RAR (Radial Acceleration Relation): is it valid?

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Cosmology 2018

Dubrovnik, October 22nd 2018

C. Di Paolo & P. Salucci

arXiv:1810.08472

Gravitational acceleration

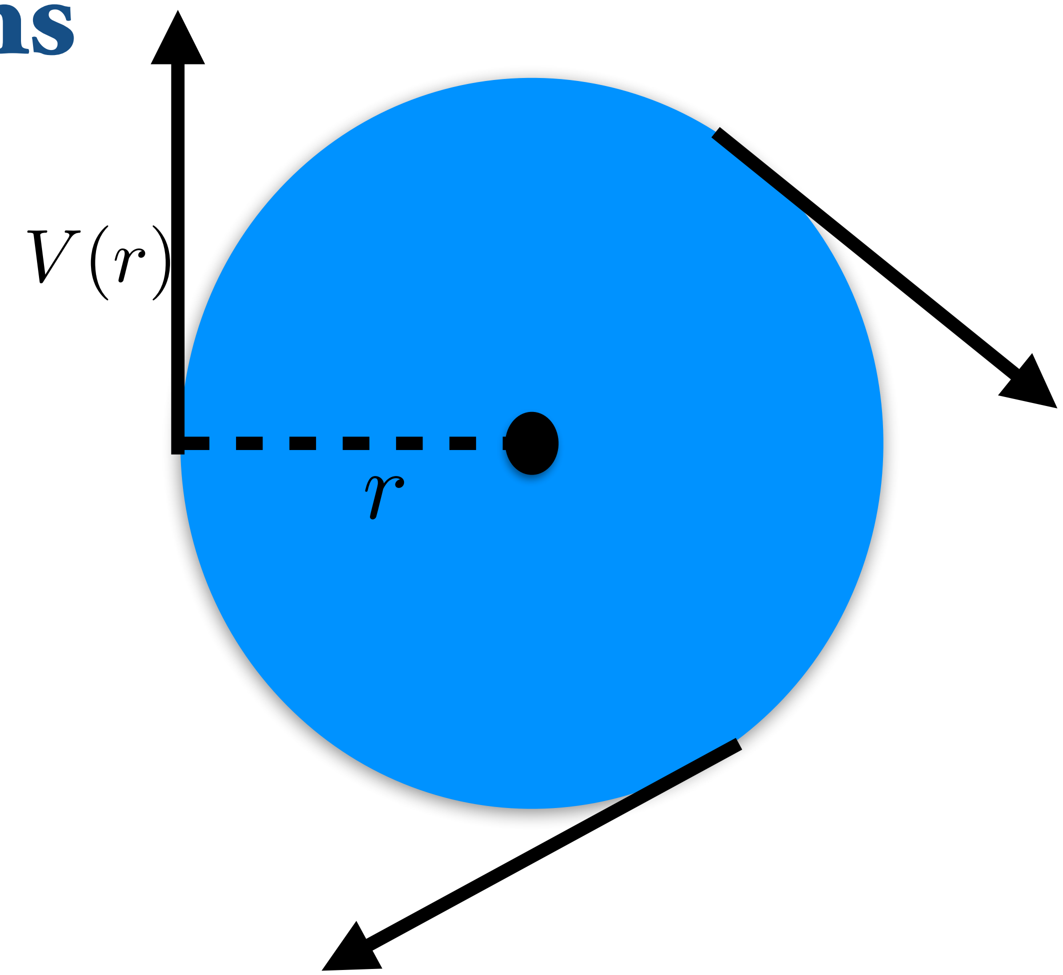
Rotating systems

stellar disc

bulge

HI gaseous disc

DM halo



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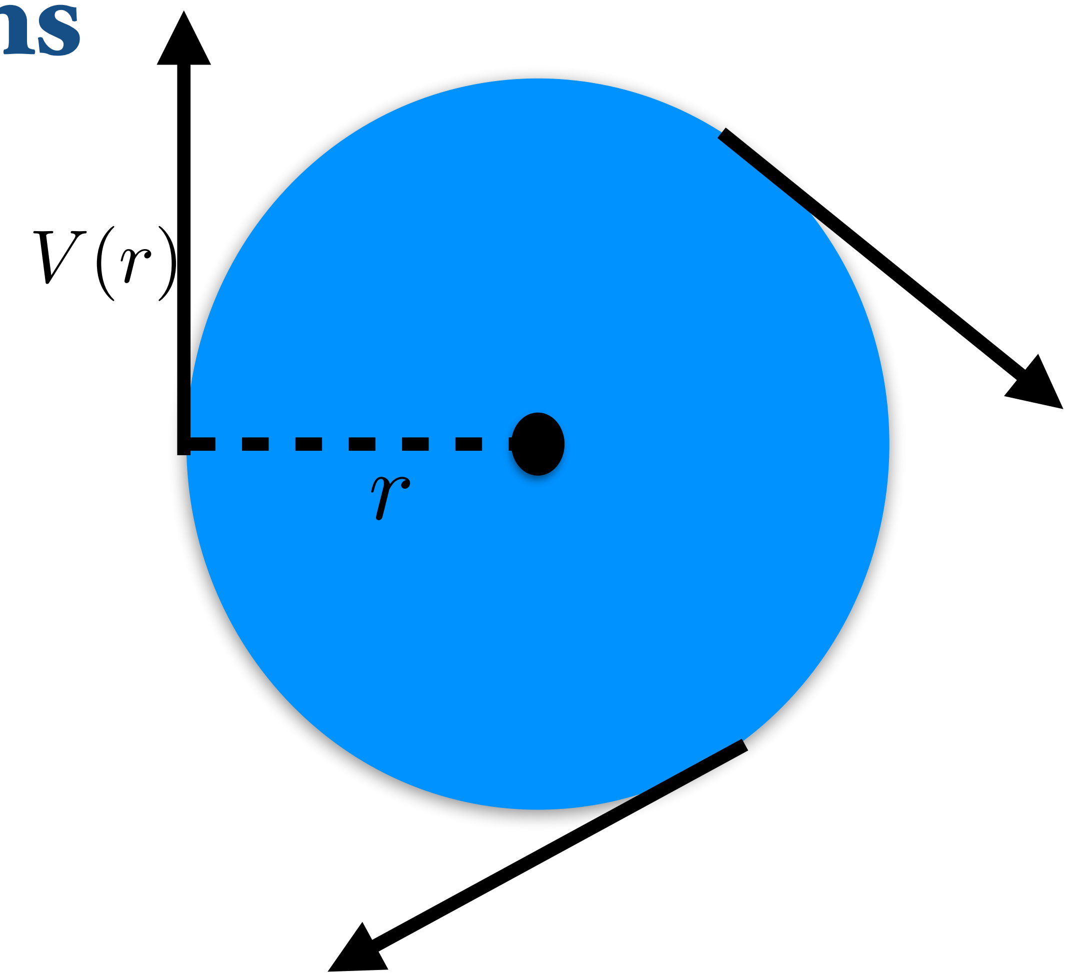

Gravitational (radial) acceleration :

$$g(r) = \frac{V^2(r)}{r} = \left| -\frac{d\Phi}{dr} \right| = G\frac{M(r)}{r^2} \qquad \left\{ M(r) = M_d(r) + M_{bu}(r) + M_{HI}(r) + M_h(r) \right.$$

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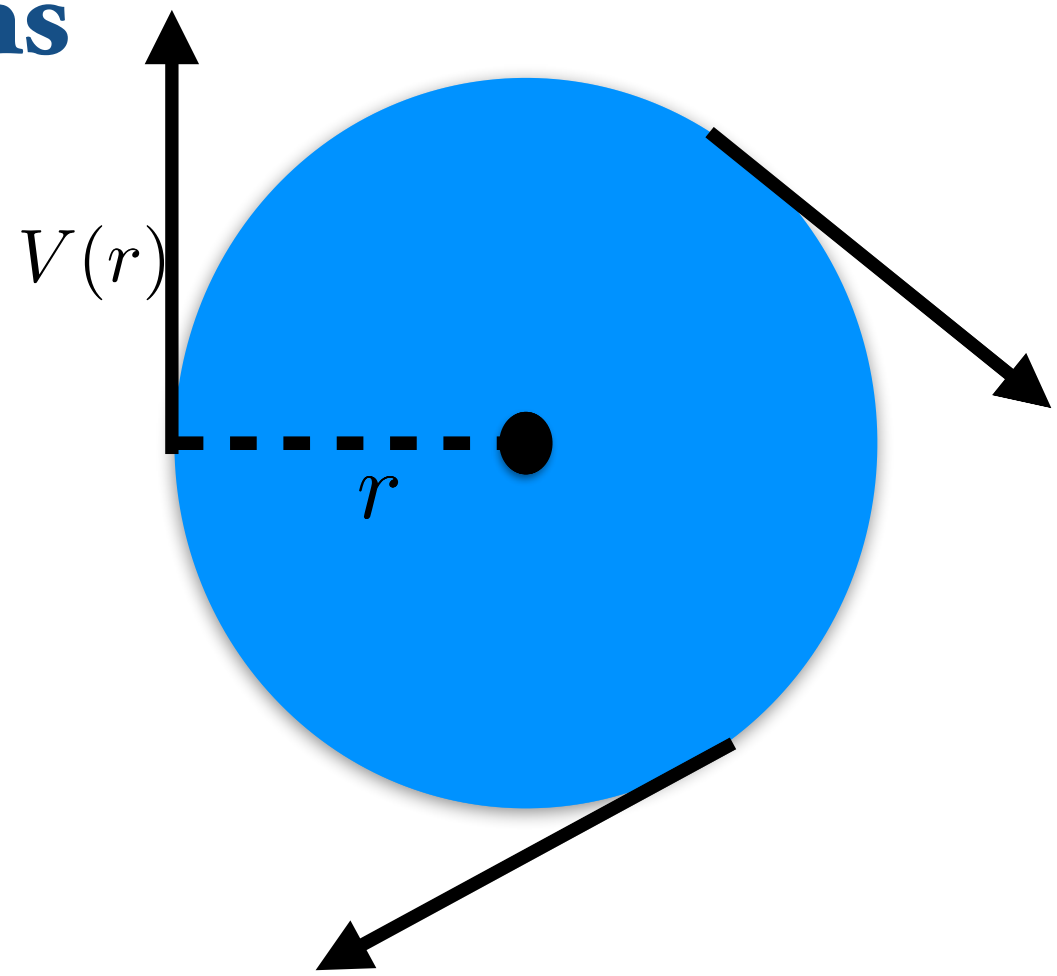

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DM halo

Baryonic component :

$$g_b(r) = \frac{V_b^2(r)}{r} = \left| -\frac{d\Phi_b}{dr} \right| = G\frac{M_b(r)}{r^2} \qquad \left\{ \begin{array}{l} M_b(r) = M_d(r) + M_{bu}(r) + M_{HI}(r) \\ V_b^2(r) = V_d^2(r) + V_{bu}^2(r) + V_{HI}^2(r) \end{array} \right.$$

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

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

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

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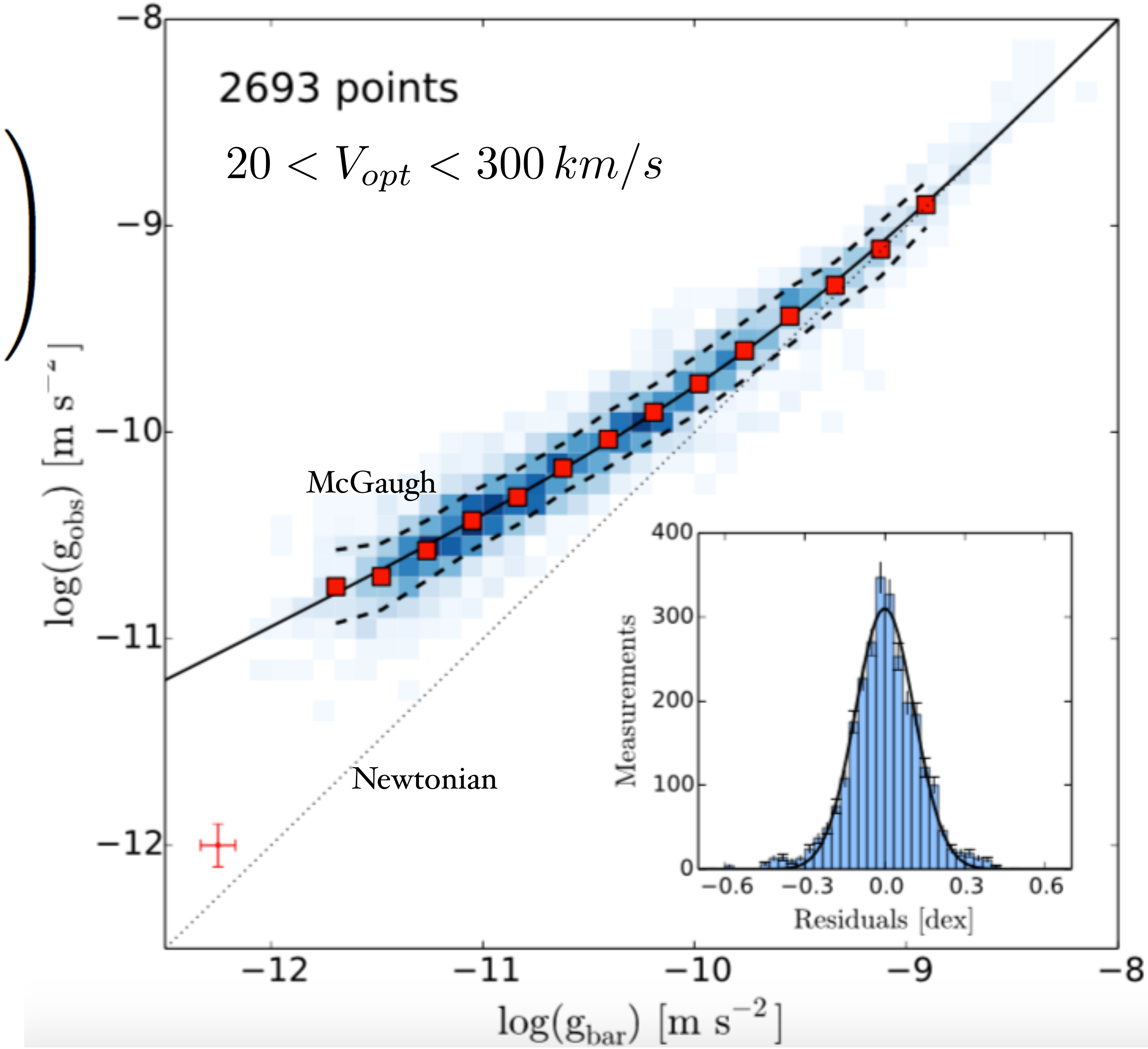

McGaugh et al. (2016)

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empirical **universal relation**

$$g = f(g_b)$$

at any radius
and
in any object

153 rotationally supported galaxies
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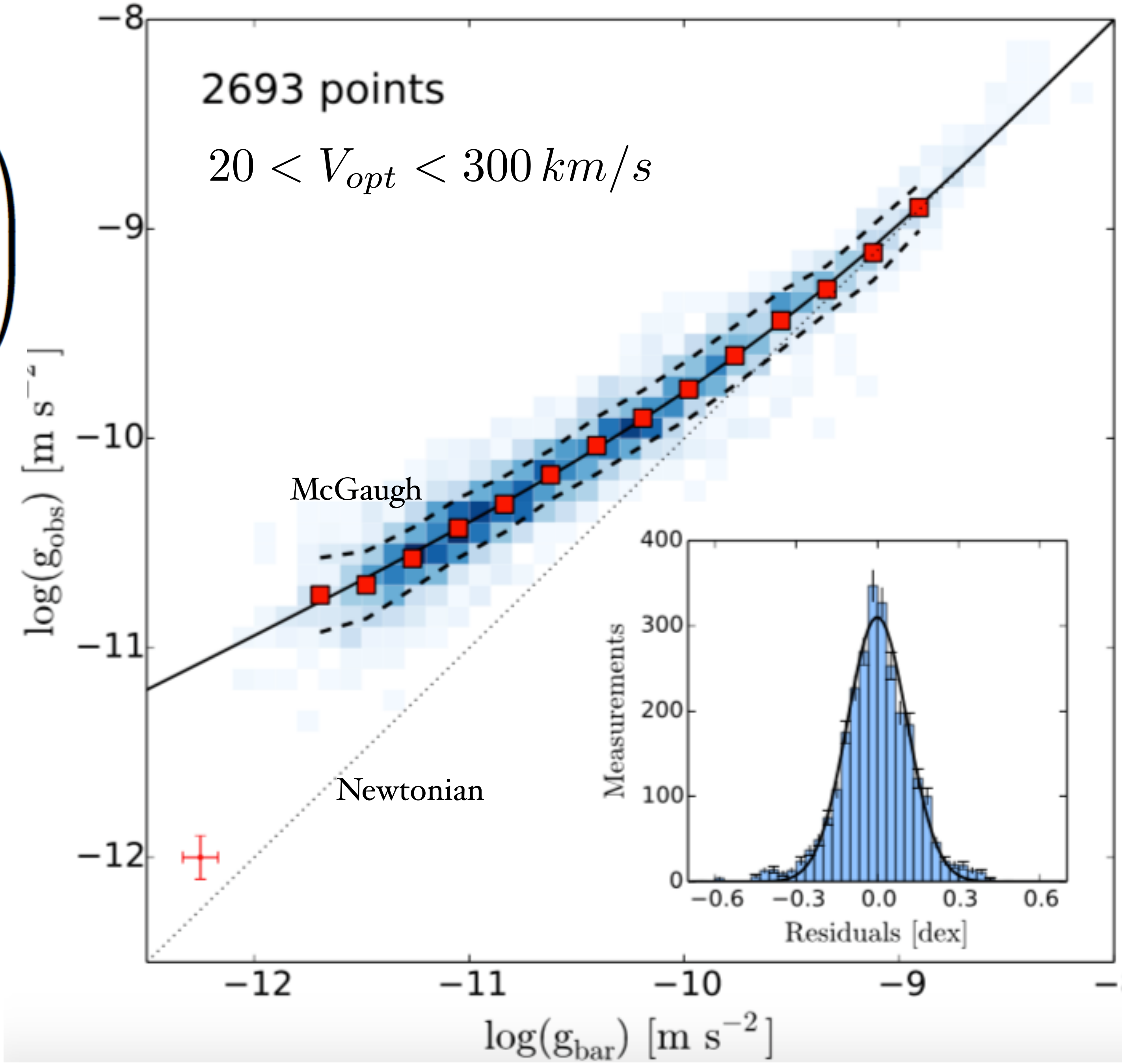

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RAR: Gravitational acceleration relation

Salucci P. → 1000 **normal Spirals**, 25000 circular velocity measurements → $70 < V_{opt} < 300\, km/s$

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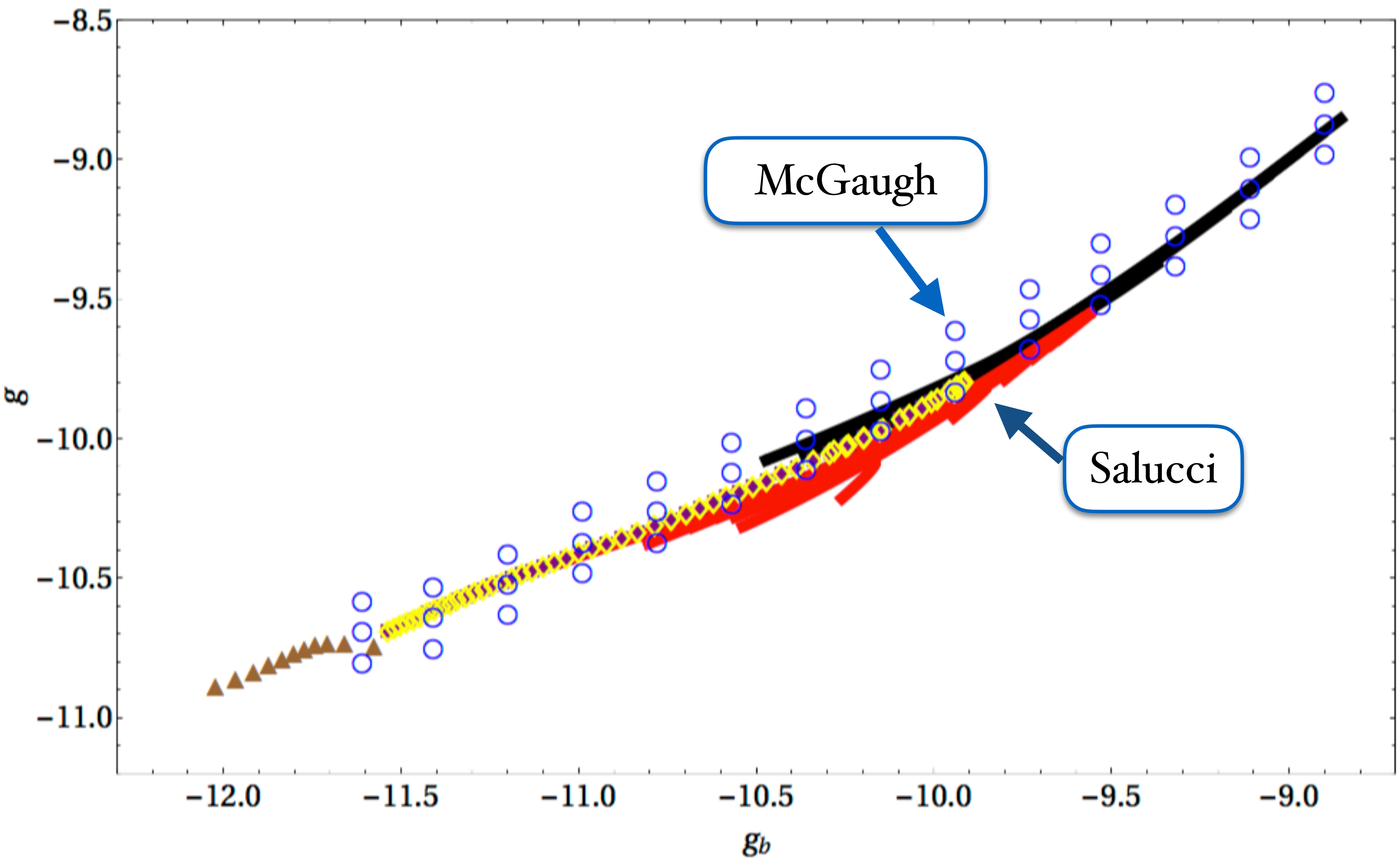


Salucci & McGaugh data

agreement

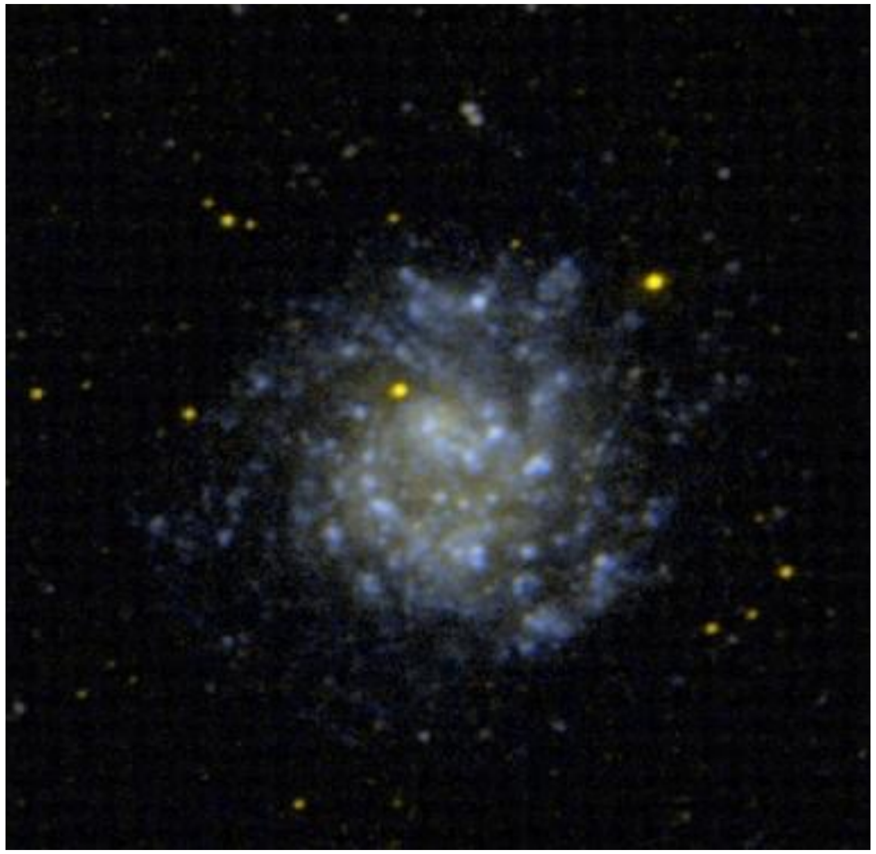
Salucci (2018)

RAR: Gravitational acceleration relation

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

303 circular velocity measurements

→ $19 < V_{opt} < 61\,km/s$



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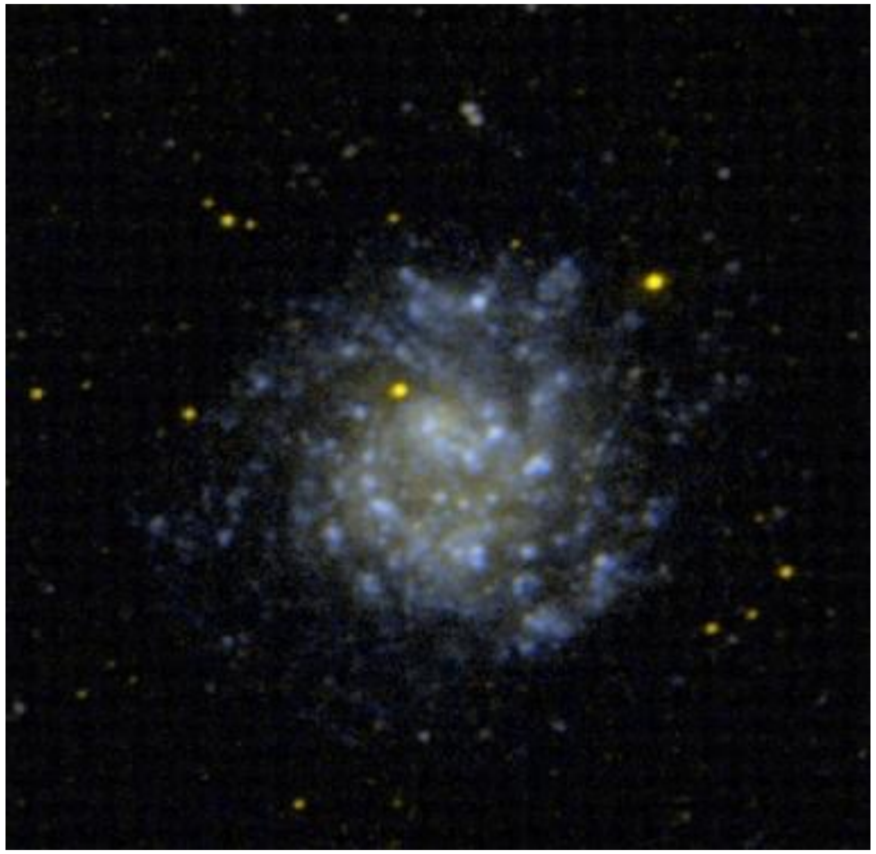

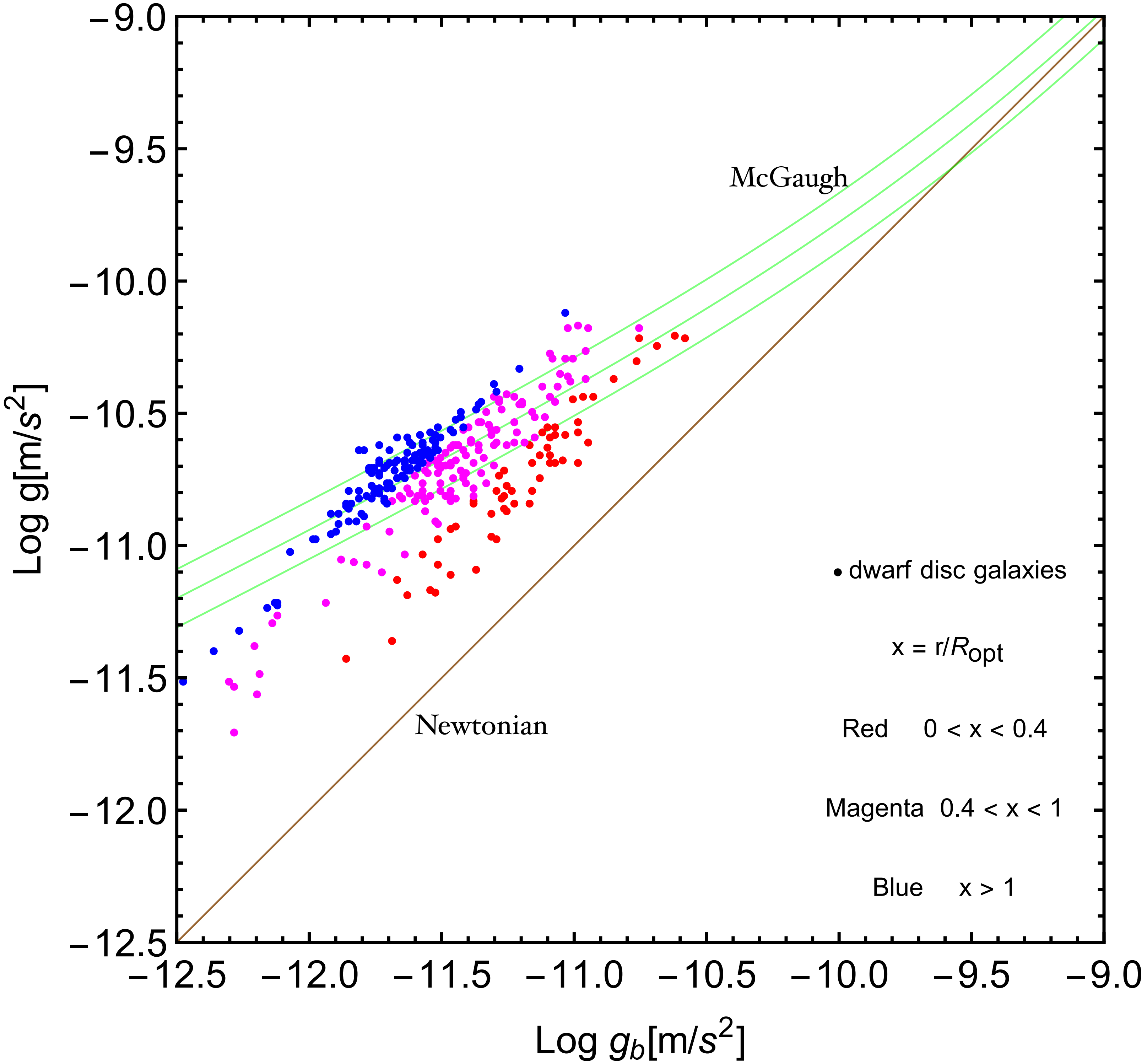

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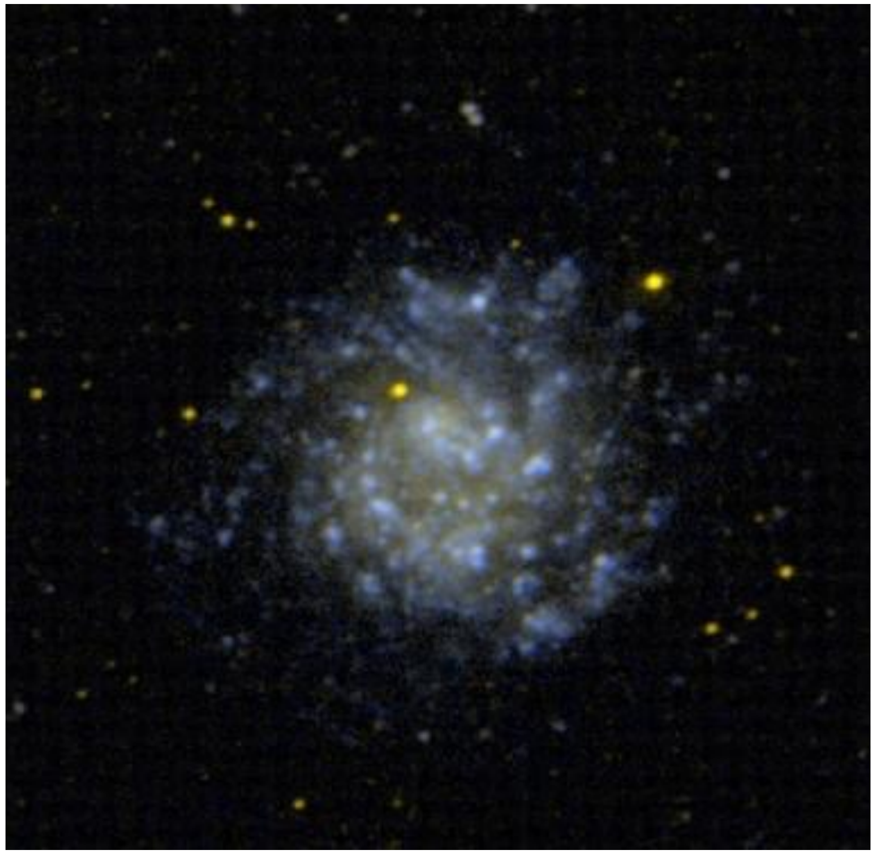
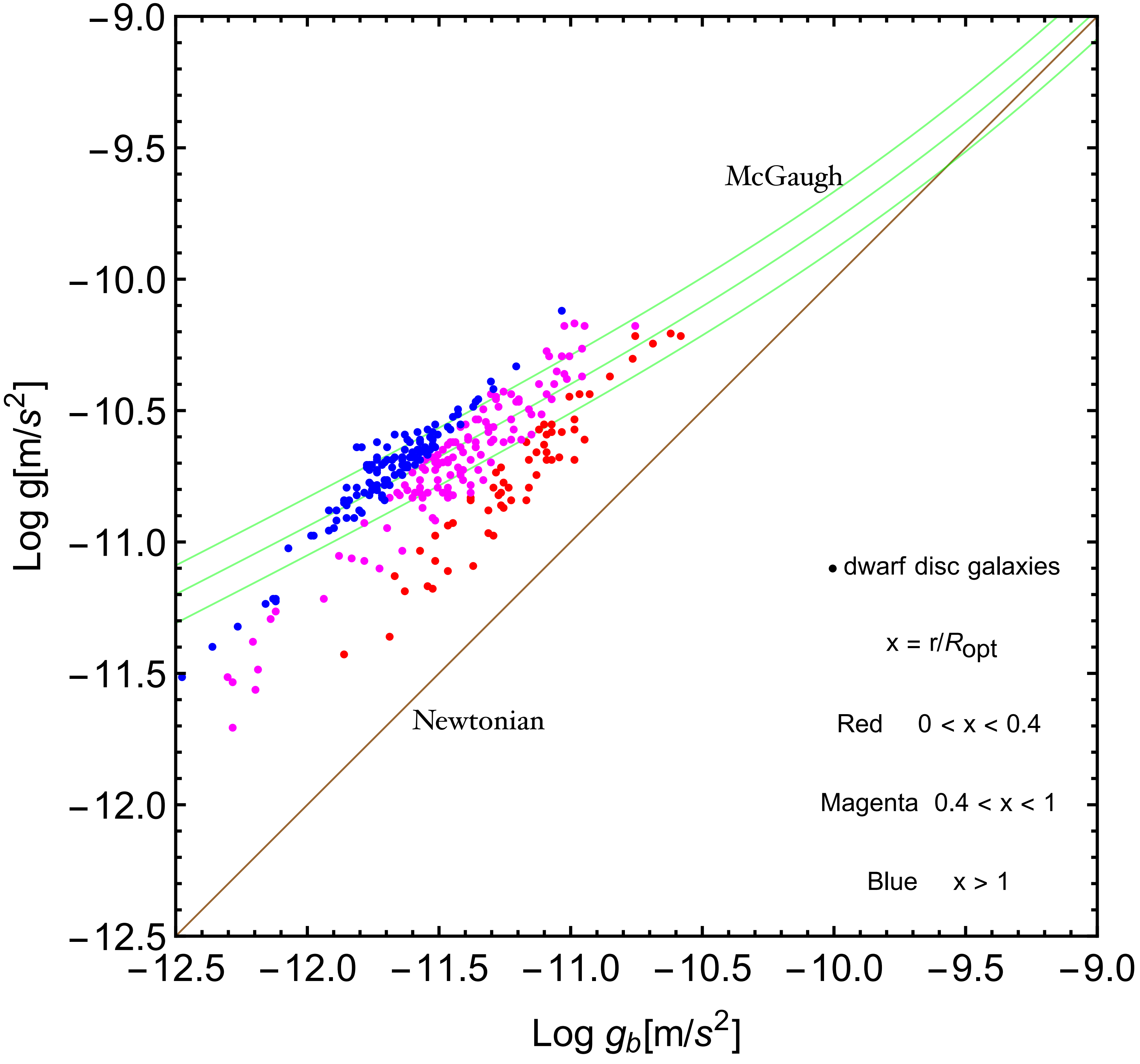




a) McGaugh relation breaks down

b) radial dependence

RAR: Gravitational acceleration relation

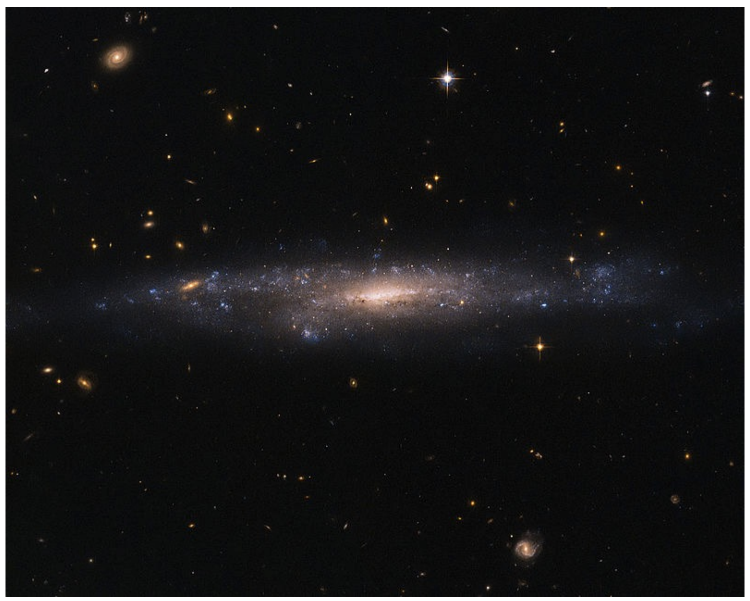
72 **Low Surface Brightness** galaxies

(Di Paolo & Salucci)

<u>1601 circular velocity measurements</u>

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

→ emit much less light per area than normal galaxies



RAR: Gravitational acceleration relation

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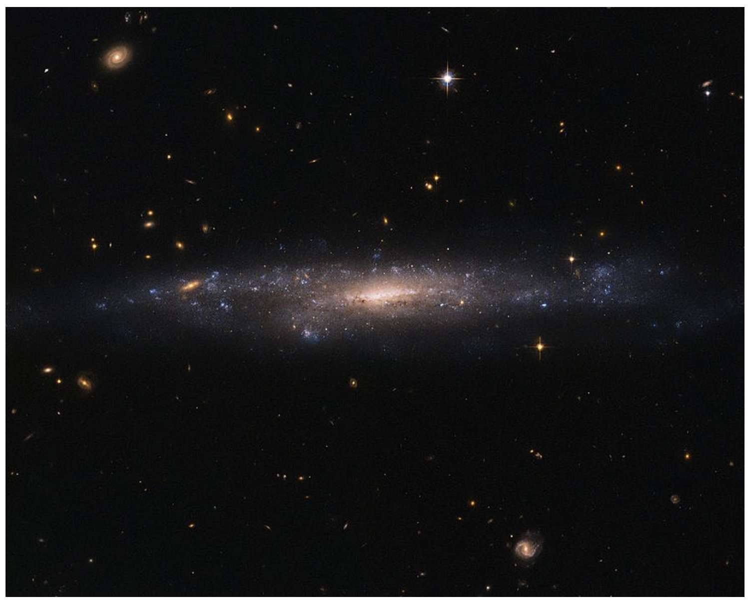
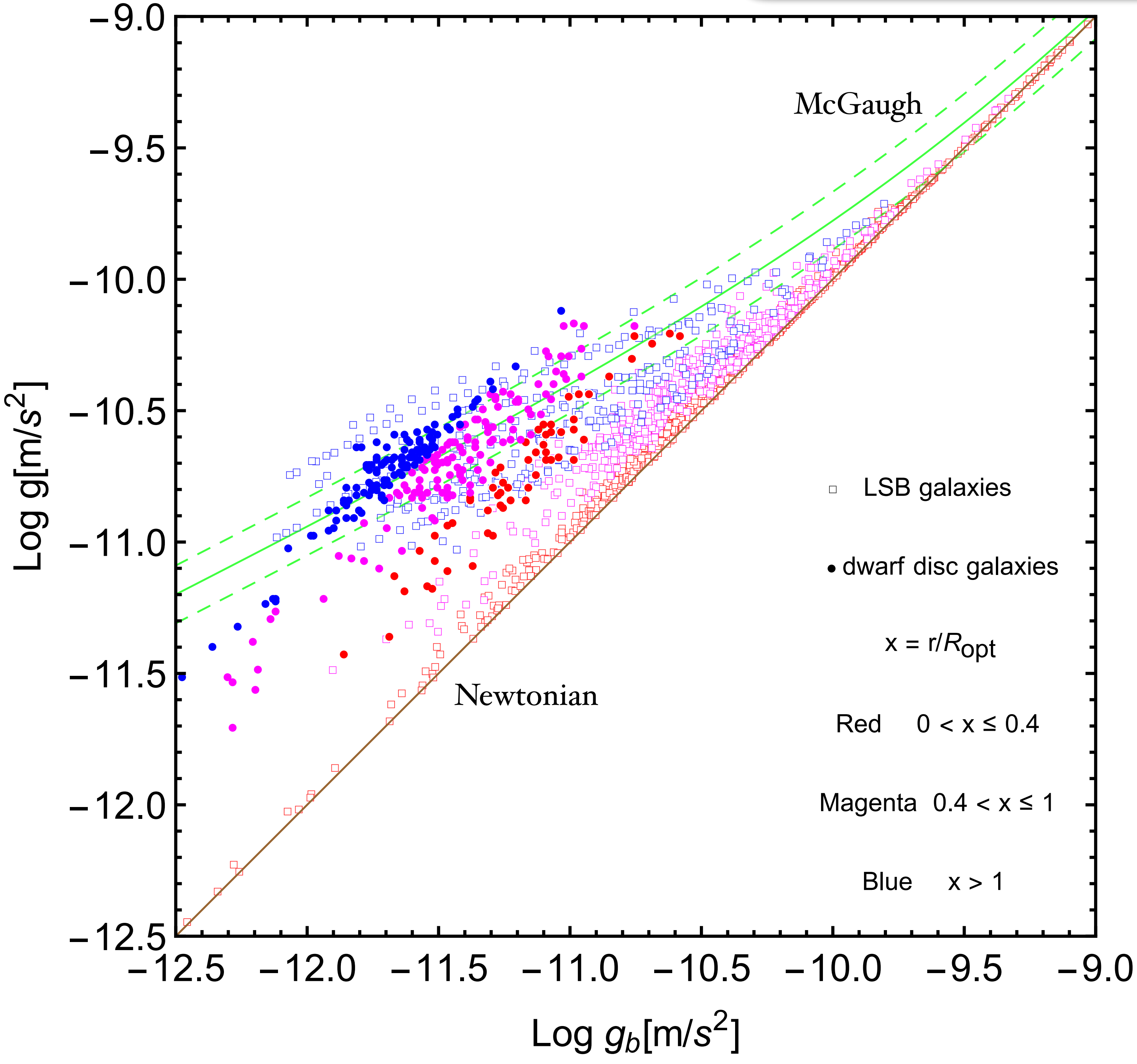




RAR: Gravitational acceleration relation

a) McGaugh relation breaks down

b) radial dependence

Why ?

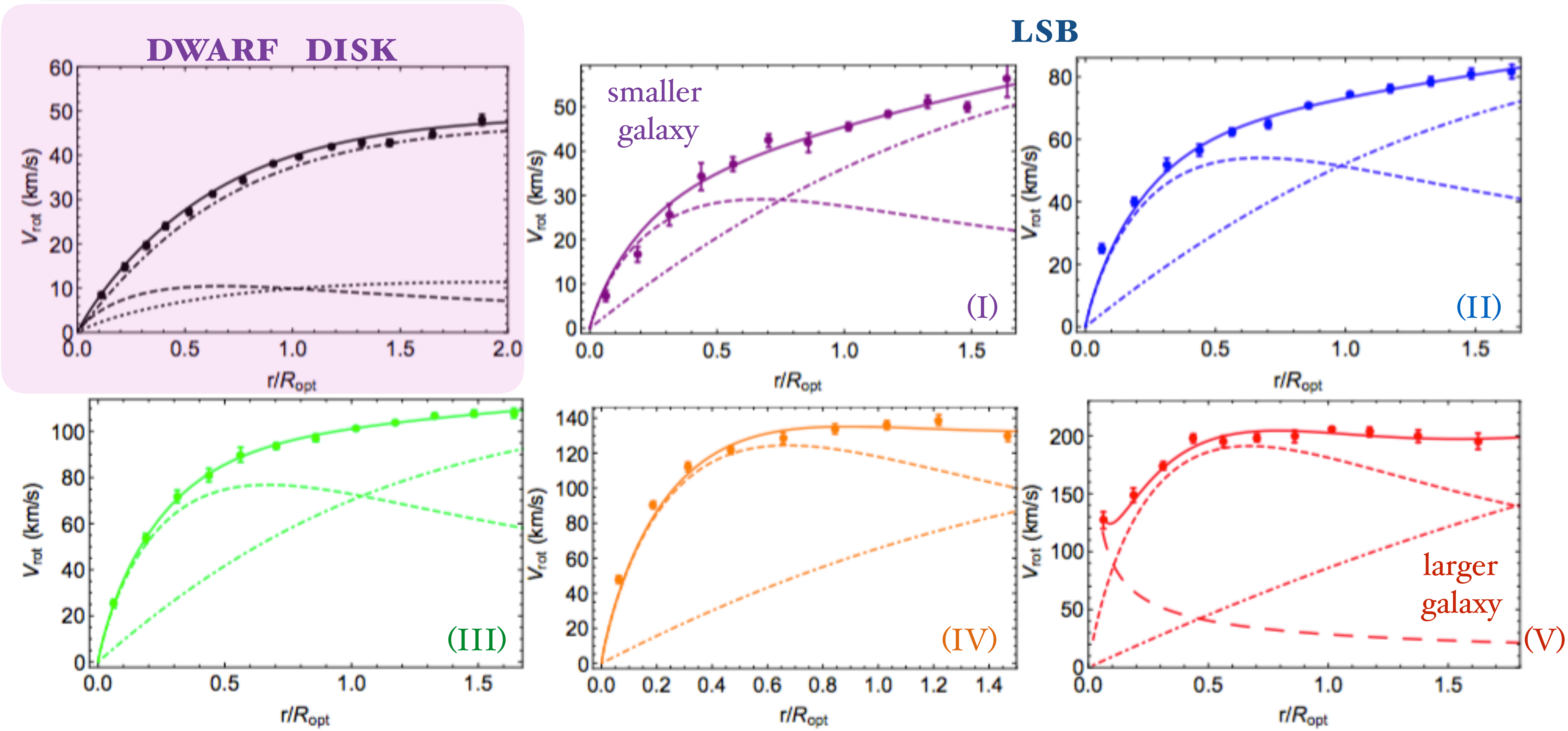
RAR: Gravitational acceleration relation

a) McGaugh relation breaks down

b) radial dependence

Why? A step back

Rotation Curves of Galaxies



RAR: Gravitational acceleration relation

Galaxy components :

- Freeman stellar disc
- Burkert (cored) DM halo
- HI gaseous disk (Dwarf Disks)
- Bulge (larger LSB galaxies)

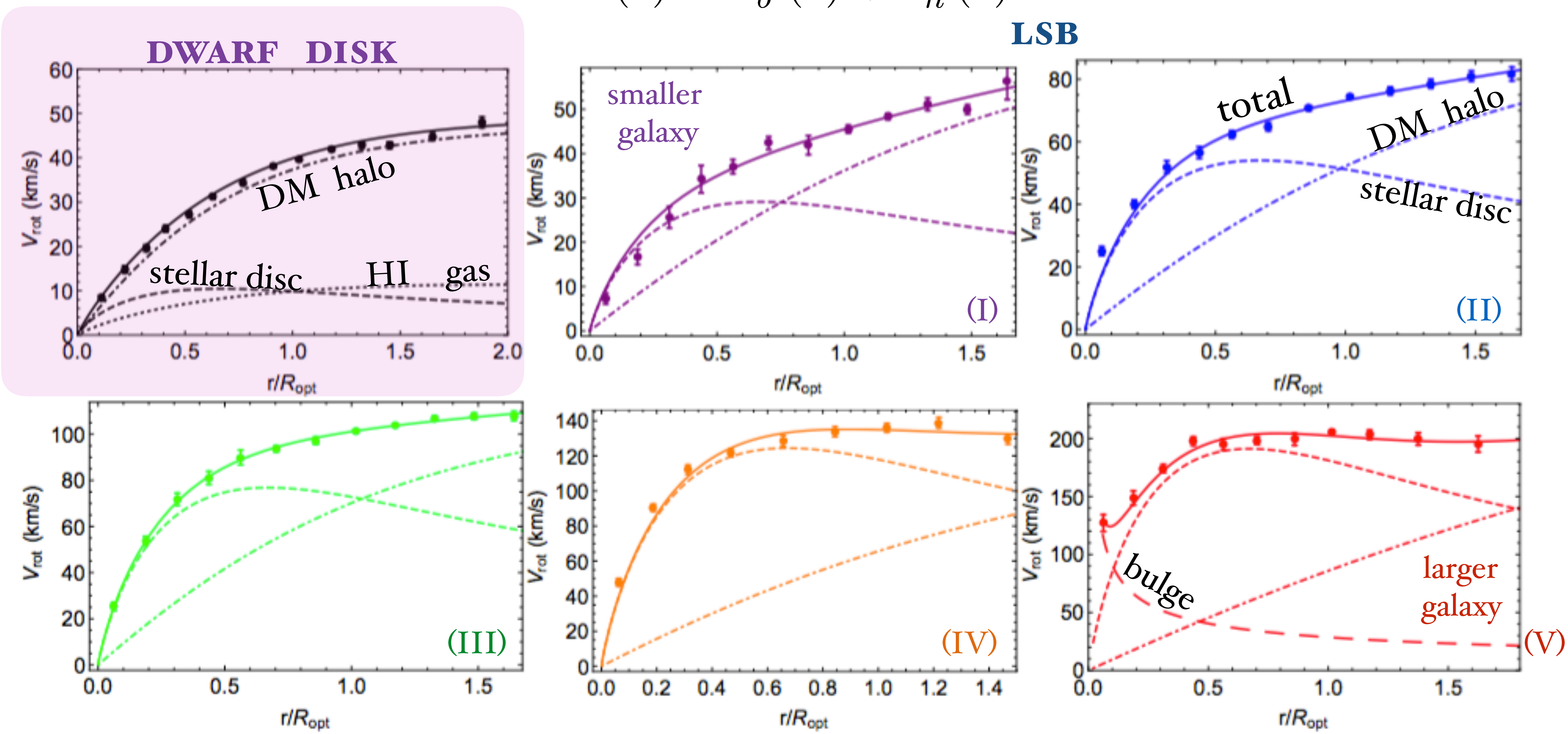
$$V_i^2(r) = G\frac{M_i(r)}{r}$$

Baryonic contribution :

$$V_b^2(r) = V_d^2(r) + V_{bu}^2(r) + V_{HI}^2(r)$$

Total contribution :

$$V^2(r) = V_b^2(r) + V_h^2(r)$$



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Total contribution :

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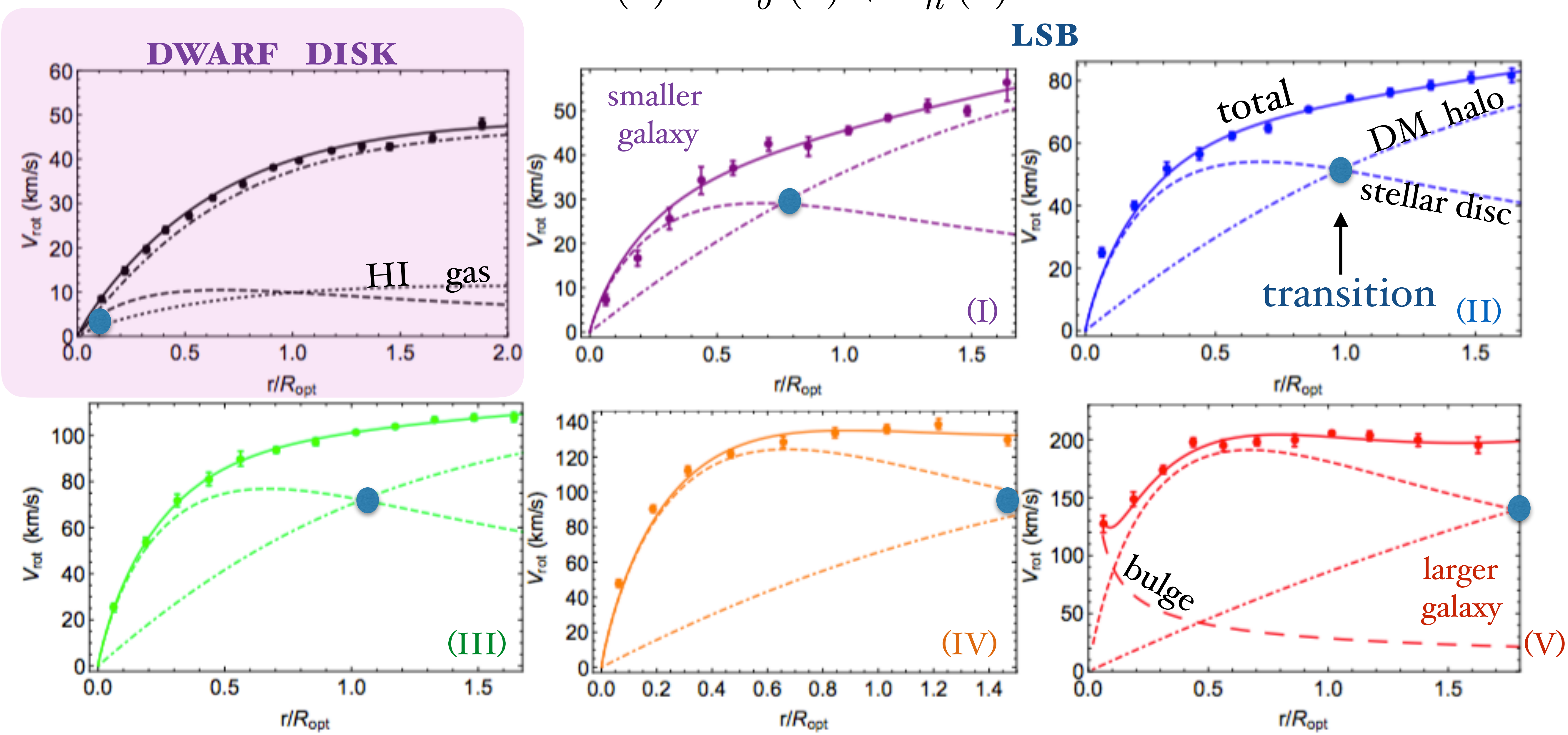
Baryonic fraction

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



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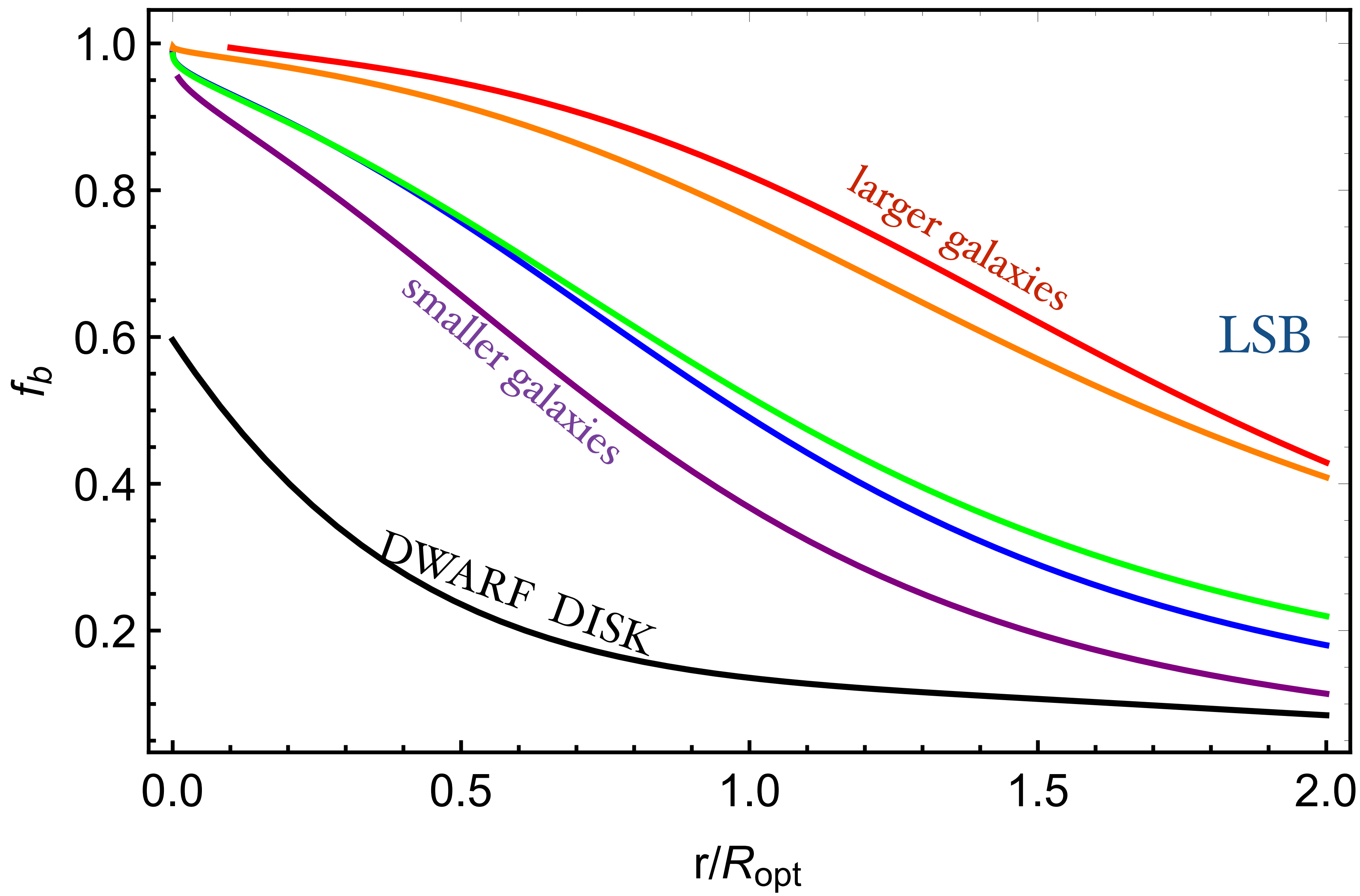
NOTE:
radial dependence



R_{opt} ➔ optical radius
size of the stellar disk
(83 % of total luminosity)

RAR: Gravitational acceleration relation

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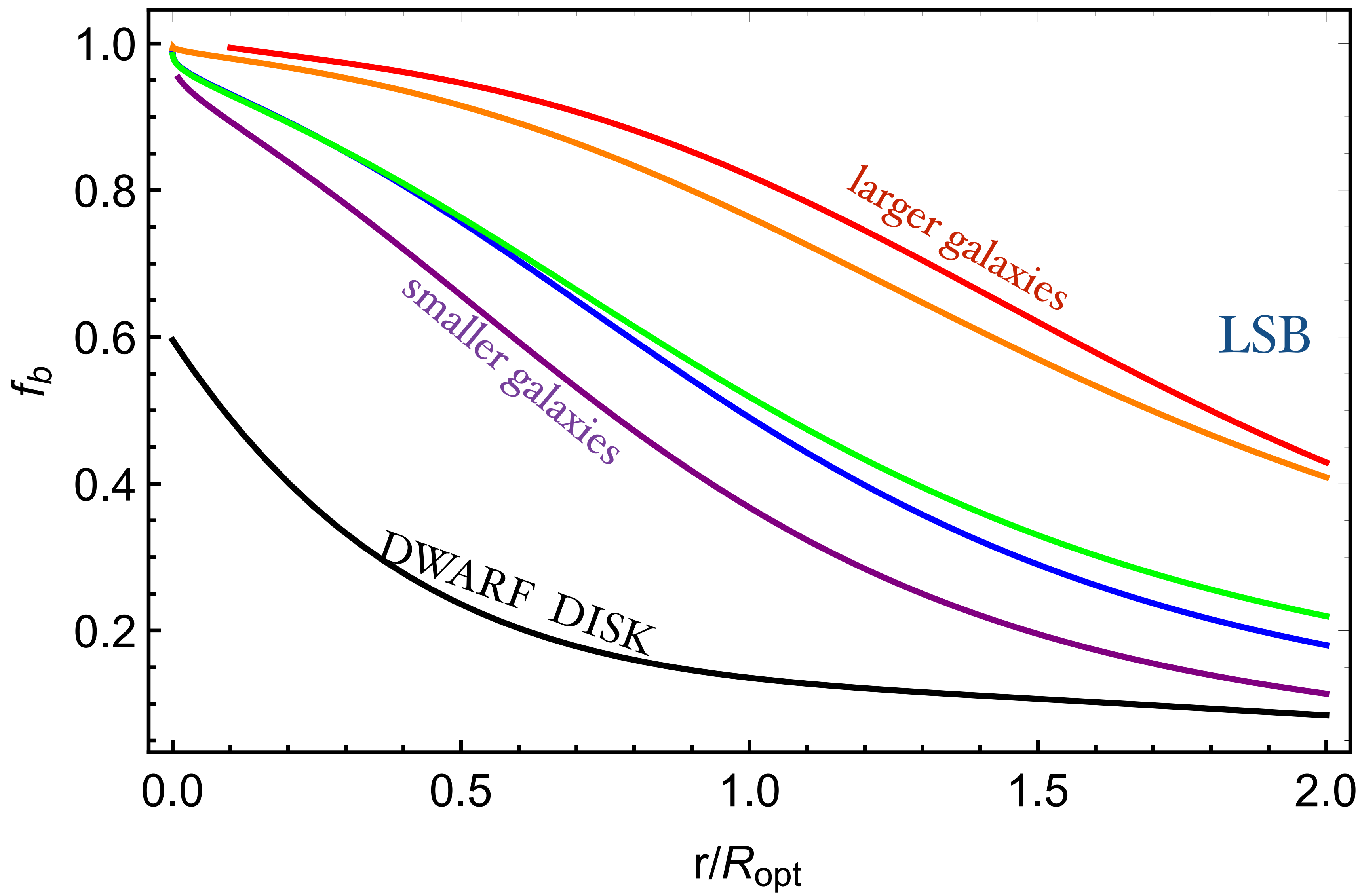

For all single data measurements ($r, V(r)$) we evaluate:

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

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

RAR: Gravitational acceleration relation

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NOTE:
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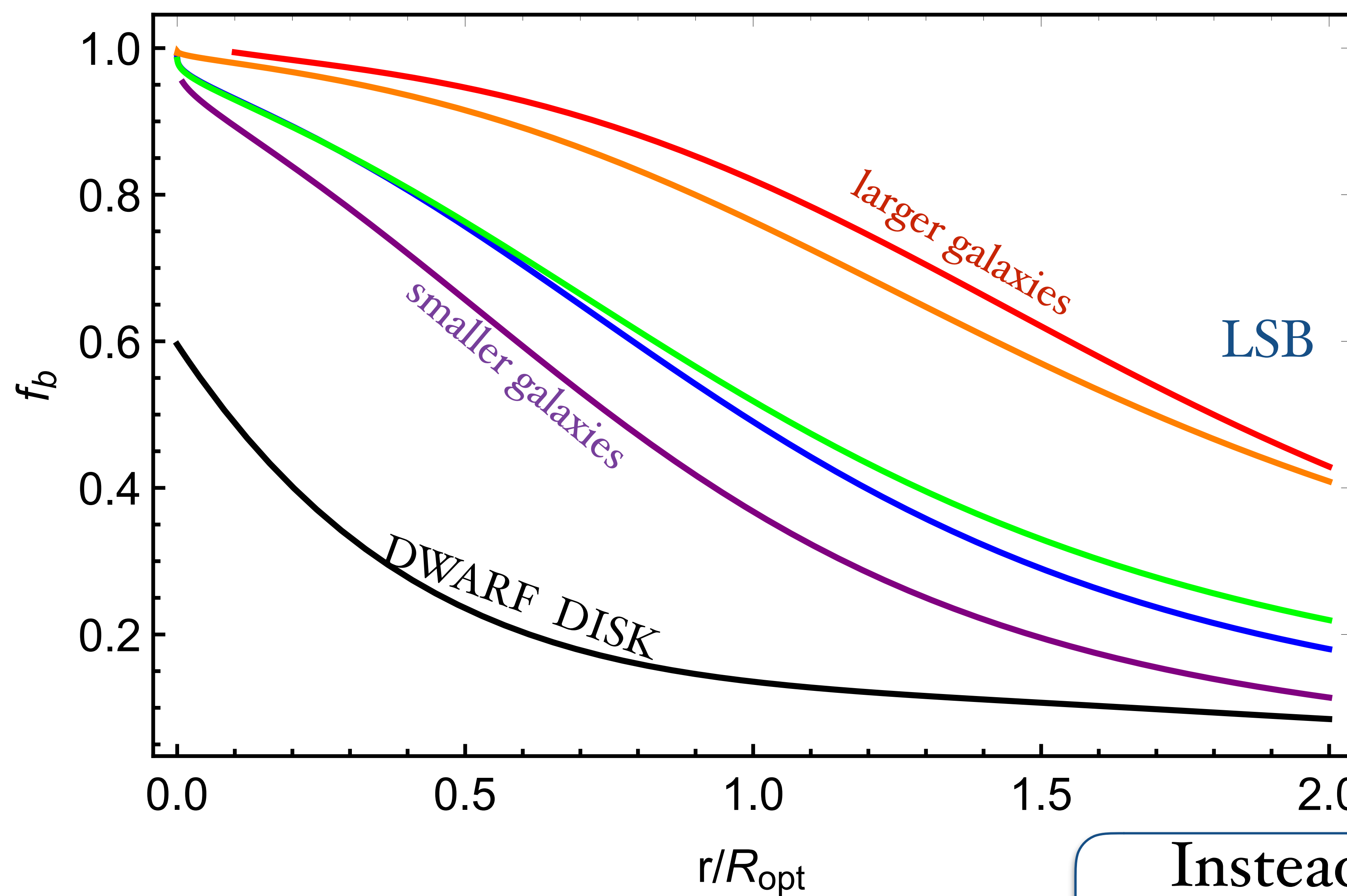

Instead McGaugh agnostic to the presence of DM

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

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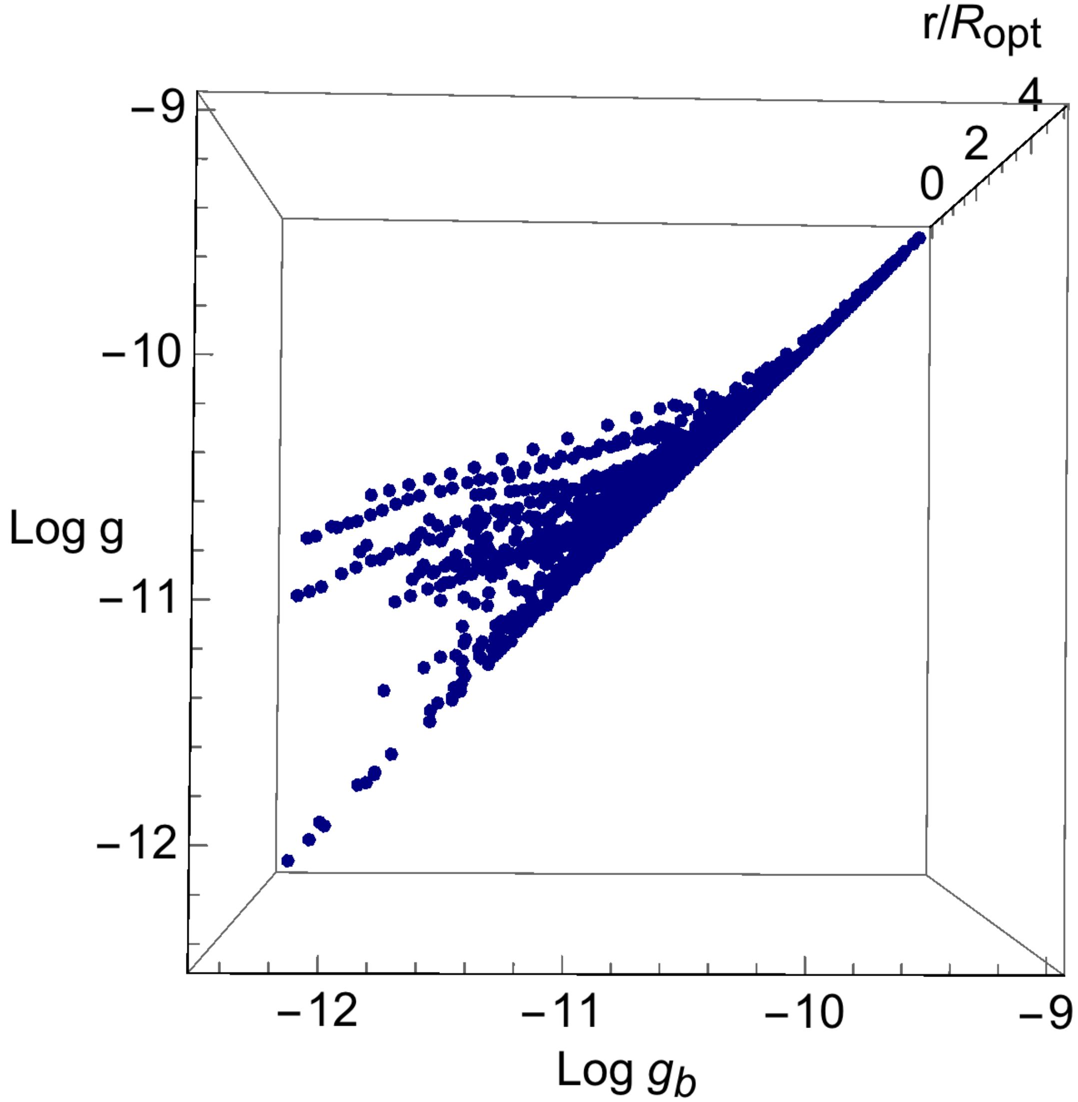
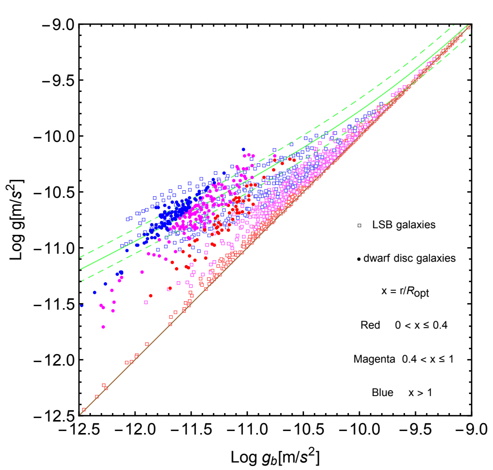
g , g_b , x **test**



LSB

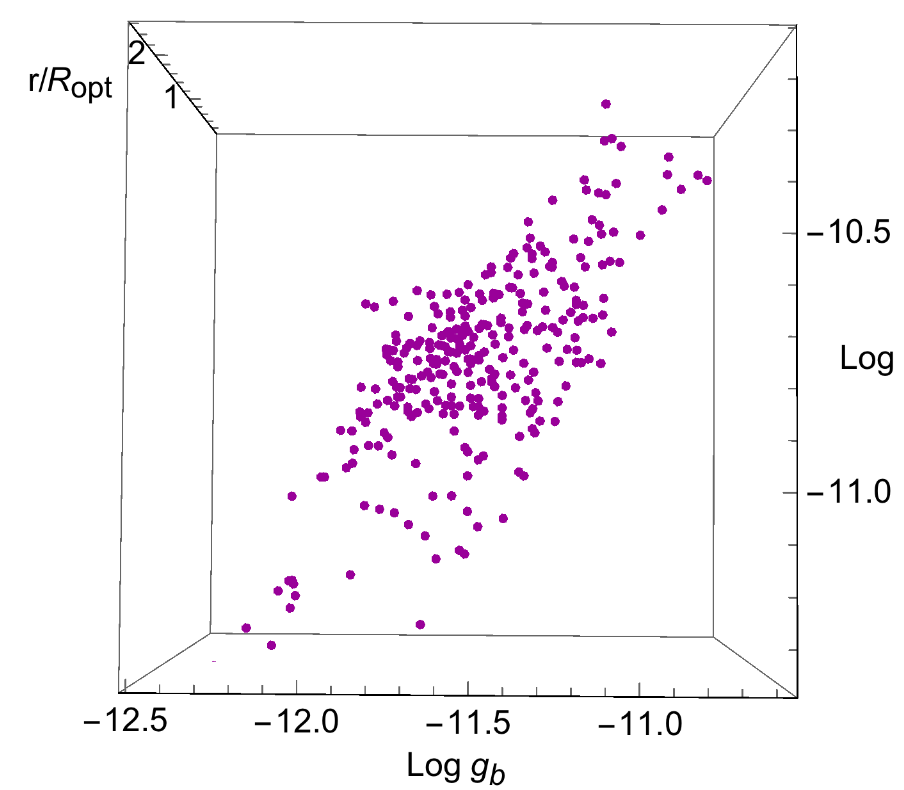
$$x = r/R_{opt}$$

g , g_b , x **test**

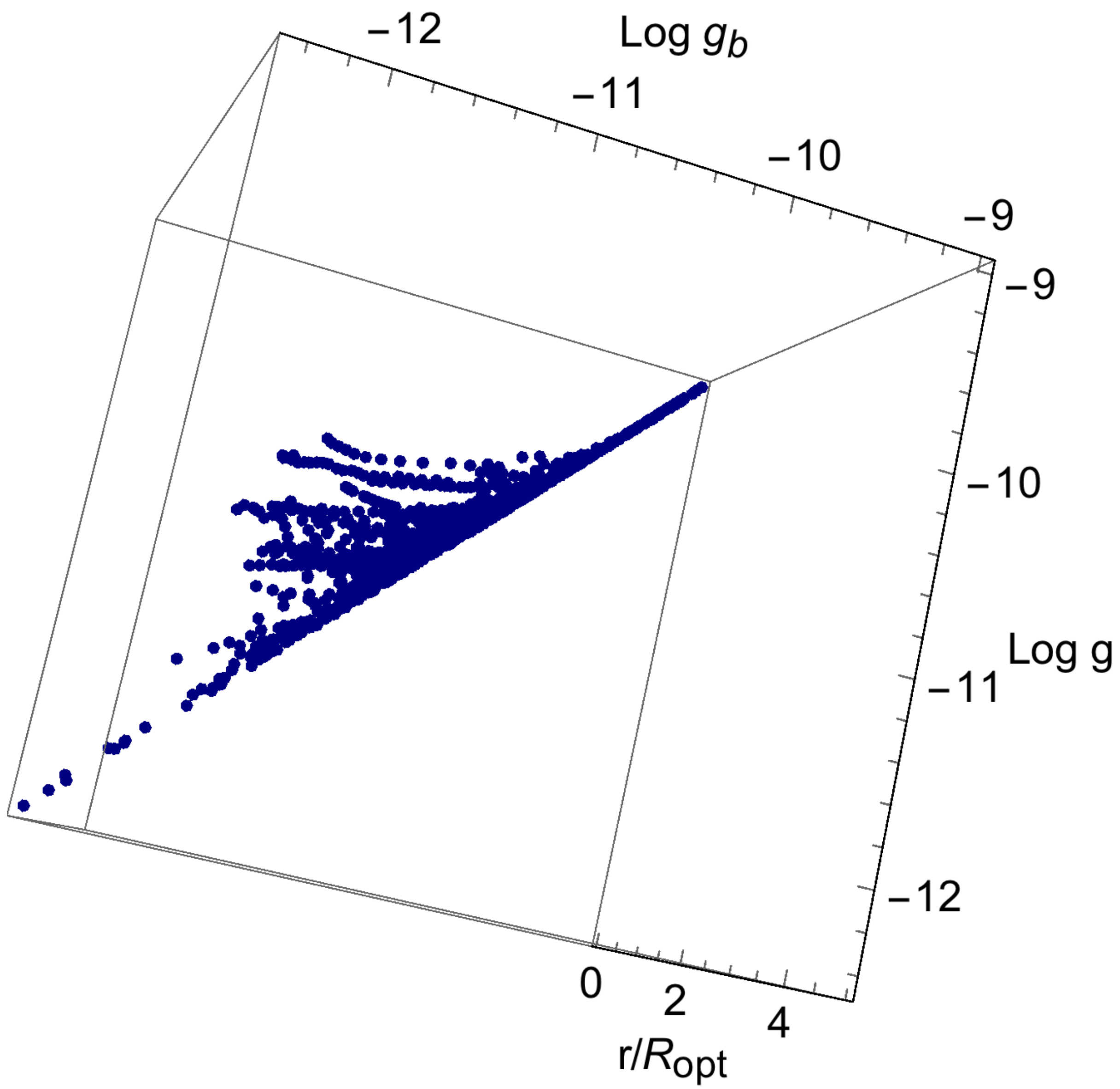


radial dependence

Dwarf disks



$g \ , \ g_b \ , \ x$ **test**



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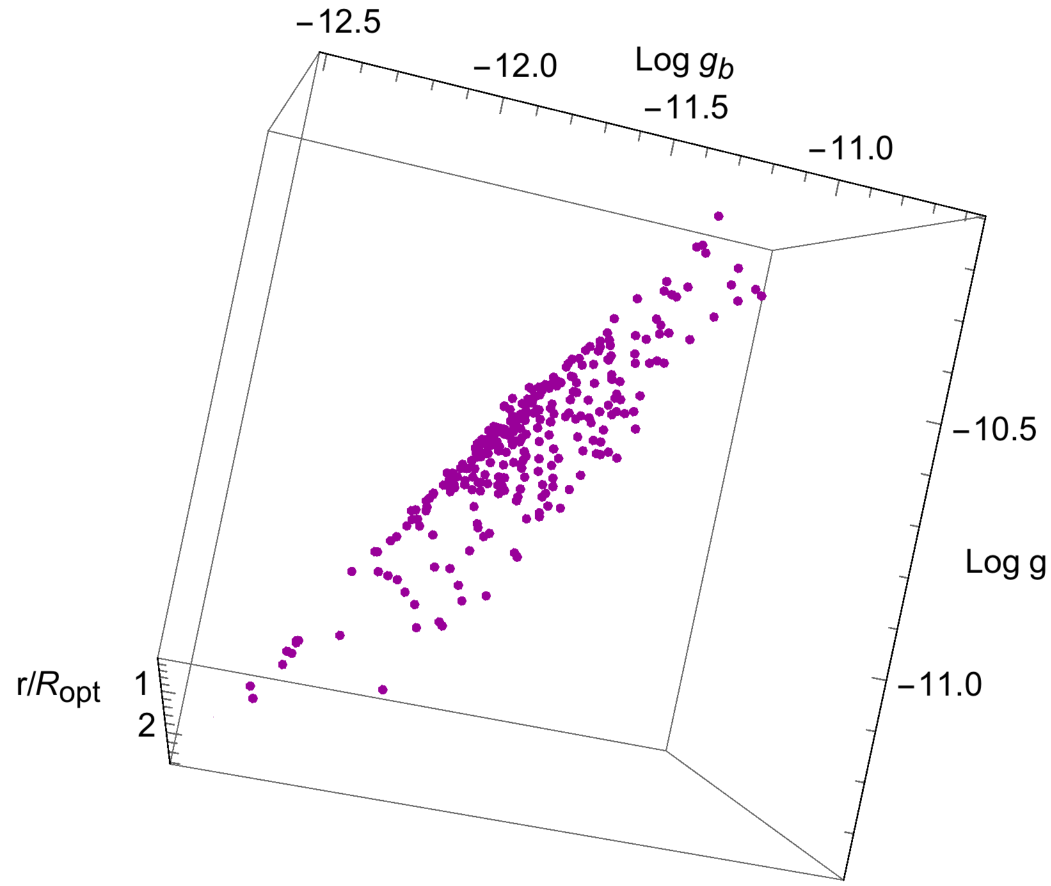

Dwarf disks

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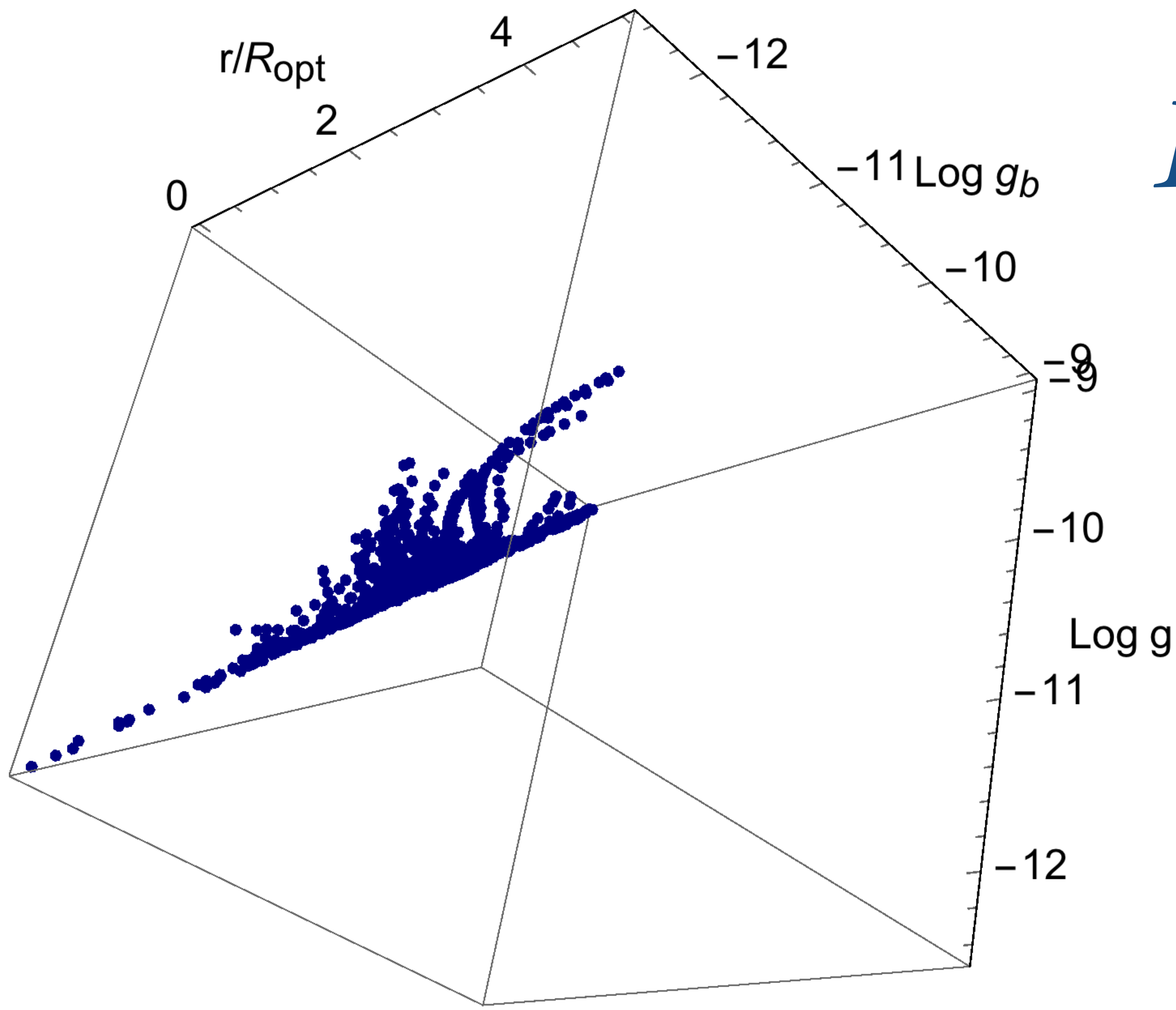
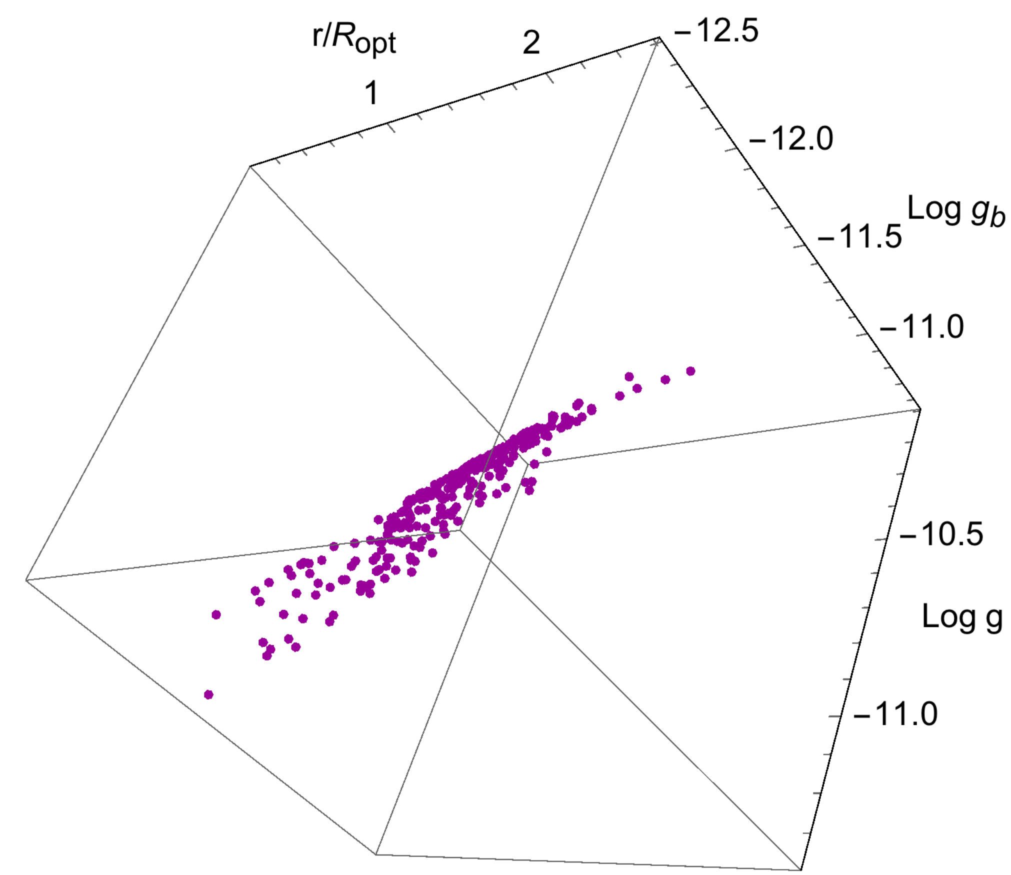
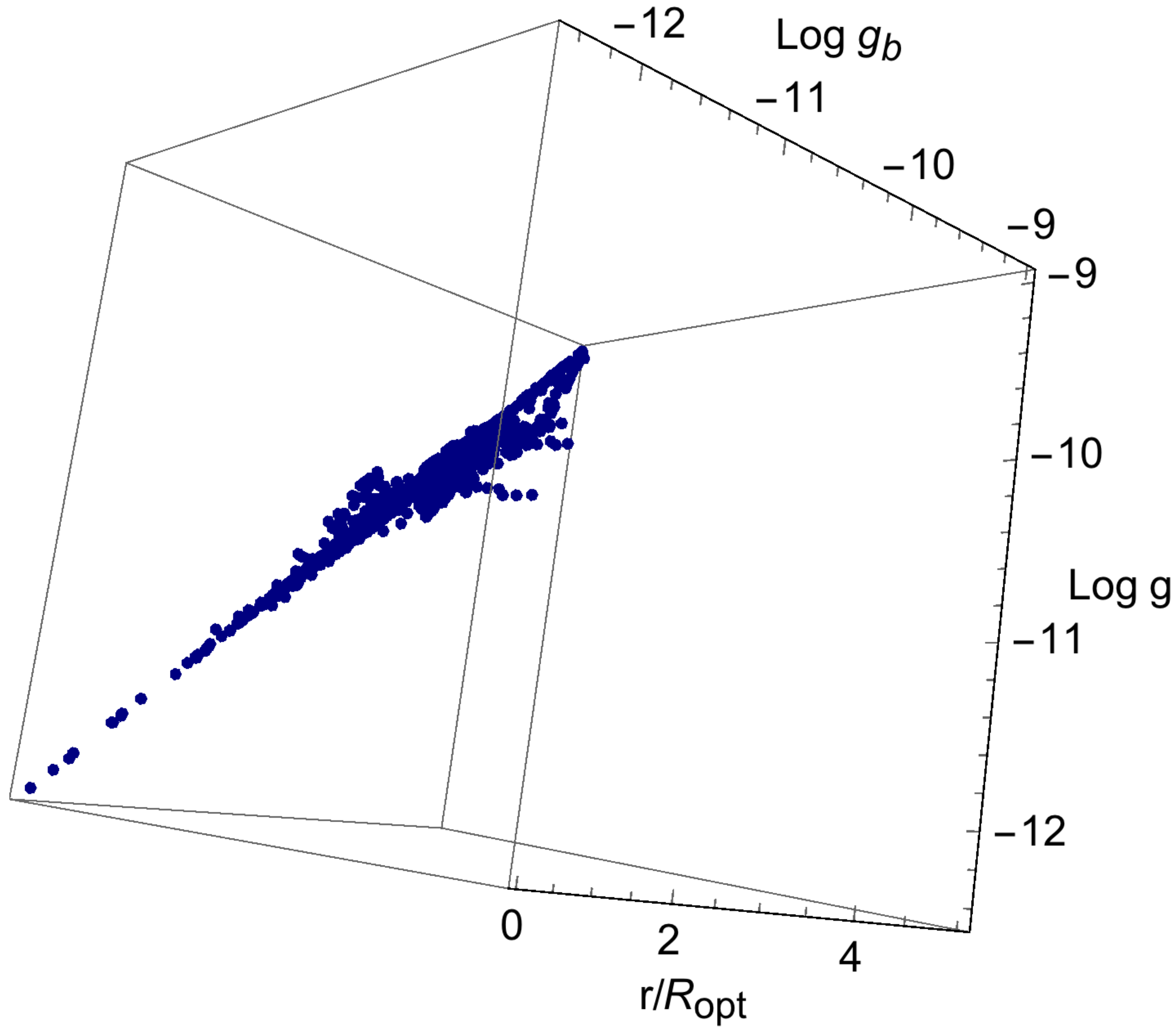




Dwarf disks

$g\ ,\ g_b\ ,\ x$ test

LSB



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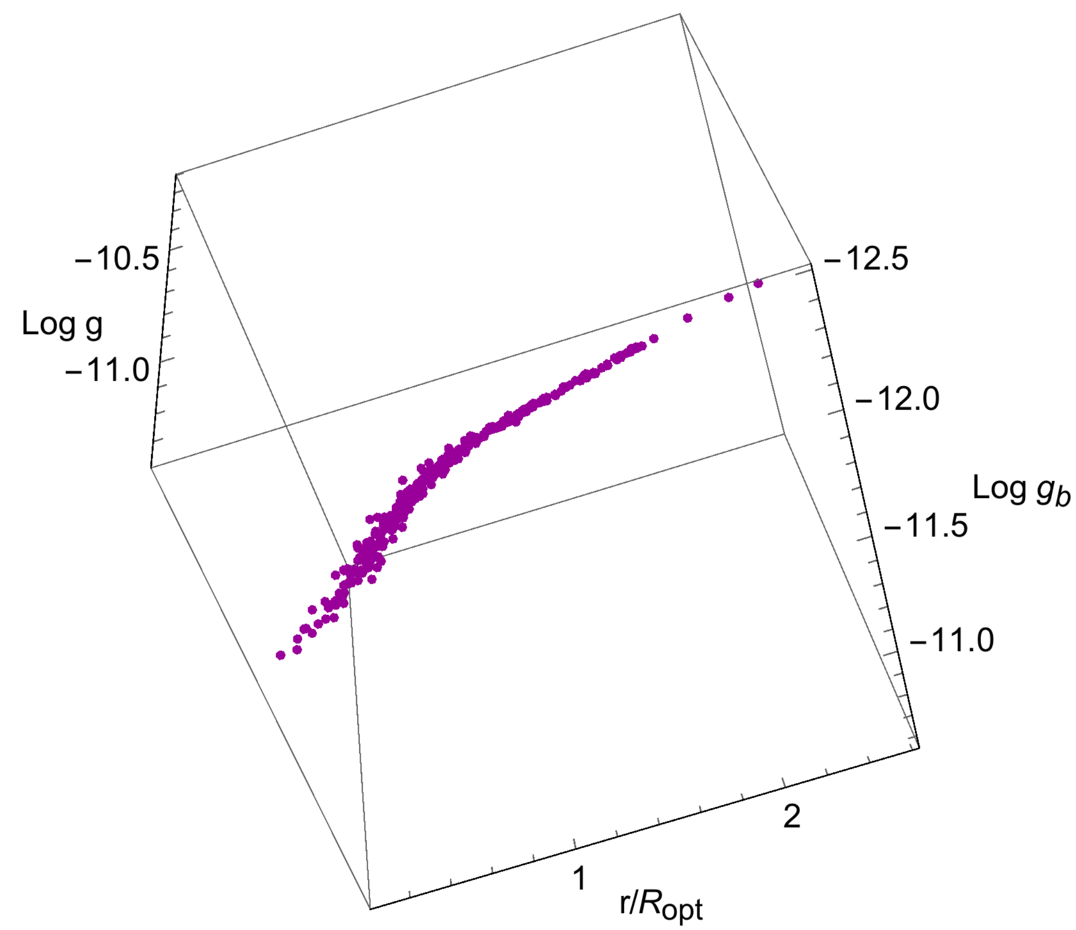

Dwarf disks

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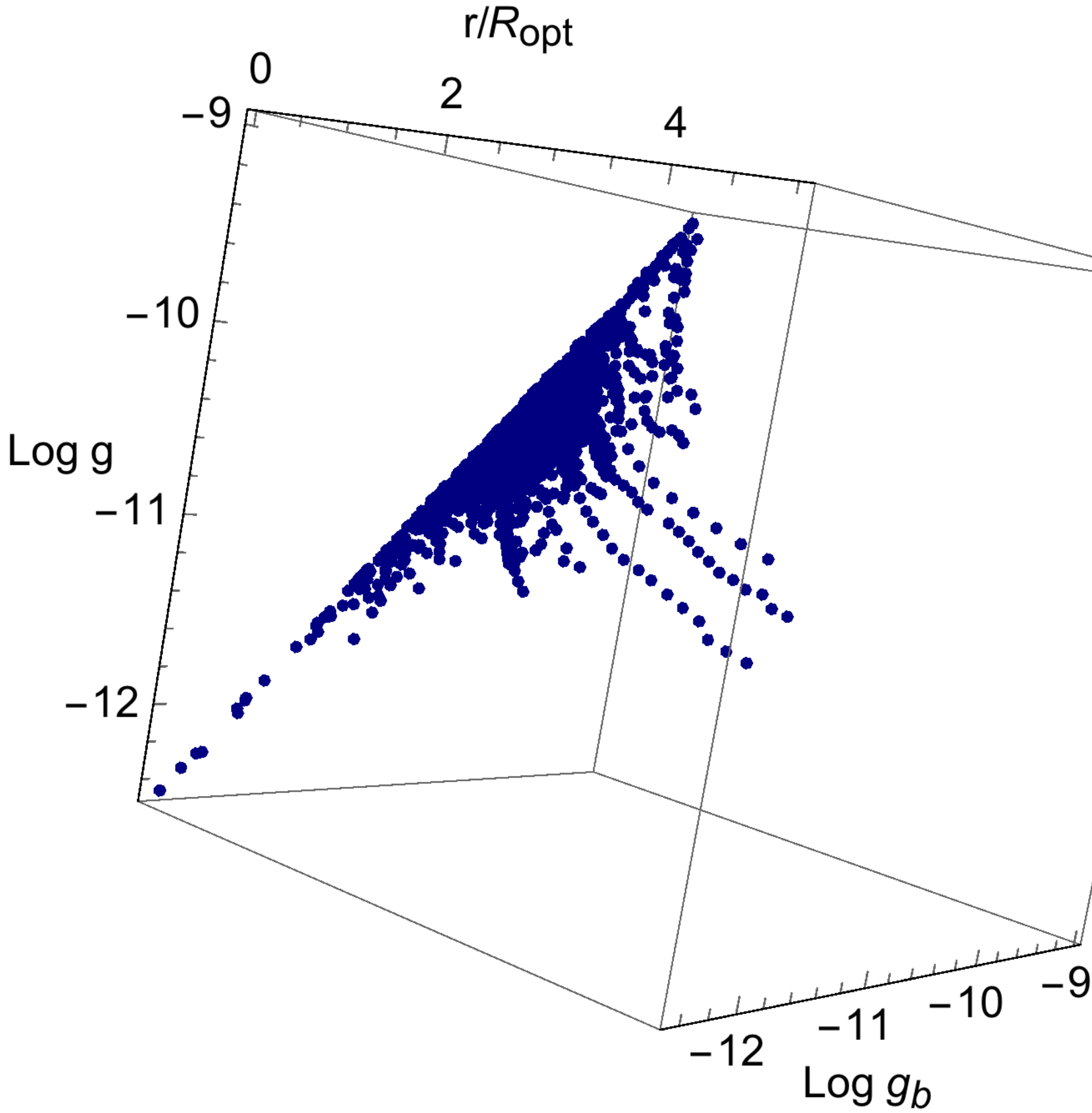
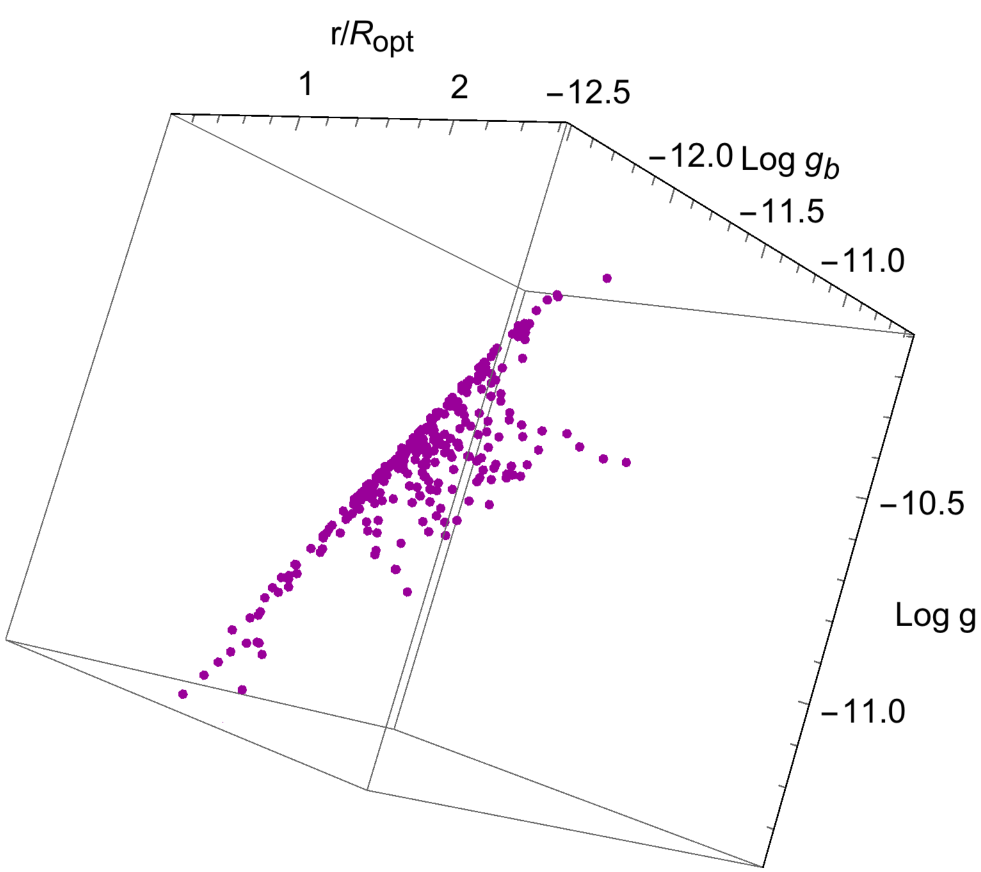


$$x = r/R_{opt}$$

g , g_b , x **test**



Dwarf disks

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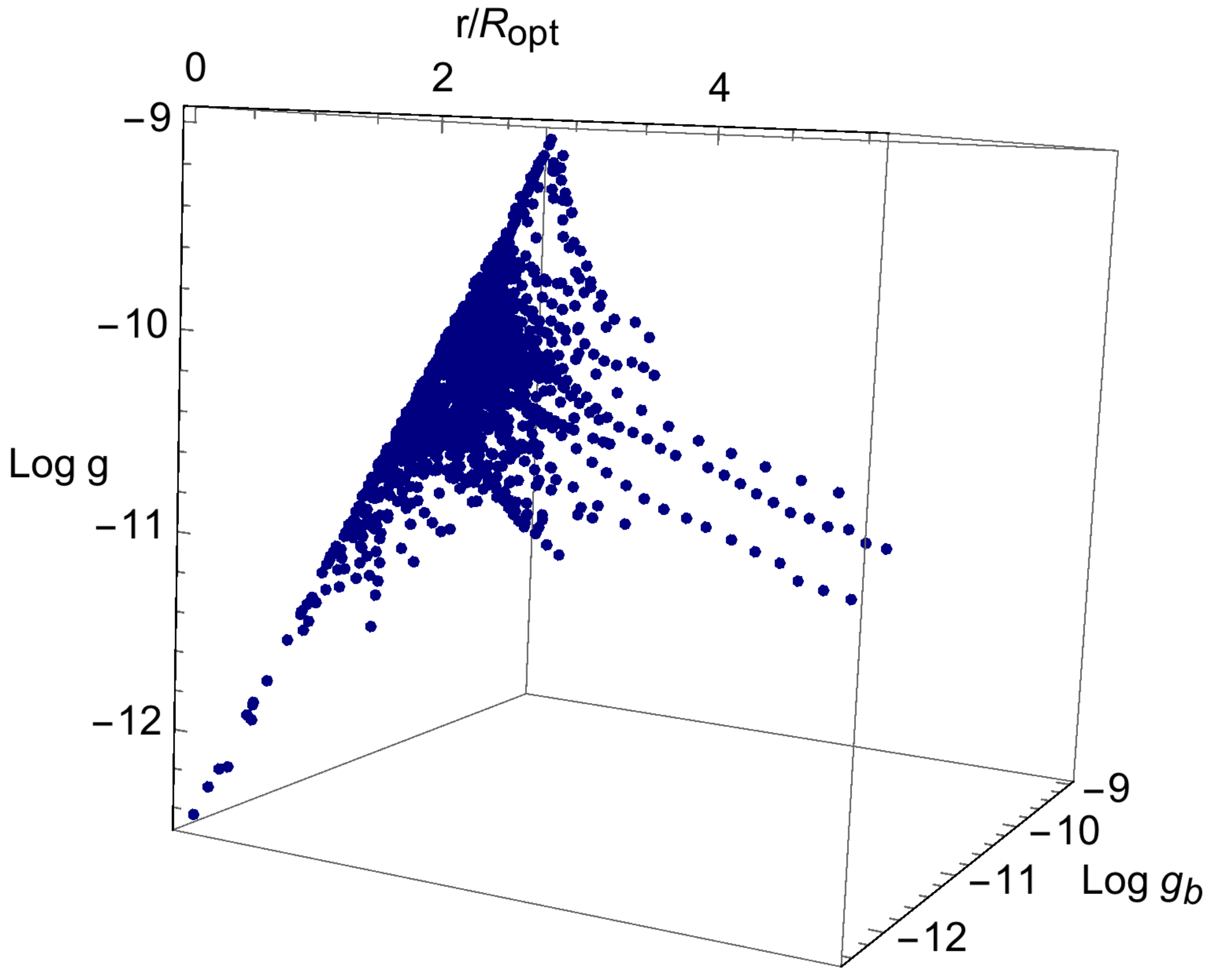

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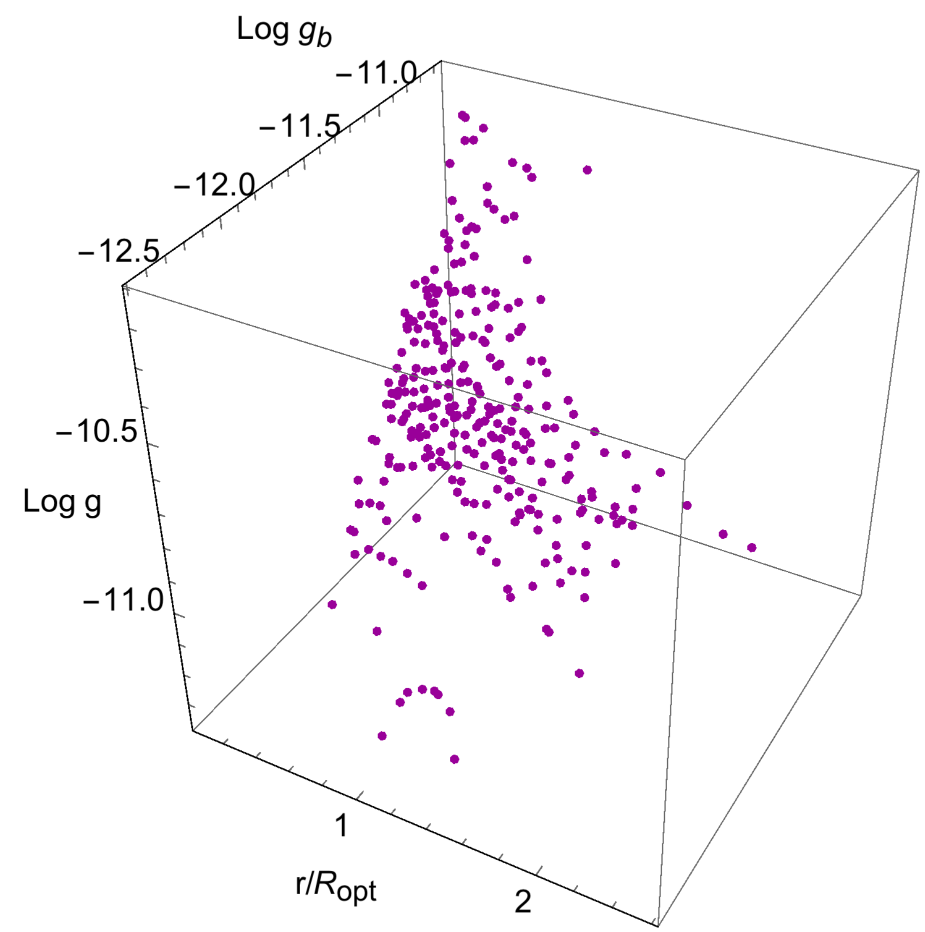

Dwarf disks

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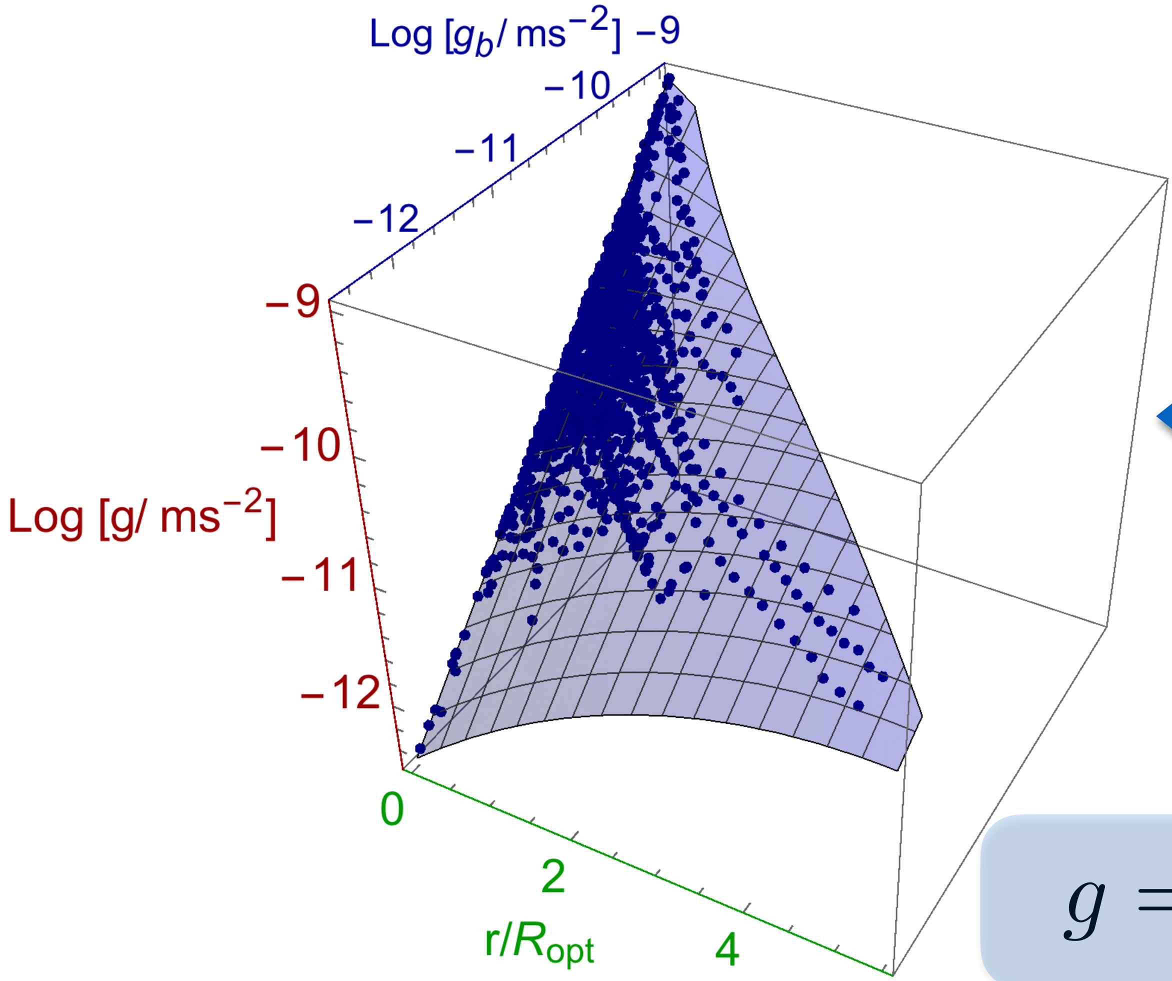


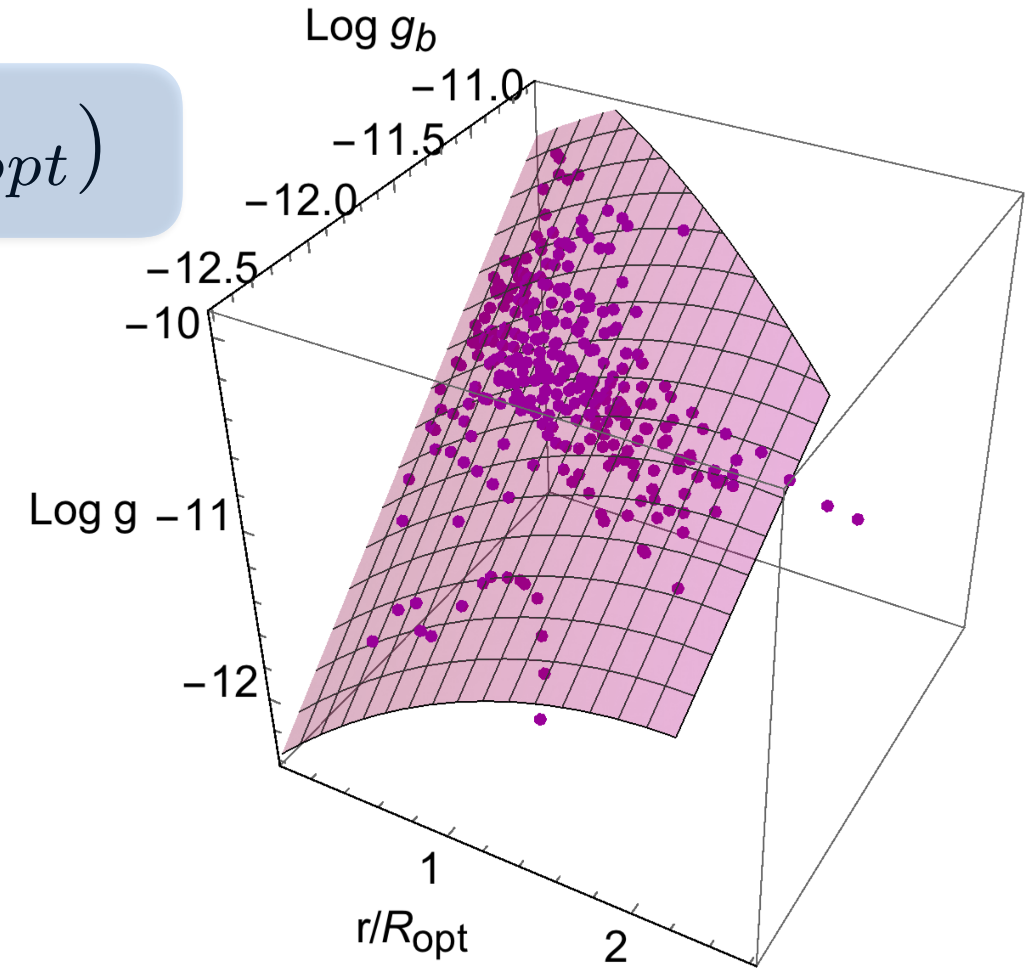
LSB

$x = r/R_{opt}$

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

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

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



Dwarf disks

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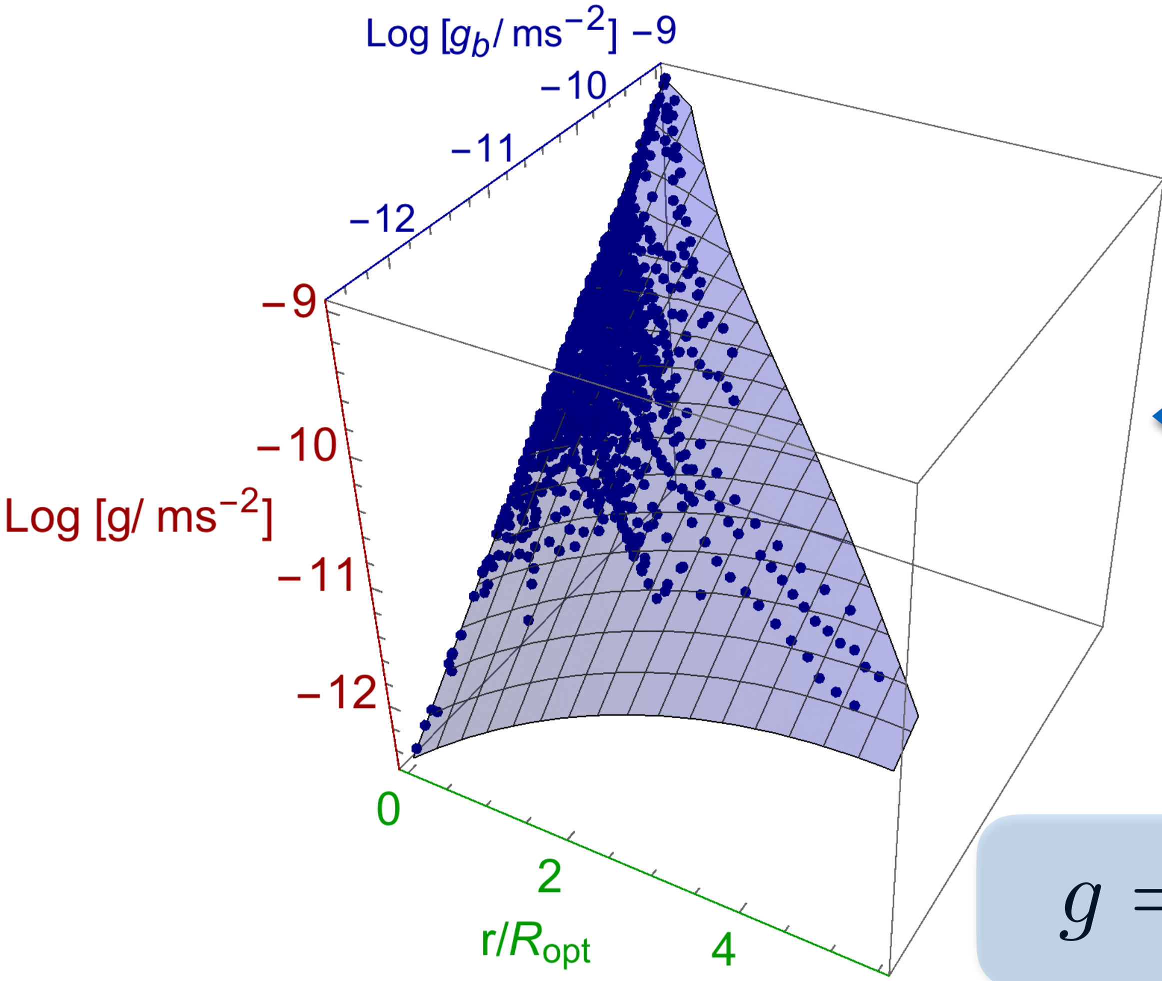

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a	b	c	d
-0.95	1.79	-9.01	-0.05

σ : 0.31 → 0.05 dex

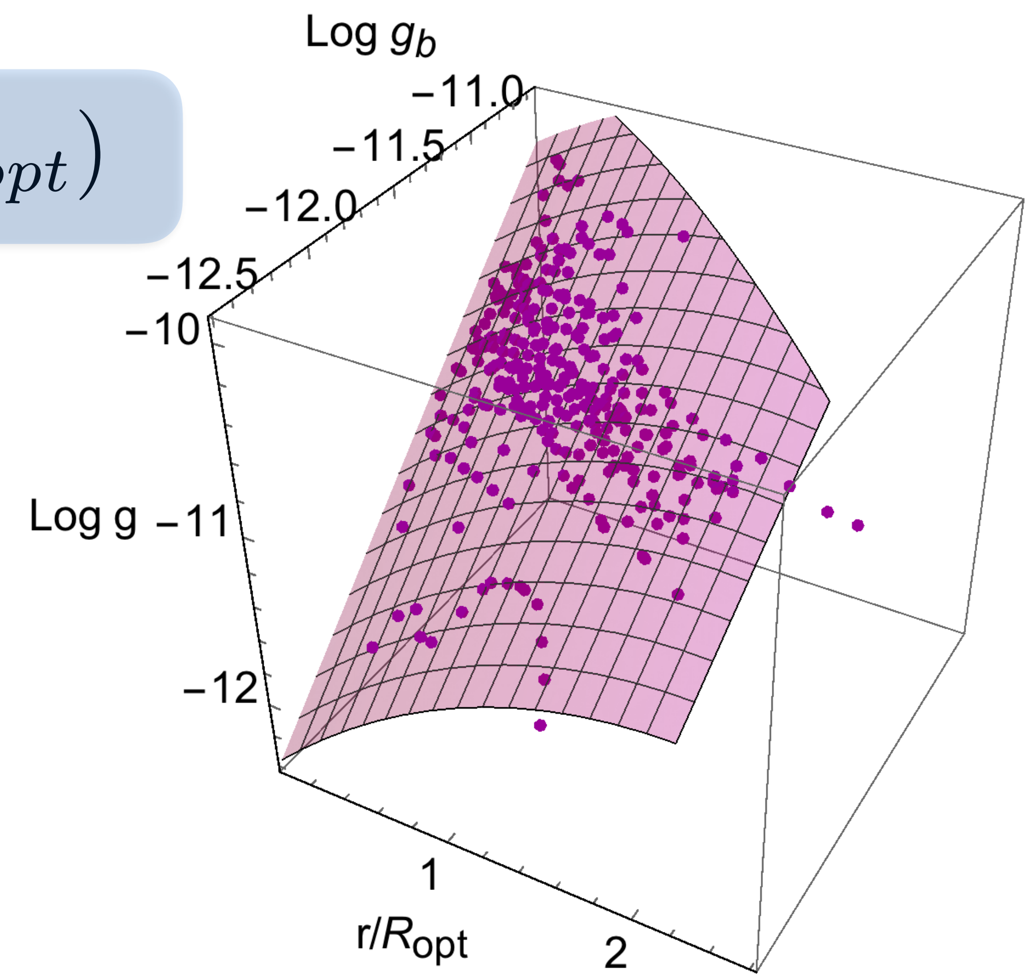
$g = f(g_b,\, r/R_{opt})$

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

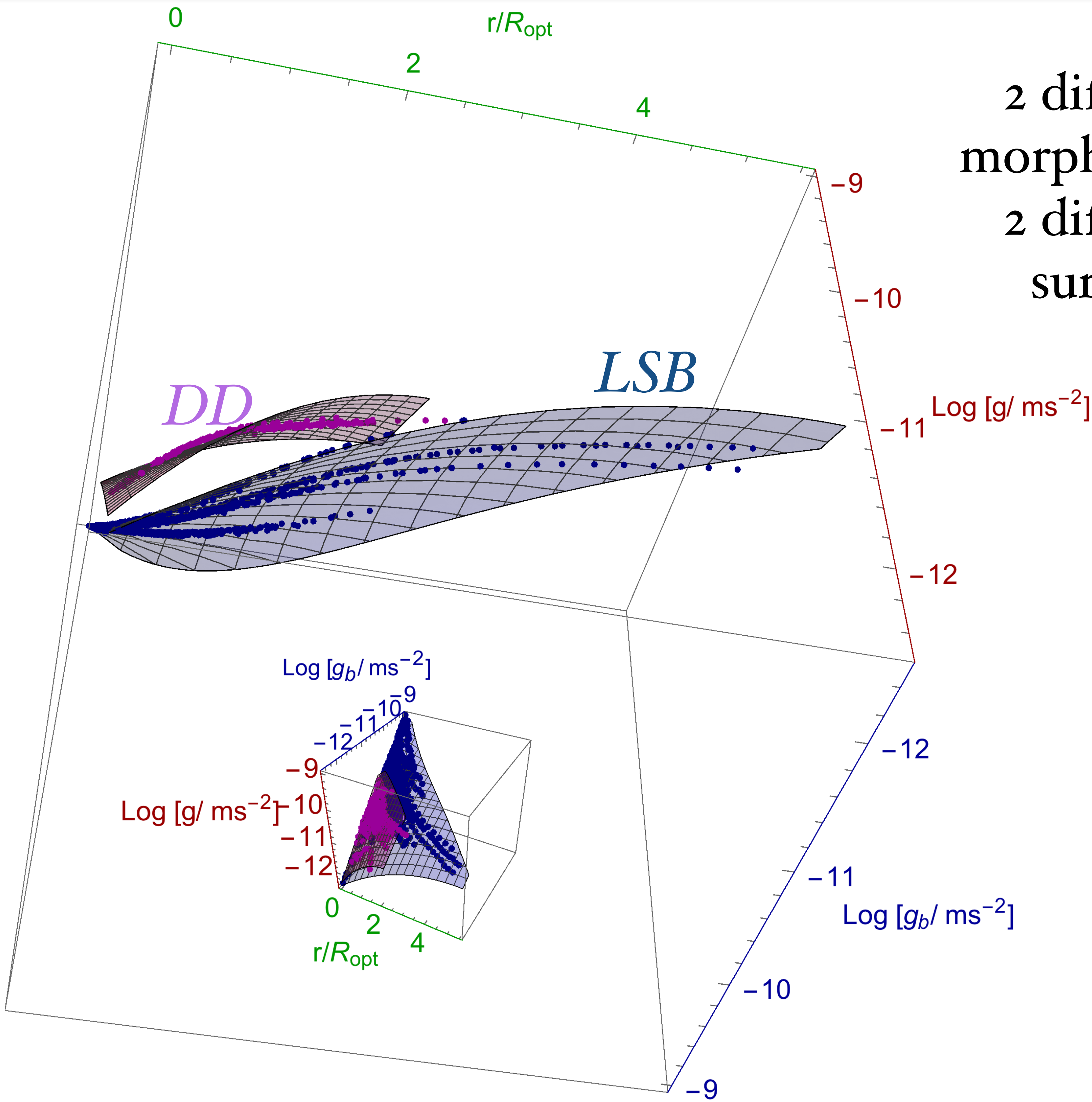
l	h	m	n	q
0.49	2.41	0.74	1.72	1.19

σ : 0.17 → 0.03 dex

Dwarf disks



g , g_b , x **test**



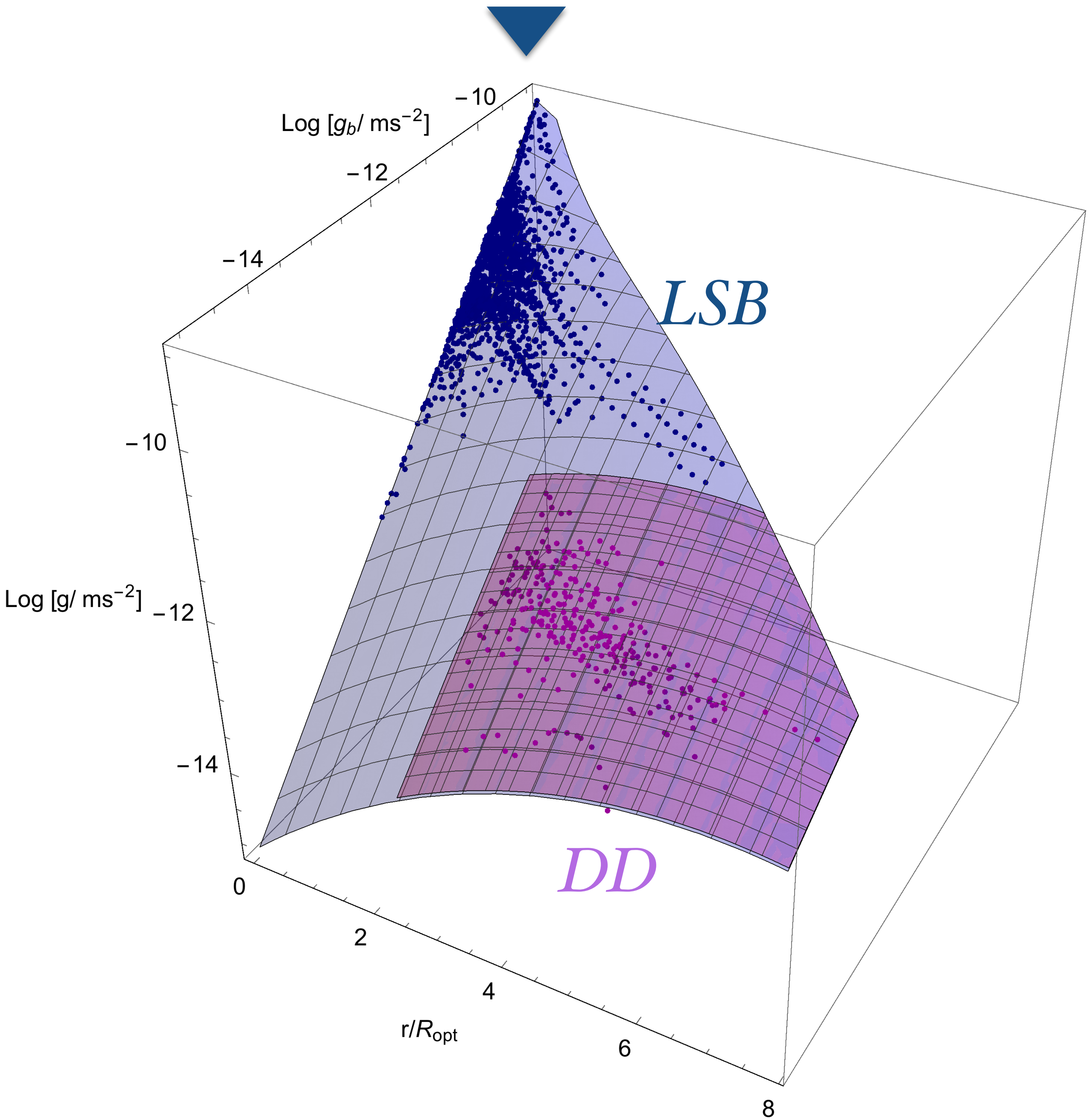
2 different morphologies, 2 different surfaces

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

g , g_b , x **test**

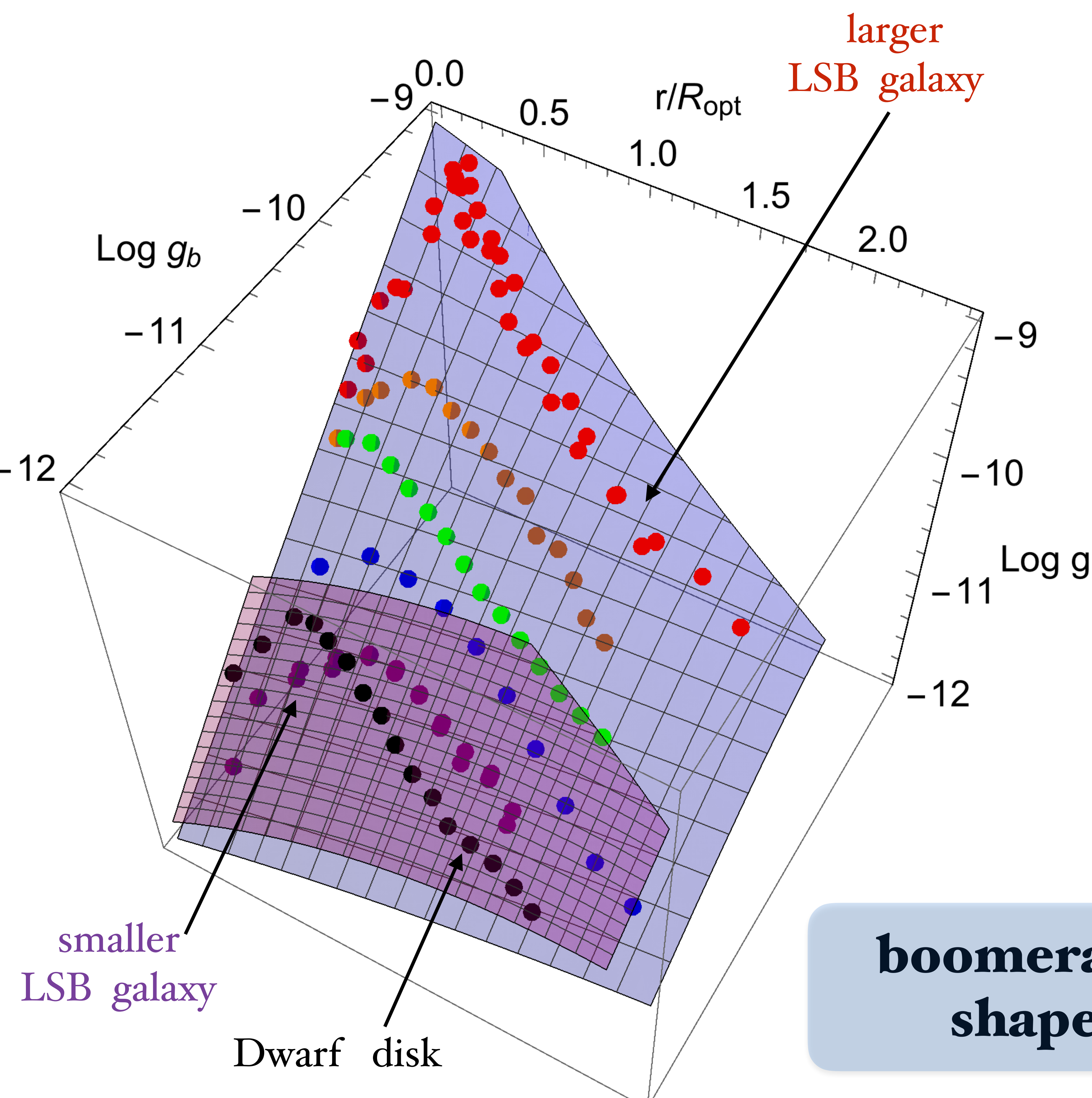
Simple translations and/or dilations

$x = r/R_{opt}$



universal relation

g , g_b , x single galaxies test



a) larger galaxies ▶ higher g and g_b

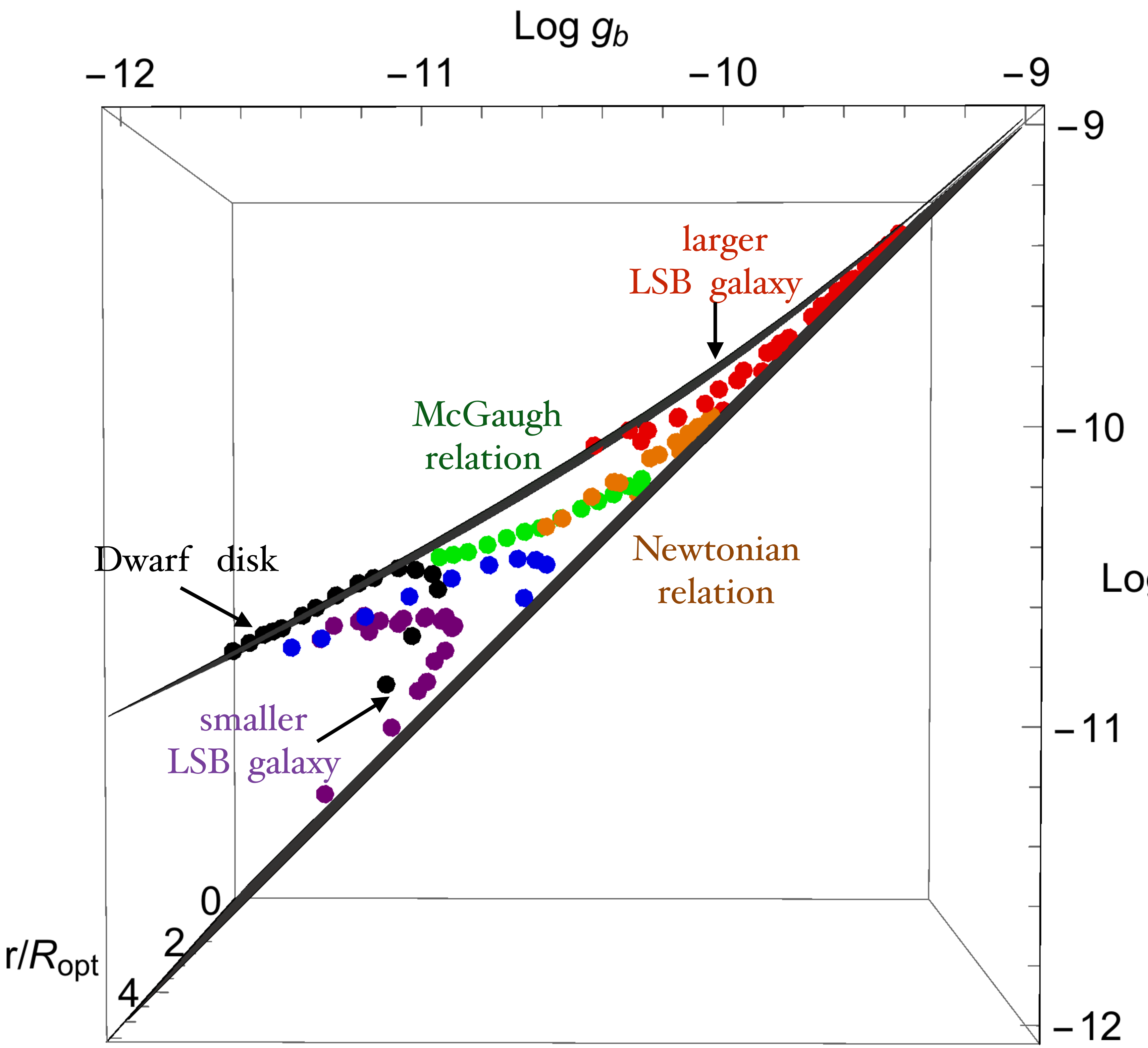
b) $g \gtrsim g_b$ growth till R_D (stellar disk scale length)

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

c) $g > g_b$ decrease beyond R_D

boomerang shape

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



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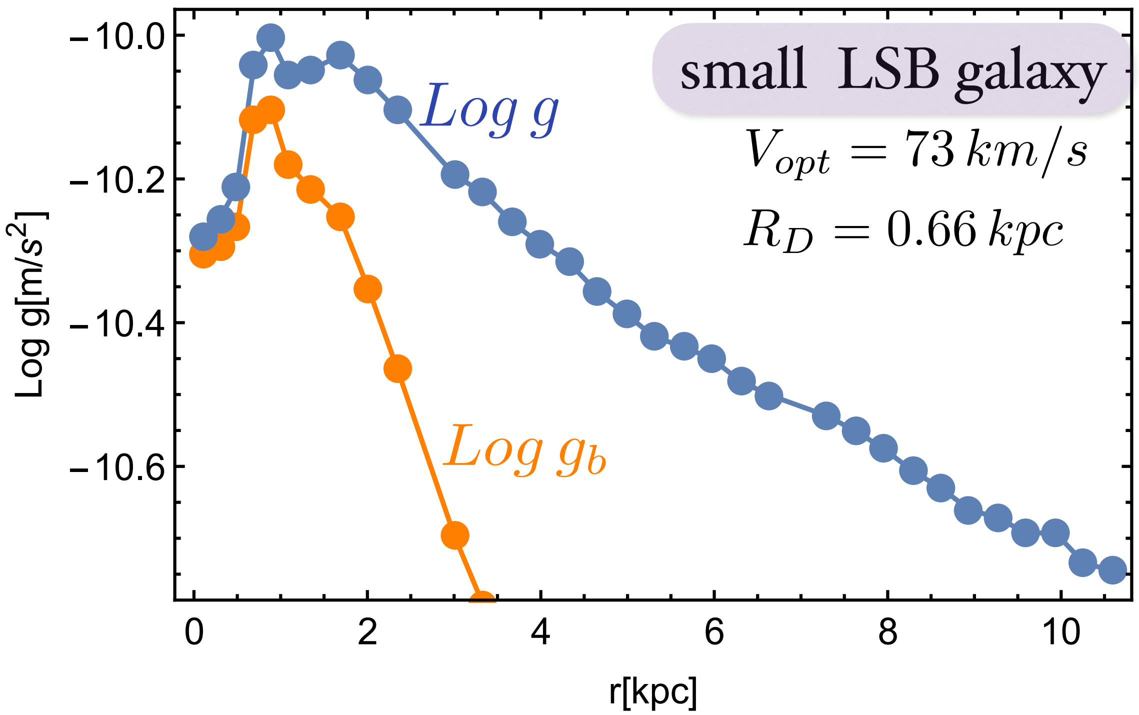
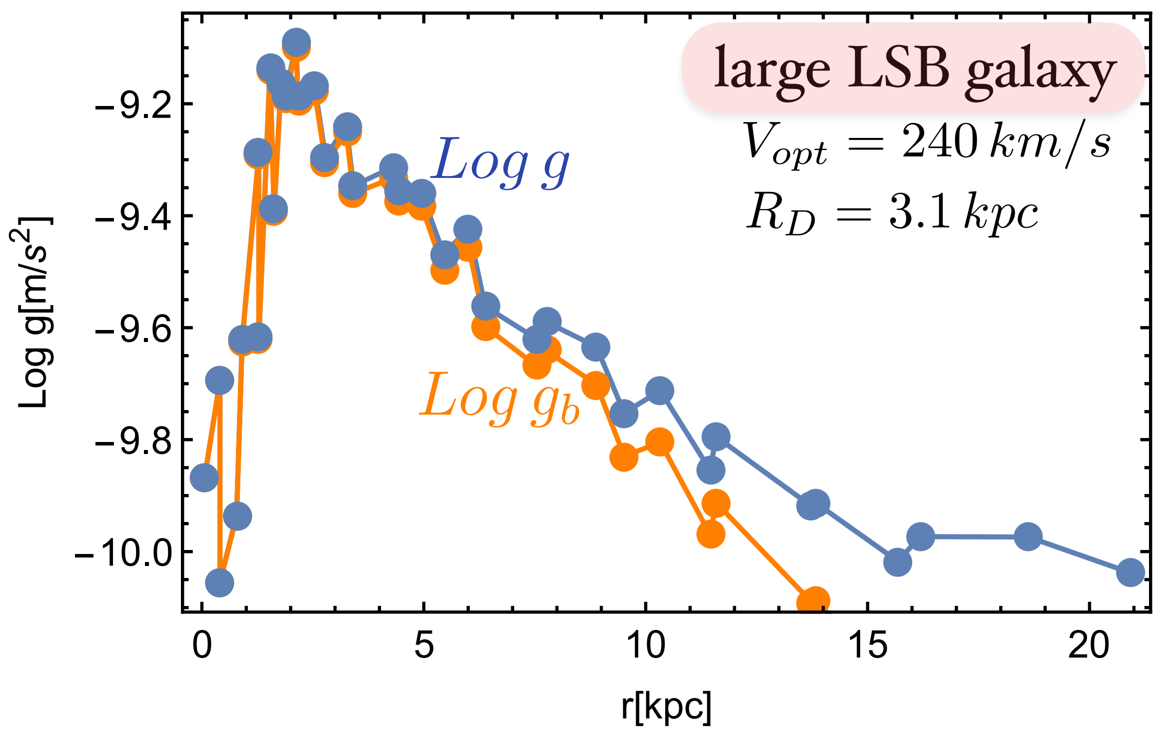
g , g_b , x single galaxies test





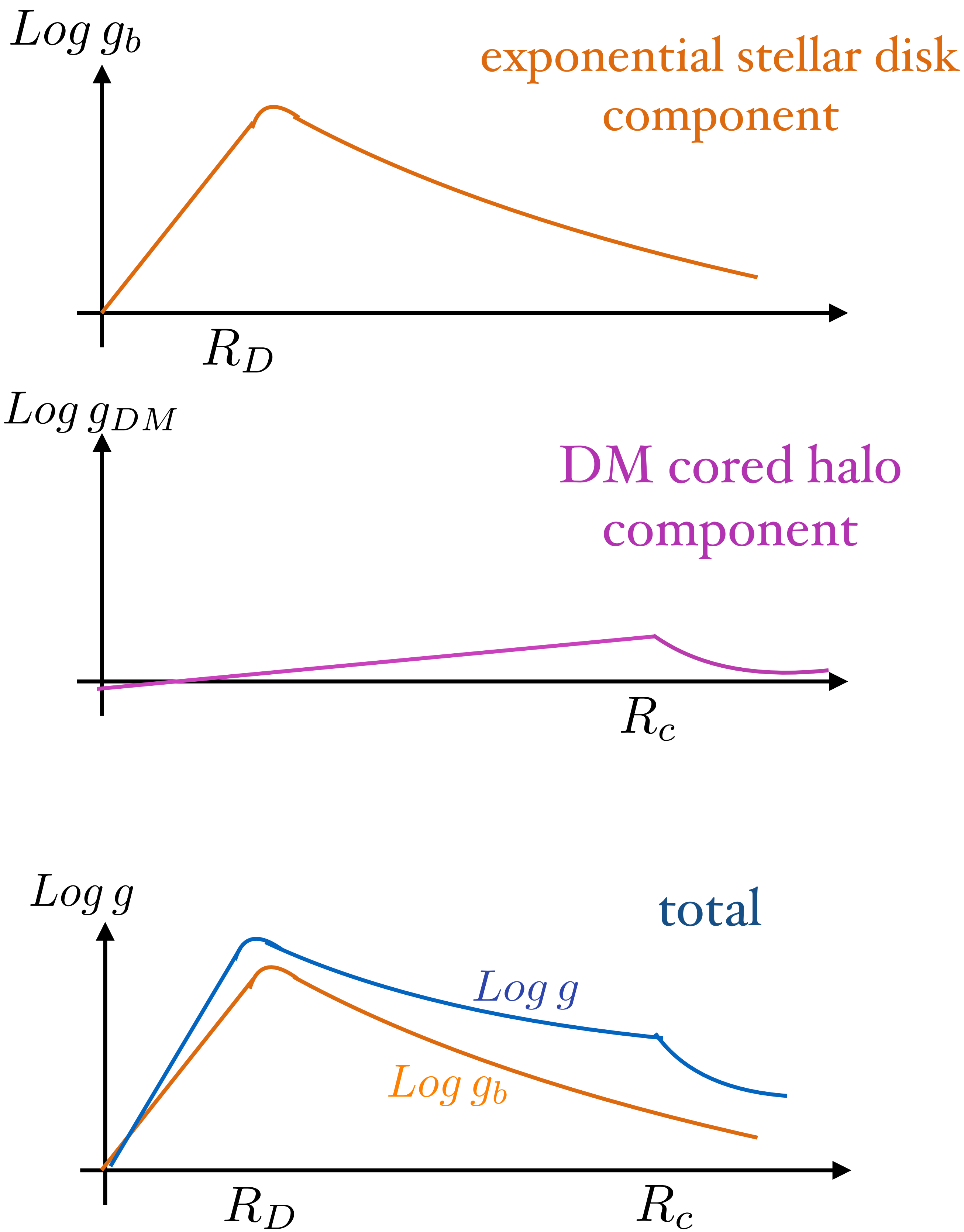
a) larger galaxies ▶ higher g and g_b

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

c) $g > g_b$ decrease beyond R_D

d) $g > g_b$ especially evident in the smallest galaxies

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

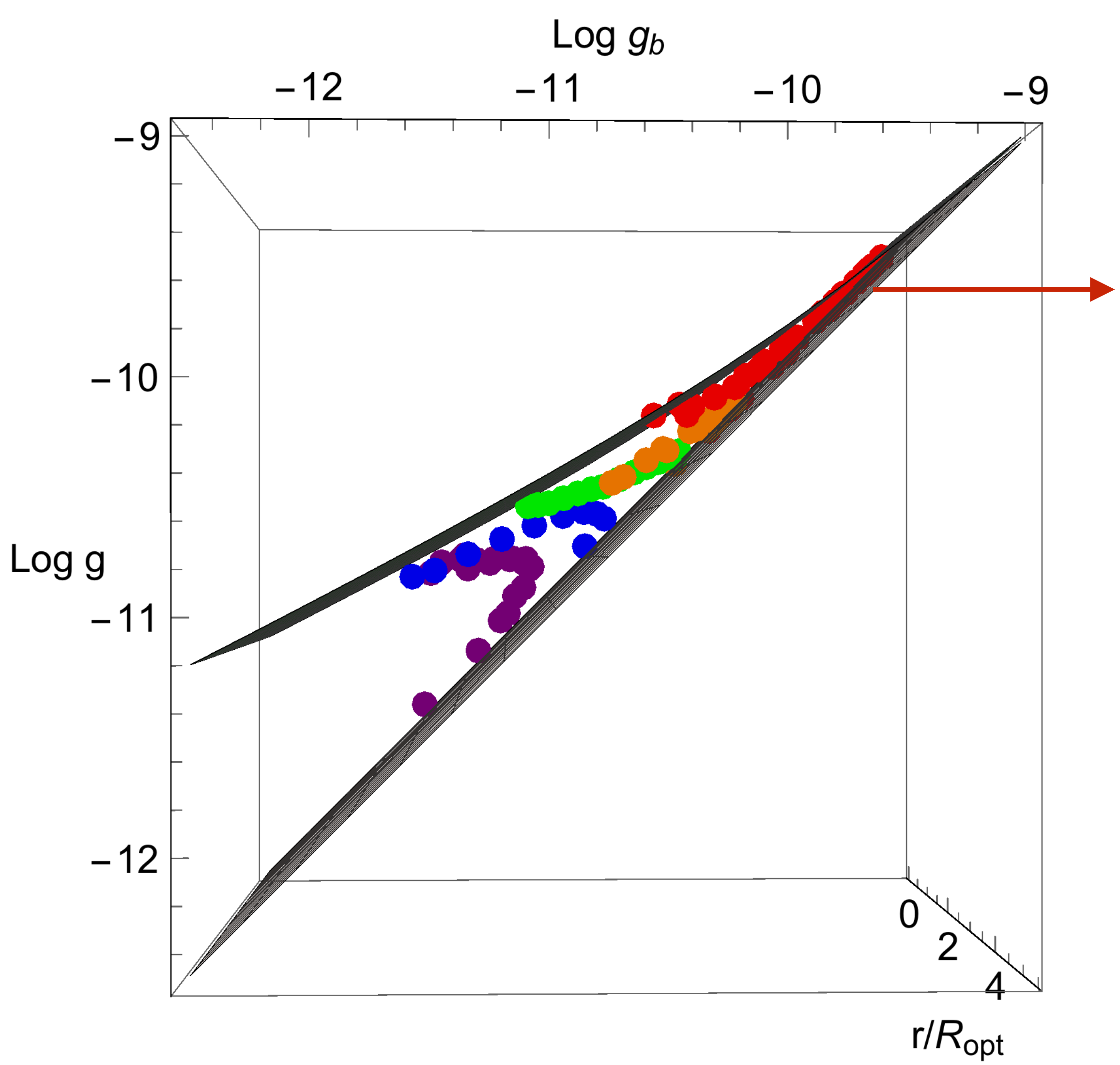
c) $g > g_b$ decrease beyond R_D

↓

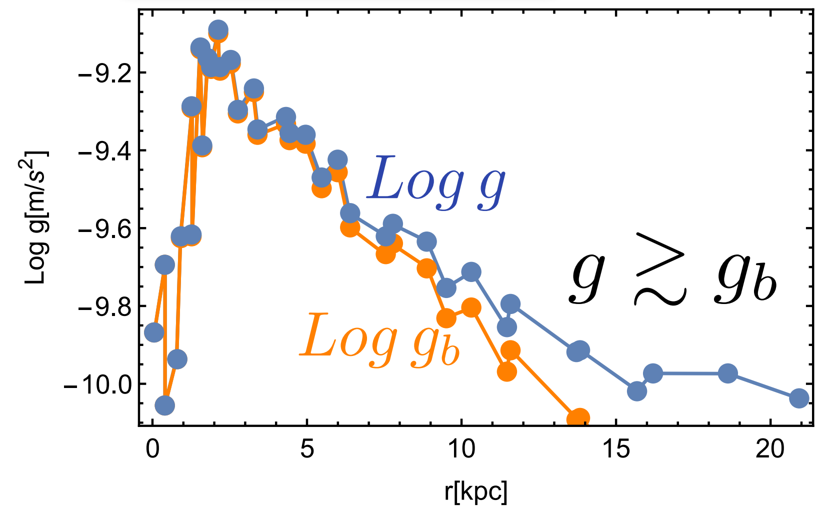
% baryonic matter < % dark matter in external region

Matter at low density in external region

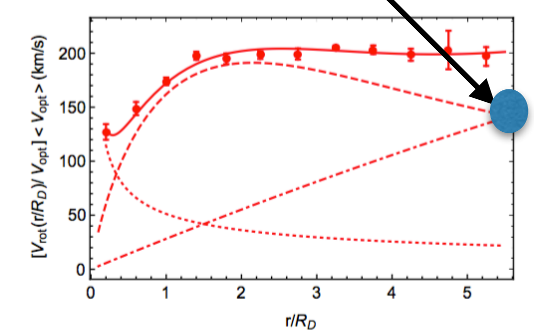
g , g_b , x interpreting the evidence



large LSB galaxy

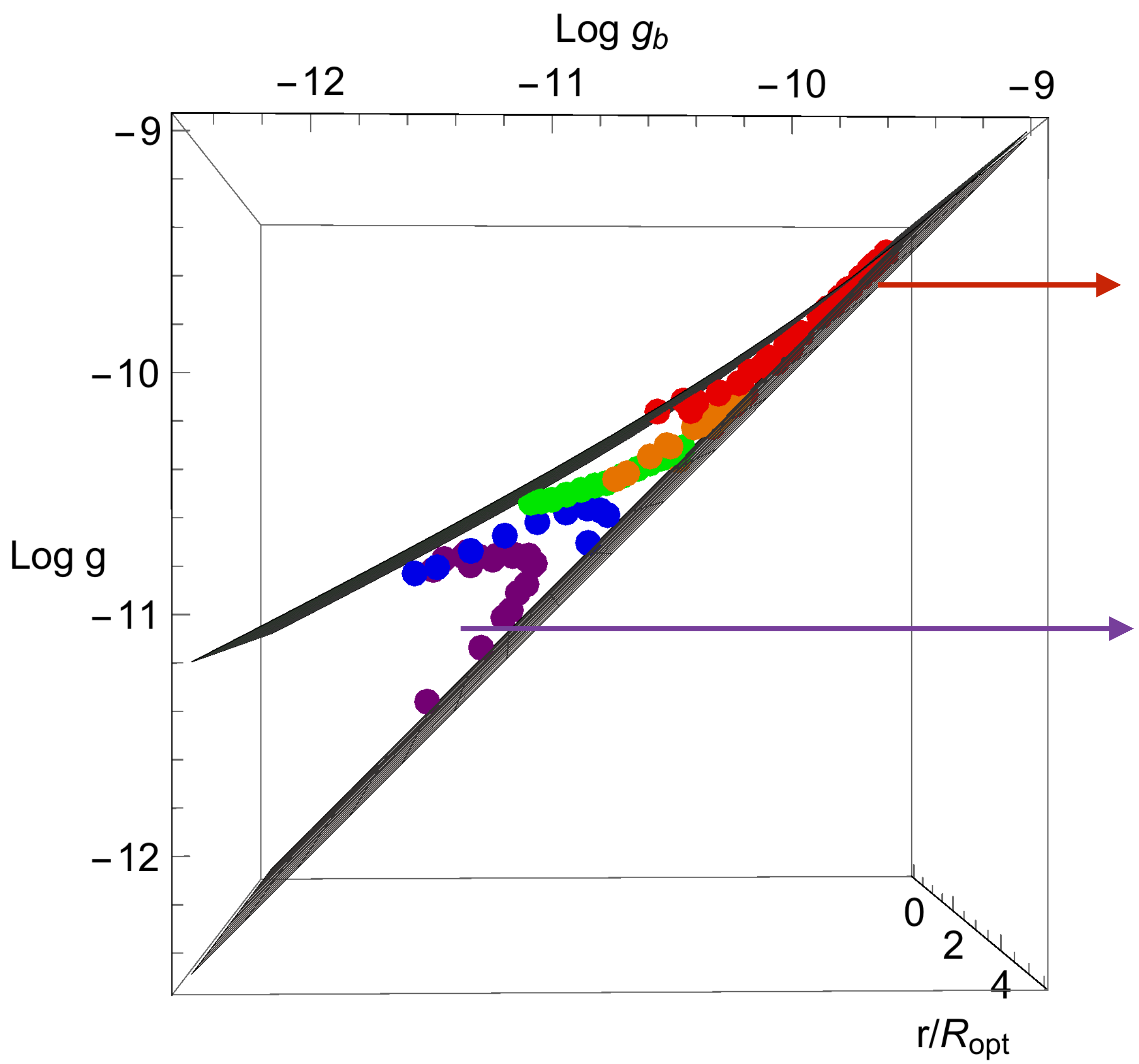


transition

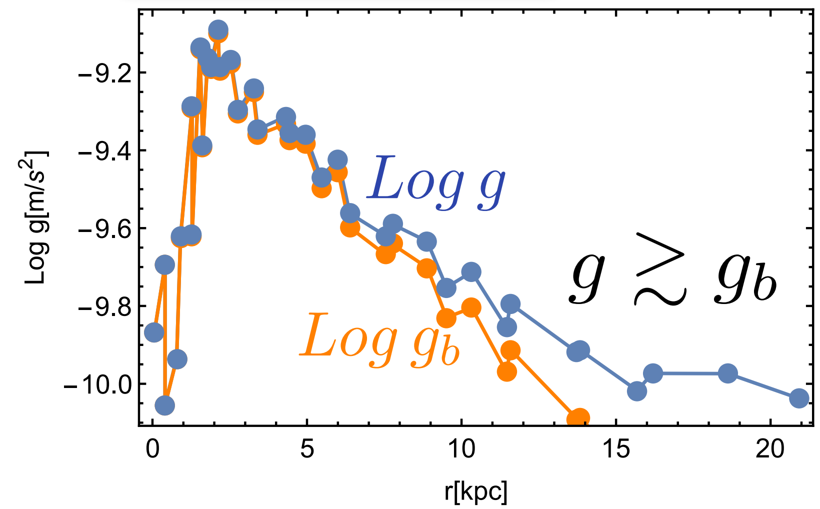


baryonic matter dominant beyond $\sim R_D$ $\quad g \gtrsim g_b$

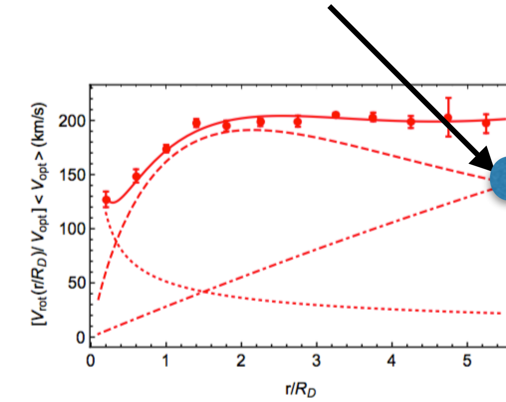
g , g_b , x interpreting the evidence



large LSB galaxy

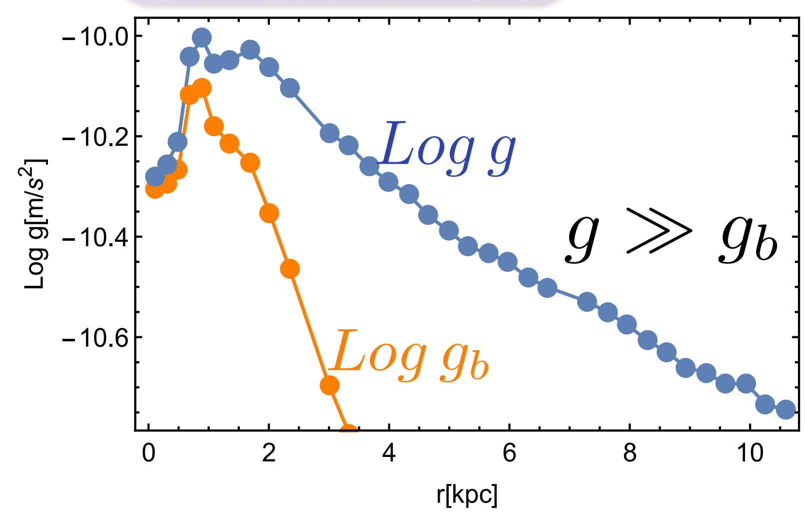


transition

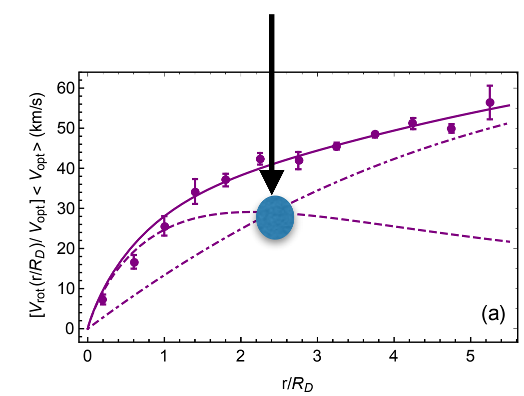


baryonic matter dominant beyond $\sim R_D$ $g \gtrsim g_b$

small LSB galaxy



transition

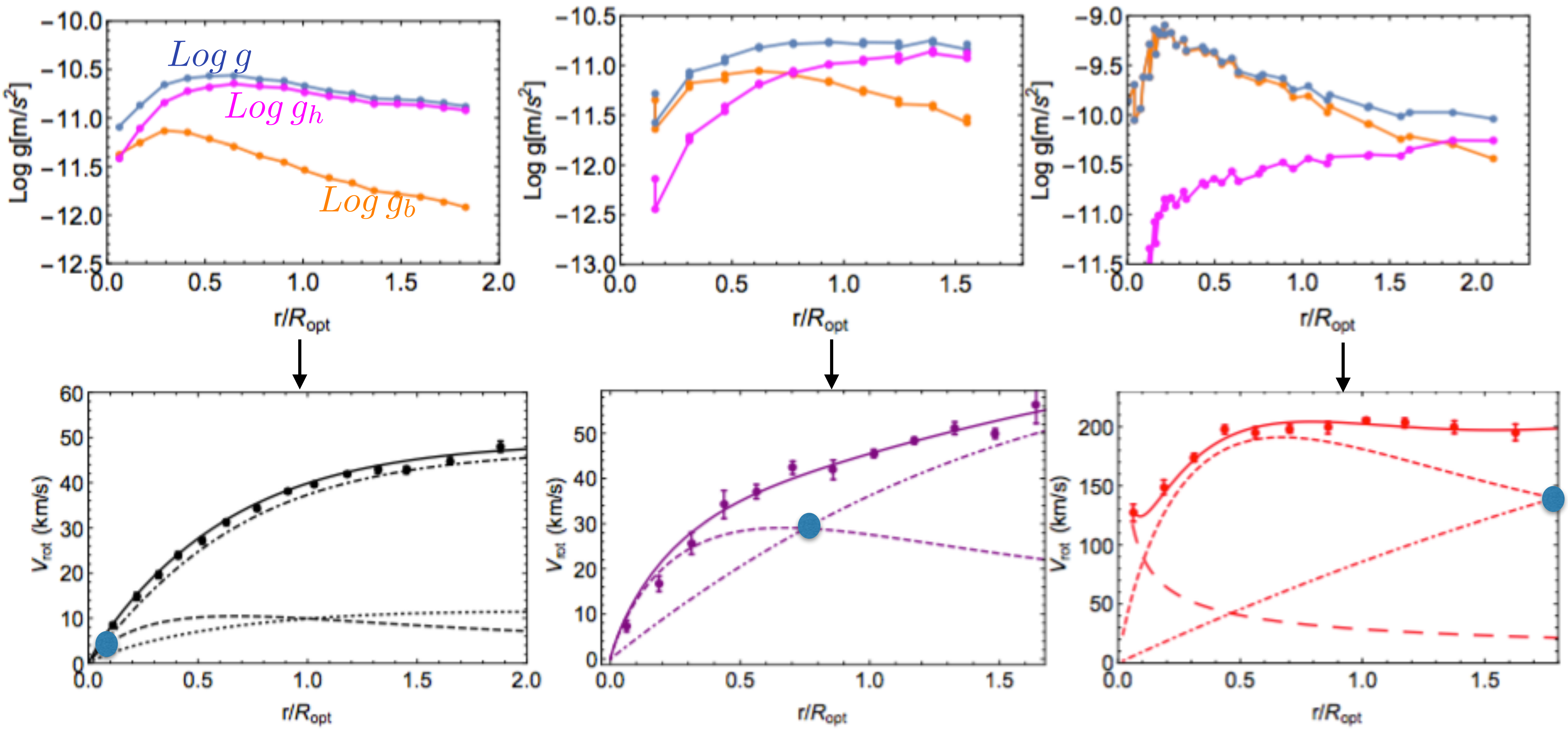


baryonic matter dominant till $\sim R_D$ $g \gg g_b$

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

Many Consequences

- enough data both inside and outside R_D to see the boomerang shape

McGaugh , Salucci
only one side

McGaugh relationship not universal

dependence on the radial coordinate

Many Consequences

- enough data both inside and outside R_D to see the boomerang shape ▶ McGaugh , Salucci only one side

McGaugh relationship not universal

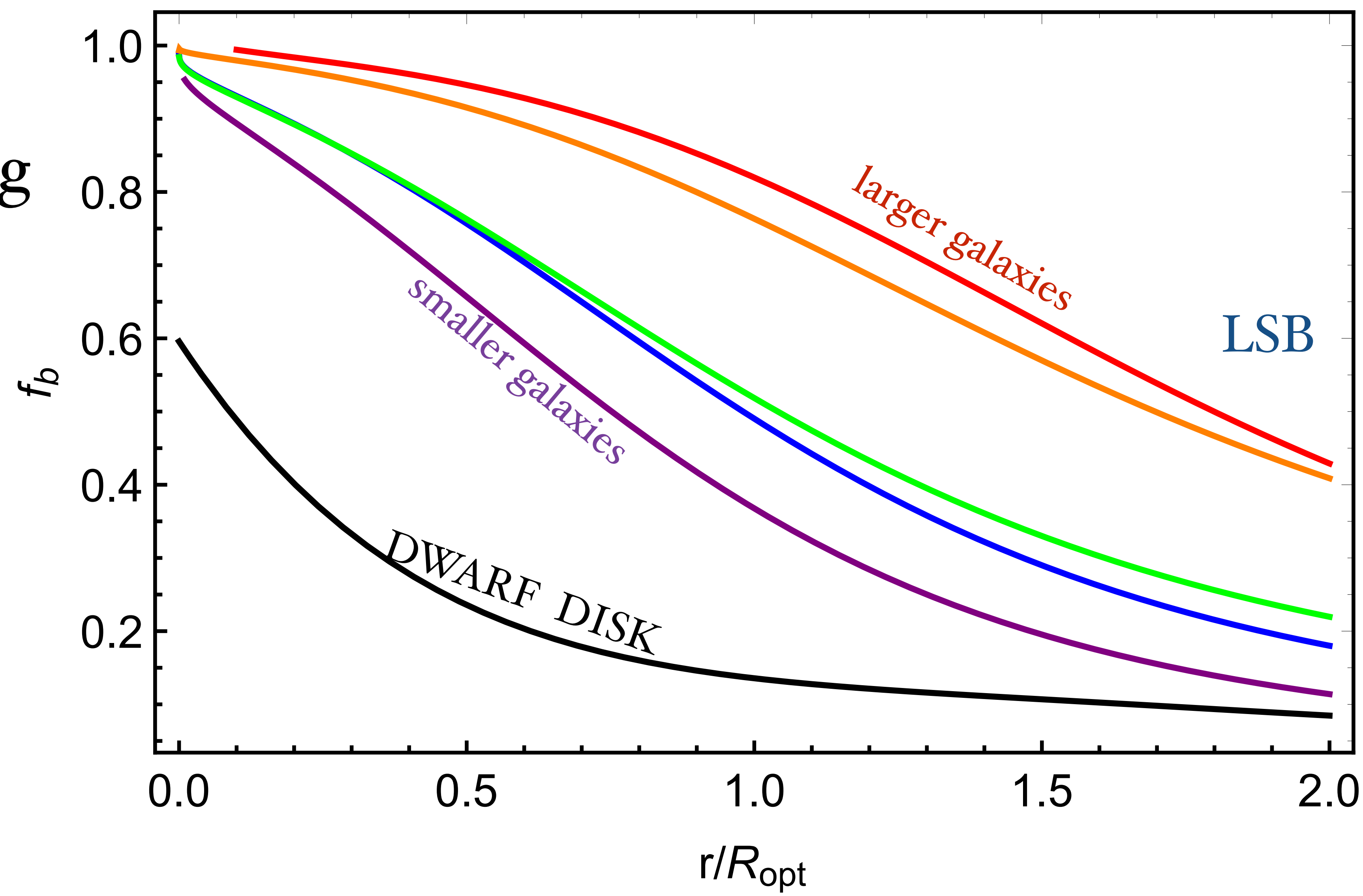
↓

dependence on the radial coordinate

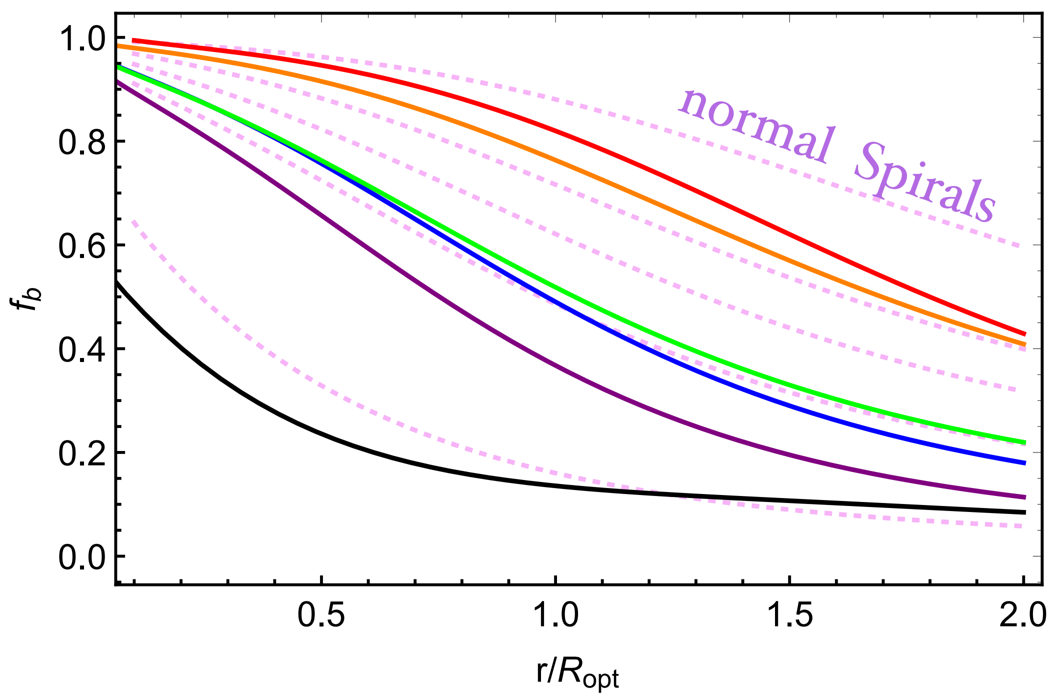
- **Baryonic fraction**

a) narrow boomerang for small $\frac{\Delta f_b}{\Delta r}$ ↓ larger galaxies

b) large boomerang for large $\frac{\Delta f_b}{\Delta r}$ ↓ smaller galaxies



Many Consequences



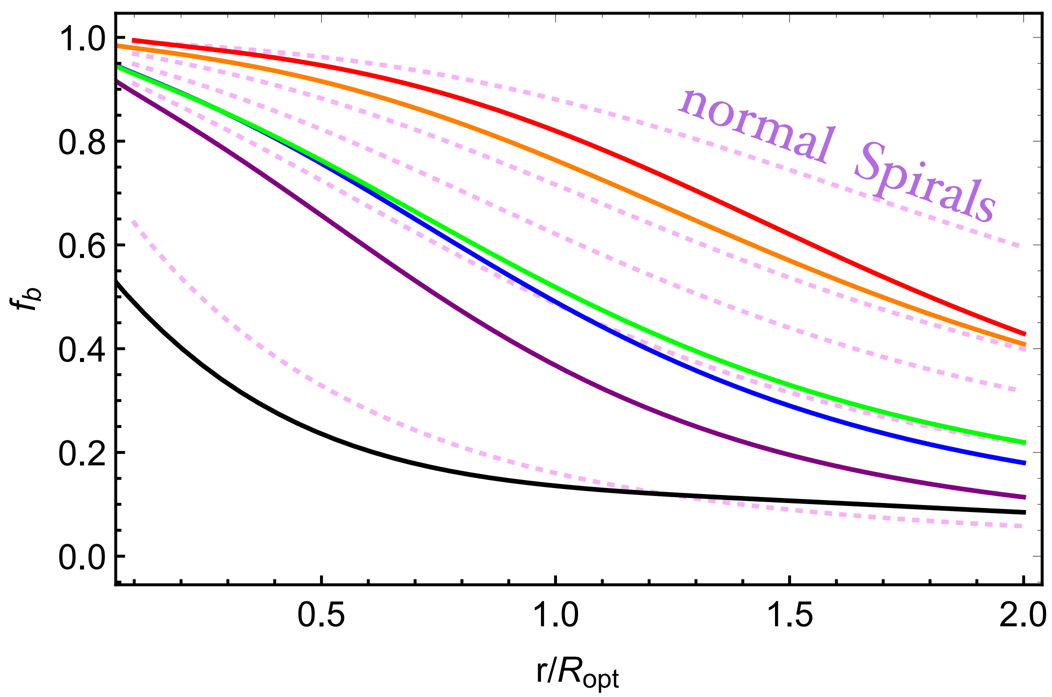
Even if

$$f_{b,LSB}(r/R_{opt}) \simeq f_{b,spirals}(r/R_{opt})$$

LSB more extended
than normal Spirals
↓

$$f_{b,LSB}(r) > f_{b,spiral}(r)$$

Many Consequences



Even if

$$f_{b,LSB}(r/R_{opt}) \simeq f_{b,spirals}(r/R_{opt})$$

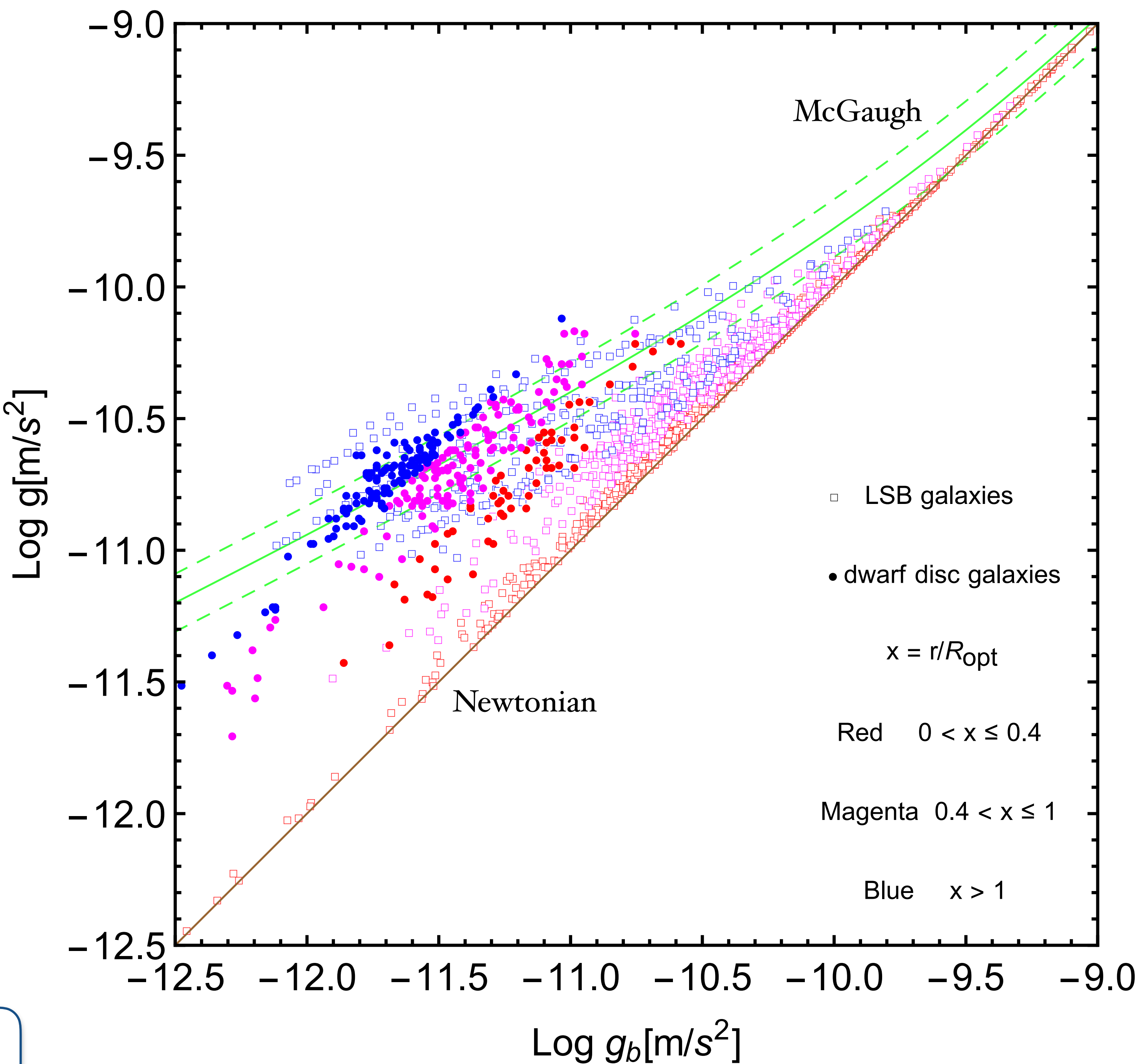
LSB more extended
than normal Spirals

↓

$$f_{b,LSB}(r) > f_{b,spiral}(r)$$

Same g_b → different g

Failure of McGaugh relation in LSB

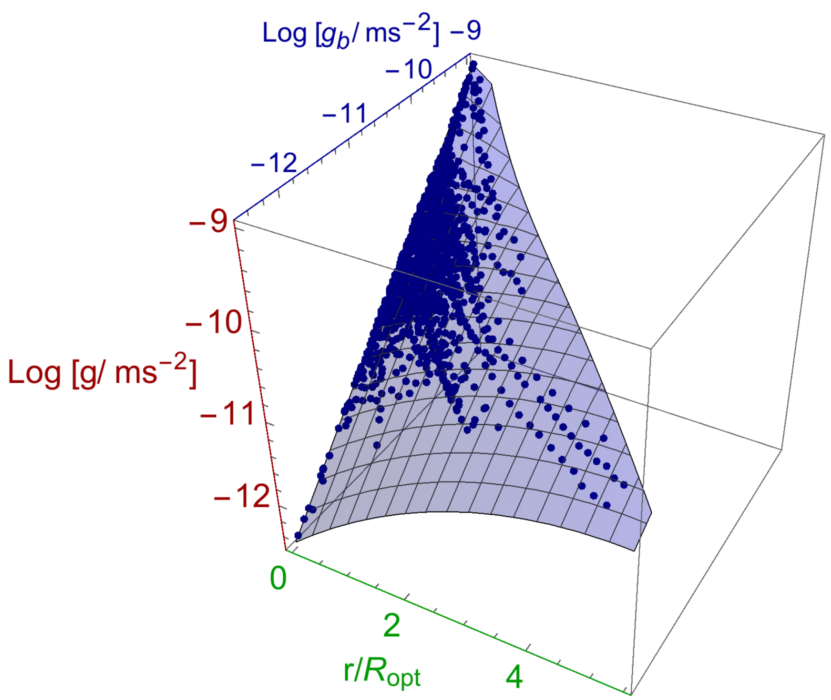


Conclusions

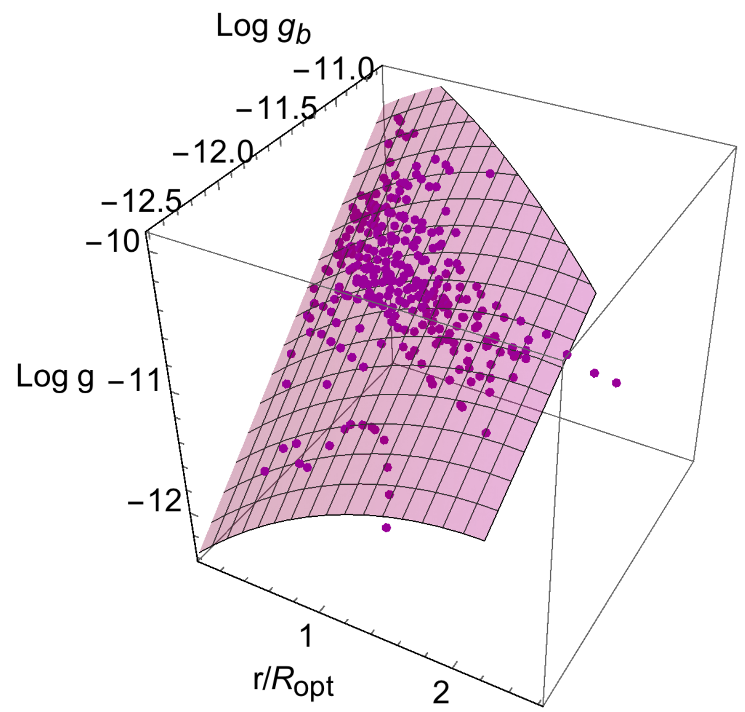
~ McGaugh relationship (**RAR**): $g = f(g_b)$ at any radius and in any object

~

LSB



Dwarf Disks



evidence of radial dependence

→ $g = f(g_b,\, r/R_{opt})$

+

morphology dependence

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

Thanks for the attention