Complementarity of Dark Energy Probes

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What to measure ?

- How much dark energy today ?
- Difference from a cosmological constant ?
- Signatures of Modified Gravity ?
- Signatures of Backreaction or Inhomogeneous Universe ?
- Clumping of dark energy ?

What observations do wee need ?

- Expansion history of the Universe ('geometry')
- growth of structures
- large scale anisotropies and power spectra for clumping of dark energy

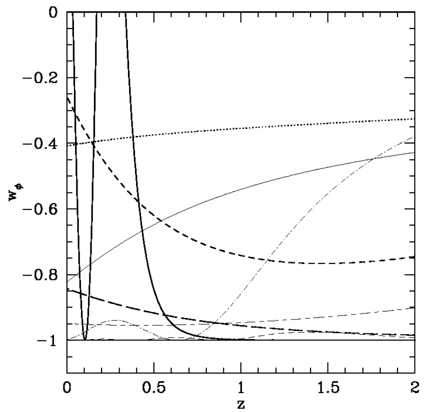
Complementarity of Future Dark Energy Probes

- Plethora of upcoming and proposed dark energy surveys
- Both NASA and ESA have put dark energy research as possible midterm missions
- Dark Energy Task Force compared different missions with a figure of merit

Ongoing, Proposed and Future 'Dark Energy' Surveys

- CFHT-SNLS,ESSENCE,SDSS-II,CfA-SP,NSF, KAIT, CSP, QUEST, HST, PanStarrs-1, PISCO, SPT,ACT, XCS, RCS2, DLS, KIDS, DEEP2, DES, HETDEX, WFMOS, PanStarrs-4, ODI, OTPLS, ALPACA, CIX, eROSITA, CCAT, LSST, DESTINY,ADEPT, SNAP, DUNE, SPACE, SKA, 10K X-ray Cluster Survey, Con-X, GSMT, JWST, ...

Parameterizations of Dark Energy

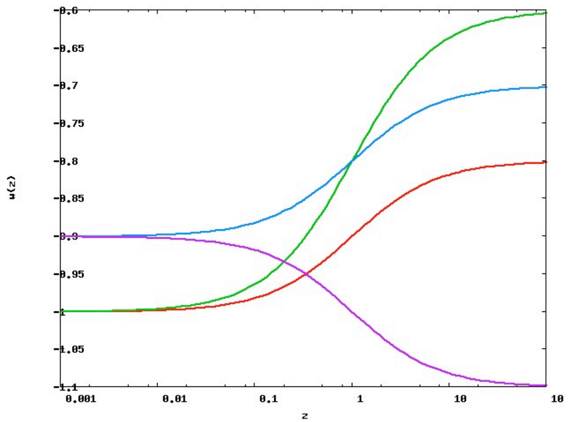


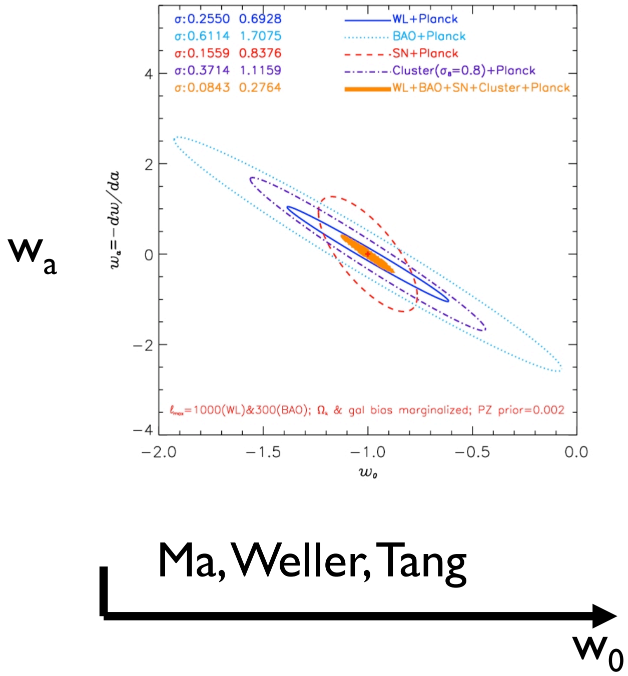
- Background evolution
  - $w = w_0$
  - $w = w_0 + w_1 z$
  - $w = w_0 + \alpha \ln(a)$ (Efstathiou 1999)
  - $w = w_0 + w_a(1-a)$ (Chevalier 2001, Linder 2003)

  - binned $w(z)$ ('parameter free')
  - binned $\rho(z)$, $H(z)$
- Perturbations: c_s^2, γ, ...

Figure of Merit

$w(a)=w_0+w_a(1-a)$





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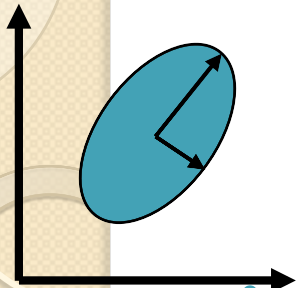
- Figure of merit: inverse area of 95% contour in w_0-w_a space
- This is some indication but be careful: parameterization imposes certain redshift sensitivity, which does not necessarily reflect particular survey

Better: Binning of w(z)

$$w(z) = \begin{cases} w_i & z \in \left(z_i - \frac{\Delta z}{2}, z_i + \frac{\Delta z}{2}\right] \\ w_h & z > z_{\max} \end{cases}$$

- typically use $\Delta z = 0.05$
- z_{max} given by particular survey
- effectively parameter free and model independent
- DISADVANTAGE: TOO MANY FREE PARAMETERS
- Hence large errorbars; however ...



Principal Component Analysis

- Calculate Fisher matrix for leading order approximation of Likelihood (Gaussian approximation)

$$F_{ij} = \left\langle \frac{\partial^2 \mathcal{L}}{\partial w_i \partial w_j} \right\rangle$$

- Diagonalize Fisher matrix do establish independent modes
- Decompose w(z) in Eigenmodes (decorrelated)

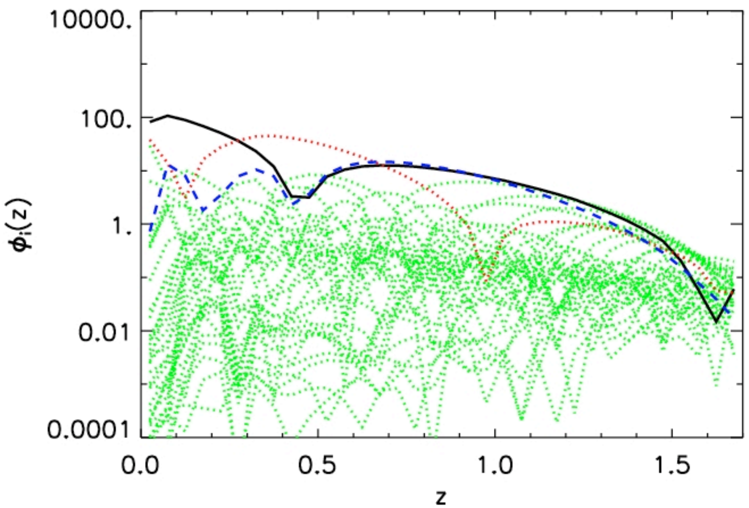
$$\Lambda = W F W^T$$

$$w(z) = w_{fid}(z) + \sum_{j=1}^{N} \alpha_j e_j(z)$$

- Inverse of eigenvalue is measure of uncertainty in Eigenmode ($\Delta\alpha_j = \lambda_j^{-1/2}$), leading Eigenmodes reflect redshift sensitivity of survey/probe
  (Huterer and Starkman 2003; Crittenden & Pogosian 2005)
- Going beyond DETF figure of merit and pivot redshift (now proposed ?)

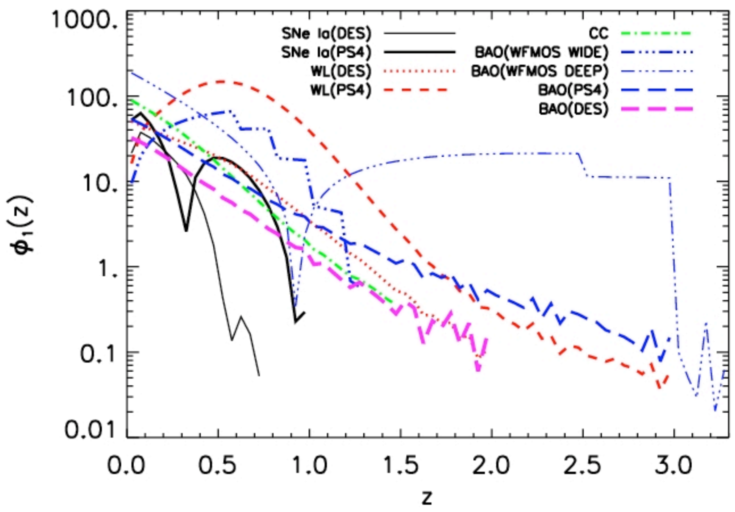
Example: Supernovae Probes

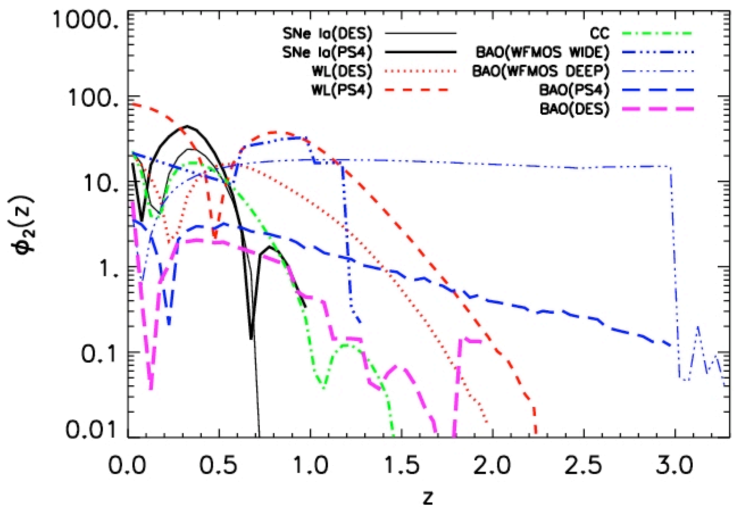
$$\phi_i = N \left| \sqrt{\lambda_i} \mathbf{e}_i(z) \right|$$



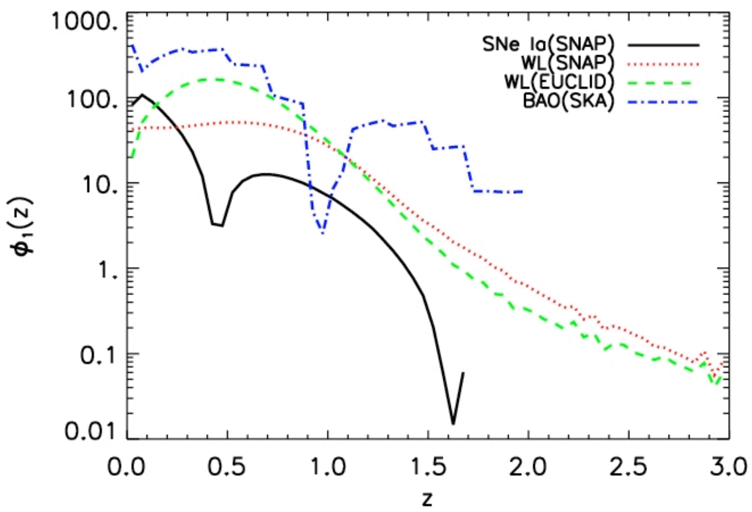
- Measure redshift – distance relation
- SNAP: 2000 SNe
- Use Planck prior and marginalize over other cosmological parameters
- Most weight at z<0.2 (DE domination)
- Modes above third are weakly constraint

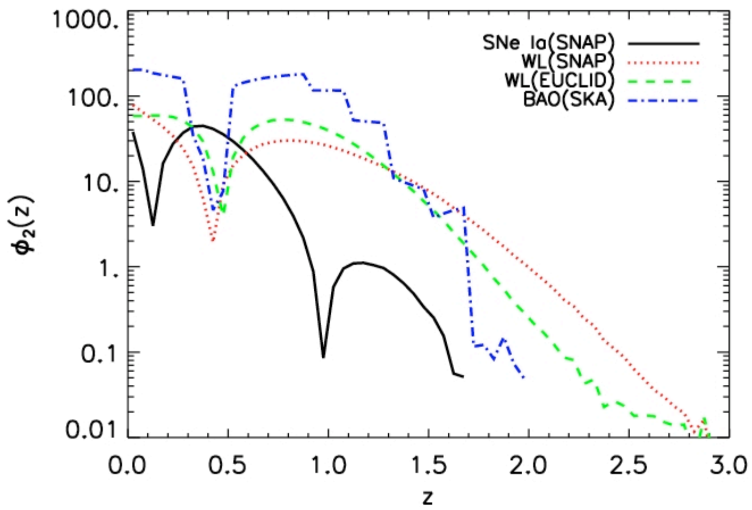
Selected Stage III probes





Selected Stage IV probes





Using Evidence to count significant number of modes

- evidence measures three effects in fitting
  - goodness of fit
  - degradation of errorbars due to increased number of parameters
  - bias between true underlying model and fiducial model

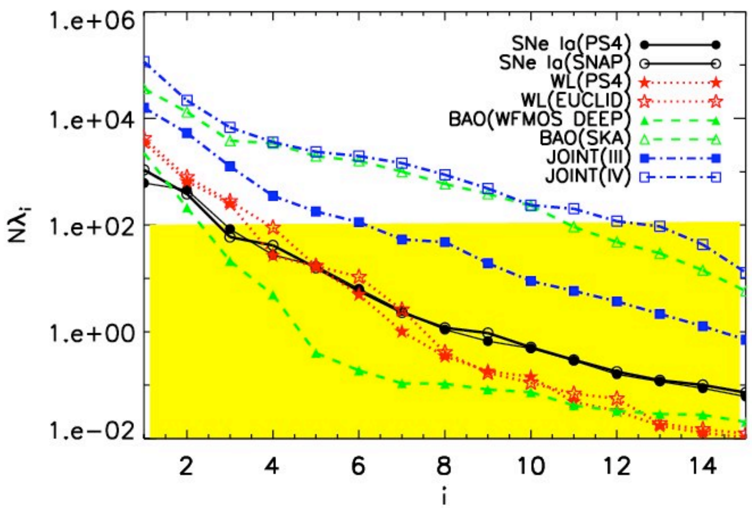
best fit

$$\mathcal{E} = P(D|H) \approx P(D|\theta_L, H) \exp(-C) \left(\frac{|F+P|}{|P|} \right)^{-1/2}$$

bias: prior-true

Occam's razor

Significance of Eigenmodes



- Rough guide for significant Eigenmodes is
  $N\lambda_i > 100$
  - under simplifying Gaussian assumptions
  - neglect bias
- However, taking only low number of Eigenmodes creates bias wrt to true model

Complete Evidence Calculation for Number of Significant Modes

Expt.	SNe Ia	WL	CC	BAO
DES	2-3	1-3	1-2	1-2
PS1	-	2-3	-	1-2
WFMOS-Wide	-	-	-	3
WFMOS-Deep	-	-	-	2-4
PS4	2-5	3		1-2
EUCLID	-	3-4	-	*
SNAP	2-5	2-3	-	-
SKA	-	-	-	9-10

strong Jeffrey's evidence (ratio: 1)

Conclusions

- Binned approach far more versatile and less biased then standard FoM
- Two possibilities to compare surveys:
  - how well are same number of parameters constrained
  - how many parameters can be constrained to a certain level
- Redshift range in binned approach credited
  - high redshift surveys do not get negative bias compared to std. FoM
- Apply for density ρ(z) and growth g(z)
- smoothness prior ?
- however measure depends on bias to true underlying model, because parameterization is generated with a priori fiducial model (w=-1 ?)