Surface densities and dark matter properties in galaxies

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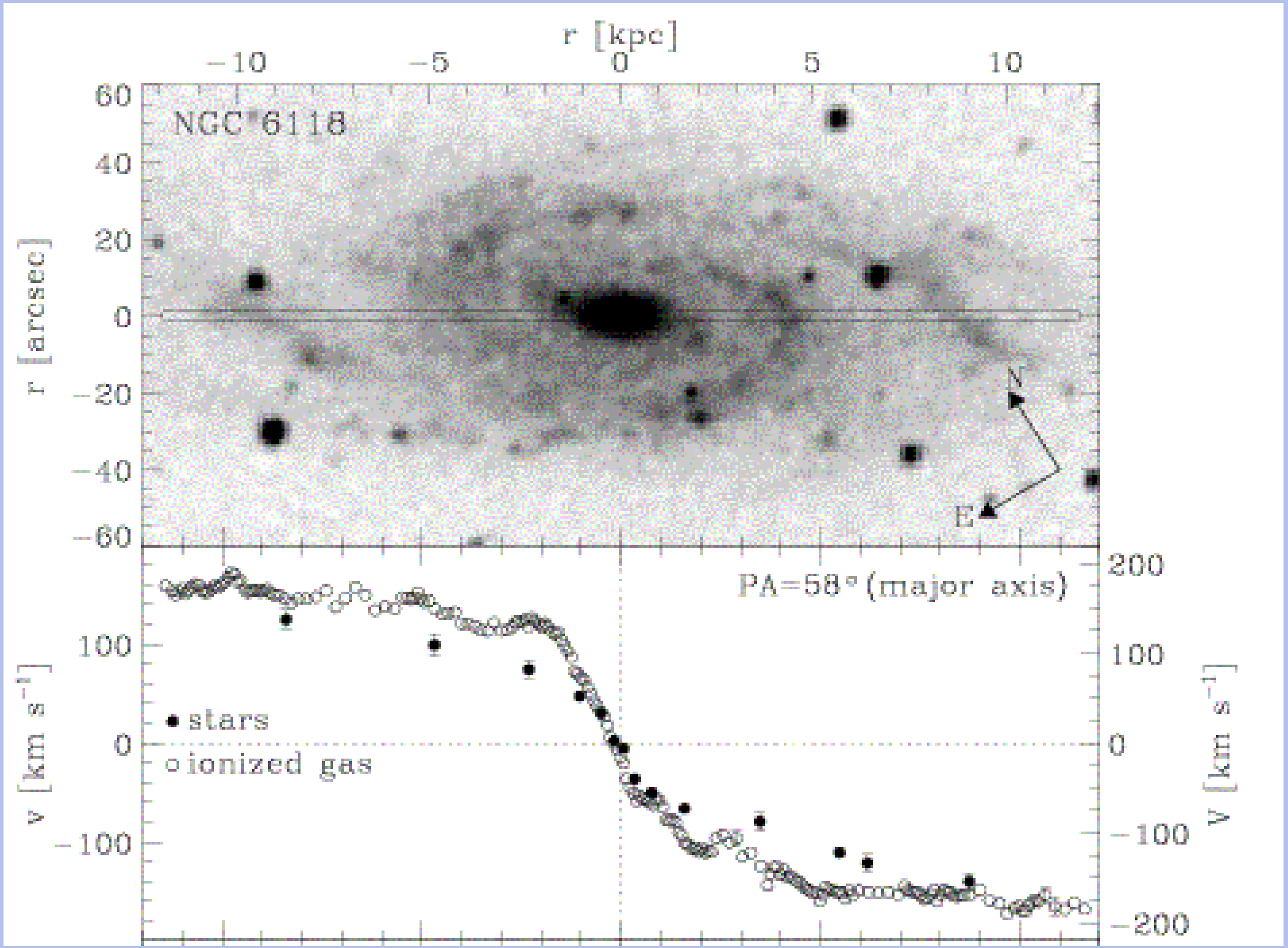
P. Salucci, B. Famaey, H. S. Zhao, F. Donato, C. Frigerio Martins,
G. Gilmore, M. I. Wilkinson

Introduction: what are rotation curves?



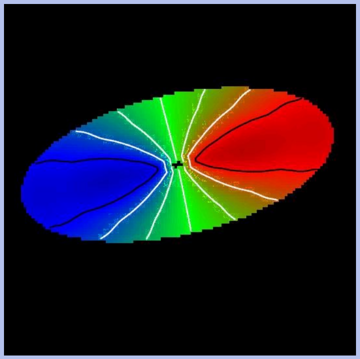
Pizzella et al. (2004)

Rotation velocity of gas and/or stars as a function of radius

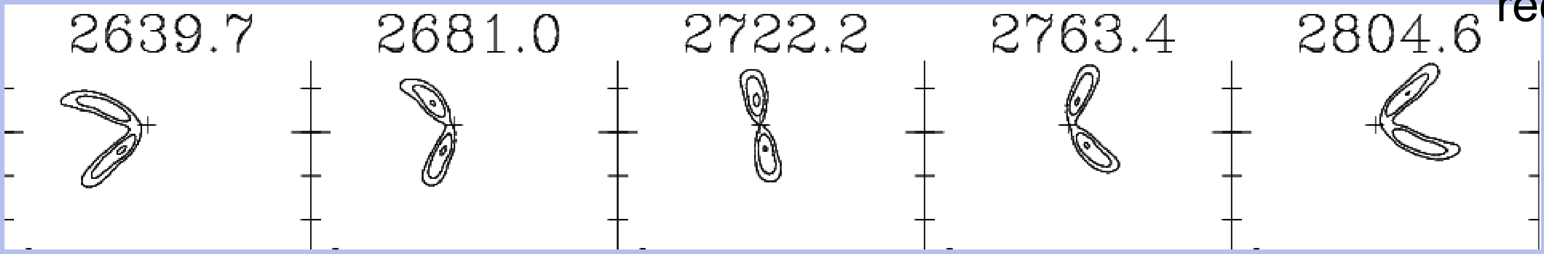
$V_{rot}(r)$: traced via different lines: Hα, HI, CO, …

Introduction: rotation curves from HI data

Rotating disk:



Data cube (series of maps @ slightly different freq.) should look like this:



receding velocity
(km/s)

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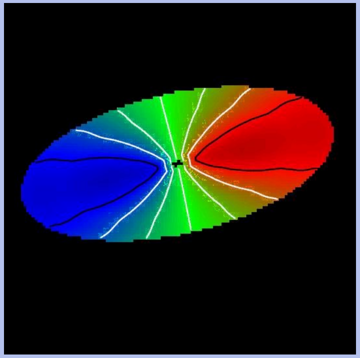

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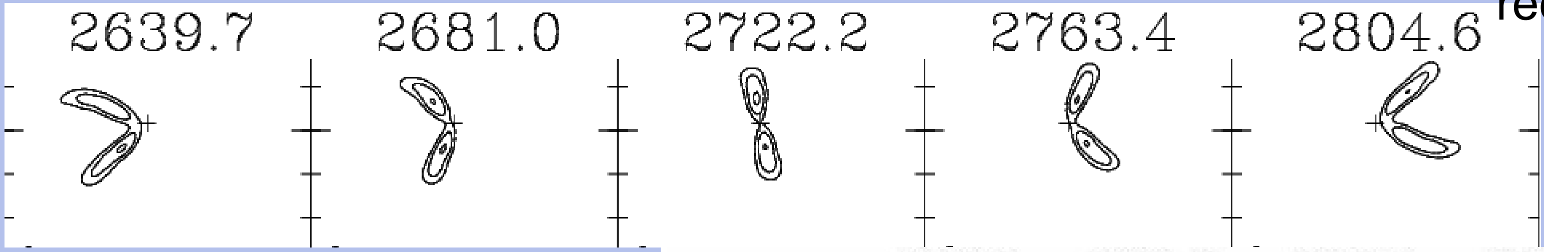
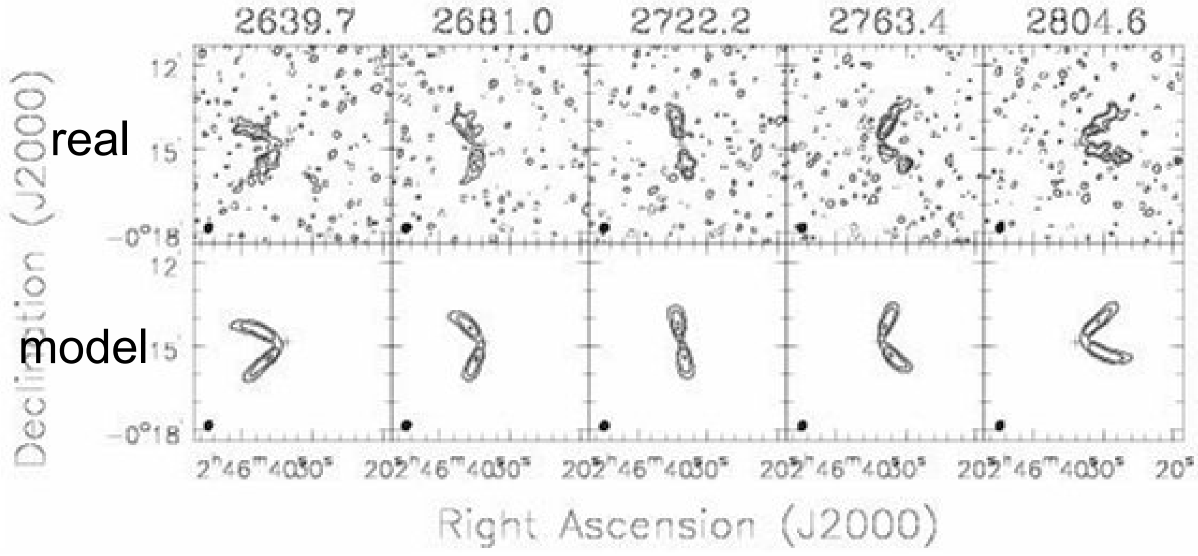


receding velocity
(km/s)

What about

real observations?

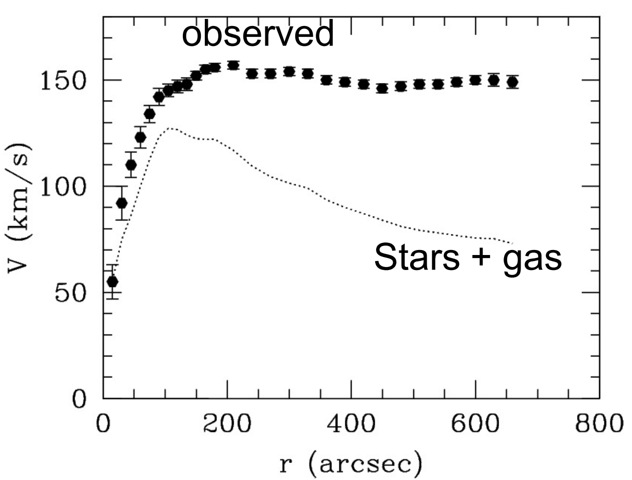


real

model

Introduction

Rotation curves do not decline as expected from the visible matter.

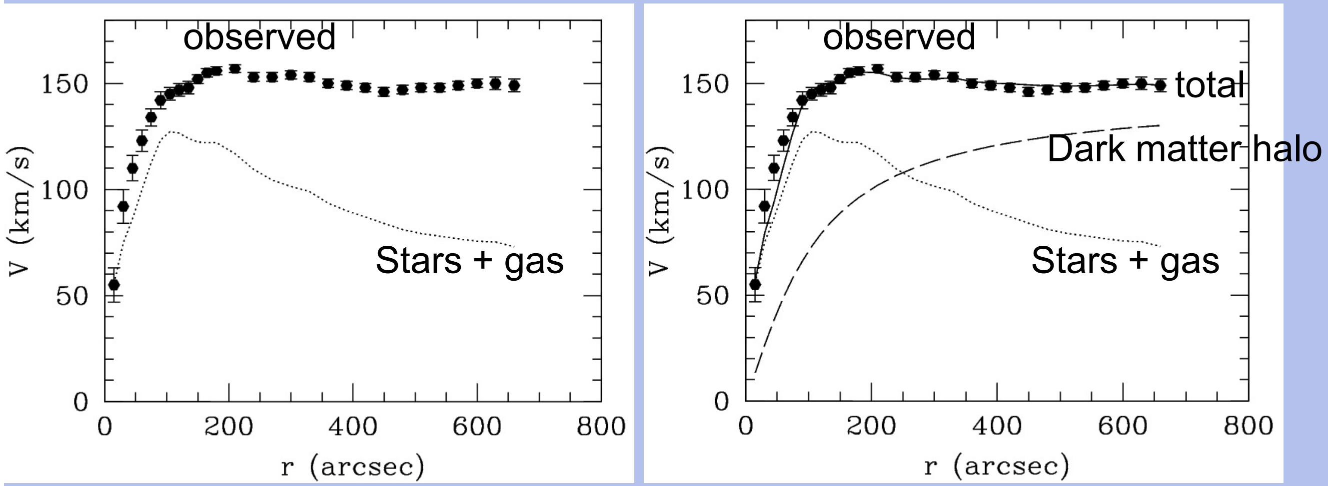


NGC 3198: adapted from Begeman et al. (1991)

Introduction

Rotation curves do not decline as expected from the visible matter.

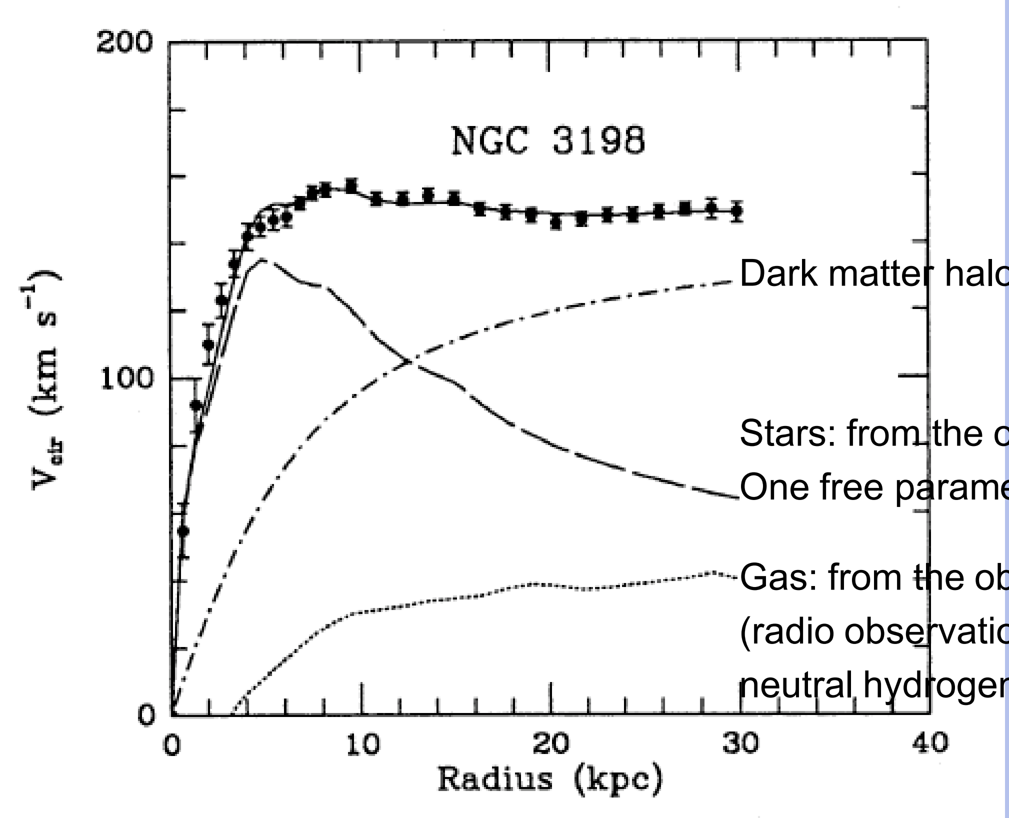
1) Dark matter



dark matter

NGC 3198: adapted from Begeman et al. (1991)

Introduction



Dark matter halo

Stars: from the observed photometry
One free parameter: the stellar mass-to-light ratio

Gas: from the observed surface density distribution
(radio observations of the 21-cm emission of
neutral hydrogen, HI)

Begeman et al. (1991)

Rotation curve decomposition

$$V_{obs}^2(r) = V_{disk}^2(r) + V_{gas}^2(r) + V_{halo}^2(r)$$

- $V_{disk}(r)$: from observed photometry, preferably NIR
  absolute scaling depends on the stellar M/L ratio
- $V_{gas}(r)$: from HI observations
- $V_{halo}(r)$: it depends on the chosen dark matter
  density distribution

- Fit usually performed by χ^2-minimisation

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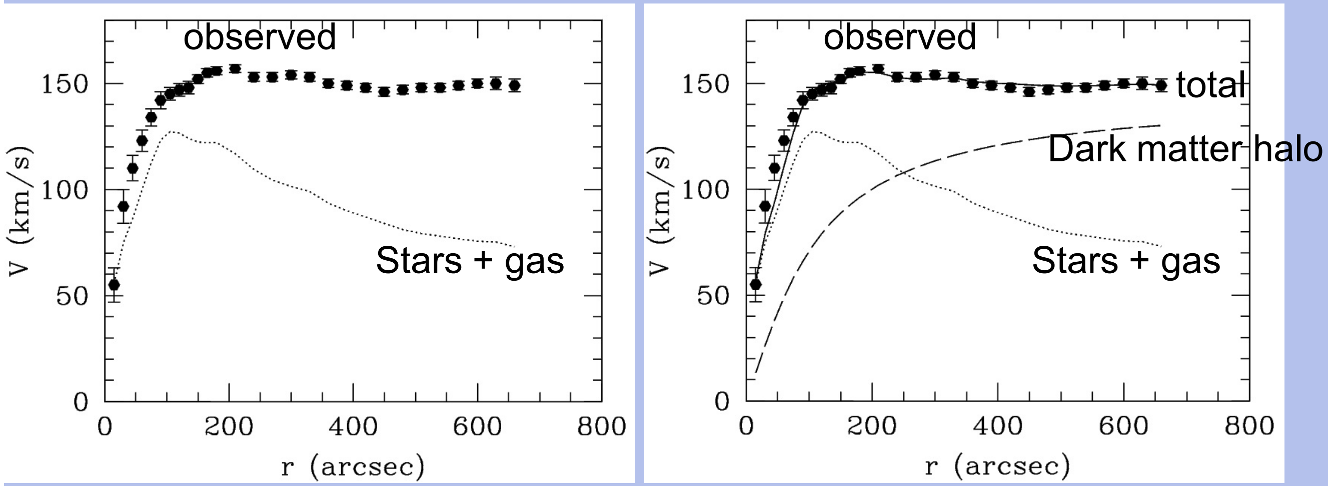


dark matter

NGC 3198: adapted from Begeman et al. (1991)

Introduction

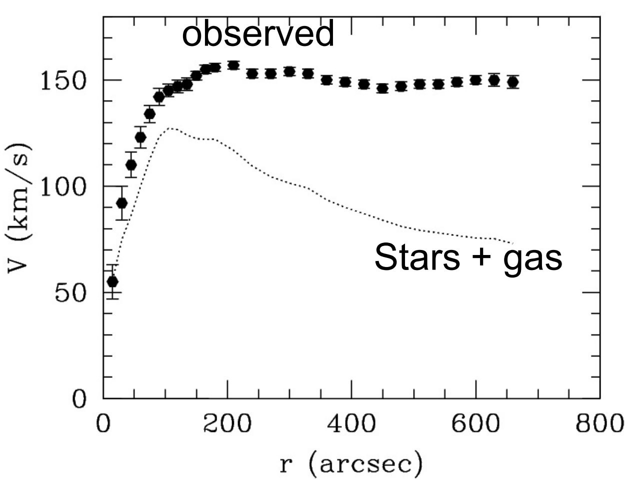
Rotation curves do not decline as expected from the visible matter.

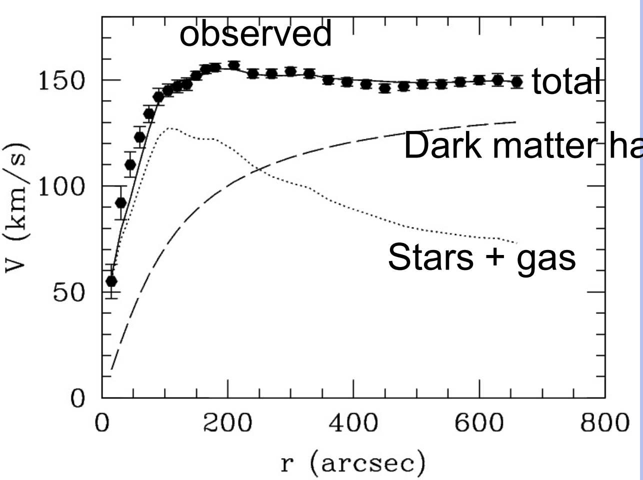
1) Dark matter halo

or

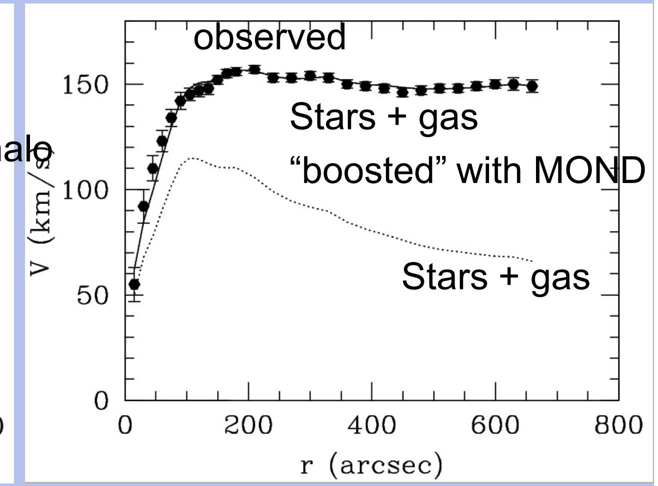
2) gravity is "boosted" below a certain acceleration **a_0~10^{-8} cm s^{-2}**

Modified Newtonian Dynamics (MOND) – Milgrom (1983)





dark matter



MOND

NGC 3198: adapted from Begeman et al. (1991)

Introduction: is MOND such a crazy idea?

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Introduction

Rotation curves do not decline as expected from the visible matter.

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Modified Newtonian Dynamics (MOND) – Milgrom (1983)

Some history: in the Solar System:

1) Perturbation in the orbit of Uranus: unseen matter or modify gravity?

Unseen matter: Neptune

2) Perihelion precession of Mercury: unseen matter or modify gravity?

Modify gravity: GR

Introduction

Rotation curves do not decline as expected from the visible matter.

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Modified Newtonian Dynamics (MOND) – Milgrom (1983)

Note that:

$a_0 \approx c\,H_0 / (2\,\pi)$

$a_0 \approx c\,(\Lambda / 3)^{1/2}$

Introduction

Rotation curves do not decline as expected from the visible matter.

1) Dark matter halo

   or

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   Modified Newtonian Dynamics (MOND) – Milgrom (1983)

- MOND explains very well galaxy kinematics
- But MOND requires some dark matter on larger scales

Introduction

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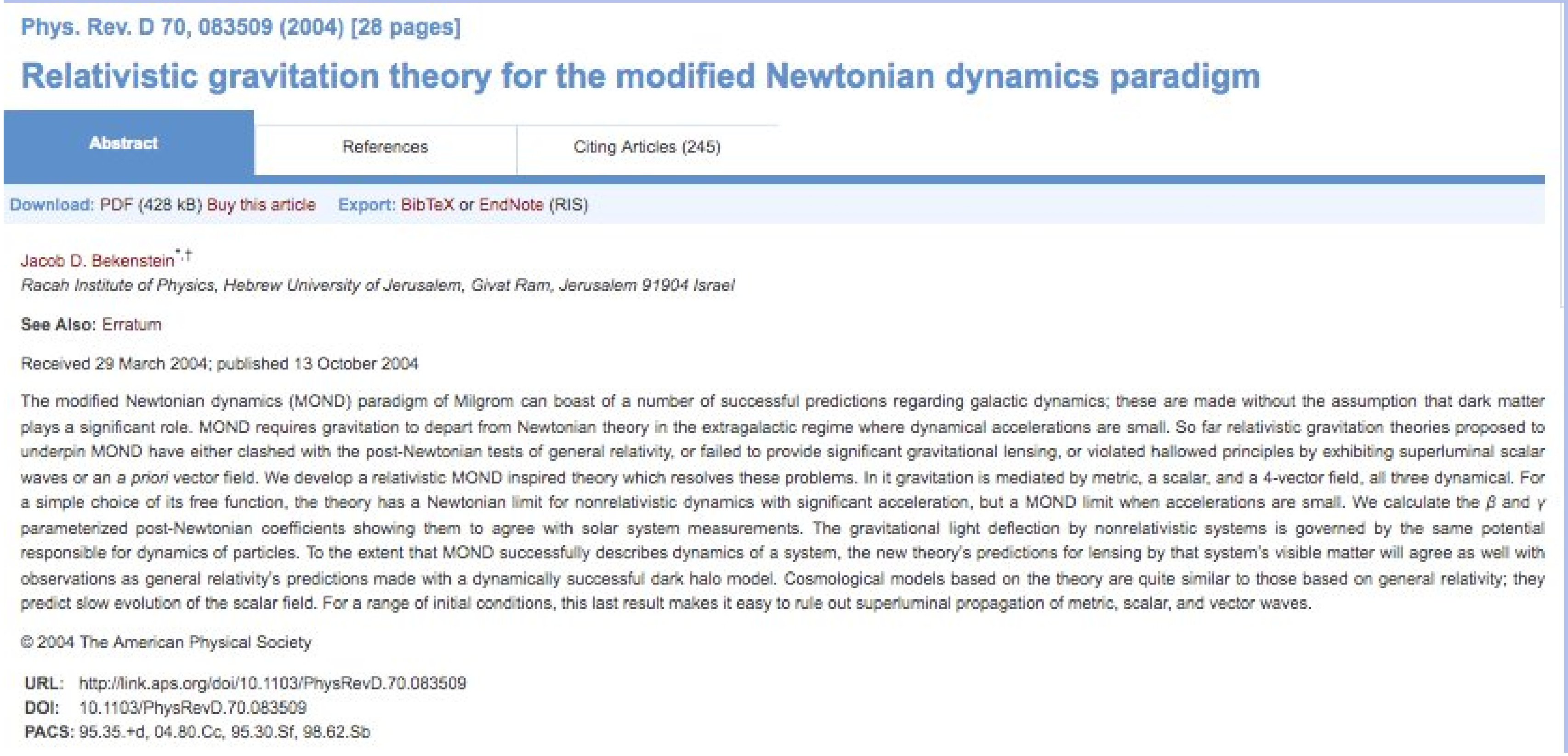
Modified Newtonian Dynamics (MOND) – Milgrom (1983)



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Relativistic gravitation theory for the modified Newtonian dynamics paradigm

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See Also: Erratum

Received 29 March 2004; published 13 October 2004

The modified Newtonian dynamics (MOND) paradigm of Milgrom can boast of a number of successful predictions regarding galactic dynamics; these are made without the assumption that dark matter plays a significant role. MOND requires gravitation to depart from Newtonian theory in the extragalactic regime where dynamical accelerations are small. So far relativistic gravitation theories proposed to underpin MOND have either clashed with the post-Newtonian tests of general relativity, or failed to provide significant gravitational lensing, or violated hallowed principles by exhibiting superluminal scalar waves or an *a priori* vector field. We develop a relativistic MOND inspired theory which resolves these problems. In it gravitation is mediated by metric, a scalar, and a 4-vector field, all three dynamical. For a simple choice of its free function, the theory has a Newtonian limit for nonrelativistic dynamics with significant acceleration, but a MOND limit when accelerations are small. We calculate the β and γ parameterized post-Newtonian coefficients showing them to agree with solar system measurements. The gravitational light deflection by nonrelativistic systems is governed by the same potential responsible for dynamics of particles. To the extent that MOND successfully describes dynamics of a system, the new theory's predictions for lensing by that system's visible matter will agree as well with observations as general relativity's predictions made with a dynamically successful dark halo model. Cosmological models based on the theory are quite similar to those based on general relativity; they predict slow evolution of the scalar field. For a range of initial conditions, this last result makes it easy to rule out superluminal propagation of metric, scalar, and vector waves.

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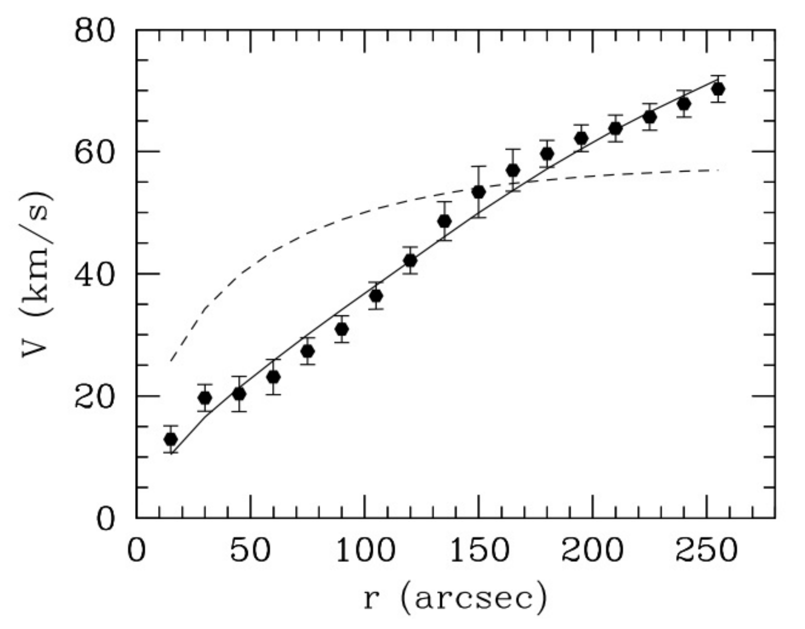
Introduction

- Cold Dark Matter works well on large scales (Cosmic Microwave Background, large scale structure,...)
- But problems on galaxy scales!

- cusp/core problem :



core
(constant density at
the centre)

cusp
($\rho \approx r^{-1}$: the NFW halo)

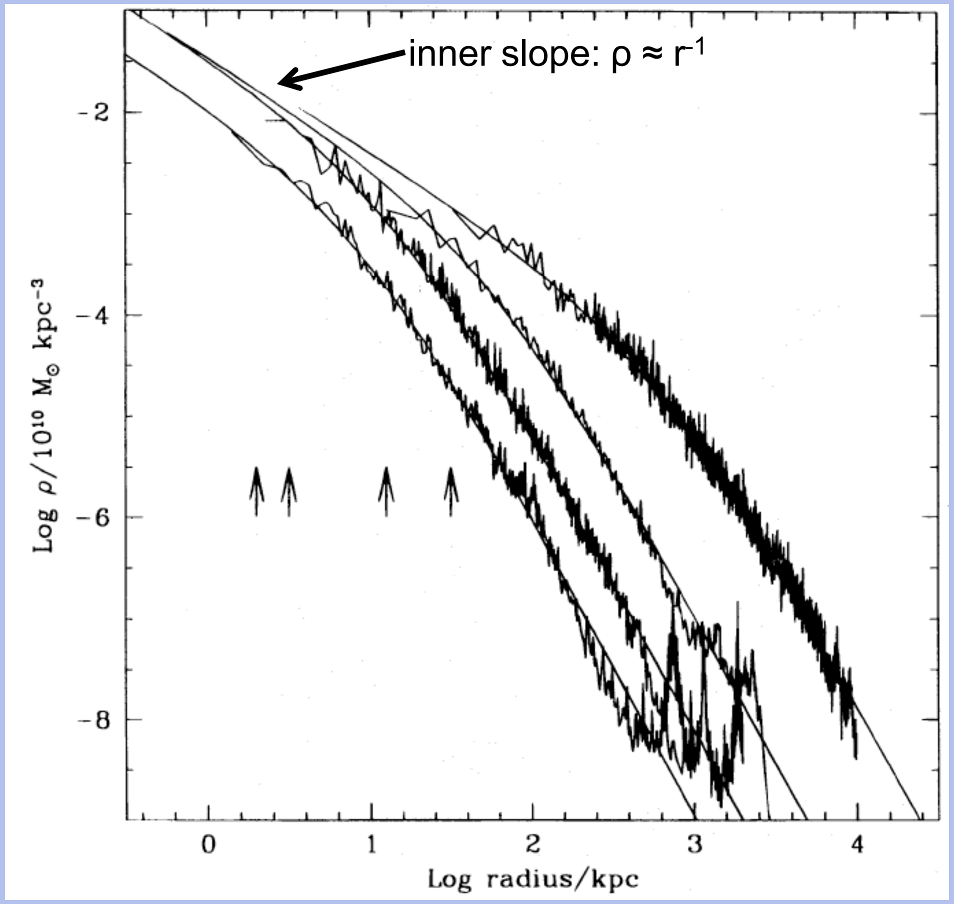
Gentile et al. (2005)

Best understood effect of baryons: adiabatic contraction

It would make CDM halos even more concentrated…

The core/cusp problem

N-body simulations in Cold Dark Matter lead to dark matter halos with “cuspy” density profiles:



Log Density

Log Radius

Navarro, Frenk & White (1996)

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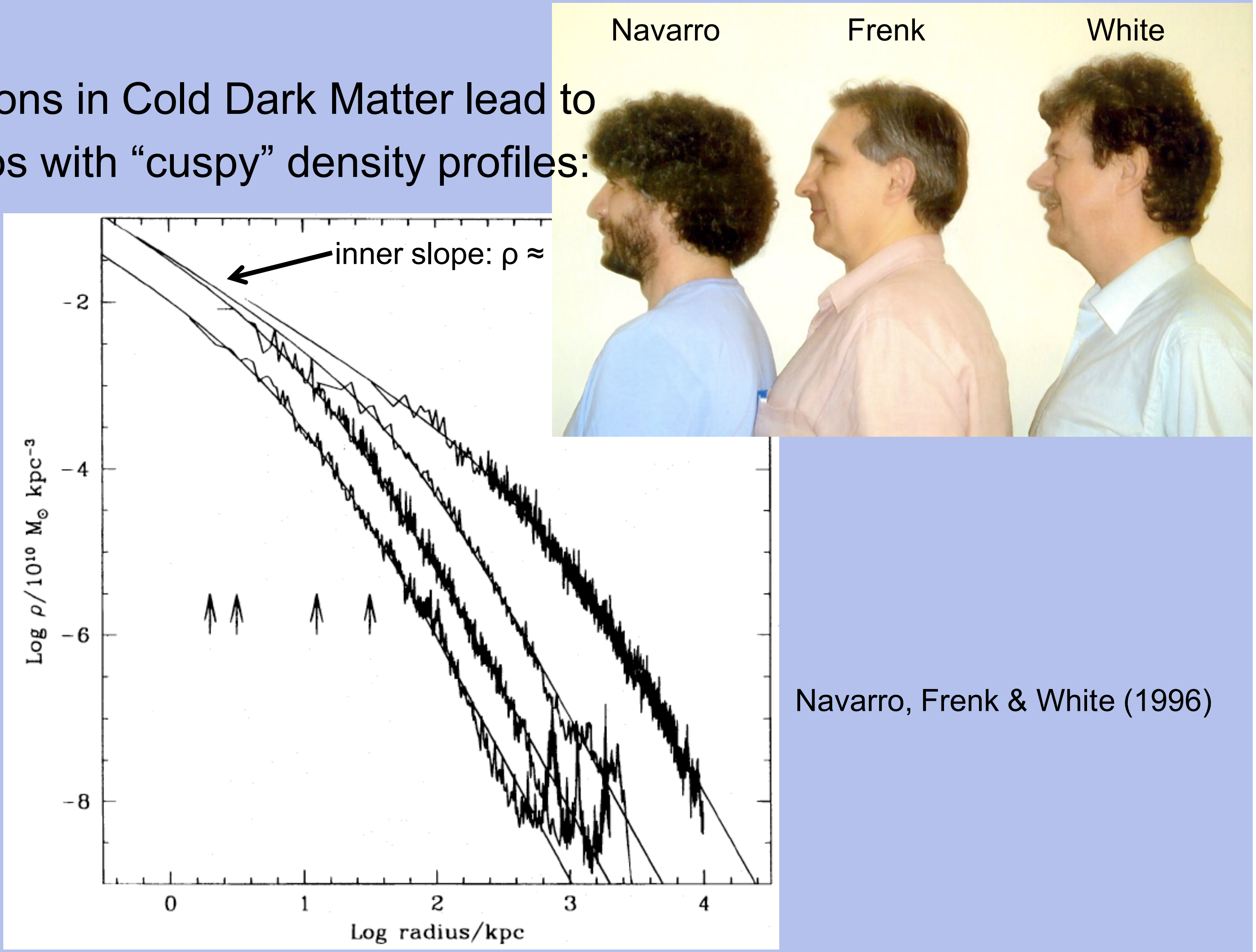


Log Density

Log Radius

Navarro, Frenk & White (1996)

The core/cusp problem

In successive modifications of the NFW profile (Moore, Einasto, etc.),

either

1) changes are not significant (for the radial range probed by data in galaxies)

or

2) changes make the profiles even cuspier

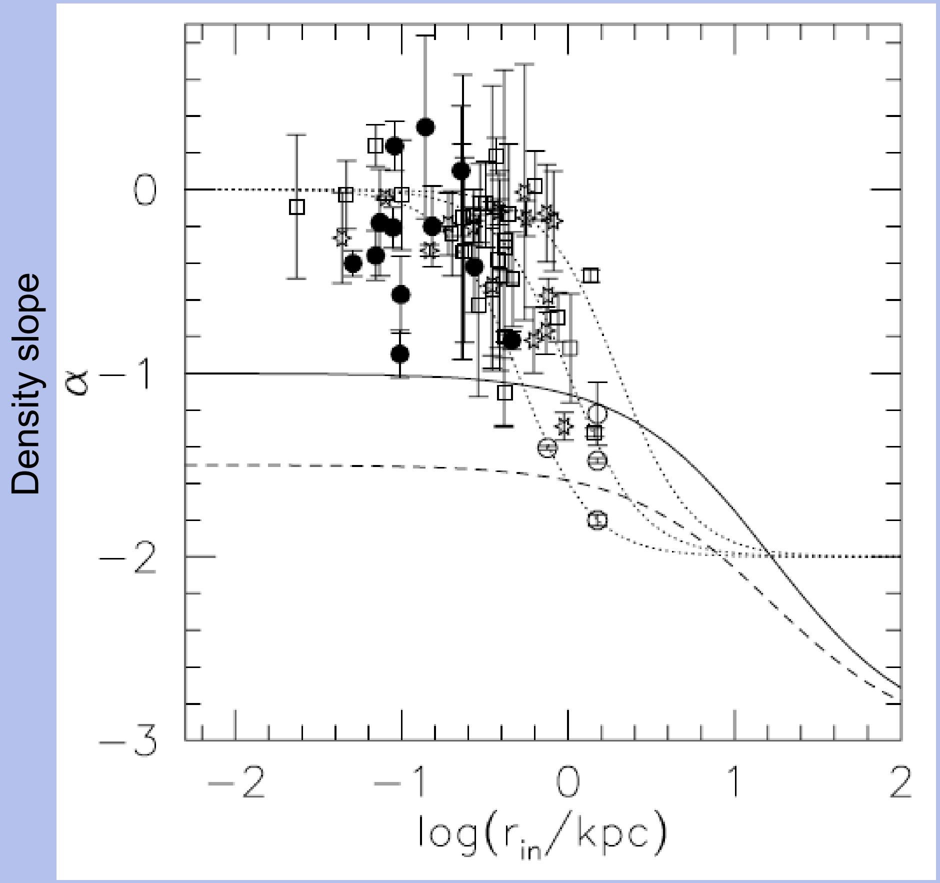
But see Andrea Lapi’s talk.

The core/cusp problem

Observations instead…

$\rho \approx r^0$ in the centre

i.e.: a constant density core



de Blok & Bosma (2002)

The core/cusp problem

Observations instead…

Example: the galaxy ESO 79-G14

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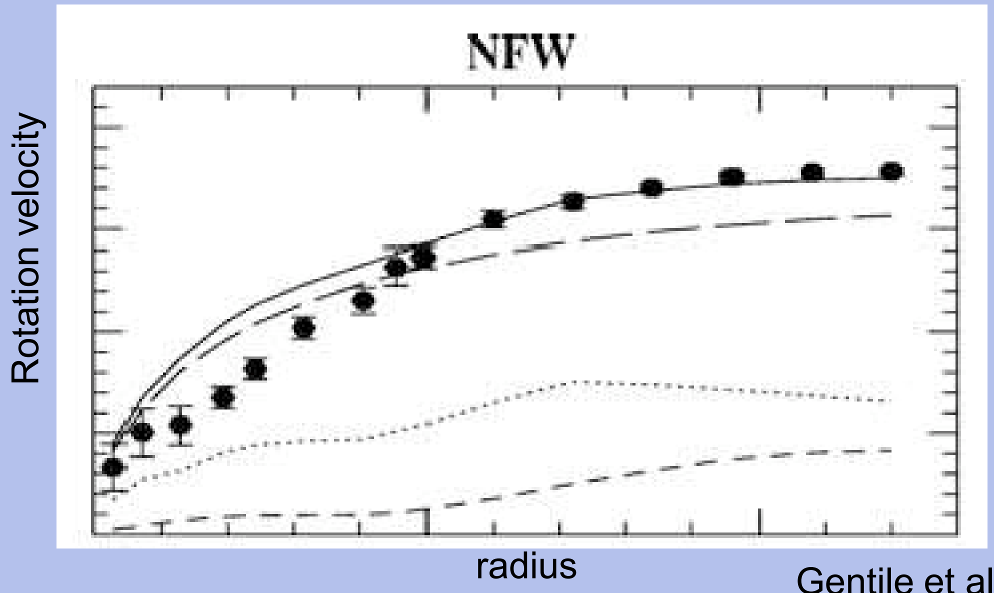


Gentile et al. (2004)

Initial doubts about evidence against cusps (systematic effects) seem to be overcome (e.g. Gentile+05, de Blok+08)

The core/cusp problem

This was for pure dark matter simulations: what about baryonic physics?

- Best studied effect: adiabatic contraction: it makes things worse (i.e.: halos become even cuspier)

The core/cusp problem

This was for pure dark matter simulations: what about baryonic physics?

- Best studied effect: adiabatic contraction: it makes things worse
  (i.e.: halos become even cuspier)

- Some studies find cores in simulations with also baryons
  (e.g. Mashchenko et al. 2006, Governato et al. 2010)

No consensus in the simulations community.

A long way before reproducing galaxy kinematics phenomenology
and additional constraints (e.g. baryon fraction).

The core/cusp problem

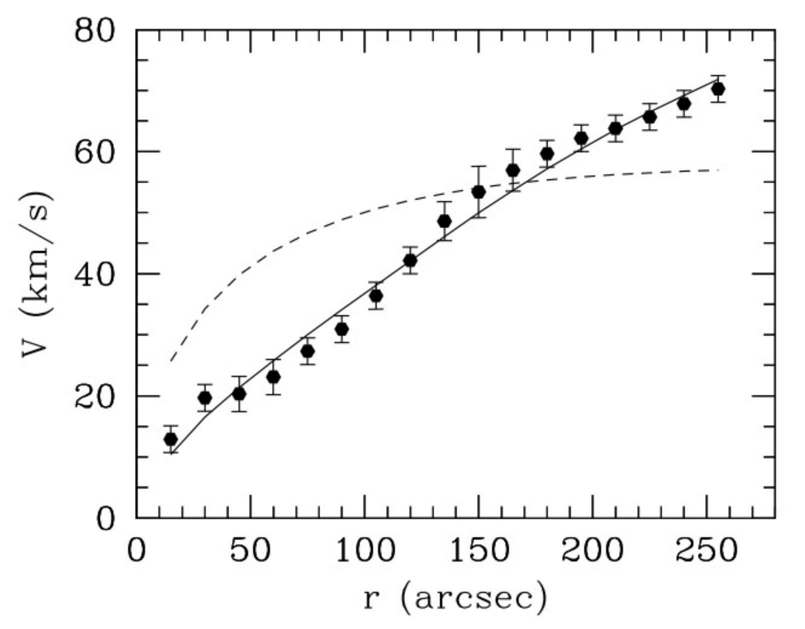
Systematic effects? Are observers not doing their job properly?

Can cusps look like cores?

de Blok (2010): pointing errors and/or non-circular motions should be much larger than they actually are (see J. van Eymeren’s talk)

The core/cusp problem

DDO 47 (dwarf irregular galaxy)



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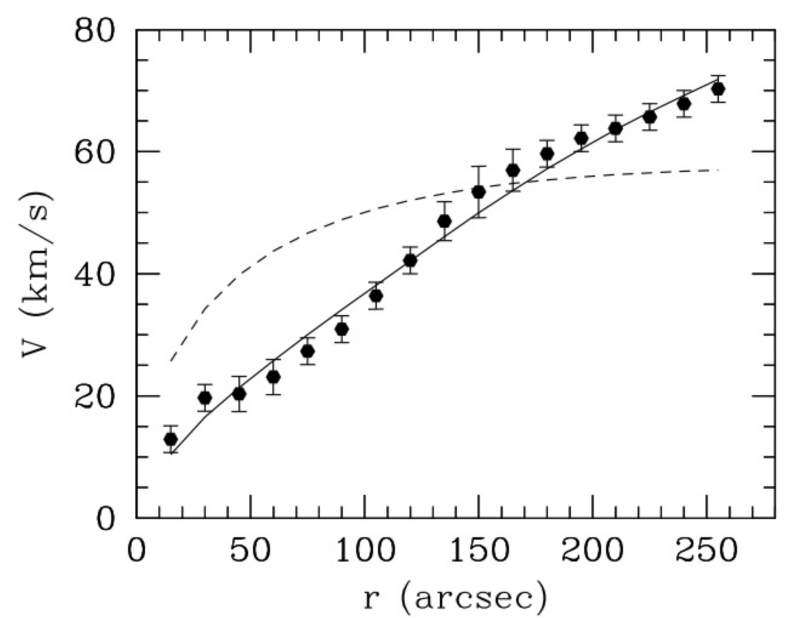

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larger than they actually are

Valenzuela et al. (2007): pressure support from 10^5 K gas?
Comparison with 2 observed rotation curves.

The Burkert halo profile

One of the most used halos with a constant density core:

The Burkert halo (Burkert 1995) :

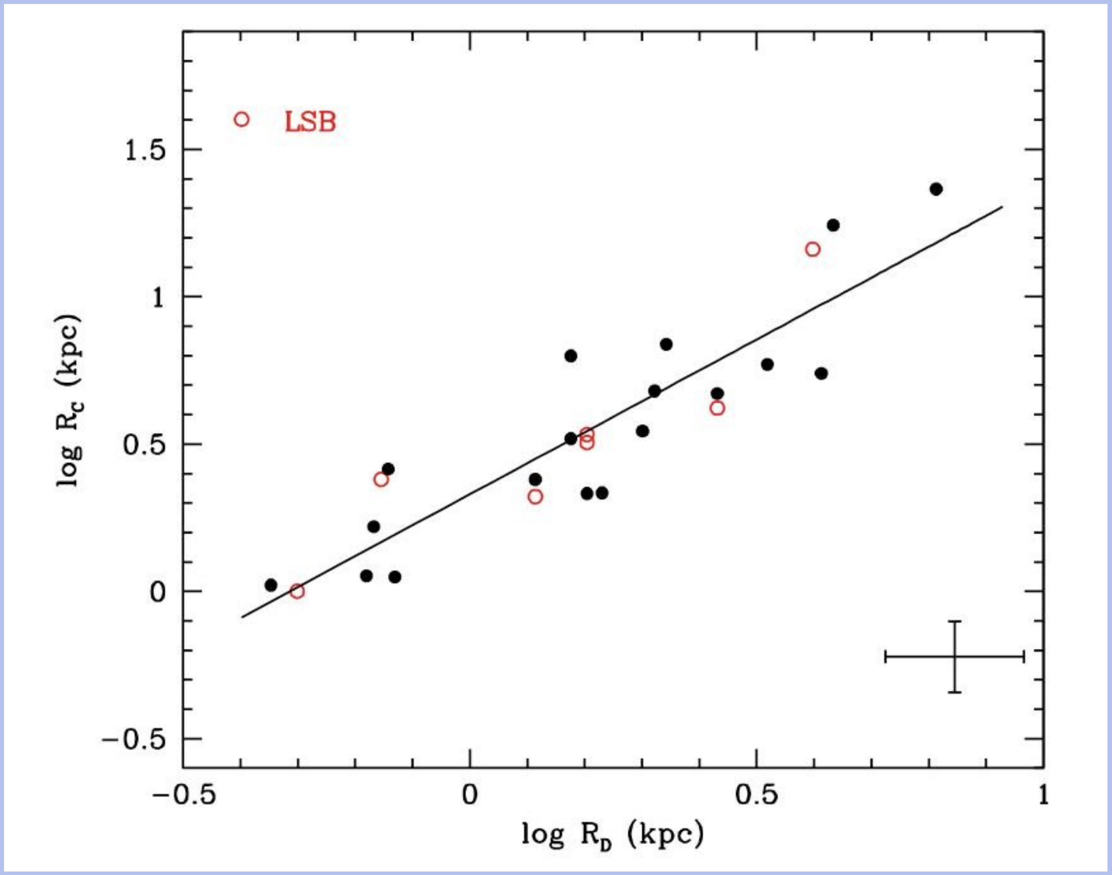
$$\rho_{\mathrm{Bur}}(r) = \frac{\rho_0 r_{\mathrm{core}}^3}{(r + r_{\mathrm{core}})\left(r^2 + r_{\mathrm{core}}^2\right)}$$

two parameters r_{core} and ρ_0

r_{core}: radius where density = $\rho_0/4$

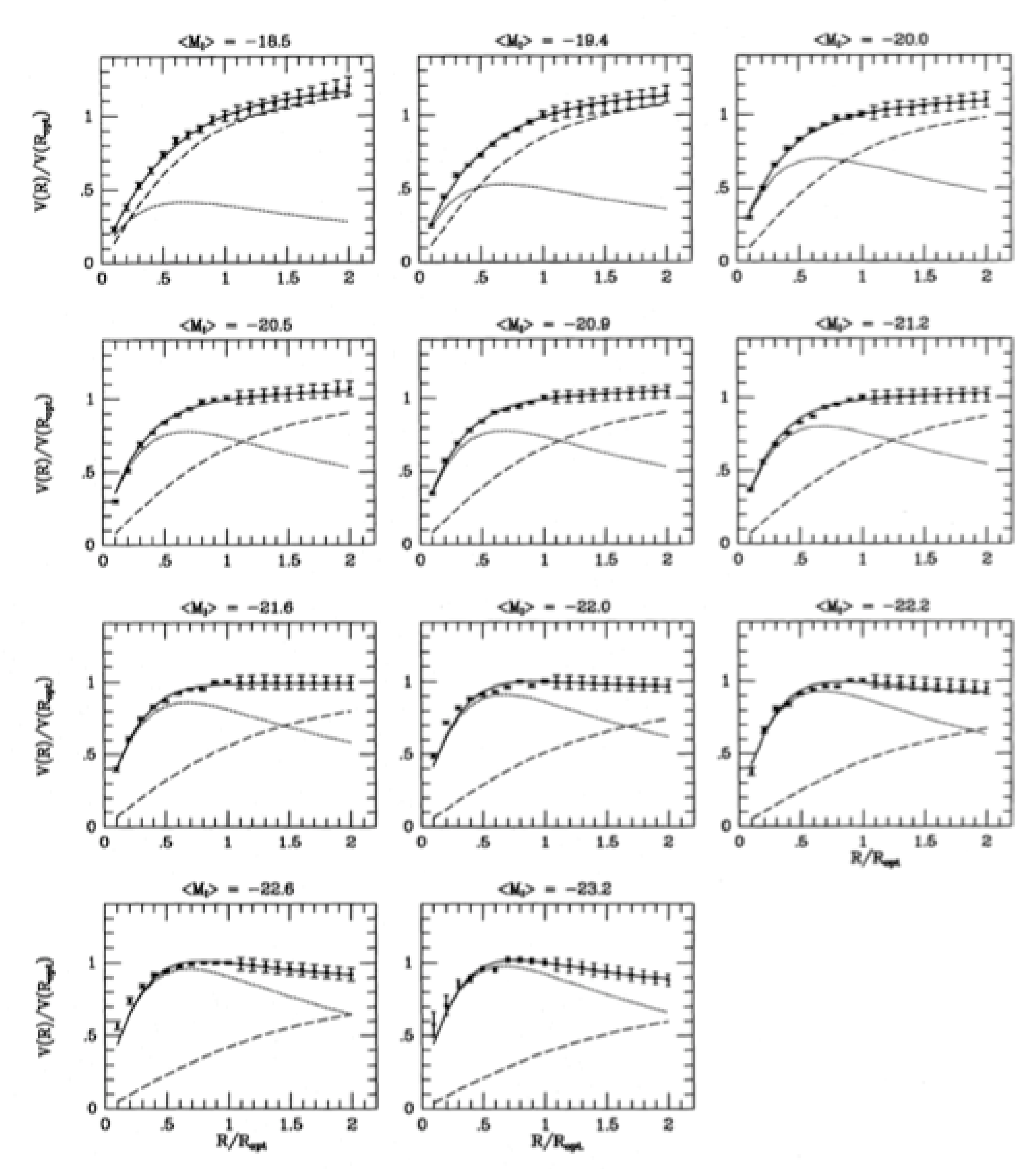
Good fit of rotation curves

Scaling relations of dark halos



In Donato, GG & Salucci (2004) we had found a correlation between halo core radius and stellar disk scale length.

The Universal Rotation Curve



Persic, Salucci & Stel (1996)
Salucci et al. (2007)

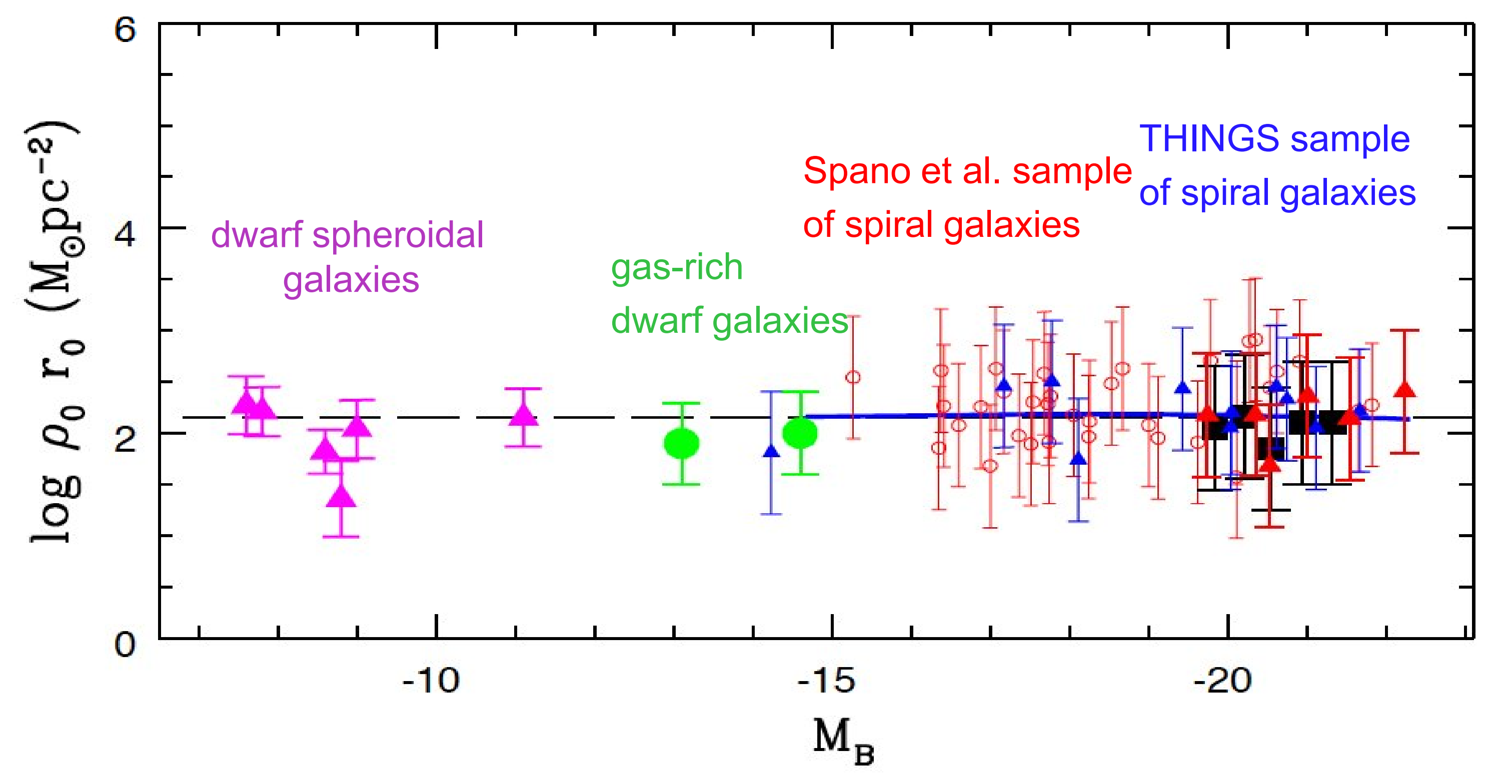
Universality of dark matter surface density

In Donato, GG, et al. (2009):
collection of high-quality rotation curves
and observed stellar kinematics
with mass models.

Galaxies of all sizes and all Hubble types.

Universality of dark matter surface density

In Donato, GG, et al. (2009): (here r_{core} is called r_0)



$\rho_0 r_0 = 141^{+82}_{-52}\ M_{sol}\ pc^{-2}$

Universality of dark matter surface density

Mean dark matter surface density within r_0 of a Burkert halo is:

$$\langle\Sigma\rangle_{0,\,\mathrm{dark}} = M_{<r_0} \big/ \pi r_0^2 \approx 0.51\rho_0 r_0 = 72^{+42}_{-27}\ M_{\odot}\mathrm{pc}^{-2}$$

where $M_{<r_0}$ is the enclosed dark matter mass within r_0

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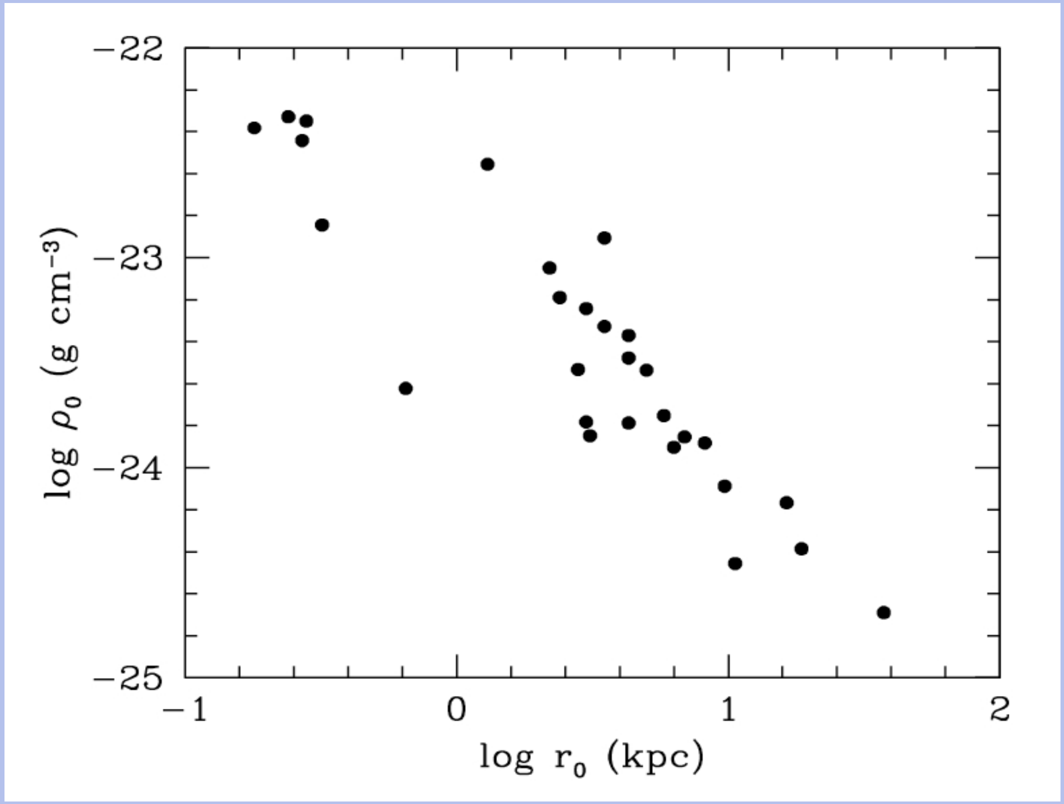
where $M_{<r_0}$ is the enclosed dark matter mass within r_0

This is equivalent to: $g_{\mathrm{dark}}(r_0) = G\pi\langle\Sigma\rangle_{0,\,\mathrm{dark}} = 3.2^{+1.8}_{-1.2}\ 10^{-9}\ \mathrm{cm\ s}^{-2}$

the **gravitational acceleration generated by dark matter at r_0** is also universal

Universality of dark matter surface density

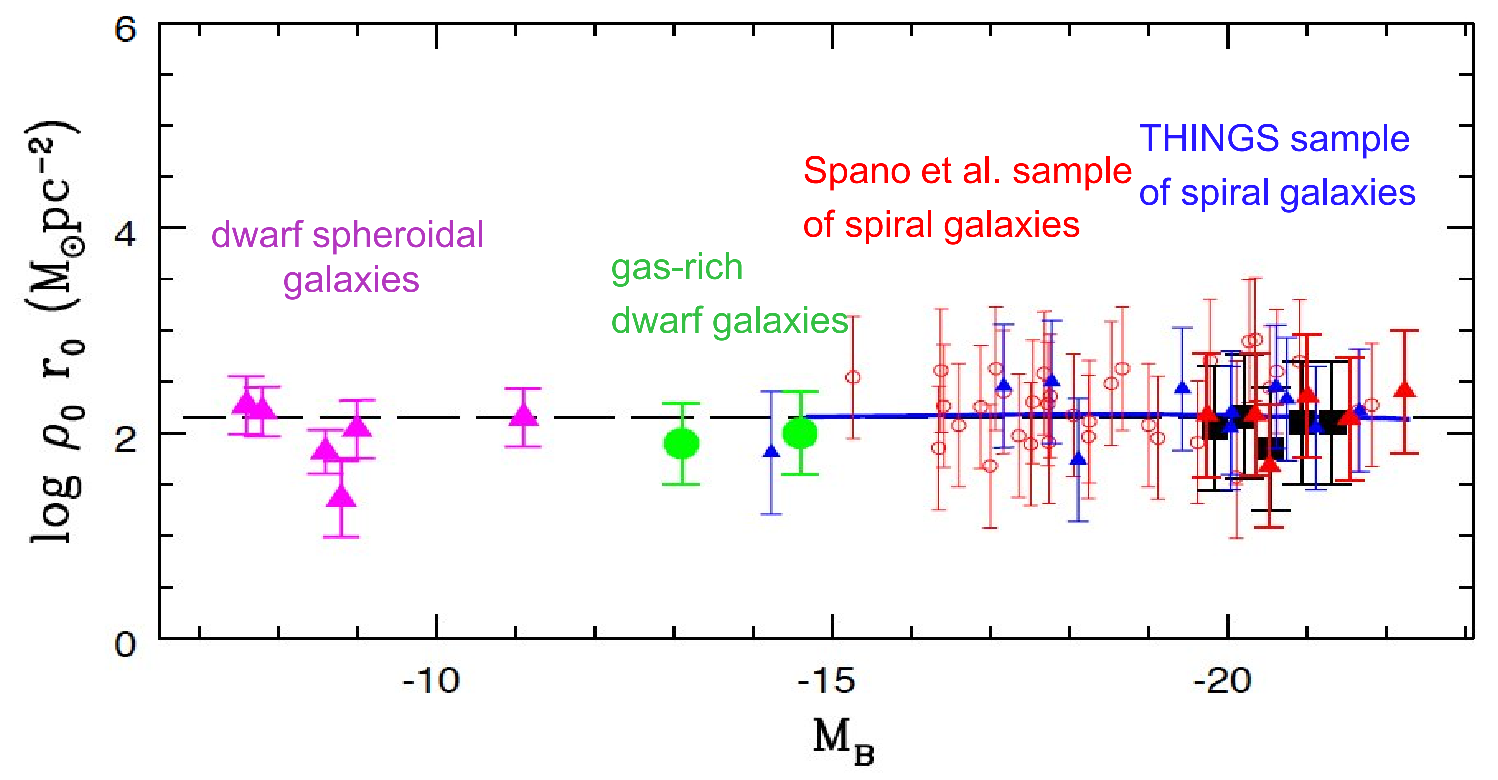
The universality of $\rho_0 r_0$ means that ρ_0 and r_0 conspire to keep the product constant (even though they vary a lot from galaxy to galaxy):



(Already noticed by Kormendy & Freeman 2004 and Spano et al. 2008 but only for spirals)

Universality of dark matter surface density

In Donato, GG, et al. (2009): (here r_{core} is called r_0)



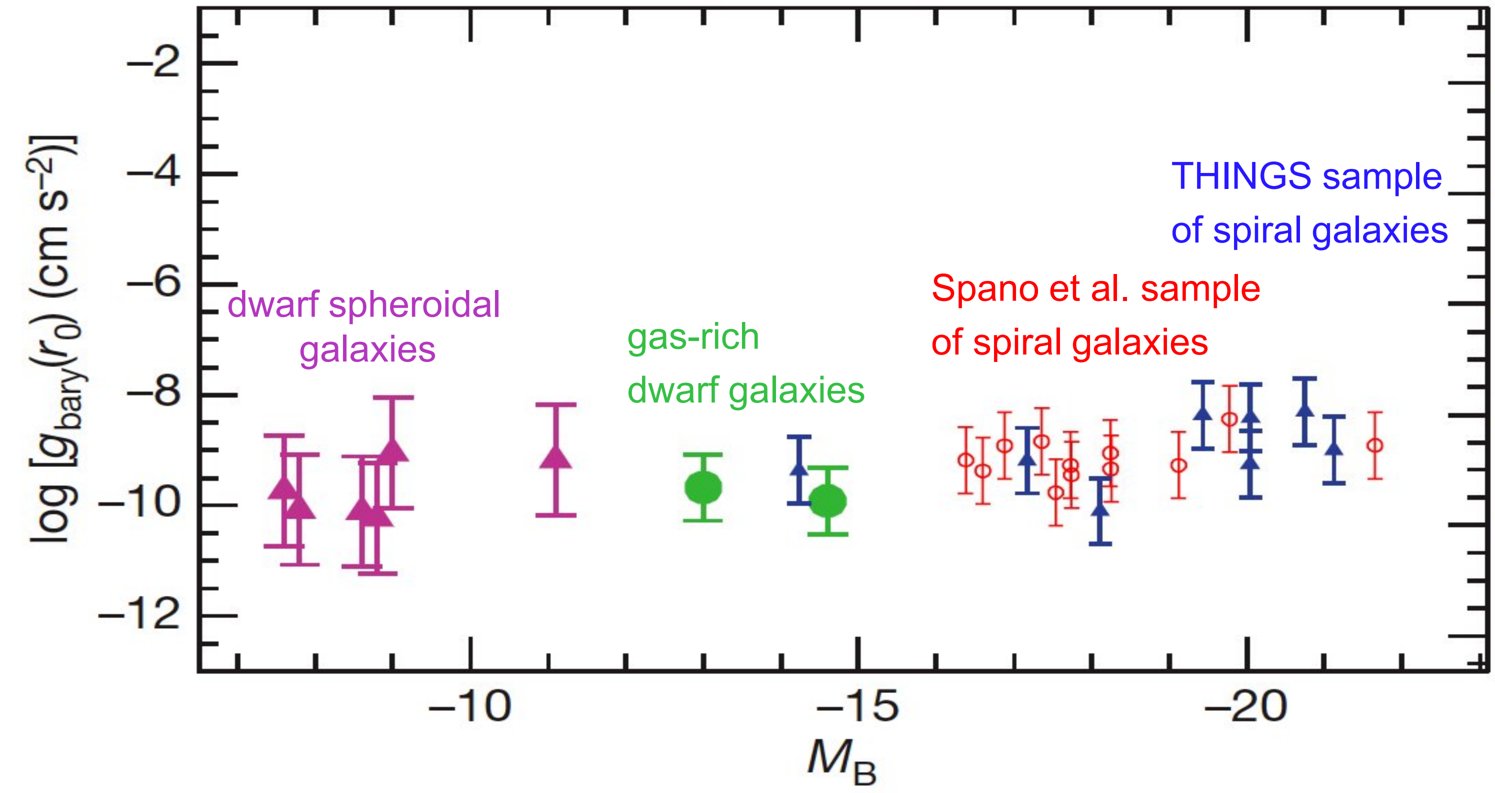
$\rho_0 r_0 = 141^{+82}_{-52}\ M_{sol}\ pc^{-2}$

Universality of dark matter surface density

What about baryons?

Universality of baryons surface density

In GG, Famaey, Zhao, Salucci (2009, Nature) we found that also the surface density of **baryons** is constant within r_0:

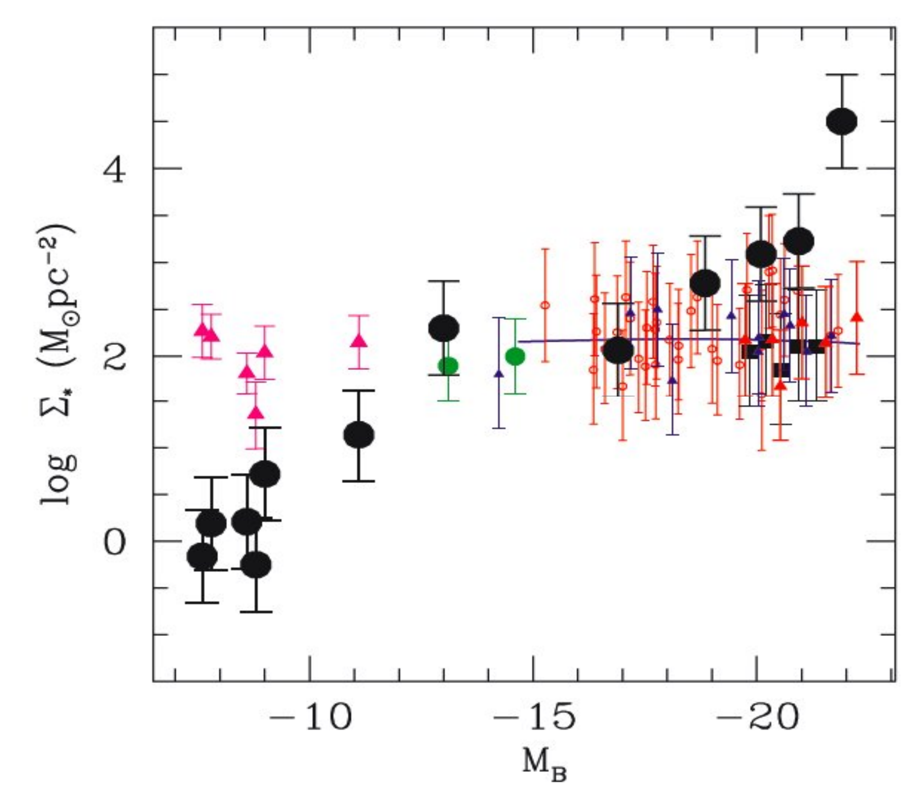


$$g_{\rm bary}(r_0) = 5.7^{+3.8}_{-2.8}\ 10^{-10}\ \rm cm\ s^{-2}$$

Universality of baryonic and dark matter surface density

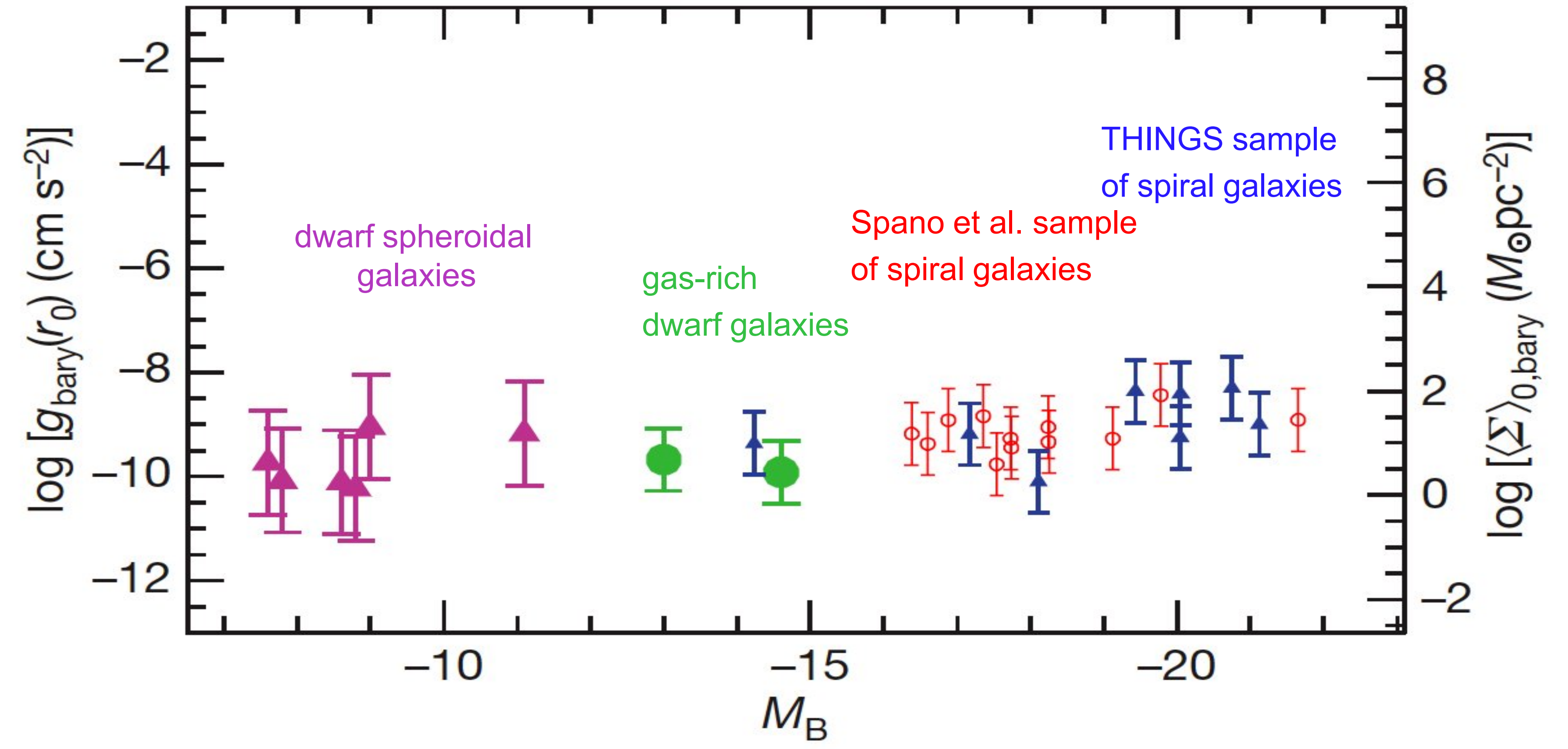
Coloured points:
average dark matter surface density within r_0

Black points:
central surface density of baryons
(not the average one within r_0)



Universality of baryonic and baryons surface density

What can we learn from the universality of **both** dark matter and baryonic surface densities within r_0 ?



Universality of baryonic and dark matter surface density

Universality of baryonic and dark matter surface density

- At r_0, the dark-to-luminous matter ratio is ≈ the same for every galaxy, but the total ratio is not.

- At r_0, the gravitational acceleration due to dark matter and the gravitational acceleration due to baryons are ≈ the same for every galaxy

→ 1) dark matter “knows” what baryons are doing
2) weirdly, r_0 can be determined from the distribution of baryons

Universality of baryonic and dark matter surface density

Maybe an unknown interaction

between dark matter and baryons (other than gravity)?

Dark matter particle with a mass of 1-2 keV (de Vega, Salucci, Sanchez 2010)?

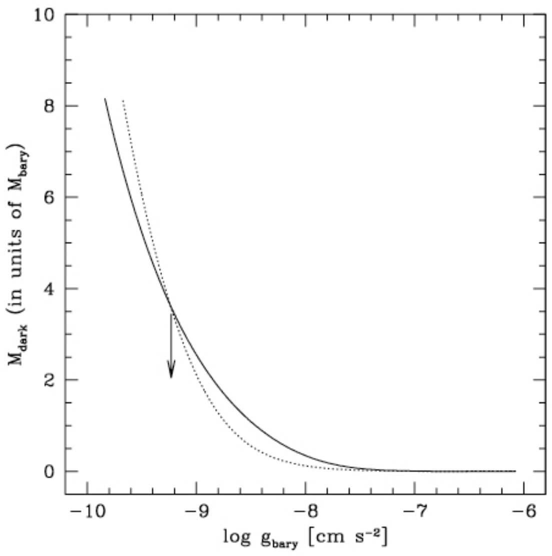
Universality of baryonic and dark matter surface density

MOND can explain these relations quite naturally.

First thought: $a_0/(2\pi G) = 138\ M_{sol}\ pc^{-2}$

$(\rho_0 r_0$ was $141^{+82}_{-52}\ M_{sol}\ pc^{-2})$

We can compare the “phantom dark matter” halo associated to MOND ($M_{phantomDM} = M_{totalNewton} - M_{baryonsNewton}$) with the Burkert halo.



Universality of baryonic and dark matter surface density

What next?

- Increase the sample statistics
- Extend to higher and lower masses

Conclusions

- Evidence for cores over cusps

- Core radius r_0 of a DM halo: size of the central constant density region.

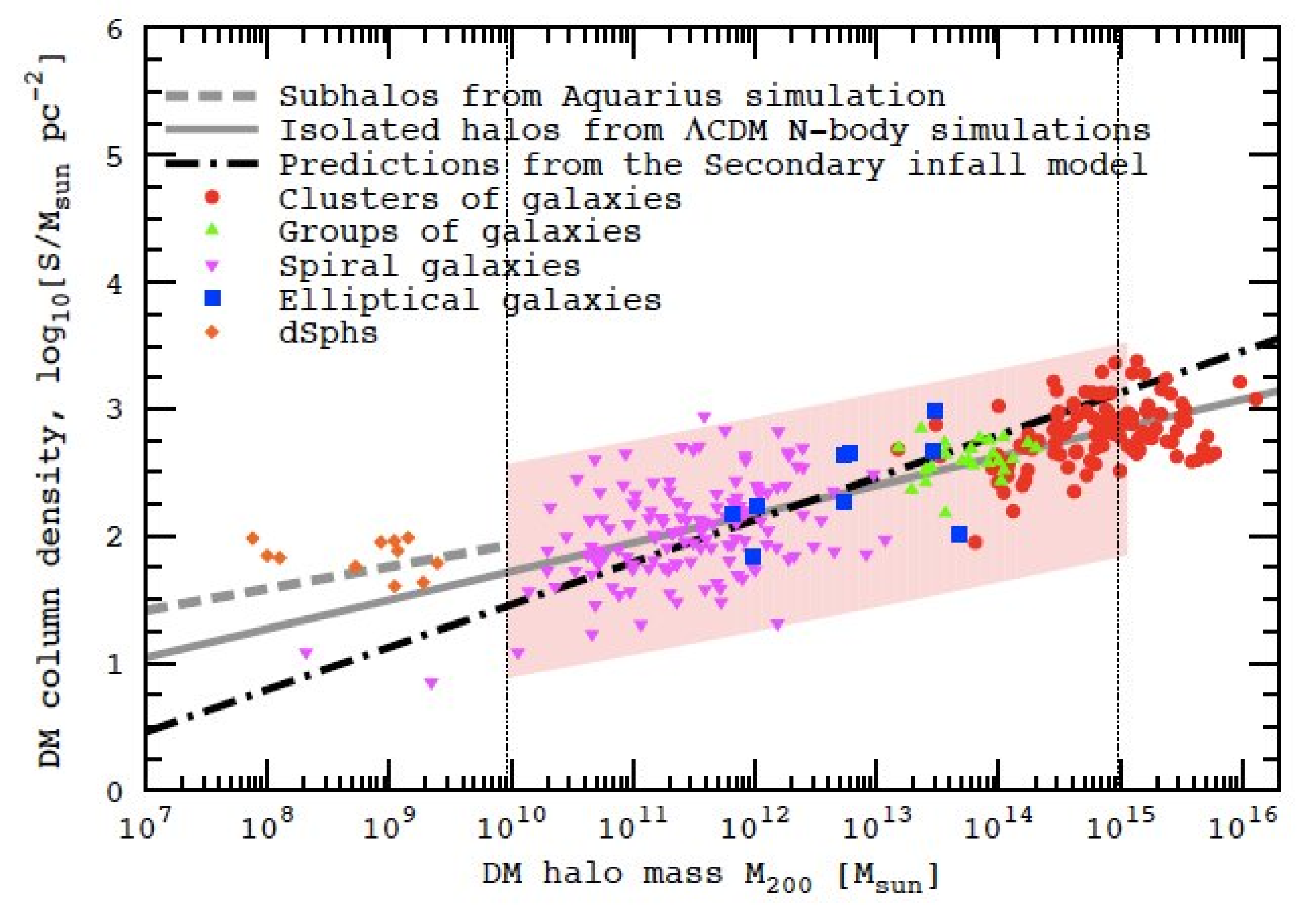
- Donato, GG, et al. (2009): the average DM surface density within r_0 (or equivalently the DM gravitational accel. at r_0) is universal in galaxies.

- In GG, Famaey, Zhao, Salucci (2009, Nature) we showed that the same is true for the average baryonic surface density within r_0 (or equivalently the baryonic gravitational acceleration at r_0: $g_{\rm bary}(r_0) = 5.7^{+3.8}_{-2.8}\ 10^{-10}\ \mathrm{cm\ s^{-2}}$)

- Unknown fine-tuned process in galaxy formation?

- Unknown interaction between dark matter and baryons?

Comments on Boyarsky et al.'s follow-up



Comments on Boyarsky et al.’s follow-up

- They don’t say where they take their sources from

- Single slope or break around a few x 10^{12} M_{sol}?

- Their parameters come from NFW fits: bad fits in a lot of cases

- Their parameters come from NFW fits: unrealistic parameters in a lot of cases (e.g. NGC 224 has M_{200}=1.2e13 M_{sol})

- Some sources are plotted twice (e.g. M31 and NGC 224 are the same object)