Testing dark matter and modified gravity at astrophysical scales

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FAPES
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Brief historical notes on dark matter

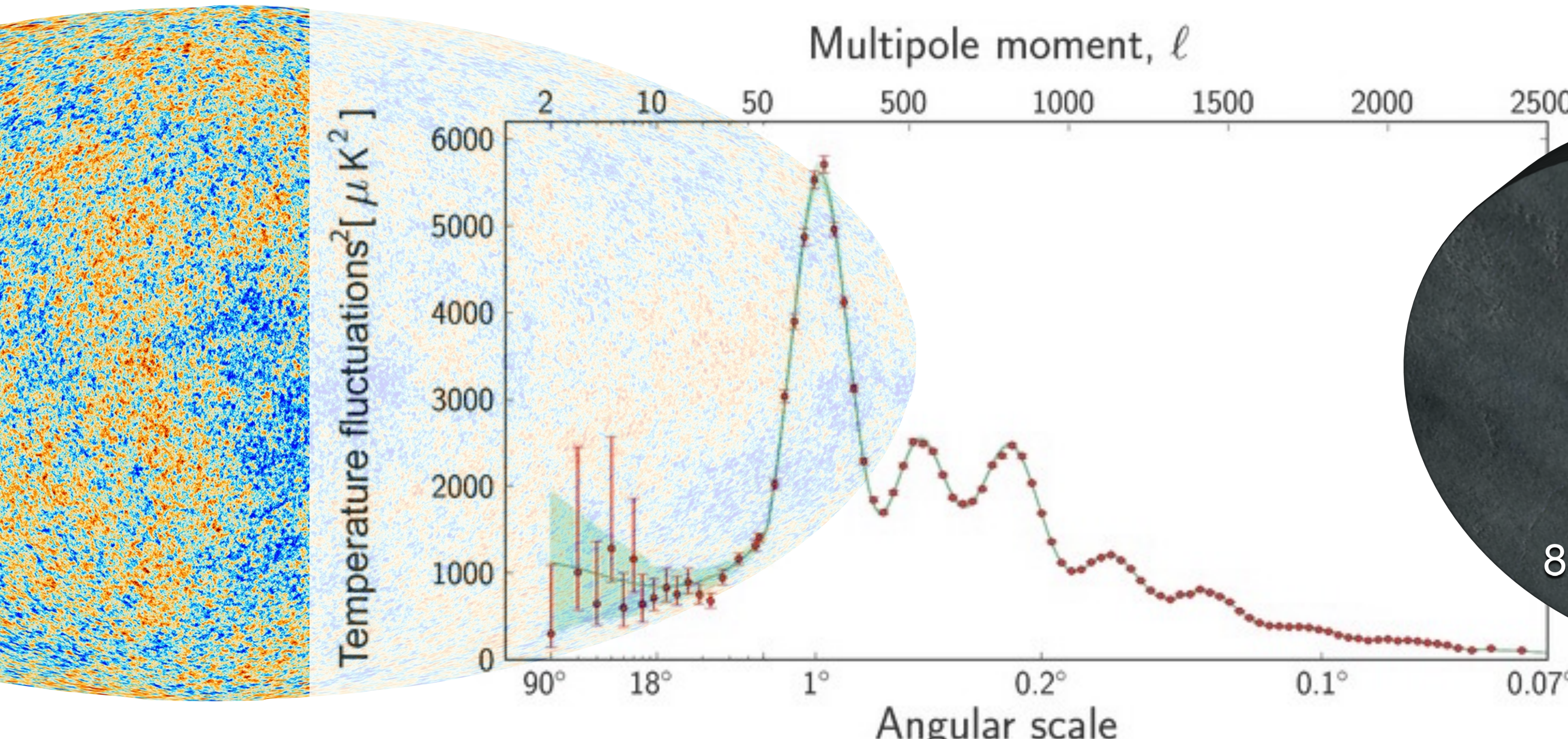
- It is a long history, whose evidence was gradually accumulated.

- 1933. Fritz Zwicky develops new methods and estimate the mass of the Coma cluster from two different procedures: from the observed light and from the galaxies velocities. He found that the mass inferred from the velocities was many times larger than that inferred from the light [Zwicky, Helv. physica acta (1933); ApJ (1937)].

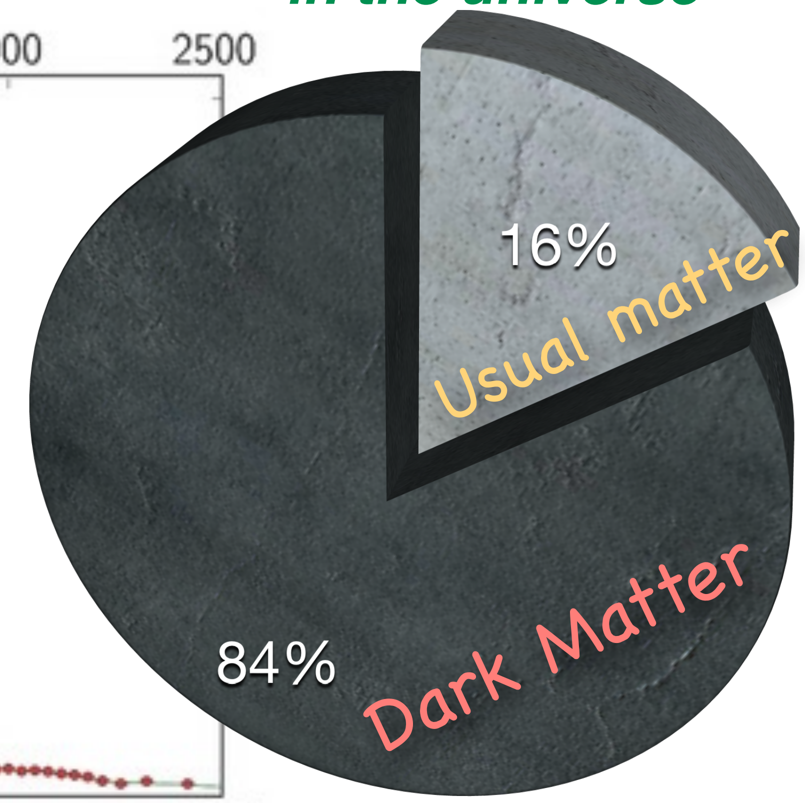
- 1960's-1970's. Vera Rubin and Kent Ford study galaxy rotation curves (optical part). Morton Roberts, Robert Whitehurst and others extend the rotation curves to the radio (21 cm). By the end of the 70's decade: dark matter becomes a frequent research topic [Sofue & Rubin, Ann. Rev. Astron. Astrophys. 39 (2001) 137-174].

- From the 80's, different confirmations on dark matter appear: gravitational lensing, x-ray from clusters (…), and latter the CMB anisotropies. Also from the 80's some alternative approaches based on gravity modifications in place of dark matter started to appear. [Milgrom ApJ 1983…].

Cosmological perturbations and dark matter



Matter content in the universe

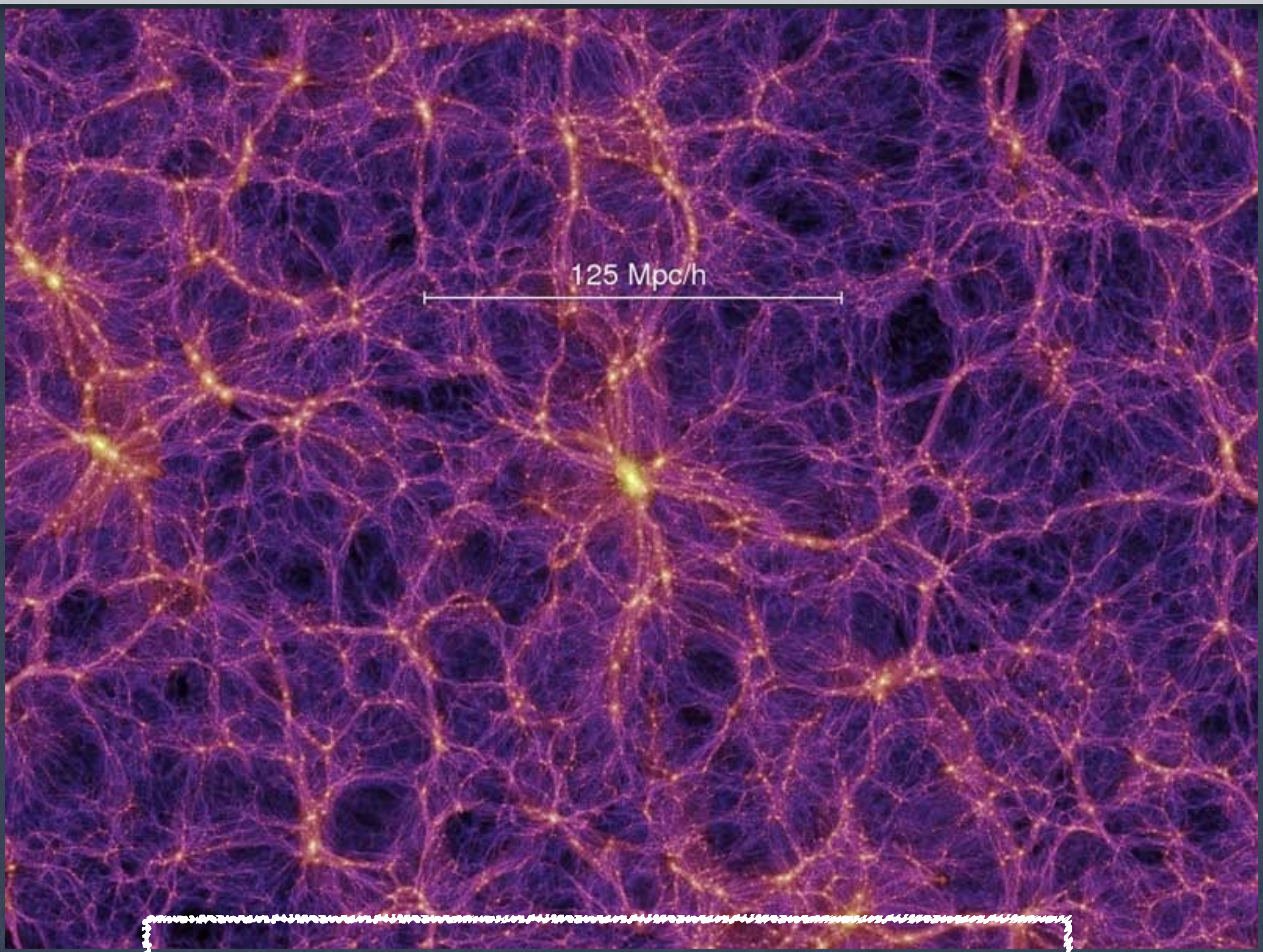


Cosmic Microwave Background (CMB, data from Planck)

It points out that the universe needs a large abundance of dark matter — about 5 times more dark matter than standard (baryonic) matter.

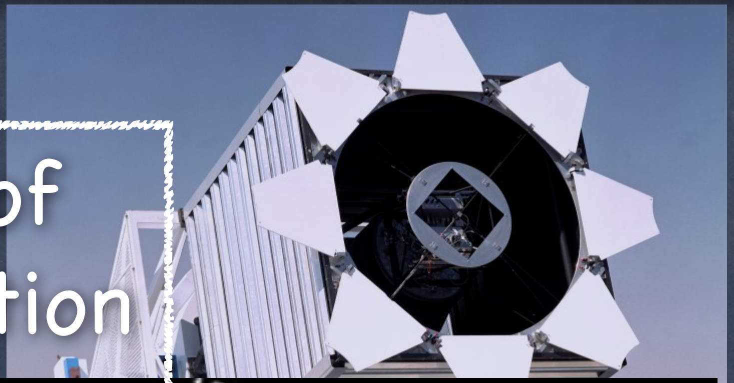
The simples type of dark matter that satisfies the data is Cold Dark Matter — i.e., heavy, non-relativistic particles with only gravitational interactions.

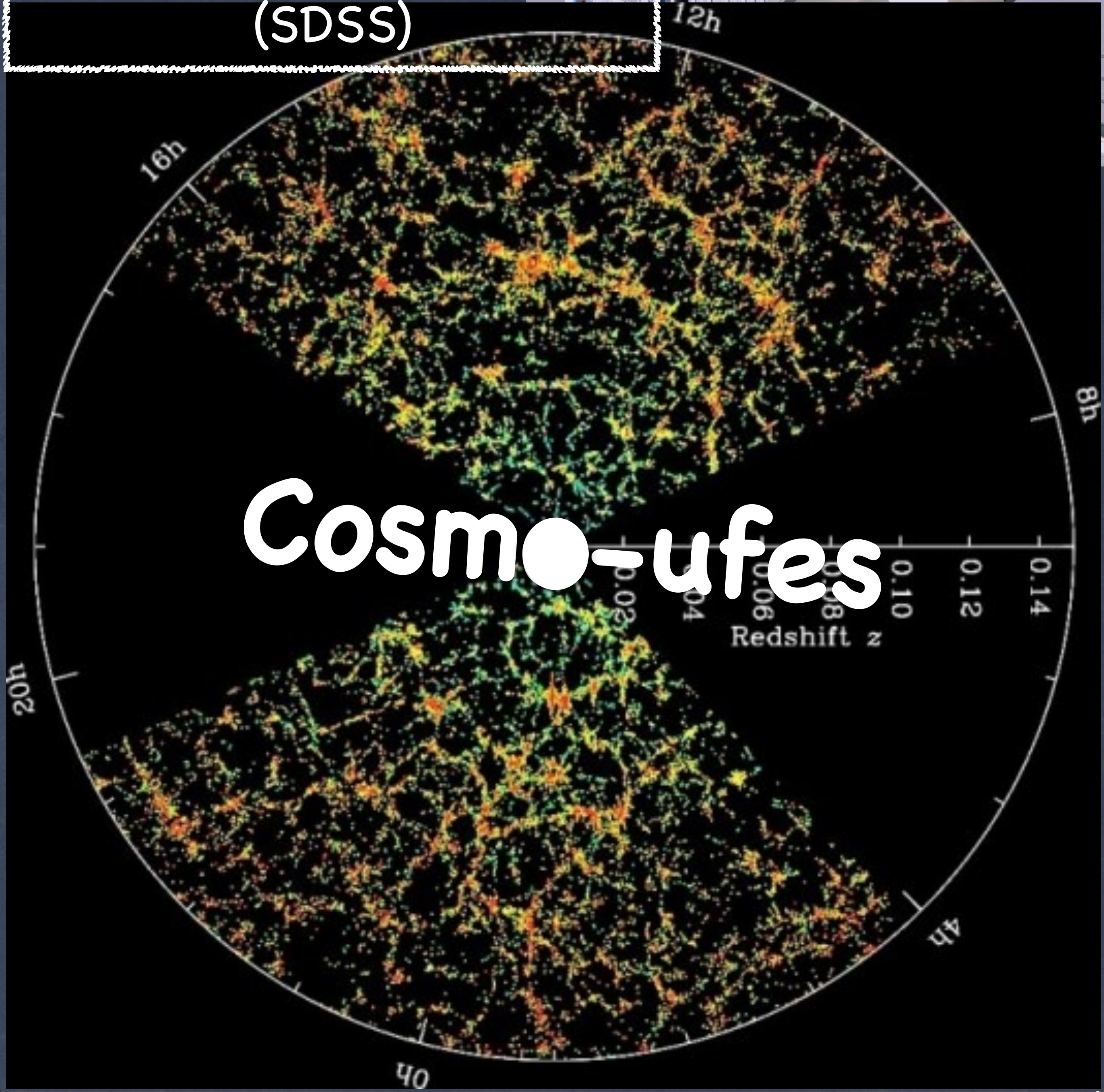
The cosmic web: dark matter in the universe



Simulation result for a universe with dark matter particles only
(Millennium)

Observation of galaxy distribution
(SDSS)

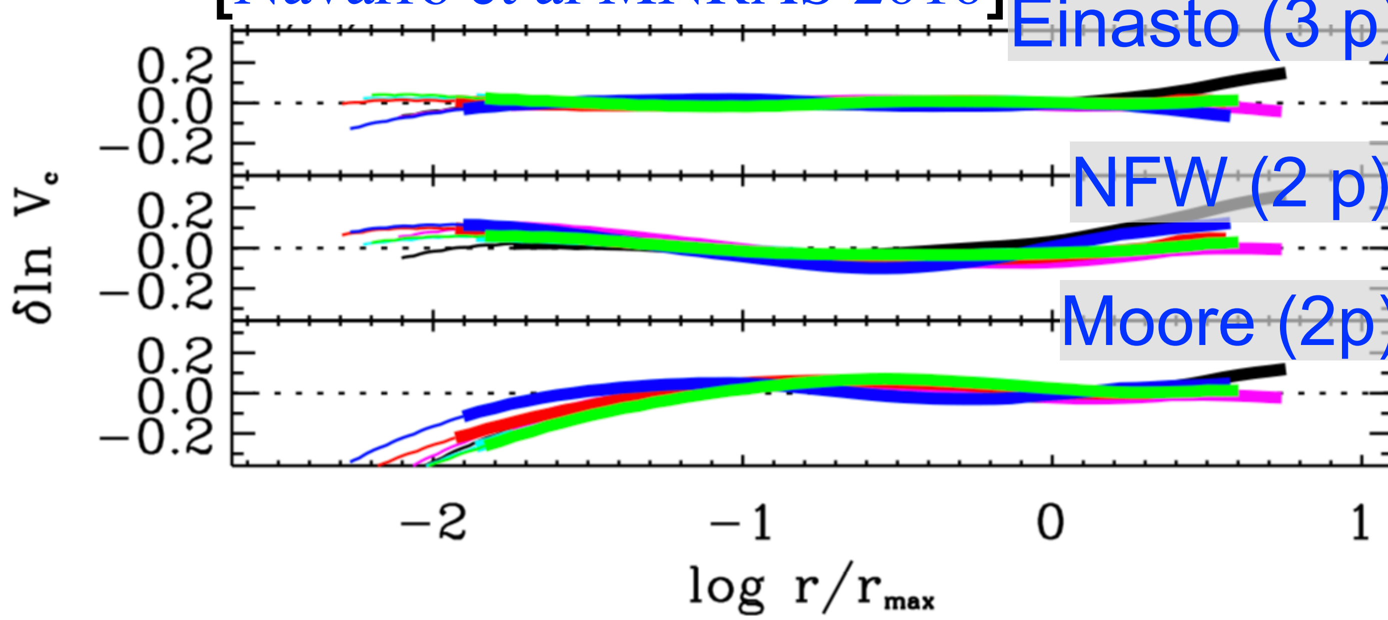




- Dark matter only (DMO) simulations lead to NFW-like halos for galaxies [Navarro et al ApJ 1996, 1997, MNRAS 2010]:

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

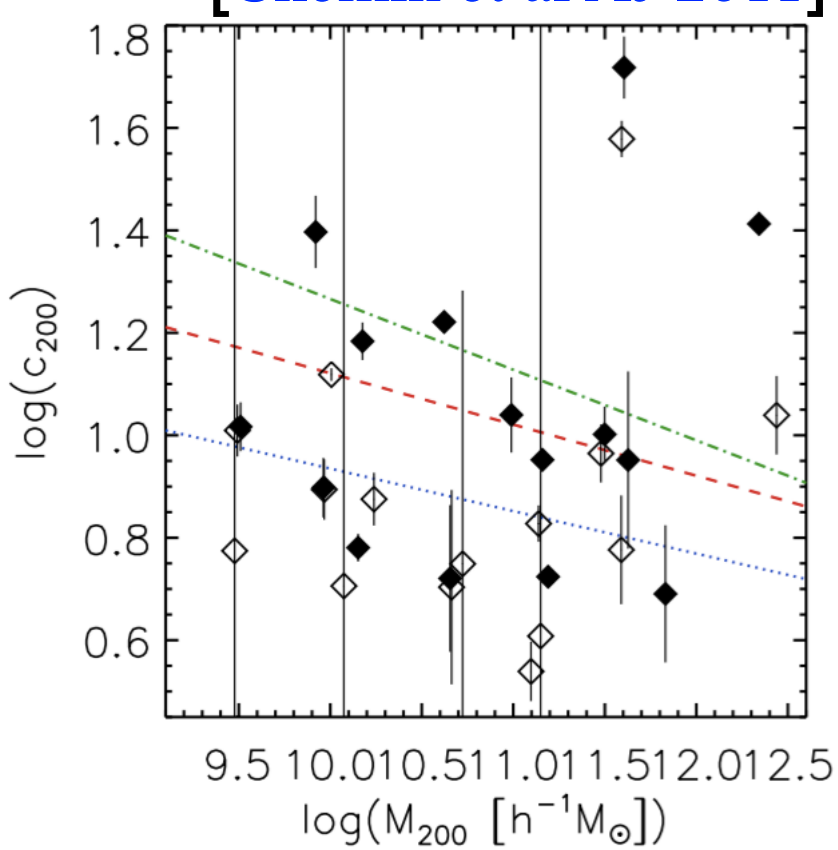
[Navarro et al MNRAS 2010]



- Two parameters halo.

- Simulations also indicate a correlation between them.

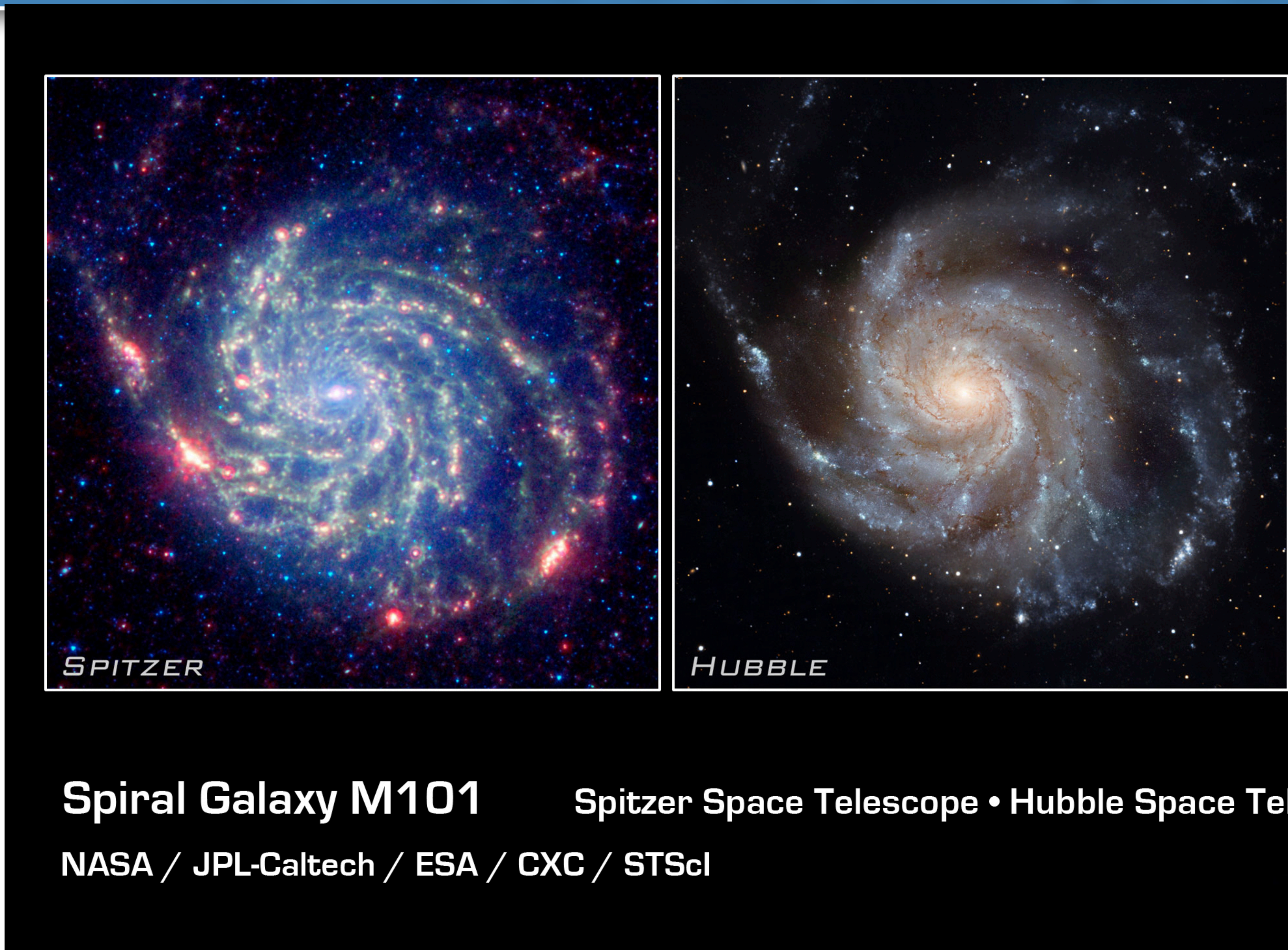
[Chemin et al AJ 2011]

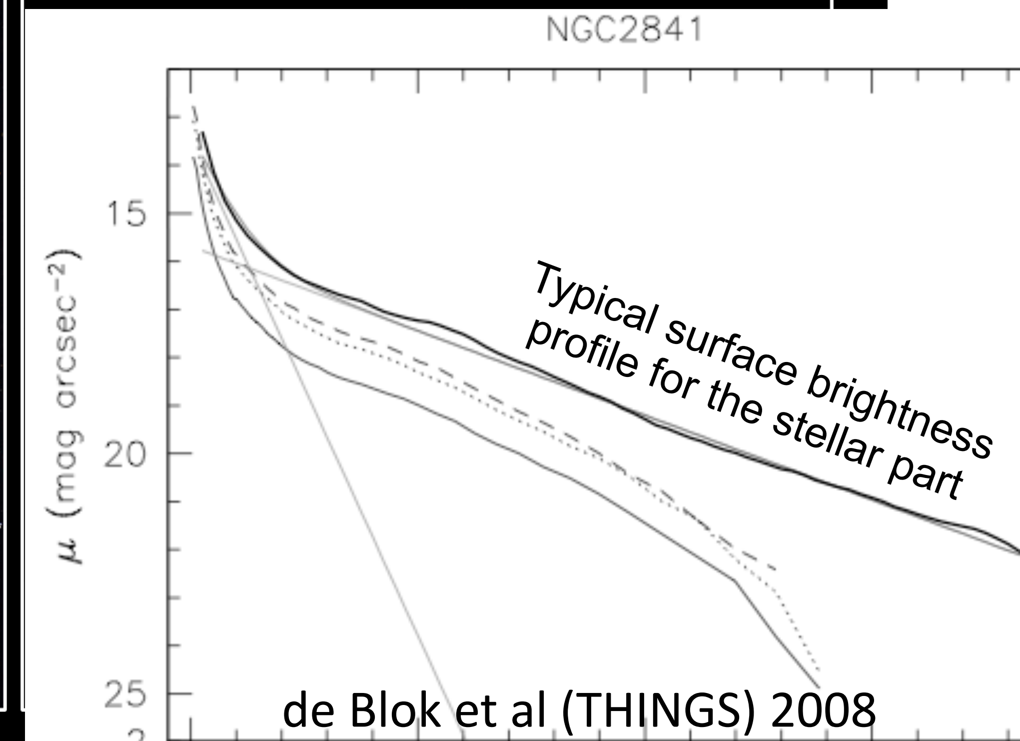


- Sometimes the correlation is strongly assumed to write a 1-parameter NFW halo. And from this case the strongest discrepancies are found with observational data. [e.g., Gentile et al ApJ (2005)].

- Galaxy data have tensions with such correlations [e.g., Chemin et al AJ 2011].

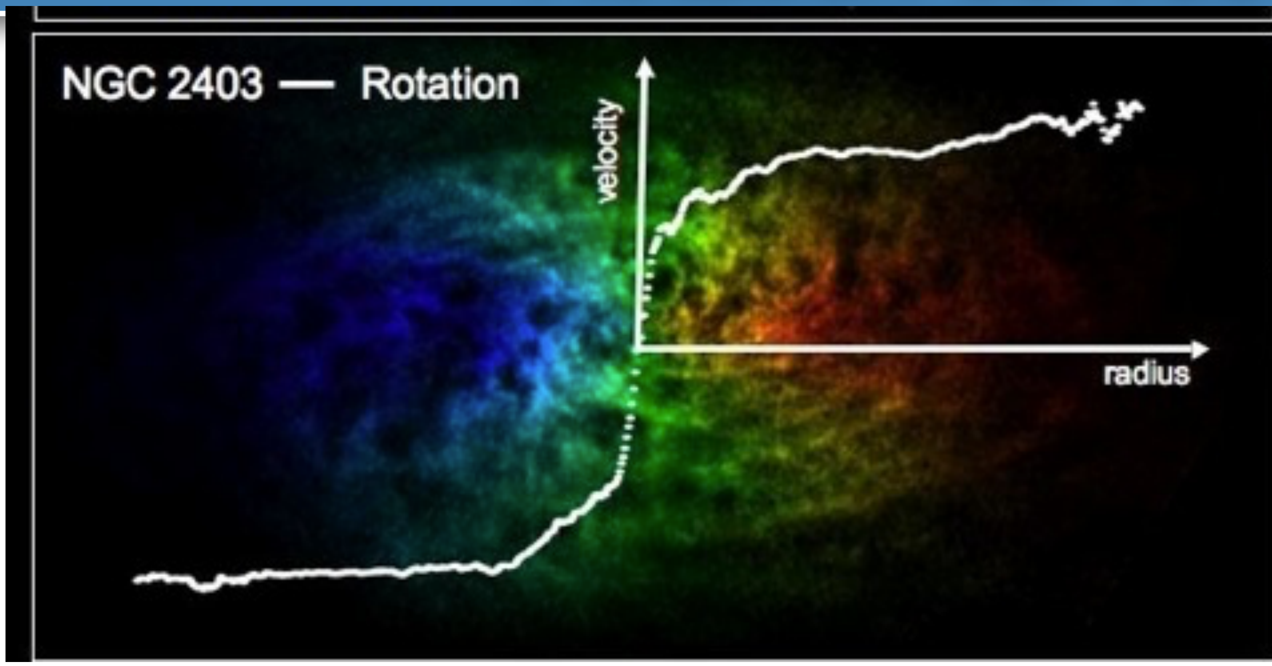
Near infrared for the stellar part and 21 cm for the HI





THINGS survey
Very Large Array (VLA)+
Spitzer

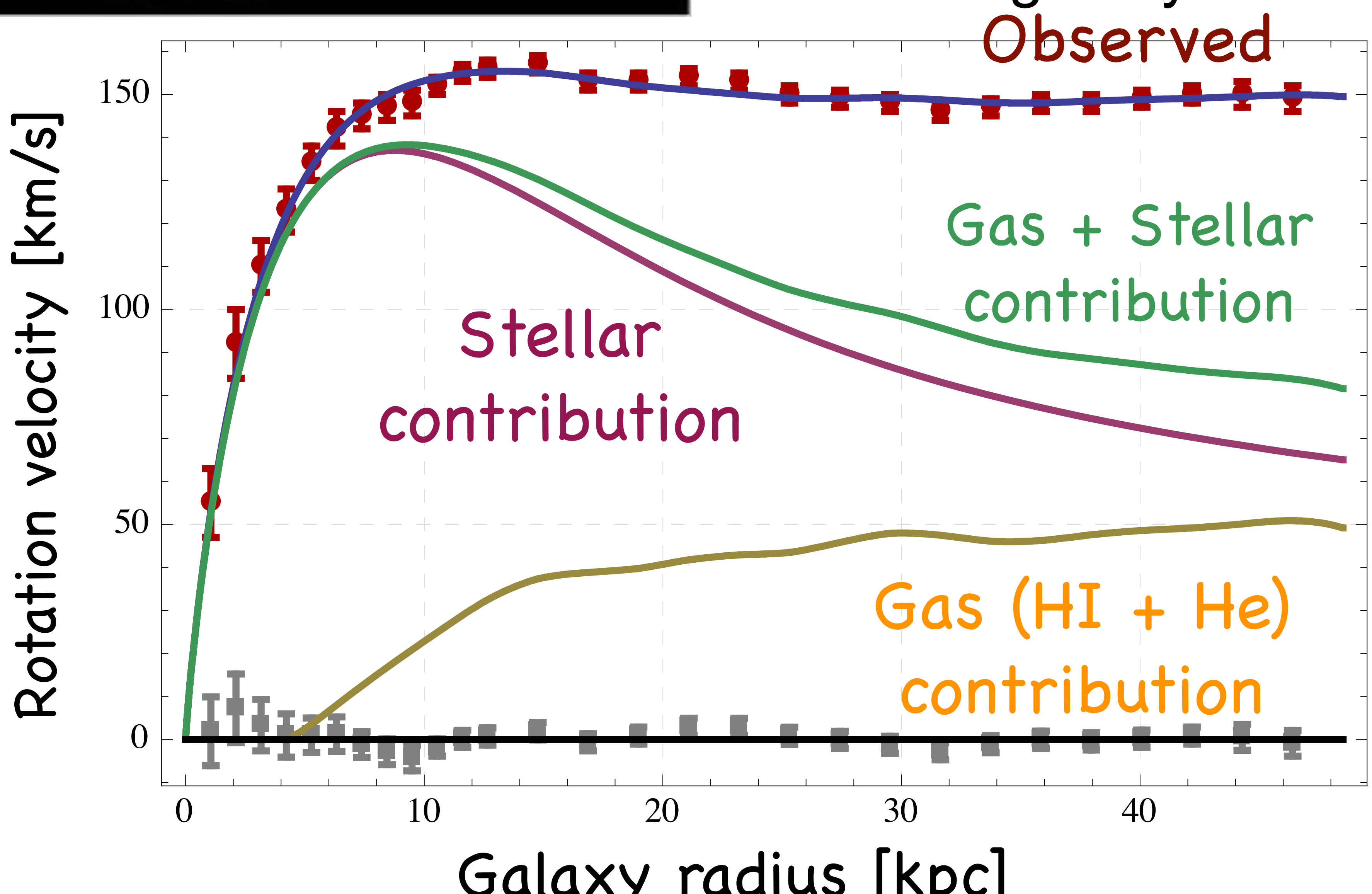
Rotation curves of galaxies: a draft



Rotation curves are obtained from local redshift measurements.

It can be contrasted with the mass inferred from the light distribution.

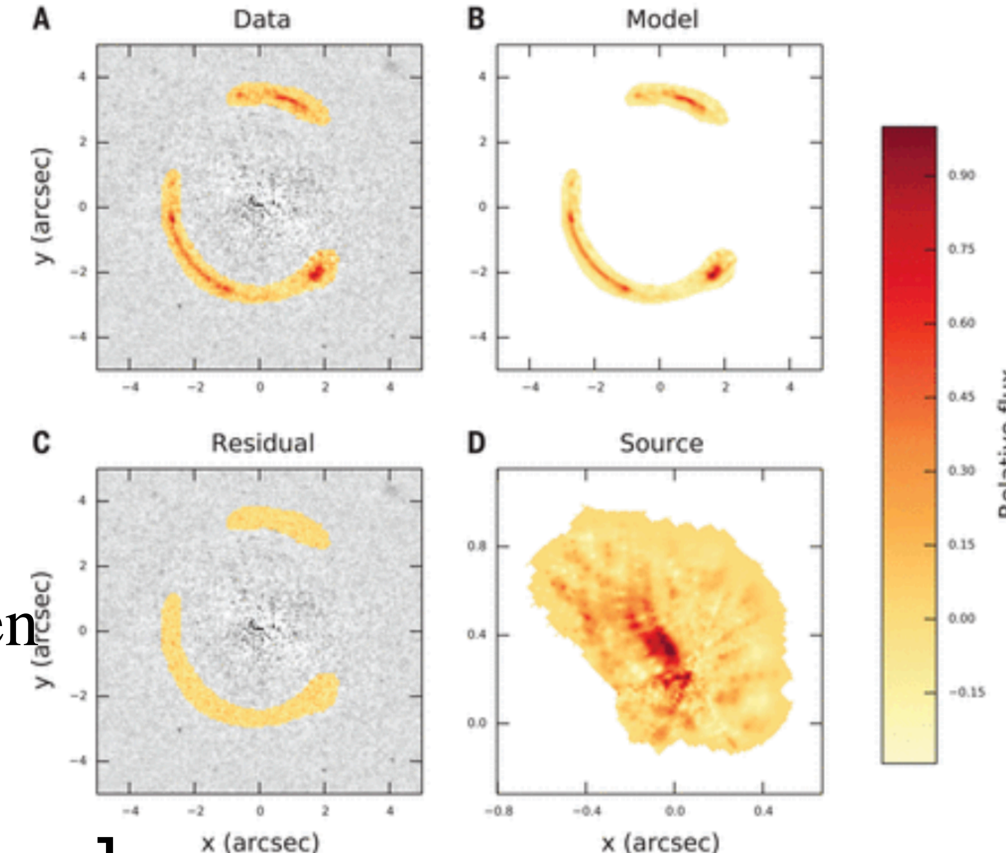
Newtonian gravity is sufficient.

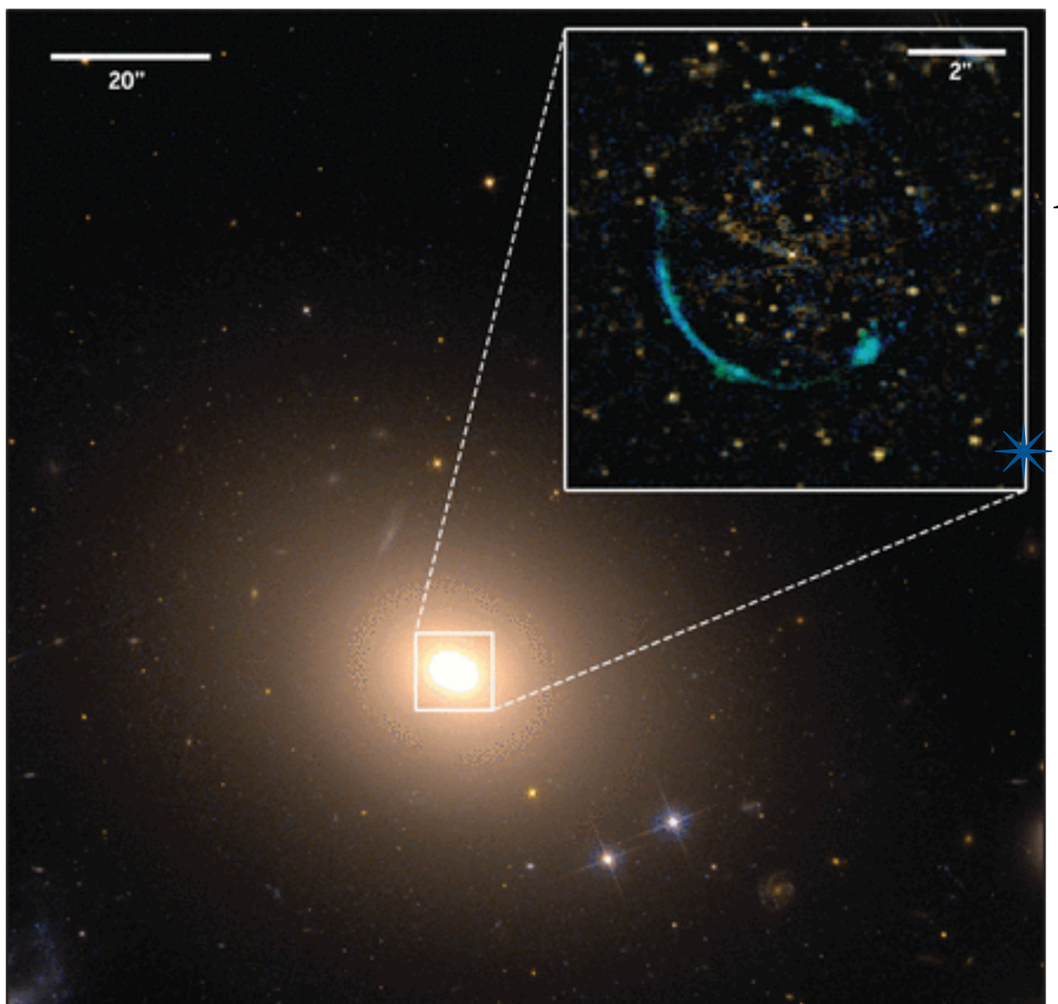


Internal dynamics + Lensing data: a GR test

It is starting to be possible to constrain dark matter in galaxies using the internal dynamics and lensing data from the same galaxy.

Which leads to constraints on the modified gravity "slip" parameter (the ratio between the spatial and time scalar perturbations).

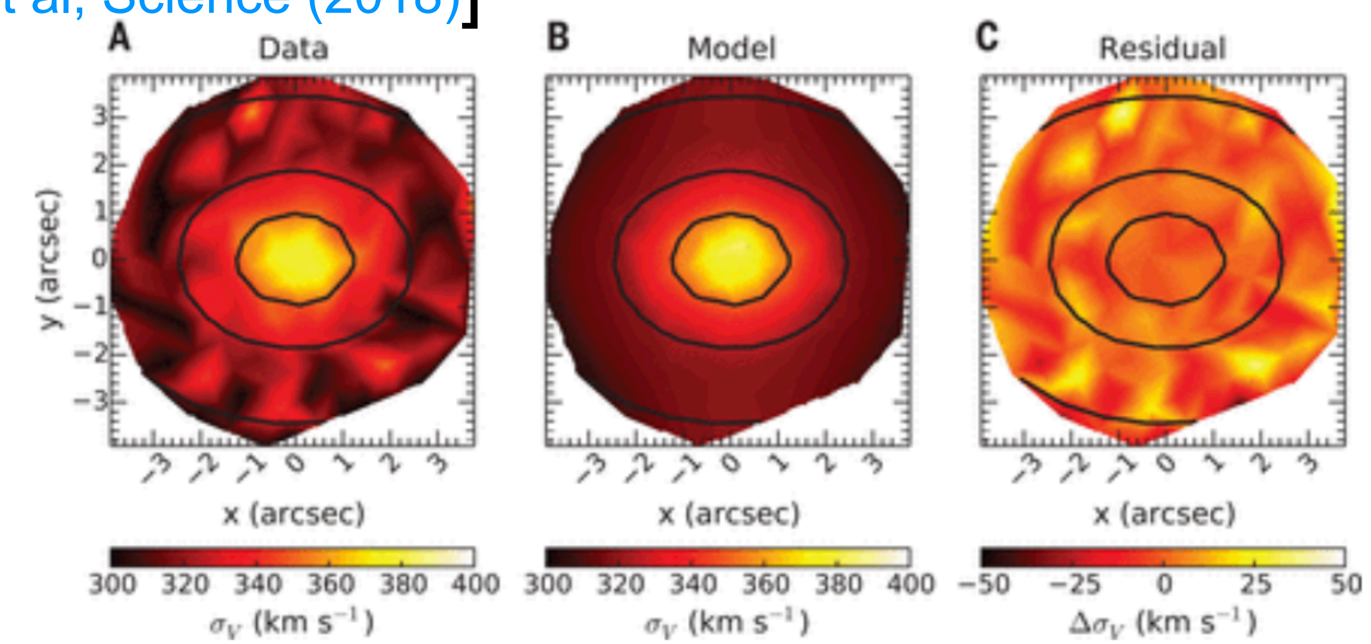




$$M_{\rm dyn} = \frac{1+\eta}{2} M_{\rm len}$$

$$\eta = 0.97 \pm 0.09$$

[Collett, T et al, Science (2018)]



Small scale issues

- There are many papers on the small scale issues.

- None of the issues proves that CDM is wrong (in my opinion at least).

- If CDM is right, the interplay between baryons and dark matter is not simple (and we do not understand all the relevant details). Alternative approaches can simplify aspects of this interplay.

Internal dynamics

- Core-cusp issue (aka, diversity problem)
- RAR (radial acceleration relation)
  (internal dynamics are diverse, but not too much)

Satellites

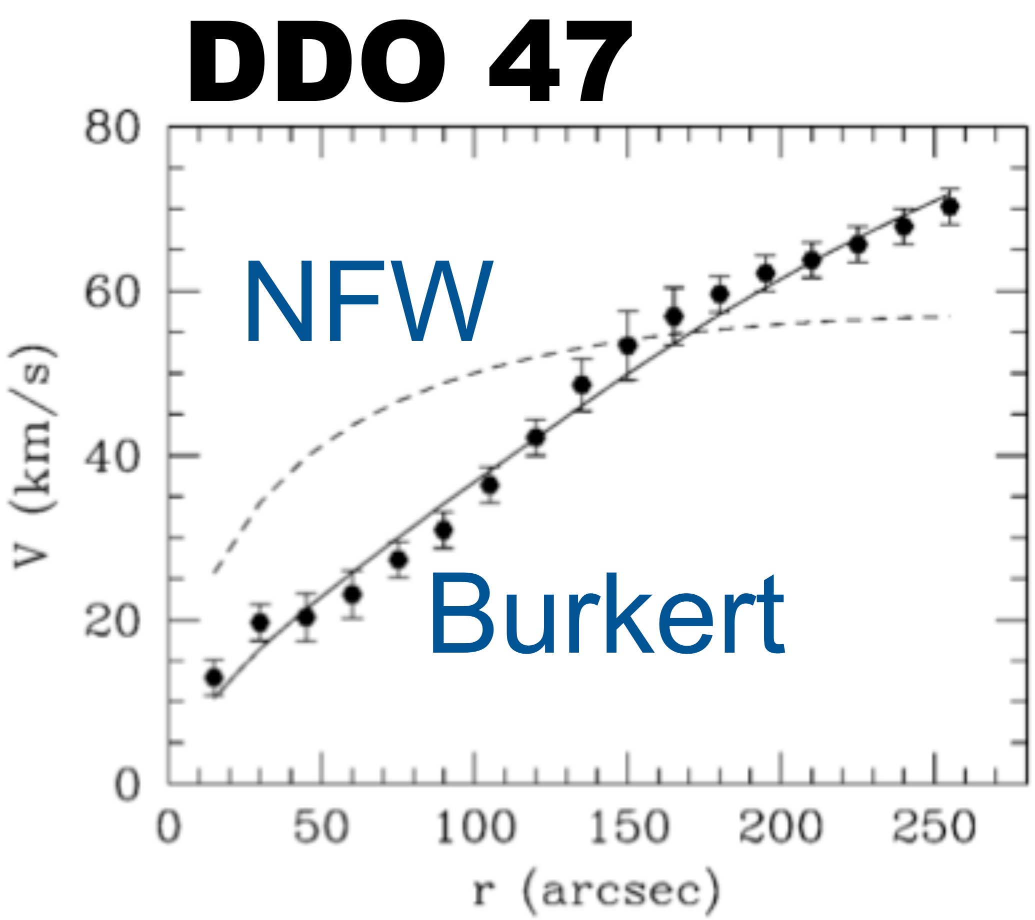
- Missing satellites (seems solved)
- The too-big-to-fail (essentially ok)
- Satellites alignment (unclear)

Alternatives from CDM

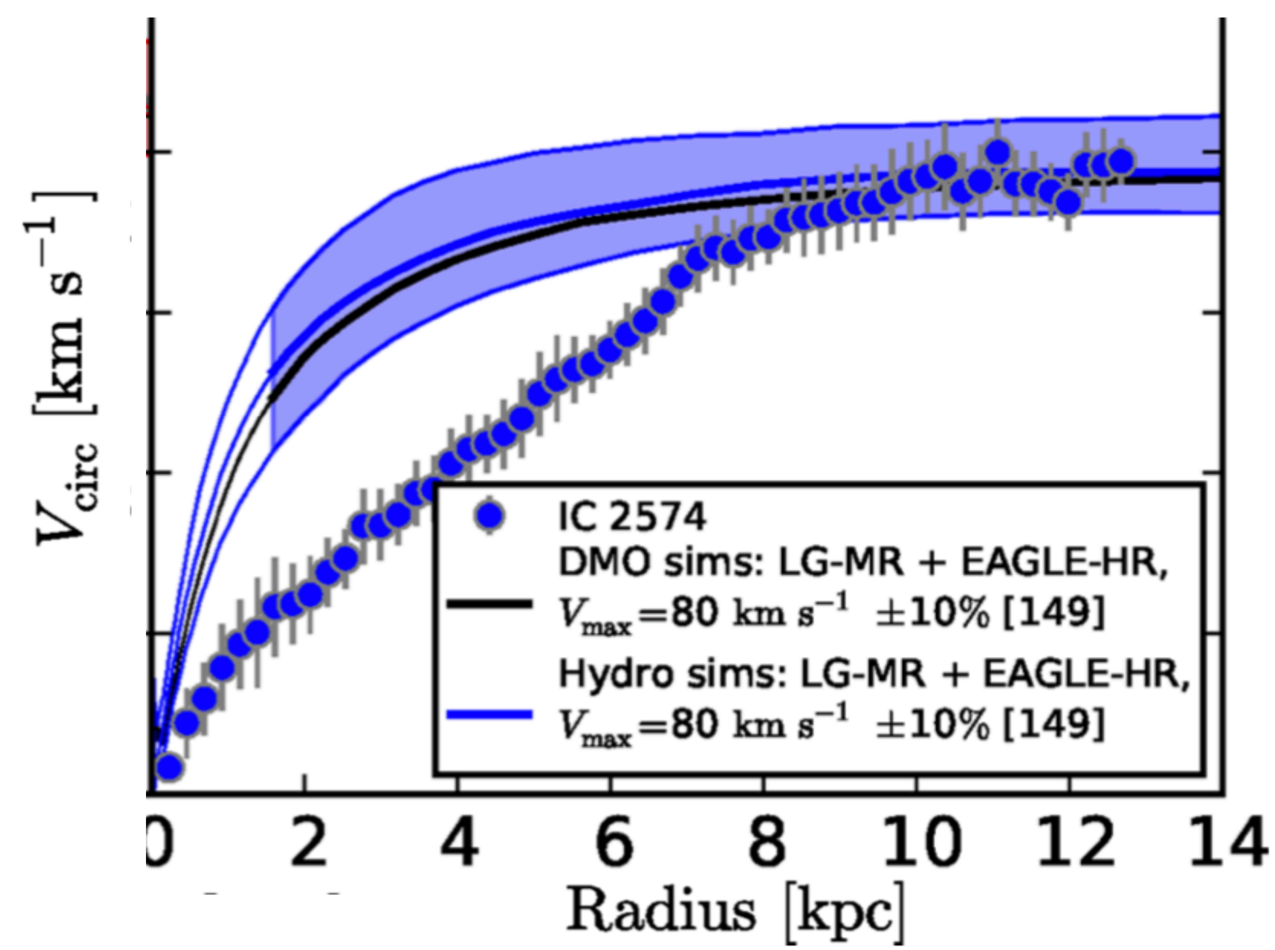
- Inside the CDM approach, there are many possible (approximate) realizations, including:
    - WIMPs, axions, primordial black holes…
- Particle approaches that deviate significantly from CDM include (all of these are in part motivated from the small scale issues):
    - WDM, SIDM, ULDM…
- The most radical alternatives are those without dark matter and modified gravity in its place.
    - MOND posits that, for very small accelerations, Newtonian gravitational force becomes stronger. Although "ugly", it achieved some phenomenological success that more "elegant" approaches have not.
- Removing dark matter is not the only motivation for modified gravity.

- The core-cusp issue refers to a possible conflict between observations and simulations, it is one of the main and most persistent small scale issues of LCDM [e.g., Moore et al, Nature 1994; de Blok, Adv.Astron. 2009].

- Currently, it is commonly considered to be related to a diversity problem and an inner mass deficit, instead of a universal slope issue. [Oman et al, MNRAS 2015].



[Gentile et al ApJ (2005)]

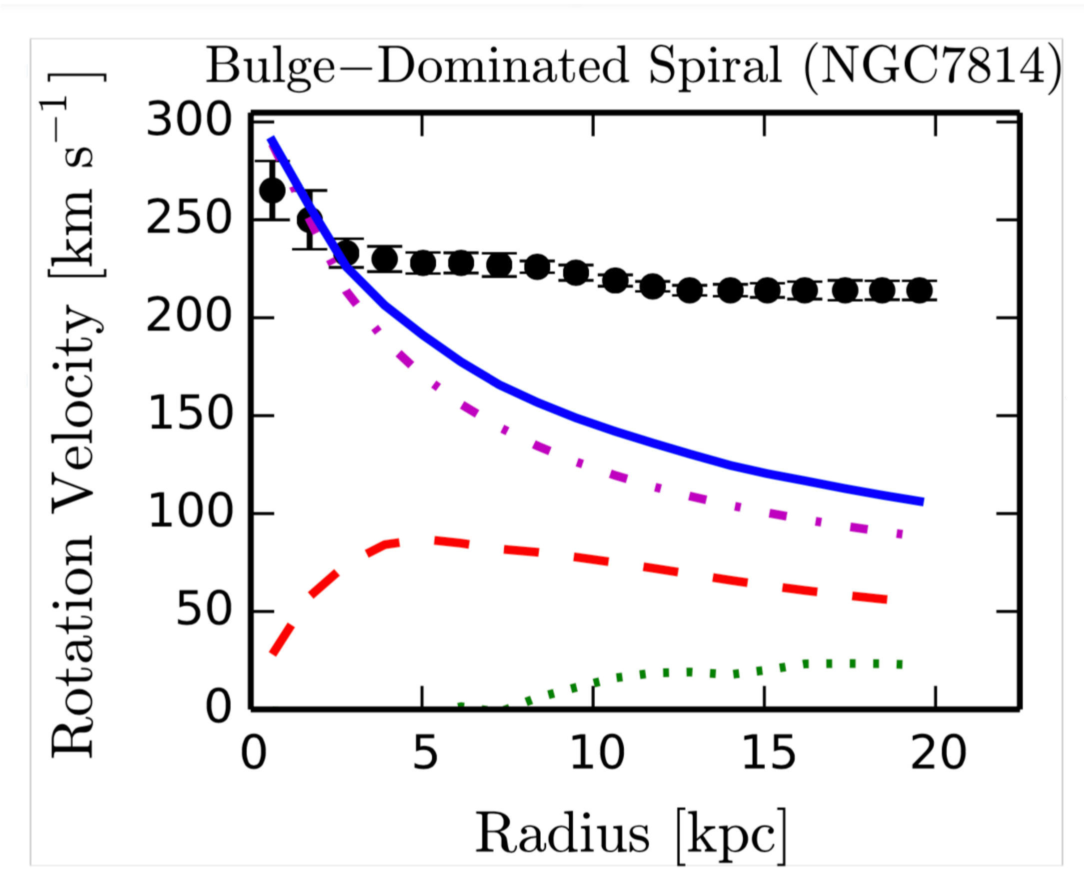


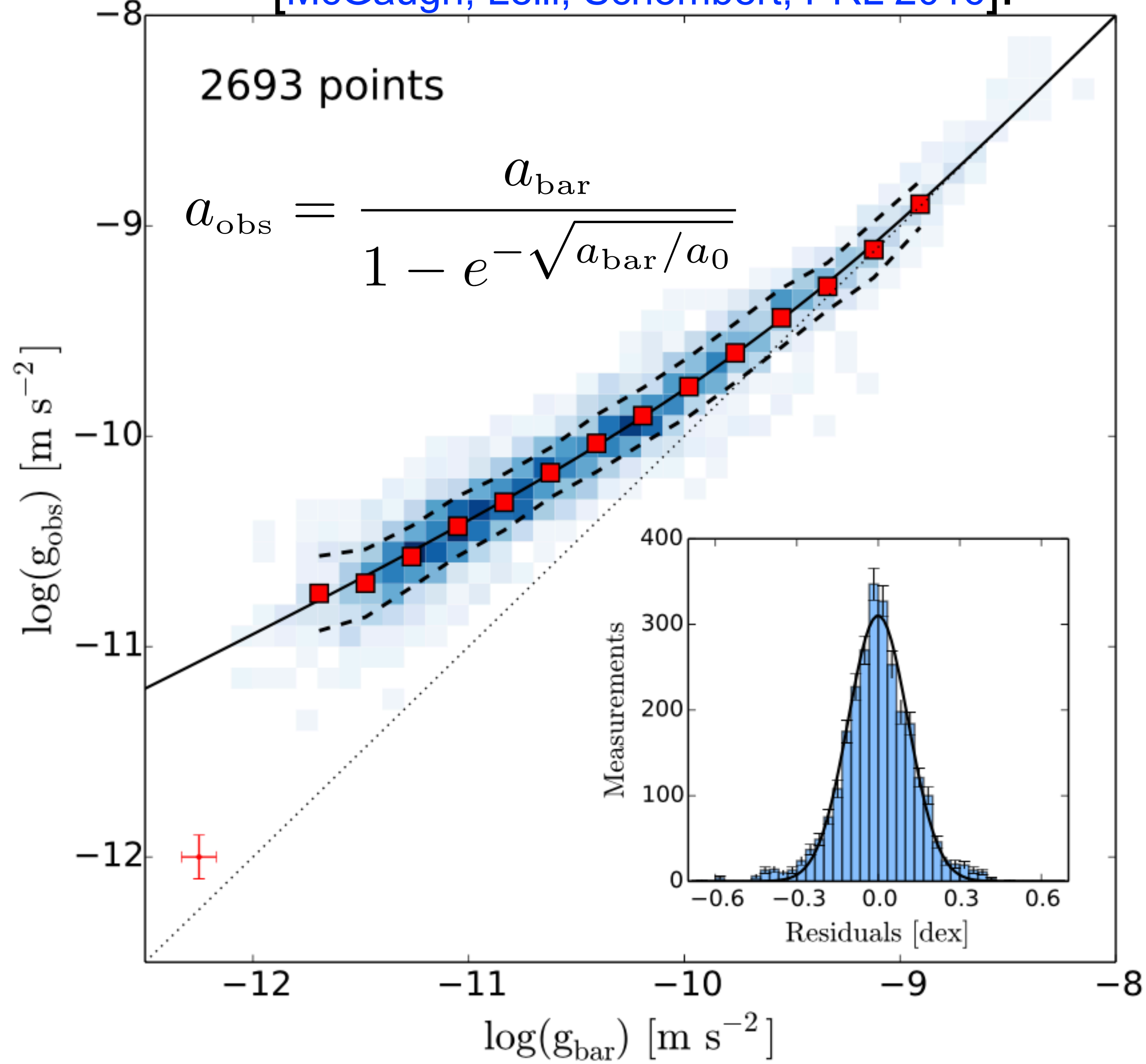
[Oman et al, MNRAS 2015].

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].





Inferred from the circular velocity

Inferred from the luminosity

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

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

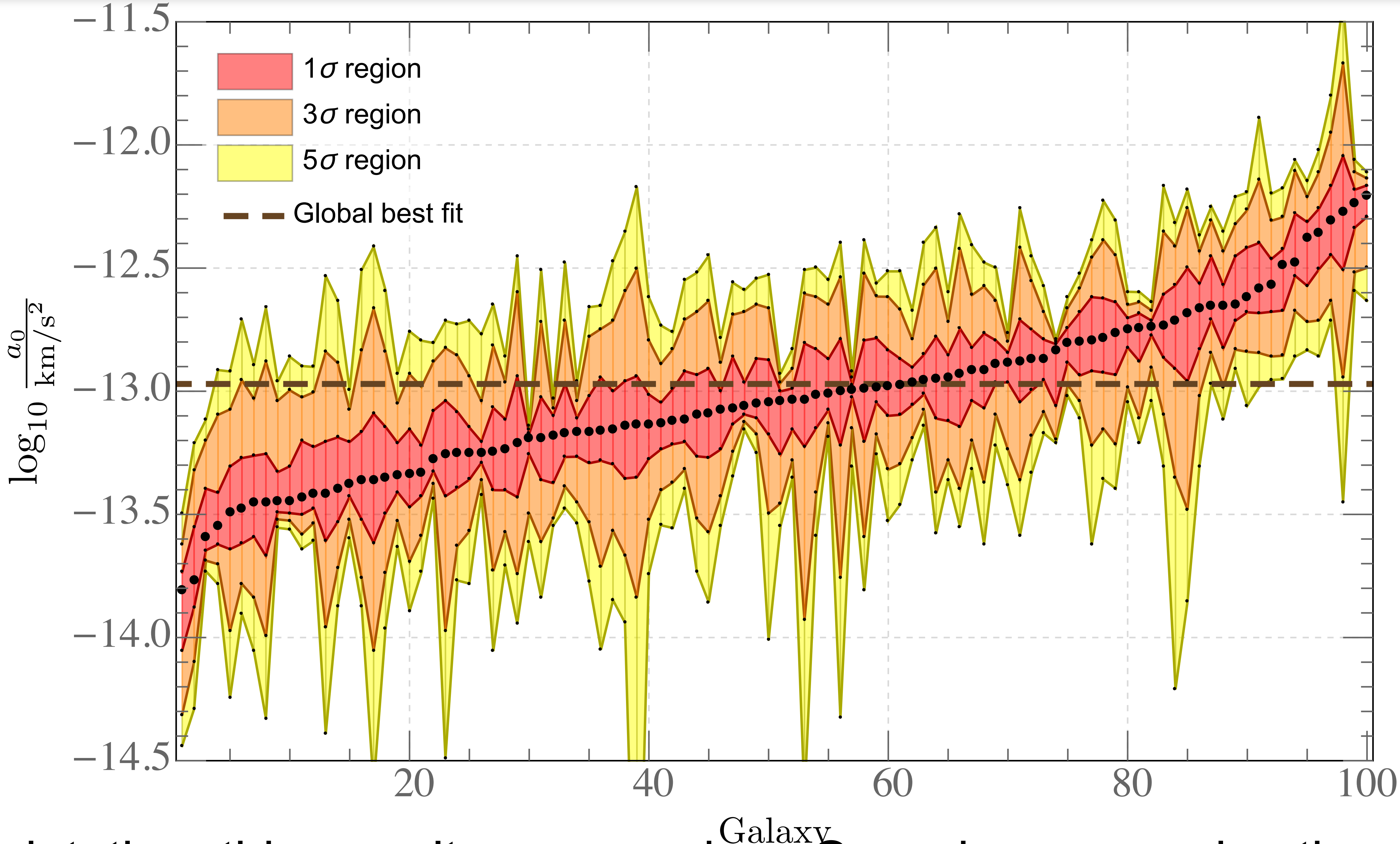
Davi C. Rodrigues[1,2*], Valerio Marra[1,2*], Antonino del Popolo[3,4,5] and Zahra Davari[6]

- 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.

Is there a common acceleration scale? - Main analysis



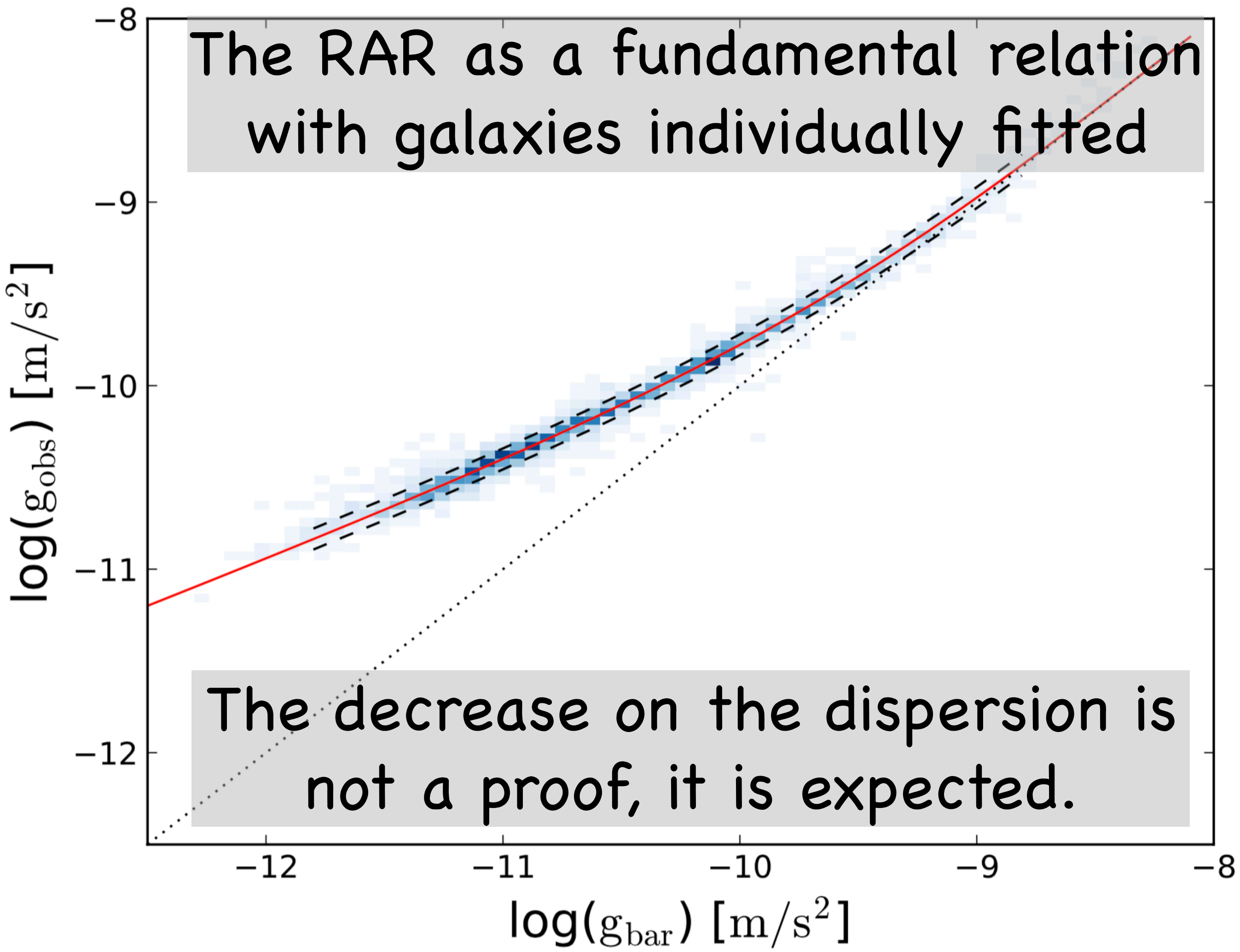
To sintetize this result, we used a Gaussian approximation on the posteriors, implying that MOND is reject at > 10σ.

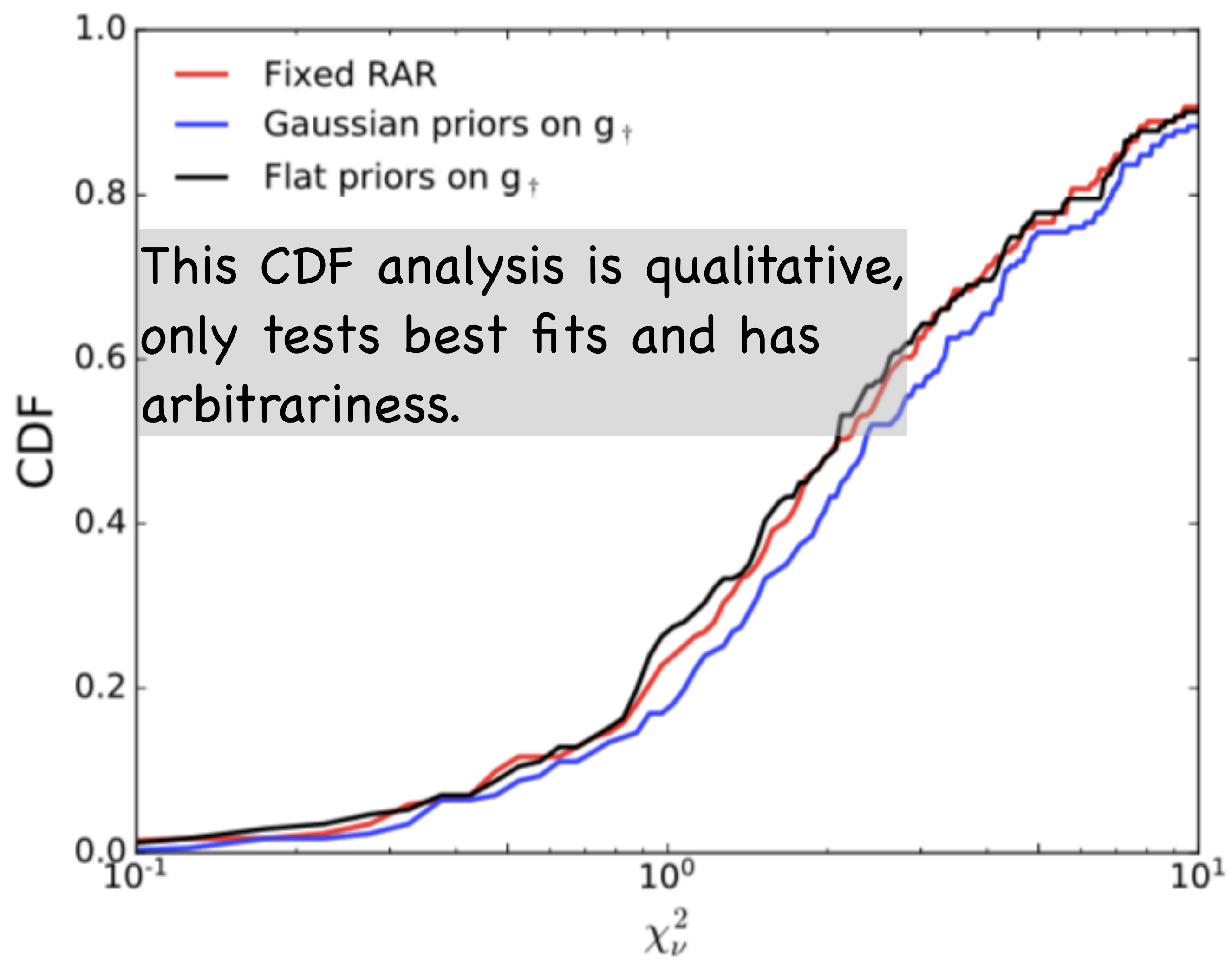
	$\log_{10} a_0$	1σ (32%)	3σ (0.27%)	5σ (5.7×10^{-7})
RAR-inspired	-12.970	71%	31%	15%

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.

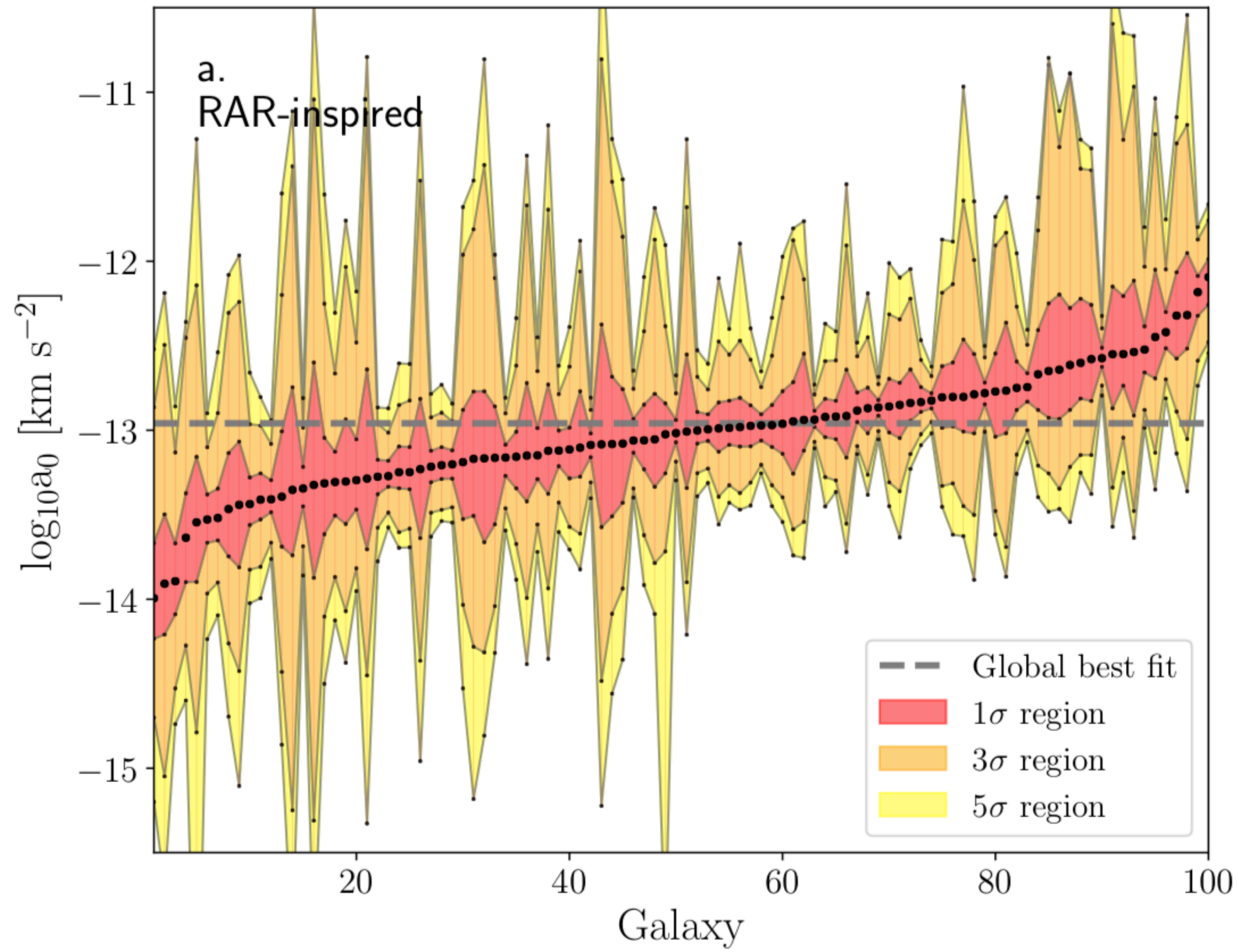
- We see no technical errors in both approaches (we rederived their results), they used tests that could not be sensitive to the issues that we raised. Namely, they tested best fits, while we tested the compatibility between credible intervals.

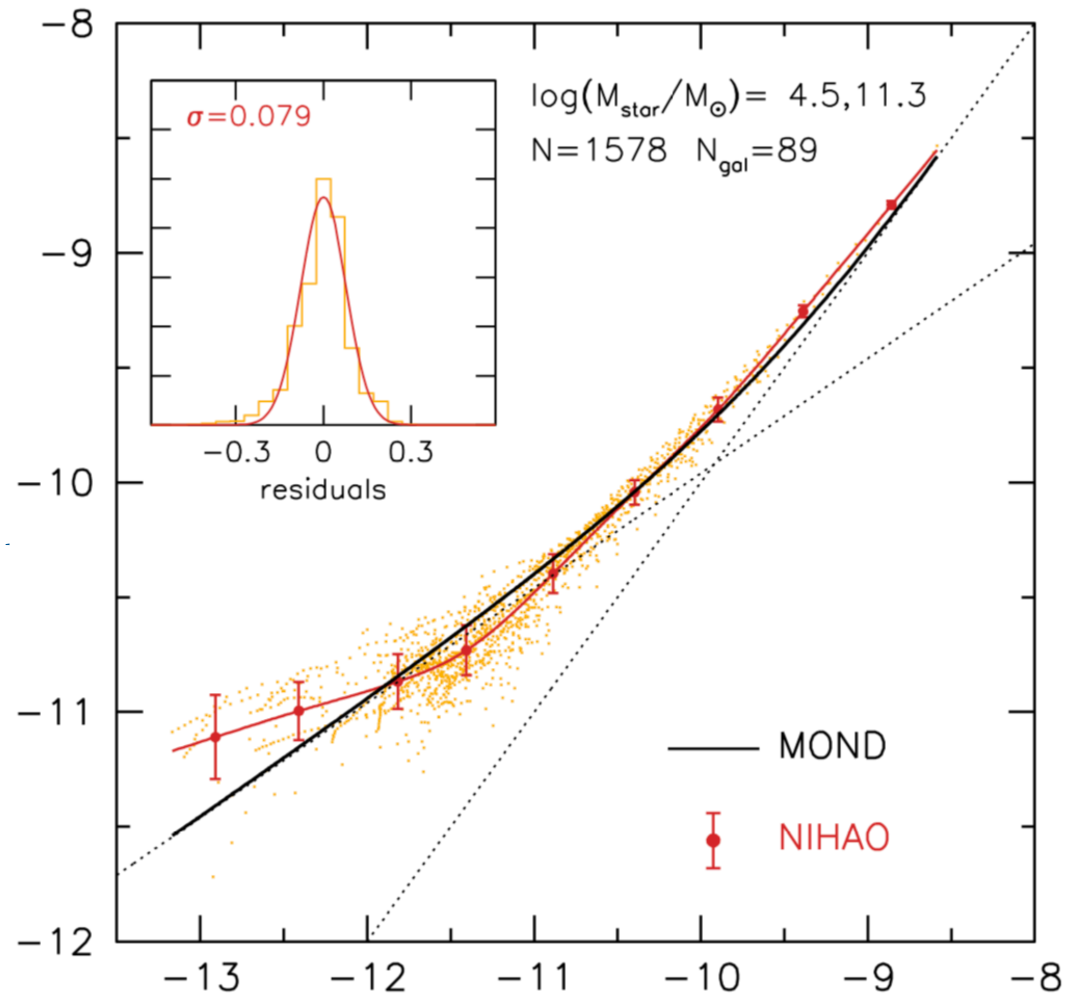




- [Chang & Zhou, MNRAS 2019] - Repeats all our approach but using exactly the same priors of [Li et al A&A 2018]: as we expected, our conclusions remain valid, i.e. a fundamental acceleration is rejected at high confidence.

[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.

Improving the statistics

- [Cameron et al, Nat.Astro. 2020] in particular criticized our approach for using that Gaussian approximation on the comparison of the posteriors. In our reply [Rodrigues et al, Nat.Astro. 2020] we argue that they are fine considering our context (and that they are not a novelty [e.g., Riess et al, Astrophys.J. 2019]).

- In [Marra, Rodrigues, de Almeida, 2002.03946] we improve the statistics of our approach; both by adopting nuisance parameters and priors better adapted to the observational uncertainties and avoiding the Gaussian approximation.

- Our conclusions are the same: MOND is rejected at a high confidence; but the improved methods we consider are relevant for the area (i.e., not for this issue on MOND in particular).

Pipeline

It imports SPARC data, defines likelihoods.

MAGMA
github.com/davi-rodrigues/MAGMA

Best fits are found and used to speed MCMC.

MCMC on the above exported data.

emcee
github.com/dfm/emcee

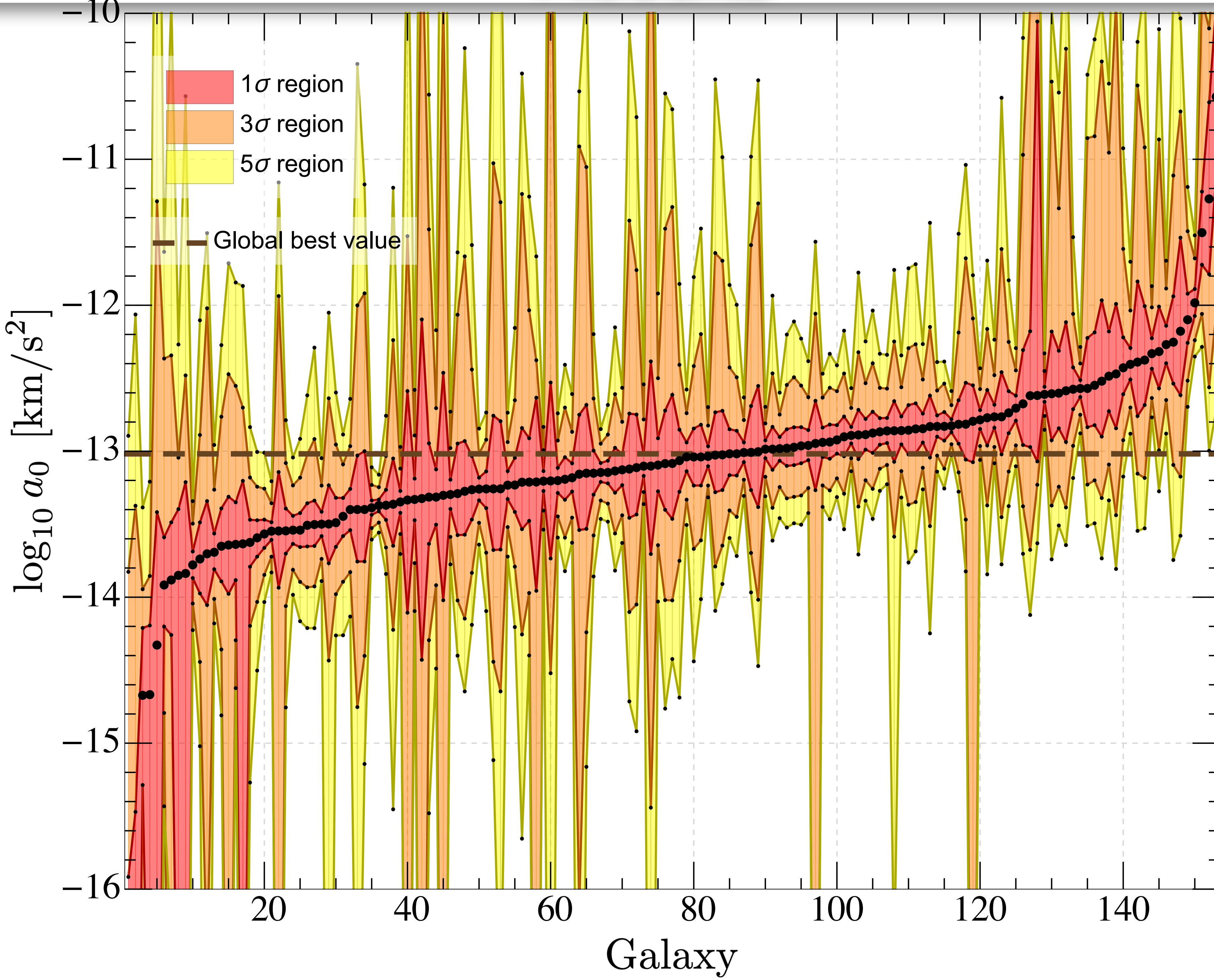
mBayes
github.com/valerio-marra/mBayes

Grid Bayesian analysis, used as a cross-check

Compatibility of A_0 posteriors

Code based on [Marra et al].

Results



1σ region
3σ region
5σ region
Global best value
$\log_{10} a_0$ [km/s^2]
−10
−11
−12
−13
−14
−15
−16
20
40
60
80
100
120
140
Galaxy

Results

* To compare the posteriors, computing their tension, we extend the tension approach of [Verde, Protopapas, Jimenez, Phys.Dark.Univers. 2013].

* A quantity X^2 is introduced, which is the log of the ratio of two Bayesian evidences. It is computed for the observational data, yielding 1465.

* To assess the meaning of that value, we use Monte Carlo simulations, assuming that MOND is correct.

* The observational data is rejected as a MOND realization at > 5.7σ.

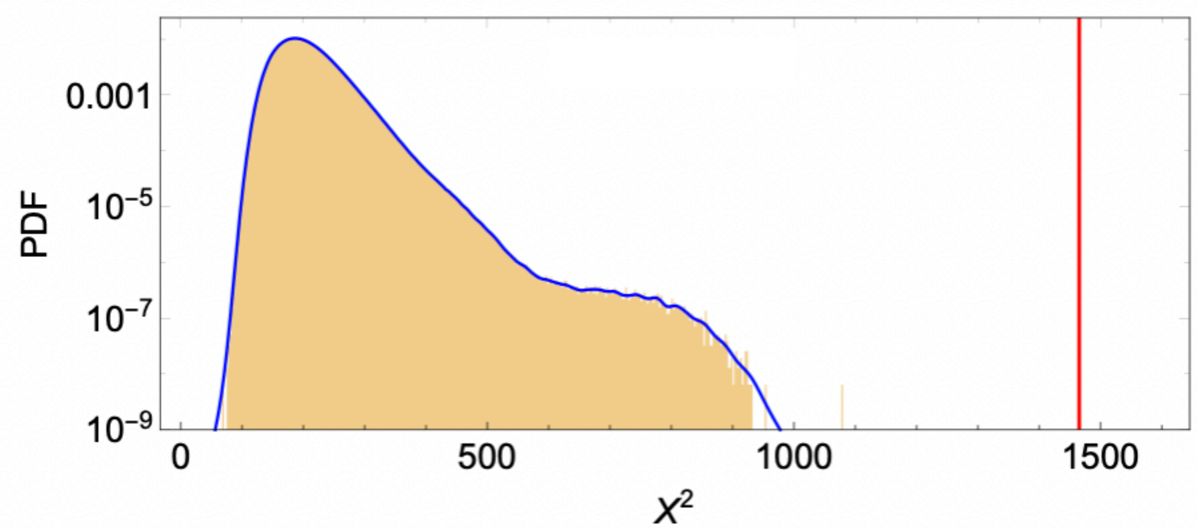


Figure 3. Numerical X^2 distribution found from 6.2×10^7 Monte Carlo simulations for the RAR sample ($\mathcal{S}_1$). The histogram on the simulations results is in yellow. The blue line is the smoothed empirical distribution. Vertical red line marks the X^2 value found from the observational data (1465) for this sample.

Results

Tension-based method	$\mathcal{S}_1$ (RAR sample)
rejection of fundamental a_0	$> 5.7\sigma$

R18 Gaussian method	$\mathcal{S}_1$ (RAR sample)
rejection of fundamental a_0	28σ

Conclusions

- ✳ CDM is the favoured type of dark matter, but there are still many unknowns within CDM.
- ✳ Small scale issues is a window towards understanding dark matter and the baryonic feedback. Developments for both are important.
- ✳ The case of modified gravity without dark matter is the most radical change with respect to CDM. It has lead to relevant insights that, in my opinion, should not be dismissed. But it is a too rigid framework that is not supported from the data.
- ✳ Phenomenologically, the RAR is a useful relation that captures the average interplay between dark matter and baryons at the galactic level.
- ✳ It was originally seen as a triumph for MOND, 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.