

Dark Energy

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ccc-Paris, 17-20/12/02

- 1) Observations (\square_{\square_0} , \square_{\square_0} , \square_{x_0} , W_X)
- 2) A dark energy dominated Universe
- 3) Dark energy candidates: the problems they solve, the problems they introduce
- 4) How to discriminate among them

$$1 + z = a^{\alpha} \quad (a_0 = 1)$$

$$ds^2 = dt^2 - a(t)^2 \frac{dr^2}{K r^2} + r^2 d\Omega^2$$

$$K_0 = \frac{K}{H_0^2}$$

$$\dot{a} \equiv H^2 = H_0^2 [M_0(1+z)^3 + X_0(1+z)^{3(W_X+1)} + K_0(1+z)^2]$$

$$W_X \equiv \frac{\rho_X}{\rho_X}$$

$$rad0 \quad 10^4$$

$$\square_{i0} = \frac{\square_{i0}}{\square_{c0}} \quad \square_{c0} = \frac{3H_0^2}{8\square G_N}$$

Background parameters:

$$H_0, \square_{\square 0}, \square_{\square 0}, \square_{X0}, W_X \quad \text{with} \quad \square_{\square 0} + \square_{\square 0} + \square_{X0} = 1$$

$$d(\Box a^3) = \Box p da^3, \quad \frac{p}{\Box} = W \quad \Box \Box a^{\Box 3(W+1)}$$

- Non-interacting fluids: EoS determines dilution:
 $(W_{rad}=1/3, W_M=0, W_K=-1/3, W_{vac}=-1, \dots)$

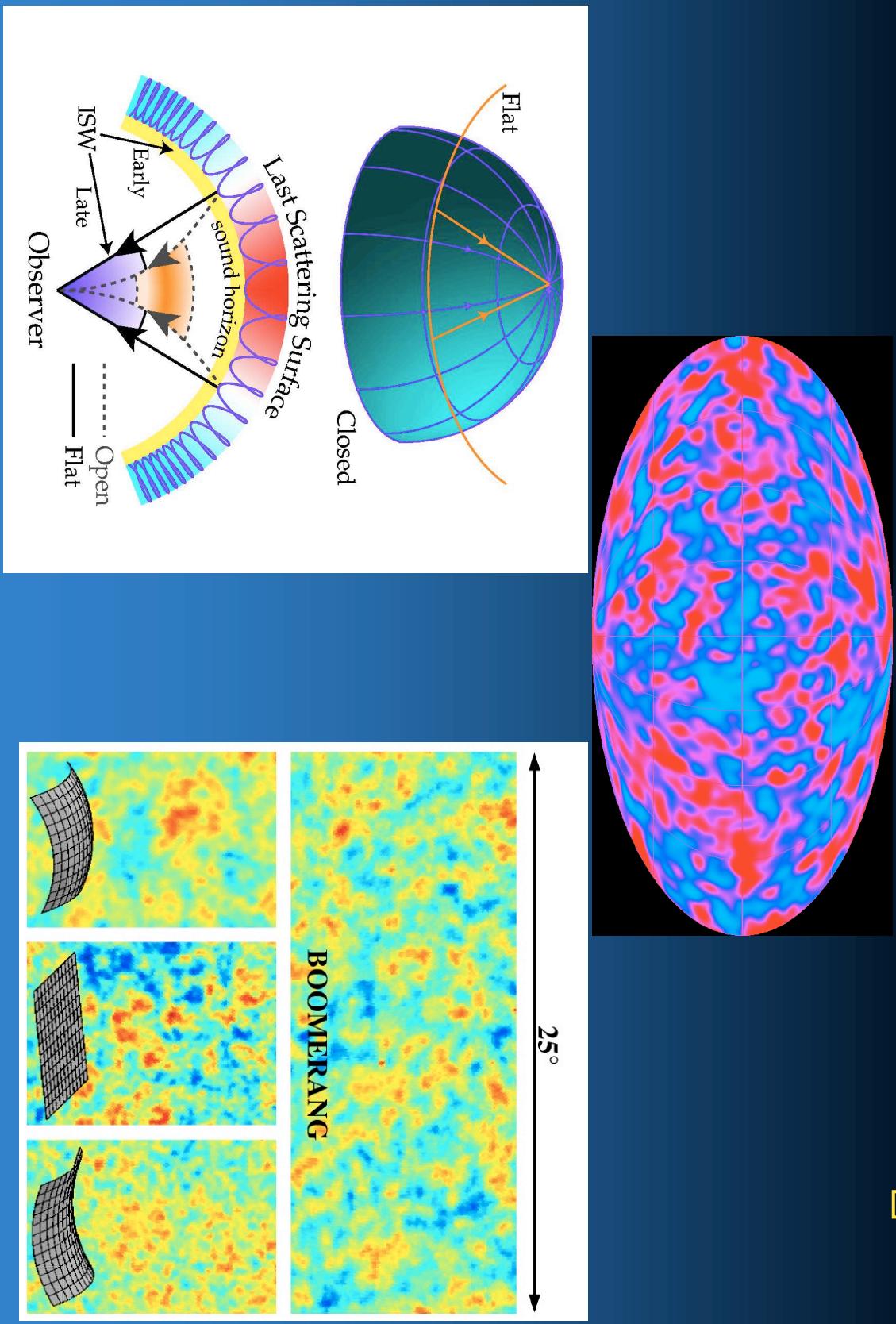
In general (DEC): $|W| \leq 1$ if $\Box > 0$, and $W = -1$ if $\Box < 0$

- If two \Box_{io} 's = $O(1)$ \Box coincidence(s)!
 $\Box_i / \Box_j = \Box_{io} / \Box_{j_0} (1+z)^{3(W_i - W_j)}$

$$\frac{\ddot{a}}{a} = \Box \frac{H_0^2}{2} \left[\Box_{M0} (1+z)^3 + (1+3W_{X0}) \Box_{X0} (1+z)^{3(W_X+1)} \right]$$

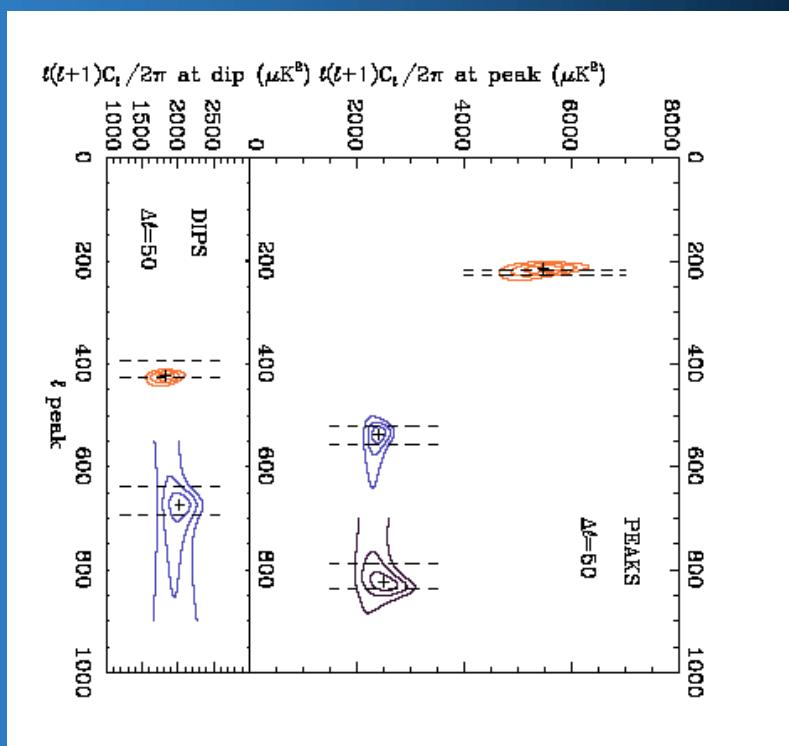
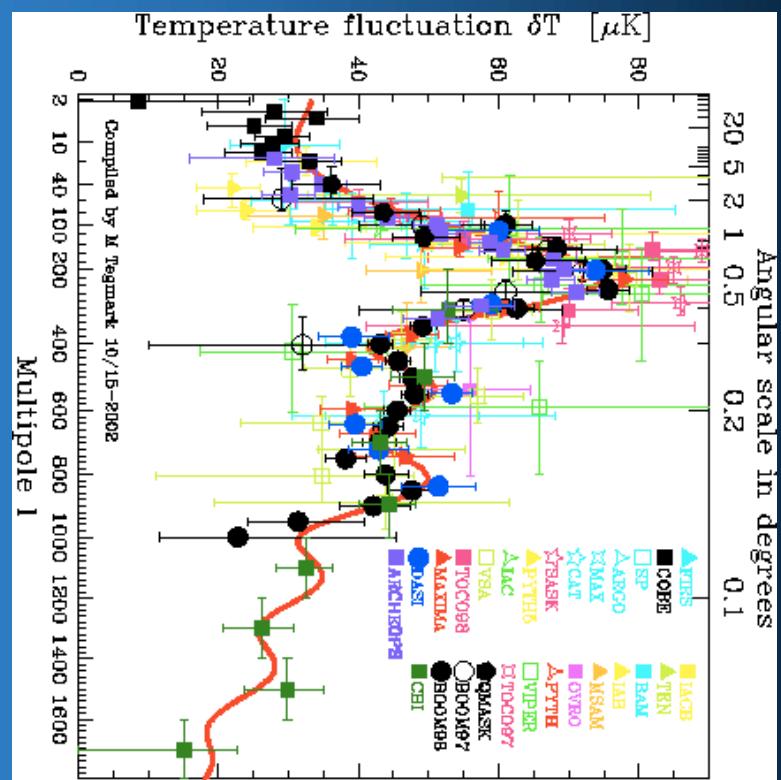
- Acceleration today if $W_X < -1/3 - \Box_{M0} / \Box_{X0}$

CMB and Universe Geometry: $\square \square 0$



$$\square_{\text{peak}} \approx V_s t_{\text{dec}} \quad \square_{\text{peak}} \approx Z_{\text{dec}} \square_{\text{peak}} / d(z_{\text{dec}})$$

$$\square_{\text{peak}} \approx 180^\circ / \square_{\text{peak}} \approx 220 / (1 - \square_{\square_0})^{1/2}$$

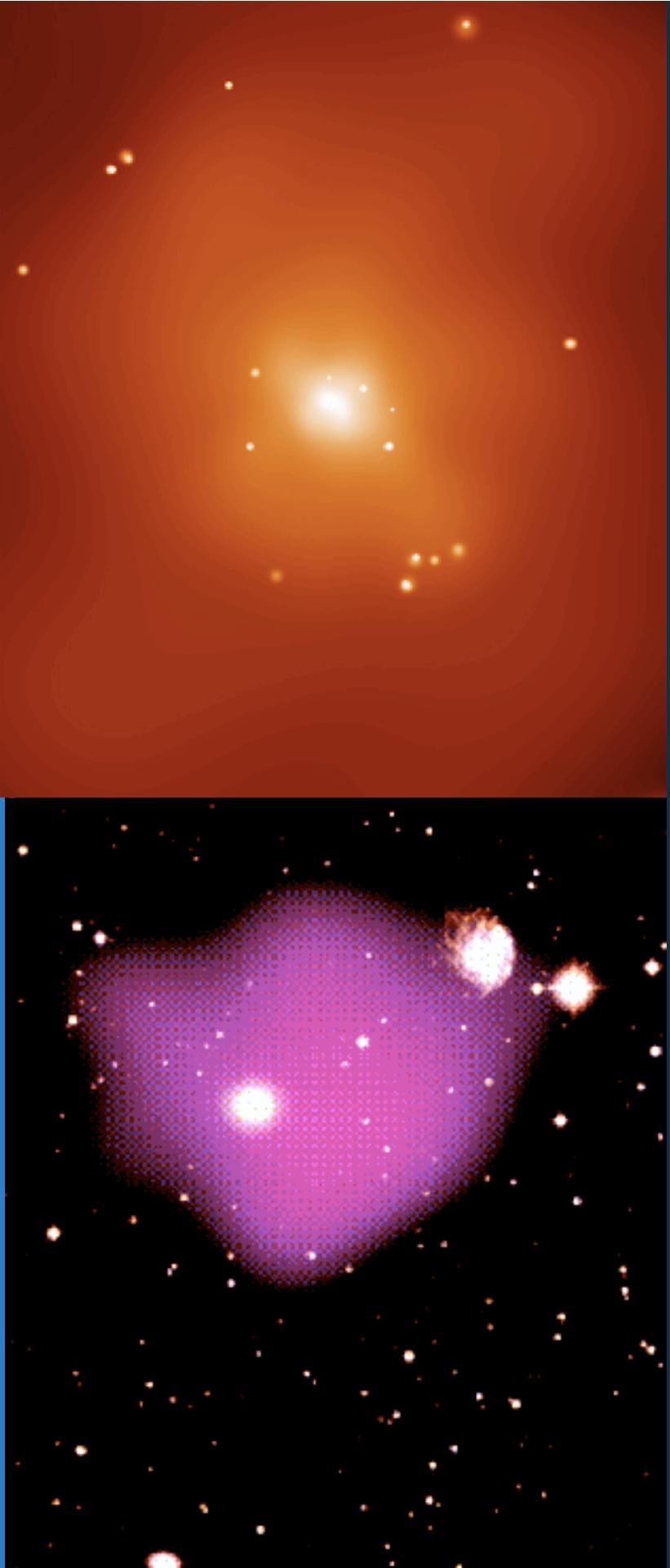


CMB update Oct 2002
(from Tegmark)

$\square_{\text{peak}} = 216 \pm 6$
(from Boomerang astro-ph/0212229)

$$-0.09 \leq \square_{\square_0} \leq 0.02 \quad \text{Flat Universe}$$

Weighing the (Dark) Matter: \square_M



NGC 720 (From Chandra)
(From ROSAT)

Rich Clusters of Galaxies: $r \approx$ few Mpc, $M \gtrsim 10^{15} M_{\text{sun}}$

($1 \text{ Mpc} = 3.3 \cdot 10^6$ light years)

White et al. ('93): $f_b \equiv M_b/M \approx \Omega_{b0}/\Omega_{M0}$

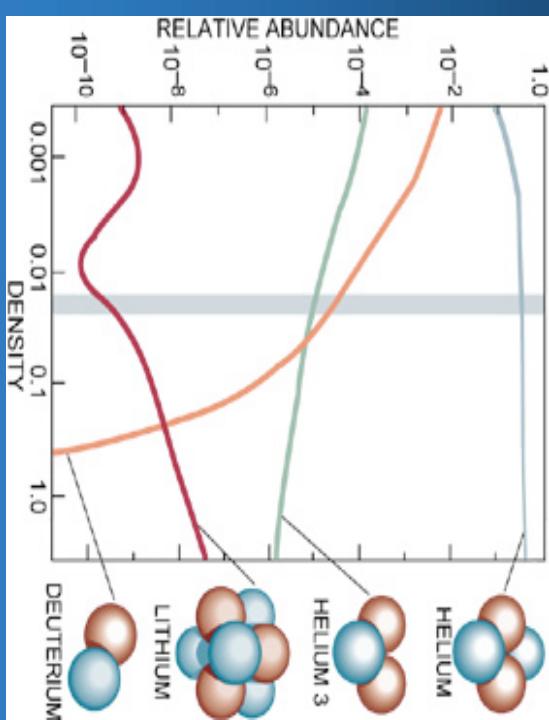
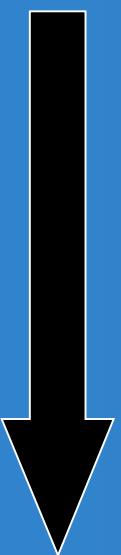
1) take Ω_{b0} from BBN theory,

$$0.018 \leq \Omega_{b0} h^2 \leq 0.022 \text{ (Burles et al.)}$$

$$[0.006 \leq \Omega_{b0} h^2 \leq 0.017 \text{ (Cyburt et al.)}]$$

$$h \equiv H_0/(100 \text{ } Km s^{-1} Mpc^{-1}) = 0.67 \pm 0.07$$

2) Measure f_b (see below)



$$\Omega_{M0} = \Omega_{b0} / f_b$$

Most of the cluster baryons are in hot ($T \sim 10$ KeV) gas

Gas mass determined via:

1) X-ray flux ($\sim \square_{\text{gas}}^2$)

2) Sunyaev-Zel'dovich effect (scattering of electrons from the gas on CMB photons)  distortions in the CMB ($\sim \square_{\text{gas}} T_e$)

Total cluster mass determined via:

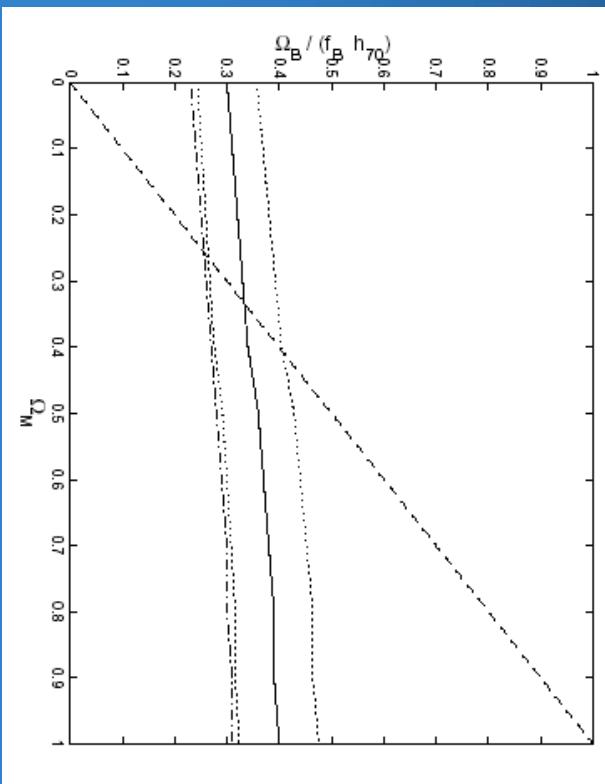
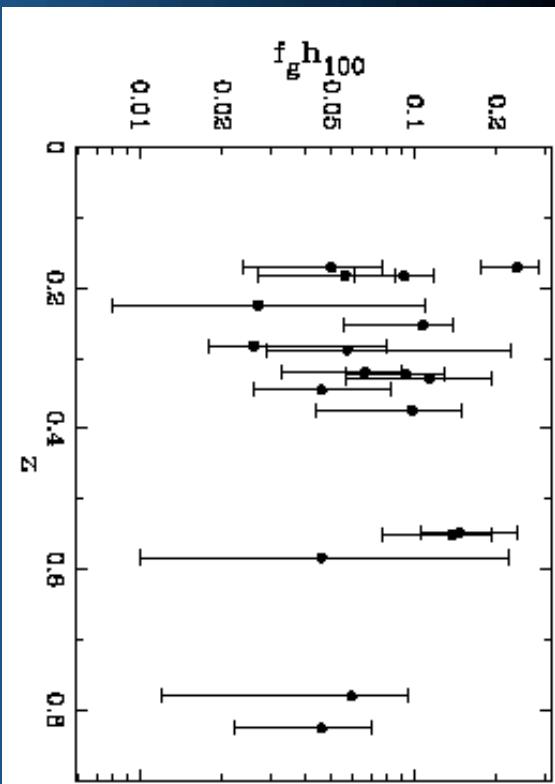
- 1) Motions of cluster galaxies + virial theorem
- 2) Pressure of the gas + hydrostatic equilibrium
- 3) Gravitational lensing

$$f_{\text{gas}} = (0.075 \pm 0.002) h^{-3/2} (\text{X-ray})$$

$$f_{\text{gas}} = (0.081 \pm 0.001) h^{-1} (\text{SZ})$$



SZ (Grego et al.)



$\square M_0 = \square_{b0} / f_b = 0.25 \pm 0.05$
(Carlstrom et al. 2001)

Further determinations of \square_{M0}

✓ Cluster abundance vs. redshift

✓ Matter Power Spectrum
 $(\square_{\text{break}} \sim 50 \square_{M0}^{-1} h^2 \text{ Mpc})$

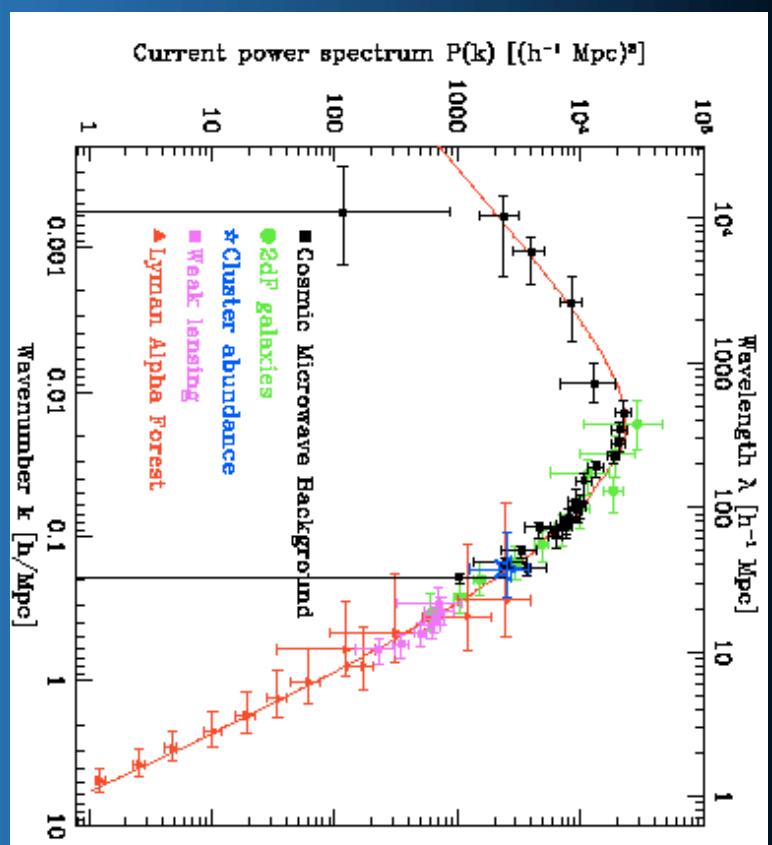
✓ Peculiar velocities and lensing

✓ CMB anisotropies

✓ M/L ratio

✓ ...

$0.15 \leq \square_{M0} \leq 0.4$



SUMMARY: $h \sim 0.7$, $|w_k| < 0.1$, $w_M \sim 0.3$,



1) $w_X = 1 - w_K - w_M \sim 0.7$

70% of the energy density of the Universe is smoothly distributed on scales $< O(100 \text{ Mpc})$:

DARK ENERGY

- 2) $w_{X_0} = ?$ determine the EoS via its effects on expansion, distance measurements, galaxy counts, lensing, growth of perturbations, CMB, ...

Test 1: Age of the Universe

Lookback time:

$$t_0 \square t_* = \int_{t_*}^{t_0} dt = \int_{1/(1+z_*)}^1 \frac{da}{aH(a)}$$

$$\downarrow \text{Age: } t_0 = \frac{1}{H_0} \int_0^{\infty} \frac{dz}{(1+z)E(z)}$$

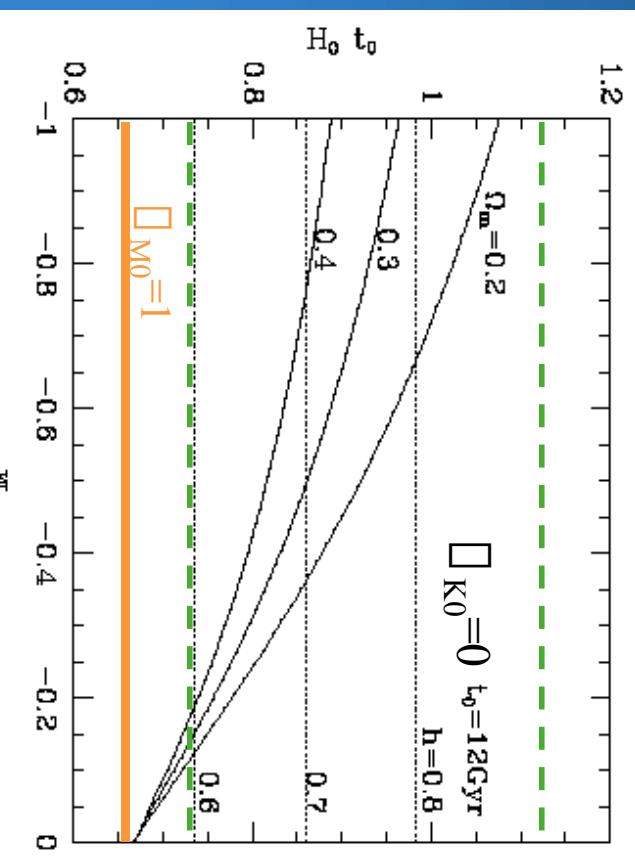
$$E(z) = \left[\Omega_M(1+z)^3 + \Omega_X(1+z)^{3(W_X+1)} + \Omega_K(1+z)^2 \right]^{1/2}$$

$t_0 = t_{\text{GC}} + 0.8 \text{ Gyr}$ (Krauss et al.)

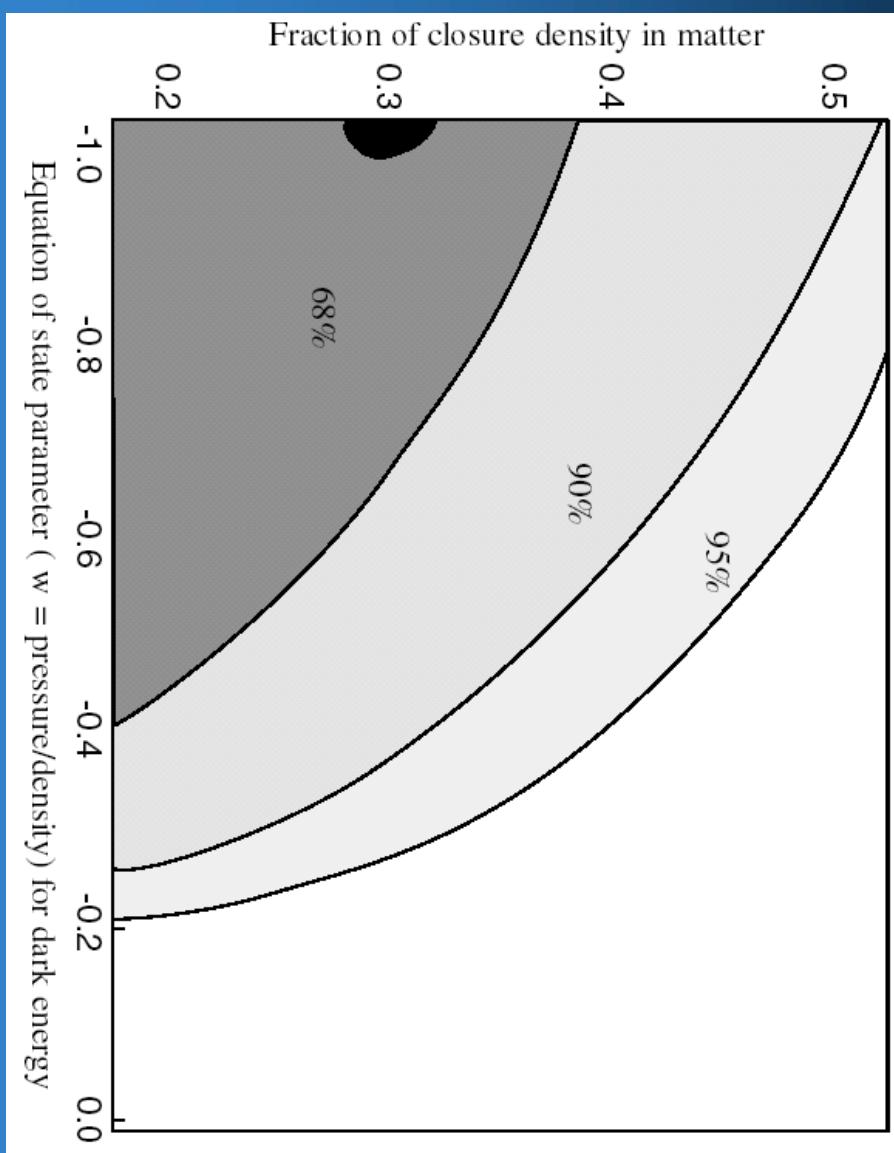


$11 \text{ Gyr} < t_0 < 17 \text{ Gyr}$

$0.72 < H_0 t_0 < 1.17$ (95 % C.L.)

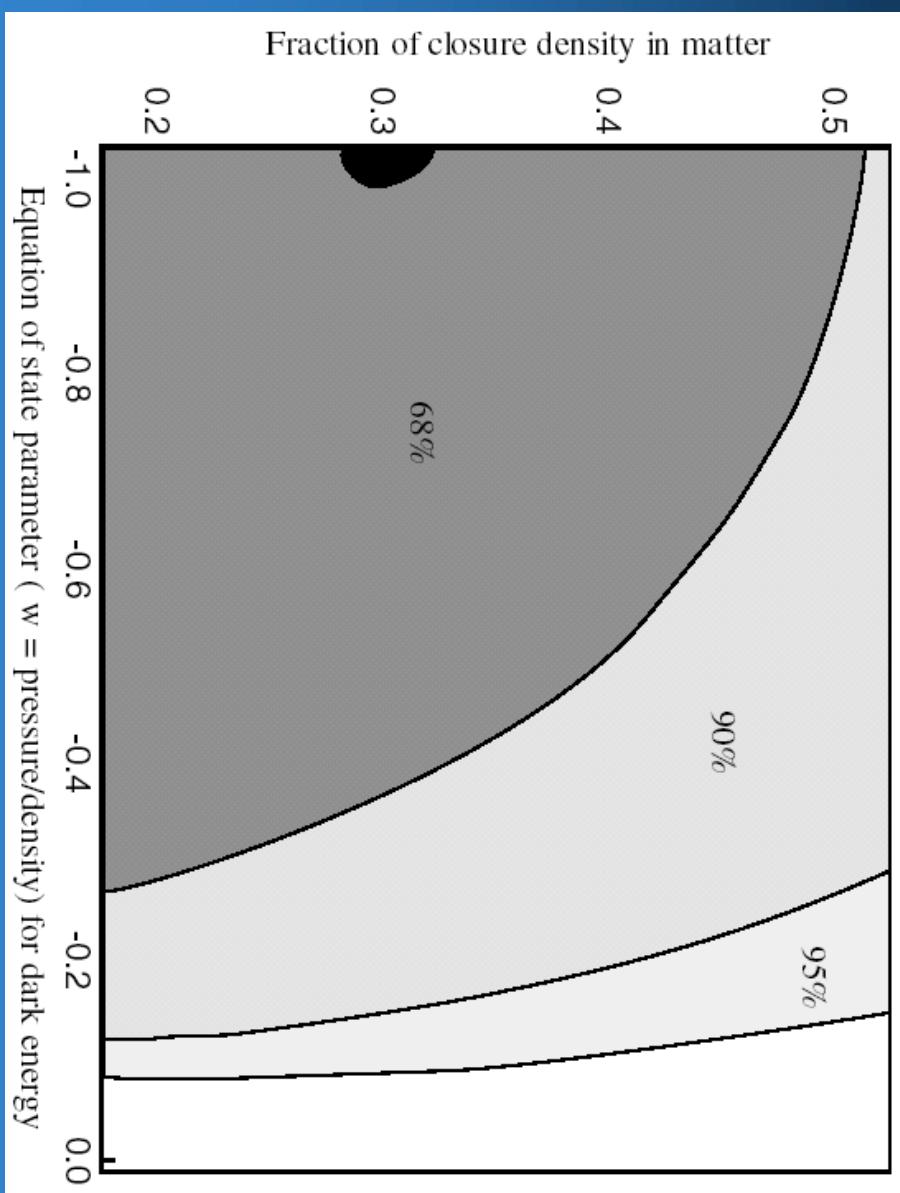


Age + Flatness $\square \square x_0 \sim 0.7$, $W_{x_0} < -0.2$



$$H_0 = 70 \text{ Km s}^{-1} \text{ Mpc}^{-1}$$

Age + Flatness $\square \square x_0 \sim 0.7$, $W_{x_0} < -0.2$



Test 2: Supernovae Ia

Luminosity distance:

$$d_L \equiv \sqrt{\frac{L}{4\Box F}}$$

L=absolute luminosity
F=measured flux

SN of luminosity L at (r_z, t_z):

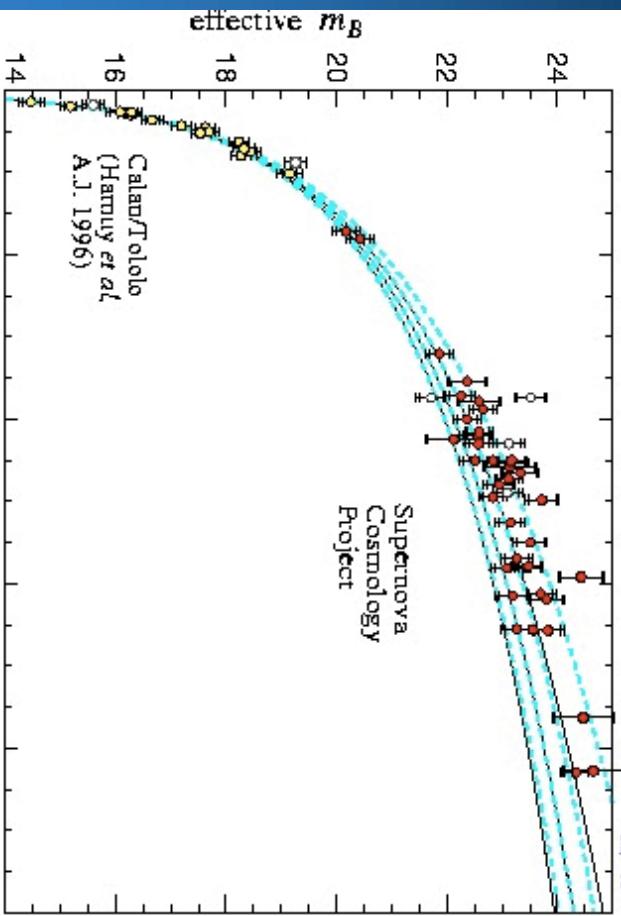
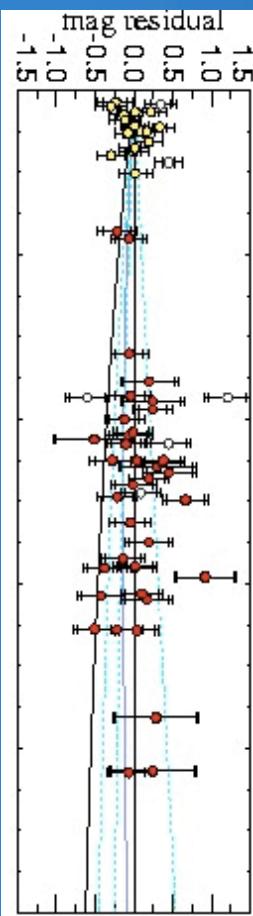
$$F = \frac{L}{4\Box a_0^2 r_z^2 (1+z)^2} \quad d_L = a_0 r_z (1+z)$$

Light travels on geodesics ($ds^2=0$):

$$\Box \frac{dr}{\sqrt{1 \Box K r^2}} = \Box \frac{dt}{a(t)} \quad r_z = \frac{\sin(\sqrt{\Box_{K0}} \Box dz / E(z))}{H_0 \sqrt{\Box_{K0}}}$$

If all SNe have the same L

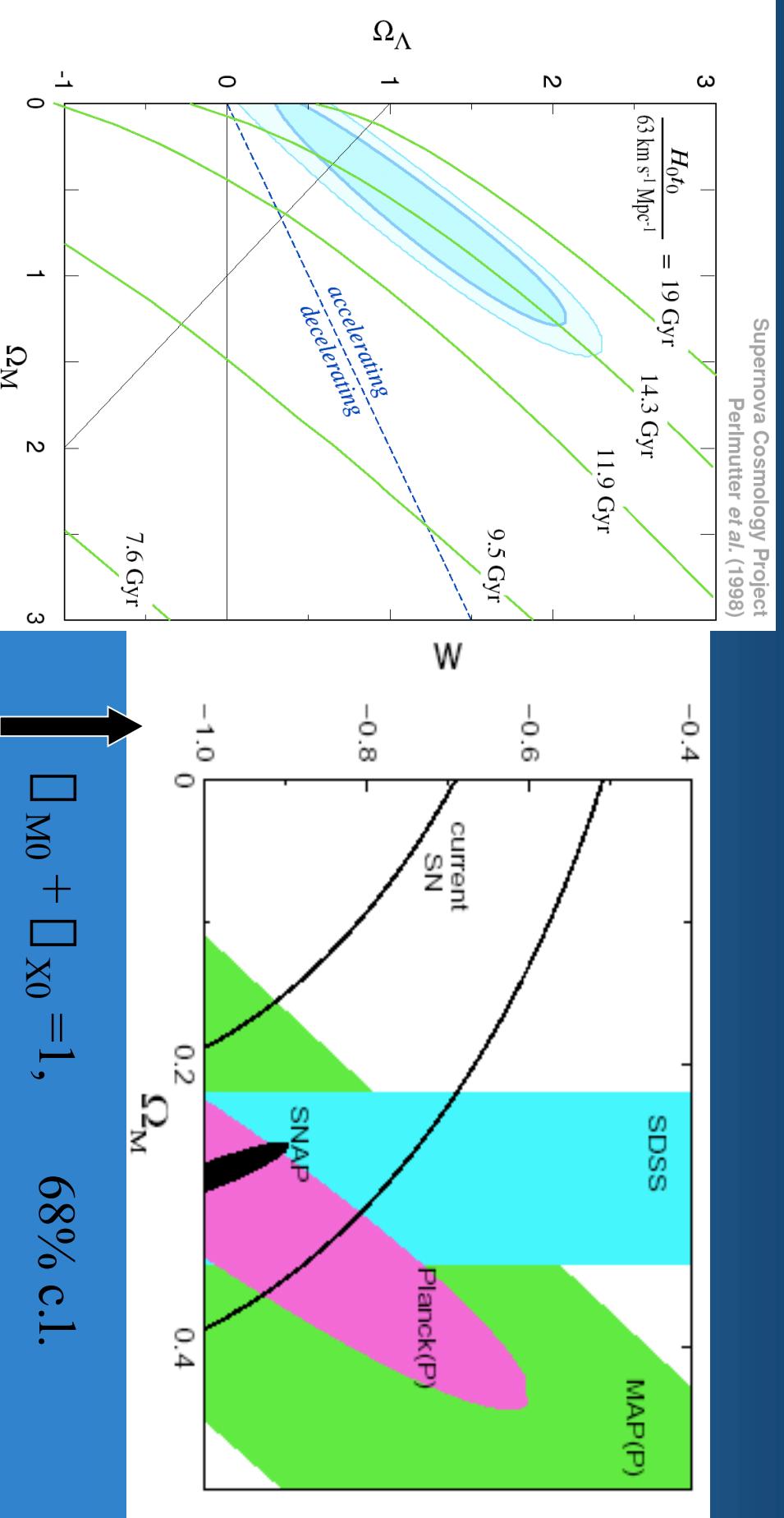
$$d_L = d_L(z; H_0, \Box M_0, \Box K_0, \Box X_0, W_{X0})$$



$$\text{for moderate } z\text{'s... } H_0 d_L(z) = z + (1-q_0)/2 z^2 + \dots$$

$$q_0 \equiv \square - \frac{\ddot{a}}{aH_0^2} = \frac{1}{2} [\square M_0 + (1 + 3W_{x0})\square_{x0}]$$

Deceleration parameter

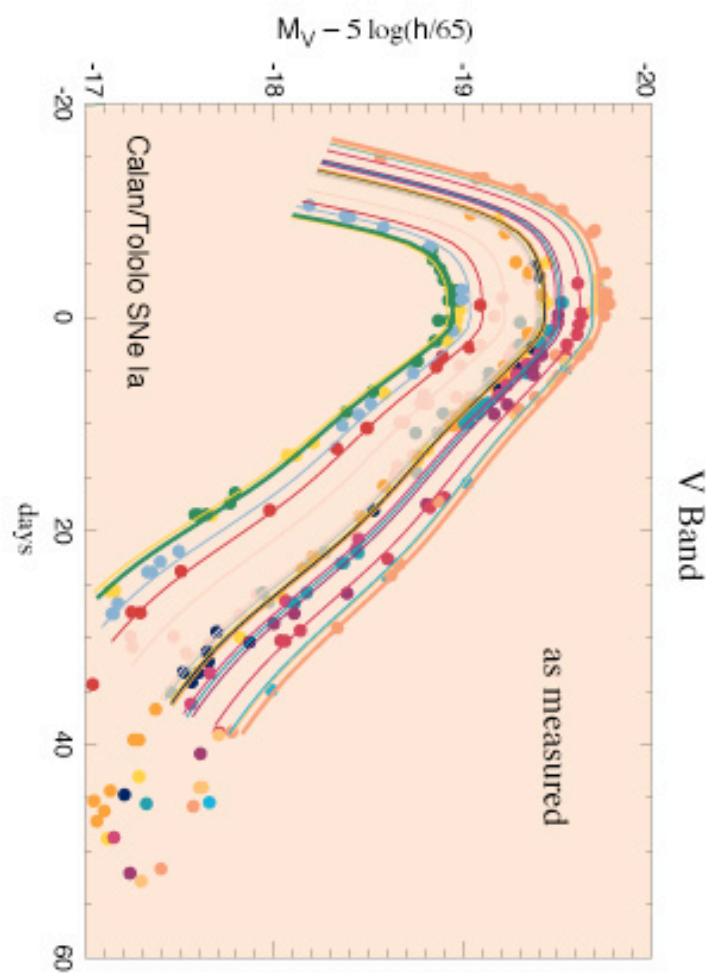
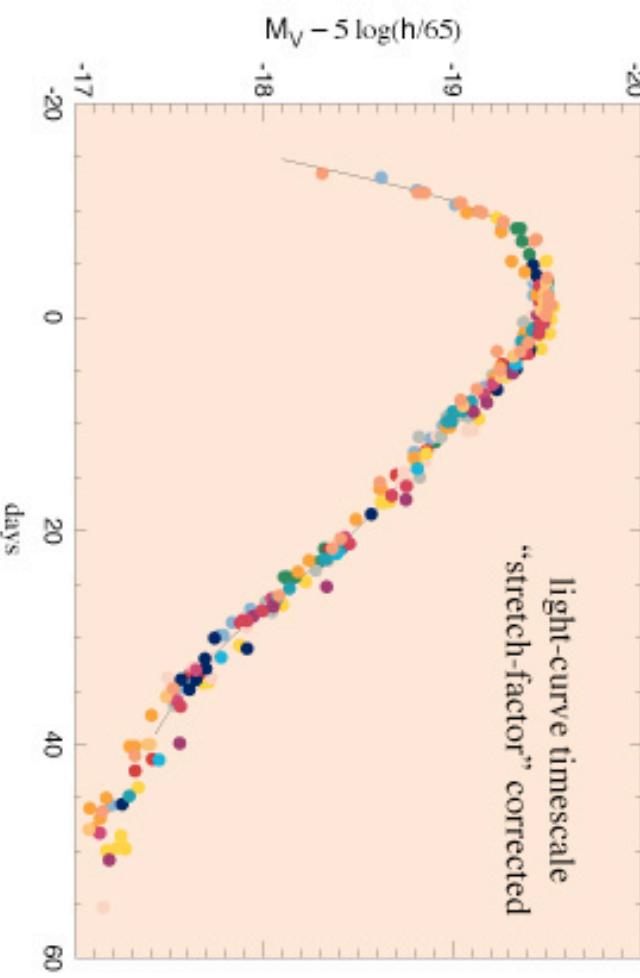


SNeIa are turned into
'standard candles'

Systematics (evolution,
dust, ...)?

Look for very distant

SNe ($z > 1$) (Hubble, SNAP)



Test 3: Growth of structures

$$\square = \frac{\square_M}{\square_m}$$

Matter fluctuations (X not fluctuating)

$$\ddot{\square}_k + 2H\dot{\square}_k - 4\square G\square_M\square_k = 0$$

$$\square = \log(a)$$

$$\square_k \square + \frac{H\square}{H\square} + \frac{H\square}{H\square} \frac{3}{2} \square_M \square_k = 0$$

$$\square_M = \square_{M0} (1+z)^3, \quad \square_x = \square_{x0} (1+z)^{3(W_X+1)}$$

Fluctuations stop growing when $\square_M < \square_x$, i.e. at

$$1 + z_X = \frac{\square_{X0}}{\square_{M0}}^{1/3 W_X}$$

The more $W_X < 0$, the longer matter fluctuations grow.

Estimator of structure growth:

\square_8 = rms mass fluctuation in spheres of radius 8 h⁻¹ Mpc (~clusters)

$$P(k) \equiv \langle |\square_k|^2 \rangle$$



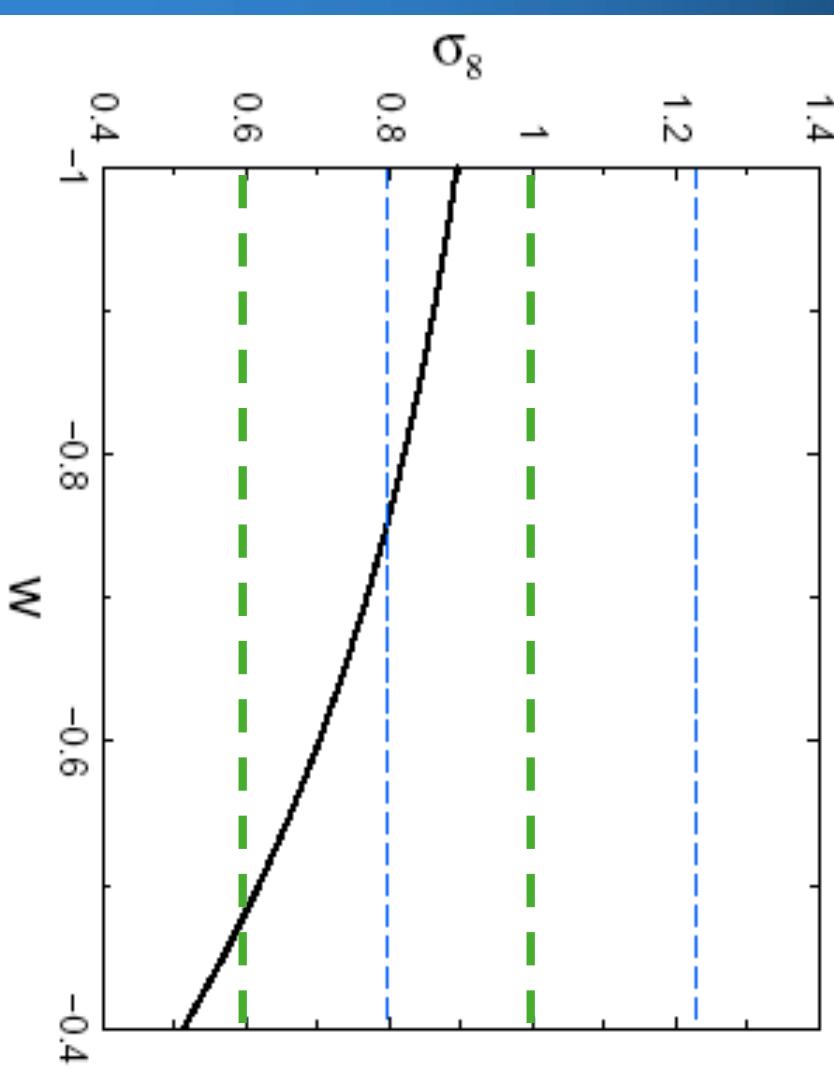
$$\square_r^2 \equiv \frac{dk}{k} \frac{k^3 P(k)}{2 \square^2} \left[\frac{3 j_1(kr)}{kr} \right]^2 \quad (r=8h^{-1}\text{Mpc})$$

$$\square_8 = 0.8 \pm 0.2$$

(Tegmark Zaldarriaga 2002)



$$W_X < -0.5$$



Test 4: Number Counts

The volume of space back to a specified redshift depends on cosmology:

$$\frac{dV}{dz d\Omega} = \frac{r^2}{\sqrt{1 - K r^2}} \frac{dr}{dz} = \frac{r^2(z)}{H_0 E(z)}$$

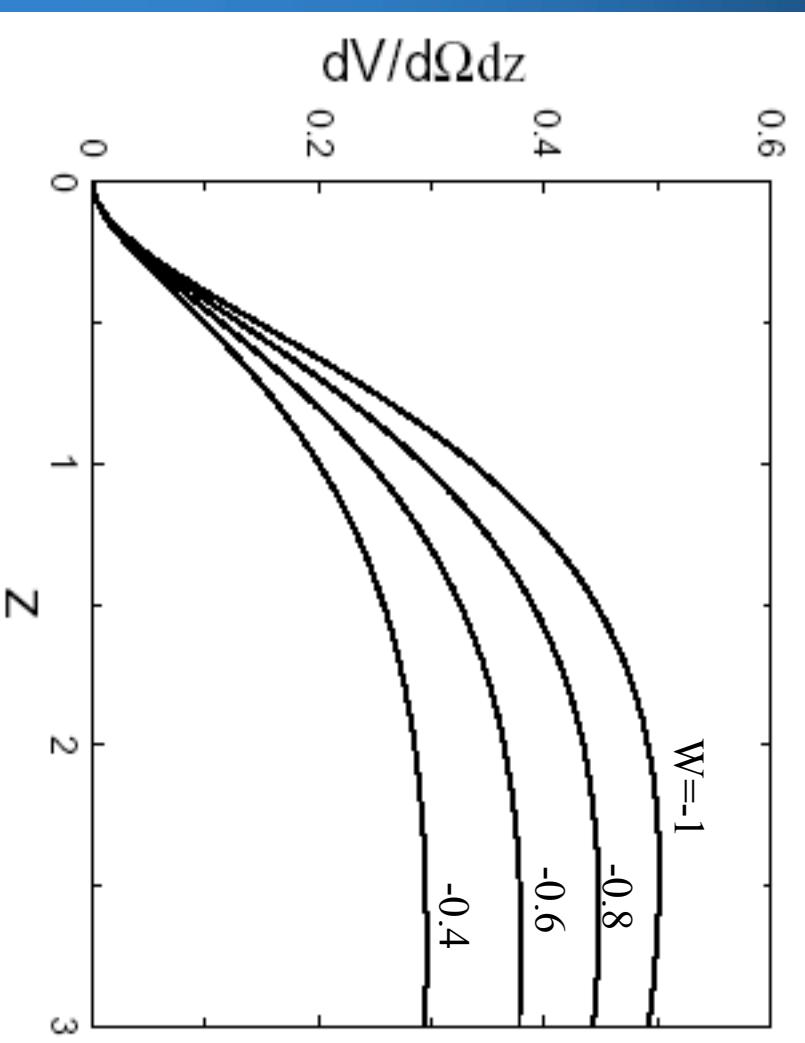
Find a population of objects 'independent' on history, and count the apparent density of them.

Ex: Galaxies (ex. DEEP

survey),

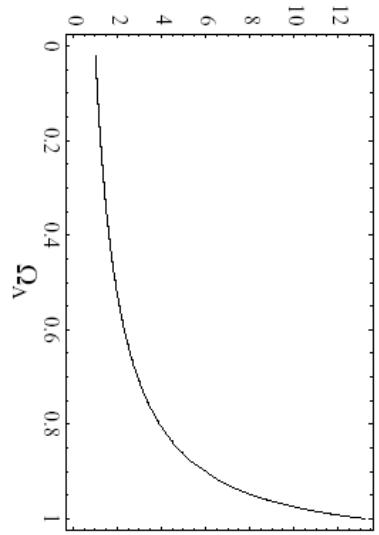
Gravitational lenses (CLASS),

...



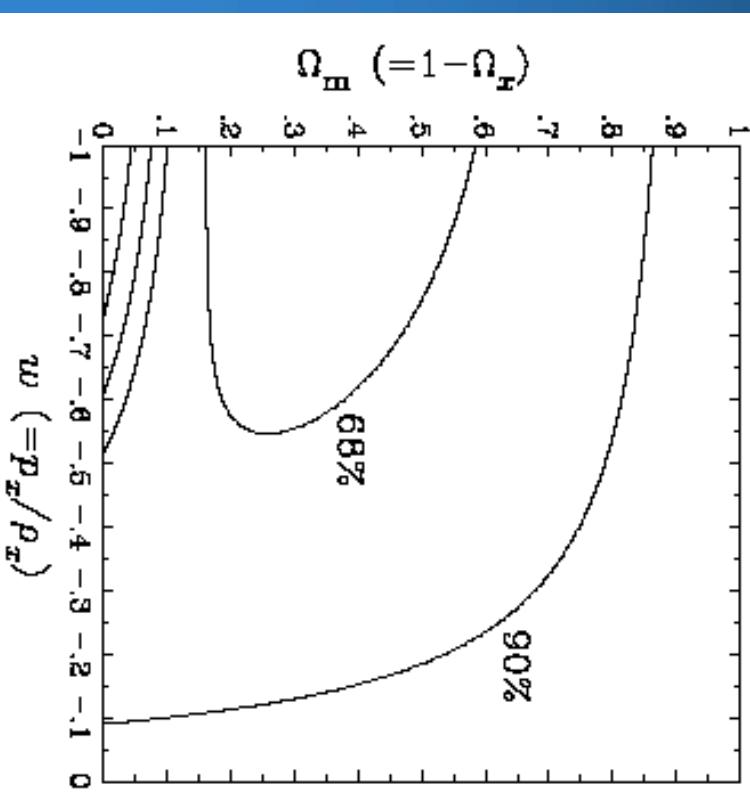
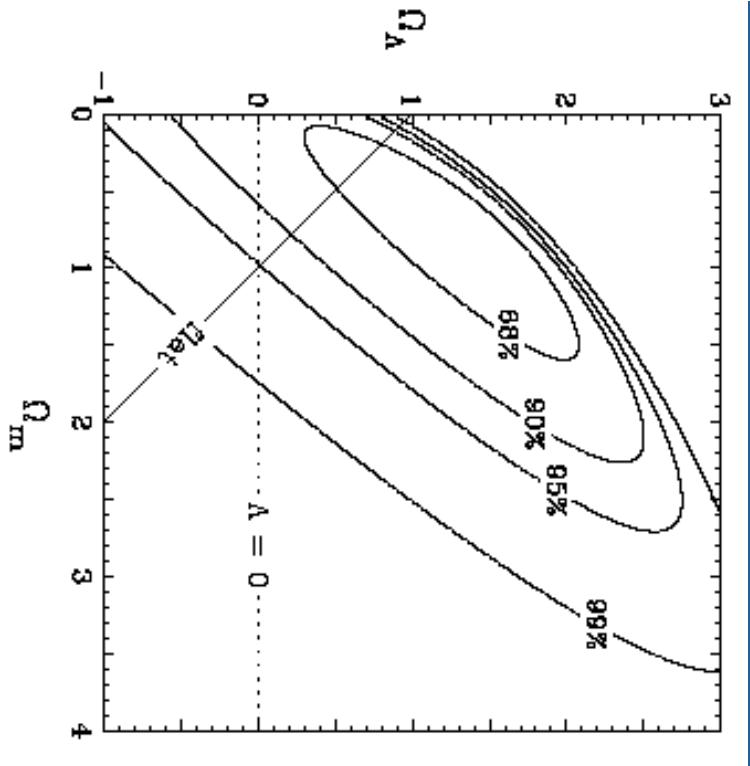
Gravitational lensing

Lens Probability



Probability
Of being lensed
For a source at $z=2$
(normalized to $\Omega_M=1$)

Chae et al. (CLASS): 13 lensed radio sources (out of ~ 9000)

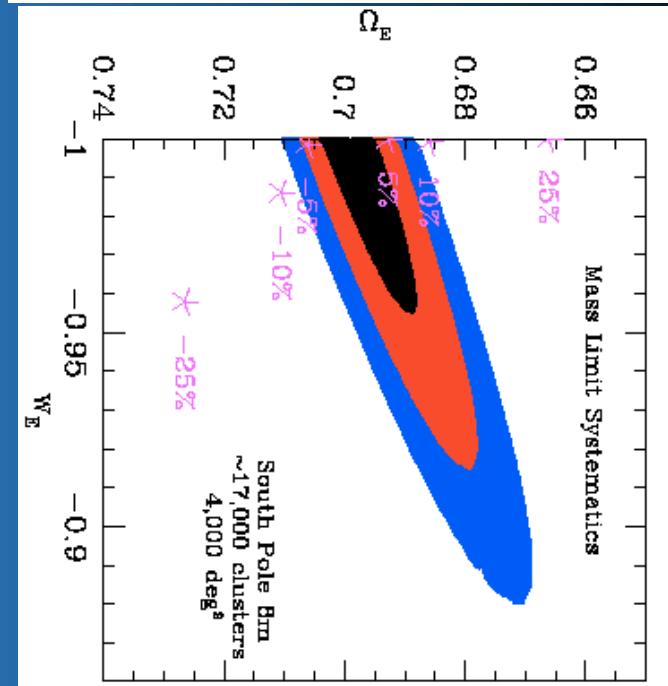
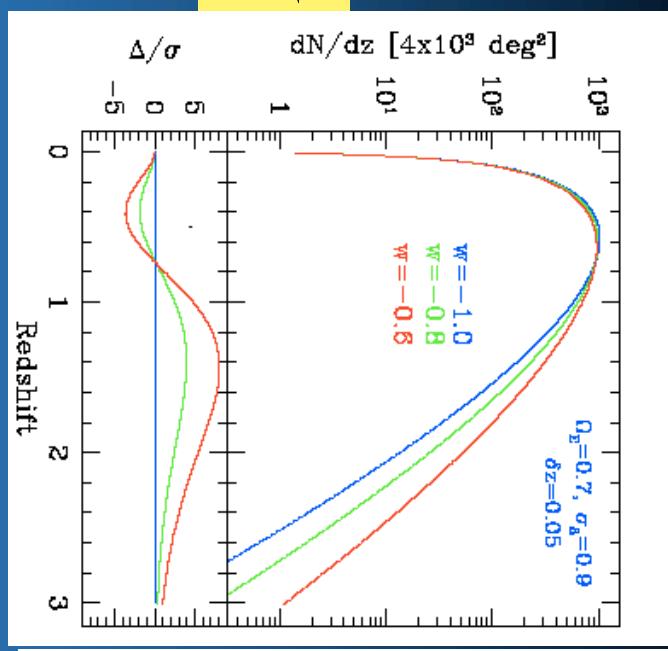


Test 5: Future Tests

-Cluster Number

vs. redshift

$$\frac{dN}{dz} = \frac{dV}{dz dM} \int_{M_{\text{lim}}(z)}^{\infty} \frac{dn}{dM}$$



Exp. Sensitive to $\square(M, z)$

-Alcock-Paczynsky: $\square \square$ vs. $\square z$

- ...

Conclusions (part I)

- 1) Solid evidence for $\Omega_{k0} \sim 0$ (CMBR), $0.15 < \Omega_{m0} < 0.4$
 **SIZABLE component of the energy density of the present Universe ($\Omega_{x0} \sim 1 - \Omega_{m0}$) is smooth**
- 2) Strong evidence for a negative Ω_{x0} , (Age+Flatness, Ω_8), maybe even accelerating ($\Omega_{x0} < -1/3$, mainly from SNeI SNAP: ~ 4000 SNe Ia up to $z \sim 1.8$))
- 3) It is true that we have entered the E.P.C. (Era of Precision Cosmology) ... but the results are frightening!!
95% of the Universe is made up of unknown particles and mysterious 'fluids'....
- 4) Open the Pandora's box of Dark Energy (Ω , equivalence principle, Susy, $\Box\Box/\Box$, naturalness, axions, ...) \square Part II