Galaxy Structure Observations and Cored Density Profiles

CHANGING DIRECTION IT IS TIME FOR WDM

Paolo Salucci

SISSA , INFN TS, GSSI L'Aquila

18th Paris Cosmology Colloquium Chalonge,
Observatoire de Paris 23,-25 JULY 2014

DARK MATTER IN GALAXIES
CDM PARADIGM

- We know the simple observational scenario we need to know.
- A new elementary dark particle from a particular extension of the Standard Model of Elementary Particles provides the Universe with the required collision less massive particle behind the Dark Matter Phenomenon.
- the particle has left its imprint in the baryonic content of the Universe; we can predict its astrophysical impact by means of simulations and analytical modelling
- we can verify this by means of properly suited observations
- we will find out the dark particle by means of accelerator measurements or in non-accelerator detectors by direct or indirect ways.

After 30 years since the Dark Matter Phenomenon has emerged

Progresses in detecting the searched particle have been very few, if any.

No dark particle has been “produced” or "seen" at CERN

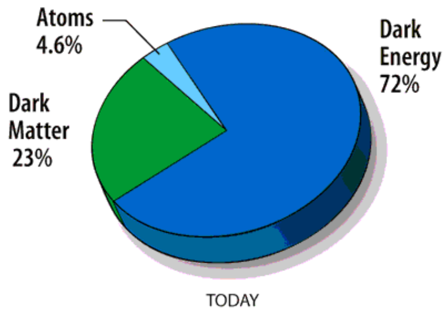
no dark particle has been detected in the many underground dark matter experiments

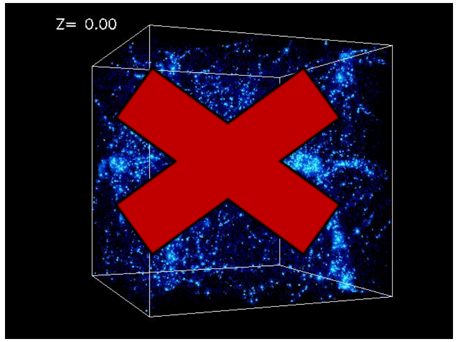
no dark particle has exposed itself by emitting radiation while annihilating with its antiparticle in the centers of Earth, Sun and Galaxy.

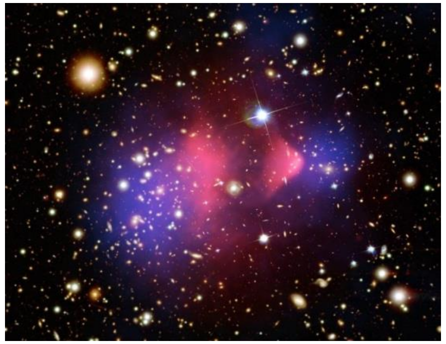
the number of dark halos and their density profiles are very different with respect to those that are predicted within the CDM paradigm.

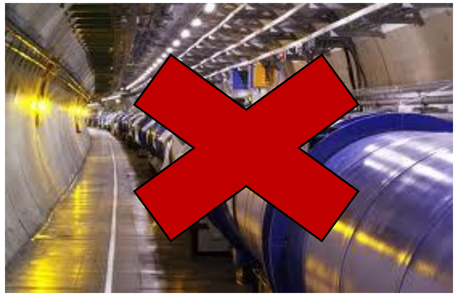
- very serious lack of the "prova regina" that a collision less COLD elementary particle runs the Universe.

Dark Matter is the main protagonist in the Universe





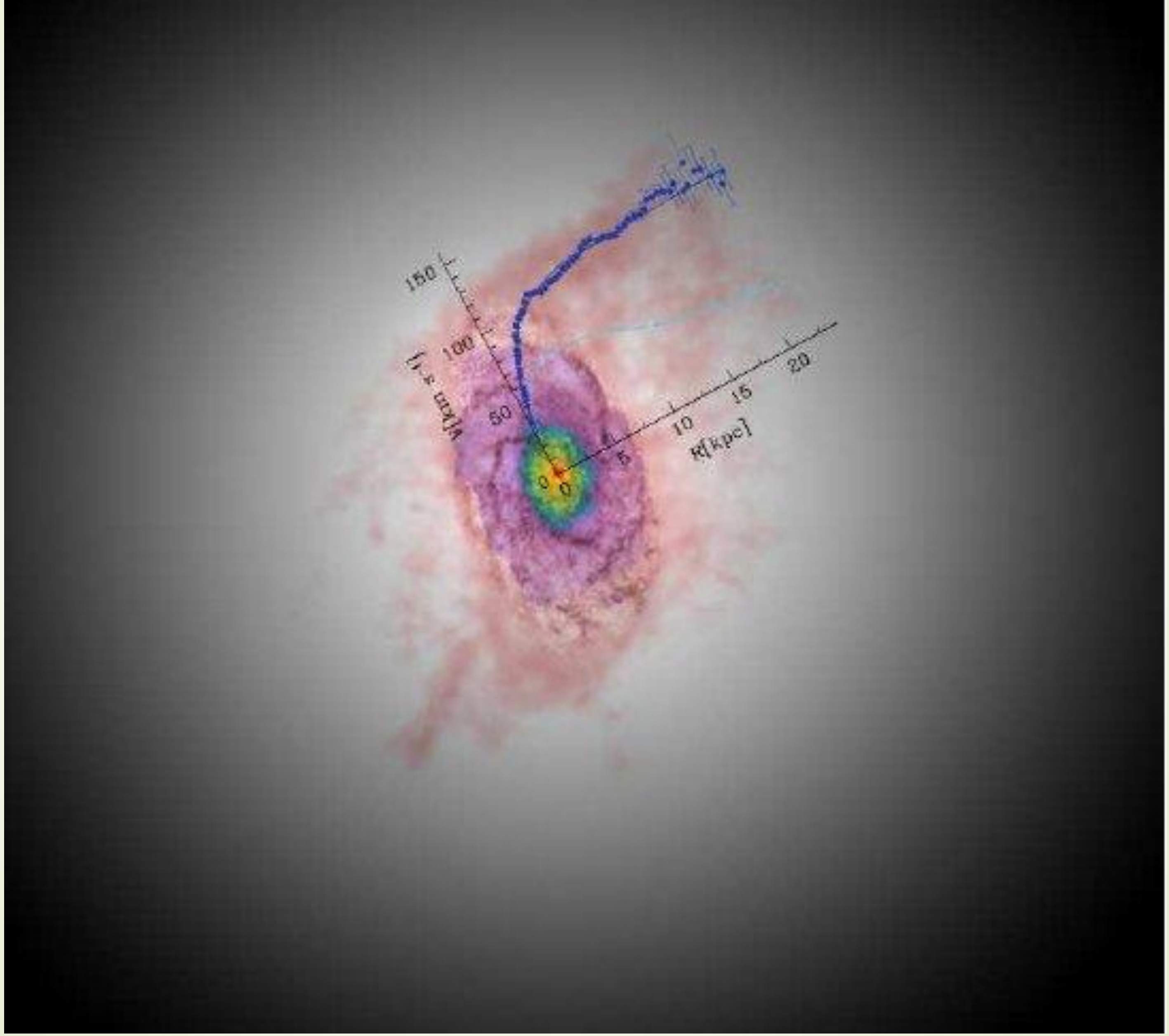




CHANGING PARADIGM: WDM is Dark Matter in Galaxies

Dark Matter in Spirals, Ellipticals, dSphs
Dark and Luminous Matter in galaxies.
Phenomenology of the mass distribution in Galaxies.

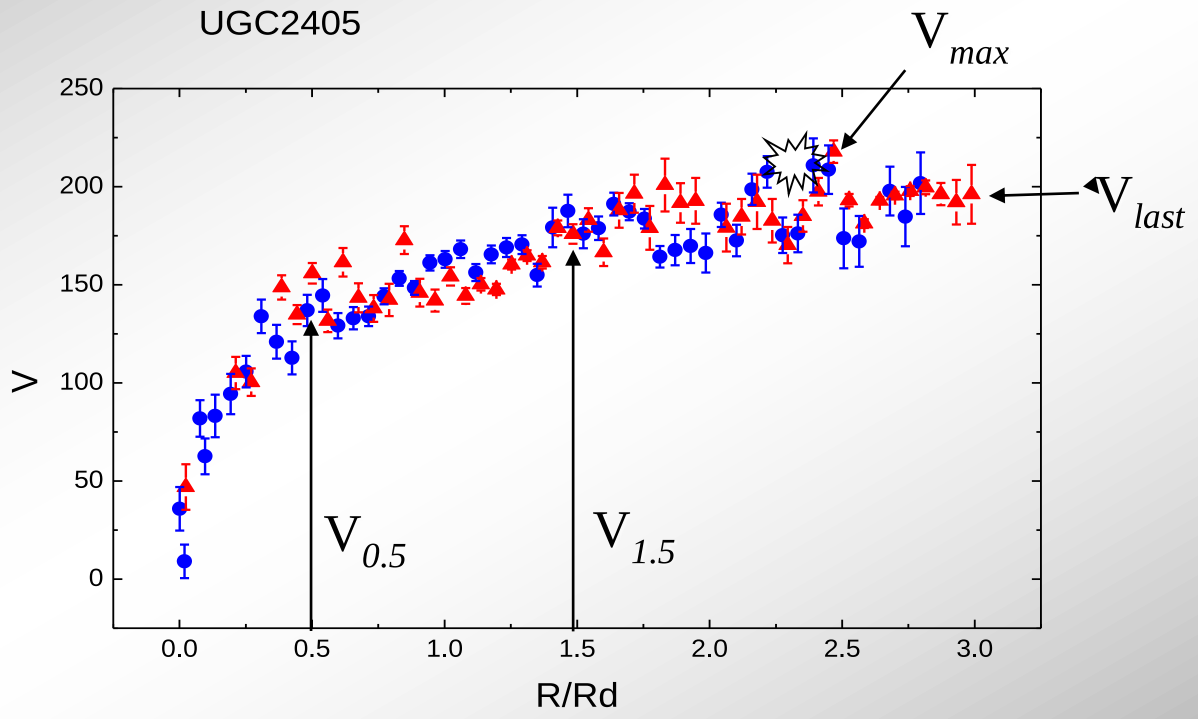
kinematics



Radial Tully Fisher

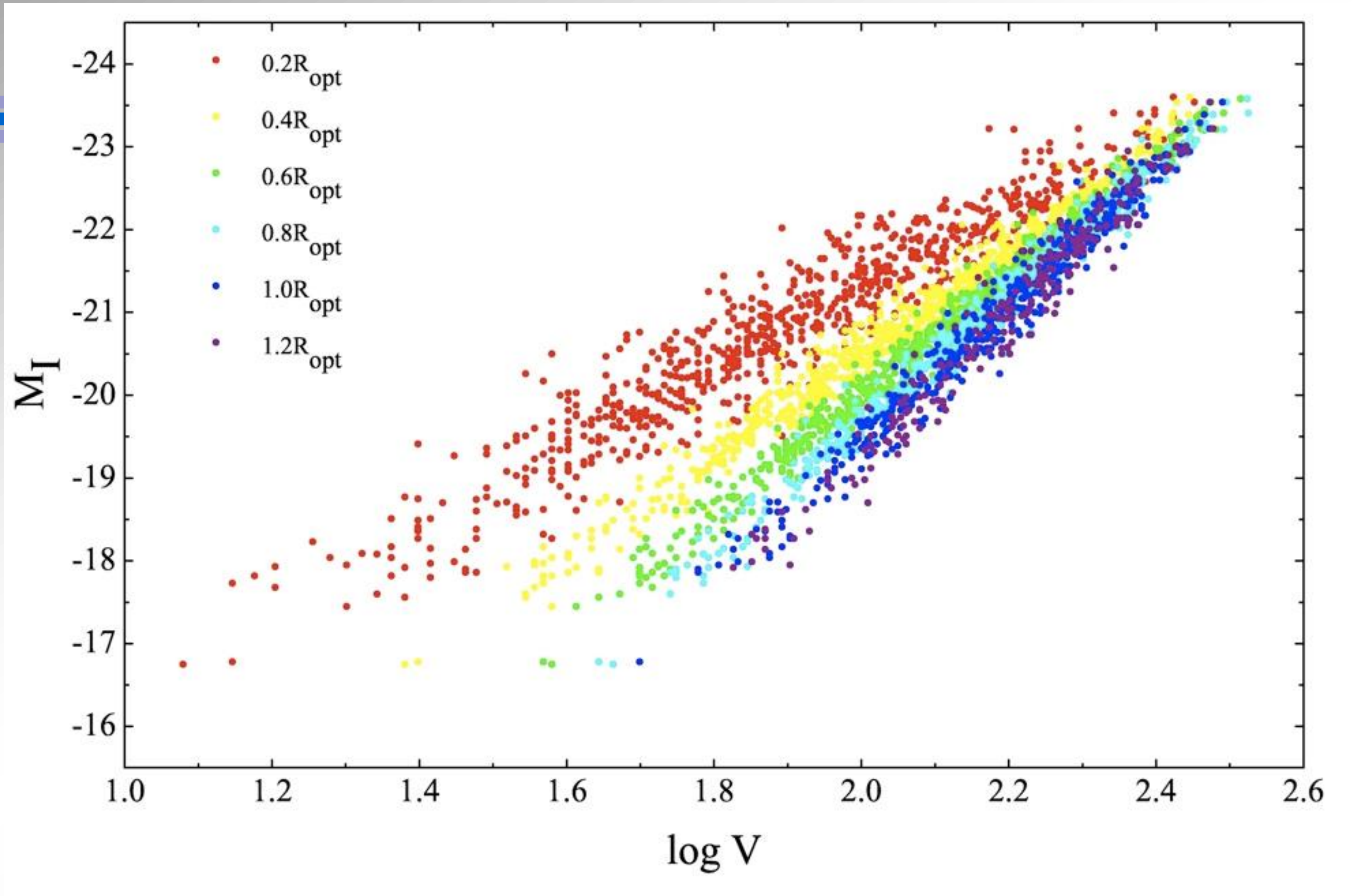
The relation: *magnitude* vs log *velocity* @ different *radii:* $x_i R_D$, [x_i=0.5,1,…5]

$M = a_i + b_i \log V(x_i R_D)$



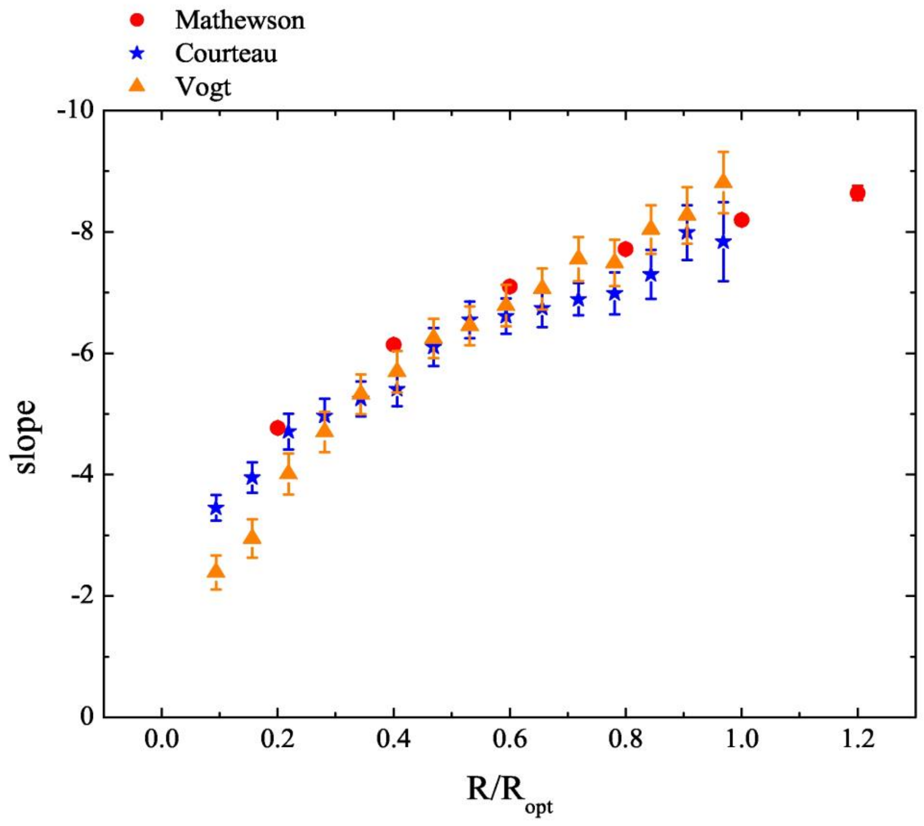
No change in slope b_i implies: a) no DM or b) a constant fraction of DM at any radius

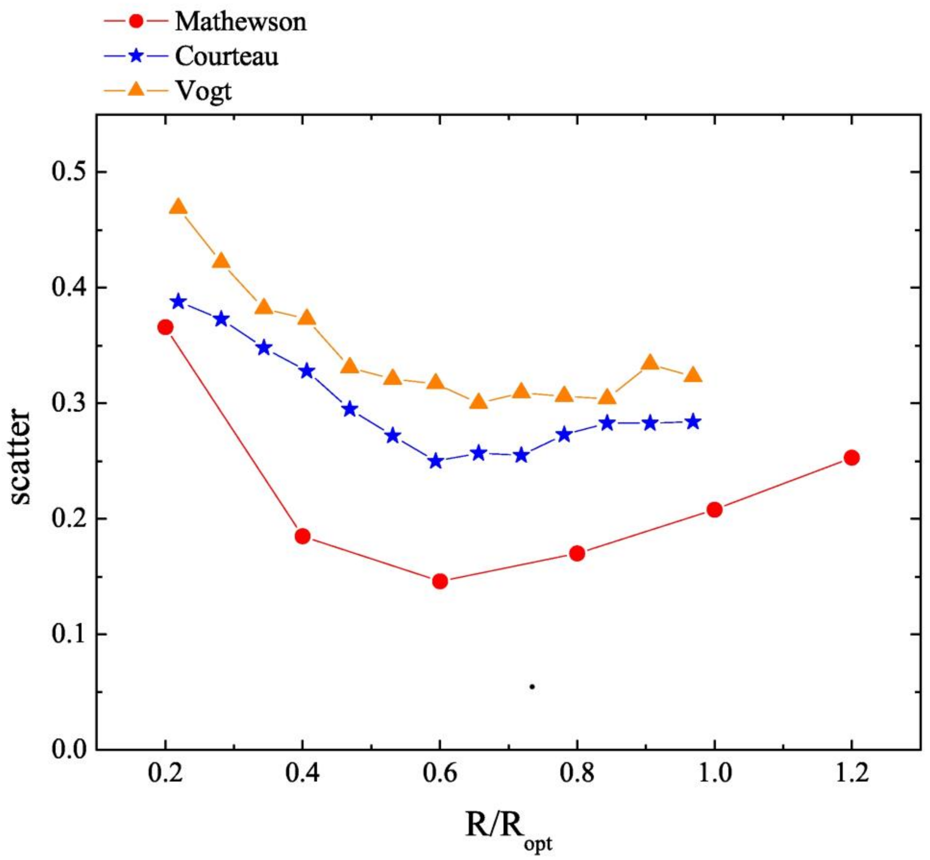
Radial TF relationships



Slope and scatter of the radial TF-relations:

$$M_B = a_i + b_i \log V(x_i R_D)$$





T
8

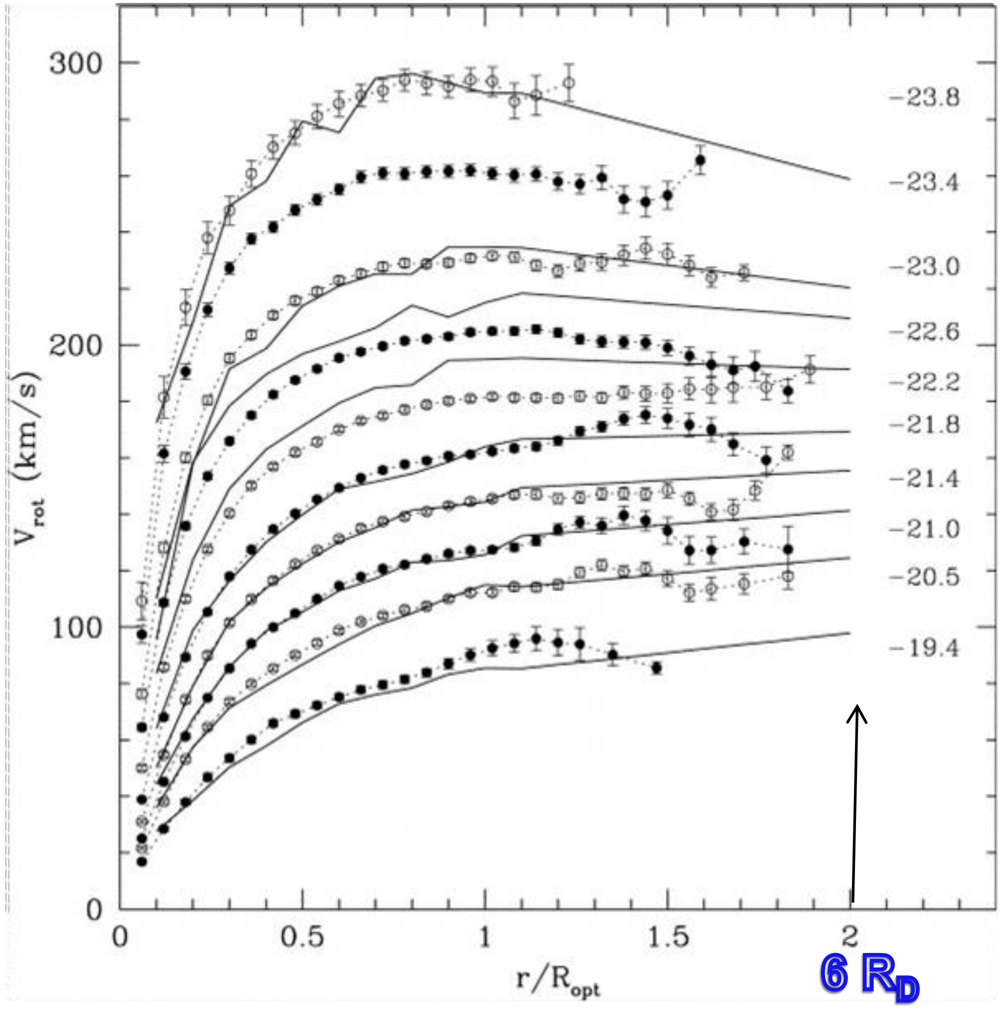
The minimum scatter: 0.2 mag at 2.2 R_D

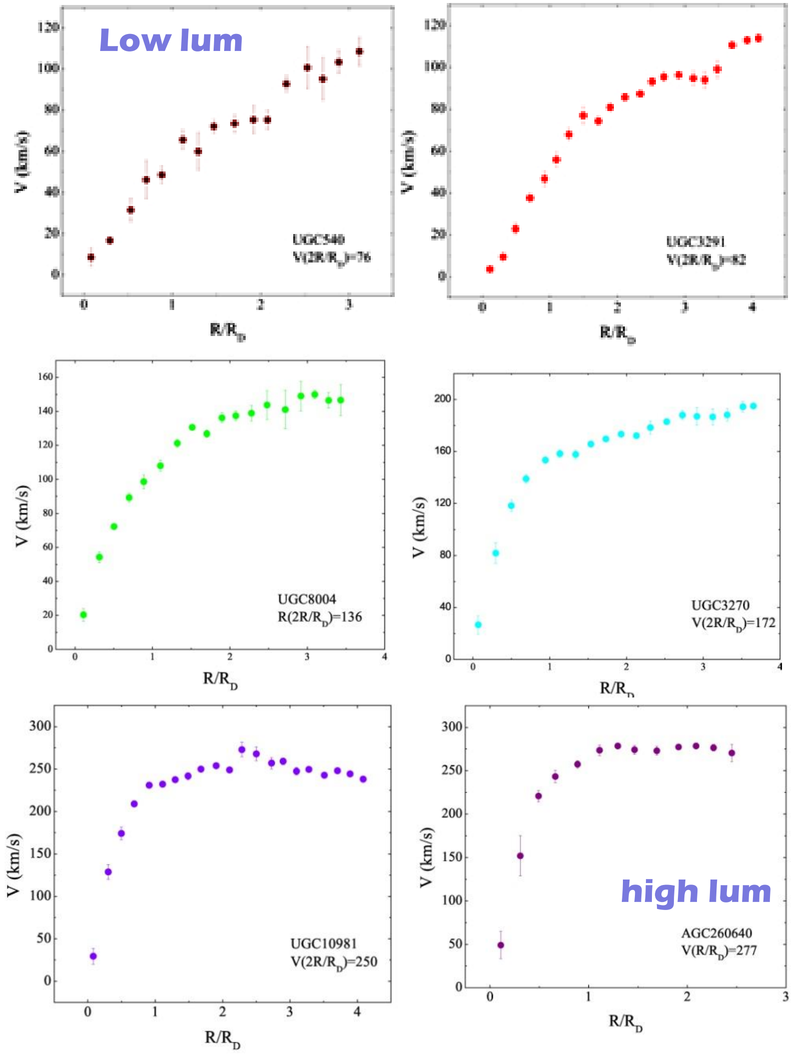
Implication: DM emerges at large radii

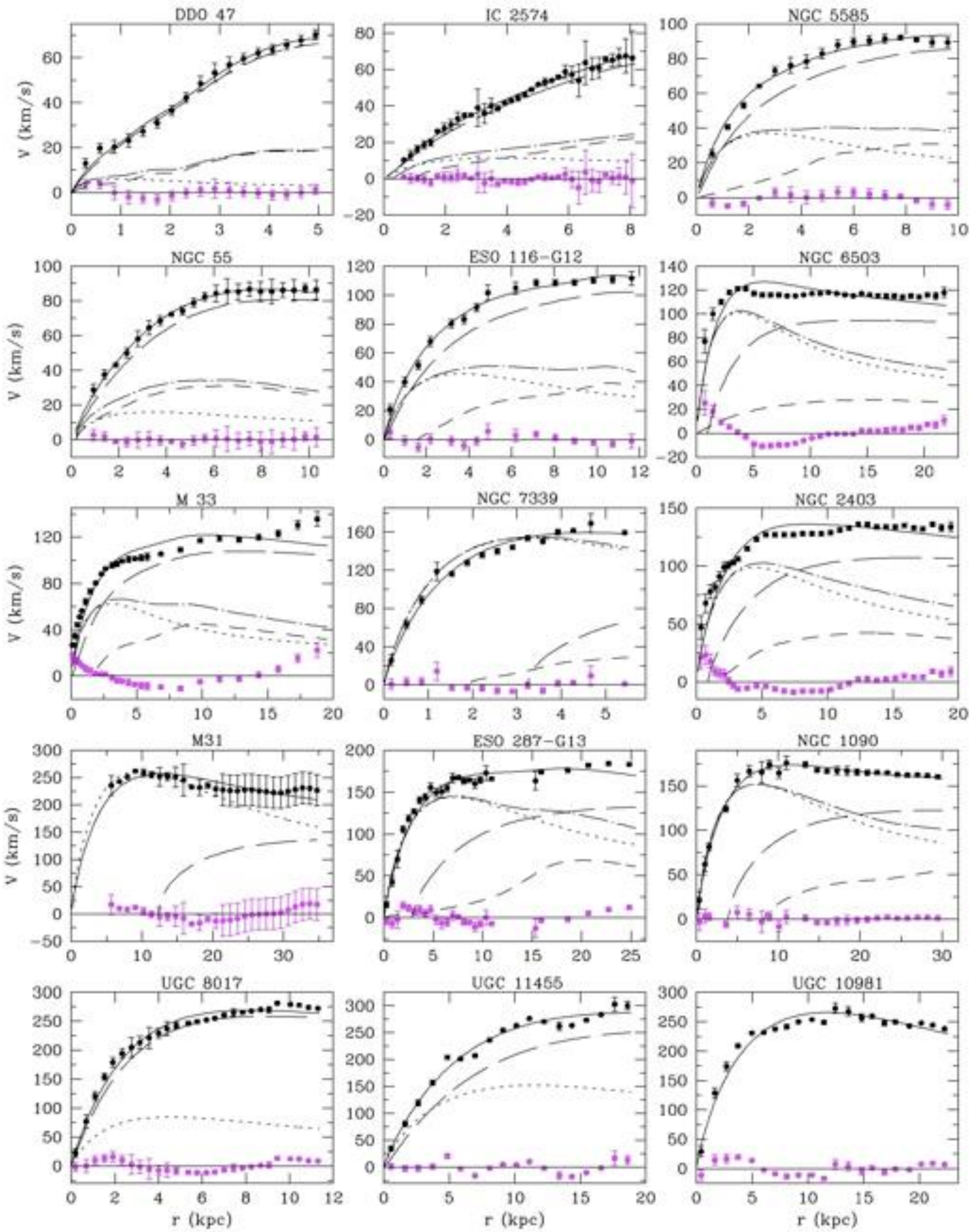
Rotation Curves

TYPICAL INDIVIDUAL RCs SHOWN BY INCREASING LUMINOSITY

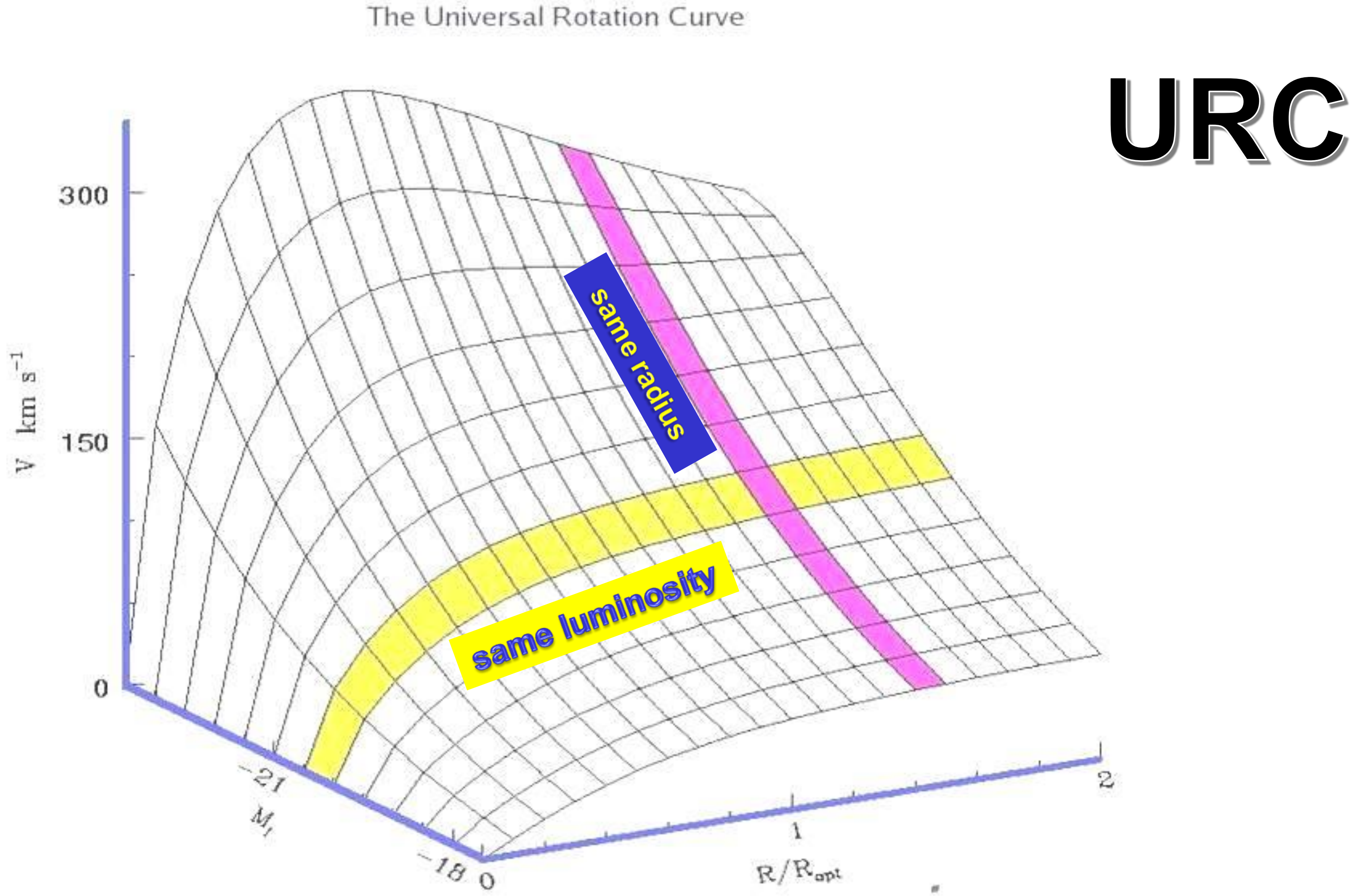
Coadded from 3200 individual RCs





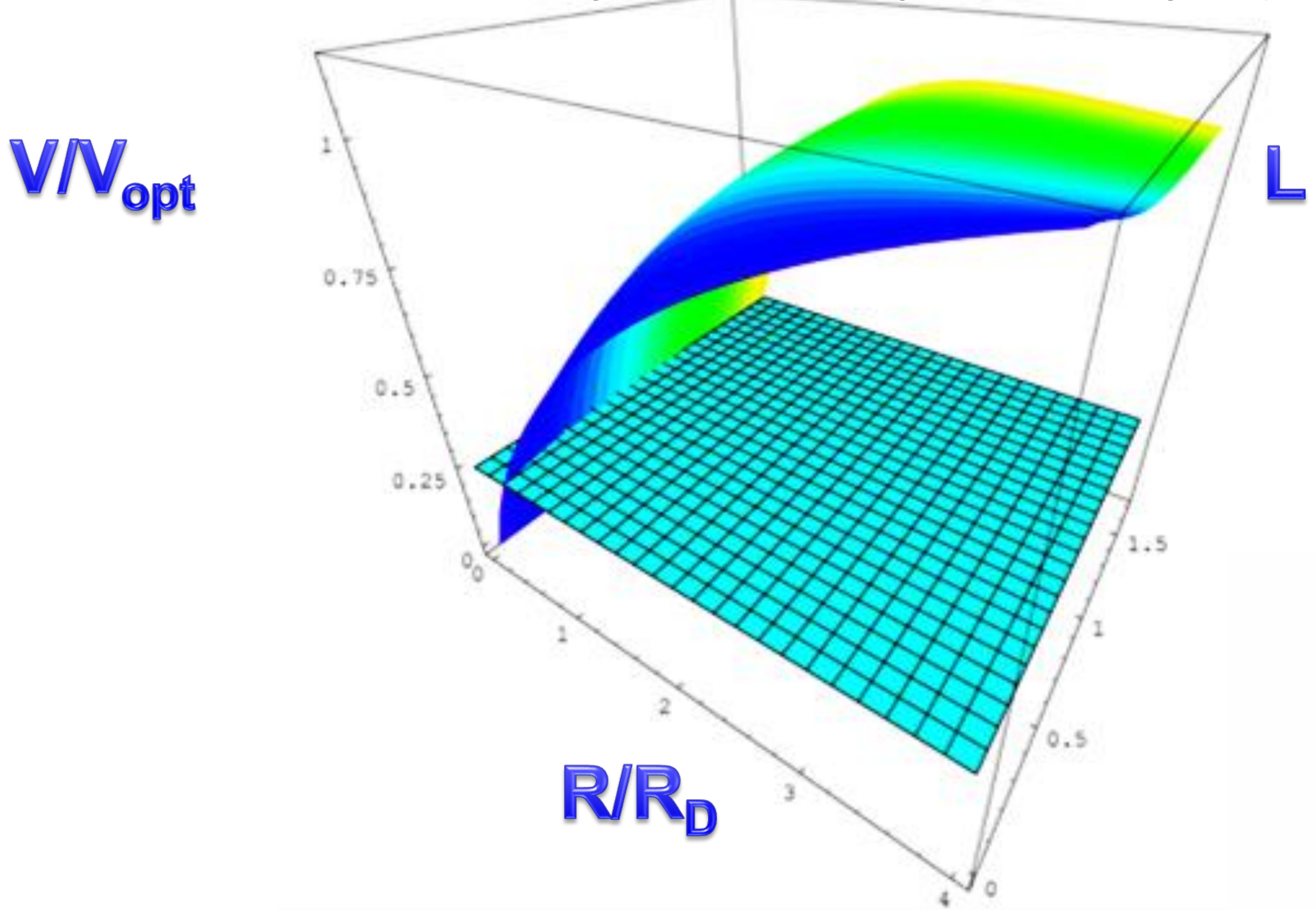

DDO 47
IC 2574
NGC 5585
NGC 55
ESO 116-G12
NGC 6503
M 33
NGC 7339
NGC 2403
M31
ESO 287-G13
NGC 1090
UGC 8017
UGC 11455
UGC 10981
V (km/s)
r (kpc)

The Cosmic Variance of V measured in galaxies of same luminosity L at the same radius $x=R/R_D$ is negligible compared to the variations that V shows as x and L varies.



The Concept of the Universal Rotation Curve (URC)

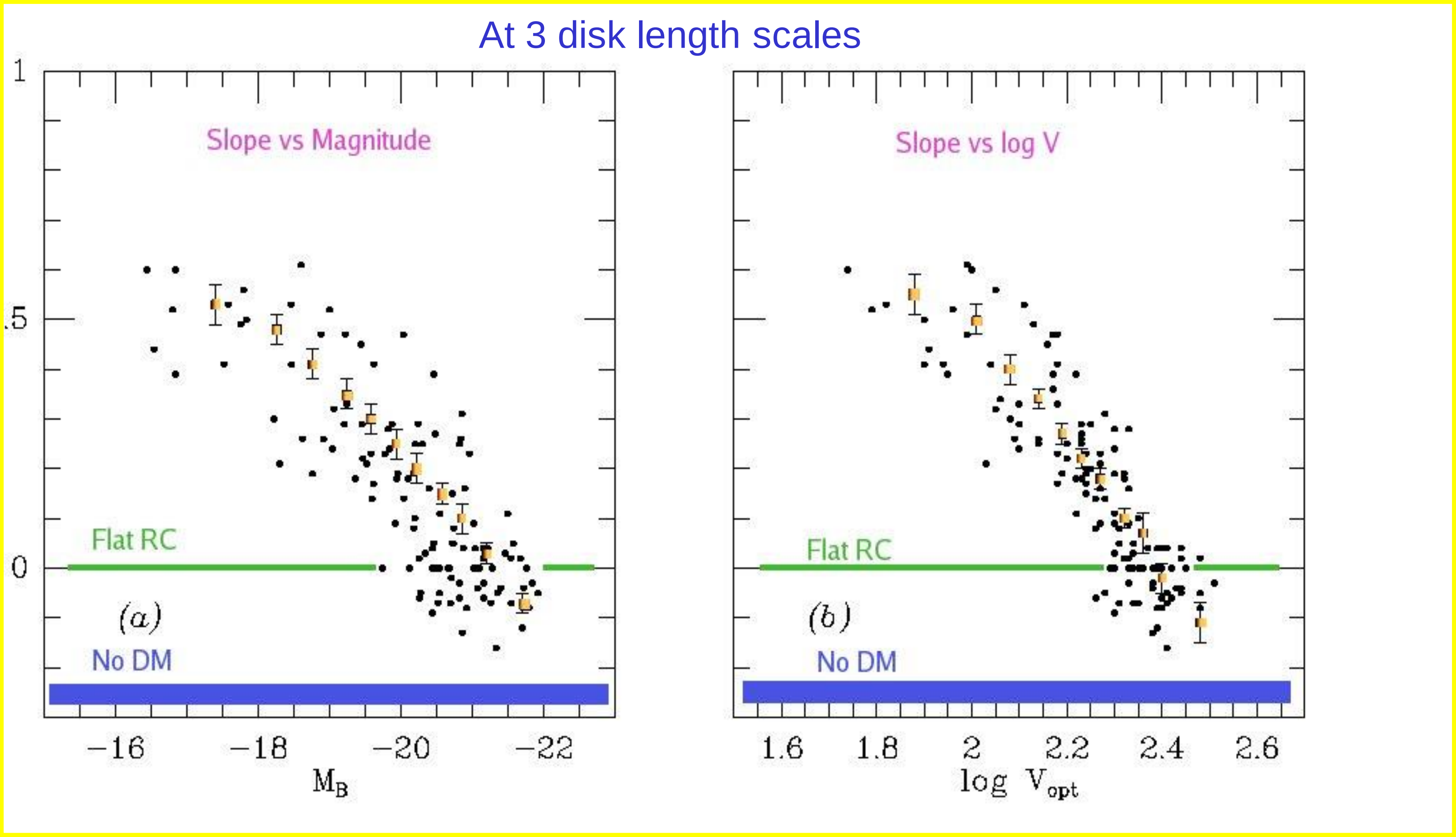
Every RC can be represented by: V(x,L) x=R/R_D



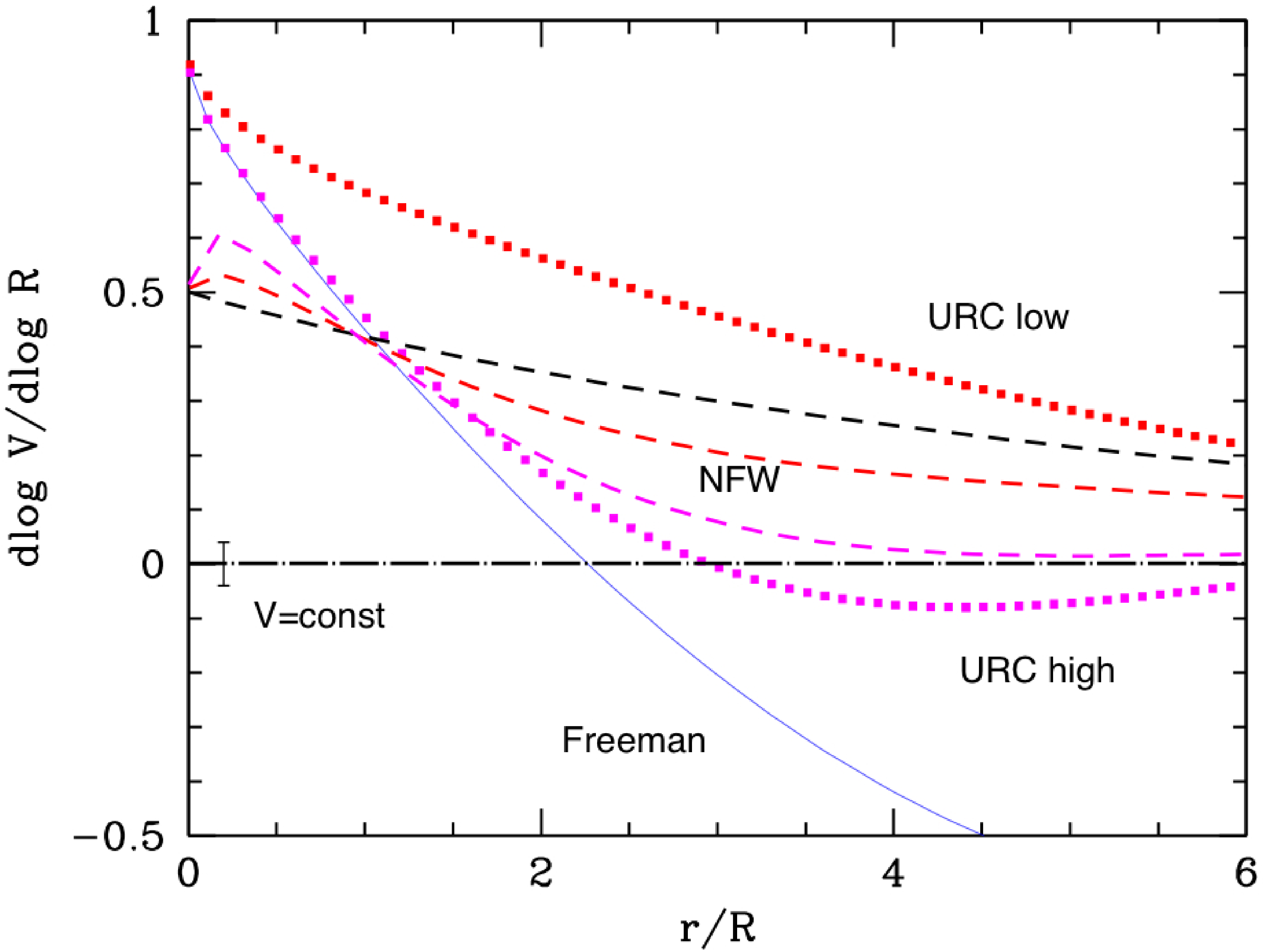
The URC out to 6 R_D is derived directly from observations

Extrapolation of URC out to virial radius by using V(R_{vir})

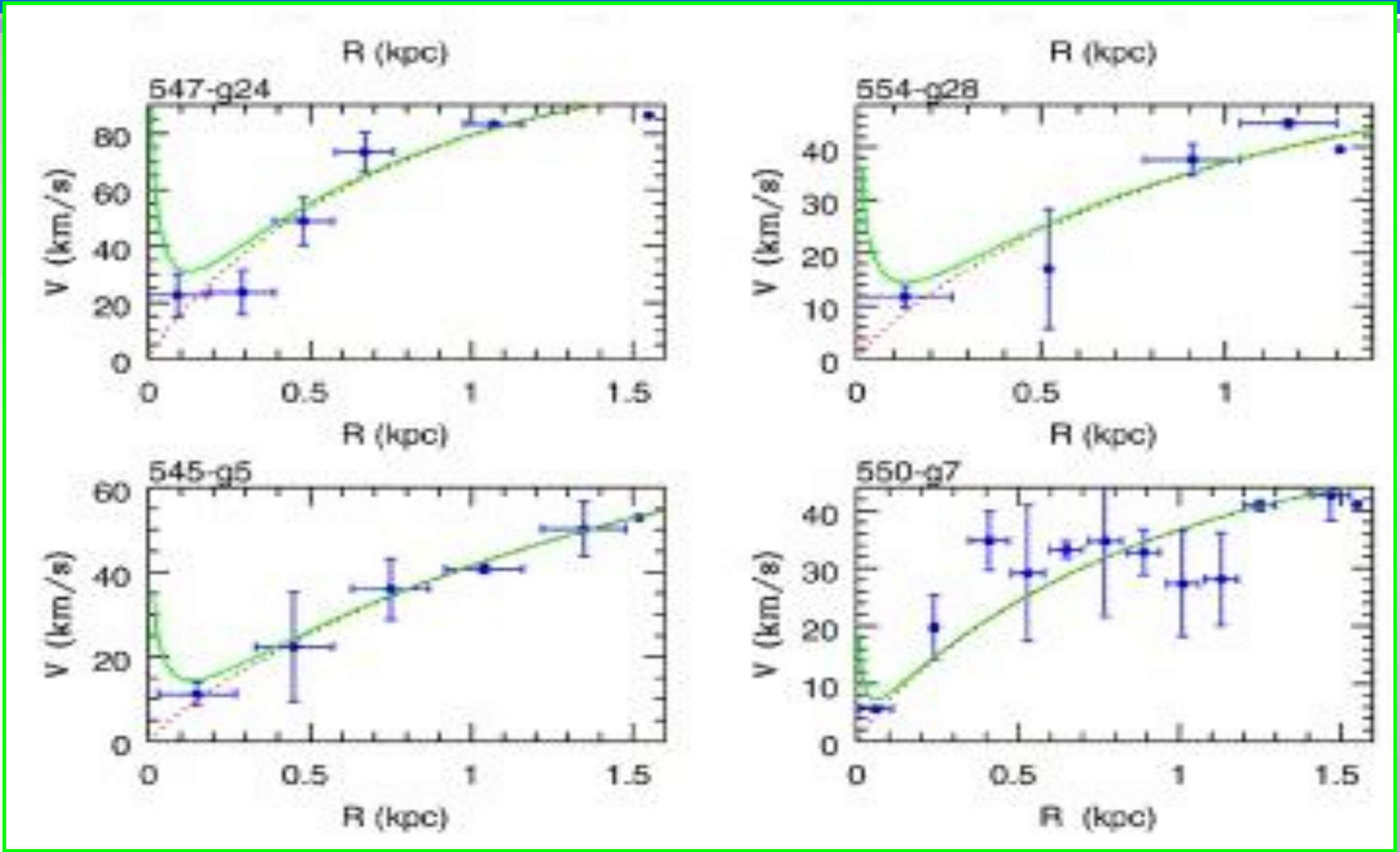
RC slopes vary among galaxies and within them.
They indicate the presence and the amount of dark matter.



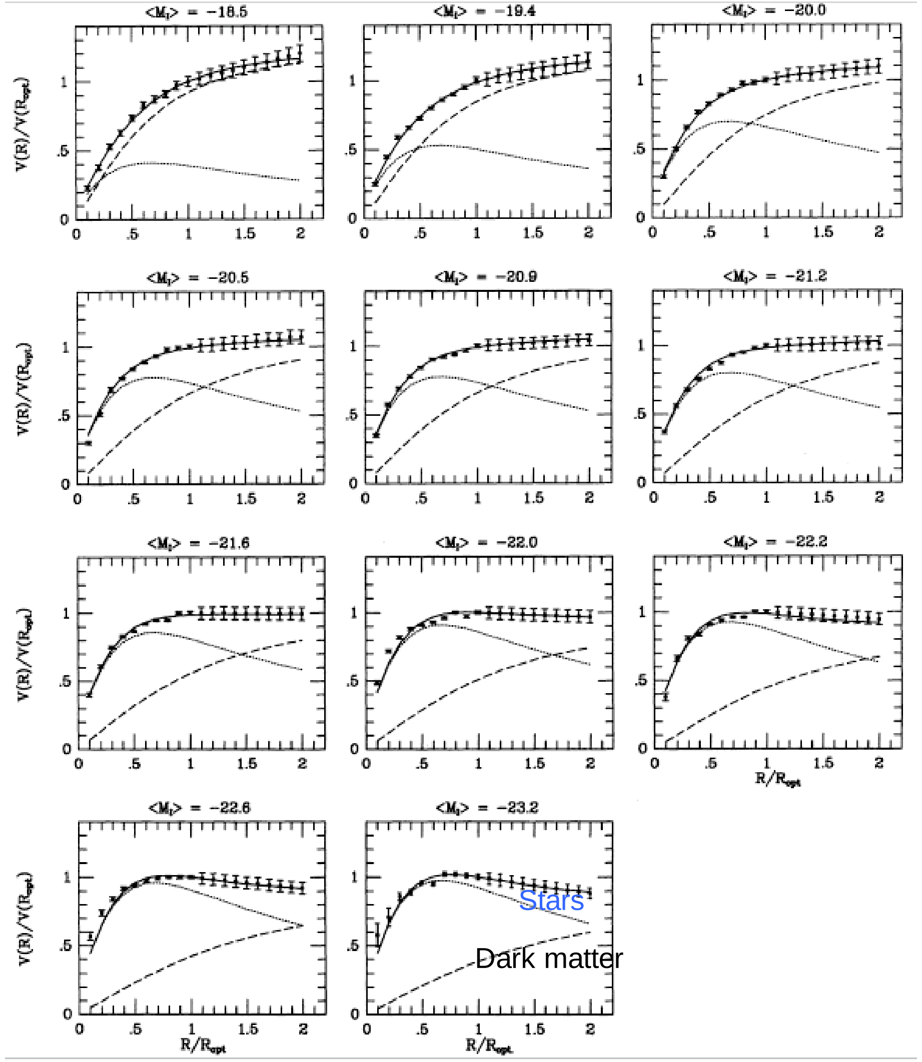
The slope of the RC



Modelling the very inner circular velocities:
light traces the mass



Modelling the Universal Rotation Curve



Rotation velocity

Stellar contribution

$$V_{\rm URC}\left(\frac{R}{R_{\rm opt}}\right) = V(R_{\rm opt})\left\{\left(0.72 + 0.44\log\frac{L}{L_*}\right)\frac{1.97x^{1.22}}{(x^2+0.78^2)^{1.43}} + 1.6\exp\left[-0.4(L/L_*)\right]\frac{x^2}{x^2+1.5^2\left(\frac{L}{L_*}\right)^{0.4}}\right\}^{1/2}\ {\rm km\ s^{-1}}$$

Dark matter halo contribution

Rotation curve analysis

From data to mass models

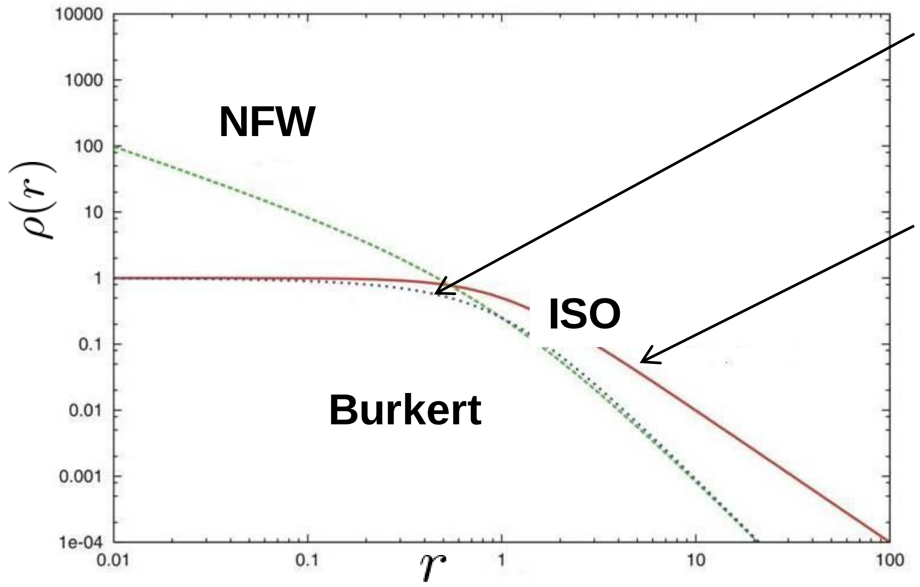
$$V^2(R) = V^2_{halo}(R) + V^2_{HI}(R) + V^2_{disk}(R)$$

observations = model

- V^2_{disk} **from I-band photometry**
- V^2_{HI} **from HI observations**
- V^2_{halo} **different choices for the DM halo density**

Dark halos with central constant density (Burkert, Isothermal)

Dark halos with central cusps (NFW, Einasto)



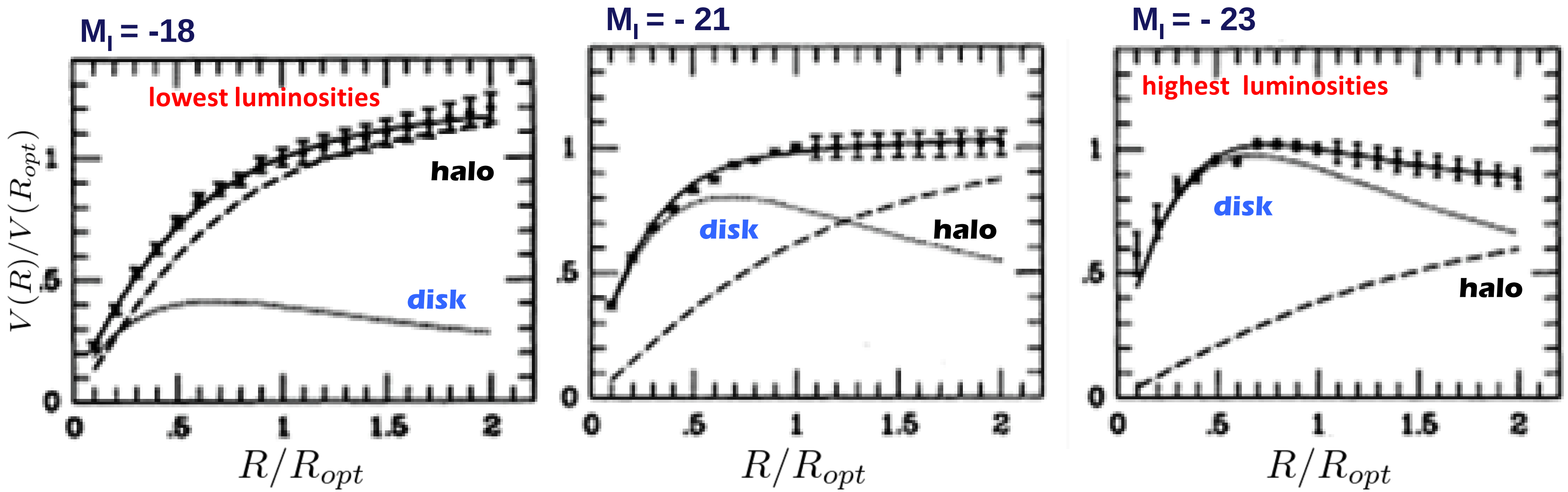
$$\rho(r) = \frac{\rho_0}{(1 + r/r_0)(1 + (r/r_0)^2)}$$

$$\rho(r) = \frac{\rho_0}{1 + (r/r_0)^2}$$

$\rho(r) = A\, r^{-\gamma}$, $\gamma \to 0$ does not converge

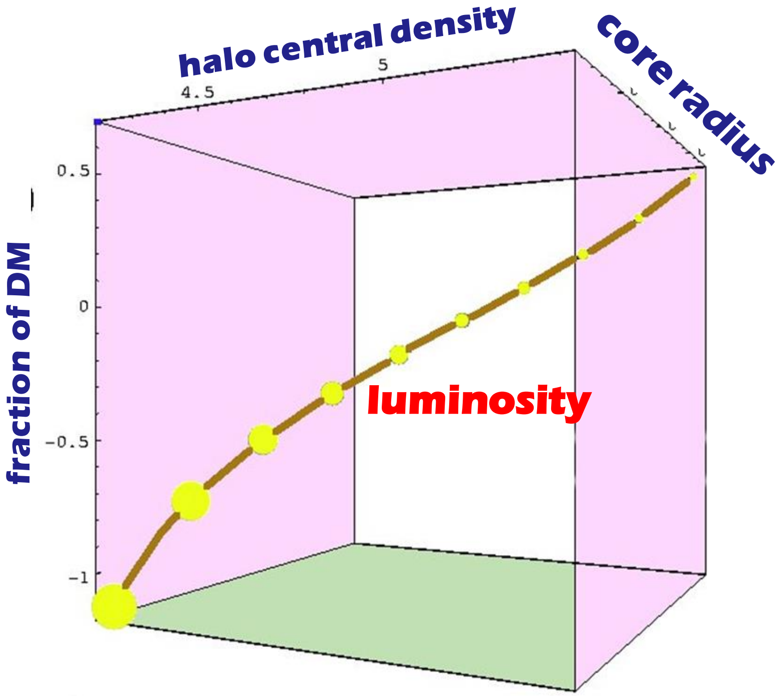
The mass model has 3 free parameters:
disk mass
halo central density
Halo core radius (length-scale)
Obtained by best fitting method

MASS MODELLING RESULTS

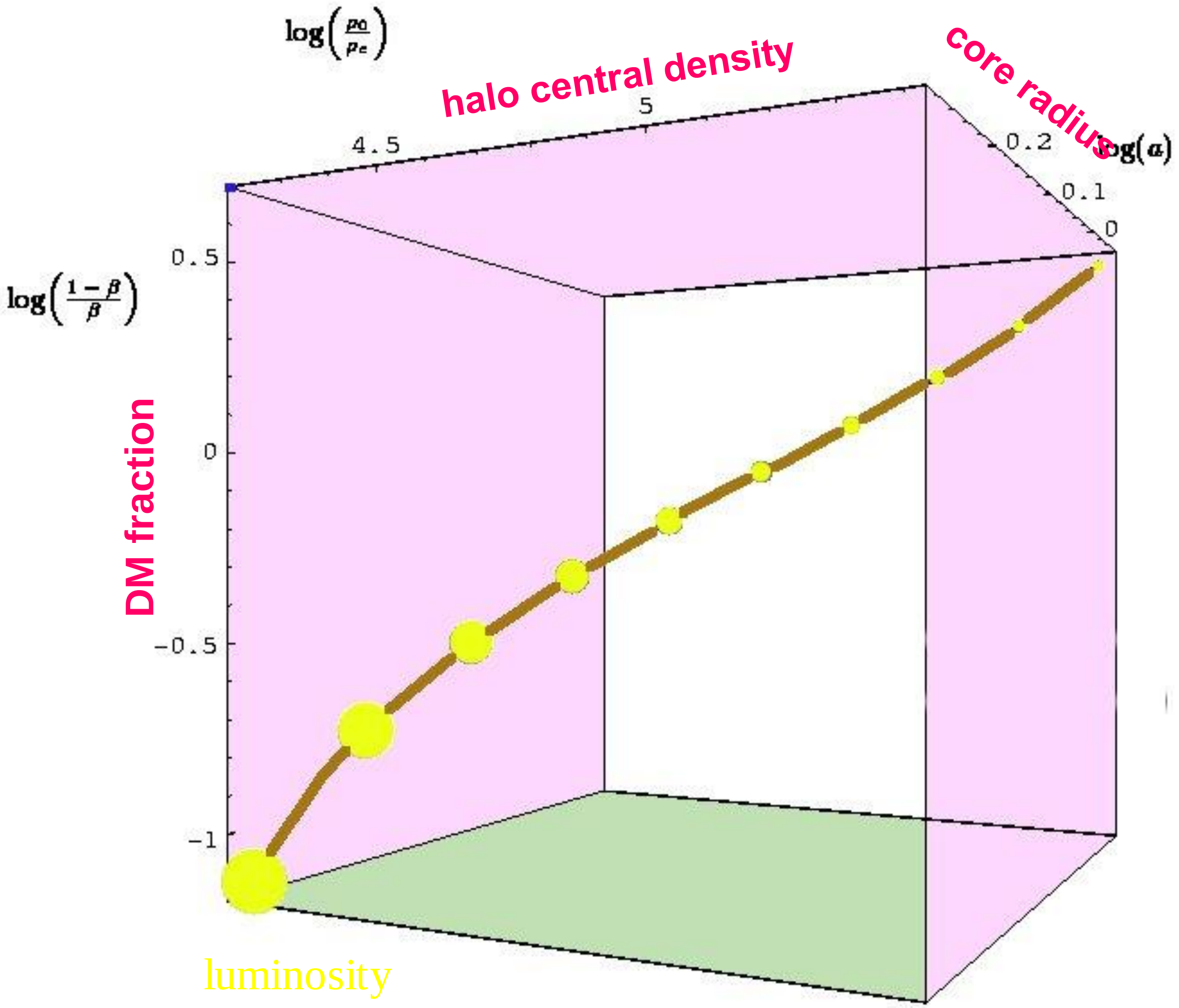


All structural DM and LM parameters are related with luminosity.

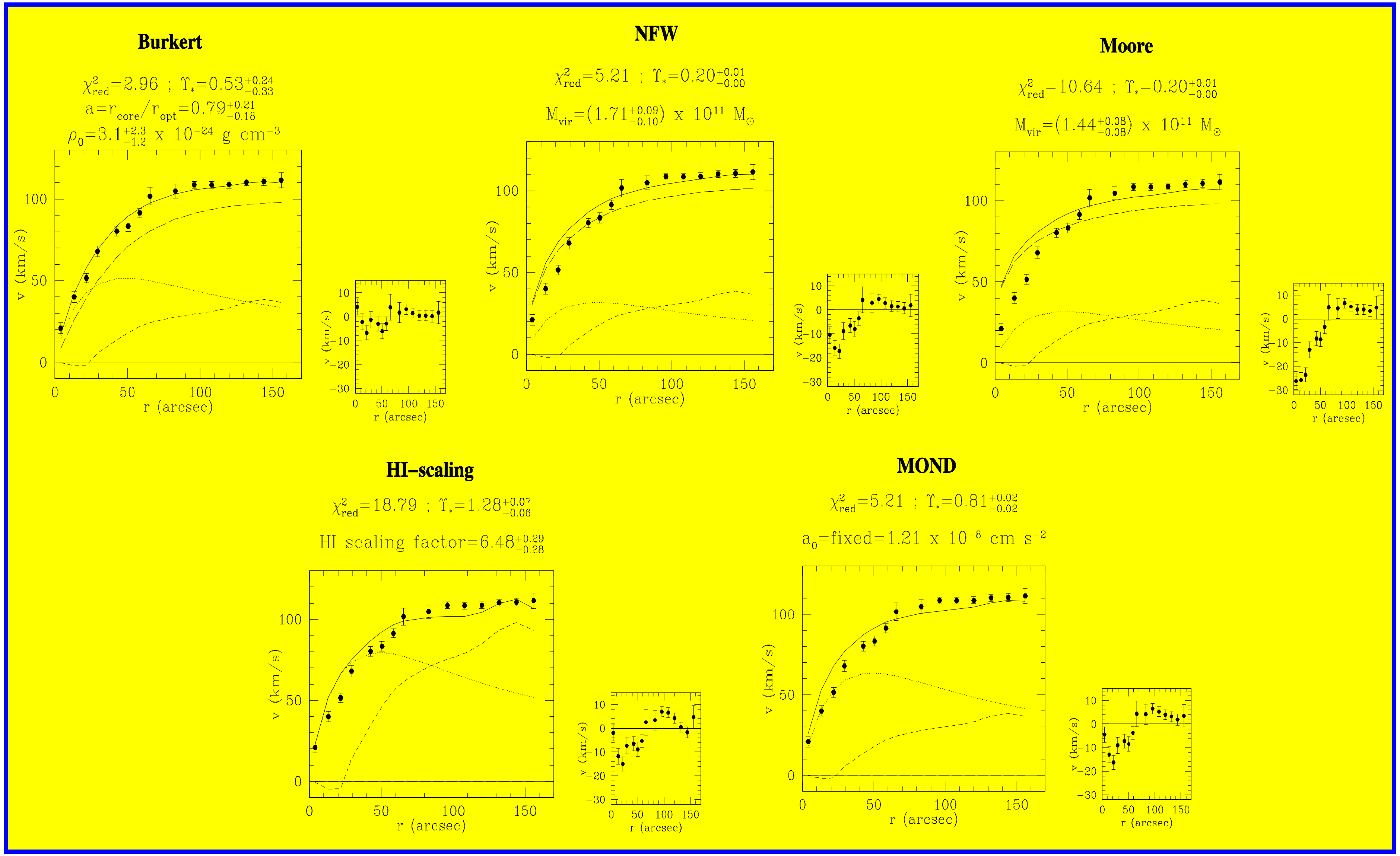
Smaller galaxies are denser and have a higher proportion of dark matter.



A family governed by luminosity



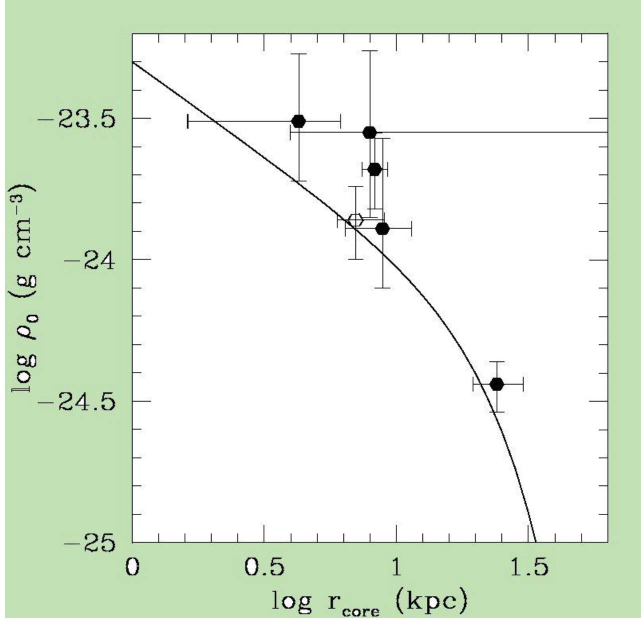
A test case: ESO 116-G12

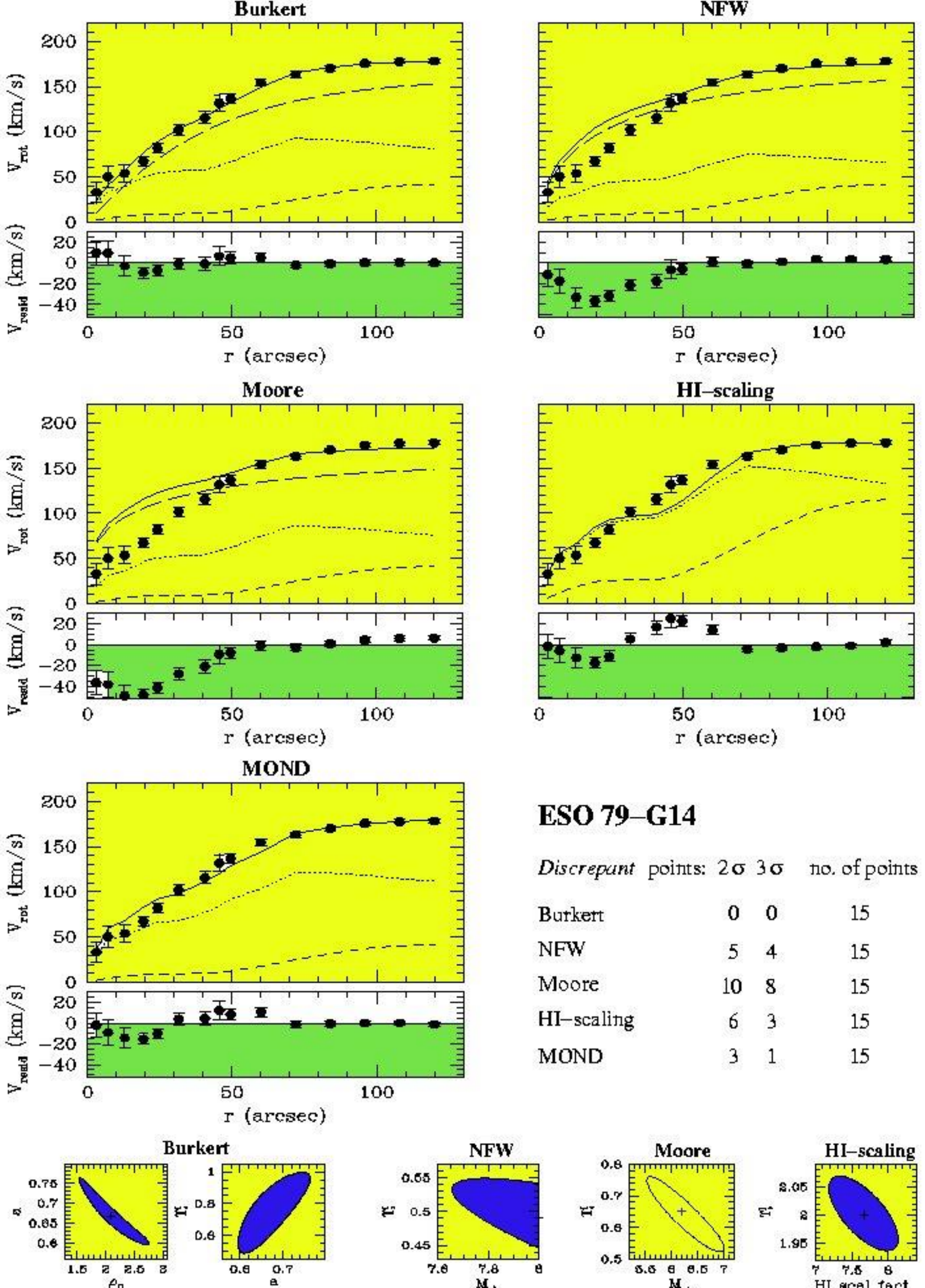


Cored halos the best fits

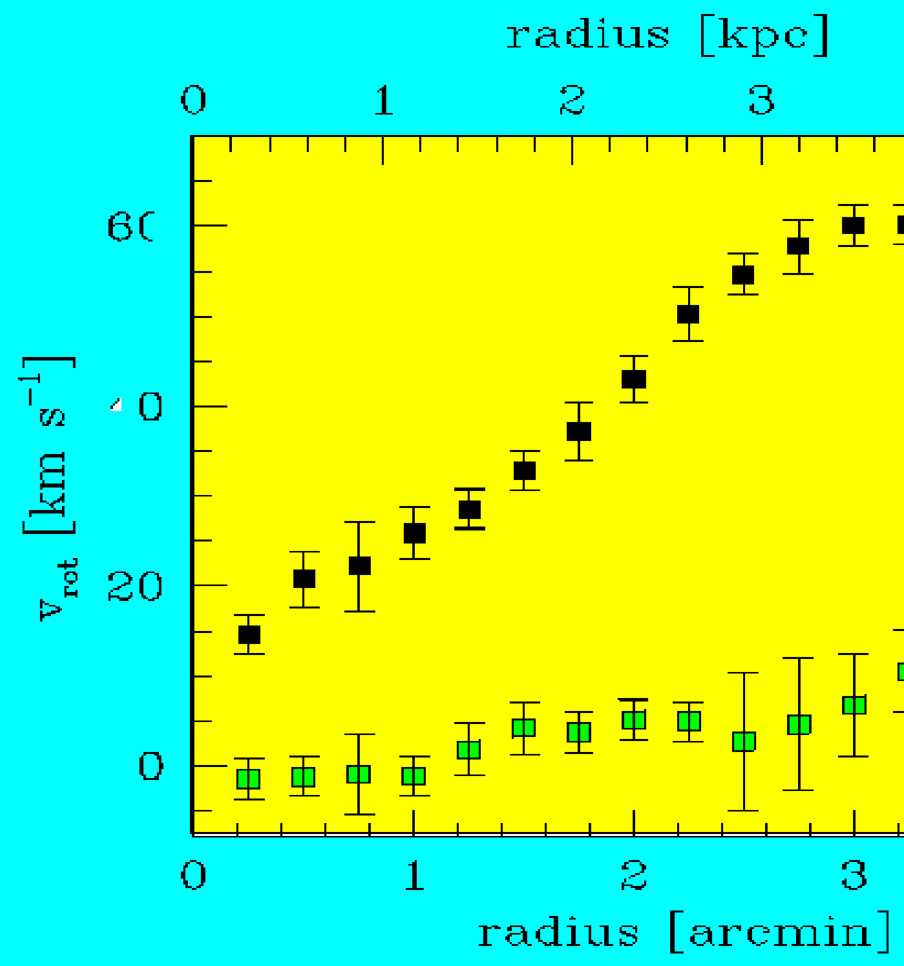
50 objects investigated
NFW inconsistent

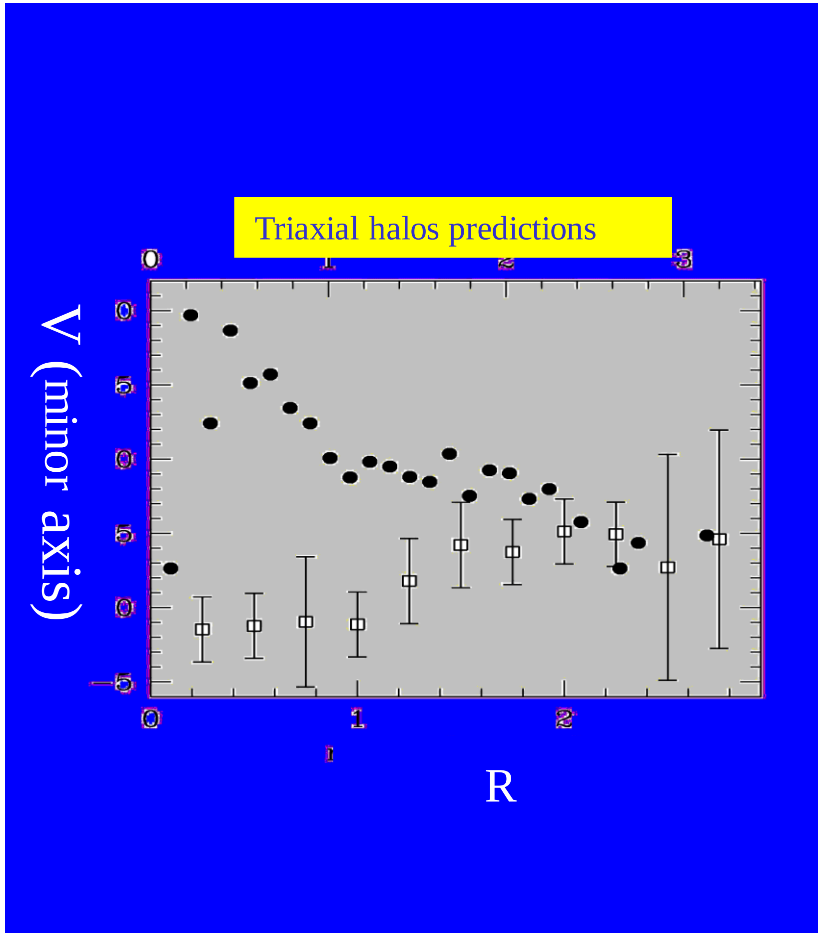
Density vs core radius





DDO 47: non circular motions ?

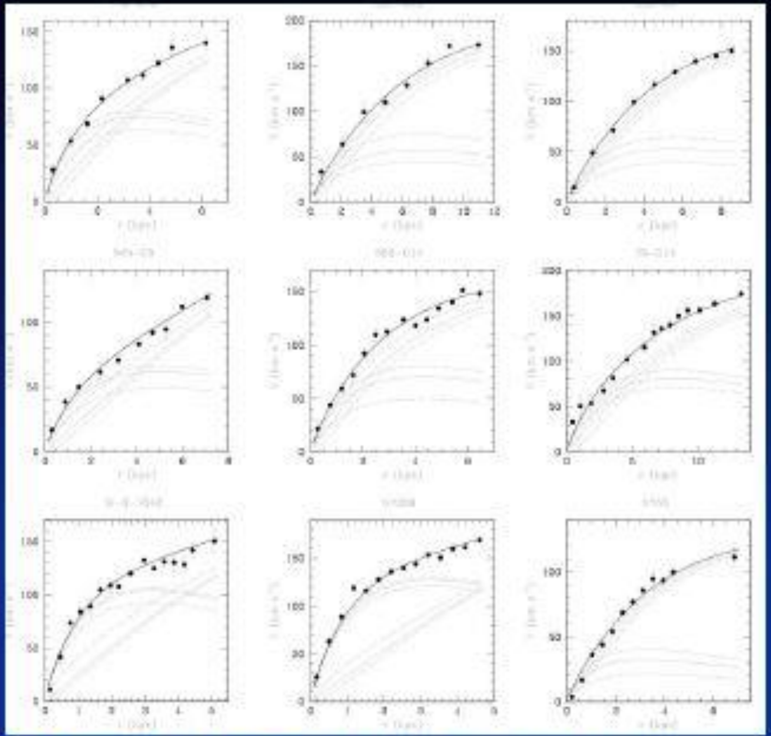


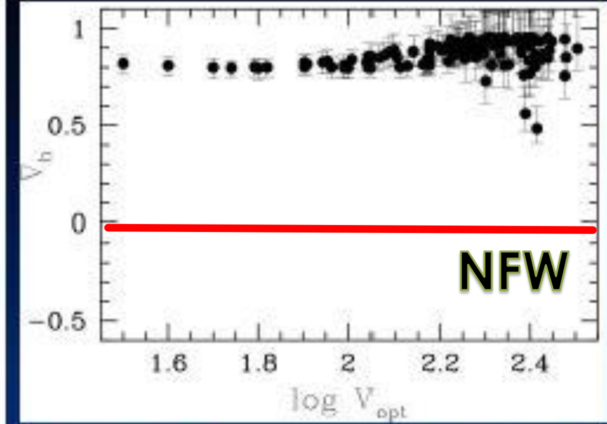


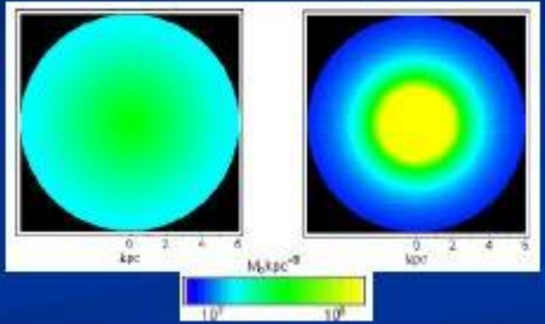
PROOFS OF CORES

Results from Trieste: analysis of high quality RCs

URC fits to RCs

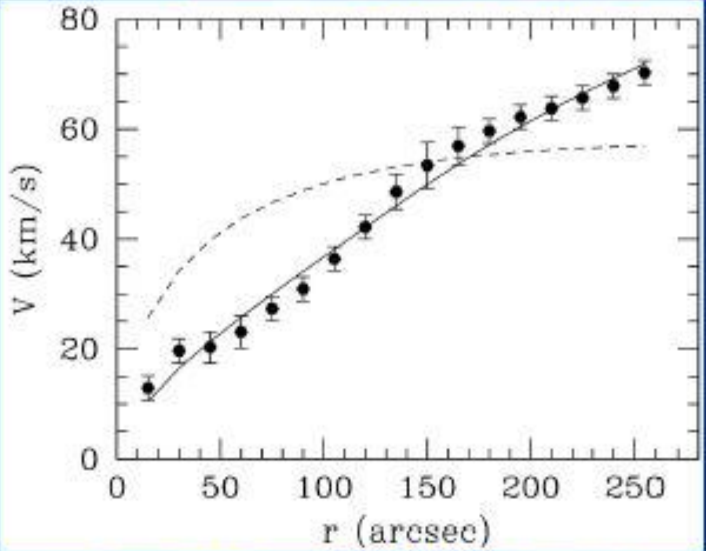




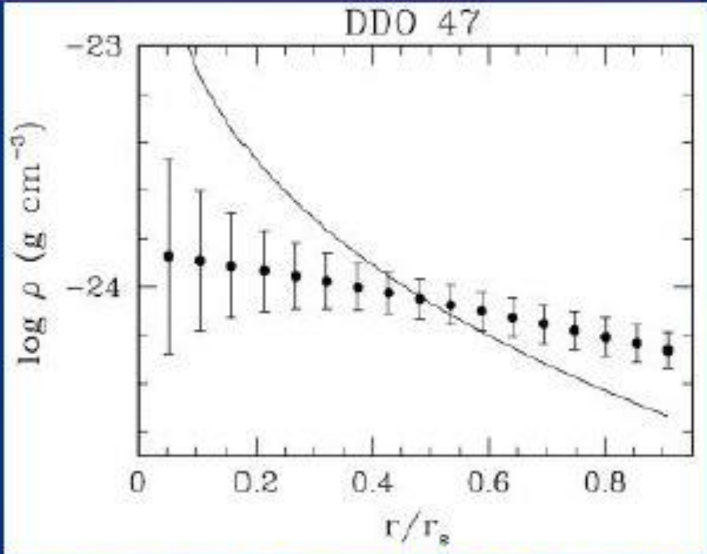


Borriello & Salucci, MNRAS 323, 285 (2001)

DDO 47



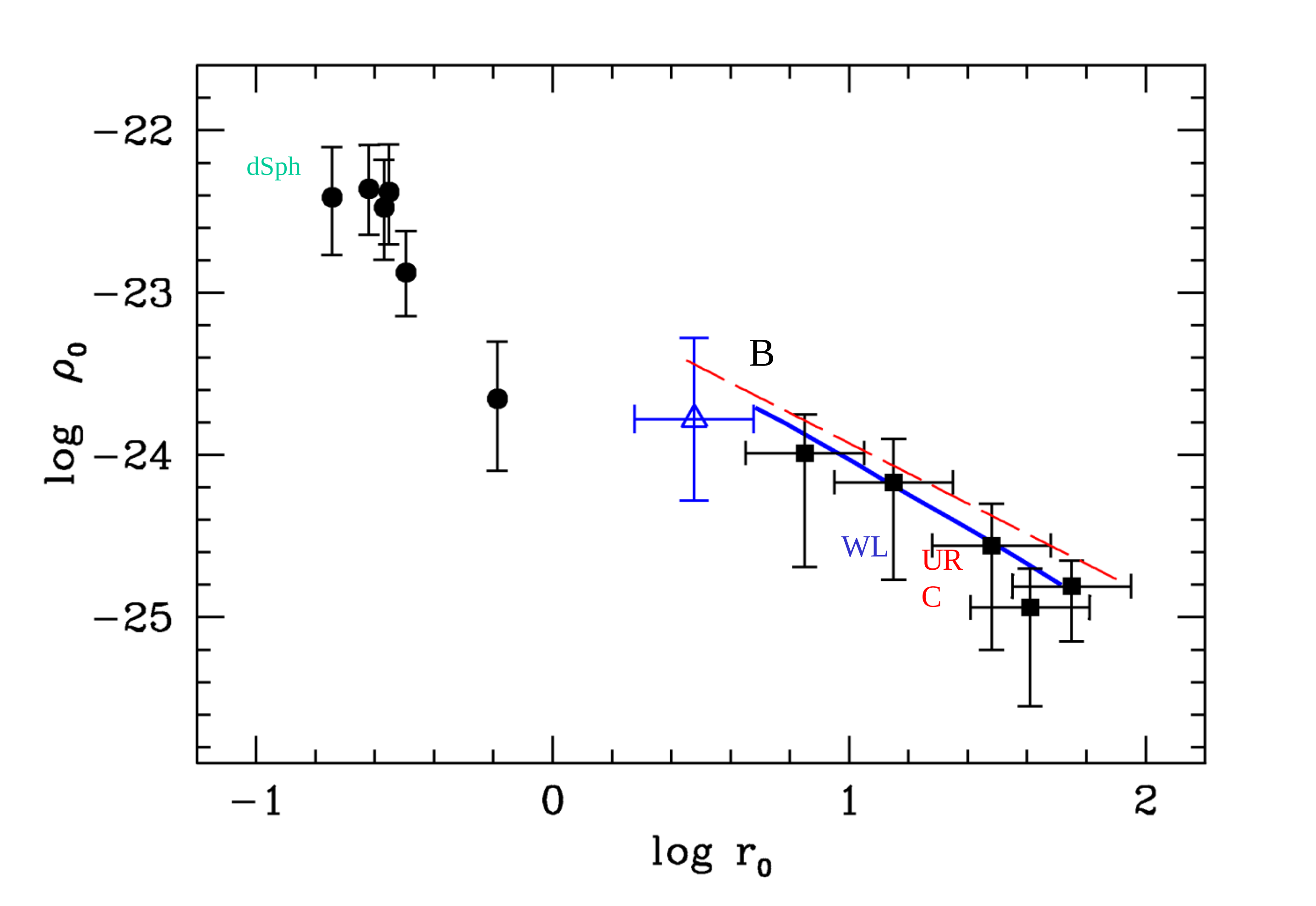
Gentile et al., ApJ 634, L145 (2005)



Gentile, Tonini & Salucci, A&A 467, 925 (2007)

Halo central density vs core radius scaling

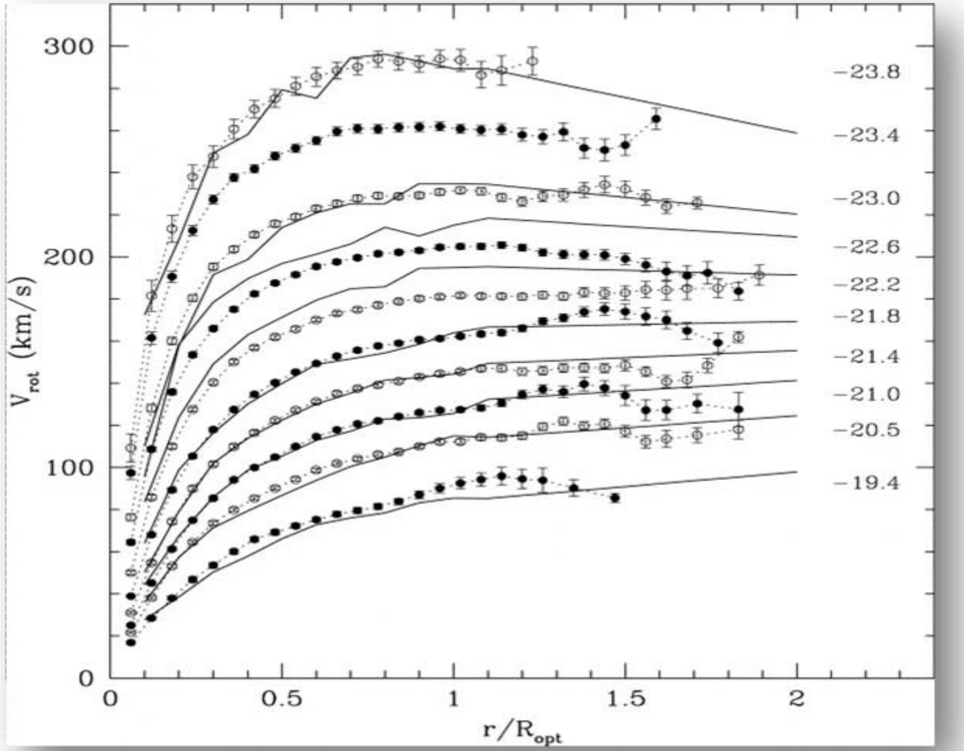
$\rho_0 = 10^{-23} (r_0 / kpc)^{-1} g/cm^3$



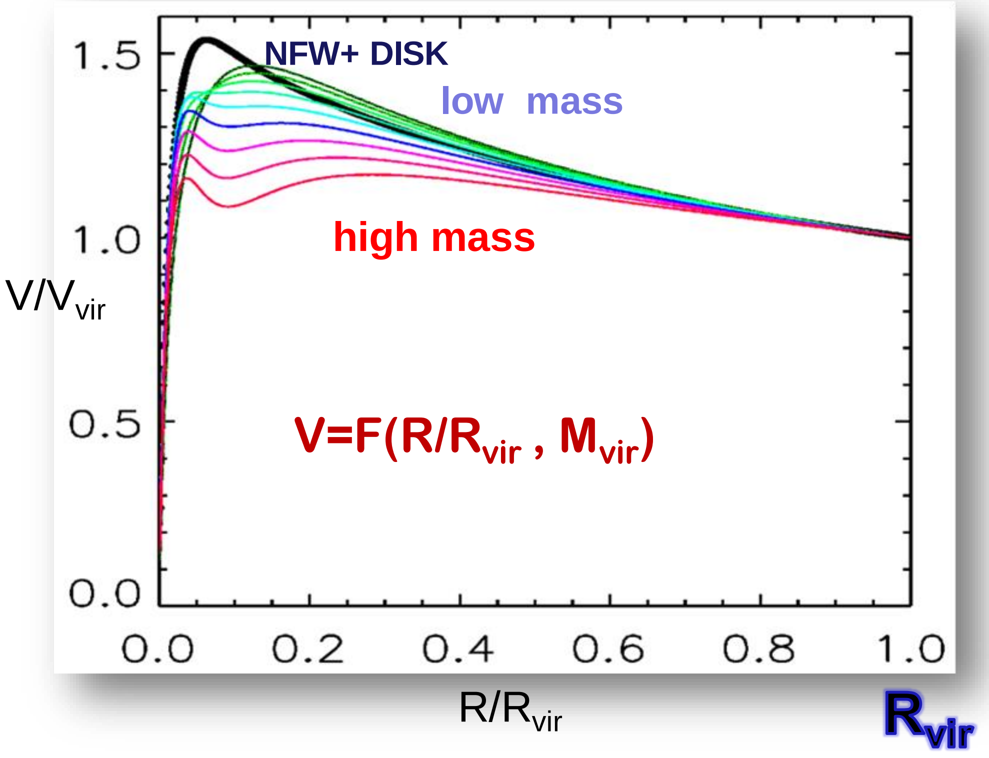
Universal Mass Distribution

URC

V=F(R/R_D , M_I)

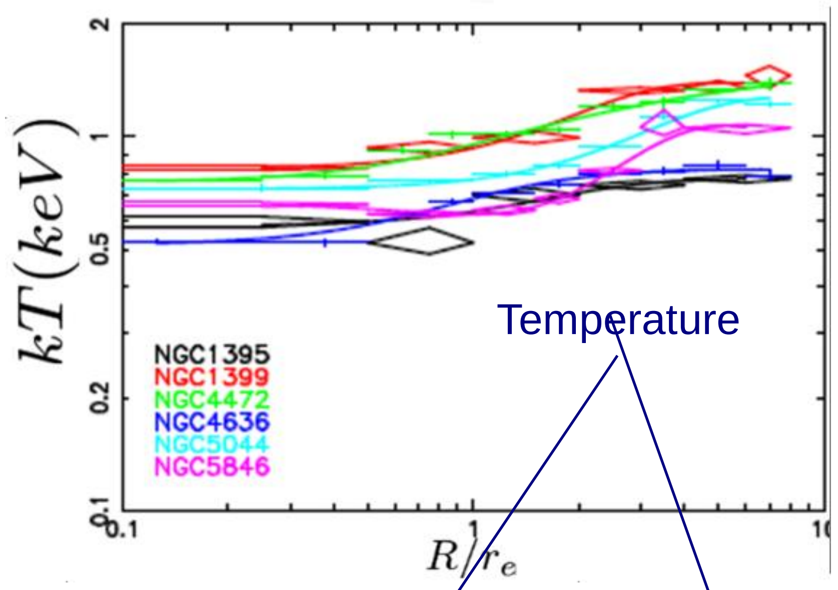


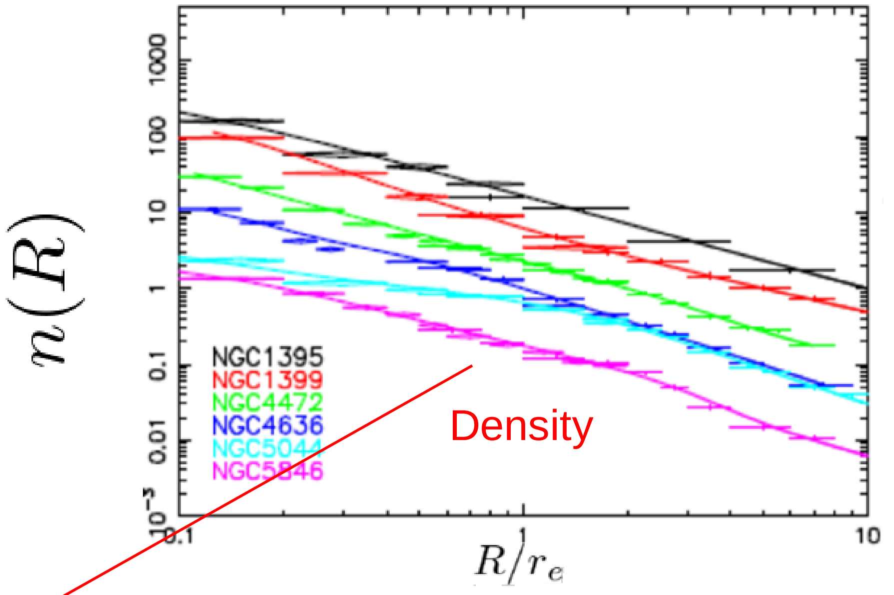
URC out to R_{vir} and ΛCDM model



Mass Profiles from X-ray

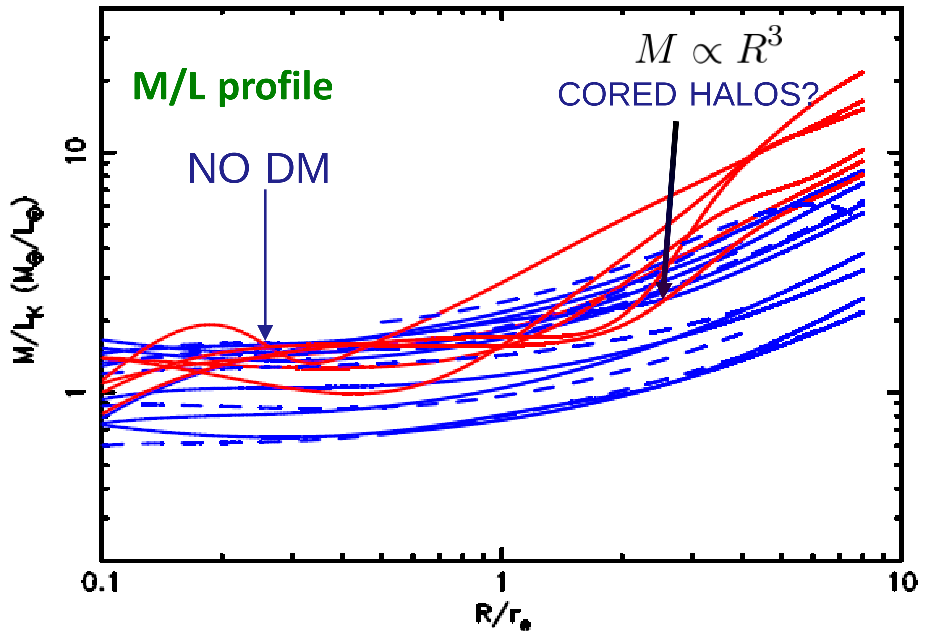
Nigishita et al 2009





$$M(R) = -\frac{kT(R)\cdot R}{G\mu m_p}\left(\frac{d\ln n(R)}{d\ln R} + \frac{d\ln T(R)}{d\ln R}\right)$$

Hydrostatic Equilibrium



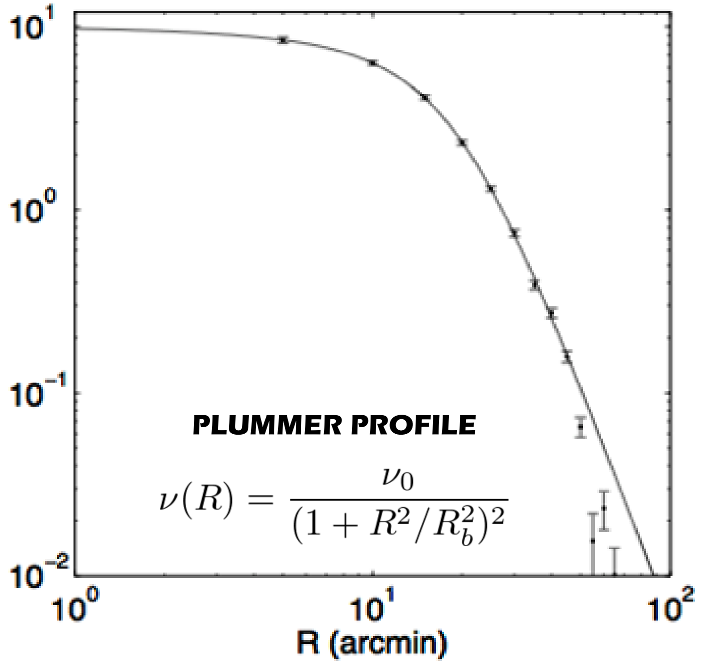
Mass profiles of dSphs

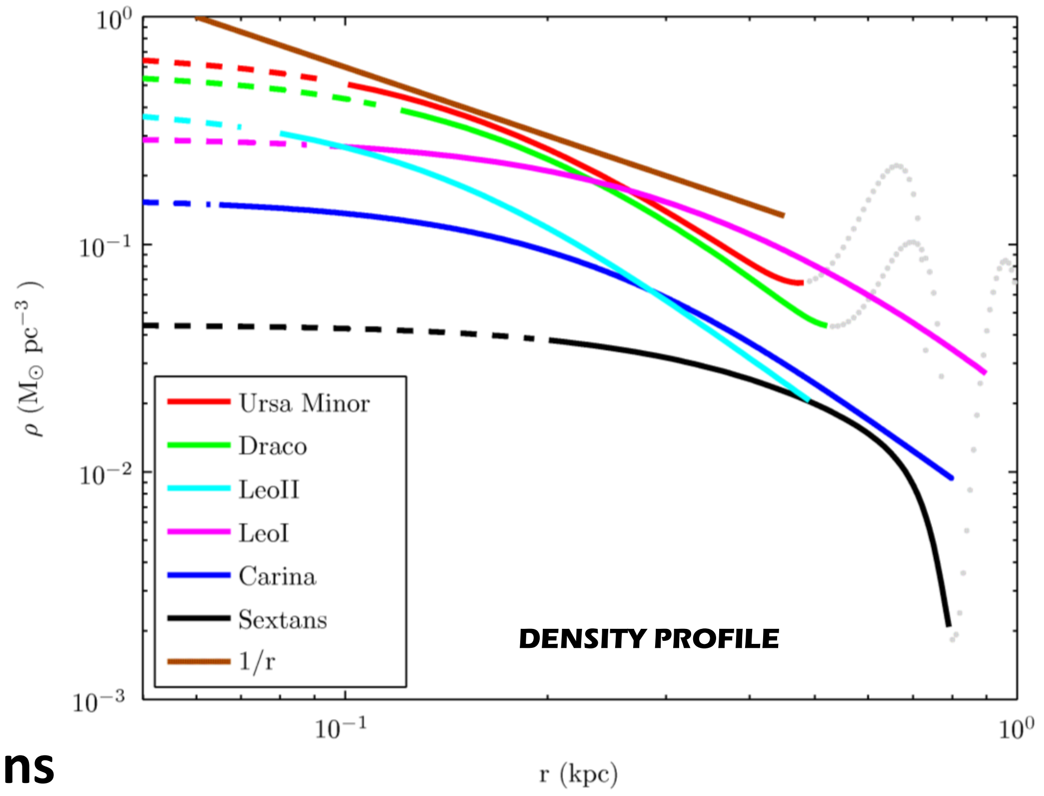
$$M(r) = -\frac{r^2}{G}\left(\frac{1}{\nu}\frac{\mathrm{d}\,\nu\sigma_r^2}{\mathrm{d}\,r} + 2\,\frac{\beta\sigma_r^2}{r}\right)$$

Jeans' models provide the most objective sample comparison

Jeans equation relates kinematics, light and underlying mass distribution

Make assumptions on the velocity anisotropy and then fit the dispersion profile

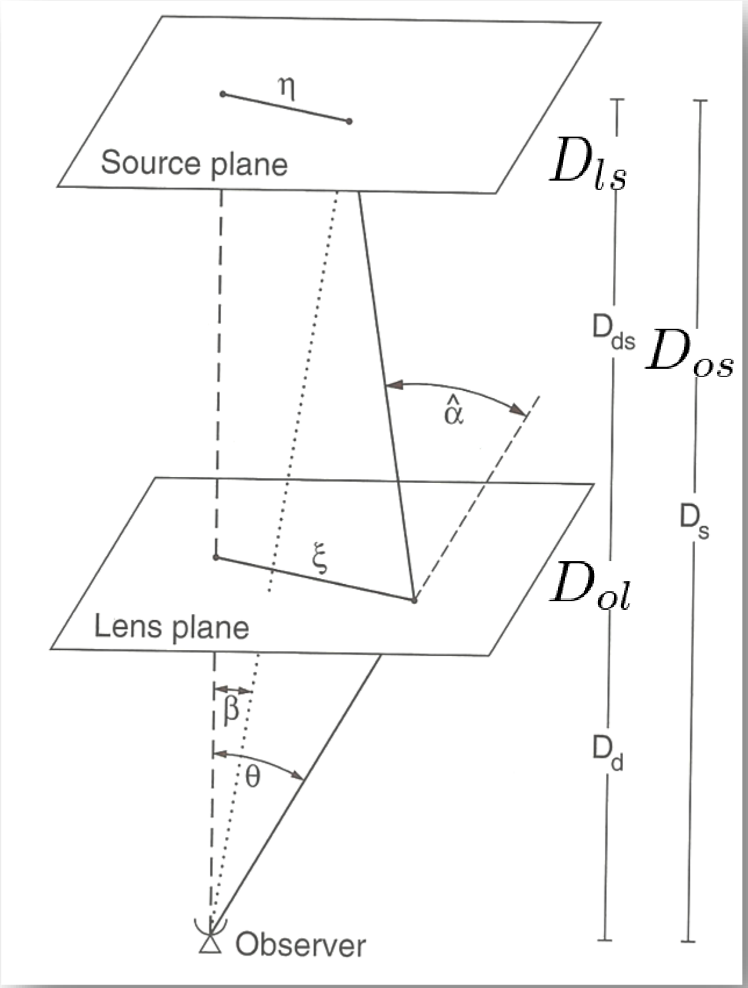




Results point to cored distributions

Gilmore et al 2007

Mass profiles from weak lensing



Lensing equation for the observed tangential shear

e.g. Schneider,1996

$$\langle \gamma_t \rangle \equiv \frac{\bar{\Sigma}(R) - \Sigma(R)}{\Sigma_c(R)}$$

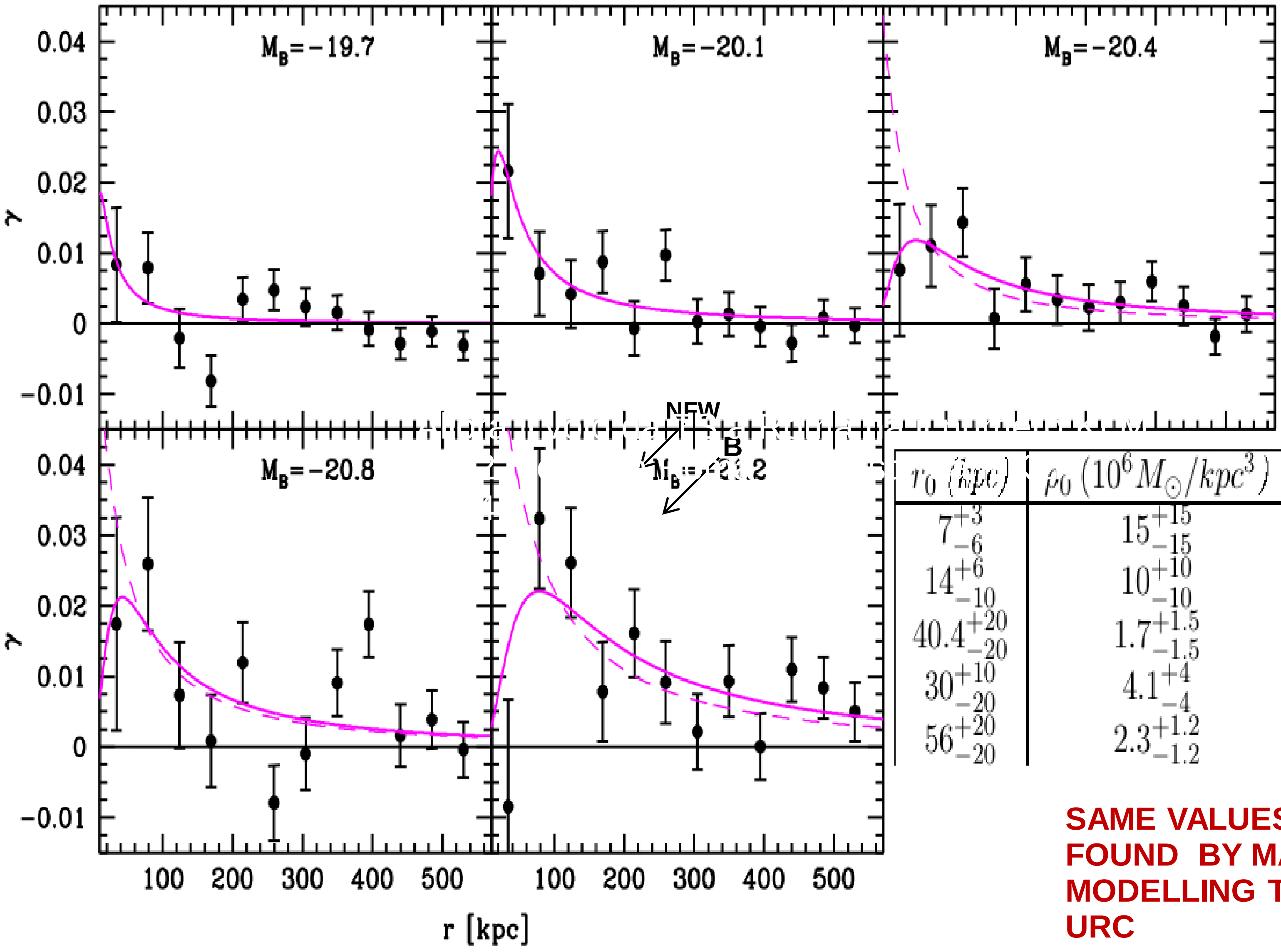
$$\bar{\Sigma} = \frac{M(R)}{4\pi R^2}$$

$$R = \theta D_{ol}$$

$$\Sigma_c = \frac{c^2}{4\pi G} \frac{D_{os}}{D_{ol} D_{ls}}$$

OUTER DM HALOS

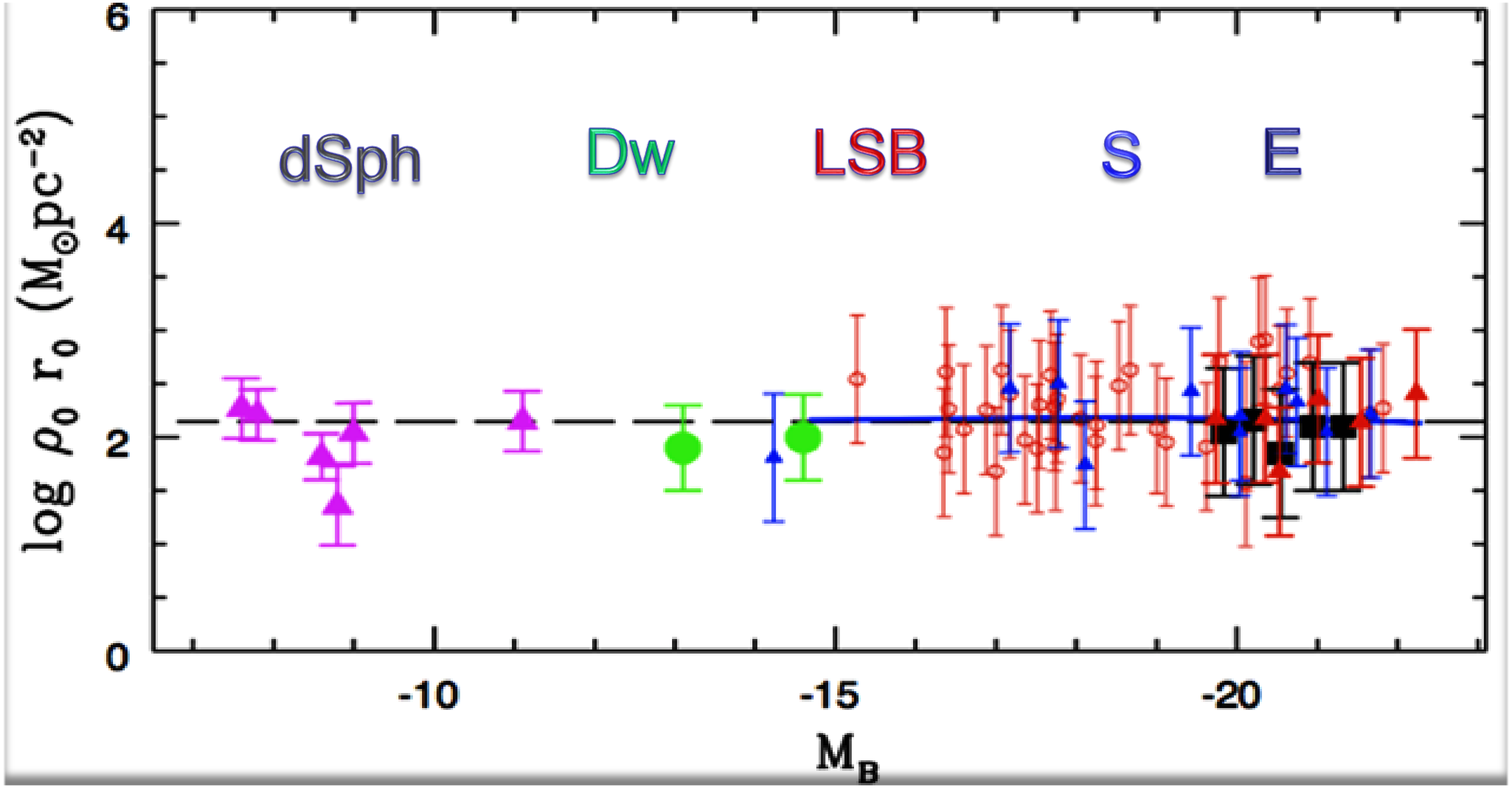
Donato et al 2009



r_0 (kpc)	$\rho_0\ (10^6 M_\odot/kpc^3)$
7^{+3}_{-6}	15^{+15}_{-15}
14^{+6}_{-10}	10^{+10}_{-10}
40.4^{+20}_{-20}	$1.7^{+1.5}_{-1.5}$
30^{+10}_{-20}	4.1^{+4}_{-4}
56^{+20}_{-20}	$2.3^{+1.2}_{-1.2}$

SAME VALUES FOUND BY MASS MODELLING THE URC

GALAXY HALOS: AN UNIFIED VISION

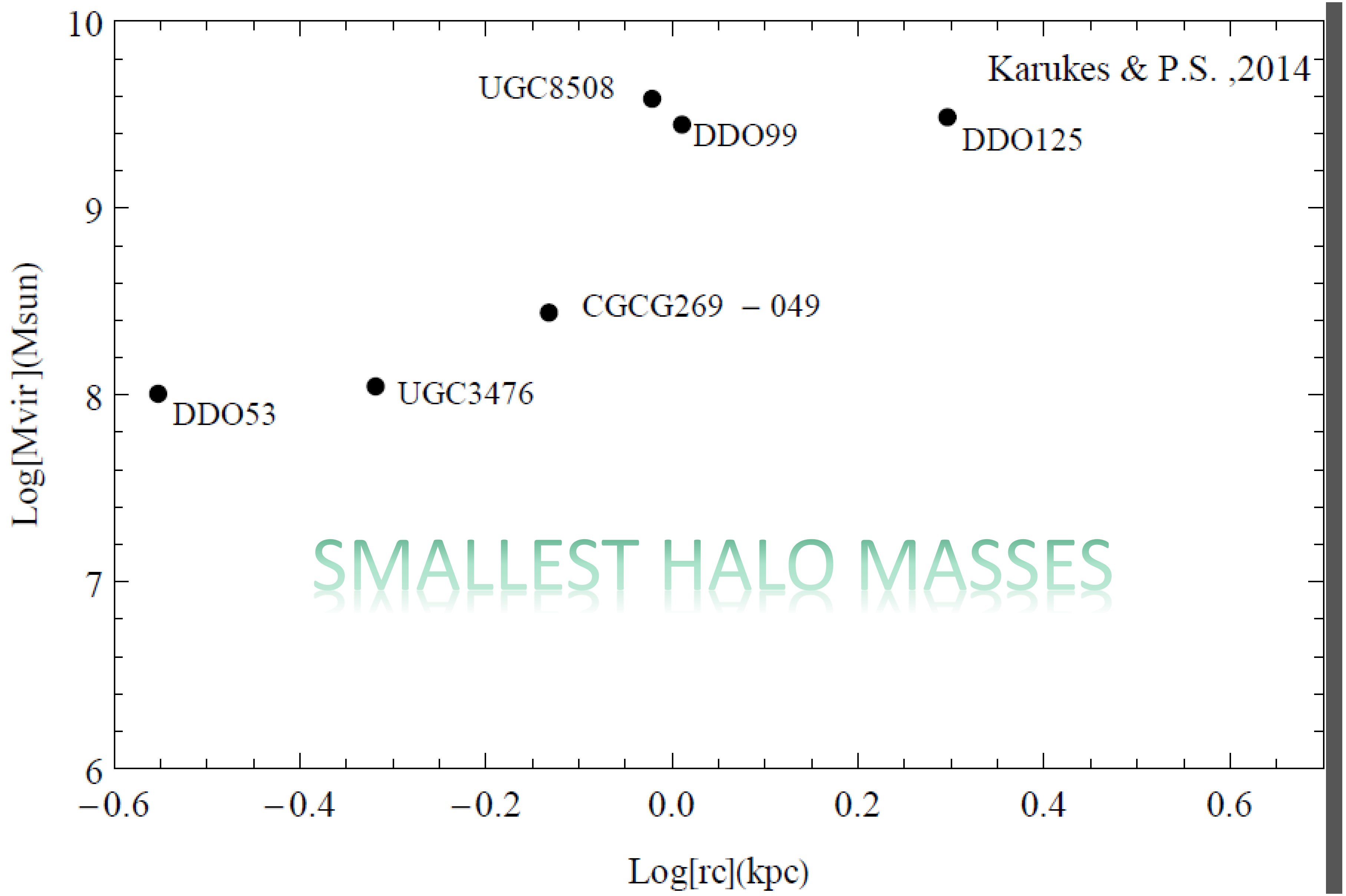


Universal Density Profile

$$\log(\rho_0/g\ cm^{-3}) = -23.773 - 0.547 \log\left(\frac{M_{vir}}{10^{11} M_\odot}\right)$$

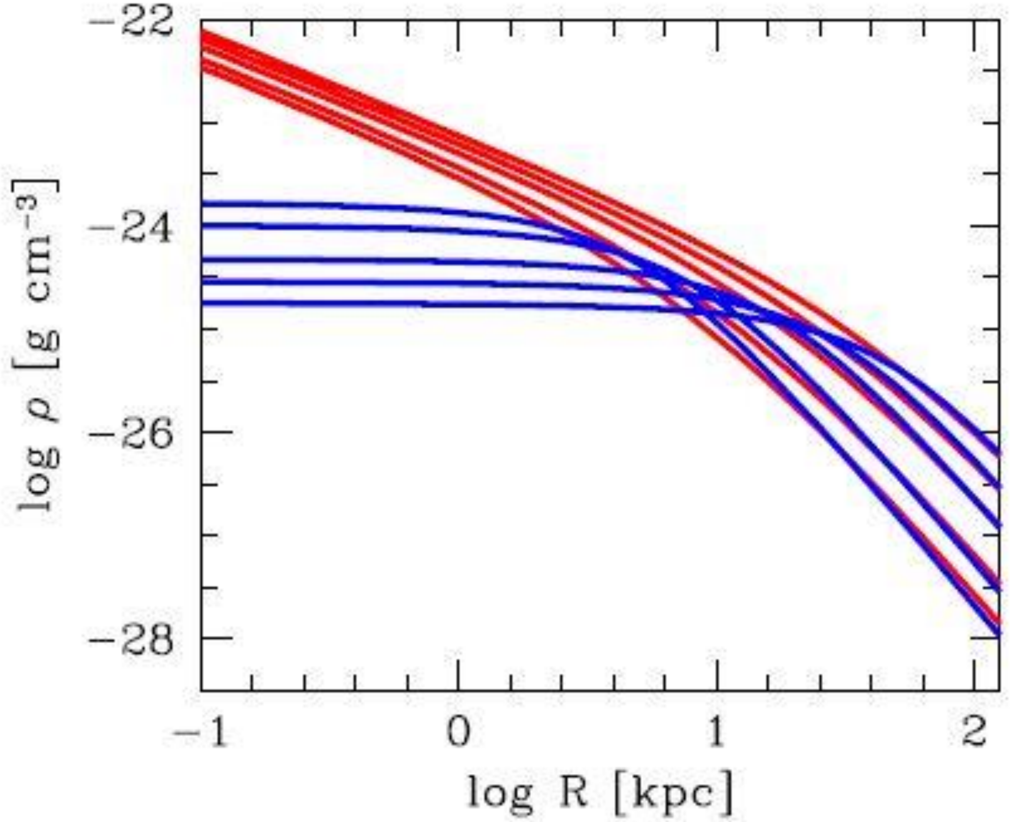
$$\log(r_0/kpc) = 0.71 + 0.547 \log\left(\frac{M_{vir}}{10^{11} M_\odot}\right),$$

$$M_D(M_{vir}) = \frac{2.4 \times 10^{10} \left(\frac{M_{vir}}{3\times10^{11}}\right)^{2.73}}{1.5 + \left(\frac{M_{vir}}{3\times10^{11}}\right)^{1.9}},$$

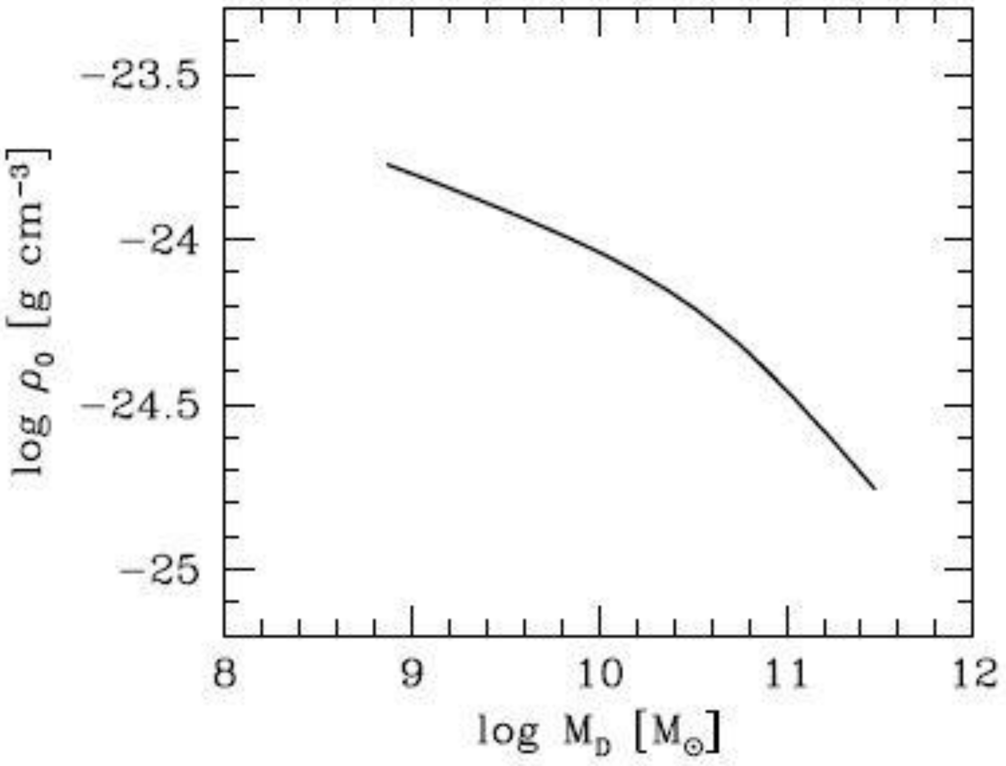


Karukes & P.S. ,2014
UGC8508
DDO99
DDO125
CGCG269 – 049
UGC3476
DDO53
SMALLEST HALO MASSES
Log[Mvir](Msun)
Log[rc](kpc)
10
9
8
7
6
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6

DMP



−22
−24
−26
−28
−1
0
1
2
log ρ [g cm^{-3}]
log R [kpc]



−23.5
−24
−24.5
−25
8
9
10
11
12
log ρ_0 [g cm^{-3}]
log M_D [$M_\odot$]

STRUCTURE OF WDM HALOS

DeVega,Sancez and P.S.

cle. For self-gravitating systems, the potential $\mu(\mathbf{r})$ is proportional to the gravitational potential $\phi(\mathbf{r})$,

$$\mu(\mathbf{r}) = \mu_0 - m\,\phi(\mathbf{r}) \;, \tag{1}$$

μ_0 being a constant, and obeys the **self-consistent** and **nonlinear** Poisson equation

$$\nabla^2\mu(\mathbf{r}) = -4\,\pi\,g\,G\,m^2\int\frac{d^3p}{(2\,\pi\,\hbar)^3}\,f\left(\frac{p^2}{2\,m} - \mu(\mathbf{r})\right) \;. \tag{2}$$

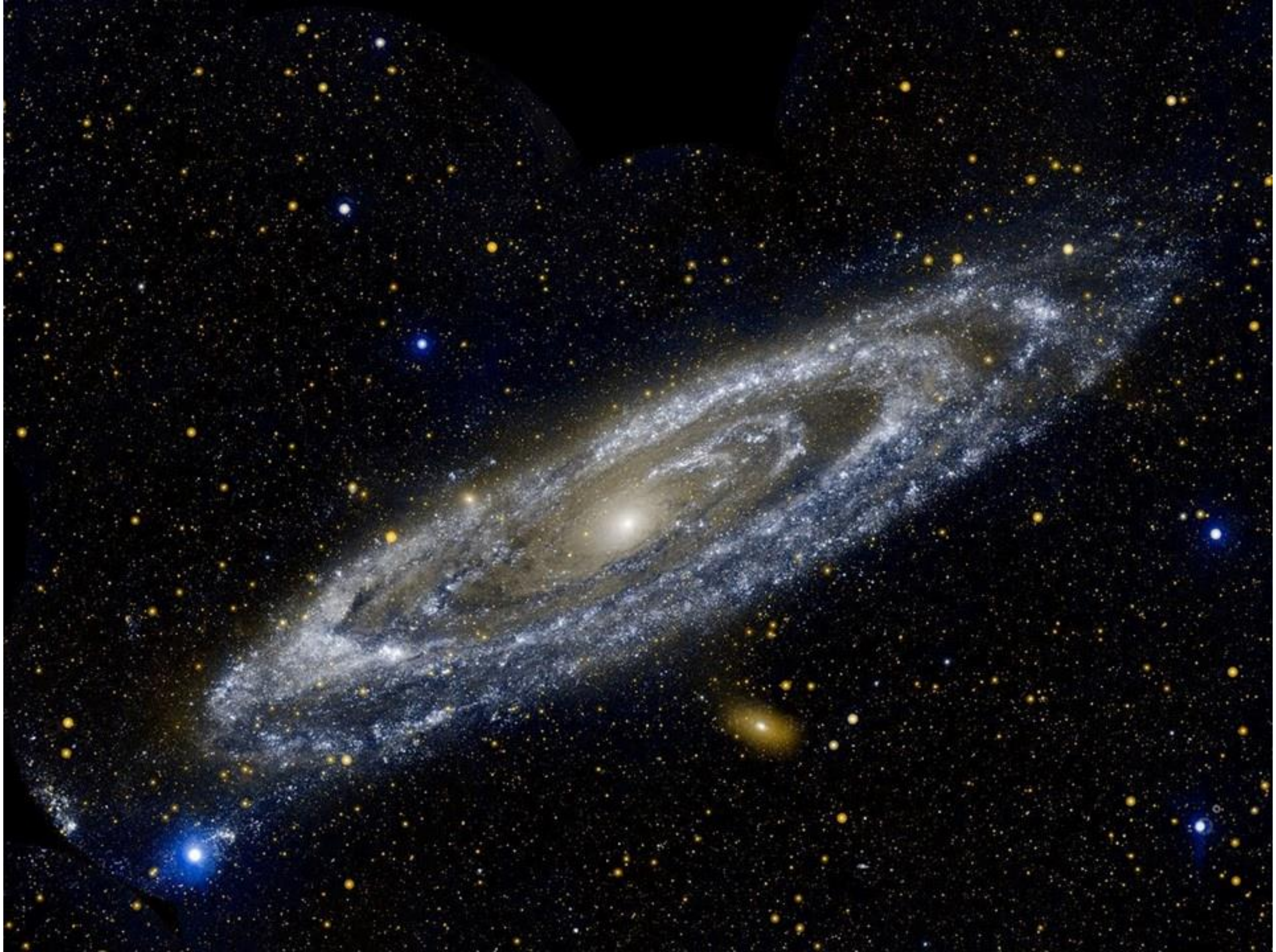
$$\frac{d^2\mu}{dr^2} + \frac{2}{r}\,\frac{d\mu}{dr} = -4\pi\,G\,m\,\rho(r) =$$

$$= -\frac{4\,G\,m^2}{\pi\,\hbar^3}\int_0^\infty dp\,p^2\,f\left(\frac{p^2}{2m} - \mu(r)\right)$$

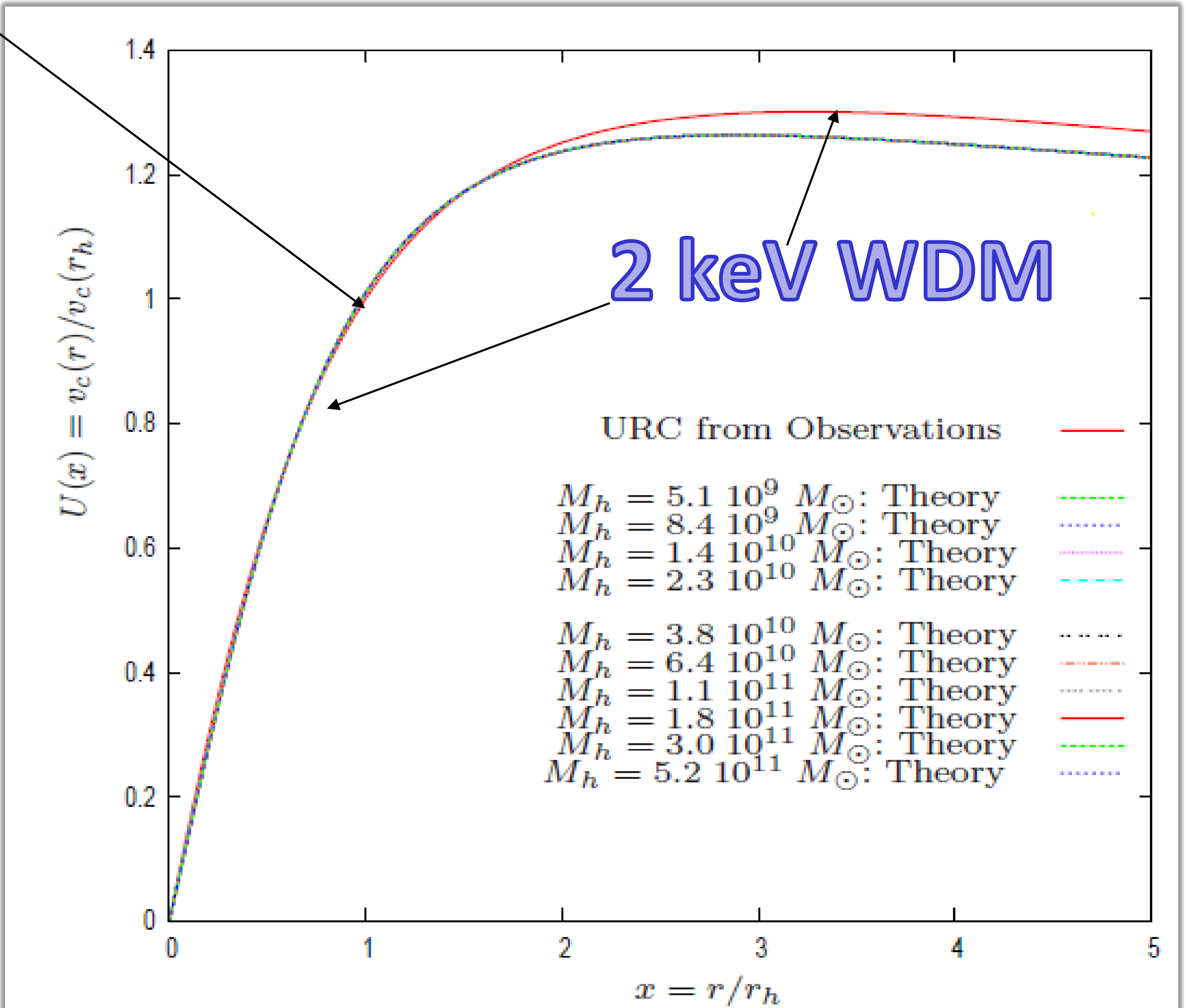
2013a,b). We choose for the energy distribution function a Fermi–Dirac distribution

$$f(E) = \frac{1}{e^{E/E_0} + 1} \;,$$

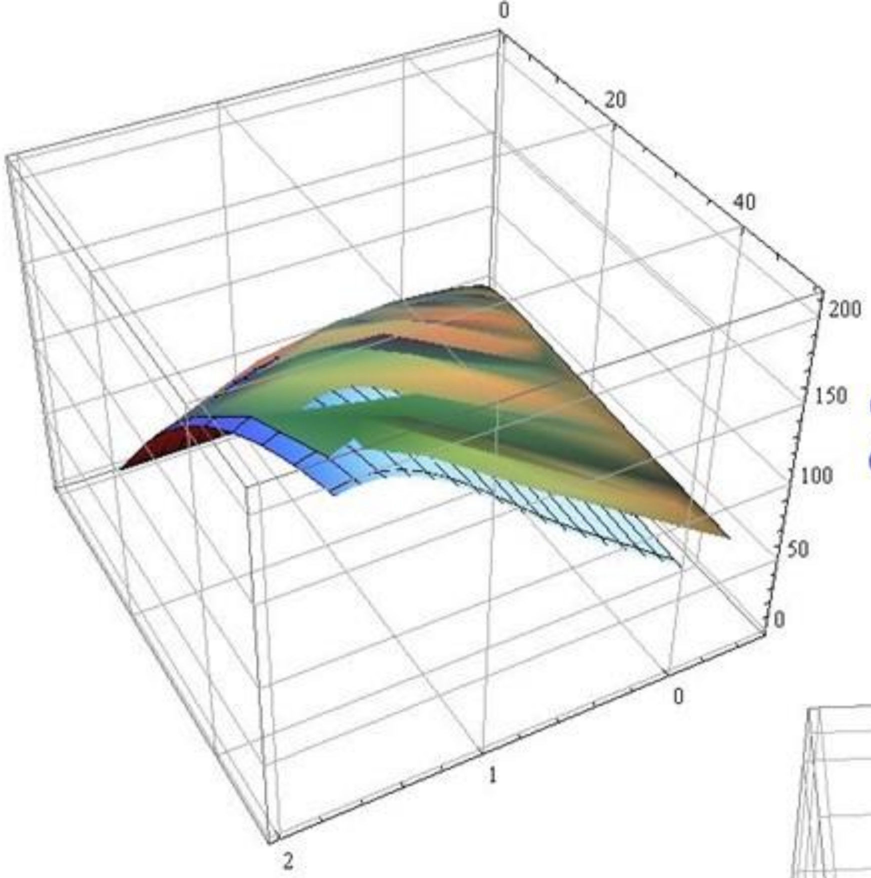
where E_0 is the characteristic one–particle energy scale. E_0 plays the role of an effective temperature scale and depends on the galaxy mass. The Fermi–Dirac distribution function

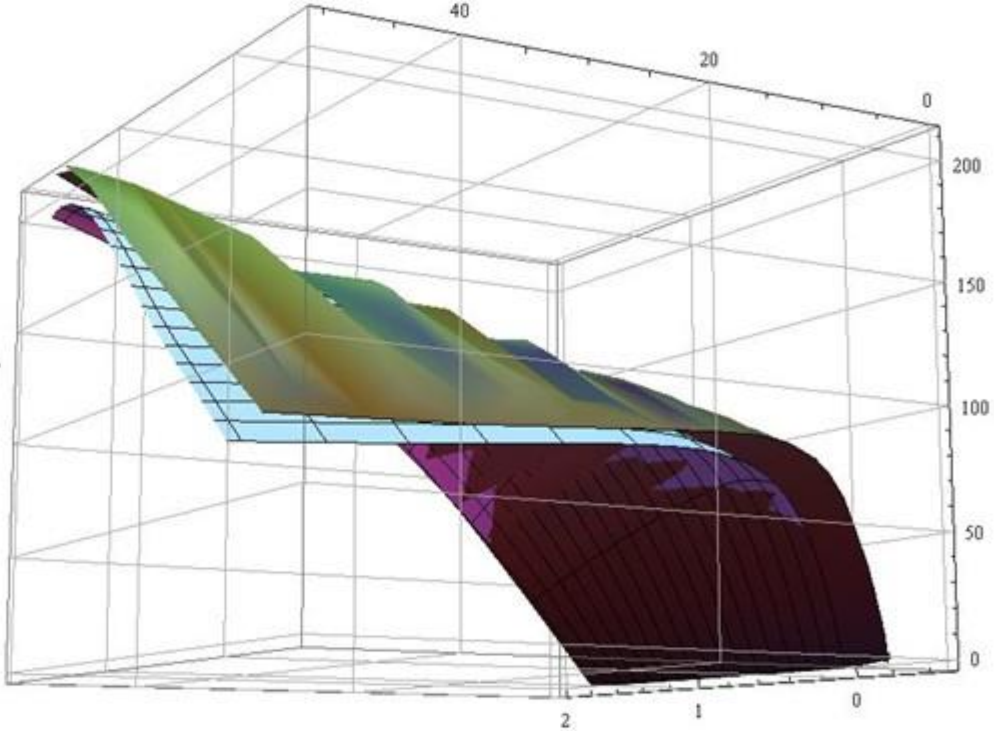


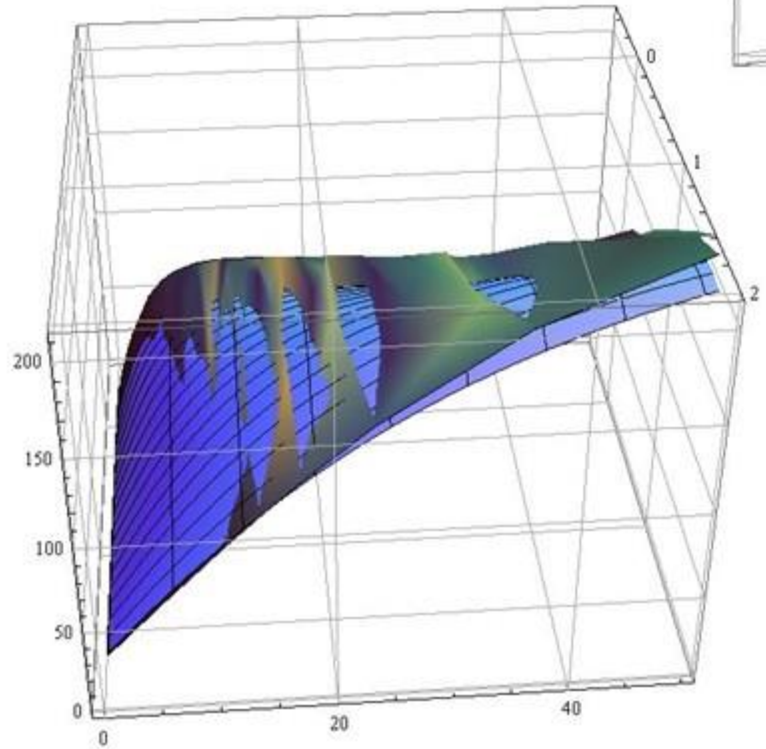
Universal Rotation Curve Halo component



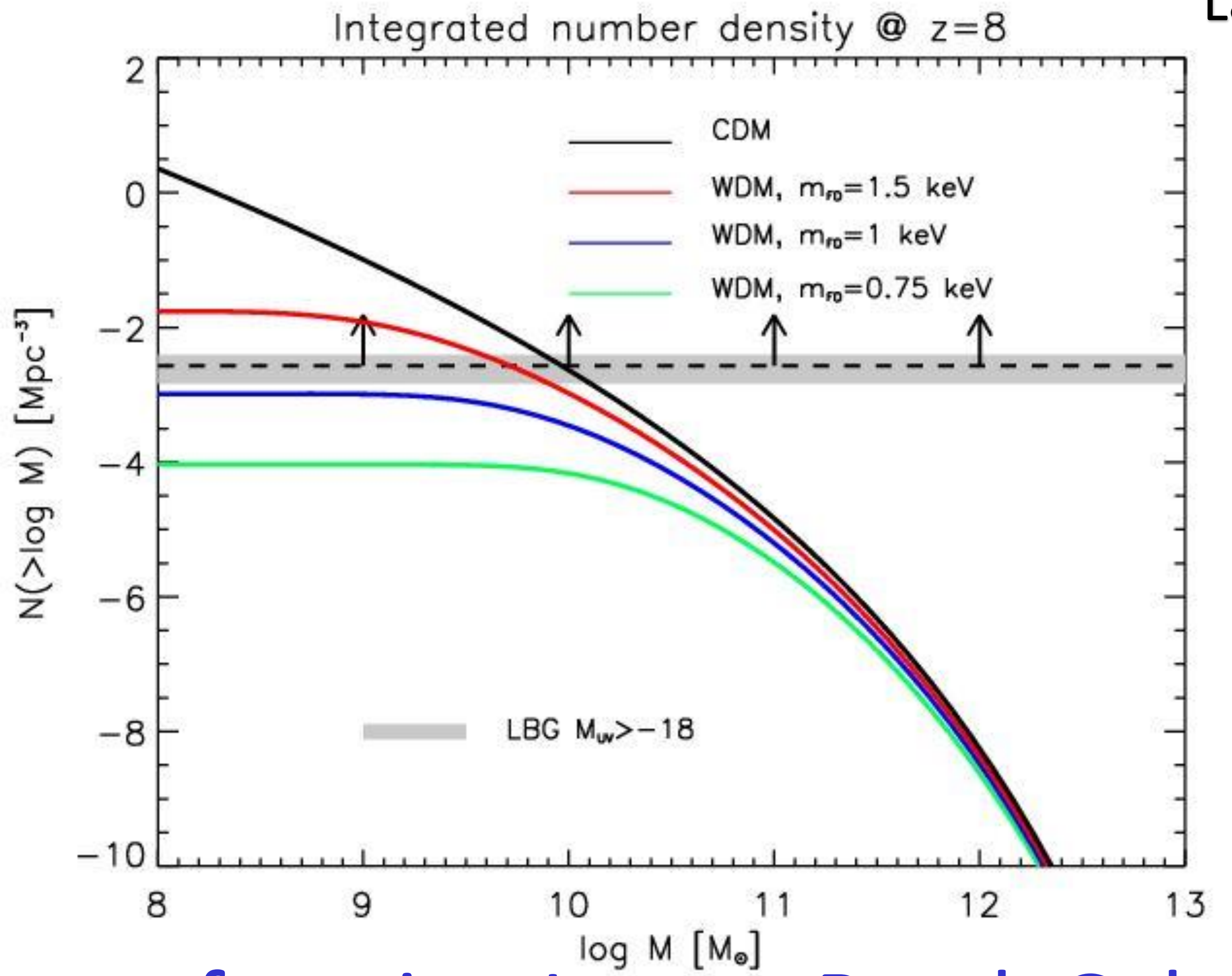
2 keV th
2-10 keV X



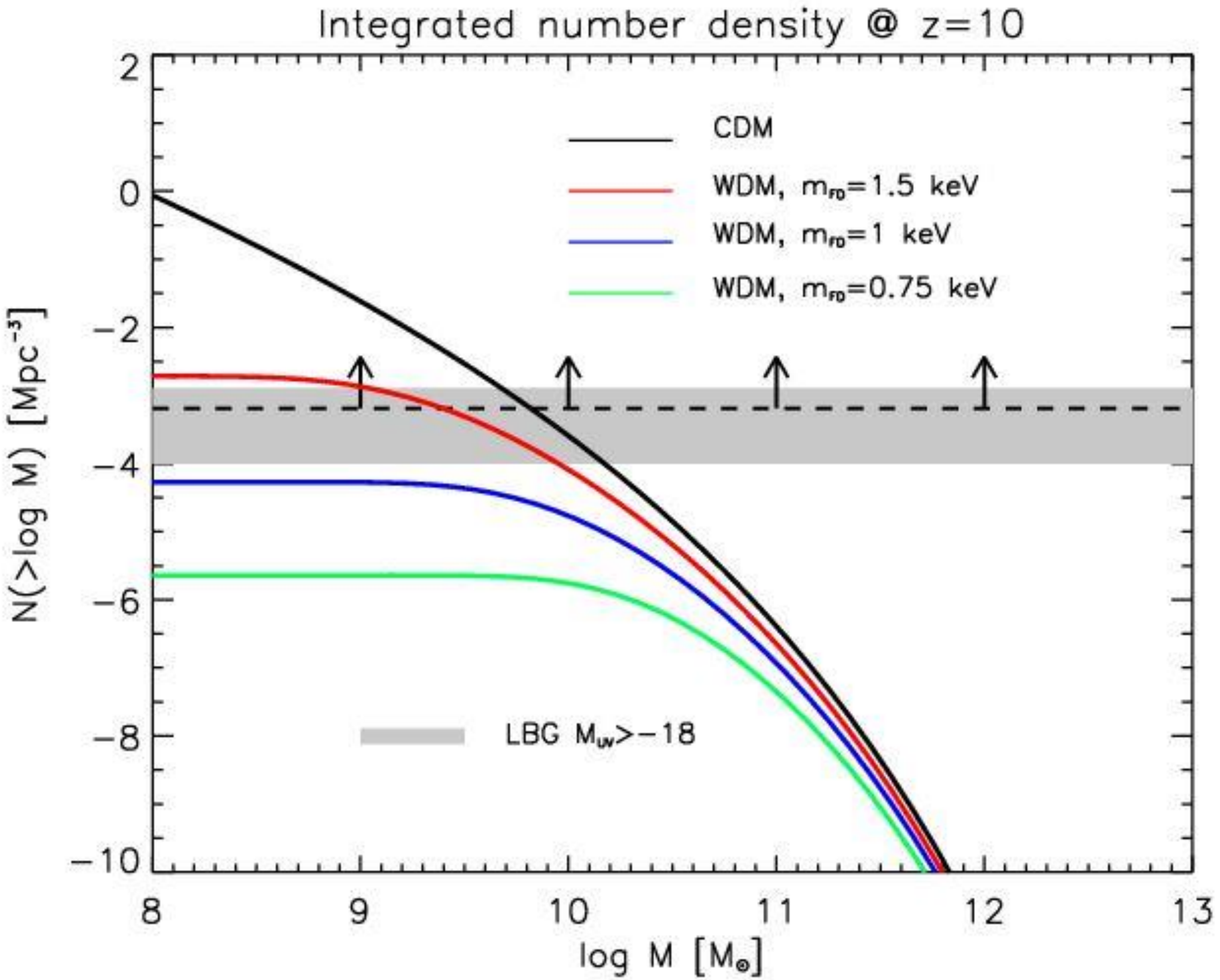




Lapi, Salucci, Danese



mass function Lyman Break Galaxies


Integrated number density @ z=10
CDM
WDM, m_FD=1.5 keV
WDM, m_FD=1 keV
WDM, m_FD=0.75 keV
LBG M_UV>−18
N(>log M) [Mpc^-3]
log M [M⊙]
2
0
−2
−4
−6
−8
−10
8
9
10
11
12
13

CONCLUSIONS

- Dark Matter has a very rich observational phenomenology
- Theories based on strong pre-judices or supposed miracles simply cannot work. Reality is too complex.
- The baggage of observational phenomena that theorists must bring with them in their enterprise of investigating the Universe is a big one
- Theories, like WDM, that consider, seriously from the beninning, the Observational Universe, have a chance to solve the greatest mystery of the