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Extending the Radial Acceleration Relation using Weak Gravitational Lensing with the Kilo-Degree Survey

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ABSTRACT
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1 INTRODUCTION

It has been known for several decades that the outer regions of galaxies rotate faster than would be expected from Newtonian dynamics based on their luminous, or 'baryonic', mass. This was first discovered by Rubin (1983) through measuring galactic rotation curves of optical disks, and by Bosma (1981) through measuring hydrogen profiles at radii beyond the disk. The excess gravity implied by these measurements has been generally attributed to an unknown and invisible substance named Dark Matter (DM), a term coined more than forty years prior by Zwicky (1937) when he discovered the so-called 'missing mass problem' through the dynamics of galaxies in clusters.

Following more recent observations using Weak gravitational Lensing (WL, Hoekstra et al. 2004; von der Linden et al. 2014; Mandelbaum 2015), Baryon Acoustic Oscillations (BAO's, Eisenstein et al. 2005; Blake et al. 2011) and the Cosmic Microwave background (CMB, Spergel et al. 2003; Planck XVI 2014), Cold Dark Matter[1] (CDM) became a key ingredient of the current standard model of cosmology: the ΛCDM model. In this paradigm, CDM accounts for $\Omega_{\rm CDM} = 0.266$ of the critical density in the Universe, while baryonic matter only accounts for $\Omega_{\rm CDM} = 0.049$ (Planck VI 2018). The cosmological constant Λ, which is necessary to explain the accelerated expansion of the Universe and is usually associated with Dark Energy (DE), accounts for $\Omega_\Lambda = 0.685$.

Although the ΛCDM model successfully describes the behavior of DM on a wide range of scales, no conclusive evidence for the existence of DM particles has been found so far (despite years of enormous effort; for an overview, see Bertone et al. 2005; Bertone & Tait 2018). This still leaves some room for alternative theories of gravity, such as Modified Newtonian Dynamics (MOND, Milgrom 1983) and the more recent theory of Emergent Gravity (EG, Verlinde 2016). In these theories particle DM does not exist, and all gravity is due to the baryonic matter (or, in the case of EG, the interaction between baryons and the entropy associated with DE). Hence, one of the main properties of these theories is that the mass discrepancy in galaxies correlates strongly with their baryonic mass distribution.

Such a correlation has indeed been widely observed. First astronomers discovered the Tully-Fisher relation (TFR, Tully & Fisher 1977) between the luminosity of a spiral galaxy and its asymptotic rotation velocity (Pierce & Tully 1988; Bernstein et al. 1994). Since this corresponds to a relation between the baryonic and the total galaxy mass, this has later been named the 'baryonic' TFR (BTFR, McGaugh et al. 2000; McGaugh 2012). As the radial resolution of observations increased, astronomers found a strong correlation between the observed rotation velocity $v_{\rm obs}(r)$ as a function of galaxy radius r, and the enclosed luminous mass $M_{\rm b}(<r)$ (Sanders 1986, 1996; McGaugh 2004; Sanders & Noordermeer 2007; Wu & Kroupa 2015). Since $M_{\rm b}(<r)$ corresponds to the expected gravitational acceleration $g_{\rm b}(r)$ from baryonic matter, and the observed gravitational acceleration can be calculated through $g_{\rm obs}(r) = v^2_{\rm obs}(r)/r$, this relation has been named the Radial Acceleration Relation (RAR)[2].

Particularly, the latest results from McGaugh et al. (2016) (hereafter M16) have measured the RAR relation with unprecedented accuracy, using the Spitzer Photometry and Accurate Rotation Curves (SPARC, Lelli et al. 2016) data of 153 late-type galaxies. Their results showed a tight correlation between $g_{\rm obs}$ and $g_{\rm bar}$, which they could fit using a simple double power law (Eq. 4 in M16) depending only on $g_{\rm bar}$ and one free parameter: the acceleration scale $g_\dagger$ where Newtonian gravity appears to break down. This sparked the interest of scientists working on alternative theories of gravity, but also of those in favor of a statistical explanation of the RAR within the ΛCDM framework (Keller & Wadsley 2017; Desmond 2017; Ludlow et al. 2017).

The latter possibility was quantified by Navarro et al. (2017) (hereafter N17) who used a range of simplifying assumptions based on galaxy observations and DM simulations, in order to create an analytical galaxy+halo model. The goal of their model was to reconstruct the RAR in galaxies, in particular the value of a_0: the acceleration scale where the relation transitions from the baryon-dominated to the DM-dominated regime (which is equivalent to $g_\dagger$), and $a_{\rm min}$: the minimum acceleration probed by galaxy disks. Based on their results, they claimed that the RAR can be explained within the ΛCDM framework, at the accelerations probed by galaxy rotation curves (i.e. $g_{\rm obs} > a_{\rm min}$). However, since their model relies on the fact that luminous kinematic tracers in galaxies only probe a limited radial range, N17 predicted that extending observations to radii beyond the disk (which correspond to lower gravitational accelerations) would lead to systematic deviations from the simple relation posed by M16.

The goal of this work is to extend observations of the RAR to lower accelerations, which are not measurable using galaxy rotation curves. To this end we use gravitational lensing: the perturbation of light inside a gravitational potential as described by General Relativity (GR). In particular, we use the method of Galaxy-Galaxy Lensing (GGL): the statistical measurement of the coherent image distortion (shear) of a field of background galaxies by the gravitational potential of a sample of foreground galaxies (for examples, see e.g. Fischer et al. 2000; Hoekstra et al. 2004; Mandelbaum et al. 2006; van Uitert et al. 2016). Using GGL we can measure the average (apparent) density distribution of galaxies up to a radius of 3 Mpc, roughly a 100 times larger than the radius of the luminous disk (~ 30 kpc), corresponding to a value of $g_{\rm bar}$ that is 3 orders of magnitude lower than those measurable with galaxy rotation curves.

First, we measure the baryonic and total density profiles of our galaxies through their luminosities and GGL profiles. These measurements will be performed using photometric data from Sloan Digital Sky Survey (Abazajian et al. 2009, SDSS,) and the VISTA Kilo-Degree Infrared Galaxy survey (Edge et al. 2013, VIKING), and WL data from the Kilo-

[1] DM particles that moved at non-relativistic speeds at the time of recombination, as favoured by measurements of the CBM (Planck XVI 2014) and the Lyman-α forest (Viel et al. 2013).

[2] Another well-established name for this same relation is the Mass-Discrepency Acceleration Relation (MDAR), which refers to the correspondance between the observed baryonic/total mass and the inferred mass discrepency commonly attributed to DM. Throughout this work we use the term RAR for brevity.

Degree Survey (KiDS; de Jong et al. 2013). We then translate these measurements into the baryonic and observed radial accelerations, $g_{\rm bar}$ and $g_{\rm obs}$. Finally, we compare the resulting RAR to predictions from different modified gravity theories (MOND and EG) and ΛCDM.

The ΛCDM predictions will not only be provided by the N17 analytical model, but also by two mock galaxy catalogues based on two different DM simulations. One is the Marenostrum Institut de Ciències de l'Espai (MICE) Galaxy and Halo Light-cone catalog (Carretero et al. 2015; Hoffmann et al. 2015), which is based on the MICE Grand Challenge lightcone simulation (MICE-GC, Fosalba et al. 2015a,b; Crocce et al. 2015). The other mock galaxy catalog is based on a suite of large-volume cosmological hydrodynamical simulations, which is called the BAryons and HAloes of MAssive Systems (BAHAMAS) project (McCarthy et al. 2017). Our final goal is to distinguish which of the aforementioned predictions best describe the RAR at lower accelerations.

Having over ... foreground galaxies at our disposal, we are able to select specific galaxy samples designed to optimally test these predictions. Particularly, we note that most models (MOND, EG, and the N17 analytical DM model) focus on the description of individual, isolated galaxies. In order to test them, therefore, we select a sample of galaxies whose lensing profiles are not affected by their neighbors within the radius of our measurement. In contrast, the predictions from the MICE and BAHAMAS simulations can be tested for both isolated and non-isolated galaxy samples.

Furthermore, we note that all models give a specific prediction regarding the dependence of the RAR on baryonic galaxy mass. According to the MOND and EG theories, the relation between $g_{\rm bar}$ and $g_{\rm obs}$ should remain intact in the regime beyond the disk, independent of the disk mass. Within the ΛCDM paradigm, however, all predictions (analytical and simulated) are based on a 'stellar-to-halo-mass relation' which is not constant as a function of baryonic galaxy mass. By splitting our foreground galaxies into bins of increasing stellar mass, we are able to better distinguish the predictions of these different models.

Our paper is structured as follows: In Sect. 2 we introduce our main datasets: both the KiDS and GAMA galaxy surveys which are used to perform the GGL measurements, and the MICE and BAHAMAS simulations & mock galaxy catalogues to which we compare our results. Sect. 3 describes our analysis of these (mock) datasets as we select our isolated foreground galaxy sample, perform the GGL measurements, and translate the results into the RAR. Sect. 4 contains a description of the theoretical predictions to which we compare our observations: MOND, EG and the N17 analytical DM model. In Sect. 5 we present the resulting RAR measurements and model comparison. Sect. 6 contains the discussion and conclusion.

Throughout this work we adopt the WMAP 9-year (Hinshaw et al. 2013) cosmological parameters : $\Omega_{\rm m} = 0.2793$, $\sigma_8 = 0.821$, $\Omega_\Lambda = 0.7207$, and $H_0 = 70\,{\rm km\,s^{-1}Mpc^{-1}}$, which were used as the basis of the BAHAMAS simulation. The cosmological parameters used in creating the MICE-GC simulations are: $\Omega_{\rm m} = 0.25$, $\sigma_8 = 0.8$, $\Omega_\Lambda = 0.75$, and $H_0 = 70\,{\rm km\,s^{-1}Mpc^{-1}}$. Throughout the paper we use the reduced Hubble constant $h_{70} \equiv H_0/(70\,{\rm km\,s^{-1}Mpc^{-1}})$.

2 DATA

2.1 KiDS source galaxies

We use Galaxy-Galaxy Lensing (GGL) to measure the gravitational potential around a sample of foreground galaxies (lenses), by measuring the image distortion (shear) of a field of background galaxies (sources). These sources are observed using OmegaCAM (Kuijken 2011): a 268-million pixel CCD mosaic camera mounted on the VLT Survey Telescope (Capaccioli & Schipani 2011). Over the past seven years these instruments have performed KiDS, a photometric survey in the *ugri* bands, which is especially designed to perform WL measurements (de Jong et al. 2013).

GGL studies with KiDS have hitherto been performed in combination with the spectroscopic GAMA survey (see Sect. 2.2 below). Already since the previous data release (KiDS-DR3, de Jong et al. 2017) the KiDS survey completely covers the 286 deg^2 GAMA area. Although the final survey will span 1350 deg^2 on the sky, the current state-of-the-art is the 4th Data Release (KiDS-DR4, Kuijken et al. 2019) containing observations from 1006 square-degree survey tiles. The measurement of the source shapes and photometric redshifts are performed in similar fashion to de Jong et al. (2017). Changes and improvements to these methods are described in Kuijken et al. (2019).

The measurements of the galaxy shapes are based on the r-band data, since this filter was used during the darkest time (moon distance > 90 deg) and with the best atmospheric seeing conditions (< 0.8 arcsec). The r-band observations are co-added using the THELI pipeline (Erben et al. 2013), which is improved through the addition of an illumination correction. From these images the galaxy positions are detected through the SEXTRACTOR algorithm (Bertin & Arnouts 1996). After detection, the shapes of the galaxies are measured using the lensfit pipeline (Miller et al. 2007, 2013), which includes a self-calibration algorithm based on Fenech Conti et al. (2017).

The u, g and i bands are observed for the purpose of creating the photometric redshift and stellar mass estimates. In addition, the VISTA Kilo-degree INfrared Galaxy survey (VIKING, Edge et al. 2013) performed on the VISTA telescope adds the $ZYJHK_{\rm s}$ bands. All bands are reduced and co-added using the Astro-WISE pipeline (McFarland et al. 2013). The galaxy colours, which form the basis of the photometric redshift measurements, are measured from these images using the Gaussian Apertrue and PSF pipeline (GAaP Kuijken 2008; Kuijken et al. 2015).

The addition of the lower frequency VISTA data allows us to extend the redshift estimates out to $0.1 < z_{\rm B} < 1.2$ (instead of $0.1 < z_{\rm B} < 0.9$ in KiDS-DR3), where $z_{\rm B}$ is the best-fit photometric redshift of the sources (Benítez 2000; Hildebrandt et al. 2012). However, when performing our lensing measurements (see 3.1) we use the total redshift probability distribution $n_{\rm z}$ of the full source population. This $n_{\rm z}$ is calculated using the direct calibration method (DIR, Hildebrandt et al. 2017), and circumvents the inherent bias related to photometric redshift estimates of individual sources.

2.2 GAMA foreground galaxies

Although the final RAR measurements will be performed using exclusively the KiDS-1000 data, the set of foreground galaxies observed by the spectroscopic GAMA survey (Driver et al. 2011) function both as a model and validation sample for the KiDS foreground galaxies. The survey was performed by the Anglo-Australian Telescope with the AAOmega spectrograph, and targeted more than 180 000 galaxies that were selected from SDSS. For this study we use the GAMA II data release (Liske et al. 2015) consisting of three equatorial regions (G09, G12 and G15). These regions span a total area of $\sim 180\,\mathrm{deg}^2$ on the sky, completely overlapping with KiDS.

GAMA has a redshift range of $0 < z < 0.5$, with a redshift completeness of 98.5% down to Petrosian r-band magnitude $m_\mathrm{r} = 19.8\,\mathrm{mag}$. We limit our GAMA foreground sample to galaxies with the recommended redshift quality: $n_\mathrm{Q} \geq 3$. This smaller sample of spectroscopic redshifts are used to train the photometric machine-learning (ML) redshifts of our larger sample of KiDS foreground galaxies (see Sect. 2.3). Despite being smaller, GAMA's accurate redshifts are highly advantageous when measuring the ESD profiles of galaxies (see Sect. 3.1). Also, in combination with its high redshift completeness, GAMA allows for a better application of the isolation criterion. We therefore check that the results from the KiDS-only measurements are consistent with those from KiDS-GAMA at all times.

To measure RAR with KiDS-GAMA, we need individual stellar masses M_* for each GAMA galaxy. These are measured from their $ugrizZYJHK$ spectral energy distributions[3] measured by SDSS and the VISTA Kilo-Degree Infrared Galaxy survey (VIKING, Edge et al. 2013), by fitting them with Bruzual & Charlot (2003) stellar population synthesis models. Following the procedure described by Taylor et al. (2011), we account for flux falling outside the automatically selected aperture using the 'flux-scale' correction.

2.3 KiDS foreground selection

Still need to know:

- Maciek's GL-KiDS selection criteria for K1000.
- Angus' stellar mass method for K1000.

2.4 MICE mock galaxies

In order to compare our observations to predictions from ΛCDM, we adopt two different DM simulations. One of these is the MICE-GC N-body simulation, which contains $\sim 7{\times}10^{10}$ DM particles in a $(3072\,h_{70}^{-1}\mathrm{Mpc})^3$ comoving volume (Fosalba et al. 2015b). From this simulation the MICE collaboration constructed a $\sim 5000\,\mathrm{deg}^2$ lightcone with a maximum redshift of $z = 1.4$. The DM halos in this lightcone are identified using a Friend-of-Friend (FOF) algorithm on the particles. Halos are considered 'resolved' down to 20 particles, corresponding to a halos with a mass of $6 \times 10^{11}\,h_{70}^{-2}\mathrm{M}_\odot$. The DM halos were populated with galaxies using a hybrid Halo Occupation Distribution (HOD) and Halo Abundance Matching (HAM) prescription (Carretero et al. 2015; Crocce et al. 2015).

Every galaxy has sky coordinates, redshifts, comoving distances, apparent magnitudes and absolute magnitudes assigned to them. We use the SDSS apparent r-band magnitudes m_r, as these most closely match those from KiDS (see Brouwer et al. 2018). We can therefore limit the MICE galaxies to the same apparent magnitude as the GL-KiDS sample: $m_\mathrm{r} < 20.2\,\mathrm{mag}$, in order to create a GL-MICE foreground galaxy sample. We also use the same redshift limit: $z < 0.5$. The absolute magnitudes of the mock galaxies go down to $M_\mathrm{r} < -18.9$ (*should we apply a cut here?*). In the MICECATv2.0 catalogue[4] which we use in this work, each galaxy is also assigned a stellar mass M_* needed in order to compute the RAR (see Sect. 3.2). These stellar masses are determined from the galaxy luminosities L using Bell & de Jong (2001) M/L ratios.

In addition, each galaxy has a pair of lensing shear values associated with it (γ_1 and γ_2, with respect to the Cartesian coordinate system). These shear values were calculated from healpix weak lensing maps that were constructed using the 'onion shell method' (Fosalba et al. 2008, 2015a). The lensing map of MICECATv2.0 has an improved resolution of 0.43arcmin, which is almost twice smaller than that of MICECATv1.0. The MICE shears allow us approximate the lensing analysis we perform on our KiDS data (as described in Section 3.1) using the MICE simulation. To create a sample of MICE background galaxies for the lensing analysis, we apply limits on the MICE mock galaxies' redshifts and apparent magnitudes which are analogous to those applied to the KiDS source sample: $0.1 < z < 0.9$, $m_\mathrm{r} > 20$ (see Hildebrandt et al. 2017 and Sect. 2.1; note that uncertainties in the KiDS z_B are not accounted for in this selection). We also apply an absolute magnitude cut of $M_\mathrm{r} > 19.3\,\mathrm{mag}$, in order to resemble the KiDS source redshift distribution more closely.

The MICE-GC mock catalogue also features very accurate clustering. At lower redshifts ($z < 0.25$) the clustering of the mock galaxies as a function of luminosity is constructed to reproduce the SDSS clustering observations Zehavi et al. (2011), while at higher redshifts ($0.45{<}z{<}1.1$) it was validated against Cosmic Evolution Survey (COSMOS, Ilbert et al. 2009). This makes MICE especially suitable to reproduce the RAR at larger scales where neighboring galaxies start to affect the lensing signal, and to test criteria on galaxy the isolation (see Section 3.3).

Because the MICE mock catalogue consists of one large realization, it is not possible to estimate the covariance matrix on the measured lensing signal. However, we can split this realization into multiple smaller areas in order to estimate the 'sample variance': the difference between astrophysical measurements from different parts of the sky.

2.5 Bahamas mock galaxies

Written by Kyle.

[3] The spectral energy distributions are constrained to the rest frame wavelenght range $3000 - 110000$ Å.

[4] The MICECATv2.0 catalogue is available through CosmoHub (`https://cosmohub.pic.es`).

3 DATA ANALYSIS

3.1 Lensing measurement

We recognize that, by using the unadulterated GGL equations to measure the (apparent) density distribution around foreground galaxies, we necessarily assume that the laws of GR hold with respect to the deflection of light by a gravitational potential. We motivate in Sect. 4.1 and 4.2 why this assumption holds for the modified gravity theories we test in this work.

3.2 Conversion to radial acceleration

- Describe SIS method (Margot).
- ~~Describe interpolation method (Kyle).~~
- Test both methods using the Bahamas simulation.

3.2.1 Piece-wise power law density profile

We can instead assume a more self-consistent form for the volume density profile and parametrize it as a piece-wise power law constrained to be continuous. This comes at the cost of needing to invert the non-linear function $\Delta\Sigma(\rho)$, which we achieve via an iterative method. We choose to parametrize $\rho(r)$ in terms of N pairs of values (r_n, ρ_n) such that the slope a_n and normalization b_n of the power law profile segments are:

$$\log\rho = a_n \log(r) + b_n \tag{1}$$

$$a_n = \frac{\log(\rho_{n+1}) - \log(\rho_n)}{\log(r_{n+1}) - \log(r_n)} \tag{2}$$

$$b_n = \log(\rho_n) - a_n \log(r_n) \tag{3}$$

$$(a_n, b_n) = \begin{cases} (a_0, b_0) & \text{if } r < r_0 \\ (a_n, b_n) & \text{if } r_n \leq r < r_{n+1} \\ (a_{N-1}, b_{N-1}) & \text{if } r \geq r_N \end{cases} \tag{4}$$

(Throughout, log denotes the natural logarithm.) We provide an expression for the discrete excess surface density profile in terms of the volume density profile, i.e. the function to be inverted, in Appendix A.

In order to invert $\Delta\Sigma_m(\rho_n)$, we take as constant the values $\{R_m\}$, $\{\Delta\Sigma_m\}_{\rm obs}$ and $\{r_n\}$. We then propose an initial guess $\{\rho_n\}$ which we perturb iteratively, calculating the corresponding $\{\Delta\Sigma_m\}$ at each iteration and comparing with $\{\Delta\Sigma_m\}_{\rm obs}$ via the likelihood function:

$$\log\mathcal{L} \propto -\frac{1}{2}(\Delta\Sigma_{\rm obs} - \Delta\Sigma)^{\rm T}\Sigma^{-1}(\Delta\Sigma_{\rm obs} - \Delta\Sigma) \tag{5}$$

Note that Σ is the covariance matrix for the $\Delta\Sigma_{\rm obs}$, not to be confused with the surface density. We use the package EMCEE (Foreman-Mackey et al. 2013) to estimate the posterior probability distribution of $\{\rho_n\}$, and subsequently of the corresponding $\{g_{{\rm obs},n}\}$ via integration of the volume density profile.

3.3 Isolated galaxy selection

After performing the measurement of the RAR using GGL, our final goal is to compare the results to different analytical models (see Sect. 4) and N-body simulations (see Sect. 2.4 and 2.5) which make specific predictions on the galaxy-halo connection. While the simulations are designed to describe galaxies in their cosmological environment, the analytical models mainly focus on the description of individual, isolated galaxies. This means that, in order to test the latter, we need to select galaxies that are (as much as possible) isolated. The main goal being that their GGL profiles are not significantly affected by neighboring, within the radius of the lensing measurement.

As a general rule, we define our isolated lens sample as: galaxies that do not have any neighbors with a stellar mass $M_{\rm nb}$ greater then a fraction $f_{\rm mass}$ of their stellar mass M_*, within a spherical radius of $R_{\rm iso}$. We determine the optimal values of $f_{\rm mass}$ and $R_{\rm iso}$ ...

4 THEORETICAL PREDICTIONS

4.1 Modified Newtonian Dynamics

With his theory of Modified Newtonian Dynamics (MOND), Milgrom (1983) postulated that the 'missing mass problem' in galaxies is not caused by an undiscovered fundamental particle, but that instead our current gravitational theory should be revised. MOND's basic premise is that one can adjust Newtons second law of motion ($F = ma$) by inserting a general function $\mu(a/a_0)$, which only comes into play when the acceleration a of a test mass m is much smaller than a critical acceleration a_0. The goal of this function is to facilitate the discovered flat rotation curves in the outskirts of galaxies, while still reproducing the Newtonian behavior of the inner disk. In short, the force F becomes:

$$F(a) = m\,\mu(\frac{a}{a_0})\,a\,, \quad \mu(x \gg 1) \approx 1\,,\ \mu(x \ll 1) \approx x\,. \tag{6}$$

This implies that $a \gg a_0$ represents the Newtonian regime where $F_{\rm N} = m\,a_{\rm N}$ as expected, while $a \gg a_0$ represents the 'deep-MOND' regime where $F_{\rm dm} = m\,a_{\rm dM}^2/a_0$. In a circular orbit, this is reflected in the deep-MOND gravitational acceleration $g_{\rm dM} \equiv a_{\rm dM}$ as follows:

$$F_{\rm dM} = m\frac{a_{\rm dM}^2}{a_0} = \frac{G\,Mm}{r^2} \qquad \rightarrow g_{\rm dM} = \sqrt{a_0\frac{GM}{r^2}}\,. \tag{7}$$

This can be written in terms of the expected baryonic acceleration $g_{\rm bar} = GM/r^2$ as follows:

$$g_{\rm dM}(g_{\rm bar}) = \sqrt{a_0\,g_{\rm bar}}\,, \tag{8}$$

which demonstrates that MOND predicts a very simple relation for the RAR: $g_{\rm obs} = g_{\rm bar}$ in the Newtonian regime ($g_{\rm obs} \gg a_0$), and following Eq. 7 in the deep-MOND regime ($g_{\rm obs} \ll a_0$). However, since $\mu(a/a_0)$ (also known as the 'interpolating function') is not specified by Milgrom (1983), there is no specific constraint on the behavior of this relation in between the two regimes. In the work of Milgrom & Sanders (2008), several families of interpolation functions are discussed. Selecting the third family (given by their Eq. 13) with constant parameter $\alpha = 1/2$, provides the function that M16 later used to fit to their measurement of the RAR using rotation curves 153 galaxies. This relation can be written as:

$$g_{\rm obs} = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/a_0}}}\,. \tag{9}$$

where $a_0 \equiv g_\dagger$ corresponds to the fitting parameter constrained by M16 to be $g_\dagger = 1.20 \pm 26 \times 10^{-10}{\rm m/s^2}$. Since

Eq. 9 (equal to Eq. 4 in M16) is also considered a viable version of the MOND interpolation function by Milgrom & Sanders (2008), we will consider it the baseline prediction of MOND in this work. As the baseline value of a_0, we will likewise use the value of $g_\dagger$ measured by M16, since it exactly corresponds to the value of $a_0 = 1.2 \times 10^{-10}\mathrm{m/s^2}$ considered canonical in MOND since it's first measurement by Begeman et al. (1991), using rotation curves of 10 galaxies.

4.2 Emergent Gravity

The work of Verlinde (2016) (V16 hereafter), which is embedded in the framework of string theory and holography, shares the view that the missing mass problem is to be solved through a revision of our current gravitational theory. Building on the ideas of Jacobson (1995, 2016); Padmanabhan (2010); Faulkner et al. (2014) and his own previous work (Verlinde 2011), V16 abandons the notion of gravity as a fundamental force. Instead, it emerges from an underlying microscopic description of space-time, in which the notion of gravity has no a-priori meaning.

The aforementioned earlier works have shown that constructing a theory EG in a static ('anti-de Sitter') universe allows for the re-derivation Einstein's laws of GR. A distinguishing feature of V16 is that it attempts to describe an expanding ('de Sitter') universe, which is filled with a DE component. This results in a new volume law for gravitational entropy caused by DE, in addition to the area law normally used to retrieve Einsteinian gravity. According to V16, energy that is concentrated in the form of a baryonic mass distribution causes an elastic response in the entropy of the surrounding DE. This results in an additional gravitational component at scales set by the 'Hubble acceleration scale' $a_0 = cH_0$. Here c is the speed of light, and H_0 is the current Hubble constant which measures the Universe's expansion velocity.

Because this extra gravitational component is predicted to explain the effects usually attributed to DM, it is often expressed as an apparent dark matter (ADM) distribution:

$$M_\mathrm{D}^2(r) = \frac{cH_0 r^2}{6G} \frac{d\left(M_\mathrm{b}(r) r\right)}{dr} \,. \tag{10}$$

Thus the ADM distribution is completely defined by the baryonic mass distribution $M_\mathrm{b}(r)$ as a function of the spherical radius r, and a set of known physical constants.

Since we measure the ESD profiles of galaxies at projected radial distances $R > 30\, h_{70}^{-1}\mathrm{Mpc}$, we can assume that their baryonic component is enclosed within the minimal measurement radius (see also Brouwer et al. 2017). This is equivalent to describing the galaxy as a point mass M_b, which allows us to simplify Eq. 10 to:

$$M_\mathrm{D}(r) = \sqrt{\frac{cH_0\, M_\mathrm{b}}{6\, G}}\, r \,. \tag{11}$$

Now the total enclosed mass, $M_\mathrm{EG}(r) = M_\mathrm{b} + M_\mathrm{D}(r)$, can be used to calculate the predicted gravitational acceleration $g_\mathrm{EG}(r)$ as follows:

$$g_\mathrm{EG}(r) = \frac{GM_\mathrm{EG}(r)}{r^2} = \frac{GM_\mathrm{b}}{r^2} + \sqrt{\frac{cH_0}{6}}\, \frac{\sqrt{GM_\mathrm{b}}}{r} \,. \tag{12}$$

In terms of the expected baryonic acceleration $g_\mathrm{bar}(r) = GM_\mathrm{b}/r^2$, this simplifies even further to:

$$g_\mathrm{EG}(g_\mathrm{bar}) = g_\mathrm{bar} + \sqrt{\frac{cH_0}{6}}\, \sqrt{g_\mathrm{bar}} \,. \tag{13}$$

Note that Eq. 10 is only a macroscopic approximation of the underlying microscopic phenomena described at the start of this section, and is thus only valid for static, spherically symmetric and isolated baryonic mass distributions. For this reason, we select only the most isolated galaxies from our sample (see Sect. 3.3), such that our WL measurements are not influenced by neighboring galaxies. In addition, cosmological evolution of the H_0 parameter is not yet implemented in the theory, restricting its validity to galaxies with relatively low redshifts. However, we calculate that at our mean lens redshift ($\langle z \rangle \sim 0.2$) using an evolving $H(z)$ would result in only a 5% difference in our ESD measurements, based on the background cosmology used in this work.

In order to test V16 using the standard WL methodology, we need to assume that the deflection of photons by a gravitational potential in this alternative theory corresponds to that in GR. This assumption is justified because, in EG's original (anti-de Sitter) form, Einstein's laws emerge from its underlying description of space-time. The additional gravitational force described by ADM does not affect this underlying theory, which is an effective description of GR. Therefore, we assume that the gravitational potential of an ADM distribution produces the same lensing shear as an equivalent distribution of actual matter.

4.3 Analytical CDM model

To help guide an intuitive interpretation of the lensing RAR within the framework of the ΛCDM theory, we make use of the simple model of N17 which combines a basic model of galactic structure and scaling relations to predict the RAR. We refer to N17 for a full description, but give a summary here. A galaxy of a given stellar (or baryonic – there is no distinction in this model) mass occupies a dark matter halo of a mass fixed by the abundance matching relation of Behroozi et al. (2013). The dark halo concentration is fixed to the cosmological mean for haloes of that mass (Ludlow et al. 2014). The baryonic disc follows an exponential surface density profile with a half-mass size fixed to 0.2× the scale radius of the dark halo (N17). The above is sufficient to specify the cumlative mass profile of both the baryonic and dark components of the model galaxy; calculating g_obs and g_bar is then straightforward.

5 RESULTS

Write when the results are ready. I still need:

- The K1000 lensing catalogues with ANNz redshifts and stellar masses.
- The results from the Bahamas simulation.

5.1 Isolated galaxies

6 DISCUSSION AND CONCLUSION

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ACKNOWLEDGEMENTS

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APPENDIX A: EXCESS SURFACE DENSITY PROFILE OF A PIECE-WISE POWER LAW VOLUME DENSITY PROFILE

The excess surface density profile is measured in a series of discrete radial bins with edges R_m. The representative value at the centre of the bin – here we define the bin centre as $\frac{1}{2}(R_m + R_{m+1})$, i.e. not the 'logarithmic centre' $\sqrt{R_m R_{m+1}}$, which ensures accuracy in the calculation of the mean enclosed surface density – is $\Delta\Sigma_m = \overline{\Sigma}_m - \Sigma_m$, where $\overline{\Sigma}_m$ is the mean surface density within $\frac{1}{2}(R_m + R_{m+1})$ and Σ_m is the surface density averaged over the interval $[R_m, R_{m+1})$. We give an expression for this discrete excess surface density profile in terms of the parametric form for $\rho(r)$ given in Eq. 4.

The mean enclosed surface density is:

$$\overline{\Sigma}_m = \frac{1}{\pi R_m R_{m+1}} \left[I_1(0, \sqrt{R_0 R_1}, \tilde{a}_0, \tilde{b}_0) + \sum_{k=0}^{m} I_1(\sqrt{R_m R_{m+1}}, \sqrt{R_{m+1} R_{m+2}}, \tilde{a}_m, \tilde{b}_m) \right] \tag{A1}$$

$$\tilde{a}_m = \frac{\log(\Sigma_{m+1}) - \log(\Sigma_m)}{\frac{1}{2}\left(\log(R_{m+2}) - \log(R_m)\right)} \tag{A2}$$

$$\tilde{b}_m = \log(\Sigma_m) - \frac{1}{2}\tilde{a}_m \log(R_m R_{m+1}) \tag{A3}$$

$$I_1(R_i, R_j, \tilde{a}, \tilde{b}) = \frac{2\pi e^{\tilde{b}}}{\tilde{a}+2}\left(R_j^{a+2} - R_i^{a+2}\right) \tag{A4}$$

and the local surface density is given by:

$$\Sigma_m = \sum_{n=0}^{N-1} \begin{cases} 0 & \text{if } r_{n+1} < R_m \\ \frac{4e^{b_n}}{R_{m+1}^2 - R_m^2}\left(-I_2(r_{n+1}, R_m, a_n)\right) & \text{if } r_n < R_m \text{ and } R_m \le r_{n+1} < R_{m+1} \\ \frac{4e^{b_n}}{R_{m+1}^2 - R_m^2}\left(I_2(r_{n+1}, R_{m+1}, a_n) - I_2(r_{n+1}, R_m, a_n)\right) & \text{if } r_n < R_m \text{ and } r_{n+1} \ge R_{m+1} \\ \frac{4e^{b_n}}{R_{m+1}^2 - R_m^2}\left(I_2(r_{n+1}, r_n, a_n) - I_2(r_{n+1}, R_m, a_n)\right. & \\ \quad + I_2(r_n, R_m, a_n) + I_2(r_{n+1}, R_{m+1}, a_n) & \\ \quad \left. - I_2(r_{n+1}, r_n, a_n)\right) & \text{if } R_m \le r_n < R_{m+1} \text{ and } r_n \ge R_{m+1} \\ \frac{4e^{b_n}}{R_{m+1}^2 - R_m^2}\left(I_2(r_{n+1}, R_{m+1}, a_n) - I_2(r_{n+1}, R_m, a_n)\right. & \\ \quad \left. - I_2(r_n, R_{m+1}, a_n) + I_2(r_n, R_m, a_n)\right) & \text{if } r_n \ge R_{m+1} \\ \frac{4e^{b_n}}{R_{m+1}^2 - R_m^2}\left(I_2(r_{n+1}, r_n, a_n) - I_2(r_{n+1}, R_m, a_n)\right. & \\ \quad \left. + I_2(r_n, R_m, a_n) - I_2(r_{n+1}, r_n, a_n)\right) & \text{if } r_n \ge R_m \text{ and } r_{n+1} < R_m \end{cases} \tag{A5}$$

$$I_2(r, R, a) = \begin{cases} -\frac{1}{3} R^{a+3} \left(\frac{r^2}{R^2} - 1\right)^{\frac{3}{2}} {}_2\mathrm{F}_1\left(\frac{3}{2}, -\frac{a}{2}; \frac{5}{2}; 1 - \frac{r^2}{R^2}\right) & \text{if } r \text{ is finite} \\ \frac{\sqrt{\pi}}{2} \frac{\Gamma\left(-\frac{a+1}{2}\right)}{\Gamma\left(-\frac{a}{2}\right)} \frac{R^{a+3}}{a+3} & \text{if } r = \infty \end{cases} \tag{A6}$$

where ${}_2\mathrm{F}_1(\cdot, \cdot; \cdot; \cdot)$ is the Gaussian hypergeometric function and $\Gamma(\cdot)$ is the Gamma function.

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