The radial acceleration relation of simulated local satellite galaxies

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My take-home message

The radial acceleration relation (RAR) of local satellite galaxies is a powerful test to probe ΛCDM vs. MOND

Garaldi, Romano-Díaz, Porciani & Pawlowski, 2018, *Physical Review Letters*

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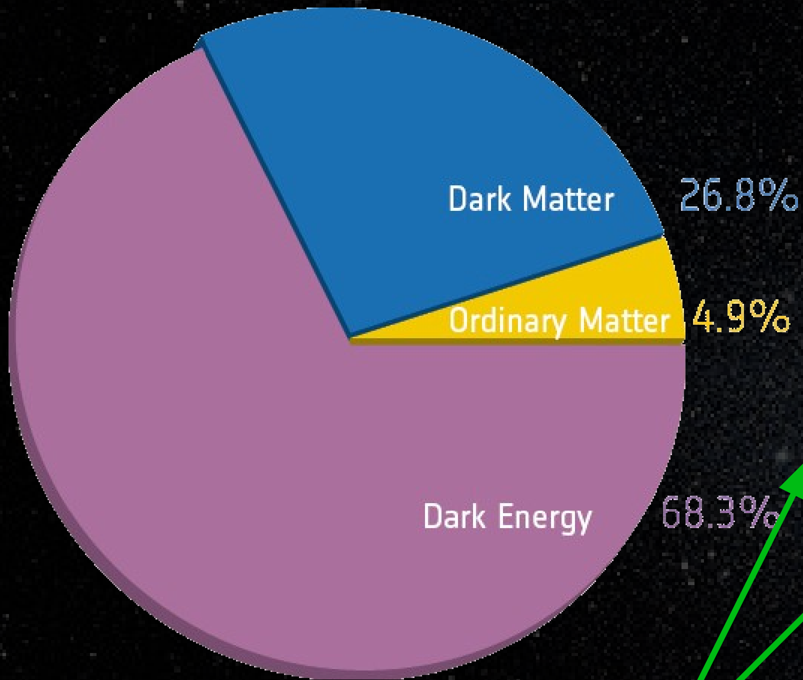
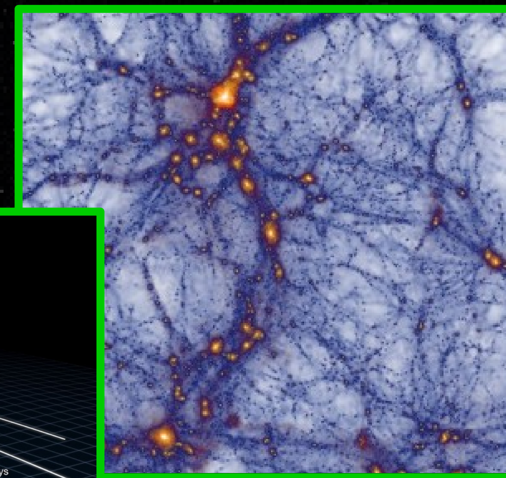
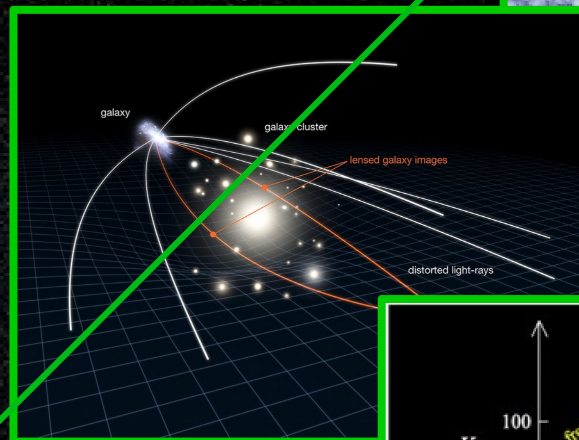
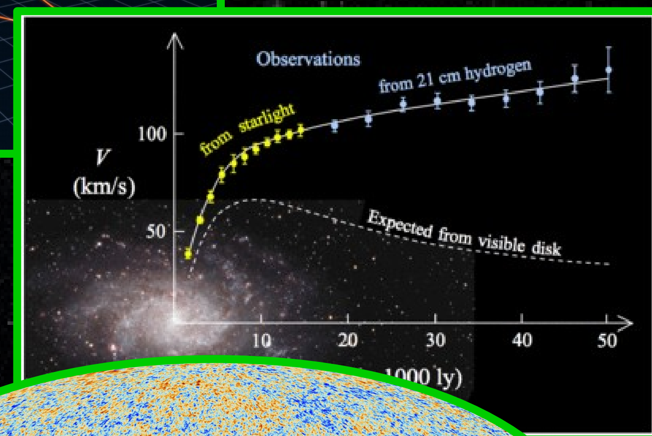
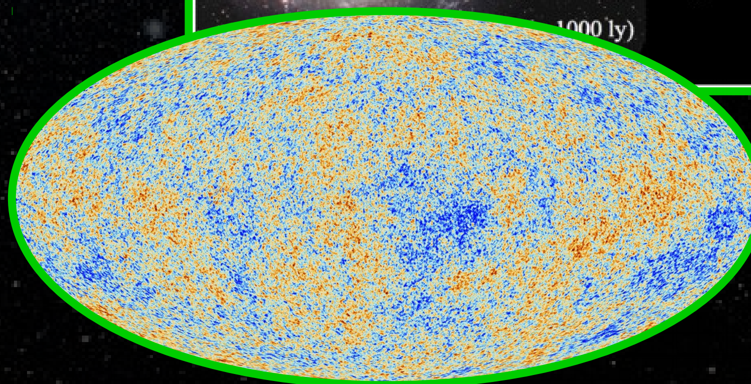
The standard cosmological model (ΛCDM)











- Concordance model
- Dark matter not detected
- Dark energy has unclear origin
- Requires an inflation period

Modified Newtonian Dynamics (MOND)

MOND is a modification of the gravitational or inertia law.

$$a\,\mu(a/a_0) = a_N$$

- Galactic rotation curves with no dark matter
- Relativistic extension(s) have problems with the speed of gravitational wave
- No cosmological predictions

a = MOND-predicted acceleration

μ = interpolation function

a_N = Newtonian acceleration

a_0 = universal constant $\approx 1.2 \times 10^{-10}$ m s^{-2}

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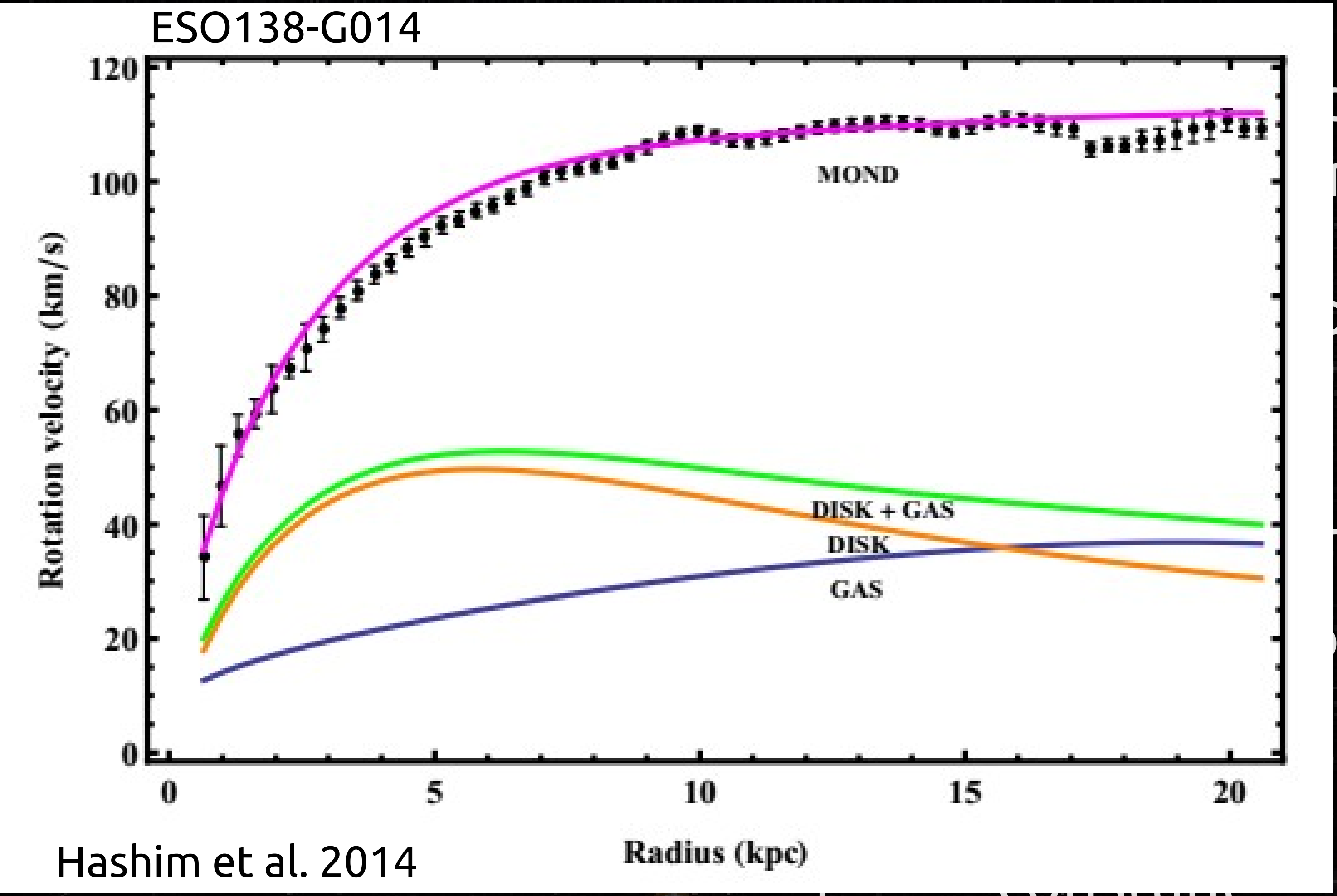

dicted

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on

- Ga
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- Re
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constant

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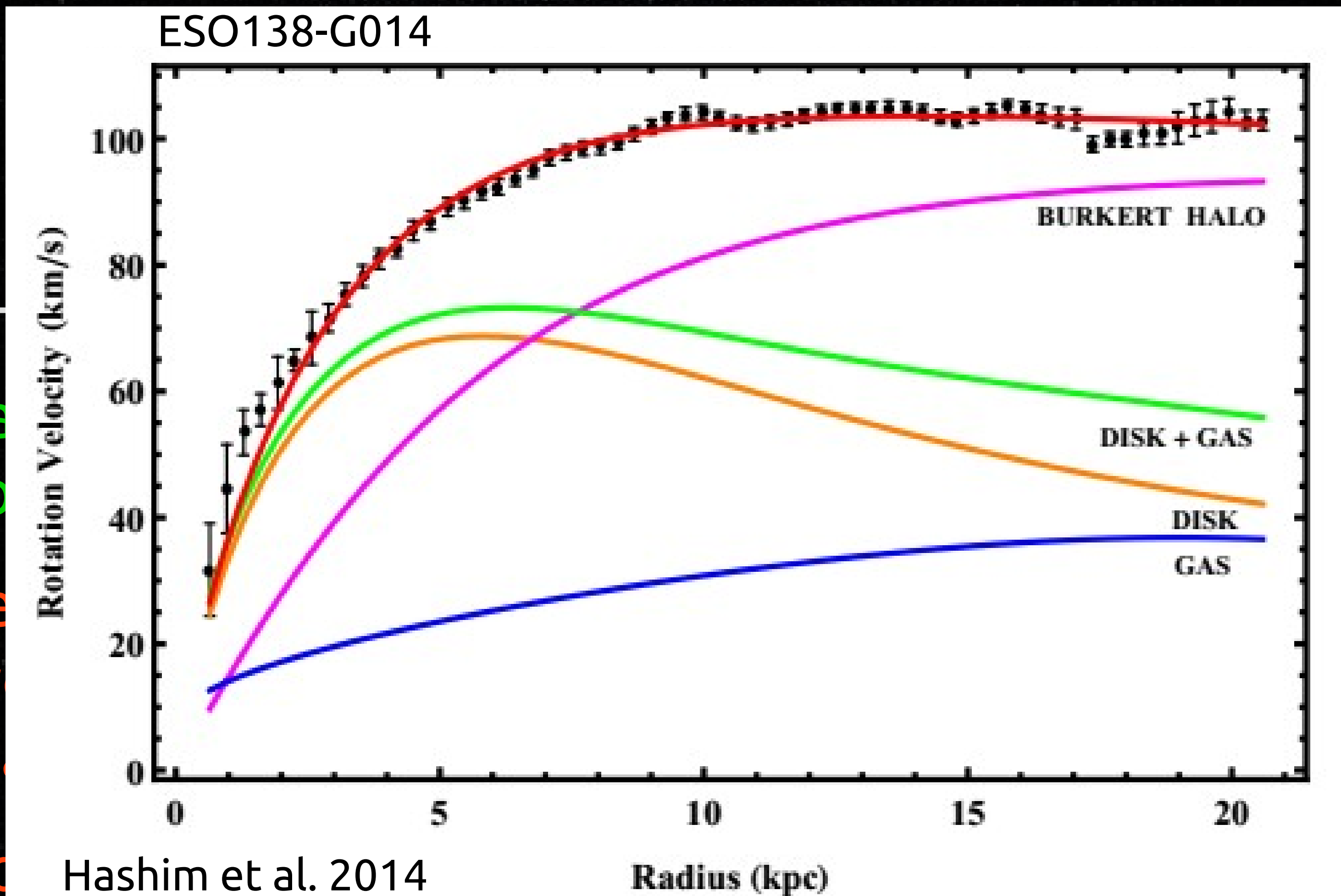

dicted
n
on
n
on
constant

- Ga
  no
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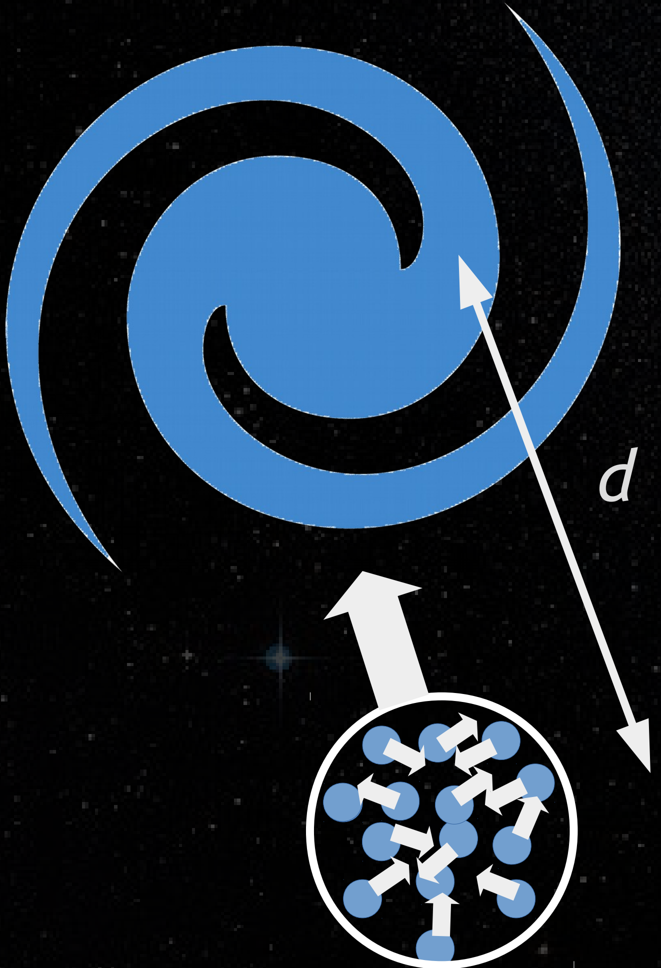
- No

The External Field Effect (EFE)

MOND is a non-linear theory → internal and external accelerations can *not* be decoupled.



If $g_{in} < g_{ext} < a_0$ the internal motion depends on g_{ext} / a_0

→ the acceleration (mass) inferred from internal motion (e.g. velocity dispersion) depends on g_{ext} , hence on *d*

No ΛCDM analog!

The Radial Acceleration Relation (RAR)

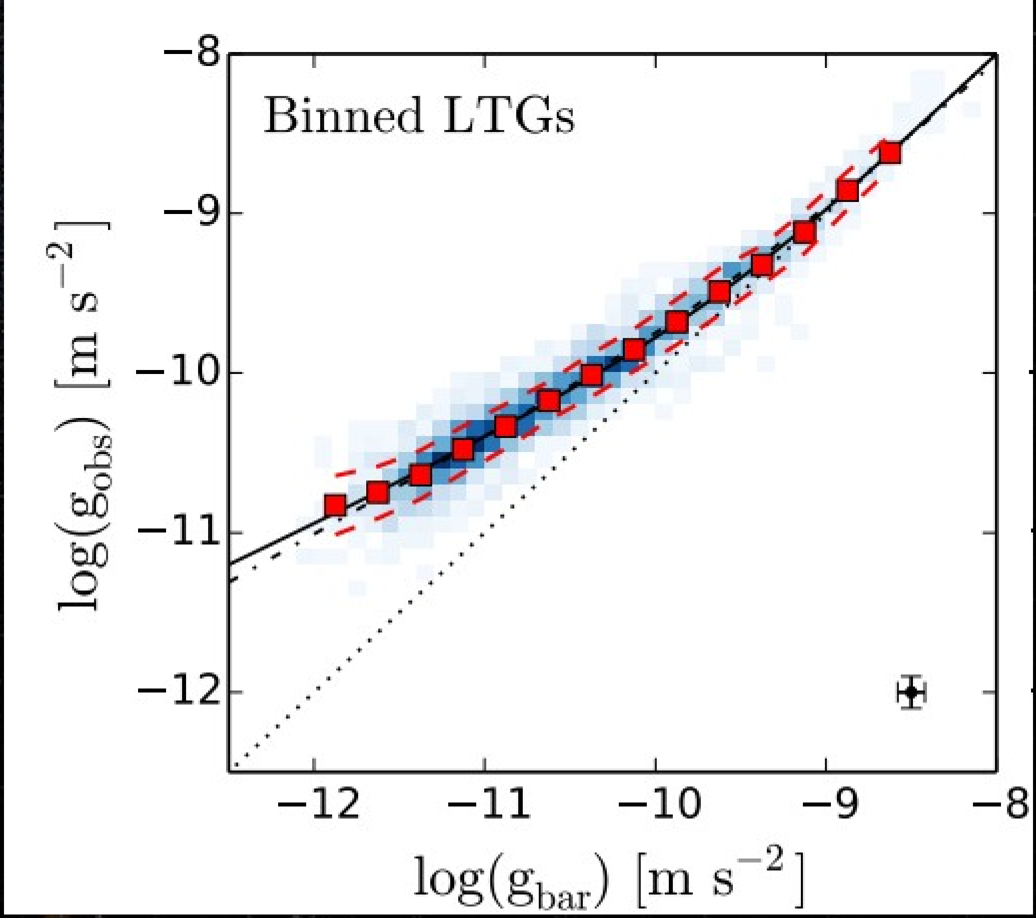
Tight, *universal* correlation between the total and baryonic acceleration inside galaxies

- Well fitted by

$$g_{\rm obs} = \frac{g_{\rm bar}}{1 - e^{\sqrt{g_{\rm bar}/g_\dagger}}}$$

with $g_\dagger \approx a_0$

- Compatible with zero intrinsic scatter



Lelli et al. 2017

The Radial Acceleration Relation (RAR)

- *Post*-dicted in ΛCDM, with larger intrinsic scatter (Santos-Santos et al. 2016, Di Cintio et al. 2016, Keller & Wadsley 2017, Ludlow et al. 2017)

- Suggested to be a natural consequence of galaxy formation (Navarro et al. 2017, Keller & Wadsley 2017)

- Robust against changes in the feedback model (Ludlow et al. 2017)

The Radial Acceleration Relation (RAR)

Dwarf spheroidals (dSph) do not follow the RAR of larger galaxies.

Credits: ESA

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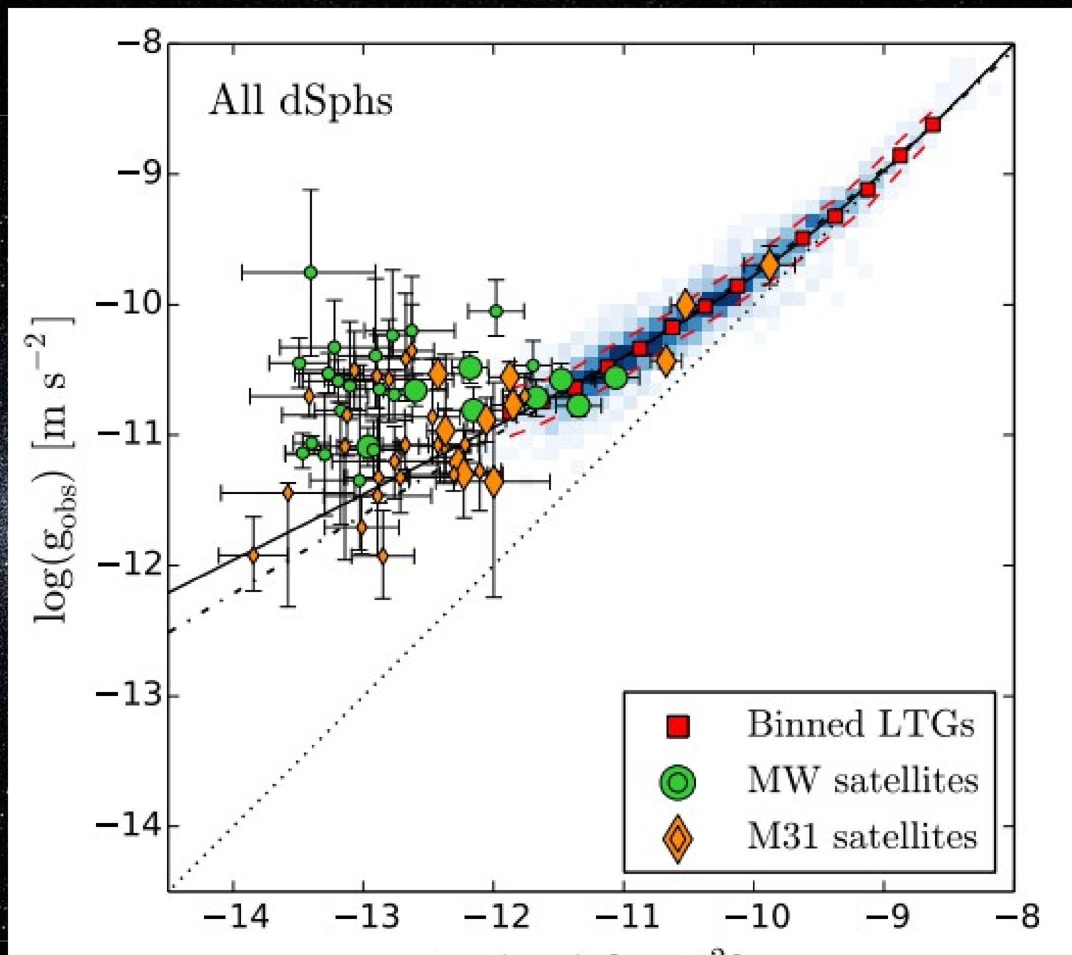


Credits: ESA

Lelli et al. 2017

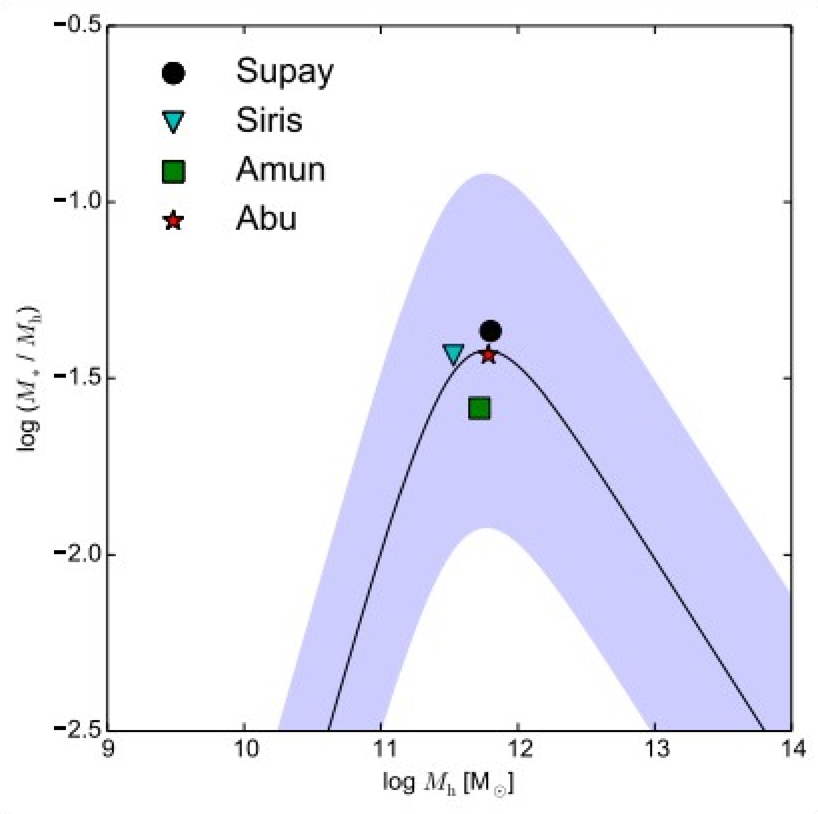

The ZOMG simulation suite

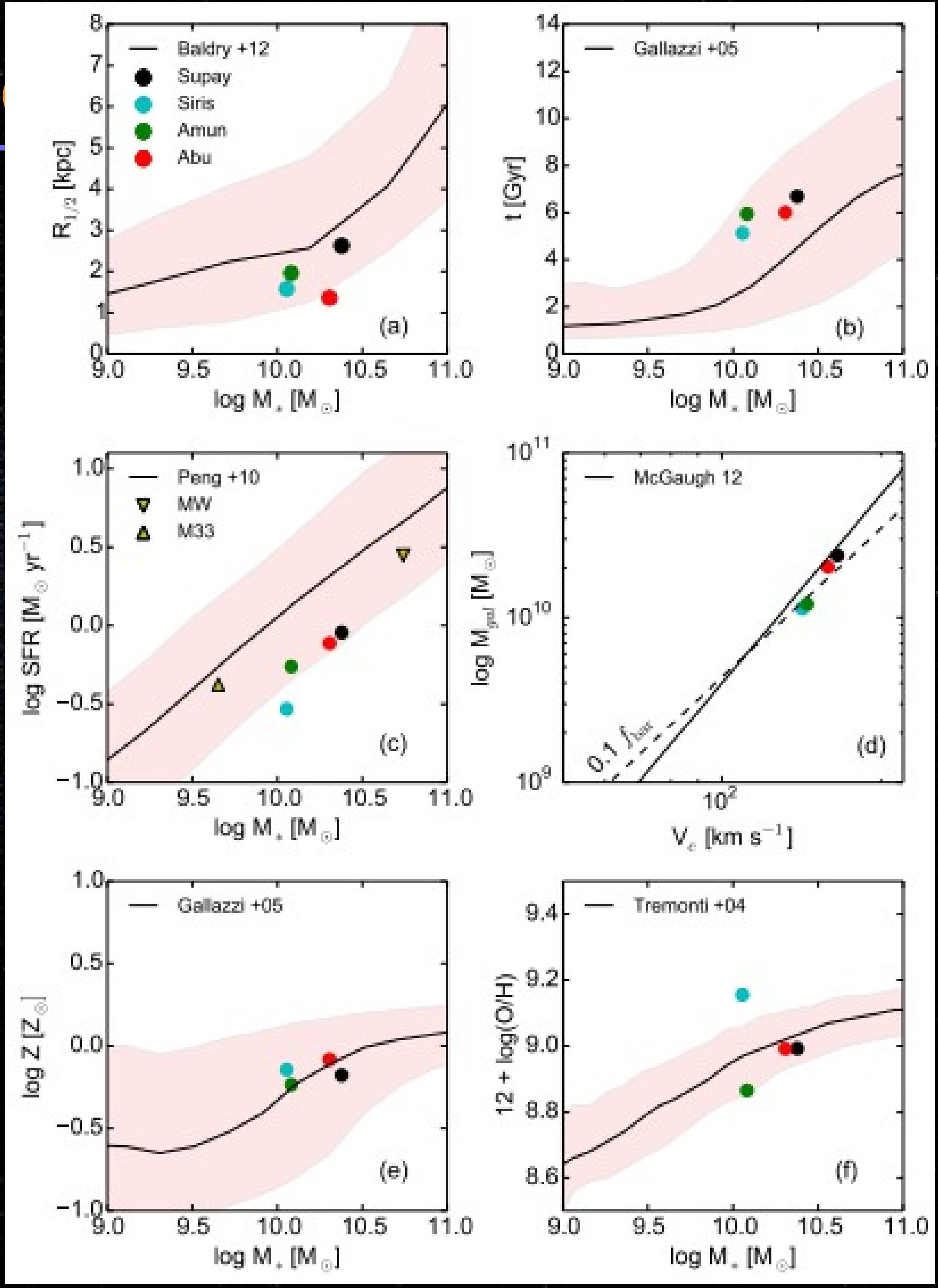
The ZOMG simulation suite

- 4 **MW-like** galaxies
- $M_{halo} \sim 5 \times 10^{11}\ M_\odot$
- Zoom-in → high space and time resolution
  - $\Delta t = 20$ Myr
  - $M_{DM} \sim 10^5\ M_\odot$
  - $M_* \sim M_{gas} \sim 10^4\ M_\odot$
- P-Gadget3, Planck ΛCDM cosmology

Credits: ZOMG collaboration

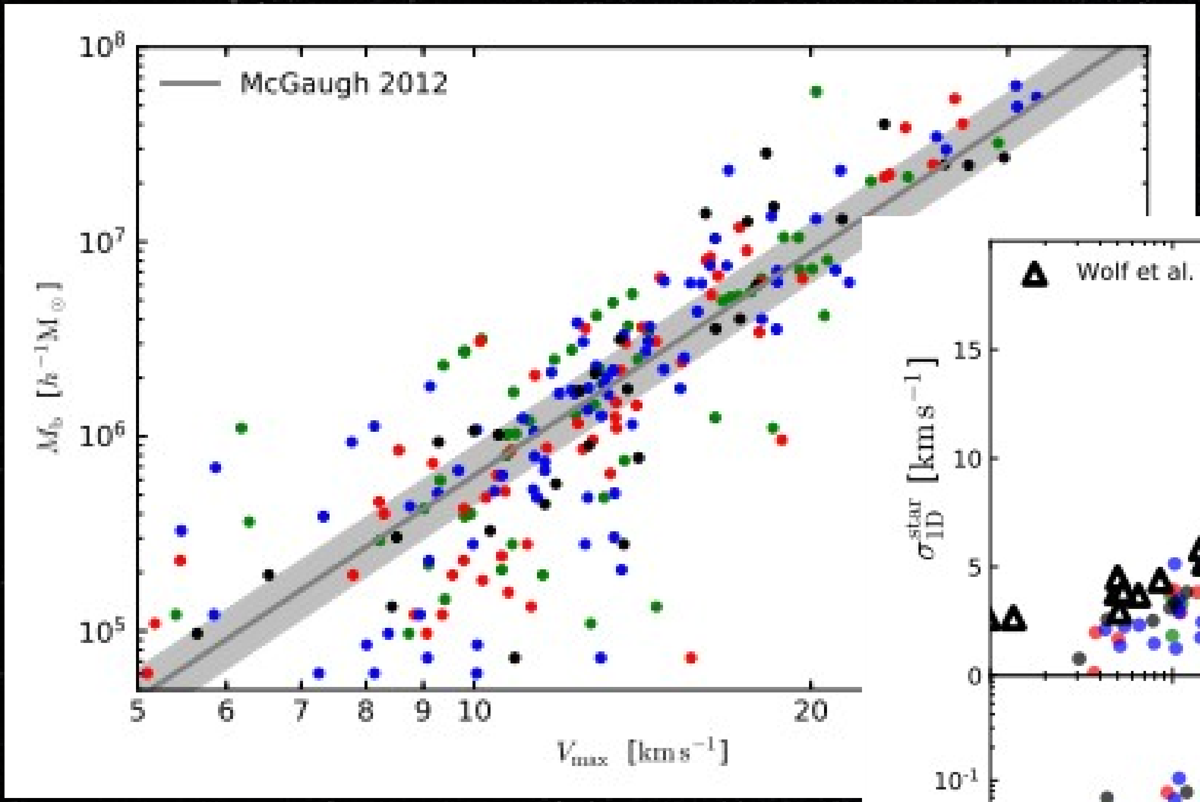
The ZOMG simulati

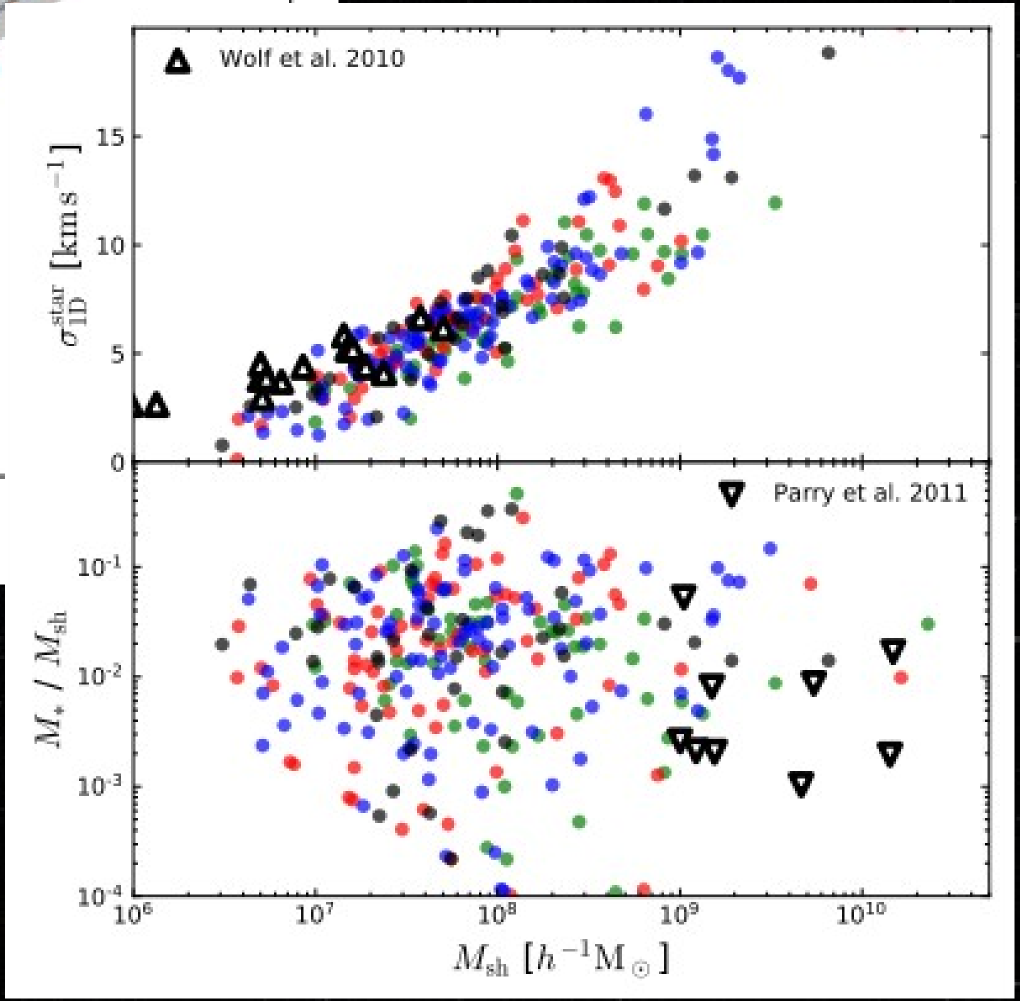




Romano-Diaz, EG, et al. 2017

The ZOMG simulation suite

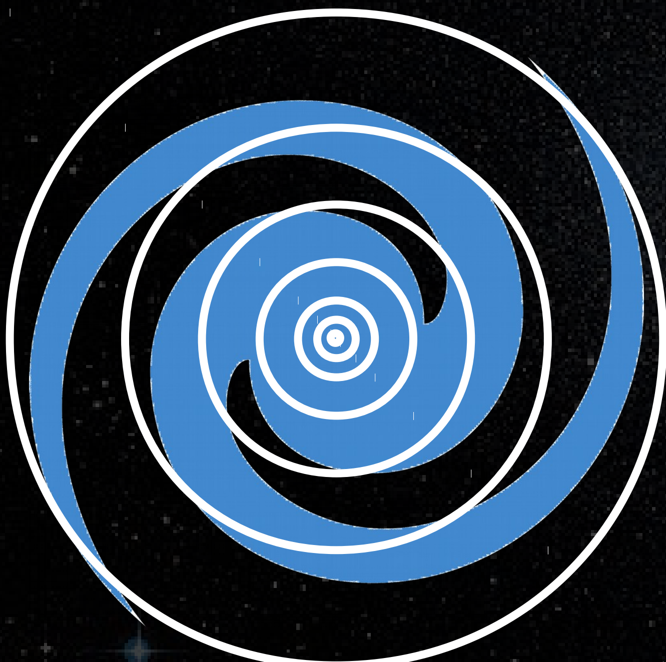




Garaldi et al. 2017

Measuring accelerations

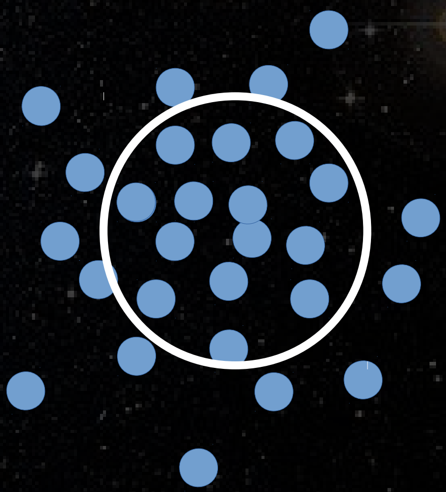
Centrals



high-quality sample
→ same results

$$a_x = G\,\frac{M_x(<r)}{r^2}$$

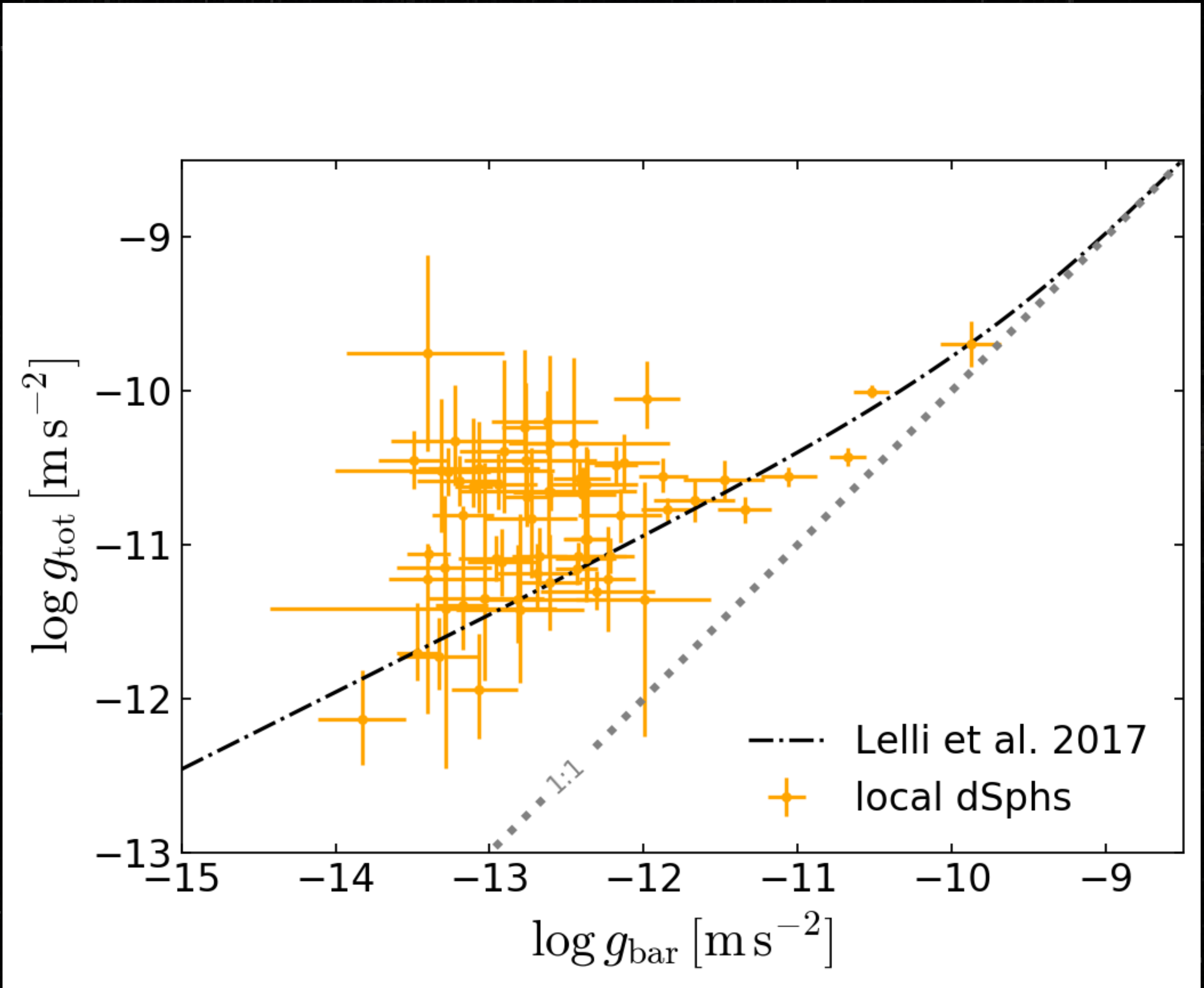
Satellites



$M_{DM} > 10^7\ M_{sun}$ & $M_* > 10^5\ M_{sun}$


RAR fitting

No special RAR for ΛCDM dSph



Garaldi et al. 2018, PRL

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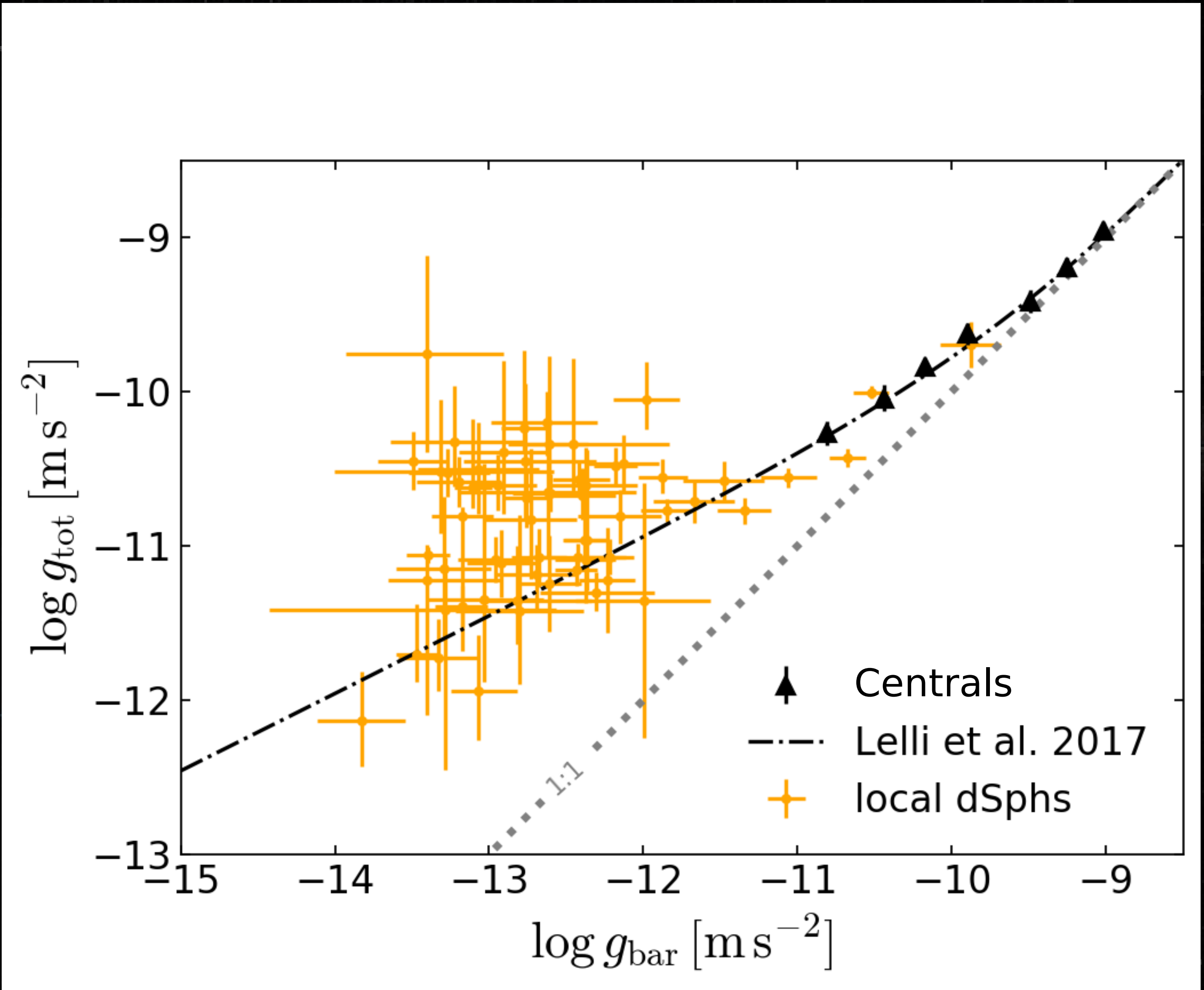

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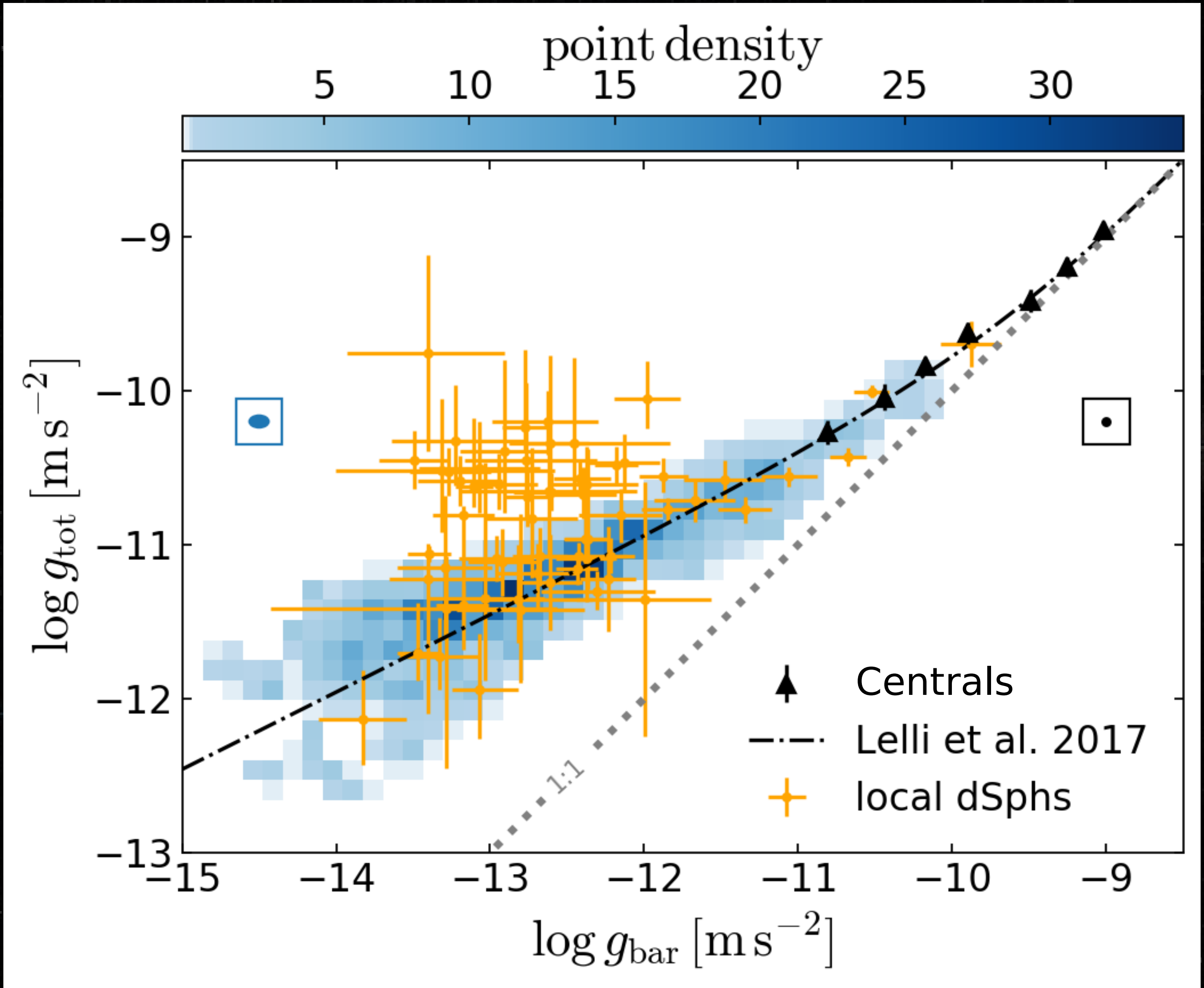

Garaldi et al. 2018, PRL

RAR fitting: ODR (Orthogonal Distance Regression)

Traditional way to fit RAR, yields

$$g_\dagger = (1.19 \pm 0.02) \times 10^{-10} \text{ m s}^{-2}$$

fully compatible with observed value (Lelli *et al.* 2018)

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However,

the intrinsic scatter σ_{int} is computed *a posteriori*

RAR fitting: Bayesian approach

Custom Gaussian likelihood in log space

$$\mathcal{L} = \prod_i \int \mathrm{d}x_{\mathrm{true}} \frac{1}{\sqrt{(2\pi)^k |\det \Sigma|}} \mathrm{e}^{-\frac{1}{2} v_i^{\mathrm{T}} \Sigma_i^{-1} v_i}$$

$$v_i^{\mathrm{T}} = (x_i - x_{\mathrm{true}}, y_i - f(x_{\mathrm{true}}, g_\dagger))$$

$$\Sigma = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 + \sigma_{\mathrm{int}}^2 \end{bmatrix}$$

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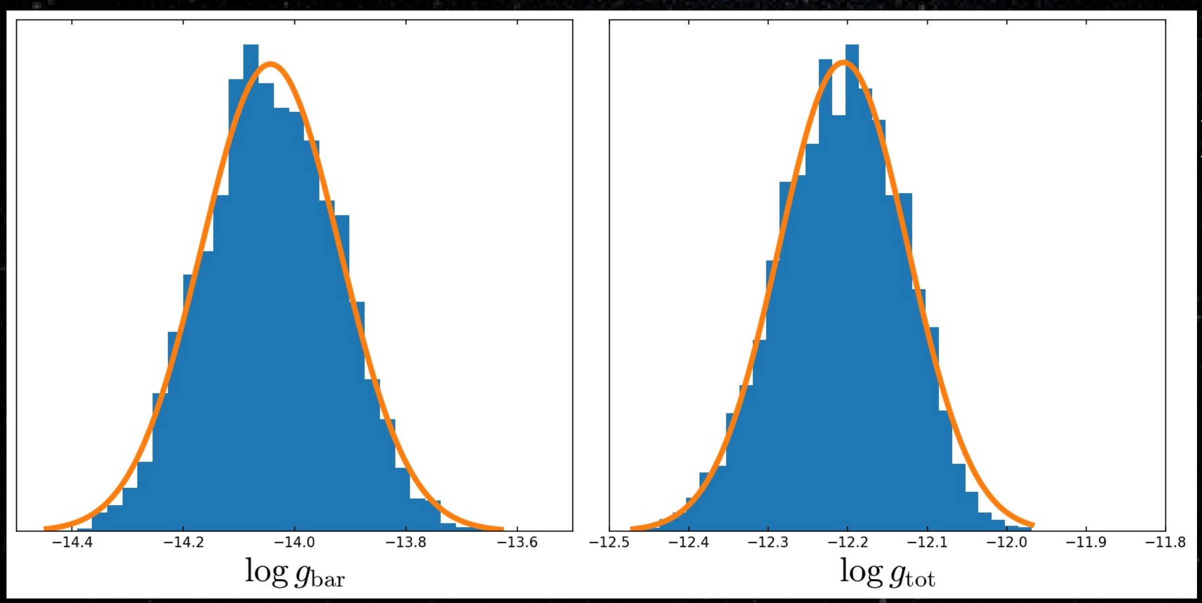

$\mathrm{rue}, g_\dagger))$

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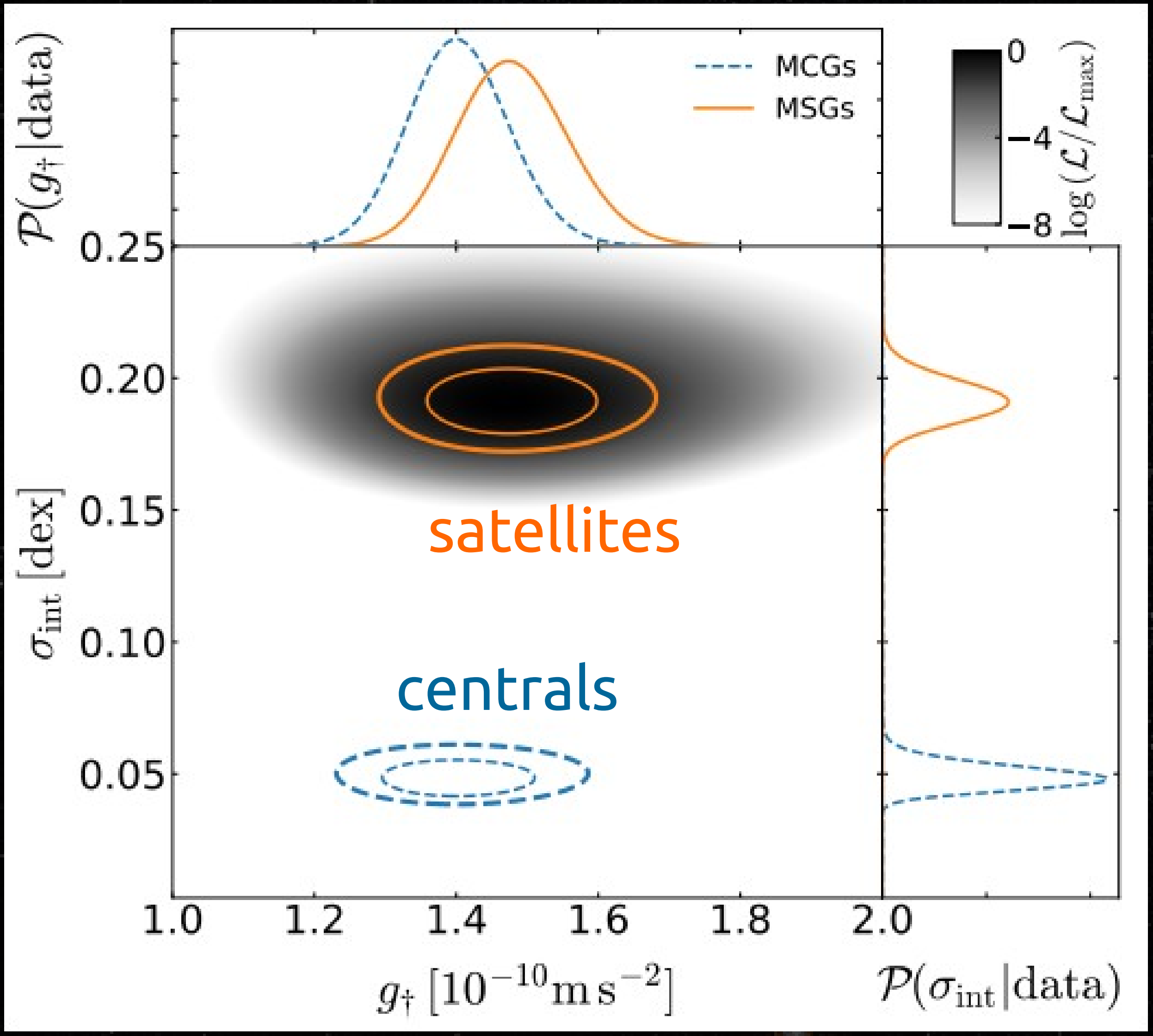
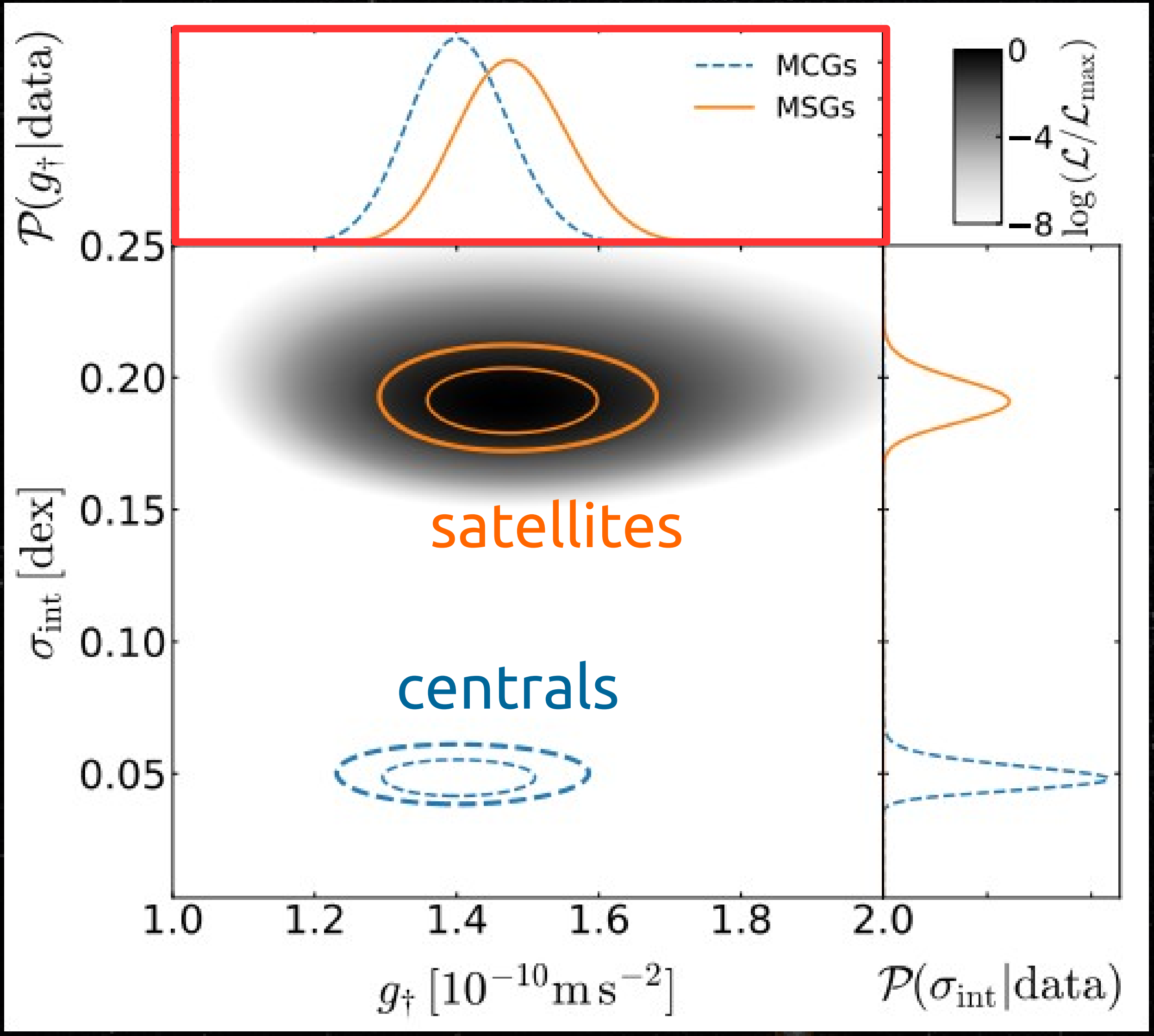


Centrals:
$g_\dagger$ = (1.40 ± 0.07) x 10^{-10} m s^{-2}
σ_{int} = (0.048 ± 0.005) dex

Satellites:
$g_\dagger$ = (1.48 ± 0.08) x 10^{-10} m s^{-2}
σ_{int} = (0.192 ± 0.008) dex

Garaldi et al. 2018, PRL

RAR fitting: Bayesian approach



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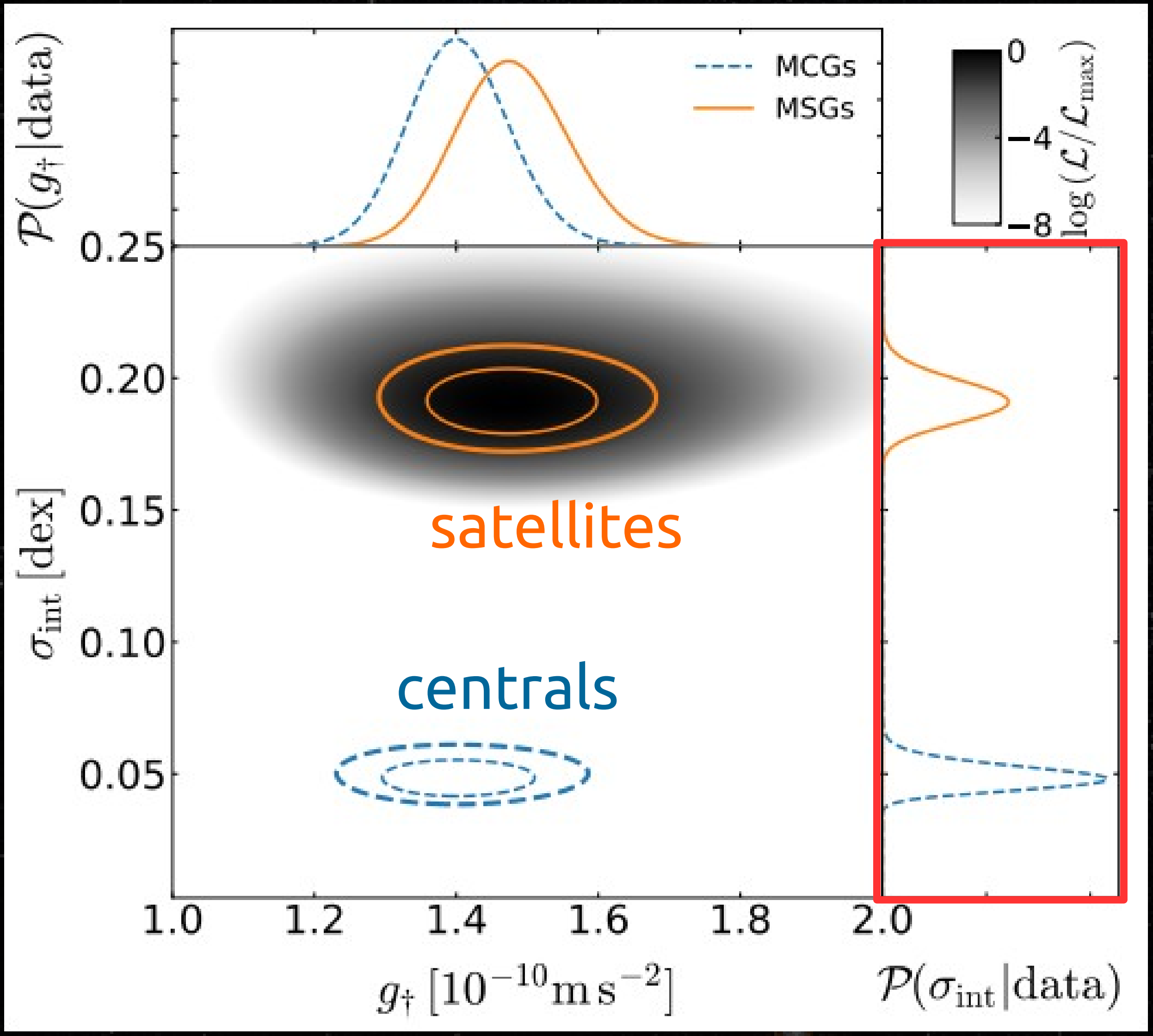

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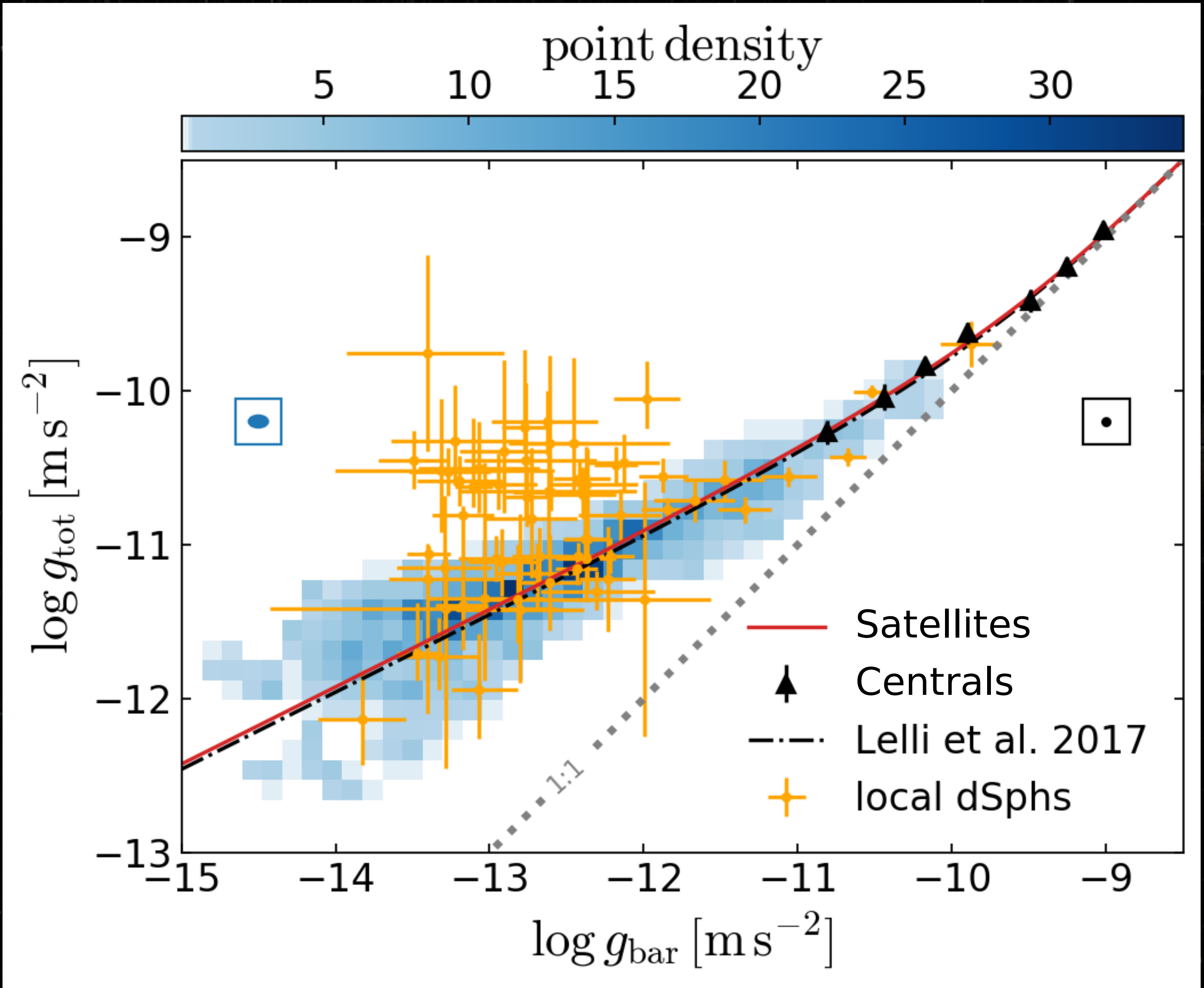
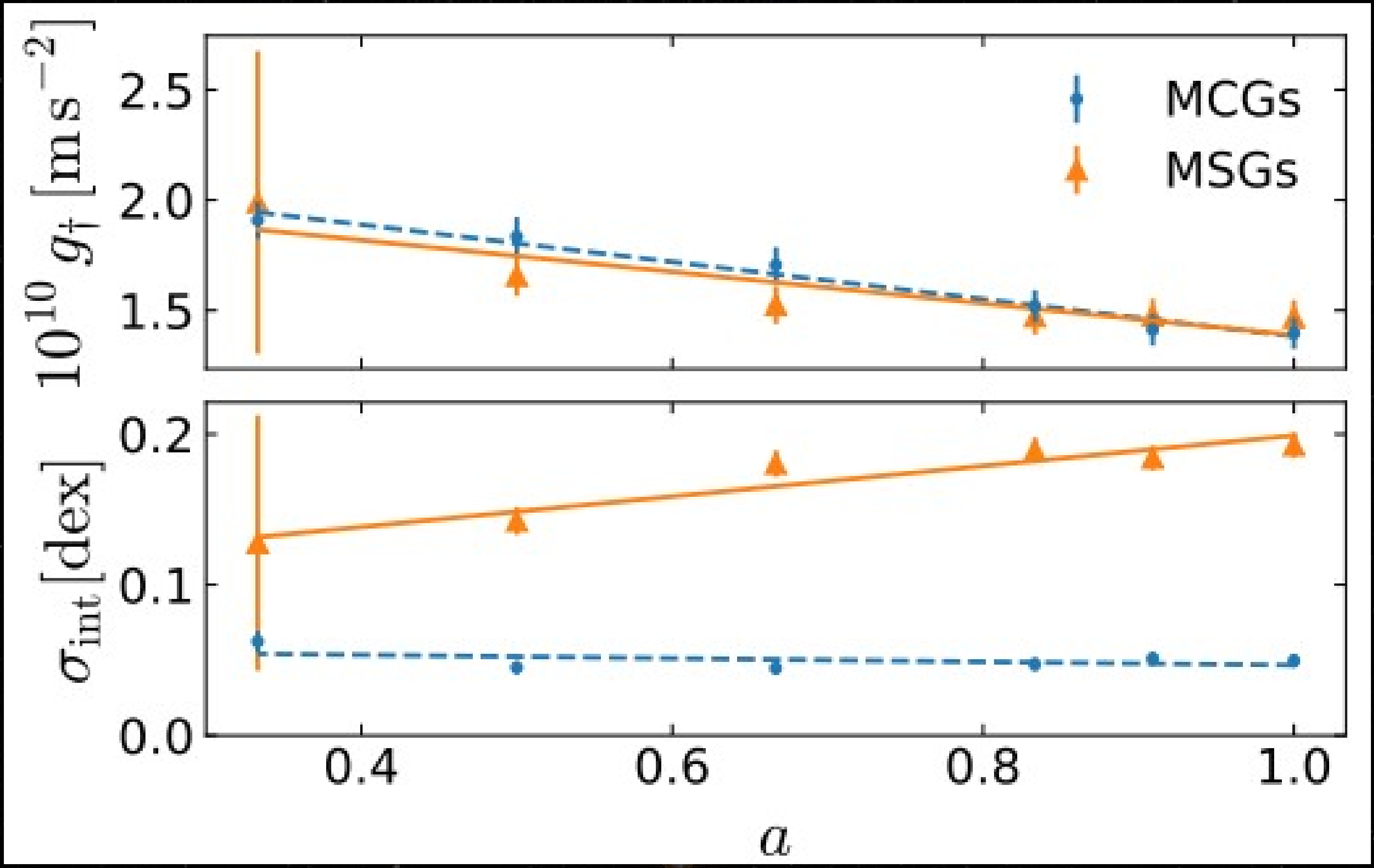


Garaldi et al. 2018, PRL


Time evolution

$g_\dagger$ evolves linearly with a_{exp}



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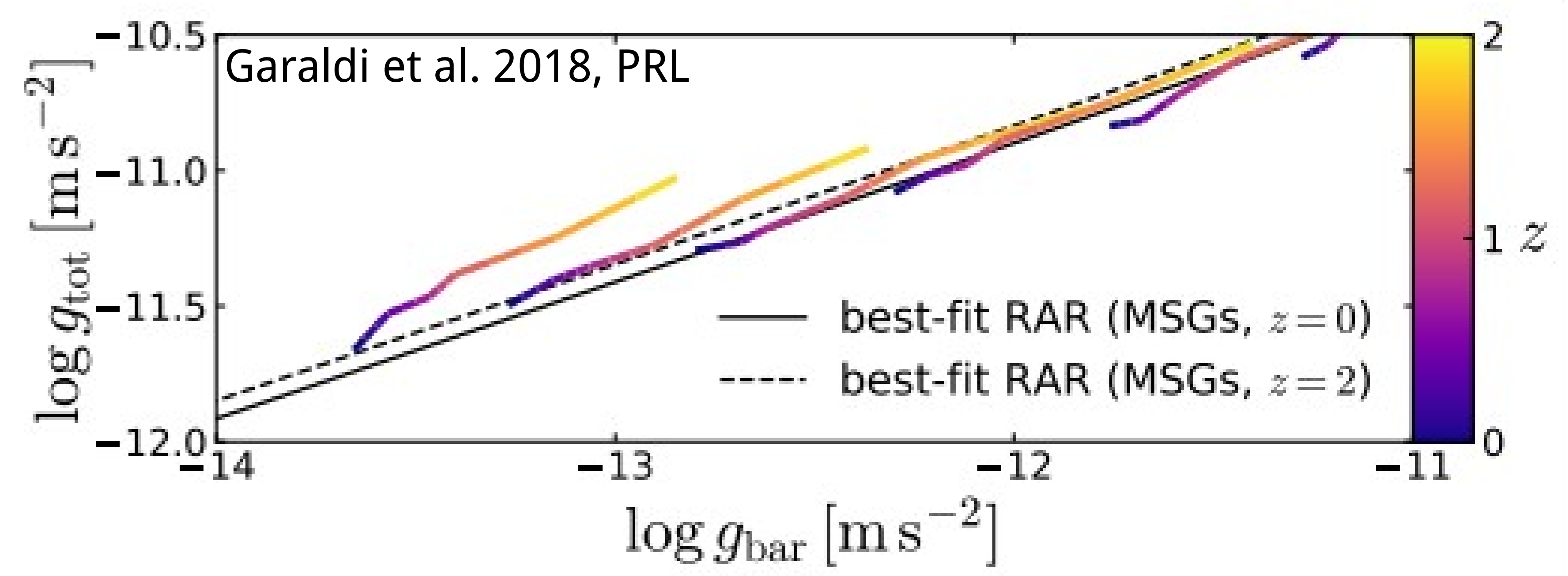
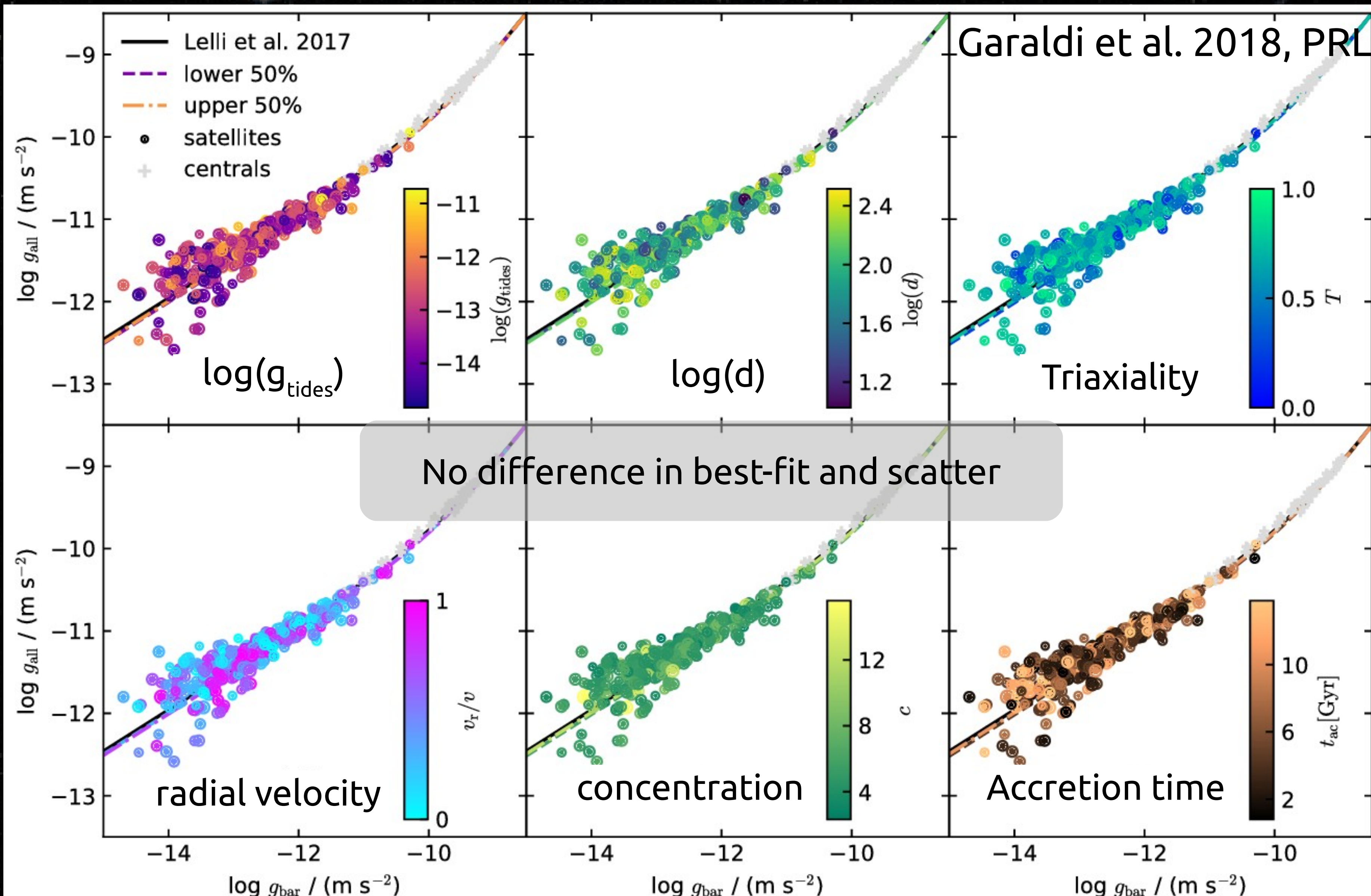


Satellites move *along* the RAR.


Testing MOND and GR
with satellites

No secondary dependence



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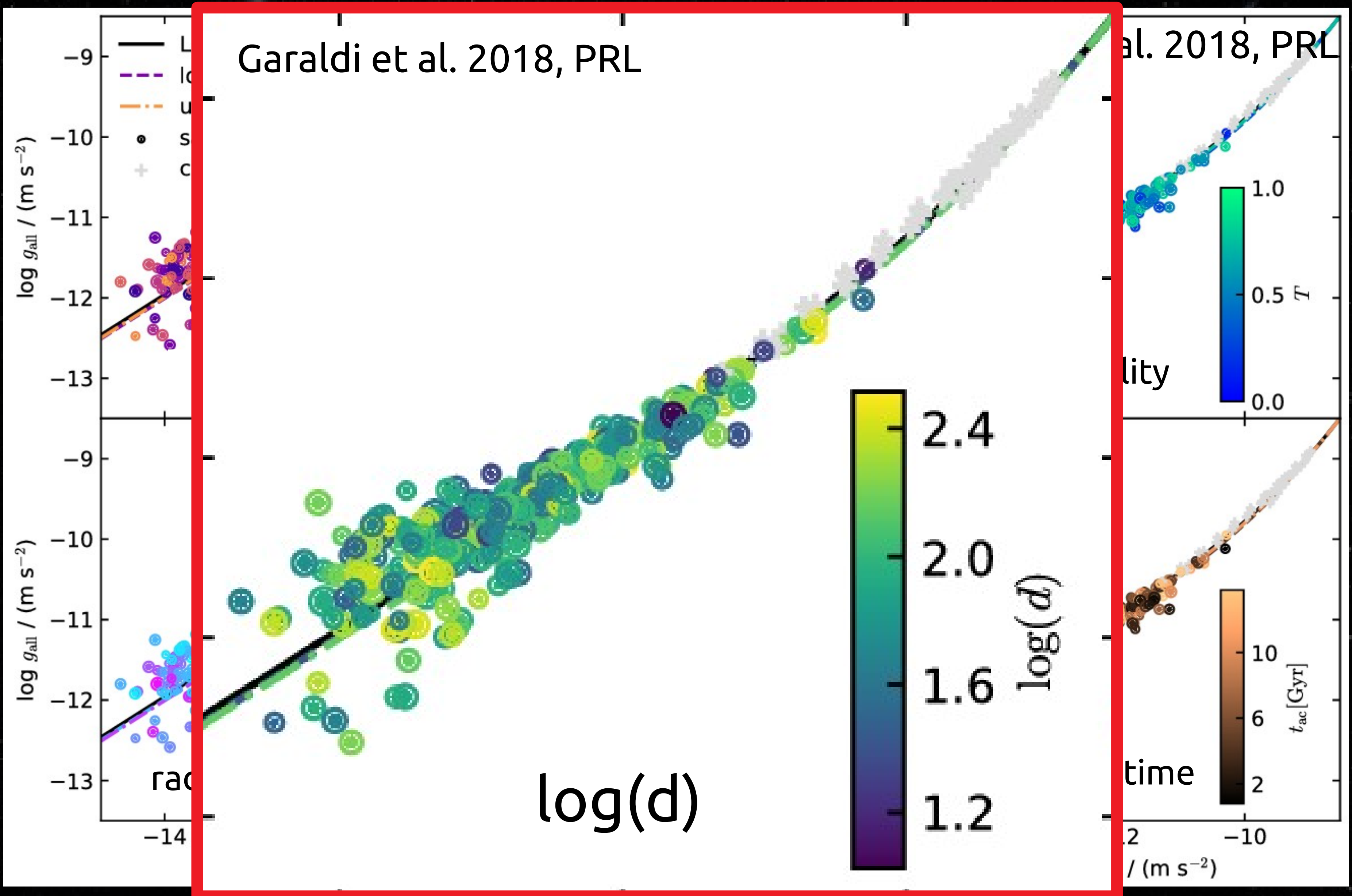


A cosmological test using satellites

ΛCDM: RAR does *not* depend on the satellite-host distance

MOND: total internal acceleration depends on the satellite-host distance (external field effect)

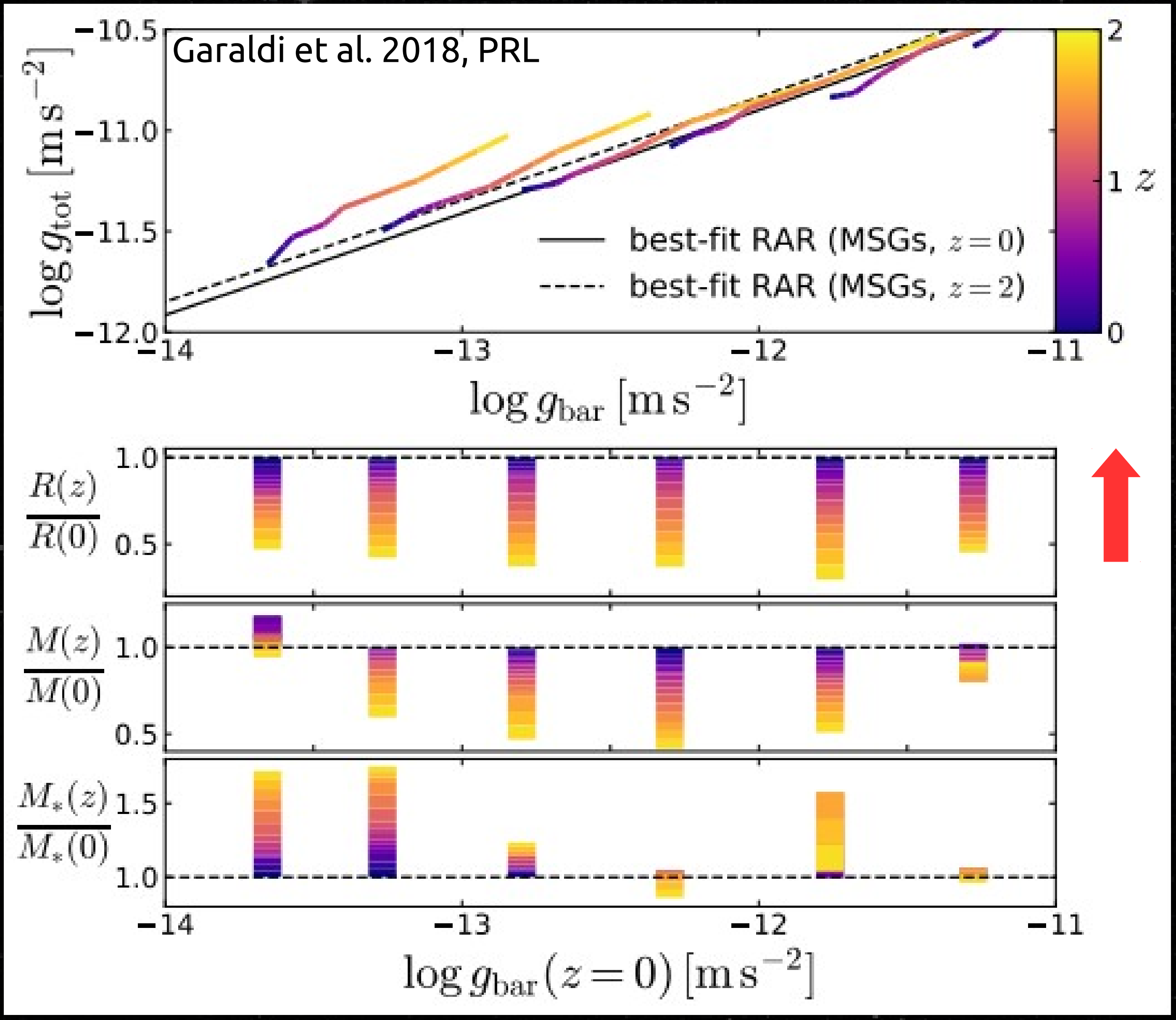
⬇

Accurate measurement of g_x and distances could tell apart ΛCDM and MOND.

Conclusions

- In ΛCDM, satellites follow the same RAR as bigger galaxies, but with larger scatter
- Linear evolution of $g_\dagger$ with a_{exp}, $\sigma_{int} \approx$ constant
- No secondary dependence of the RAR in ΛCDM → a cosmological test with satellites
- Requires precise data *and* modelling

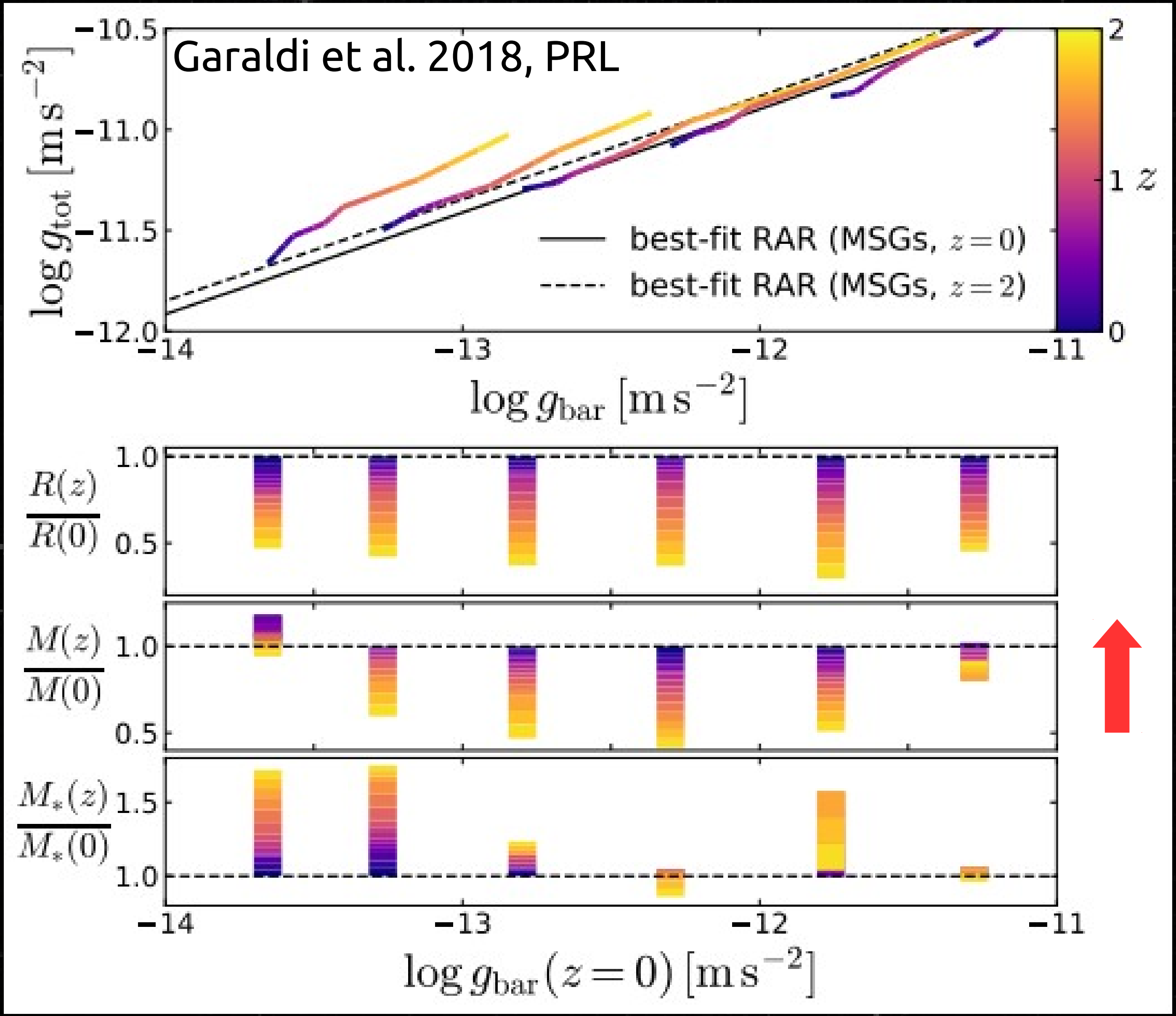
$g_\dagger$ evolves linearly with a_{exp}



Satellites move *along* the RAR.

Their radius *increases*

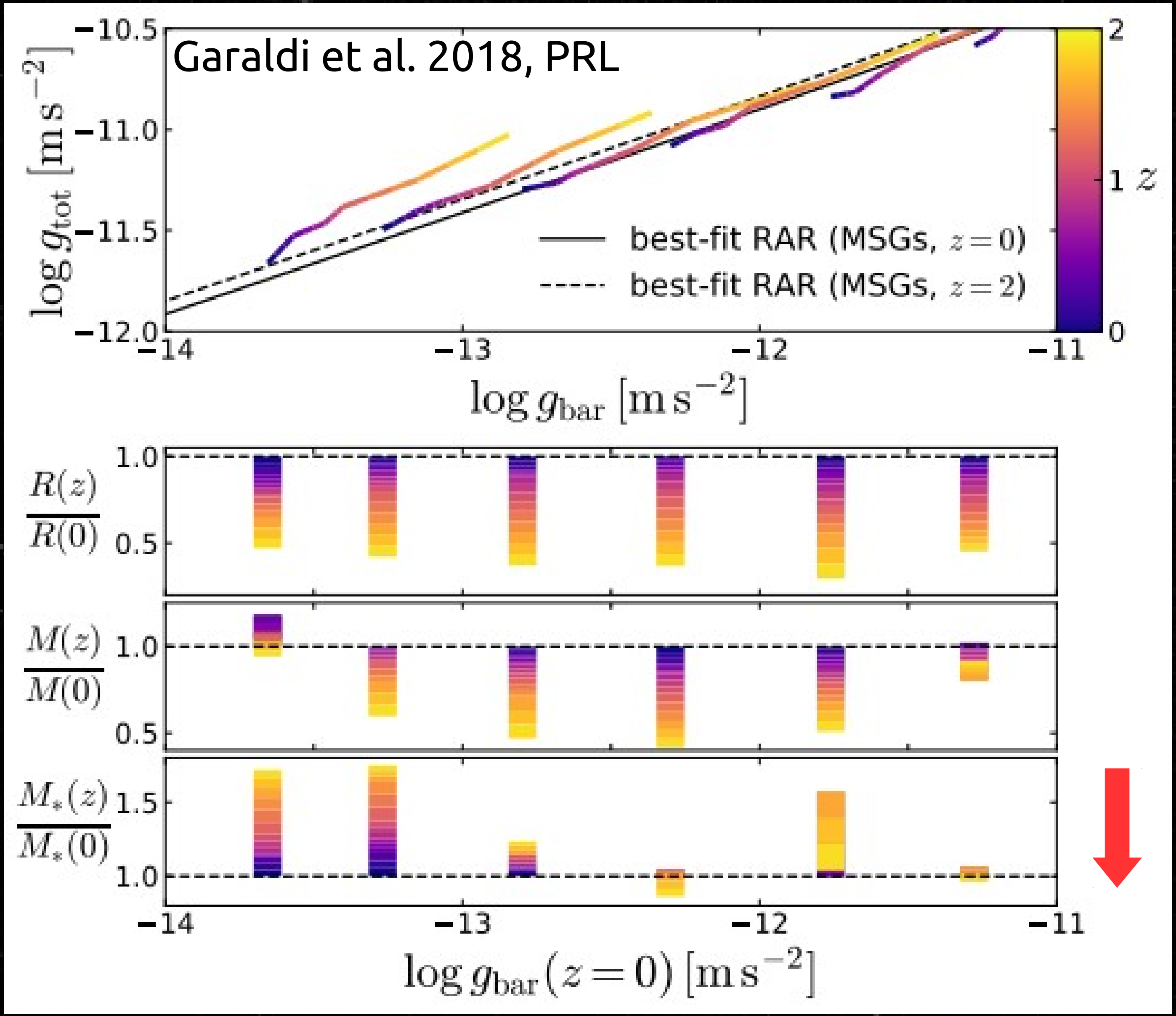
$g_\dagger$ evolves linearly with a_{exp}



Satellites move *along* the RAR.

Their radius *increases*, as well as their total mass.

$g_\dagger$ evolves linearly with a_{exp}

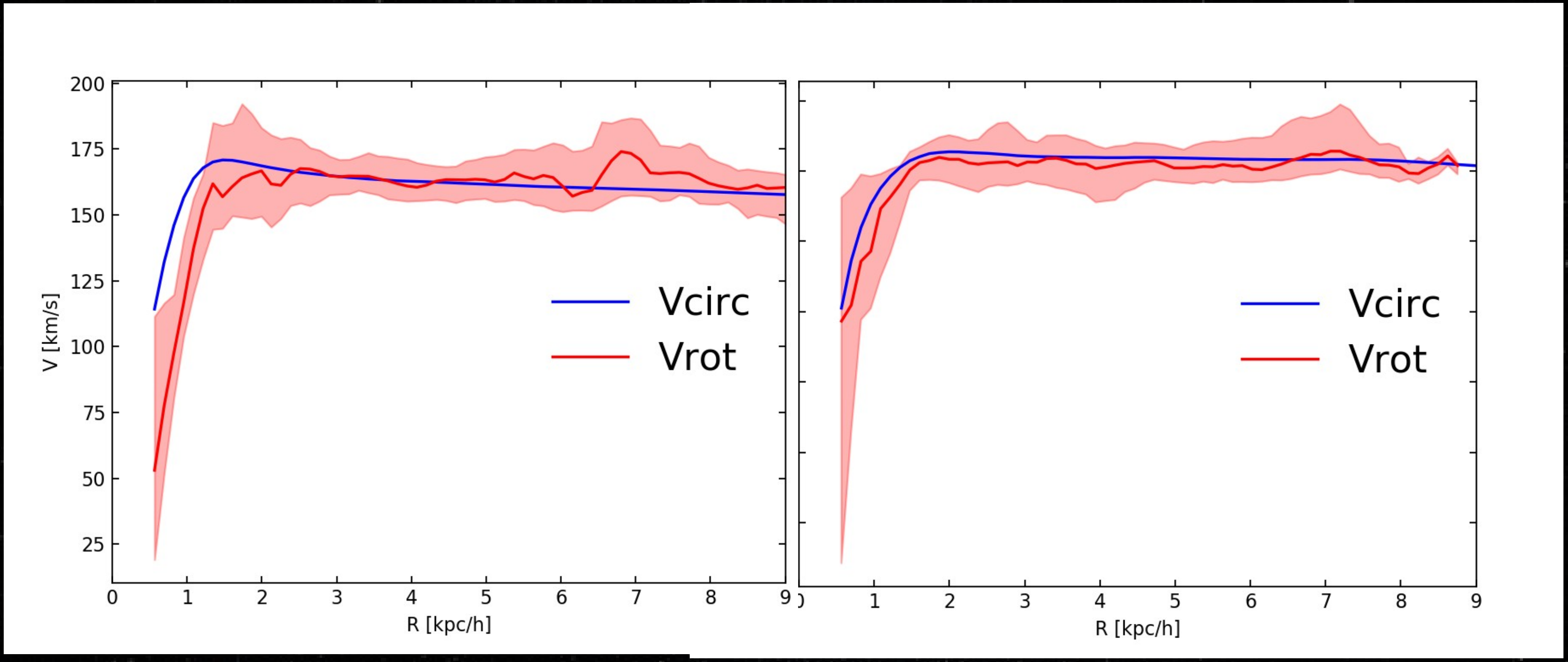


Satellites move *along* the RAR.

Their radius *increases*, as well as their total mass.

But their stellar mass *decreases*.

Vcirc vs. Vrot



Vcirc – enclosed mass
Vrot – gas kinematics

RAR vs. Double Power Law