Improved Constraints on Dark Energy From Chandra X-ray Observations of the Largest Relaxed Galaxy Clusters

S.W. Allen et al.

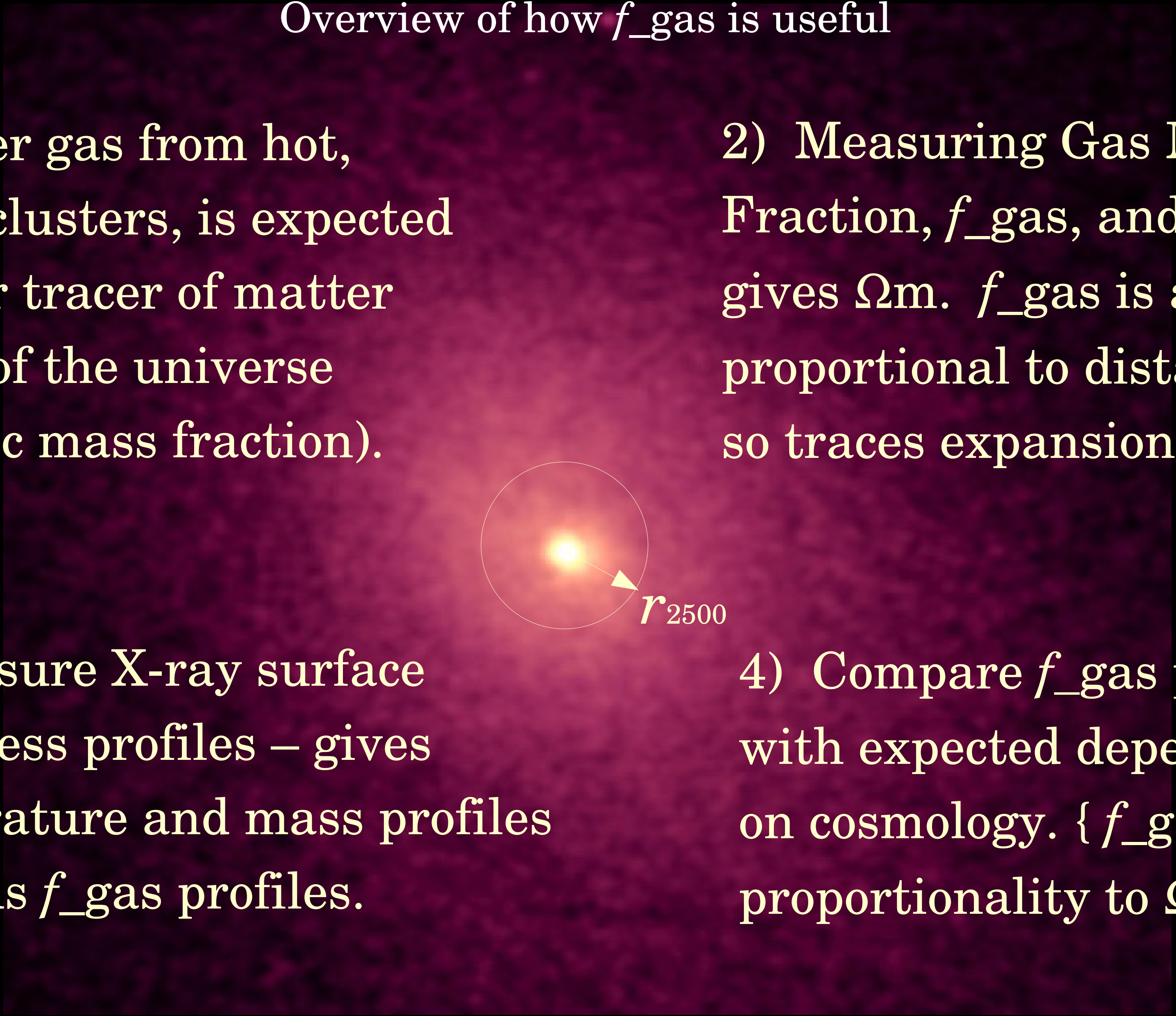
(Measuring Ω_Λ and Ω_m using X-ray Gas Mass Fraction)

Technique

Overview of how *f*_gas is useful

1) Cluster gas from hot, relaxed clusters, is expected to be fair tracer of matter content of the universe (Baryonic mass fraction).

2) Measuring Gas Mass Fraction, *f*_gas, and using Ωb, gives Ωm. *f*_gas is also proportional to distances, and so traces expansion.



3) Measure X-ray surface brightness profiles – gives Temperature and mass profiles and thus *f*_gas profiles.

4) Compare *f*_gas profiles with expected dependence on cosmology. { *f*_gas*(*z*)*, and proportionality to Ωm }

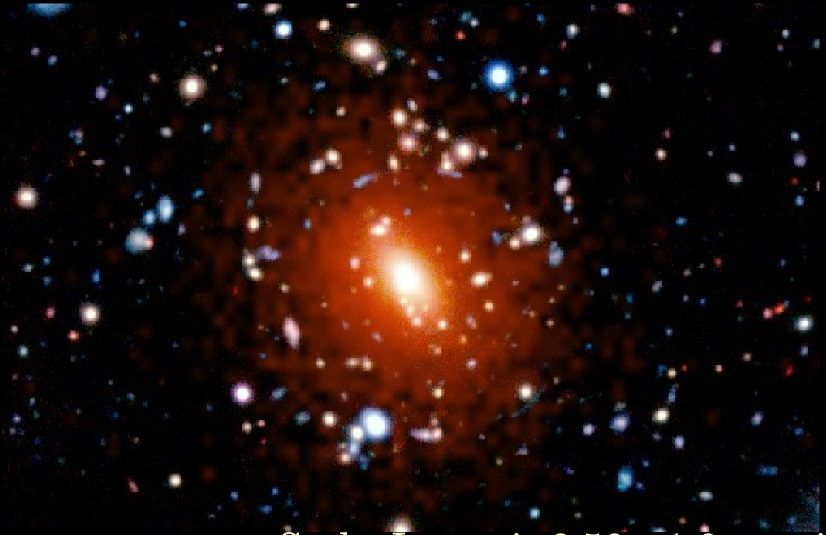
Scale: Image is 4 arcmin on a side(Credit: NASA/CXC/UCI/A.Lewis et al.)

Data Sample

And Technical Details

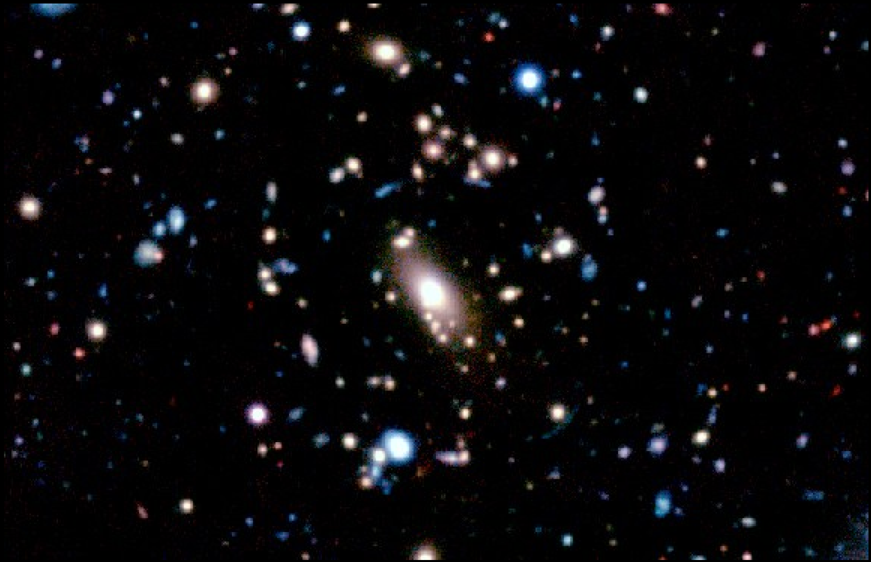
- 42 Clusters
- $0.05 < z < 1.1$
- At Chandra Observatory bet. 1999 – 2005
- Morphologically selected the following:
  - Hot: $kT > 5$ keV ($T \sim 5.8 * 10^{10}$ K)
    - f_{gas} does not depend on temperature for hot systems.
  - Dynamically Relaxed
    - Allows hydrostatic equilibrium assumption
- At Right: A galaxy cluster from data set.

MACSJ1423.8+2404



Scale: Image is 2.56 x 1.6 arcmin

(Credit: NAOJ/Subaru/H.Ebeling)

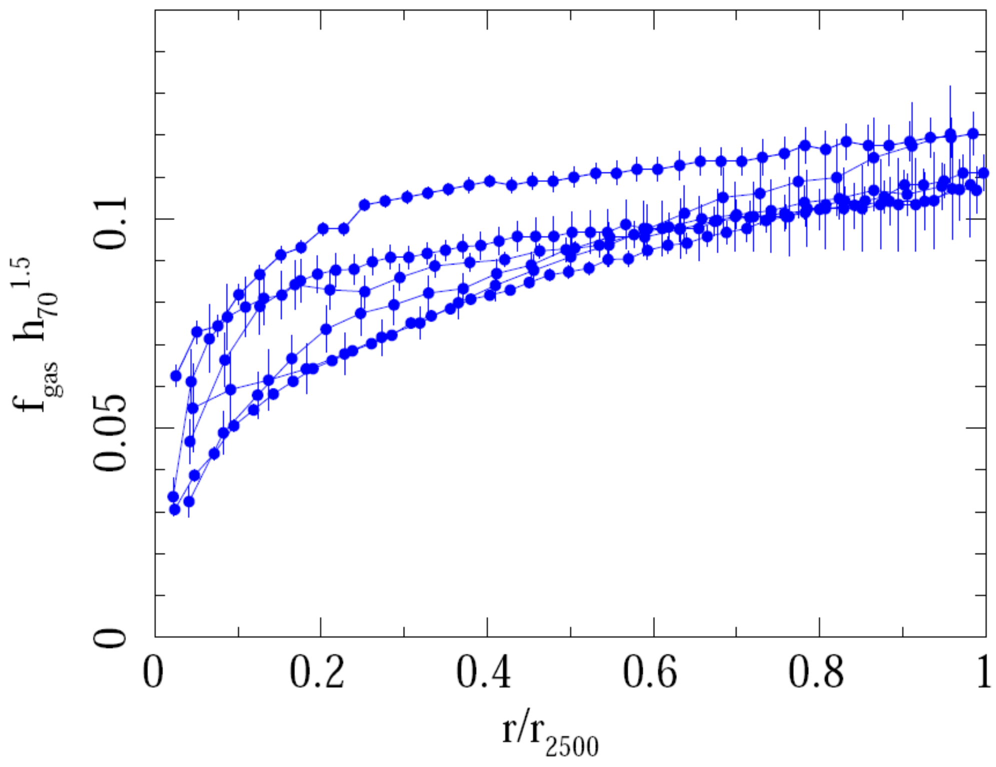


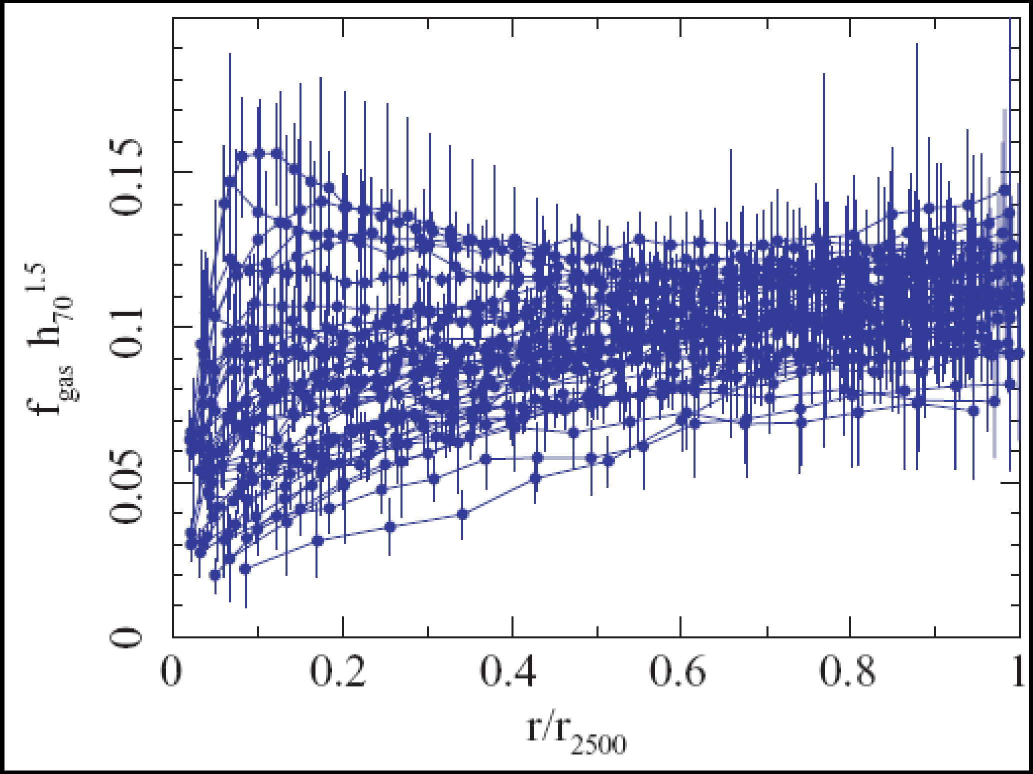
Scale: Image is 2.56 x 1.6 arcmin

(Credit: Optical: NAOJ/Subaru/H. Ebeling; X-Ray: NASA/CXC/IoA/S.Allen et al.)

Fgas Measurements

- Don't show measured surface-brightness profiles, or other data.
- But show radial profiles of *f_gas*, obtained from measured surface brightness profiles, and assumed NFW dark matter distribution. (Note convergence at *r*2500)
- Pick value of *f_gas* at *r*2500 (used in *f_gas(z)* plots)
- Systematic errors up to 15 %



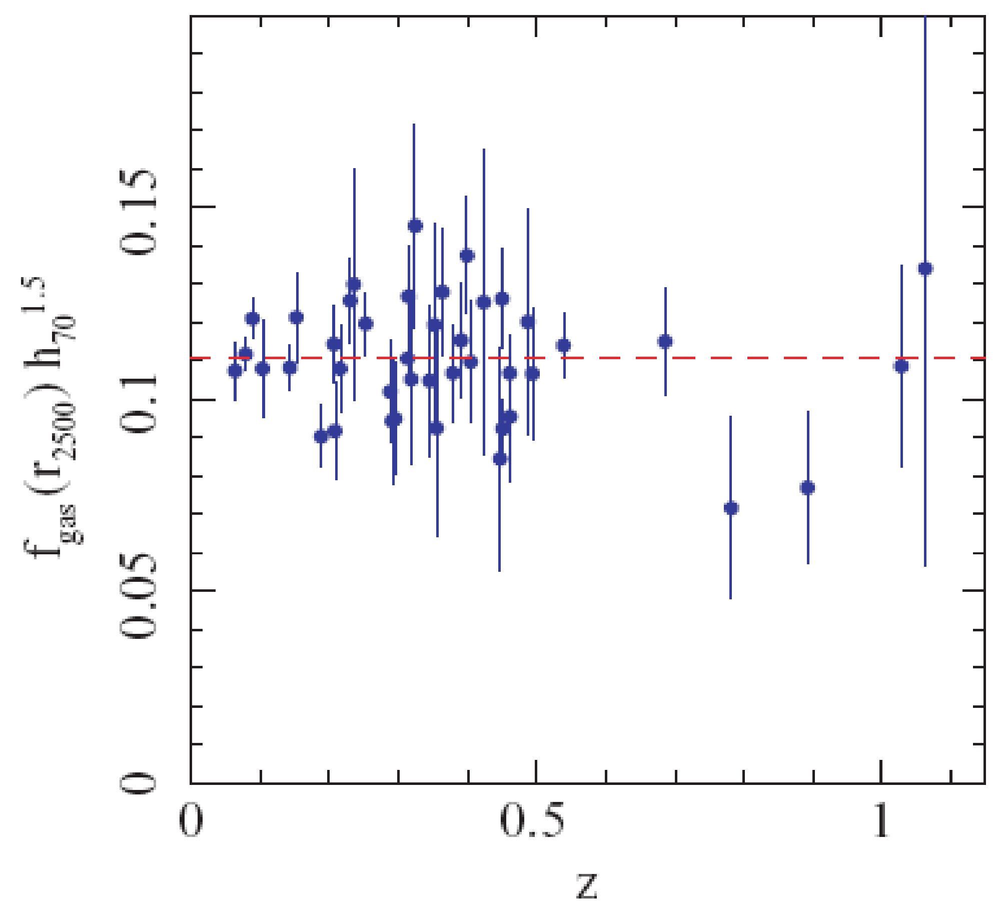


Variation of Fgas with redshift

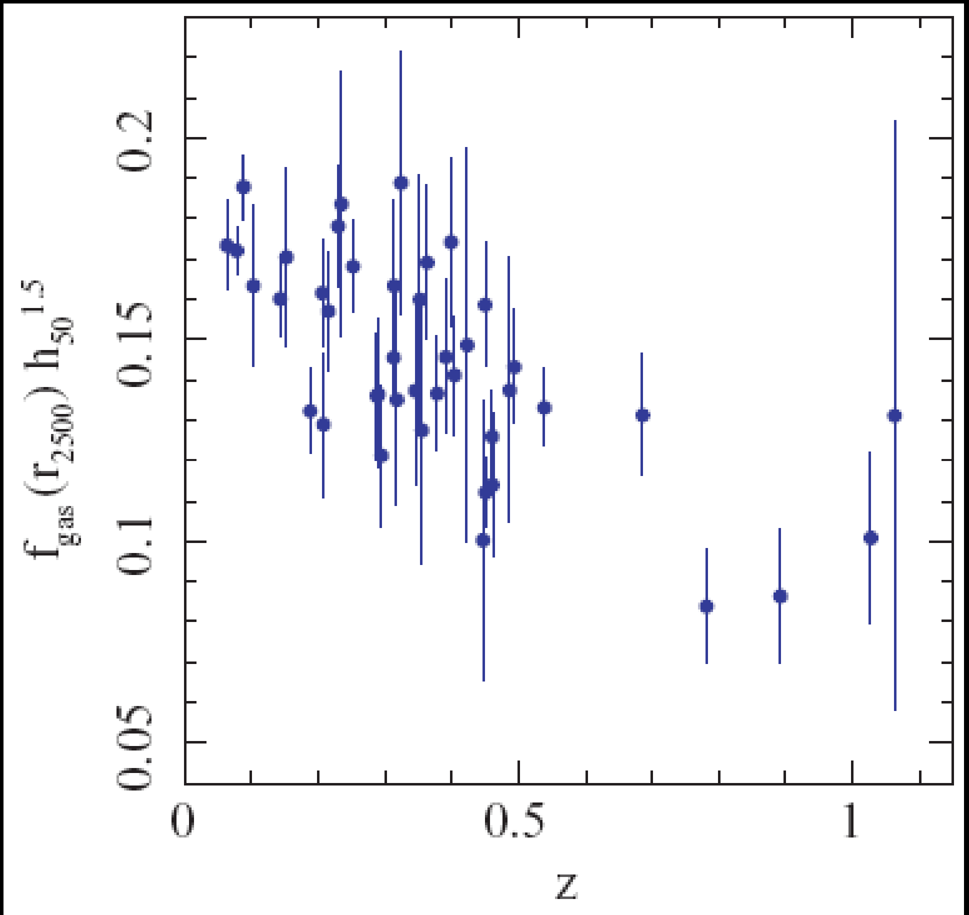
$$f_{\mathrm{gas}}^{\Lambda\mathrm{CDM}}(z) = \frac{K A \gamma b(z)}{1+s(z)} \left(\frac{\Omega_{\mathrm{b}}}{\Omega_{\mathrm{m}}}\right) \left[\frac{d_{\mathrm{A}}^{\Lambda\mathrm{CDM}}(z)}{d_{\mathrm{A}}(z)}\right]^{1.5}$$

From Hydrodynamic simulations, expect correct cosmology to give no variation of *f*_gas with redshift.

ΛCDM: Ωm = .3, $\Omega\Lambda$ = 0.7, *h* = 0.7



SCDM: Ωm = 1, *h* = 0.5



Tested Models of Dark Energy

LCDM: $w = -1$

Other Constant w:

(including $w<-1$)

Evolving w: $$w = \frac{w_{\mathrm{et}} z + w_0 z_{\mathrm{t}}}{z + z_{\mathrm{t}}} = \frac{w_{\mathrm{et}}(1-a)a_{\mathrm{t}} + w_0(1-a_{\mathrm{t}})a}{a(1-2a_{\mathrm{t}}) + a_{\mathrm{t}}}$$

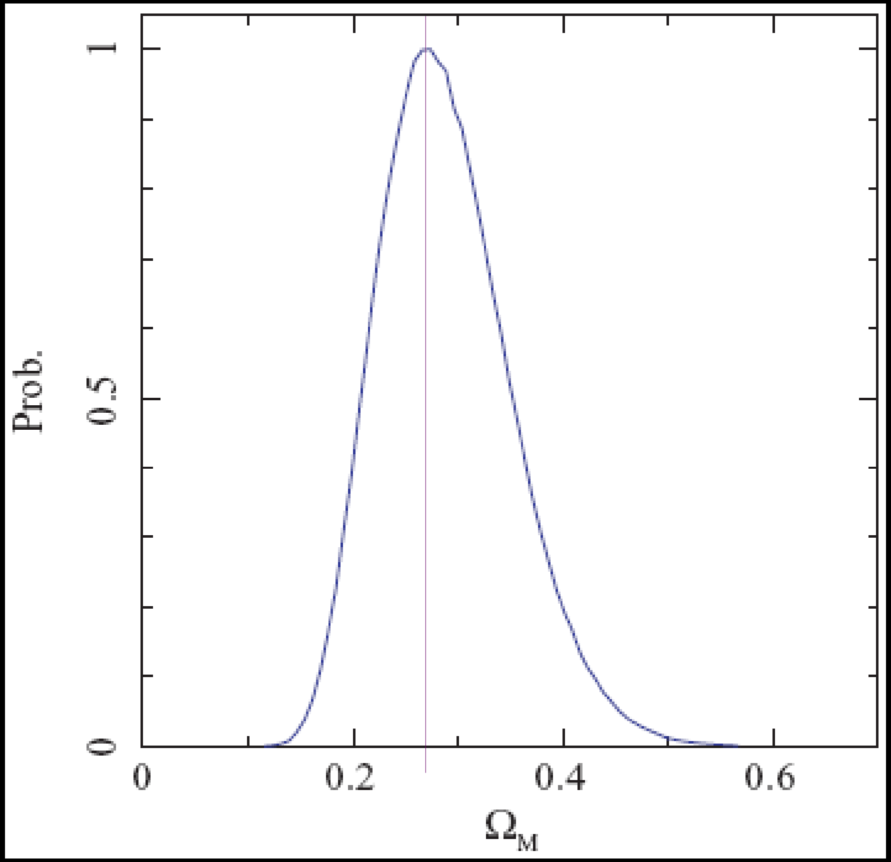
et = early time

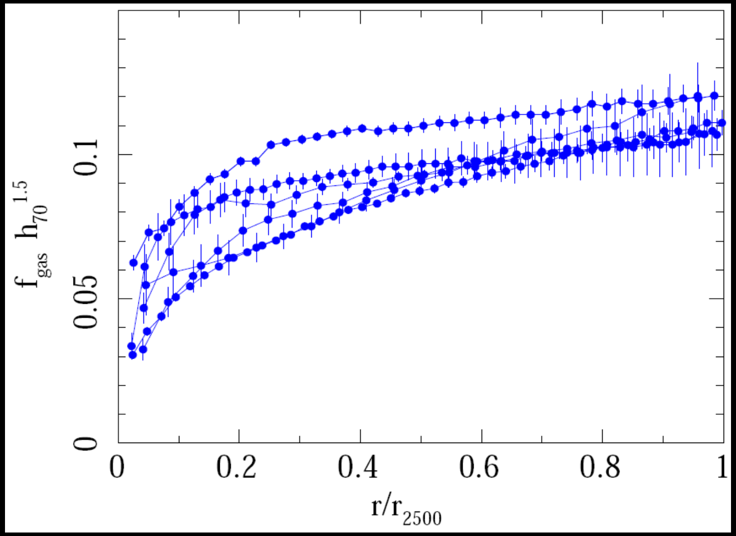
o = present time

t = at transition

Ωm Constraint

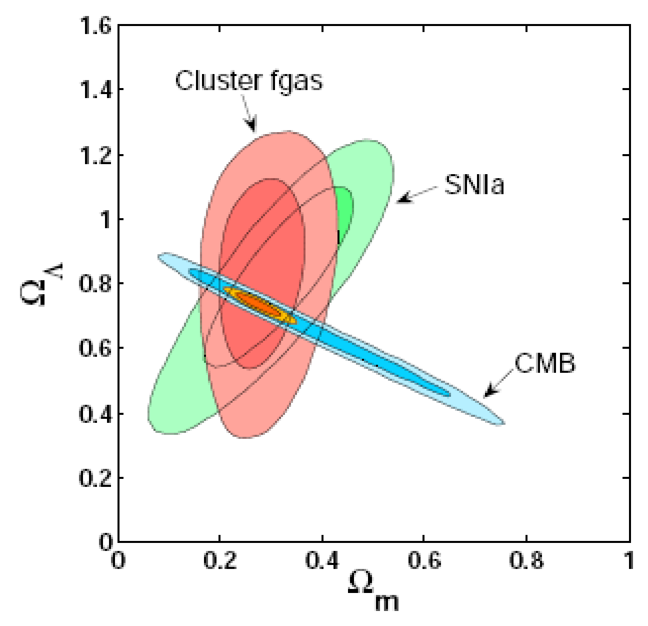
Ωm = 0.28 +/-0.06 (68% Confidence) for ΛCDM





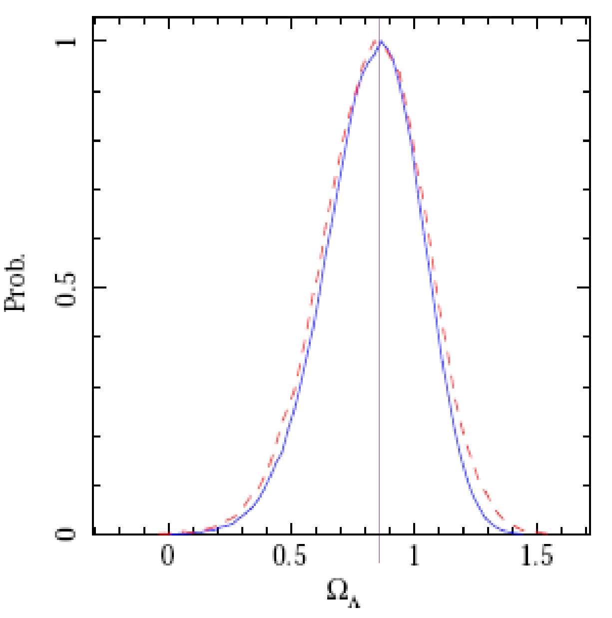
Above analysis done with 6 lowest redshift clusters shown at right. Value in good agreement with value obtained from rest of

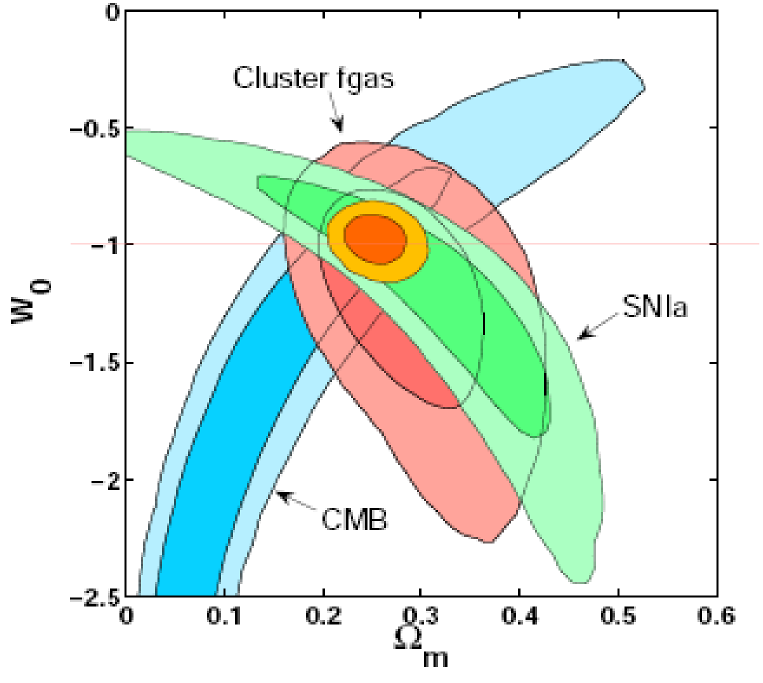
Constraints on Lambda-CDM



$\Omega_\Lambda = 0.86$ +/- .21

Cited as Dark Energy Detection

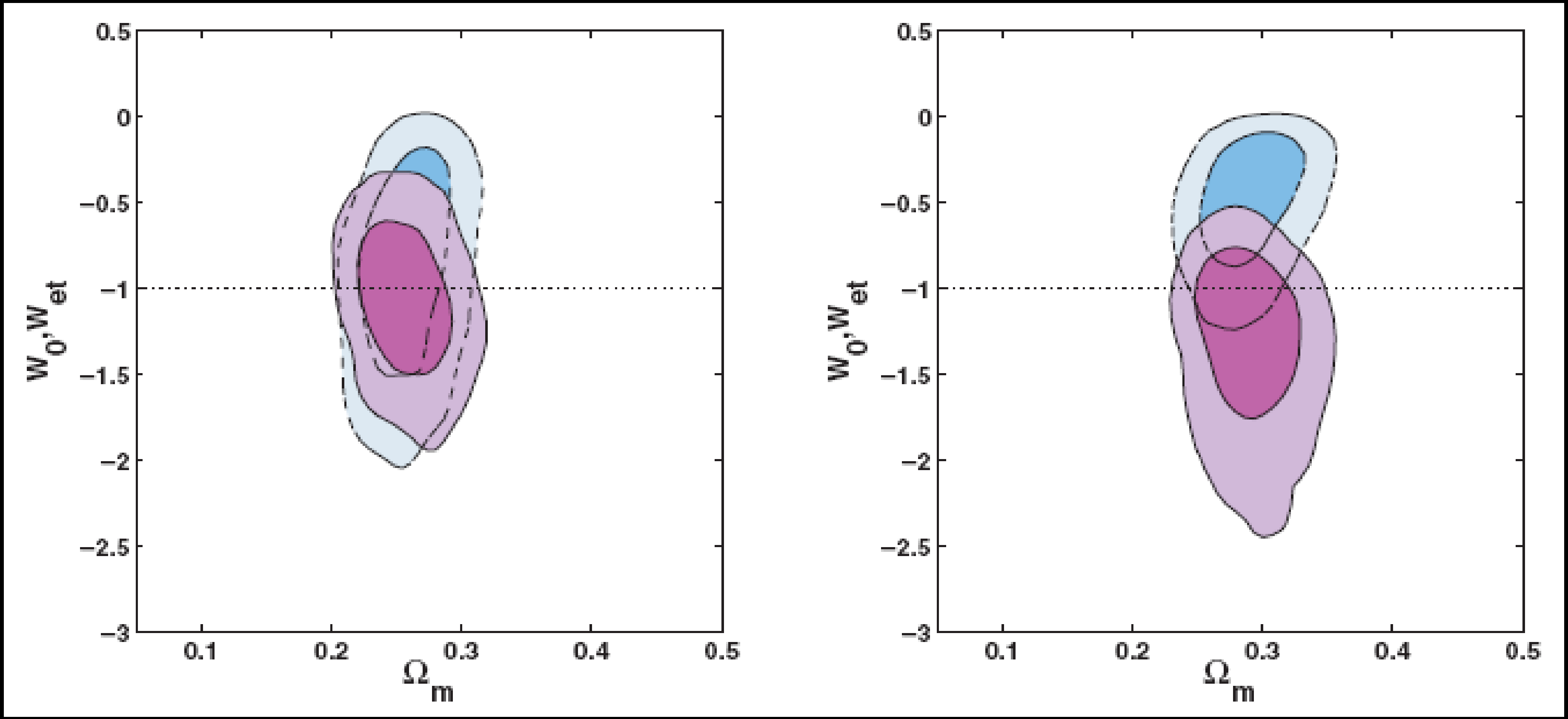




Constraints on w evolution

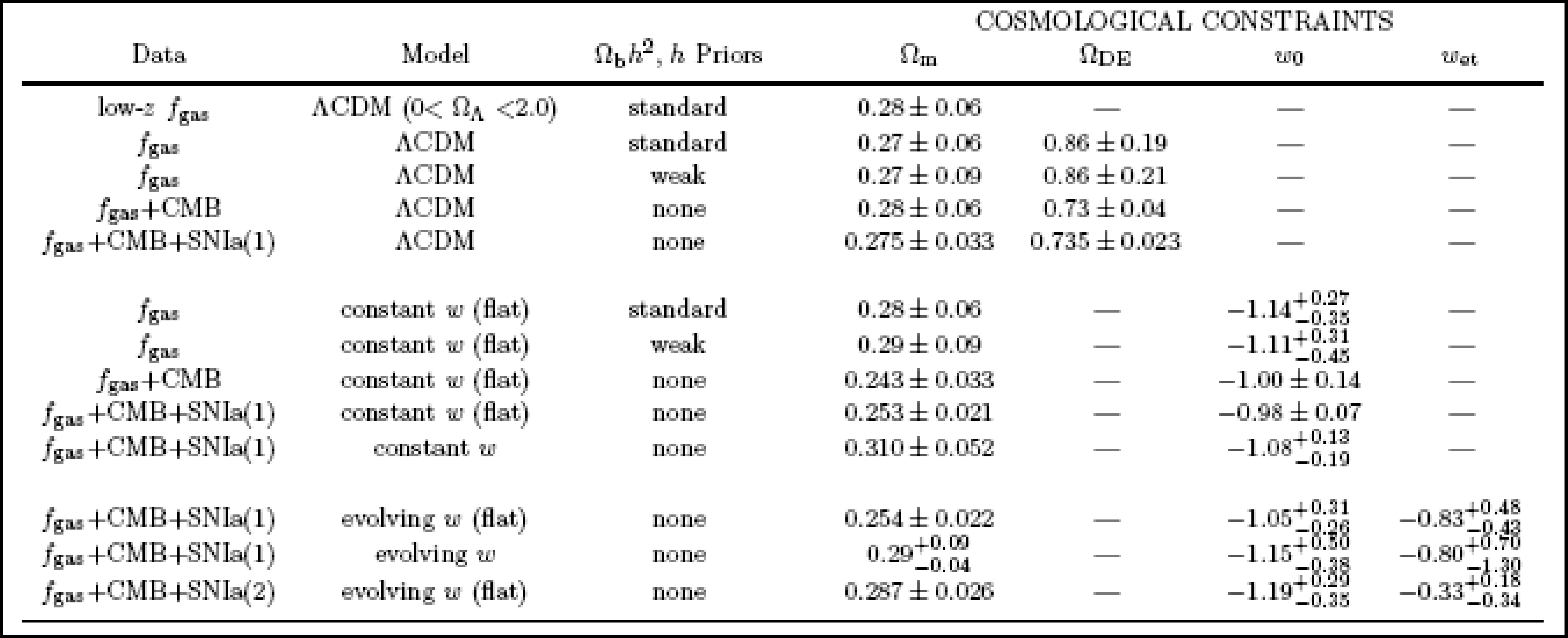
Davis et al.

Reiss et al.



Consistent with no evolution in w

Constraints: Summary/Uncertainties



			COSMOLOGICAL CONSTRAINTS			
Data	Model	$\Omega_b h^2$, h Priors	Ω_m	Ω_{DE}	w_0	w_{et}
low-z f_{gas}	ΛCDM ($0< \Omega_\Lambda <2.0$)	standard	0.28 ± 0.06	—	—	—
f_{gas}	ΛCDM	standard	0.27 ± 0.06	0.86 ± 0.19	—	—
f_{gas}	ΛCDM	weak	0.27 ± 0.09	0.86 ± 0.21	—	—
f_{gas}+CMB	ΛCDM	none	0.28 ± 0.06	0.73 ± 0.04	—	—
f_{gas}+CMB+SNIa(1)	ΛCDM	none	0.275 ± 0.033	0.735 ± 0.023	—	—
f_{gas}	constant w (flat)	standard	0.28 ± 0.06	—	$-1.14^{+0.27}_{-0.35}$	—
f_{gas}	constant w (flat)	weak	0.29 ± 0.09	—	$-1.11^{+0.31}_{-0.45}$	—
f_{gas}+CMB	constant w (flat)	none	0.243 ± 0.033	—	-1.00 ± 0.14	—
f_{gas}+CMB+SNIa(1)	constant w (flat)	none	0.253 ± 0.021	—	-0.98 ± 0.07	—
f_{gas}+CMB+SNIa(1)	constant w	none	0.310 ± 0.052	—	$-1.08^{+0.13}_{-0.19}$	—
f_{gas}+CMB+SNIa(1)	evolving w (flat)	none	0.254 ± 0.022	—	$-1.05^{+0.31}_{-0.26}$	$-0.83^{+0.48}_{-0.43}$
f_{gas}+CMB+SNIa(1)	evolving w	none	$0.29^{+0.09}_{-0.04}$	—	$-1.15^{+0.50}_{-0.38}$	$-0.80^{+0.70}_{-1.30}$
f_{gas}+CMB+SNIa(2)	evolving w (flat)	none	0.287 ± 0.026	—	$-1.19^{+0.29}_{-0.35}$	$-0.33^{+0.18}_{-0.34}$

10-15 % systematic uncertainty from : x-ray modeling (lots of assumptions), instrument calibration, non-thermal pressure support

Assumptions of spherical symmetry, hydrostatic equilibrium, dark matter profile (NFW), ...

Results comparable with SNIa data according to wo, Ωm ellipses.

Five Year WMAP Observations: Cosmological Interpretation

E. Komatsu et. al.

Constraining Dark Energy Models Via Accurately Measured Distances to Specific Epochs

Distance Priors

2 Distance ratios, associated w/ decoupling epoch, can be measured very precisely by locating peaks and troughs of acoustic oscillations in CMB:

$D_A(z^*)/r_s(z^*)$
$D_A(z^*)/H(z^*)/c$

$D_A(z^*)$: Proper distance (not comoving) to decoupling epoch
$r_s(z^*)$: Comoving size of the sound horizon at the decoupling epoch.
$H(z^*)/c$: Hubble horizon size at the decoupling epoch
z^*: Defines decoupling epoch

$$l_A \equiv (1+z_*)\frac{\pi D_A(z_*)}{r_s(z_*)}$$

$$R(z_*) \equiv \sqrt{\Omega_m H_0^2}(1+z_*)D_A(z_*)$$

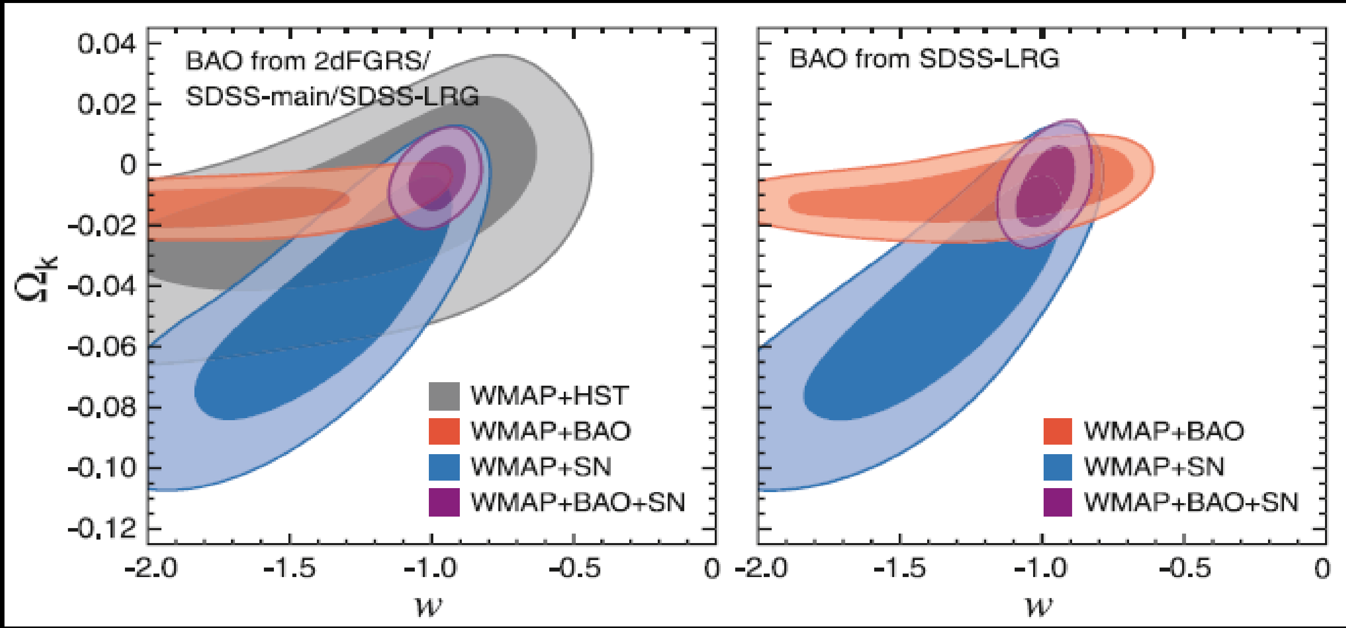
$$z_* = 1048\left[1+0.00124(\Omega_b h^2)^{-0.738}\right]\left[1+g_1\left(\Omega_m h^2\right)^{g_2}\right]$$

$$g_1 = \frac{0.0783(\Omega_b h^2)^{-0.238}}{1+39.5(\Omega_b h^2)^{0.763}}$$

$$g_2 = \frac{0.560}{1+21.1(\Omega_b h^2)^{1.81}}$$

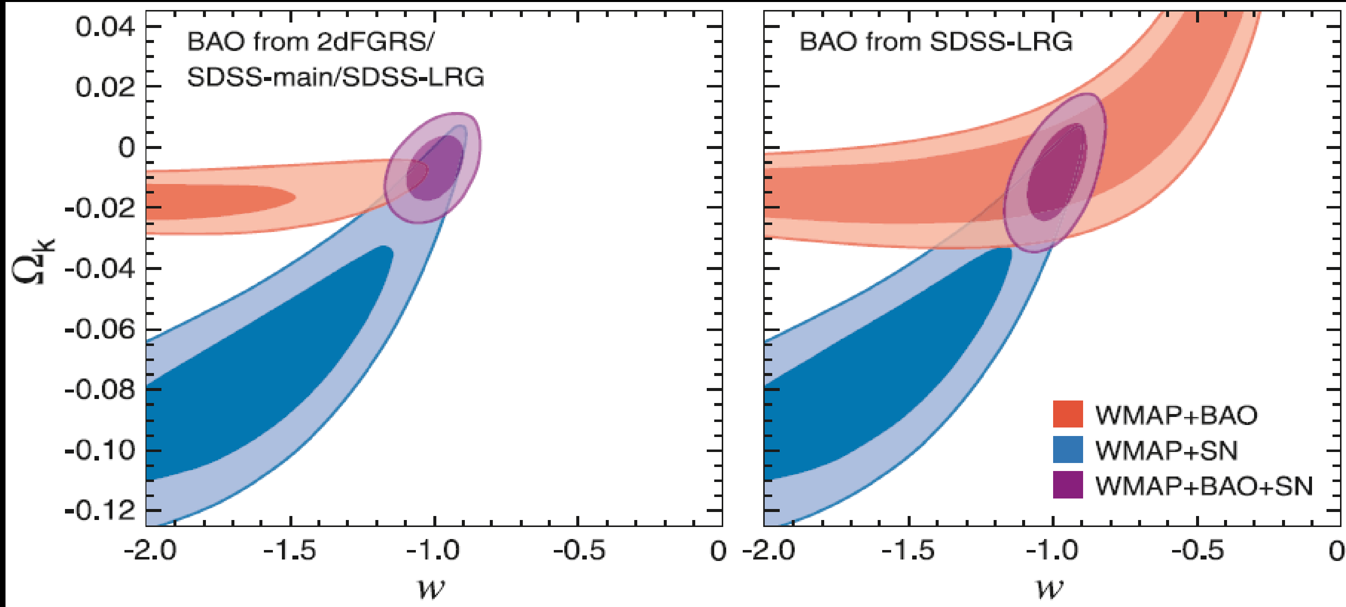
Priors alone provide decent results

Major Caveat: Full WMAP Analysis



Requires assumption of cosmology!

Just distance priors



How to use priors to constrain cosmology

Chi Square!

$$\chi^2_{WMAP} \equiv -2 \ln L = (x_i - d_i)(C^{-1})_{ij}(x_j - d_j)$$

$$x_i = (l_A, R, z_*)$$

Computed using favorite cosmology (Ωm, Ωb *H*o, etc..)

Minimize Chi Square with respect to *H*o, Ωb, Ωm, which leaves you with a distribution of w(a) and Ωk

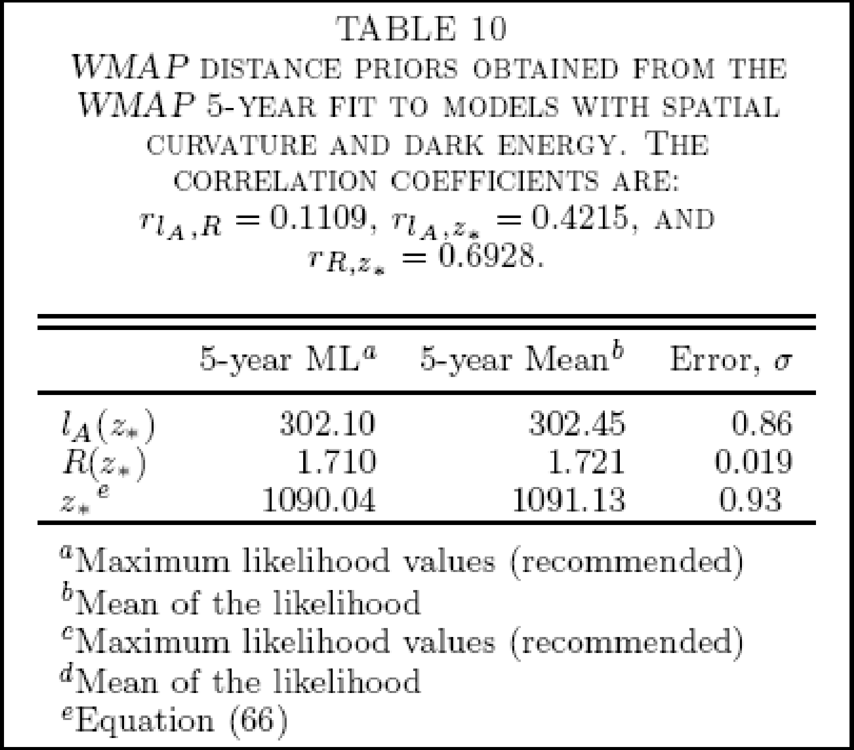


TABLE 10

WMAP DISTANCE PRIORS OBTAINED FROM THE *WMAP* 5-YEAR FIT TO MODELS WITH SPATIAL CURVATURE AND DARK ENERGY. THE CORRELATION COEFFICIENTS ARE: $r_{l_A,R} = 0.1109$, $r_{l_A,z_*} = 0.4215$, AND $r_{R,z_*} = 0.6928$.

	5-year ML[a]	5-year Mean[b]	Error, σ
$l_A(z_*)$	302.10	302.45	0.86
$R(z_*)$	1.710	1.721	0.019
z_*[e]	1090.04	1091.13	0.93

[a] Maximum likelihood values (recommended)

[b] Mean of the likelihood

[c] Maximum likelihood values (recommended)

[d] Mean of the likelihood

[e] Equation (66)

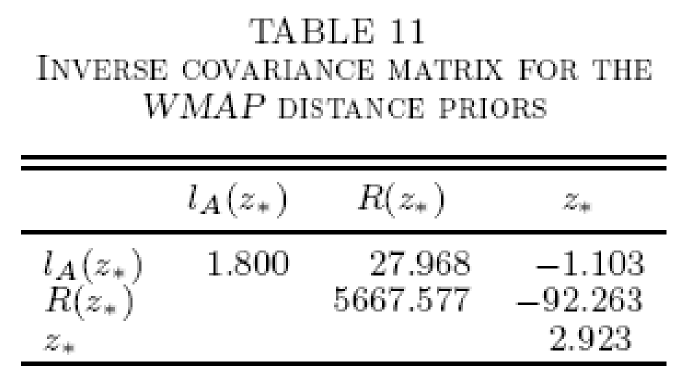
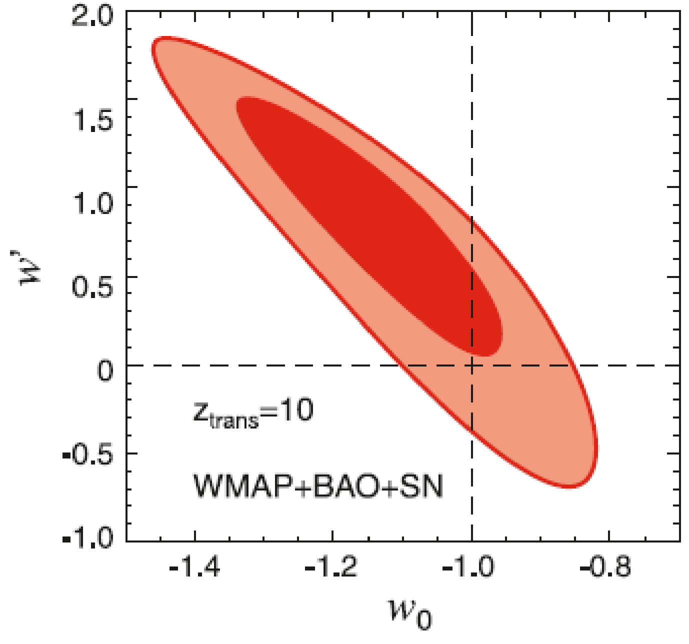


TABLE 11

INVERSE COVARIANCE MATRIX FOR THE *WMAP* DISTANCE PRIORS

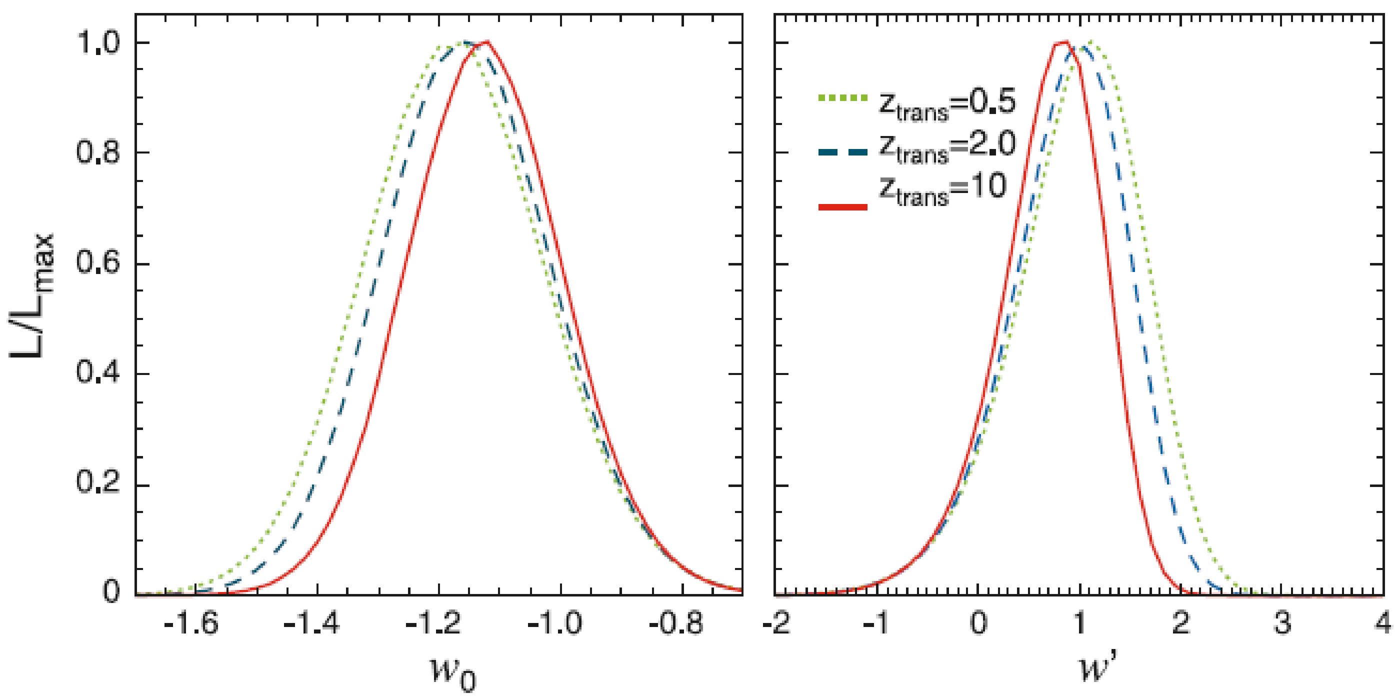
	$l_A(z_*)$	$R(z_*)$	z_*
$l_A(z_*)$	1.800	27.968	−1.103
$R(z_*)$		5667.577	−92.263
z_*			2.923

Measured w Evolution



$$w(a) = \frac{a\tilde{w}(a)}{a + a_{\mathrm{trans}}} - \frac{a_{\mathrm{trans}}}{a + a_{\mathrm{trans}}}$$

$$\tilde{w}(a) = \tilde{w}_0 + (1 - a)\tilde{w}_a.$$



EXTRA SLIDES ....

Dark Energy equation of state

$w_{\rm early} = -1$ and $w_{\rm late} = w_0 + (1-a)w_a$

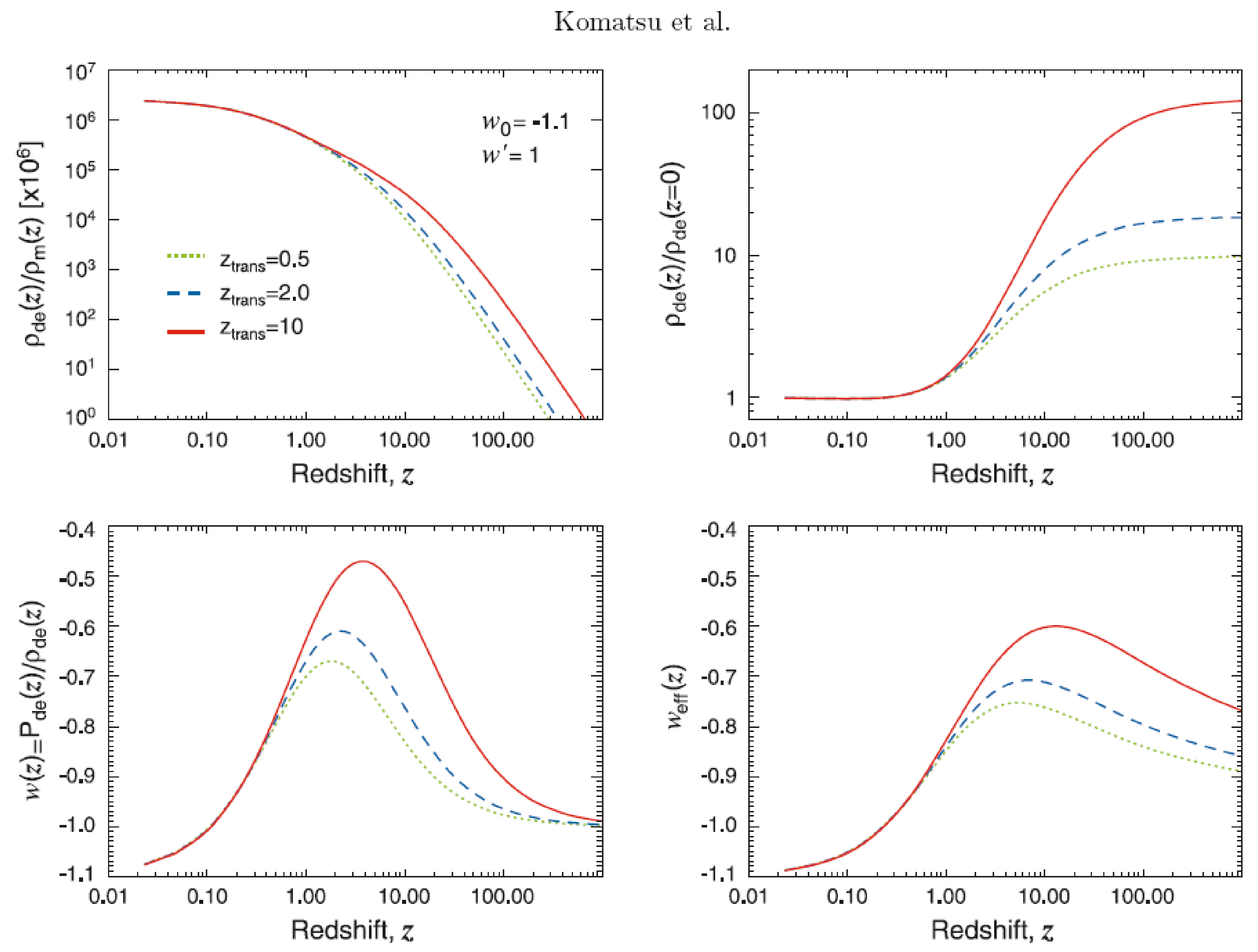
$$w(a) = \tilde{w}(a) f(a/a_{\rm trans}) + (-1)\left[1 - f(a/a_{\rm trans})\right]$$

$f(x)$ goes to zero for $x \ll 1$, and to unity for $x \gg 1$

$$w(a) = \frac{a\tilde{w}(a)}{a + a_{\rm trans}} - \frac{a_{\rm trans}}{a + a_{\rm trans}}$$

$$\tilde{w}(a) = \tilde{w}_0 + (1-a)\tilde{w}_a.$$

Dark Energy Models



Komatsu et al.