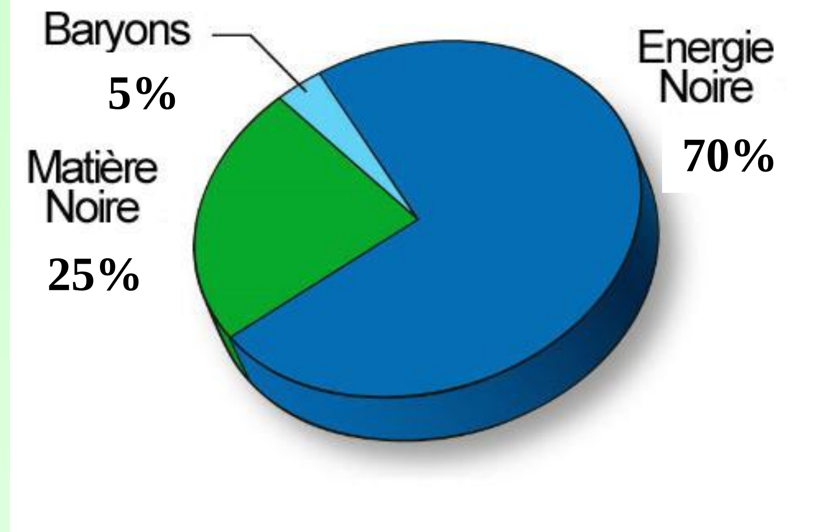
Status of the Dark matter problem



WMAP+Planck

Françoise Combes
Observatoire de Paris

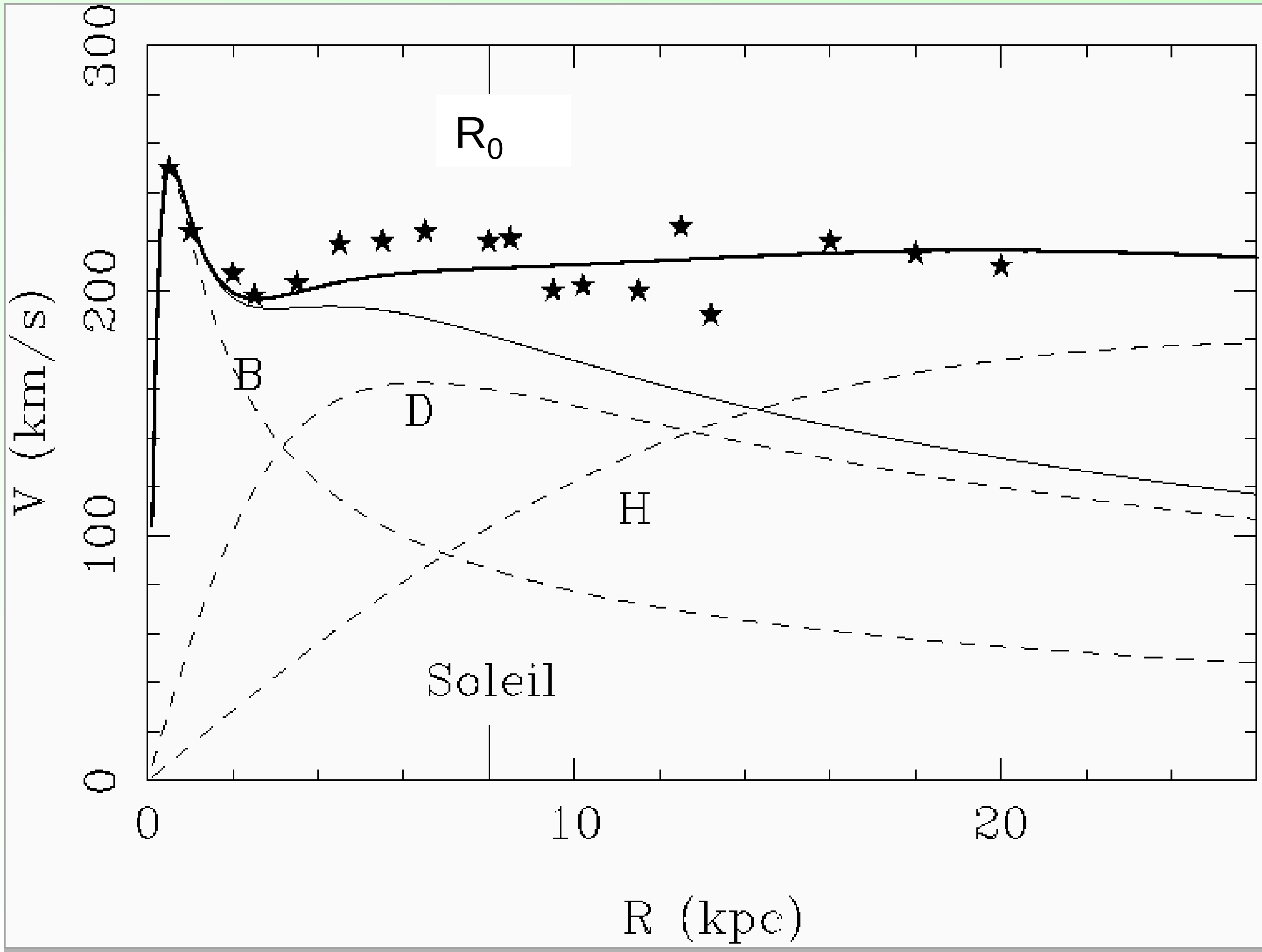
Friday November 29, 2013

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 *(forgotten during 40 yrs)*

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



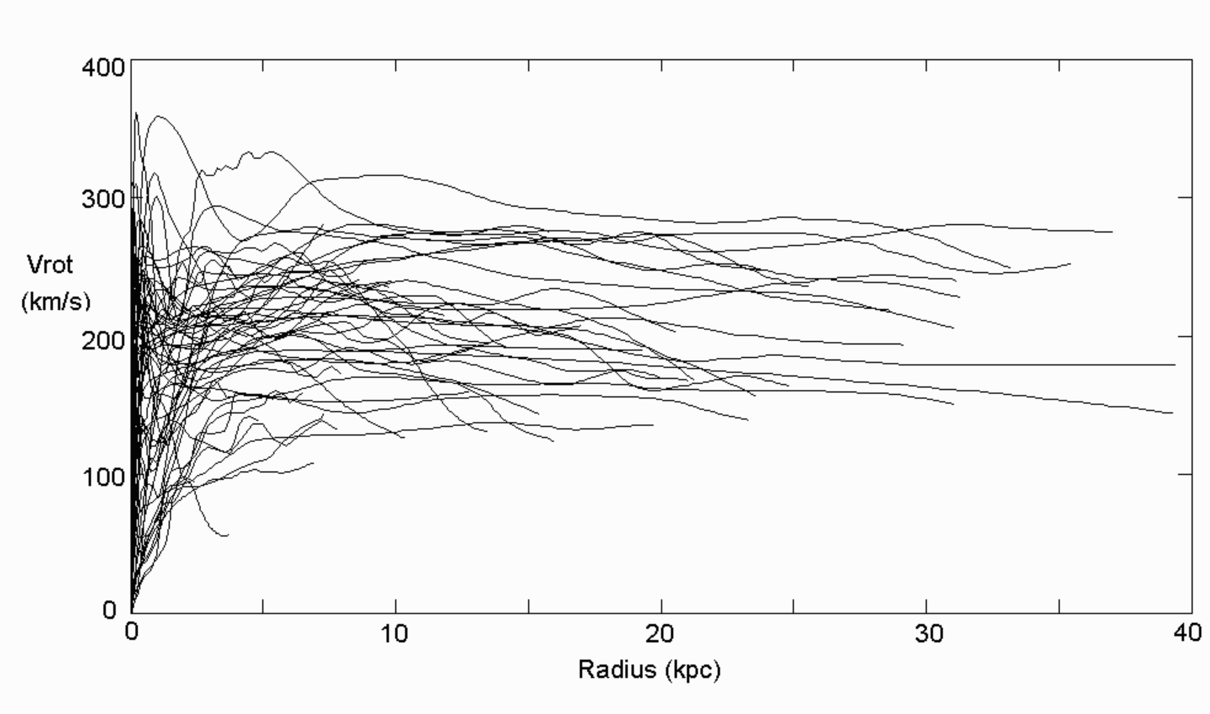
Problem of DM,
below a certain
Acceleration

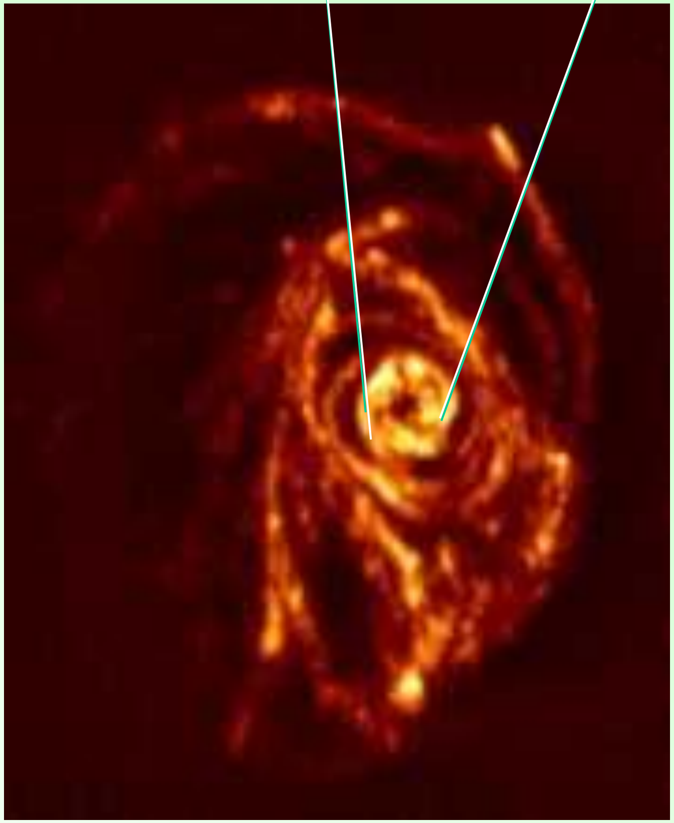
R > Ro

Galaxies with HI

M83: optical

HI: cartography of atomic hydrogen
Wavelength 21cm



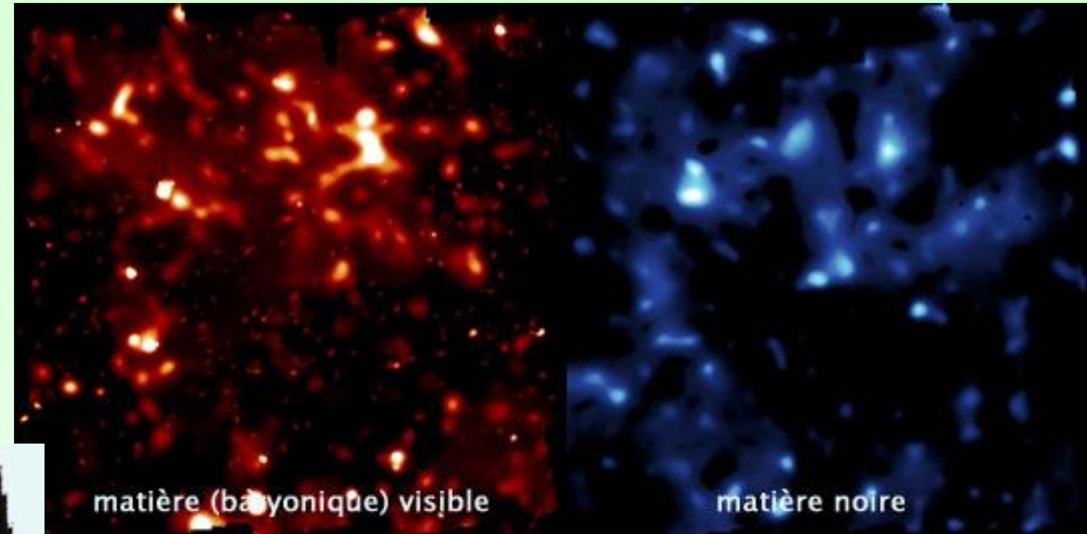


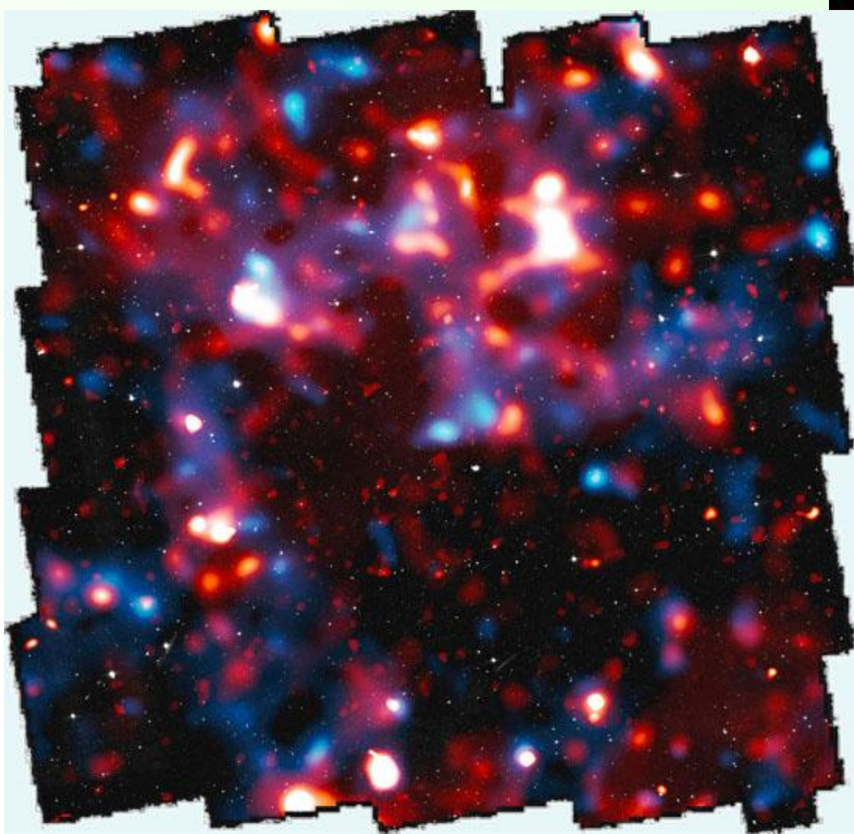
HI in M83: a galaxy similar to the Milky Way

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

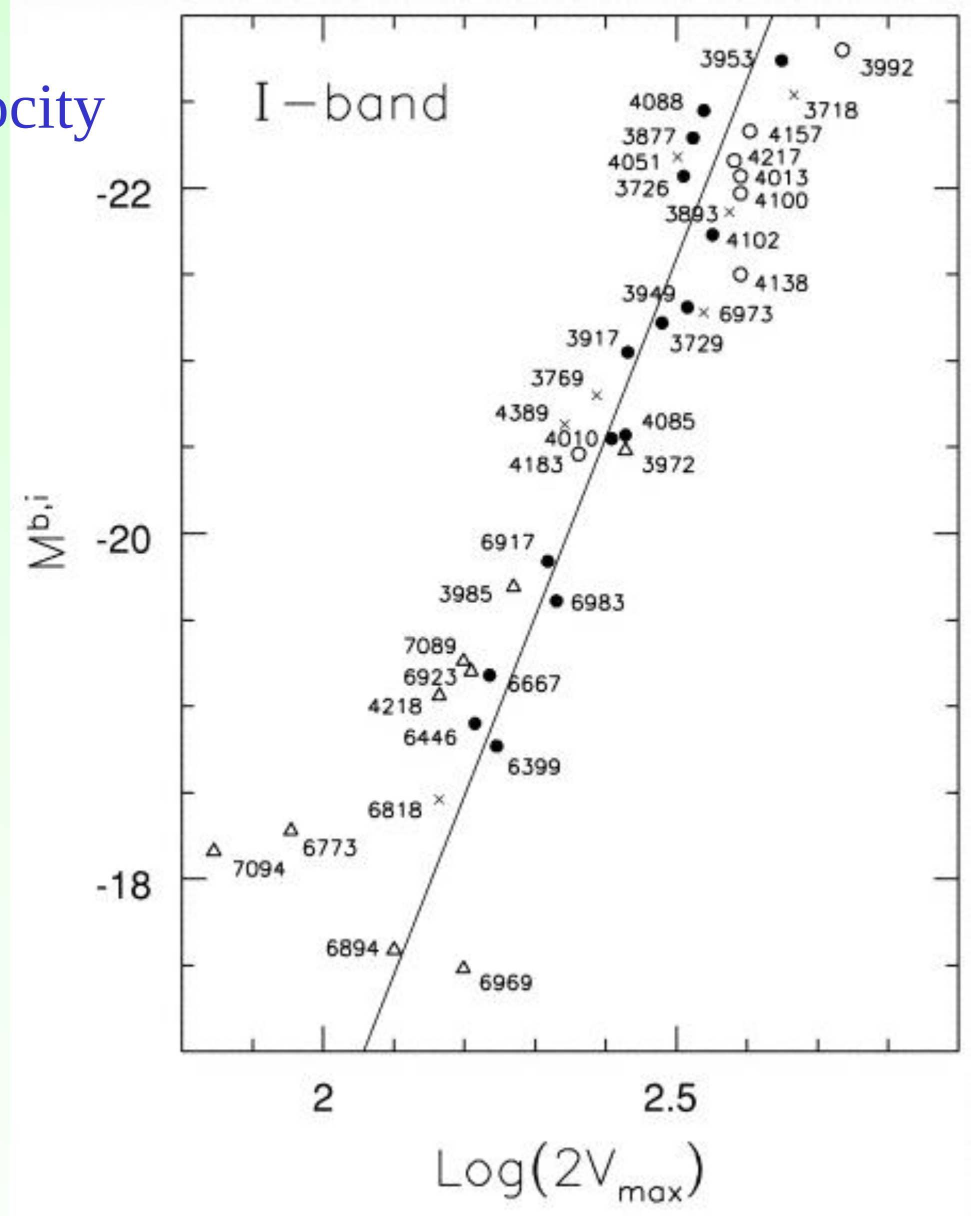
ΔV corrected from inclination

Much less scatter in I or K-band

(no extinction)

Correlation with Vflat

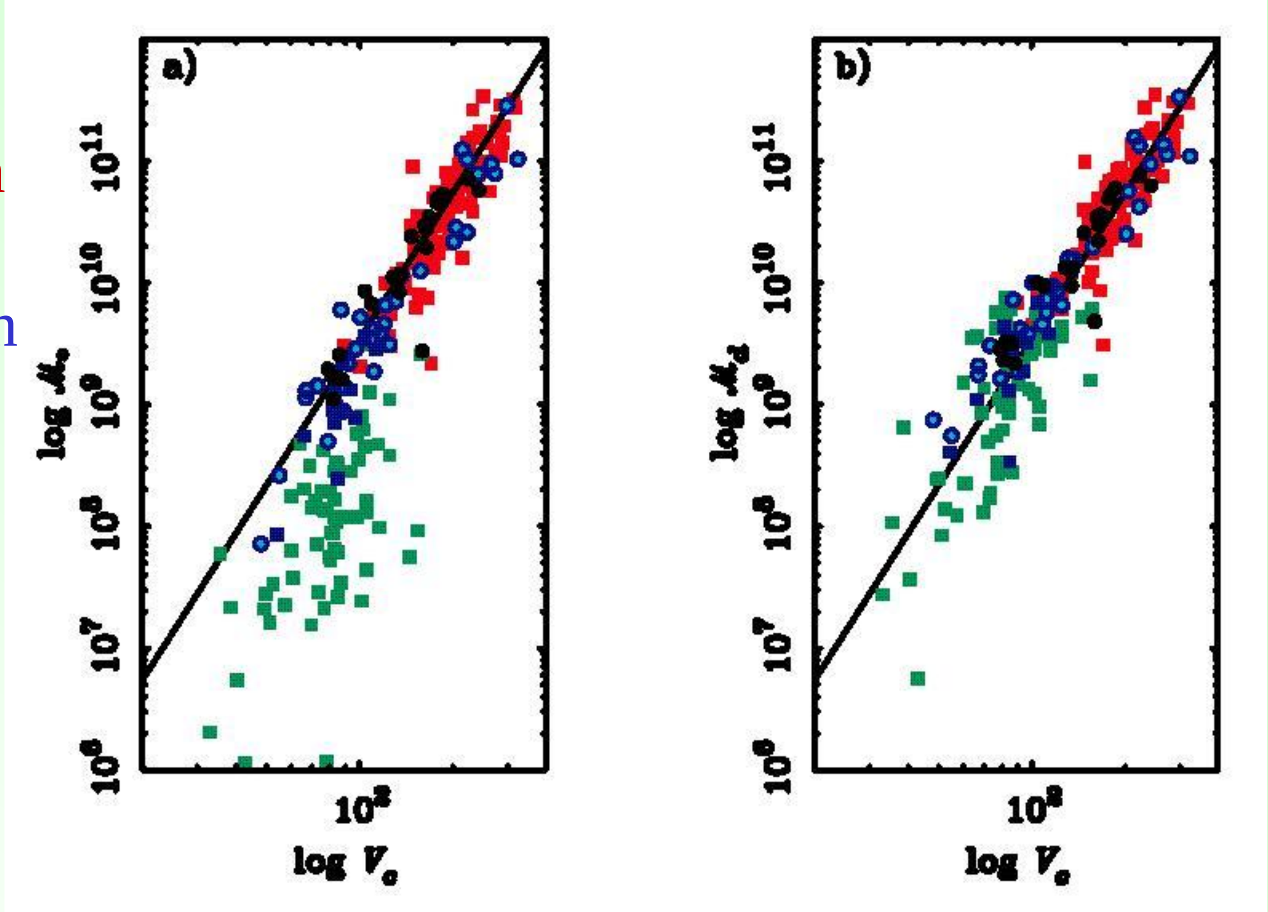
Better than Vmax



Ursa cluster

Verheijen 2001

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

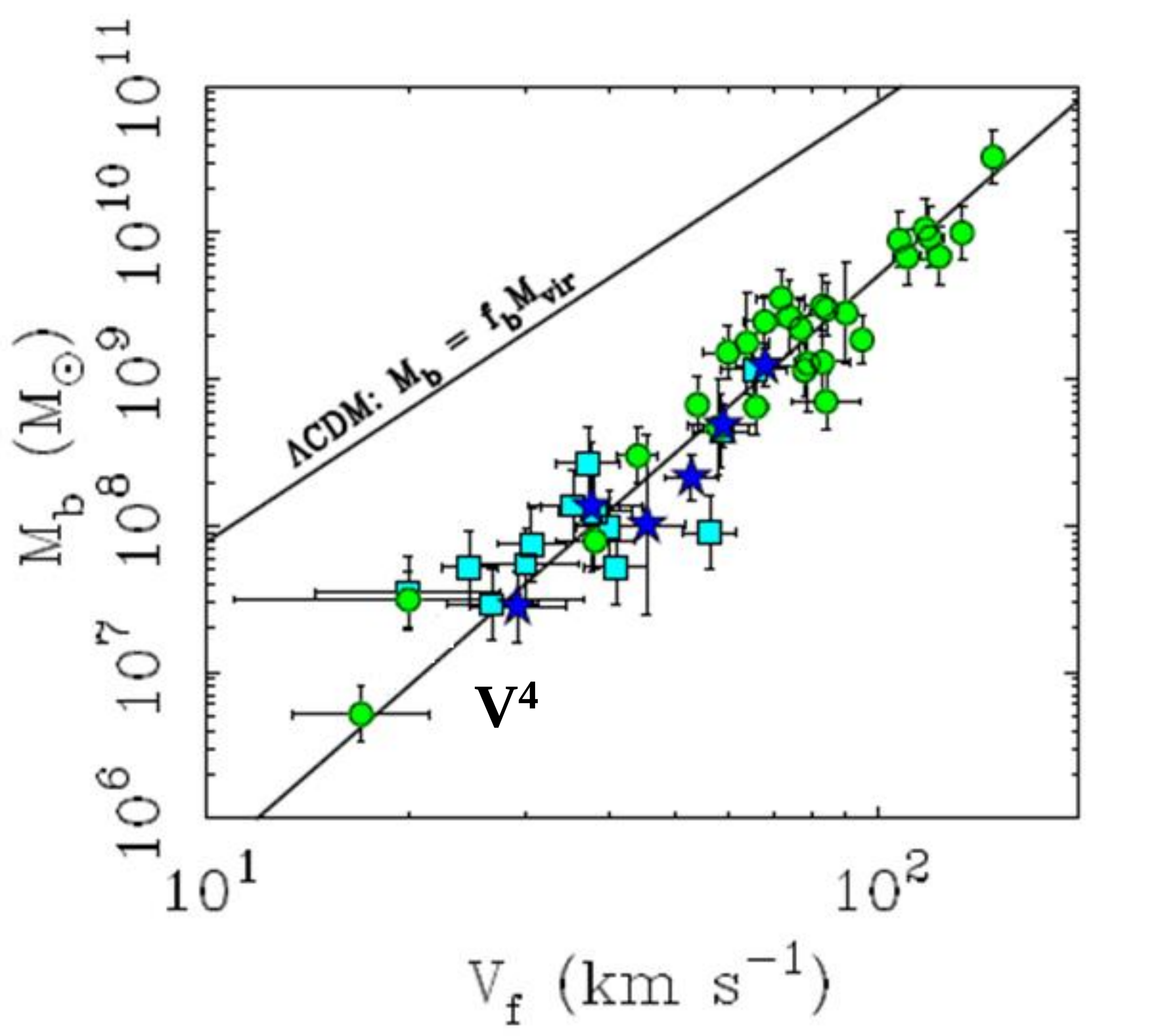


Relation $M_{baryons}$ with Rotational V

$M_b \sim V_c^4$

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

Baryonic Tully-Fisher relation



McGaugh 2011

f_b baryon fraction= 17%

CDM: Cold Dark Matter

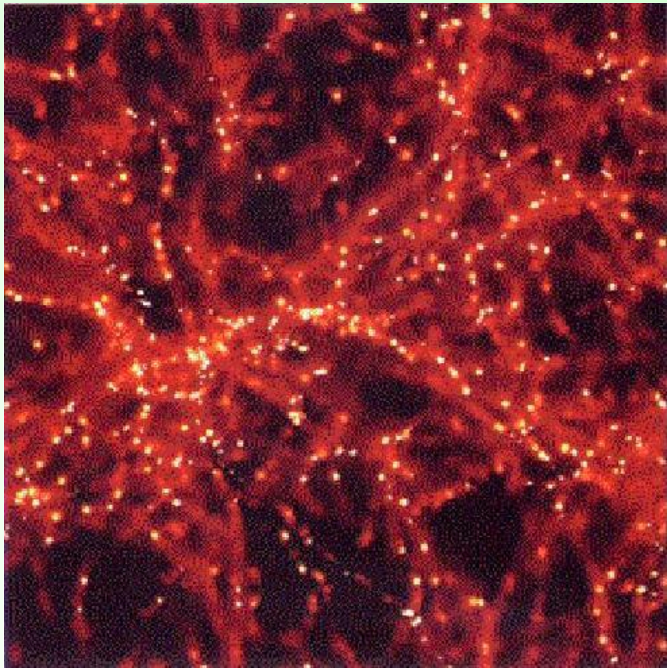
Λ dark energy

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

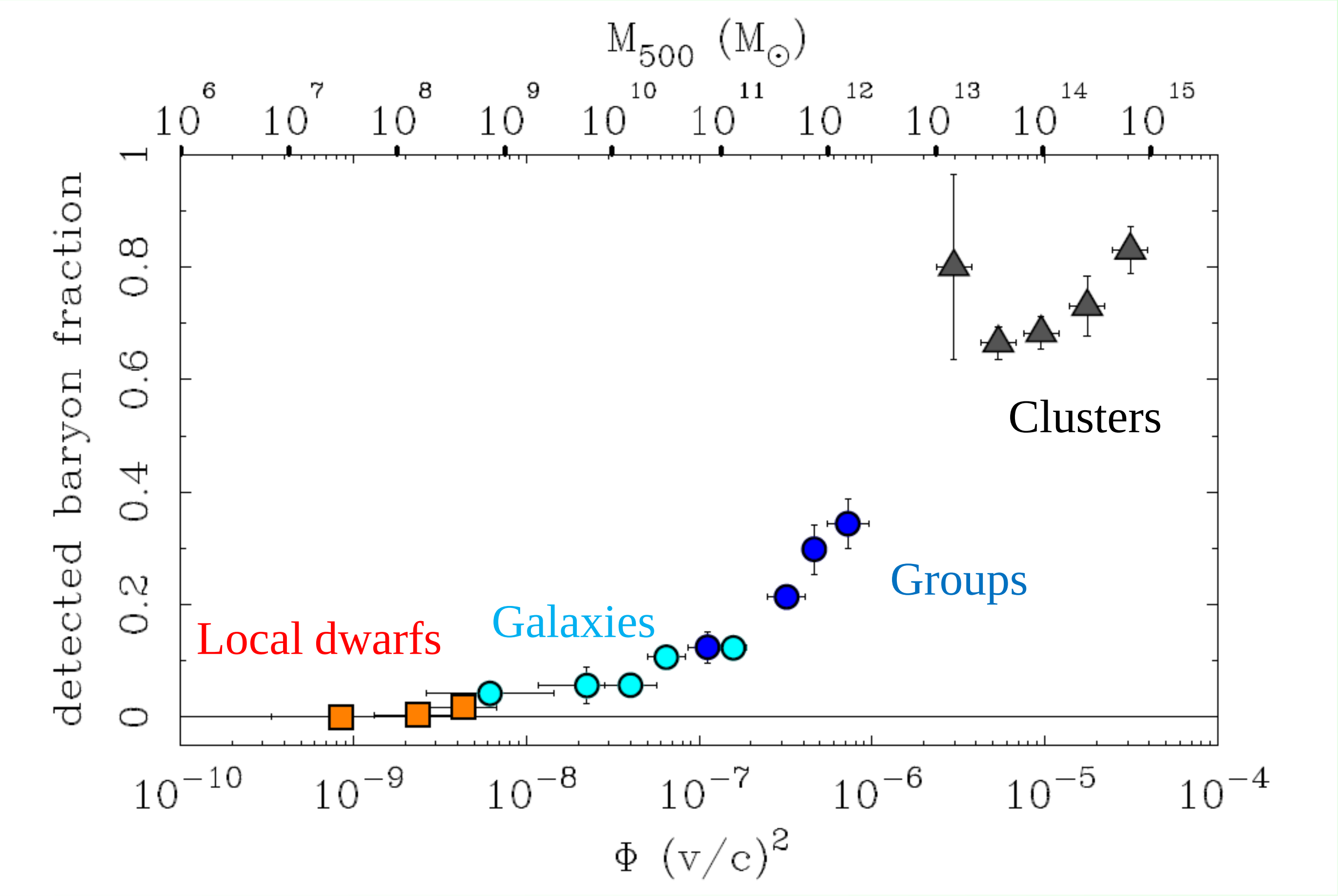


➔65% are not yet identified or localised!

Most of them are not in galaxies

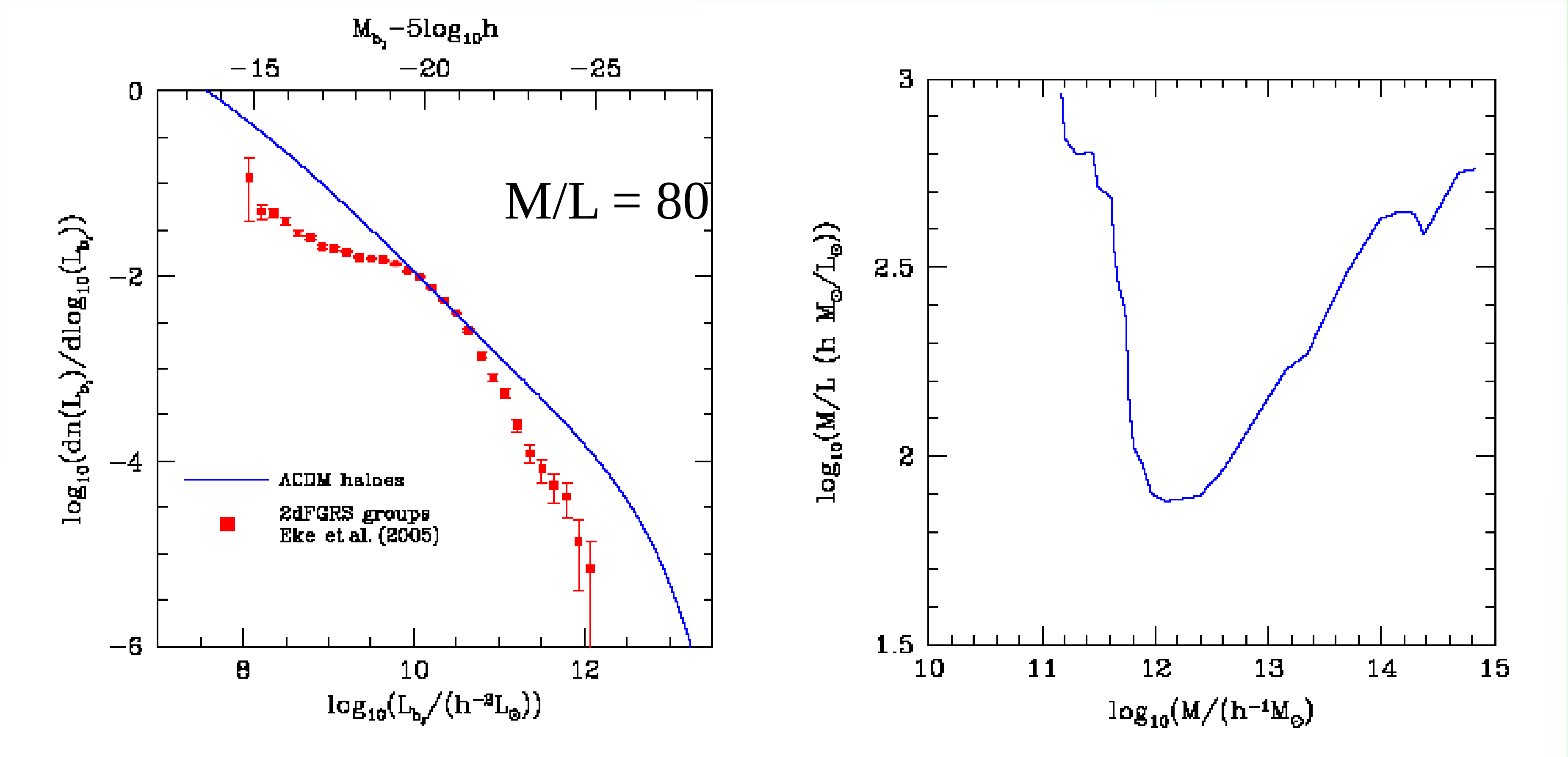
Fraction of baryons detected

Fraction = Mb / (0.17 M500) M500 dynamical mass within R500
R500 radius where the density is 500 times the mean cosmic density



Mass & Light Distribution Functions

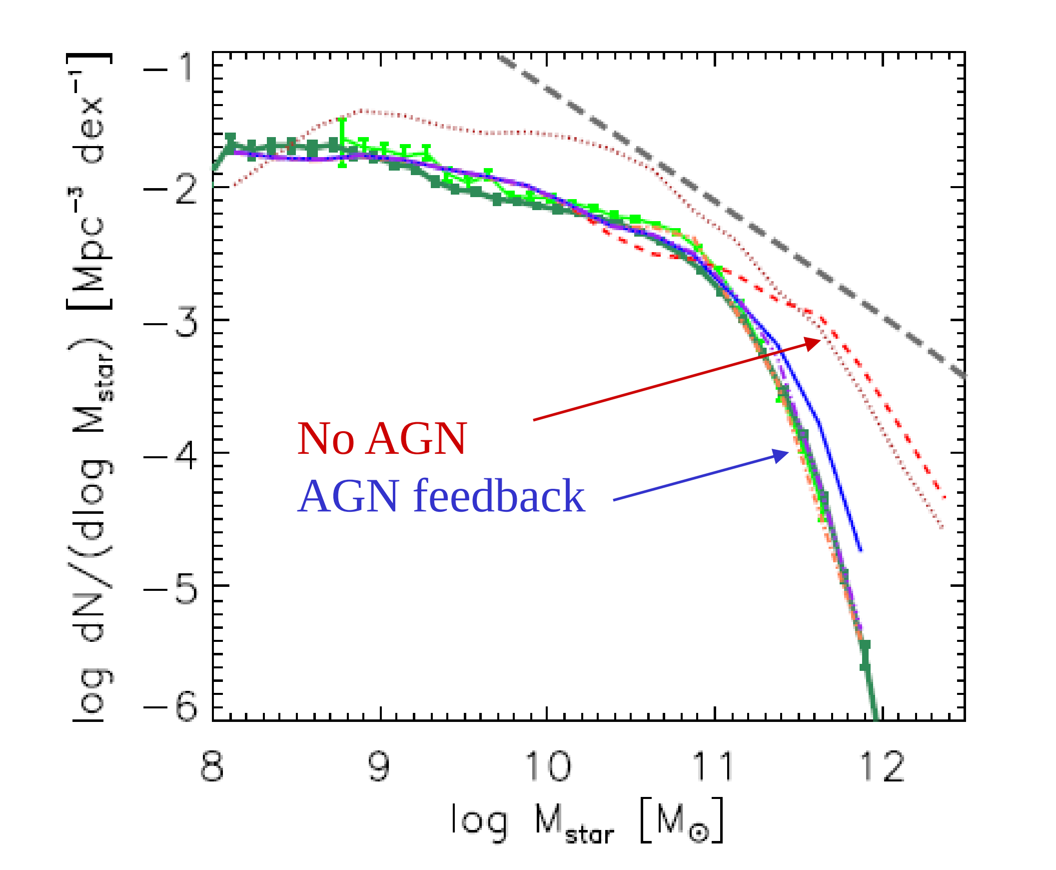
ΛCDM: Too many bright and too many faint galaxies



Baugh 2006, Eke et al 2006, Jenkins et al 2001

Star Formation Feedback to fit faint end

Gas is heated in dwarfs, but falls in heavier haloes
➔ worsen the bright end problem



➔ Requires AGN feedback at the bright end

Somerville et al 2008

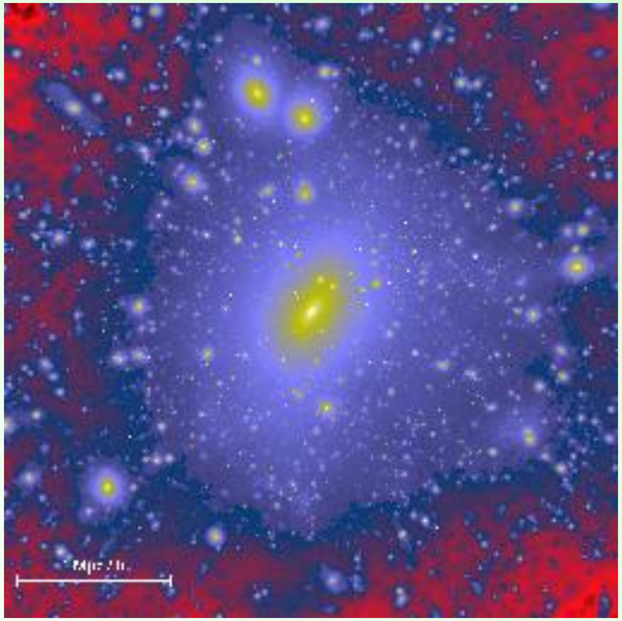
Problems of the standard Λ-CDM model

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

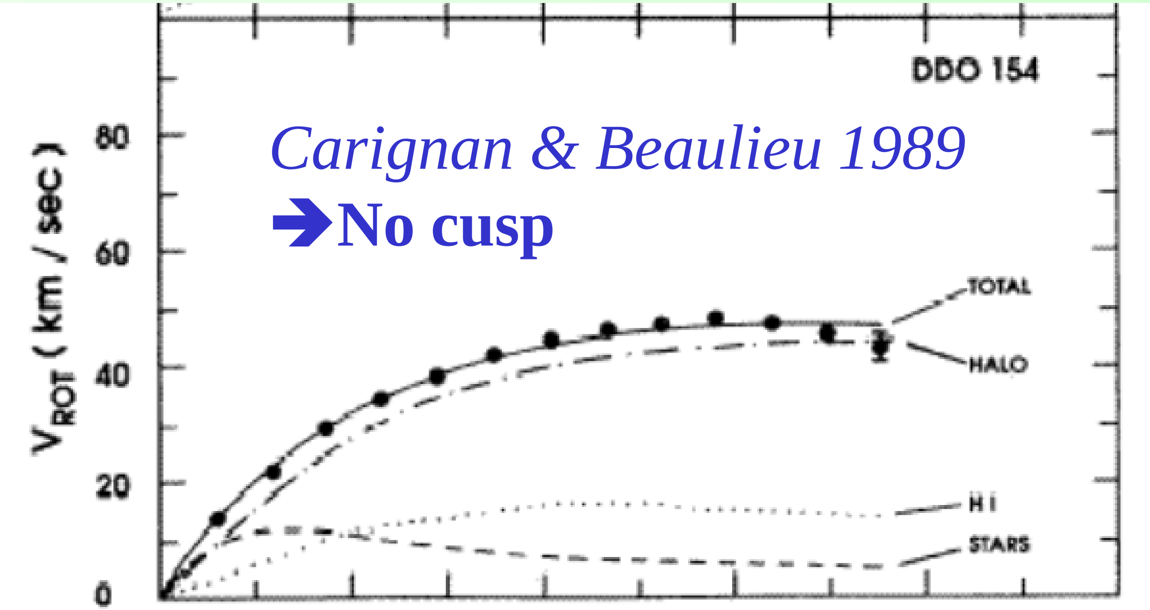
➔Low angular momentum of baryons, and as a consequence formation of much too small galaxy disks

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

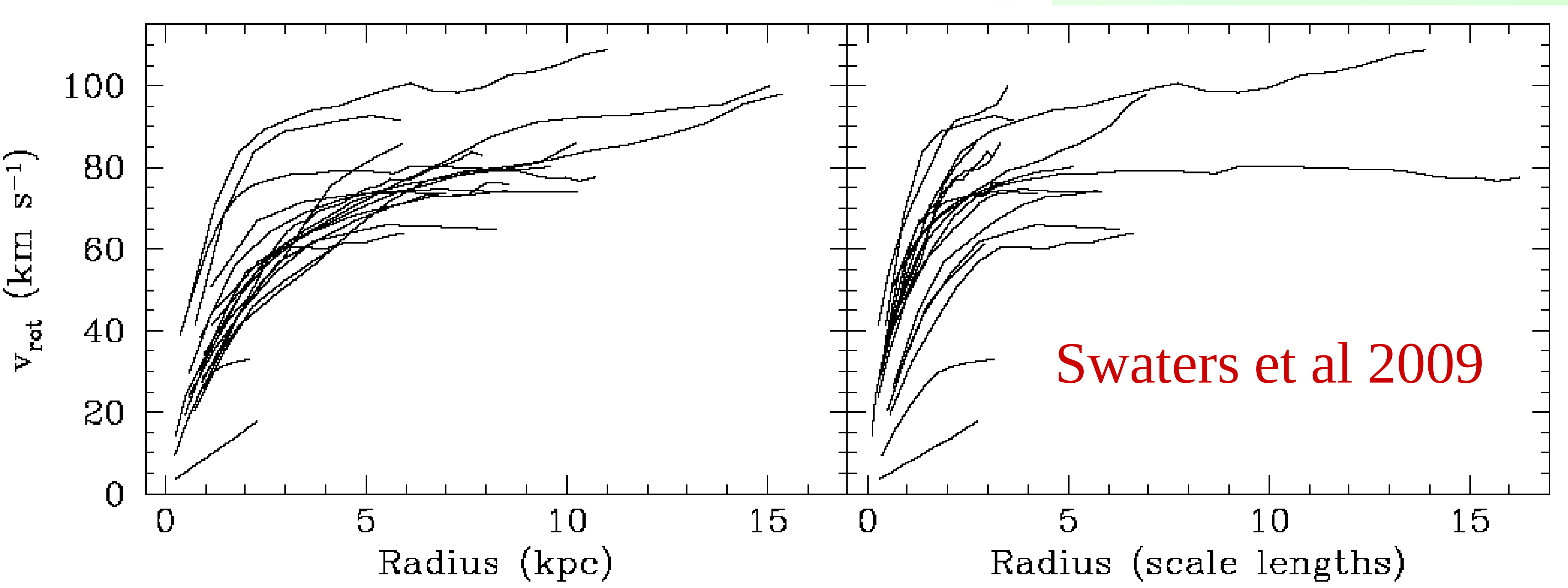
The solution to all these problems could come from some baryonic physics (SF, feedback?), or lack of spatial resolution in simulations, or wrong nature of dark matter?

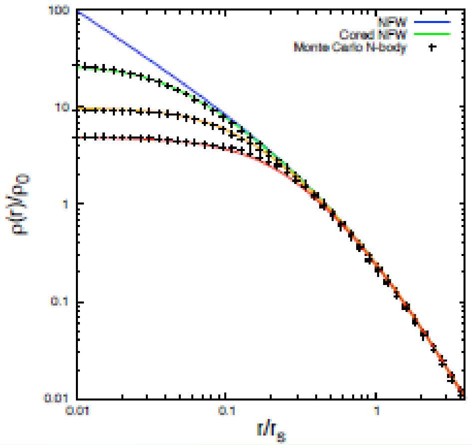


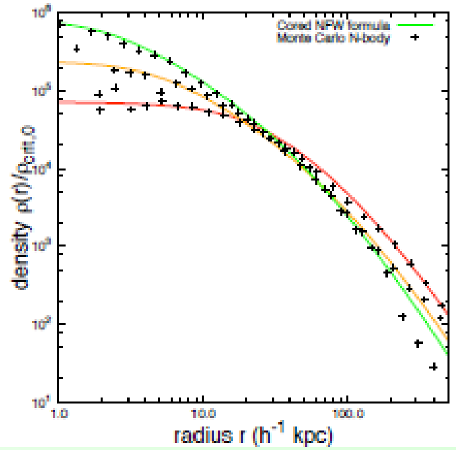
Dwarf Irr : DDO154 the prototype



Low surface brightness galaxies are dominated by dark matter



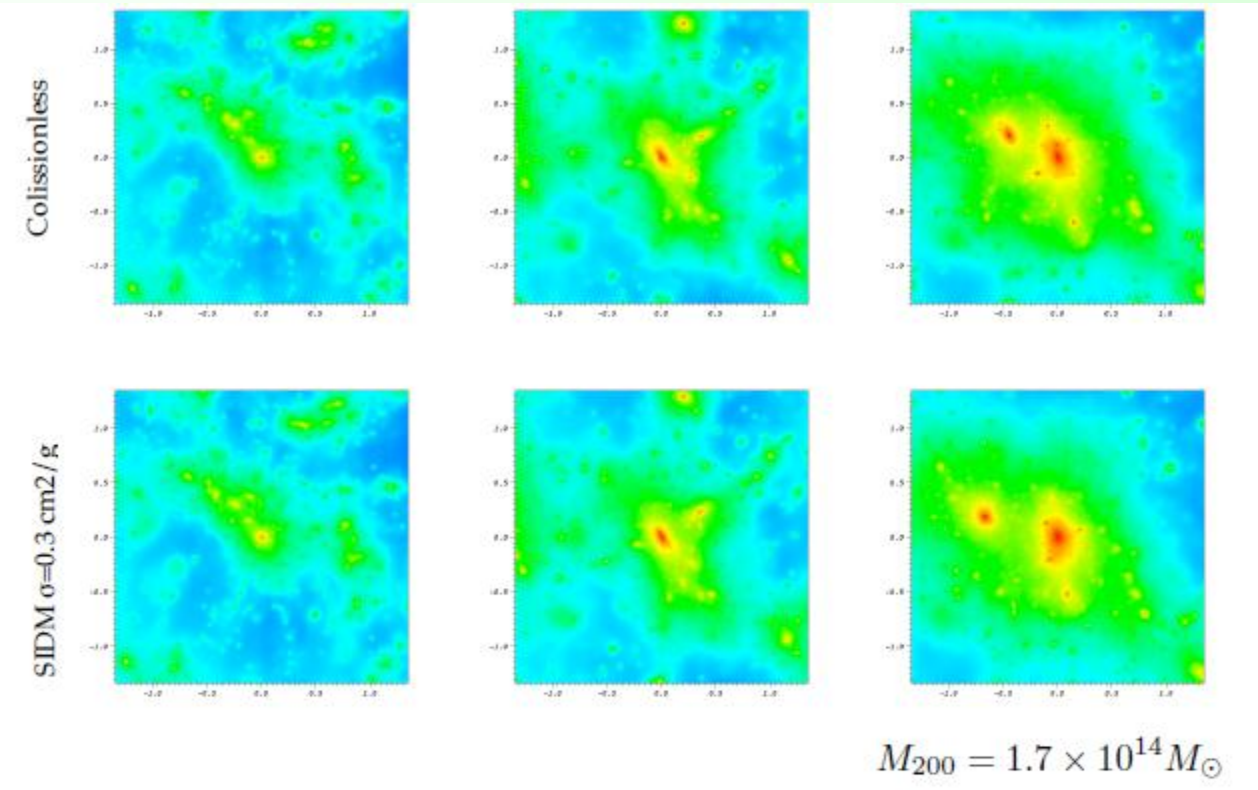




SIDM Self-interacting DM

Size of cusps depends on the galaxy. Dwarfs rc ~10kpc

SIDM cross section is fit to galaxies, then too big for clusters.



Collisionless

SIDM simulations

Koda et al 2011

Self-interacting Dark matter vdSIDM

Velocity-dependent cross-sections?

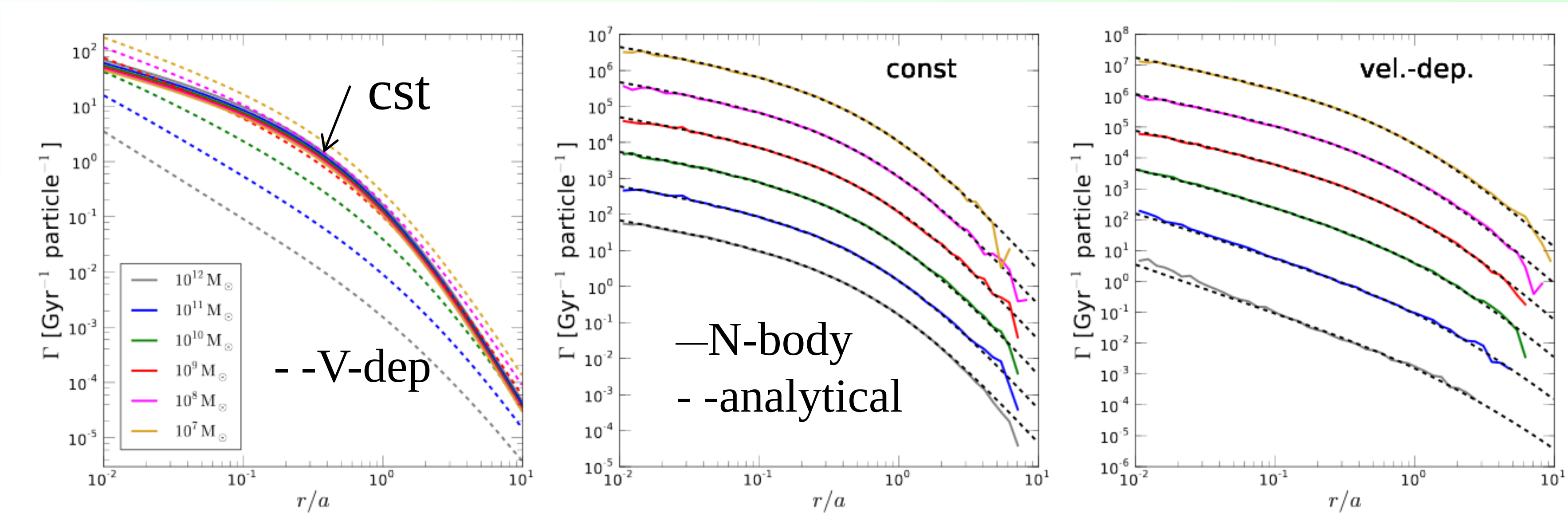
In $v^{-\alpha}$

Or a Yukawa potential, instead (Loeb & Weiner 2011)

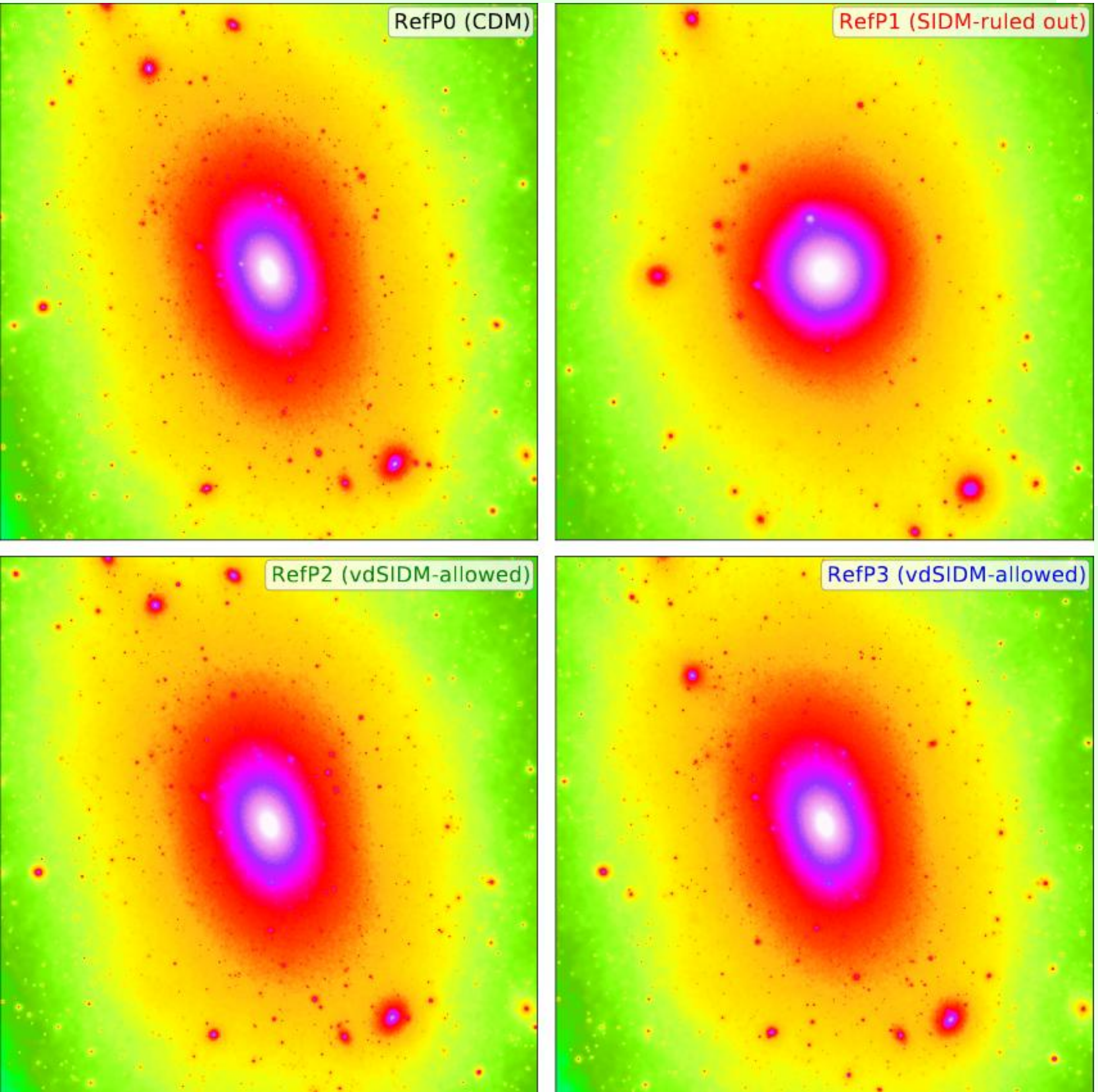
Dark force ➔ V-dependent scattering

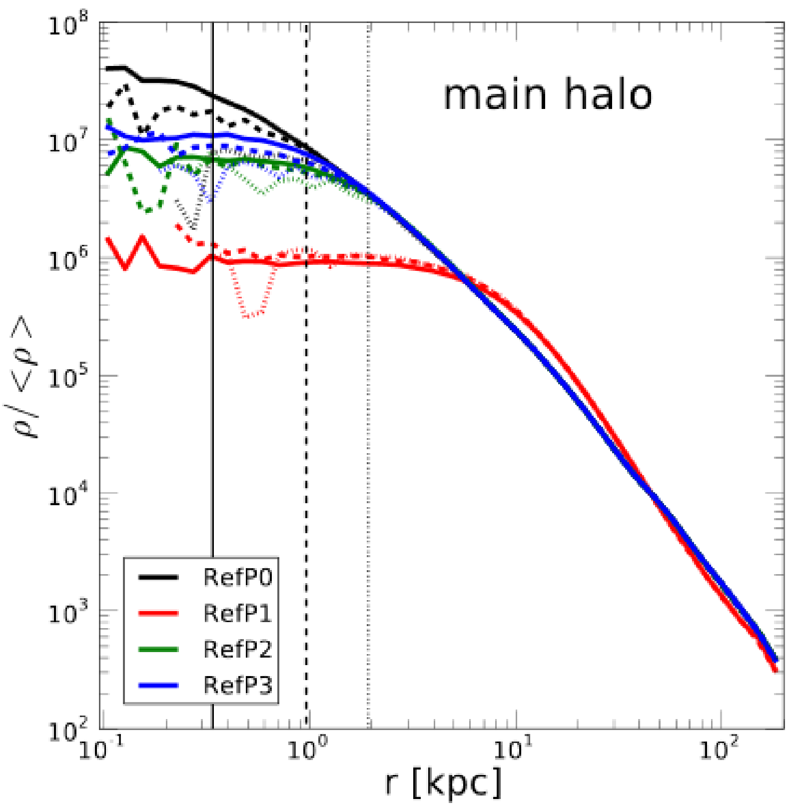
vdSIDM simulations, with the self-scattering mediated by a Yukawa field, gauge boson mϕ (//scattering in a Coulomb screened plasma)

Vogelsberger et al 2012



vdSIDM results



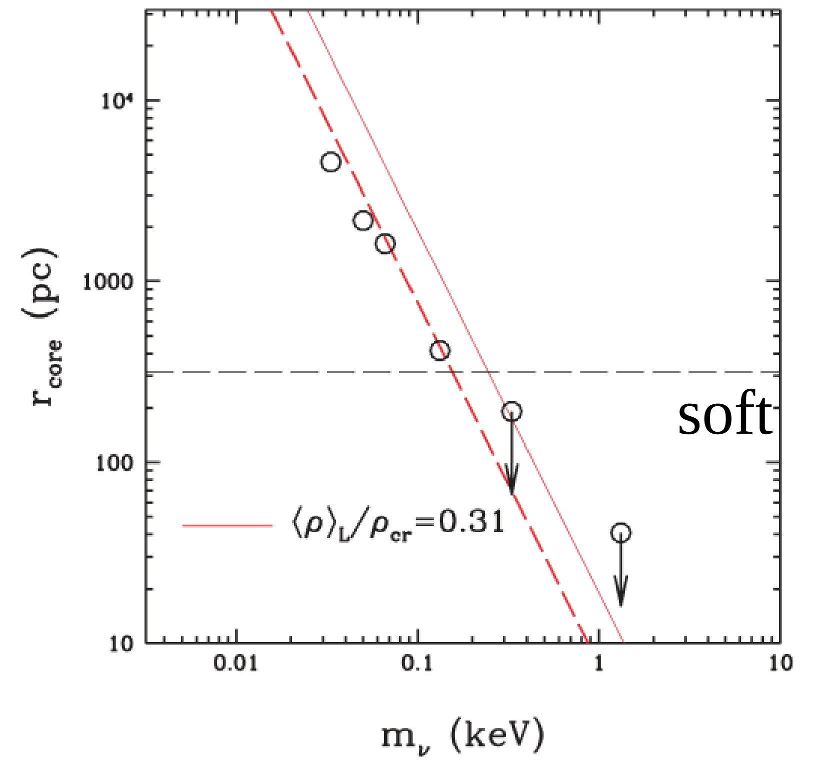


Elastic scattering: **missing satellites problem still there**

May be with energy exchange?

Vogelsberger et al 2012

Problems of the WDM

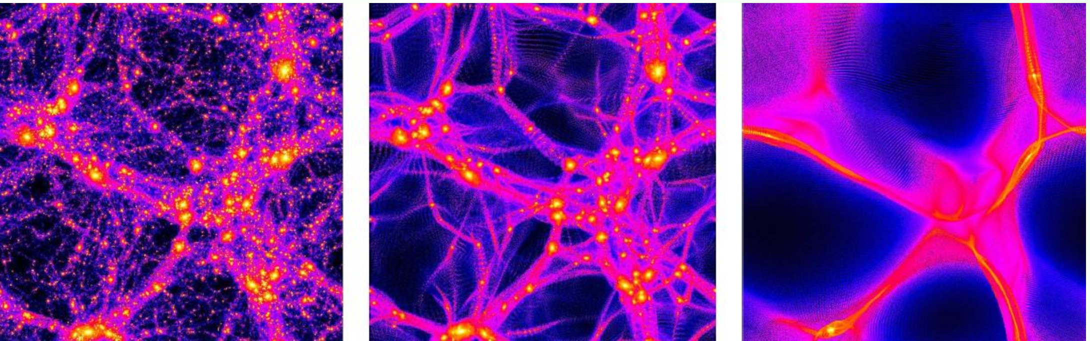


To account for dwarf galaxy cores,
m <~0.1 kev (Liouville theorem $Q=\rho/\sigma^3$)

But for large scales 3-10kev
is required *(Quantum mechanics effects intervene only at 0.1-1pc for 2kev)*

Dwarf galaxies have to be formed anyway, with a kpc scale cores.

But the m_{WDM} required for their core suppress the dwarf formation



Maccio et al 2012, 13

Cusps and Warm DM (WDM)

The density profile **is universal: NFW,** for HDM, WDM and CDM *(Wang & White 2009)*

➔The universality is not due to mergers

In monolithic collapse, same features

Concentrations, cusps, shapes of haloes

Spins of haloes, kinematics

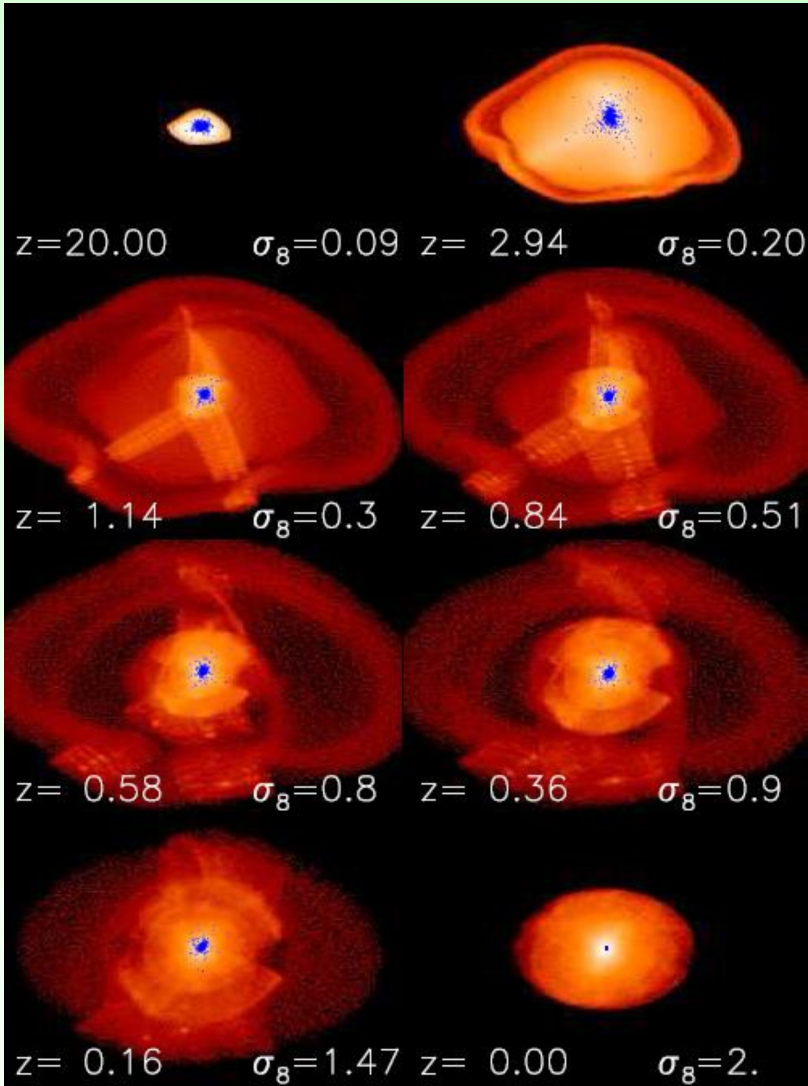
The only big difference is the power spectrum

➔Can be fitted, to limit small scales

Temperature at decoupling, could limit phase-space densities, but $r_c/r_{200} < 10^{-3}$

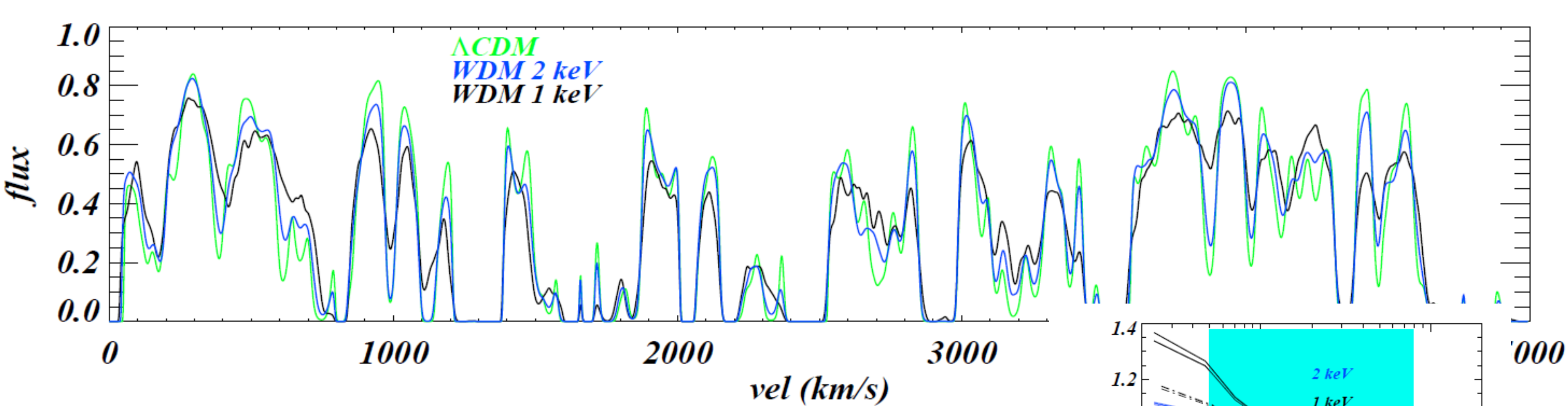
Cores in galaxies $r_c/r_{200} = 5\%$

Villaescusa-Navarro, Dalal (2011)

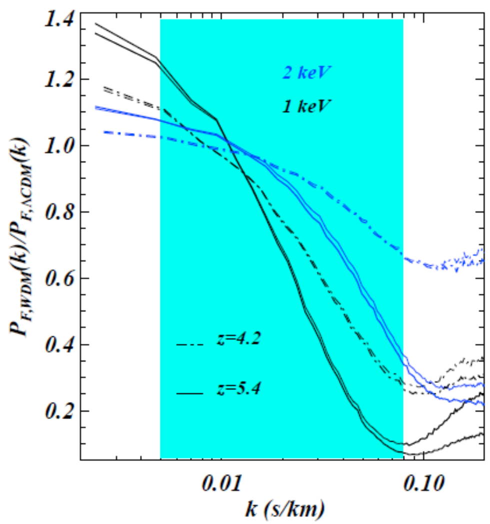


Ly-α constraints on WDM

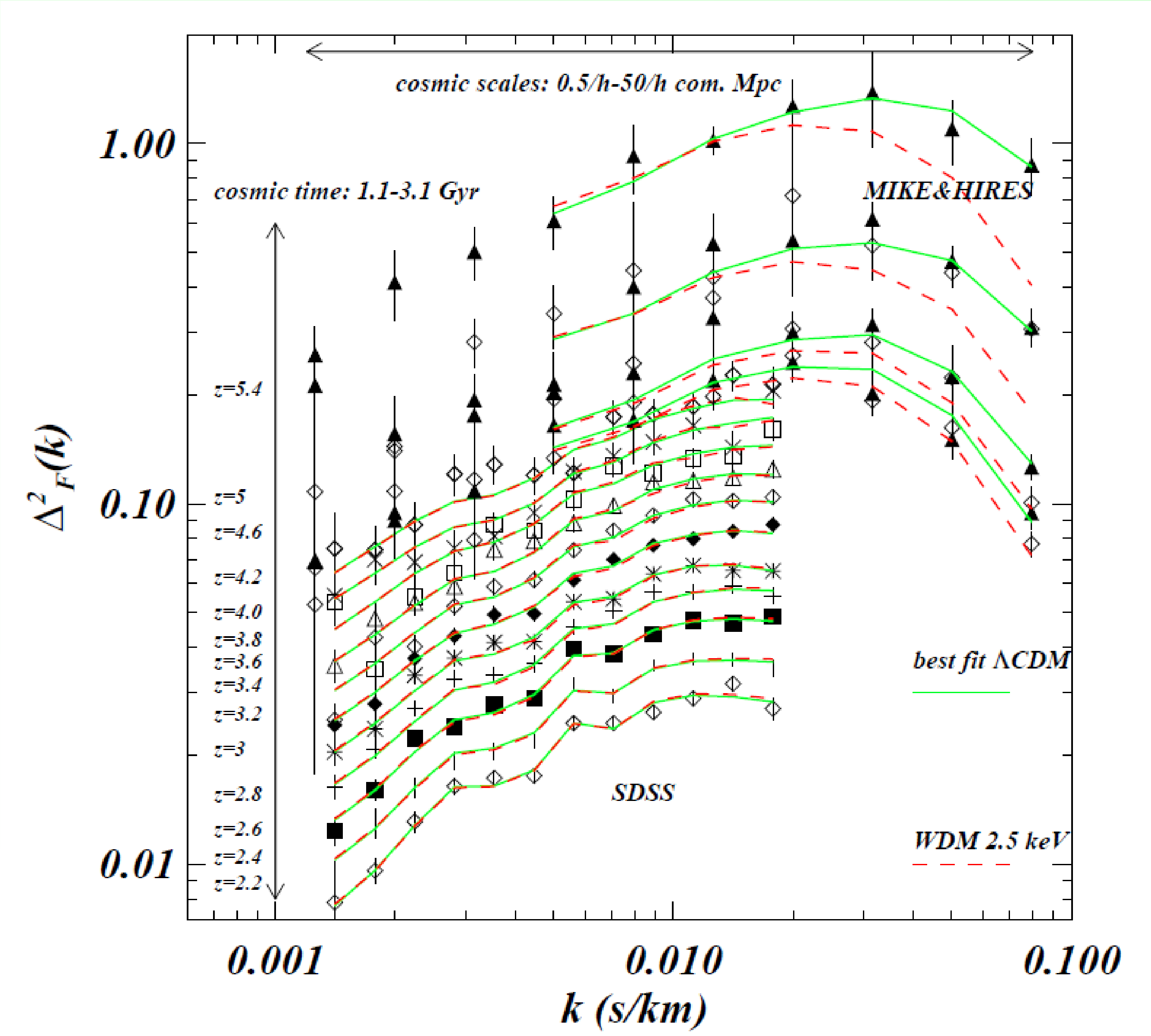
25 quasars z >4: HIRES spectra from the Keck, *Viel et al 2013*
+ MIKE (Magellan)
Lyman-α forest, compared with simulations predictions
m_{WDM} > 3.3 kev (2σ)



1D power-spectrum, predicted
By models



Best fit CDM/WDM



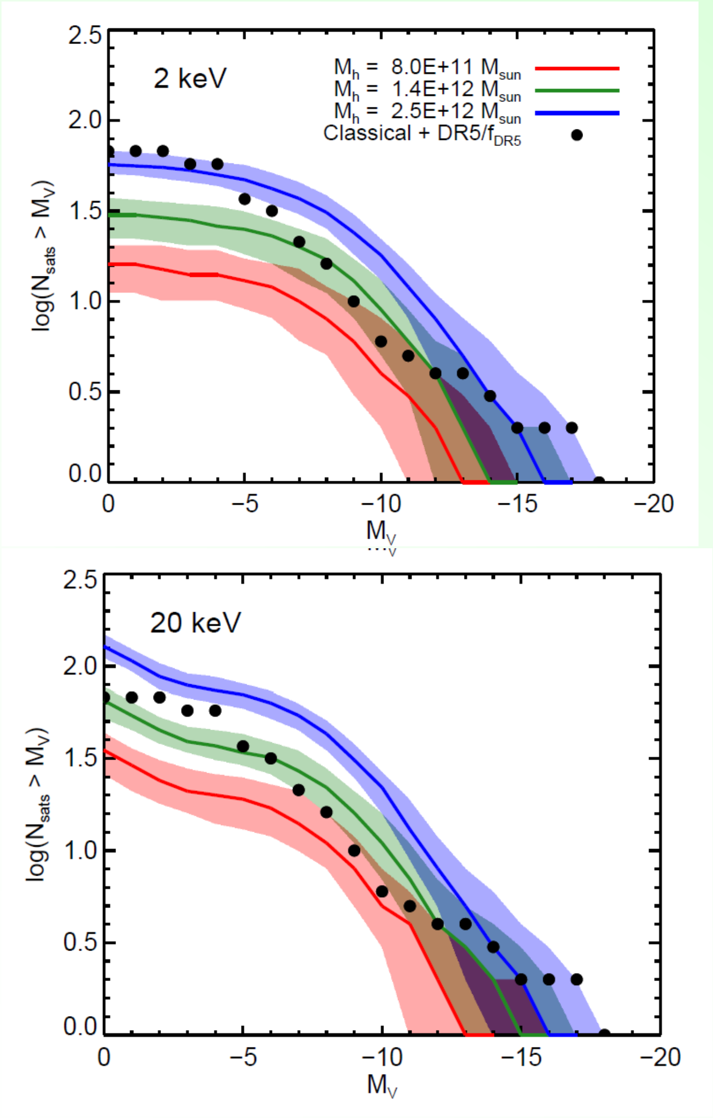
Viel et al 2013

MIKE+
HIRES+
SDSS
Flux power spectrum
Dim-less units

Compared to models

Constraints on mWDM

N(satellites)



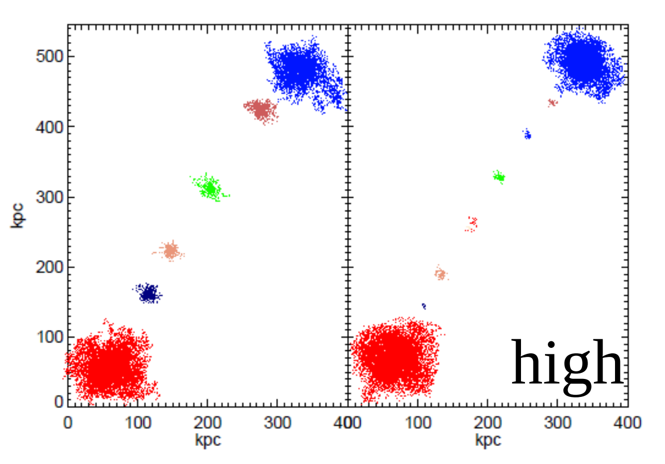
Two contradictory goals

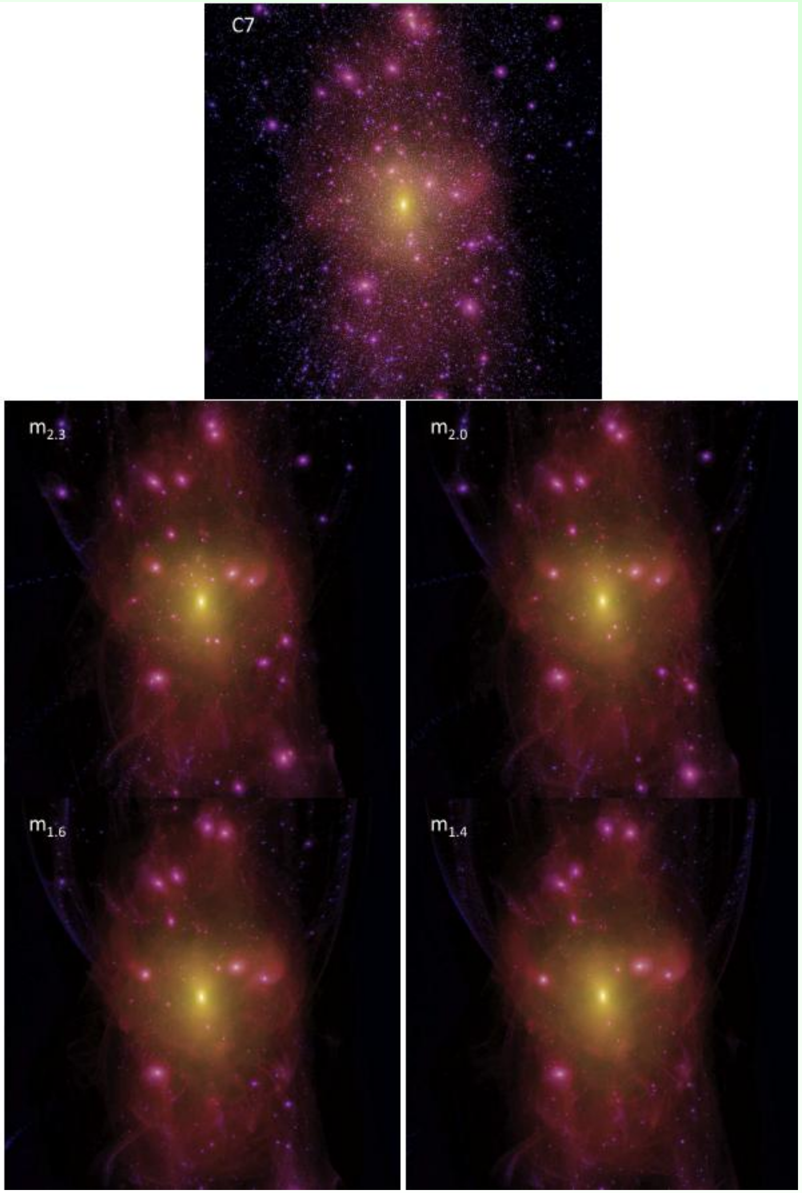
1- Have a low mWDM to reduce the mass concentration (core/cusp pb)
Low m, later formation, when the Universe density is low

2- Have a high enough mWDM to have enough dwarfs
(free-streaming)

Kennedy, Frenk, Cole et al 2013

Structure formation in WDM

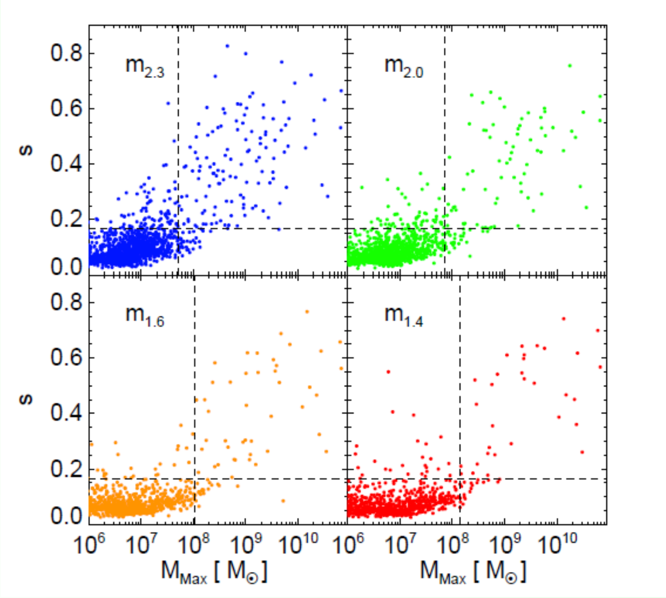




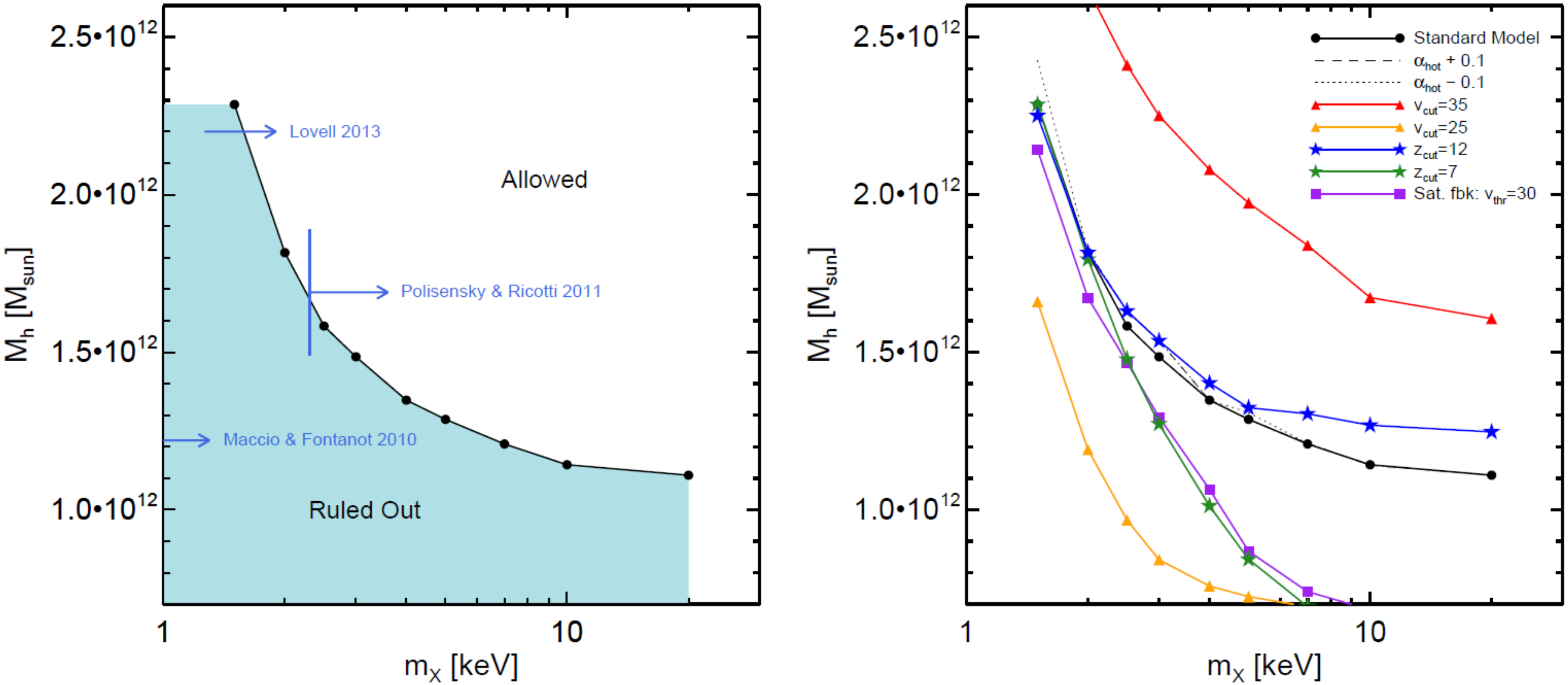
High resolution is needed

Spurious fragmentations have been reported, below smoothing length

Lovell et al 2013



Depends on the MW mass



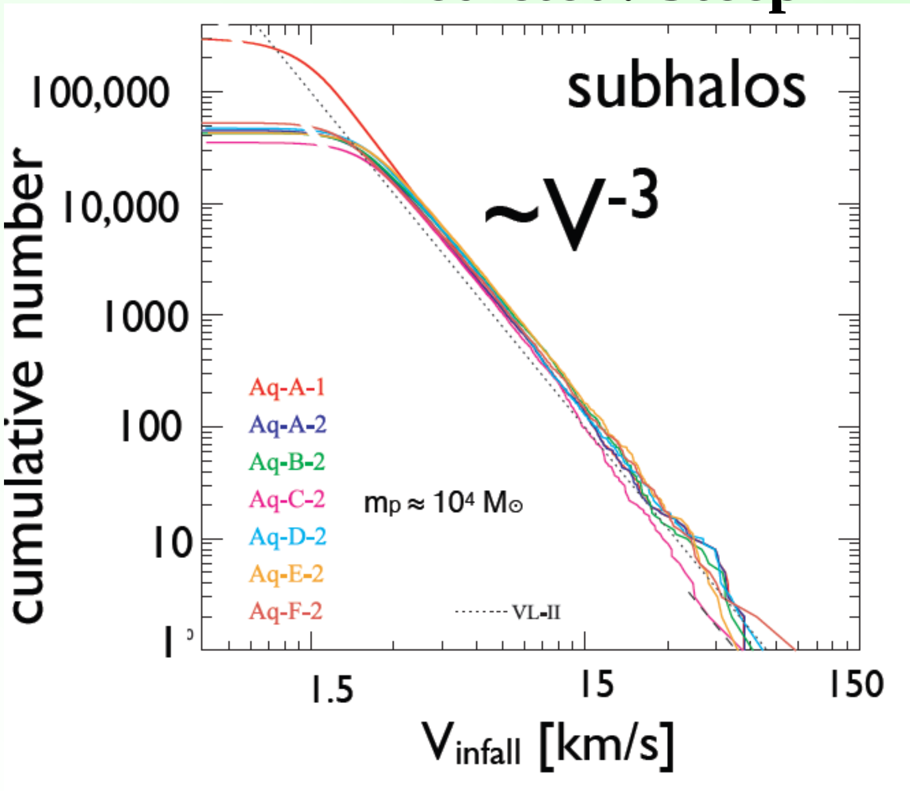
If the MW mass < 1.2 $10^{12} M_o$, WDM is ruled out

Kennedy et al 2013

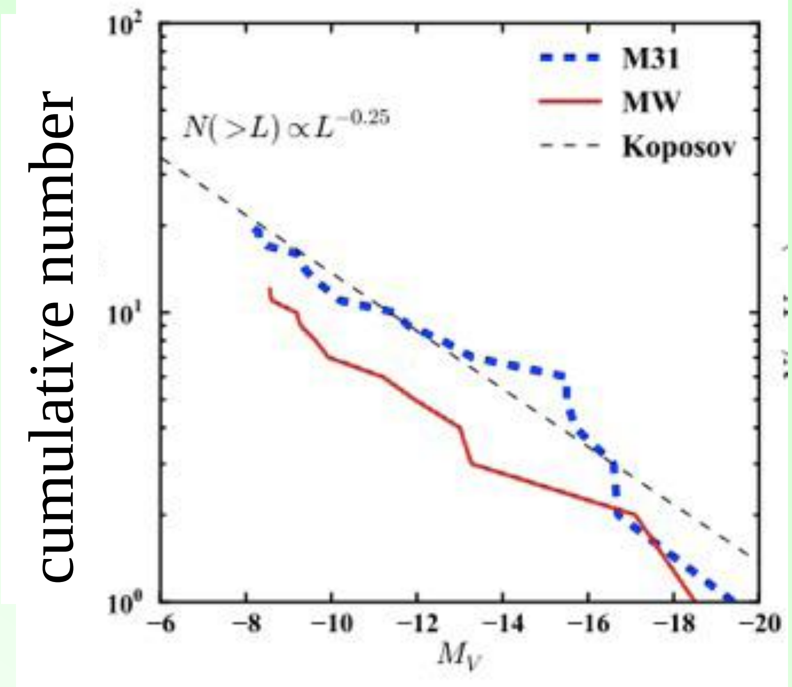
Missing satellites

Aquarius simulations of MW

Predicted: Steep



Observed: flat



Springel et al. 2008

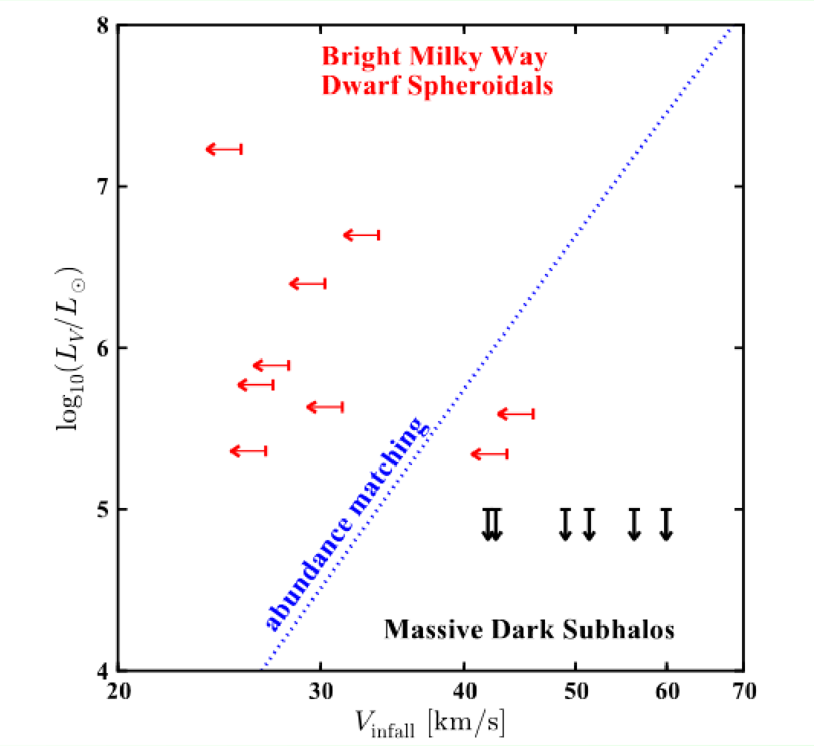
Boylan-Kolchin et al. 2011

Dwarf Spheroidals

Fornax, Leo I, Sculptor, Leo II, Sextans, Carina, Ursa Minor, CanesVenatici I, Draco

Very low surface brightness
and dominated by dark matter

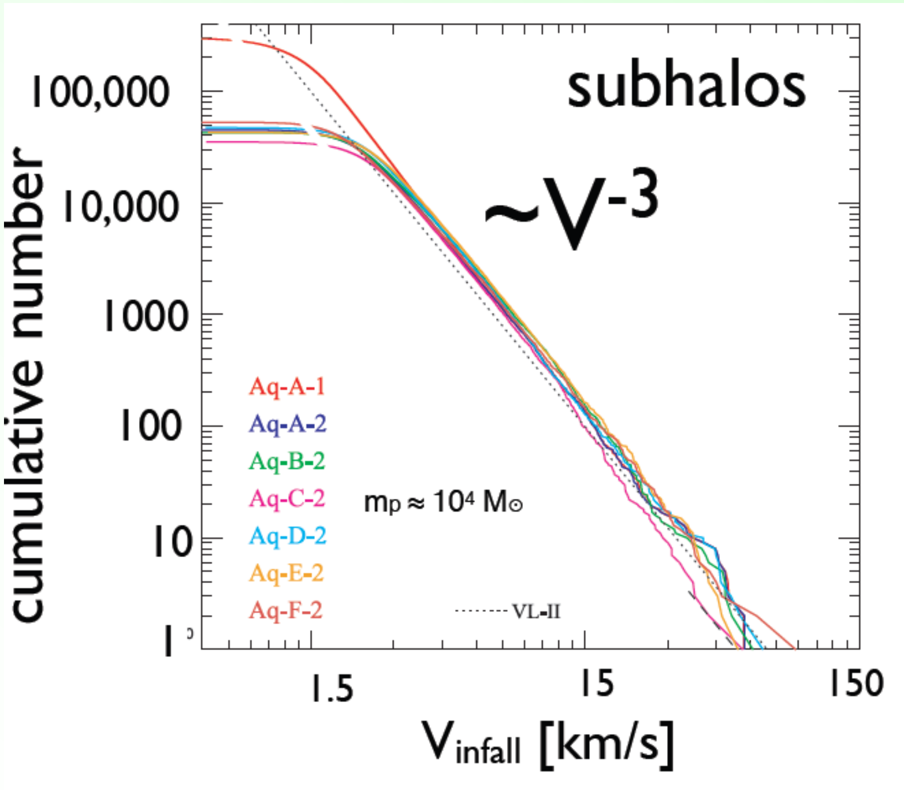
These dSph are not obtained
In CDM simulations

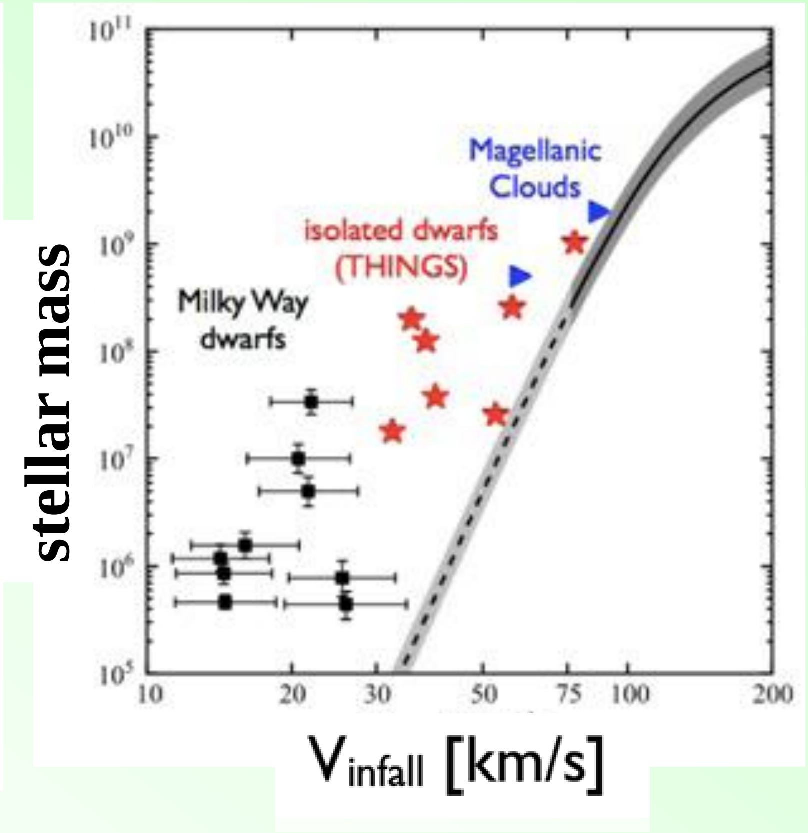


$L_v > 10^5 L_o$
Boylan-Kolchin et al 2011

Abundance matching for satellites

Stellar mass matching

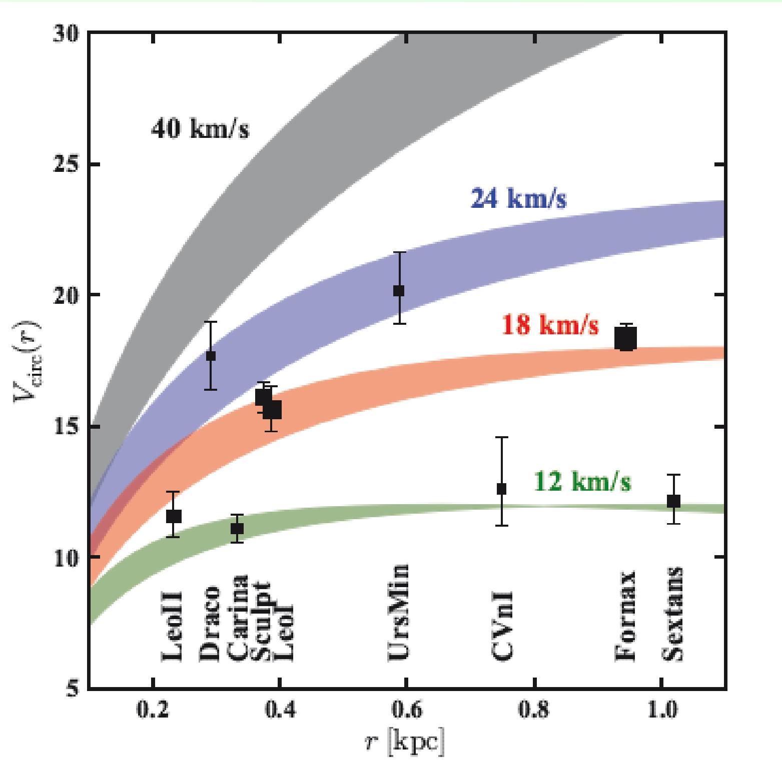




Springel et al. 2008

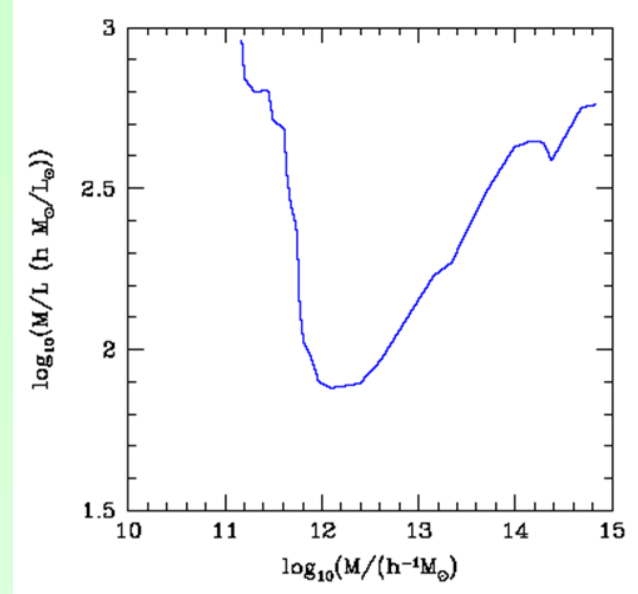
Boylan-Kolchin et al. 2011

Misfits of satellites



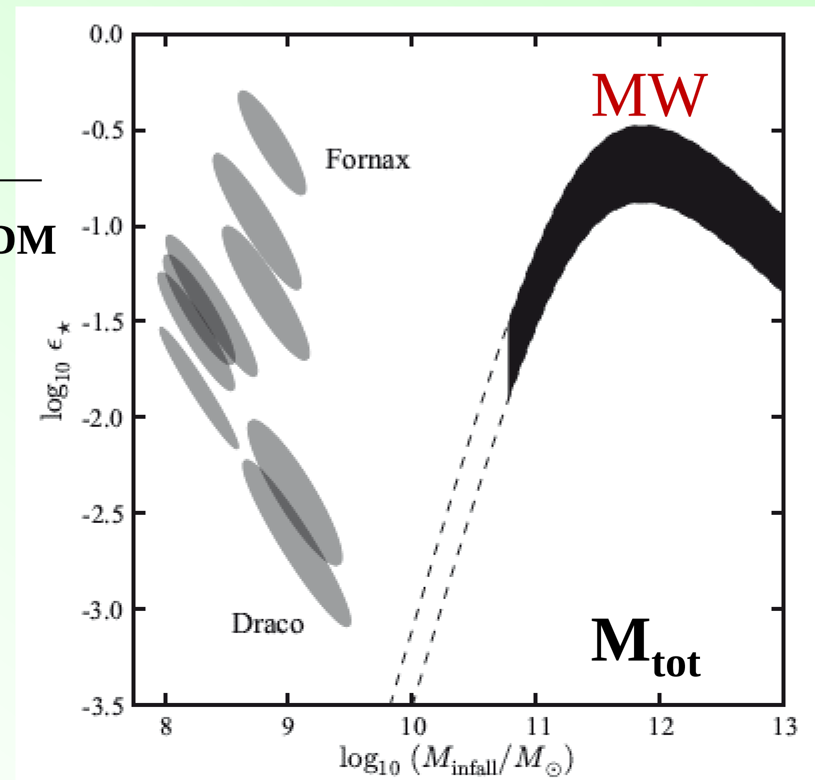
Boylan-Kolchin et al 2012

9-10 satellites with $L_V > 10^5$Lo



From halo abundance matching,
the efficiency to form stars is derived,
➔must peak at 20% of baryons in stars at M_{tot} ~10^{12}Mo (MW-type galaxies)

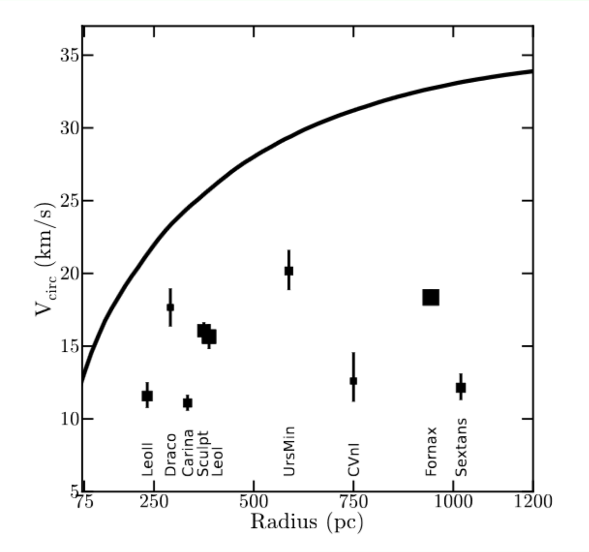
$$\frac{M_*}{f_b\, M_{DM}}$$



Too Big To Fail (TBTF) problem

Dwarf Spheroidals of the Local Group, $M_* \sim 10^6$ Mo, Vcir vs R

Numerical simulations predict dense cusps, which cannot correspond to any of the dSph observed (*Boylan-Kolchin et al 2012*)



Repeated blow-out due to supernovae have been simulated, to destroy the haloes

A single burst of the same total mass is better

But 40 000 SN are required with 100% efficiency

➔ SF feedback cannot solve the problem

Garrison-Kimmel et al 2013

Alternative theories of gravity

Scalar-tensor theories
Chameleon
Einstein-Aether Theories
Modifed Newtonian dynamics

Tensor-Vector-Scalar Theories
Bekenstein TeVeS

Other theories, for dark energy, degravitation..
higher order derivatives f(R)
Higher Dimensional Theories of Gravity
Branes

MOND =MOdified Newtonian Dynamics
Modification at weak acceleration

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

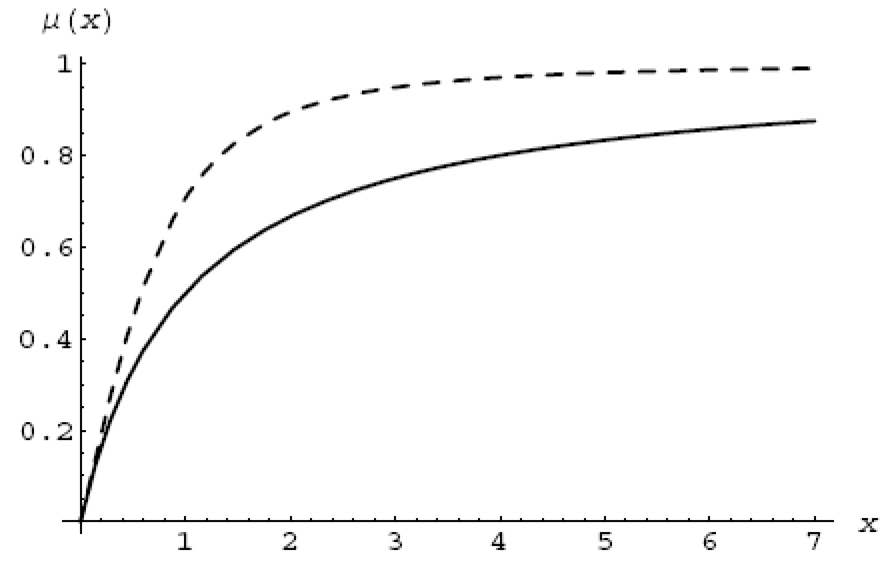
$a_N \sim 1/r^2$ ➔ $a \sim 1/r$ ➔ $V^2 = cste$

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

➔ $a^2 \sim V^4/R^2 \sim GM/R^2$ (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



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

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

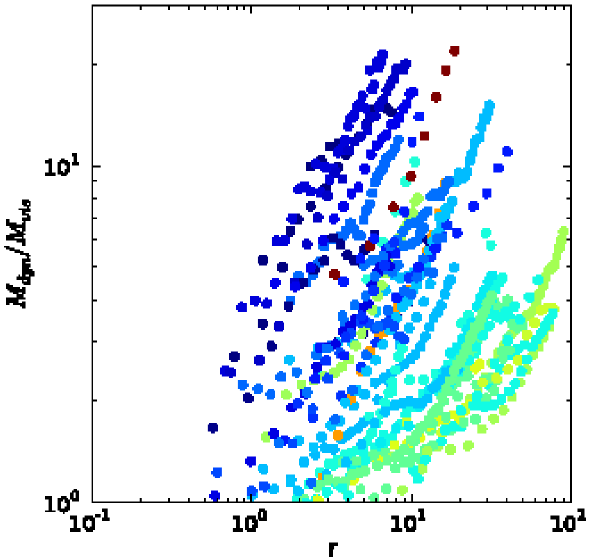
Covariant theory: TeVeS

Account for lensing

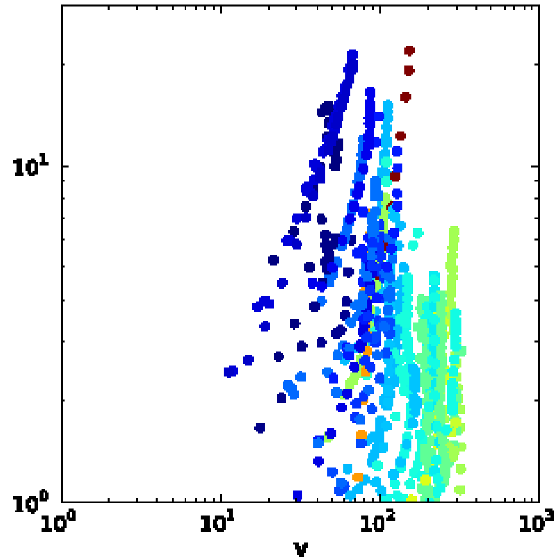
Dynamic Mass / Visible Mass

The ratio remarquably depends on acceleration,

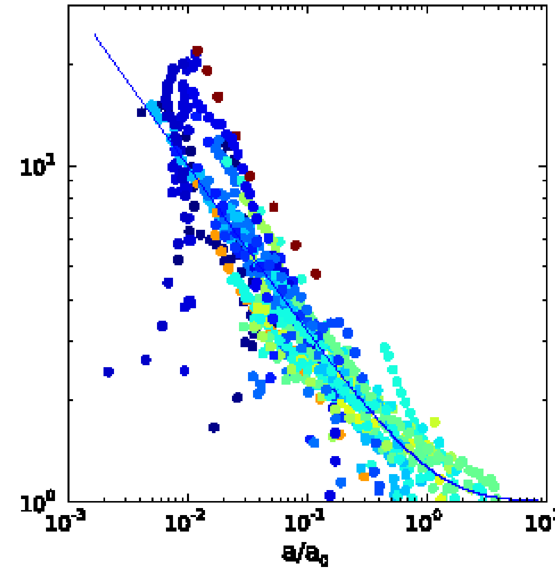
➔ The only variable controling the gravity regime universally



Radius



Velocity

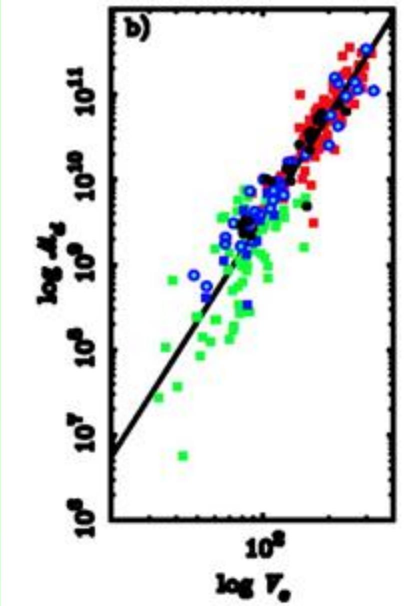


Acceleration

Tully-Fisher relation

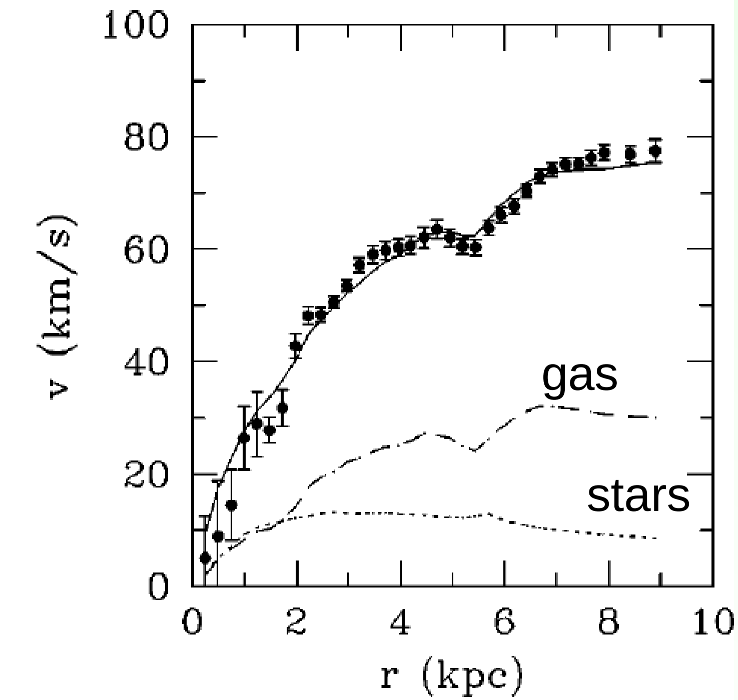
$$g_M^2 = a_0 g_N = a_0 GM/r^2 = V^4/r^2$$

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

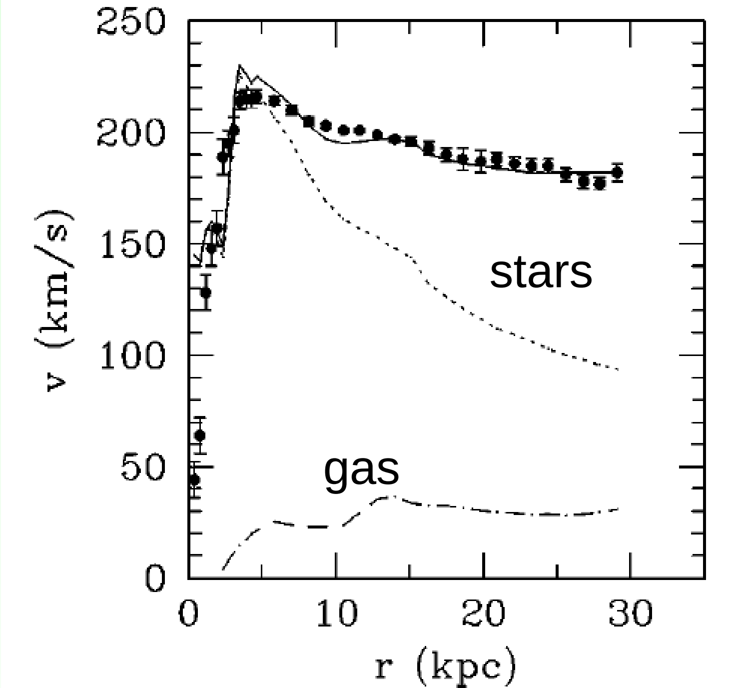


Rotation curves are fit for all types (dwarfs **LSB**, giant **HSB**)

LSB N1560



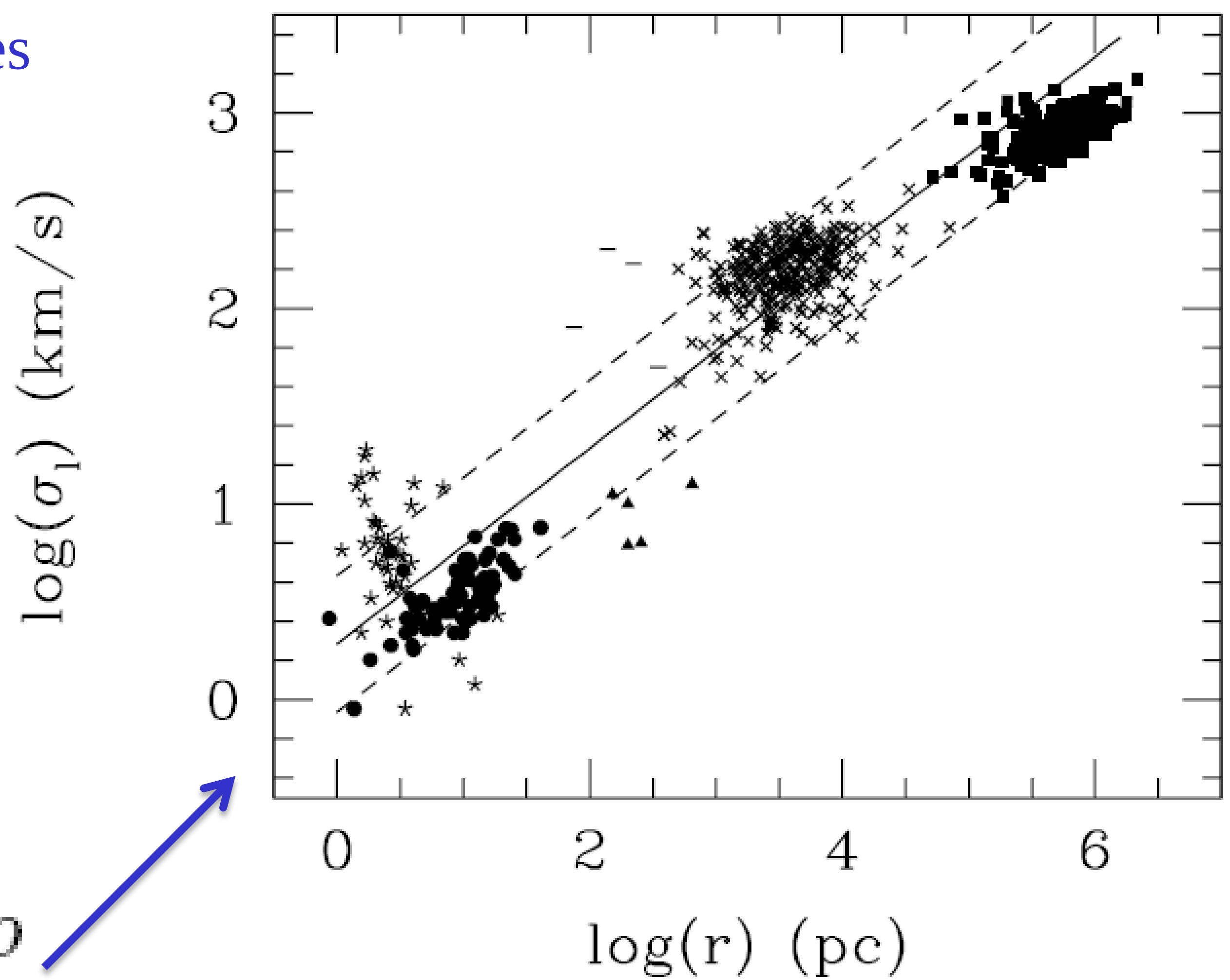
HSB N2903



Pressure-supported systems

Sanders & McGaugh 2002

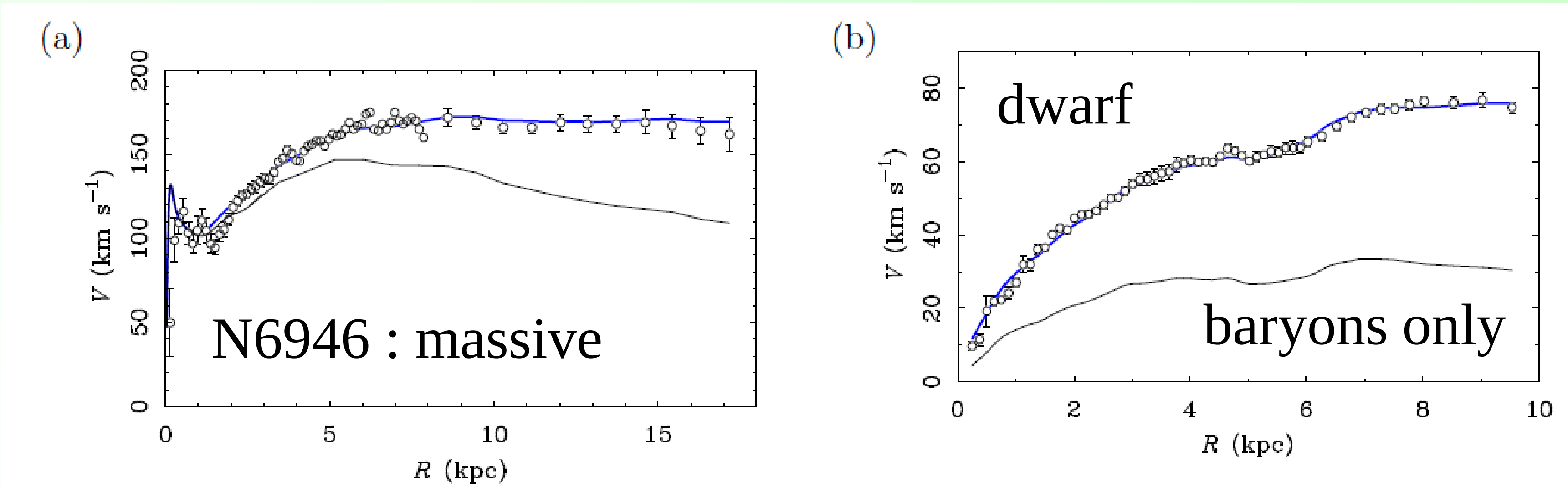
From GC to galaxies
and clusters

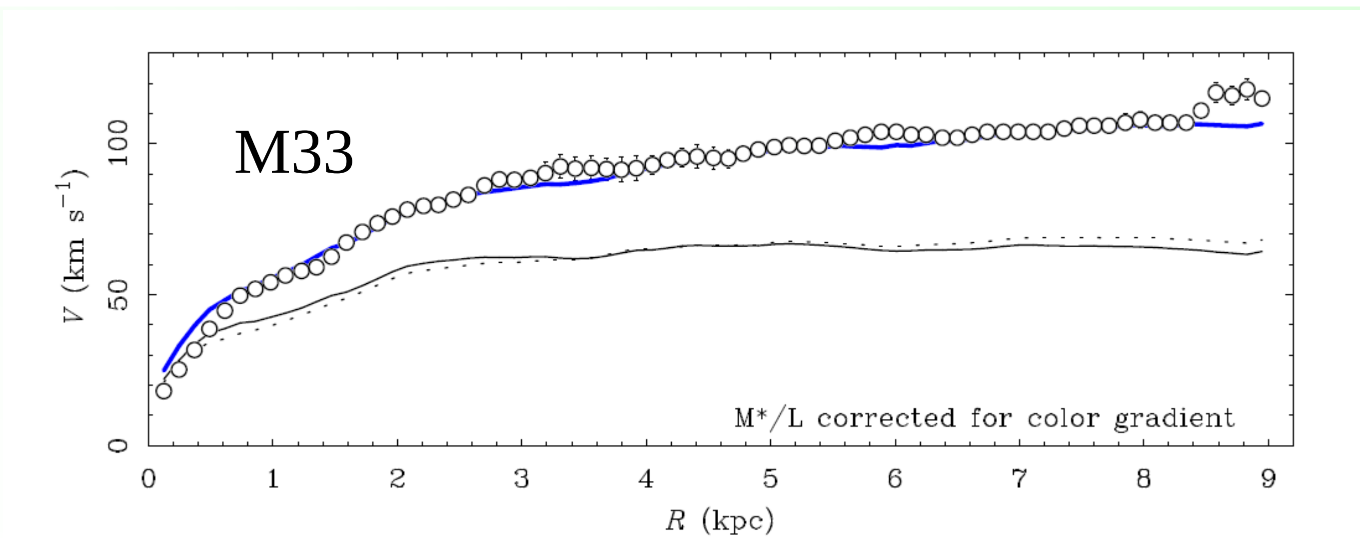


$$\sigma_l^2/r = a_o$$

Multiple rotation curves..

All types, all masses, with the same parameter a0,
universal for ~1000 curves *Sanders & Verheijen 1998*





Problems of MOND in galaxy clusters

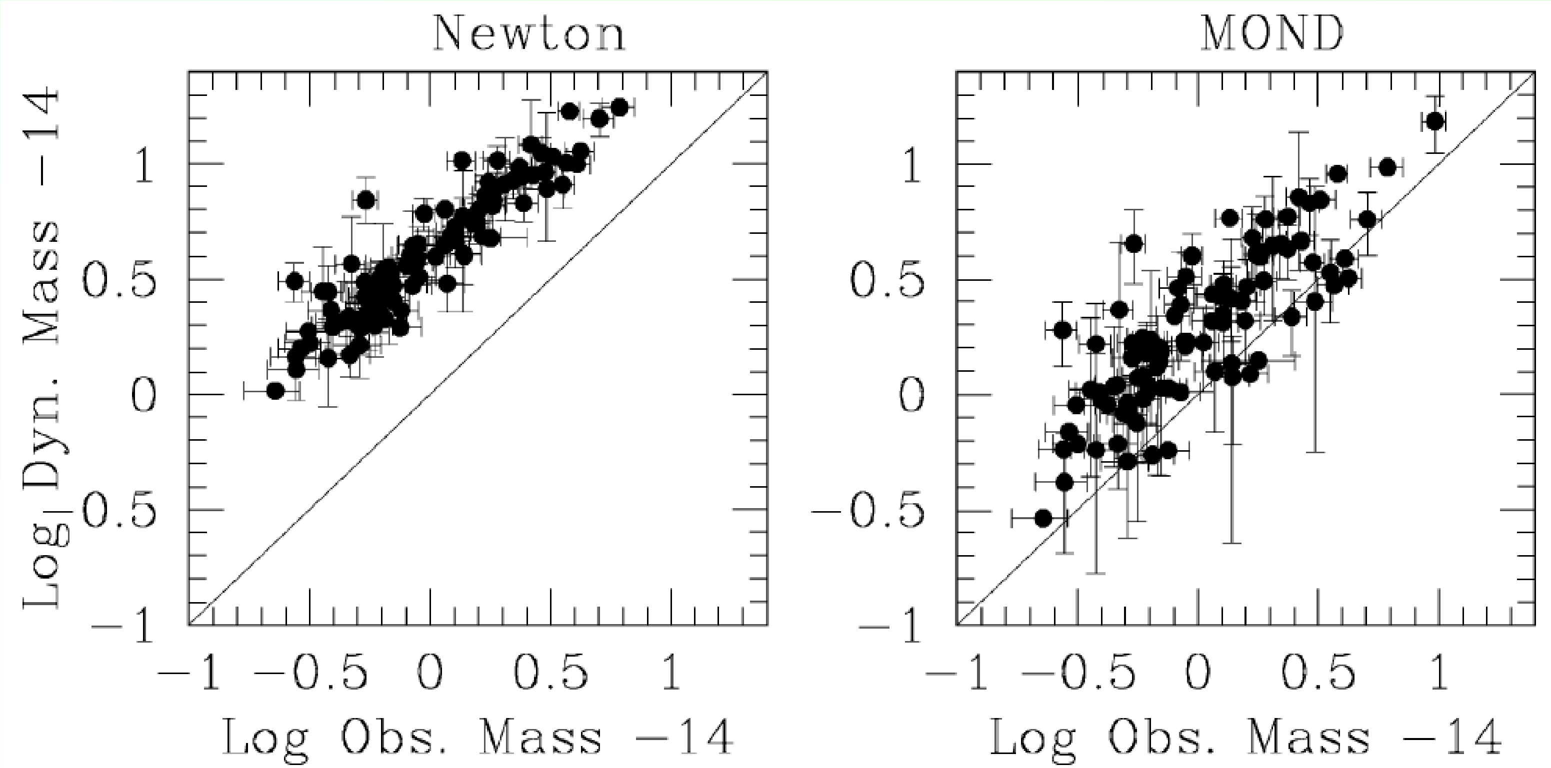
Inside galaxy clusters, there still exists some missing mass, which cannot be explained by MOND, since **the cluster center** is only moderately in the MOND regime (~0.5 a_0)

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

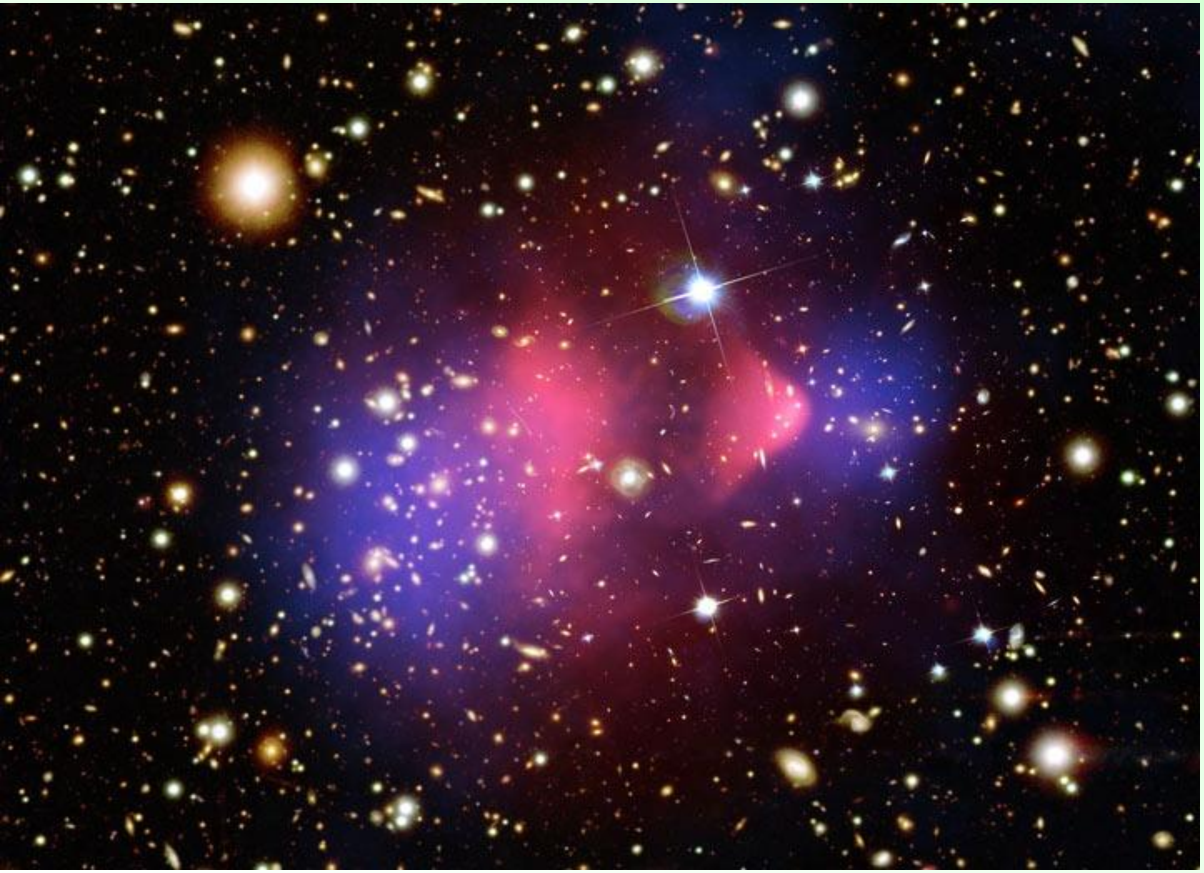


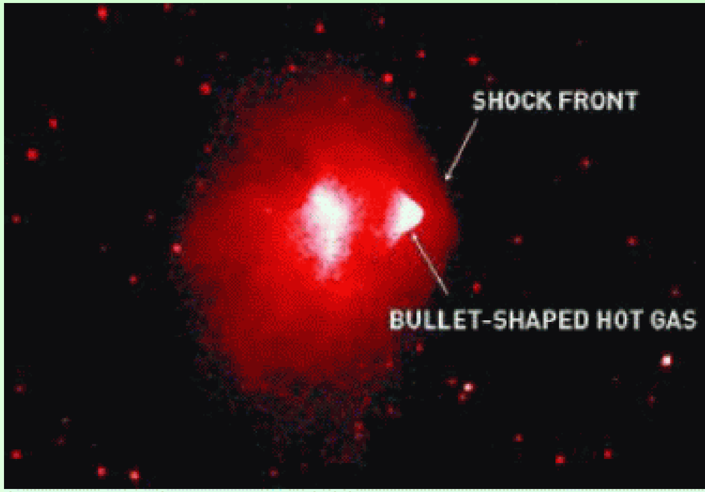
According to baryon physics, cold gas could accumulate at the cluster centers

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)

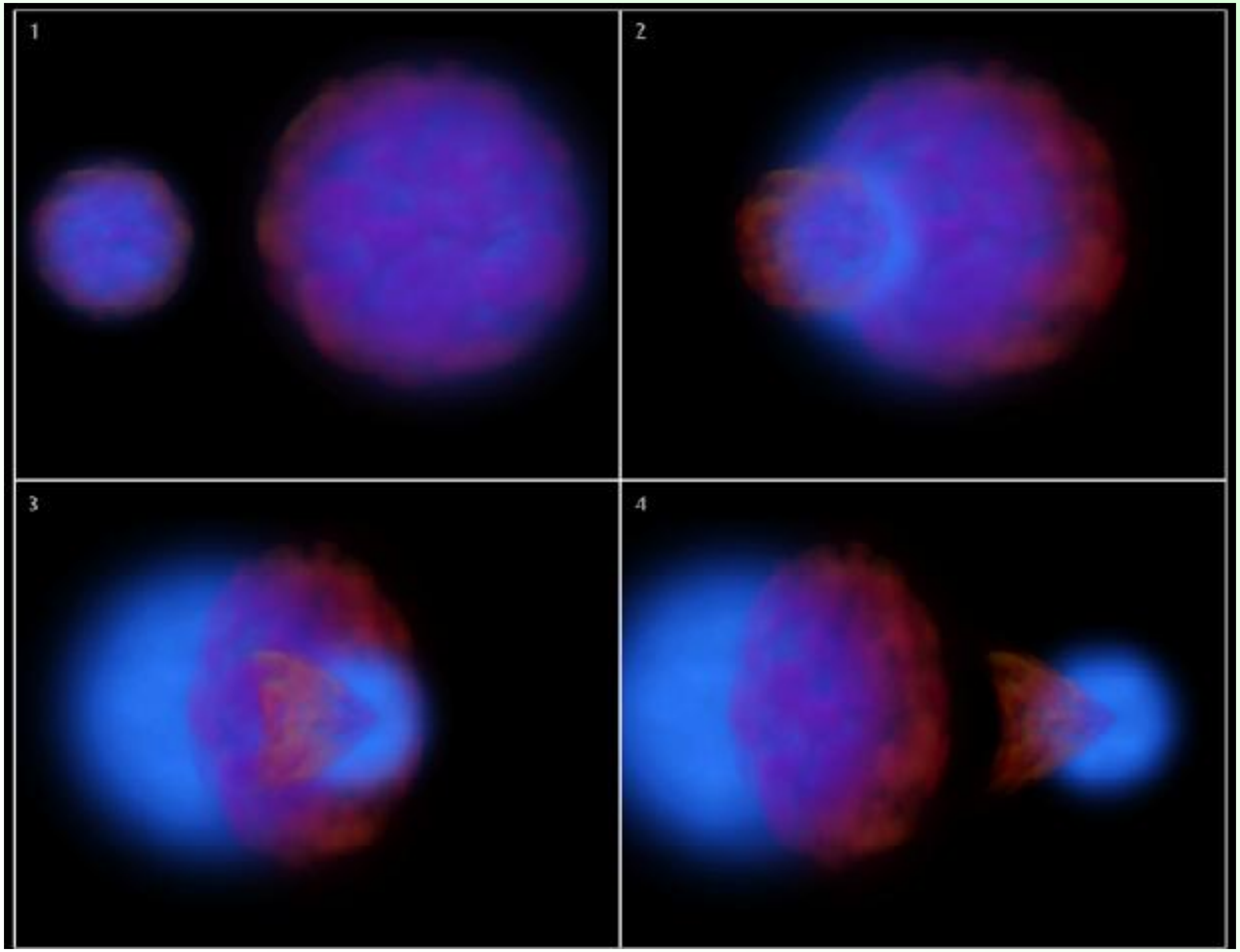
CDM simulation

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

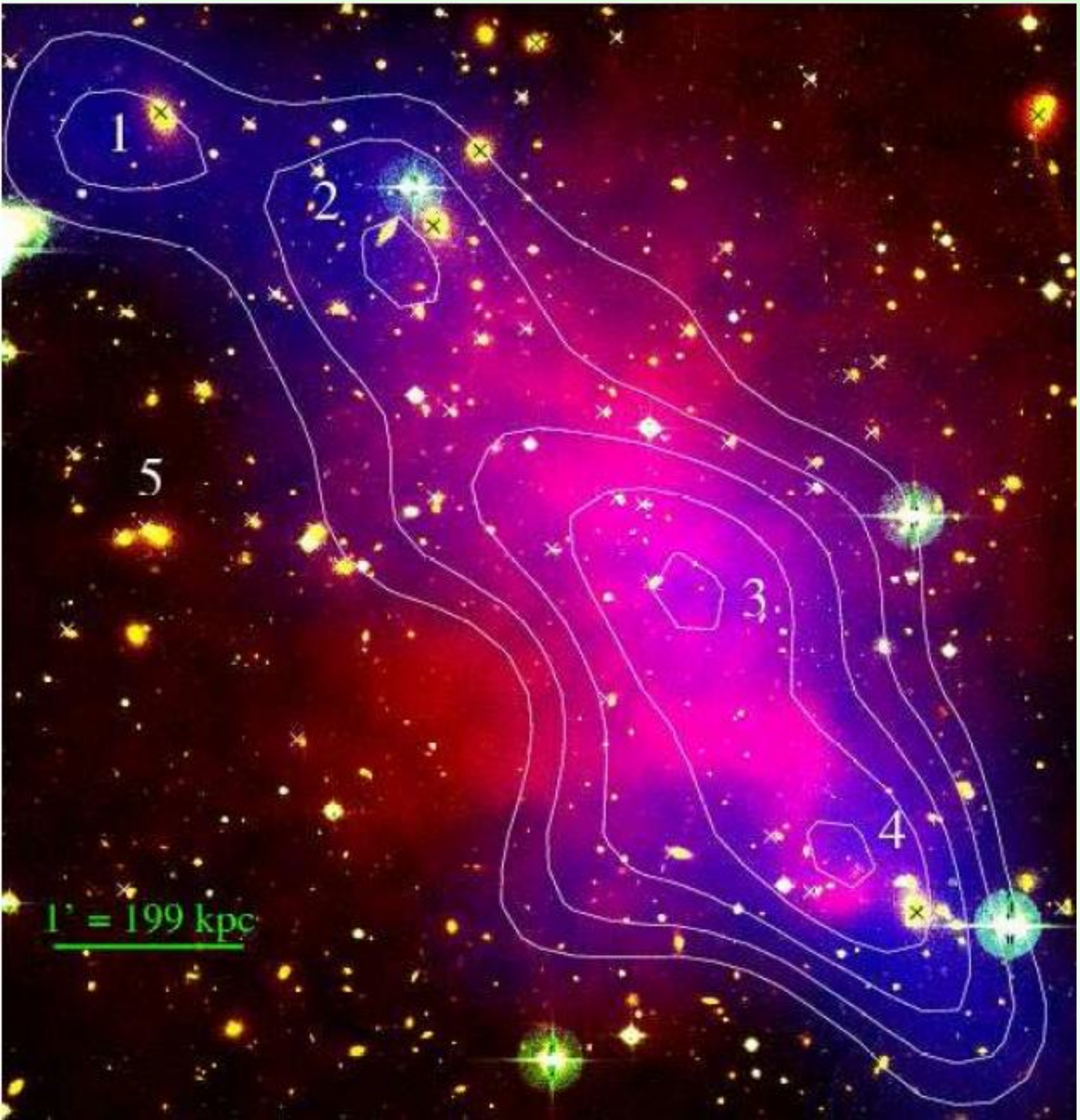
Linares et al 2009

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

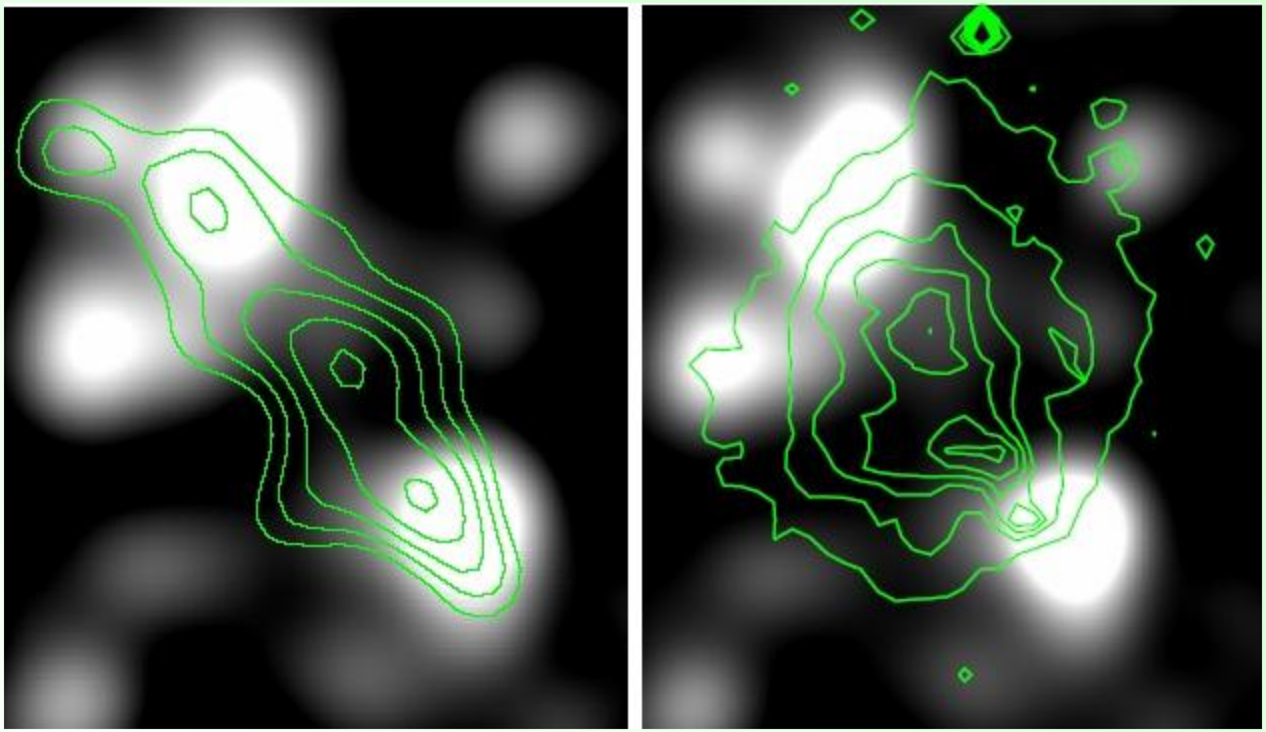
Contours= lensing

➔Massive DM core Coinciding with X gas but devoid of galaxies

Cosmic train wreck

Opposite case!

Abell 520 merging clusters



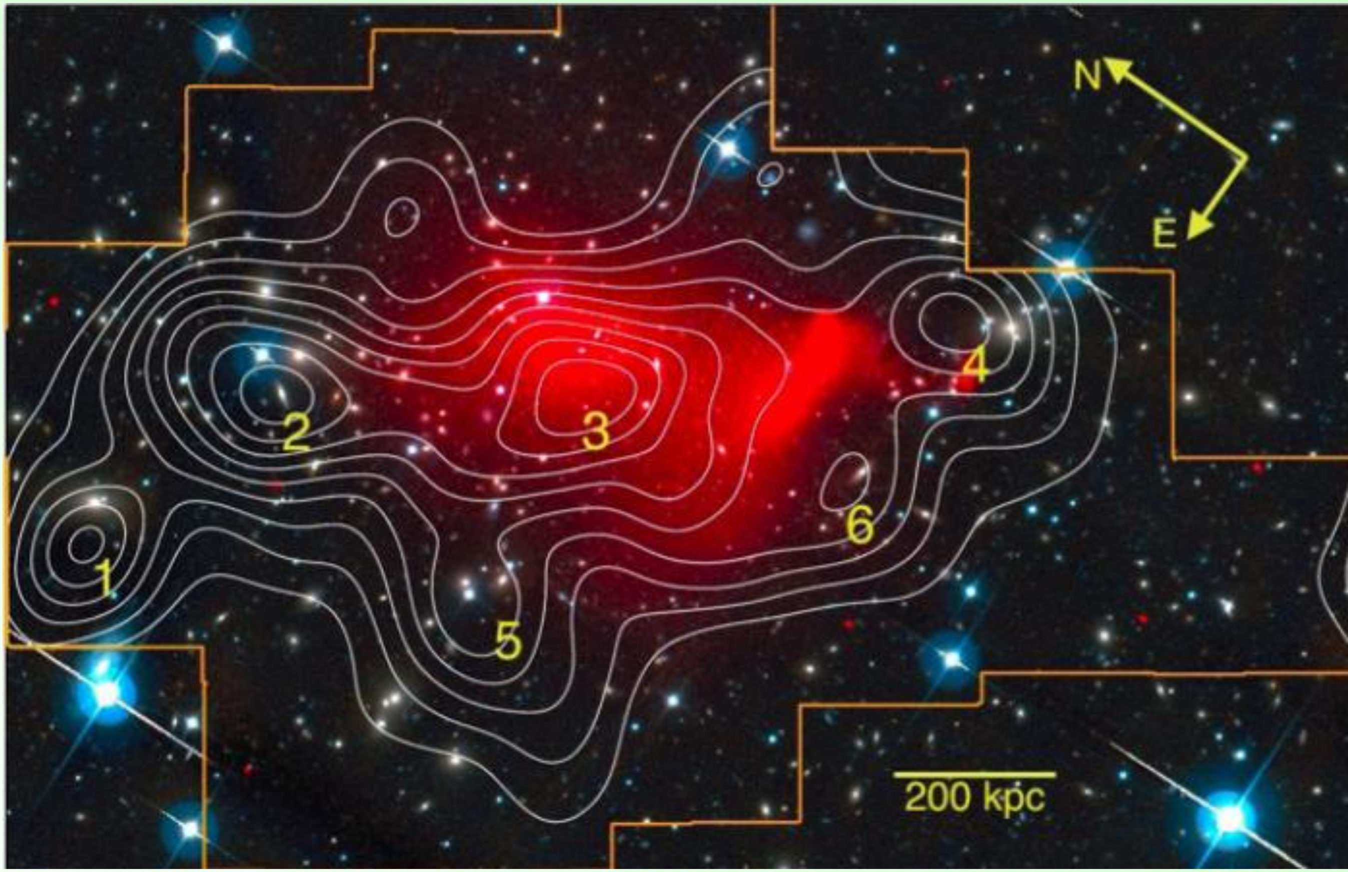
Contours=total mass   Contours = X-ray gas

How are the galaxies ejected from the CDM peak??

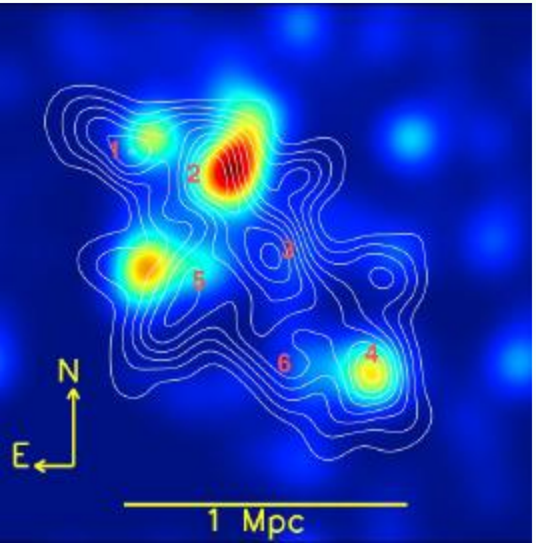
A520: Dark core with X-ray

Jee et al 2012

Dark core at 10σ
Contours of DM
(weak lensing HST)
on X-ray (red)



B-band CFH (blue)



Collisional dark matter? σ_{DM}/m_{DM} ~3.8cm^2/g
Real counter-example of the bullet
where $\sigma_{DM}/m_{DM} < 1$ cm^2/g

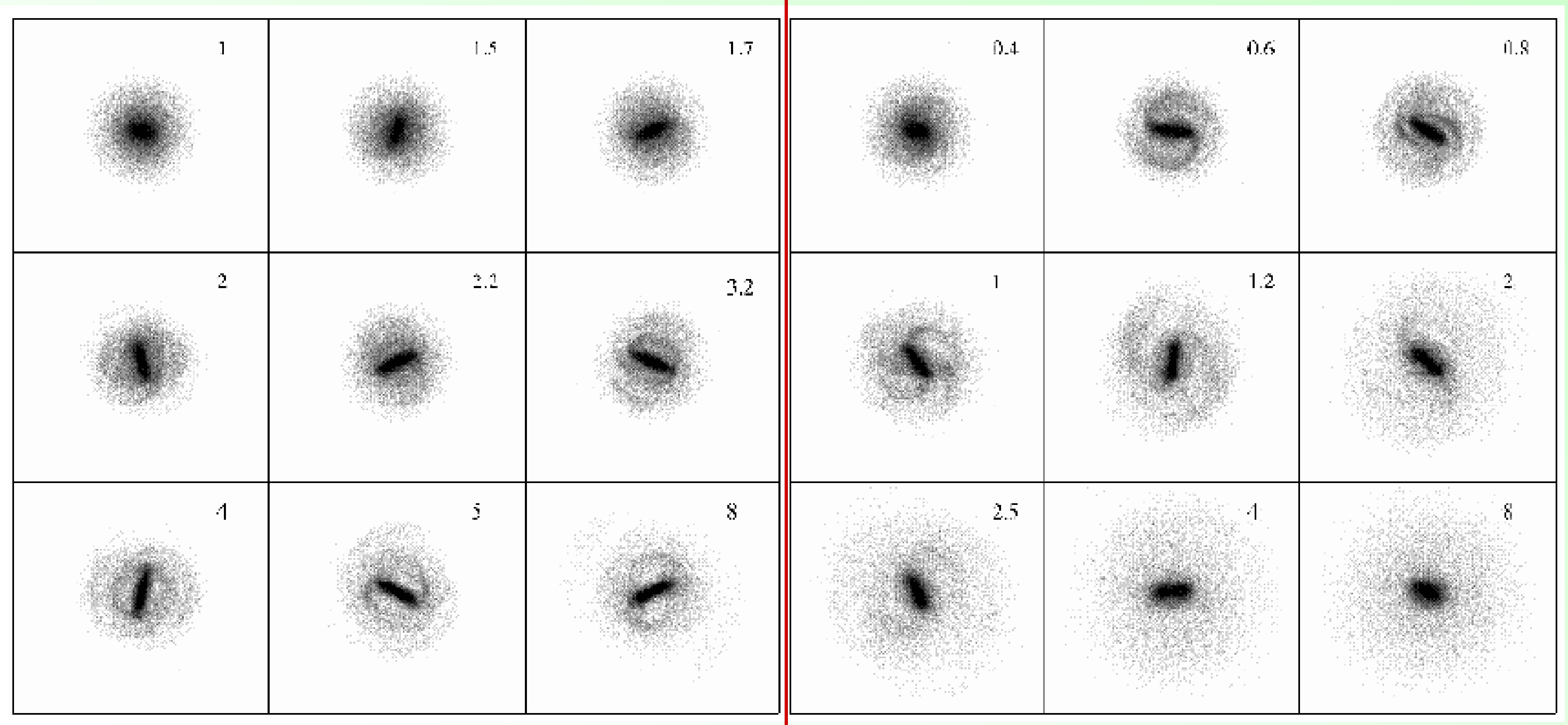
Constraints
from galaxy dynamics and observations

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

--Galaxy interactions
--Bars and their pattern speeds
--Different dynamical friction

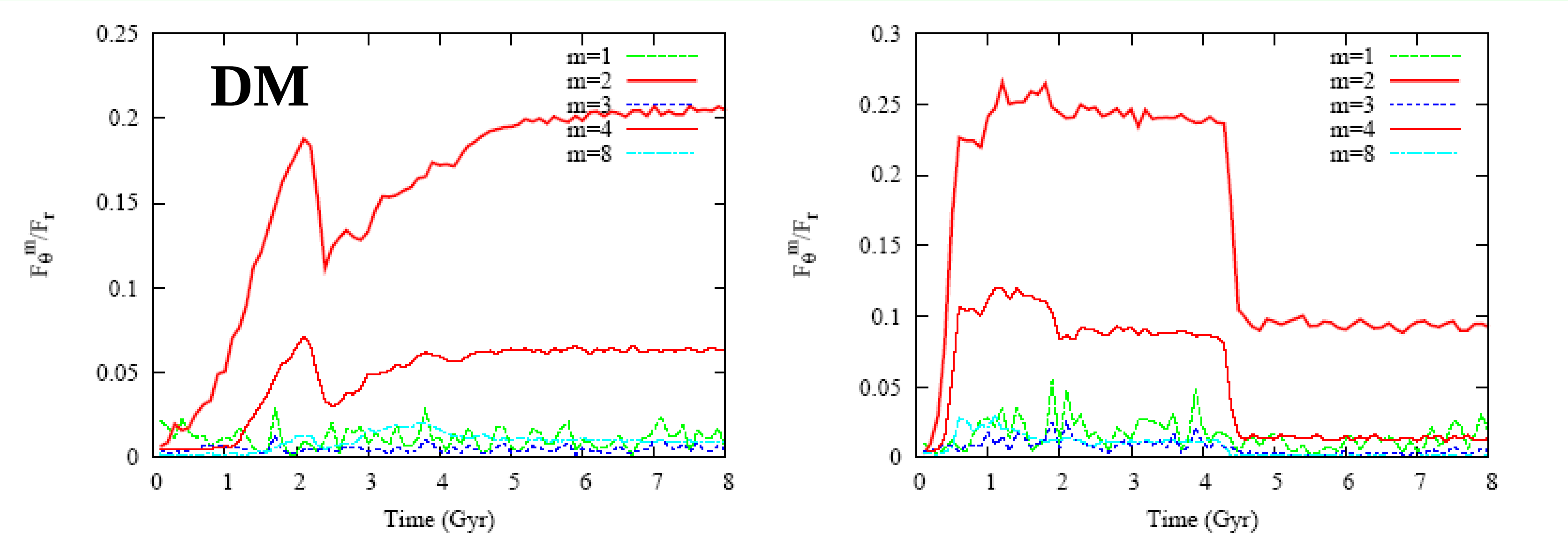
Influence of DM halo

With DM halo | Without DM (MOND)

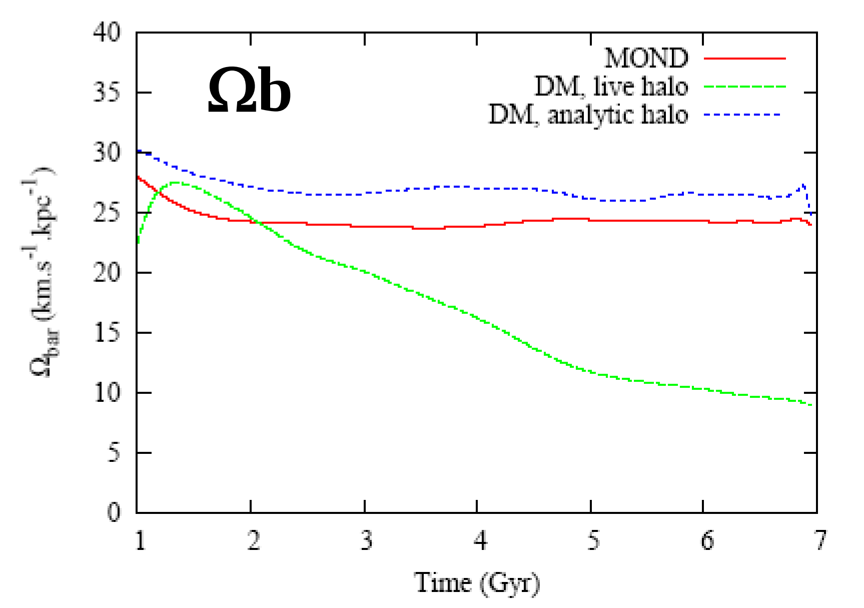


Tiret & Combes 2007

Bar strength and pattern speed with and w/o DM



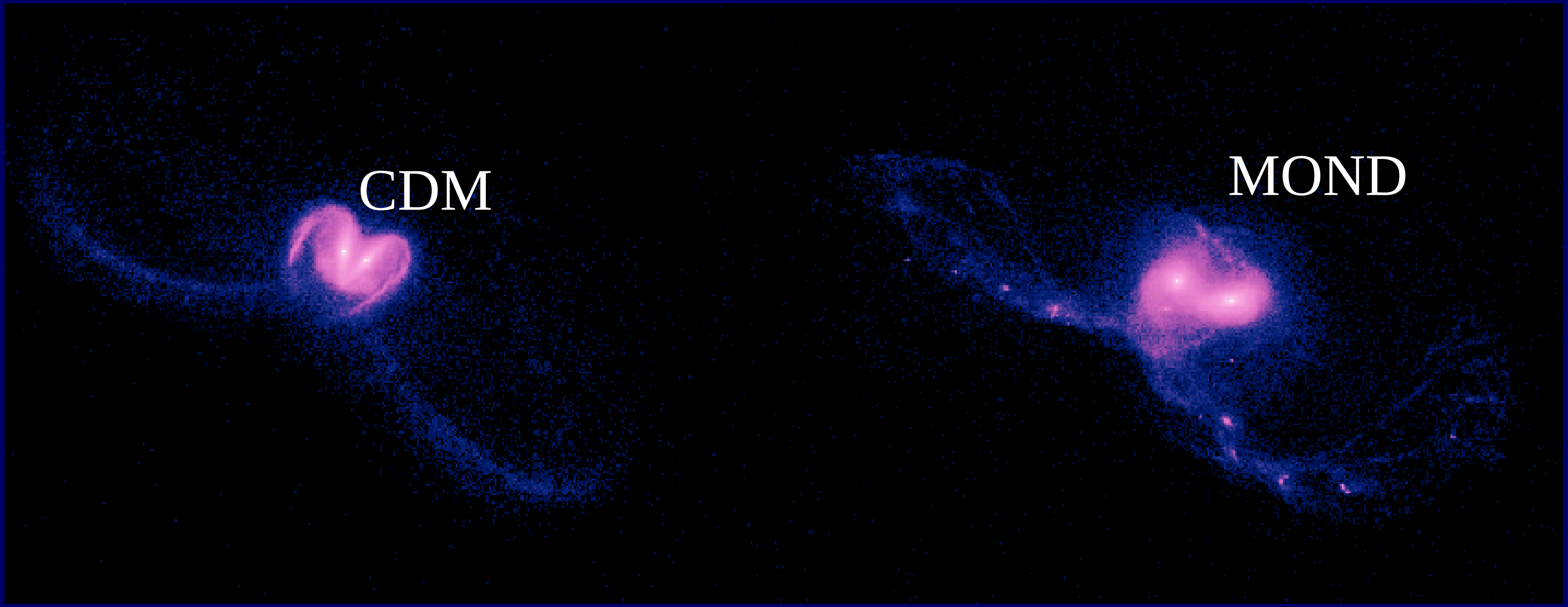
With DM, the bar appears later, and can reform after the peanut weakening through halo AM exchange,
➔But Ωb falls off



Tiret & Combes 2007

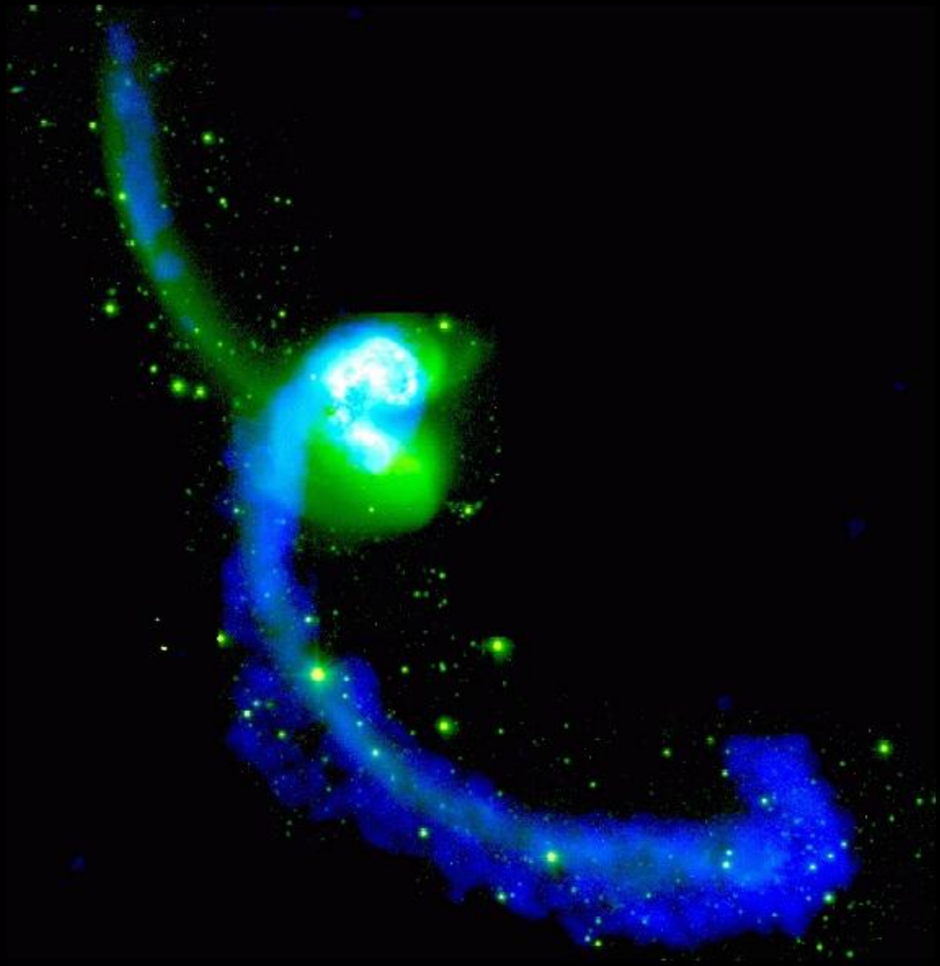
Interactions of galaxies: the Antennae: MOND versus CDM

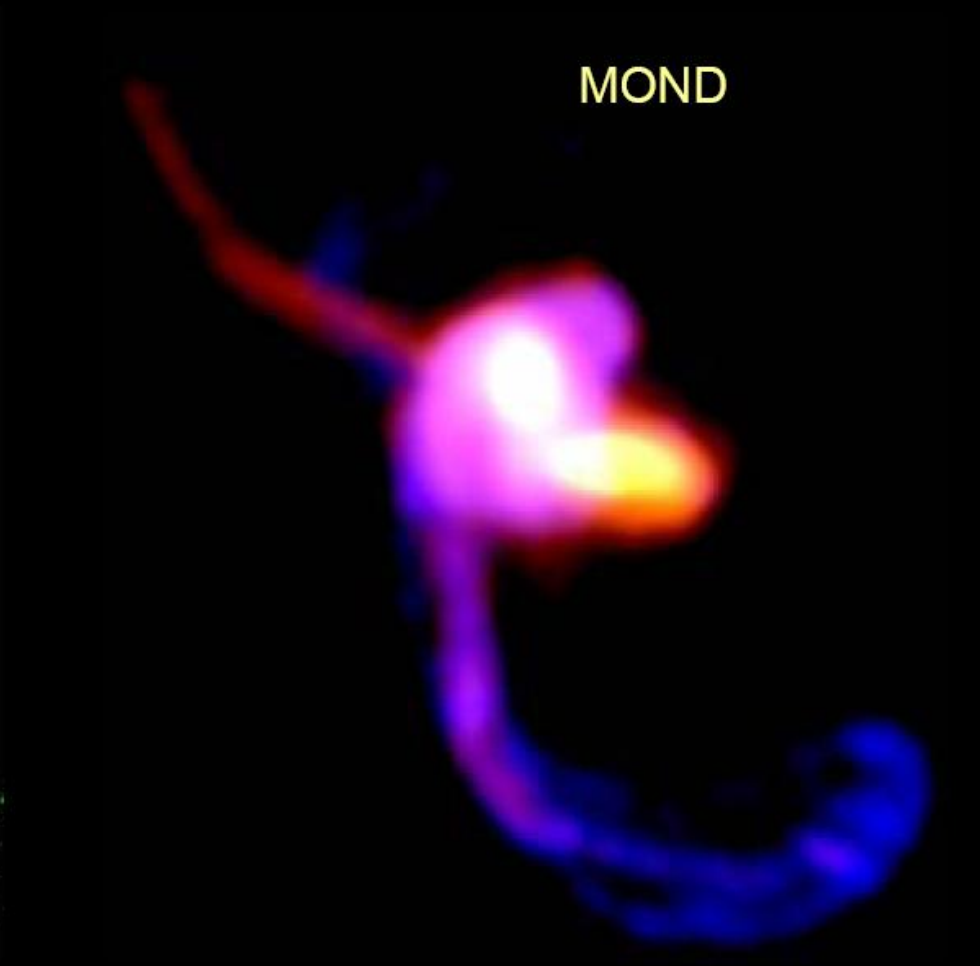
Dynamical friction is much lower with MOND: mergers last much longer



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

Simulations of the Antennae





Dynamical friction

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

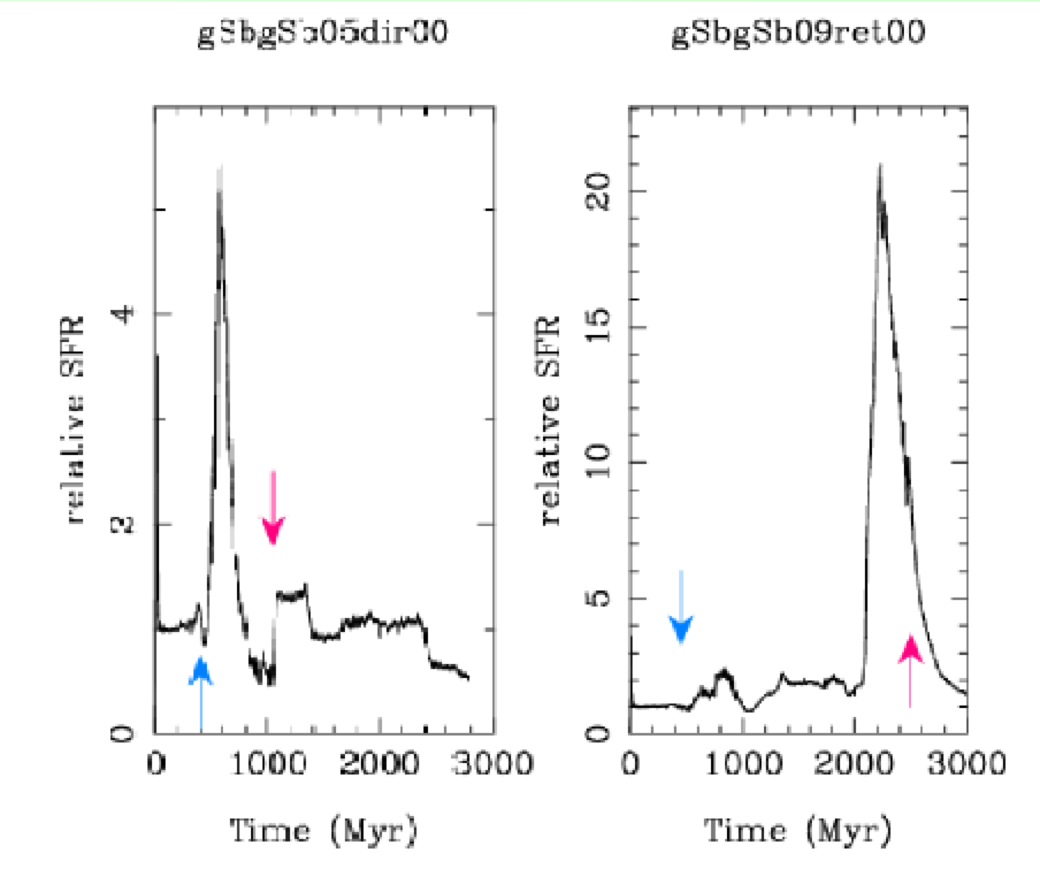
Merger induced starbursts degeneracy

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

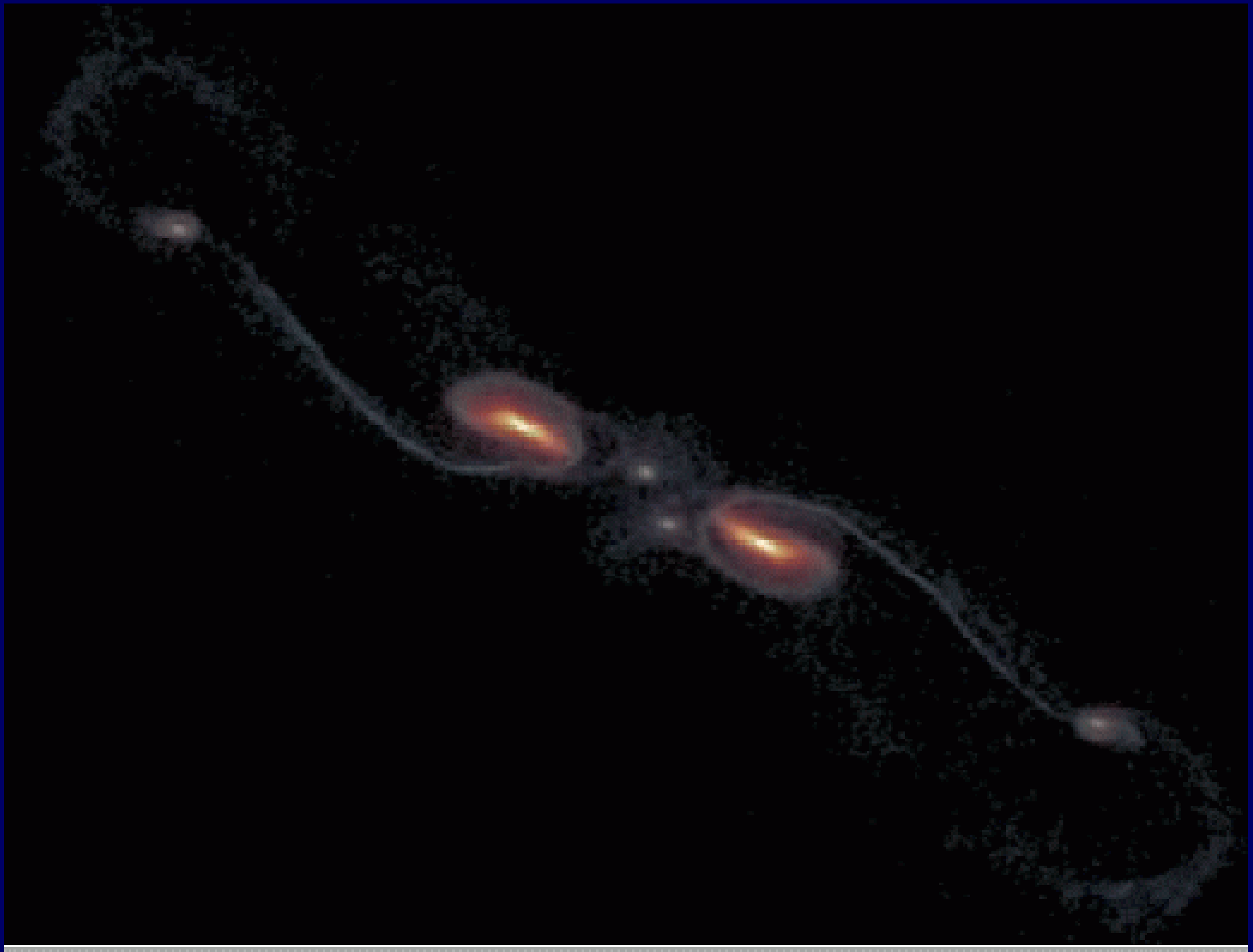


Di Matteo et al 2007

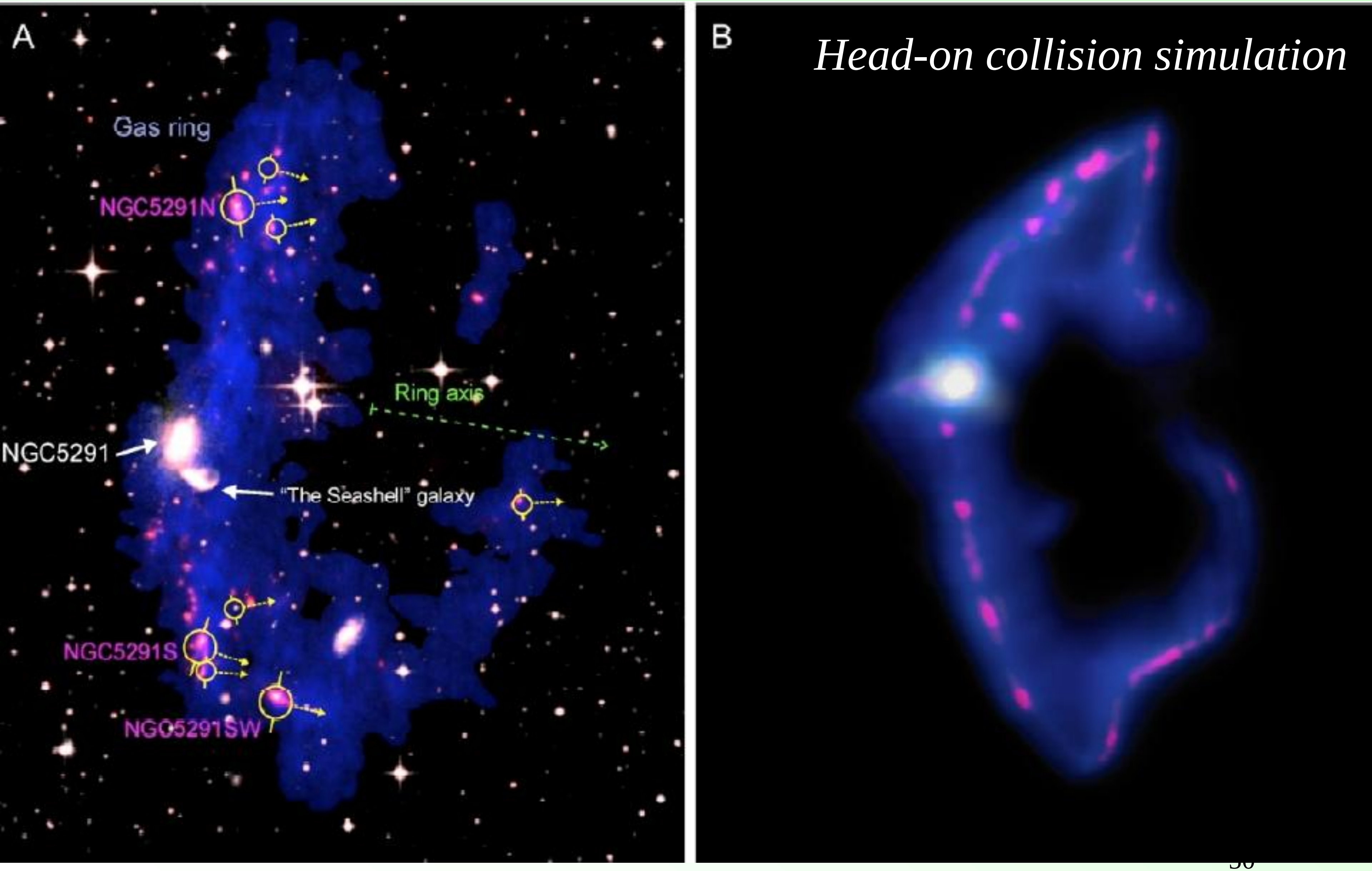
Formation of Tidal Dwarf Galaxies

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)

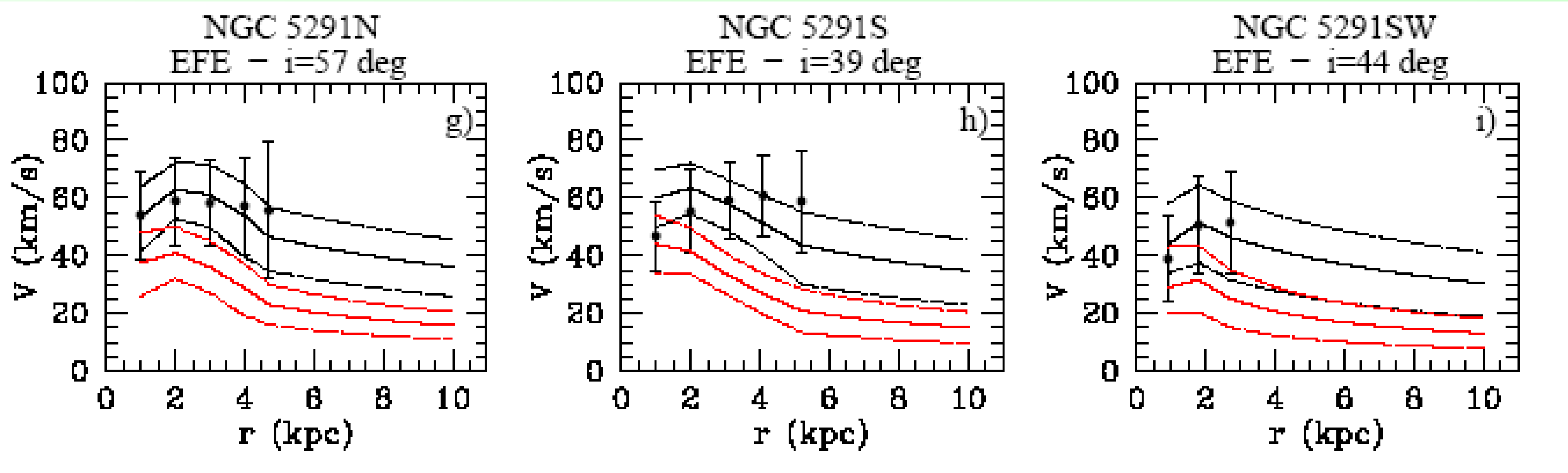


TDG in N5291 HI ring



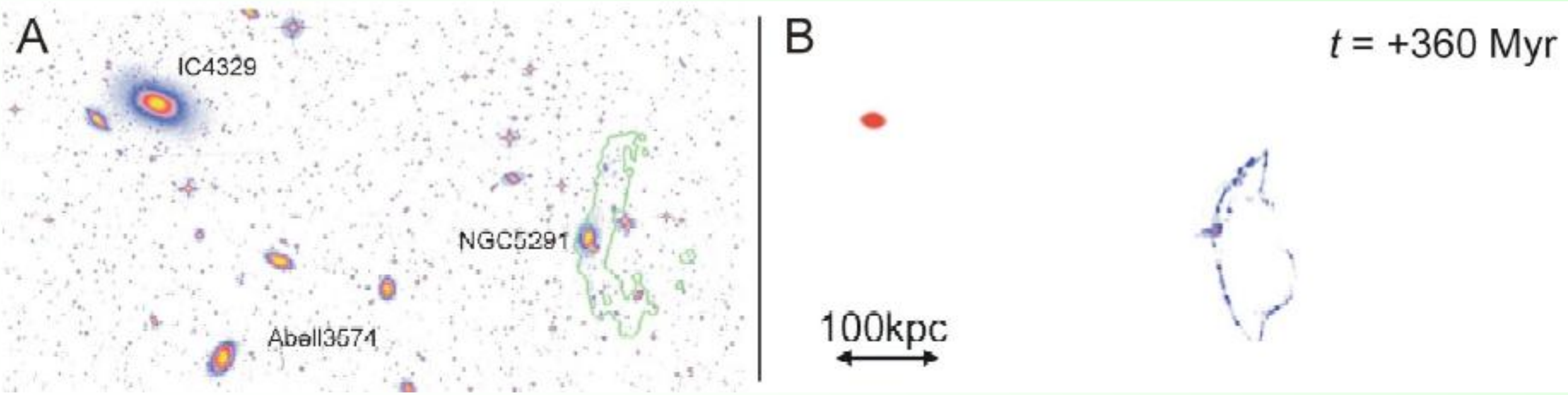
Bournaud et al 2007

Dynamics of the TDGs



With MOND, *Gentile et al 2007*

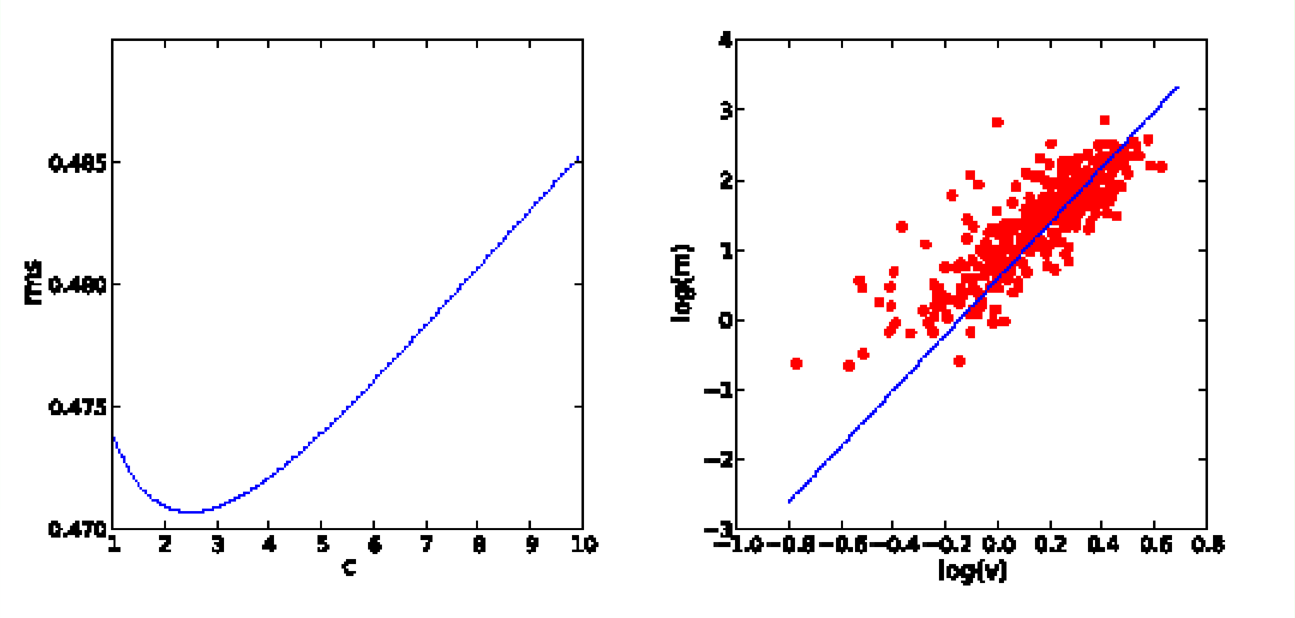
All inclinations= 45°, from simulations (Bournaud et al 07) ➔ dark H_2



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?

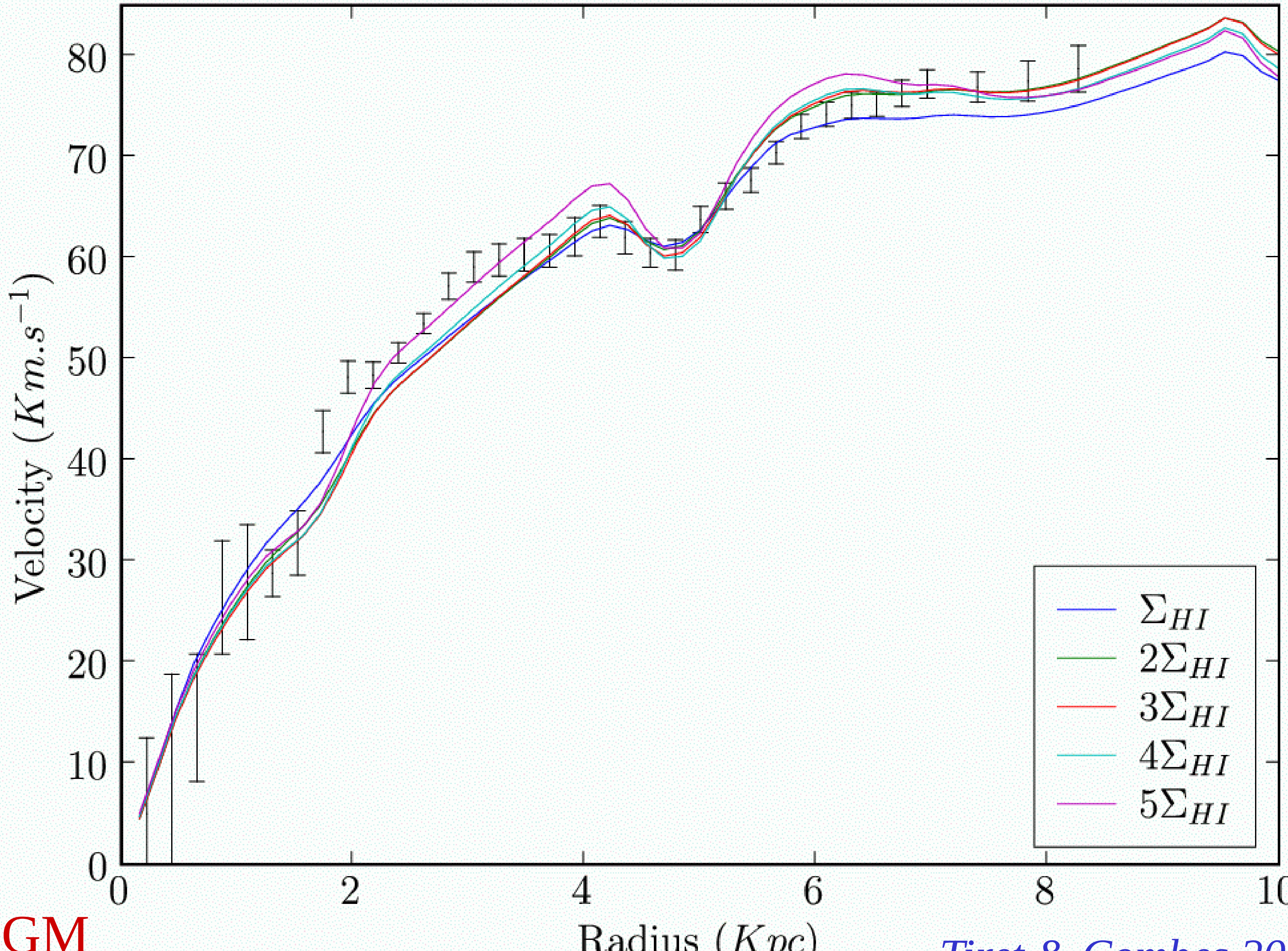
Fit of ~50 rotation curves, c=M(dark)/MHI



Tiret & Combes 08, Milgrom 07

Combination with MOND

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



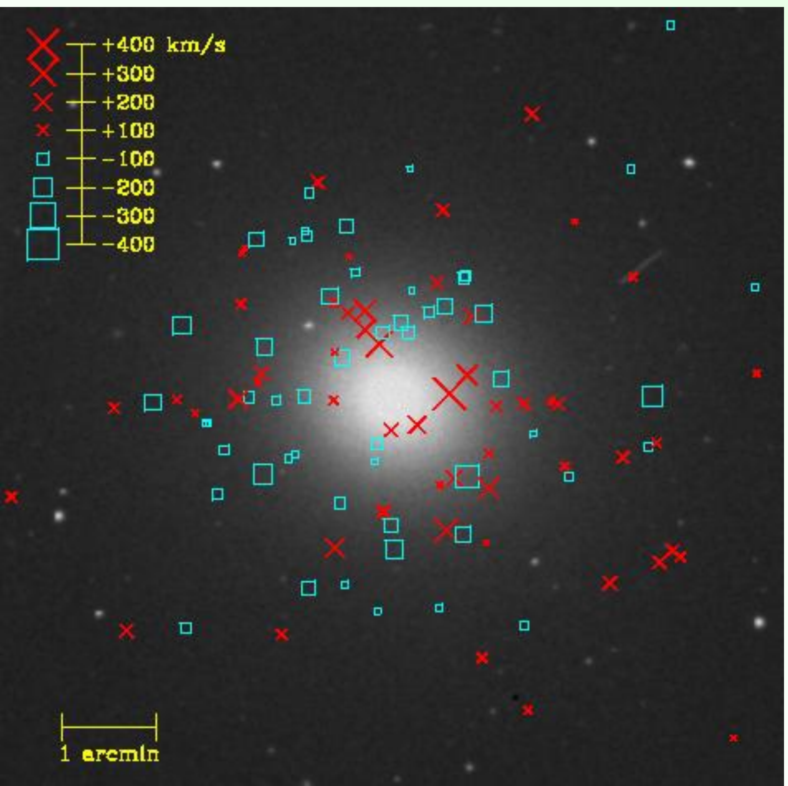
$V^4 = a_0 GM$

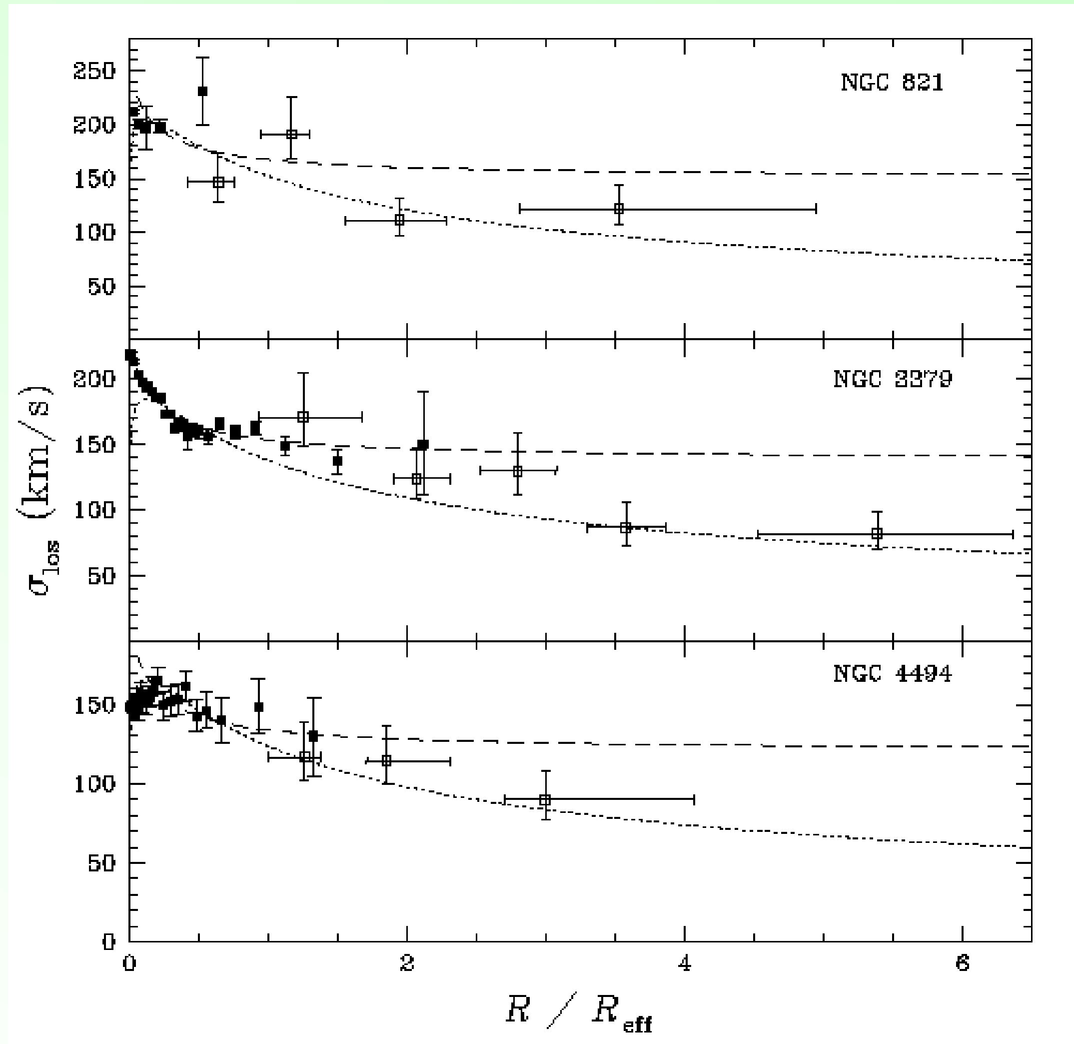
Tiret & Combes 2008

Dark matter in Ellipticals

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

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

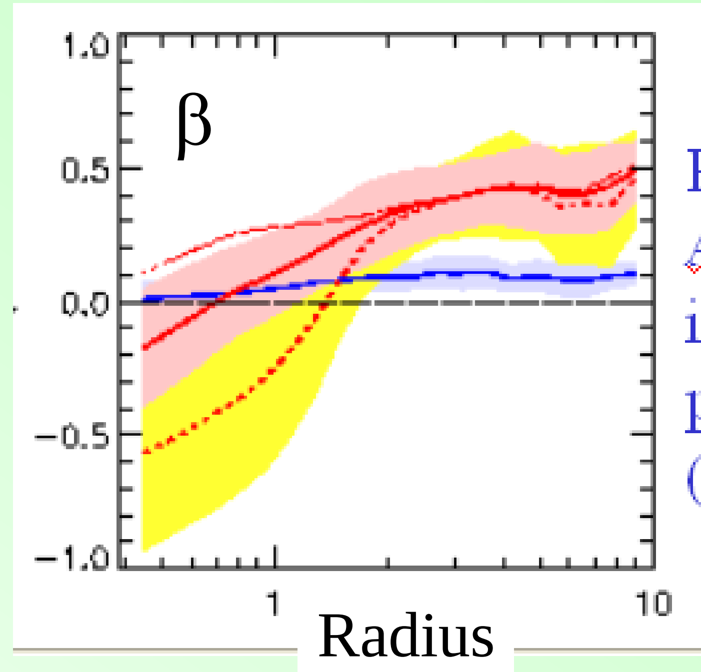




Anisotropy of velocities

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

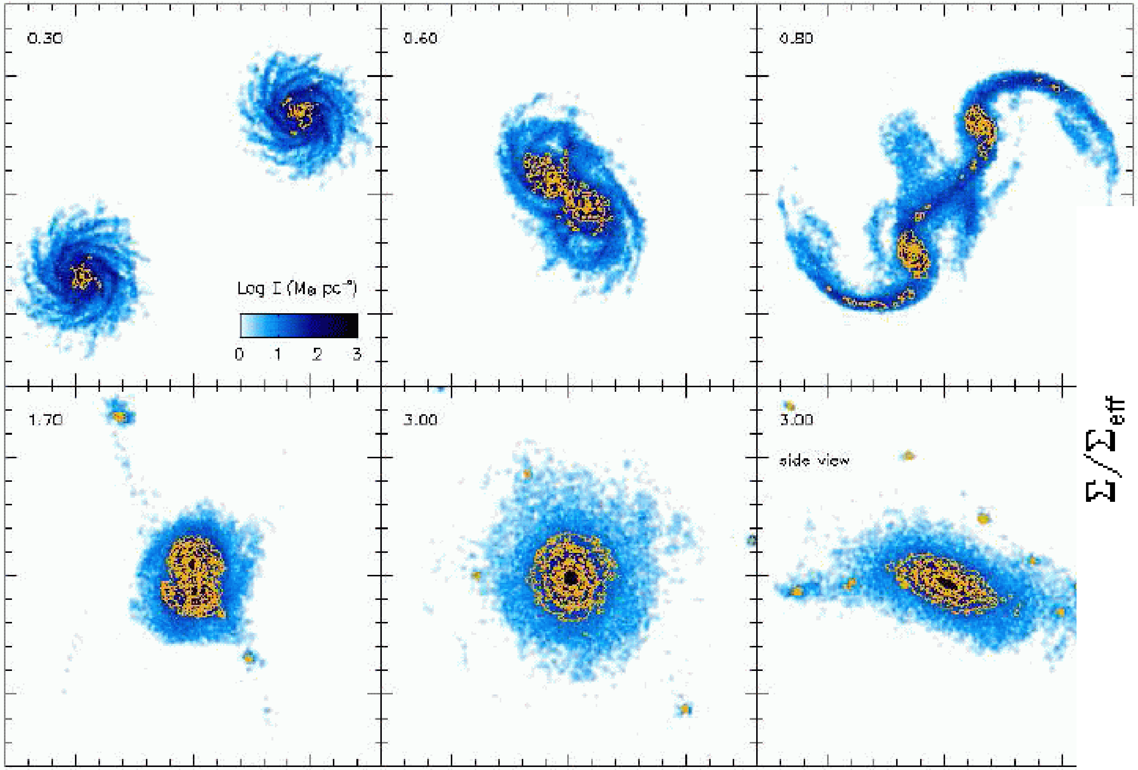
β circular, isotropic and radial orbits

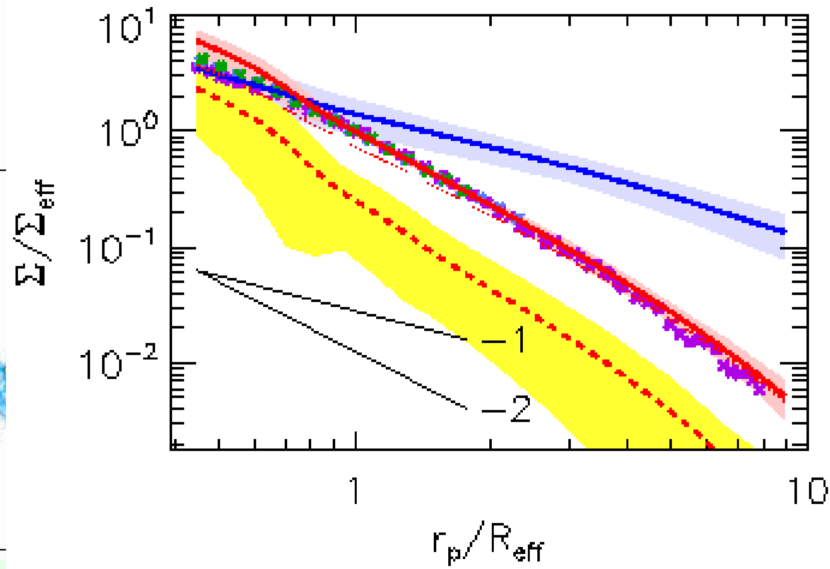


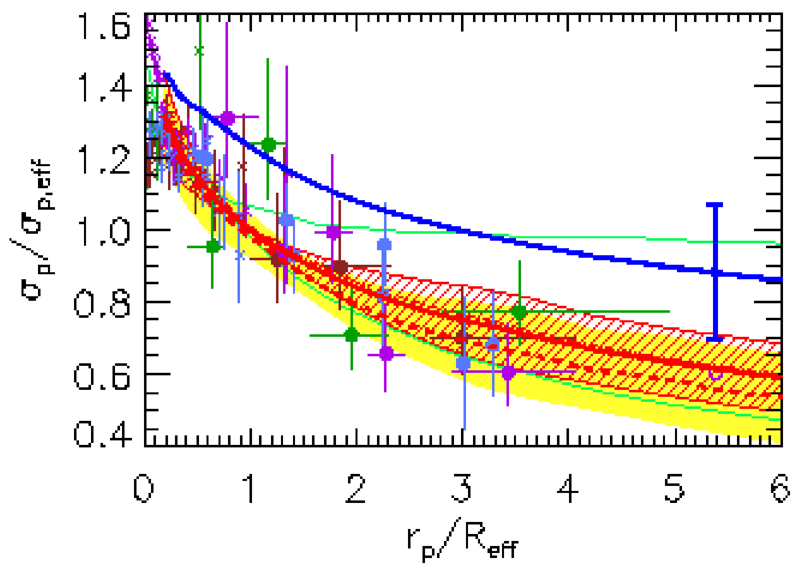
When galaxy form by mergers, orbits in the outer parts are strongly radial, which could explain the low projected dispersion (Dekel et al 2005)

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

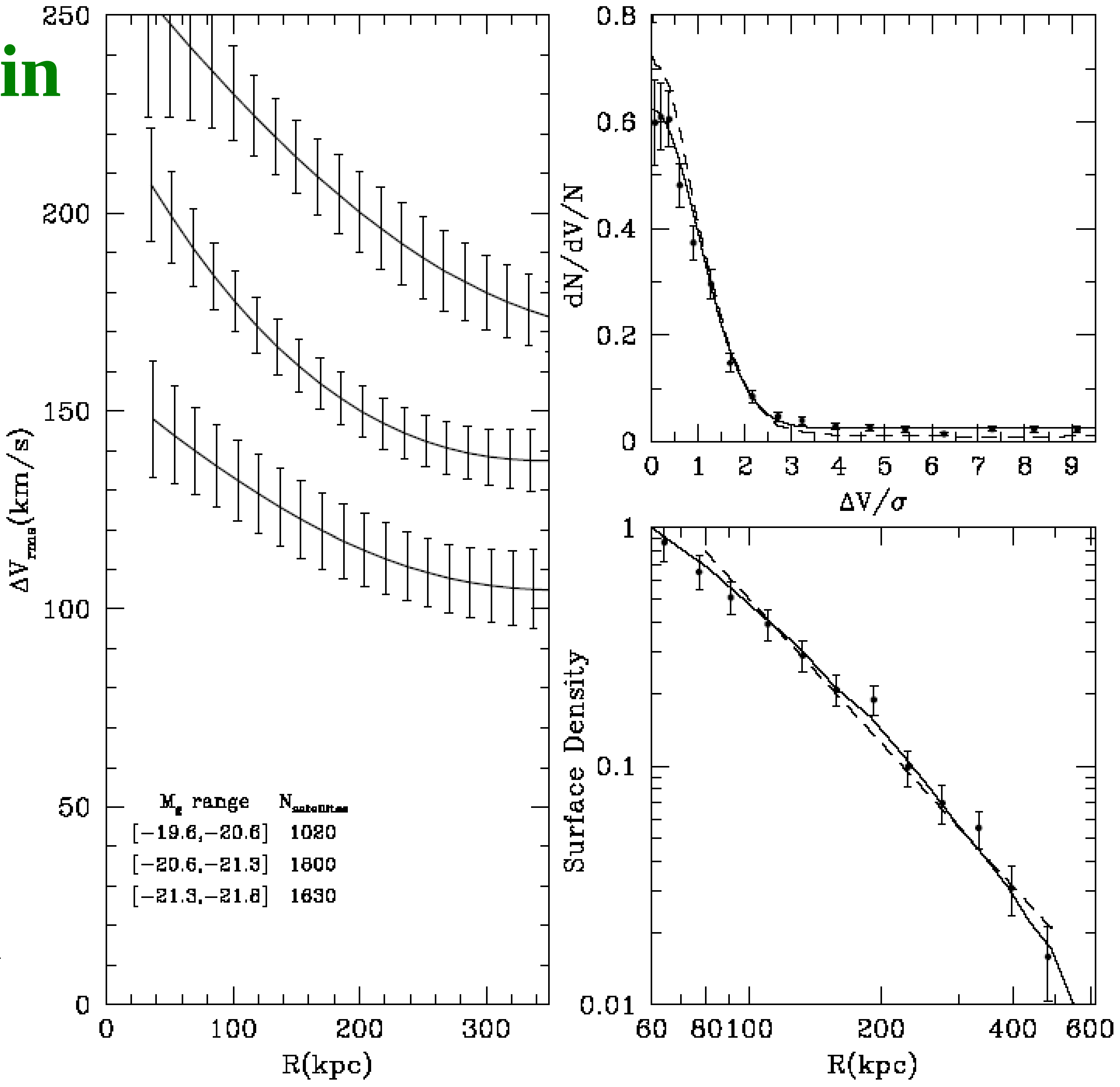
See also McKay et al (2002) $\sigma \sim L^{0.5}$ from 1225 SDSS satellites
M_{260} in agreement with lensing results
But flat velocity dispersion recovered (as if $\rho \sim r^{-2}$)

Satellites in SDSS

Klypin & Prada 2009

Statistical satellites

Only 1 or 0 for each galaxy

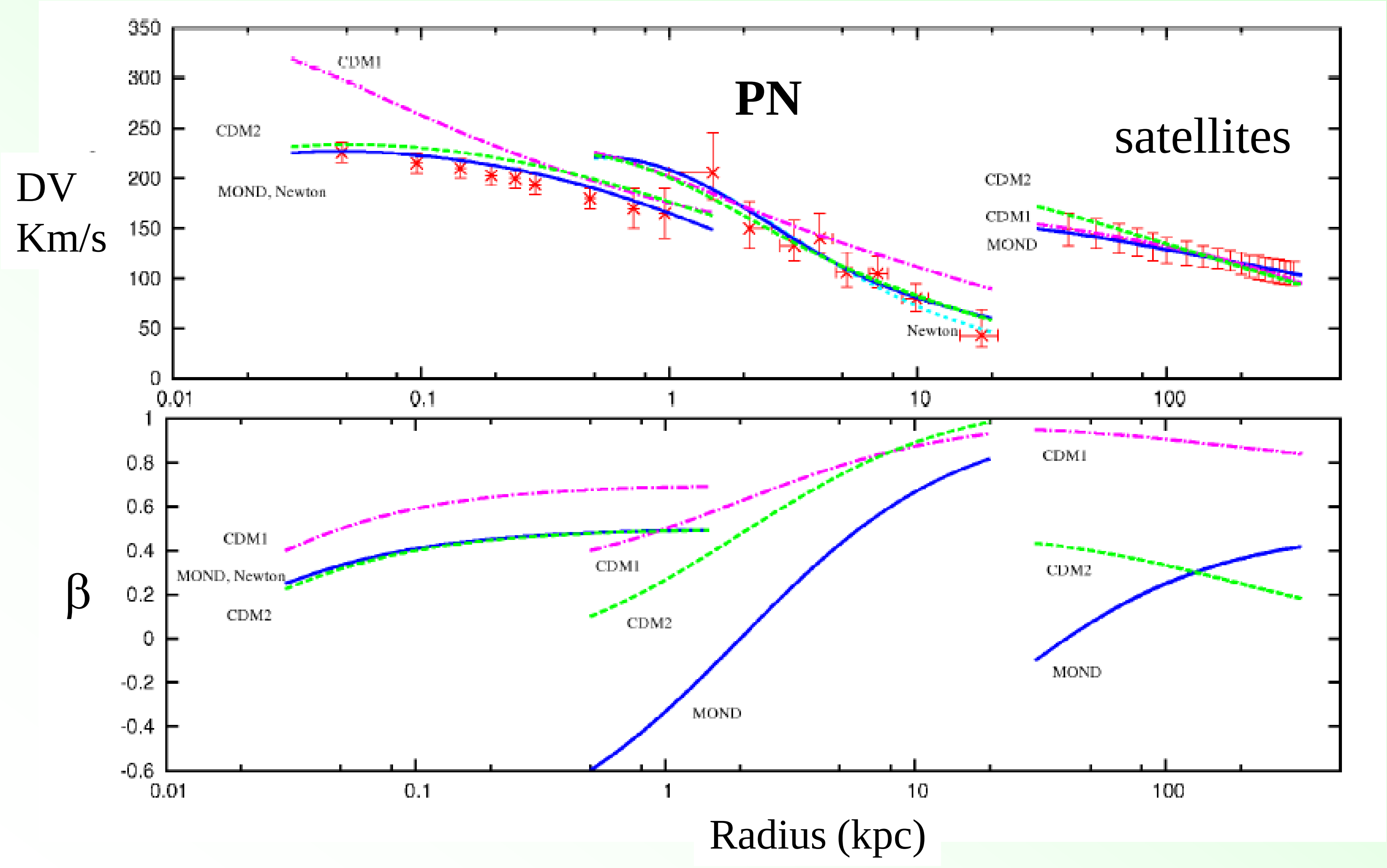


Test of the SDSS satellites

2 types of CDM CDM1: NFW cusp

CDM2: as required by rotation curves

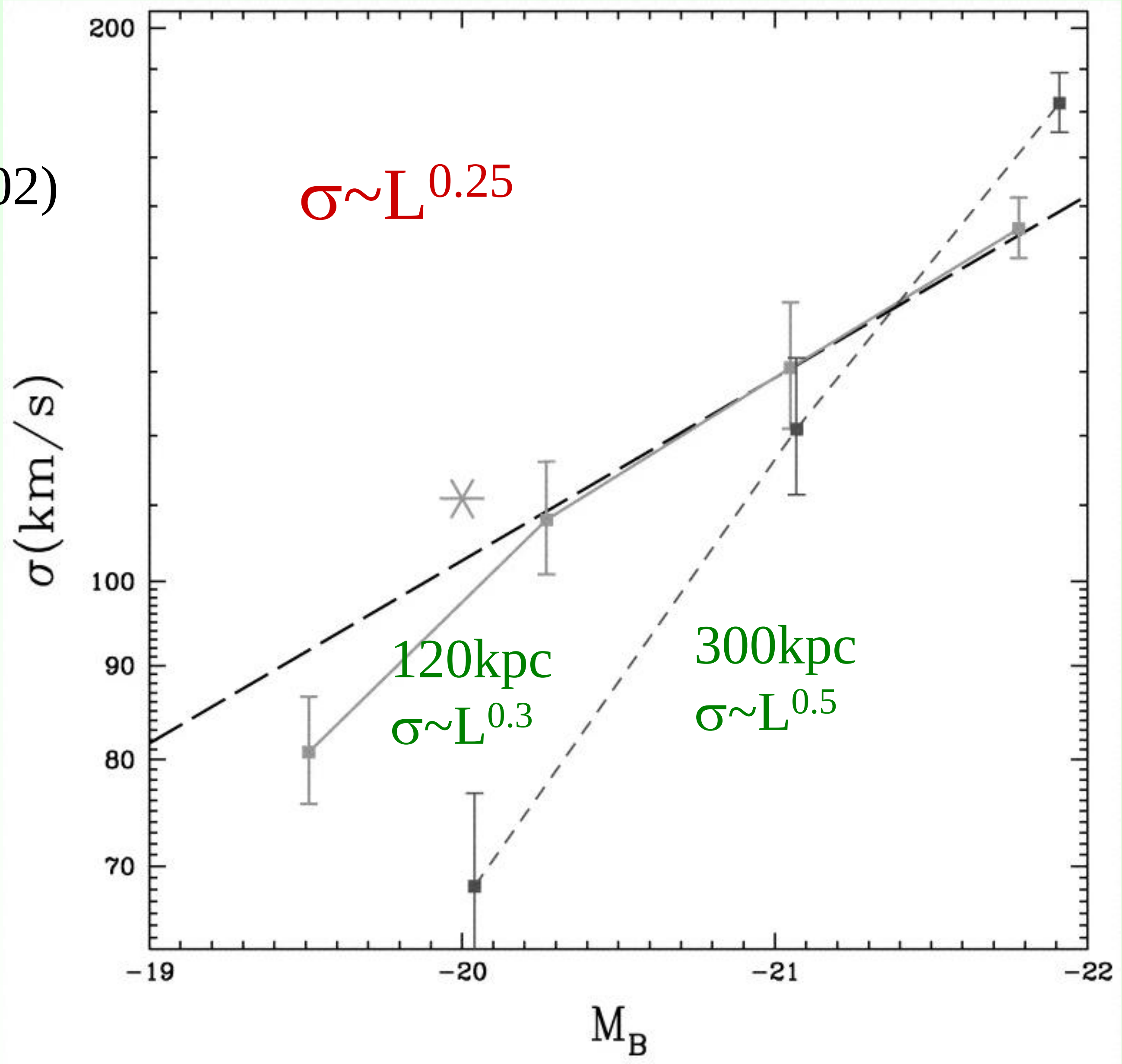
Tiret et al 2007



Tully Fisher Equivalent

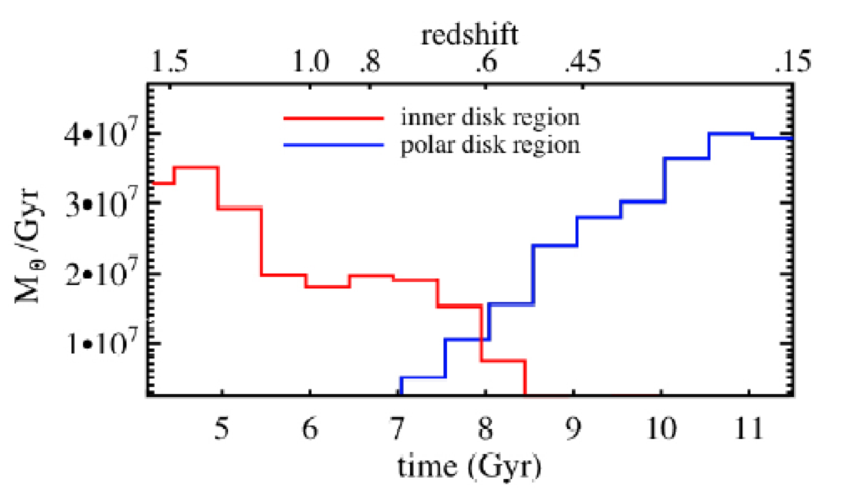
Asterisk: Lenses
(Hoekstra et al 2002)

--- TF normal spirals
(Verheijen 2001)



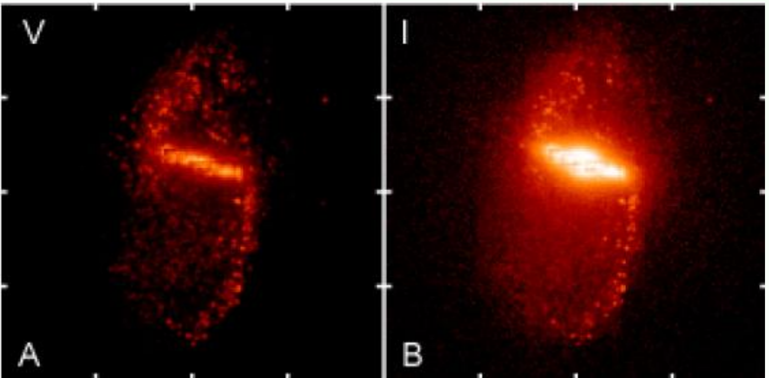
Prada et al (2003)

Polar rings from cosmic gas accretion

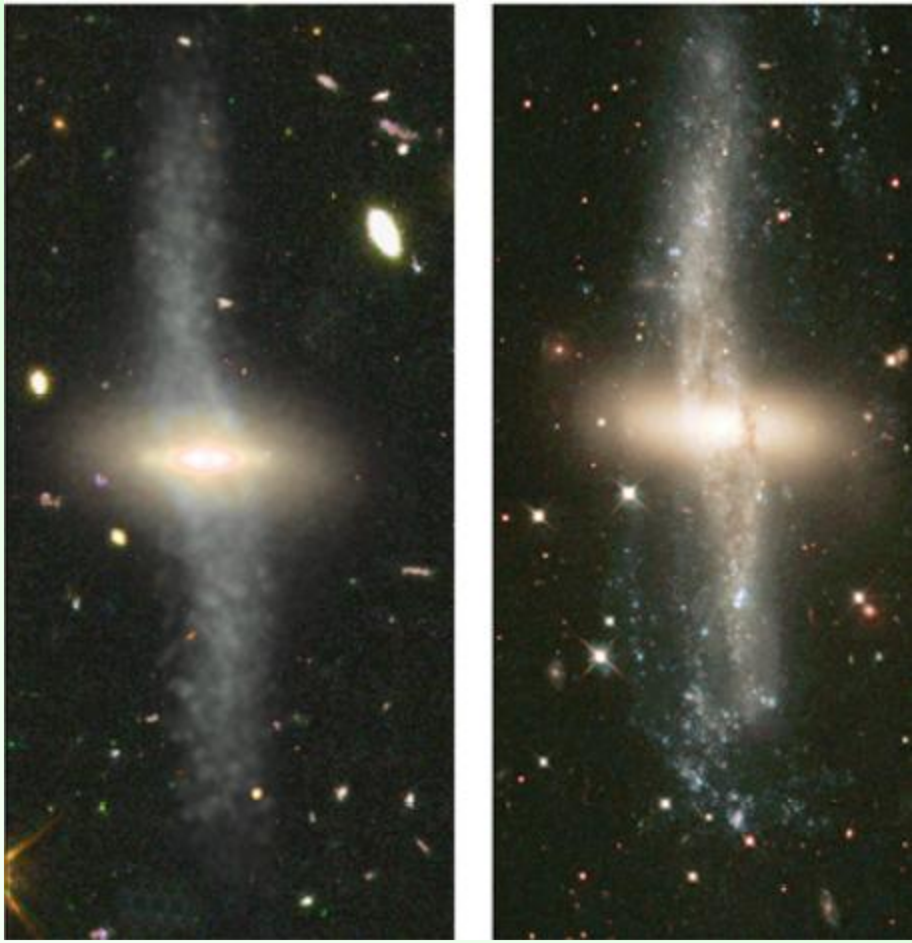


➔After 1.5 Gyr, interaction between the two disks destroys the PRG

➔Velocity curve about the same in both equatorial and polar planes

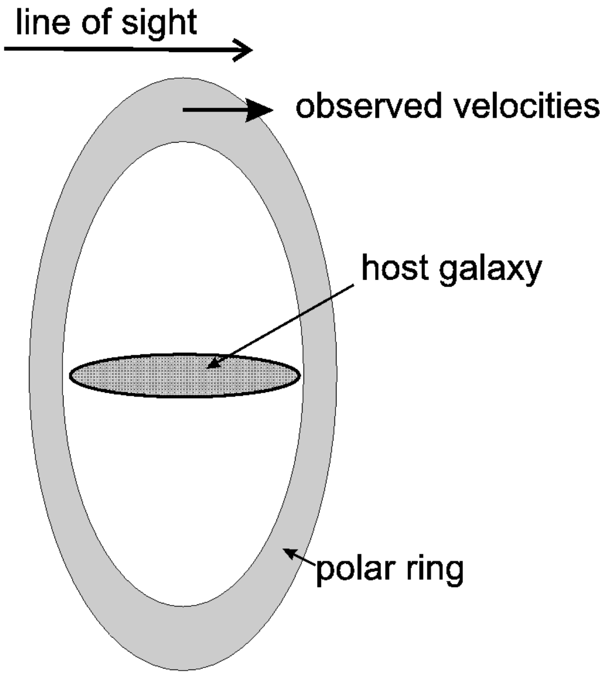


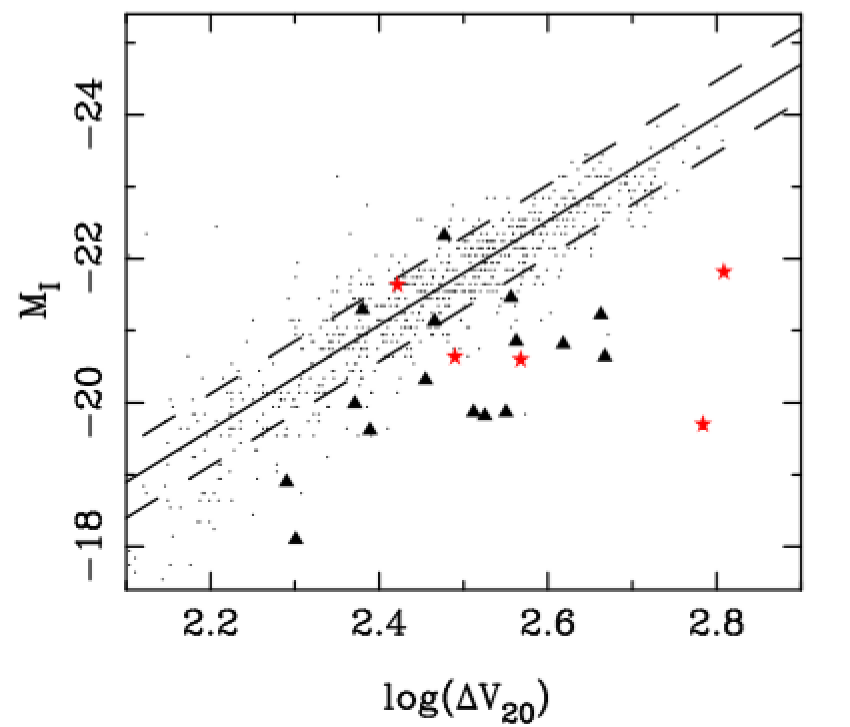
Also Snaith et al 2012

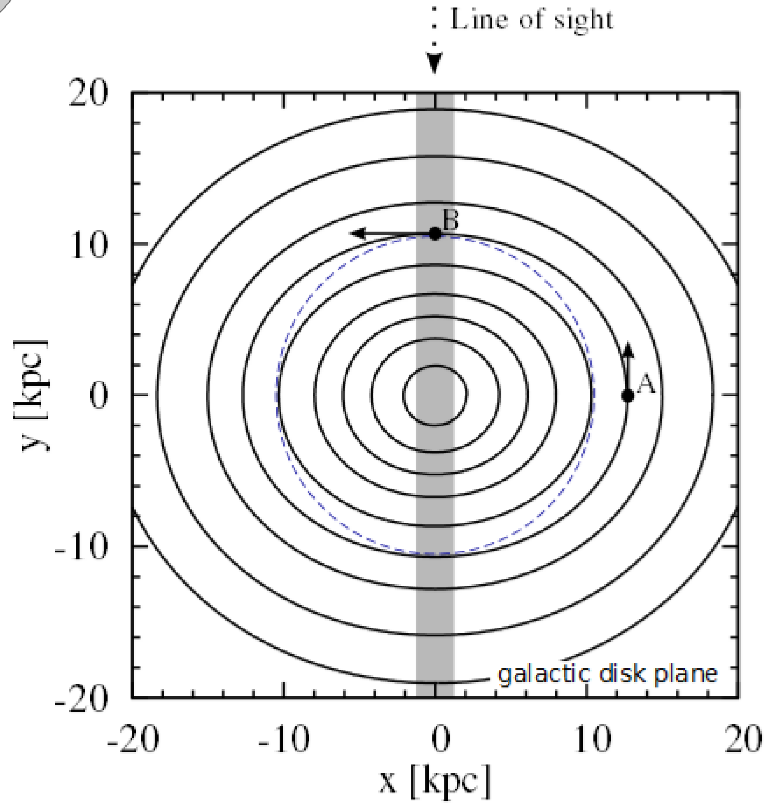


Brook et al 2008

The TF of Polar Ring Galaxies

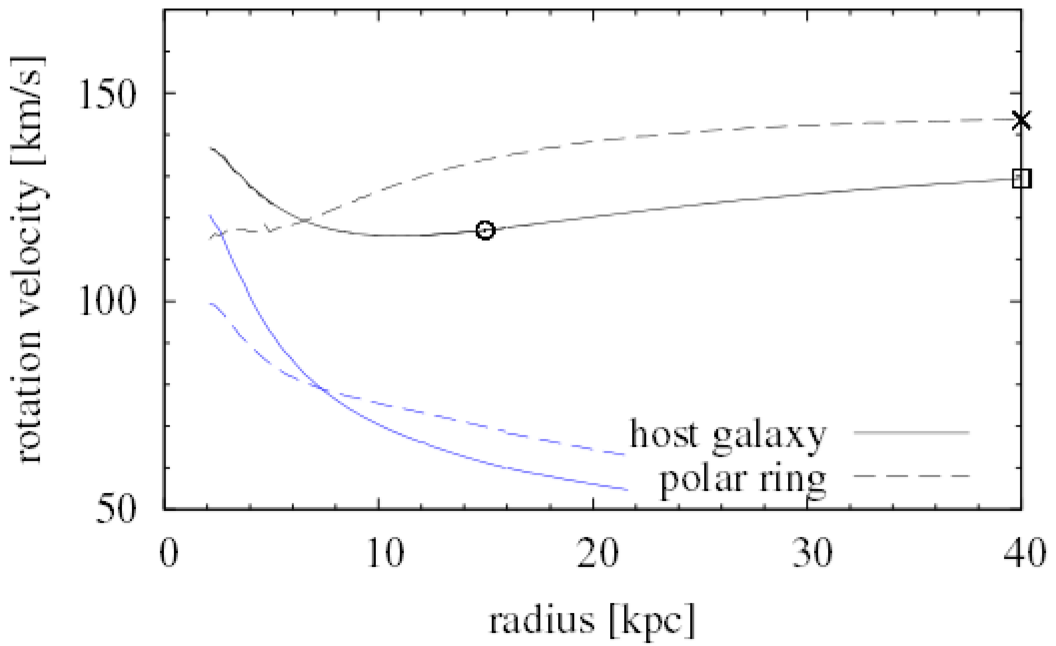




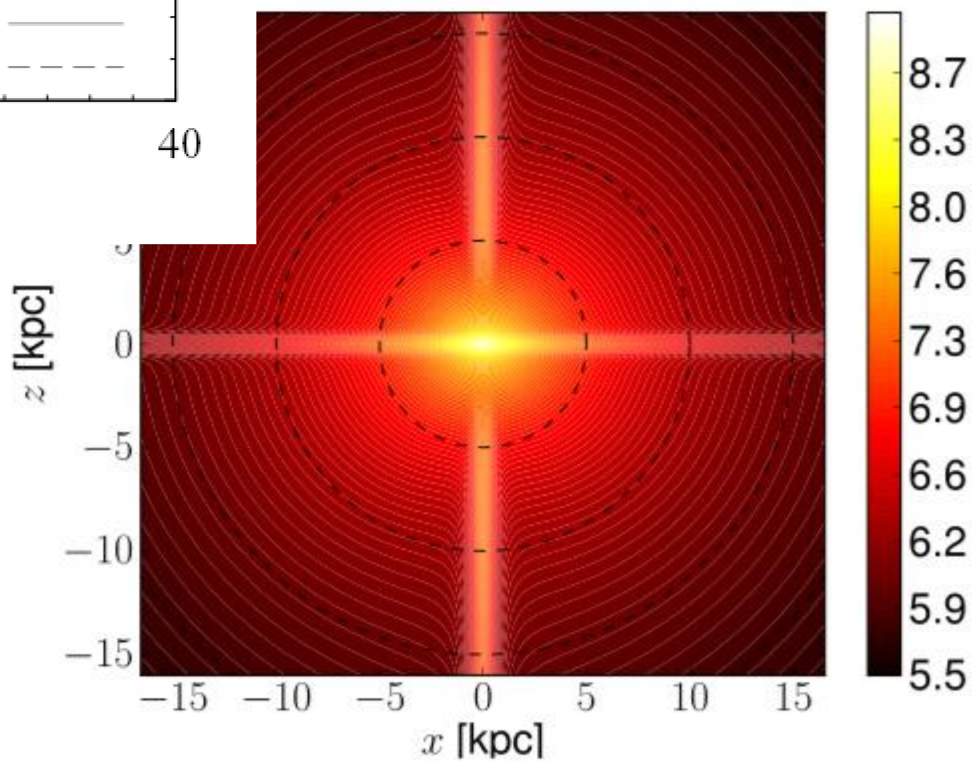


Iodice et al 2003
Combes et al 2013

Polar Ring Galaxies with MOND



Map of the phantom dark matter

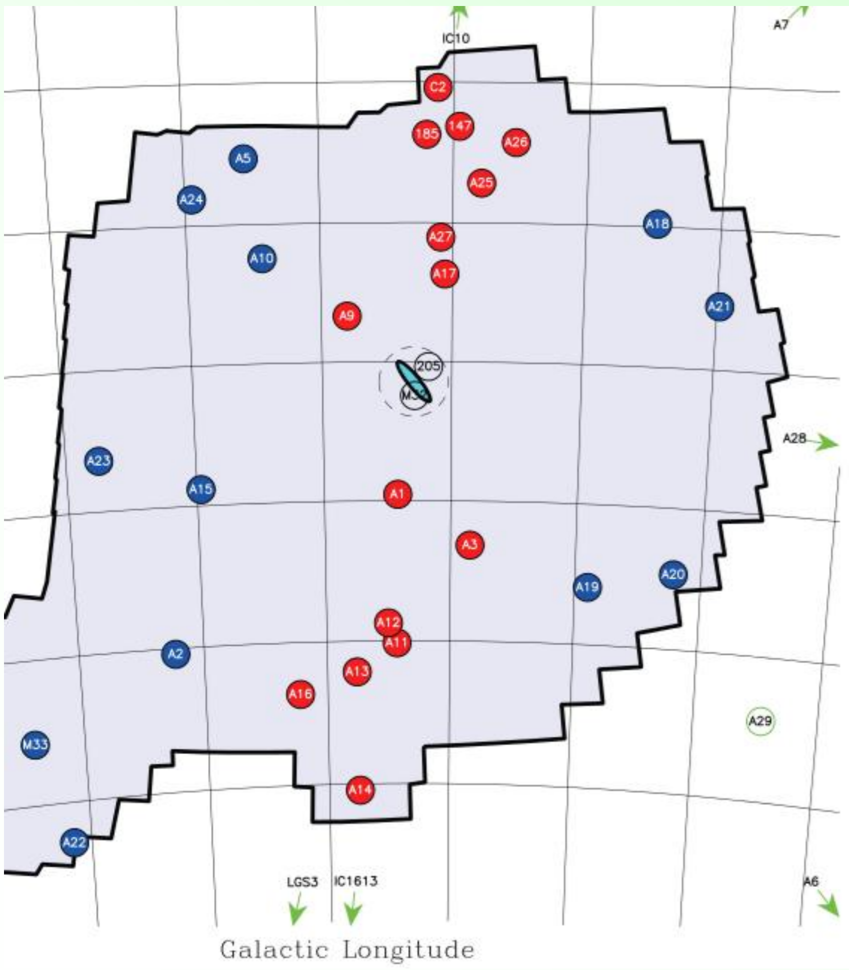


Lüghausen et al 2013

Disks of Satellites, MW, M31

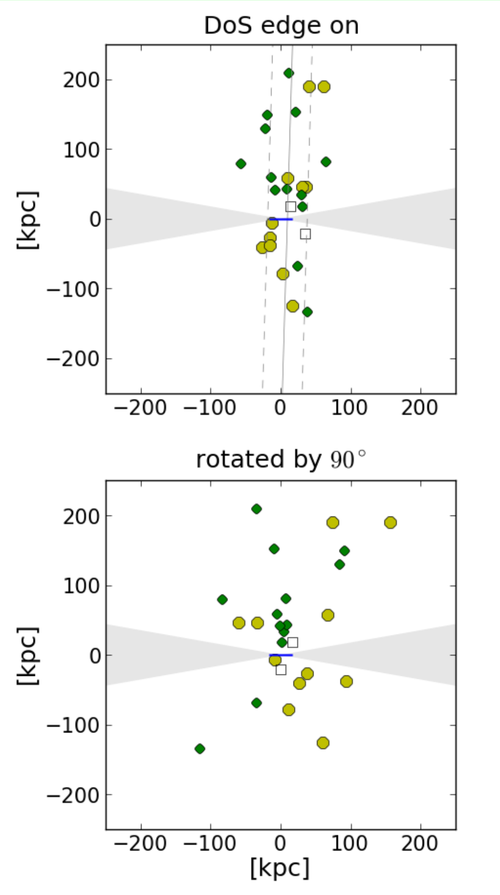
Ibata et al 2013, Nature

Pawlowski et al 2012



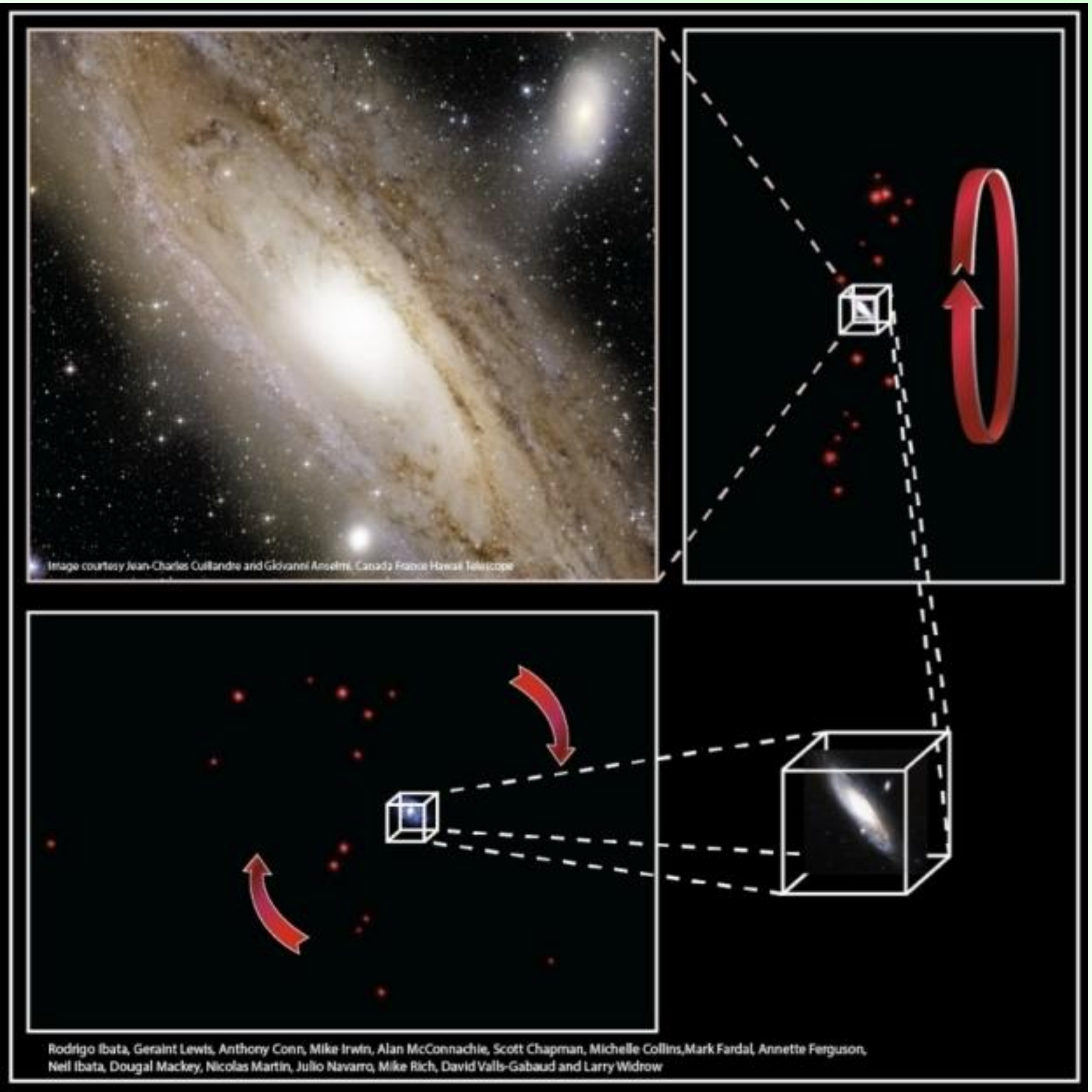
Rotationnally supported plane of satellites

Never found in CDM simulations



Metz et al 2008

Are all these satellites Tidal dwarfs (TDG)?



When 2 spiral galaxies merge, the tidal tails follow the initial plane orientations

➔Explain the alignment

However, the TDG formed have no dark matter

In the MW, M31,
these dwarfs are dominated by dark matter

MOND cosmological simulations

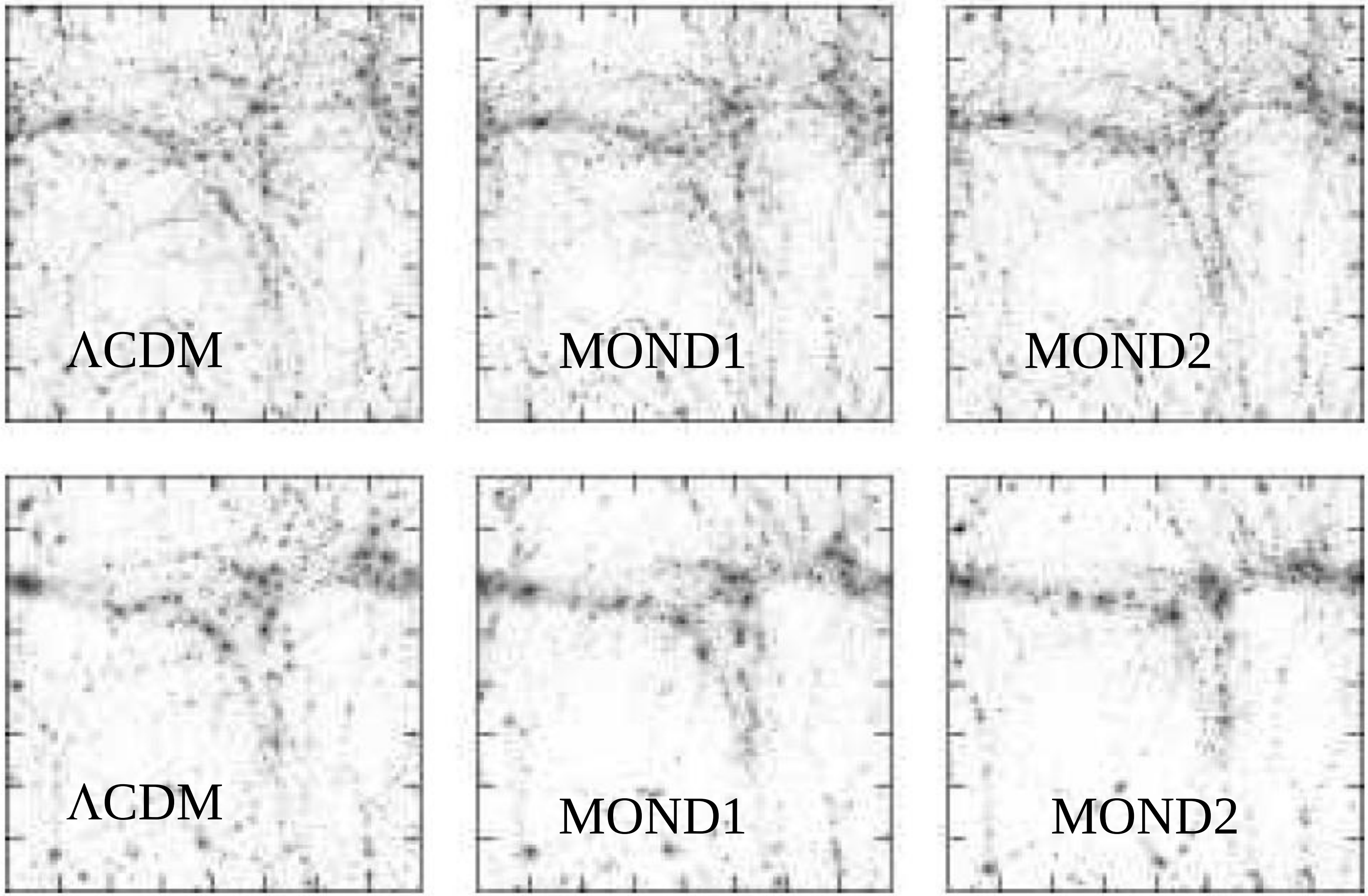
Starting z=50, dissipationless matter, 2 low Ω models + ΛCDM

Easier to form large masses early

Llinares et al 2009

z=2

z=5



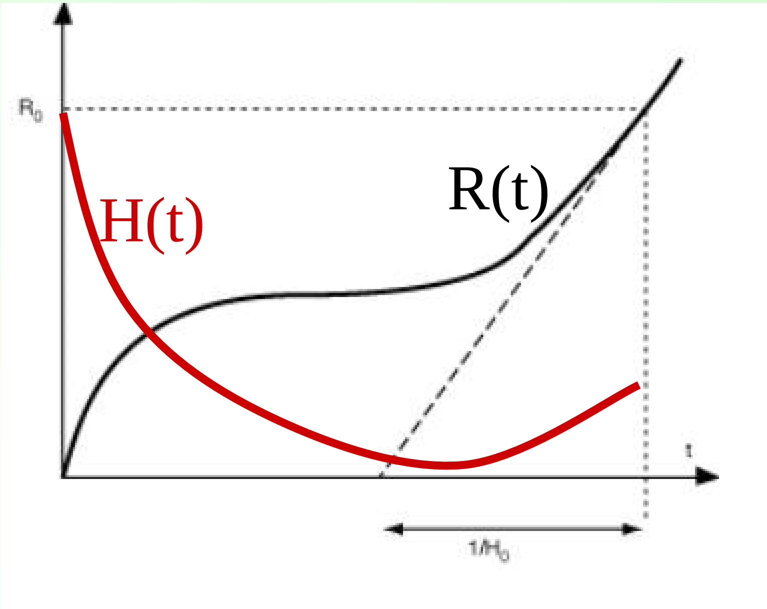
Evolution with time

Does the critical acceleration vary?

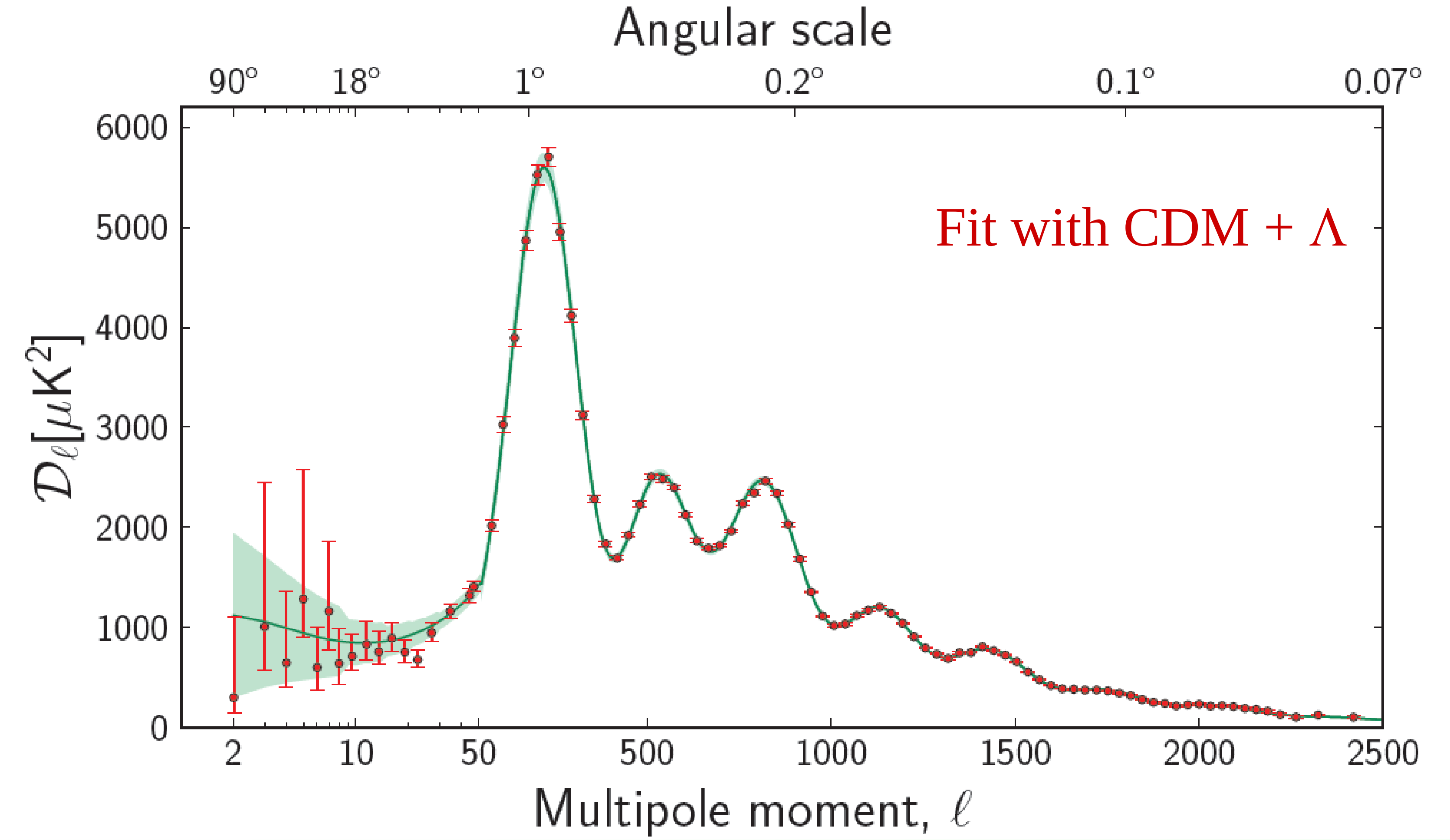
$a_0 \sim c\, H_o$, or also $a_0 \sim c\, (\Lambda/3)^{1/2}$

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

Open question, as is the evolution of Ω_Λ



Fit of CMB data, Planck coll

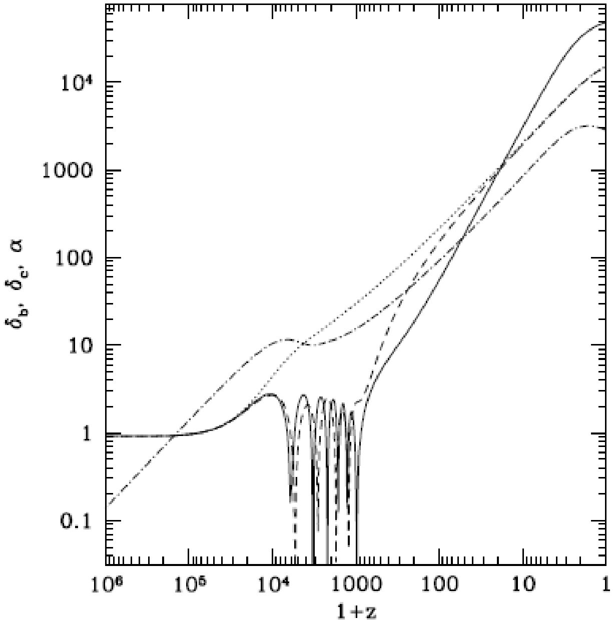


Challenge for MOND: must include massive neutrinos 1-2eV

Ω_Λ=78% Ω_ν=17% Ω_b=5%

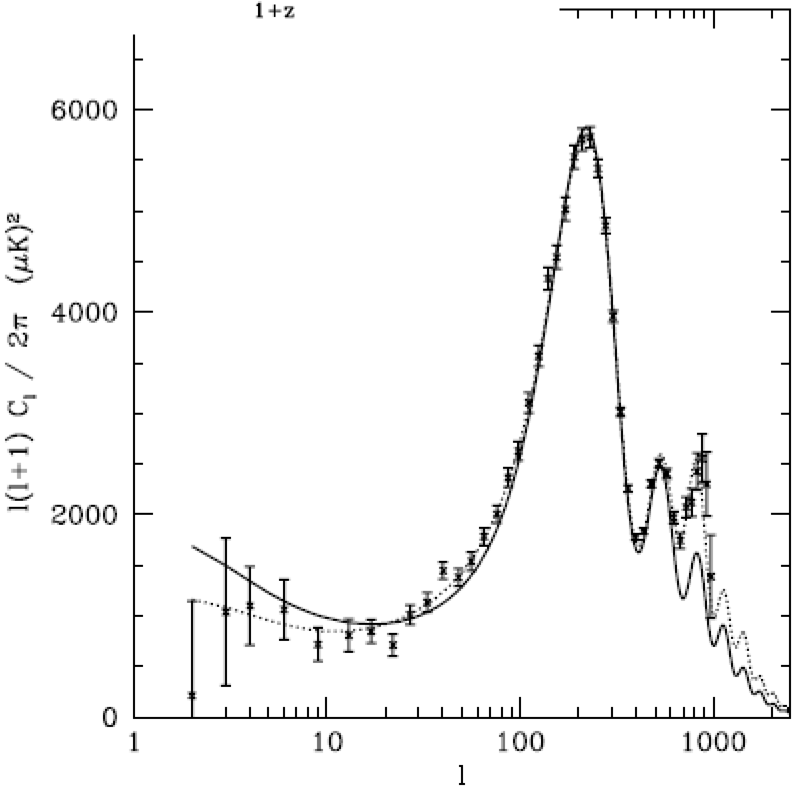
TeVeS: CMB and LSS

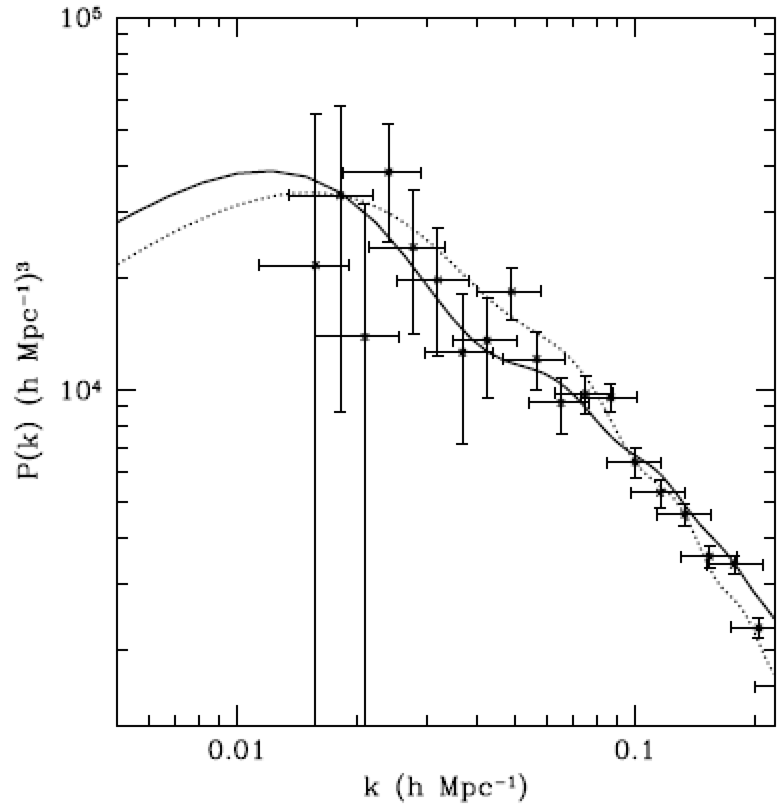
Skordis 2009



Growth of structures due to the vector field

Scalar field ➔ aceleration of expansion, DE

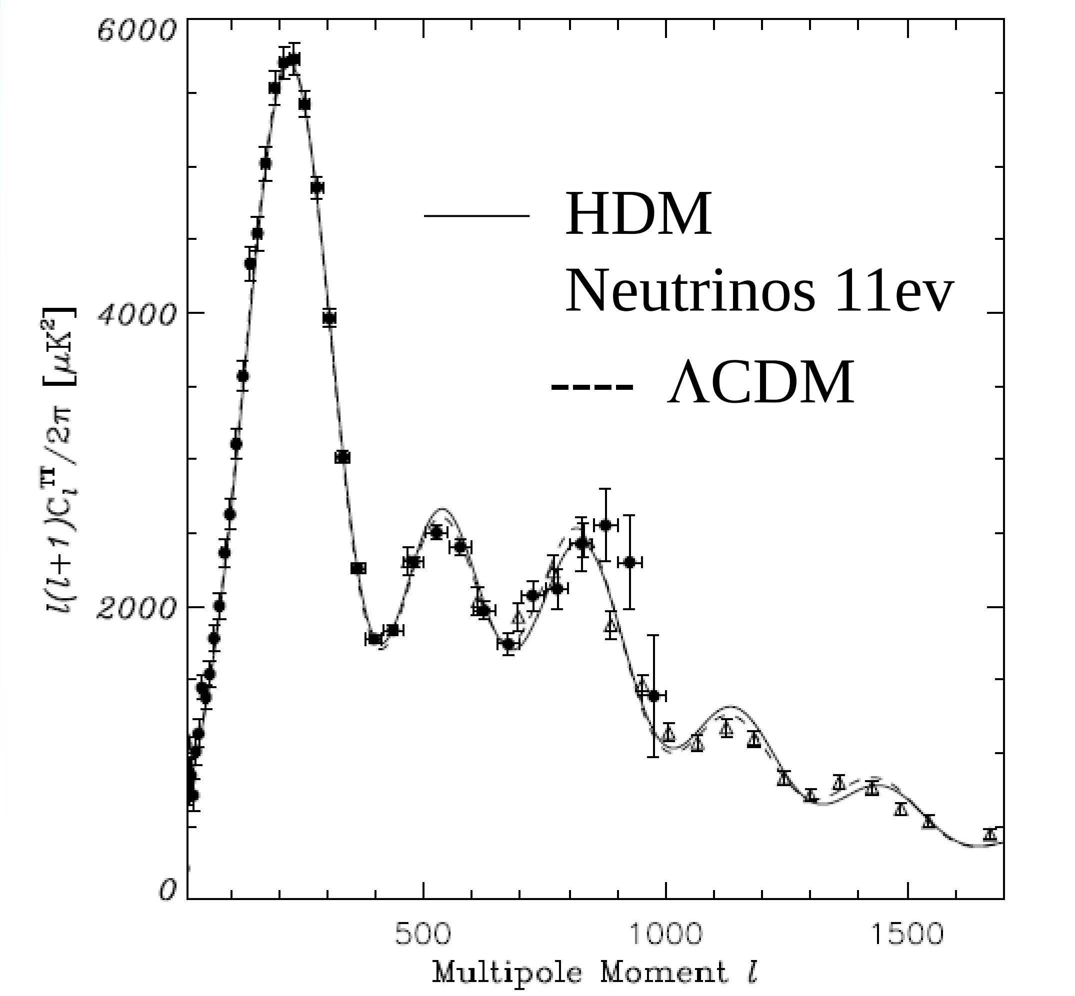




WMAP-5 + ACBAR

The 3rd peak is not lower (damped) than the 2nd peak

There must exists something else: sterile neutrinos, or other terms in relativistic theory (BSTV)



Angus (2011)

Conclusion: Success and Problems of each model

CDM: great success at large scale, but problems at galaxy scales
WDM: does not solve the cusps, not enough small-scale power
MOND solves the problems of galaxies,
but has to solve its own problem at group and cluster scales
(neutrinos, baryons..)

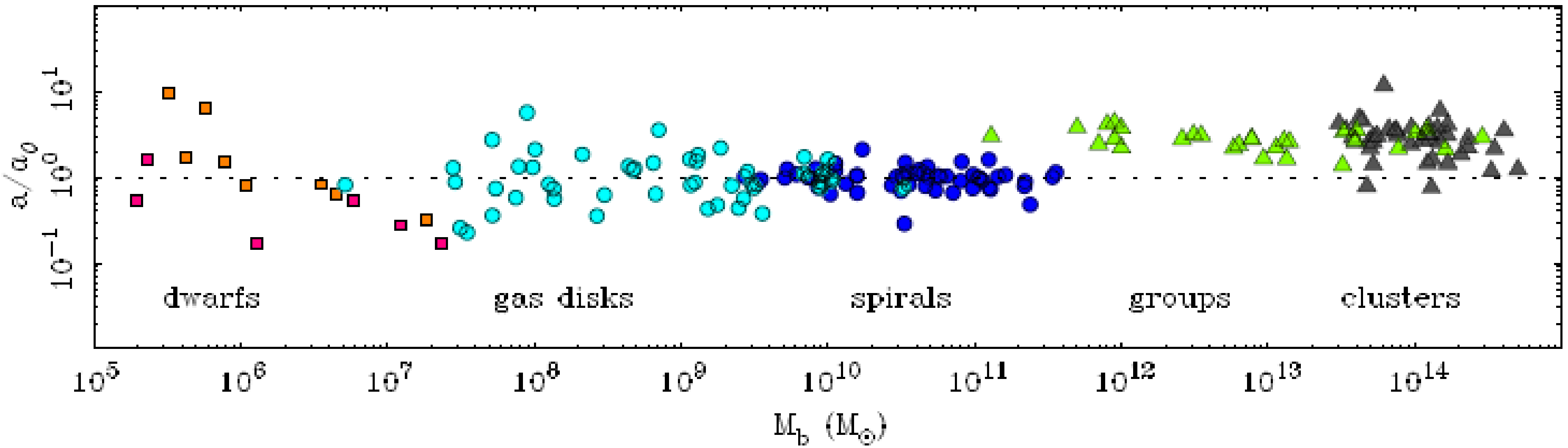
➔ More tuned SN and AGN feedback, to solve CDM models
Numerical simulations with improved physics, resolution

➔ Lorentz covariant theory, TeVeS (Bekenstein 2004) with
a lot of varieties (GEA, BSTV, k-essence..)

➔ Different metric (BIMOND), still free parameters to explore

Other propositions? Modif of inertia?, non-local? Dipolar DM..

Acceleration parameter a ~ V_f^4/M_b



Famaey & McGaugh 2012