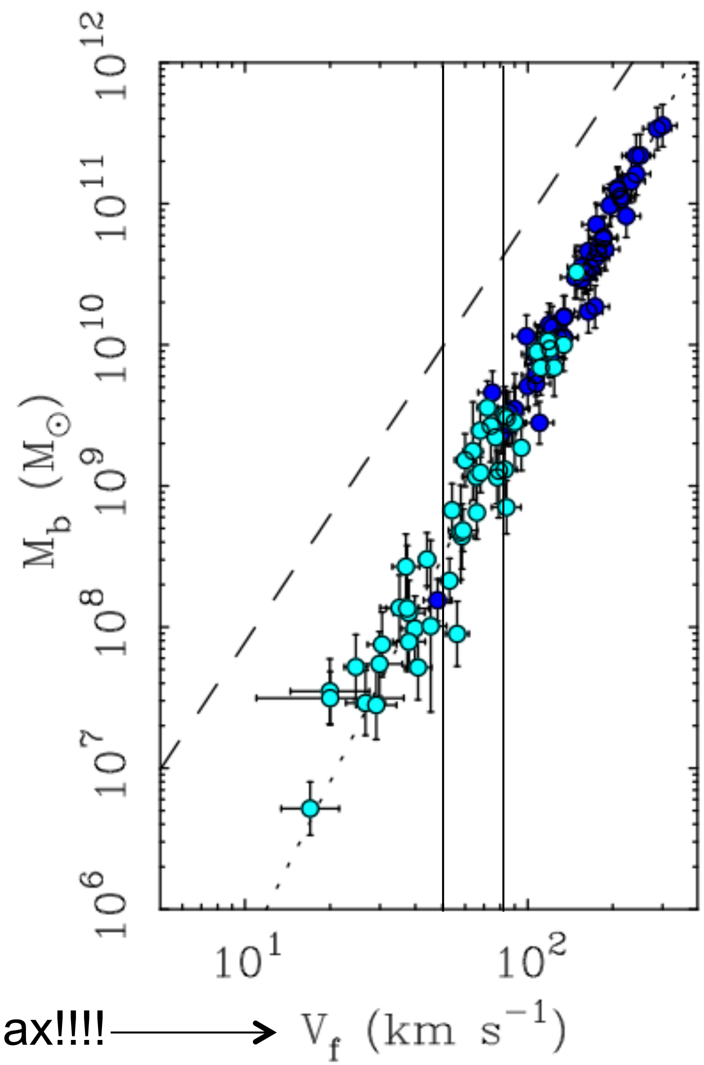
Kroupa, Famaey, et al. (2010)

Andromeda



Ibata et al. (2013)

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

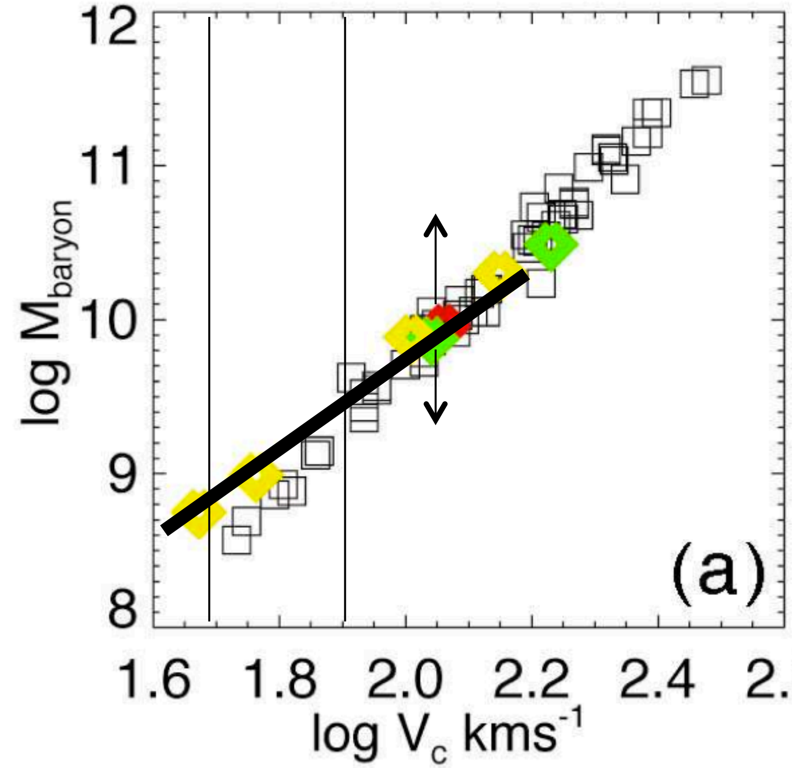


Not Vmax!!!! →

↓

Slope of 3.5

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



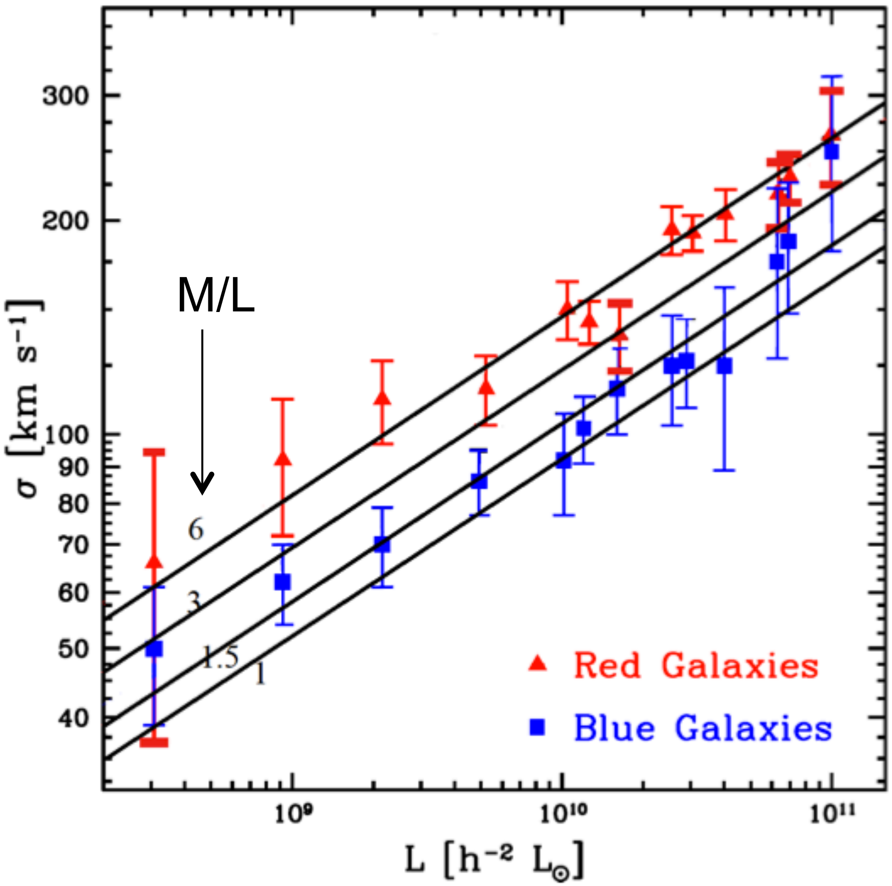
Baryonic Tully-Fisher relation:
$\text{Log } M_b = 4 \log V - \log \beta$

Zero-point defines an acceleration constant $a_0 \approx V^4/(GM_b) \approx 10^{-10}$ m/s^2
Such that $\beta = Ga_0$

$a_0^2 \sim \Lambda$

$\phi=(GMa_0)^{1/2}\ln(r)$ at large r from lensing too

Isothermal potential up to 300 kpc for isolated gals!



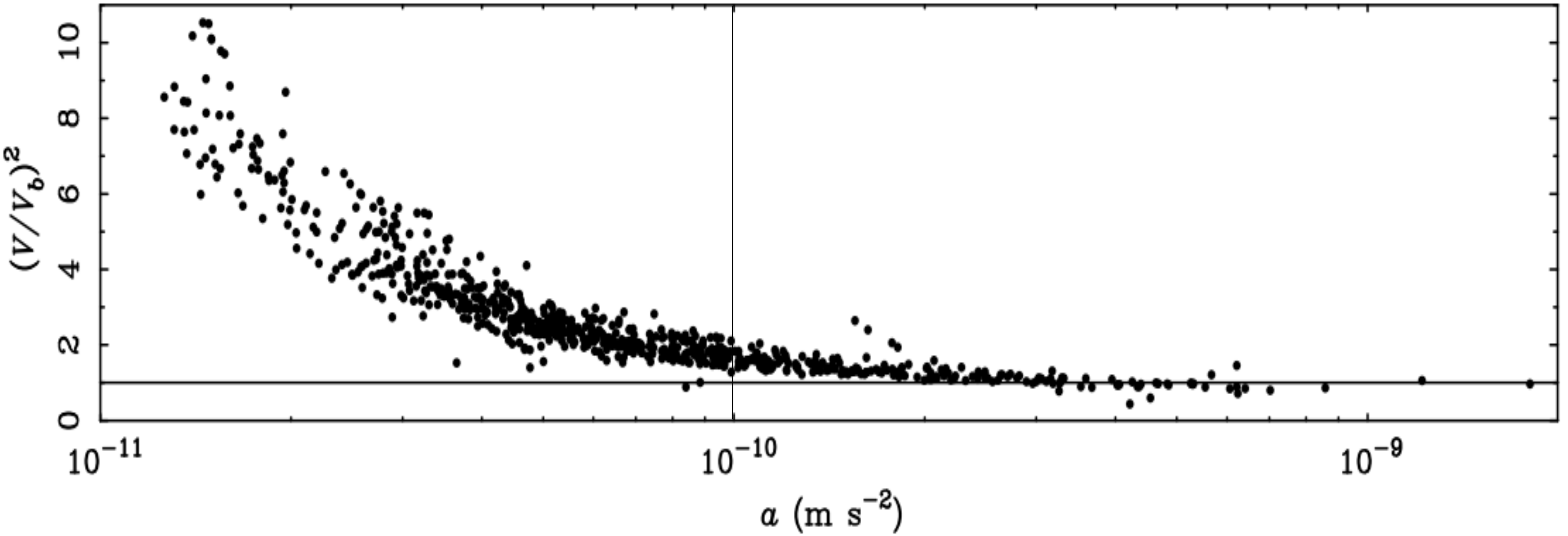
$$M_h(<r) = \left(\frac{2\sigma^2}{G}\right) r.$$

$$\sigma = \left(\frac{MGa_0}{4}\right)^{1/4}$$

Brimioulle et al. – Milgrom 2013

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

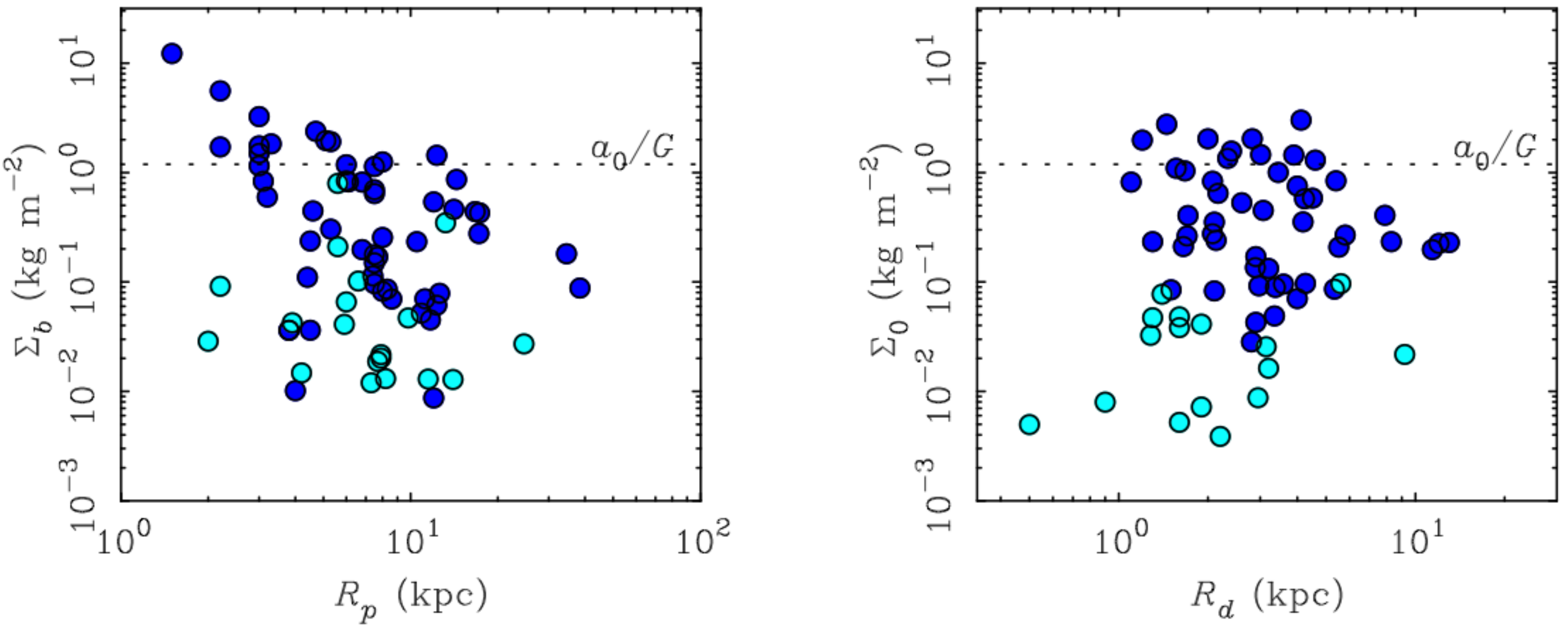
In the DM framework this is a fully **independent** role of a_0



McGaugh (2004)
Famaey & McGaugh (2012)

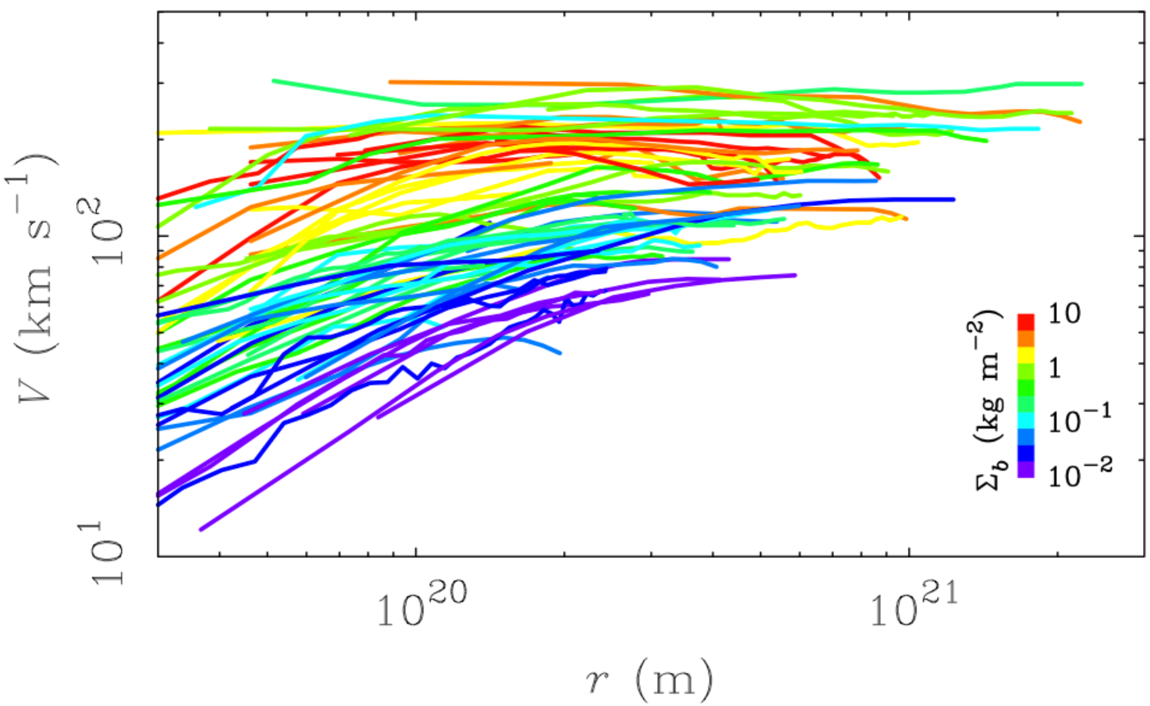
The same acceleration constant a_0 defines a critical baryonic surface density for disk stability a_0/G

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

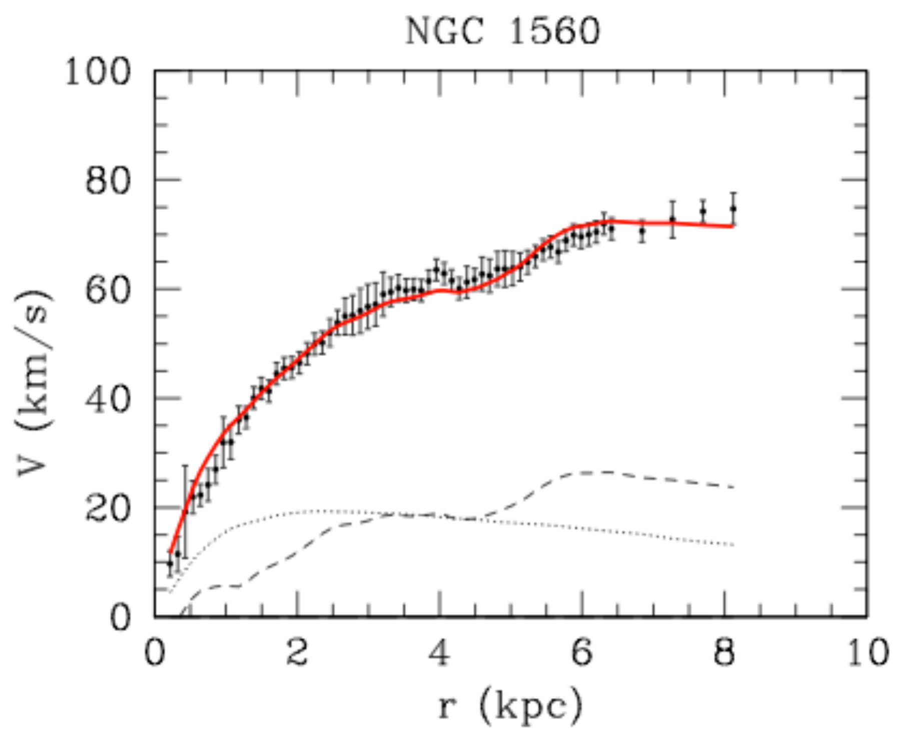


Famaey & McGaugh (2012)

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



Famaey & McGaugh (2012)



Gentile et al. (2010)

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:

$$g = g_N \quad \text{if } g \gg a_0$$
$$g = (g_N\, a_0)^{1/2} \quad \text{if } g \ll a_0$$

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 $\boldsymbol{G} \rightarrow \boldsymbol{0}$

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 surface density and **steepness** of RC

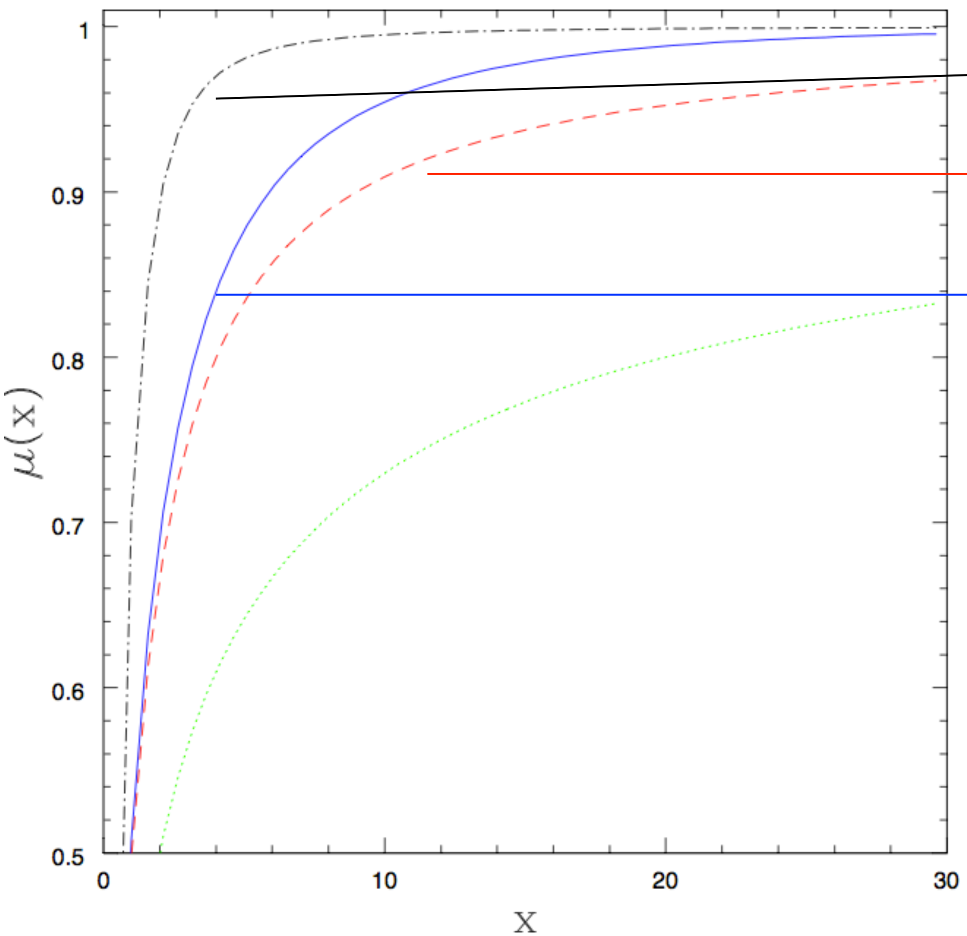
6) Features in the baryonic distribution imply features in the RC

In practice: cf. dielectric

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

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)



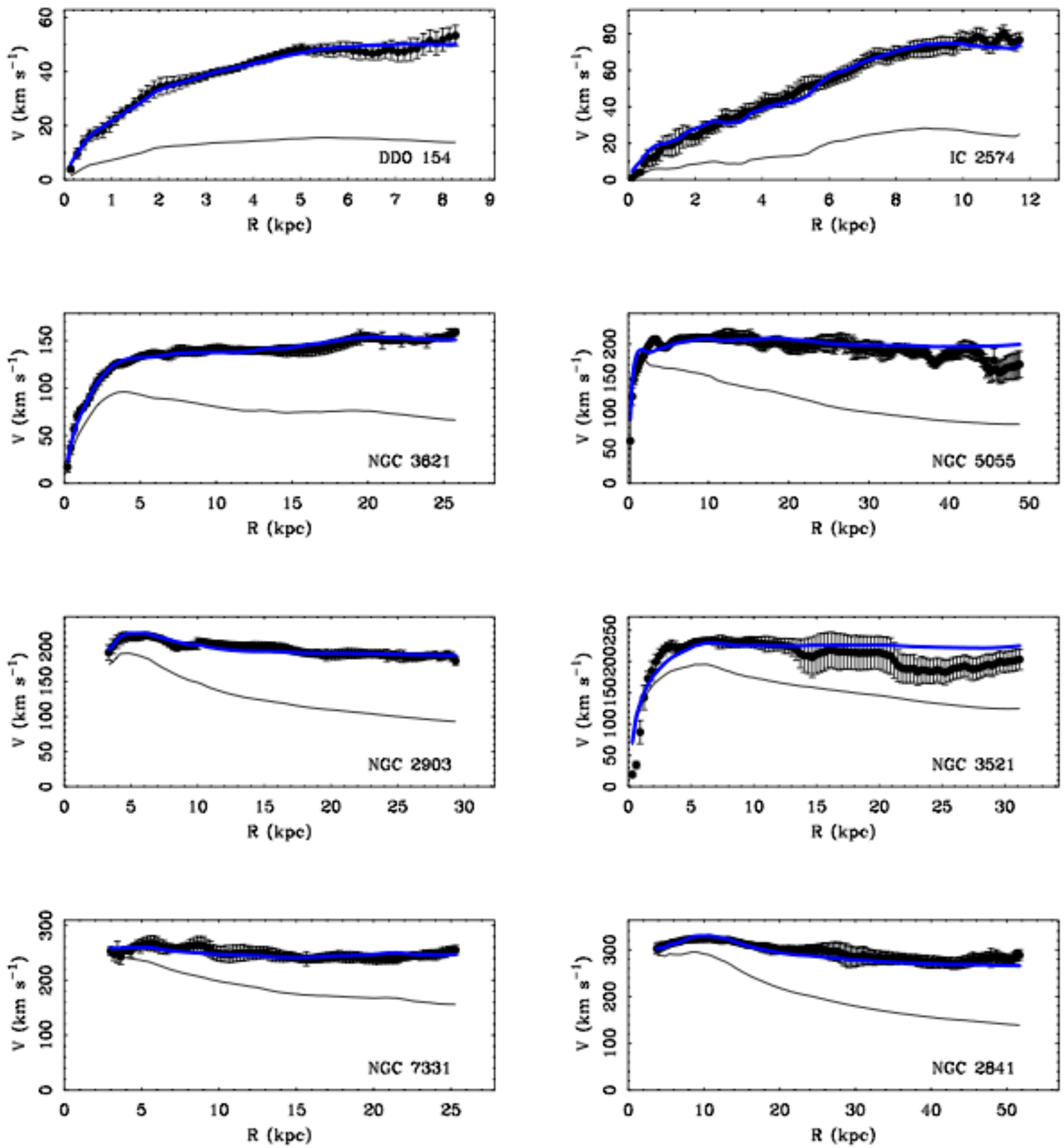
$\mu(x) = x/(1+x^2)^{1/2}$

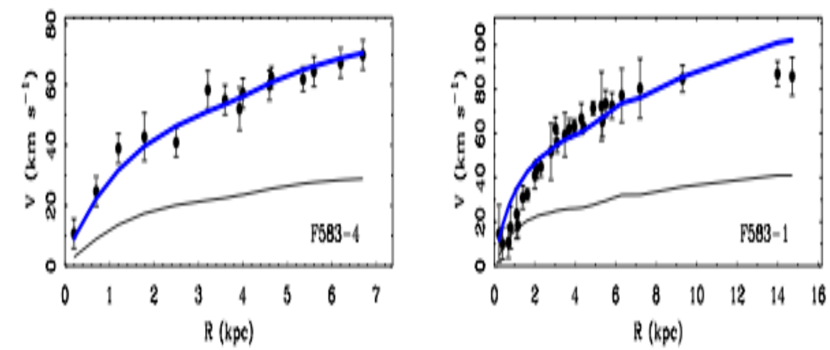
$\mu(x) = x/(1+x)$

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

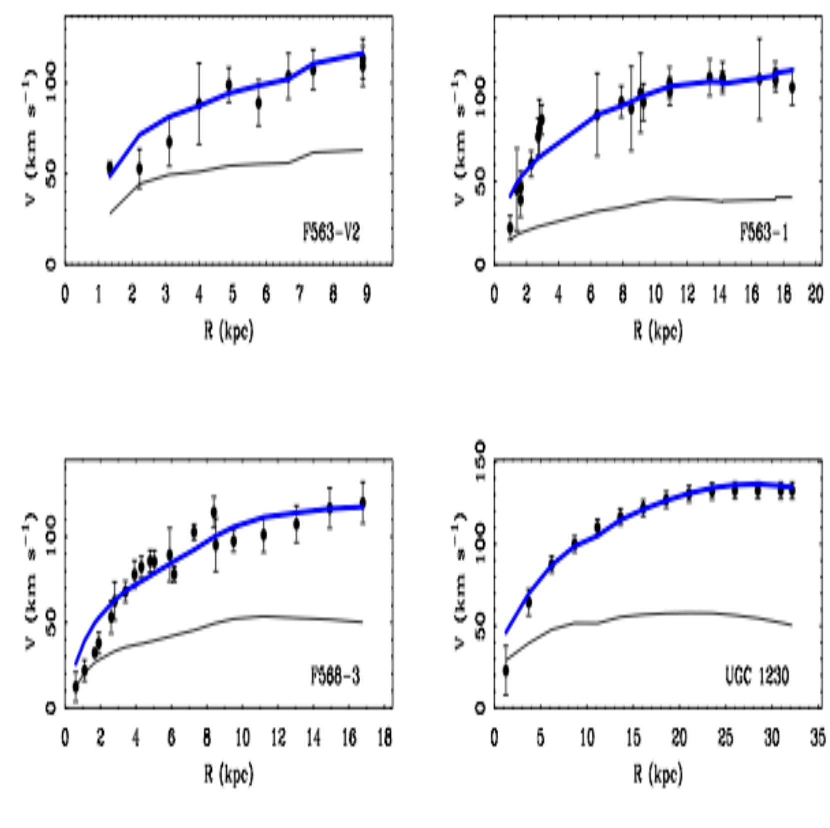
Famaey & McGaugh (2012)

Rotation curves



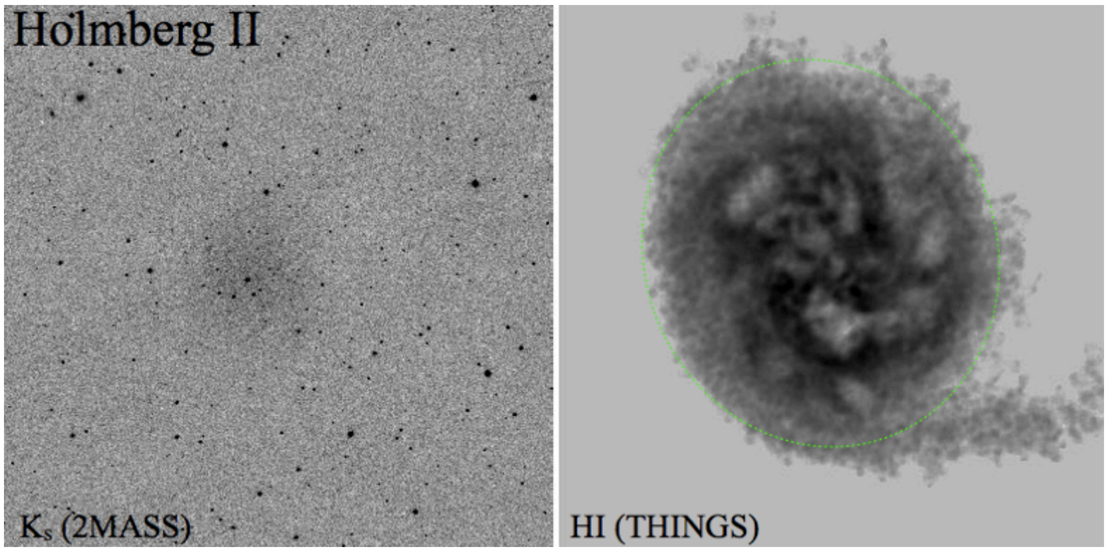


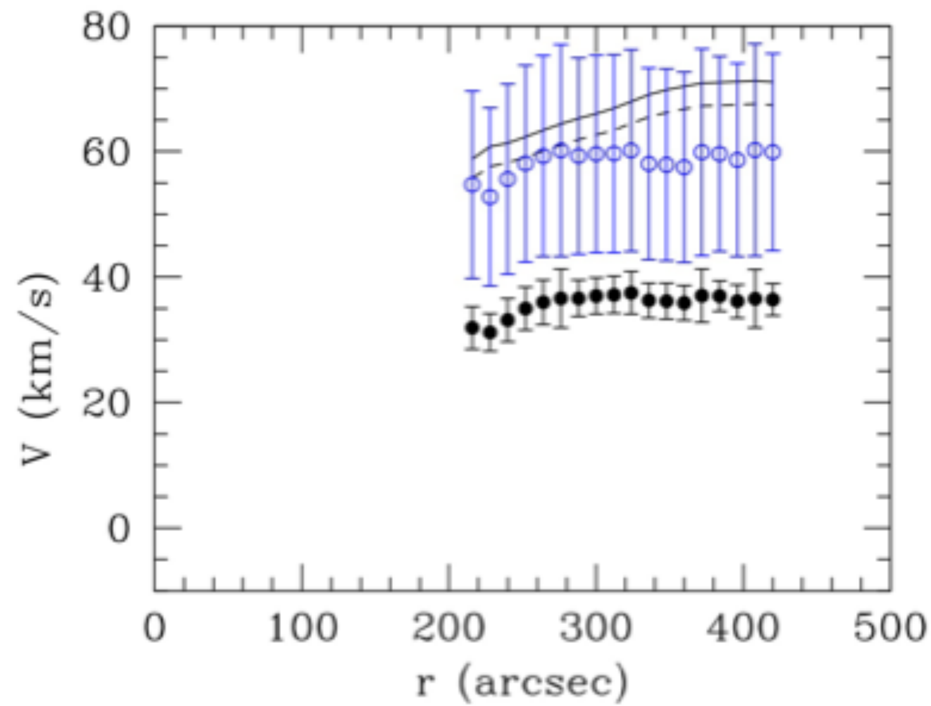
$\nu(x) = 1/[1- exp(-x^{1/2})]$



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

Holmberg II





Bureau & Carignan 2002 derive inclination of i=84° in outer parts (i=0° is face-on), Oh et al. 2011 derive **i=50°**, but Gentile et al. 2012 (with Oh) decrease it to **i=27°+-7°**

MOND as a modification of classical gravity

$$S_N = \underbrace{\int \frac{\rho \mathbf{v}^2}{2} d^3x\, dt - \int \rho \Phi_N d^3x\, dt}_{\text{matter action}} - \int \underbrace{\frac{|\nabla \Phi_N|^2}{8\pi G}} d^3x\, dt$$

$$\rightarrow \frac{a_0^2 F(|\nabla \Phi|^2/a_0^2)}{8\pi G}$$

$$\nabla . [\, \mu\, (|\nabla\Phi|/a_0)\, \nabla\Phi] = 4\, \pi G\, \rho_{bar}$$

Bekenstein & Milgrom (1984)

Other formulation: -> $[2\nabla\Phi.\nabla\Phi_N - a_0^2 Q(|\nabla\Phi_N|^2/a_0^2)]$

$$\nabla^2\, \Phi = \nabla . [\, \nu\, (|\nabla\Phi_N|/a_0)\, \nabla\Phi_N]$$

QUMOND: Milgrom (2010)

Differing slightly outside of spherical symmetry

External field effect

In reality, ***no*** isolated systems: the external field in which an object is plunged influences the **internal** dynamics

For instance, Milky Way in the slowly varying Great Attractor gravitational field (0.01-0.03 a_0) → gives right escape speed

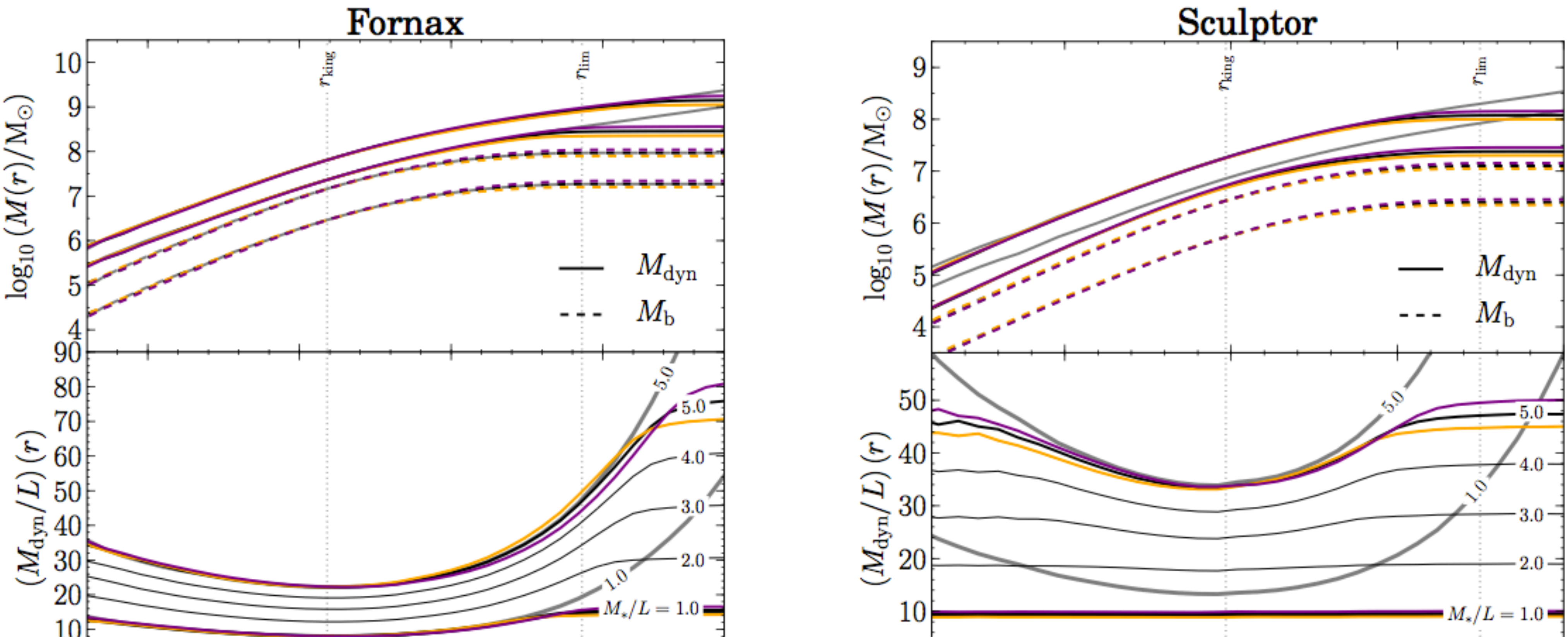
$$\nabla . [(\mathbf{g}+\mathbf{g_e}) \, \mu \, (|\mathbf{g}+\mathbf{g_e}| / a_0)] = \nabla . (\mathbf{g_n}+\mathbf{g_{ne}})$$

In 1D:

$$\mathbf{g_n} = \mathbf{g} \, \mu \, (|\mathbf{g}+\mathbf{g_e}| / a_0) + \mathbf{g_e} \, [\mu \, (|\mathbf{g}+\mathbf{g_e}| / a_0) - \mu \, (|\mathbf{g_e}| / a_0)]$$

When $|\mathbf{g}|$ -> 0 : $\mathbf{g_n} = \mathbf{g} \, \mu \, (|\mathbf{g_e}| / a_0)$, r^{-2} force, r^{-1} potential !

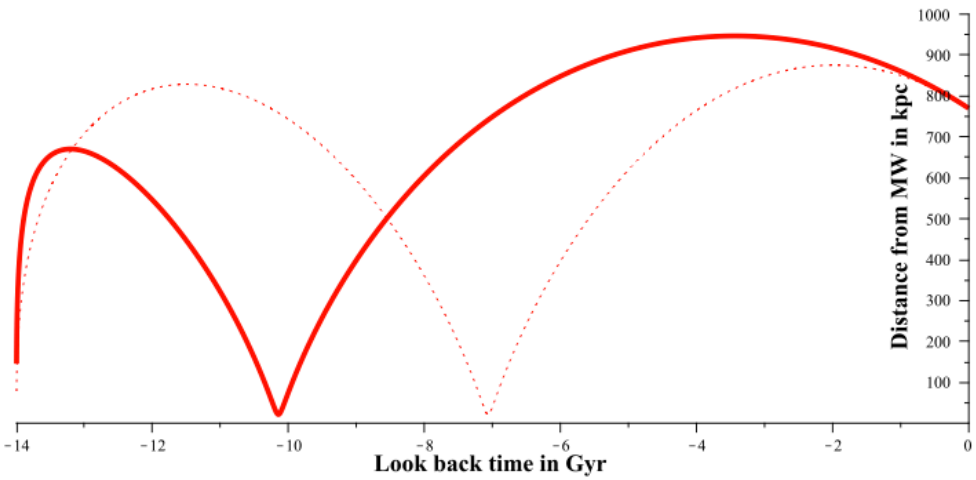
Dwarf spheroidals

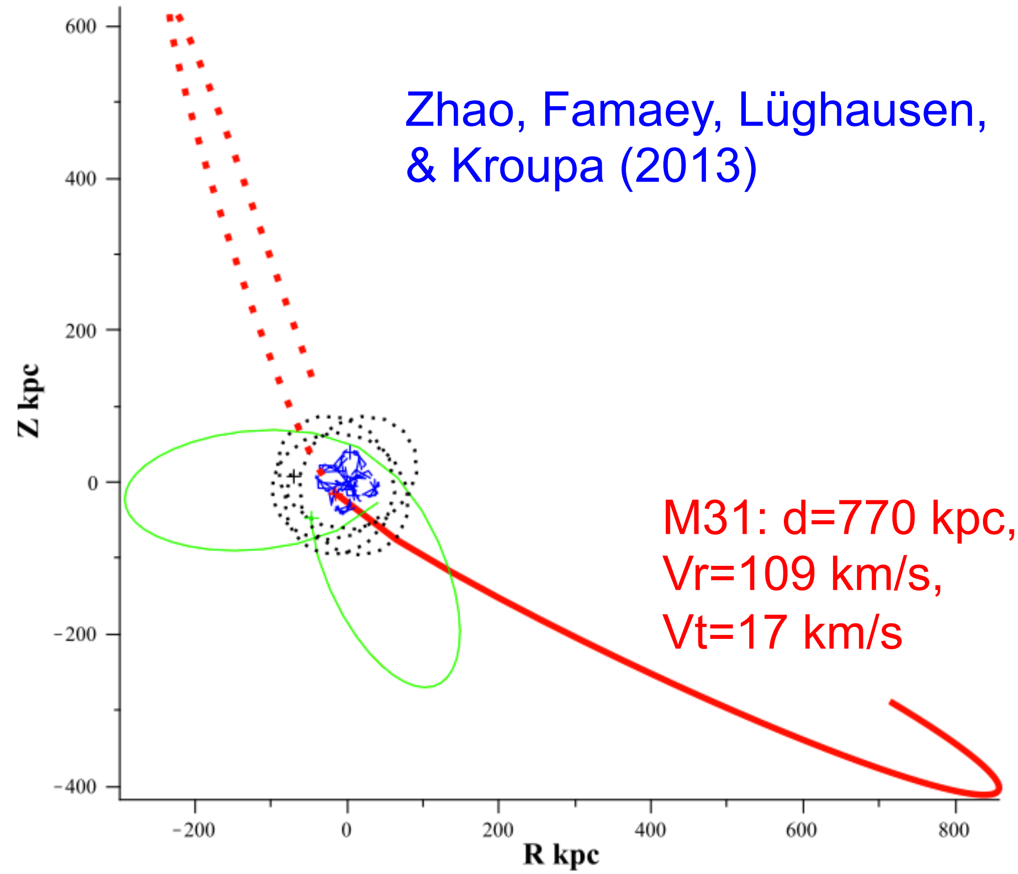


	$M_{0.1}/L_{V,0.1}$		$M_{0.3}/L_{V,0.3}$		$M_{r_{\rm max}}/L_{V,{\rm tot}}$	
	predicted	observed	predicted	observed	predicted	observed
Fornax	[10.9, 29.9]	$12.9^{+7.5}_{-4.3}$	[8.1, 22.8]	$6.8^{+0.5}_{-0.7}$	[14.3, 47.9]	12
Sculptor	[8.9, 40.5]	40^{+74}_{-26}	[8.9, 33.7]	23^{+2}_{-7}	[8.9, 50.1]	38
Sextans	[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

Local Group Orbits

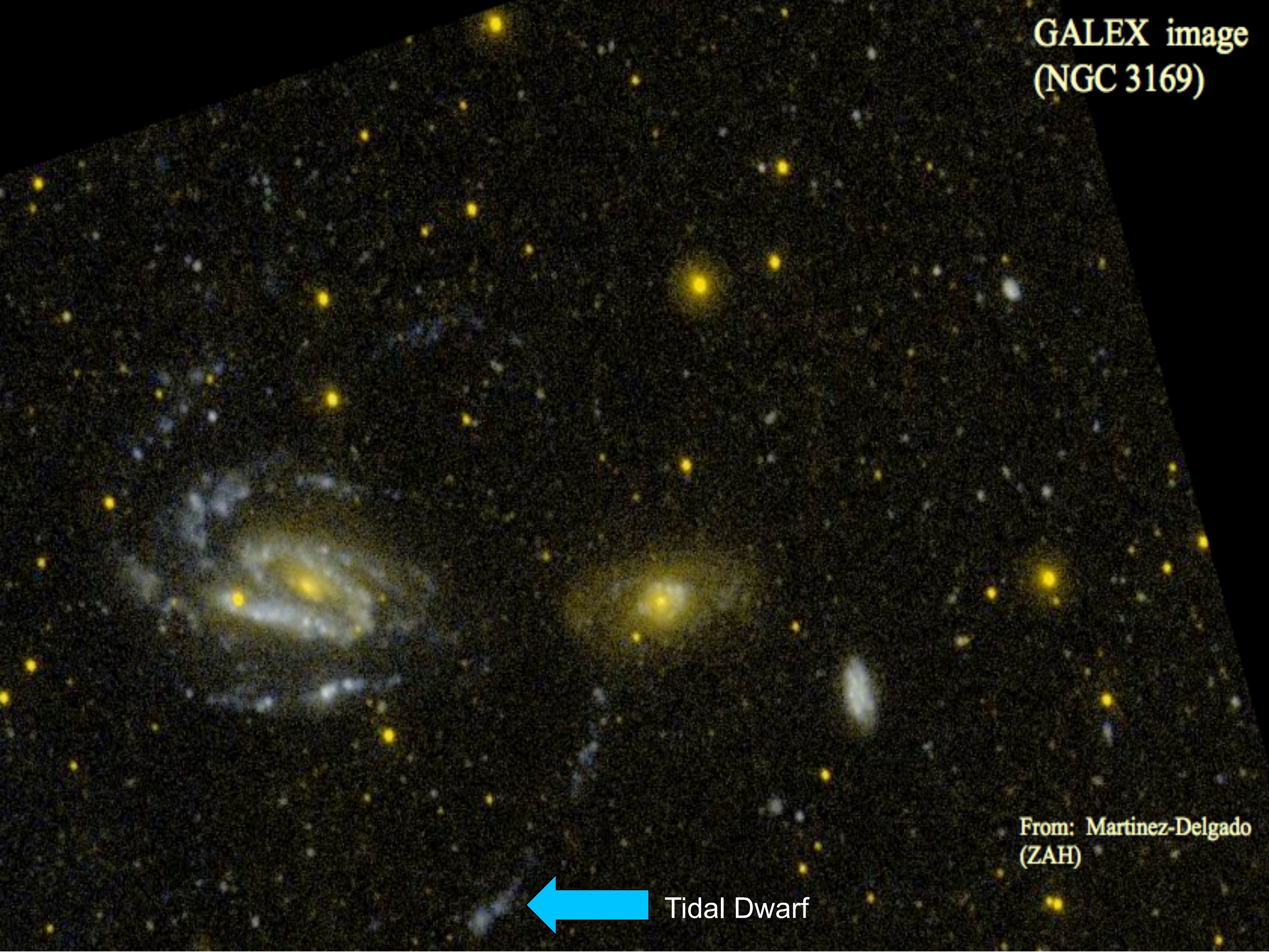
$$F_{2\text{body}} = \frac{2}{3}\left[(m_1+m_2)^{3/2} - m_1^{3/2} - m_2^{3/2}\right]\frac{\sqrt{Ga_0}}{r}, \quad \frac{d^2}{dt^2}\mathbf{r}_{12} = K\mathbf{r}_{12} - \frac{m_1+m_2}{m_1}\left[\frac{\mathbf{F}_{12}}{m_2}\right], \quad K \equiv \frac{\mathrm{d}^2 a}{a\mathrm{d}t^2}$$





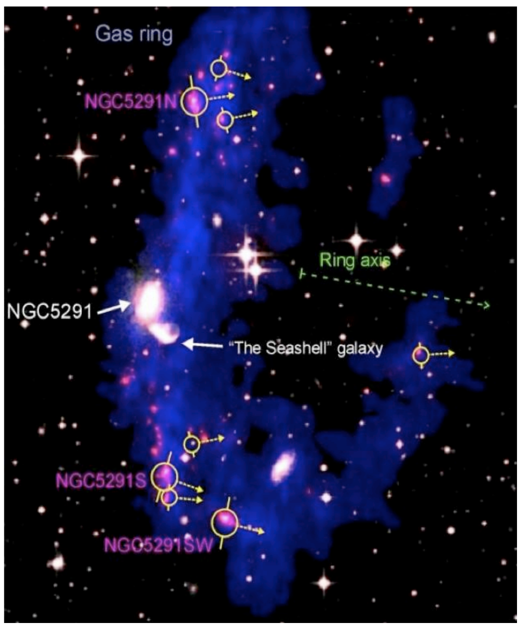
$$F_{12} \approx \frac{\tilde{G} m_1 m_2}{r_{12}^2}, \quad \tilde{G} \equiv G\left[1 + \left(y + \frac{g_{\text{ext}}^2}{a_0^2}\right)^{-\alpha}\right]^{\frac{1}{2\alpha}}$$

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


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

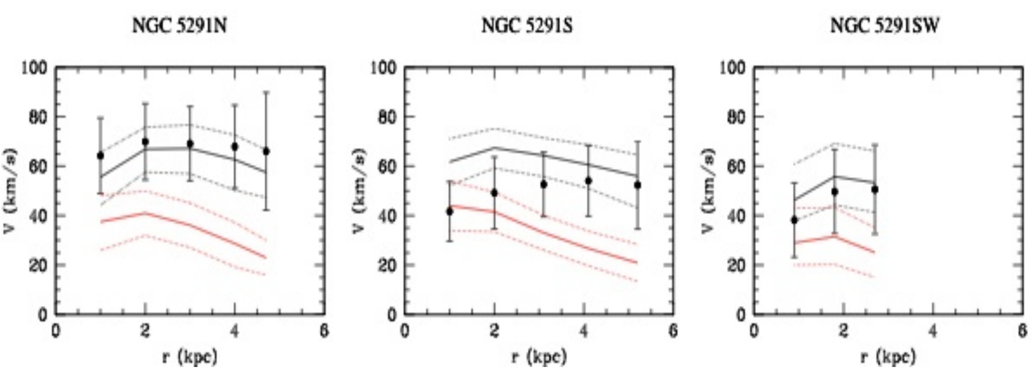
Bournaud et al. (2007)

Milgrom (2007)

Gentile, Famaey et al. (2007)

~~CDM~~

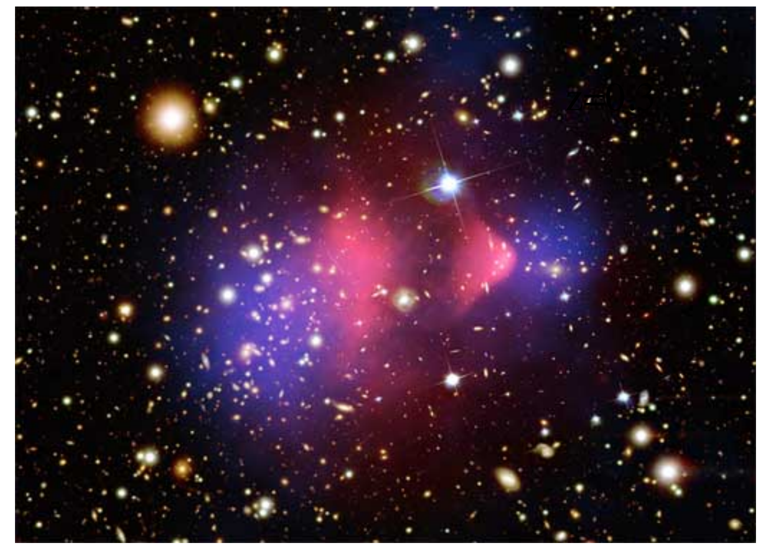
MOND



Large pressure-supported not very gas-dense

CDM

~~MOND~~

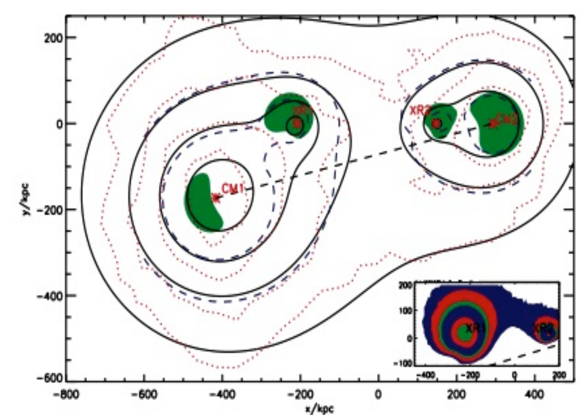


The Bullet Cluster

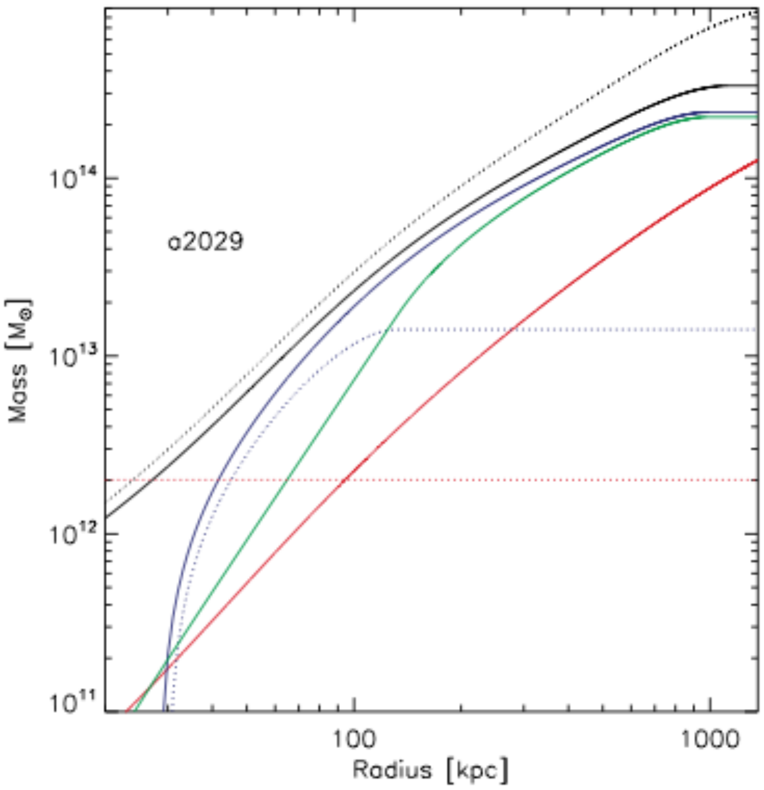
Clowe et al. (2006)

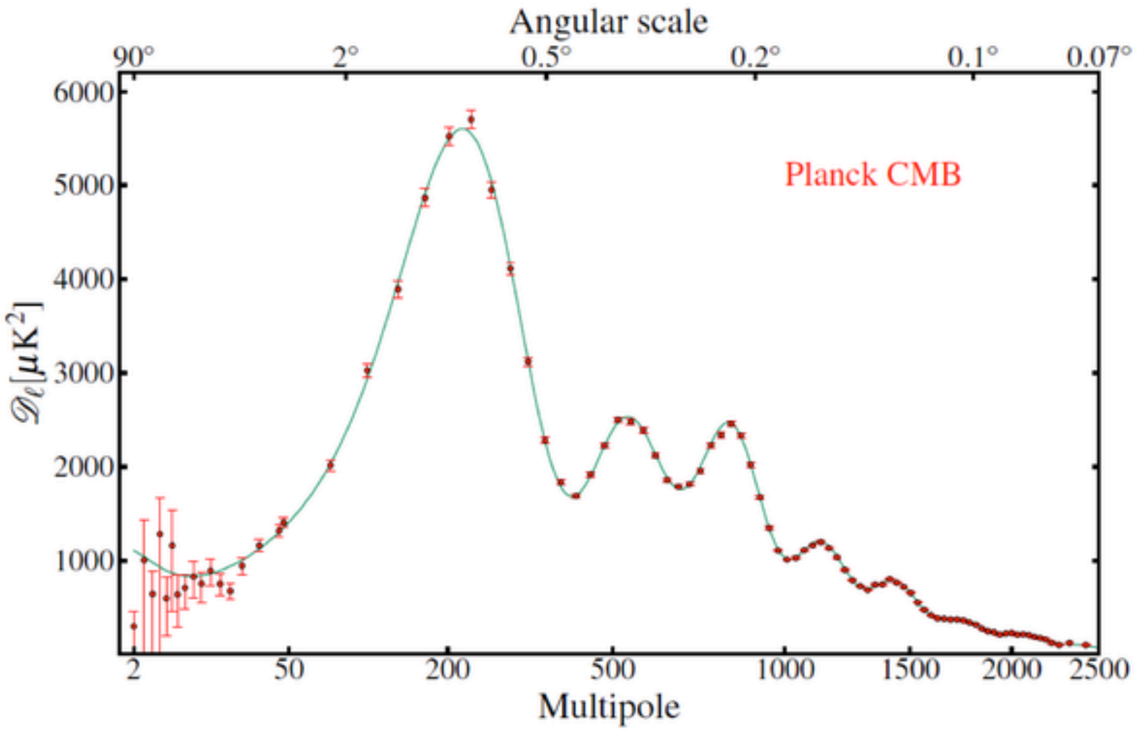
Angus, Shan, Zhao & Famaey (2007)

But speed 3000 km/s?



Large scales!!!





Angus, Famaey & Buote (2008)

Planck

Dipolar Dark Matter?

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

$$\frac{d\mathbf{v}}{dt} = \mathbf{g} - \mathbf{f},$$

$$\frac{d^2\boldsymbol{\xi}}{dt^2} = \mathbf{f} + \frac{1}{\rho}\nabla[W(P) - PW'(P)] + (\mathbf{P}\nabla)\mathbf{g},$$

$$-\nabla.(\mathbf{g} - 4\pi\mathbf{P}) = 4\pi G(\rho_b + \rho).$$

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

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

Blanchet & Le Tiec 2009

Reproduces CMB & all concordance cosmology to first order !!

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…*

Vector fields

TeVeS: introduce vector field and

$$g_{\mu\nu} \equiv e^{-2\phi}\tilde{g}_{\mu\nu} - 2\sinh(2\phi)U_\mu U_\nu$$

Or directly use a « vector field k-essence »:

$$S_U \equiv -\frac{c^4}{16\pi G l^2}\int d^4x\sqrt{-g}\,\left[f(X_{\rm gea}) - l^2\lambda(g^{\mu\nu}U_\mu U_\nu + 1)\right]$$

$$X_{\rm gea} = l^2 K^{\alpha\beta\mu\nu}U_{\beta,\alpha}U_{\nu,\mu}.$$

Combination of 4 terms that are products of metric and vector

BIMOND

« Equivalent » of acceleration in GR: Christoffel symbol

$$\frac{d^2x^\mu}{d\tau^2} = -\Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau}$$

Not a tensor but the subtraction of two is

=> BIMOND

$$S \equiv S_{\mathrm{m}}[\mathrm{matter}, g_{\mu\nu}] + S_{\mathrm{m}}[\mathrm{twin\ matter}, \hat{g}_{\mu\nu}] + \frac{c^4}{16\pi G}\int d^4x[\alpha\sqrt{-\hat{g}}\hat{R} + \beta\sqrt{-g}R - 2(g\hat{g})^{1/4}l^{-2}f(X)]$$

$$X = l^2 g^{\mu\nu}(C^\alpha_{\mu\beta}C^\beta_{\nu\alpha} - C^\alpha_{\mu\nu}C^\beta_{\beta\alpha}).$$

$$C^\alpha_{\mu\nu} = \Gamma^\alpha_{\mu\nu} - \hat{\Gamma}^\alpha_{\mu\nu}$$