Dark Energy: Systematic Requirements and Future Prospects

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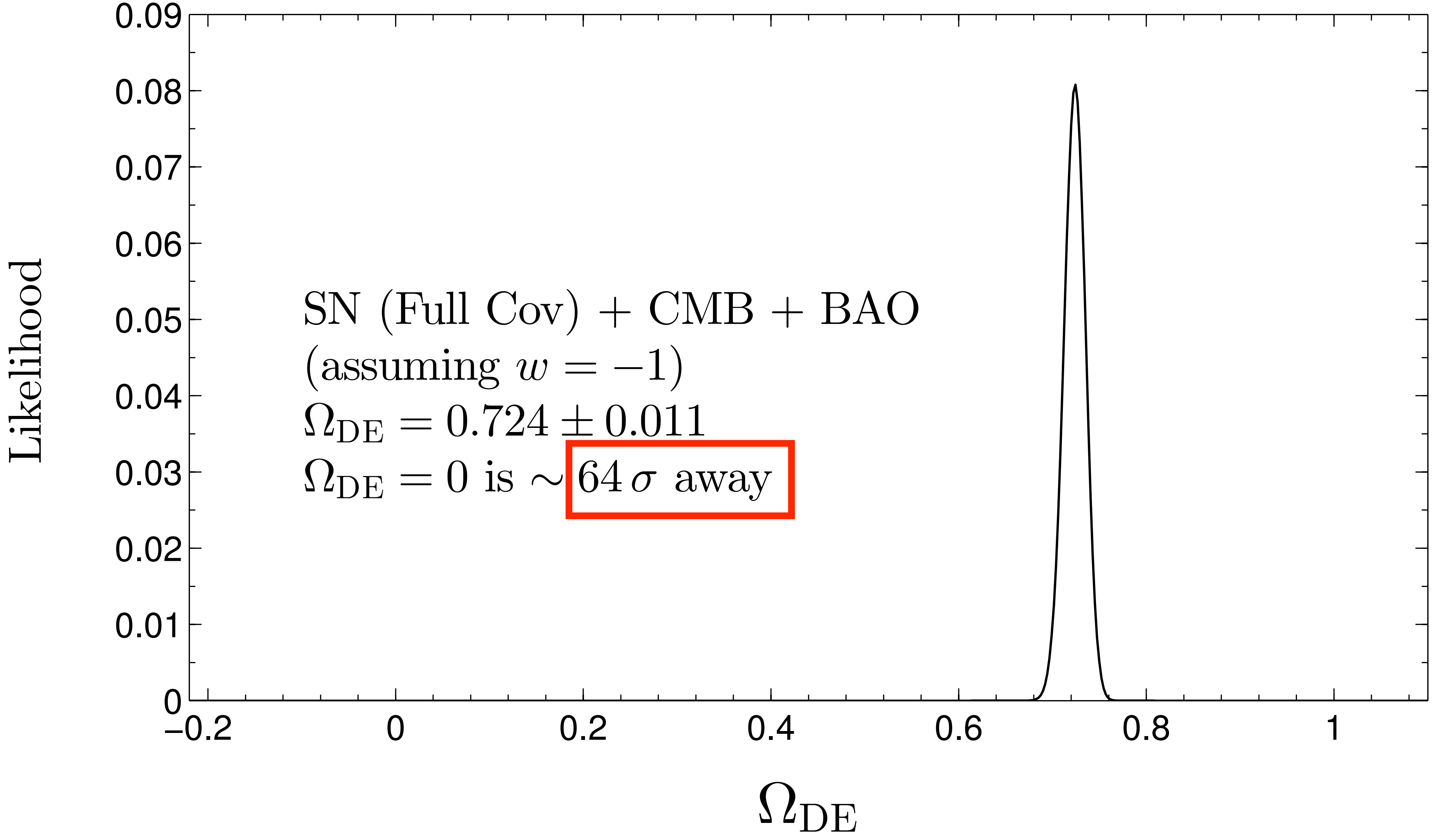
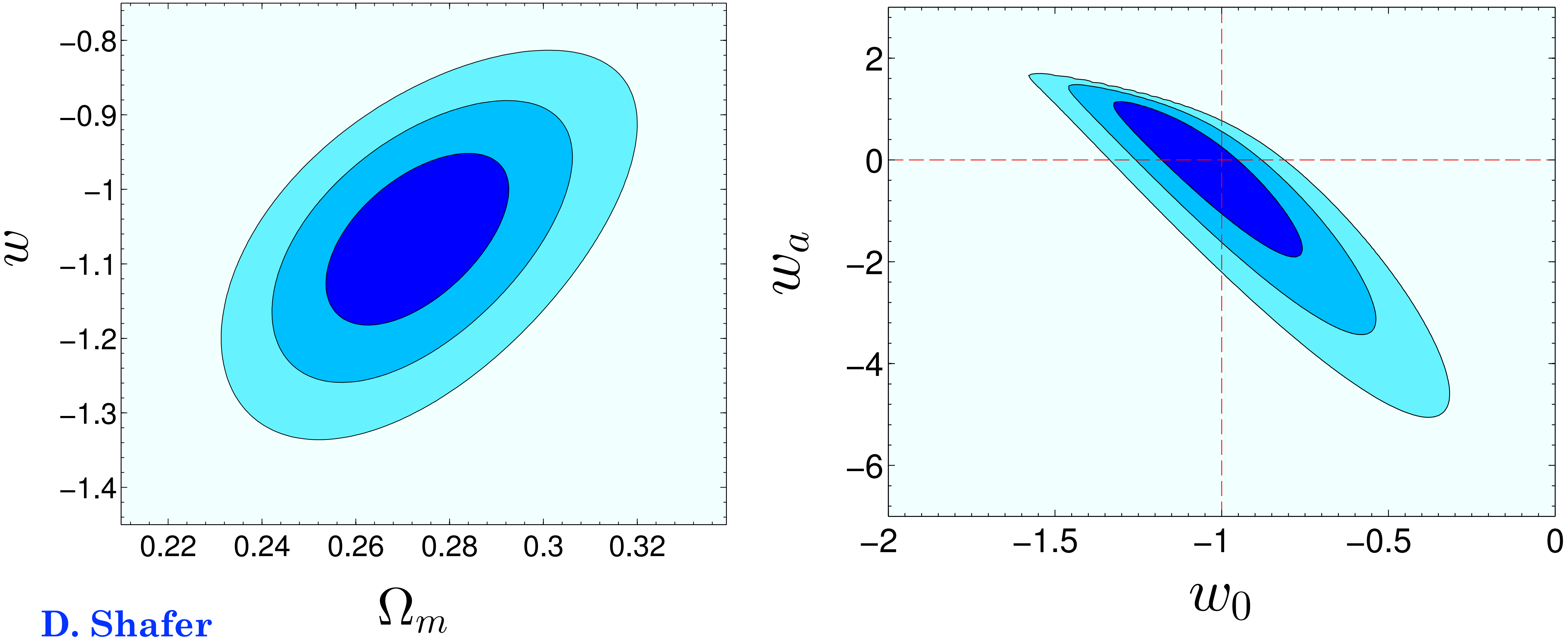
Current evidence for dark energy is impressively strong



D. Shafer

Since the discovery of acceleration, constraints have converged to w ≈ –1

SN + BAO + CMB



D. Shafer

But we can do much better; need:

- Better mapping of expansion history
- Precision measurements of growth history.

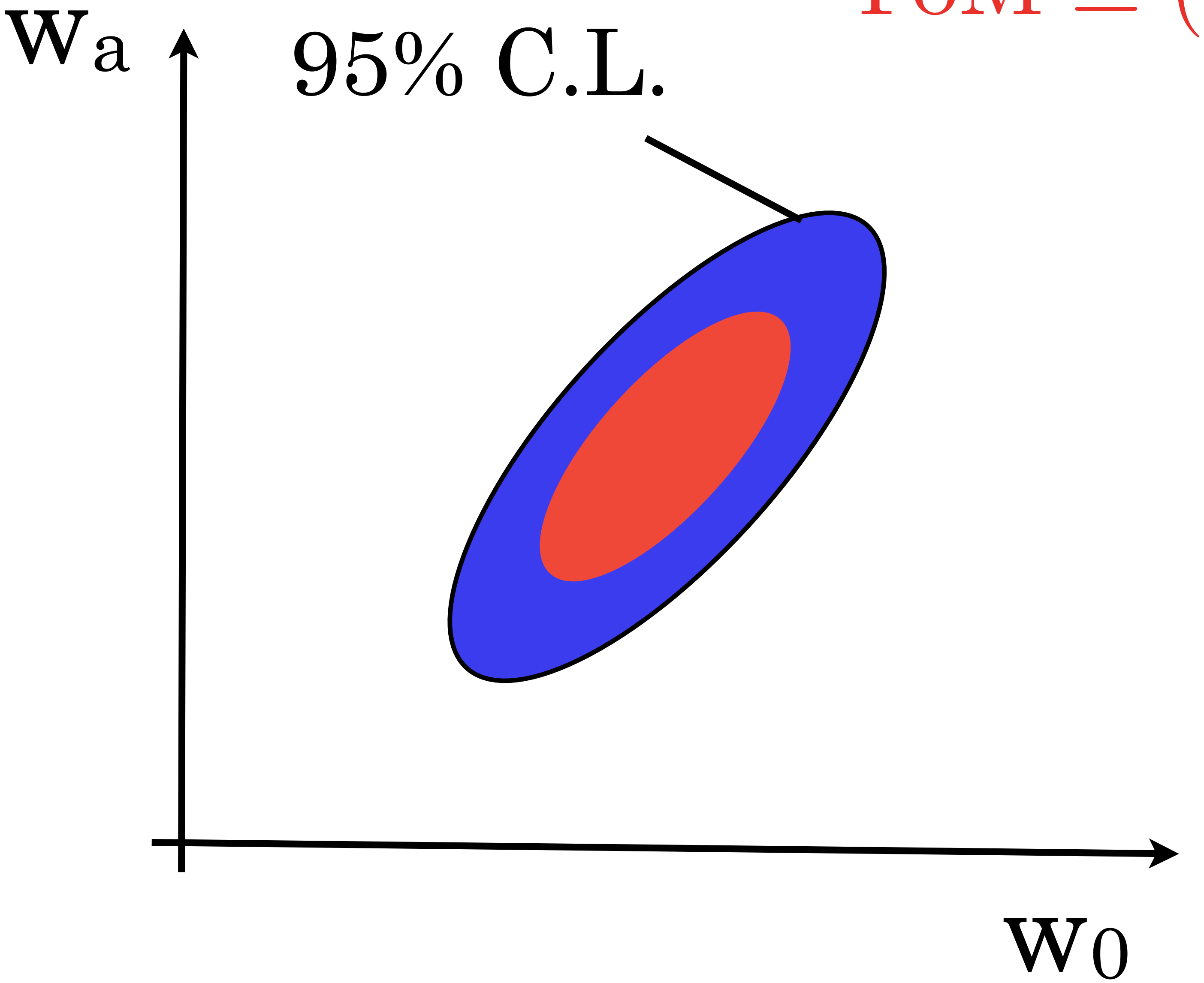
Figures of Merit (FoMs)

Most common choice:

area of the (95%) ellipse in the w_0-w_a plane

(DETF report 2006)

$$\mathrm{FoM} \equiv \left(\det \mathbf{C_{w_0 w_a}}\right)^{-1/2} \approx \frac{6.17\pi}{A_{95}}$$



Or, simply:

$$\mathrm{FoM} \equiv \frac{1}{\sigma_{w_{\mathrm{pivot}}} \times \sigma_{w_a}}$$

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

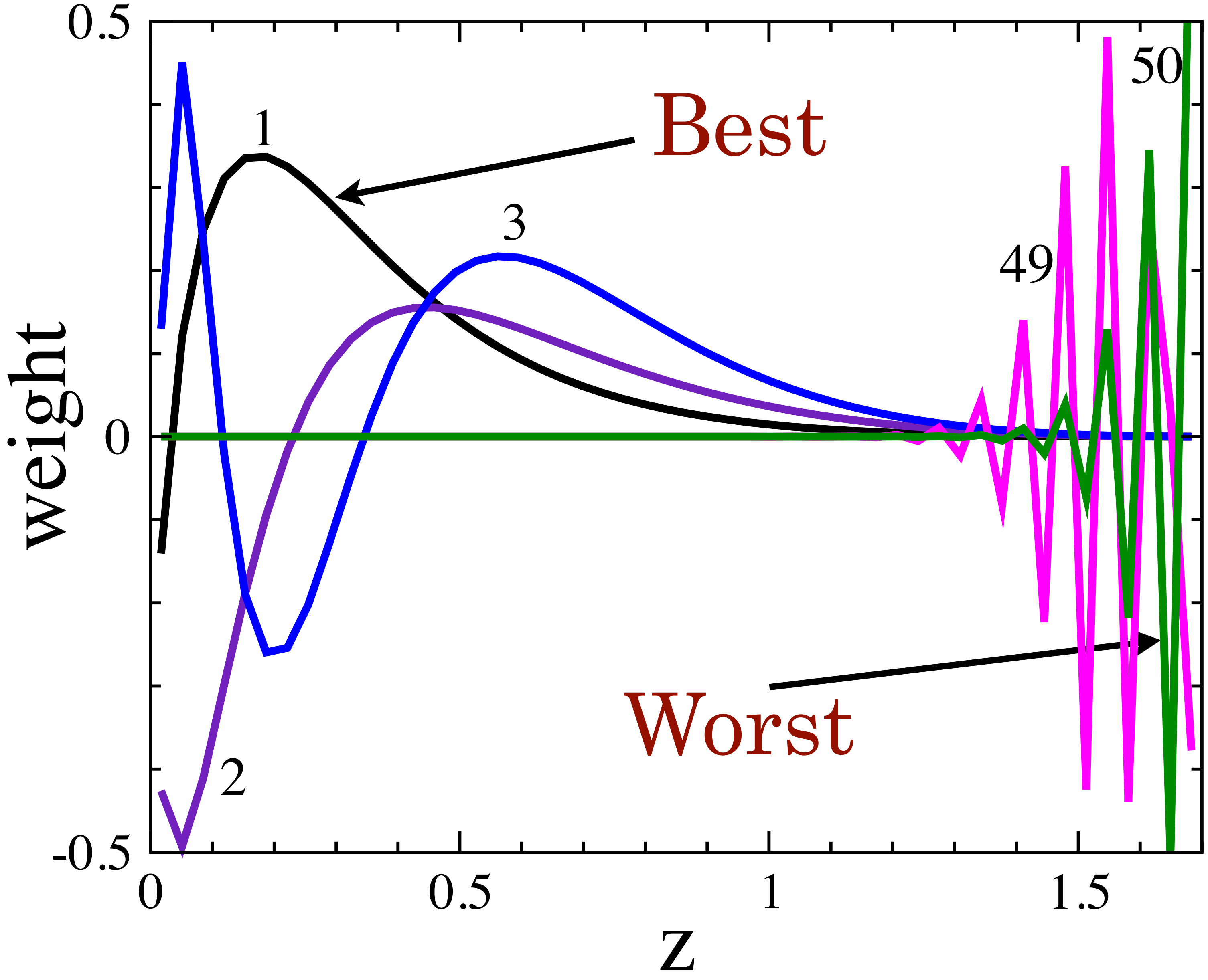
Disadvantages:

- 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)

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

Uncorrelated by construction

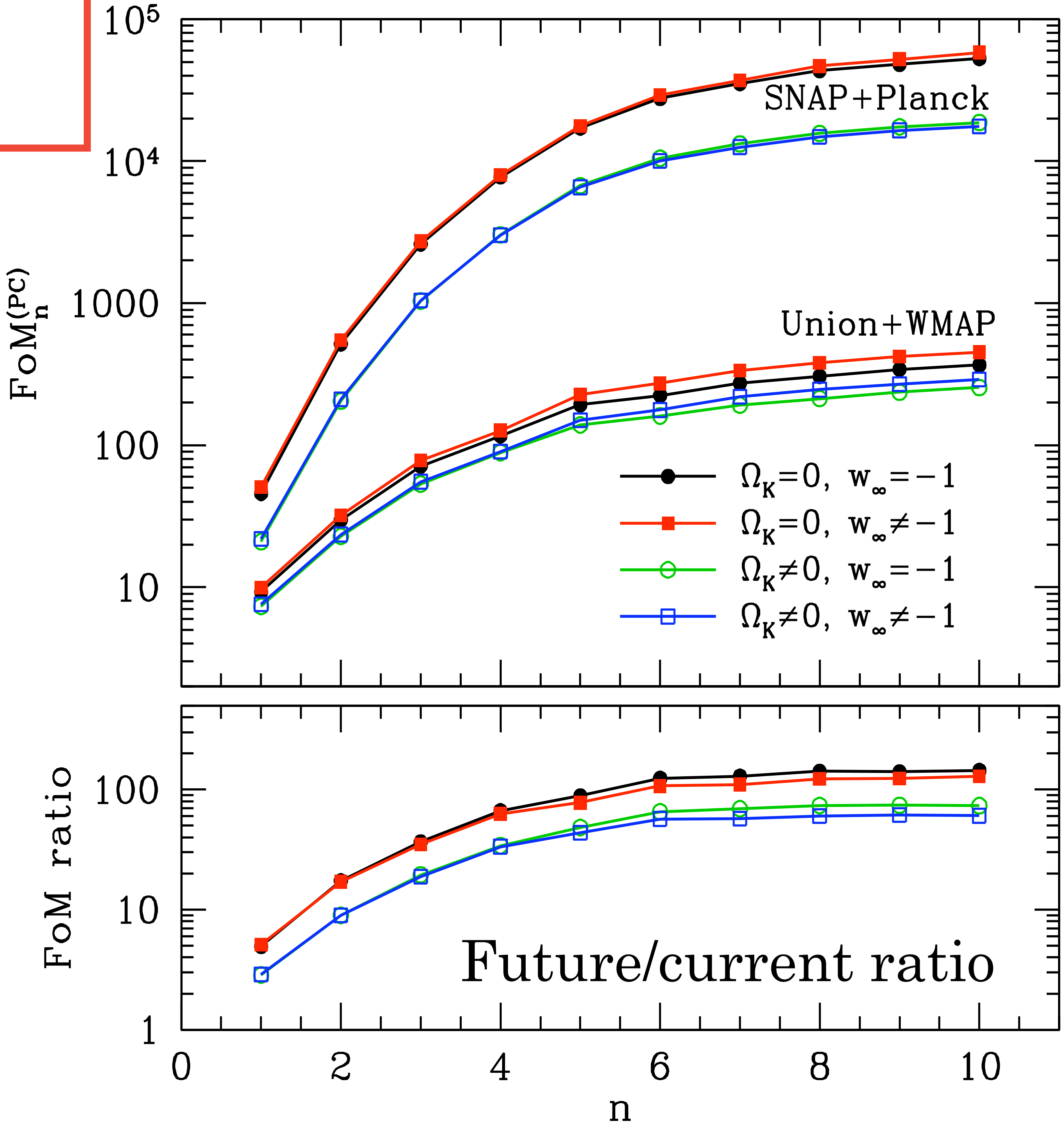


- Shows where sensitivity of any given survey is greatest
- Can be used to study optimization of surveys
- Can be used to make “model-independent” statements about DE

Generalizing FoM to many parameters - PCs of w(z)

$$\boxed{\mathrm{FoM}_n^{(\mathrm{PC})} \equiv \left(\frac{\det \mathbf{C}_n}{\det \mathbf{C}_n^{(\mathrm{prior})}} \right)^{-1/2}}$$

(proportional to volume of n-dim ellipsoid)



Mortonson, Hu & Huterer 2010
(see also FoMSWG; Albrecht et al 2009)

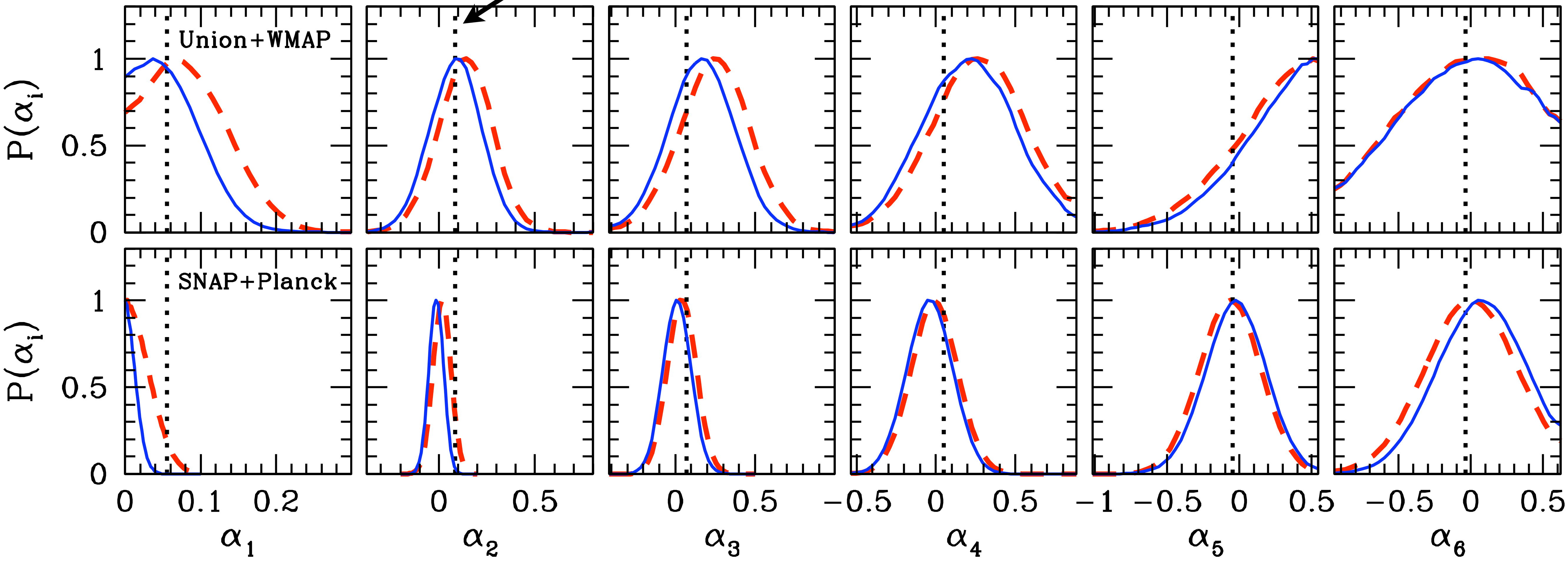
In *principal*, constraints are good...

(components)

values for specific scalar-field model

Top row:

Current Data



Bottom Row:

Future Data

(assumes fiducial α_i=0)

— Flat

------------ Curved

Mortonson, Hu & Huterer 2010

But what about Modified Gravity FoM?

Currently standard MG FoM:
The growth index γ

Linder 2005

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

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

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

⇒ Search for deviation from 0.55 (± small correction)

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

Advantages and disadvantages:

Pros: extremely easy to use/calculate

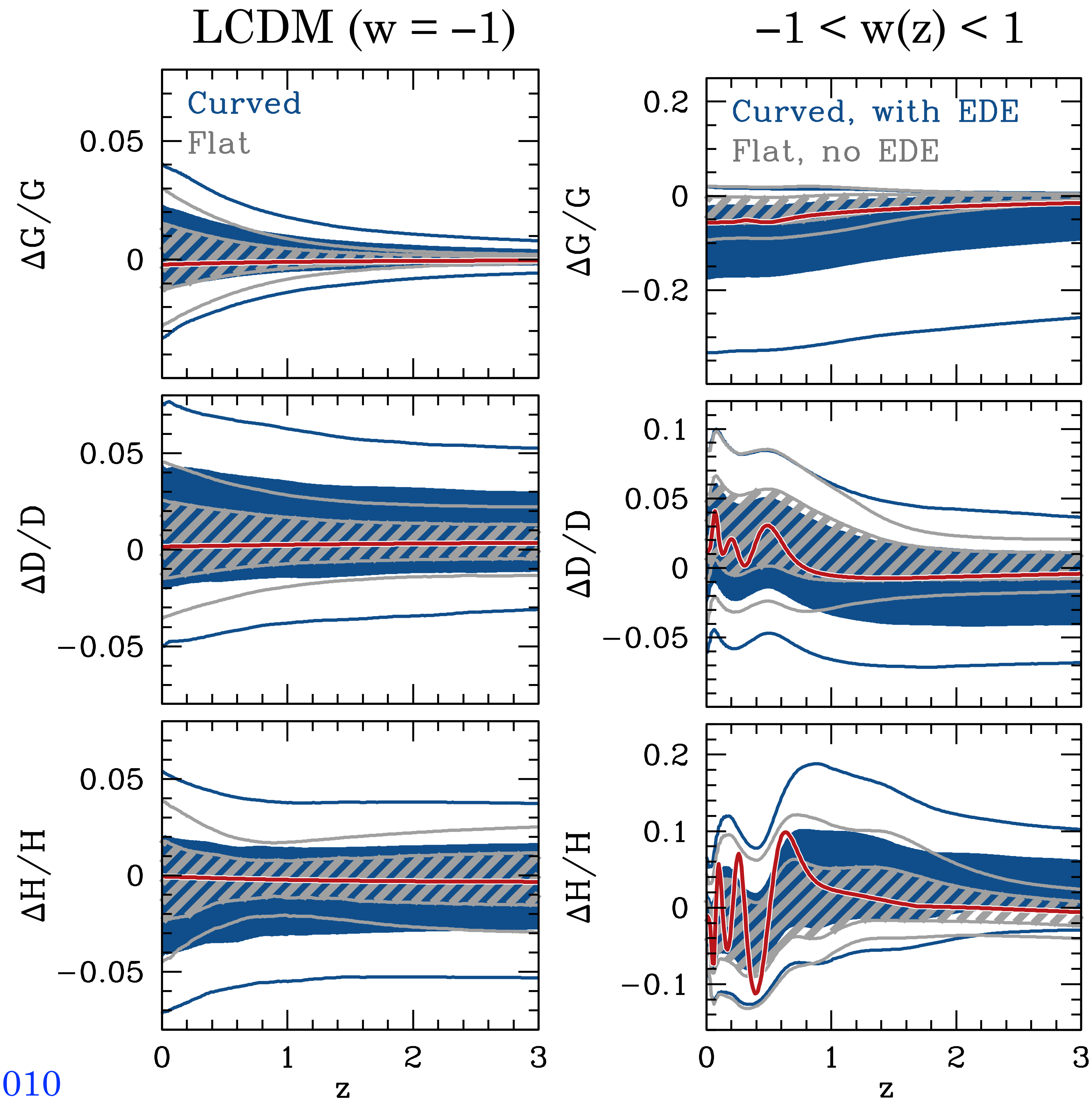
Cons: growth in MG is typically scale-dependent, g = g(a,k)

Falsifying general classes of DE models

Predictions on D/G/H
(68% and 95%)
from **current data**
(SN+CMB+BAO+H$_0$)

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: (true sys. – estimated sys.) difference
- Self-calibration: measuring systematics internally from survey

Specifically for 3 probes:

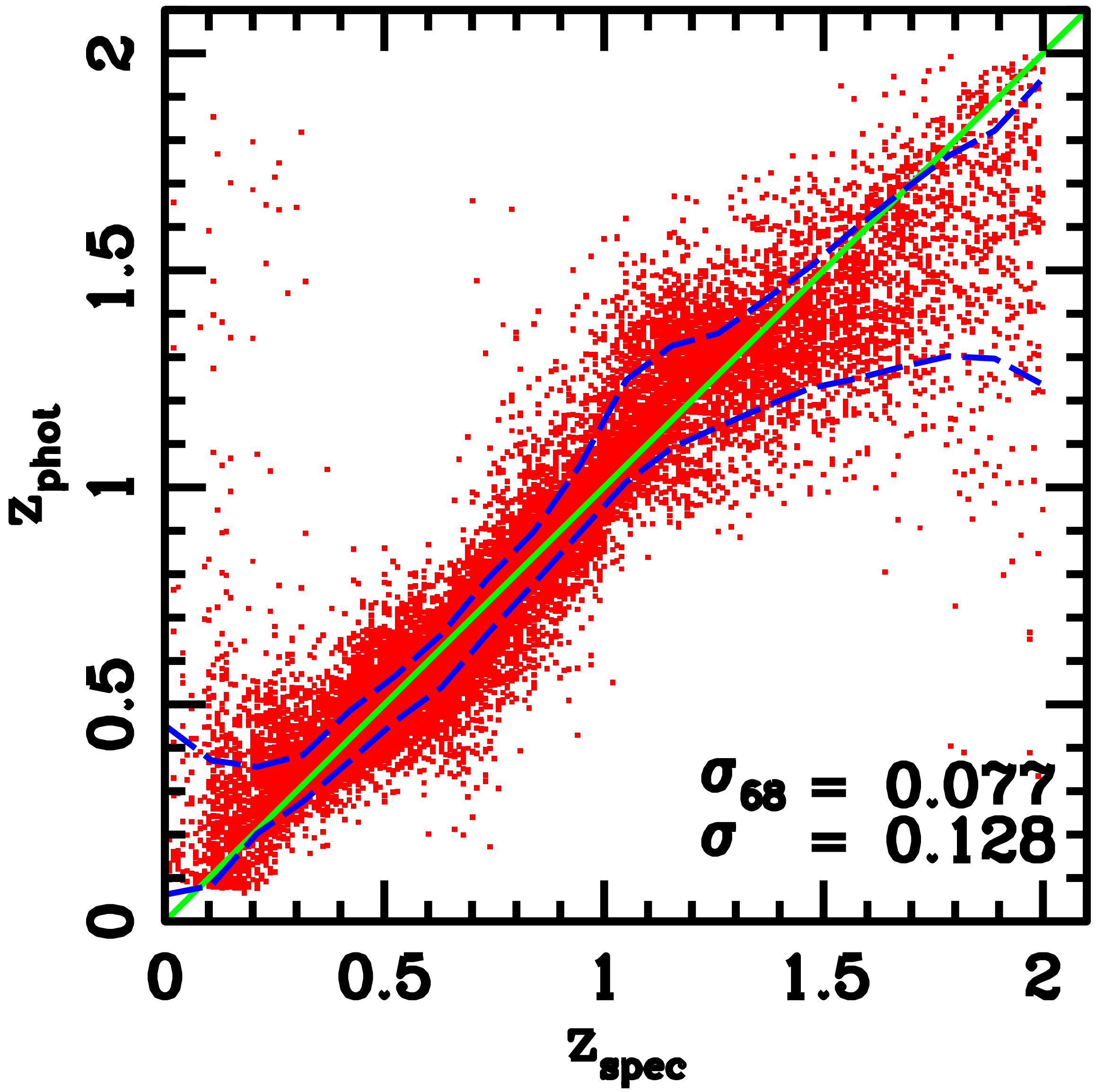
Supernovae: each SN provides info about DE; can choose a “golden subsample” to limit systematics

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

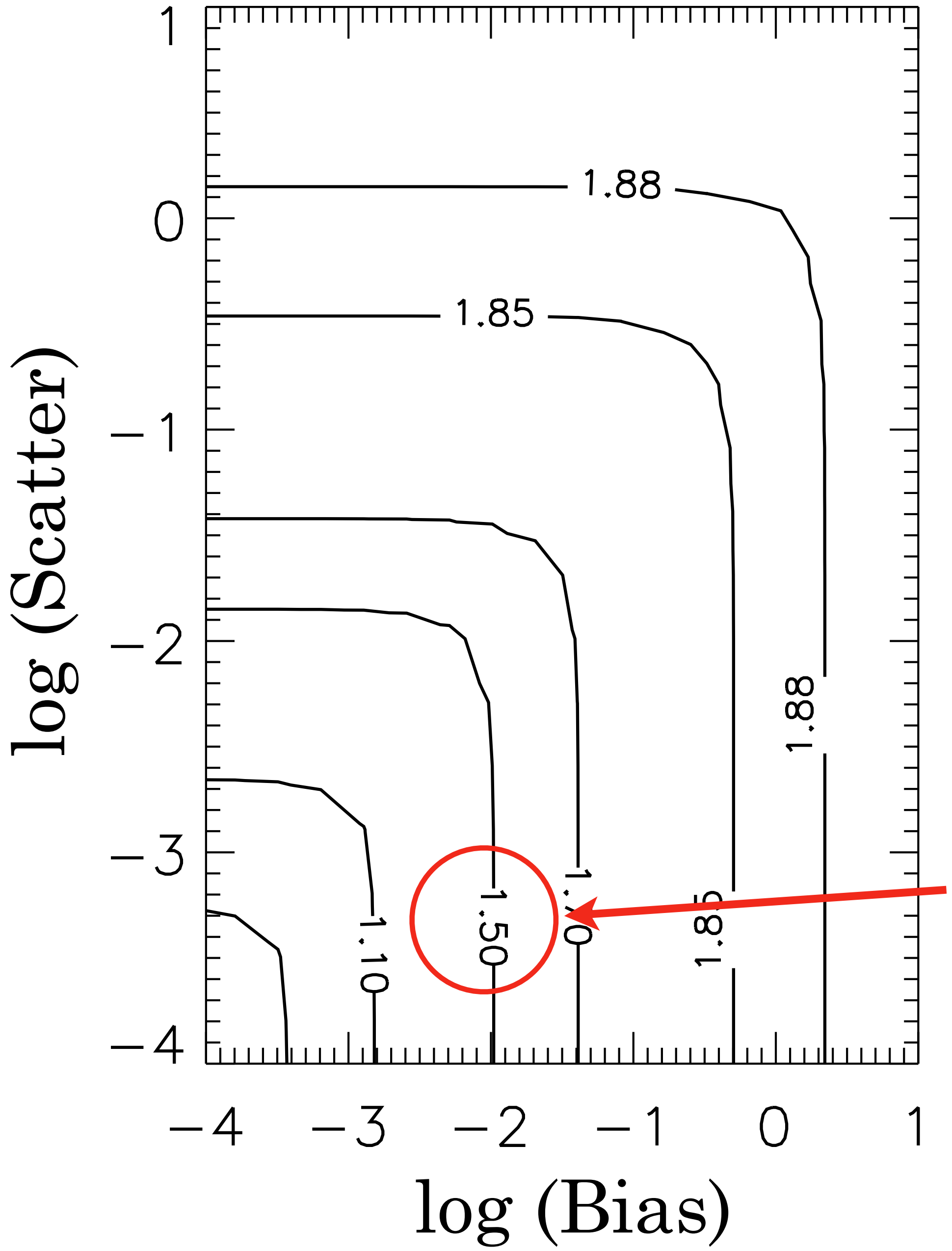
Poster child of systematics: photometric redshift errors

Example



C. Cunha

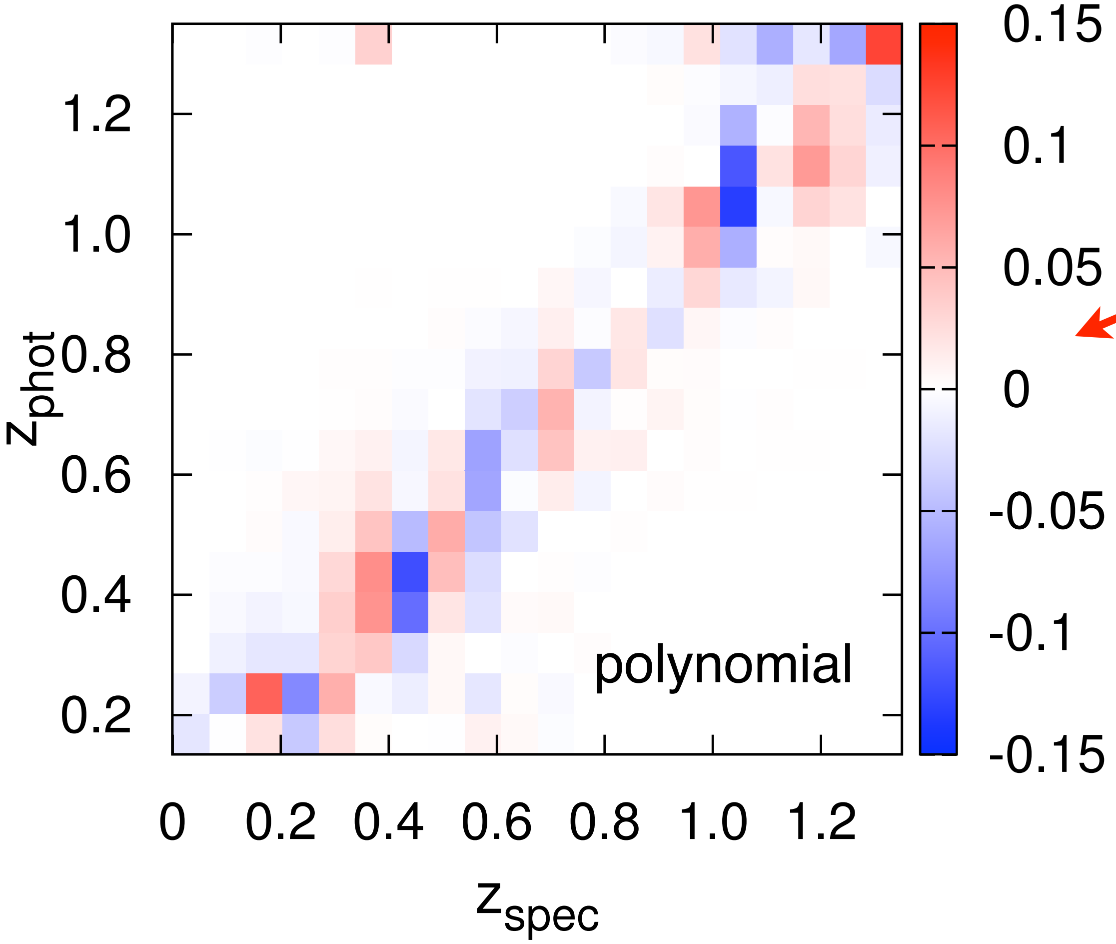
Requirements



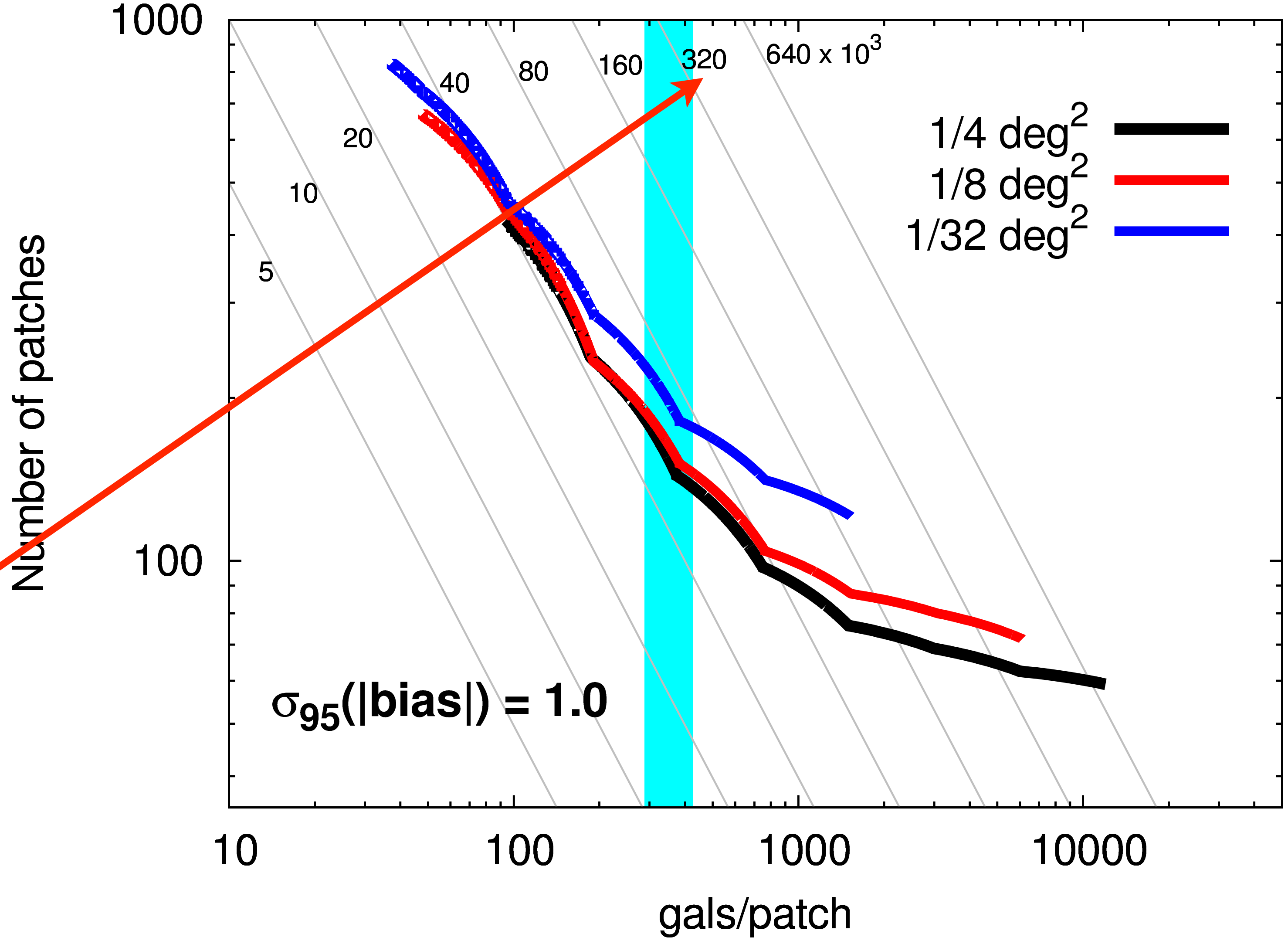
50% error degradation

Ma, Hu & Huterer 2006

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



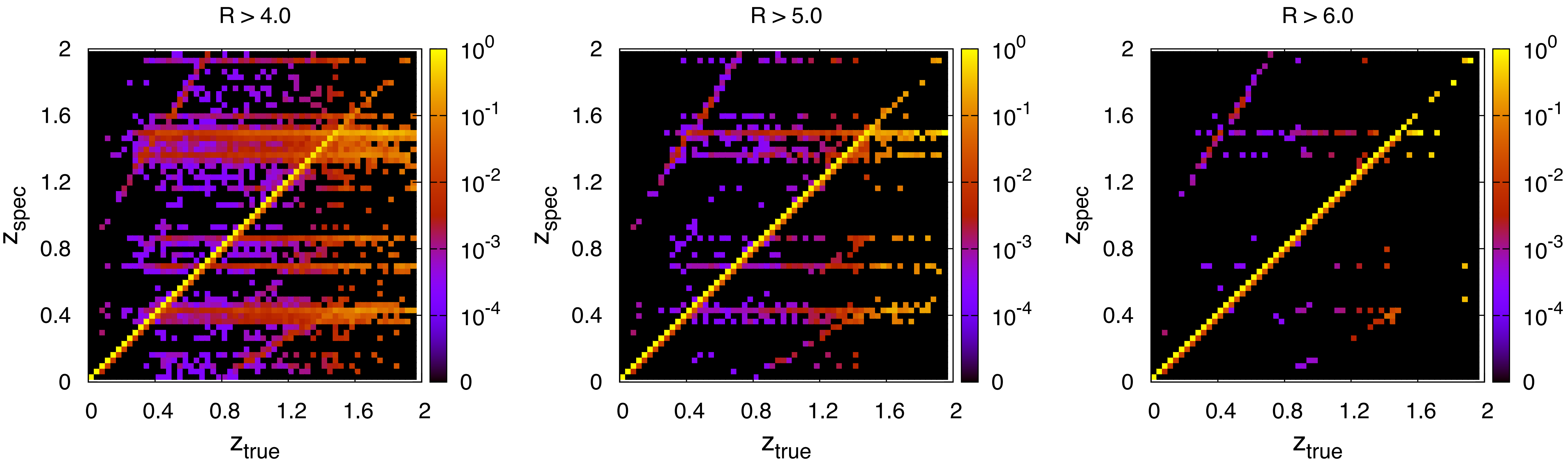
Need to consider the full $P(z_s\,|\,z_p)$: difference (true P – estimated P) generates cosmological biases



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



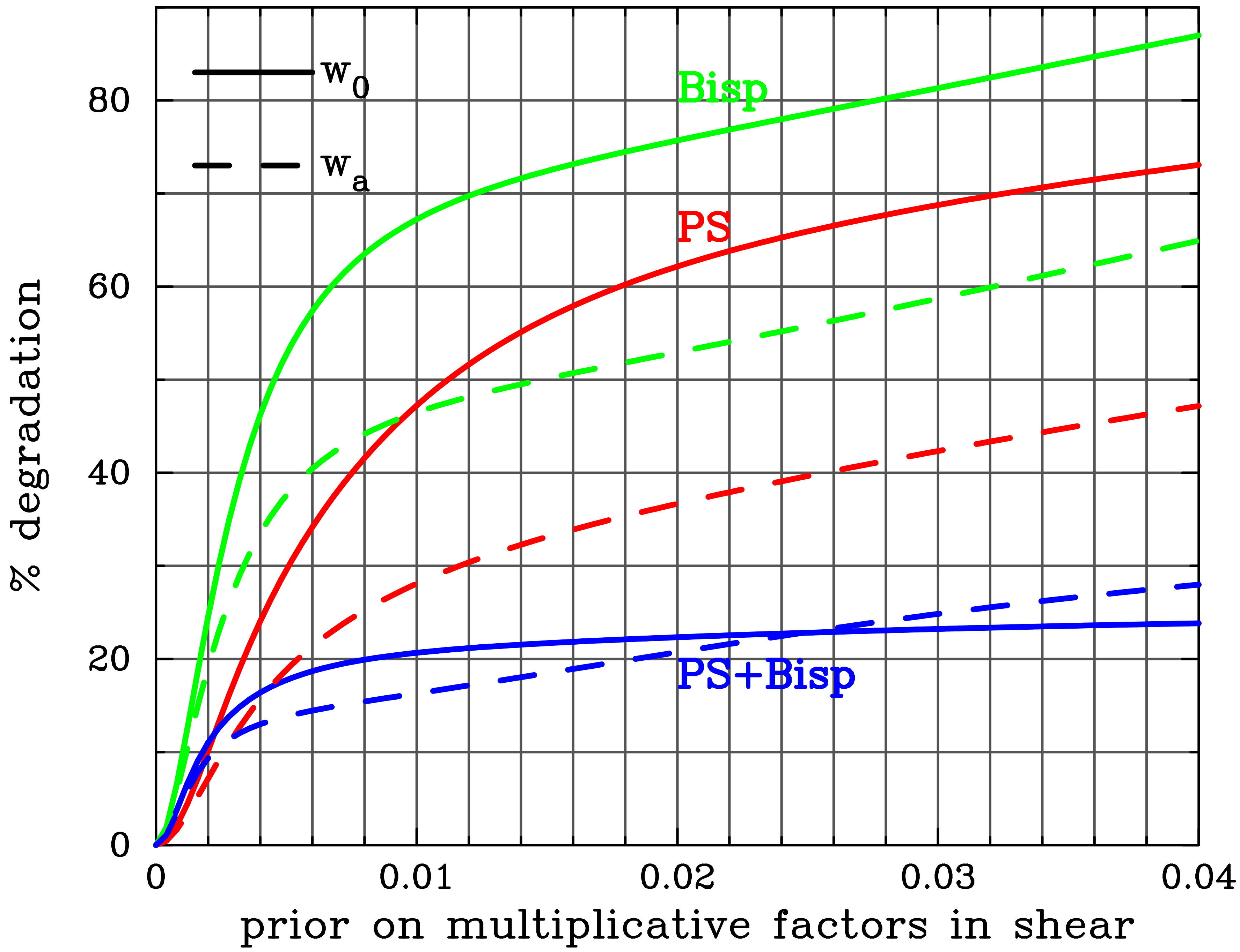
Increasing quality threshold (R) of spectroscopic zs

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)

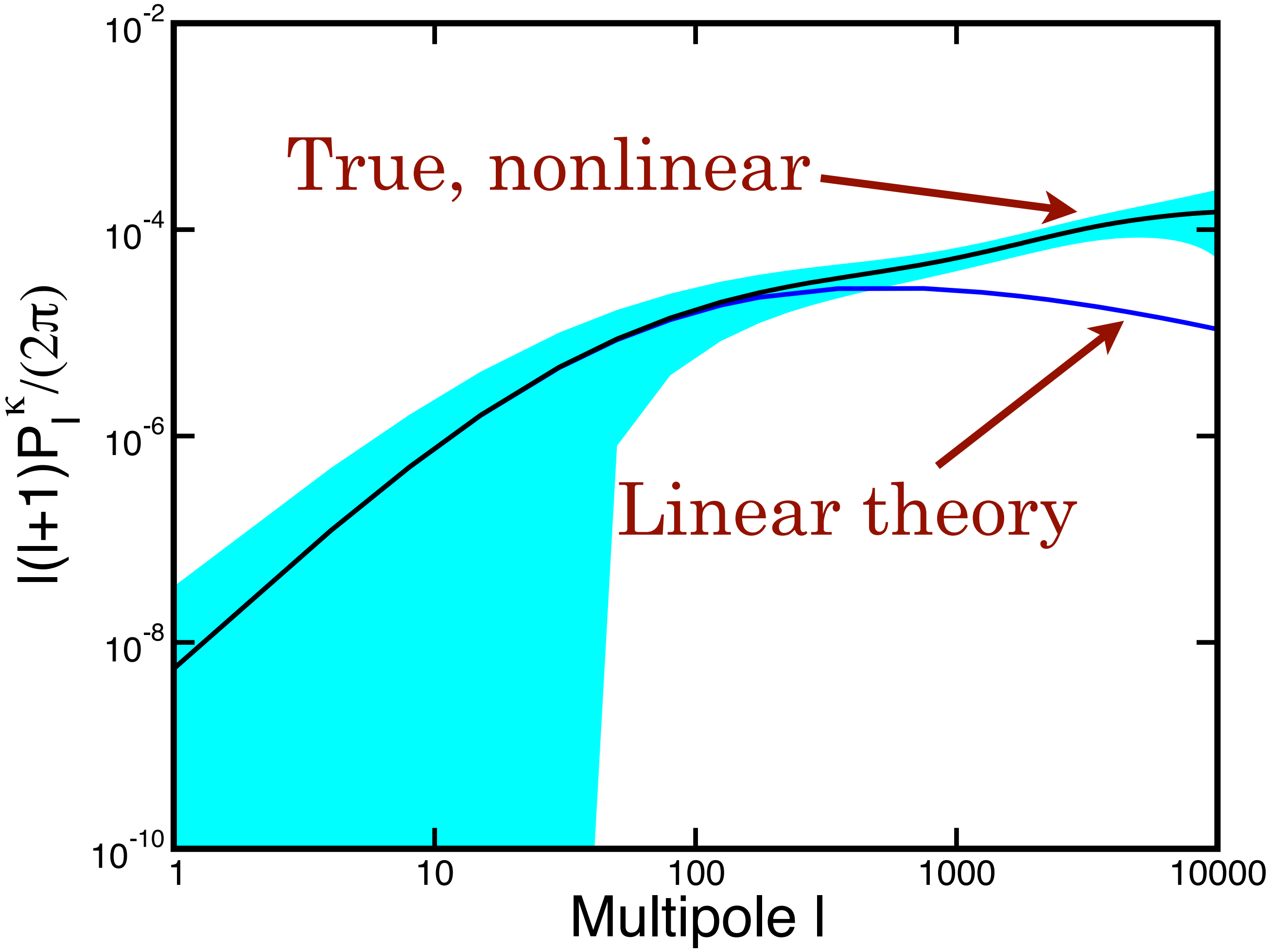
$$\gamma(z_i) = \gamma(z_i) \times g_i$$



Requirement: (few)×10^{-3} averaged over redshift bin

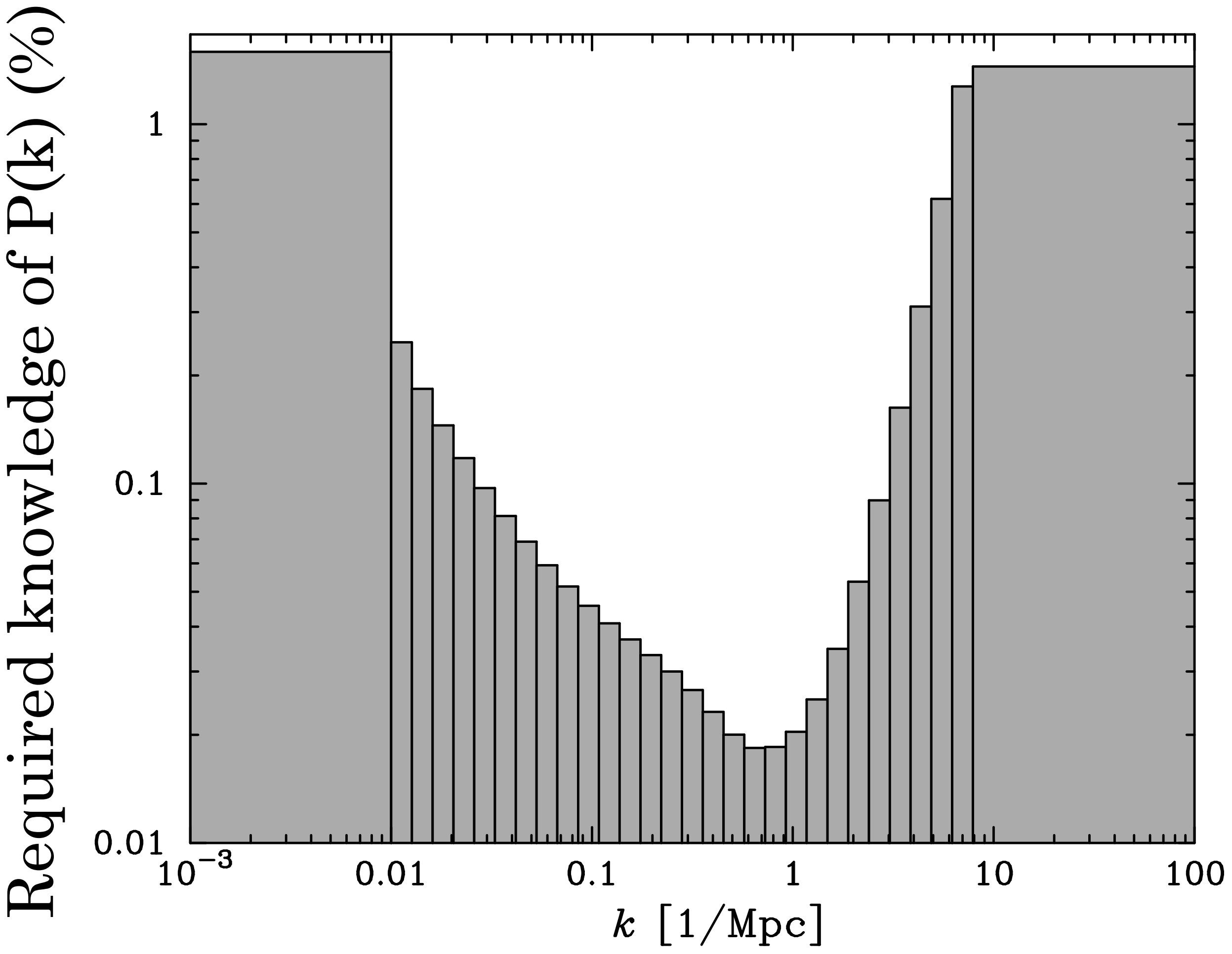
Theory Systematics example (WL)

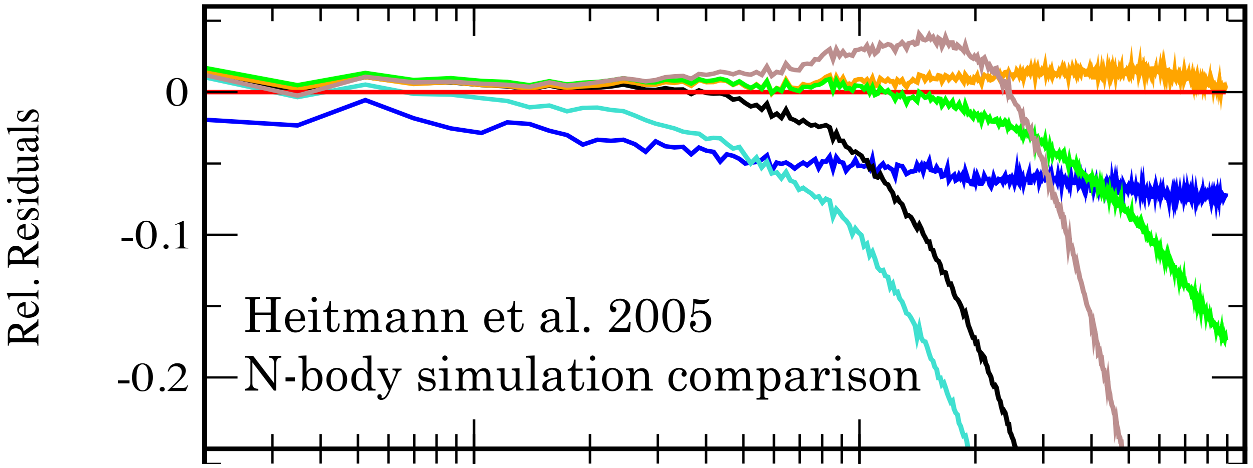
Using simulations to calibrate power spectrum at nonlinear scales



True, nonlinear

Linear theory





Heitmann et al. 2005
N-body simulation comparison

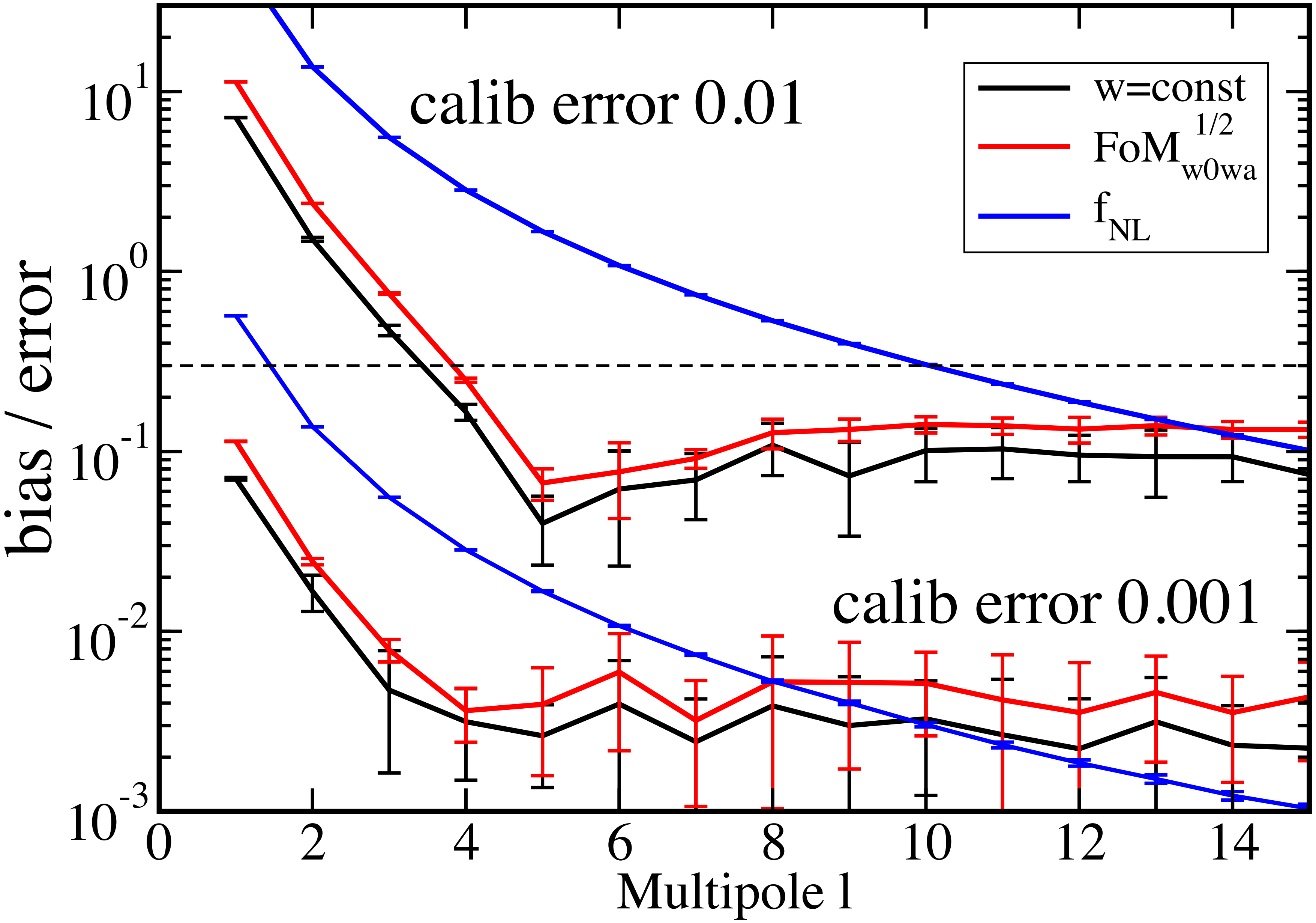
Sets quantitative goals for accuracy of simulations

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 $\Rightarrow$ their careful modeling and understanding is key