International X-ray Observatory (IXO)

Probing dark energy with future X-ray gas mass fraction studies

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We examine the ability of a future X-ray observatory, with capabilities similar to those planned for the International X-ray Observatory (IXO) mission, to constrain dark energy via measurements of the cluster X-ray gas mass fraction, f_{gas}. Forthcoming large X-ray and SZ galaxy cluster surveys, from missions such as, Spectrum-RG/eROSITA, SPT, ACT or Planck, will find hot, X-ray luminous clusters out to high redshifts. Short snapshot observations with the new X-ray observatory should then be able to identify a sample of ~500 hot (kT>~5keV), X-ray bright, suitably relaxed systems, to later re-observed them with longer exposure times (~20ks per cluster on average) and measure f_{gas} to a precision of ~5 per cent. We study the ability to constrain dark energy using such sample. Our analysis uses a Markov Chain Monte Carlo method which fully captures the relevant degeneracies between parameters and facilitates the incorporation of priors and systematic uncertainties in the analysis. We explore the effects of such uncertainties for scenarios ranging from optimistic to pessimistic. We find that the f_{gas} experiment offers a competitive and complementary approach to the best other large, planned dark energy experiments, with a comparable Dark Energy Task Force (DETF) [1] figure of merit (FoM) of 15-40, with the possibility of boosting these values by 40 per cent or more by optimizing the redshift distribution of target clusters. The f_{gas} experiment will provide tight constraints on the mean matter and dark energy densities, with a peak sensitivity for dark energy work at redshifts midway between those of supernovae and baryon acoustic oscillation(BAO)/weak lensing/cluster number counts experiments. In combination, these experiments should enable a precise measurement of the evolution of dark energy.

The dark energy model and the DETF FoM

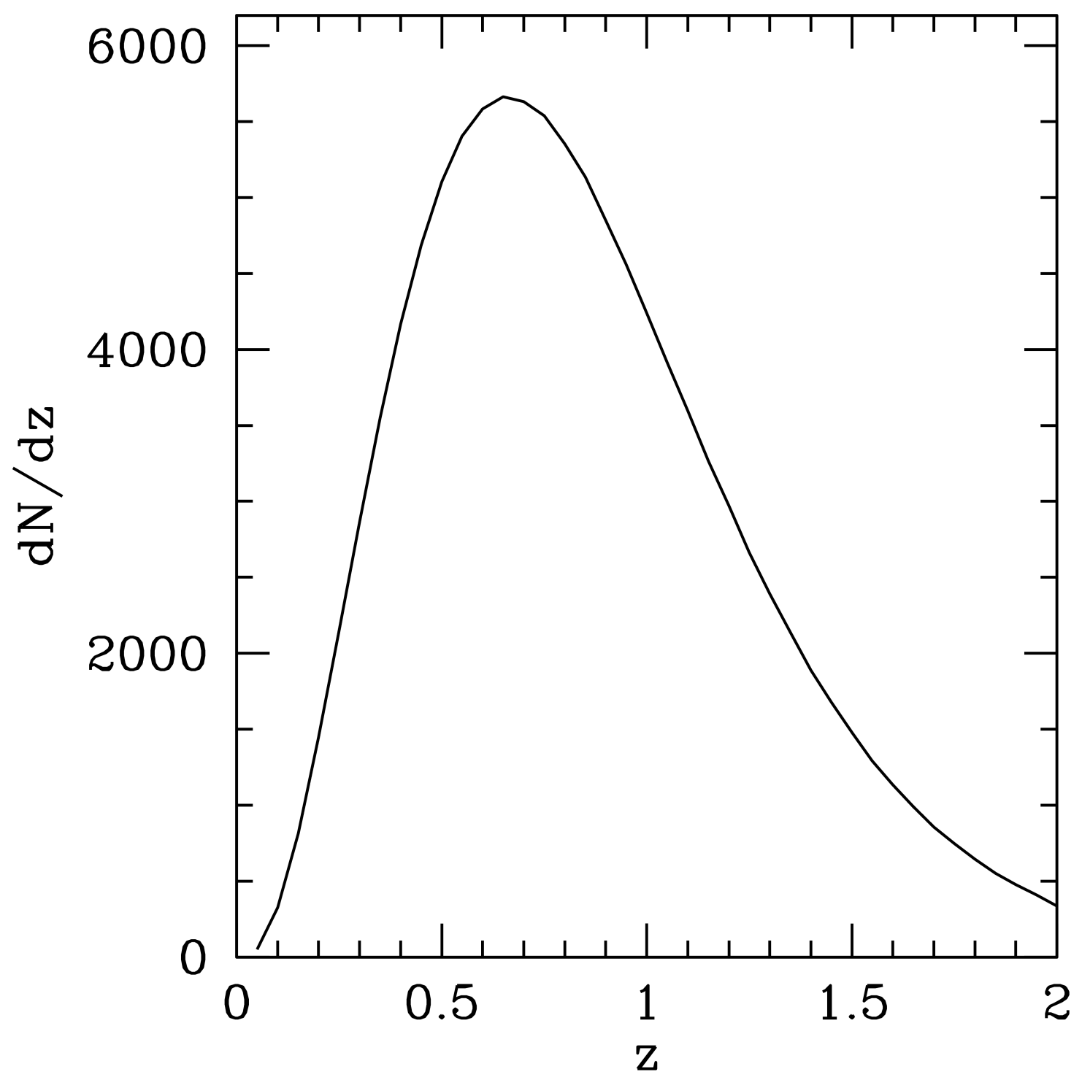
We characterize the evolution of dark energy by its energy density in units of the critical density, Ω_{de}, and its equation of state, w. Following the DETF, we parameterize the evolution of the dark energy equation of state as $w(a)=w_0+w_a(1-a)$ [2,3], for which a cosmological constant has w(a)=-1. **Using this parameterization, the DETF define a FoM that is used to compare the constraining power of different dark energy experiments.** The DETF showed that since there is little correlation in the w_p-w_a plane, the area is proportional to the product of the standard deviations $\sigma(w_p)x\sigma(w_a)$; where $w_p=w(a_p)$ is the pivot value of w(a), i.e., the value of w(a) at which its uncertainty is minimized [4].

For the more detailed MCMC analysis used here, however, we obtain slightly asymmetric probability distributions for these parameters in some cases, although to either side of the peak can be modeled as Gaussians. Therefore, we use **$FoM=[\sigma(w_p)x\sigma(w_a)]^{-1}$**, where $\sigma(w_p)=[\sigma_{up}(w_p)+\sigma_{down}(w_p)]/2$ and $\sigma(w_a)=[\sigma_{up}(w_a)+\sigma_{down}(w_a)]/2$, and $\sigma_{up}(w_p)$, $\sigma_{down}(w_p)$, $\sigma_{up}(w_a)$, and $\sigma_{down}(w_a)$ the standard deviations of the Gaussians to either side of the peak. This allows a direct comparison with the results reported by the DETF.

A strategy for future f_{gas} work

- We assume that a future f_{gas} experiment will be carried out by an X-ray observatory with capabilities comparable to those of IXO. The major improvements of such mission with respect to current X-ray observatories are in collecting area (~100 times larger than Chandra), and spectral resolution.
- We assume that the f_{gas} experiment will be preceded by, and will build upon, forthcoming X-ray and/or SZ cluster surveys that will scan a significant fraction of the sky and find a large number of hot, X-ray luminous, high-z clusters. These surveys will provide the initial target lists for the f_{gas} experiment as well as allowing an array of complementary cosmological tests based on the power spectrum and mass function of galaxy clusters [1,7].
- From initial surveys of tens of thousands of clusters, the ~4000 most X-ray luminous (or highest integrated SZ flux) clusters will be identified. The new X-ray observatory will then be used to take short snapshot exposures (~1ks) of these clusters, to identify the most apparently dynamically relaxed systems that are most suitable for f_{gas} work [5]. The selection of relaxed clusters is likely to be based primarily on X-ray morphology, but will also utilize the high spectral resolution capabilities to measure bulk gas motions.
- Current studies of the Massive Cluster Survey (MACS) [6] show that at redshifts z<0.5 approximately 1/4 clusters are sufficiently relaxed for f_{gas} work [5]. We (conservatively) use a factor 1/8 obtaining a sample of ~500 f_{gas} clusters (or 1/16 obtaining a sample of ~250).
- The most relaxed clusters will be re-observed with deeper exposures to measure the gas mass fraction to the required level of precision. For the 500-cluster sample, we assume an average exposure time per cluster of ~20ks. For the 250-cluster sample, the typical exposure is ~40ks. In both cases, the total time required to complete the f_{gas} observations will be ~<15Ms. For the assumed instrument characteristics, we expect statistical uncertainties in the f_{gas} measurements resulting from 20ks (40) exposures of ~5 (3.5) per cent, which corresponds to ~3.3 (2.3) per cent in distance.

The redshift distribution of clusters



- We calculate the redshift distribution of clusters from a simulated X-ray luminosity function (based on the work of [7]) for a given cosmology and a future, X-ray cluster survey. Following [7], for the mass-observable relations we use the data of [8]. We select clusters from this distribution using the same criterion (kT>5keV) than we use for current data [5].

Fig. 1: The redshift distribution of clusters above the Spectrum-RG/eROSITAX-ray flux limit with temperatures kT>5keV. A sky coverage of 50 per cent is assumed. This redshift distribution has been used to generate the mock f_{gas} data set.

Comparing f_{gas} with the best other large, planned dark energy experiments studied by the DETF

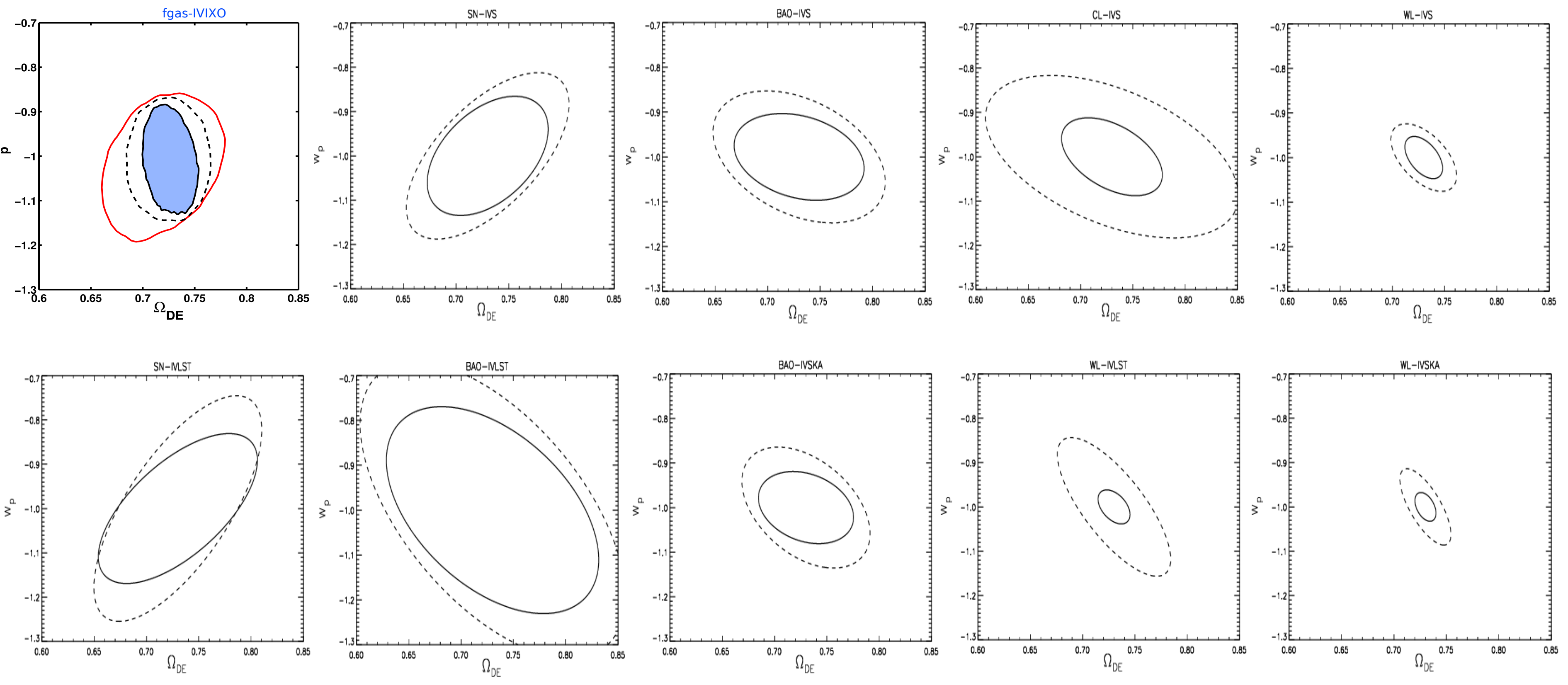


Fig. 2: 95 per cent confidence contours in the Ω_{de}-w_p plane for large (DETF `stage IV'), planned dark energy experiments (+Planck) from the results of the DETF [1], and including our results for the f_{gas} experiment (+Planck) (left top panel). Top panels show space-based missions from left to right: f_{gas}; SNIa; BAO; Cluster number counts; Weak Lensing (WL). Bottom panels show ground-based missions from left to right: SNIa; BAO (LSST); BAO (SKA); WL (LSST); WL (SKA). For the f_{gas} experiment, the blue, solid contour corresponds to using optimistic (2 per cent) systematic allowances, the dashed line to using standard (5 per cent) allowances, and the red line to using pessimistic (10 per cent) allowances (see below for details). For the other experiments, the solid line corresponds to the optimistic scenario, and the dashed line to the pessimistic.

Constraints on the evolution of dark energy

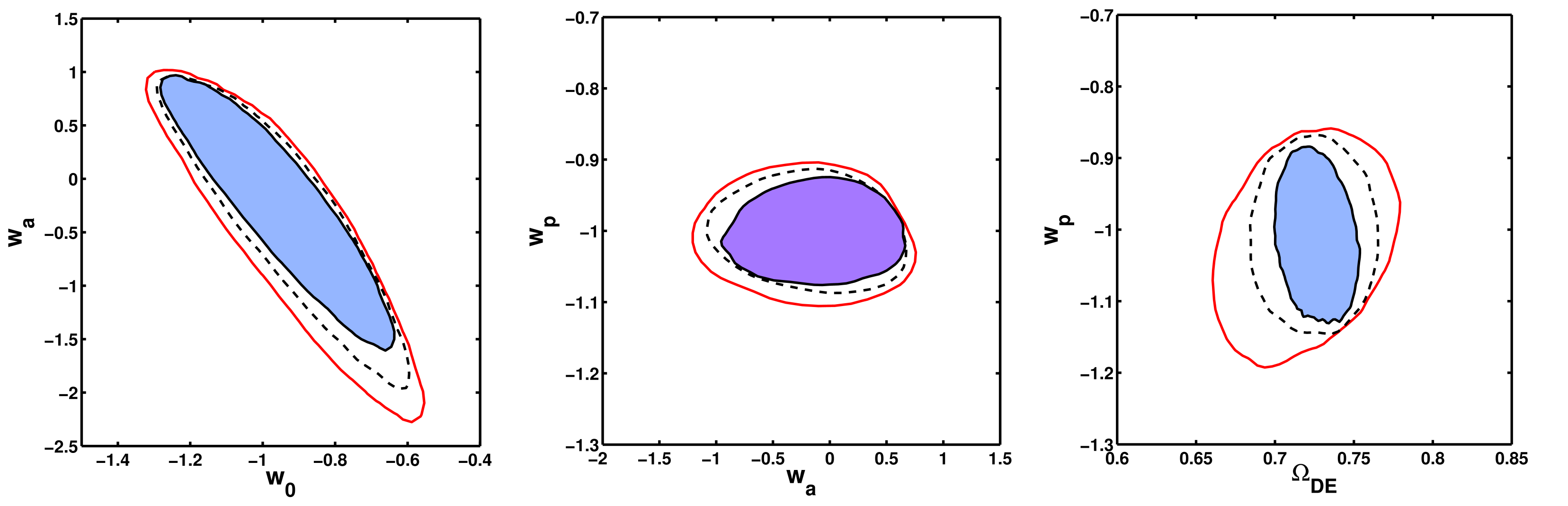
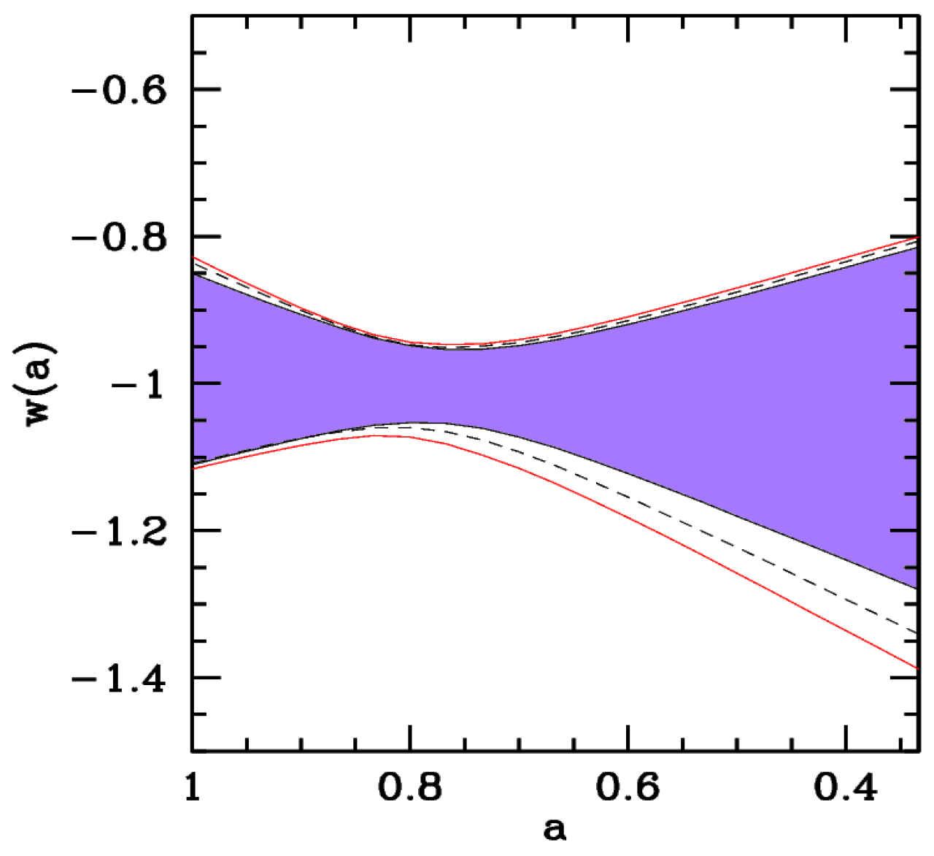


Fig. 3: (Left panel) The 95 per cent confidence contours in the w_0-w_a plane for the default dark energy model using the optimistic (blue, solid contour), standard (dashed contour) and pessimistic (red contour) allowances. (Middle panel) The 68 per cent confidence contours in the w_p-w_a plane. The marginalized 1σ confidence intervals on w_a and w_p are used to calculate the FoM. The figure confirms that w_a and w_p are not strongly correlated, as assumed in the definition of the FoM above. For completeness, the right panel is the same as the left top panel of Fig. 2.



- In the MCMC analysis we include 2 (optimistic), 5 (standard), and 10 (pessimistic) per cent allowances to the following systematic uncertainties: gas depletion factor and its linear (and quadratic) evolution, calibration and modeling, baryonic mass in stars and its linear (and quadratic) evolution, non-thermal pressure support in the gas, γ (8 or 16 per cent) .
- Along with the default dark energy model, we also study the following cases: including dark energy clustering, using a more conservative CMB data set, quadratic evolutions, the 250-sample, doubling γ or adding the X-ray+SZ experiment. We obtain FoM's in the ranges 34-43 (optimistic), 21-33 (standard), 15-29 (pessimistic).

Fig. 4: The 1σ confidence contours on the evolution of the dark energy equation of state as a function of scale factor, w(a). Results are shown for the default dark energy model using the optimistic (2 per cent; shaded, purple region), standard (5 per cent; dashed line) and pessimistic (10 per cent; solid, red line) systematic allowances. The tightest constraints on w(a) occur at the pivot scale factor, a_p~0.8 (z_p~0.25).

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