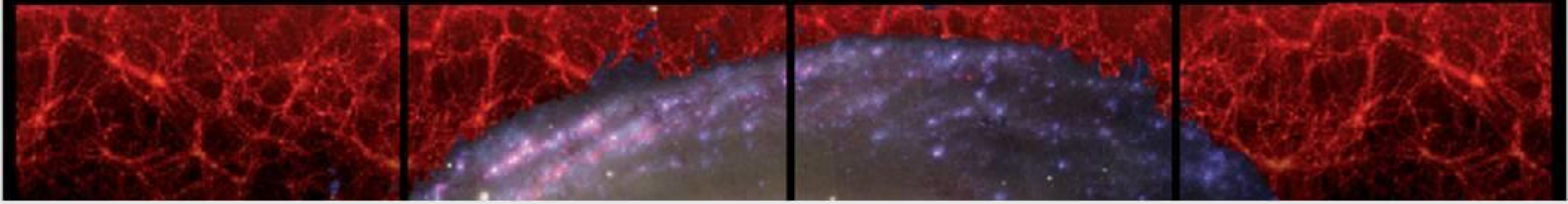


Structural properties of Galaxies lead to WDM: The case of Dwarf Disks

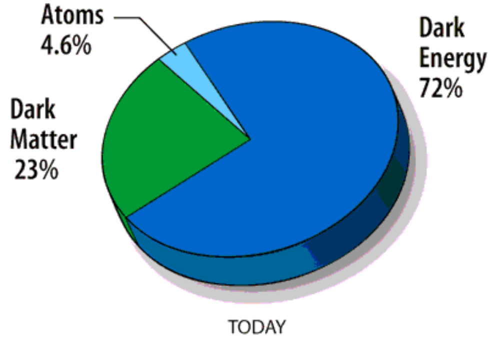
PAOLO SALUCCI
SISSA, GSSI

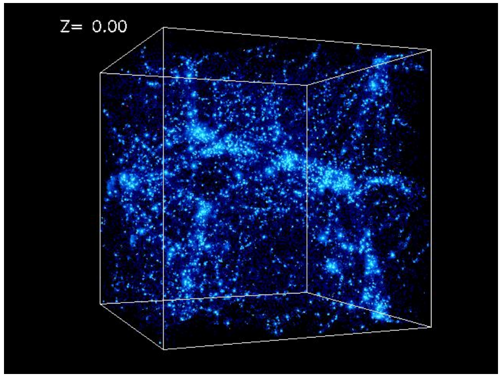
Kate Karukes
Phd SISSA

CIAS, Meudon, 2016

Outline

Dark Matter is a main **protagonist** in the Universe





In the mass distribution of the structures of the Universe we detect a dark massive component Atoms cannot develop these structures neither be responsable of this component

Standard Model of Elementary particles has not

Details of the In the mass distribution in galaxies play today a new role

-were often found incompatible with all-DM LCDM predictions (1996-2014)
-lead to a LWDM scenario and falsify the baryonically fine-tuned LCDM scenario (2014 -)

R


Wimp
HIGGSINO
DARK PHOTONS
GRAVITINO
DARK MATTER
e
e
DARK ELECTRONS
PROTON
PHOTON
e-
NEUTRINO
MUON
NEUTRON
QUARK
VISIBLE MATTER
NEUTRALINO
AXION
AXION
DARK NEUTRON
Wimp

CDM PARADIGM

We know the dark particle ab initio

we will detect the dark particle by means of accelerator measurements or in non-accelerator detectors by direct or indirect ways.

Observations of dark matter are serves just for cosmo astrophysicsio

They must verify the scenario

After 30 years CDM

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.

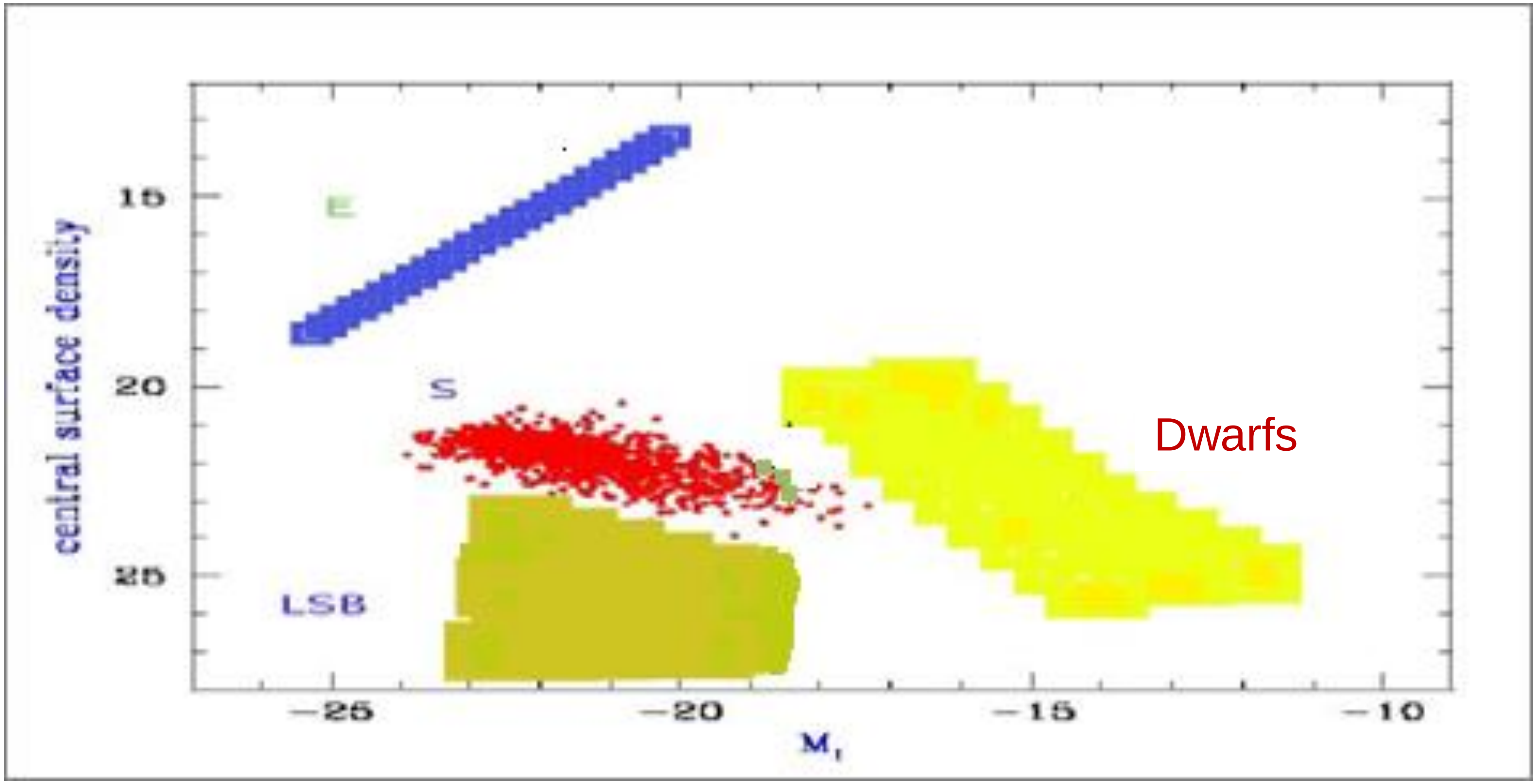
the number of dark halos and their density profiles are very different with respect to those that are predicted within the CDM paradigm.

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

The Realm of Galaxies

The range of galaxies in magnitudes, types and central surface densities : 15 mag, 4 types, 16 mag arsec^{-2}

Central surface brightness vs galaxy magnitude



The distribution of luminous matter :

Spirals : stellar disk +bulge +HI disk

Ellipticals & dwarfs E: stellar spheroid

Universal Density Profile

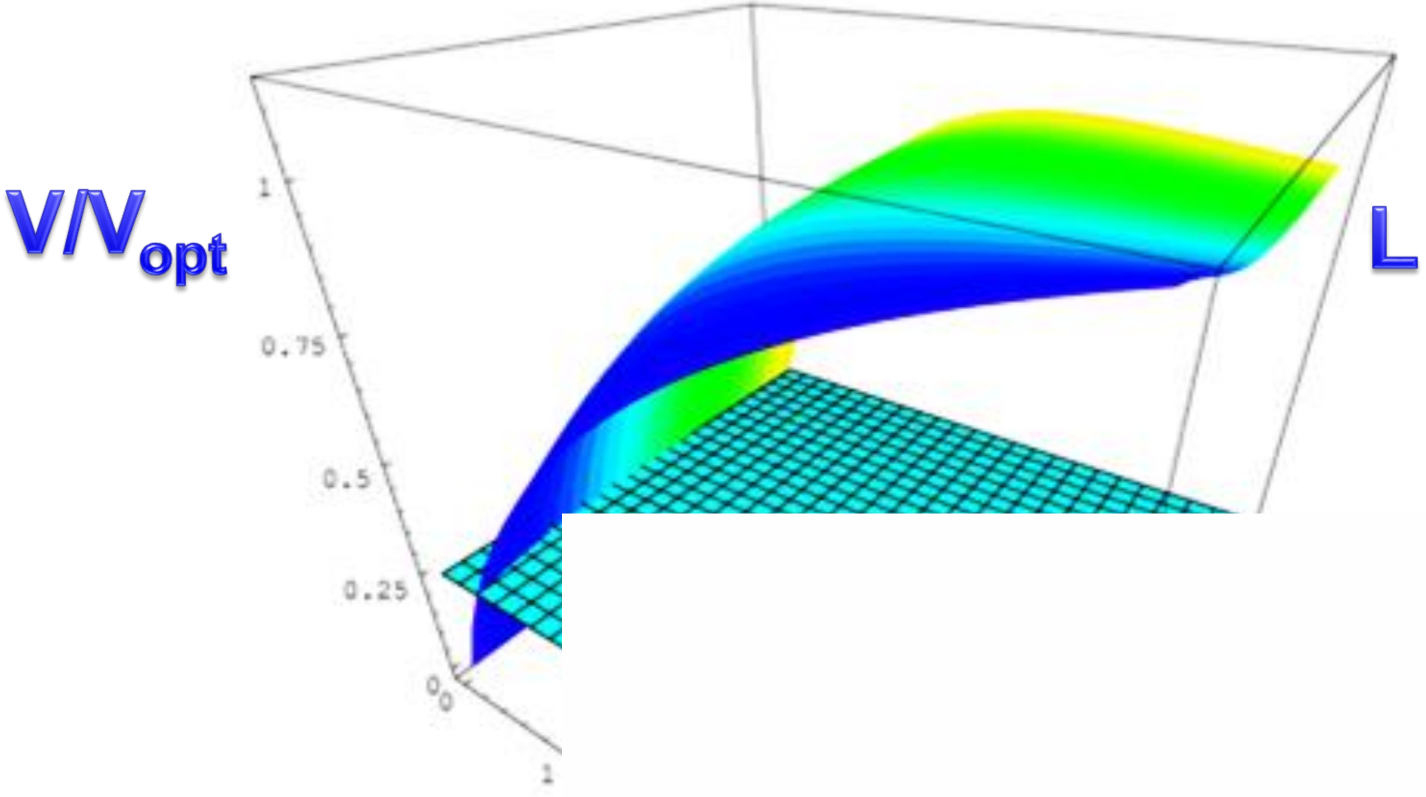
$$\log(\rho_0/g\ cm^{-3}) = -23.773 - 0.547 \log\left(\frac{M_{vir}}{10^{11} M_\odot}\right)$$

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

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

The Concept of the Universal Rotation Curve (URC)

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

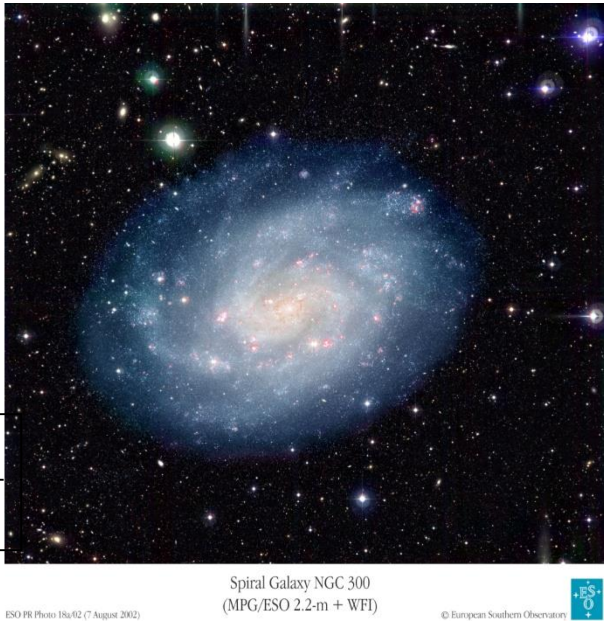


The URC out to 6 R_D is derived di

Spirals best place to investigate DM

M33 disk very smooth, truncated at 4 scale-lengths

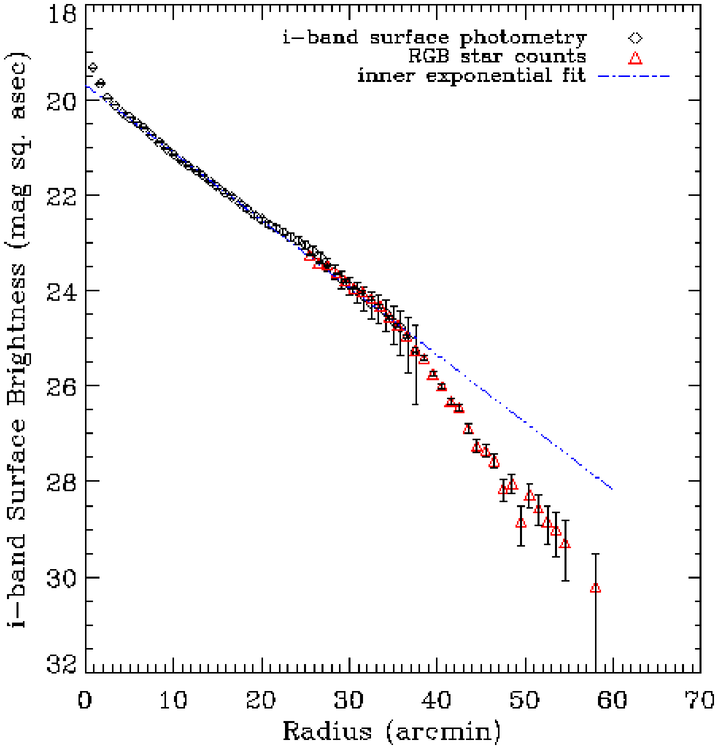
NGC 300 exponential disk for at least 10 scale-lengths



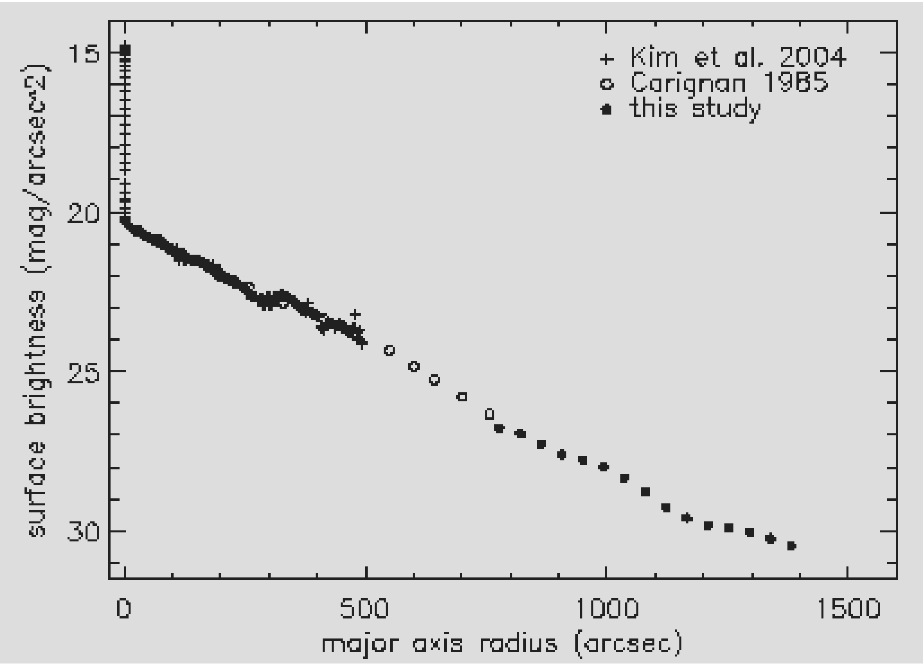
$$I(r) = I_0 e^{-r/R_D}$$

R_D lenght scale of the disk

Freeman, 1970



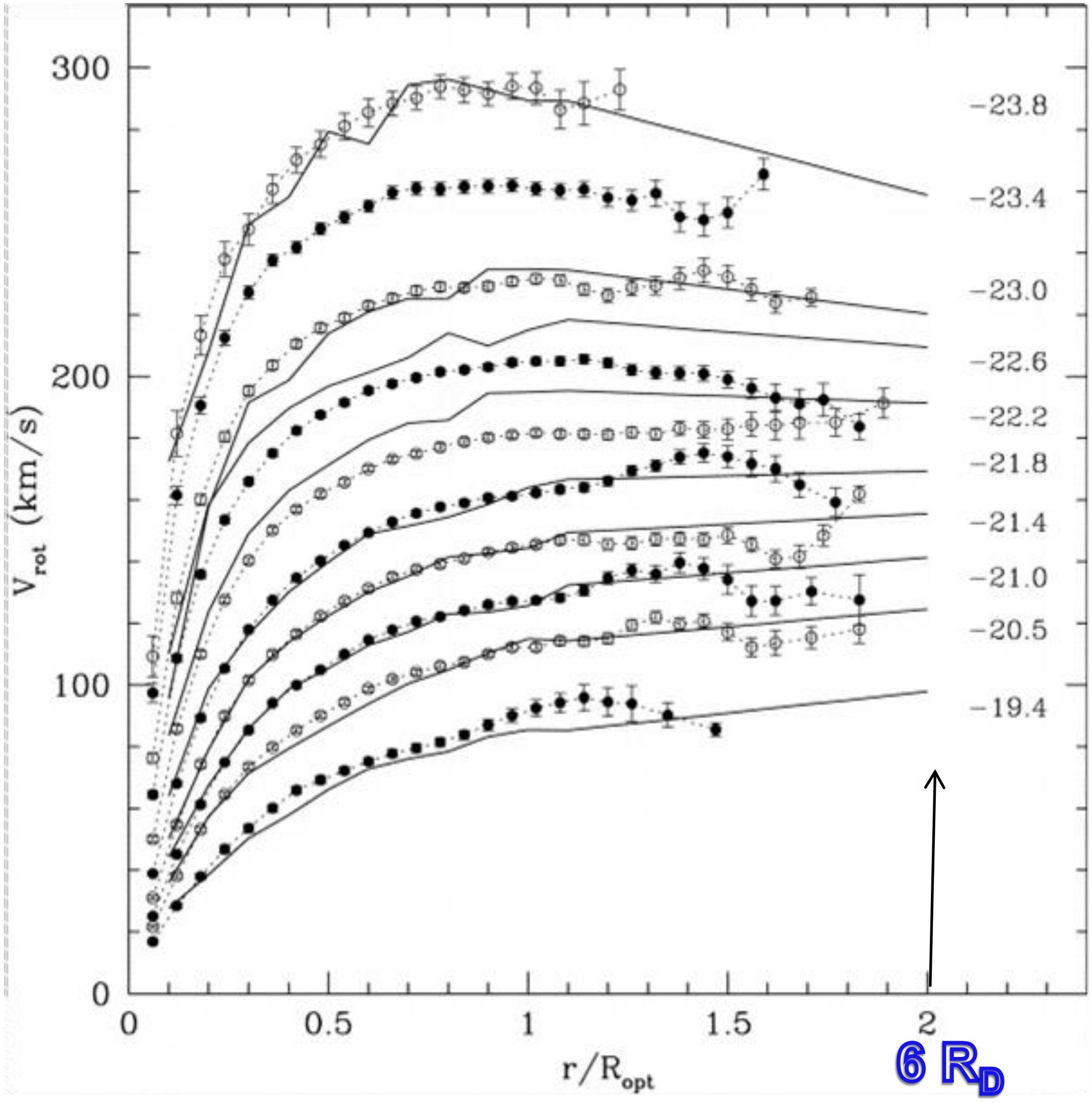
Ferguson et al 2003



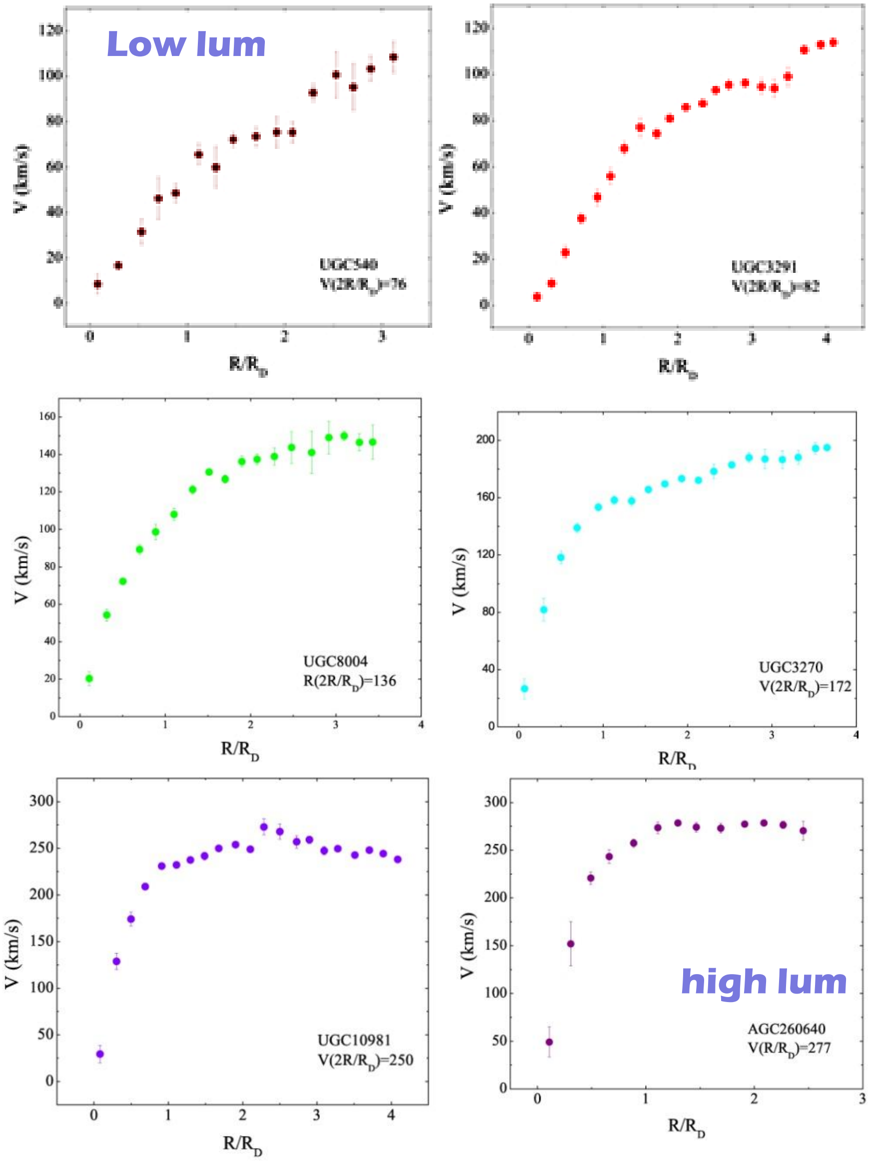
Bland-Hawthorn et al 2005

Rotation Curves (1991-2007)

Coadded from 3200 individual RCs



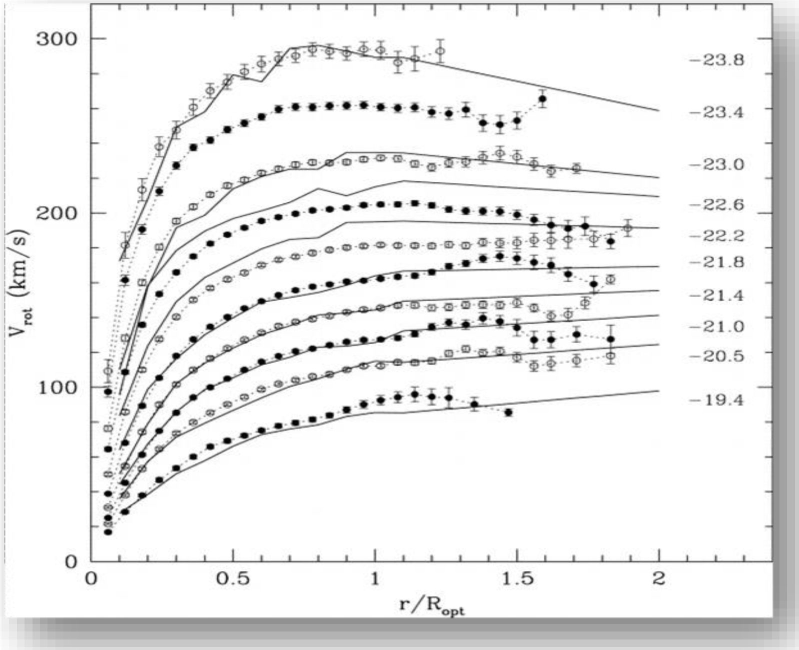
TYPICAL INDIVIDUAL RCs OF INCREASING LUMINOSITY



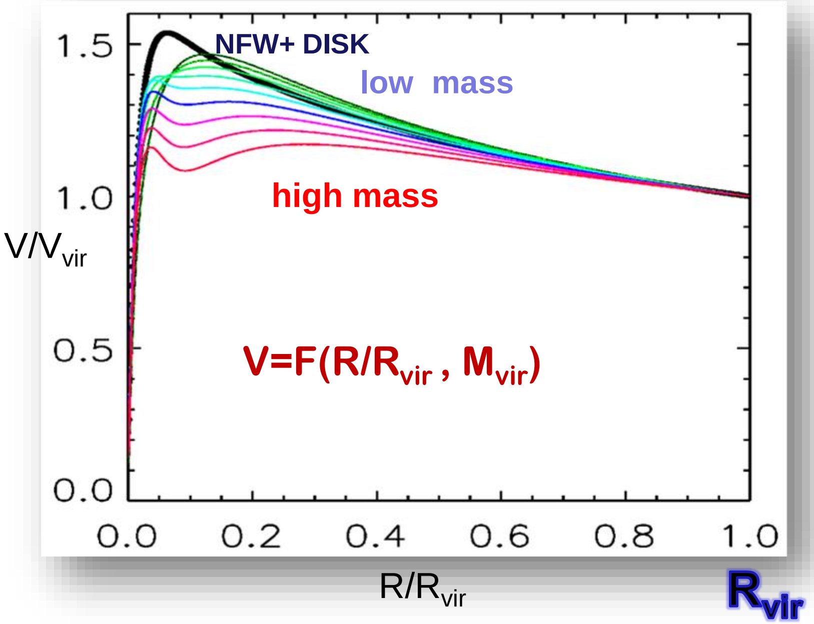
Universal Mass Distribution

URC

$V=F(R/R_D , M_I)$



URC out to R_{vir} and ΛCDM model



$V=F(R/R_{vir} , M_{vir})$

ΛCDM Dark Matter Density Profiles from N-body simulations

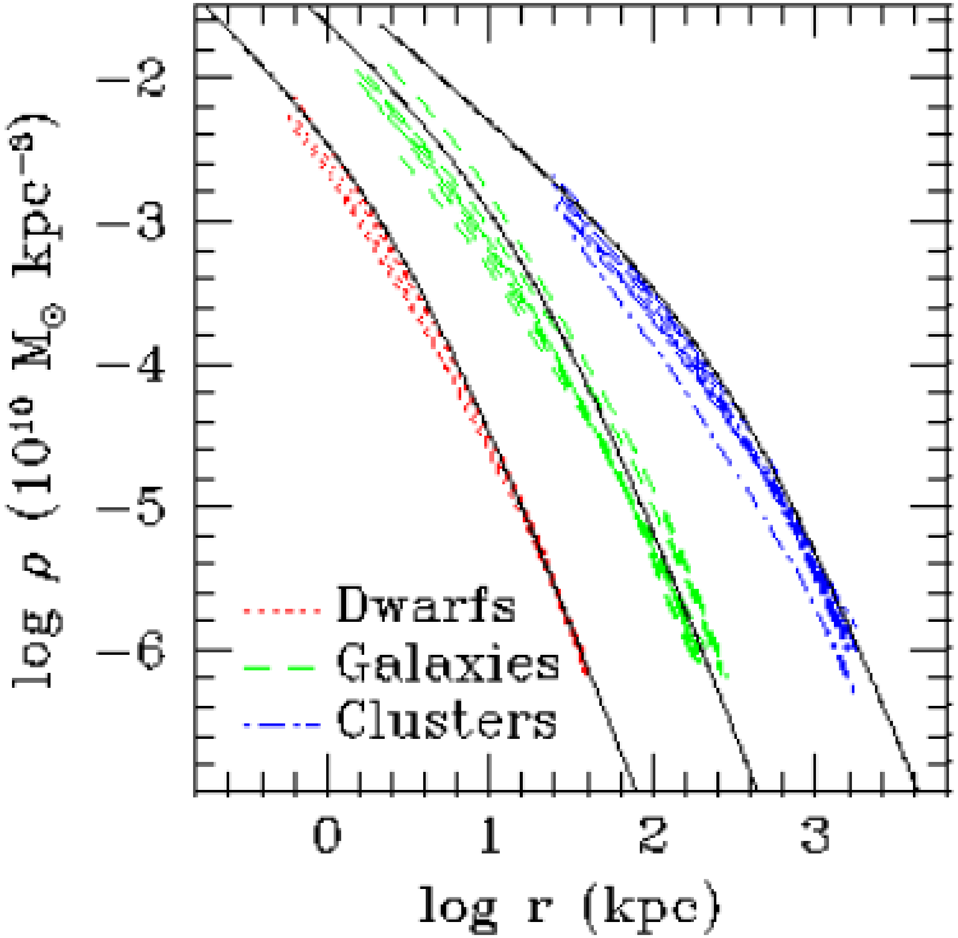
The density of virialized DM halos of any mass is empirically described at all times by an Universal profile (Navarro+96, 97, NFW).

$$\rho_{NFW}(r) = \delta\rho_c \frac{r_s}{r} \frac{1}{(1+r/r_s)^2}$$

$$c = \frac{R_{vir}}{r_s}$$

$$R_{vir} = 260 \left(\frac{M_{vir}}{10^{12}\ M_\odot}\right)^{1/3} kpc$$

$$c(M_{vir}) = 9.35 \left(\frac{M_{vir}}{10^{12}\ M_\odot}\right)^{-0.09}$$



Klypin, 2010

Pure DM LCDM -> Occam razor

Rotation curve analysis

From data to mass models

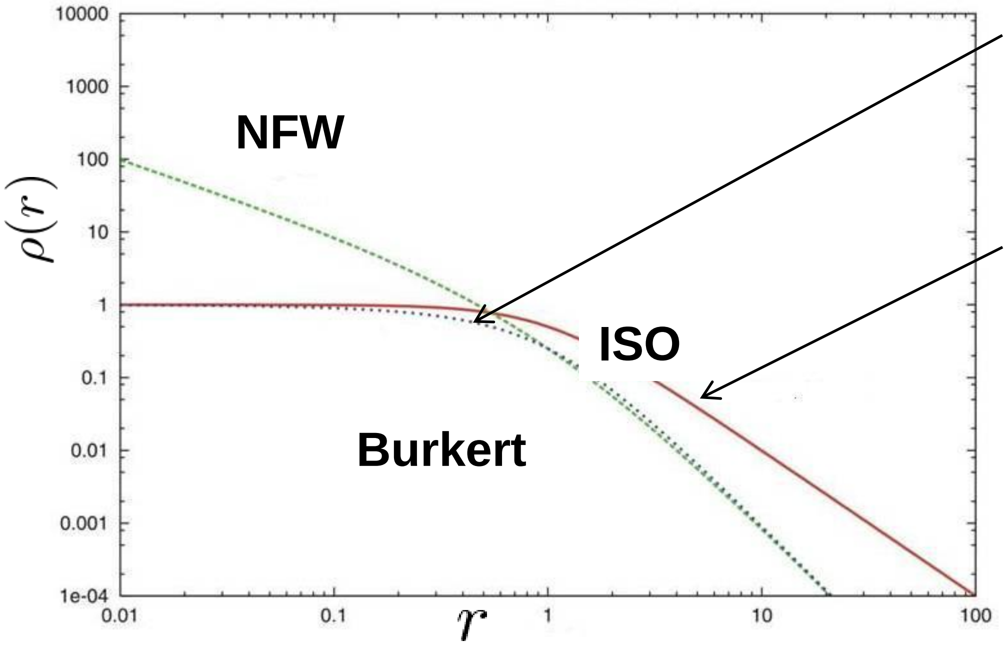
$$V^2(R) = V^2_{halo}(R) + V^2_{HI}(R) + V^2_{disk}(R)$$

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)

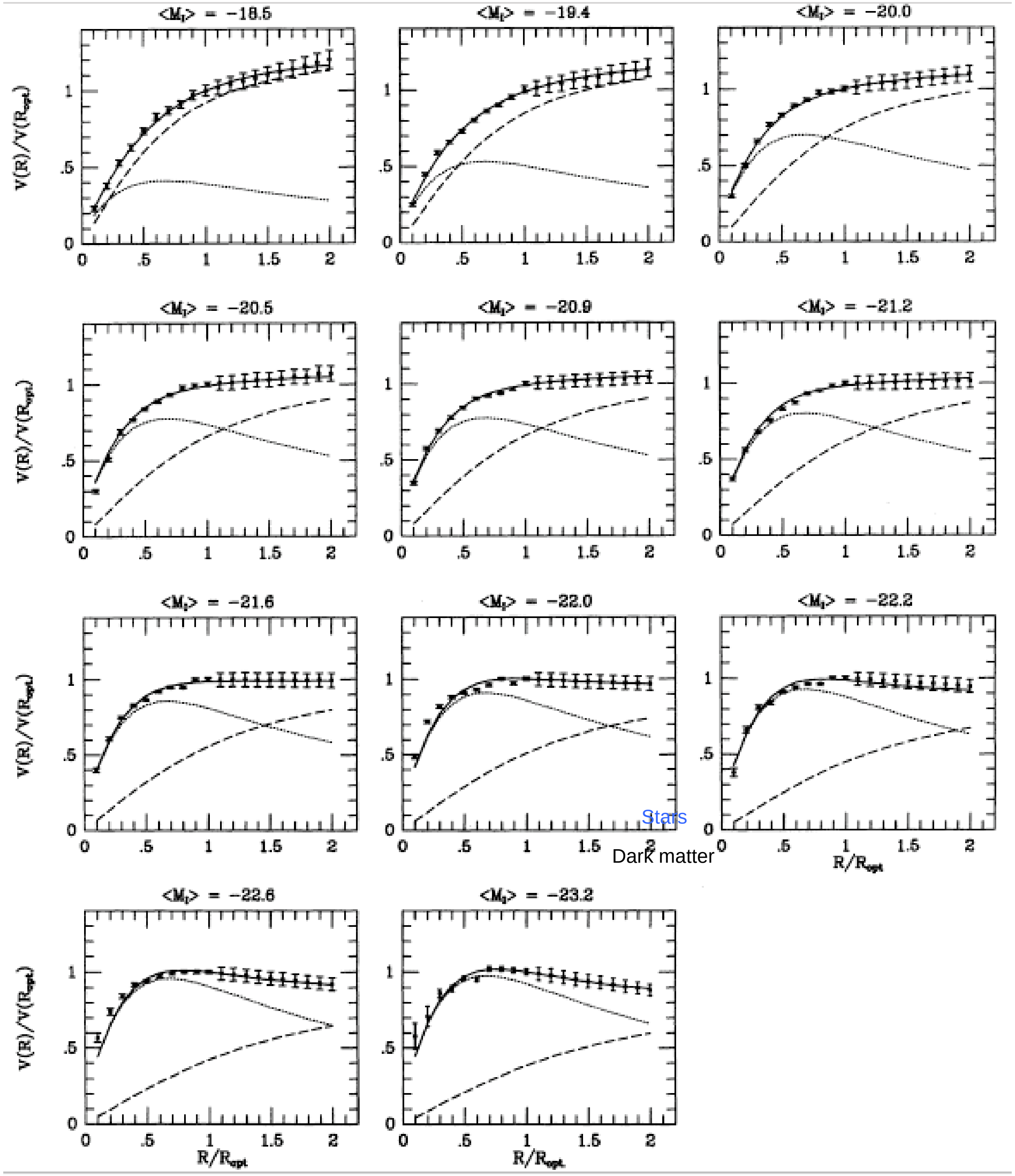


$$\rho(r) = \frac{\rho_0}{(1 + r/r_0)(1 + (r/r_0)^2)}$$

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

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

Modelling the Universal Rotation Curve



*M*_B < -17.5

Rotation Velocity

Stellar contribution

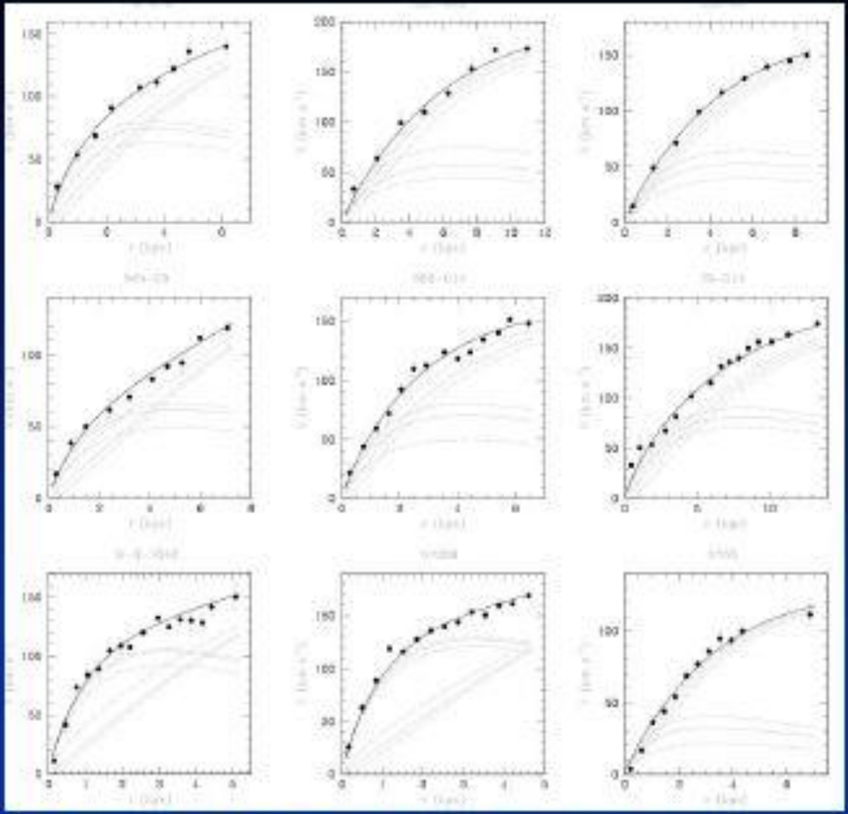
$$V_{\mathrm{URC}}\left(\frac{R}{R_{\mathrm{opt}}}\right)=V(R_{\mathrm{opt}})\left\{\left(0.72+0.44\log\frac{L}{L_*}\right)\frac{1.97x^{1.22}}{(x^2+0.78^2)^{1.43}}+1.6\exp[-0.4(L/L_*)]\frac{x^2}{x^2+1.5^2\left(\frac{L}{L_*}\right)^{0.4}}\right\}^{1/2}\ \mathrm{km\ s^{-1}}$$

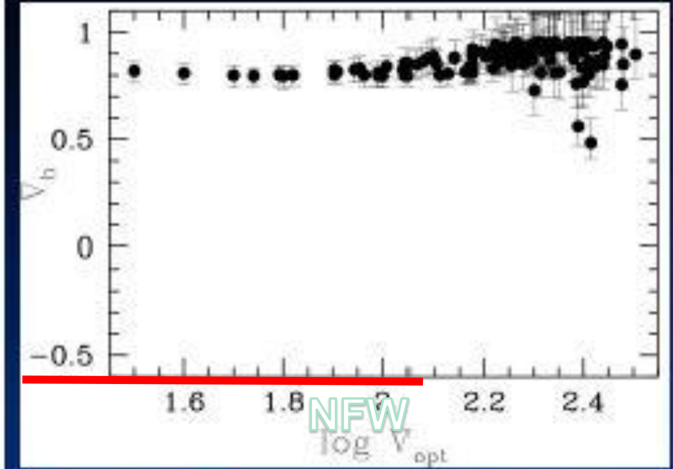
Dark matter halo contribution

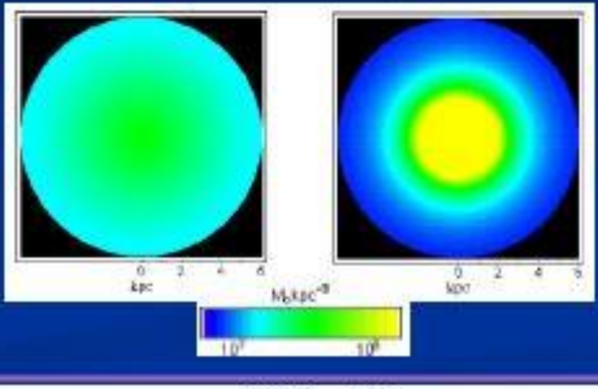
Results from Trieste: analysis of high quality RCs

URC fits to RCs

PROOFS
OF CORES
DISPROOF
OF CUSPS

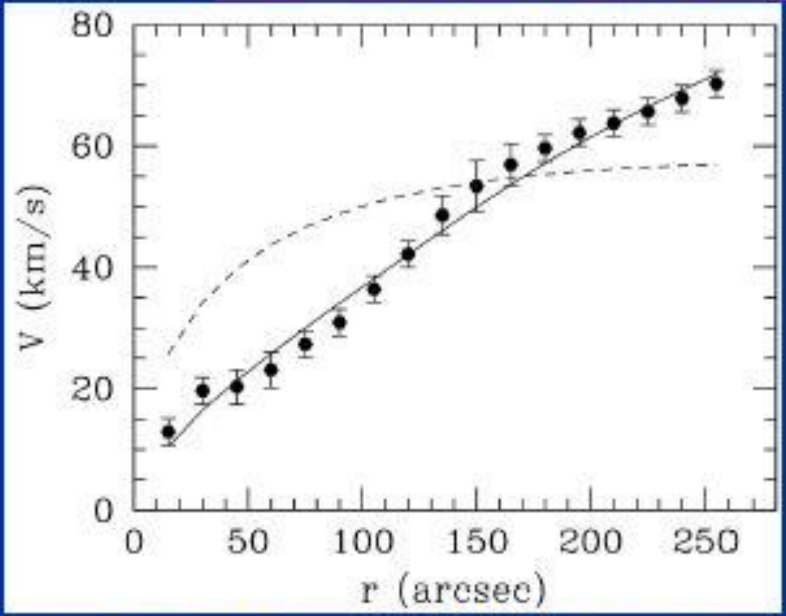




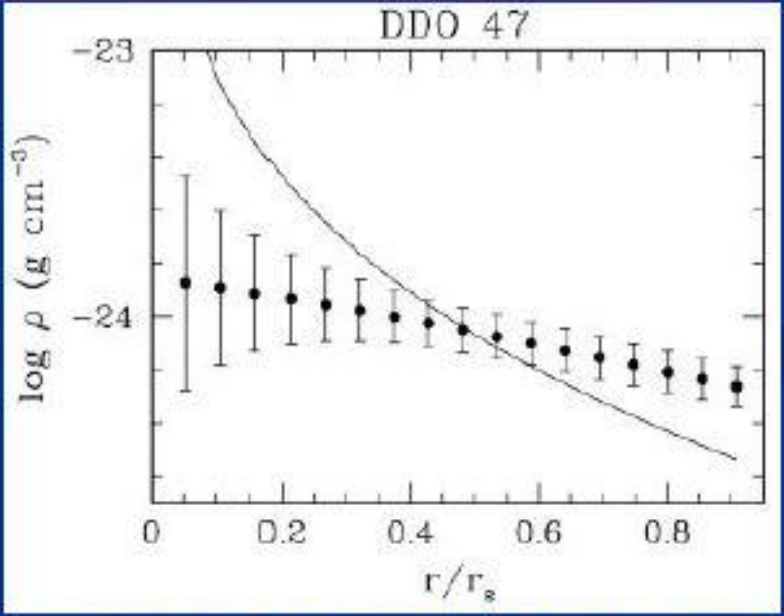


Borriello & Salucci, MNRAS 323, 285 (2001)

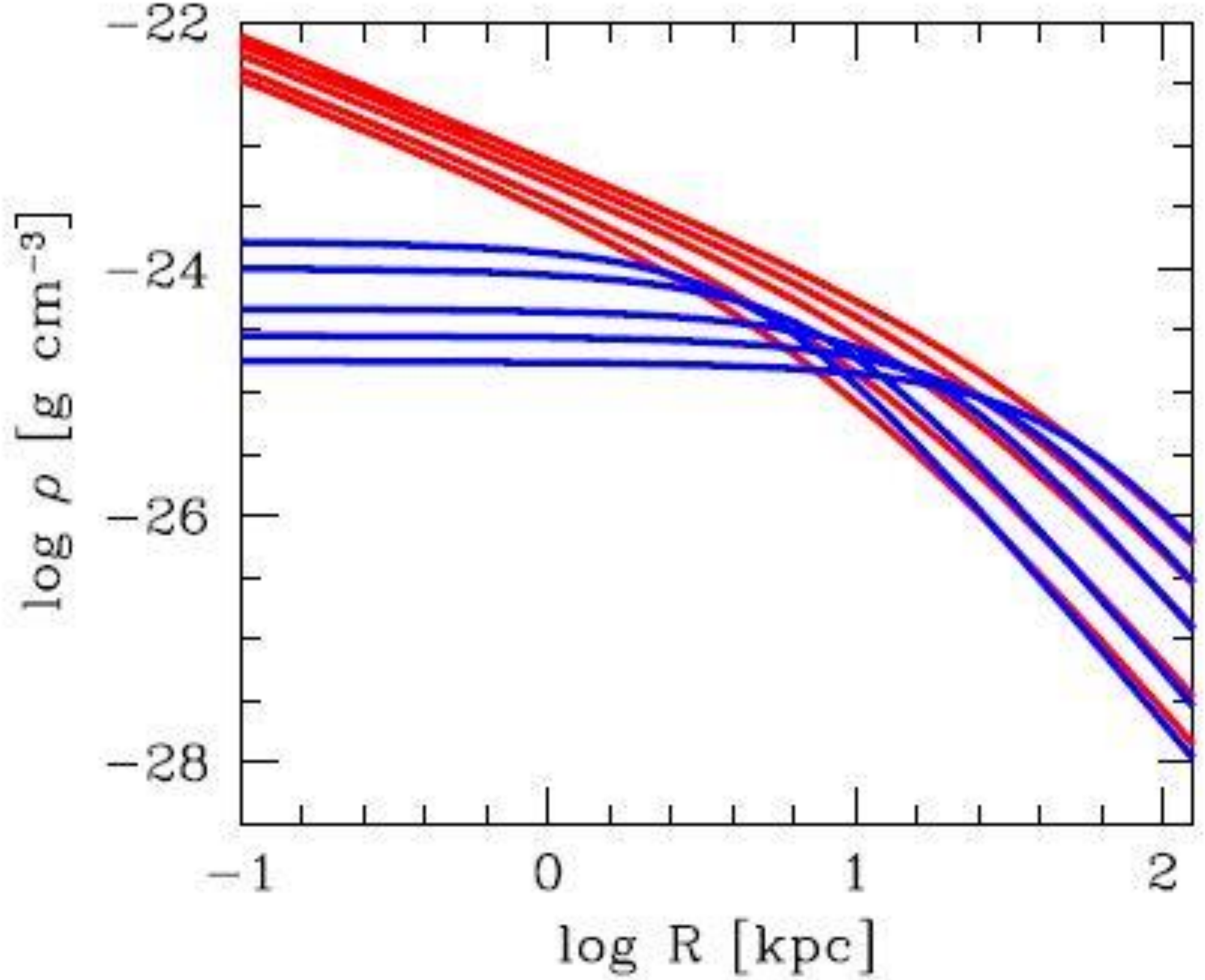
DDO 47



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



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

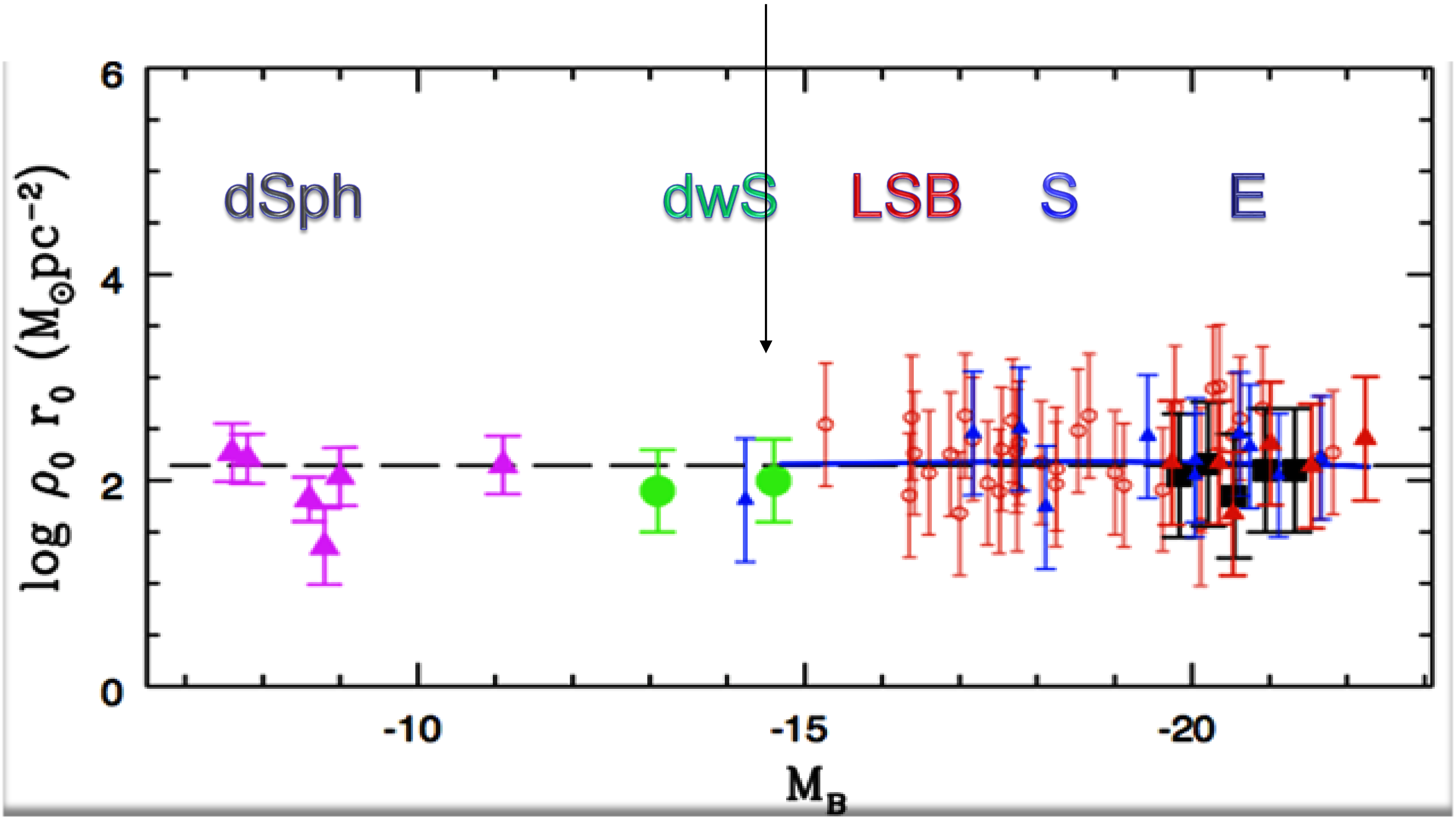


−22
−24
−26
−28
log ρ [g cm^{-3}]
−1
0
1
2
log R [kpc]

GALAXY HALOS STRUCTURAL PARAMETRES

ΛCDM → heavy ΛBCDM regime

eg (di Cintio 15, Frenk 15)



Core radii between 0.1 kpc to 100 kpc

Observational rotation curves and density profiles versus the Thomas–Fermi galaxy structure theory

H. J. de Vega,[1,2]★ P. Salucci[3] and N. G. Sanchez[2]

[1] *Sorbonne Universités, UPMC (Univ. Paris VI), CNRS, Laboratoire Associé au CNRS UMR 7589, Tour 13-14, 4ème. et 5ème. étage, Boîte 126, 4, Place Jussieu, F-75252 Paris, France*
[2] *Observatoire de Paris, LERMA, Laboratoire Associé au CNRS UMR 8112, 61, Avenue de l'Observatoire, F-75014 Paris, France*
[3] *SISSA/ISAS and INFN, Trieste, Iniziativa Specifica QSKY, via Bonomea 265, I-34136 Trieste, Italy*

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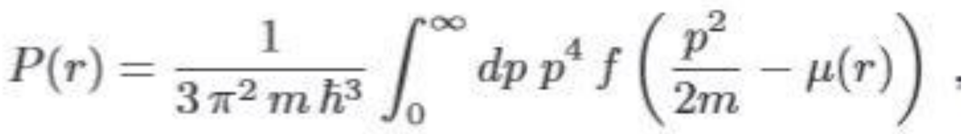
ABSTRACT

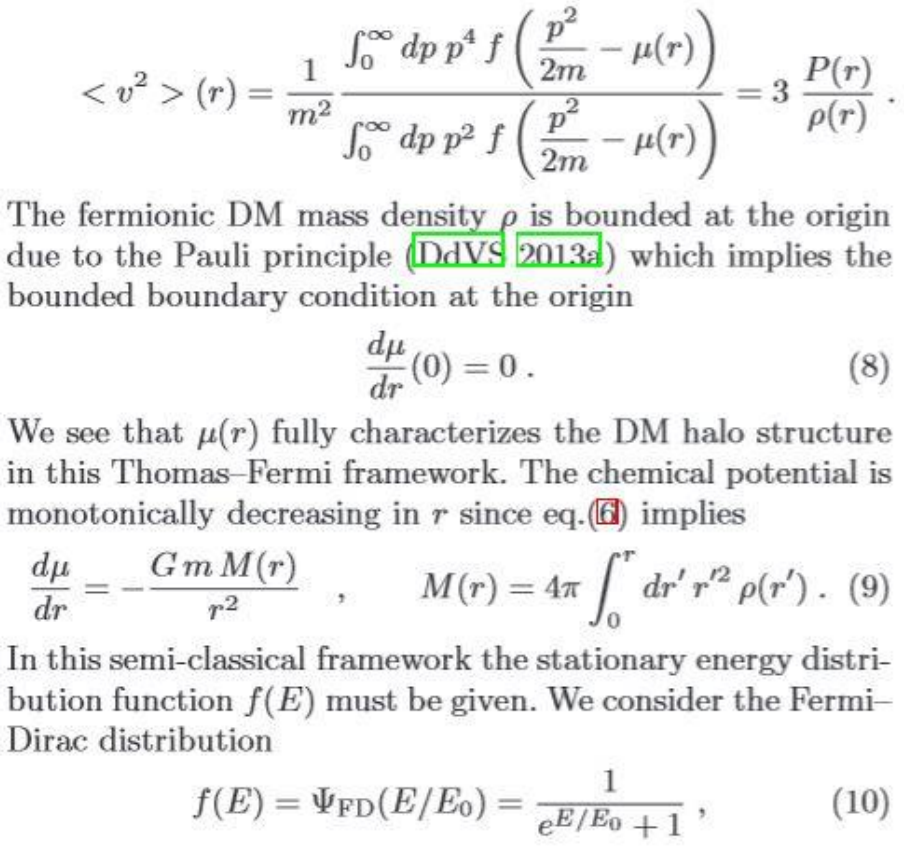
The Thomas–Fermi approach to galaxy structure determines self-consistently the gravitational potential of the fermionic warm dark matter (WDM) given its distribution function $f(E)$. This framework is appropriate for macroscopic quantum systems as neutron stars, white dwarfs and WDM galaxies. Compact dwarf galaxies are near the quantum degenerate regime, while large galaxies are in the classical Boltzmann regime. We derive analytic scaling relations for the main galaxy magnitudes: halo radius r_h, mass M_h and phase-space density. Small deviations from the exact scaling show up for compact dwarfs due to quantum macroscopic effects. We contrast the theoretical curves for the circular galaxy velocities $v_c(r)$ and density profiles $\rho(r)$ with those obtained from observations using the empirical Burkert profile. Results are independent of any WDM particle physics model, they only follow from the gravitational interaction of the WDM particles and their fermionic nature. The theoretical rotation curves and density profiles reproduce very well the observational curves for $r \lesssim r_h$ obtained from 10 different and independent sets of data for galaxy masses from 5×10^9 to $5 \times 10^{11}\ M_\odot$. Our normalized theoretical circular velocities and normalized density profiles turn to be universal functions of r/r_h for all galaxies. In addition, they agree extremely well with the observational curves described by the Burkert profile for $r \lesssim 2\ r_h$. These results show that the Thomas–Fermi approach correctly describes the galaxy structures.



$$P(r) = \frac{1}{3\,\pi^2\,m\,\hbar^3} \int_0^\infty dp\, p^4\, f\left(\frac{p^2}{2m} - \mu(r)\right) ,$$

pseudo-pressure

pseudo-equation of state



$$< v^2 > (r) = \frac{1}{m^2} \frac{\int_0^\infty dp\, p^4\, f\left(\frac{p^2}{2m} - \mu(r)\right)}{\int_0^\infty dp\, p^2\, f\left(\frac{p^2}{2m} - \mu(r)\right)} = 3\, \frac{P(r)}{\rho(r)} .$$

The fermionic DM mass density ρ is bounded at the origin due to the Pauli principle (DdVS 2013a) which implies the bounded boundary condition at the origin

Pauli Principle

$$\frac{d\mu}{dr}(0) = 0 . \qquad (8)$$

We see that $\mu(r)$ fully characterizes the DM halo structure in this Thomas–Fermi framework. The chemical potential is monotonically decreasing in r since eq.(6) implies

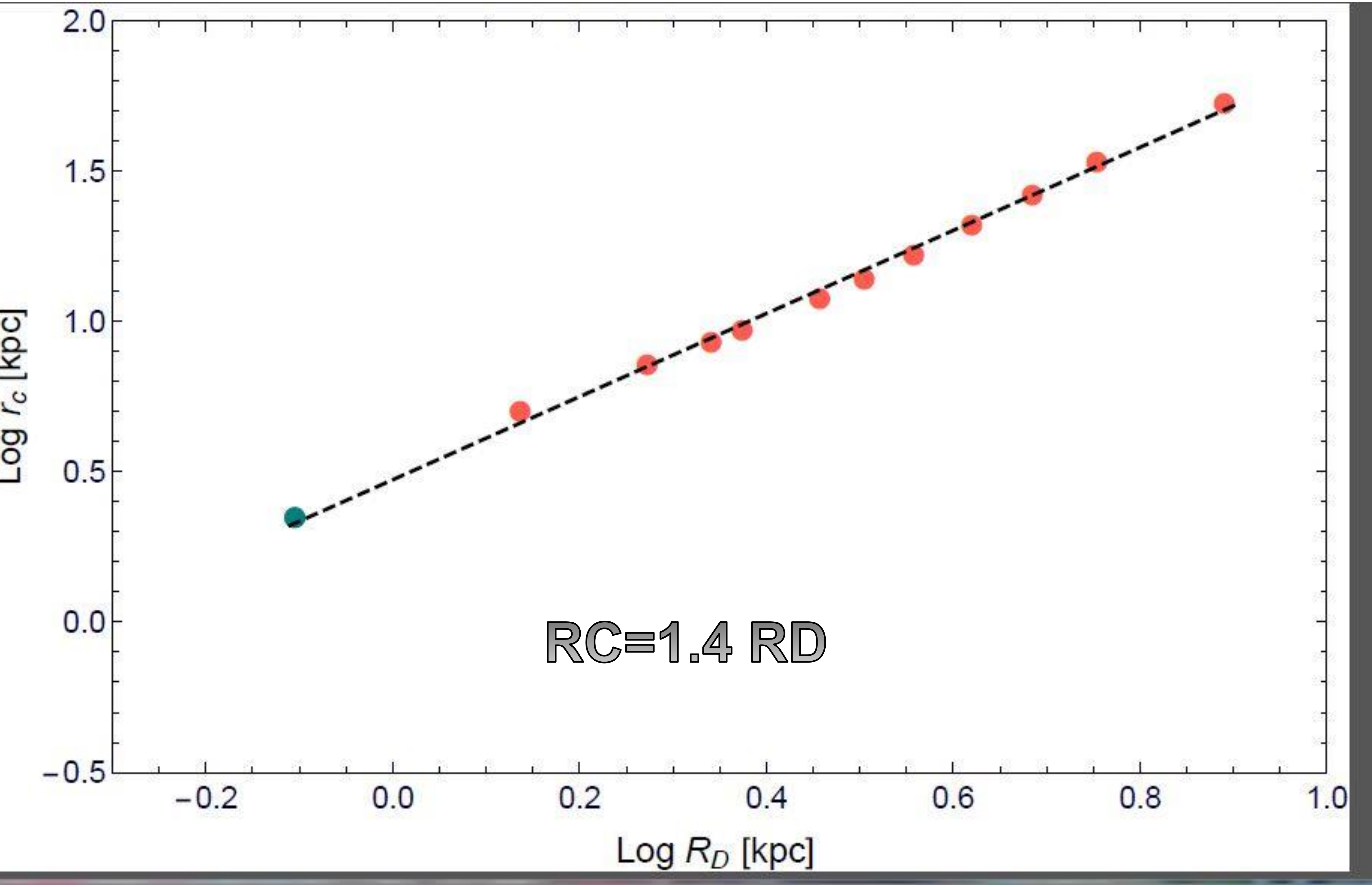
Newton Gravity

$$\frac{d\mu}{dr} = -\frac{G\,m\,M(r)}{r^2} \quad , \qquad M(r) = 4\pi \int_0^r dr'\, r'^2\, \rho(r') . \quad (9)$$

In this semi-classical framework the stationary energy distribution function $f(E)$ must be given. We consider the Fermi–Dirac distribution

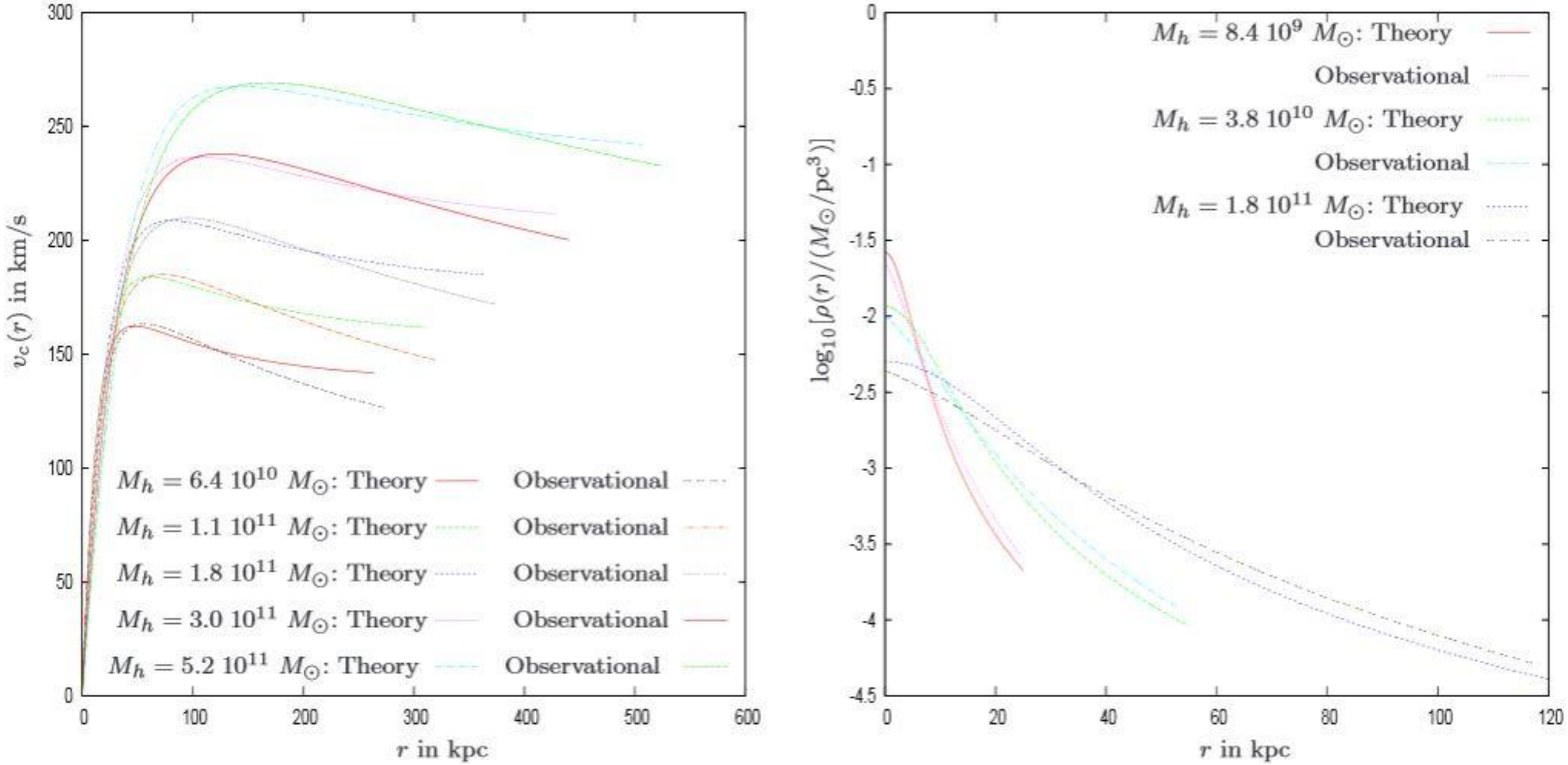
Fermi distribution

$$f(E) = \Psi_{\rm FD}(E/E_0) = \frac{1}{e^{E/E_0} + 1} , \qquad (10)$$



RC=1.4 RD

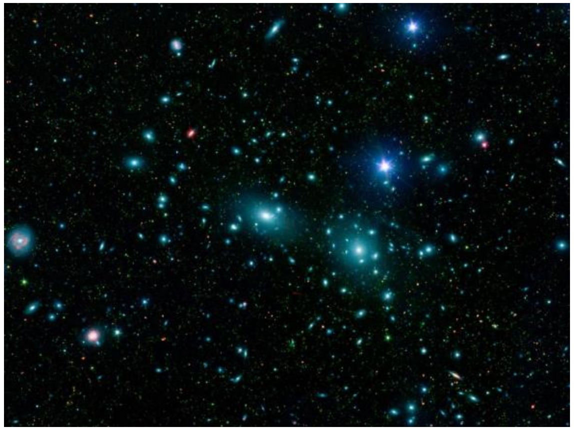
free parameters of the model: m, $T_0(M_h)$



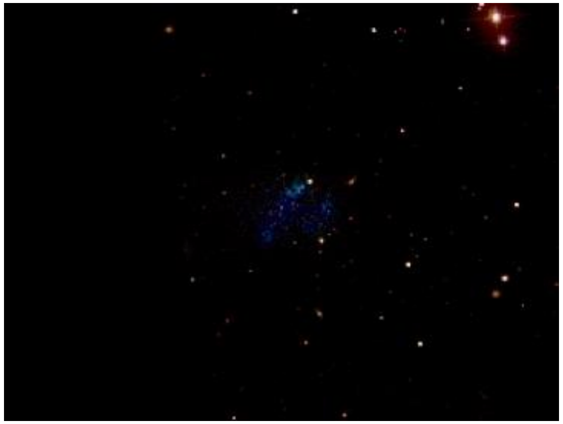
SMALLEST GALAXIES

the most numerous ones
the more DM dominated
the densest objects
the first born
immune by LBCDM

dSph
complex dynamics

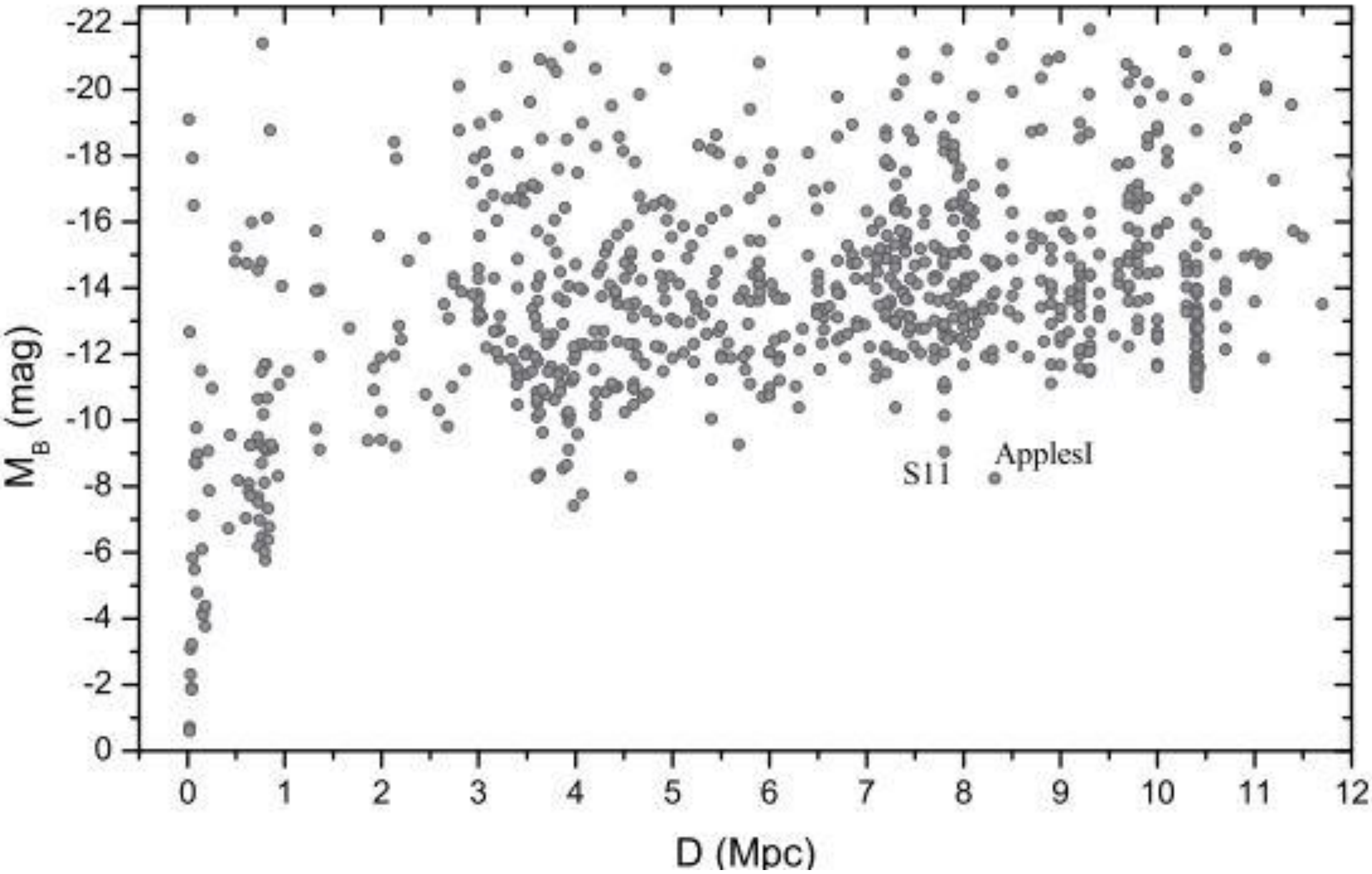


dwS
simple dynamics

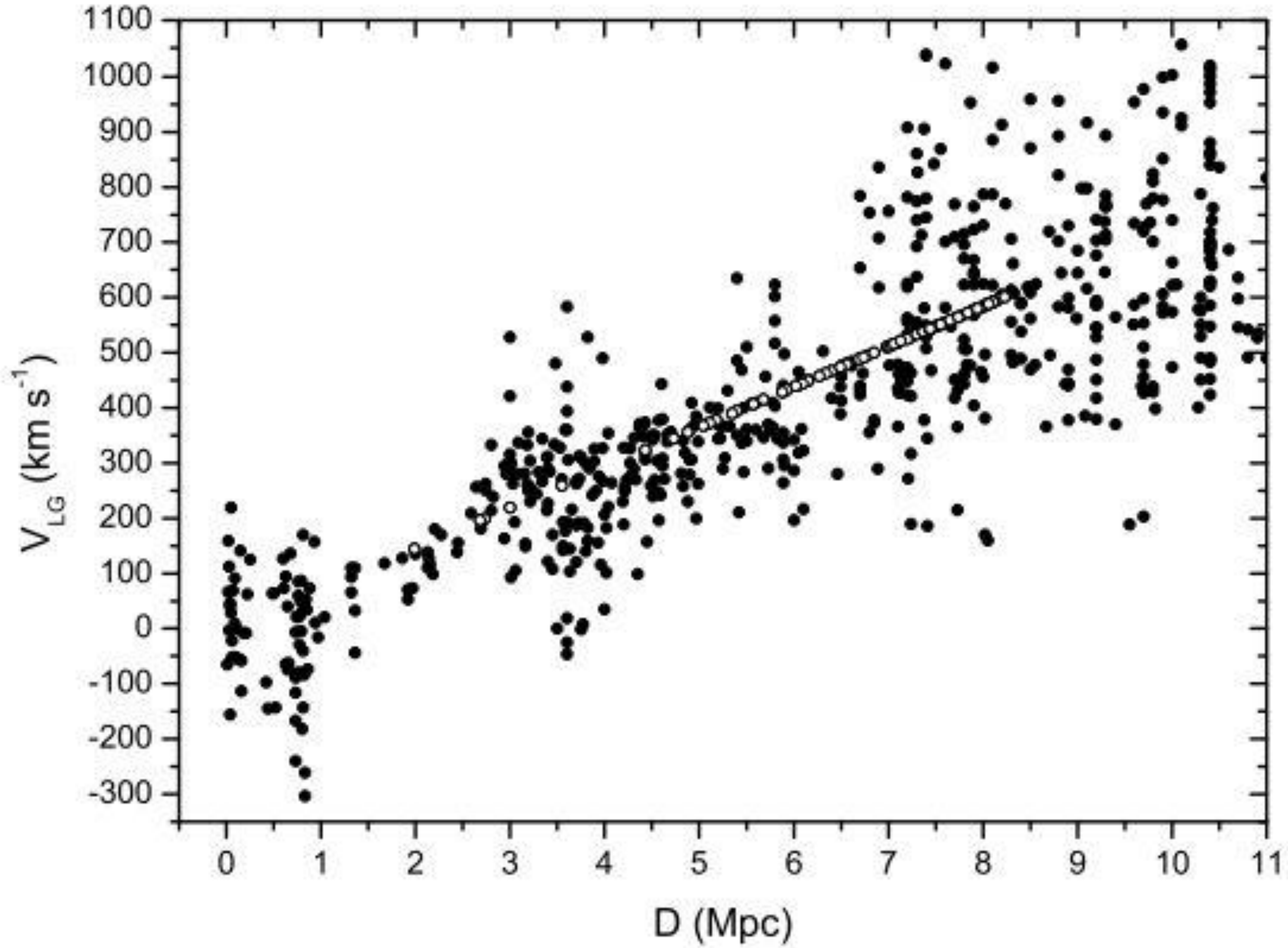


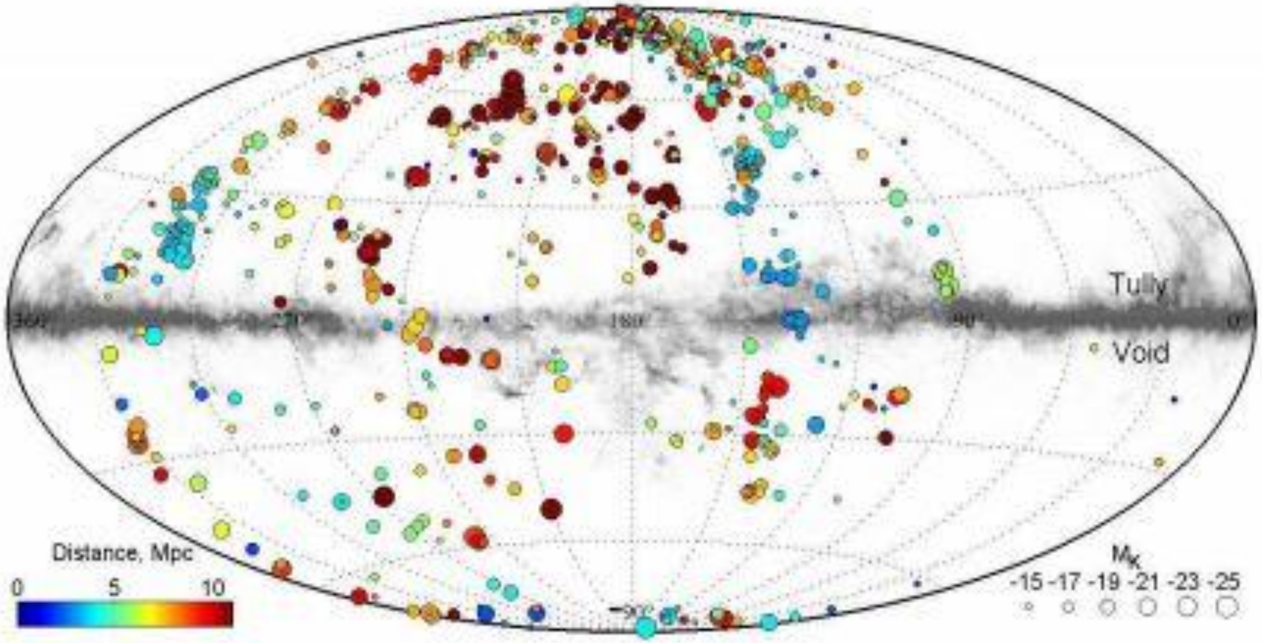
Updated Nearby Galaxy Catalog.

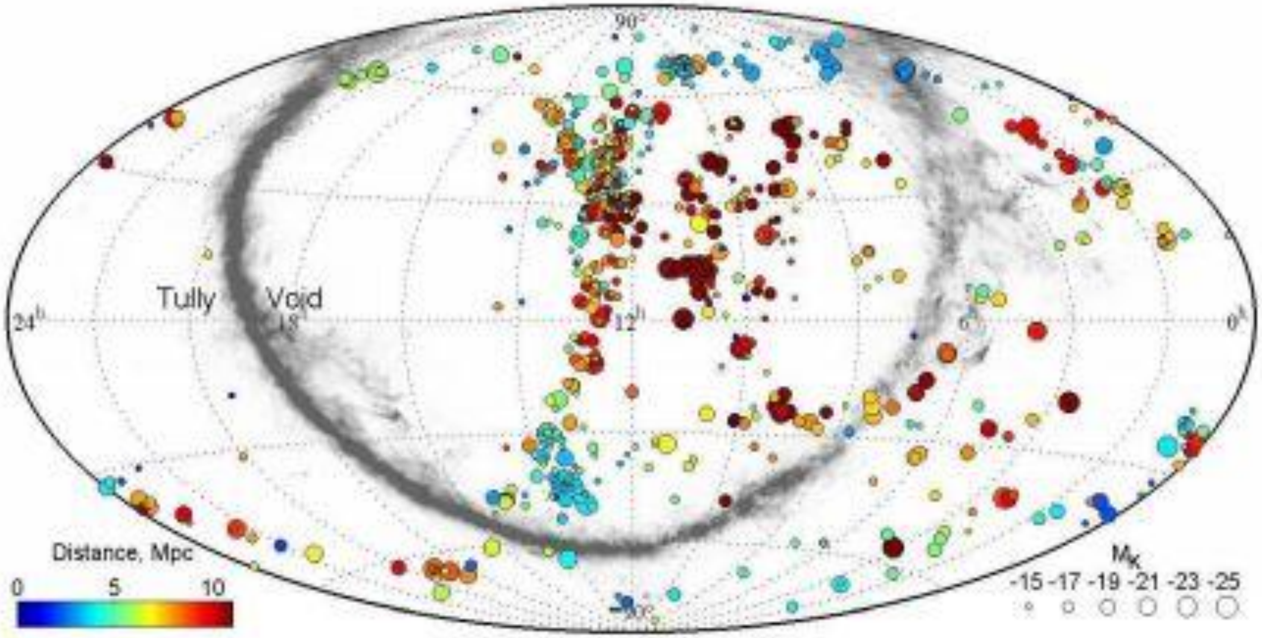
Igor D. Karachentsev, Dmitry I. Makarov and Elena I. Kaisina



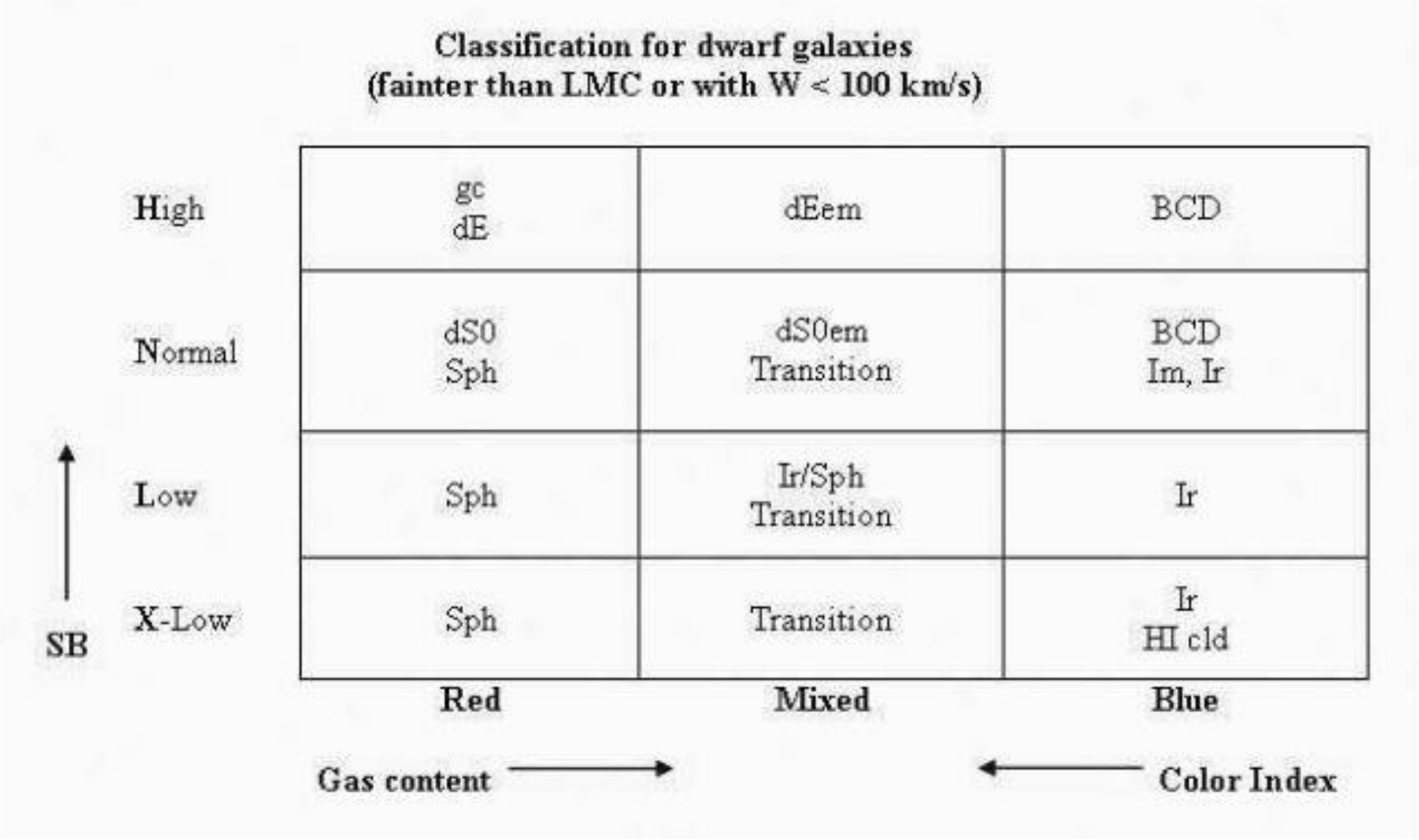
Hubble Flow


1100
1000
900
800
700
600
500
400
300
200
100
0
-100
-200
-300
V_{LG} (km s^{-1})
0
1
2
3
4
5
6
7
8
9
10
11
D (Mpc)


Tully
Void
360°
270°
180°
90°
0°
-90°
Distance, Mpc
0
5
10
M_K
-15 -17 -19 -21 -23 -25


90°
Tully
Void
24h
18h
12h
6h
0h
-90°
Distance, Mpc
0
5
10
M_K
-15 -17 -19 -21 -23 -25

Classification of Dwarfs



Classification for dwarf galaxies
(fainter than LMC or with W < 100 km/s)

SB ↑	Red	Mixed	Blue
High	gc dE	dEem	BCD
Normal	dS0 Sph	dS0em Transition	BCD Im, Ir
Low	Sph	Ir/Sph Transition	Ir
X-Low	Sph	Transition	Ir HI cld

Gas content →

← **Color Index**

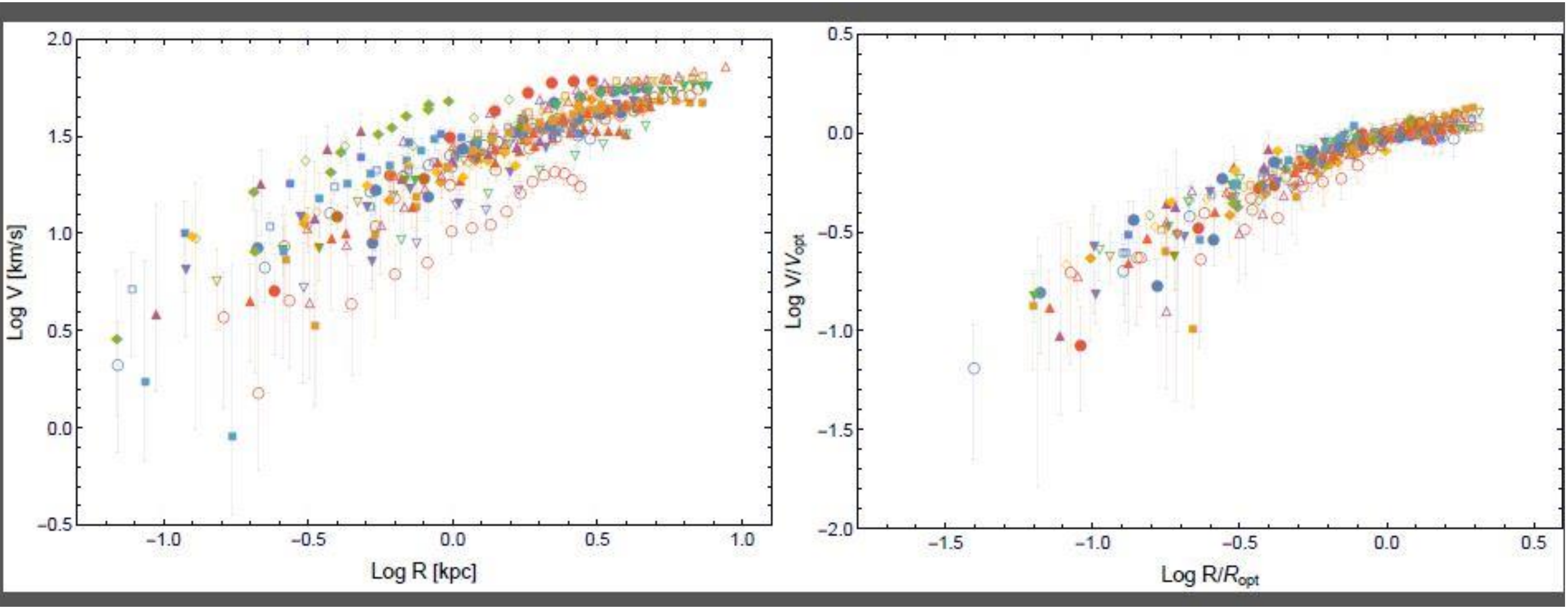
DD Sample
36 objects

NGC6822	0.5	-; 10	0.56	b	35.0
UGC7916	9.1	-; 2	1.63	l	37.0
UGC5918	7.45	-; 2	1.23	2	45.0
AndIV	7.17	-;11	0.48	11	32.2
UGC7232	2.82	-; 2	0.21	h	37.0
DDO133	4.85	-; 3	0.9	m	42.4
UGC8508	2.69	1; 3,12	0.28	n	40.0
UGC2455	7.8	-; 2	1.06	l	47.0

Notes. RC & R_D references: Moiseev (2014)-1, Swaters et al. (2009)-2, Oh et al. (2015)-3, Lelli et al. (2014)-4, Epinat et al. (2008)-5, entile et al. (2010)-6, Stil & Israel (2002)-7 Gentile et al. (2012)-9, Weldrake et al. (2003)-10, Karachentsev et al. (2016)-11, Ott et al. (2012)-12, van Zee (2001)-a, Hunter & Elmegreen (2004)-b, Sharina et al. (2008)-c, Bershady et al. (2010)-e, Parodi et al. (2002)-f, imard et al. (2011)-g, Martin (1998)-h, Hunter et al. (2011)-m, Herrmann et al. (2013)-l, Yoshino & Yamauchi (2015)-k, Hunter et al. (2012)-n

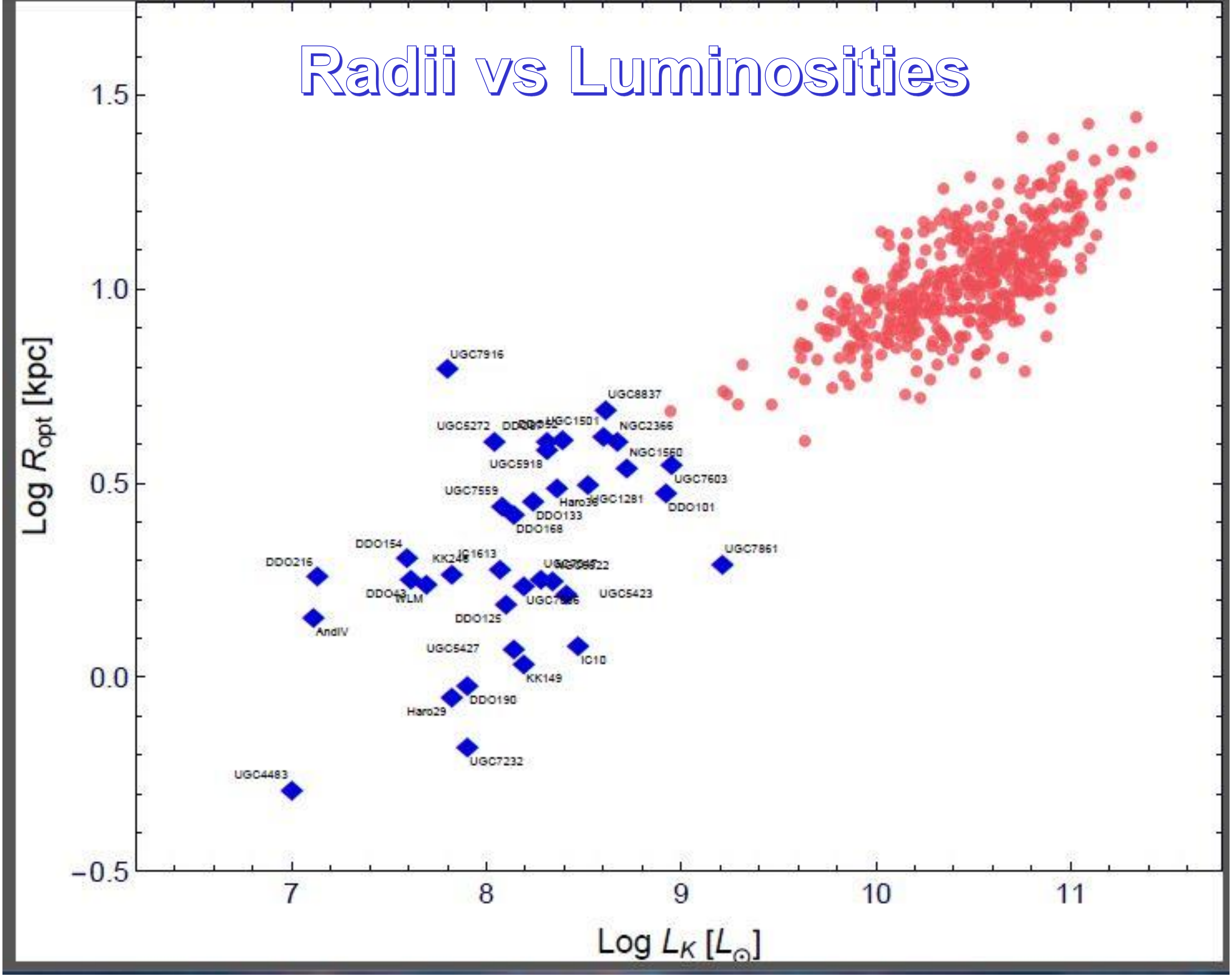
36 Individual RCs

Double Normalized

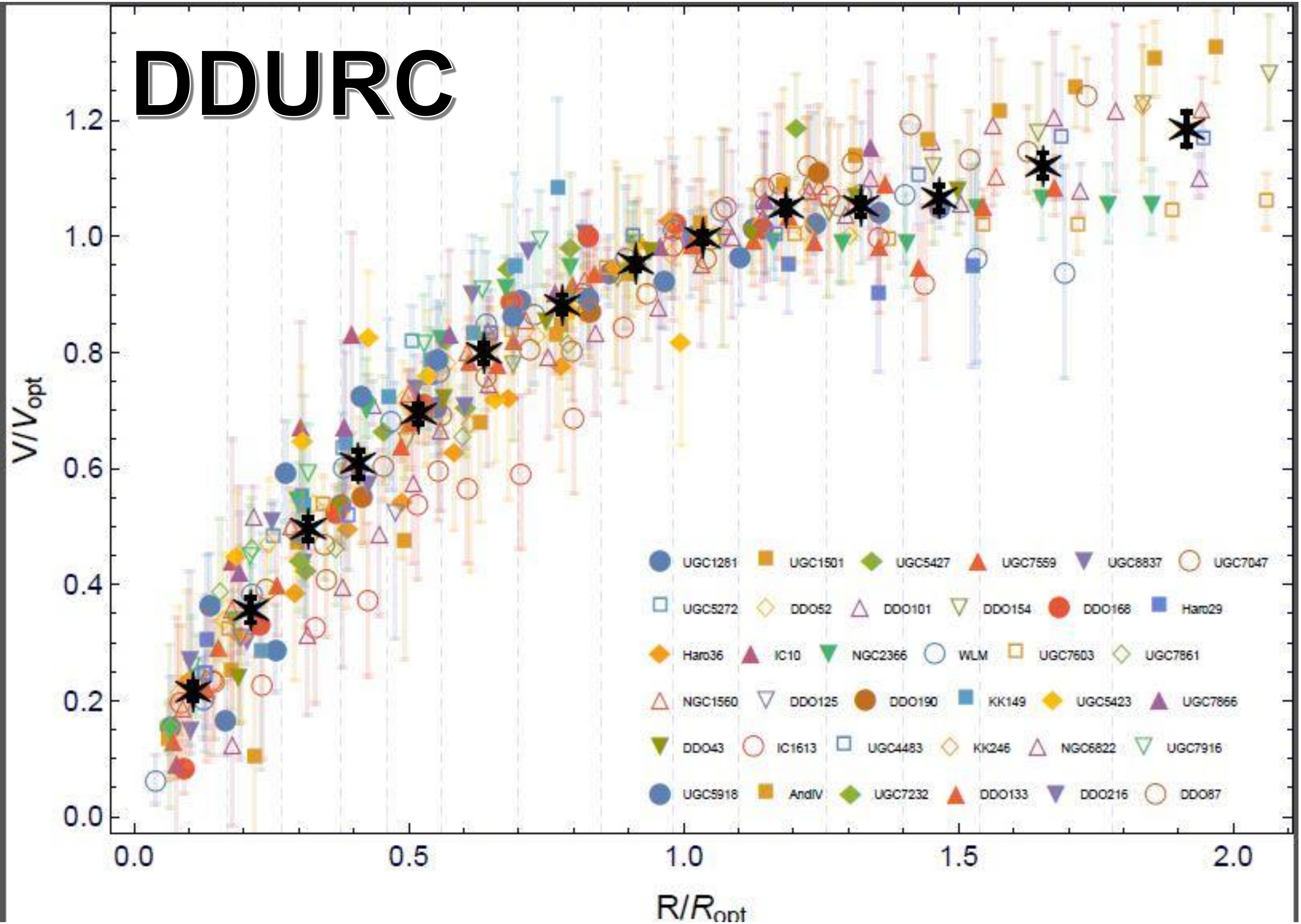


$$V_{DN} = V(R/R_{opt})/V_{opt}$$

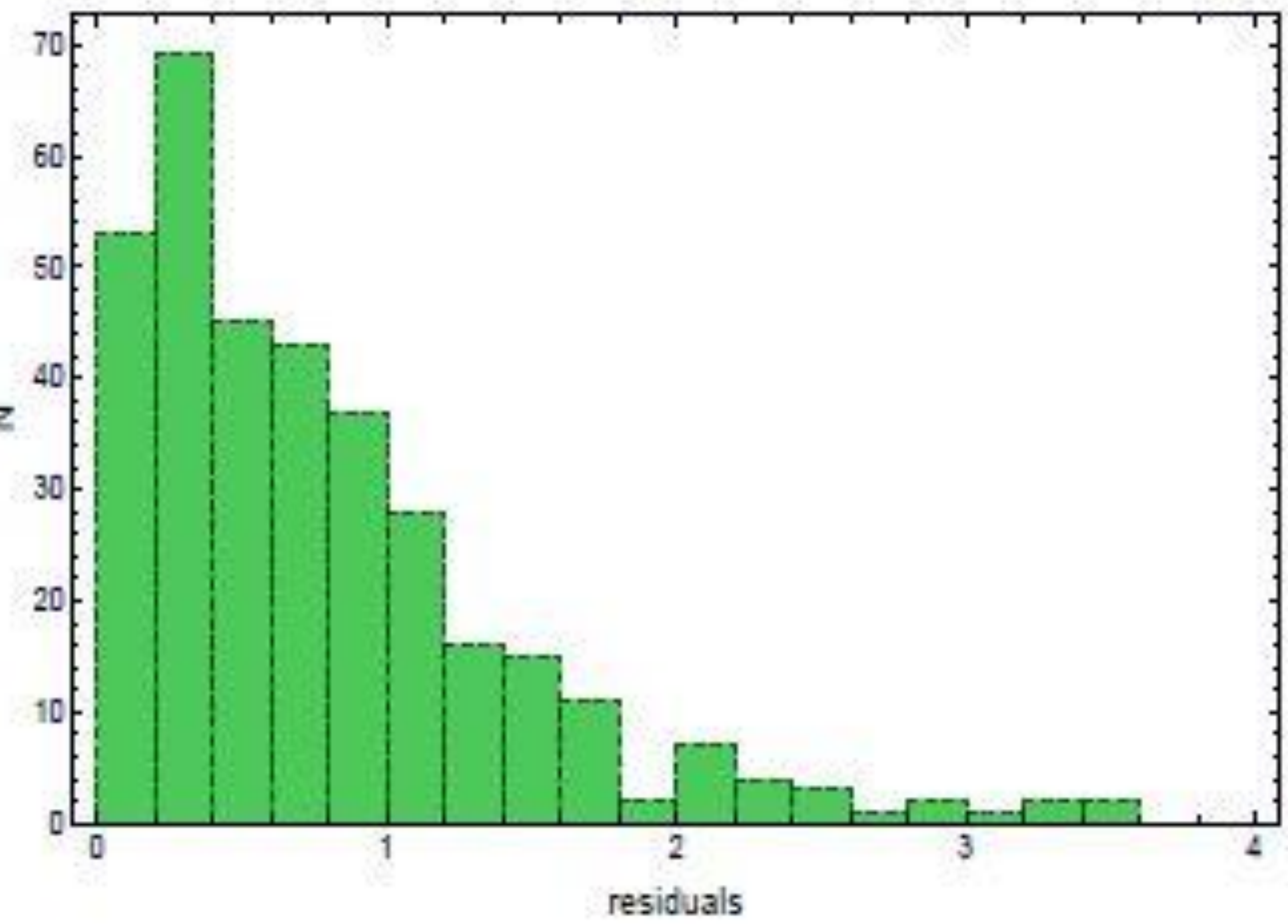
Radii vs Luminosities



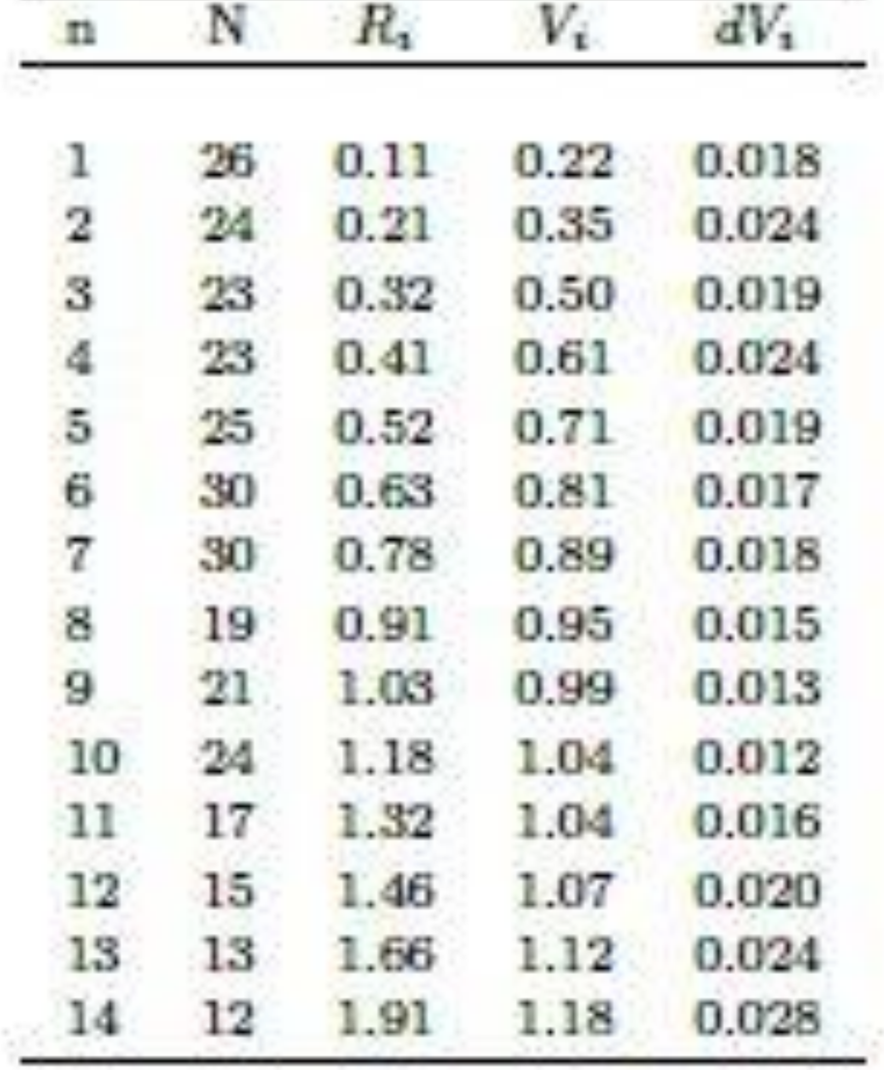
DDURC



V/V_opt
R/R_opt
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.0
0.5
1.0
1.5
2.0
UGC1281
UGC1501
UGC5427
UGC7559
UGC8837
UGC7047
UGC5272
DDO52
DDO101
DDO154
DDO168
Haro29
Haro36
IC10
NGC2366
WLM
UGC7603
UGC7861
NGC1560
DDO125
DDO190
KK149
UGC5423
UGC7866
DDO43
IC1613
UGC4483
KK246
NGC6822
UGC7916
UGC5918
AndIV
UGC7232
DDO133
DDO216
DDO87


70
60
50
40
30
20
10
0
N
0
1
2
3
4
residuals

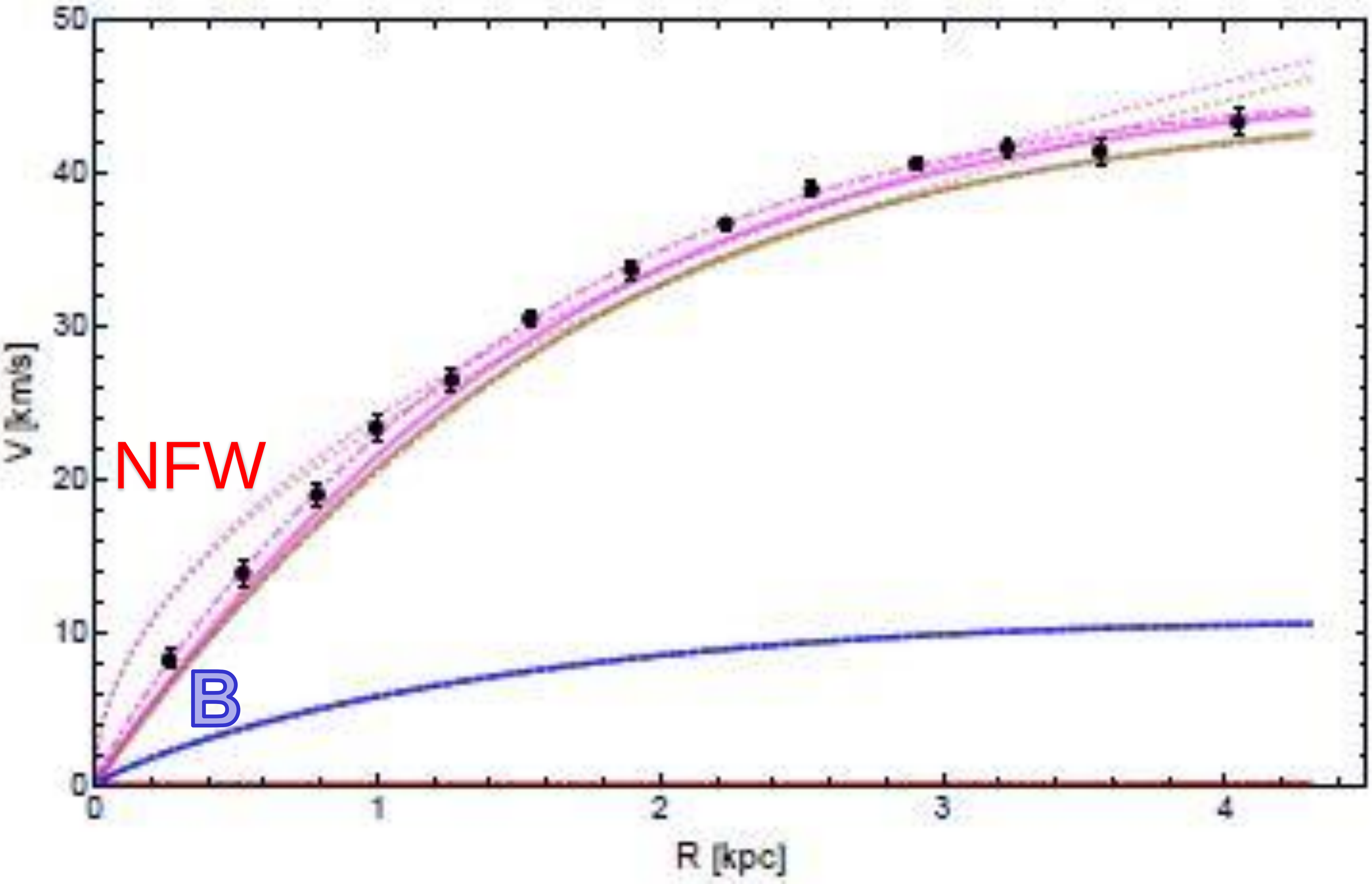
The DD URC



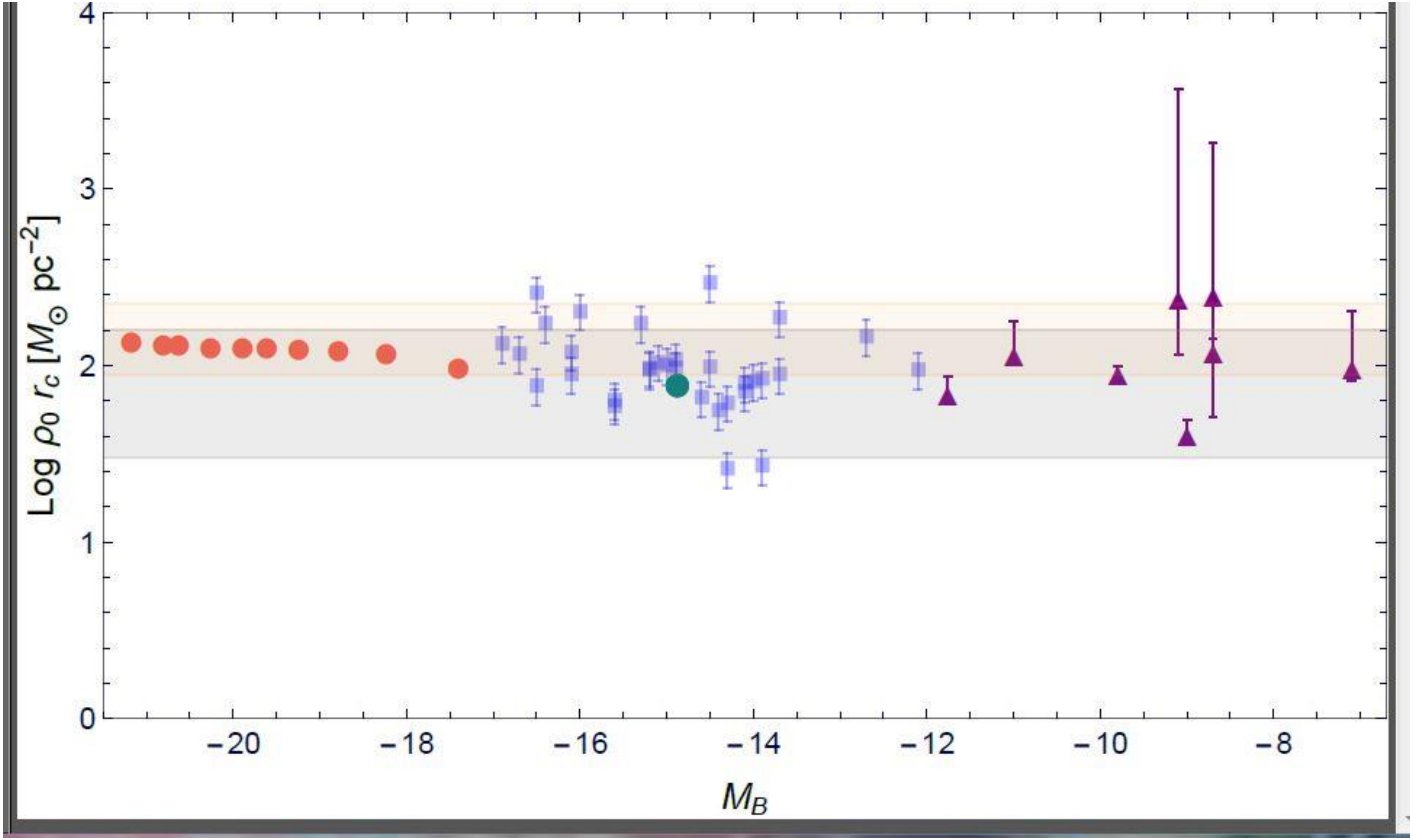
		R_{opt}	V_{opt}	V_{opt}
n	N	R_i	V_i	dV_i
1	26	0.11	0.22	0.018
2	24	0.21	0.35	0.024
3	23	0.32	0.50	0.019
4	23	0.41	0.61	0.024
5	25	0.52	0.71	0.019
6	30	0.63	0.81	0.017
7	30	0.78	0.89	0.018
8	19	0.91	0.95	0.015
9	21	1.03	0.99	0.013
10	24	1.18	1.04	0.012
11	17	1.32	1.04	0.016
12	15	1.46	1.07	0.020
13	13	1.66	1.12	0.024
14	12	1.91	1.18	0.028

$V(R/R_{opt})/V_{opt}$

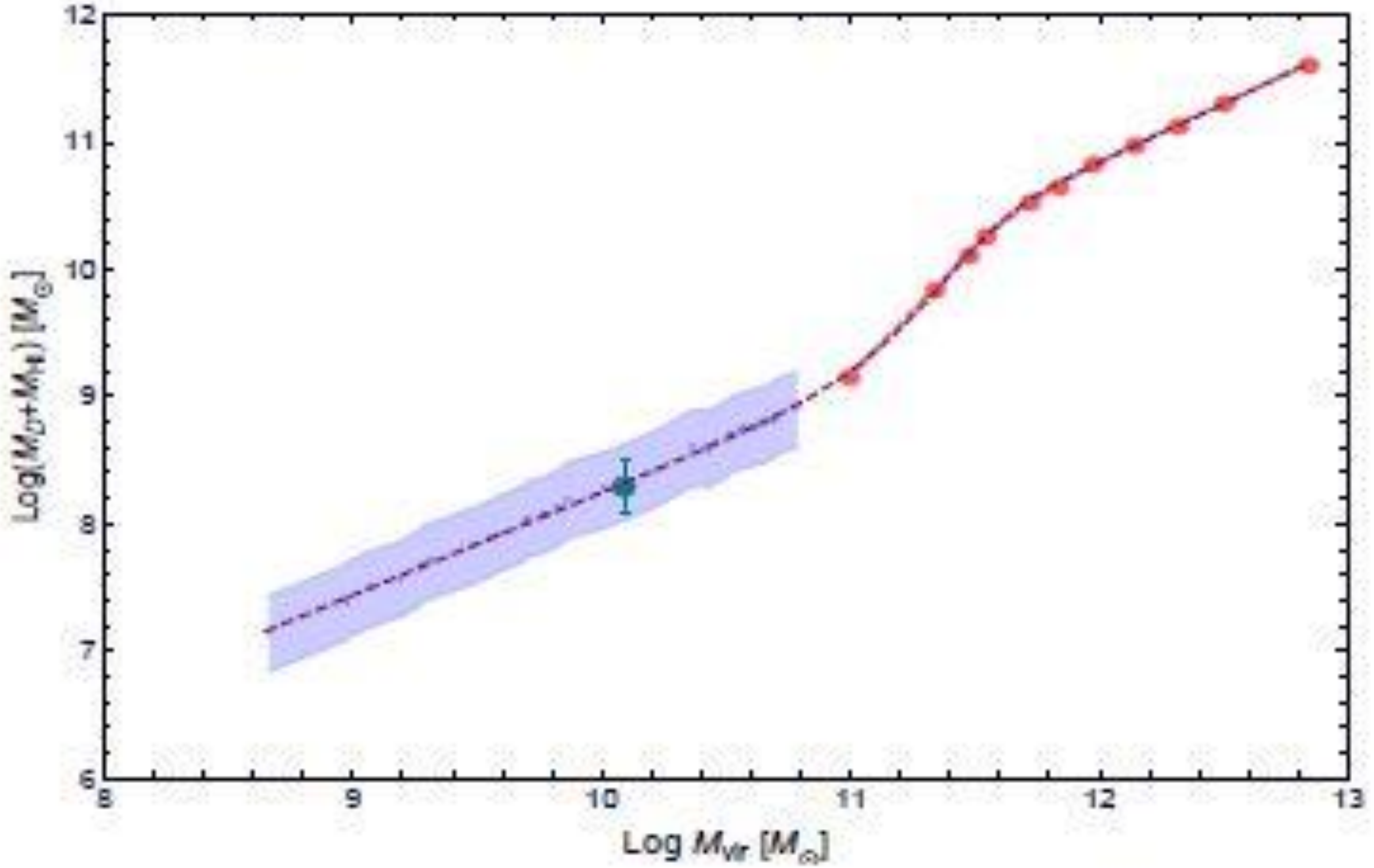
Modelling the DD URC



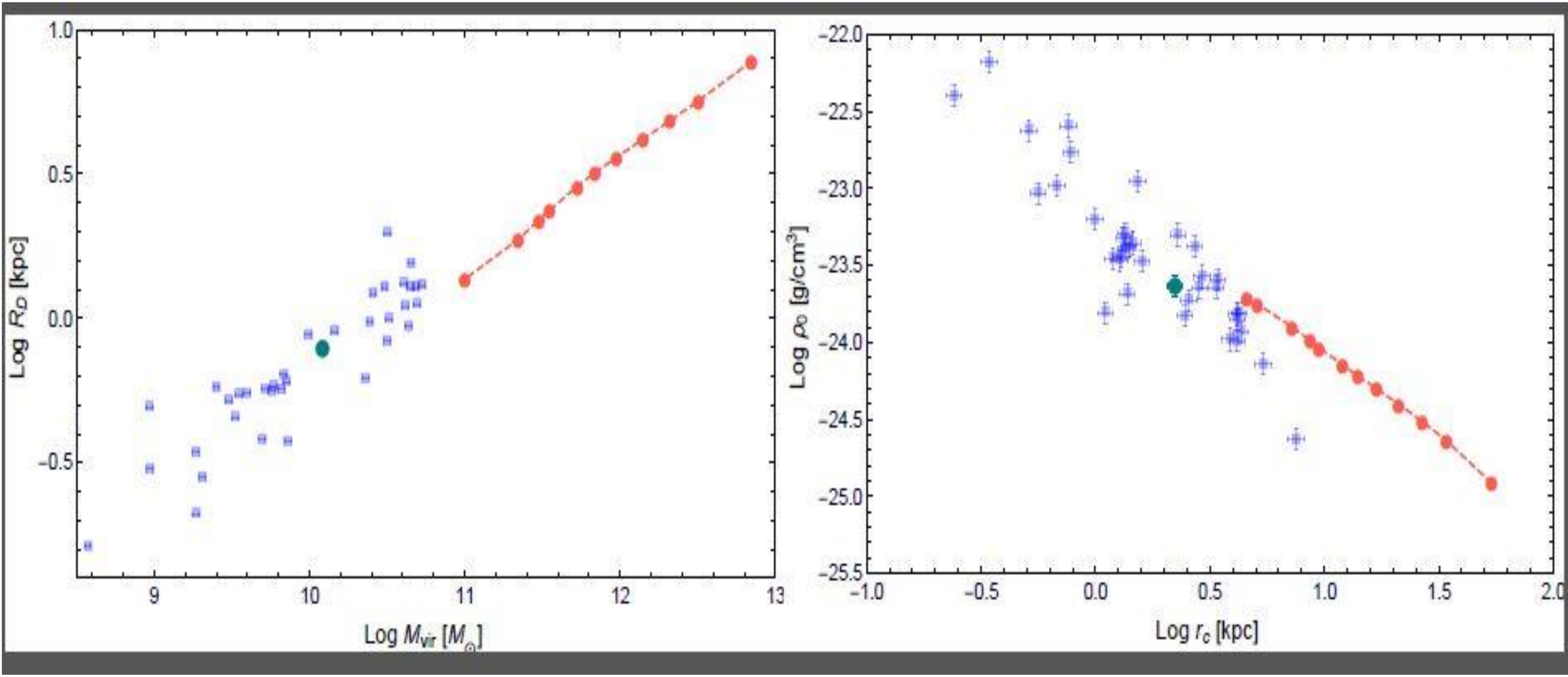
Central DM surface density



Baryonic – halo masses relationship



DD structural relationships



not anymore a Universal Curve

CONCLUSIONS

Cosmo-astrophysical Observations are an Unique Portal to the nature of DM & galaxies Formation and Evolution

The amazing properties of the mass distribution of Dark Matter in very different types of galaxies clearly indicates for a Warm Dark Particle

Other possibilties are too much fine tuned and or ineffective to explain the observational scenario.