Radial Acceleration Relation & Mass-Velocity Dispersion Relation on BCG-cluster Scales

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Reference: Tian et al. (2020), ApJ, 896, 70; Tian et al. (2021a), ApJ, 910, 56; Tian et al. (2021b), ApJL, 917, L24

6 Jun. 2023, MOND40, St. Andrews

Outline

- Introduction
- Scaling Relations in Galaxies
  - Radial Acceleration Relation (RAR)
  - Baryonic Tully-Fisher Relation (BFTR)
- Scaling Relations on BCG-Cluster Scales
  - Radial Acceleration Relation (RAR)
  - Mass-Velocity Dispersion Relation (MVDR)
- Remarks

"Missing Mass Problem"

- Definitions of two accelerations:

Newton's law		**Newton's gravity**
$\boldsymbol{g_{obs} \equiv \lvert -\nabla\Phi_{obs} \rvert}$	$=?$	$\boldsymbol{g_{bar} \equiv \frac{GM_{bar}(<r)}{r^2}}$

- Asumming $g_{obs} = g_{bar}$, mass discrepnacy is expected.
  "dark matter" is introduced to resolve the insufficient baryonic mass.
- **What if $g_{obs} \neq g_{bar}$? Acceleration discrepancy instead.**

Selected for a Viewpoint in *Physics*
PRL **117,** 201101 (2016) PHYSICAL REVIEW LETTERS week ending 11 NOVEMBER 2016

Radial Acceleration Relation in Rotationally Supported Galaxies

Stacy S. McGaugh and Federico Lelli
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Department of Physics, University of Oregon, Eugene, Oregon 97403, USA
(Received 18 May 2016; revised manuscript received 7 July 2016; published 9 November 2016)

Independent measurements for two-axis:

- **Vertical axis (g_{obs})**

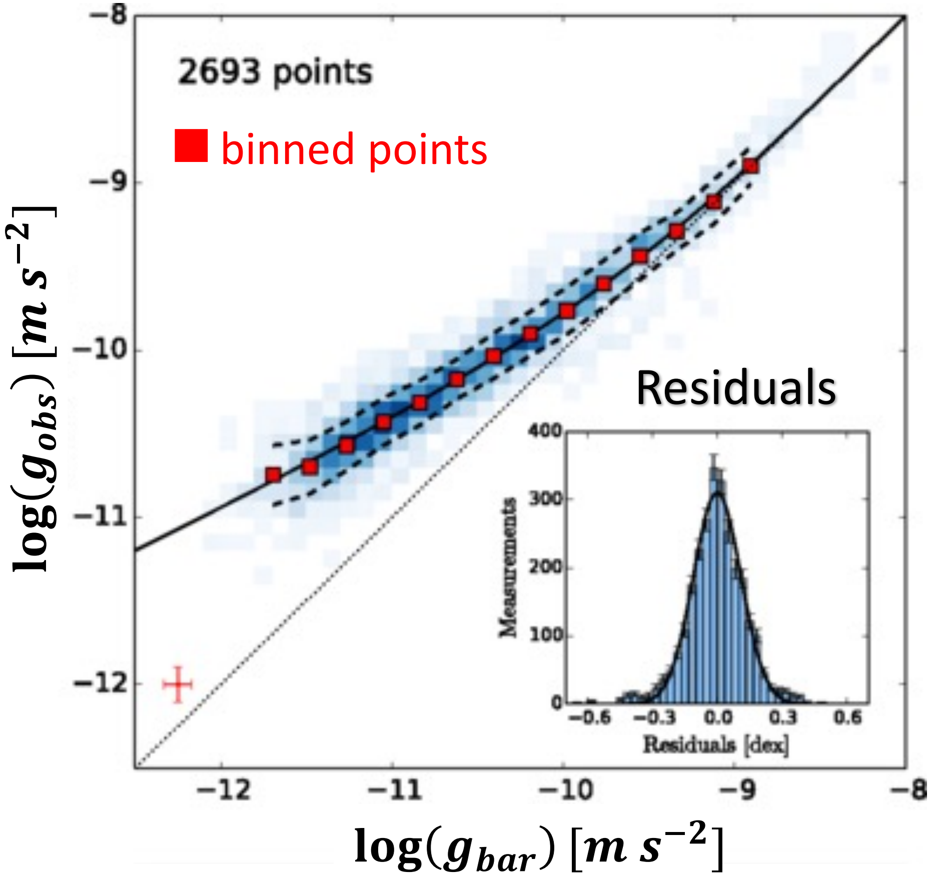
$$g_{obs} = \frac{V^2}{r}$$

- **Horizontal axis (g_{bar})**

$$g_{bar} = \frac{GM_{bar}(< r)}{r^2}$$

$$M_{bar} = M_{star} + M_{gas}$$

Radial Acceleration Relation

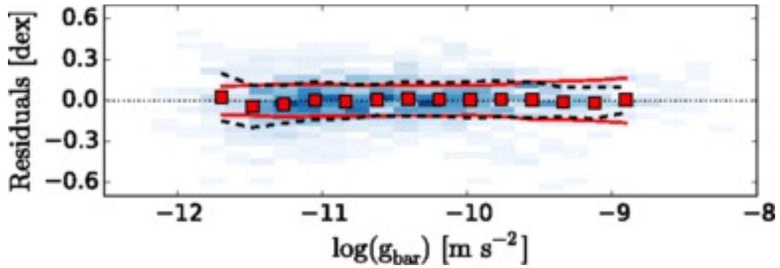


The tight relation gives

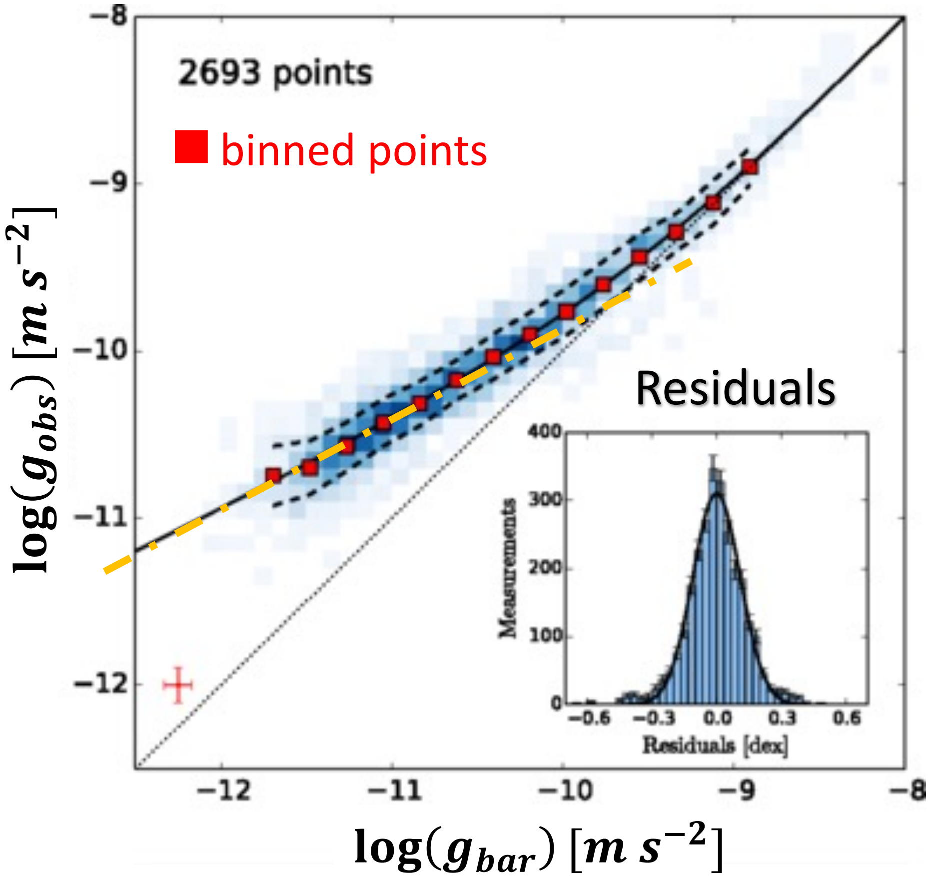
$$g_{obs} = \frac{g_{bar}}{1 - e^{-\sqrt{g_{bar}/g_\dagger}}}$$

$$g_\dagger = (1.20 \pm 0.02)\times 10^{-10}\ ms^{-2}$$

The residuals of $\log(g_{bar})$



Baryonic Tully-Fisher Relation



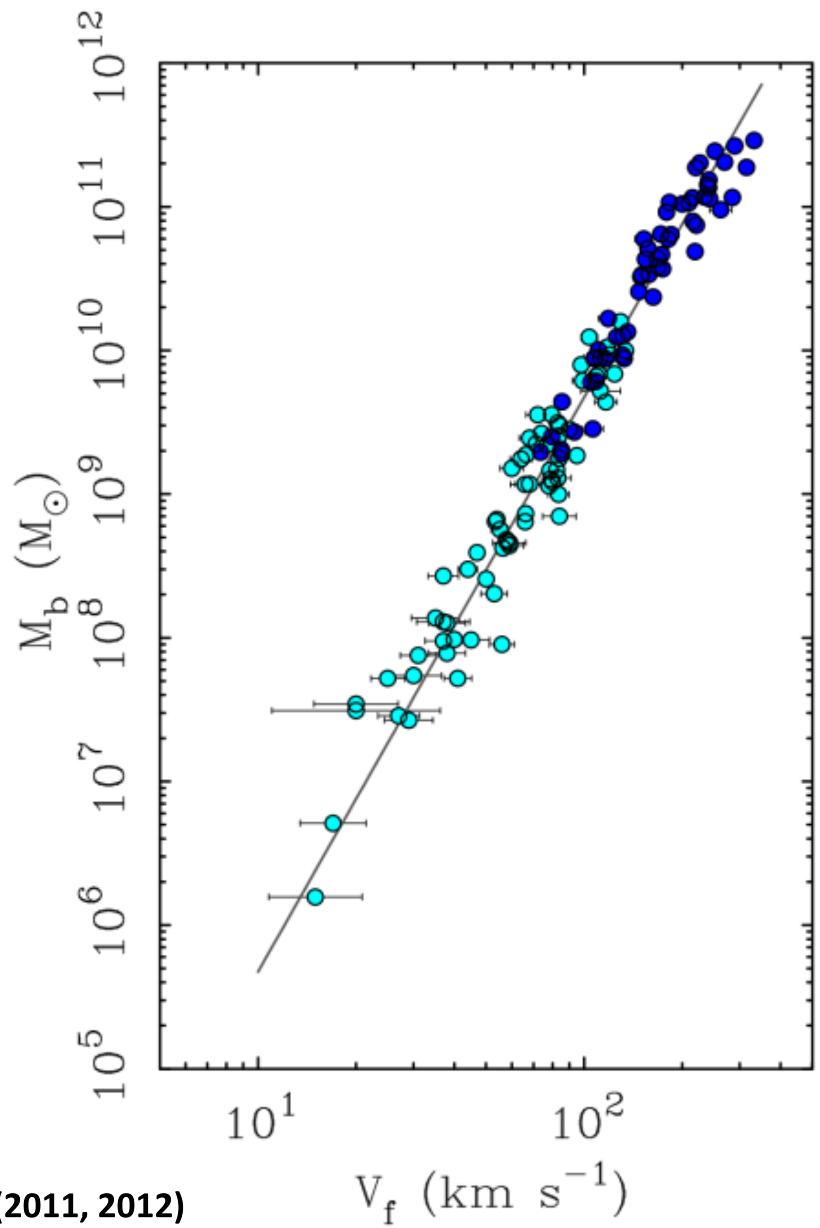
McGaugh et al. (2016), PRL, 117, 201101

$$g_{obs} = \sqrt{g_{bar}\, g_{\dagger}}$$

$$g_{obs} = \frac{v^2}{r};\quad g_{bar} = \frac{GM_{bar}}{r^2}$$

$$\rightarrow \frac{v^4}{r^2} = \frac{GM_{bar}g_{\dagger}}{r^2}$$

$$\rightarrow v^4 = GM_{bar}g_{\dagger}$$



McGaugh (2011, 2012)

MOND in Galaxy Clusters

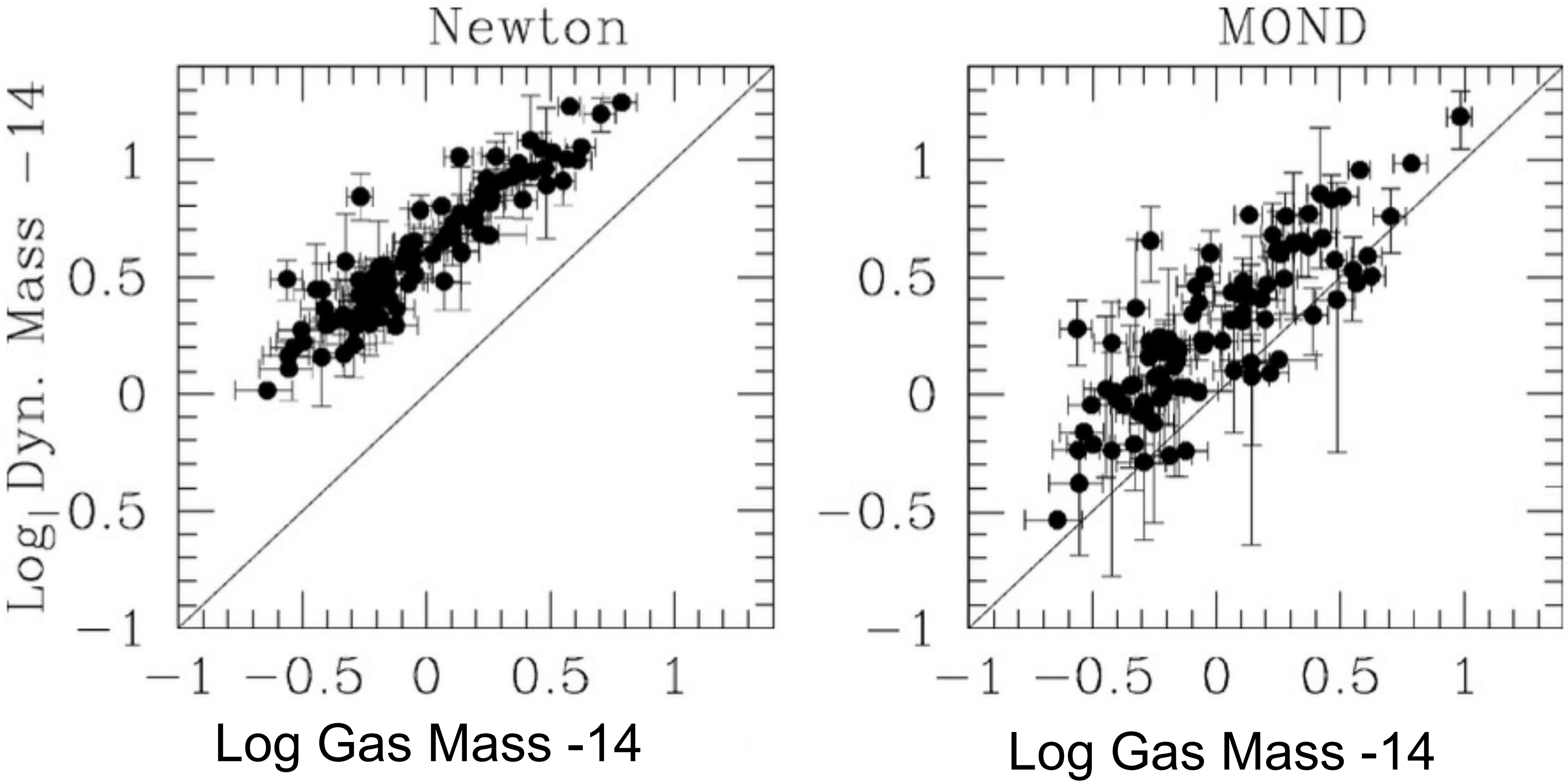
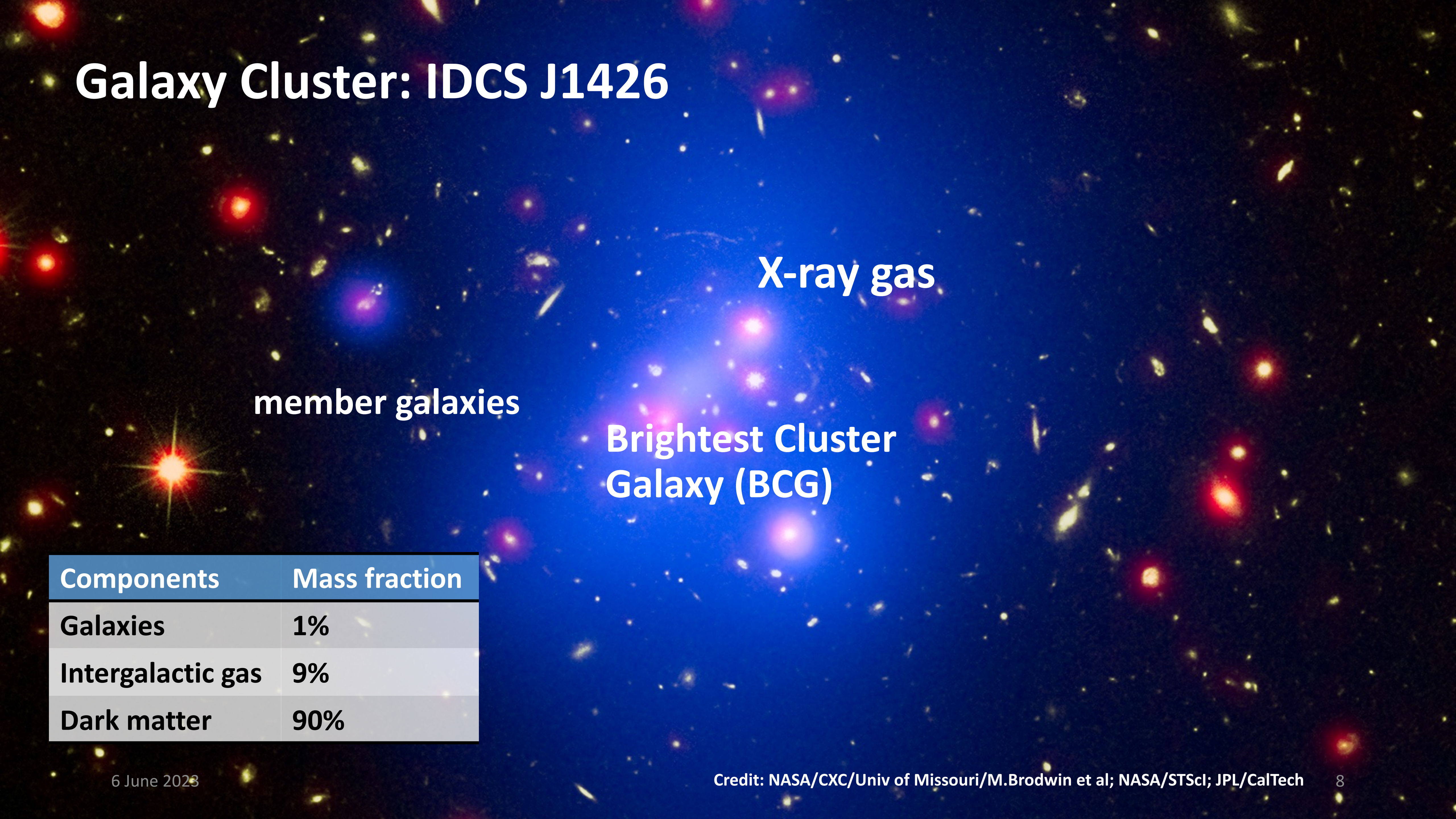


Figure 10 (*Left*) the Newtonian dynamical mass of clusters of galaxies within an observed cutoff radius (r_{out}) vs. the total observable mass in 93 X-ray-emitting clusters of galaxies (White et al. 1997). The solid line corresponds to $M_{dyn} = M_{obs}$ (no discrepancy). (*Right*) the MOND dynamical mass within r_{out} vs. the total observable mass for the same X-ray-emitting clusters. From Sanders (1999).

Lensing RAR on Cluster Scales?

Galaxy Cluster: IDCS J1426

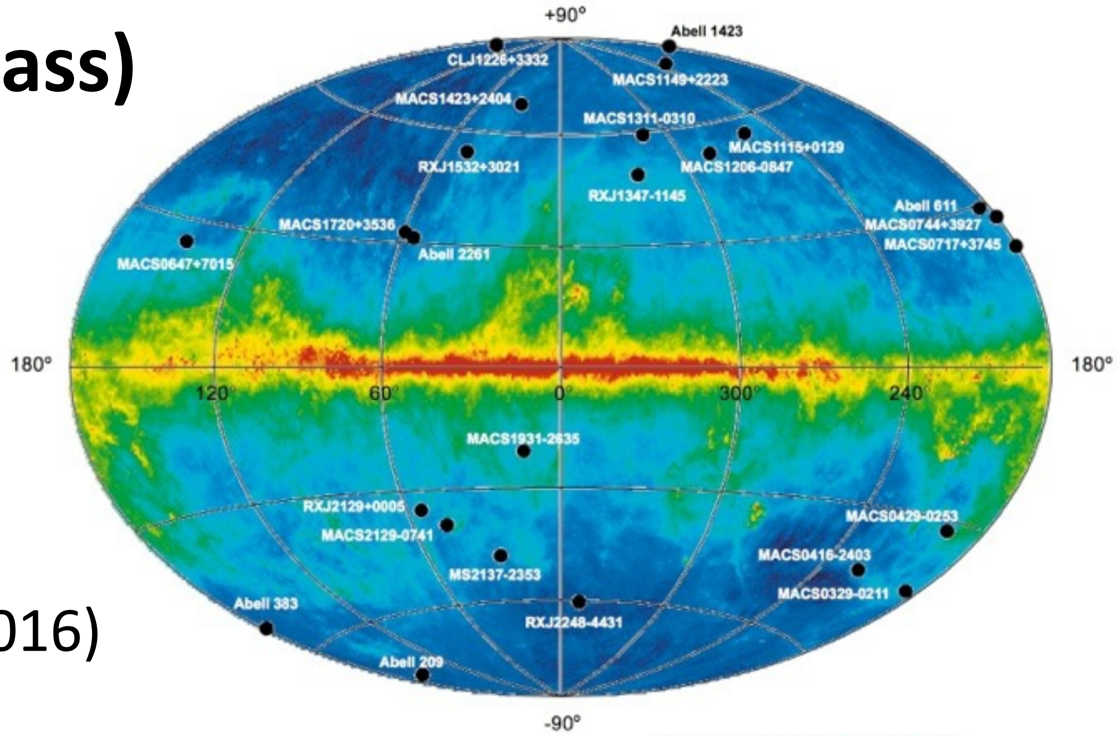


Components	Mass fraction
Galaxies	1%
Intergalactic gas	9%
Dark matter	90%

Credit: NASA/CXC/Univ of Missouri/M.Brodwin et al; NASA/STScI; JPL/CalTech

Ingredients in Galaxy Clusters

- **Cluster Lensing And Supernova survey with Hubble (CLASH)**
- **Observational Mass (Lensing Mass)**
  - Strong & Weak-Lensing (Umetsu+ 2016)
- **Baryonic Mass**
  - X-ray gas (Donahue+ 2014)
  - Stellar mass (Chiu+ 2018)
  - Brightest Cluster Galaxy (BCG; Cooke+ 2016)



CLASH CLUSTER SAMPLE
(Galactic Coordinates)

THE ASTROPHYSICAL JOURNAL, 896:70 (10pp), 2020 June 10
https://doi.org/10.3847/1538-4357/ab8e3d

The Radial Acceleration Relation in CLASH Galaxy Clusters

Yong Tian[1], Keiichi Umetsu[2], Chung-Ming Ko[1,3], Megan Donahue[4], and I-Non Chiu[2]
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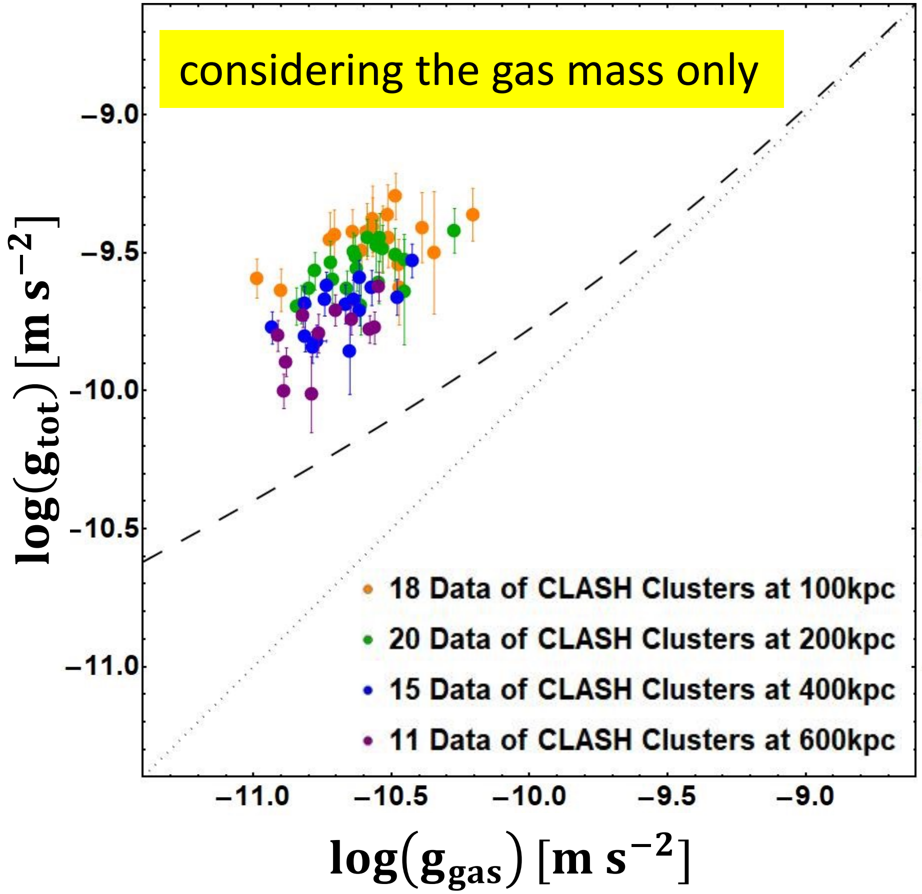
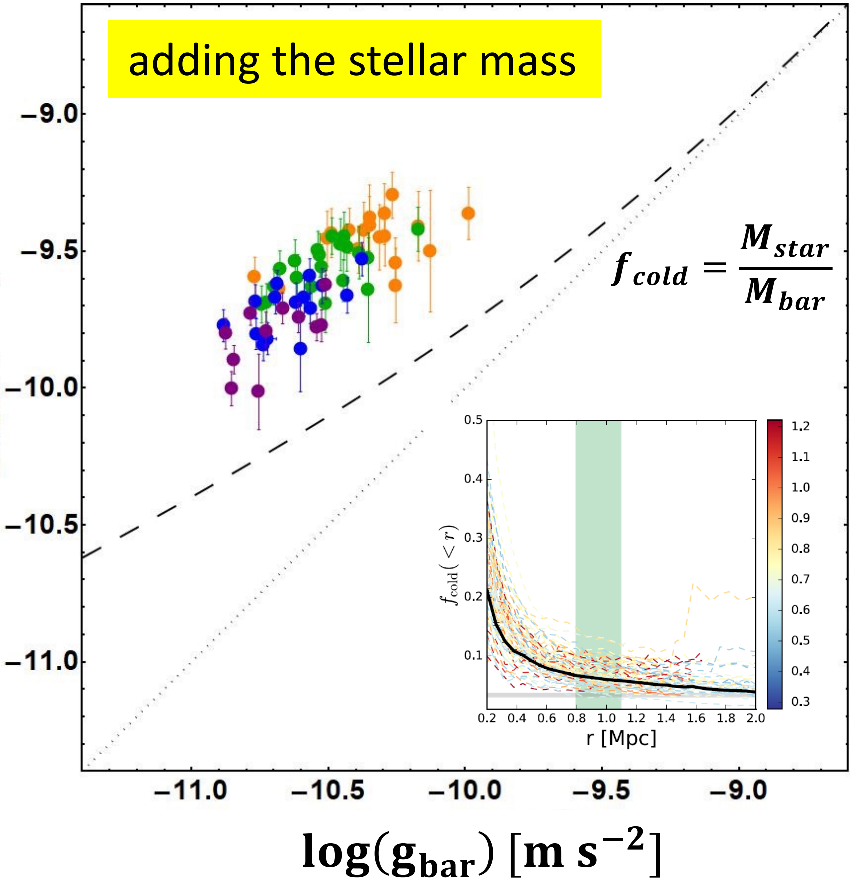
Received 2020 January 19; revised 2020 April 23; accepted 2020 April 27; published 2020 June 15





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The Radial Acceleration Relation in CLASH Galaxy Clusters

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[1] Institute of Astronomy, National Central University, Taoyuan 32001, Taiwan; yongtian@gm.astro.ncu.edu.tw
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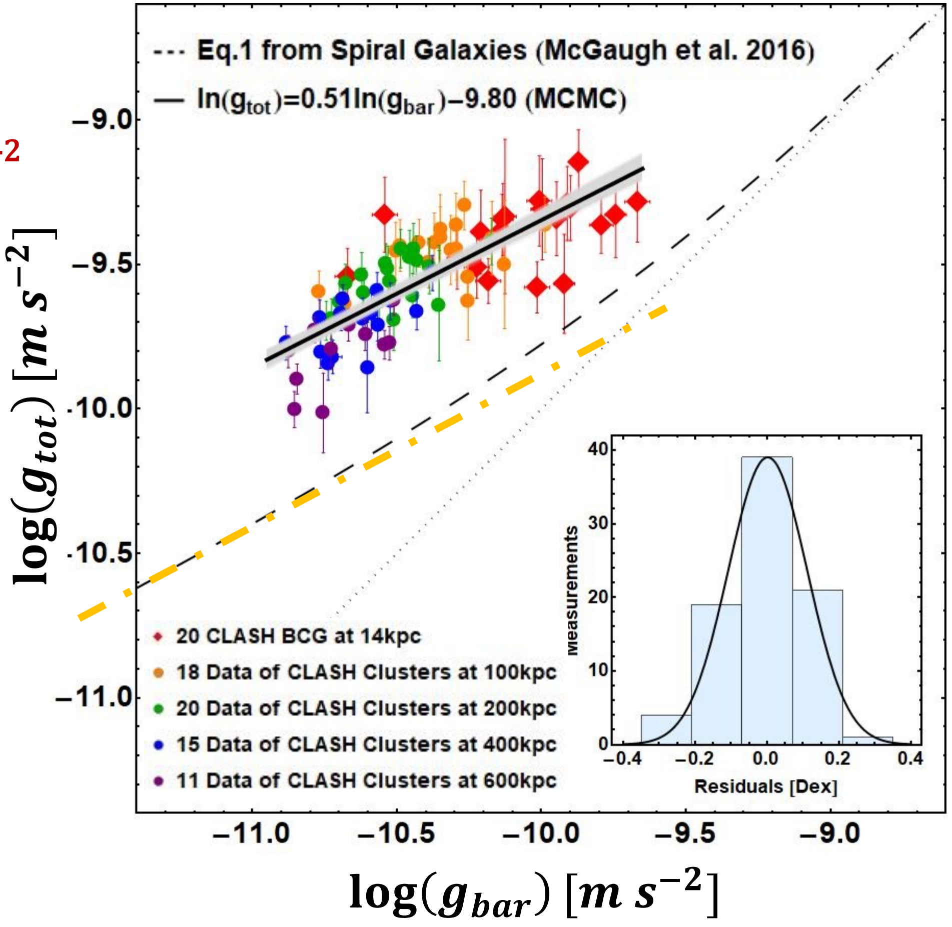
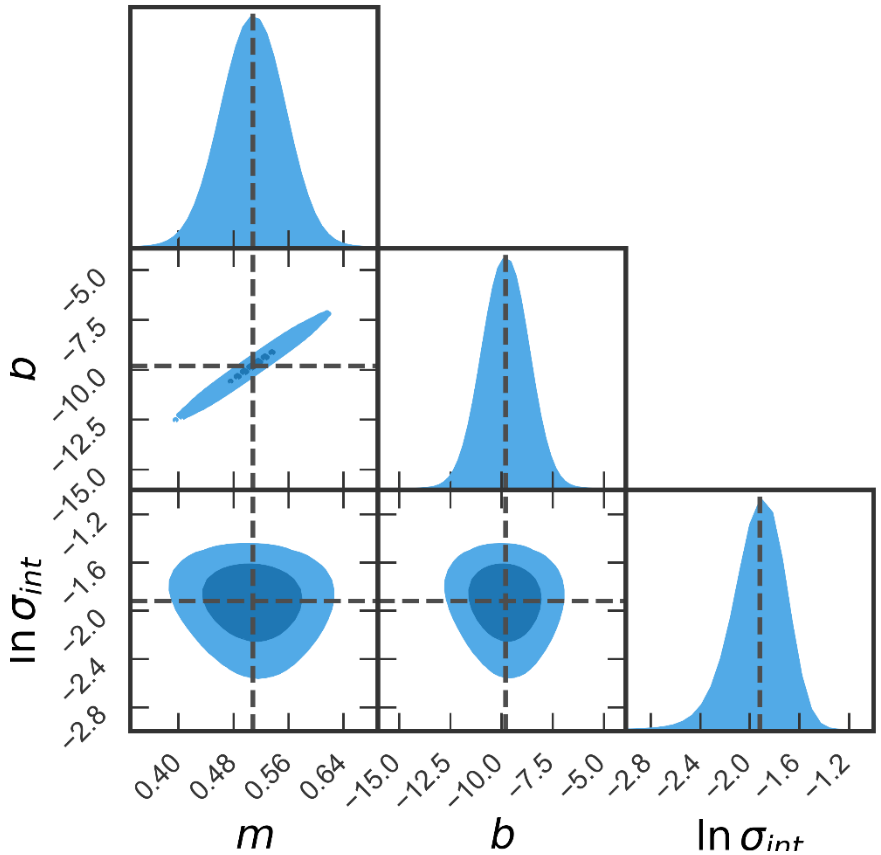
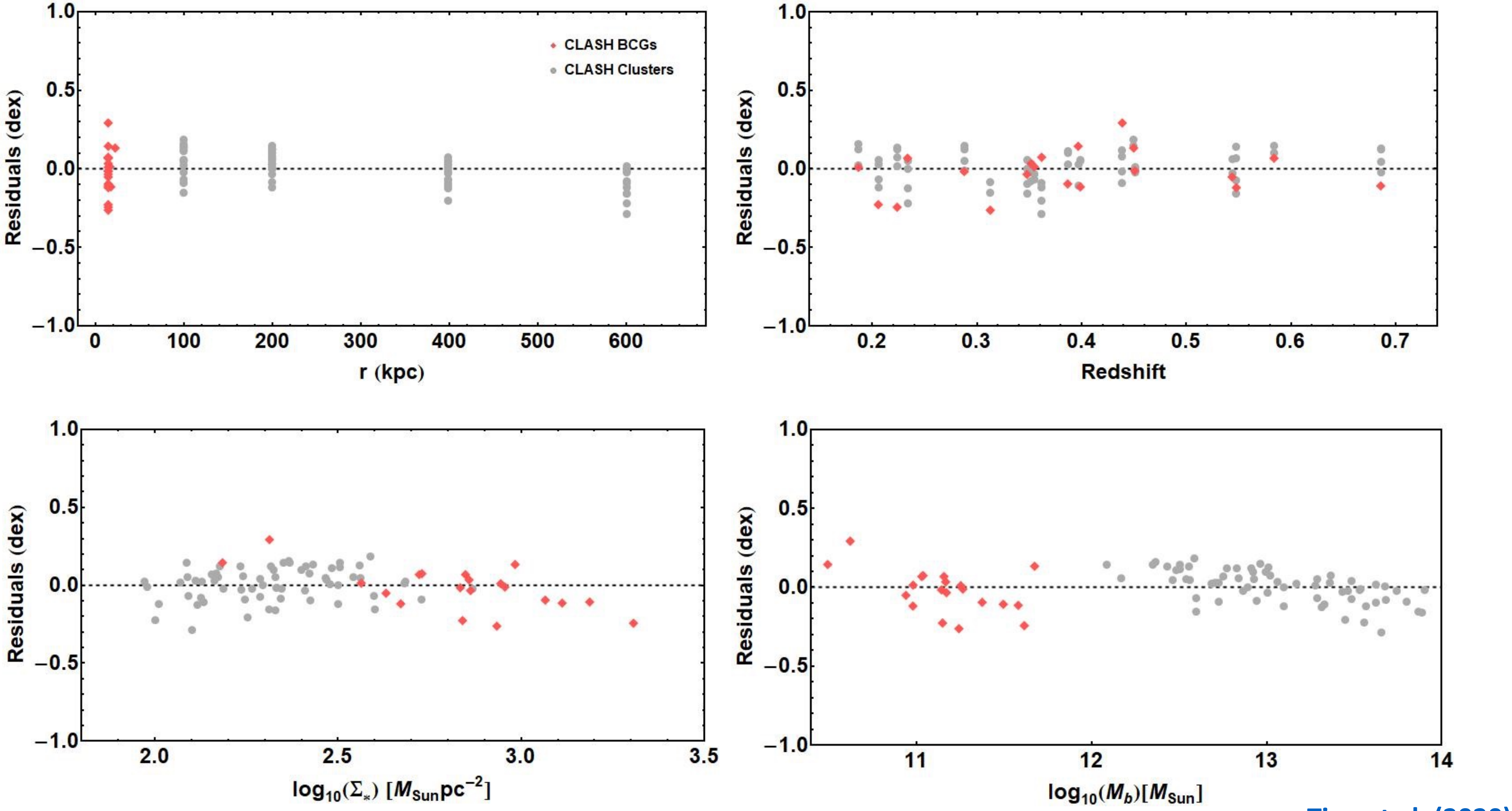
$$g_{tot} = \sqrt{g_{bar}\, g_{\ddagger}}$$

$$g_{\ddagger} = (2.0 \pm 0.1) \times 10^{-9}\ \mathrm{ms^{-2}}$$





Residuals in CLASH RAR



Tian et al. (2020), ApJ, 896, 70

Four Issues in CLASH RAR

Four Issues in RAR (Desmond 2017; Lelli+ 2017)

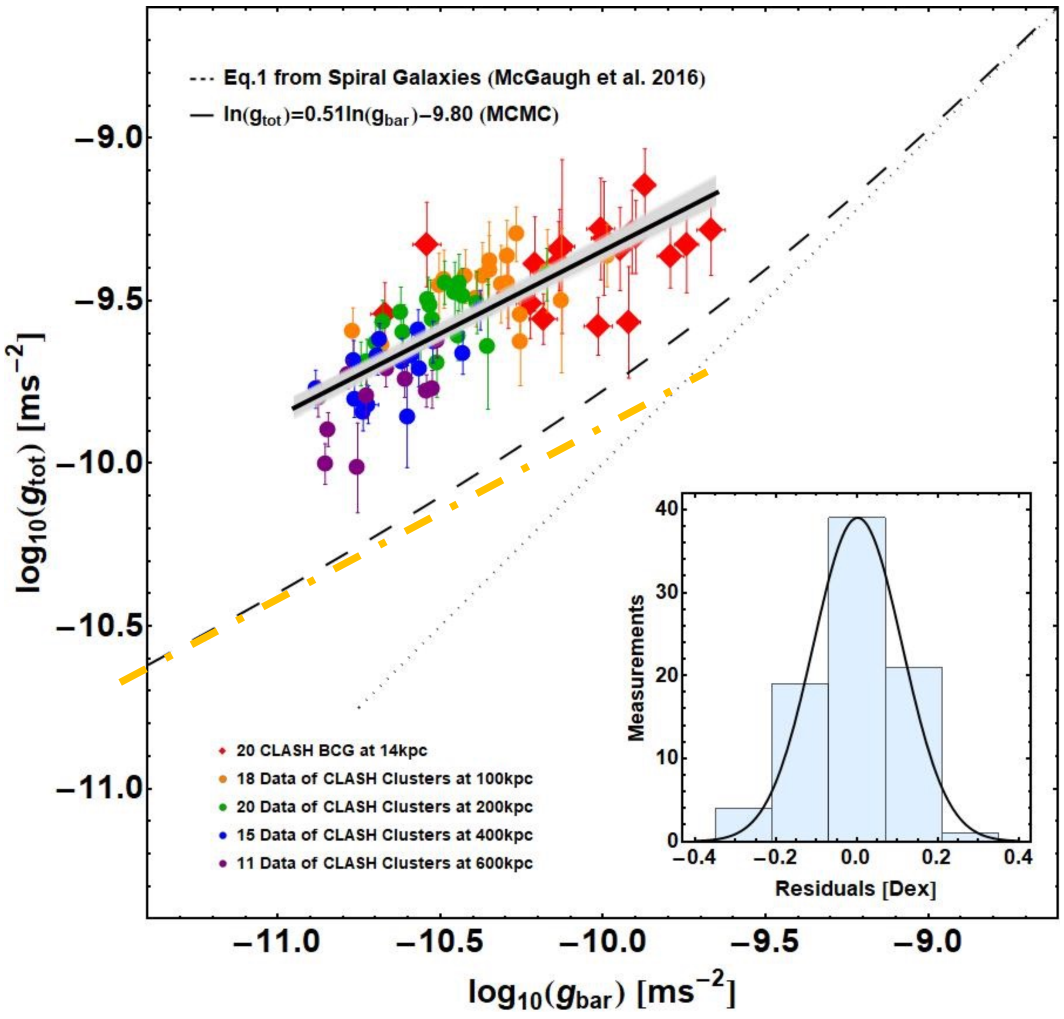
i. **the acceleration scale $g_{\dagger}=1.20\times10^{-10}\,\mathrm{ms^{-2}}$;**
ii. **the low-acceleration slope (0.5);**
iii. **the intrinsic tightness (≤ 0.11 dex);**
iv. **no correlations between residuals and other galaxy properties.**

Four Issues in CLASH RAR (Tian+ 2020)

i. **a new acceleration scale $g_{\ddagger}=(2.0\pm0.1)\times10^{-9}\,\mathrm{ms^{-2}}$;**
ii. **the acceleration slope (0.5);**
iii. **lognormal intrinsic scatter $14.7^{+2.9}_{-2.8}\%$;**
iv. **a small correlation between residuals and radius.**

Implication by the CLASH RAR

The CLASH RAR



Implication:

Mass-Velocity Dispersion Relation

$$g_{obs} = \sqrt{g_{bar}\, g_{\ddagger}}$$

$$g_{obs} \propto \frac{\sigma^2}{r}\,;\ \ g_{bar} = \frac{GM_{bar}}{r^2}$$

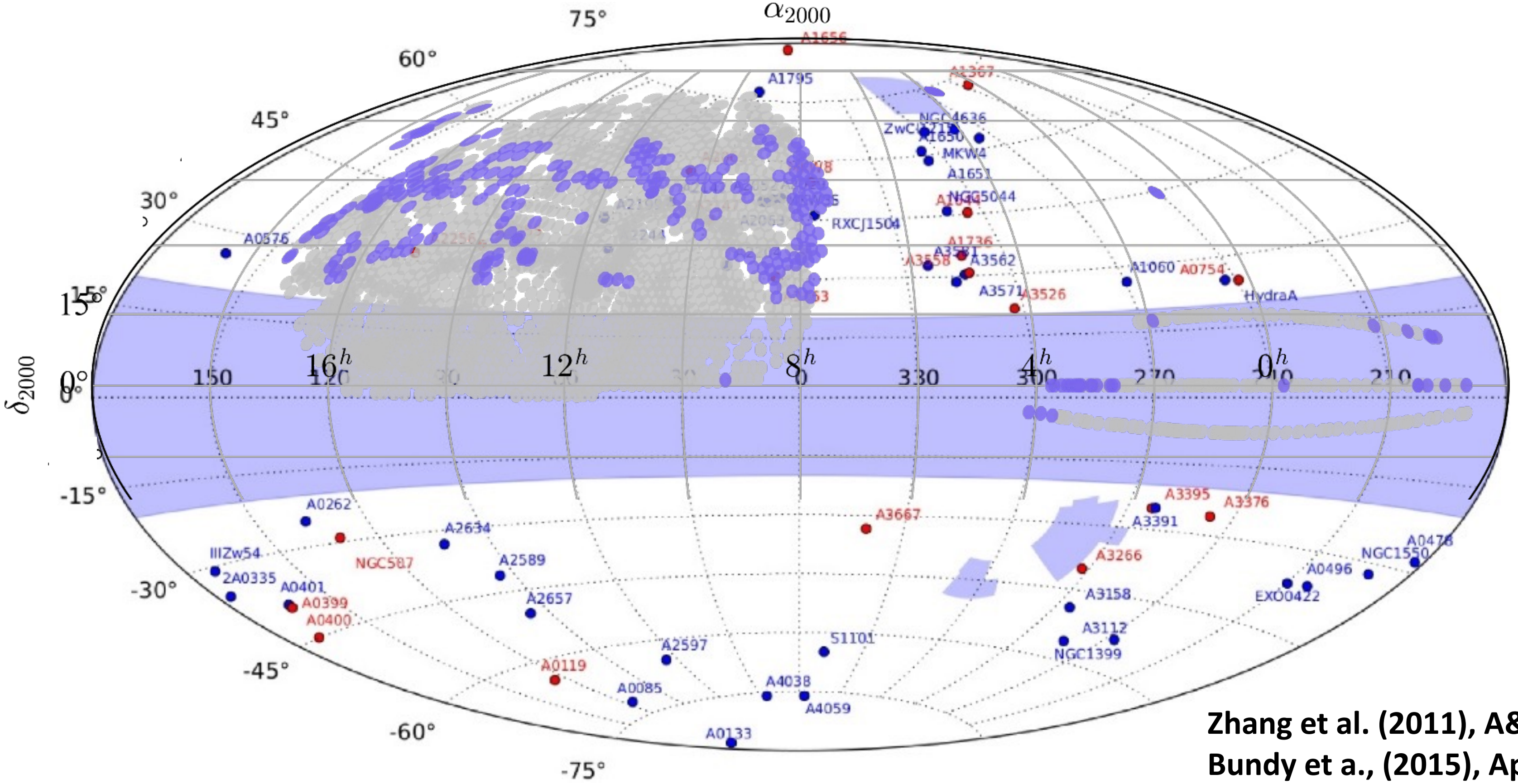
$$\rightarrow \sigma^4 \propto\ GM_{bar} g_{\ddagger}$$

Tian et al. (2020), ApJ, 896, 70

The MVDR on BCG-Cluster Scales?

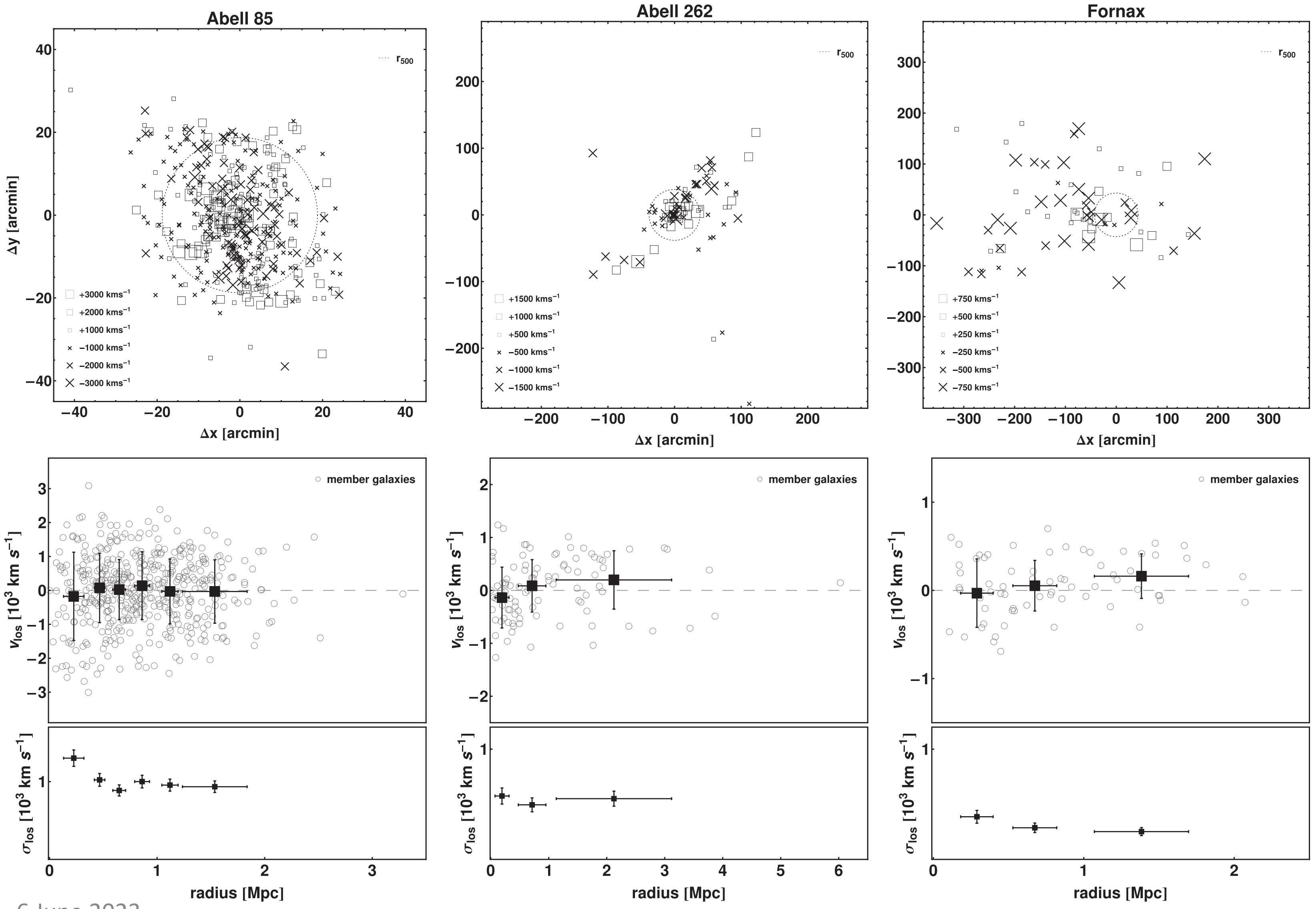
BCG and galaxy cluster samples

- ❑ **29 galaxy clusters in the HIFLUGCS** ([Tian et al. 2021a, ApJ, 910, 56])
- ❑ **54 BCGs in MaNGA MPL-7** ([Tian et al. 2021b, ApJL, 917, L24])



Zhang et al. (2011), A&A, 526, A105;
Bundy et a., (2015), ApJ, 798, 7

Flat Velocity Dispersion Profiles



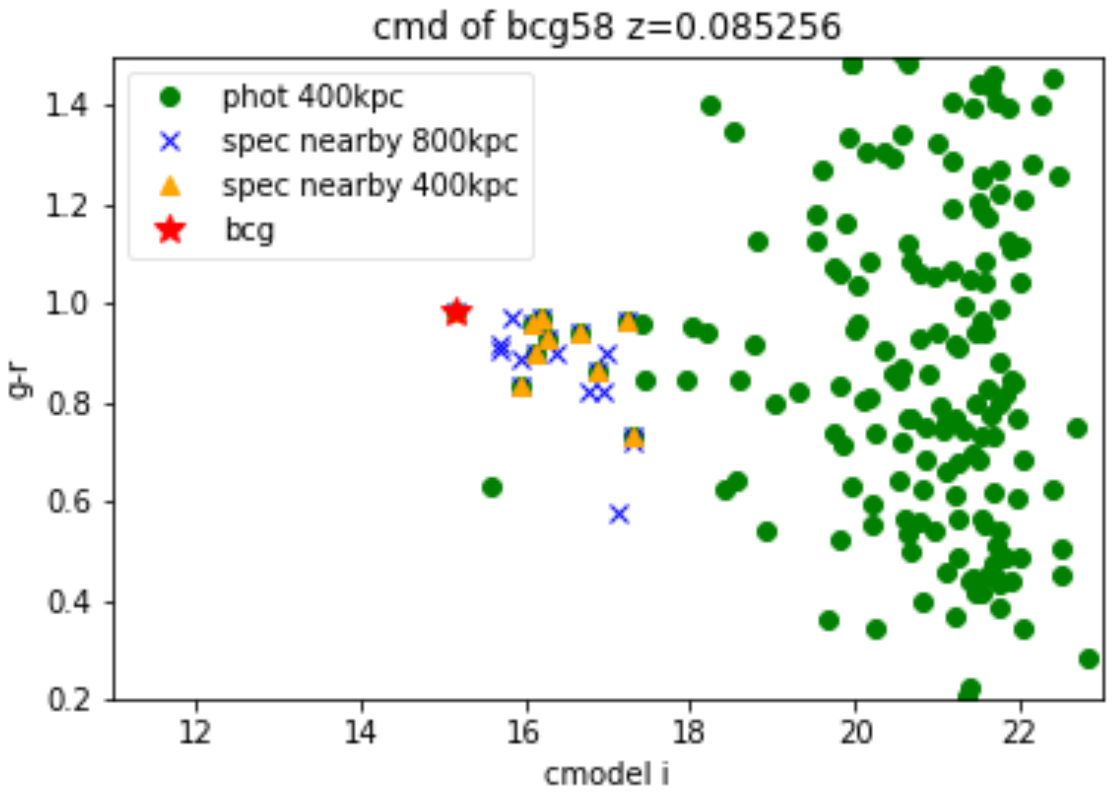
Three examples of HIFLUGCS clusters.

Upper panel: the spatial distributions are relative to the center point of the BCG.
Middle panel: the relative los velocity (V_{los}) distribution is in terms of the projected radius relative to the BCG.
Lower panel: the los velocity dispersion (σ_{los}) presents a flat tail for each cluster.

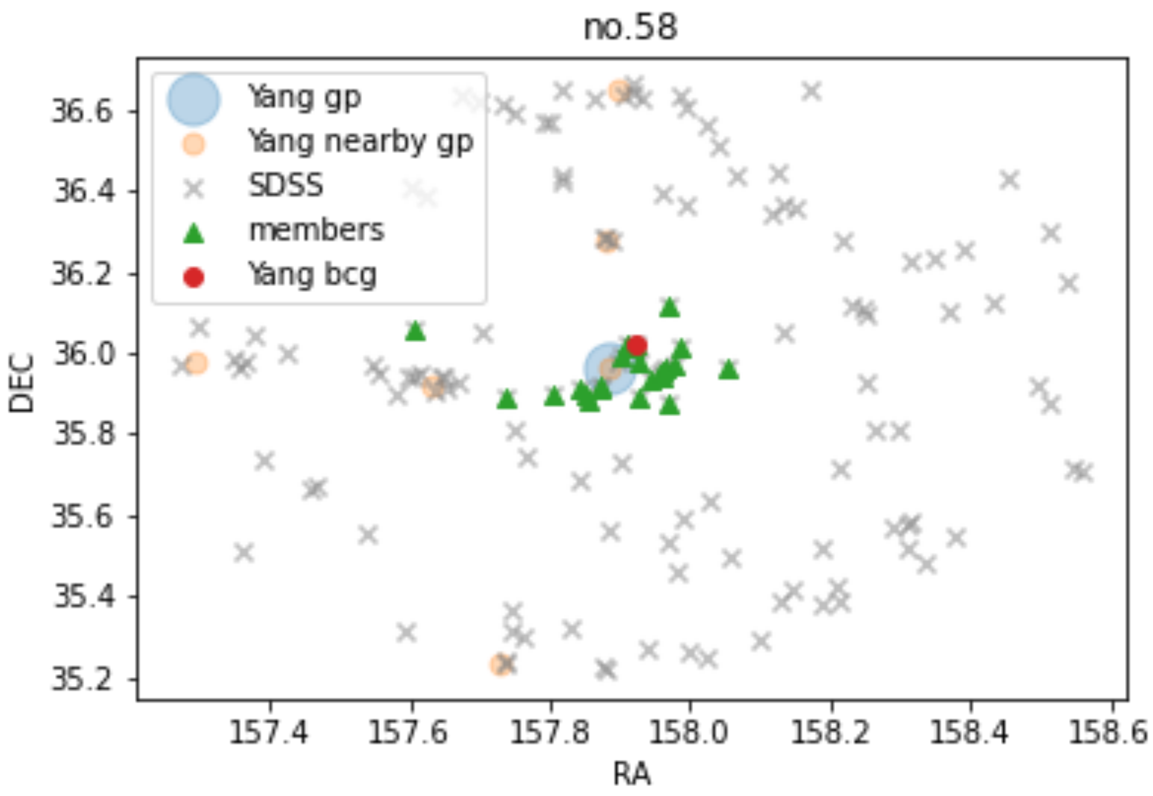
Tian et al. (2021a), ApJ, 910, 56

Identifying BCGs in MaNGA

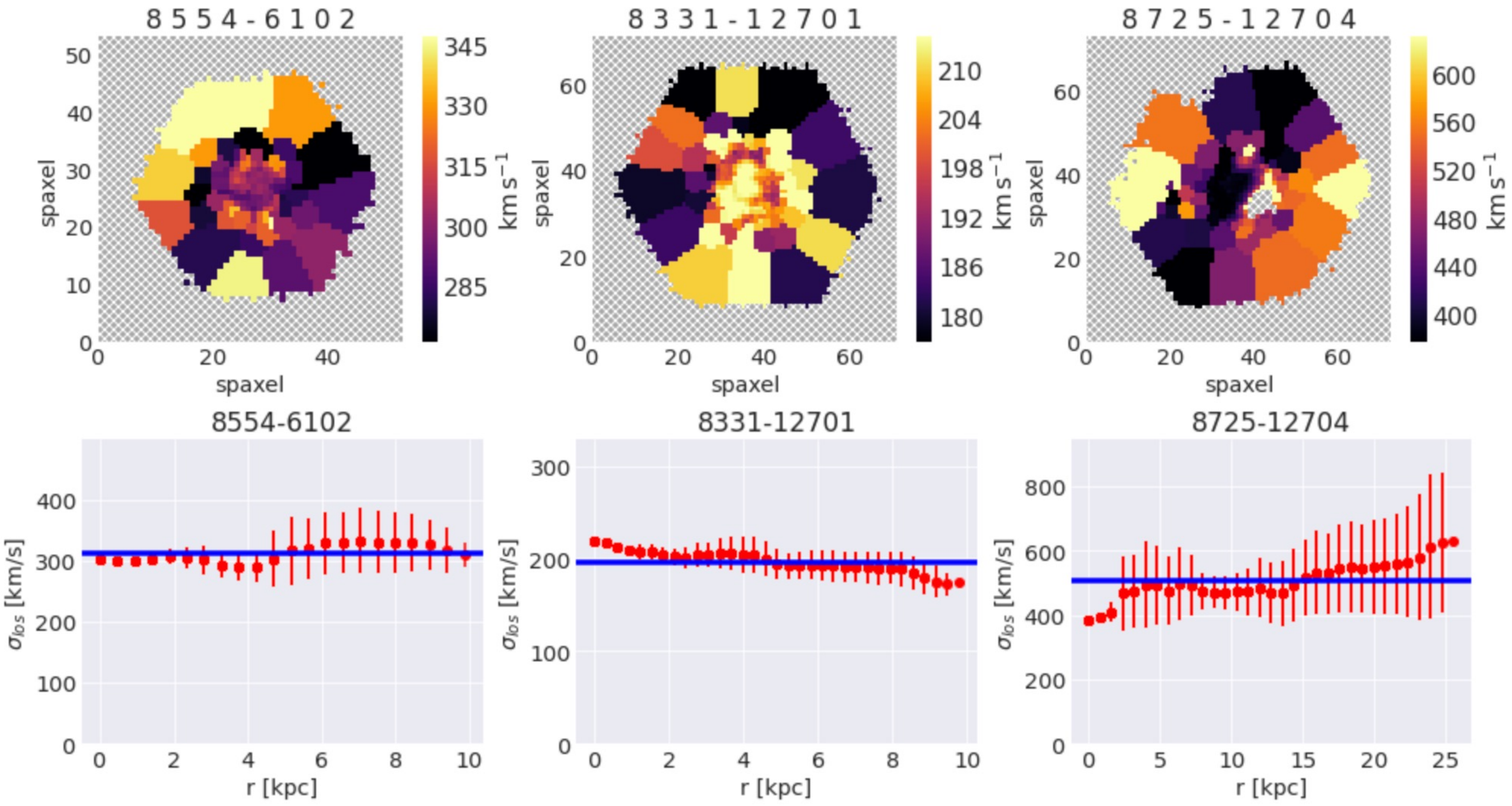
Color-Magnitude



Membership Distribution



Flat Velocity Dispersion Profiles



Three examples of MaNGA BCGs.
Upper panel: the map plot of Spaxel data for the stellar velocity dispersion.
Lower panel: velocity dispersion profiles in terms of radius. MaNGA BCGs present a flat velocity dispersion profile.

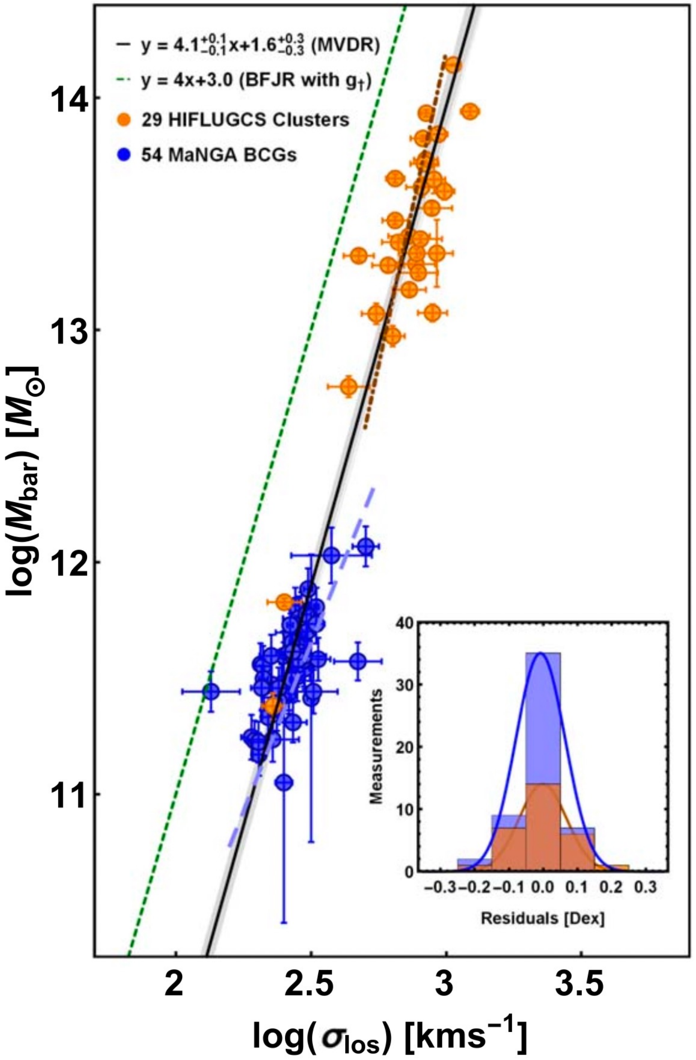
[Tian et al. (2021b), ApJL, 917, L24]

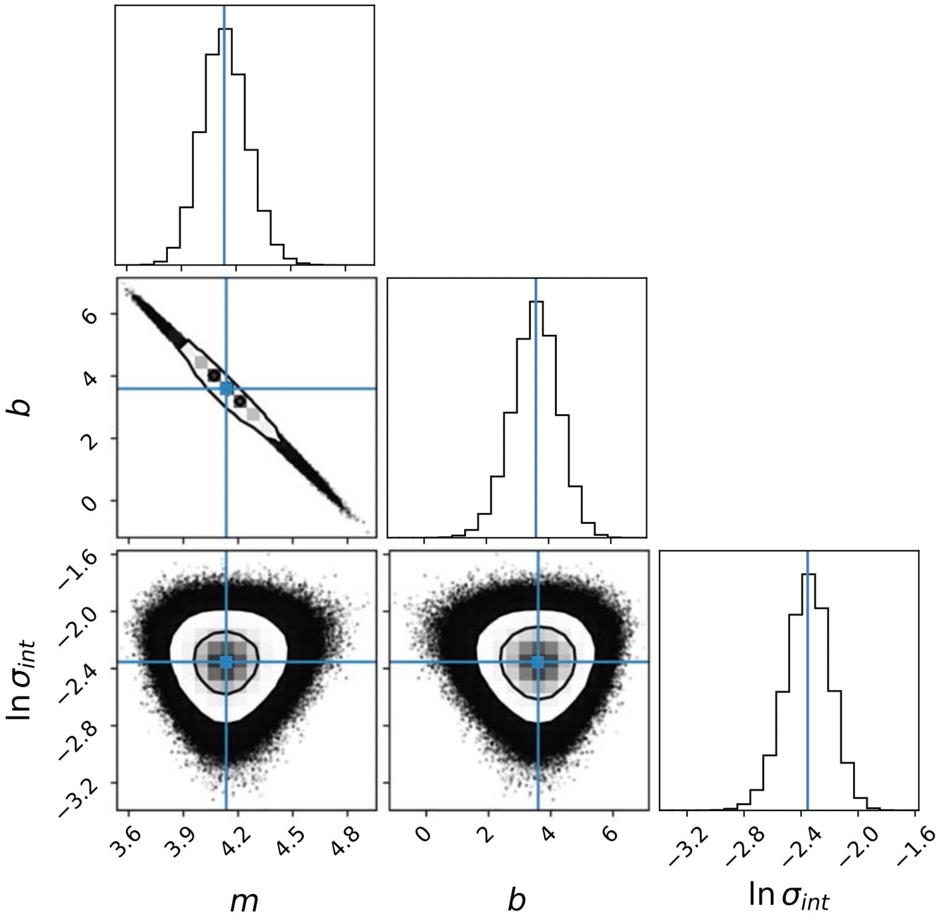
The Astrophysical Journal Letters, 917:L24 (6pp), 2021 August 20
https://doi.org/10.3847/2041-8213/ac1a18

Mass–Velocity Dispersion Relation in MaNGA Brightest Cluster Galaxies

Yong Tian[1], Han Cheng[1], Stacy S. McGaugh[2], Chung-Ming Ko[1,3,†], and Yun-Hsin Hsu[4,5]

The MVDR of both BCGs and clusters. Left panel: the blue circles represent 54 MaNGA BCGs while the orange circles indicate 29 HIFLUGCS clusters in Tian et al. (2021a). Right panel: triangle diagrams of the regression parameters. Black contours represent 1σ and 2σ confidence regions.





[Tian et al. (2021b), ApJL, 917, L24](https://doi.org/10.3847/2041-8213/ac1a18)

Dynamical RAR on BCG-Cluster Scales?

A Distinct Radial Acceleration Relation across Brightest Cluster Galaxies and Galaxy Clusters

Yong Tian [1] Chung-Ming Ko [1,2] Pengfei Li [3,*] Stacy S. McGaugh [4,†] and Shemile L. Poblete [1]

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[3] Leibniz-Institute for Astrophysics, An der Sternwarte 16, 14482 Potsdam, Germany
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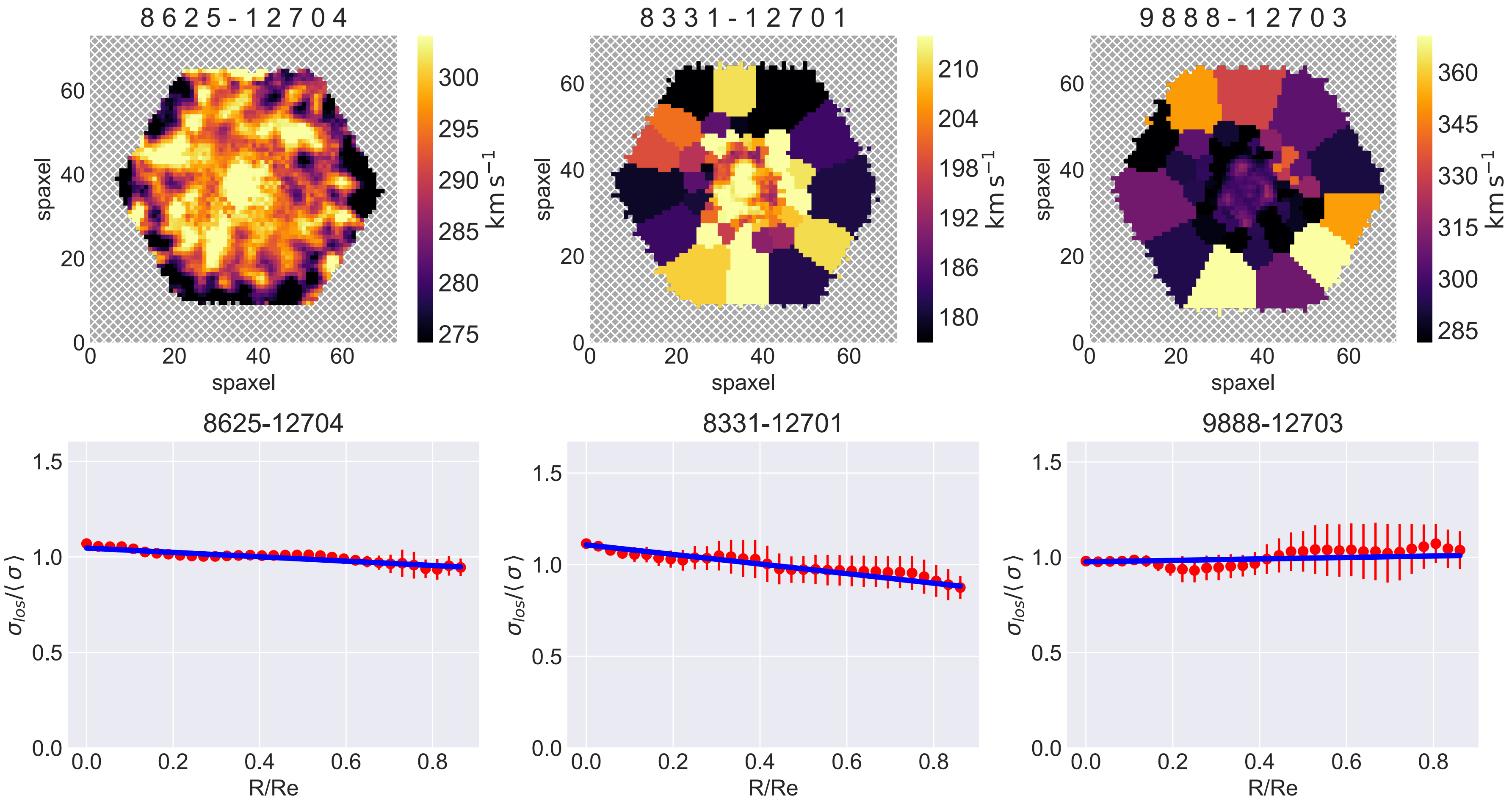
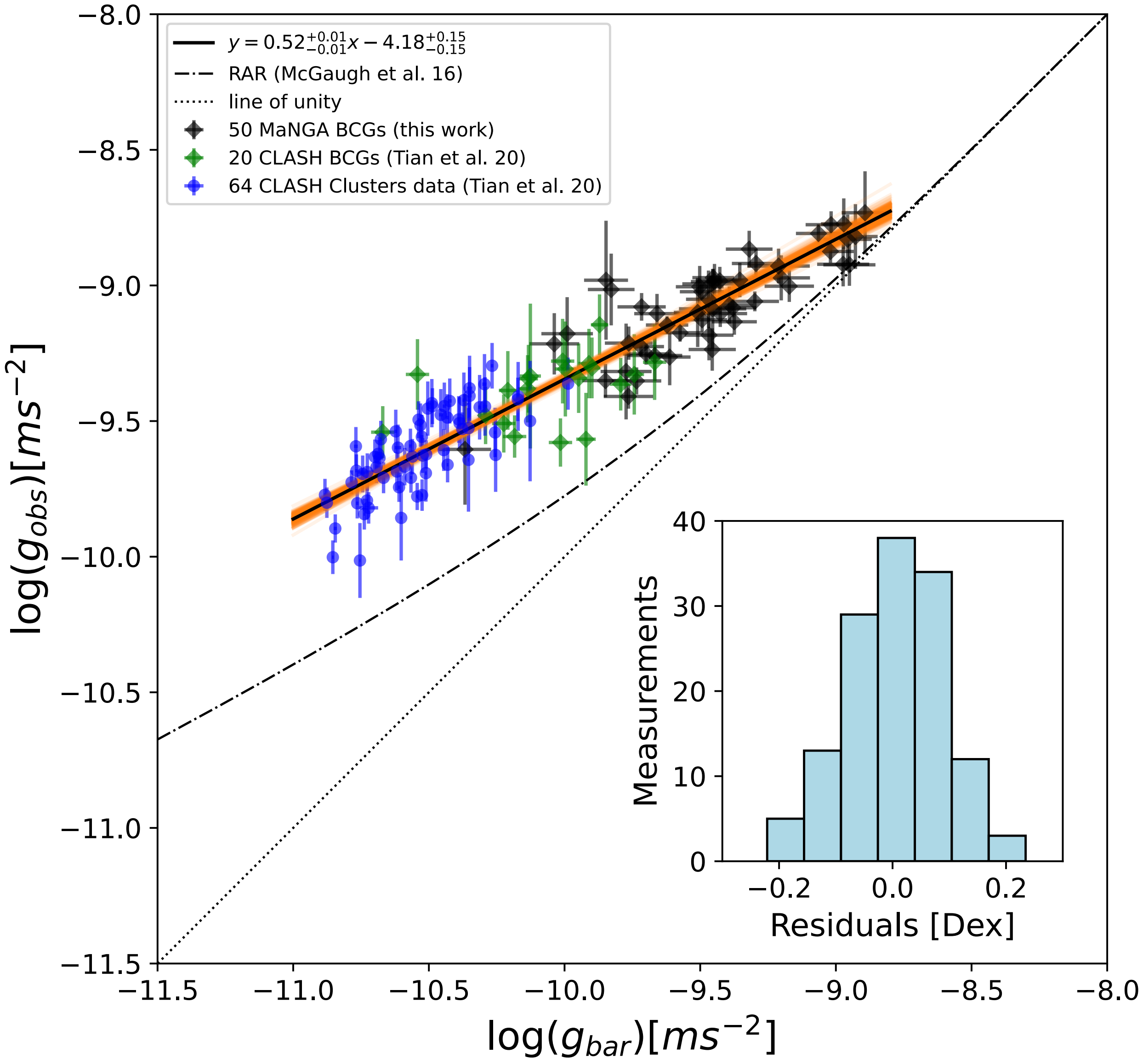
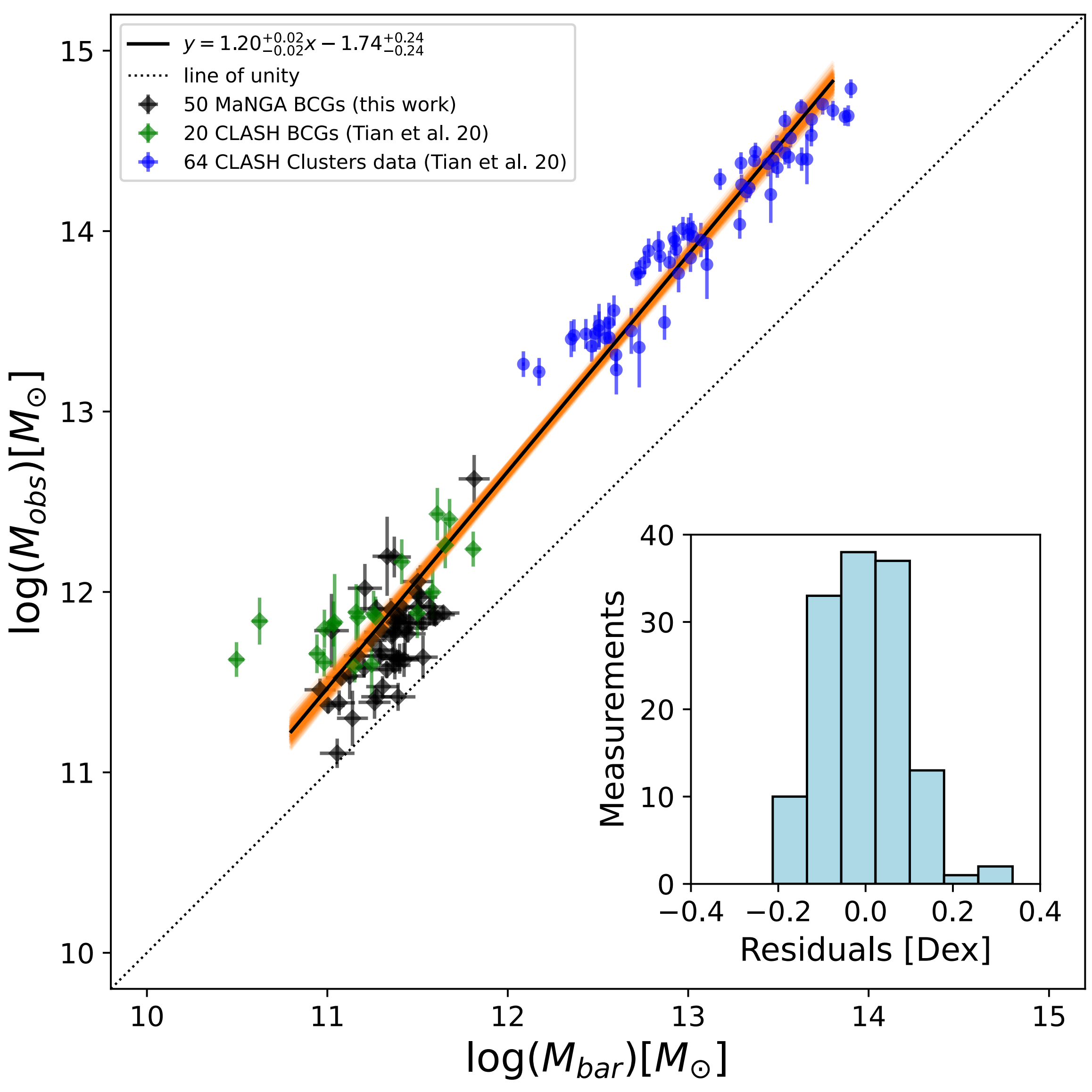






Tian et al. (2023) submitted to ApJL

The Implication by Acceleration Scale

Scale Lenth Implied by Acceleration Scale

$$a \approx \frac{\sigma^2}{r_\dagger} \approx g_\dagger$$

$$r_\dagger = \sigma^2 g_\dagger^{-1}$$

Milgrom (1984), ApJ, 287,571

$$a \approx \frac{\sigma^2}{r_\ddagger} \approx g_\ddagger$$

$$r_\ddagger = \sigma^2 g_\ddagger^{-1}$$

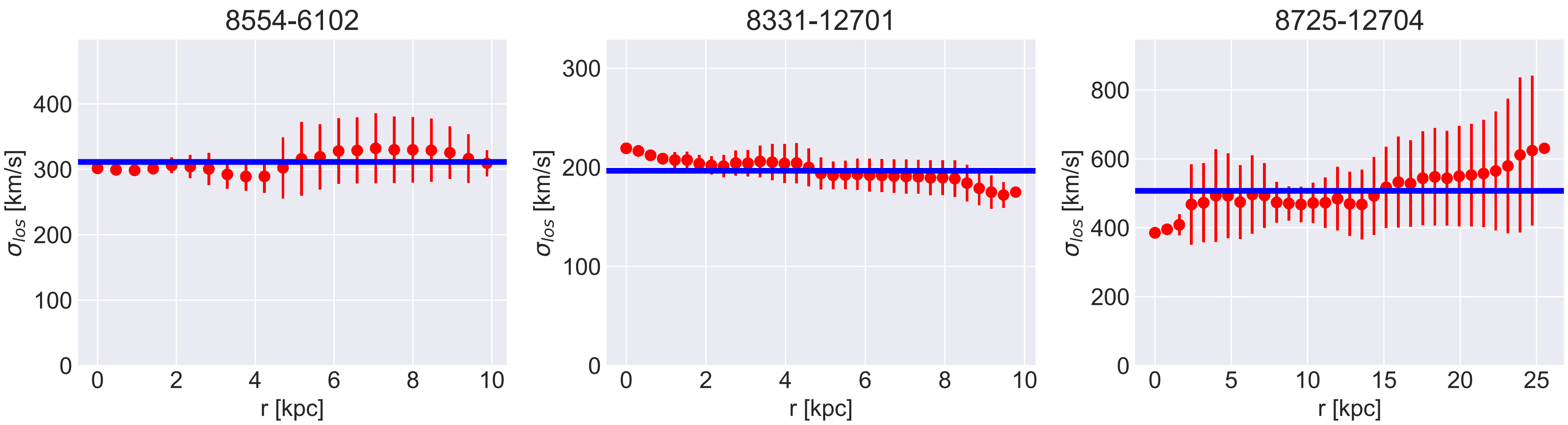
Tian et al. (2021b), ApJL, 917, L24

If σ ranges in 100-200 km/s for ellipitcals and 200-300 km/s for BCGs, we have different scale lenths for the flat tails.

$$r_\dagger \sim 2.6 - 10.7\ kpc$$

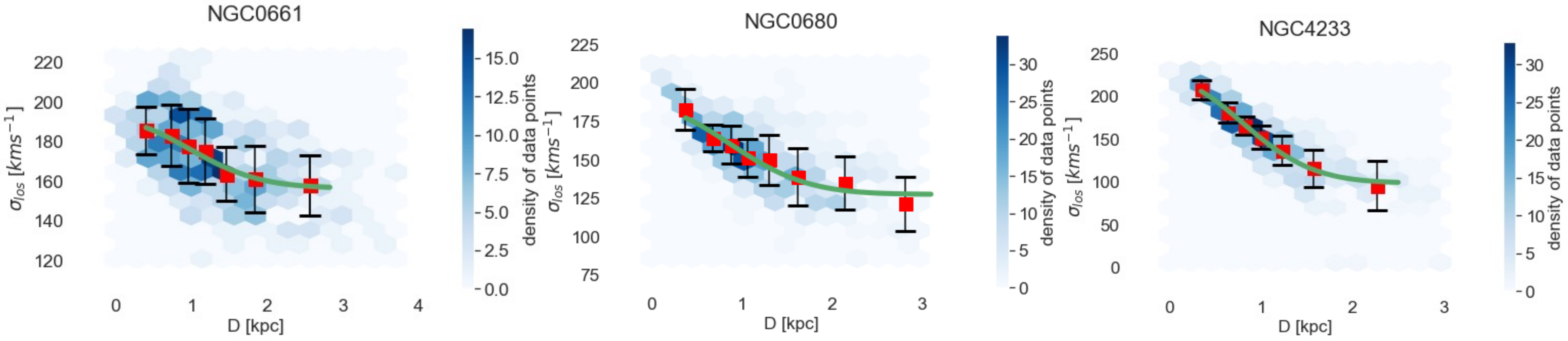
$$r_\ddagger \sim 0.6 - 1.5\ kpc$$

Velocity Dispersion Profiles in Ellipitical Galaxies



Three examples of MaNGA BCGs.

[Tian et al. (2021b), ApJL, 917, L24](#)



Three examples of ATLAS^{3D} ellipticals.

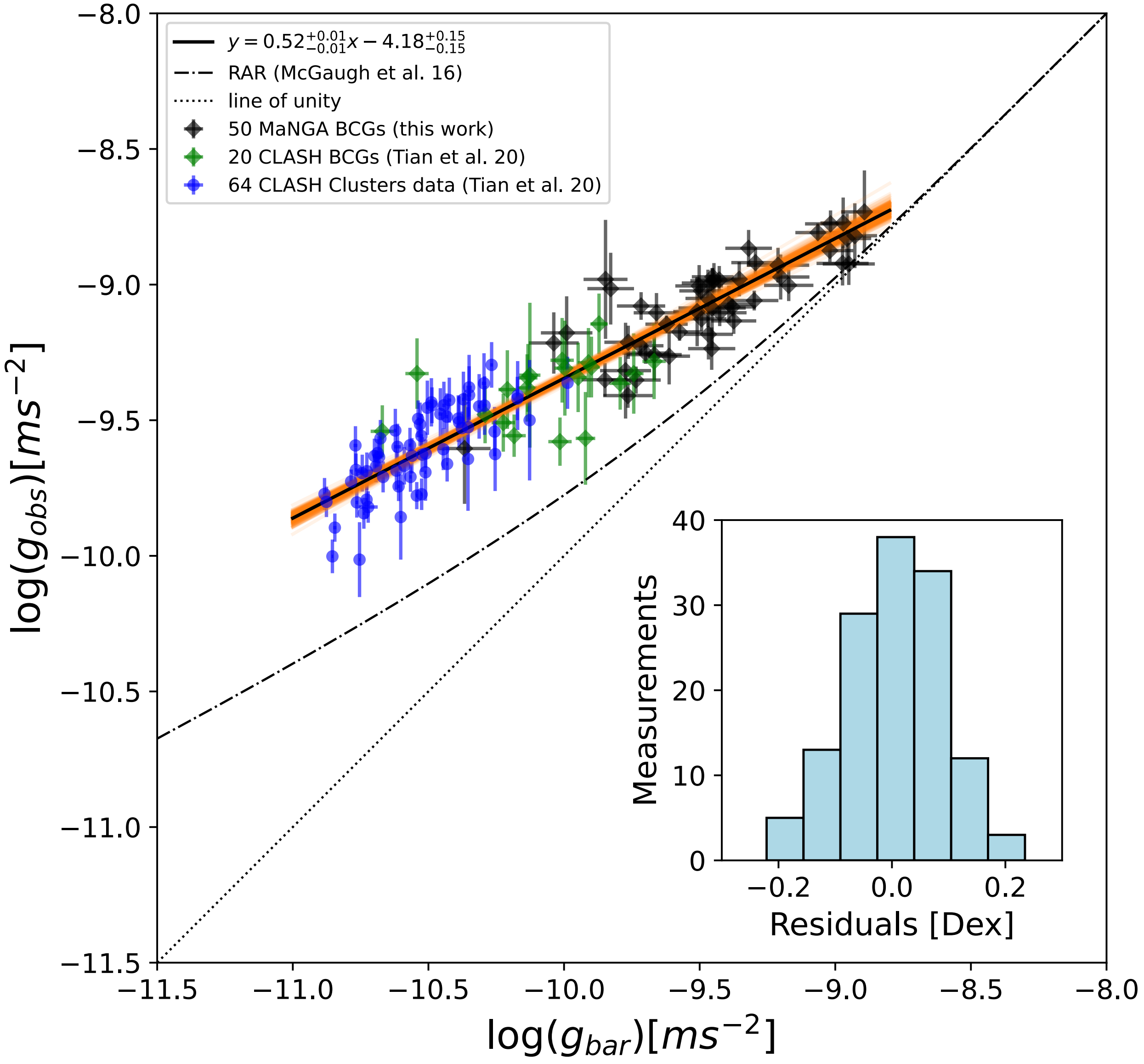
Remarks

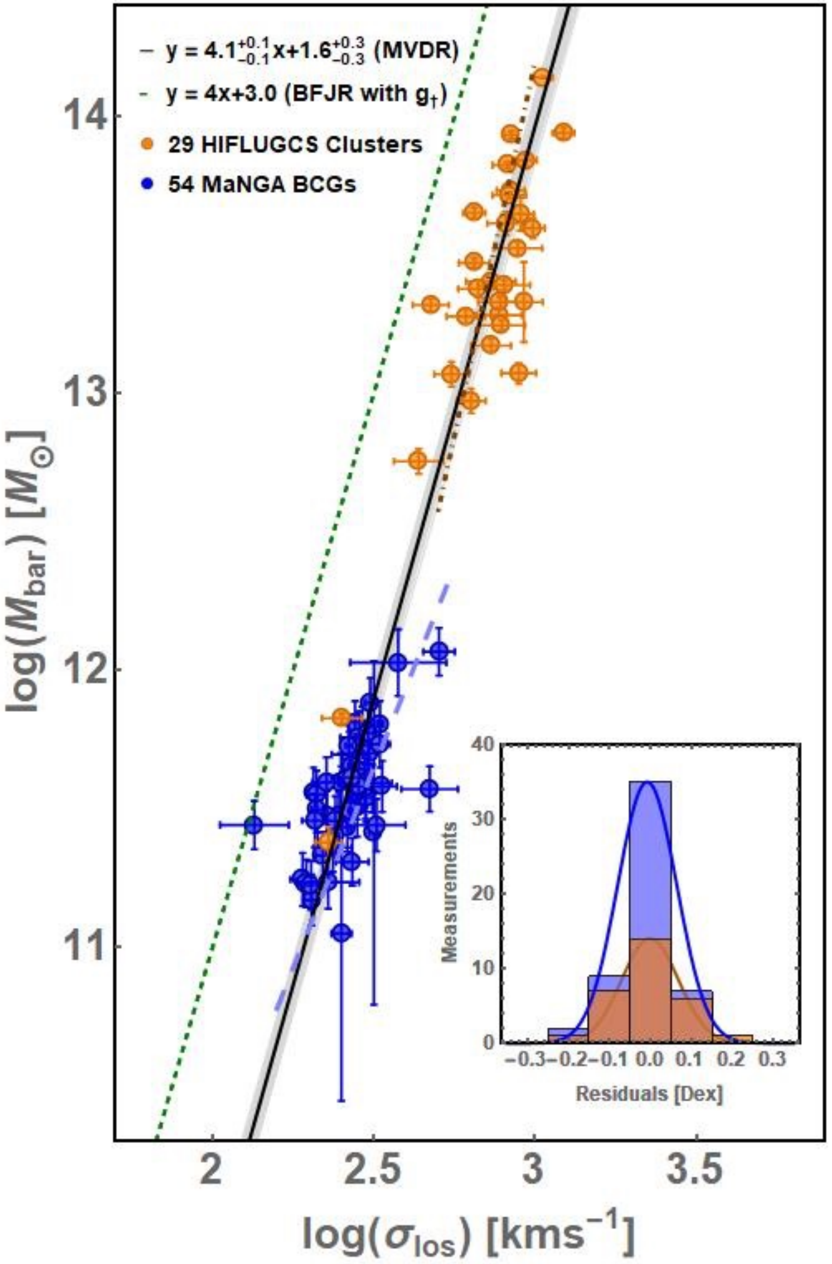
	Dynamics	Kinematics
Solar System	Newton's Law	Kepler's Law
Spirals	RAR	Tully-Fisher
Ellipticals	RAR	Faber-Jackson
BCG-Cluster	CLASH RAR	MVDR

Remarks

1. **Nearly flat velocity dispersion profiles have been observed in both MaNGA Brightest Cluster Galaxies (BCGs) and HIFLUGCS clusters.**
2. **A distinct Radial Acceleration Relation (RAR), is represented as $\mathbf{g}_{\mathbf{tot}} = \sqrt{\mathbf{g}_{\mathbf{bar}}\,\mathbf{g}_{\ddagger}}$, with $\mathbf{g}_{\ddagger} = (\mathbf{2.0} \pm \mathbf{0.1})\times\mathbf{10}^{-\mathbf{9}}\boldsymbol{m}\boldsymbol{s}^{-\mathbf{2}}$, is unveiled through the data gathered from 50 MaNGA BCGs, 20 CLASH BCGs, and 20 CLASH clusters with a tiny intrinsic scatter.**
3. **A Mass-Velocity Dispersion Relation, also known as a parallel Faber-Jackson Relation, is demonstrated by 50 MaNGA BCGs and 29 HIFLUGCS clusters. The relation aligns with the implications of the RAR on BCG-cluster scales.**

CLASH RAR & MVDR



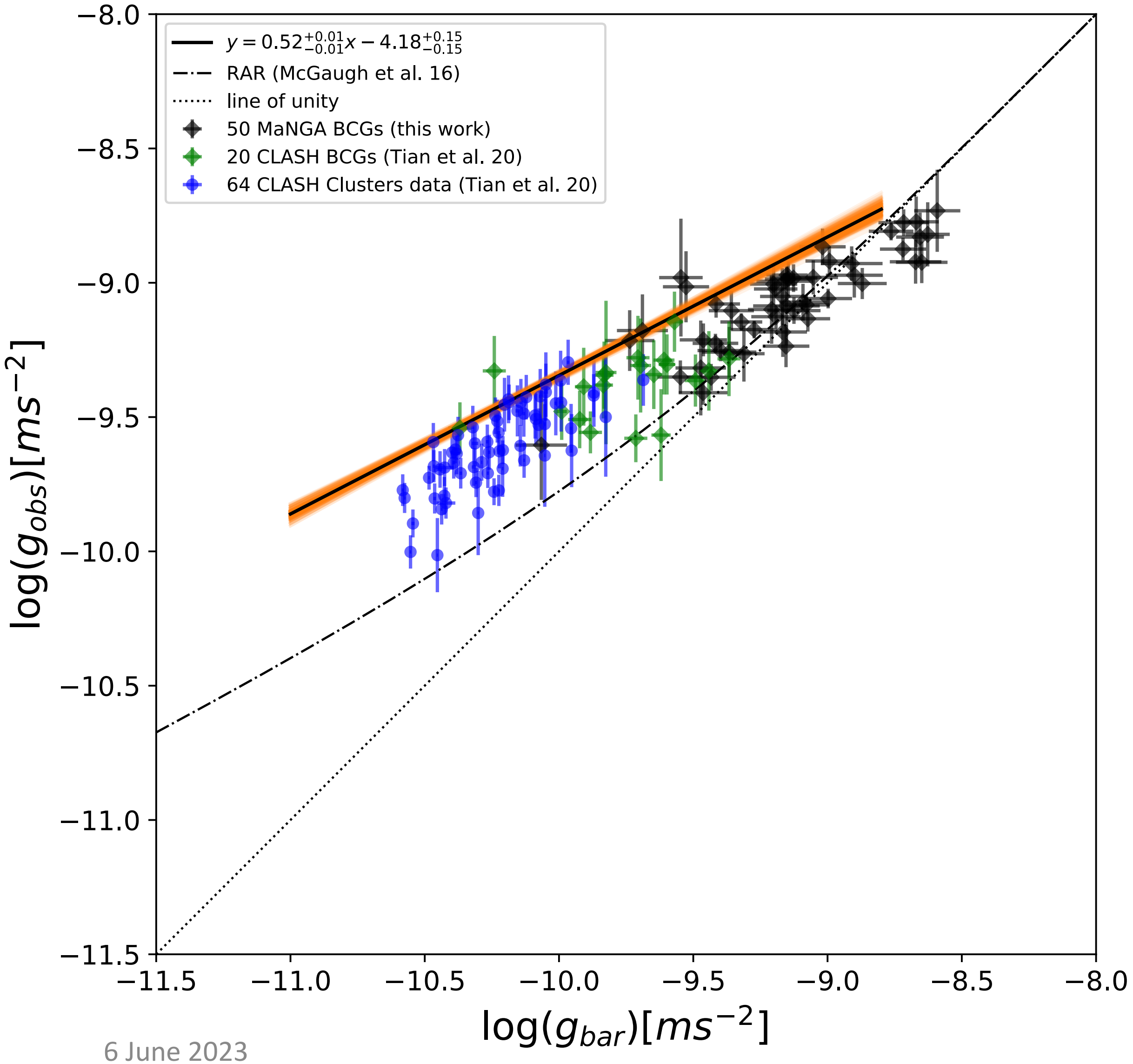


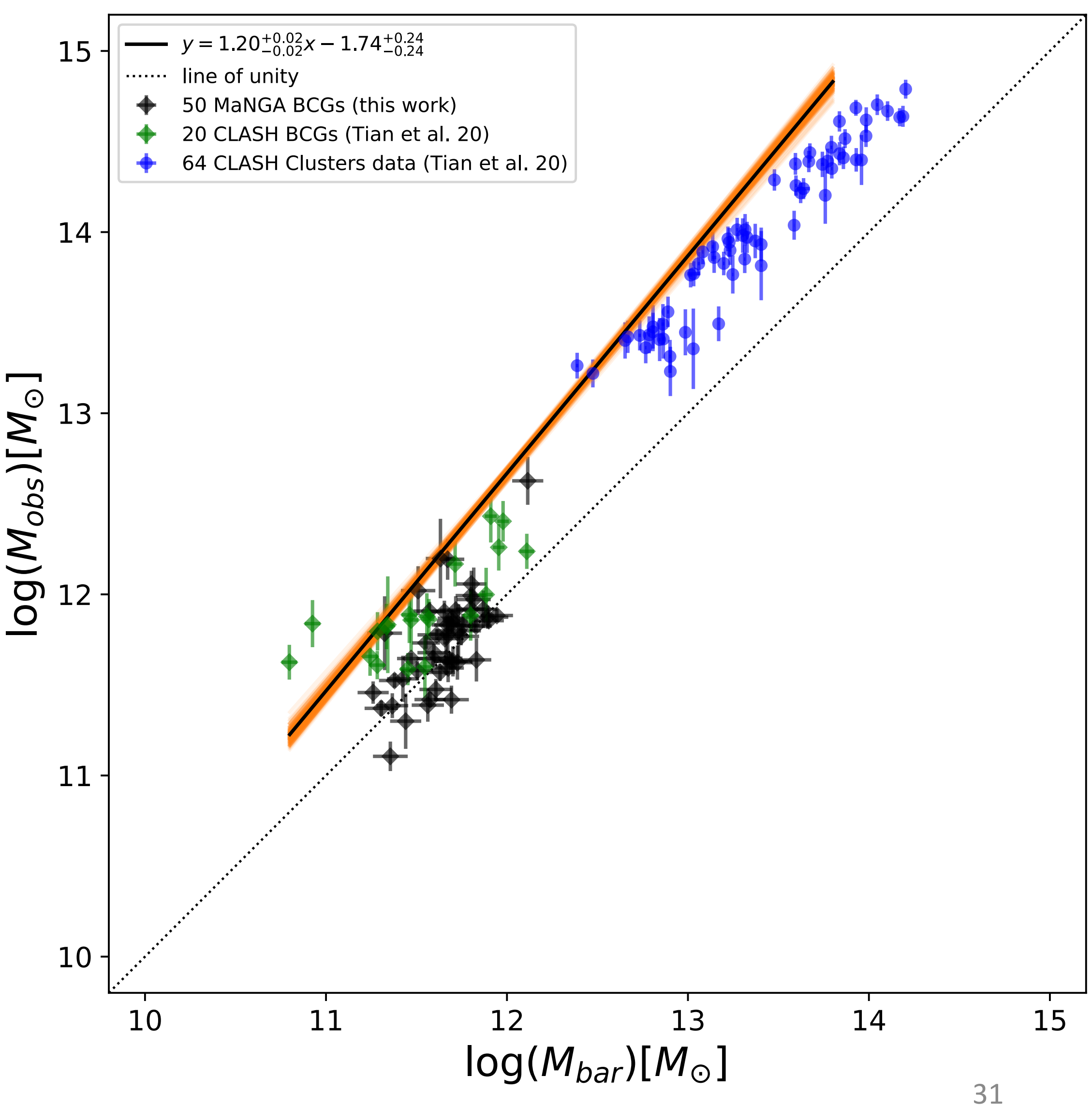
Tian et al. (2020), ApJ, 896, 70 ; Tian et al. (2023) submitted to ApJL

Tian et al. (2021b), ApJL, 917, L24

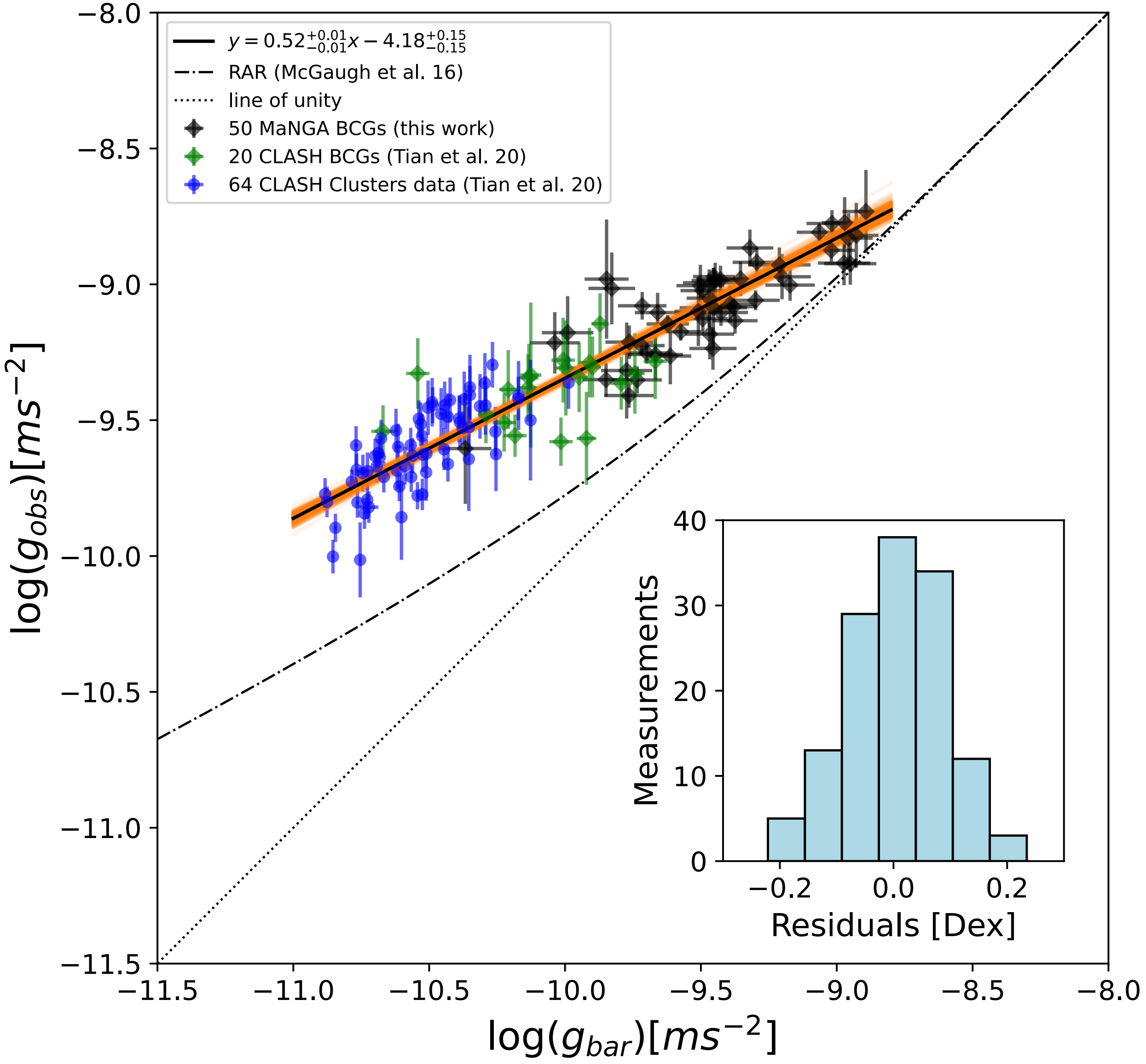
Q&A

Residual Missing Mass





Residual Missing Mass



$$\sqrt{g_{\text{bar}}\, g_{\ddagger}} \approx \frac{g_{\text{M}}}{1 - e^{-\sqrt{g_{\text{M}}/g_{\dagger}}}}.$$

The residual missing mass depends on baryonic acceleration.

For examples,

If $g_{bar} = 2.1\times10^{-10} ms^{-2}, M_M/M_{bar} \approx 2.7;$
If $g_{bar} = 1.3\times10^{-11} ms^{-2}, M_M/M_{bar} \approx 7.3.$

Tian et al. (2020), ApJ, 896, 70

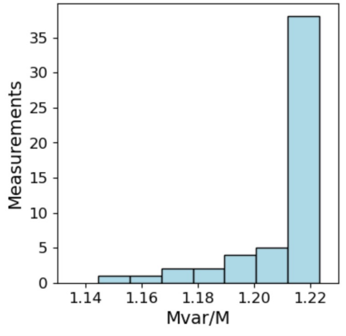
M_*/L Gradient

Table 1. Parameter values for M/L gradient strength (equation 2) driven by different assump about the IMF (fixed or variable) used in this study.

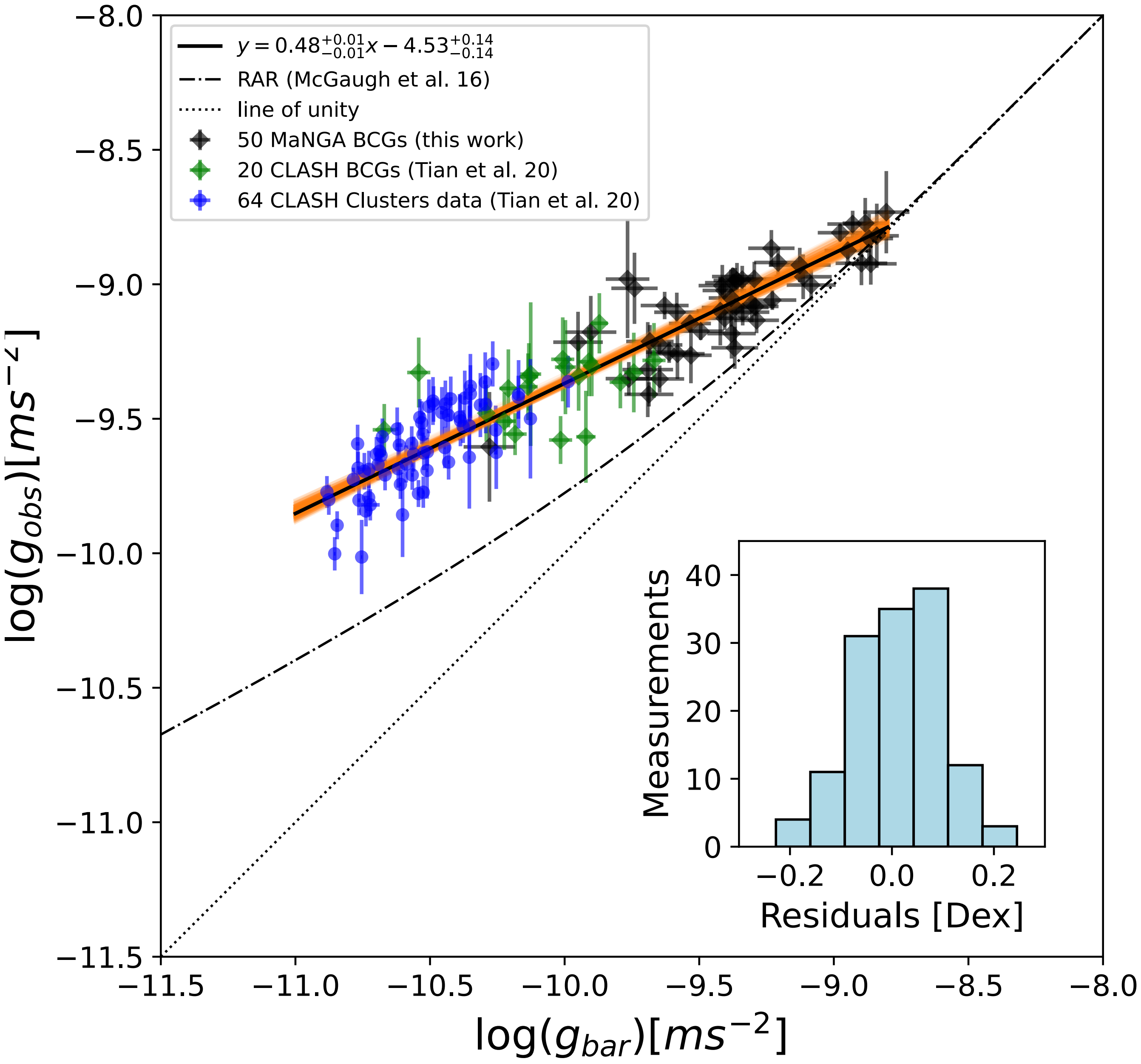
Model	IMF-var.	α	β	Source
Fixed IMF	No	0.39	1.00	Chabrier
$\text{Salp}^{\text{IN}}\text{-Chab}^{\text{OUT}}$	Yes	1.29	3.33	Salpeter-Chabrier
vD17	Yes	2.33	6.00	van Dokkum et al.

$$\Upsilon_*(R) = \Upsilon_{*0}\,(1 + \alpha - \beta\, R/R_e) \quad \text{if} \quad R/R_e \leq \alpha/\beta,$$

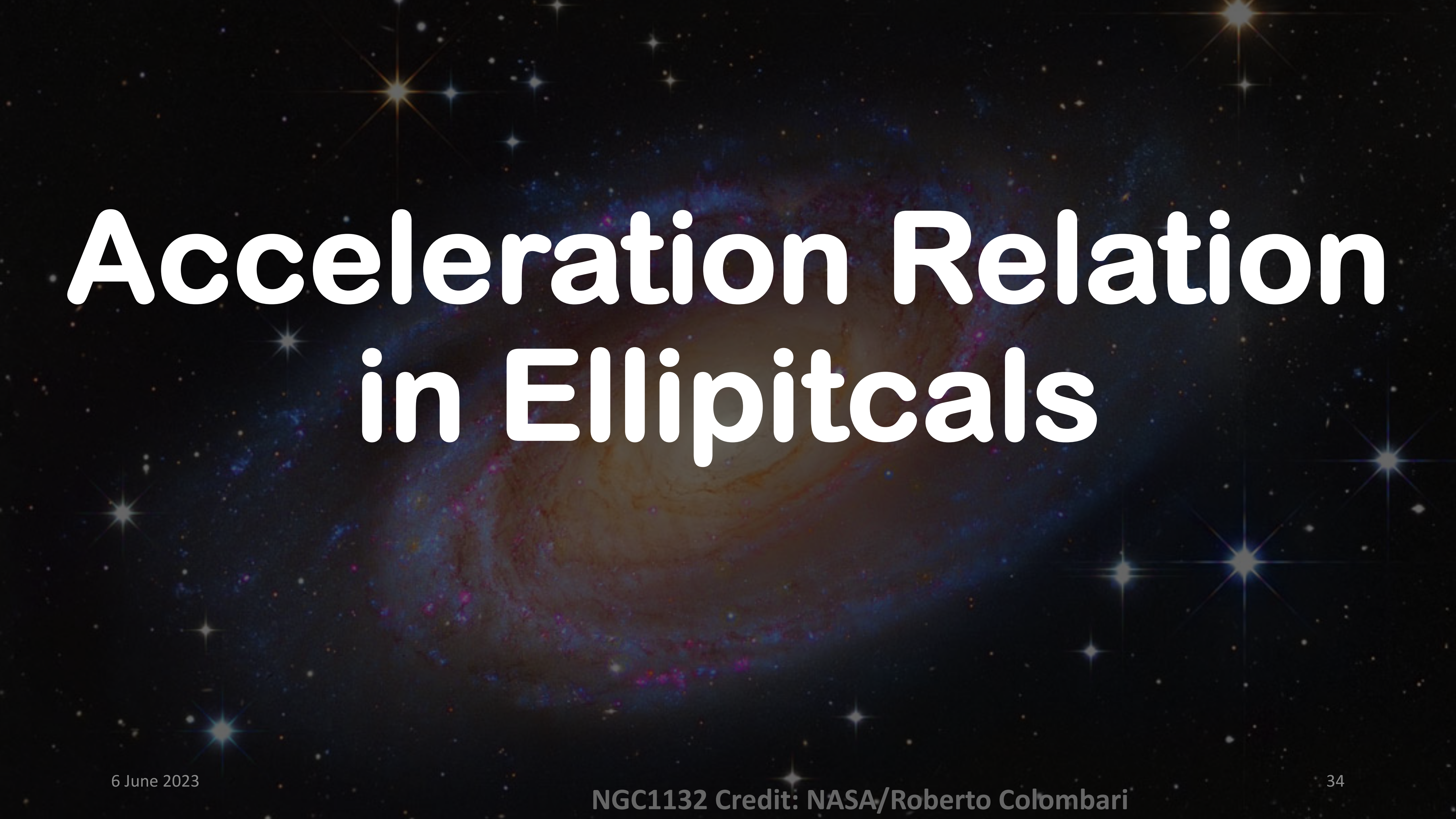
$$M_\infty \equiv 2\pi \int_0^\infty dR\, R\, J(R) = \Upsilon_{*0} L\, (1 + g(n, \alpha, \beta)),$$



The baryonic mass is increased by around 10-20%.



Acceleration Relation in Ellipitcals



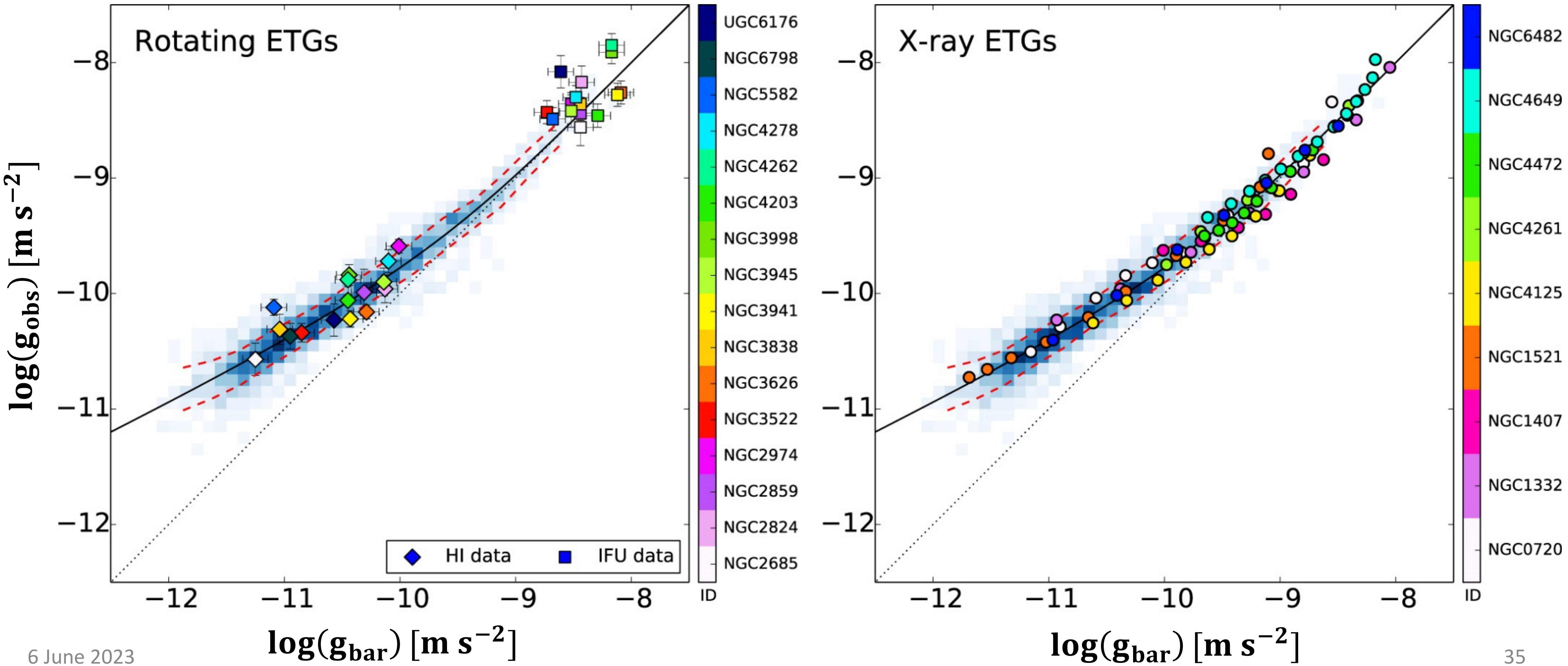
NGC1132 Credit: NASA/Roberto Colombari

The Astrophysical Journal, 836:152 (23pp), 2017 February 20
https://doi.org/10.3847/1538-4357/836/2/152

One Law to Rule Them All: The Radial Acceleration Relation of Galaxies

Federico Lelli[1,2,5], Stacy S. McGaugh[1], James M. Schombert[3], and Marcel S. Pawlowski[1,4,6]

Radial Acceleration Relation



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 488, L41–L46 (2019)
doi:10.1093/mnrasl/slz095

Halo acceleration relation

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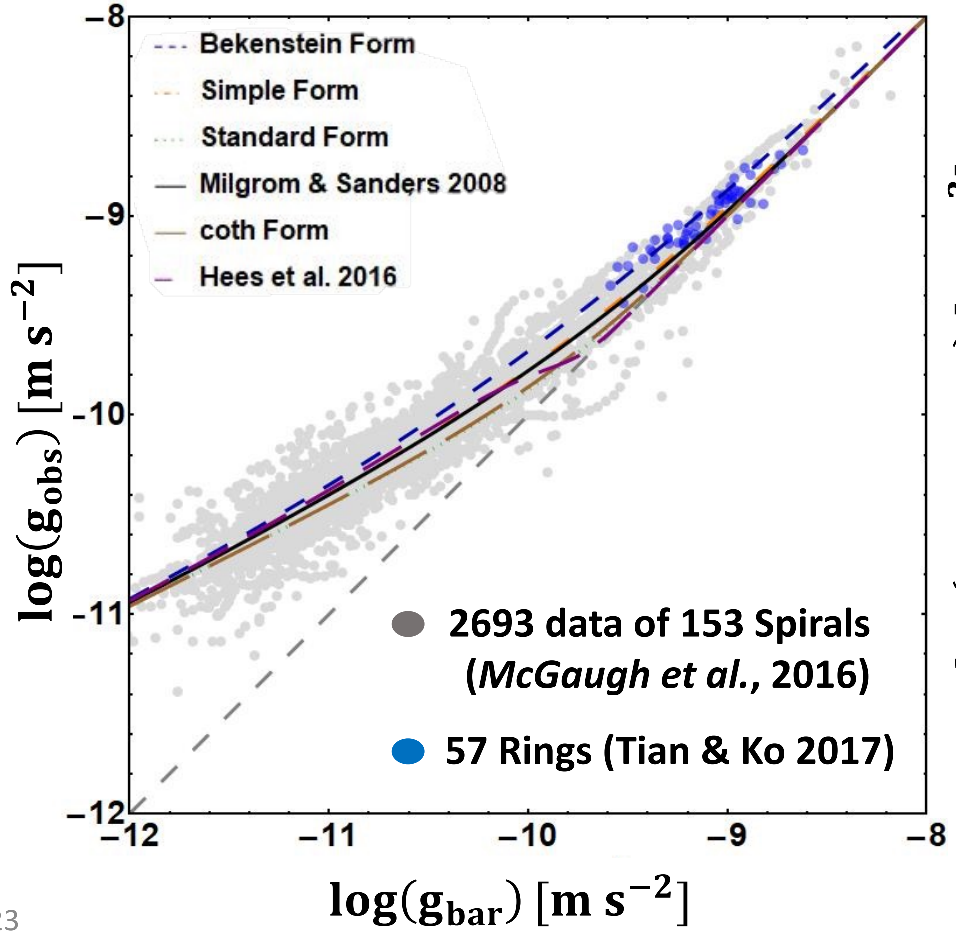
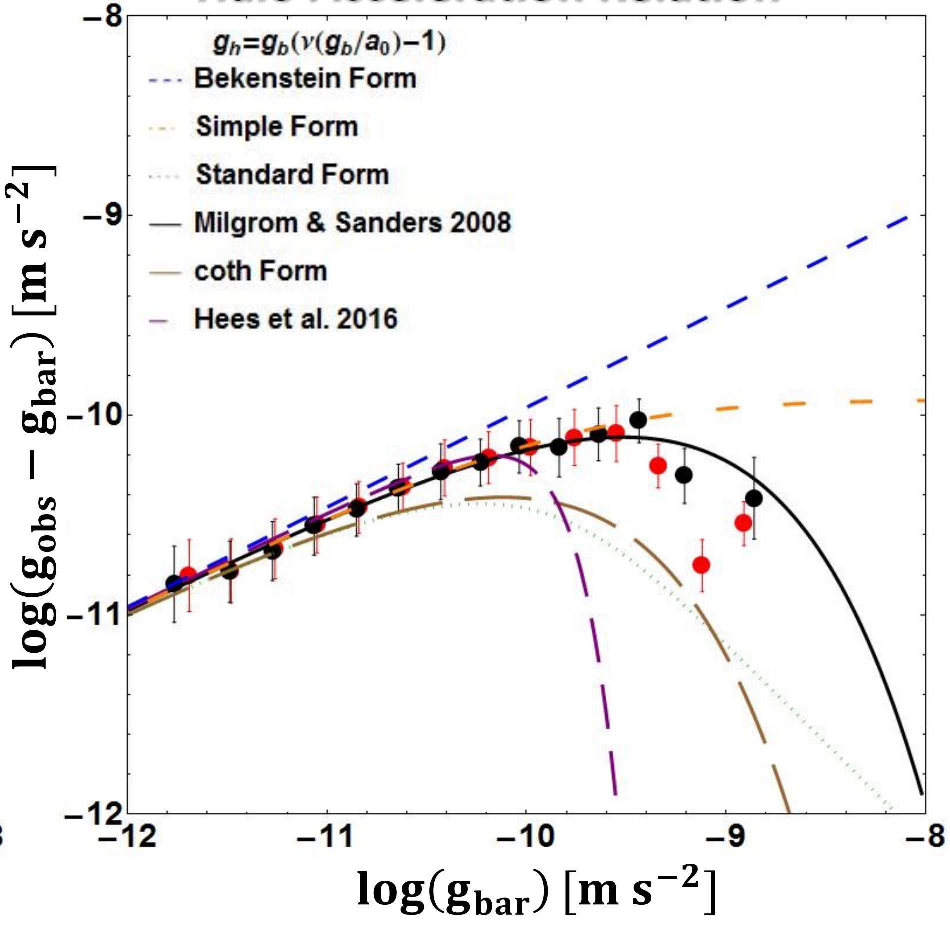
Radial Acceleration Relation



Halo Acceleration Relation



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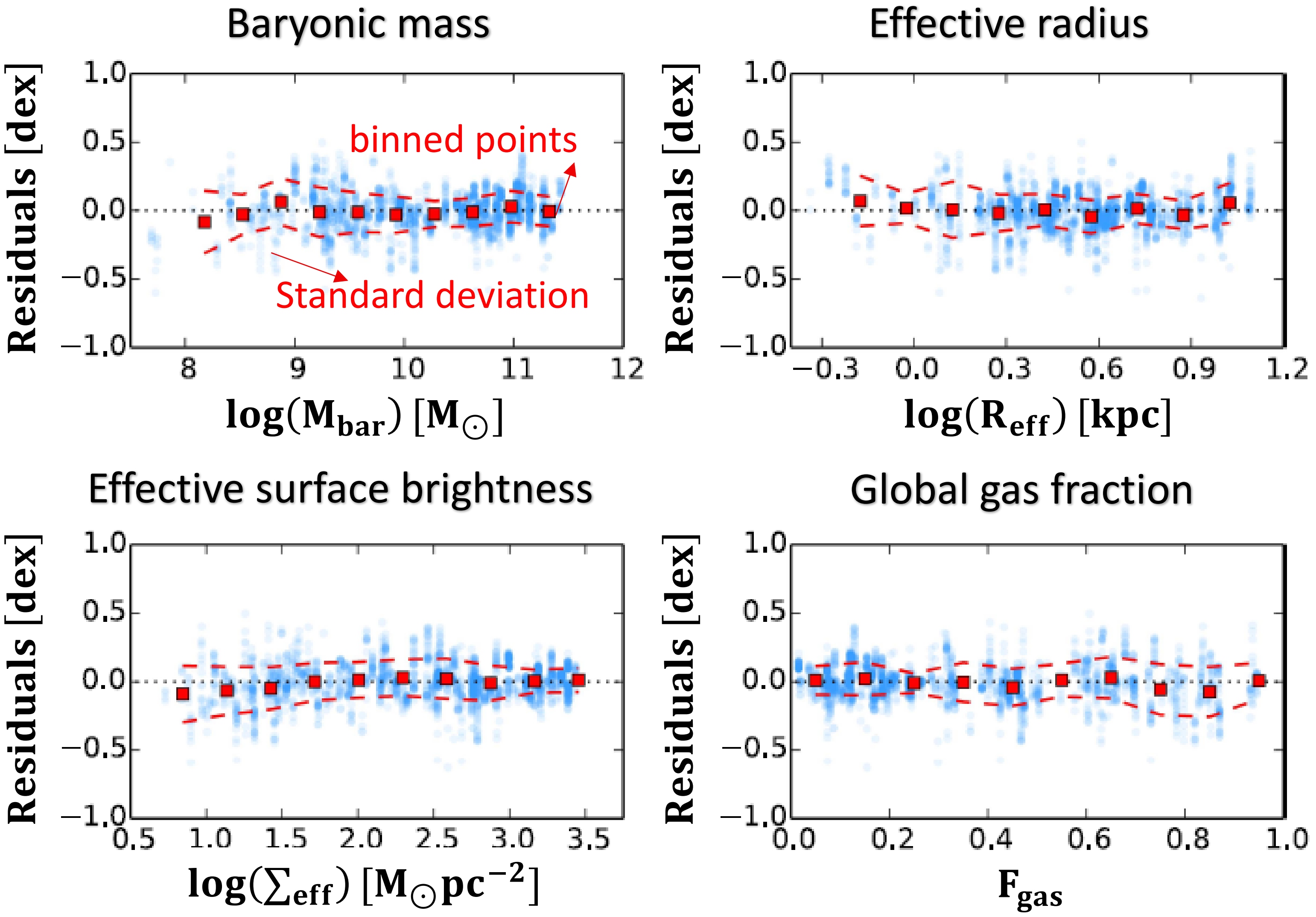
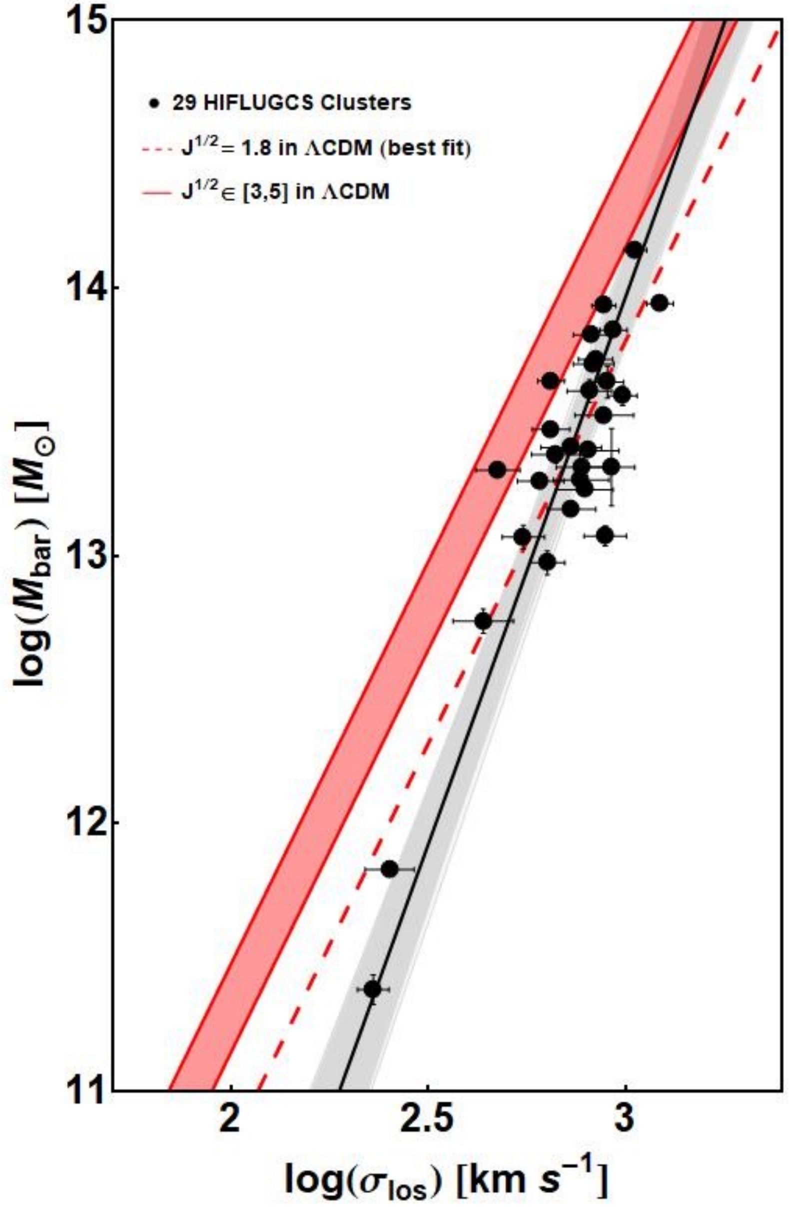
One Law to Rule Them All: The Radial Acceleration Relation of Galaxies

Federico Lelli[1,2,5], Stacy S. McGaugh[1], James M. Schombert[3], and Marcel S. Pawlowski[1,4,6]



The vertical clumps of data are due to individual objects: each galaxy contributes with several points to the RAR.

Implication in ΛCDM Model



The enclosed total mass within the radius in ΛCDM model is given by (Mo et al. 1998)

$$M_\Delta = \frac{4\pi}{3}(\Delta\rho_{crit})r_\Delta^3$$

Where $\rho_{crit}=3H_0^2/8\pi G$ is the critical density of the universe.

To relate the DM mass with velocity dispersion, we consider the gravitational potential traced by the velocity dispersion as

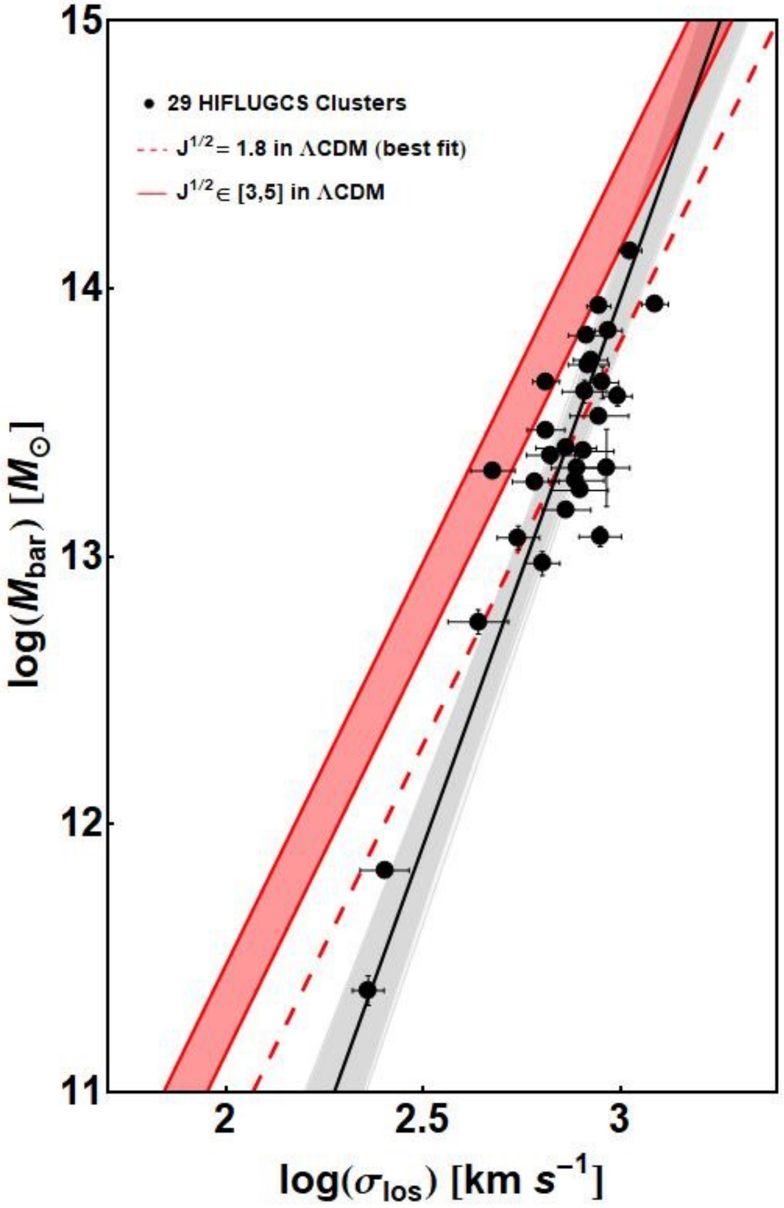
$$\frac{\mathrm{GM}_\Delta}{r_\Delta^2} = \frac{J^{1/2}\sigma^2}{r_\Delta}$$

Thus, we have

$$M_\Delta = \frac{\sqrt{2}J^{3/4}}{\sqrt{\Delta}GH_0}\sigma^3$$

Tian et al. (2021a), ApJ, 910, 56

Implication in ΛCDM Model



The ΛCDM model in pressure supported systems gives the dynamical MVDR as

$$M_{500} \propto \sigma_{los}^3$$

By adopting the cosmic baryon faction, we have

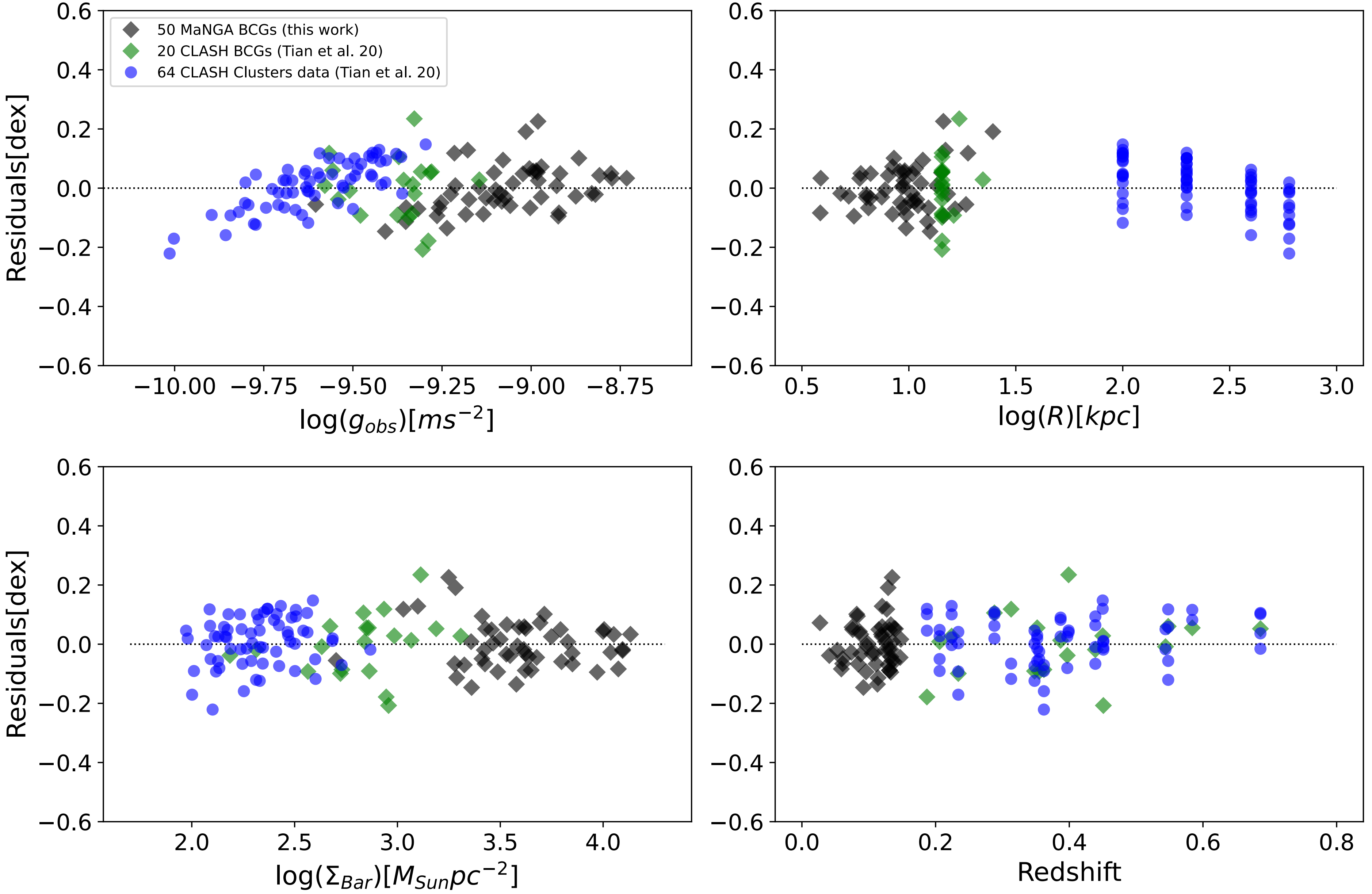
$$f_{bar} = M_{bar}/M_{500}$$

Thus, ΛCDM model predicts different slope comparing with the empirical MVDR

$$M_{bar} \propto \sigma_{los}^3$$

$$\log(M_{\rm bar}) = 3\log(\sigma_{\rm los}) + \log\left(\frac{\sqrt{2}\,J^{3/4} f_{\rm bar}}{\sqrt{500}\,GH_0}\right).$$

Tian et al. (2021a), ApJ, 910, 56



Tian et al. (2023) submitted to ApJL

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The Radial Acceleration Relation in CLASH Galaxy Clusters

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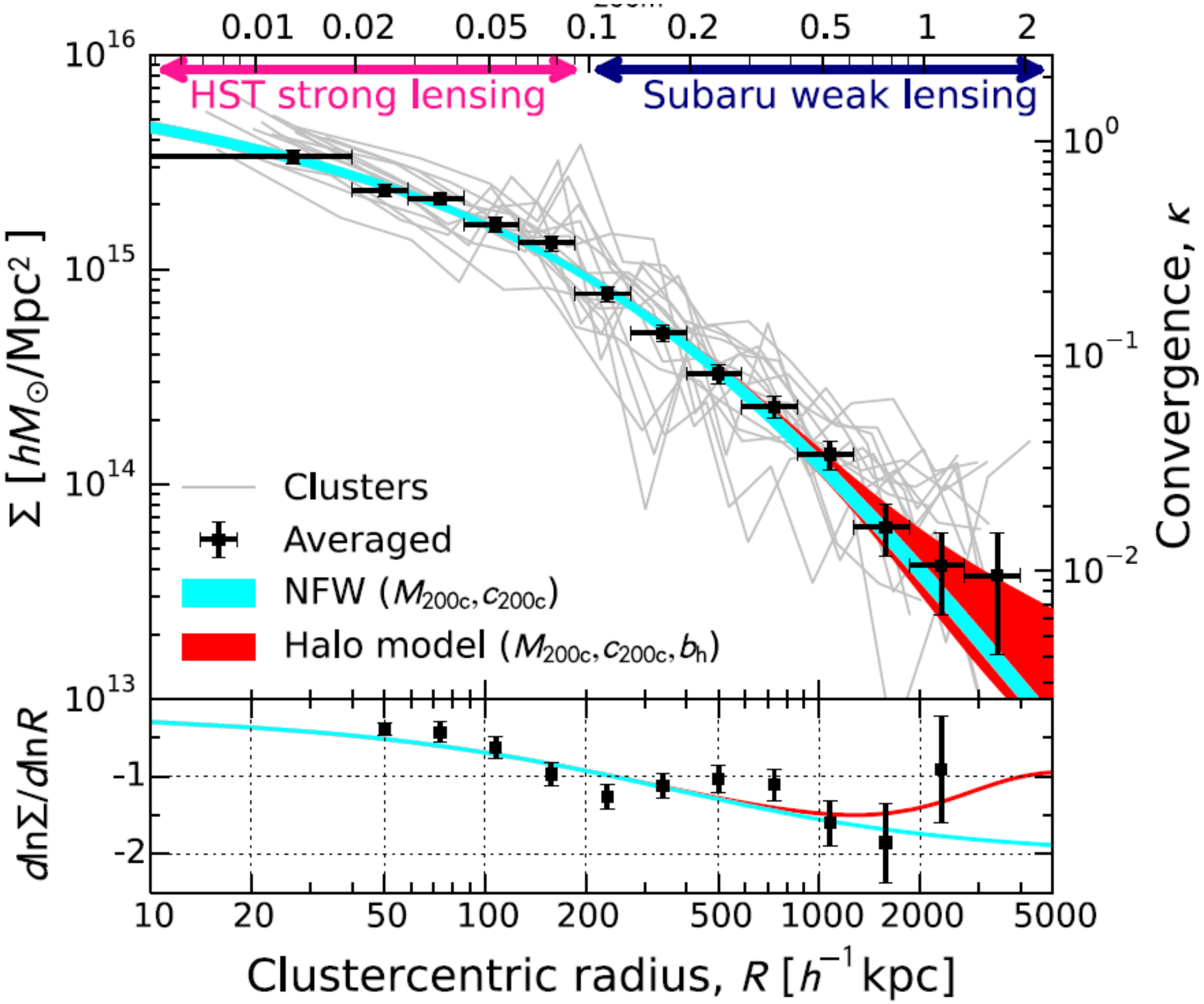

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