Alternative to the standard cosmological model

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Dark matter in galaxies poses a list of interesting open questions leading to essential information on either

(i) the galaxy formation process,

(ii) the very nature of dark matter

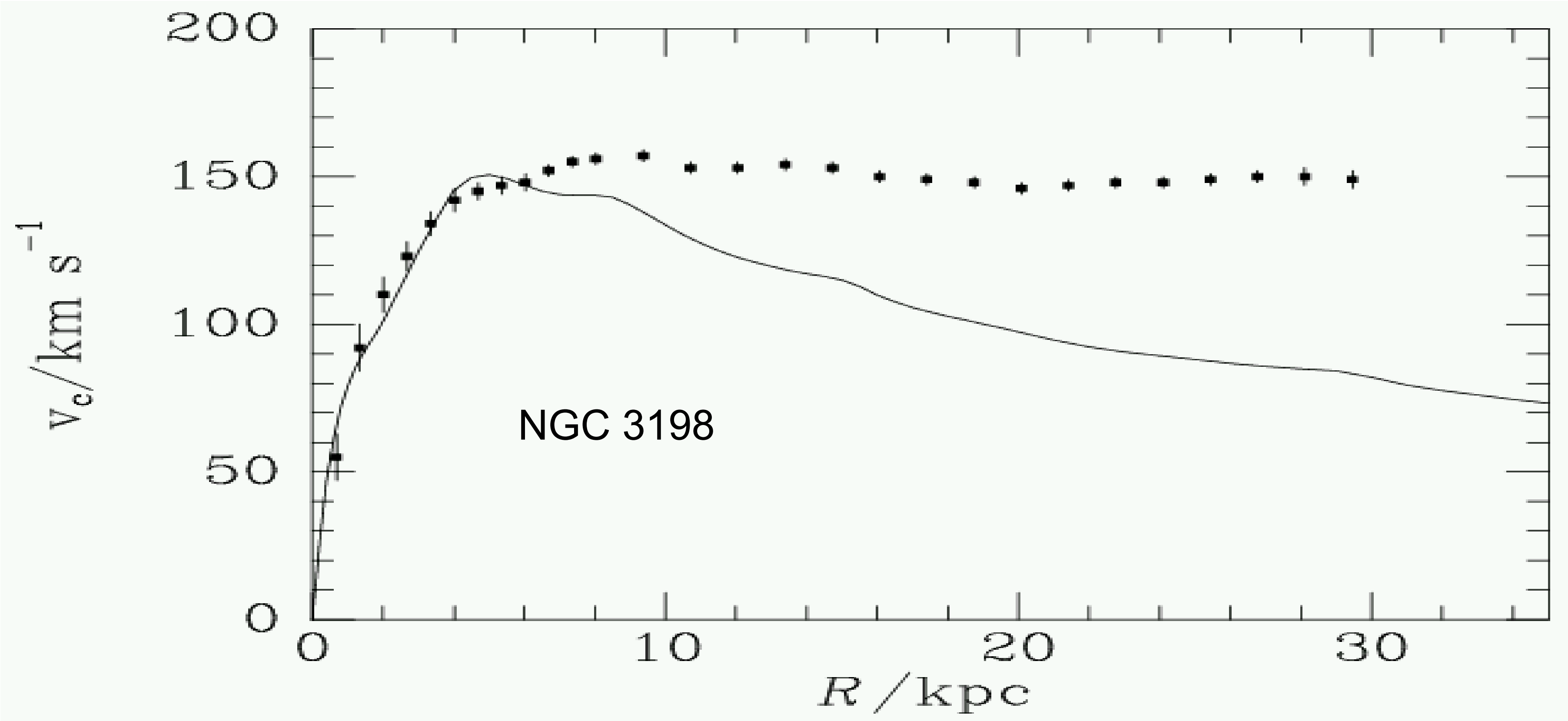
or (iii) even on its existence in galaxies

Plan of the lecture

1. (1h) Introduce 5 observational challenges for the standard picture

2. (1h) More speculative: could some of these challenges point towards an alternative cosmological model? Strengths and weaknesses…

Galactic rotation curves



$(R\ |\partial\Phi_{bar}/\partial R|)^{1/2} = V_{c\ bar}$ too low in the galactic plane compared to observed V_c

=> DARK MATTER HALO

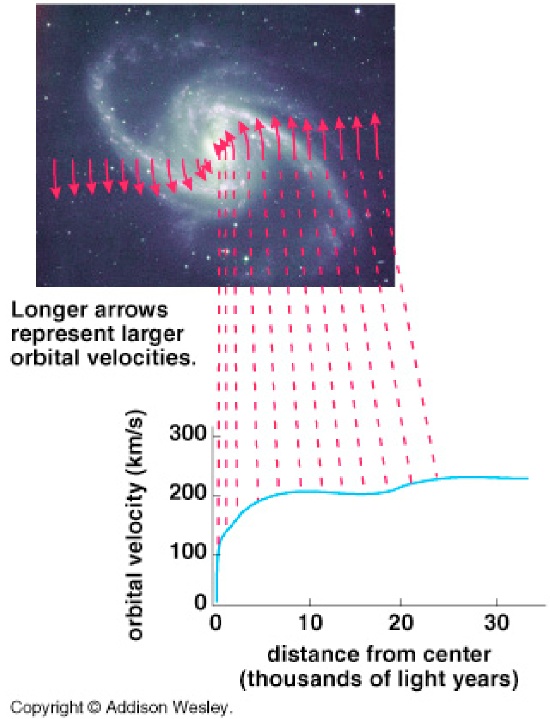
OBSERVATIONS:

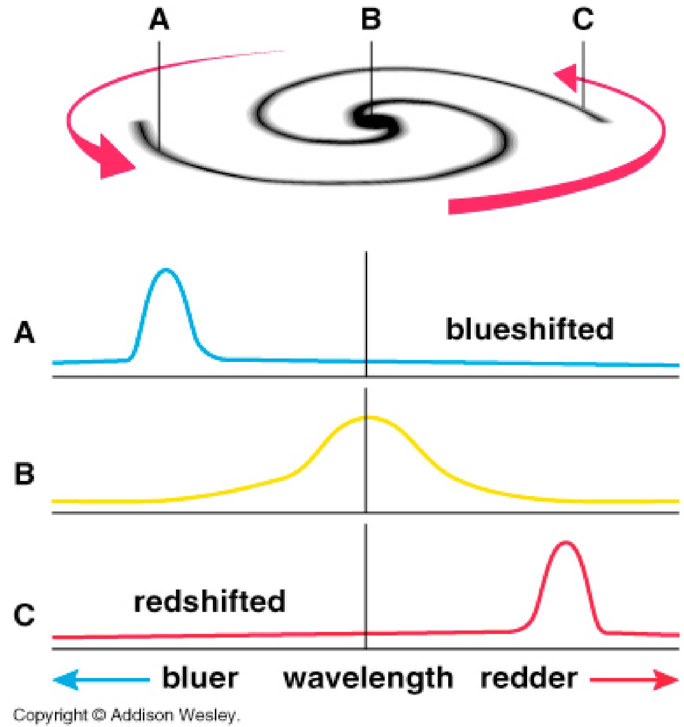
Symmetric circular rotation of a disk characterized by:

- Sky coordinates of the galaxy centre
- Systemic velocity V_{sys}
- Circular velocity $V(R)$
- Inclination angle $i = \arccos\left(\frac{a}{b}\right)$

$$V_{obs}(\xi,\eta) = V_{sys} + V(R)\cos\theta\,\sin i$$

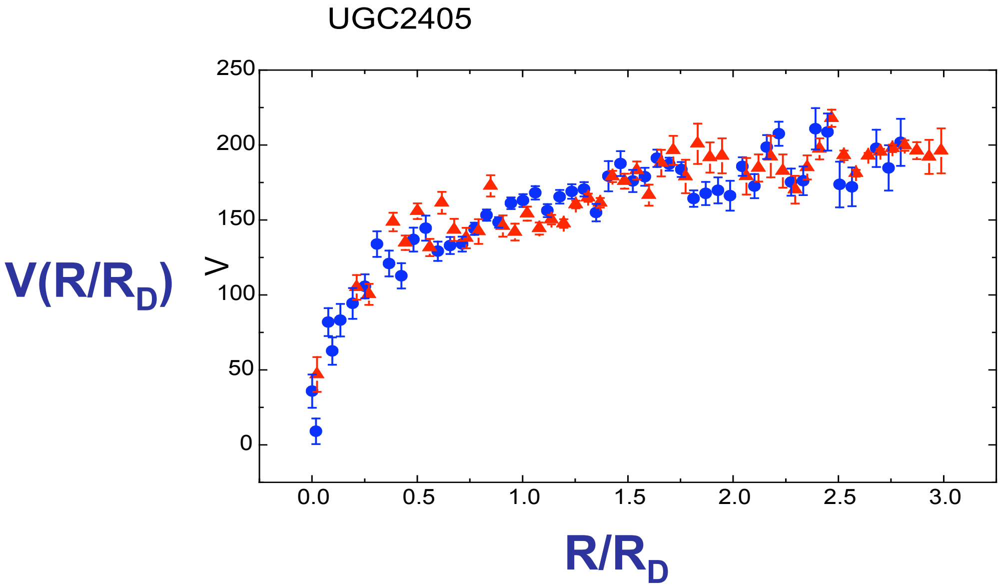
θ= azimuthal angle





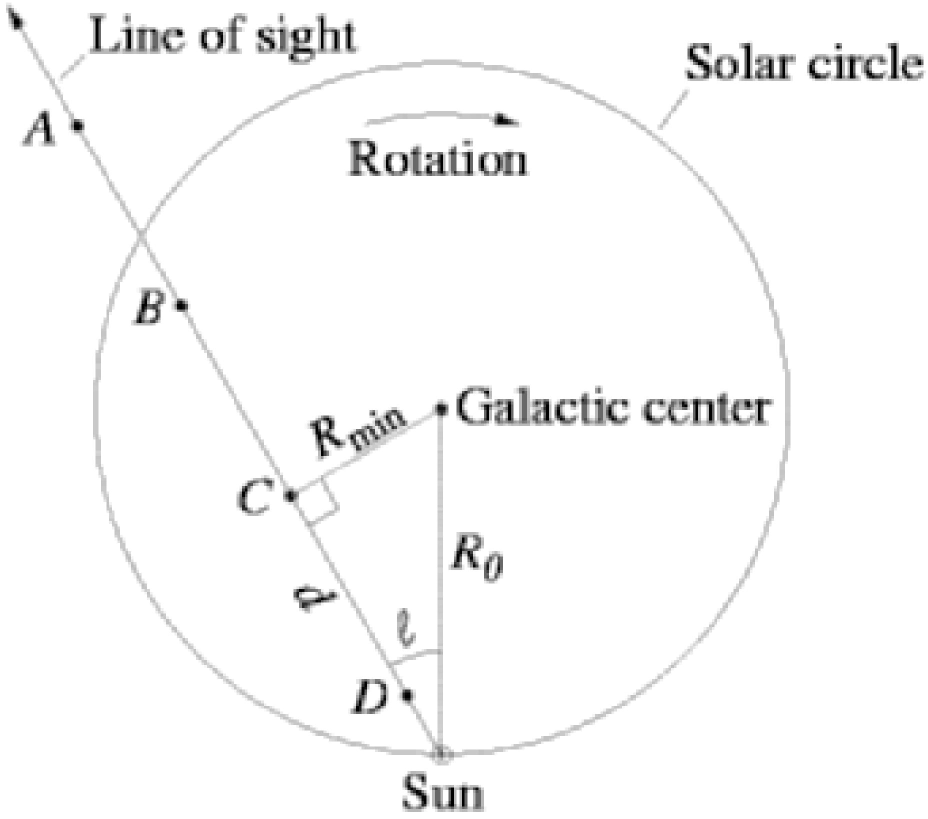
Example of a recent high quality RC:

Radial coordinate in units of R_D



The Milky Way

Measure the « Terminal Velocity Curve » (TVC)



$$V_c(R_{min} = R_0 \sin l) = | V_t(l) + V_0 \sin(l) |$$

Dissipating a misunderstanding

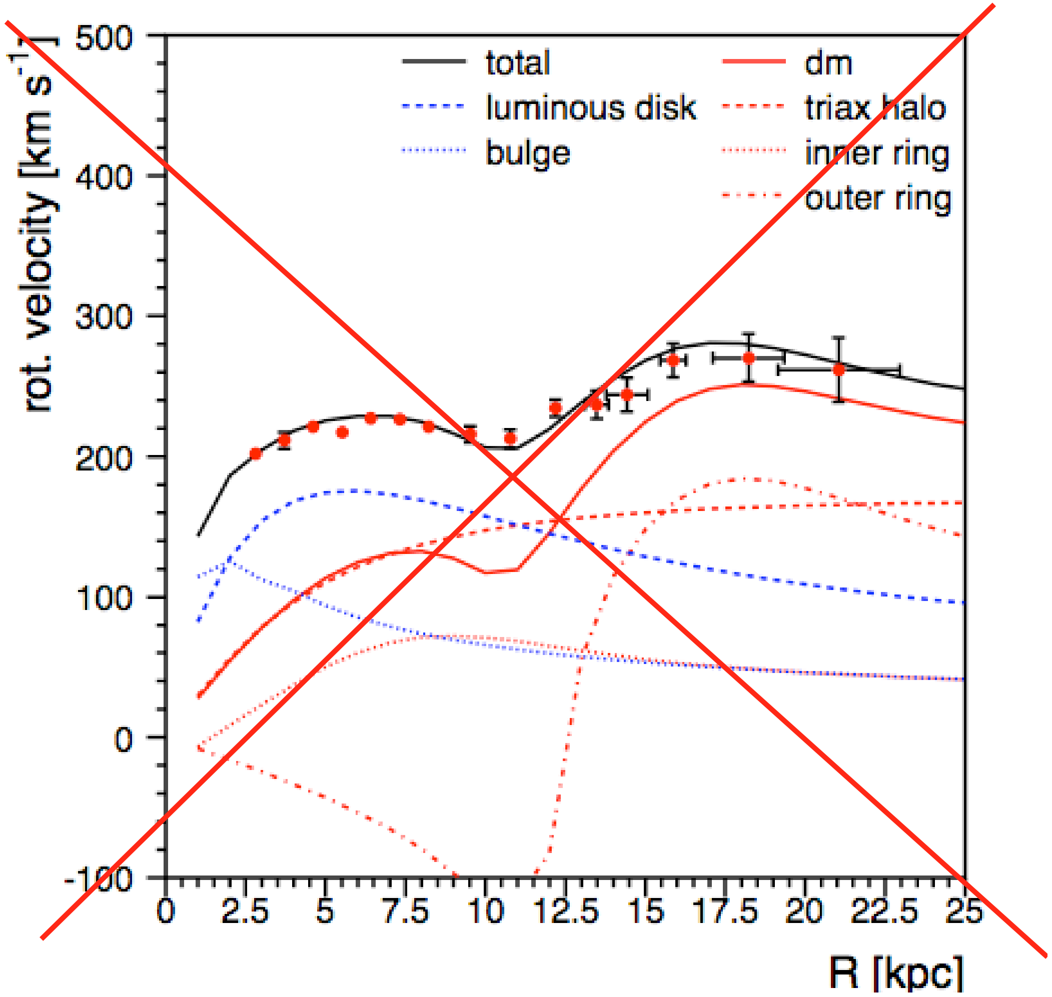
It is often argued that a ring of DM is present around R=13kpc

At $R<R_0$:

$V_c(R_0 \sin l)=V_t + V_0 \sin l$

BUT at $R>R_0$:

One needs the **distance** of tracers (cepheids P-L relation)



Binney & Dehnen (1997):
data compatible with a gently declining RC if overdensity of TRACERS

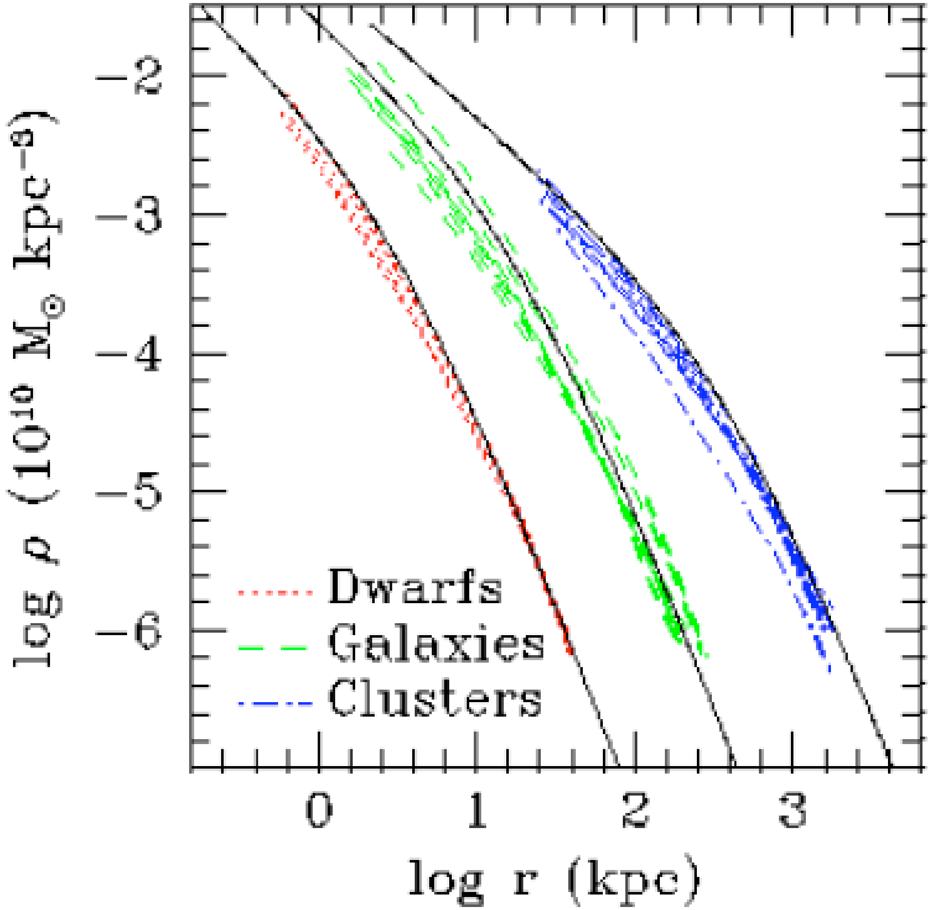
Open question 1: the cusp problem

NFW dark matter Profiles from N-body simulations

In ΛCDM scenario the density profile for virialized DM halos of all masses of all masses is empirically described at all times by the universal NFW formula (Navarro+96,97).

$$\rho(r)/\rho_{crit} \approx \delta\ r_s / r(1 + r/r_s)^2$$
$$= \rho_s\, r_s^3 / r(r^2+r_s^2)$$

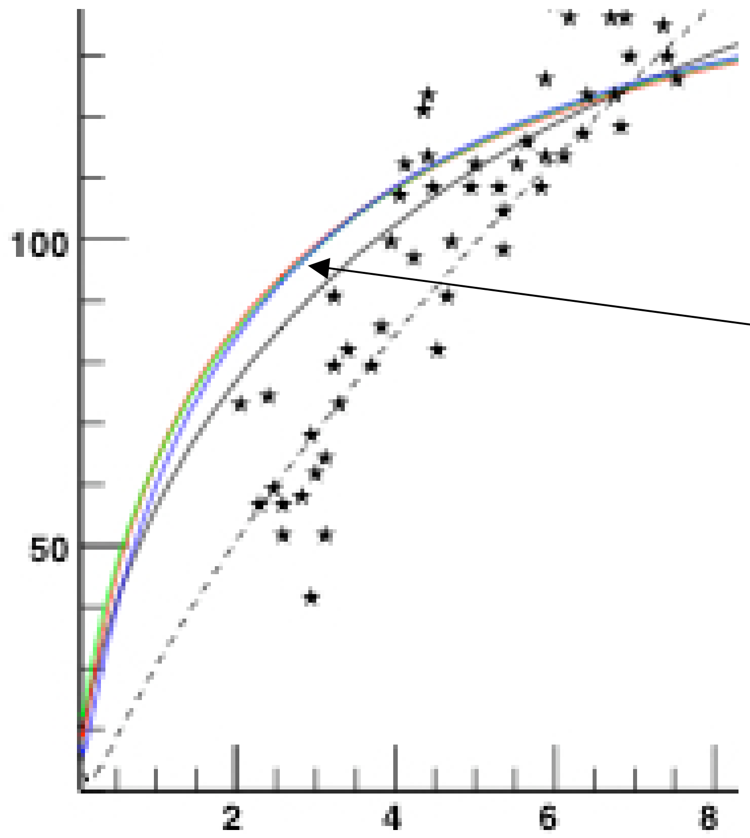
More massive halos have larger overdensities δ.



Inner rotation curve of the MW

$V_c(R_0 \sin l) = V_t + V_0 \sin l$

$V_{cDM} = (V_c^2 - V_{cbar}{}^2)^{1/2}$

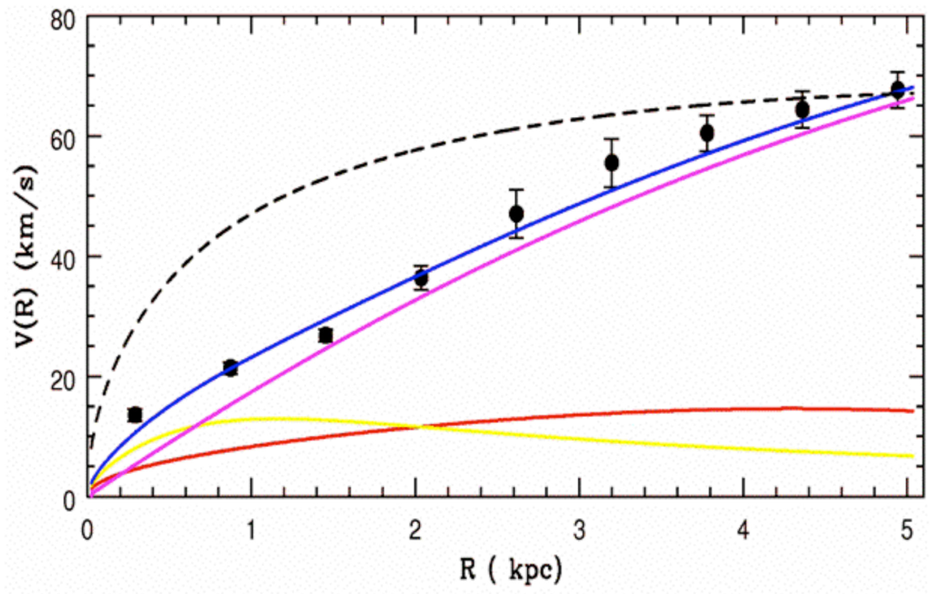


NFW profile overpredicts DM density at the center

Confirmed by microlensing optical depth

In other galaxies too

DDO 47



General results from several samples including THINGS, HI survey of uniform and high quality data
+ microlensing optical depth and gas flow in the MW

- No DM halo elongation
- Cored halos often preferred over NFW

Tri-axiality and non-circular motions cannot explain the CDM/NFW cusp/core discrepancy. Including feedback from baryons (bar? No…)

Governato et al: best attempt but too high baryon fraction

Aquarius simulations, highest resolutions to date.

Results: Einasto profiles (Navarro et al. 2010)

$$\ln \rho(r)/\rho_{-2} = -2/\alpha \left[(r/r_{-2})^{\alpha} - 1\right]$$

with r_{-2} determining size and α dependent slightly on mass (α **= 0.17** for MW-type halo from CDM simulations)

Slope $\mathbf{d\ln\rho/d\ln r \propto -r^{\alpha}}$ goes from -1.4 at r=1 kpc to -0.8 at r=100 pc

Only fits with $\alpha \gg \alpha_{sim}$ OK

Open question 2: missing satellites?

Mass function of luminous satellites

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

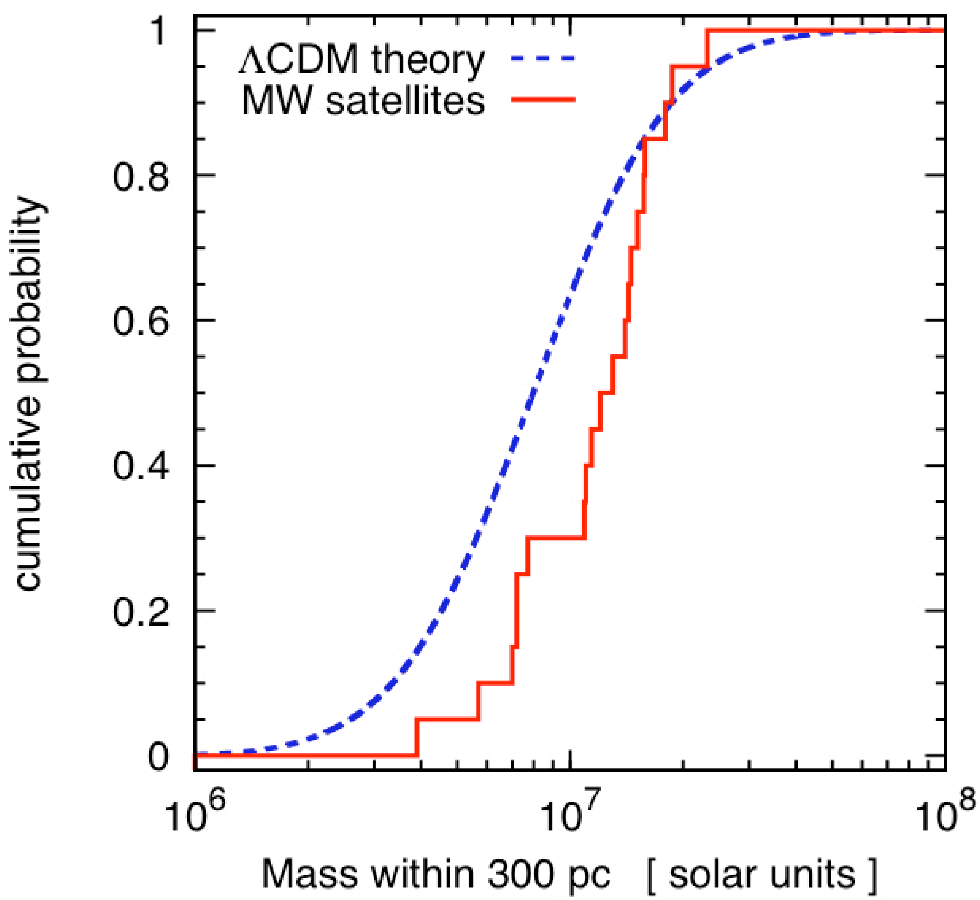
-> Is the missing satellite problem solved?

No: the mass function of **luminous** halos disagrees with the expectations from CDM

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

with

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



Kroupa et al. (2010)

Open question 3:
phase-space correlation of satellites?

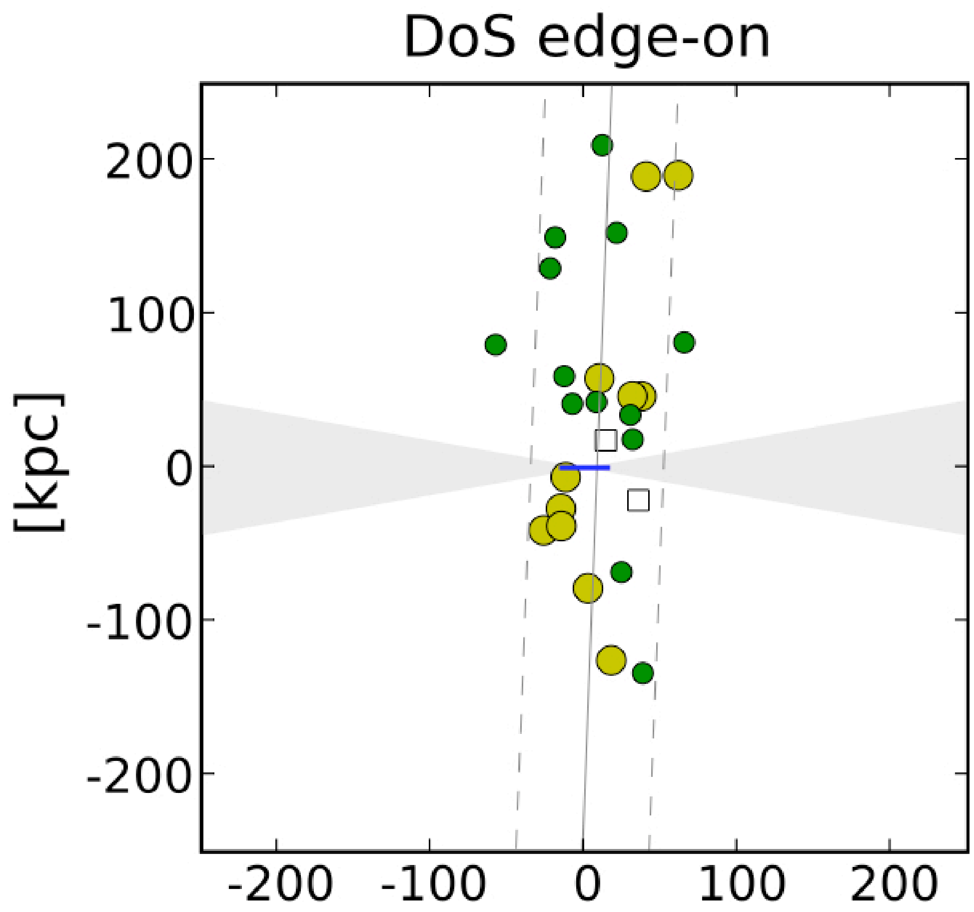
The Holmberg plane of satellites

Seems not to be found in external galaxies (M31, SDSS) **but** still very much there in the Milky Way!

-> Wait for Pan-Starrs…

-> then, if it remains, what does it mean? Not expected in CDM simulations

-> TDGs ? But where are the primordial DM halos around the MW then?



Kroupa et al. (2010)

Open question 4:
reproducing the local void?

Distribution of galaxies in the LV

562 galaxies with

1Mpc < d < 8Mpc

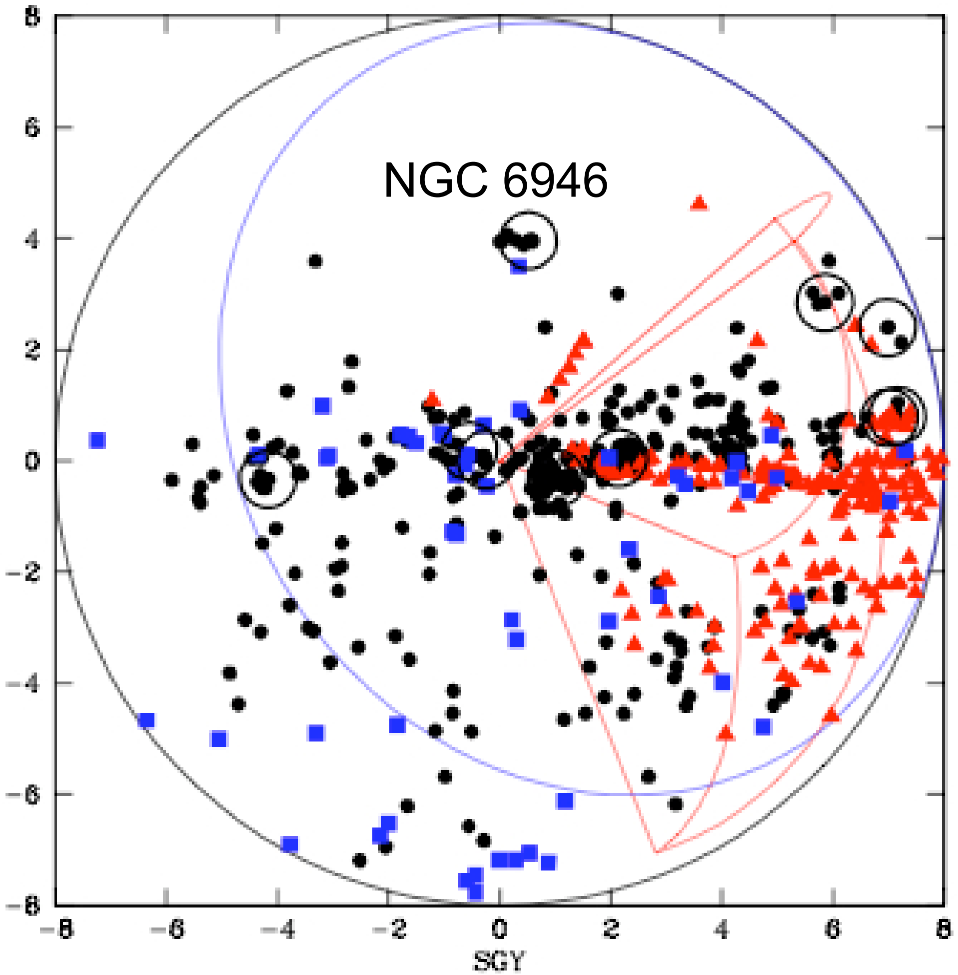
5% are >2Mpc above the local sheet

Among the 10 most luminous ones (circles),

3 are >2Mpc above the local sheet

-> too few and too large galaxies in underdense regions (different from missing sat)

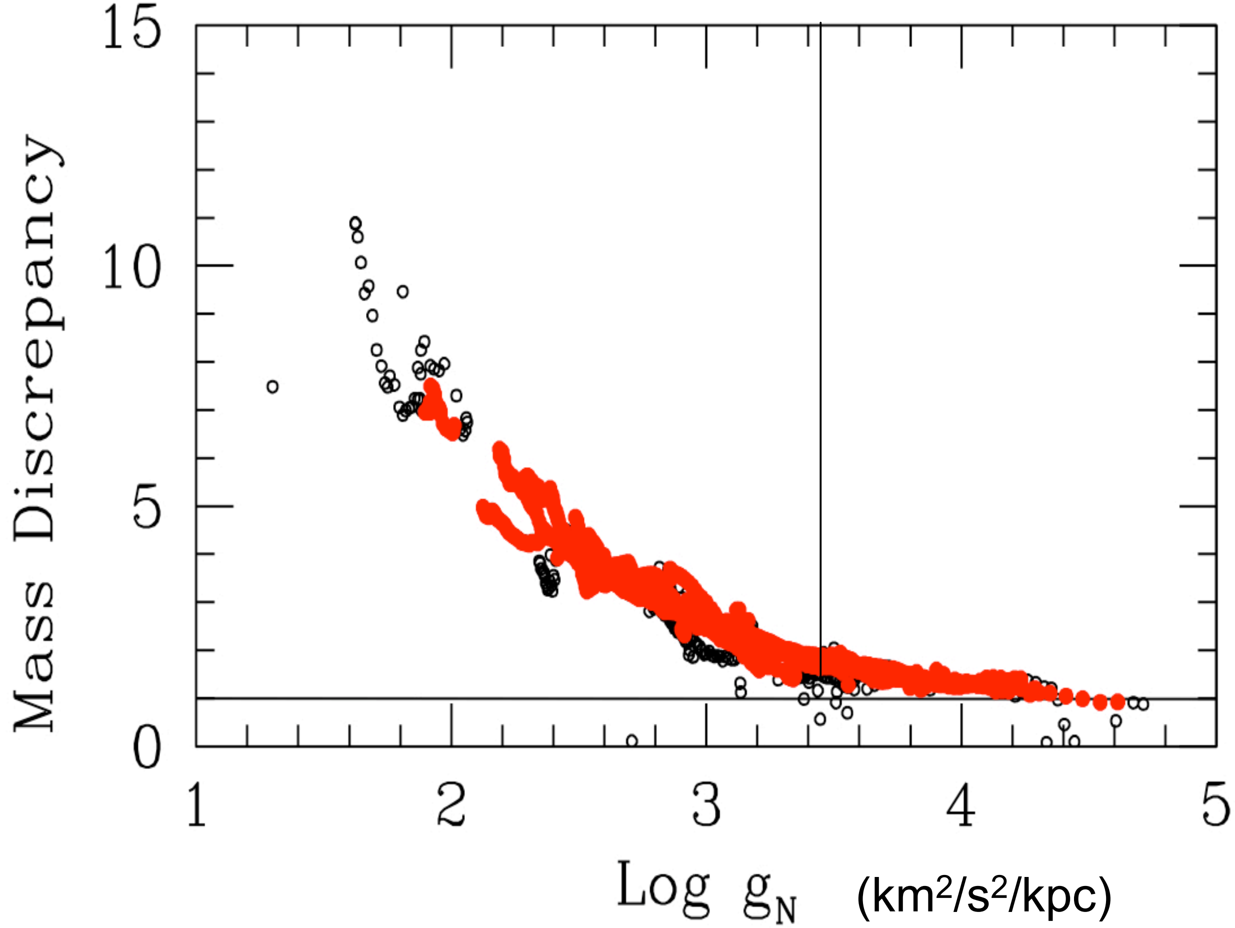
HIPASS + SDSS



Peebles & Nusser (2010)

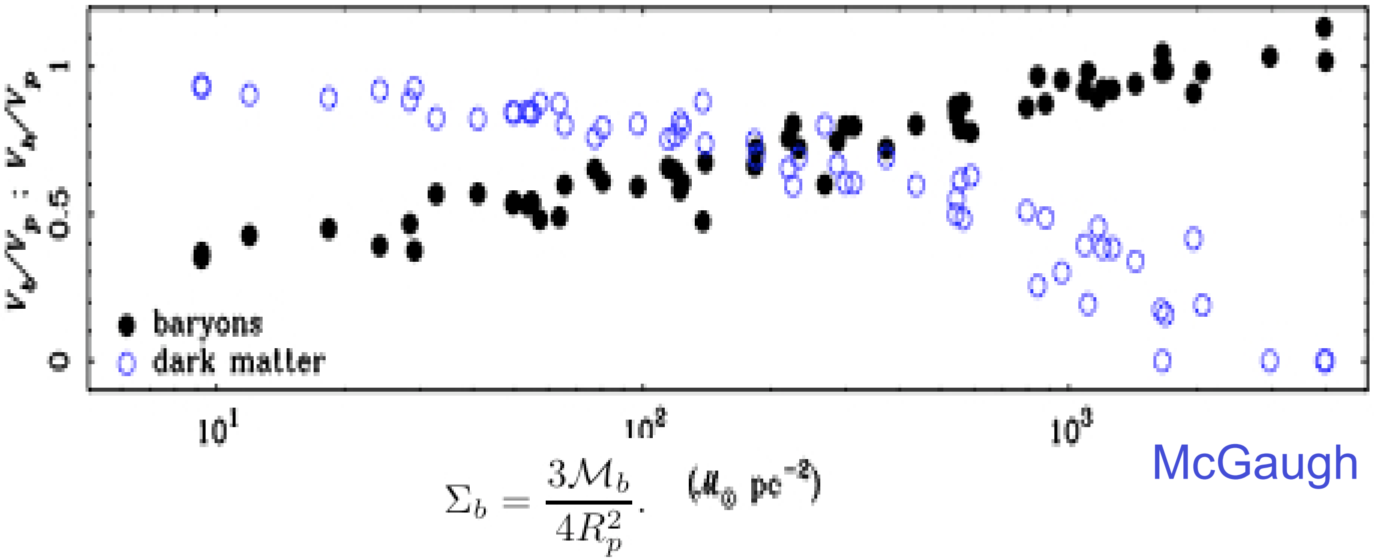
Open question 5: reproducing the mass discrepancy-acceleration relation?

Mass Discrepancy vs Acceleration



McGaugh 2004; Gentile, Famaey & de Blok 2010

A fine balance of DM and baryons



McGaugh (2005)

R_p= radius of max contribution of both gas and stars to the RC

Comparing the contribution of baryons to the RC as a function of surface density (proxy for characteristic acceleration)

This could point at some sort of repulsion between surface densities of baryons and DM

MDA (and this MDsurfden) is *history-independent* !

Asymptotes to Baryonic Tully-Fisher

At small accelerations, the mass discrepancy is

$\boxed{M_{tot}/M_{bar} = a_0/a}$ where $a_0 \approx 3600$ km^2/s^2/kpc

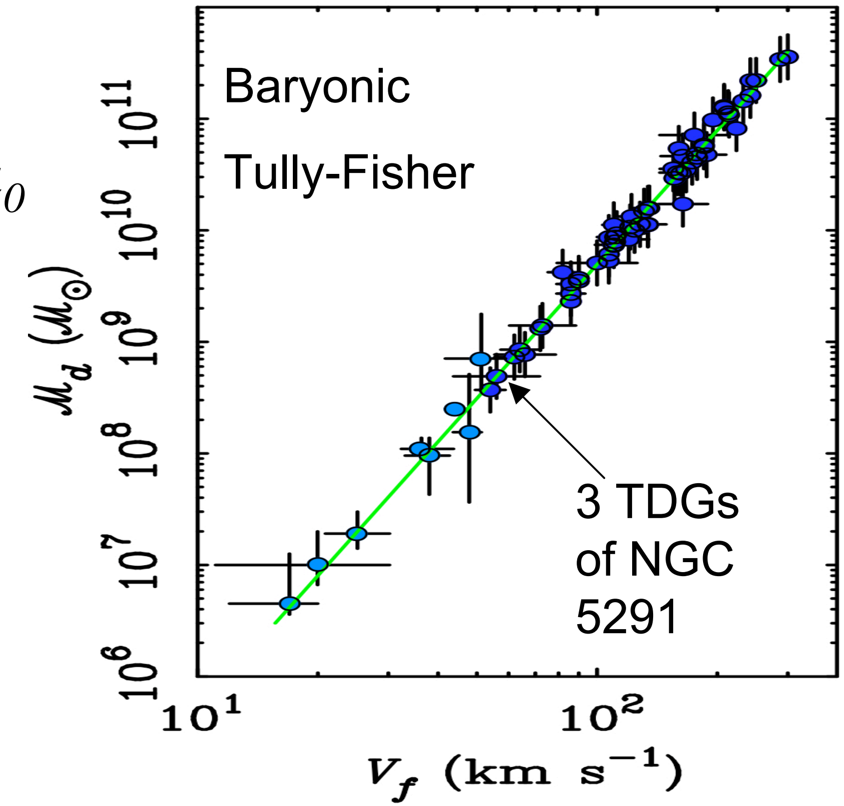
$V_f^2 = GM_{tot}/r = GM_{bar}a_0/(ar) = GM_{bar}a_0/V_f^2$

$V^4 \propto M_{bar}$

More precisely:

$\log M_{bar} = 4 \log V_f - \log Ga_0$

reproduces slope, zero-point,
and small (zero) scatter



e.g. Trachternach et al. 2009

The MDA can be summarized by Milgrom's formula

Correlation summarized by this formula in galaxies (Milgrom 1983):

$\mu\ (V^2/ra_0)\ V^2/r = g_{\mathrm{N\ bar}}$ where $a_0 \sim cH_0 \sim c\Lambda^{1/2}$

with $\mu(x) = x$ for $x \ll 1$ => Tully-Fisher slope = 4

$\mu(x) = 1$ for $x \gg 1$

This formula fits >2000 galaxy rotation curves data points!

Independent roles of a_0 :

1) Zero-point of the Tully-Fisher relation (observed with small scatter):

$4 \log V_f = \log M_{\mathrm{bar}} + \log Ga_0$

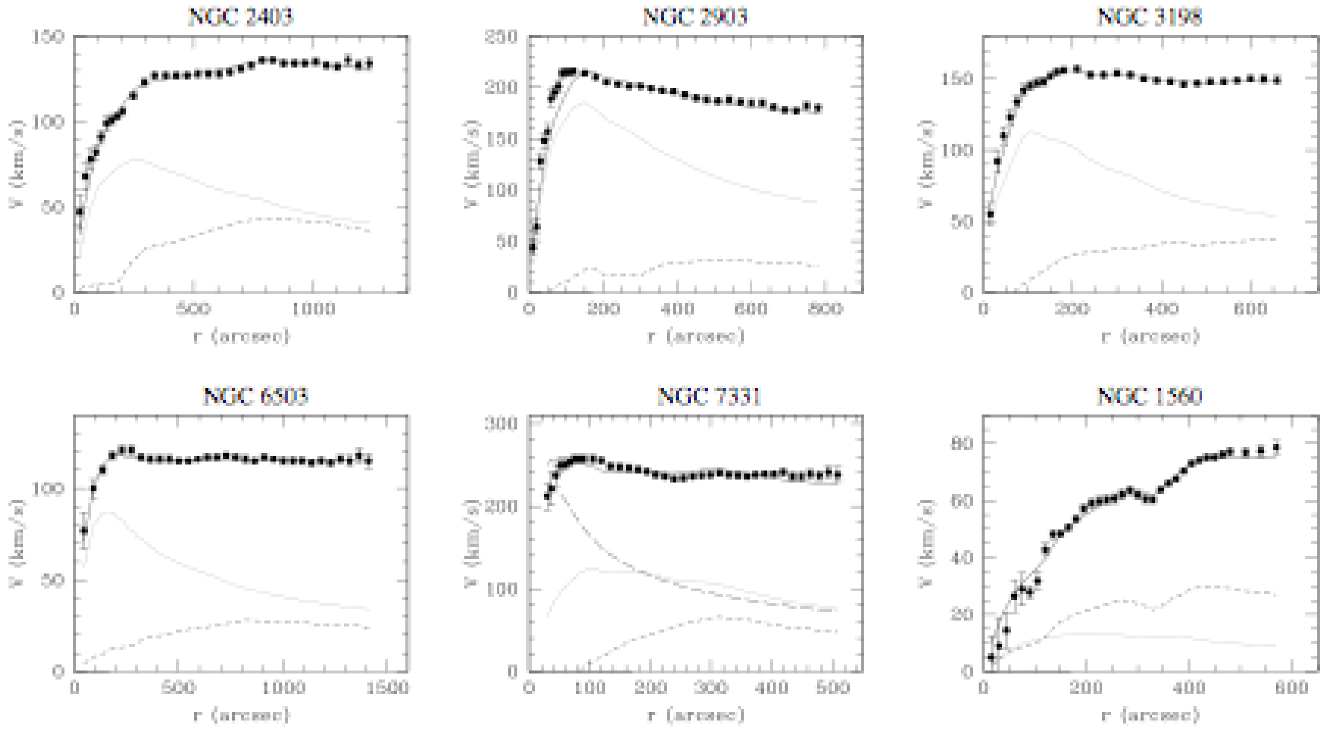
2) Discrepancy always appear at $V^2/r \sim a_0$ => in LSB where $\Sigma << a_0/G$

Corresponding modification of Newtonian gravity (MOND):

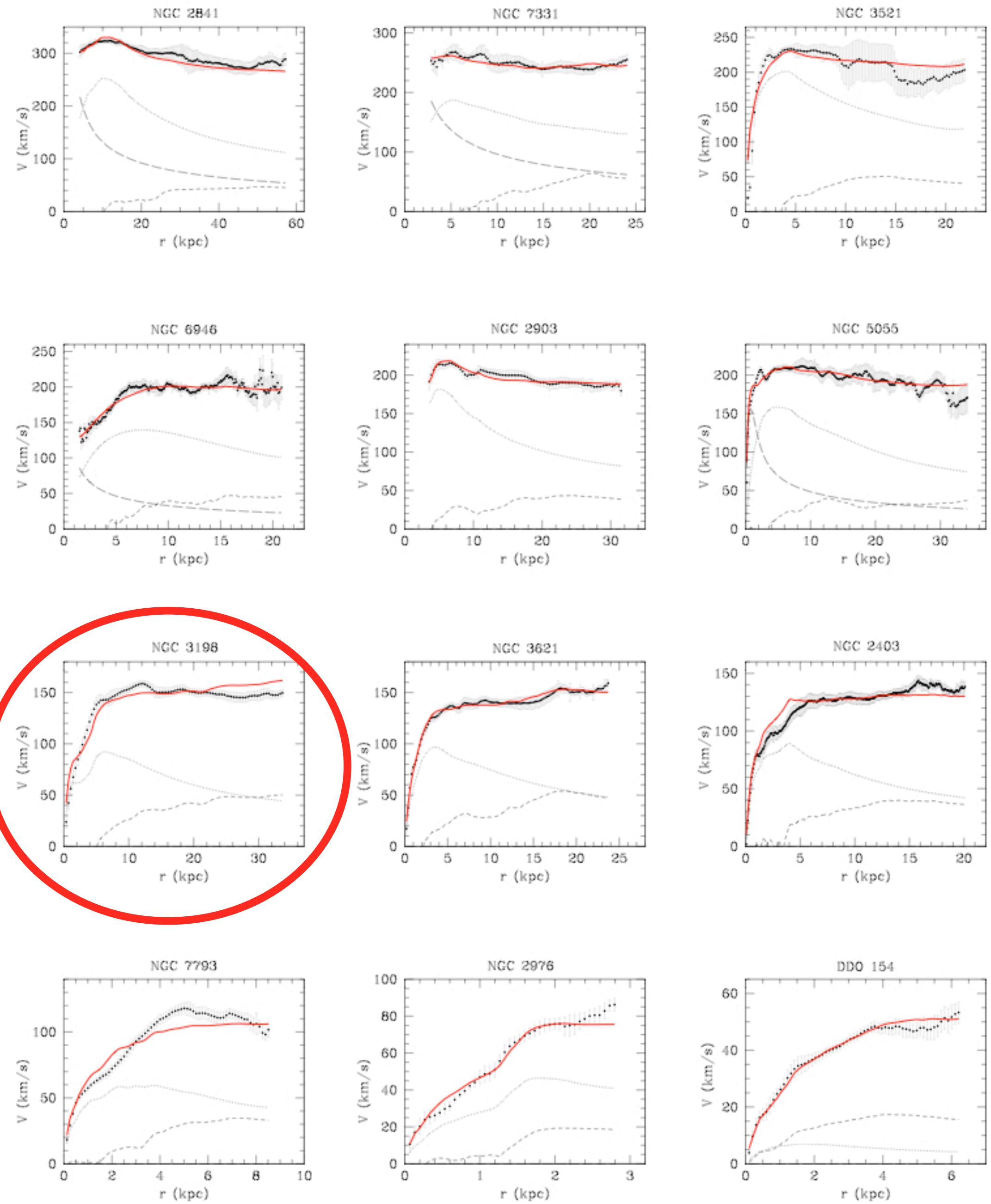
$$\boxed{\nabla . \left[\mu \left(|\nabla\Phi| / a_0 \right) \nabla\Phi \right] = 4 \pi G \rho_{bar}}$$

$$\Phi(r) \sim (GMa_0)^{1/2} \ln(r)$$

MOND



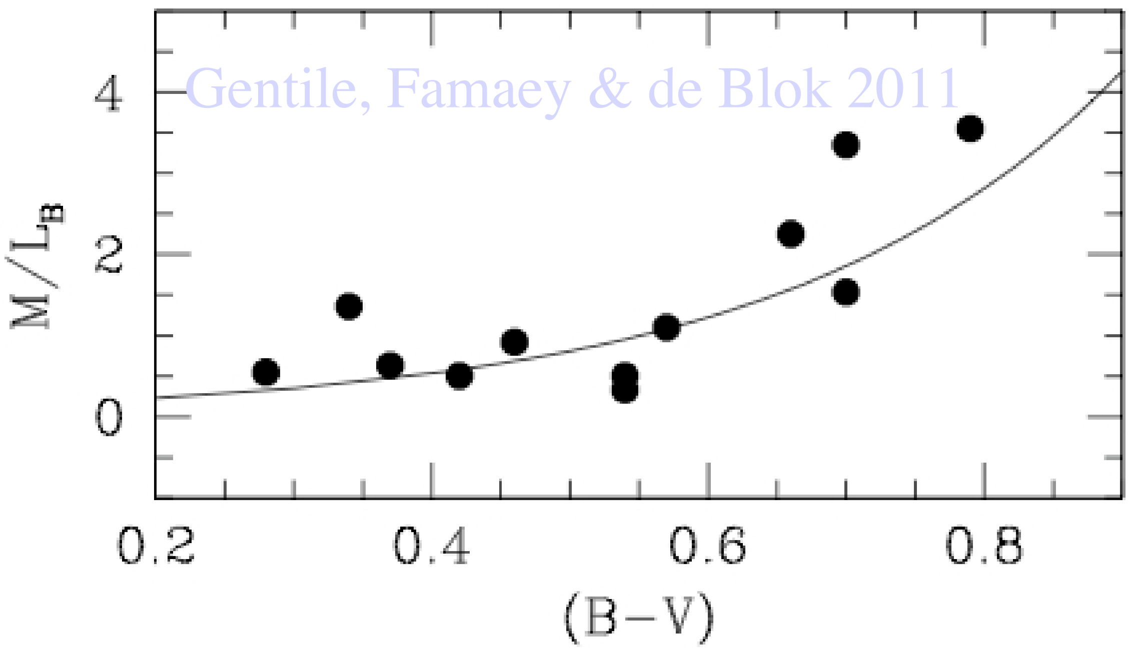
Famaey et al. (2007)



Might indicate a smaller

a_0=0.9 x 10-8 cm/s^2

THINGS (Gentile, Famaey & de Blok 2011)



M/L follows predictions of population synthesis models

Non-isolated systems

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 a_0)

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

In spherical symmetry:

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

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

Escape speed

$$\frac{1}{2}v_{\rm esc}^2(r) = \Phi(\infty) - \Phi(r)$$

Apply a $0.01a_0$ external field to the Milky Way, calculate the escape speed from the solar neighbourhood

-> v_{esc}= 545 km/s as observed !

Famaey, Bruneton & Zhao 2007

Wu et al. 2007

Does MOND always work?

No: pressure-supported systems can be really problematic!

Galaxy clusters: lensing and dynamics require additional dark matter (about as much as baryonic matter, a factor of 10 in the central parts)

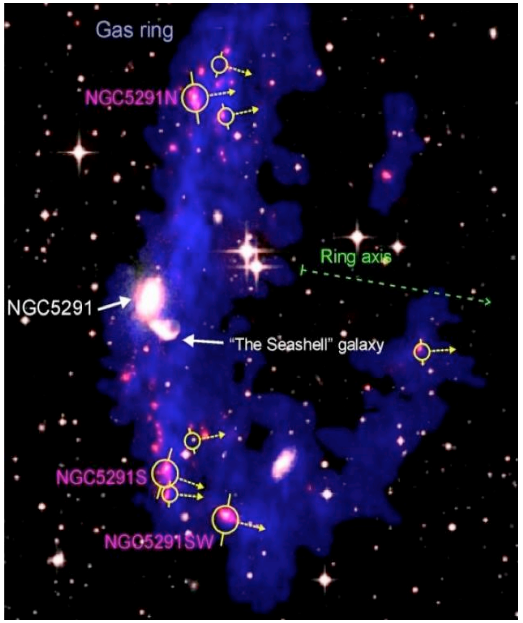
Velocity dispersion profiles and strong lensing of **elliptical galaxies**: generally ok in the field, but a few outliers inside groups and clusters

Velocity dispersion profiles of **dwarf spheroidals**: generally ok but not (yet) for Sextans and Draco, and stability must be checked. The new ultra-faint dwarfs cannot be in equilibrium (old TDGs?)

The total velocity dispersion in the **globular clusters** Pal 14 and Pal 4 (but not Pal 3) might be problematic for MOND (predicts 1 km/s instead of 0.5 km/s observed). But very few stars. NGC 2419 also problematic: orbit of the GC…?

Two case studies

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



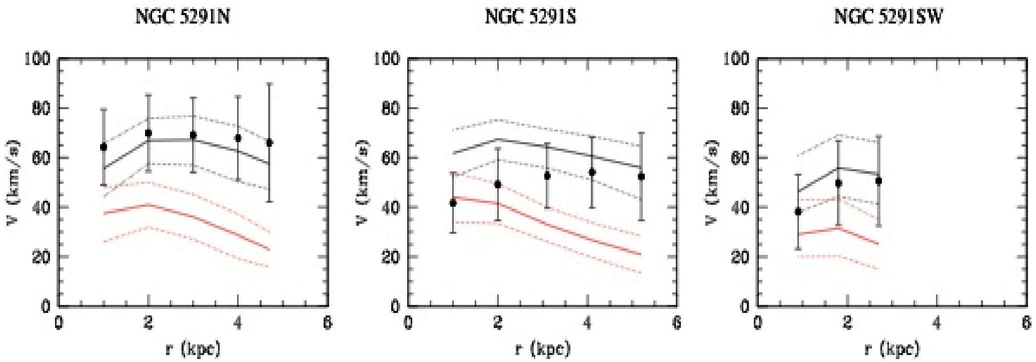
Tidal dwarf galaxies in NGC 5291

Bournaud et al. (2007)

Gentile, Famaey et al. (2007)

~~CDM~~

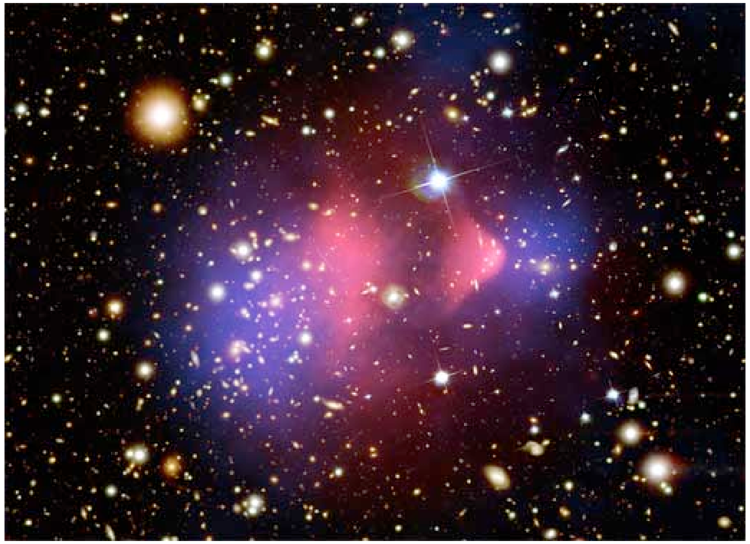
MOND



Pressure-supported not very gas-dense

CDM

~~MOND~~

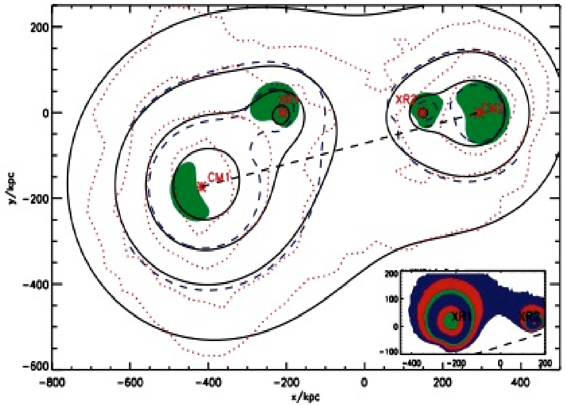


The Bullet Cluster

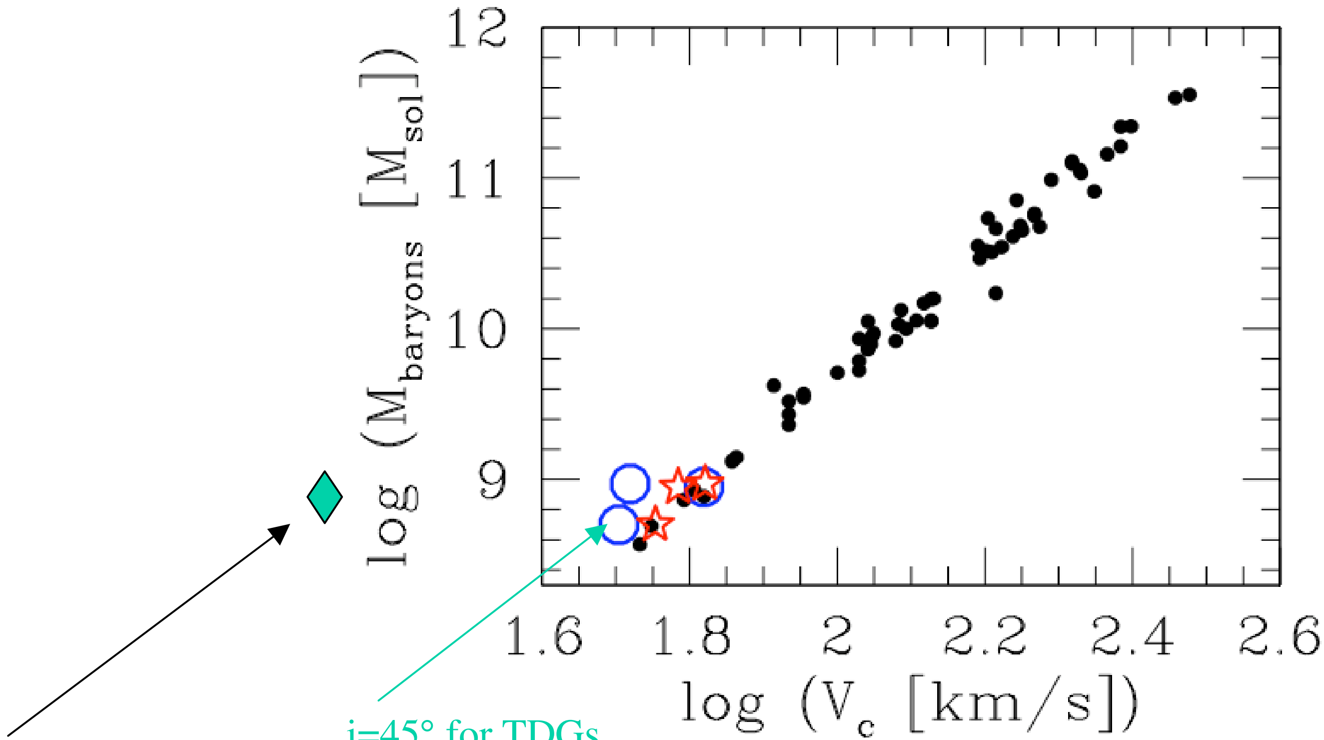
Clowe et al. (2006)

Angus, Shan, Zhao & Famaey (2007)

But speed 4000 km/s?



TDGs on the Tully-Fisher relation



Why does the MDA work in CDM and BDM galaxies???

Model-independent statements

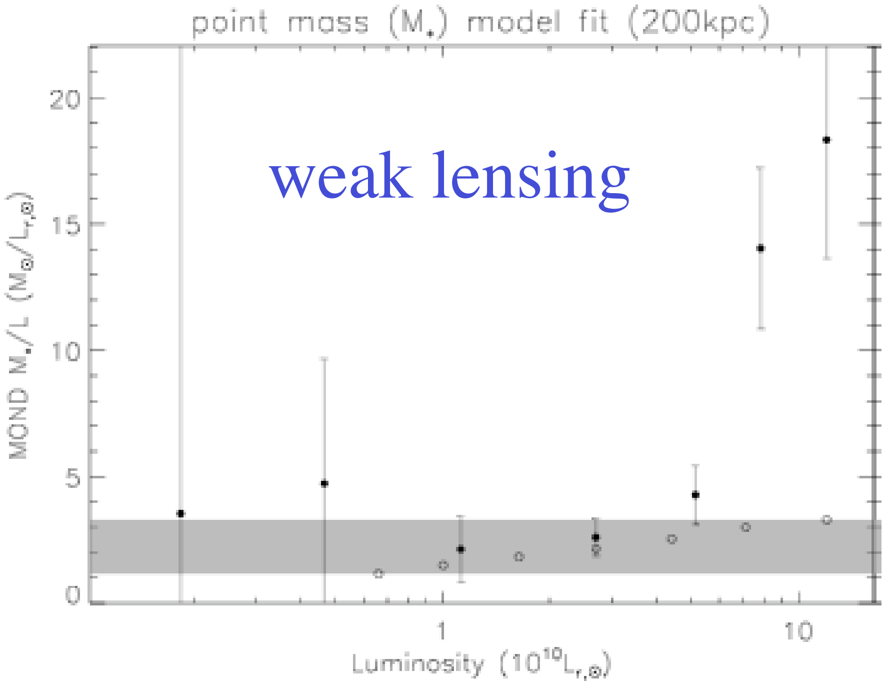
Independently from the theoretical framework, the MOND formula is an extremely efficient way of predicting the gravitational field in rotationally supported galaxies (with a relatively high gas density $> \sim 10^{-21}$ kg/m^3)

Any galaxy formation theory should be able to ultimately reproduce the MOND formula (or MDA) as a scaling relation for spirals (and TDGs)

What makes it difficult is that it is history-independent!

Another model-independent statement

The MOND recipe breaks down in ***some*** pressure-supported systems with a low gas density **(especially in galaxy groups and clusters)**



Something breaks down at a baryonic mass of $\sim 10^{12}$ M_{sun}

(notice also that the mass is probed at very large radii)

A modified gravity theory

There exists many relativistic theories reproducing MOND. Here is an example

The difficult thing is to have lensing and dynamics governed by the same potential

In GR, the geodesic equation is:

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

reducing for timelike geodesics in weak-field to

$d^2x^k / d\tau^2 = - \Gamma^k_{00}(dx^0/d\tau)^2 = - \Gamma^k_{00}$

thus depending only on g_{00} (but not for nulll geodesics)

TeVeS

Einstein equations relate metric to stress-energy tensor just like Poisson equation relates potential to density. In weak-field:

$$g'_{00} = - e^{2\Phi N} \qquad = - 1 - 2\Phi_N$$

$$g'_{ij} = e^{-2\Phi N} \delta_{ij} = (1 - 2\Phi_N) \delta_{ij}$$

Idea: replace GR with a theory reducing to the SAME metric but replacing Φ_N by Φ obeying MOND

Add a scalar field and couple matter to

$$g'_{\alpha\beta} = e^{2\phi} g_{\alpha\beta}$$

… with action of ϕ governed by a free function depending on (grad ϕ)^2, works for dynamics, but *doesnt work for lensing*

TeVeS

Add a scalar field and a vector field and couple matter to

$$g'_{\alpha\beta} = e^{-2\phi}(g_{\alpha\beta} + U_\alpha U_\beta) - e^{2\phi} U_\alpha U_\beta$$

with $g^{\alpha\beta} U\alpha U\beta = -1$, timelike in static situations, and action $S = S_g + S_s + S_v + S_m$,

with action S_s of ϕ governed by a free function depending on $(\text{grad } \phi)^2$

=> ϕ ***obeys a B-M equation***, and plays the role of the dark matter potential (dynamics and lensing are governed by the **same** physical metric *g'*)

Hot Dark Matter + relativistic MOND?

Ordinary neutrinos of 2 eV (experimental model-independent limit) are **not enough** to explain the MOND discrepancy in X-ray emitting groups (too high phase-space density needed)

=> Maybe another fermionic dark **HDM** particle? (hot light sterile neutrinos with $m_\nu \sim 10$eV ?)

=> plays the role of CDM in the early Universe, then MOND-like gravity boosts structure formation (FASTER STRUCTURE FORMATION HELPS LOCAL VOID) … to be investigated until DM is detected directly

=> Maybe **CDM and no MOND**?… but then one must in any case understand why it does reproduce so precisely the MOND relation for all galaxies…

EXCITING TIMES AHEAD