Universal properties of Dark Matter halos

Oleg Ruchayskiy

Ecole Polytechnique Fédérale de Lausanne

March 30, 2010

SnowCluster

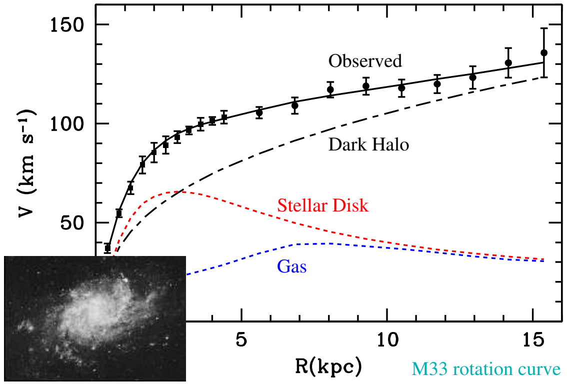
Based on...

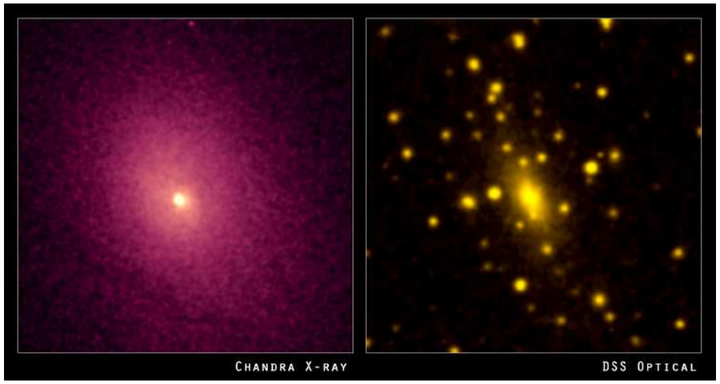
- Boyarsky, **O.R.**, Iakubovskyi, Macciò, Malyshev
  "New evidence for dark matter" arXiv:0911.1774 [astro-ph.CO]

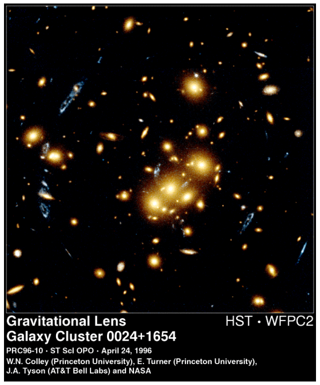
- Boyarsky, Neronov, **O.R.**, Tkachev
  "Universal properties of Dark Matter halos"
  arXiv:0911.3396 [astro-ph.CO]

- Boyarsky, **O.R.** **"New probe of modified gravity"**
  arXiv:1001.0565 [hep-th]

Tracers of gravitational potential







- Rotation curves of stars in galaxies and of galaxies in clusters
- Distribution of intracluster gas
- Gravitational lensing data

These phenomena are **independent tracers** of gravitational potentials in astrophysical systems. They all show that dynamics is dominated by a matter that is not observed in any part of electromagnetic spectrum.

Any universal properties of DM distributions in objects?

DM density profiles - ISO

- Flat rotational velocity curves mean that the total mass growth **linearly** with radius

- (Pseudo)-isothermal sphere

$$\rho_{\text{ISO}}(r) = \frac{v_\infty^2}{4\pi G}\frac{1}{r^2 + \boldsymbol{r_c}^2}$$

  gives asymptotically flat rotation curve

- Two parameters:
  - **core radius** r_c
  - **central density** $\boldsymbol{\rho_c} = \dfrac{v_\infty^2}{4\pi G r_c^2}$

- $M(< r) \propto r$ – infinite mass of a halo?

DM density profiles - NFW

Navarro, Frenk, & White'96

- Density profile first appeared in numerical simulations

$$\rho_{\text{NFW}}(r) = \frac{\boldsymbol{\rho_s\, r_s}}{r(1+r/\boldsymbol{r_s})^2}$$

- Two parameters: ρ_s and r_s:

$$\left.\frac{d\log\rho_{\text{NFW}}}{d\log r}\right|_{r=r_s} = -2$$

- Mass of the halo grows slower $M_{\text{NFW}}(<r) \propto \log(r)$
- Introduce a "size of a halo" – r_{200}:

$$M_{\text{NFW}}(<r_{200}) = \frac{4\pi}{3}\times 200\times\rho_{crit}\times r_{200}^3$$

- and a **concentration** parameter $c_{200} = r_{200}/r_s$

DM density profiles - Burkert

- Density profile first appeared in numerical simulations Burkert'95

$$\rho_{\text{BURK}}(r) = \frac{\boldsymbol{\rho_0}\,\boldsymbol{r_0}}{(r+\boldsymbol{r_0})(1+r^2/\boldsymbol{r_0}^2)}$$

- Cored profile with r^{-3} asymptotics
- Introduced to fit dark matter distribution in dwarf spiral galaxies
- **Two parameters are strongly correlated?**
- For observed halos $\rho_0 \propto r_0^{-2/3}$
- For simulated halos parameters of NFW are related:

$$c_{200} \propto M_{200}^{-\kappa}, \qquad \kappa \sim 0.1$$

Universal properties of DM distributions?

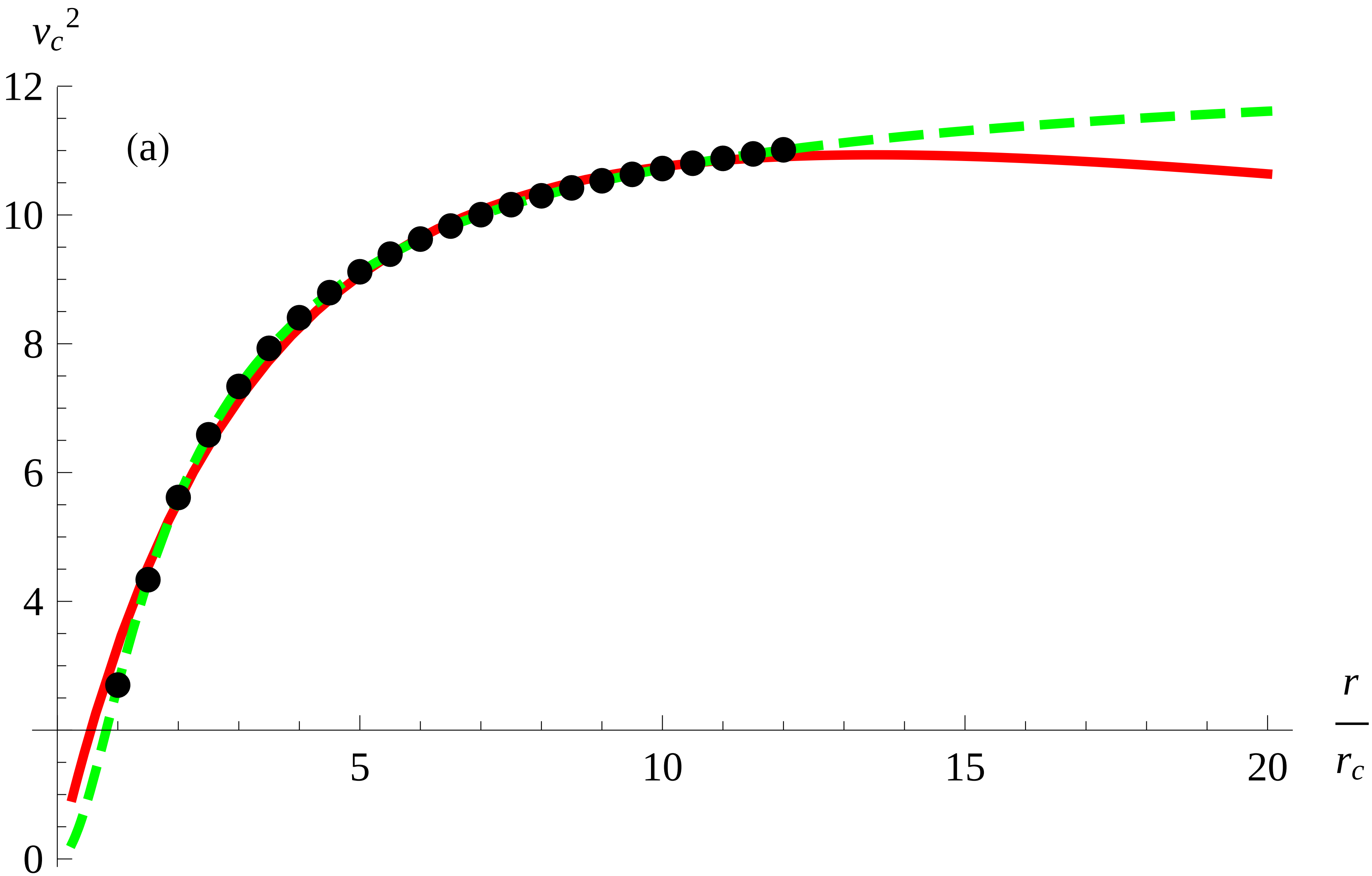
- There exist many works on dark matter distribution in individual objects

- Different methods (rotation curves, X-rays, weak lensing, ...). Different observational groups fit the mass distribution with different density profiles (isothermal sphere, Navarro-Frenk-White, Burkert, Einasto ...)

- Important questions:
  - What properties to compare?
  - Often fits to different DM density profiles exist for the same object. How to relate their parameters?
  - Any universality is observed?

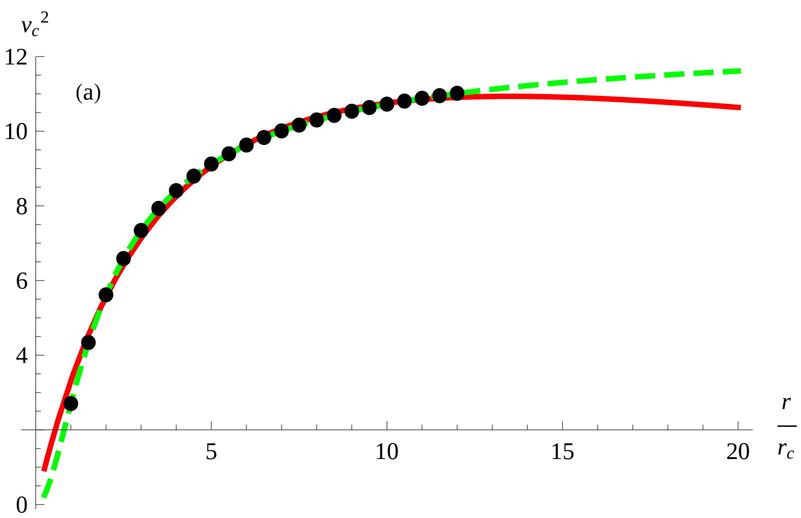
Circular velocity: ISO vs NFW

$$v_c^2 = \frac{GM(<r)}{r}$$



Comparing DM density profiles

- Fitting the same (simulated) data with two different profiles

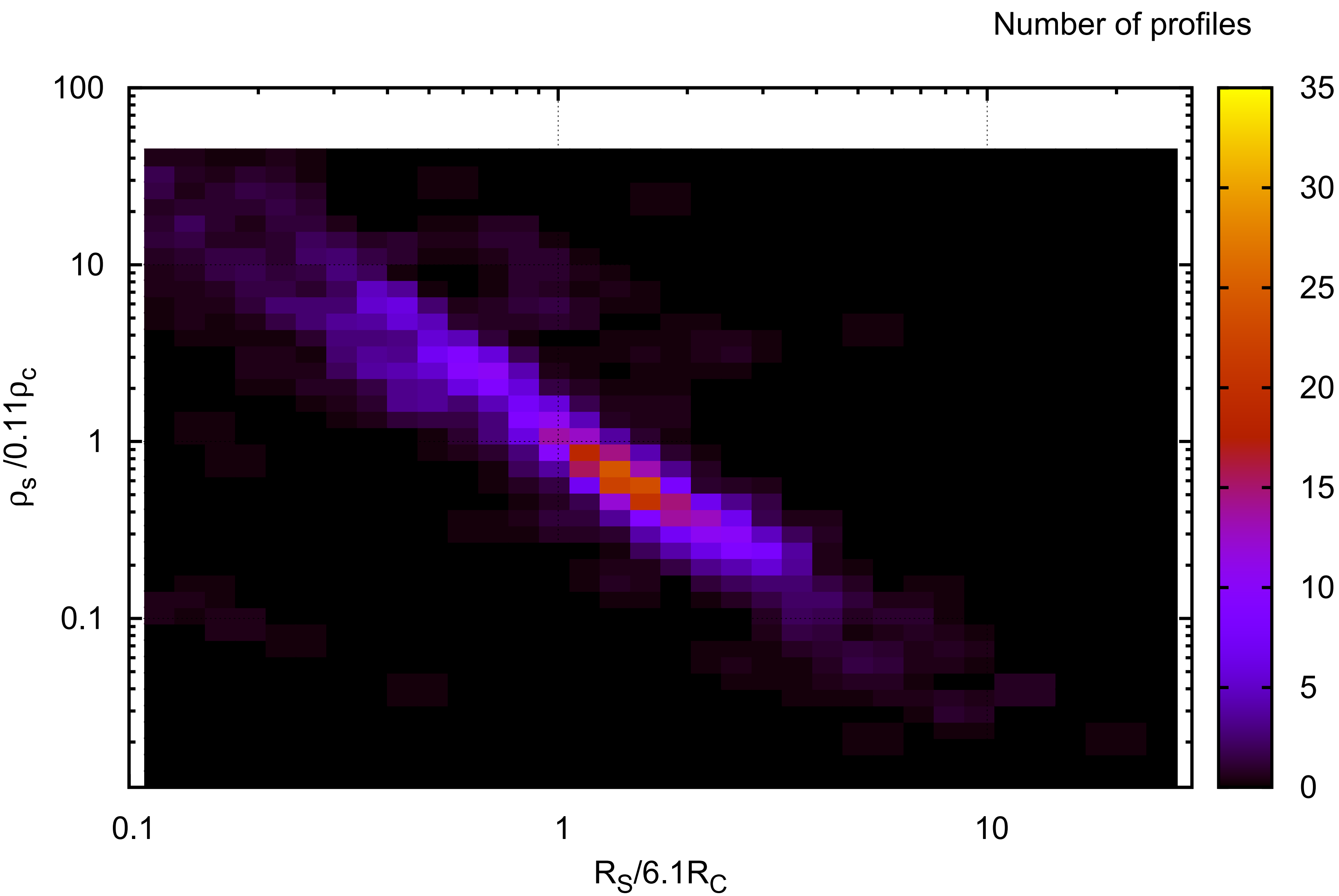


- one finds a relation between parameters of two DM density distribution, fitting the same data 0911.1774
  - NFW vs. ISO : $r_s \simeq 6.1\, r_c$; $\rho_s \simeq 0.11\, \rho_c$
  - NFW vs. BURK : $r_s \simeq 1.6 r_B$; $\rho_s \simeq 0.37 \rho_B$

- Is this relation actually observed?

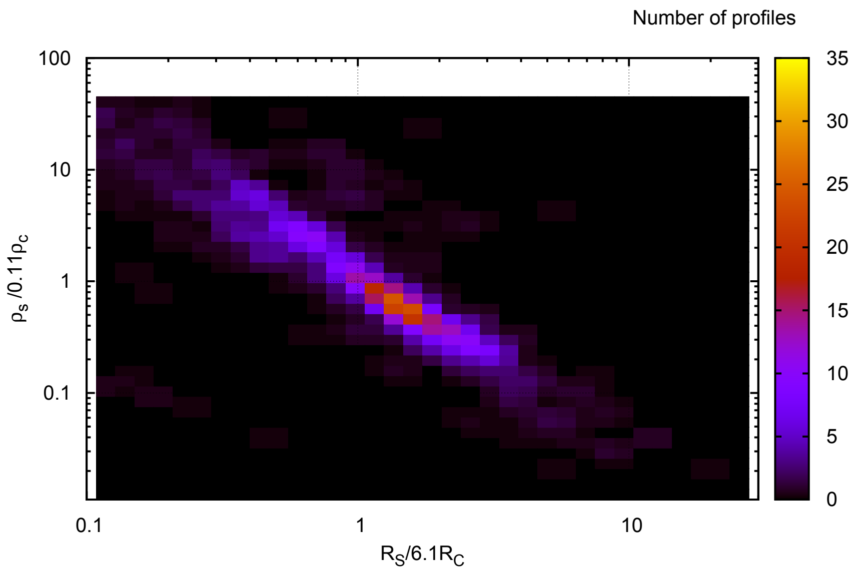
NFW vs. ISO

Take objects with both NFW and ISO DM profiles



DM column density

- Most of the objects obey the derived relation between parameters of DM density profiles



- For most of them $\rho_s r_s \propto \rho_c r_c$

- Observable $\propto \rho_c \times r_c$ – not sensitive to the choice of dark matter density profile?

- **Dark matter column density** (averaged within $r_\star$)

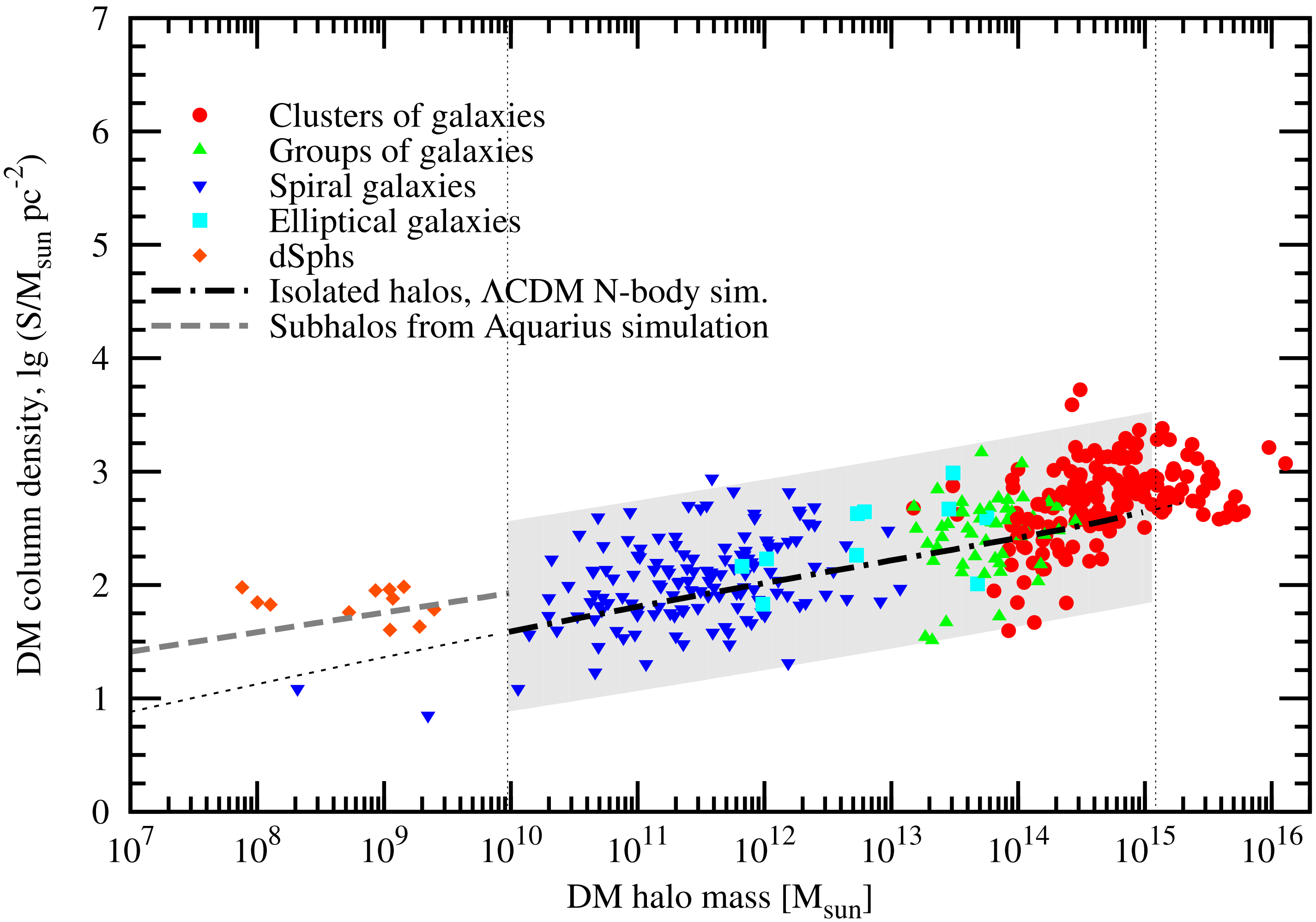
$$\mathcal{S} = \int_{\text{l.o.s.}} \rho_{\text{DM}}(r)dl \propto \rho_\star r_\star$$

- $r_\star$ is a characteristic scale ($r_\star = r_s$ for NFW, $r_\star = 6.1 r_c$ for ISO); $\rho_\star$ – average density inside $r_\star$

A catalog

- Going through the literature we compiled a "catalog" of $\sim$**1000** DM density profiles for $\sim$**300** individual objects, ranging from dwarf spheroidal satellites of the Milky Way to galaxy clusters... 0911.1774
- Blindly remove "bad data" (e.g. profiles where quoted uncertainty in parameters is more than factor of 10; profiles for which $r_{data} \ll r_\star$, etc.)
- Average all selected profiles for the same object (about 3 per object)
- All data are cosmologically close (can neglect evolution with redshift)

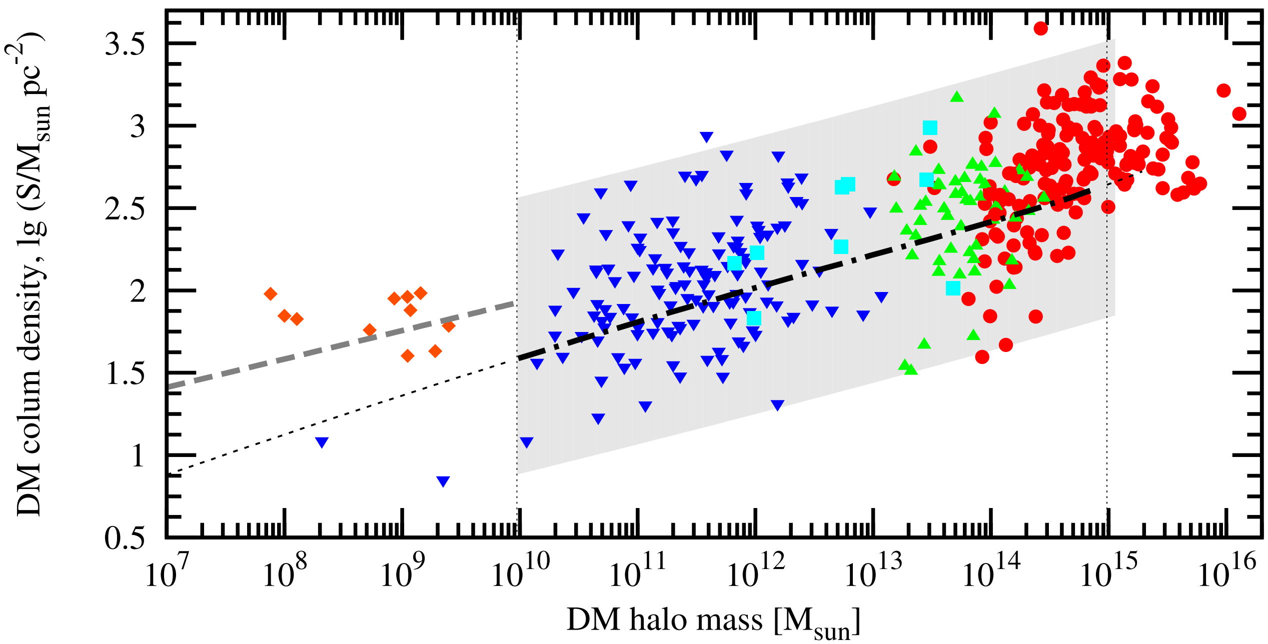
Observations vs. simulations



0911.1774

$$\mathcal{S} \sim M_{\text{halo}}^{0.2\ldots}$$

Universal scaling of DM column density

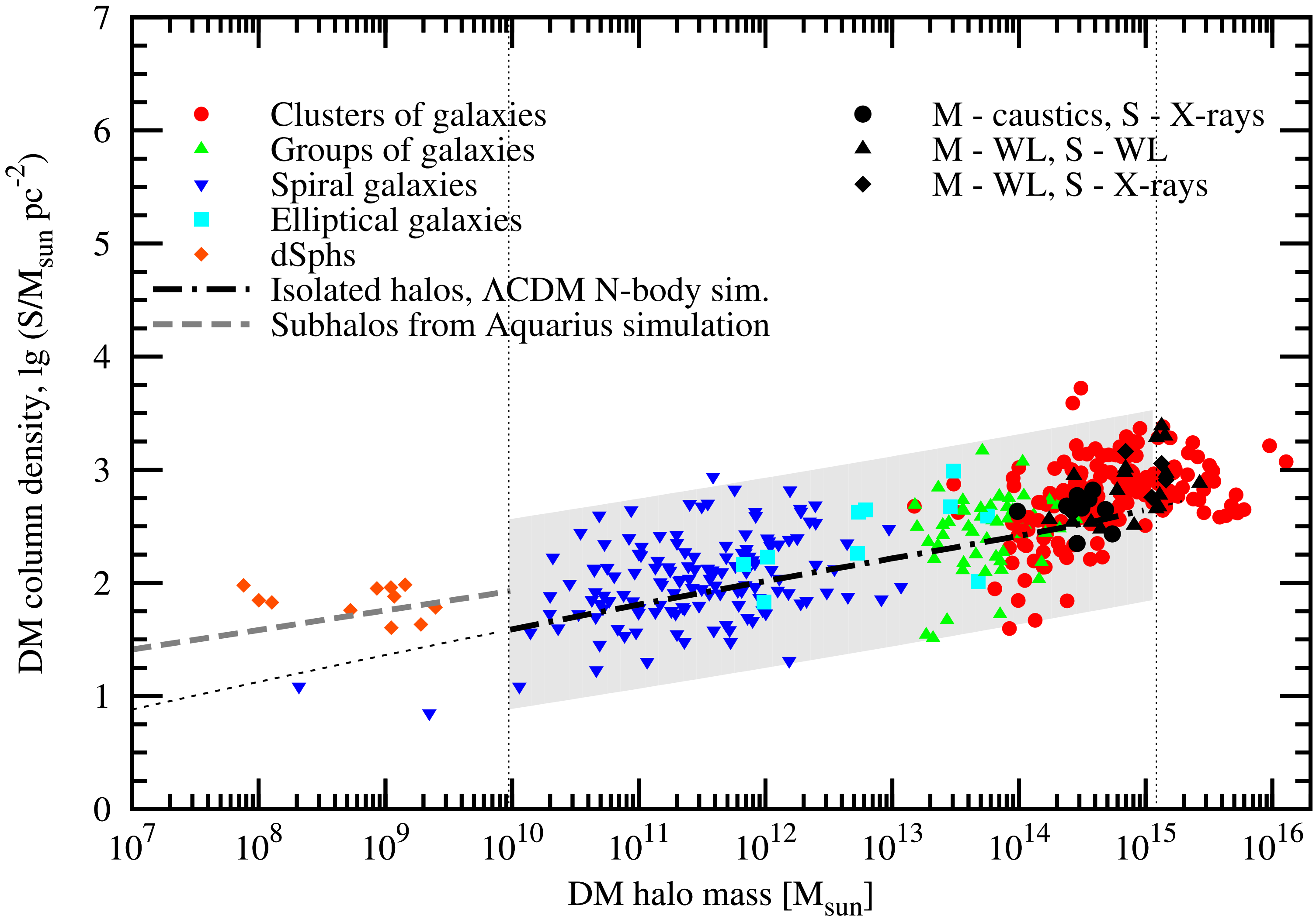


- The relation between $\mathcal{S}$ and M_{halo} is observed for halos of all scales **0911.1774** (for all observed halo masses from $10^8 M_\odot$ to $10^{15} M_\odot$) – **new proof that dark matter exists**!

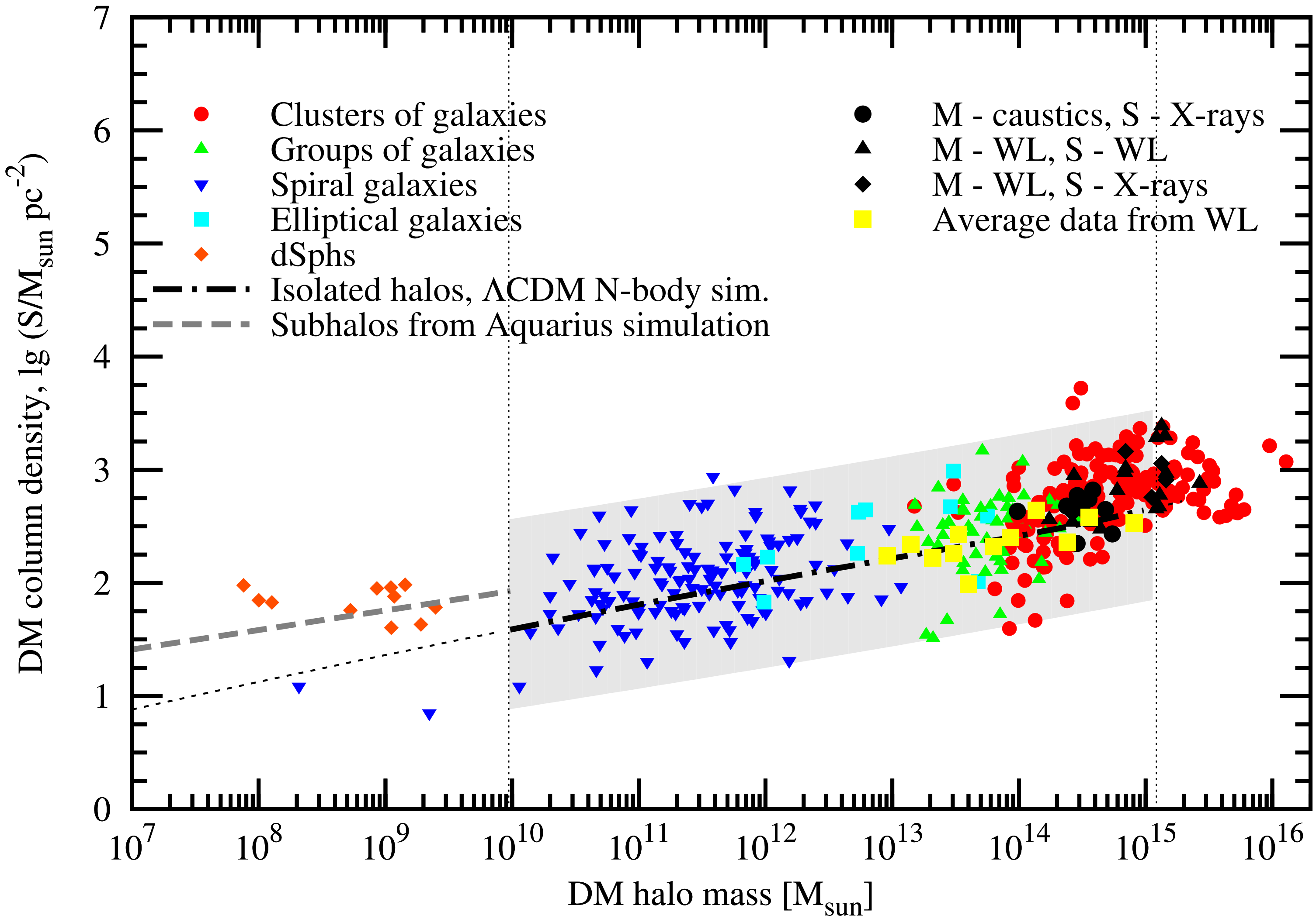
- The median value and scatter coincide remarkably well with **pure dark matter** numerical simulations

Independent determination of mass

work in progress

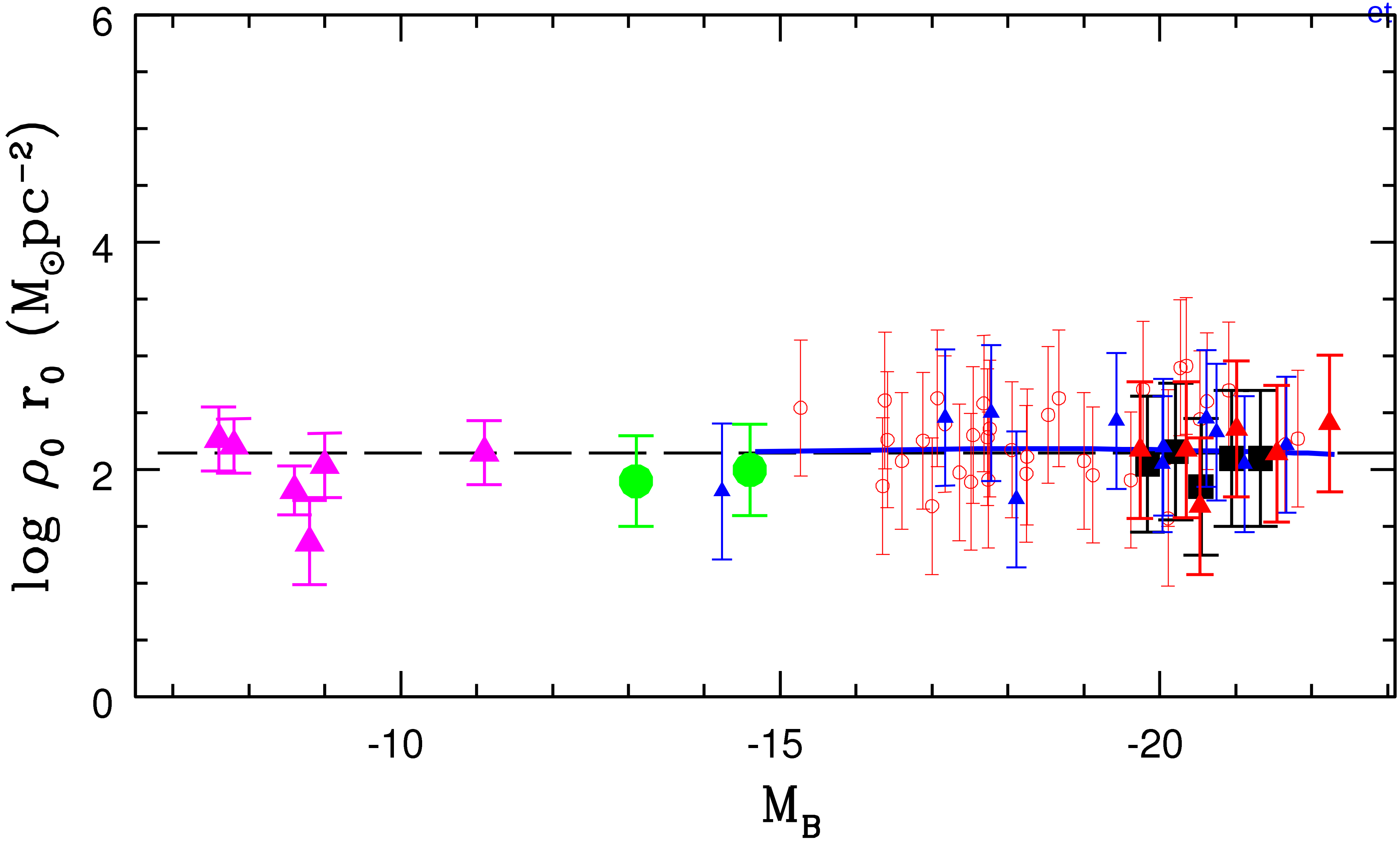


Independent determination of mass



Constant surface density?

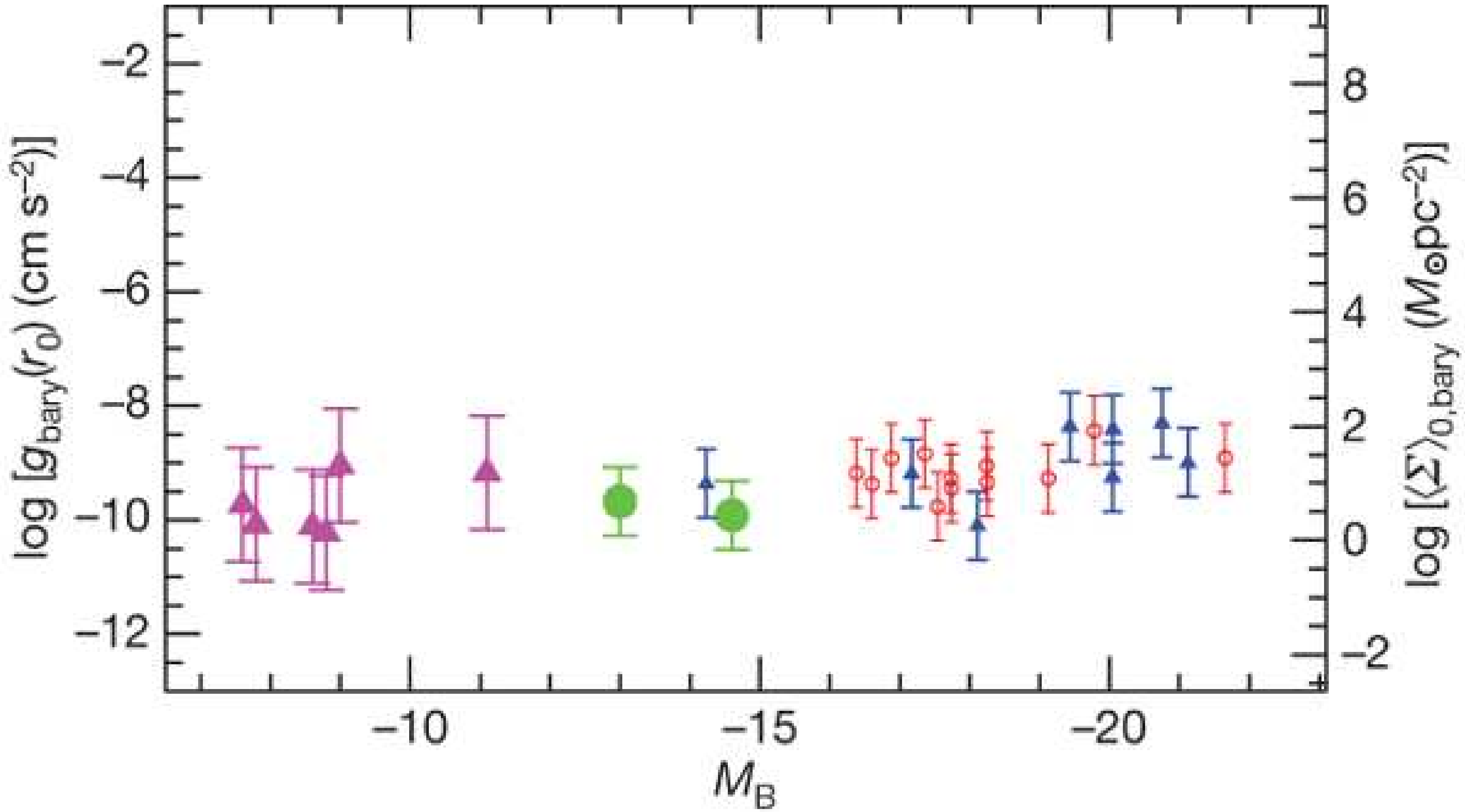
Donato et al.'09, Gentile et al.'09



DM surface density for different types of galaxies.

An evidence in favor of MOND?

Gentile et al.
Nature’09



Baryonic surface density for different types of galaxies.

Qualitative understanding?

- **Gravitational collapse:** gravitational potential energy $\mathcal{U} \propto \frac{GM}{R}$ balances kinetic energy of cosmological expansion $\mathcal{K} \propto H^2 R^2$

- The sphere of influence of the DM halo (*sphere of zero velocity*, *turn-around radius*)

$$R_{\text{ta}} \propto \left(\frac{GM_{\text{ta}}}{H^2(t)}\right)^{1/3}$$

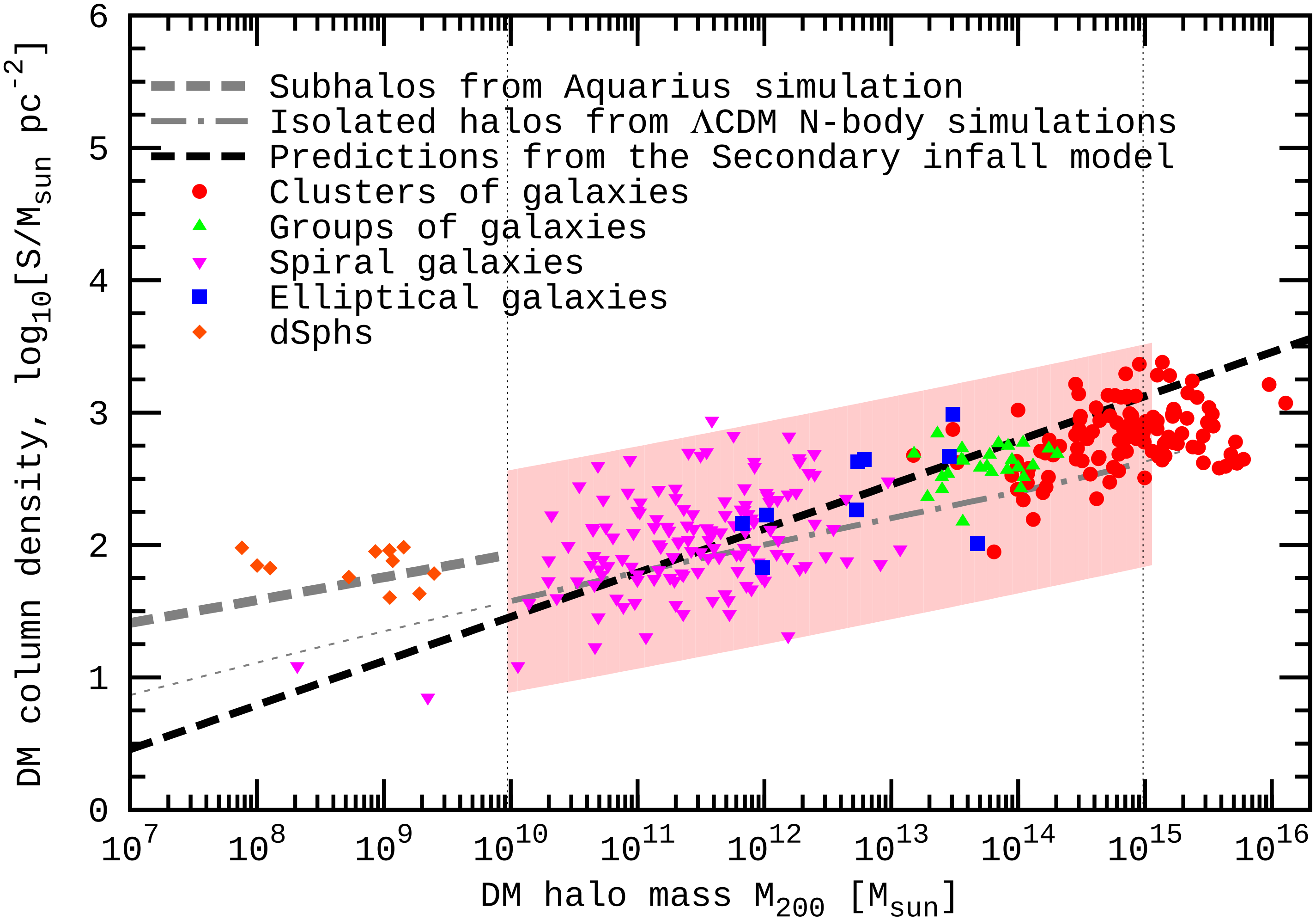
- The density inside the turn-around radius is **the same for objects of all masses** and is determined by cosmology $\rho_{\text{ta}}(t) \propto \bar{\rho}_M(t)$

- Almost self-similar solutions would give

$$\mathcal{S} \propto \rho_{\textbf{ta}} R_{\textbf{ta}} \propto c(M) \cdot M_{\textbf{ta}}^{1/3}$$

- Observationally, the "**concentration parameter**" $c = R_{\text{ta}}/r_\star$ is a weak function of mass $c(M) \propto M^{-0.1}$

DM column density in infall model



$$\mathcal{S} \sim \left(M_{\text{halo}}\right)^{1/3-0.1}$$

arxiv:0911.3396

Large scale modifications of gravity

- A possible set of consistent (as a spin-2 field theory) large scale modifications of gravity is described by two parameters – scale r_c and a number $0 \leq \alpha < 1$ G.Dvali et al.

- In these models (DGP, "degravitation") gravity becomes weaker at large scales – Universe accelerates

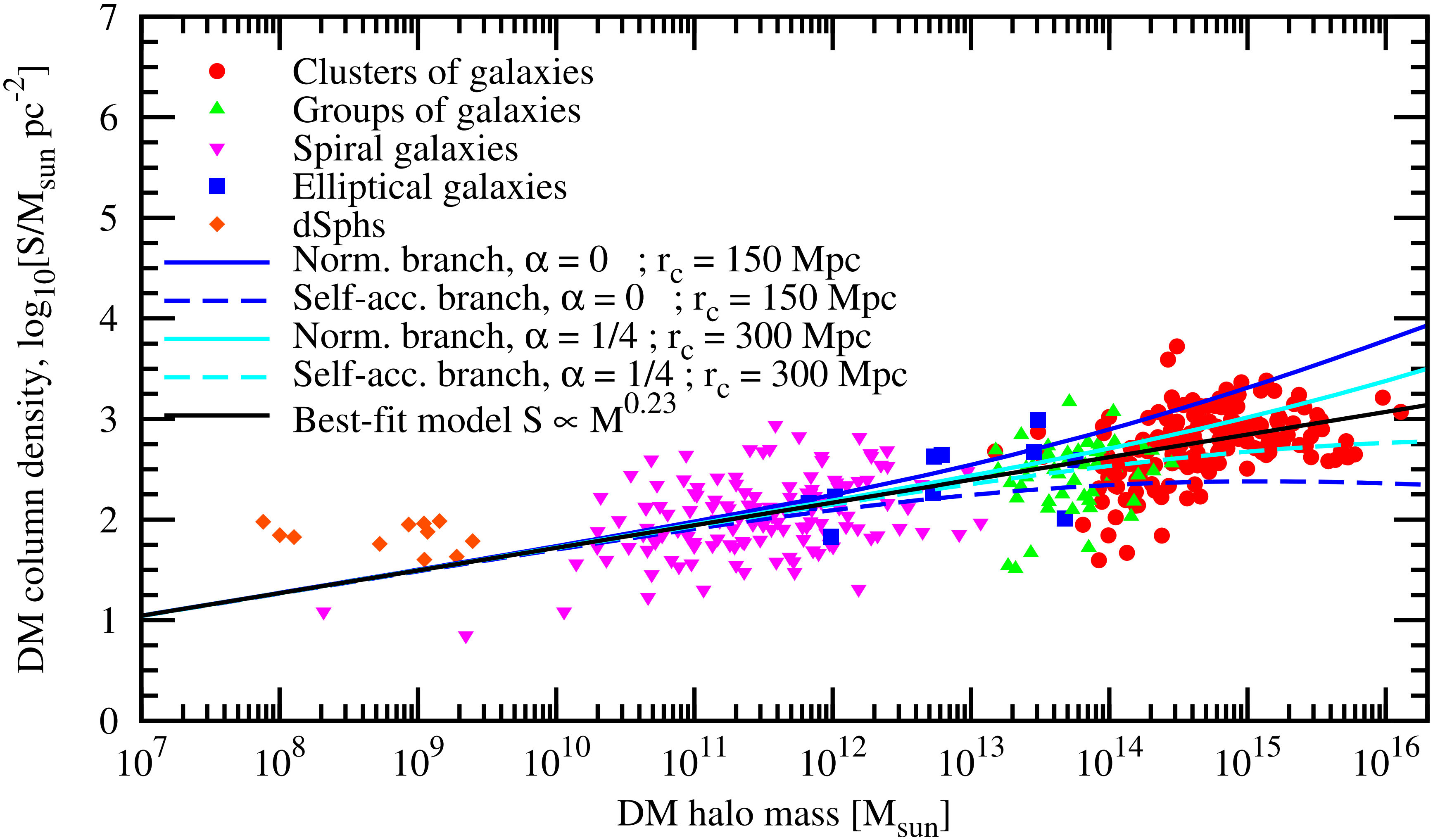
$$\phi(r) = \begin{cases} \dfrac{GM}{r}, & r \ll r_c \\ \dfrac{GM}{r^{n(\alpha)}}, & r \gg r_c \end{cases}$$

- Cosmological expansion

$$H^2(z) = H_0^2 \left(\sqrt{\Omega_M (1+z)^3 + \Omega_{r_c}} + \sqrt{\Omega_{r_c}} \right)^2$$

Restrictions on modifications of gravity

1001.0565



Universal relation at all observed scales

- The relation between $\mathcal{S}$ and M_{halo} is observed for halos of **all** scales. The data spans many orders of magnitude in halo masses ($10^8 M_\odot$ – $10^{15} M_\odot$) – all scales at which DM is observed
- Reproduces remarkably well (best-fit value, scatter, slope of subhalos) predictions of pure CDM N-body numerical simulations
- No visible features – universal (**scale-free**) dark matter down to the lowest observed scales and masses?
- Baryons do not affect “N-body relation” significantly.
- Can probe large scale modifications of gravity and non-CDM dark matter models (semi-analytically)
- Process the data in a uniform way to get the error-bars right

Thank you for your attention