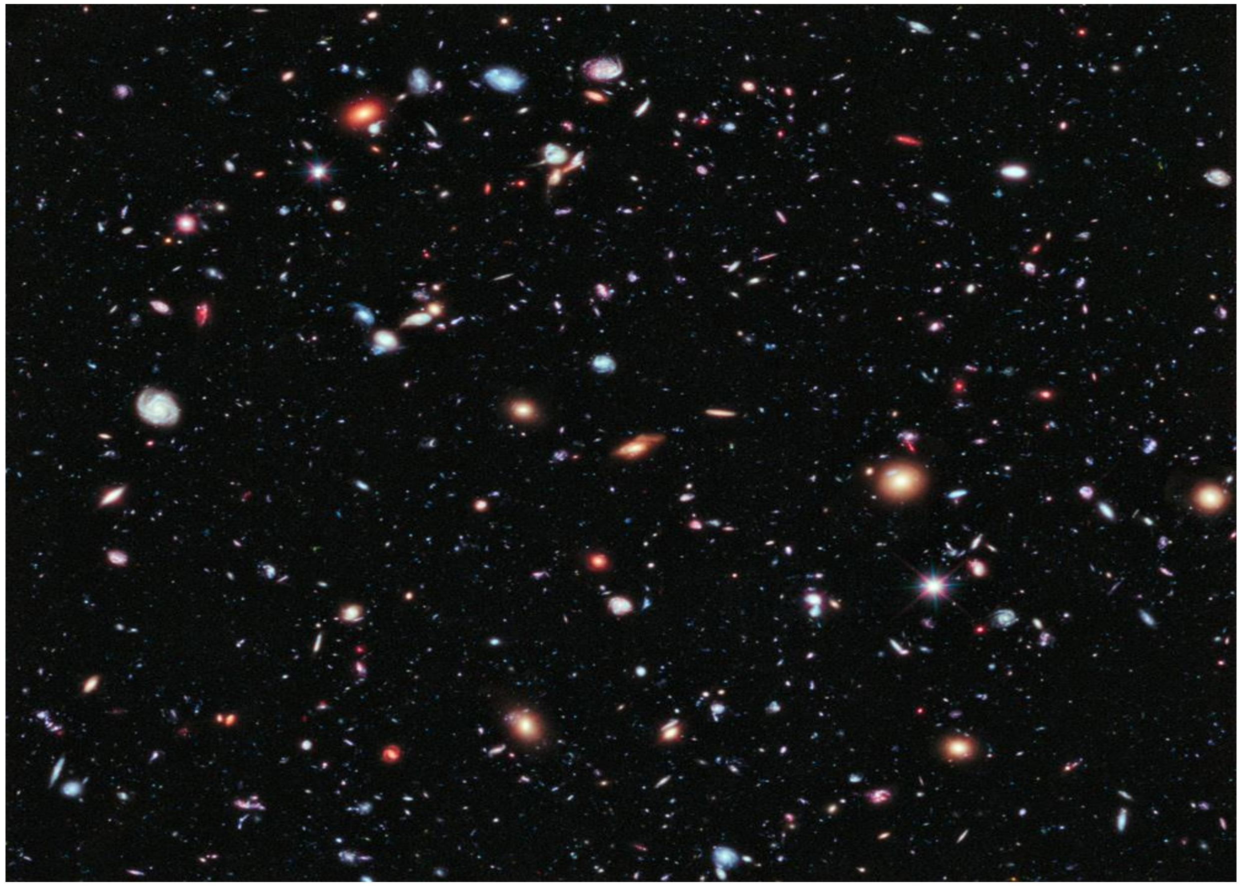
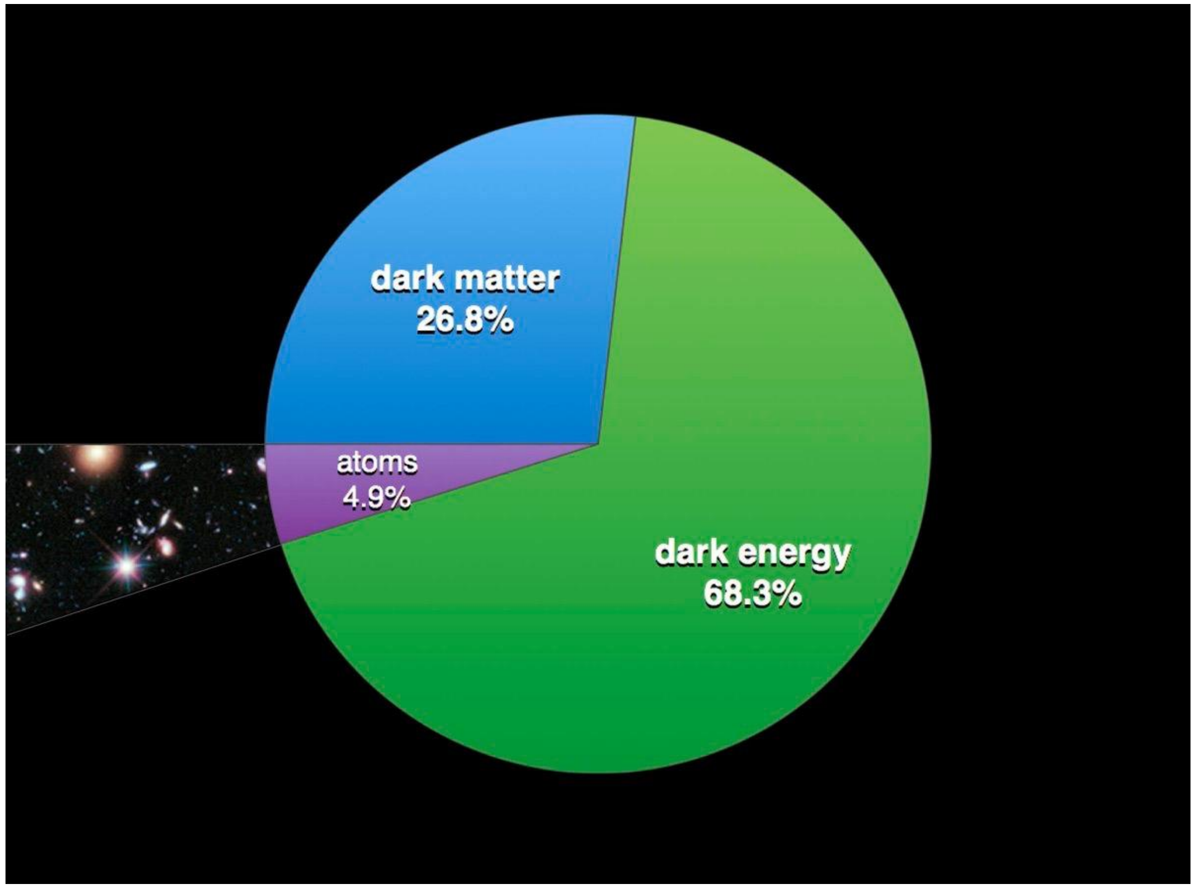
Fundamental properties of the dark and the luminous matter from Low Surface Brightness discs

Paolo Salucci

SISSA

Universe Webinar | keV Warm Dark Matter in Agreement with Observations in Tribute to Héctor J. De Vega



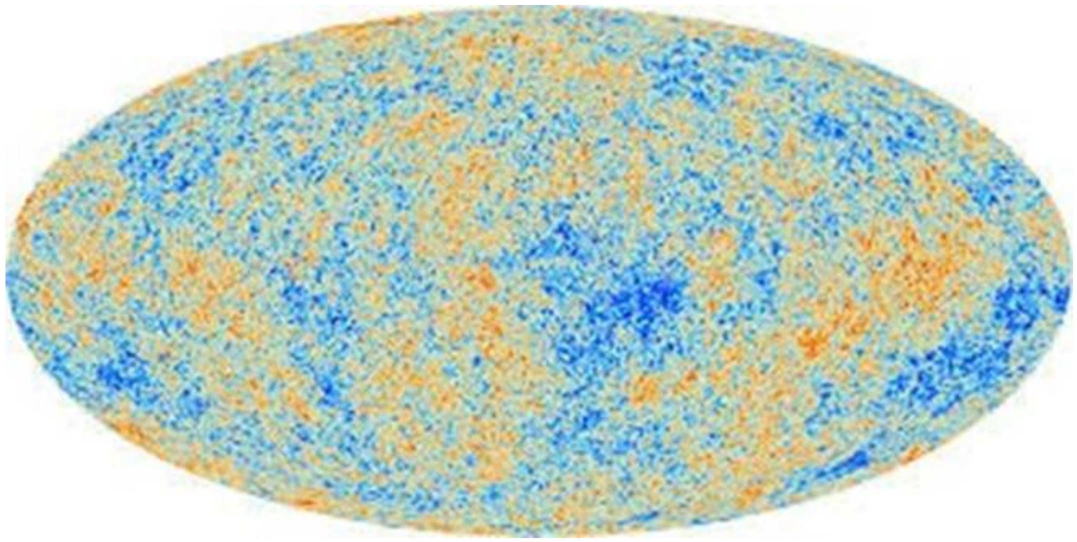


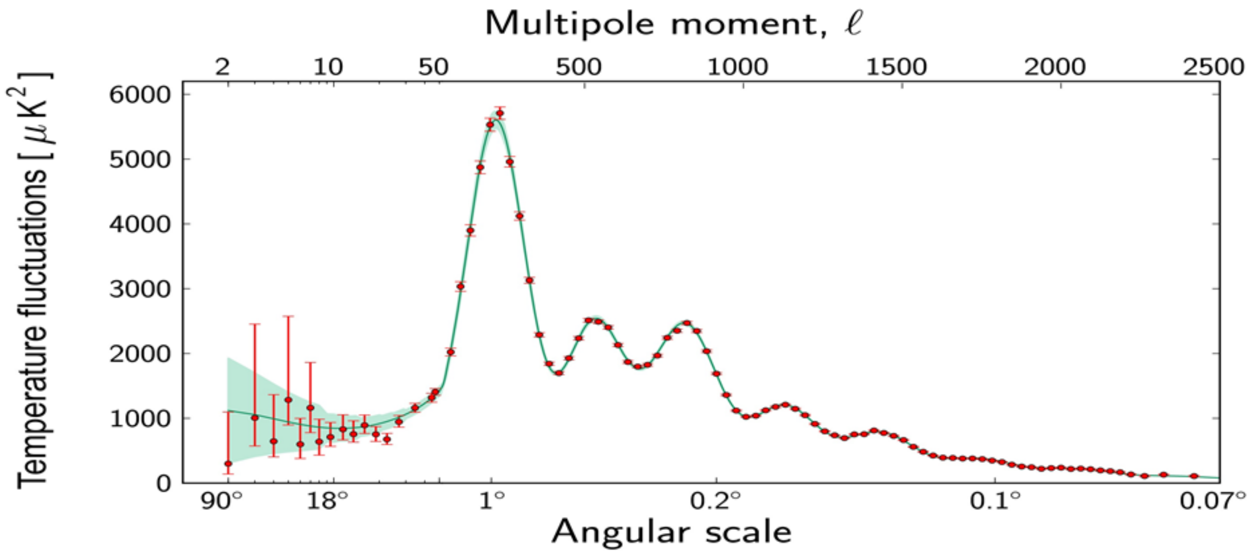
What we can observe by means of telescopes is the light emitted by stars, dust and gas, but they are only the tip of an iceberg.

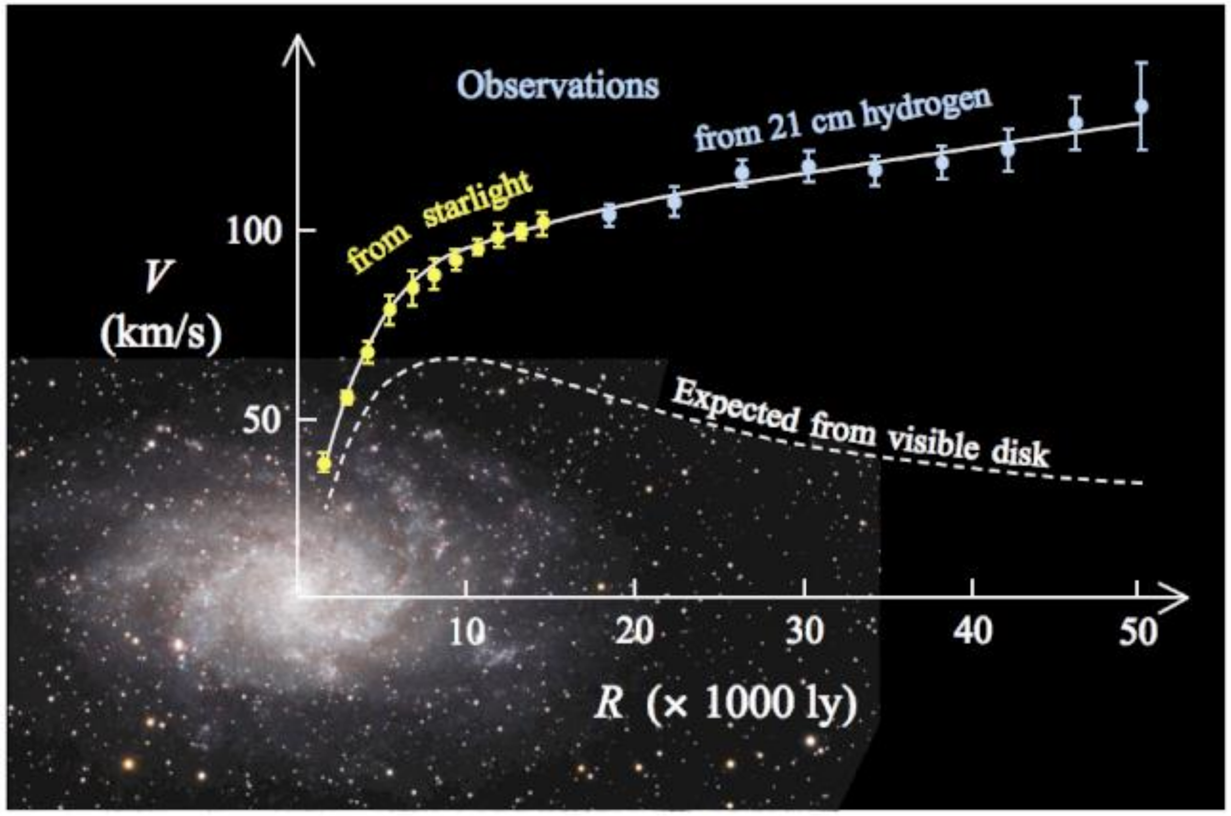
Dark matter (DM) is a type of matter hypothesized to account for effects that appear to be the result of invisible mass.

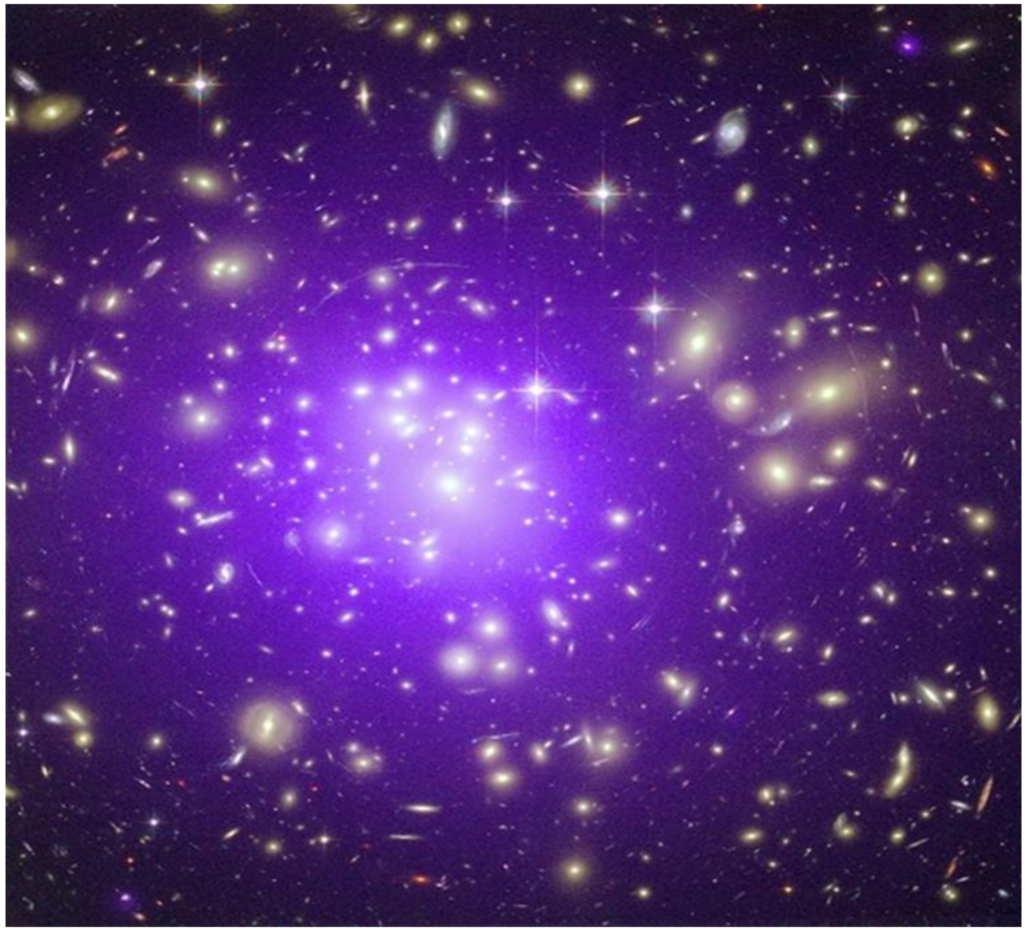
The existence and properties of dark matter can be inferred from its gravitational effects on visible matter.

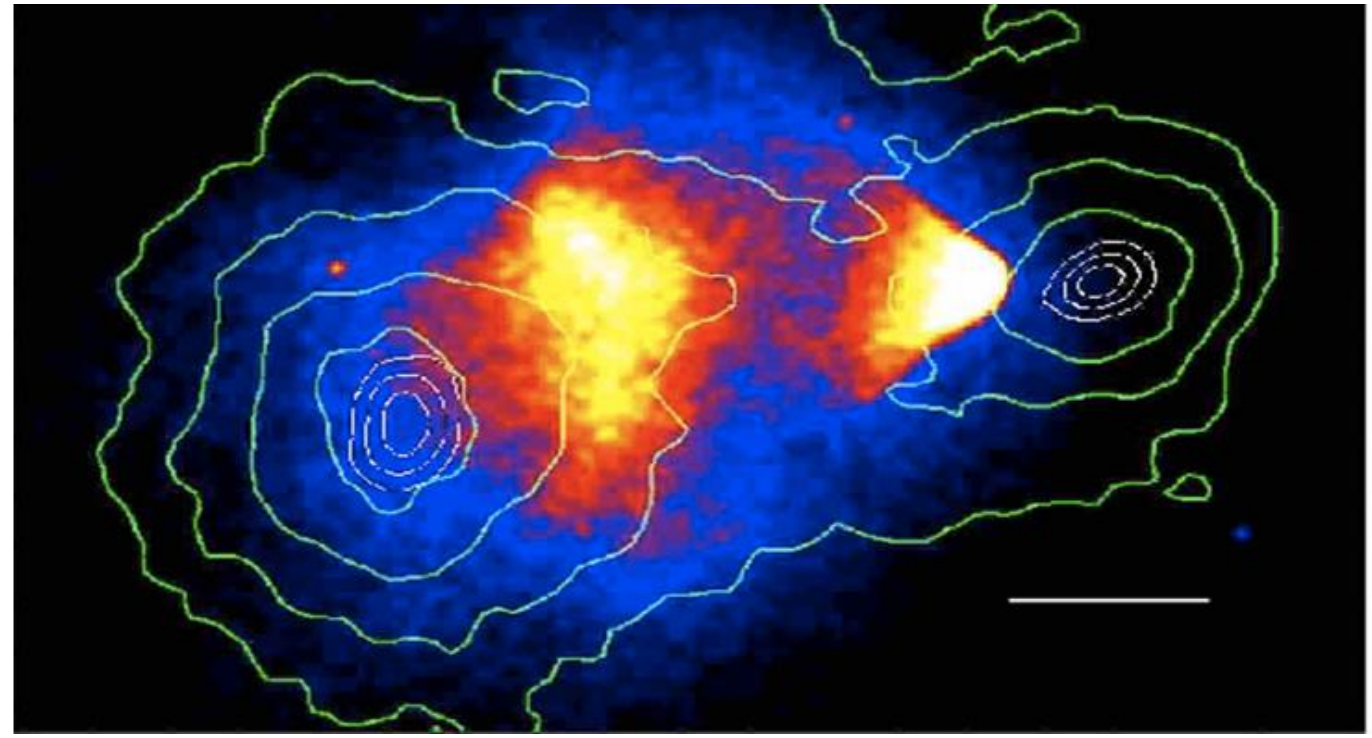
Many OBSERVATIONS:











What is the NATURE of dark matter (DM)?

It must barely interact with ordinary baryonic matter and radiation, except through gravity

It remains unknown

DM particle CANDIDATES

WIMP (Weakly interacting massive particles)

Relic DM particle from the early Universe

- **DM abundance in the Universe**
- **Interaction via the electroweak force**

→ **100 GeV mass range**

with non-relativistic velocities since its decoupling time

Clump in small structures (galaxies) and aggregation to form larger structures (bottom-up theory)

Supersymmetric extensions of the standard model of particle physics predict a new particle with these properties

Cold Dark Matter (CDM)

Collisionless CDM

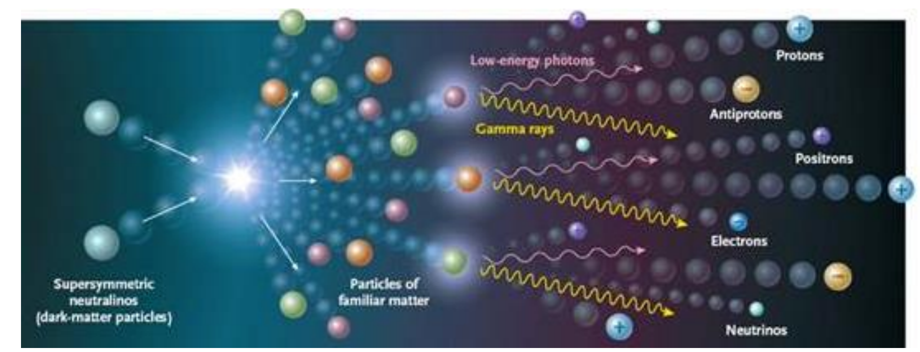
ΛCDM N-body simulations

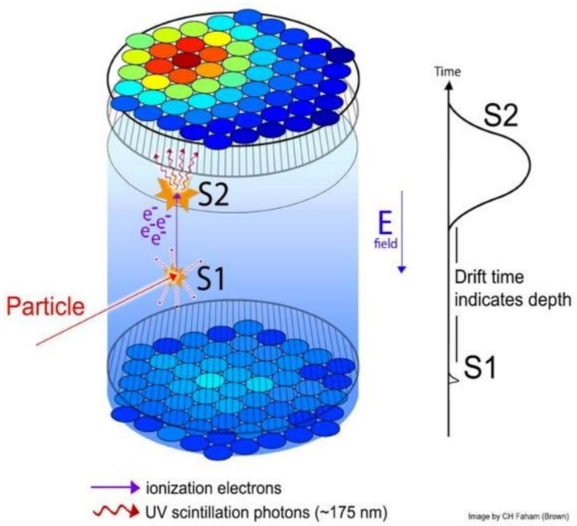
CUSPY profile

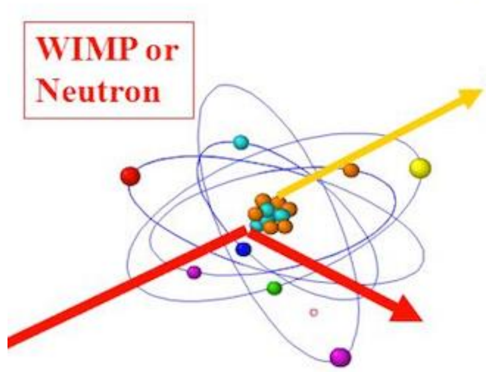
$$\rho_{NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

WIMP particle has not yet been observed directly

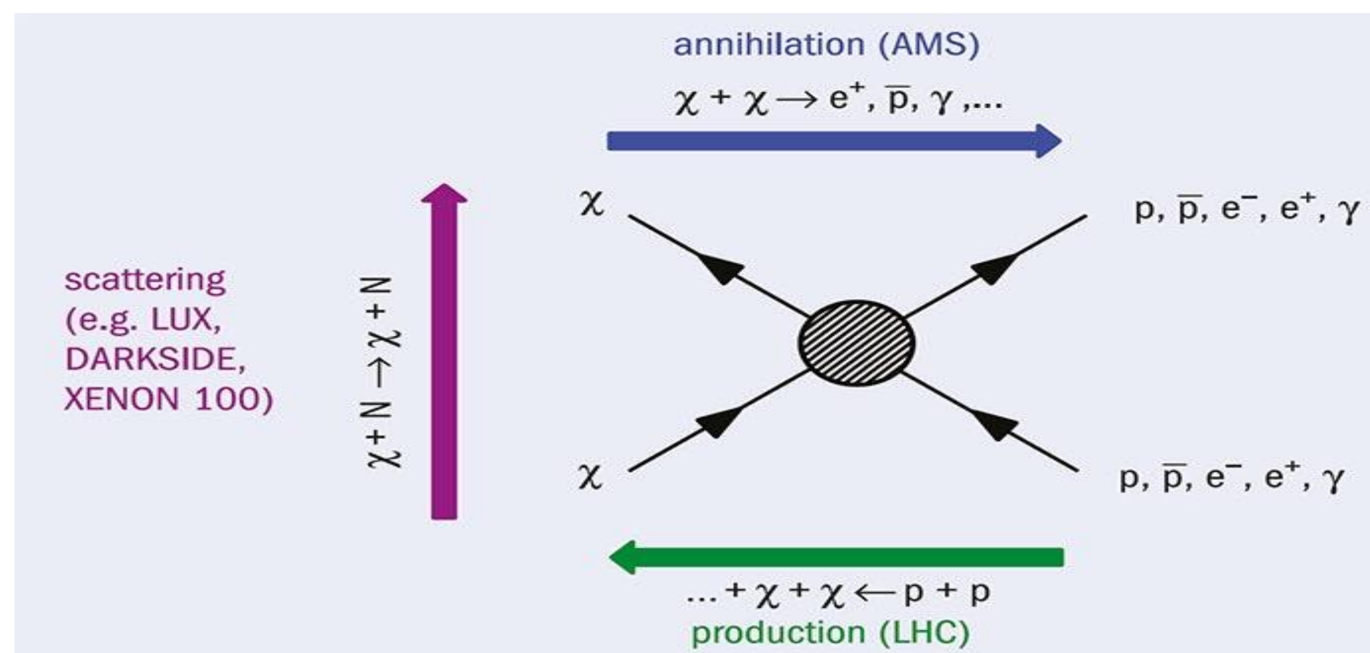
indirect research







direct research



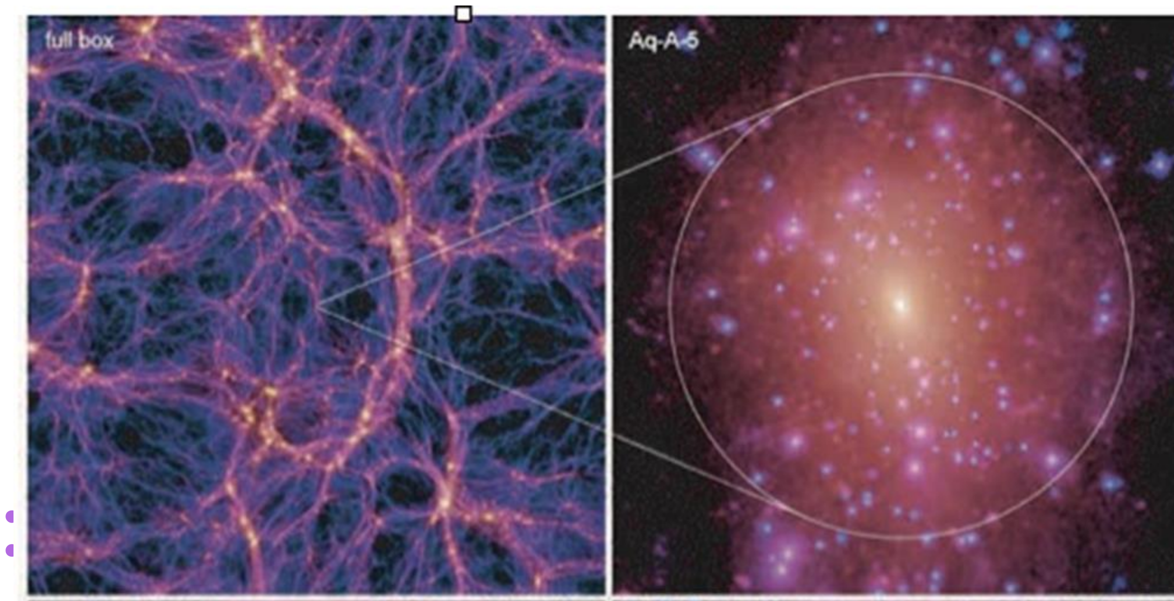
colliders production

LHC

Issues with the main DM scenario

N-body simulations ΛCDM

Success on large scale structure $\gtrsim 50\, kpc$

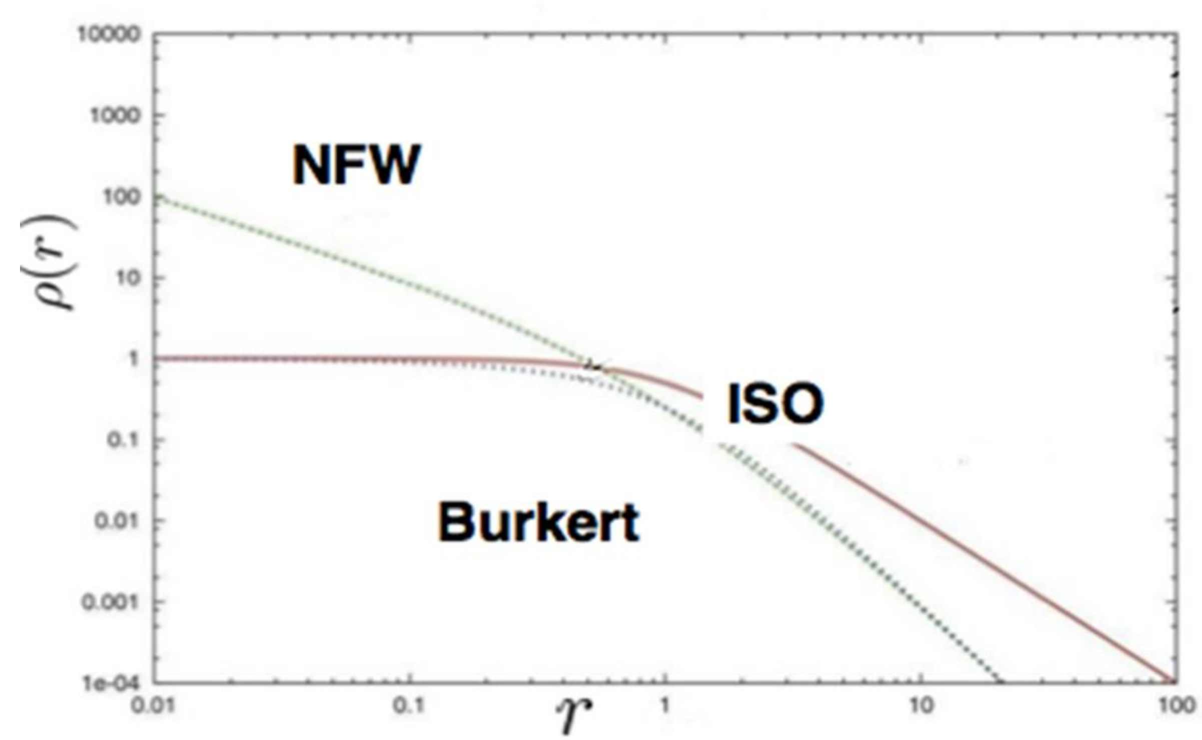


missing satellite problem
too big to fail problem

Core - cusp problem in any galaxy:

- CDM ► cusp $\rho(r) \sim r^{-1}$

- Observations ► core $\rho(r) = const.$

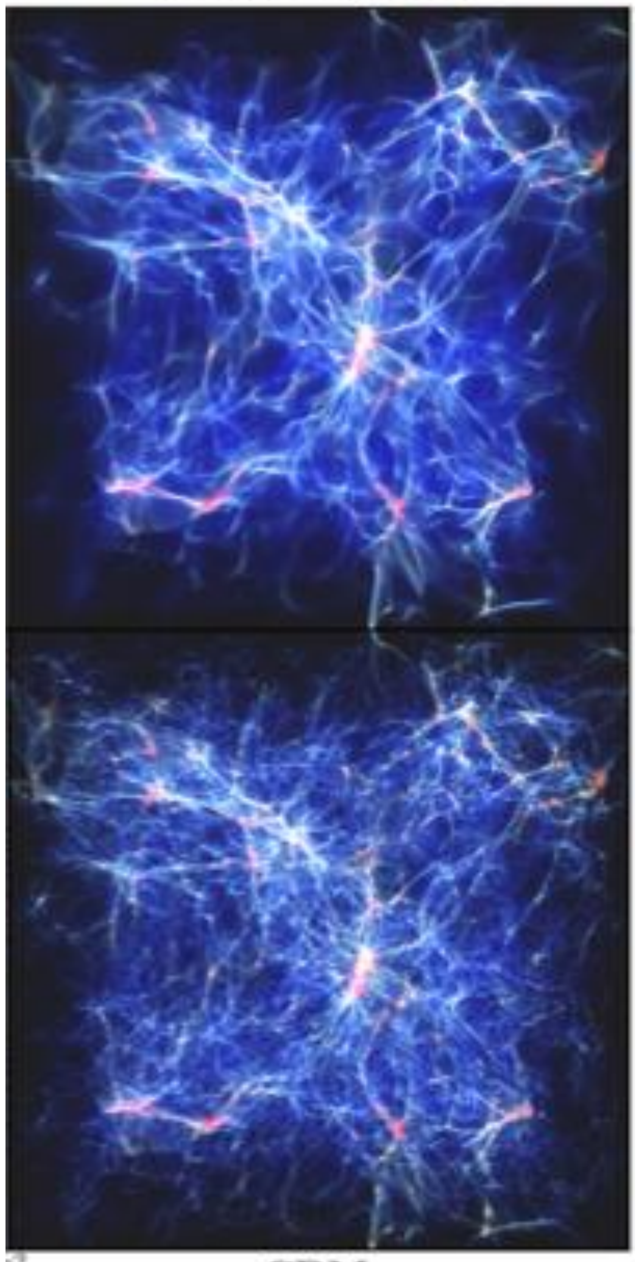


Different DM particle CANDIDATE

Warm dark matter particle (WDM)
keV mass range

- DM particles decouples from the cosmological plasma when it is still mildly relativistic. ► It overcomes the problem on small scales

- WDM is fermionic a quantum pressure emerges ► possibility of forming cored distribution



Viel at al. 2016

CDM Proposed solution:

baryonic matter feedback from supernovae explosions, stellar winds, gas outflow

However:

- challenges in dwarf and large spirals

- challenges in fine-tuned process

in Low Surface Brightness galaxies?

DM distribution in galaxies

Ellipticals

- dominated by random motions
- kinematics is very uncertain
- nuisance anisotropy parameter, which is font of degeneracy

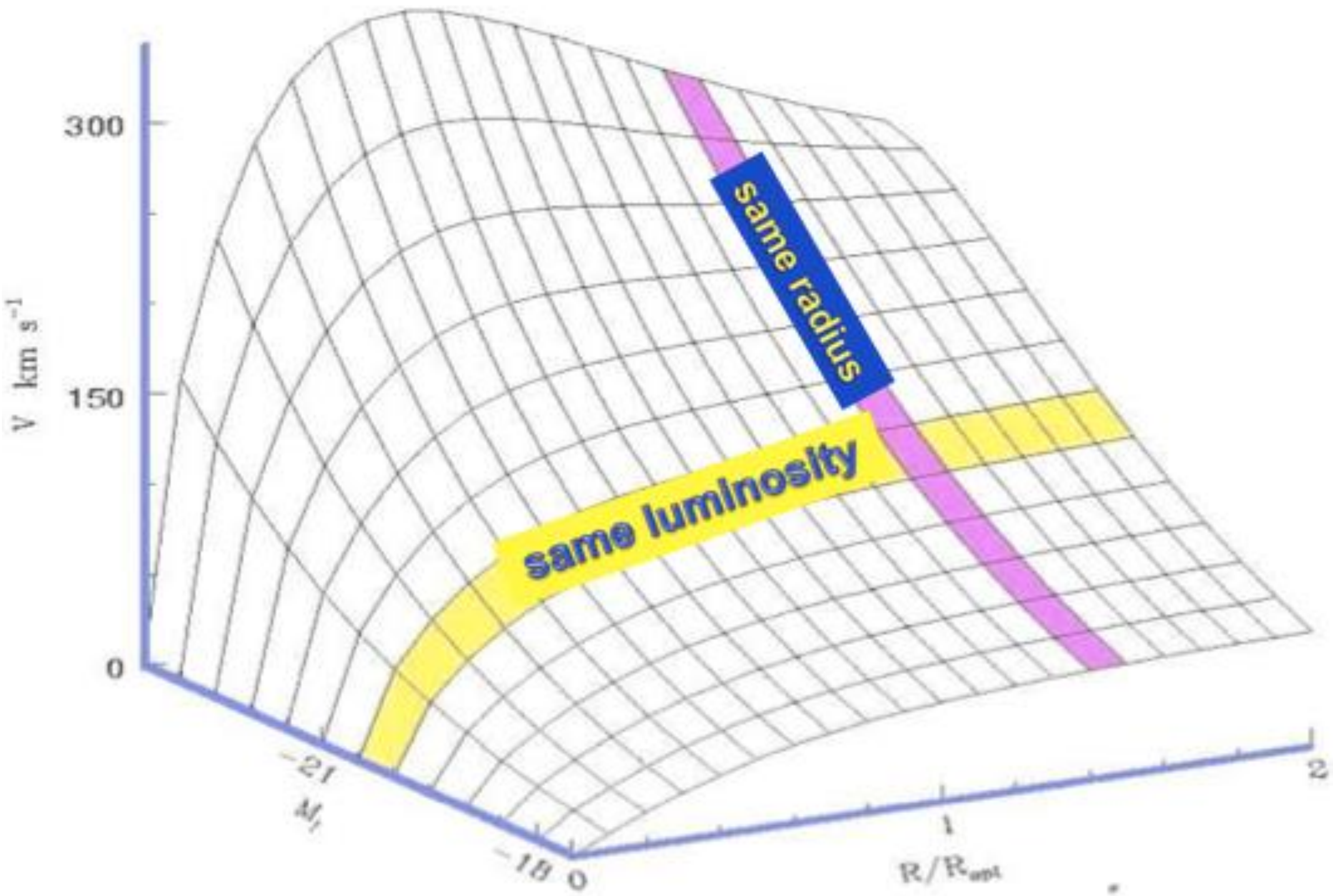
Disc galaxies

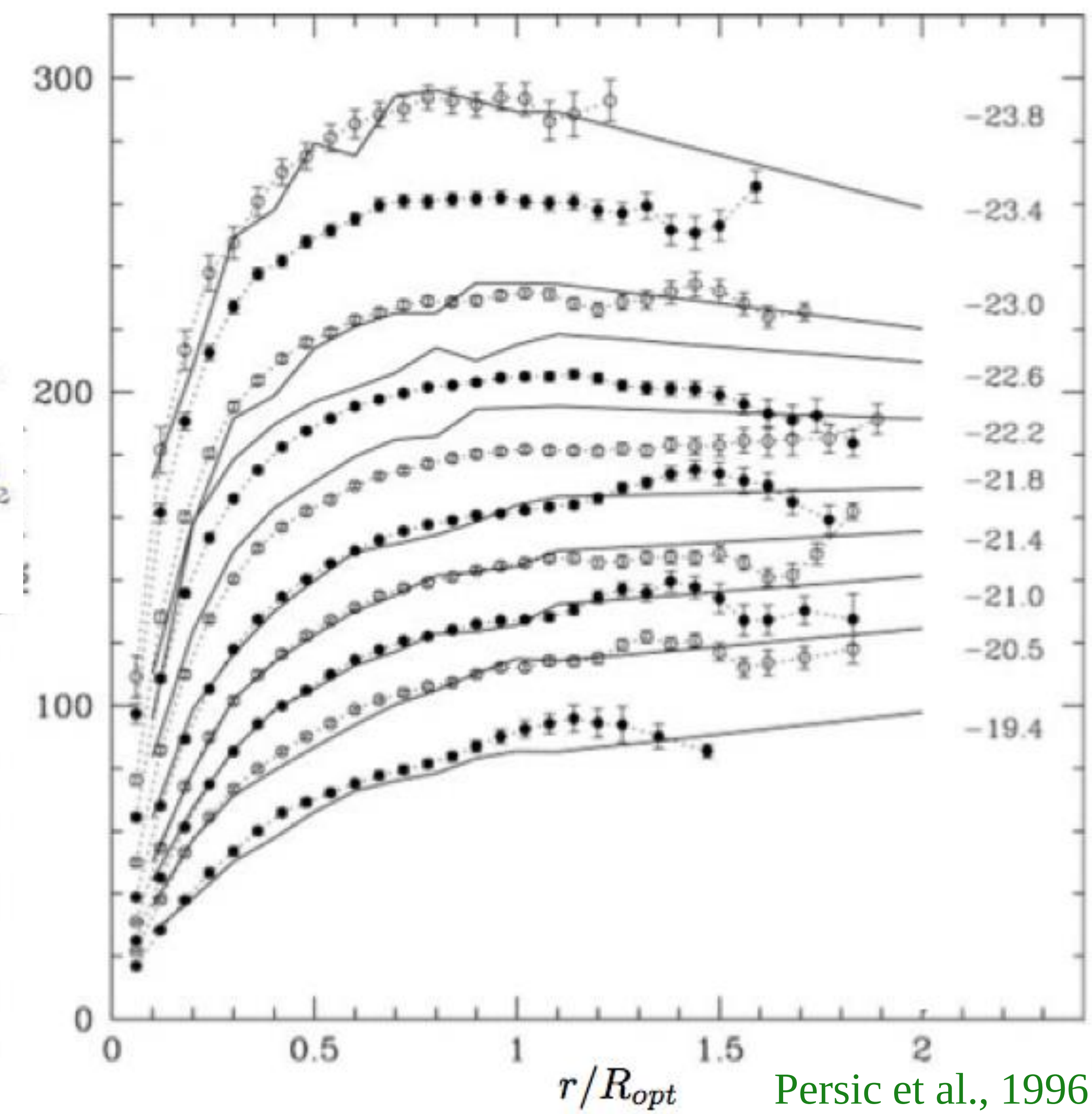
- rotational supported systems
- rather simple kinematics

$$V_{tot}^2(r) = r\frac{d}{d\,r}\phi_{tot}(r) = V_d^2(r) + V_{HI}^2(r) + V_{bu}^2(r) + V_h^2(r)$$

Universal Rotation Curve (URC)

stacked analysis

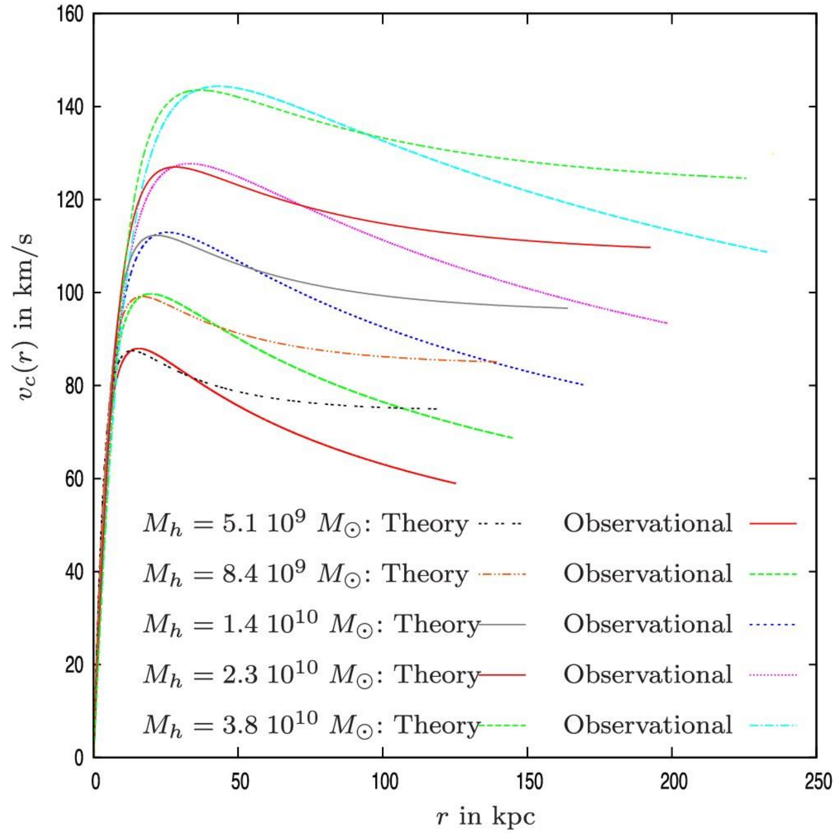


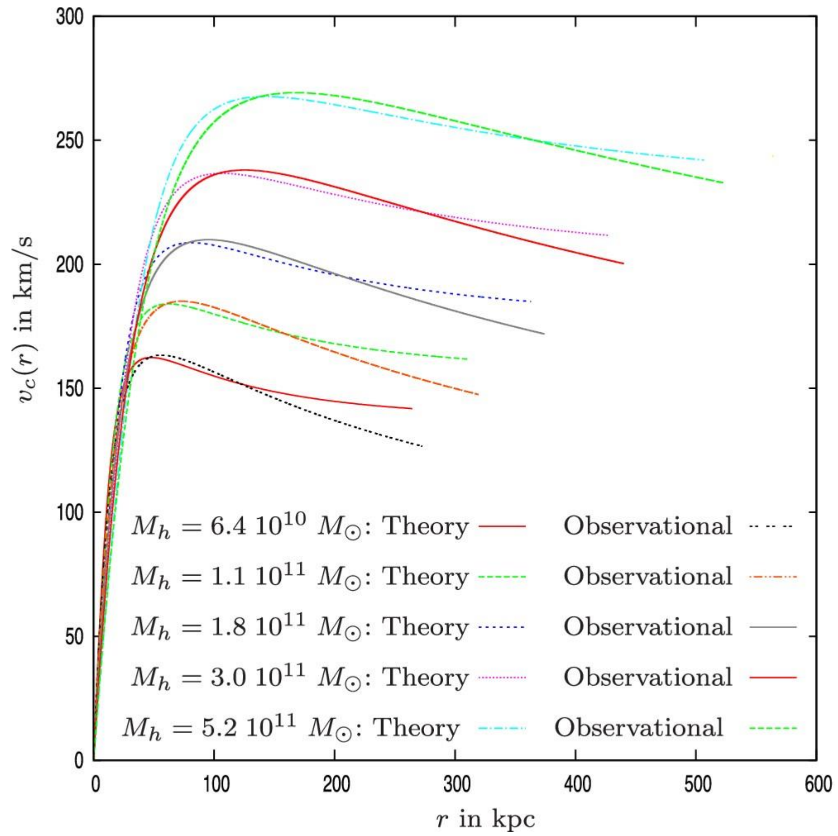


Persic et al., 1996

RCs gradual change from small to large galaxies

The velocity rotation curves $v_c(r)$ in km s^{-1}.

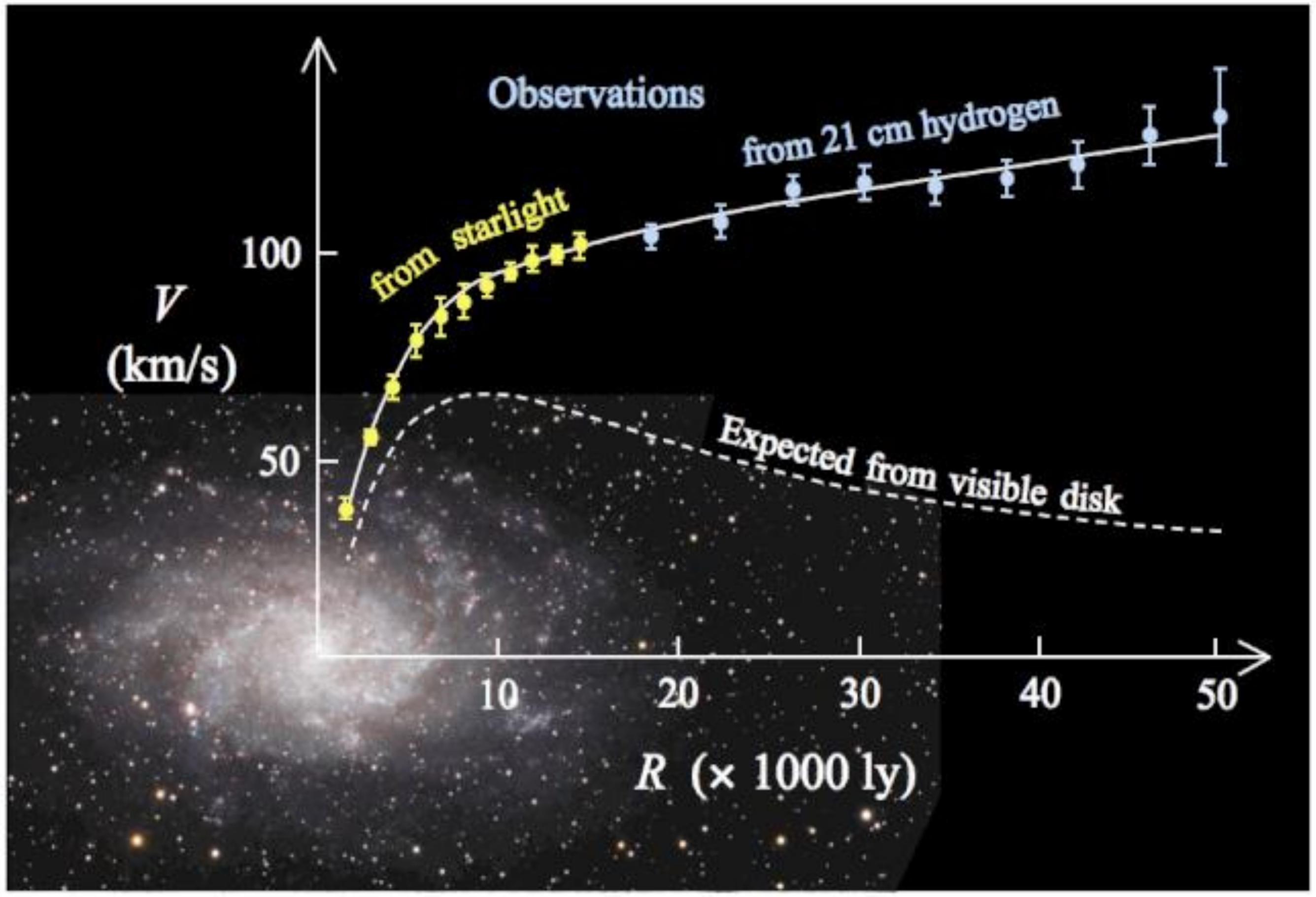




$$\frac{\mathrm{d}^2\mu}{\mathrm{dr}^2} + \frac{2}{r}\,\frac{\mathrm{d}\mu}{\mathrm{dr}} = -\,4\pi\, G\, m\, \rho(r)$$
$$= -\,\frac{4\,G\,m^2}{\pi\,\hbar^3}\int_0^\infty \mathrm{d}p\, p^2\ f\left(\frac{p^2}{2m} - \mu(r)\right),$$

Mon Not R Astron Soc, Volume 442, Issue 3, 11 August 2014, Pages 2717–2727, https://doi.org/10.1093/mnras/stu972 DeVega et al.

DM distribution in disc galaxies



circular velocity rotation curves (RC)

Corbelli and Salucci, 2000

$$V_{tot}^2(r) = r\frac{d}{dr}\phi_{tot}(r) = \boxed{V_d^2(r)} + V_{HI}^2(r) + V_{bu}^2(r) + V_h^2(r)$$

Exponential (Freeman) stellar disc

$$\mu(R) = \mu_0 e^{-R/R_d}$$

$$V_d^2(r) = \frac{1}{2}\frac{G\,M_d}{R_d}(3.2\,r/R_{opt})^2(I_0K_0 - I_1K_1)$$

$$V_{tot}^2(r) = r\frac{d}{dr}\phi_{tot}(r) = V_d^2(r) + V_{HI}^2(r) + V_{bu}^2(r) + V_h^2(r)$$

Exponential (Freeman) stellar disc ▶

$R_{opt} = 3.2 R_d$ **optical radius** size of the stellar disk (83 %of total luminosity)

$$V_{tot}^2(r) = r\frac{d}{dr}\phi_{tot}(r) = V_d^2(r) + \boxed{V_{HI}^2(r)} + V_{bu}^2(r) + V_h^2(r)$$

gaseous HI disc ▶

$$\Sigma_{HI}(R) = \Sigma_{HI,0} e^{-R/3\,R_d}$$

$$V_{HI}^2(R) = \frac{1}{2}\frac{GM_{HI}}{3R_D}(1.1\,R/R_{opt})^2(I_0K_0 - I_1K_1)$$

$$V_{tot}^2(r) = r\frac{d}{dr}\phi_{tot}(r) = V_d^2(r) + V_{HI}^2(r) + V_{bu}^2(r) + V_h^2(r)$$

stellar bulge ▶

$$V_{bu}^2(r) = \alpha_{bu} V_{in}^2 \left(\frac{r}{r_{in}}\right)^{-1}$$

$$V_{tot}^2(r) = r\frac{d}{dr}\phi_{tot}(r) = V_d^2(r) + V_{HI}^2(r) + V_{bu}^2(r) + V_h^2(r)$$

spherical dark matter halo ▶

$$\rho_{DM}(r) = \frac{\rho_0 r_0^3}{(r + r_0)(r^2 + r_0^2)}$$

Burkert cored profile

$$M_{DM}(r) = \int_0^r 4\pi\tilde{r}^2 \rho_{DM}(\tilde{r})\, d\tilde{r}$$

$$V_h^2(r) = G\frac{M_{DM}(r)}{r}$$

RC fit ▶ **best fit parameters** ▶ **DM properties**

Low Surface Brightness (LSB) disc galaxies

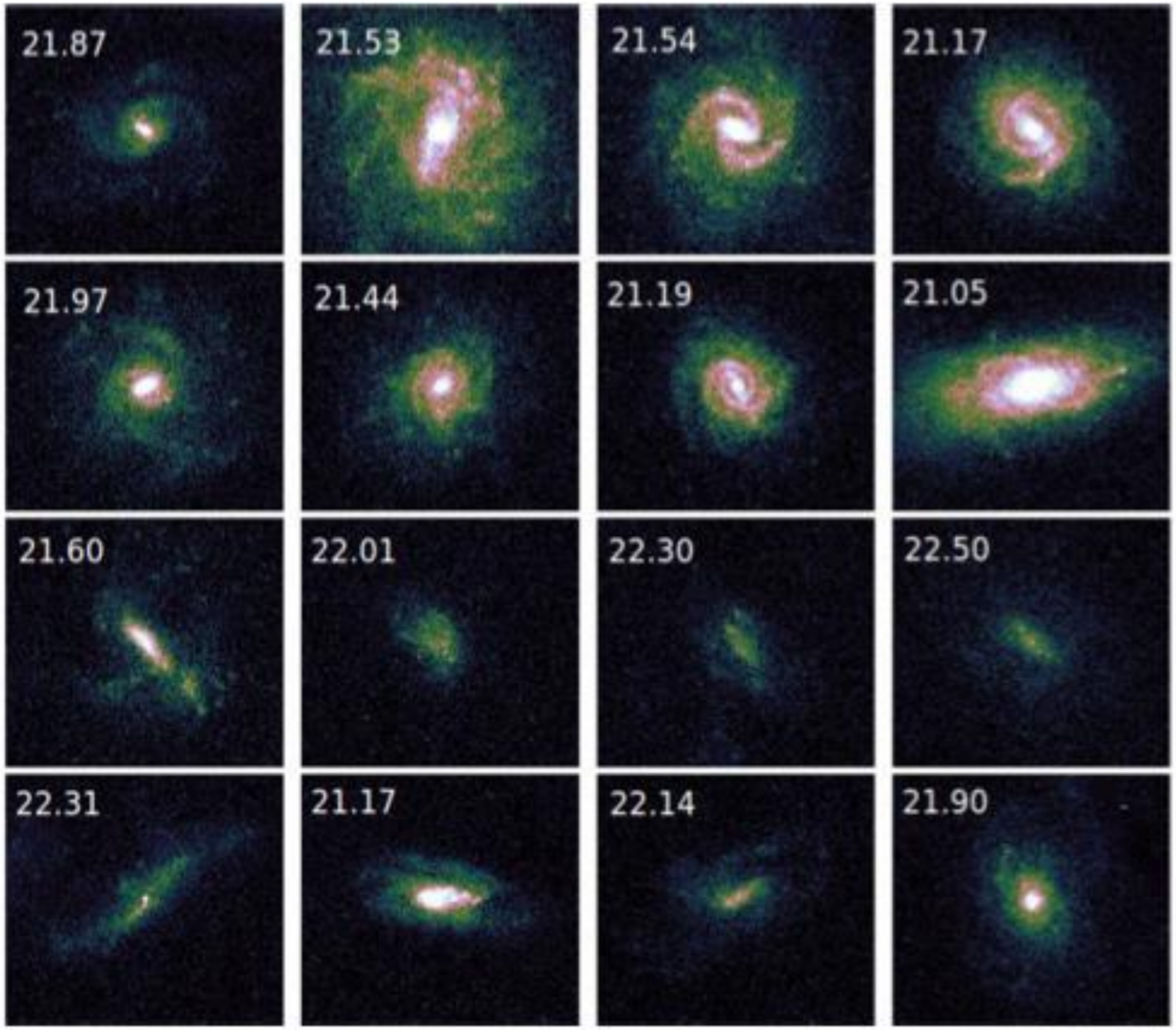
rotating disc systems which emit an amount of light per area smaller than normal spirals (4-10 times fainter)

$$\mu_{0,B} \gtrsim 23\, mag\, arcsec^{-2}$$

$$\mu_{0,R} \gtrsim 21\, mag\, arcsec^{-2}$$

diffuse, low-density exponential stellar discs

$$\Sigma_* \simeq 12.3\, M_\odot/pc^2$$



Cohen et al., 2018

Low Surface Brightness (LSB) disc galaxies

full population of galaxies, ranging from small ($10^7 M_\odot$) to very large (more than $10^{10} M_\odot$) stellar disc mass M_d

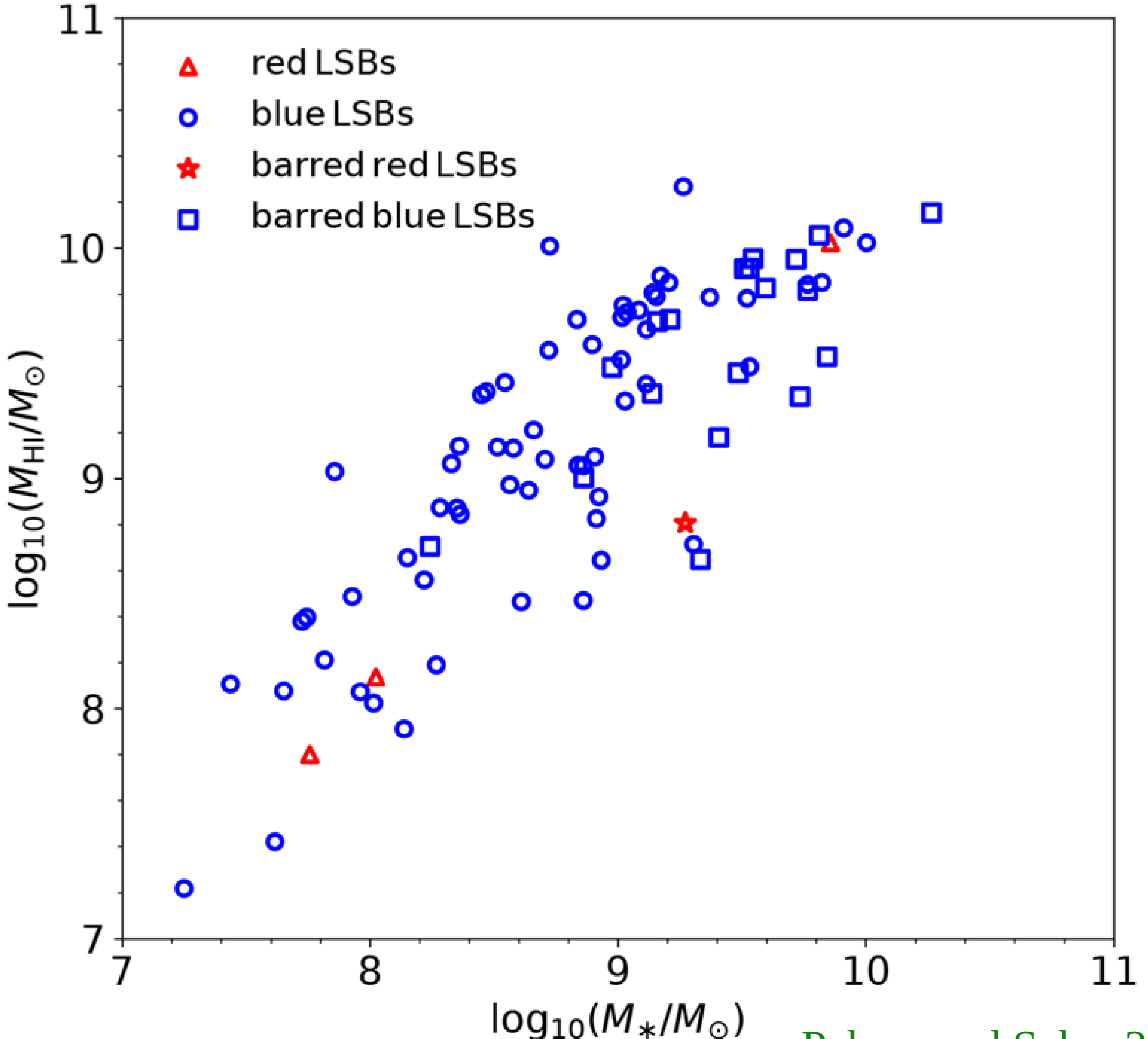
Typical size:

fraction of kpc $< R_d <$ tens of kpc

Typical magnitude:

$-20 \lesssim M_B \lesssim -10$

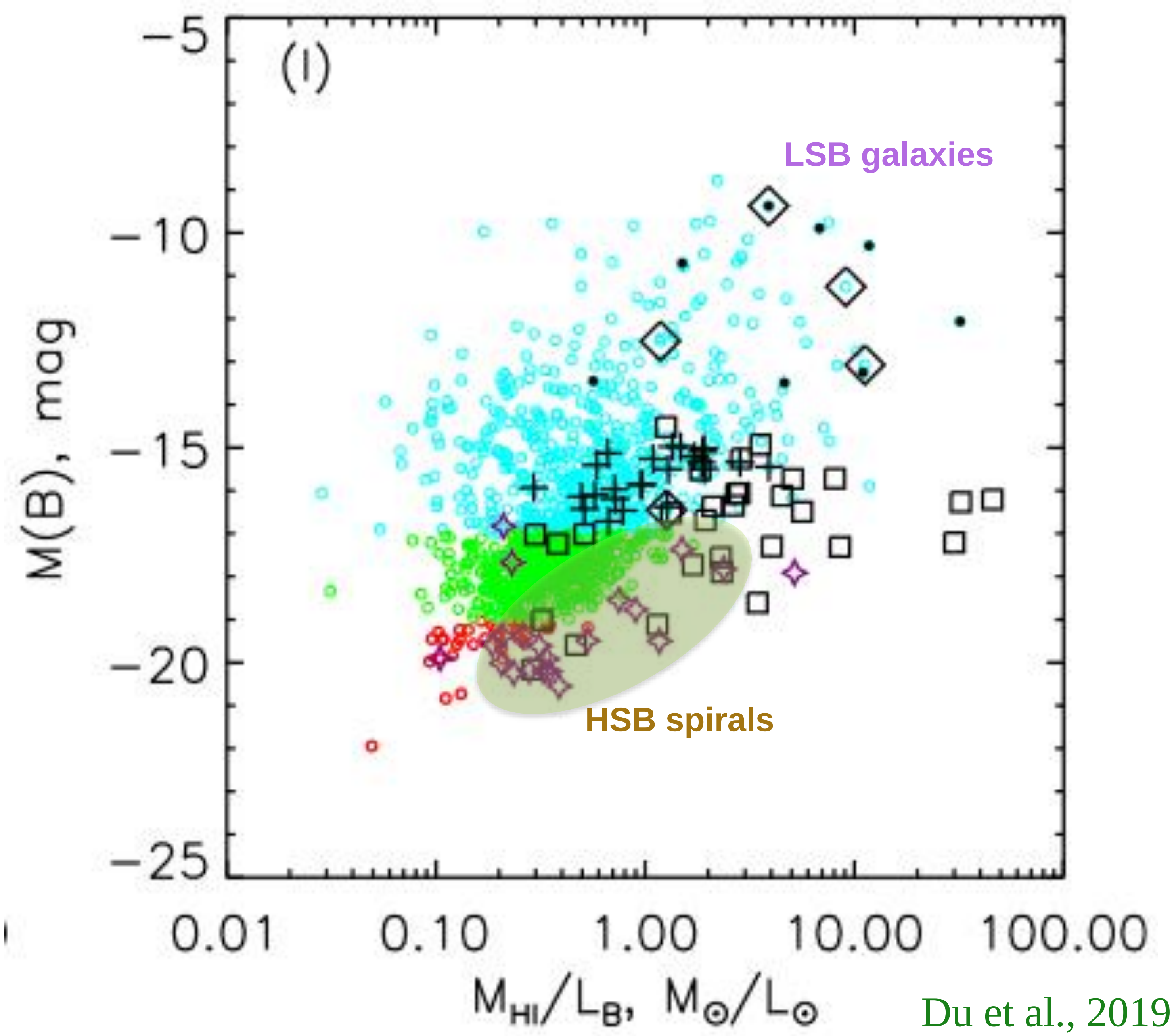
$-23 \lesssim M_R \lesssim -14$



Pahwa and Saha, 2018

Low Surface Brightness (LSB) disc galaxies

Values of M_{HI}/L_B in LSBs range from $\simeq 0.1$ to $\simeq 10$



Du et al., 2019

Typical LSBs gaseous disc

$$M_{HI} \simeq M_d$$

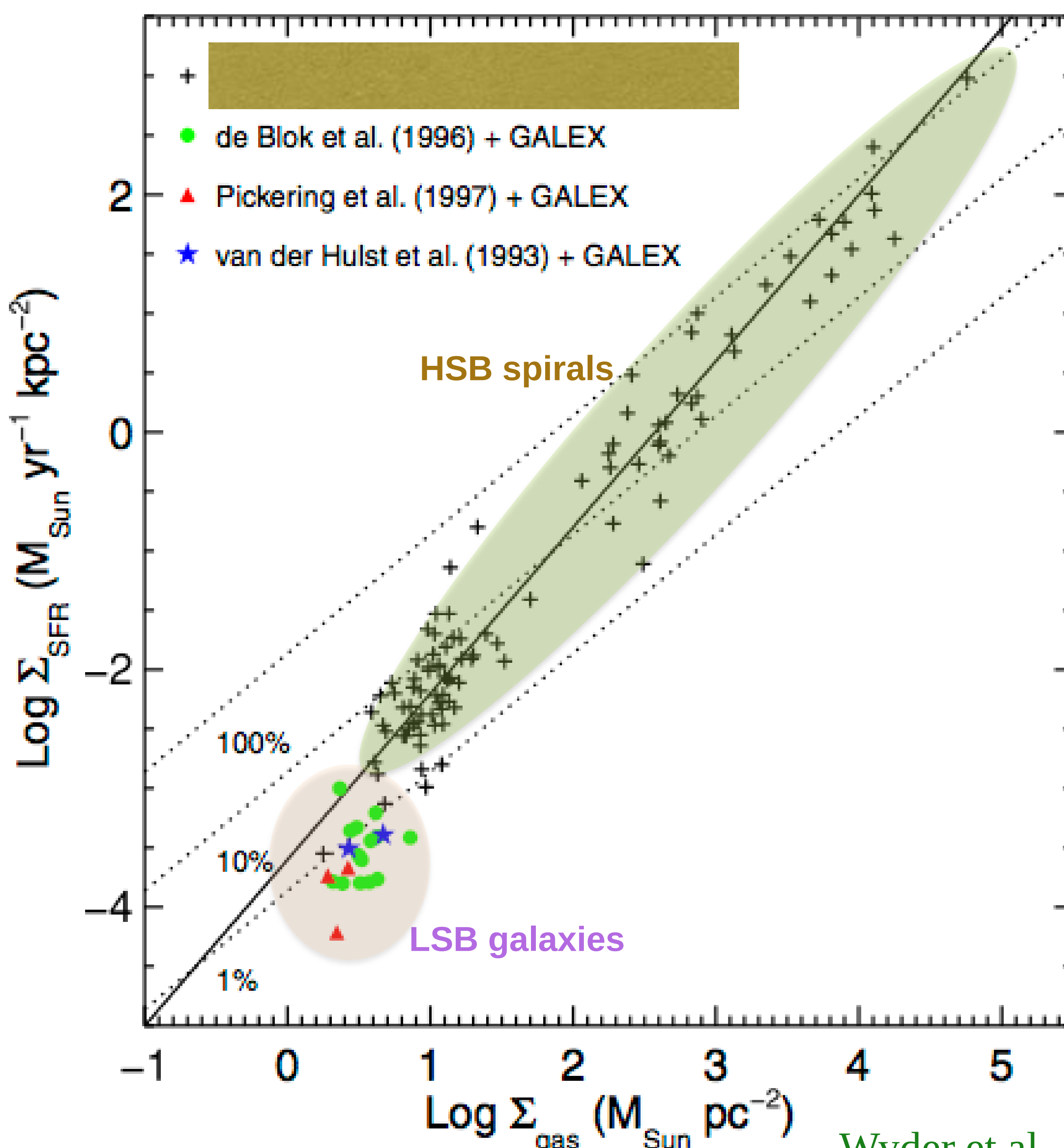
Characteristic low density

$$\Sigma_{HI} \simeq 5\, M_{\odot} pc^{-2}$$

likely prevents an efficient star formation

$$\text{SFR} \lesssim 0.1\, M_{\odot} yr^{-1}$$

$$\Sigma_{SFR} \lesssim 10^{-3} M_{\odot} yr^{-1} kpc^{-2}$$



Wyder et al., 2009

Low Surface Brightness (LSB) disc galaxies

very low content in metal and dust

stellar population appears to be uniformly distributed in the stellar disc

- generally isolated systems, located on the edges of large-scale structure

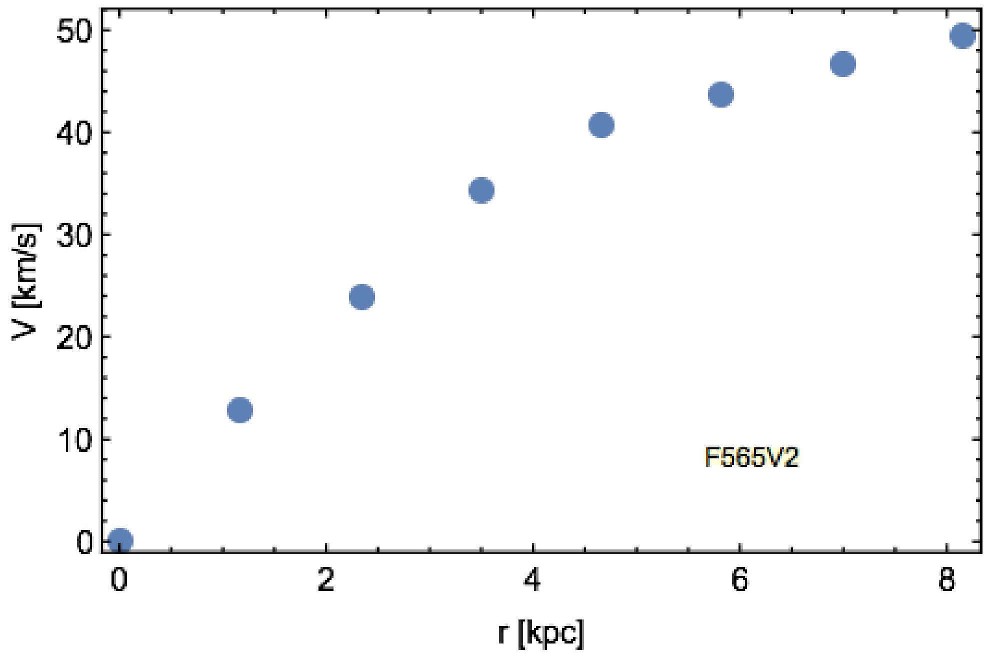
- LSBs are not the faded remnants of HSBs that have ceased star formation,

LSBs are likely slowly evolving galaxies

-

URC method applied to the LSB galaxies

LSB rotation curve

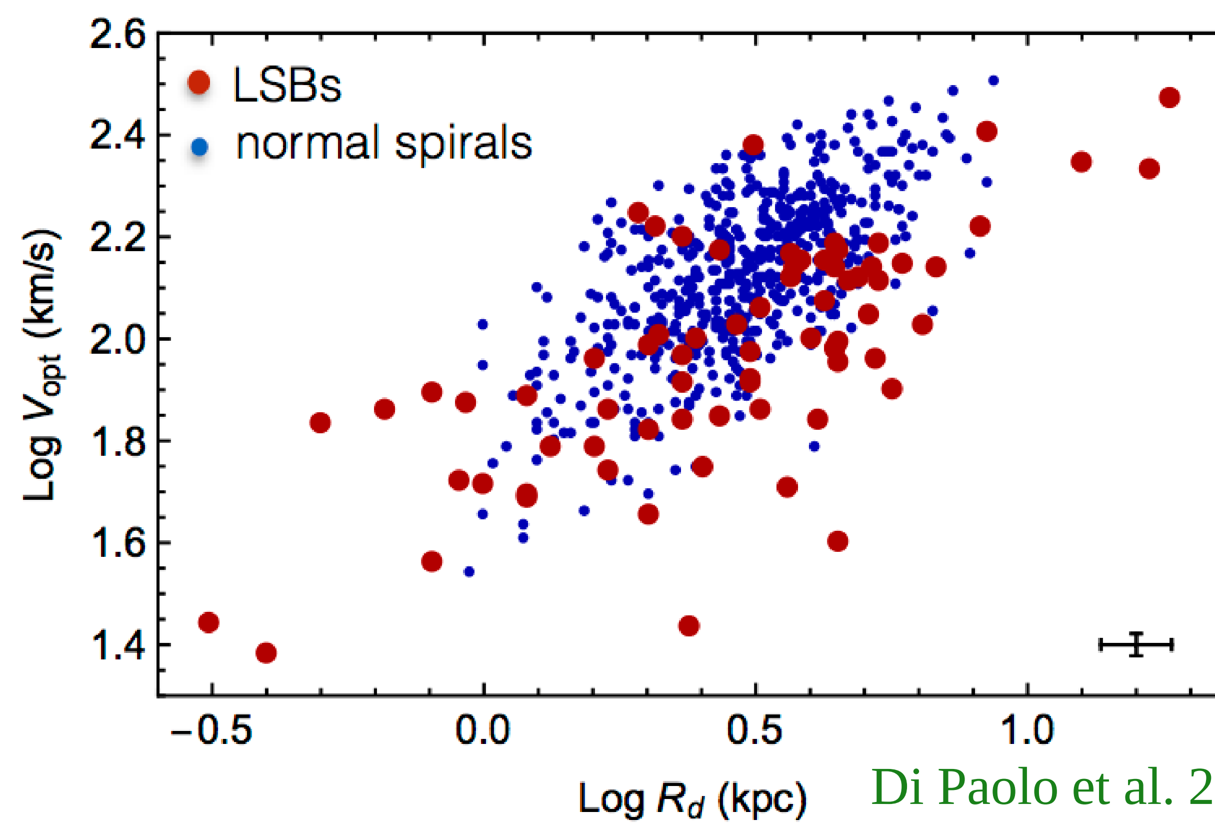


72 Low Surface Brightness galaxies
(Di Paolo, Salucci, Erkurt (2019))
1601 circular velocity measurements

$\boxed{R_d}$ = disk scale length exponential stellar disk

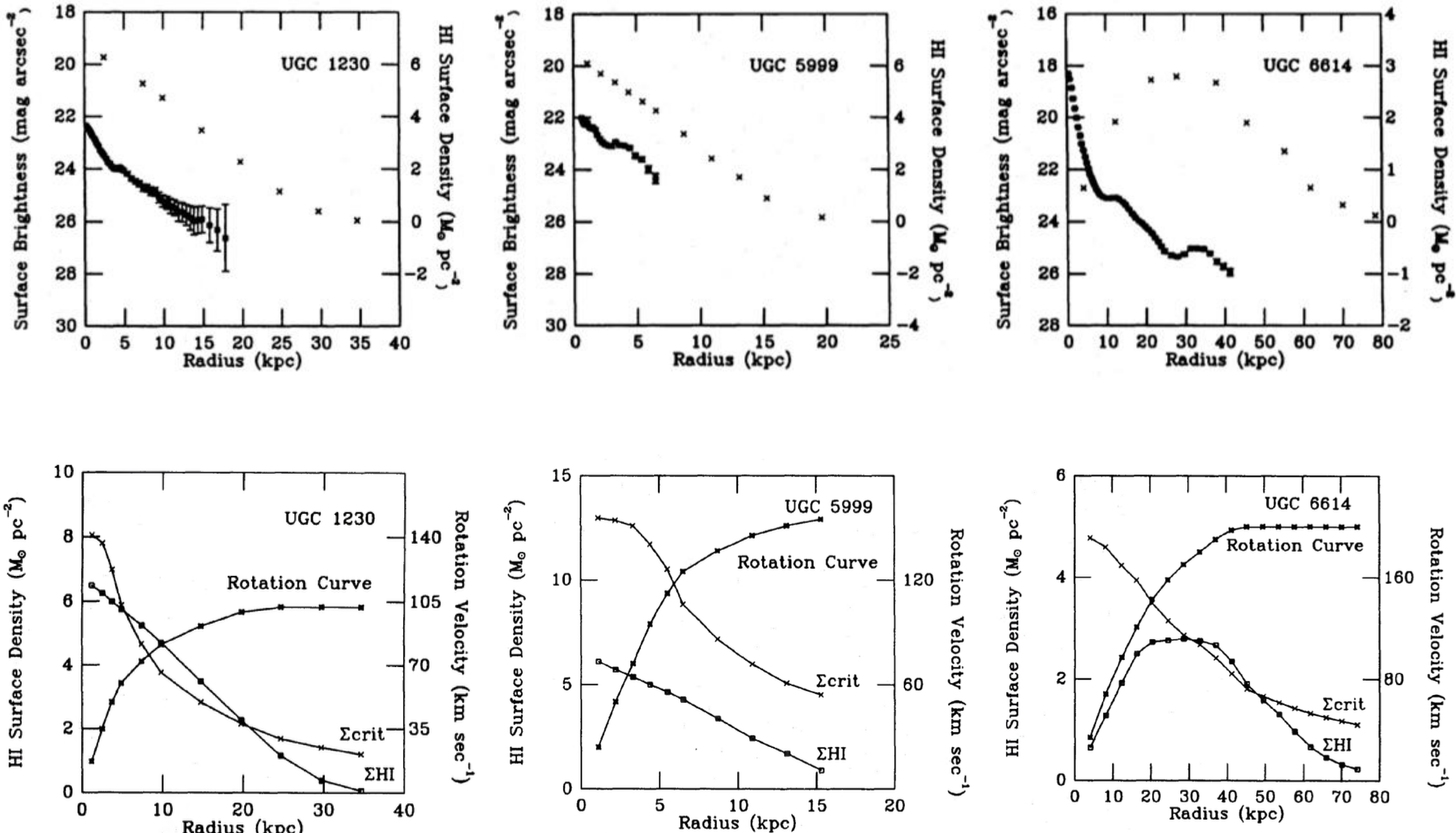
optical radius $\boxed{R_{opt}} = 3.2 R_d$ → 83 % total luminosity

optical velocity $\boxed{V_{opt}} = V(R_{opt})$



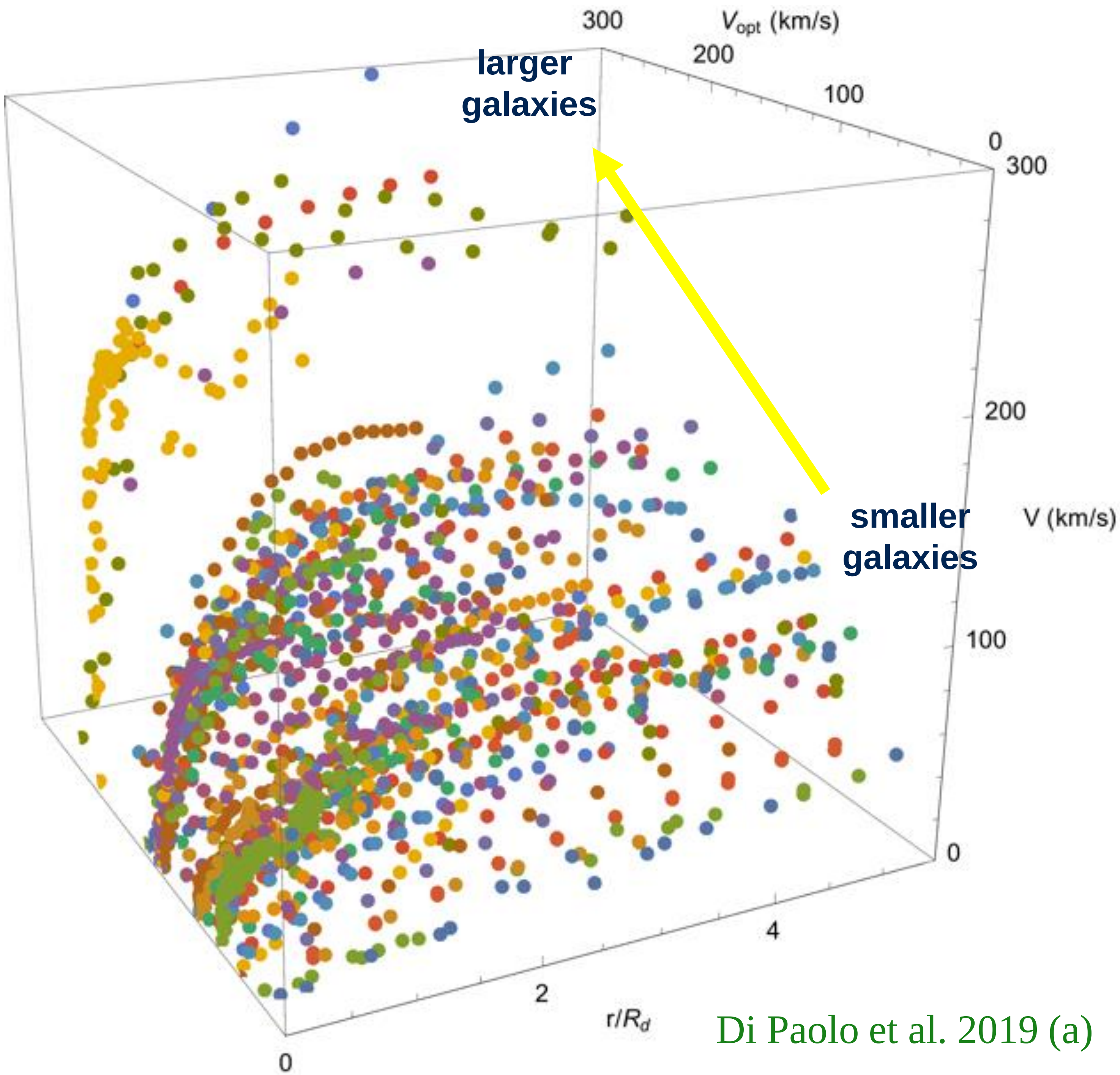
Di Paolo et al. 2019 (a)

Low Surface Brightness galaxies (LSBs)



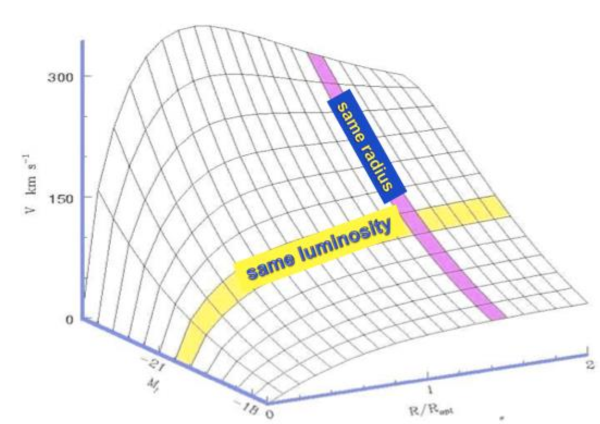
van der Hulst et al. 1993

URC method applied to the LSB galaxies



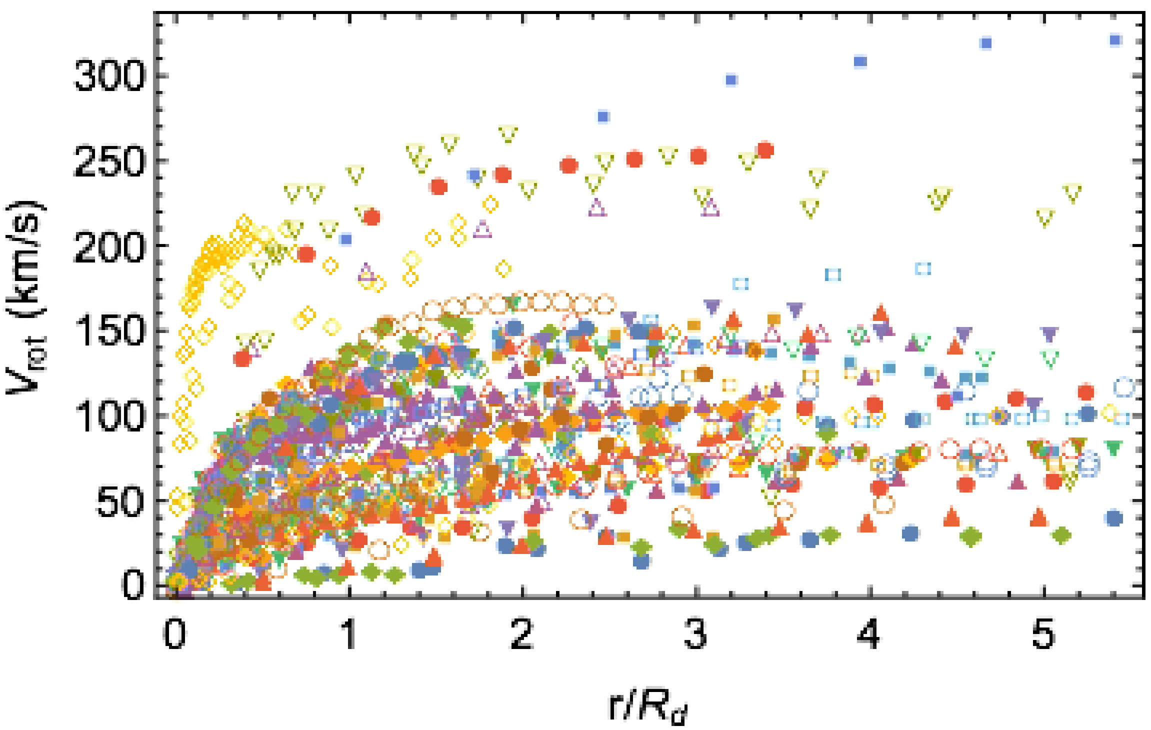
Di Paolo et al. 2019 (a)

LSBs rotation curves Show a universal trend



Persic, Salucci, Stel, 2007

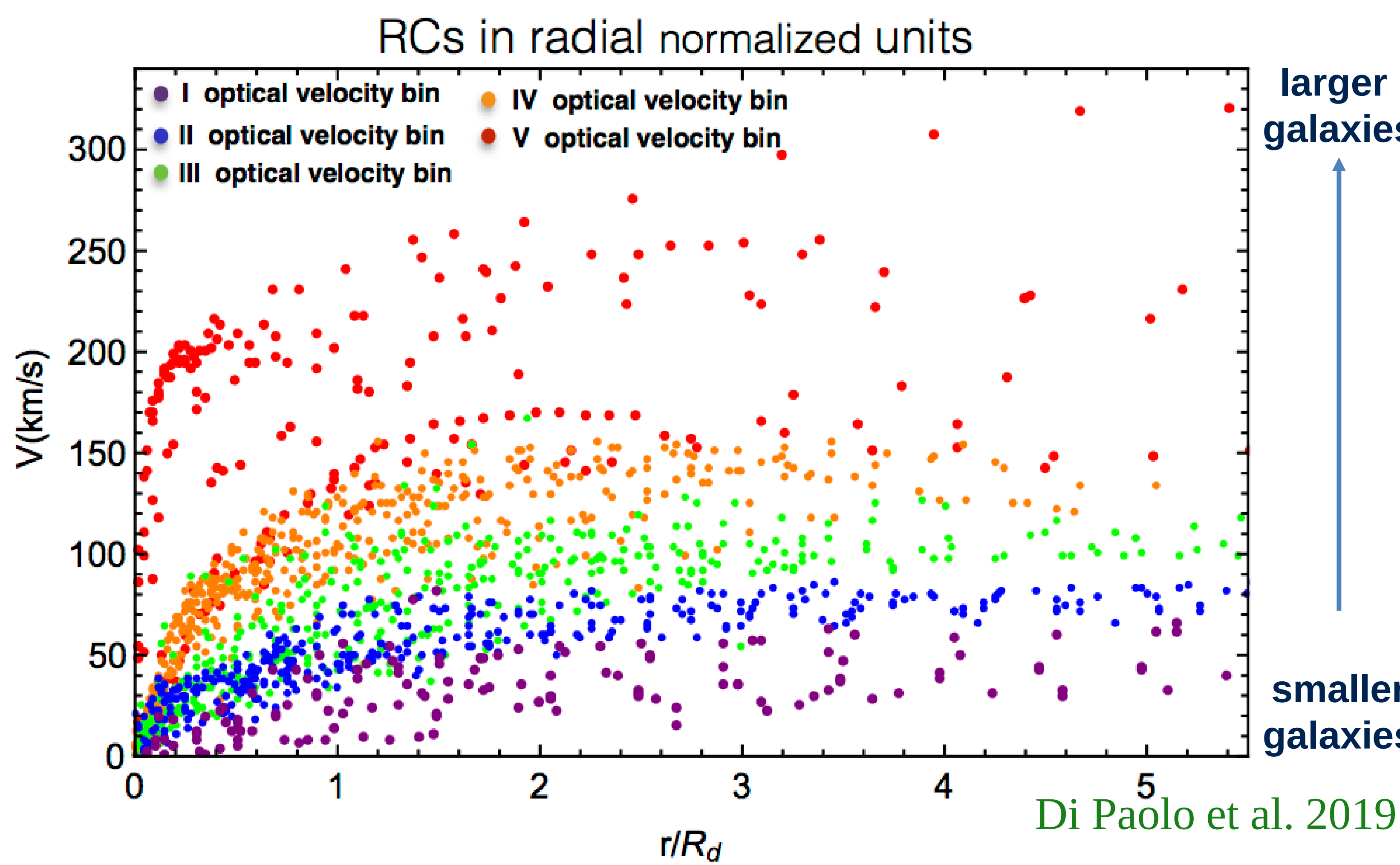
Rotation curves BINNING



Vel.Bin	Vel.Range km/s	N.galaxies	$\langle V_{opt} \rangle$ km/s	$\langle R_D \rangle$ kpc	N.data
(1)	(2)	(3)	(4)	(5)	(6)
1	24-60	13	43.5	1.7	151
2	60-85	17	73.3	2.2	393
3	85-120	17	100.6	3.7	419
4	120-154	15	140.6	4.5	441
5	154-300	10	205.6	7.9	210

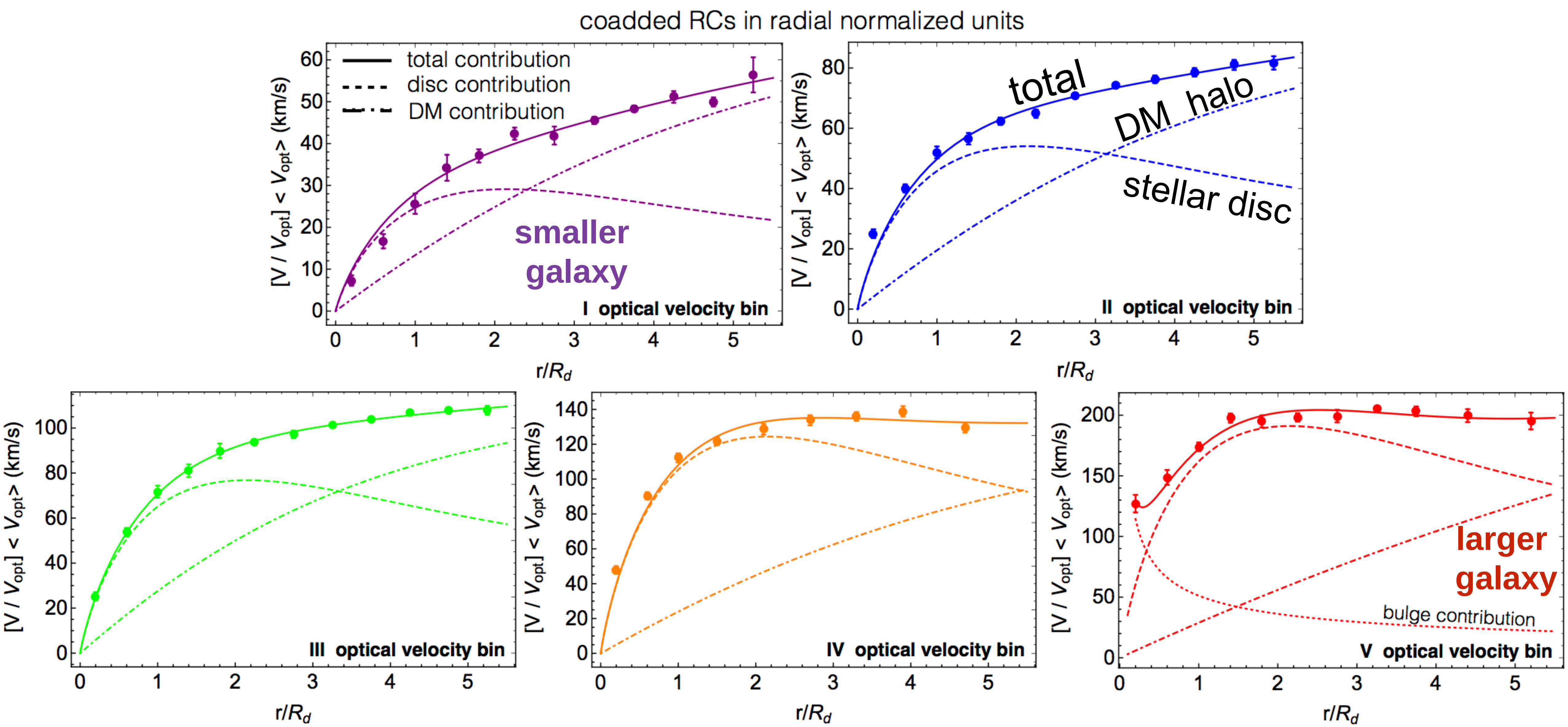
Division in 5 velocity bins

inner curvature more similar



Di Paolo et al. 2019 (a)

Mass Modeling 5 coadded RCs



$$V^2(r) = V_d^2(r) + V_{DM}^2(r)$$

exponential stellar disc

DM spherical cored halo (Burkert)

3 free parameters :

M_d = stellar disc mass

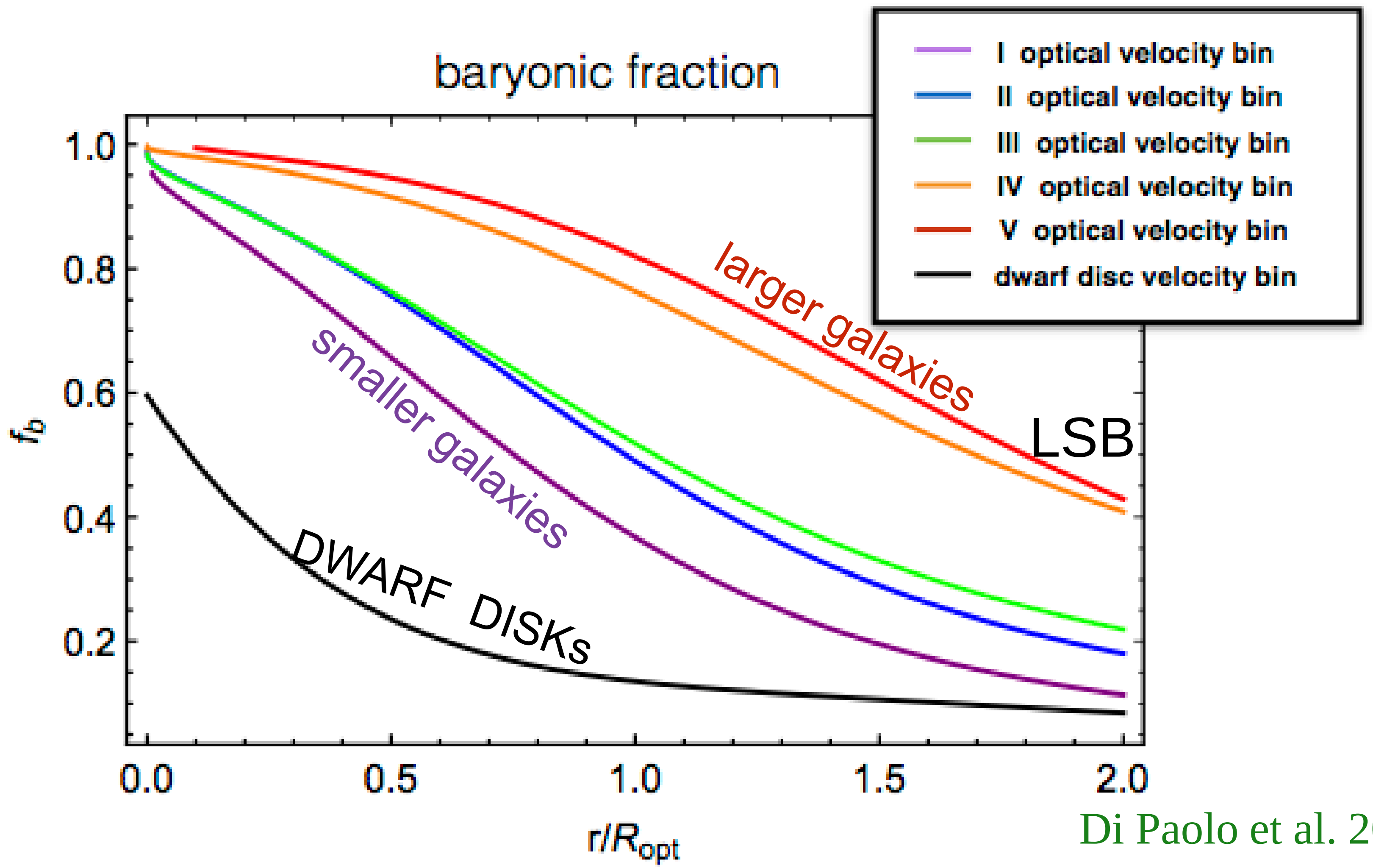
r_0 = DM halo's core radius

ρ_0 = DM halo's central mass density

Mass Modeling   5 coadded   RCs

Baryonic fraction :

$$f_b(r) = \frac{V_b^2(r)}{V^2(r)}$$



Di Paolo et al. 2019 (a)

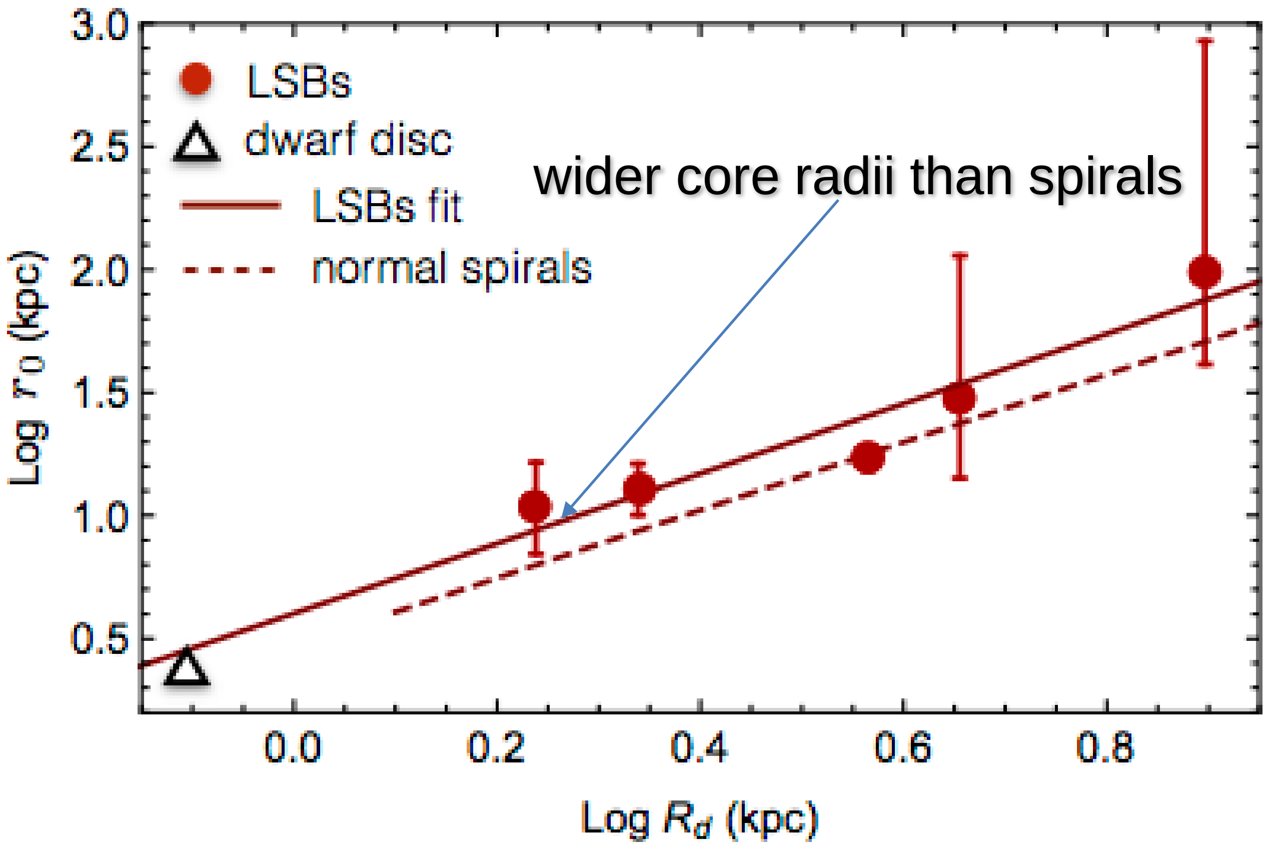
NOTE:

- radial dependence of f_b
- different $f_b(r)$ in galaxies of different size
- different $f_b(r)$ in galaxies of different morphology

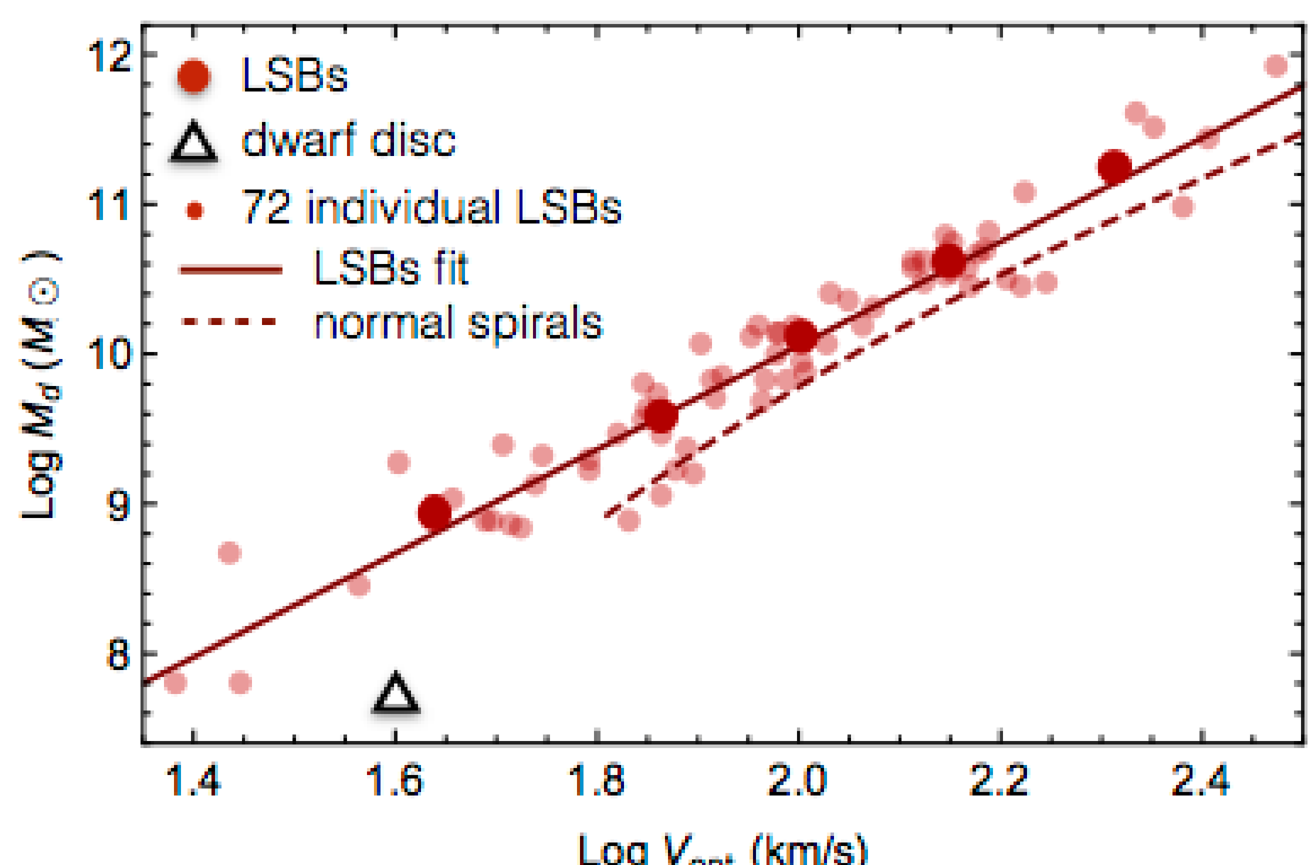
Scaling laws for LSBs

Similar to the HSB spirals scaling laws

$$Log\, r_0 = 0.60 + 1.42\, Log\, R_d$$



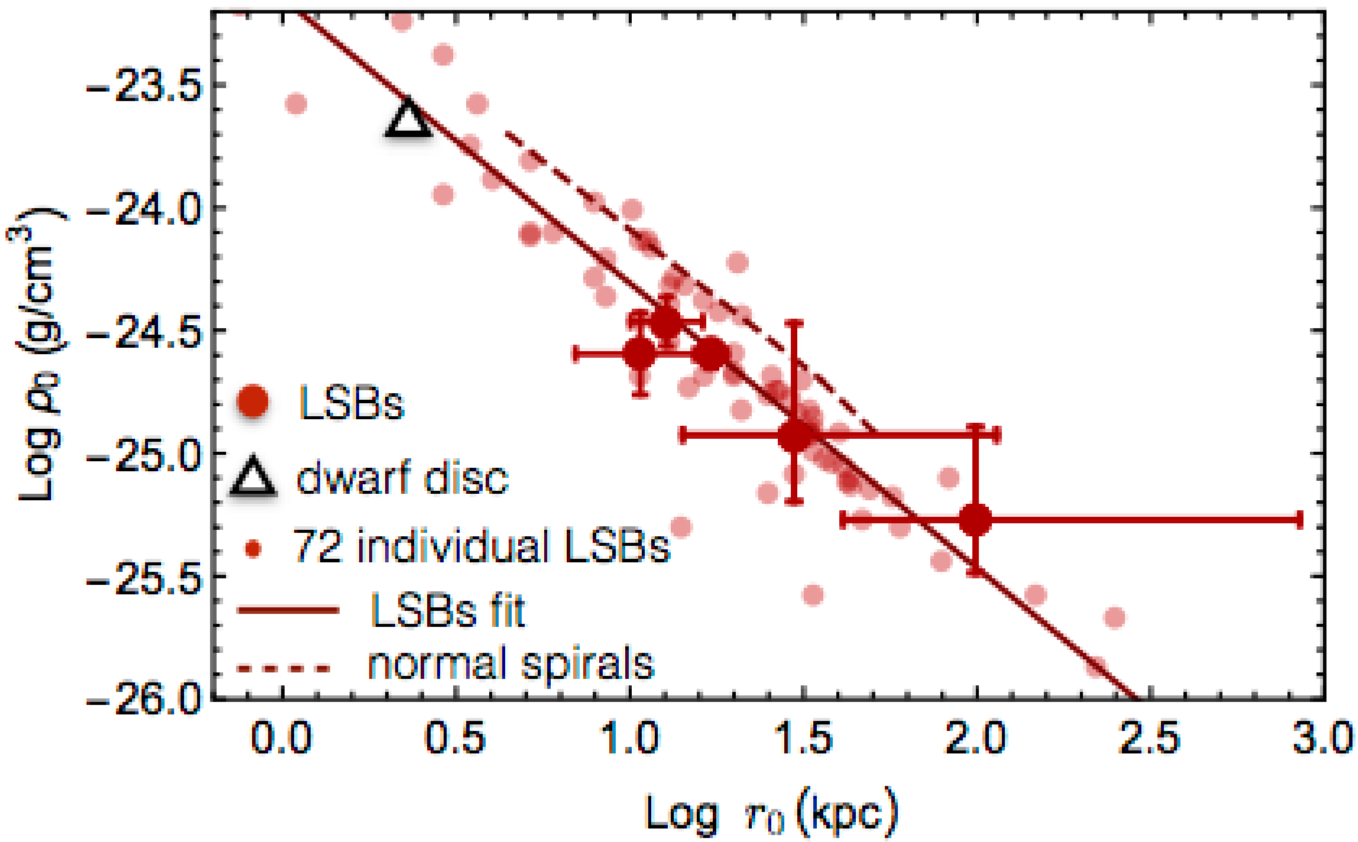
$$Log\, M_d = 3.12 + 3.47\, Log\, V_{opt}$$



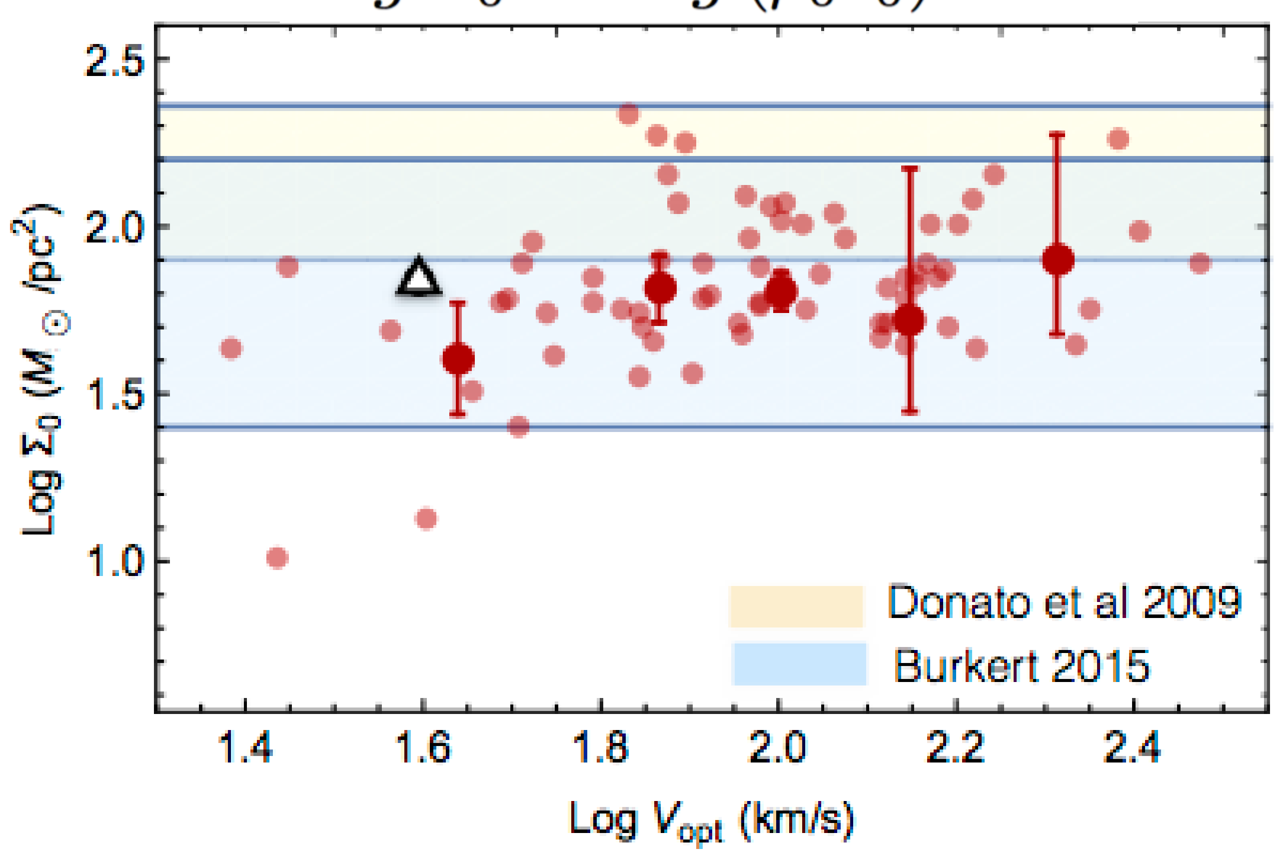
Di Paolo et al. 2019 (a)

Scaling laws for LSBs

$$Log\,\rho_0 = -23.15 - 1.16\,Log\,r_0$$



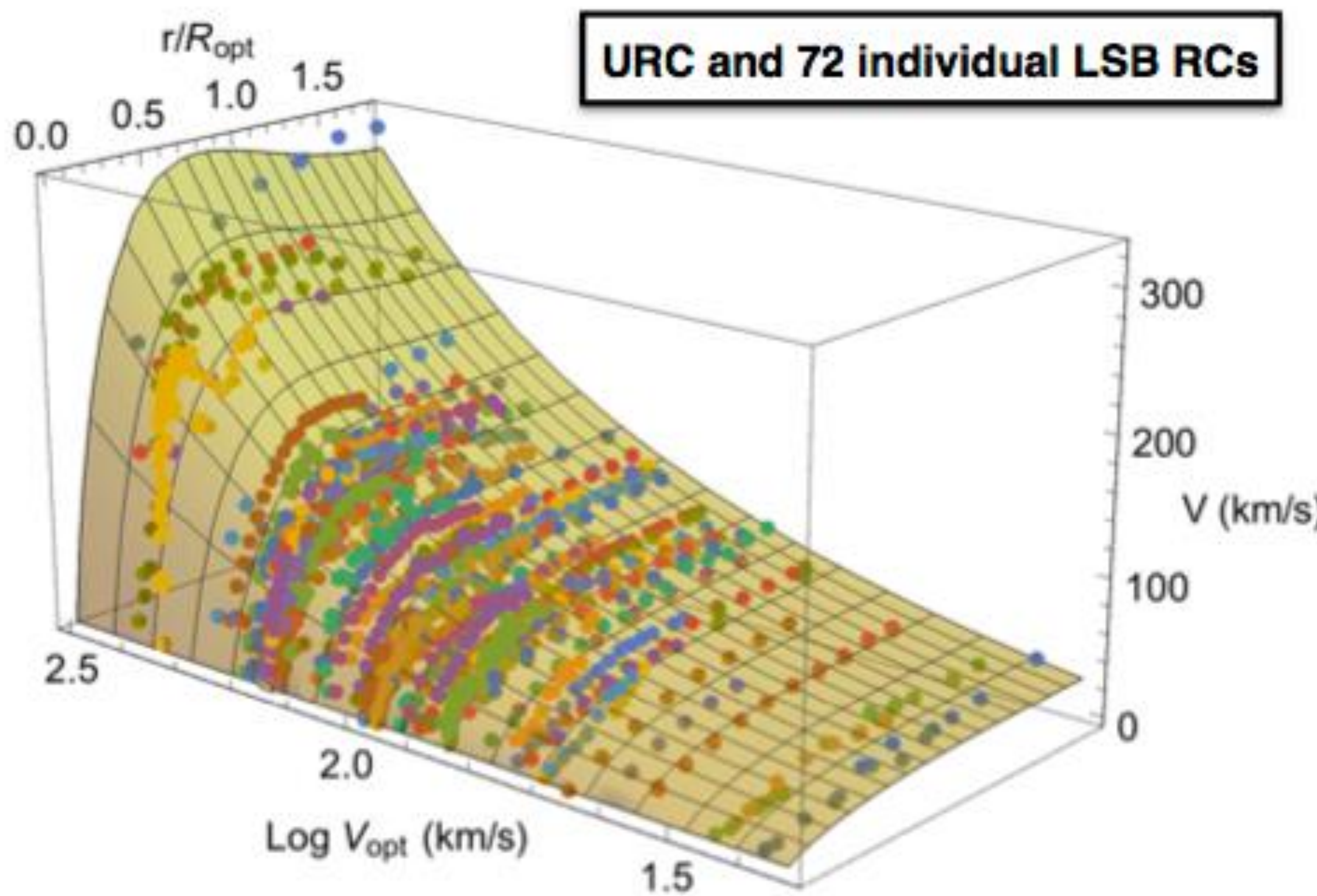
$$Log\,\Sigma_0 = Log\,(\rho_0 r_0) \simeq 1.9$$



Di Paolo et al. 2019 (a)

Universal Rotation Curve

$$\Delta V / V \simeq 8\%$$

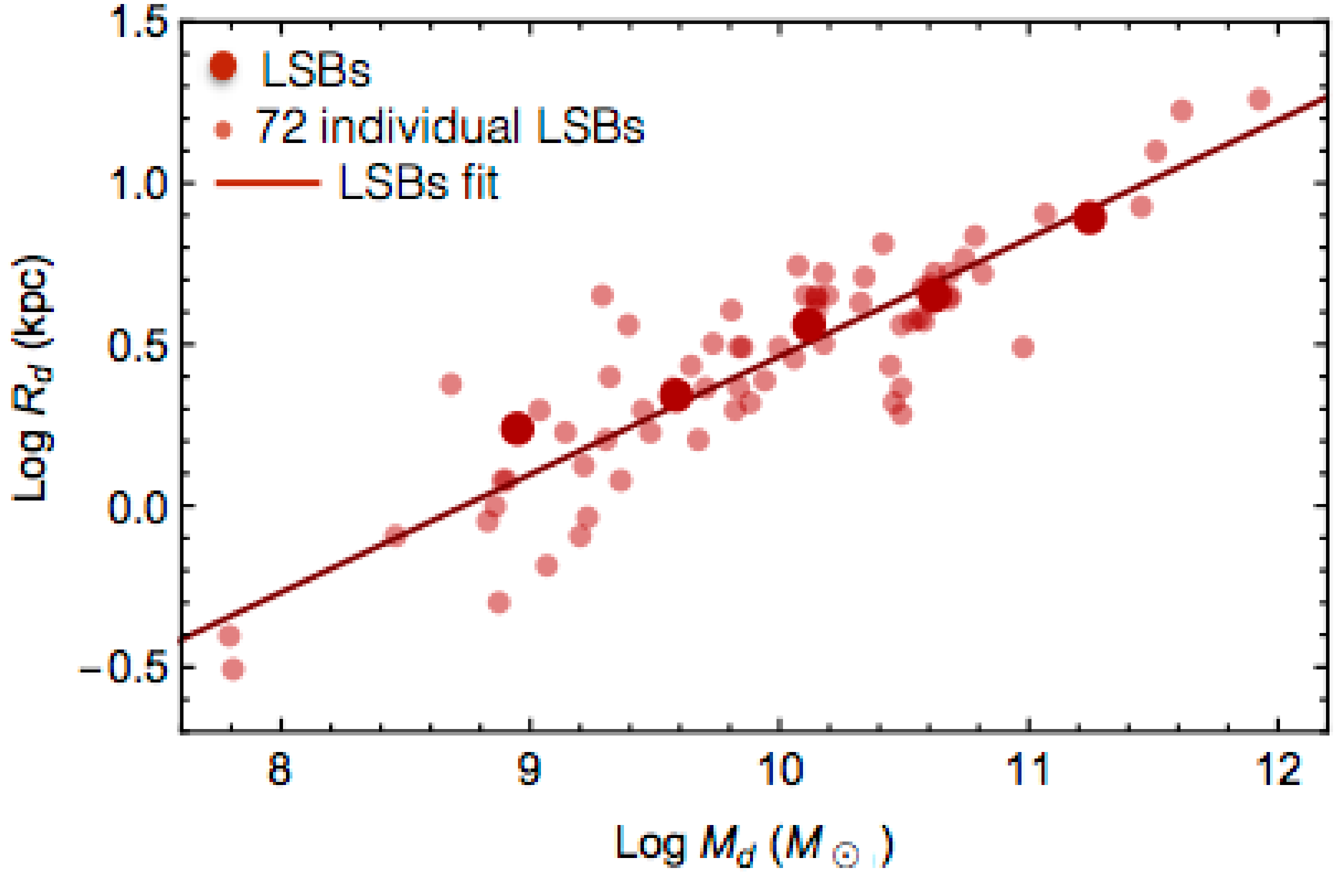


$$V^2(r/R_{opt}) = V_d^2(r/R_{opt}) + V_{DM}^2(r/R_{opt}) \longrightarrow \textbf{function of } V_{opt}$$

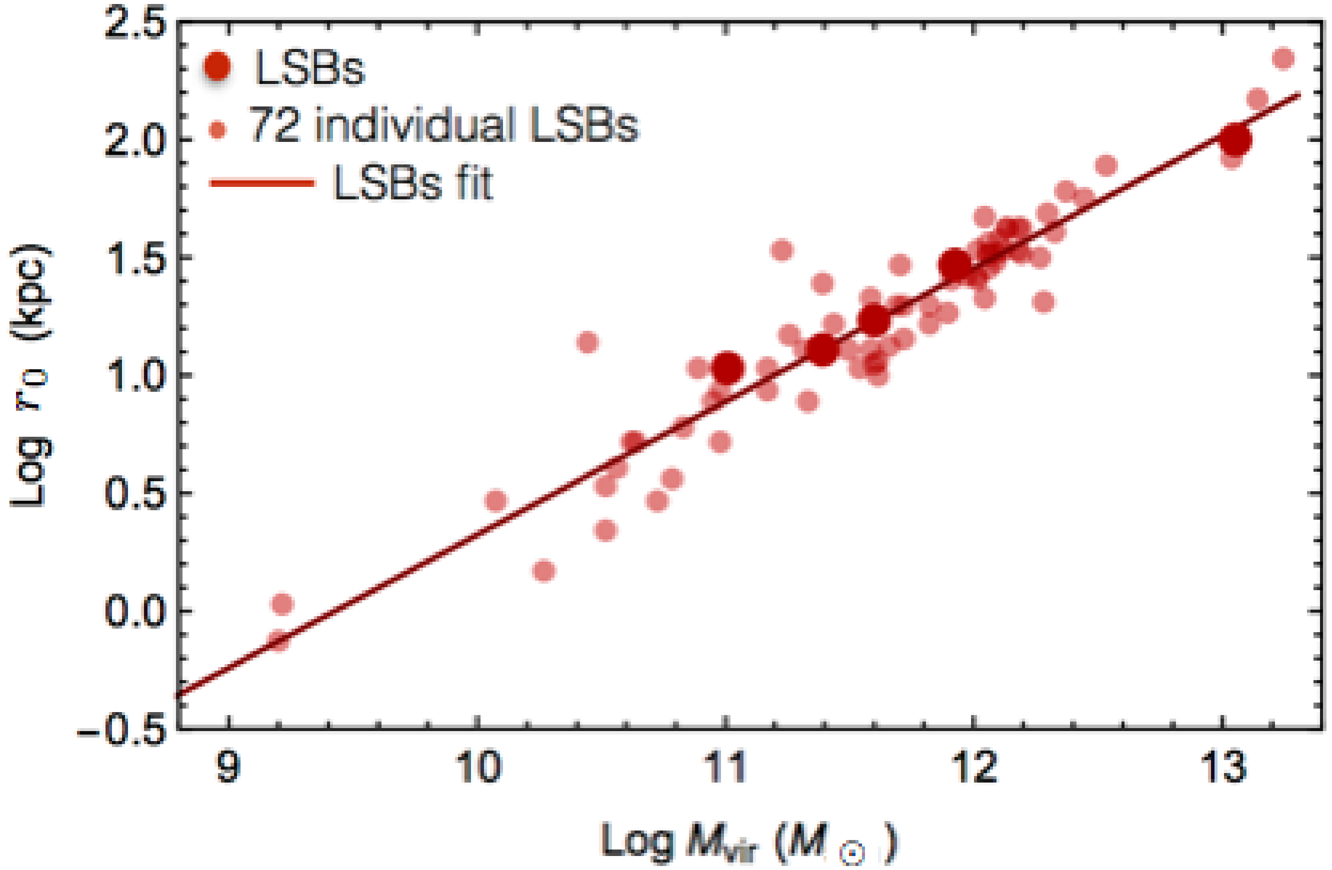
Di Paolo et al. 2019 (a)

Scaling laws for LSBs

$$Log\,R_d = -3.19 + 0.36\,Log\,M_d$$



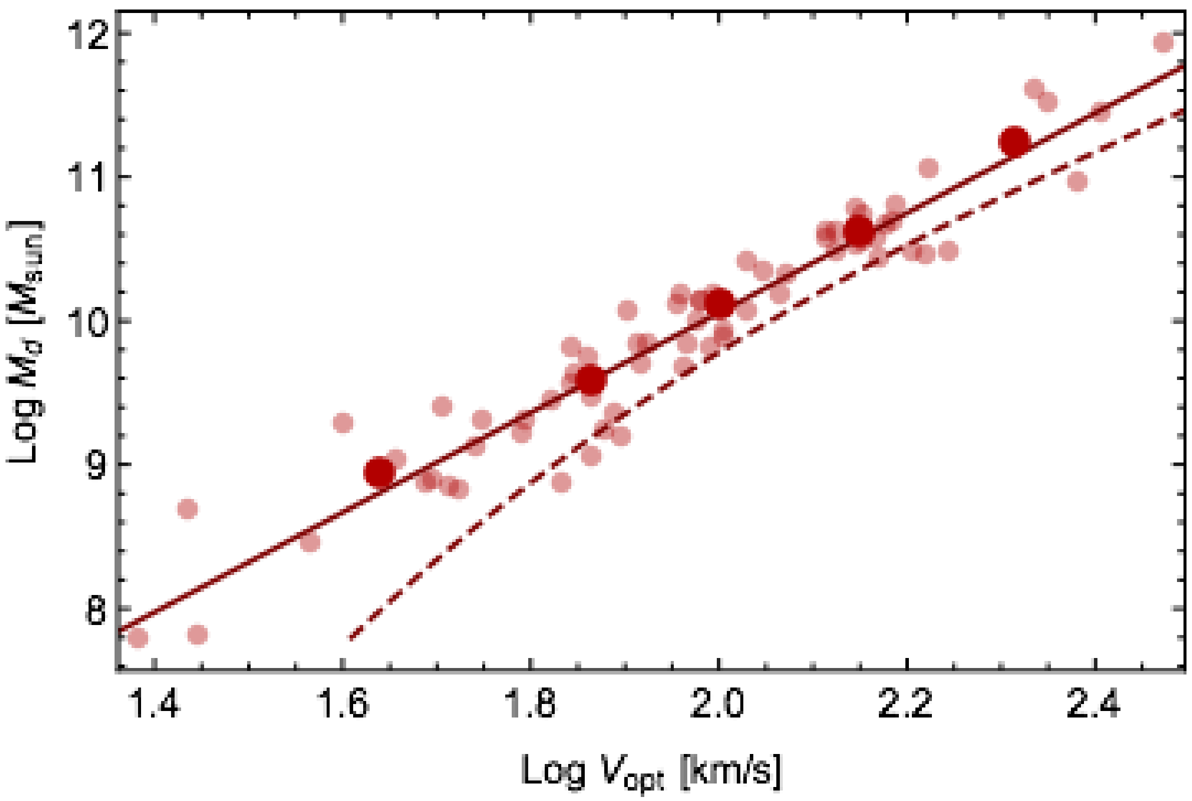
$$Log\,r_0 = -5.32 + 0.56\,Log\,M_{vir}$$

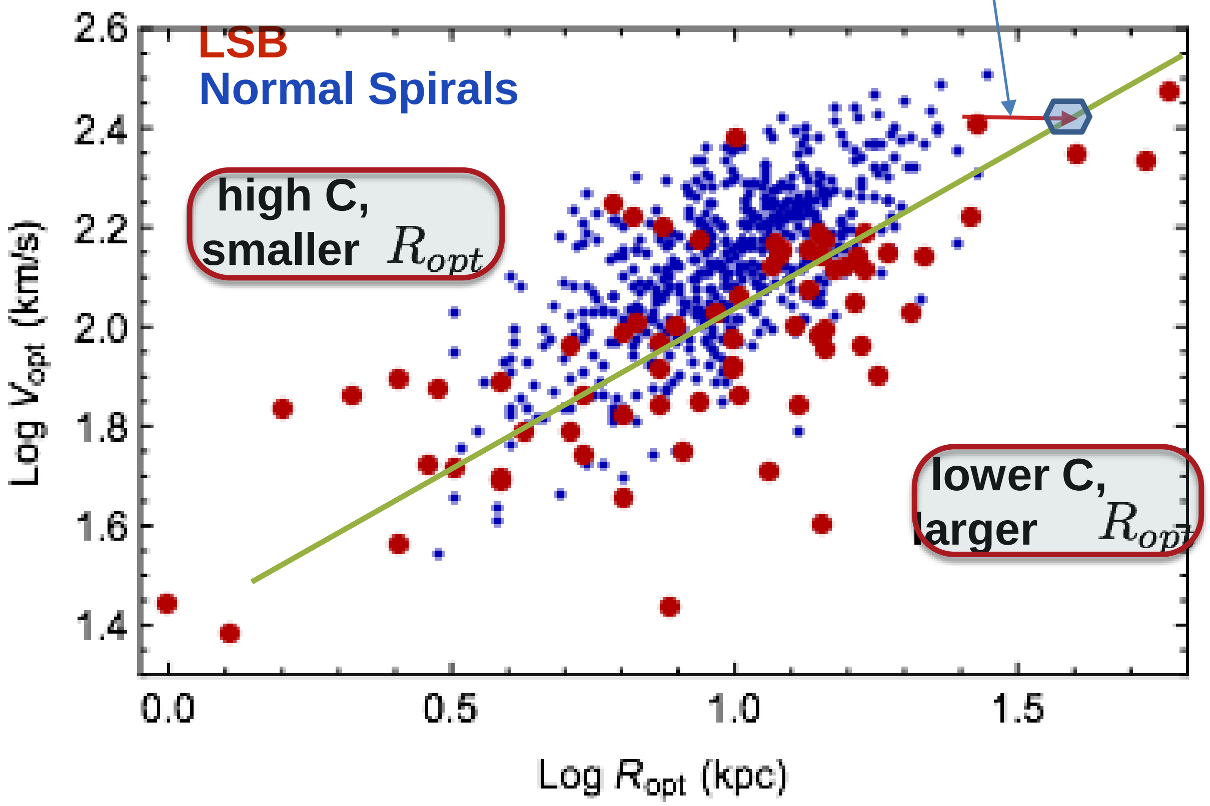


Di Paolo et al. 2019 (a)

Compactness

Log C



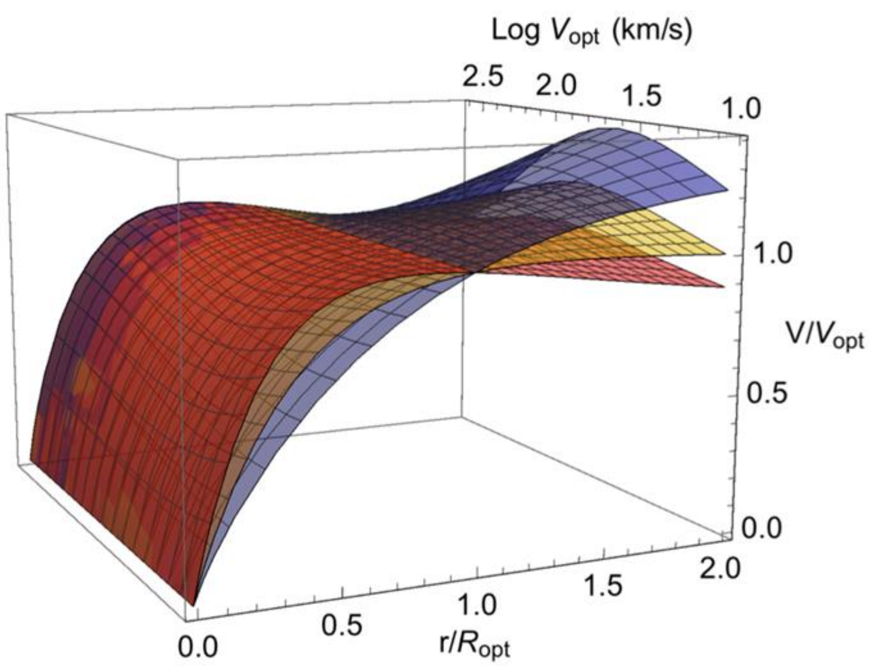


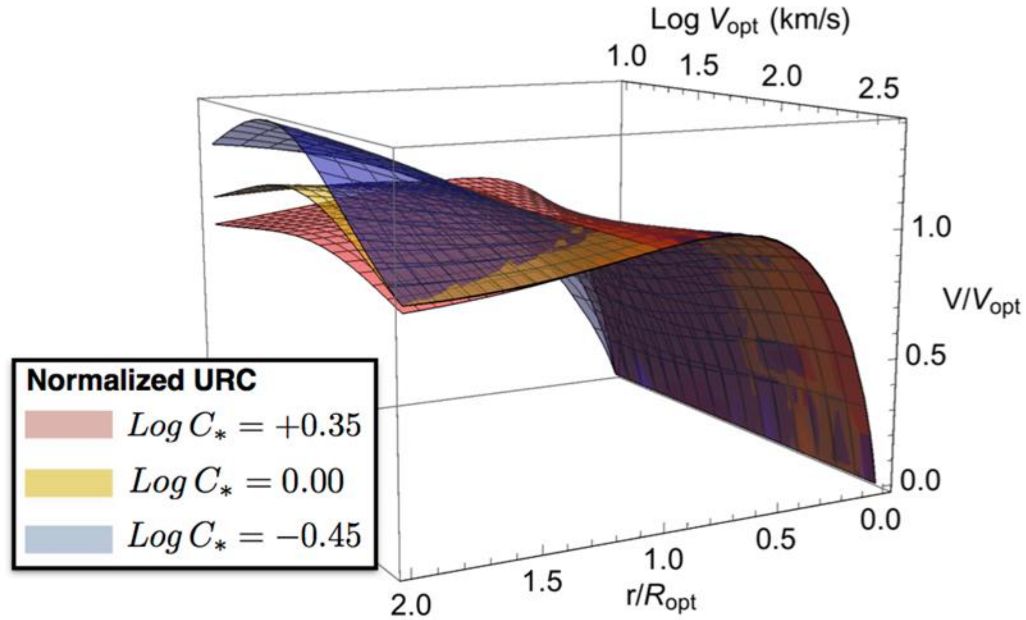
COMPACTNESS (C):

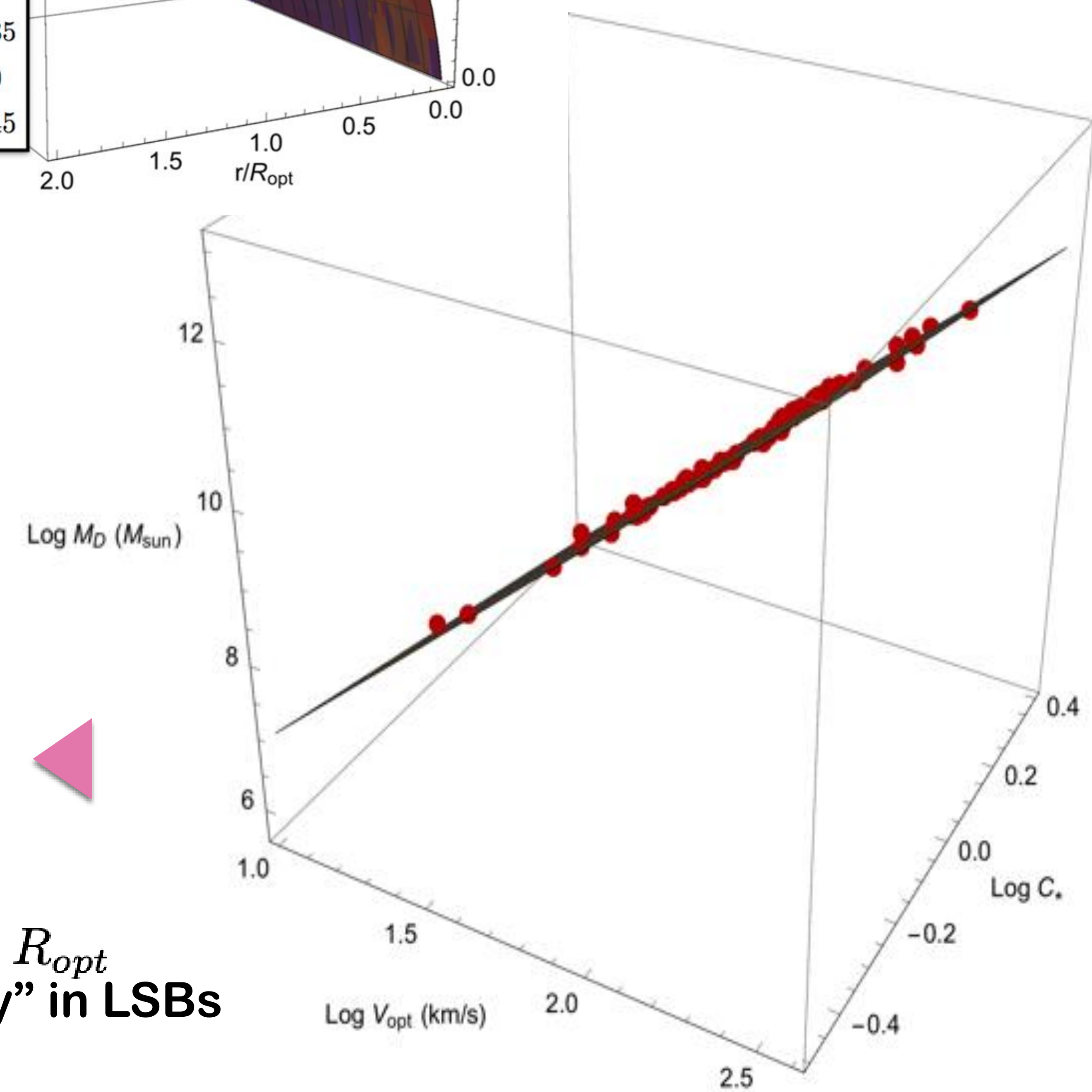
discrepancy between the measured R_{opt}
and the expected value $\bar{R}_{opt}$

Di Paolo et al. 2019 (a)

$$V_{urc}(r,R_D,V_{opt},C)^2 = V_d(r,R_D(V_{opt},C),M_D(V_{opt},C))^2 + V_h(r,r_0(V_{opt},C),\rho_0(V_{opt},C))^2$$



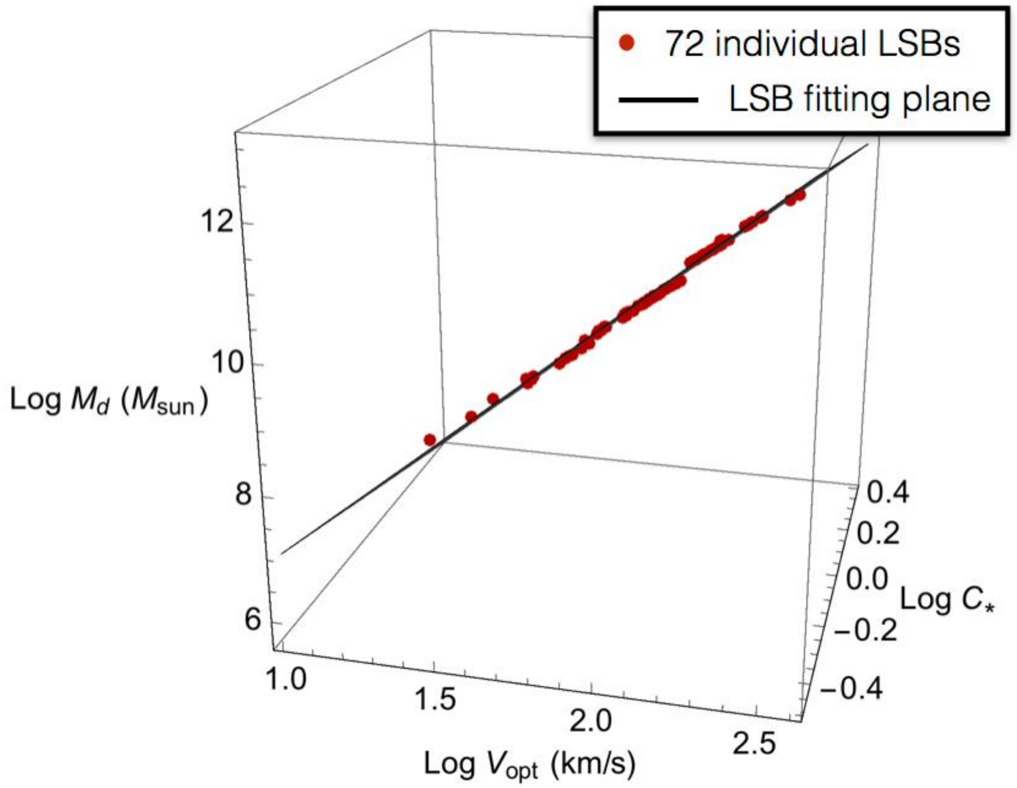


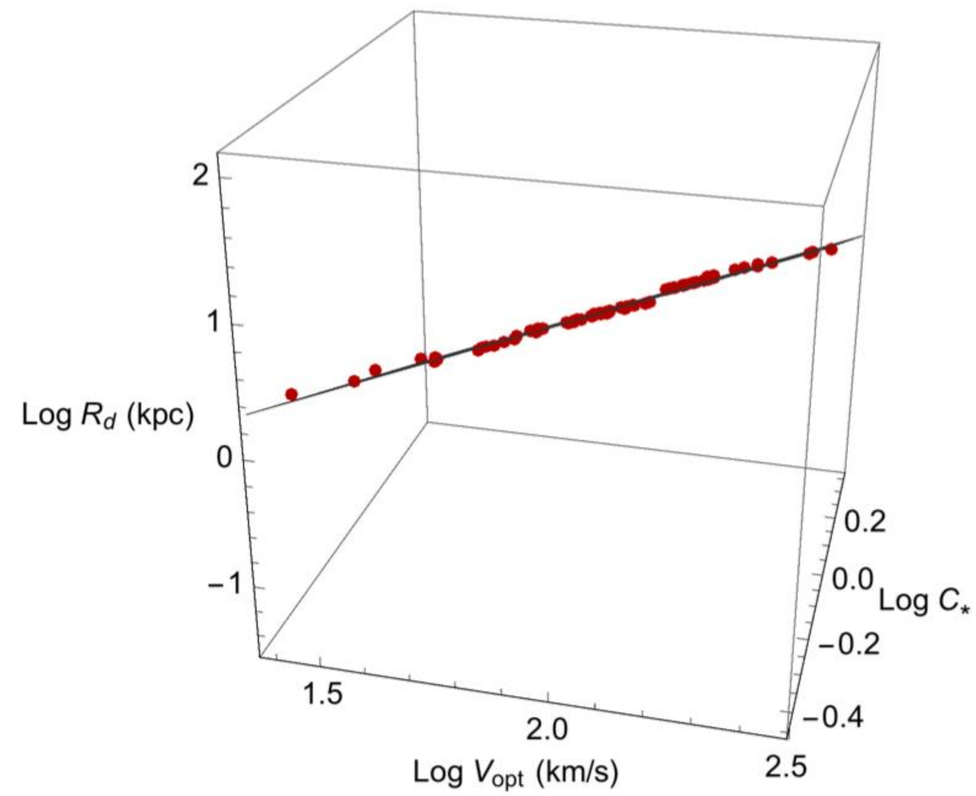


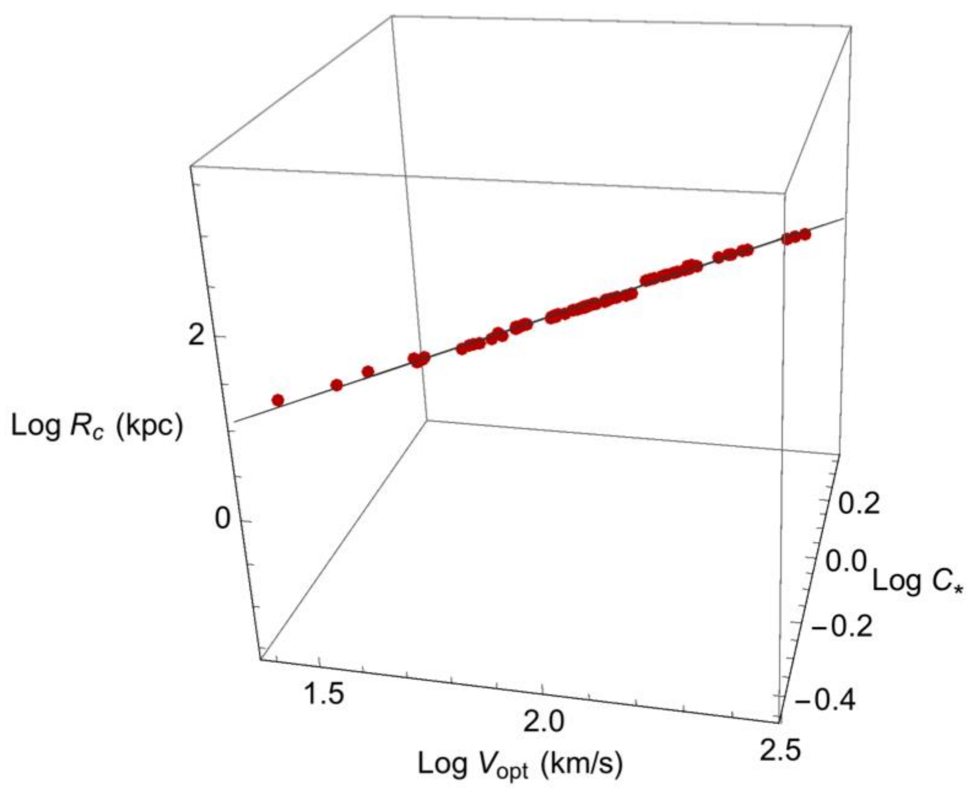
Reduced scatter
after
the COMPACTNESS
introduction

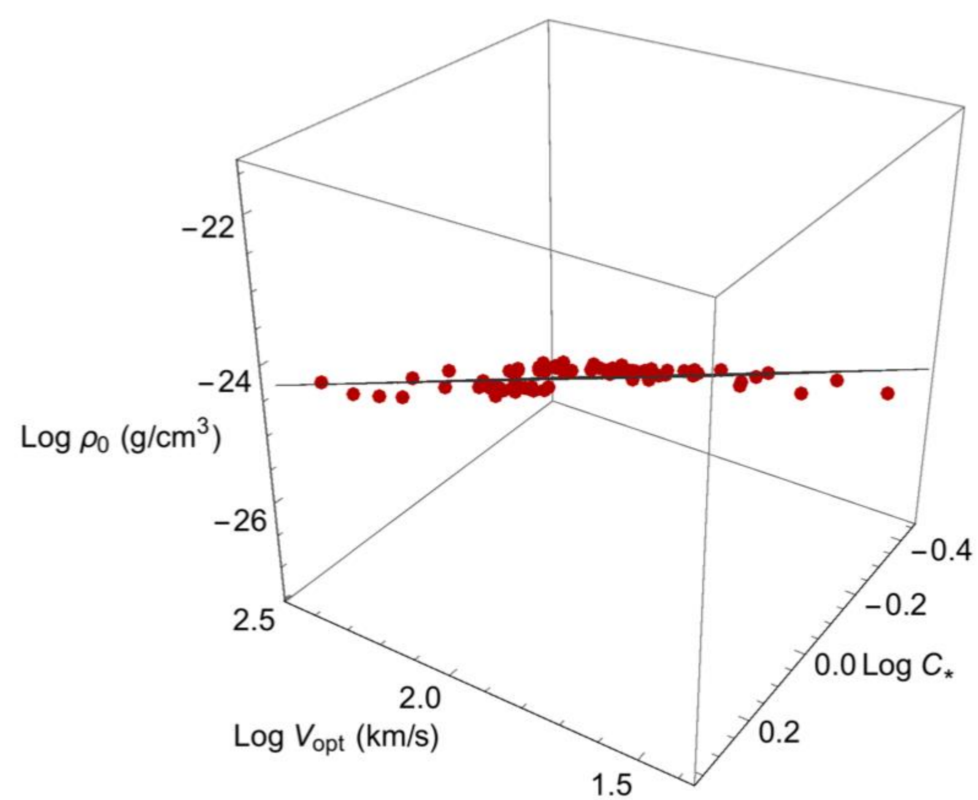
important parameter with V_{opt} R_{opt}
In rder to have a "better universality" in LSBs

Low Surface Brightness galaxies (LSBs)



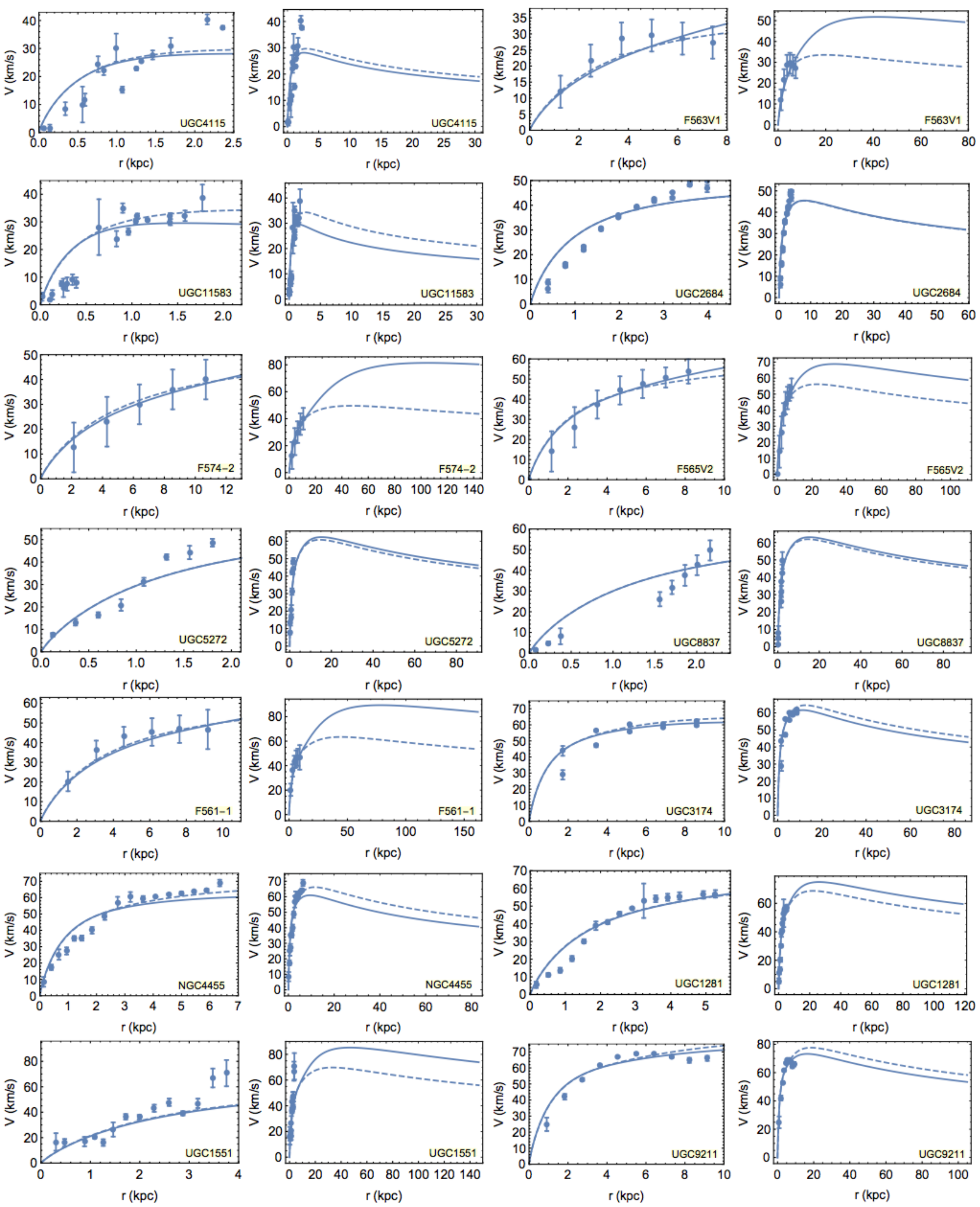






Universal Rotation Curve

$$\Delta V/\,V \simeq 8\%$$



Di Paolo et al. 2019 (a)

WHAT IS DARK MATTER?

Constant density central regions in all LSBs

- R_d vs r_0

Relation & Co.
Portal btween Dark and Luminous matter

in the ΛCDM scenario + baryonic feedback :

- challenge in dwarf and large spirals

- challenge in fine-tuning parameters

- Challenge at higher levels in LSB galaxies

-

Specific power spectrum of dark matter AND DM pressure plus some direct interaction between dark matter (DM) and luminous matter (LM).
Requirements possible for keV WDM
Start from halos made by collisionless particle inconsistent with present data

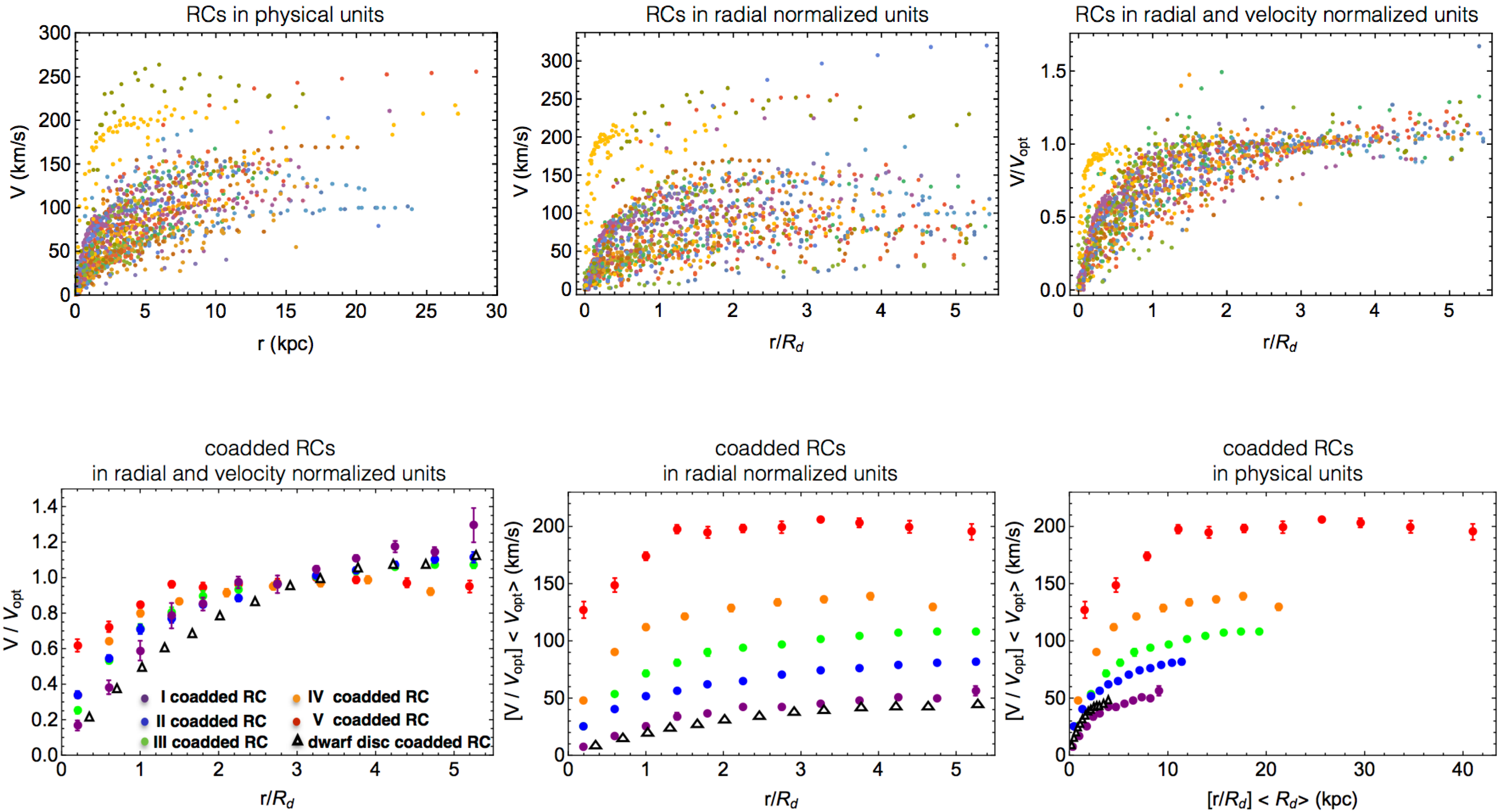
Conclusion

- The LM-DM interaction might be a necessary key to understand the DM phenomenon: WDM passes The test

- to reproduce the observed core in the galactic DM halo
- the empirical relationships between the galactic properties

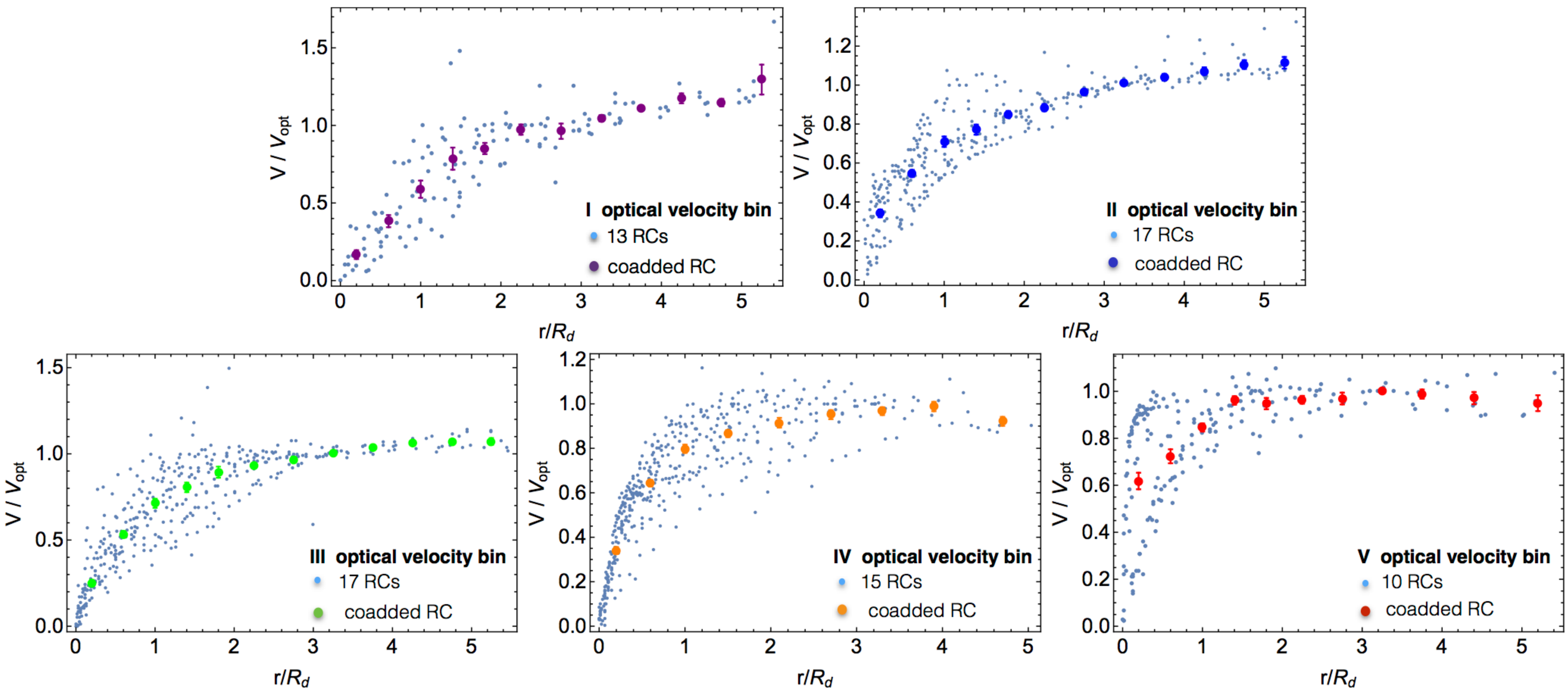
-

Low Surface Brightness galaxies (LSBs)



Low Surface Brightness galaxies (LSBs)

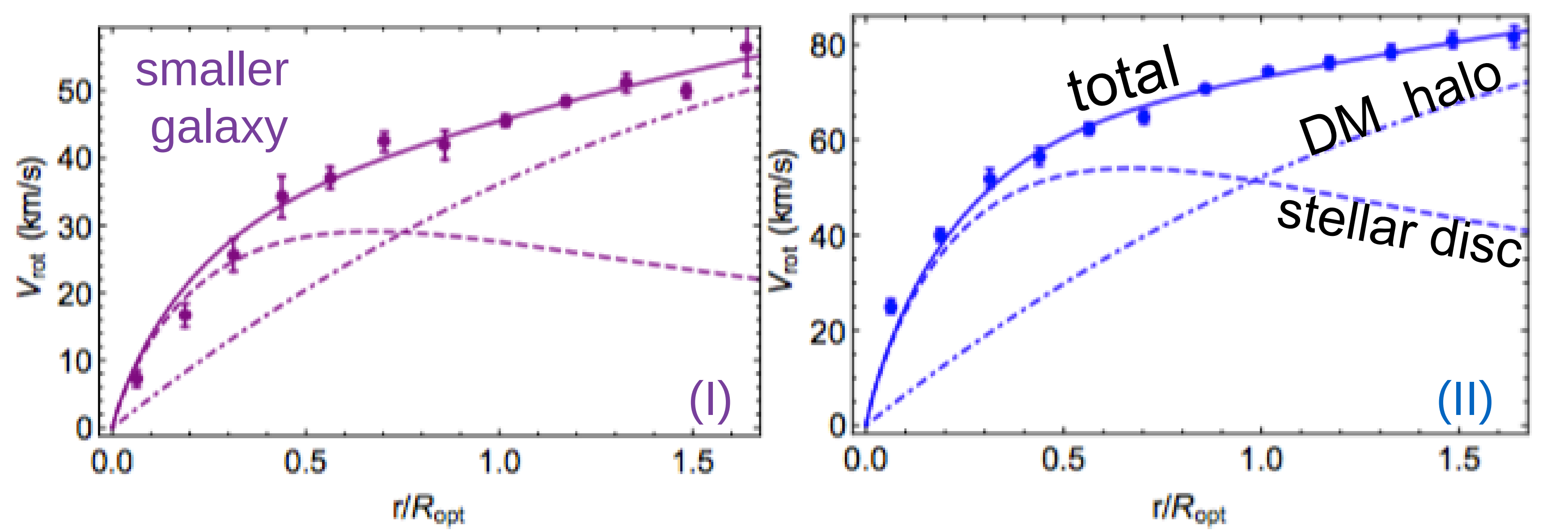
RCs and their coadded RCs in radial and velocity normalized units

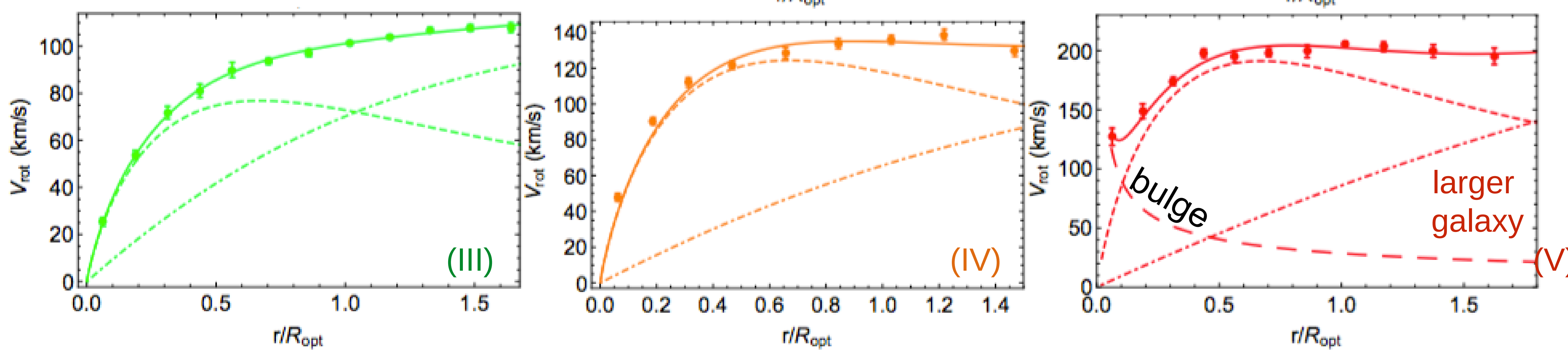


Low Surface Brightness galaxies (LSBs)

Mass Modelling

5 co-added RCs





Vel. Bin	$\langle\rho_0\rangle$	$\langle R_c\rangle$	$\langle M_D\rangle$	$\langle M_{vir}\rangle$	$\alpha(R_{opt})$
	$10^{-3}\ M_\odot/pc^3$	kpc	$10^8\ M_\odot$	$10^{11}\ M_\odot$	
(1)	(2)	(3)	(4)	(5)	(6)
1	3.7 ± 1.4	10.7 ± 4.3	8.8 ± 1.8	1.0 ± 0.4	0.37
2	5.1 ± 1.1	12.8 ± 3.0	38 ± 3	2.4 ± 0.9	0.49
3	3.7 ± 0.5	17.1 ± 1.9	130 ± 5	4.0 ± 1.3	0.52
4	$1.7^{+3.2}_{-1.1}$	$29.7^{+84.1}_{-22.0}$	421 ± 40	8.4 ± 3.5	0.76
5	$0.8^{+1.1}_{-0.4}$	$99.1^{+750.5}_{-87.5}$	1730 ± 117	112 ± 55	0.82

$$V_i^2(r) = G\frac{M_i(r)}{r}$$

$$\alpha = \frac{\langle V_D^2(R_{opt})\rangle}{\langle V_{tot}^2(R_{opt})\rangle}$$

baryonic fraction

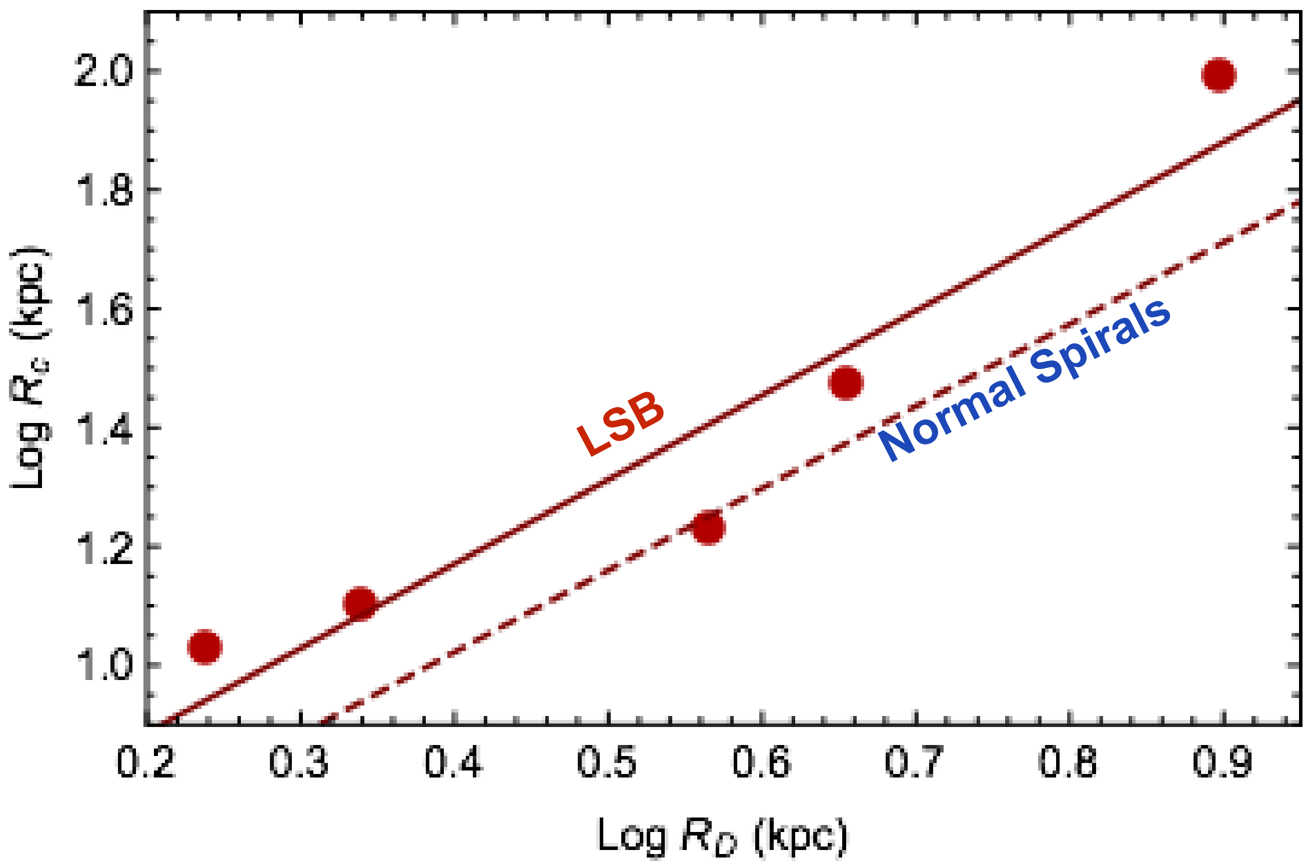
Low Surface Brightness galaxies (LSBs)

DENORMALIZATION

takes into account that all the double normalised RCs are similar to their co-added double normalised RC in **each single velocity bin**

good approximation :

the relations obtained for the co-added RCs are assumed to be true also for the single galaxies



$$R_c/R_d^{1.42} = const.$$

one relation in all velocity bins ▶ R_c

$$\frac{M_d}{V_{opt}^2 R_{opt}} = const.$$

one different value in each velocity bin ▶ M_d

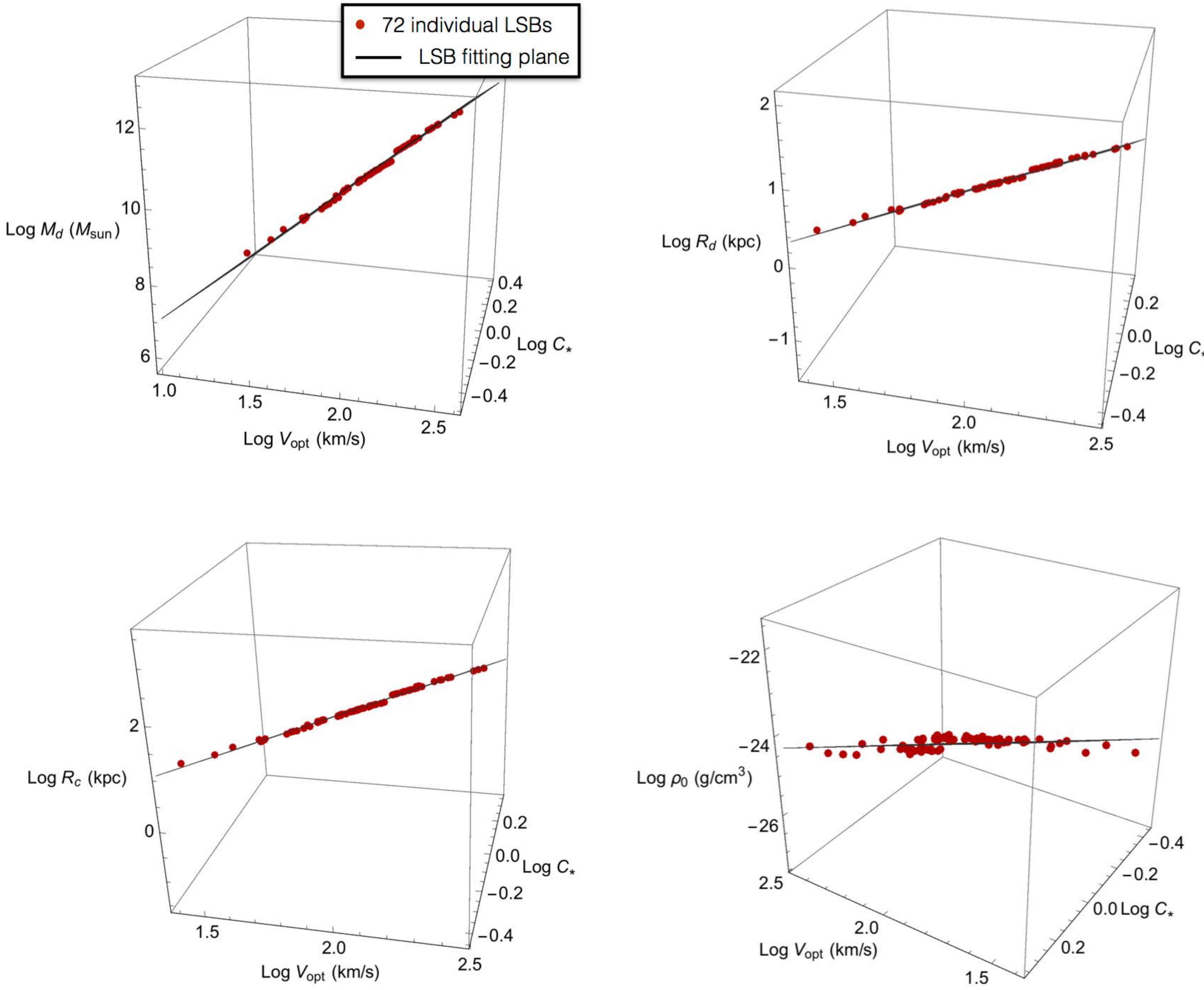
$$M_{DM}(R_{opt}) = G^{-1}(1-\alpha)V_{opt}^2 R_{opt}$$

$$\alpha = \frac{V_d^2(R_{opt})}{V^2(R_{opt})}$$ = baryonic fraction at optical radius, one different valuein each velocity bin

$$M_{DM}(r) = 2\pi\rho_0 R_c^3[ln(1+r/R_c) - tg^{-1}(r/R_c) + 0.5ln(1+(r/R_c)^2)]$$

for a DM cored Burkert profile ▶ ρ_0

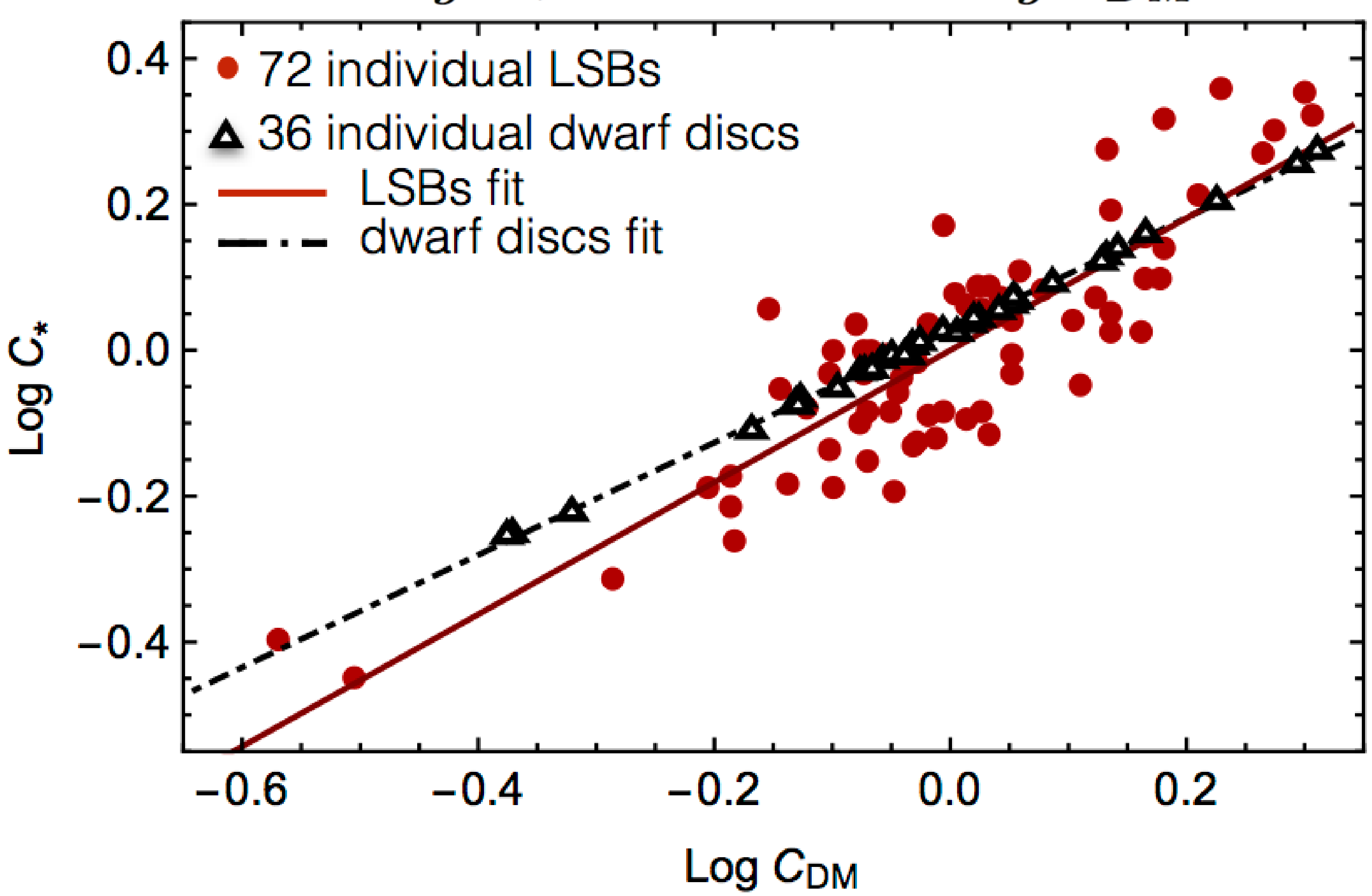
Low Surface Brightness galaxies (LSBs)



Compactness

Similar to the dwarf discs relation

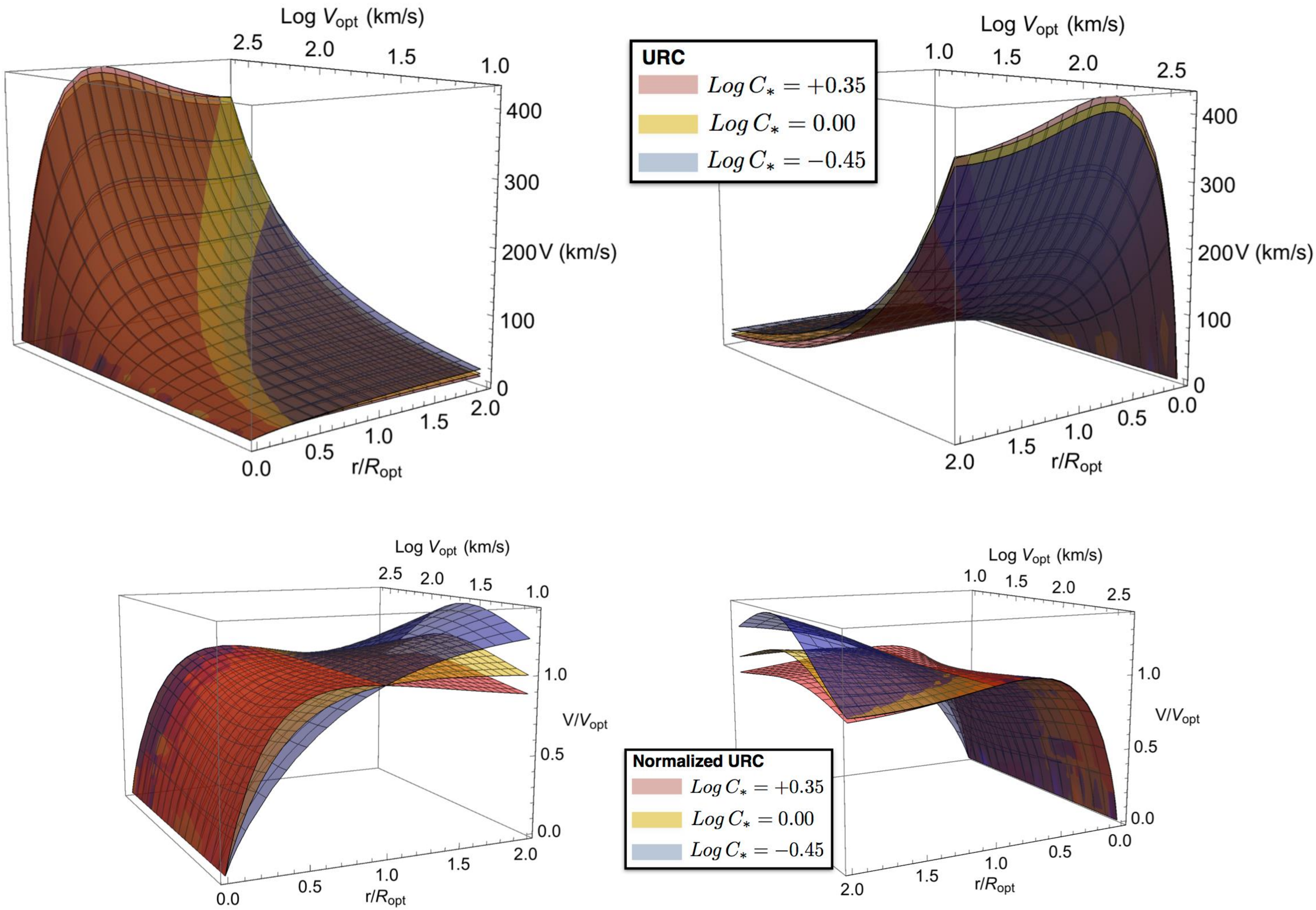
$$Log\ C_* = 0.00 + 0.90\ Log\ C_{DM}$$



Strong correlation between the stellar and the DM compactness

Di Paolo et al. 2019 (a)

Low Surface Brightness galaxies (LSBs)



e lower bound on the mass of a fermionic DM candidate fr
known small Dwarf Spheroidal galaxies

ADVANTAGES:

- model independent $\longrightarrow$ does not require any assumption on initial distribution or evolution of DM particles

- relaxed the relation $R_h = R_{\frac{1}{2}}$

THOMAS-FERMI MODEL

galactic halo made of a fermionic self-gravitating gas

at a finite temperature T_0

$\Phi(r)$: mean field gravitational potential, with spherical symmetry

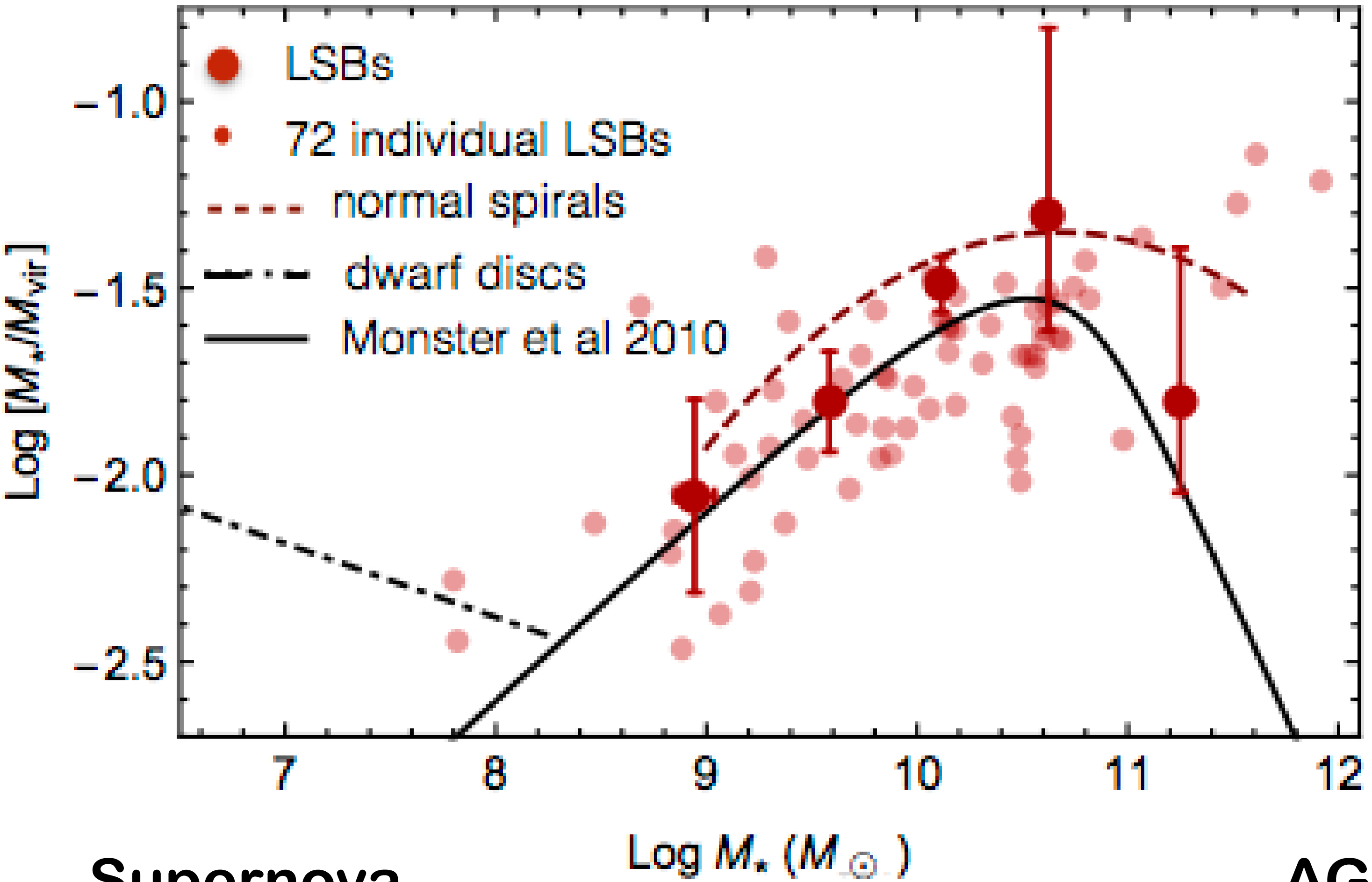
Poisson equation
$$\begin{cases} \frac{d\phi(r)}{dr} = G\frac{M(r)}{r^2} \\ \frac{dM(r)}{dr} = 4\pi r^2 \rho(r) \end{cases}$$

$$\rho(r) = mn(r) = \frac{gm}{2\pi^2\hbar^3}\int_0^\infty p^2\,dp\,f\left[\frac{p^2}{2m} - \mu(r)\right] \qquad g = 2$$

$f(E)$ $\qquad E = p^2/(2m) - \mu(r)$ $\qquad \mu(r) = \tilde{\mu}_0 - m\Phi(r)$

$$f_{FD}(E) = \frac{1}{1 + exp(E/T_0)}$$

Fraction of baryonic matter in LSBs versus their mass in stars



Supernova feedback

AGN feedback

Di Paolo et al. 2019 (a)

[illegible] masses for DM particle

Not so stringent

but very robust result because:

- generic fermionic DM particle
- model independent → based only on present phase-space density of DM particles in galaxies
- relaxed the relation $R_h = R_{\frac{1}{2}}$