Dark Energy: Systematic Requirements and Future Prospects

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Current evidence for dark energy is impressively strong.

SN (Full Cov) + CMB + BAO (assuming $w = -1$)

$\Omega_{DE} = 0.724 \pm 0.011$

$\Omega_{DE} = 0$ is $\sim 64\sigma$ away
Since the discovery of acceleration, constraints have converged to $w \approx -1$

**SN + BAO + CMB**

But we can do much better; need:
- Better mapping of expansion history
- Precision measurements of growth history.
Figures of Merit (FoMs)

Most common choice:
area of the (95%) ellipse in the \(w_0-w_a\) plane
(DETF report 2006)

\[
\text{FoM} \equiv (\det \mathbf{C}_{w_0w_a})^{-1/2} \approx \frac{6.17\pi}{A_{95}}
\]

Or, simply:

\[
\text{FoM} \equiv \frac{1}{\sigma_{w_{\text{pivot}}} \times \sigma_{w_a}}
\]
DETF FoM - pros and cons

Advantages:

• Captures not only $w=$const but also variation in $w(z)$
• $(w_0, w_a)$ parametrization surprisingly flexible yet very simple
• Easy to compute and intuitive

Disadvantages:

• Fails to capture non-canonical $w(z)$ models, or ones with early DE
• Does not address anything about modified gravity vs. DE
• Not particularly designed to measure departures from LCDM
Extending the DETF FoM: using principal components (PCs)

- Shows where sensitivity of any given survey is greatest
- Can be used to study optimization of surveys
- Can be used to make “model-independent” statements about DE

These are best-to-worst measured linear combinations of $w(z)$

Uncorrelated by construction
Generalizing FoM to many parameters - PCs of $w(z)$

$$
\text{FoM}^{(PC)}_n \equiv \left( \frac{\det C_n}{\det C_{n}^{(\text{prior})}} \right)^{-1/2}
$$

(proportional to volume of n-dim ellipsoid)

Mortonson, Hu & Huterer 2010
(see also FoMSWG; Albrecht et al 2009)
In *principal*, constraints are good...

(components)

Top row:
**Current Data**

Bottom Row:
**Future Data**
(assumes fiducial $\alpha_i=0$)

values for specific scalar-field model

Mortonson, Hu & Huterer 2010
But what about **Modified Gravity FoM**?

Currently standard MG FoM:

The growth index $\gamma$ \hfill Linder 2005

$$g(a) \equiv \frac{\delta}{a} = \exp \left[ \int_0^a d\ln a' \left[ \Omega_M(a')^\gamma - 1 \right] \right]$$

Excellent fit to GR with dark energy with any $w(z)$:

$$\gamma = 0.55 + 0.05 \left[ 1 + w(z = 1) \right]$$

$\Rightarrow$ Search for deviation from 0.55 ($\pm$ small correction)

Adopted, in addition to PC FoM, by FoMSWG (Albrecht et al 2009)

Advantages and disadvantages:

**Pros**: extremely easy to use/calculate

**Cons**: growth in MG is typically scale-dependent, $g = g(a,k)$
Falsifying general classes of DE models

Predictions on D/G/H (68% and 95%) from current data (SN+CMB+BAO+H₀)

Allowed deviations around best-fit LCDM value shown

Red curve: sample model consistent with data

Mortonson, Hu & Huterer 2010
Systematic errors

- Already limiting factor in measurements
- Will definitely be limiting factor with WFIRST-type quality data
- Quantity of interest: \((\text{true sys.} - \text{estimated sys.})\) difference
- Self-calibration: measuring systematics internally from survey
Specifically for 3 probes:

**Supernovae**: each SN provides info about DE; can choose a “golden subsample” to limit systematics.

**BAO**: relatively systematics-free (additional info in RSD and $P(k)$, but also additional systematics!)

**Weak lensing**: control of systematics most challenging, but great potential, esp in providing info on growth.
Poster child of systematics: photometric redshift errors

Example

Requirements

C. Cunha

Ma, Hu & Huterer 2006
Note: scatter $\sigma$, or even $\sigma(z)$ and bias$(z)$, are NOT sufficient to describe effects of photo-z errors on DE

Need to consider the full $P(z_s | z_p)$:

- **difference** (true $P$ – estimated $P$) generates cosmological biases

Only then can you derive survey requirements (here, size of spectroscopic follow-up)

Cunha, Huterer, Busha & Wechsler 2012
Spectroscopic failures (shown below) lead to increased photo-z errors, and thus DE biases.

Increasing quality threshold (R) of spectroscopic zs

Final requirement (based on end-to-end simulation): must have <1% fraction of wrong spectroscopic redshifts

Cunha et al, in prep.
Another example (WL): Multiplicative errors in shear ($g_i$)

$$\gamma(z_i) = \gamma(z_i) \times g_i$$

Requirement: \((\text{few}) \times 10^{-3}\) averaged over redshift bin
Theory Systematics example (WL)

Using simulations to calibrate power spectrum at nonlinear scales

Sets quantitative goals for accuracy of simulations

Huterer & Takada 2005
From space, one automatically **ameliorates or altogether avoids** some of the most pernicious systematics!

Example: most common **calibration errors** e.g. atmospheric spatially varying extinction.

Effect of calib errors on cosmo parameters from P(k) measurements:

Huterer et al, in prep.
Conclusions

- Sophisticated figures of merit exist to quantify mapping expansion history; simple ones for growth
- Tests of growth/expansion beyond FoMs
- Systematic control is key to Stage III experiments and beyond
- Self-calibrating is powerful, but can’t self-calibrate everything
- From space, circumvent some dangerous systematics; others remain ⇒ their careful modeling and understanding is key