EMERGENT GRAVITY FAILS TO EXPLAIN COLOR-DEPENDENT GALAXY-GALAXY LENSING SIGNAL FROM SDSS DR7

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ABSTRACT

We test Verlinde’s Emergent Gravity (EG) theory using galaxy-galaxy lensing technique based on SDSS DR7 data. In the EG scenario, we do not expect color dependence of the galaxy sample in the ‘apparent dark matter’ predicted by EG, which is exerted only by the baryonic mass. If the baryonic mass is similar, then the predicted lensing profiles from the baryonic mass should be similar according to EG, regardless of the color of the galaxy sample. We use the stellar mass of the galaxy as a proxy of its baryonic mass. We divide our galaxy sample into 5 stellar mass bins, and further classify them as red and blue subsamples in each stellar mass bin. If we set halo mass and concentration as free parameters, ΛCDM is favored by our data in terms of the reduced χ², while EG fails to explain the color dependence of ESDs from galaxy-galaxy lensing measurement.

Subject headings: gravitational theory: emergent gravity; cosmology: gravitational lensing; galaxies: clusters: general

1. INTRODUCTION

Today, the concordance cosmological model where dark matter and dark energy form about 95 percent of the energy density of the Universe is supported by a plethora of observations including those of the Cosmic Microwave Background (CMB) (see e.g., Planck Collaboration et al. 2016), Supernovae of Type Ia (see e.g., Perlmutter et al. 1999), Baryon Acoustic Oscillations (BAO) (see e.g., Eisenstein et al. 2005) as well as weak lensing (see e.g., Heymans et al. 2012; Kuijken et al. 2015; Shi et al. 2017). The observational data from the above probes can be described by merely half a dozen major parameters, a.k.a ΛCDM, despite a recent claim of 5.3σ tension in H₀ between CMB probe (Planck Collaboration et al. 2018) and strong lensing time delay project H0LiCOW (Wong et al. 2019), SH0ES project (Riess et al. 2016). Regardless of this success, the dark matter still remains a mystery.

The concept of dark matter was first introduced by Zwicky (1937) based on the anomalous dynamics of galaxies in clusters, which required excess gravitational influence than that from the baryonic component only. Observations of galaxy rotation curves (Bosma 1981; Sofue & Rubin 2001) further confirm this anomalous behaviour. These observations require the presence of dark matter that can not be detected in any electromagnetic observations which dominates the matter sector of the Universe. Since then, the study of the properties of dark matter has become one of the frontier fields from both particle physics perspective and modified gravity scenario.

There are plenty of models from particle physics and possible detection experiments in literature ranging from light boson model [e.g. axion dark matter (Duffy & van Bibber 2009), which arises from the Peccei-Quinn solution] to the strong CP problem [sterile neutrino as potential candidate (Kisslinger & Das 2019)] and weakly interacting massive particles predicted by R-parity-conserving supersymmetry (Jungman et al. 1996). And so far, there are no experiments that can confirm any of the models, neither earth based labs (Kang et al. 2010; Zhang et al. 2019; Aprile et al. 2019) nor space based detection (Di Mauro et al. 2020; Ding et al. 2019).

On the other hand, some researchers try to view dark matter as the modification of the theory of gravity. For example, MOdified Newtonian Dynamics or MOND (Milgrom 1983, 2011, 2020) explains the high speed stars in galaxies by adding interpolation function to modify the acceleration of Newtonian theory. Bekenstein (2004) further improves MOND by considering gravity as a mixture of dynamics of metric, a scalar, and a 4-vector field, a.k.a TeVeS, which can predict consistent weak lensing signals. Milgrom (2013) claims that MOND prediction agrees with the velocity dispersion to r band luminosity relation $\sigma - L_r(h^{-2} L_\odot)$ based on the CFHT data (Heymans et al. 2013), but without comparison of the galaxy-galaxy lensing profiles directly as...
in Brouwer et al. (2017). Chae et al. (2020) finds evidence that supports MOND gravity from the observations of Spitzer Photometry and Accurate Rotation Curves (SPARC).

Among the various MOND models, there is a unique one based on an entropic scenario. Verlinde (2016) reconsidered the gravity as the underlying microscopic description inspired by the laws of black hole thermodynamics (Bardeen et al. 1973), i.e. Emergent Gravity (EG). Brouwer et al. (2017) firstly tested this assumption using galaxy-galaxy lensing technique based on the data from KiDs (de Jong et al. 2013) and GAMA (Driver et al. 2009), they claimed that both dark matter scenario and EG can fit the galaxy-galaxy lensing signal equally well.

ZuHone & Sinns (2019) tested Emergent Gravity using relaxed galaxy clusters and found that inclusion of the central galaxy improves agreement between observations and the theory in the inner regions ($r \leq 30$ kpc). On larger scales, the predictions are discrepant with observations and ΛCDM models fit the observations better. However, Halenka & Miller (2020) found that there is enough freedom in the EG theory for it to agree with the data as well as ΛCDM, especially after accounting for possible observational systematics. Baryonic physics complicates the inference of the underlying gas density profile and weakens the constraining power of observations.

In this paper, we re-test this theory by using a much larger survey data from Sloan Digital Sky Survey (SDSS) DR7 (Abazajian et al. 2009) as well as two cosmology models in ΛCDM framework, i.e. WMAP5 (Komatsu et al. 2009) and PLANCK18 (Planck Collaboration et al. 2018). We minimize the complicated modeling of massive clusters by only selecting single galaxy systems from the Yang et al. (2007) catalog with mean halo mass log $M \leq 13.5 h^{-1} M_\odot$. None of the systems have X ray detection, which further minimizes the hot baryonic contribution. With this data set, we are able to select isolated galaxies. Our sample is at least 5 times bigger than that used in (Brouwer et al. 2017) as we use the group catalog built by (Yang et al. 2007). The models of galaxy-galaxy lensing signals from both EG and ΛCDM are described in Sec. 2. We introduce the lensing data and methodology in Sec. 3. The results are given in Sec. 4. Finally, we summarize and discuss in Sec. 5.

2. THE GALAXY-GALAXY LENSING MODELS

2.1. Lensing model in Emergent Gravity

The tangential distortions of background galaxy shapes caused by weak gravitational lensing are proportional to the excess surface density (ESD), $\Delta \Sigma$, which is the difference in the average surface density within a projected radius $R$ and the surface density at radius $R$. The ESD is related to the tangential shear $\gamma_t(R)$ by a factor $\Sigma_c$

$$\gamma_t(R) \Sigma_c = \Delta \Sigma(R) = \Sigma(\leq R) - \Sigma(R), \quad (1)$$

where $\Sigma_c$ is the critical density dependent upon the geometric distances between the observer, lens and the source galaxy. For the ΛCDM case, we refer to Yang et al. (2006) for detailed formulation, which is well established in galaxy-galaxy lensing studies.

In Emergent Gravity (hereafter EG) scenario, a term additional to the normal baryonic mass contribution and that can act as an apparent dark matter contribution. Based on Verlinde (2016), the extra term of gravitational potential is exerted by the entropy displacement from total galaxy mass $M_g(r)$, where $M(r)$ is the mass enclosed within a radius $r$. This mass includes stellar mass and cold gas components. As a result, the apparent mass $M_a(r)$ is related to $M_g(r)$ via

$$M_a^2(r) = \frac{c H_0 r^2}{6 G} \frac{d[M_g(r)r]}{dr}. \quad (2)$$

As in Brouwer et al. (2017), for a typical mass of $M = 10^{10} h^{-2} M_\odot$, EG becomes significant over scale larger than $2 h^{-1}$ kpc. We measure our galaxy-galaxy lensing signal from 0.01 $h^{-1}$ Mpc all the way to 1 $h^{-1}$ Mpc to empirically test the scale dependence of both theories. We follow Brouwer et al. (2017) that beyond 30 $h^{-1}$ kpc, the galaxy can be considered a point mass. We exclude the first data point within 30 $h^{-1}$ kpc. In Sec. 4, we calculate the $\chi^2$ excluding the first data point of each of the measurements below this scale.

From Eq. 2, we get the mass distribution

$$M_a(r) = \left[\frac{c H_0 r^2}{6 G} \left(M_g(r) + \frac{r}{c^2} \frac{\partial M_g(r)}{\partial r}\right)\right]^{0.5}$$

and the second term on the right hand side is gone under the point mass assumption, i.e. $M_g(r) = M_g$ and we can treat the factor $\sqrt{\frac{c H_0}{M_g}}$ as a combined constant $C_a$, also following Brouwer et al. (2017). The density profile can be related to the derivative of the mass distribution

$$\rho_{EG}(r) = \frac{1}{4 \pi r^2} \frac{dM_a(r)}{dr} = C_a \sqrt{M_g \over 4 \pi r^2}. \quad (3)$$

The 2D surface density at projected distance R is then bearing the form

$$\Sigma_{EG}(R) = \int_{-\infty}^{\infty} \rho_{EG}(R, \chi) d\chi = C_a \sqrt{M_g \over 4 R}. \quad (4)$$

where $\chi^2$ and $\chi$ with $R$ as the projected distance and $\chi$ as the distance along the line of sight. Then the ESD of EG point mass can be calculated

$$\Delta \Sigma_{EG}(R) = C_a \sqrt{M_g \over 4 R}. \quad (5)$$

which happens to be the same as Eq. 4. Together with the original baryonic mass contribution, the total ESD profile as predicted by EG is

$$\Delta \Sigma(R)_{alt} = \frac{M_g}{\pi R^2} + \Delta \Sigma_{EG}(R). \quad (6)$$

In the ΛCDM scenario, the dark matter density profile can be accurately described by an NFW profile (Navarro et al. 1997). When converting the 3D NFW profile to the 2D ESD, it differs from the EG profile.

2.2. Lensing model in ΛCDM

We model the the ESD based on the NFW density profile with two free parameters namely, halo mass and concentration parameters, and we label this model as...
'NFW'. We use Yang et al. (2006) formulation to model the ESD given a halo mass based on an NFW dark matter halo profile Navarro et al. (1997),

\[
\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2},
\]

with \(\rho_0 = \frac{\bar{\rho}_H}{\Omega_m h^2}\), where \(\Delta_{\text{vir}} = 200\), \(I = \frac{1}{\pi} \int_0^\infty \frac{x\rho_H(x)}{(1 + x)^2} dx\). Here \(c\) is the concentration parameter defined as the ratio between the virial radius of a halo and its characteristic scale radius \(r_s\).

Recently, the group catalog was also updated to include abundance matching based halo mass estimation in both the WMAP5 and PLANCK18 cosmology. We will therefore further examine the cosmology dependence.

In \(\Lambda\)CDM scenario, the ESD is composed of the following simple two components: host halo mass and the stellar mass,

\[
\Delta \Sigma(R) = \Delta \Sigma_{\text{host}}(R) + \Delta \Sigma_s. \tag{8}
\]

We do not include two halo term, which is the signal caused by the large scale structure due to the fact that we select the isolated galaxies and we only measure our signal to \(1\, h^{-1}\)Mpc. The contribution of the stellar components from the lens galaxy can be modeled as a point mass

\[
\Delta \Sigma_s(R) = \frac{M_s}{\pi R^2}. \tag{9}
\]

\(\Delta \Sigma_{\text{host}}\) is the contribution of the halo given that the galaxy is perfectly located at the center.

3. THE GALAXY-GALAXY LENSING SIGNALS

In this section, we describe the data we use to measure the galaxy-galaxy lensing signals.

3.1. Lenses

The lenses are selected from the galaxy group catalog constructed from the spectroscopic SDSS survey (DR7) (Yang et al. 2007), which is based on a halo-based group finding algorithm (Yang et al. 2005). Recently, Yang et al. (2020) extended this group finder so that it can deal with galaxies with photometric and spectroscopic redshifts simultaneously, and successfully applied it to the DESI Legacy surveys data release 8 (Dey et al. 2019). The strength of this algorithm is related with its iteration nature and the application of an adaptive filter according to the general properties of the dark matter halos. It starts with assuming each galaxy is a potential group candidate and then calculates the total luminosity of each system. The halo mass is then estimated based on abundance matching. After the halo mass estimation, the other quantities such as velocity dispersion, and virial radius e.t.c are then deduced. The member galaxies are determined by selecting galaxies that meet the criteria, which include distance and redshift information. All the above procedures are iterated several times till the mass-to-light ratios converge. There are systems with only one central galaxy, meaning that there are no other galaxies brighter than the magnitude limit \(r = 17.77\) within projected virial radius and with \(\Delta z = |z_i - z_{\text{group}}|\) less than the virial velocity of the dark matter halo along the line-of-sight direction.

In total, there are 472419 groups in the sample. In order to minimize the effects of nearby structures, we only select single galaxy systems which further reduce the number to 400608. The stellar mass of each galaxy is computed using stellar mass-to-light ratio and color from Bell et al. (2003), but with a Kroupa IMF (Kroupa 2001). This leads to a -0.1 correction to the stellar mass-to-light ratio relation. The statistical scatter of color-based stellar M/L ratio is about 20\%. Systematics rising from galaxy age, dust and bursts of star formation in total contribute \(\sim 0.1\)dex scatter. In general, the scatter may induce some Eddington bias to the average stellar mass of galaxies. However, since the total amount of scatter is quite small, the overall Eddington bias can only leads to \(\sim 0.03\) dex overestimation of stellar mass, which will not impact any of our results significantly.

The sample is sub-divided into different stellar mass bins following Brouwer et al. (2017). We add one more stellar mass bin compared to their study, with \(\log M_{\text{st}}\) mass \(\geq 11.0\) due to the larger sample size. The mean redshift of our sample is lower than Brouwer et al. (2017), so our work is complementary to theirs as low \(z\) test and it provides better agreement with a small redshift assumption of EG model. Moreover, our samples are at least five times larger to improve the measurement.

The vertical dashed lines in Fig. 1 divide our sample in 5 \(M_s\) bins. We further sub-divide our sample of galaxies in to blue star forming galaxies and red passive galaxies based on a cut in the color magnitude plane from Yang et al. (2008) such that

\[
0.1(g - r) = 1.022 - 0.0652x - 0.0031x^2, \tag{10}
\]

where \(x = 0.1M_s - 5\log h + 23.0\), and \(0.1M_s - 5\log h\) is the absolute magnitude of galaxy after \(K\) correction and evolution correction to redshift \(z=0.1\). The statistics of

\[\text{Fig. 1.— This is the 2D distribution contour plot between the color and stellar mass of lens galaxy sample. The dashed vertical lines divide the plot into 5 stellar mass regions, each region is further divided into red and blue sub samples. The overlap region between the blue and red are due to the fact that the threshold is calculated using color and r band magnitude rather than stellar mass.}\]
the our sub-samples is given in Table. 1 and illustrated in Fig. 1. The overlap between the red and blue contours are due to the fact that threshold in Equation 10 is calculated based on color and magnitude, while Fig. 1 is the color and stellar mass 2D distribution.

We treat the gas contribution following Brouwer et al. (2017); Boselli et al. (2014) for the blue galaxies, which applies a factor \( f_{\text{cold}} \) so that the total galaxy mass \( M_g \) can be written as

\[
M_g = M_*(1 + f_{\text{cold}}). \tag{11}
\]

Boselli et al. (2014) gives an empirical form of \( f_{\text{cold}} \) based on Herschel Reference Survey (Boselli et al. 2010)

\[
\log(f_{\text{cold}}) = -0.69\log(M_* h^{-2} M_\odot) + 6.63. \tag{12}
\]

For the red galaxy, we apply a constant fraction of 1%, which is the upper limit from Boselli et al. (2014) for early-type galaxies. We do not take the hot gas into consideration so far because firstly, the dominant factor is stellar mass as in Brouwer et al. (2017), as we focus on the point mass contribution by selecting single galaxy system, and the hot gas contribution is less than the 0.1dex systematic for the stellar mass estimation.

We also add the fitted NFW halo mass for each sample with errors in Sec. 4.

3.2. Sources and estimator

For the source catalog, we use the shape catalog created by Luo et al. (2017b) based on SDSS DR7 imaging data. The DR7 imaging data, with u, g, r, i and z band, covers about 8423 square degrees of the LEGACY sky (~230 million distinct photometric objects). The total number of objects identified as galaxies is around 150 million. The final shape catalog for our study contains about 40 million galaxies with position, shape, shape error and photoZ information based on Csabai et al. (2007), which fits a local color-color hyper-plane with nearest 100 objects.

The shear signals \( \Delta \Sigma(R) \) can be measured by the weighted mean of source galaxy shapes,

\[
\Delta \Sigma(R) = \frac{1}{2R} \sum \frac{w(R) \Sigma_{\text{cls}}}{\sum w_i}, \tag{13}
\]

where \( w_i \) is the weight for each source galaxy. \( \Sigma_{\text{cls}} = \frac{\sigma^2}{\sigma^2_{\text{sky}} + \sigma^2_{\text{shape}}} \) is the critical density for each lens-source pair. We measure the signal in 6 equal logarithm bins in projected co-moving distance from 0.01Mpc/h to 1Mpc/h. The weighting term is composed by shape noise \( \sigma_{\text{shape}} \), and that from sky \( \sigma_{\text{sky}} \)

\[
w = \frac{1}{\left(\sigma^2_{\text{sky}} + \sigma^2_{\text{shape}}\right)} \Sigma^2_{\text{cls}}. \tag{14}
\]

We correct the dilution effect by calculating the boost factor, which is from the contamination of non-lensed galaxies due to inaccurate photometric redshift

\[
B(R) = \frac{N_{\text{rand}}}{N_{\text{lens}}} \sum \frac{w_{\text{ls}}}{\sum w_{\text{rs}}}. \tag{15}
\]

\( N_{\text{lens}} \) and \( N_{\text{rand}} \) are the number of lens galaxy of each sample and corresponding random sample. The weights \( w_{\text{ls}}(w_{\text{rs}}) \) correspond to each lens (random position, \( N(\text{rand}) = N(\text{lens}) \)) as in Eq. 14.

The \( \chi^2 \) can be calculated as

\[
\chi^2 = ((\text{data} - \text{model})^T C^{-1} (\text{data} - \text{model})), \tag{16}
\]

where \( C^{-1} \) is the inverse covariance matrix. We further add photometric redshift systematic from weak lensing measurement to the trace of covariance matrix when we calculate the \( \chi^2 \). We estimated the systematics caused by photometric redshift to be 2.7% (Luo et al. 2017b) for the most massive stellar mass bin.

4. RESULTS

In this section, we describe the results from the comparison between the EG and ΛCDM model. Our use of a larger data set, allows us to obtain high SNR measurement of galaxy-galaxy lensing signals even after we split the sample into red and blue lens samples to study the color dependence. The SNR is ranging from 17.6 for blue galaxy sample to 28.1 for red galaxy sample based on Eq.(5) in Leauthaud et al. (2017).

Fig. 2 is the comparison between the data and different models, i.e. NFW (\( M_h, c \) as free parameters) and Emergent Gravity (EG). It is well known that the lensing signal is dependent on several cosmological parameters, e.g. \( \Omega_m, \sigma_8 \) and Hubble parameter. Whereas EG depends only on Hubble parameter as shown in Eq. 2.

That is why EG shows stronger cosmology variance than ΛCDM in terms of reduced \( \chi^2 \). Apparently, EG prefers PLANCK18 cosmology with reduced \( \chi^2 = 1.907 \) to WMAP5 (reduced \( \chi^2 = 2.959 \)) as in Table. 2. We exclude the first data points from all measurements because it is below 30kpc/h, but still show the \( \chi^2 \) in Table 2 (inside the parenthesis) by including the first data points to see the difference.

Our measurement at small stellar mass bins have very high signal to noise ratio. And due to the selection of isolated systems, we have less contribution from adjacent structure. Therefore, the decreasing feature in the first two stellar mass bins play an important role to the whole \( \chi^2 \). We do not use the extended model as in Brouwer et al. (2017), because the extended model only make the \( \chi^2 \) larger.

We show the color dependence in PLANCK18 cosmology in Fig. 3. The NFW model with free halo mass and concentration, apparently is favored by the data, especially the blue data. Fig. 3 shows the ESD profile from the first three stellar mass bins in PLANCK18 cosmology. Due to larger signal to noise ratio, the rest of two ESD profiles from massive stellar mass bins do not carry so much information.

In the left panel of Fig. 3, there is significant difference between the ESDs from red and blue lenses. The ESD from the red lens is larger than their blue counterpart with 0.164dex difference in stellar mass but 0.605dex difference in halo mass in PLANCK18 cosmology. The stellar mass difference shrinks to 0.014dex, but the halo mass difference is 0.526dex for the second stellar mass bin sample. The third stellar mass bin sample has almost identical stellar mass for blue and red galaxy, but the halo mass difference is still up to 0.498dex.

Comparing to the halo masses directly provided in the group catalog, the first three stellar mass bins have
TABLE 1

Properties of the lens samples created for this paper. \( \log(M_{W5}/h^{-1}\text{M}_\odot) \) and \( \log(M_{P18}/h^{-1}\text{M}_\odot) \) are the weak lensing fitted mass for the two different cosmologies.

| log \( M_{st} \) range | Num  | \( \langle z \rangle \) | \( \langle \log(M_{st}/h^{-2}\text{M}_\odot) \rangle \) | \( \log(M_{W5}/h^{-1}\text{M}_\odot) \) | \( \log(M_{P18}/h^{-1}\text{M}_\odot) \) |
|------------------------|------|----------------|-----------------|----------------|----------------|
| 8.5-10.5               | 216  | 0.078         | 10.001          | 11.563\(^{+0.059}_{-0.062}\) | 11.686\(^{+0.063}_{-0.062}\) |
| RED                    | 69   | 0.074         | 10.180          | 11.861\(^{+0.067}_{-0.073}\) | 11.983\(^{+0.070}_{-0.076}\) |
| BLUE                   | 146  | 0.079         | 9.916           | 11.354\(^{+0.099}_{-0.112}\) | 11.378\(^{+0.099}_{-0.113}\) |
| 10.5-10.8              | 104  | 0.123         | 10.648          | 11.935\(^{+0.087}_{-0.088}\) | 12.210\(^{+0.072}_{-0.075}\) |
| RED                    | 61   | 0.115         | 10.654          | 12.086\(^{+0.108}_{-0.108}\) | 12.284\(^{+0.089}_{-0.093}\) |
| BLUE                   | 43   | 0.134         | 10.640          | 11.761\(^{+0.149}_{-0.187}\) | 11.758\(^{+0.161}_{-0.207}\) |
| 10.8-10.9              | 28   | 0.143         | 10.848          | 12.493\(^{+0.121}_{-0.119}\) | 12.725\(^{+0.105}_{-0.105}\) |
| RED                    | 19   | 0.140         | 10.849          | 12.566\(^{+0.108}_{-0.108}\) | 12.810\(^{+0.104}_{-0.107}\) |
| BLUE                   | 9    | 0.151         | 10.847          | 12.346\(^{+0.367}_{-0.346}\) | 12.312\(^{+0.399}_{-0.385}\) |
| 10.9-11.0              | 22   | 0.155         | 10.946          | 12.449\(^{+0.189}_{-0.187}\) | 12.596\(^{+0.220}_{-0.247}\) |
| RED                    | 16   | 0.155         | 10.948          | 12.516\(^{+0.218}_{-0.217}\) | 12.948\(^{+0.569}_{-0.465}\) |
| BLUE                   | 5    | 0.156         | 10.944          | 12.218\(^{+0.566}_{-0.609}\) | 12.601\(^{+0.228}_{-0.271}\) |
| 11.0-above             | 24   | 0.165         | 11.087          | 12.673\(^{+0.104}_{-0.102}\) | 13.000\(^{+0.174}_{-0.169}\) |
| RED                    | 20   | 0.166         | 11.119          | 12.733\(^{+0.106}_{-0.103}\) | 13.075\(^{+0.081}_{-0.084}\) |
| BLUE                   | 4    | 0.158         | 11.096          | 12.155\(^{+0.578}_{-0.577}\) | 12.426\(^{+0.656}_{-0.656}\) |

Fig. 2.— *Left:* The prediction of emergent gravity is shown in green and the prediction of ΛCDM model is shown in blue with PLANCK18. Comparing to the weak lensing signal shown in black dots with errorbars. *Right:* Same as left figure but with WMAP5 cosmology. The excluded data points in our analysis are shown as empty circles at scale smaller than 30 h\(^{-1}\)kpc.

Fig. 3.— From left to right, these are the plots of stellar mass bin 1, 2 and 3 based on PLANCK18 cosmology. The red and blue dots are the measurement from red and blue galaxy samples. We exclude the first data points within 30 h\(^{-1}\)kpc as empty circles. The empty circle at large scale in the middle panel denotes a negative value. The red and blue solid lines are the EG model, dashed lines are from NFW model. The bandwidth from EG model is due to the 0.1dex systematic from stellar mass estimation based on the method of Bell et al. (2003).
consistent halo mass estimation for the whole sample after considering 0.07 Eddington bias estimated from Luo et al. (2018). The last two shows significant discrepancy with abundance matching halo mass, 0.5dex difference in the last stellar mass bin. We attribute this to the selection effect that we only select single galaxy system. Fig. 4 shows the Stellar mass to Halo Mass Relation (SHMR) of our measurement. Our measurement agrees well with both observational calibration (Leauthaud et al. 2017) and simulation calibration (Girelli et al. 2020) except for the most massive stellar mass bin. That is due to our simple NFW model and the selection of single galaxy systems. The multi-galaxy systems in stellar mass bin 4 is about 20.3% and 33.4% for stellar mass bin 5. We re-calculate the multi-galaxy sample halo mass for those two bins in PLANCK18 cosmology and obtain higher halo mass than the single systems in the same stellar mass bin, which are 12.873 and 13.533 respectively. If we simply take the weighted average halo mass together with single systems, we get 12.654 ± 0.23dex and 13.178 ± 0.08dex, vs 12.985 and 13.299 from abundance matching.

**TABLE 2**

| Cosmology     | NFW \(\chi^2/\text{dof}=15\) | EG \(\chi^2/\text{dof}=25\) |
|---------------|------------------------------|-----------------------------|
| WMAP5         | 0.949(1.453)                 | 2.959(3.739)                |
| RED           | 0.717(1.433)                 | 1.861(3.397)                |
| BLUE          | 0.731(0.682)                 | 2.431(2.985)                |
| PLANCK18      | 0.656(0.966)                 | 1.590(1.770)                |
| RED           | 0.718(0.885)                 | 1.792(1.762)                |
| BLUE          | 0.659(0.626)                 | 2.730(2.391)                |

We also further test the possible contribution of faint satellites out of SDSS spectroscopic detection limit at r band model magnitude 17.77 around massive stellar mass bins, based on illustrisTNG300-3 (Nelson et al. 2018) low resolution hydro-simulation. IllustrisTNG-300-3 has 100 snapshots from z at 127, with 302.6 h\(^{-1}\)Mpc box size, dark matter particle mass \(3.8 \times 10^8 M_\odot\) and gas, stellar cell mass \(7.0 \times 10^8 M_\odot\). We download group catalog from snapshot 91 at z=0.1 as well as processed offsets file to obtain the information of dark matter and gas, stellar particles for each halo and its subhalo. We select four samples based on halo mass (weak lensing mass±error) and stellar mass from Table 3.1. The stellar particles inside 100kpc with respect to the centroids of the stacked dark matter particles, are considered to be from the central galaxies. This criteria is based on the 50kpc offcenter effect (Luo et al. 2017a) and the galaxy size 50kpc cited from Chen et al. (2019). The ratio between stellar particles outside this radius and the ones inside this radius is the rough estimation of the contribution of satellite galaxies in general. Fig. 5 is an example of halo from the simulation defined by rockstar software (Behroozi et al. 2013), the black dots are the dark matter particles and the red dots are the stellar particles, the boundary of the halo is not regular but roughly about the virial radius of a halo. We find 10% for the most massive stellar mass bin, and this dramatically decreases to 1.0% for the second most massive stellar mass bin. This dramatic decrease may be due to the resolution of the suit of simulations we used here. However, we still can consider the 10% as an upper limit for the satellite contribution. Further more, in observational data, the secondary satellite is beyond 17.77 in r band, so in reality this is less than 10%. And the contribution for the rest can be neglected. So the "unobserved" faint galaxies do not contribute significantly to the EG in our analysis. About 5.7% galaxies (36, 759) in the sample are brighter than r band 17.77, but without spectroscopic redshift measurements due to fiber collision effect. According to Zehavi et al. (2002), roughly 60% of the fiber-collision galaxies have a redshift within 500 km s\(^{-1}\). In Yang et al. (2007), they assign redshift of their nearest neighbours in the group finding procedure. As a result, the single system does not have close companion with...
fiber collision galaxies, therefore our results are not affected by fiber collision effect.

In a word, our results are robust against potential influence from either fiber collision galaxies and faint galaxies with r band magnitude fainter than 17.77.

5. SUMMARY AND DISCUSSION

We select isolated galaxy systems from SDSS DR7 group catalog Yang et al. (2007), with recent updated halo mass estimation. This update doubles the number of lens galaxy at small stellar mass bins compared to the sample used in Chen et al. (2019), which enables us to measure high SNR ESD for those samples (17.6 for blue galaxy sample to 28.1 for red galaxy sample). Furthermore, we split each stellar mass sample into blue and red to test the color dependence.

We model the ESD profile with NFW profiles, setting halo mass and concentration as free parameters based on two cosmologies, i.e. WMAP5 and PLANCK18. The most significant difference is from the ESD between red and blue lens samples. The ESDs from the blue samples in the same stellar mass bin have lower amplitude than their red counterparts, indicating smaller halo mass. Because “apparent dark matter” ESD in EG framework remains the same as long as the stellar mass is the same. This can be clearly seen in stellar mass bin 2 and 3 where the stellar mass has only 0.014dex to 0.020dex difference, while the halo mass have up to 5σ difference.

We also further test the validity of our selection of isolated systems using illustrisTNG300-3 (Nelson et al. 2018), and we found that the contribution of possible satellite out of SDSS spectroscopic detection limit is 10% for the most massive stellar mass bin and 1% for the second most massive stellar mass bin. This effect can be neglected for the rest of the samples.

In general, EG scenario of gravity failed to explain the color dependence of the galaxy-galaxy lensing signal and we summarise as follows:

- The EG favors PLANCK18 cosmology with reduced \( \chi^2_{\text{reduced}} = 1.907 \) to WMAP5 \( \chi^2_{\text{reduced}} = 2.959 \) with degrees of freedom of 15 for NFW and 25 for EG. The NFW model shows significant lower reduced \( \chi^2 \) value than those from EG already without red and blue dichotomy, which are 0.868(0.996) for WMAP5 cosmology and 0.949(1.453).

- The most significant difference is from the first three stellar mass bins after the red and blue classification. For instance, in PLANCK18 cosmology the reduced \( \chi^2 \) is 0.718(0.885) for red lens sample and 0.659(0.626) for blue sample, and these values are increased to 1.792(1.762) and 2.730(2.931) respectively in EG model.

- The halo mass discrepancy betweenundance matching and NFW model fitting is significant for the last two stellar mass bins, this is due to the combination of selection effect and abundance matching method.

- Our results are consistent with Zu & Mandelbaum (2016) in that the halo mass of blue galaxies in the same stellar mass bins are smaller than that of red galaxies.

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