Complementary Probes of Dark Energy

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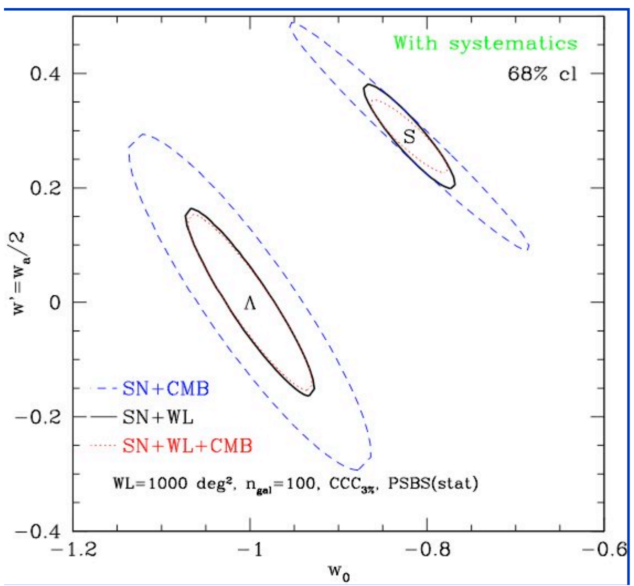
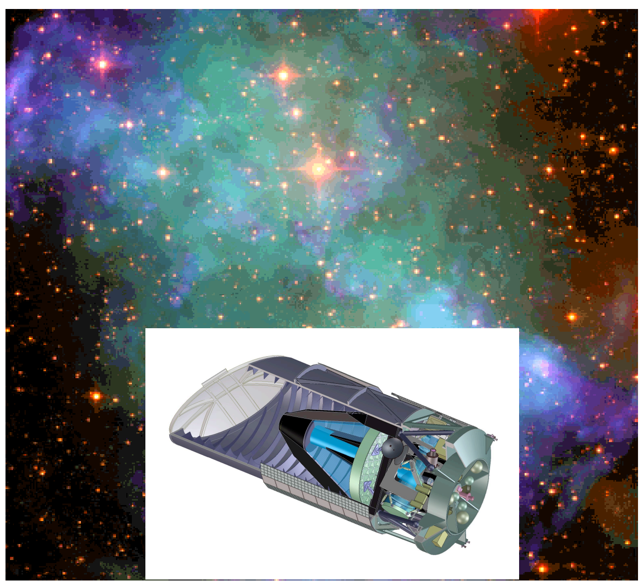
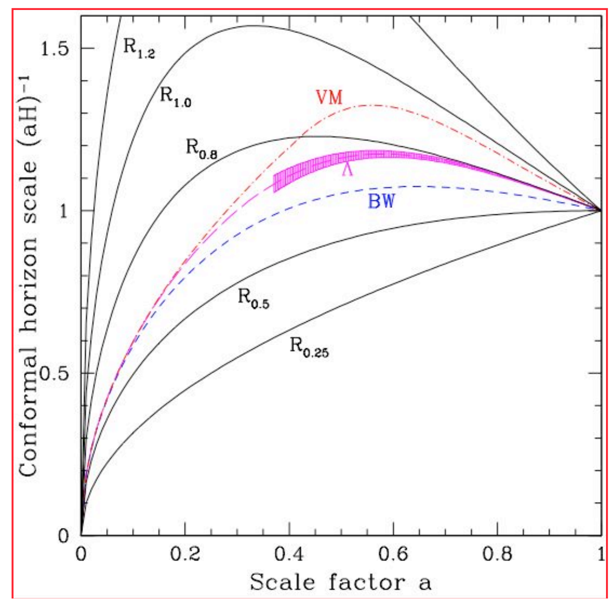


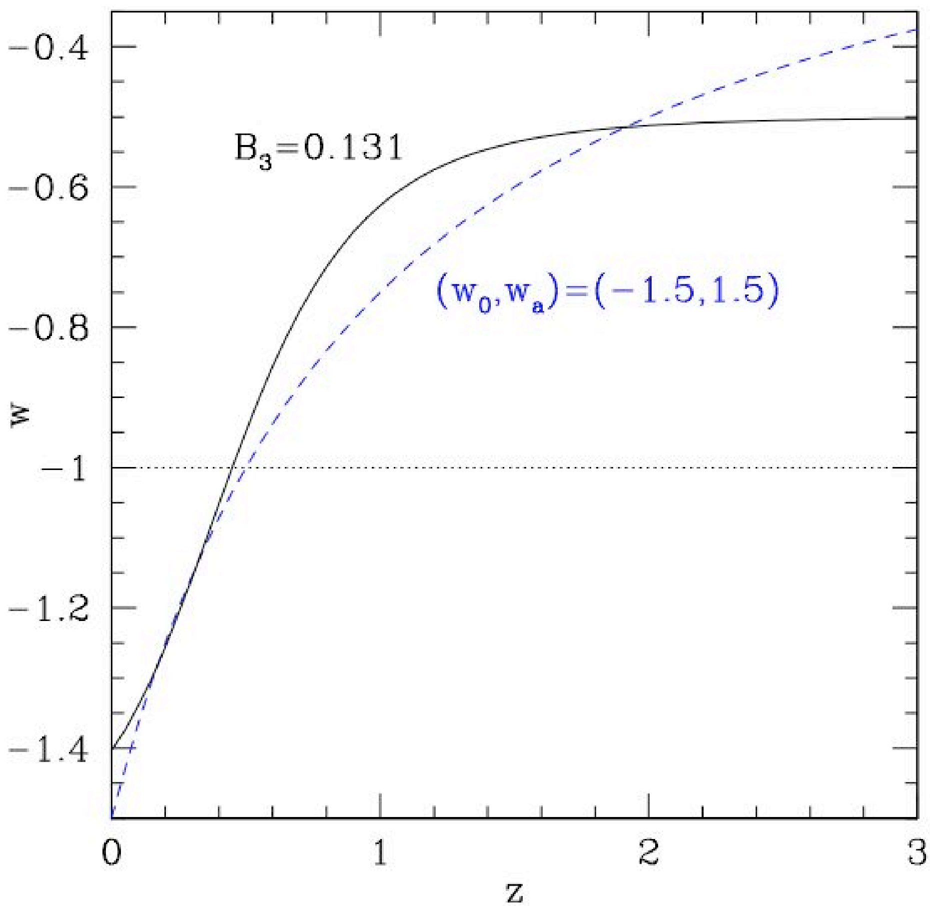




To Λ or not to Λ

$w_{const}=-1.05^{+0.15}_{-0.20}\pm 0.09$ (Knop et al. 2003) [SN+LSS+CMB]

$w_{const}=-1.08^{+0.18}_{-0.20}\pm ?$ (Riess et al. 2004) [SN+LSS+CMB]



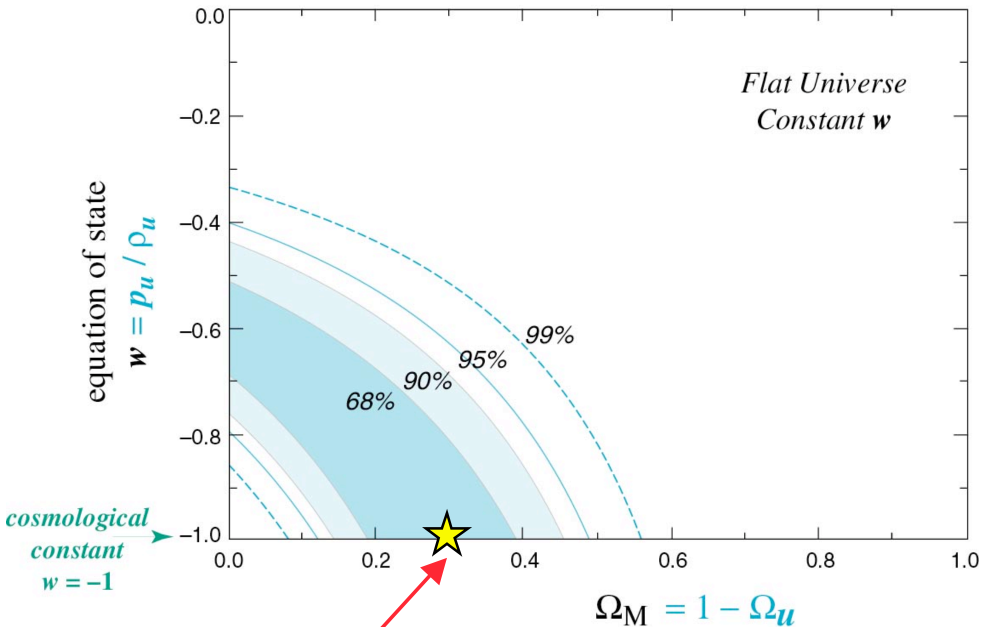
Both models fit ΛCDM in

- CMB d_{lss} to <0.1%
- Structure growth to <4%
- SN distances to <0.1 mag

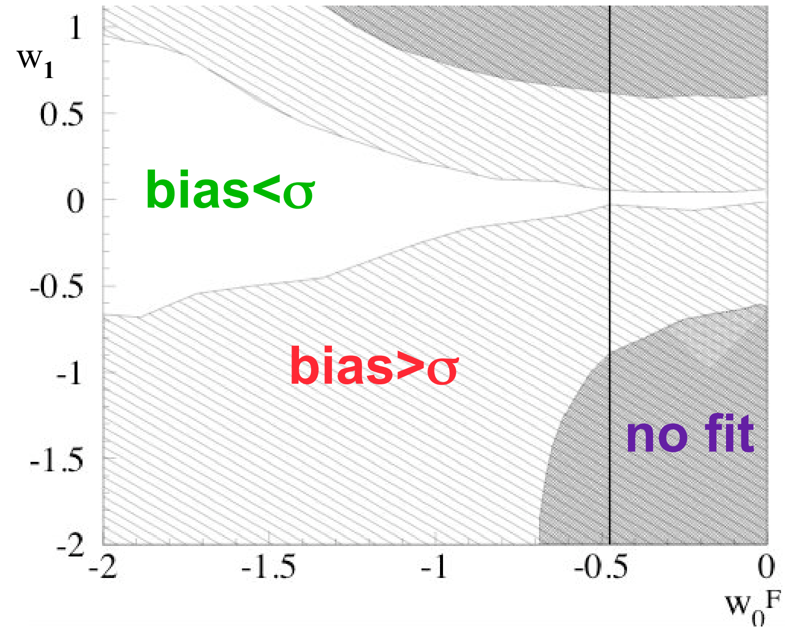
Future: $\delta w_{const}=0.05$

- Can distinguish these extremes from Λ
- But not from w=-1.2

Beyond Λ, Beyond w_{const}



Ω_M=0.3, w=-1 OR
Ω_M=0.27, w_0=-0.8, w'=-0.6



Virey et al. 2004

Λ can be deceiving:

- **Models with (even strong) w′ can look like w_{const}=-1**
- **Attractor (but w′):** Linde linear, Steinhardt cyclic, Linder RipStop
- **Attractor (but w′): Scalar-tensor** (Matarrese et al.)

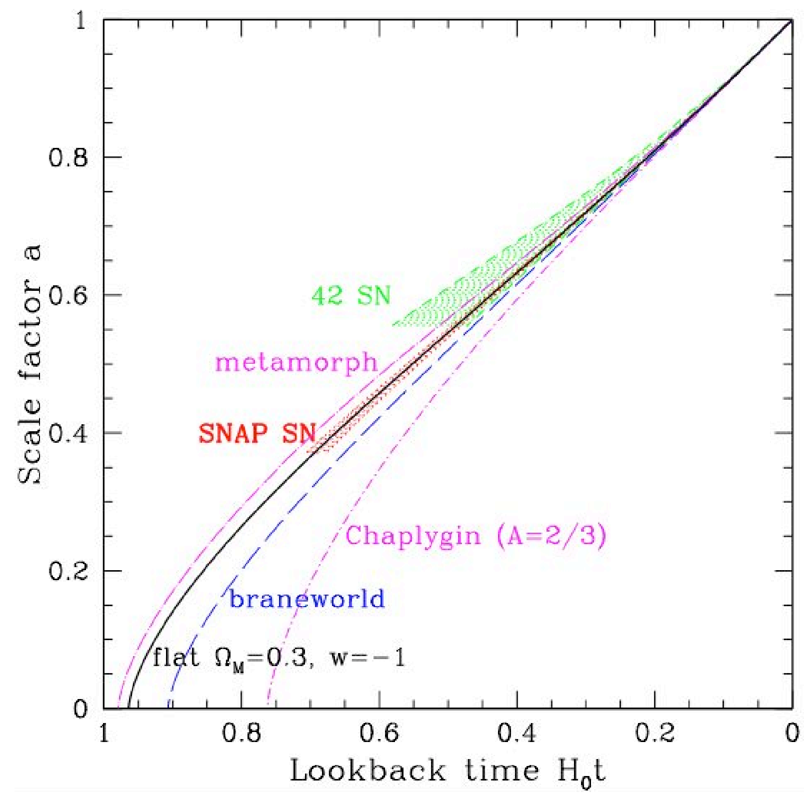
The Greatest Generation

Acceleration explicit in expansion history a(t)
Alterations to Friedmann expansion → *w(z)*

$H^2 = (8\pi/3)\,\rho_m + \delta H^2(z) \rightarrow w(z) = -1 + (1/3)\, d\,\ln(\delta H^2) / d\,\ln(1+z)$ Linder 2003

The next generation…

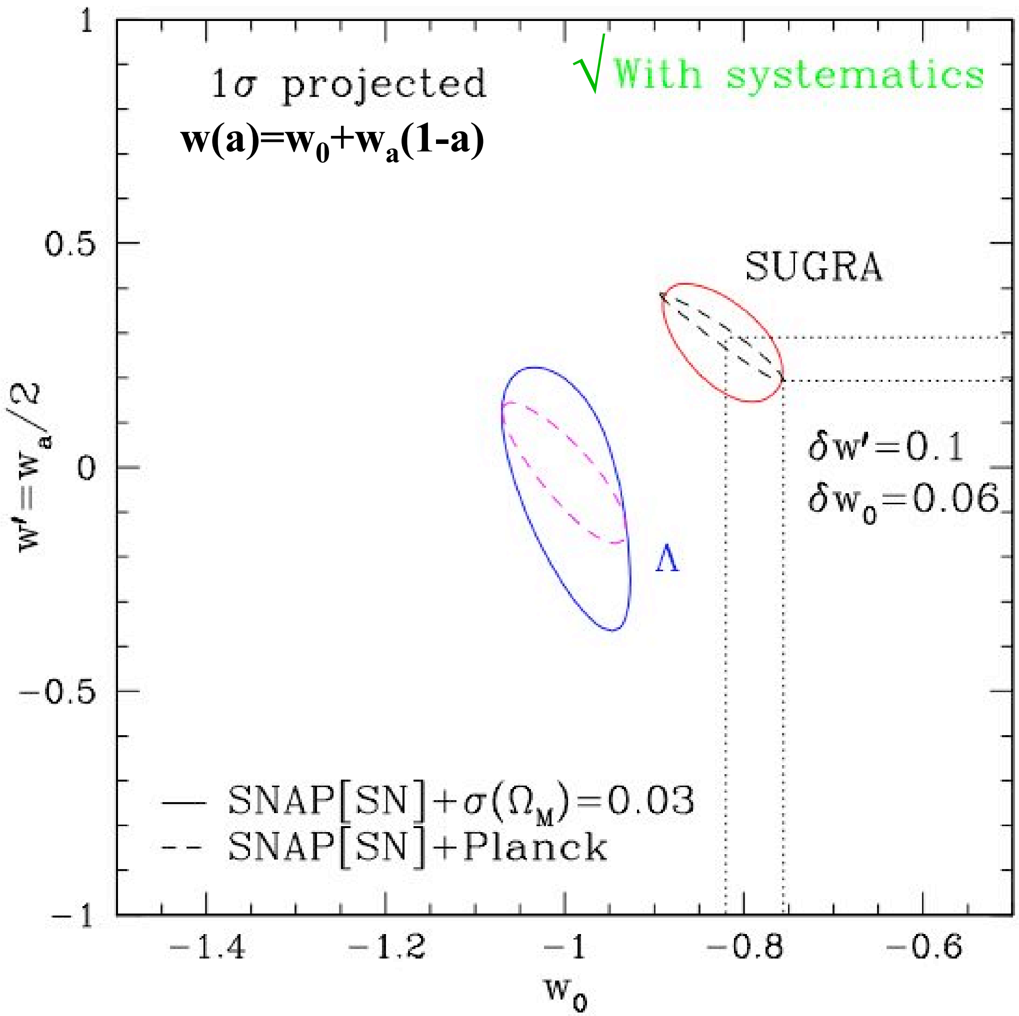
Geometric –
SN Ia, SN II, Weak Lensing, Baryon Oscillations
Geometry+Mass –
Weak Lensing, Strong Lensing
Geometry+Mass+Gas –
SZ Effect, Cluster Counts



Cleanly understood astrophysics leads to cosmology

Complementarity

What is precise? What is accurate?
What plays well with others?



SN+CMB have excellent complementarity, equal to a prior $\sigma(\Omega_M)\leq 0.01$.

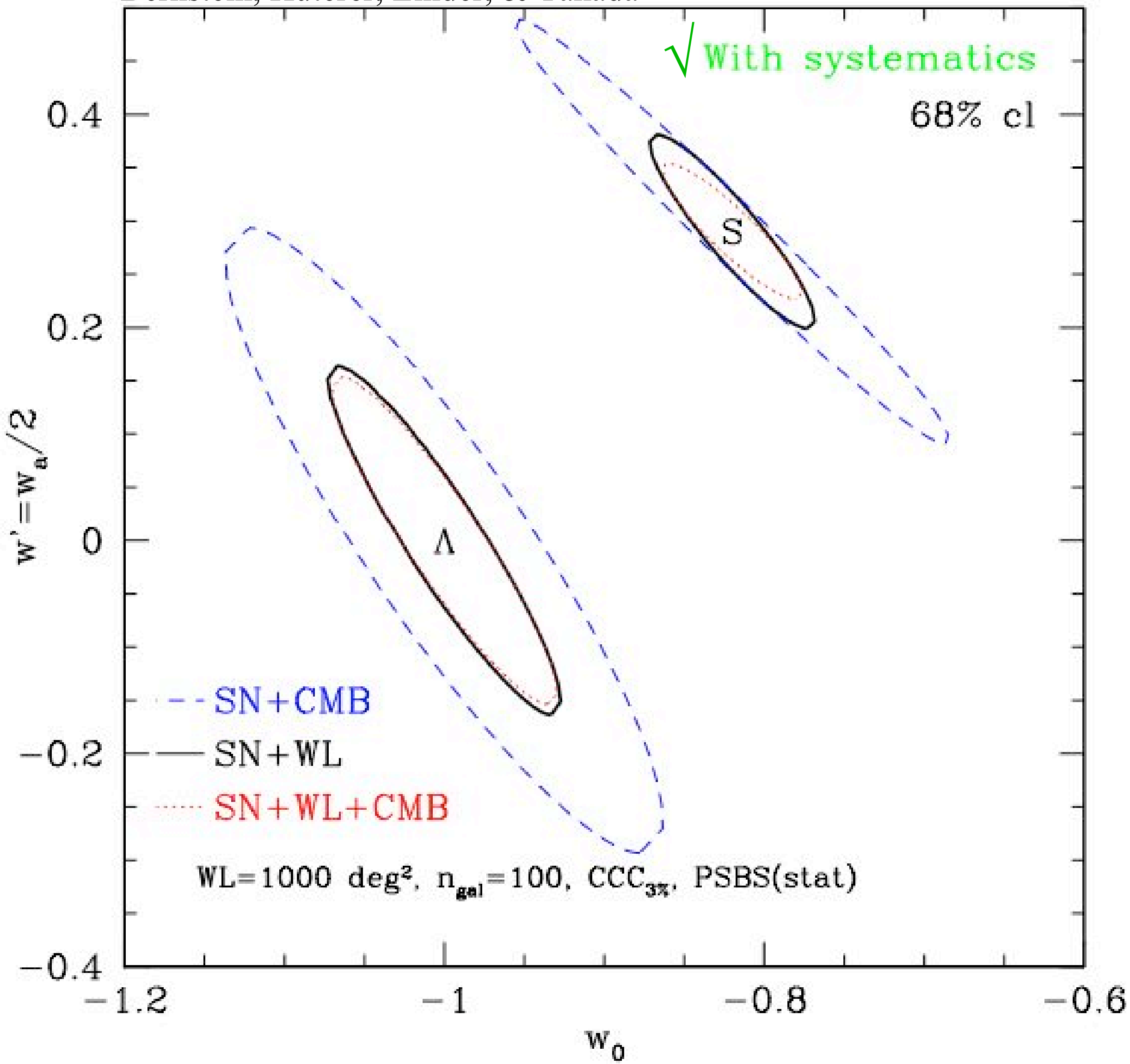
Frieman, Huterer, Linder, & Turner 2003

SN+CMB can detect time variation w´ at 99% cl

(e.g. SUGRA).

Supernovae + Weak Lensing

Bernstein, Huterer, Linder, & Takada



- **Comprehensive:** ***no external priors required!***
- **Independent test of flatness to 1-2%**
- **Complementary:** ***w_0*** **to 5%,** ***w'*** **to 0.11 (*with systematics*)**
- **Flexible: ignorance of systematics - 1000 sq.deg? Panoramic available.**

Systematics and Statistics

Supernovae:

~2000 SN (statistics + like vs. like), spectra, optical/NIR, homogeneous sample, z=0.1-1.7

⇒ Space ~2000 SN, <0.02^{m} (1%)

Weak Lensing:

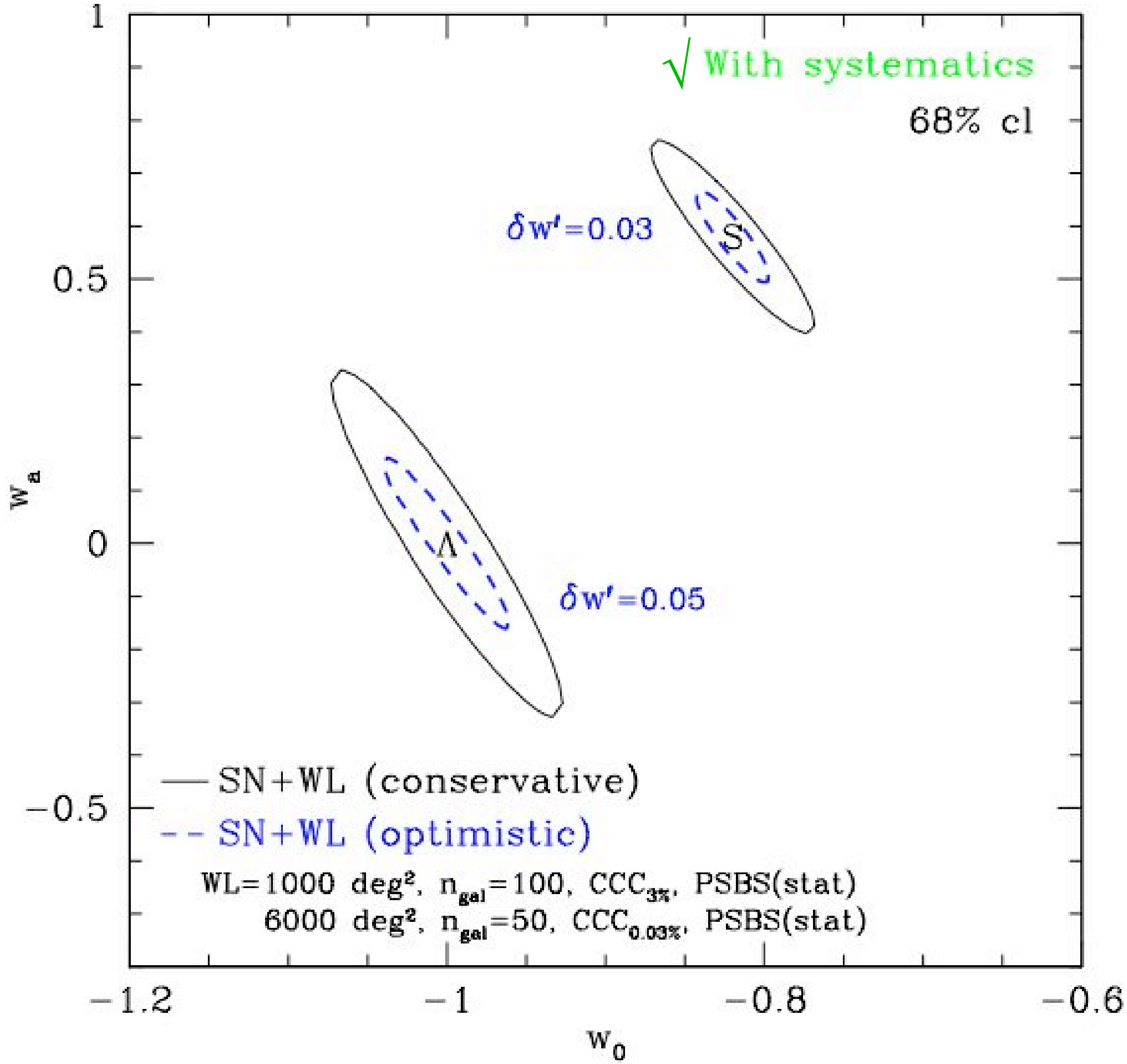
shape noise, sample variance, linear and nonlinear mass spectrum (low *l* and high *l*), PSF resolution and stability, photo-z

⇒ need space, wide area (>1000 deg^2?), ground

Parameter estimations from SN+WL(space) *including systematics*

Matter density:	0.30 ± 0.01
Dark energy density:	0.70 ± 0.01
"Springiness of space" (w):	-1.00 ± 0.05
Time variation of "springiness" (w´):	0.00 ± 0.11

Rosy View of Dark Energy



Systematics will impose a floor on precision gained from wider areas.

Challenge: usable f_{sky}, control systematics

Structure Growth: Linear

Baryon oscillations:

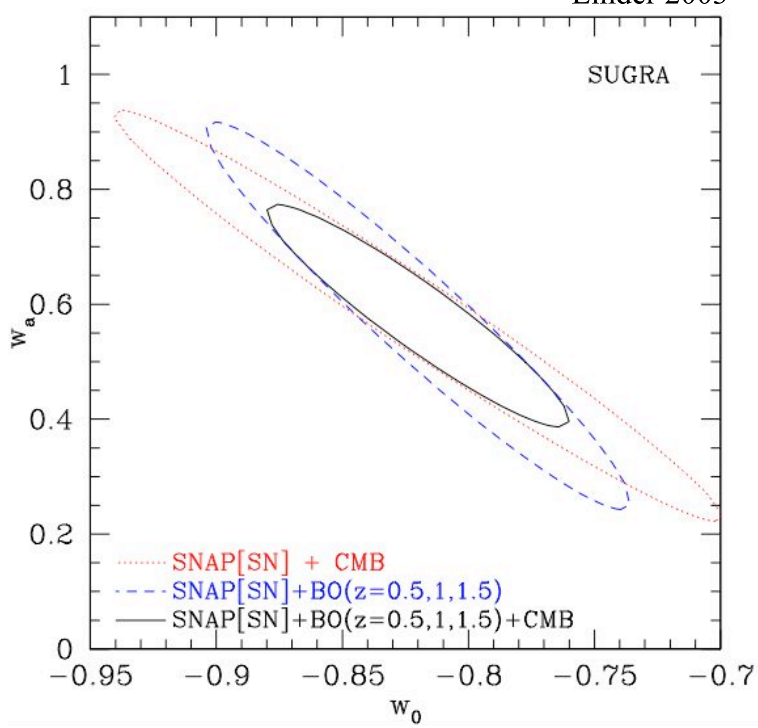
- Standard ruler: ratio of wiggle scale to sound horizon
  → $H(z) / (\Omega_m h^2)^{1/2}$

- Just like CMB – simple, linear physics

KAOS [NOAO study]
Kilo-Aperture Optical Spectrograph
Galaxy redshift survey (400dF)
4000 spectra at once

Baryon oscillations have excellent complementarity with SN (if not Λ)

Linder 2003



Structure Growth: Nonlinear

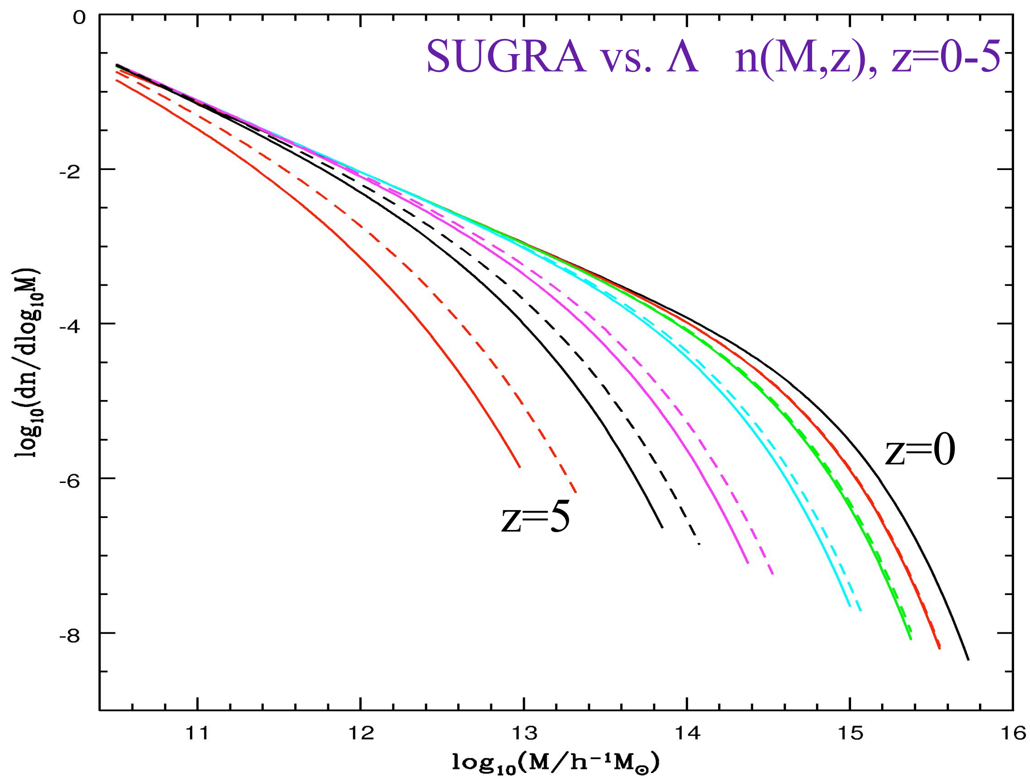
Effects of dynamical dark energy on structure formation

- **Cluster abundances most sensitive at high z, high mass**
- **Systematics in observations, theory, interpretation!**
- **Mass threshold uncertainty of 0.1 dex gives**

δw_{const}~0.1 [M. White], $\delta w'$~?

Halo abundance simulations
Linder & Jenkins 2003

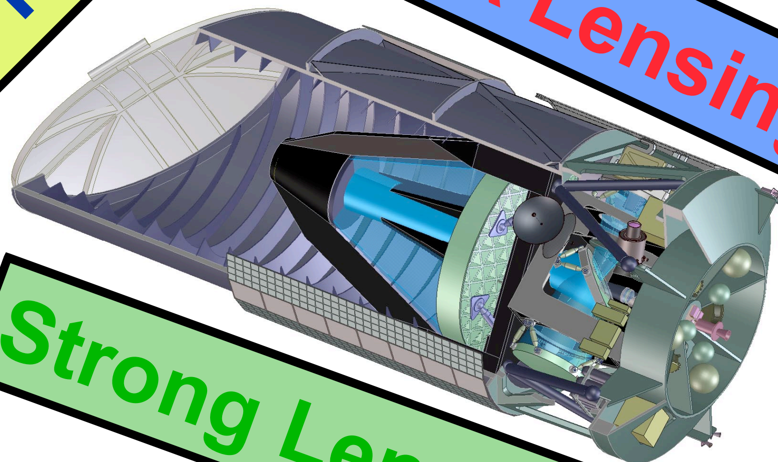
cf. Klypin, Macciò, Mainini & Bonometto 2003; Dolag et al. 2003



Joint Dark Energy Measures

SN Ia

Weak Lensing

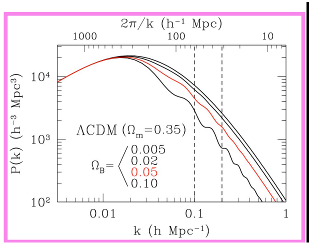


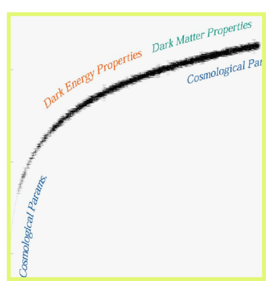
SN II

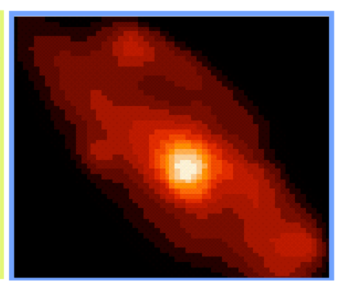
Strong Lensing

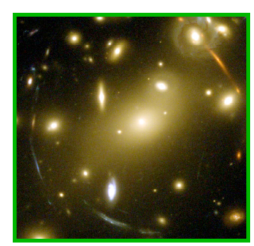
Baryon Oscillations

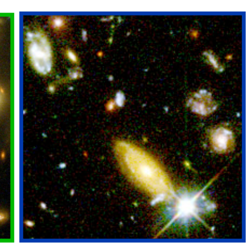
Clusters



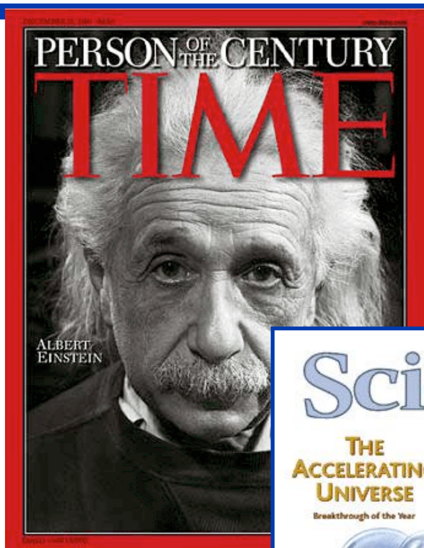








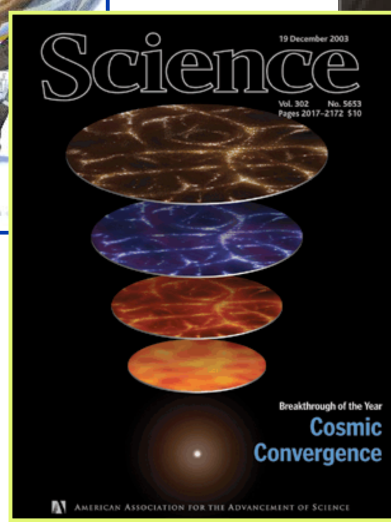
Frontiers of the Universe



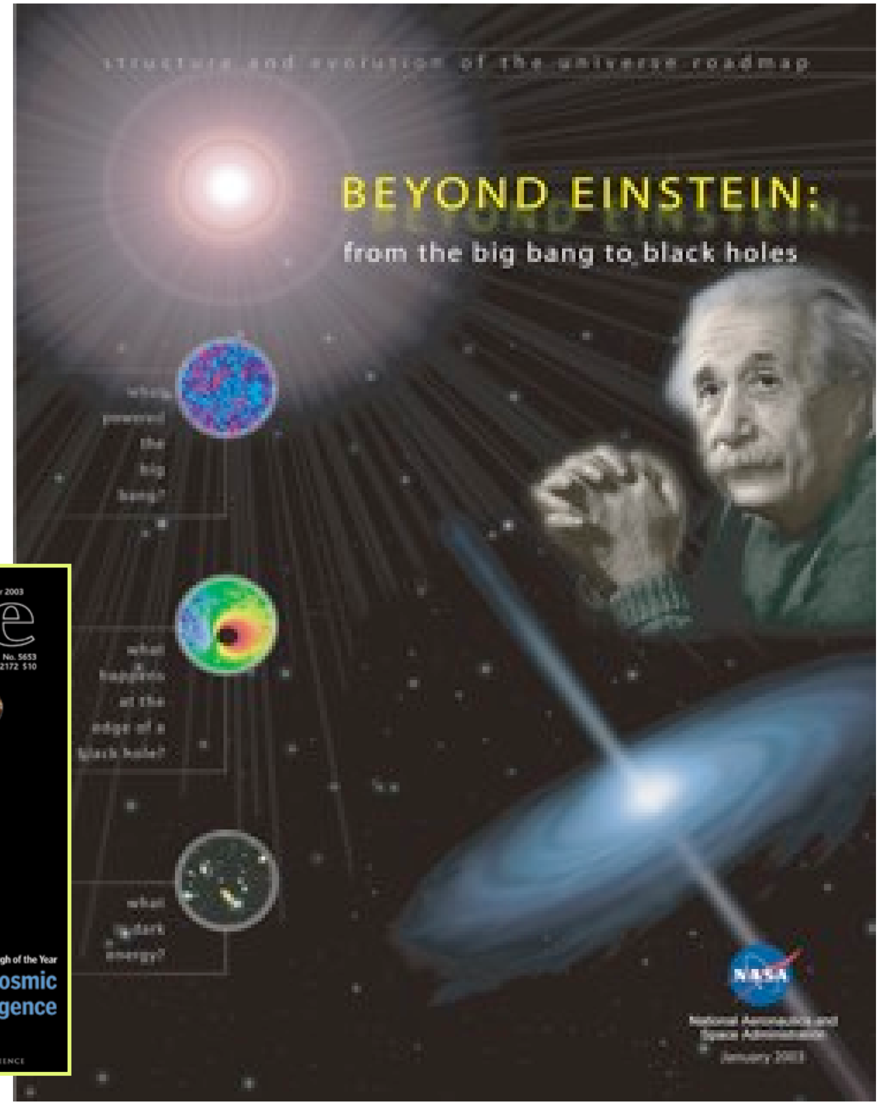
1919

Breakthrough
of the Year

1998



2003



Cosmology holds the key to new physics in the next decade.