The Discrepancy between Dynamical and Baryonic Surface Density of Elliptical Galaxies

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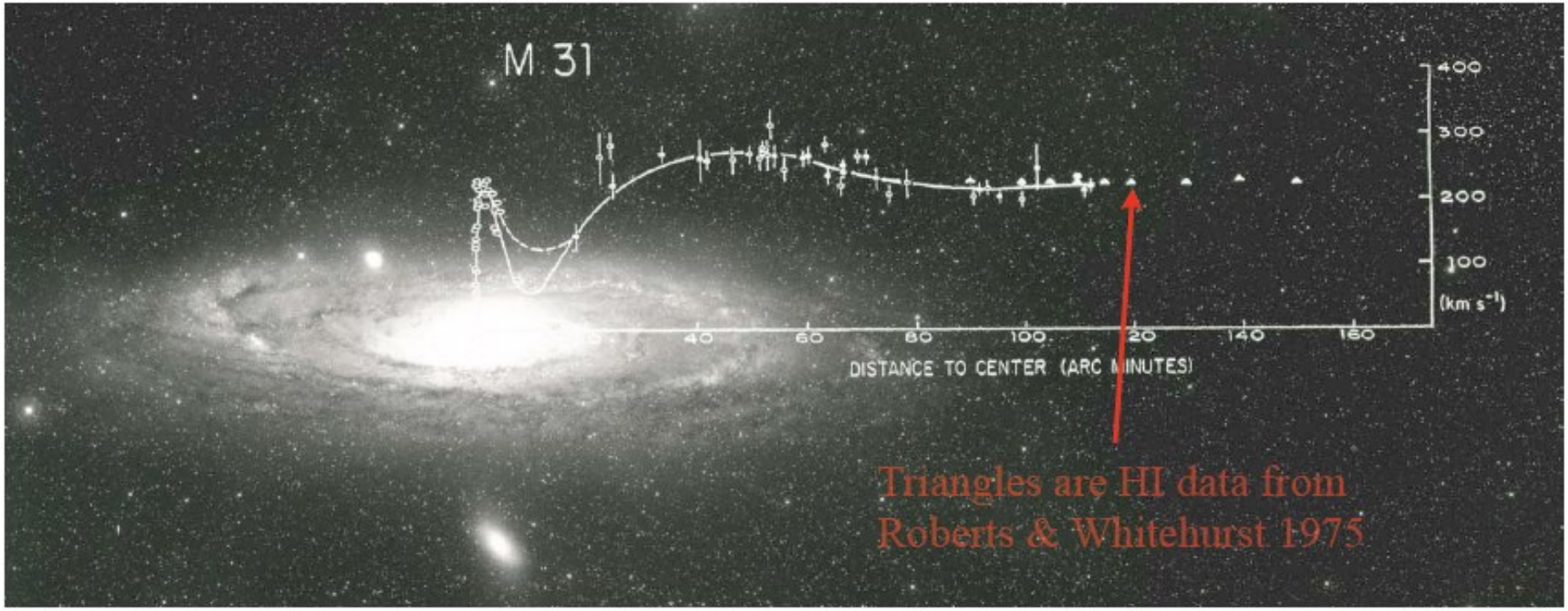
4th Jul. APRIM, Taipei

Outline

- The “Missing Mass” Problem
- Mass Acceleration-Discrepancy Relation
- Surface Density Discrepancy
  - Spiral Galaxies
  - Elliptical Galaxies
- Summary

Flat Rational Curves



1970 ApJ 159, 379

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

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

THE ASTROPHYSICAL JOURNAL, 609:652–666, 2004 July 10

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

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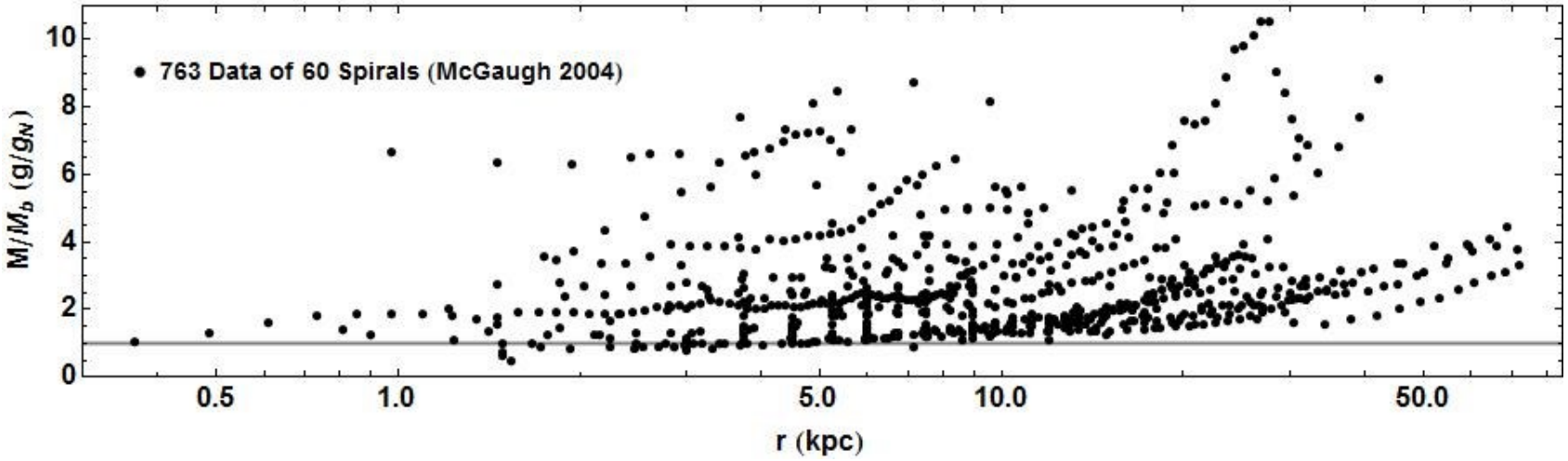
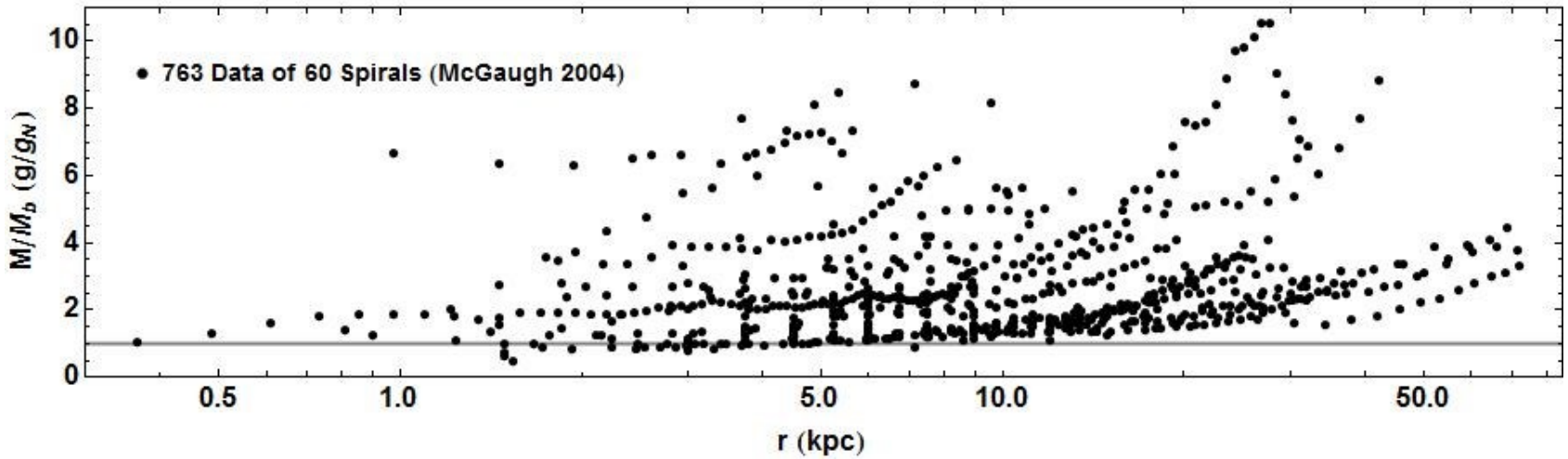
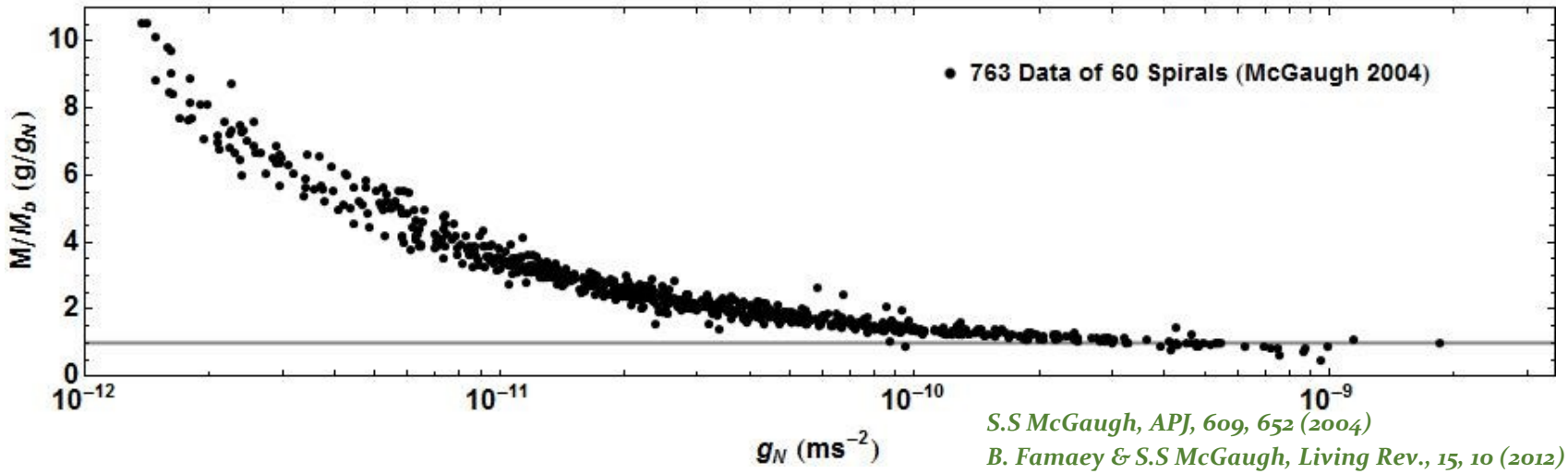
$$g(r) = \frac{GM(r)}{r^2} = \frac{V^2}{r} \qquad \frac{g(r)}{g_{\rm N}(r)} = \frac{M(r)}{M_{\rm b}(r)} = \frac{V^2}{V_{\rm b}^2}$$



Mass Discrepancy-Acceleration Relation

$$g(r) = \frac{GM(r)}{r^2} = \frac{V^2}{r} \qquad \frac{g(r)}{g_{\rm N}(r)} = \frac{M(r)}{M_{\rm b}(r)} = \frac{V^2}{V_{\rm b}^2}$$





S.S McGaugh, APJ, 609, 652 (2004)
B. Famaey & S.S McGaugh, Living Rev., 15, 10 (2012)

The Astrophysical Journal Letters, 827:L19 (6pp), 2016 August 10 doi:10.3847/2041-8205/827/1/L19

CrossMark

THE RELATION BETWEEN STELLAR AND DYNAMICAL SURFACE DENSITIES IN THE CENTRAL REGIONS OF DISK GALAXIES

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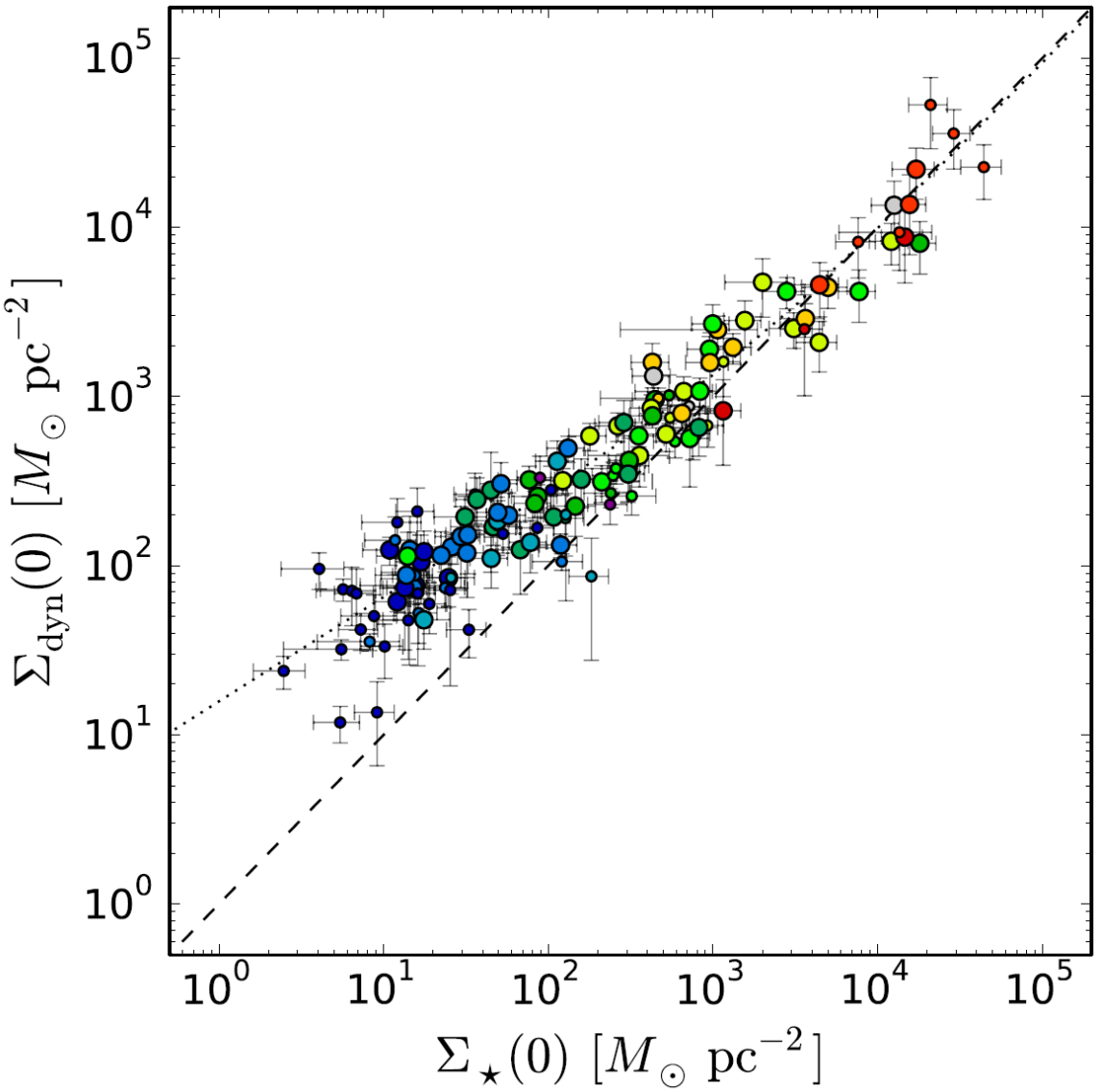
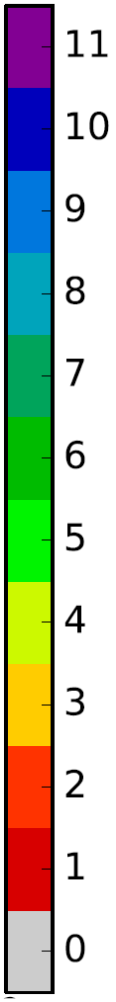
- **135 galaxies from SPARC database with high-quality HI rotation curves and Spitzer surface photometry.**
- **Dynamical surface density can be calculated from HI rotation curves by**

$$\Sigma_{\rm dyn}(0) = \frac{1}{2\pi G}\int_0^\infty \frac{V^2(R)}{R^2}dR,$$

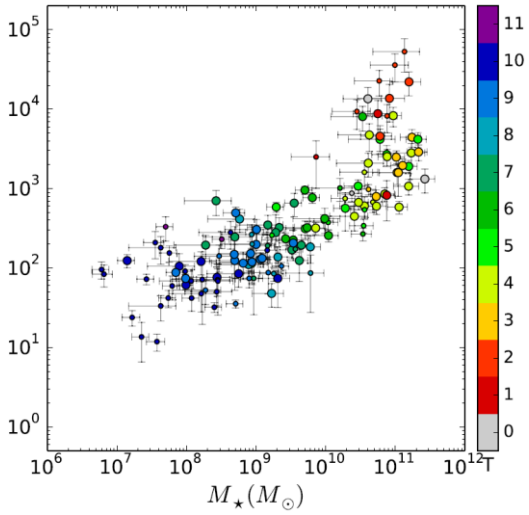
- **Stellar surface density can be estimated from the near-IR surface brightness.**

Mass Discrepancy in Surface Density





$$\Sigma = \frac{M}{\pi r^2} \approx \frac{a}{G}$$



$$\Sigma_{\rm dyn}(0) = \Sigma_0 \left[1 + \frac{\Sigma_\star(0)}{\Sigma_{\rm crit}}\right]^{\alpha-\beta} \left[\frac{\Sigma_\star(0)}{\Sigma_{\rm crit}}\right]^{\beta}$$

$$\alpha = 0.97 \pm 0.06$$
$$\beta = 0.61 \pm 0.04$$
$$\Sigma_0 = \Sigma_{\rm crit} = 1271 \pm 463 \quad [M_\odot\ {\rm pc}^{-2}].$$

F. Lelli et. al., APJL, 827, L19 (2016)

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

Radial Acceleration Relation in Rotationally Supported Galaxies

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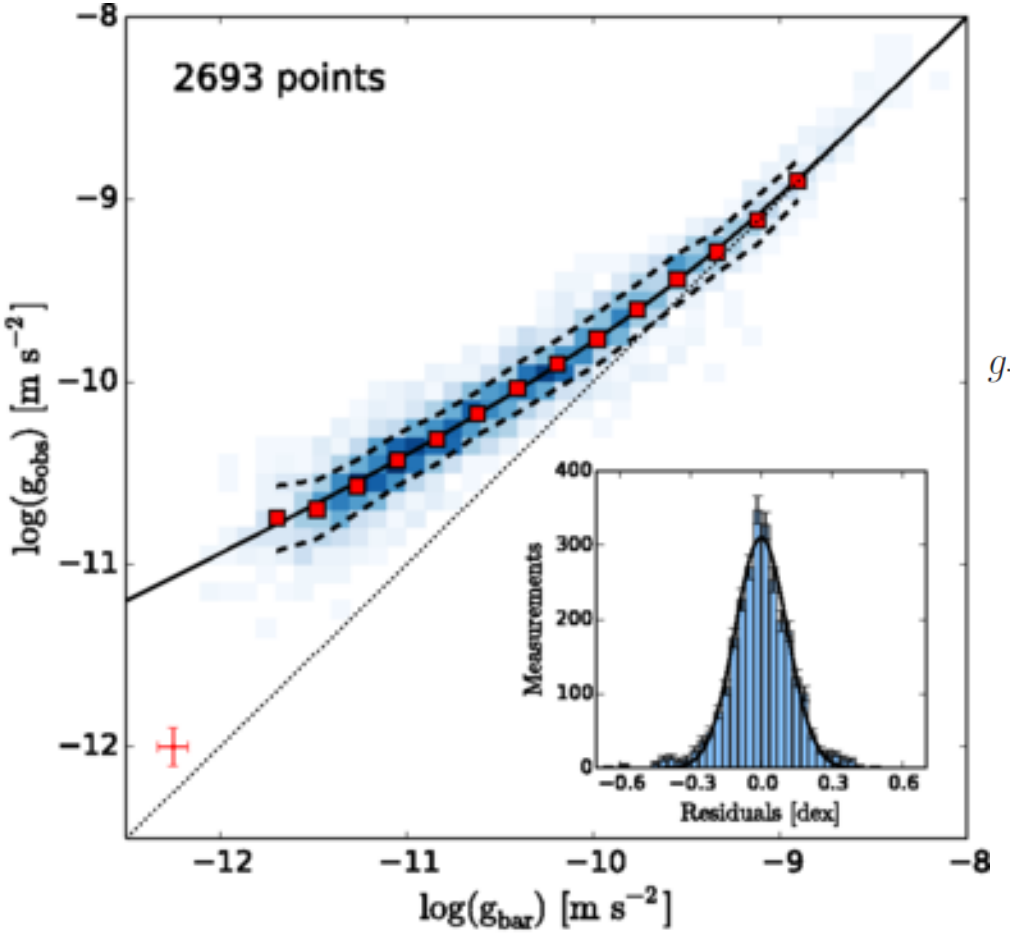
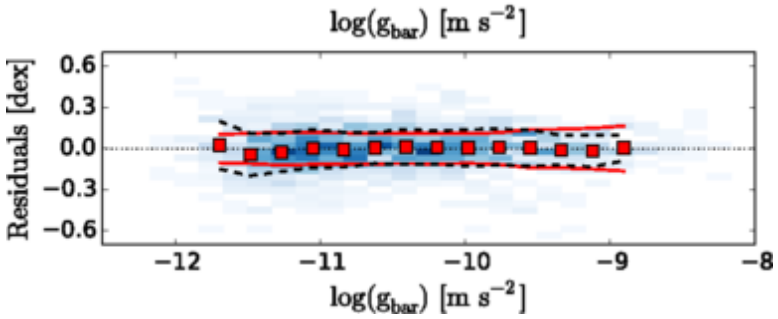
(Received 18 May 2016; revised manuscript received 7 July 2016; published 9 November 2016)



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

$$g_\dagger = 1.20 \pm 0.02\,(\text{random}) \pm 0.24\,(\text{syst}) \times 10^{-10}\ \text{ms}^{-2}$$



Elliptical Galaxies?

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **460,** 4492–4512 (2016)
Advance Access publication 2016 May 25

doi:10.1093/mnras/stw1248

An extensive catalogue of early-type galaxies in the nearby Universe

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ABSTRACT

We present a catalogue of 1715 early-type galaxies from the literature, spanning the luminosity range from faint dwarf spheroidal galaxies to giant elliptical galaxies. The aim of this catalogue

Table 11. Structural properties and internal dynamics of the galaxies in this catalogue. A portion of the table is shown here for guidance regarding its contents and form. A detailed description of the contents of this table is given in Section 7.2. The table in its entirety can be downloaded at http://www.astro-udec.cl/mf/catalogue/.

id	R_e (pc)	dR_e (pc)	s.	n	dn	s.	σ_e (km s^{-1})	$+$dσ_e (km s^{-1})	$-$dσ_e (km s^{-1})	s.	σ_0 (km s^{-1})	$+$dσ_0 (km s^{-1})	$-$dσ_0 (km s^{-1})	s.	v_{rot} (km s^{-1})	$+$dv_{rot} (km s^{-1})	$-$dv_{rot} (km s^{-1})	s.	M_{dyn} [lg($M_\odot$)]	dM_{dyn} [lg($M_\odot$)]	s.
501	1879.9	188.0	1	2.8	0.4	1	75.7	3.8	3.8	1	76.7	3.8	3.8	1	58.3	−9.9	−9.9	1	9.75	0.09	1
502	2433.1	243.3	1	4.2	1.7	1	82.0	4.1	4.1	1	91.8	4.6	4.6	1	21.9	−9.9	−9.9	1	9.70	0.09	1
503	2043.4	204.3	1	8.4	2.0	1	128.5	6.4	6.4	1	132.4	6.6	6.6	1	36.2	−9.9	−9.9	1	10.23	0.09	1
504	6949.9	−9.9	2	5.2	2.2	0	267.3	−9.9	−9.9	101	290.4	−9.9	−9.9	2	−9.9	−9.9	−9.9	0	11.68	−99.99	101
505	2393.8	239.4	1	4.4	0.4	1	62.2	3.1	3.1	1	56.2	2.8	2.8	1	8.5	−9.9	−9.9	1	9.65	0.09	1

Table 15. Stellar populations of the galaxies in this catalogue. A portion of the table is shown here for guidance regarding its contents and form. A detailed description of the contents of this table is given in Section 8.2. The table in its entirety can be downloaded at http://www.astro-udec.cl/mf/catalogue/.

id	t (Gyr)	$+$dt (Gyr)	$-$dt (Gyr)	s.	[Z/H]	$+$d[Z/H]	$-$d[Z/H]	s.	M_s lg($M_\odot$)	dM_s lg($M_\odot$)	s.
501	3.5	0.6	0.6	1	−0.38	0.06	0.06	1	9.81	−99.99	1011
502	1.0	0.1	0.1	1	0.18	0.06	0.06	1	9.68	−99.99	1011
503	9.7	1.6	1.6	1	−0.36	0.05	0.05	1	10.09	−99.99	1011
504	−9.9	−9.9	−9.9	0	0.06	99.99	99.99	1020	11.46	−99.99	1020
505	2.5	0.3	0.3	1	−0.78	0.06	0.06	1	9.18	−99.99	1011

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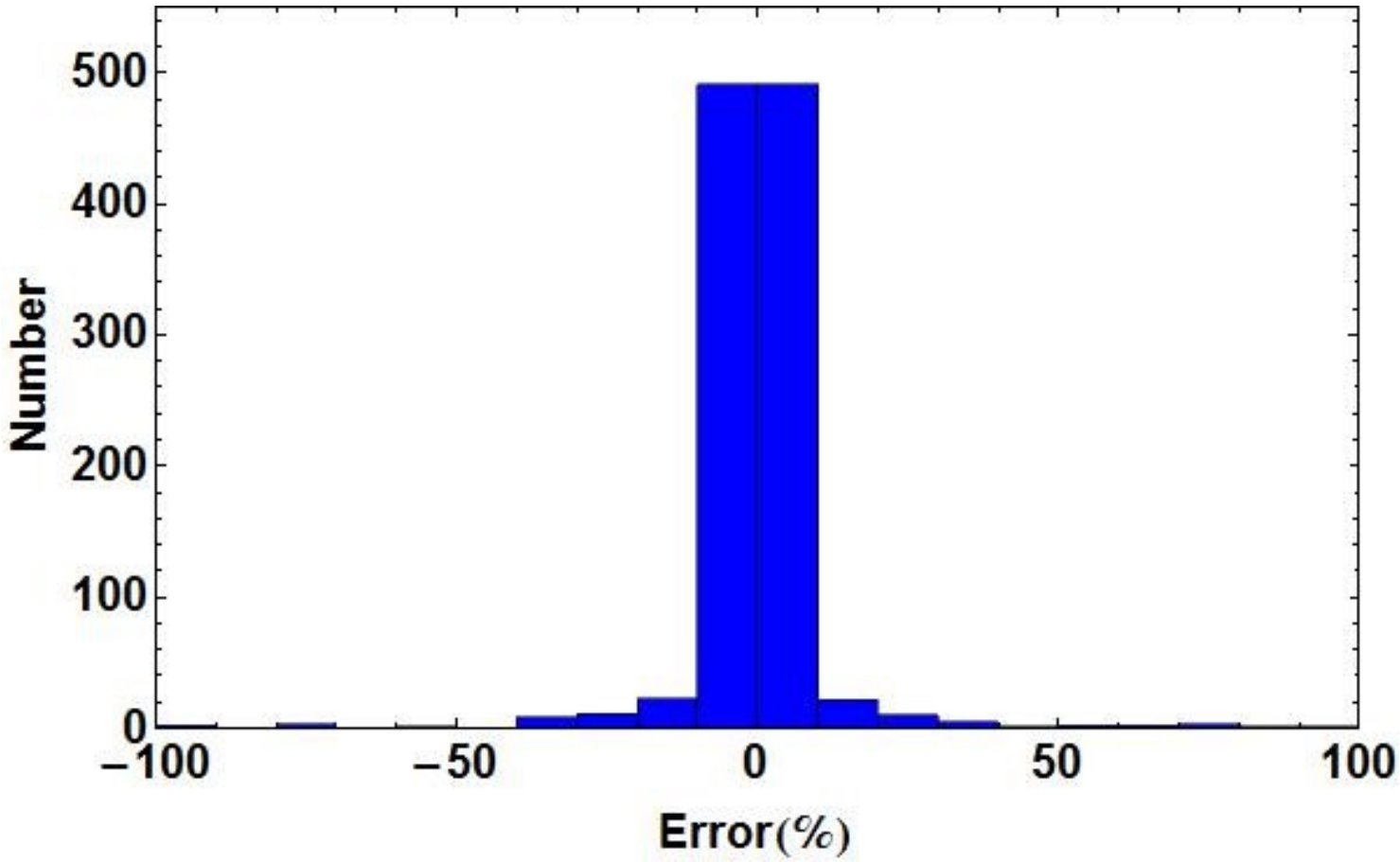
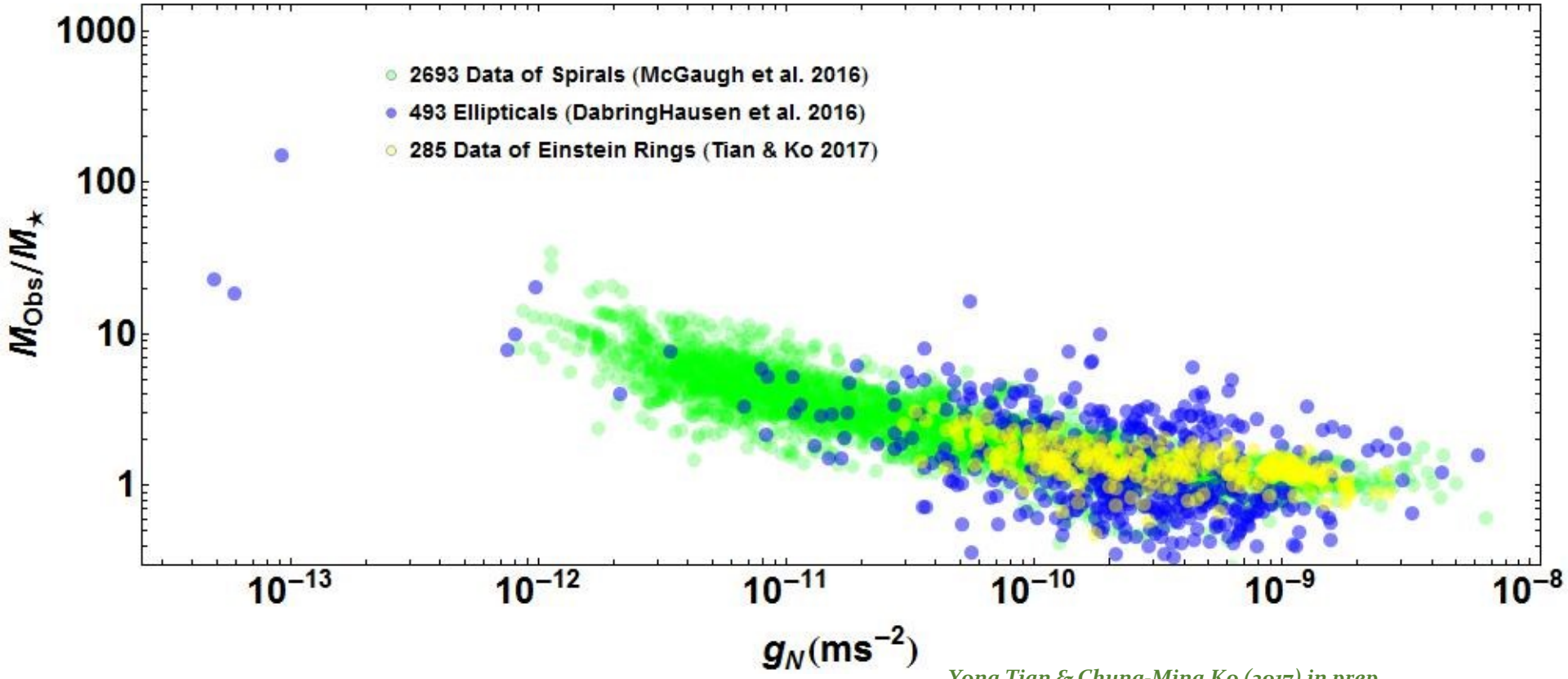
Accepted 2016 May 23. Received 2016 May 21; in original form 2015 September 5



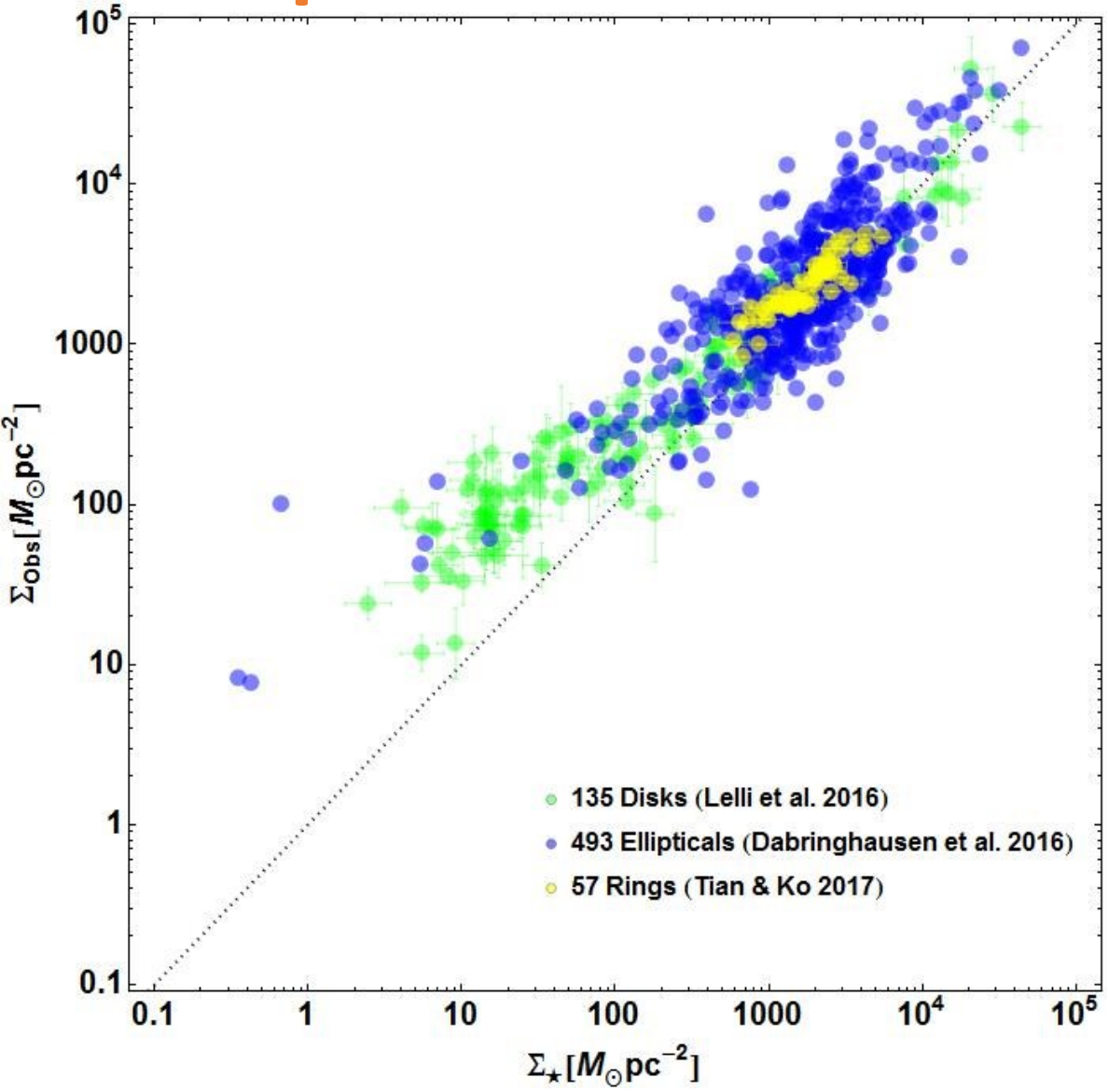
Mass Discrepancy-Acceleration Relation in Elliptical Galaxies

$$g(r) = \frac{GM(r)}{r^2} \qquad \frac{g(r)}{g_{\rm N}(r)} = \frac{M(r)}{M_{\rm b}(r)}$$



Yong Tian & Chung-Ming Ko (2017) in prep.

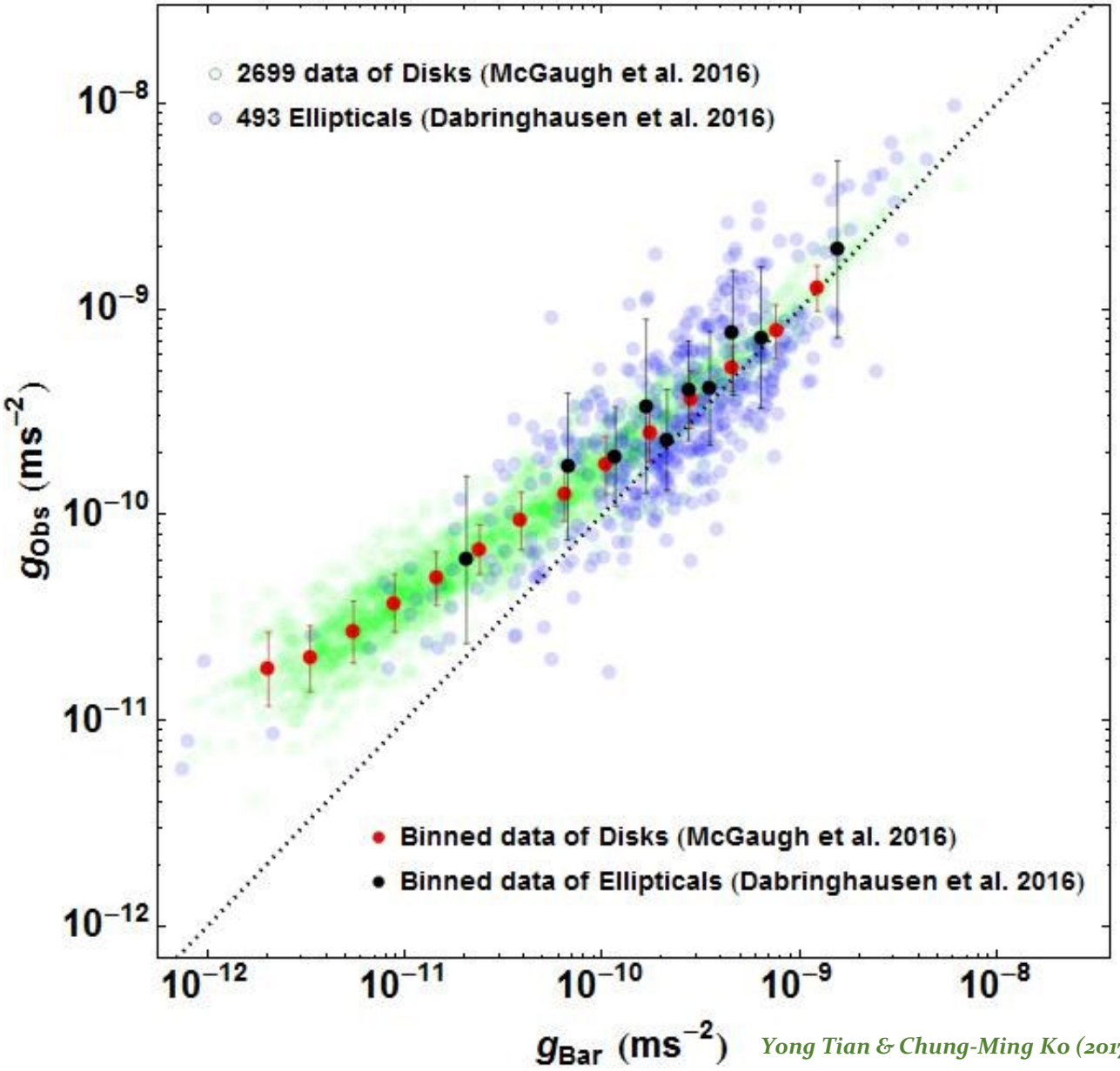
Surface Density Discrepancy in Elliptical Galaxies



$$\Sigma = \frac{M}{\pi r^2} \approx \frac{a}{G}$$

Yong Tian & Chung-Ming Ko (2017) in prep.

Radial Acceleration Relation



Yong Tian & Chung-Ming Ko (2017) in prep.

Surface Density Discrepancy in Modified Newtonian Dynamics

- **Modified Newtonian Dynamics (MOND)**

$$g \approx g_N \nu(g_N/a_0)$$

$$\nu(y \gg 1) \approx 1$$
$$\nu(y \ll 1) \approx y^{-1/2}$$

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

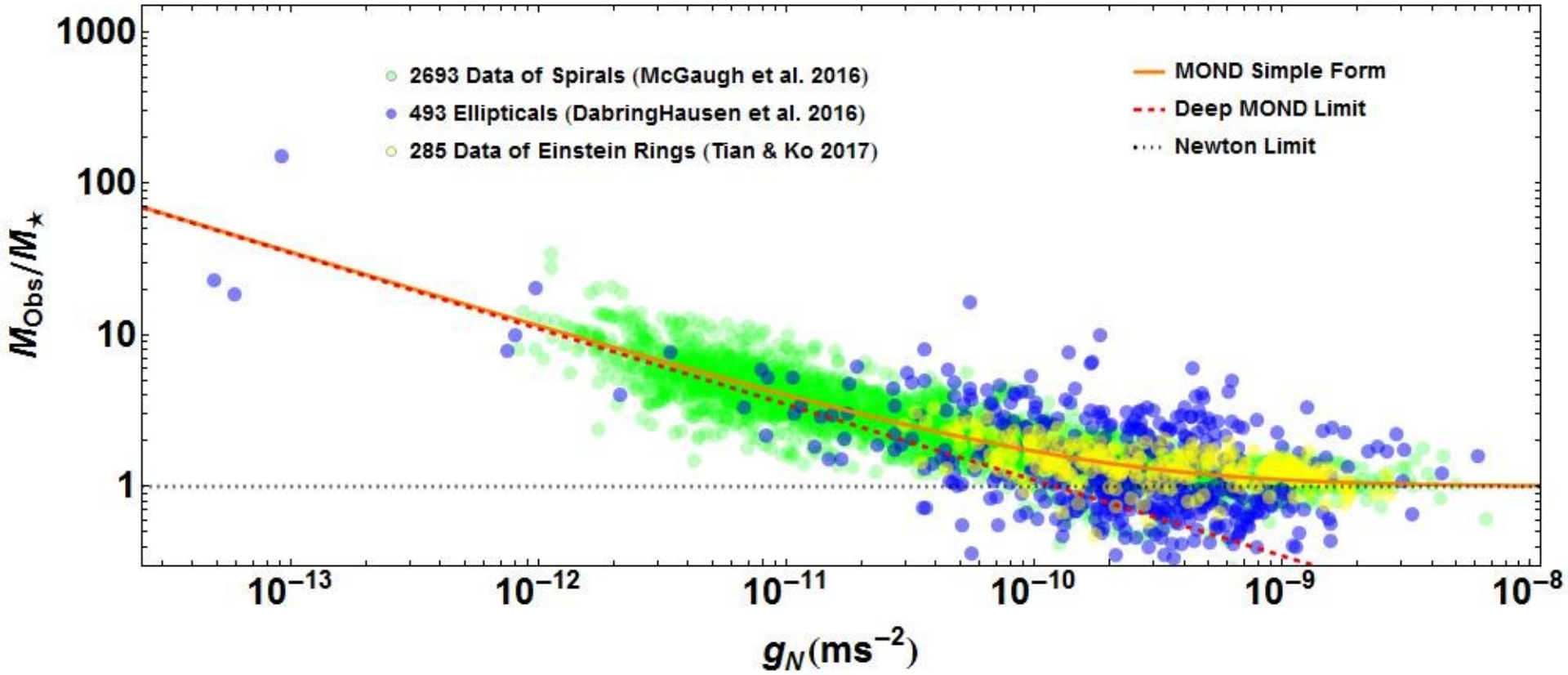
- **The surface density** $\Sigma = \frac{M}{\pi r^2} \approx \frac{a}{G}$
- **In MOND, the criterion is** $\Sigma_0 \equiv \frac{a_0}{G} = 276\, M_\odot\, pc^{-2}$
- **High-Surface-Density galaxies are as $\Sigma > \Sigma_0$**
- **Low-Surface-Density galaxies are as $\Sigma < \Sigma_0$**

Milgrom, ApJ (1983)

Sanders & McGaugh, ARAA (2002)

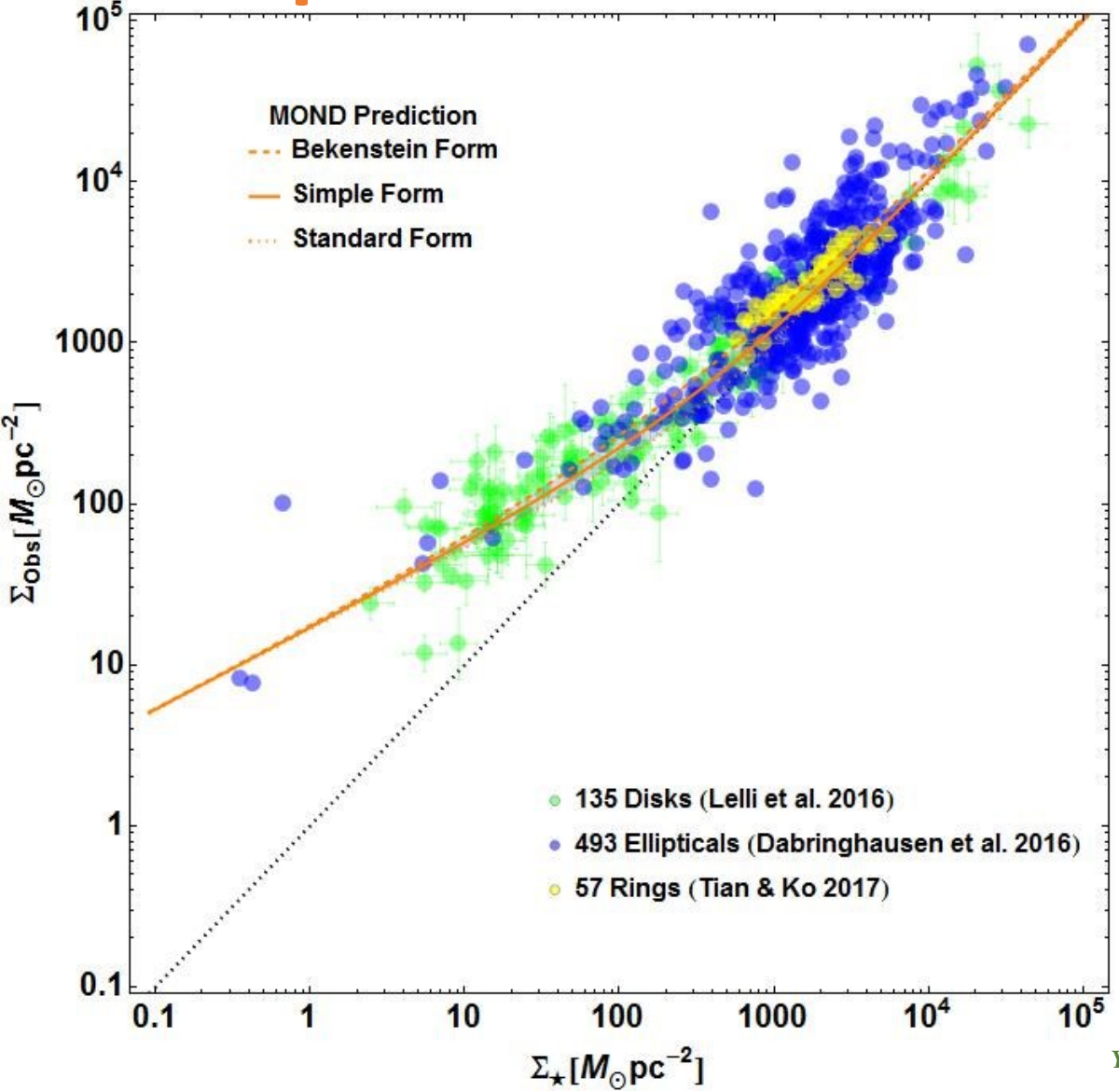
Mass Discrepancy-Acceleration Relation in Elliptical Galaxies

$$g(r) = \frac{GM(r)}{r^2} \qquad \frac{g(r)}{g_{\rm N}(r)} = \frac{M(r)}{M_{\rm b}(r)} = \nu(y)$$



Yong Tian & Chung-Ming Ko (2017) in prep.

Surface Density Discrepancy in Elliptical Galaxies



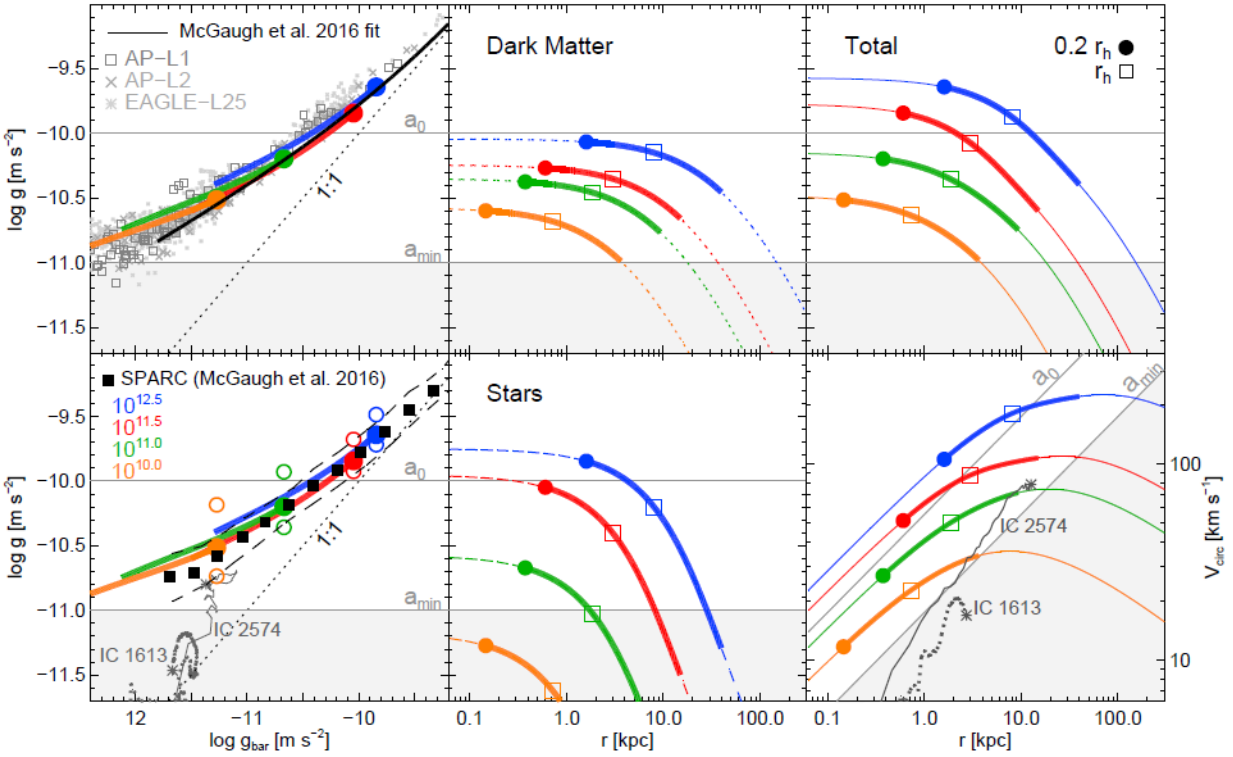
$$\Sigma = \frac{M}{\pi r^2} \approx \frac{a}{G}$$

$$\Sigma_0 \equiv \frac{\mathfrak{a}_0}{G} = 276\, M_\odot\, pc^{-2}$$

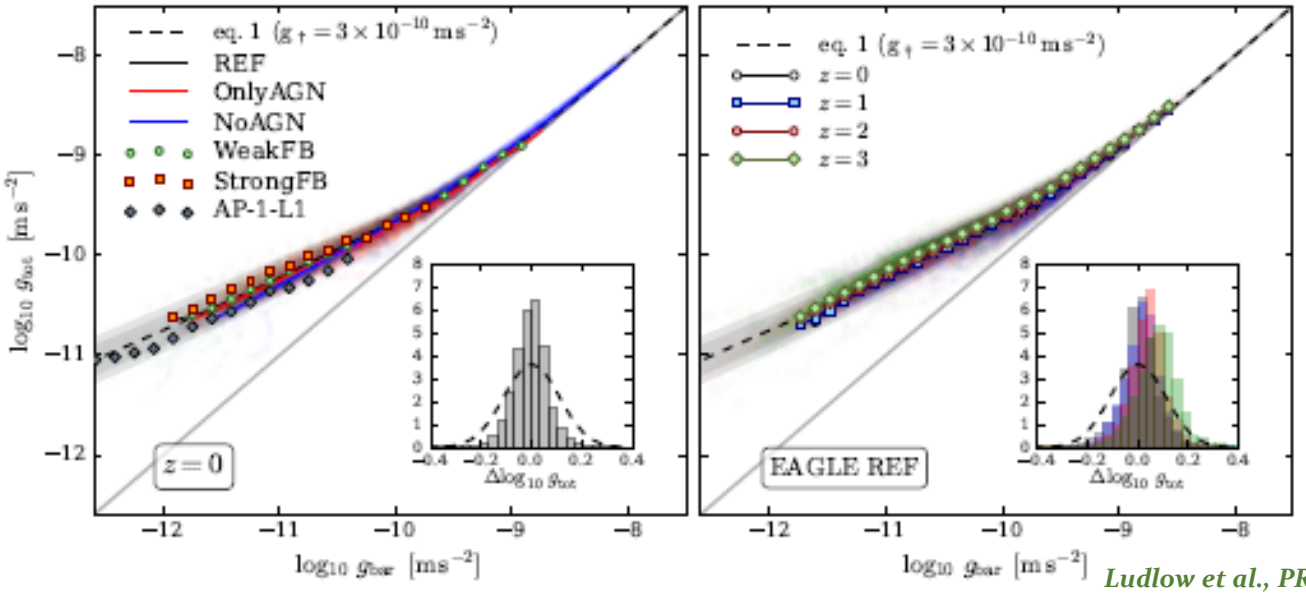
Yong Tian & Chung-Ming Ko (2017) in prep.

ΛCDM

- **Semi-empirical models (Navarro et al. 2016)**
- **Hydro-dynamical simulations (Wu & Kroupa 2015; Ludlow et al. 2017)**



Navarro et al. 2016 (arXiv:1612.06239)



Ludlow et al., PRL, 2017

Summary

- **Mass Acceleration-Discrepancy Relation (MDAR) and Surface Density Discrepancy in Elliptical galaxies is consistency with the result in the spiral galaxies.**
- **MDAR and Surface Density Discrepancy can be explained in MOND and ΛCDM.**

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If σ_0 and R_e are known for an ETG in this catalogue, its dynamical mass is calculated with

$$M_{\rm dyn} = \frac{K_{\rm V}}{G} R_{\rm e} \sigma_0^2, \tag{13}$$

where $K_{\rm V}$ is a factor that depends on the shape of the density profile of the ETG and G is the gravitational constant. We approximate $K_{\rm V}$ with equation 11 in Bertin, Ciotti & Del Principe (2002), i.e.

$$K_{\rm V}(n) = \frac{73.32}{10.465 + (n - 0.94)^2} + 0.954, \tag{14}$$

where n is the Sérsic index.

$$\log_{10}\left(\frac{\sigma_0}{\rm km\,s^{-1}}\right) = 1.0478 \log_{10}\left(\frac{\sigma_{\rm e}}{\rm km\,s^{-1}}\right) - 0.0909 \tag{11}$$