Probing the Dark Universe

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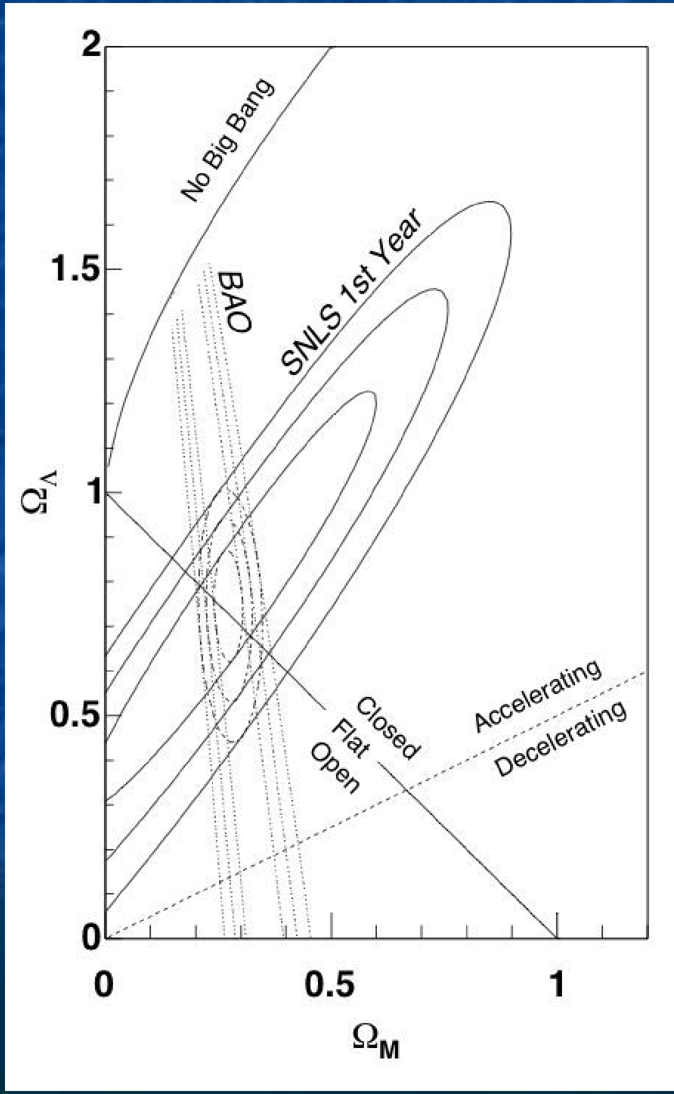
Outline

- Dark Energy
- Standard rulers - Baryonic Oscillations
- Designing WFMOS
- Future experiments & model selection

Dark Energy

- The Universe is accelerating, but why…
  - Cosmological Constant (Λ)
  - Field (quintessence etc)
  - Modification of gravity at large scales
  - Other..
- No evidence for time variation in the dark energy, so Λ is the best model.



Probing the Dark Energy

- Measuring distances
  - Standard candles (Sn-Ia)
  - Standard rulers (Baryonic oscillations)
- Structure formation
  - Weak gravitational lensing
  - Gravitational potential (ISW)

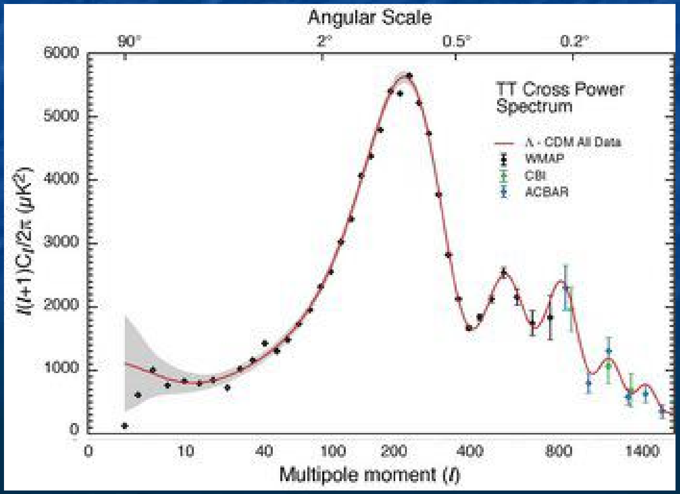
WFMOS

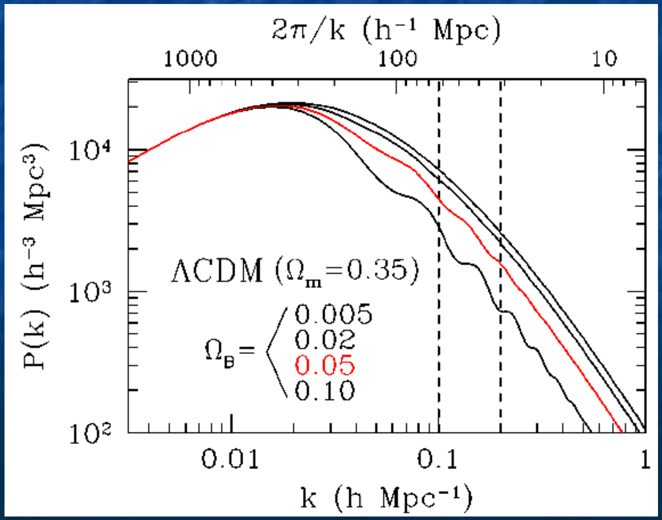
with Bassett, Blake, Kunz, Nichol
and WFMOS consortium

- WFMOS:
  - Wide-Field (1.5^{o} aperture diameter),
  - Fiber-Fed Optical ("Echidna"-style fiber-optic focal plane)
  - Multi-Object (Over 20,000 astronomical spectra per night)
  - Spectrograph (Moderate to high resolution (R=1000-40,000))
- Concept stage; design studies for Gemini underway.
- Objective: to detect Baryonic Oscillations in the large-scale structure and so conduct an independent probe of the dark energy.

Baryonic Oscillations

- Oscillations in the baryon-photon fluid in the early universe are imprinted into the matter power spectra.
- Fundamental wavelength given by sound horizon at recombination.
- Already detected by SDSS and 2dF (Jan 2005), oscillation positions measured to 4% accuracy





Angular diameter distance

- By comparing the size of these oscillations to the CMB, we can measure the angular diameter distance relative to the sound horizon, x=r/*s* (Blake and Glazebrook, 2003).

$$s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_r} \frac{c_s}{(a + a_{eq})^{1/2}} da$$

- By separating the power spectrum into its tangential and radial components, we can measure the comoving distance and its rate of change.

$$x = \frac{1}{s}\frac{dr}{dz} = \frac{1}{s}\frac{c}{H(z)}$$

Survey Design

- How do we optimize a survey to maximize its performance in constraining the dark energy?
- At which redshifts should we take measurements to have the greatest sensitivity to the dark energy parameters?
- Should it survey a wide area at low redshift, or a small number of thin ‘pencil beam’ surveys going to a greater depth (or a mixture of the two)?

IPSO

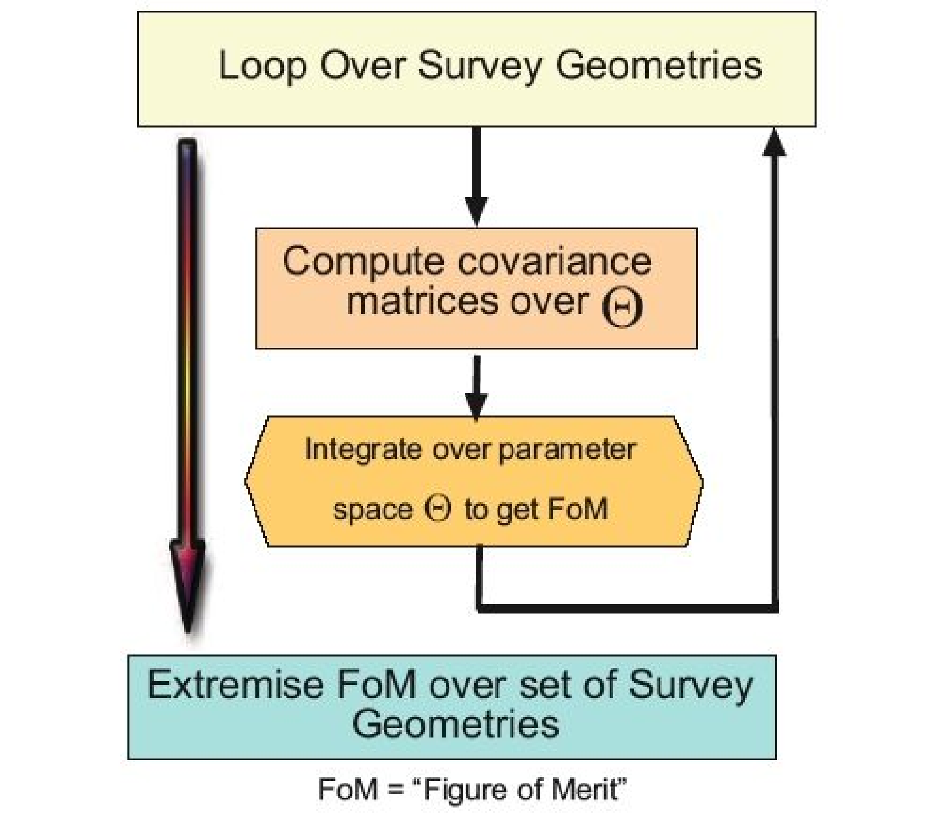
- Integrated Parameter Survey Optimisation (Bassett 2004; Bassett, Parkinson and Nichol 2005)

$$FoM(s) = \int_{Q} I(s,q_m)\,dq_m$$

The Figure of Merit is the integral of the performance (*I*) over the cosmological parameters.

- D-optimality: performance (*I*) is measured as the determinant of the Fisher matrix of the dark energy parameters (w_0, w_a) [using Linder expansion $w(a)=w_0+(1-a)w_a$].

Procedure


Loop Over Survey Geometries
Compute covariance matrices over Θ
Integrate over parameter space Θ to get FoM
Extremise FoM over set of Survey Geometries
FoM = "Figure of Merit"

Optimisation Procedure

- Select survey configuration (area coverage, redshift bins, exposure time etc.)
- Estimate number density of galaxies using LFs.
- Estimate error on $D_A(z)$ and $H(z)$ using scaling relations.
- Calculate Fisher matrix of parameters, using distance data plus relevant priors (Planck+SDSS).
- Invert Fisher matrix and calculate FoM.
- Monte-carlo markov chain search over survey configuration parameter space, attempting to minimize determinant.

Survey Parameters

- Time: split between the high and low redshift regions. Total time = 1500 hours (expected observing time over three years).
- Area: different areas assigned to high and low redshift regions.
- Number of pointings: generated from area and time.
- Redshift binning: Redshift regions broken down into a number of bins.

Scaling Relations

With Blake, Bassett, Glazebrook, Kunz and Nichol

- Two sources of statistical error
  - Sample variance: the number of independent wavelengths that can fit into the survey volume.

$$\left(\frac{\sigma_P}{P}\right)^2 = 2\,\frac{(2\pi)^3}{V}\,\frac{1}{4\pi k^2 \Delta k}$$

    Sample variance must be <2%, so survey volume at least $1.8 * V_{Sloan}$.
  - Shot noise: the imperfect sampling of the fluctuations by the finite number of galaxies (i.e. $nP >> 1$). Number of galaxies $> 10^6$.

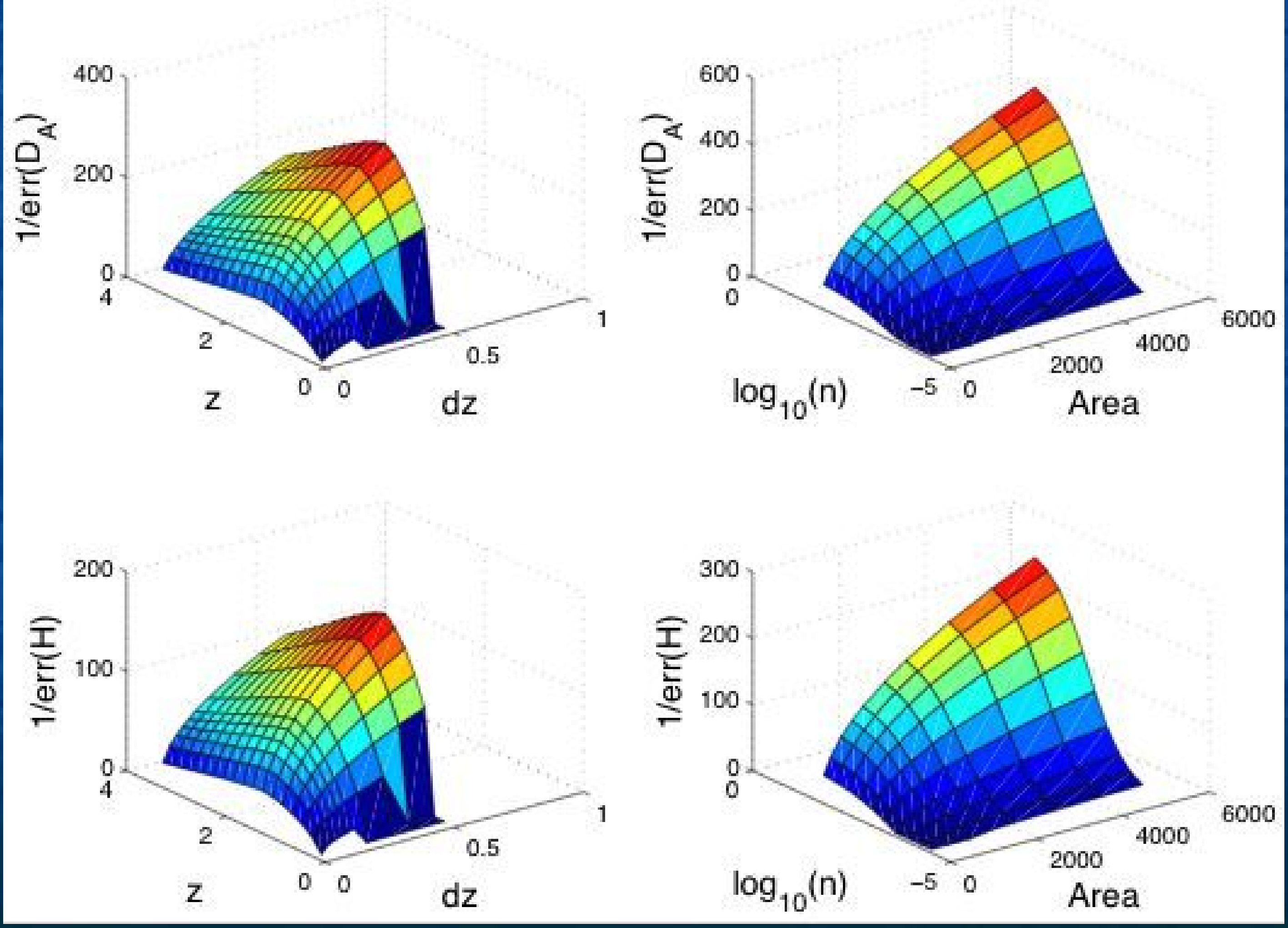
Fitting Formulae

- It is computationally intensive to find full error covariances for power spectrum (requires FFTs).
- Computed errors on x and x' for a grid of survey parameters and derived fitting formula.
- For photo-z surveys, assumed Gaussian photometric error σ_r.

$$err(x,x') = err_0 \sqrt{\frac{V_0}{V}} \sqrt{\frac{\sigma_r}{\sigma_{r,0}}} \left(1 + \frac{n_{eff}}{n} \frac{D(z_0)^2}{b_0^2 D(z)^2} \right) \left(\frac{z_m}{z} \right)^{\gamma} \qquad z < z_m$$

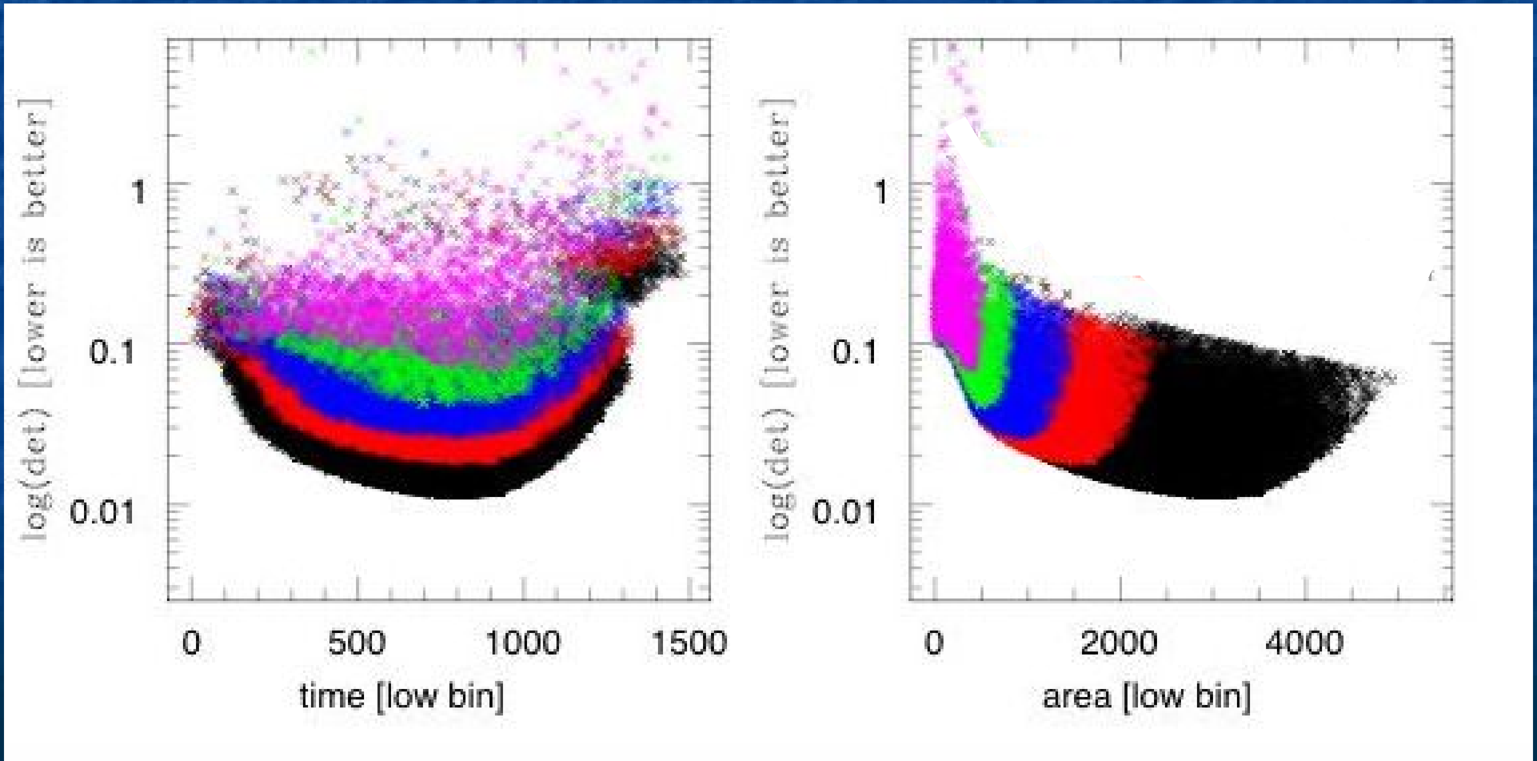
$$err(x,x') = err_0 \sqrt{\frac{V_0}{V}} \sqrt{\frac{\sigma_r}{\sigma_{r,0}}} \left(1 + \frac{n_{eff}}{n} \frac{D(z_0)^2}{b_0^2 D(z)^2} \right) \qquad z > z_m$$

Fitting Formulae (2)



Low redshift bin (0.5-1.3)

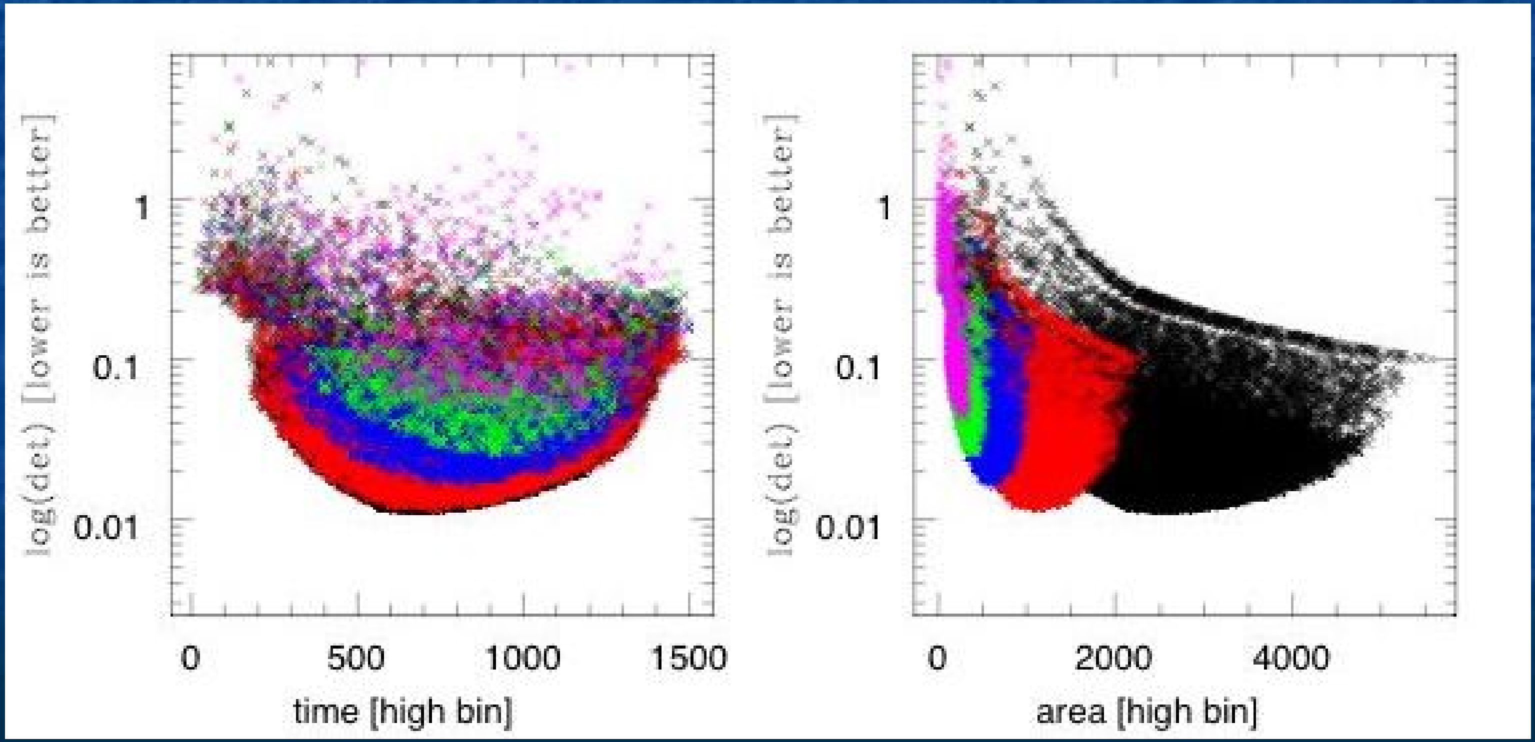
For the first case, we fixed the redshift bins, and consider only a ΛCDM fiducial cosmology.



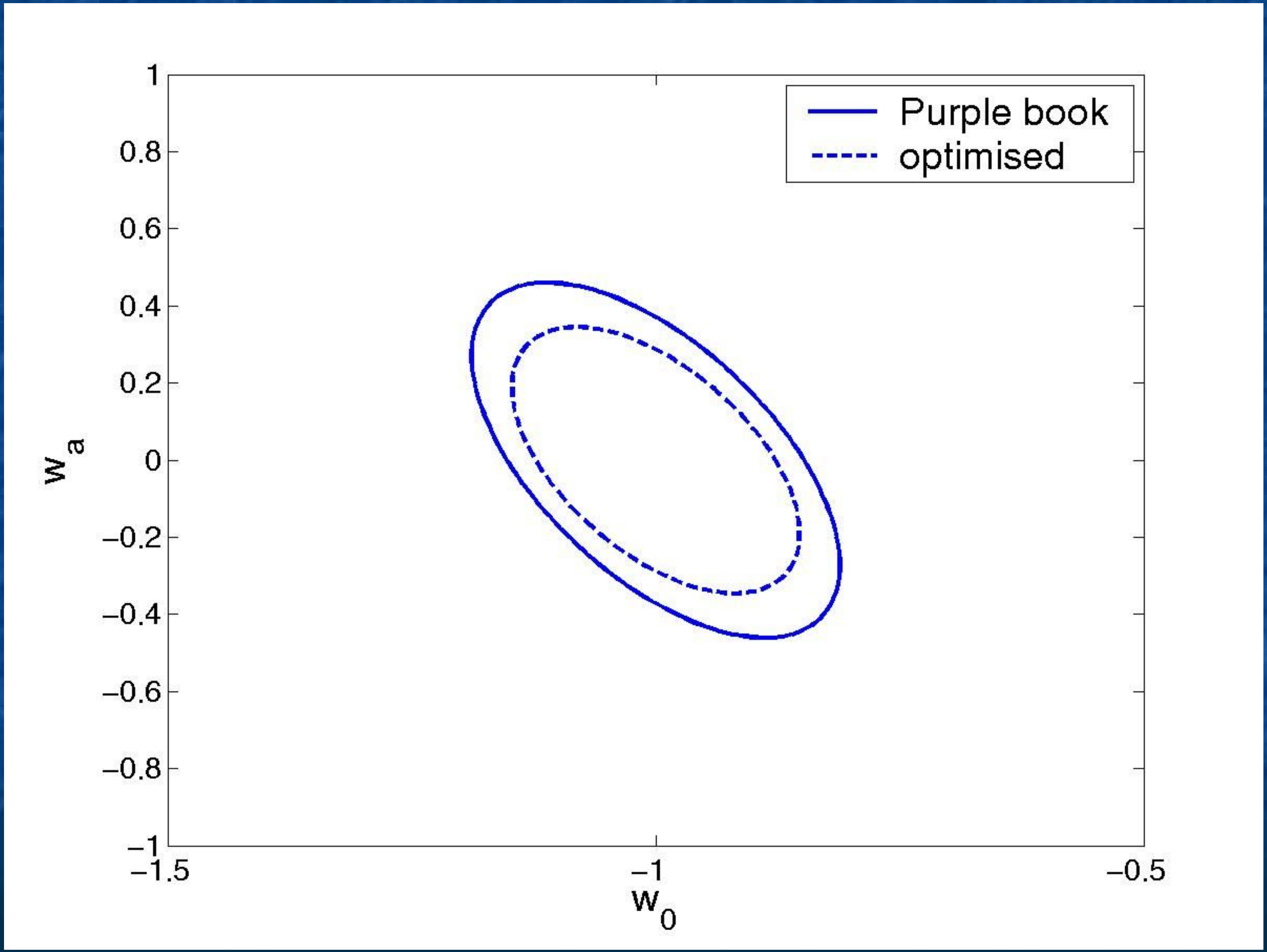
High redshift bin (2.5-3.5)

Colours represent number of pointings per FOV,

black=1, red=2, blue=3, green=4 and magenta=5.



Error ellipse



Design Objectives

- Using these techniques we can optimise:
  - The observational area in the low and high redshift regimes
  - The number of redshift bins in each regime
  - The redshifts of the bins
  - The number of spectroscopic fibres
  - The gain in information from pushing into the redshift desert.

Model Selection

With Corasiniti, Kunz, Liddle and Mukherjee

- We use Fisher matrix approach to predict effectiveness of experiments to constrain new cosmological parameters.
- But these new parameters have not yet been detected with current data (e.g. equation of state $w = -1$, with some errors)
- Model selection statistics (such as the Bayesian evidence) decide if new parameter is required by data.

Evidence

- Bayes' theorem gives posterior probability of parameters (θ) of a model (H) give data (D)

$$P(\theta|D,H) = \frac{P(D|\theta,H)P(\theta|H)}{P(D|H)}$$

- Marginalising over θ, the evidence is

$$E = P(D|H) = \int d\theta P(D|\theta,H)P(\theta|H)$$

- Evidenc ta over the prior parameter space of the model.

Bayes' Factor

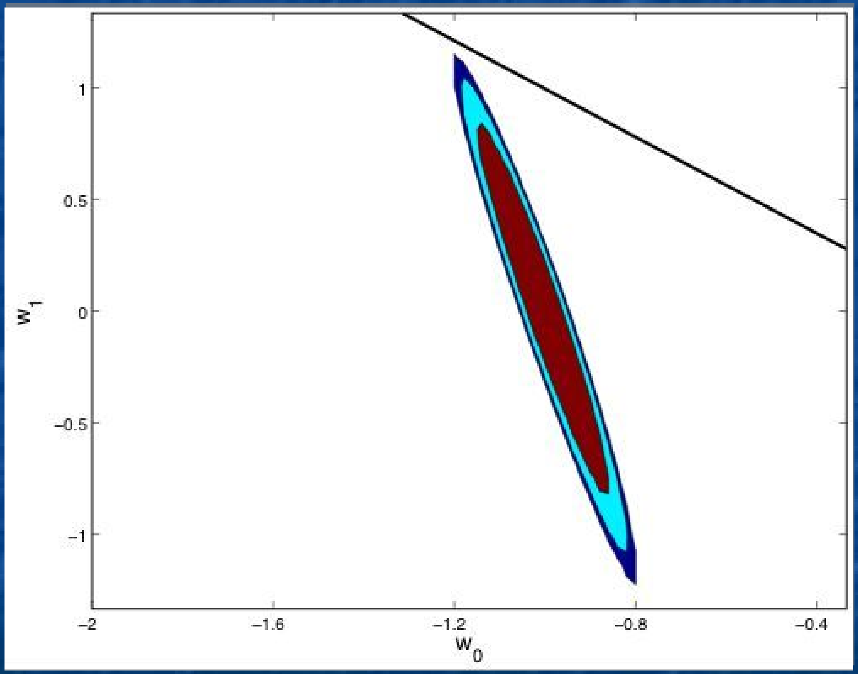
- Jeffrey's (1961) scale:

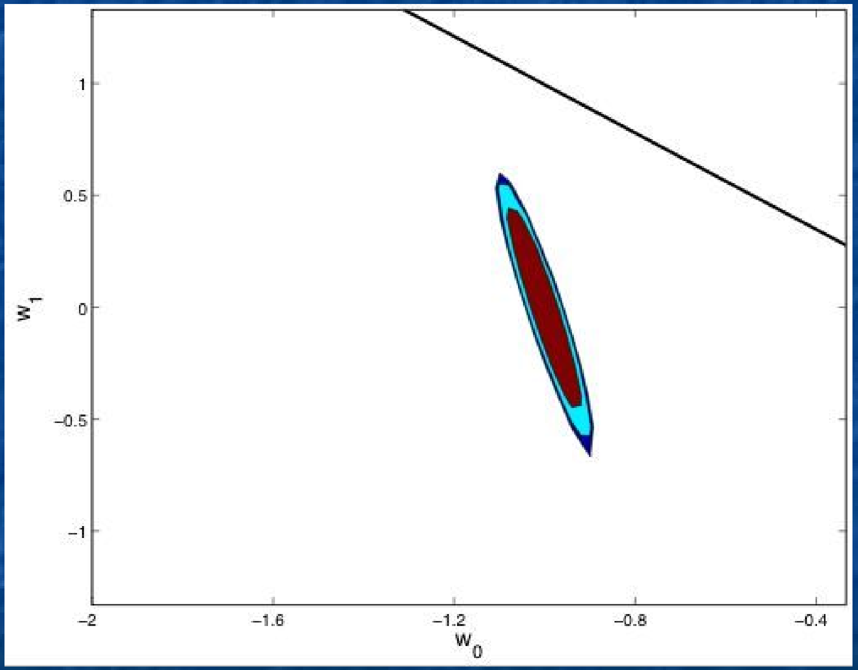
$1 < \Delta\ln(E) < 2.5$	substantial
$2.5 < \Delta\ln(E) < 5$	strong
$\Delta\ln(E) > 5$	decisive

- Bayes' Factor = ratio of evidences * ratio of prior probabilities

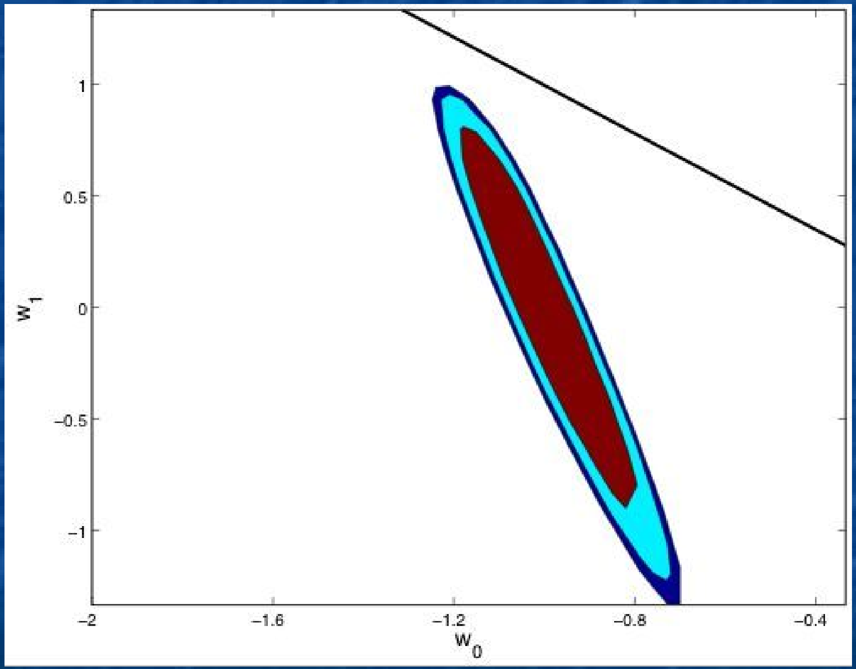
$$B_{12} = \frac{P(H_1|D)}{P(H_2|D)} = \frac{P(D|H_1)P(H_1)}{P(D|H_2)P(H_2)}$$

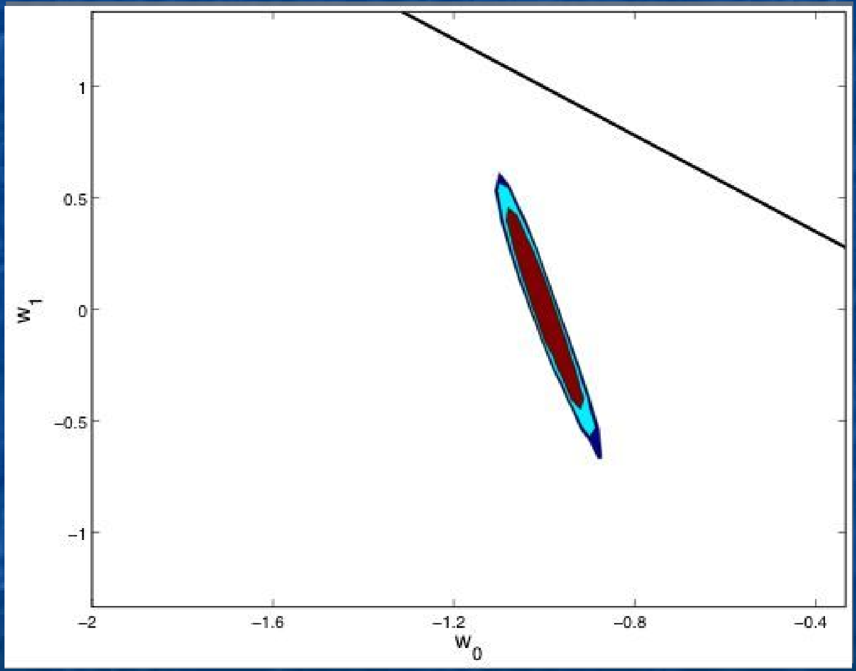
SN-Ia: SNAP vs. JEDI





BAO: WFMOS vs. JEDI





Conclusions

- The next generation of dark energy surveys will constrain the available parameter space.
- At regions close to w_0=-1 w_a=0, it is difficult to distinguish between Λ and evolving dark energy. This region will shrink as the experiments become more effective.
- Optimisation is a useful technique for the design of dark energy experiments that can be applied generally.