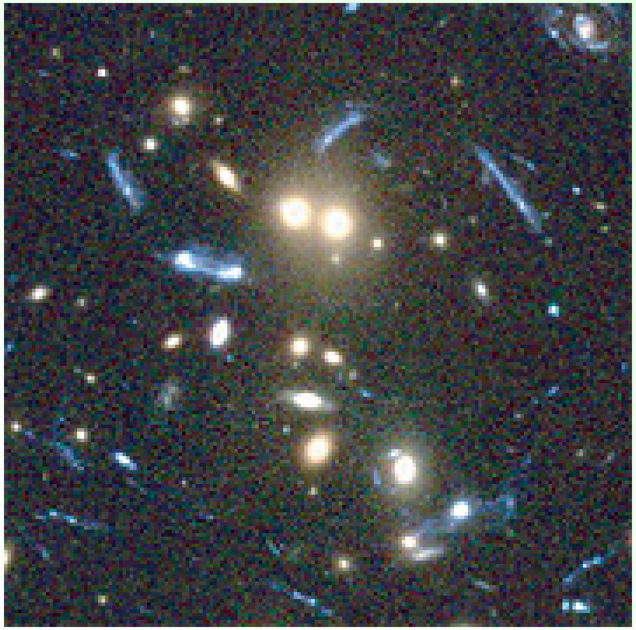
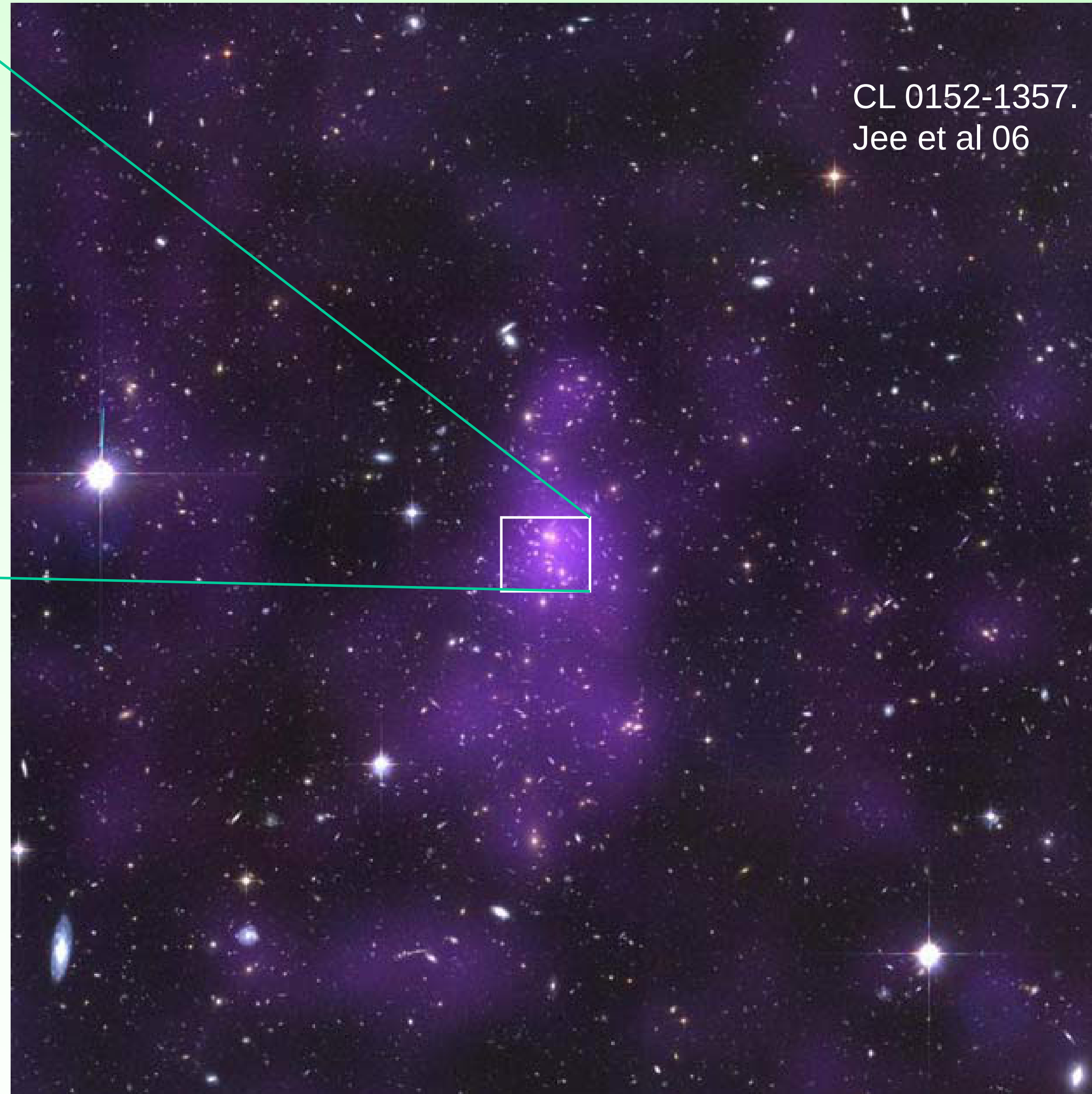
Galaxy Dynamics with MOND





Françoise Combes
Observatoire de Paris

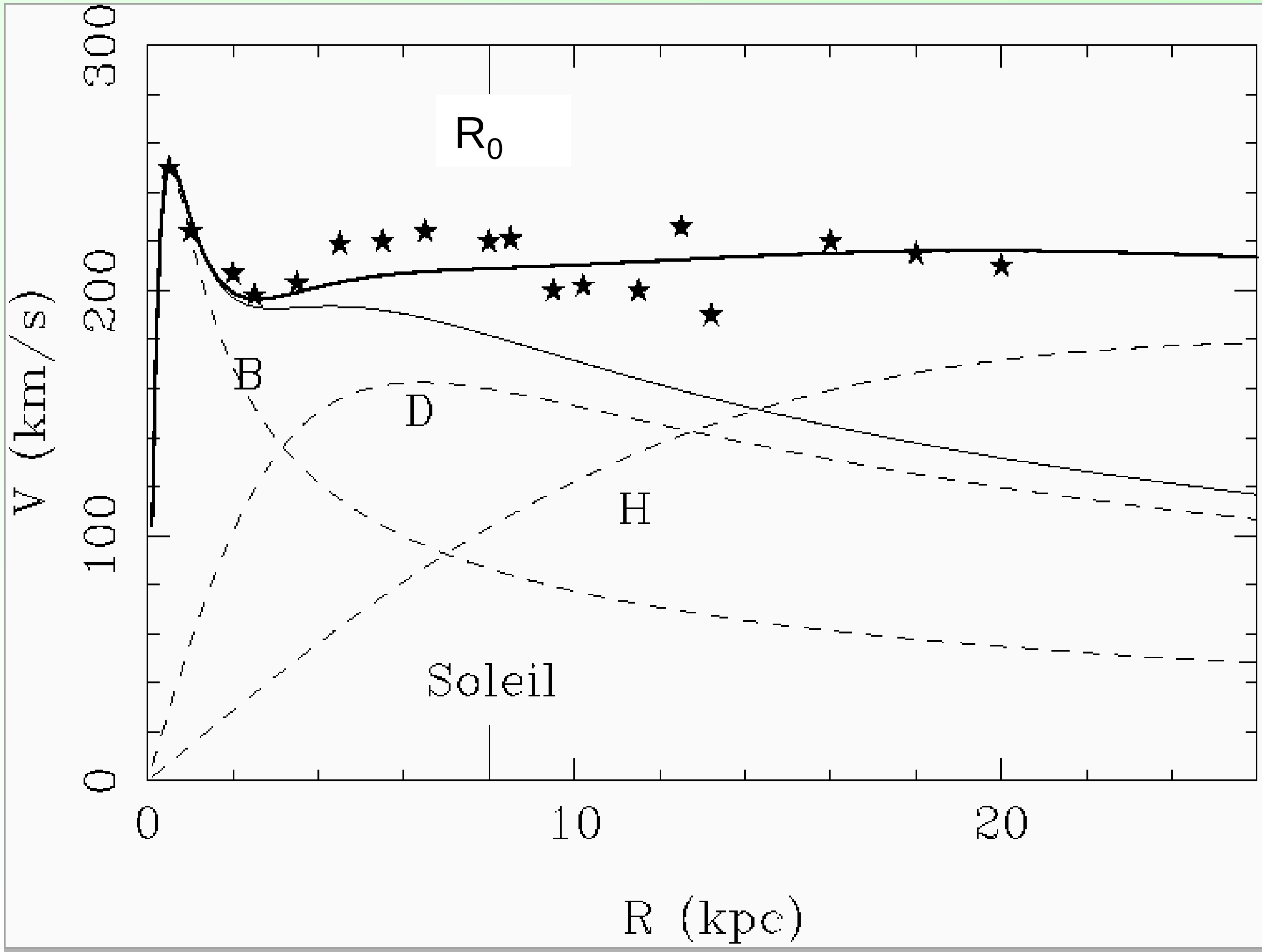
Friday 26 March 2010

l'Observatoire de Paris
LERMA
Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

Evidences of dark matter

➔ **Galaxy clusters**, Virial /visible mass ~100 (Zwicky 1937)
Coma cluster: galaxy velocity dispersion

➔**Rotation curves**
for instance
our Galaxy,
The Mikly Way

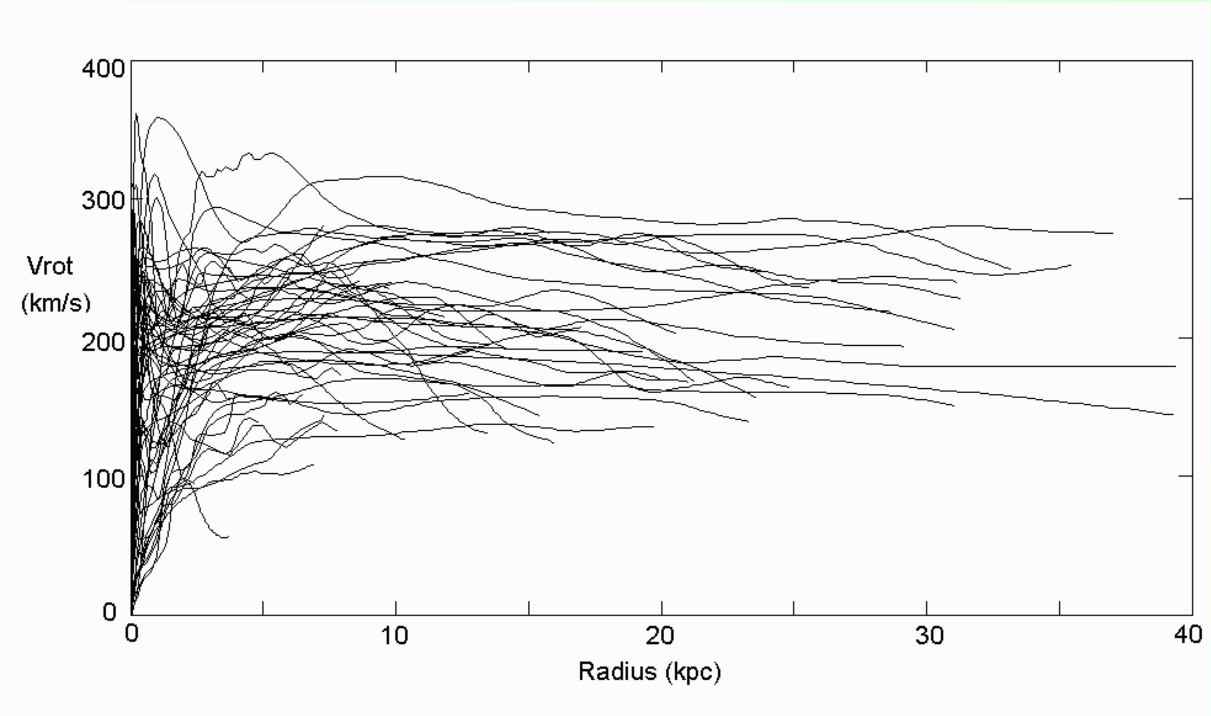


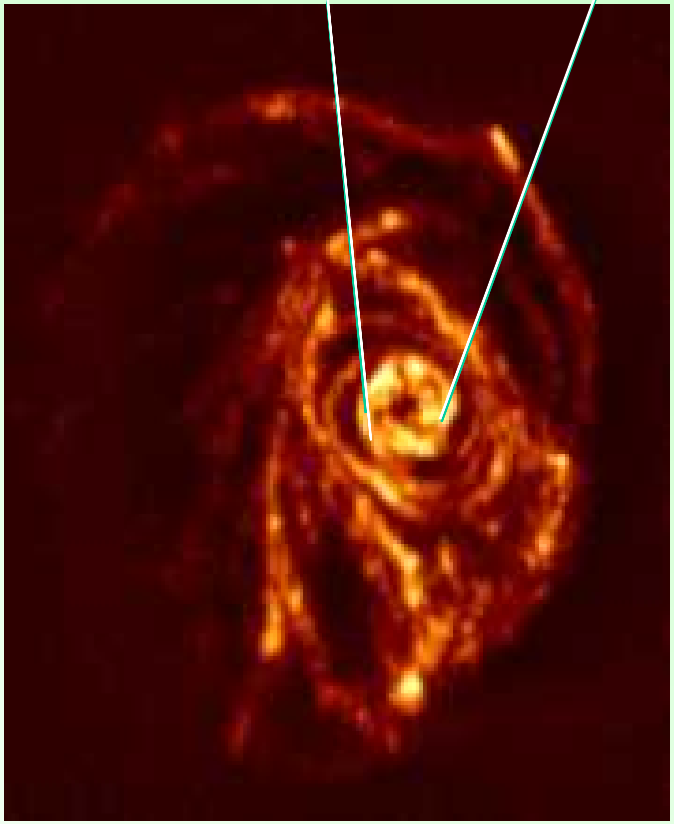
Well beyond the visible mass,
The velocity remains high, instead of
$V^2 \sim GM/r$
(Kepler)

Galaxies with HI

M83: optical

HI: cartography of atomic hydrogen
Wavelength 21cm



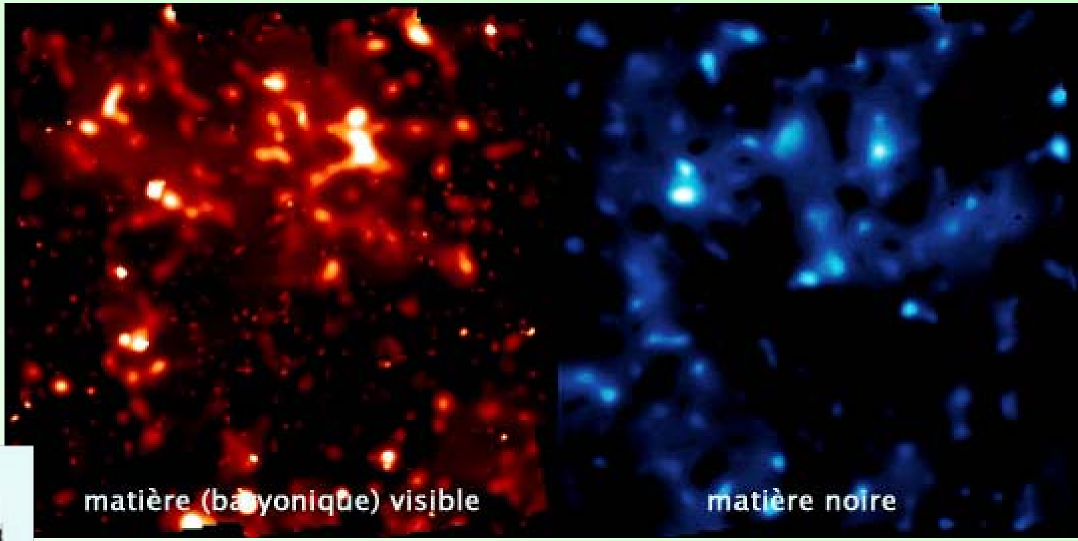


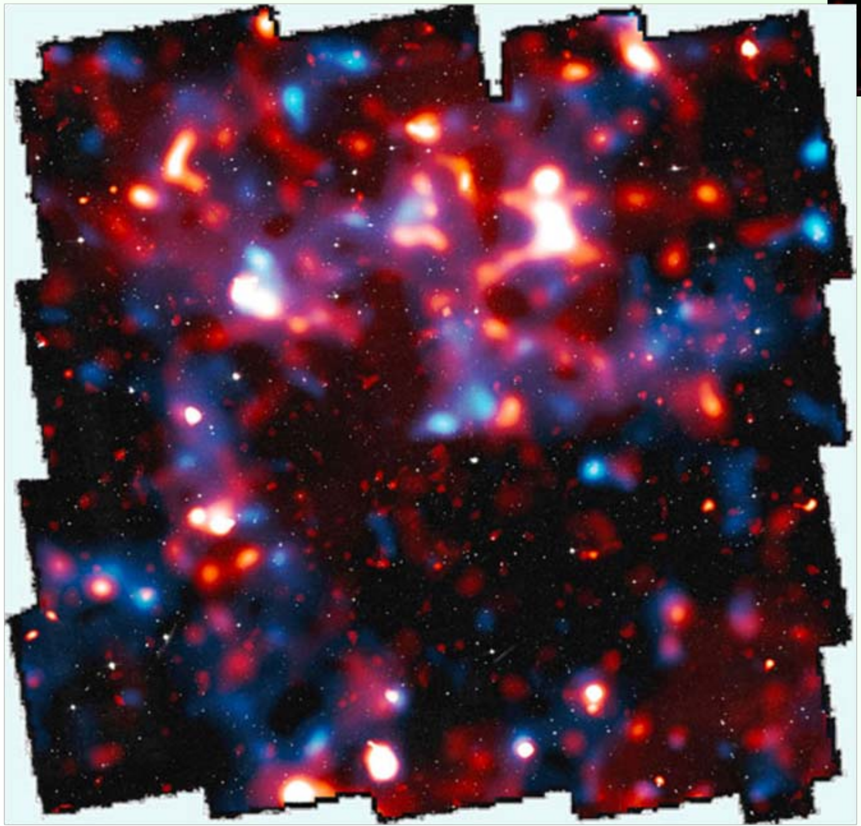
HI in M83: a galaxy similar to the Milky Way

Gravitationnal shear, weak lensing

Red: X-ray gas
Blue: total matter

Cosmos field





Constraints on the Dark Matter, and Dark Energy

Massey et al 2007

Tully-Fisher relation

Relation between maximum velocity and luminosity

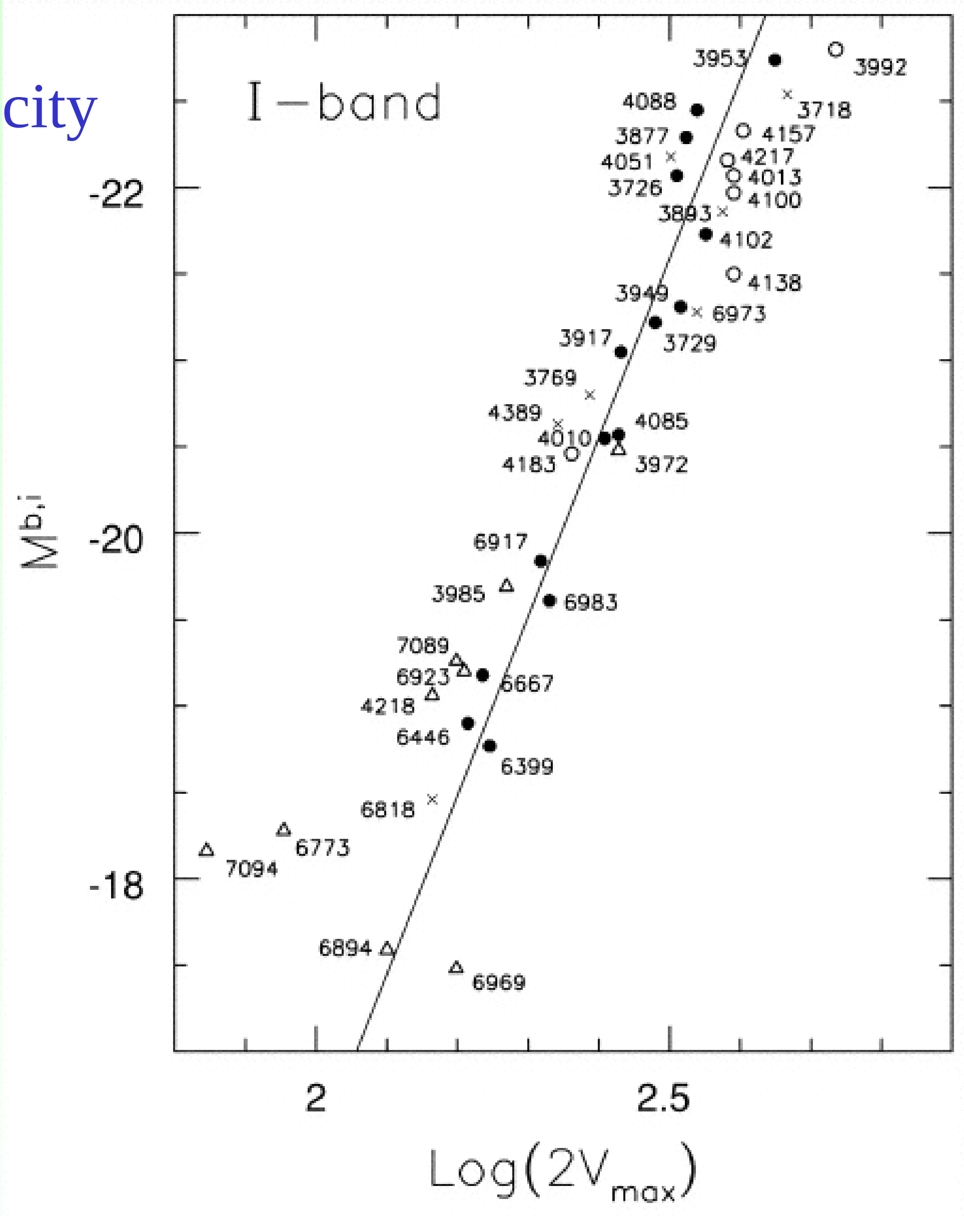
ΔV corrected from inclination

Much less scatter in I or K-band

(no extinction)

Correlation with Vflat

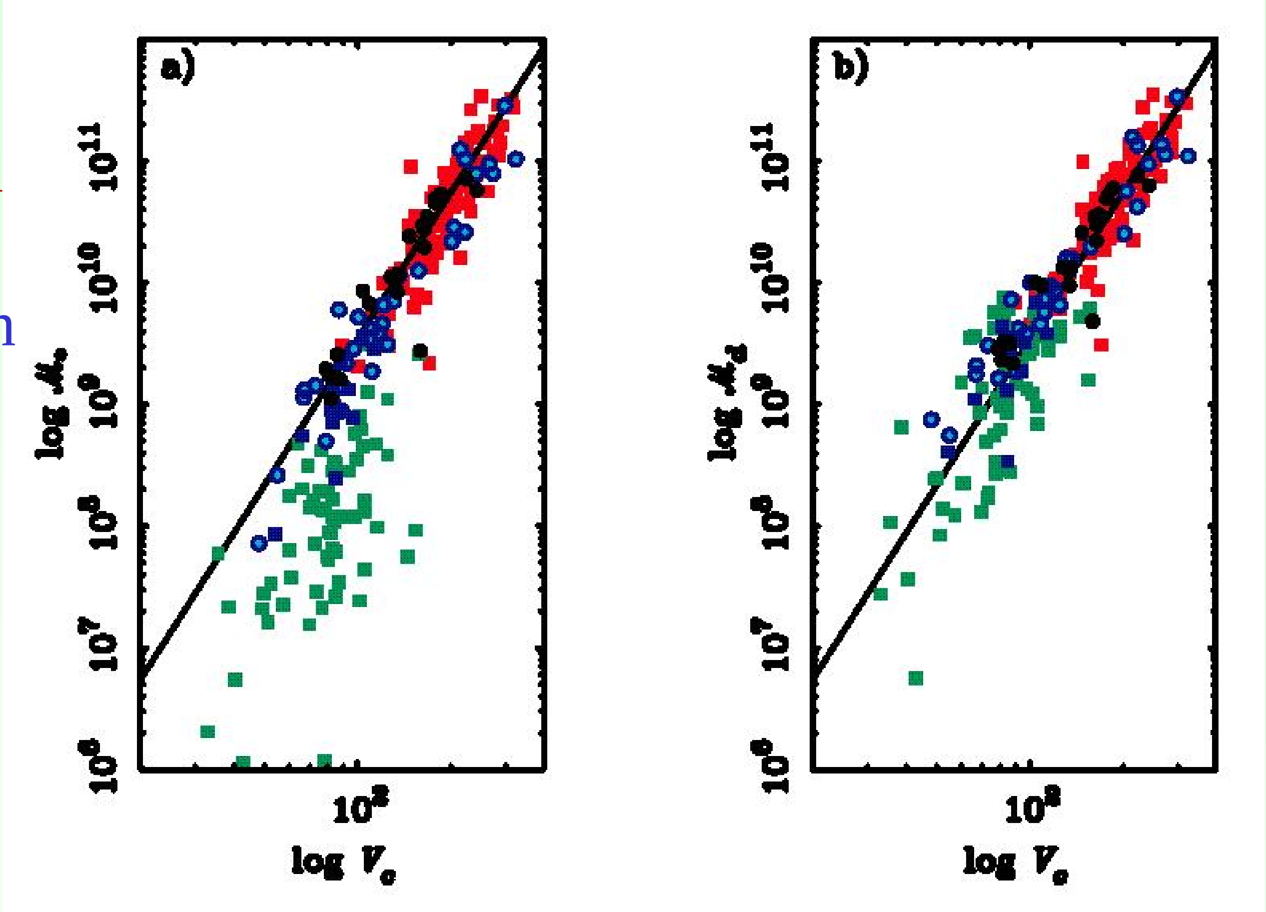
Better than Vmax



Uma cluster

Verheijen 2001

Tully-Fisher relation
for gaseous galaxies
works much better in
adding gas mass



Relation $M_{baryons}$
with Rotational V

$M_b \sim V_c^4$

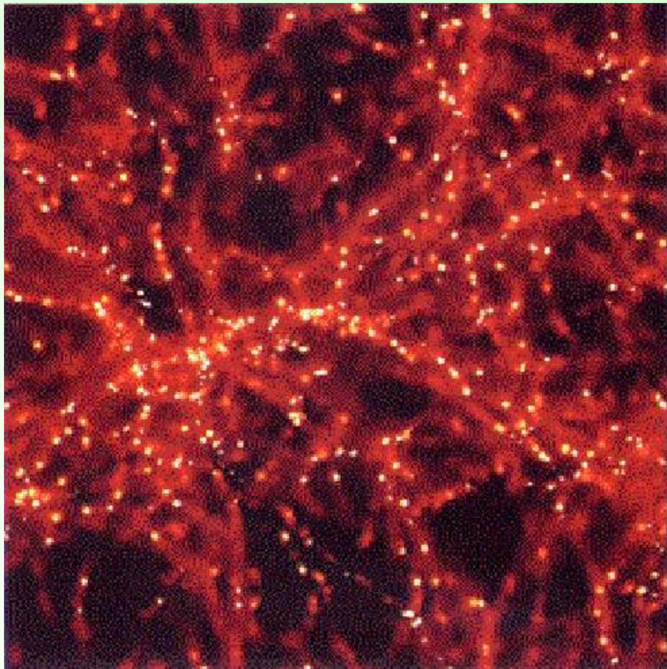
McGaugh et al (2000) ➔ **Baryonic Tully-Fisher**

Where are the baryons?

➔6% in galaxies ; 3% in galaxy clusters as hot X-ray gas

➔<18% in the Lyman-alpha forest (cosmic filaments)

➔5-10% in the WHIM (Warm-Hot Intergalactic Medium) 10^5-10^6K OVI lines



➔65% are not yet identified or localised!

Most of them are not in galaxies

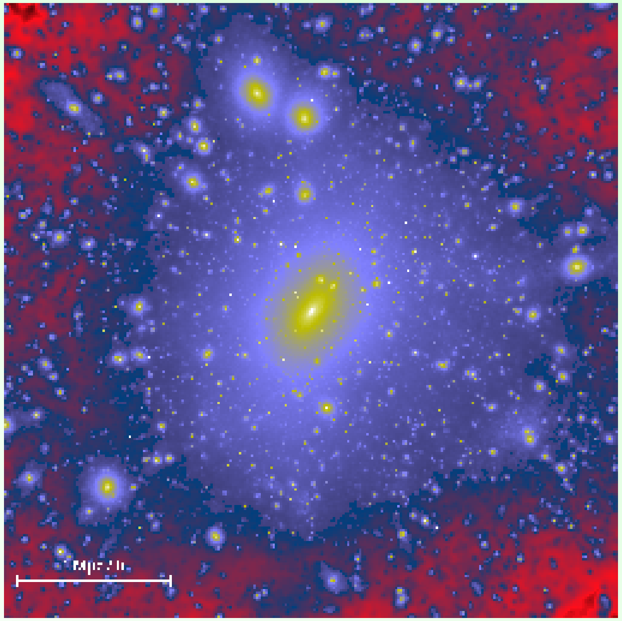
Problems of the standard Λ-CDM model

➔Prediction of cusps in galaxy center, which are in particular absent in dw-Irr, dominated by dark matter

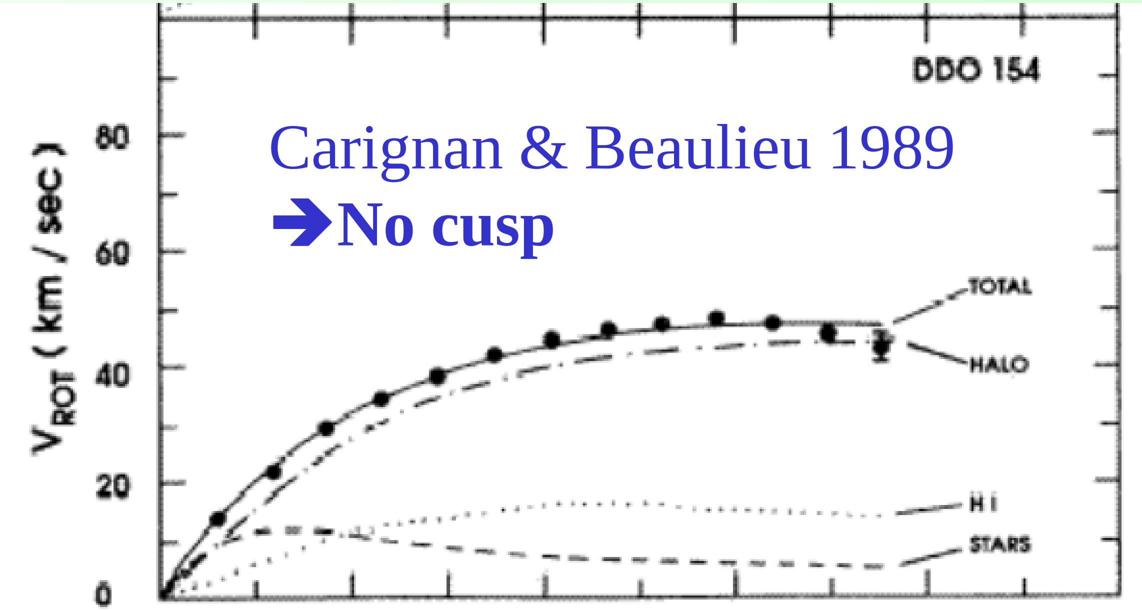
➔Low angular momentum of baryons, and as a consequence formation of much too small galaxy disks

➔ Prediction of a large number of small halos, not observed

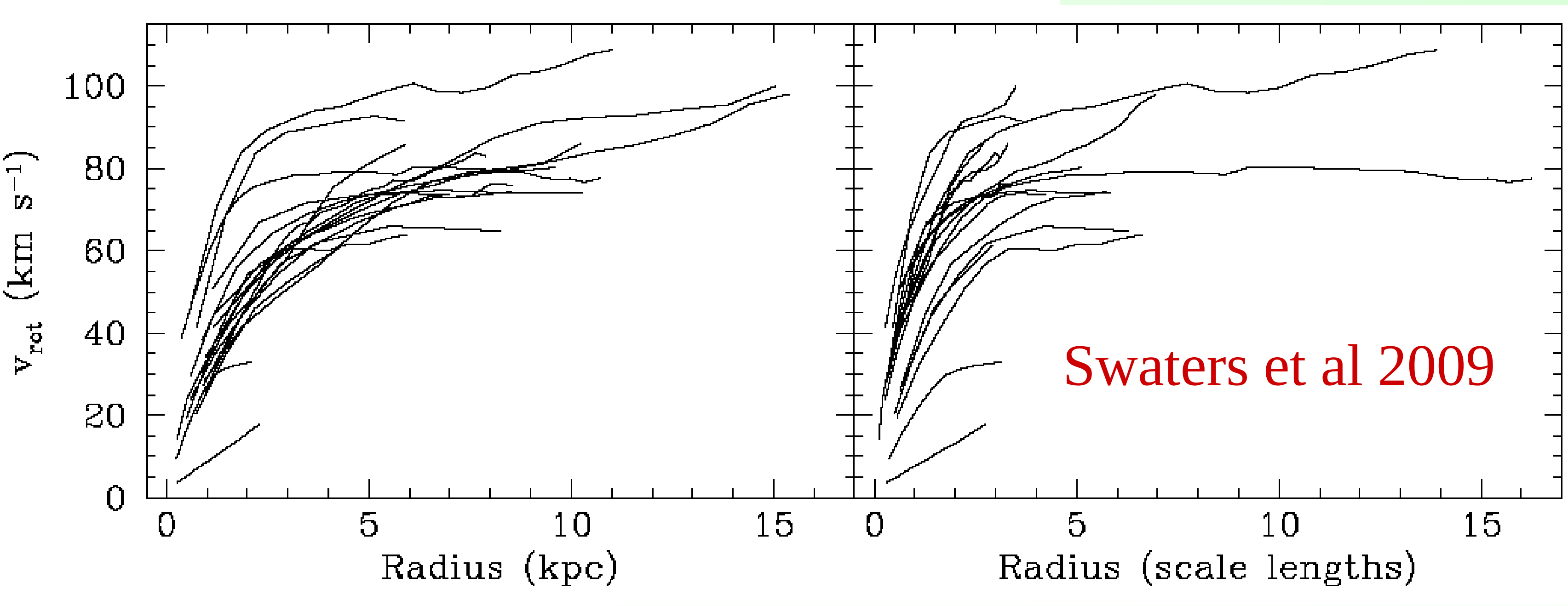
The solution to all these problems could come from unrealistic baryonic physics (SF, feedback?), or lack of spatial resolution in simulations, or wrong nature of dark matter?



Dwarf Irr : DDO154 the prototype



Even the LSB late-type galaxies are dominated by baryons (stars) in their centers



MOND =MOdified Newtonian Dynamics
Modification at weak acceleration

$a = (a_0\, a_N)^{1/2}$

$$\nabla \cdot [\mu(|\nabla\phi|/a_0)\nabla\phi] = 4\pi G\rho$$

$a_N \sim 1/r^2$ ➔ $a \sim 1/r$ ➔ $V^2 = \text{cste}$

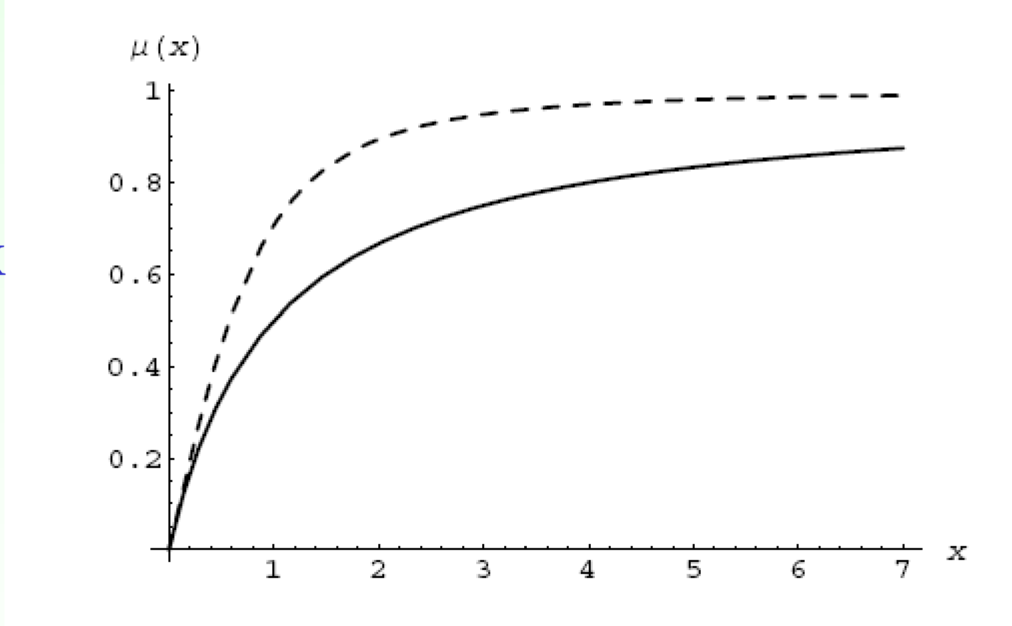
➔ $a^2 \sim V^4/R^2 \sim GM/R^2$ (TF) (Milgrom 1983)

$a_N = a\ \mu(x)$

$x = a/a_0$ $a_0 = 1.2\ 10^{-10}$ m/s^2 or 1 Angstroms/s^2

$x \ll 1$ Mondian regime $\mu(x) \rightarrow x$

$x \gg 1$ Newtonian $\mu(x) \rightarrow 1$



Covariant theory, general relativistic

TeVeS Tensor/Vector/Scalar
Bekenstein (2004)
To replace General relativity in weak curvature

$$\mu(y) = \frac{\sqrt{y/3}}{1 - \frac{4\pi\alpha}{k}\sqrt{y/3}}$$

➔ Introduces a 5th force, violation of SEP (not of WEP)

Can get out naturally from some string theory models (Mavromatos & Sakellariadou 2007)

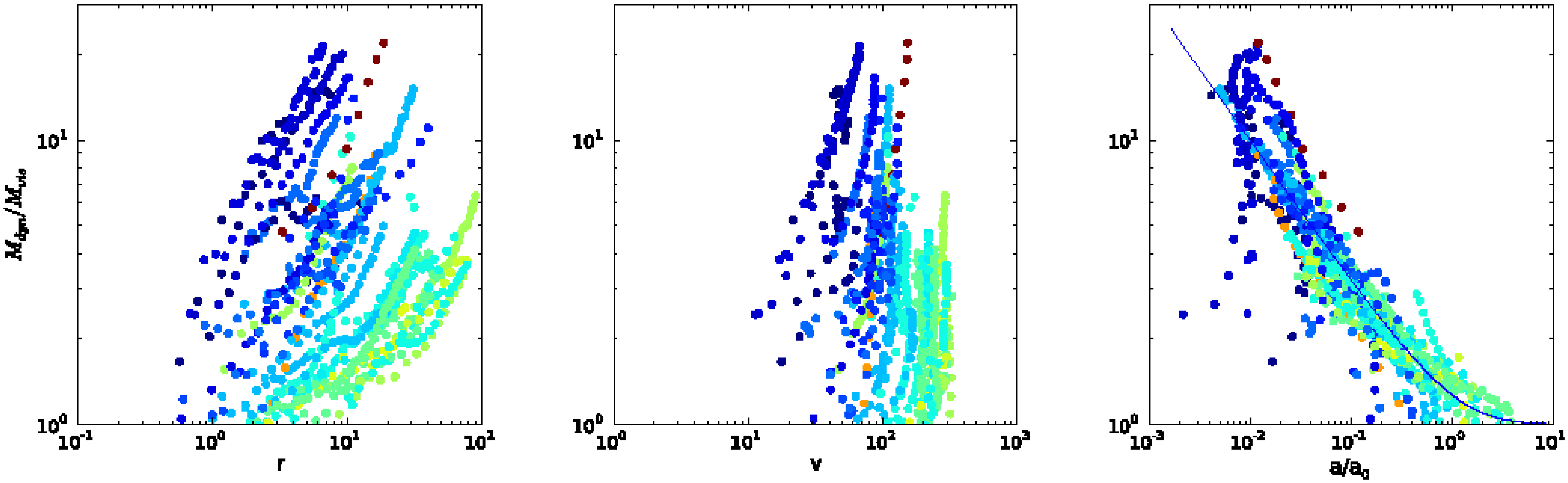
Einstein aether developments
Many other tentative theories

Recent developments: Vector field with non-linear coupling with space-time metric (Zloznik et al, 2007, Zhao, 2008)

Dynamic Mass / Visible Mass

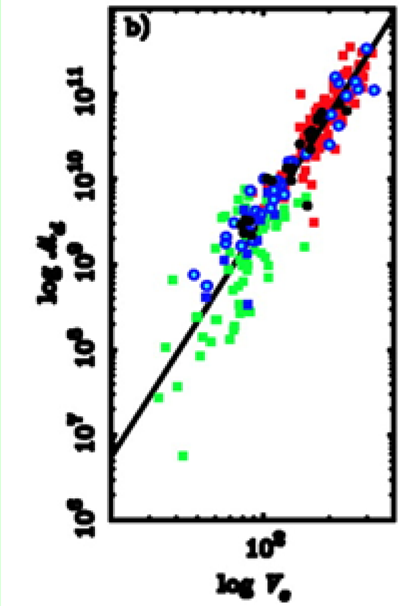
The ratio remarquably depends on acceleration,

➔ The only variable controling the gravity regime universally



Radius Velocity Acceleration

Tully-Fisher relation

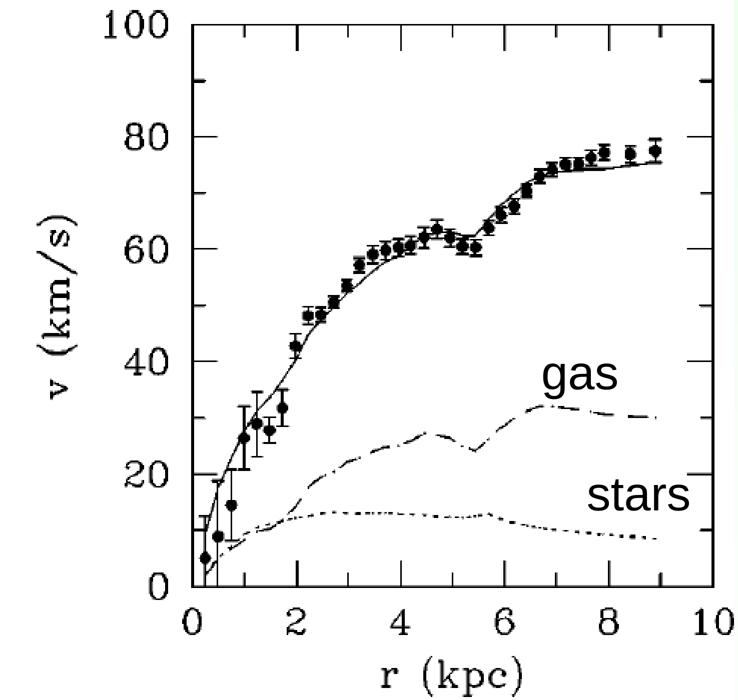


$$g_M^2 = a_0 g_N = a_0 GM/r^2 = V^4/r^2$$

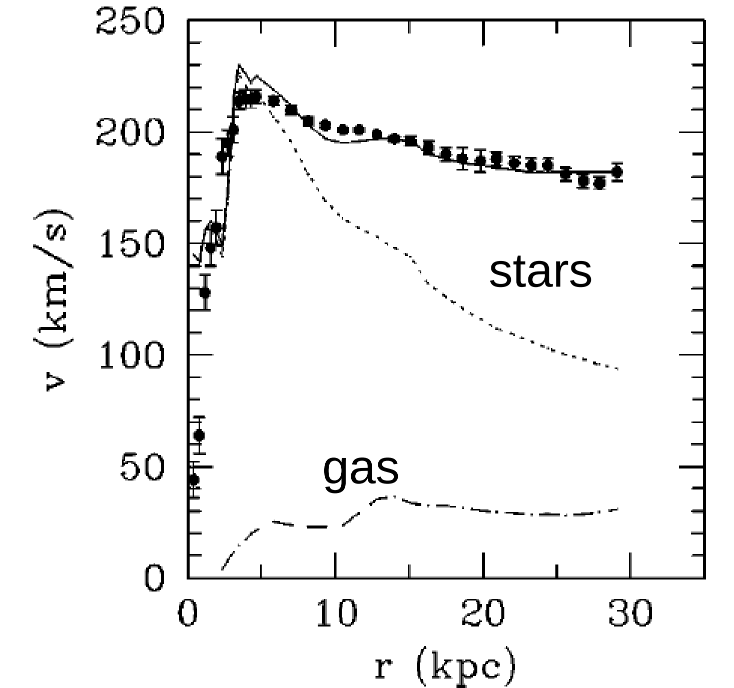
$$\rightarrow V^4 = a_0\, GM$$

Rotation curves are fit for all types
(dwarfs **LSB**, giant **HSB**)

LSB N1560



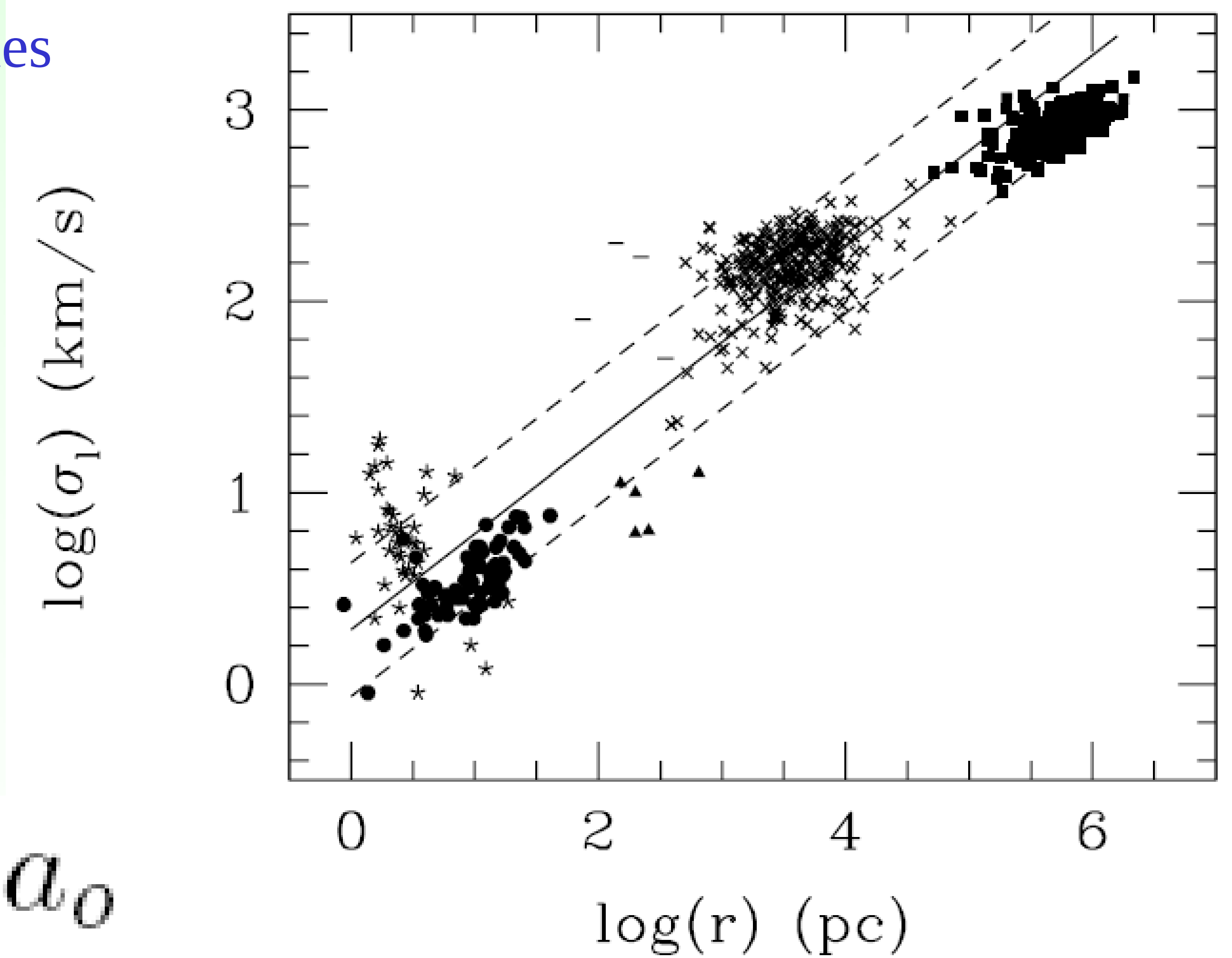
HSB N2903



Pressure-supported systems

Sanders & McGaugh 2002

From GC to galaxies and clusters

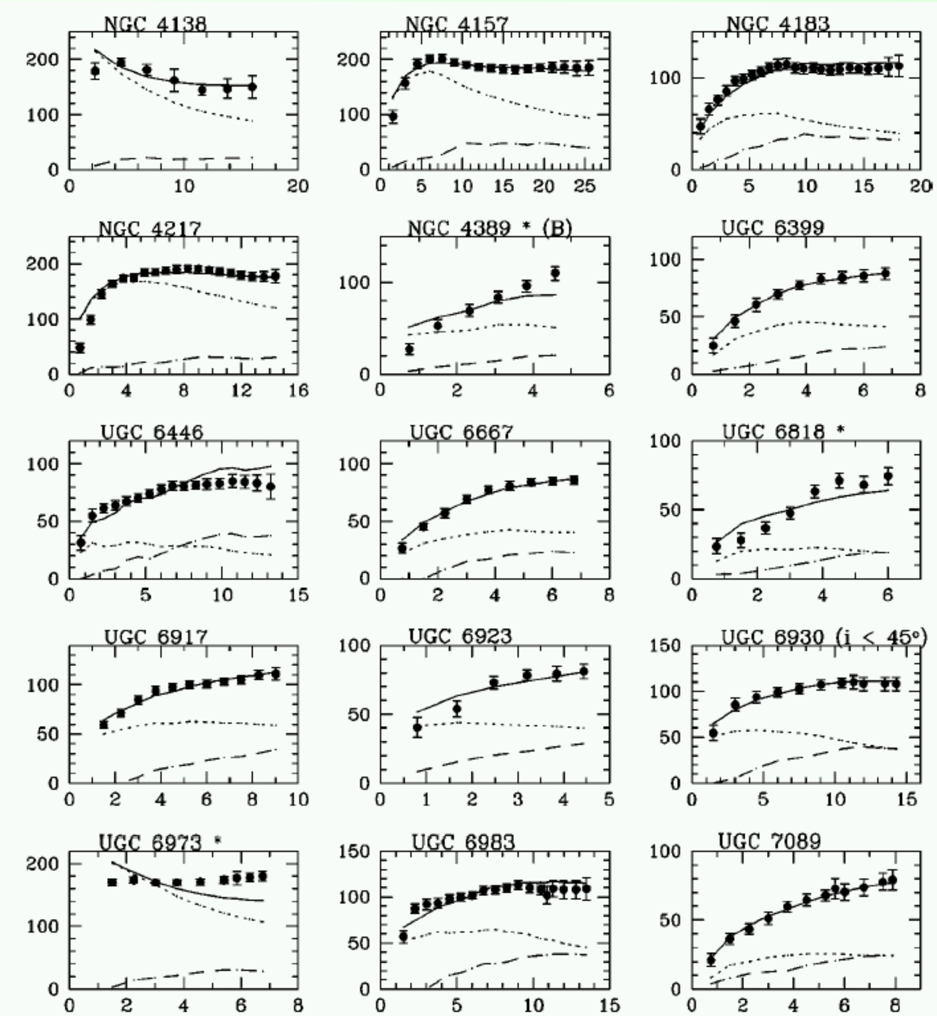


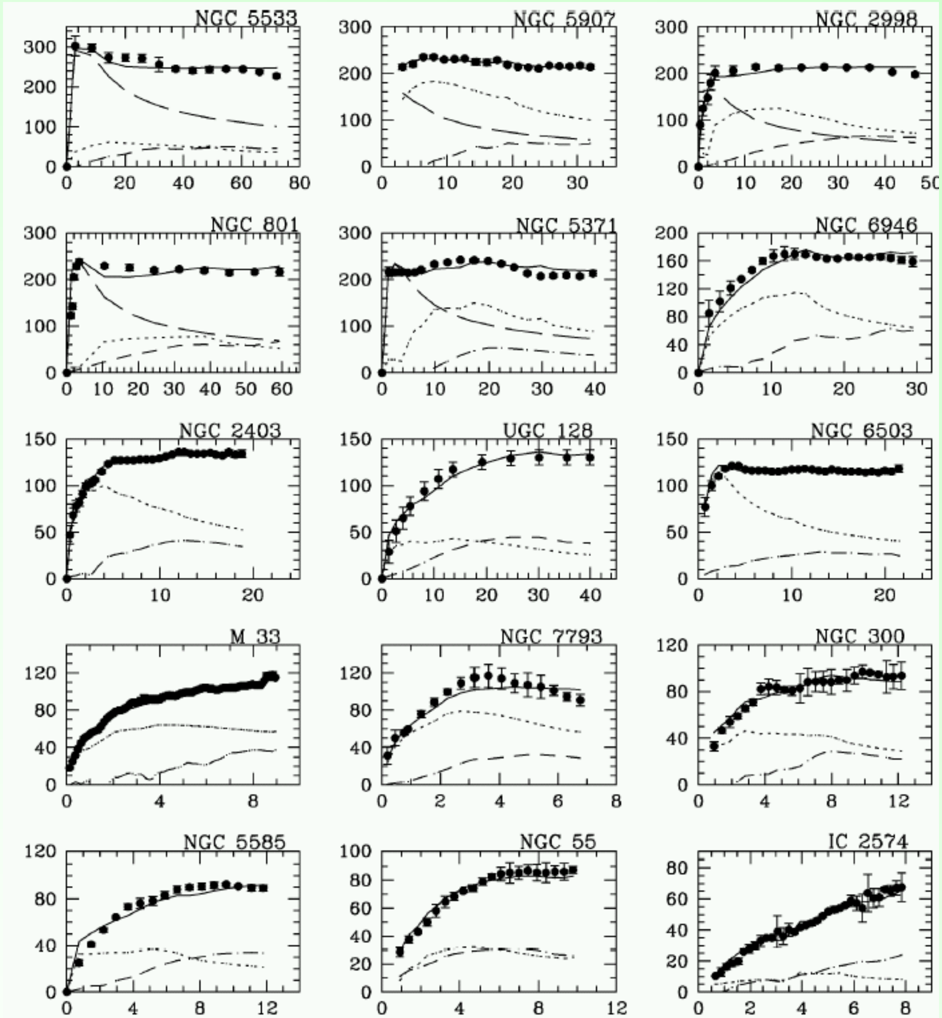
$$\sigma_l^2/r = a_o$$

Multiple rotation curves..

Sanders & Verheijen 1998, all types, all masses

--- gas, …. Stellar disk, – – – bulge





Problems of MOND in galaxy clusters

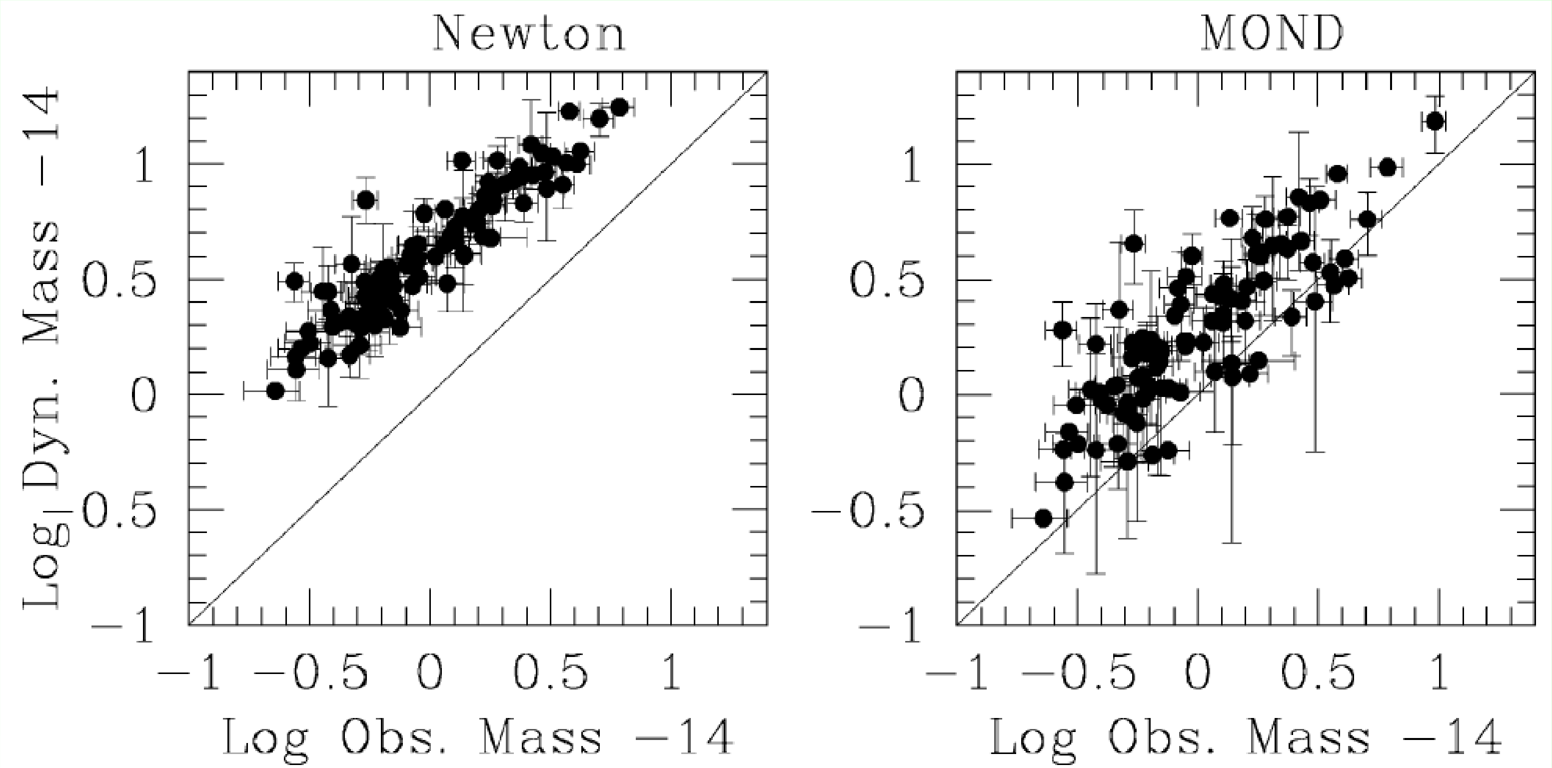
Inside galaxy clusters, there still existing some missing mass, which cannot be explained by MOND, since **the cluster center** is only moderately in the MOND regime (~0.5 a_0)

Observations in X-rays: hot gas in hydrostatic equilibrium, and weak gravitational lenses (shear)

MOND reduces by a factor 2 the missing mass
➔It remains another component, which could be neutrinos….
(plus baryons)

The baryon fraction is not the universal one in clusters
(so baryons could still exist in the standard ΛCDM model)
But if CDM does not exist, there is no limiting fraction

MOND & galaxy clusters

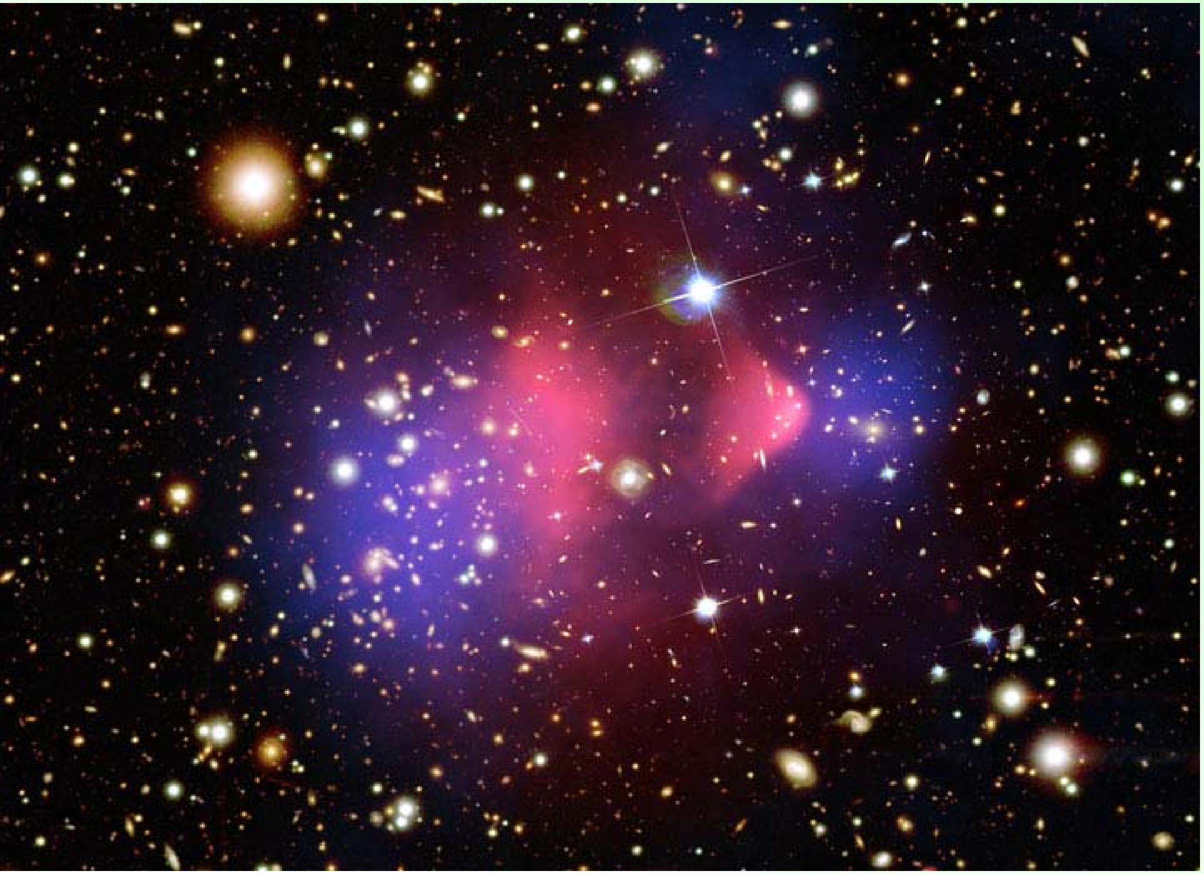


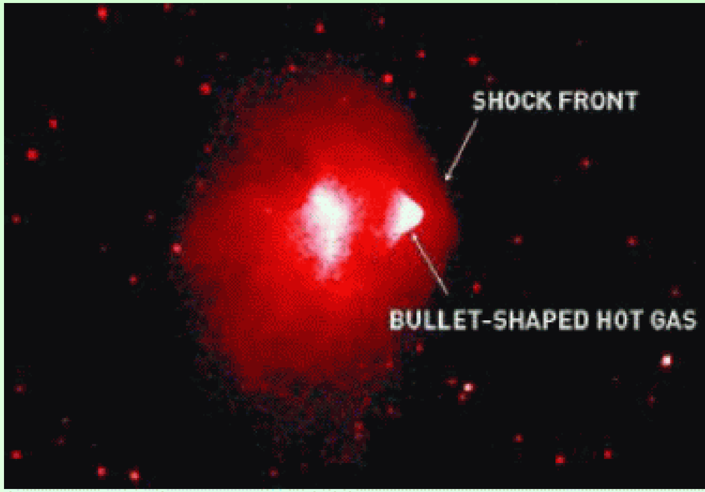
According to baryon physics, cold gas could accumulate at the cluster centers

Alternatively, neutrinos could represent 2x more mass than the baryons

The bullet cluster

X-ray gas





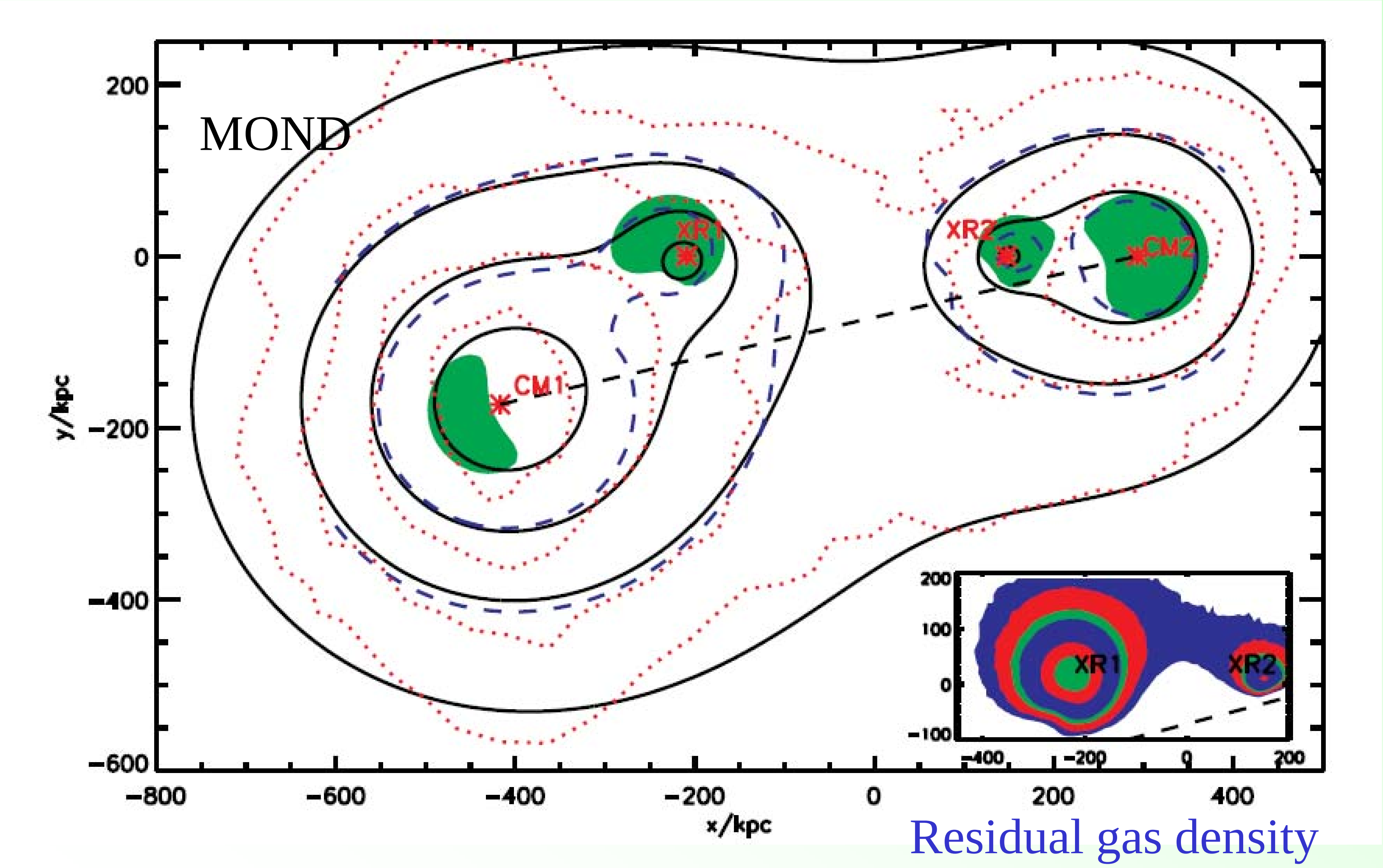
Proof of the existence of non-baryonic matter

Total mass

Accounted for in MOND + neutrinos (2eV, Angus et al 2006)

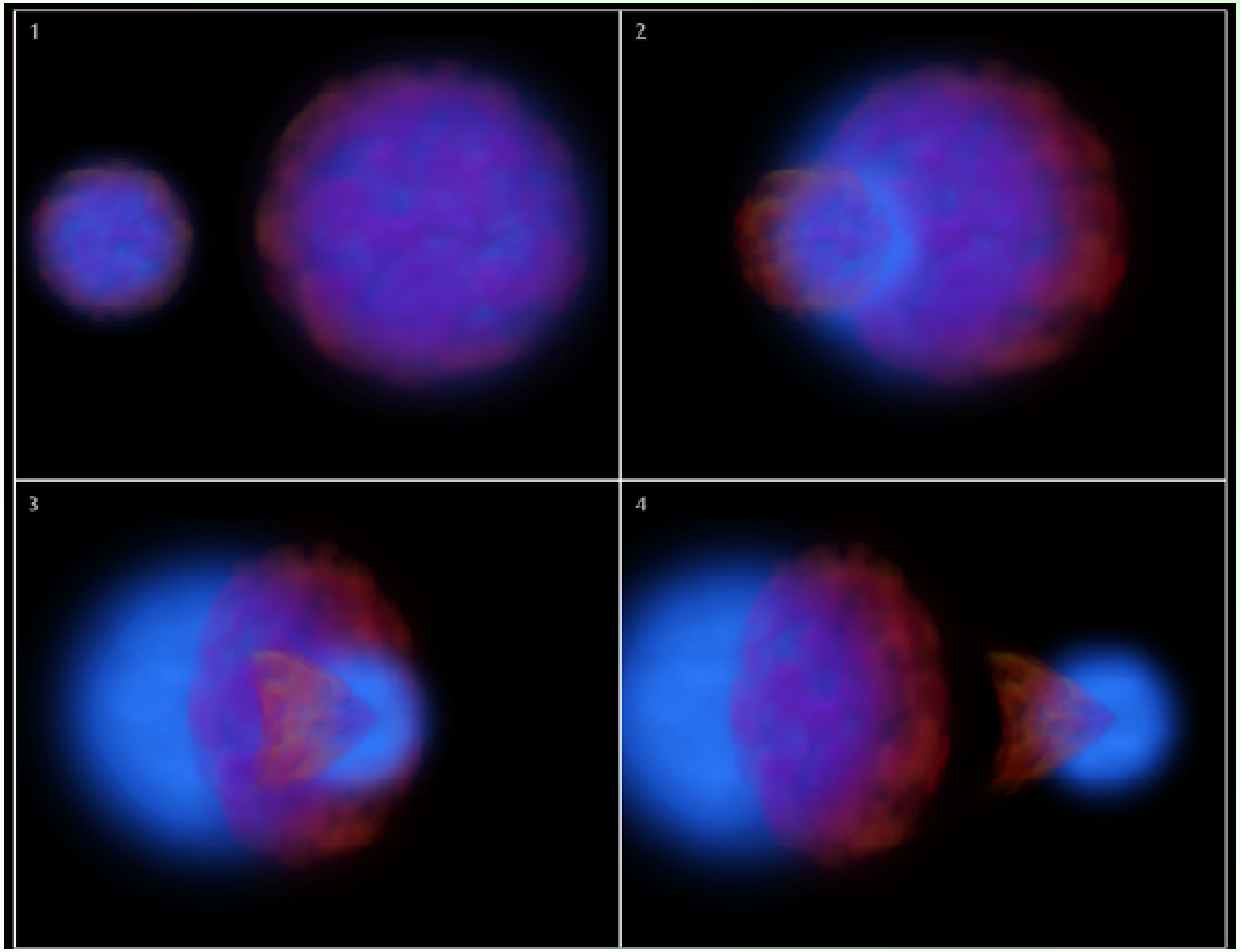
Model of the bullet in MOND

…….Clowe et al 2006, Angus et al 2007



CDM simulation

Collision velocity from the bow-shock = 4700±500km/s (Mach 3)
Hayashi & White 2006 Farrar & Rosen 2007
➔impossible to reconcile with CDM
Milosavljevic et al 2007, Springel & Farrar 2007



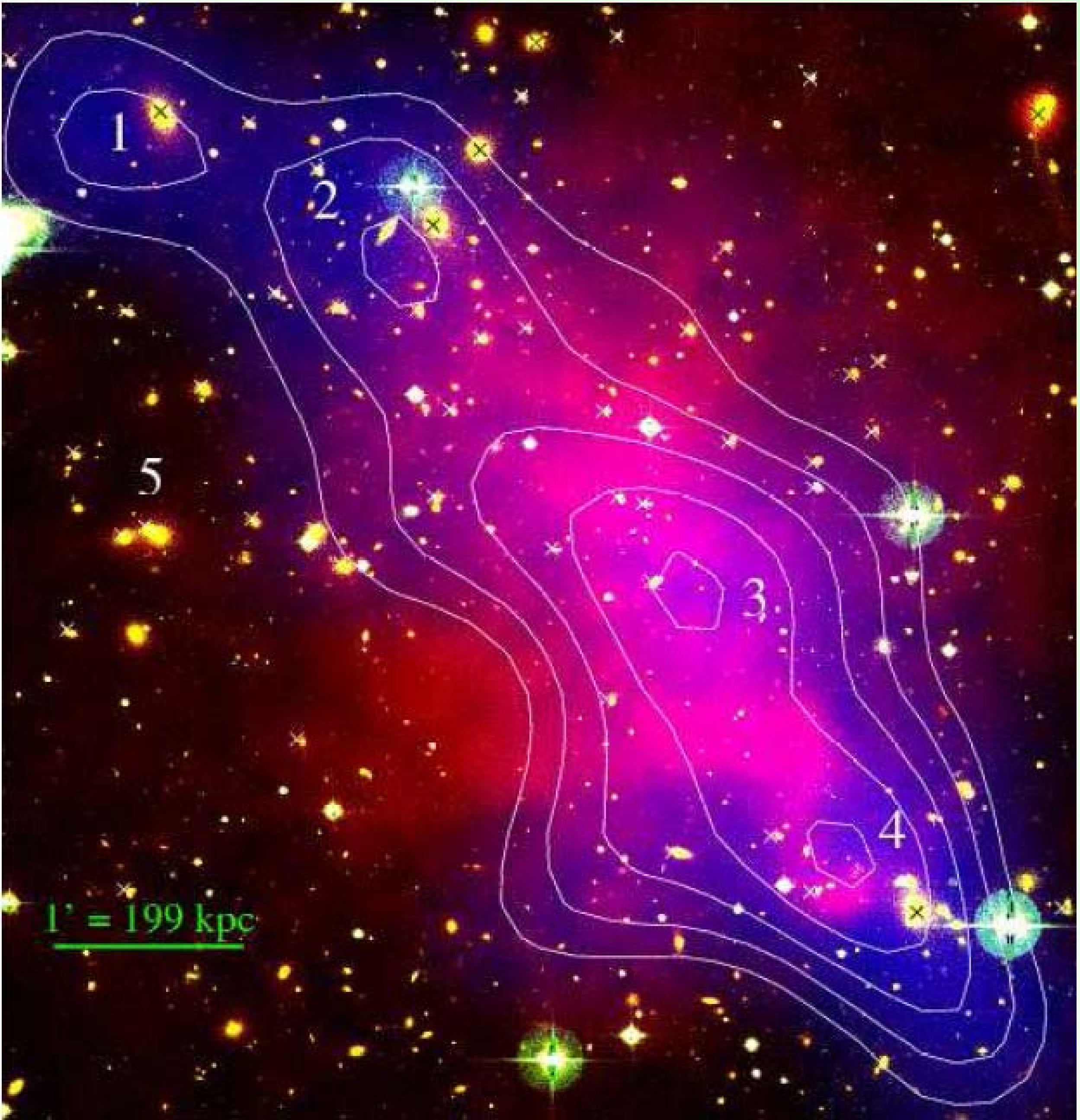
CDM can only
V < 3500 km/s
MOND > 4500 km/s
Relative velocities between halos
4 times higher in MOND
Linares et al 2009

Collision by 16% over-estimated?

V_gas could be higher than V_CDM

Mahdavi et al 2007

Abell 520
z=0.201

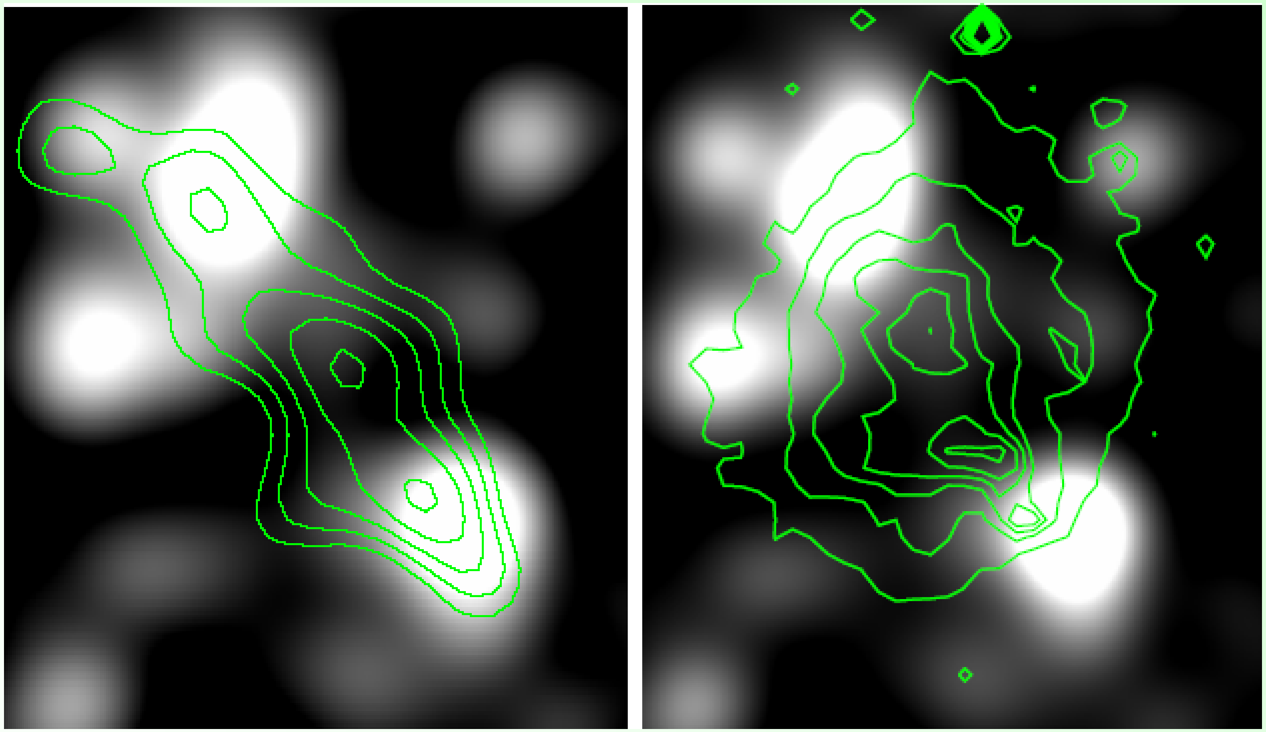


Red= X-ray gas
Contours= lensing
➔Massive DM core
Coinciding with X gas
but devoid of galaxies

Cosmic train wreck

Opposite case!

Abell 520 merging clusters



Contours=total mass　　Contours = X-ray gas

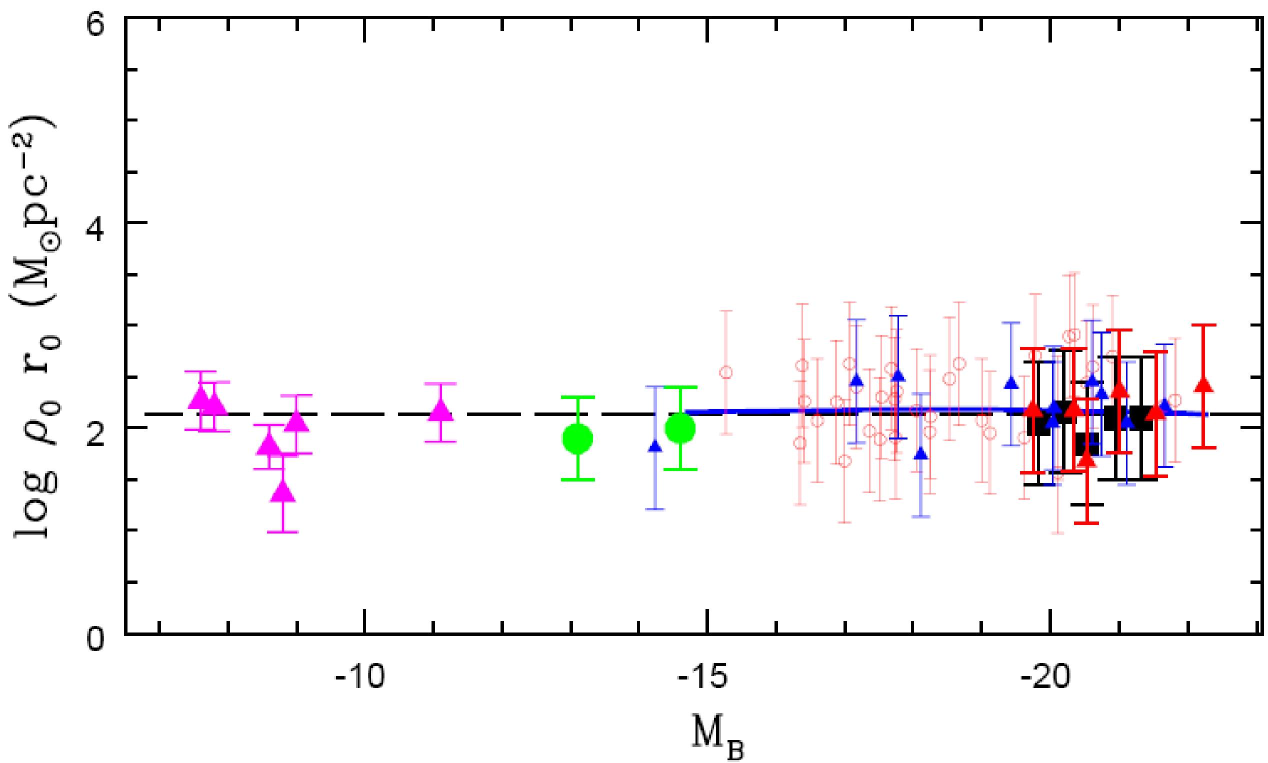
How are the galaxies ejected from the CDM peak??

Constraints on MOND
from galaxy dynamics and observations

Are the stability, evolution & formation of galaxies stringent tests of the theory**?**

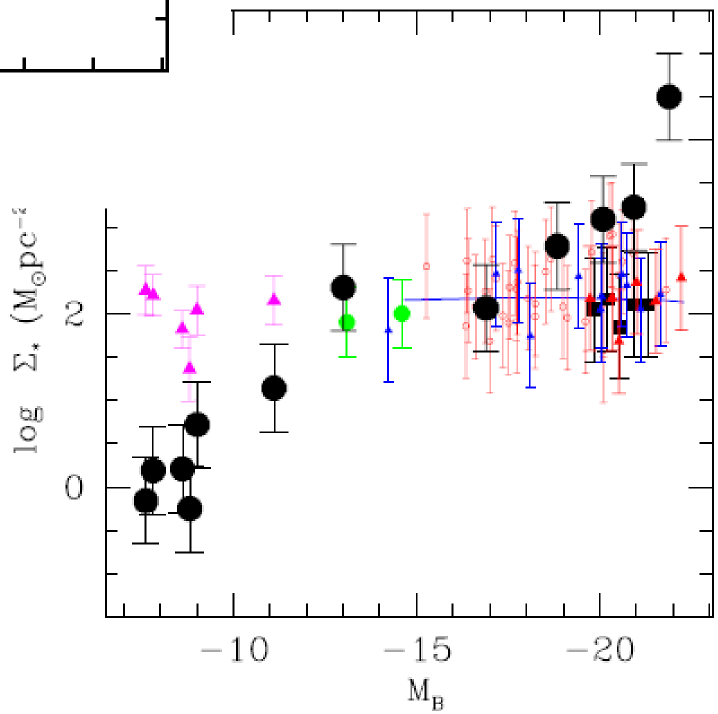
Can we determine the form of the interpolation function μ?

Scaling laws, DM surface density



Kormendy & Freeman 2004
Gilmore et al 2007, **Donato et al 2009**

$\Sigma_M = 142\ M_o/pc^2$



$$\Sigma(0) = \int_{-\infty}^{\infty} \rho_p dz = \Sigma_M[\mathcal{U}(\infty) - \mathcal{U}(0)] = \Sigma_M \int_0^{\infty} L(x)dx \equiv \lambda\Sigma_M,$$

Implications

➔ $\Sigma_M = 138\ (a_0/1.2\ \mathrm{E10 m/s^2})\ M_o/pc^2$

In MOND: the « phantom » dark matter added under the Newton hypothesis, has the appearance of a Cste Σ, $\propto$ a0 (Milgrom 2009)

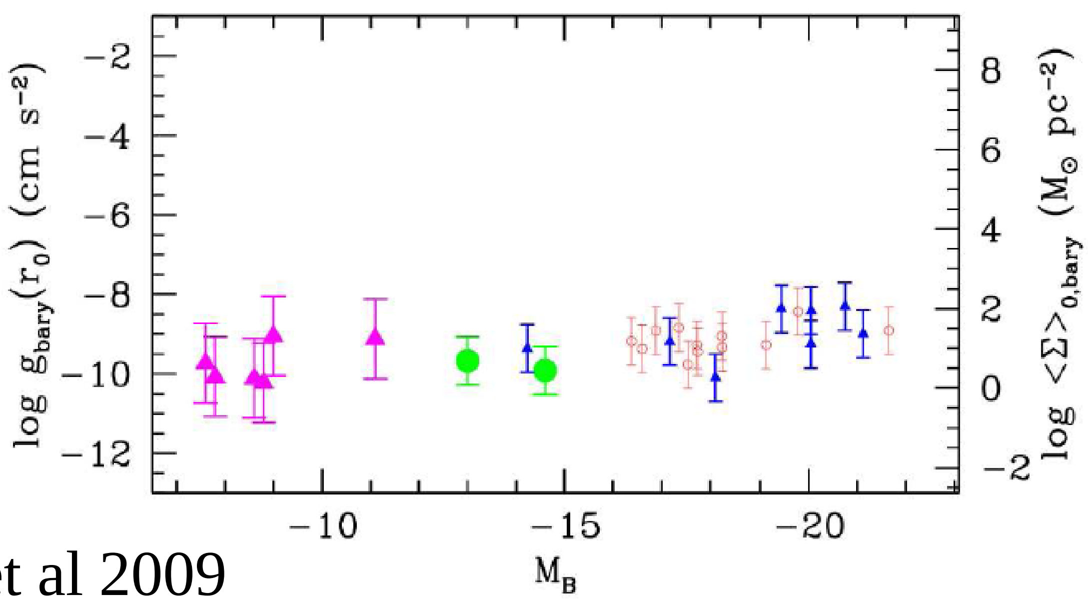
Large central Σb means high DM core radius

The DM core radius is where the acceleration falls below $6\ 10^{-10}\ \mathrm{m/s^2}$

At least if the central parts are Newtonian

It is possible to have systems with lower densities ~0.5 Σ_M

Not in the Donato et al sample



Gentile et al 2009

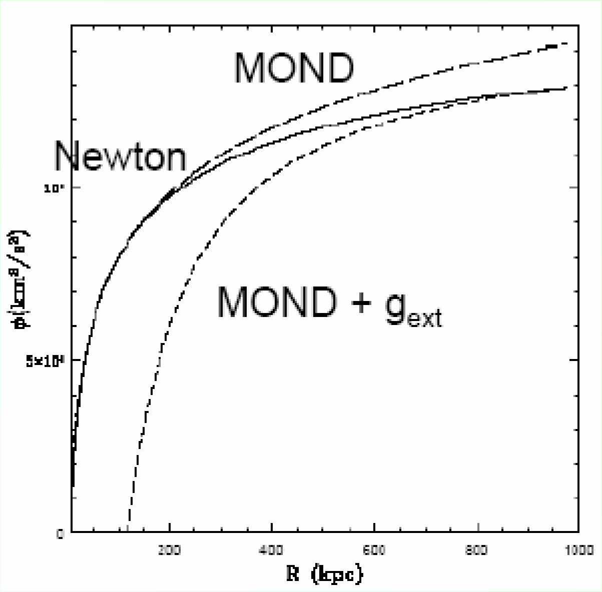
Escape velocity

Potential in the MONDian regime $\Phi(r) = (GMa_0)^{1/2} \ln r$

$\frac{1}{2} V_{esc}^2 = \Phi(\infty) - \Phi(r)$ ➔ no escape possible!

But a galaxy is never totally isolated ➔ External field effect (EFE)

$$-\nabla \cdot [\mu(x)\mathbf{g}] = 4\pi G\rho(X, Y, Z), \qquad x \equiv \frac{|\mathbf{g}|}{a_0}.$$



EFE: External Field Effect

If external field g_e, is in the **X** direction

At large radii, it is equivalent to a dilatation Δ

$$\Phi_{\rm int}^{\infty}(X, Y, Z) = -\frac{GM_{\rm int}}{\mu_m \sqrt{(1+\Delta)(Y^2+Z^2)+X^2+s^2}},$$

Define an internal potential $\Phi_{\rm int}$

$$\nabla^2 \Phi_{\rm int} + \Delta \frac{\partial^2}{\partial X^2} \Phi_{\rm int} \rightarrow 4\pi G\rho/\mu_m,$$

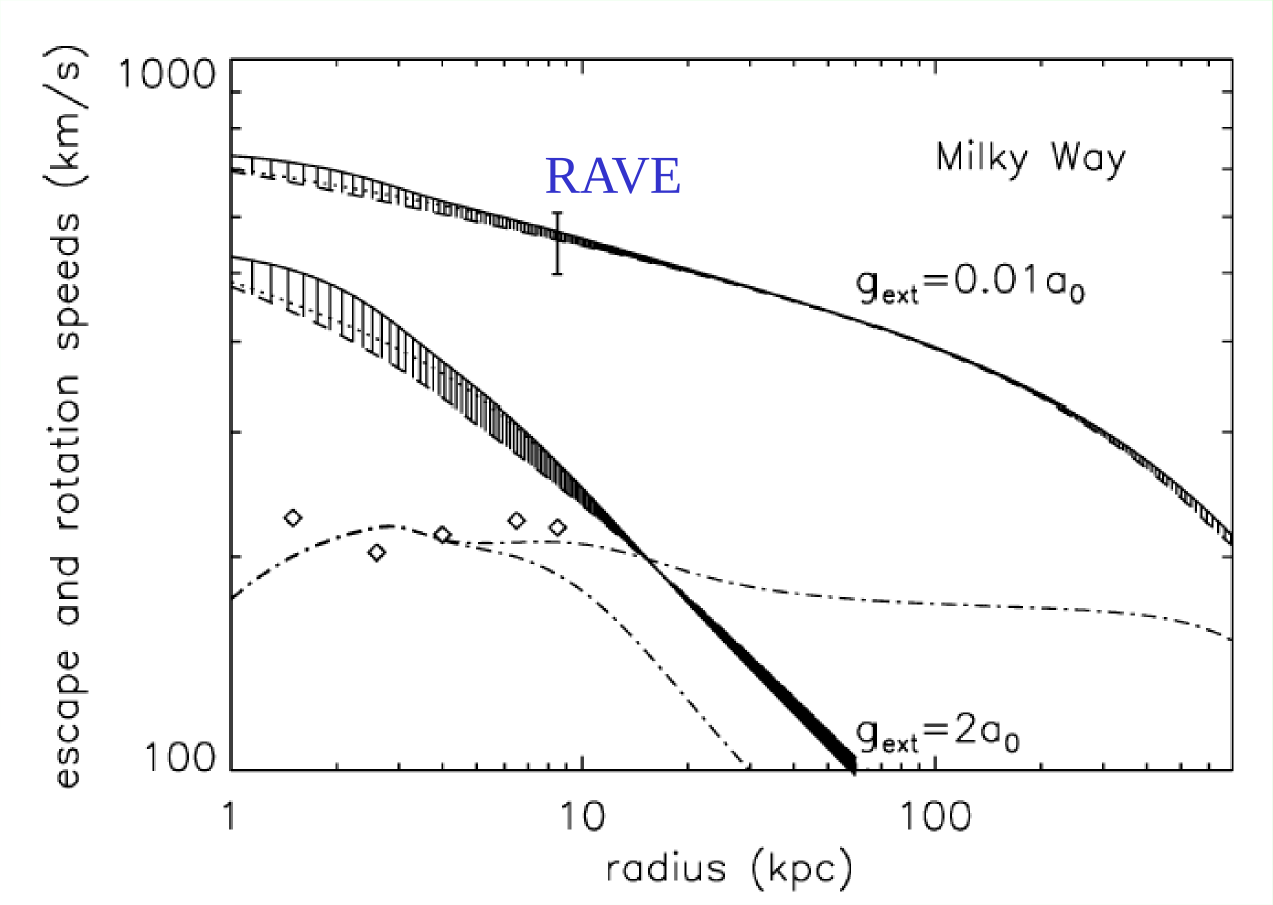
Where $g \ll g_e \ll a_0$

Keplerian dependence, with renormalization $G \rightarrow Ga_0/g_e$

Milky Way: effect from Andromeda

Observations RAVE (Smith et al 2007) ➔ $498 < v_{esc} < 608 kms^{-1}$

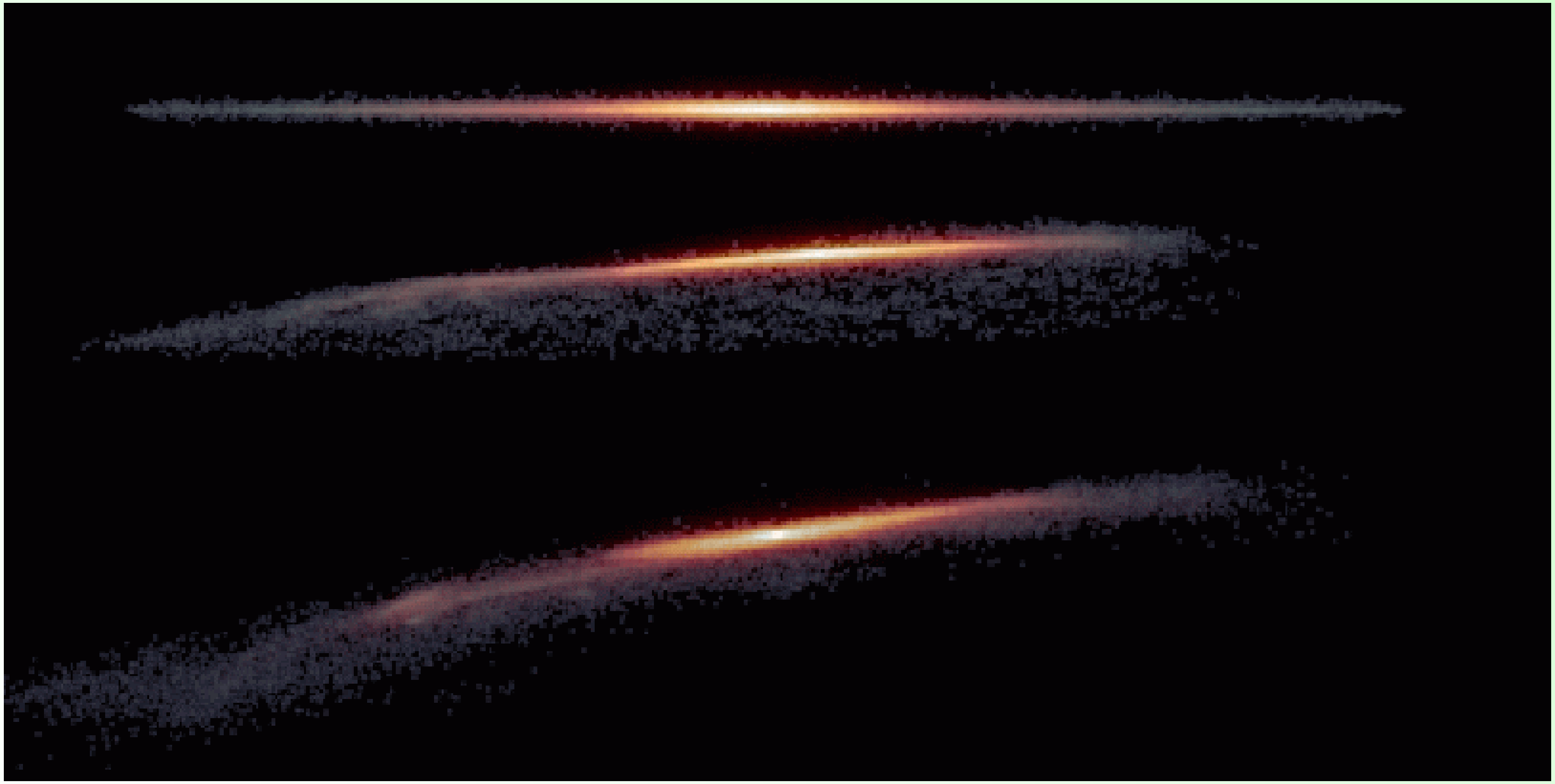
544 km/s ➔ $g_e = a_0/100$



Wu et al 2007 Simulations with the Besançon model of MW

EFE: precession

Newton: no effect

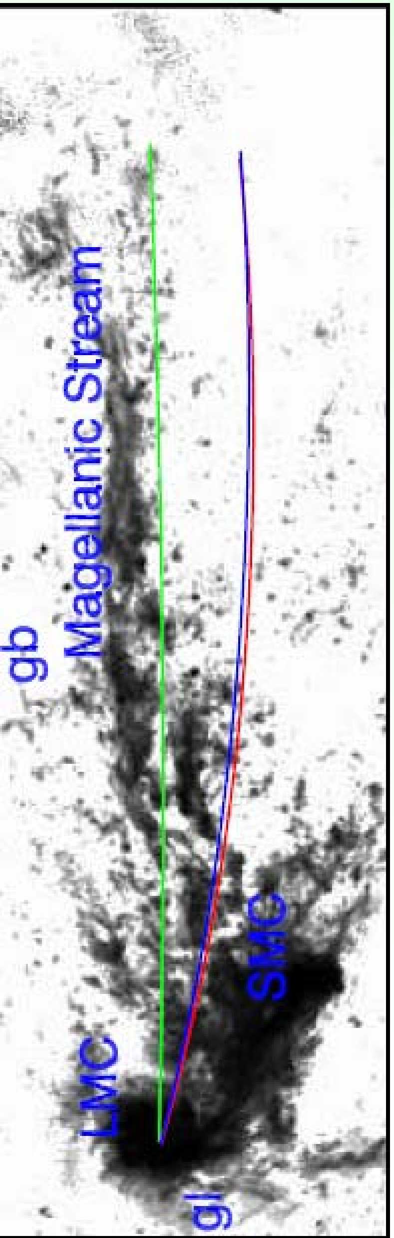


MOND: non-linear effect, gravitationnal torque and precession

Violation of the strong equivalence principle

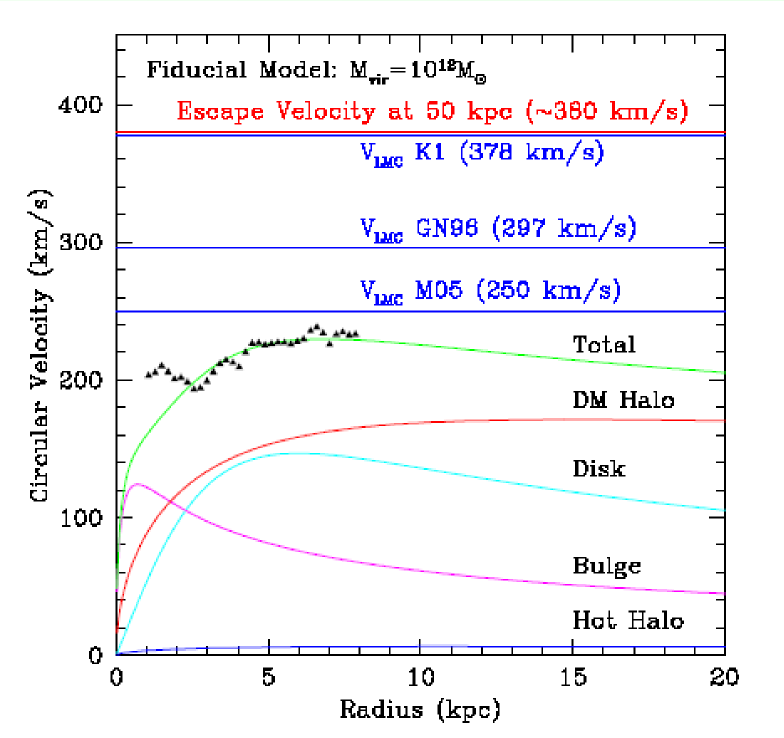
➔ Origine of Warps? (also Brada & Milgrom 2000, LMC/MW)

Orbit of the LMC (Large Magellanic Cloud)



Recent proper motions measurements with **HST**
Reveal that the velocity of the LMC is 378km/s
(SMC 302km/s)
Kallivayalil et al 2006, Piatek et al 2007
100km/s higher than before, close to escape
➔First passage of LMC+SMC
➔Origin of the Magellanic Stream? *Besla et al 2007*

Tidal forces,
or ram-pressure stripping?
Efficiency?
Ruzicka et al 2008,
Mastropietro 2008



Stability of galaxy disks

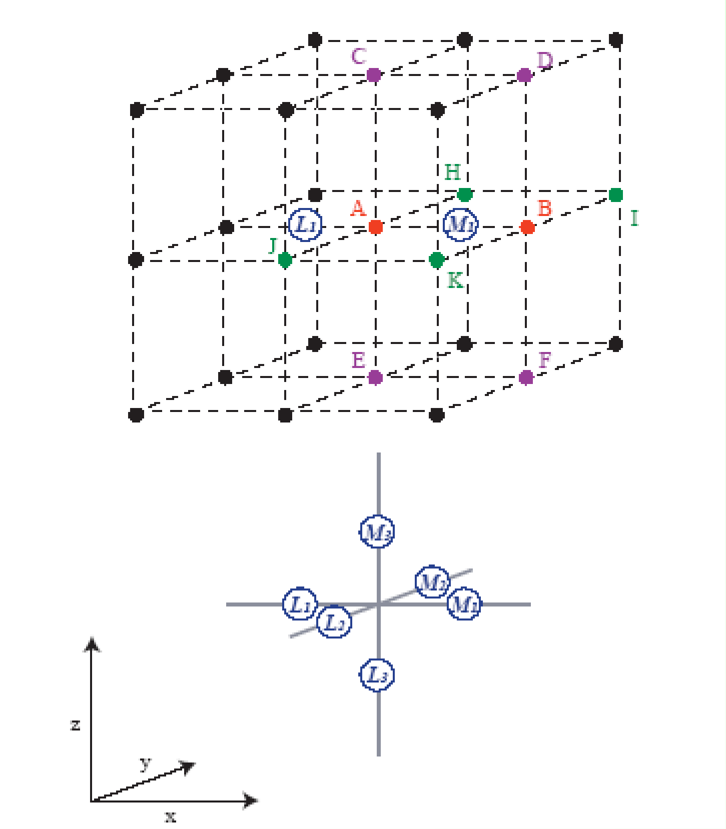
spirals and bars are the motor of evolution

CDM: Spheroidal haloes stabilise the disks
MOND; disks are entirely self-gravitating

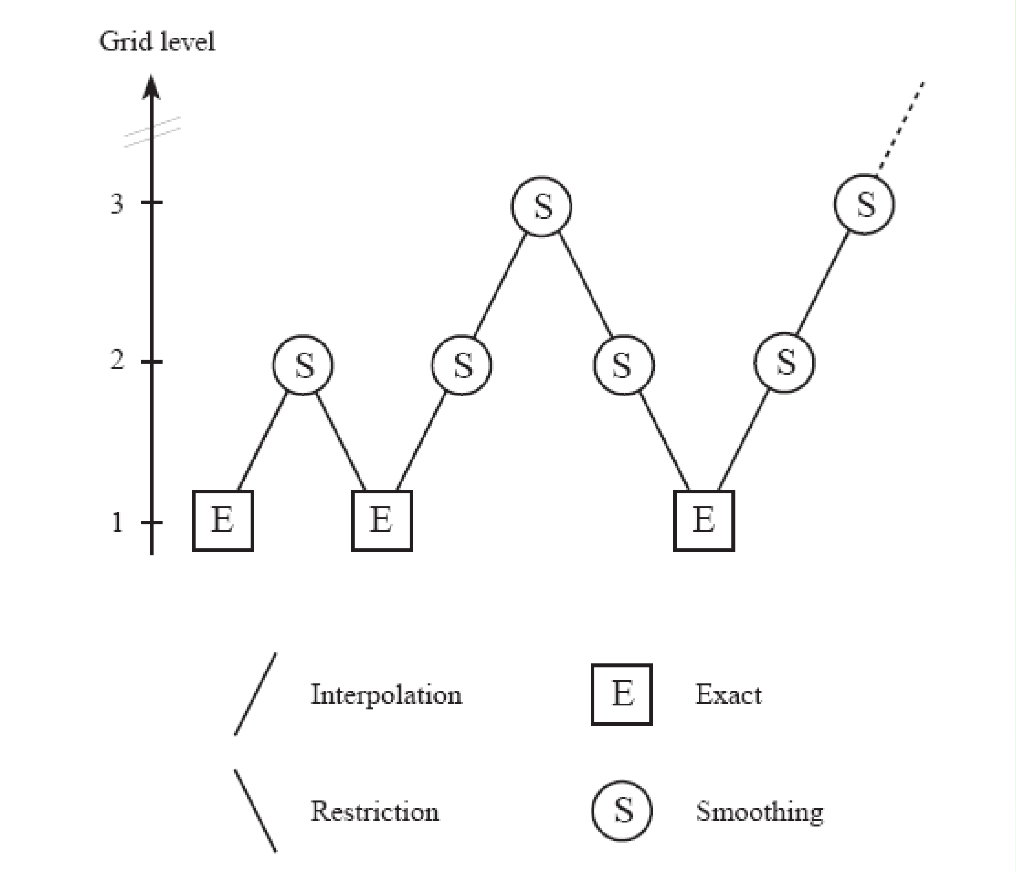
However, the gravity law is not linear
but in $M^{1/2}$ in the MOND regime

Bars grow when angular momentum is transfered
➔ accepted by spheroidal haloes

Disk dynamics in MOND
Multi-grid algorithm



$$\nabla[\mu(|\nabla\Phi|/a_0)\nabla\Phi] = 4\pi G\rho,$$

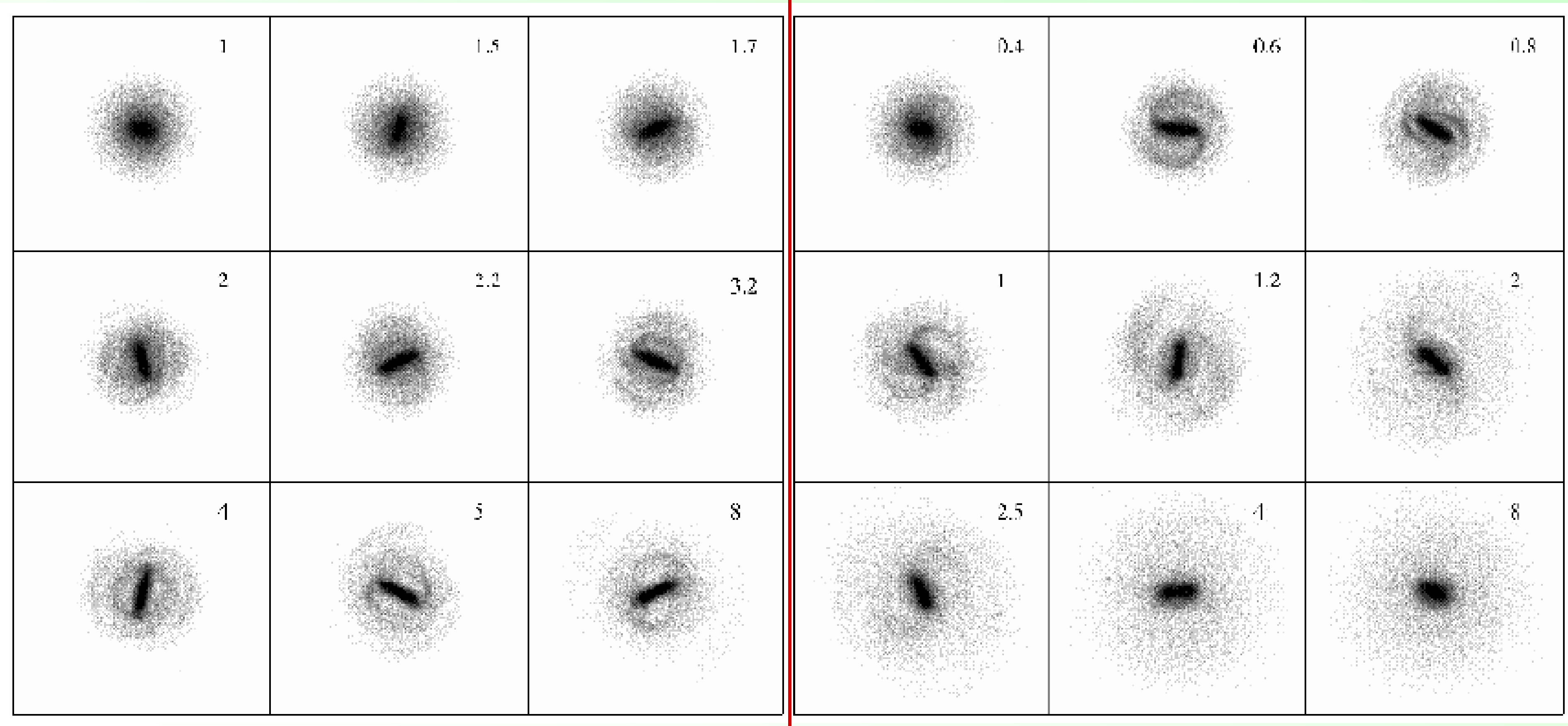


Finite Differences
+ adaptative grid

Influence of DM halo

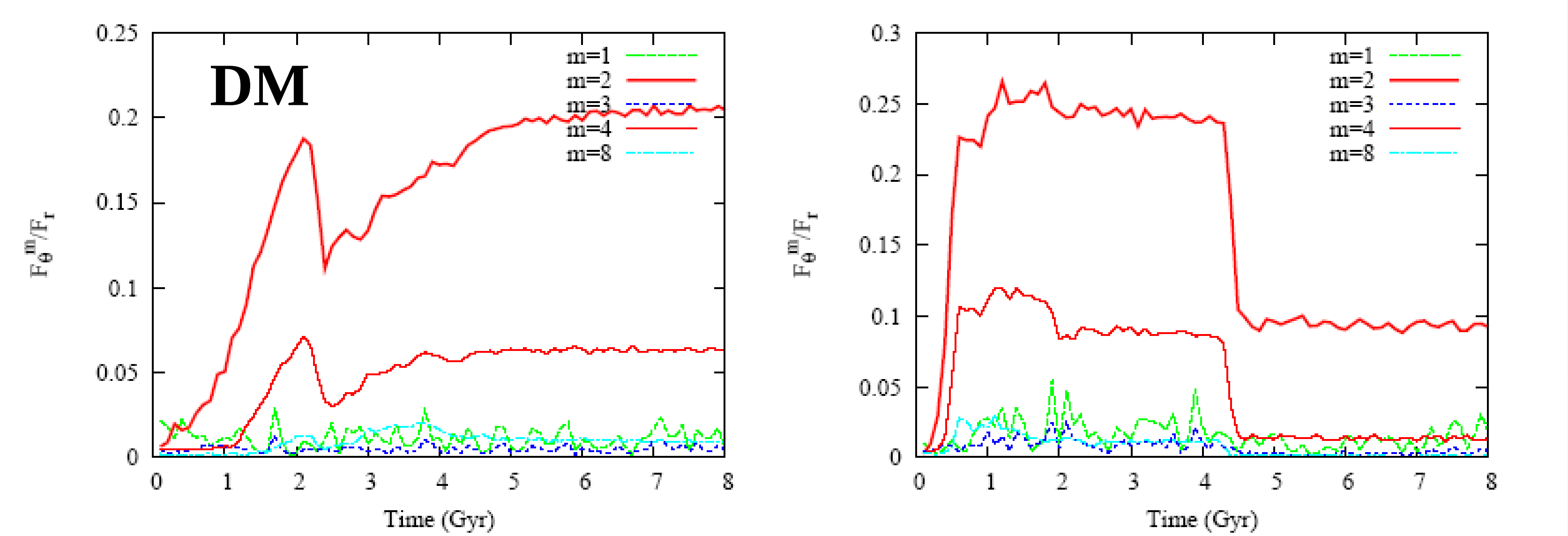
With DM halo

Without DM (MOND)



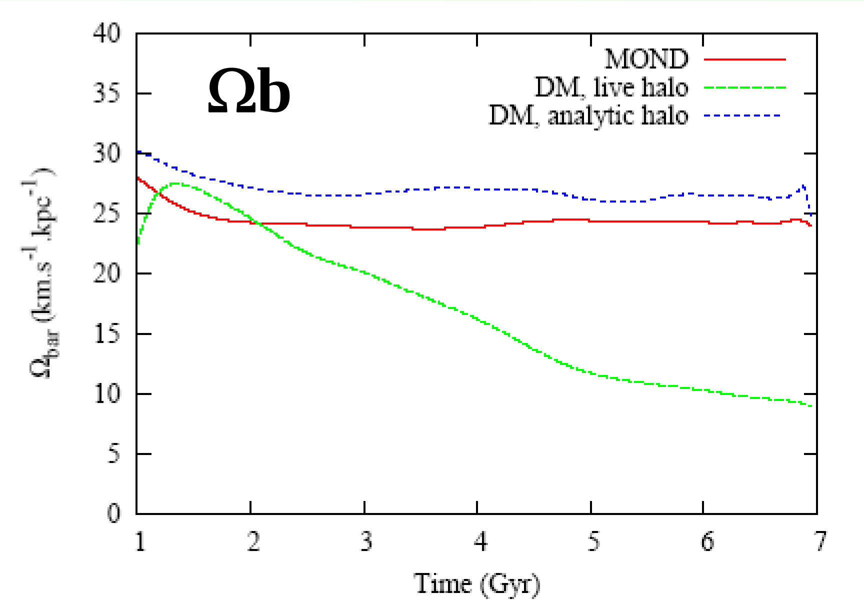
Tiret & Combes 2007

Bar strength and pattern speed with and w/o DM



With DM, the bar appears later, and can reform after the peanut weakening through halo AM exchange,

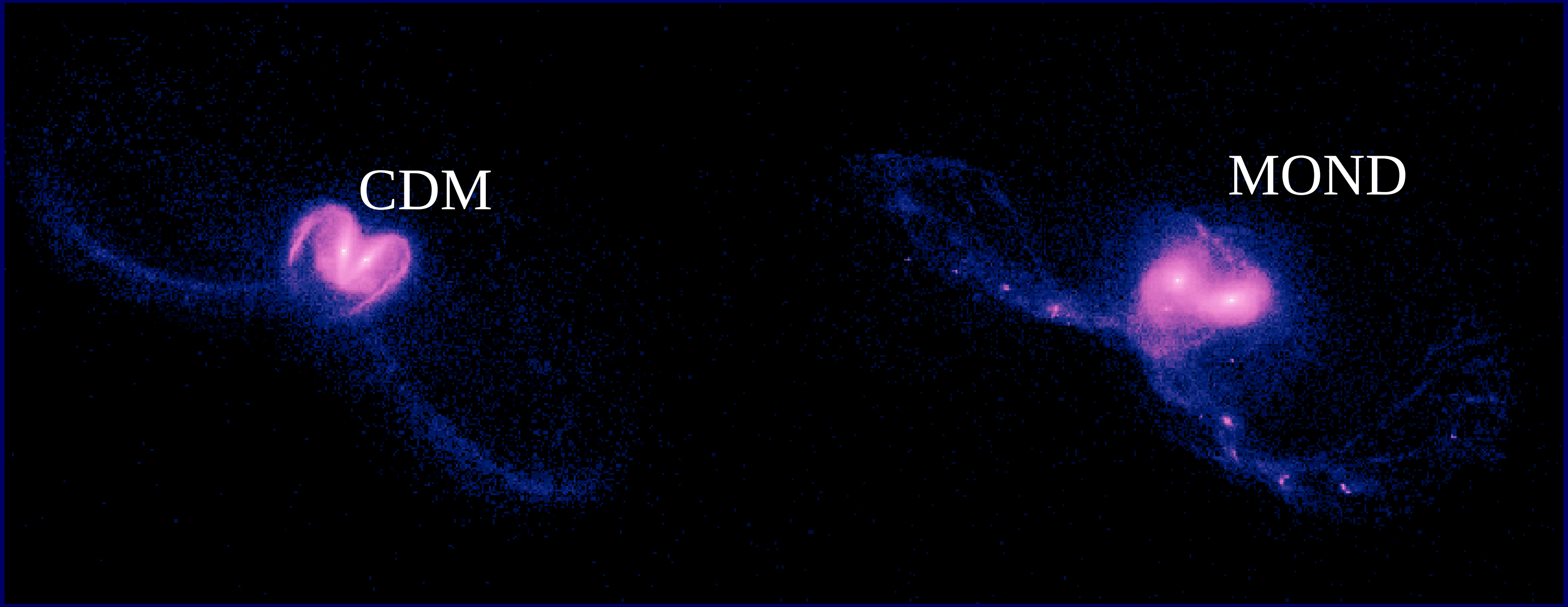
➔But Ωb falls off



Tiret & Combes 2007

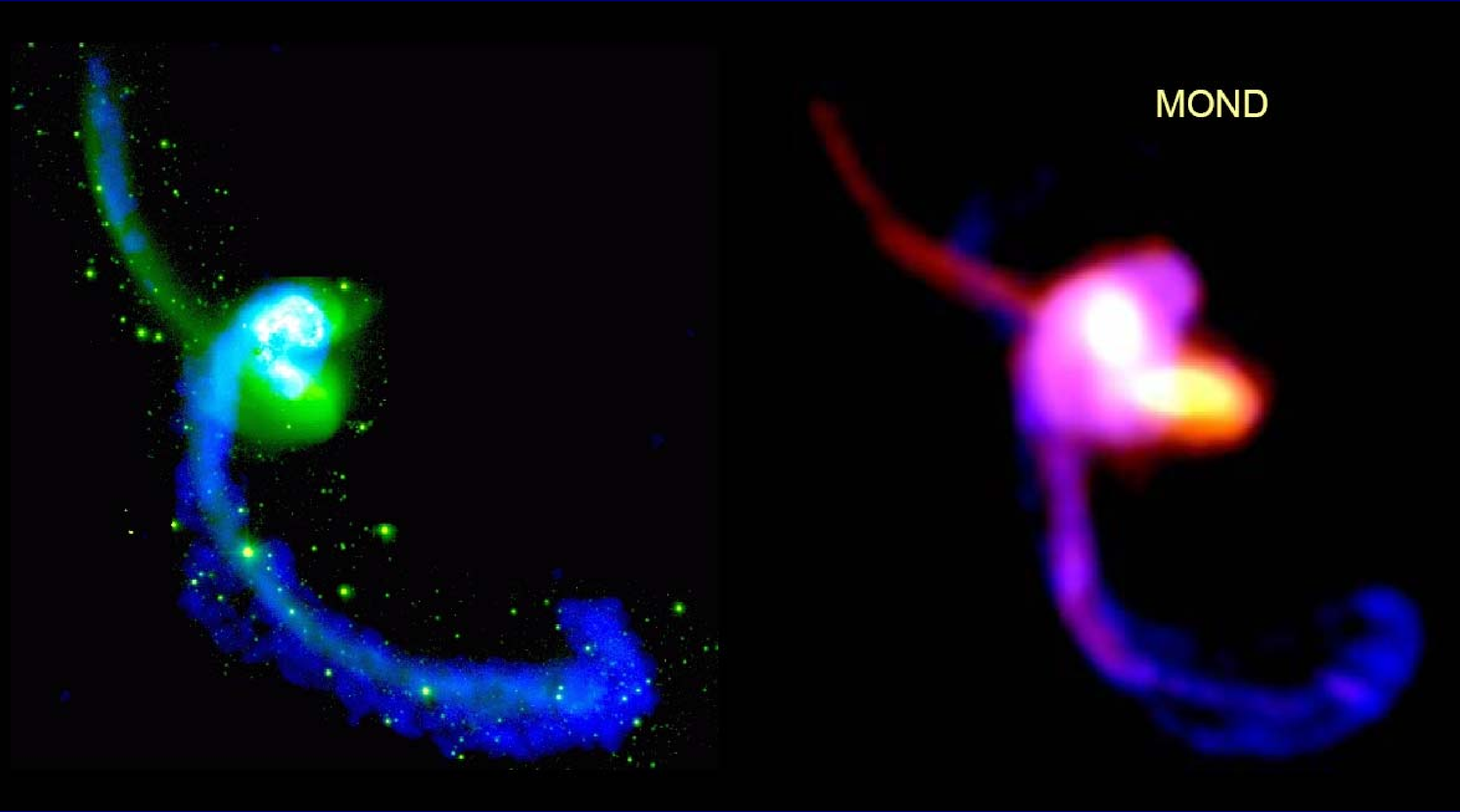
Interactions of galaxies: the Antennae: MOND versus CDM

Dynamical friction is much lower with MOND: mergers last much longer

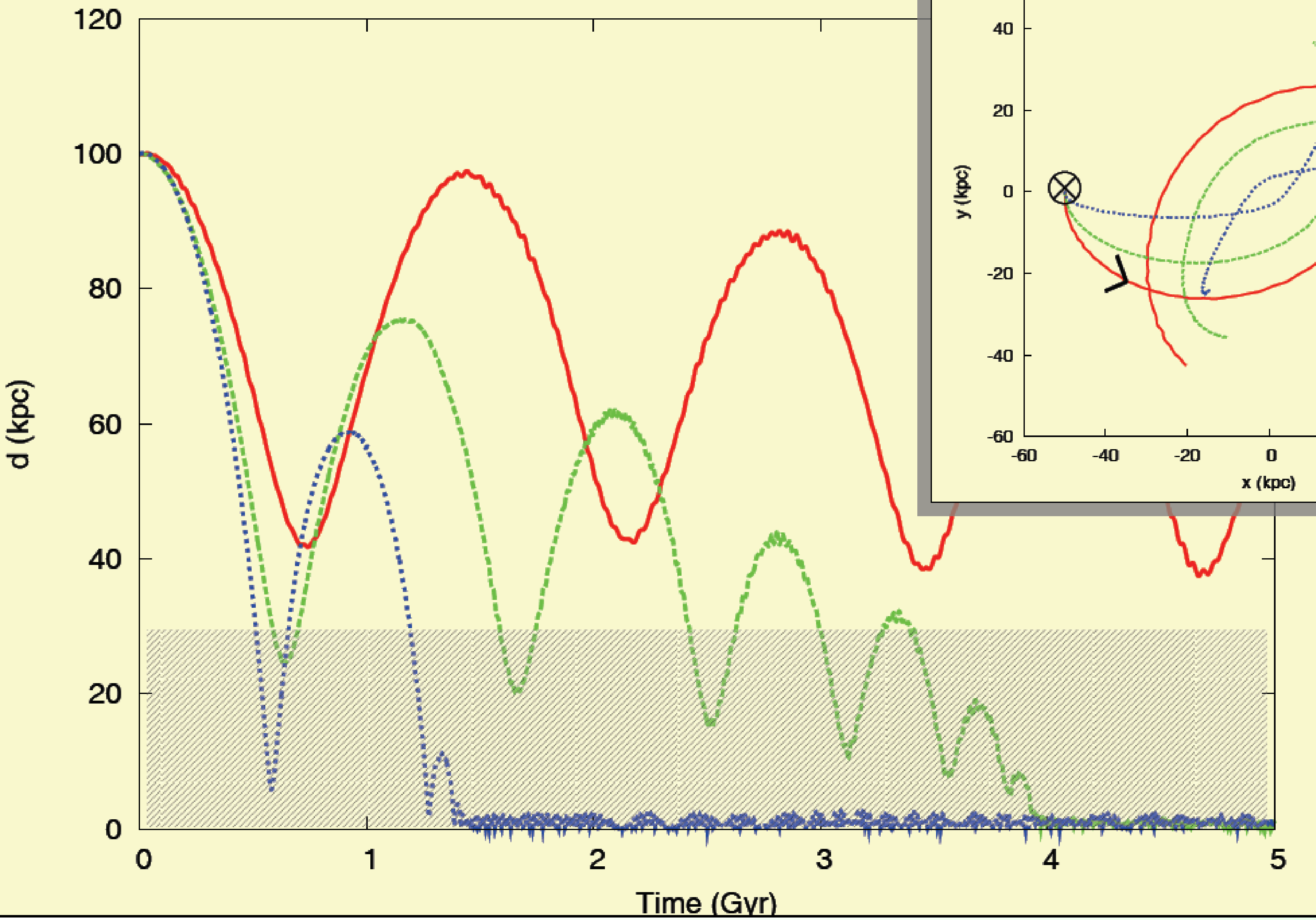


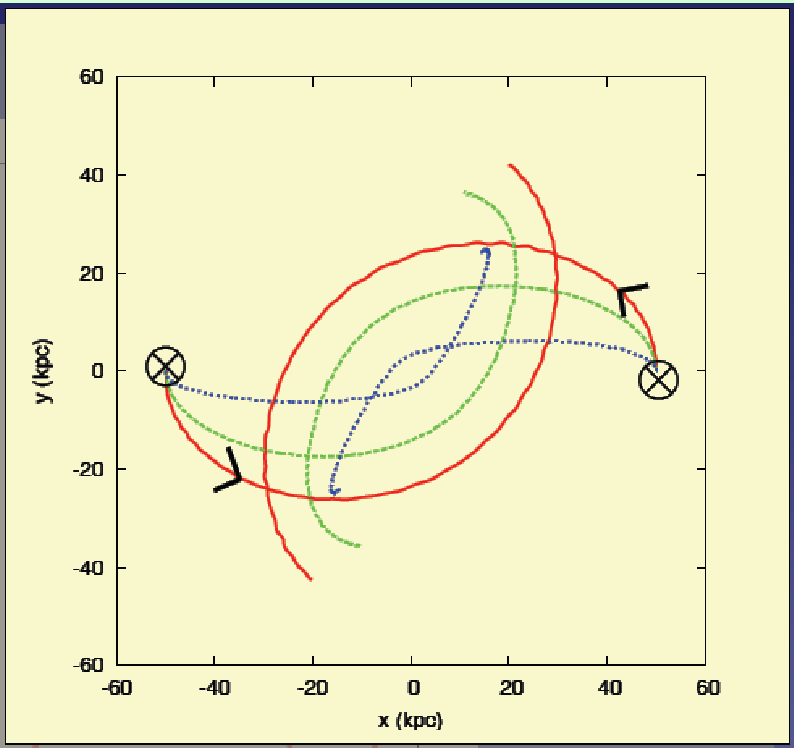
Also much longer time-scale for merging of dissipationless galaxies (Nipoti et al 2007)

Simulations of the Antennae



Dynamical friction





Dynamical friction

Analytically, the dynamical friction is **predicted stronger** with MOND than in the equivalent Newtonian system with dark matter

Ciotti & Binney 2004 (CB04), Nipoti et al 2008

However simulations show DF **less efficient** in galaxy interactions
In CDM, a lot of particles acquire E and AM, and DF concept applicable
➔ In MOND, a small number of particles in the outer parts acquire big quantities (no analytical treatment)

Nipoti et al 2007, Tiret & Combes 2007

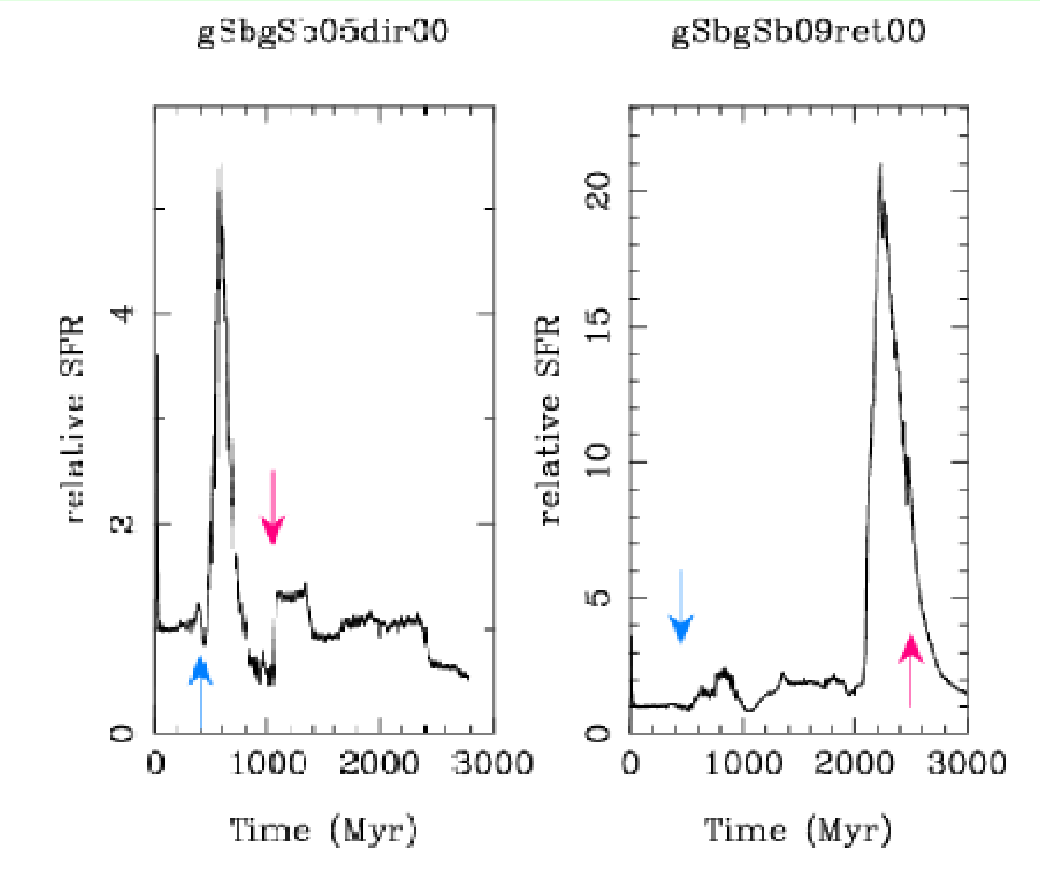
Merger induced starbursts degeneracy

CDM: dynamical friction on DM particles very efficient
➔ mergers in one passage

MOND: with the same angular momentum, merger will require many passages

Starburst at each passage when minimal approach

➔ Number of "merger/SB" can be explained both ways



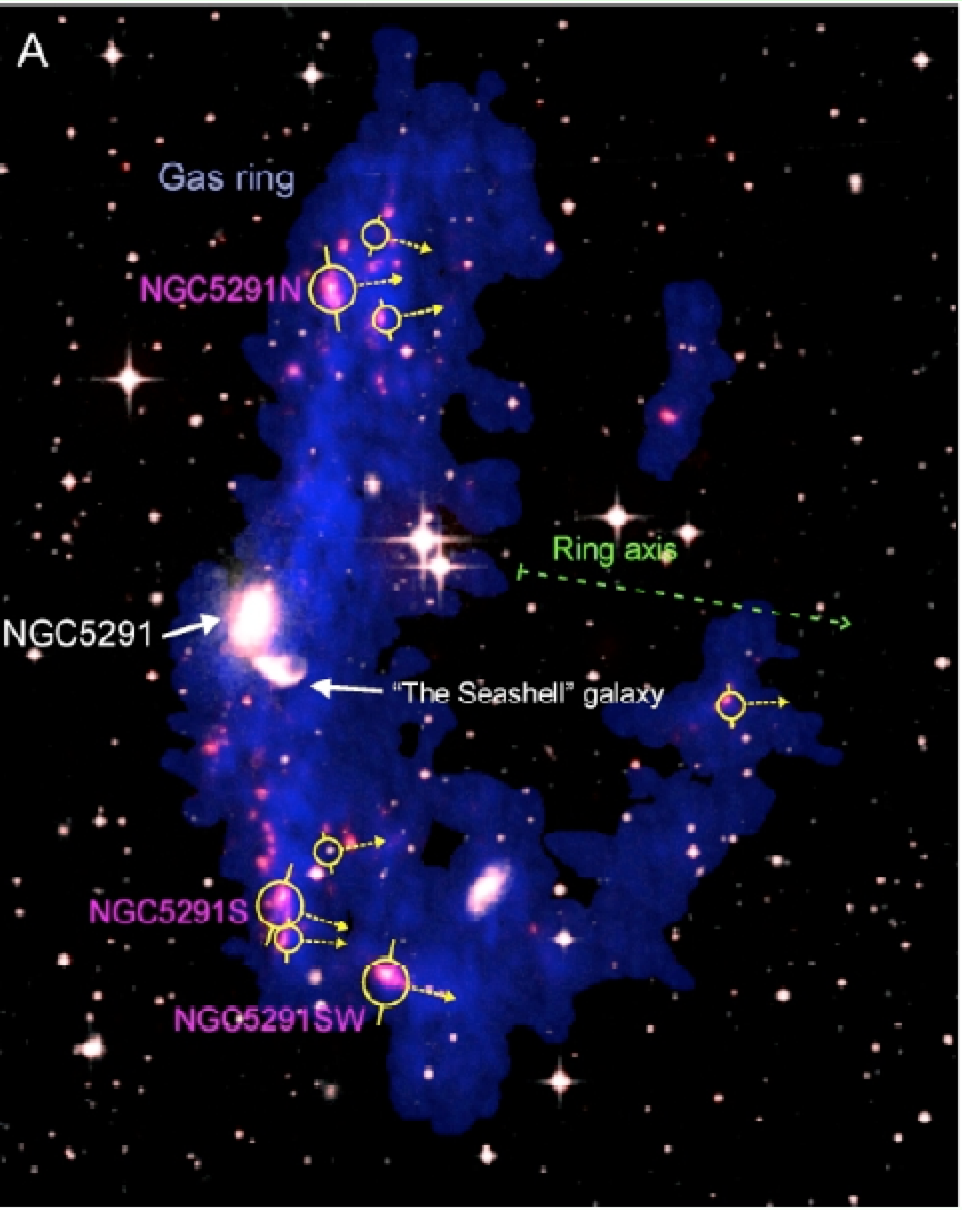
Di Matteo et al 2007

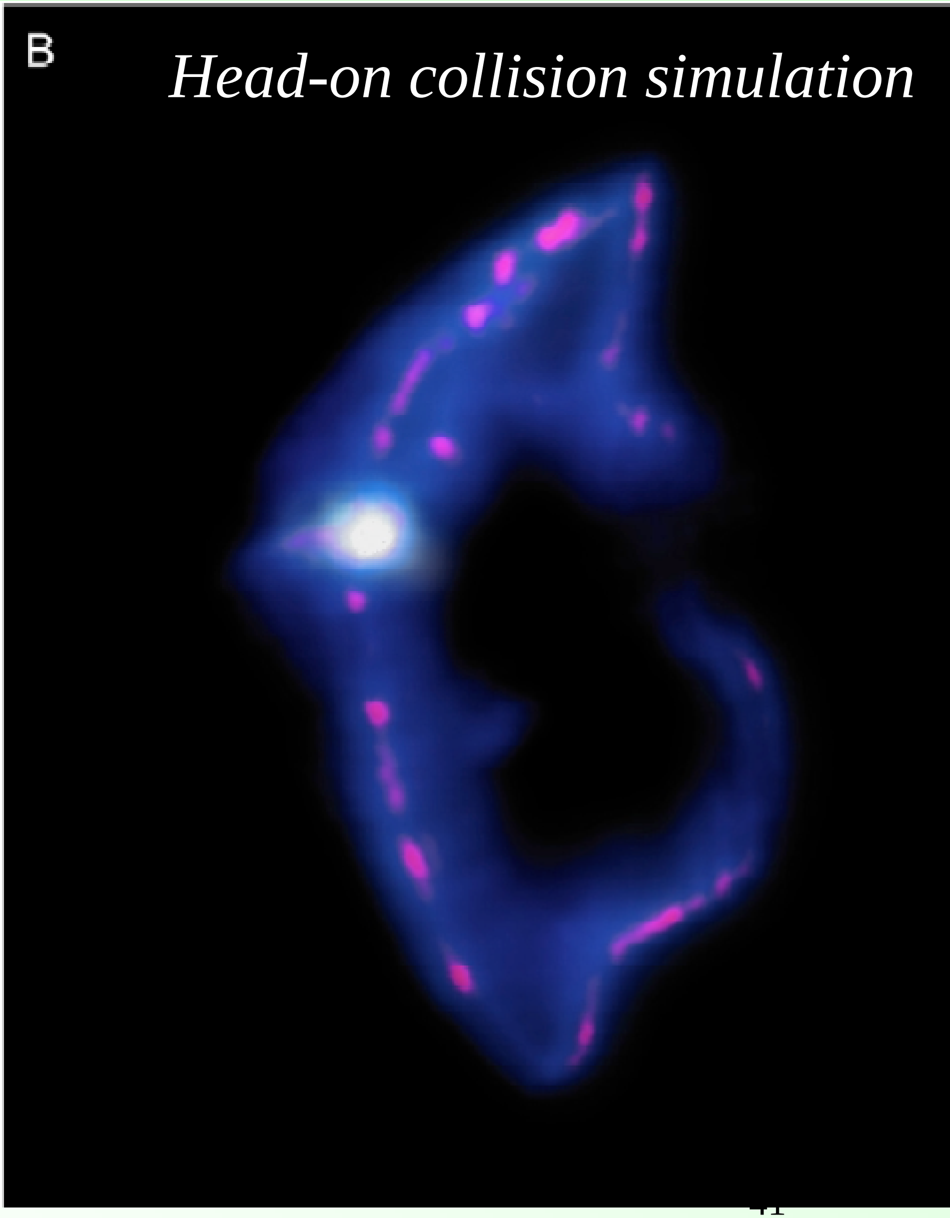
Formation of Tidal Dwarf Galaxies

Exchange of AM is within the disk: ➔much easier with MOND to form TDG

In DM, requires very extended DM distribution (Bournaud et al 03)

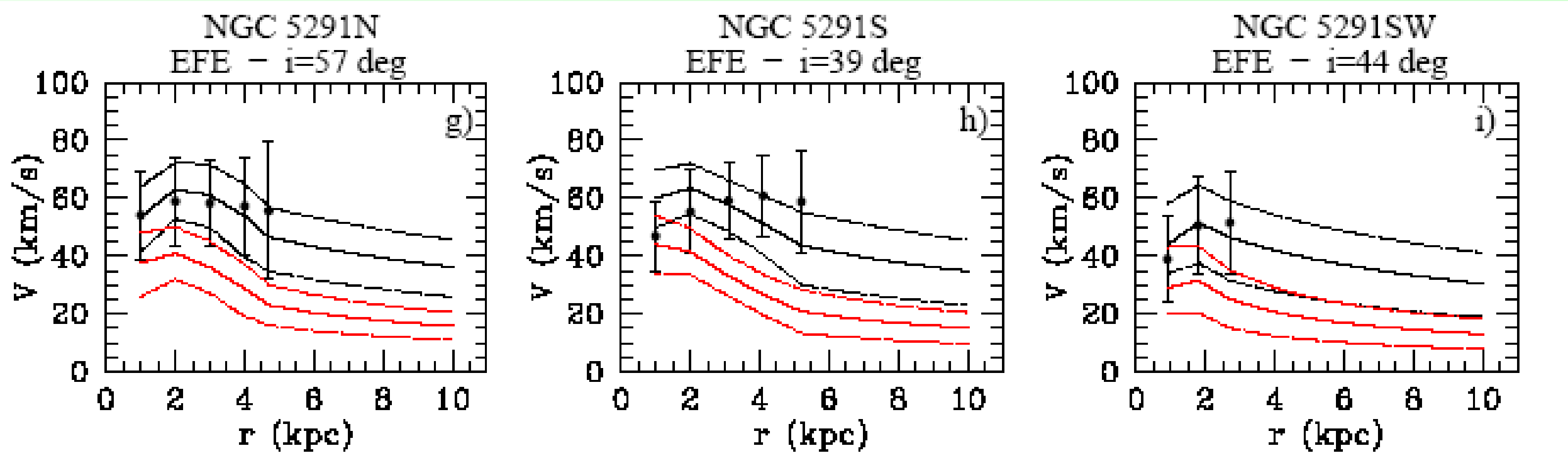
TDG in N5291 HI ring





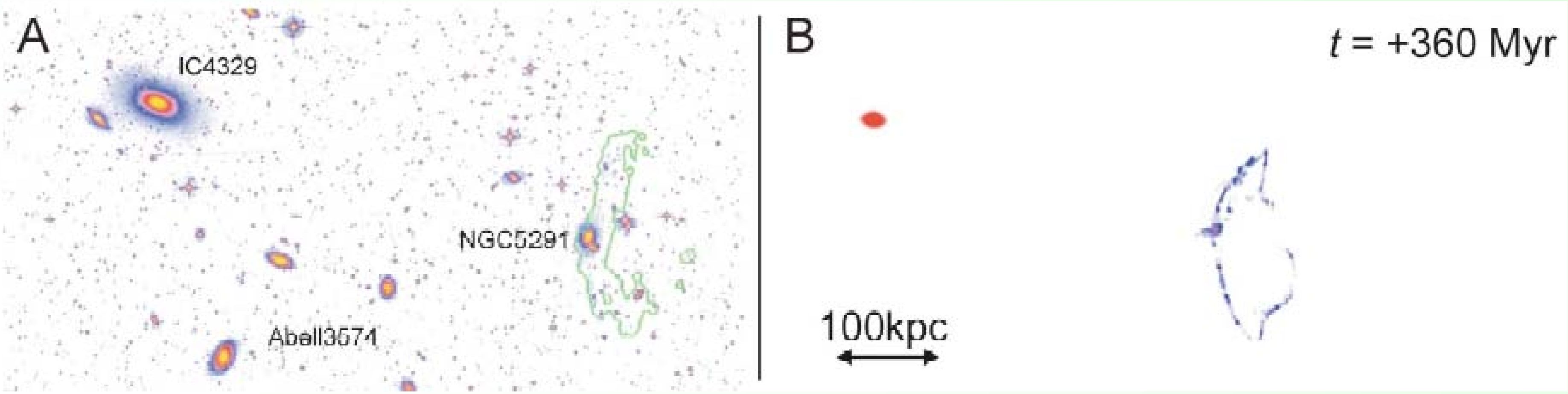
Bournaud et al 2007

Dynamics of the TDGs



With MOND, *Gentile et al 2007*

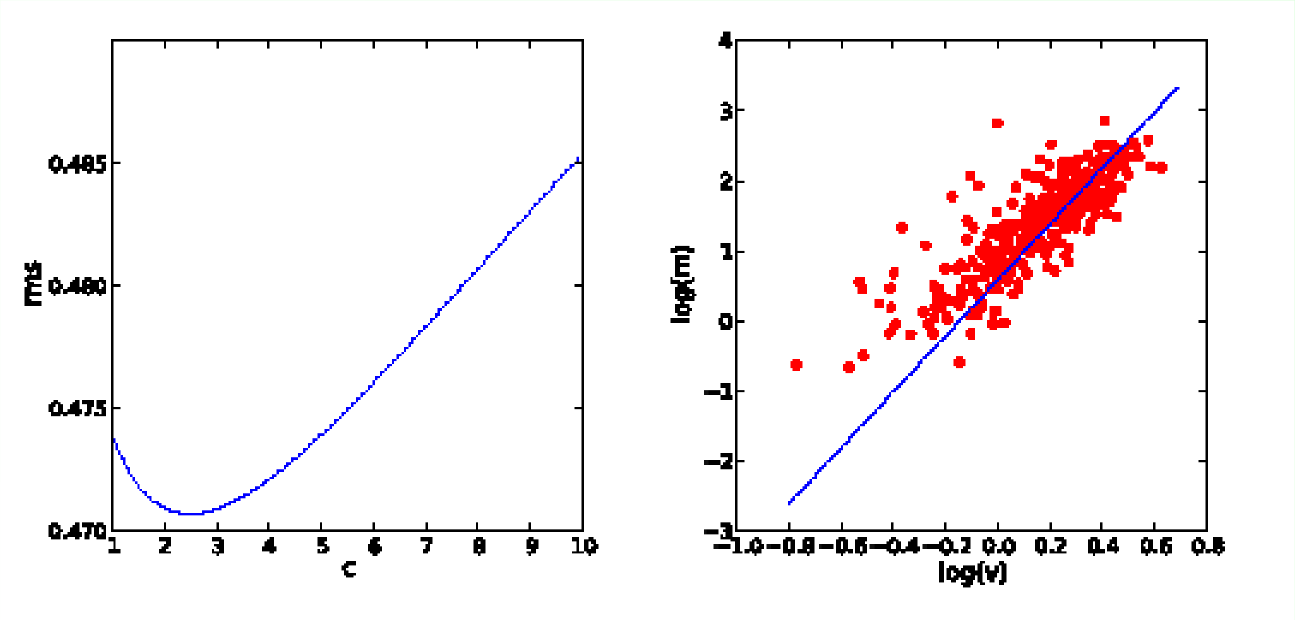
All inclinations= 45°, from simulations (Bournaud et al 07) ➔ dark H_2



MOND and the dark baryons

Is MOND compatible with the existence of dark gas
in galaxies? What fraction provides the best fit to the rotation curves?

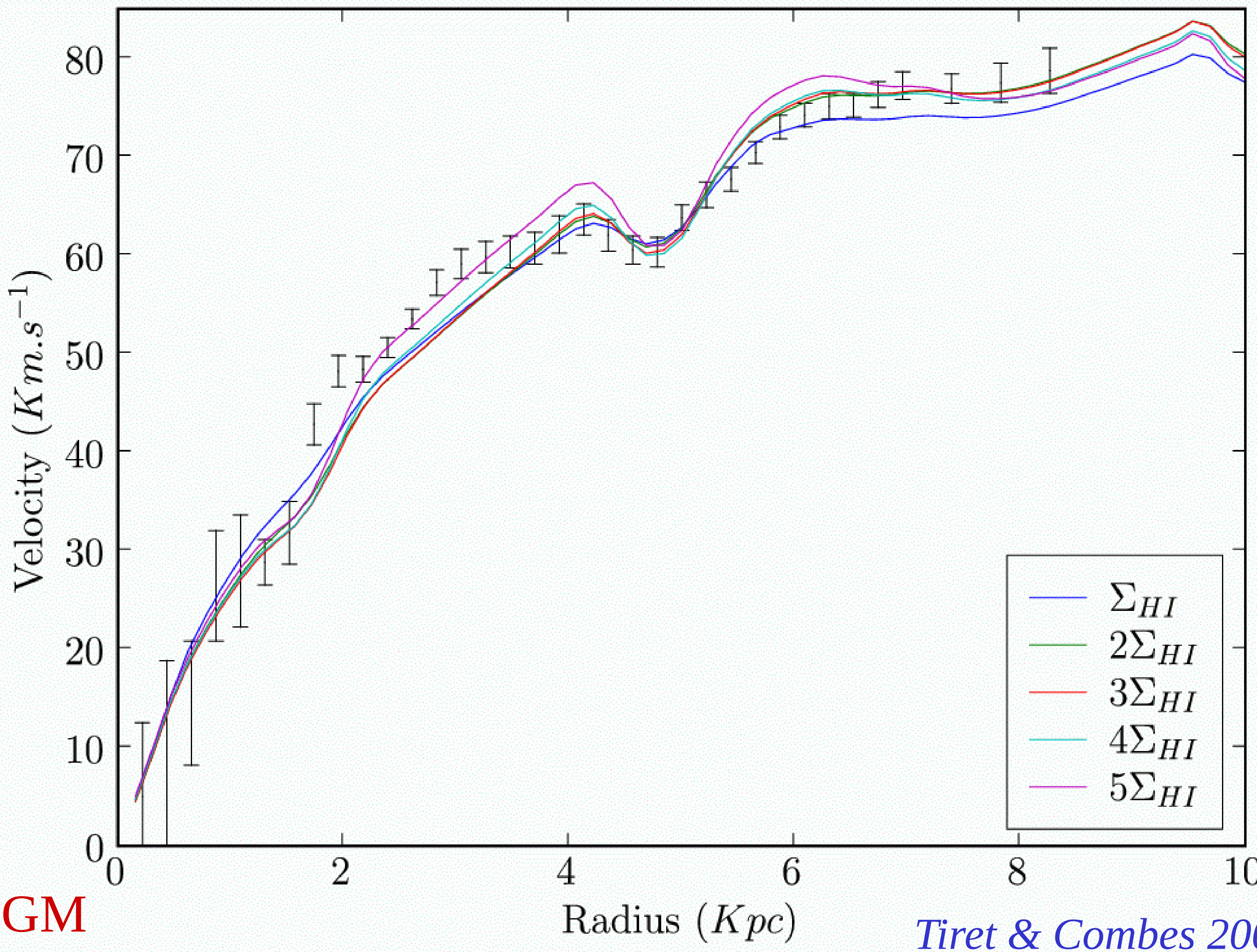
Fit of ~50 rotation curves, c=M(dark)/MHI



Tiret & Combes 08, Milgrom 07

Combination with MOND

NGC 1560: fits with variation of a_0 ~ 1/(gas/HI)



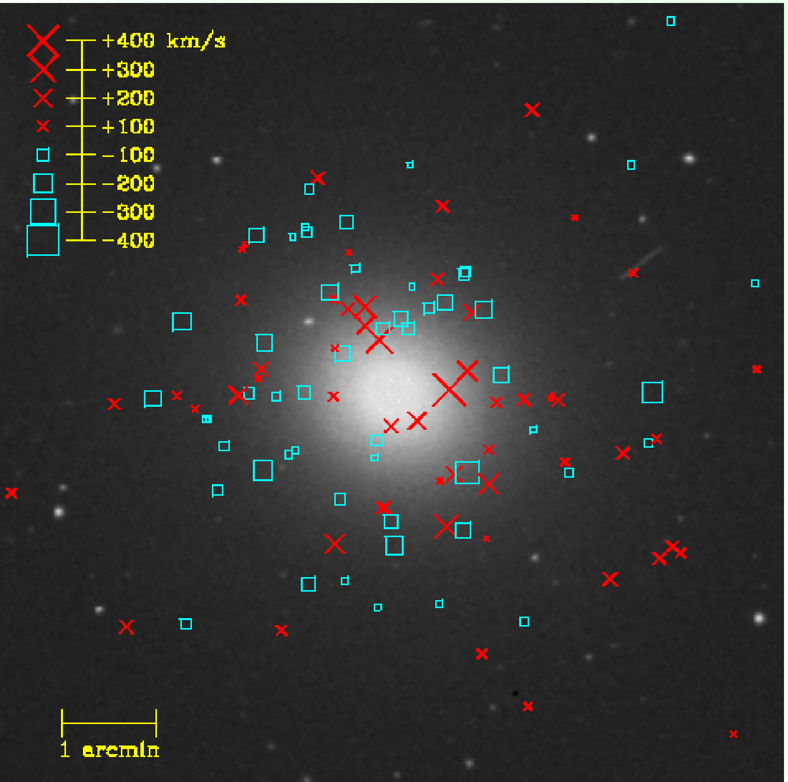
$V^4 = a_0 GM$

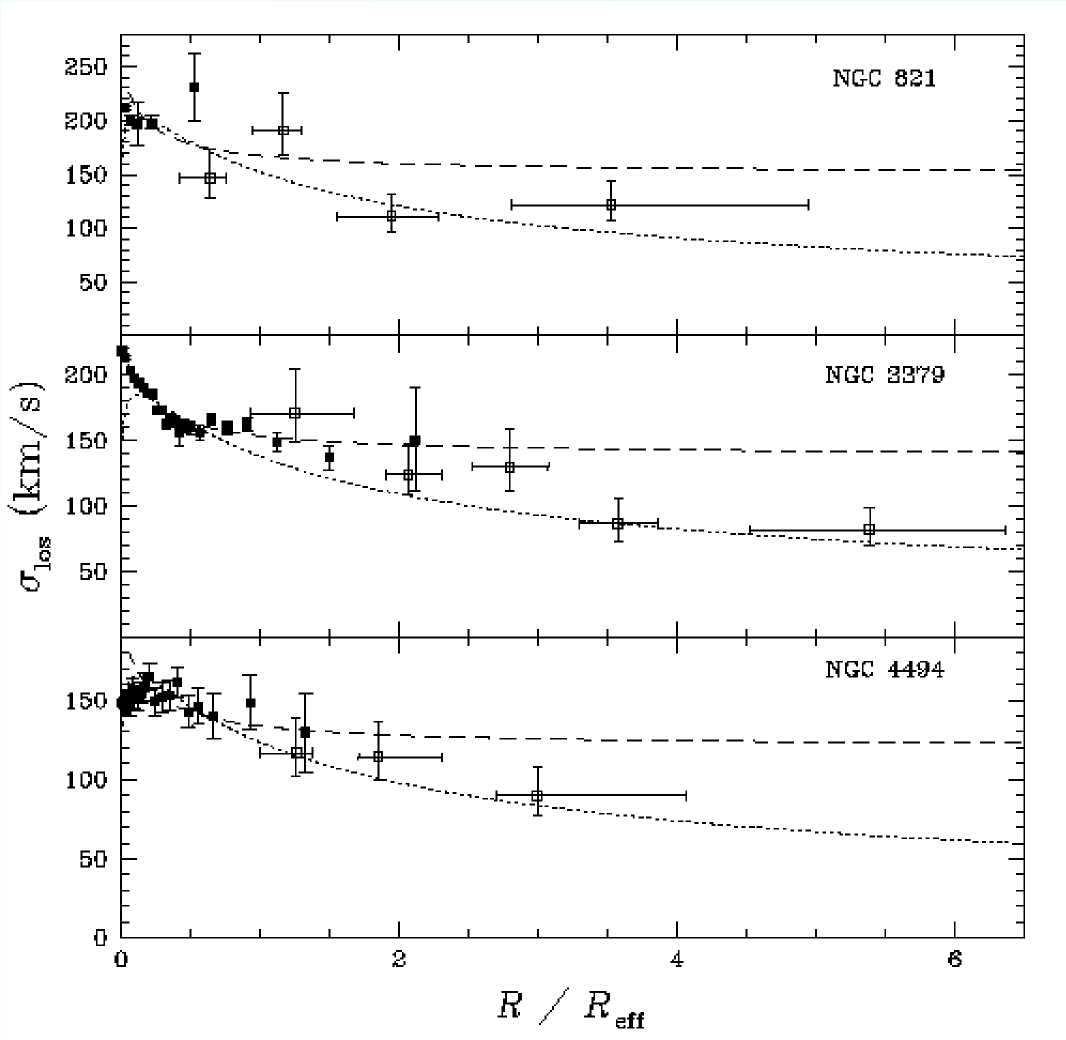
Tiret & Combes 2008

Dark matter in Ellipticals

Planetary Nebulae: Romanowsky et al 2003
Dearth of dark matter??

….. Visible matter (isotropic)
- - - isothermal (isotropic)

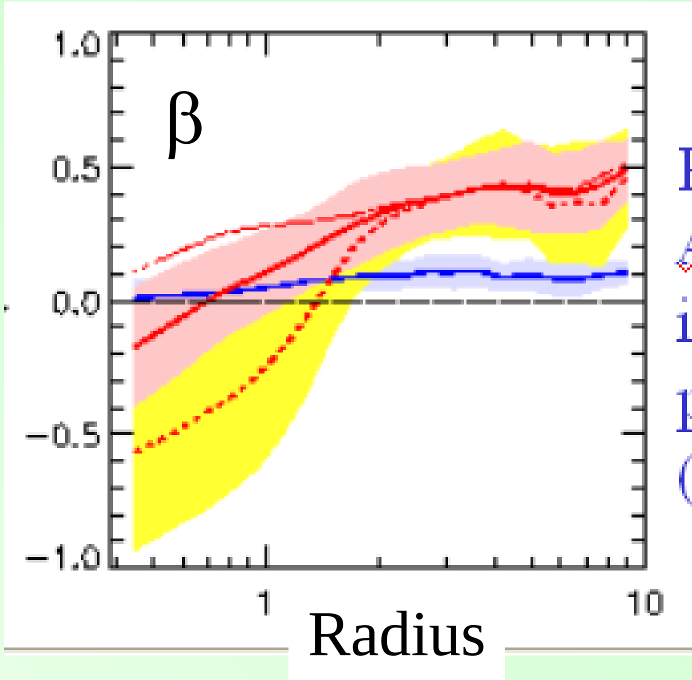




Anisotropy of velocities

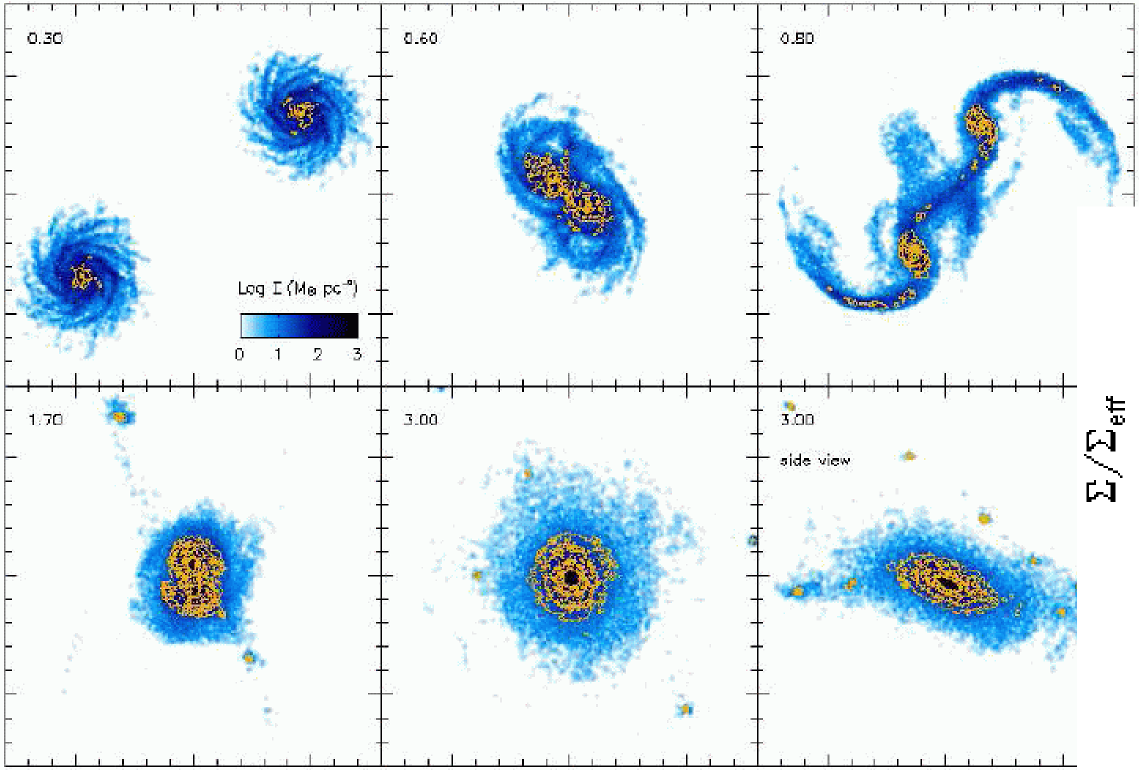
$\beta = 1 - \sigma^2_\theta/\sigma^2_r$, $-\propto$, 0, 1

β circular, isotropic and radial orbits

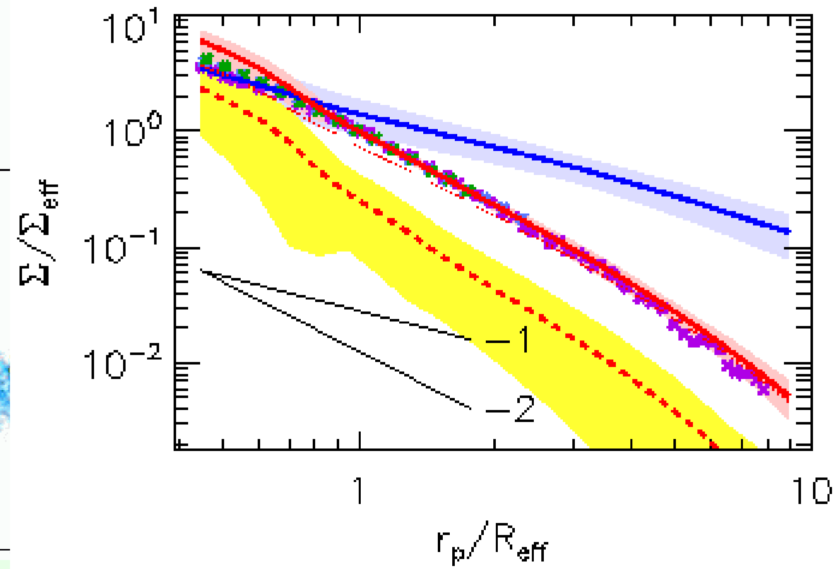


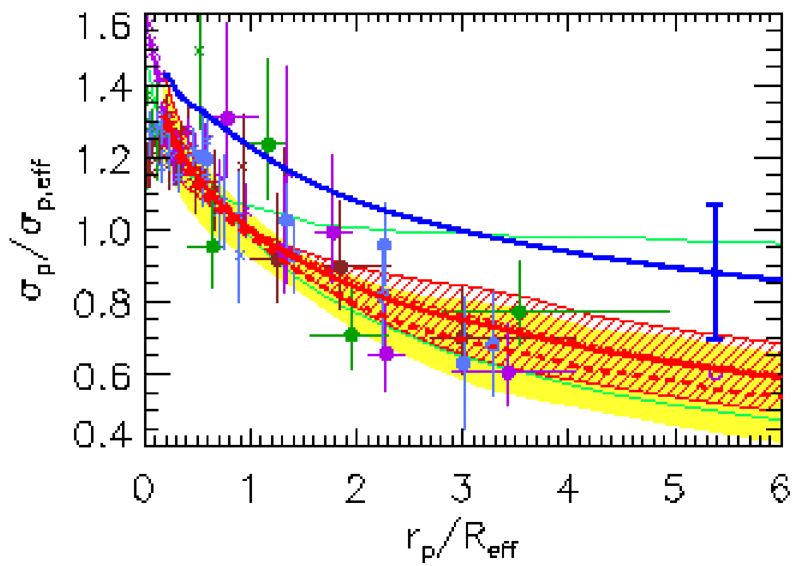
When galaxy form by mergers, orbits in the outer parts are strongly radial, which could explain the low projected dispersion (Dekel et al 2005)

The observation of the velocity profile is somewhat degenerate and cannot lead to the dark matter content univocally



Young stars are
in yellow contours





Comparison with data for
N821 (green), N3379(violet)
N4494 (brown), N4697 (blue)

DM profile from satellites

SDSS, 2500 deg^2, 3000 satellites Mb=-16, -18 (galaxies –14)
Removal of interlopers
σ_v =120km/s at 20kpc and 60km/s at 350kpc (Prada et al 2003)

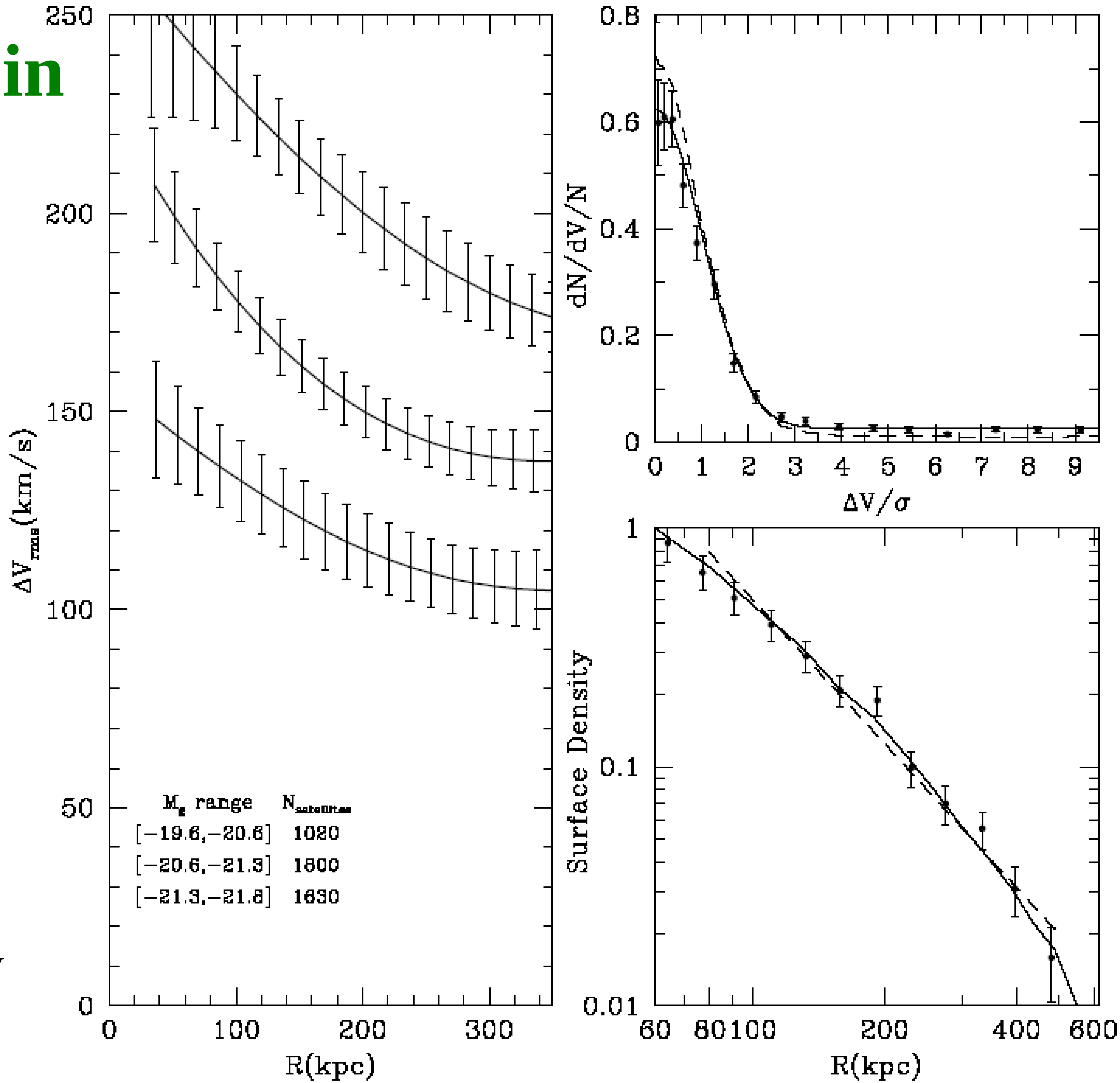
➔Declines agree with $\rho \sim r^{-3}$ of NFW (CDM profile)

σ_v within 100kpc varies as $L^{0.3}$, quite close to TF relation

In average 2 satellites per galaxy, and 0.2 interlopers

See also McKay et al (2002) $\sigma \sim L^{0.5}$ from 1225 SDSS satellites
M_{260} in agreement with lensing results
But flat velocity dispersion recovered (as if $\rho \sim r^{-2}$)

Satellites in SDSS



Klypin & Prada 2009

Statistical satellites

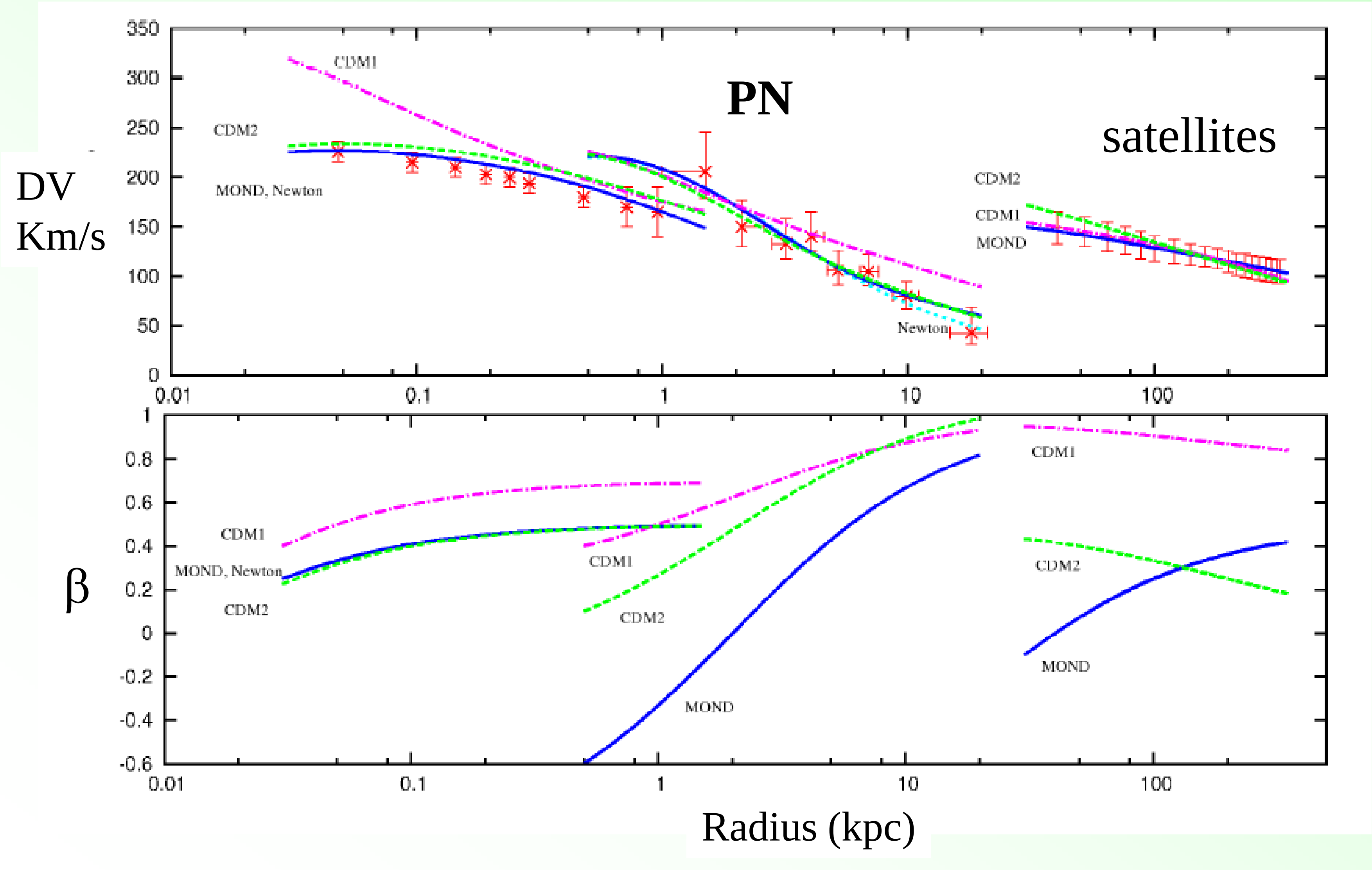
Only 1 or 0 for each galaxy

Test of the SDSS satellites

2 types of CDM CDM1: NFW cusp

Tiret et al 2007

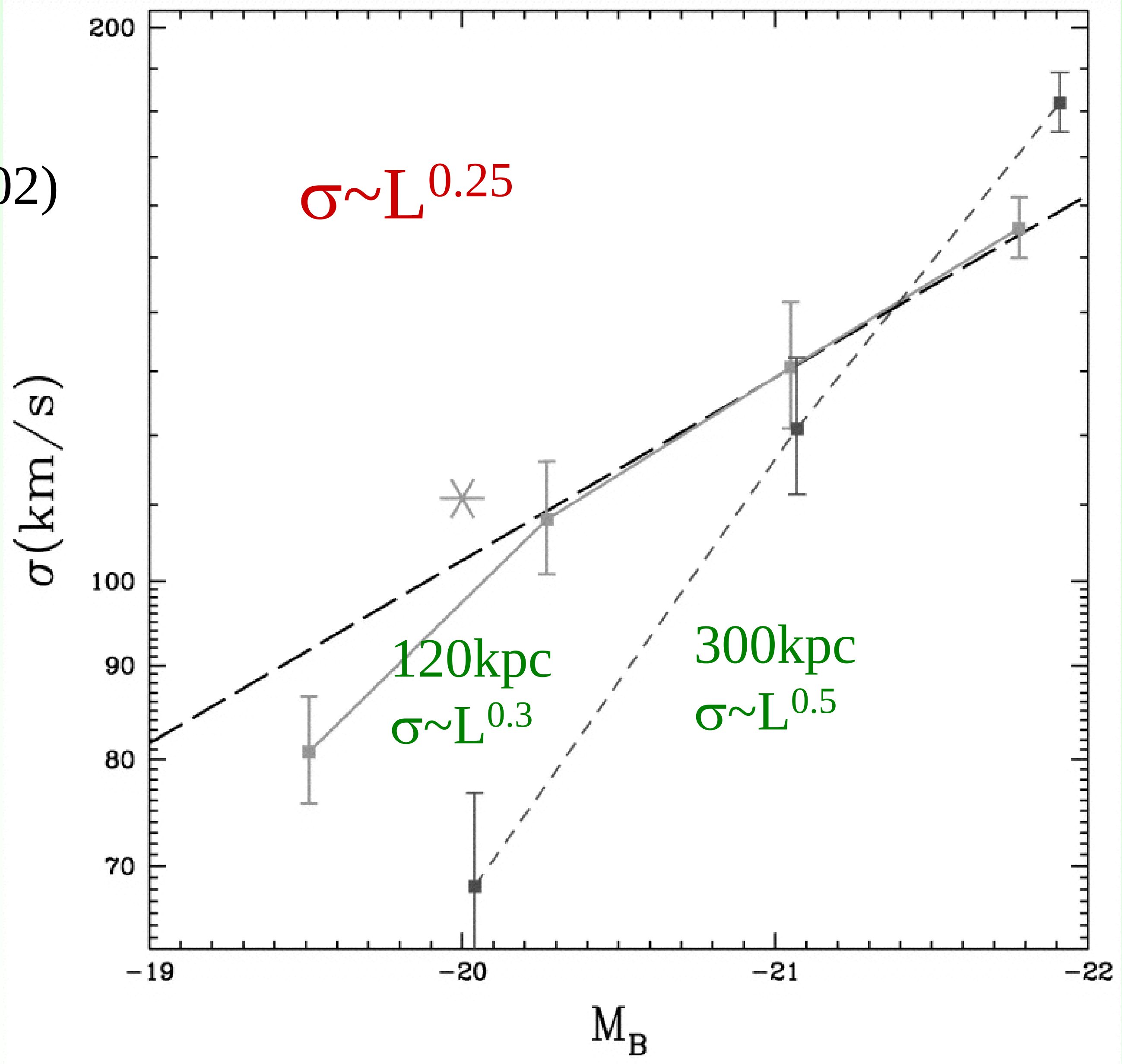
CDM2: as required by rotation curves



Tully Fisher Equivalent

Asterisk: Lenses (Hoekstra et al 2002)

--- TF normal spirals
(Verheijen 2001)



Prada et al (2003)

Large scale structure

In comoving coordinates: $\mathbf{r} = a\,\mathbf{x}$, $\mathbf{v} = da/dt\,\mathbf{x} + a\,\mathbf{u}$

➔ $\Delta\Phi = 4\pi G\,\delta\rho$

$\mu(g_M/\gamma)\,g_M = g_N + C$ $\mathbf{C} = \mathrm{rot}\,(\mathbf{h})$ γ critical acceleration (=a0)

Previous approximations h=0 (Nusser 2002, Knebe & Gibson 2004)

Newton and MOND accelerations are then parallel

Start from a cosmological Newton+ CDM → then find MOND produces as much clustering (γ = cste)

$\delta \sim \mathbf{a}^2$, instead of $\delta \sim \mathbf{a}$ for Newton+ CDM

New code AMIGA, taking into account the curl (Llinares et al 2009)

Initial conditions from CMBFAST, displacements (Zeldovich approx)

128^3 grid, $32h^{-1}$ Mpc, *assuming Newtonian initial state*

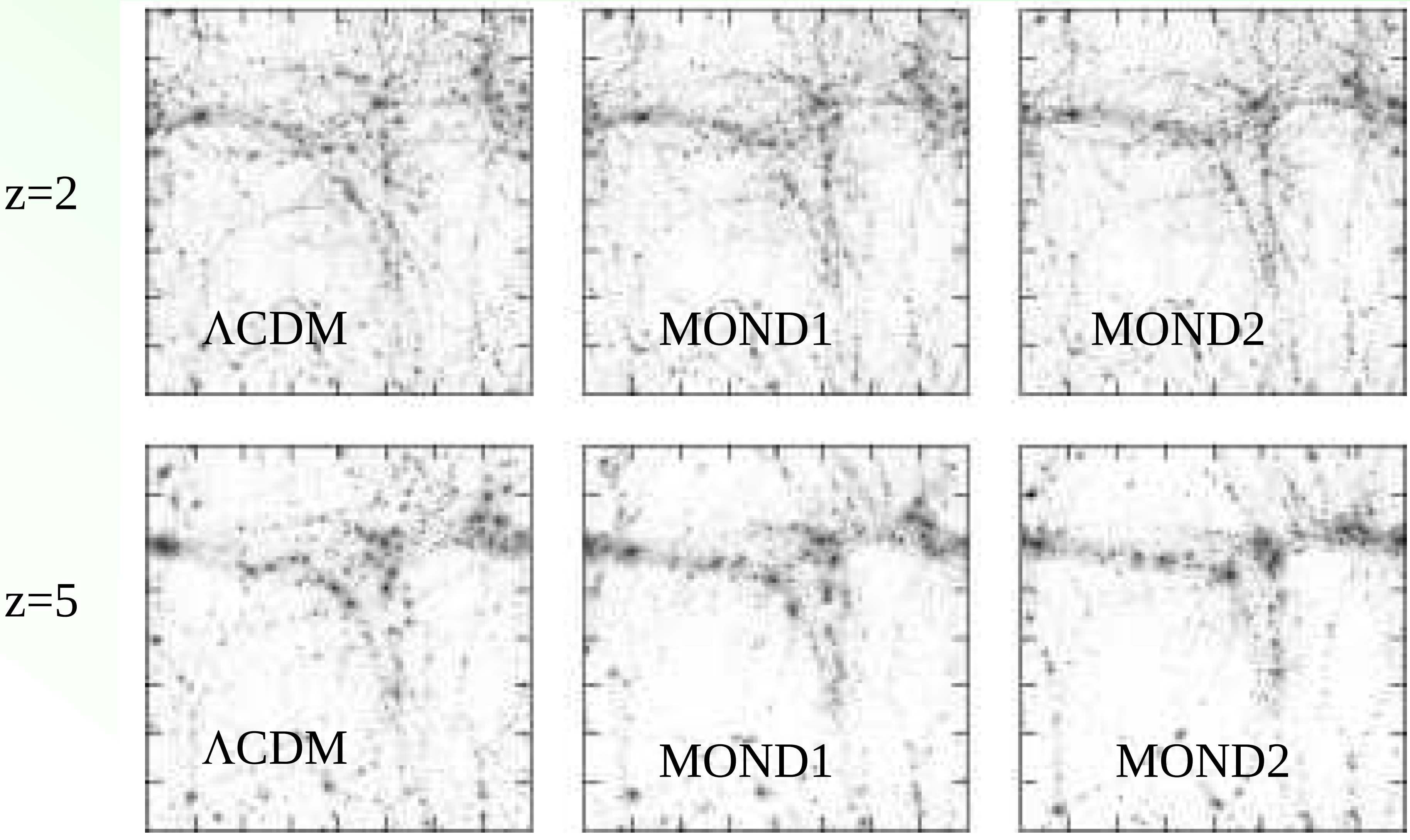
➔For that critical acceleration γ varies with time

$$\boldsymbol{\gamma = a\,\gamma 0}$$

MOND cosmological simulations

Starting z=50, dissipationless matter, 2 low Ω models + ΛCDM

Llinares et al 2009



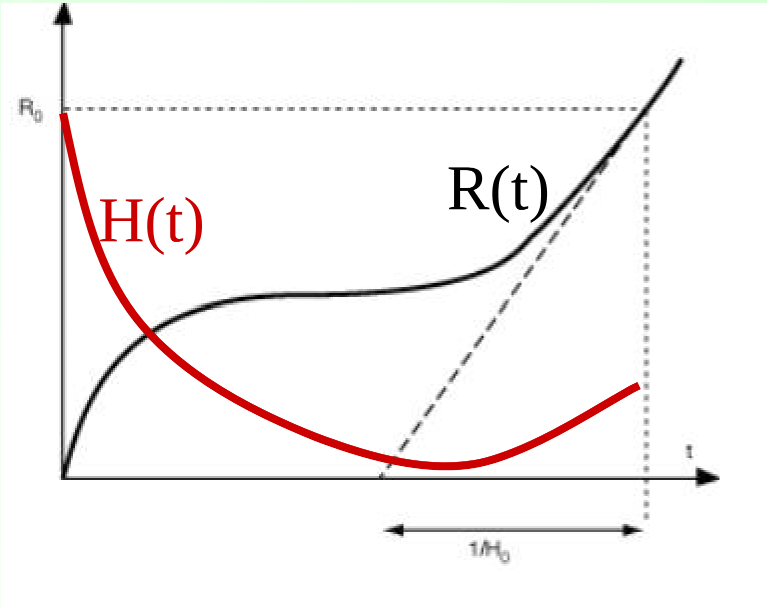
Evolution with time

Does the critical acceleration vary?

$$a_0 \sim c\, H_o, \quad \text{or also} \quad a_0 \sim c\, (\Lambda/3)^{1/2}$$

Possible to imagine variations, in either way (more or less MOND in the early universe)

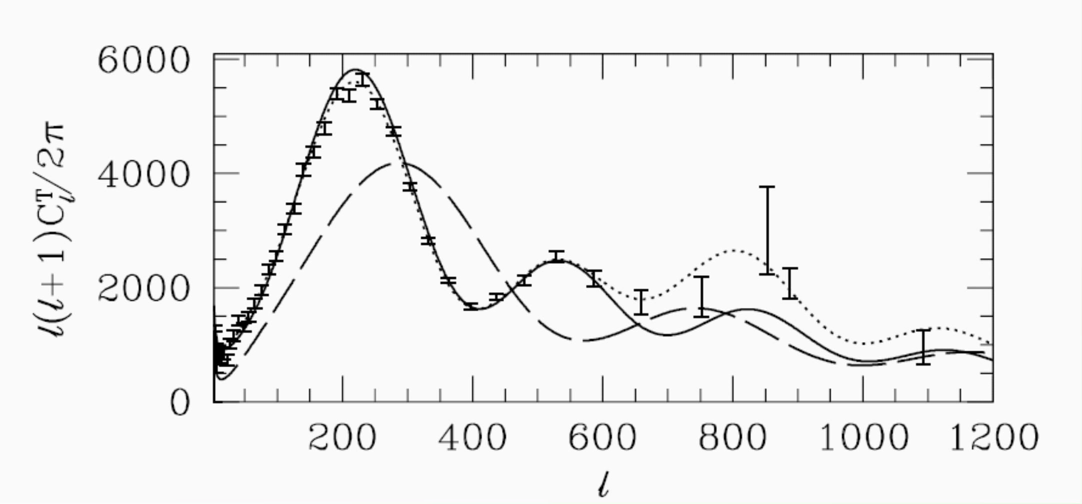
Open question, as is the evolution of Ω_Λ

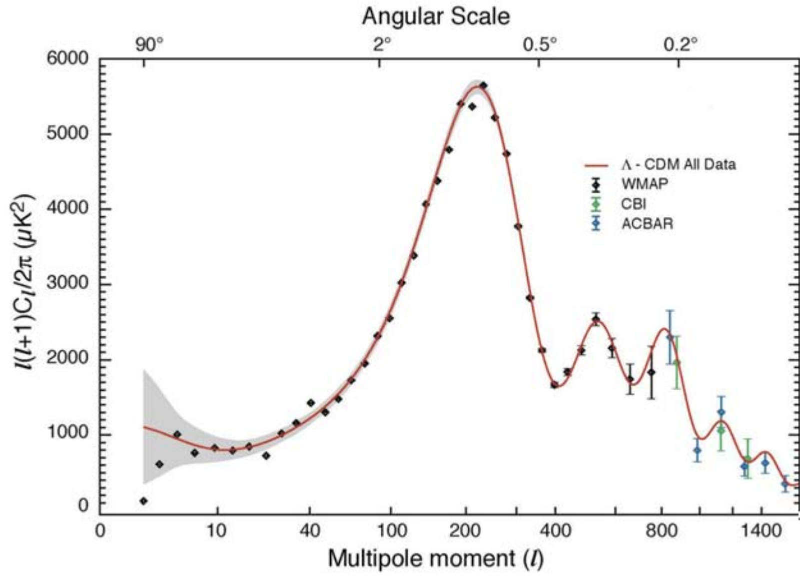


MOND: fit of CMB data, WMAP

Include massive neutrinos 1-2eV

Fit with MOND (no-DM) of Acoustic peaks (Skordis et al 2006)





——: Ω_Λ=78% Ω_ν=17% Ω_b=5% MOND

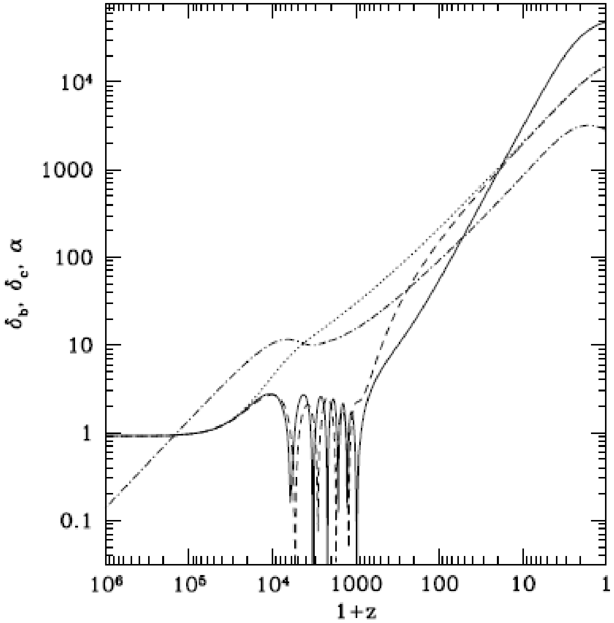
-- - : Ω_Λ=95% Ω_b=5%

·······: ΛCDM

Fit with CDM + Λ

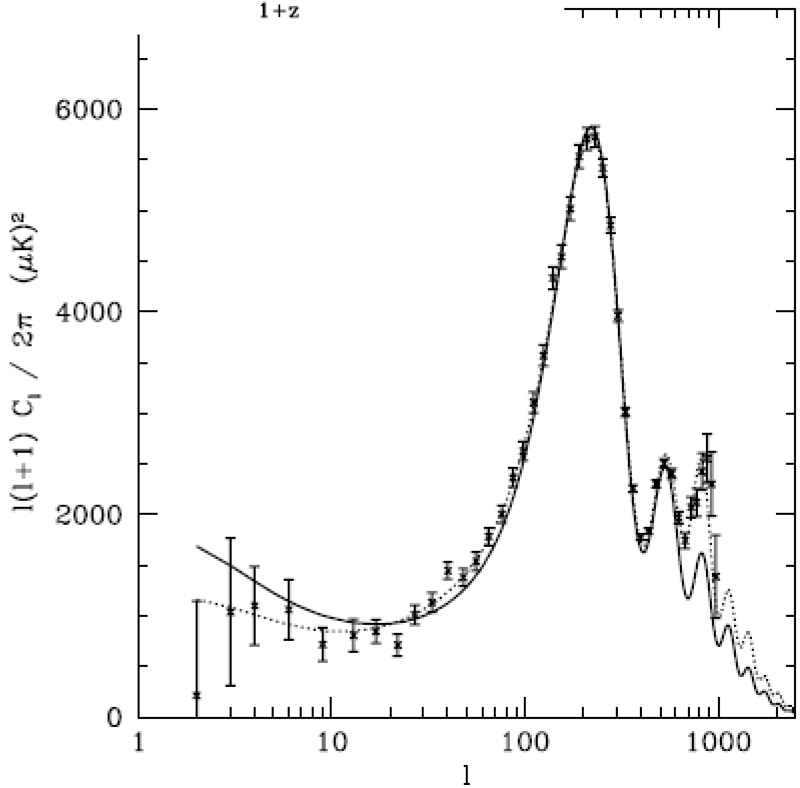
TeVeS: CMB and LSS

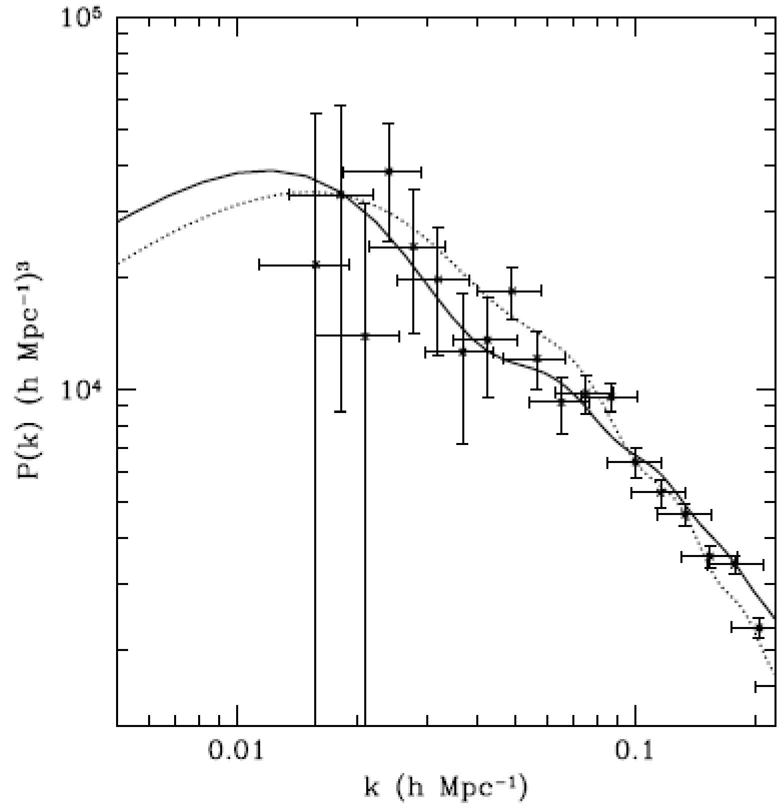
Skordis 2009



Growth of structures due to the vector field

Scalar field ➔ aceleration of expansion, DE





Other possibilities

GEA: Generalized Einstein Ether theories

Zloznik et al 2006, Ferreira et al 2009

From TeVeS, suppression of one degree of freedom,
Supress the scalar field, in combining with the Vector Field
Which is now no longer unit timelike (but timelike)

Physical metric (no longer Einstein-frame metric)

➔Retrieve the MOND phenomenology
Vector field sourcing potential wells

Many other possibilities to explore

Conclusion: Success and Problems

CDM: great success at large scale, but problems at galaxy scales
MOND solves the problems of galaxies,
but has to solve its own problem at group and cluster scales
(neutrinos, baryons..)

➔Observational tests could constrain the various MOND models

➔Lorentz covariant theory, TeVeS (Bekenstein 2004)
➔Different metric, some free parameters still
[a0 ~c H0 today, but does it vary with time?]

Numerous other propositions: Einstein Aether (scalar field),
Vector field, etc..

Tests of General Relativity

- Detection through weak lensing of deviation from GR at cosmic scales *Rachel Bean (2009)*

- ISW *(Integrated Sachs-Wolfe effect)* WMAP

Correlated with 2MASS and SDSS

With COSMOS HST deep field, and weak lensing

Cosmological constant, or quintessence?

Modified gravity: f(R), DGP (Dvali-Gabadadze-Poratti)-branes, TeVeS, Yukawa models, etc..

Not only acceleration of expansion, but effect on LSS growth

Could raise the degeneracy

First detection η<1 ?

$$ds^2 = -a^2(\tau)\{d\tau^2[1+2\psi(\mathrm{x},\tau)] + d\mathrm{x}^2[1-2\phi(\mathrm{x},t)]\}$$

Where ψ and ϕ are the two newtonian potentials
for the temporal and spatial perturbations of the metric resp.

$$\eta(k,a) \equiv \frac{\phi(k,a)}{\psi(k,a)}$$

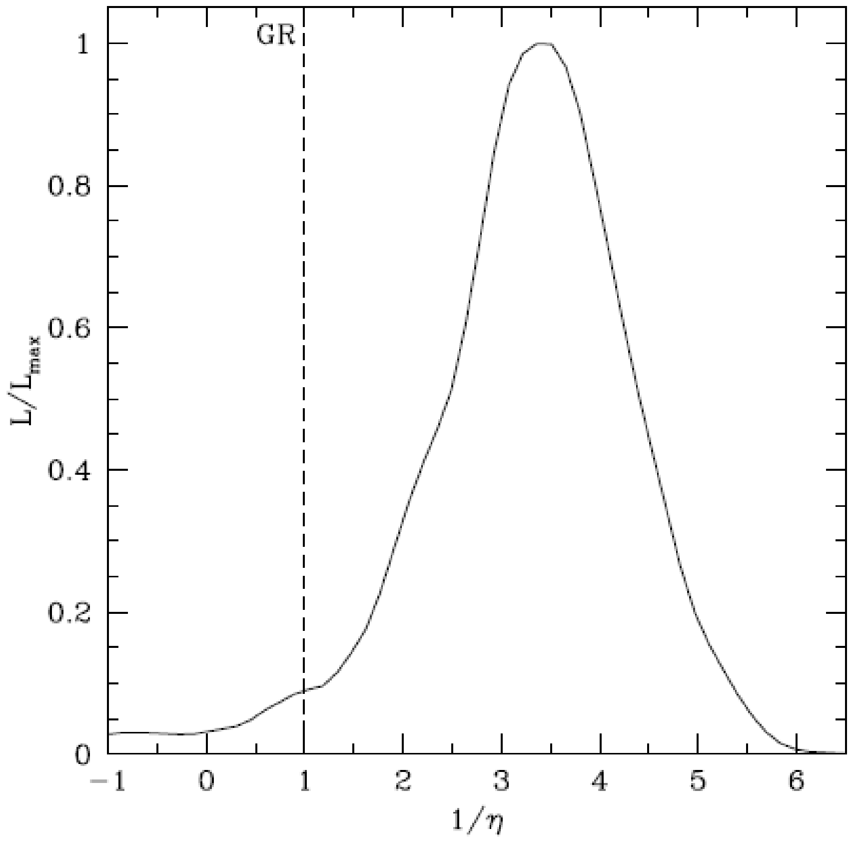
$$\gamma(k,a) \equiv \frac{\ln(\dot{\delta}_c/\mathcal{H}\delta_c)}{\ln \Omega_m(a)}$$

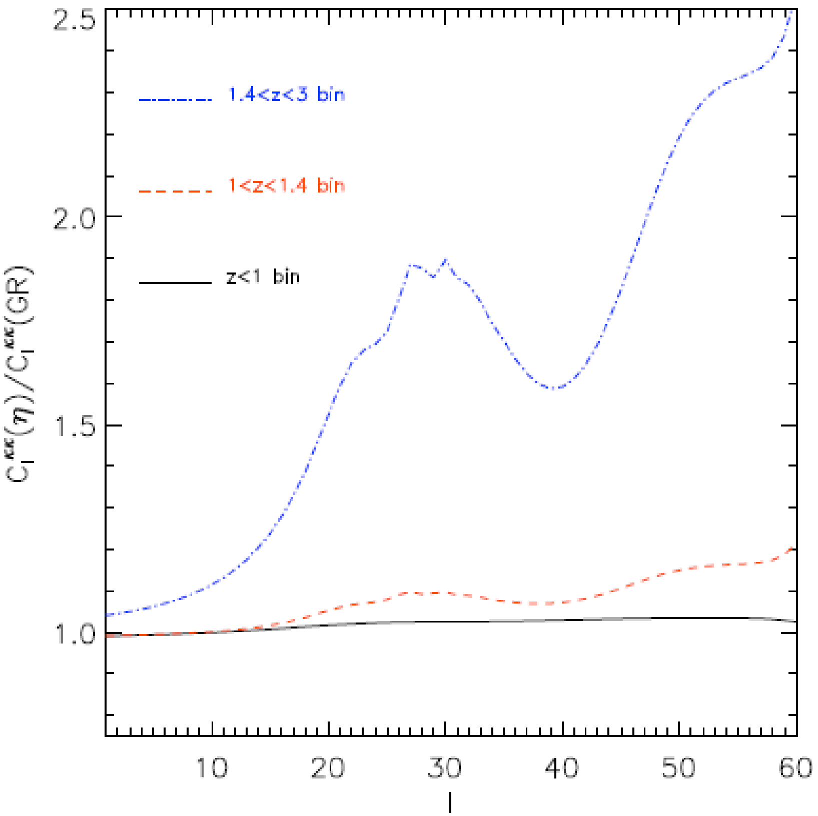
η= 1, if GR is verified even if γ the growth rate can be modified

Analysis of all data, BAO, CMB, Union SNIa, Cosmos, WL..
And ISW from WMAP and surveys (2MASS, SDSS)

➔ GR disfavored at 98% level

Evidence of deviation from GR





COSMOS WL brings evidence that DE is a modification of GR
More than a cosmological constant (Bean 2009)
To be confirmed with DES, LSST, etc..