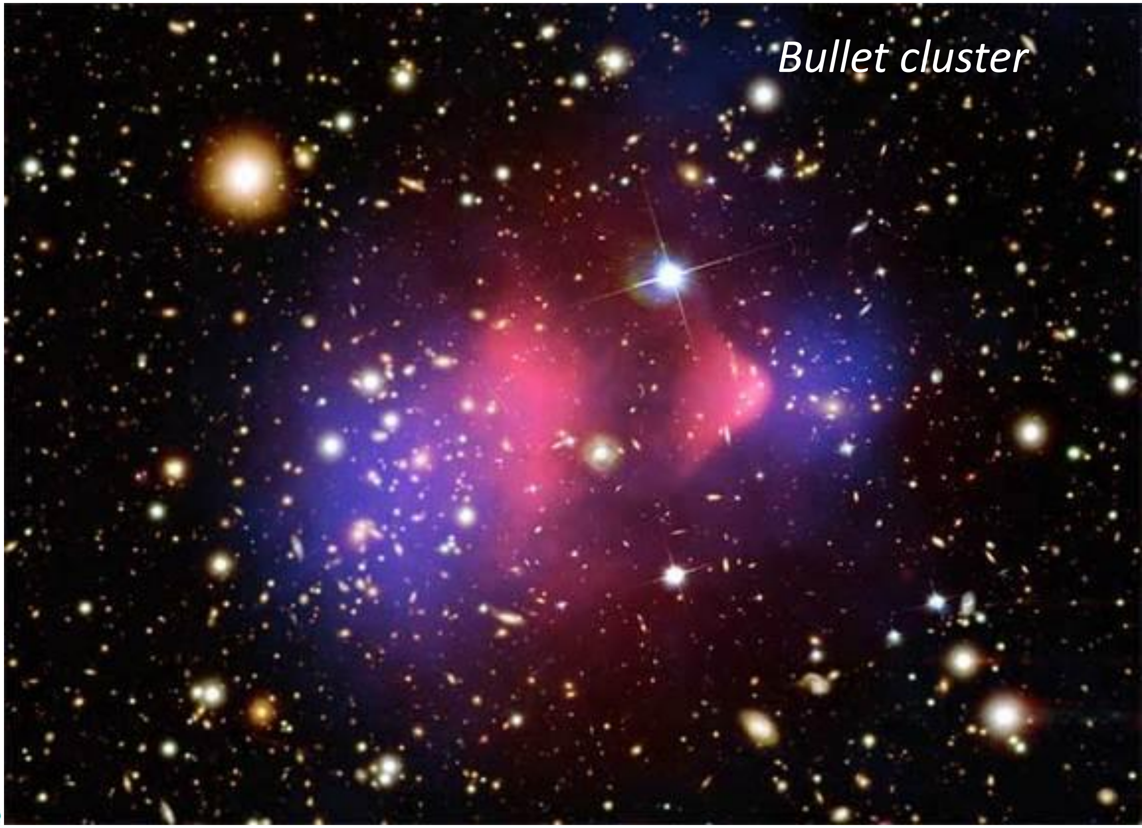
Dark Matter from an Astrophysics Perspective

Chaire Galaxies et Cosmologie



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13 Octobre, 2017

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

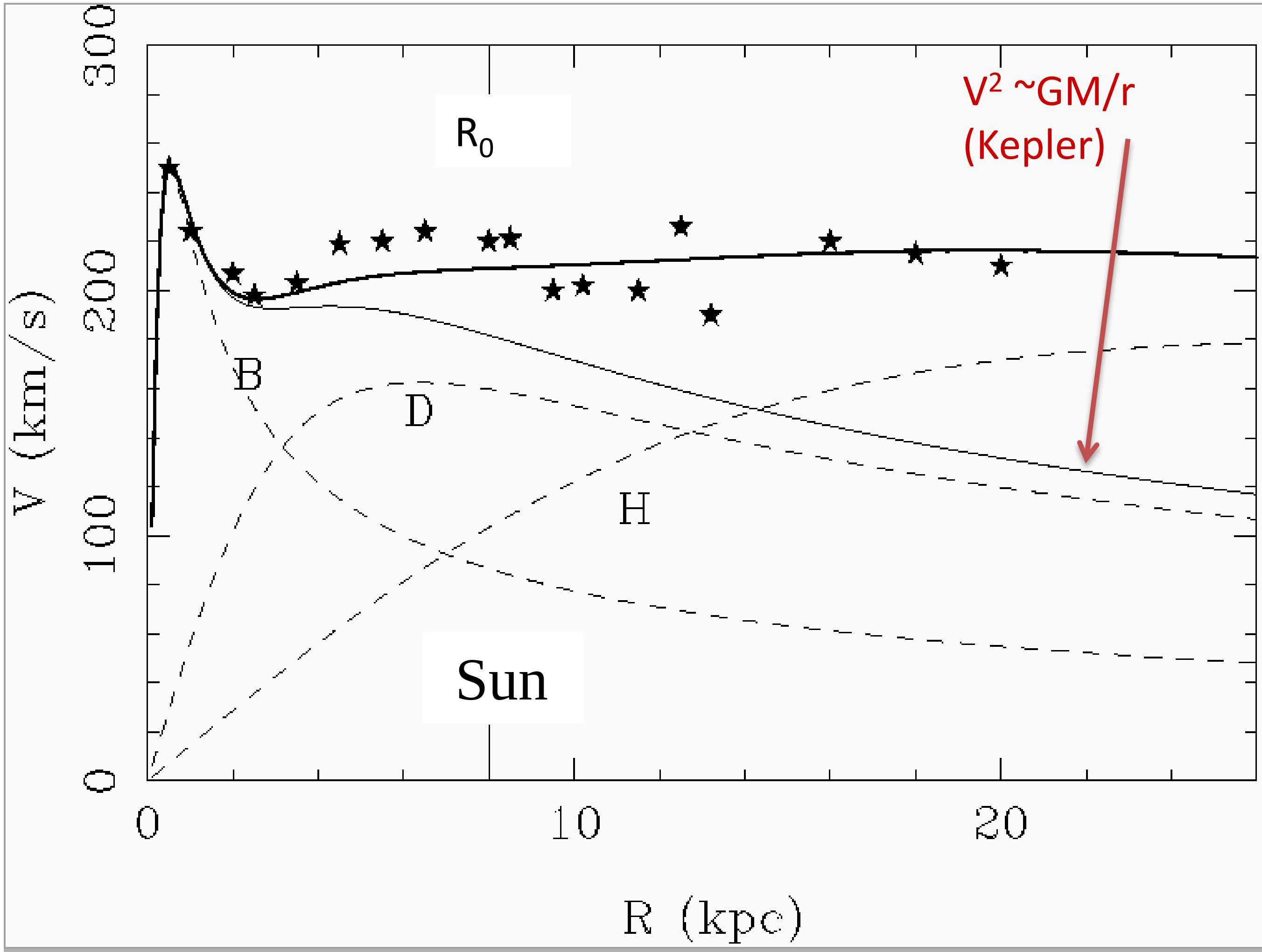
Outline

- Rotation curves, Universal RC, RAR Radial acceleration relation
- Where are the baryons?
- Tully-Fisher and scaling relations
- Too many dwarfs, Too Big To Fail (TBTF)
- Galaxy clusters: Bullets
- Neutrinos, Ly-α bounds
- Primary black holes PBH

Galaxy Rotation Curves

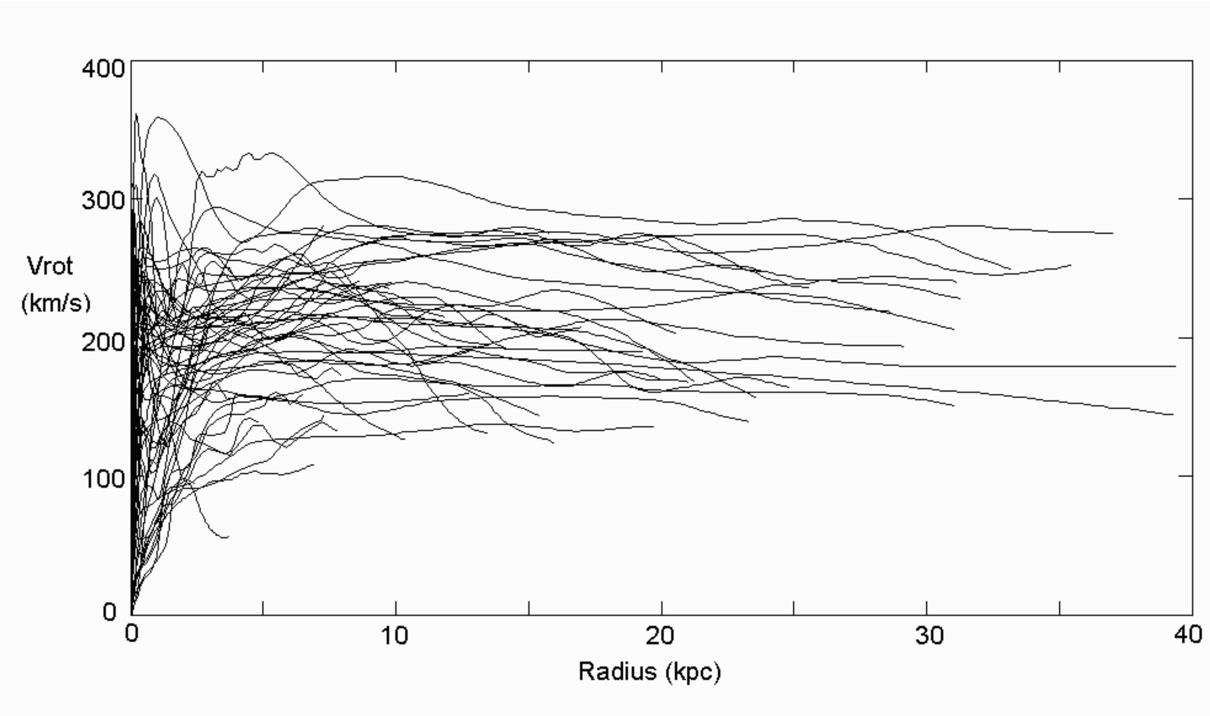
➔**Around galaxies**, dark matter haloes
1960 -1980: difficult to measure, uncertain M/L ratio

➔**Rotation curves**, cf our Galaxy, The Milky Way

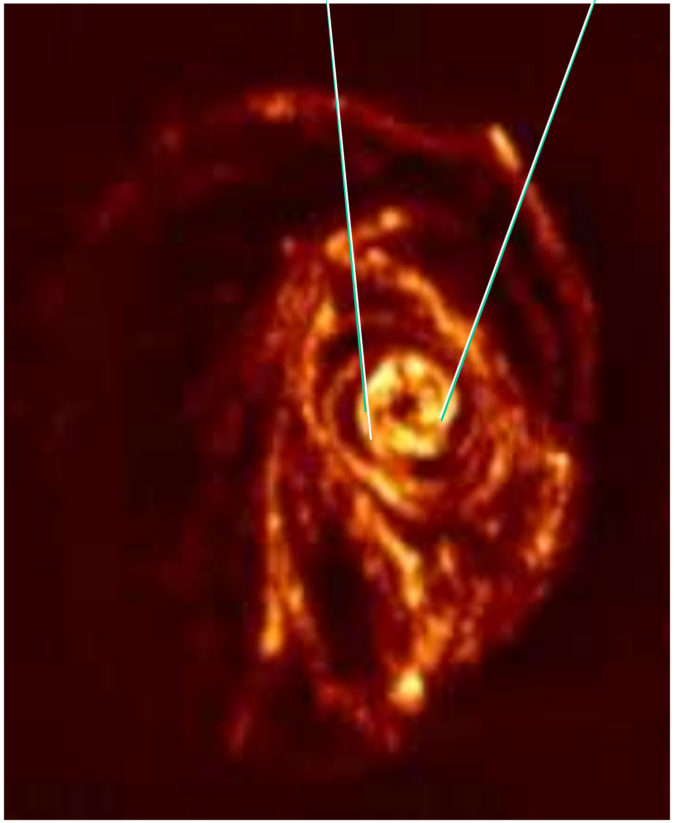


Outer disks of neutral hydrogen HI

HI: maps of atomic hydrogen
21cm wavelength



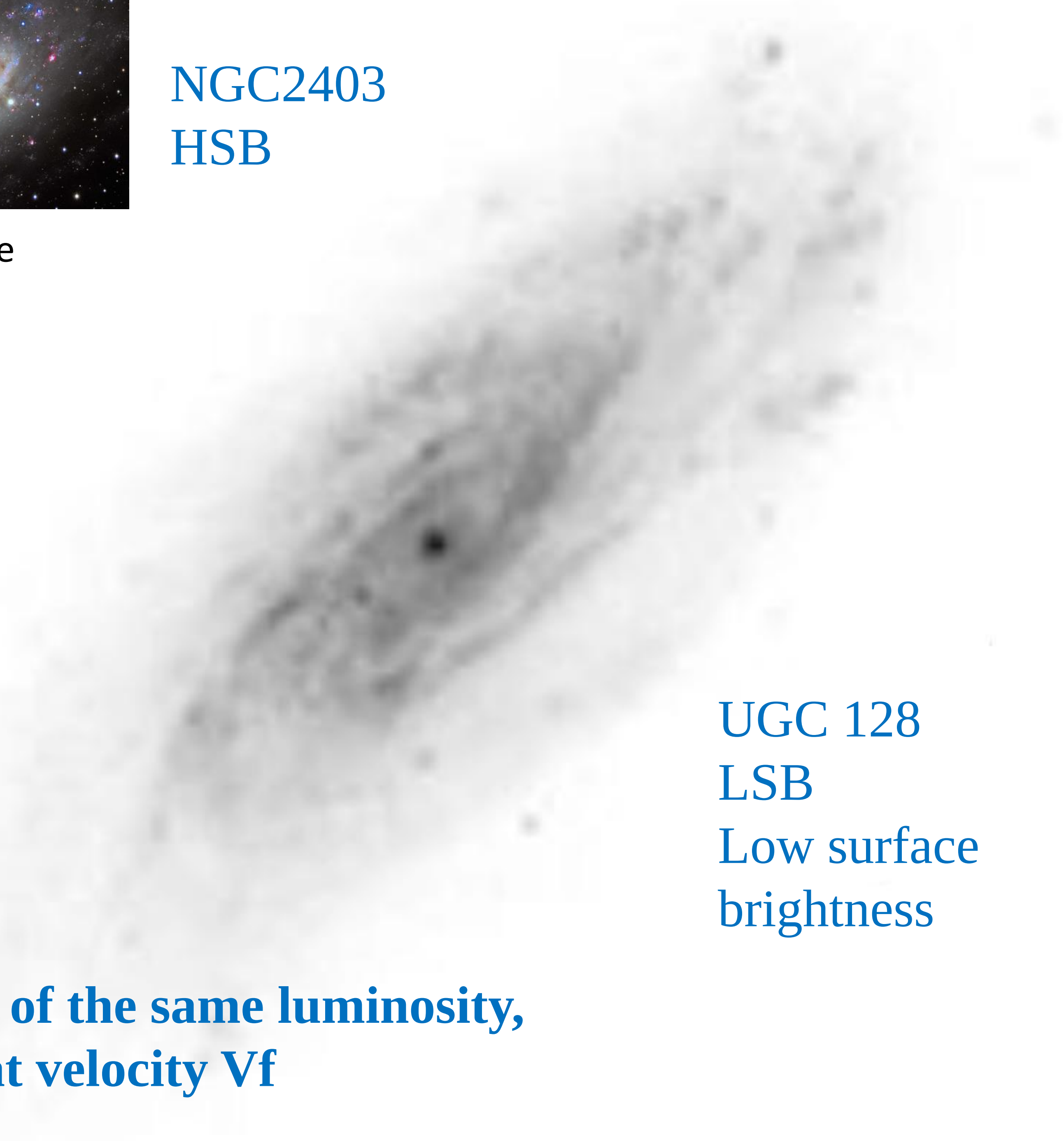
M83: optical



HI in M83: a galaxy similar to the Milky Way

NGC2403
HSB

At the same scale

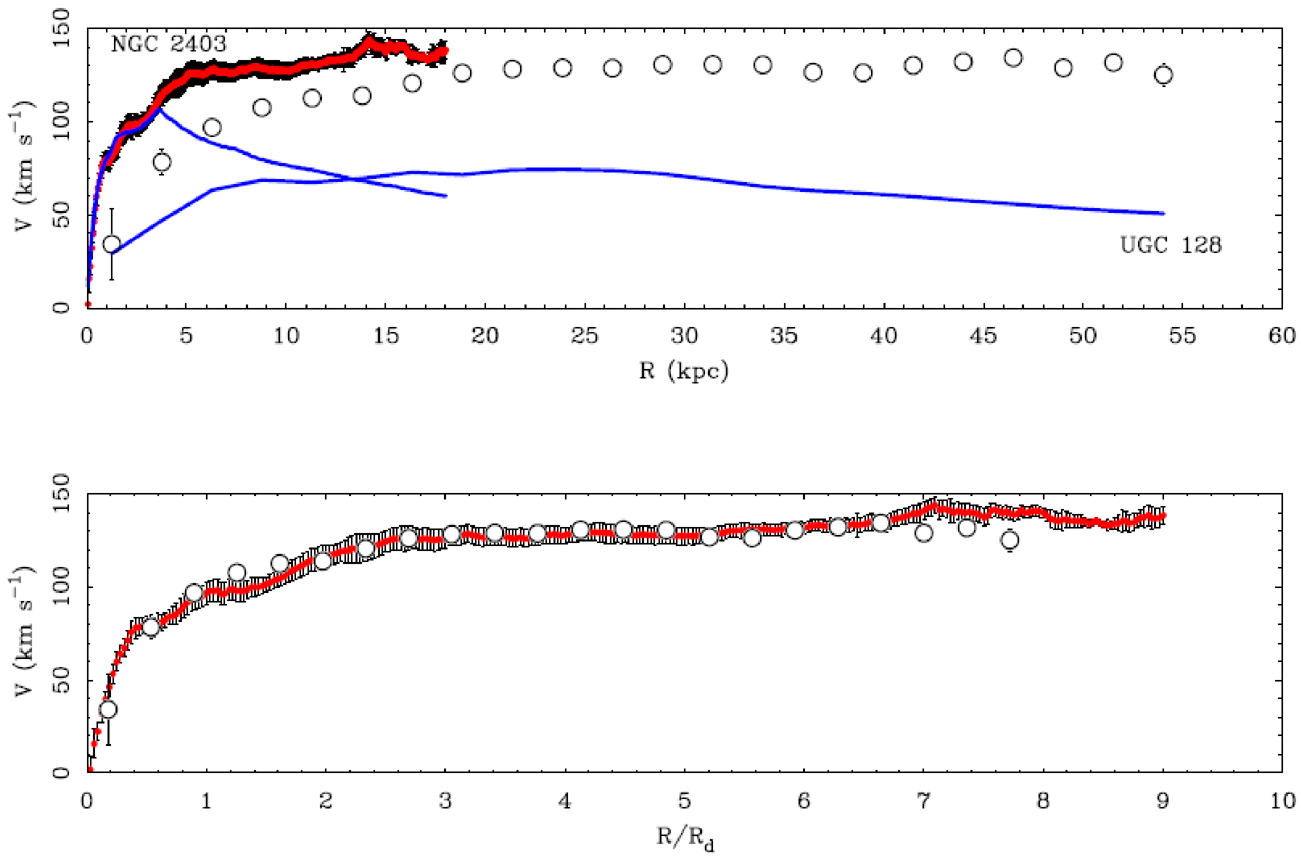


UGC 128
LSB
Low surface
brightness

Two galaxies of the same luminosity,
And same flat velocity Vf

Normalisation to R_d exponential disk

Several ways to do
-- maximum disk
-- same dark halo
-- normalisation to the optical disk

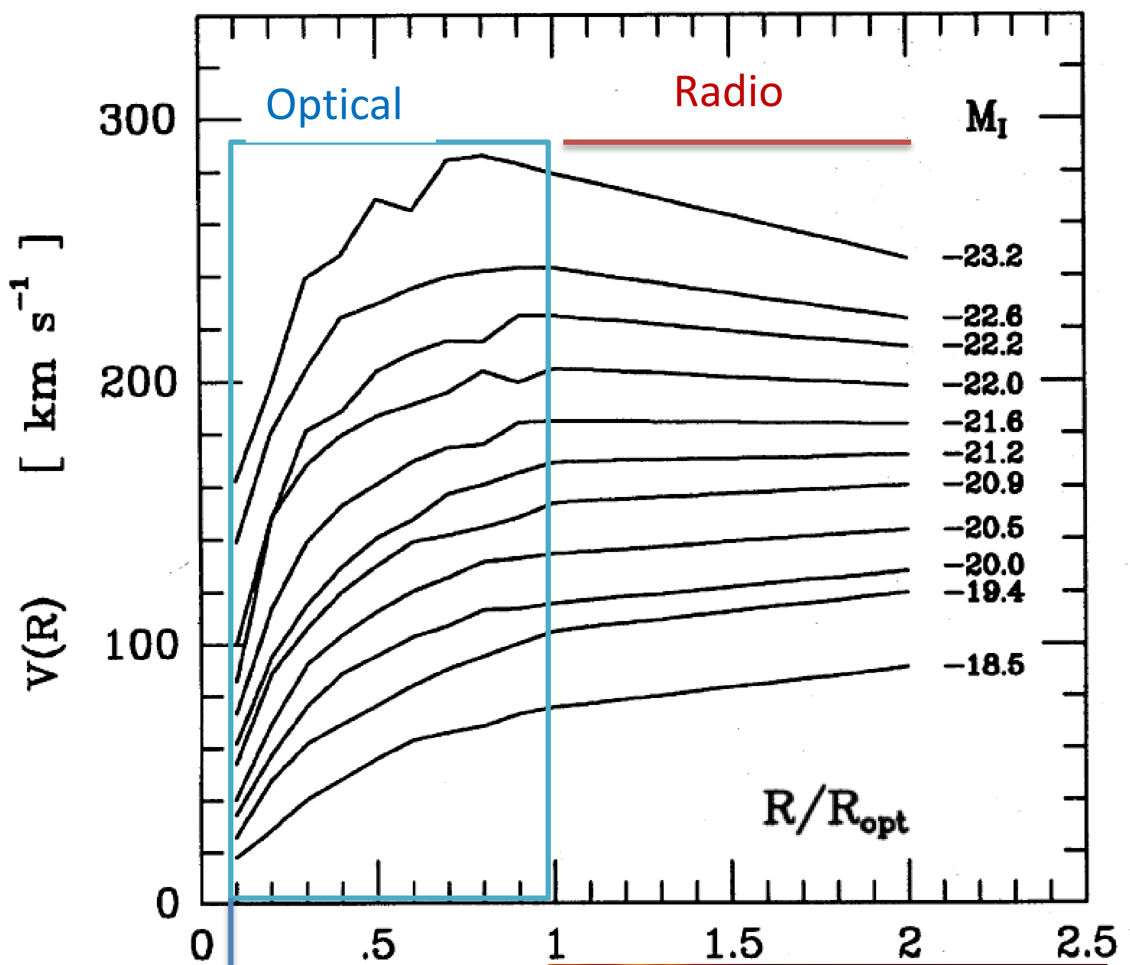


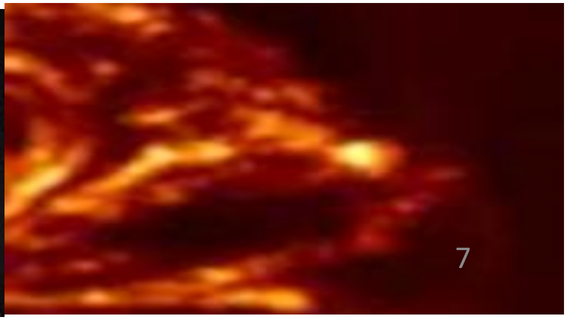
McGaugh 2014

The universal rotation curve

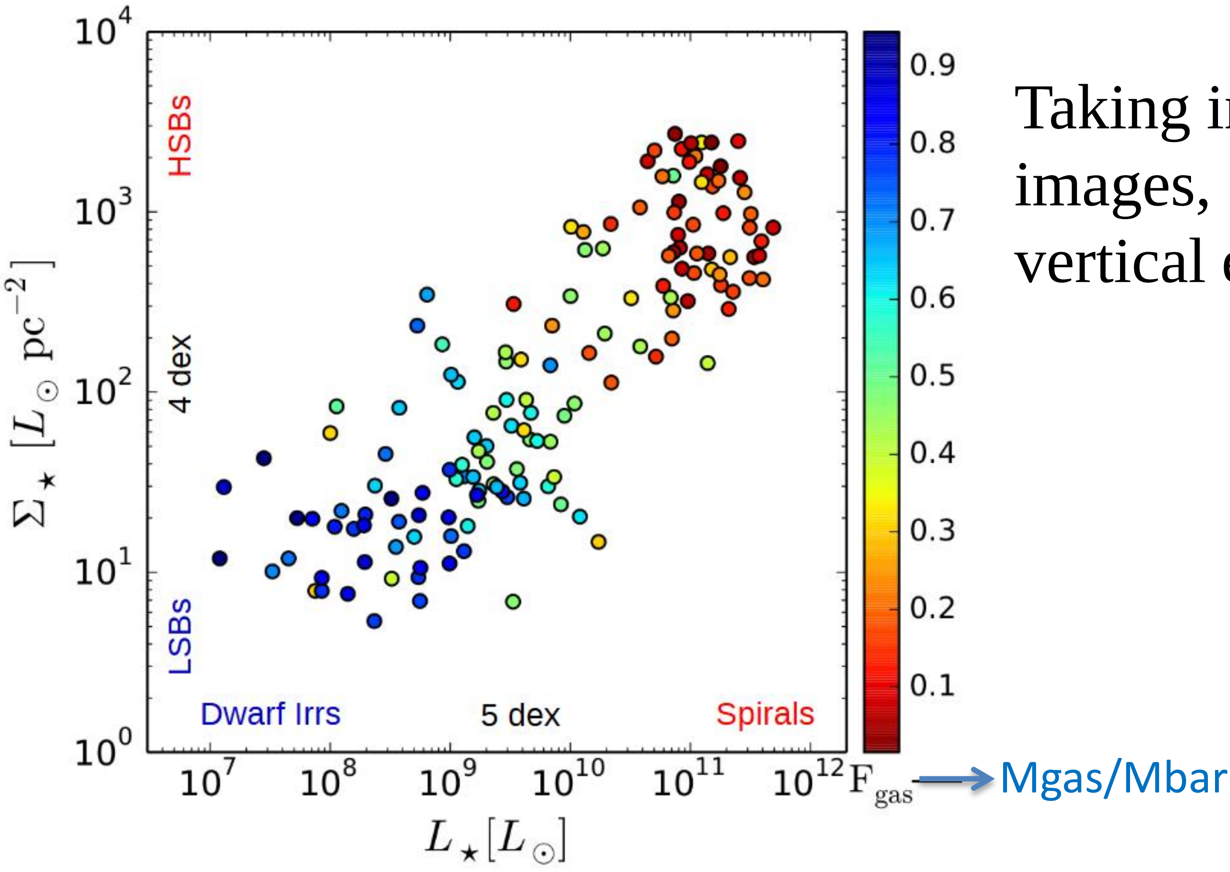
The total mass of dark halo
is not well known
Mass increases like R
Where does it stop?

Universality is obtained
if baryons determine
the total mass
distribution





RAR: the Radial Acceleration Relation

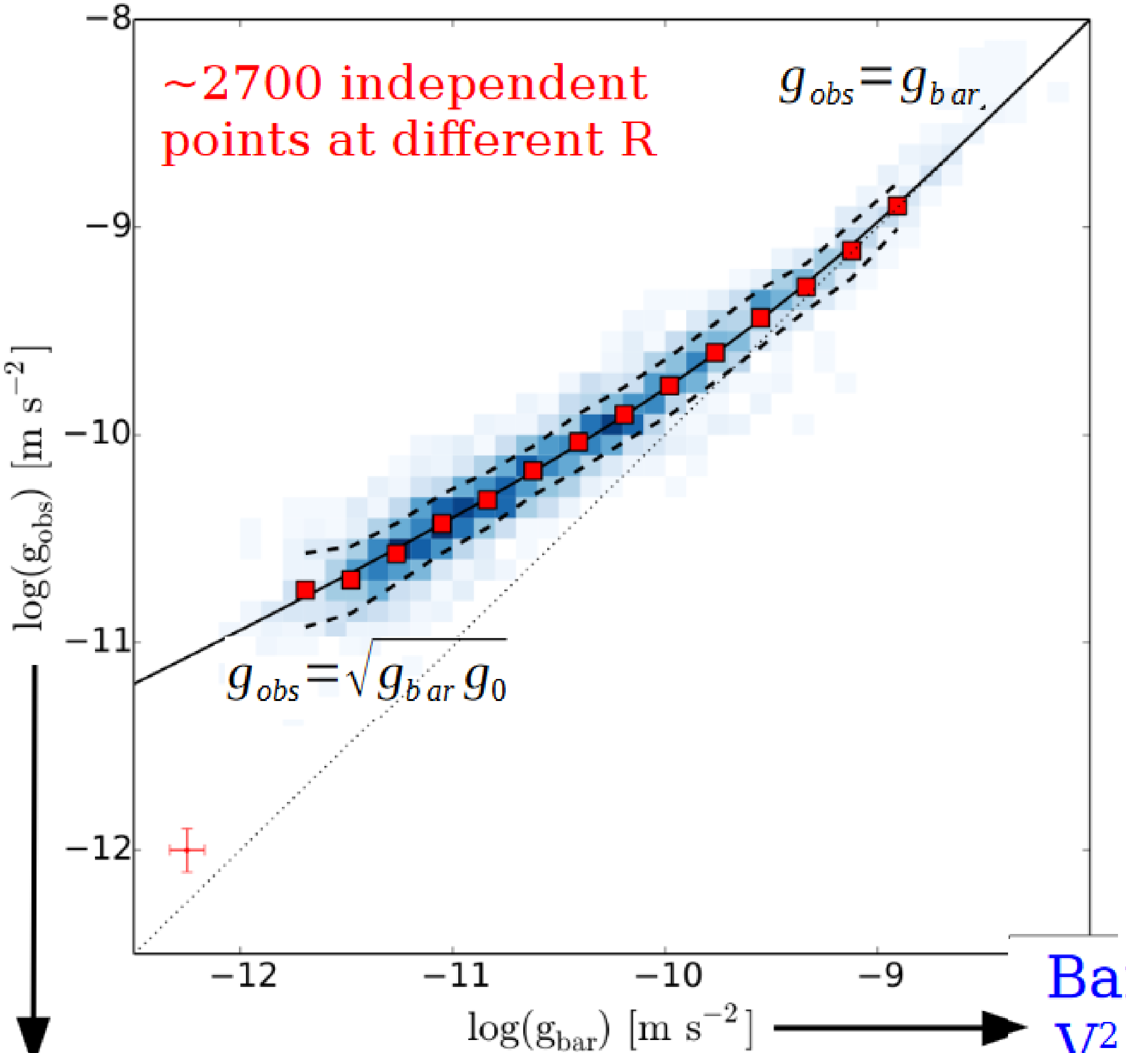


Taking into account multi-band images, ➔ M/L estimations vertical equilibrium, etc.

SPARC sample of 175 galaxies, with clean RC

Lelli et al 2016, 2017

RAR: the Radial Acceleration Relation



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

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

Where are the baryons?

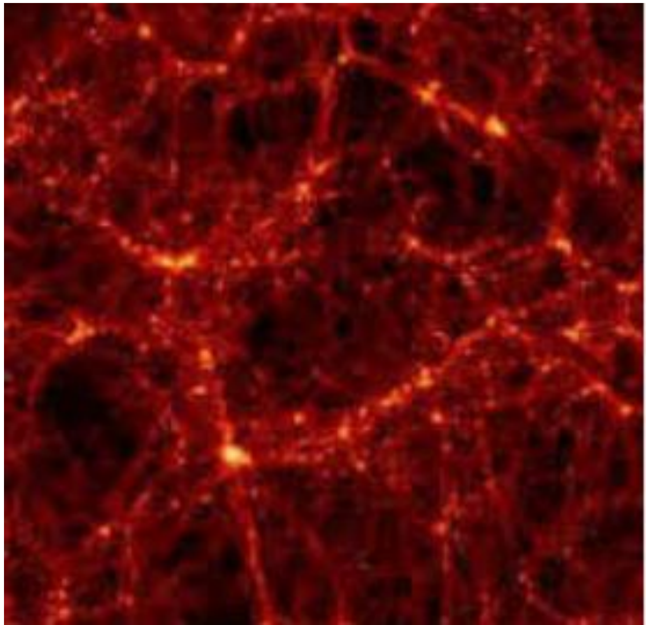
➔6% in galaxies (stars); 3% in galaxy clusters, X-ray gas

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

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

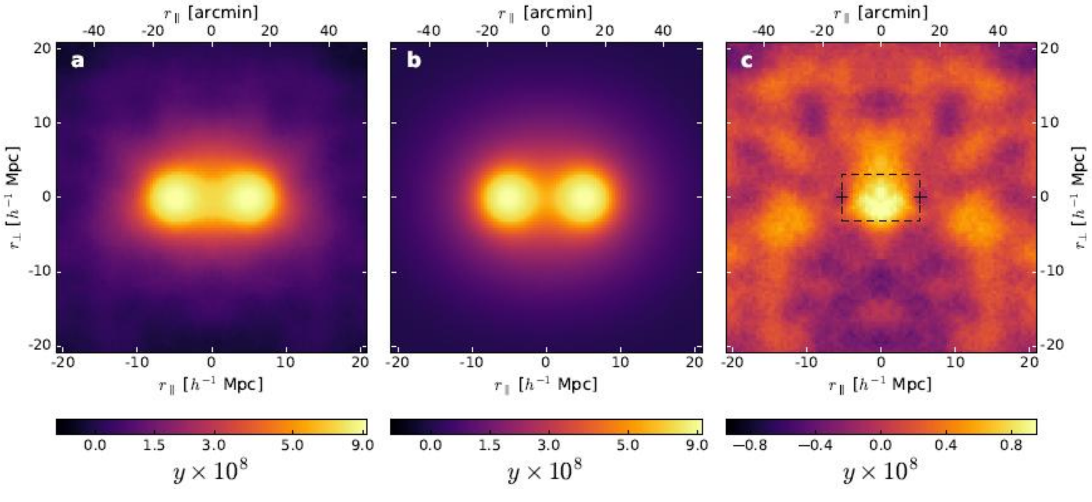
➔63% are not yet identified!

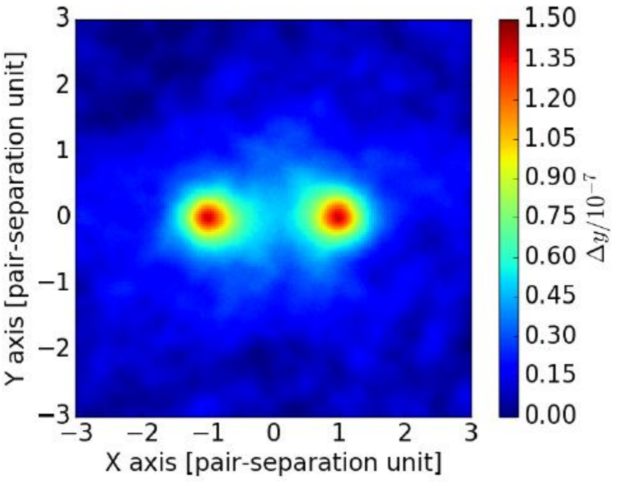
The majority are not in galaxies



Recent developments (SZ)

Tanimura et al (2017) and de Graaff et al (2017)
Stacking Planck data, between two massive red galaxies (LRG),
About 300 000 galaxies from the SDSS, ➔**5σ detection**
Each has a halo of about 10^{13} Mo,
Pair distance 5Mpc (halo of 1 Mpc)





De Graaff et al: Density contrast of 6 Tanimura et al Contrast of 3

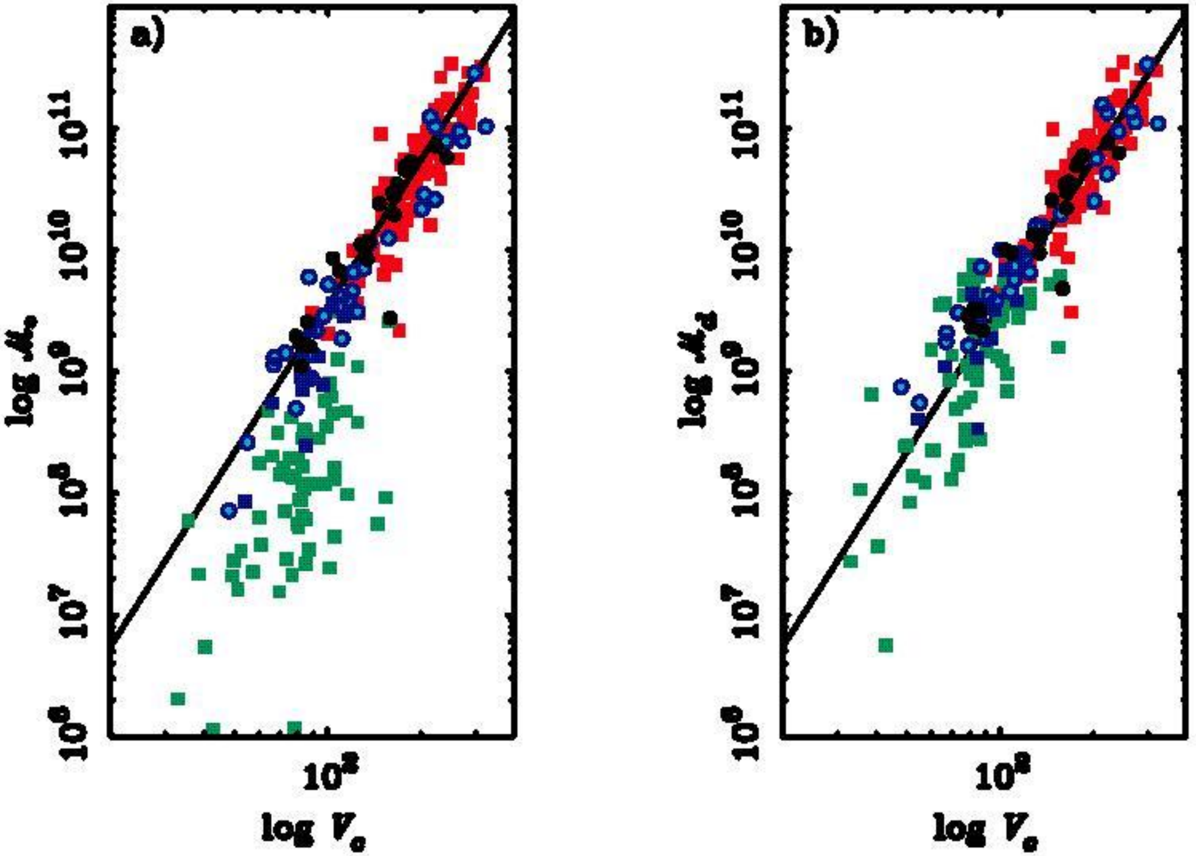
May be 30% of the baryons in the ionized phase

Tully-Fisher relation

Relation between maximum velocity and luminosity

For dwarf galaxies which have more gas than stars in mass

➔take into account the gas mass



Relation $M_{baryons}$ with V Rotation

$M_b \sim V_c^4$

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

Tully-Fisher relation

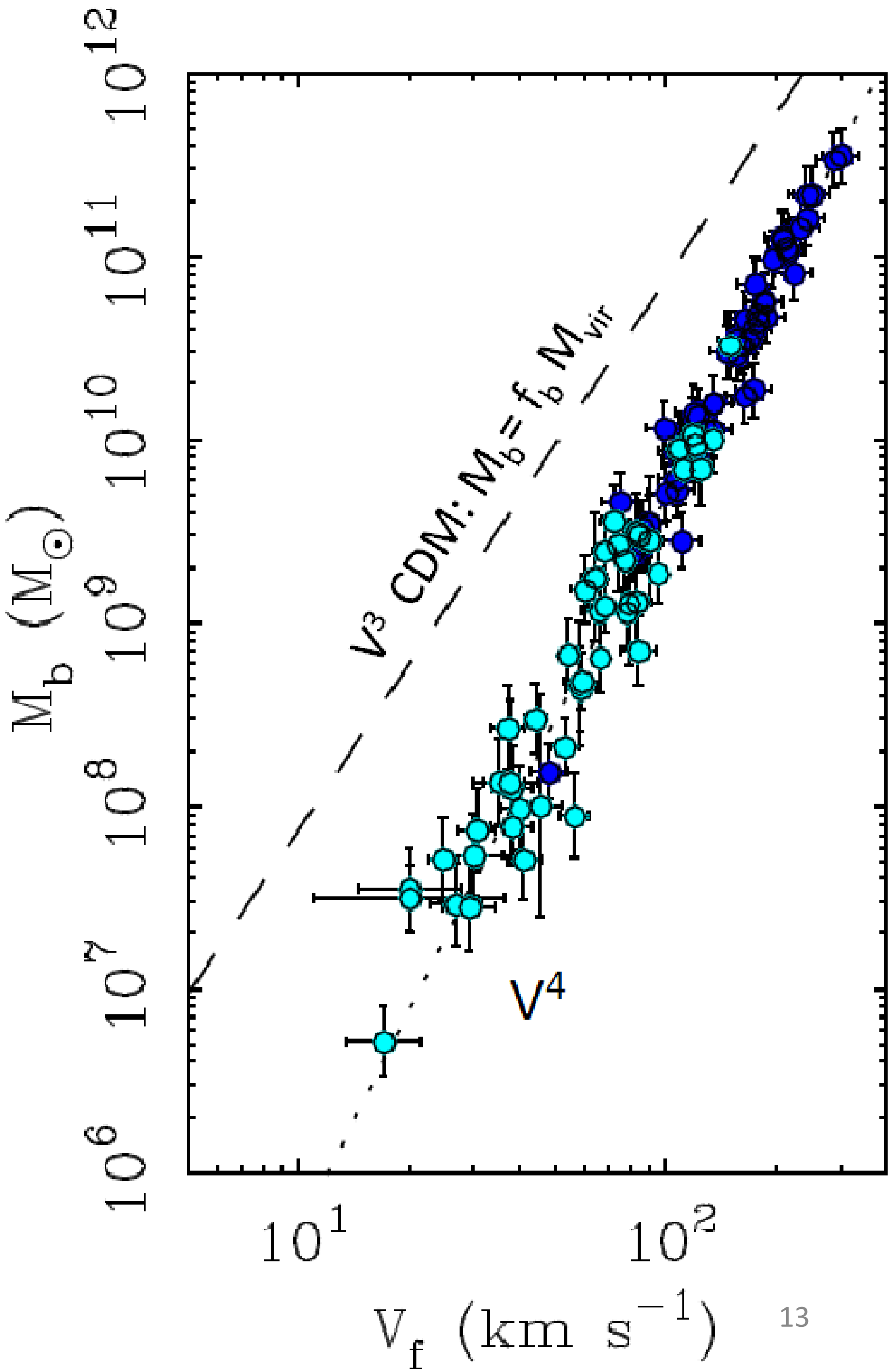
f_b universal fraction
of baryons= 17%

The prediction of the standard
 CDM model has a slope 3
$M_b \sim V_c^3$

Moreover, there are too many
 baryons in galaxies

In particular for small masses
by a factor 10-100

Famaey & McGaugh 2012



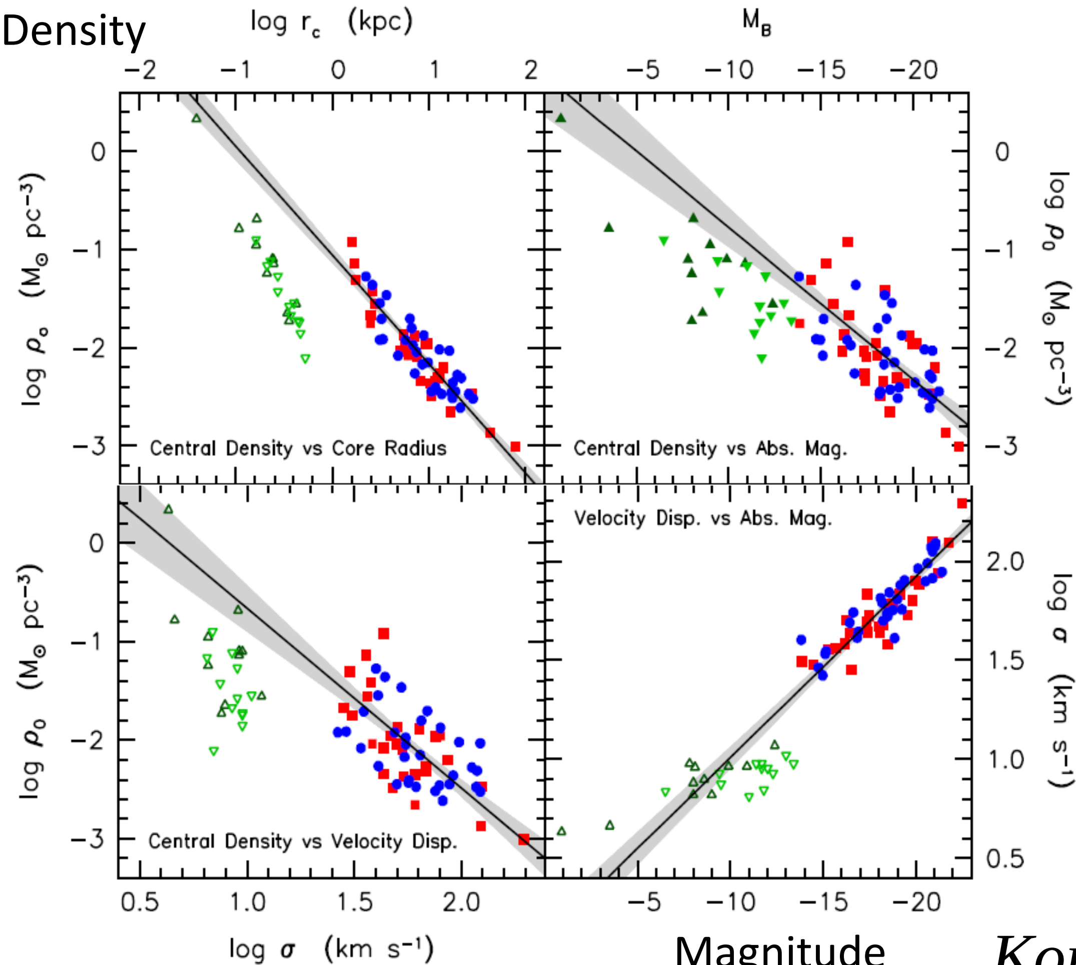
Scaling laws including dwarfs

DM parameters from a rotation curve decomposition, or Jeans equations

ITS Isothermal sphere $\sigma^2 = \left(4\pi G \rho_\circ r_c^2\right)/9$ $V_c(r) \sim r \quad r < r_c$

$V_c = cst \quad r > r_c$

Density



Magnitude

Velocity dispersion

Green: dSph△ dIm ▽

Red & blue Sc-Im

Blue Isothermal sphere halos

Red pseudo-isothermal sphere

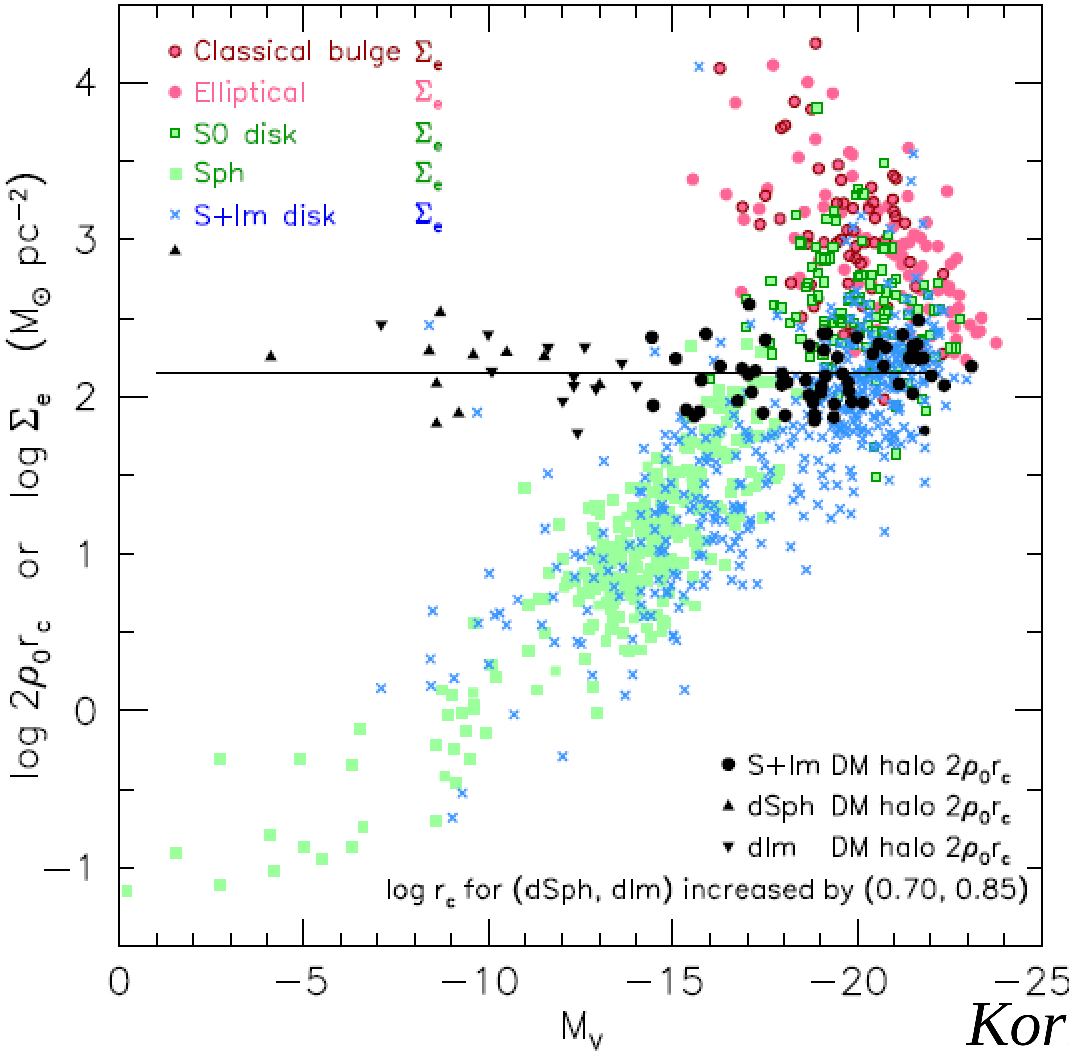
➔Possible to drive back dSph and dIM on the curve assuming baryon loss

$\rho_o \sim 1/r_c$

Kormendy & Freeman 2016

Constant surface density for DM?

If the dwarfs are driven back on the curve (M_B, r_c, σ)



However dwarfs are multiple
What about UDG?

Interesting to see that the stellar surface density Σ* changes behaviour from non-dominant to dominant
➔Small systems brighter

Kormendy & Freeman 2016

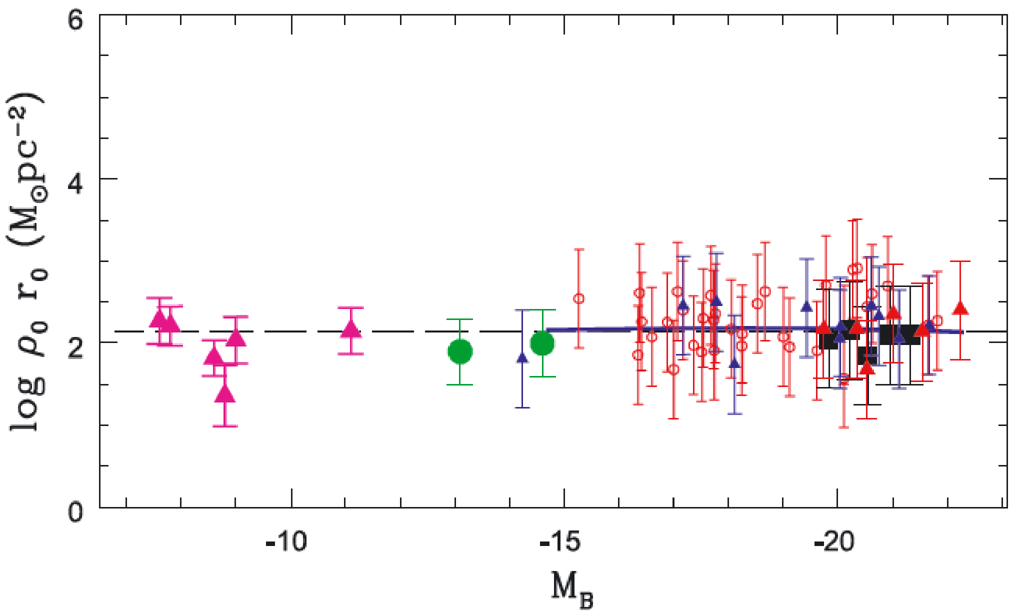
Constant DM surface density

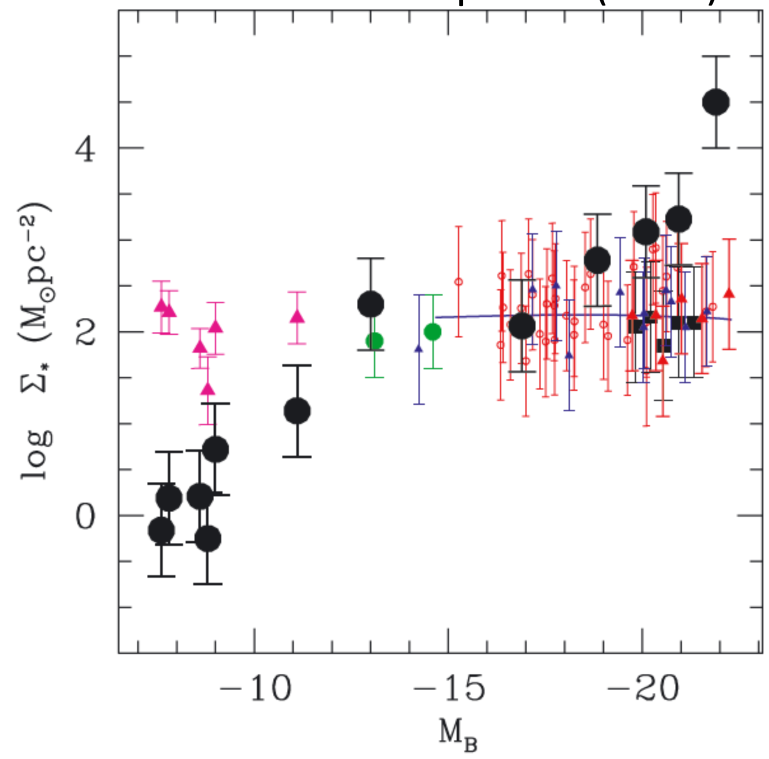
1000 spiral + dwarf galaxies *Donato et al 2009*

Sc, Sm, dIm, weak lensing..

$$\rho(r) = \frac{\rho_0 \, r_0^3}{(r + r_0)\left(r^2 + r_0^2\right)}$$

Burkert profile (1995)

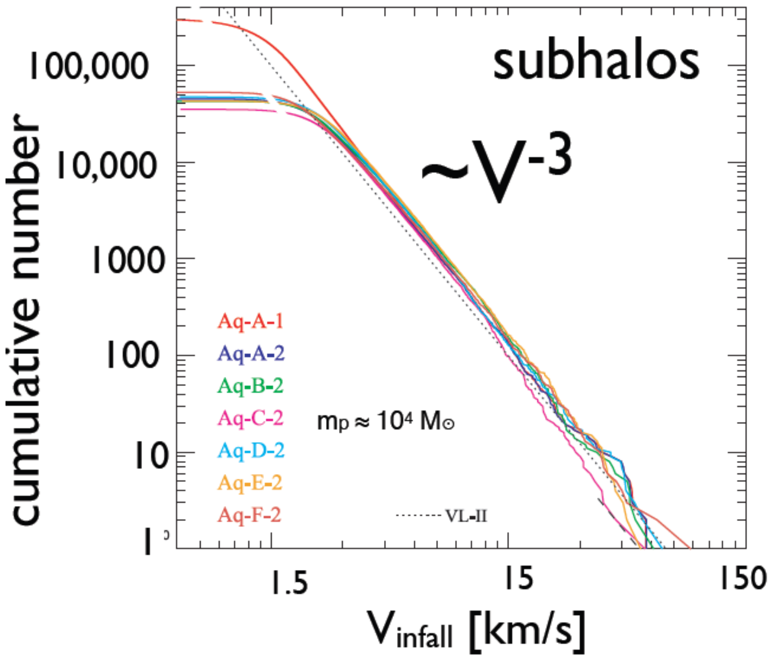




Σ_{DM}~150 Mo/pc^2

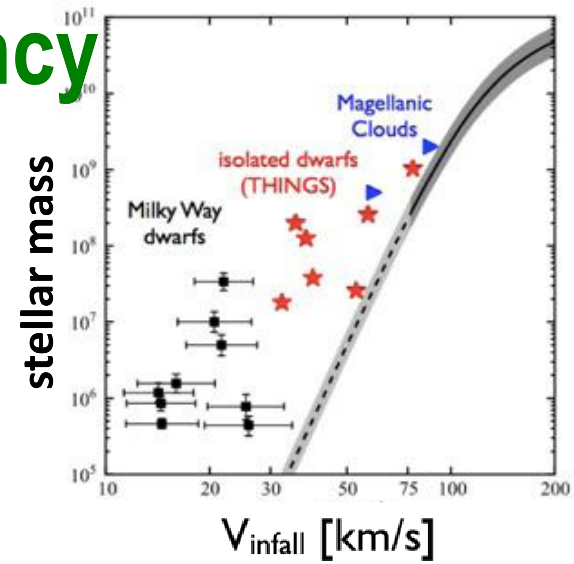
Contrary to the stellar surface density which increases with M

Missing satellites and SF efficiency



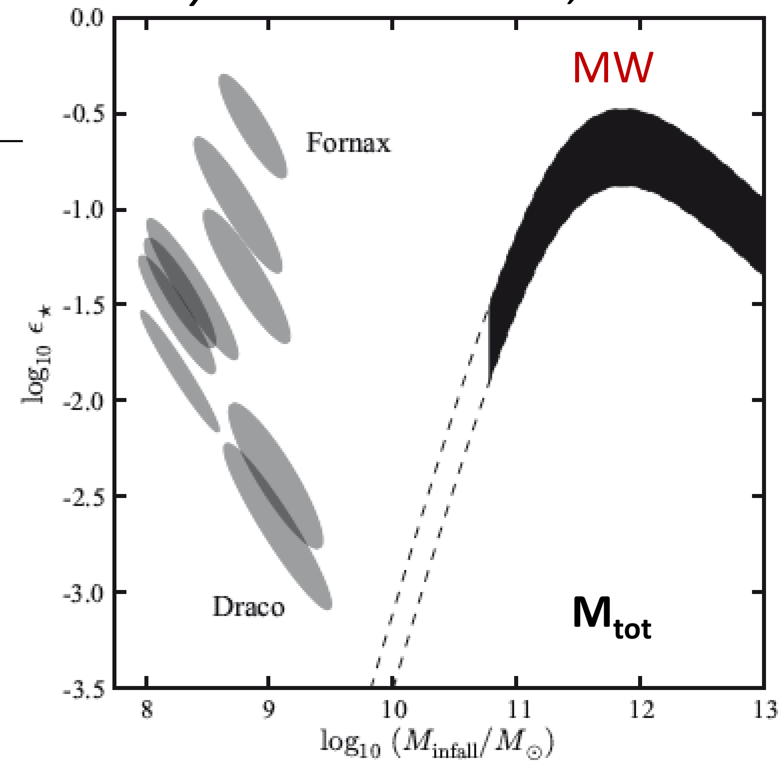
Springel et al. 2008

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



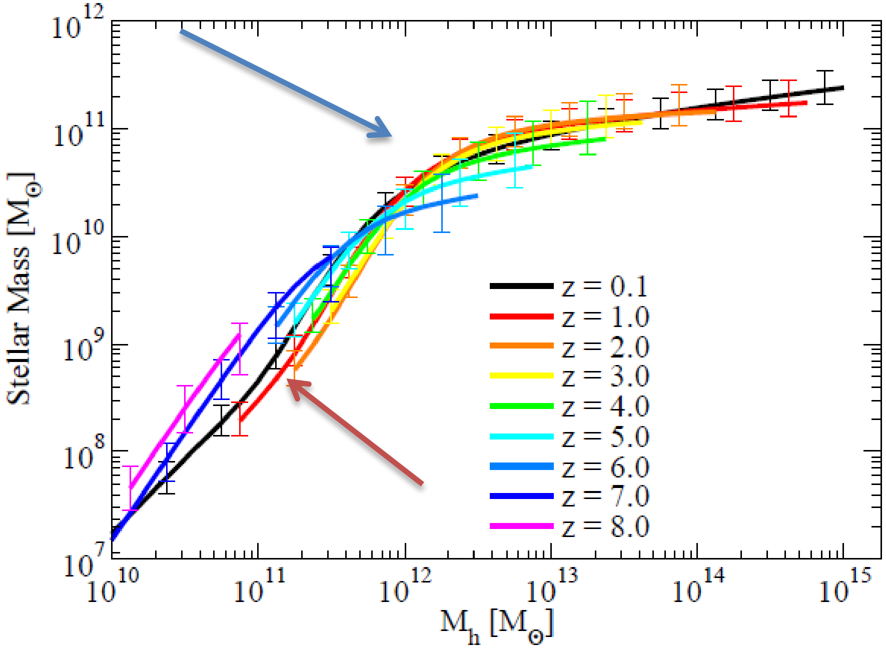
Boylan-Kolchin et al , 2011-12

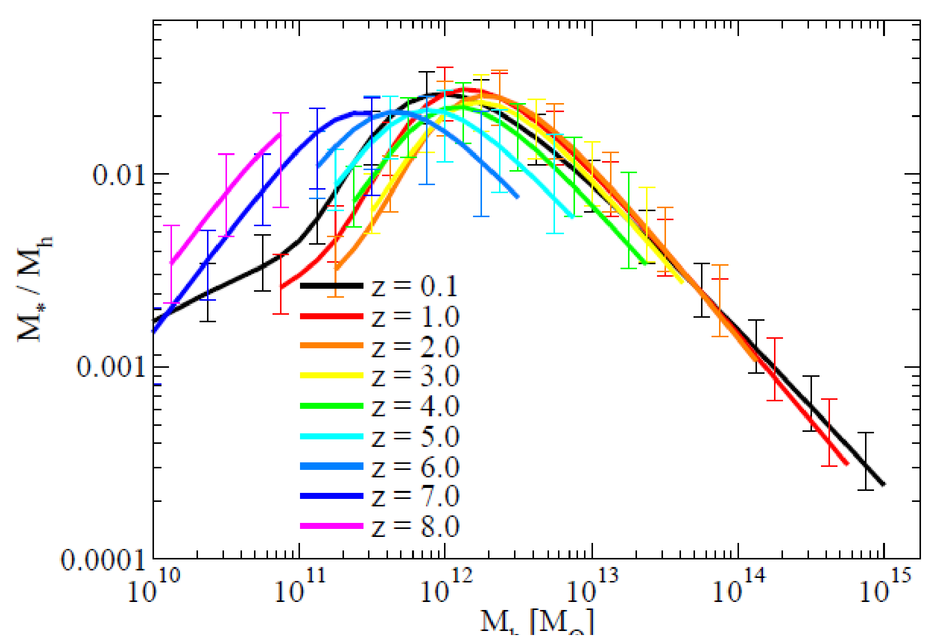
$\frac{M_*}{f_b M_{DM}}$



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)

Dwarfs and DM as a function of redshift



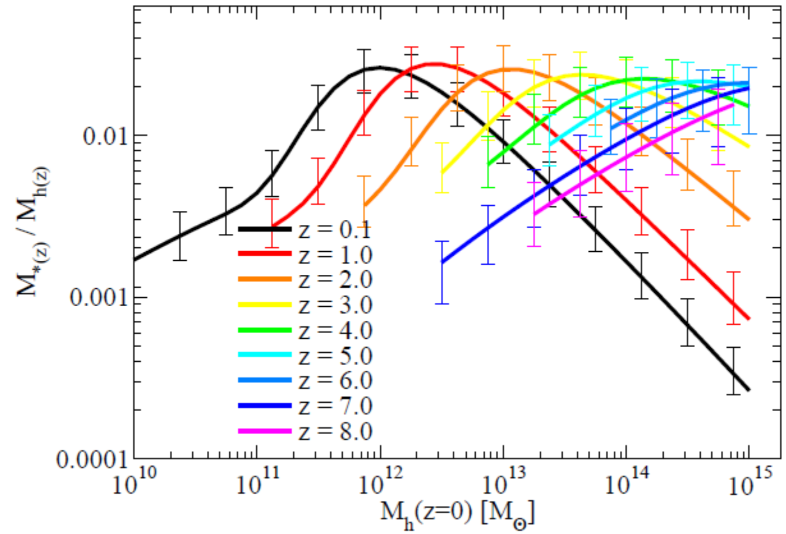


Massive halos form stars actively in the past, then drop after a peak

Dwarfs today are less active

Always the same peak

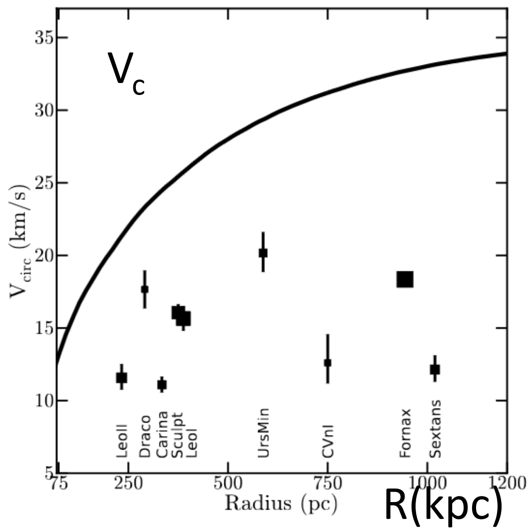
The most efficient Mh=10^{12}Mo



Behroozi et al 2013

Galaxies « Too Big To Fail » (TBTF)

Spheroidal dwarfs of the Local Group, $M_* \sim 10^6$ Mo, Vcir vs R
Simulations predict dense cusps, which do not correspond to any dSph observed (*Boylan-Kolchin et al 2012*)



Repeated epidodes of ejection by supernovae have been simulated, to destroy halos

A single ejection of the same total mass is more efficient

40 000 SN are required with 100% efficiency

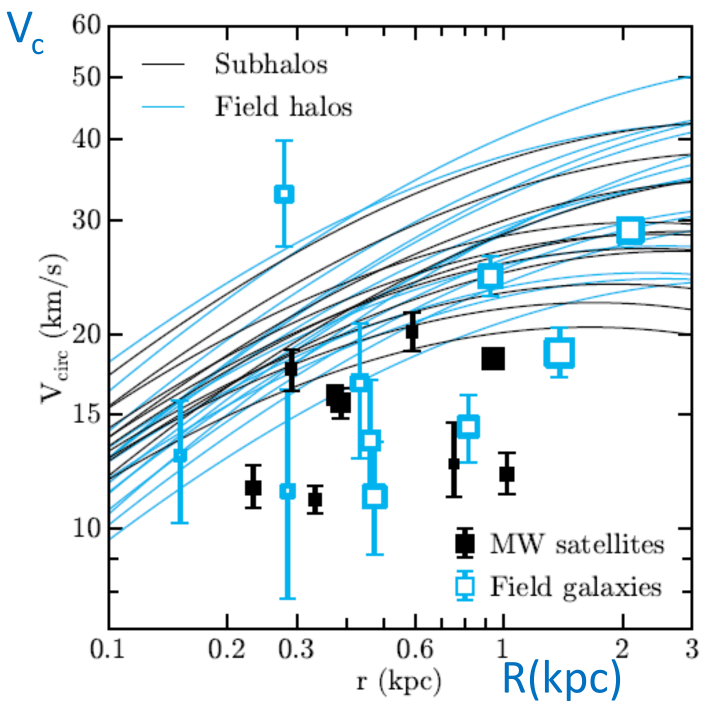
➔ SN feedback cannot solve the problem

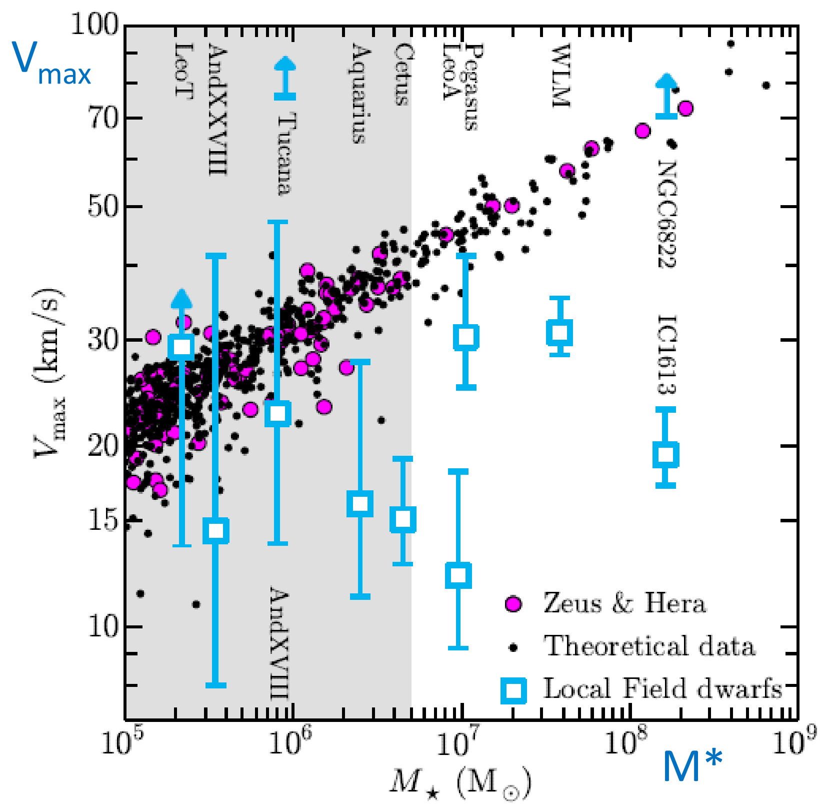
Garrison-Kimmel et al 2013

Comparison with simulations

ELVIS: series of 48 simulations representing the MW and satellites within 300kpc, at least 25 satellites TBTF V> 25km/s, where star formation cannot be avoided through reionisation $M^* > 10^6 M_\odot$

Vmax not related to M* ➔ **no tidal effects, nor ram pressure**

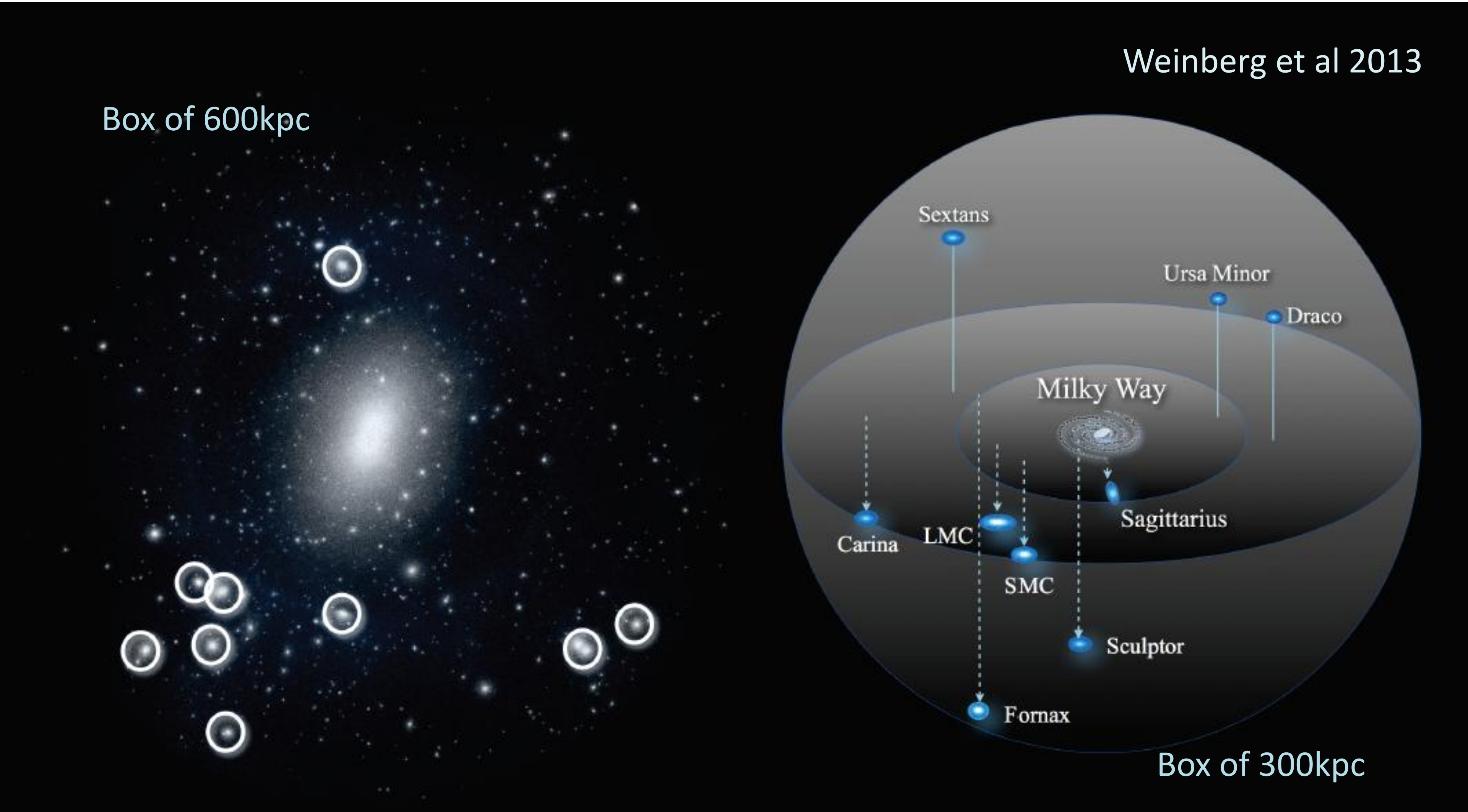




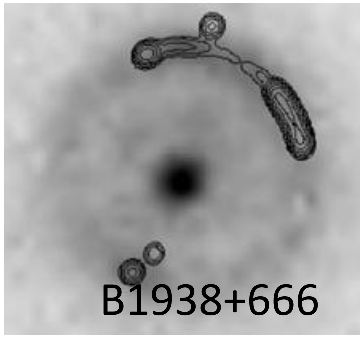
Garrison-Kimmel et al 2015

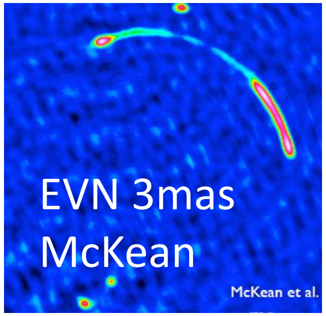
The Milky Way satellites

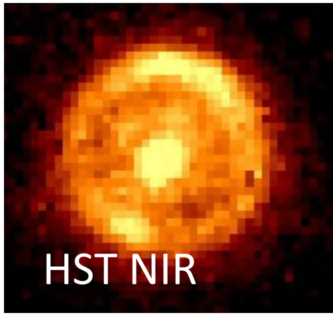
Number of satellites, concentration and velocity dispersion
DM Profile – Satellites too close (MW, Andromeda, etc..)



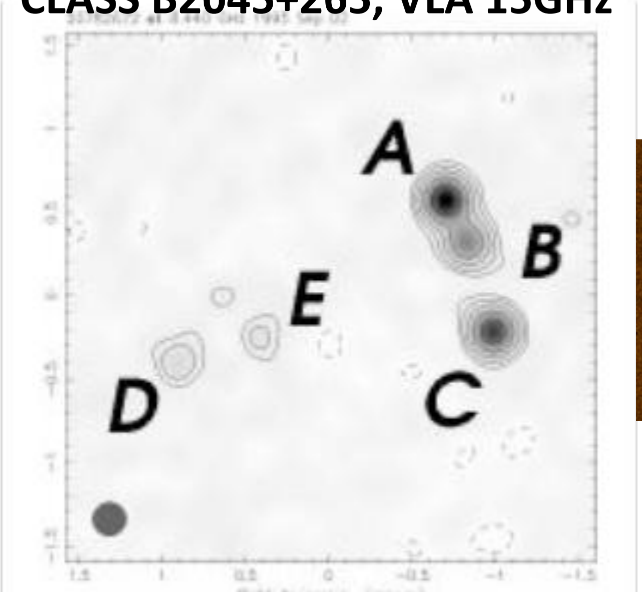
Lensing to detect sub-haloes



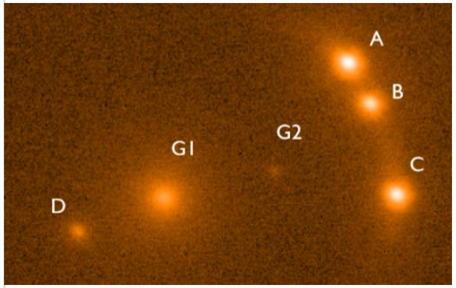




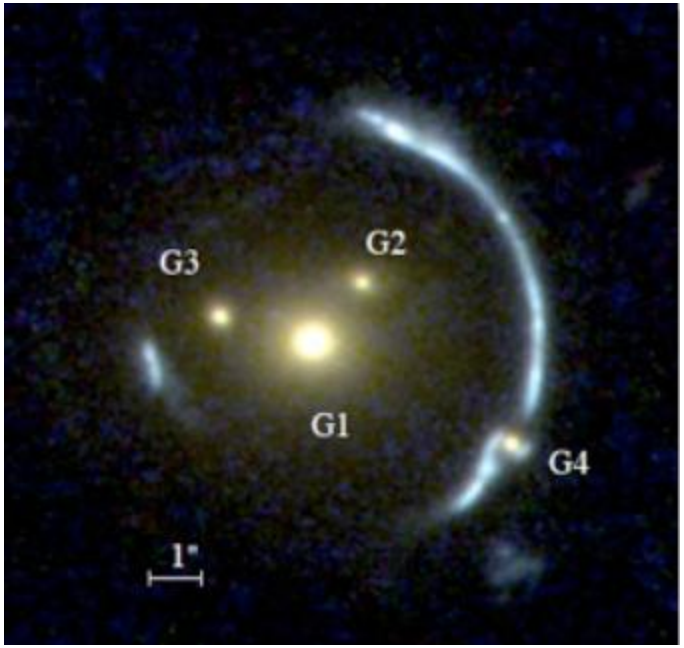
CLASS B2045+265, VLA 15GHz



NIR, Keck



Dwarf G2: lens



E=G1

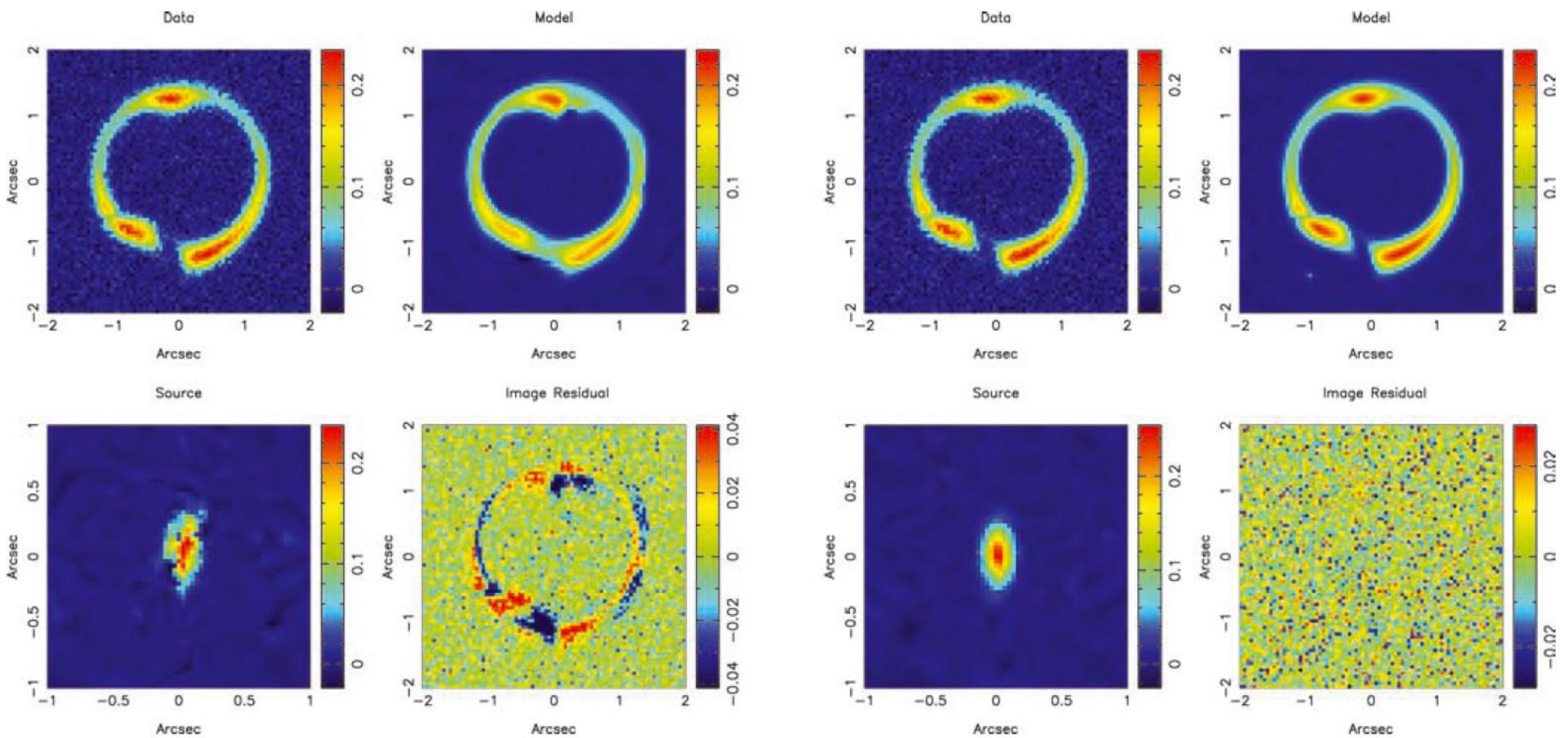
Detect sub-structures as anomalous flux ratios between images

sub-structures seen as brightness anomalies

➔Until now: only bright dwarfs found
No need of dark halos

Sub-structure:
source or lens?

Degeneracy source-lens



Smooth Potential

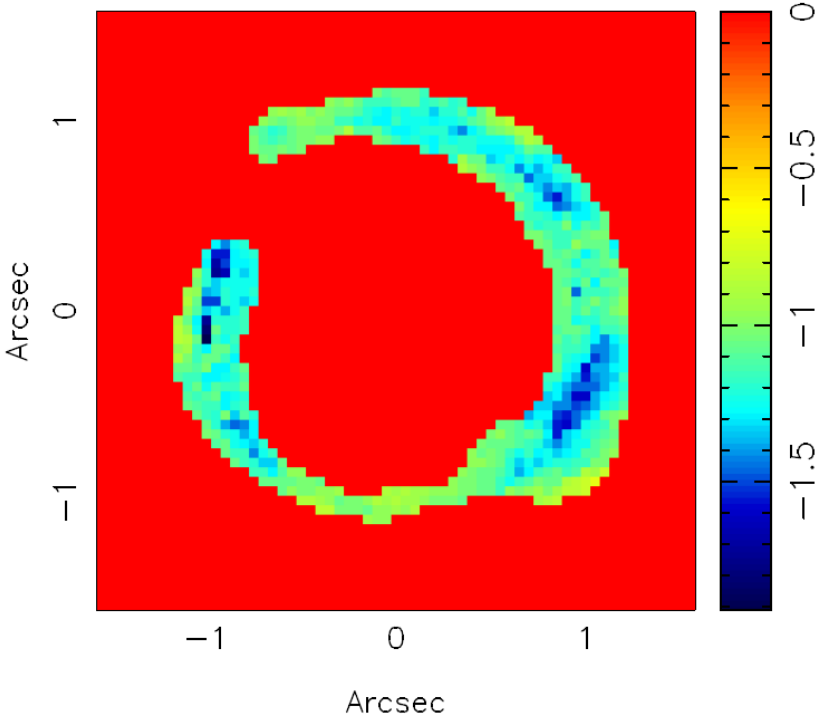
$M_{sub} = 10^9 M_\odot$

Possible to detect $M > 10^7 M_\odot$ on the Einstein ring, or $M > 10^9 M_\odot$ close to the ring

Vegetti et al 2009

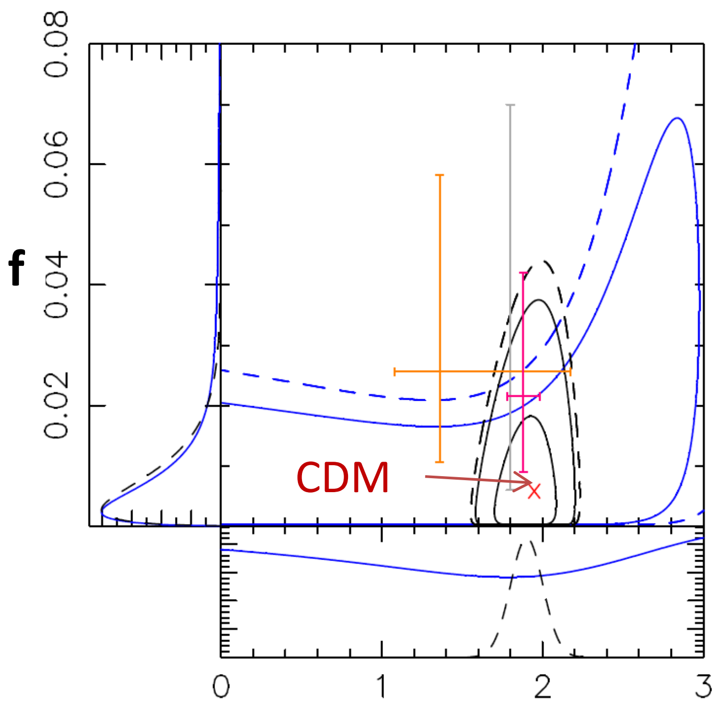
Present Constraints, 12 Einstein rings

The smallest M detectable,
unit $10^{10}M_\odot$



SDSS J0252+0039, Vegetti et al 2014

No « dark » structure detected,
One bright sub-structure detected
$<z>=0.2$, $<\sigma> = 270$km/s

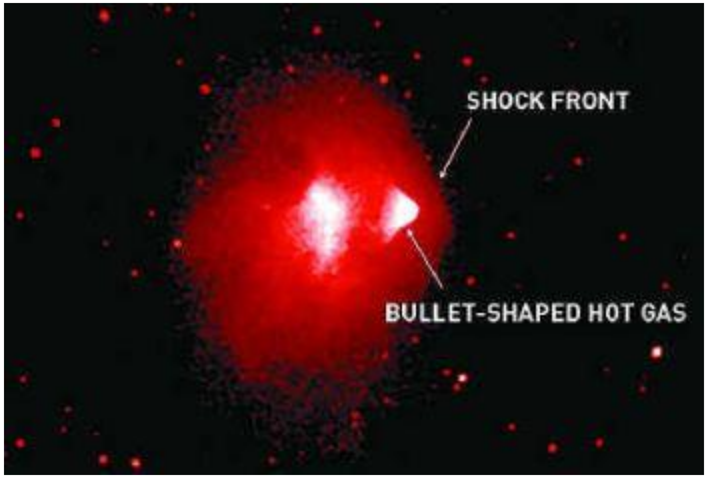


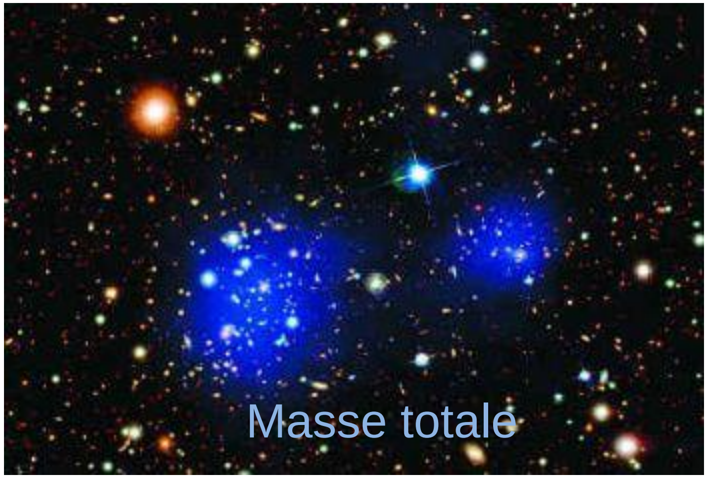
α= pente de la fonction de masse

f< 0.006 mass fraction in the
sub-structures a < 1.90

The bullet cluster

Gas X





Rare case of violent collision, allowing to separate components

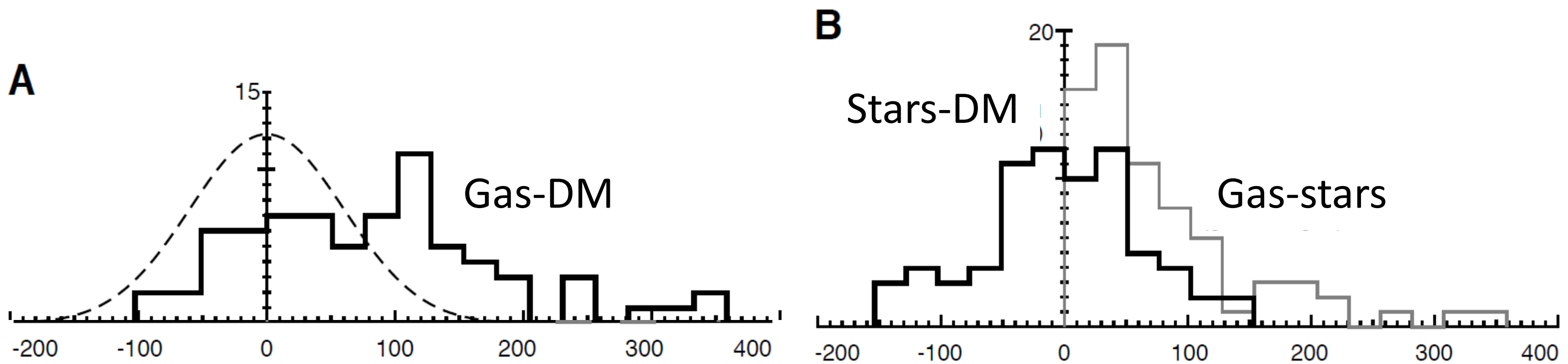
➔ Limit on $\sigma_{DM}/m_{DM} < 1\ cm^2/g$

For modified gravity, need of non-collisionnal matter: neutrinos or dark baryons

V=4700km/s (Mach 3)

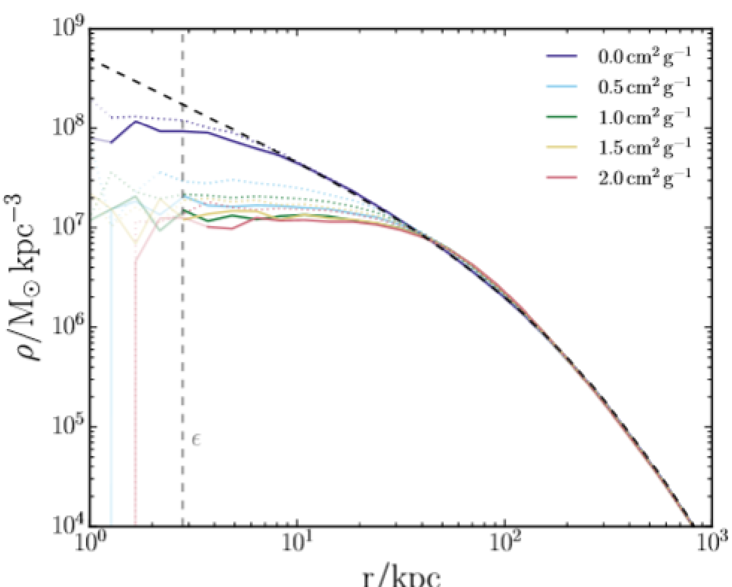
MCC: Merging cluster collaboration

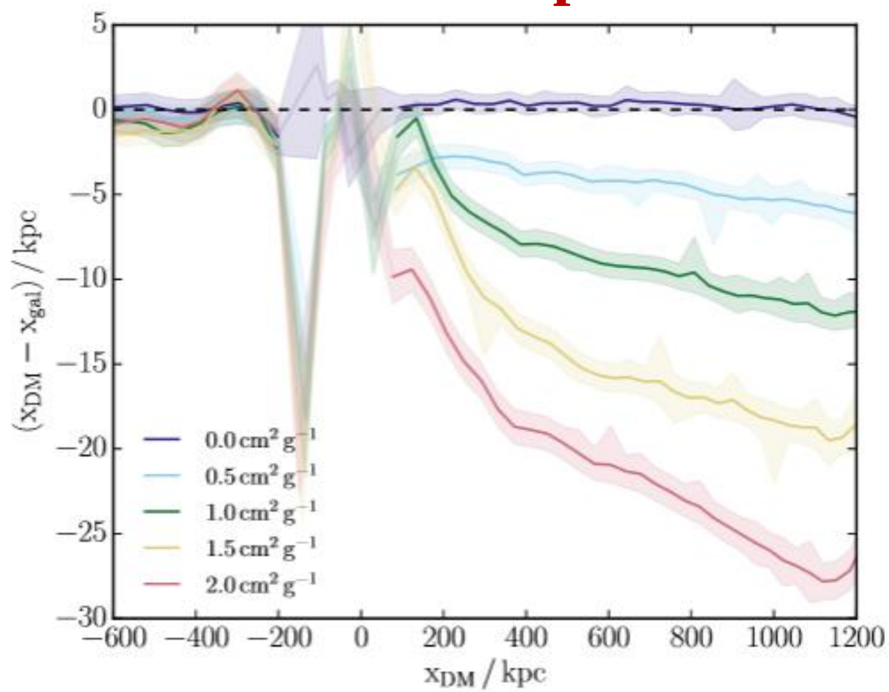
How many cases observed? Now a sample of 72
Including lower mass clusters and groups, *Harvey et al 2015*
$\sigma/m < 0.47\ cm^2/g$



SIDM and the Bullet cluster

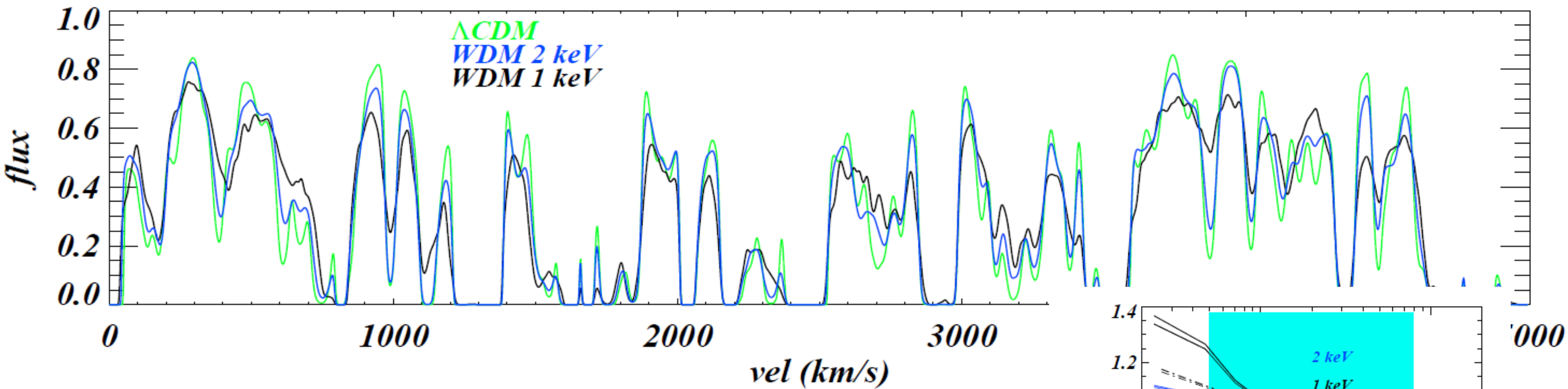
Robertson et al 2017, new Gadget3 simulations, with gas and SIDM
➔Offset between stars and DM, but depends on the way to measure the offsets
The upper limit on the cross section was overstated
Instead of $\sigma/m < 1.25$ cm^2/g , now $\sigma/m < 2$ cm^2/g
Gas is also introducing asymmetries
➔ Moreover in anisotropic σ(v), the **DM offset can be supressed!**
Then no limit on σ



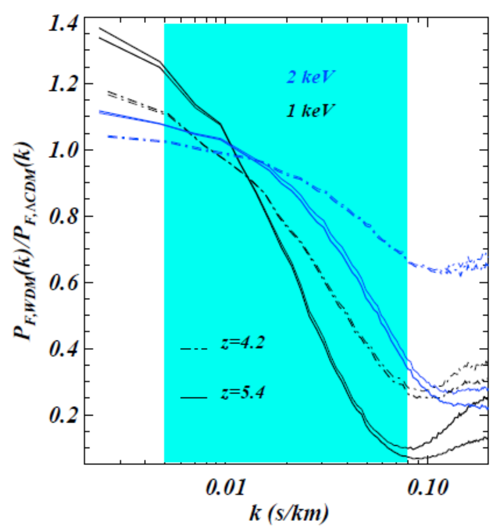


Ly-α: constraints on WDM

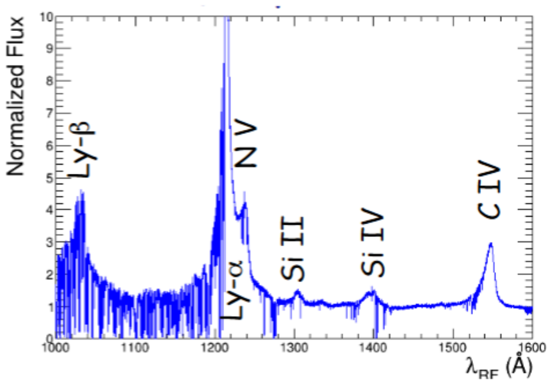
25 quasars z >4: HIRES spectra on Keck, *Viel et al 2013*
+ MIKE (Magellan)
Lyman-α forest comparison with simulations
m_{WDM} > 3.3 kev (2σ)

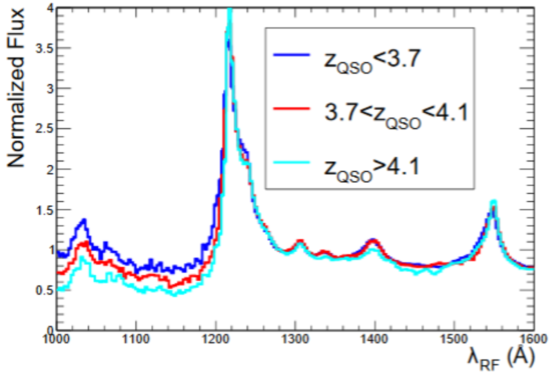


Power spectrum 1D
Predicted by models



Sterile Neutrinos as dark matter





BOSS, SDSS-III
XQ-100, VLT-Xshooter

$\Sigma m_\nu < 0.8$ eV
For ΛCDM models

For ΛWDM models, $\mathbf{m_X > 4.17}$ **keV** early decoupled thermal relics
$\mathbf{m_s > 25}$ **keV** non-resonantly produced right-handed neutrinos
Yeche et al (2017)
Combining with the HIRES data from Viel et al, , $\mathbf{m_X > 4.65}$ **keV**
and $\mathbf{m_s > 28.8}$ **keV**

X =DW neutrinos produced at T~100MeV
RPSN distributed with lower momenta than the NRP ones

Primordial Black holes as DM

$\mathbf{R_S = 2GM/c^2 = 3(M/M_O)\ km \Rightarrow \rho_S = 10^{18}(M/M_O)^{-2}\ g/cm^3}$

Small black holes can only form in early Universe
cf. cosmological density $\rho \sim 1/(Gt^2) \sim 10^6(t/s)^{-2} g/cm^3$

➔PBHs should form with horizon mass at formation $M_{hor}(t)$ in ct
$M_{PBH} \sim c^3t/G = 10^{-5}$g at 10^{-43}s (minimum)
10^{15}g at 10^{-23}s (evaporating now)
$1M_O$ at 10^{-5}s (maximum)

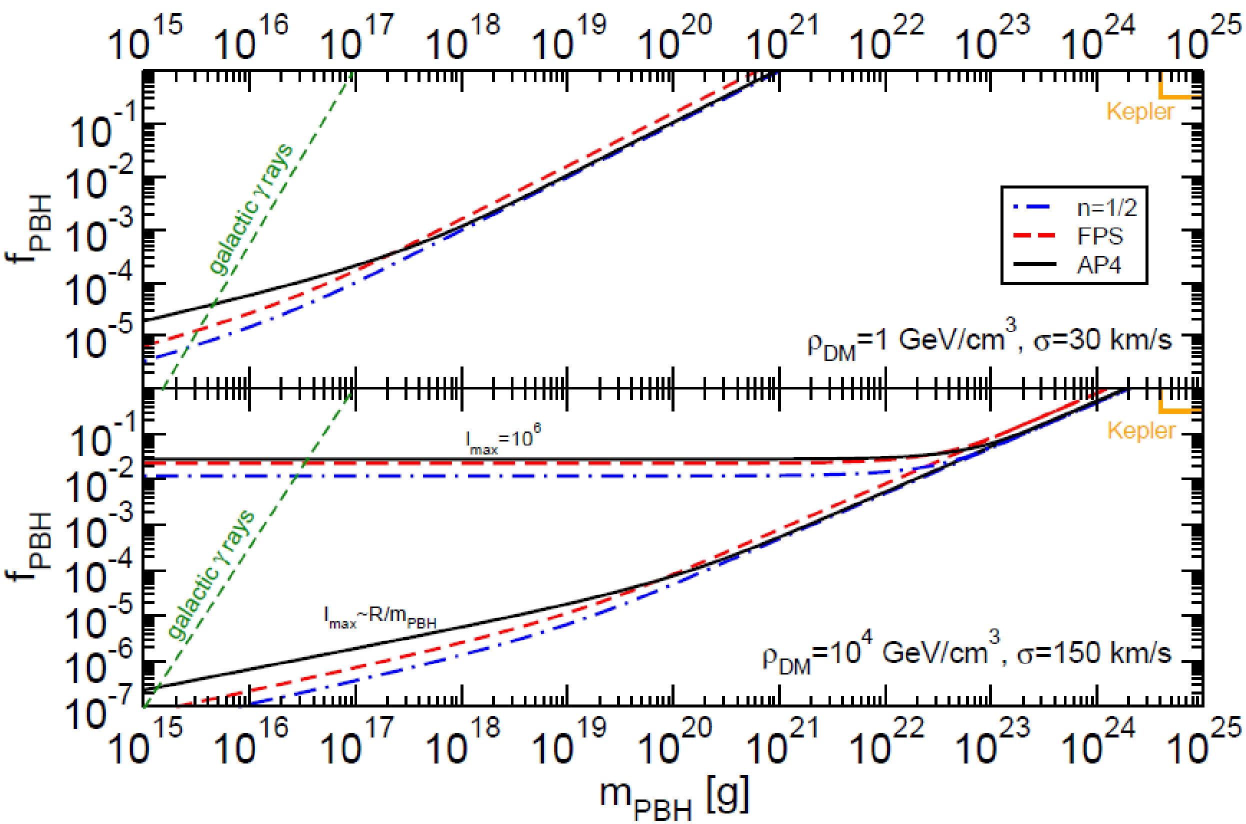
PBH formation requires strong inhomogeneities in the early universe
Inflation, and recollapsing local regions
+phase transition, bubble collisions, collapse of strings or domain walls

e.g. Carr et al 2010, 2016

Exclusion of the last mass window for PBH as DM

Encounter between a NS and the PBH
➔ Much more energy than for a star

$$\Delta E = \frac{m_{\rm PBH}^2}{R}\frac{2\gamma}{(1-n)}l_{\rm max}^{1-n}$$



n ~0.5
γ~1 depends on EOS

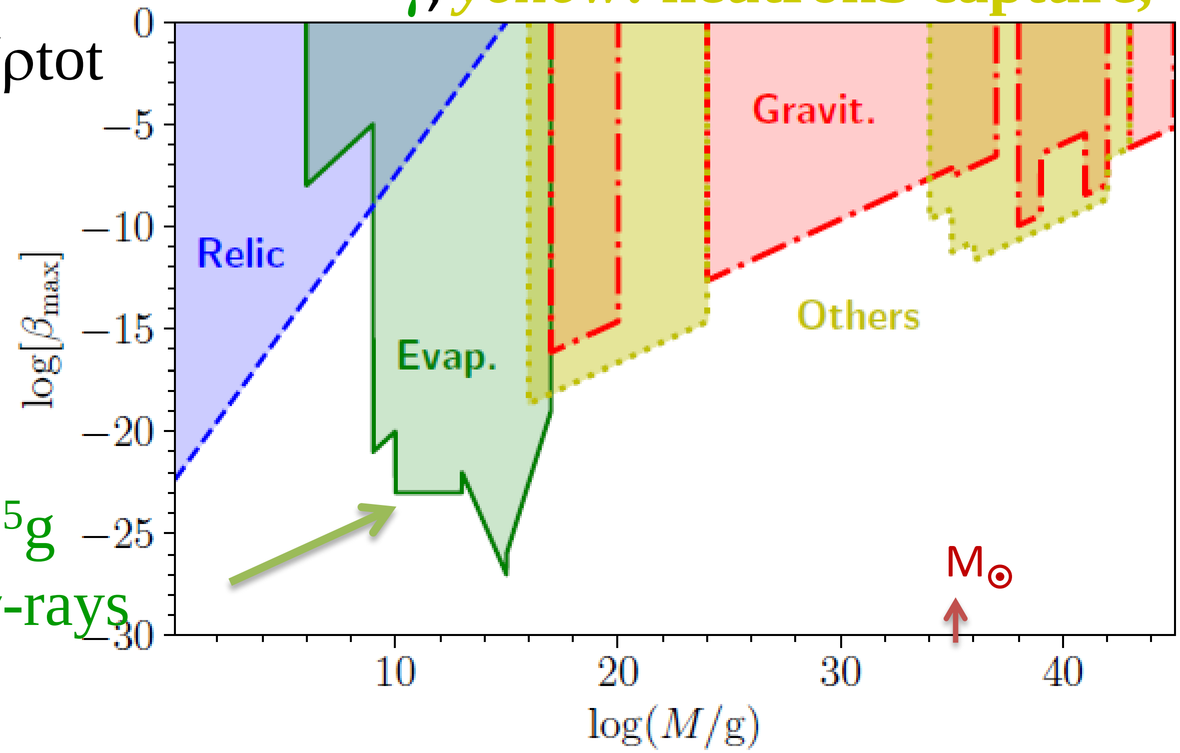
Kepler microlensing

Pani & Loeb 2014

Primordial Black holes

γ, *yellow*: neutronS capture, GW

β = ρPBH/ρtot



NS destroyed by the PBH
Capela et al 13

GW emitted in hyperbolic encounters
Garcia-Bellido 17

For M~10^{15}g too many γ-rays produced

Since PBH form in the radiative era, they can be considered as non-baryonic, and =CDM

However, their mass is limited by MACHOS, EROS experiments

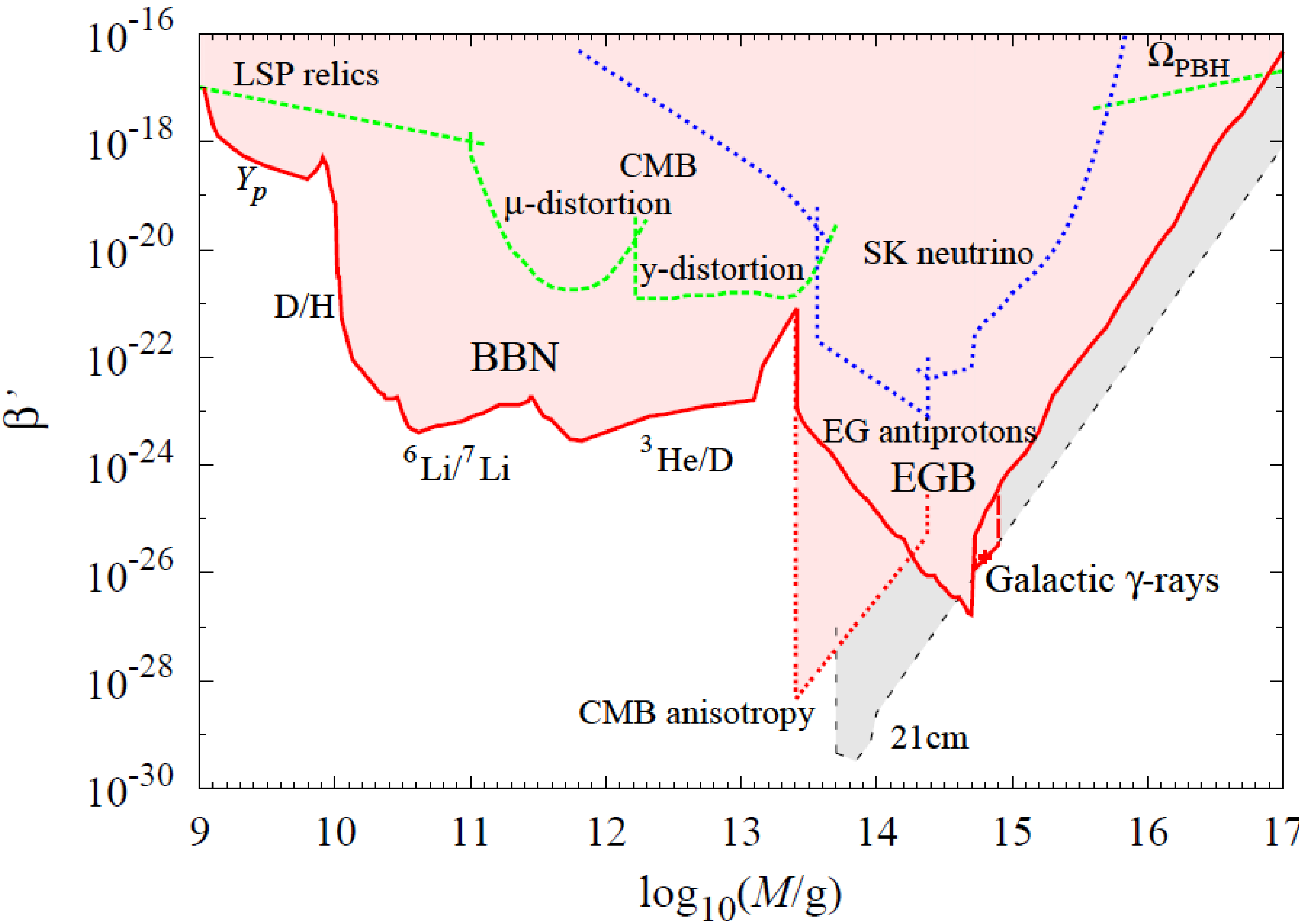
Small masses evaporate and create perturbations not seen in the CMB

Planck-mass relics of evaporation?

Gutierrez et al 2017

Constraints from the BBN, CMB..

LSP =Lightest super-symmetric particle (SUSY, SUGRA) formed in the evaporation of PBH

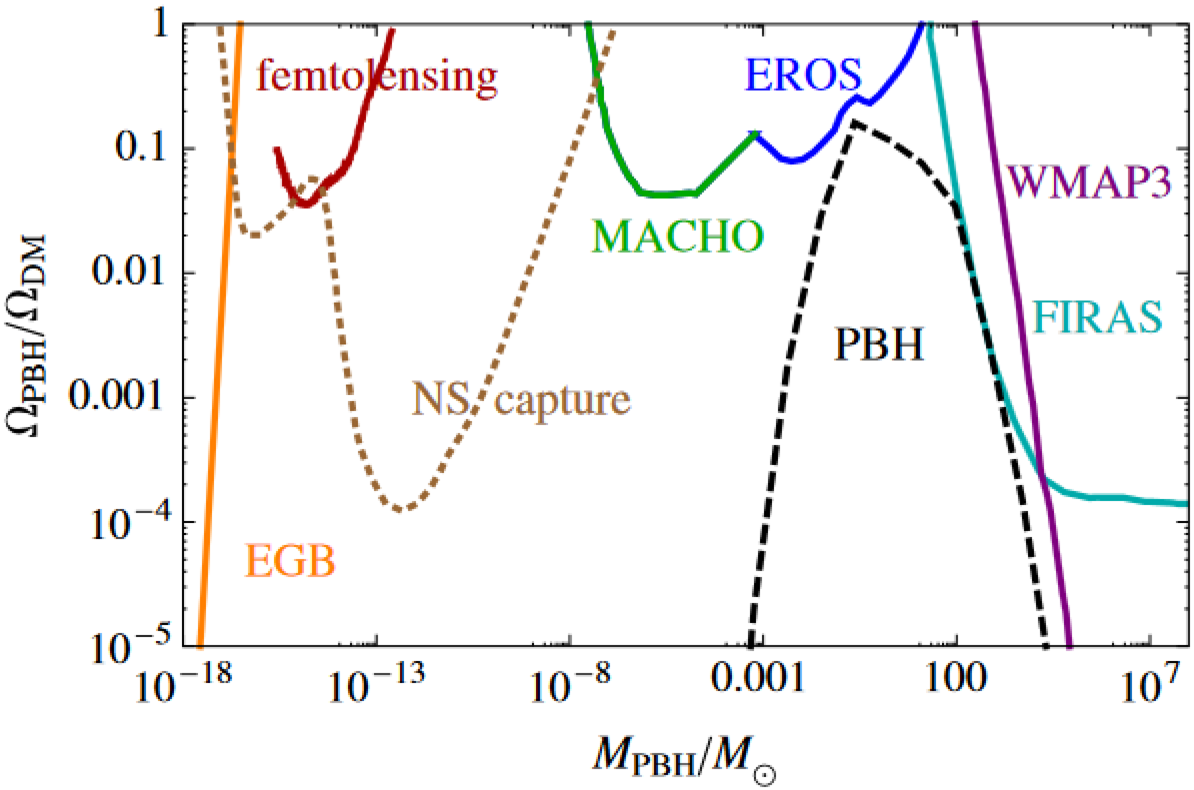


BBN, LSP relics
CMB distortions
Neutrino relics
Extragal cosmic rays
Gamma-rays

Carr et al 2010

Specific scenarios for PBH

Only a very constrained IMF for PBH is possible, but the spectrum is very narrow. In that case, constraints from CMB distortion are severe (Gutierrez et al 2017)

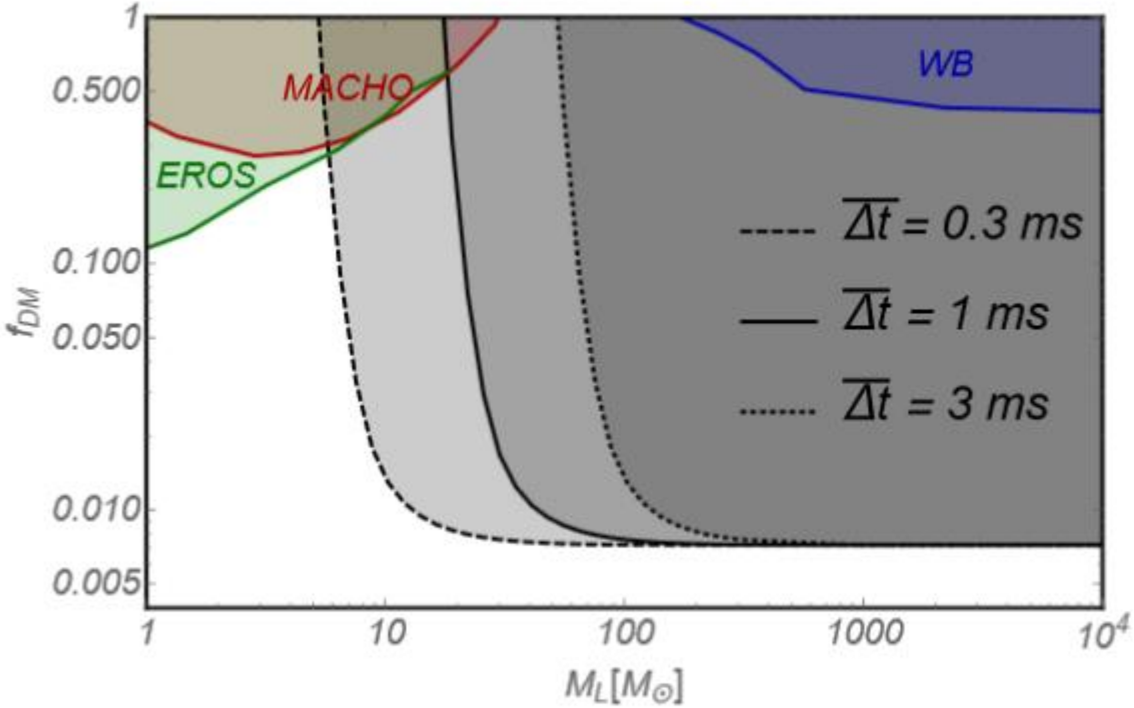


GRB Femtolensing and picolensing of microlensing of stars (MACHO) and quasars (QSO), millilensing of compact radio sources (RS),

wide binary disruption (WB), globular cluster disruption (GC), dynamical friction (DF), disk heating (DH), generation of large-scale structure through Poisson fluctuations (LSS), accretion on the CMB (FIRAS, WMAP3), and gravitational waves (GW)

Clesse & Garcia-Bellido 2015

Intermediate mass IMBH



Munoz, Kovetz et al 2016

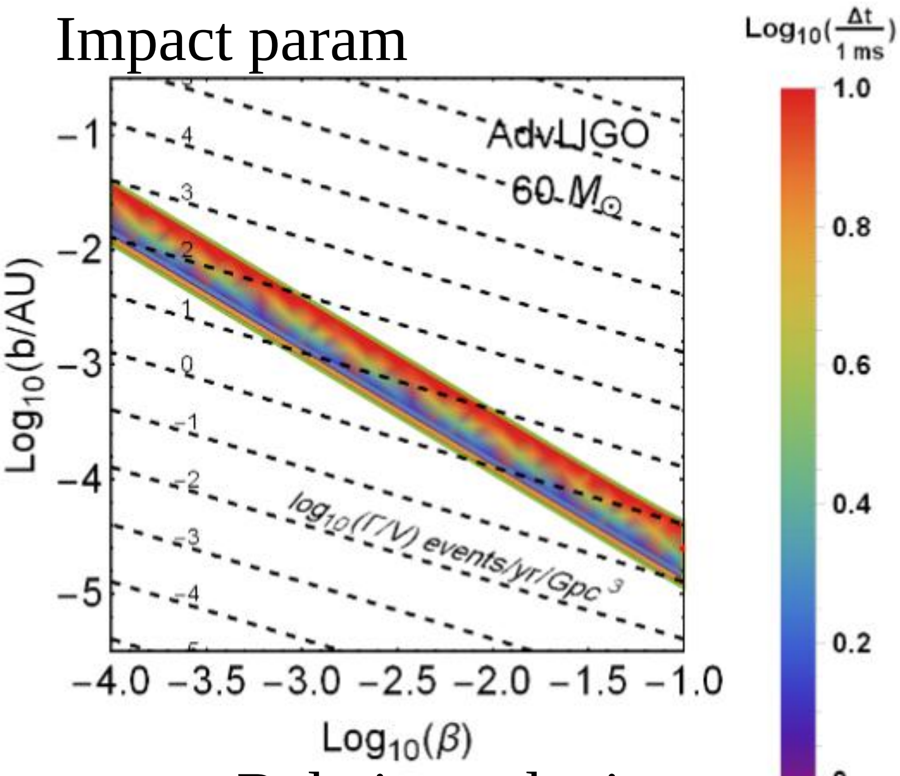
Strong lensing of FRB by IMBH, could produce repeated FRB, with time delay ΔT

Sasaki et al 2016: LIGO GW150914 could be from PBH mergers,
But with $\mathbf{f_{DM}}$ **small**
Eroshenko 2016, considers the effect of inflationary DM density
Perturbations, and additional tidal forces, the merger rate of PBHs
is suppressed by a factor ~2. PBHs could constitute only
f ~5 10^{-4} -10^{-3} of DM

GW bursts

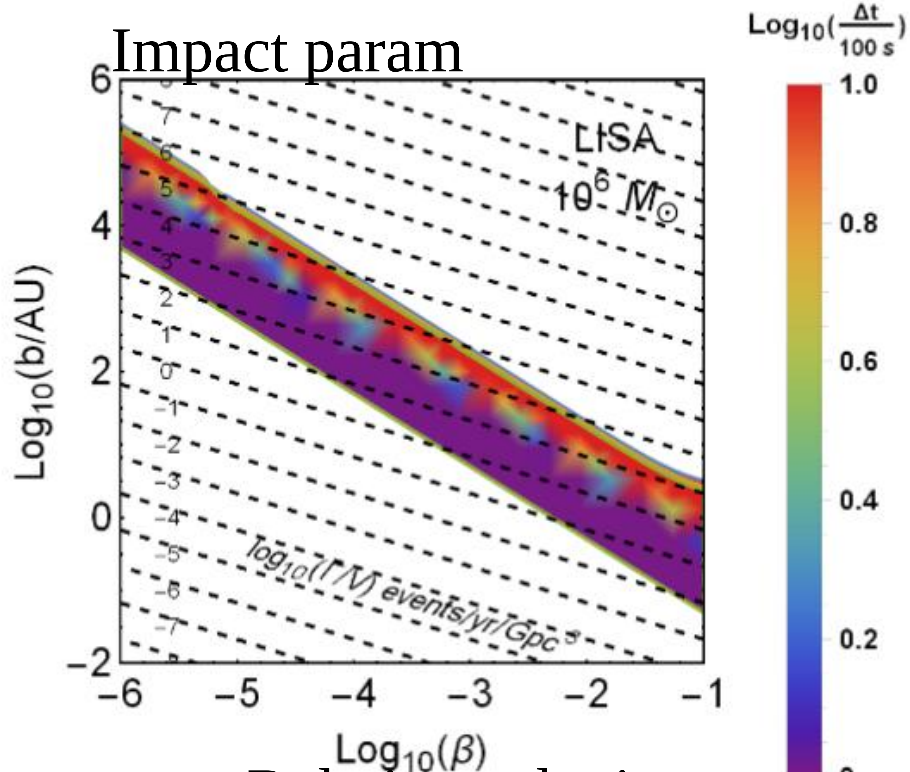
Hyperbolic or parabolic encounters: quite different signatures than for mergers of two BH

Impact param



Relative velocity

Impact param



Relative velocity

Garcia-Bellido & Nesseris 2017

Summary

- ➔ Rotation curves, Universal RC, RAR Radial acceleration relation
- ➔ Where are the baryons? Still 60% unidentified
- ➔ Tully-Fisher and scaling relations: the main issue: feedback?
- ➔ Too many dwarfs, Too Big To Fail (TBTF), still severe pb
- ➔ Galaxy clusters: Bullets, **$\sigma/m < 0.47$ cm^2/g,** or may be no
- ➔ Neutrinos, Ly-α bounds: **$m_X > 4.65$ keV and $m_s > 28.8$ keV**
- ➔ Primary black holes PBH: all windows closed?