

iCosmo: an interactive cosmology package

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ABSTRACT

Aims. The interactive software package iCosmo, designed to perform cosmological calculations is described.

Methods. iCosmo is a software package to perform interactive cosmological calculations for the low-redshift universe. Computing distance measures, the matter power spectrum, and the growth factor is supported for any values of the cosmological parameters. It also computes derived observable quantities for several cosmological probes such as cosmic shear, baryon acoustic oscillations, and type Ia supernovae. The associated errors for these observable quantities can be derived for customised surveys, or for pre-set values corresponding to current or planned instruments. The code also allows for calculation of cosmological forecasts with Fisher matrices, which can be manipulated to combine different surveys and cosmological probes. The code is written in the IDL language and thus benefits from the convenient interactive features and scientific libraries available in this language. iCosmo can also be used as an engine to perform cosmological calculations in batch mode, and forms a convenient adaptive platform for the development of further cosmological modules. With its extensive documentation, it may also serve as a useful resource for teaching and for newcomers to the field of cosmology.

Results. The iCosmo package is described with a number of examples and command sequences. The code is freely available with documentation at <http://www.icosmo.org>, along with an interactive web interface and is part of the *Initiative for Cosmology*, a common archive for cosmological resources.

Key words. cosmology: miscellaneous – cosmology: theory – cosmological parameters – methods: numerical

1. Introduction

Cosmology is a rapidly advancing field thanks to recent progress in instrumentation, numerical simulations, and theoretical methods. The past few decades have provided a previously inaccessible wealth of data with the advent of large surveys of the cosmic microwave background, galaxy clustering, cosmic shear, clusters, and supernovae (see [Spergel et al. 2007](#); [Dunkley et al. 2009](#), for more recent results and references therein). One of the challenges of cosmology is to link the derived observable quantities from these cosmological surveys with the parameters of an underlying cosmological model. Another necessary task is to predict the performance of future surveys and future observational probes in order to maximise the potential of future experiments. Existing publicly available computational tools ([Seljak & Zaldarriaga 1996](#); [Lewis et al. 2000](#); [Lewis & Bridle 2002](#)) are widely used within the cosmological community, yet there is at present no unified tool that considers the low-redshift universe and its associated probes.

In this paper, we present iCosmo, a software package that performs interactive cosmological calculations. The code can also be used as an engine to perform predictions for any cosmological model, and it also forms a convenient platform for developing further cosmological modules. With its extensive documentation, it may also serve as a useful resource for teaching and for newcomers in the field of cosmology.

The code calculates distance measures, the linear and non-linear matter power spectrum, the growth factor, volume

elements and other quantities for any CDM cosmological model. It also computes derived observable quantities for several cosmological probes such as cosmic shear, baryonic acoustic oscillations (BAO), and type Ia supernovae. The associated errors for these observables can be described for arbitrary survey parameters, or alternatively, for a number of preset values corresponding to planned surveys and experiments. The code also provides forecasts for future cosmological surveys, by allowing the user to compute, manipulate, and combine Fisher matrices. The code is written in the IDL language, so it benefits from the simple syntax, large scientific libraries and convenient interactive plotting environment of this language. In particular, all the above calculations can be completed in only a few lines of code.

The code is freely available at <http://www.icosmo.org> with full documentation and help files. It is part of the *Initiative for Cosmology* web site, and it includes an interactive web interface (see description in [Kitching et al. 2009](#)).

In this paper, we describe the main features of iCosmo and provide several examples illustrating its use. In Sect. 2, we describe the main conventions and architecture of the code. In Sect. 3 we describe how the code can quickly calculate the evolution of the main cosmological quantities, such as distance measures and growth factor, as a function of redshift. In Sect. 4, we describe how iCosmo calculates the derived observable quantities for cosmic shear, BAO and type Ia supernovae. Section 5 shows how the code can compute and manipulate Fisher matrices. Our conclusions and possible future developments are presented in Sect. 6.

Table 1. Main iCosmo routines and a brief description of their use.

Directory	Routine	Description
cosmo	set_fiducial	Create fiducial parameter structure
	mk_cosmo	Compute basic cosmological quantities
	get_pk	Extracts 3D power spectrum
expt	mk_survey	Compute survey parameters
lensing	mk_cl_tomo	Compute shear power spectrum
	mk_cl_cov_tomo	Compute covariance errors
	mk_fisher_lens	Compute cosmic shear Fisher matrix and errors
bao	mk_bao	Compute BAO distance measures
	mk_bao_cov	Compute BAO covariance errors
	mk_fisher_bao	Compute BAO Fisher matrix and errors
sne	mk_sne	Compute SNe magnitude-redshift relation
	mk_sne_cov	Compute SNe covariance errors
	mk_fisher_sne	Compute SNe Fisher matrix
fisher	check_matrix	Check matrix is positive definite
	comb_fisher	Combine two Fisher matrices
	margin_fisher	Marginalise over unwanted parameters
plotting	plt_cosmo	Plot cosmology parameters
	plt_pk	Plot 3D matter power spectrum
	plt_sv	Plot survey properties
	plt_cl	Plot cosmic shear correlation function
	plt_bao	Plot BAO distance measures
	plt_sne	Plot supernova magnitude-redshift relation
	plt_fisher	Plot Fisher matrix errors (combined 1D and 2D errors)
	plt_fisher_1p	Plot 1D likelihood errors
plt_fisher_2p	Plot 2D error ellipses	

2. General presentation

The iCosmo code is a package of routines written in the IDL language. It is divided into several directories corresponding to the different levels of the calculations:

- **general**, **plotting**: General utility and plotting routines;
- **cosmo**, **expt**: Routines to define fiducial cosmological and survey parameters and compute basic cosmological quantities;
- **lensing**, **bao**, **sne**: Routines to compute cosmic shear, BAO and type Ia supernovae observables;
- **fisher**: Routines to create, plot and manipulate Fisher matrices for cosmological forecasts.

The routines in each of the directories make use of the variable structures in IDL. Their functionality is indicated by the first few letters of their name with the following conventions:

- **set**: set up basic structures with calculation variables;
- **mk**: make or compute a new structure using the information in an input structure;
- **get**: get a substructure or derived quantity from an existing structure;
- **plt**: plot;
- **rd**, **wt**: read and write data from and into a file.

A description of the main iCosmo routines and associated directories can be found in Table 1. Detailed explanations for any of the routines can be obtained by typing `icosmo_help`, “*routine name*” at the IDL command line. A `readme` file is available in the distribution and gives installation instructions and a quick start tutorial.

Table 2 shows an example of a typical call sequence for iCosmo, with the different levels of the code separated by horizontal lines. The following sections describe the use of each level of the code with examples of call sequences and output figures.

3. Basic cosmological quantities

The first level in iCosmo defines the cosmological model and computes basic cosmological quantities; see, e.g., Peacock (1999) for their definitions and Refregier et al. (2004) for conventions. The first step is to define the fiducial parameter structure using the `set_fiducial` function (see Inst. 1 in Table 2). The resulting `fid` structure contains the following three substructures:

- **cosmo**: input cosmological parameters;
- **expt**: experiment parameters, such as survey area, number of galaxies or SNe as a function of redshift, or preset surveys;
- **calc**: calculation parameters, such as redshift and k -range, fitting functions, etc.

These parameters have default values that can be easily modified using the syntax of instruction 1 in Table 2.

The next step is to compute all the basic cosmological quantities using the `mk_cosmo` function (see Inst. 2 in Table 2). The resulting `cosmo` structure is organised into several substructures:

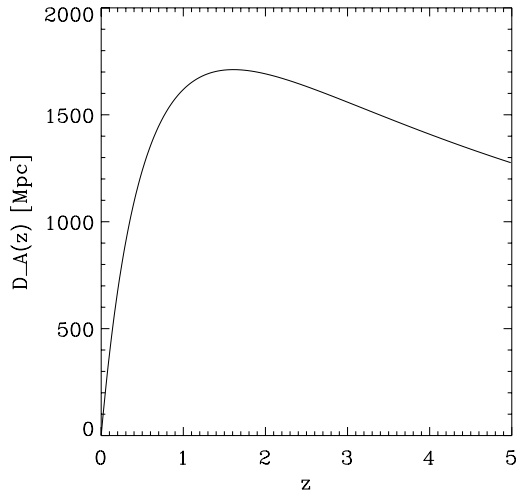
- **const**: all original fiducial quantities, as well as constant quantities derived from the fiducial parameters (e.g., the Hubble radius);
- **evol**: evolving scalar quantities such as distance measures, the growth factor, tabulated as a function of redshift;
- **pk**: Linear and non-linear matter power spectrum $P(k, z)$ tabulated as a function of wavenumber k and redshift z .

The evolving scalar quantities can then be plotted easily using the `plt_cosmo` routine (see Inst. 3 in Table 2). As an example, the following call sequence:

```
> fid=set_fiducial(cosmo={w0:-0.9},calc={fit_tk:1})
> cosmo=mk_cosmo(fid)
> plt_cosmo,cosmo,"z","da"
```

Table 2. Example of a typical call sequence for iCosmo, with different levels of the code separated by horizontal lines.

Instruction	Description
1 <code>fid=set_fiducial(cosmo_in={omega_m:0.31})</code>	Set fiducial parameters, choosing a non-default value of the parameter Ω_m
2 <code>cosmo=mk_cosmo(fid)</code>	Compute basic cosmological quantities (e.g., distance measures, power spectrum)
3 <code>plt_cosmo,cosmo,"z", "da"</code>	Plot angular-diameter distance $D_A(z)$ as a function of redshift z
4 <code>plt_pk,cosmo,z=0</code>	Plot non-linear matter power spectrum $P(k)$ at $z = 0$
5 <code>sv=mk_survey(fid,"sv1")</code>	Read survey parameters for the preset DUNE experiment
6 <code>cl=mk_cl_tomo(fid,cosmo,sv)</code>	Compute cosmic shear power spectrum C_l
7 <code>cl_cov=mk_cl_cov_tomo(fid,cl,sv)</code>	Compute cosmic shear power spectrum errors
8 <code>plt_cl,cl,[0,0],cl_cov,/errors</code>	Plot shear power spectrum and associated errors
9 <code>fish=mk_fisher_lens(fid,sv)</code>	Compute Fisher matrix for the specified lensing survey
10 <code>margin_fisher,fish,fish2,[0,1,1,0,0,0,0,0]</code>	Marginalise Fisher matrix over unwanted parameters
11 <code>plt_fisher_2p,fisher2</code>	Plot Fisher matrix error constraints for interesting parameters w_0 and w_a


Fig. 1. Example of an iCosmo output showing the angular-diameter distance $D_A(z)$ as a function of redshift. See text for command sequence.

produces Fig. 1 which shows the angular diameter distance $D_A(z)$ as a function of redshift z , defined in a flat universe by

$$D_A(z) = \frac{\chi(z)}{1+z}, \quad \chi(z) = \int_0^z \frac{cdz'}{H(z')}, \quad (1)$$

where $\chi(z)$ represents the comoving radial distance, $H(z)$ the Hubble parameter, and c the speed of light. In all figures below, the fiducial cosmology is set to $[h = 0.7, \Omega_b = 0.045, \Omega_m = 0.3, \Omega_\Lambda = 0.7, w_0 = -0.95, w_a = 0.0, n = 1.0, \tau = 0.09, \sigma_8 = 0.8]$, unless otherwise stipulated. For example, the call sequence above changes w_0 to -0.9 , which is used in the rest of this paper.

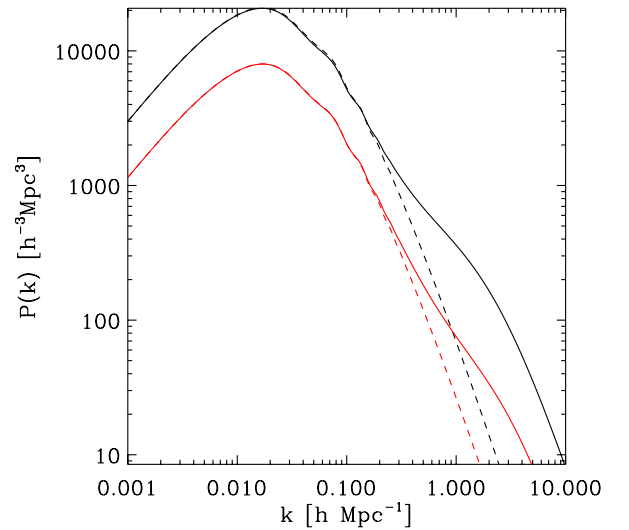
As an example of the plotting functionality, the plotting routine `plt_pk` can be used to plot the matter power spectrum $P(k, z)$ as a function of wavenumber k at a redshift z , where $P(k)$ is defined as

$$\langle \delta(\mathbf{k})\delta^*(\mathbf{k}') \rangle = (2\pi)^3 \delta^3(\mathbf{k} - \mathbf{k}') P(k), \quad (2)$$

and $\delta(\mathbf{k})$ represents matter fluctuations in Fourier space. For example, Fig. 2 shows the linear and non-linear power spectrum at $z = 0$ and 1 and is produced by the additional sequence:

```
> plt_pk,cosmo,z=0,xran=[0.001,10.]
> plt_pk,cosmo,z=0,/over,/linear,linestyle=2
> plt_pk,cosmo,z=1,/over,color=2
> plt_pk,cosmo,z=1,/over,/linear,linestyle=2,
color=2
```

The keyword `over` can be used to overlay several results on a single figure.


Fig. 2. Matter power spectrum at $z = 0$ and 1, for top and bottom lines, respectively. Linear and non-linear power spectra are shown as dashed and solid lines. These plots were derived using the `plt_pk` routine.

4. Derived cosmological observable quantities

The next level of iCosmo consists in the calculations of the derived observables related to different cosmological probes. At present, cosmic shear, baryon acoustic oscillations, and type Ia supernovae are supported. The underlying physics of each of these probes is described below.

4.1. Cosmic shear

As light travels towards us from distant galaxies, its path is perturbed by intervening matter along the line of sight. This causes distortions in the background images and is known as gravitational lensing. To first order this can be described by a distortion matrix:

$$\Psi_{ij} \equiv \frac{\partial(\delta\theta_i)}{\partial\theta_j} \equiv \begin{pmatrix} \kappa + \gamma_1 & \gamma_2 \\ \gamma_2 & \kappa - \gamma_1 \end{pmatrix}, \quad (3)$$

where $\delta\theta_i(\theta)$ is the deflection vector that results from the lensing. The distortion matrix captures two effects of gravitational lensing: the observed image can be dilated or contracted, which is described by the convergence κ , and the image can also be stretched and compressed along (and at 45° from) the x -axis, which is described by the shear component γ_1 (γ_2).

Cosmic shear – the statistical measure of shear (γ_1, γ_2), uses the two point function of the shear field as a cosmological observable, given by

$$C_{ij}(\ell) = \frac{9}{16} \left(\frac{H_0}{c} \right)^4 \Omega_m^2 \int_0^{\chi_h} d\chi \left[\frac{g_i(\chi)}{ar(\chi)} \right] \left[\frac{g_j(\chi)}{ar(\chi)} \right] P\left(\frac{l}{r}, \chi\right), \quad (4)$$

where the weighting function is given by

$$g_i(\chi) = \int_{\chi}^{\chi_h} d\chi' n_i(\chi') \frac{r(\chi)r(\chi' - \chi)}{r(\chi')}, \quad (5)$$

where $r = \frac{D_A}{a}$ and D_A is the angular-diameter distance. In Eq. (4), the auto-correlation is given for $i = j$ and the cross-correlation for $i \neq j$, where i and j correspond to galaxy populations at different redshifts. The galaxy distribution function is given by $n_i(\chi)$, i.e. the probability of finding a galaxy at a distance χ , and is normalised to $\int d\chi n_i(\chi) = 1$.

In iCosmo, cosmic shear is implemented using shear power spectrum tomography as described in references Hu (1999), Hu & Jain (2004), Refregier et al. (2004) and Amara & Réfrégier (2007). The uncertainties $\Delta C_{ij}(\ell)$ are calculated under the assumption that the two-point function is Gaussian.

4.2. Baryon acoustic oscillations

In the early Universe, just before decoupling, baryons and photons were coupled through Thomson scattering and Coulomb interactions. The photon-baryon fluid was subject to two competing effects: collapse due to gravitational instability and repulsion due to outward pressure. These two effects created oscillations in the fluctuation field, visible today in the Cosmic Microwave Background (CMB, Peebles & Yu 1970; Sunyaev & Zeldovich 1970), as well as in the galaxy distribution. In Fourier space, this effect corresponds to a series of acoustic peaks, dubbed Baryon Acoustic Oscillations (BAOs). They can be visualised by considering the ratio of a matter power spectrum with baryons, to one without: $P^b(k)/P^{\text{nob}}(k)$, and in this case are also called “wiggles”.

By measuring the BAOs in the matter power spectrum, it is possible to extract a characteristic BAO scale present in both the radial (y) and tangential (y') directions (see Sect. 2.2 of Blake et al. 2006):

$$y = \frac{r(z)}{s}, \quad y' = \frac{c}{H(z)s}, \quad (6)$$

where $r(z)$ corresponds to the comoving radial distance, $H(z)$ to the Hubble parameter, s to the comoving sound horizon at recombination and c to the speed of light. The reviews by Peacock et al. (2006) and Albrecht et al. (2006) concluded that the measurement of the BAO scale was a fundamental tool for future precision cosmology.

To use the information contained in the BAO scale, it is necessary to have an estimate of the accuracy with which a given survey can measure the scale. In the current version of iCosmo, we use the analytic expression derived in Blake et al. (2006) for the accuracy of the measurement on the BAO scale (though there are several approaches for using information from BAOs, as shown in Rassat et al. 2008). This analytic expression was derived from simulations and depends on the central redshift z of the survey, the total volume V of the survey, and the average number density of galaxies. For the moment, photometric redshift errors are not included in the iCosmo BAO module, though it is given in the accuracy expression of Blake et al. (2006). The expression for the accuracy measurement is given by Eqs. (6)–(9) in Blake et al. (2006).

4.3. Type Ia supernovae

Type Ia supernovae are assumed in cosmology to behave as *standard candles*; i.e., the rate with which the brightness of a supernova declines is assumed proportional to its intrinsic luminosity. Thus by measuring the light curves of distant supernovae, it is possible to measure their distance, and by obtaining spectra one can compare their distance-redshift relation, which is highly dependent on cosmological parameters.

The derived observable for type Ia supernovae is therefore the apparent magnitude $m(z)$ at a given redshift z , related to the luminosity distance by

$$m(z) = M + 5 \log_{10} D_L(z), \quad (7)$$

where the H_0 -independent luminosity distance $D_L(z)$ is given by

$$D_L(z) \equiv (H_0/c)(1+z)\chi(z). \quad (8)$$

The normalisation parameter M is given by

$$M = M - 5 \log_{10}(H_0/c) + \text{cst}, \quad (9)$$

where M is the absolute magnitude.

The uncertainty on the magnitude is given by Kim et al. (2004):

$$\Delta m(z) = \sqrt{\sigma_m^2 + \left(\frac{5\sigma_v}{cz \ln 10} \right)^2 + N_z \delta_m^2}, \quad (10)$$

where σ_v accounts for the scatter in peculiar velocities, σ_m the observed variance, and N_z is the number of supernovae redshift bins.

4.4. Derived cosmological observables with iCosmo

A typical call sequence is given in Instructions 5–8 in Table 2. The sequence first defines the survey using `mk_survey` and then computes the derived observable using `mk_cl_tomo`, `mk_bao`, `mk_sne`, for lensing tomography, BAO and SNe, respectively. The statistical errors in these observables for the fiducial survey can be derived using the corresponding `mk_cov` routines listed in Table 1.

As an example, the following produces Fig. 3, a plot of cosmic shear power spectra for DUNE (Refregier et al. 2008) with its associated 1σ error bars:

```
> fid=set_fiducial("DUNE",
expt_in={sv1_n_zbin:2})
> cosmo=mk_cosmo(fid)
> sv=mk_survey(fid,"sv1")
> cl=mk_cl_tomo(fid,cosmo,sv)
> cl_cov=mk_cl_cov_tomo(fid,cl,sv)
> plt_cl,cl,[1,1],cl_cov,/errors,yran=[1e-7,1e-3]
> plt_cl,cl,[0,1],cl_cov,/errors,/over,
linestyle=1
> plt_cl,cl,[0,0],cl_cov,/errors,/over,
linestyle=2
```

The different power spectra correspond to two different tomographic redshift bins with median redshifts 0.68 and 1.36, as well as their cross-power spectra. Similar call sequences can produce predictions and errors for the BAO distance measures and for SNe Hubble diagrams.

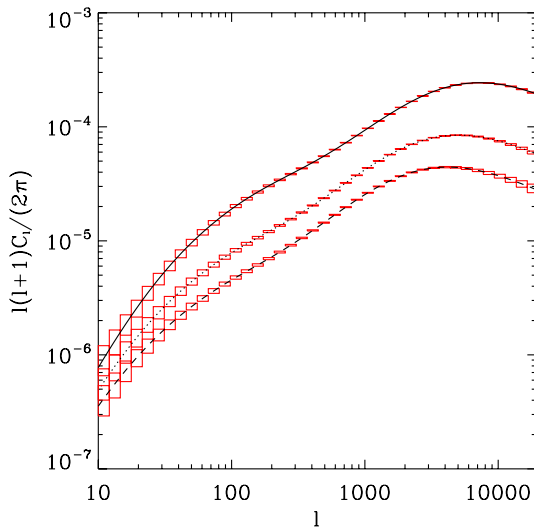


Fig. 3. The cosmic shear power spectrum and associated 1σ error bars for the DUNE/Euclid cosmic shear survey for the 1st (upper line) and 2nd (middle line) tomographic bins (with median redshifts of 0.68 and 1.36 respectively) as well as the cross-correlation between the bins (lower line).

5. Fisher matrices

The final level of iCosmo is related to the computation and manipulation of Fisher matrices to assess the constraints on cosmological parameters that can be achieved with future surveys.

5.1. The Fisher information matrix

It is possible to forecast the precision with which a given experiment can constrain cosmological parameters using the Fisher Information Matrix (FIM, see Tegmark et al. 1997, for a detailed derivation). A method based on the FIM requires the following ingredients as input:

- A set of cosmological parameters $\theta = (\theta_1, \theta_2, \dots, \theta_i)$ for which one requires predicted constraints;
- A choice of underlying fiducial cosmology;
- A set of measurements $\mathbf{x} = (x_1, x_2, \dots, x_n)$, for e.g., this could be the shear power spectrum $C(\ell)$ over a range $\ell = 1 \dots n$;
- A cosmological model for how the observable depends on cosmological parameters, i.e. a model for calculating $C(\ell) = C(\ell, \theta)$;
- An estimate of the uncertainty on the observable, i.e. in our example an estimate of $\Delta C(\ell)$. This may depend on the experiment (instrument noise, shot noise, etc.) as well as on the data estimator (cosmic variance).

With the above inputs, it is possible to calculate the FIM, whose components are denoted as F_{ij} :

$$F_{ij} = \left\langle \frac{\partial^2 \mathbf{L}}{\partial \theta_i \partial \theta_j} \right\rangle, \quad (11)$$

where $\mathbf{L} = -\ln L$, and $L = L(\mathbf{x}, \theta)$ is the likelihood function or the probability distribution of the data \mathbf{x} , which depends on some cosmological parameter set θ .

In practise, for a given observable $C(\ell, \theta)$, assumed to have Gaussian errors, the Fisher matrix can be calculated using

$$F_{ij} \simeq \sum_{\ell} \frac{1}{[\Delta C(\ell)]^2} \frac{\partial C(\ell, \theta)}{\partial \theta_i} \frac{\partial C(\ell, \theta)}{\partial \theta_j}. \quad (12)$$

For example, the coefficients of the Fisher matrix for the supernovae calculation is obtained by calculating (see Tegmark et al. 1998; Huterer & Turner 2001)

$$F_{ij}^{\text{SN Ia}} = \sum_z \frac{1}{[\Delta m(z)]^2} \frac{\partial m(z)}{\partial \theta_i} \frac{\partial m(z)}{\partial \theta_j}, \quad (13)$$

where the sum is over redshift bin.

When a vector of parameters are allowed to vary, *marginalised* parameter constraints $\Delta \theta_i^{\text{marg}}$ can be obtained by

$$\Delta \theta_i^{\text{marg}} \geq \sqrt{(F^{-1})_{ii}}. \quad (14)$$

This equation provides a *lower* limit on the constraints one can expect to attain for a given survey and fiducial cosmology. When all other cosmological parameters are fixed, the constraint on a parameter θ_i^{fix} can be estimated by

$$\Delta \theta_i^{\text{fix}} \geq \frac{1}{\sqrt{F_{ii}}}. \quad (15)$$

5.2. Calculating Fisher matrices with iCosmo

For this purpose, Fisher matrices can first be computed using the `mk_fisher` routines for each probe (see Table 1). The computation is done by taking excursions from the fiducial cosmological model for each of the parameters of interest. Fisher matrices can be combined using the `combine_fisher` routine to derive joint cosmological constraints with several surveys and probes. The routine `margin_fisher` can be used to marginalise over unwanted parameters. The resulting constraints can be plotted using the `plt_fisher` routines.

A typical call sequence to compute and plot Fisher matrices can be found in instructions 9–11 in Table 2. As an example, the following sequence computes the Fisher matrices for a DUNE cosmic shear survey, a full sky BAO spectroscopic survey (20 000 deg²), and their combination:

```
> fid_lens=set_fiducial("DUNE")
> fid_bao=set_fiducial("bao_halfsky")
>
> sv_lens=mk_survey(fid_lens, "sv1")
> sv_bao=mk_survey(fid_bao, "sv2")
>
> f_lens=mk_fisher_lens(fid_lens, sv_lens)
> f_bao=mk_fisher_bao(fid_bao, sv_bao)
> f_comb=comb_fisher(f_lens, f_bao)
```

The following call sequence produces Fig. 4 showing the 68% CL constraints on the dark energy parameters Ω_{DE} and w_0 expected for each surveys separately (blue and red ellipse) and jointly (solid green ellipse).

```
> margin_fisher, f_lens, f_lens2, [0, 1, 0, 0, 0, 0, 0, 1]
> margin_fisher, f_bao, f_bao2, [0, 1, 0, 0, 0, 1]
> margin_fisher, f_comb, f_comb2, [0, 1, 0, 0, 0, 0, 0, 1]
> plt_fisher_2p, f_bao2, /nofill, color=2
```

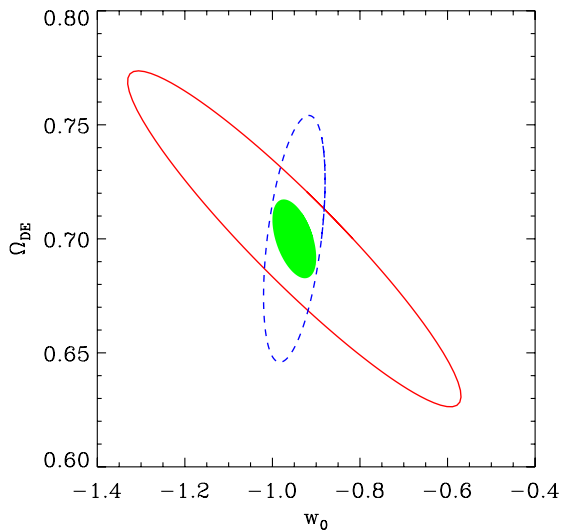


Fig. 4. Marginalised 68% CL constraints on the dark energy parameters Ω_{DE} and w_0 , expected for the DUNE cosmic shear (blue), a full sky BAO survey (red) and their combination (solid green). This figure was derived using the Fisher matrix routines of *iCosmo*.

```
> plt_fisher_2p, f_lens2, /nofill, $
linestyle=2, /over
> plt_fisher_2p, f_comb2, /over, color=3
```

The `margin_fisher` routine was used to retain only the parameters to be plotted, and marginalise over all the other parameters.

6. Conclusions

The *iCosmo* package provides a convenient and flexible interactive tool for cosmological calculations, and it can also be used as a computation engine in batch mode. With all the built-in IDL libraries, it is also a convenient platform for developing other cosmological routines and for teaching. The code, along with an

interactive web tool [Kitching et al. \(2009\)](#) and various cosmological resources are freely available at <http://www.icosmo.org>.

In the future, we plan to add more features to the code, such as the halo model, higher order clustering statistics, and interfaces with CMB Boltzmann codes. Contributions from the community are encouraged.

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