Complementarity in Dark Energy measurements

Complementarity of optical data in constraining dark energy

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The situation:

- SN 1A (Riess et al. 04)
- CMB (WMAP ext)
- CMB+ H prior (HST Key project)
- LSS (2dF Verde et al. 02)

(figure by L. Verde)
Assuming a flat Universe....
Assuming a flat Universe….

But, why constant?

CMB (WMAPext)

CMB+Galaxy surveys

SN (Riess et al 04)
Assuming a flat Universe…

But, why \( w \) constant? Why flatness?
THE SYMPTOMS
Or OBSERVATIONAL EFFECTS of DARK ENERGY

Recession velocity vs brightness of standard candles: dL(z)

CMB acoustic peaks: Da to last scattering

LSS: perturbations amplitude today, to be compared with CMB (or Matter density today)
HOW TO MAKE A DIAGNOSIS?

Any modification of gravity of the form of $f(R)$ can be written as a quintessence model for $a(t)$.

This degeneracy is lifted when considering the growth of structure.

Effort in determining what the growth of structure is in a given Dark Energy model!

combination of approaches!
We can “measure” dark energy because of its effects on the expansion history of the universe and the growth of structure.

SN: measure \( d_L = (1 + z) \int_0^z (1 + z') \frac{dt}{dz'} \)

CMB: \( \theta_A \) and ISW \( \rightarrow S_a(t) \)

LSS or LENSING: \( S_g(z) \) or \( \rightarrow S_a(t) \)

AGES: \( H(z) \rightarrow S_a(t) \)

Standard clocks:
\[
H_0^{-1} \frac{dz}{dt} = -(1 + z)^{5/2} \left\{ \Omega_m(0) + \Omega_Q(0) \exp \left[ 3 \int_0^z \frac{dz'}{(1 + z')} w_Q \right] \right\}^{1/2}
\]

See Rocky&Josh talks.
COMPLEMENTARITY IS THE KEY!

The questions we want to ask:

- Is it a cosmological constant?
- A rolling scalar field? A fluid?
- Is it a $w = -1$? $w(z)$?
- Is it a breakdown of GR at horizon scales?

Example:

Measurements of the growth of cosmological structures will help to disentangle the two cases.

Things could be "going wrong" in other ways

Backreaction…

For not mentioning: control of systematics!
MEASURING DARK ENERGY

Two ways (you may not have thought about) in which GEMINI & SUBARU can make a difference

- optical follow up for SZ surveys
  - Clusters weak lensing masses
  - Provide redshifts

- Provide spectra of old high-redshift galaxies

Bonds
CD’s

Highly volatile mutual funds
Surveys like ACT and SPT will detect thousands of clusters via the SZ effect.

Clusters number counts $\nu$ growth of structure:

Very sensitive to dark energy but also to clusters masses

(& clusters physics)

Fig. From Mohr et al 02

Optical follow up needed for redshifts and weak lensing masses

www.hep.upenn.edu/act  http://spt.uchicago.edu
Using the KSZ signal

The peculiar velocity field is sensitive to the onset of the late acceleration of the Universe.

Recall that KSZ

\[ \delta T_{kSZ} \propto n_e v_e \cdot n \]

The power spectrum of the velocities is

\[ P_{vv}(k) = \left( H(z) \left| \frac{dD_\delta}{dz} \right| \right)^2 \frac{P_m(k)}{k^2} = D_v^2 \frac{P_m(k)}{k^2}, \]

Clusters probe linear scales

Not “POTENT”, need redshifts not distances
KSZ sensitivity to w

Sensitive to growth of velocity
Insensitive to knowing the clusters mass (not counting clusters)
Redshifts needed $W(z)$!

(from Hernandez-Monteagudo et al.2005)
With J. Simon & R. Jimenez: Let’s be bold…

Let’s assume that the dark energy is given by a scalar field, this description includes the cosmological constant case.

…and try to reconstruct the shape of the potential

Theory wants $V(q)$ … but we can’t observe q

So we will go for $V(z)$ then find a way to get back to $V(q)$

$V(q) = H/m_p - 1/2(r_t + p_t)$

A FLAT potential $\rightarrow$ Cosmological constant

$V(z) = \lambda(1+z)\alpha$ $\rightarrow$ Ratra-Peebles case of a constant w

See also Parkinson talk
A mini-inflation?

Introduce quantities similar to the horizon flow parameters in inflation

\[ \varepsilon_{n+1} = \frac{d \log |\varepsilon_n|}{dN}, \quad N = \log \frac{a}{a_i}, \quad \varepsilon_0 = \frac{H(N_i)}{H(N)} \]

Turns out that if you know \( \rho_m, H, \Phi \) and assume a flat universe and standard GR*

you can reconstruct \( V(z) \)

Integration of a differential equation gives you \( q(z) \)

which you can use to get back \( V(q) \)

* If you want to see the equations for the case of corrections to standard GR, please go to sec II of astro-ph/0412269
Unfortunately….

Data are not yet good enough for a fully non-parametric reconstruction

**Chebyshev** to the rescue…

\[
V(z) = \sum_{n=0}^{M} \lambda_n T_n[x(z)], \quad x(z) = \frac{2z}{z_{\text{max}}} - 1
\]
No data, priors only

\[ K > 0 \quad \rho_T > 0 \quad \text{that is} \quad H^2 > 0 \quad V_0 + K_0 = \Omega_{Q,0} \rho_c \quad \text{Flatness} \]

\[ \Omega_{m,0} = 0.27 \pm 0.07 \quad \text{From large-scale structure!} \]
At $z=0$ $dz/dt$ gives $H_0$ and we have SDSS galaxies: $H(z) = -\frac{1}{(1+z)} \frac{dz}{dt}$

Similar trend found by Bernardi et al. (astro-ph/0509360) using alpha-enhanced models

THE EDGE for $z<0.2$

The value of $H_0$
GDDS + high z radiogalaxies + Treu et al. 2000 sample

McCarthy et al. 2004

From Simon, Verde, Jimenez (2005)
No data, priors only

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Using galaxy ages

From Simon, Verde, Jimenez (2005)
As a benchmark let’s consider the Supernovae
CONTRAINTS ON W

\[ w < -0.9 \quad \text{if} \quad V(z) = (1 + az) \quad \text{a} = 3(w + 1) \]

\[ w_0 = -1 \quad \text{(in the w, wa parameterization)} \]
Imagine what you could do with 2000 “cosmic chronometers”....
CONCLUSIONS

**Complementarity**
Observations relying on different physics and affected by different systematics.

Optical observations are a key ingredient.

Two additional methods on the market:
KSZ and cosmic chronometers.

And I have not mentioned:
Weak lensing, supernovae, cross-correlation of LSS with e.g. CMB, lensing and CMB, Baryonic oscillations, ……

The meeting is still young.
3: Reconstruct $w(z)$: cosmic chronometers

Old, passively evolving galaxies

Is it possible to obtain accurate ages?

(From Jimenez, LV, Treu, Stern 2003)
3: Simulating the “edge”