LSB (Low Surface Brightness) galaxies: new hints for dark matter?

AstroTS

Trieste, June 26 2019

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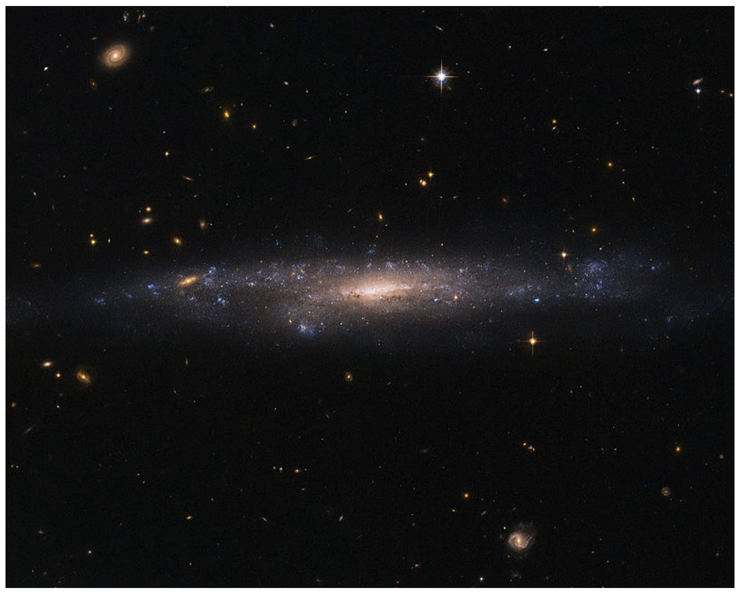
LSB galaxies rotation curves

emit much less light per area than normal galaxies

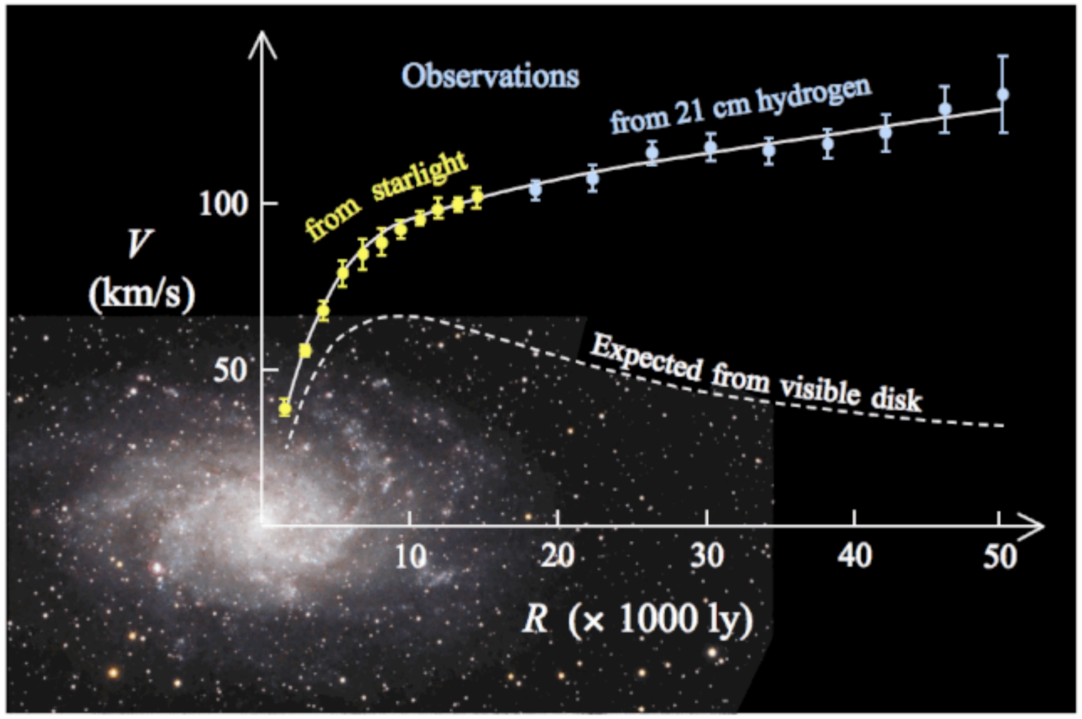


UGC 477

MALIN 1

- Although following the large-scale structure of galaxies, they are locally more isolated than other galaxies
    - Extended gas disks with low gas surface densities
- Low metallicities makes gas cooling difficult and the stars difficult to form
    - Likely evolving very slowly with very low star formation rates

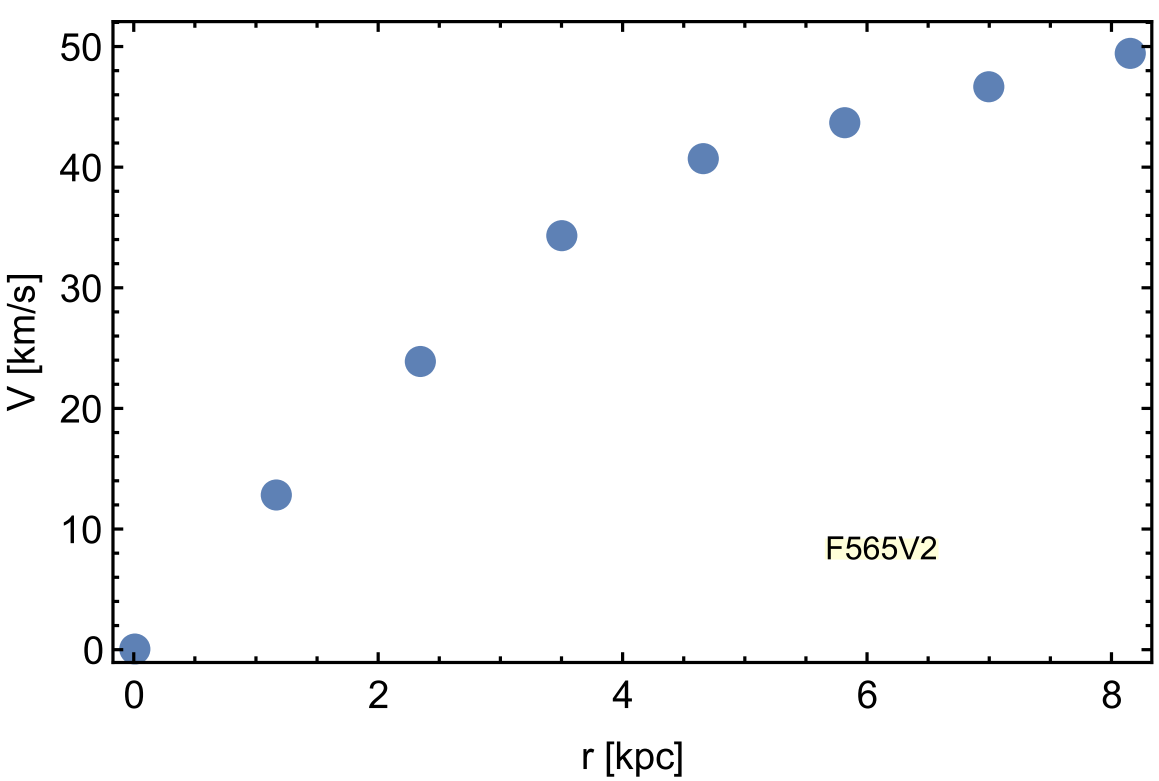
LSB galaxies rotation curves

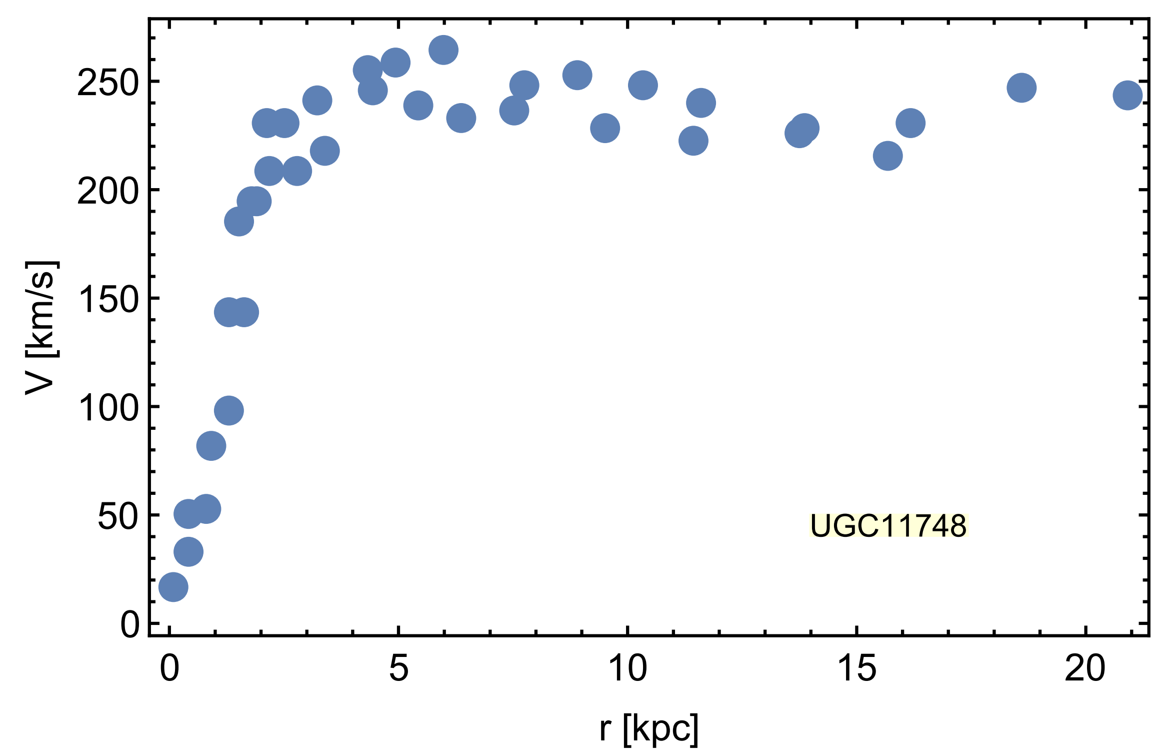


R_D = disk scale length exponential stellar disk

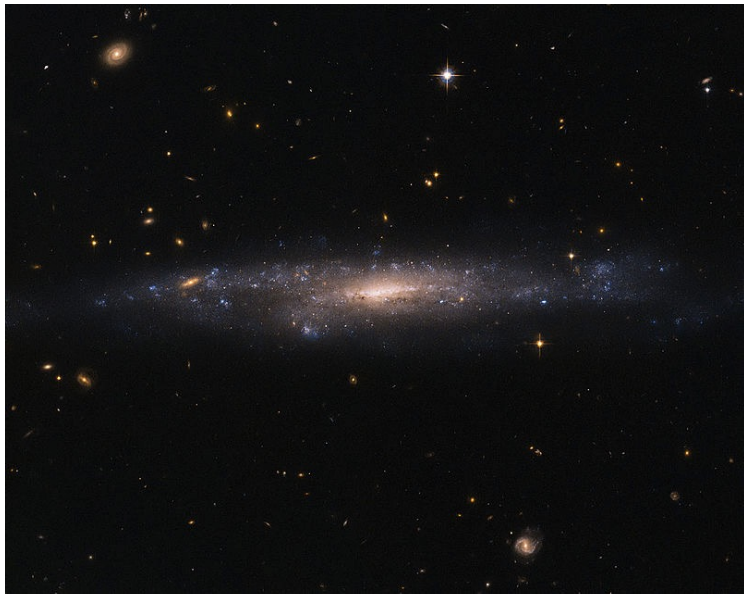
$R_{opt} = 3.2\, R_D$ → 83 % total luminosity

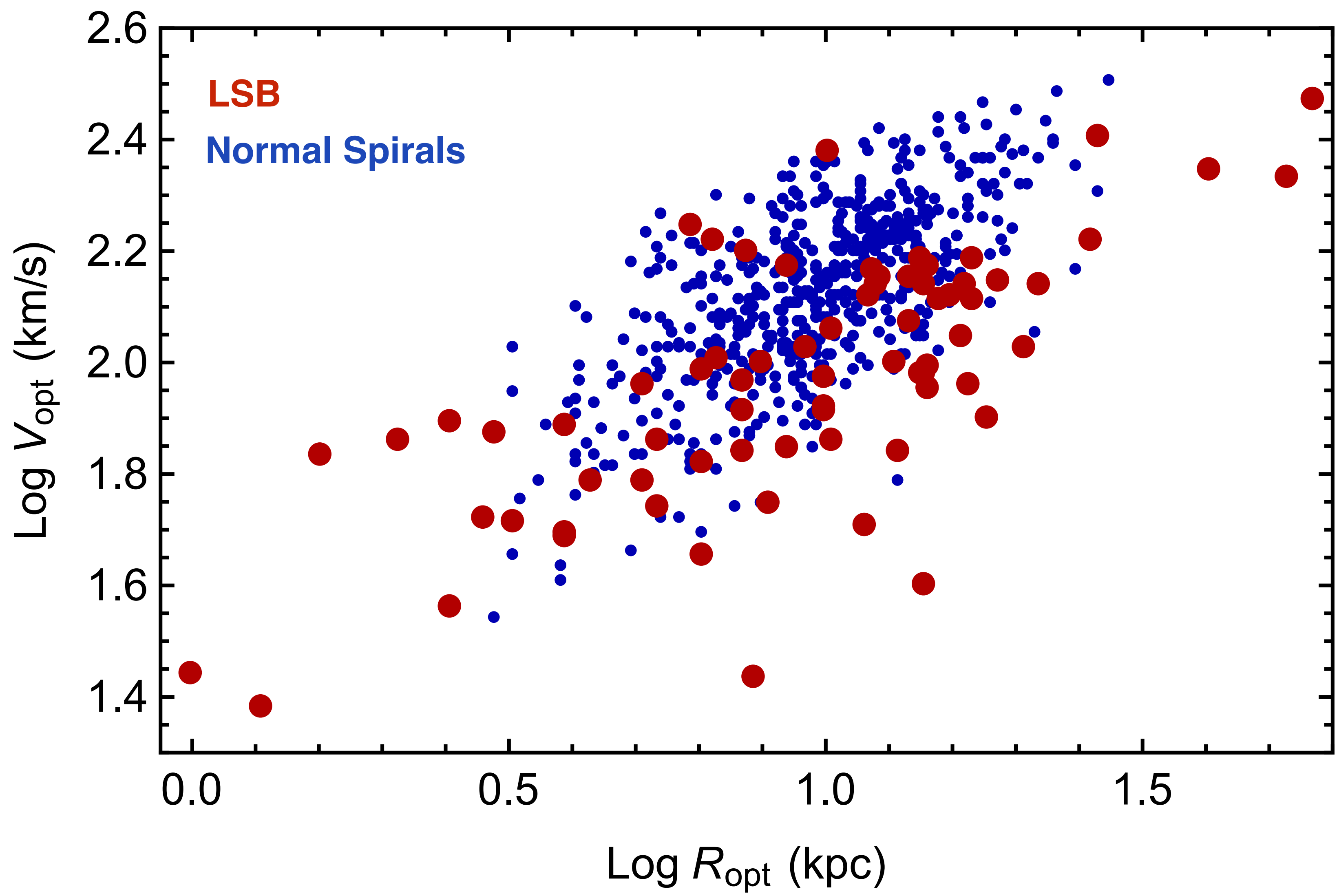
$V_{opt} = V(R_{opt})$





Low Surface Brightness galaxies (LSBs)





72 **Low Surface Brightness** galaxies

(Di Paolo, Salucci, Erkurt (2018))

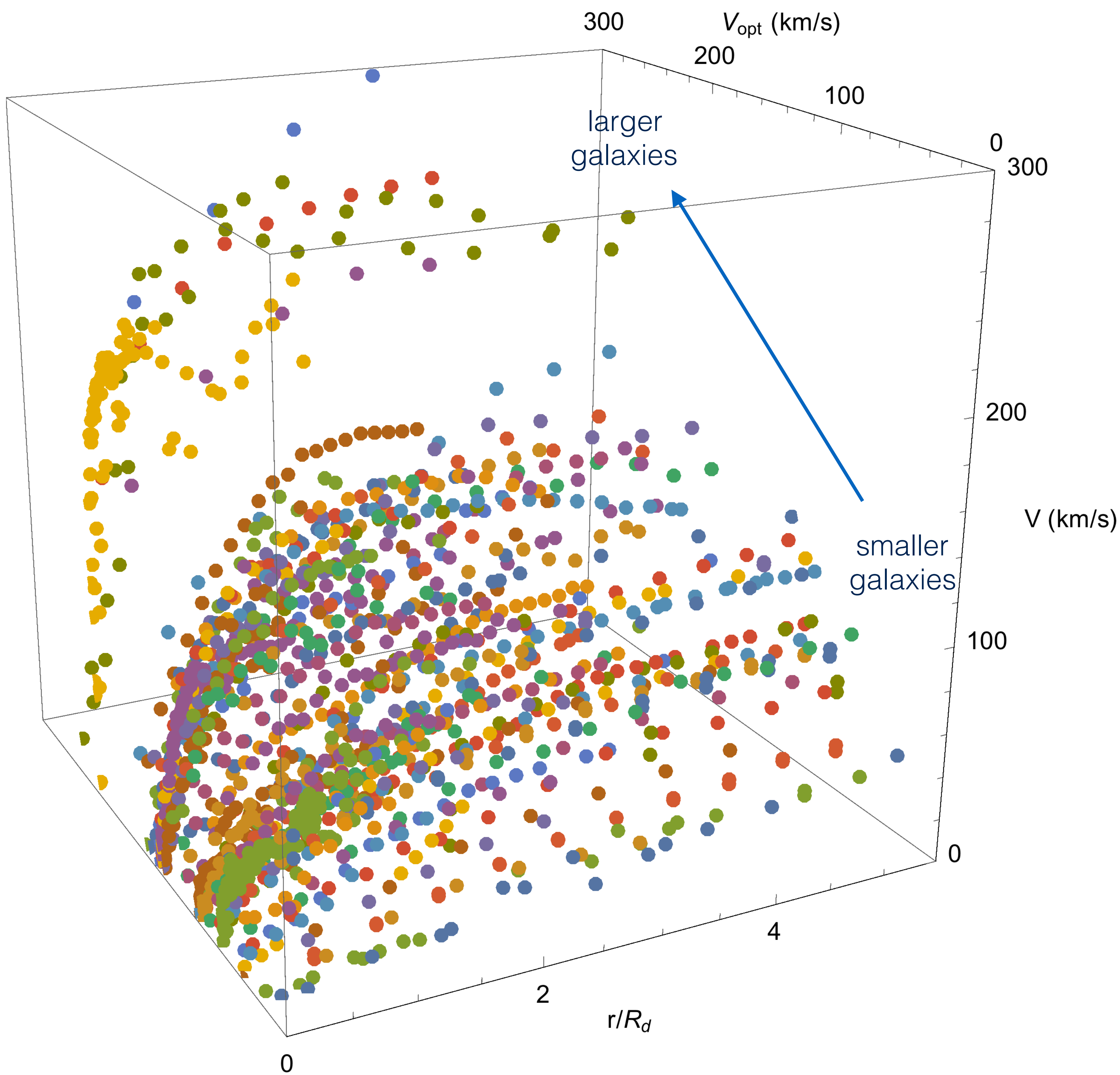
<u>1601 circular velocity measurements</u>

$24 < V_{opt} < 300\, km/s$

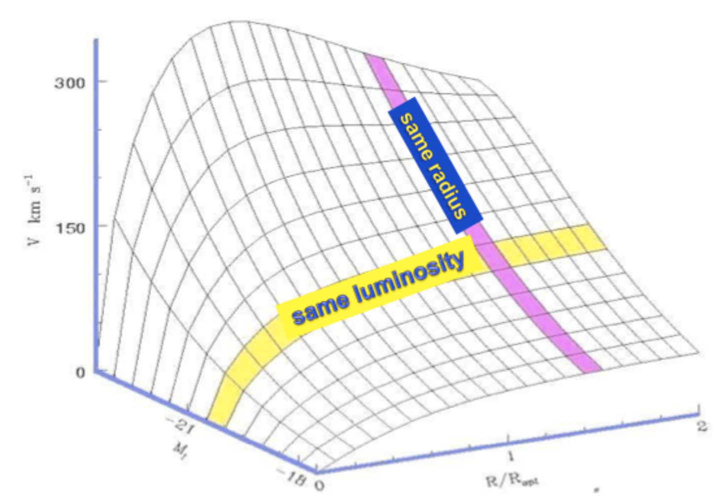
emit much less light per area than normal galaxies

https://arxiv.org/abs/1805.07165

Low Surface Brightness galaxies (LSBs)

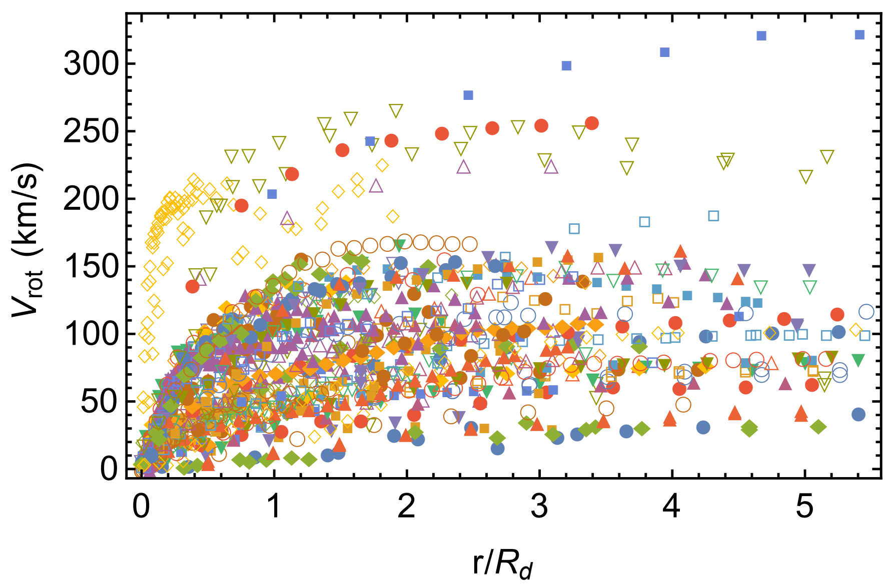


LSBs
rotation curves
show
a
universal trend



Persic, Salucci, Stel, 2007

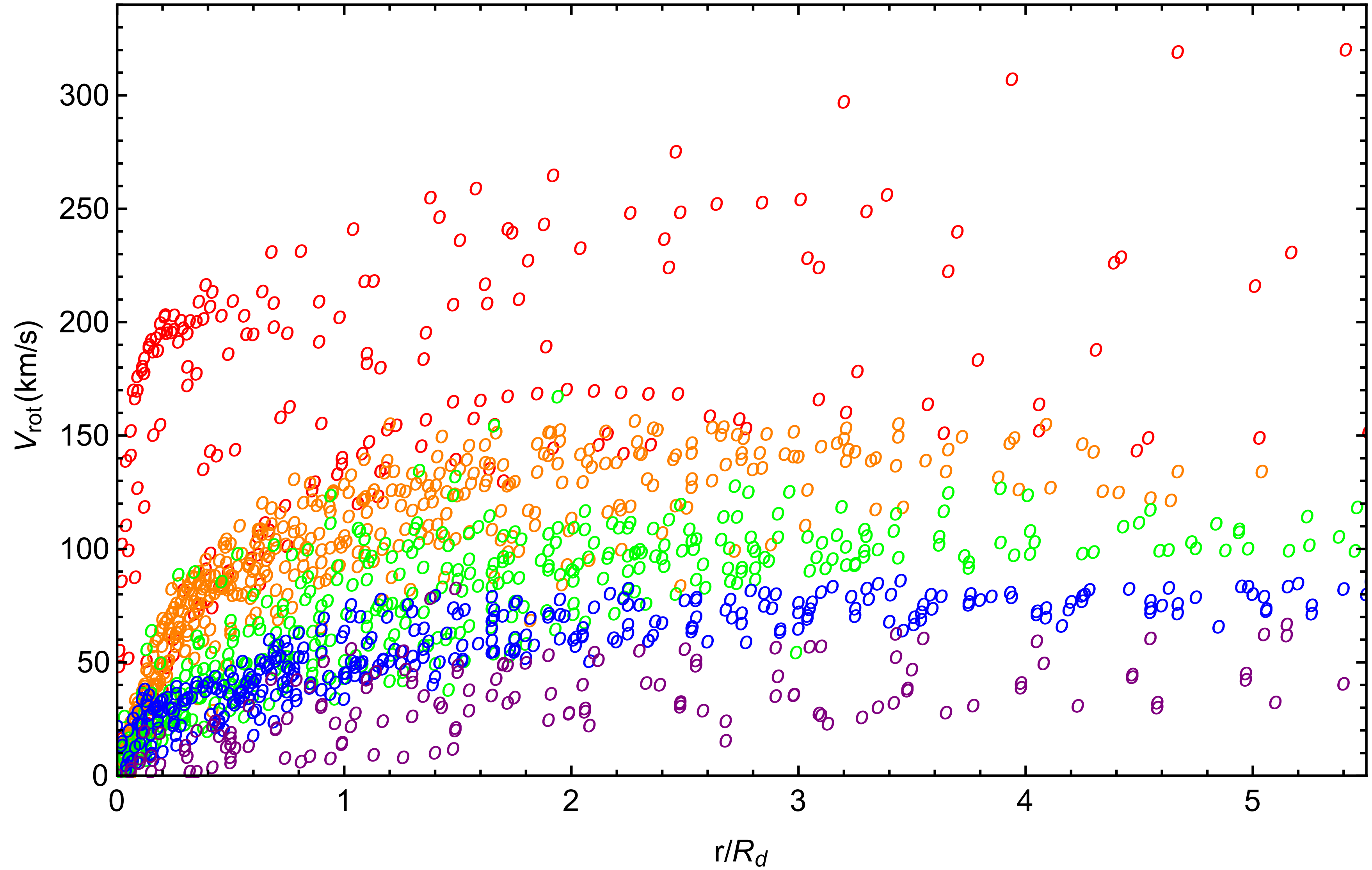
Low Surface Brightness galaxies (LSBs)



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

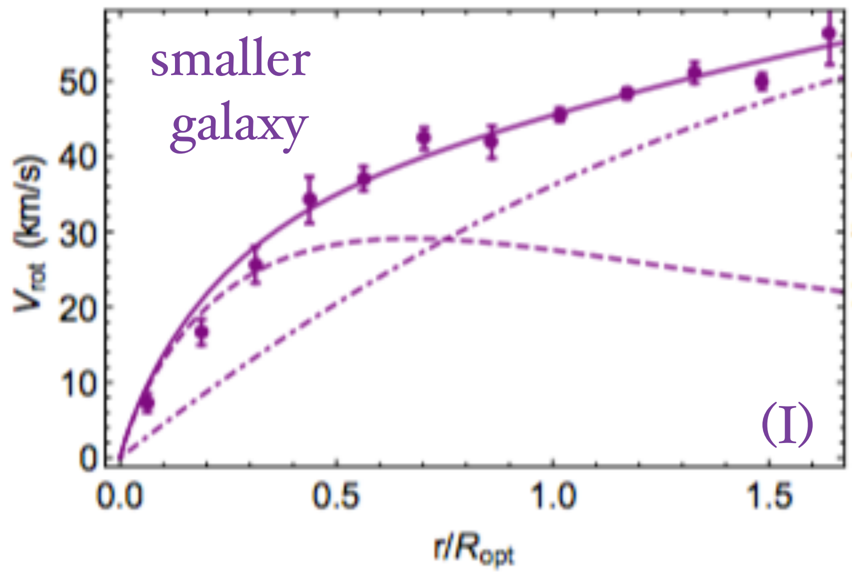
inner curvature
more similar

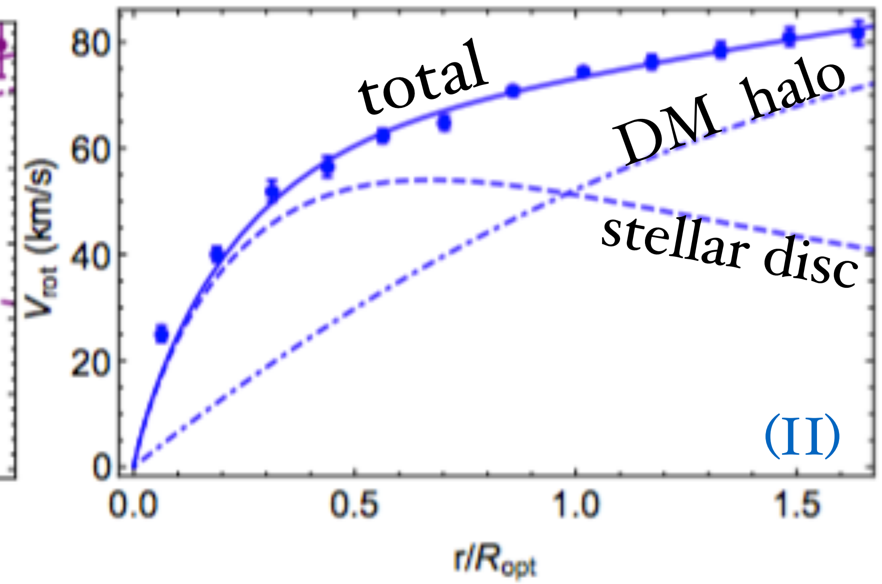


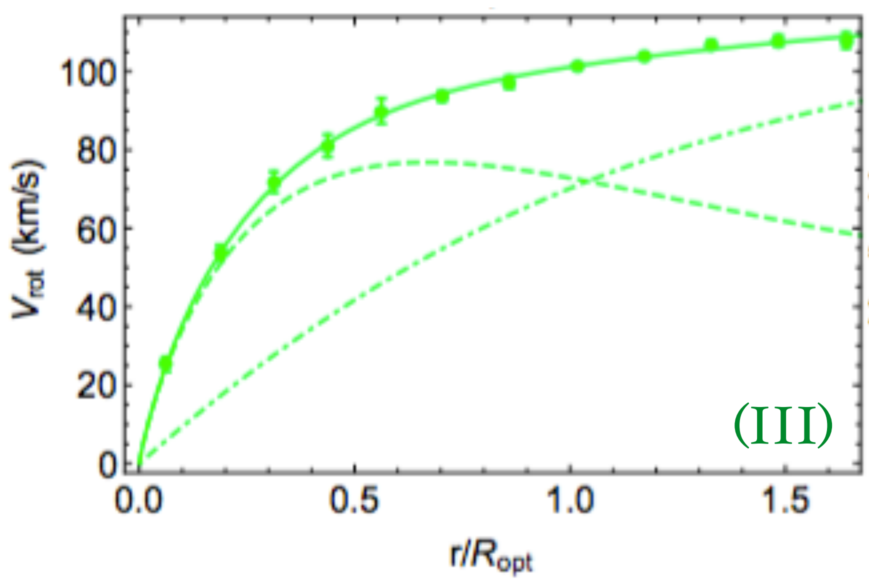
Low Surface Brightness galaxies (LSBs)

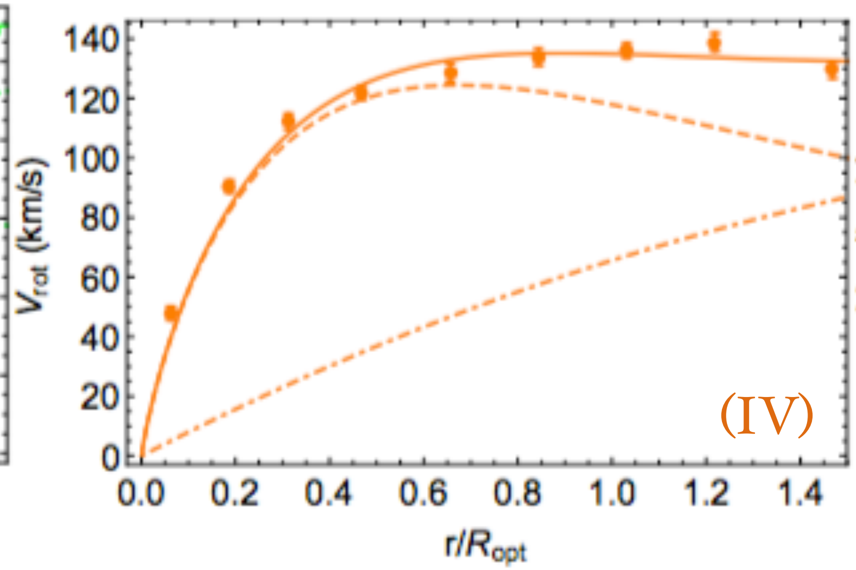
Mass Modelling

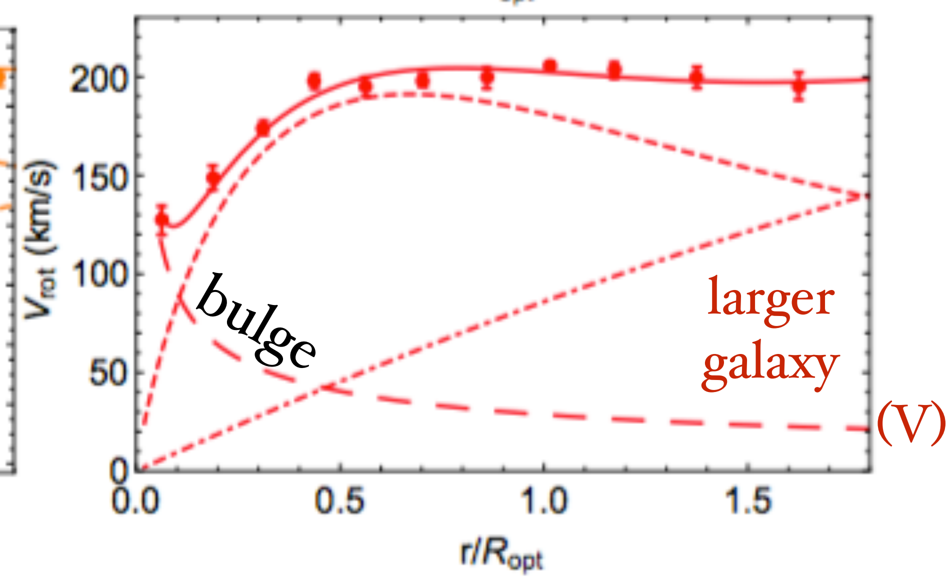
5 co-added RCs











Fitting model for the co-added RC :

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

- $V_d^2(r)$ ↓ exponential stellar disc
- $V_{DM}^2(r)$ ↓ DM spherical cored halo (Burkert)

3 free parameters :

- M_d stellar disc mass
- R_c DM halo's core radius
- ρ_0 DM halo's central mass density

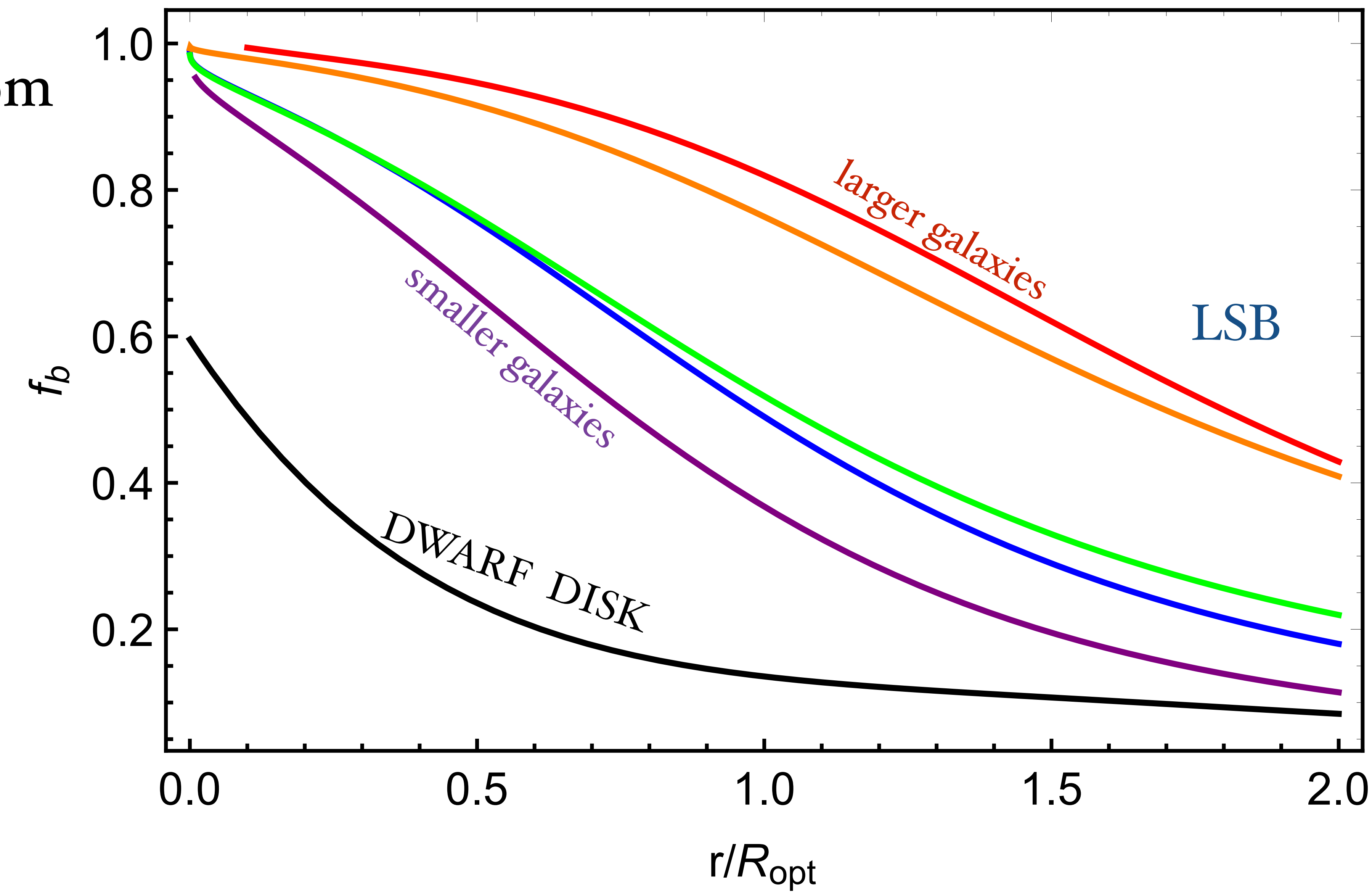
Low Surface Brightness galaxies (LSBs)

Contribution to the circular velocity from the i-component:

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

Baryonic fraction :

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

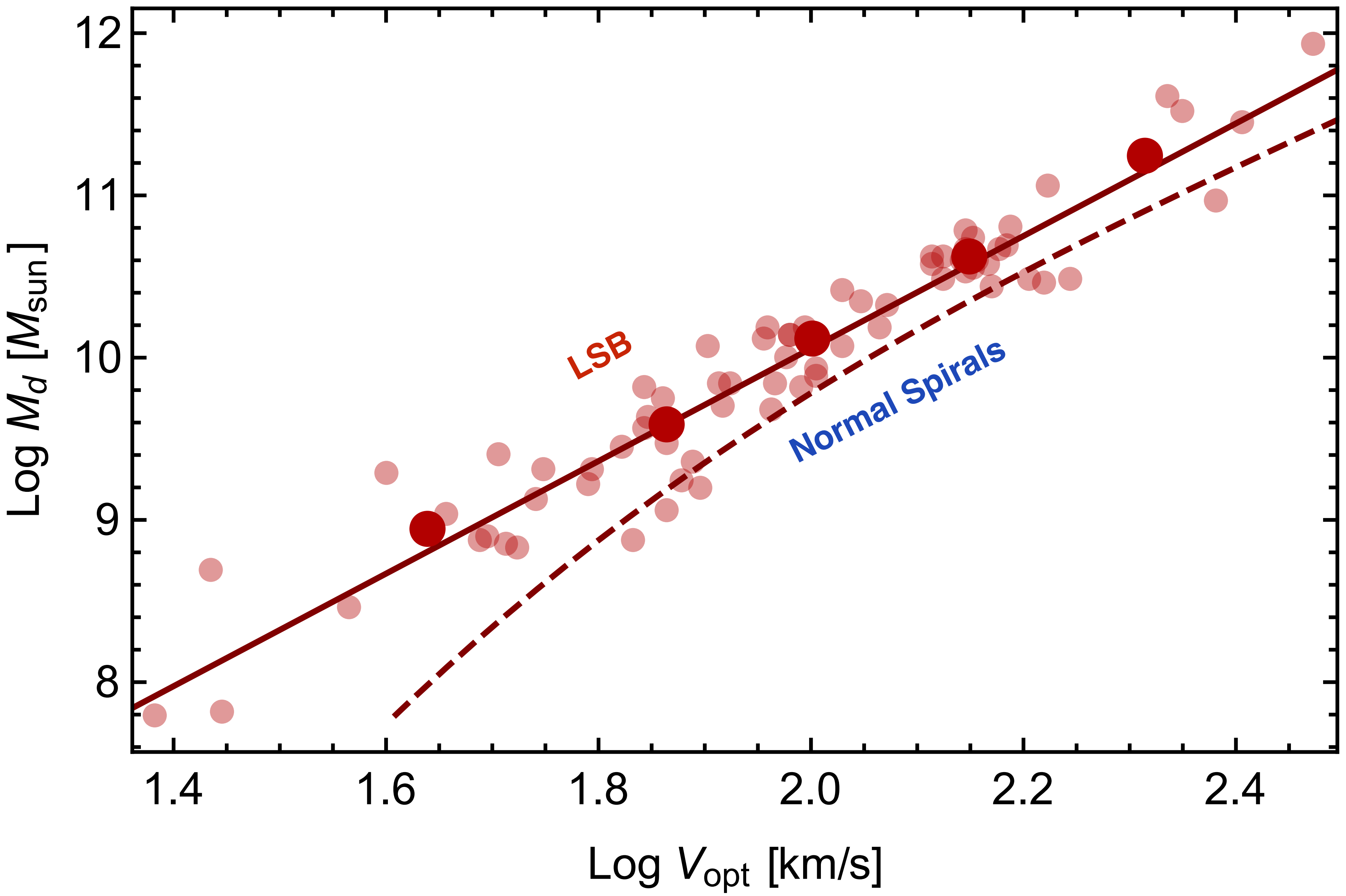


NOTE:
- radial dependence of f_b
- different $f_b(r)$ in galaxies of different size
- different $f_b(r)$ in galaxies of different morphology

Low Surface Brightness galaxies (LSBs)

DENORMALIZATION PROCESS

All the basis to construct the **SCALING RELATIONS** are known

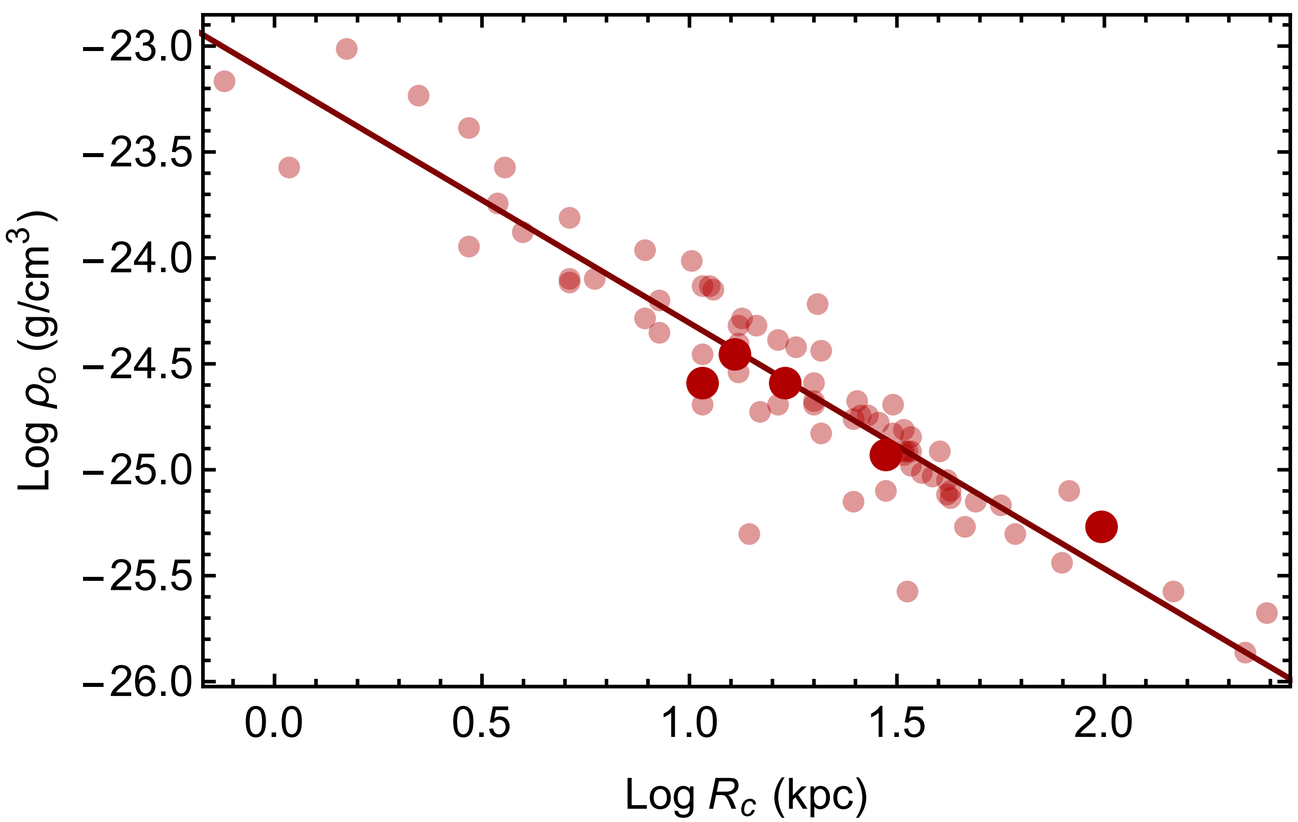


LSBs
and
Normal Spirals
scaling relations

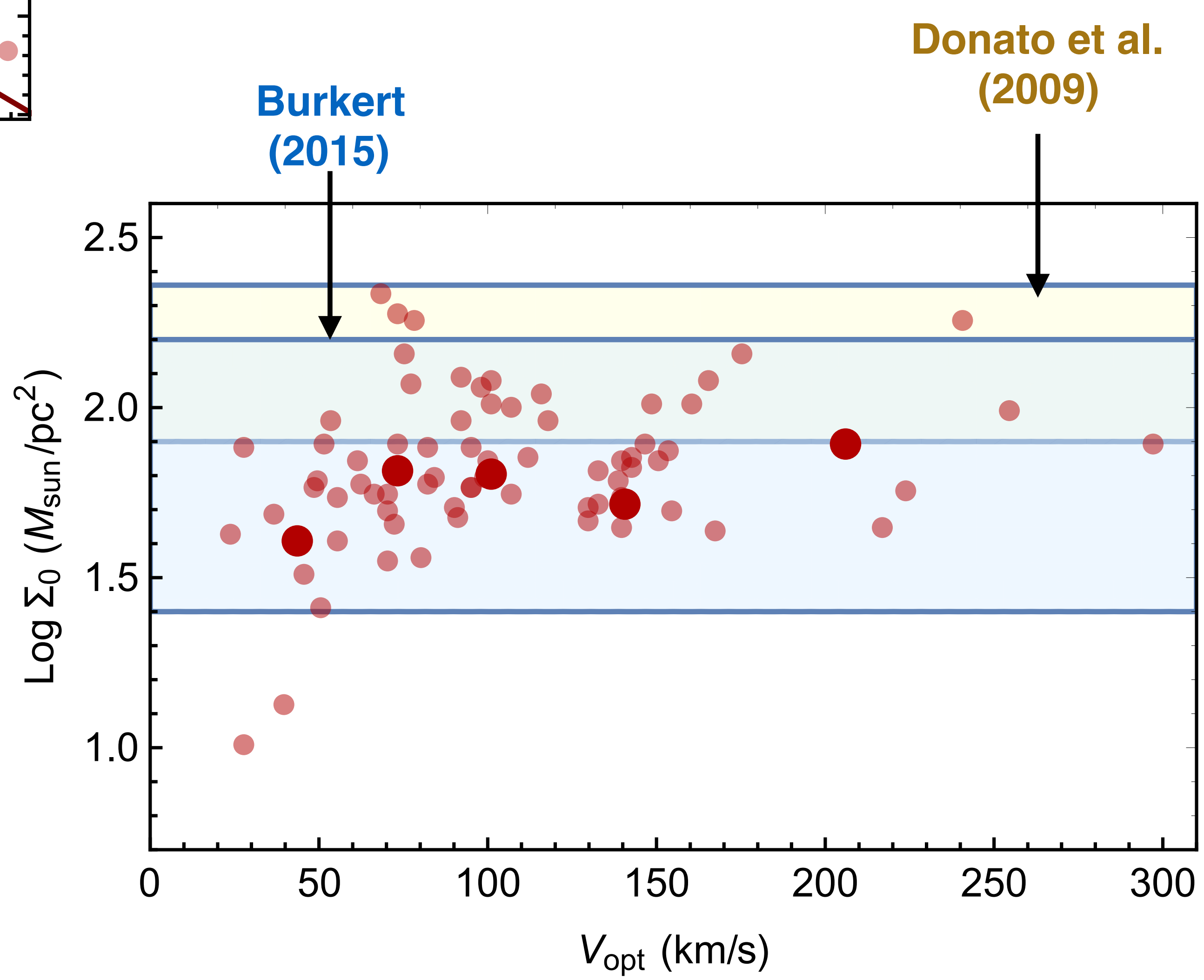
similar,
but not identical

Low Surface Brightness galaxies (LSBs)

All the basis to construct the **SCALING RELATIONS** are known



smaller galaxies,
higher central DM mass density

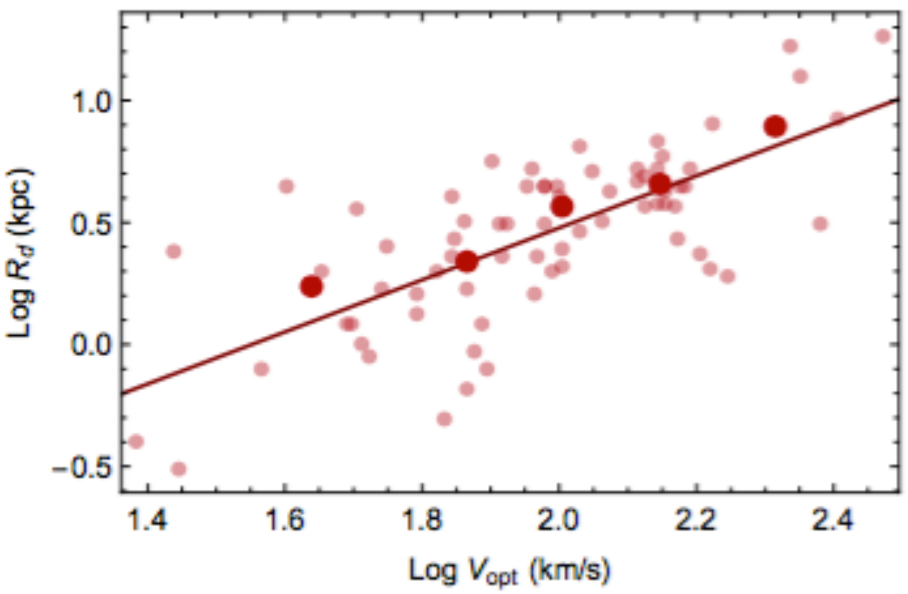


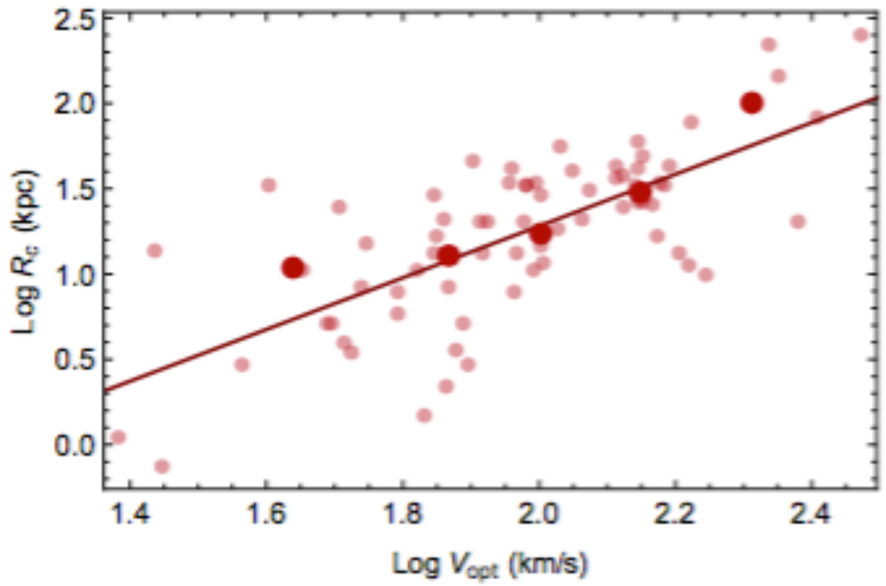
constant surface density

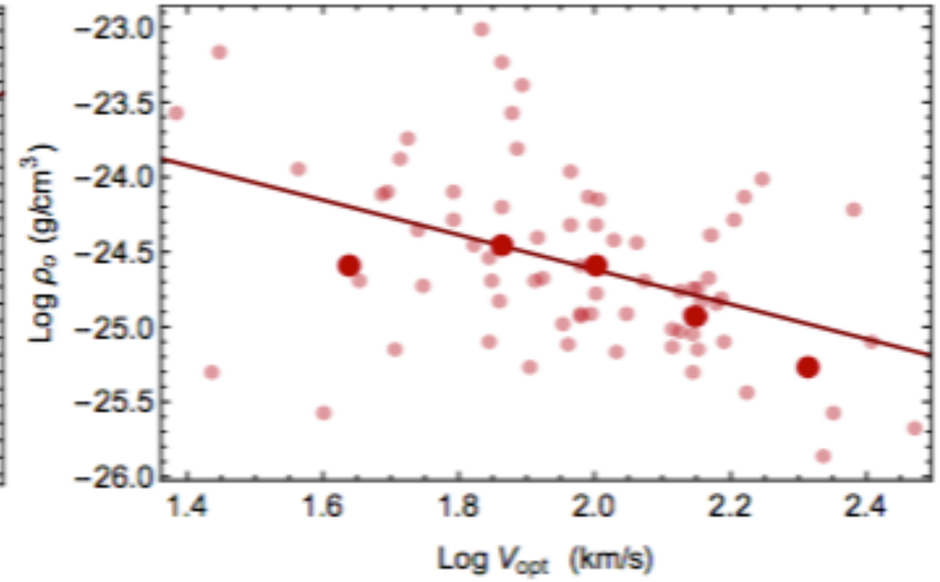
$$\Sigma_0 = \rho_0 R_c$$

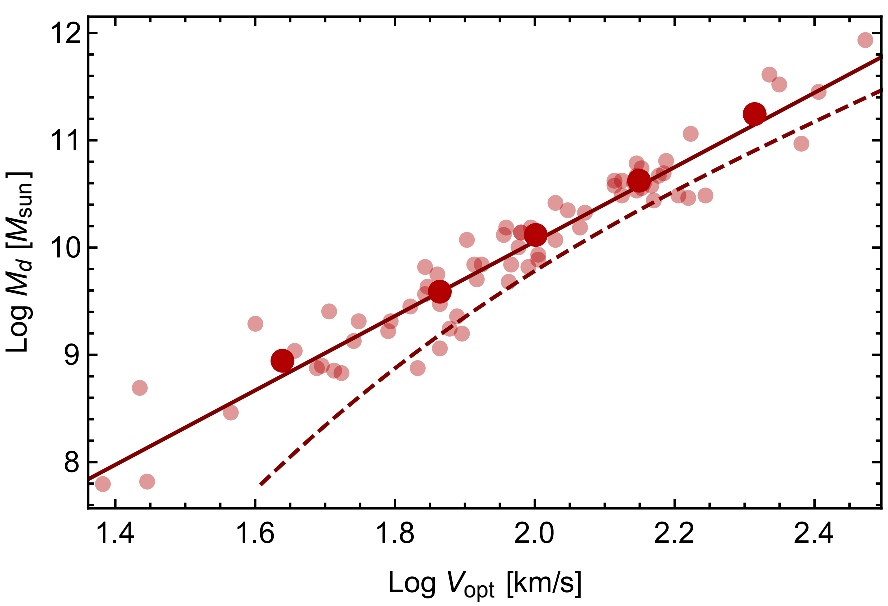
Low Surface Brightness galaxies (LSBs)

All the basis to construct the **Universal Rotation Curve (URC)** are known









From the fitting scaling relations:

$$R_d = f_1(V_{opt})$$

$$R_c = f_2(V_{opt})$$

$$M_d = f_3(V_{opt})$$

$$\rho_0 = f_4(V_{opt})$$

ROTATION CURVE

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

or equally

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

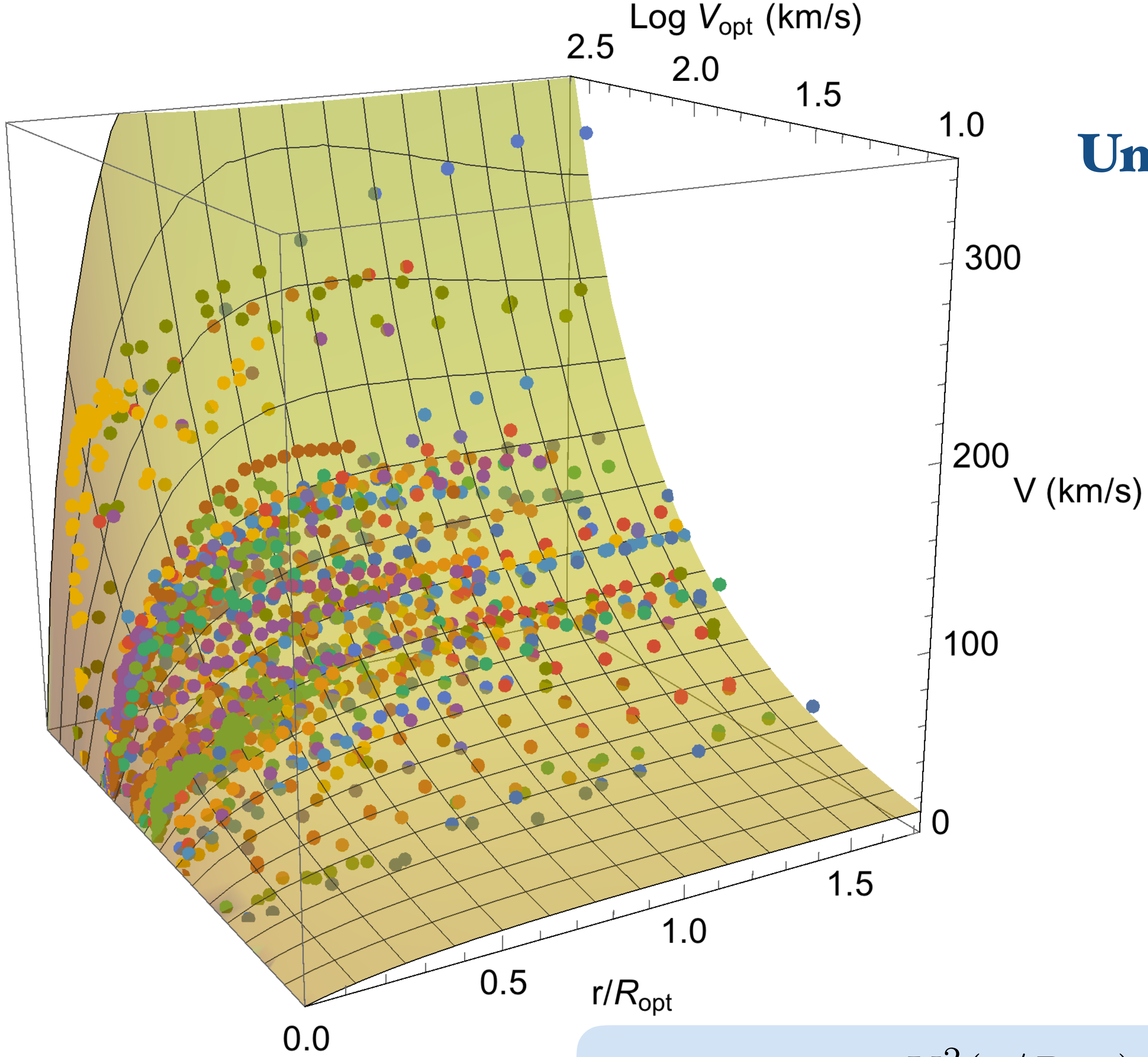
function of

$$R_d\ ,\quad R_c\ ,\quad M_d\ ,\quad \rho_0$$

RESULT $$V^2(r/R_{opt}) = V_d^2(r/R_{opt}) + V_{DM}^2(r/R_{opt})$$

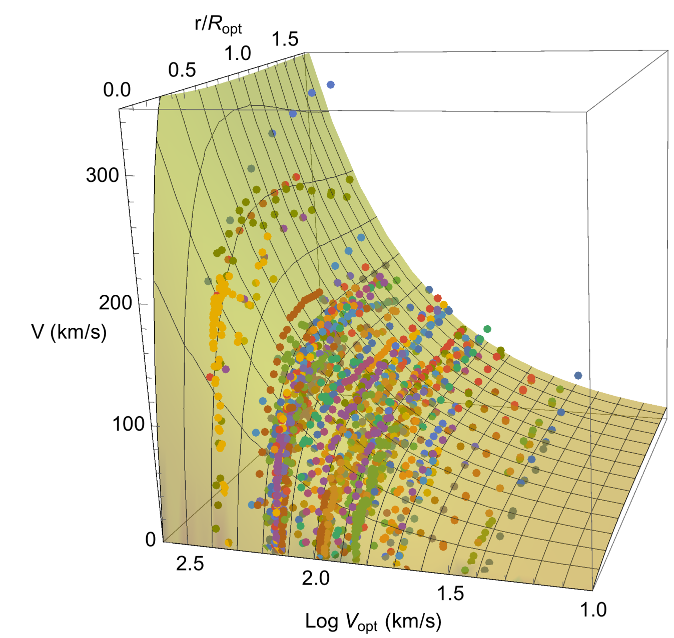
function of V_{opt}

Low Surface Brightness galaxies (LSBs)



the LSB galaxies

Universal Rotation Curve (URC)

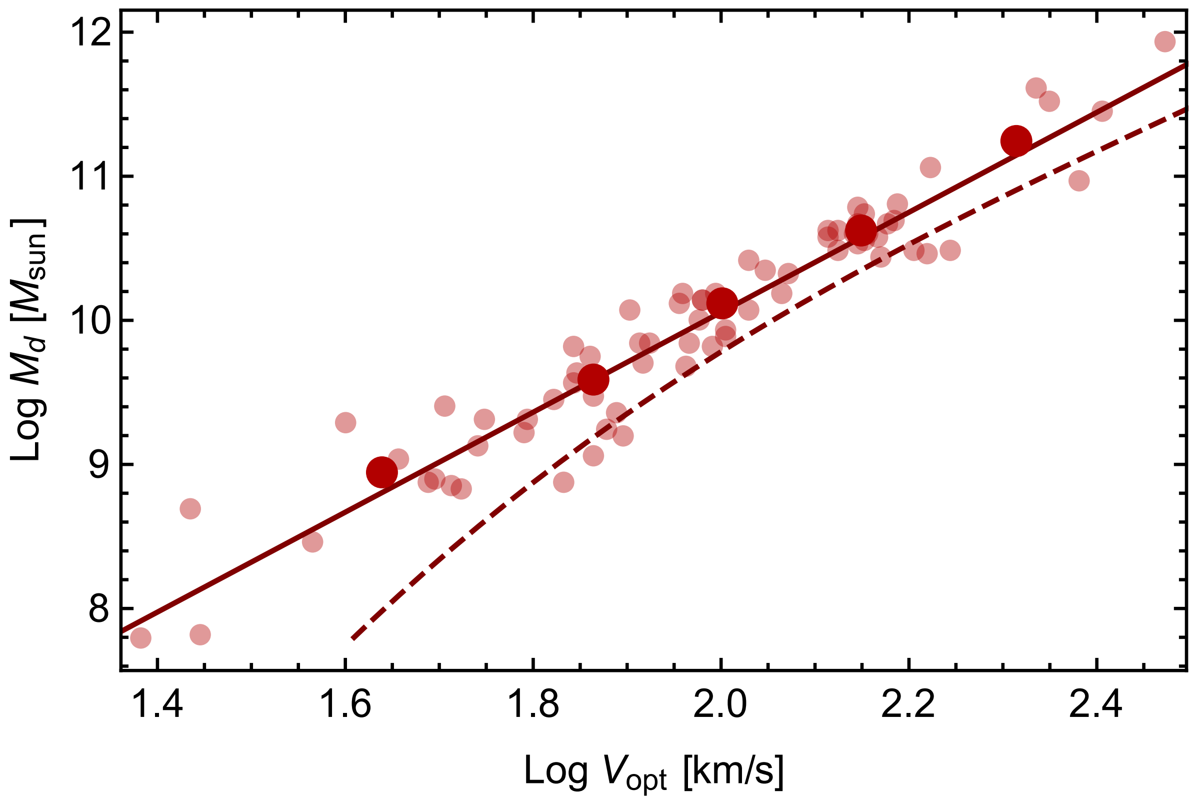


RESULT $$V^2(r/R_{opt}) = V_d^2(r/R_{opt}) + V_{DM}^2(r/R_{opt})$$

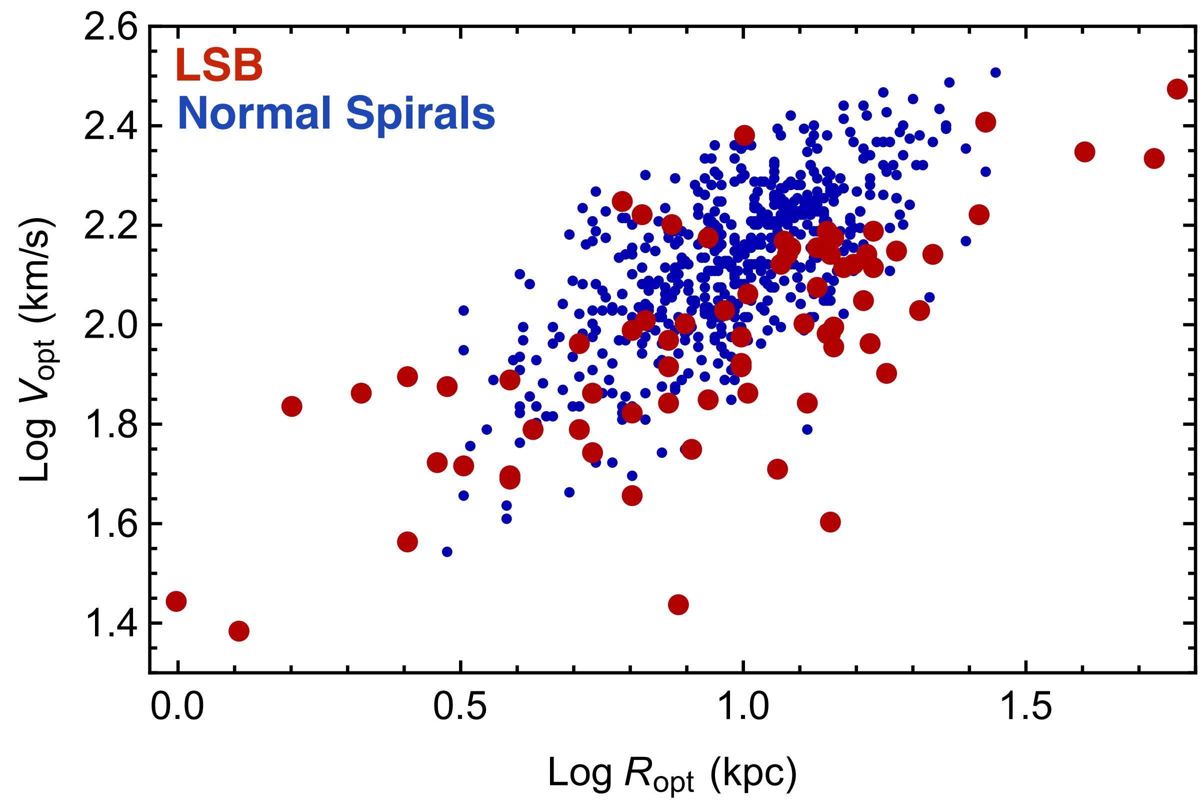
function of V_{opt}

Low Surface Brightness galaxies (LSBs)

Moreover, further improvements by also including the **compactness**...indeed:



Anyway ... high scatter



Low Surface Brightness galaxies (LSBs)

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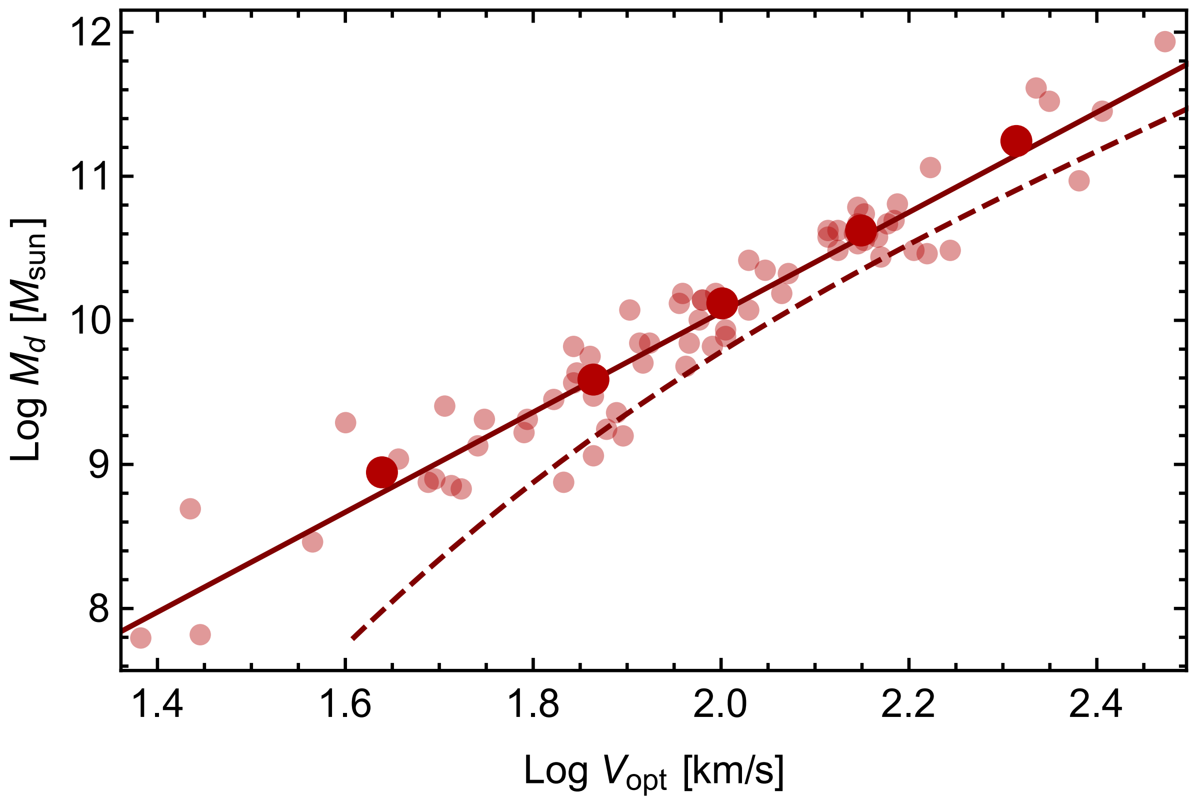

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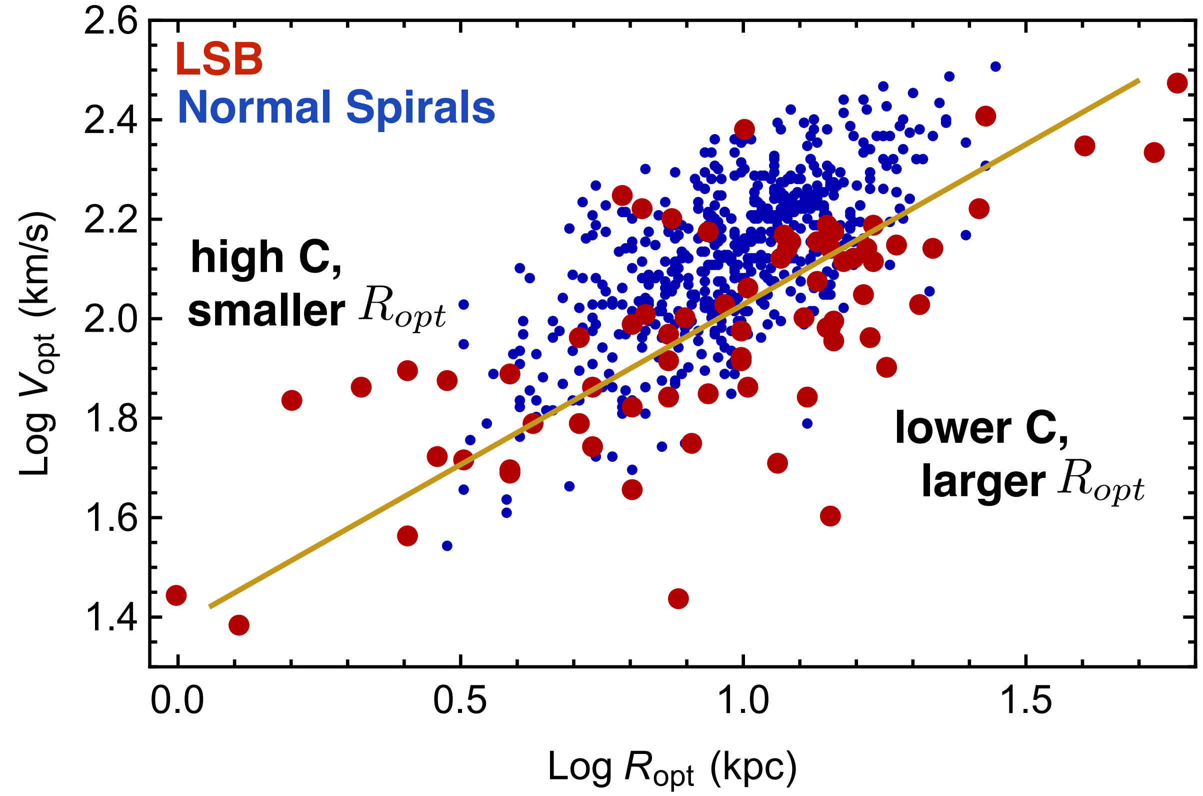
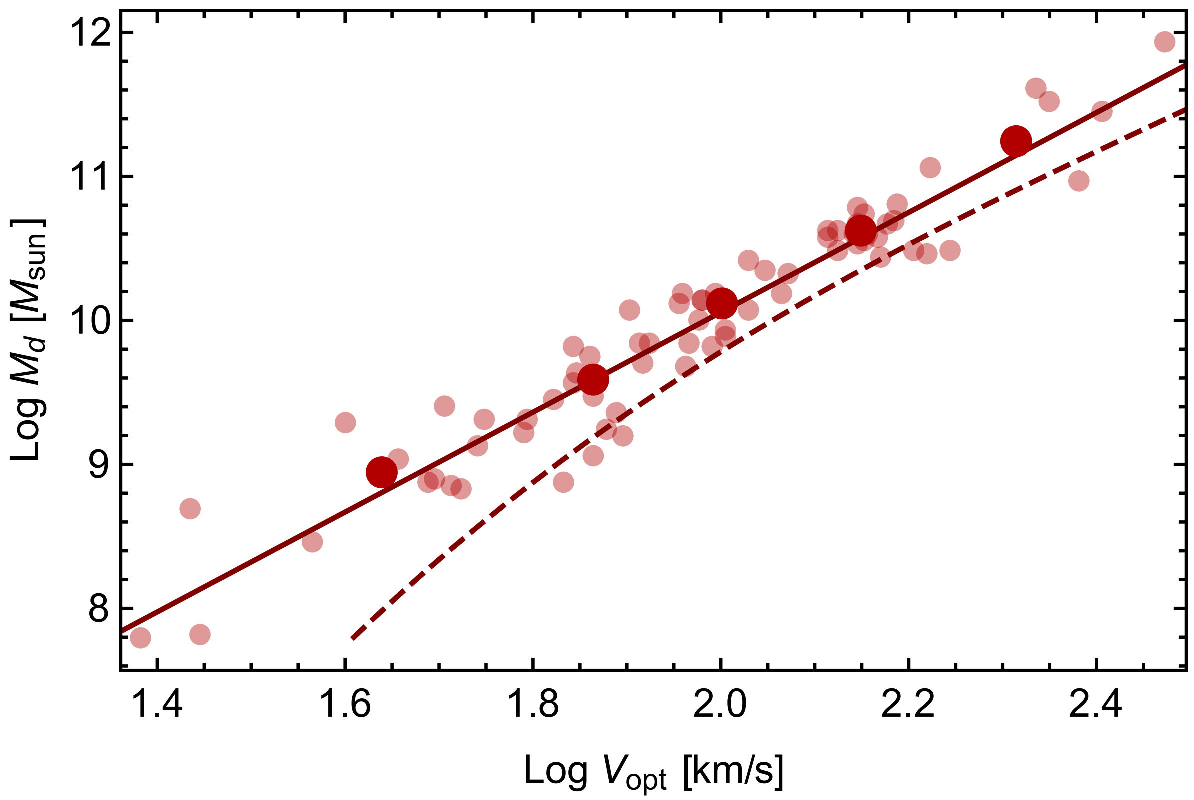


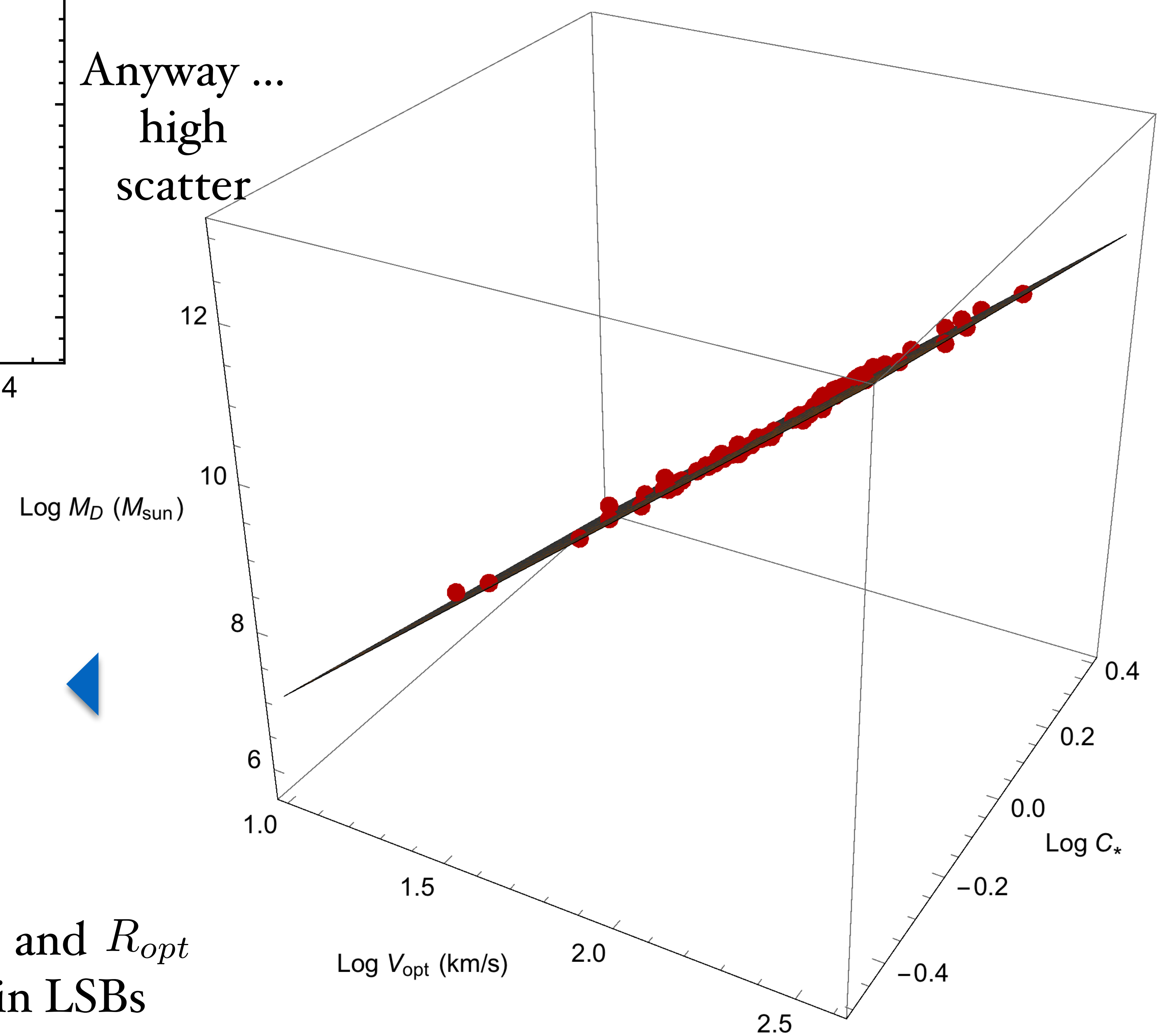
COMPACTNESS (C):
discrepancy between the measured R_{opt} and a mean expected value $\bar{R}_{opt}$

Low Surface Brightness galaxies (LSBs)

Moreover, further improvements by also including the **compactness**...indeed:



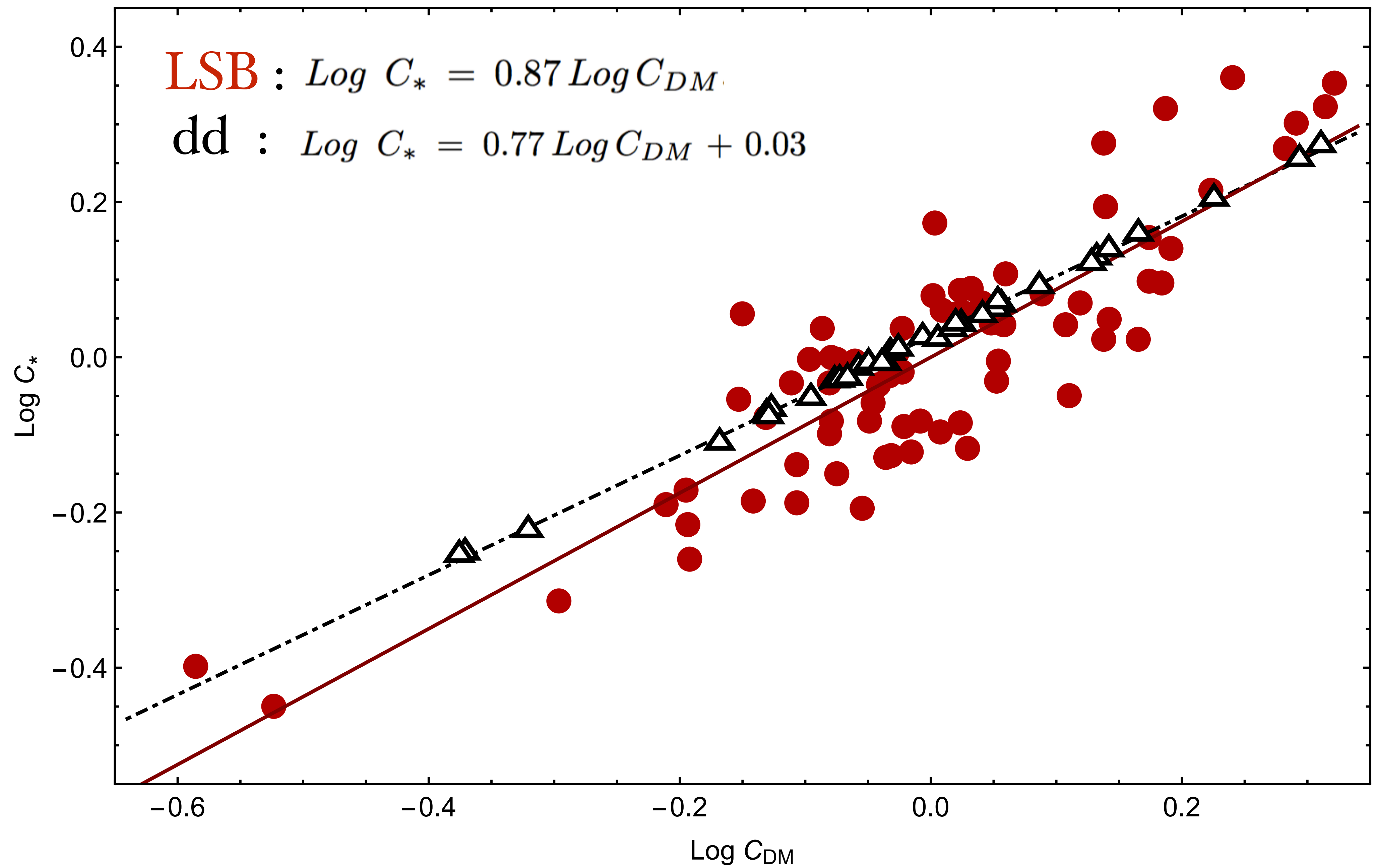
Anyway ...
high
scatter



Reduced scatter
after
the **COMPACTNESS**
introduction

important parameter further than V_{opt} and R_{opt}
in order to have a "better universality" in LSBs

Compactness



higher stellar compactness ⟷ higher DM compactness

Why?

RAR: Gravitational acceleration relation

McGaugh relation between
gravitational acceleration $g(r)$
and
baryonic acceleration $g_b(r)$

153 rotationally supported galaxies
from SPARC sample,
2963 circular velocity measurements

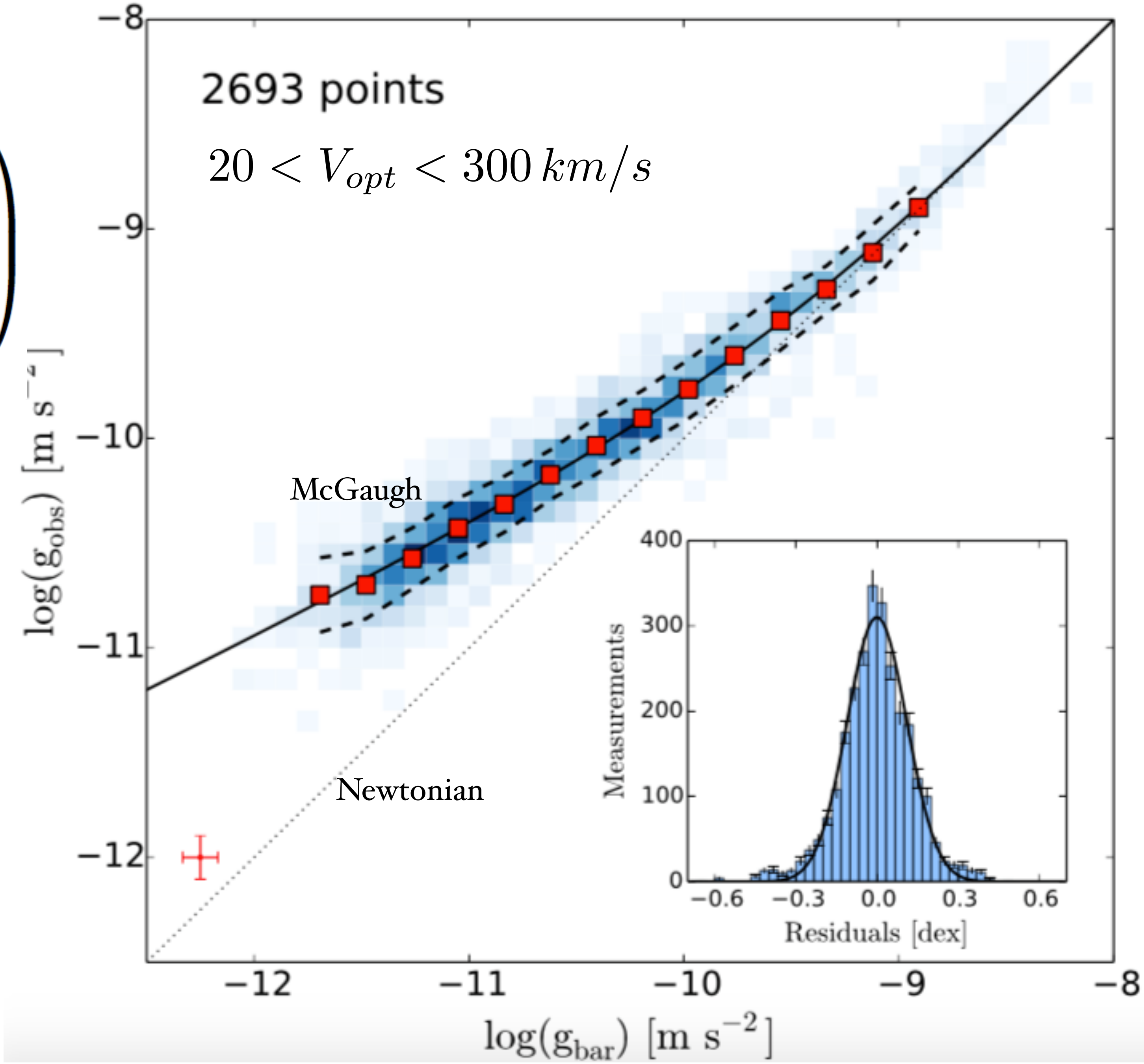
$$Log\, g(r) = Log\left(\frac{g_b(r)}{1 - exp\left(-\sqrt{\frac{g_b(r)}{g_\dagger}}\right)}\right)$$

$$g_\dagger = 1.2 \times 10^{-10} m s^{-2}$$

empirical **universal relation**

$$g = f(g_b)$$

at any radius
and
in any object



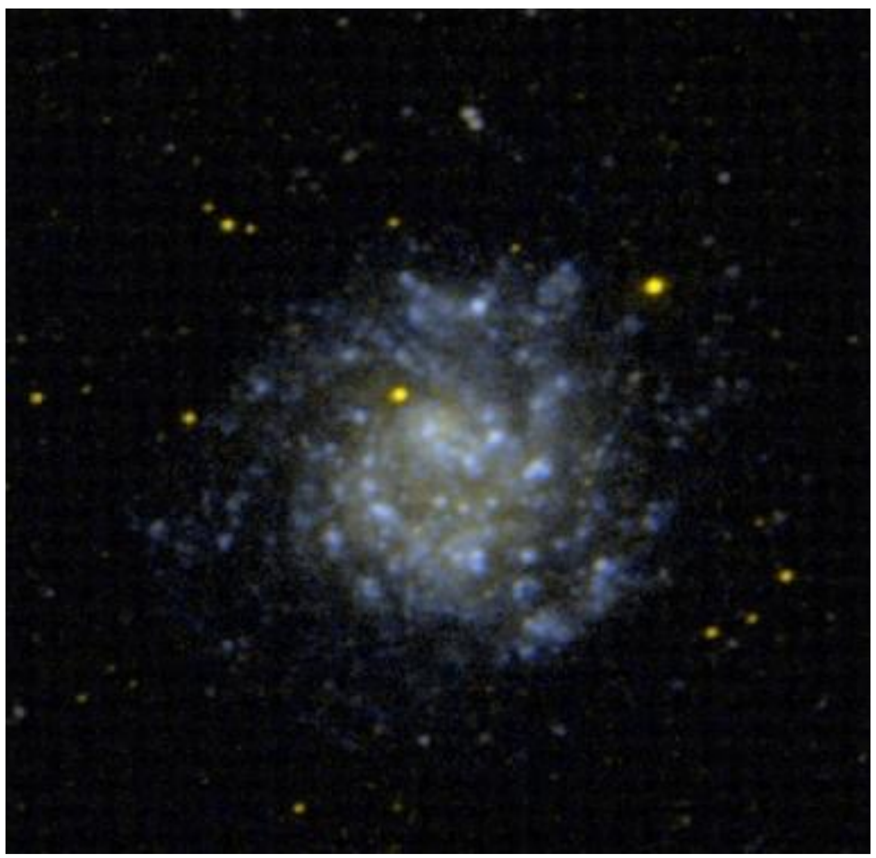
McGaugh et al. (2016)

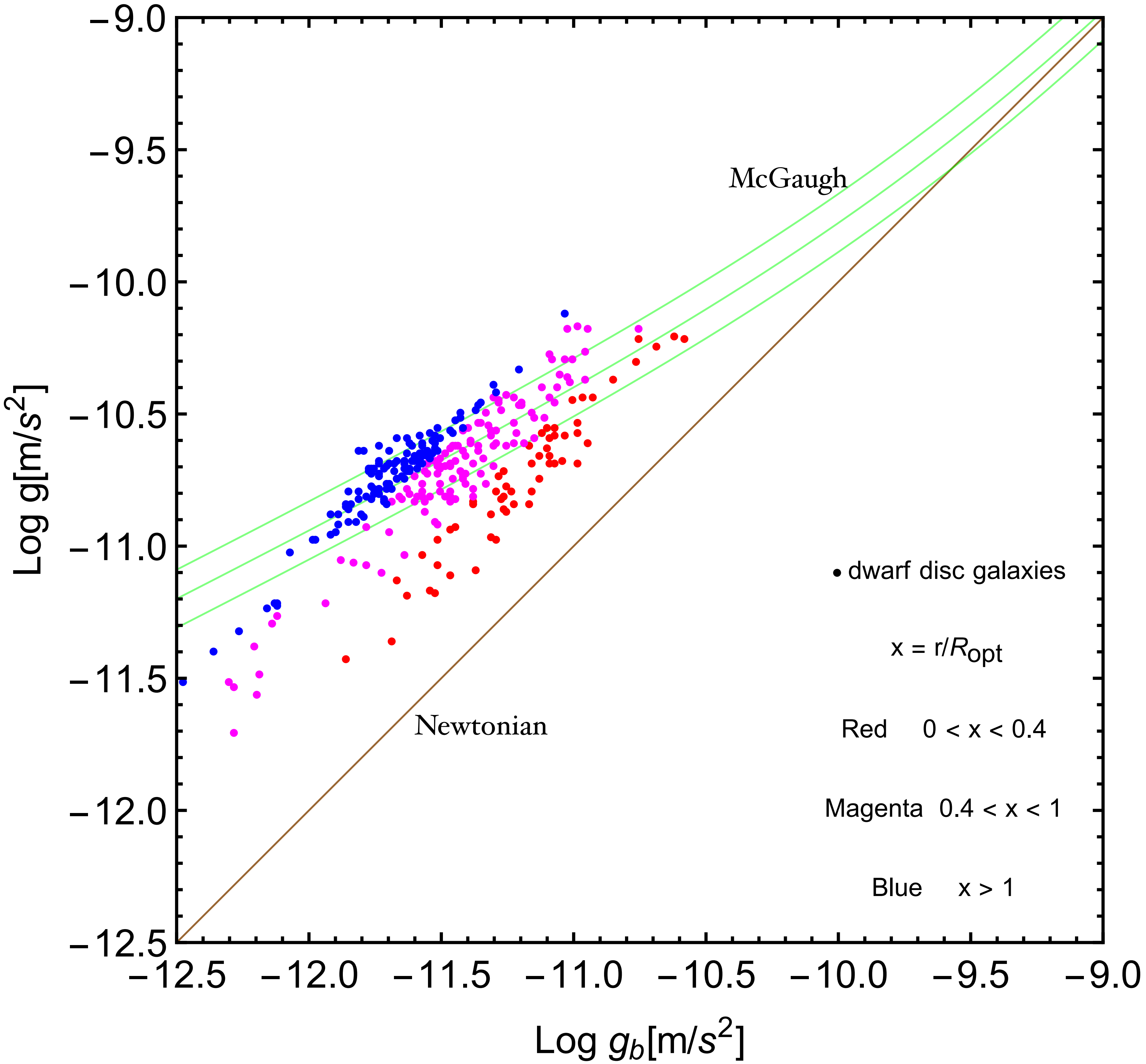
RAR: Gravitational acceleration relation

36 **dwarf disk galaxies** (Karukes & Salucci)

303 circular velocity measurements

→ $19 < V_{opt} < 61\, km/s$





a) McGaugh relation breaks down

b) radial dependence

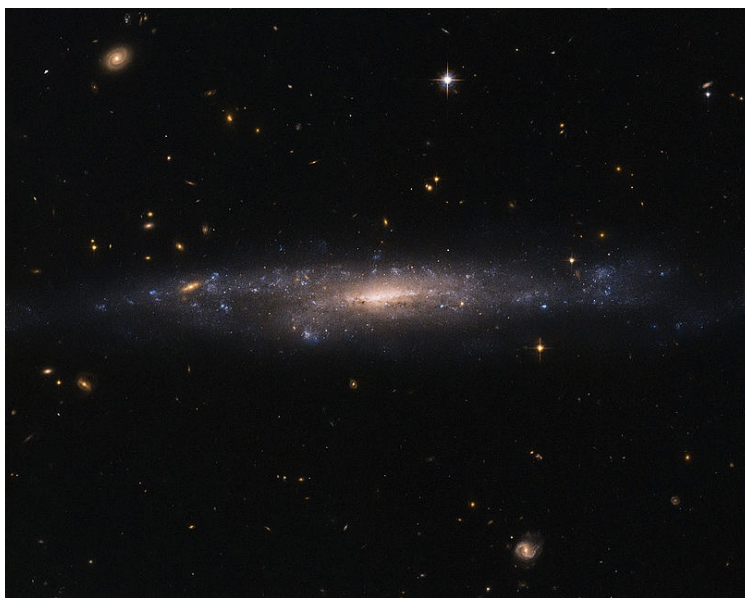
RAR: Gravitational acceleration relation

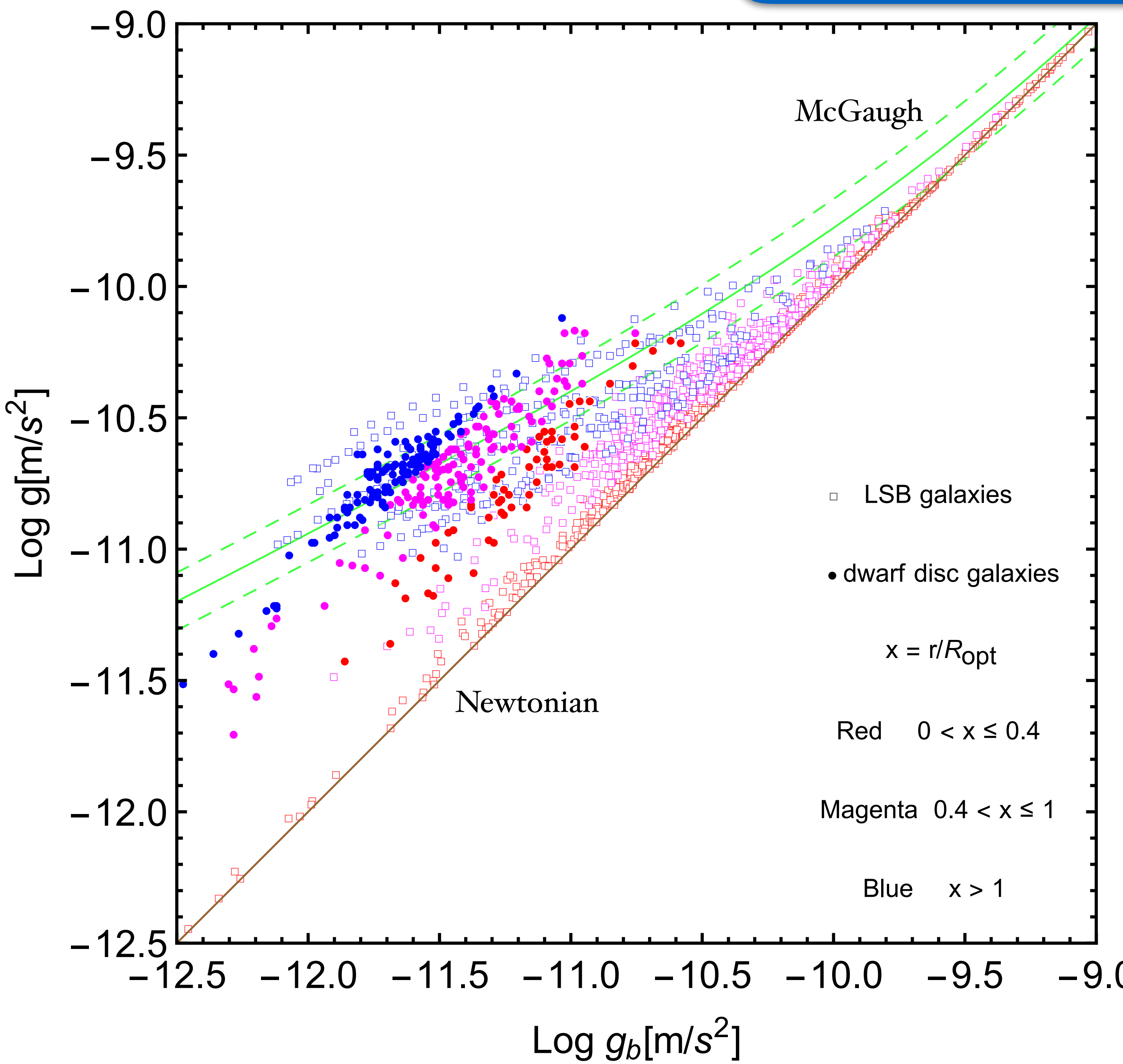
72 **Low Surface Brightness** galaxies

(Di Paolo & Salucci)

1601 circular velocity measurements

$24 < V_{opt} < 300\ km/s$ → emit much less light per area than normal galaxies



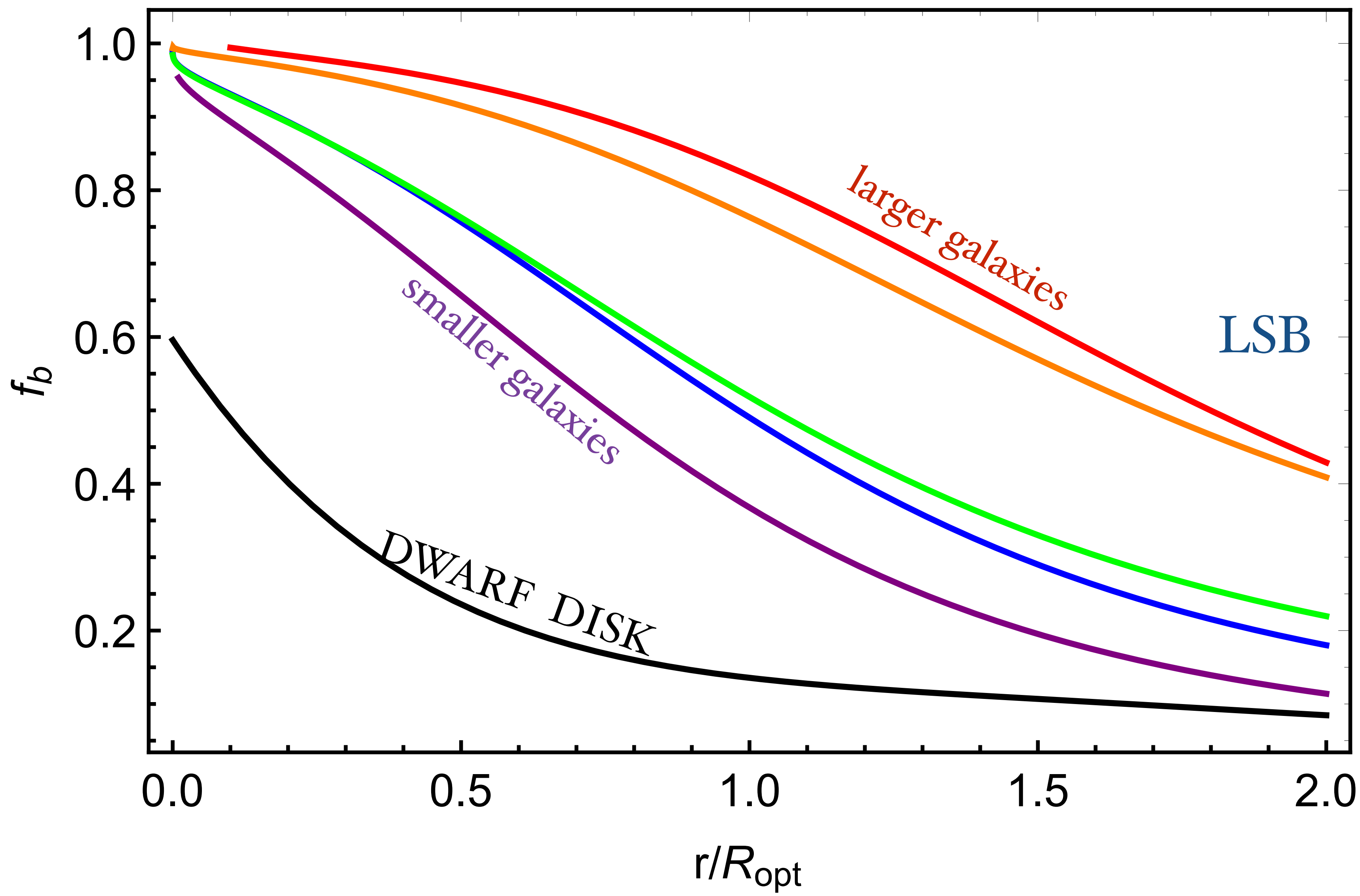


RAR: Gravitational acceleration relation

Baryonic fraction

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

NOTE:
radial dependence

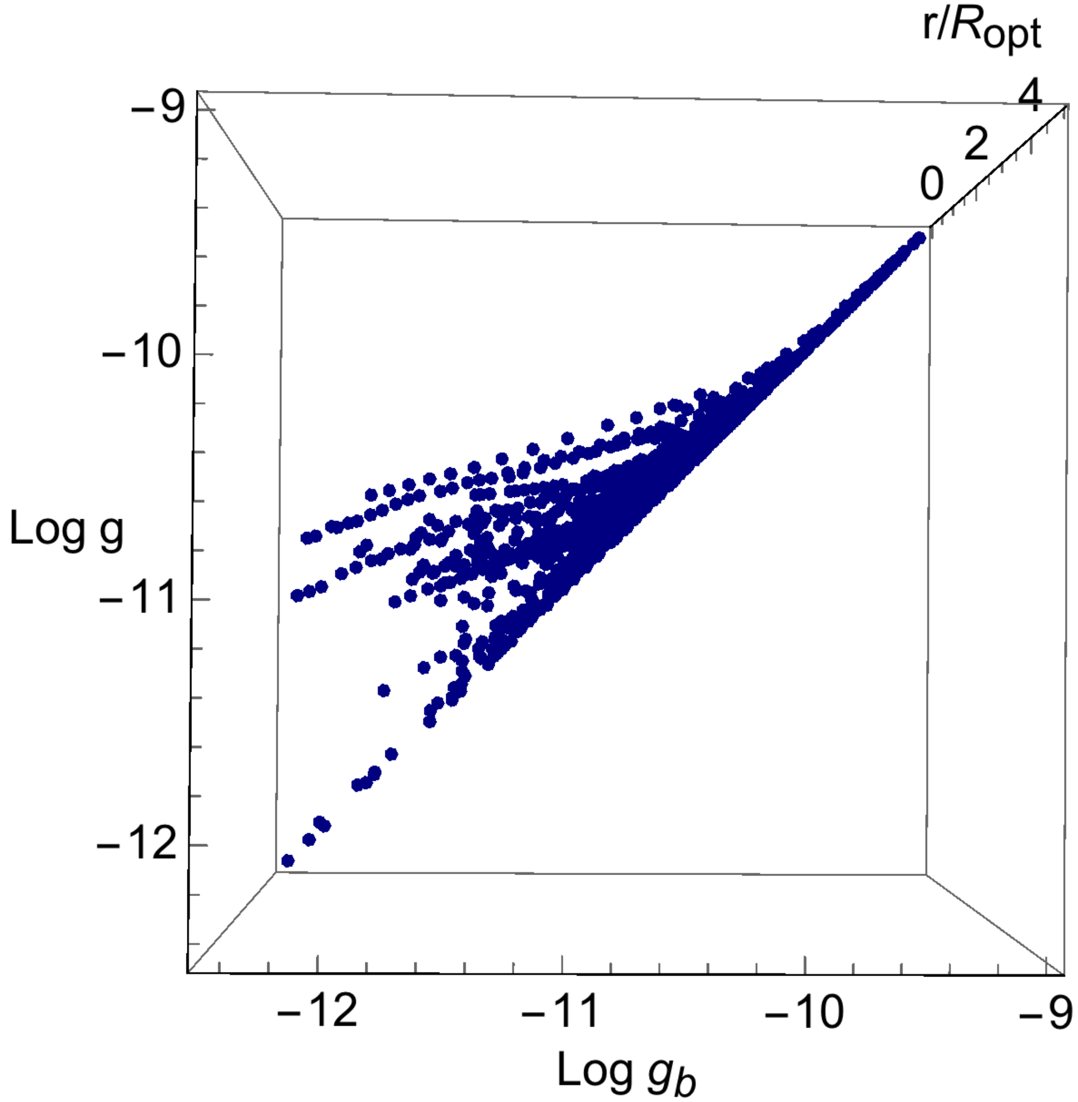


For all single data measurements ($r, V(r)$) we evaluate:

$g(r) = V^2(r)/r$ ➡ only from observations (errors $\simeq 10\%$)

$g_b(r) = f_b(r)g(r)$ ➡ from observations + curves modelling (errors $\simeq 20 - 30\%$)

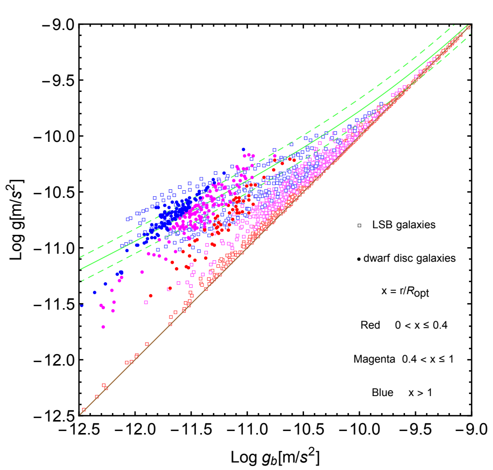
g , g_b , x **test**



LSB

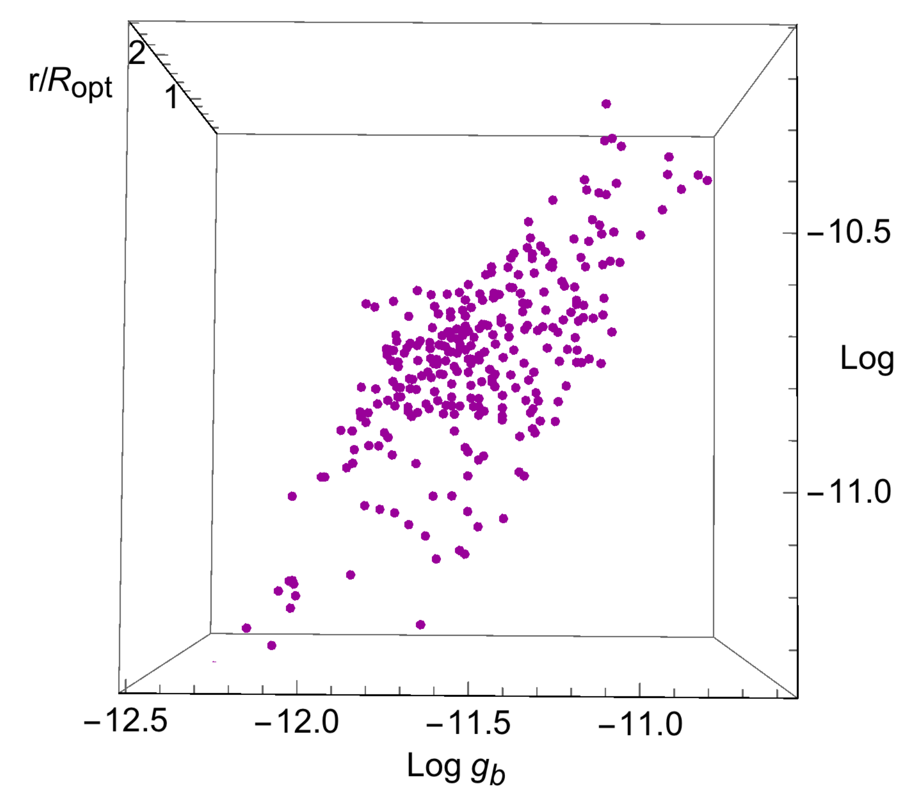
$x = r/R_{opt}$

g , g_b , x **test**

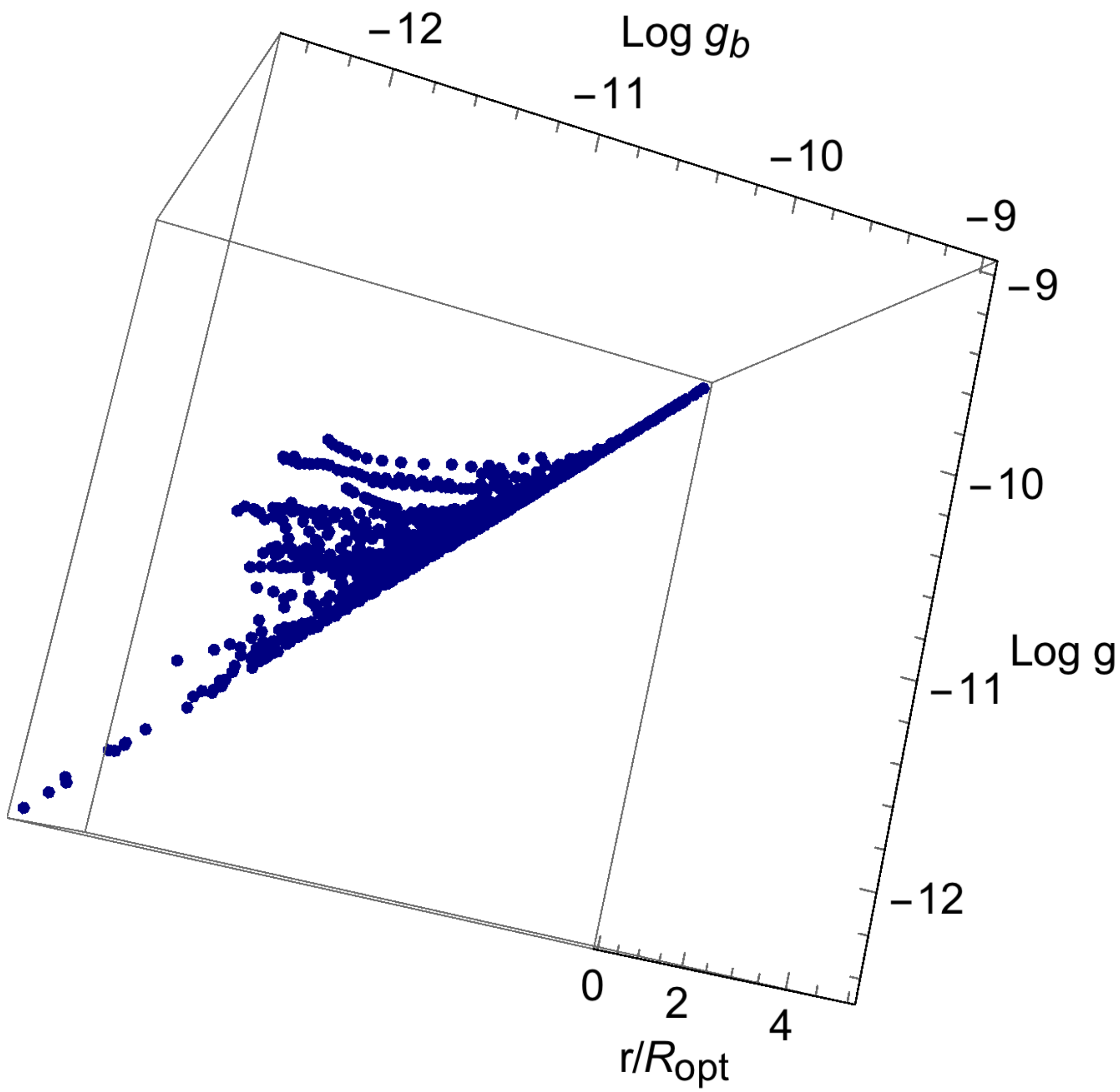


radial dependence

Dwarf disks



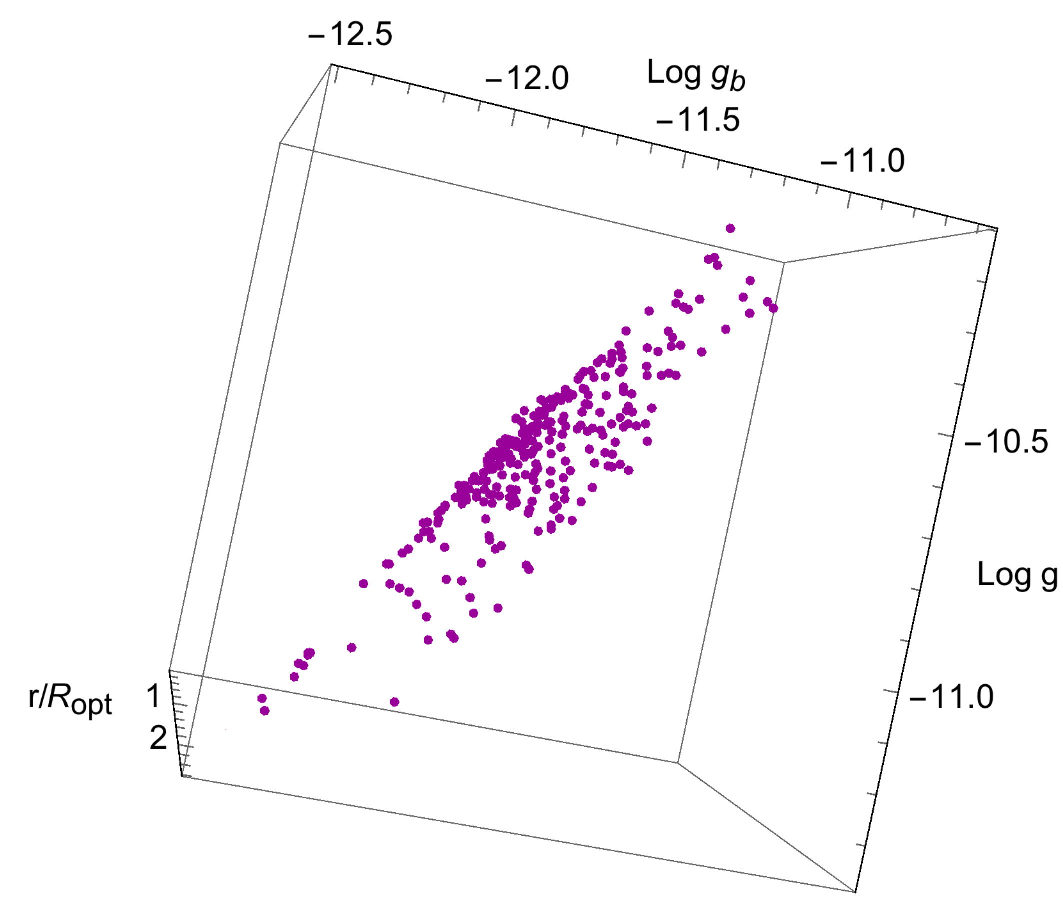
g , g_b , x test



LSB

$$x = r/R_{opt}$$

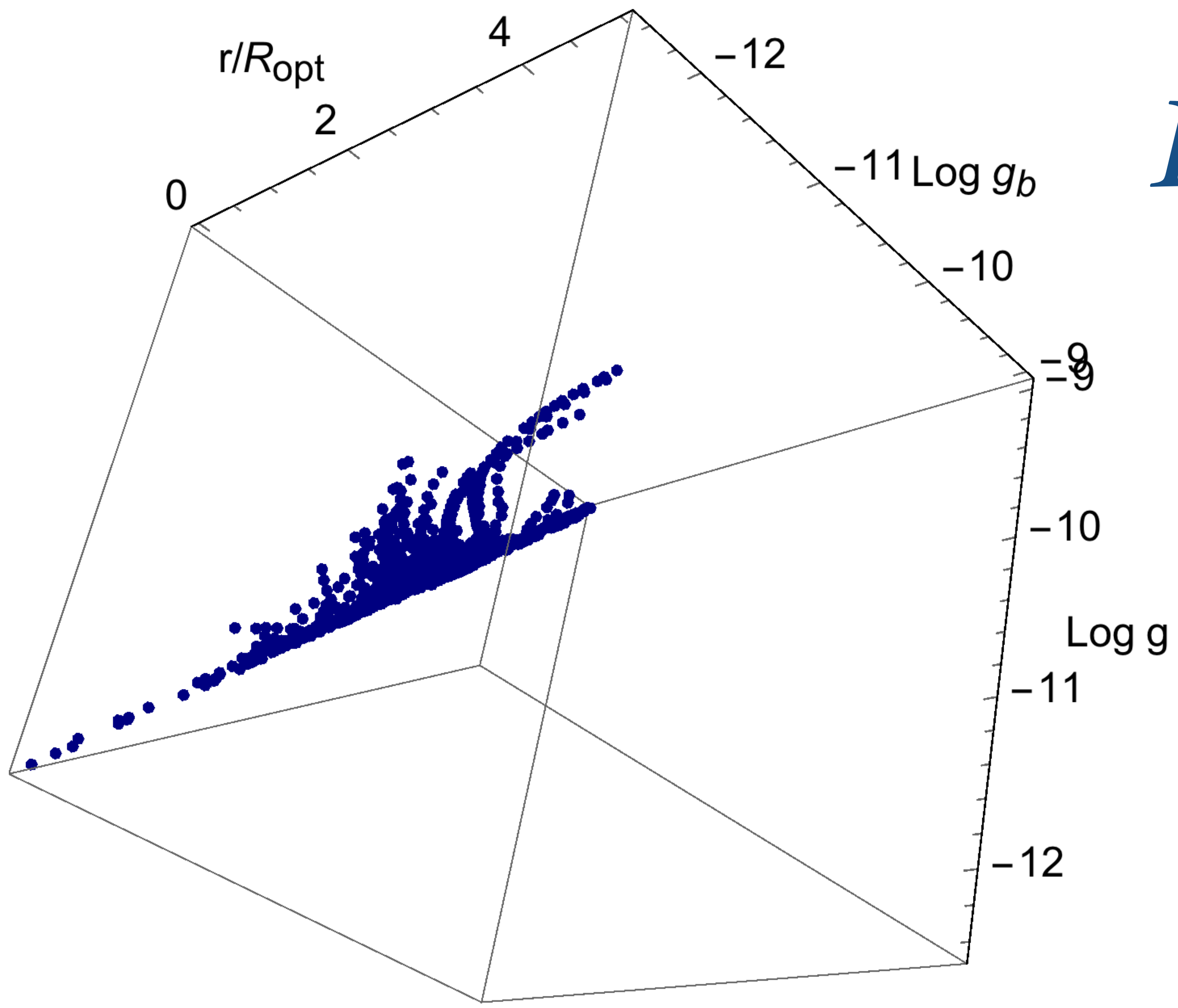
g , g_b , x test



Dwarf disks

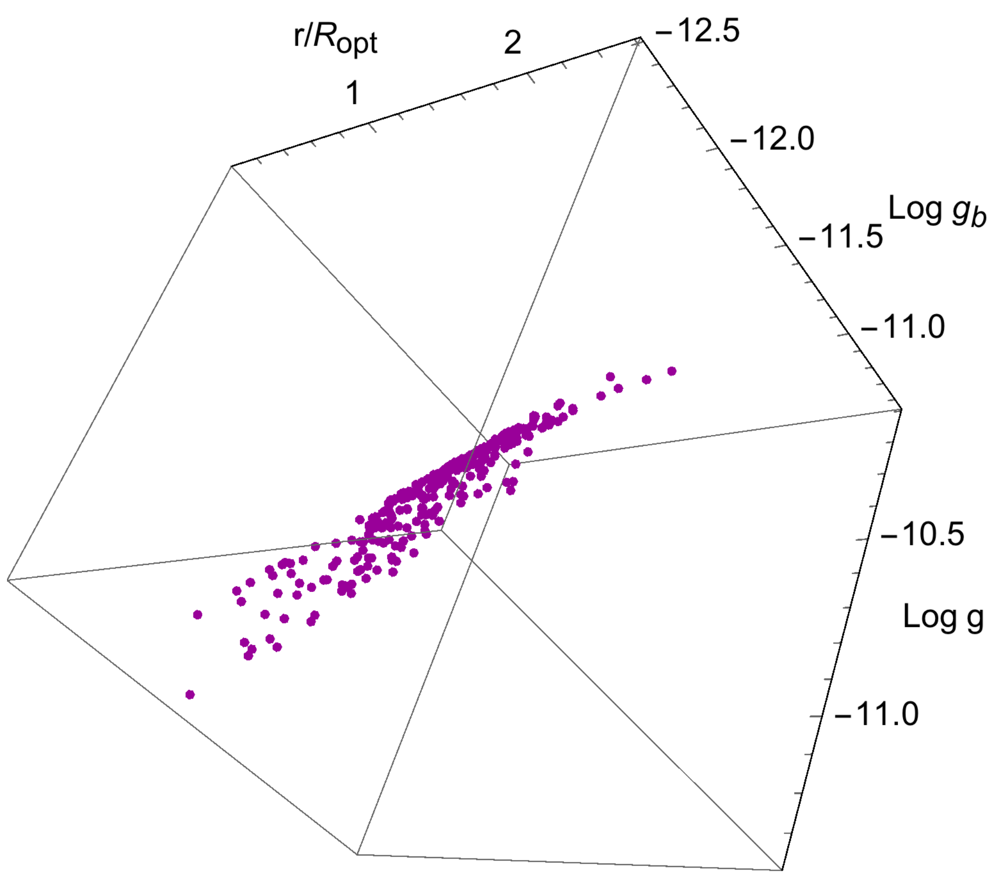
g , g_b , x test

LSB



$x = r/R_{opt}$

g , g_b , x test



Dwarf disks

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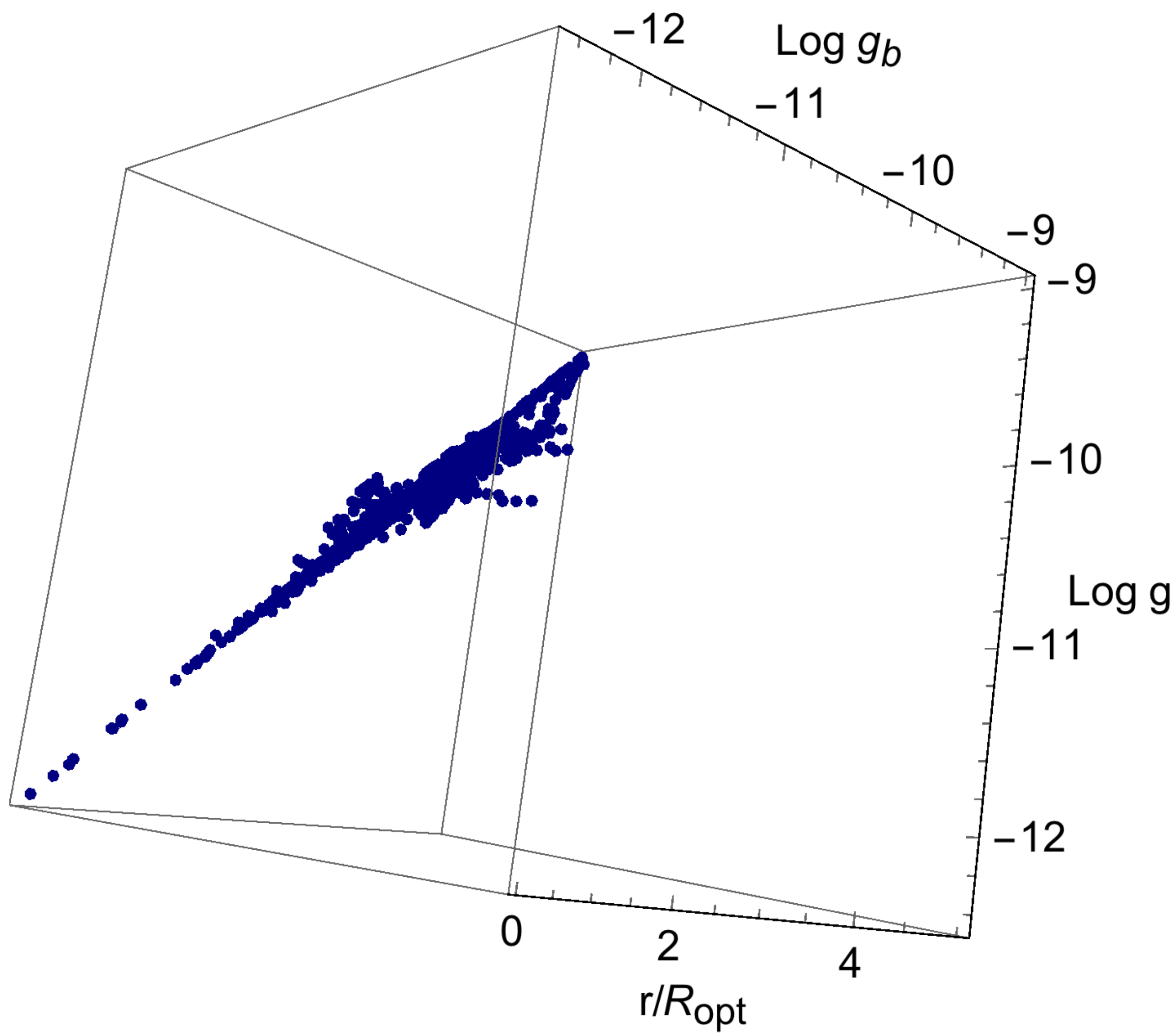

LSB

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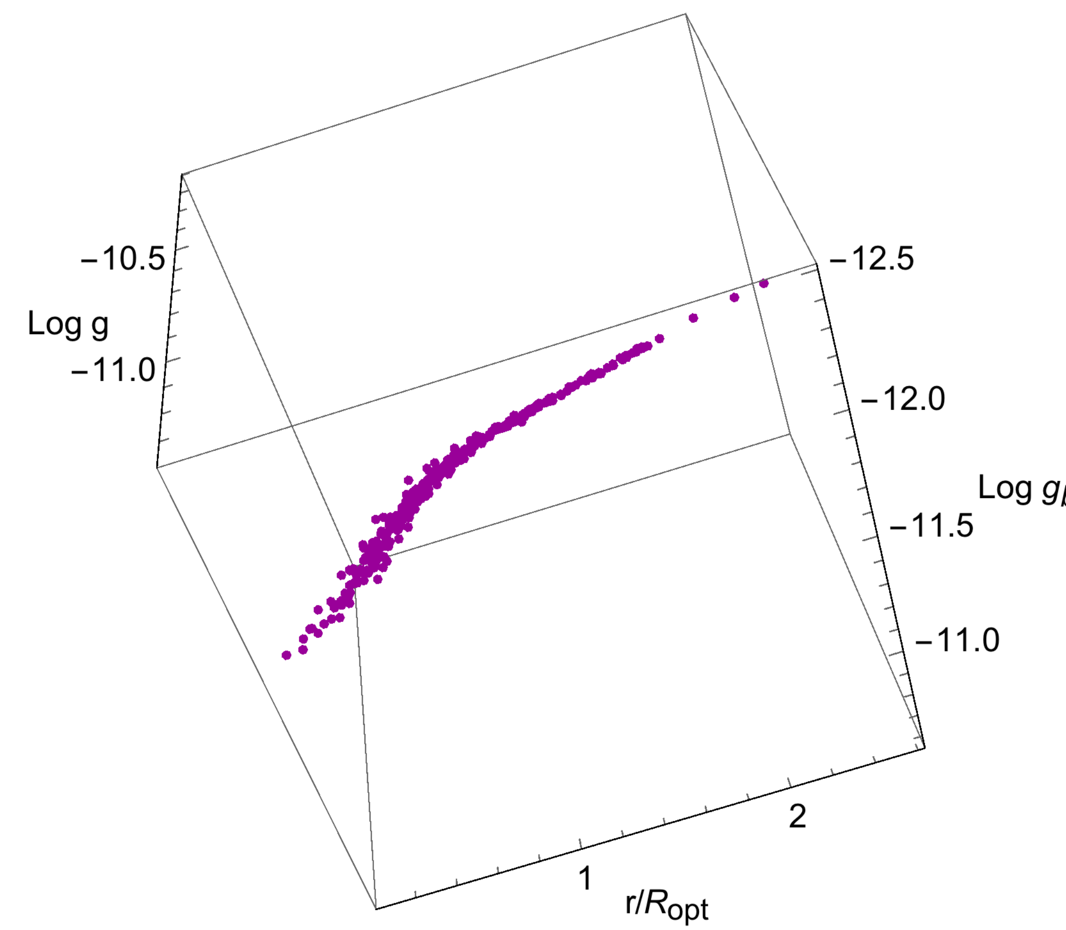
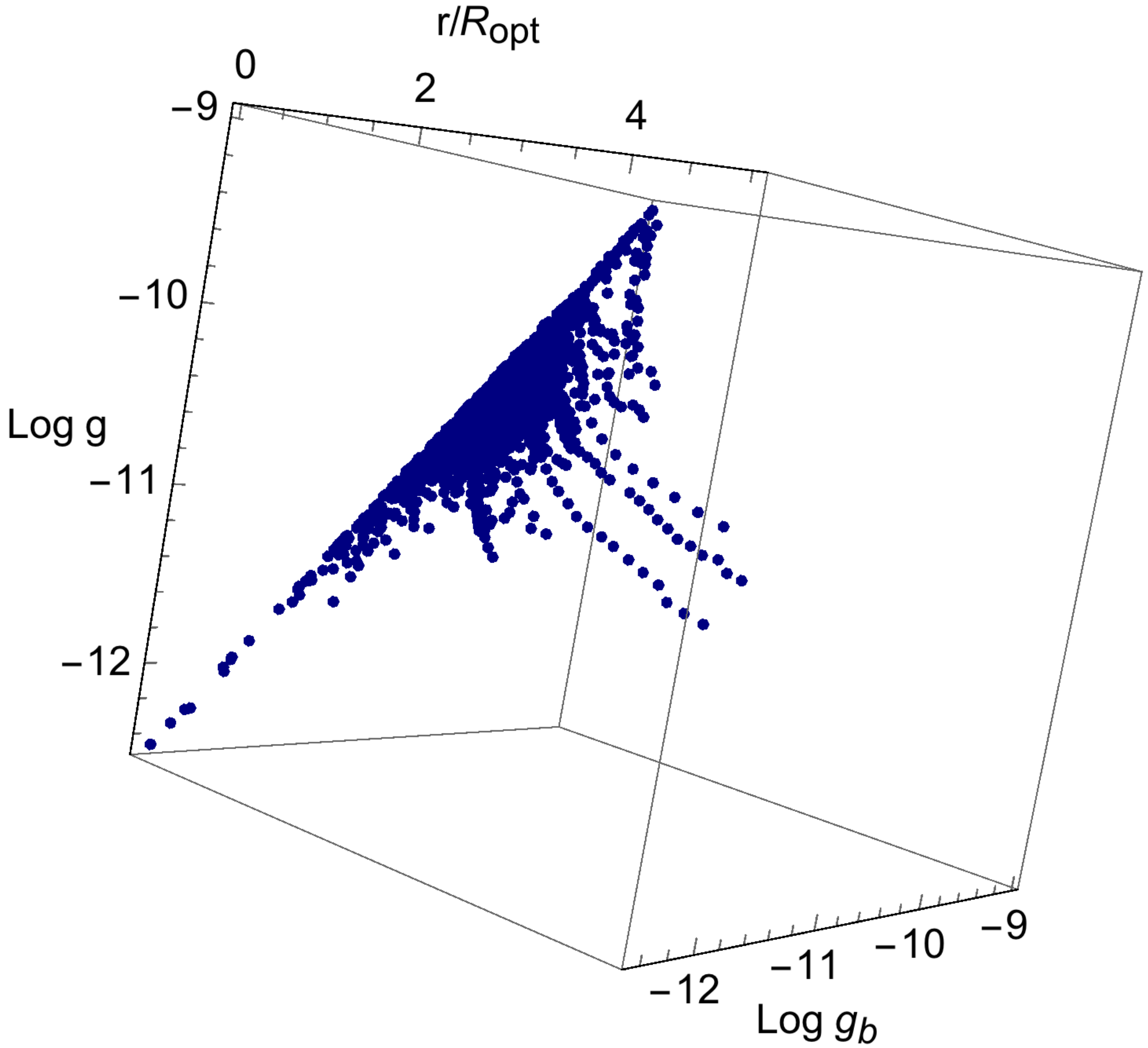


Dwarf disks

g , g_b , x test



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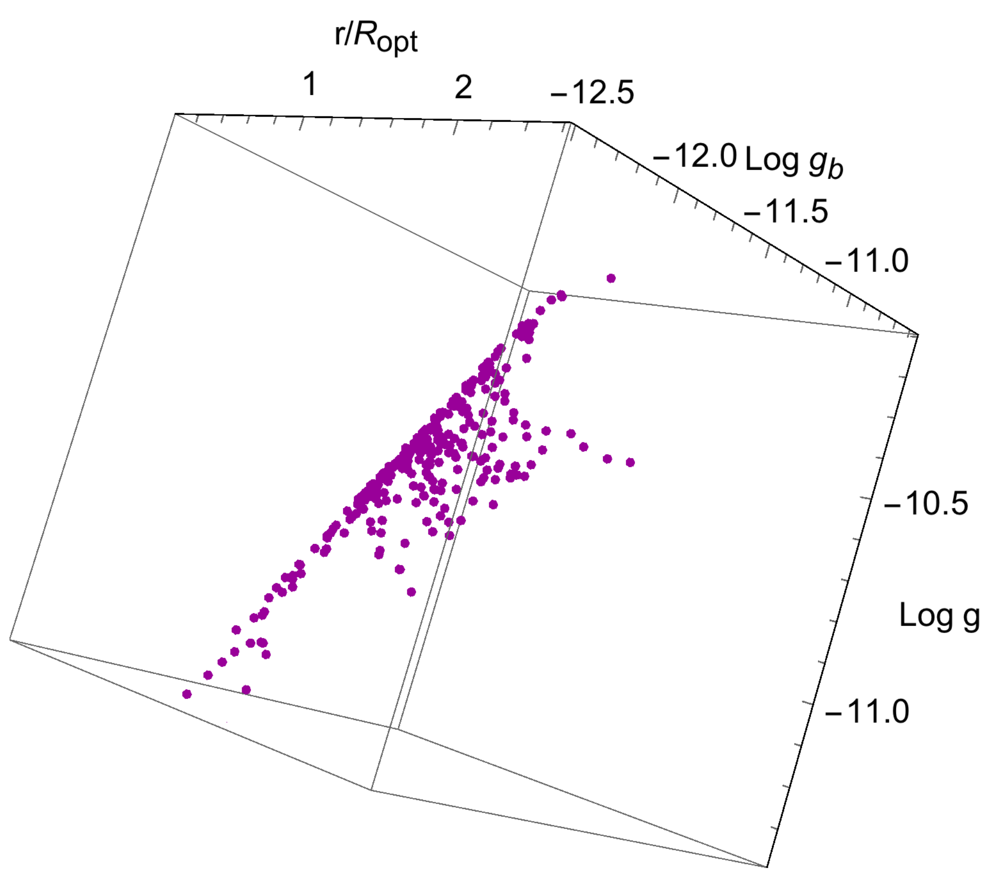
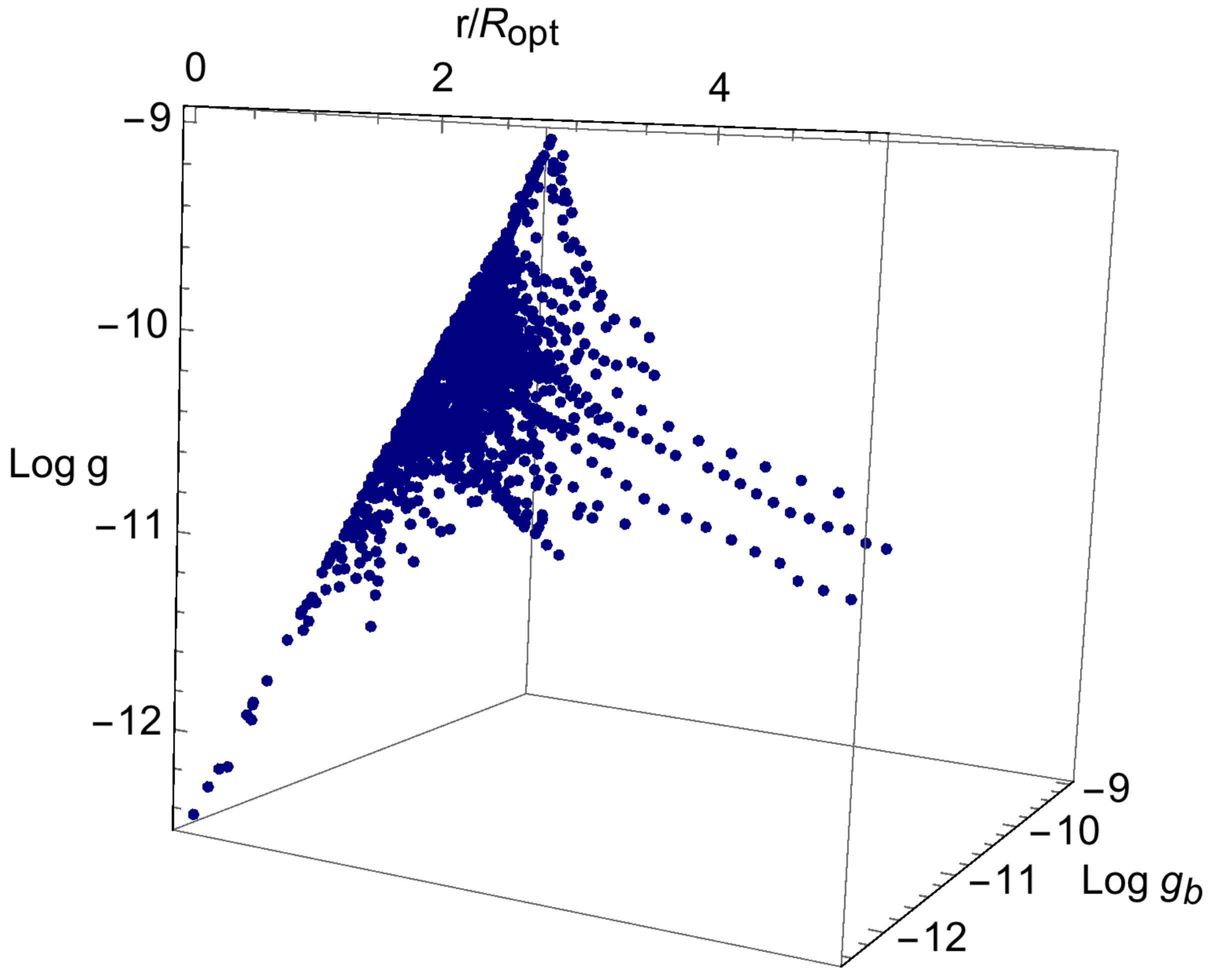
g , g_b , x test



Dwarf disks

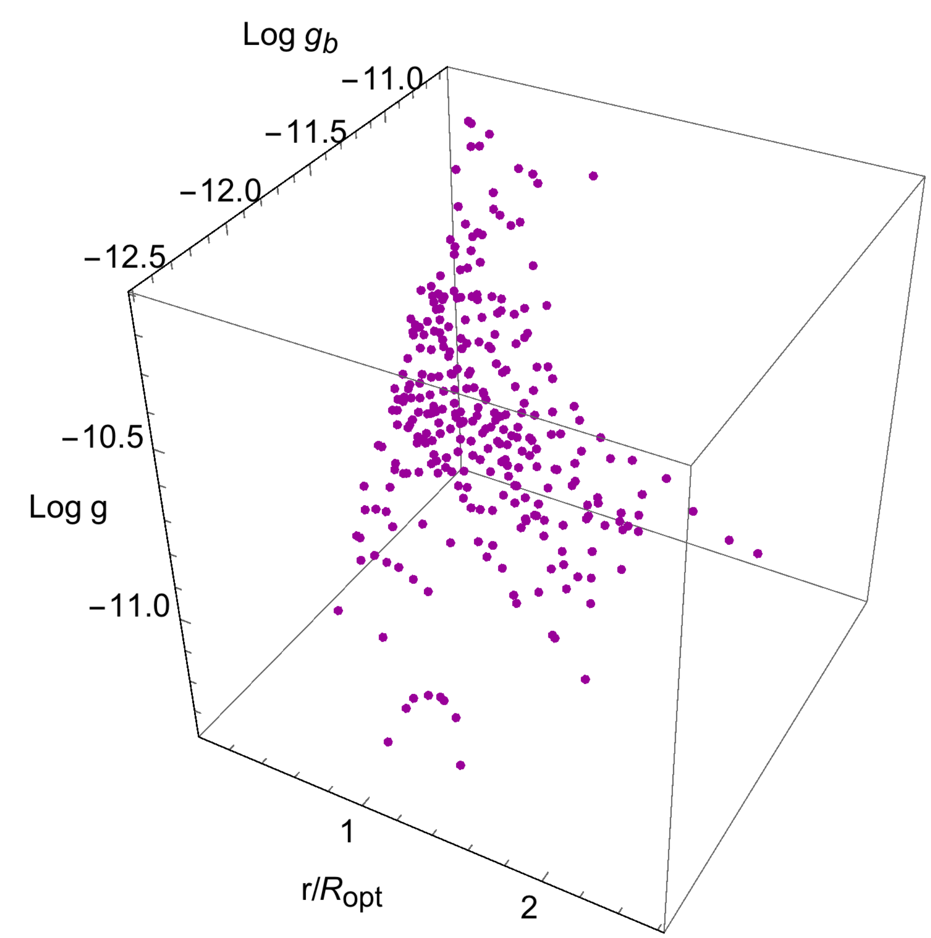
g , g_b , x **test**



LSB

$x = r/R_{opt}$

g , g_b , x **test**

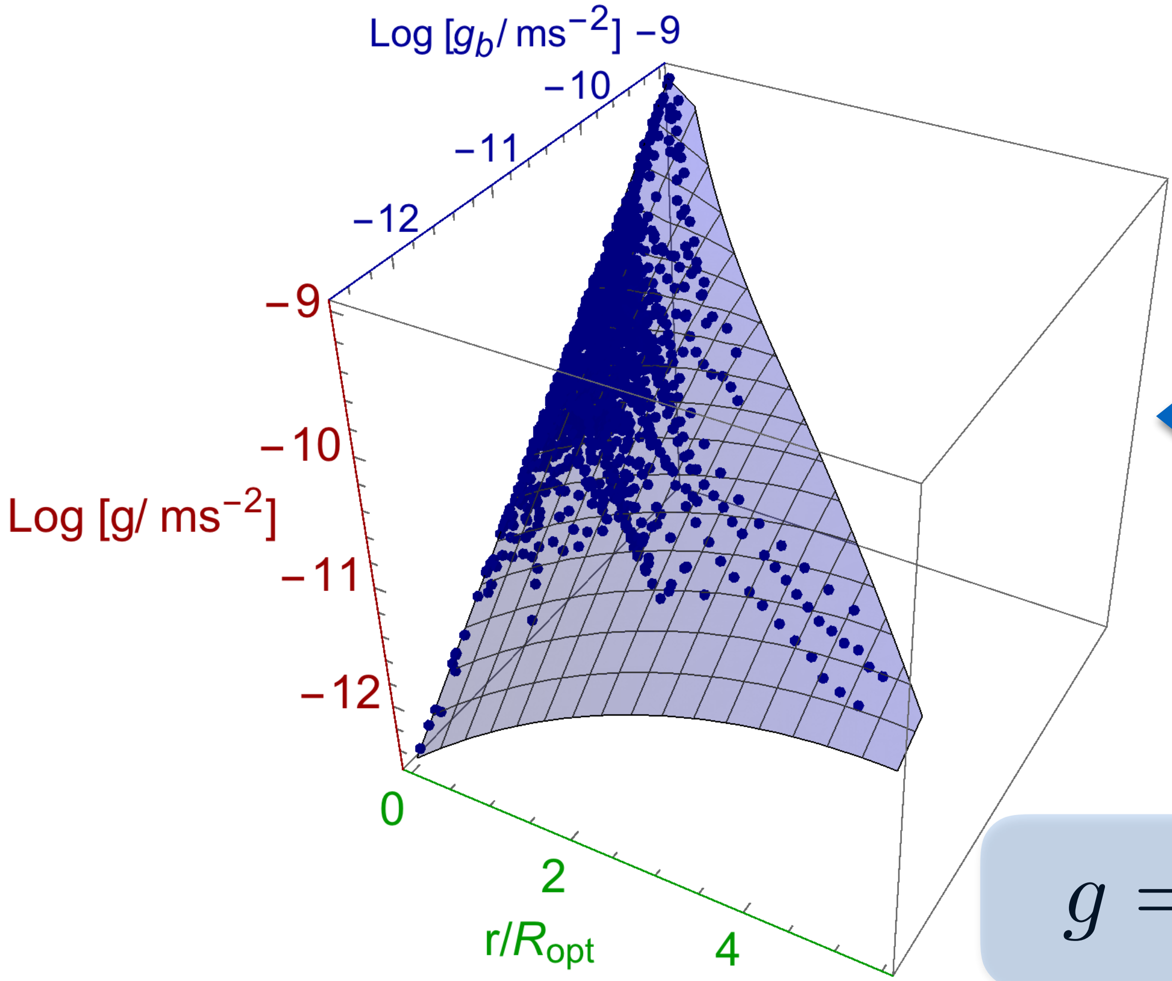


Dwarf disks

g , g_b , x **test**

$$x = r/R_{opt}$$

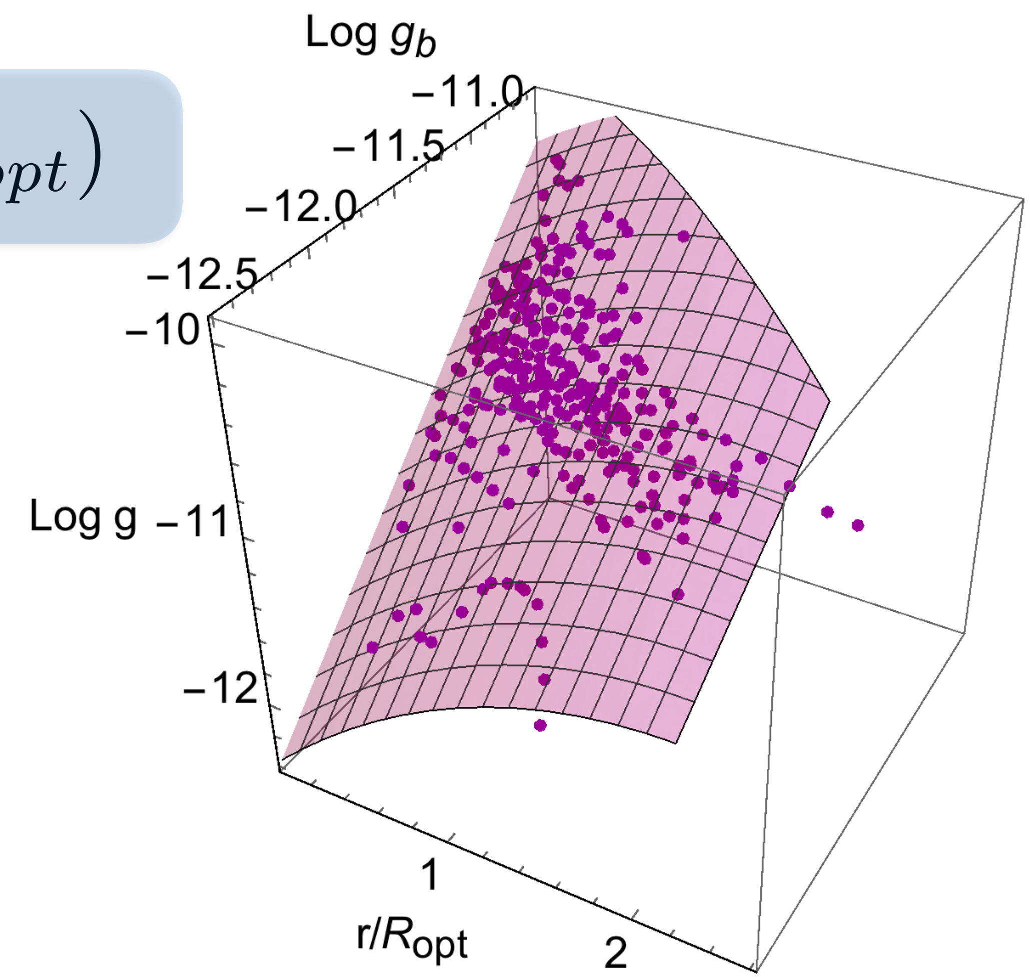
LSB



$$Log\, g_{LSB}(x,\, Log\, g_b) = (1 + a\, x)\, Log\, g_b + \\ + b\, x\, Log\,[1 - exp(-\sqrt{g_b(r)/g_\dagger})] \\ + c\, x + d\, x^2 \quad ,$$

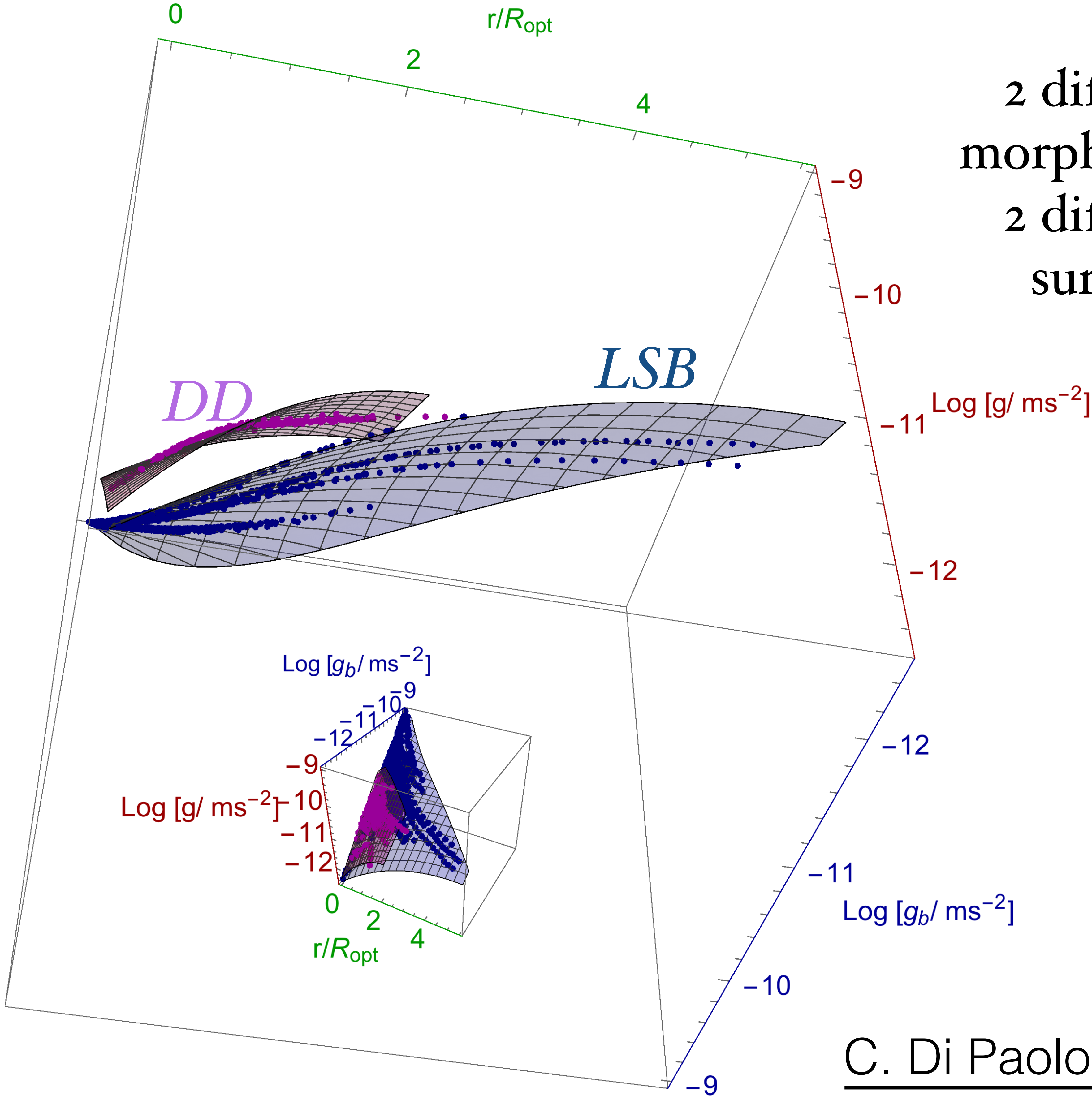
$$g = f(g_b,\, r/R_{opt})$$

$$Log\, g_{DD}(x,\, Log\, g_b) = \\ Log\, g_{LSB}\left(\frac{x}{l} + h,\, \frac{Log\, g_b}{m} + n\right) + q$$



Dwarf disks

g , g_b , x **test**



2 different morphologies, 2 different surfaces

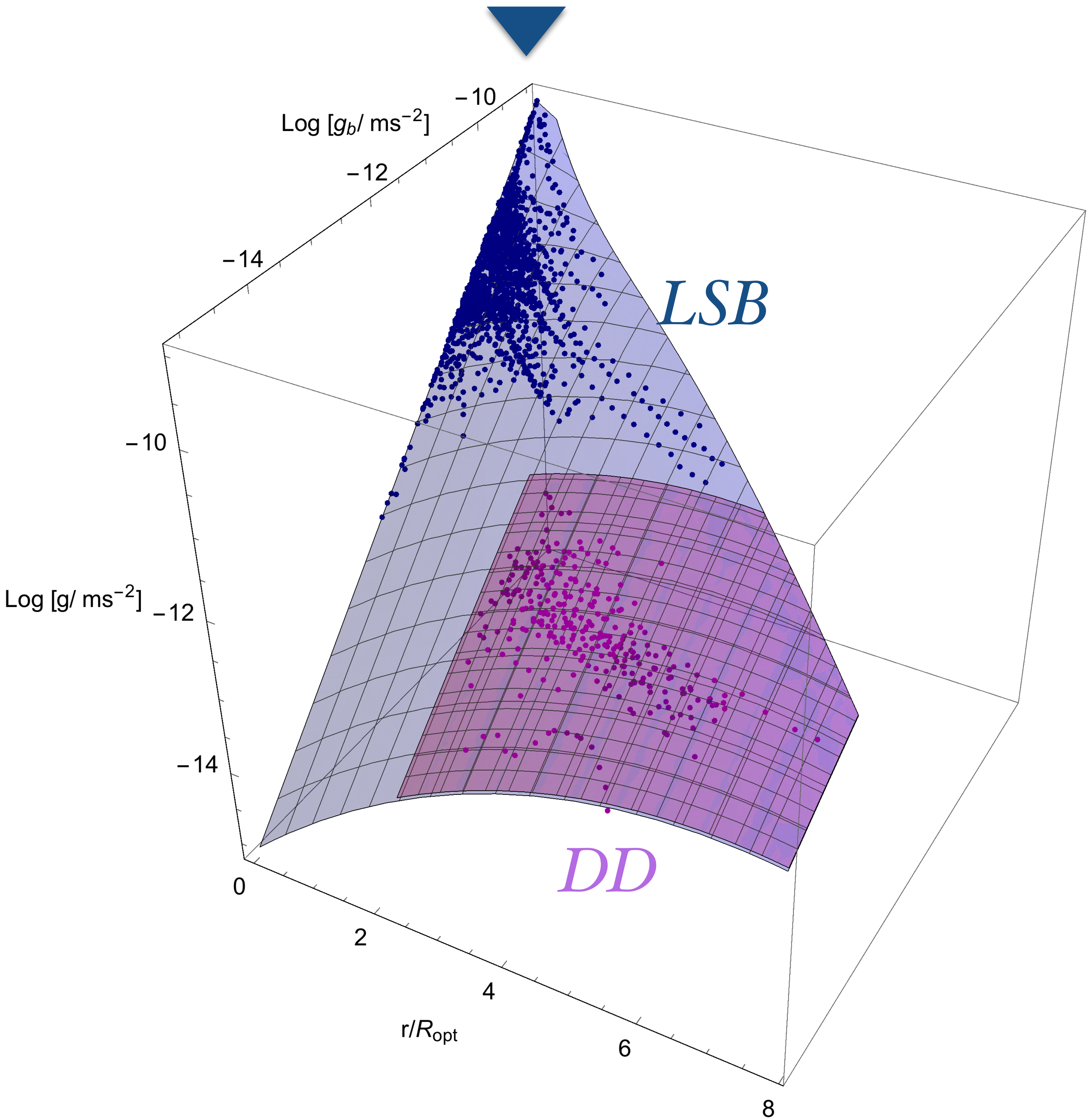
$$x = r/R_{opt}$$

C. Di Paolo et al, 2019, ApJ, 873,106

g , g_b , x **test**

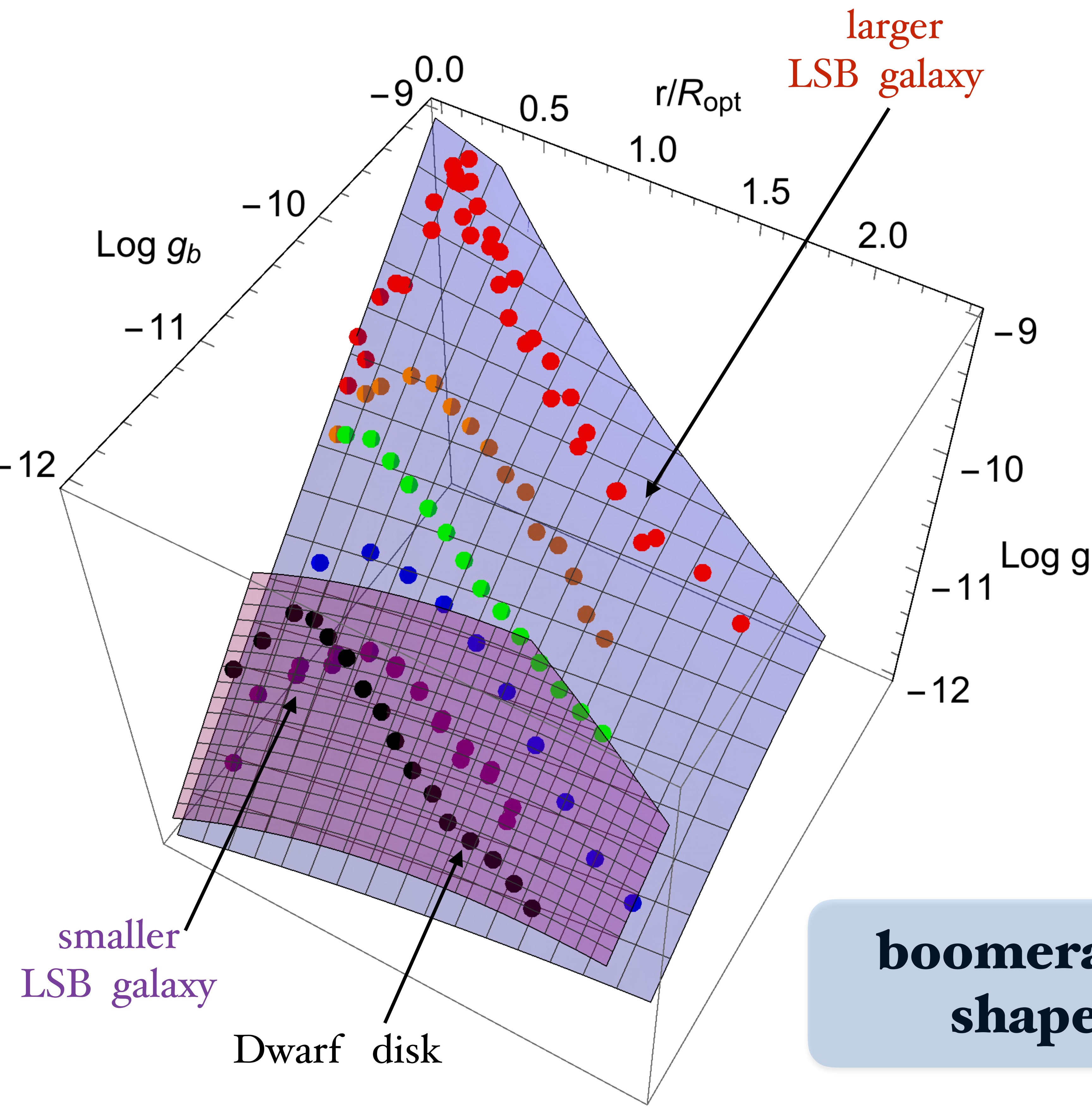
Simple translations and/or dilations

$x = r/R_{opt}$



universal relation

g , g_b , x **single galaxies test**



a) larger galaxies ▶ higher g and g_b

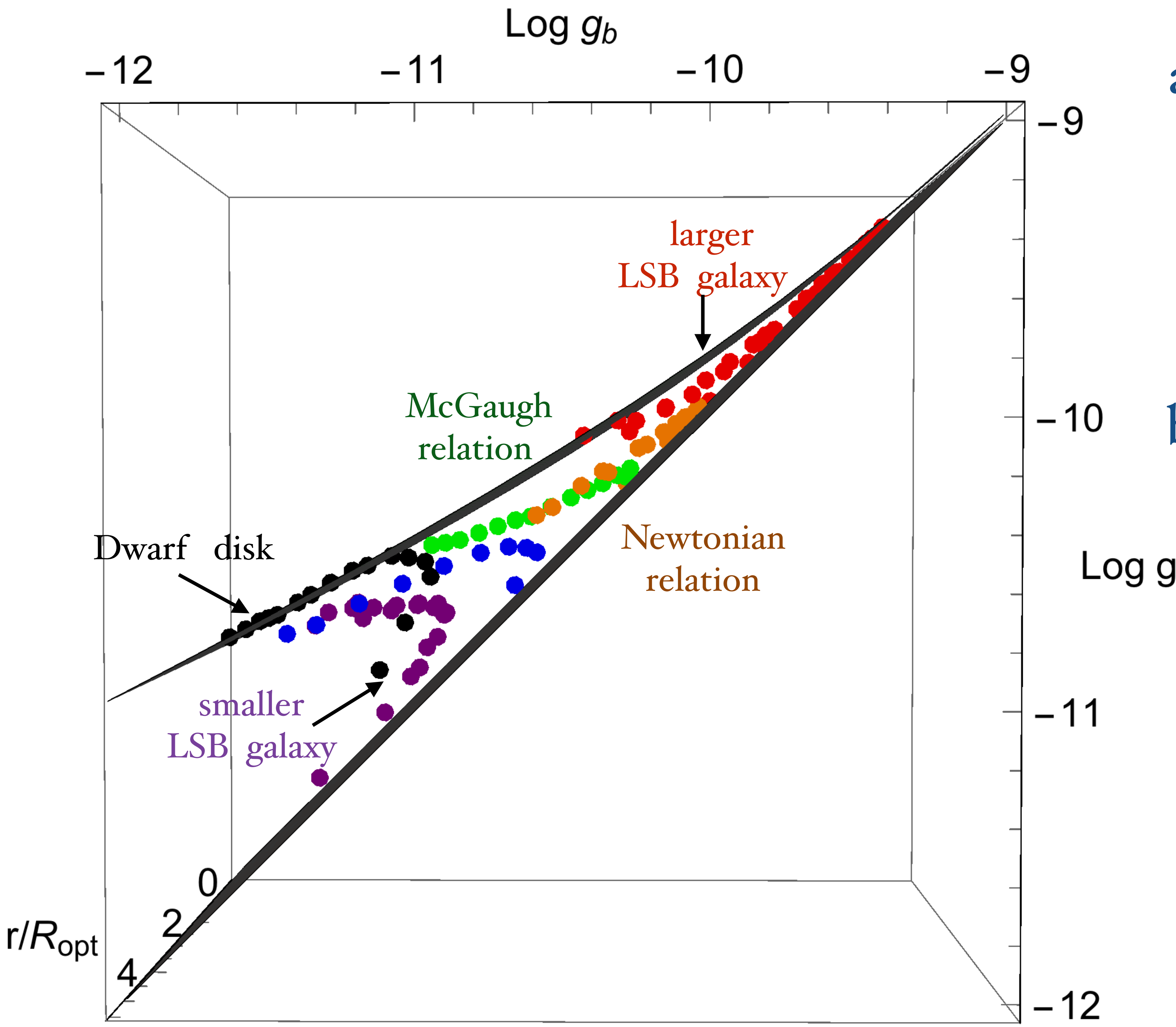
b) $g \gtrsim g_b$ growth till R_D (stellar disk scale length)

$$R_D = R_{opt}/3.2$$

c) $g > g_b$ decrease beyond R_D

boomerang shape

g , g_b , x **single galaxies test**



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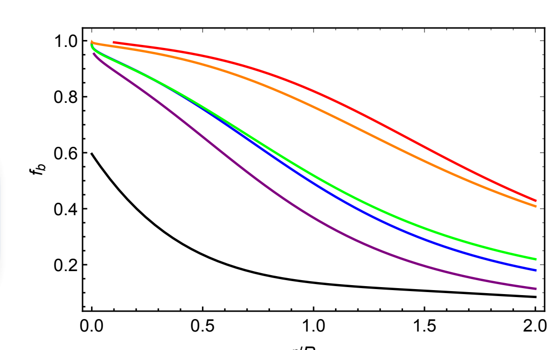
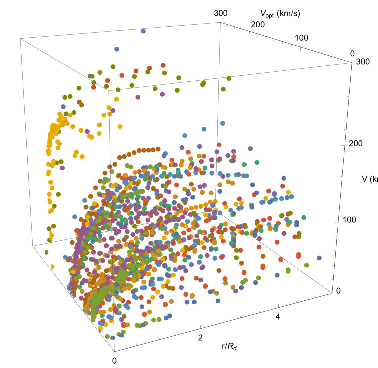
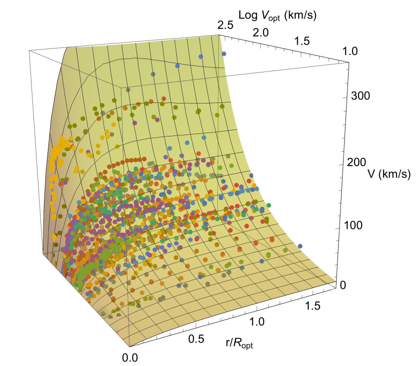


The results depend on the mass distribution properties

Conclusions from LSB analysis

- LSB galaxies give rise to the **URC**

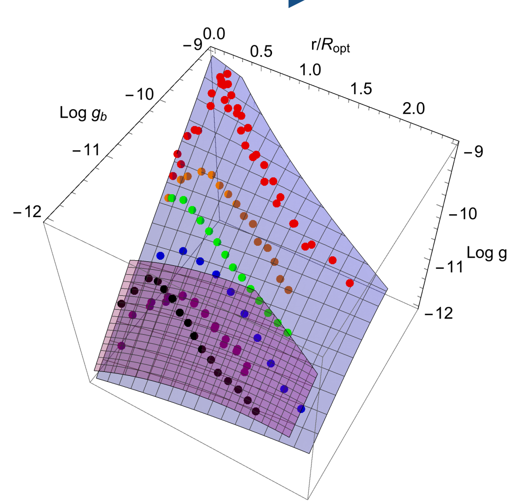




- LSB **scaling relations** similar but not identical to normal Spirals ones

- relevance of the **compactness** in LSB galaxies ⟶ **new hints?**

- **phenomenological understanding** of our results and McGaugh results ⟶ in the standard **baryonic + dark matter** scenario and mass distribution properties

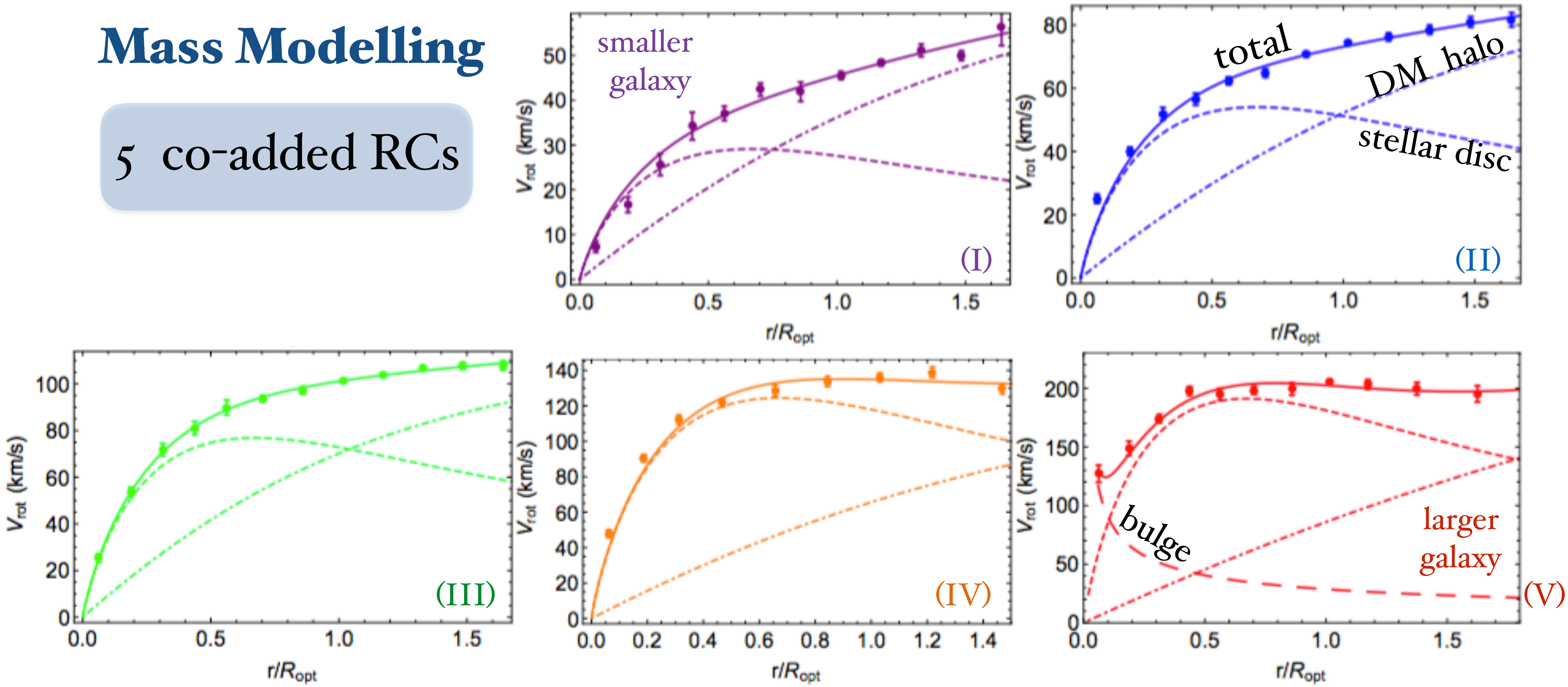


Thanks for
the attention

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

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

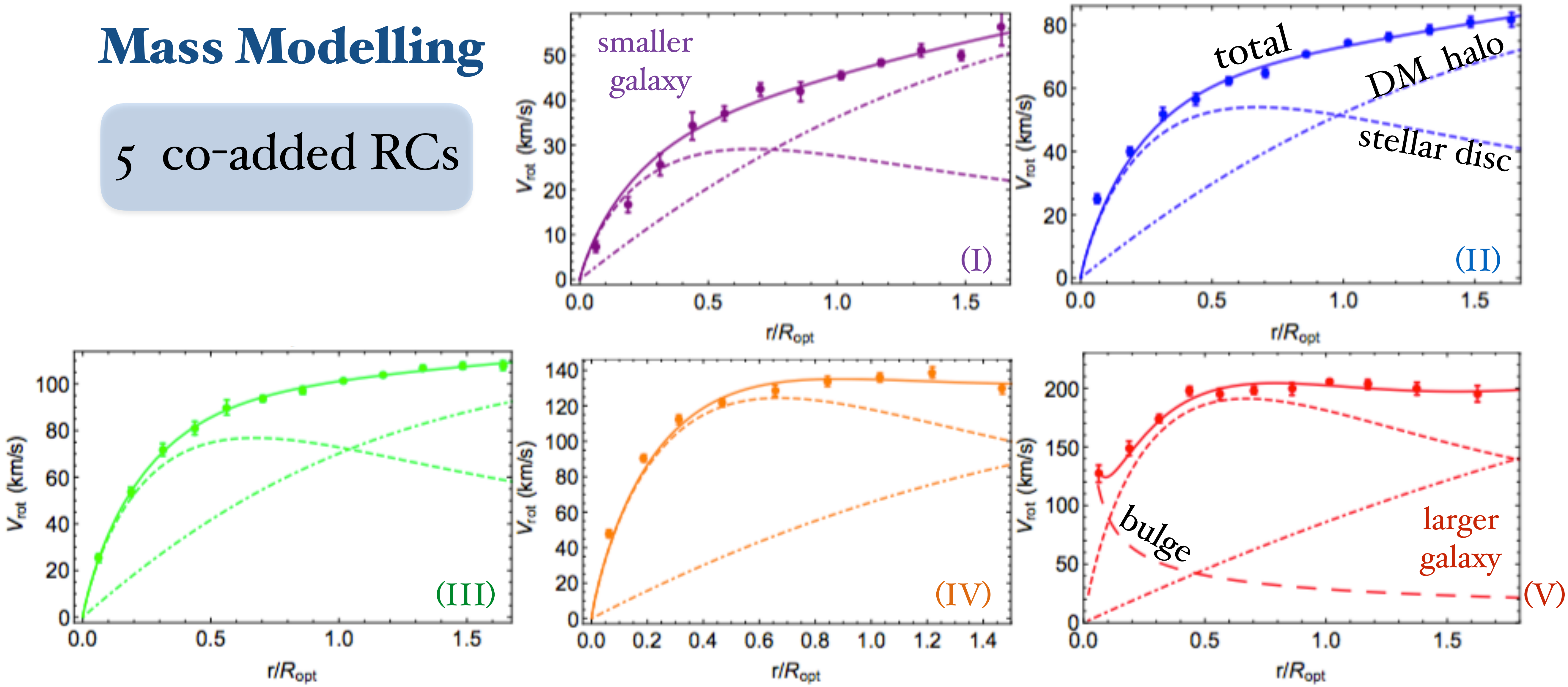
$$\alpha = \frac{\langle V_D^2(R_{opt})\rangle}{\langle V_{tot}^2(R_{opt})\rangle}$$

↓ baryonic fraction

Low Surface Brightness galaxies (LSBs)

Mass Modelling

5 co-added RCs



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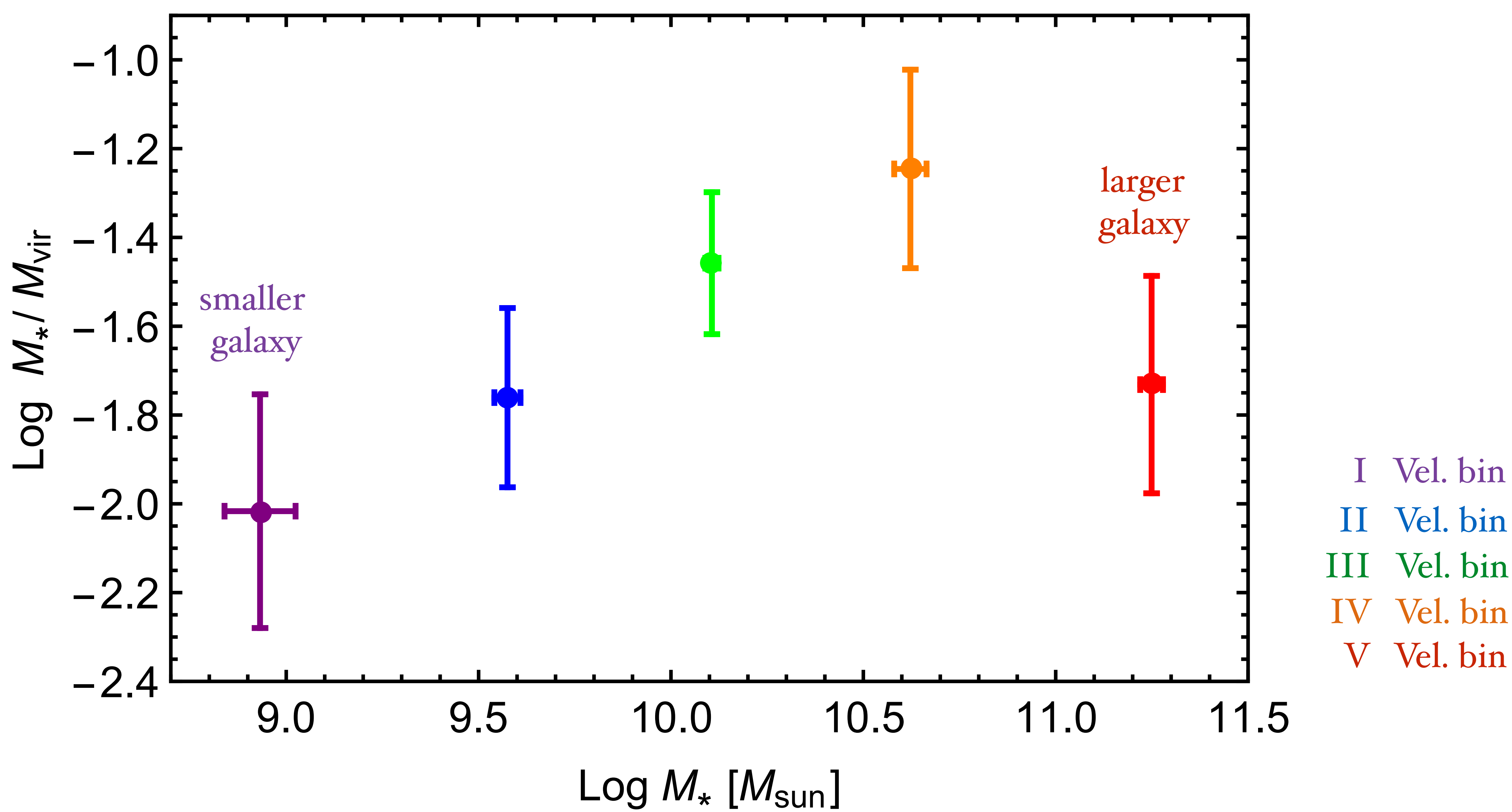
Low Surface Brightness galaxies (LSBs)

Baryonic fraction in the whole galaxy



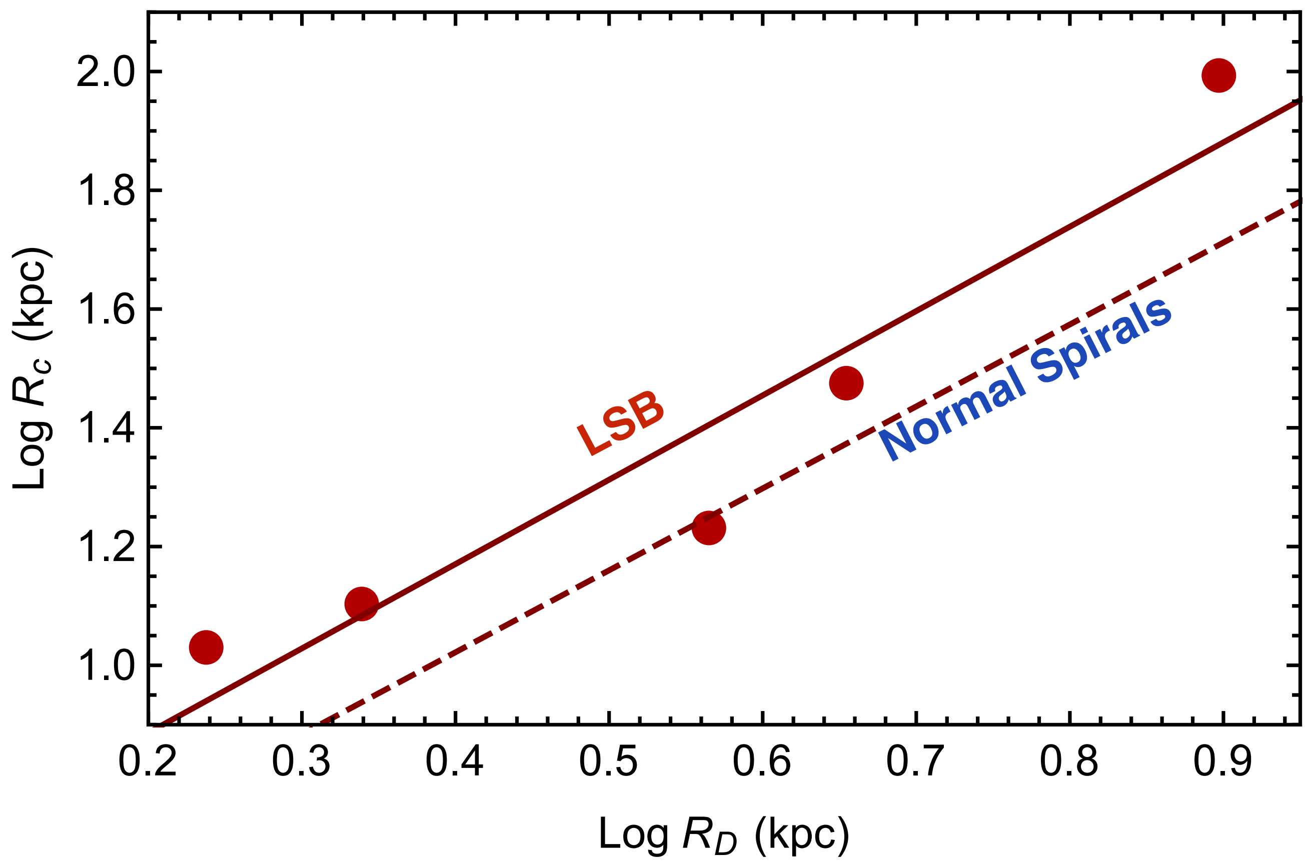
Low Surface Brightness galaxies (LSBs)

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

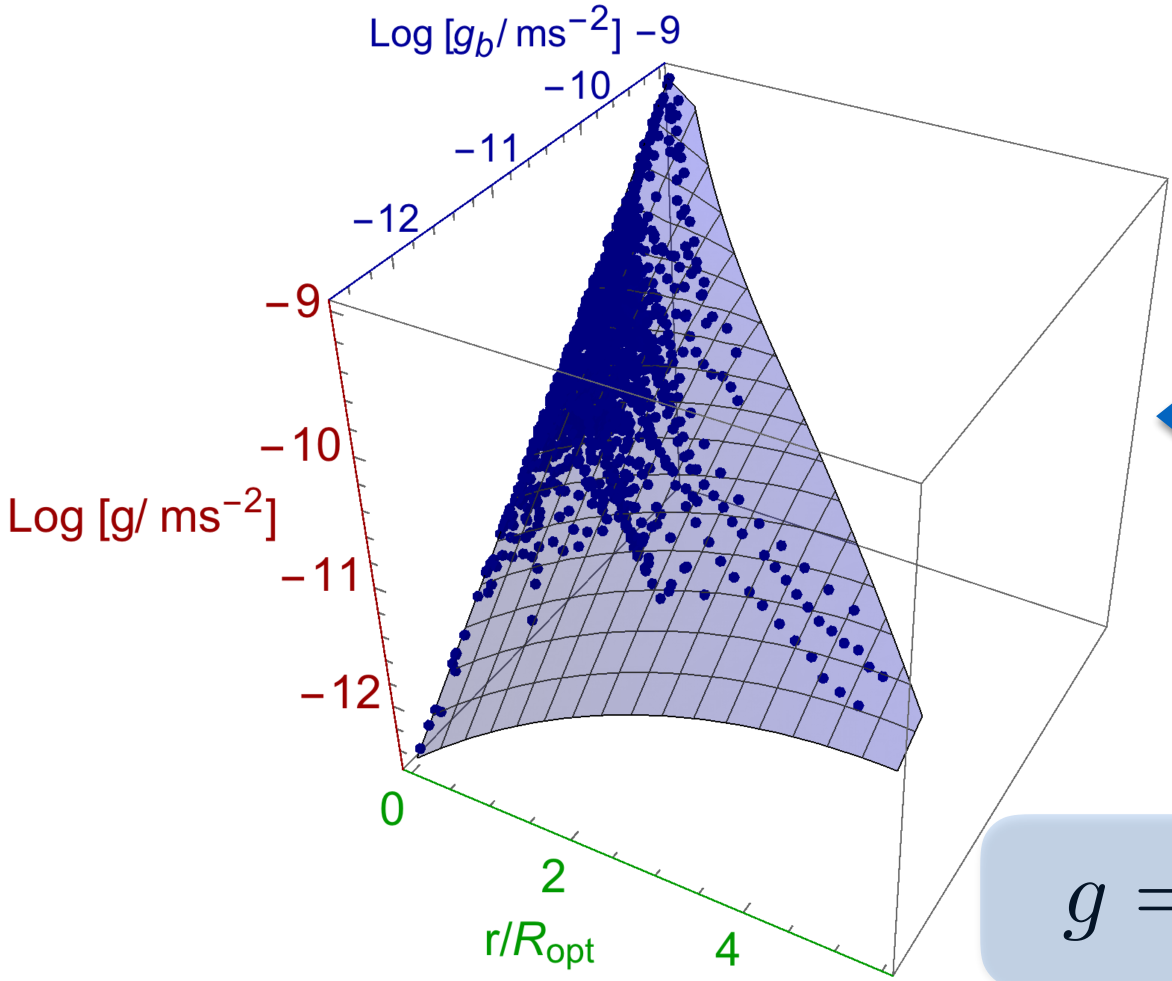
$$M_{DM}(R_{opt}) = G^{-1}(1-\alpha)V_{opt}^2 R_{opt}$$

$$\alpha = \frac{V_d^2(R_{opt})}{V^2(R_{opt})}$$ = 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

g , g_b , x **test**



LSB

$$x = r/R_{opt}$$

$$Log\, g_{LSB}(x,\, Log\, g_b) = (1 + a\,x)\, Log\, g_b + \\ + b\,x\, Log\,[1 - exp(-\sqrt{g_b(r)/g_\dagger})] \\ + c\,x + d\,x^2 \quad ,$$

a	b	c	d
-0.95	1.79	-9.01	-0.05

σ : 0.31 → 0.05 dex

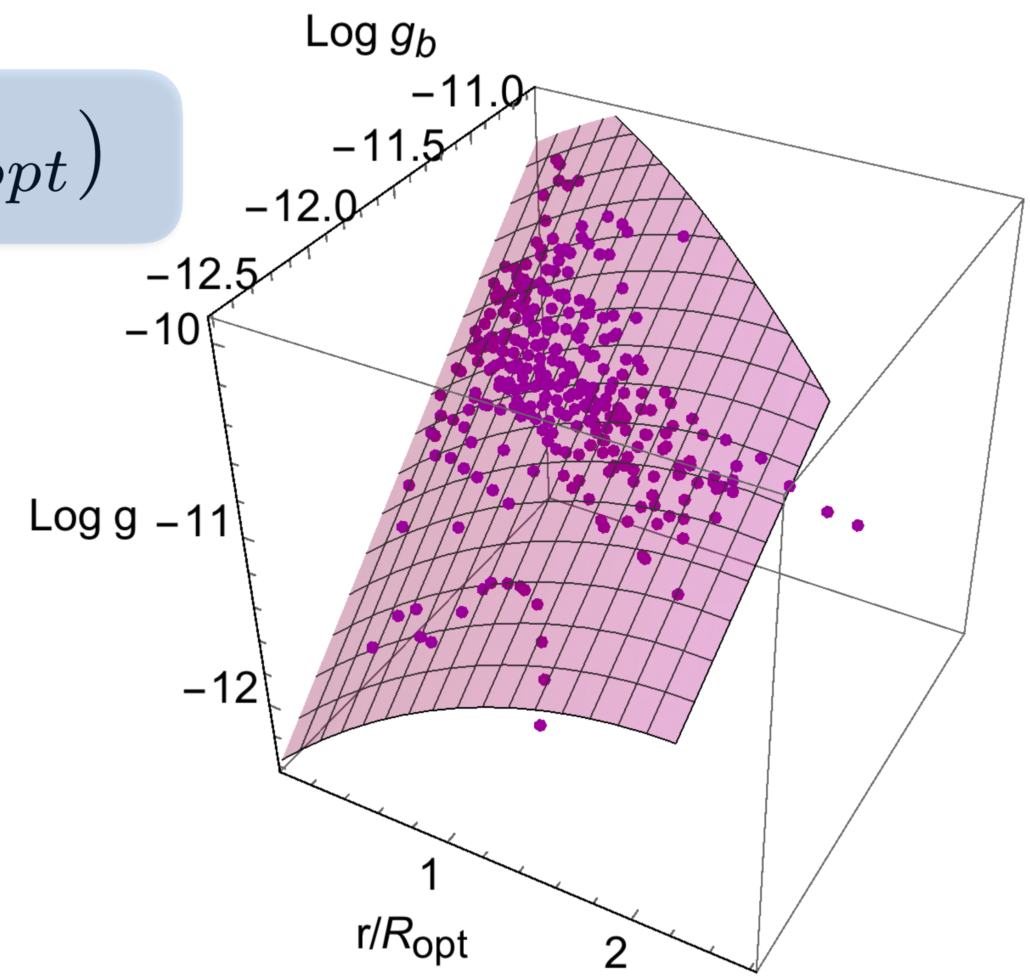
$$g = f(g_b,\, r/R_{opt})$$

$$Log\, g_{DD}(x,\, Log\, g_b) = \\ Log\, g_{LSB}\left(\frac{x}{l} + h,\, \frac{Log\, g_b}{m} + n\right) + q$$

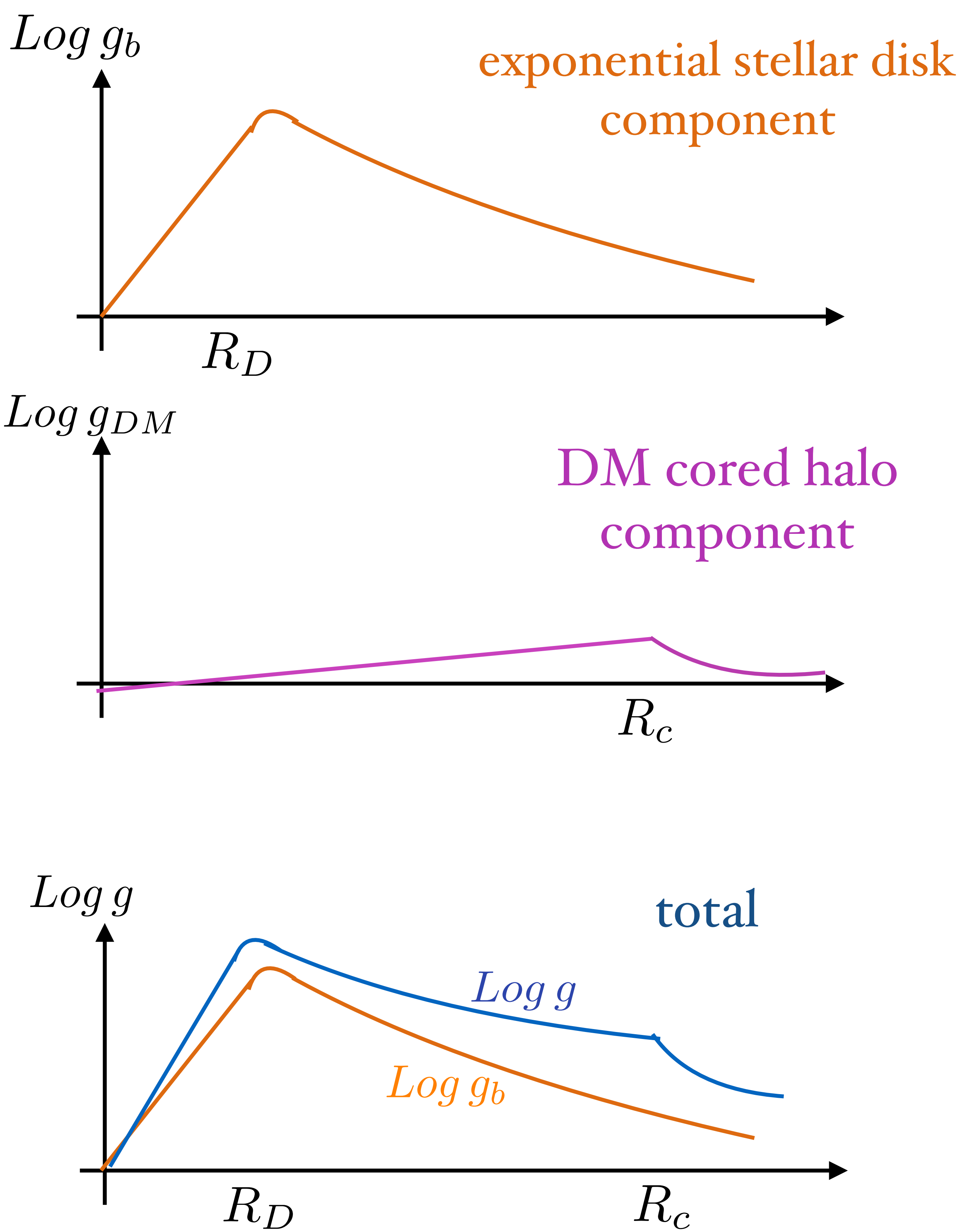
l	h	m	n	q
0.49	2.41	0.74	1.72	1.19

σ : 0.17 → 0.03 dex

Dwarf disks



g , g_b , x interpreting the evidence



a) larger galaxies ▶ higher g and g_b

b) $g \gtrsim g_b$ growth till R_D (disk scale length)

↓

% baryonic matter > % dark matter inside R_D

The bulk of matter at high density is inside R_D

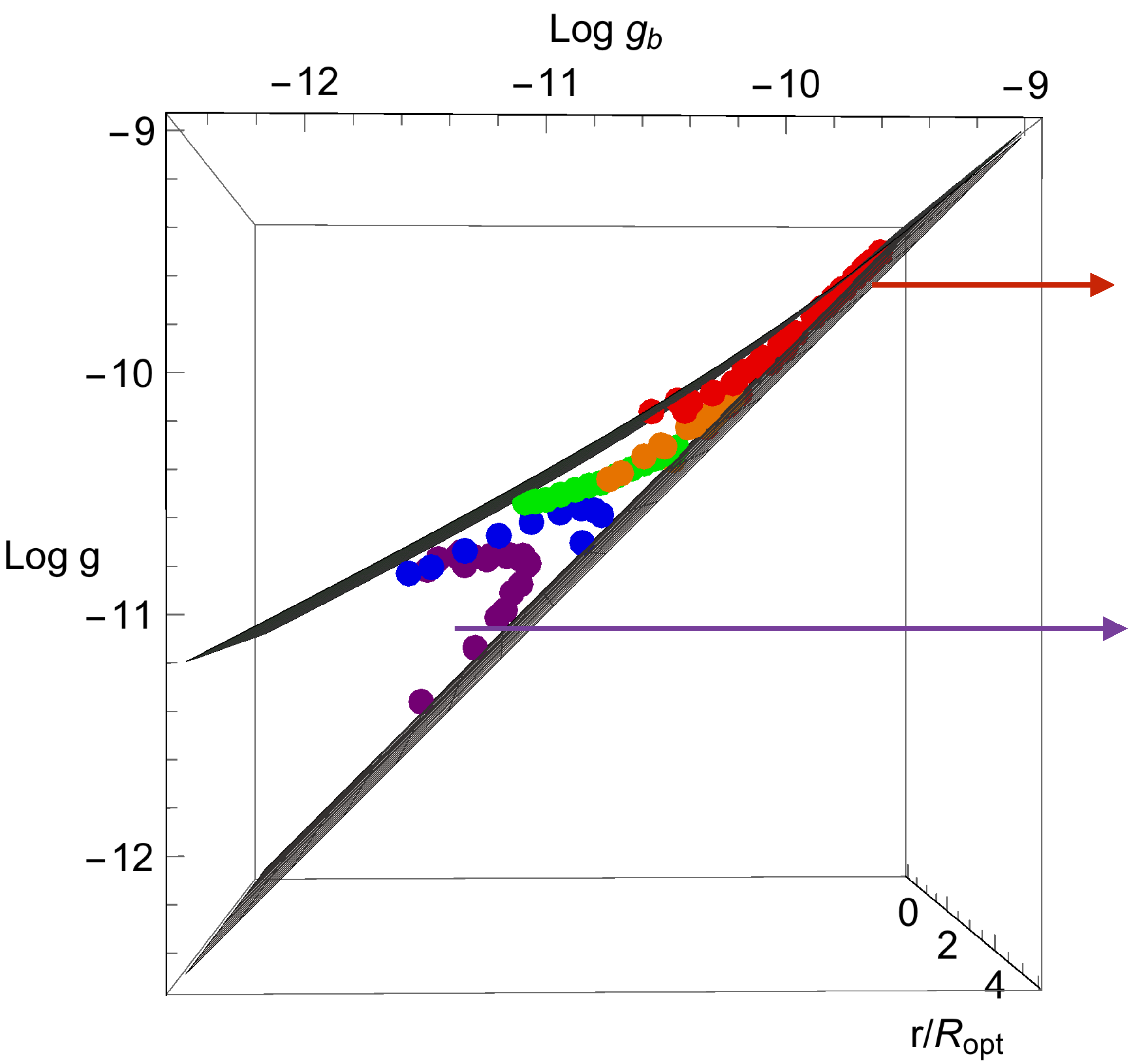
c) $g > g_b$ decrease beyond R_D

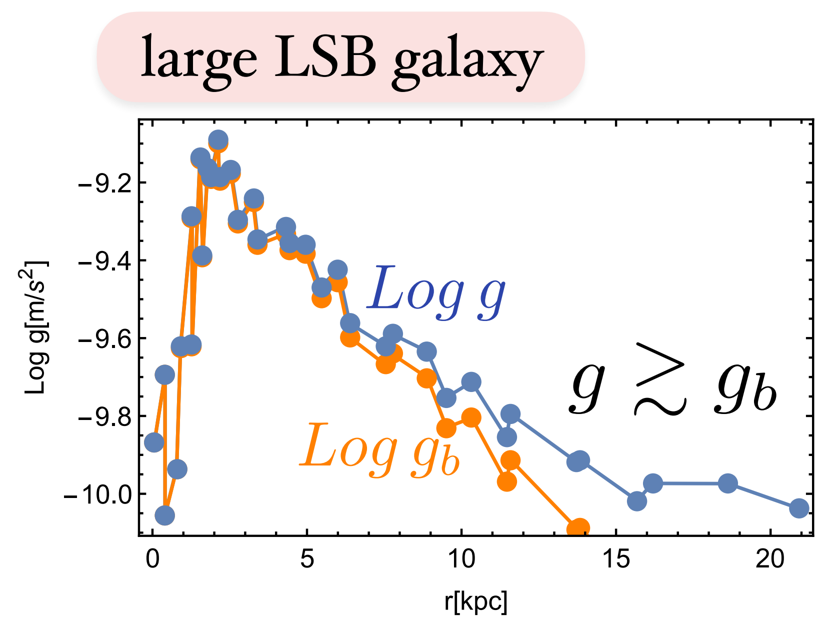
↓

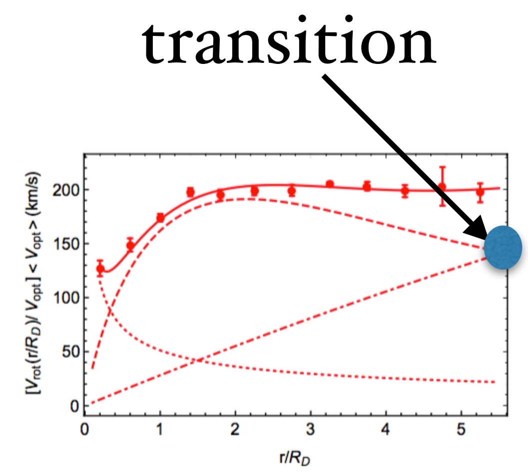
% baryonic matter < % dark matter in external region

Matter at low density in external region

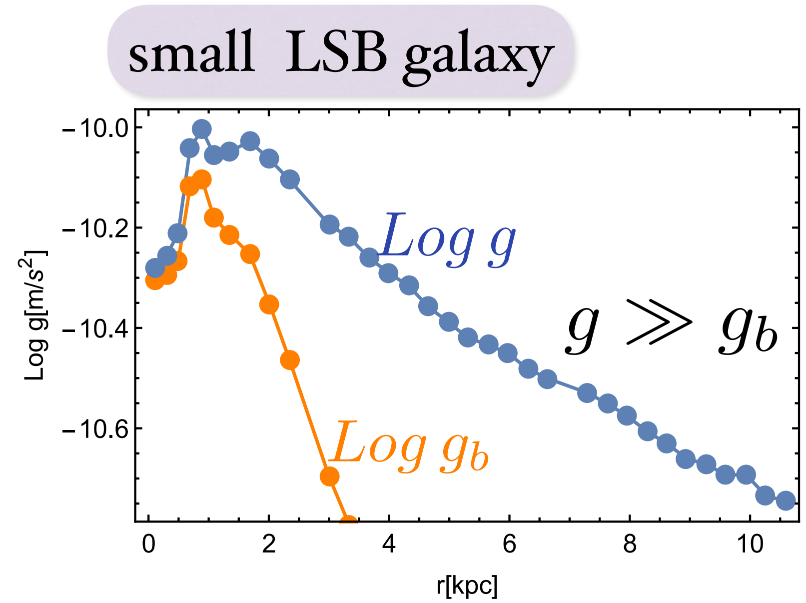
g , g_b , x interpreting the evidence

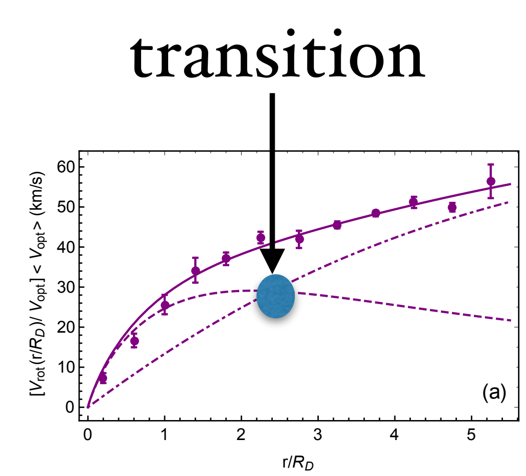






baryonic matter dominant beyond $\sim R_D$ $\quad g \gtrsim g_b$



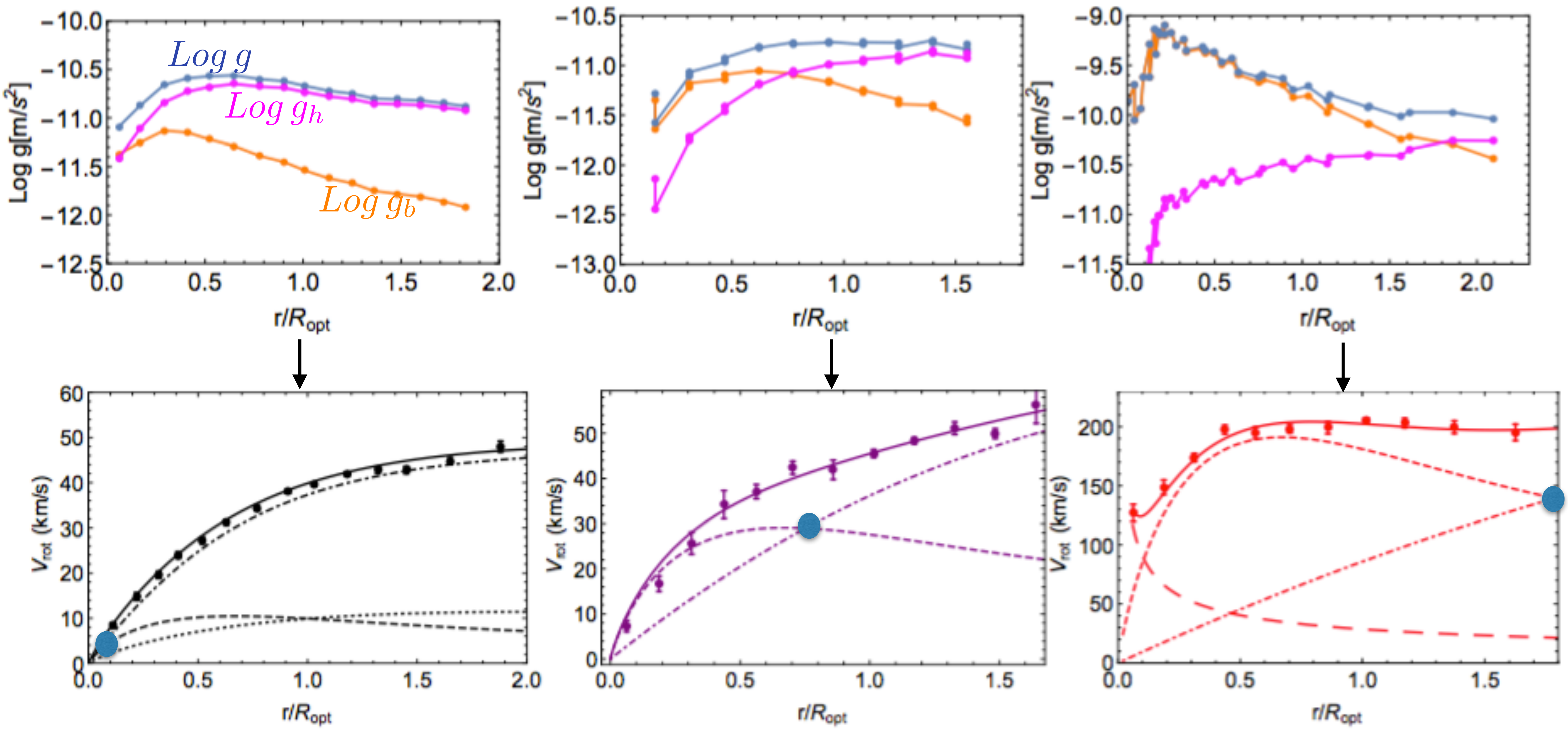


baryonic matter dominant till $\sim R_D$ $\quad g \gg g_b$

g , g_b , x interpreting the evidence

For completeness:

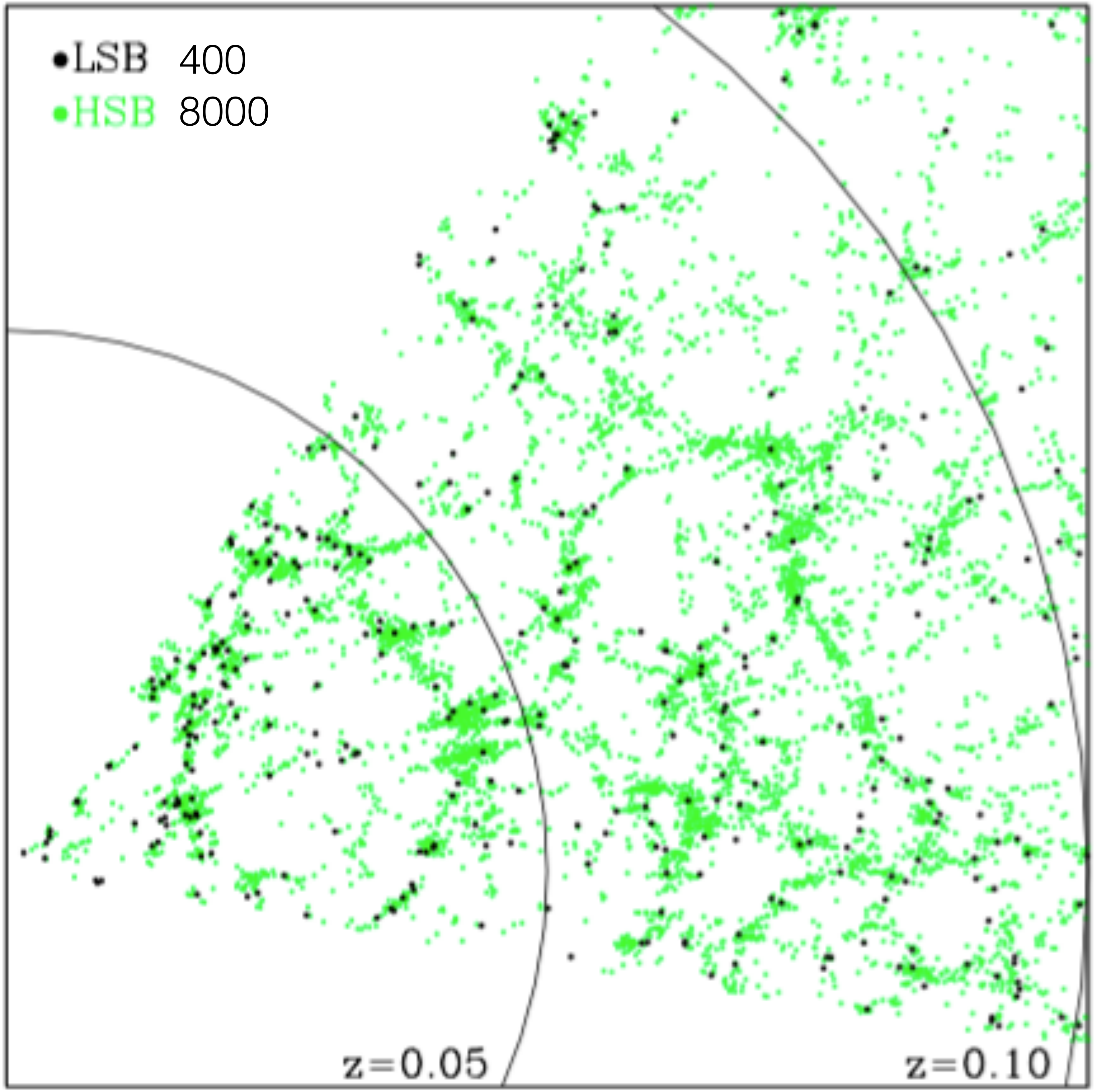
Dwarf Disk | small LSB galaxy | large LSB galaxy



dark matter dominated
in central region

→ $g \gg g_b$ everywhere in Dwarf Disk

Low Surface Brightness galaxies (LSBs)



from SDSS

Rosenbaum & Bomas, 2004