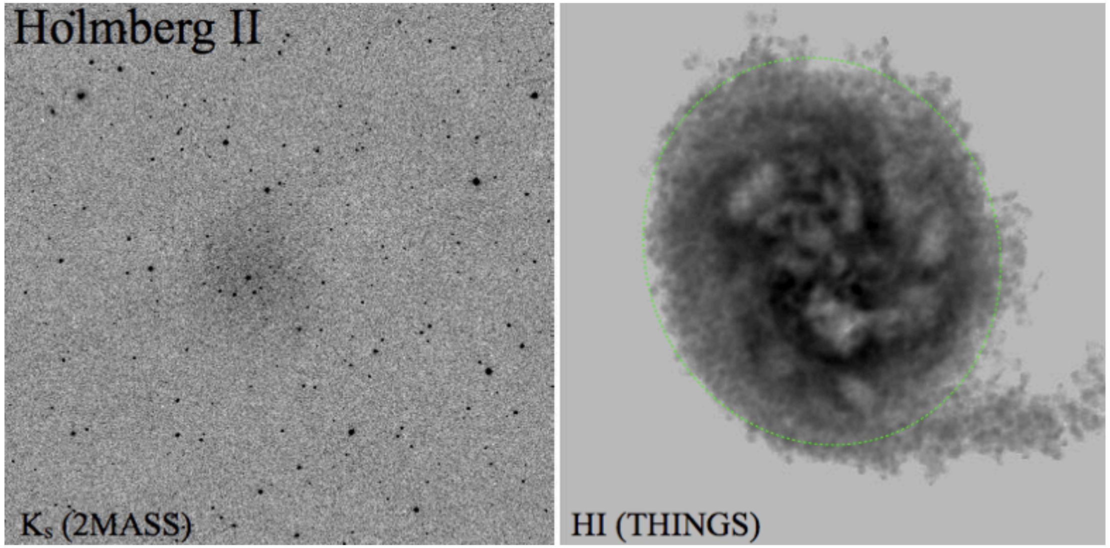
Some recent results on MOND

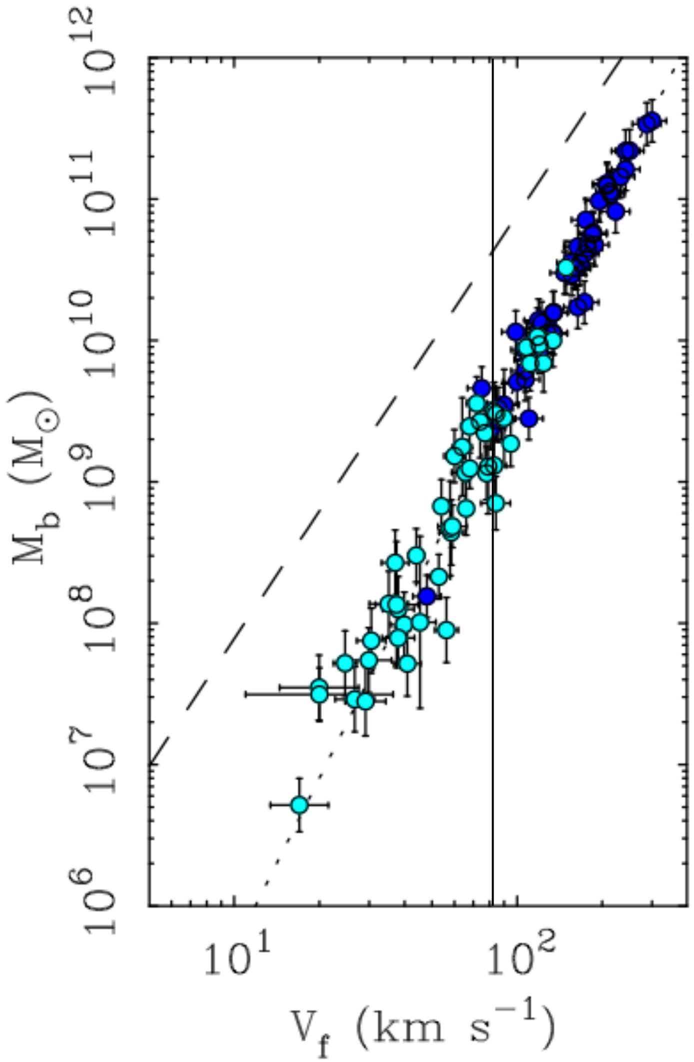


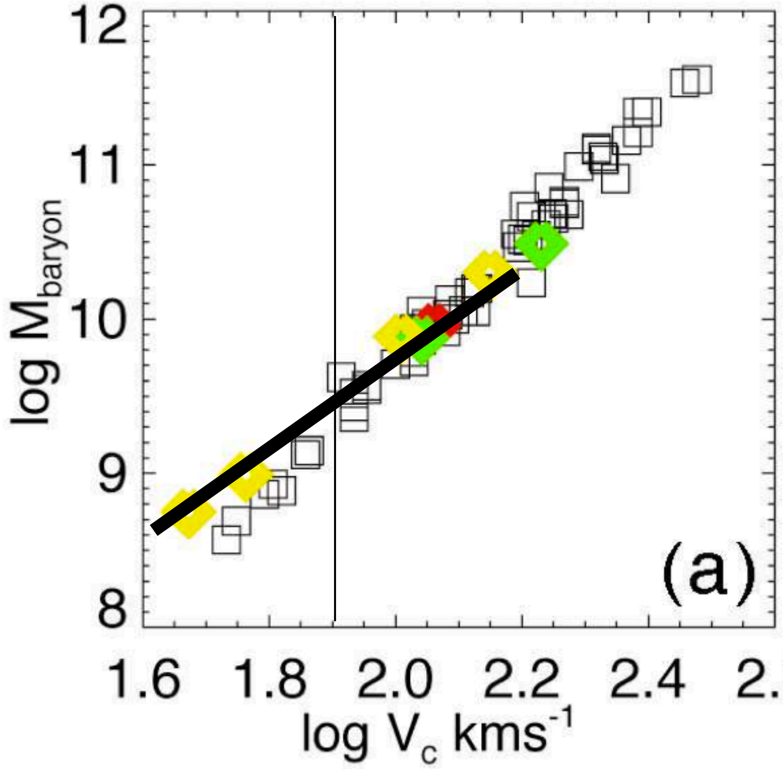
B. Famaey (Observatoire Astronomique de Strasbourg)

Or what particle dark matter cannot do for you…

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**





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

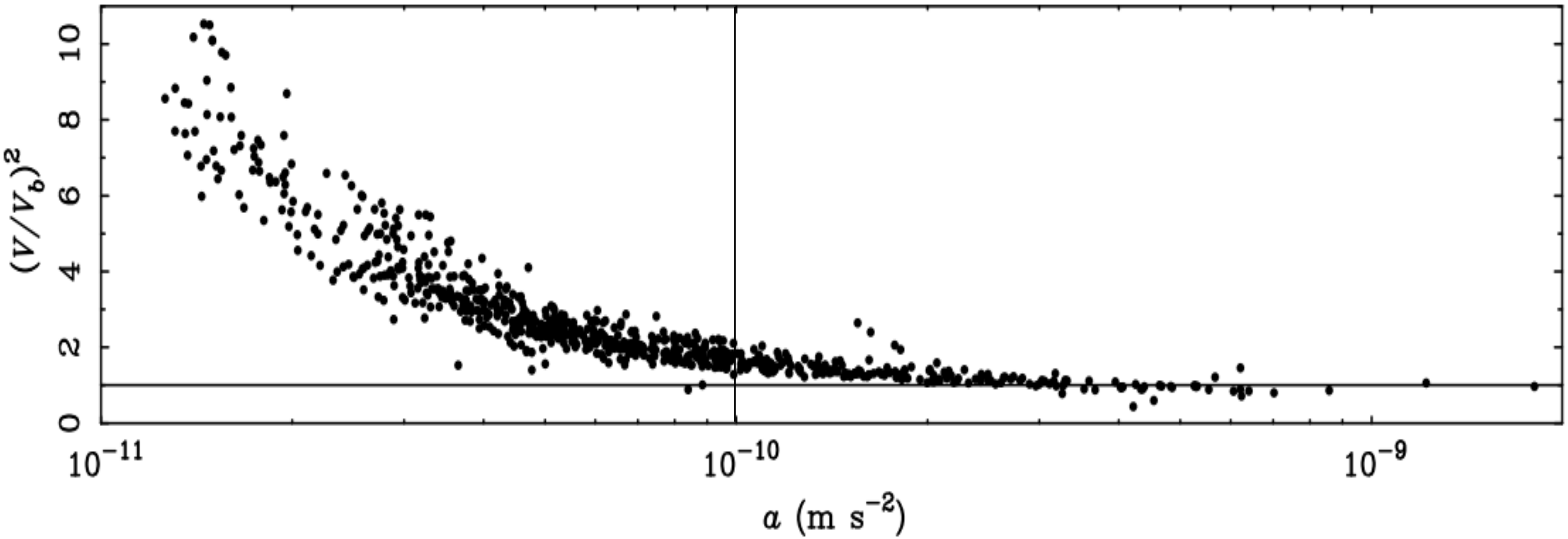
Baryonic Tully-Fisher relation:
Log M_b = 4 log V – log β

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:

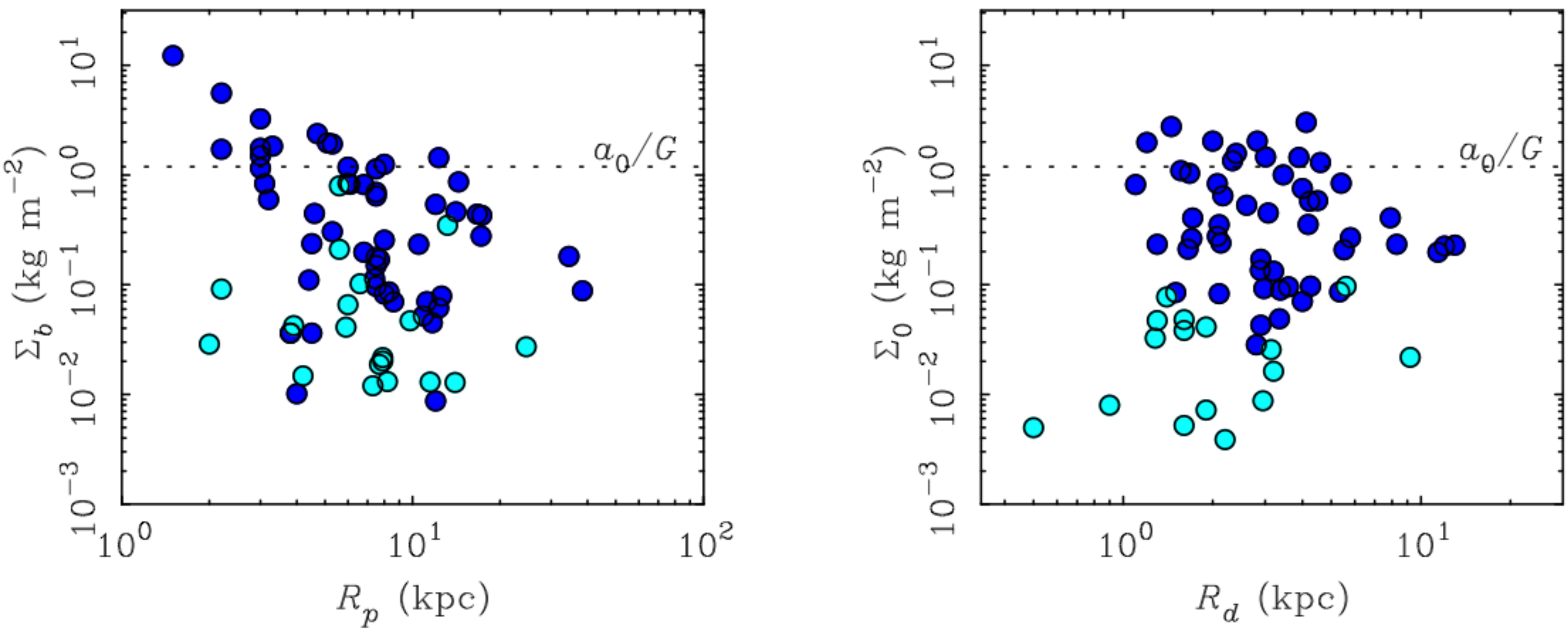
In the DM framework this is a fully **independent** role of a_0



McGaugh (2004)
Famaey & McGaugh (2012)

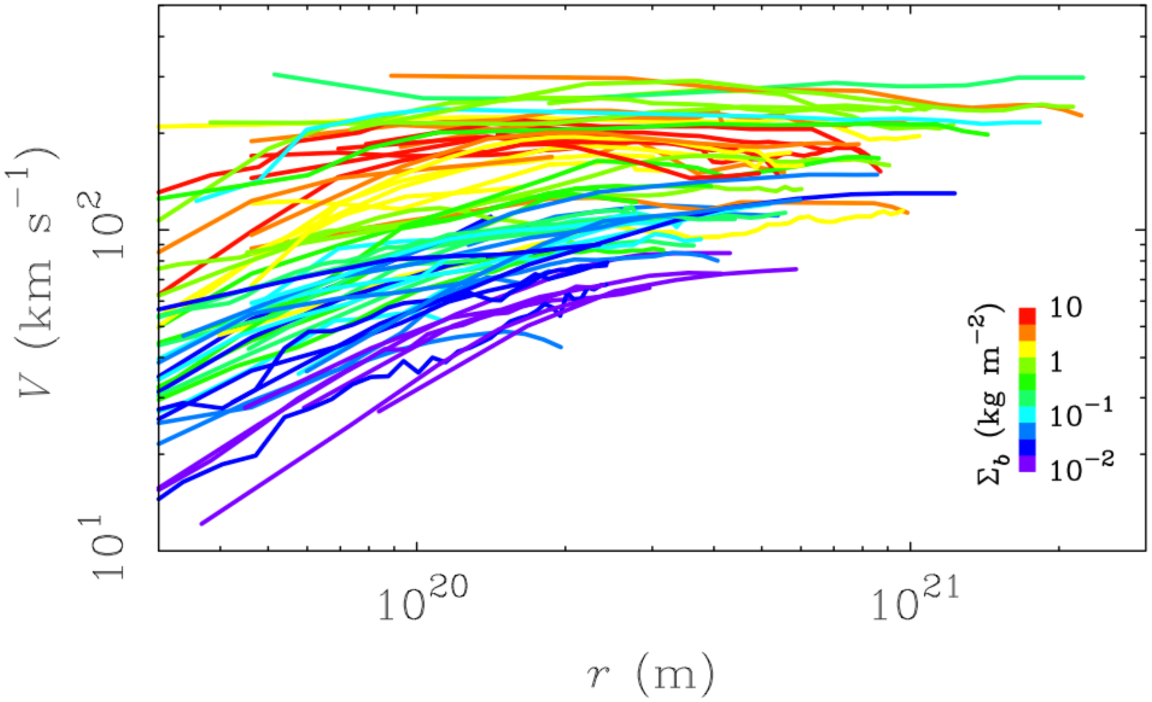
The same acceleration constant a_0 defines a critical baryonic surface density for disk stability a_0/G

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

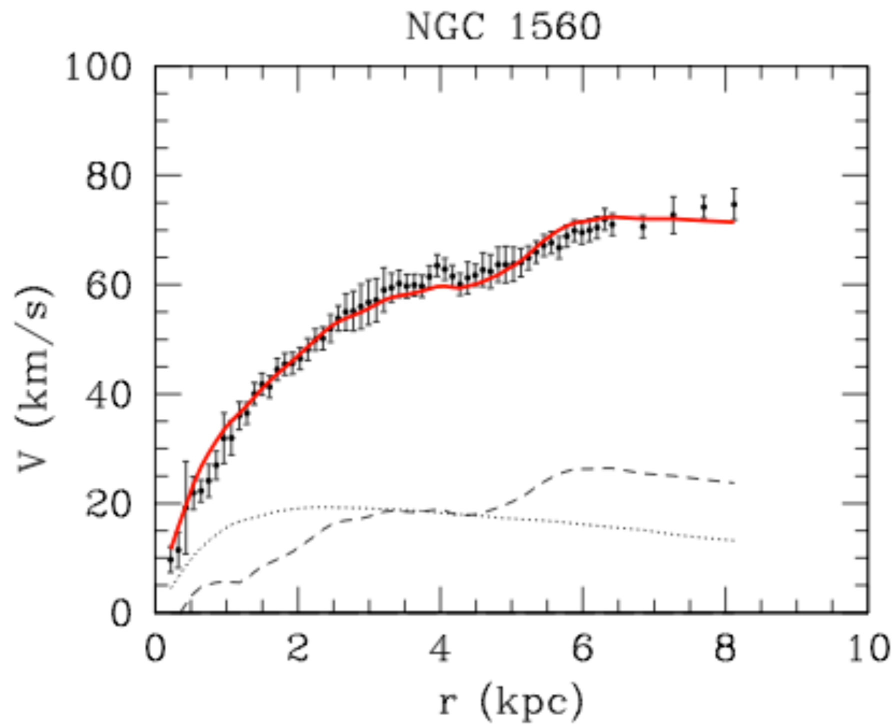


Famaey & McGaugh (2012)

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



Famaey & McGaugh (2012)



Gentile et al. (2010)

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)

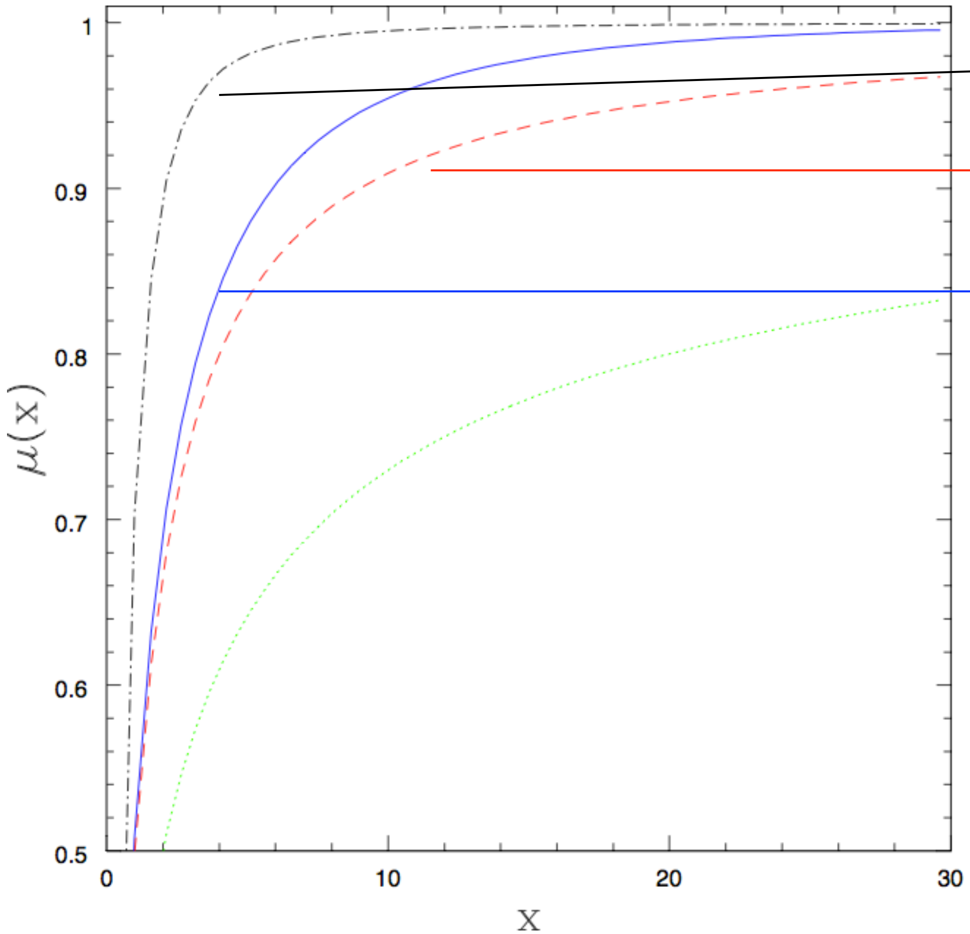
Note: formally, deep-MOND limit for $\boldsymbol{a_0} \rightarrow \infty$ and $\boldsymbol{G} \rightarrow \boldsymbol{0}$

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)



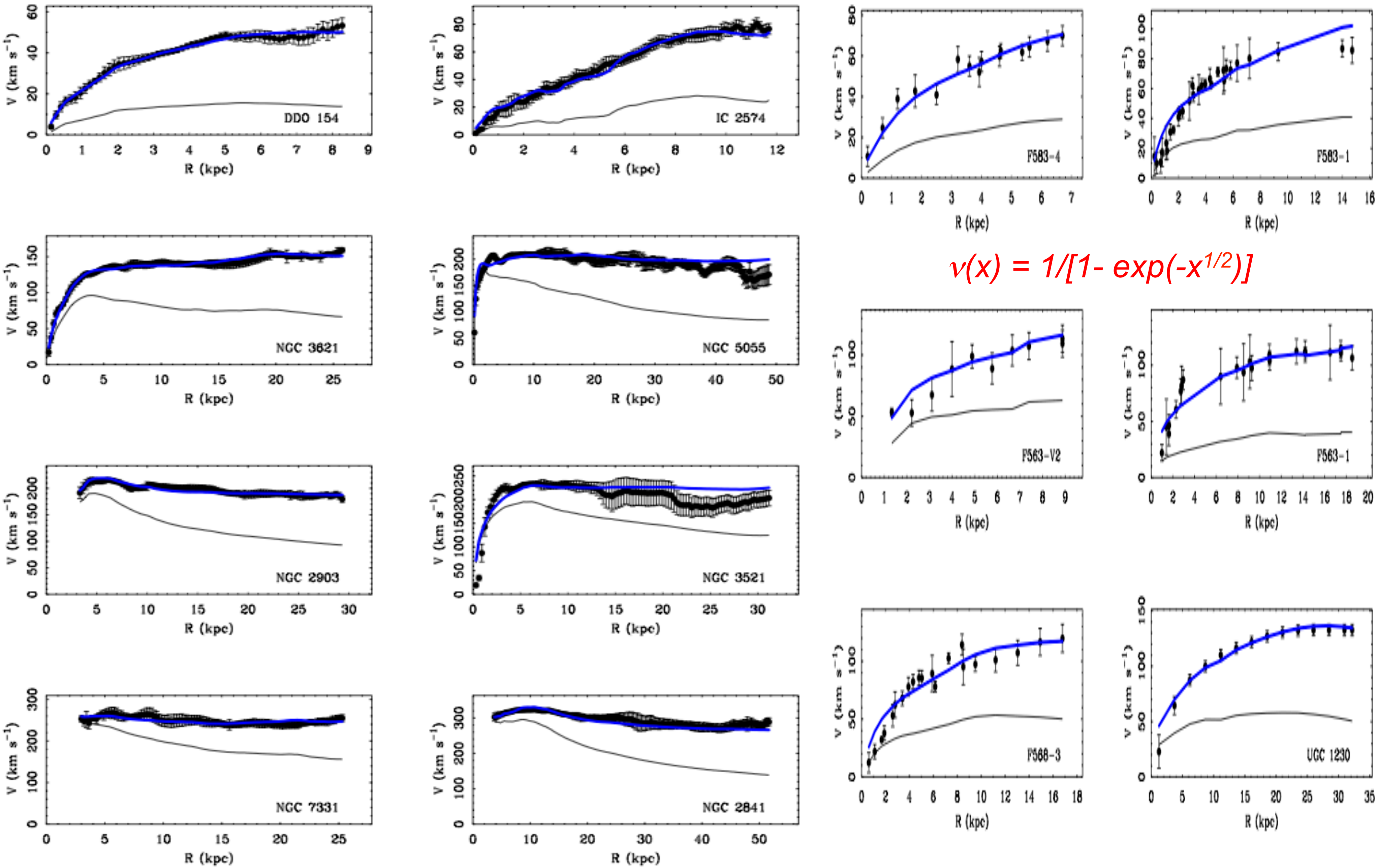
$\mu(x) = x/(1+x^2)^{1/2}$

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

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

Famaey & McGaugh (2012)

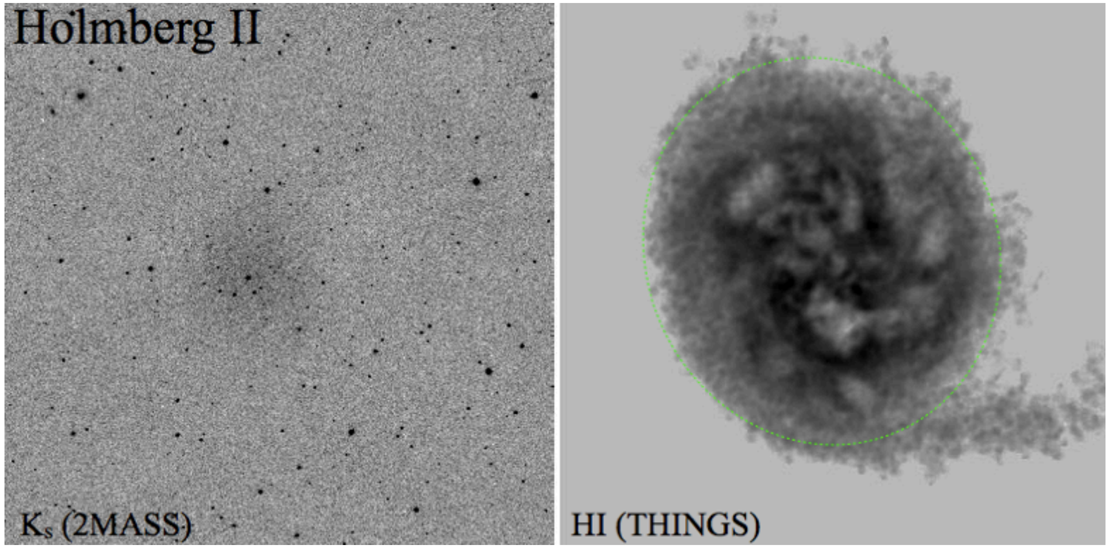
Rotation curves

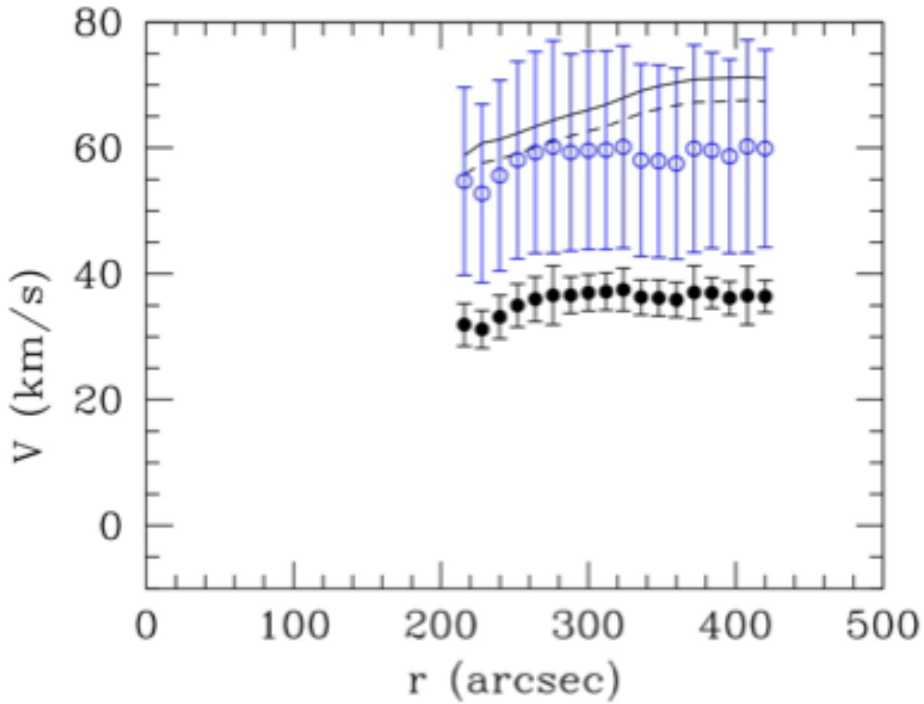


$\nu(x) = 1/[1 - \exp(-x^{1/2})]$

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

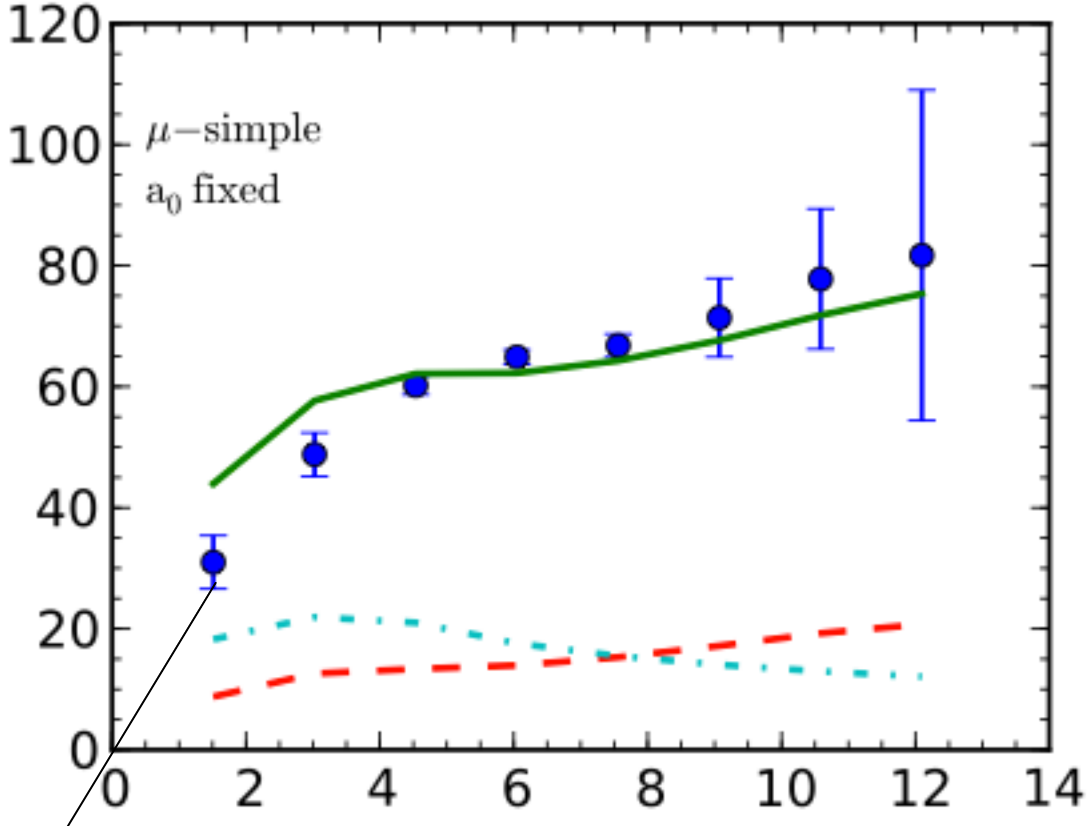
Holmberg II





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°**

NGC 3109



Weak bar

MOND as a modification of classical gravity

$$S_N = \int \frac{\rho \mathbf{v}^2}{2} d^3x\, dt - \int \rho \Phi_N d^3x\, dt - \int \underbrace{\frac{|\nabla \Phi_N|^2}{8\pi G}}_{\to \frac{a_0^2 F(|\nabla\Phi|^2/a_0^2)}{8\pi G}} d^3x\, dt.$$

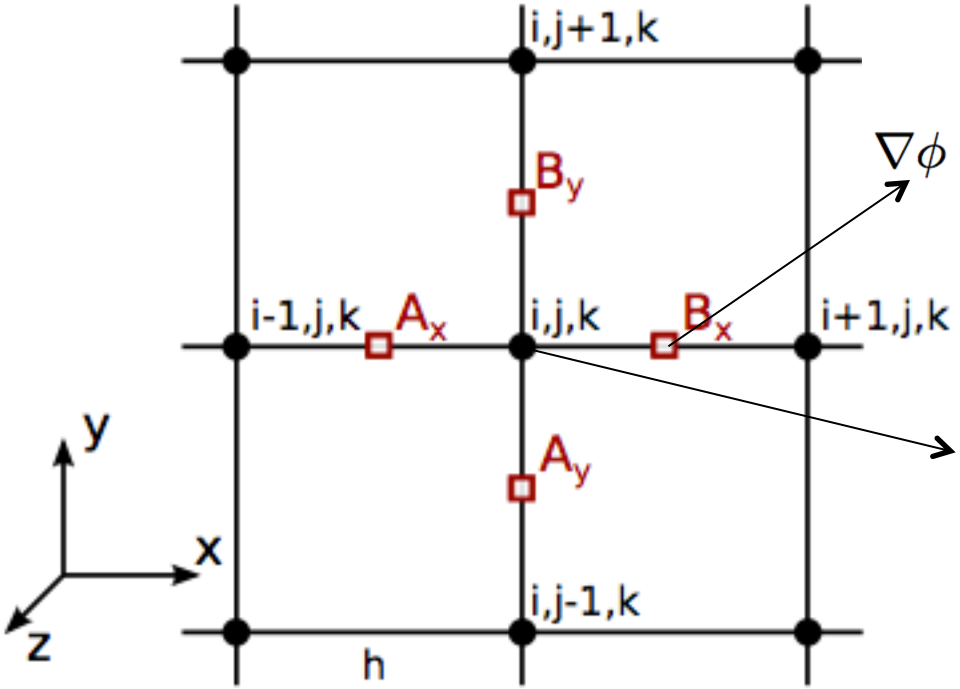
$$\nabla . [\, \mu\, (\,|\nabla\Phi|/a_0)\, \nabla\Phi] = 4\,\pi G\, \rho_{bar}$$ Bekenstein & Milgrom (1984)

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

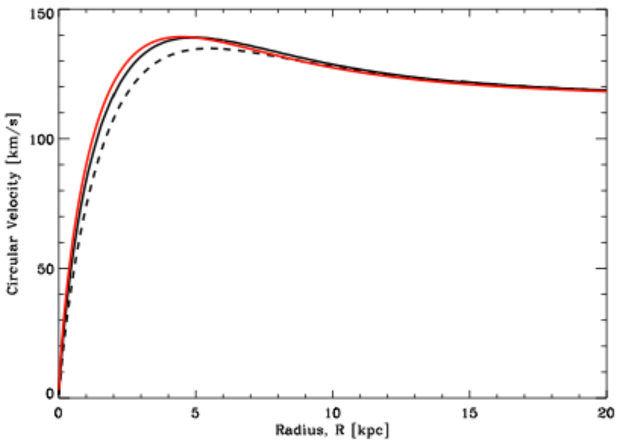
Numerical solver (QUMOND)



$$\nabla\phi = \frac{1}{4h}\begin{pmatrix} 4\left(\phi^{\mathrm{i+1,j,k}} - \phi^{\mathrm{i,j,k}}\right) \\ \phi^{\mathrm{i+1,j+1,k}} - \phi^{\mathrm{i+1,j\text{-}1,k}} + \phi^{\mathrm{i,j+1,k}} - \phi^{\mathrm{i,j\text{-}1,k}} \\ \phi^{\mathrm{i,j,k+1}} - \phi^{\mathrm{i,j,k\text{-}1}} + \phi^{\mathrm{i+1,j,k+1}} - \phi^{\mathrm{i+1,j,k\text{-}1}} \end{pmatrix}$$

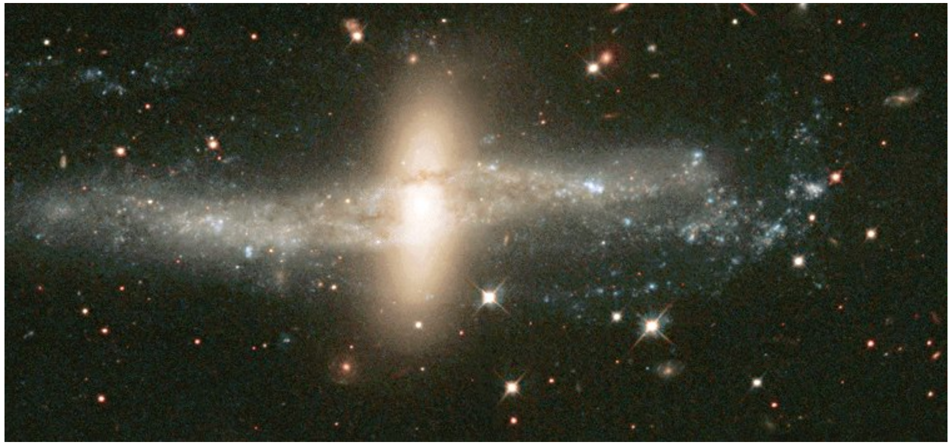
$$\begin{aligned}\rho_{\mathrm{ph}}^{\mathrm{i,j,k}} = \frac{1}{4\pi G}\frac{1}{h^2}\Big[& \left(\phi^{\mathrm{i+1,j,k}} - \phi^{\mathrm{i,j,k}}\right)\nu_{\mathrm{Bx}} \\ & - \left(\phi^{\mathrm{i,j,k}} - \phi^{\mathrm{i\text{-}1,j,k}}\right)\nu_{\mathrm{Ax}} \\ & + \left(\phi^{\mathrm{i,j+1,k}} - \phi^{\mathrm{i,j,k}}\right)\nu_{\mathrm{By}} \\ & - \left(\phi^{\mathrm{i,j,k}} - \phi^{\mathrm{i,j\text{-}1,k}}\right)\nu_{\mathrm{Ay}} \\ & + \left(\phi^{\mathrm{i,j,k+1}} - \phi^{\mathrm{i,j,k}}\right)\nu_{\mathrm{Bz}} \\ & - \left(\phi^{\mathrm{i,j,k}} - \phi^{\mathrm{i,j,k\text{-}1}}\right)\nu_{\mathrm{Az}} \Big]\end{aligned}$$

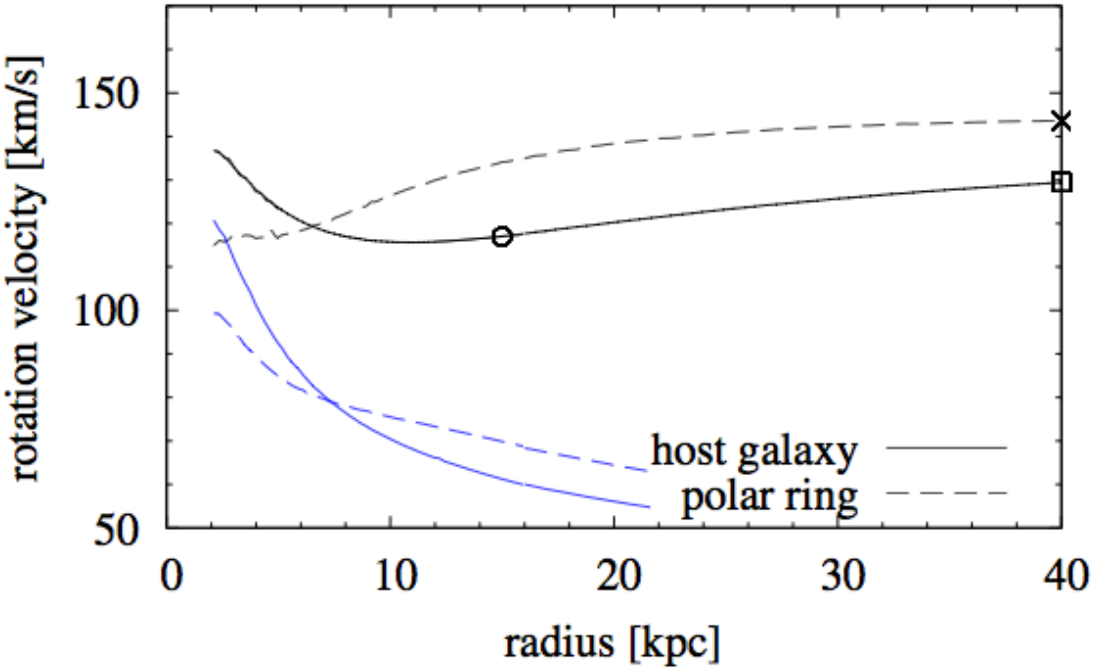
e.g., Lüghausen, Famaey, Kroupa, et al. (2013)

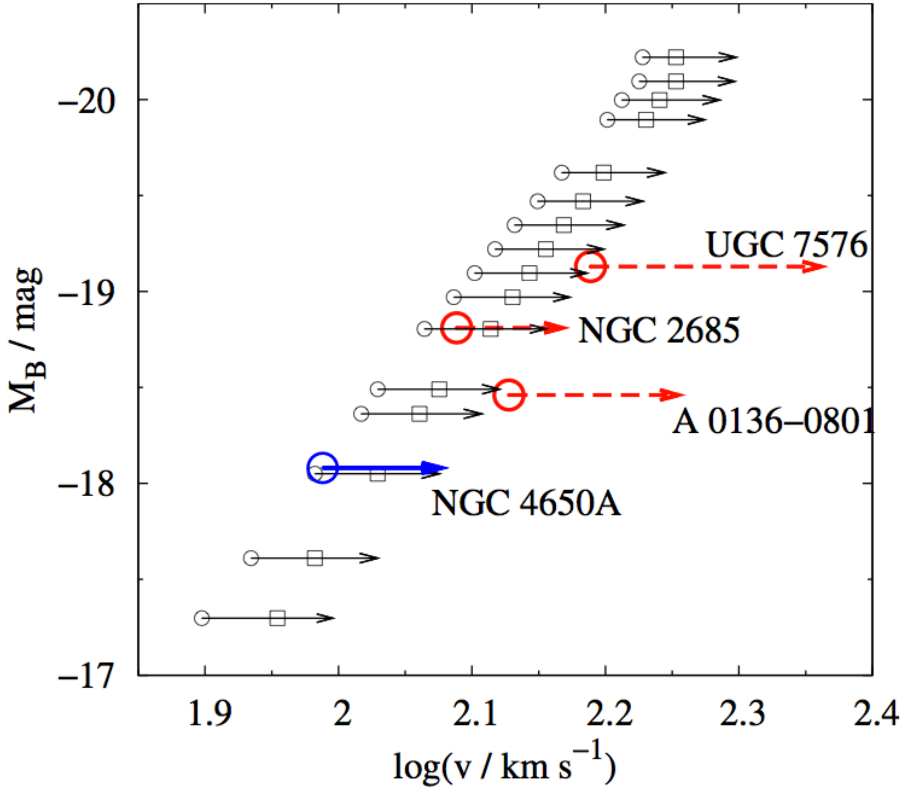


Angus, van der Heyden, Famaey, et al. (2013)

Polar ring galaxies



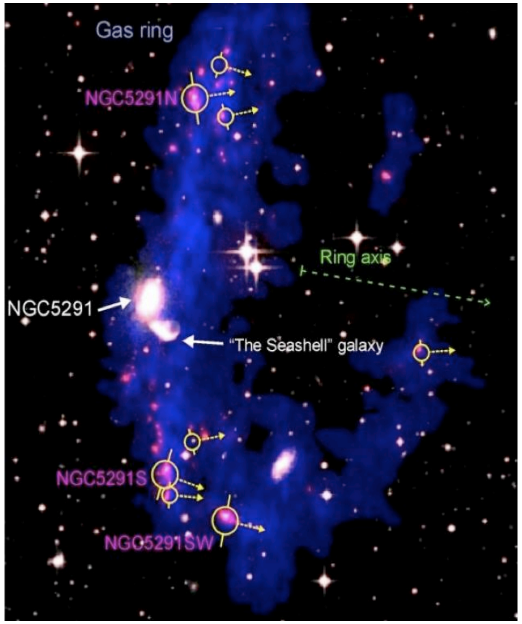




Lüghausen, Famaey, Kroupa, et al. (2013)

Separating baryons from particle DM

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



Tidal dwarf galaxies in NGC 5291

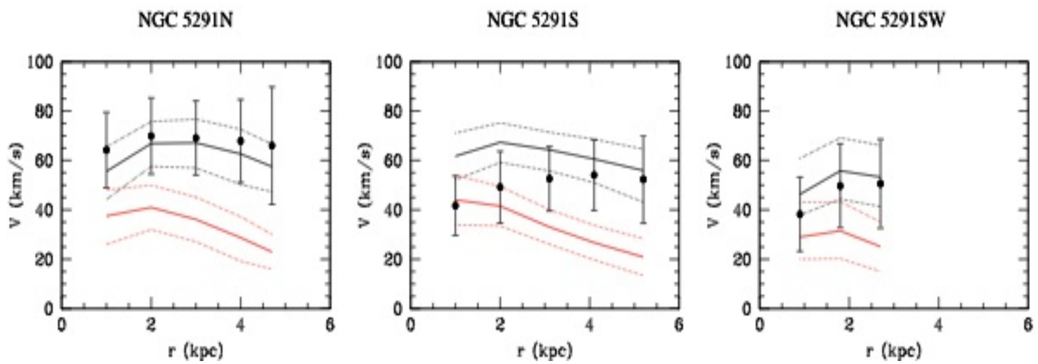
Bournaud et al. (2007)

Milgrom (2007)

Gentile, Famaey et al. (2007)

~~CDM~~

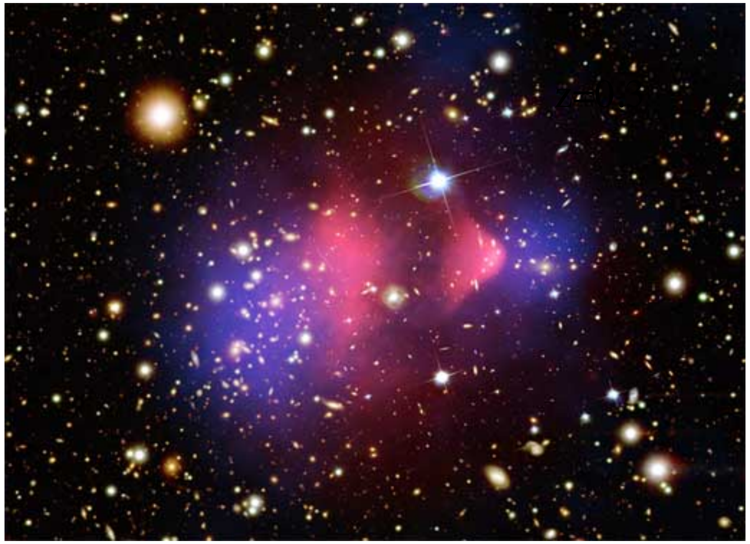
MOND



Large pressure-supported not very gas-dense

CDM

~~MOND~~

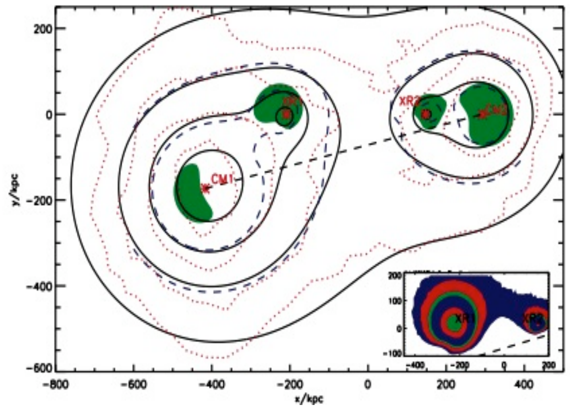


The Bullet Cluster

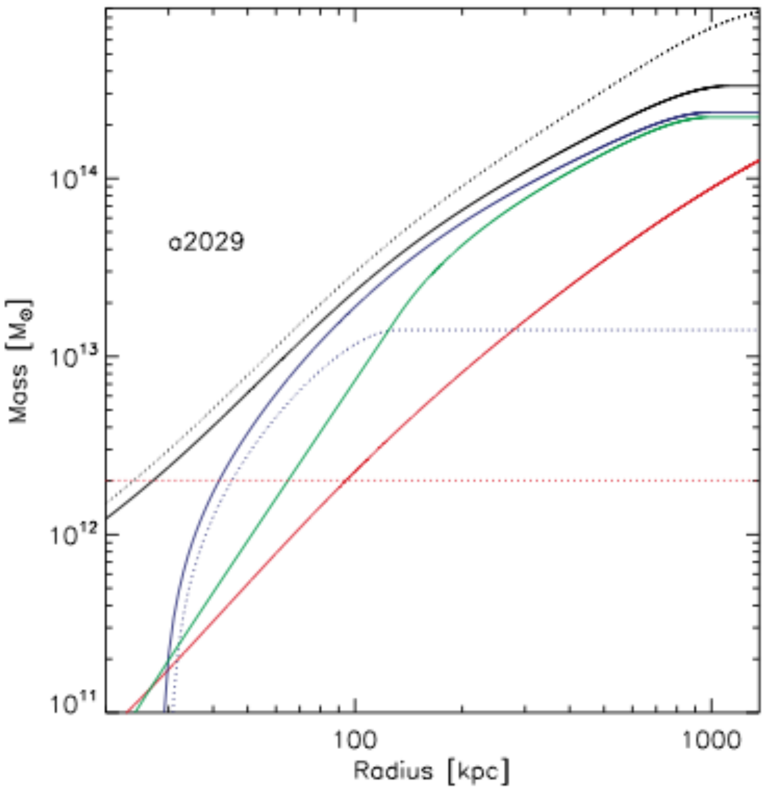
Clowe et al. (2006)

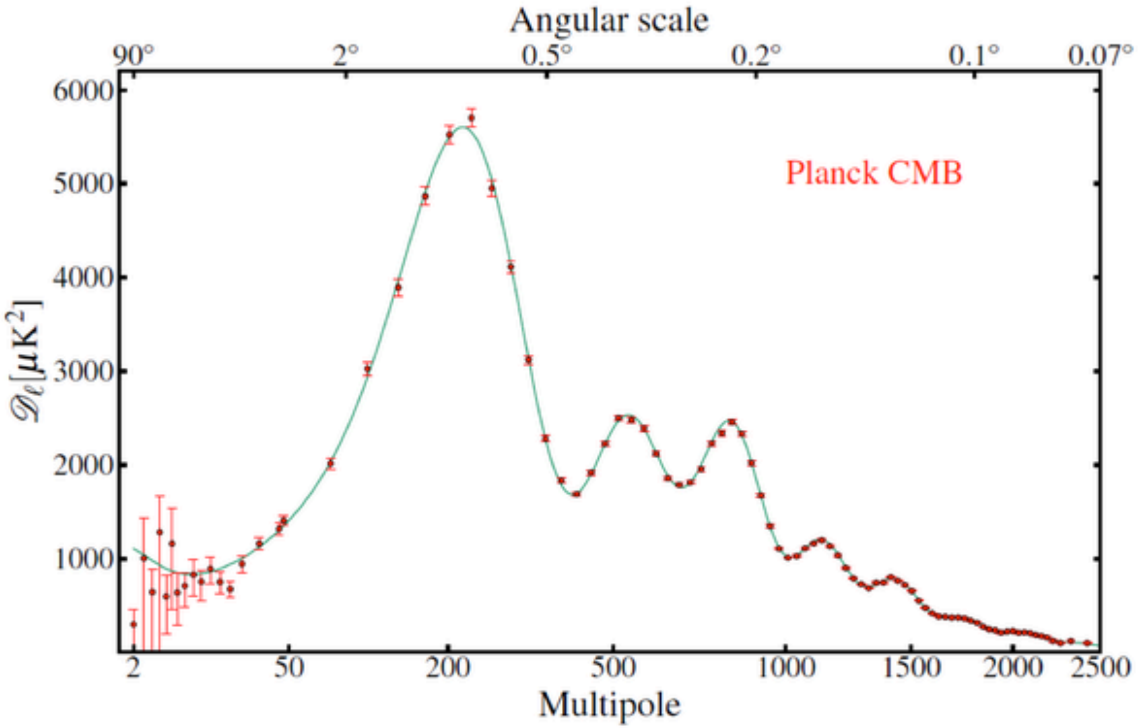
Angus, Shan, Zhao & Famaey (2007)

But speed 3000 km/s?



Large scales!!



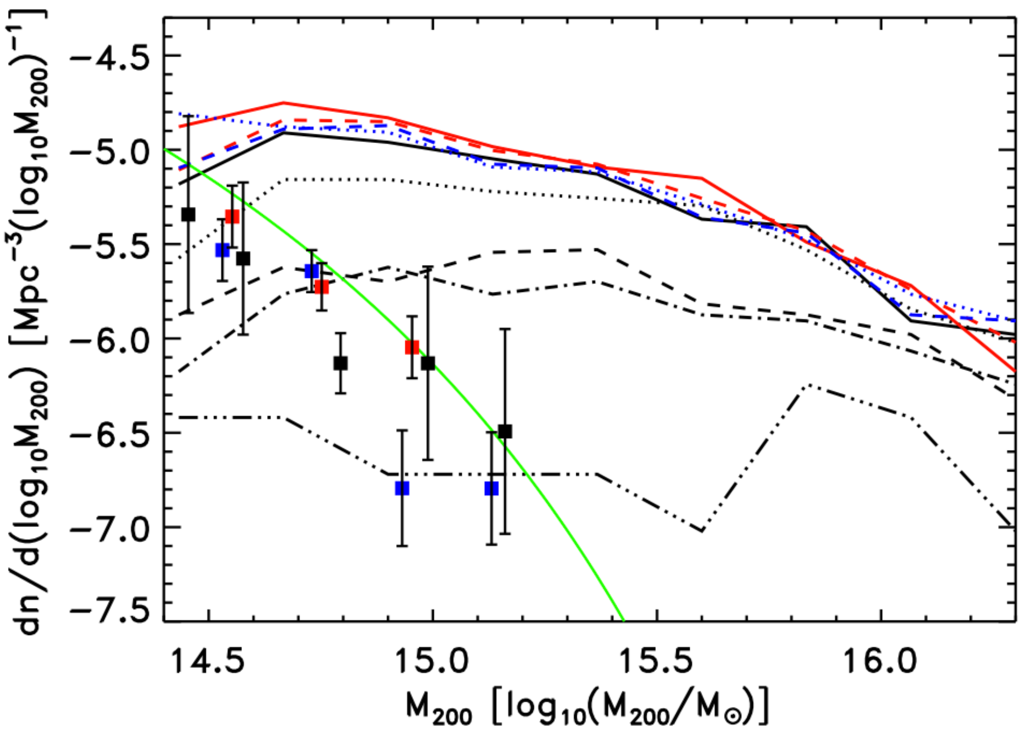


Angus, Famaey & Buote (2008)

Hot dark matter?

Very simple non-covariant model, starts from a HDM universe in GR at z=200

256^3 particles in boxes of 256 Mpc/h , low mass resolution of ~10^{10} Msun



Angus et al (2013)

Dipolar Dark Matter

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

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

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

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

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

Blanchet & Le Tiec 2009

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

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

Not a tensor but the subtraction of two is

=> BIMOND

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

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