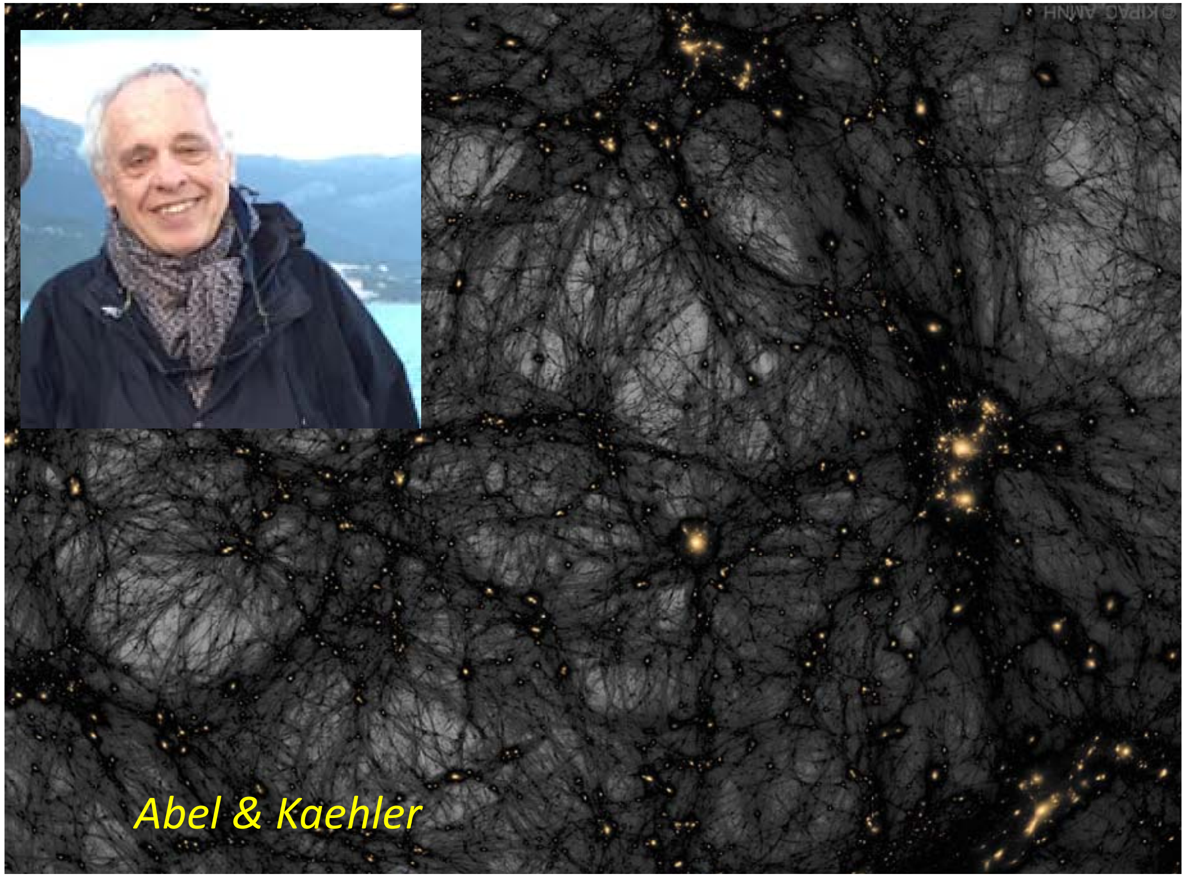
Dark matter or modified gravity?

COLLÈGE DE FRANCE
1530

Chaire Galaxies et Cosmologie

Françoise Combes

11 December, 2017



l'Observatoire de Paris

LERMA

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

Why modified gravity?

CDM models beautifully account for LSS, CMB, galaxy formation

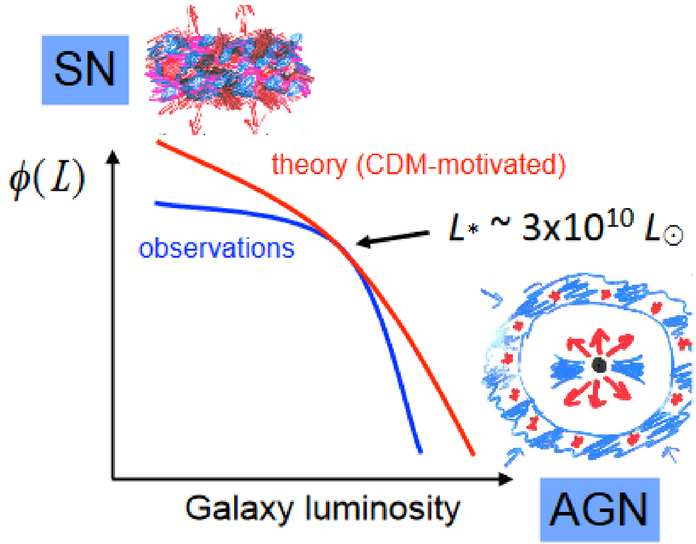
But remain some puzzles: 1 **No DM particle in LHC, Lux, Xenon1t**

Dark energy, cosmological constant and vacuum quantum energy:
➔Fine tuning problem (60-120 ordres of magnitude)

At galaxy scale: CDM conundrums

-- cuspy DM profiles
-- missing satellites
-- TBTF problem
-- angular momentum
-- bulgeless galaxies

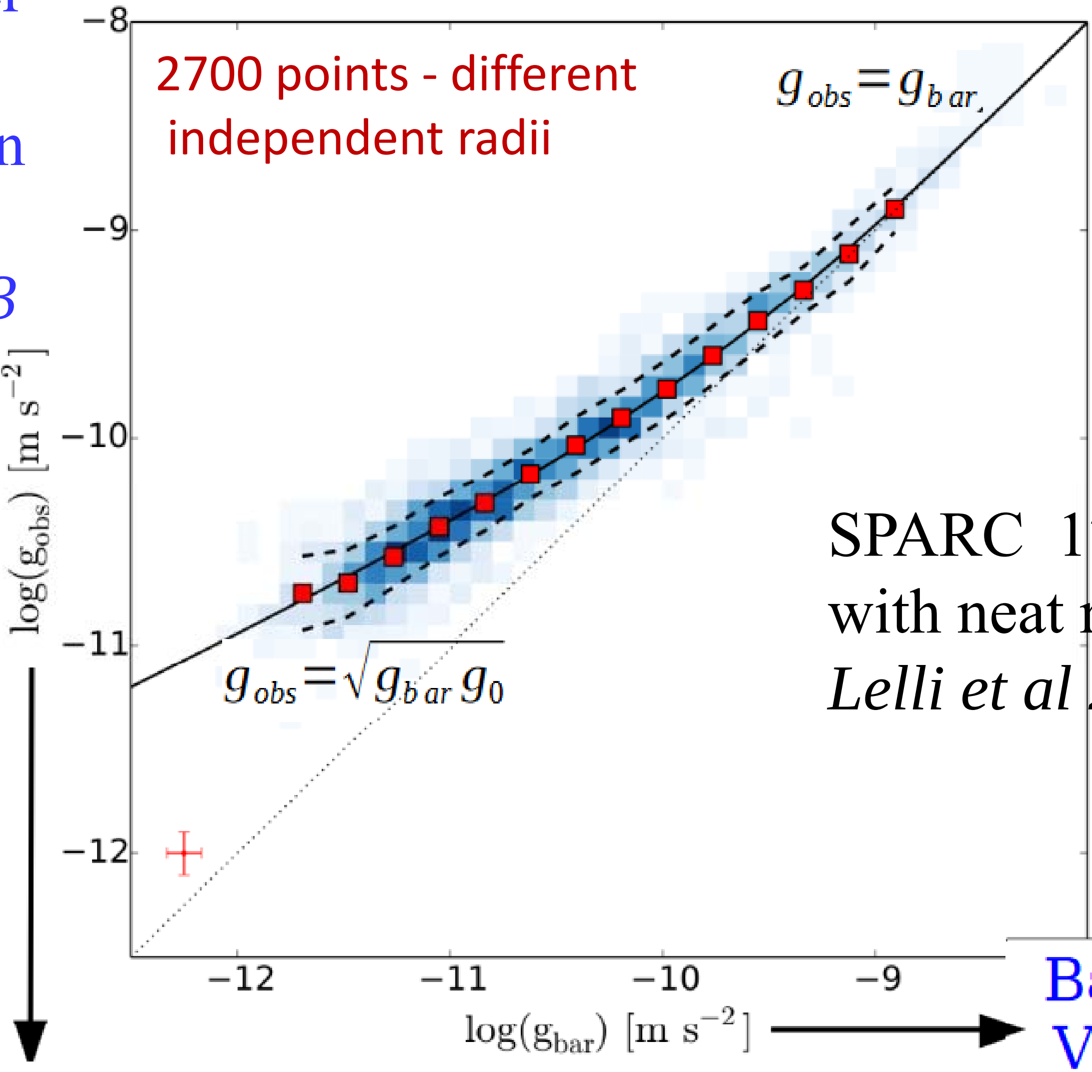
Solutions in SN and AGN feedback?



Silk & Mamon 2012

Radial Acceleration Relation (RAR)

Dark matter at weak acceleration
➔MOND
Milgrom 83



SPARC 175 galaxies, with neat rotation curves
Lelli et al 2016, 2017

Total Acceleration: $V^2_{obs}/R = -\nabla\Phi_{tot}$

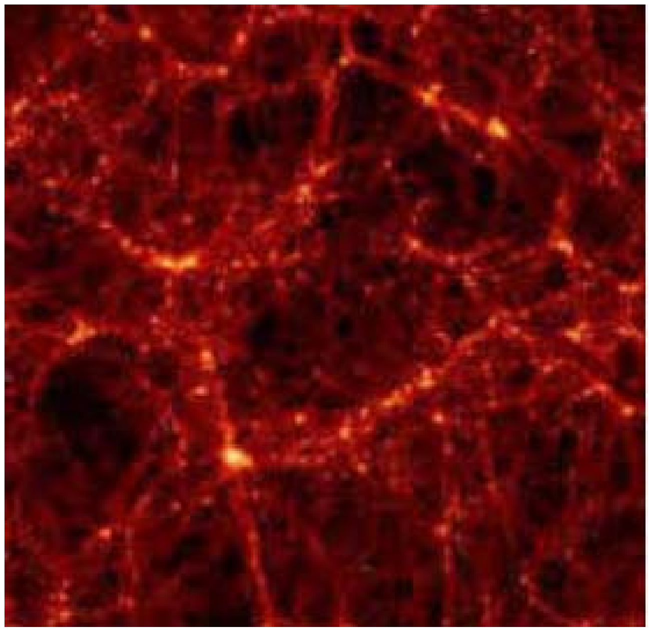
Baryonic Force:
$V^2_{bar}/R = -\nabla\Phi_{bar}$
$\nabla^2\Phi_{bar} = 4\pi G\, \rho_{bar}$

Where are the baryons?

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

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

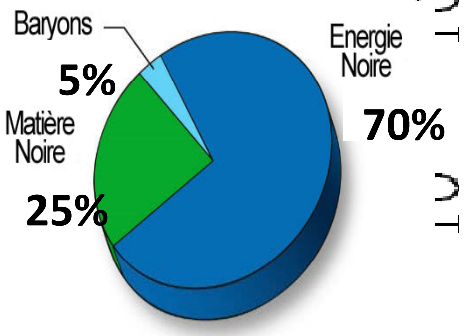
➔~10% in the WHIM (Warm-Hot Intergalactic Medium) 10^5-10^6K OVI lines



➔63% are not yet identified or localised!

Most of them are not in galaxies

Baryons outside galaxies

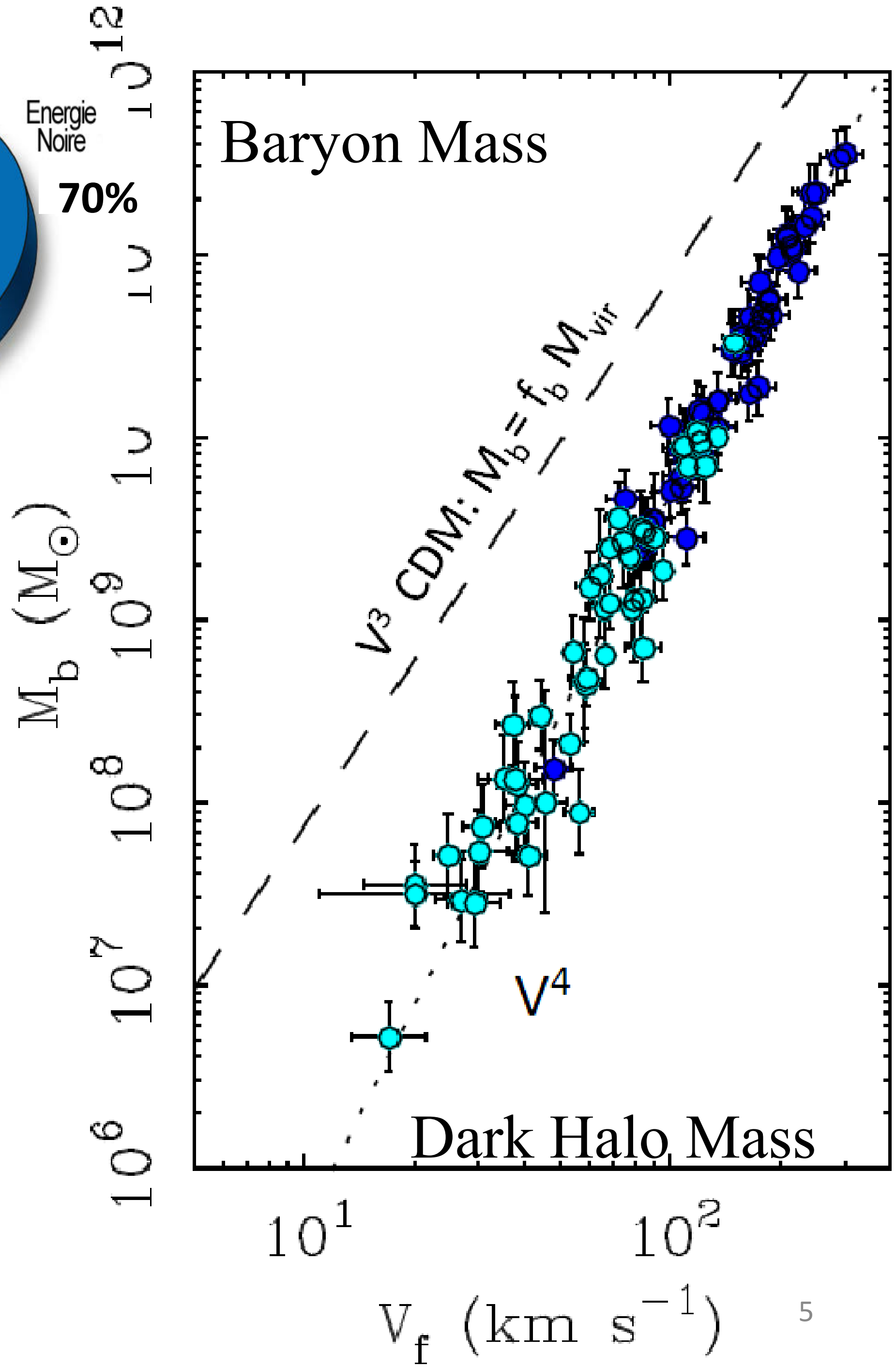


f_b universal fraction of baryons= 17%

The first prediction of CDM model (without feedback)
$\mathbf{M_b \sim V_c^3}$

In fact, very few baryons in galaxies

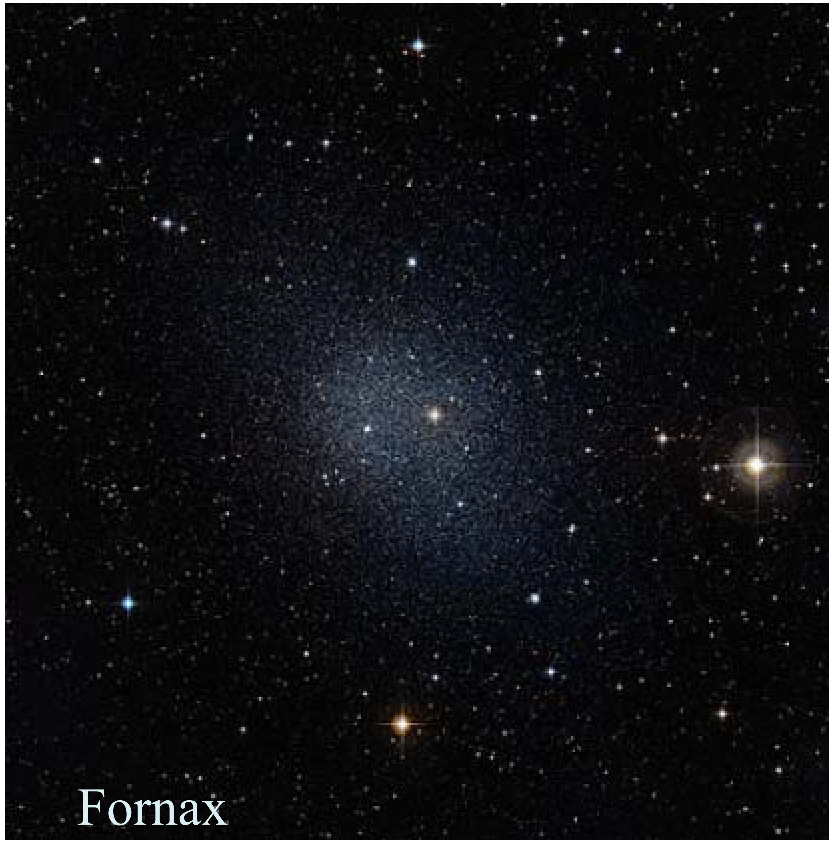
For the lower masses a factor 10-100



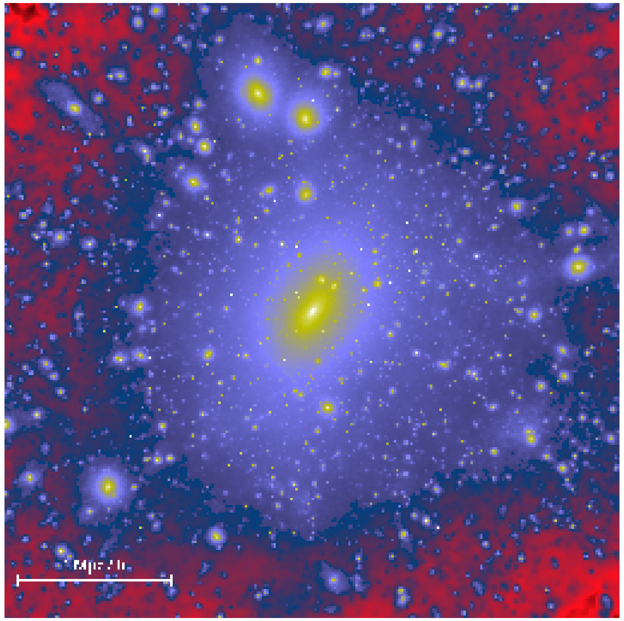
Famaey & McGaugh 2012

Dwarf Spheroidals

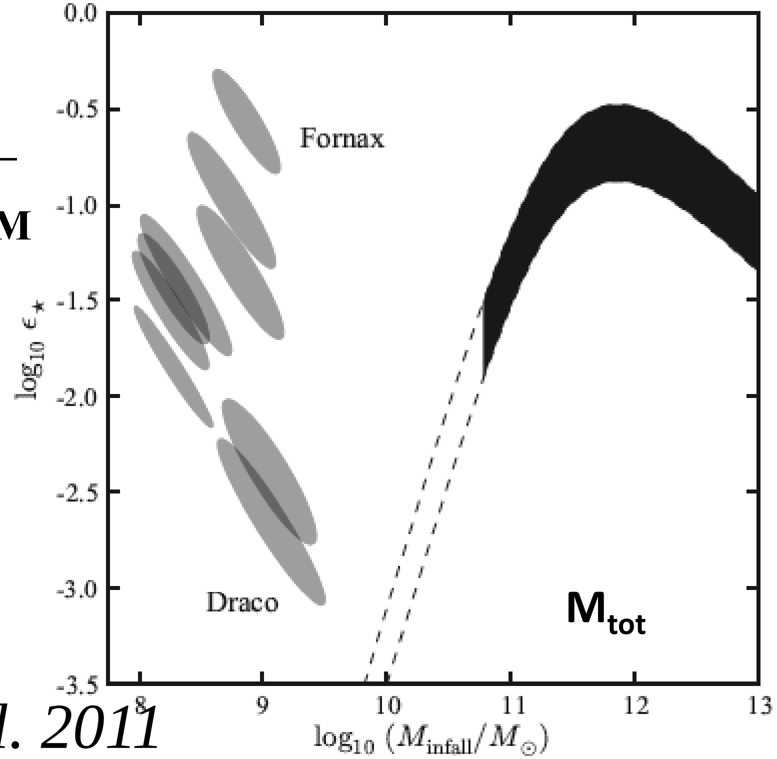
Fornax, Leo I, Sculptor, Leo II, Sextans, Carina, Ursa Minor, CanesVenatici I, Draco



Missing satellites problem



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



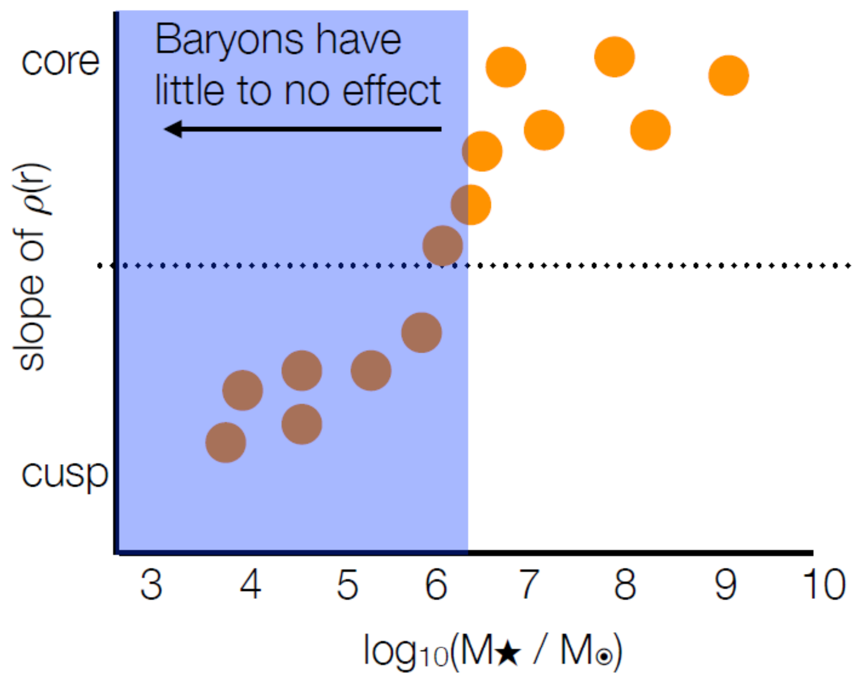
LSB systems, dominated by DM

These dSph are not formed in CDM simulations

Boylan-Kolchin et al. 2011

Alternatives

Bullock & Boylan-Kolchin 17

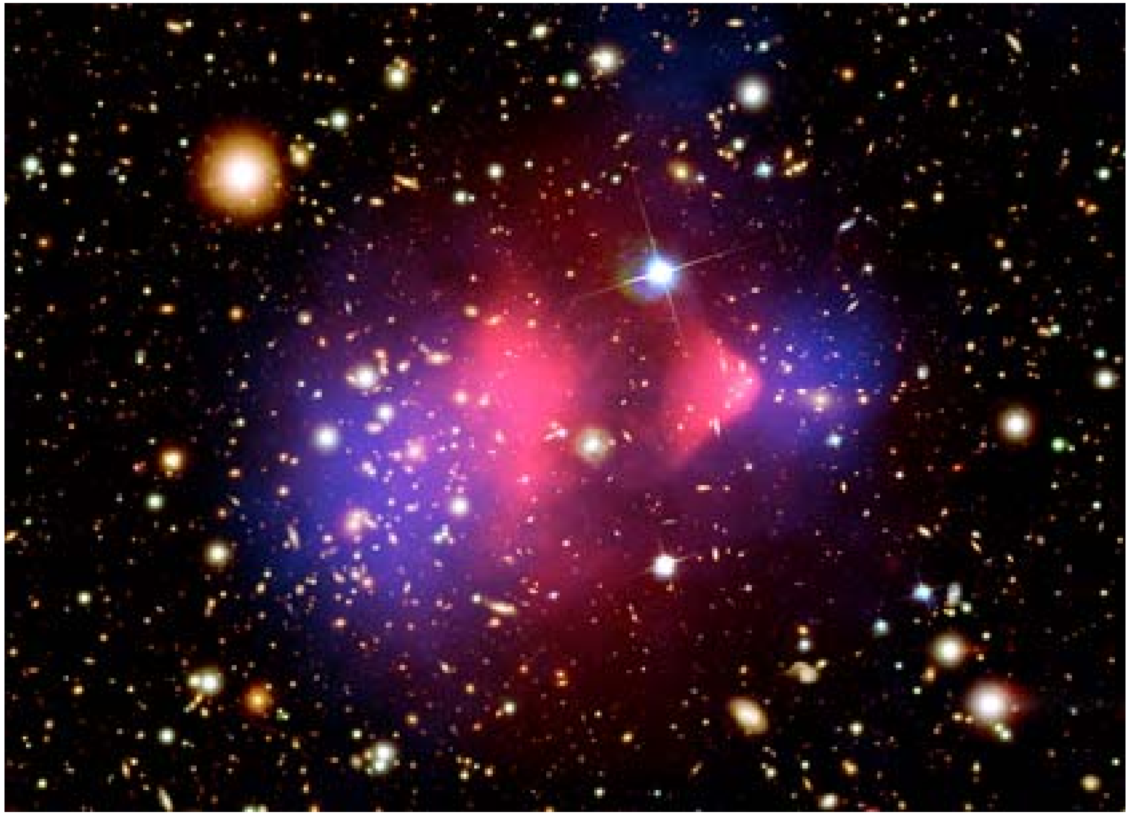


No baryonic effect below

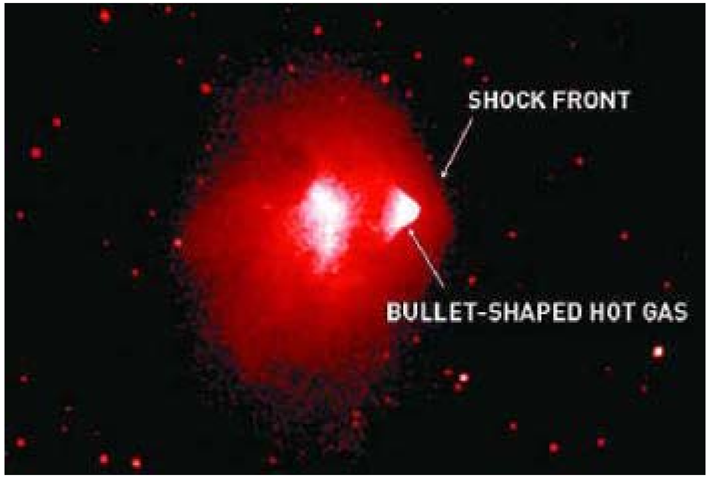
$M_{*} = 3\ 10^{6}\ M_{\odot}$ - $M_{vir} = 10^{10}\ M_{\odot}$

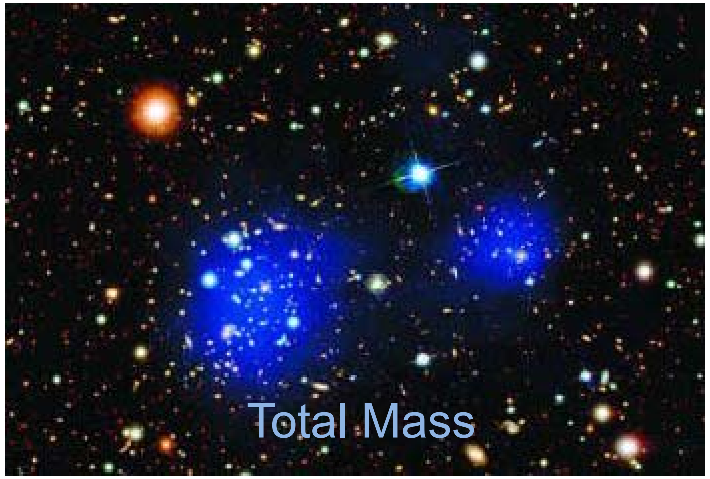
- ► Self-Interacting Dark Matter (**SIDM**)
- ► Warm Dark Matter (**WDM**)
- ► Ultra-light Axions: quantum effects on galaxy scale
- ► Modified Gravity (**MOND** / TeVeS, Einstein-aether, etc.)
- ► Dipolar dark matter: massive bigravity theory *(Blanchet, Heisenberg 17)*
- ► Superfluid Dark Matter: phonons mimick MOND *(Khoury 16)*

The bullet cluster



Very hot X-ray gas





Violent collision, unique occasion to separate components

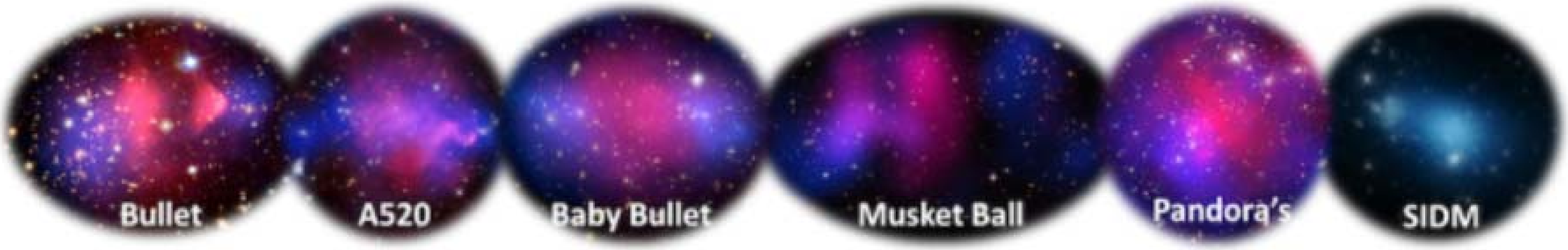
➔Limit on $\sigma_{DM}/m_{DM} < 1\ cm^2/g$

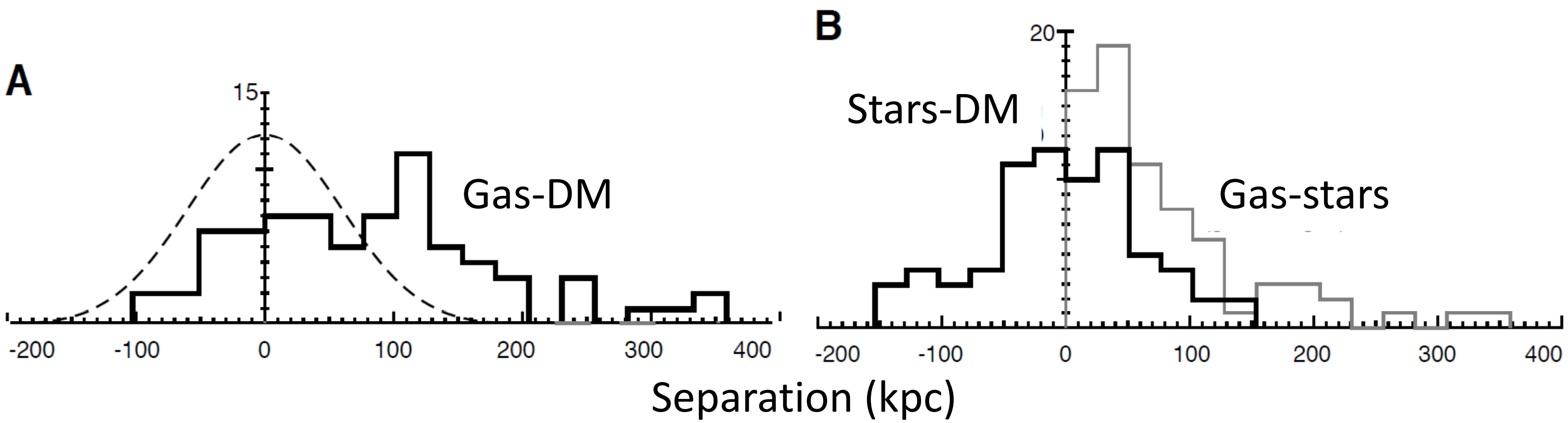
V=4700km/s (Mach 3)

For modified gravity models: ➔ neutrinos or dark baryons

A large number of collisions

Today, a sample of 72
With low-mass clusters and groups, *Harvey et al 2015*
$\sigma/m < 0.47\ cm^2/g$ [SIDM requires $\sigma/m= 0.5\text{-}3\ cm^2/g$ *(Valli & Yu 17)*]





Scenarios of bulge formation

Mergers:
Major mergers form generally a spheroid
In minor mergers, disks are more easily kept and enrich the classical bulge

Secular evolution:
bars and vertical resonance elevate stars in the center into a pseudo-bulge: intermediate between a spheroid and a disk
More frequent for late-type galaxies

Clumpy galaxies at high z can also form a bulge, through dynamical friction

➔ **Problems to form bulgeless galaxies**

Frequency of bulge-less galaxies

Locally, about 2/3 or the bright spirals are bulgeless, or low-bulge
Kormendy & Fisher 2008, *Weinzirl et al 2009*, *Karachentseva 2016*
Some of the rest have both a classical bulge and a pseudo-bulge
Plus nuclear clusters *(Böker et al 2002)*

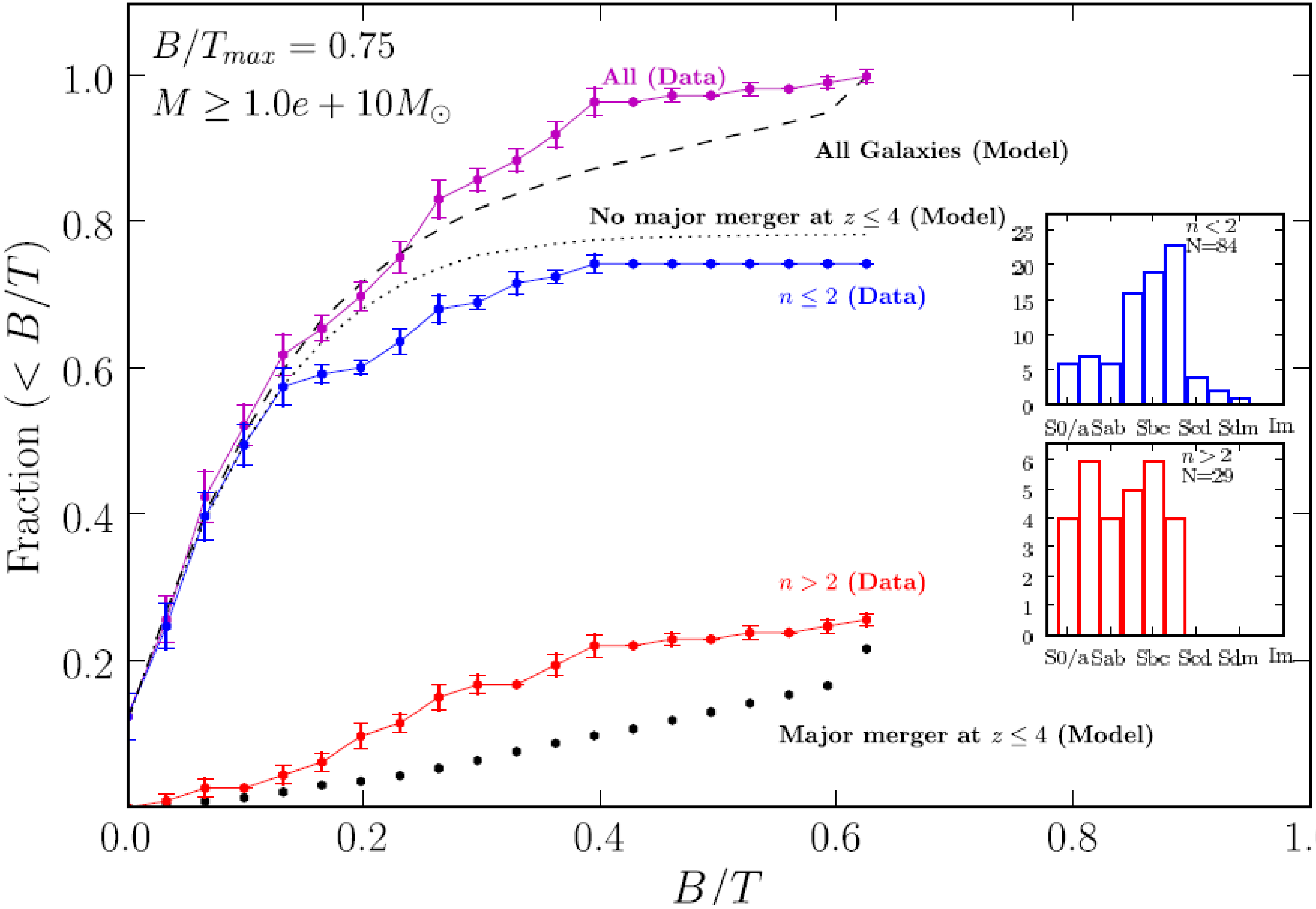
Frequency of edge-on superthin galaxies *(Kautsch et al 2006)*
1/3 of galaxies are completely bulgeless

SDSS sample : 20% of bright spirals are bulgeless until z=0.03
(Barazza et al 2008)
Disk-dominated galaxies are more barred than bulge-dominated ones

How can this be reconciled with the hierarchical scenario?

Low Bulge Mass in spiral galaxies

Sersic index n=2 separate classical bulges from secular ones



Weinzirl et al 2009

Bulge formation within MOND

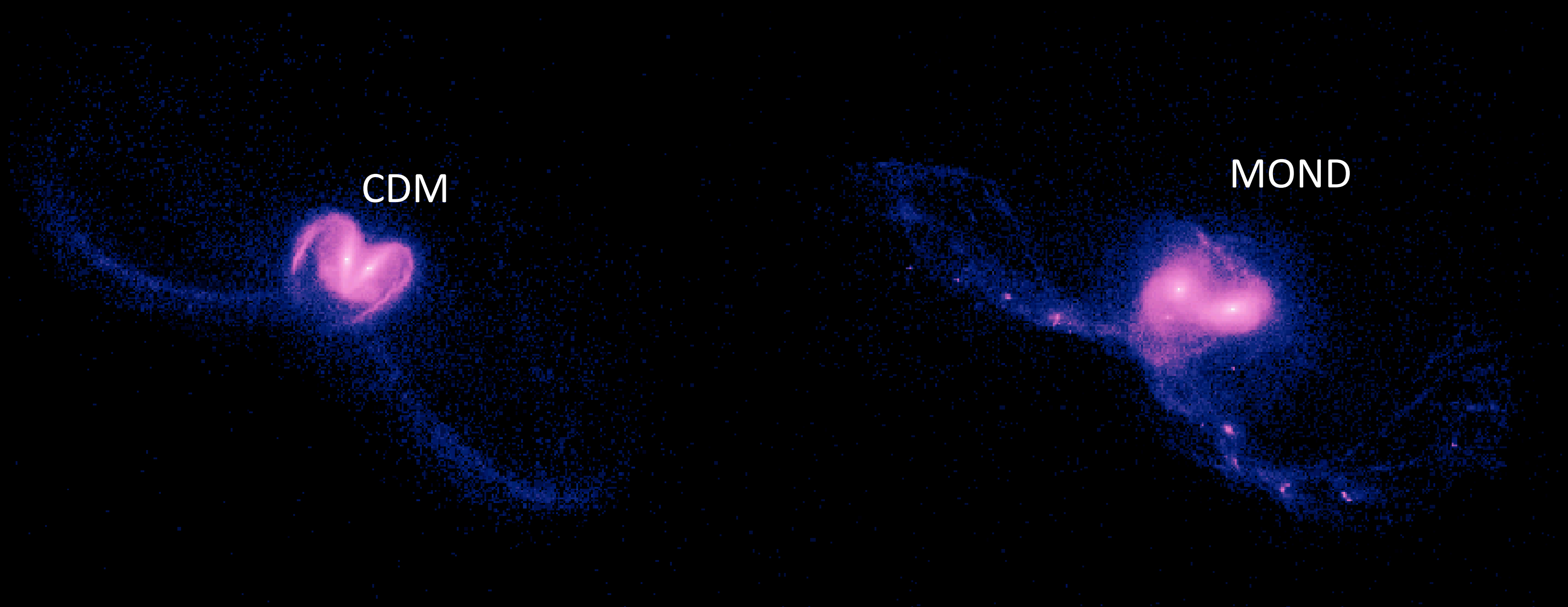
Mergers much less frequent

Due to dynamical friction much less efficient
because of lack of dark matter halo

Two bound galaxies will orbit for Gyrs befor the orbital energy
is lost and the merger could occur

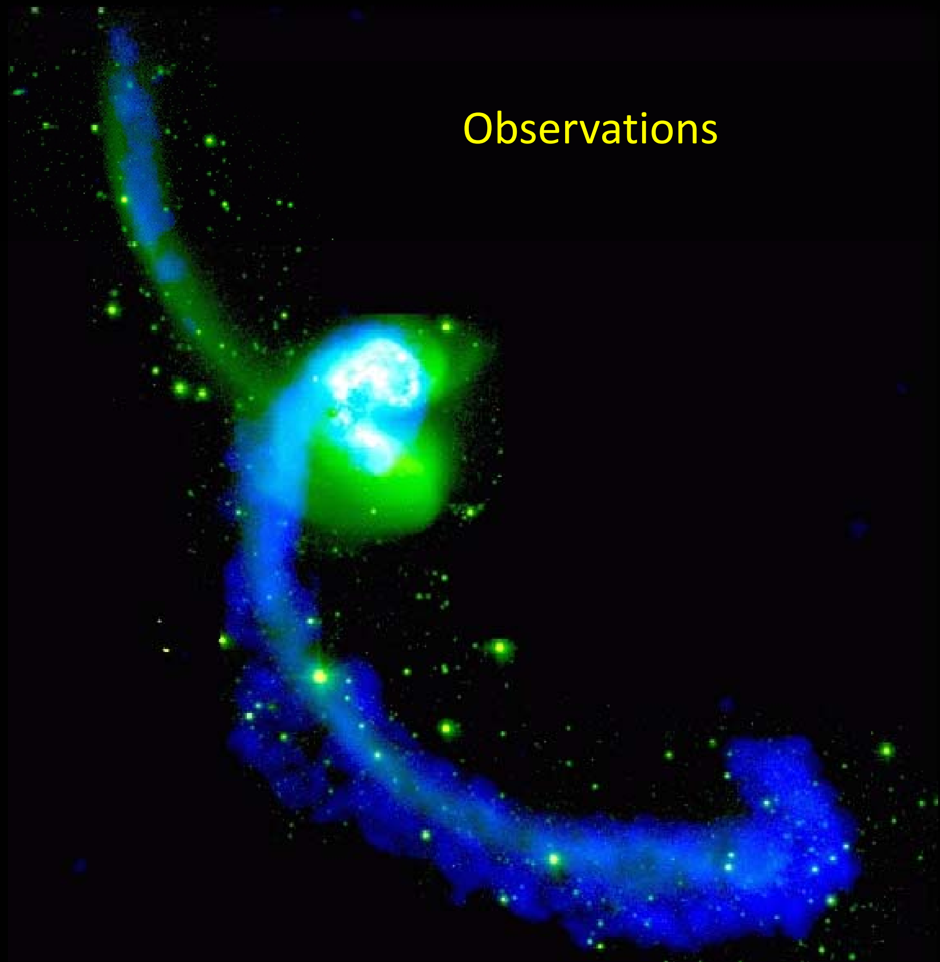
Interactions of galaxies: the Antennae MOND versus CDM

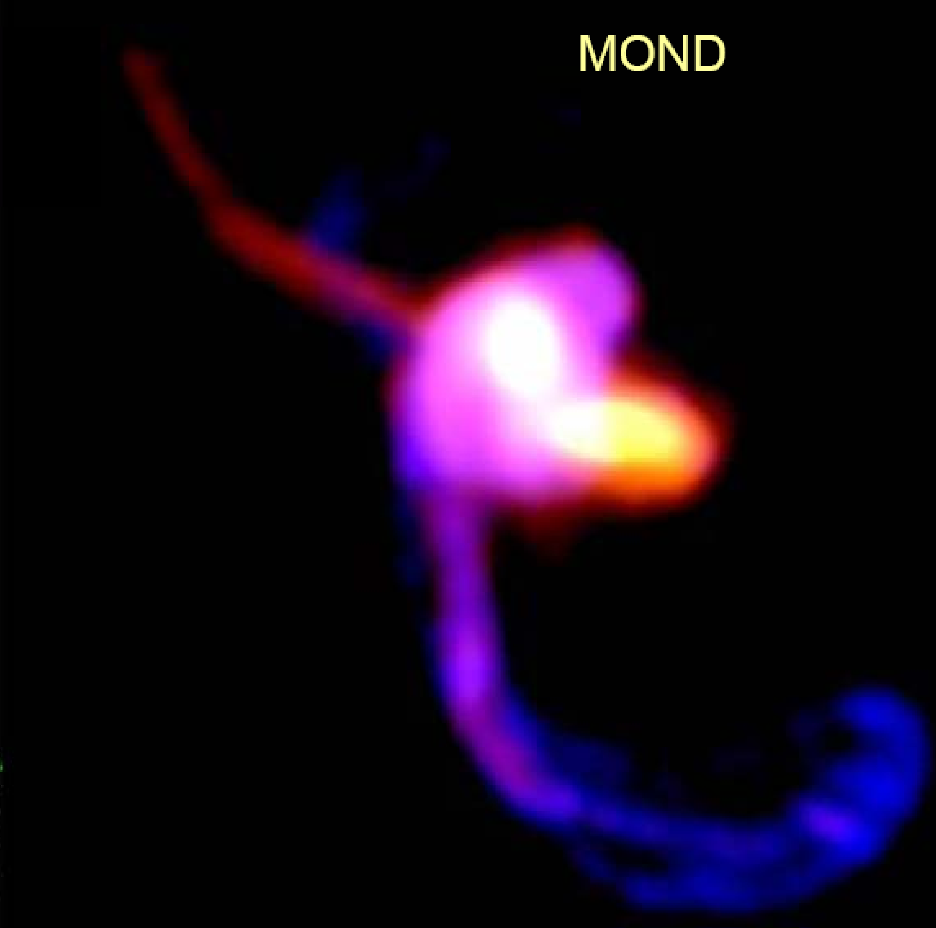
The dynamical friction is much weaker with MOND: the galaxy mergers last a longer time



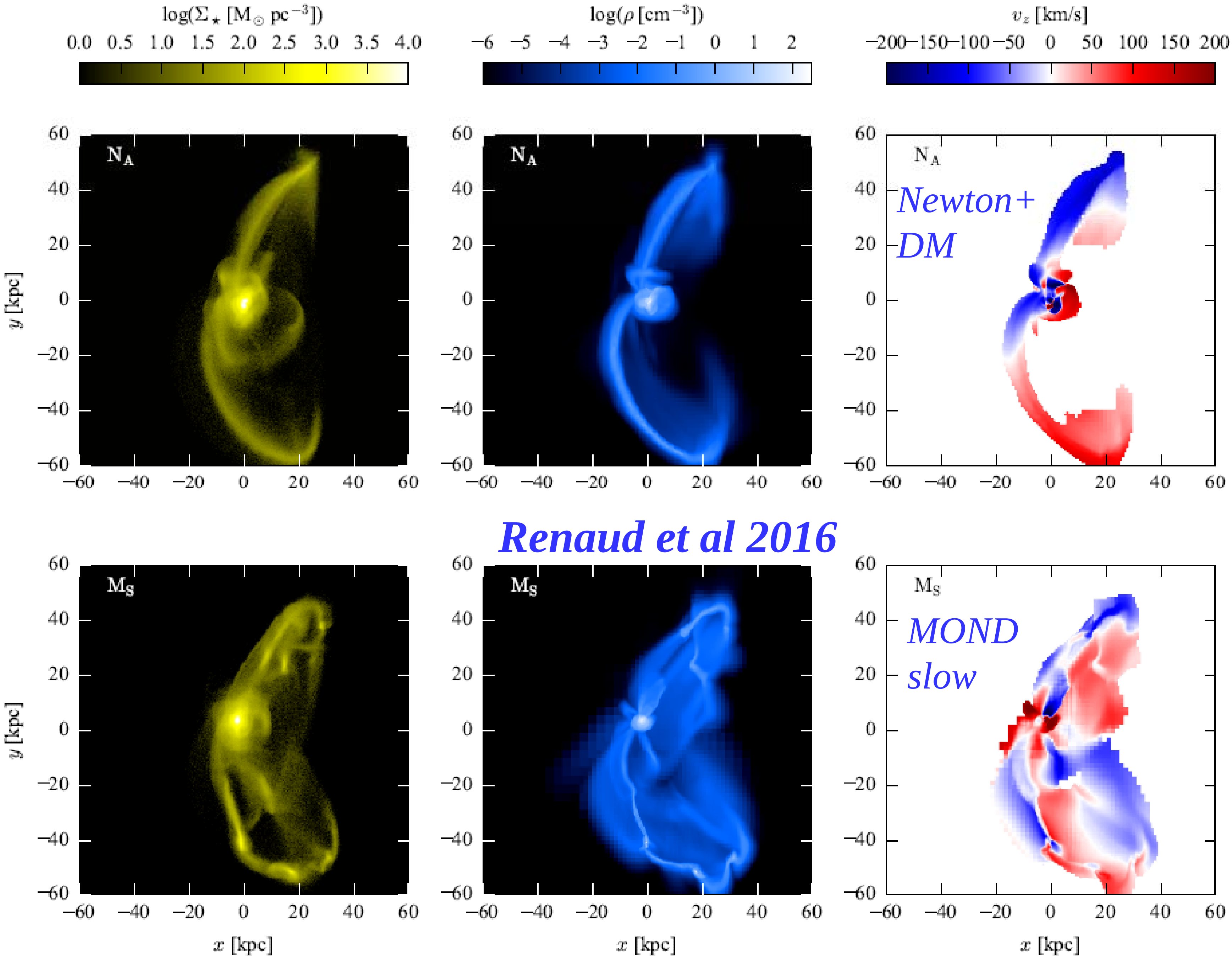
Same result found for spherical galaxies containing only stars (Nipoti et al 2007)

Simulations of the Antennae
Degeneracy: starburst at each pericentre?



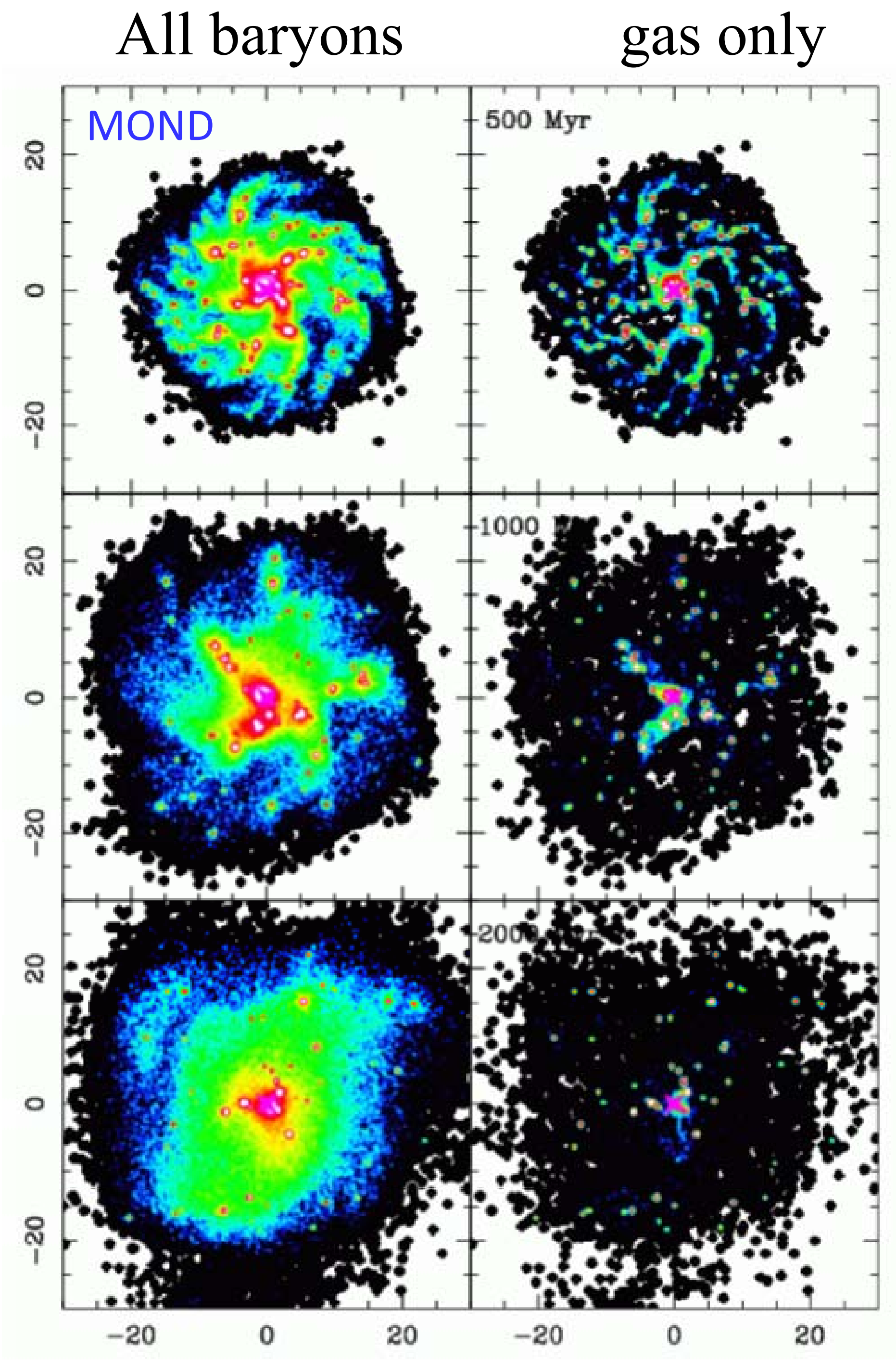


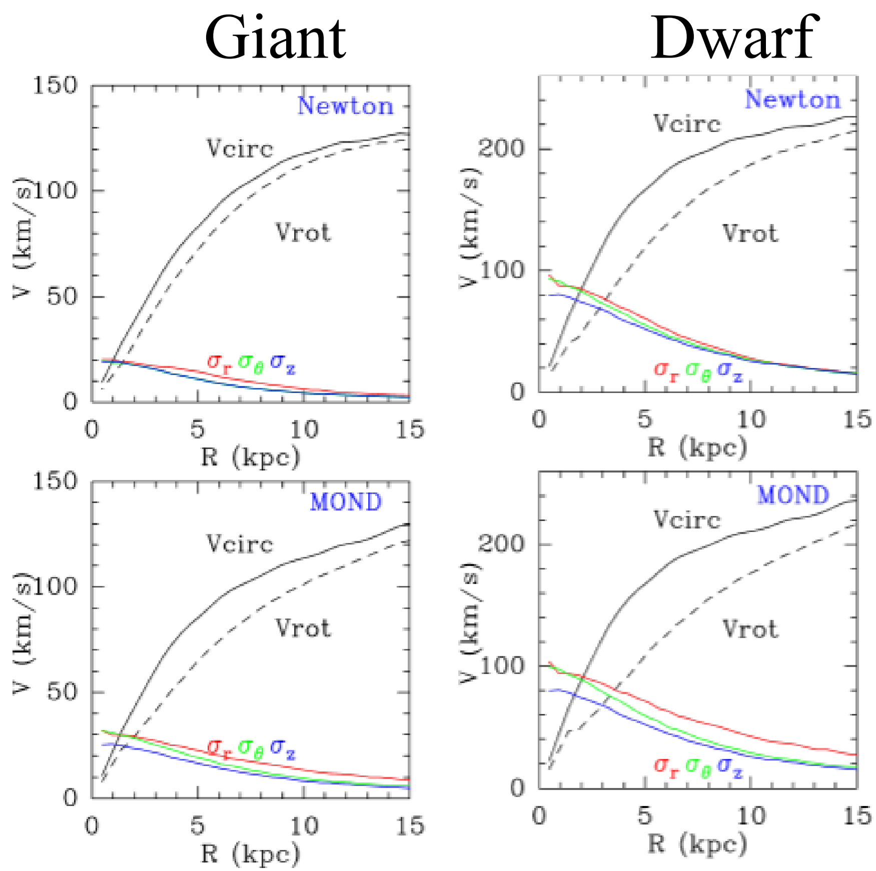
Tidal tails are longer at last passage



log(Σ⋆ [M⊙ pc−3])
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
log(ρ [cm−3])
−6 −5 −4 −3 −2 −1 0 1 2
v_z [km/s]
−200 −150 −100 −50 0 50 100 150 200
N_A
Newton+
DM
Renaud et al 2016
M_S
MOND
slow
y [kpc]
x [kpc]
60 40 20 0 −20 −40 −60
−60 −40 −20 0 20 40 60

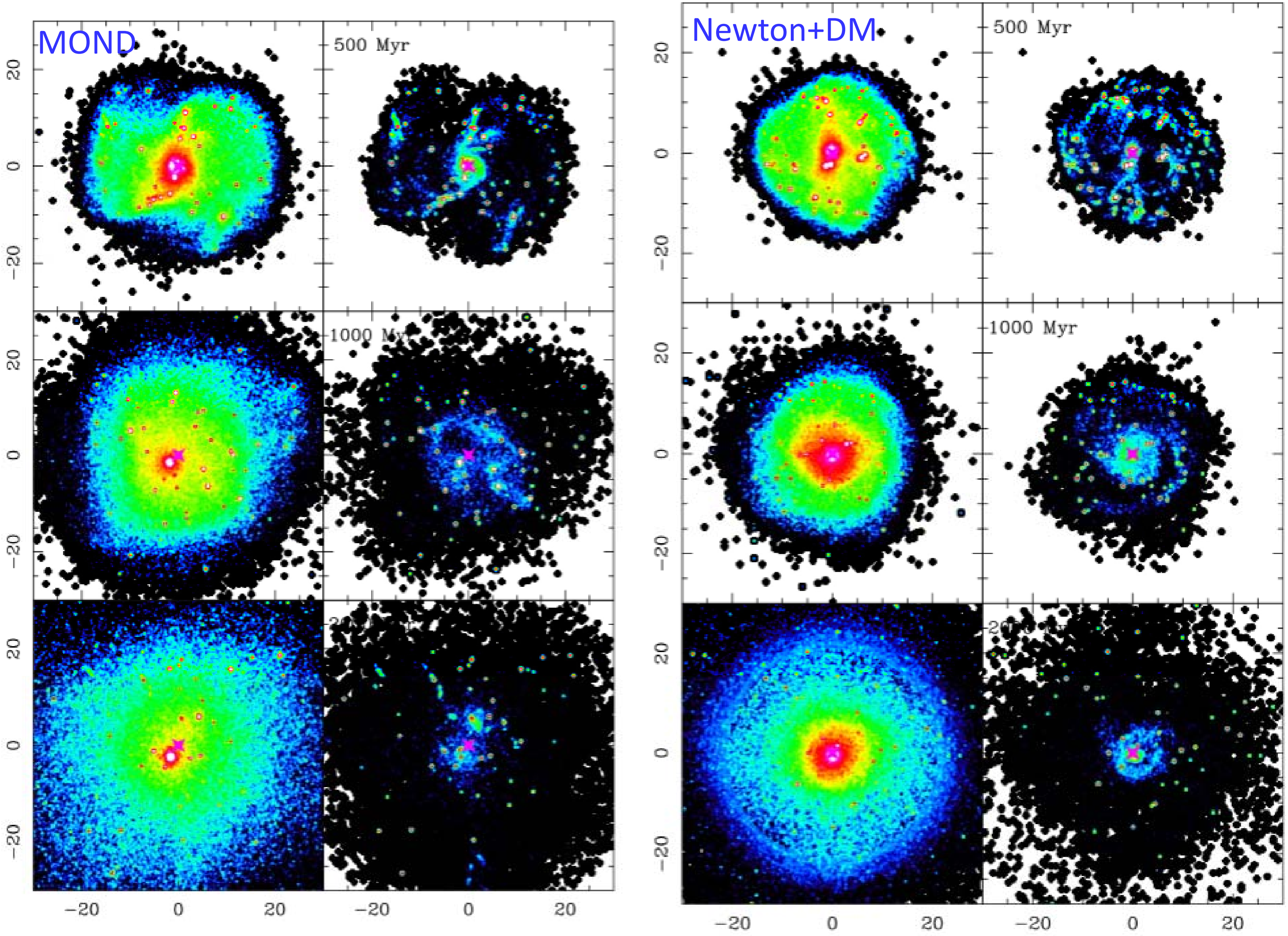
Dwarf clumpy galaxies in MOND





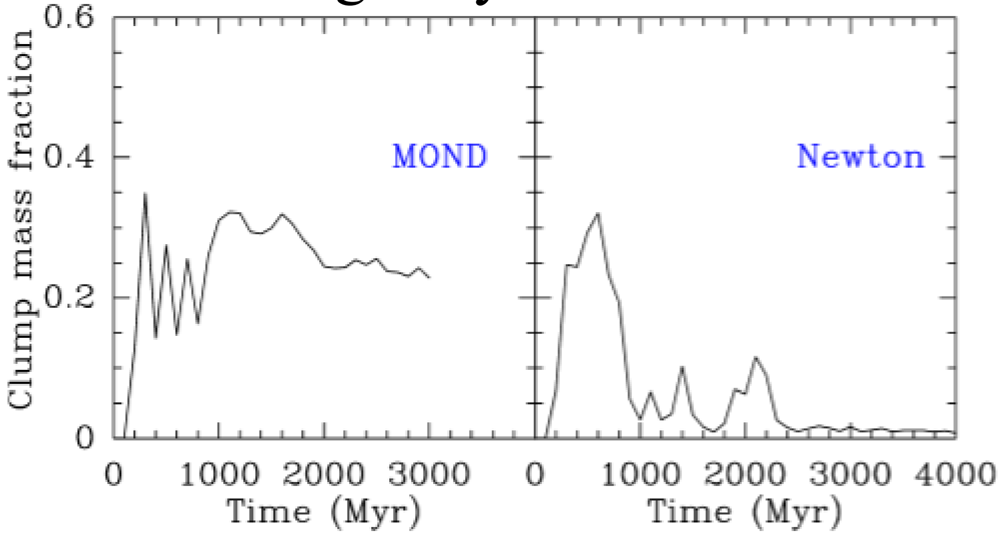
Combes 2014

Giant galaxy with MOND and Newton+DM



Clump mass fraction

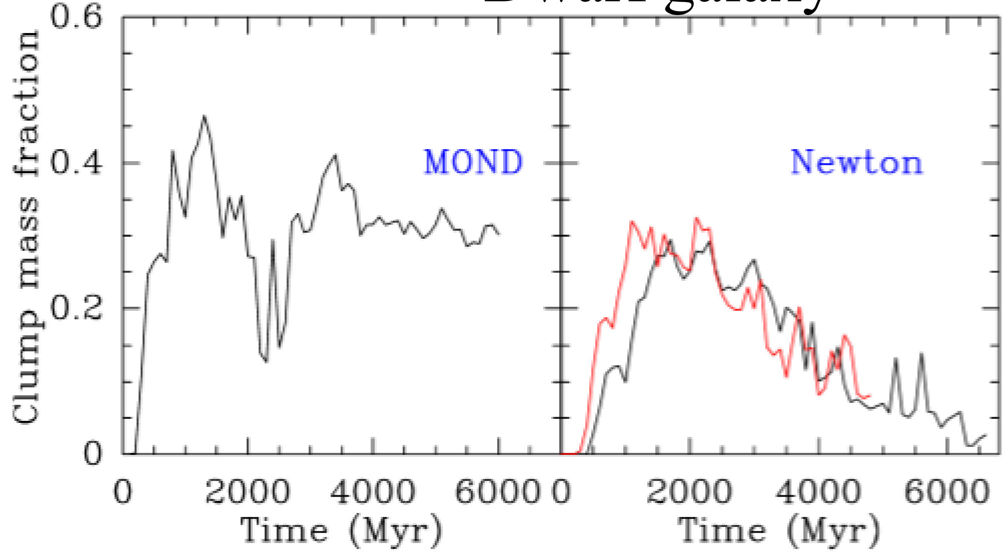
Giant galaxy



Newton+DM
Clumps fall inwards to the center to form a bulge by dynamical friction

MOND: clumps do not coalesce into bulges: they are eroded by SN feedback and shear forces.

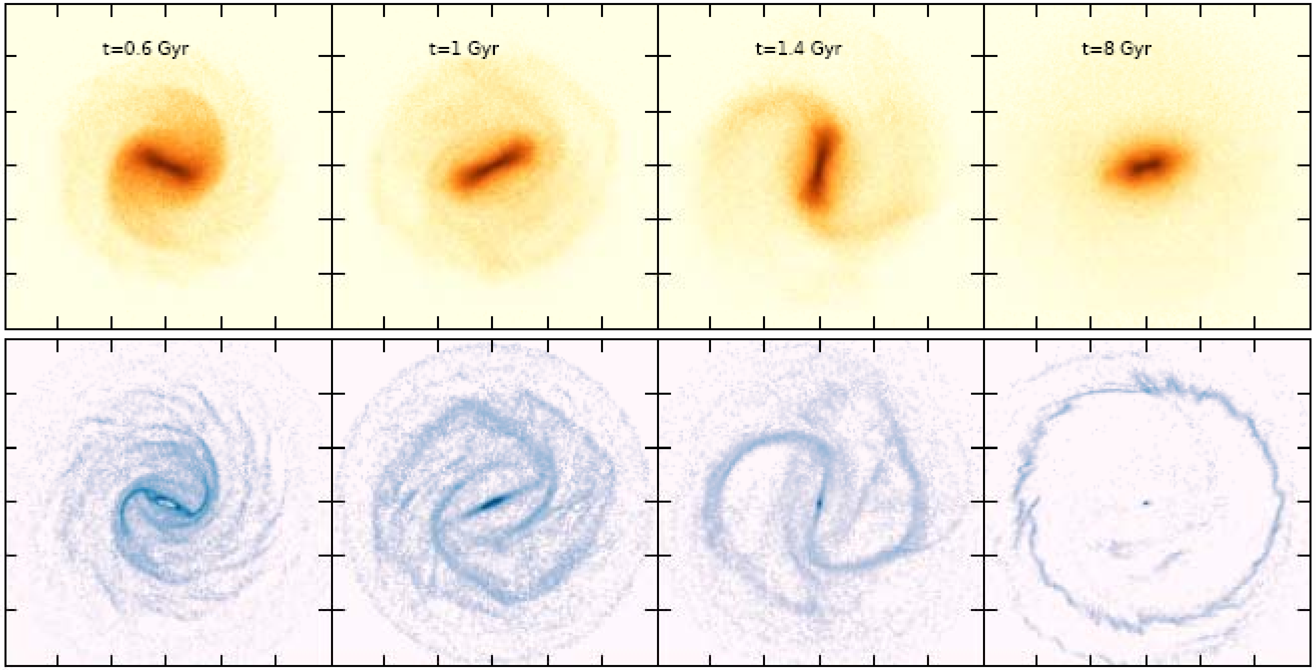
Dwarf galaxy

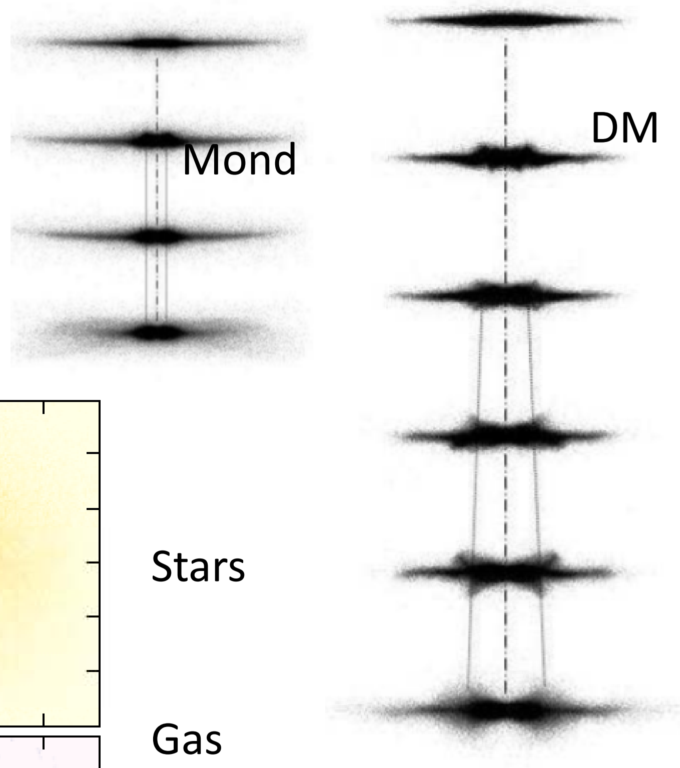


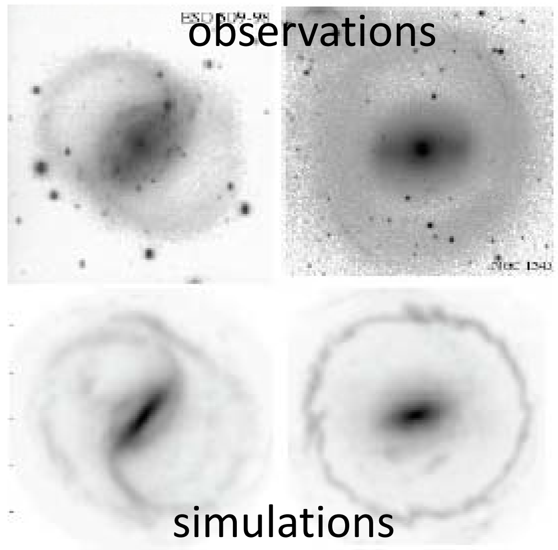
In red, 513^3, with 8 times the number of particles

Influence of dark halo

Dynamics of galaxies,
Formation of spirals and bars





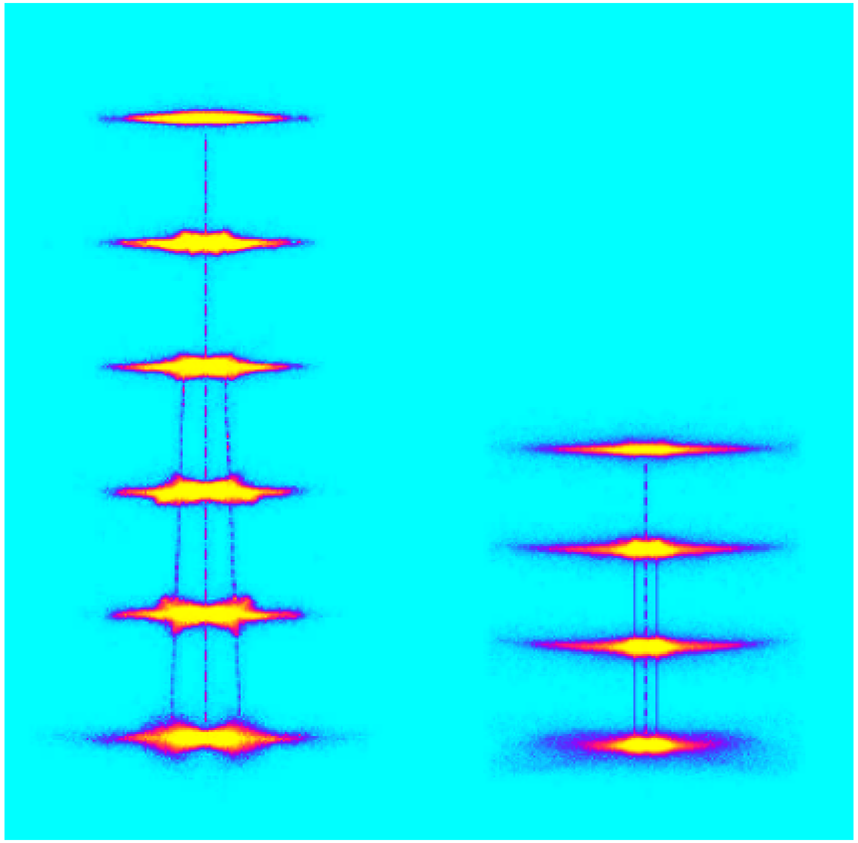


Rings at resonances
➔ Give the bar pattern speed

Tiret & Combes 2007

Bar pattern speed with DM and MOND

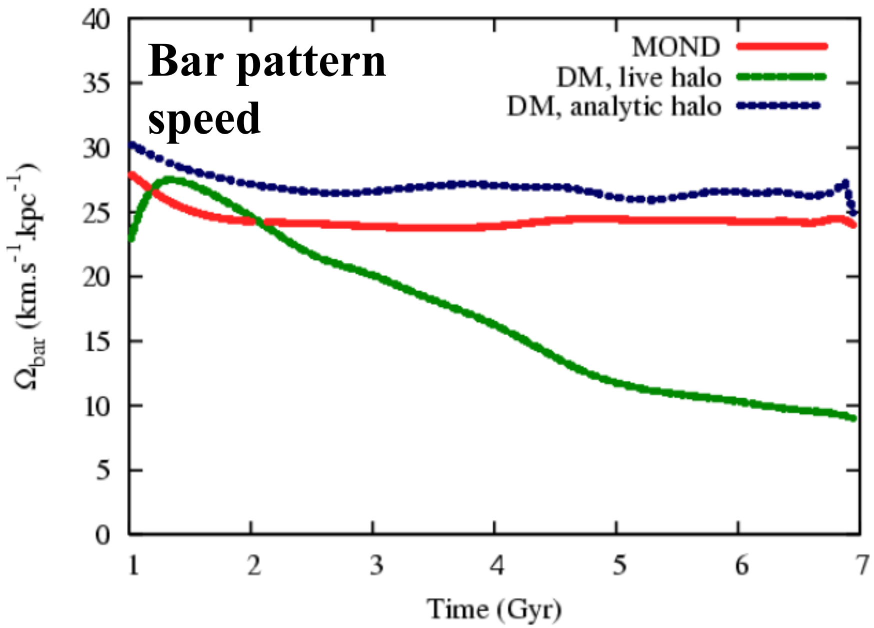
With DM MOND



Dynamical friction is much larger with DM haloes

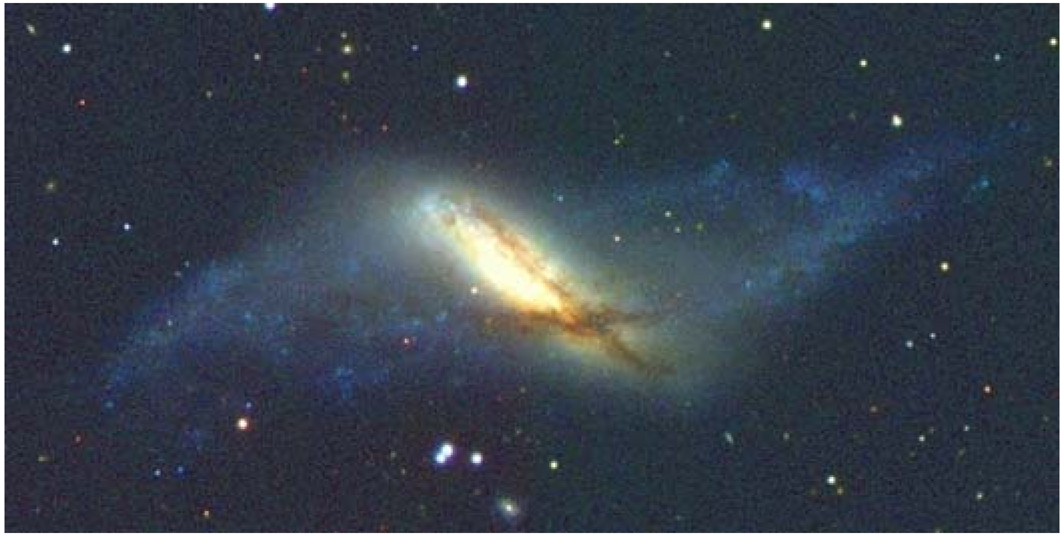
Slows down the bar

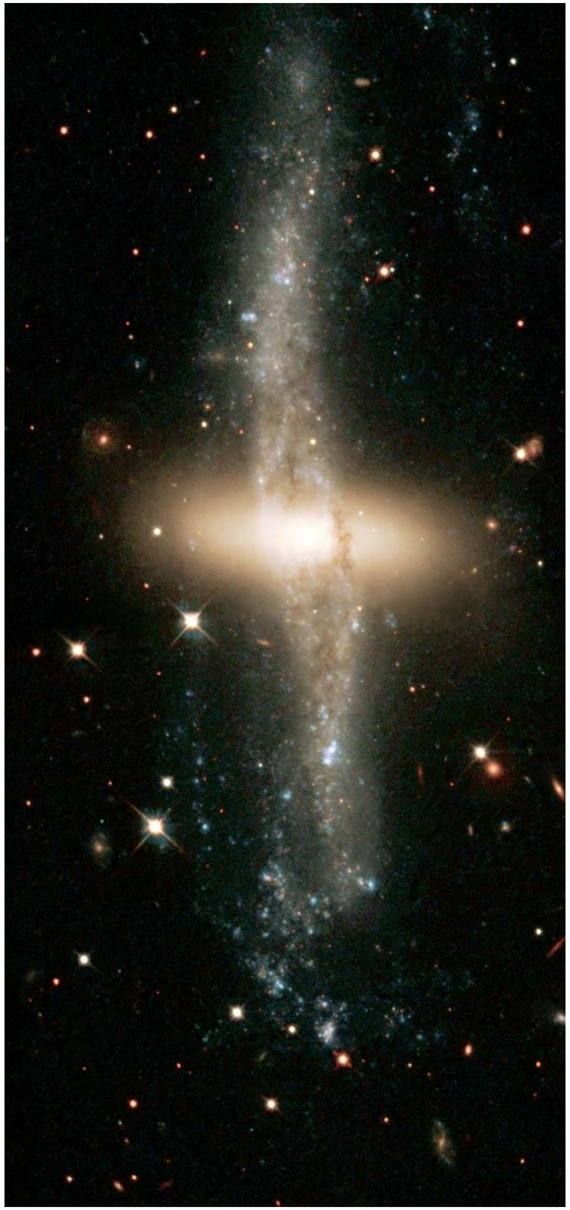
➔ Different vertical resonances



Tiret & Combes 2007

Polar rings and cosmic accretion

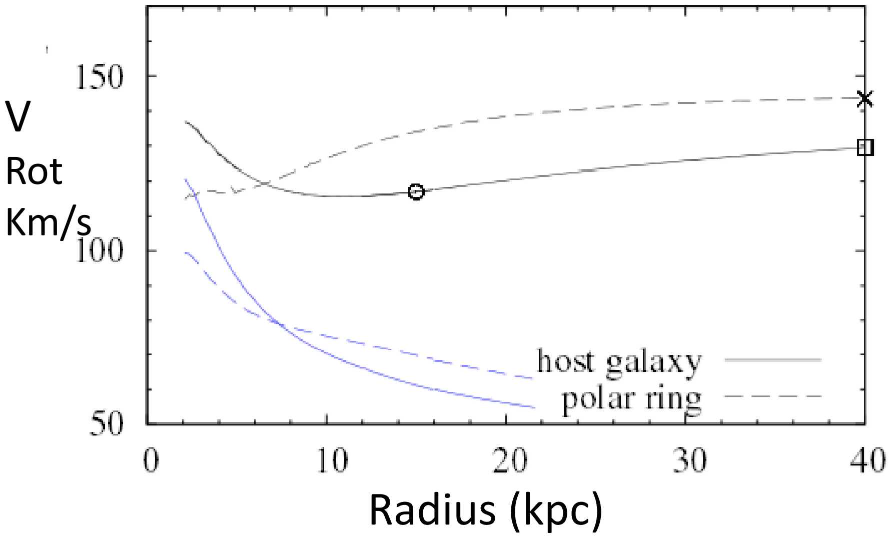




➔Polar rings are a unique occasion to probe dark matter distribution in 3D

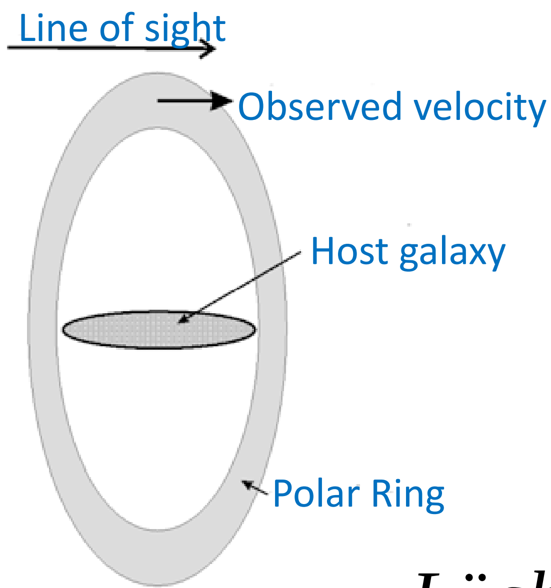
➔Rotation speed observed larger in the polar disk than in the equatorial one

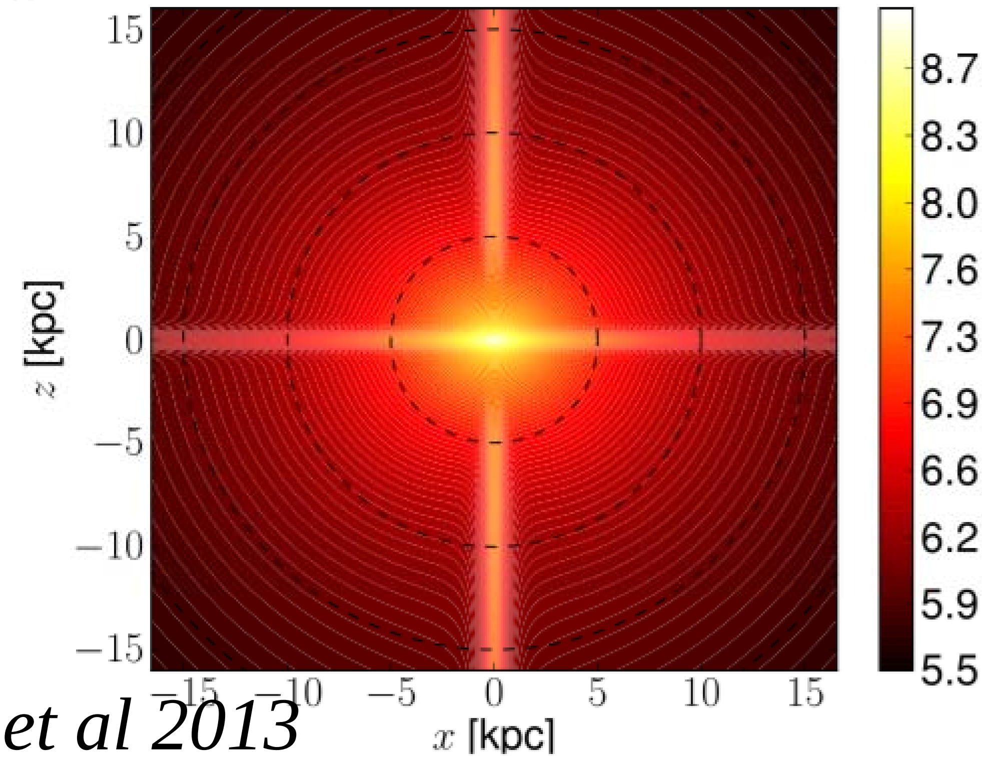
Polar rings with MOND



➔Larger velocity in the polar plane obtained naturally

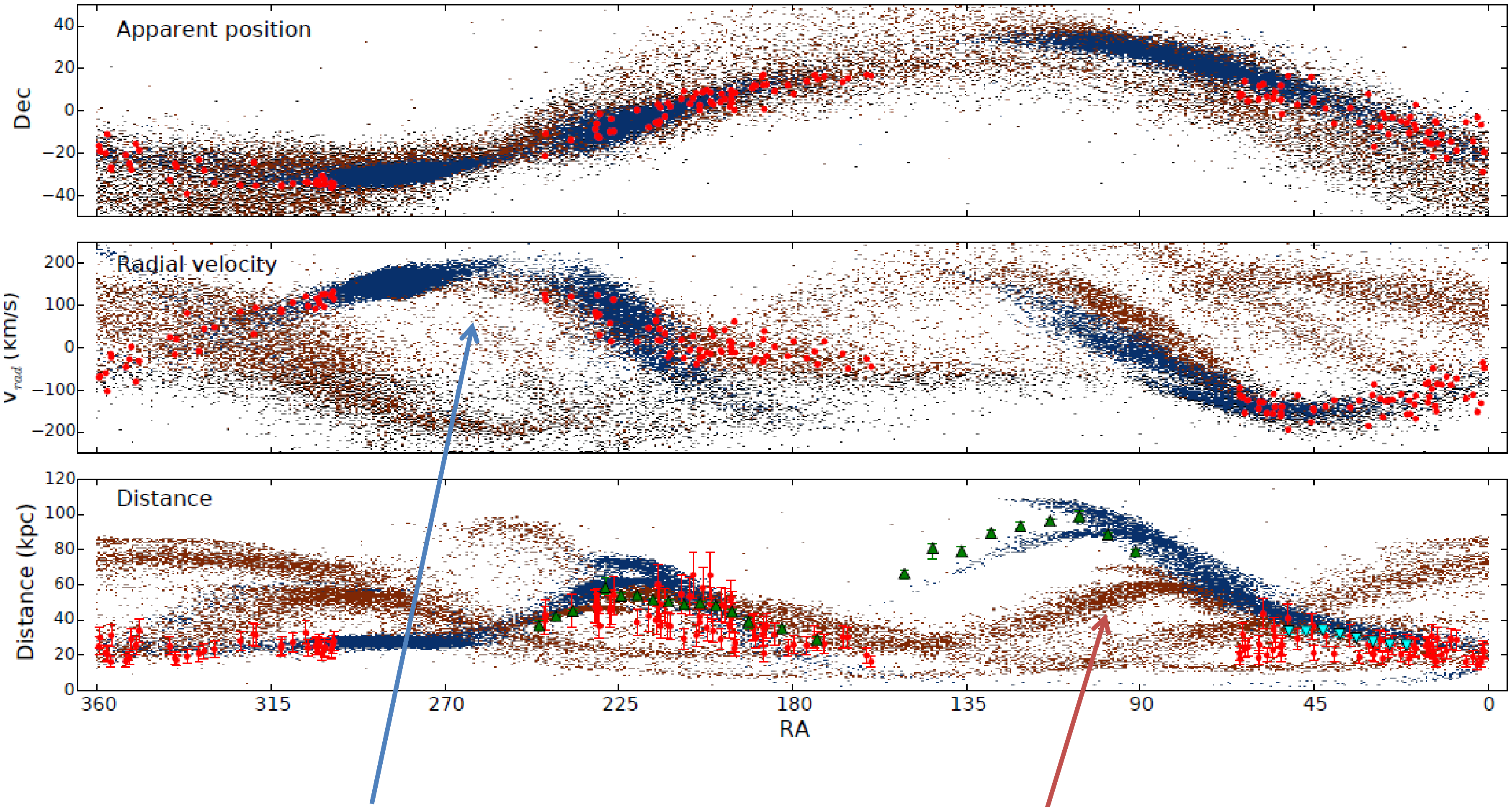
Map of the phantom dark matter





Lüghausen et al 2013

Sag dwarf satellite with MOND, and Newton



Blue MOND simulation (Thomas et al 2017)

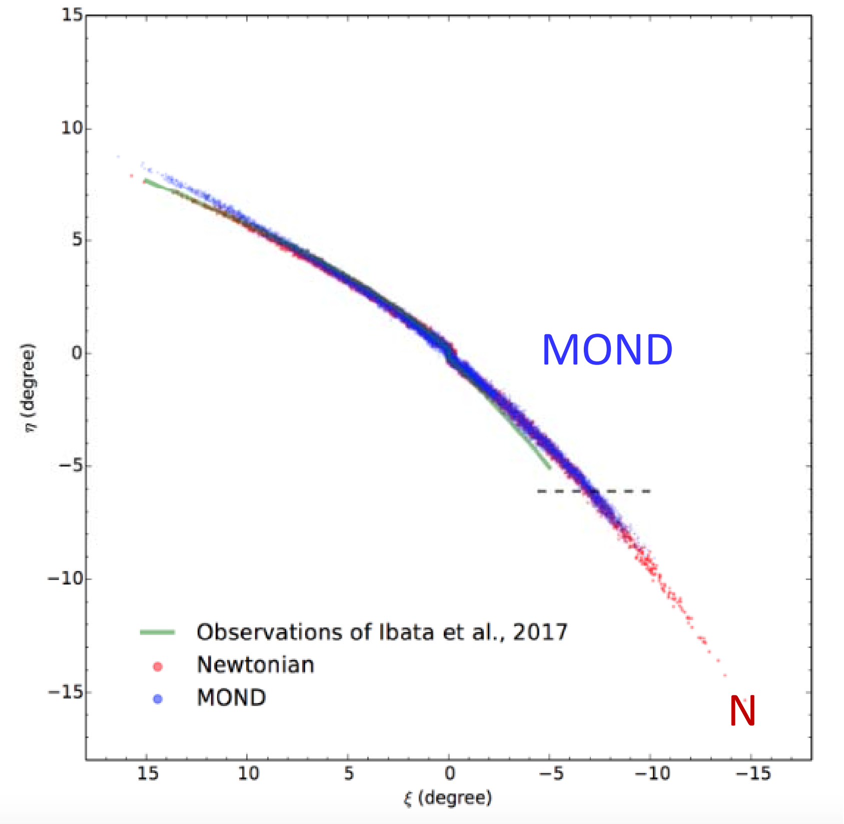
Orange: Newton (Law & Majewski 2010)

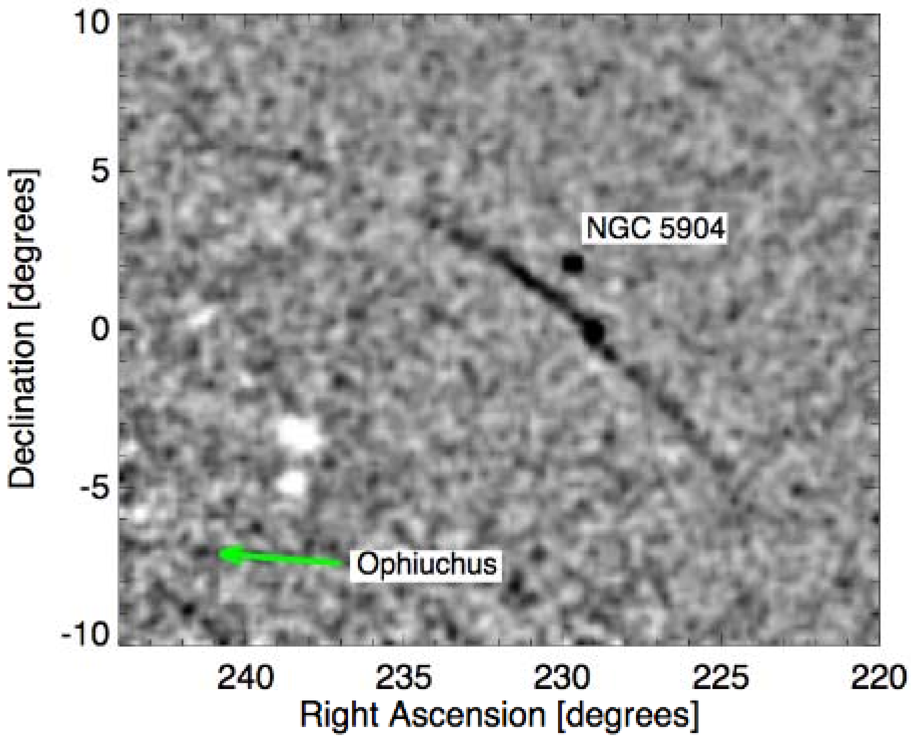
Violation of SEP: Pal5 tails

Bernard et al 2016
PAN-STARRS1

Close glob. cluster (23.5 kpc), tidal radius ~ 145 pc

EFE breaks the SEP



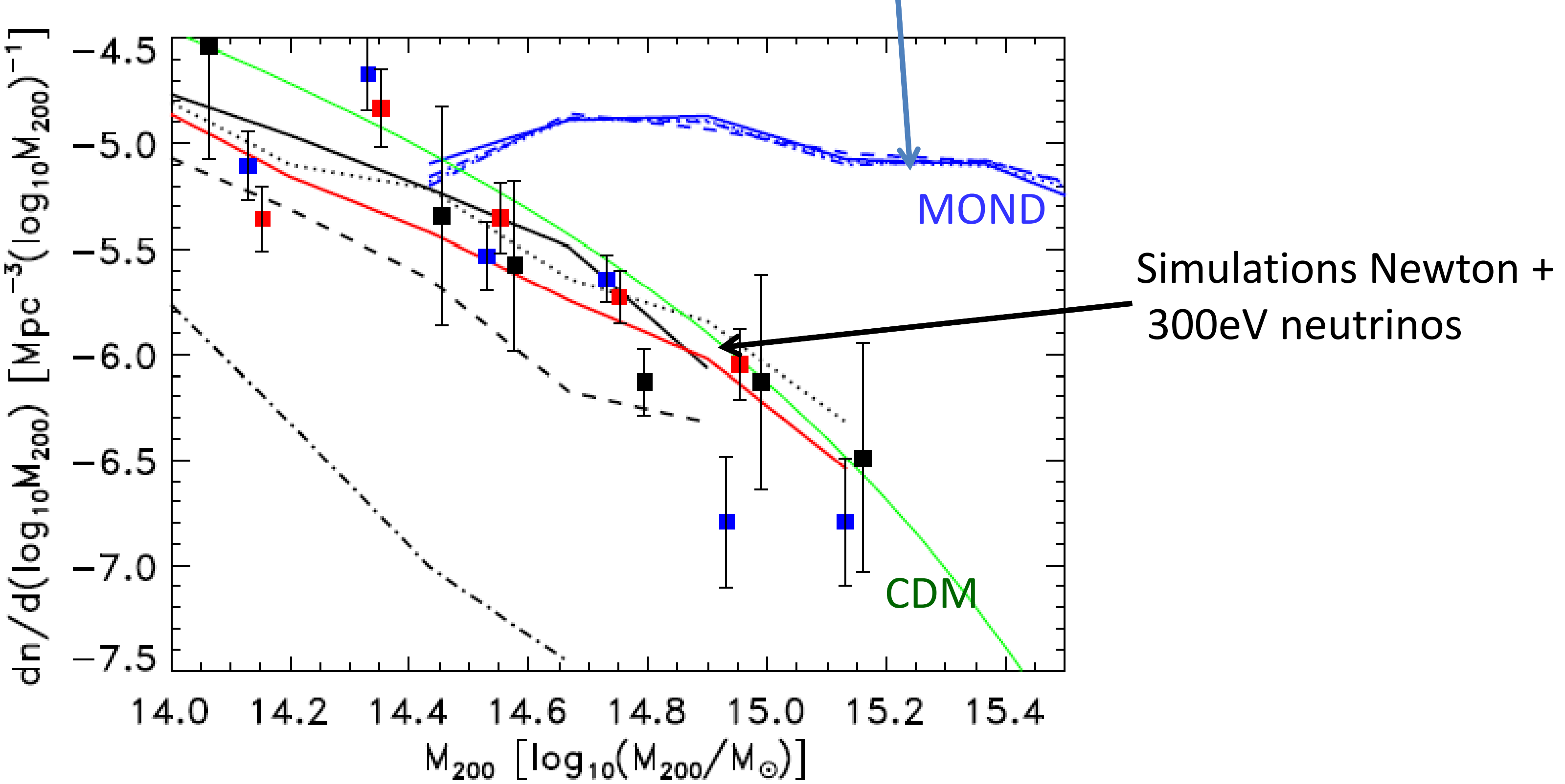


Tidal stream asymmetry:
trailing arm ~ 6 kpc leading ~ 3.5 kpc

Almost factor of 2 in stream surface brightness at 1 kpc from GC
Famaey 2017

Failure of MOND +sterile neutrinos

For galaxy formation and cosmology
MOND has to add sterile neutrinos
But without succeeding to reproduce the Large-Scale Structures
Angus et al 2014
Two many large haloes are formed



Where do we stand?

Galaxies & visible gas: **0.5%** of the total
Baryonic matter (5%): of which 60% non identified

Non-baryonic dark matter:
Particules still unknown, beyond the standard model
Masses from 10^{-6} eV (axions) to 10^{12} eV (WIMPs)
Wanted **since 33yrs**

➔Neutrinos, constraints Ly-α : **m_X > 4.65 keV (thermal)**
and m_s > 28.8 keV (non-resonant)

Problems of standard DM models at galaxy scale
➔ solution in baryonic physics?
➔ **Or modified gravity**