Universität Bielefeld

Cosmic Acceleration

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- minimal cosmological model
- evidence for accelerated expansion of the Universe
- some open issues

Erice 2010

A short history of the cosmological standard model

cosmological inflation and cold dark matter (early 1980s) $\Rightarrow$
Einstein-de Sitter model (isotropic, homogeneous, $K=0$ and $p=0$)

1993: q_0 from radio galaxies agrees with EdS ($q_0=\frac{1}{2}$) Kellermann 1993

1995: new determinations of t_0 (Hipparcos) and H_0 (HST) $\Rightarrow$
"age crisis", e.g. Bolte & Hogan 1995; Ostrikder & Steinhardt 1995

low density, cosmological constant, neutrinos, inhomogeneities, ???

1998/1999: "supernova revolution" ruled out EdS
$\Lambda > 0$ at 3σ Riess et al. 1998, Perlmutter et al. 1999

2000: 1^{st} acoustic CMB peak Toco, Boomerang & Maxima $\Rightarrow \Omega_{\text{tot}} \approx 1$
Miller et al. 1999, de Bernardis et al. 2000, Hanany et al. 2000 needs H_0!

The minimal cosmological model

relies on

◇ the standard model of particle physics T_0, Ω_b, (Ω_ν)

◇ the Einstein equation with a cosmological constant H_0, Λ

◇ comological inflation:

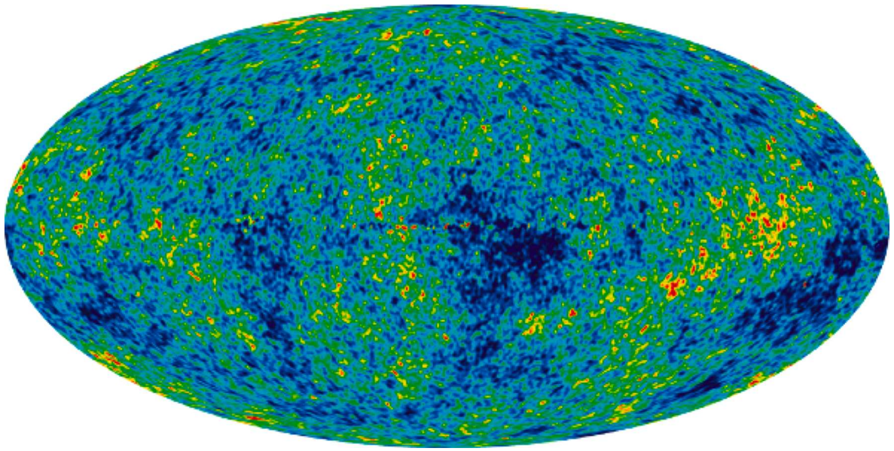
isotropy, homogeity and spatial flatness

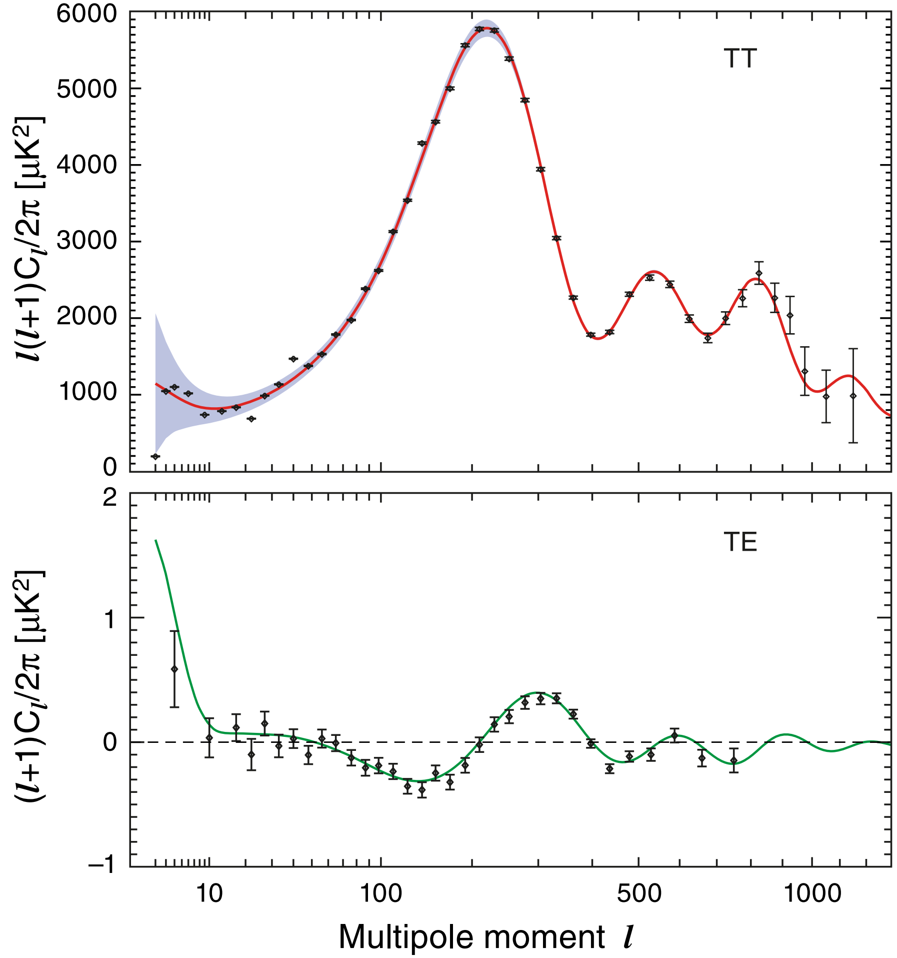
gaussian, scale-invariant and isentropic fluctuations A, n, (r)

◇ the existence of dark matter $\Omega_\mathrm{cdm} = 1 - \Omega_\mathrm{b} - \Omega_\Lambda$

and astrophysical parameters that encode complex physics $\tau, b, \mathcal{M}, \ldots$

The cosmic microwave sky $(z \sim 1100)$

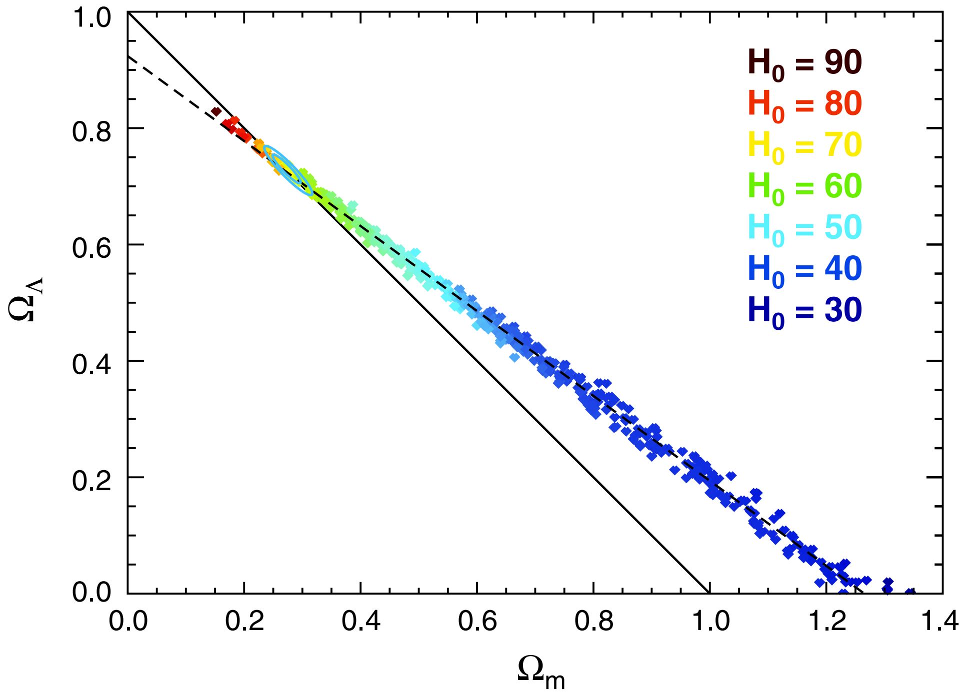




Larson et al. 2010

WMAP 7yr ILC map

Information from low redshift



Larson et al 2010

Hubble law $z < 0.1$

$H_0 = 74.2 \pm 3.6$ km/s/Mpc

Riess et al 2009

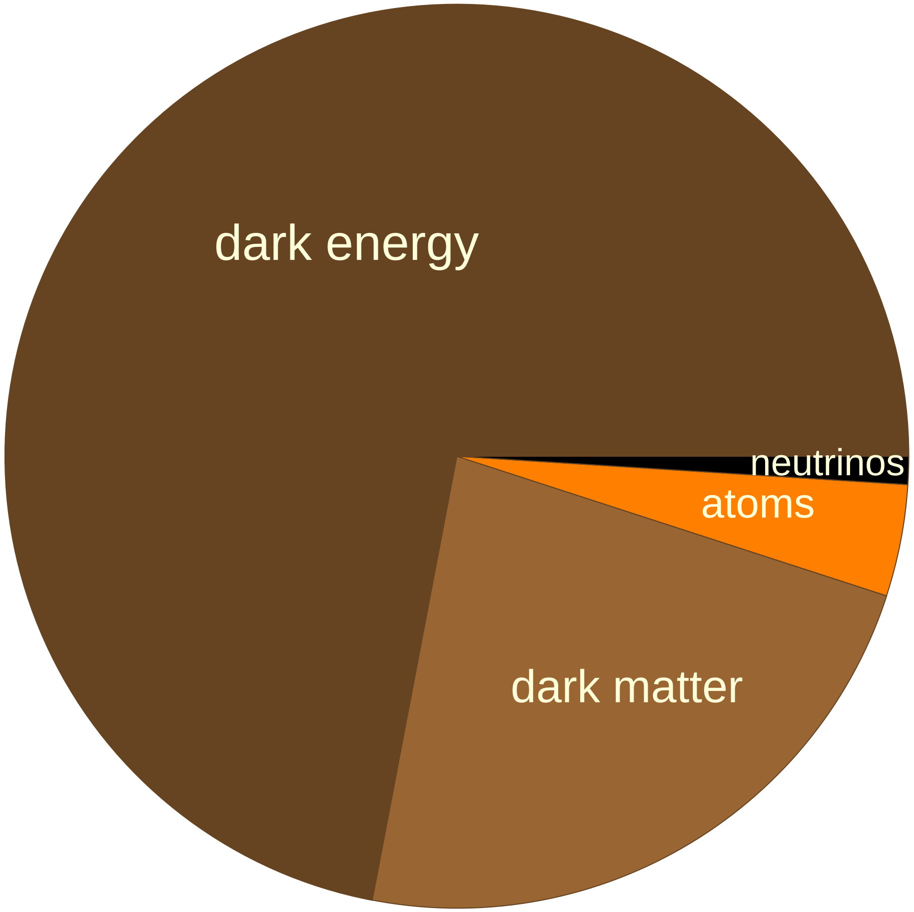
large scale structure $z < 1$

baryon acoustic oscillations

Reid et al 2010

Percival et al 2010

The cosmic energy budget (WMAP 7yr + H0 + BAO)



ΛCDM and massive νs fit to CMB/BAO/SNIa:

72% dark energy

23% cold dark matter

5% atoms

$<$ 1% neutrinos

all $\pm$1%

95% dark physics

What is the dark physics?

1. cosmological constant Λ

2. dark energy $p < -\epsilon/3$
   quintessence, k-essence, Chaplygin gas, ...

3. modified gravity
   $f(R)$, other curvature invariants, non-minimal couplings, ...

4. wrong interpretation of data
   cosmological backreaction, evolution effects, inhomogeneities, ...

Cosmological backreaction: an alternative?

coincidence problem(s):

Why is $\Omega_\Lambda(t_0) \sim \Omega_\mathrm{m}(t_0)$? Why is $z_\mathrm{nl}(R_\mathrm{eq} \sim 100\ \mathrm{Mpc}) \sim z_\mathrm{acc}$?

e.g. Shapely supercluster, Sloan great wall, biggest voids

de linked to structure formation? Zimdahl et al. 2001, Schwarz 2002

averaging problem:

Einstein tensor (averaged metric) $\neq$ averaged Einstein tensor (metric)

How big is the difference? Ellis, Buchert, Räsänen,. . .

most observations are averages, e.g. H_0, q_0, $P(k)$, BAO scale

Cosmic acceleration

Einstein's gravity and isotropy and homogeneity imply

a scale factor; $r_{\text{ph}} = a(t)r$

$$-3\frac{\ddot{a}}{a} = 4\pi G(\epsilon + 3p)$$

Thus, $\ddot{a} < 0$ for "known" forms of energy/matter

deceleration $q \equiv -(\ddot{a}/a)/H^2$

measure sign of q as model-independent as possible

others make assumptions on $w = \frac{p}{\epsilon}$ e.g. Riess & Turner 2002

Kinematic tests based on distance measurements

comoving distance

$$d_{\mathrm{c}} = \frac{1}{H_0\sqrt{|\Omega_k|}}\mathcal{S}\left(\int_0^z \frac{H_0\sqrt{|\Omega_k|}}{H(z')}\mathrm{d}z'\right), \quad \mathcal{S} = \{\sinh, \mathrm{id}, \sin\} \text{ for } k = \{-1, 0, 1\}$$

luminosity distance

$$d_{\mathrm{l}} \equiv \sqrt{\frac{L}{4\pi F}} = (1+z)d_{\mathrm{c}} \approx \frac{1}{H_0}\left(z + (1-q_0)\frac{z^2}{2} + \ldots\right)$$

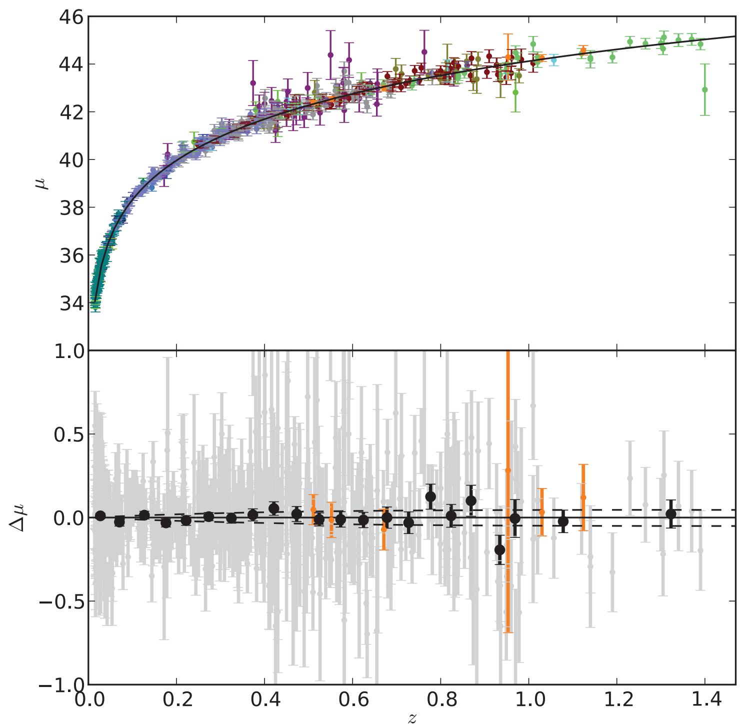
SNIa (if standard candles)

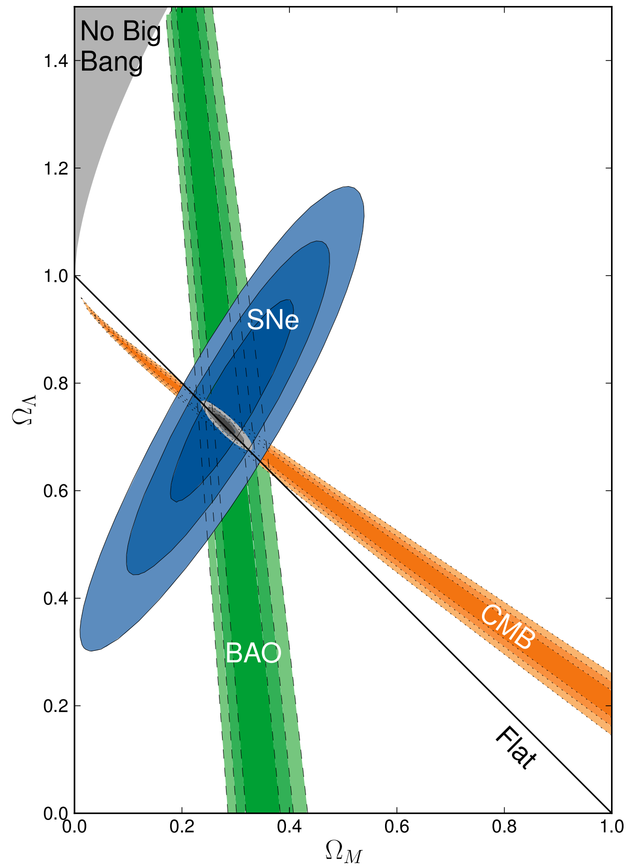
angular distance

$$d_{\mathrm{a}} \equiv \frac{s}{\delta} = \frac{d_{\mathrm{c}}}{1+z} \approx \frac{1}{H_0}\left(z - (1+q_0)\frac{z^2}{2} + \ldots\right)$$

FRII radio galaxies (if standard size) or baryon acoustic oscillations (CMB, LSS)

Supernovae Ia (z up to $\sim$ 1)





Union2: Amanullah et al. 2010

How strong is the evidence for acceleration?

test: **assume isotropy and homogeneity**

but neither Einstein's equations nor particular cosmic substratum

null hypothesis $q(z) \geq 0, \forall z \quad \Rightarrow \quad d_{\mathrm{l}}(z) \leq \frac{(1+z)}{H_0\sqrt{|\Omega_k|}} \mathcal{S}\left(\sqrt{|\Omega_k|}\, \ln(1+z)\right)$

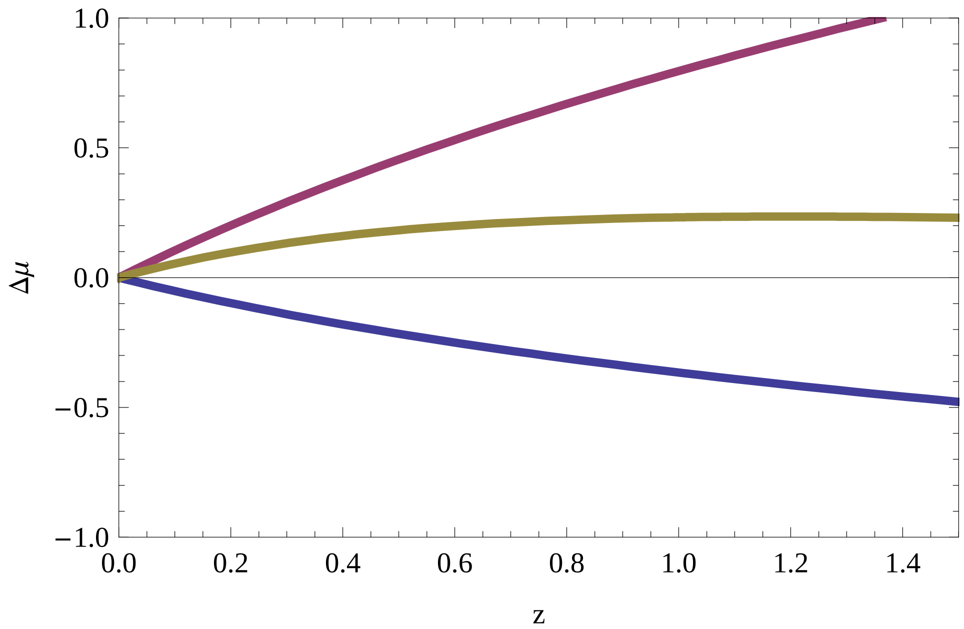
violation of null hypothesis $\Rightarrow$ acceleration

Seikel & Schwarz 2008

Distance modulus — theoretical expectation

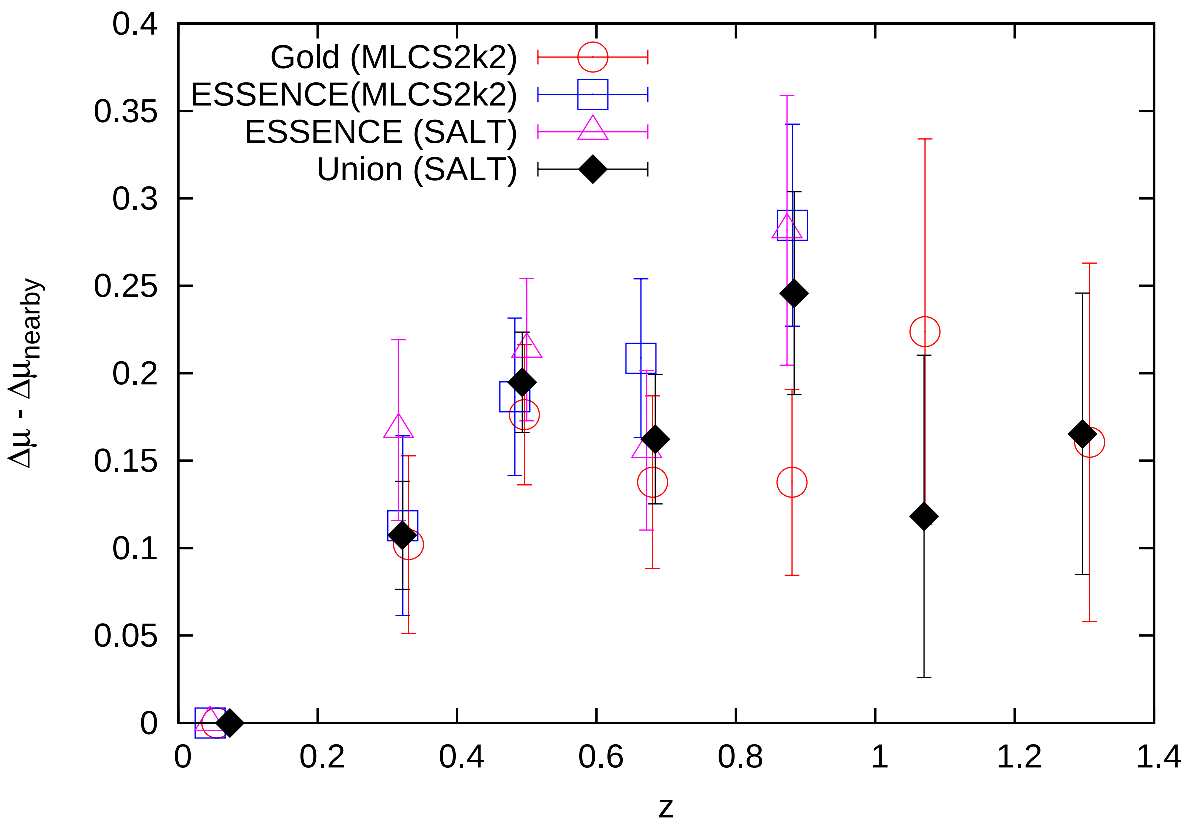
distance modulus $\mu \equiv m - M = 5\log(d_{\rm l}/\mathrm{Mpc}) + 25$

null hypothesis: $\Delta\mu \equiv \mu_{\rm obs} - \mu(q=0) \leq 0$



de Sitter, ΛCDM, Einstein-de Sitter

Model- and calibration-independent test



Seikel & Schwarz 2009

$\delta_H \approx 0.05 \rightarrow \delta\mu \approx 0.1$

calibrate on first bin!

acceleration at

4.3σ Gold (MLCS2k2)

5.2σ Essence (MLCS2k2)

5.6σ Essence (SALT)

7.2σ Union (SALT)

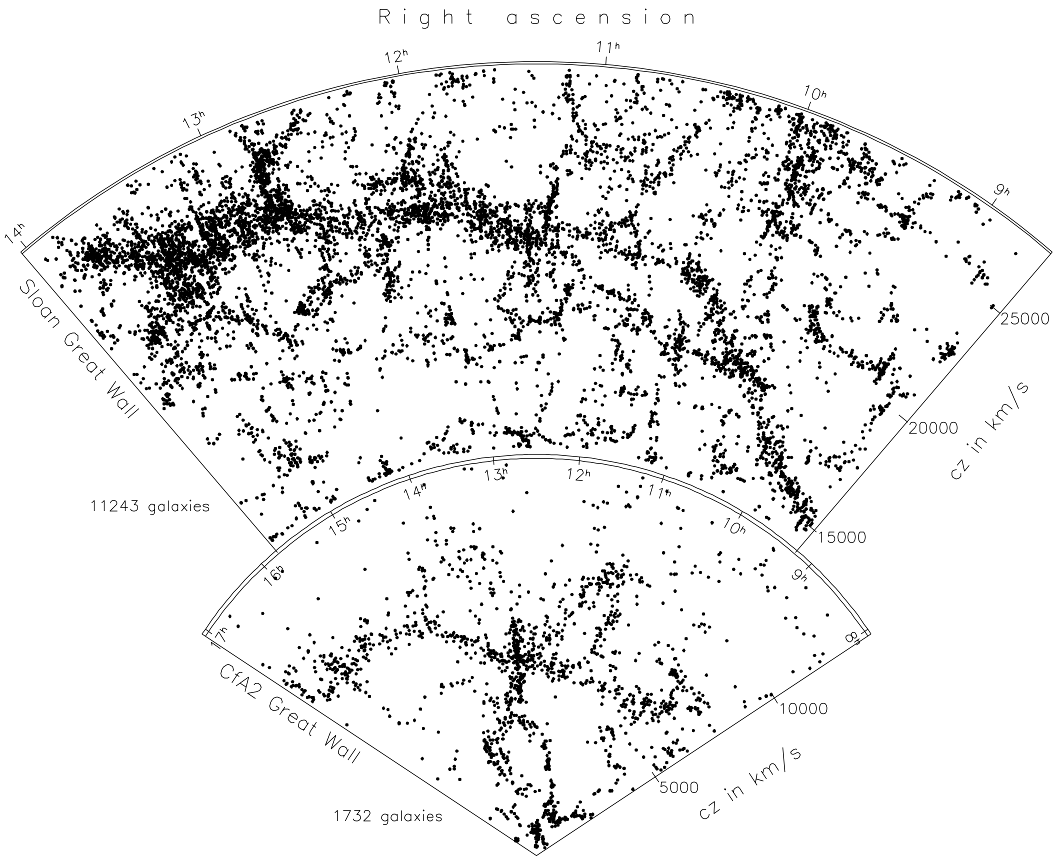
But, first bin at $z < 0.1$!

small volume $V < 10^{-3} V_{\mathrm{H}}$

Anisotropies?

Inhomogeneities?

The local Universe — $z < 0.1$ or $d < 400$ Mpc



Sloan Great Wall

400 Mpc long

$cz \leq 30{,}000$ km/s $\Leftrightarrow$

$z \leq 0.1$

Gott et al. 2005

other big structures:

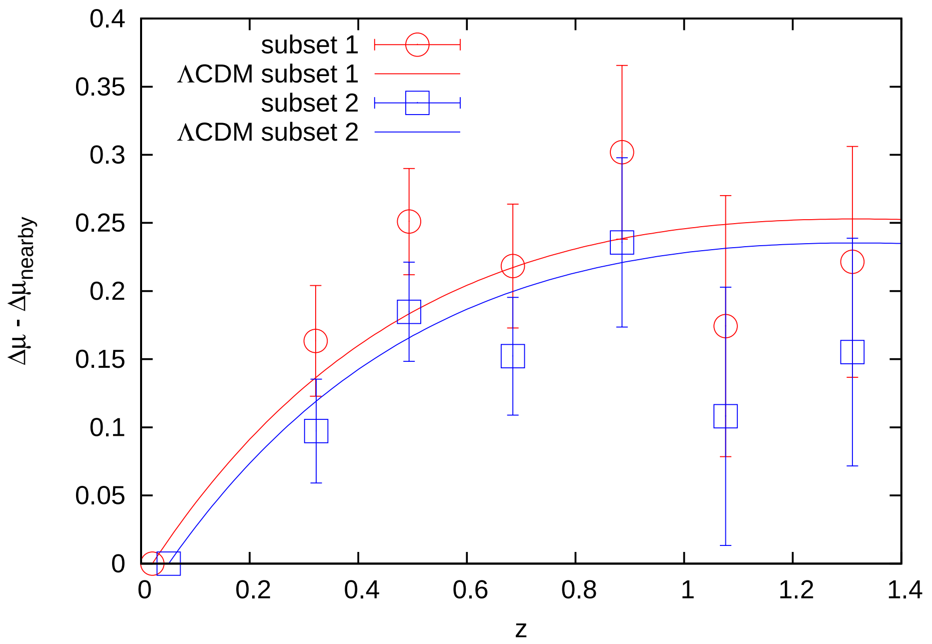
voids at 100 Mpc scale

superclusters

at few 10 Mpc

e.g. Shapely cluster

Normalisation dependent evidence



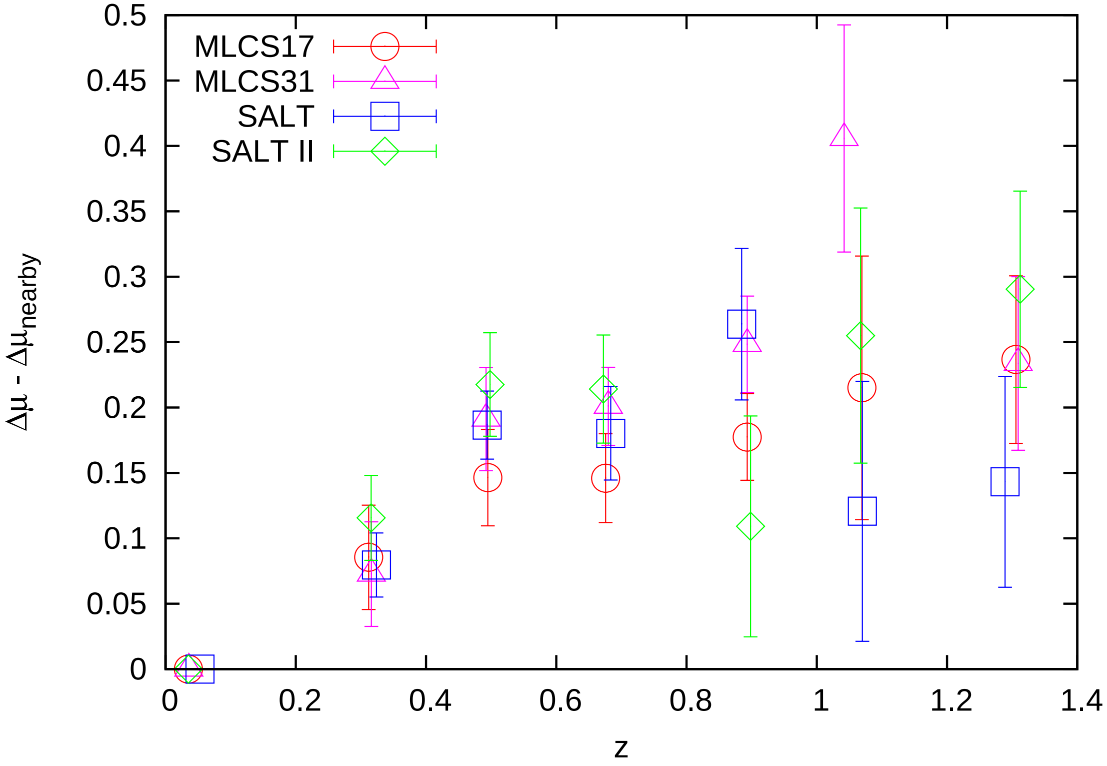
Seikel & Schwarz 2009

Union set, split 1st bin ($z < 0.1$) into two samples of 25 SNe each

1st sample 6.3σ, 2nd sample 4.9σ evidence

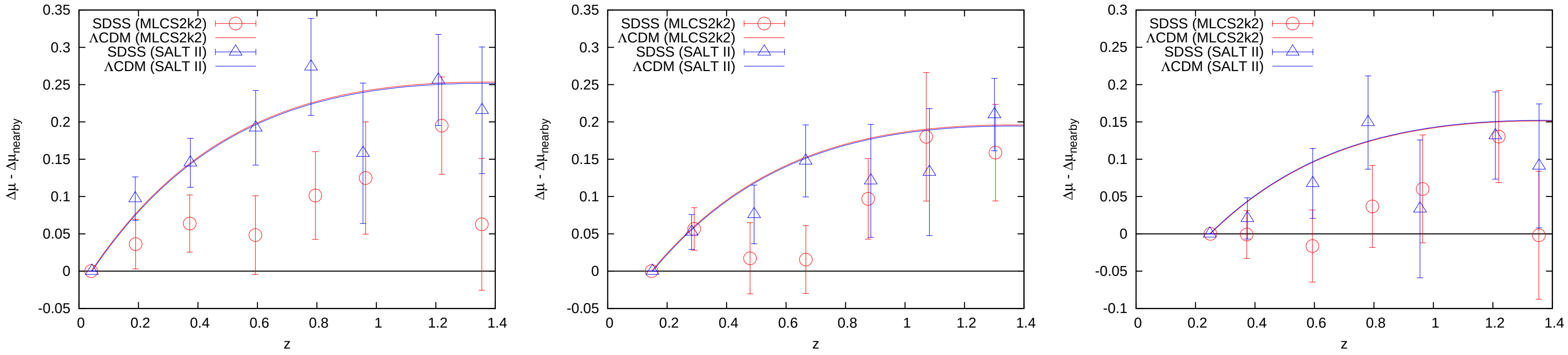
local structure?

Constitution set (~ 200 SN at $z < 0.2$) – light curve fitters



Seikel & Schwarz (in prep.)

SDSS SN (intermediate z) – light curve fitter



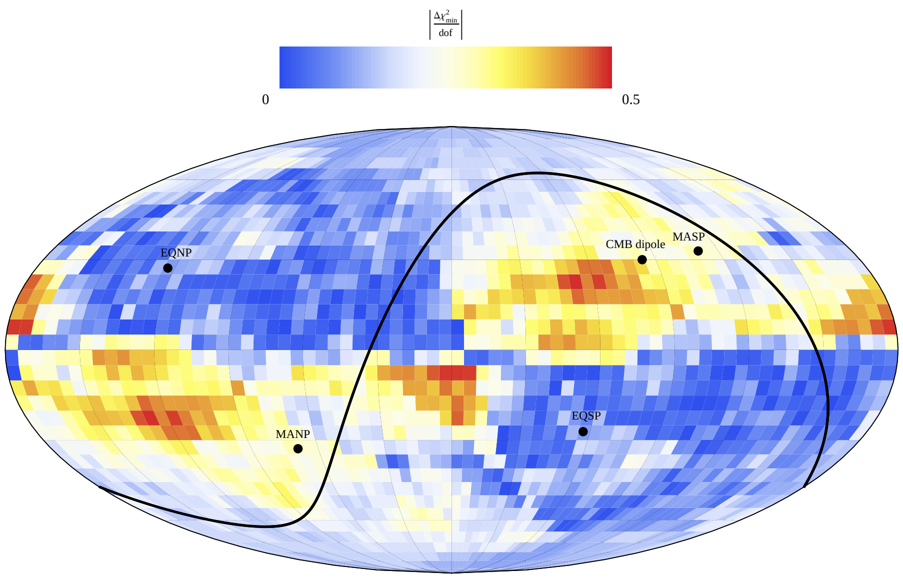
inconsistent results

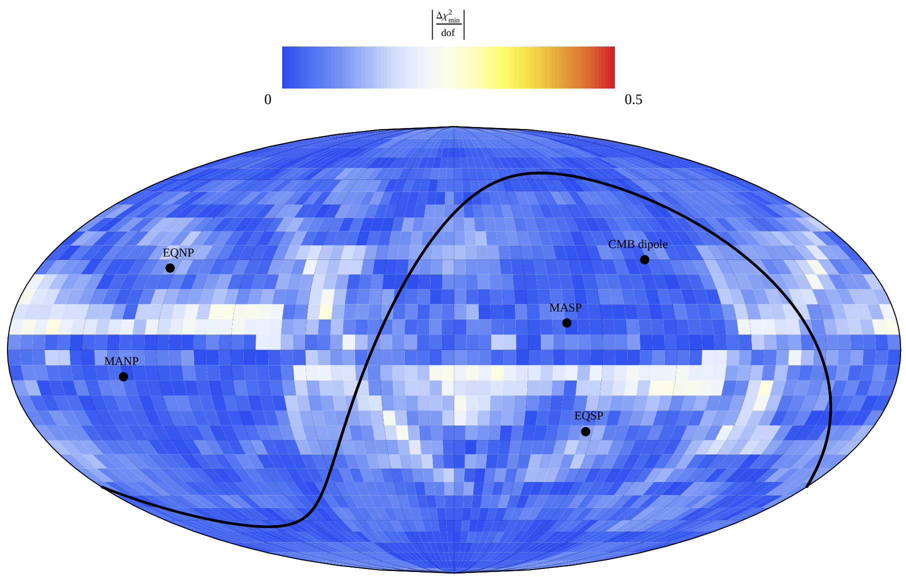
Seikel & Schwarz (in prep.)

(An)isotropy of the low z Hubble diagram

Hubble diagrams from opposite hemispheres Schwarz & Weinhorst 2007

Constitution set Hicken et al 2009: $\Delta(\chi^2/\text{dof})$ at $z < 0.2$



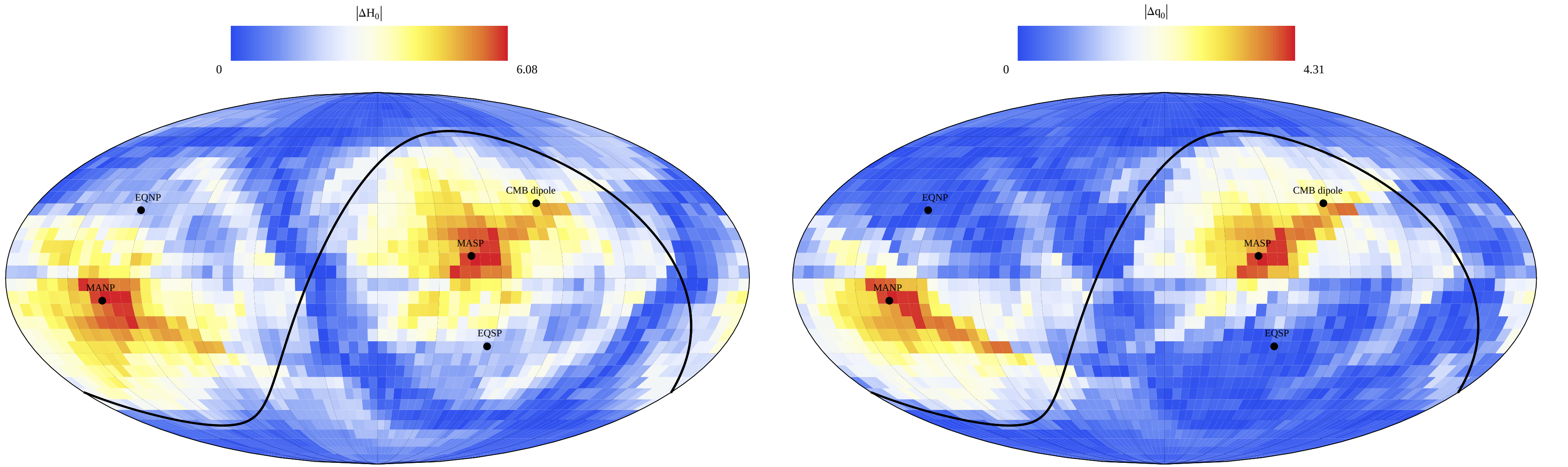


MLCS31

SALT2

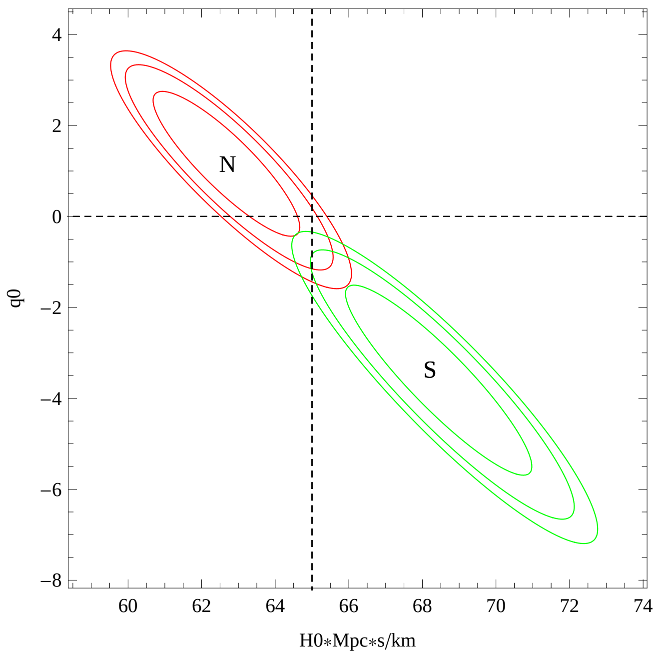
(An)isotropy of the low z Hubble diagram

Hubble diagrams from opposite hemispheres Schwarz & Weinhorst 2007
Constitution set (SALT2) Hicken et al 2009 at $z < 0.2$

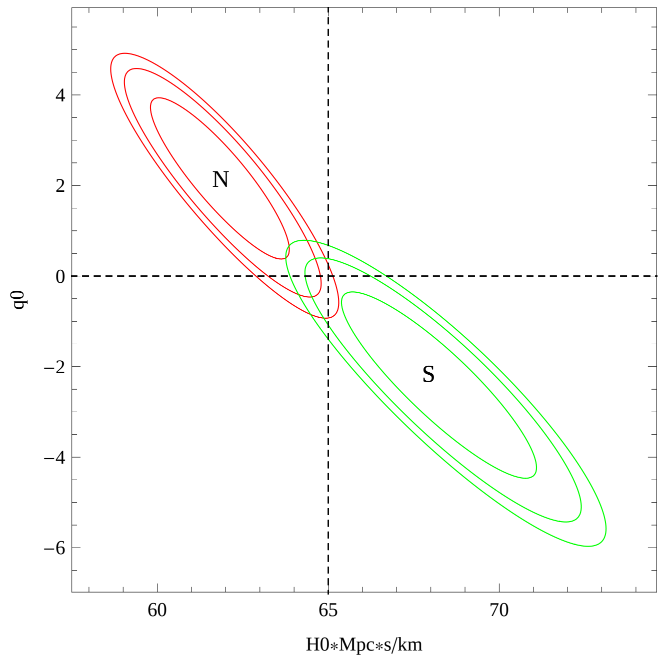


systematic effect or bulk flow? Kalus & Schwarz (in prep.)

(An)isotropy of the low z Hubble diagram



MLCS31



SALT2

$\frac{\Delta H_0}{H_0} \sim 0.05$ at $z < 0.2$ Schwarz & Weinhorst 2007, Kalus & Schwarz (in prep.)

Summary

- minimal set of assumptions: isotropy and homogeneity
  first bin is crucial, SALT fitter gives higher evidences

- Union set (SALT) and Constitution set (SALT and MLCS31)
  accelerated expansion at $> 7\sigma$, if K=0
  drop flatness $\Rightarrow$ reduces to 4σ for open models

- homogeneity of SNe is not established
  anisotropy of SN Ia Hubble diagram found at $z < 0.2$ $\delta\mu \sim 0.1$mag
  systematic error or bulk flow due to local structure?
  e.g. Haugbolle et al. 2006, Hannestad et al. 2007

- next: try to establish isotropy and homogeneity from SN