XXXII Canary Islands Winter School of Astrophysics

# Galaxy clusters in the local Universe

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Lecture 3:

The properties of

# Dark matter & gravitation

as inferred from the internal structure of clusters of galaxies

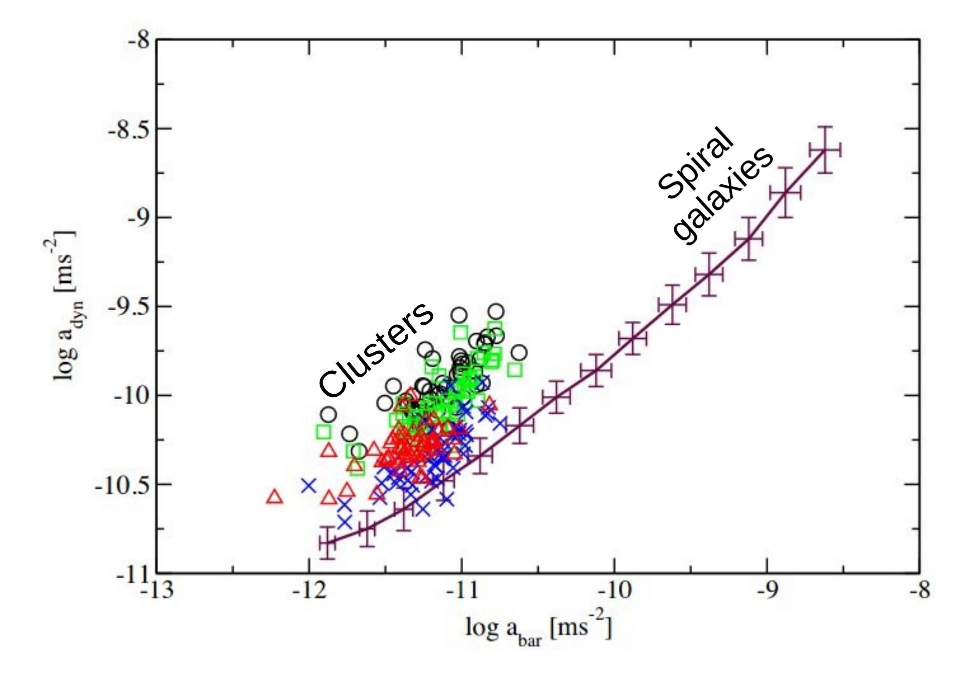
# Dark matter & gravitation

## Cluster collisions

DM vs. MOdified Newtonian Dynamics (**MOND**) or MOdified Gravity (MOG)

MOND *(Milgrom 1983)* cannot fit the Bullet without an additional dark mass component; massive 2 eV neutrinos have been suggested *(Angus et al. 2007)*, but particle physics experiments now set an upper limit of 1.1 eV *(KATRIN collaboration 2019)*

*(Markevitch et al.; Clowe et al. 2004)*




In addition, the tight correlation between baryonic and dynamical mass observed in spiral galaxies (RAR, *McGaugh 2004*) is not obeyed by clusters of galaxies, ruling out the universality of MOND accelration parameter *(Chan & Del Popolo 2020)*

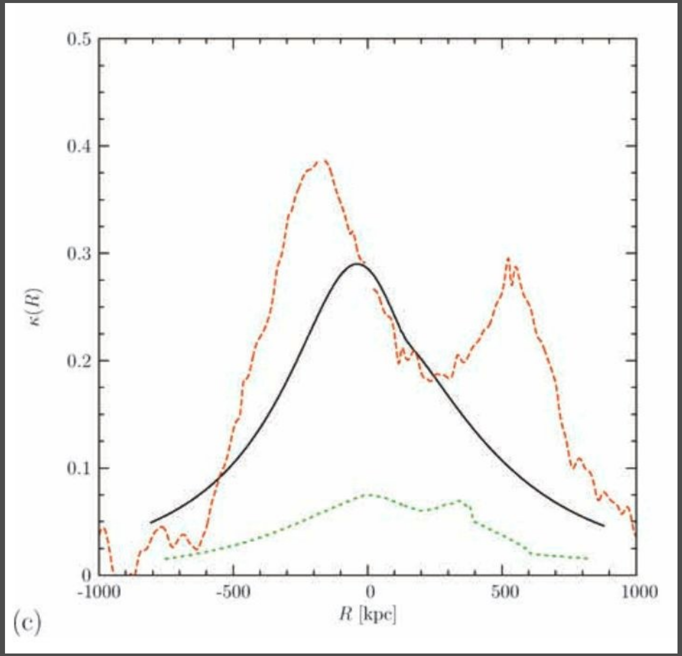
# Dark matter & gravitation

## Cluster collisions

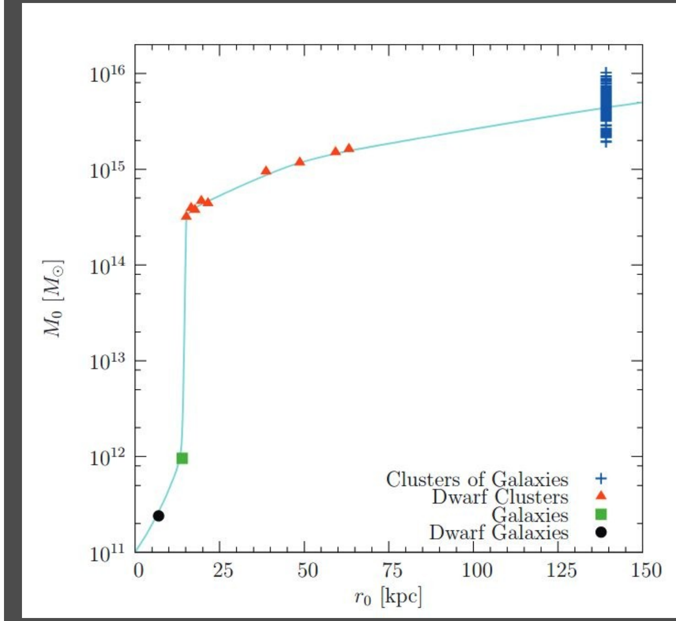
DM vs. MOdified Newtonian Dynamics (MOND) or MOdified Gravity (**MOG**)

*(Markevitch et al.; Clowe et al. 2004)*

MOG *(Moffat 2005)* does not seem to provide an excellent fit to the Bullet either *(Brownstein & Moffat 2007),* but it is not ruled out because of considerable freedom in the parameters of the theory




Convergence k-map (orange) and MOG k-model (black) and difference (green) attributed to (unaccounted for) galaxies



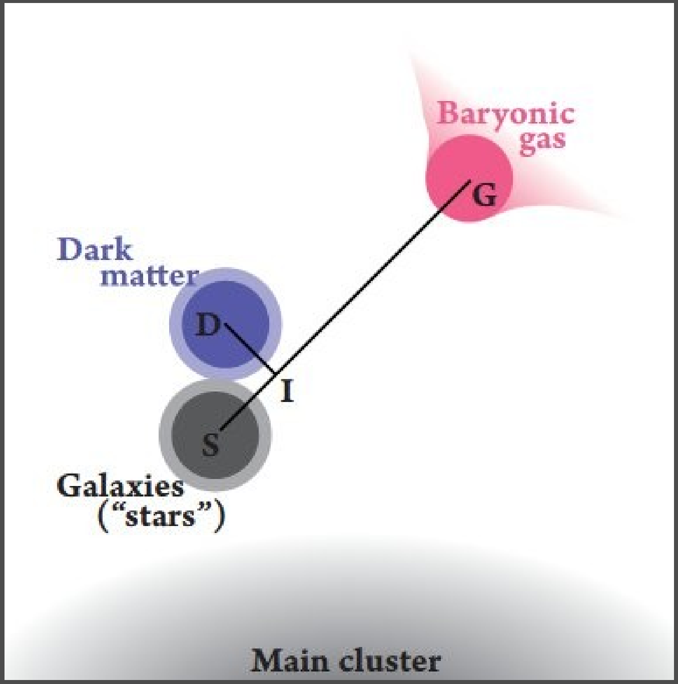

The MOG parameters are not universal, they have different values in different systems

# Dark matter & gravitation

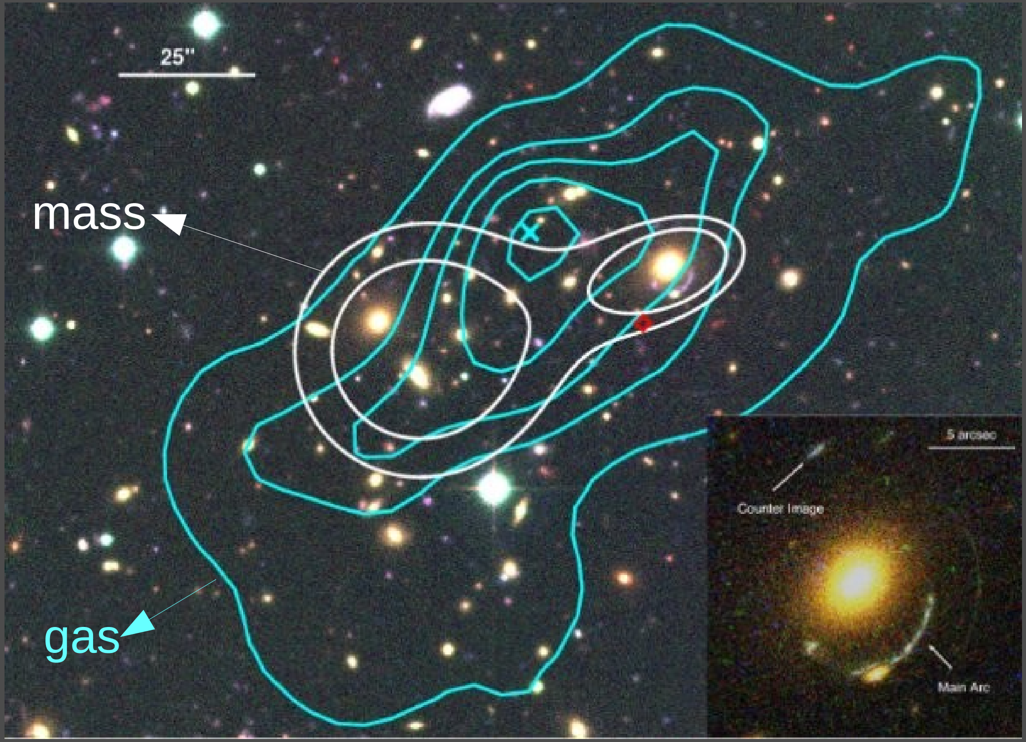
## Cluster collisions

Offset positions between galaxies, gas and DM (from gravitational lensing) constrain the **cross-section-to-mass ratio σ/m** of DM (*Markevitch et al. 2004*):

Estimates from the Bullet and other clusters typically gives **$\sigma/m < 2$ cm$^2$ g$^{-1}$** *(Wittman et al. 2018)*




*Harvey et al. (2014)*



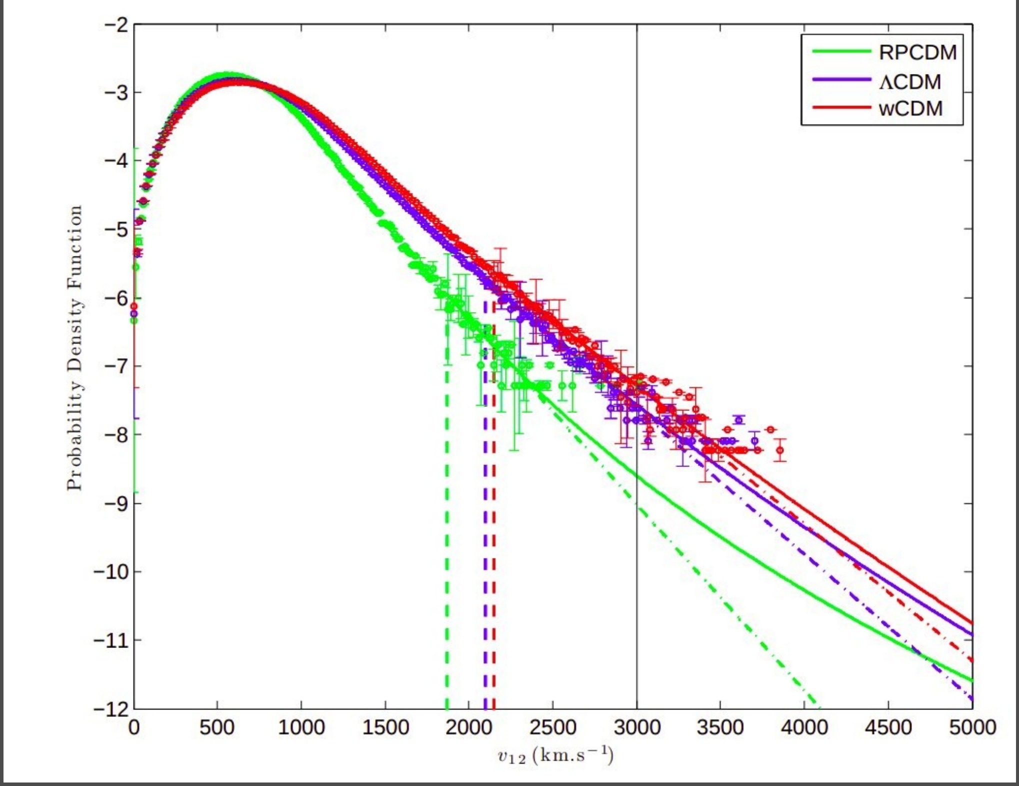

*Gastaldello et al. (2015), the Bullet 'group'*

# Dark matter & gravitation

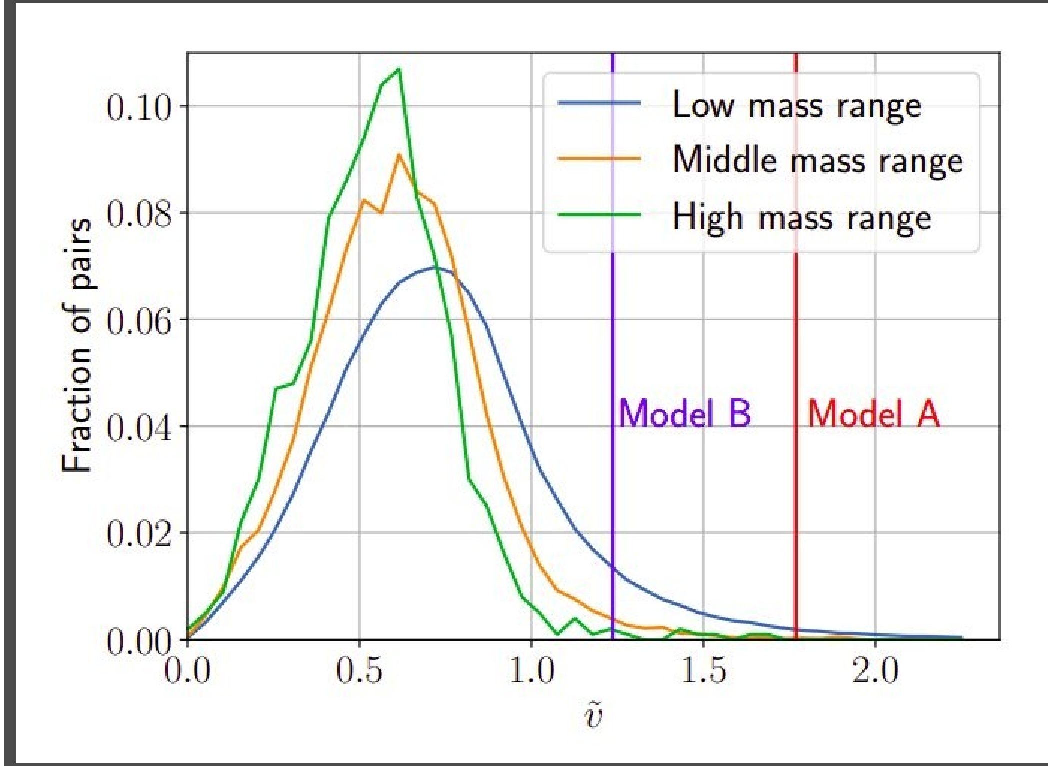
## Cluster collisions

The relative **velocity** of colliding clusters-subclusters as a function of their masses can be used to constrain the cosmoogical model (*Hayashi & Whte 2006*)

**High-speed collisions of massive clusters are rare** (impossible?) in the ΛCDM cosmology




*Bouillot et al. (2015):* the probability of detecting the Bullet cluster collision velocity in thee cosmologies

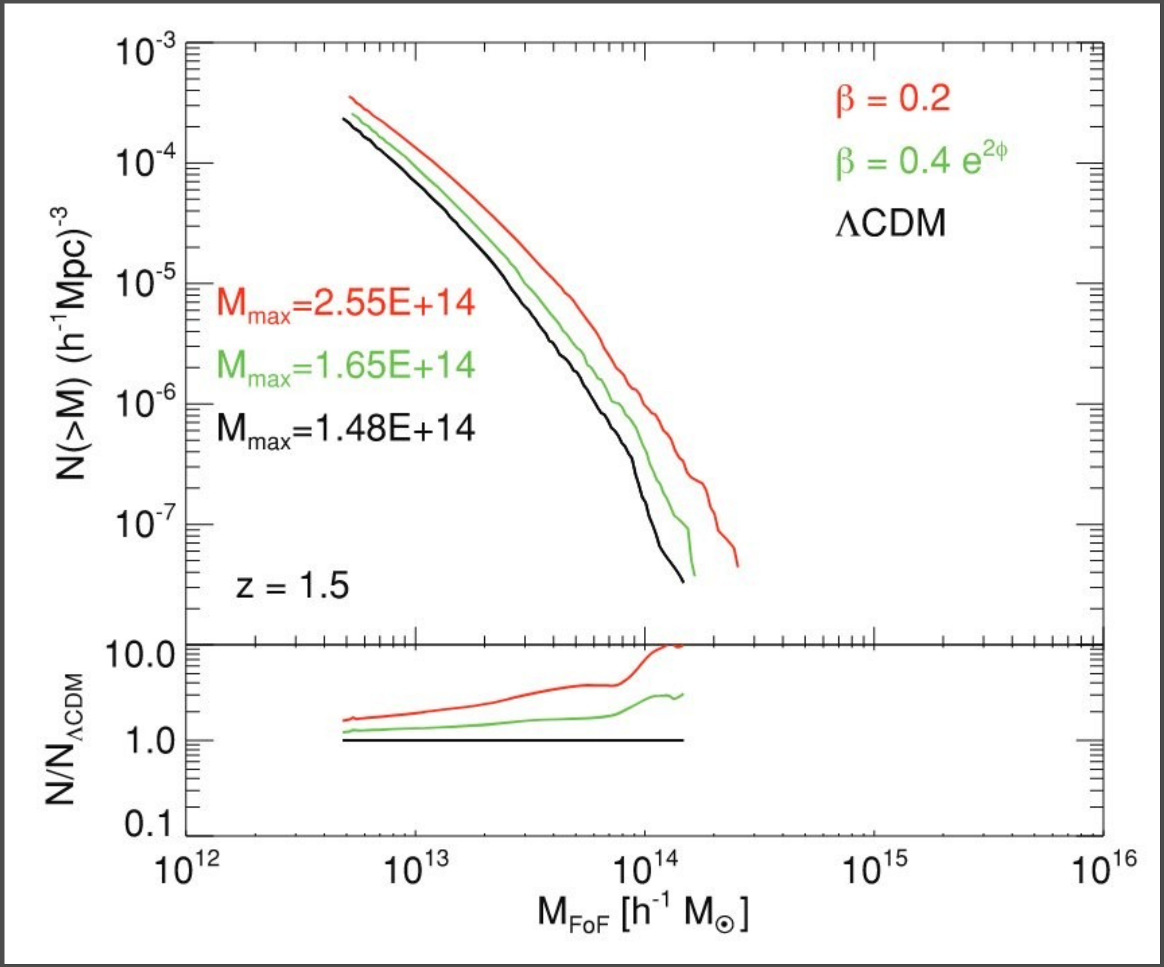



*Asencio et al. (2021):* the fraction of pairs with a given collision velocity compared to that of the El Gordo cluster

# Dark matter & gravitation

## Cluster masses

The probability of detecting a **very massive cluster at high redshift** is low in the ΛCDM cosmology, but can be higher in alternative cosmologies (such as coupled DM-Dark Energy, *Baldi & Pettorino 2011*)



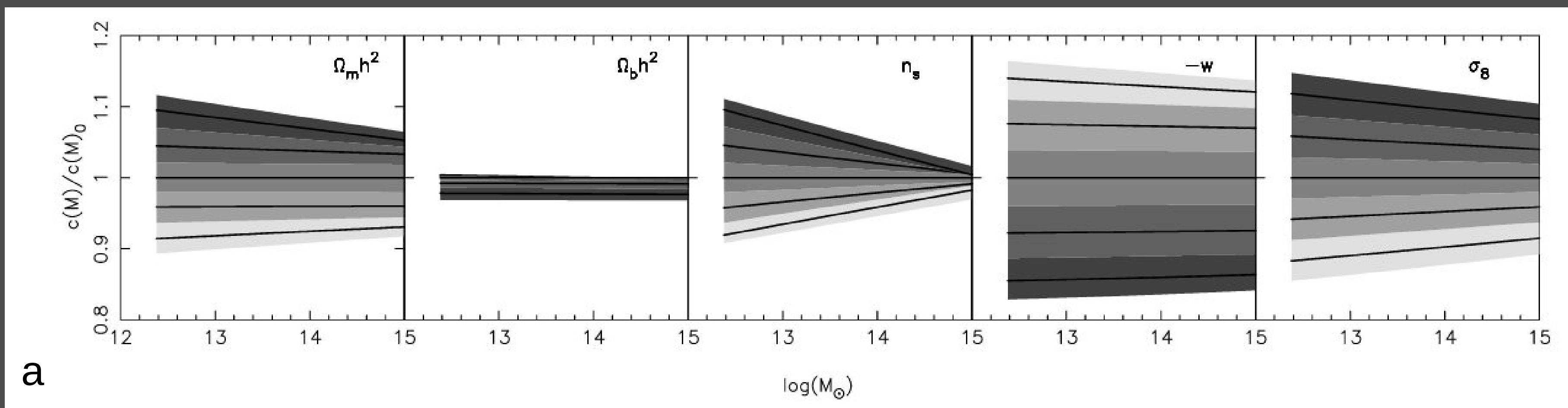

Red and green curves: two coupled DM-DE cosmological models

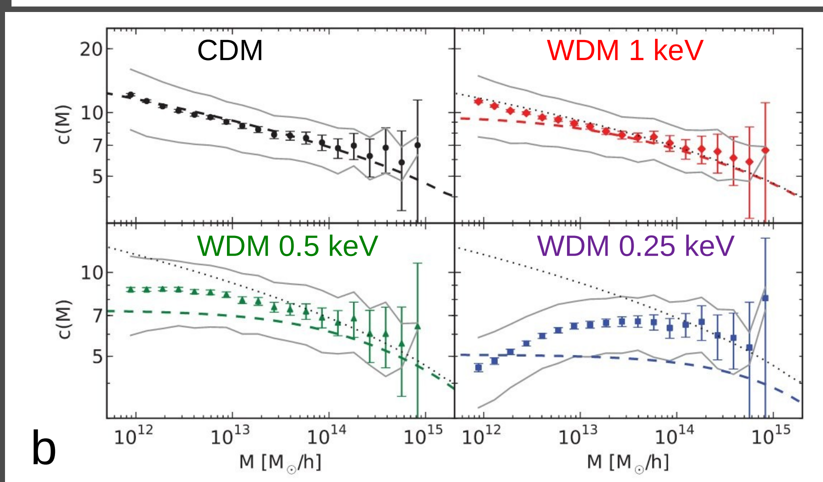
# Dark matter & gravitation

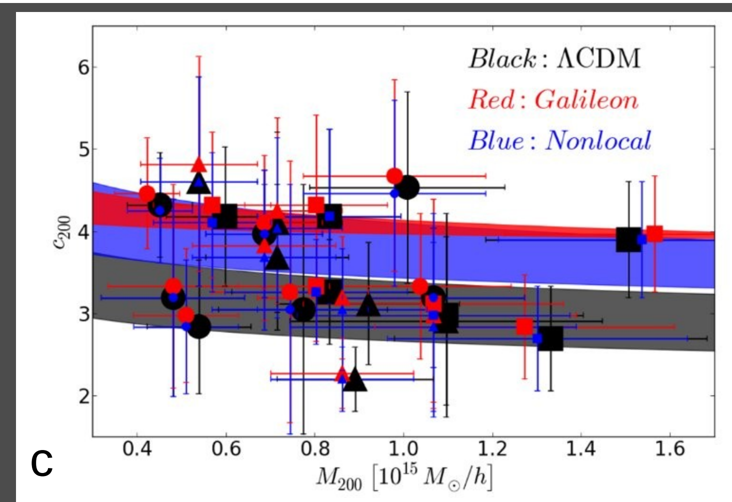
## The concentration-mass relation

Can constrain:

- the parameters of ΛCDM *(Fig.* **a**: *Kwan et al. 2013)*
- the nature of DM *(Fig.* **b**: *Schneider et al. 2012)*
- the theory of gravitation *(Fig.* **c**: *Barreira et al. 2015)*



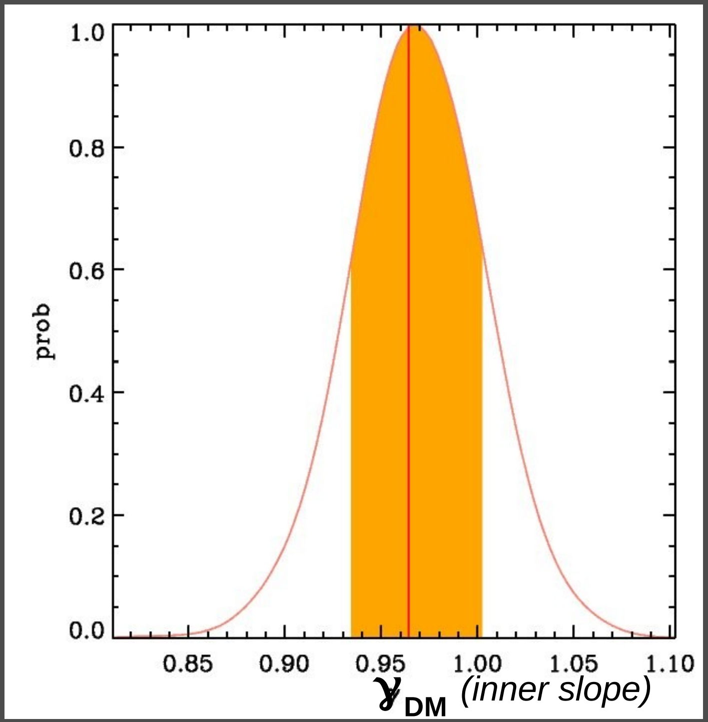
# Dark matter & gravitation

## Cluster mass density profile ρ(r)

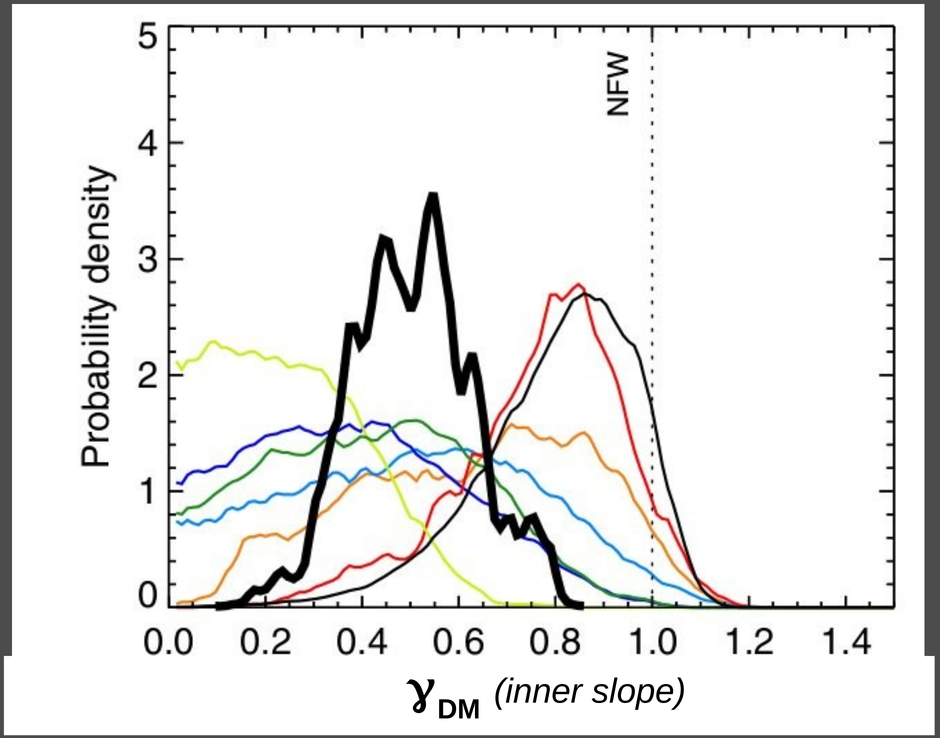
The shape of ρ(r) can differentiate between different models of DM:

**most important is the behavior at r→0, i.e. the inner slope $\gamma_{DM}$**

CDM is predicted to have a NFW behavior ($\gamma_{DM}$=1), deviations suggest different kind of DM, but baryonic processes (feedback from central AGN, dynamical friction, adiabatic contraction...) can also change $\gamma_{DM}$




*Sartoris, AB et al. (2020):* cluster RXC J2248.7-4431 inner slope of DM ρ(r→0): $\gamma_{DM}$ = -d ln ρ/ d ln r = 0.97 ± 0.04
**fully consistent with NFW**

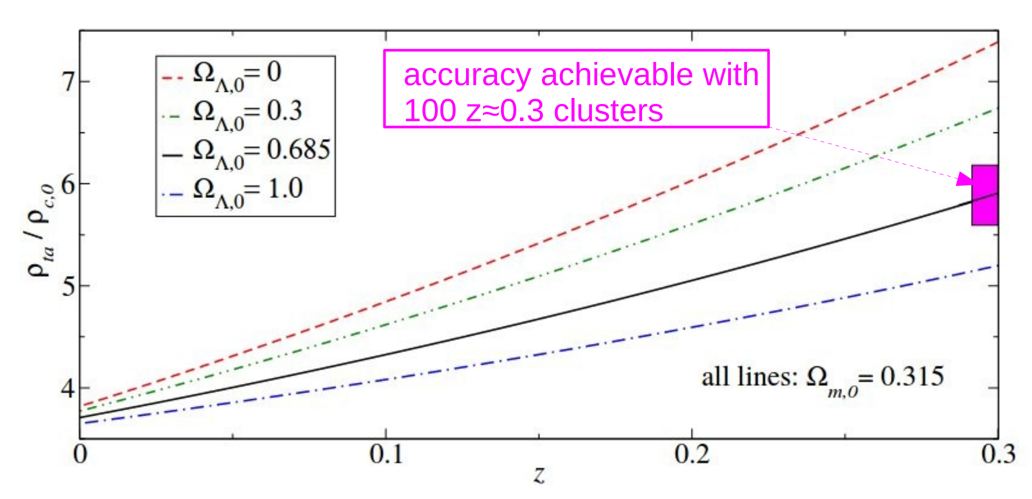



*Newman et al. (2013):* seven clusters, average inner slope of DM ρ(r→0): $\gamma_{DM}$ = -d ln ρ/ d ln r = 0.5 ± 0.13,
**inconsistent with NFW** ⇒ Self-interacting DM?

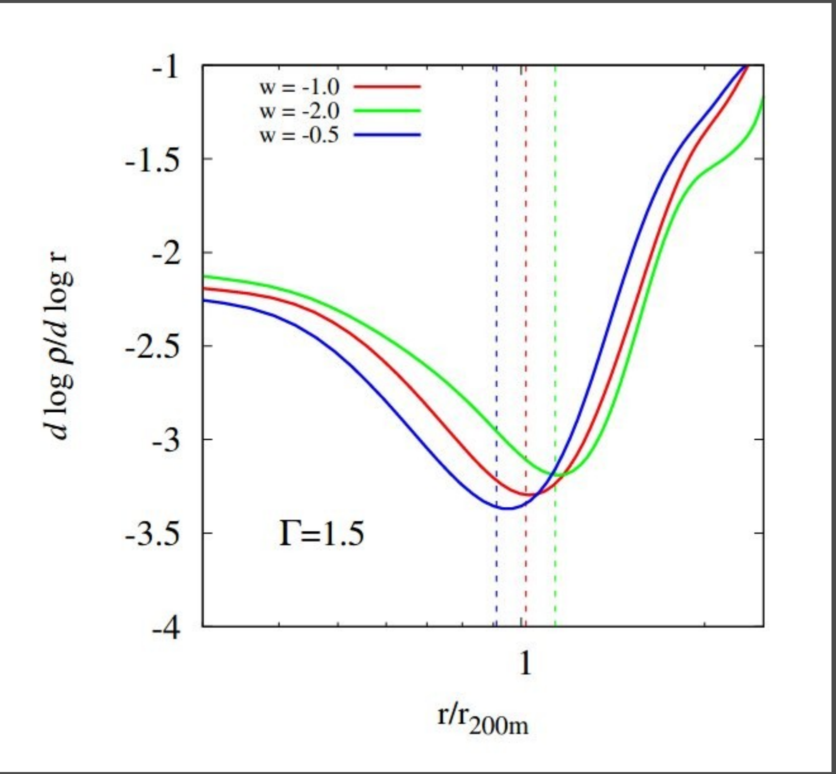
# Dark matter & gravitation

## Cluster mass density profile ρ(r)

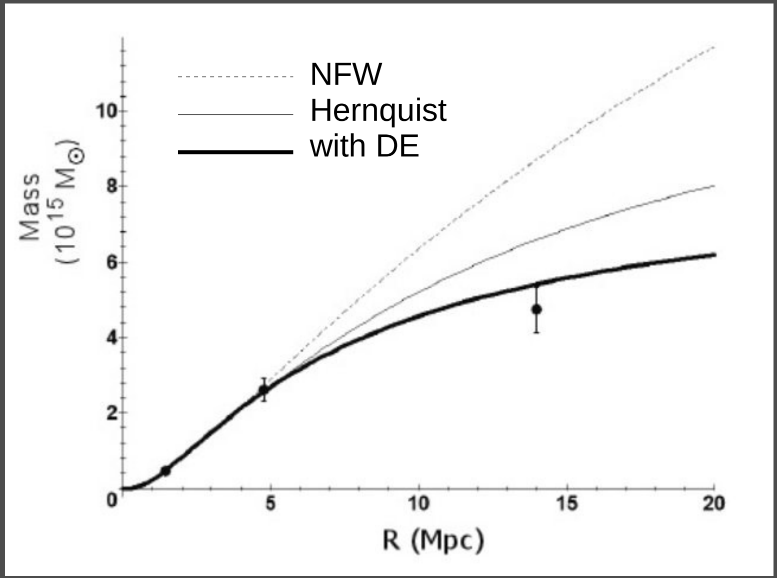
The shape of ρ(r) can constrain cosmological parameters in the ΛCDM model:




The density at the turnaround radius is a probe of $\Omega_\Lambda$, independent of $\Omega_m$ *(Pavlidou et al. 2020)*




The splashback radius depends on the equation of state of Dark Energy, w≡P/ρ *(Adhikari et al. 2018)*



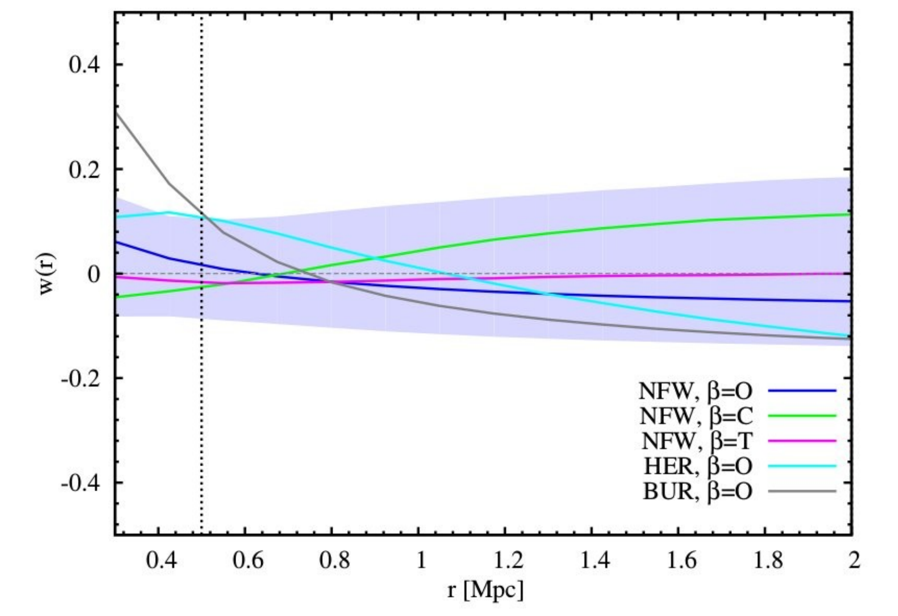

The mass profile of the Abell 1656 cluster *(*data *from Geller et al. 1999, 2011)* fit with models with and without Dark Energy *(Chernin et al. 2013)*

# Dark matter & gravitation

## Cluster mass density profile ρ(r)

Better constraints on the properties of DM and gravitation can be obtained by comparing mass density profiles obtained from gravitational lensing with those obtained from the galaxy phase-space distribution...
**...because gravitational lensing ρ(r) is obtained using relativistic tracers (photons), while galaxies are not relativistic,** and they feel different gravitational potentials when DM or gravitation differ from the standard expectations.

E.g., if DM is not pressure-less, since both density and pressure contribute to the grav. field, tracers with different velocities (photons vs galaxies) feel the two contributions differently *(Faber & Visser 2006)*




By comparing the ρ(r) of a cluster as obtained from gravitational lensing to the ρ(r) as obtained from the phase-space distribution of cluster galaxies, *Sartoris, AB et al. (2014)* constrained DM to be pressure-less

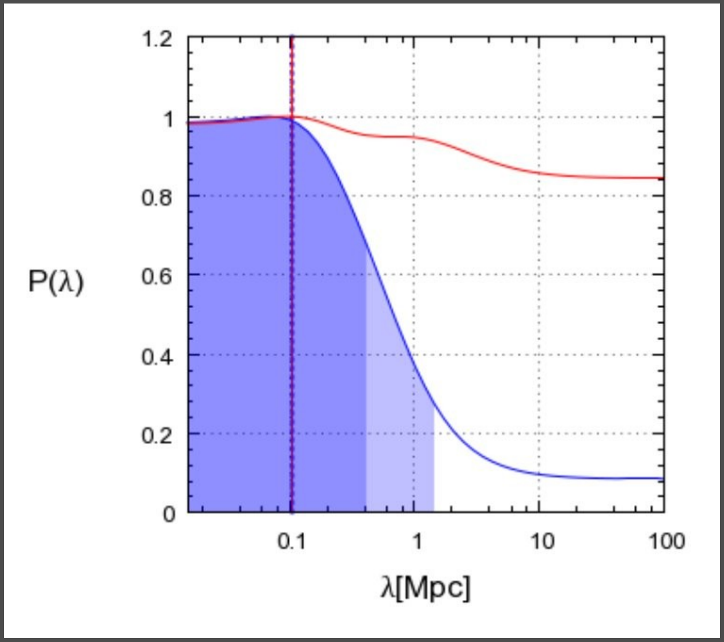
$$w(r) = \frac{p_r(r) + 2\,p_t(r)}{3\,c^2 \rho(r)}$$

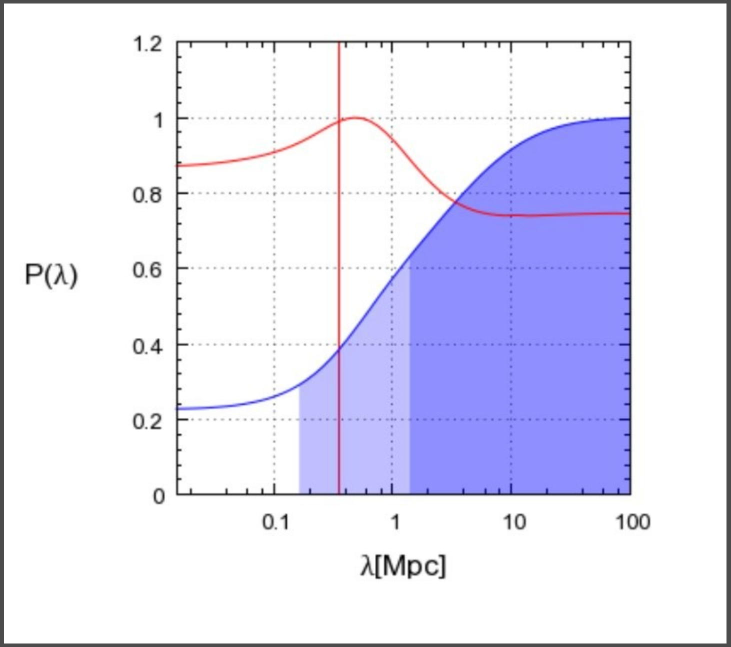
# Dark matter & gravitation

## Cluster mass density profile ρ(r)

Better constraints on the properties of DM and gravitation can be obtained by comparing mass density profiles obtained from gravitational lensing with those obtained from the galaxy phase-space distribution...
**...because gravitational lensing ρ(r) is obtained using relativistic tracers (photons), while galaxies are not relativistic,** and they feel different gravitational potentials when DM or gravitation differ from the standard expectations.

E.g. in f(R) gravity, that differs from GR by a scalar field with interaction range λ, non-relativistic tracers only feel the timelike metric component of the grav. potential



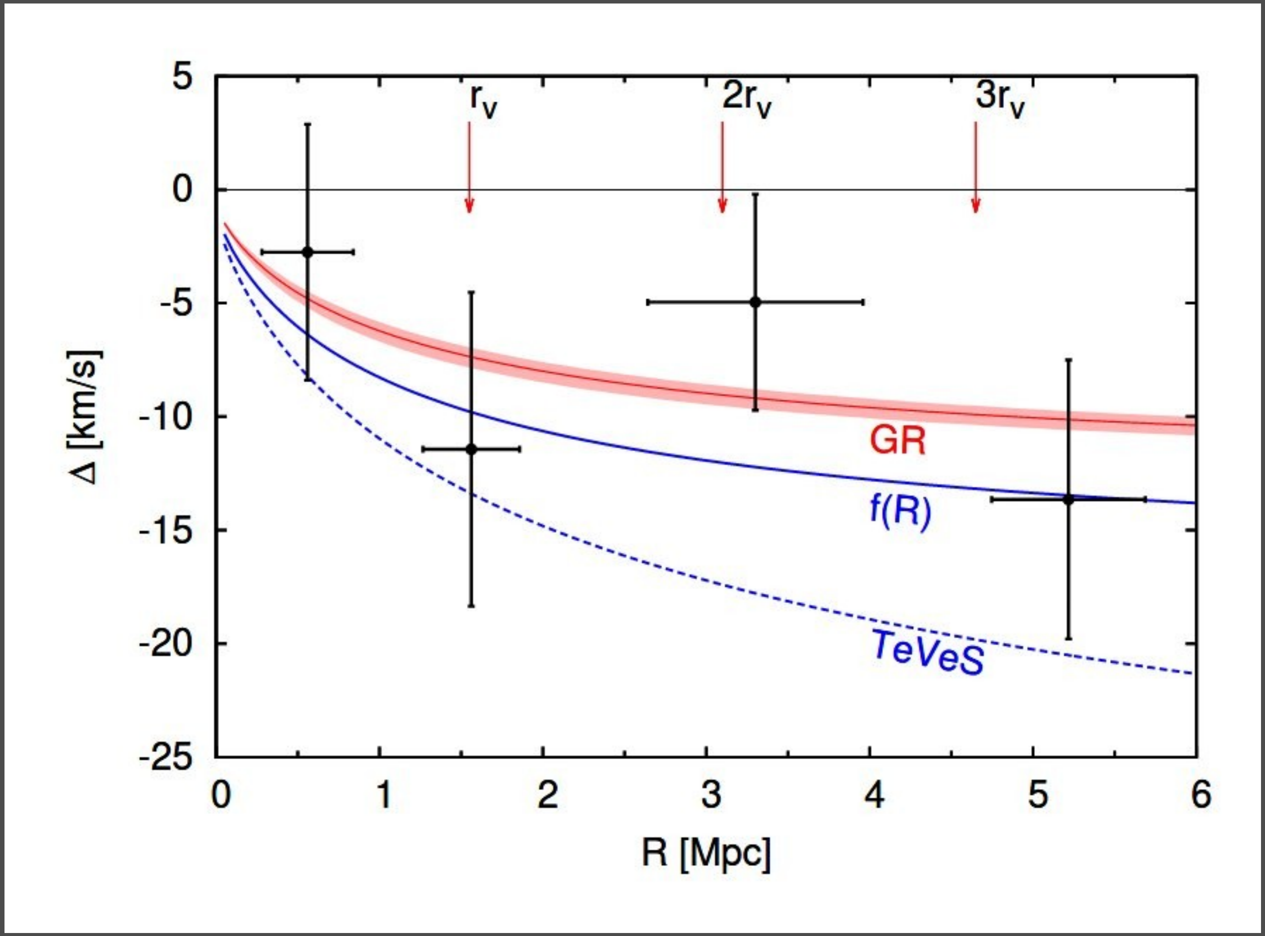




*Pizzuti et al. (2017):* the scalar field interaction range λ is consistent with 0 in a cluster, but it is significantly > 0 in another cluster.
*Red curves indicate results from using only galaxies as tracers, blue curves show the improvement when gravitational lensing is added to the analysis.*

# Dark matter & gravitation

## Cluster internal kinematics

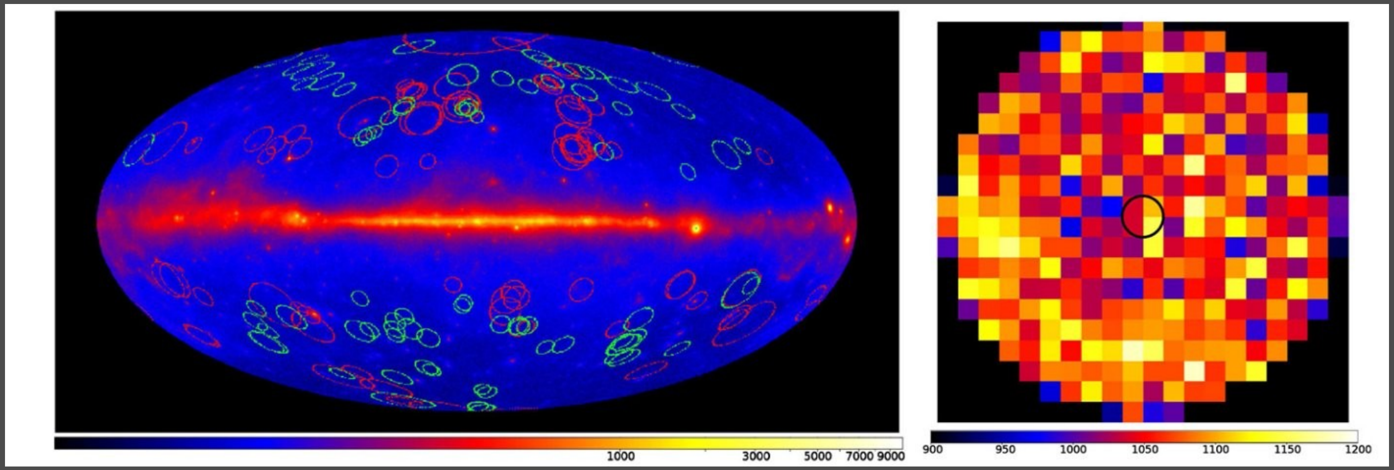
The light from the central galaxy in a cluster potential well is red-shifted because of gravity *(Cappi 1995),* the effect depends on the model of gravitation *(Wojtak et al. 2011)*



# Dark matter & gravitation

## Direct detection

If DM is self-interacting, it is expected to decay in $\gamma$-rays; none detected so far from custers




*Left*: positions of clusters (green circles) in the all-sky Fermi-LAT photon map. *Right*: Stacked cluster image *(Griffin et al. 2014)*

Radio emission is present but at low levels in most clusters. Assuming it results from DM annihilation into relativistic electrons and *positrons (Colafrancesco et al. 2006)*, an upper limit can be set on the DM annihilation cross-section *(Storm et al. 2013)*