

La matière noire dans l'Univers ou test de la gravité

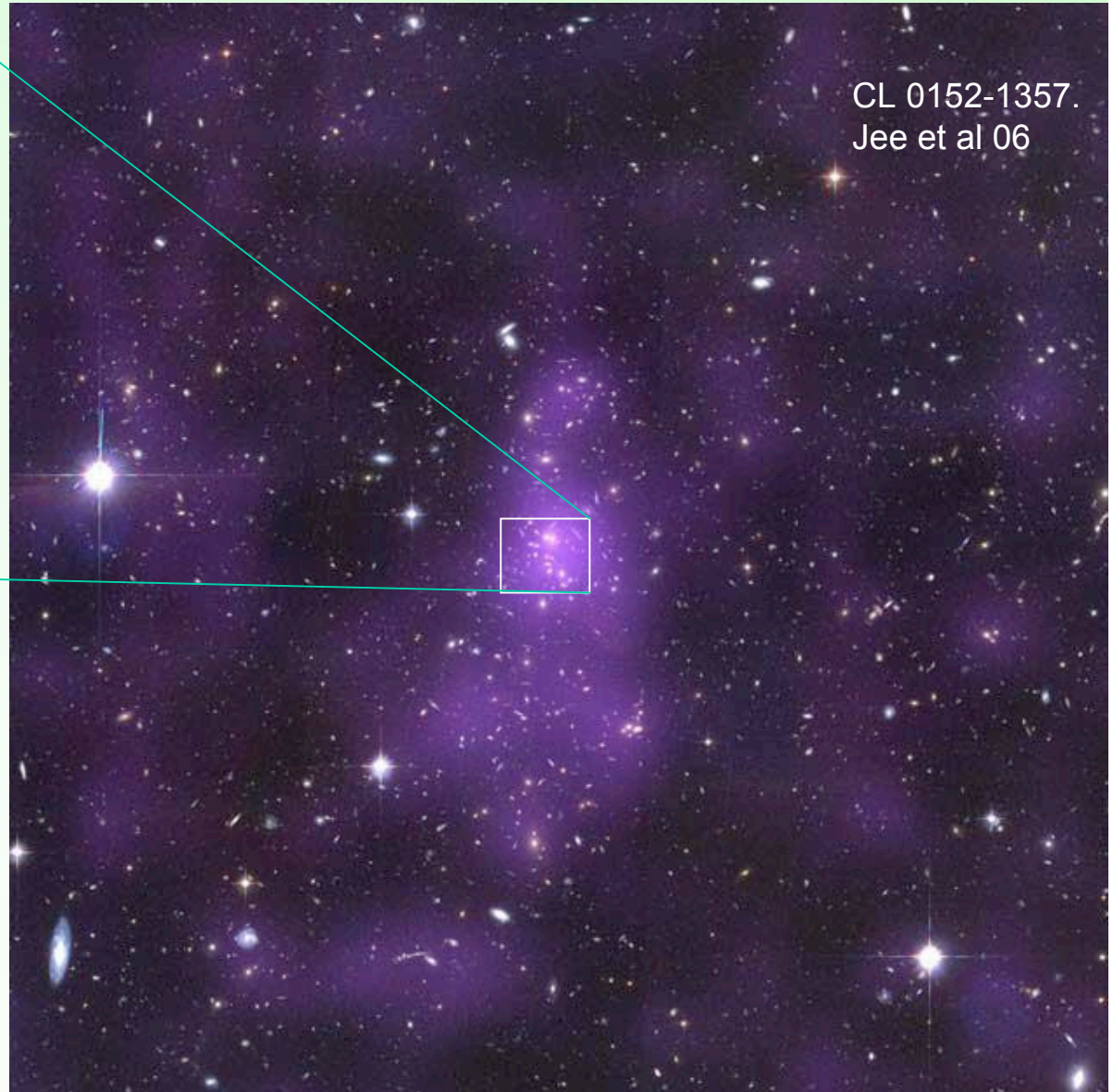


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Lundi 30 Novembre 2009



Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique



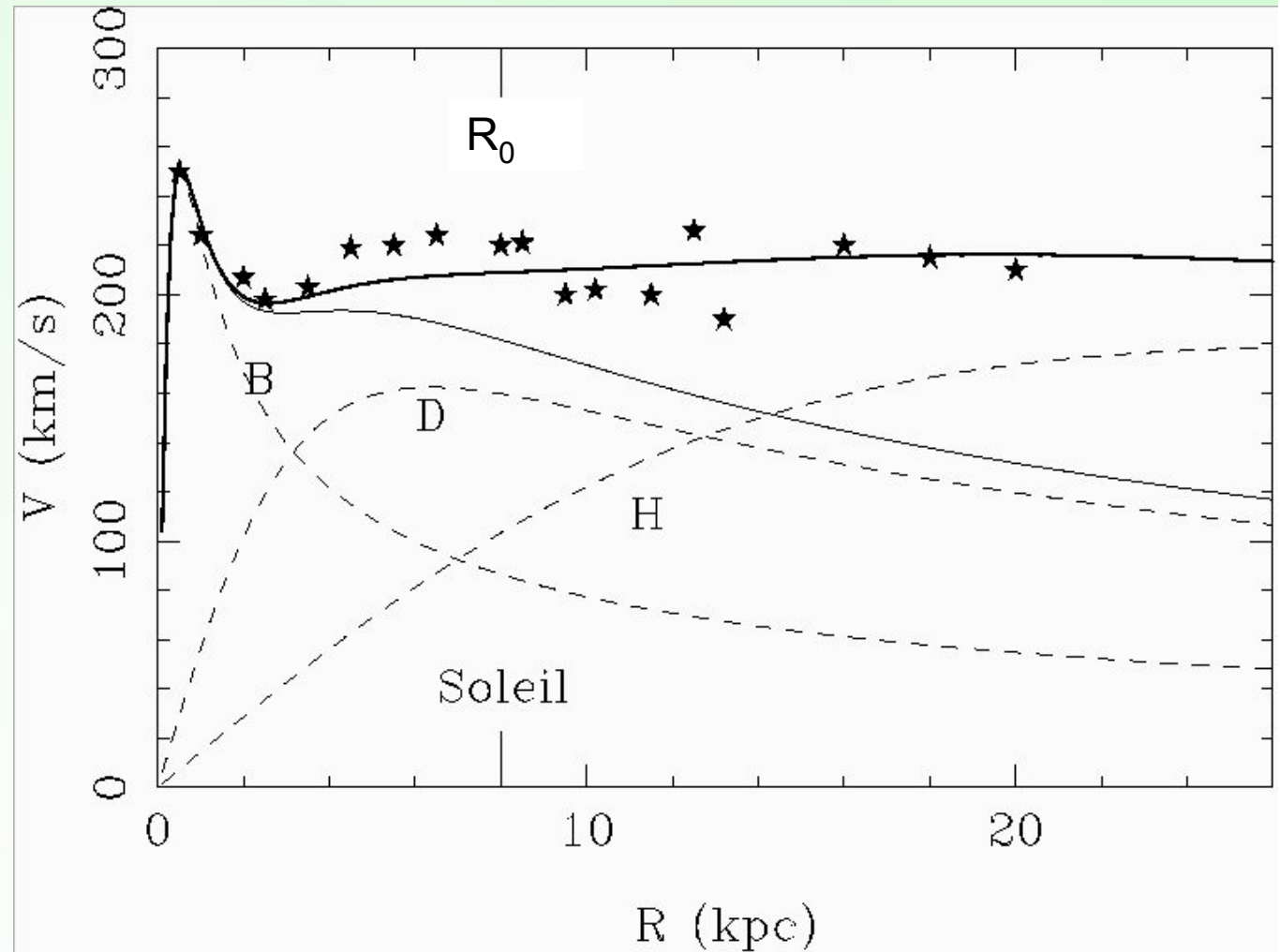
Evidences de la matière noire

→ Amas de galaxies, Masse viriel / masse visible ~ 100 (Zwicky 1937)

Amas de Coma: vitesses des galaxies entre elles

→ Courbes de rotation, par ex notre Galaxie, la Voie Lactée

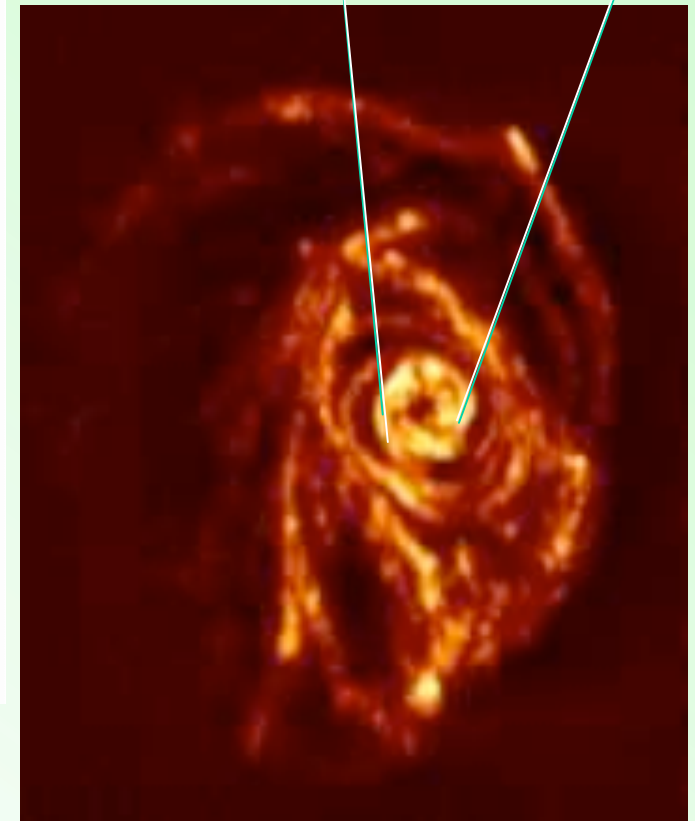
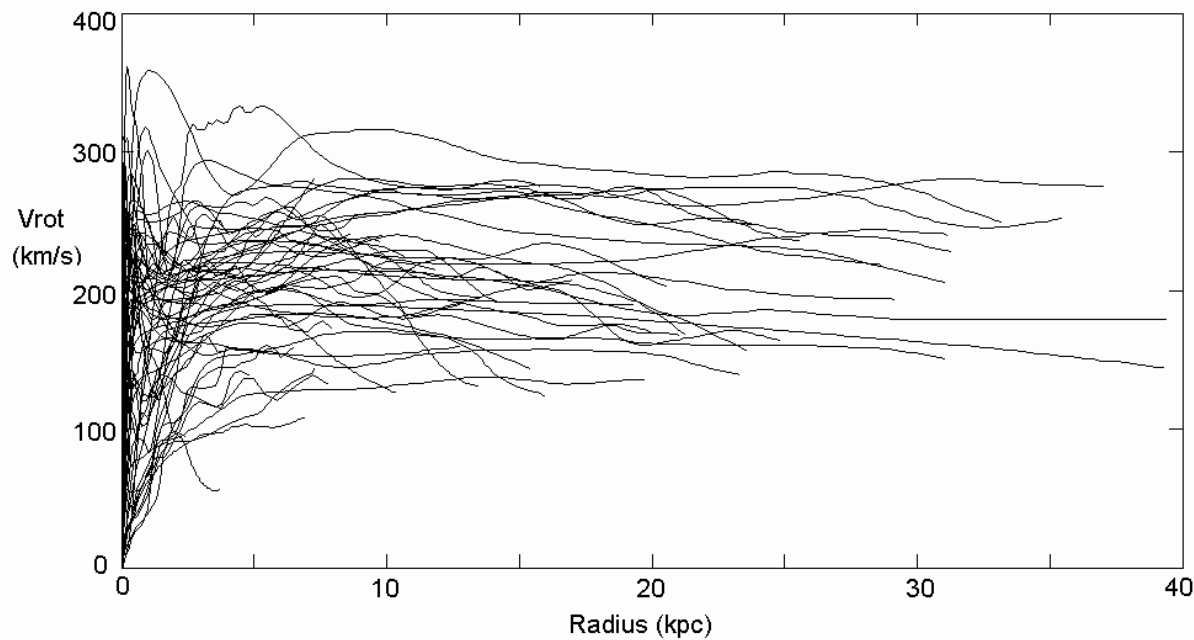
Bien au-delà de la masse visible, la vitesse reste grande, au lieu de $V^2 \sim GM/r$ (Képler)



Galaxies avec HI

M83: optique

HI: cartographie de l'hydrogène atomique
Longueur d'onde 21cm



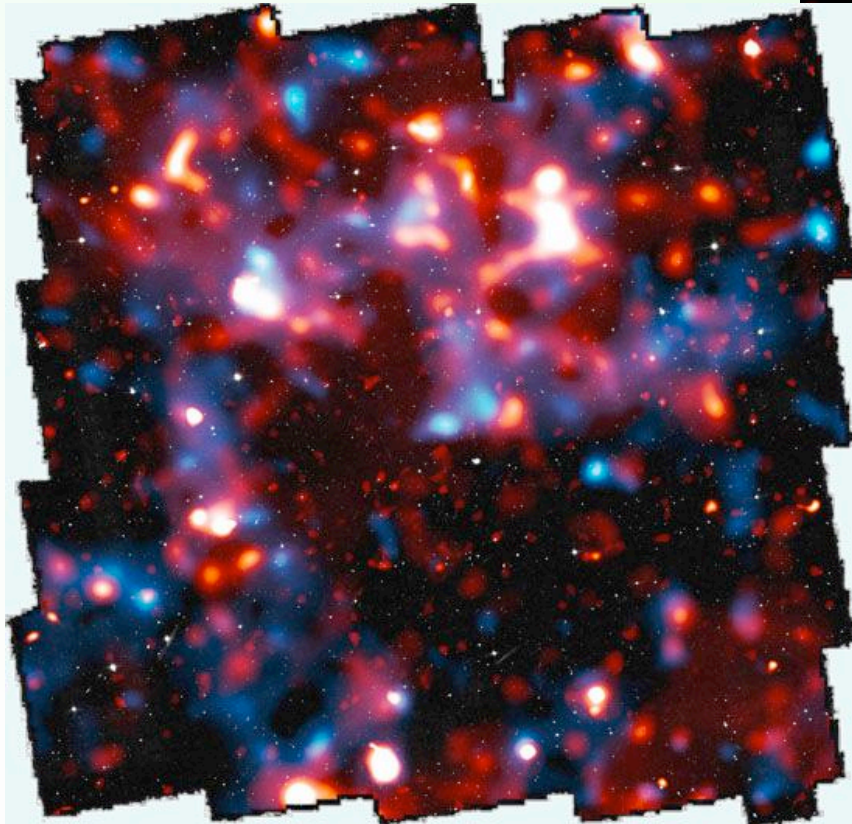
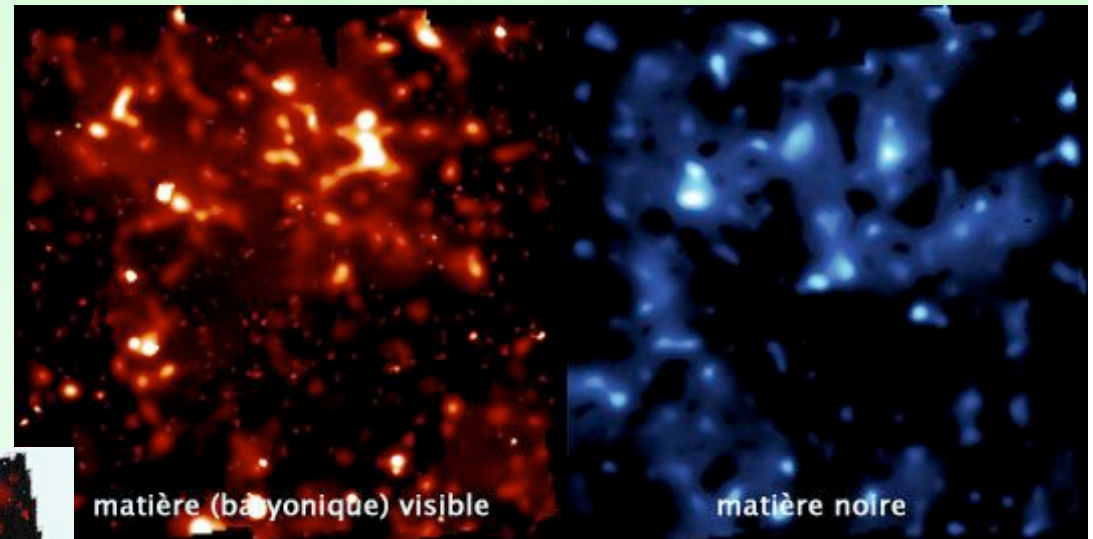
HI dans M83: une galaxie semblable à la Voie Lactée³

Cisaillement gravitationnel

Rouge: gaz X

Bleu: matière totale

Champ Cosmos



**Contraintes sur la
Matière noire, et aussi
Énergie noire**

Massey et al 2007

Tully-Fisher relation

Relation between maximum velocity
and luminosity

ΔV corrected from inclination

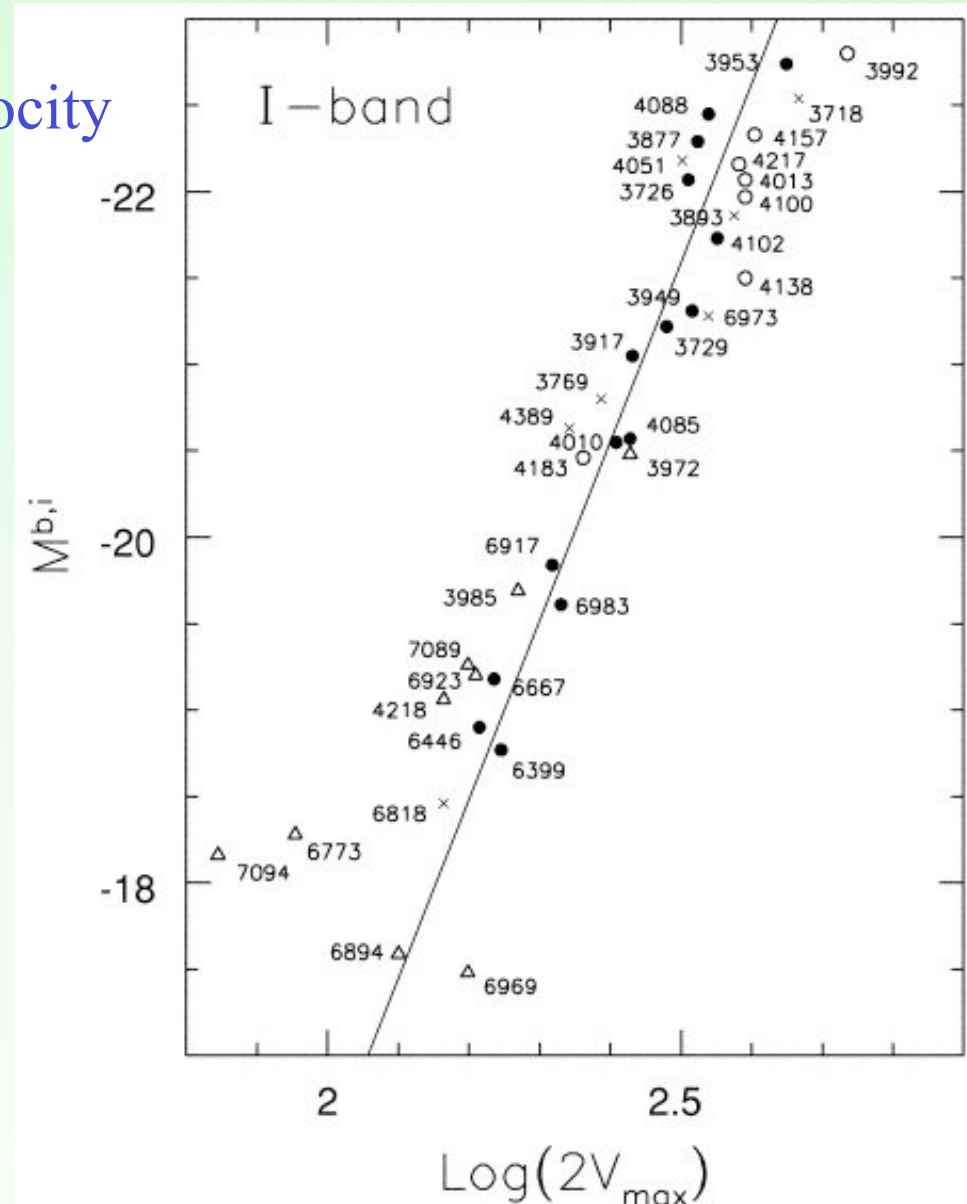
Much less scatter in I or K-band
(no extinction)

Correlation with V_{flat}

Better than V_{max}

Uma cluster

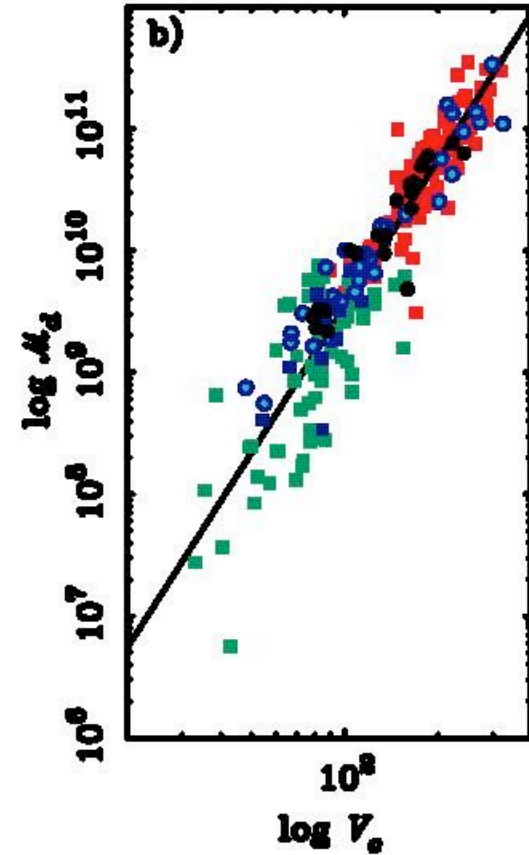
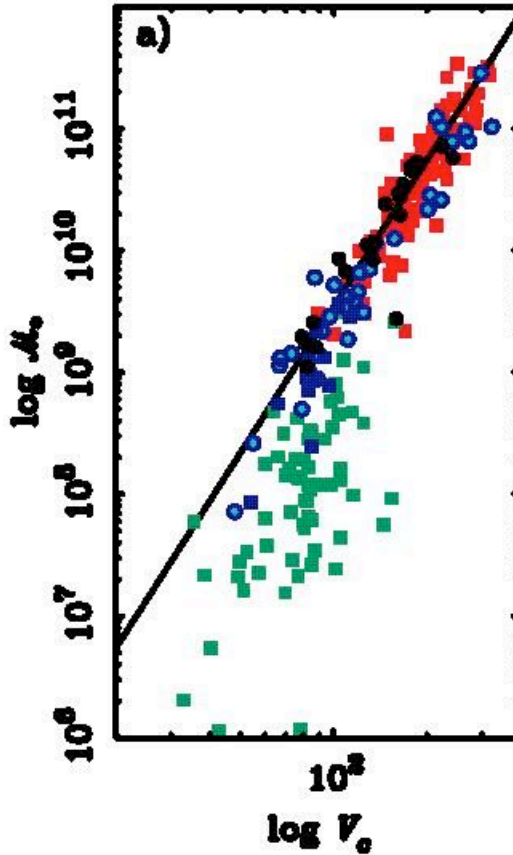
Verheijen 2001



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**

Solutions

→ Recherche directe et indirecte de Matière Noire exotique (CDM)

→ ou bien gravité modifiée?

Mais il reste toujours de la matière noire ordinaire

Hypothèses pour les baryons noirs

Baryons en **objets compacts** (naines brunes, naines blanches, trous noirs) sont soit éliminés par les expériences de micro-lensing ou souffrent de problèmes majeurs
(Alcock et al 2001, Lasserre et al 2000)

→ Meilleure hypothèse, c'est du gaz,

Soit **du gaz chaud** dans le milieu intergalactique et inter-amas

Soit **du gaz froid** au voisinage des galaxies

(Pfenniger & Combes 94)

Où sont les Baryons?

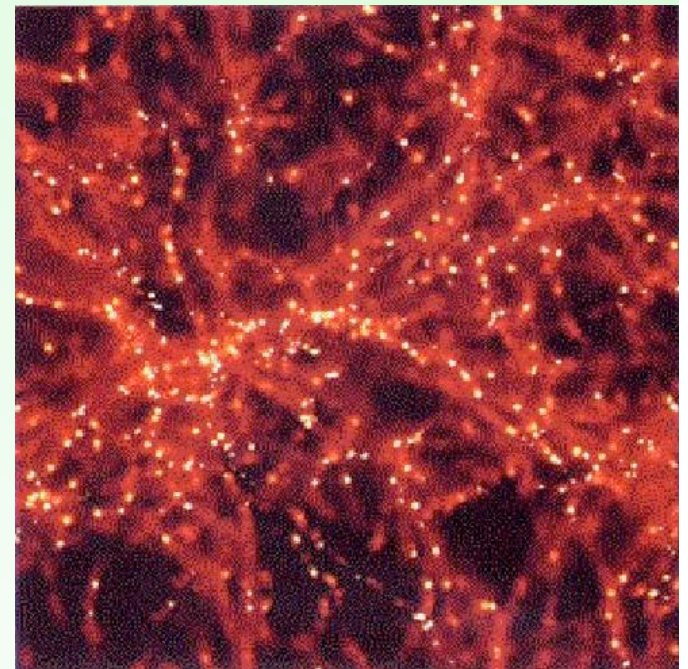
→ 6% dans les galaxies ; 3% dans les amas de galaxies gaz X

→ <18% dans la forêt Lyman-alpha (filaments cosmiques)

→ 5-10% dans le WHIM (Warm-Hot Intergalactic Medium) 10^5 - 10^6 K
Raies de OVI

→ 65% ne sont pas encore identifiés!

La majorité ne sont pas dans les galaxies



Problèmes du modèle standard Λ -CDM

→ Prédiction de **cuspidés au centre des galaxies**, en particulier absentes dans les naines Irr, dominées par la matière noire

→ Faible moment angulaire des baryons, et en conséquence **formation de disques de galaxies bcp trop petits**

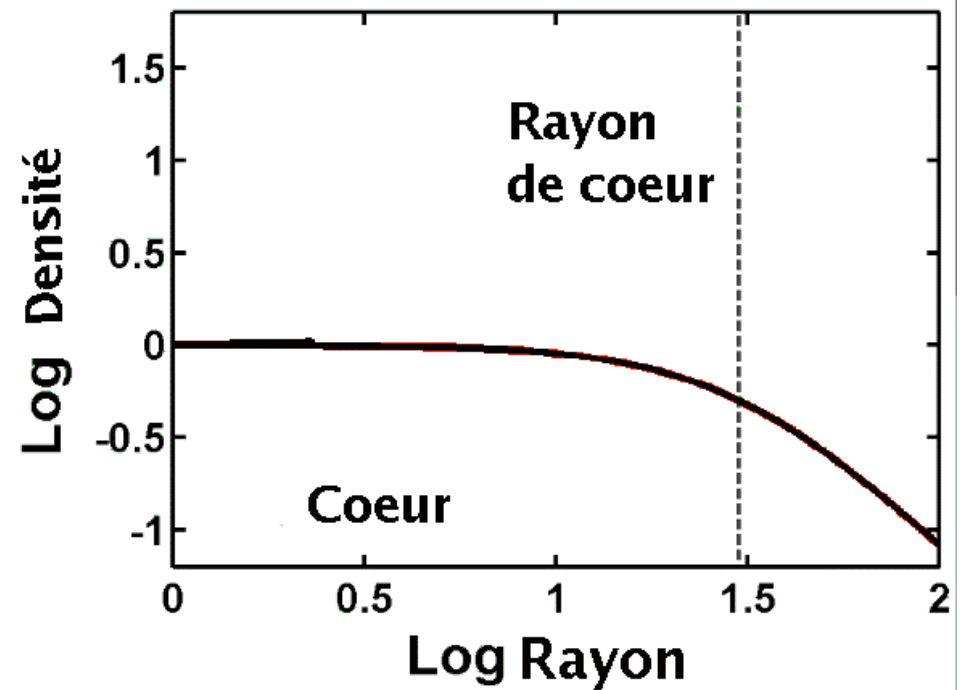
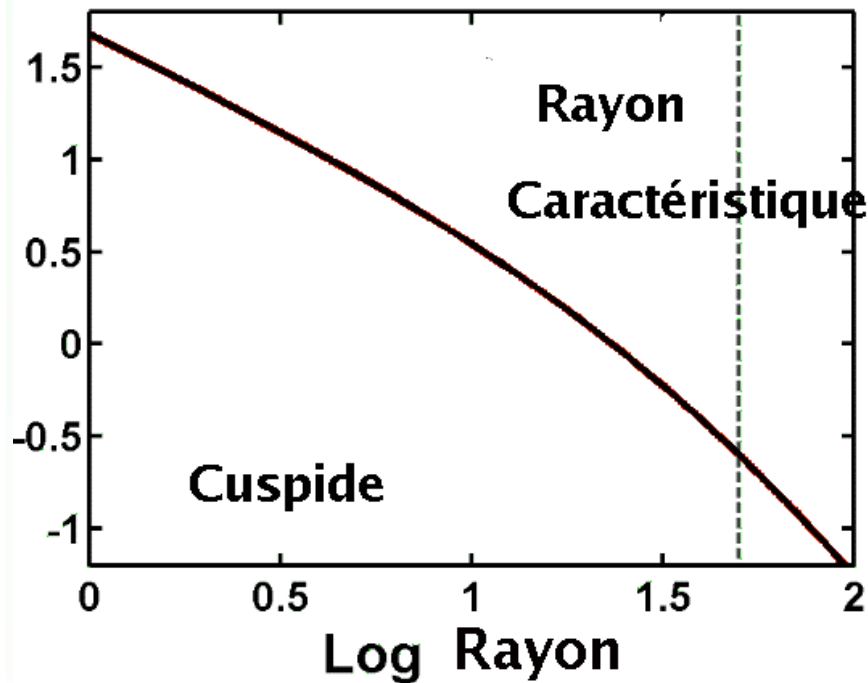
→ Prédiction d'un grand **nombre de petits halos**, non observés

La solution à ces problèmes viendrait-elle du manque de réalisme des processus physiques (SF, feedback?), du manque de résolution des simulations, ou de la nature de la matière noire?

Prédictions Λ CDM: « cusp » ou « core »

Distribution radiale de la densité de matière noire

Loi de puissance de la densité $\alpha \sim -1-1.5$, observations $\alpha \sim 0$



Moment angulaire et formation des disques

Les baryons perdent leur moment angulaire (AM) au profit de la CDM

Paradigme: baryons initialement → même AM spécifique que DM

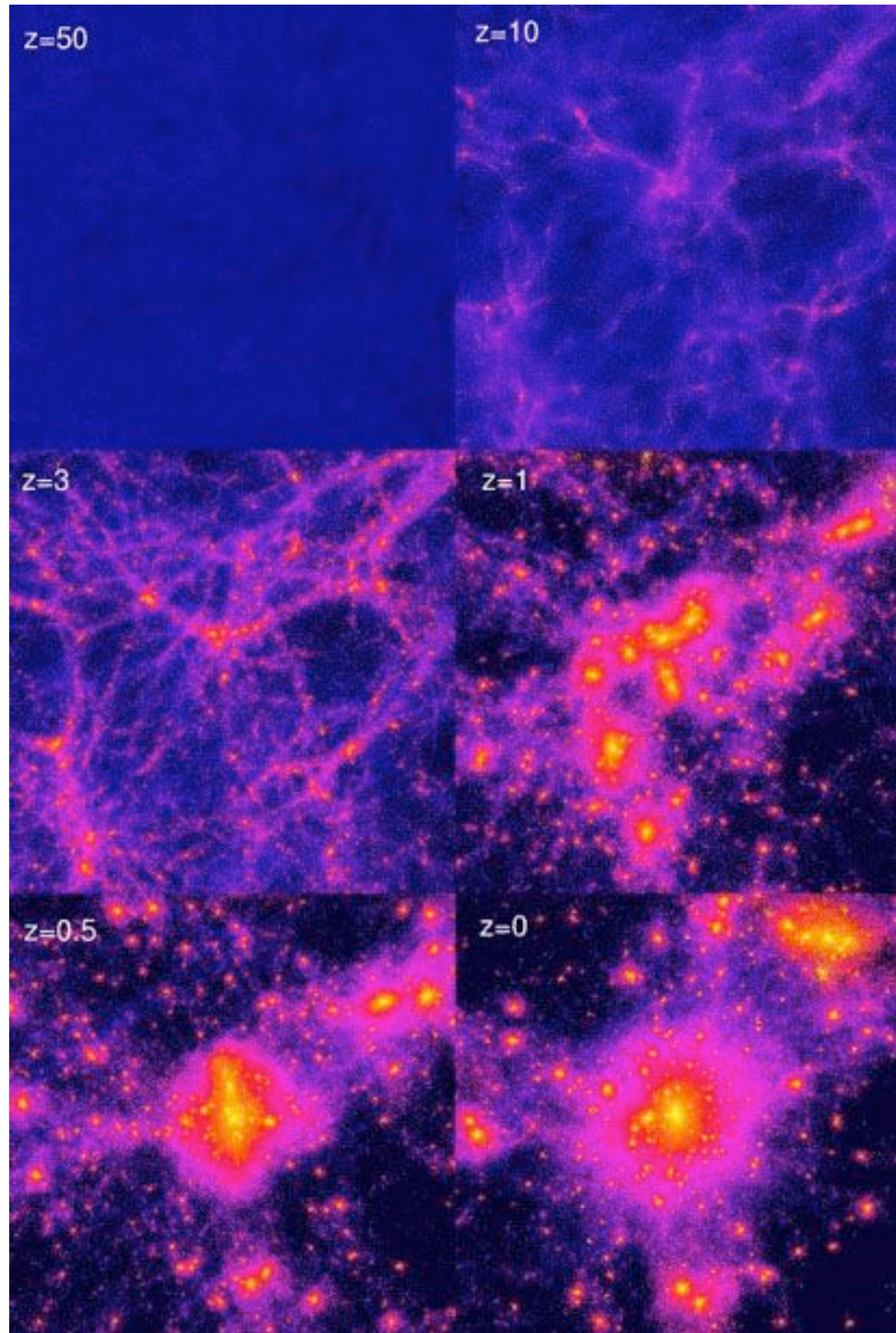
Le gaz est chaud, chauffé par les chocs à la température Viriel du halo

→ Une autre façon d'assembler la masse est l'accrétion de gaz froid

Le gaz est canalisé le long des filaments, modérément chauffé par des chocs faibles, et rayonne rapidement

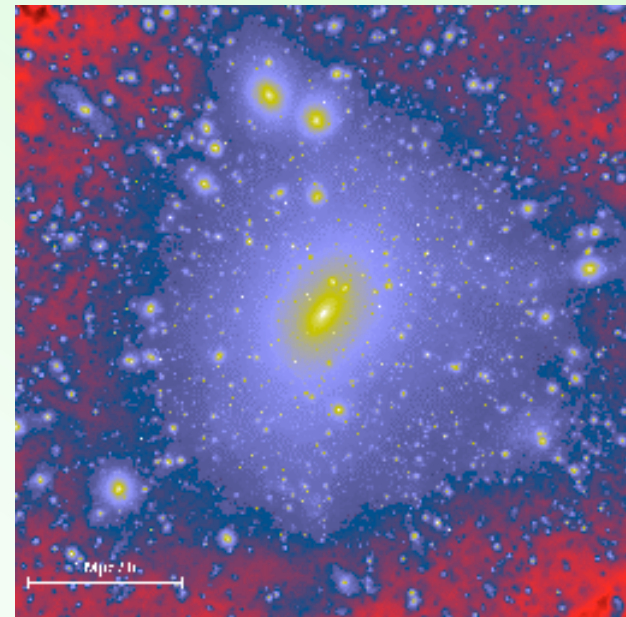
L'accrétion n'est pas sphérique, le gaz garde son moment angulaire

Gaz en rotation autour des galaxies, **plus facile de former des disques**



Trop de petites structures

Aujourd'hui, les simulations CDM prédisent 100 fois trop de petits halos autour des galaxies comme la Voie Lactée



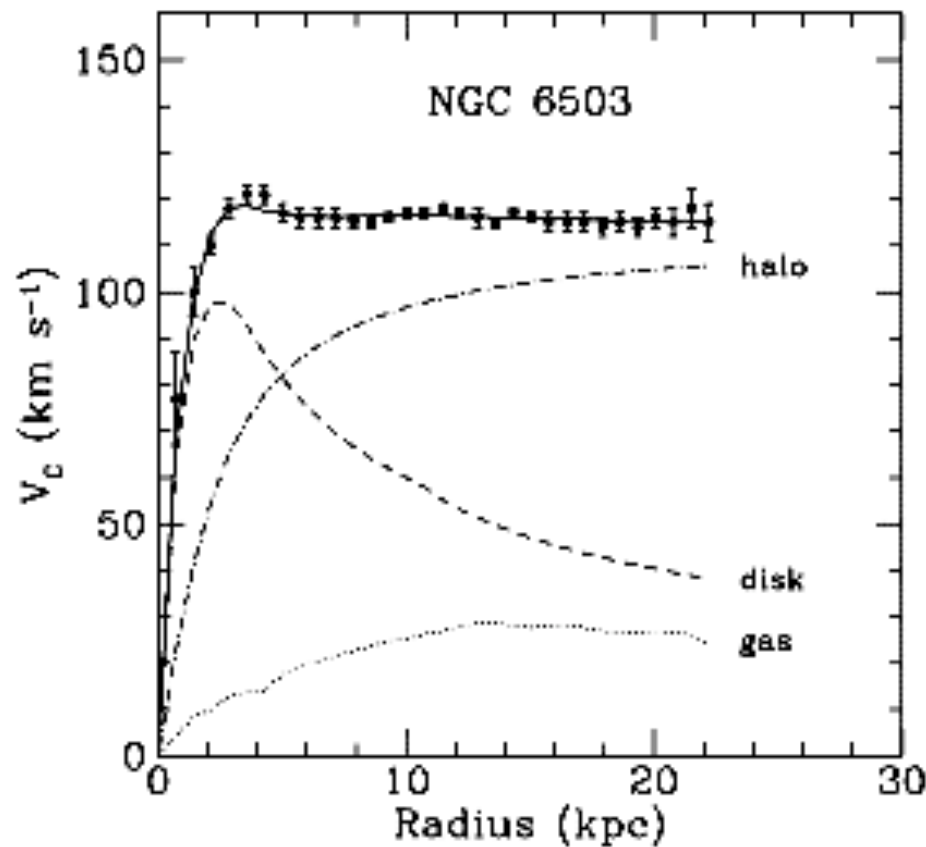
Autre solution pour les courbes de rotation des galaxies

Sans matière noire, mais

une modification de la loi de Newton

(Milgrom 1983)

**MOND =
MODified Newtonian Dynamics**



Modification a faible accélération

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

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

$$\rightarrow a^2 \sim V^4/R^2 \sim GM/R^2 \text{ (Tully-Fisher)}$$

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

(Milgrom 2008)

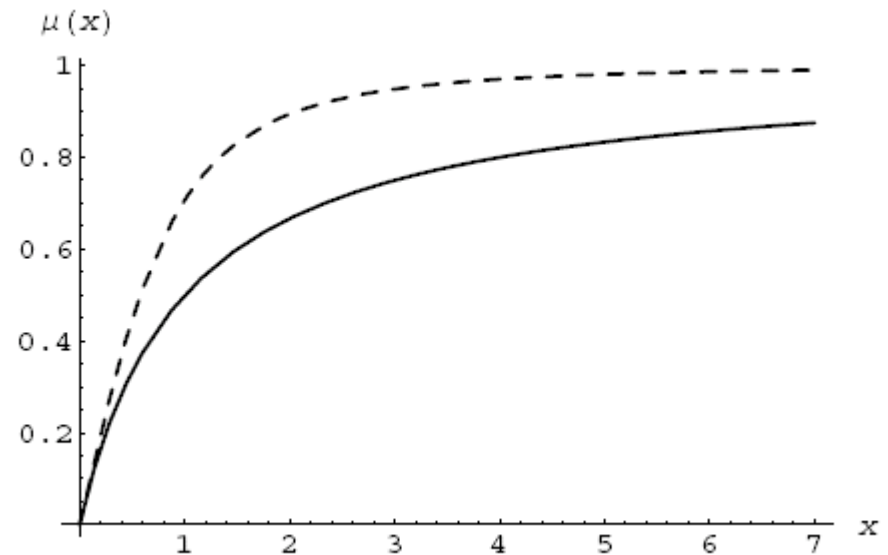
$$a_N = a \mu(x)$$

$$x = a/a_0 \quad a_0 = 1.2 \cdot 10^{-10} \text{ m/s}^2$$

soit 1 Angstroms/s²

$x \ll 1$ Régime Mondien $\mu(x) \rightarrow x$

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

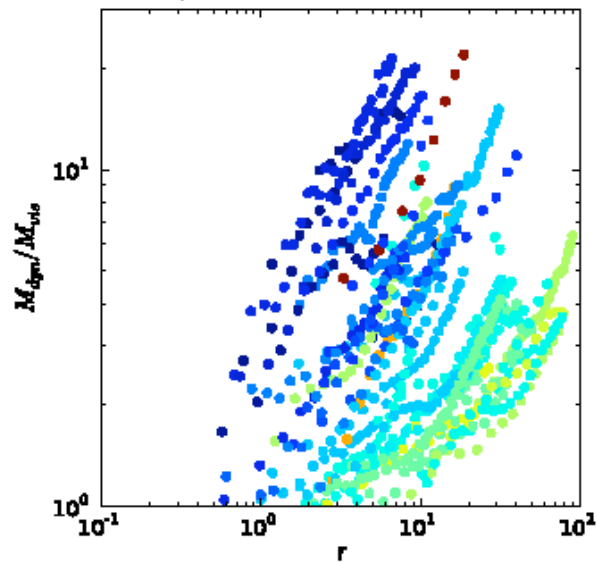


Masse dynamique / Masse visible

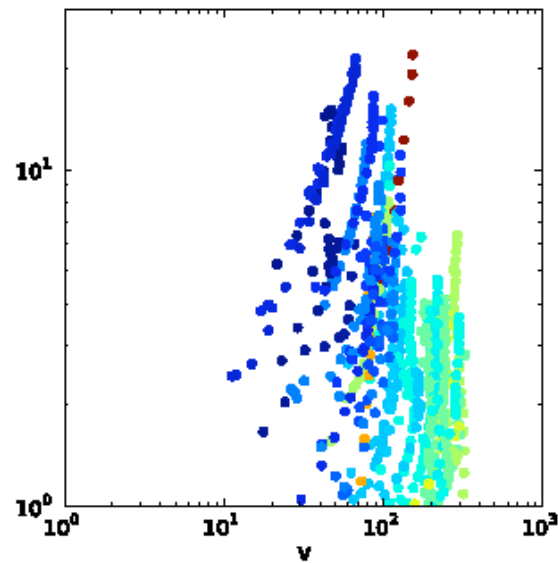
Le rapport dépend remarquablement de l'accélération,

→ Seule quantité qui fasse changer de régime de façon universelle

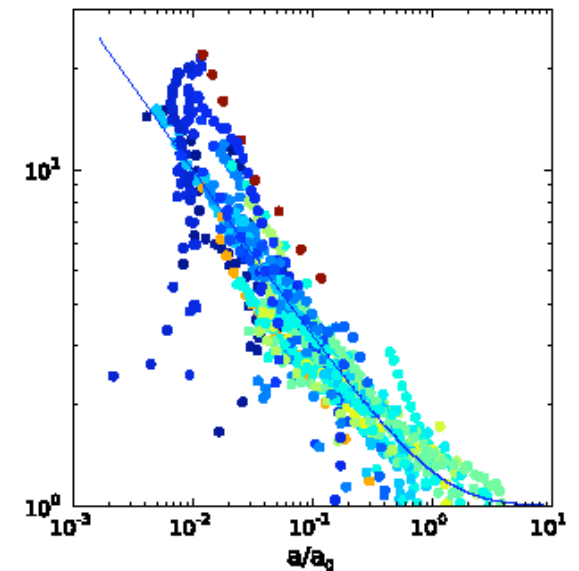
$M_{\text{dyn}}/M_{\text{vis}}$



Radius



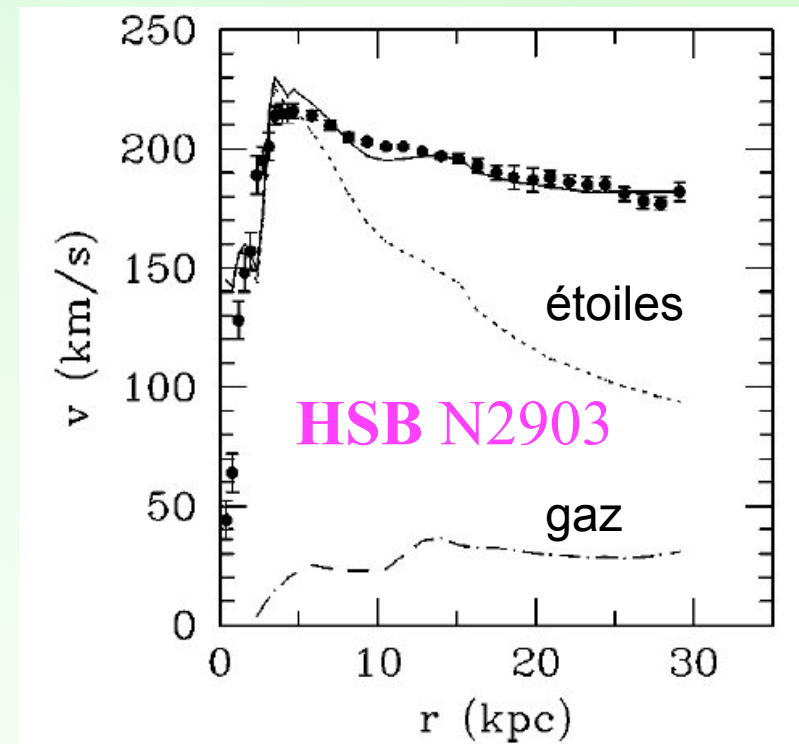
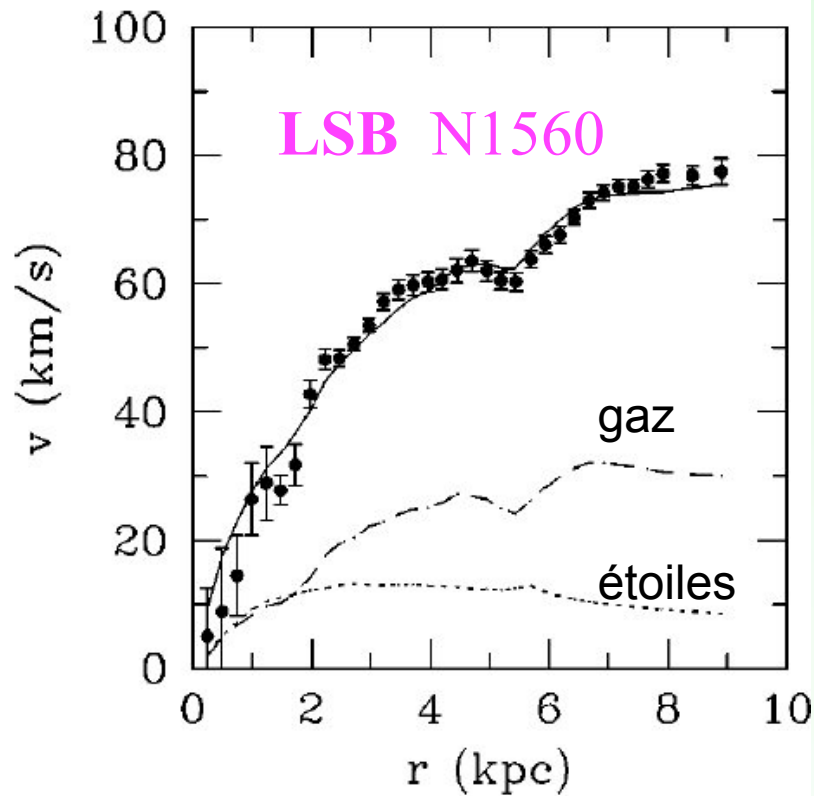
Velocity



Acceleration/ a_0

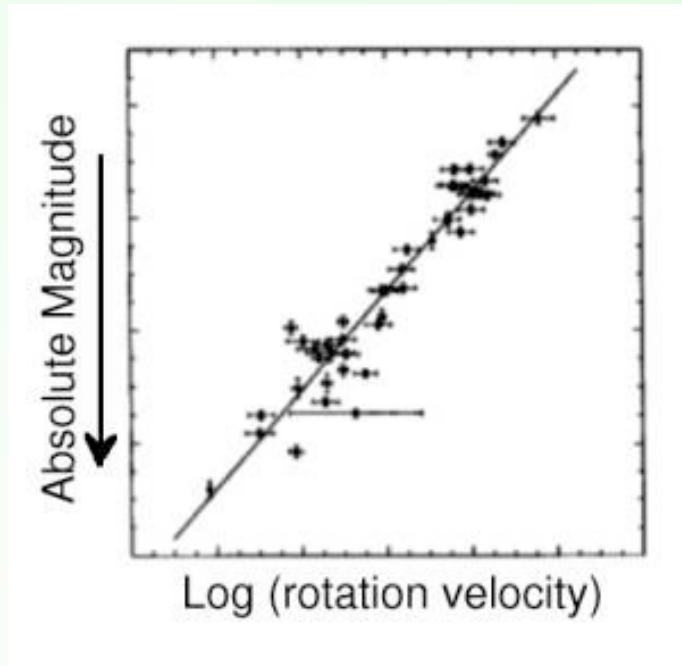
Ajustement selon la densité de surface

Les courbes de rotation sont ajustées parfaitement, quel que soit le type morphologique (naines **LSB**, géantes **HSB**)



Loi de Tully-Fisher

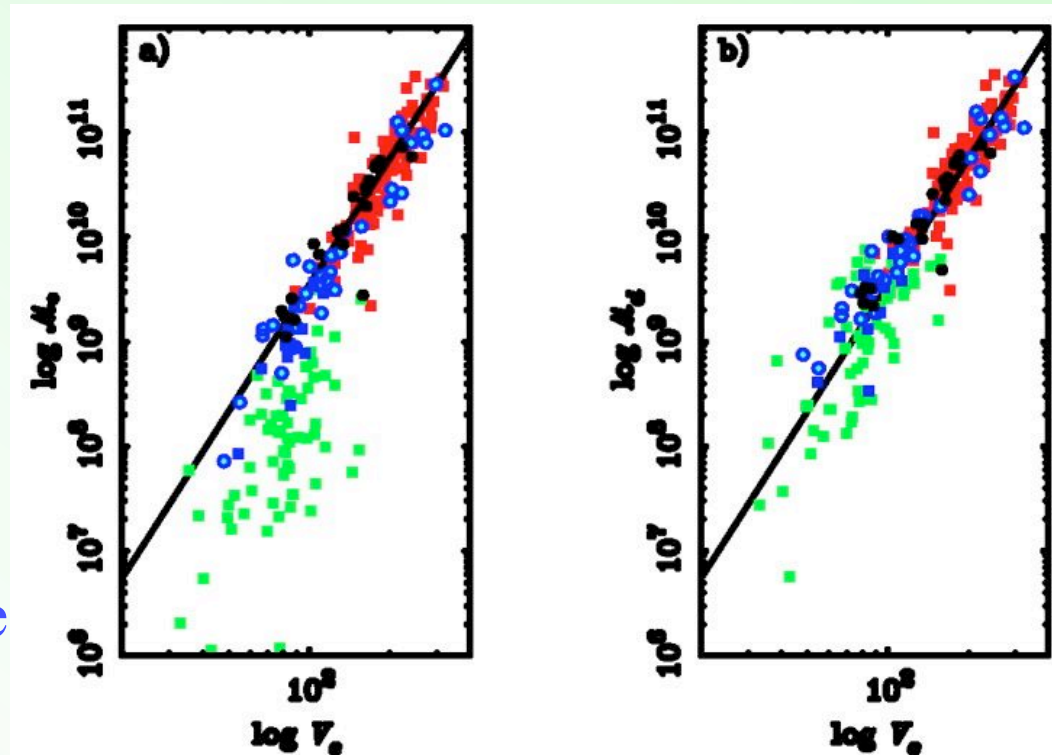
$$\text{Luminosité} \sim \Delta V_{\text{rot}}^4$$



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

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

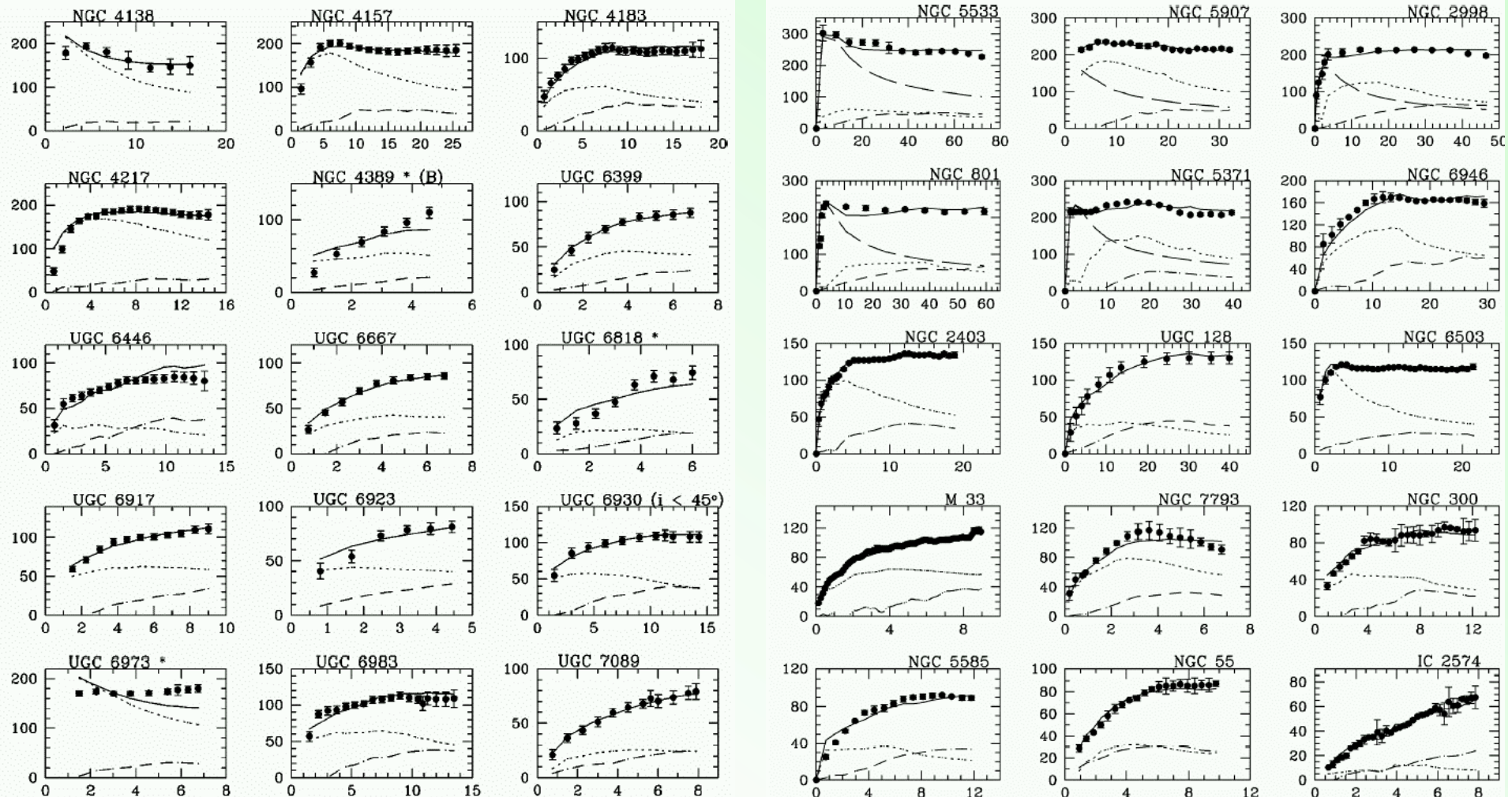
Les galaxies naines, dominées par le gaz, vérifient aussi la relation, si l'on prend en compte la masse HI



Courbes de rotation multiples..

Sanders & Verheijen 1998, tous types, toutes masses

--- gas, disque stellaire, --- bulbe



Problèmes de MOND dans les amas

A l'intérieur des amas de galaxies, il existe encore de la DM, qui ne peut pas être expliquée par MOND, car **le centre de l'amas** n'est que modérément dans le régime MOND ($0.5 a_0$)

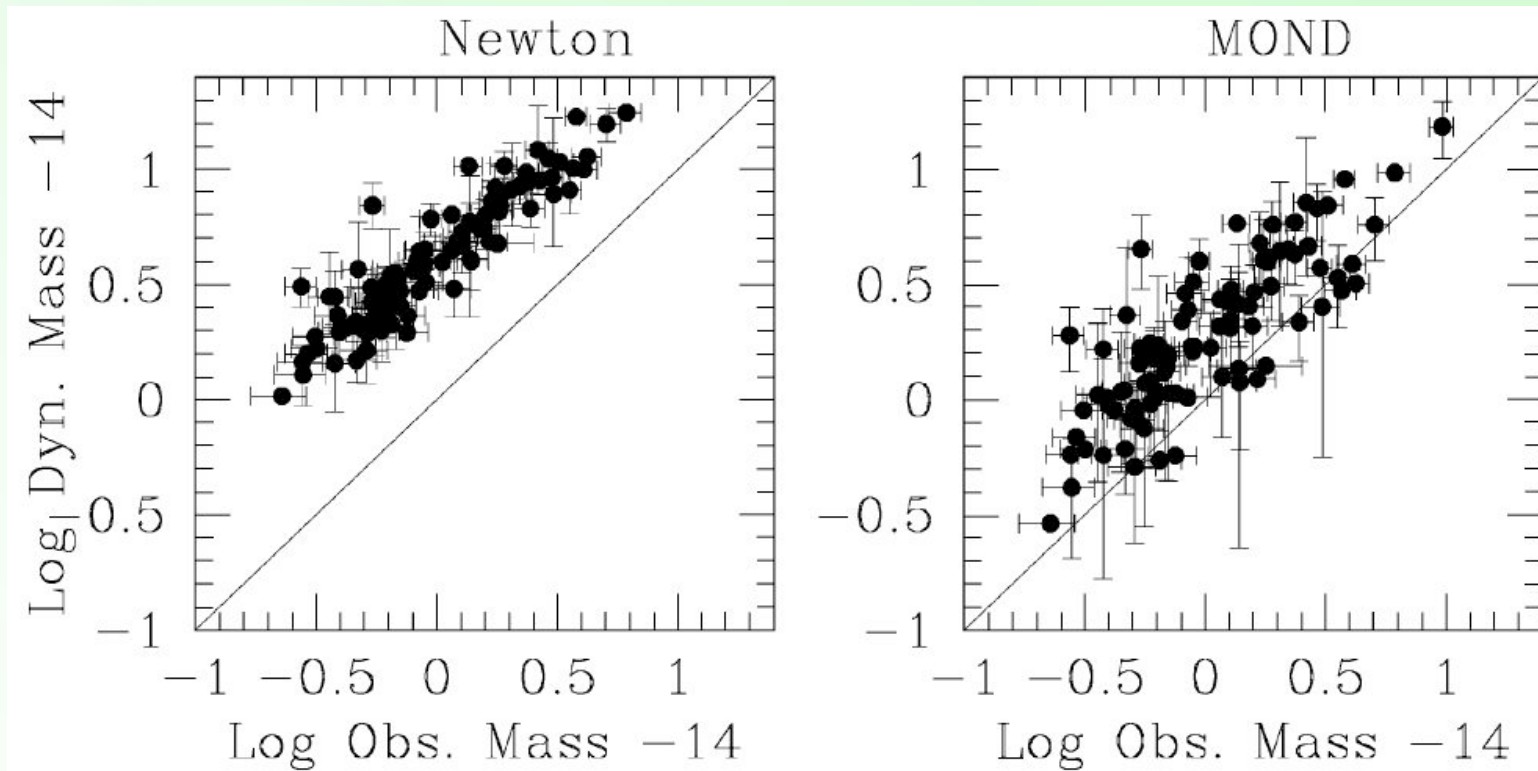
Données en rayons-X: gaz chaud en équilibre hydrostatique, et les lentilles gravitationnelles faibles (cisaillement)

MOND réduit d'un facteur 2 la masse manquante

→ Il reste une autre composante, qui pourrait être des neutrinos....
(plus des baryons)

La fraction baryonique observée n'est pas totalement la fraction universelle (15%) attendue

MOND et les amas

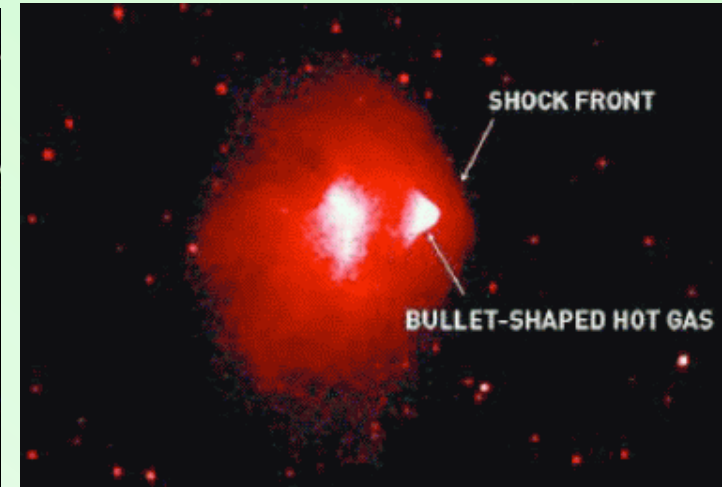
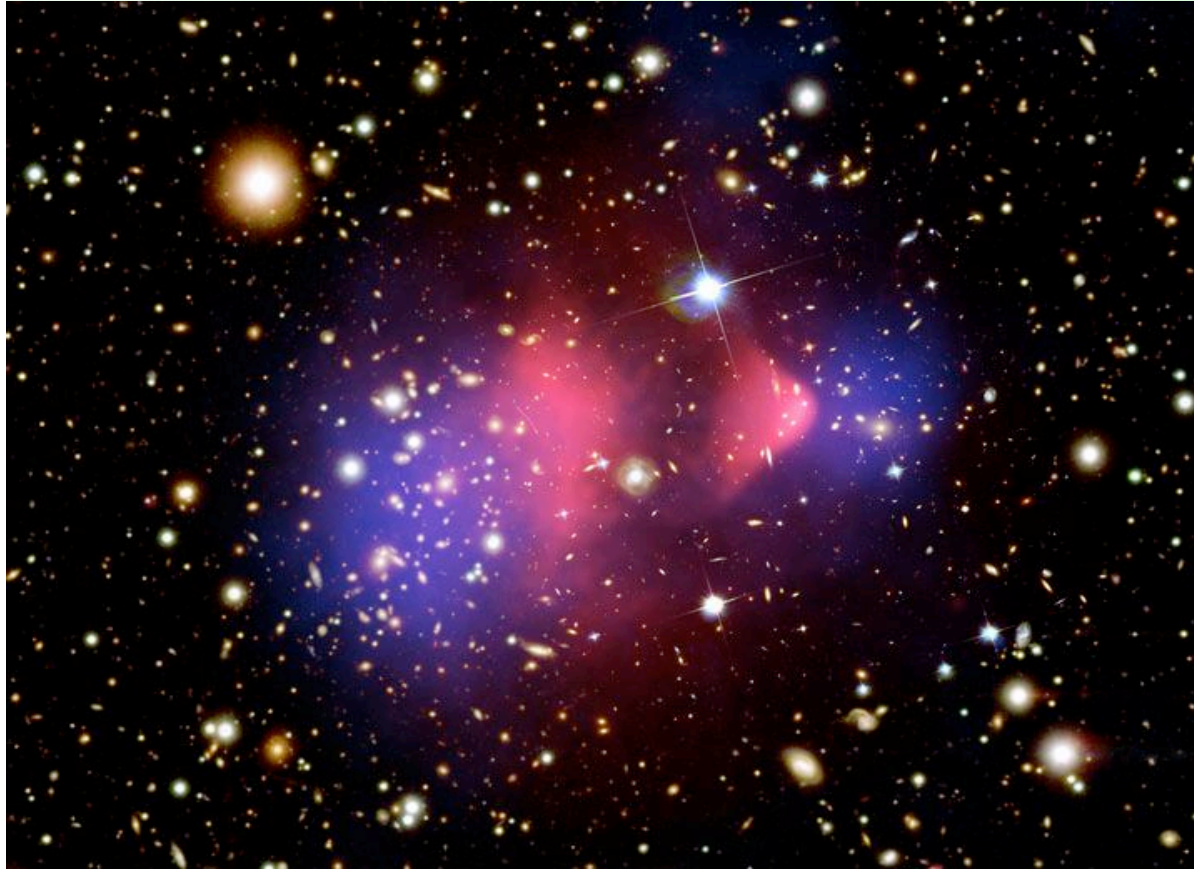


Selon la physique des baryons, du gaz froid pourrait se trouver au centre des amas (flots de refroidissement)

D'autre part, les neutrinos pourrait représenter 2x plus de masse que les baryons

L'amas du boulet

Gaz X



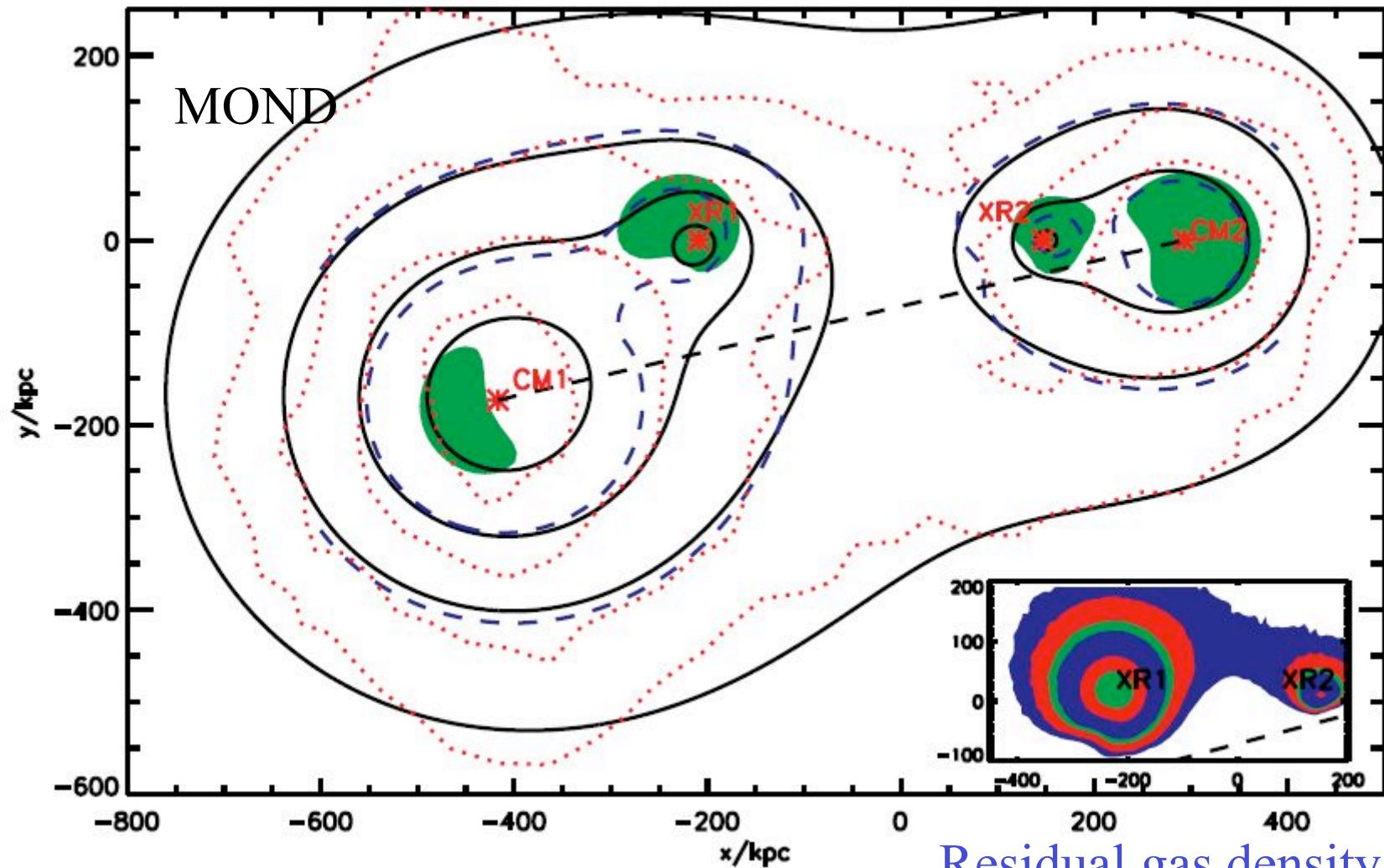
Preuve de l'existence de matière
Non-baryonique?

Masse totale

Explicable avec MOND + neutrinos (% habituel, Angus et al²¹ 2006)

Model of the bullet in MOND (Angus et al 2007)

..... Clowe et al 2006



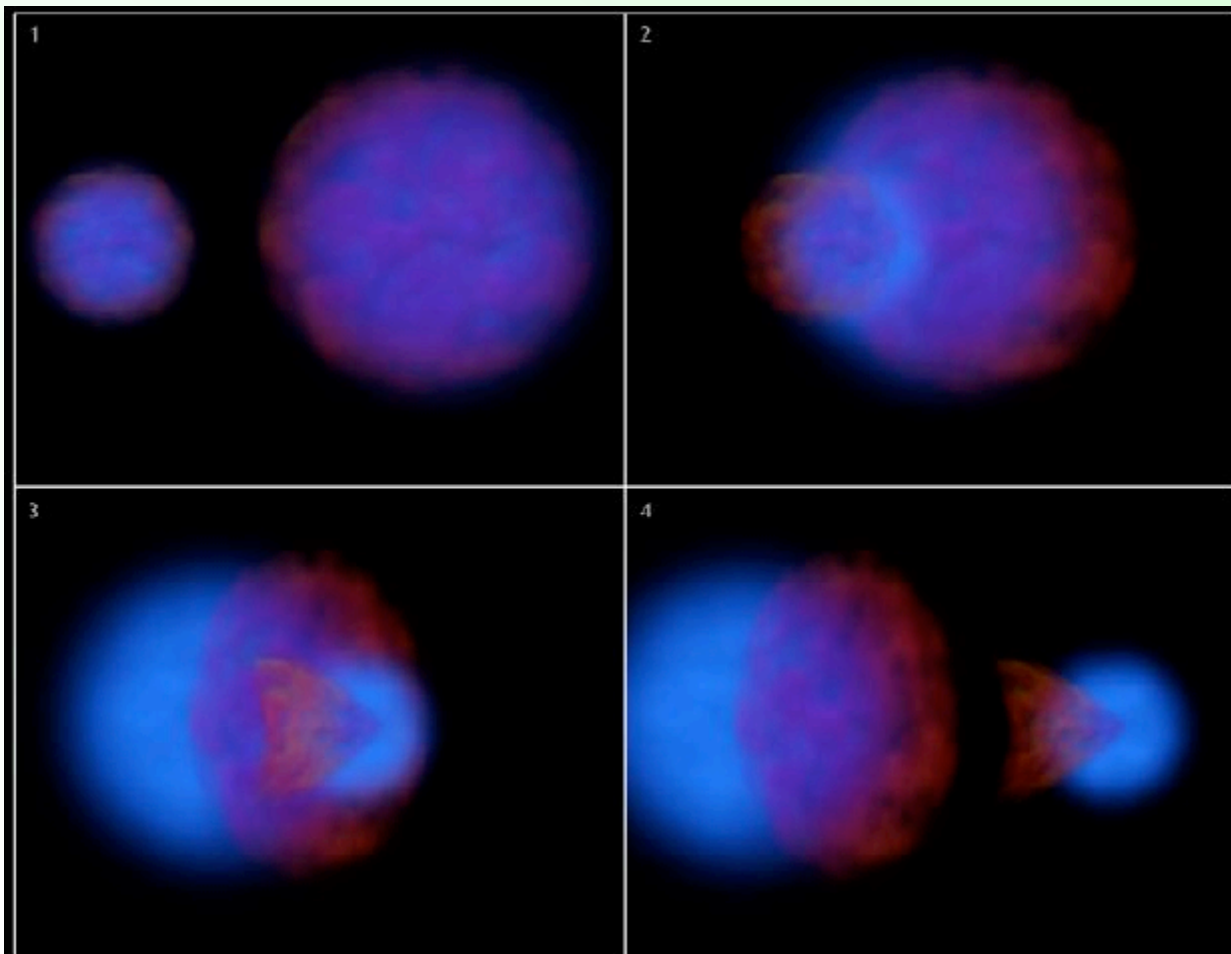
CDM simulation

Collision velocity from the bow-shock = $4700 \pm 500 \text{ km/s}$ (Mach 3)

Hayashi & White 2006 Farrar & Rosen 2007

→ impossible to reconcile with CDM

Milosavljevic et al 2007, Springel & Farrar 2007



CDM can only
 $V < 3500 \text{ km/s}$
MOND $> 4500 \text{ km/s}$

Collision by 16%
over-estimated?

V_{gas} could be higher
than V_{CDM} 23

Mahdavi et al 2007

Abell 520

$z=0.201$

Red= X-ray gas

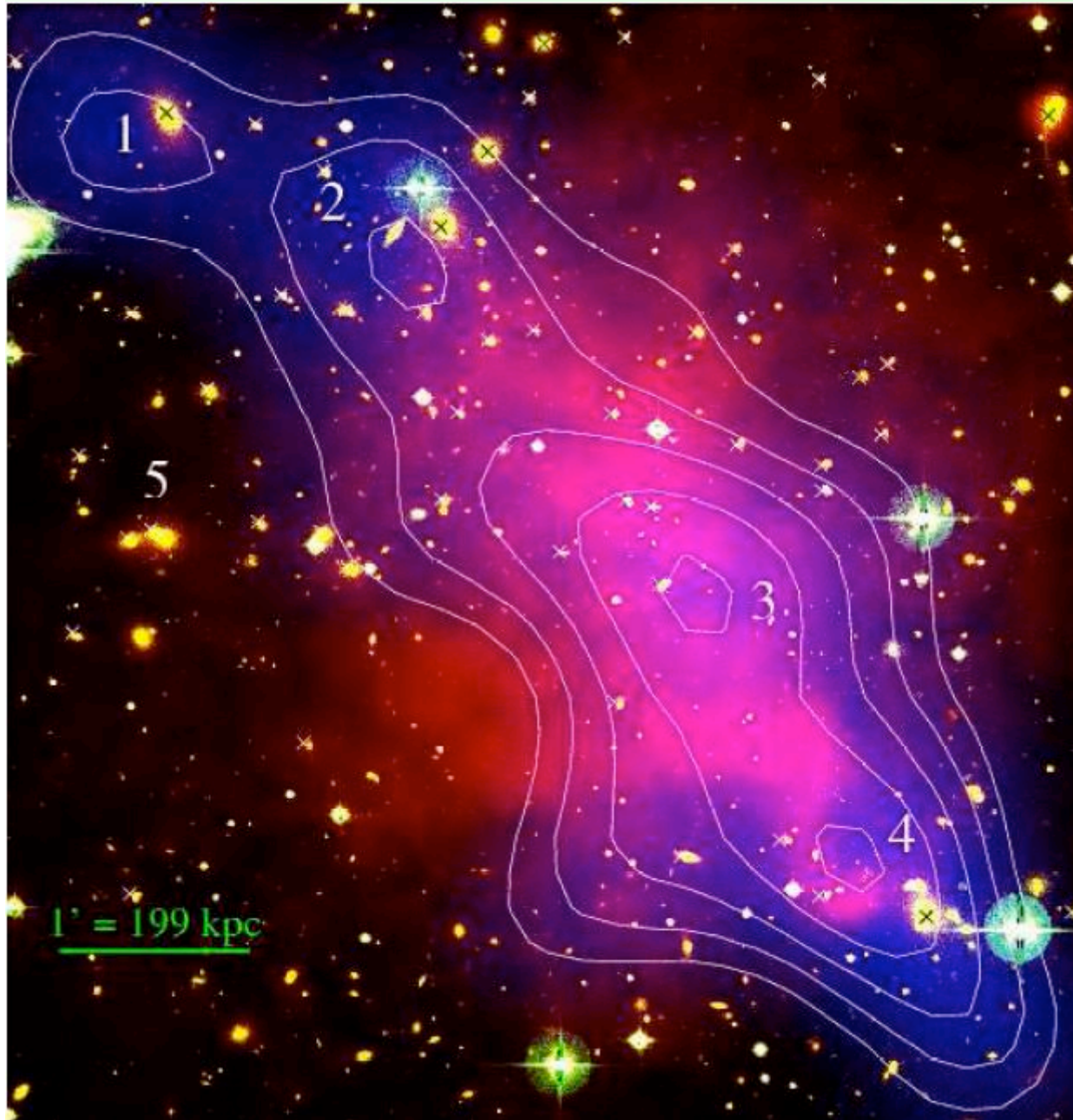
Contours= lensing

→ Massive DM core

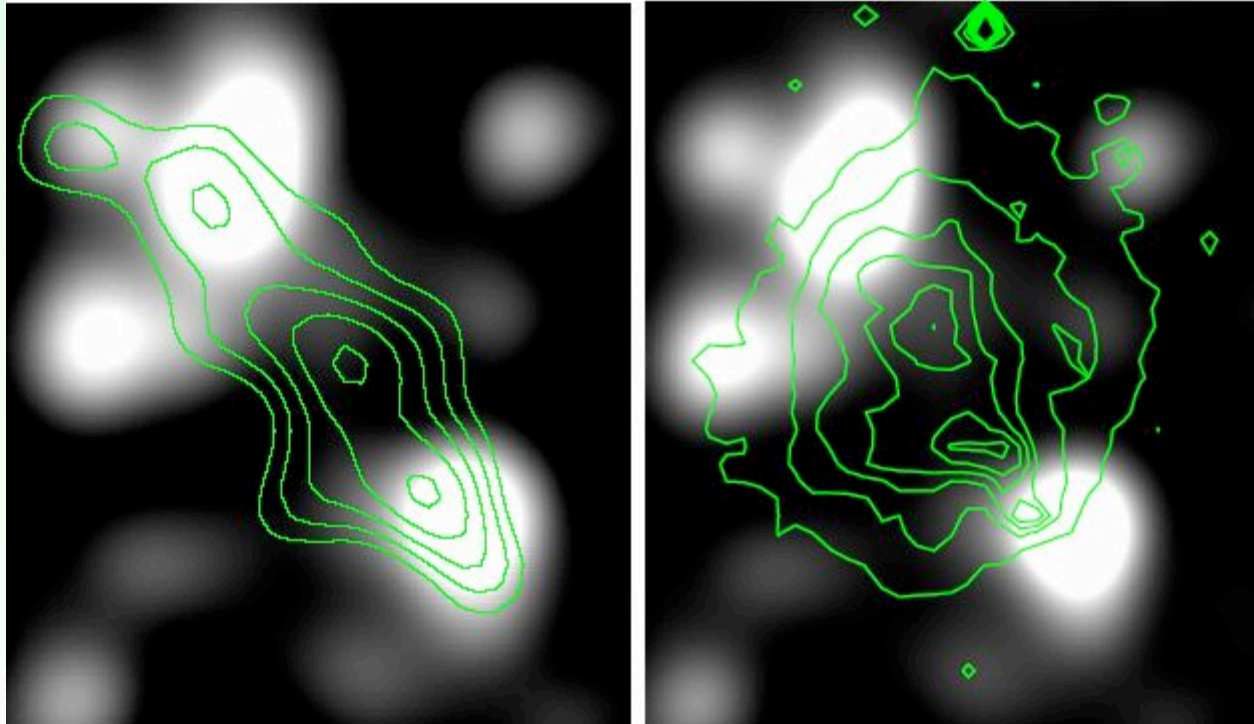
Coinciding with X gas
but devoid of galaxies

Cosmic train wreck

Opposite case!



Abell 520 merging clusters



Contours=total mass

Contours = X-ray gas

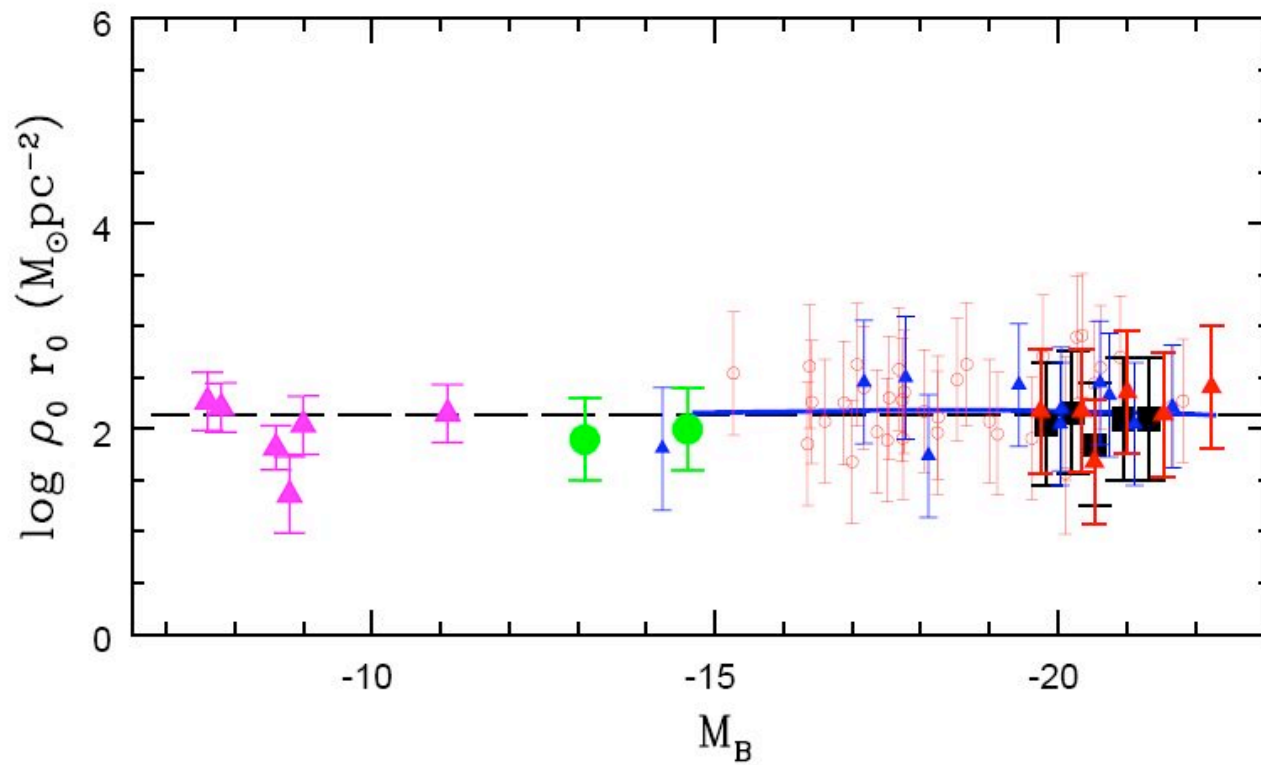
How are the galaxies ejected from the CDM peak??

Constraints on MOND from galaxy dynamics and observations

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

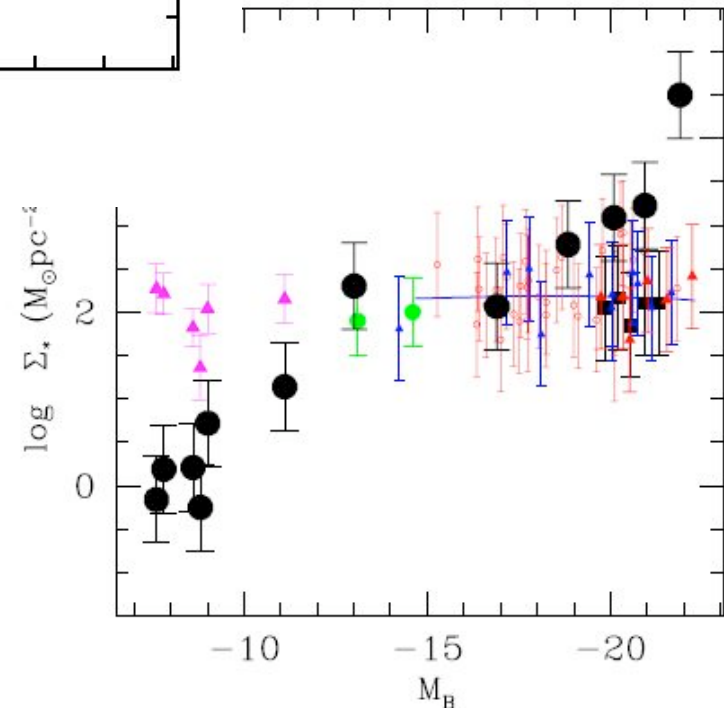
Can we determine the form of the interpolation function μ ?

Scaling laws, DM surface density



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

$$\Sigma_M = 142 M_\odot/\text{pc}^2$$



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

Implications

→ $\Sigma_M = 138 (a_0/1.2 \text{ E}10\text{m/s}^2) M_\odot/\text{pc}^2$

In MOND: the « phantom »
dark matter added under
the Newton hypothesis,
has the appearance of a
Cste Σ , $\propto a_0$
(Milgrom 2009)

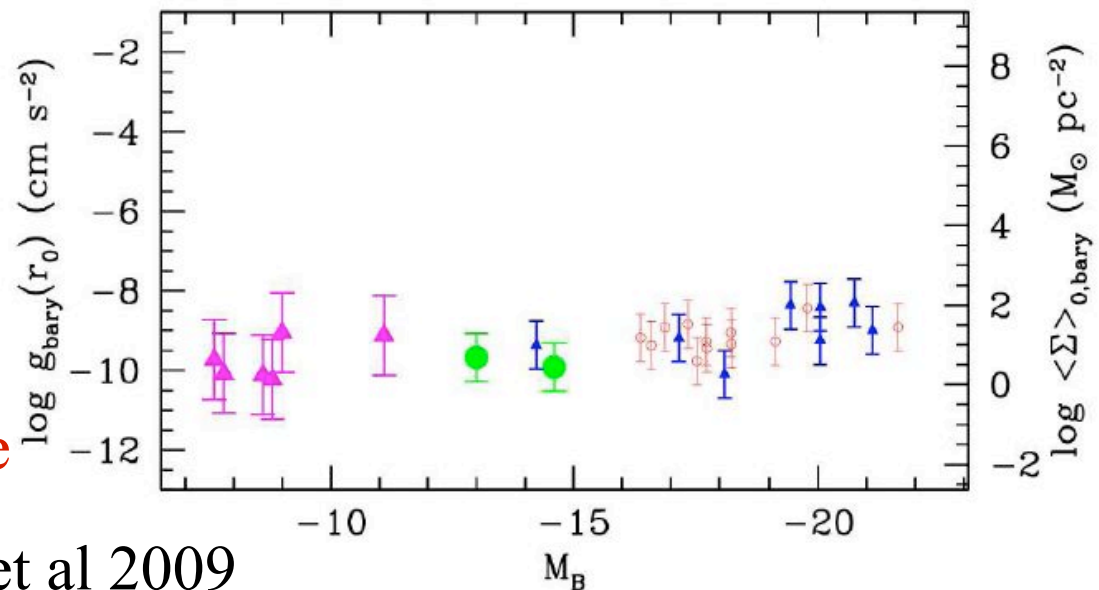
At least if the central parts
are Newtonian

It is possible to have systems
with lower densities $\sim 0.5 \Sigma_M$

Not in the Donato et al sample

Large central Σ_b means
high DM core radius

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



Gentile et al 2009

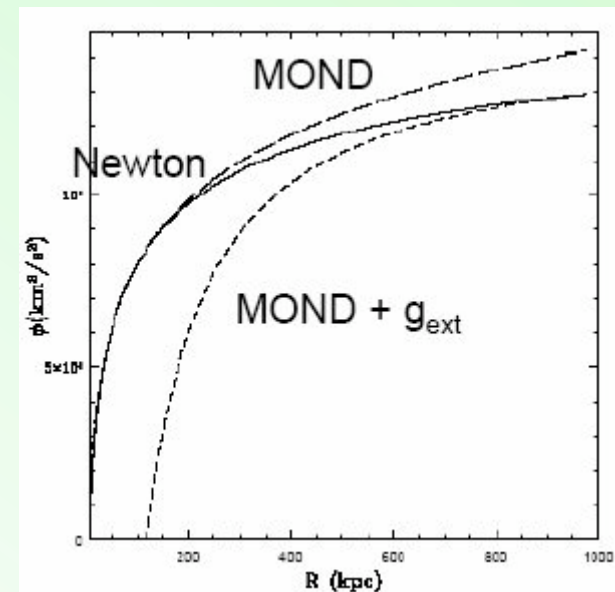
Vitesse d'échappement

Potentiel en régime MONDien $\Phi(r) = (GMa_0)^{1/2} \ln r$

$\frac{1}{2} V_{\text{esc}}^2 = \Phi(\infty) - \Phi(r) \rightarrow$ pas d'échappement possible!

Mais une galaxie n'est jamais totalement isolée \rightarrow Effet du Champ extérieur

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



EFE: External Field Effect

If external field g_e is in the X direction

At large radii, it is equivalent to a dilatation Δ

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

Define an internal potential Φ_{int}

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

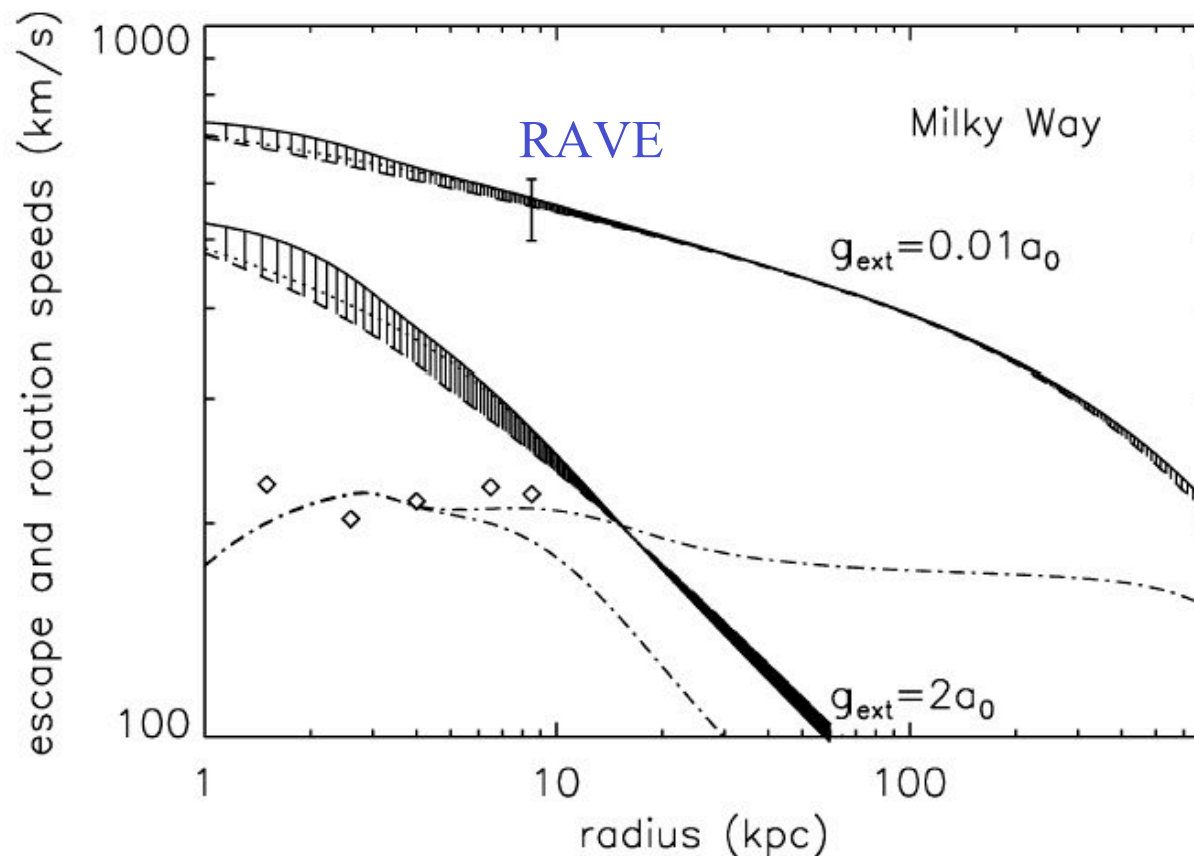
Where $g \ll g_e \ll a_0$

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

Voie Lactée: effet d'Andromède

Observations RAVE (Smith et al 2007) $\rightarrow 498 < v_{\text{esc}} < 608 \text{ km s}^{-1}$

544 km/s $\rightarrow g_e = a_0/100$



Wu et al 2007
Simulations avec
le modèle de
Besançon

Stability of galaxy disks

spirals and bars are the motor of evolution

CDM: Spheroidal haloes stabilise the disks

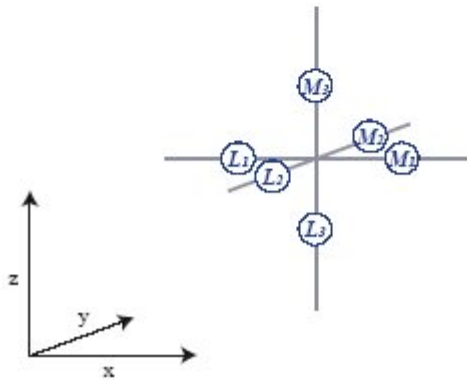
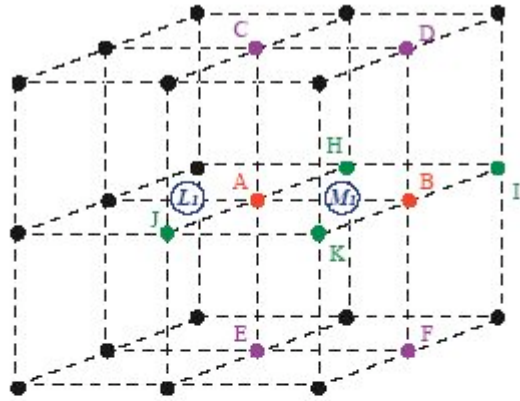
MOND; disks are entirely self-gravitating

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

Bars grow when angular momentum is transferred
→ accepted by spheroidal haloes

Disk dynamics in MOND

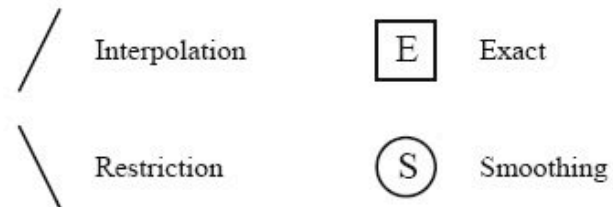
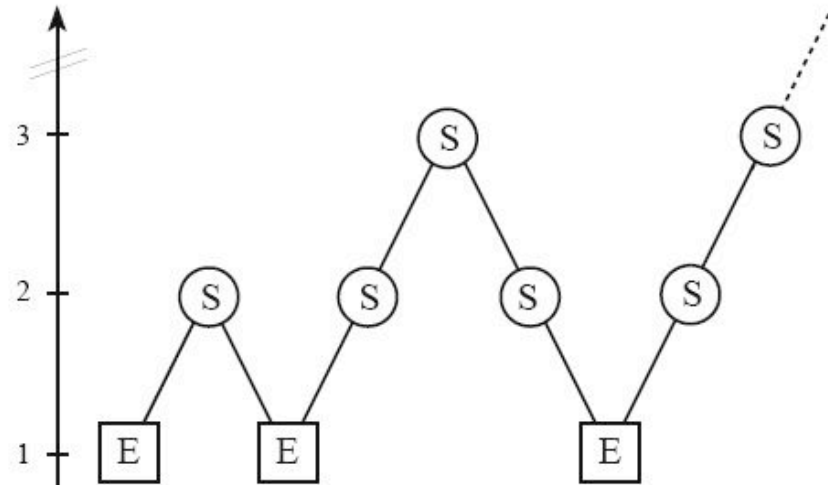
Multi-grid algorithm



Finite Differences
+ adaptive grid

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

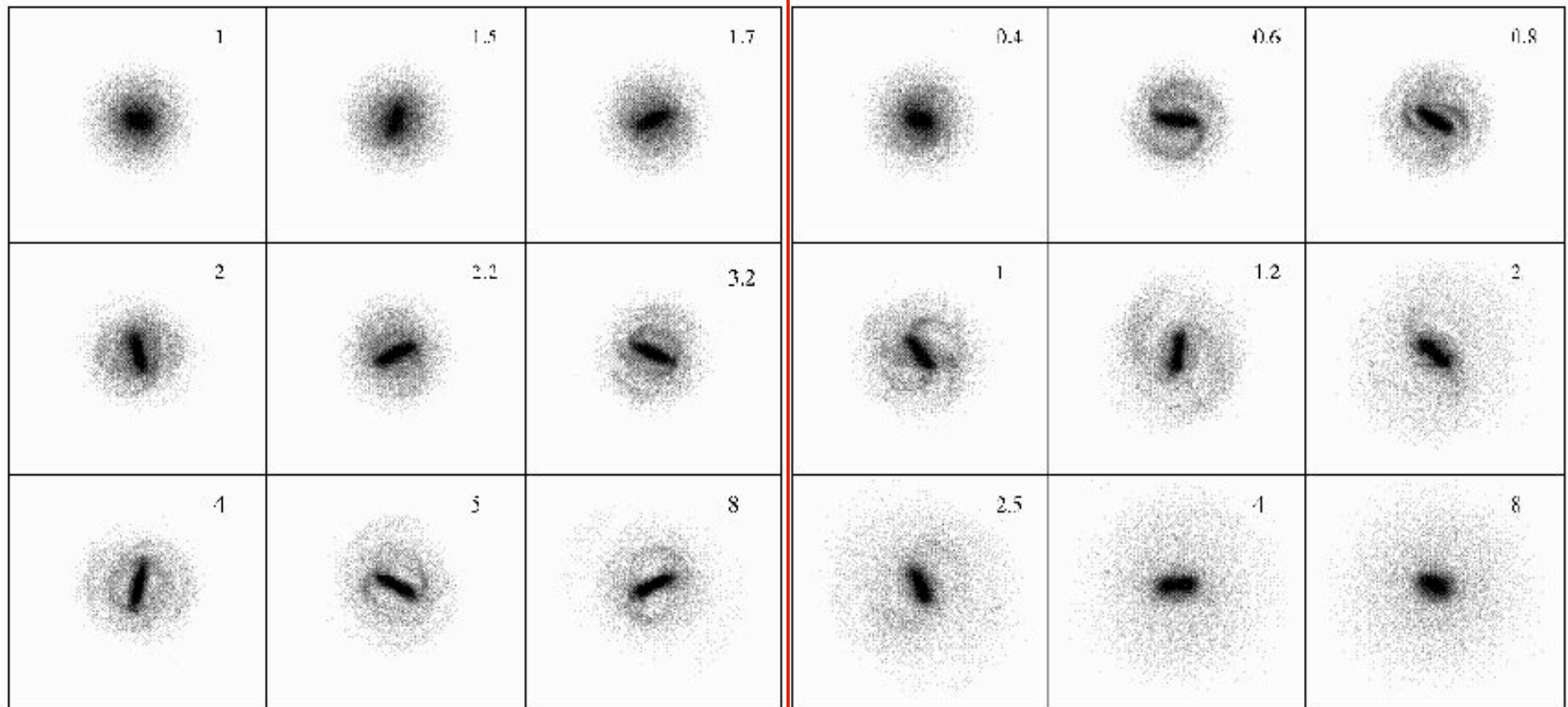
Grid level



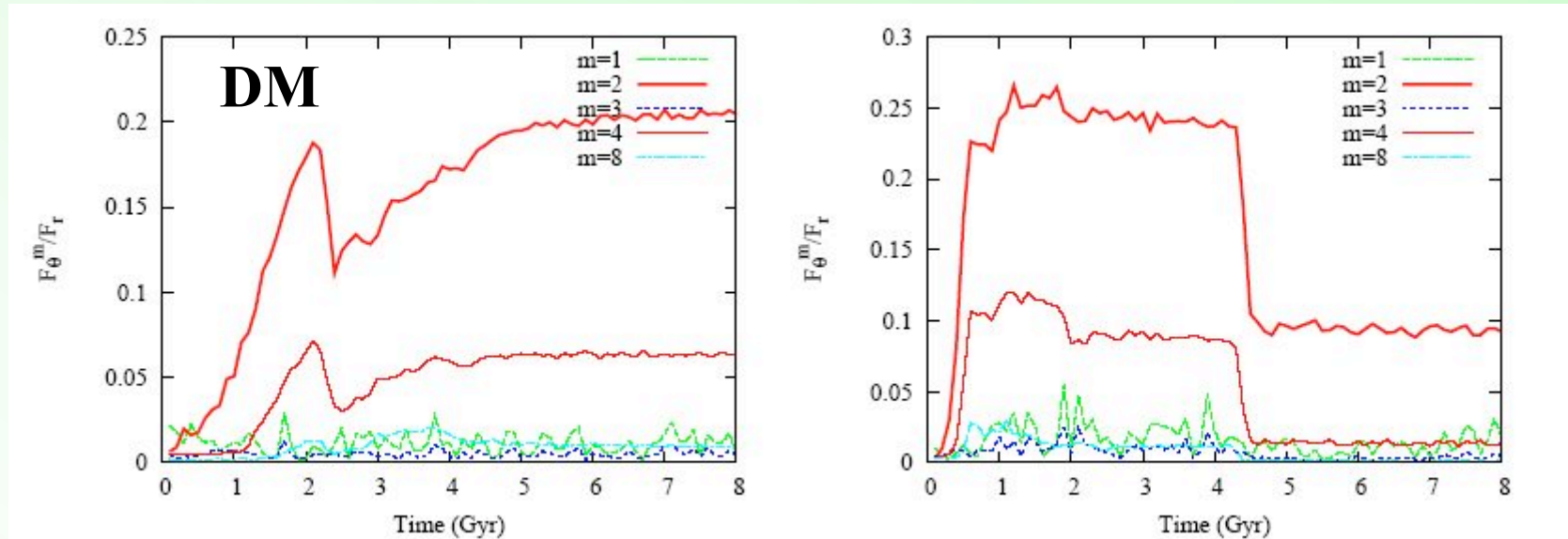
Influence of DM halo

With DM halo

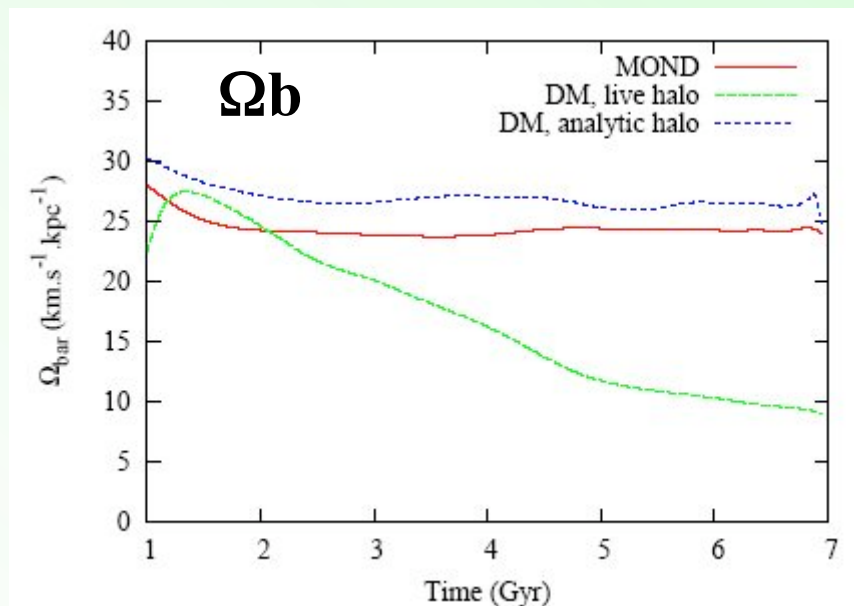
Without DM (MOND)



Bar strength and pattern speed with and w/o DM

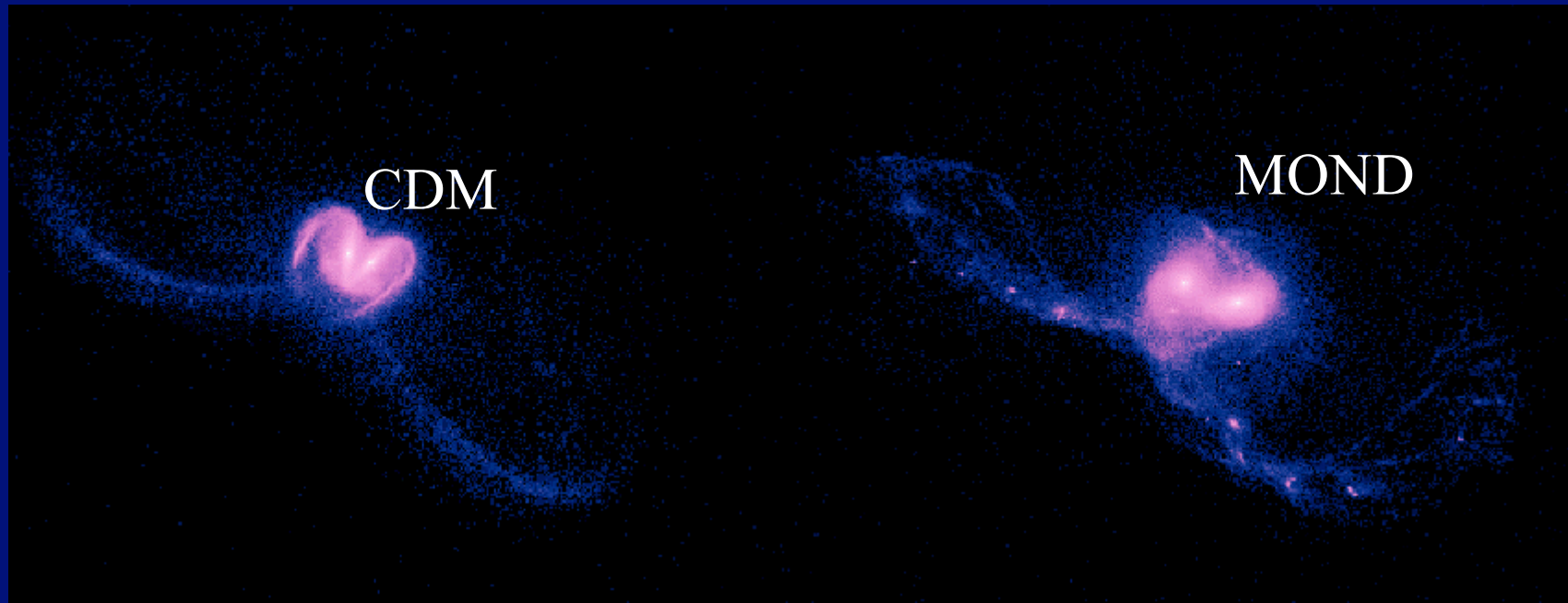


With DM, the bar appears later, and can reform after the peanut weakening through halo AM exchange, → But Ω_b falls off



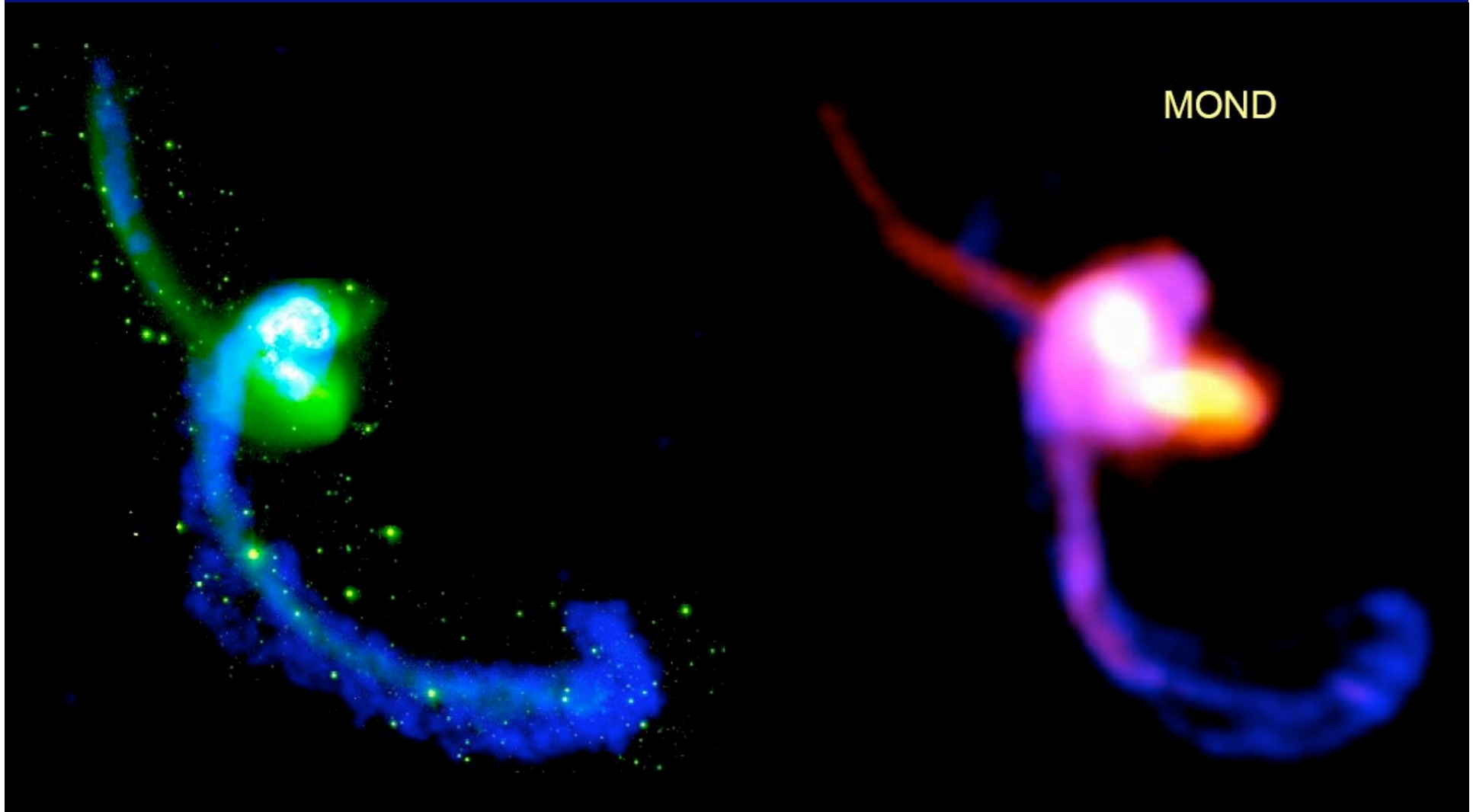
Interactions of galaxies: the Antennae: MOND versus CDM

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

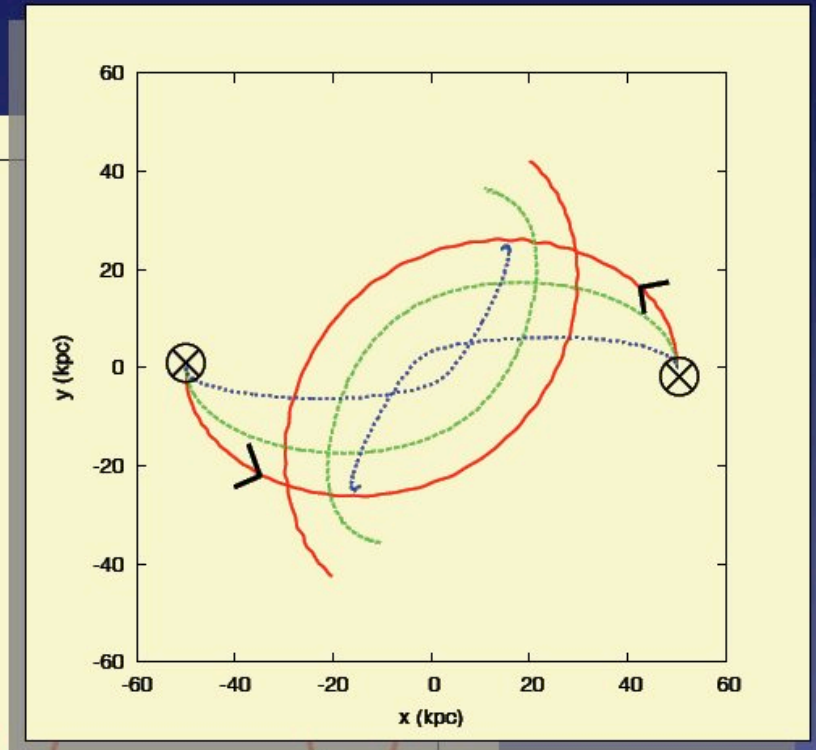
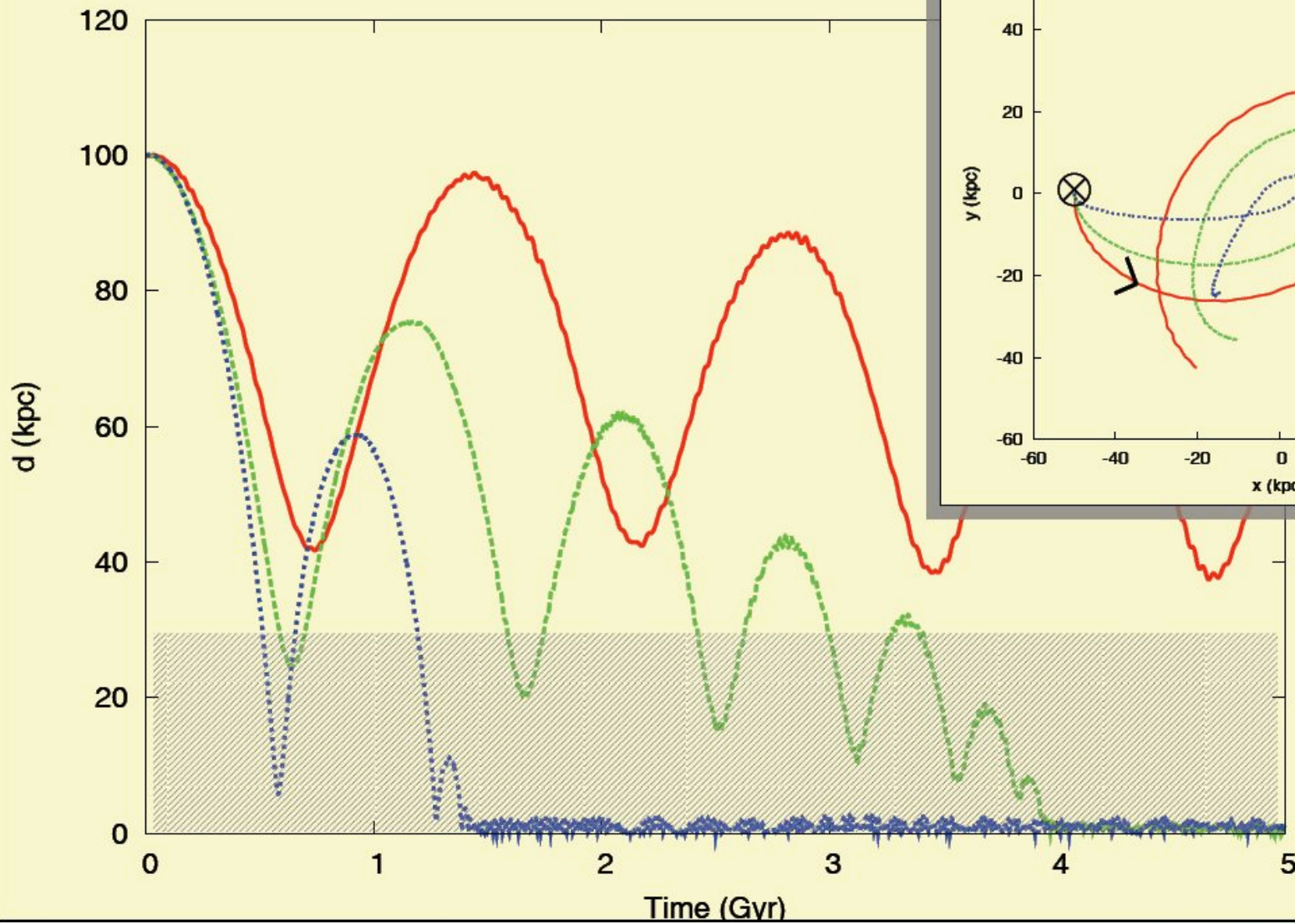


Also much longer time-scale for
merging of dissipationless galaxies (Nipoti et al 2007)

Simulations of the Antennae



Friction Dynamique



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

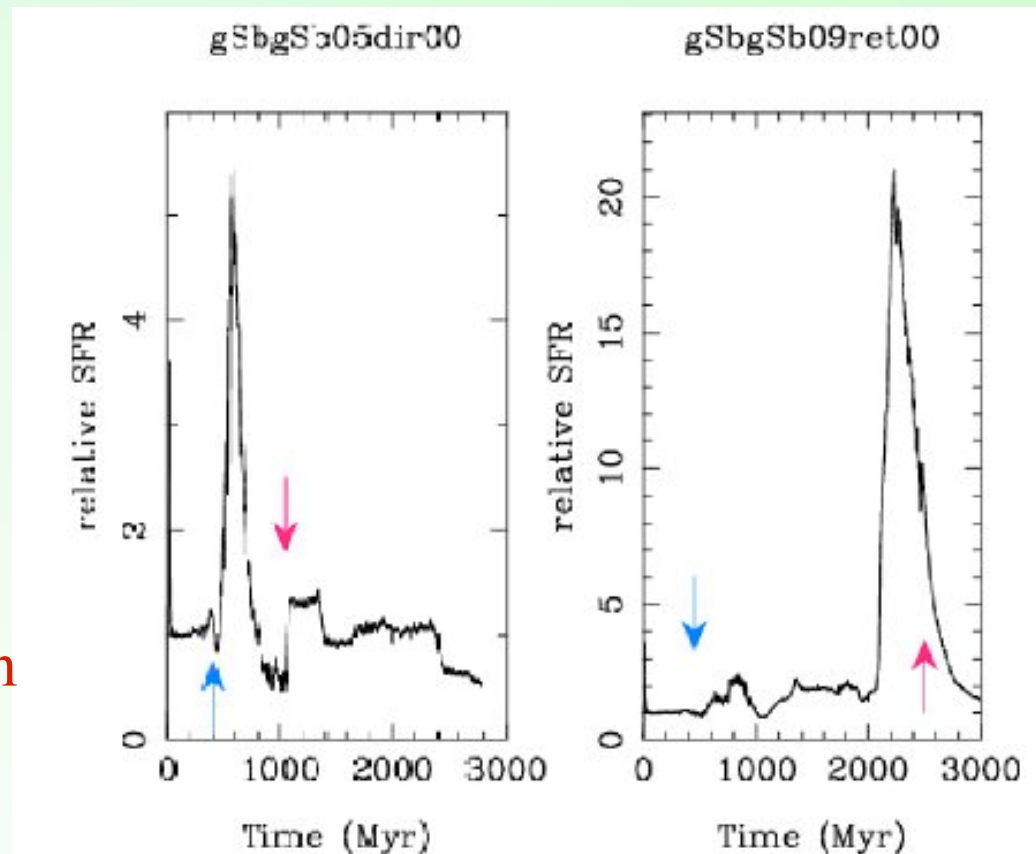
Merger induced starbursts degeneracy

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



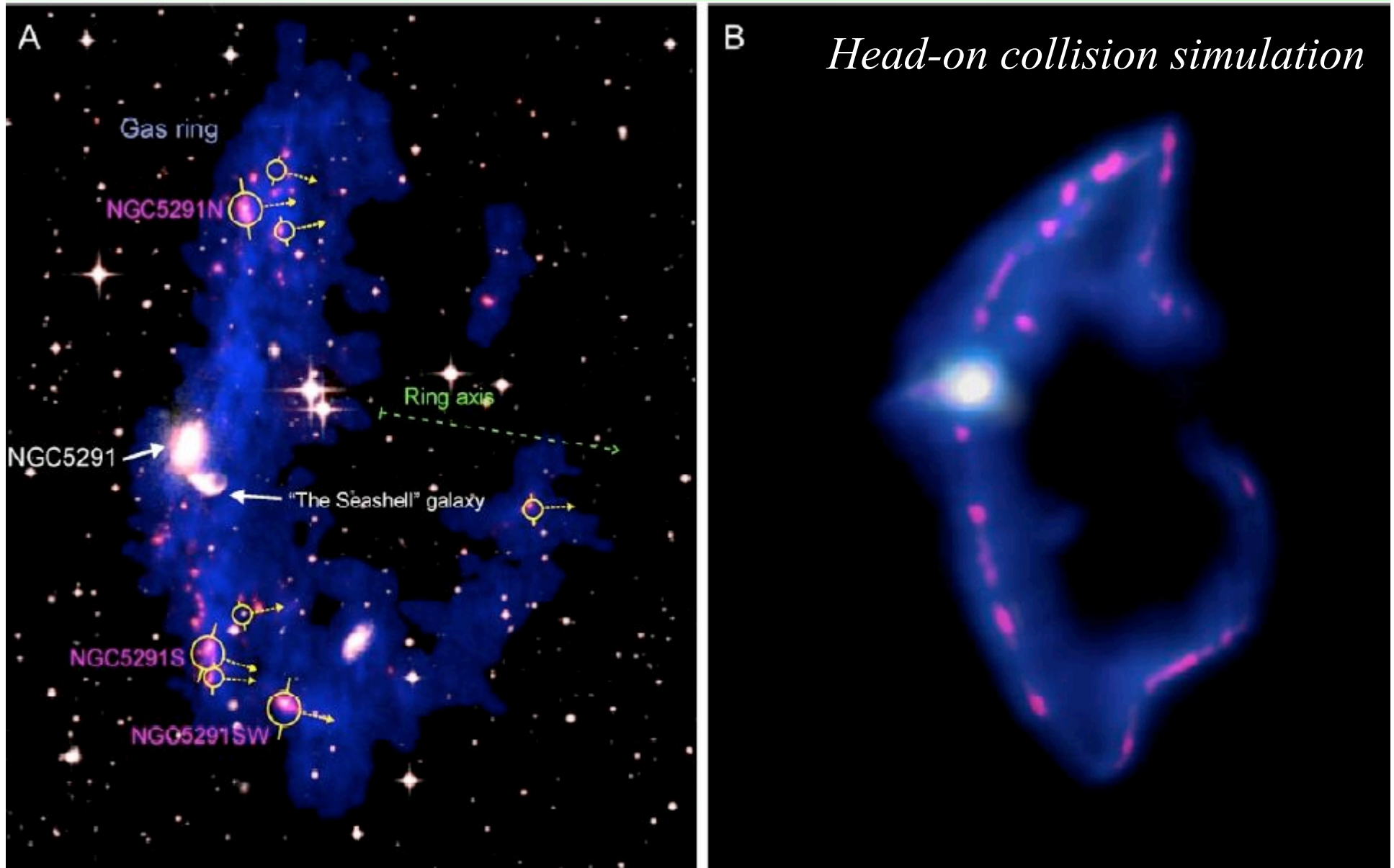
Formation of Tidal Dwarf Galaxies

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)

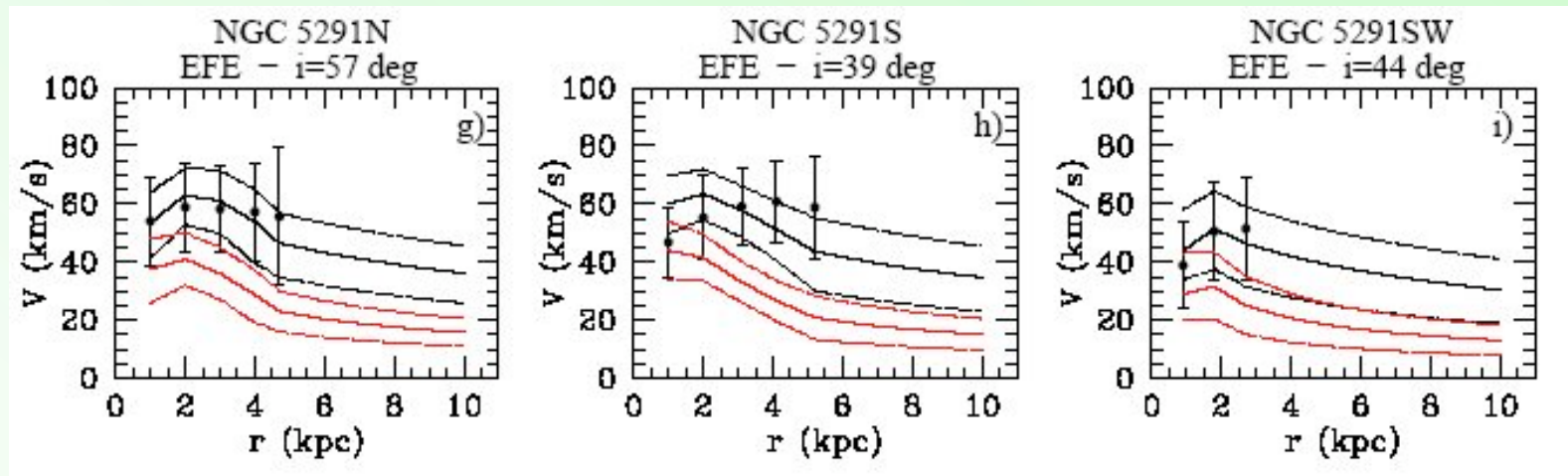


TDG in N5291 HI ring



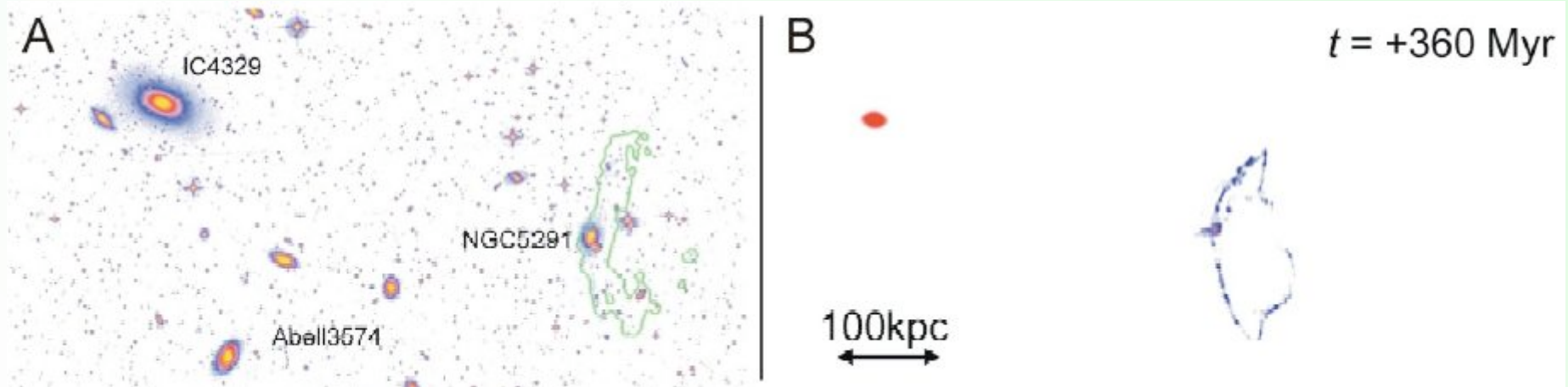
Bournaud et al 2007

Dynamics of the TDGs



With MOND, *Gentile et al 2007*

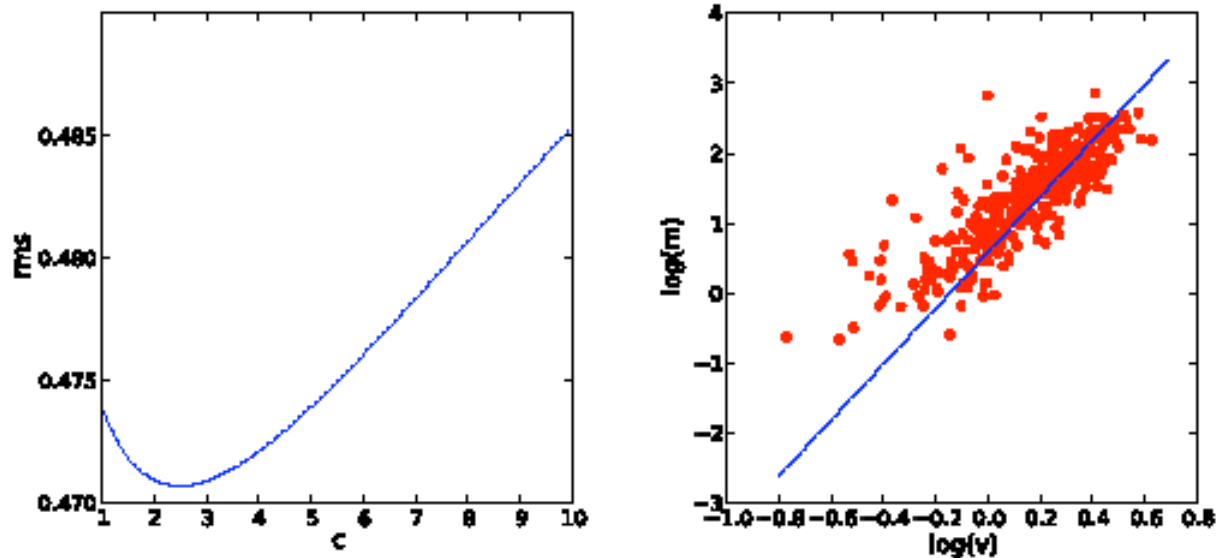
All inclinations = 45° , from simulations (Bournaud et al 07) \rightarrow dark H_2



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?

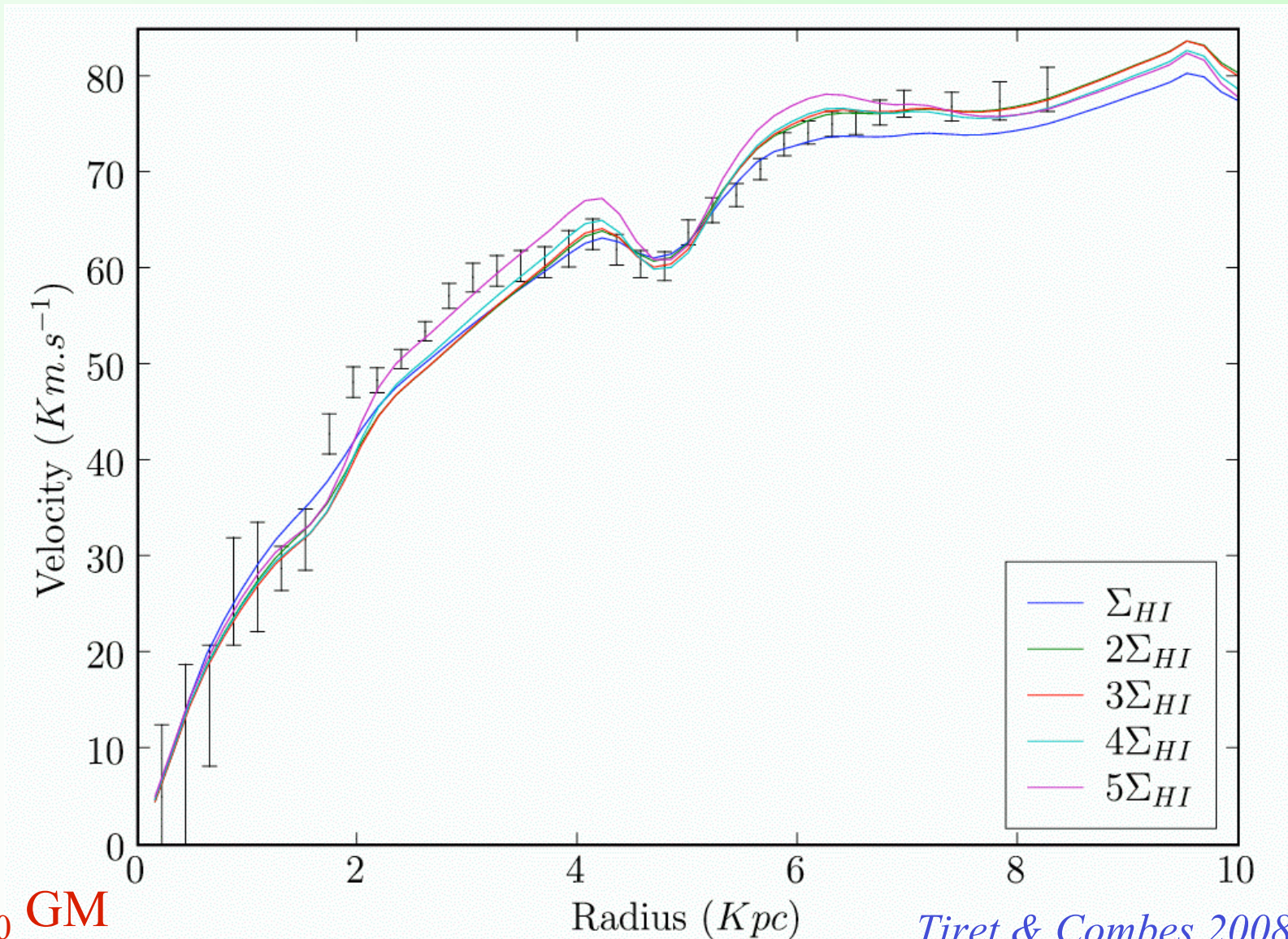
Fit of ~ 50 rotation curves, $c = M(\text{dark})/M_{\text{HI}}$



Tiret & Combes 08, Milgrom 07

Combination with MOND

NGC 1560: fits with variation of $a_0 \sim 1/(\text{gas}/\text{HI})$



$$V^4 = a_0 GM$$

Tiret & Combes 2008

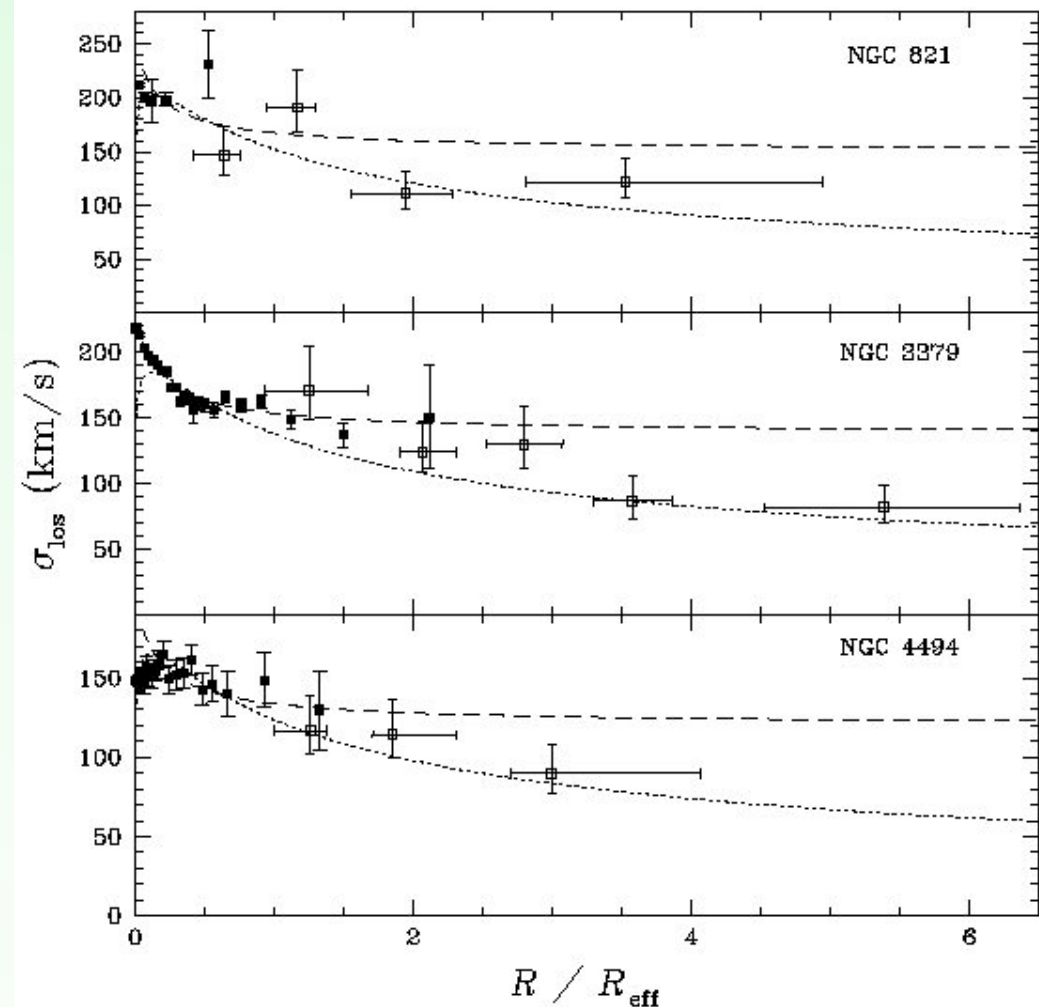
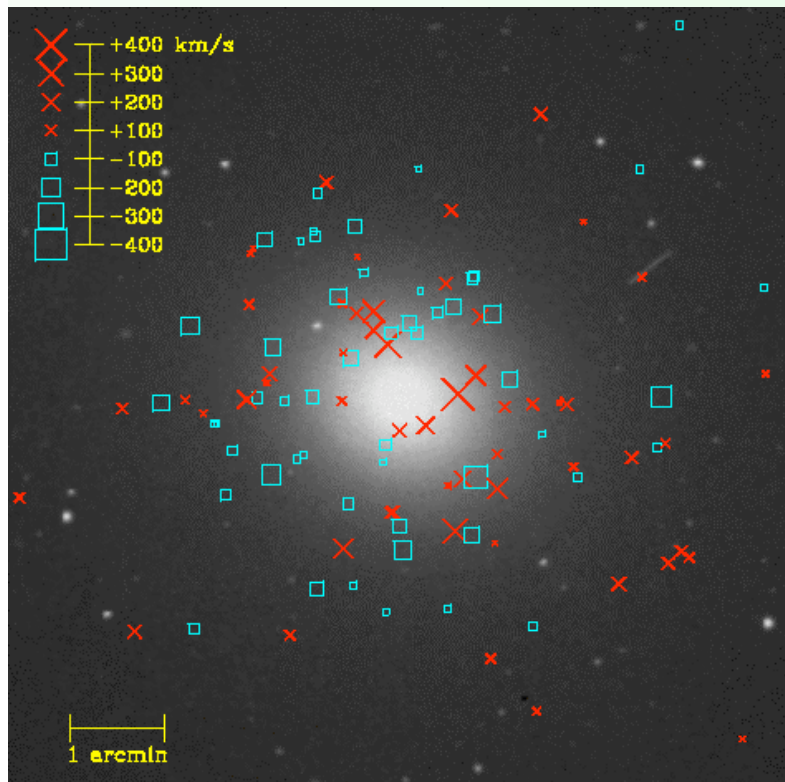
Dark matter in Ellipticals

Planetary Nebulae: Romanowsky et al 2003

Dearth of dark matter??

..... Visible matter (isotropic)

- - - isothermal (isotropic)

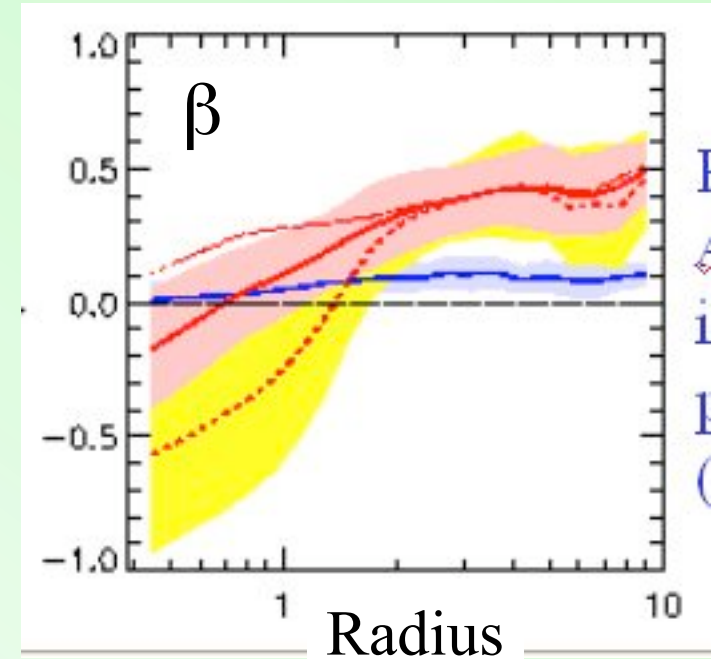


Anisotropy of velocities

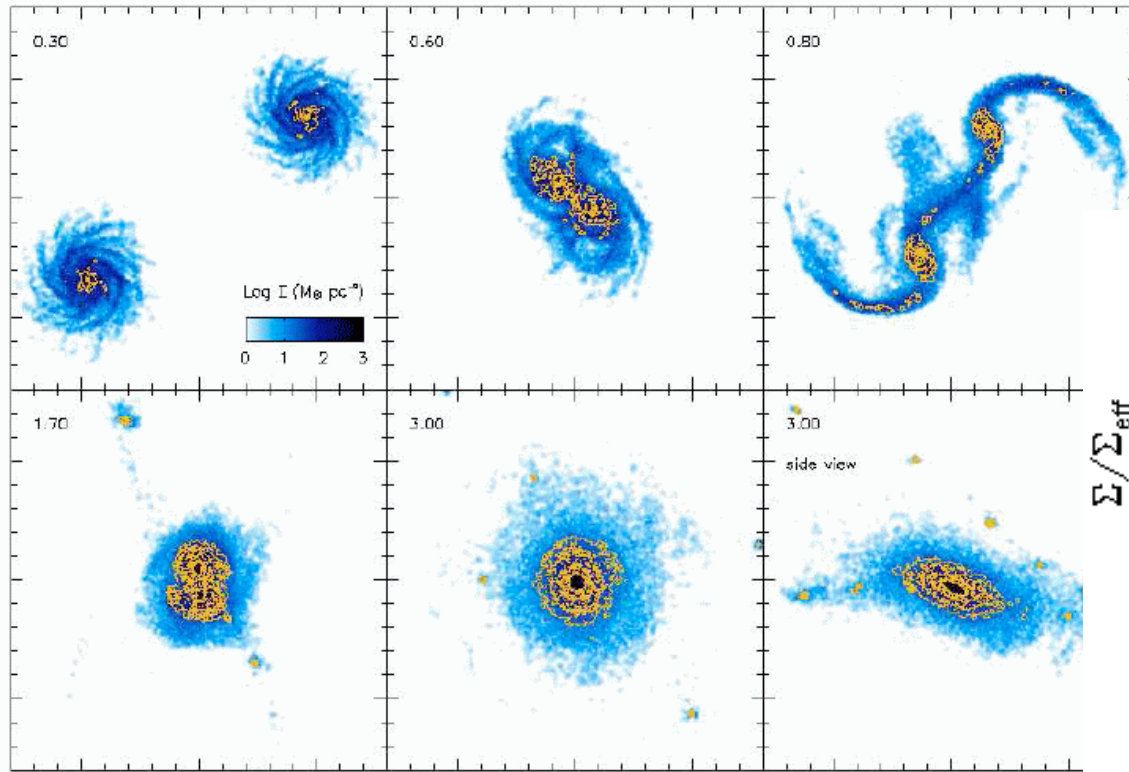
$$\beta = 1 - \sigma_{\theta}^2 / \sigma_r^2, \quad -\infty, 0, 1$$

β circular, isotropic and radial orbits

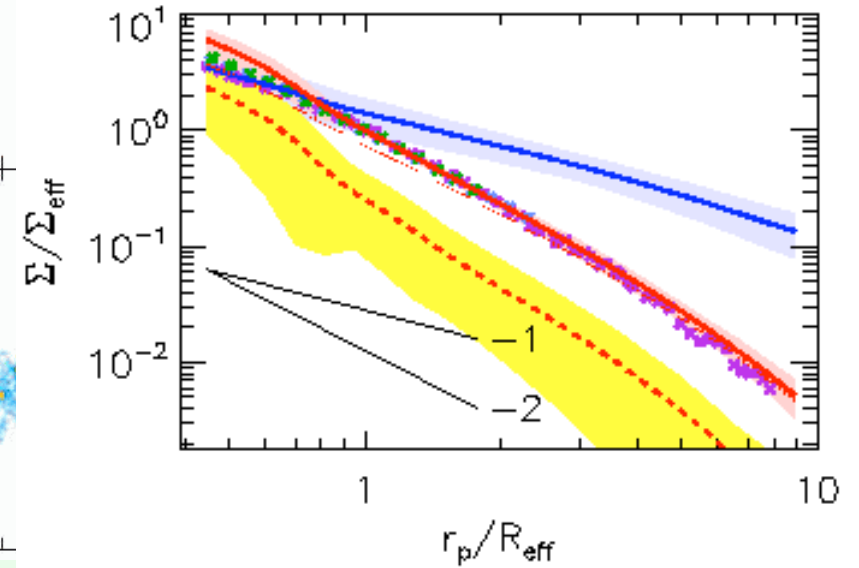
When galaxy form by mergers, orbits in the outer parts are strongly radial, which could explain the low projected dispersion (Dekel et al 2005)



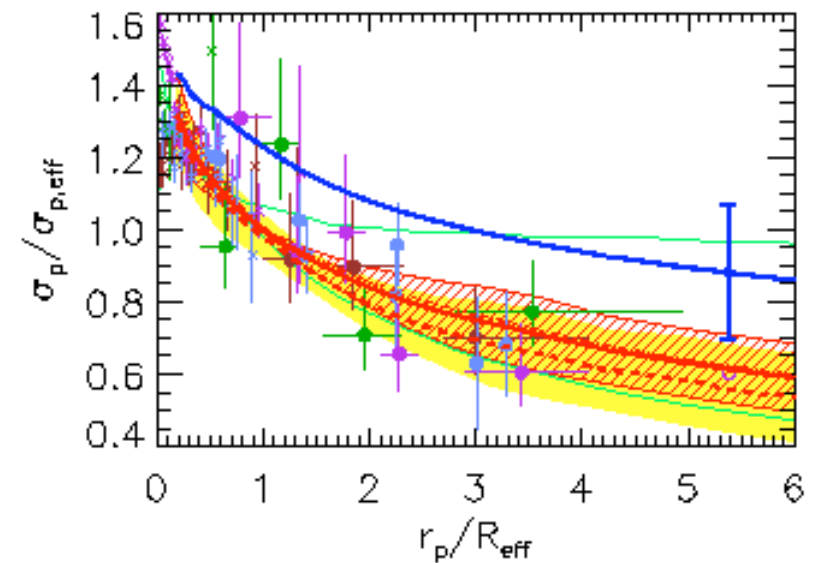
The observation of the velocity profile is somewhat degenerate and cannot lead to the dark matter content univocally



Young stars are
in yellow contours



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



DM profile from satellites

SDSS, 2500 deg², 3000 satellites $M_b = -16, -18$ (galaxies -14)

Removal of interlopers

$\sigma_v = 120 \text{ km/s}$ 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

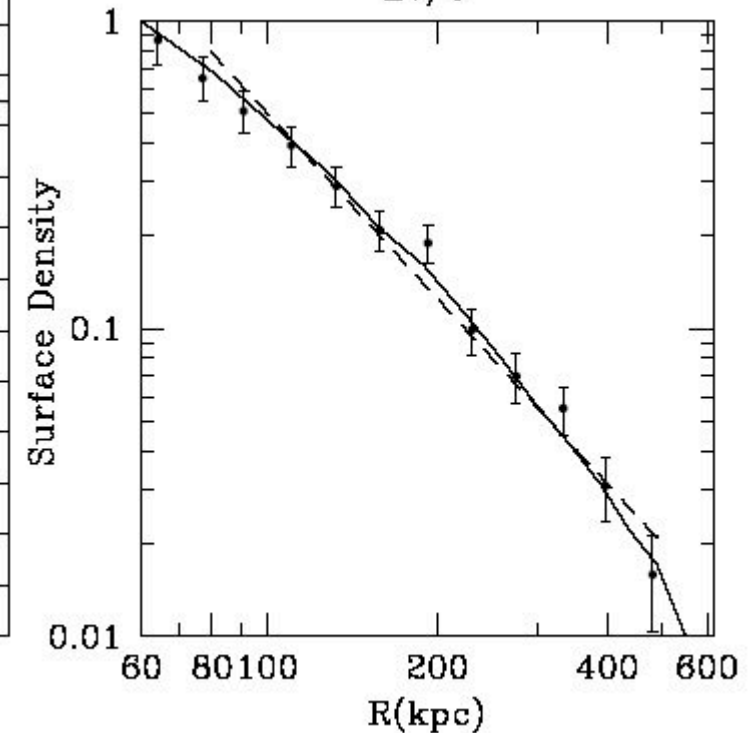
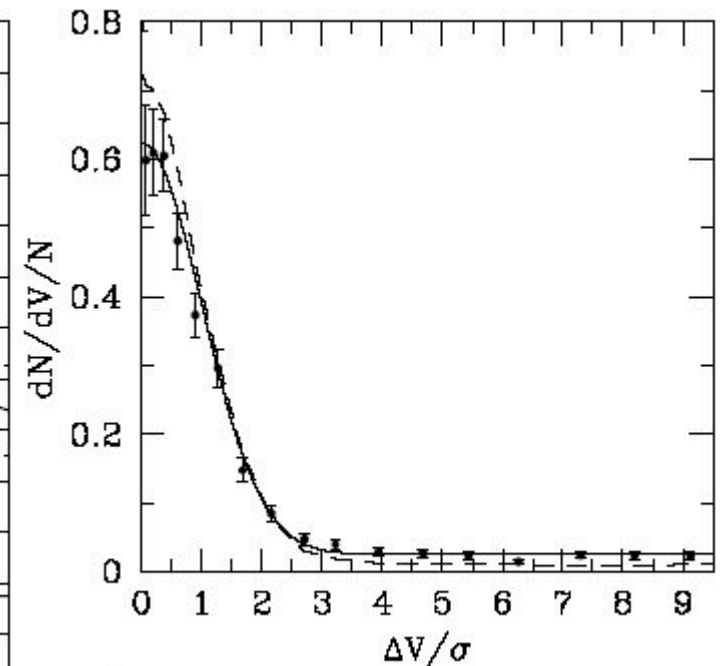
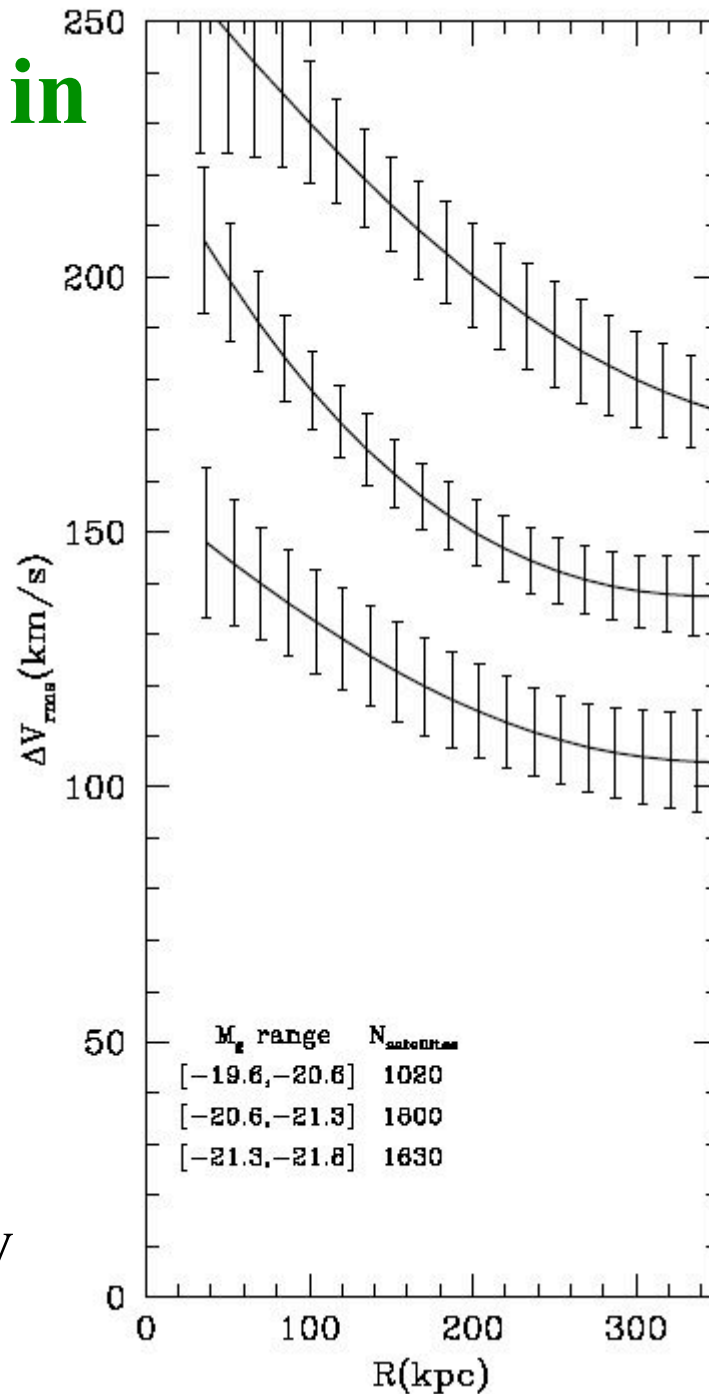
But flat velocity dispersion recovered (as if $\rho \sim r^{-2}$)

Satellites in SDSS

Klypin & Prada 2009

Statistical satellites

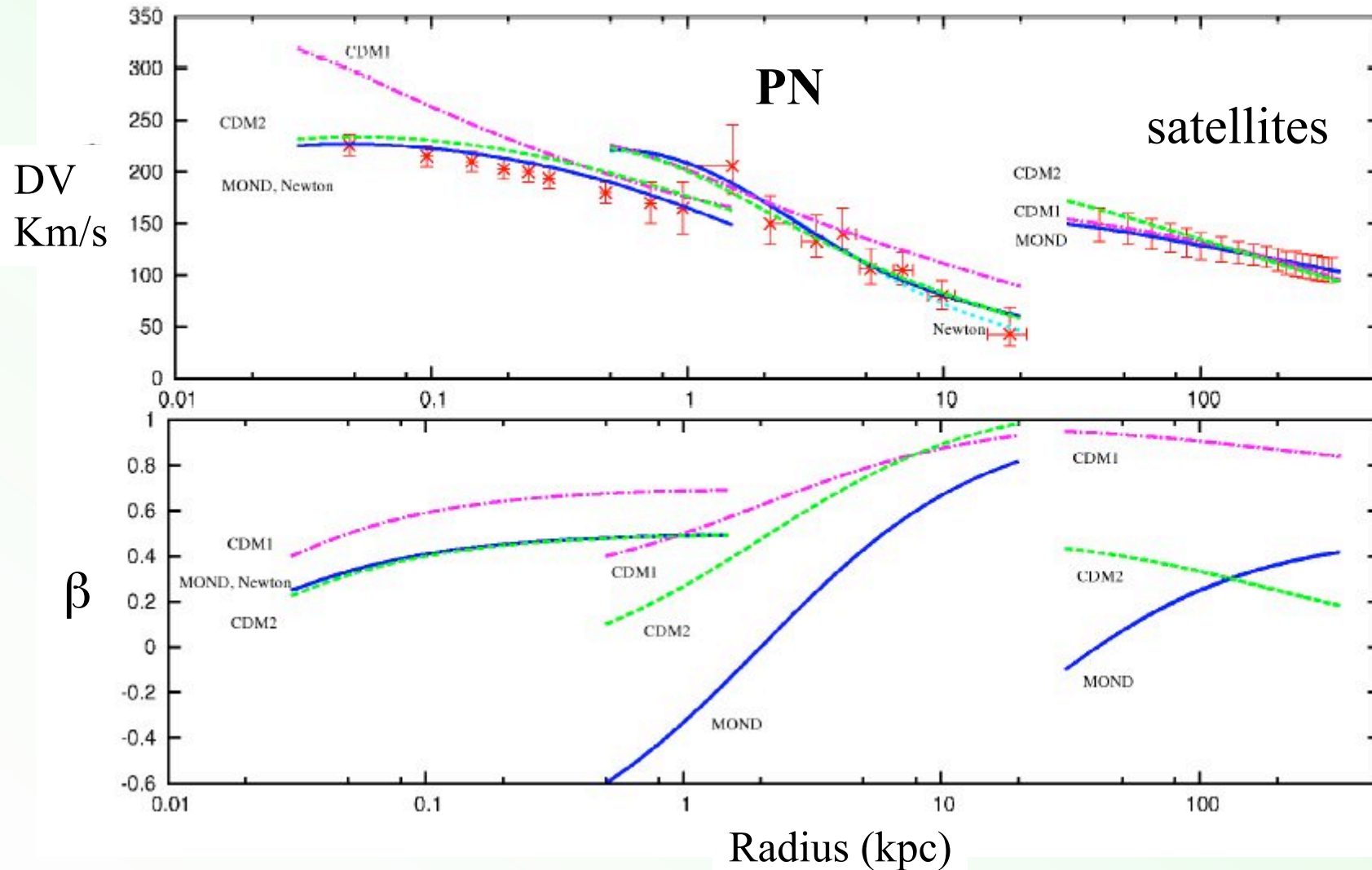
Only 1 or 0 for each galaxy



Test of the SDSS satellites

2 types of CDM CDM1: NFW cusp
CDM2: as required by rotation curves

Tiret et al 2007

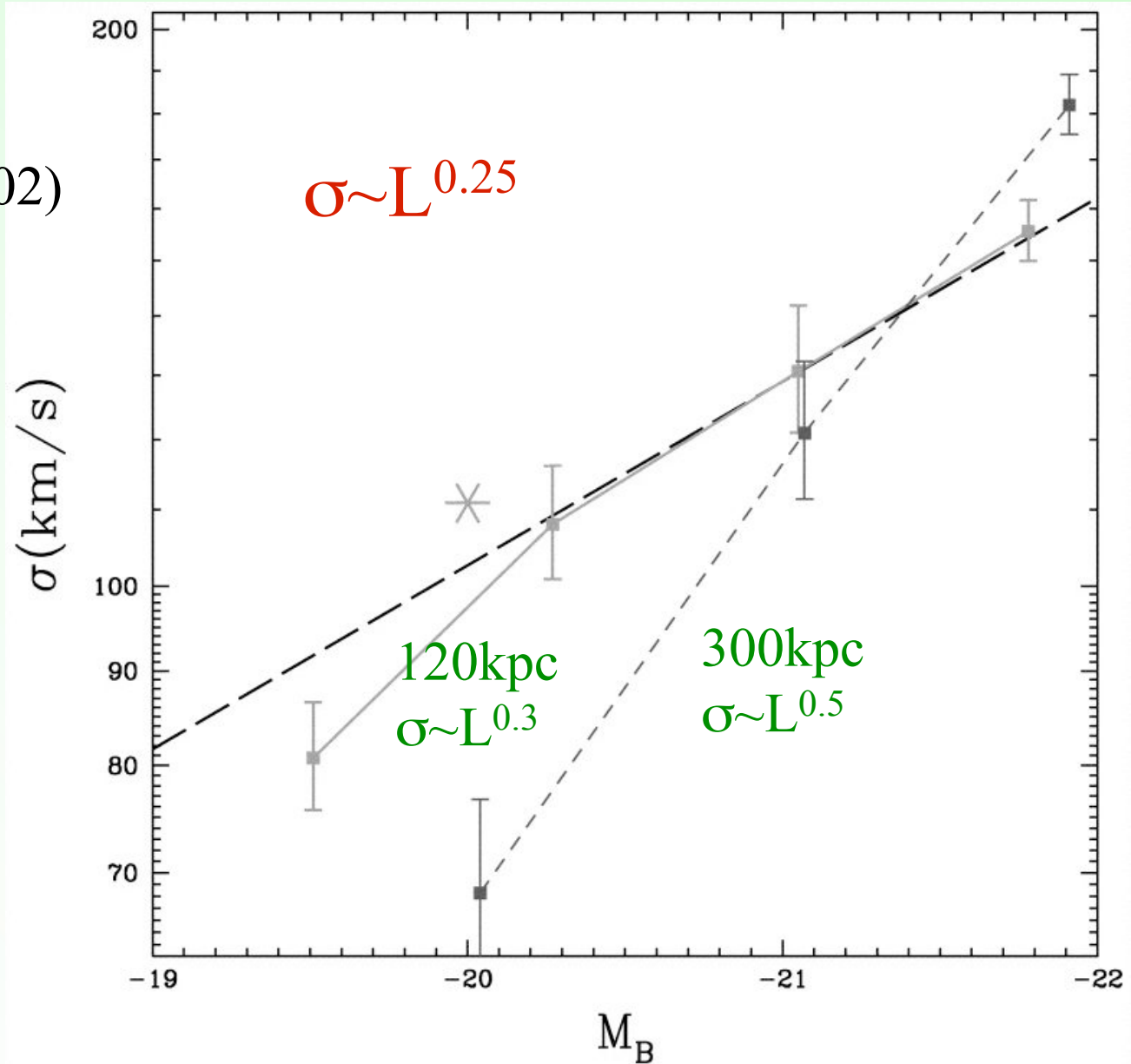


Tully Fisher Equivalent

Asterisk: Lenses
(Hoekstra et al 2002)

--- TF normal
spirals
(Verheijen 2001)

Prada et al (2003)



Large scale structure

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

$$\rightarrow \Delta\Phi = 4\pi G \delta\rho$$

$$\mu (g_M/\gamma) g_M = g_N + \mathbf{C} \quad \mathbf{C} = \text{rot}(\mathbf{h}) \quad \gamma \text{ critical acceleration } (=a_0)$$

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

Newton and MOND accelerations are then parallel

Start from a cosmological Newton+ CDM \rightarrow then find MOND produces as much clustering ($\gamma = \text{cste}$)

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

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

Initial conditions from CMBFAST, displacements (Zeldovich approx)

128³ grid, 32h⁻¹ Mpc, *assuming Newtonian initial state*

\rightarrow For that critical acceleration γ varies with time

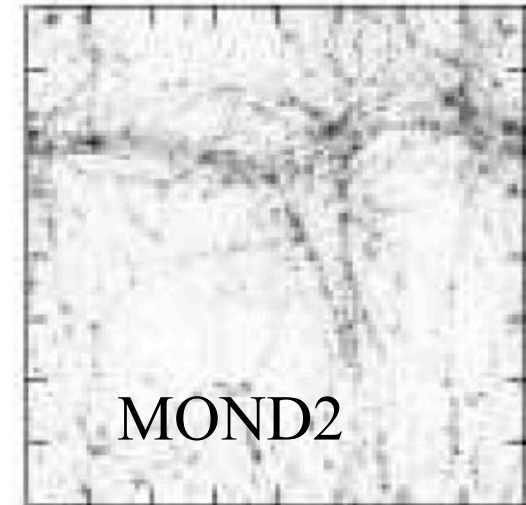
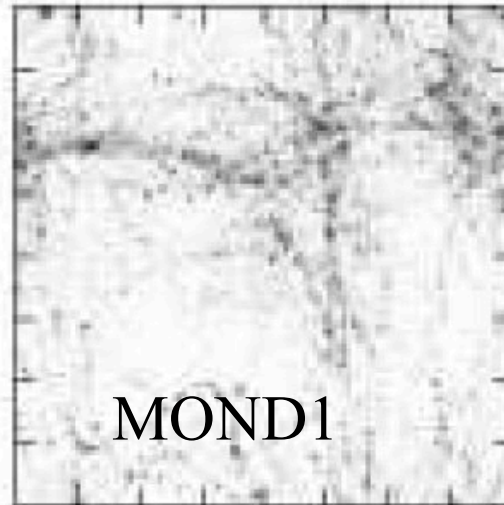
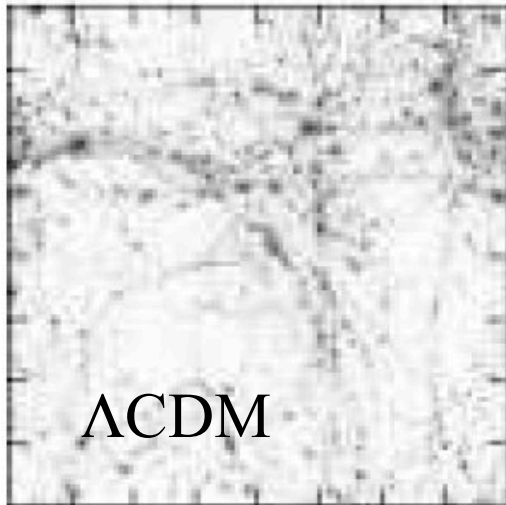
$$\gamma = a \gamma_0$$

MOND cosmological simulations

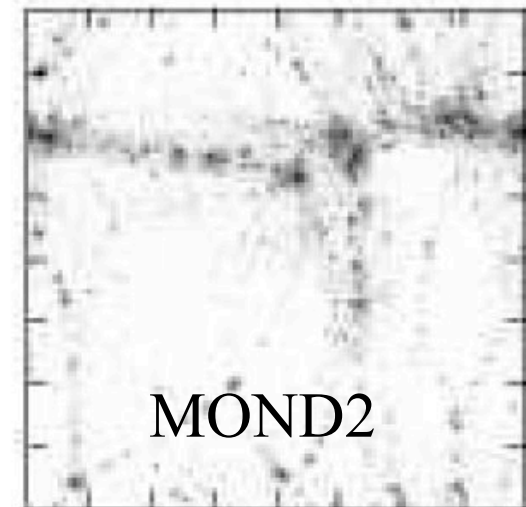
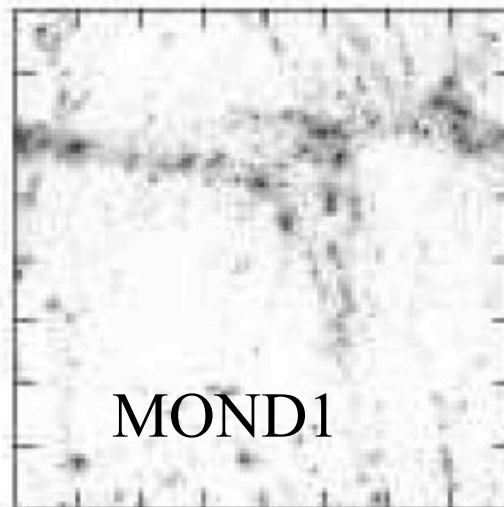
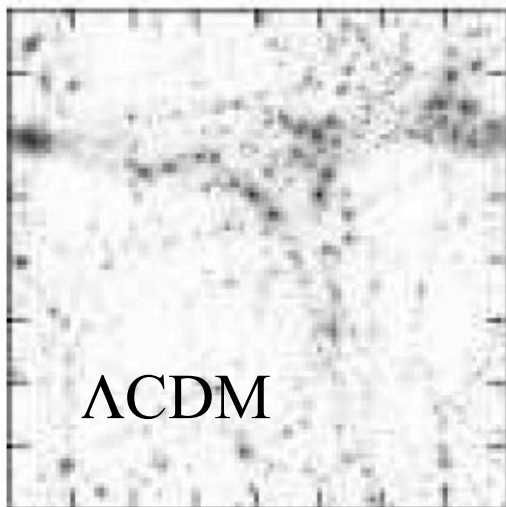
Starting $z=50$, dissipationless matter, 2 low Ω models + Λ CDM

Llinares et al 2009

$z=2$



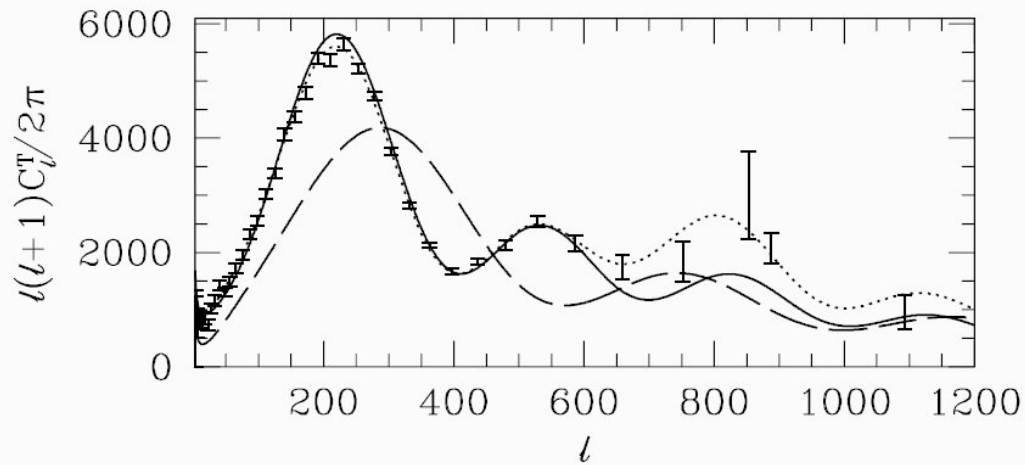
$z=5$



MOND: fit des data CMB, WMAP

Inclut les neutrinos massifs 1-2eV

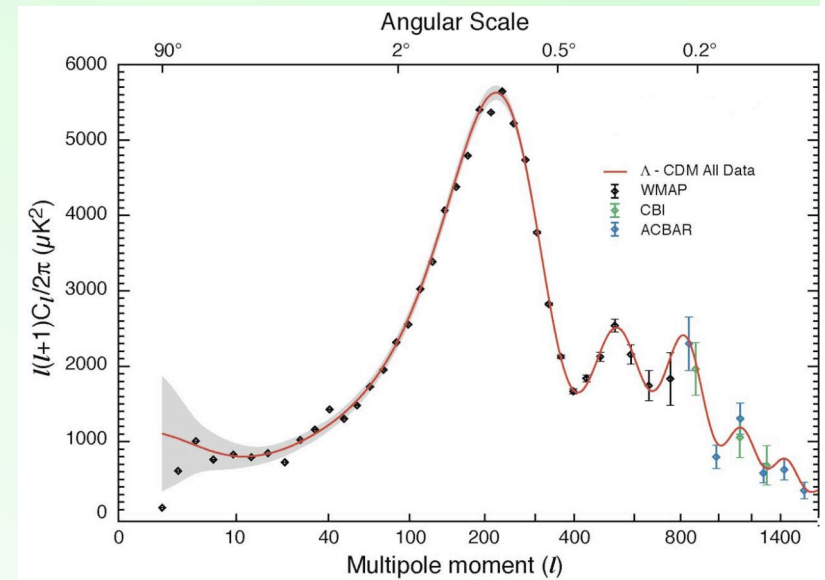
Fit par MOND
(sans aucune-CDM) des
pics acoustiques
(Skordis et al 2006)



—: $\Omega_{\Lambda}=78\%$ $\Omega_{\nu}=17\%$ $\Omega_{\text{b}}=5\%$ MOND

- - : $\Omega_{\Lambda}=95\%$ $\Omega_{\text{b}}=5\%$

.....: Λ CDM

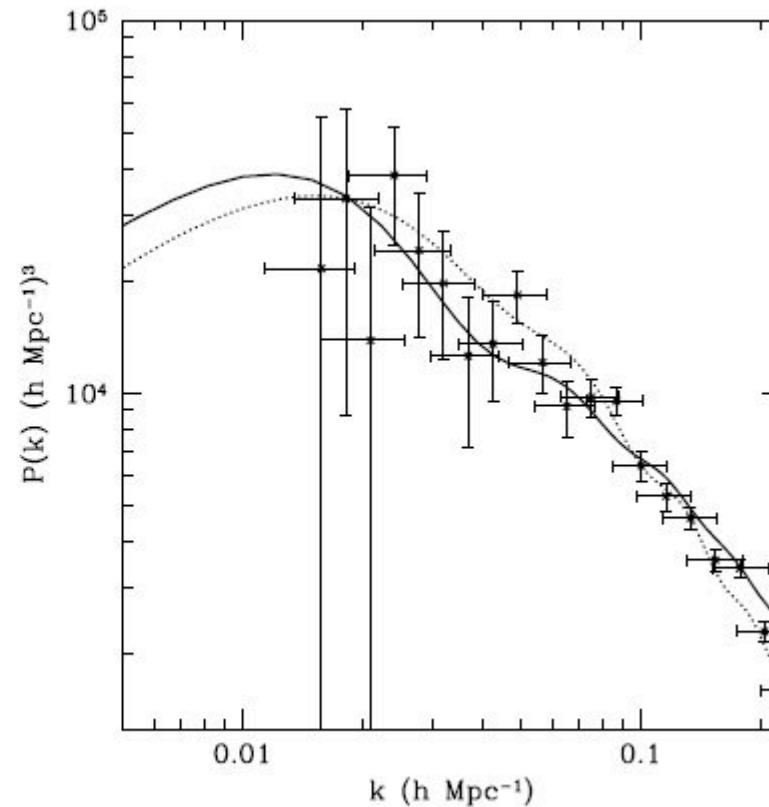
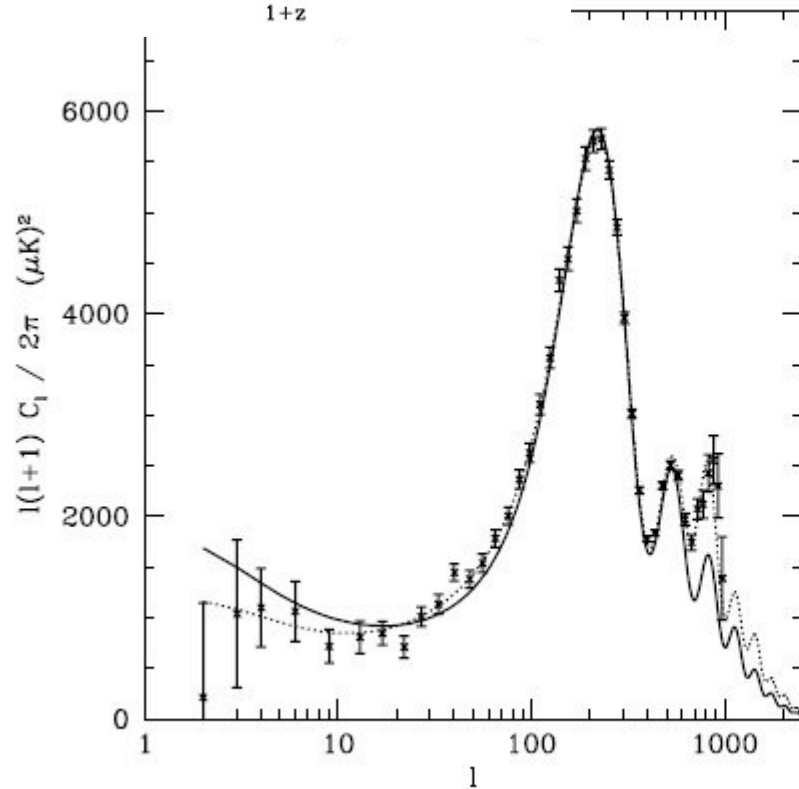
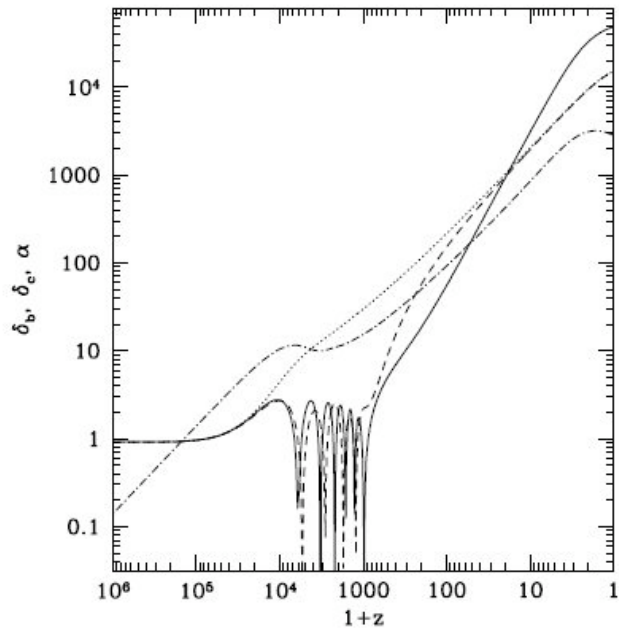


Fit avec CDM + Λ

TeVS: CMB and LSS

Skordis 2009

Growth of structures due to the vector field
Scalar field \rightarrow acceleration 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,
Suppress the scalar field, in combination 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)

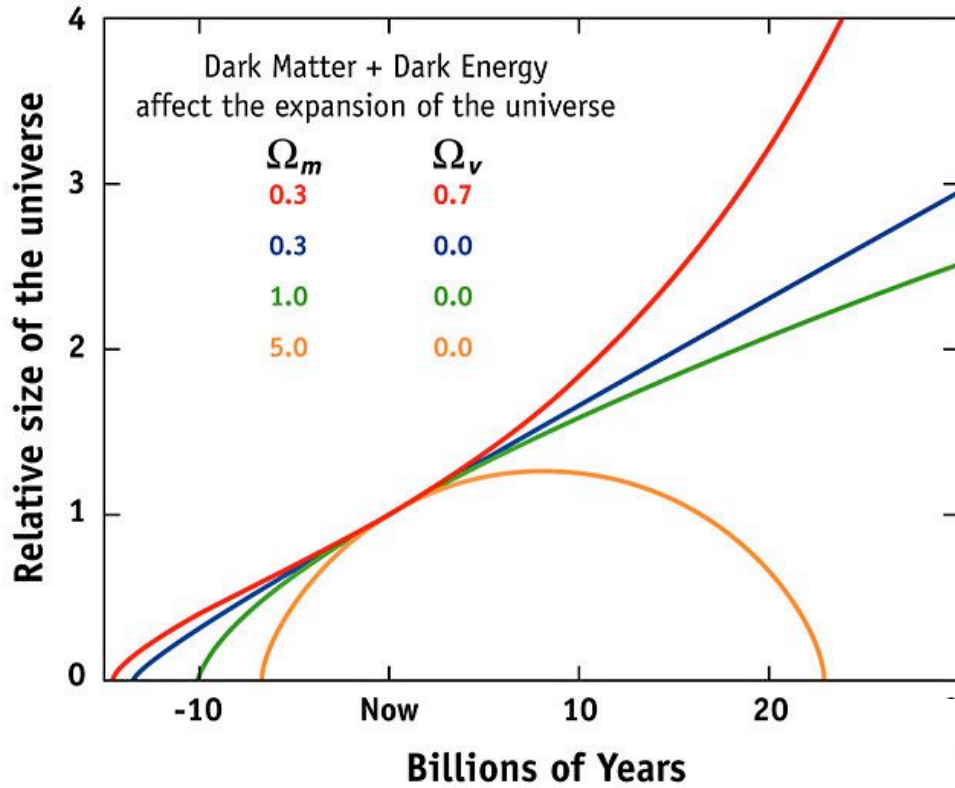
→ Different metric, some free parameters still

[$a_0 \sim c H_0$ today, but does it vary with time?]

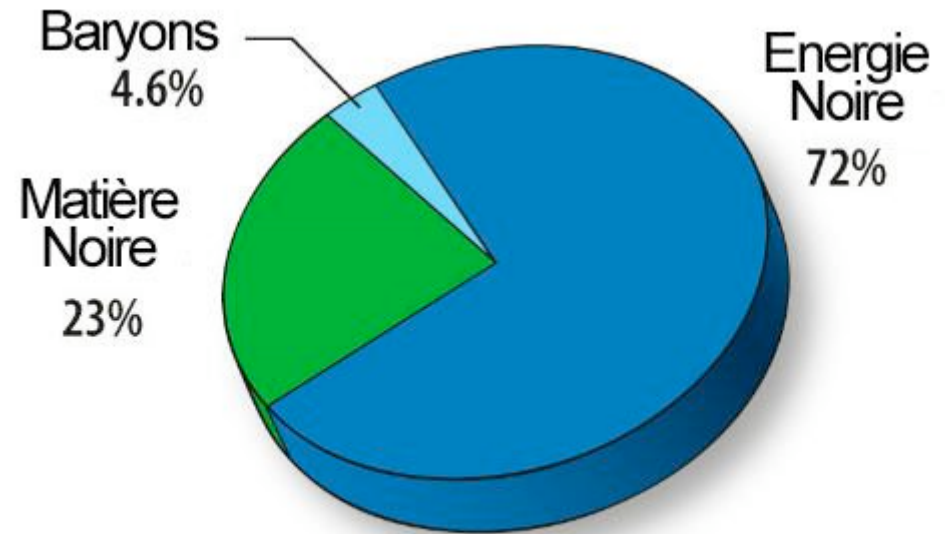
Numerous other propositions: Einstein Aether (scalar field),

Vector field, etc..

EXPANSION OF THE UNIVERSE



Problem of dark energy



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 $\eta < 1$

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

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

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

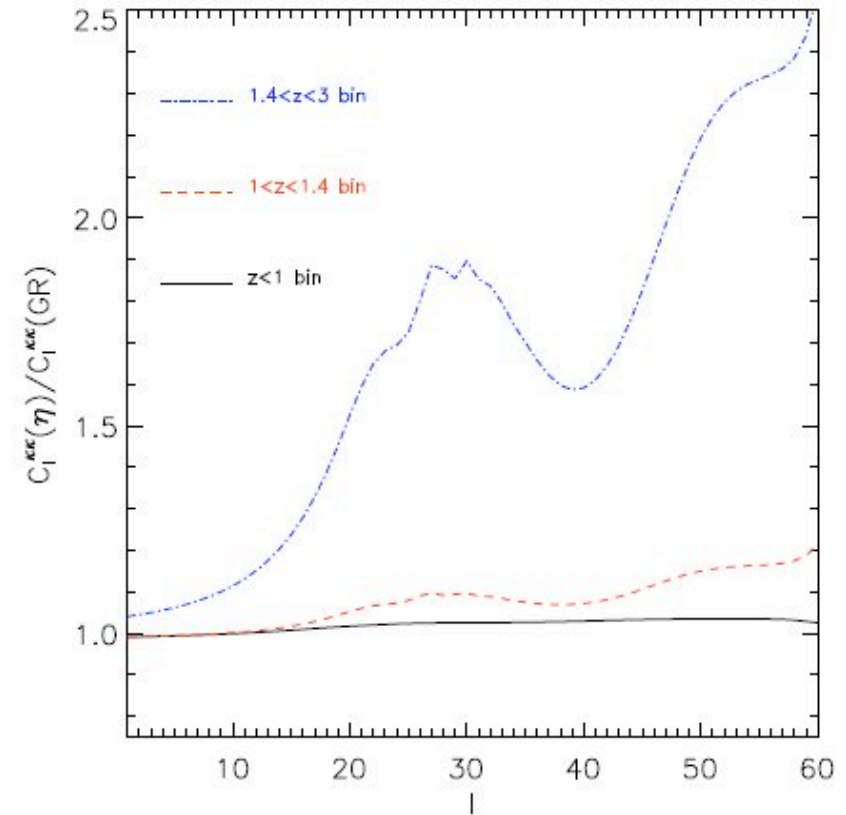
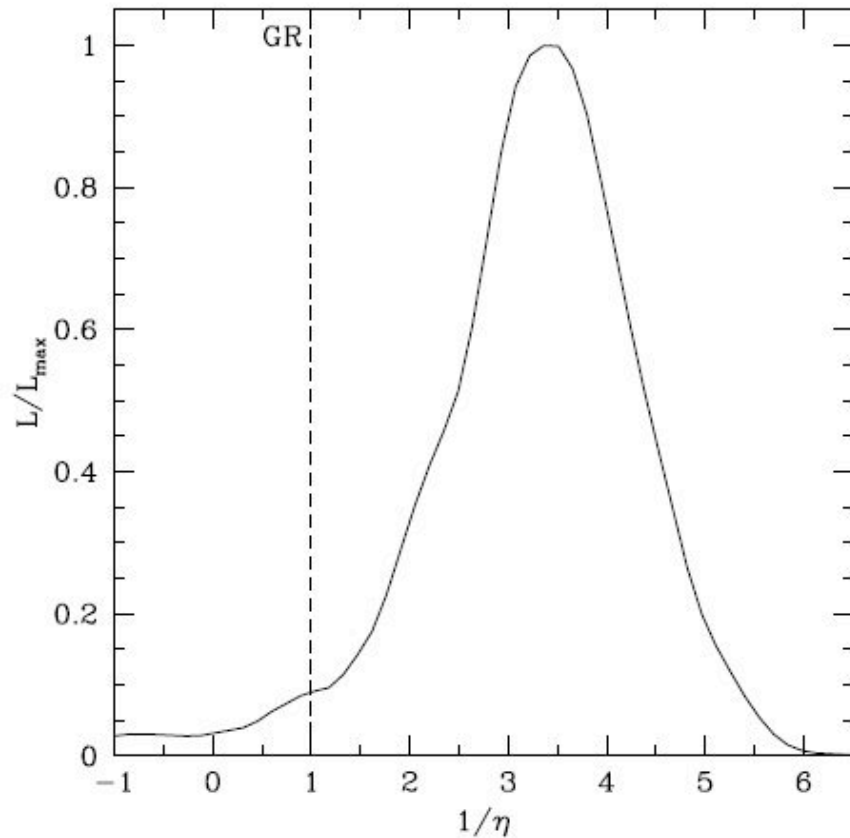
$$\gamma(k, a) \equiv \frac{\ln(\dot{\delta}_c / \mathcal{H} \delta_c)}{\ln \Omega_m(a)}$$

$\eta = 1$, 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..