Constraining the Dark Energy Potential with BAO Surveys

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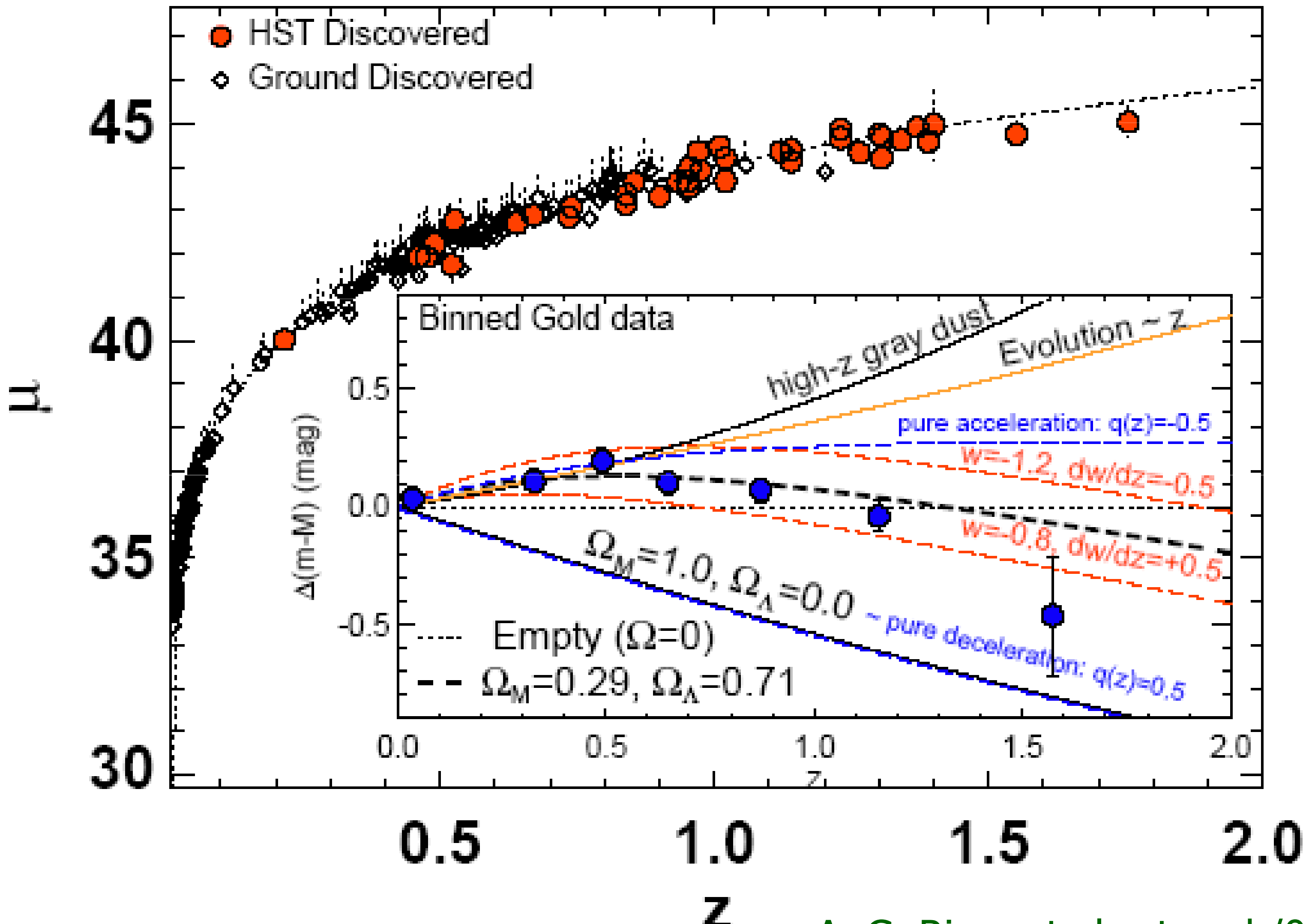
The Accelerating Universe: SNIa



A. G. Riess et al astro-ph/0611572

The Accelerating Universe

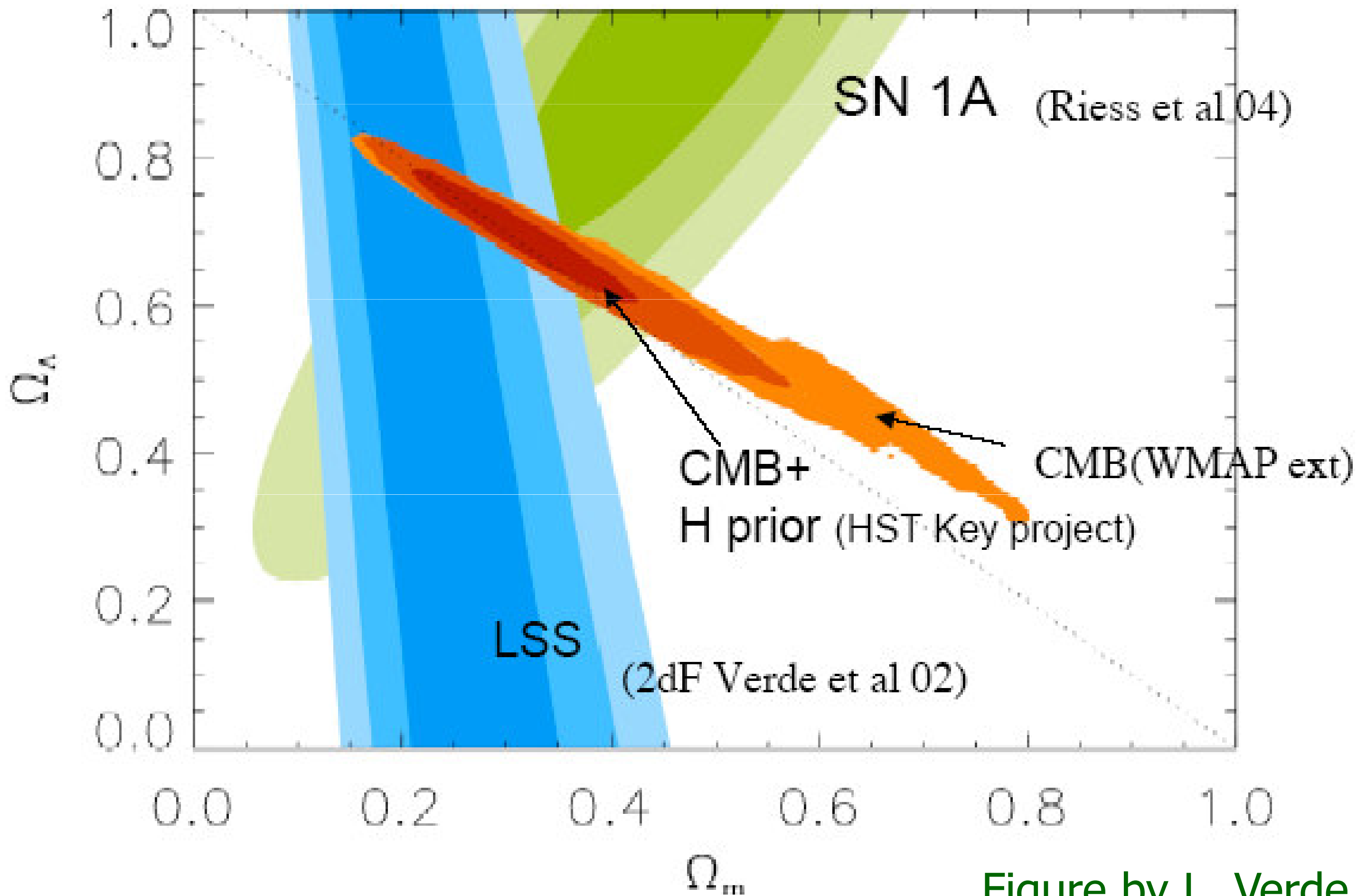


Figure by L. Verde

The Friedmann Equations

Einstein's Equations + Homogeneity and Isotropy

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = -\kappa T_{\mu\nu}$$

FRW Metric

with $\kappa = 8\pi G$

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right)$$

Friedmann Equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\kappa}{3}\rho - k\frac{c^2}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{\kappa}{6}(\rho + 3p)$$

For $\ddot{a} > 0$ We need $3p < -\rho$ but

$$\begin{cases} p = 0 & \text{for matter} \\ p = \dfrac{\rho}{3} & \text{for radiation} \end{cases}$$

Cosmological Constant

Adding a *Cosmological Constant* Λ to the Einstein Equation

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} - \Lambda g_{\mu\nu} = -\kappa T_{\mu\nu}$$

The Friedmann Equations become

$$\begin{cases} H^2 = \left(\dfrac{\dot{a}}{a}\right)^2 = \dfrac{\kappa}{3}\rho + \dfrac{\Lambda}{3} - k\dfrac{c^2}{a^2} \\ \dfrac{\ddot{a}}{a} = -\dfrac{\kappa}{6}(\rho + 3p) + \dfrac{\Lambda}{3} \end{cases}$$

with $\kappa = 8\pi G$

If Λ dominates $\ddot{a} > 0$

Modifying the Cosmological Constant

But what if Λ is not a constant?

Alternative parameterizations of Dark Energy

- Constant equation of state

$$p = -\rho = -\frac{\Lambda}{8\pi G} \qquad \Rightarrow \qquad p = w\rho$$

- More general equations of state

$$w(z) = w_0 + w' z \qquad\qquad w(a) = w_0 + w_a (1-a)$$

DE task force

A More general parameterization

But nature could be much more general than that…

If Dark Energy came from the potential of a scalar field $V(\phi)$

$$\rho_\phi = K + V(\phi) \qquad p_\phi = K - V(\phi) \qquad \text{with} \qquad K = \frac{1}{2}\dot{\phi}^2$$

The Friedmann Equations become

$$\begin{cases} H^2 = \dfrac{\kappa}{3}(\rho + V + K) - k\dfrac{c^2}{a^2} \\ \dfrac{\ddot{a}}{a} = -\dfrac{\kappa}{6}\left(\rho + 3p + 4K - 2V(\phi)\right) \end{cases}$$

If $V(\phi)$ dominates we can also have $\ddot{a} > 0$

but $V(z)$ could be a very general function of z

A More general parameterization

Even if $V(z)$ is a general function we need to parameterize it and try to fit it to data

We expand the potential in Chebyshev polynomials

$$V(z) \approx \sum_{n=0}^{N} \lambda_n T_n \left(2\frac{z}{z_{\max}} - 1 \right)$$

with $z_{\max}$ the maximum redshift of the survey

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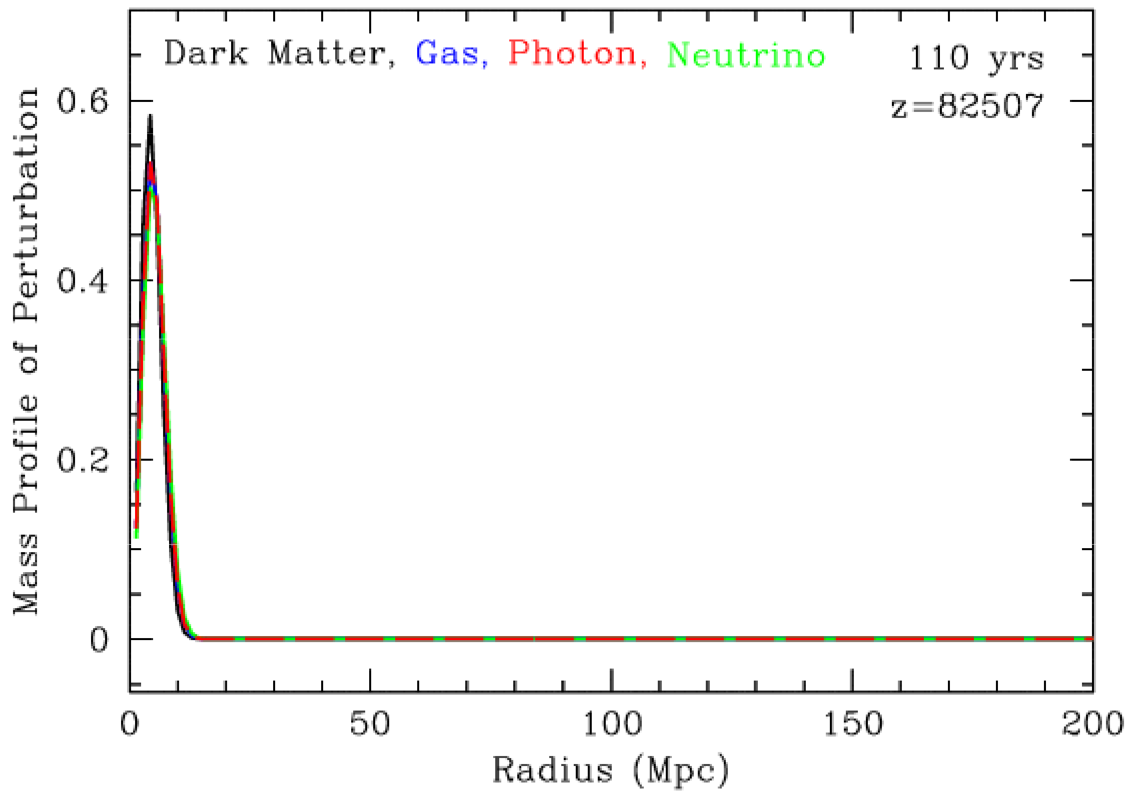
We will study the constraints that BAO surveys can place on the first three coefficients λ_i

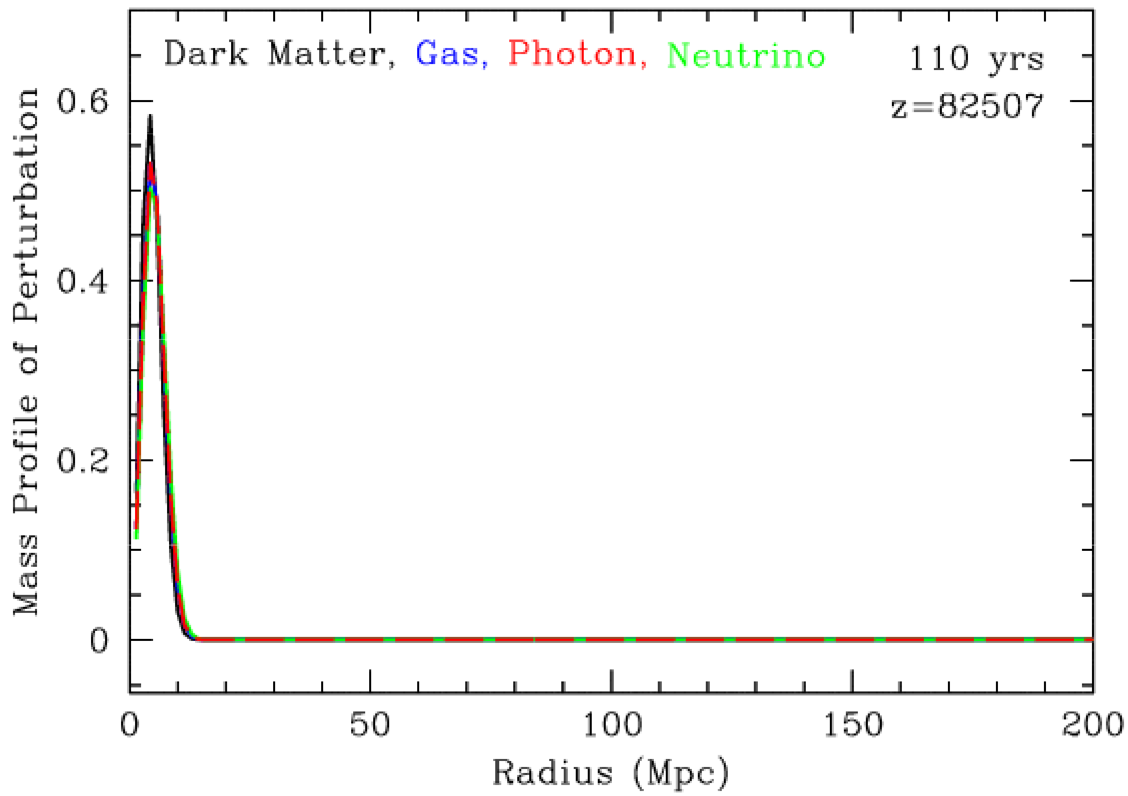
BAO



Dark Matter Baryons Photons Neutrinos

Animation by D. Eisenstein

BAO



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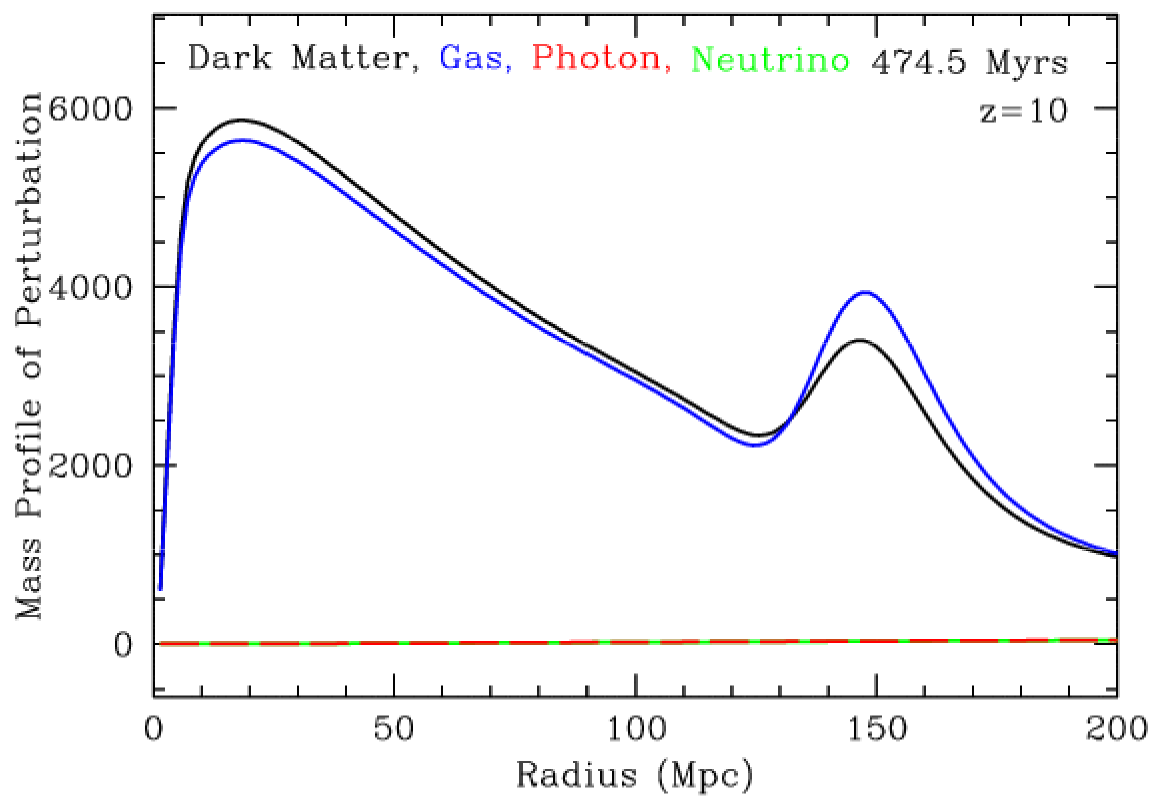

Dark Matter Baryons Photons Neutrinos

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BAO

The distance traveled by sound until recombination

Rs= 153.3 ± 2.0 Mpc   WMAP 5th year

provides a "standard ruler"

Measuring its transverse size $\Delta\theta$ gives:

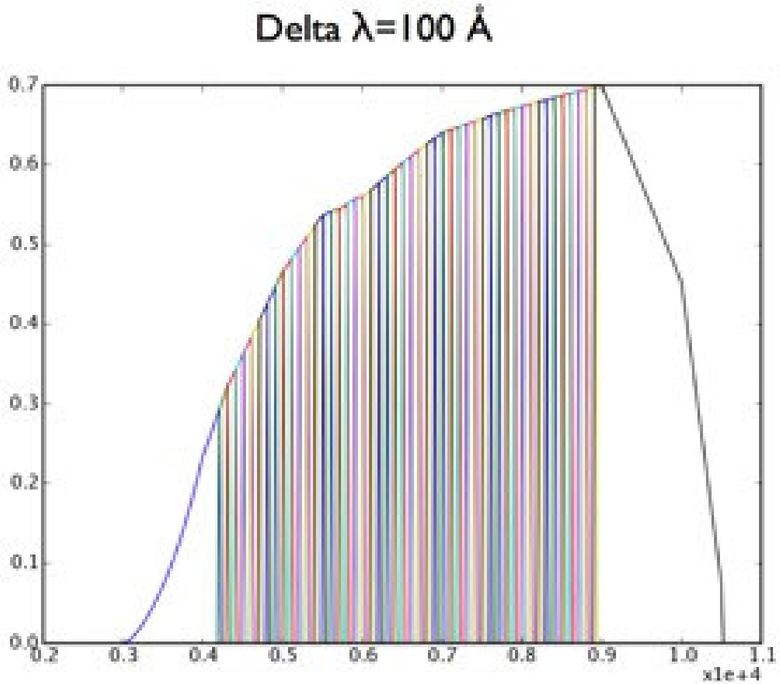
$$d_A^{co} = \int_0^z \frac{c}{H(z')} dz' = \frac{R_s}{\Delta\theta}$$

Measuring its radial size Δz gives:

$$H(z) = \frac{c\Delta z}{R_s}$$

PAU (Physics of the Accelating Universe)

PAU is a photometric survey but with ~ 40 filters of ~100 Å



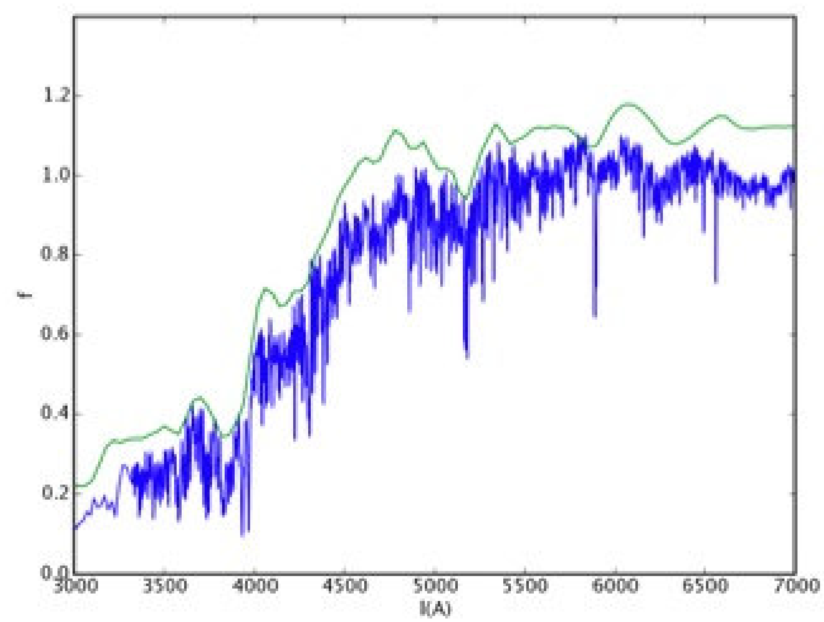


Figure by T. Benítez

This allows to measure the redshift with $\sigma_z \sim 0.0035(1+z)$

Will measure between $z = 0.1\text{-}1$

Adept (Advanced DE Physics Telescope)

Space–based telescope
to probe DE through
observation of SN Ia and BAO

Spectroscopic redshifts

Can go deeper in redshift, will measure between $z = 1\text{-}2$

BAO Errors

In C. Blake et al. 2005 several BAO surveys were simulated and a formula to estimate the precision of the survey was fitted

$$\sigma_H(z_i) = x_0^H \frac{4}{3}\sqrt{\frac{V_0}{V_i}} f_{nl}(z_i)$$

$$\sigma_d(z_i) = x_0^d \frac{4}{3}\sqrt{\frac{V_0}{V_i}} f_{nl}(z_i)$$

$$f_{nl}(z_i) = \begin{cases} 1 & z > 1.4 \\ \left(\frac{1.4}{z}\right)^{1/2} & z < 1.4 \end{cases}$$

$$x_0^d = 0.0085$$

$$x_0^H = 0.0148$$

$$V = \frac{2.16}{h^3} Gpc^3$$

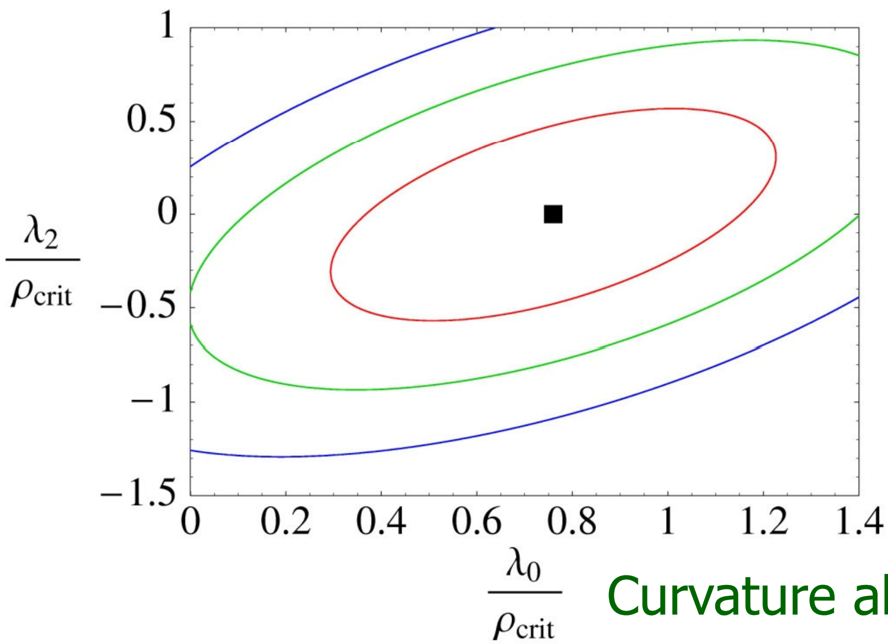
We have studied two future BAO surveys: PAU and Adept

PAU	Adept
A=10000 square degrees	A=30000 square degrees
9 redshift bins	10 redshift bins
between 0.1 and 1	between 1 and 2

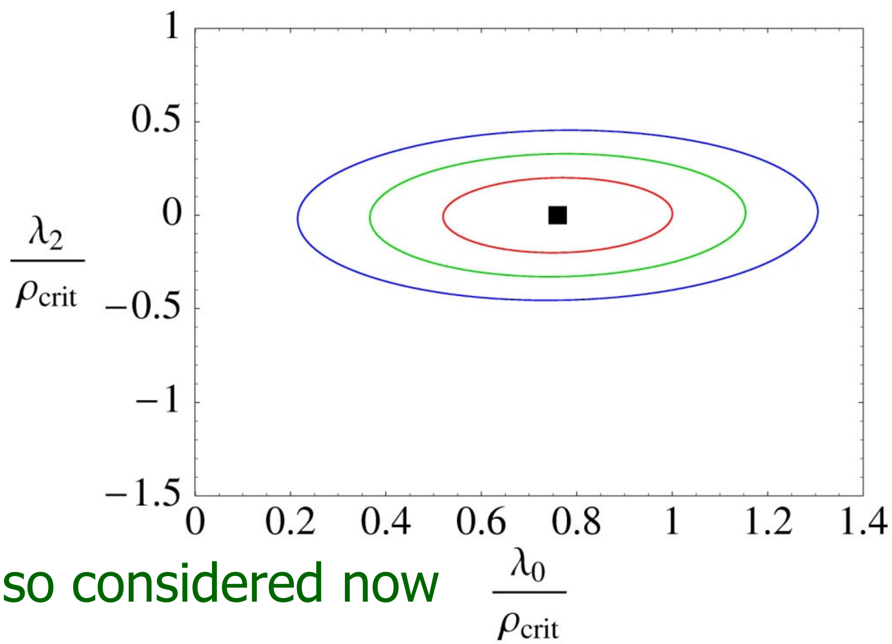
The importance of measuring along the line of sight

Using BAO as Standard Ruler

Information on $d_A(z)$ only



Information on H(z) only



Curvature also considered now

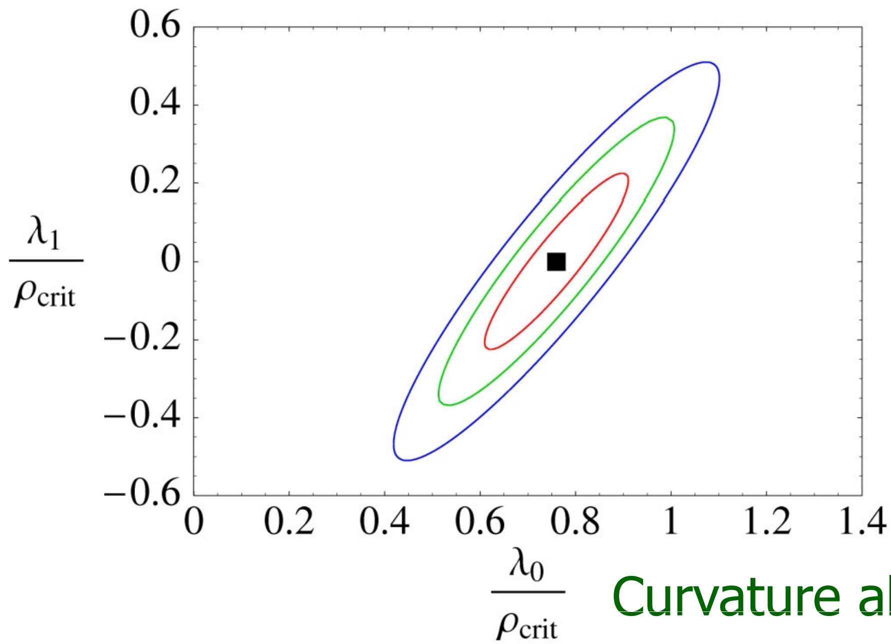
Adept 1, 2 and 3 σ constraints on the first 3 coefficients

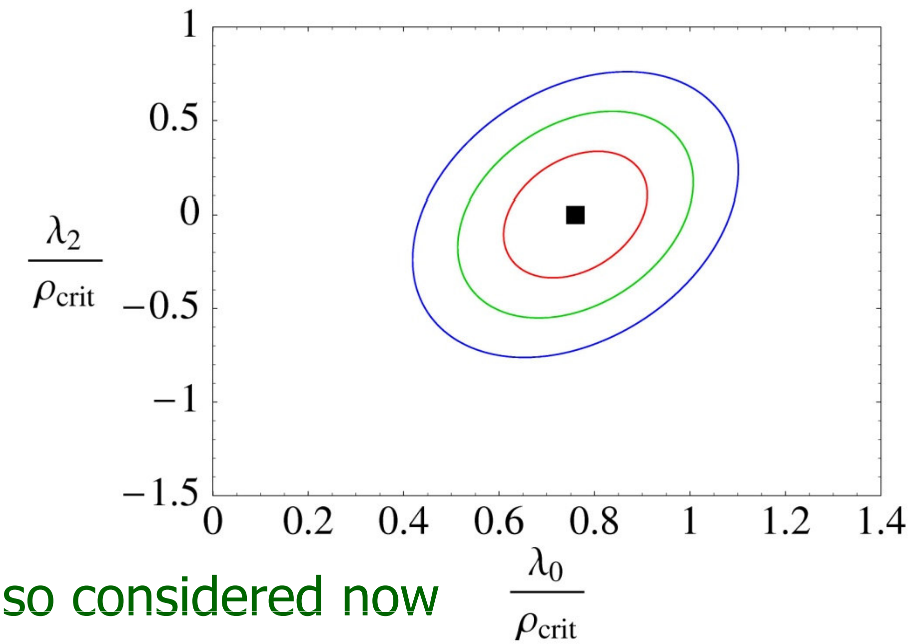
Assuming a ΛCDM model $\Omega_{m0} = 0.24$

and 1 σ priors on $\Omega_{m0}h^2$ (0.01), Ω_{k0} (0.03) and H_0 (8Km/s/Mpc)

PAU

Using BAO as Standard Ruler





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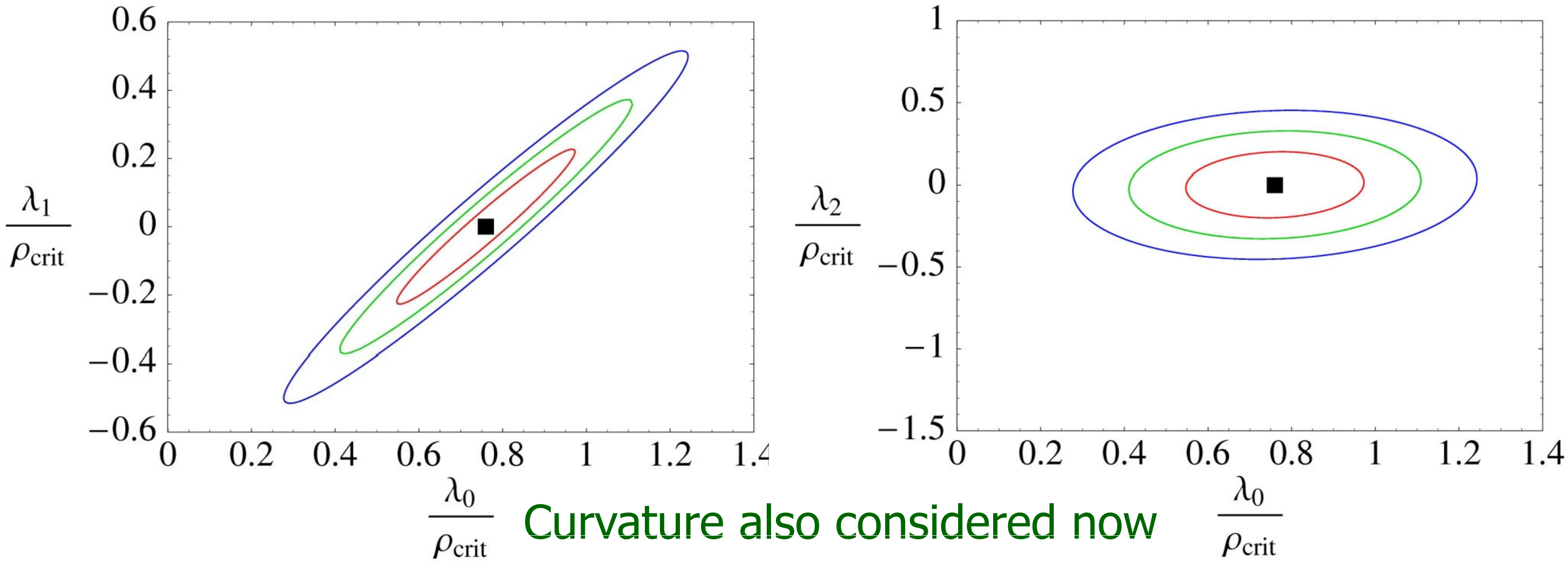
Adept

Using BAO as Standard Ruler



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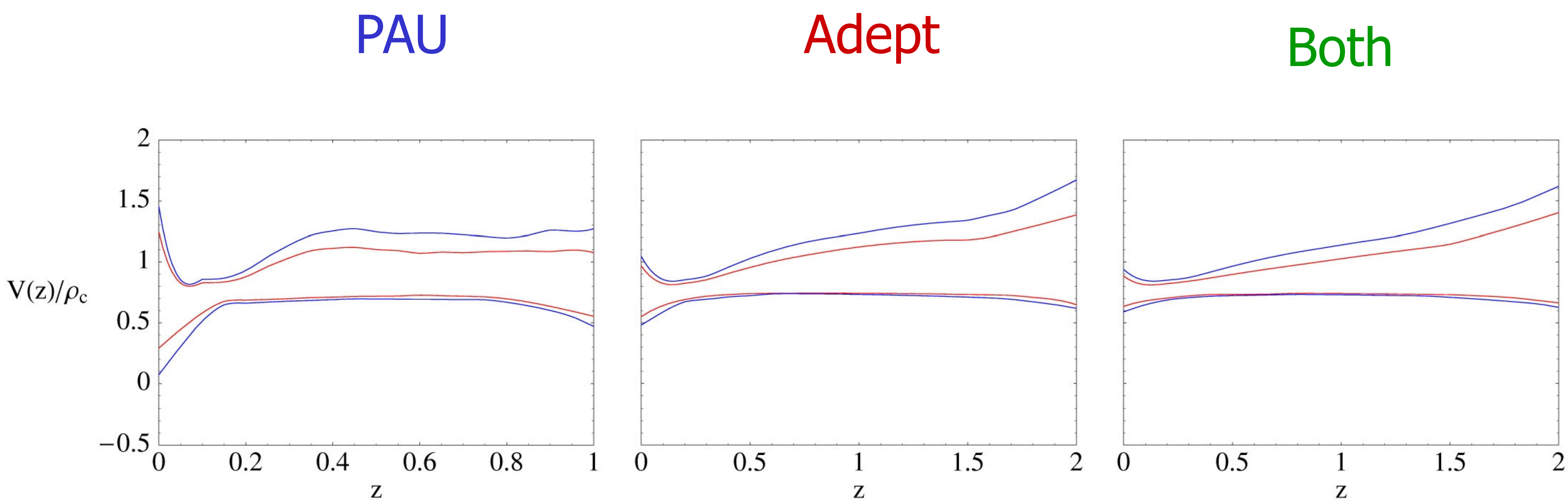
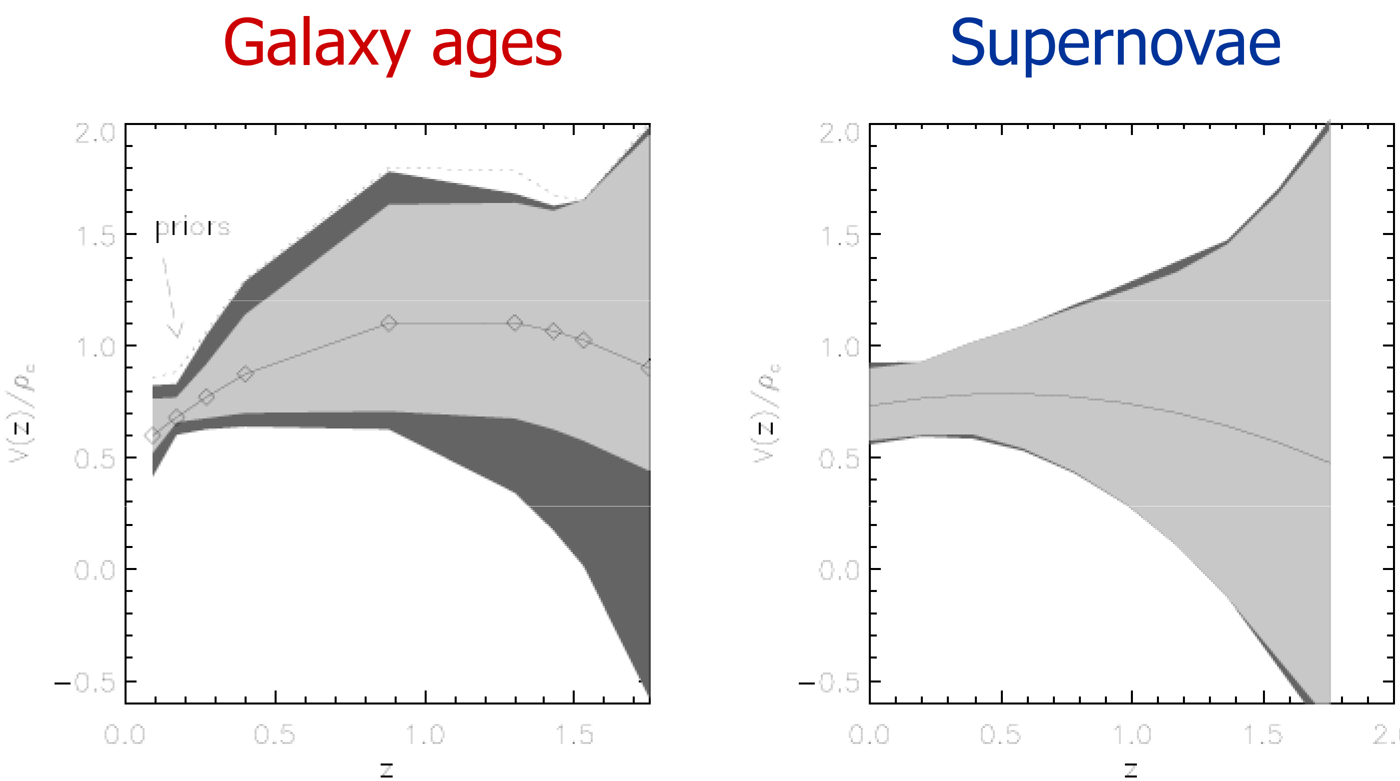
Constraints on the potential



$$V(z) \approx \sum_{n=0}^{N} \lambda_n T_n\left(2\frac{z}{z_{\max}} - 1\right)$$

1 and 2 σ constraints on the potential

Constraints on the potential



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1 and 2 σ constraints on the potential

DE Equation of State

What about parameterizing Dark Energy through its equation of state *w(z)*?

w(z) can also be expanded in Chebyshev Polynomials:

$$w(z) \approx \sum_{n=0}^{N} w_n T_n \left(2 \frac{z}{z_{\max}} - 1 \right)$$

If $w > -1$ the two descriptions are equivalent

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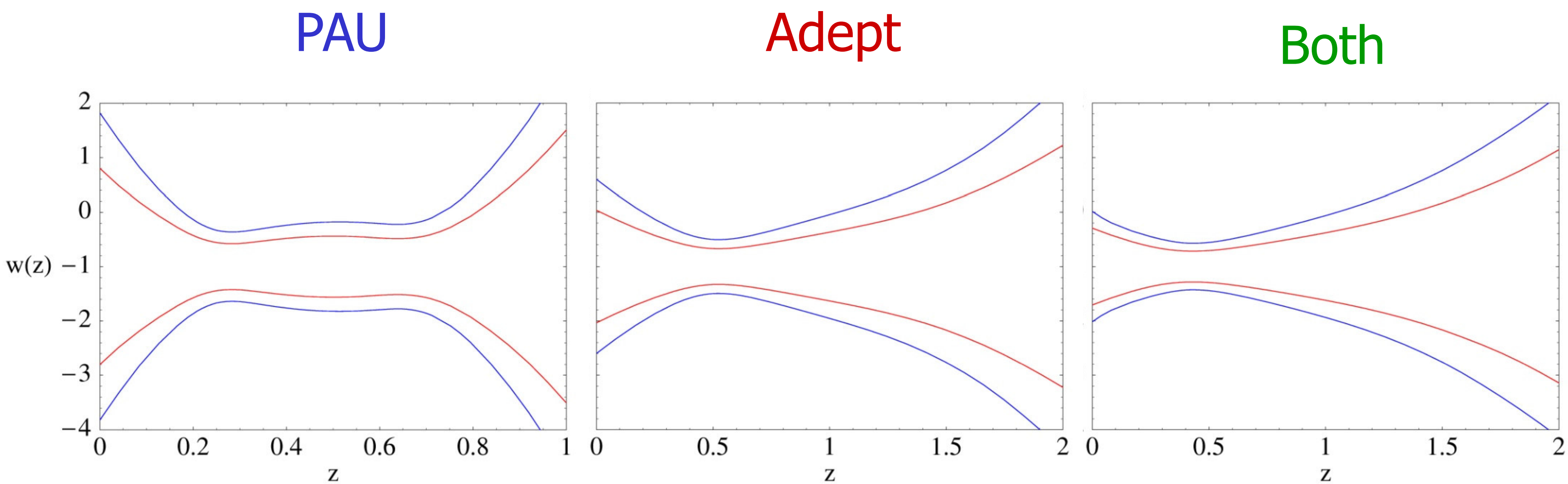
Constraints on the equation of state

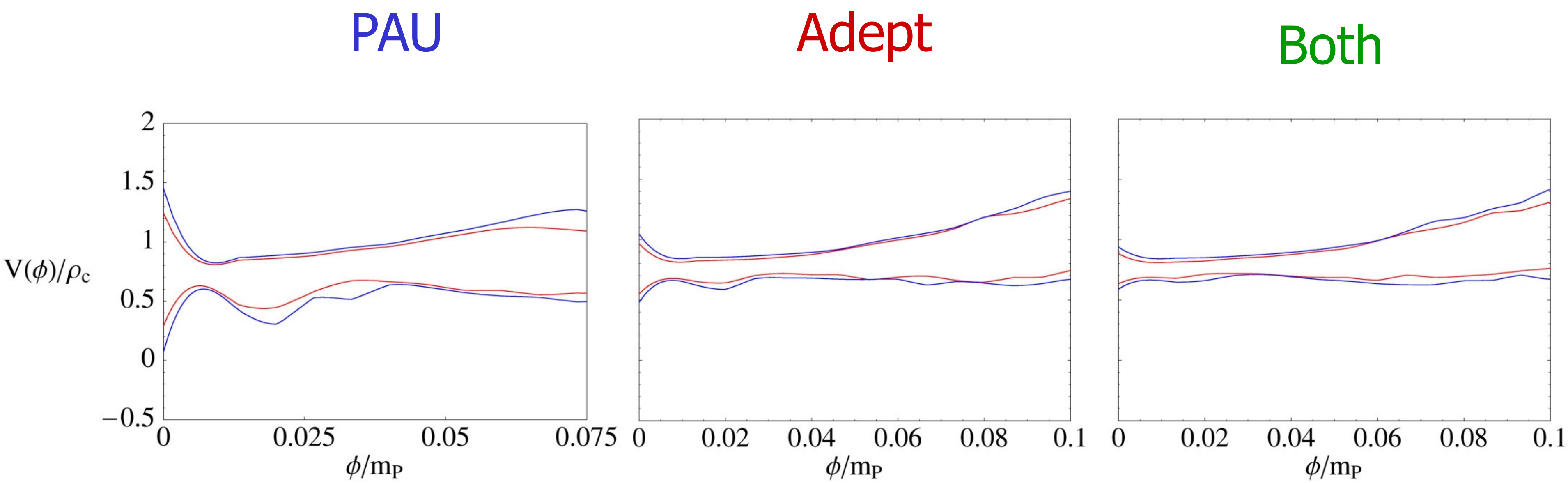


1 and 2 σ constraints on the equation of state

Conclusions

- A non parametric reconstruction of dynamical DE requires a precise measurement of H(z) and H’(z)
  - BAO can directly probe H(z)
  - H’(z) much more challenging observationally
- Lacking a measurement of H’(z) we need a parameterization of DE to fit data
- Future BAO experiments can constrain V(z) and w(z)
- Excellent probes of dynamical DE

Constraints on the potential



1 and 2 σ constraints on the potential

Reconstruction of the potential

From the Friedmann Equations

$$V(z) = (3 - \varepsilon_1)\frac{H^2}{\kappa} + \frac{1}{2}(p_T - \rho_T)$$

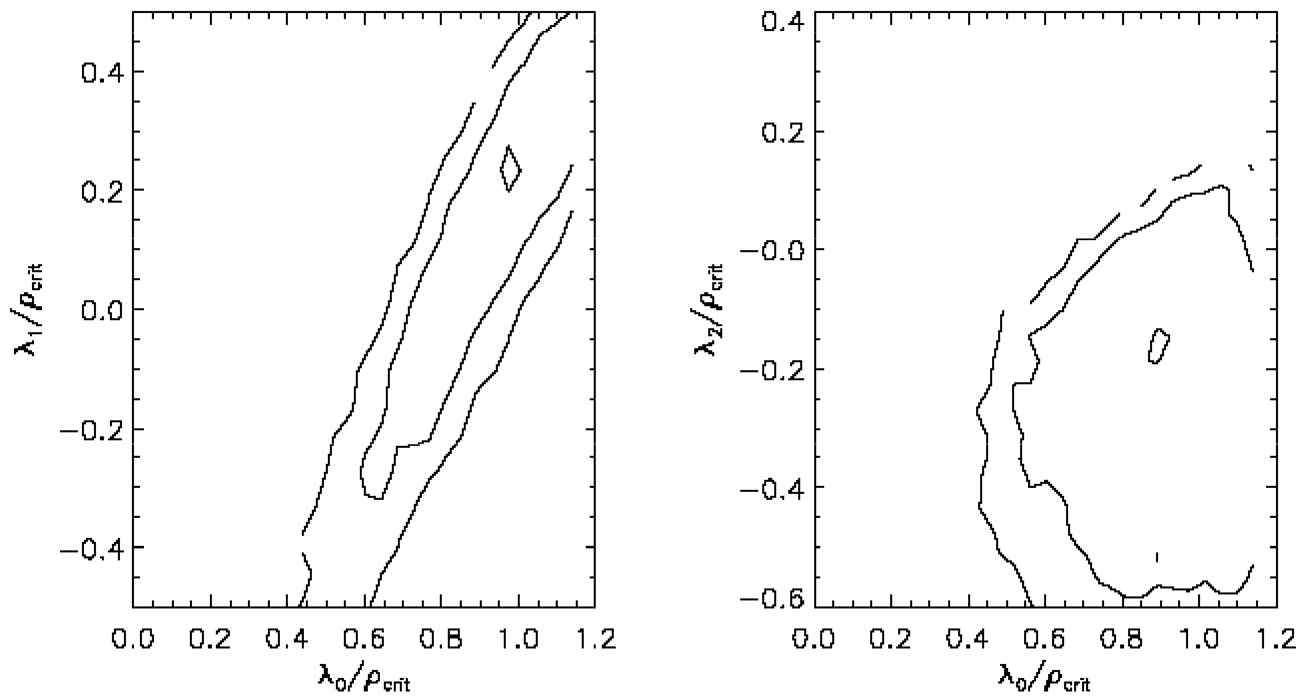
with

$$\varepsilon_1 = -\frac{\dot{H}}{H^2} = 1 - \frac{\ddot{a}}{a}H^{-2} = \frac{dH}{dz}\frac{(1+z)}{H}$$

H(z) and H'(z) needed to reconstruct V(z)

Galaxy Ages

Using Relative Galaxy Ages as Standard Chronometers



1 and 2 σ contours

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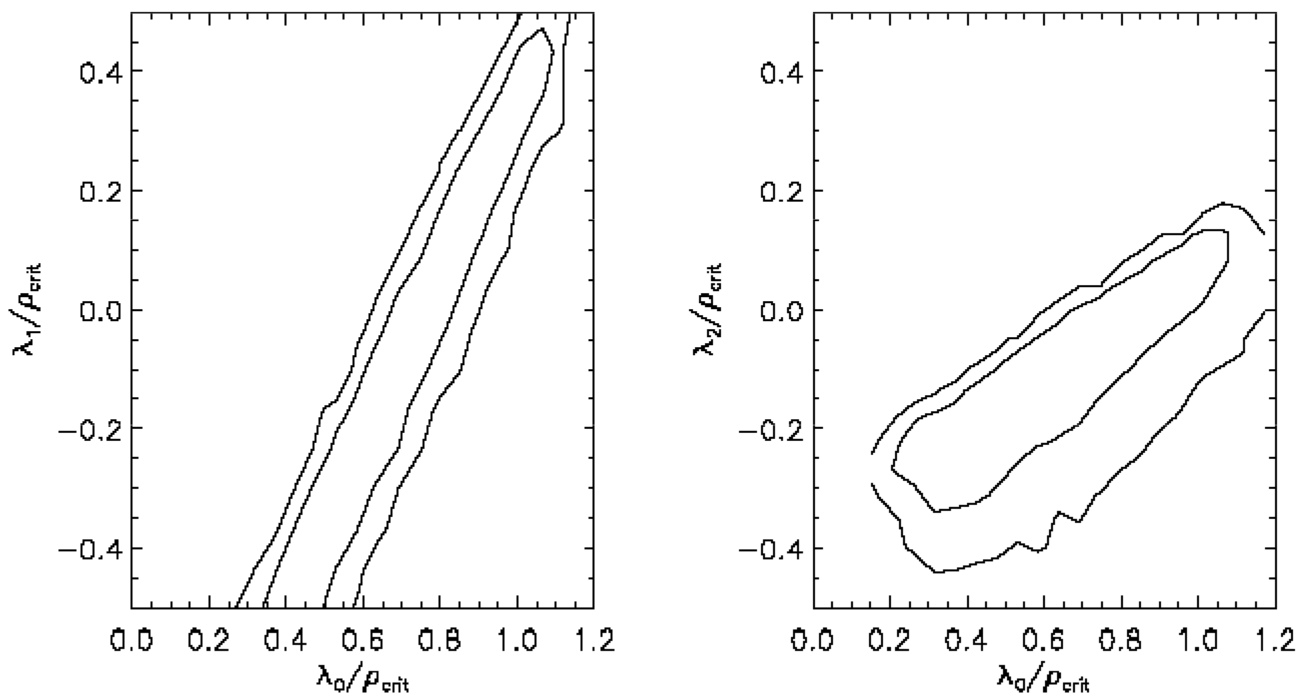
Supernovae

Using SN as Standard Candles



1 and 2 σ contours

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From the supernovae data of A. G. Riess et al astro-ph/0402512