J-PAS: forecasts on interacting dark energy from baryon acoustic oscillations and redshift-space distortions

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ABSTRACT
We estimate the constraining power of J-PAS for parameters of an interacting dark energy cosmology. The survey is expected to map several millions of luminous red galaxies, emission line galaxies and quasars in an area of thousands of square degrees in the northern sky with precise photometric redshift measurements. Forecasts for the DESI and Euclid surveys are also evaluated and compared to J-PAS. With the Fisher matrix approach, we find that J-PAS can place constraints on the interaction parameter comparable to those from DESI, with an absolute uncertainty of about 0.02, when the interaction term is proportional to the dark matter energy density, and almost as good, of about 0.01, when the interaction is proportional to the dark energy density. For the equation of state of dark energy, the constraints from J-PAS are slightly better in the two cases (uncertainties 0.04–0.05 against 0.05–0.07 around the fiducial value −1). Both surveys stay behind Euclid but follow it closely, imposing comparable constraints in all specific cases considered.

Key words: cosmology: theory – dark energy – methods: data analysis – surveys – large-scale structure of Universe – cosmological parameters

1 INTRODUCTION
The lack of knowledge regarding the nature of the dark sector, especially the cosmic acceleration (Riess et al. 1998; Perlmutter et al. 1999), has led to a continuous endeavor to understand the origin of such accelerated expansion and its dynamics. Several ongoing and upcoming spectroscopic, photometric and radio surveys have been proposed to address this problem, including DES (The Dark Energy Survey Collaboration 2005), LSST (LSST Science Collaboration et al. 2009), eBOSS (Dawson et al. 2016), DESI (DESI Collaboration et al. 2016), Euclid (Laureijs et al. 2011), BINGO (Battye et al. 2012; Wunschke & the BINGO Collaboration 2018) and SKA (Maartens et al. 2015). Among them, the Javalambre-Physics of the Accelerated Universe Astrophysical Survey (J-PAS, Benítez et al. 2009, 2014) is a multi narrow-band photometric survey which will cover up to 8500 square degrees of the northern sky and measure 0.003 (1 + z) precision photometric redshifts for 9 × 10^7 luminous red galaxies (LRG) and emission line galaxies (ELG) plus several millions of quasars (QSO). In addition, it aims to detect and measure the mass of 7 × 10^5 galaxy clusters and groups, improving the constrains on dark energy.

On the theoretical side, deviations from the A-Cold Dark Matter (ΛCDM) model have been proposed over the years, whose alternatives to the cosmological constant include canonical and non-canonical scalar fields (Peebles & Ratra 1988; Ratra & Peebles 1988; Frieman et al. 1992, 1995; Caldwell et al. 1998; Padmanabhan 2002; Brax & Martin 1999; Copeland et al. 2000), holographic dark energy (Hsu

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densities are of the same order of magnitude despite the fact they
density of the Universe. Its components, dubbed dark matter and dark
energy (Stojkovic et al. 2008; Greenwood et al. 2009; Abdalla et al.
2013; Shaferloo et al. 2018; Stachowski et al. 2017; Szydlowski
et al. 2017; Landim & Abdalla 2017; Landim 2018), among others.
One interesting possibility to consider is when we allow an exchange of energy-momentum between the two components of
the dark sector (Wetterich 1995; Amendola 2000). This mechanism
could be one reason why dark energy (DE) and dark matter (DM)
contribute to the present Universe with comparable energy
densities, alleviating the coincidence problem (Zimdahl et al. 2001;
Cimento et al. 2003). Models of interacting DE have been widely ex-
plored in the literature (Amendola 2000; Guo & Zhang 2005; Cai &
Wang 2005; Guo et al. 2005; Bi et al. 2005; Gumjudpai et al. 2005;
Yin et al. 2007; Wang et al. 2005, 2006a,b, 2008; Costa et al. 2014;
Väliiviita et al. 2010; Martinelli et al. 2010; Honoroz et al. 2010;
Salvatelli et al. 2013, 2014; D’Amico et al. 2016; Di Valentino
et al. 2017; Murgia et al. 2016; Ferreira et al. 2017; Costa et al.
2015; Marcondes et al. 2016; Costa et al. 2017; Bernardi & Landim
2017; Wang et al. 2016; Costa et al. 2018).

In this work, we consider a phenomenological description of
the DE-DM interaction and use the Fisher matrix formalism to
assess the capability of baryon acoustic oscillations (BAO) and
redshift-space distortions (RSD), as observed by J-PAS, to improve
the constraints on the equation of state (EoS) of dark energy and on
the coupling constant. We also take advantage of the added power
including a field derived from Lagrangian models have been con-
considered in other works (Micheletti et al. 2009; Costa et al. 2015;
D’Amico et al. 2016; Landim & Abdalla 2017). However, as we
still do not know the correct theory to describe DM and DE, we
can investigate an interaction between them from phenomenologi-
ical arguments. In this work, we assume a phenomenological cou-
pling $Q$ which, in the generic case, have contributions proportional
to the DM and DE densities
\begin{equation}
Q = 3H(\xi_c \rho_c + \xi_d \rho_d),
\end{equation}
where $\xi_c$ and $\xi_d$ are the corresponding coupling constants.

Interacting DE models with constant EoS have already been shown
to suffer from instabilities with respect to curvature and DE
perturbations (Väliiviita et al. 2008; He et al. 2009). Table 1 sum-
marizes the allowed regions for the interaction and the DE EoS
cparameters as shown by He et al. (2009) and Gavela et al. (2009).
However, this is likely a problem related to the oversimplicity of
the interaction, which can be overcome in a more sophisticated La-
grangian description as in Costa et al. (2015). See also Wang et al.
(2016) for a review on interacting models.

### Table 1. Stability conditions on the EoS and interaction sign for the phe-
nomenological interacting DE model.

| Case | Constant EoS and interaction sign |
|------|----------------------------------|
| $Q = \rho_d (\xi_c = 0)$ | $w < -1$ and $\xi_d > 0$; or $-1 < w < 0$ and $\xi_d < 0$ |
| $Q = \rho_c (\xi_d = 0)$ | $w < -1$, $\forall \xi_c$ |
| $\xi_d \neq 0$ and $\xi_c \neq 0$ | $w < -1$, $\xi_d > 0$, $\forall \xi_c$ |

3 THE DATA SET

The data considered correspond to the two-point function or, more
precisely, the power spectrum of the clustering of some type of
galaxy or quasar. J-PAS will be able to detect millions of luminous
red galaxies, emission line galaxies and quasars. Table 2 gives the
expected number densities as a function of redshift for different
tracers. In the plane-parallel (distant observer, $k^2 = k_\parallel^2 + k_\perp^2$)
approximation, the observed galaxy power spectrum is given by (Seo &
Eisenstein 2003; Wang et al. 2010)

\begin{equation}
P_{g, obs} = \left[ \frac{D_A^0(z)}{D_A(z)} \right]^2 \frac{H(z)}{H^0(z)} \left( \sigma_{8s}(z) + b \beta(z) \sigma_{8s} \mu^2 \right)^2 C(k) + P_{dust}.
\end{equation}
cosine of the angle between the wavevector and the line of sight, unit here and in the following tables is to allow a better comparison.

where \( \beta \) is the bias between matter and galaxy overdensities. The RSD parameter \( \beta \) is equal to the matter growth rate divided by the bias, \( \frac{f}{\beta} = k_1/k \) is the cosine of the angle between the wavevector and the line of sight, \( C(k) \equiv \rho_c(k)/\sigma^2_{M,0}(z) \) is the normalized true matter power spectrum and \( P_{\text{shot}} \) parametrizes a residual shot noise.

The galaxy overdensity is related to the matter overdensity through a bias, \( \delta_g = b(k, z) \delta_m \), which in general can be a function of the scale and redshift. Here, we assume that the bias depends only on the redshift and is given, for each tracer, by (Ross et al. 2009; DESI Collaboration et al. 2016)

\[
b_{\text{BAO}}(z) = \frac{1.7}{D(z)} \quad b_{\text{LLG}}(z) = \frac{0.84}{D(z)} \quad b_{\text{QSO}}(z) = 0.53 + 0.289 (1 + z)^2,
\]

where \( D(z) = \exp \left[ - \int_0^z dz' f_{\text{m}}/(1 + z') \right] \) is the growth factor normalized to 1 today and \( f_{\text{m}} = \frac{d \ln \delta_m}{d \ln a} \) is the matter growth rate. In our calculations we use weak Gaussian priors for the biases, with variances \( \sigma_b = 0.5 \).

We also compare our results for J-PAS with the expected results from DESI and Euclid. The number densities we are assuming are presented in Table 3 for the DESI survey and in Table 4 for Euclid. DESI has the same bias as those in eq. (5); on the other hand, we use \( b(z) = \sqrt{1 + z} \) in the case of Euclid (Laureijs et al. 2011; Wang et al. 2010; Orsi et al. 2010). This choice of bias is a good approximation to studies from semianalytic models of galaxy formation as in Orsi et al. (2010) (see, for example, Giammanzi et al. 2012). Although this choice is different from the one made for J-PAS and DESI, our results are only weakly dependent on it as we are considering information from the BAO wiggles only (Rassat et al. 2008).

Two scenarios are considered for the J-PAS survey, a more conservative initial expectation with a survey area of 4000 deg\(^2\) and a possible future best case scenario with 8500 deg\(^2\). The DESI and Euclid survey areas are estimated as 14000 and 15000 deg\(^2\), respectively. The redshift errors are assumed to be 0.003 (1 + \( z \)) for J-PAS and 0.001 (1 + \( z \)) for DESI and Euclid.

### Table 2. Number densities of luminous red galaxies, emission line galaxies and quasars for J-PAS, in units of \( 10^{-5} h^3 \text{Mpc}^{-3} \).

| \( z \) | LRG | ELG | QSO |
|-------|-----|-----|-----|
| 0.3   | 226.6 | 2956.6 | 0.45 |
| 0.5   | 156.3 | 1181.1 | 1.14 |
| 0.7   | 68.8  | 502.1  | 1.61 |
| 0.9   | 12.0  | 138.0  | 2.27 |
| 1.1   | 0.9   | 41.2   | 2.86 |
| 1.3   | 0     | 6.7    | 3.60 |
| 1.5   | 0     | 0      | 3.21 |
| 1.7   | 0     | 0      | 2.86 |
| 1.9   | 0     | 0      | 2.55 |
| 2.1   | 0     | 0      | 2.27 |
| 2.3   | 0     | 0      | 2.03 |
| 2.5   | 0     | 0      | 1.81 |
| 2.7   | 0     | 0      | 1.61 |
| 3.1   | 0     | 0      | 1.43 |
| 3.3   | 0     | 0      | 1.28 |
| 3.5   | 0     | 0      | 1.14 |
| 3.7   | 0     | 0      | 0.91 |
| 3.9   | 0     | 0      | 0.72 |

### Table 3. Number densities of luminous red galaxies, emission line galaxies and quasars for DESI, in units of \( 10^{-5} h^3 \text{Mpc}^{-3} \).

| \( z \) | LRG | ELG | QSO |
|-------|-----|-----|-----|
| 0.65  | 49  | 18  | 2.8 |
| 0.75  | 49  | 110 | 2.7 |
| 0.85  | 29  | 83  | 2.6 |
| 0.95  | 10  | 81  | 2.6 |
| 1.05  | 2.0 | 51  | 2.6 |
| 1.15  | 1.0 | 45  | 2.5 |
| 1.25  | 0   | 42  | 2.5 |
| 1.35  | 0   | 15  | 2.5 |
| 1.45  | 0   | 13  | 2.4 |
| 1.55  | 0   | 9.0 | 2.4 |
| 1.65  | 0   | 3.0 | 2.3 |
| 1.75  | 0   | 0   | 2.3 |
| 1.85  | 0   | 0   | 2.2 |

### Table 4. Number densities of emission line galaxies for Euclid, in units of \( 10^{-5} h^3 \text{Mpc}^{-3} \).

| \( z \) | ELG |
|-------|-----|
| 0.6   | 356 |
| 0.8   | 242 |
| 1.0   | 181 |
| 1.2   | 144 |
| 1.4   | 99  |
| 1.8   | 33  |

### 4 THE MODIFIED RSD PARAMETER

Measurements of \( \beta \) from the power spectra or peculiar velocities are based on its correspondence with the velocity divergence \( \theta \) as established by the continuity equation. Since this equation is violated in interacting models, we must make sure to use the correct quantity that corresponds to the velocity field when confronting our model with observations or making forecasts for some experiment (see, for example, Marcondes et al. 2016; Borges & Wands 2017; Kimura et al. 2018).

For an interacting DE model with coupling given by eq. (3), the continuity equation for DM at first order in perturbations in the sub-horizon limit \( (k \gg H) \) reads

\[
\delta_v' + 3H\xi_{\rho \rho} \frac{\rho_d}{\rho_m} \left( \delta_m - \delta_v \right) + \theta_c = 0.
\]

In this equation, we now express, for convenience, the evolution in terms of the conformal time \( \tau \), with the prime representing \( d/d\tau \) and \( H = a'/a \). The total matter density is \( \rho_m = \rho_b + \rho_c \) and its perturbation \( \delta_m = (\rho_b/\rho_m) \delta_b + (\rho_c/\rho_m) \delta_c \). Thus, its (conformal) time derivative is given by

\[
\rho_m \delta_m' = -3H\xi_{\rho \rho} (\delta_m - \delta_v) - 3H\xi_{\rho \rho} (\delta_m - \delta_v) - (\rho_b/\rho_m) \rho_b' + (\rho_c/\rho_m) \rho_c'.
\]

where the continuity equations for baryons and DM have been used. This expression can be rewritten as

\[
\dot{\rho}_m \left( 1 + \frac{\rho_b}{\rho_m} \right) + \frac{\rho_b}{\rho_m} \left( 1 + \frac{\rho_c}{\rho_m} \right) \frac{\rho_b'}{\rho_m} + \frac{\rho_c'}{\rho_m} = 0.
\]

We can now recognize the term \( (\rho_b/\rho_m) \rho_b' = \rho_m' \) as \( \theta_c' \), as...
usual, and express the continuity equation corrected for the interaction
\[ \mathcal{H} \delta_m + \theta_m = 0, \]  
where
\[ f_m = \frac{d \ln \sigma_m}{d \ln a} + 3 \left( \frac{\xi_i \rho_i + \xi_R \rho_R}{\rho_m} - \frac{\xi_i \rho_m}{\rho_m \delta_m} \right) \]  
is the growth rate for the interacting model minus the effects of interaction (to make the continuity equation compatible with redshift-space distortion measurements). This represents contributions from two averages of the two coupling constants $\xi$ and $\xi_R$, one is weighted by the background densities of DE and DM, the other, with opposite sign, weighted by the perturbation to the densities.

Keeping the assumption that galaxies trace the matter field according to $\delta_g = b \delta_m$ and $\theta_g = \theta_m = \theta$, the galaxy continuity equation is now
\[ \mathcal{H} \delta_g + \theta = 0, \]  
where $\beta = \frac{f_m}{b}$ is the quantity that must replace $\beta$ in eq. (4) for the interacting model.

5 THE FISHER MATRIX FORMALISM

The Fisher matrix given by eqs. (13) and (15) allows us to define the Fisher information density per unit of phase space volume $(2\pi)^3 d^3 x d^3 k$ as (aside from the phenomenological exponential factors)
\[ \Phi = \frac{1}{2} \left[ n_f z P_f (k, z) \right]^2. \]  

For surveys which are able to combine multiple tracers of large-scale structure, the Fisher information density can be generalized to (Abramo & Leonard 2013)
\[ \Phi_{\text{diag}}(x, k) = \frac{1}{4} \left[ \delta_{\text{diag}} X_\alpha + U_{\alpha} U_{\beta} (1 - X) \right], \]  
where $\alpha, \beta = 1, \ldots, N$ are the different types of galaxies, $X_n = n_n P_n (k, z)$ such that $X = \sum X_n$ and $U_n = \delta_X / (1 + X)$. Hence, the Fisher matrix can be generalized for a multi-tracer analysis as
\[ F_{ij} = \sum_{n, m} \int \frac{d^3 x}{(2\pi)^3} f_n \frac{d \ln X_n}{d \theta_i} f_m \frac{d \ln X_m}{d \theta_j} e^{2 \phi_i \phi_j} \rho_f \left( \frac{4 \pi}{3} \right)^{\frac{3}{2}} \frac{3}{2} \times \exp \left[ -k^2 \Sigma_c^2 - k^2 \tilde{\Sigma}^2 \left( \Sigma_c^2 - \Sigma_\perp^2 \right) \right]. \]  

Using this expression we can properly take into account multiple tracers in our analysis. For instance, we can combine the expected results from LRG, ELG and QSO, all together.

Another important result is that we can transform a Fisher matrix defined in terms of a set of $N_\theta$ parameters, $\{\theta_i\}$, into a set of $N_\phi$ parameters, $\{\phi_i\}$, as long as $N_{\theta} < N_{\phi}$. The Fisher matrix transformation is defined by
\[ F_{\phi,\theta} = \sum_{i, j} \frac{\partial \theta_i}{\partial \phi_j} F_{ij} \frac{\partial \phi_j}{\partial \theta_i}. \]  

In our analysis, we begin with a set of parameters $\bar{\theta} = (\ln H(z), \ln D_A(z), f(z), \sigma_8(z), P_{\text{obs}}, \Omega_m h^2, \Omega_L h^2, n_s)$, where $f(z) = \frac{f_m(z)}{b}$ observed. Note that some parameters are local, i.e. they assume different values at each redshift bin, while others are global. For a multi-species analysis, each tracer has its own bias and, hence, different values of $\sigma_8$. Later, we marginalize over all these parameters except $\ln H(z), \ln D_A(z)$ and $f(z)$, which carry all the information about BAO and RSD. Finally, we project from those parameters to our final set of cosmological parameters, which are given here by $\Omega_m, \Omega_L, \xi$ and $\xi_R$.

Our fiducial cosmology is a flat \textsc{lcdm} model with a physical baryon density $\Omega_m h^2 = 0.0226$, cold dark matter density $\Omega_{\text{cdm}} h^2 = 0.121$, and neutrino density parameter, $\Omega_{\nu} h^2 = 0.00064$ (assuming only one massive neutrino). The reduced Hubble constant is $h = 0.68$ (with a prior $\sigma_8 = 0.1$), DE equation of state $w = -1$, amplitude parameter $A_s = 2.1 \times 10^{-9}$ and scalar spectral index $n_s = 0.96$. Planck priors are used to calibrate the BAO scale only.

Our Fisher code receives as input background and perturbed quantities such as the Hubble rate and the linear matter power spectrum, which were calculated using a modified version of the \textsc{CAMB} code (Lewis et al. 2000; Costa 2014) that takes into account the necessary modifications for an interacting dark energy model.

6 RESULTS

We now present the expected constraints on the parameters, as well as the two-parameter joint constraints for the different cases of our interacting model. Two scenarios are considered: one using information from $H(z)$ and $D_A(z)$ only, and the other adding information from $f(z)$ besides $H(z)$ and $D_A(z)$. The two cases are labelled...
served to be very degenerated. The results are dominated by our priors. 

Table 5. Marginalized uncertainties for the three surveys, without RSD, for the case where the interacting coupling term is proportional to dark energy density, $Q \propto \rho_d$. The parameters we are concerned, $\Omega_f$, $w$ and $\xi_d$ are observed to be very degenerated. The results are dominated by our priors.

| Uncertainty | LRG | ELG | QSO | Multi-tracer |
|-------------|-----|-----|-----|-------------|
| $\sigma_{\Omega_f}$ | 0.552 | 0.547 | 0.546 | 0.546 |
| $\sigma_w$ | 0.856 | 0.813 | 0.811 | 0.798 |
| $\sigma_{\xi_d}$ | 0.800 | 0.796 | 0.795 | 0.795 |
| J-PAS (4000 deg$^2$) | | |
| $\sigma_{\Omega_f}$ | 0.549 | 0.547 | 0.546 | 0.546 |
| $\sigma_w$ | 0.824 | 0.803 | 0.803 | 0.796 |
| $\sigma_{\xi_d}$ | 0.797 | 0.796 | 0.795 | 0.795 |
| J-PAS (8500 deg$^2$) | | |
| DESI | $\sigma_{\Omega_f}$ | 0.547 | 0.546 | 0.546 | 0.546 |
| $\sigma_w$ | 0.809 | 0.797 | 0.813 | 0.796 |
| $\sigma_{\xi_d}$ | 0.796 | 0.795 | 0.795 | 0.795 |
| Euclid | $\sigma_{\Omega_f}$ | 0.795 | | |
| $\sigma_w$ | 0.795 | | |
| $\sigma_{\xi_d}$ | 0.795 | | |

“without RSD” and “with RSD” and, in both, we run our analysis for the two J-PAS survey areas described in section 3. We are also conservative regarding the number density of quasars, taking 90 per cent of the densities predicted in previous work (Abramo et al. 2012), and the ability to recover quasi-non-linear scales (reconstruction), which means that if we achieve successful reconstruction with J-PAS, then the constraints from the actual data could be further improved.

Note that we are more concerned here with the marginalized uncertainties on the parameters, under the assumption that they should not vary considerably over the parameter space, i.e., they are not strongly dependent on the choice of fiducial parameters. In fact, one should note that these results do not include any prior information about the allowed region for $\Omega_f$, $w$ and $\xi_d$, which will certainly not be true in the actual data analysis when we will have to restrict the parameters to the stability regions listed in Table 1.

The uncertainties on $H(z)$, $D_s(z)$ and $f(z)$ are shown in Fig. 1 together with the effect of the interaction on these functions. We can see that an interacting dark energy induces deviations from our fiducial cosmology. This effect is stronger for higher redshifts in $H(z)$, $D_s(z)$ and $f(z)$ with $Q \propto \rho_d$. Thus, quasars at high redshifts are expected to produce competitive constraints on the interaction in our models.

Before we discuss our results, we would like to emphasize that when the interaction is proportional to the DE density, we have two distinct regions of stability. One is characterized by the DE equation of state in the phantom regime $w < -1$, in which case the interaction must be positive, and the other quintessence-like case $-1 < w < 0$, for which $Q$ must be negative. In the Fisher matrix analysis we perform here, there is no need to make explicit those two regions separately. The results are consistent with one another and, hence, we will not make such distinction hereafter. The reader, however, must be aware of the stable regions according to Table 1. For all the results below we use conservative Gaussian priors on the uncertainties of $\Omega_f$, $w$ and $\xi_d$.

The marginalized constraints for the case $Q \propto \rho_d$ are shown in Tables 5 (without RSD) and 6 (with RSD). We present the results for two J-PAS areas, together with the expected results for DESI and Euclid. We observe that, when information from RSD is not considered, our three parameters of interest are very degenerate. The constraints are dominated by our priors on $\Omega_f$, $w$ and $\xi_d$. The inclusion of RSD information breaks the strong degeneracy presented before.

Table 6. Marginalized uncertainties for the three surveys, with RSD, for the case where the interacting coupling term is proportional to dark energy density, $Q \propto \rho_d$. The inclusion of RSD information breaks the strong degeneracy presented before.

| Uncertainty | LRG | ELG | QSO | Multi-tracer |
|-------------|-----|-----|-----|-------------|
| $\sigma_{\Omega_f}$ | 0.064 | 0.030 | 0.024 | 0.011 |
| $\sigma_w$ | 0.251 | 0.114 | 0.157 | 0.058 |
| $\sigma_{\xi_d}$ | 0.080 | 0.025 | 0.030 | 0.016 |
| J-PAS (4000 deg$^2$) | | |
| $\sigma_{\Omega_f}$ | 0.044 | 0.021 | 0.016 | 0.008 |
| $\sigma_w$ | 0.173 | 0.078 | 0.108 | 0.040 |
| $\sigma_{\xi_d}$ | 0.055 | 0.017 | 0.021 | 0.011 |
| J-PAS (8500 deg$^2$) | | |
| DESI | $\sigma_{\Omega_f}$ | 0.032 | 0.013 | 0.026 | 0.010 |
| $\sigma_w$ | 0.145 | 0.058 | 0.162 | 0.047 |
| $\sigma_{\xi_d}$ | 0.041 | 0.009 | 0.026 | 0.008 |
| Euclid | $\sigma_{\Omega_f}$ | 0.006 | | |
| $\sigma_w$ | 0.028 | | |
| $\sigma_{\xi_d}$ | 0.004 | | |

None of the tracers nor any survey was able to break this degeneracy and produce significant constraints. However, the inclusion of RSD introduces new information that alleviates the degeneracy. In this case, the prior uncertainties are not important and we obtain constraints of a few per cent as observed in Table 6. Comparing the multi-tracer analysis for the three surveys (actually we are not using multi-tracer for Euclid, only ELG), we see that J-PAS can produce slightly better constraints than DESI for the dark energy density parameter and the equation of state. This is associated with the expected values for QSO, which are denser and reach higher redshifts in J-PAS. The joint constraints for $\Omega_f$, $w$ and $\xi_d$ are shown in Fig. 2 for the two areas and for the different tracers with J-PAS.

The same is done for the case $Q \propto \rho_c$, presented in Tables 7 (without RSD) and 8 (with RSD) and in Fig. 3. In this case, the resulting parameters are not as degenerate as in the previous case. The constraints on $H(z)$ and $D_s(z)$ can provide significant information and our prior is not as dominant as before. For instance, in the multi-tracer analysis, the prior uncertainties only alter our results at $\sim 2$ per cent for J-PAS 4000 deg$^2$ and at $\sim 1$ per cent for J-PAS 8500 deg$^2$. Table 7 shows us that J-PAS can put better constraints than DESI and Euclid when we only consider BAO information.
Table 8. Marginalized uncertainties for the three surveys, with RSD, for the case where the interacting coupling term is proportional to dark matter density, $Q \propto \rho_c$.  

| Uncertainty | LRG | ELG | QSO | Multi-tracer |
|-------------|-----|-----|-----|-------------|
| J-PAS (4000 deg$^2$) | $\sigma_{z_0}$ | 0.174 | 0.064 | 0.083 | 0.030 |
| | $\sigma_w$ | 0.379 | 0.161 | 0.308 | 0.074 |
| | $\sigma_{\sigma}$ | 0.228 | 0.082 | 0.074 | 0.037 |
| J-PAS (8500 deg$^2$) | $\sigma_{z_0}$ | 0.123 | 0.044 | 0.058 | 0.021 |
| | $\sigma_w$ | 0.267 | 0.111 | 0.213 | 0.051 |
| | $\sigma_{\sigma}$ | 0.161 | 0.056 | 0.051 | 0.026 |
| DESI | $\sigma_{z_0}$ | 0.122 | 0.030 | 0.076 | 0.025 |
| | $\sigma_w$ | 0.284 | 0.086 | 0.243 | 0.071 |
| | $\sigma_{\sigma}$ | 0.146 | 0.030 | 0.076 | 0.026 |
| Euclid | $\sigma_{z_0}$ | 0.012 |
| | $\sigma_w$ | 0.039 |
| | $\sigma_{\sigma}$ | 0.013 |

In this model, again, the constraints from LRG, ELG and QSO indicate that QSO are playing the role in this leadership here. Including information from RSD can improve the results even more. However, the constraints in this case are not as sensitive to RSD as when $Q \propto \rho_d$, as could be expected from Fig. 1. J-PAS still provides better results than DESI with RSD information, but Euclid gives an uncertainty on the coupling constant twice as better.

For the last case considered, $Q \propto \rho_d + \rho_c$, we give the results for the marginalized constraints in Tables 9 (without RSD) and 10 (with RSD). As one could expect, in this scenario we see characteristics combined from both previous cases. The measurements of $H(z)$ and $D_A(z)$ give significant information, especially at high redshifts, as in $Q \propto \rho_c$. The constraints are also very sensitive to RSD as in $Q \propto \rho_d$.

Using information from BAO and RSD, we compare the expected confidence regions of J-PAS (8500 deg$^2$), DESI and Euclid, all with multiple tracers except Euclid, which has only one kind of tracer. The results for the cases $Q \propto \rho_d$ and $Q \propto \rho_c$ are presented
Figure 2. Case $Q \propto \rho_d (\xi \equiv \xi_d)$. The ellipses represent the 68 per cent uncertainty around the fiducial $\Lambda$CDM model. The thin and thick lines correspond to results considering the survey areas of 4000 and 8500 deg$^2$, respectively. The red contours are for LRG, green for ELG, blue for QSO, and black for the Multi-tracer analysis, all with RSD.

Figure 3. Case $Q \propto \rho_c (\xi \equiv \xi_c)$. The ellipses represent the 68 per cent uncertainty around the fiducial $\Lambda$CDM model. The thin and thick lines correspond to results considering the survey areas of 4000 and 8500 deg$^2$, respectively. The red contours are for LRG, green for ELG, blue for QSO, and black for the Multi-tracer analysis, all with RSD.
in Figs. 4 and 5. Even though Euclid has only one kind of tracer, it shows the best constraints in those figures. This is related to its large survey area, high galaxy number densities and small redshift errors. On the other hand, although DESI covers a larger area in the sky and has a smaller redshift error than J-PAS, their constraints are comparable because of the larger redshift range of J-PAS.

It is important to notice that, in our analysis, we are considering the number densities of galaxies for DESI and Euclid as those given by DESI Collaboration et al. (2016) and Laureijs et al. (2011), respectively. Thus, neither DESI nor Euclid cover low redshift galaxies (while J-PAS does). However, adding low redshift data from other survey, such as the Sloan Digital Sky Survey (SDSS, Blanton et al. 2017), for instance, would improve the constraints found for them in this paper.

Finally, we see that the results for our interacting DE model are very sensitive to the use of redshift-space distortions. This is certainly true for an interaction proportional to the DE density, where loose constraints dominated by our priors tighten considerably when we include RSD, but also in the other cases, in which the constraints can improve by a factor of 10 in some scenarios. This was also clear in previous publications (Murgia et al. 2016; Costa et al. 2017; Li et al. 2018). We note that high redshift measurements tend to place better constraints, as the interaction yields stronger de-

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**Table 9.** Marginalized uncertainties for the three surveys, without RSD, for the case where the interacting coupling term is proportional to the sum of the dark sector energy densities, $Q = \rho_d + \rho_\xi (\xi_c = \xi_d \equiv \xi)$.

| Uncertainty | LRG | ELG | QSO | Multi-tracer |
|-------------|-----|-----|-----|--------------|
| J-PAS (4000 deg$^2$) | $\sigma_{\Omega_d}$ | 0.708 | 0.670 | 0.354 | 0.204 |
| | $\sigma_{\omega}$ | 1.146 | 1.103 | 0.795 | 0.396 |
| | $\sigma_{\xi}$ | 0.585 | 0.528 | 0.217 | 0.133 |
| J-PAS (8500 deg$^2$) | $\sigma_{\Omega_d}$ | 0.697 | 0.623 | 0.260 | 0.143 |
| | $\sigma_{\omega}$ | 1.117 | 1.022 | 0.583 | 0.277 |
| | $\sigma_{\xi}$ | 0.573 | 0.490 | 0.159 | 0.093 |
| DESI | $\sigma_{\Omega_d}$ | 0.679 | 0.406 | 0.578 | 0.284 |
| | $\sigma_{\omega}$ | 1.104 | 0.701 | 1.069 | 0.490 |
| | $\sigma_{\xi}$ | 0.546 | 0.305 | 0.412 | 0.212 |
| Euclid | $\sigma_{\Omega_d}$ | 0.185 |
| | $\sigma_{\omega}$ | 0.336 |
| | $\sigma_{\xi}$ | 0.132 |

**Table 10.** Marginalized uncertainties for the three surveys, with RSD, for the case where the interacting coupling term is proportional to the sum of the dark sector energy densities, $Q = \rho_d + \rho_\xi (\xi_c = \xi_d \equiv \xi)$.

| Uncertainty | LRG | ELG | QSO | Multi-tracer |
|-------------|-----|-----|-----|--------------|
| J-PAS (4000 deg$^2$) | $\sigma_{\Omega_d}$ | 0.051 | 0.030 | 0.058 | 0.019 |
| | $\sigma_{\omega}$ | 0.178 | 0.094 | 0.141 | 0.041 |
| | $\sigma_{\xi}$ | 0.110 | 0.035 | 0.041 | 0.019 |
| J-PAS (8500 deg$^2$) | $\sigma_{\Omega_d}$ | 0.035 | 0.021 | 0.040 | 0.013 |
| | $\sigma_{\omega}$ | 0.123 | 0.065 | 0.097 | 0.028 |
| | $\sigma_{\xi}$ | 0.076 | 0.024 | 0.028 | 0.013 |
| DESI | $\sigma_{\Omega_d}$ | 0.024 | 0.012 | 0.034 | 0.011 |
| | $\sigma_{\omega}$ | 0.093 | 0.048 | 0.127 | 0.038 |
| | $\sigma_{\xi}$ | 0.054 | 0.013 | 0.036 | 0.011 |
| Euclid | $\sigma_{\Omega_d}$ | 0.008 |
| | $\sigma_{\omega}$ | 0.025 |
| | $\sigma_{\xi}$ | 0.006 |
J-PAS forecasts on interacting dark energy

Figure 5. Comparison of the 68 per cent uncertainties around the fiducial ΛCDM model for the J-PAS (8500 deg$^2$), Euclid and DESI surveys including information from BAO and RSD in a multi-tracer analysis. Case $Q \propto \rho_c$ ($\xi \equiv \xi_d$).

Figure 6. Constraint on $\xi_d$ as a function of the redshift $z$ under the different survey configurations, case $Q \propto \rho_d$ ($\xi \equiv \xi_d$).

In this work, we use information from baryon acoustic oscillations and redshift-space distortions to estimate the constraining power of the J-PAS survey for parameters of an interacting dark energy model. The analysis is done using the Fisher matrix formalism and Planck priors were only used to calibrate the BAO scale.

Employing the whole galaxy power spectrum, we marginalize over several cosmological parameters ending up with three local parameters, $\ln H(z)$, $\ln D_A(z)$ and $f_s(z)$, which basically carry information about the BAO scale and RSD. Then, we project the expected constraints on those parameters on constraints over our interacting dark energy model, which is described by the dark energy density fraction $\Omega_d$, the equation of state $w$, and the interaction parameter $\xi_c$ or $\xi_d$.

We consider the effect of different tracers (i.e. LRG, ELG and QSO) of the underlying matter distribution on the constraints and, also, a multi-tracer analysis. The impact of the survey area is also take into account and the results are compared with those from DESI and Euclid.

We find that, with J-PAS data in the near future, we shall be...
able to determine the interaction parameter with a maximum precision of $\sigma_{\xi_i} \sim 0.02$ when the interaction term is proportional to the DM energy density and of $\sigma_{\xi_i} \sim 0.01$ when the interaction is proportional to the DE density. These numbers are similar to the constraints predicted by DESI. For the constant equation of state of dark energy, the best predicted constraints from J-PAS are slightly better than those from DESI in both interacting cases: $\sigma_{\xi_i}$ about 0.04–0.05 against 0.05–0.07 around the fiducial value $w = -1$. In terms of constraining power and in the context of our interacting model, both surveys are behind Euclid but get close to it, projecting comparable constraints on the relevant parameters in all specific cases considered.

Finally, we would like to emphasize some limitations and possible extensions of this work:

- As it is well known, the Fisher matrix formalism provides the best case scenario for a forecast. A natural extension should properly explore the space of parameters as in a Monte Carlo approach. In this case, the unstable regions presented in Table 1 would be avoided by some priors.
- Also two aspects that could impair the J-PAS constraints in comparison to DESI and Euclid are a more realistic photo-z error distribution (with longer tails and more outliers than a Gaussian distribution) and the contamination of our galaxy sample by stars (and by tracers of a different type). This will become clearer in the next months with ongoing J-PAS proof-of-concept tests.
- We have only taken into account contributions from BAO and RSD. However, J-PAS is able to do more. A more complete analysis could combine information from supernovae type Ia, weak lensing and galaxy clusters.

- At $z \geq 2$, J-PAS will be able to detect a significant population of Lyman $\alpha$ Emitters (LAEs) (more numerous than QSOs) that is not taken into account in this analysis. This could significantly enhance the importance of high-z constraints.
- The likelihood function for every survey will depend strongly on the range of scales that is used to measure $P(k)$. This is especially important for RSD analysis. Also, the assembly bias, the description of non-linear density and velocity field regimes, and the impact of galaxy formation in general could make the modeling of RSDs significantly more challenging, e.g. Orsi & Angulo (2018). This could either bias the constraints, or dramatically weaken the contribution of RSDs to the overall constraints.

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