中央大學天文研究所
Graduate Institute of Astronomy, NCU

The Radial Acceleration Relation in CLASH Galaxy Clusters

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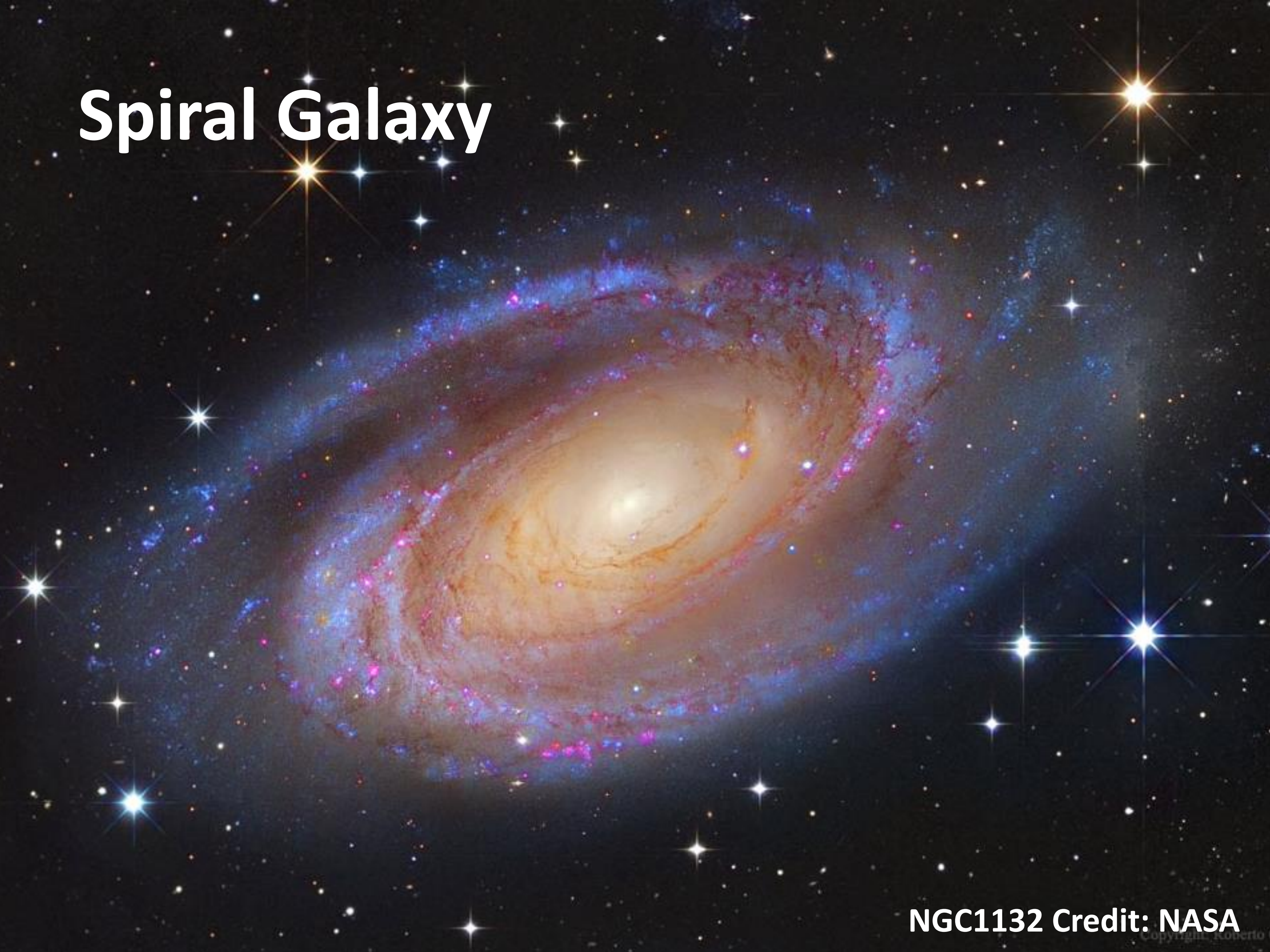
24 April, VIA

Outline

- **Flat Rotation Curve**
- **Radial Acceleration Relation (RAR)**
  - four issues
  - three possibilities
- **CLASH RAR in galaxy clusters**
  - four issues
  - prediction for the kinematic scaling relation
  - semi-analytical model
  - implications for residual missing mass in MOND
- **Remarks**

Spiral Galaxy



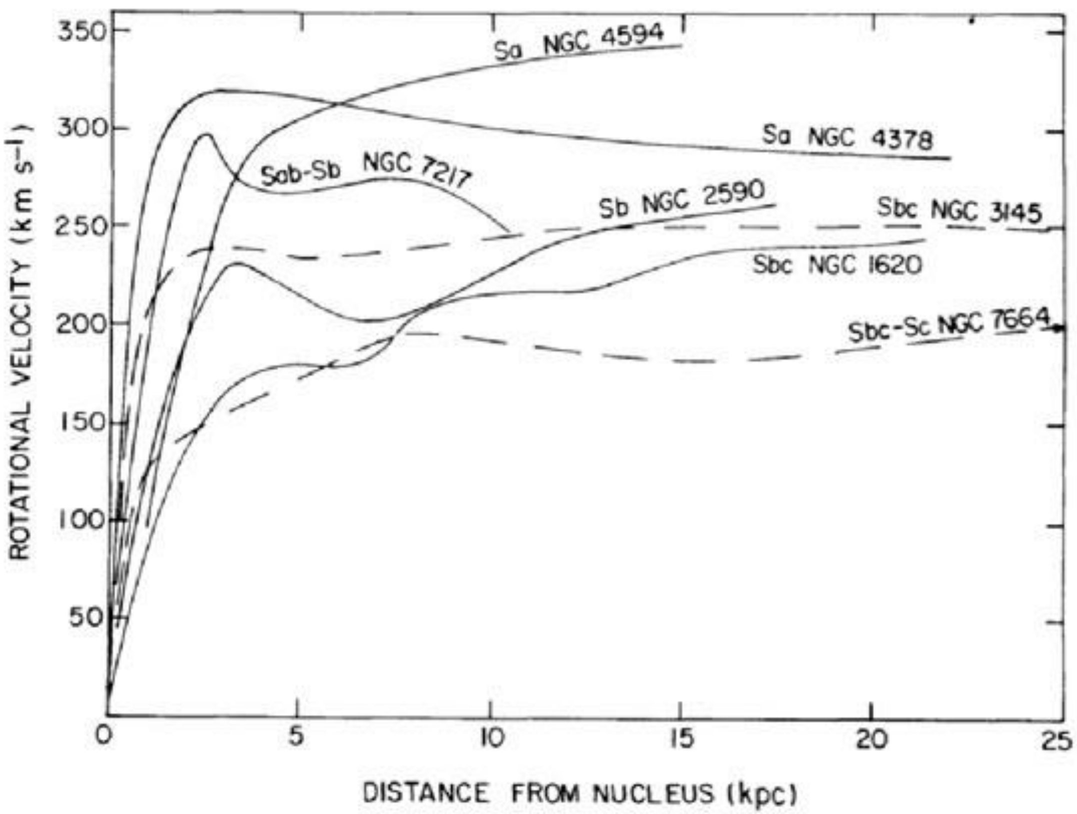
NGC1132 Credit: NASA

Flat Rotation Curve

Vera Rubin

Albert Bosma

$$\frac{v^2}{r} = \frac{GM}{r^2} \rightarrow \quad v \propto \frac{1}{\sqrt{r}}$$



Rubin et al. ApJL (1978)

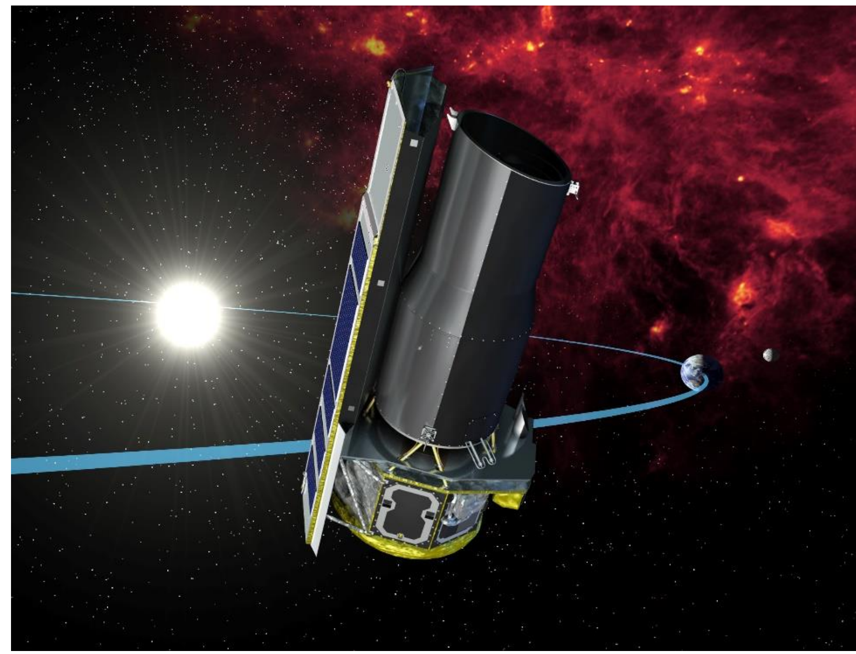
Tight Relation in the "Missing Mass" Problem?

NGC1132 Credit: NASA

SPARC

Spitzer Photometry & Accurate Rotation Curves

- SPARC: 175 spiral galaxies
- Dynamical mass
  - HI/Hα rotation curves
- Baryonic mass
  - Gas mass (HI gas)
  - Stellar mass (NIR 3.6 μm)



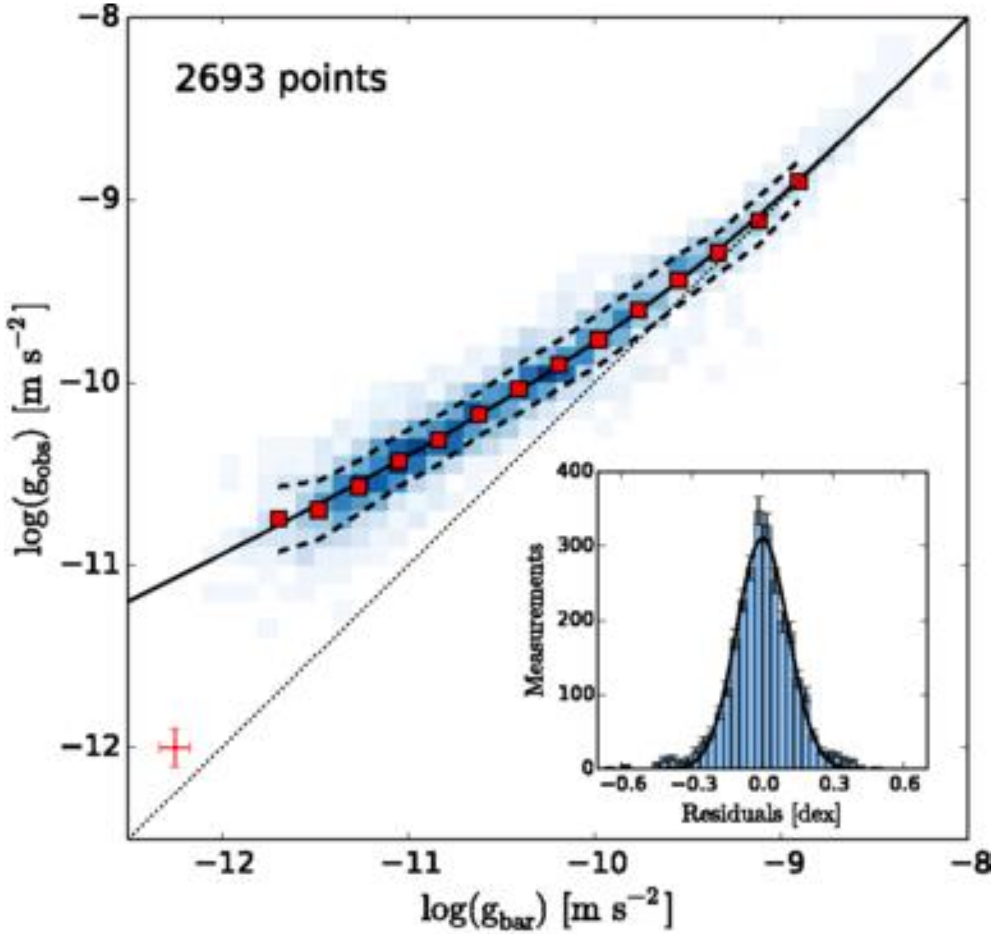
Spitzer Space Telescope

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
Department of Astronomy, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, Ohio 44106, USA

James M. Schombert
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})**

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

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

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

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

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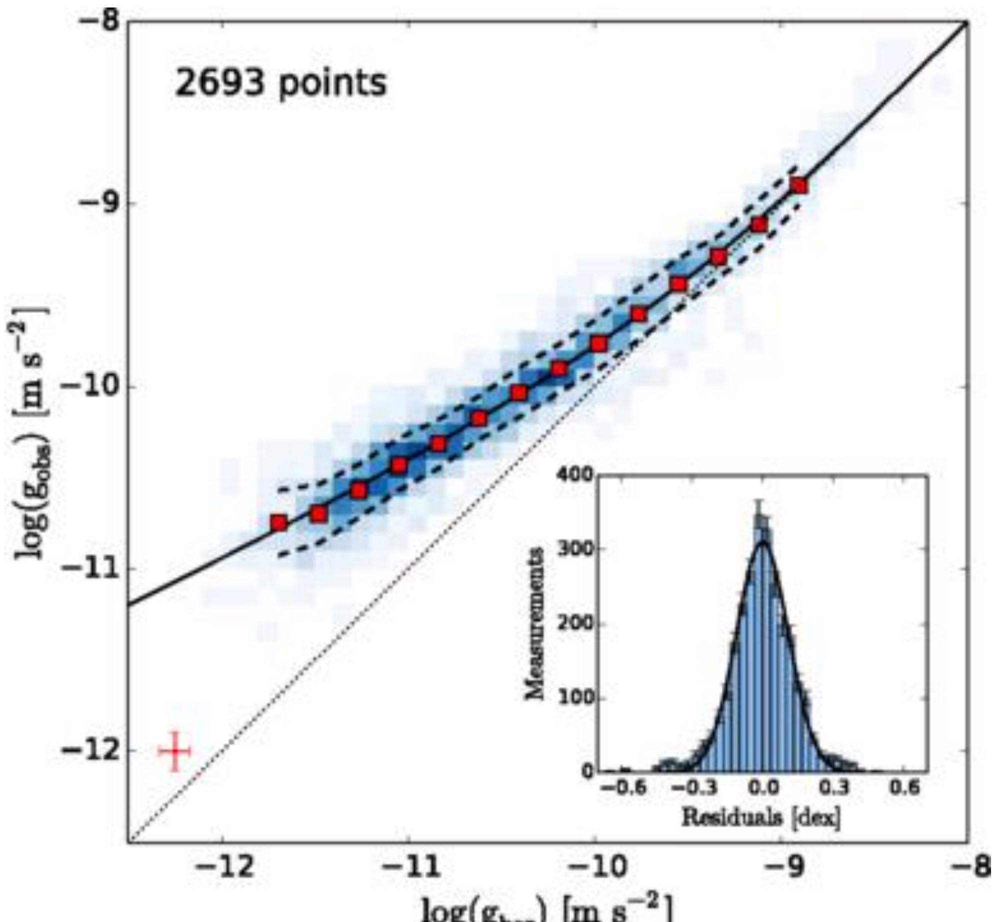
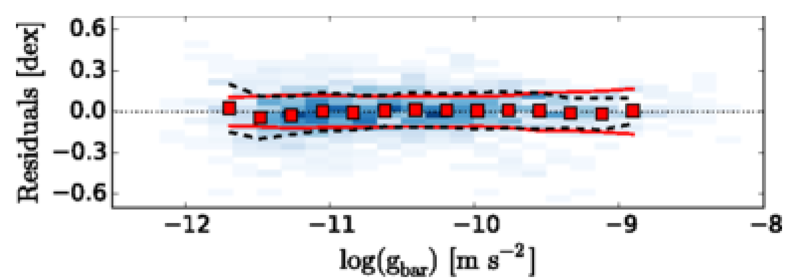


The tight relation gives

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

$$g_{\dagger} = (1.20 \pm 0.26) \times 10^{-10}\, ms^{-2}$$



RAR in Elliptical Galaxies

NGC1132 Credit: NASA

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]
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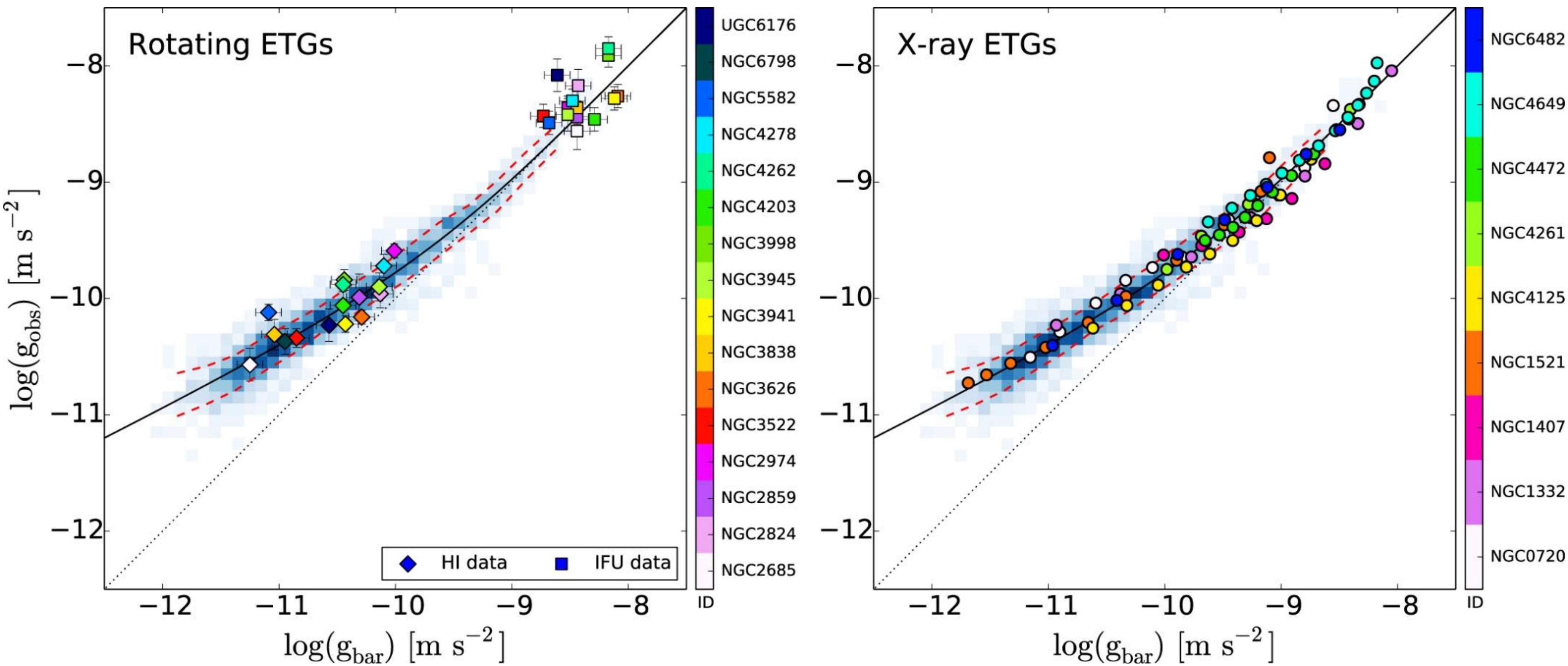
[4] Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
Received 2016 October 26; revised 2017 January 12; accepted 2017 January 12; published 2017 February 16



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

Halo acceleration relation

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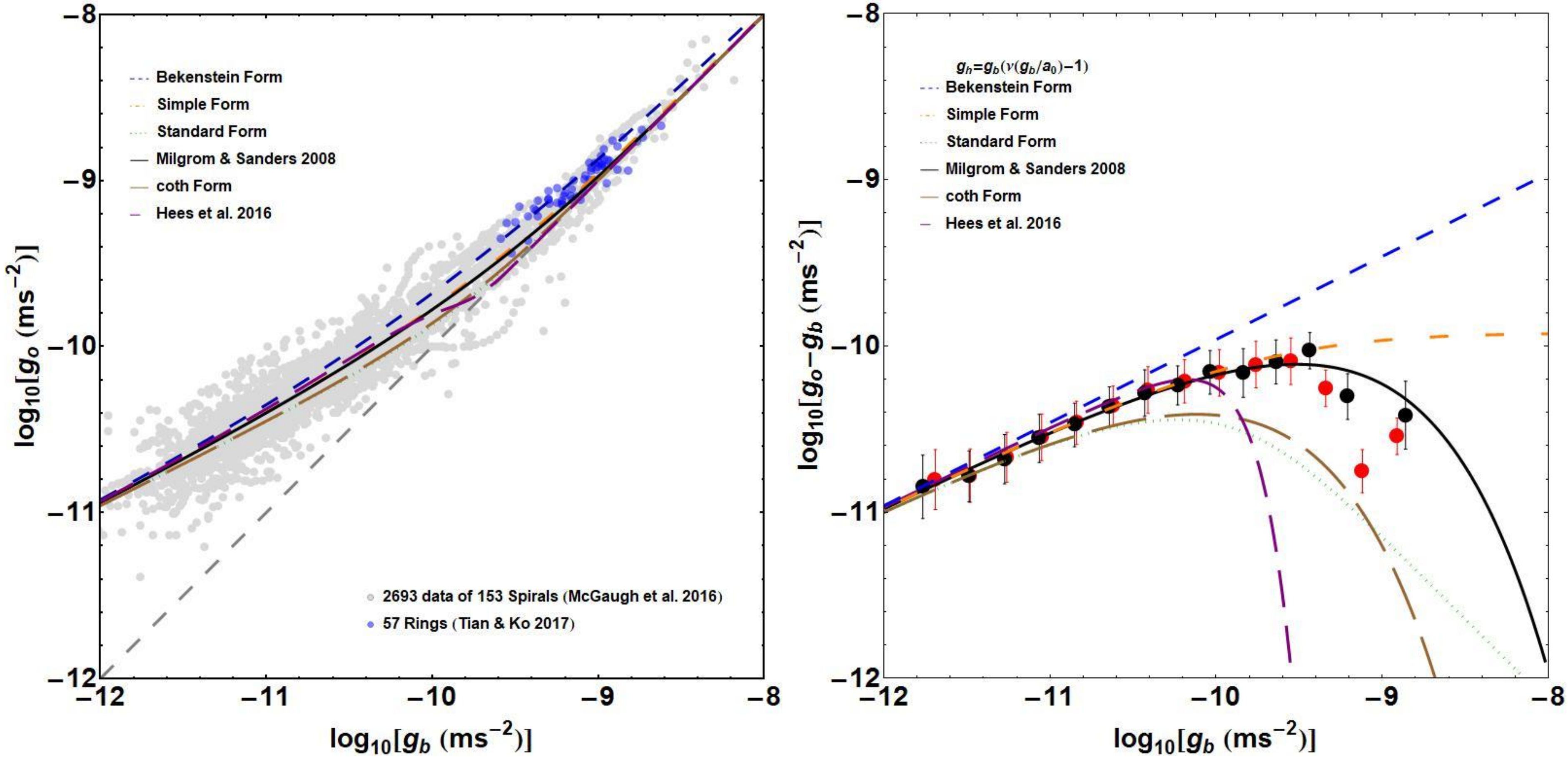


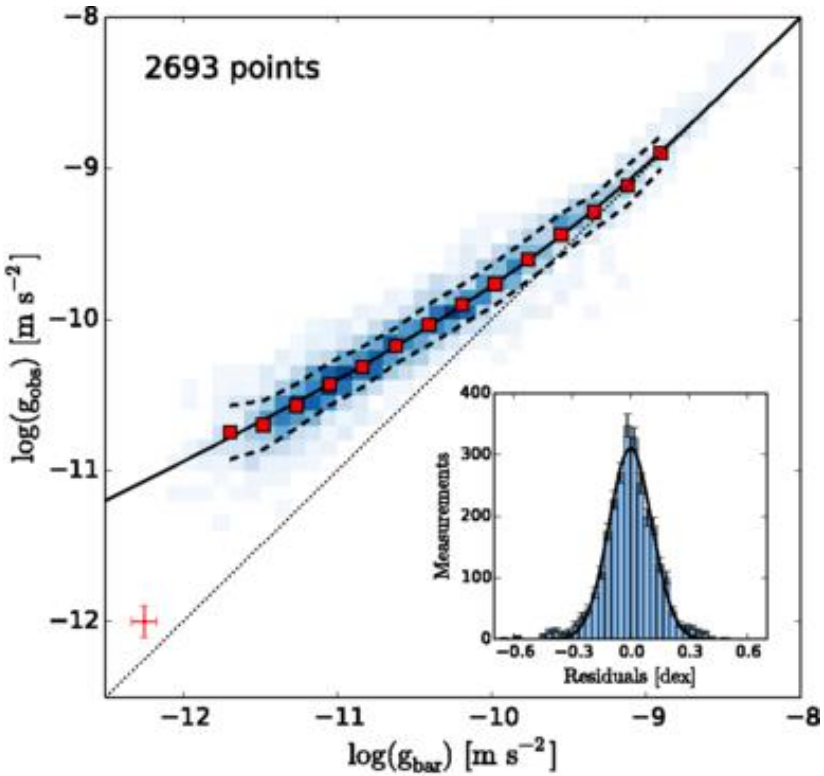
Four Issues from RAR

NGC1132 Credit: NASA

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **464**, 4160–4175 (2017) doi:10.1093/mnras/stw2571
Advance Access publication 2016 October 8

A statistical investigation of the mass discrepancy–acceleration relation

Harry Desmond[1,2★]
[1]*Kavli Institute for Particle Astrophysics and Cosmology and Physics Department, Stanford University, Stanford, CA 94305, USA*
[2]*SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA*



Four Issues:

(Desmond 2017; Lelli et al. 2017)

i. **The physical origin of the acceleration scale** $g_\dagger=1.20\times10^{-10}$ ms^{-2}**;**
ii. **The physical origin of the low-acceleration slope (0.5);**
iii. **The intrinsic tightness of the relation (<0.11 dex);**
iv. **The lack of correlations between residuals and other galaxy properties.**

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

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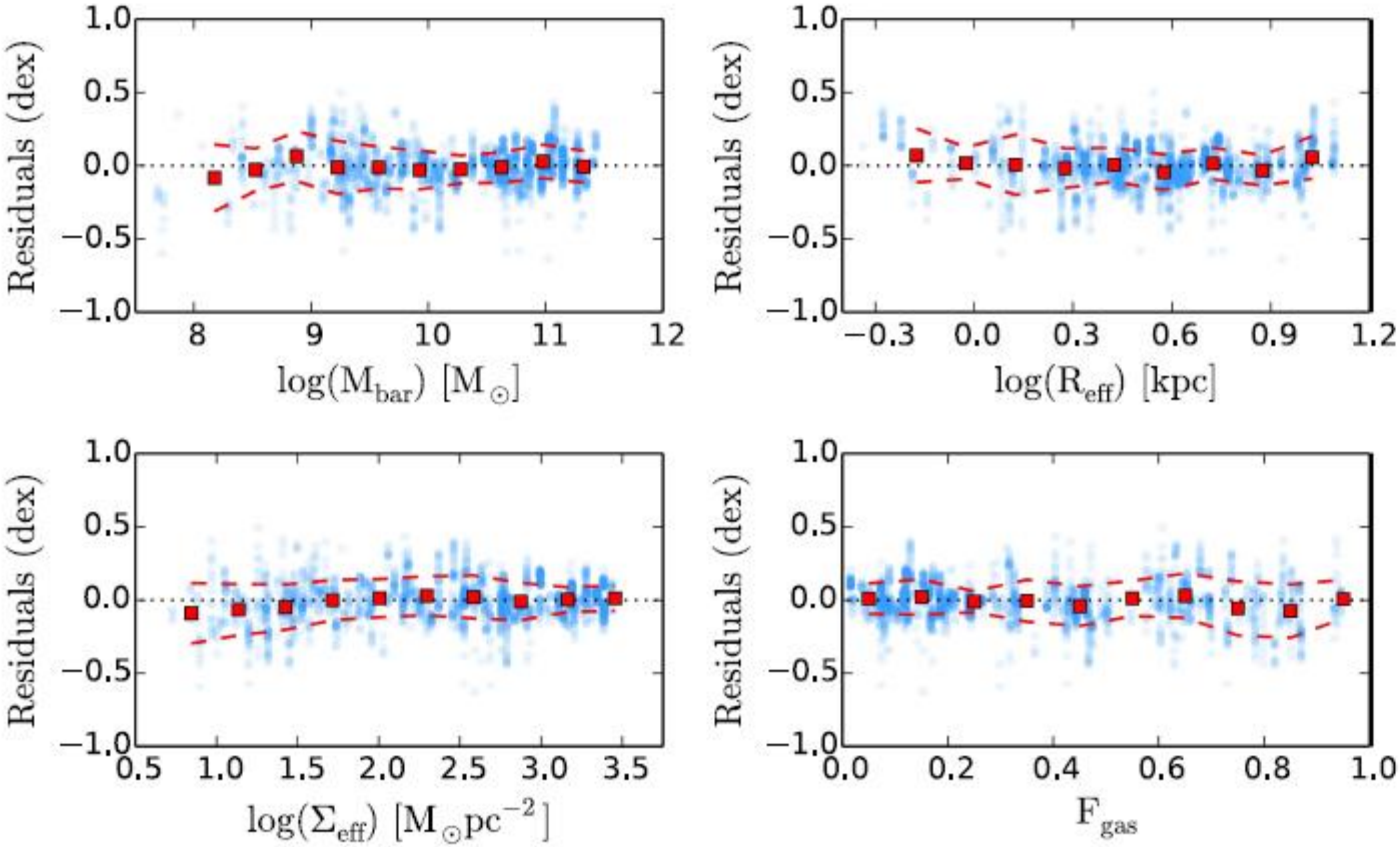

Figure 5. Residuals vs. baryonic mass (top left), effective radius (top right), effective surface brightness (bottom left), and global gas fraction (bottom right). Squares and dashed lines show the mean and standard deviation of binned residuals, respectively. The vertical clumps of data are due to individual objects: each galaxy contributes with several points to the radial acceleration relation.

THE ASTROPHYSICAL JOURNAL, 836:152 (23pp), 2017 February 20 https://doi.org/10.3847/1538-4357/836/2/152

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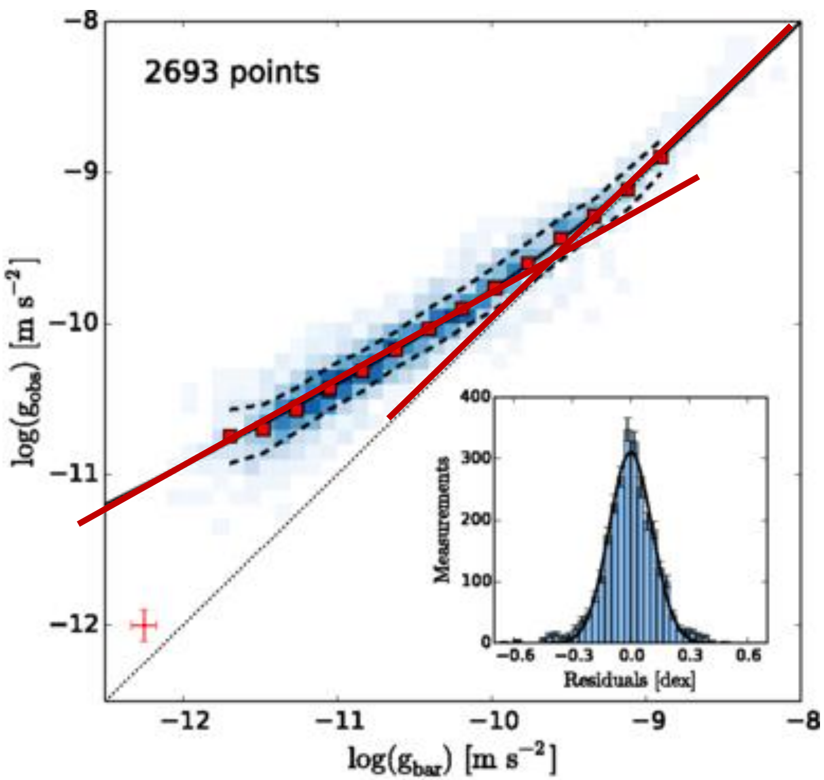


i. the acceleration scale $g_\dagger = 1.20\times10^{-10}$ ms^{-2};
turning point of two broken power laws

ii. the low-acceleration slope (0.5);

$$g_{obs} = (g_{bar}\, g_\dagger)^{1/2}$$

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

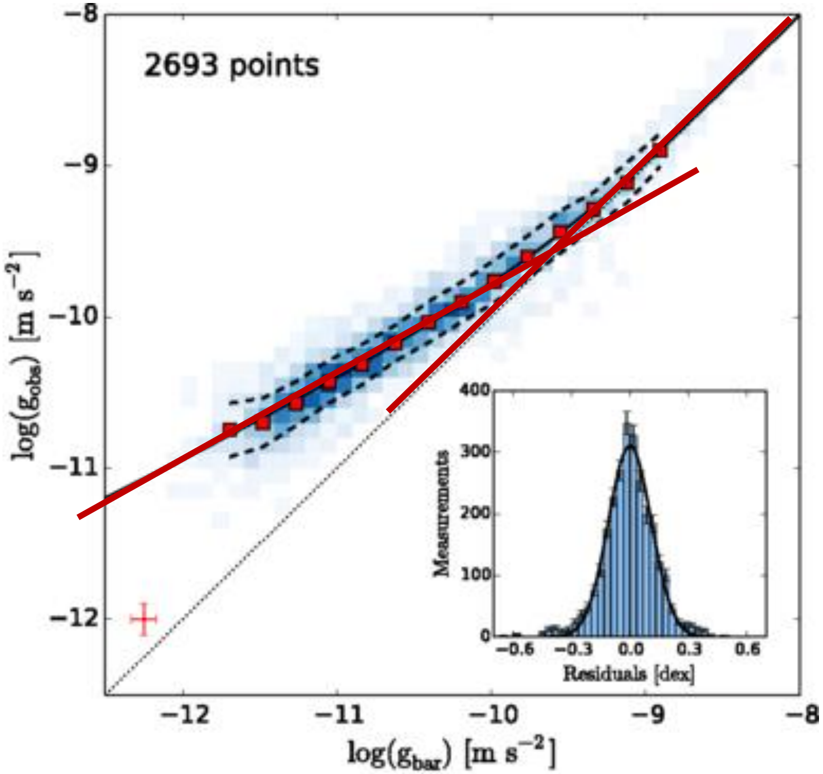
$$\rightarrow \frac{V^4}{r^2} = \frac{GM_{bar} g_\dagger}{r^2} \rightarrow V^4 = GM_{bar} g_\dagger$$

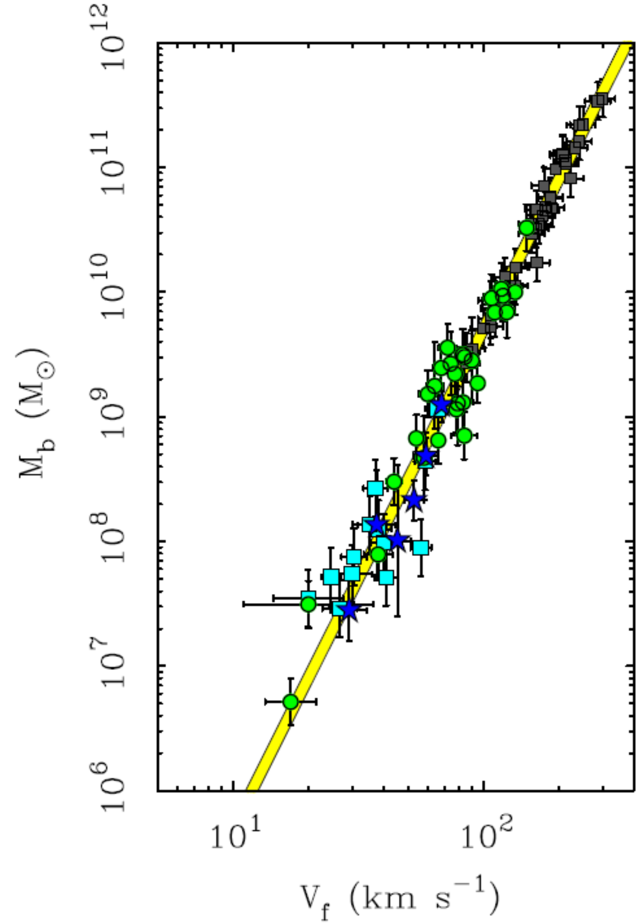
Baryonic Tully-Fisher Relation

The Astronomical Journal, 143:40 (15pp), 2012 February
doi:10.1088/0004-6256/143/2/40

THE BARYONIC TULLY–FISHER RELATION OF GAS-RICH GALAXIES AS A TEST OF ΛCDM AND MOND

Stacy S. McGaugh
Department of Astronomy, University of Maryland College Park, MD 20742-2421, USA
Received 2010 December 6; accepted 2011 December 7; published 2012 January 12





Dynamics & Kinematics

	Dynamics	Kinematics
Solar System	Newton’s Law	Kepler’s Law
Spirals	RAR	Tully-Fisher
Ellipticals	RAR	Faber-Jackson

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PRL **117,** 201101 (2016) PHYSICAL REVIEW LETTERS week ending 11 NOVEMBER 2016

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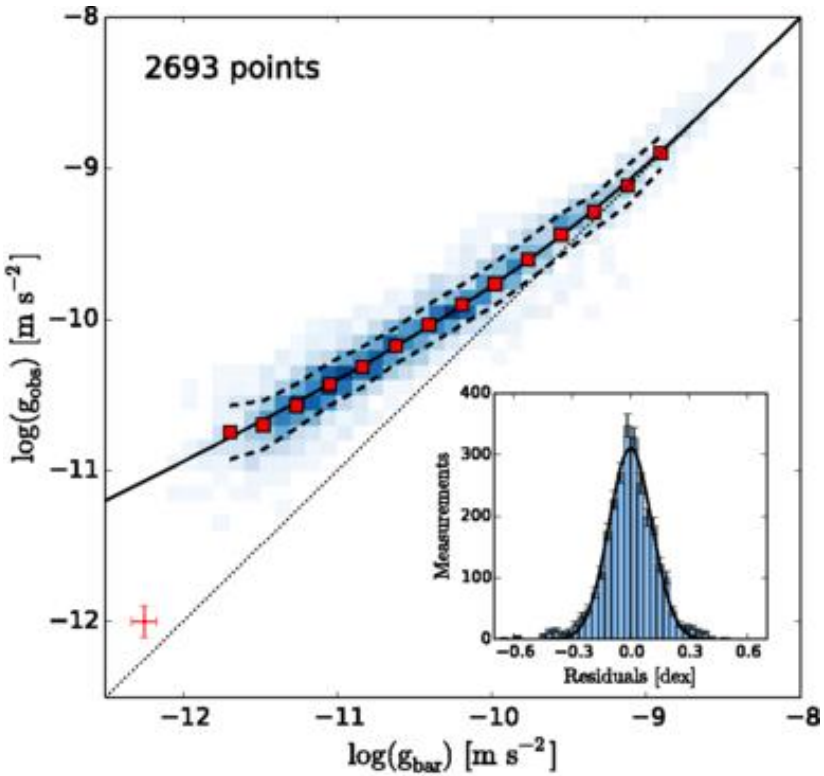

Three possible explanations:

(McGaugh et al. 2016; Lelli et al. 2017)

1. **Galaxy formation processes in the CDM model;**
   (hydro-dynamical simulation: Wu & Kroupa 2015; Ludlow et al. 2017; semi-empirical model: Di Cintio & Lelli 2016; Navarro et al. 2017; Desmond 2017)
2. **New “dark sector” physics;**
   (dipolar DM: Blanchet & Le Tiec 2008, 2009;
   dark-fluid: Zhao &Li 2010; Khoury 2015)
3. **New dynamical laws.**
   (Milgrom 1983)

THE ASTROPHYSICAL JOURNAL, 512:L23–L26, 1999 February 10

THE VIRIAL DISCREPANCY IN CLUSTERS OF GALAXIES IN THE CONTEXT OF MODIFIED NEWTONIAN DYNAMICS

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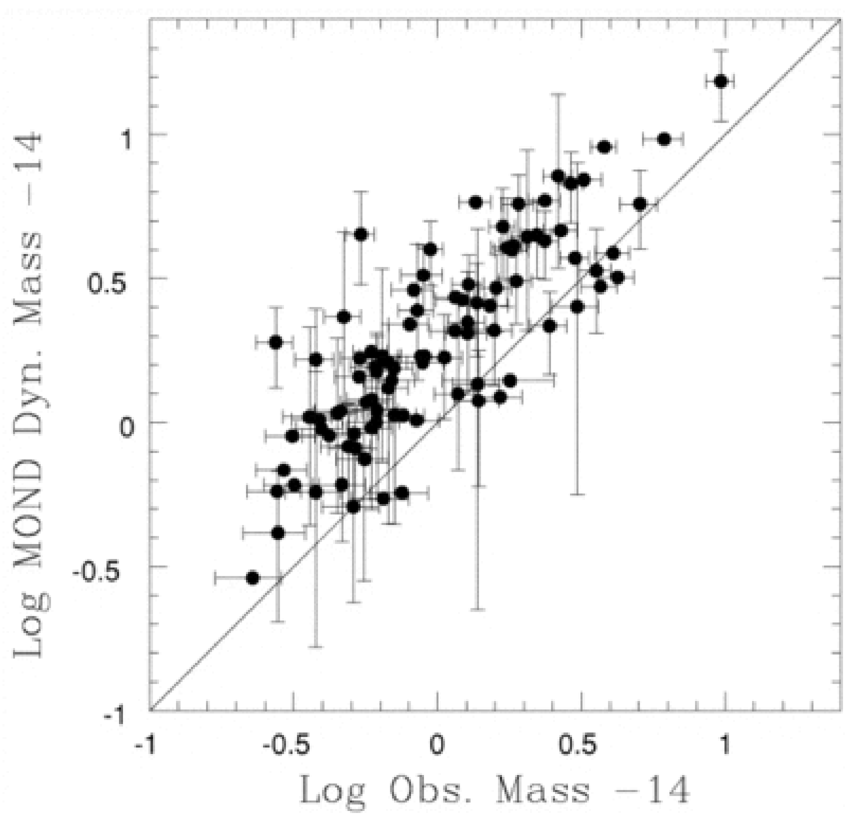
Received 1998 October 16; accepted 1998 December 9; published 1998 December 22



The residual missing mass in MOND in clusters:

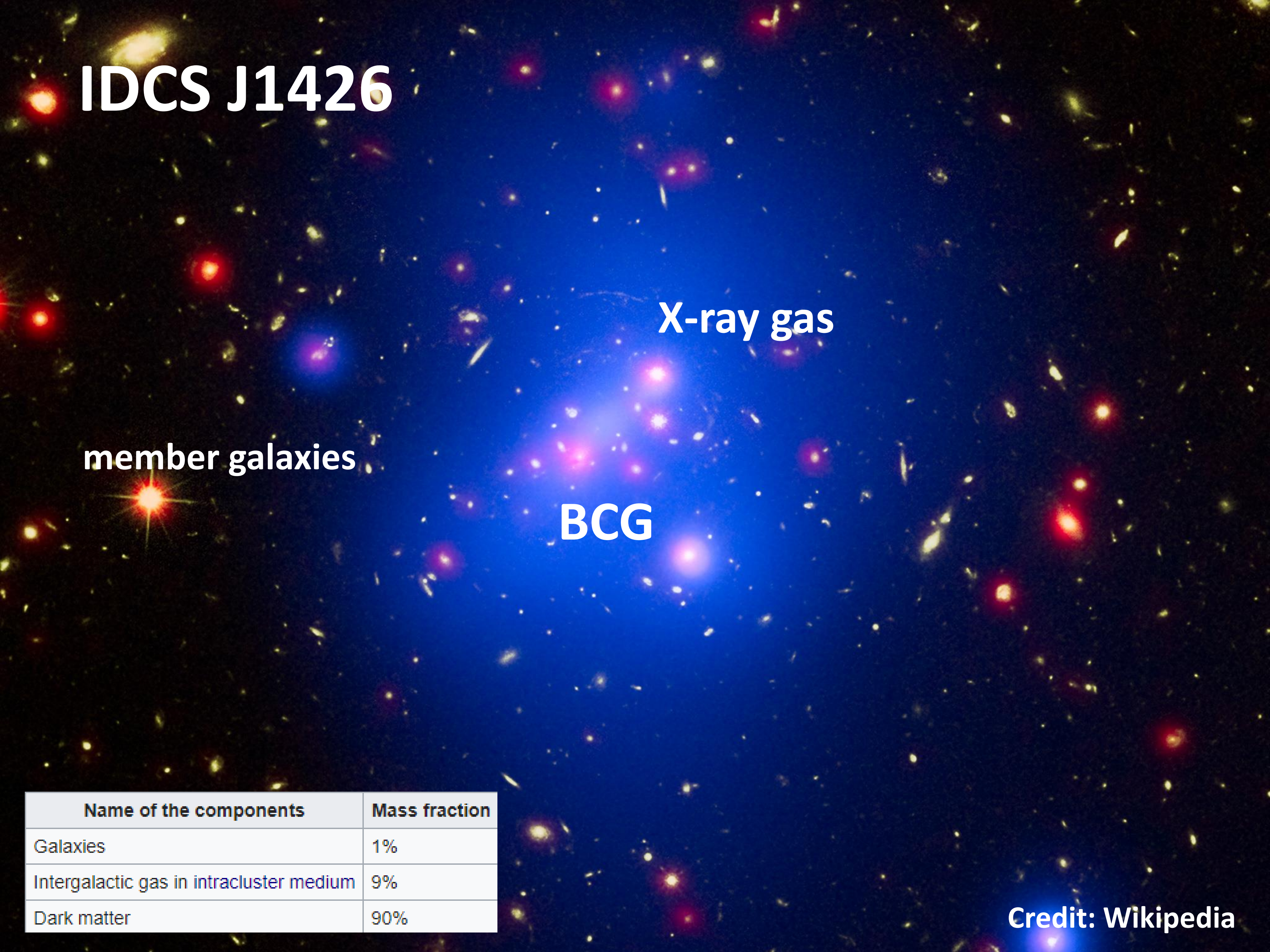
M_M : The baryonic mass estimated by MOND;
M_{bar} : The baryonic mass by observation.

MOND is not enough for accounting the missing mass in galaxy cluster by a factor of two:

$$\left\langle \frac{M_M}{M_{bar}} \right\rangle \approx 2$$

Pointecouteau & Silk 2005; Sanders 1999, 2003.


RAR in
Galaxy Clusters



Name of the components	Mass fraction
Galaxies	1%
Intergalactic gas in intracluster medium	9%
Dark matter	90%

Ingredient in Galaxy Clusters

- **Observational Mass ($M_o(<r)$)**
  - Strong & Weak-Lensing (Umetsu+ 2016)
- **Baryonic Mass ($M_b(<r)$)**
  - X-ray gas (Donahue+ 2014)
  - Stellar mass (Chiu+ 2018)
  - BCG (Cooke+ 2016)

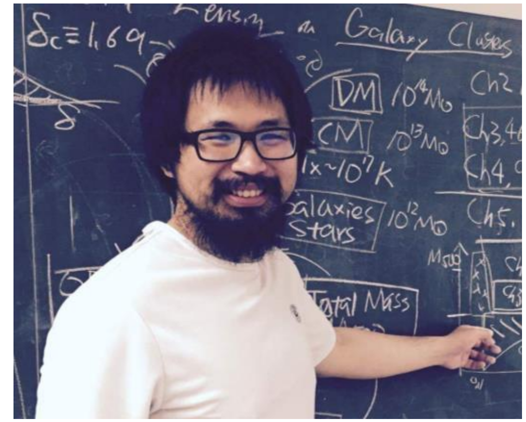
Collaborators

CLASH Team

Dr. Keiichi Umetsu
Research fellow, ASIAA

Prof. Megan Donahue
Michigan State University

SPT Team (South Pole Telescope)



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Post-doc, ASIAA

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Dr. Yong Tian
Post-doc, NCU

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 199:25 (23pp), 2012 April doi:10.1088/0067-0049/199/2/25

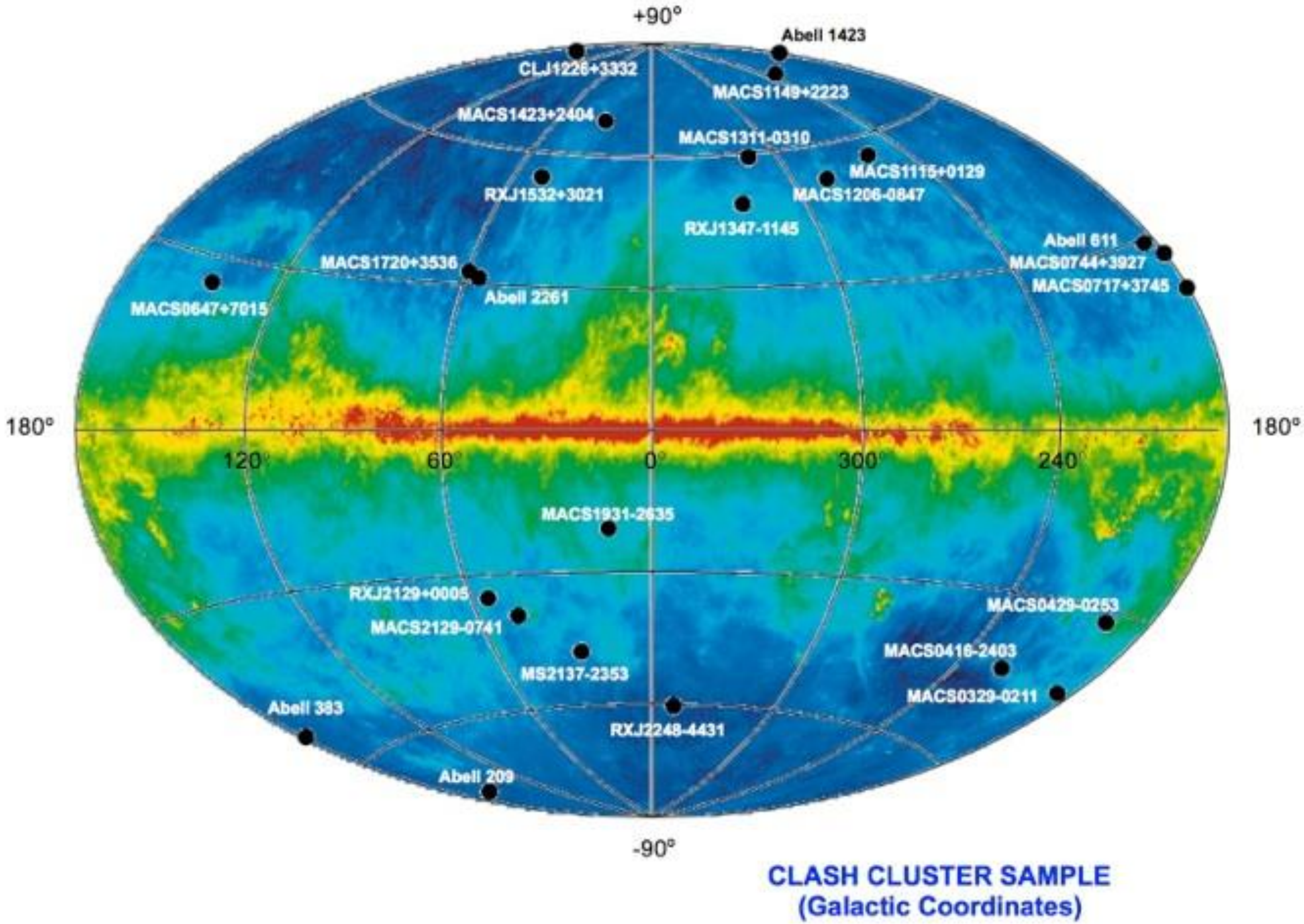
THE CLUSTER LENSING AND SUPERNOVA SURVEY WITH HUBBLE: AN OVERVIEW

MARC POSTMAN[1], DAN COE[1], NARCISO BENÍTEZ[2], LARRY BRADLEY[1], TOM BROADHURST[3], MEGAN DONAHUE[4], HOLLAND FORD[5], OR GRAUR[6], GENEVIEVE GRAVES[7], STEPHANIE JOUVEL[8], ANTON KOEKEMOER[1], DORON LEMZE[5], ELINOR MEDEZINSKI[5], ALBERTO MOLINO[2], LEONIDAS MOUSTAKAS[9], SARA OGAZ[1], ADAM RIESS[1,5], STEVE RODNEY[5], PIERO ROSATI[10], KEIICHI UMETSU[11], WEI ZHENG[5], ADI ZITRIN[6], MATTHIAS BARTELMANN[12], RYCHARD BOUWENS[13], NICOLE CZAKON[8], SUNIL GOLWALA[8], OLE HOST[14], LEOPOLDO INFANTE[15], SAURABH JHA[16], YOLANDA JIMENEZ-TEJA[2], DANIEL KELSON[17], OFER LAHAV[14], RUTH LAZKOZ[3], DANI MAOZ[6], CURTIS MCCULLY[16], PETER MELCHIOR[18], MASSIMO MENEGHETTI[19], JULIAN MERTEN[12], JOHN MOUSTAKAS[20], MARIO NONINO[21], BRANDON PATEL[16], ENIKÖ REGÖS[22], JACK SAYERS[8], STELLA SEITZ[23], AND ARJEN VAN DER WEL[24]
[1] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21208, USA; postman@stsci.edu

The Cluster Lensing And Supernova survey with Hubble (CLASH)

- 524-orbit *Hubble* Space Telescope (HST) Multi-Cycle Treasury program
- 25 high-mass galaxy clusters with $M_{500} \geq 4 \times 10^{14}$ Msun
- 25 high-temperature galaxy clusters with $T_X \geq 6$ keV

CLASH Galaxy Clusters



Ingredient in Galaxy Clusters

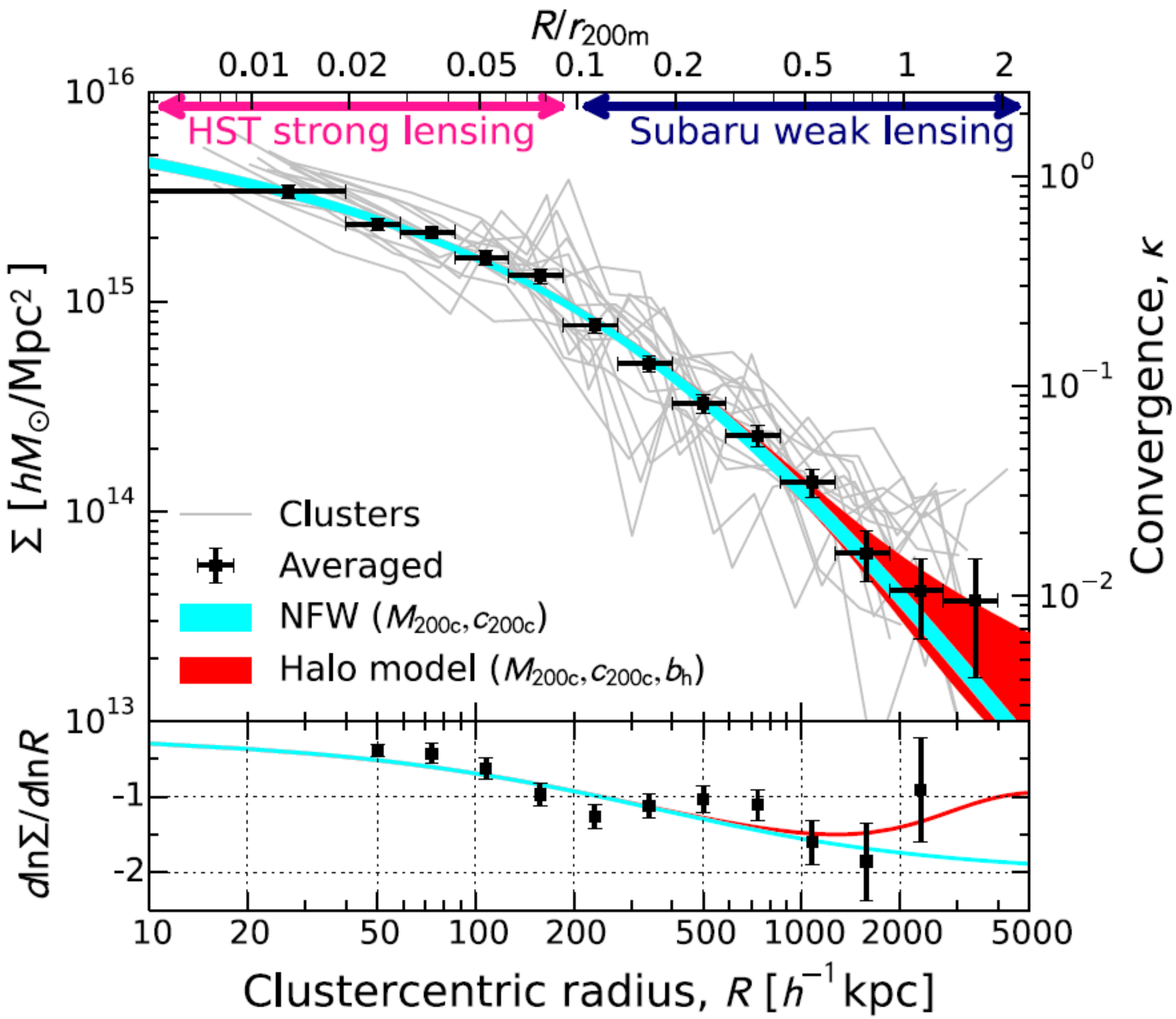
- **Observational Mass ($M_o(<r)$)**
  - Strong & Weak-Lensing (Umetsu+ 2016)
- **Baryonic Mass ($M_b(<r)$)**
  - X-ray gas (Donahue+ 2014)
  - Stellar mass (Chiu+ 2018)
  - BCG (Cooke+ 2016)

Gravitational Lensing

The Astrophysical Journal, 821:116 (29pp), 2016 April 20
doi:10.3847/0004-637X/821/2/116

CLASH: JOINT ANALYSIS OF STRONG-LENSING, WEAK-LENSING SHEAR, AND MAGNIFICATION DATA FOR 20 GALAXY CLUSTERS*

Keiichi Umetsu[1], Adi Zitrin[2,10], Daniel Gruen[3,4,5,6,11], Julian Merten[7], Megan Donahue[8], and Marc Postman[9]
[1] Institute of Astronomy and Astrophysics, Academia Sinica, P. O. Box 23-141, Taipei 10617, Taiwan; keiichi@asiaa.sinica.edu.tw



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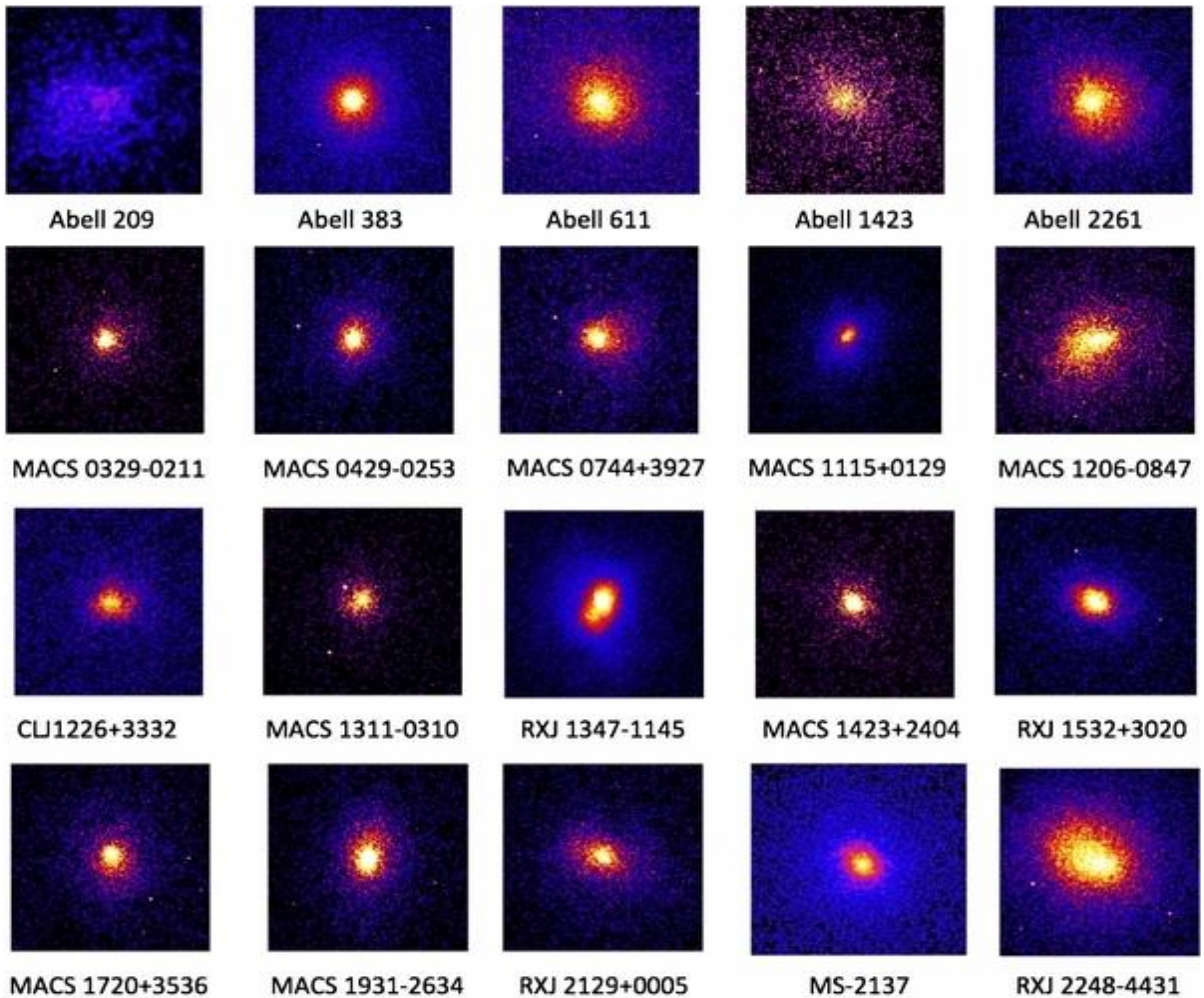
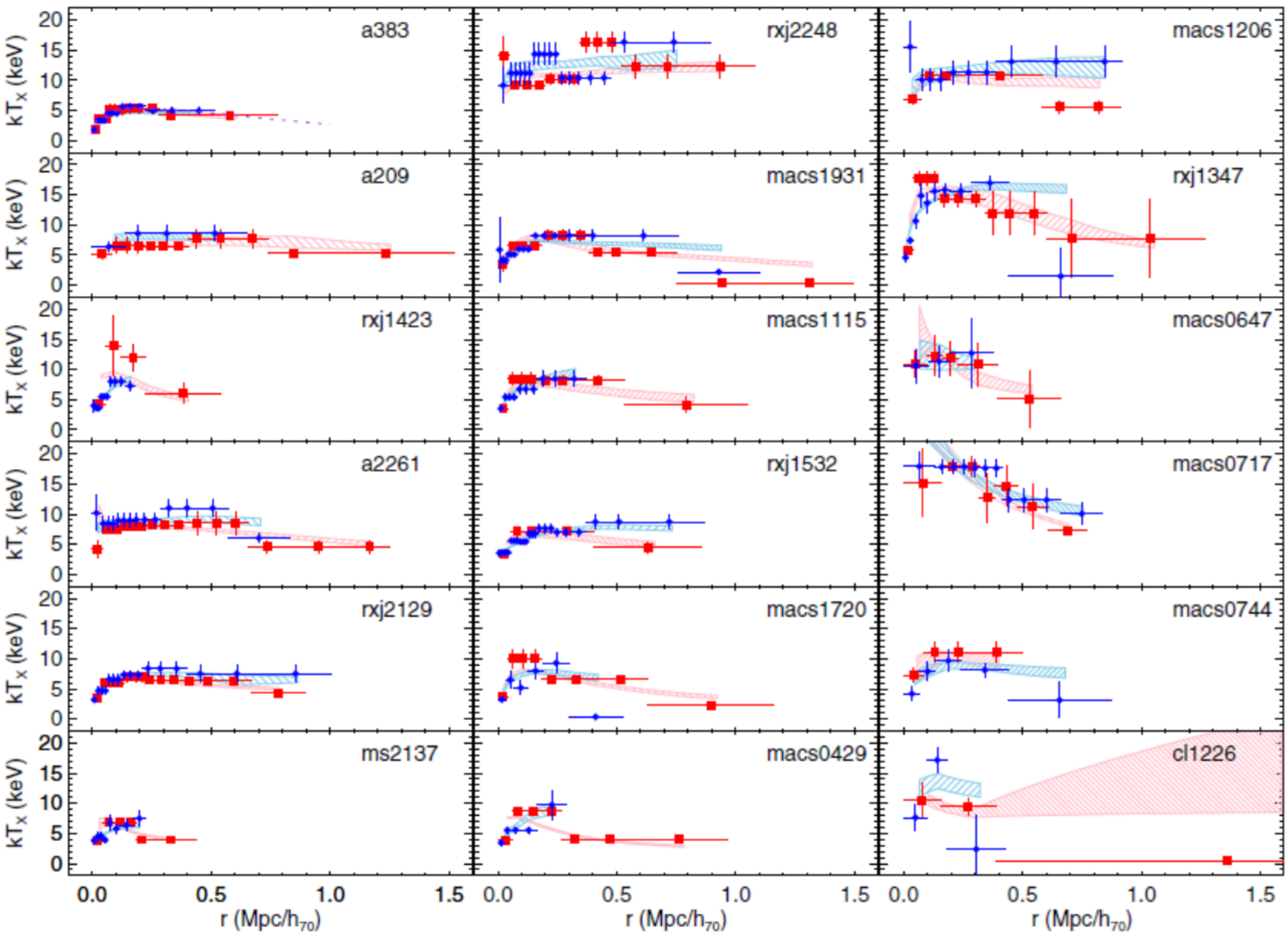
Chandra X-ray images



The Astrophysical Journal, 794:136 (21pp), 2014 October 20
doi:10.1088/0004-637X/794/2/136

CLASH-X: A COMPARISON OF LENSING AND X-RAY TECHNIQUES FOR MEASURING THE MASS PROFILES OF GALAXY CLUSTERS

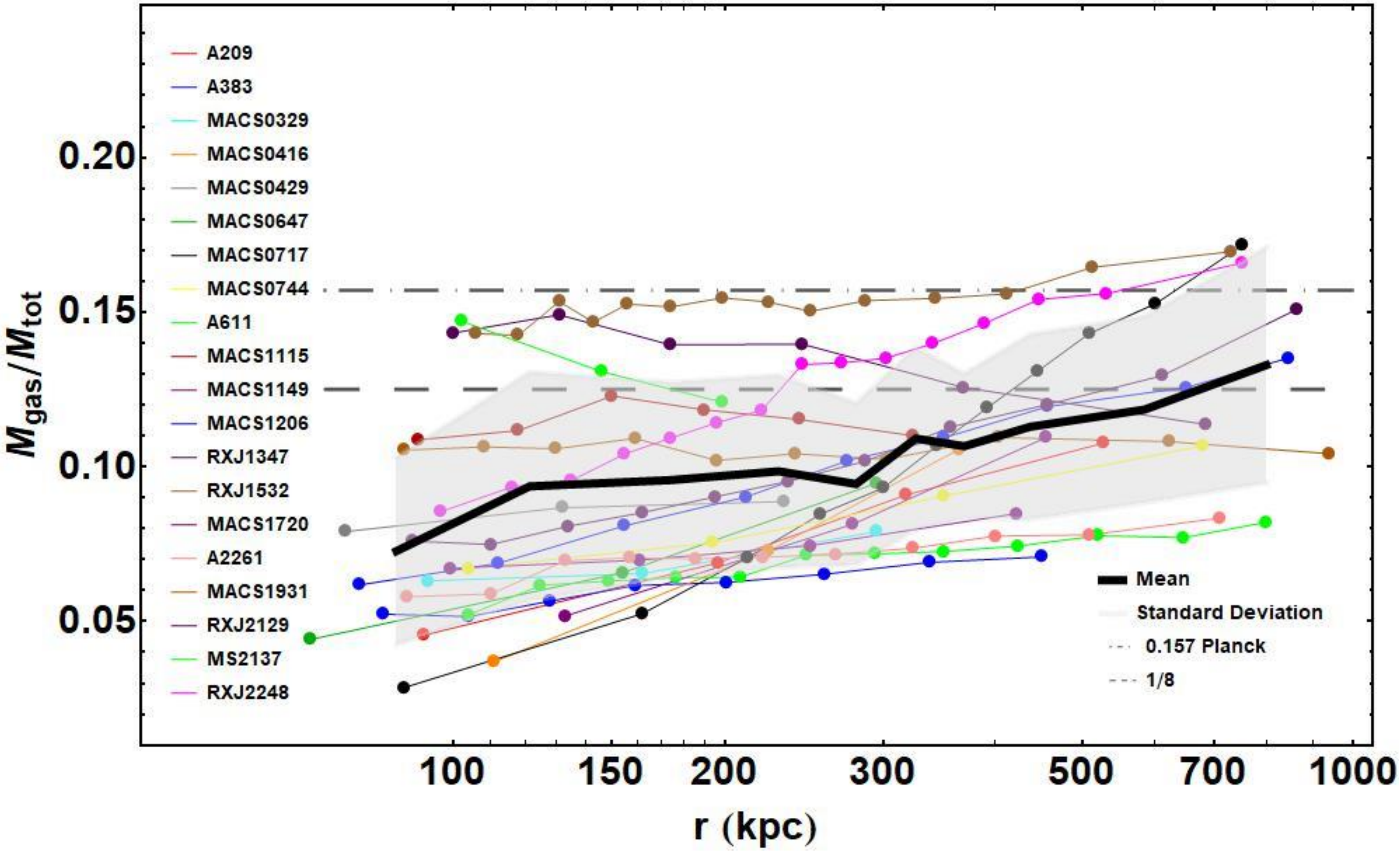
Megan Donahue[1], G. Mark Voit[1], Andisheh Mahdavi[2], Keiichi Umetsu[3,4], Stefano Ettori[5], Julian Merten[6],



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]

Draft version February 21, 2020



Yong Tian[1], Keiichi Umetsu[2], Chung-Ming Ko[1,3], Megan Donahue[4], and I-Non Chiu[2]

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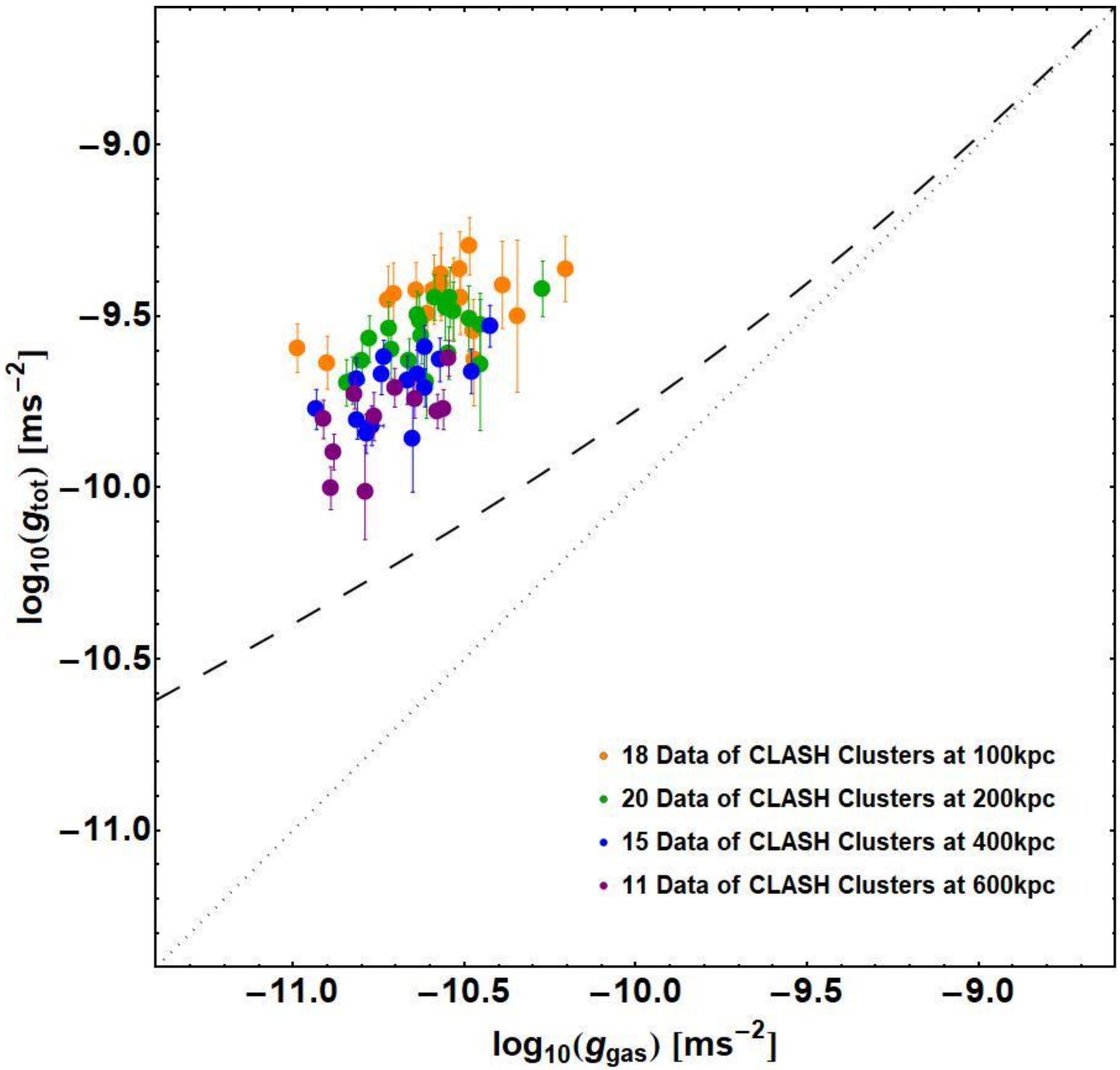

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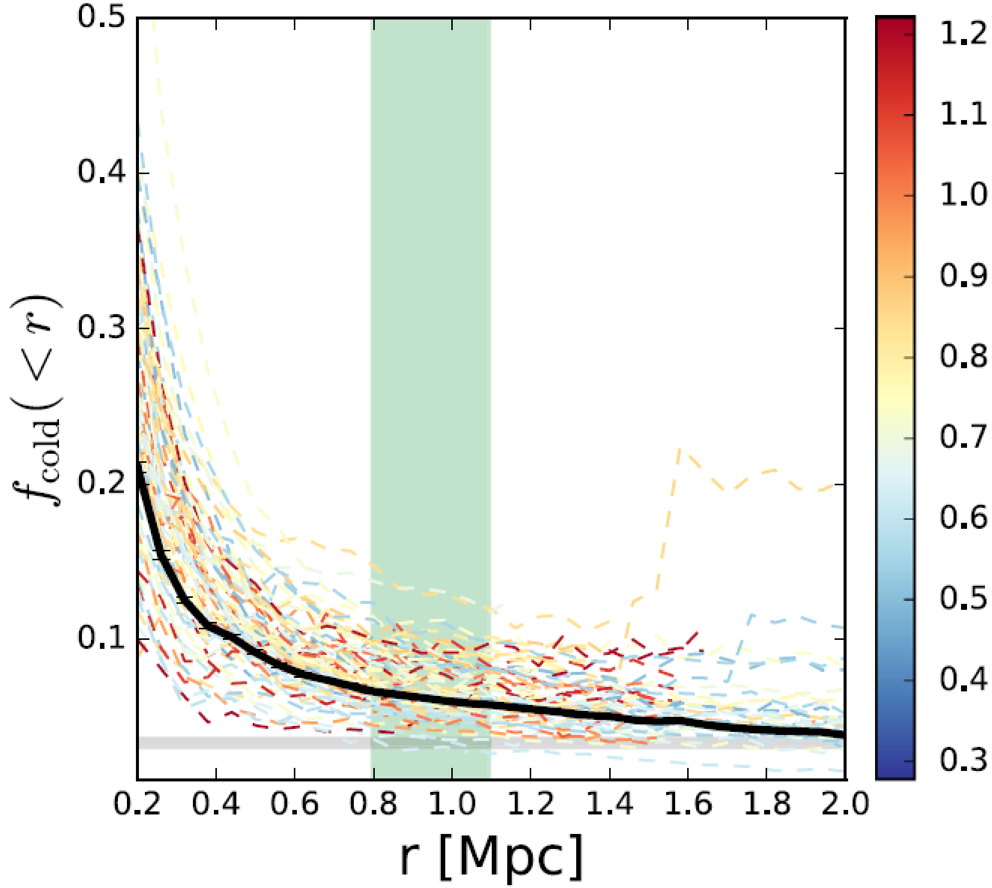
MNRAS **478**, 3072–3099 (2018)
Advance Access publication 2018 May 16
doi:10.1093/mnras/sty1284

Baryon content in a sample of 91 galaxy clusters selected by the South Pole Telescope at 0.2 < z < 1.25

I. Chiu,[1,2,3★] J. J. Mohr,[2,3,4★] M. McDonald,[5★] S. Bocquet,[6] S. Desai,[7] M. Klein,[2,4]



$$f_{cold} \equiv \frac{M_{stellar}}{M_{baryon}}$$

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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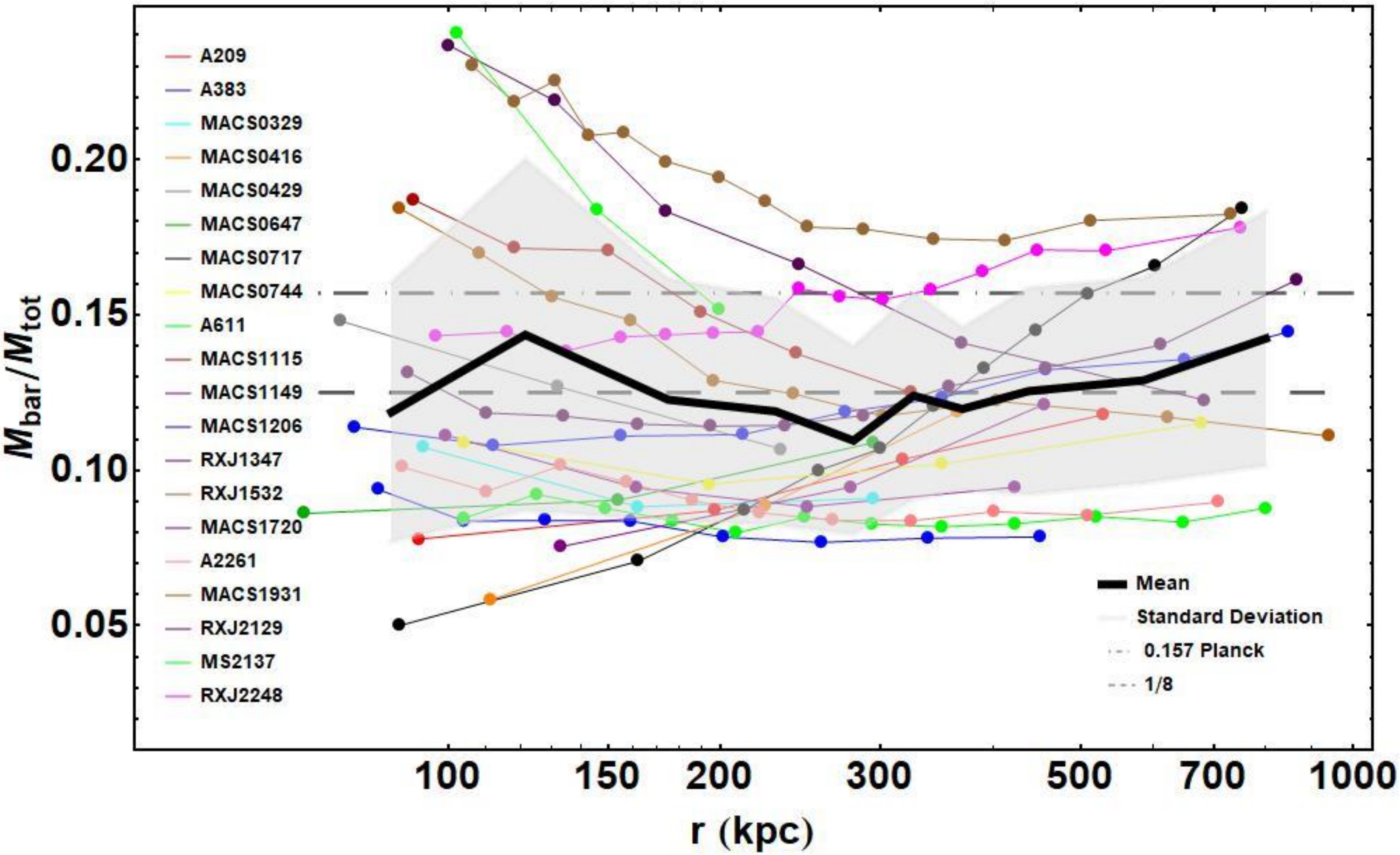

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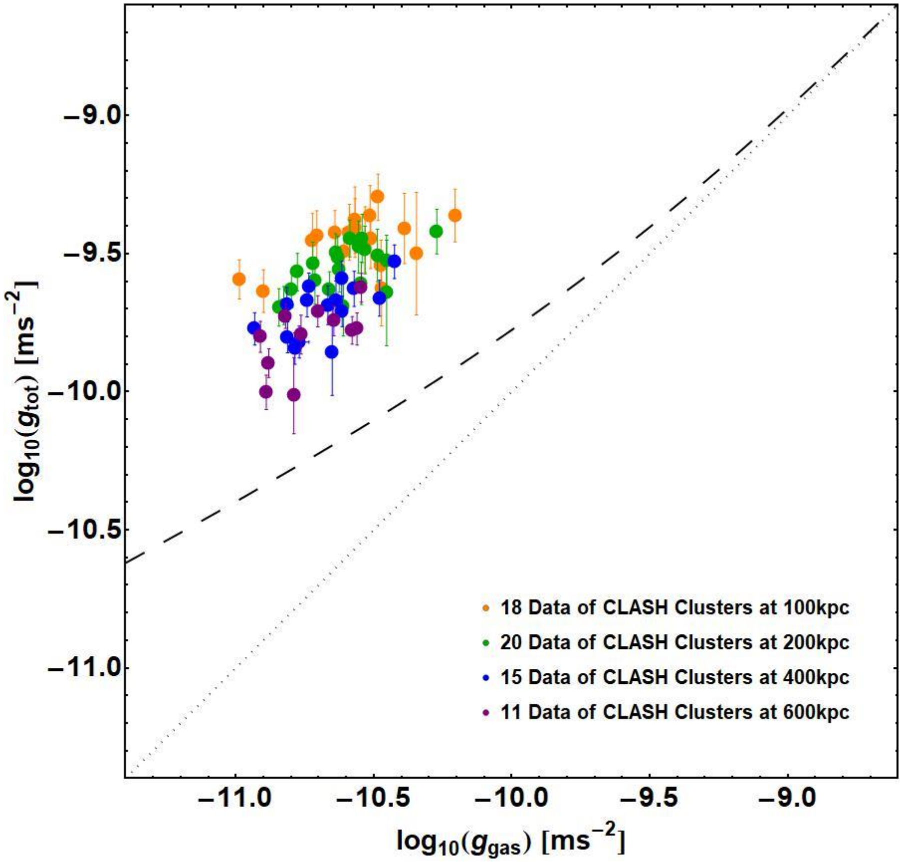

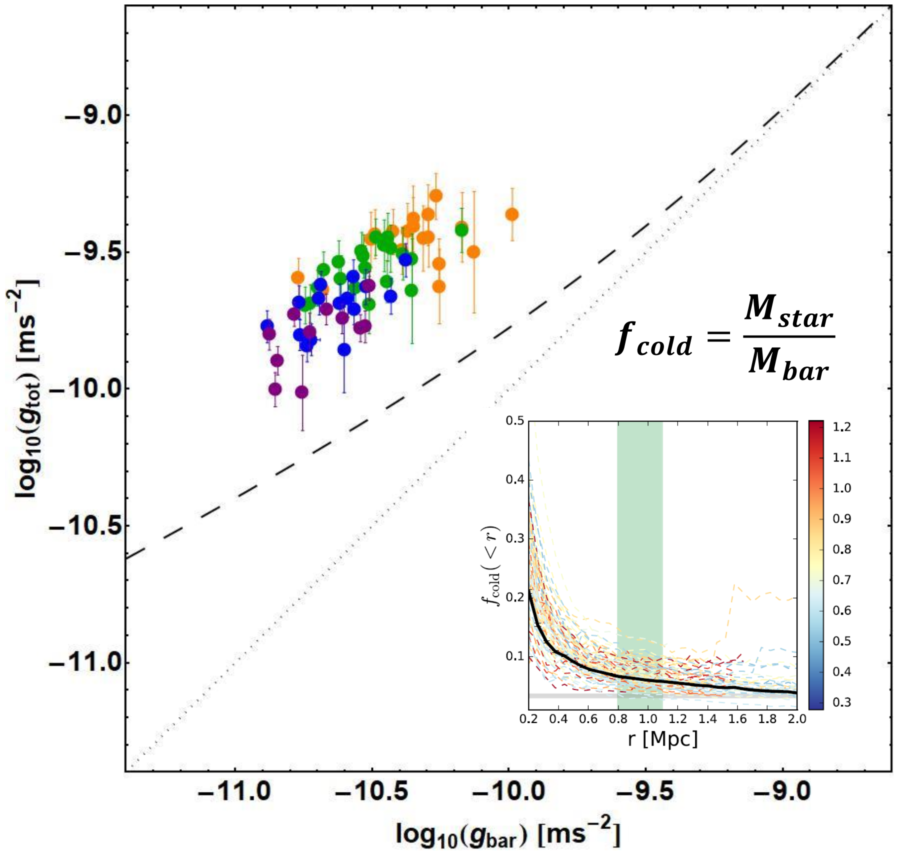

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Brightest Cluster Galaxy (BCG)

- **Brightest cluster galaxy**:
  the brightest galaxy in a cluster of galaxies .
- generally **elliptical galaxies.**
- the geometric and kinematical **center of their host galaxy cluster**;
- at the bottom of the cluster potential well;
- coincident with the peak of the cluster X-ray emission.

Abell 2262

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]

Draft version February 21, 2020

Table 1
Properties of BCGs in the CLASH sample

Name	Redshift	R.A. (J2000.0)	Decl. (J2000.0)	Band[a]	n[b]	R_e[c] (kpc)	r[d] (kpc)	M_{star}[e] $(10^{11} M_\odot)$	M_{gas}[f] $(10^{11} M_\odot)$	M_{tot}[g] $(10^{11} M_\odot)$
Abell 383	0.187	02 : 48 : 03.38	−03 : 31 : 45.02	F110W	2.34	17.0 ± 0.09	14.3	4.45	1.78 ± 0.09	7.55 ± 2.23
Abell 209	0.206	01 : 31 : 52.55	−13 : 36 : 40.50	F125W	2.62	22.1 ± 0.14	14.3	4.85	-	3.87 ± 0.79
Abell 2261	0.224	17 : 22 : 27.21	+32 : 07 : 57.62	F125W	1.74	18.7 ± 0.08	23.6	12.30	0.48 ± 0.03	6.44 ± 1.48
RX J2129.7+0005	0.234	21 : 29 : 39.96	+00 : 05 : 21.17	F125W	2.70	41.4 ± 0.54	14.3	5.81	2.18 ± 0.07	6.65 ± 1.91
Abell 611	0.288	08 : 00 : 56.82	+36 : 03 : 23.63	F125W	2.55	30.4 ± 0.16	22.2	6.58	0.48 ± 0.03	6.24 ± 1.81
MS2137−2353	0.313	21 : 40 : 15.16	−23 : 39 : 40.10	F125W	2.35	15.0 ± 0.04	14.3	3.65	2.94 ± 0.07	3.98 ± 1.57
RX J2248.7−4431	0.348	22 : 48 : 43.97	−44 : 31 : 51.14	F140W	2.45	34.5 ± 0.20	30.3	8.09	1.01 ± 0.03	6.19 ± 2.16
MACS J1115.9+0129	0.355	11 : 15 : 51.91	+01 : 29 : 55.00	F140W	3.83	52.9 ± 0.93	16.2	3.00	5.80 ± 0.19	6.25 ± 1.53
MACS J1931.8−2635	0.352	19 : 31 : 49.70	−26 : 34 : 32.22	F140W	3.49	33.2 ± 0.38	14.3	6.92	1.47 ± 0.02	7.21 ± 2.90
RX J1532.9+3021	0.362	15 : 32 : 53.78	+30 : 20 : 59.43	F140W	2.81	21.8 ± 0.14	14.3	3.34	1.13 ± 0.04	6.80 ± 4.18
MACS J1720.3+	0.387	17 : 20 : 16.75	+35 : 36 : 26.24	F140W	2.63	17.2 ± 0.06	23.6	6.59	1.15 ± 0.03	6.83 ± 2.07
MACS J0416.1−2403	0.397	04 : 16 : 09.15	−24 : 04 : 02.99	F140W	3.78	56.2 ± 0.81	14.3	3.14	-	4.22 ± 0.94
MACS J0429.6−0253	0.399	04 : 29 : 36.00	−02 : 53 : 06.78	F140W	1.80	29.3 ± 0.08	17.2	11.90	6.71 ± 0.55	9.98 ± 3.40
MACS J1206.2−0847	0.439	12 : 06 : 12.15	−08 : 48 : 03.32	F140W	3.65	44.8 ± 0.52	14.3	3.13	-	6.90 ± 2.07
MACS J0329.7−0211	0.450	03 : 29 : 41.57	−02 : 11 : 46.33	F140W	2.76	22.9 ± 0.12	22.2	8.47	13.1 ± 0.41	25.30 ± 6.50
RX J1347.5−1145	0.451	13 : 47 : 30.61	−11 : 45 : 09.33	F140W	2.62	21.7 ± 0.12	14.3	4.52	5.11 ± 0.07	7.28 ± 1.88
MACS J1149.5+2223	0.544	11 : 49 : 35.70	+22 : 23 : 54.68	F160W	2.44	34.3 ± 0.32	14.3	4.72	-	4.54 ± 1.12
MACS J0717.5+3745	0.548	07 : 17 : 32.52	+37 : 44 : 34.84	F160W	2.49	13.2 ± 0.07	14.3	2.19	-	4.07 ± 0.73
MACS J0647.7+7015	0.584	06 : 47 : 50.65	+70 : 14 : 53.99	F160W	1.44	56.9 ± 0.29	14.3	14.70	-	7.71 ± 2.77
MACS J0744.9+3927	0.686	07 : 44 : 52.80	+39 : 27 : 26.74	F160W	2.47	14.7 ± 0.09	14.3	7.74	-	7.65 ± 2.45

[a] *HST* band corresponding to the rest-frame wavelength of 1μm.
[b] Sérsic index of the BCG obtained with GALFIT in the *HST* band corresponding to the rest-frame wavelength of 1μm.
[c] Effective radius of the BCG obtained with GALFIT in the *HST* band corresponding to the rest-frame wavelength of $1\,\mu$m.
[d] BCG centric radius for M_{star}, M_{gas}, and M_{tot} mass estimates.
[e] BCG total stellar mass $M_{star}(< r)$ estimated by Cooke et al. (2016). We assume a fractional uncertainty of 10% in our analysis.
[f] X-ray gas mass $M_{gas}(< r)$ from Donahue et al. (2014).
[g] Strong lensing mass $M_{tot}(< r)$ from Umetsu et al. (2016).

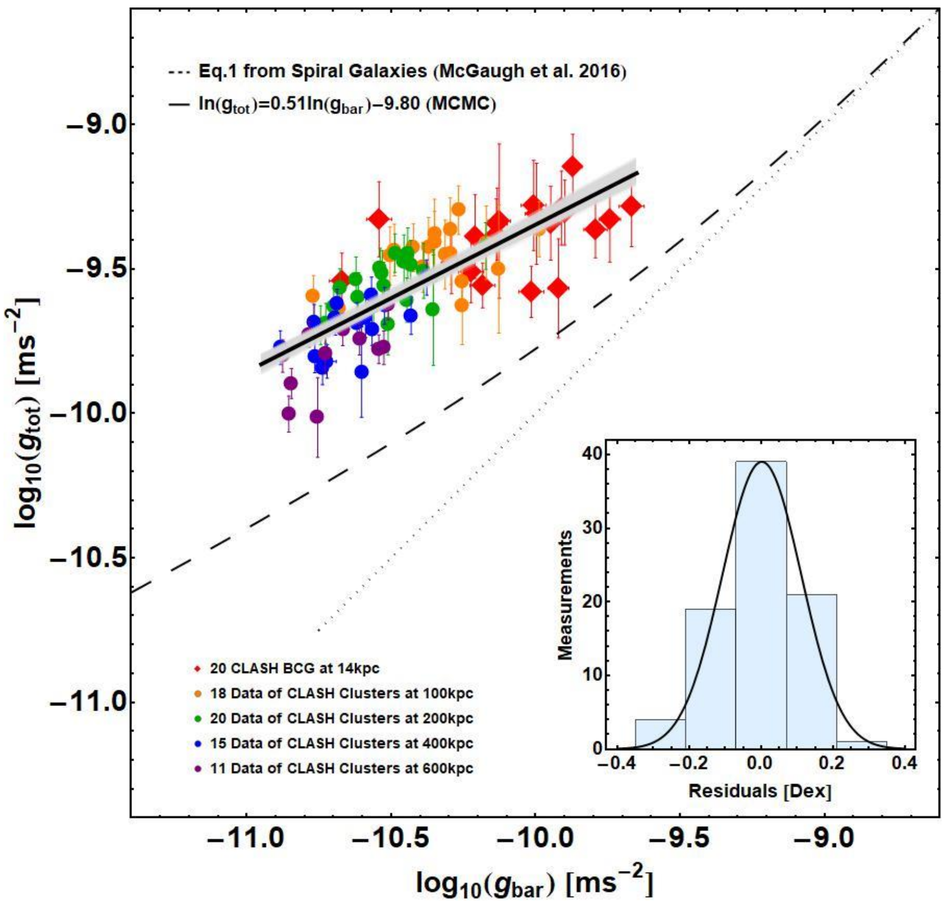
Tian et al. (2020), submitted to ApJ

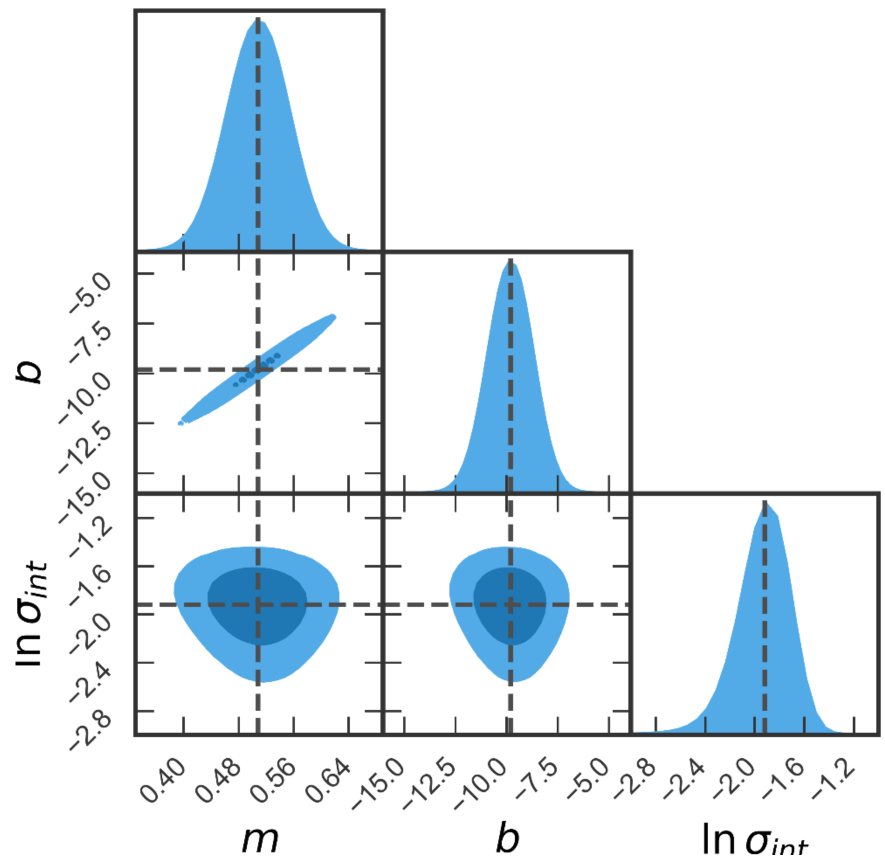
DRAFT VERSION FEBRUARY 21, 2020
Preprint typeset using LaTeX style emulateapj v. 01/23/15

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]

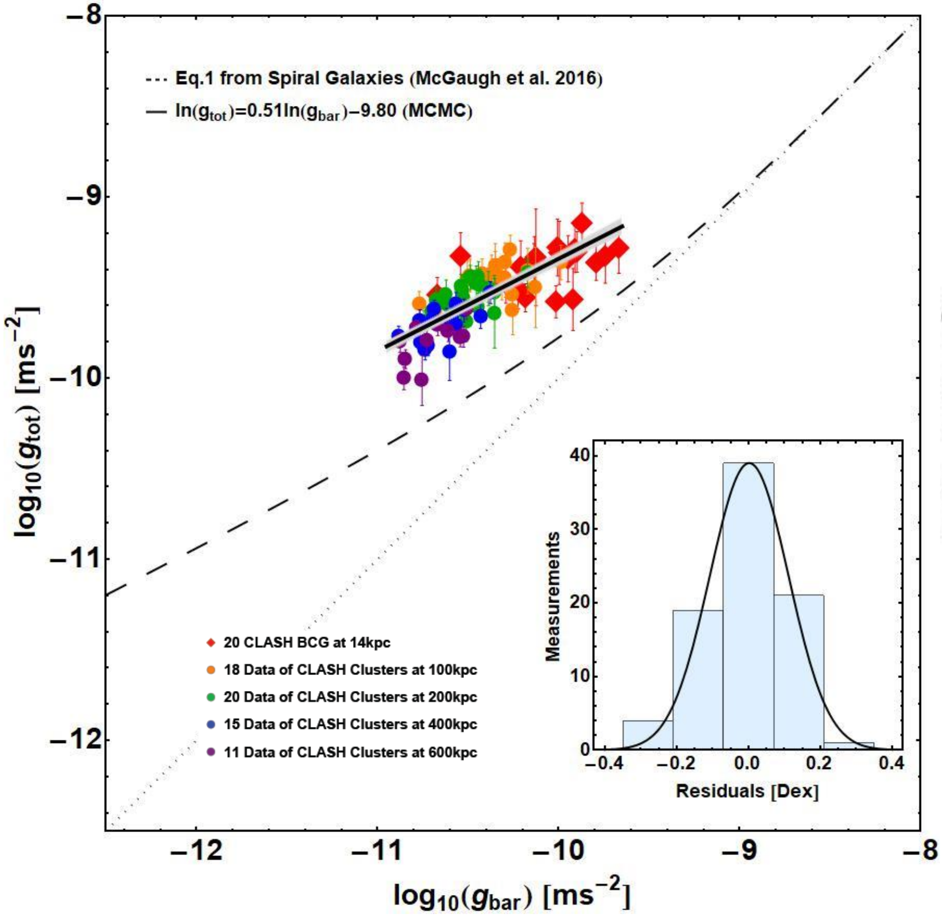
Draft version February 21, 2020

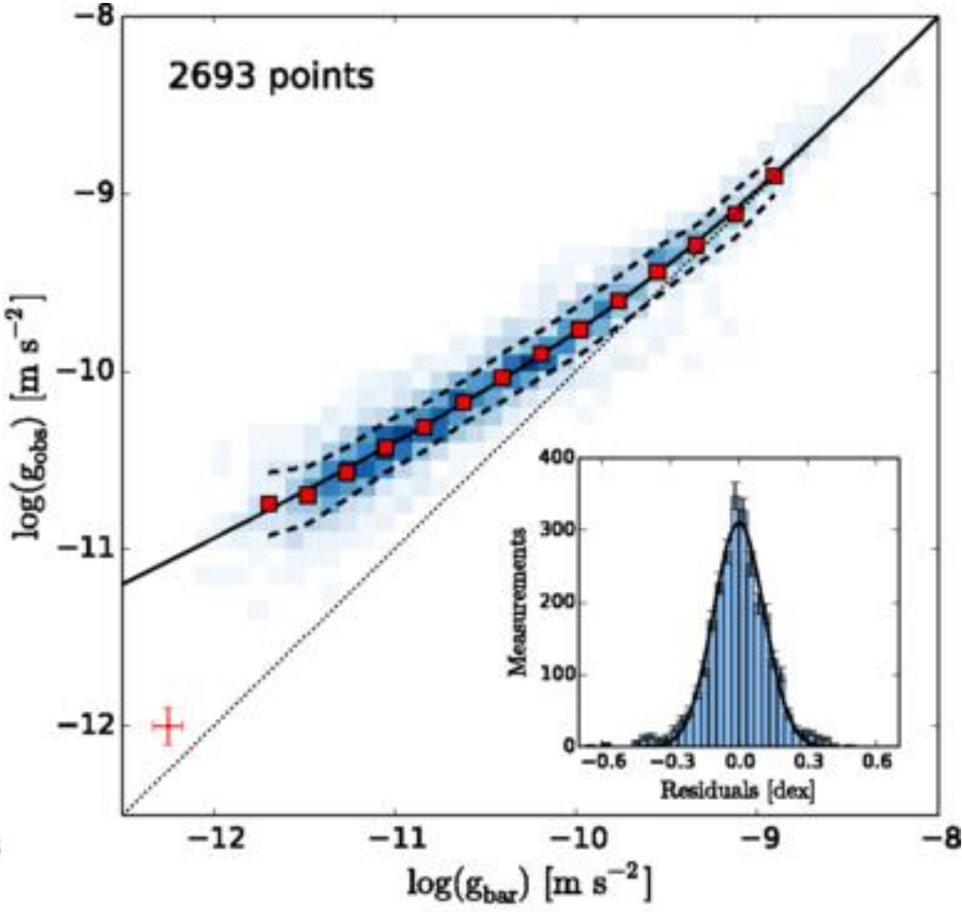




Tian et al. (2020), submitted to ApJ

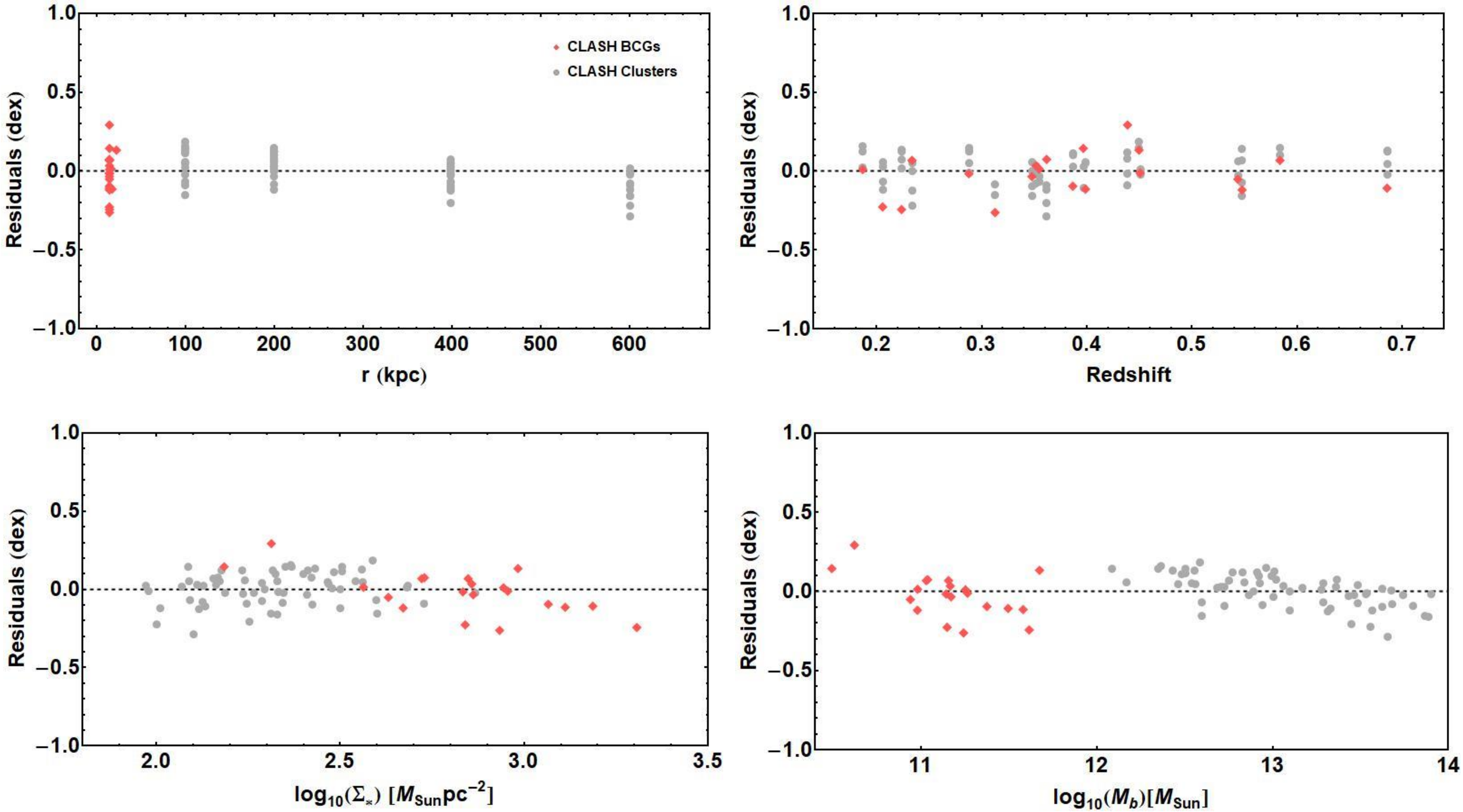
CLASH RAR & RAR





Once baryonic acceleration g_{bar} is given, one can get mass of dark matter M_{DM} from RAR or CLASH RAR depending on systems and vice versa.

Residuals in CLASH RAR



Tian et al. (2020), submitted to ApJ

Four Issues in CLASH RAR

Four Issues in RAR

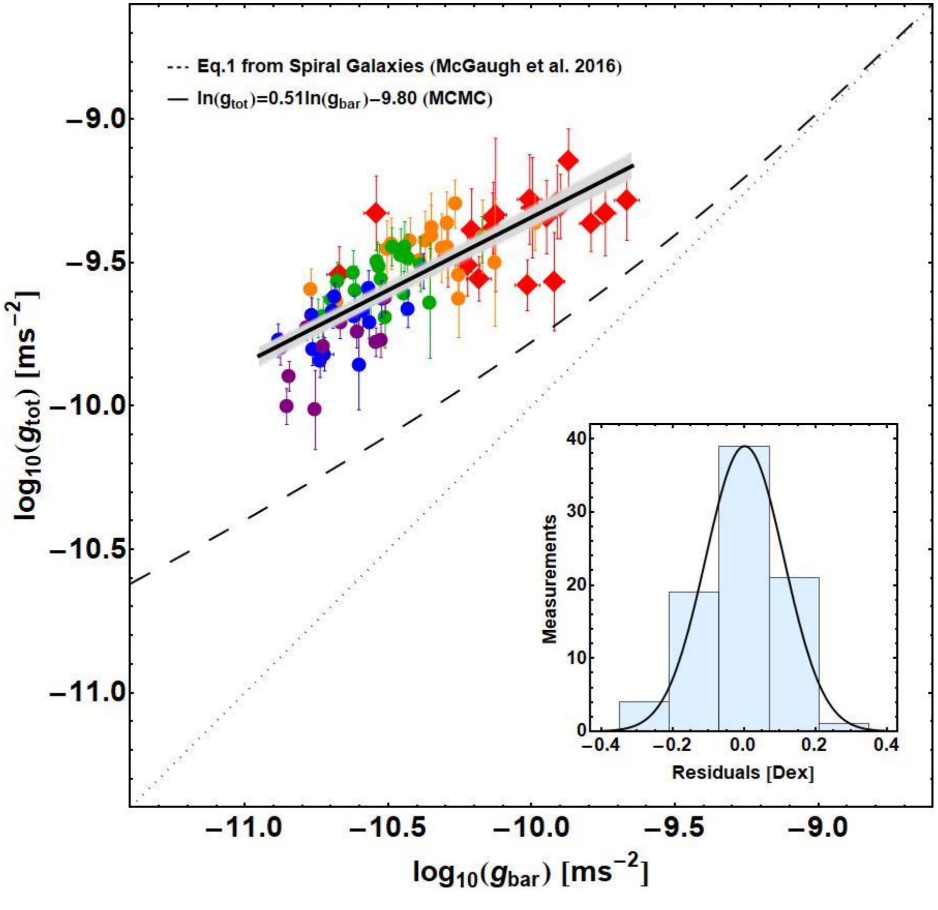
i. the acceleration scale $g_{\dagger}=1.20\times10^{-10}\,\mathrm{ms}^{-2}$;
ii. the low-acceleration slope (0.5);
iii. the intrinsic scatters (≤ 0.11 dex);
iv. no correlations between residuals and other galaxy properties.

Four Issues in CLASH RAR

i. a new acceleration scale $g_{\ddagger}=2.02\times10^{-9}\,\mathrm{ms}^{-2}$;
ii. the acceleration slope ($\simeq 0.5$);
iii. the intrinsic scatters ($\mathrm{Log}\,\sigma_{int}=0.147$);
iv. a small correlation between residuals and radius.

Tian et al. (2020), submitted to ApJ

Prediction in CLASH RAR



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

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

$$\rightarrow \frac{\sigma^4}{r^2} \propto \frac{GM_{bar} g_{\ddagger}}{r^2}$$

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

Baryonic Faber-Jackson Relation

Tian et al. (2020), submitted to ApJ

Dynamics & Kinematics

	Dynamics	Kinematics
Solar System	Newton's Law	Kepler's Law
Spirals	RAR	Tully-Fisher
Ellipticals	RAR	Faber-Jackson
Clusters	CLASH RAR	Faber-Jackson?

Semi-Analytical Model (SAM)

- In hydrostatic equilibrium, the gas pressure gradient related to total cluster mass as

$$\frac{d\,P_{gas}(r)}{dr} = -\rho_{gas}(r)\frac{GM_{tot}(r)}{r^2}.$$

- Gas pressure is defined by electron pressure as

$$P_{gas}(r) = \frac{\mu_e}{\mu}P_e(r).$$

- Assuming the electron pressure follows the GNFW profile,

$$P_e(r) = \frac{P_{ei}}{(\frac{r}{r_p})^c(1+(\frac{r}{r_p})^a)^{(b-c)/a}}.$$

- Because $\rho_{gas}(r) \ll \rho_{tot}(r)$for all r, we can assume

$$\rho_{tot}(r) = \rho_{DM}(r) + \rho_{gas}(r) \approx \rho_{DM}(r)$$

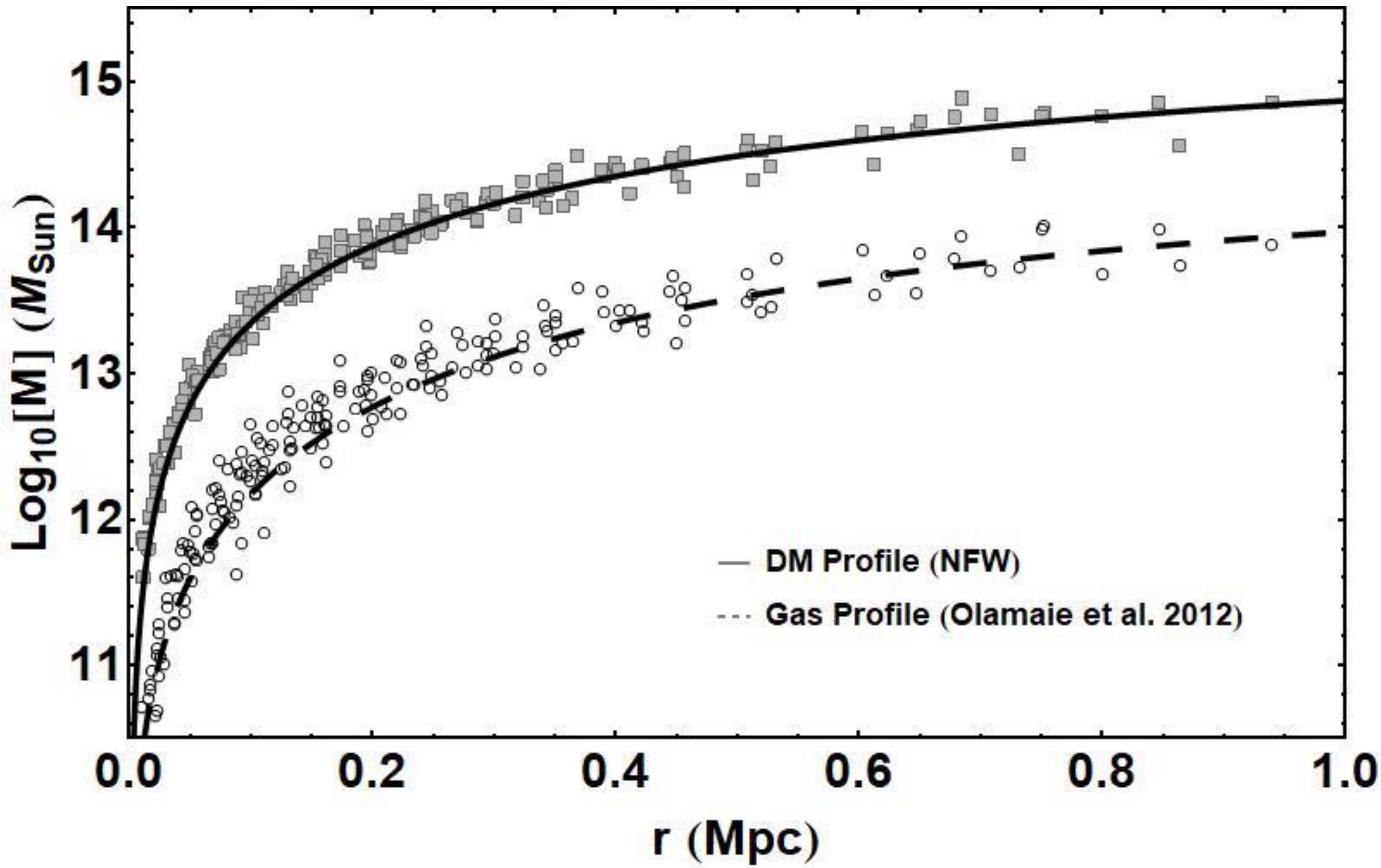
Olamaie et al. (2012), MNRAS, 423,1534

Parameters in SAM

- We assume a flat ΛCDM cosmology with $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, and a Hubble constant of $H_0 = 70 kms^{-1} Mpc^{-1}$.
- We adopt $M_{200} = 1.55 \times 10^{15} M_{sun}$ and $c_{200} = 3.28$ to describe the DM distribution $\rho_{DM}(r)$ of our sample with a median redshift of z = 0.377 (Umetsu et al. 2016).
- We assume a gas mass fraction of $f_{gas}(r_{500}) = 13\%$ (e.g., Planck Collaboration et al. 2013; Donahue et al. 2014) at $r = r_{500}$ to fix the normalization of $\rho_{gas}(r)$.

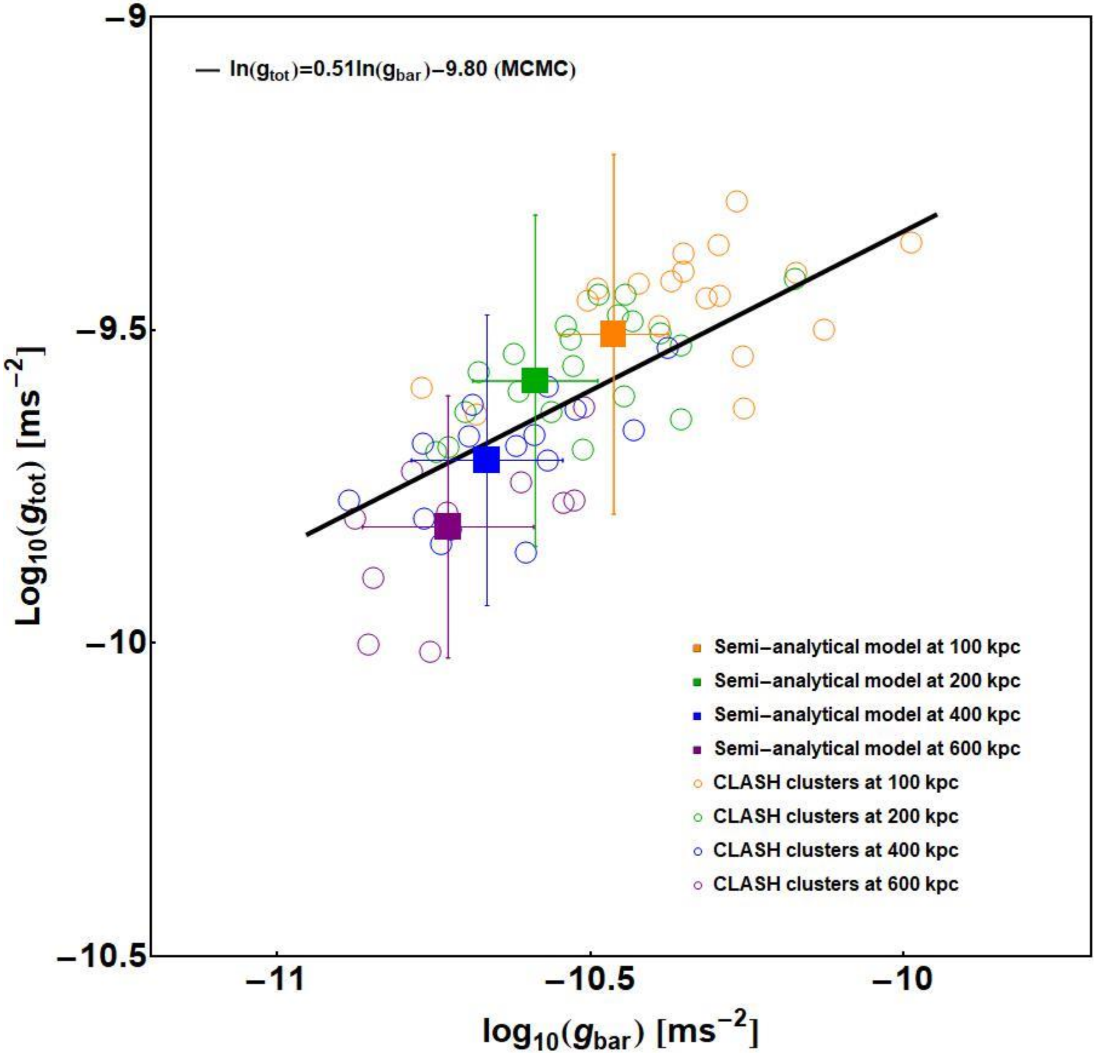
Tian et al. (2020), submitted to ApJ

Semi-Analytical Model



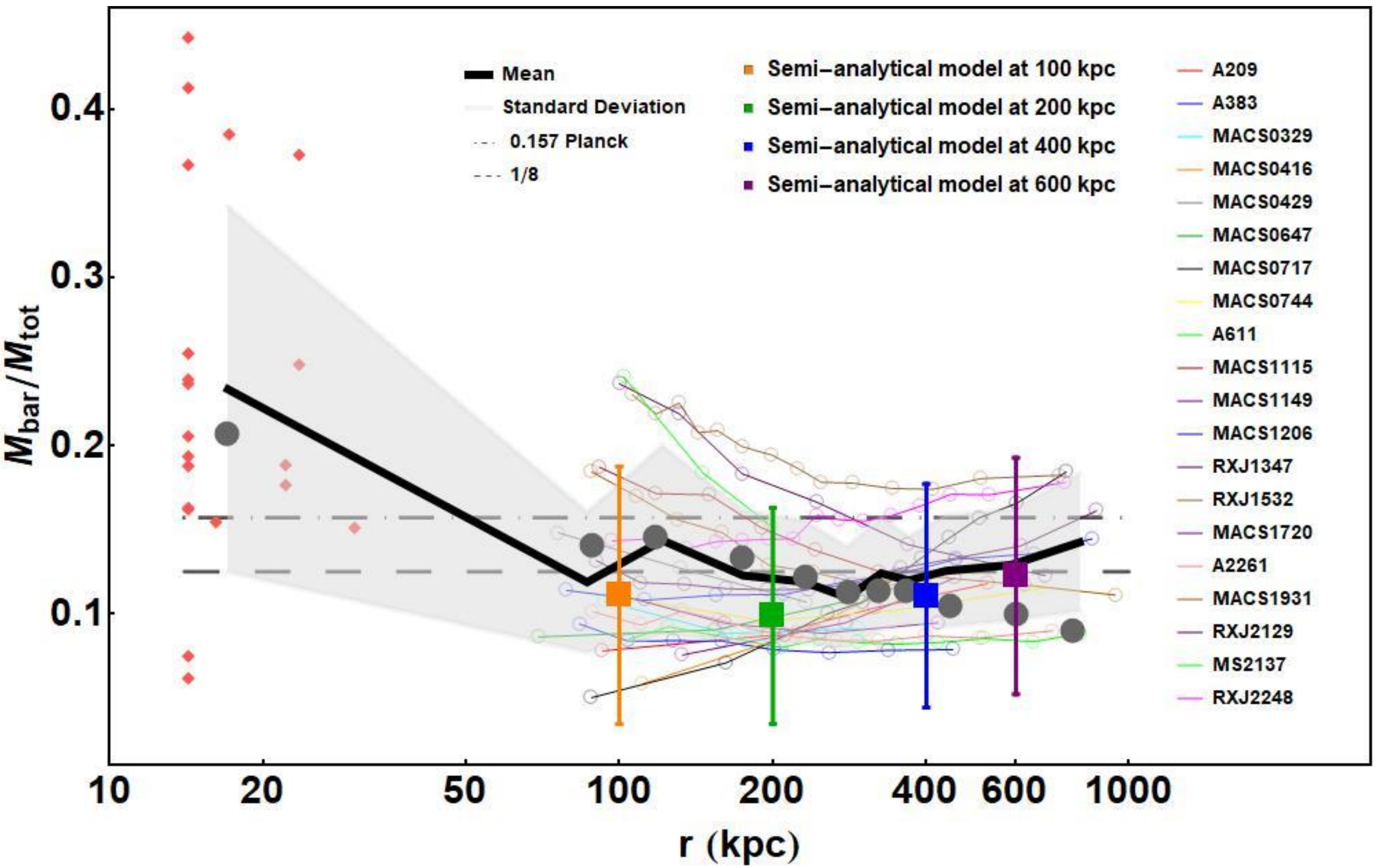
Tian et al. (2020), submitted to ApJ

Semi-Analytical Model



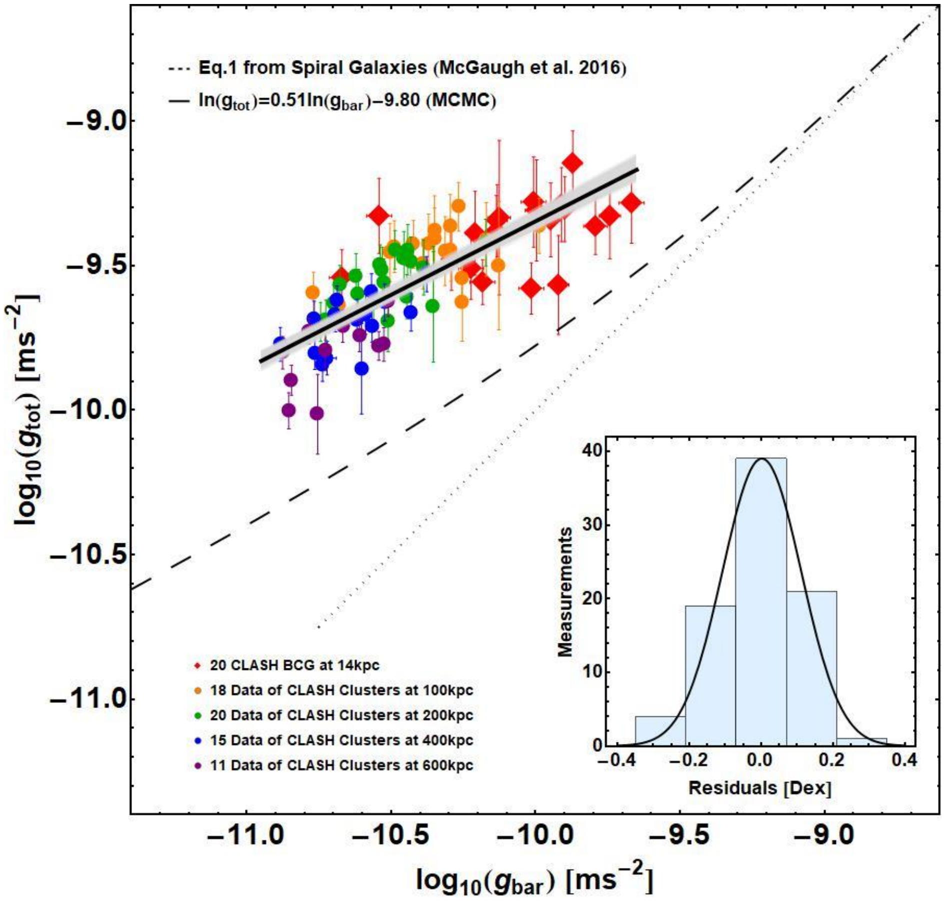
Tian et al. (2020), submitted to ApJ

Semi-Analytical Model



Tian et al. (2020), submitted to ApJ

Implications for MOND



The residual missing mass in MOND in cluster scale:

M_M : The baryonic mass estimated by MOND; M_{bar} : The baryonic mass by observation.

$$\sqrt{g_{bar} g_{\ddagger}} \approx \frac{g_M}{1 - e^{-\sqrt{g_M/g_{\dagger}}}}$$

The residual missing mass in MOND $\frac{M_M}{M_{bar}} = \frac{g_M}{g_{bar}}$

For $g_{bar} = 2.1 \times 10^{-10} ms^{-2}, \frac{M_M}{M_{bar}} = \mathbf{2.7}.$

For $g_{bar} = 1.3 \times 10^{-11} ms^{-2}, \frac{M_M}{M_{bar}} = \mathbf{7.3}.$

The residual missing mass by the CLASH RAR increases with decreasing baryonic acceleration.

Tian et al. (2020), submitted to ApJ

Remarks

- In spiral and elliptical galaxies, the RAR is well-established with the acceleration scale $g_{\dagger}=1.20\times10^{-10}$ ms^{-2}.
- In galaxy clusters, the CLASH RAR reveals a similar acceleration relation as the RAR but with a new acceleration scale: $g_{\ddagger}=2.02\times10^{-9}$ ms^{-2}.
- The CLASH RAR predicts a Baryonic Faber-Jackson Relation (BFJR), $M_{bar}g_{\ddagger}\propto\sigma^4$, in a BCG-cluster scale.
- SAM is consistent with data points and the mean relation.
- The CLASH RAR implies the residual missing mass in MOND increasing with decreasing baryonic acceleration.

Q&A

Spherical Symmetry of CLASH sample

- ❑Three-dimensional full-triaxial analyses of CLASH lensing observations found no statistical evidence for orientation bias in the CLASH sample (see Chiu et al. 2018, ApJ, 860, 126; Sereno et al. 2018, ApJL, 860, L4)
- ❑Triaxiality and orientations of clusters will introduce statistical fluctuations of the projected cluster lensing signal. It has been taken into account in the error analysis of Umetsu et al. (2016).
- ❑Terrors in our total mass estimates M(<r) from lensing include the effect of triaxiality and random orientations

The Astrophysical Journal Supplement Series, 199:25 (23pp), 2012 April
doi:10.1088/0067-0049/199/2/25

THE CLUSTER LENSING AND SUPERNOVA SURVEY WITH HUBBLE: AN OVERVIEW

Marc Postman[1], Dan Coe[1], Narciso Benítez[2], Larry Bradley[1], Tom Broadhurst[3], Megan Donahue[4], Holland Ford[5], Or Graur[6], Genevieve Graves[7], Stephanie Jouvel[8], Anton Koekemoer[1], Doron Lemze[5], Elinor Medezinski[5], Alberto Molino[2], Leonidas Moustakas[9], Sara Ogaz[1], Adam Riess[1,5], Steve Rodney[5], Piero Rosati[10], Keiichi Umetsu[11], Wei Zheng[5], Adi Zitrin[6], Matthias Bartelmann[12], Rychard Bouwens[13], Nicole Czakon[8], Sunil Golwala[8], Ole Host[14], Leopoldo Infante[15], Saurabh Jha[16], Yolanda Jimenez-Teja[2], Daniel Kelson[17], Ofer Lahav[14], Ruth Lazkoz[3], Dani Maoz[6], Curtis McCully[16], Peter Melchior[18], Massimo Meneghetti[19], Julian Merten[12], John Moustakas[20], Mario Nonino[21], Brandon Patel[16], Enikö Regös[22], Jack Sayers[8], Stella Seitz[23], and Arjen Van der Wel[24]
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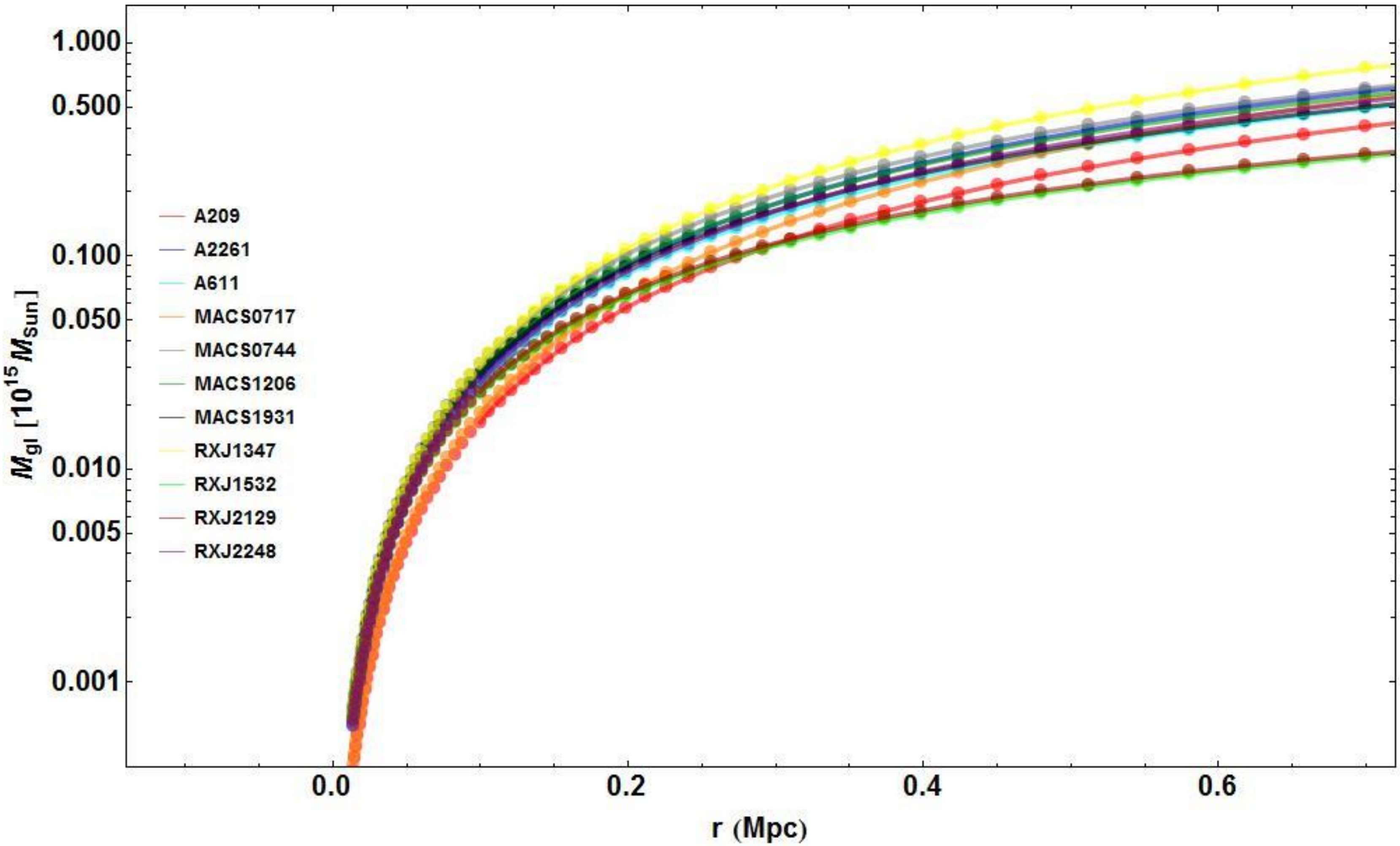
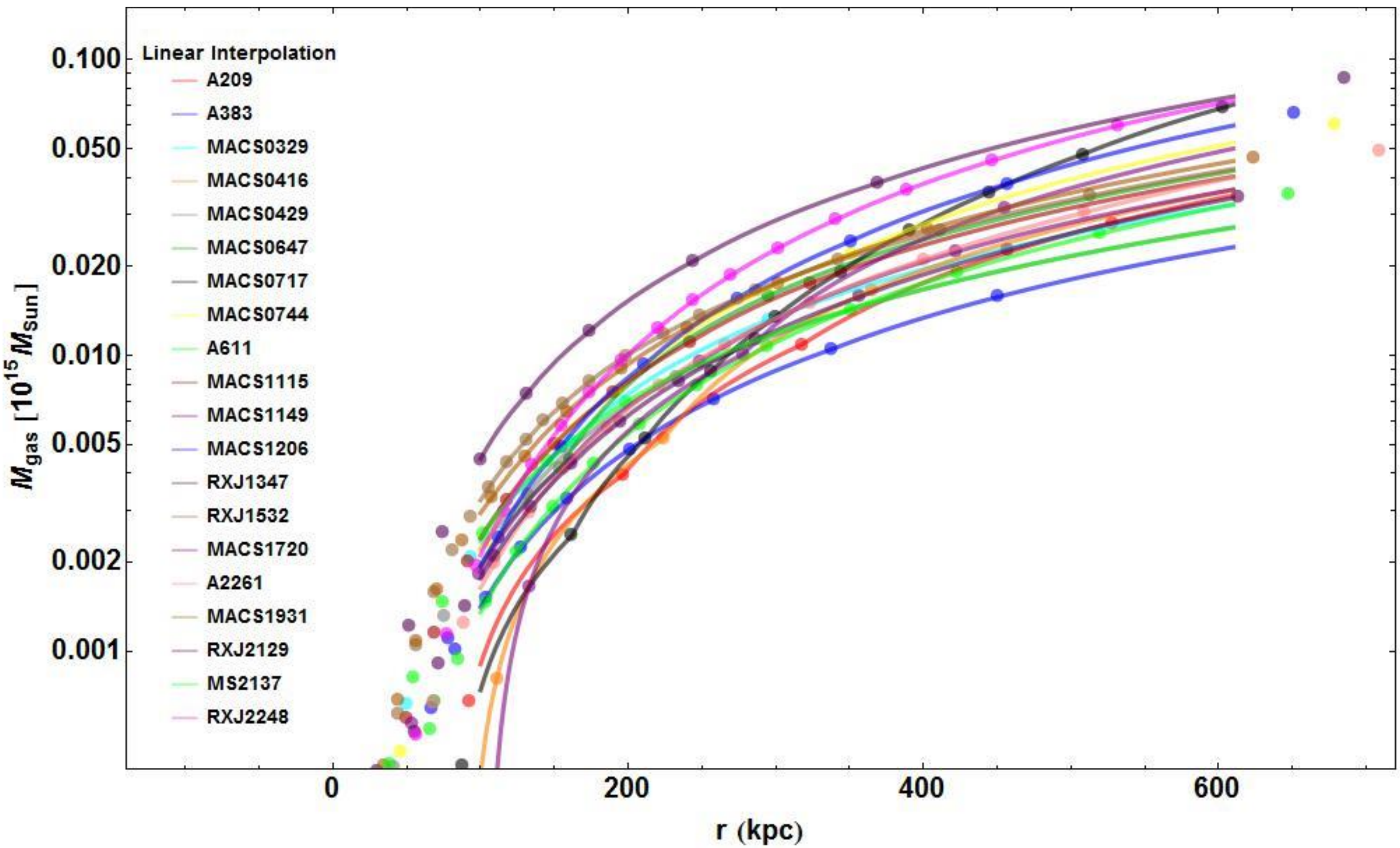
The Cluster Lensing And Supernova survey with Hubble (CLASH)

- ❑ Measure DM profiles in galaxy clusters.
- ❑ Detect Type Ia supernovae (SNe Ia) out to redshift z ~ 2.5.
- ❑ Detect the most distant galaxies yet discovered at z > 7.
- ❑ Study the internal structure and evolution of the galaxies in galaxy clusters.

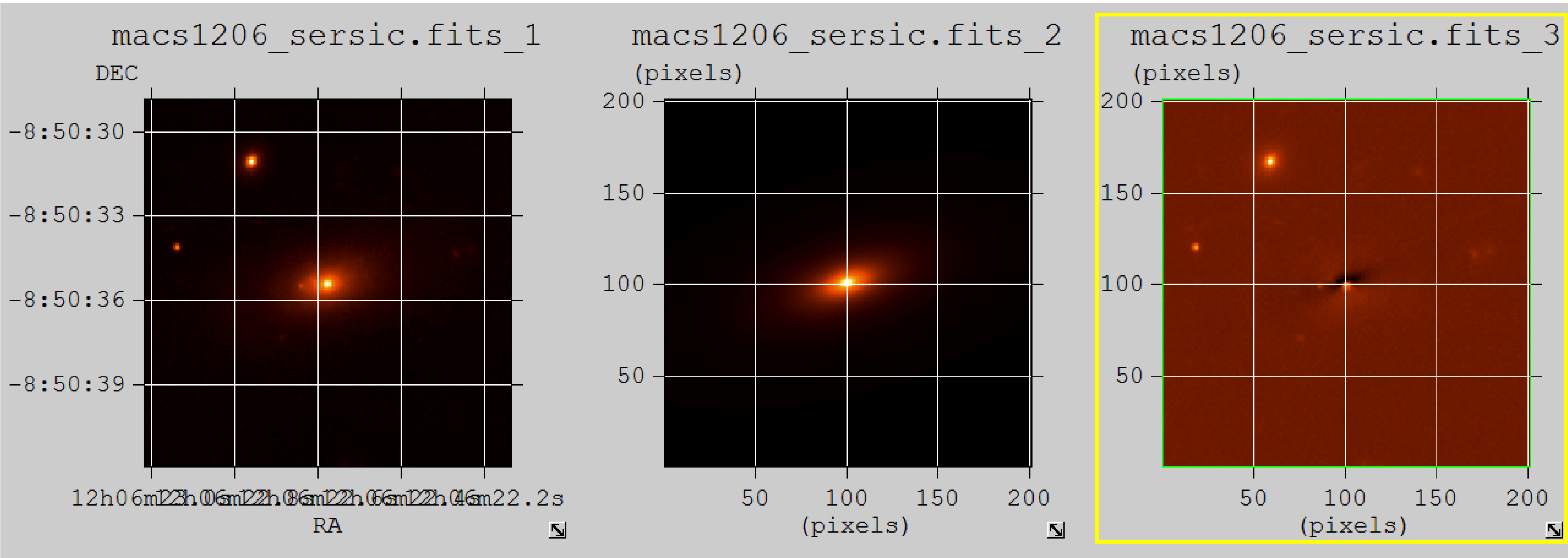
Linear Interpolation of Lensing Mass Profile



Linear Interpolation of Gas Mass Profile



Effective Radius of BCGs by GALFIT




```
Input image     : macs1206_65mas_f814w.fits[2378:2578,2340:2540]
Init. par. file : macs1206_ser.feedme
Restart file    : galfit.11
Output image    : macs1206_sersic.fits

 sersic    : ( 2477.24,  2440.29)   27.35      96.24     3.97     0.43
             (    0.13,     0.07)    0.03       5.36     0.14     0.00
 sky       : [2478.00, 2440.00]  2.25e-03  [0.00e+00]  [0.00e+00]
                                 1.77e-04  [0.00e+00]  [0.00e+00]
 Chi^2 = 6027.41143,  ndof = 40393
 Chi^2/nu = 0.149
```

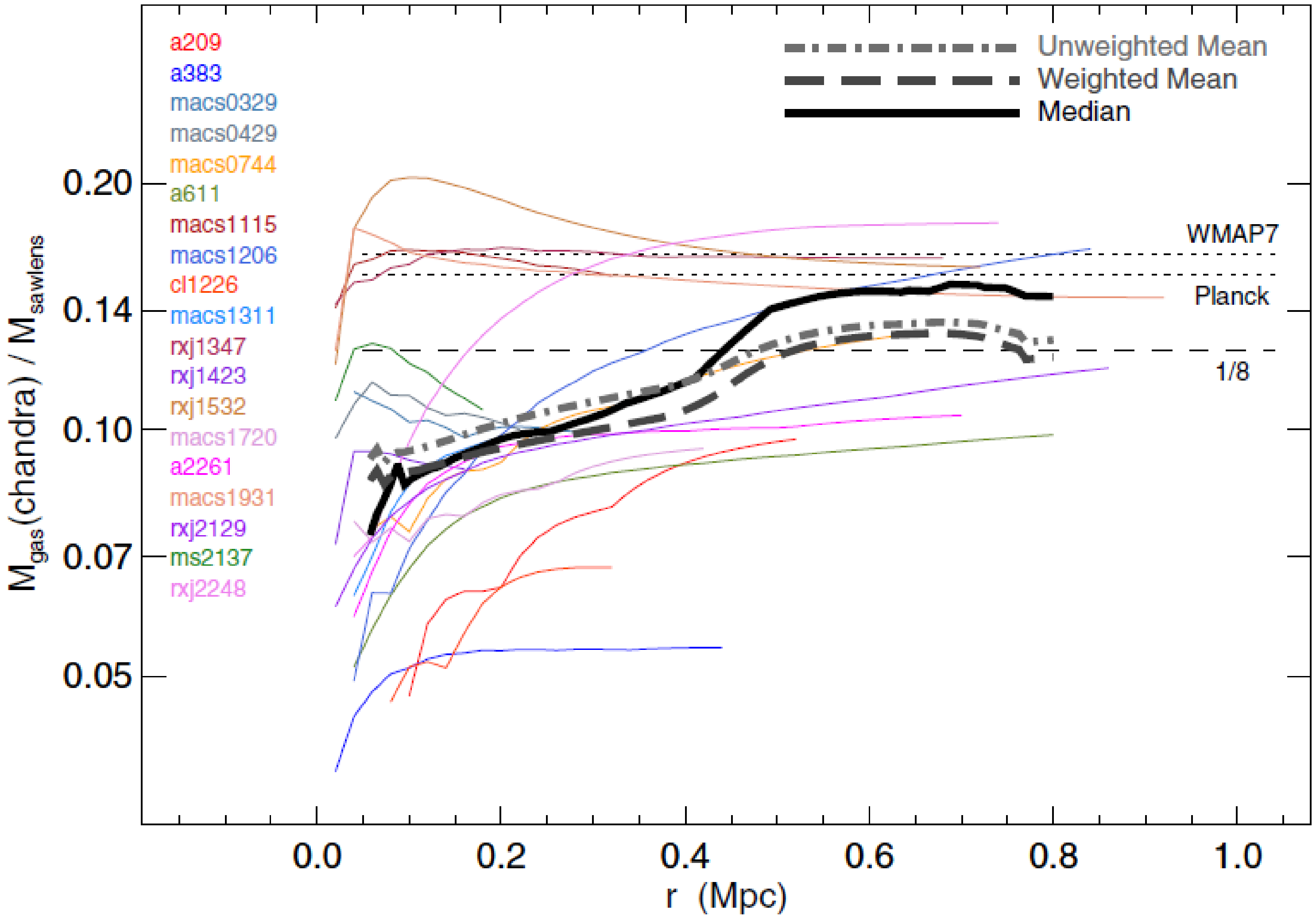
```
# Object number: 1
 0) sersic                 #  object type
 1) 2478  2440  1 1        #  position x, y
 3) 20.0000     1          #  Integrated magnitude
 4) 50          1          #  R_e (half-light radius)   [pix]
 5) 1.0         1          #  Sersic index n (de Vaucouleurs n=4)
 6) 0.0000      0          #     -----
 7) 0.0000      0          #     -----
 8) 0.0000      0          #     -----
 9) 1           1          #  axis ratio (b/a)
10) -60.3690    1          #  position angle (PA) [deg: Up=0, Left=90]
 Z) 0                      #  output option (0 = resid., 1 = Don't subtract)

# Object number: 2
 0) sky                    #  object type
 1) 1.3920      1          #  sky background at center of fitting region [ADUs]
 2) 0.0000      0          #  dsky/dx (sky gradient in x)
 3) 0.0000      0          #  dsky/dy (sky gradient in y)
 Z) 0                      #  output option (0 = resid., 1 = Don't subtract)
```

The Astrophysical Journal, 794:136 (21pp), 2014 October 20 doi:10.1088/0004-637X/794/2/136

CLASH-X: A COMPARISON OF LENSING AND X-RAY TECHNIQUES FOR MEASURING THE MASS PROFILES OF GALAXY CLUSTERS

Megan Donahue[1], G. Mark Voit[1], Andisheh Mahdavi[2], Keiichi Umetsu[3,4], Stefano Ettori[5], Julian Merten[6],



The Astrophysical Journal, 794:136 (21pp), 2014 October 20 doi:10.1088/0004-637X/794/2/136

CLASH-X: A COMPARISON OF LENSING AND X-RAY TECHNIQUES FOR MEASURING THE MASS PROFILES OF GALAXY CLUSTERS

Megan Donahue[1], G. Mark Voit[1], Andisheh Mahdavi[2], Keiichi Umetsu[3,4], Stefano Ettori[5], Julian Merten[6], Marc Postman[7], Aaron Hoffer[1], Alessandro Baldi[1], Dan Coe[7], Nicole Czakon[3,4], Mattias Bartelmann[8],

Table 4
Chandra HSE Masses

Name	v_{max} (km s^{-1})	$\sigma_{v_{max}}$	r_s (h_{70}^{-1} Mpc)	σ_{r_s}	r_{2500} (h_{70}^{-1} Mpc)	$\sigma_{r_{2500}}$	M_{2500} ($10^{14} h_{70}^{-1}$ $M_\odot$)	$\sigma_{M_{2500}}$	$f_{g,2500}$ ($h_{70}^{-3/2}$)	$\sigma_{f_{g,2500}}$	r_{500} (h_{70}^{-1} Mpc)	$\sigma_{r_{500}}$
A209	1743	126	0.745	0.653	0.47	0.014	2.49	0.36	0.11	0.005	1.31	0.16
A383	1184	29	0.22	0.017	0.436	0.007	1.42	0.07	0.107	0.003	0.94	0.021
MACS 0329−02	1485	80	0.36	0.10	0.46	0.017	2.24	0.24	0.117	0.007	1.05	0.056
MACS 0429−02	1496	171	0.30	0.10	0.486	0.034	2.49	0.57	0.105	0.01	1.07	0.105
MACS 0744+39	1631	84	0.43	0.16	0.425	0.015	2.34	0.24	0.128	0.007	1.01	0.07
A611	1678	92	0.57	0.17	0.552	0.019	3.20	0.35	0.088	0.0044	1.30	0.09
MACS 1115+01	1664	106	0.45	0.097	0.546	0.023	3.30	0.42	0.113	0.0077	1.25	0.091
A1423	1297	61	0.275	0.051	0.47	0.014	1.82	0.17	0.094	0.0037	1.03	0.042
MACS 1206−08	2002	148	0.71	0.507	0.587	0.03	4.59	0.68	0.122	0.0077	1.43	0.16
CL J1226+33*	4975		3.89	6.38	0.705	0.05	13.6	2.90	0.038	0.007	2.30	0.36
MACS 1311−03	1390	116	0.32	0.094	0.42	0.022	1.80	0.30	0.108	0.01	0.95	0.08
RX J1347	2318	57	0.403	0.03	0.735	0.012	9.14	0.45	0.104	0.003	1.60	0.035
MACS 1423+24	1579	146	0.287	0.047	0.472	0.026	2.70	0.50	0.099	0.0075	1.04	0.07
MACS 1532+30	1629	41	0.46	0.042	0.525	0.009	3.00	0.15	0.119	0.004	1.22	0.033
MACS 1720+35	1467	89	0.273	0.05	0.483	0.018	2.40	0.29	0.114	0.006	1.05	0.055
A2261	1571	56	0.304	0.059	0.567	0.013	3.24	0.23	0.1096	0.004	1.23	0.045
MACS 1931−26	1522	33	0.279	0.02	0.511	0.008	2.74	0.12	0.133	0.0035	1.11	0.023
RX J2129+00	1488	70	0.34	0.043	0.529	0.017	2.67	0.25	0.105	0.004	1.17	0.048
MS 2137-2353	1312	44	0.164	0.016	0.449	0.01	1.78	0.12	0.1205	0.0048	0.93	0.027
RX J2248−44	2272	125	0.828	0.326	0.706	0.025	7.19	0.79	0.1226	0.0067	1.71	0.14

THE ASTROPHYSICAL JOURNAL, 821:116 (29pp), 2016 April 20
doi:10.3847/0004-637X/821/2/116

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CLASH: JOINT ANALYSIS OF STRONG-LENSING, WEAK-LENSING SHEAR, AND MAGNIFICATION DATA FOR 20 GALAXY CLUSTERS*

KEIICHI UMETSU[1], ADI ZITRIN[2,10], DANIEL GRUEN[3,4,5,6,11], JULIAN MERTEN[7], MEGAN DONAHUE[8], AND MARC POSTMAN[9]
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Received 2015 July 19; accepted 2016 March 2; published 2016 April 20

Table 3
Mass Estimates for Individual CLASH Clusters

Cluster	M_{2500c} ($10^{14}\,M_{\odot}$)	M_{1000c} ($10^{14}\,M_{\odot}$)	M_{500c} ($10^{14}\,M_{\odot}$)	M_{vir}[a] ($10^{14}\,M_{\odot}$)	M_{100c} ($10^{14}\,M_{\odot}$)	M_{200m} ($10^{14}\,M_{\odot}$)	M (<1.5 Mpc) ($10^{14}\,M_{\odot}$)
X-ray Selected:							
Abell 383	2.78 ± 0.63	4.43 ± 1.16	5.88 ± 1.73	9.41 ± 3.33	9.66 ± 3.45	10.34 ± 3.78	6.95 ± 1.63
Abell 209	2.95 ± 0.68	6.18 ± 1.25	9.64 ± 1.97	19.60 ± 4.61	20.49 ± 4.88	22.36 ± 5.44	10.28 ± 1.37
Abell 2261	5.91 ± 1.03	10.85 ± 1.89	15.65 ± 3.05	28.21 ± 6.87	29.39 ± 7.26	31.41 ± 7.94	14.22 ± 1.79
RX J2129.7+0005	2.08 ± 0.44	3.35 ± 0.78	4.48 ± 1.16	7.21 ± 2.23	7.48 ± 2.34	7.87 ± 2.51	5.75 ± 1.23
Abell 611	4.13 ± 0.92	7.48 ± 1.67	10.73 ± 2.65	18.95 ± 5.77	19.99 ± 6.21	20.78 ± 6.54	11.24 ± 1.95
MS2137-2353	2.47 ± 0.72	5.21 ± 1.41	8.28 ± 2.57	16.98 ± 7.31	18.25 ± 8.12	18.91 ± 8.54	9.67 ± 2.12
RX J2248.7-4431	4.45 ± 1.05	8.42 ± 2.08	12.45 ± 3.62	22.54 ± 8.78	24.12 ± 9.68	24.53 ± 9.91	12.67 ± 2.50
MACS J1115.9+0129	3.50 ± 0.82	7.02 ± 1.43	10.67 ± 2.22	20.30 ± 4.97	21.88 ± 5.48	22.24 ± 5.60	11.55 ± 1.61
MACS J1931.8-2635	4.10 ± 1.12	7.36 ± 2.36	10.51 ± 4.05	18.02 ± 9.05	19.18 ± 9.88	19.44 ± 10.07	11.23 ± 3.07
RX J1532.9+3021	1.83 ± 1.01	3.03 ± 1.38	4.17 ± 1.71	7.04 ± 2.79	7.51 ± 3.02	7.58 ± 3.06	5.81 ± 1.63
MACS J1720.3+3536	3.92 ± 0.86	7.00 ± 1.59	9.96 ± 2.53	17.04 ± 5.39	18.29 ± 5.94	18.30 ± 5.94	11.02 ± 2.05
MACS J0429.6-0253	2.85 ± 0.70	4.92 ± 1.32	6.85 ± 2.10	11.35 ± 4.33	12.15 ± 4.76	12.13 ± 4.74	8.40 ± 2.03
MACS J1206.2-0847	4.62 ± 1.01	8.47 ± 1.63	12.24 ± 2.49	21.35 ± 5.29	23.18 ± 5.94	22.82 ± 5.81	12.98 ± 1.84
MACS J0329.7-0211	3.29 ± 0.64	5.02 ± 1.00	6.51 ± 1.37	9.72 ± 2.30	10.35 ± 2.50	10.21 ± 2.45	7.94 ± 1.36
RX J1347.5-1145	7.65 ± 1.63	14.91 ± 2.98	22.33 ± 4.89	40.66 ± 11.13	44.50 ± 12.60	43.59 ± 12.25	19.33 ± 2.61
MACS J0744.9+3927	4.32 ± 1.02	8.12 ± 1.76	11.94 ± 2.81	20.57 ± 5.98	23.21 ± 7.08	21.32 ± 6.29	13.96 ± 2.39

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THE MASS DISCREPANCY–ACCELERATION RELATION: DISK MASS AND THE DARK MATTER DISTRIBUTION

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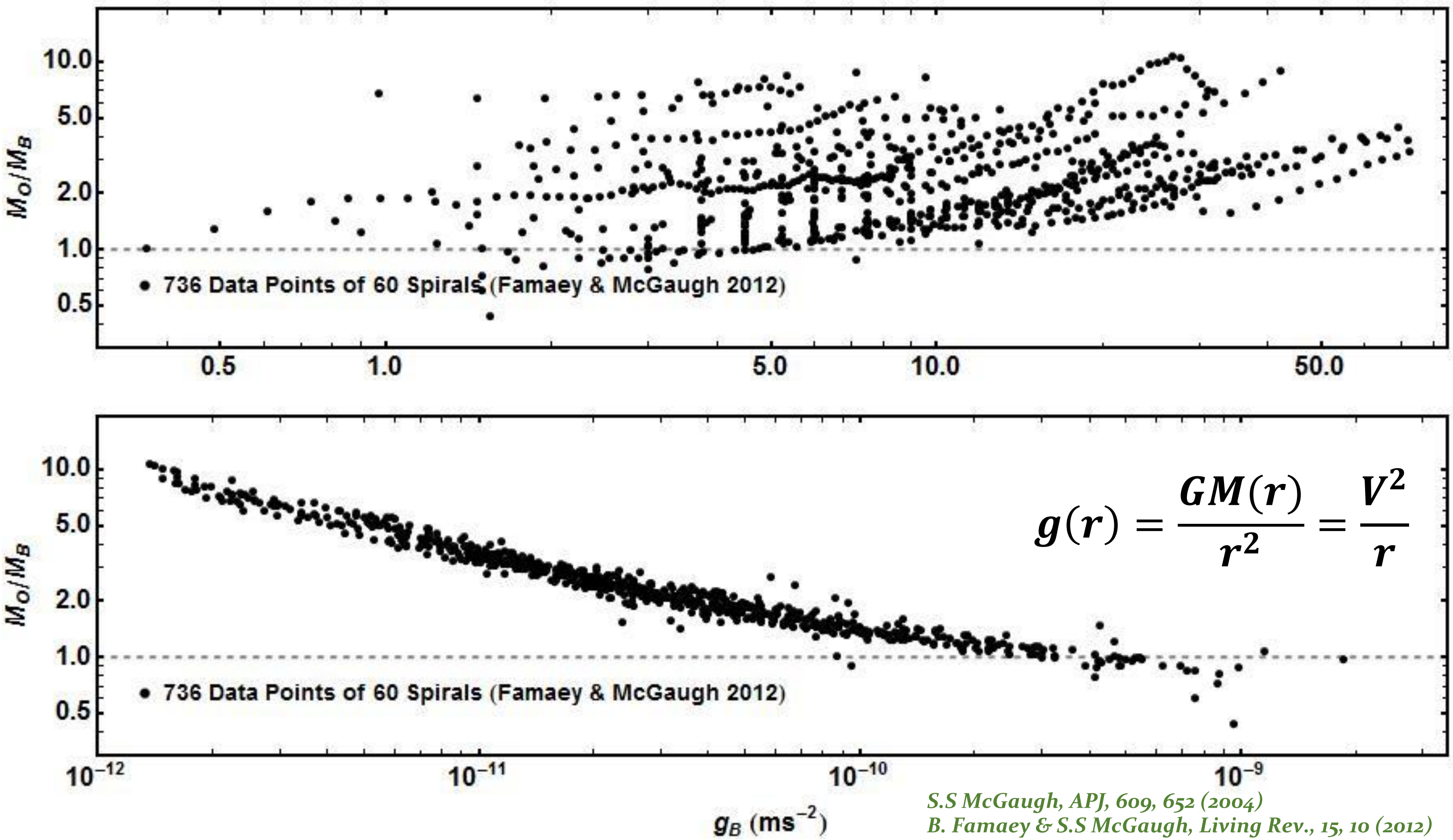

$$g(r) = \frac{GM(r)}{r^2} = \frac{V^2}{r}$$

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Mass-Discrepancy Acceleration Relation: A Natural Outcome of Galaxy Formation in Cold Dark Matter Halos

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