Baryonic Feedback Measurement From KV450 Cosmic Shear Analysis

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Abstract

While baryonic feedback is one of the most important astrophysical systematics that we need to address in order to achieve precision cosmology, few weak lensing studies have directly measured its impact on the matter power spectrum. We report measurement of the baryonic feedback parameter with the constraints on its lower and upper limits from cosmic shear. We use the public data from the Kilo-Degree Survey and the VISTA Kilo-Degree Infrared Galaxy Survey spanning 450 deg\textsuperscript{2}. Estimating both cosmological and feedback parameters simultaneously, we obtain $A_b = 1.01^{+0.40}_{-0.85}$, which shows a consistency with the dark matter-only (DMO) case at the $\sim 1.2\sigma$ level and a tendency toward positive feedback. The $A_b = 0$ (0.81) value corresponds to the DMO (OWLS AGN) case. Despite this full constraint of the feedback parameter, our $S_8 (=\sigma_8\sqrt{\Omega_m/0.3})$ measurement (0.739$^{+0.035}_{-0.036}$) shifts by only $\sim 6\%$ of the statistical error, compared to the previous measurement. When we assume the flat ΛCDM cosmology favored by the Nine-Year Wilkinson Microwave Anisotropy Probe (Planck) result, the feedback parameter is constrained to be $A_b = 1.21^{+0.61}_{-0.54}$ (1.60$^{+0.53}_{-0.52}$), which excludes the DMO case at the $\sim 2.2\sigma (\sim 3.1\sigma)$ level.

Unified Astronomy Thesaurus concepts: Cosmology (343); Cosmological parameters from large-scale structure (340); Gravitational lensing shear (671); Weak gravitational lensing (1797); Large-scale structure of the universe (902); Astrophysical processes (104); Observational cosmology (1146)

1. Introduction

Weak gravitational lensing (WL) is one of the most powerful probes of dark energy. Stage IV WL projects, such as the Vera C. Rubin Observatory (Ivezic et al. 2019), Euclid (Laureijs et al. 2011), Nancy Grace Roman Space Telescope (Spergel et al. 2015), etc., are expected to start their missions in the current decade by measuring subtle shape distortions from billions of distant galaxies to pursue this goal. Certainly, the superb statistical power from these Stage IV experiments will enable the so-called precision cosmology era only if we manage to control their systematic errors below or comparable to the statistical ones.

Accurate determination of the change in the total matter power spectrum (PS) due to baryon physics with respect to the dark matter-only (DMO) case is one of the most difficult challenges in theoretical systematics. Unlike cold dark matter, which is believed to interact only through gravity, it is difficult to perform robust numerical simulations with baryonic feedback because its impact is dominated by so-called sub-grid physics. Fortunately, there have been positive developments on this lately, helped by more efforts in observations, calibration strategies, simulation cost reduction, etc., but there are clear degeneracies in sub-grid physics that need to be quantified. Currently, non-negligible discrepancies in baryonic feedback prediction among different state-of-the-art simulations exist.

The requirement of the matter PS prediction accuracy in the precision cosmology era is very stringent. Huterer & Takada (2005) estimated that an accuracy of 1%–2% is needed for the $k$ range 0.1 $h$ Mpc$^{-1}$ $\lesssim k \lesssim 10$ $h$ Mpc$^{-1}$ in order to fully utilize the statistical power of Stage IV data. When photometric redshift uncertainty is included, a much tighter (0.5%) requirement over a larger $k$ range (0.01 $h$ Mpc$^{-1}$ $\lesssim k \lesssim 5$ $h$ Mpc$^{-1}$) is suggested by Hearin et al. (2012).

The traditional approach to addressing the baryonic effect in cosmological WL analysis is to simply truncate the observed correlation function/PS on small scales (see Chisari et al. 2019, for review) or to employ modified estimators (e.g., COSEBIs, Asgari et al. 2020) that filter out the part heavily influenced by baryonic physics. The obvious drawback of these methods is non-negligible reduction of the statistical power, particularly because the WL signal-to-noise ratio (S/N) is high on the nonlinear (thus small) scales. Also, the absence of the consensus on the optimal baryonic feedback recipe provides ambiguity in determining the exact cutoff scale.

Alternatively, recent studies suggest empirical modeling of the matter PS modification based on hydrodynamical cosmological simulations (e.g., Semboloni et al. 2011, 2013). Although no consensus is present regarding the exact feedback strength and scale, one can parameterize the effect by recognizing the patterns in the matter PS modification in different simulations. Eifler et al. (2015) propose the principal component analysis (PCA) as a method to recognize the pattern. One can then either discard the components sensitive to the baryonic feedback or use them to model the effect. The potential weakness of this approach is that the resulting principal components are sensitive to the choice of the sample. In other words, unless the sample includes a sufficiently broad range of feedback scenarios, the performance can be non-negligibly compromised (Mohammed & Gnedin 2018). Another approach is to simply parameterize the deviation of the matter PS from the DMO PS in a model-independent way. For example, (Harnois-Déraps et al. 2015, hereafter HD15) demonstrate that description of the PS ratio variation for OverWhelmingly Large cosmological hydrodynamical Simulations (OWLS; Schaye et al. 2010; van Daalen et al. 2011) with 15 parameters provides <5% precision. Chisari et al. (2018) show that their four-parameter description is adequate to provide a good (<5%) fit to Horizon-AGN by using the baryonic correction model (Schneider &
Teyssier 2015). Recently, van Daalen et al. (2020) present an empirical model based on numerical simulations with a wide range of feedback models, which requires only a single parameter.

A halo model-based approach is introduced by Mead et al. (2015, hereafter M15), who propose to model the modification of the matter PS with the halo properties affected by baryonic feedback. The authors note that the two parameters of their halo model, which are linearly related with each other, are sensitive to different feedback scenarios in OWLS. Thus, they propose a method to model the feedback with a single parameter. Although subject to further analysis with a broader range of feedback cases, this provides a convenient formalism to characterize the baryonic feedback effect, in particular, for the current Stage III WL studies, which do not yet provide sufficient statistical power to discriminate subtle differences in various feedback scenarios.

Also, a hybrid approach modifying DMO simulation results with baryonic halo properties has been suggested (Schneider et al. 2019). This “baryonification” method applies small shifts to the particles in the DMO halos to effect the baryonic feedback. Because baryonic effects are empirically parametrized, the approach enables fast realizations of many nonlinear cosmic density fields with varying baryonic parameters.

Current cosmological hydrodynamics simulations calibrate their sub-grid physics recipes by ensuring that the results can reproduce some observational statistics (e.g., Schaye et al. 2015; McCarthy et al. 2017; Pillepich et al. 2017; Springel et al. 2017) such as scaling relations, gas fractions, etc. However, because the recipes are degenerate, the calibration parameters cannot be determined uniquely. The large discrepancy seen in the prediction of the matter power spectrum among the different simulations clearly demonstrates the current limitation. Recently, a novel approach was proposed by Debackere et al. (2020), who measured the power suppression due to baryonic feedback based on the empirical approach combining X-ray hot gas observations and Halo Occupation Distribution (HOD) modeling. Compared to the previous simulation-based approach, there is a clear merit for this approach because it does not rely on the aforementioned sub-grid physics. Nevertheless, this study too has to rely on a number of astrophysical/cosmological assumptions including HOD models, matter density profiles, X-ray emissivity, cluster/group mass function, galaxy bias, etc.

One critical cross-check in the baryonic feedback study is a measurement of the feedback impact from the shape of the matter power spectrum, which is directly probed by cosmic shear. Although this approach is not entirely assumption-free, it does not rely on the observational priors such as scaling relations, gas fractions, etc. that the previous studies require.

To date, few observational studies have placed direct constraints on the baryonic impact on the matter PS with WL measurements. HD15 applied their 15-parameter parametric baryonic feedback models to the Canada–France–Hawaii Telescope Lensing Survey (CFHTLenS) cosmic shear data. They found that the DMO model (zero neutrino mass and no baryonic feedback) is rejected at the $>2\sigma$ level from their $p$-value test. Köhlinger et al. (2017) applied the HD15 model to the Kilo-Degree Survey (KiDS) 450 sq. deg. data and measured only the upper limit. Most cosmology studies with KiDS (Hildebrandt et al. 2016; Joudaki et al. 2017, 2018; van Uitert et al. 2018; Hildebrandt et al. 2020) used the M15 model to marginalize over the baryonic feedback effect, unable to confine the feedback parameter posterior within their prior intervals. In the cosmic shear studies with Hyper Suprime-Cam (HSC) (Hikage et al. 2019; Hamana et al. 2020), the results are consistent with the DMO case, presumably because of the conservative cuts in the cosmic shear measurements.

Based on the Deep Lens Survey (DLS) and the M15 model, (Yoon et al. 2019, hereafter Y19) presented the baryonic feedback measurement, constraining both the lower and upper bounds of the feedback parameter. Although the area is small ($\sim$20 sq. deg), the DLS depth is high, reaching down to $\sim$26.5th in $B$, $V$, $R$, and $\varepsilon$. This enables competitive constraints on cosmological parameters (e.g., $S_8 = 0.810 \pm 0.030$) compared to those of most Stage II and some early Stage III results. The DLS result is one of the few recent WL studies, whose measurements are highly consistent with the Planck value, $S_8 = 0.832 \pm 0.013$ (Planck Collaboration et al. 2020b).

However, it is difficult to interpret the Y19 result because, taken at face value, the measurement implies that the feedback strength should be much higher than the recipes in most state-of-the-art hydrodynamical cosmological simulations. As discussed in Y19, the insufficient degree of freedom in the M15 model may be one of the possible causes for this result. Also, we can consider possibilities that some other residual astrophysical systematics can masquerade as baryonic feedback. One such potentially relevant astrophysical systematic error in Y19 is a nonlinear galaxy bias (Asgari et al. 2021a) because the measurement is obtained from the combination of galaxy clustering and galaxy–galaxy lensing under the assumption that the galaxy bias is linear at $l < 2000$.

In this letter, we report measurement of baryonic feedback parameter from the KiDS-VIKING 450 sq. degree data (KV450). Specifically, we use the public data set used in Hildebrandt et al. (2020, hereafter H20). Because the H20 study is based on cosmic shear, the nonlinear galaxy bias that may potentially have affected the Y19 result is not an issue in the current analysis. Also, as the KV450 WL pipeline is completely independent of the DLS one, consistent detection between the two different data sets serves as a crucial consistency check.

2. Data

The details of KV450 and its catalog used for cosmic shear analysis are described in Wright et al. (2019) and H20. Below we only provide a brief description. The KV450 shape catalog was produced using lensfit and the calibration methods described in Miller et al. (2007, 2013), Kannawadi et al. (2019), Fenech Conti et al. (2017), while the photo-$\gamma$ catalog was based on BPZ (Benítez 2000) trained with the following spectroscopic samples: zCOSMOS (Lilly et al. 2009), DEEP2 (Newman et al. 2013), VVDS (Le Fèvre et al. 2013), GAMA-G15Deep (Kafle et al. 2018), and CDFS (Le Fèvre et al. 2013; Vanzella et al. 2008; Vaccari et al. 2016; Jarvis et al. 2013).

We use the same five tomographic binning schemes: $z_b \in [0.1, 0.3], [0.3, 0.5], [0.5, 0.7], [0.7, 0.9],$ and $[0.9, 1.2]$ as in H20. After confirming that our analysis pipeline reproduces the identical posteriors of H20 with the original data vectors and covariances, we choose to use finer angular binning for our subsequent analysis because we find that this increase in the number of angular bins improves the cosmological constraints for some parameters. In H20, $\xi(\theta)$ were measured using 7/6 bins for the scale range [0.50, 72] ((4.2, 300)] arcmin uniformly divided in logarithmic scale. We choose 10(8) bins for $\xi(\theta)$ over the similar angular range [0.50, 103]((4.2, 300)]. Figure 1
The total number of free parameters is 14.

The H20 binning case is an arti-
significant improvement over the “haloﬁt” model (Smith et al.
approach with more physically-motivated seven⁶ halo para-
can cover a wider range of cosmologies including
different levels of baryonic feedback. Also, this parameteriza-
tion allows us to interpret the PS variation across different
cosmological/feedback simulations in the astrophysical
context.

The cosmology-dependent halo model parameters were
determined using the power spectra derived from the COSMIC
EMU (Heitmann et al. 2010, 2013). Using different baryonic
feedback settings of OWLS, M15 find that among these seven
halo parameters, the two parameters, namely the minimum halo
concentration A and the halo bloating factor $\eta_0$ need to be
adjusted to accommodate the resulting change in the PS shape.
In addition, although the number of the simulation sets is
limited, they suggest that the two parameters are related as
follows (Joudaki et al. 2018):

$$\eta_0 = 0.98 - 0.12A,$$

where $\eta_0 = \eta + 0.3\sigma_8(z)$. The A values of 2.32 and 3.13
correspond to the AGN and DMO cases, respectively. This
linear relation has been used/tested in many cosmological
studies with different A ranges (e.g., [2.32, 3.13] in Hikage et al.
2019, [2, 3.13] in H20, [2, 4] in van Uitrct et al. 2018 and
Hildebrandt et al. 2016, [2, 4]/[1, 10] in Joudaki et al. 2017,
and [1, 4]/[1, 10] in Joudaki et al. 2018).

In this study, we redeﬁne the baryonic feedback parameter as
follows:

$$A_b \equiv 3.13 - A.$$  

This deﬁnition makes a positive departure of $A_b$ from zero (i.e.,
$A = 3.13$, DM-only case) mean positive feedback with a larger
value corresponding to stronger feedback.

3.2. Prior Settings

We use the same settings as in H20 in order to avoid
potential confusion in interpretation and also enable a fair
comparison of the resulting cosmological parameters. Exceptions
are made for the matter PS spectral index $n_s$ and the
baryonic feedback $A_b$ parameters because of the reasons
explained below.

As illustrated in Figure 2, the change in the matter PS at
$k \geq 1 \text{ Mpc}^{-1}$ due to the variation in $n_s \in [0.7, 1.3]$ is similar to
the one due to the variation in $A_b \in [-0.87, 2.13]$. This causes
a degeneracy between the two parameters in their posterior
distributions as shown in Figure 2. Consequently, within the
statistical noise level of KV450, it is difﬁcult to distinguish
their impacts. Since H20 used $n_s \in [0.7, 1.3]$, their $A_b$ posterior
is not bounded. We argue that the H20 $n_s$ prior interval is too
wide because it corresponds to the $\pm 75\sigma$ range of the Planck
constraint $n_s = 0.965 \pm 0.004$ (Planck Collaboration et al.
2020b) or $\pm 21\sigma$ range of the Nine-Year Wilkinson
Microwave Anisotropy (WMAP9) result $n_s = 0.972 \pm 0.013$
(Hinshaw et al. 2013). Therefore, we choose to use the interval
$n_s \in [0.87,1.07]$ as our fiducial prior, which is still very
conservative, corresponding to $\pm 25 (8)\sigma$ range of the Planck
(WMAP9) measurement. Similarly narrower $n_s$ intervals are
used by the Hyper Suprime-Cam surveys (Hikage et al. 2019),

3.3. Analysis

### 3.1. Cosmology and Baryonic Feedback Models

We compute the linear matter PS with camb⁴ (Lewis et al.
2000; Howlett et al. 2012). To account for the nonlinear
evolution and baryonic feedback effects, we use the halo-model
based code HMcode⁵ (M15). The “halo model” approach is a

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⁴ http://camb.info

⁵ https://github.com/alexander-mead/hmcode

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Fig. 1. Effect of angular binning scheme. The same priors were applied to both
cases. We ﬁnd that the constraining power of the H20 data improves for some
cosmological parameters when we increase the number of angular bins from 7/6
(the original H20 binning scheme) bins to 10/8 bins for $\xi' (\xi'')$. The effect is most
signiﬁcant for the reduction of the degeneracy between $\Omega_m$ and $\sigma_8$; the uncertainty
of $\sigma_8$ is reduced by $\sim 20\%$. The abruptly declining left tail of the $\Omega_m$ posterior for
the H20 binning case is an artiﬁcial feature due to the employed kernel density
estimator (smoothing) for plotting. The uncertainty in $\sigma_8$ decreases by $\sim 7\%$ while
the impact on $A_b$ is negligible. Readers are reminded that the result shown here with
the H20 binning scheme (red) is our reproduction based on the modiﬁed $n_s$ and $A_b$
priors, not identical to the one in the H20 paper.

illustrates that the current binning scheme signiﬁcantly reduces
the parameter degeneracy between $\Omega_m$ and $\sigma_8$. For instance,
while the full posterior of $\Omega_m$ in H20 is not contained within the
prior interval, Figure 1 shows that the peak, lower, and upper
bounds are well-determined with our ﬁner binning scheme.
Also, the uncertainty of $\sigma_8$ is reduced by $\sim 20\%$.

Note that we do not extend the lower angular limit of H20 to
increase sensitivity to baryonic feedback because doing so will
make our result also susceptible to other systematics such as
nonlinear intrinsic alignment (Fortuna et al. 2021) and also because
the impact of baryonic feedback at the smallest scale of H20 (0.5
and 5′ in $\xi'$ and $\xi''$, respectively) is already signiﬁcant (up to
$\sim 20\%$ in the matter PS with respect to the DMO PS).

For our new binning scheme, shear-shear covariances were re-
measured using treecorr (Jarvis et al. 2004). The corresponding
covariance matrix was also re-calculated analytically with the
same recipe as used in Hildebrandt et al. (2016)/H20.

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The total number of free parameters is 14.
The error bars denote the ~68.3% confidence intervals. 1. We used the baryonic acoustic oscillation and full shape measurements of redshift space range of the Planck result - WMAP9 cosmology is assumed, we exclude the DM-only scenario at the 2.2σ level. Adding massive neutrinos virtually does not change the result. When the WMAP9 cosmology is assumed, we exclude the DM-only scenario at the 2.2σ level (~98.5%, one-sided). These measurements are summarized in Table 1.

Table 1
Baryonic Feedback and Cosmological Constraints w/different Prior Settings and External Data Combination

| Setting                              | \( A_0 \)   | \( S_8 \)   | \( \chi^2/\text{d.o.f.} \) |
|--------------------------------------|-------------|-------------|---------------------------|
| wide \( n_s \)                       | 1.52 ± 0.08 | 0.745 ± 0.041 | 1.00                      |
| fiducial \( n_s \)                   | 1.01 ± 0.04 | 0.739 ± 0.036 | 1.01                      |
| fiducial \( n_s \) + massive neutrino | 1.07 ± 0.08 | 0.737 ± 0.035 | 1.02                      |
| WMAP9 cosmology                     | 1.21 ± 0.06 | Fixed        | 0.99                      |
| Planck cosmology                    | 1.60 ± 0.03 | Fixed        | 1.01                      |
| w/ SDSS DR12²                        | 1.29 ± 0.70 | 0.774 ± 0.028 | 1.01                      |
| w/ Planck TT likelihood              | 1.32 ± 0.66 | 0.805 ± 0.019 | 1.05                      |
| w/ Planck EE likelihood              | 0.74 ± 0.74 | 0.756 ± 0.021 | 1.02                      |
| w/ Planck EE likelihood              | 0.65 ± 0.76 | 0.746 ± 0.017 | 1.02                      |

Note. The error bars denote the ~68.3% confidence intervals. 1. We used the baryonic acoustic oscillation and full shape measurements of redshift space distortion from the SDSS DR12 data (Alam et al. 2017). 2. The reduced \( \chi^2 \) values were evaluated at the best-fit locations for the cosmic shear data vector (i.e., we do not include the \( \chi^2 \) value for the external data).

Figure 3: Baryonic feedback constraints for different settings. We determine both the lower and upper limits of the \( A_0 \) posterior with the fiducial \( n_s \) prior, whereas the use of the wide \( n_s \) interval does not constrain the upper bound. Our fiducial measurement is consistent with the DM-only case at the 1.2σ level. Adding massive neutrinos virtually does not change the result. When the WMAP9 cosmology is assumed, we exclude the DM-only scenario at the 2.2σ level (~98.5%, one-sided). These measurements are summarized in Table 1.

4. Result

Our baryonic feedback measurements are summarized in Table 1 for various settings. Note that the reduced \( \chi^2 \) values were evaluated at the best-fit locations in the parameter space only for the cosmic shear data vector. This investigation is to examine whether or not our constraints on \( A_0 \) are primarily due to tensions between the KV450 and the baryonic feedback parameter \( A_0 \) is assumed to be the dominant constraint due to the variation in \( n_s \) is similar to the one due to the variation in \( A_0 \) in the [−0.87, 2.32] range. The third panel displays their posterior distributions. The wide interval in \( n_s \) (±0.7, 1.3), encompassing the ±~75σ range of the Planck result substantially weakens the constraining power in \( A_0 \). See Section 3.2 for details.

Dark Energy Surveys Year 1 study (Troxel et al. 2018), and DLS (Y19). Readers are reminded that the lower (upper) limit of the \( h \) prior interval [0.64, 0.82] used in H20 and the current study corresponds to 6.8 (5.6)\( \sigma \) of the direct (Planck) measurement (Riess et al. 2019; Planck Collaboration et al. 2020b).

We extend the prior interval of \( A_0 \) in the H20 setting because our initial experiment with the \( A_0 \) setting cannot determine the upper limit within \( A_0 \) in the [−0.87, 3.03] range. Thus, we use \( A_0 \) in the [−0.87, 3.03] range. This is also employed by Y19.
the same data. In our fiducial case, the shift in $S_8$ is only $\sim$6% of the statistical uncertainty with little change in the measurement uncertainty.

The above measurement demonstrates that KV-450 alone can put meaningful constraints on both cosmology and astrophysics simultaneously. However, a more common practice in astrophysics is to probe astrophysical properties with an assumption of a certain (fixed) cosmology. Here, we carry out such an experiment with the KV450 data. When we assume the cosmological parameters favored by the WMAP9 (Hinshaw et al. 2013) observation, we obtain $A_b = 1.21^{+0.61}_{-0.54}$. The shift in the central value is small with respect to the KV450-only case (see Figure 3) while the parameter uncertainty is reduced by $\sim$37%. Therefore, this measurement excludes the DMO case (and thus detects the baryonic feedback) at the $\sim 2.2\sigma$ level ($\sim$98.5%, one-sided). For the Planck cosmology (Planck Collaboration et al. 2020b), the central value of $A_b$ increases by $\sim$0.39 compared to the WMAP9 case, favoring stronger feedback (see Table 1). This increase in $A_b$ is by and large attributed to a significantly higher $S_8$ value favored by the Planck cosmology; stronger suppression is needed to reconcile the difference in $S_8$. Interestingly, the reduced $\chi^2$ value (1.01) when the cosmology is fixed to the Planck result is in excellent agreement with the one in the fiducial case (Table 1). This potentially provides a chance to shed light on the origin of the much-discussed $S_8$ tension between WL and Planck results. When we examined the rest of the free parameters such as shear calibration, intrinsic alignment, photo-$z$ calibration, etc., we find that the changes are negligible. Thus, one naive interpretation is that the actual strength of the baryonic feedback might be stronger than the current predictions/measurements in other studies, as discussed in Yoon et al. (2019). However, we defer the issue to our future studies when more complete baryonic feedback models become available.

In addition to the above experiment with a fixed cosmology, one can also utilize external data to constrain both cosmology and baryonic feedback. We summarize these results in Table 1. Combining KV450 with the redshift space distortion and baryonic acoustic oscillation measurement from the Sloan Digital Sky Survey Baryon Oscillation Spectroscopic Survey Data Release 12 (Alam et al. 2017) yields $A_b = 1.29_{-0.82}^{+0.20}$, which is in good agreement with the result obtained when we fix our cosmology to the WMAP9 result. A similar result is obtained when the Planck TT data (Planck Collaboration et al. 2020a) are added. However, because this external data possesses $\sim 2\sigma$ tension in $S_8$ with KV450, the interpretation should use caution. The combinations with the Planck TE and EE data, which do not present significant tensions with KV450, give consistent, but somewhat lower values.

5. Discussion and Summary

We have presented our baryonic feedback measurement from the KV450 data, constraining both the lower and upper limits of the feedback parameter. H20 could not fully constrain this feedback parameter because the prior interval in $A_b$ is too narrow and because the prior interval in $n_s$ is too wide. Readers are reminded that despite the changes of the prior intervals in these two parameters, the peak location of the $S_8$ posterior virtually remains unaffected, although its uncertainty reduces by $\sim$8%. Our best-fit value of $A_b$ lies within the H20 prior range ($\epsilon[0.1, 1.13]$).

Our analysis with the KV450 data alone leads to the feedback parameter measurement $A_b = 1.01^{+0.50}_{-0.63}$, which presents a consistency with the DMO case ($A_b = 0$) at the $\sim 1.2\sigma$ level. Under the assumption of the WMAP9 cosmology, we obtain $A_b = 1.21^{+0.61}_{-0.34}$. This result excludes the DMO case or provides evidence for baryonic feedback at the $2.2\sigma$ level ($\sim$98.5%, one-sided).

Figure 4 illustrates the level of the PS suppression at $z = 0$ due to the baryonic feedback constrained from the current study. As mentioned above, our KV450 with the WMAP9 cosmology result is $\sim 2.2\sigma$ away from the DMO case $P_{\text{hydro}}/P_{\text{DM}} = 1$. At $k = 10\, h\, \text{Mpc}^{-1}$, the amount of the PS suppression is $\sim 25\%$ and the uncertainties encompass the OWLS AGN, Illustris, and BAHAMAS 8.0 PS while the DLS result (Y19) shows some tensions with these predictions. Nevertheless, the current KV450 results are statistically consistent with the DLS ones.

A recent empirical study based on X-ray observations and halo occupation distribution modeling (Debackere et al. 2020) claims that a suppression at the $\sim 15\%$ level is expected at $k = 5–10\, h\, \text{Mpc}^{-1}$. This suppression is similar to the level predicted by the BAHAMAS 7.8 result and consistent with the current measurement at the $\sim 1\sigma$ level. Note that the prediction of Debackere et al. (2020) is based on the WMAP9 cosmology.

Asgari et al. (2021b) presented a cosmic shear analysis with the KiDS 1000 sq. degree data. Marginalizing over the interval $A_b \in [0.0, 1.13]$ (i.e., $A_b \in [2, 3.13]$ according to the notation in the paper), they obtained $A_b = 0.55_{-0.39}^{+0.28}$. As the authors noted, this is an artificial constraint because the full posterior shape is not contained within this narrow prior range. Nevertheless, its peak location is fully consistent with the current measurement.

Just one day prior to the submission of the current paper, Huang et al. (2020) uploaded their baryonic feedback measurement based on the Dark Energy Survey Year 1 (DES-Y1) data to the archive. Using the PCA approach and DES-Y1 data alone, they reported $Q_1 = 1.14_{-2.20}^{+2.05}$, where $Q_1$ is the first principal component. This result is more consistent with the null hypothesis of no feedback.

http://powerlib.strw.leidenuniv.nl

https://arxiv.org/pdf/2007.15026.pdf
component amplitude. Although the left tail of the posterior is not well-determined with the DES-Y1 data alone, the result is consistent with the DMO case ($Q_1 = 0$). When combined with the Planck (EE+lowE) and BAO data, the constraint becomes tighter $Q_1 = 1.42^{+1.63}_{-1.48}$, which is still consistent with the DMO case and excludes the most extreme scenario in their comparison sample ($Q_1 = 5.84$) at the $\sim2$ sigma level. Despite the difference in the characterization of the baryonic feedback strength, we find that the DES-Y1 measurement is fully consistent with ours, judging from their reference simulations compared with the posterior (Figure 15 of their paper).

Although we provide the constraint on the baryonic feedback parameter from cosmic shear analysis alone, the proper interpretation should await improvements of our understanding in several aspects. First, as shown in Figure 4, the current M15 one-parameter model lacks flexibility to accommodate the variation across different feedback scenarios. In particular, the power on very small scales ($k \gtrsim 10\ h\ Mpc^{-1}$) does not show the “upturns” due to baryonic cooling contraction, which however are present in most numerical studies. Second, our nonlinear intrinsic alignment model is incomplete. The current model is based on the linear formalism (Catelan et al. 2001; Hirata & Seljak 2004) with the replacement of the linear PS with the nonlinear one, which lacks solid theoretical justification. Nevertheless, given the statistical uncertainty of the KV450 data, we believe that perhaps the nonlinear effect is subdominant.

Despite the above caveats, however, the current study illustrates tremendous future opportunities that will be enabled with Stage IV WL surveys. Thanks to the unprecedented statistical powers, these studies will lead to precision cosmology as well as to a testbed for models beyond the standard $\Lambda$CDM (e.g., modified gravity, time-dependent dark energy, etc.). This can be empowered by understanding the small-scale systematics including baryonic feedback, which is a prerequisite to utilize the signals over wide scale ranges. Finally, in the future when the concordance cosmology is no longer in question, high S/N measurements of the suppressed PS shape through gravitational lensing will provide critical feedback to obscure, sub-grid physics in numerical studies.

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