An acceleration scale in galaxies and its role in fundamental physics

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Dark Side of the Universe 2019

Buenos Aires, Argentina.
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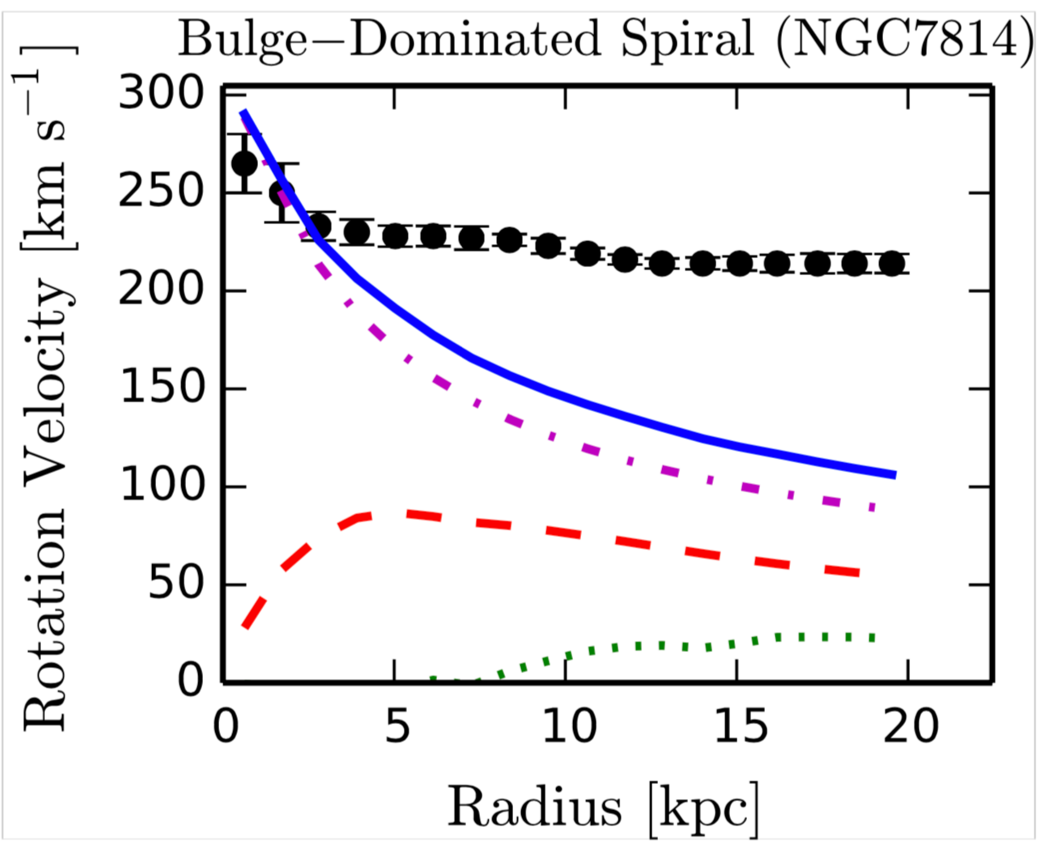
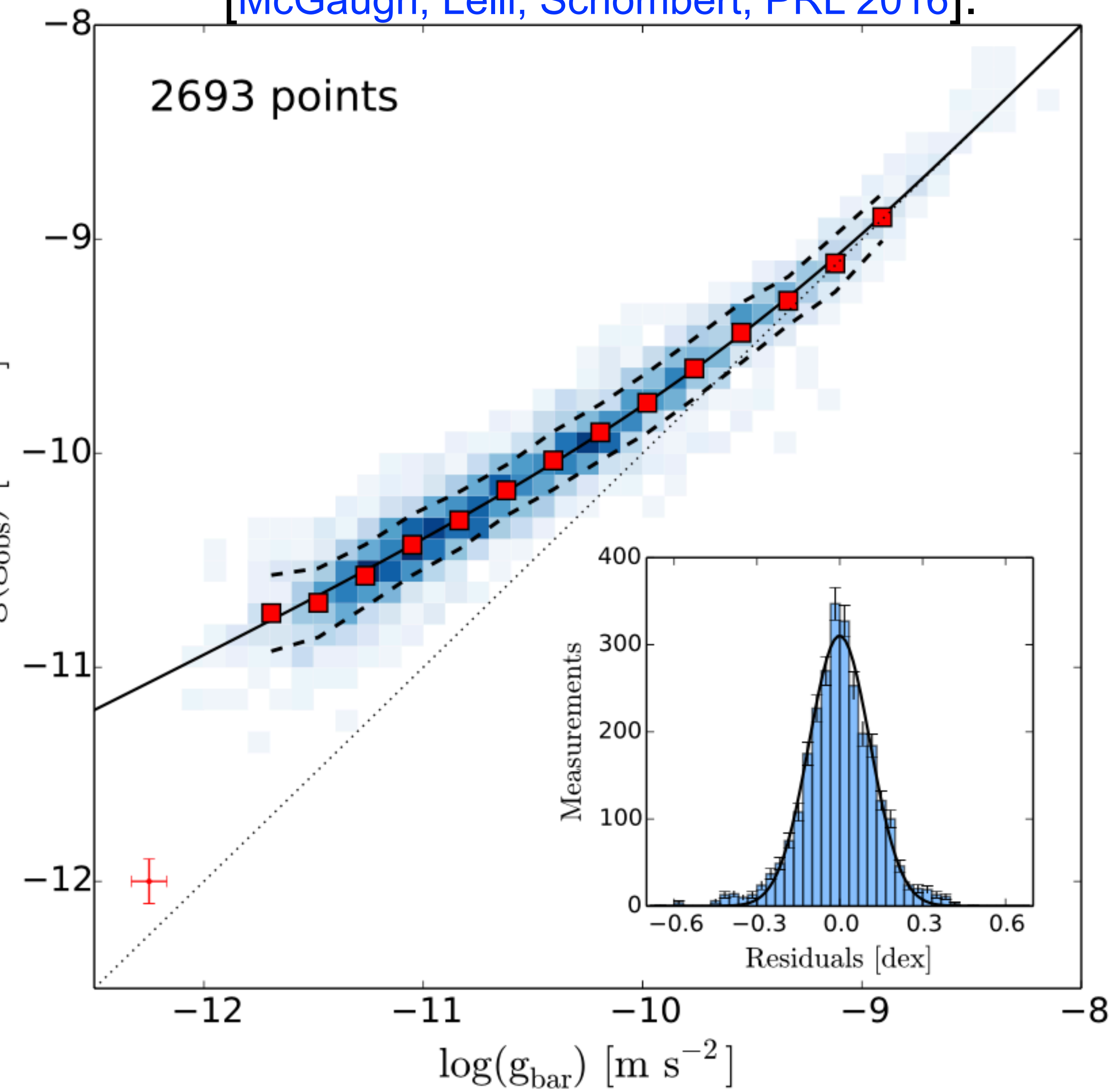
The Radial Acceleration Relation (RAR)

- There is a correlation between the observed acceleration and the acceleration inferred from baryonic matter alone.



Inferred from the circular velocity

[McGaugh, Lelli, Schombert, PRL 2016].



Inferred from the luminosity

The Radial Acceleration Relation (RAR)

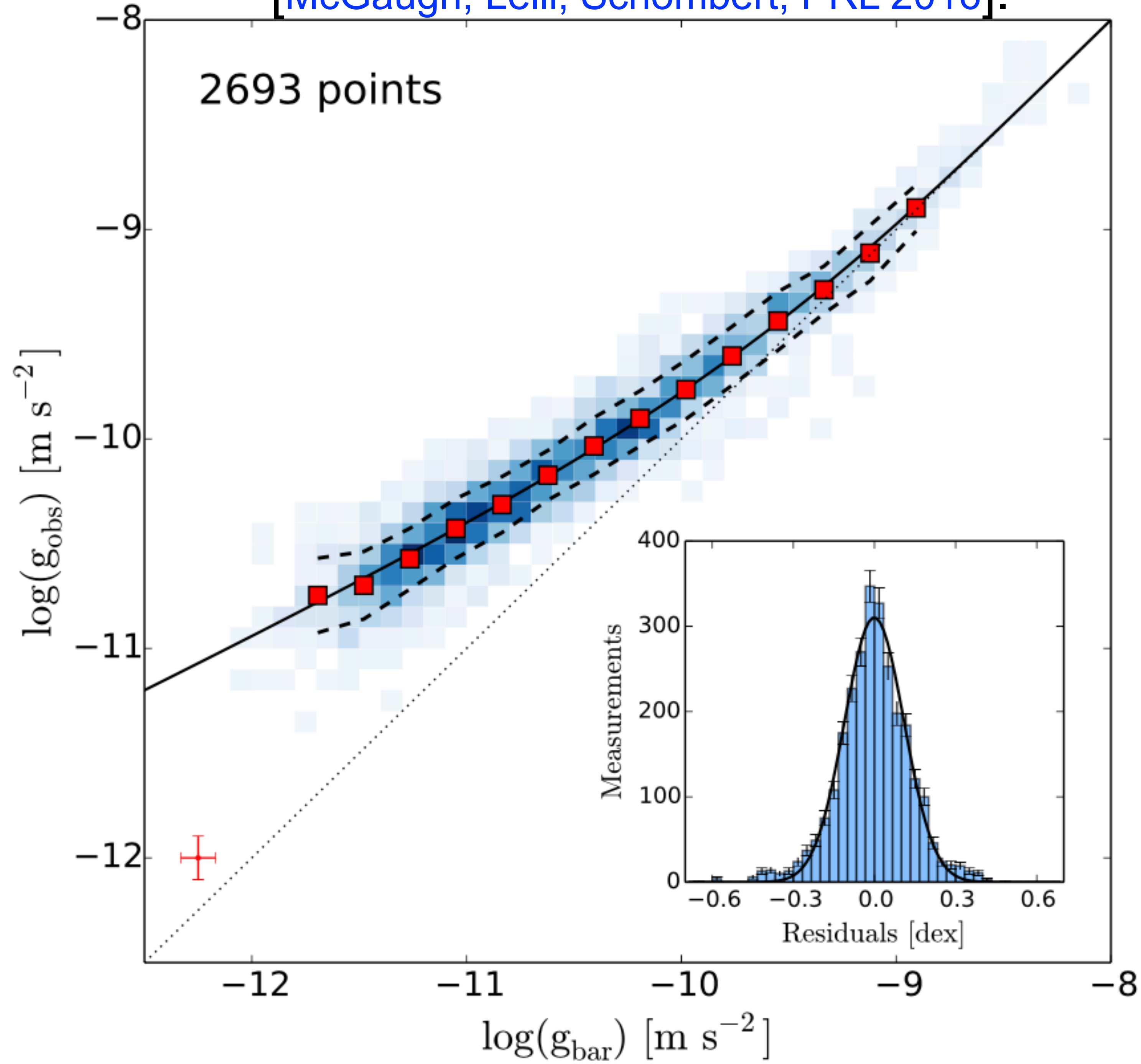
- There is a correlation between the observed acceleration and the acceleration inferred from baryonic matter alone.

[McGaugh, Lelli, Schombert, PRL 2016].

- **No assumptions on dark matter.**

- Derived from 153 of the 175 SPARC galaxies [Lelli, McGaugh, Schombert, Astron.J. 2016]. Stellar light from Spitzer 3.6 μm band.

- **Why is there an acceleration-scale dependent dynamics?**



The Radial Acceleration Relation

- Stellar light from Spitzer 3.6 μm band.

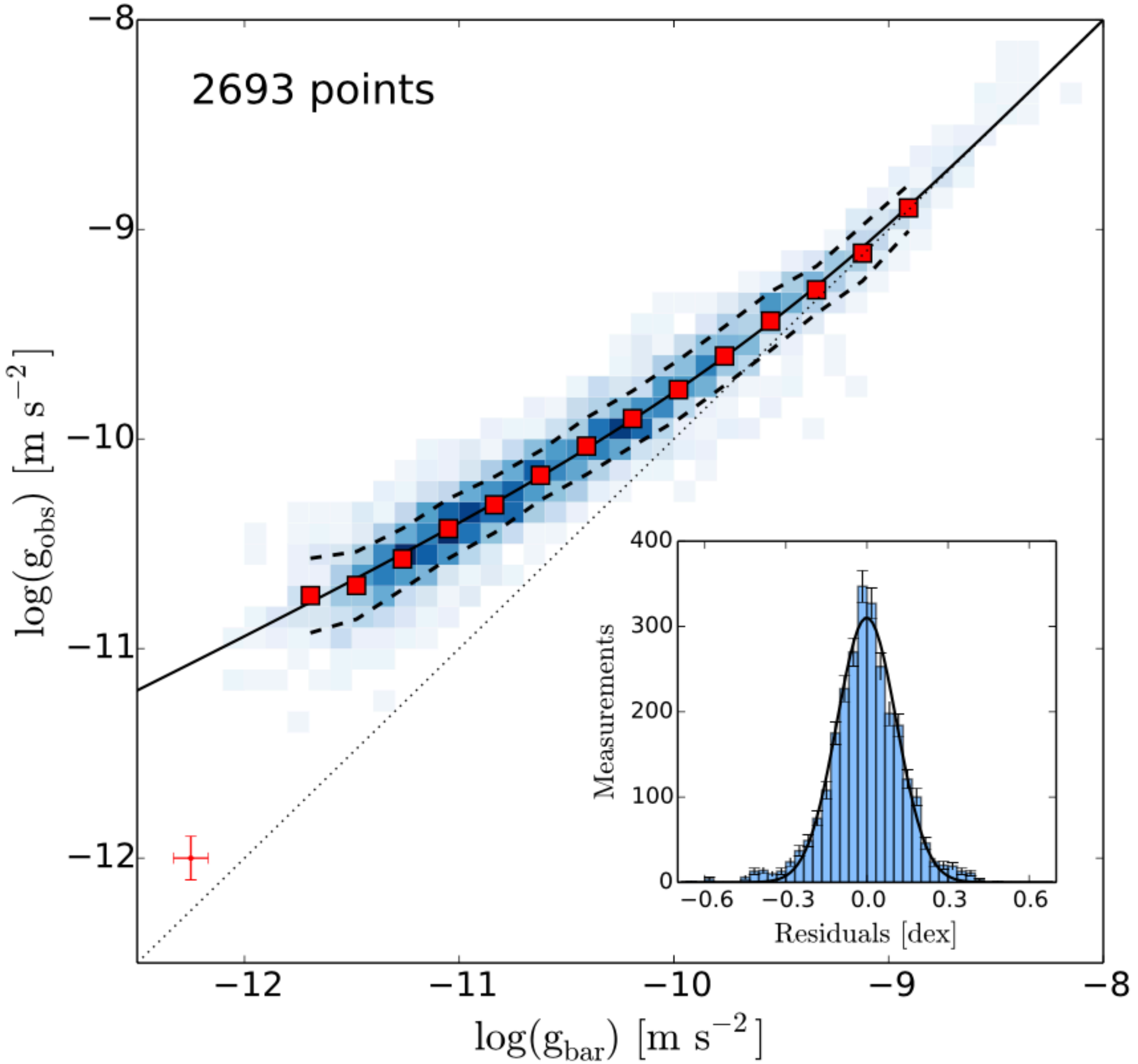
- This is a suitable band to infer stellar masses: i) negligible dust extinction, ii) small dispersion of mass-to-light ratios, which are essentially constant inside a galaxy. [Meidit et al ApJ 2014, among others]

- Expected scatter from galaxy to galaxy: 0.1 dex.

  Expected central global value: 0.4 - 0.7 $M_\odot/L_\odot$

- Mass-to-light ratios chosen for the plot:
  Disk: $\Upsilon_\star = 0.5\ M_\odot/L_\odot$,
  Bulge: $\Upsilon_\star = 0.7 M_\odot/L_\odot$.

  These values minimize the scatter, see [Lelli et al ApJ 2017], and favour the interpretation as a fundamental relation.



The correlation and its scatter

- A simple function describes very well this correlation

$$a_{\rm obs} = \frac{a_{\rm bar}}{1 - e^{-\sqrt{a_{\rm bar}/a_0}}}$$

a_0 is a constant (the acceleration scale). $a_0 = 1.20 \times 10^{-13}$ km/s^2

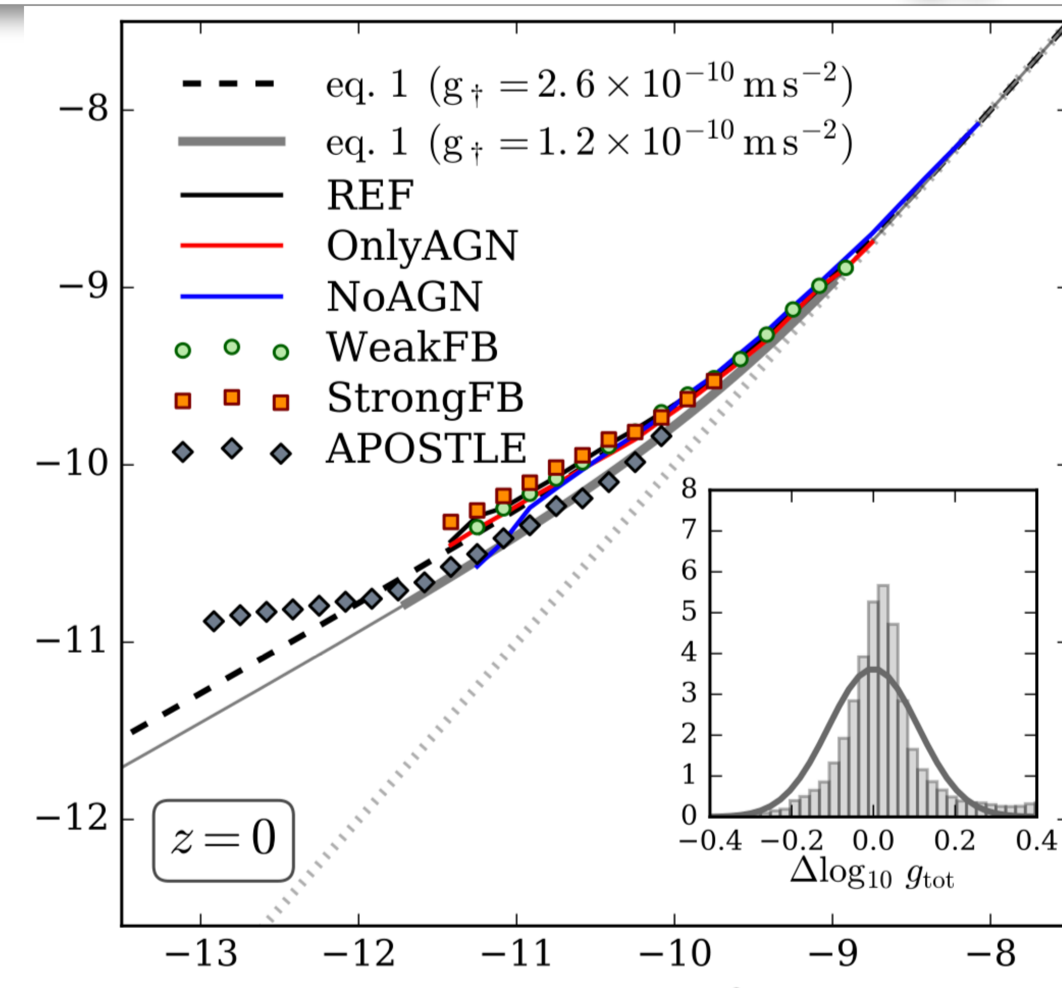
The residuals have a **scatter of 0.1 dex**.

- It is found that the average expected errors lead to an **average uncertainty of 0.1 dex**.

- Is this correlation too tight for standard cosmology to explain? Could there be something of fundamental nature in such correlation?

Can it be explained from standard CDM and cosmology?

- Results from simulations show that LCDM derives the RAR with mild dependence on feedback [Keller, Wadsley ApJ 2017; Ludlow et al PRL 2017; Navarro et al MNRAS 2017].



- However, there are complains that the agreement is not sufficiently precise or natural within LCDM; and that the RAR could be a window towards new physics [Lelli+ ApJ, 2017; Milgrom, 1609.06642; Famaey+ JCAP 2018; many others]

- Two interpretations:

1. <u>The acceleration scale a0 is an **emergent** phenomena</u>.
   As an average result from the baryonic and (possibly standard) dark matter evolution.

2. <u>The acceleration is **fundamental** (at least at the galaxy level)</u>.
   From a modified gravity or some peculiar dark matter model.

Is galaxy data compatible with a fundamental a_0?

LETTERS
https://doi.org/10.1038/s41550-018-0498-9
nature astronomy

That was our main question.

Absence of a fundamental acceleration scale in galaxies

Davi C. Rodrigues[1,2*], Valerio Marra[1,2*], Antonino del Popolo[3,4,5] and Zahra Davari[6]

- To address this issue, it is not sufficient to find a correlation with "small" scatter.

- **The credible intervals of the acceleration scale need to be evaluated.**

- Similar to what is commonly done in cosmology: different measurements of the same quantity (say, Ω_m) should be compatible.

General considerations

- We use Bayesian analysis and reduce the dependence of our results on possible uncontrolled systematics by:
  - Using nuisance parameters with flat priors:
    hence, no dependence on the central values.
  - Considering different sets of quality cuts:
    no results driven by outliers.
  - Considering two different samples of data from different groups: SPARC and THINGS;
  - Looking for results with high statistical significance.

The parameters and the priors

Parameter		Prior
$\Upsilon_{\star D}$	Stellar disc mass-to-light ratio	Factor 2 on the RAR central value: 0.25-1.0
$\Upsilon_{\star B}$	Stellar bulge mass-to-light ratio	Factor 2 on the RAR central value: 0.35-1.4
δ	Distance variation	20% variation from the central value.
a_0	acceleration scale	$a_0 > 0$

- Inclination variations are not as relevant as the other nuisance parameters (all have i > 30º). But different quality cuts on the inclination were considered, without changes to the conclusions.

The quality cuts

Quality cuts are important in our analysis and were not used as extensively as we did.

We find the a0 posteriors of all the 175 SPARC and 18 THINGS galaxies, but only some of the galaxies passed to the final analysis.

Quality cut	Description
“RAR”	It removes some SPARC galaxies not considered robust enough, as used in the original paper on the RAR. (175 -> 153)
Closed 5 σ posteriors	Removes the galaxies that are compatible with a0 = 0 at 5σ level. It is a requirement for finding well defined 5 σ contours.
5 σ	Removes galaxies with too high χ^2 : those that are already individually rejected at 5σ. (Eliminates 41 galaxies from SPARC).
Other quality cuts beyond the main analysis	3σ quality cut (62 galaxies eliminated), surface brightness quality cuts, luminosity quality cuts, distance uncertainty and inclination uncertainty.

Codes to automatically analyse hundreds of galaxies

MAGMA

https://github.com/davi-rodrigues/MAGMA

χ^2 functions

&

Best-fits via differential evolution

(to optimize the Bayesian analysis)

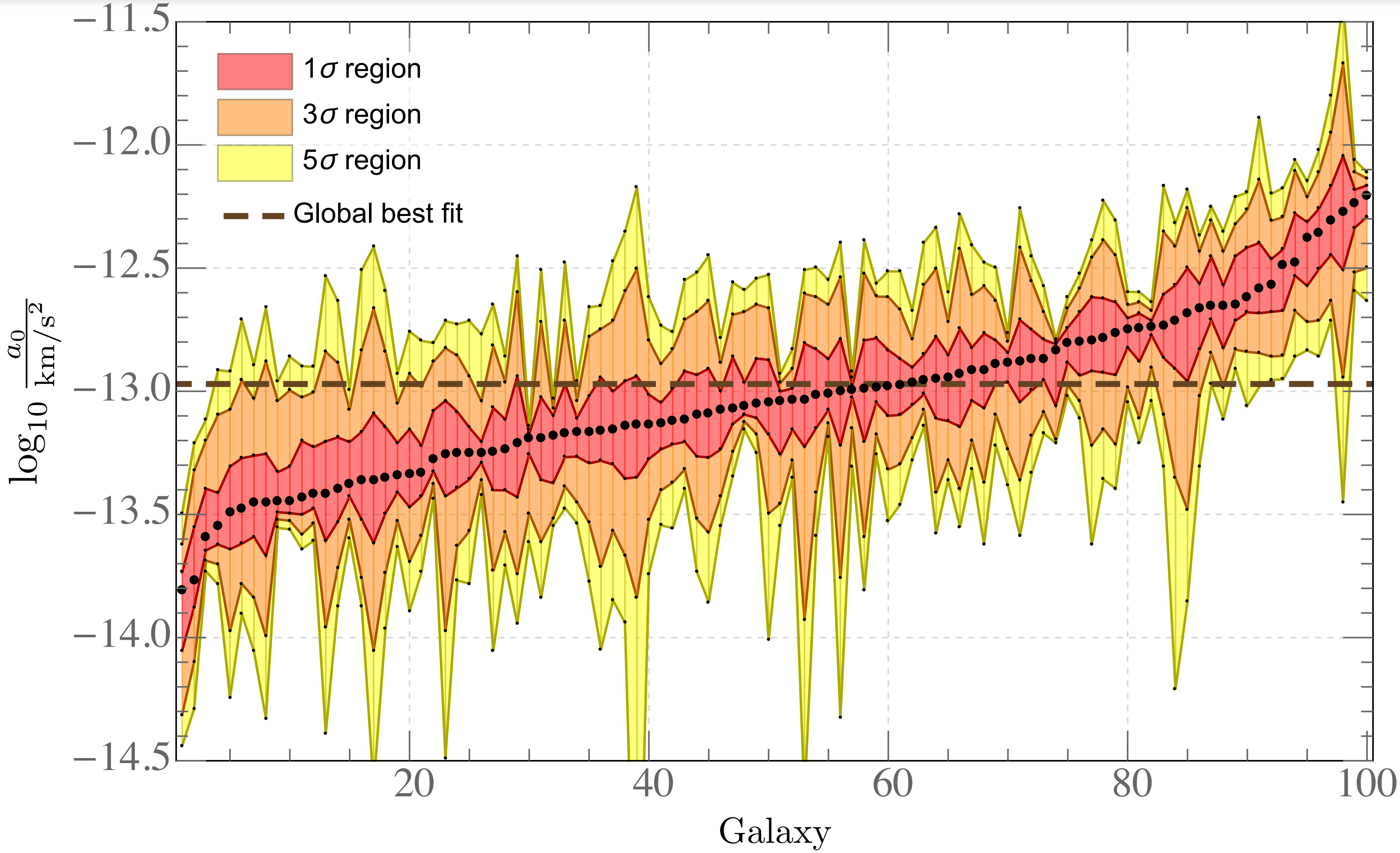
mBayes

https://github.com/valerio-marra/mBayes

Bayesian credible intervals on a0

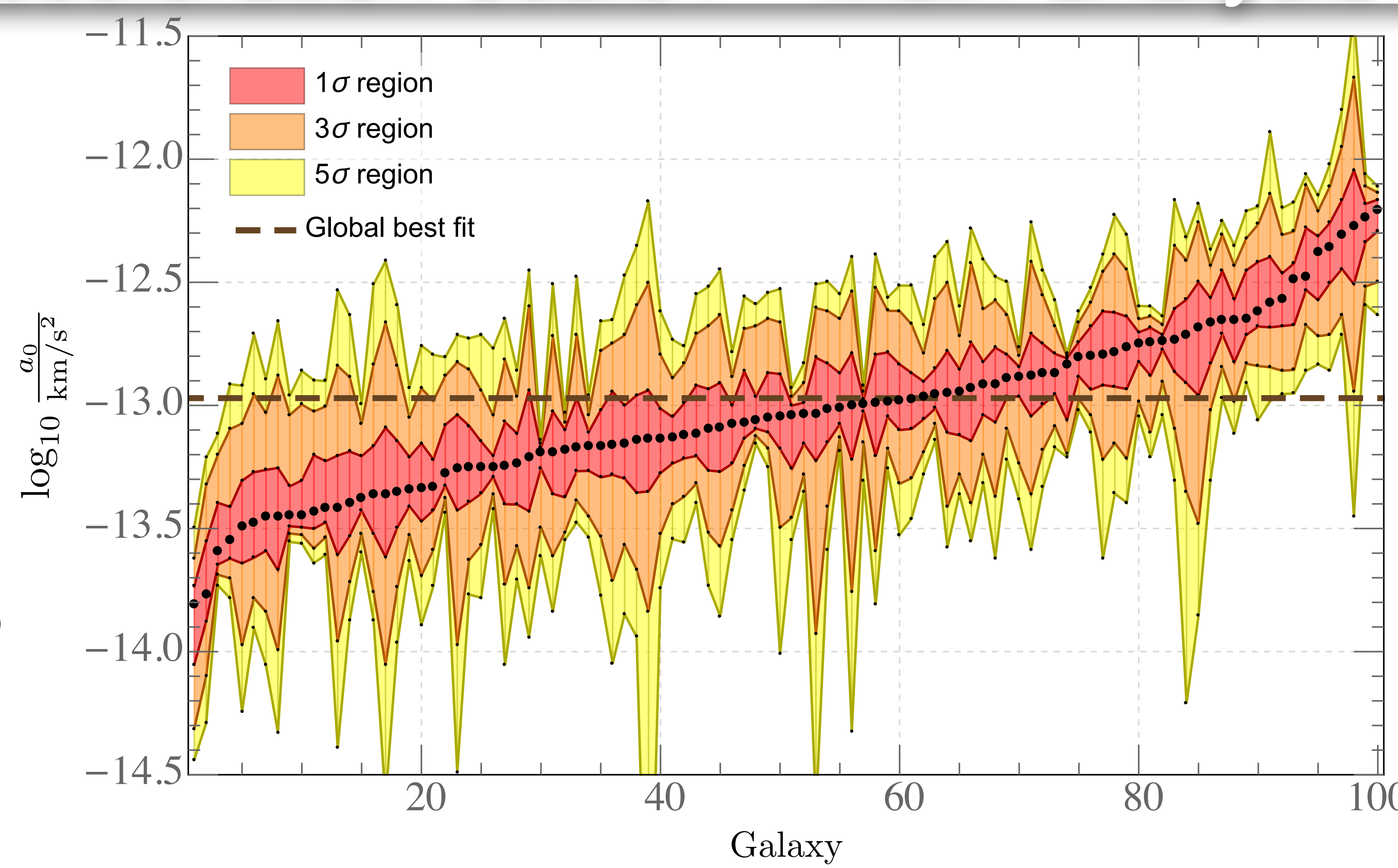
Data analysis

Is there a common acceleration scale? - Main analysis



	$\log_{10} a_0$	1σ (32%)	3σ (0.27%)	5σ (5.7×10^{-7})
RAR-inspired	-12.970	71%	31%	15%

Is there a common acceleration scale? - Main analysis



To sintetize this result into a single number, we use:

Global best fit:

$$\bar{a}_{0,j} = \int \mathrm{d}a_0 \, a_0 \, f_j(a_0) \, ,$$

$$\sigma^2_{a,j} = \int \mathrm{d}a_0 \, (a_0 - \bar{a}_{0,j})^2 \, f_j(a_0) \, ,$$

$$\chi^2(a_0) = \sum_{j=1}^{N} \frac{(\bar{a}_{0,j} - a_0)^2}{\sigma^2_{a,j}} \, ;$$

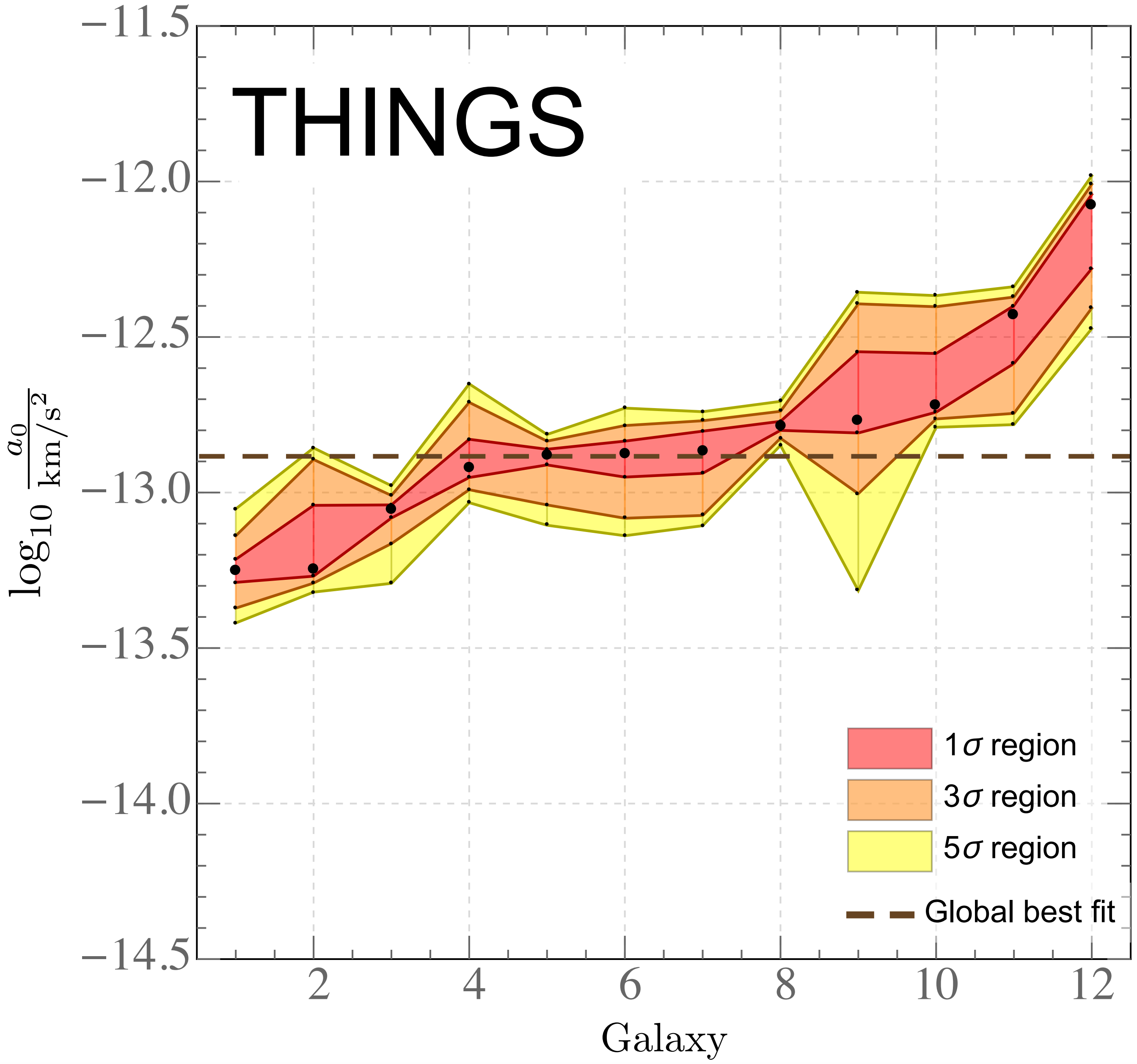
Formal confidence in rejecting a common acceleration scale:

$$n_\sigma = \frac{\chi^2(a_0^{\mathrm{bf}}) - k}{\sqrt{2k}}$$

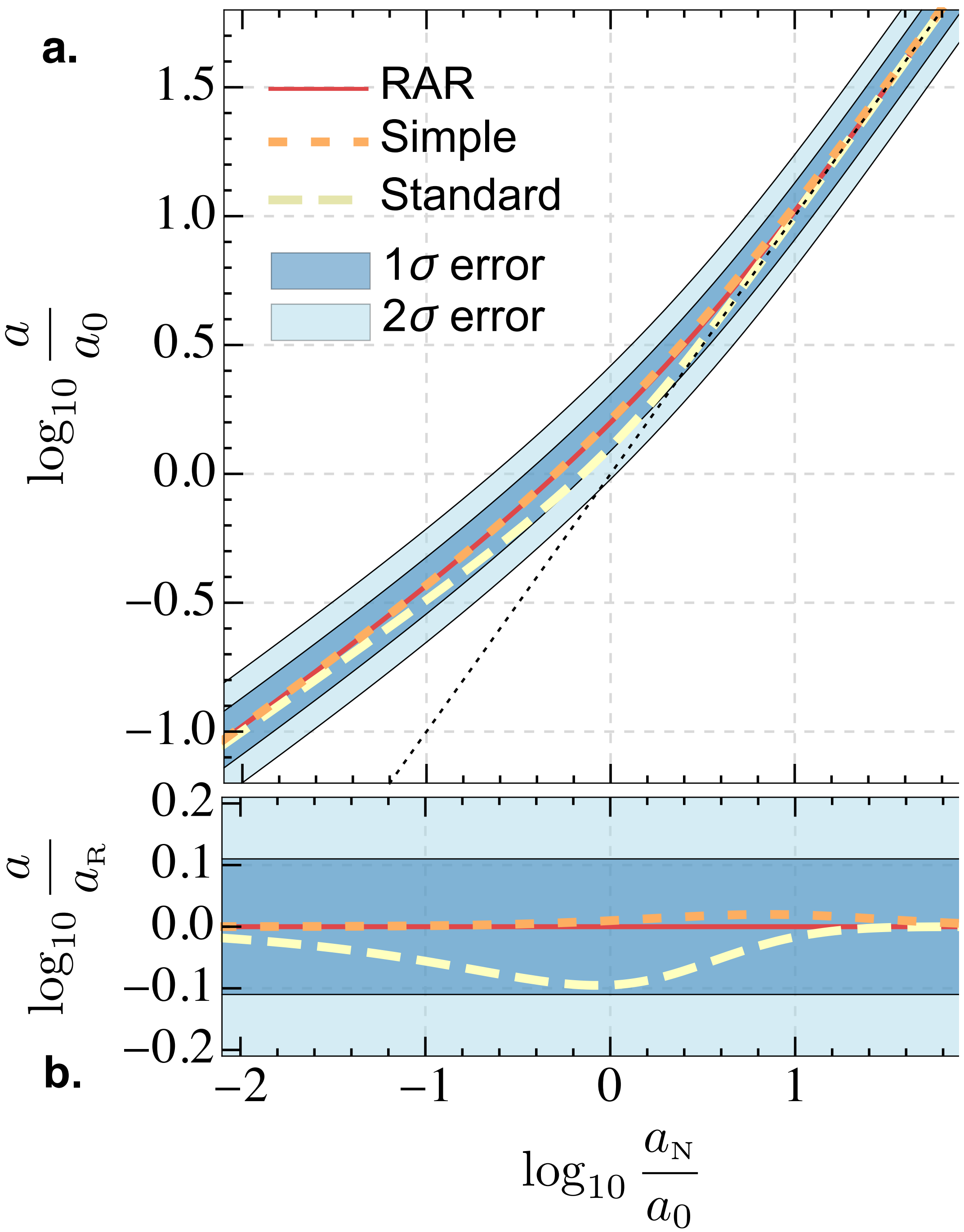
For the case above, $n_\sigma \sim 50.$

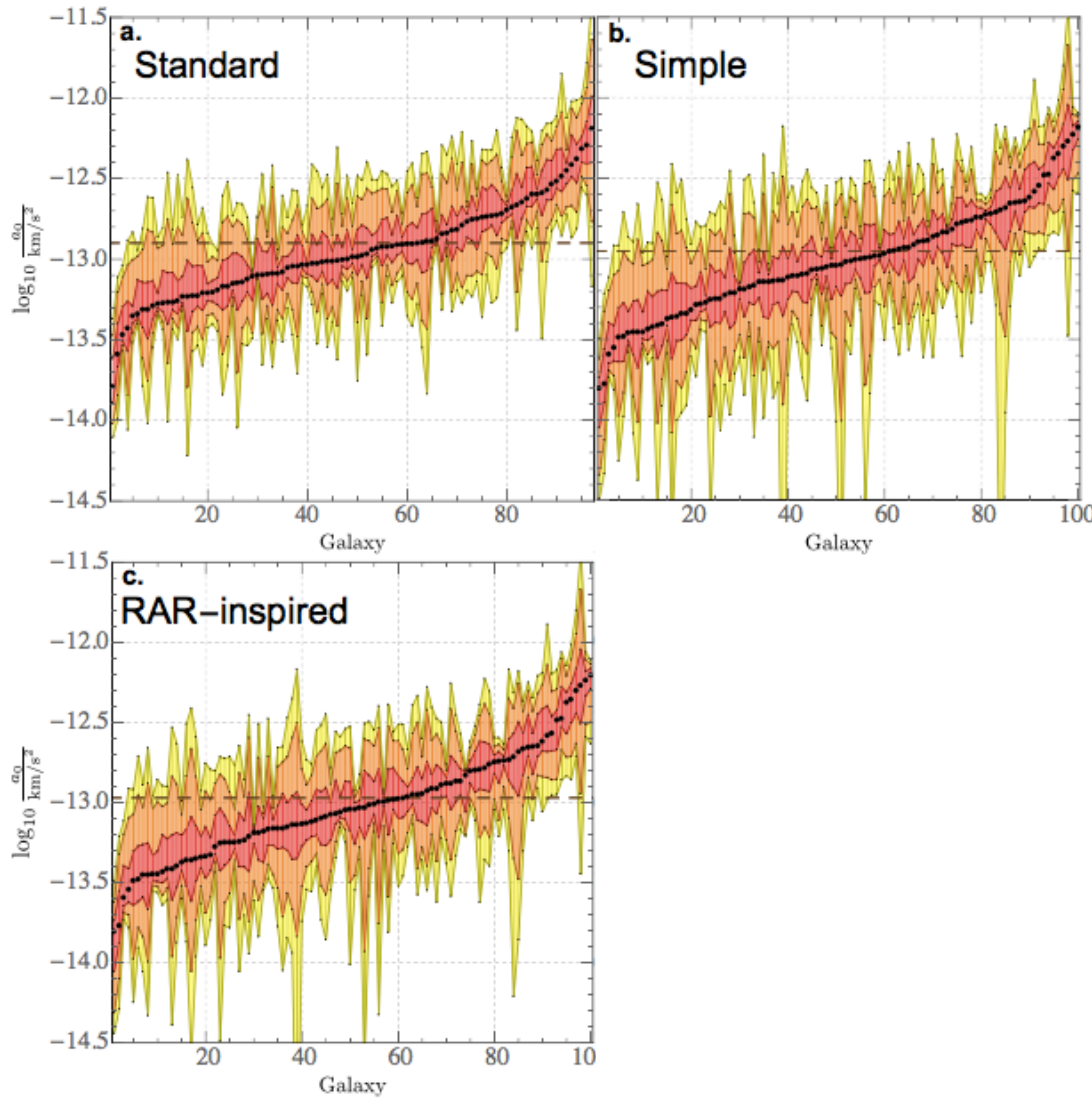
For all the cases, we find $n_\sigma > 10.$

For 18 from the original THINGS sample, the situation is qualitatively similar. 12 galaxies pass the quality cuts whose results are below.



What if another expression for the correlation is used?

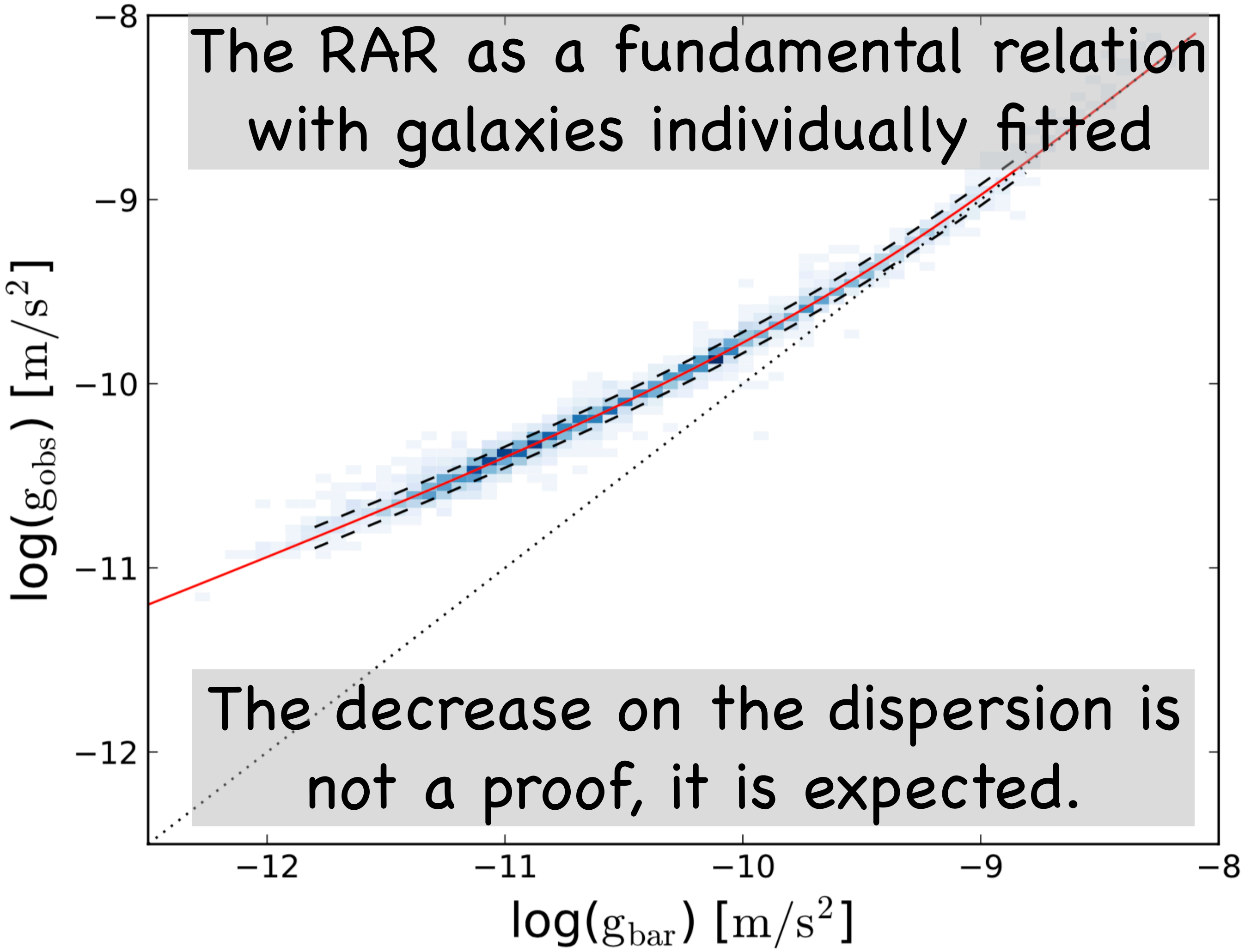


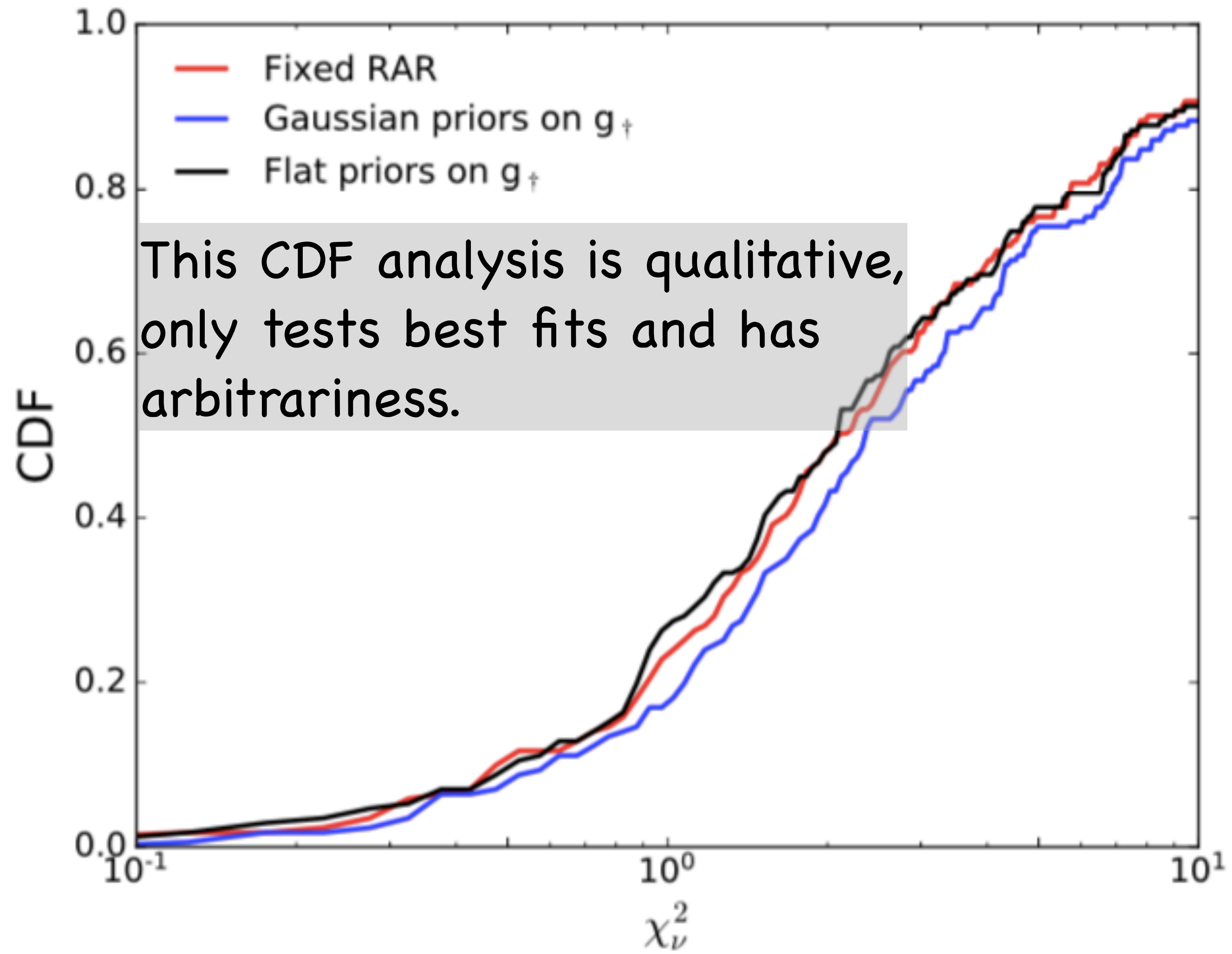


A parallel work that explored the fundamental interpretation

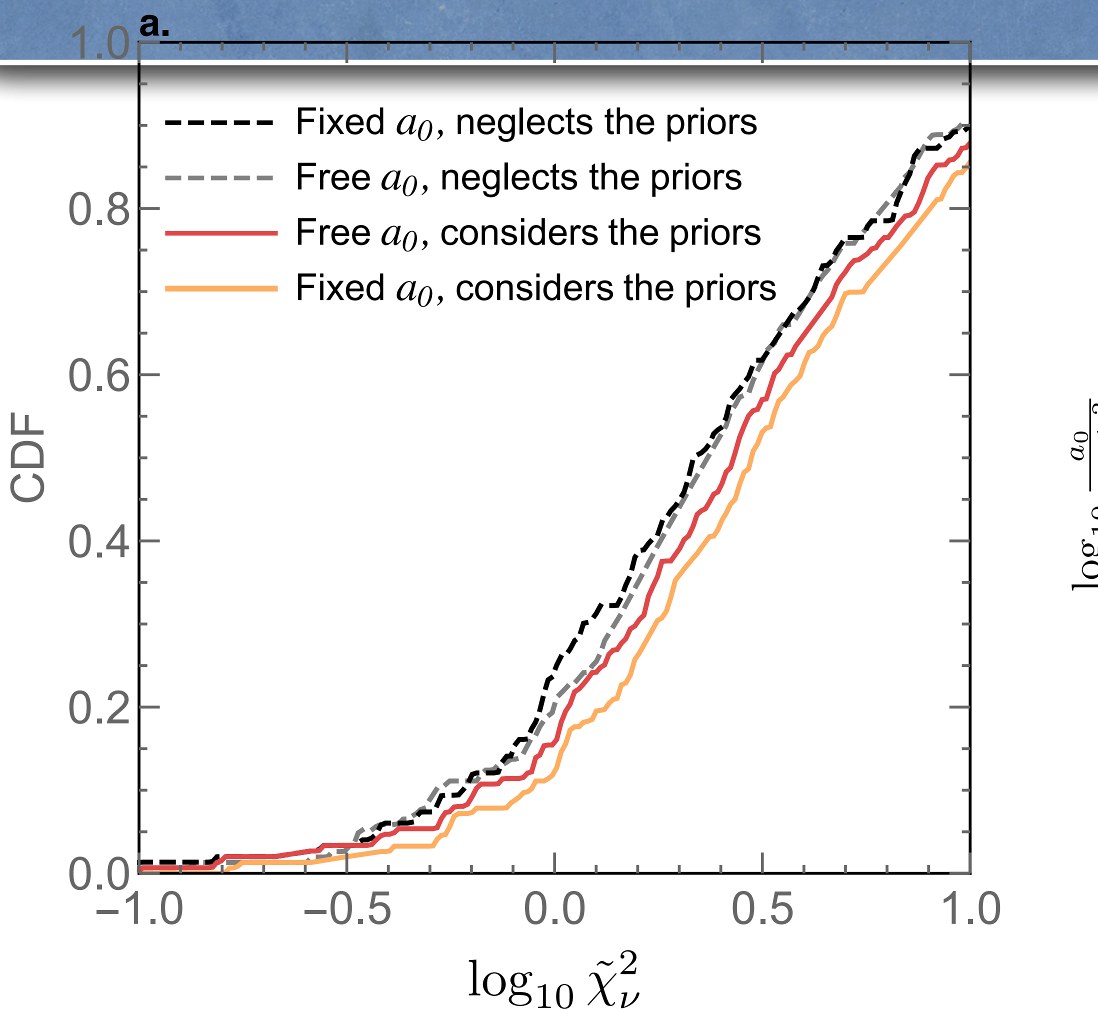
- Parallel to our work, another one [Li et al A&A 2018] claimed that all the SPARC data were consistent with a fundamental acceleration scale.

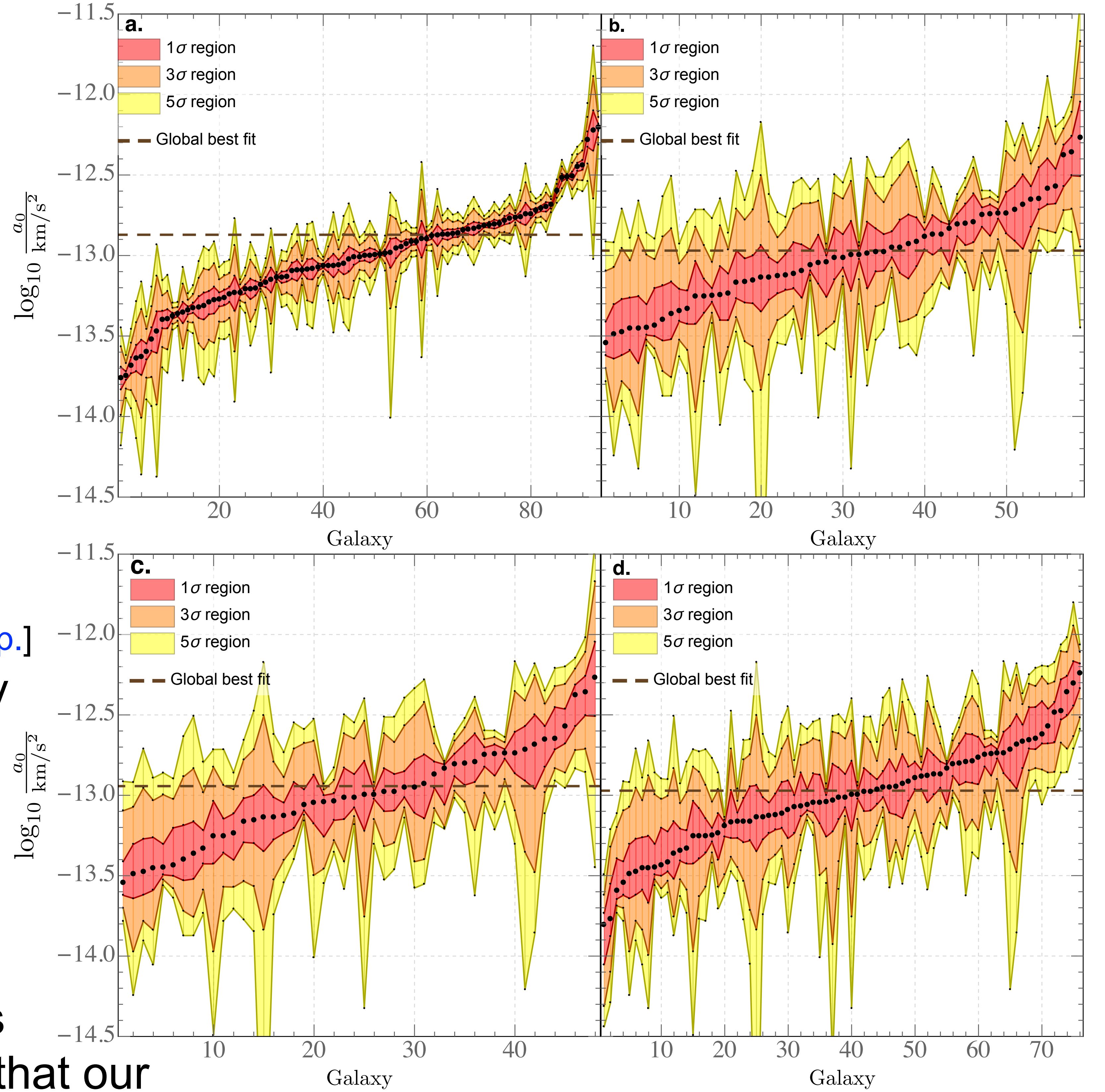
- We see no technical errors in both approaches (we rederived their results), they used tests that could not be sensitive to the issues that we raised. Namely, they tested best fits, while we tested the compatibility between credible intervals.





Our reply





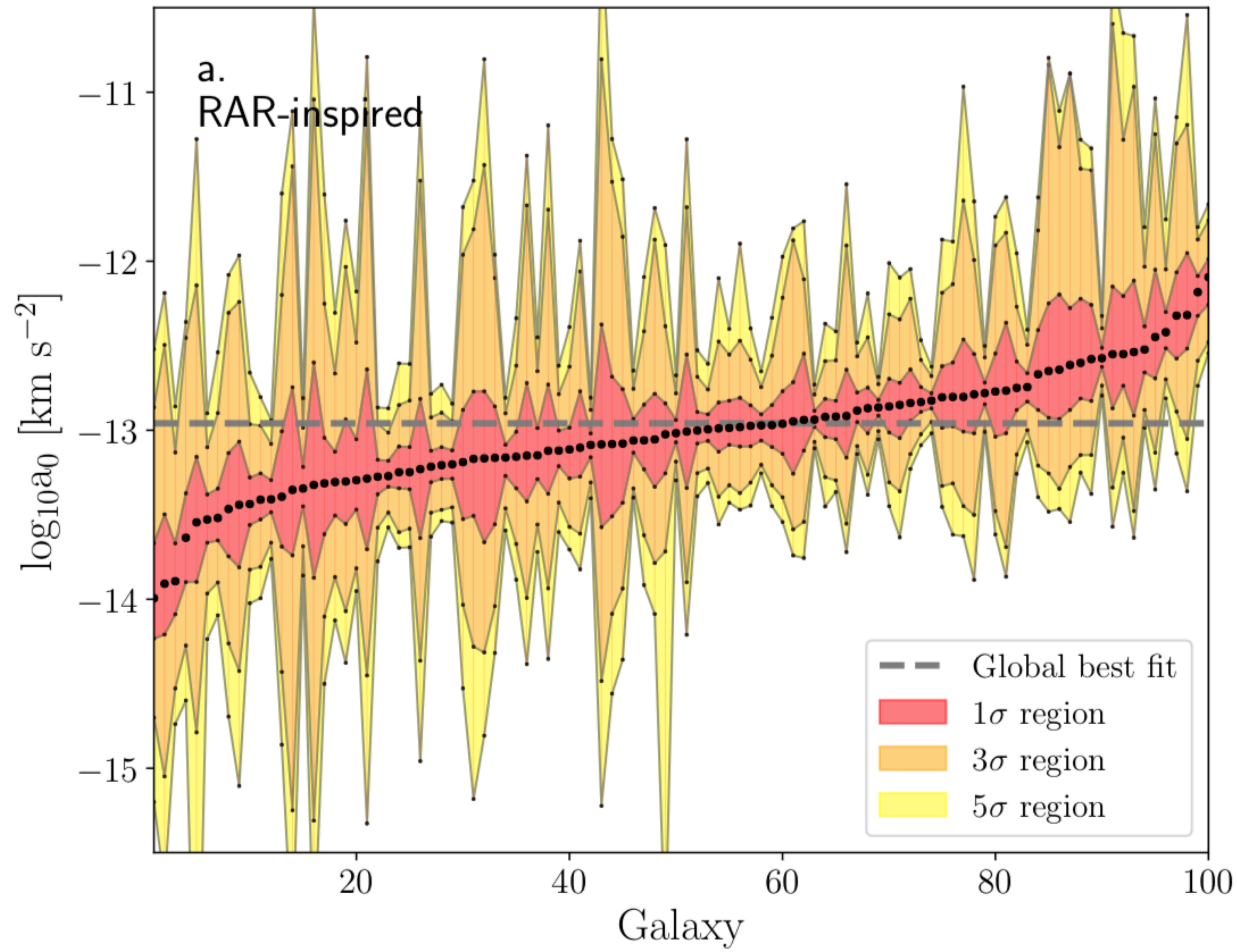
In [Rodrigues et al,Nat.Astron.(2018)-Corresp.] we answered the issues raised by [McGaugh et al & Kroupa et al]. We extended the analysis of [Li et al, A&A (2018)], showing it has arbitrariness (above).

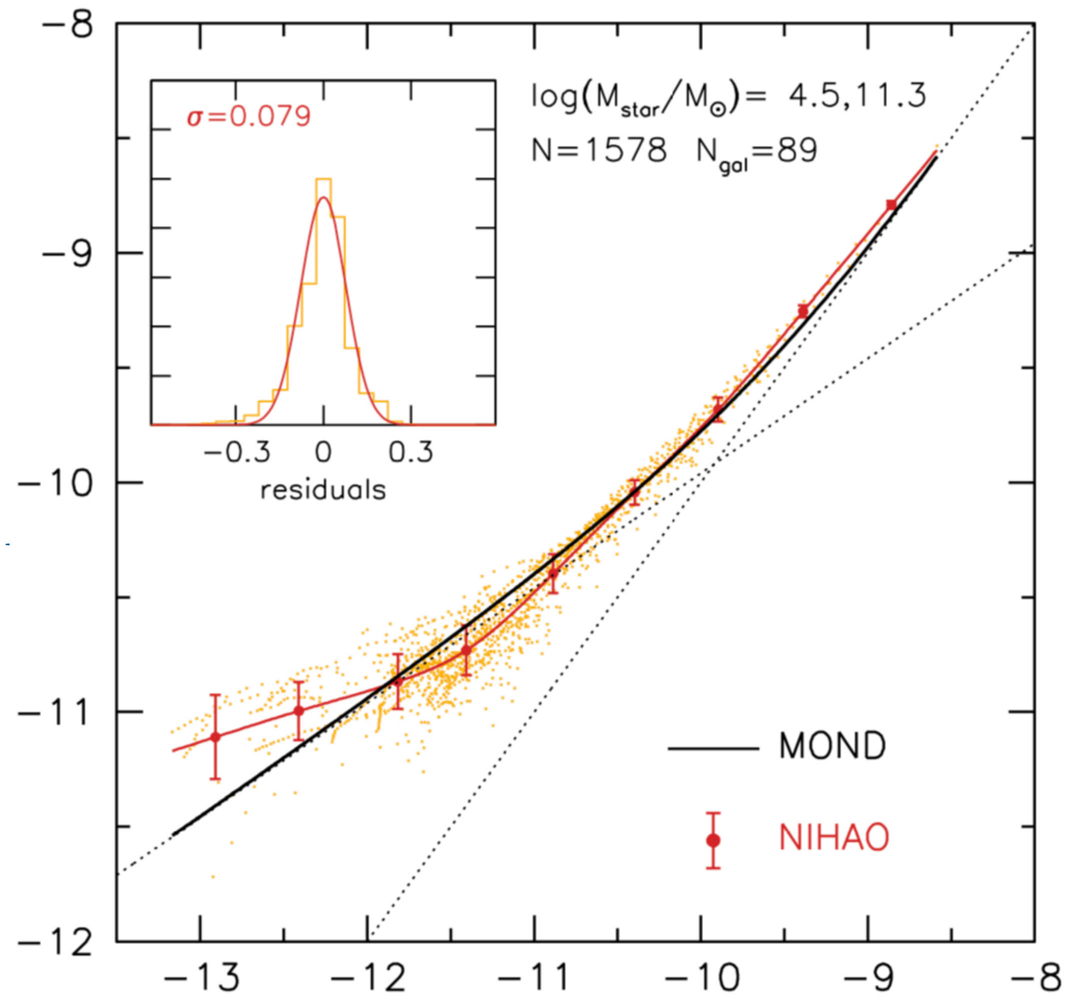
Different and stronger quality cuts were performed, showing further that our results are robust and not driven by outliers (right).

Other related and recent results

- [Chang & Zhou, MNRAS 2019] - Repeats all our approach but using exactly the same priors of [Li et al A&A 2018]: as we expected, our conclusions remain valid, i.e. a fundamental acceleration is rejected at high confidence.

[Chang & Zhou, MNRAS 2019]





[Dutton et al MNRAS 2019] - Another simulation for LCDM that further supports that the RAR dispersion can be found from LCDM within observational uncertainties.

Conclusions

- The RAR [McGaugh, Lelli, Schombert, PRL 2016] is an updated and sharper version of MDAR [Sanders, Astron. Astrophys. Rev. 1990;….].

- The RAR is a peculiar correlation that was originally seen as a triumph for MOND [Milgrom, 1609.06642;…], boosting the interest on it.

- Ironically, we used the RAR to show that its acceleration scale is not fundamental, and hence that MOND itself cannot be a gravitational theory at the scale of galaxies.

- Our work was not the first to compute "error bars" on a0 from a sample of galaxies, but it was the first to due it with Bayesian analysis (finding the 5 sigma posteriors on a0), and for a large sample (almost 200 galaxies were fitted several times).

- Our results reject that the acceleration scale of the RAR can be fundamental, and hence rejects MOND as a theory for gravity. Nonetheless, MOND can be seen as an approximation for the effective dynamics of baryons and dark matter.