Optimising the next-generation of large scale surveys

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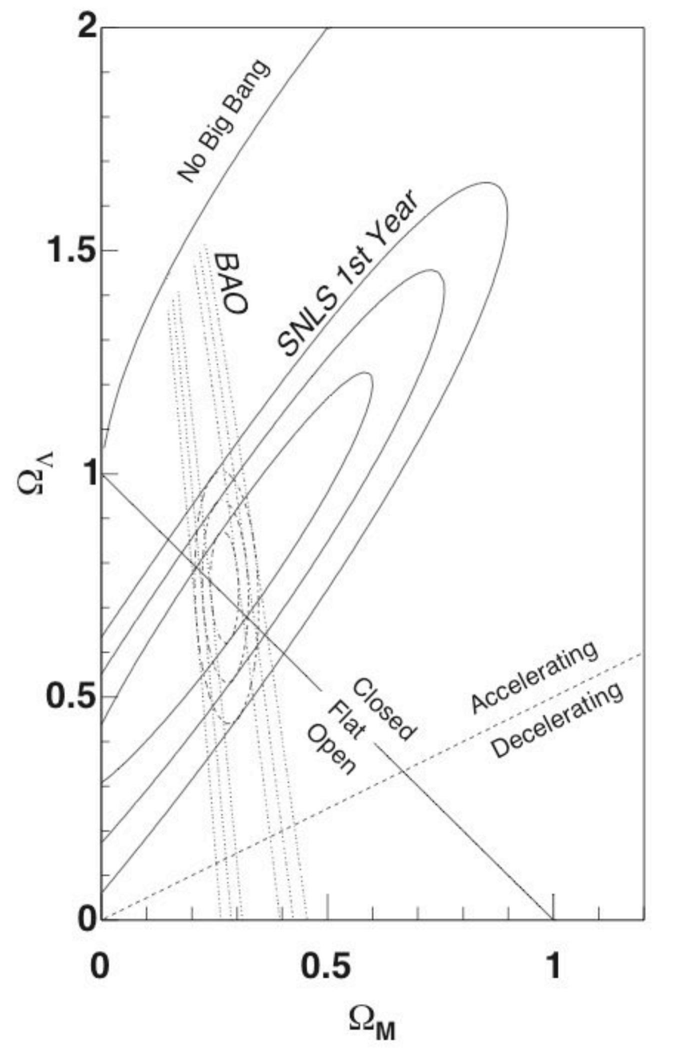
Outline

- Surveys
- Figure-of-merit
- Optimisation
- Baryon Acoustic Oscillations (WFMOS)
- Weak Lensing (Hyper-Suprime Cam)
- Conclusions

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, but errors are very large, so model space is wide open..



Comparison of Models

- The Cosmological constant (Λ)
  - Pros: Simple (single number), predicted by GR
  - Cons: Expectation of vacuum too large, why do we see it now?
- Quintessence
  - Pros: dynamical, similar to inflation
  - Cons: Requires fine tuning of I.C.s and couplings
- Modified Gravity
  - Pros: more fundamental, may explain DM
  - Cons: Difficult to make consistent with data

Probing the Dark Energy

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

Future Surveys

- Supernovae - repeated imaging with spectroscopic follow-up
  - Current: SNLS, ESSENCE, SDSS-II
  - Next gen: Pan-STARRS, DES
  - 3rd gen: LSST, JDEM
- Baryonic Acoustic Oscillations - large scale redshift survey
  - Current: WiggleZ, SDSS-II
  - Next gen: APO-SDSS, DES(photo-z), HETDEX (high-z), WFMOS, Hydrogen Sphere Survey (radio)
  - 3rd gen: LSST, JDEM, SKA (radio)
- Weak Lensing - large scale, high quality imaging survey
  - Next gen: DES, Pan-STARRS, HSC
  - 3rd gen: DUNE, JDEM, LSST

Survey Design

- How do we optimize a survey to maximize its performance in constraining the dark energy?
- What survey strategy should we take; ie.
  - What type of objects should we target?
  - At which redshifts should we take measurements?
  - 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)?
- And how do we quantify the performance of the survey?

Fisher matrix approach

- Taylor expand log likelihood around Maximum Likelihood parameter values (θ_{ML})

$$\ln L(\theta) \approx \ln L(\theta^{ML}) + \tfrac{1}{2}\sum_{ij}(\theta_i - \theta_i^{ML})^t H_{ij}(\theta_j - \theta_j^{ML})$$

$$H_{ij} = \left.\frac{\partial \ln L}{\partial \theta_i}\frac{\partial \ln L}{\partial \theta_j}\right|_{\theta^{ML}}$$

- Taking the expectation of *L* over many data realizations, we replace the Maximum Likelihood with the fiducial parameter value.
- The Fisher matrix is defined as the expectation of the Hessian

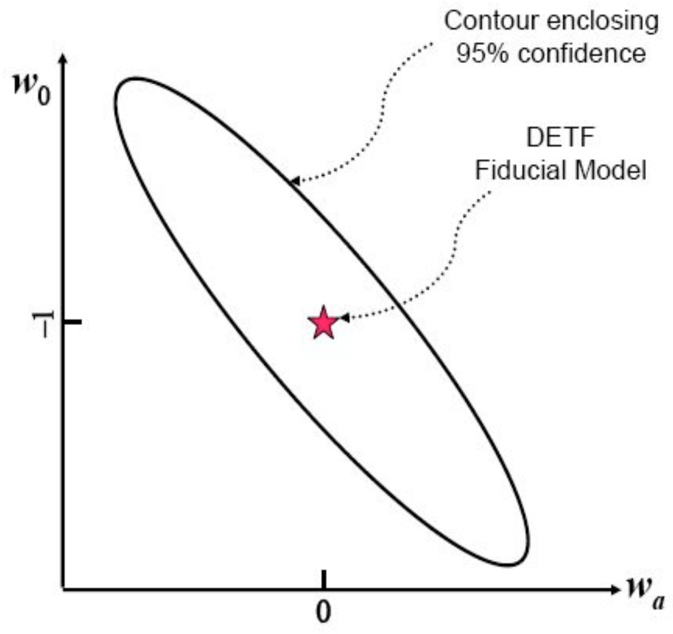
$$F_{ij} \equiv \langle H_{ij} \rangle$$

Utility, or Figures of Merit

- The determinant of the Fisher matrix, |F| (often called D-optimality), which is inversely proportional to the square of the parameter volume enclosed by the posterior.
- A common variation is to use the logarithm of the determinant, ln |F|.
- The trace of the Fisher matrix, trF, or its logarithm: this is proportional to the sum of the variances, and is often called A-optimality.
- The information gain H from performing the experiment (also often called Kullback-Leibler divergence), between the prior and posterior.

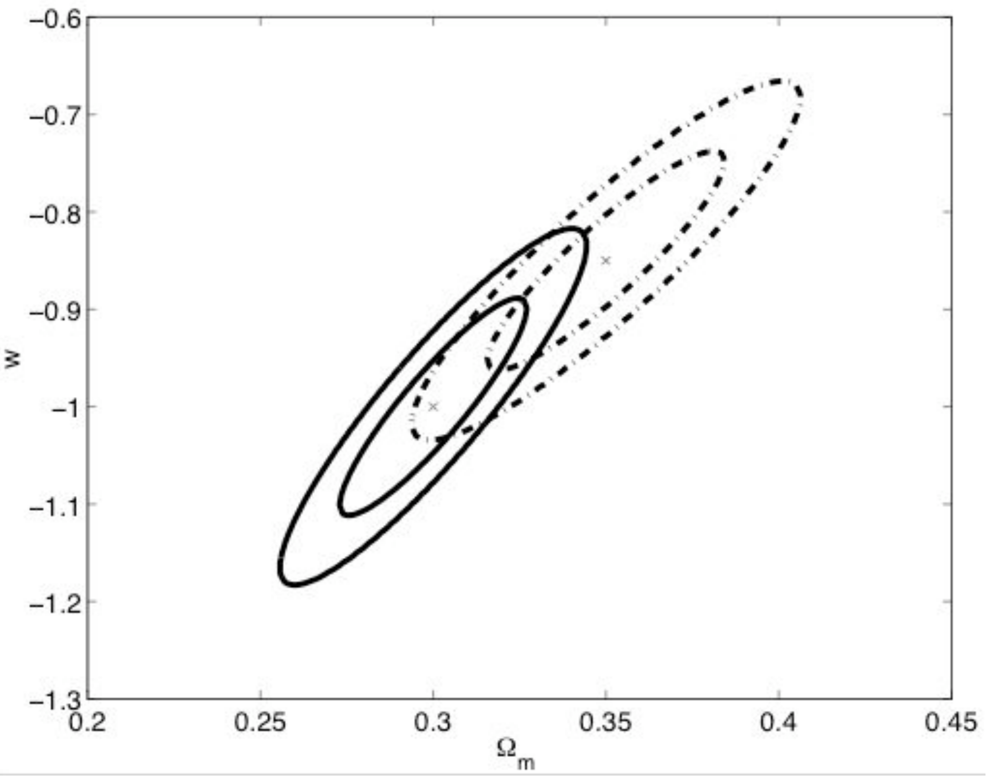
DETF Figure of Merit

- Constraining equation of state, w, and its evolution in time is seen as the primary goal.
- The DE Task force created a Figure of Merit to compare different surveys and approaches (Albrecht et al 2006)
- It is the inverse of the 95% confidence contour in the w_0, w_a plane (D-optimal)
- Often quoted as $[\sigma(w_a) \times \sigma(w_p)]^{-1}$, which is in fact sqrt$|F_{DE}|$ where $|F_{DE}|$ is the marginalised 2×2 Fisher matrix for the dark energy parameters w_0 and w_a



Effectiveness

- The errors on w (and so the FoM) of a survey depends on the fiducial cosmology.
- And even the conclusions that you draw from the data may change with the cosmology



Sampling vs. the Lever Arm

- Effectiveness is a trade off between
  - Sampling, e.g. the matter power spectrum in BAO surveys, proportional to the survey volume

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

  - The lever arm, e.g. the deepness of survey in magnitude, proportional to the exposure time

$$m_{\lim} = z_p - 2.5\log\left(\frac{S}{N}\frac{1}{g}\sqrt{\frac{B}{t}}\right)$$

- Time is the limiting factor, so deeper surveys cover less area, and vice versa.

"Lever-Arm"

- Low-z surveys only really measure expansion rate today (H_0). To measure acceleration (and rate of change of acceleration), need long baseline
- Example using Fisher matrix: measurement of Hubble parameter at redshift z to constrain DE parameters w_0 and w_a

$$F_{w_i w_j} = \frac{\partial^2(-\log L)}{\partial w_i \partial w_j} = \frac{\partial H(z)}{\partial w_i} \frac{1}{\sigma^2(H(z))} \frac{\partial H(z)}{\partial w_j}$$

Measurement error

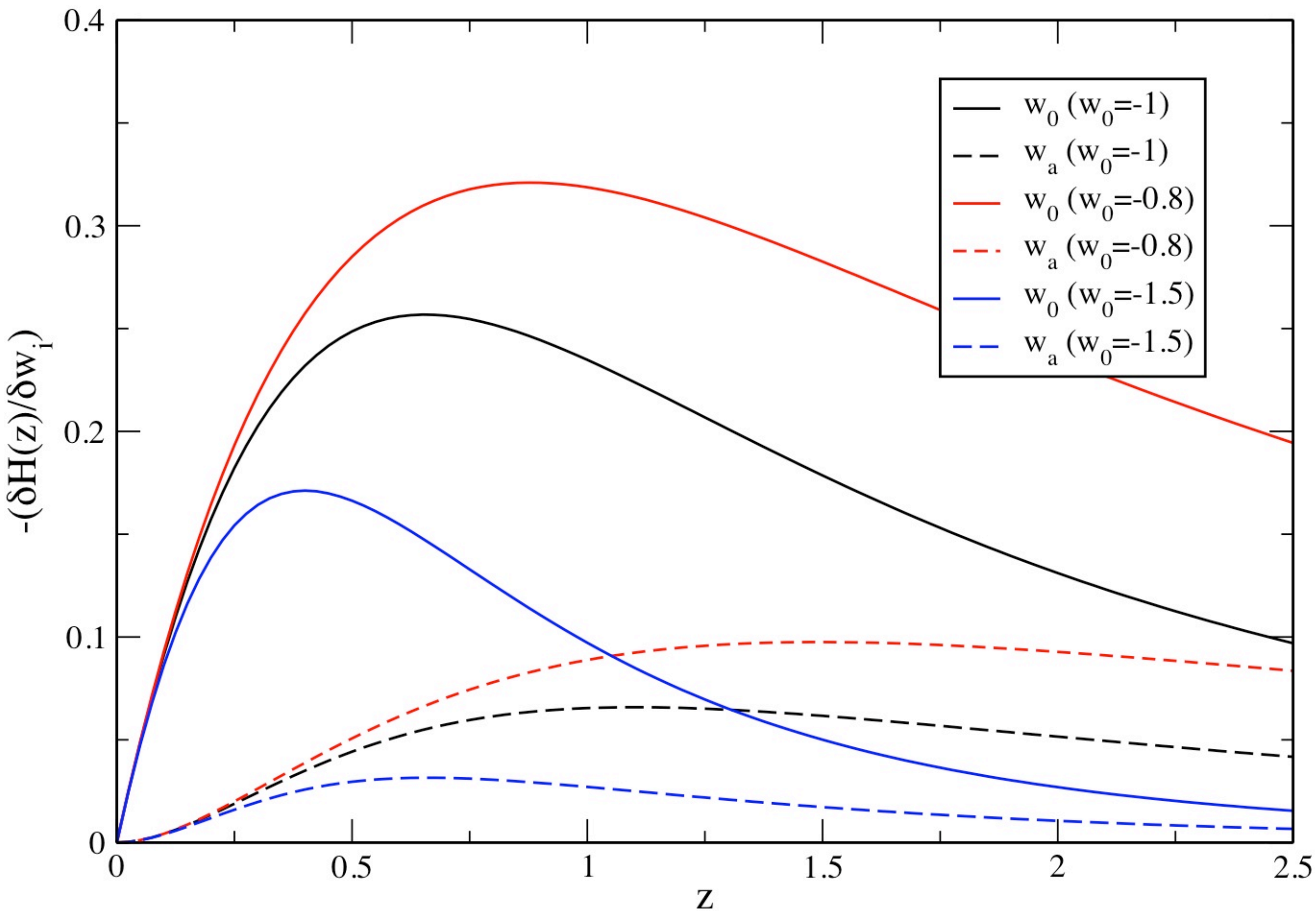
$$\frac{\partial H(z)}{\partial w_i} = -\frac{1}{2H^3(z)} \frac{\partial H^2(z)}{\partial w_i} = -\frac{H_0^2(1-\Omega_m)}{2H^3(z)} \frac{\partial f(z;w_0,w_a)}{\partial w_i}$$

$$\frac{\partial f(z;w_0,w_a)}{\partial w_0} = 3\log(1+z) f(z;w_0,w_a)$$

$$\frac{\partial f(z;w_0,w_a)}{\partial w_a} = 3\left(\log(1+z) - \frac{z}{1+z}\right) f(z;w_0,w_a)$$

Go to zero as $z \rightarrow 0$

Lever redshift



Other Figures of Merit

- Fisher Matrix (DETF Figure of Merit)
  - Assumes Gaussianity and a specific cosmology
- Integrated Parameter Survey Optimisation (Bassett 2004; Bassett, Parkinson and Nichol 2005)

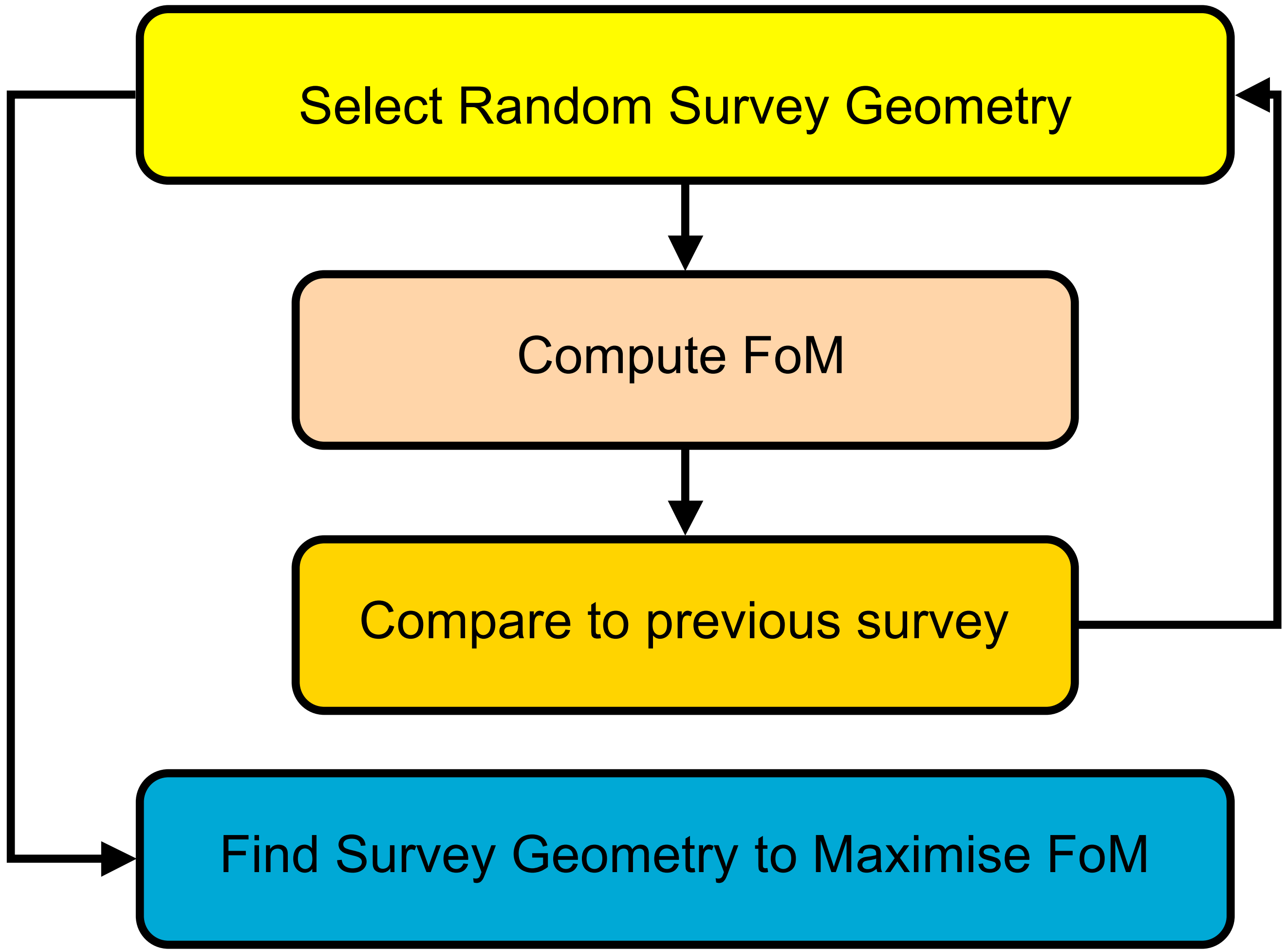
$$FoM(s) = \int_{\Theta} I(s,\theta_\mu)\,d\theta_\mu$$

  - The Figure of Merit is the integral of the performance (*I*) over the cosmological parameters.
- Bayes Factor (Mukherjee et al 2006)

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

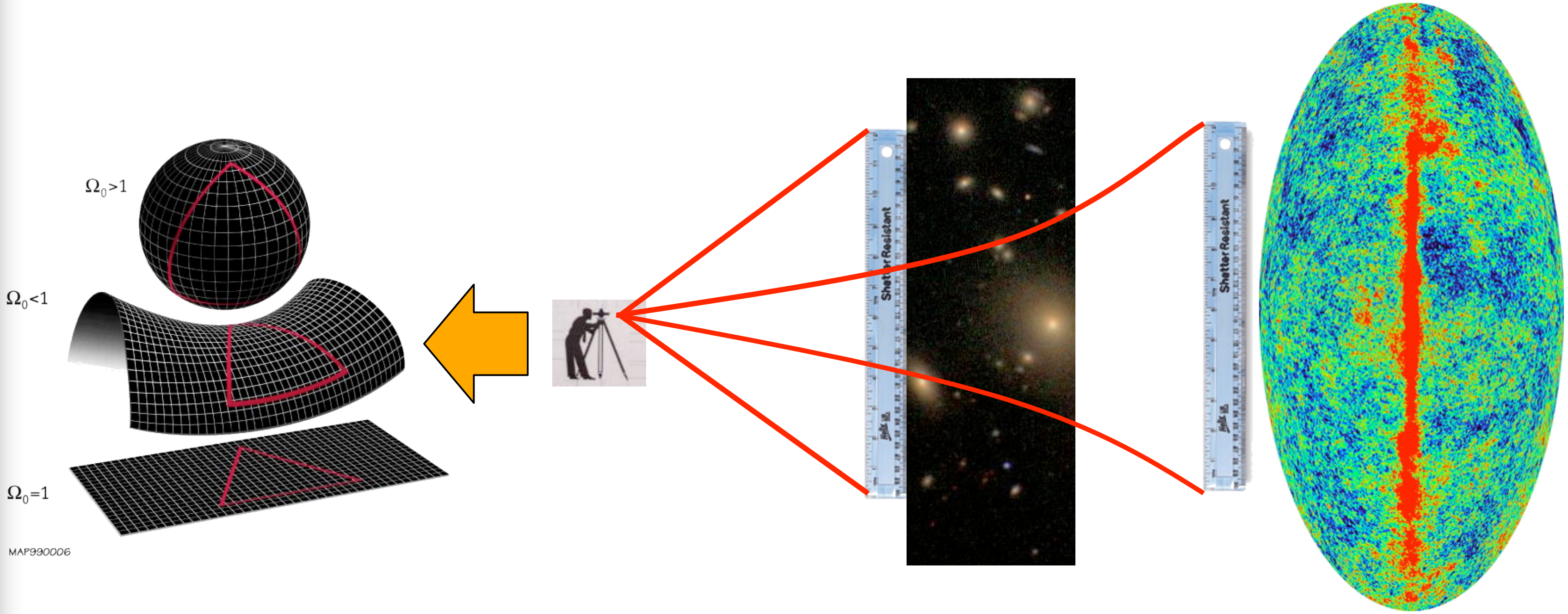
  - Compares probabilities of Lambda and evolving DE model

Optimization Process

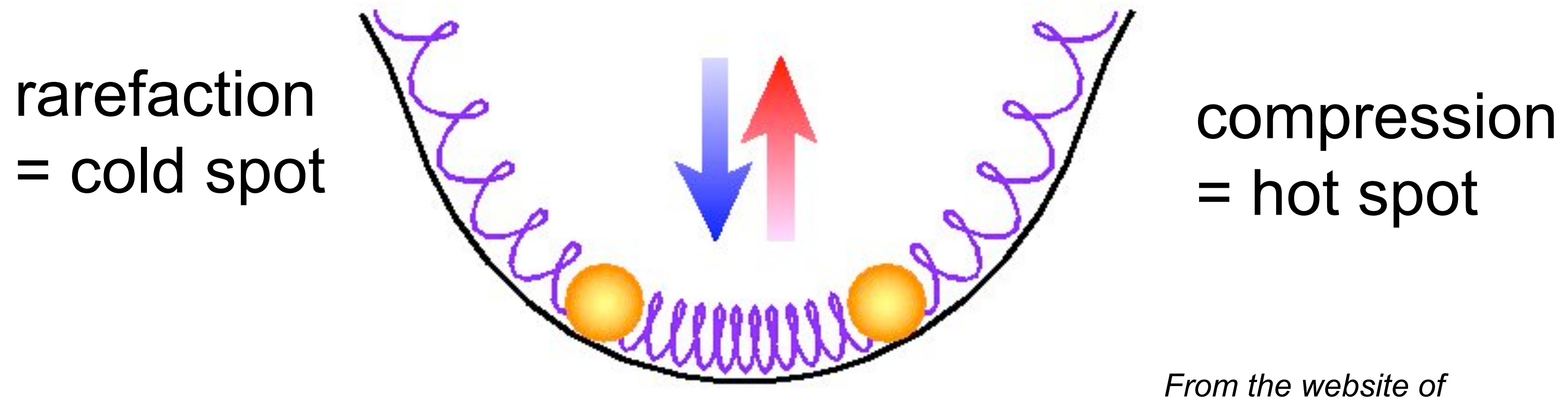


Baryon Acoustic Oscillations

- Can be used as a 'standard ruler' to probe dark energy



"Seeing Sound"

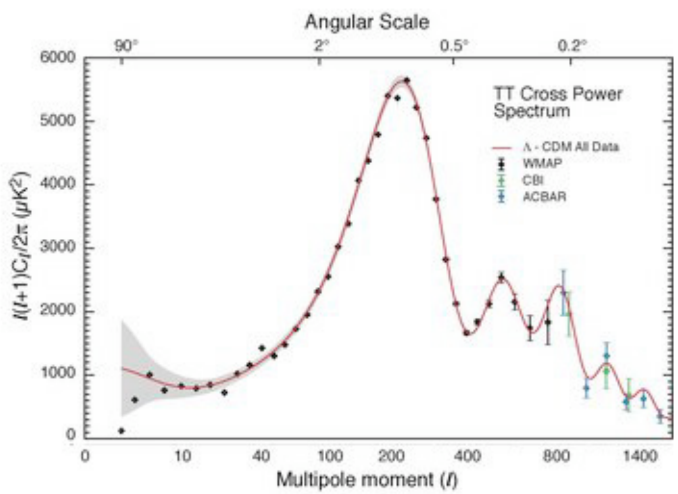


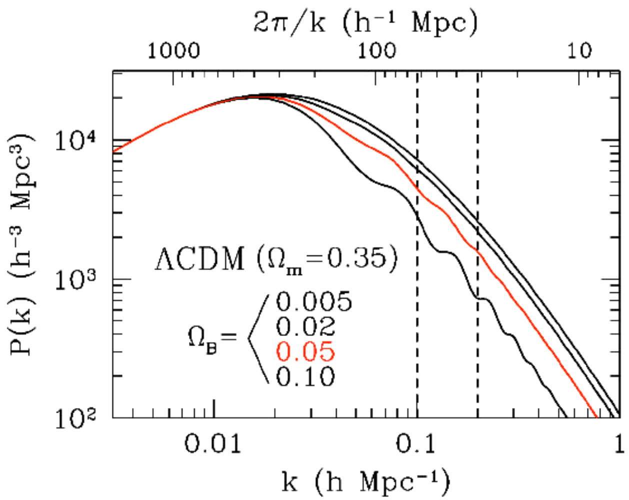
From the website of Wayne Hu

- Before recombination, the baryons and photons were tightly coupled and behaved as a single photon-baryon fluid.
- Gravity compresses the gas and the pressure restores it, so the fluid can carry acoustic oscillations - sound waves.
- Super-horizon perturbations, created in the very early universe, re-enter the horizon and drive the oscillations.

CMB and LSS

- We have already detected these oscillations imprinted in the CMB photons. The first peak corresponds to the fundamental wavelength.
- Matter falls into the potential wells and forms galaxies. But the imprint of the baryonic acoustic oscillations (BAO) remain.





Fundamental Wavelength

- At matter-radiation equality the speed of sound is 57% of the speed of light, but this falls as matter comes to dominate.
- When recombination occurs, the photons and baryons decouple and the sound speed of the fluid drops to zero very quickly.
- The oscillations are 'frozen' into the matter.
- The fundamental wavelength of these oscillations is given by the sound horizon at recombination (s).

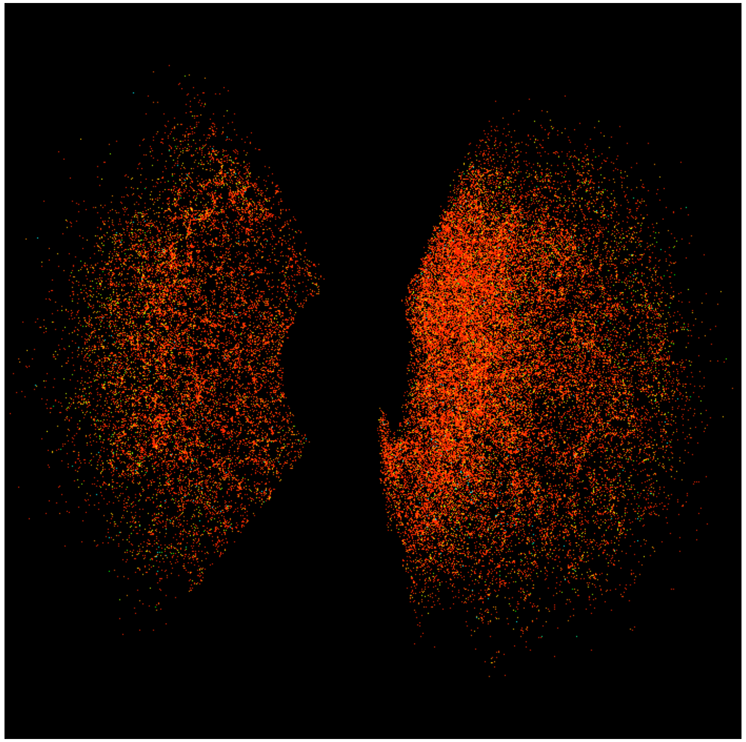
$$s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_r} \frac{c_s}{(a + a_{eq})^{1/2}} da$$

- The sound horizon measured by WMAP is 150 Mpc.
- By separating the power spectrum into its tangential and radial components, we can measure the ratio of the comoving distance (to a redshift z) to the sound horizon (x=r(z)/s) and its rate of change.

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

Large-scale surveys

- We probe the CMB by comparing temperatures at different angular separations. Every bit of the sky is accessible (in theory).
- We detect the BAO in the LSS at low redshifts using galaxies as mass tracers.
- But galaxies are sparsely populated…



Survey Requirements

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

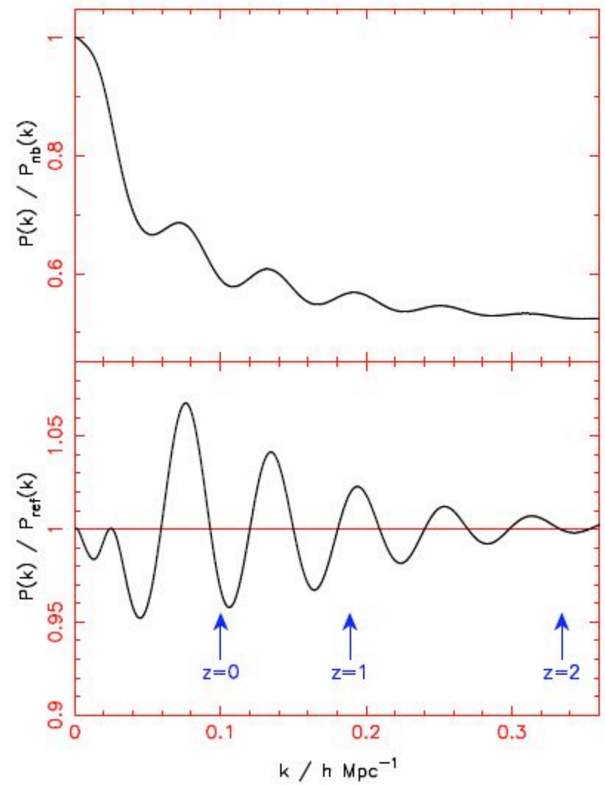
$$\left(\frac{\sigma_P}{P}\right)^2 = 2 \times \frac{(2\pi)^3}{V} \times \frac{1}{4\pi k^2 \Delta k}$$

    Sample variance must be <2%, so survey volume at least 1.8*Sloan (V_{SDSS}=2*$10^8 h^{-3}$Mpc^3).

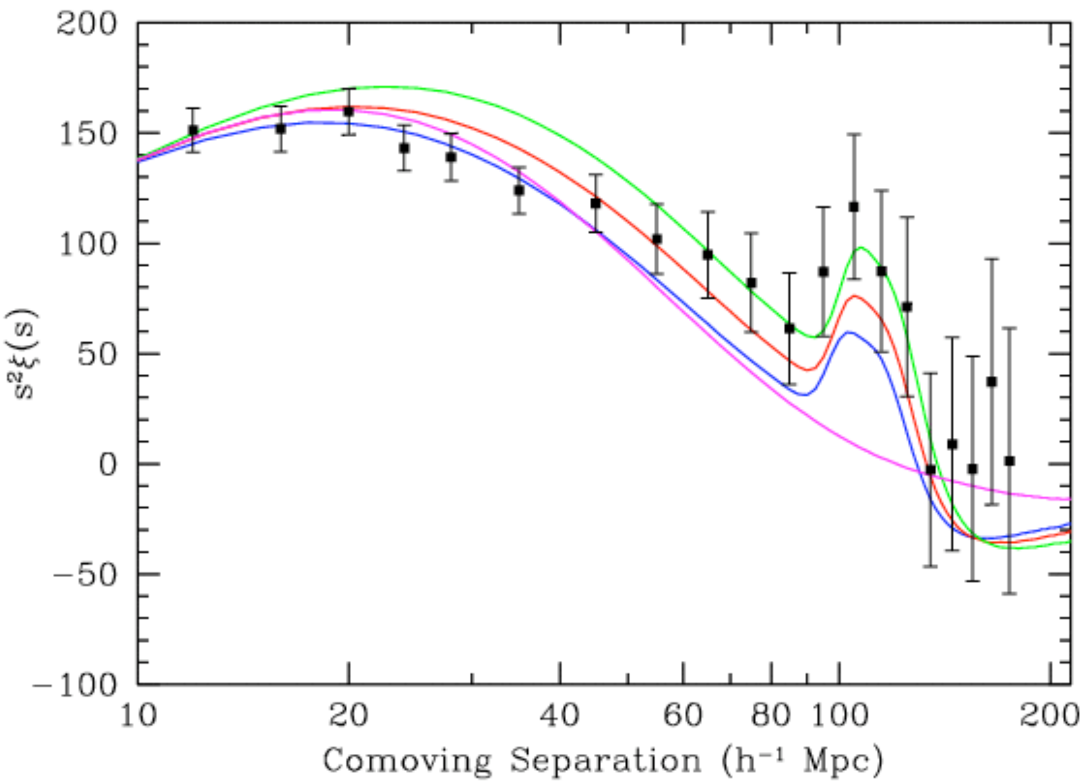
  - Shot noise: the imperfect sampling of the fluctuations by the finite number of galaxies. Assuming Poisson noise, then need nP >> 1, or number of galaxies > 10^6. Bias helps us here, as highly biased galaxies are better tracers of the underlying mass distribution.

The non-linear scale

- Cosmological structure forms from the bottom up.
- Smaller structures go non-linear earlier than larger structures (non-linear wavelength increases with time).
- This non-linear growth of structure washes out baryon oscillations, so at low redshift we have less oscillations to sample.



The Correlation Function



WFMOS

with Bassett, Blake, Glazebrook, Kunz, Nichol
and WFMOS consortium

- WFMOS:
  - Wide-Field (1.5° 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.

Standard survey

Redshift Bin	Area (sq. deg)	Time (hours)	Errors (dA & H)	
0.5-1.3	2000	900	1.0%	1.2%
2.5 -3.5	300	800	1.5%	1.8%

- In the low redshift bins, survey targets either luminous star-forming galaxies, or luminous ellipticals.
- In the high redshift bin, survey targets Lyman Break galaxies.
- No good optical candidates in redshift desert.

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 s_r.

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

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

Optimisation Procedure

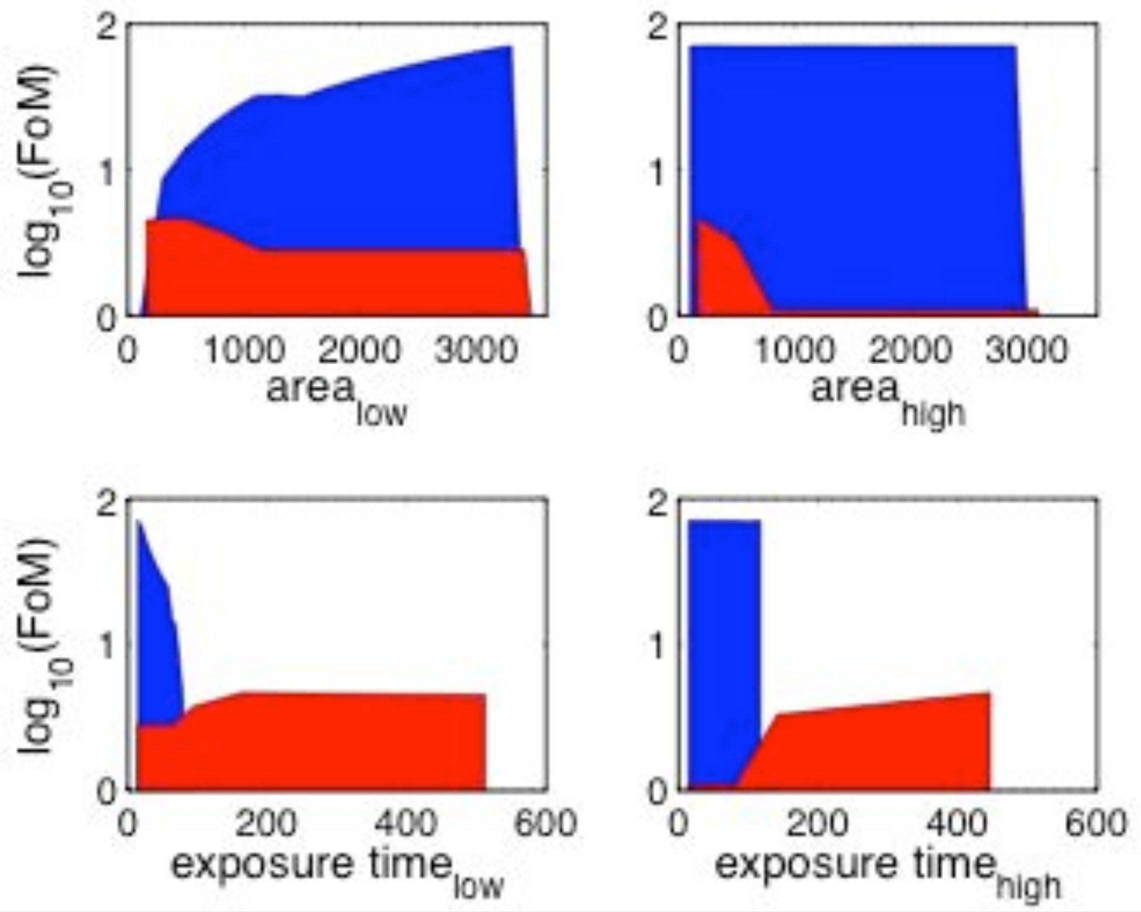
1. Select survey configuration (area coverage, redshift bins, exposure time etc.)
2. Estimate number density of galaxies using LFs.
3. Estimate error on $D_A(z)$ and $H(z)$ using scaling relations.
4. Calculate Fisher matrix of parameters, using distance data plus relevant priors (Planck+SDSS).
5. Invert Fisher matrix and calculate FoM.
6. 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.

Exposure Time & Area

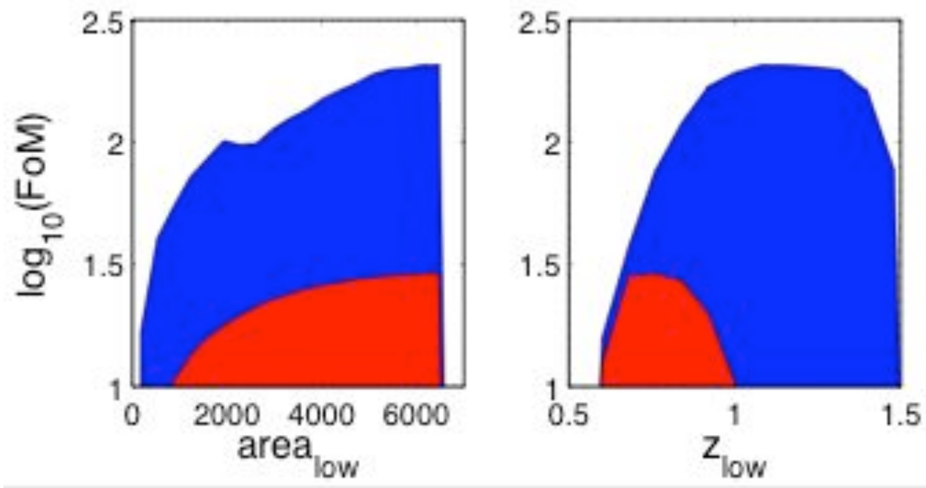
- Line emission "active" galaxies (blue) favoured over continuum "passive" galaxies (red) for both low and high redshift bins
- Cannot constrain high redshift bin, because does not contribute to FoM



Single bin: z vs. area

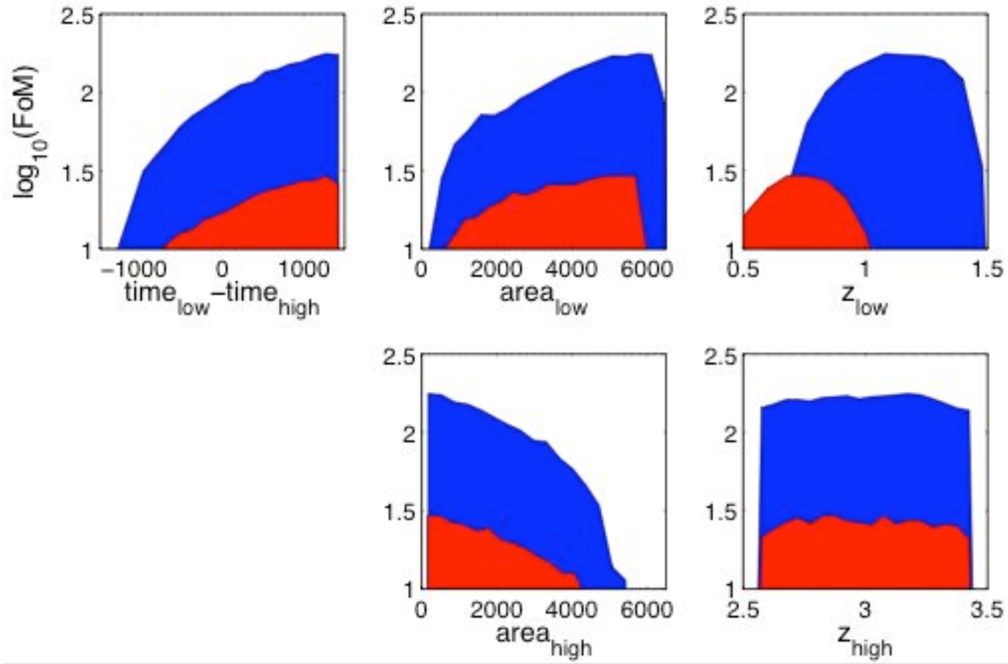
- Input galaxy population affects optimal survey
  - Blue galaxies favour higher redshift bin (z~1) than fiducial (z=0.9), while red galaxies favour lower (z~0.8)
- Optimisation seeks to maximise area and minimise exposure time

Single bin at low redshift
• total time = 1500 hrs
• redshift range and area allowed to vary



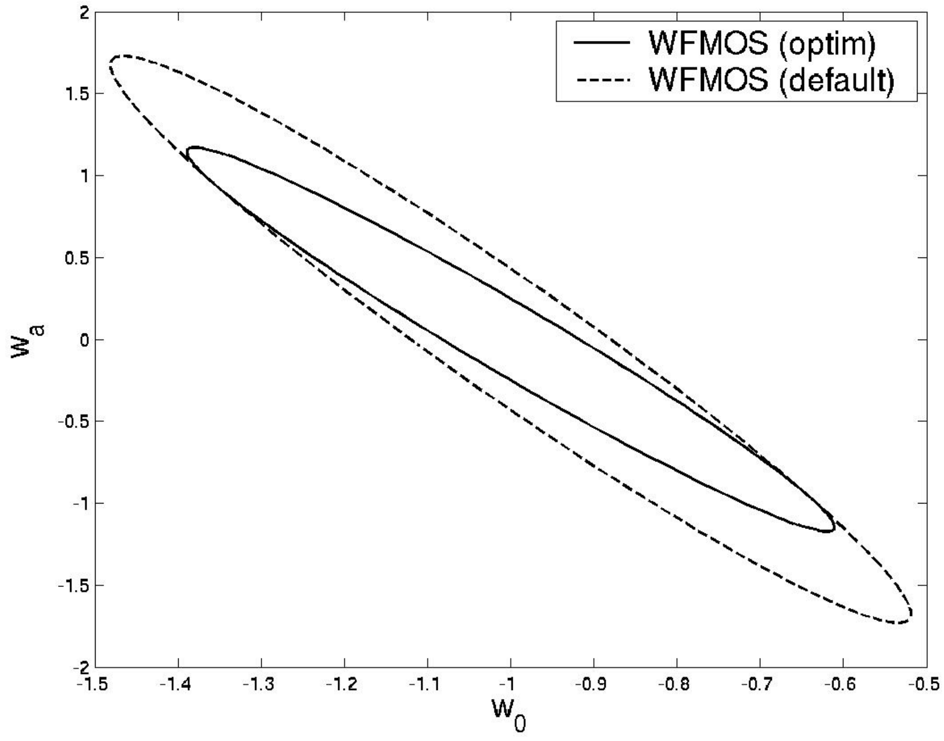
Multiple bins

- Including a 2nd bin at high redshift and allow the time diff to vary
- The best survey spends all time at low redshift.



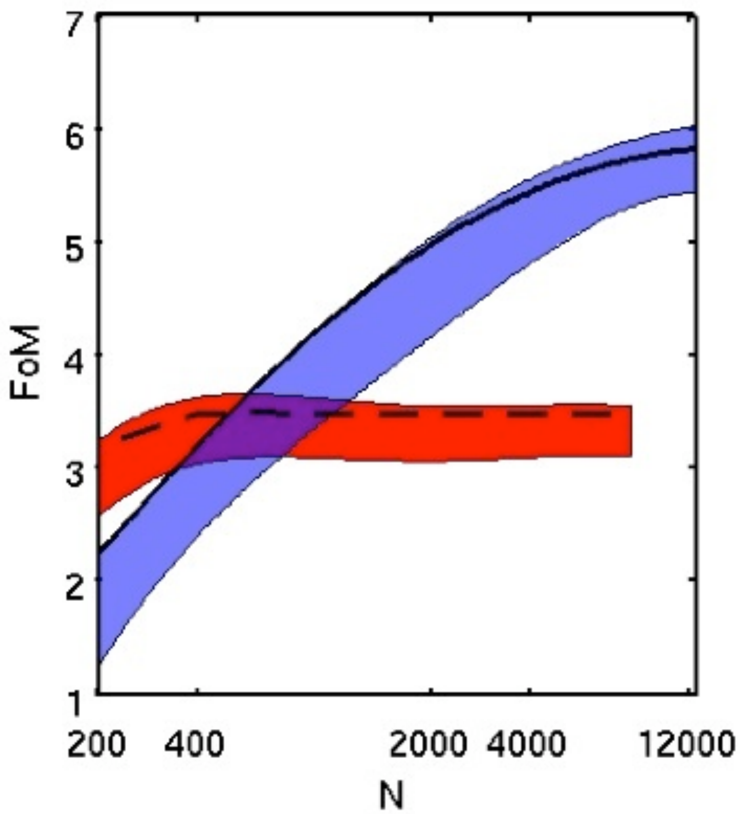
Improvement

- Optimising the survey increas the FoM by a factor of ~4, decreasing the ellipse size by 50% and the error on each parameter by 40%



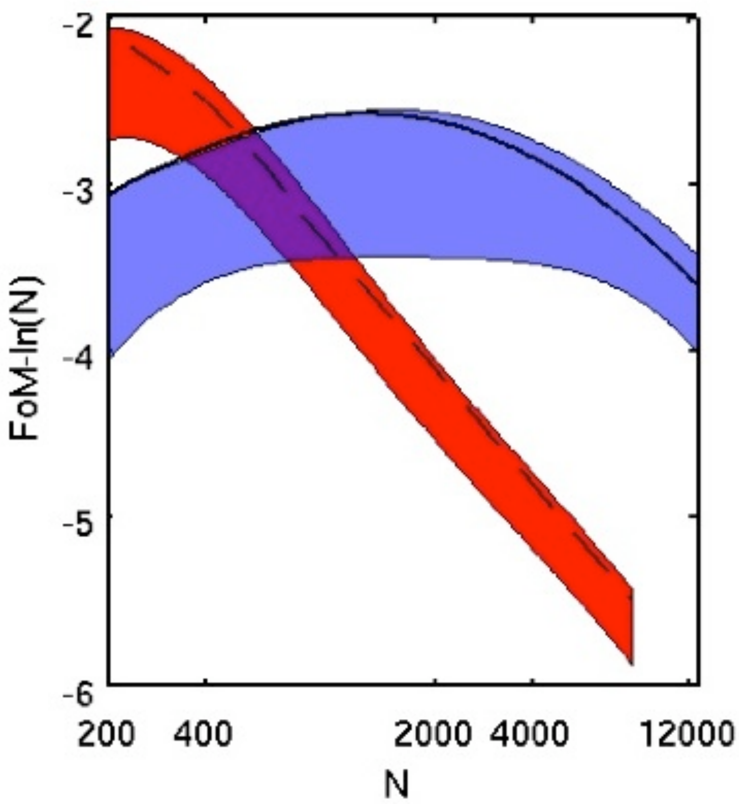
Number of fibres

- Can also use technique to optimise instrument design parameters, such as number of fibres
- For single line emission bin at low redshift, FoM asymptotes to maximum value at ~10,000 fibres.



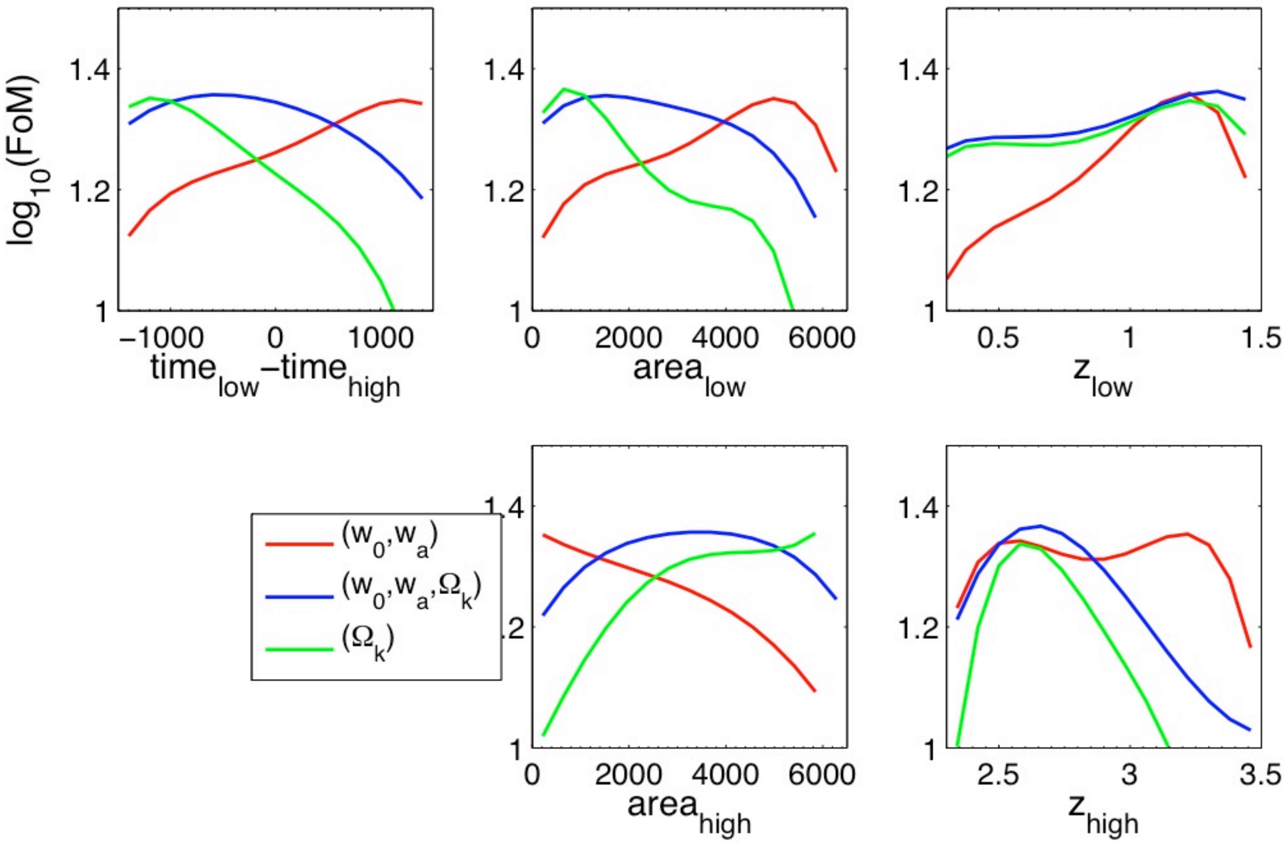
Efficiency of fibres

- Although 10,000 fibres is the best for line emission, it is not efficient as it returns only 60% usable redshifts
- Instead should look at most efficient use of fibres, which peaks around 2000 fibres
- Medium best: 3000-4000 fibres



Curvature

- It has been shown (Clarkson 2007) that curvature can confuse the issue of detecting DE dynamics.
- What happens if we include Ω_k in the FoM?



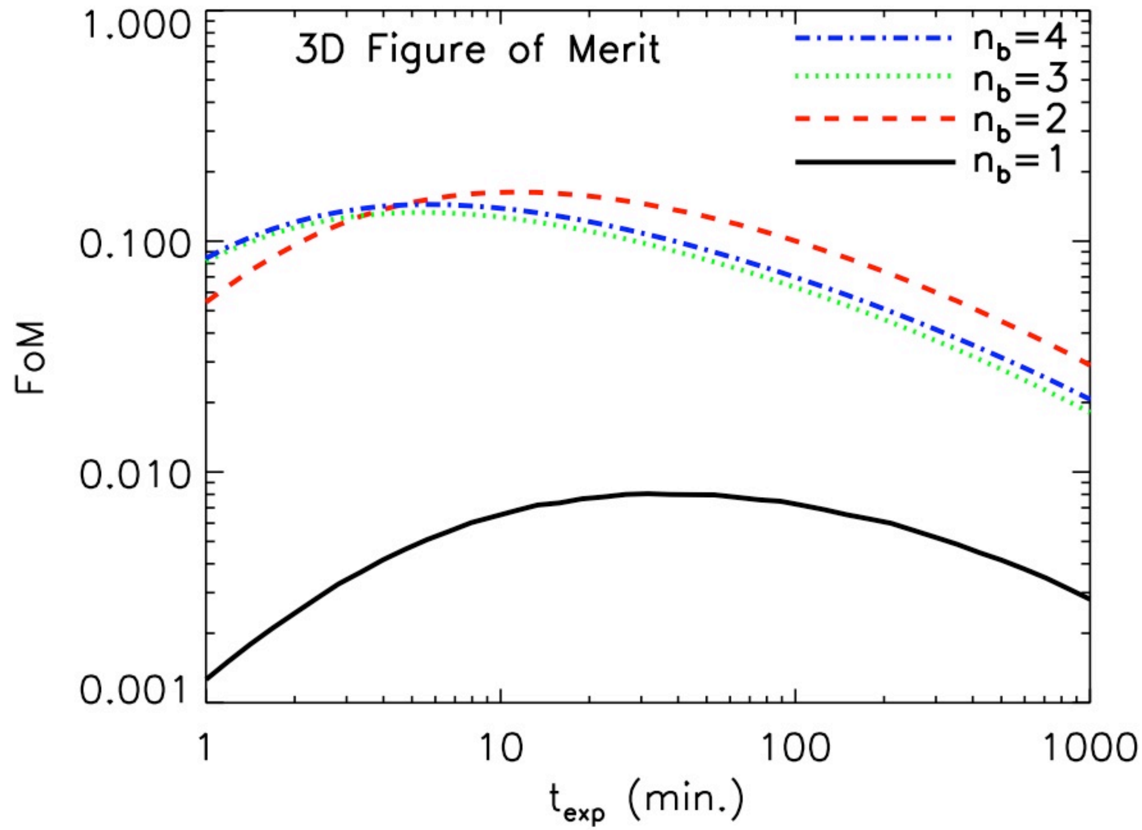
Modified gravity

With Yamamoto, Hamana, Nichol and Suto

- Measuring w(z) may not be enough
  - Modified gravity models may mimic dynamics of dynamic DE, but with different growth of structure
- Parameterize structure growth with γ parameter (Linder 2005)
$$\frac{D_1(a)}{a} \propto \exp\left[\int_0^a \frac{da'}{a'}(\Omega_m(a')^\gamma - 1)\right]$$
- By including γ in FoM, can optimise for detection of modified gravity effects on largest scales
- Weak lensing experiments most sensitive to growth of structure

FoM: 2D vs. 3D

A 2D FoM (w_0,w_a) makes different conclusions as to optimal survey compared to the 3D (w_0,w_a,γ)



Conclusions

- Designing galaxy surveys for the DE is a trade off between volume (to minimize sampling errors) and depth (to extend a larger "lever-arm")
  - This trade off is dependent on the nature of the instrument
- The optimal survey geometry changes with the choice of FoM
- The best WFMOS-type survey configuration samples active (blue) galaxies over an area of ~6000 sq. degs, with a median redshift of 1.1
- The survey parameters are not highly peaked with FoM, leaving some flexibility in survey design.