Determining the nature of DARK ENERGY

Ram Brustein

אוניברסיטת בן-גוריון

Irit Maor
Paul Steinhardt

- Input for fundamental physics
- Model independent way to extract information
- Known tests (very) sensitive to theoretical priors → challenges to experiment & theory

Focus on: Equation Of State

standard GR form

$$3H^2 = 8\pi G_N \rho$$

$$\dot{H} = -4\pi G_N (\rho + p)$$

$$\dot{\rho} + 3H(\rho + p) = 0$$

$$w_T \equiv \frac{p_T}{\rho_T} = -1 - \frac{2\dot{H}}{3H^2} = -\frac{1}{3} - \frac{2\ddot{a}a}{3\dot{a}^2}$$

FP model → EOS

EOS ⇏ FP model

- ✓Space curvature w = -1/3
- ✓Higher tensor invariants
- ✓Scalar fields
- ✓Extra dimensions
- ✓Scale dependent G_N
- ✓Modified Friedman eq.
- and more, …

"never underestimate the creativity of a theorist!"

additional possibilities:

ρ – Tegmark

state finder: $\ddot{a}_{|t=0}, \dddot{a}_{|t=0}$ Sahni et al.

Classic tests measure integrals of EOS

<u>background</u>

- luminosity distance $d_L = (1+z)r$
- volume $\frac{dV}{dz} = r^2 / H$
- angular distance $d_A = r/(1+z)$
- shear $AP(z) = \frac{\Delta\theta}{\Delta z} H(z) r(z)$

$$r = \int_1^{1+z} \frac{dx}{H(x)}$$

situation clear

<u>fluctuations</u>

- ISW
- linear/non-linear growth factors
- speed of sound

situation unclear:
Please help!

For example:
Luminosity distance d_L vs. redshift z

Textbook form is not sufficient

$$\dot{\rho}_T + 3H\rho_T(1+w_T) = 0$$

$$d\ln\rho_T = 3(1+w_T)\,d\ln z$$

$$\frac{\rho_T}{(\rho_T)_0} = \frac{H^2}{H_0^{\,2}}$$

$$\rightarrow \quad \left(\frac{H}{H_0}\right)^2 = exp\left[3\int_1^{1+z}(1+w_T(x))\,\frac{dx}{x}\right]$$

Splitting components off, for example, NR matter (dark and visible)

$$w_T = \frac{p_T}{\rho_T} = \frac{p_Q}{\rho_m + \rho_Q} = \frac{p_Q/\rho_Q}{\rho_m/\rho_Q + 1} = \frac{w_Q}{1 + g\exp\left[-3\int_1^{1+z} w_Q(x)\, d\ln x\right]}$$

$g = \Omega_m/(1-\Omega_m)$

$$d_L = \frac{(1+z)}{H_0}\int_1^{1+z} dx\; exp\left[-\frac{3}{2}\int_1^x (1+w_T(y))\frac{dy}{y}\right] =$$

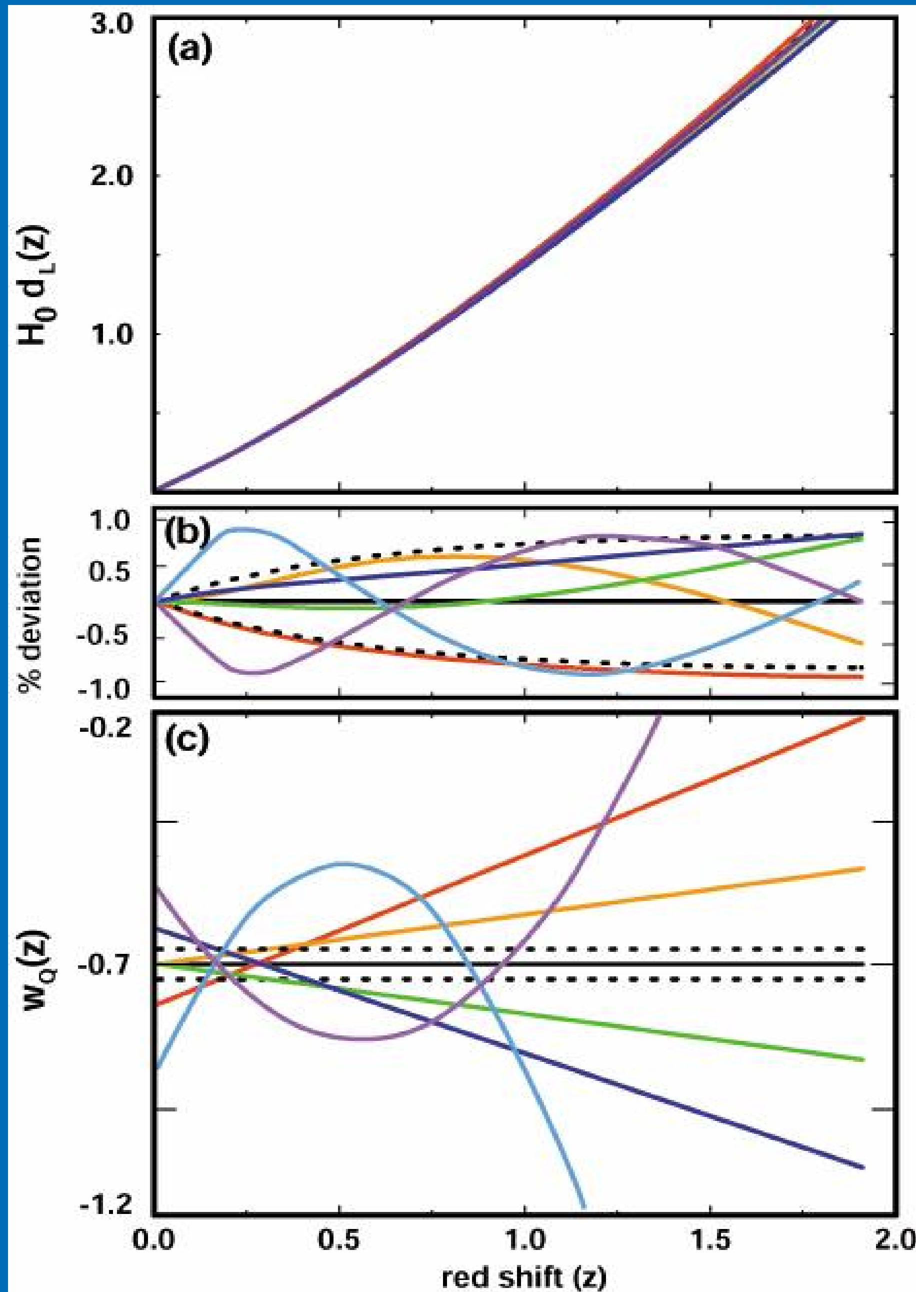
$$= \frac{(1+z)}{H_0}\int_1^{1+z} \frac{dx}{x^{3/2}} exp\left[-\frac{3}{2}\int_1^x \left(\frac{w_Q(y)}{1+g\; exp\left[-3\int_1^y w_Q(u)\frac{du}{u}\right]}\right)\frac{dy}{y}\right]$$

Degeneracy!

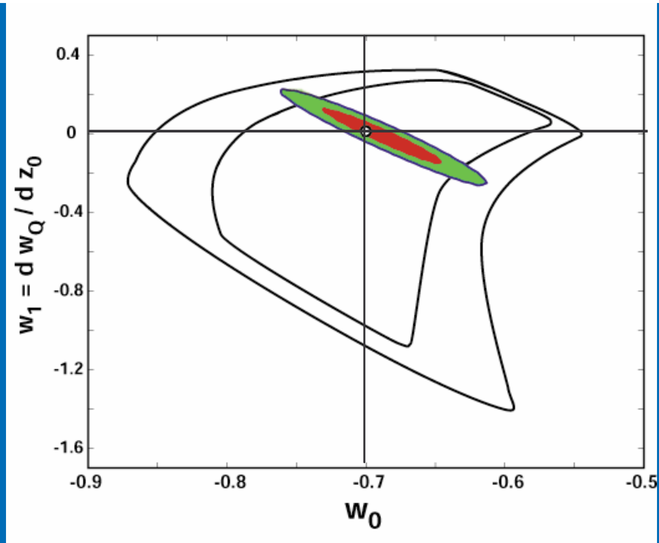
Maor et al. (2001)

a) DL
b) Δ DL/DL
c) $w_Q(z)$
For 9 different EOS

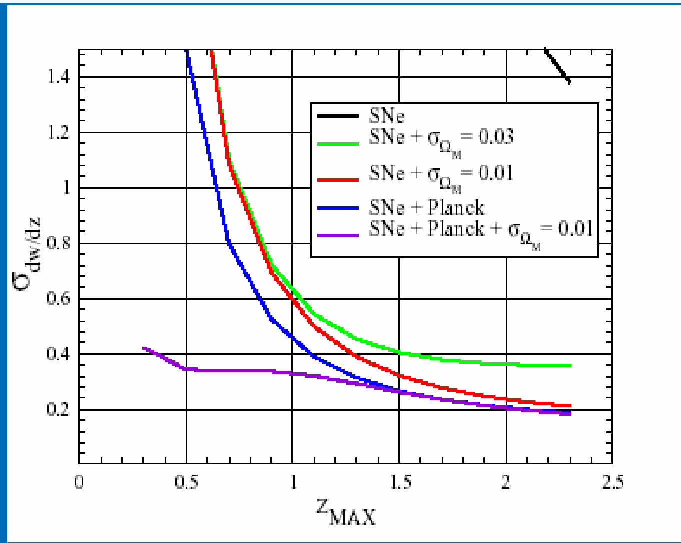
Assuming
1. perfect knowledge of Ω_M
2. flat U.



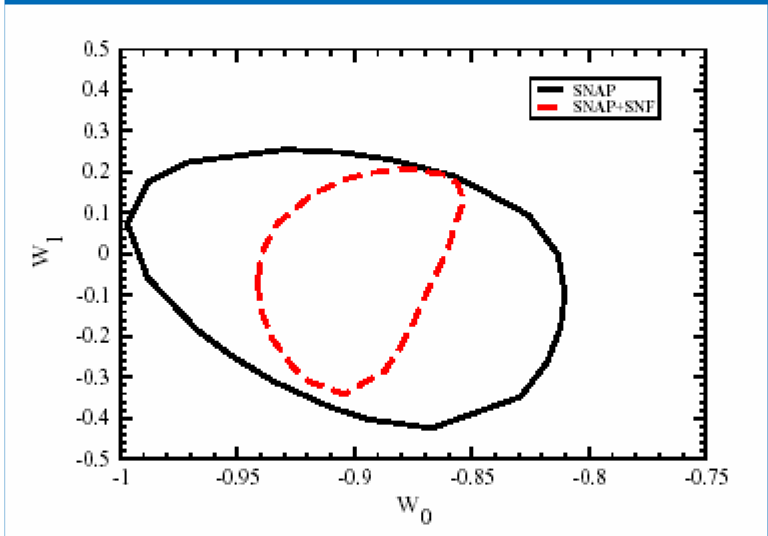
NOT MEASURE w'



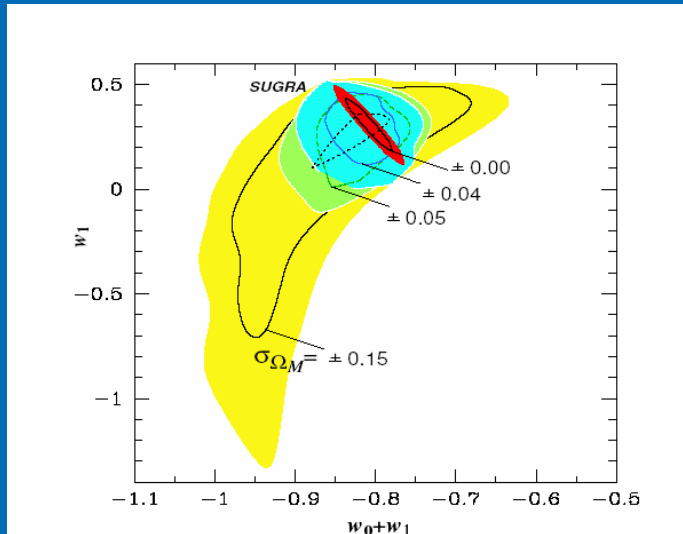
I. Maor et al



J. Frieman et al



P. Antilogus



Weller & Albrecht

Similar conclusions P. Astier, Kujat et al, E. Linder, ...

High sensitivity to choice of theoretical framework and priors

Practical implications:

$$w_\phi = \frac{p_\phi}{\rho_\phi} = \frac{\frac{1}{2}\dot{\phi}^2 - V}{\frac{1}{2}\dot{\phi}^2 + V}$$

» need to keep an open mind about priors: for example restricting w_Q>-1

Fast roll – $w_\phi \sim +1$
Slow roll – $w_\phi \sim -1$
Oscillations – $w_\phi \sim 0$

» present experimental results in a way that will allow modifying priors

$w_\phi < -1$, $w_\phi > +1$
possible, easy !!!

? use some input from theory to parametrize evolution

$$\frac{K-V}{K+V} = -10 \Rightarrow V = -\tfrac{11}{9}K$$

Breaking the Degeneracy?

I. Combine different types of high precision (~ percent) measurements *

→ about 20% in current value of w_Q & not very helpful for time-dependence, but …

- sensitivity estimates depend on actual value of EOS: away from -1 / large positive w' are best
- Hard to distinguish between different forms of DE.

* partial analysis

For example: CMB + SNIa

Maor et al (2002)
Maor & Brustein (2003)
Frieman et al,
Caldwell & Doran, ...

- DE expected to “disappear” for $z > 2$
- CMB photons travel most of the way through MD U.

➔ No gain compared to “low z” probes

- Best accuracy for d_A from CMB ~ 1% (e.g. 1st peak)

➔ CMB comparable to future SNIa experiments

(Ω_M known+ flat U.+…)

╬ Confusion about possible attainable sensitivity of other experiments (shear, volume, growth factor, …)

Breaking the Degeneracy?

II. Invent new “local” tests:

“move the detector to a different z”

III. Accept theoretical input:

e.g.: that dark energy is a CC,

a specific quintessence model, …

Measure z(t)

Jimenez & Loeb, Jimenez et al

$$1 + z(t) = \frac{a_0}{a(t)}$$

$$\dot{z}(t) = -(1+z)H$$

$$\ddot{z}(t) = (1+z)\dot{H} + \dot{z}H$$

$$\dot{H} = -\tfrac{3}{2}(1+w_T)H^2$$

$$\Rightarrow \quad \ddot{z}(t) = -\frac{\dot{z}^2}{(1+z)}\left[\tfrac{3}{2}(1+w_T)+1\right]$$

$$\Downarrow$$

$$w_T = -\tfrac{2}{3}(1+z)\frac{\ddot{z}(t)}{\dot{z}^2} - \tfrac{5}{3}$$

Practical ??

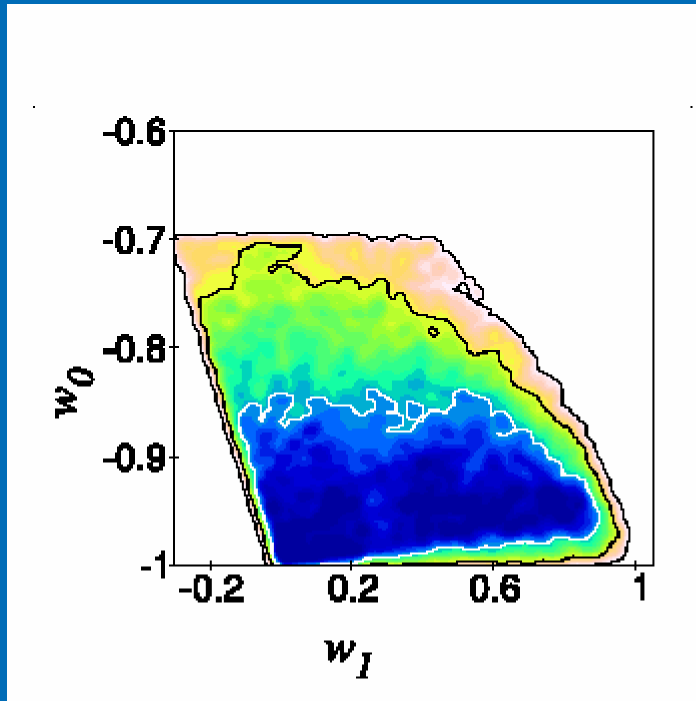
Conclusions

Known tests (very) sensitive to theoretical priors

➔ Challenges to Experiment & Theory

- **Need: public access to data**
  - ➔ **independent combined analysis**
  - ➔ **explore different priors**

- **Need:**
  - **either a new “local” test - ???**
  - **or new theoretical input - ???**
  - **or LUCK ☺**


-0.6
-0.7
-0.8
-0.9
-1
-0.2
0.2
0.6
1
w_0
w_1

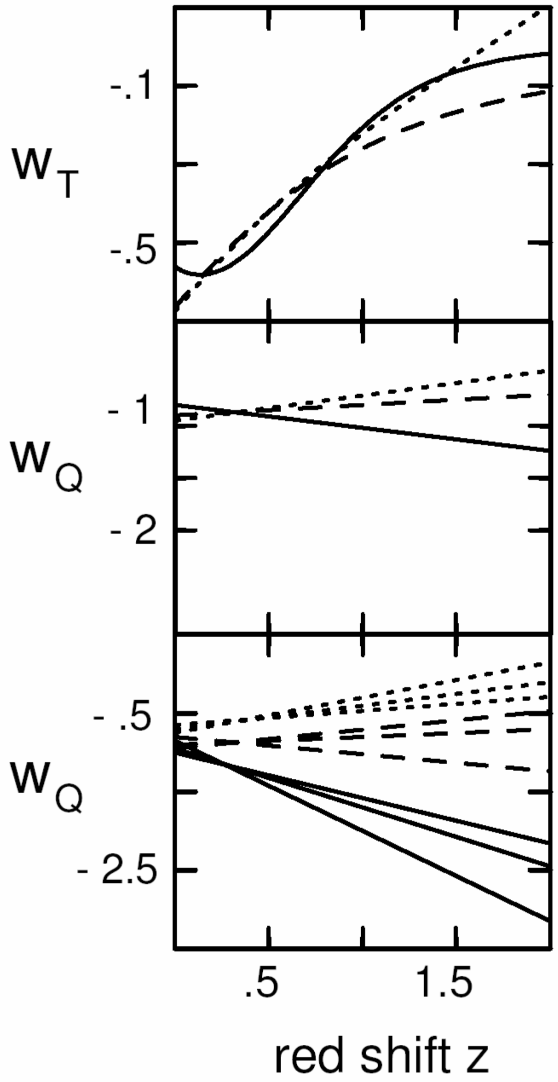


Figure 2: Models within 95% CL region of a fit to data generated from the fiducial model $(w_Q, \Omega_m) = (-1, 0.3)$ assuming $w_Q = w_0 + w_1 z$. Top: The total EOS $w_T(z)$, for three different linear models. Middle: $w_Q(z)$ assuming $\Omega_m = 0.3$ exactly, for the same linear models. Bottom: $w_Q(z)$ for nine models, assuming that $0.2 < \Omega_m < 0.4$ (no relation between the dashed, dotted and solid lines of the bottom panel to those of the middle and top ones).

- CMB vs. SN Ia

Maor & Brustein (2003)

$$\begin{aligned} d_L(x_{ls}) &= x_{ls}\int_1^{x_{ls}} \frac{dx}{H(x)} \\ &= x_{ls}\int_1^{3} \frac{dx}{H(x)} + x_{ls}\int_3^{x_{ls}} \frac{dx}{H(x)} \\ &= \frac{x_{ls}}{3} d_L(3) + \frac{x_{ls}}{H(3)}\int_3^{x_{ls}} \frac{dx}{H(x)/H(3)} \\ &= \frac{x_{ls}}{3} d_L(3) + \frac{x_{ls}}{H(3)}\int_3^{x_{ls}} \frac{dx}{(x/3)^{3/2}} \\ &= \frac{x_{ls}}{3} d_L(3) + 2x_{ls}\left(\frac{1}{\sqrt{3}} - \frac{1}{\sqrt{x_{ls}}}\right)\left(\frac{3^{3/2}}{H(3)}\right), \end{aligned}$$

$x=z+1$

$$d'_L(3) = c_1 \frac{d_L(3)}{3}$$

$$\Delta d'_L(3) = c_2 \frac{\Delta d_L(3)}{3}$$

$$\left(\frac{\Delta d_L}{d_L}\right)_{x_{ls}} \simeq \frac{2c_2 - 1}{2c_1 - 1}\left(\frac{\Delta d_L}{d_L}\right)_{x=3}$$

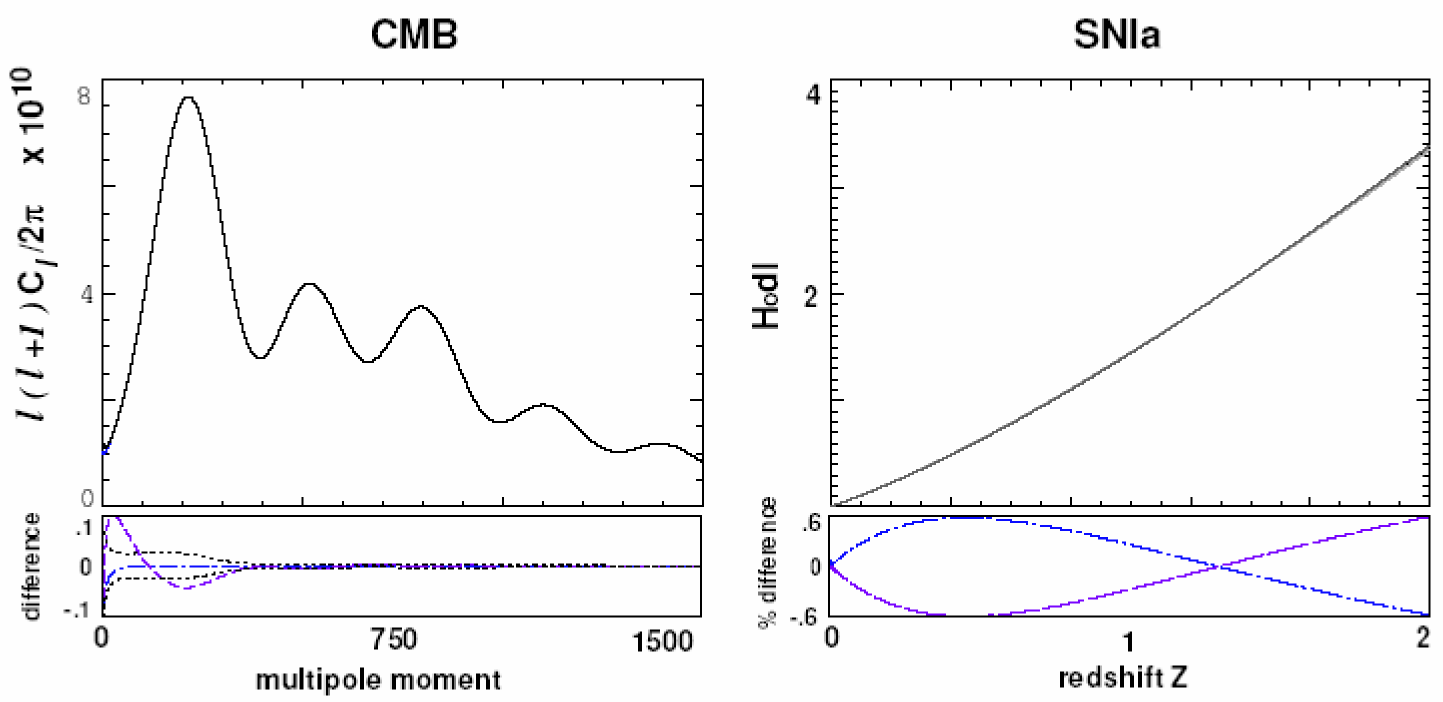


Figure 9: Illustration of the degeneracy problem for a model with constant w and two models with time-varying w as discussed in the text. The upper left hand panel compares the CMB power spectra. The lower left shows the differences between the time-varying models and the constant w model and shows that they are less than or comparable to the full-sky cosmic variance theoretical uncertainty, the envelope shown in the figure (dotted lines).

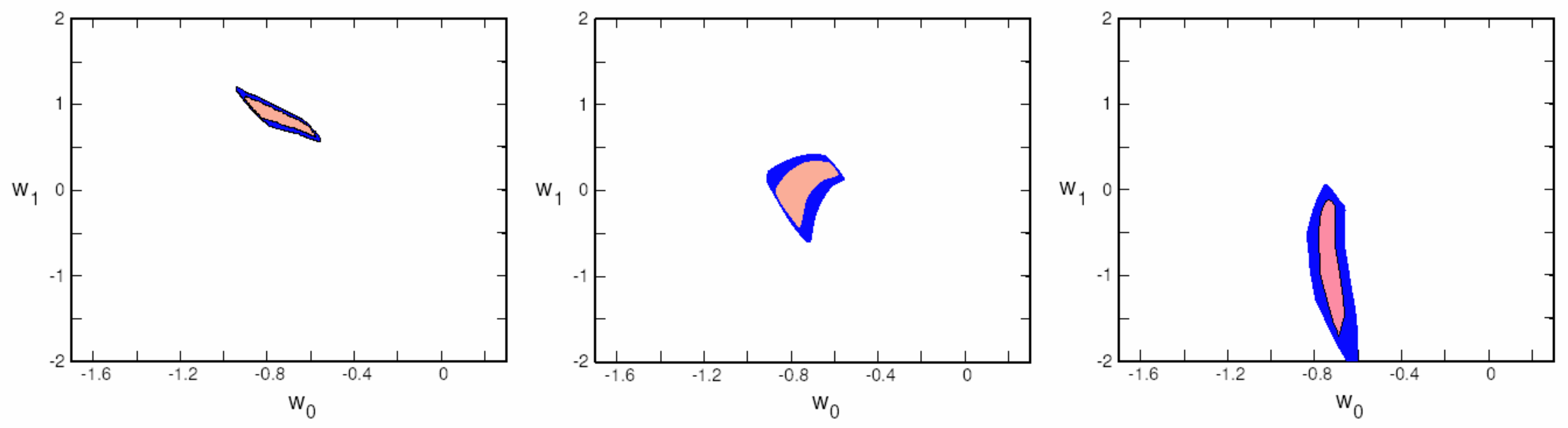


Figure 6: Likelihood contours (68% (lighter) and 95% (darker) C.L.) in the (w_0, w_1) plane, for fits to data generated from 3 different fiducial models. LEFT: $(w_0, w_1, \Omega_m) = (-0.7, 0.8, 0.3)$. MIDDLE: $(w_0, w_1, \Omega_m) = (-0.7, 0.2, 0.3)$. RIGHT: $(w_0, w_1, \Omega_m) = (-0.7, -0.8, 0.3)$. Only the results shown in the left panel are inconsistent with a constant $(w_1 = 0)$ w_Q model.

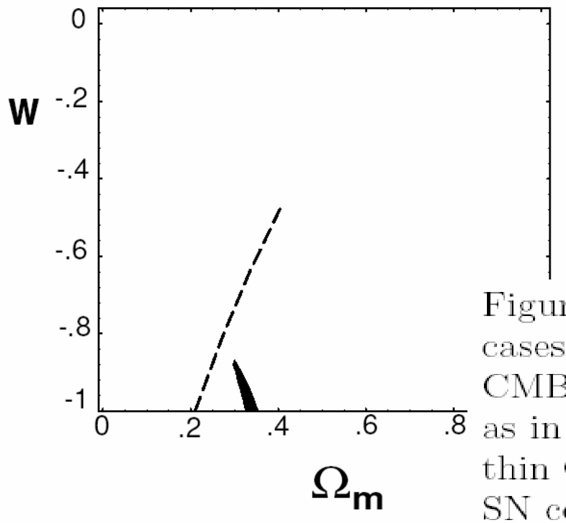


Figure 10: The same as Fig. 8 but with a fiducial model with $w_1 = 1/3$. For cases like this with very rapid time-variation in w, a symptom is that the CMB and SN degeneracy regions do not overlap. For w_1 large and positive, as in this example the SN contour (solid black) lies to the right of the very thin CMB degeneracy region (dashed curve). For w_1 large and negative, the SN contour lies to the left.

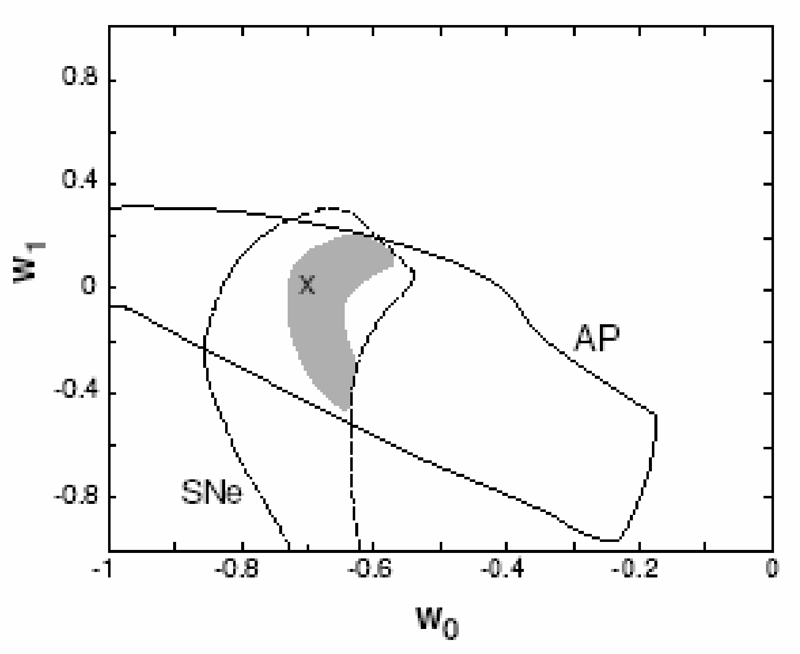


Figure 7: Two-sigma contours in the $(w_0, w_1) \equiv (w_Q(z=0), dw_Q/dz_0)$ pla
for two idealized experiments. One measures thousands of supernovae l
tween $z=0$ and $z=2$ (dashed contours). The supernovae are divided into bins with a net error of 1.4% per bin. The second experiment is an optimis
estimate for the AP test (solid contours), assuming 50 bins of Lyman-alpha clouds uniformly distributed between $z=1.5$ and $z=3$ with each bin measured with an accuracy of 3%. Both experiments assume a fiducial model with $\Omega_m = 0.3$, $\Omega_Q = 0.7$, $w_Q = -0.7 = const.$, indicated by the X. In both experiments Ω_m is marginalized over the range 0.2 to 0.4. The two-sigma joint likelihood for the two observations is shown in the shaded region.

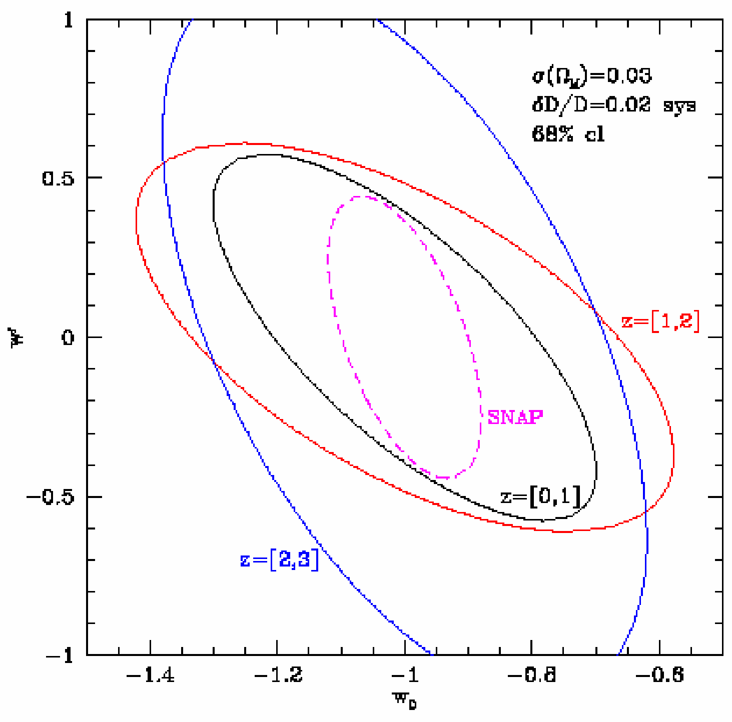


FIG. 8: Parameter estimation in the $w' - w_0$ plane, with systematics, marginalizing over Ω_m. Realistic assessment of systematics is key to evaluating the impact of the cosmic shear

Linder, astro-ph/0212...

Maor et al astro-ph/0112...