Observational Probes of Cosmic Acceleration

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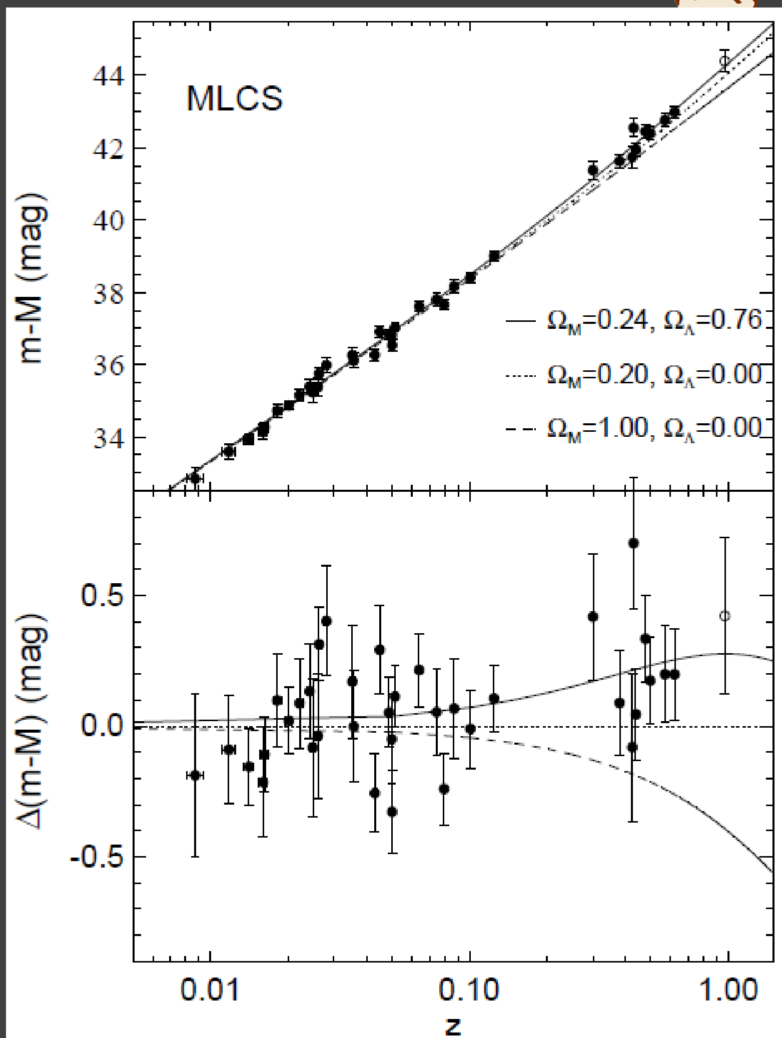
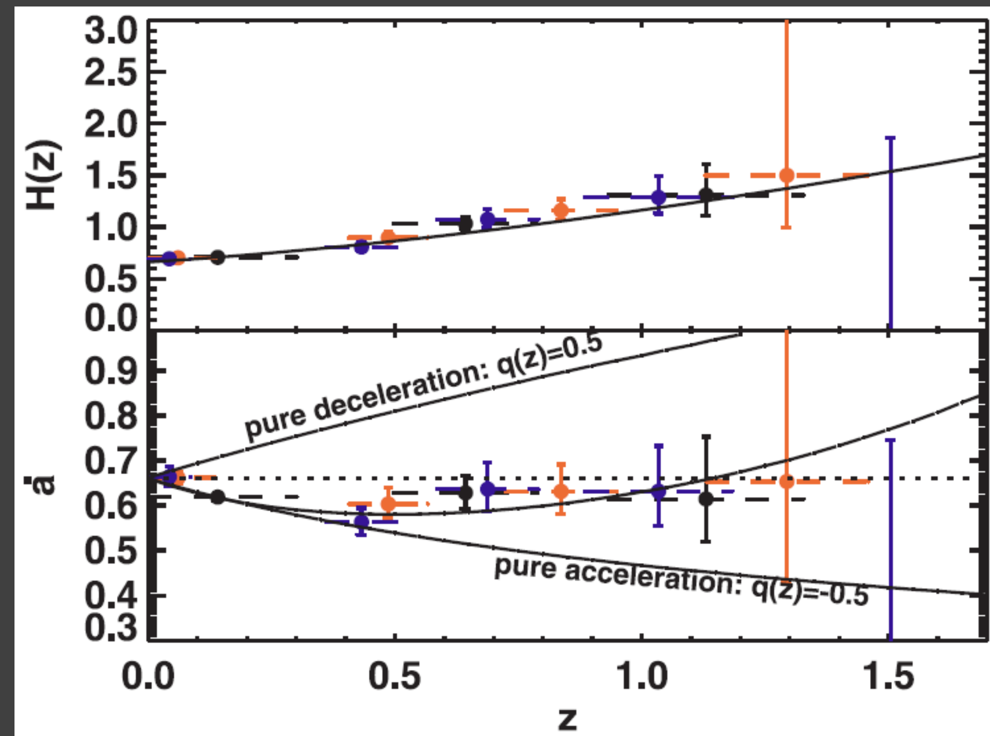
CCAPP/Ohio State

Deep Galaxy Surveys, Large-scale Structure, and Dark Energy
Valencia, March 29, 2012

A cosmic mystery



Riess et al. (1998)

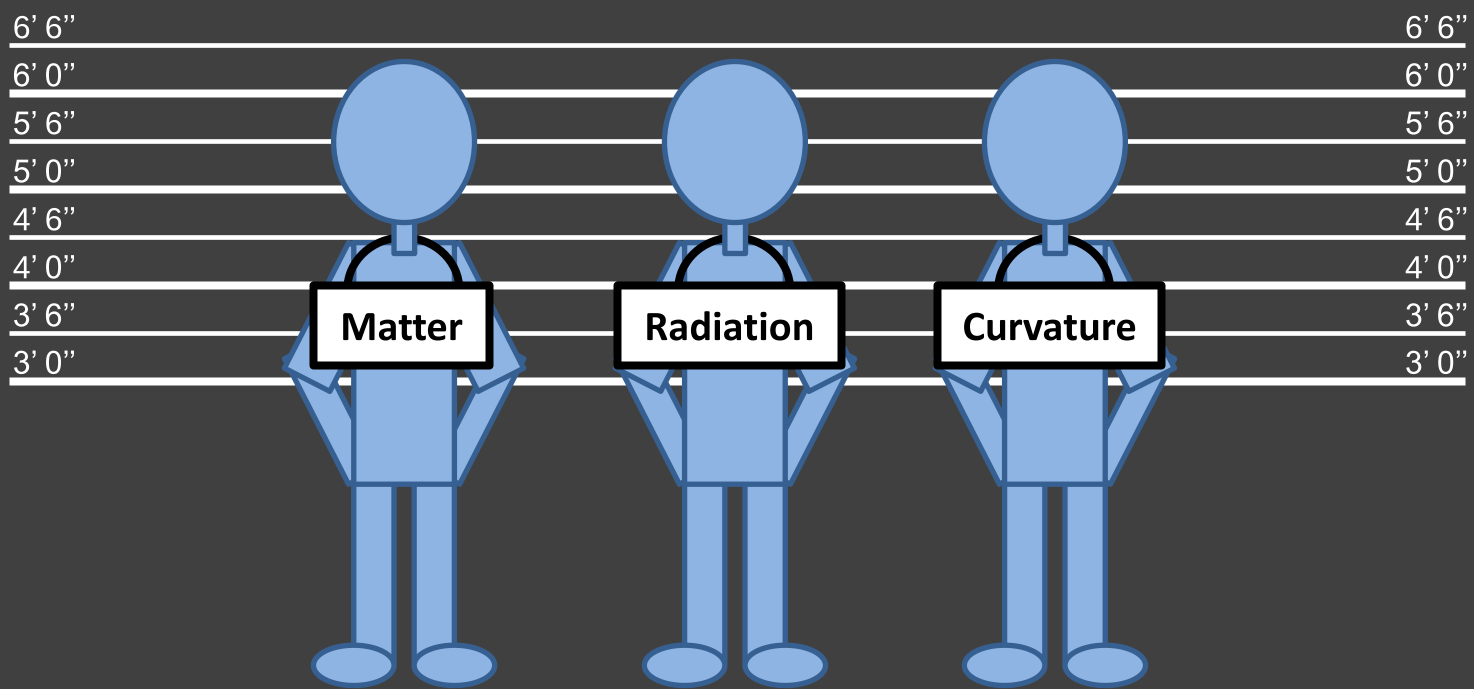


Riess et al. (2007)

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

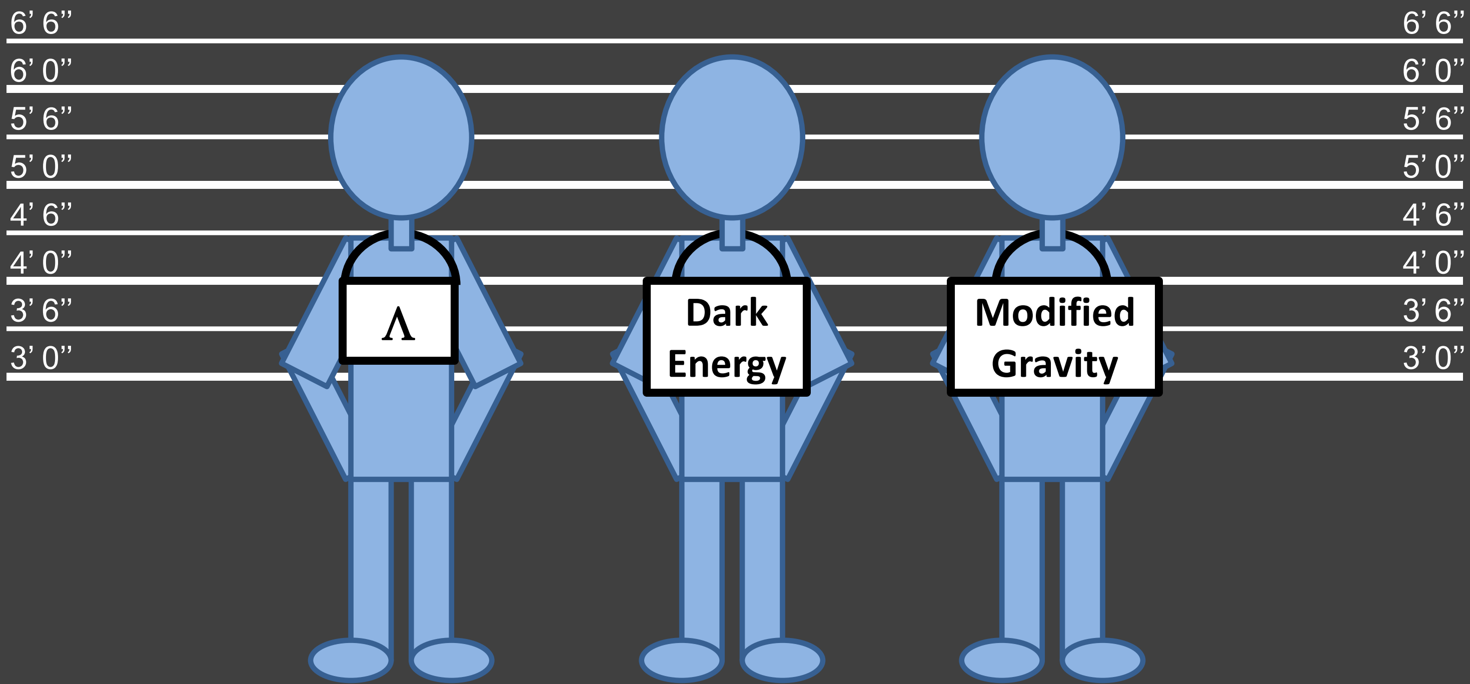
$$\ddot{a} > 0 \quad \rightarrow \quad w = \frac{p}{\rho c^2} < -\frac{1}{3}$$

The usual suspects



	$w = 0$	$w = 1/3$	$w = -1/3$
Means	✗	✗	✗
Opportunity	✗	✗	✗
Motive	✓	✓	✓

The *unusual* suspects



	w = -1	$w(z)$	$w(z)$
Means	✓	✓	✓
Opportunity	✓	✓	✓
Motive	???	???	???

How can we solve this mystery?

Theory: *Round up more suspects!*

Observations: *Look for more clues!*

- Improve accuracy of current measurements
- Explore different epochs or length scales
- Measure new quantities

“Observational Probes of Cosmic Acceleration”
arXiv: 1201.2434

D. Weinberg, M. Mortonson, D. Eisenstein, C. Hirata, A. Riess, & E. Rozo

Outline:

phenomenological parameters to distinguish between
Λ, dark energy, and modified gravity

current status and future challenges for selected probes

Stage IV forecasts with varying assumptions

Parametrizing cosmic acceleration

Expansion

Λ vs. DE:

$$w(z) = w_0 + w_a \frac{z}{1+z} = w_p + w_a \frac{z - z_p}{(1+z_p)(1+z)}$$

$\{w_0, w_a\}$ *or* $\{w_p, w_a\}$

Parametrizing cosmic acceleration

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{w$_0$, w$_a$} ***or*** ***{w$_p$, w$_a$}***

Growth of structure

DE vs. MG:

$$G(z) = \underbrace{G_9\, G_{\rm GR}(z)\, \exp\left[\Delta\gamma\right.}\left.\int_z^9 \frac{dz'}{1+z'} f_{\rm GR}(z')\ln\Omega_m(z')\right]$$

{G$_9$, Δγ}

FoMSWG, Albrecht et al. (2009)

Parametrizing cosmic acceleration

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{G_9, Δγ}

FoMSWG, Albrecht et al. (2009)

[Other interesting parameters: Ω_K, Σm_ν, n_s, f_{NL}, ...]

What quantities do different probes measure?

Large-scale structure

- Baryon acoustic oscillations: *distances*, *expansion rate*
- Redshift space distortions: *growth rate*

Weak lensing (cosmic shear): *growth function*, *distances*

Galaxy clusters: *growth function*, *volume*

Type Ia SNe: *ratios of distances*

Baryon acoustic oscillations

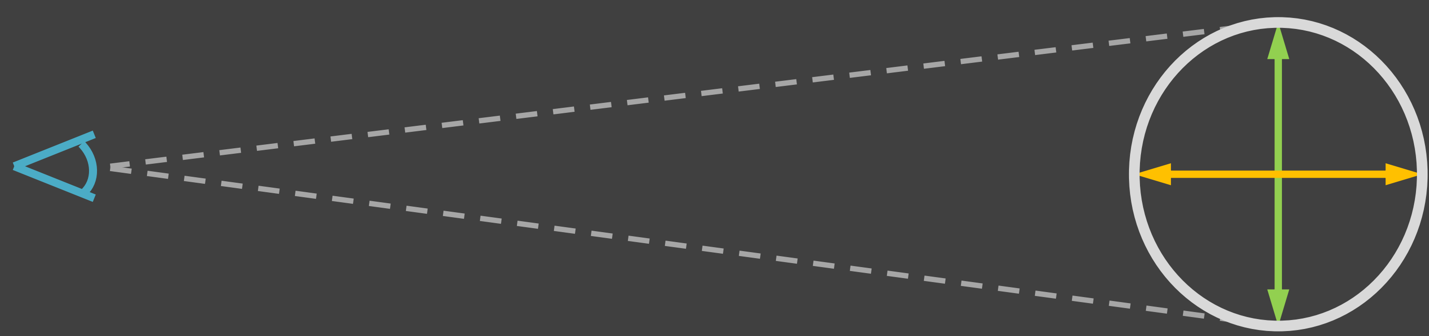
sound horizon $$r_s(z_*) = \int_{z_*}^{\infty} dz \, \frac{c_s(z)}{H(z)}$$

sound speed $$c_s = \left[3\left(1+\frac{3\rho_b}{4\rho_\gamma}\right)\right]^{-1/2}$$

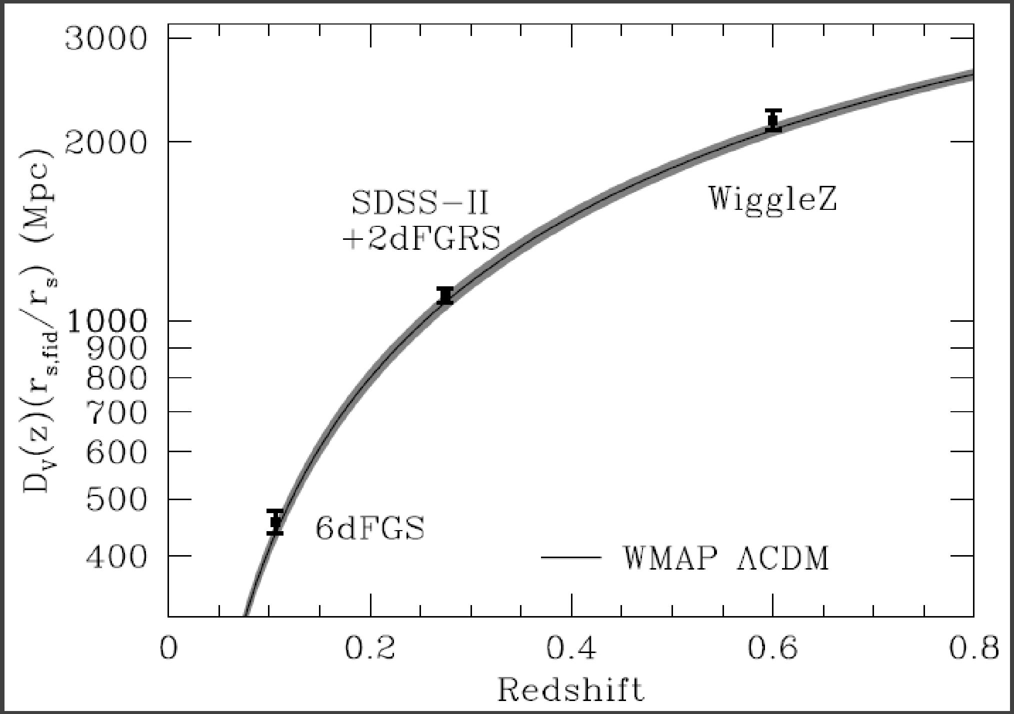
calibrated by CMB

using low z tracers, measure extent in angle: $\Delta\theta = r_s \, / \, D_A(z)$

or along line of sight: $\Delta z = c^{-1} \, r_s \, H(z)$



BAO surveys



2-5% accuracy

$D_V(z) = [cz\, D_A^2(z) / H(z)]^{1/3}$

future: separately measure $D_A(z)$ and $H(z)$ over large cosmic volume,
using different tracers to explore different redshifts
(LRGs, emission line galaxies, Lyman α forest, ...)

BAO uncertainties

Large scale: $r_s \sim 100\ h^{-1}$ Mpc

Minimizes impact of many systematic errors,
but need large volume to reduce statistical errors

Also need sufficient sampling of tracers – error per mode:

$$\sigma_P/P = 1 + 1/nP$$

Systematics:

Astrophysical

nonlinear growth, bias, redshift space distortions, reionization

Observational

Ly α – continuum fitting, 21cm – foregrounds

Cosmological

recombination, isocurvature modes – test with CMB

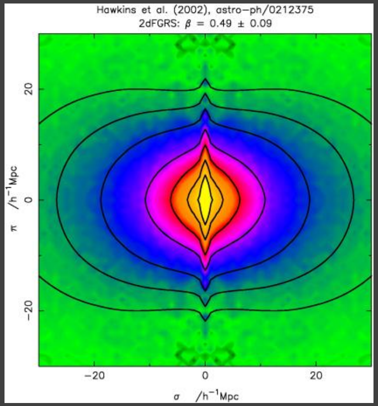
Large scale structure anisotropy

expect correlation function to be isotropic in real space

apparent anisotropy arises from:

different H and D_A from true cosmology – Alcock-Paczynski
constrains product $H(z)D_A(z)$

peculiar velocities – redshift space distortions
constrains growth $f(z)G(z)$



current measurements (VVDS, WiggleZ, SDSS)
down to ~10% accuracy at $0<z<1$

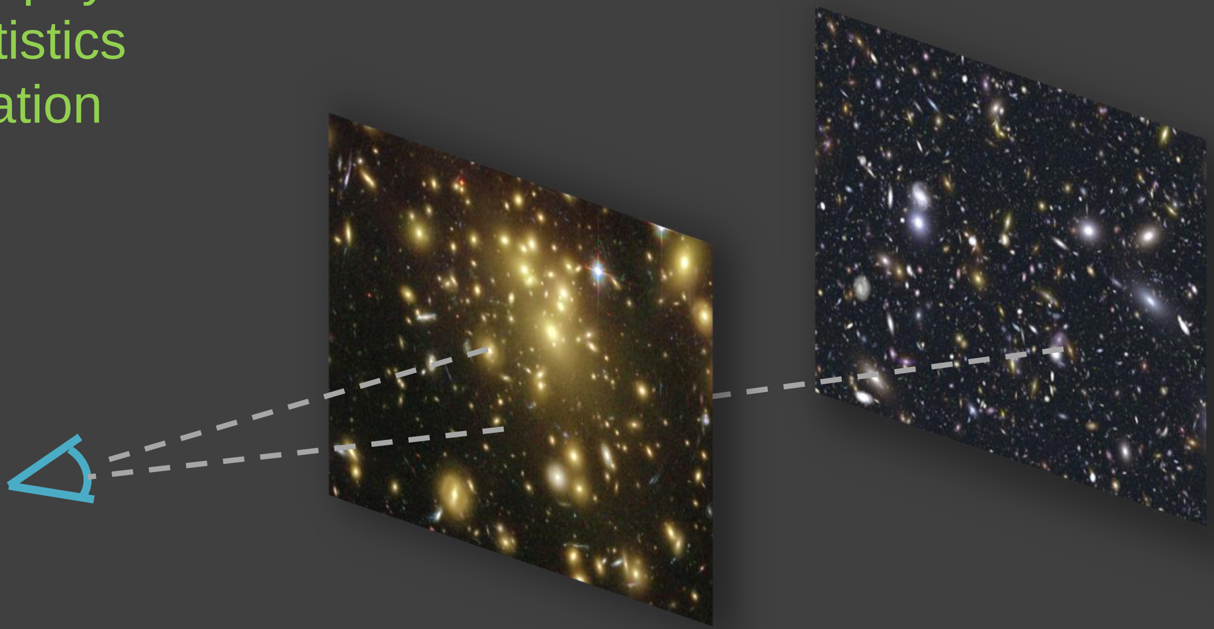
ultimate level of precision achievable is highly uncertain

need accurate modeling of nonlinear effects on smaller scales than BAO
(finger-of-God, nonlinear/scale-dependent bias)

Weak lensing

several methods, with different parameter sensitivity and systematics:

- cosmic shear
- shear tomography
- galaxy-galaxy lensing
- cosmography
- 3+ pt statistics
- magnification
- flexion
- ...



Lensing surveys

recent cosmic shear measurements:

COSMOS	~ 2 deg^2	5-15% $\sigma_8 \Omega_m^{0.6}$
CFHTLS	~ 150 deg^2	
SDSS (Stripe 82)	~ 200 deg^2	

ongoing/near future: DES, PAU, HSC, PanSTARRS, KIDS

few 1000 deg^2, 100-1000x as many galaxies

Stage IV: LSST, Euclid, WFIRST – 1/4 to 1/2 of sky

Cosmic shear uncertainties

statistical errors

large scales: cosmic variance

$$\frac{\sigma(C_{EE}(\ell))}{C_{EE}(\ell)} = \frac{1}{\sqrt{\ell\,\Delta\ell\,f_{\rm sky}}}$$

small scales: shape noise – σ_γ ~ 0.2 per shear component

$C_{EE}(l)$ best measured at l ~ 1000: 0.1% stat. errors for full sky

systematic uncertainties

PSF correction
shape measurement
photo *zs*
intrinsic alignments
matter power spectrum predictions (effects of baryons)

Clusters

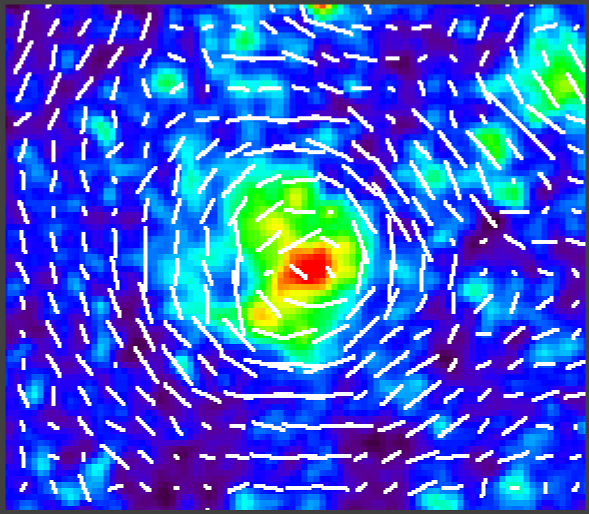
abundance of clusters with a given mass probes
volume and growth of structure – mainly $\sigma_8(z)\ \Omega_m^{0.4}$

comparison with predictions requires accurate mass proxies
(optical richness, x-ray observables, SZ effect)

for samples of >1000 clusters, uncertainty in mass-observable relation dominates over statistical errors unless masses can be calibrated with sub-percent accuracy

stacked WL around clusters may be the
best option for optical/IR samples

other issues: photo-zs, purity/completeness,
mis-centering, mass function predictions



T. Hamana

Type Ia Supernovae

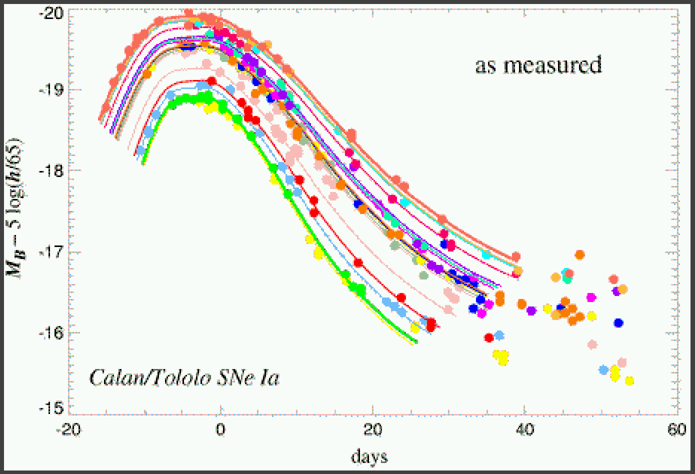
nearly standard intrinsic luminosities (σ_μ ~ 0.4 mag in V)

empirical correlations reduce scatter to σ_μ ~ 0.1 - 0.15 mag

peak luminosity – light curve shape
extinction – color

$$\mu = 5\log[H_0 d_L(z)] + \mathcal{M}$$

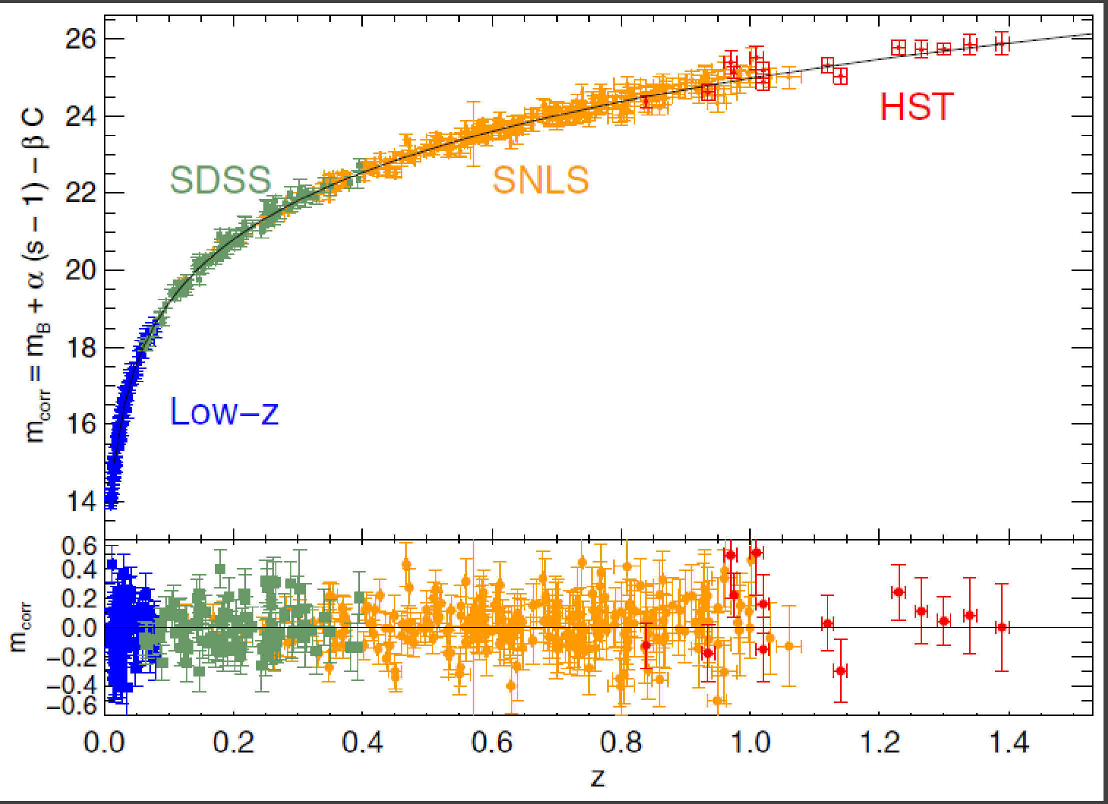
fractional distance error ~ 1/2 of mag. error



calibrate distance scale
using low-*z* SNe (*z* ~ 0.03 - 1)

need to confirm SN type
- spectra easiest, but expensive

SN samples



Conley et al. (2011)

$\sigma_w \sim 0.2$ [SN]

$\sigma_w \sim 0.1$ [SN+other]

future: PanSTARRS, DES, J-PAS, LSST, WFIRST, Euclid

near-term surveys will increase sample from several 100 to several 1000

SN uncertainties

SN constraints are limited by *systematics*

flux calibration

local vs. distant SNe – different telescopes and filters, different range of rest-frame SED

dust extinction

reduce errors by observing in IR, comparing subsamples

evolution with redshift

e.g. 0.03 mag/dex change with host galaxy stellar mass

gravitational lensing

effects can be calculated, unlikely to dominate the errors

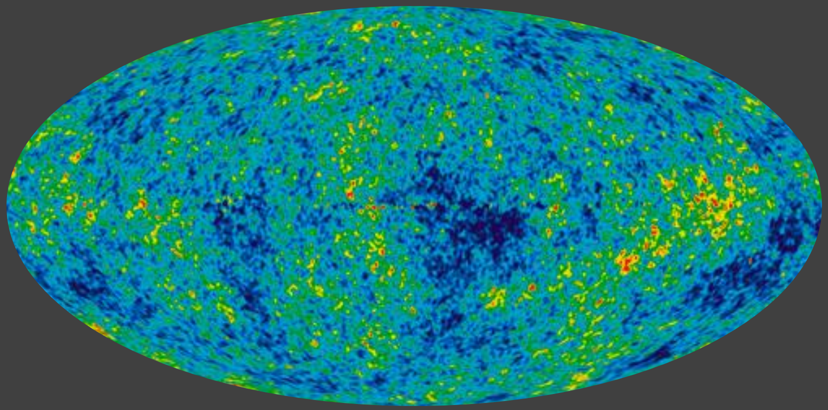
Cosmic Microwave Background

a crucial supplement to probes of cosmic acceleration:

acoustic scale — distance to z=1100

acoustic peak heights — growth normalization (G_9), matter density, baryon density, BAO calibration (sound horizon)

secondary anisotropies (ISW, SZ, lensing)



WMAP

Stage IV forecasts

fiducial assumptions:

CMB: *Planck*

SN: 0.01 mag total error per Δz=0.2 over 0.2<z<0.8
local sample at z=0.05 with same total error

BAO: 10^4 deg^2, 0<z<3
sample variance errors x 1.8 (sampling, nonlinear effects)

WL: 10^4 deg^2, 23 gal/$arcmin^2$, z_{med}=0.84 ($\gamma\gamma$, gg, γg)
marginalization over intrinsic alignments and
0.002 aggregate errors in shear calibration and mean photo-z

Order-of-magnitude improvement in parameters

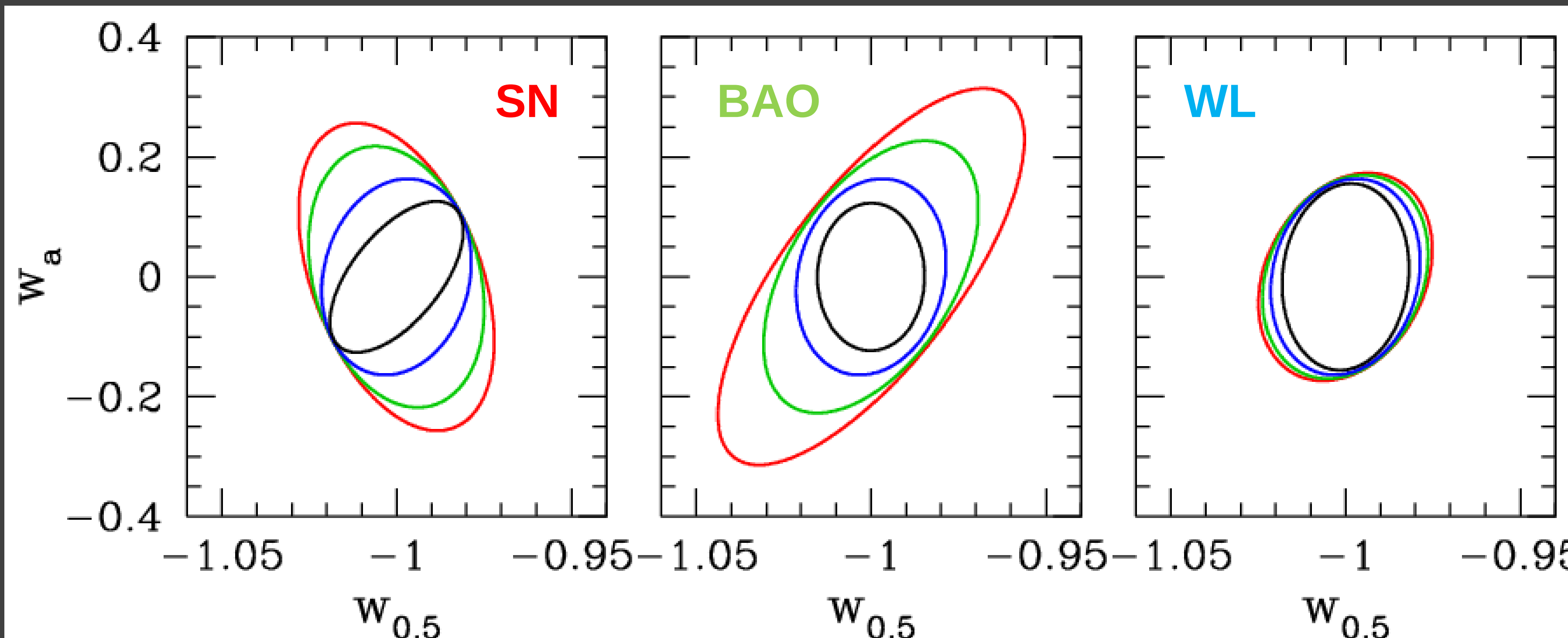
Marginalized 1-σ errors:

	w_p	w_a	$\Delta\gamma$	$\ln G_9$
Current	0.1	1	0.2	0.2
Stage III	0.03	0.3	0.1	0.05
Stage IV	0.01	0.1	0.03	0.02

Stage IV pivot redshift: $z_p \sim 0.5$

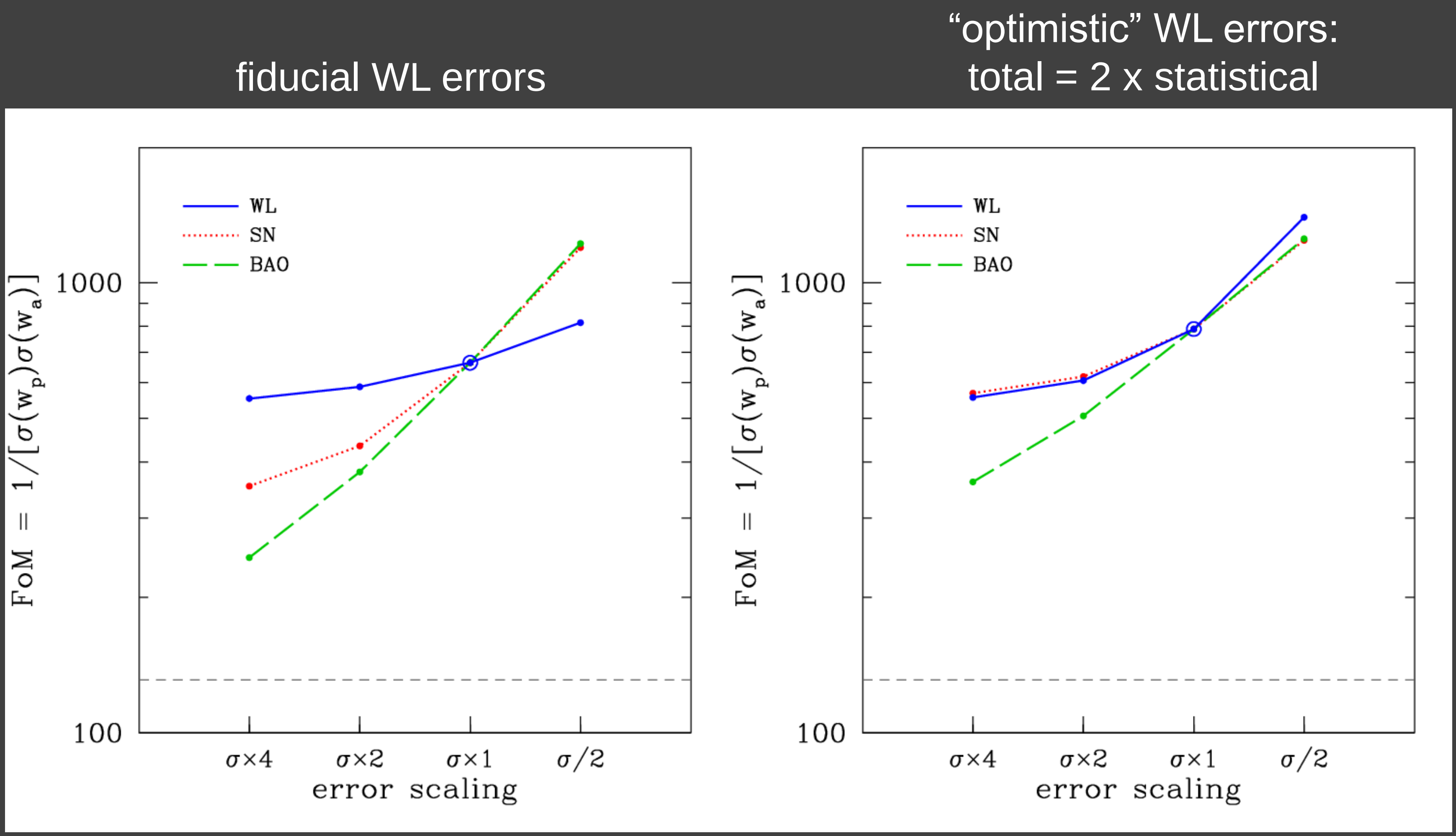
Forecast variations: expansion

$c^{-1/2}=4$ $c^{-1/2}=2$
$c^{-1/2}=1$ $c^{-1/2}=0.5$



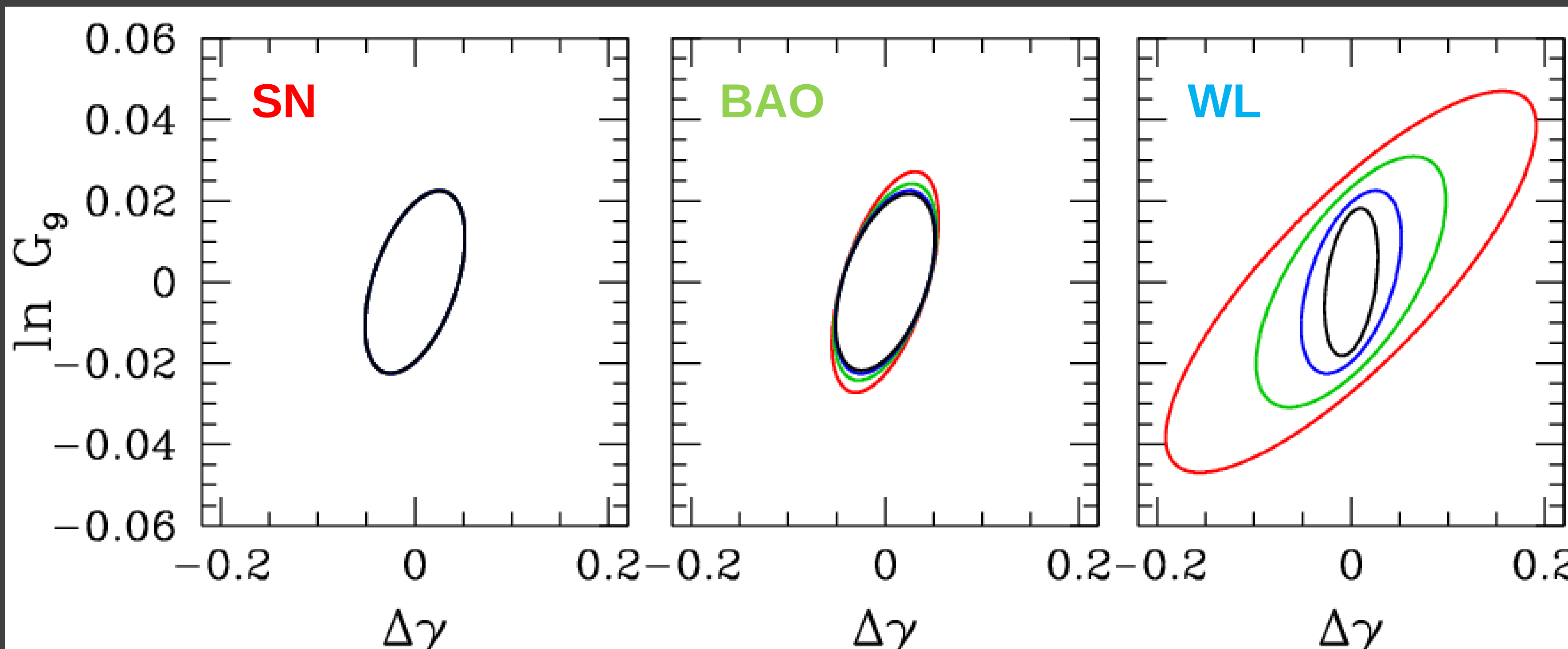
$F_{CMB}+c\,F_{SN}+F_{BAO}+F_{WL}$ $F_{CMB}+F_{SN}+c\,F_{BAO}+F_{WL}$ $F_{CMB}+F_{SN}+F_{BAO}+c\,F_{WL}$

WL systematics strongly affect errors on *w*



Forecast variations: growth

$c^{-1/2}=4$ $c^{-1/2}=2$
$c^{-1/2}=1$ $c^{-1/2}=0.5$



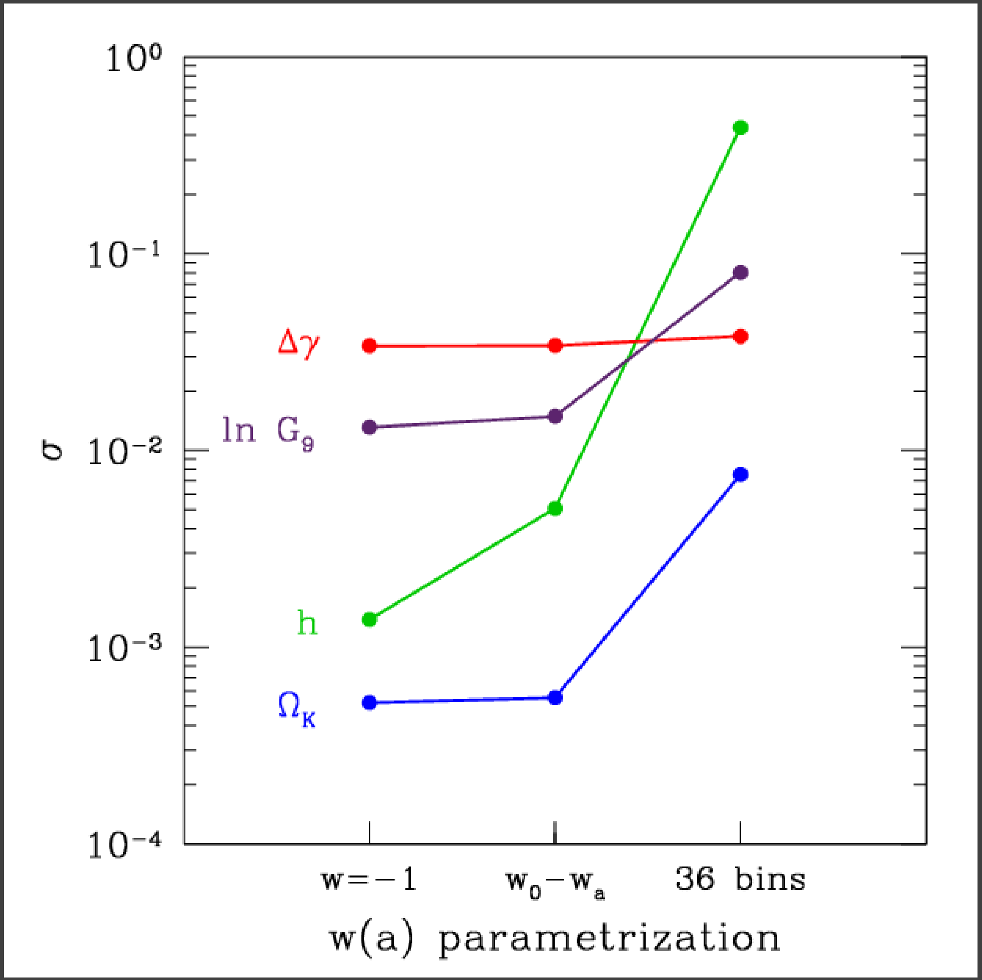
$\mathbf{F}_{CMB}+c\,\mathbf{F}_{SN}+\mathbf{F}_{BAO}+\mathbf{F}_{WL}$ $\mathbf{F}_{CMB}+\mathbf{F}_{SN}+c\,\mathbf{F}_{BAO}+\mathbf{F}_{WL}$ $\mathbf{F}_{CMB}+\mathbf{F}_{SN}+\mathbf{F}_{BAO}+c\,\mathbf{F}_{WL}$

Model dependence

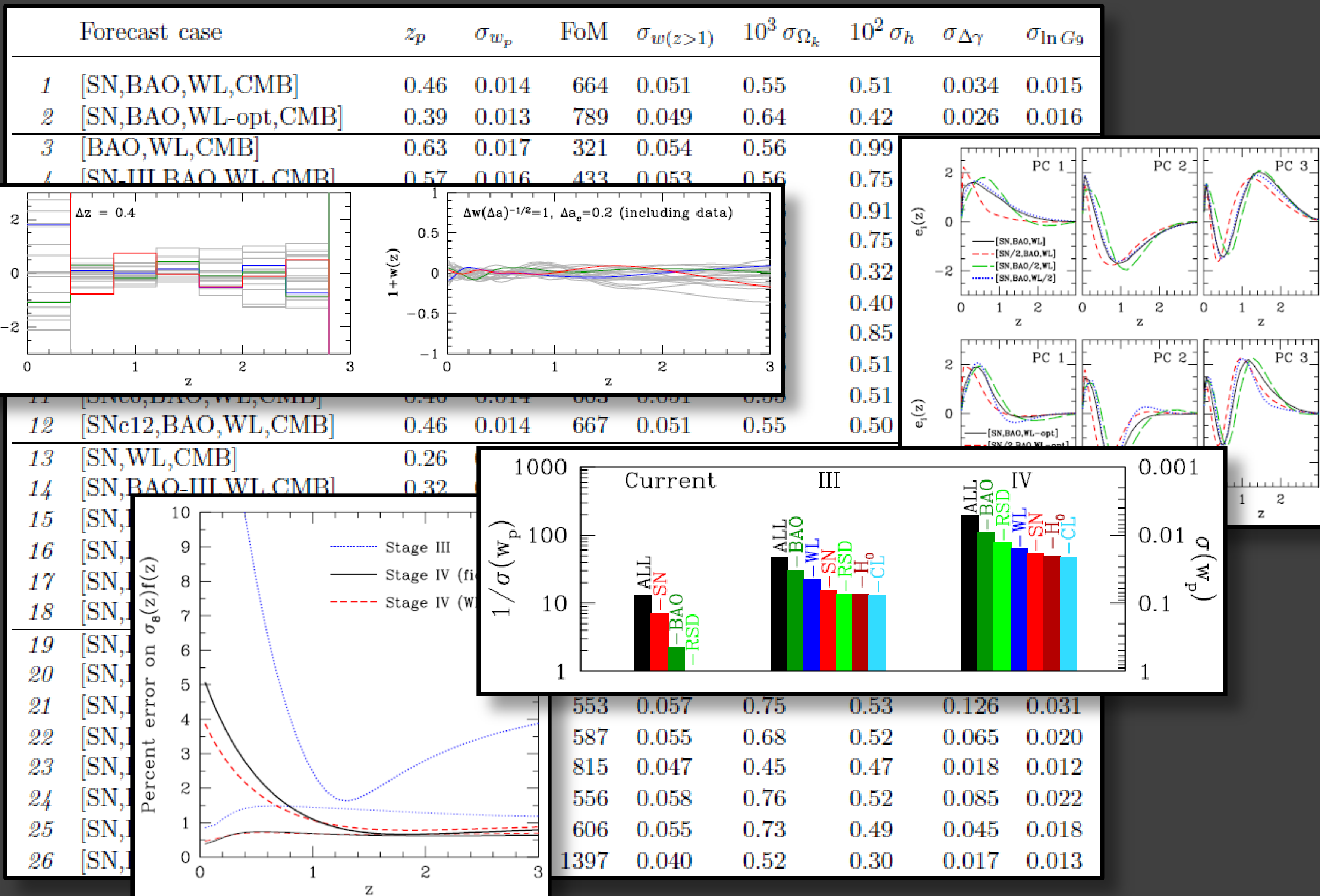
previous forecasts assumed w_0-w_a parametrization

more generally, there are variations in $w(z)$ that can't be constrained, *no matter how good the data are*

those variations are degenerate with certain other parameters



...and much more!



There are many promising methods
for demystifying cosmic acceleration

Larger surveys and better understanding of systematics will reduce uncertainties on several key parameters by an order of magnitude

These improvements will help us determine which of our unusual suspects is responsible for acceleration, or perhaps push us to look for new explanations