Dark energy?

Dominik J. Schwarz

- minimal cosmological model (ΛCDM)
- evidence for accelerated expansion/dark energy
- untested assumptions of the ΛCDM model
- structure formation, backreaction and effective cosmic forces

DESY theory workshop 2004

ΛCDM model

matter: $\Omega_{\rm m} \equiv \Omega_{\rm b} + \Omega_{\rm cdm}, P_{\rm m} = 0$

cosmological constant: $\Omega_\Lambda, P_\Lambda = -\epsilon_\Lambda = -\Lambda/(8\pi G)$

flat: $\Omega_m + \Omega_\Lambda = 1$ cosmological inflation

primordial isentropic fluctuations: $\mathcal{P}(k) \approx A(k_*)(k/k_*)^{n-1} = \mathcal{O}(10^{-9})$

slow-roll inflation

can fit all cosmological observations

age, expansion rate, light elements, cmb, lss, sn1a, clusters, weak lensing, ...

CMB observations: WMAP

primordial, isentropic fluctuations

Euclidean geometry

7 parameter fit to

WMAPext & $h > 0.5$ & $\tau < 0.3$:

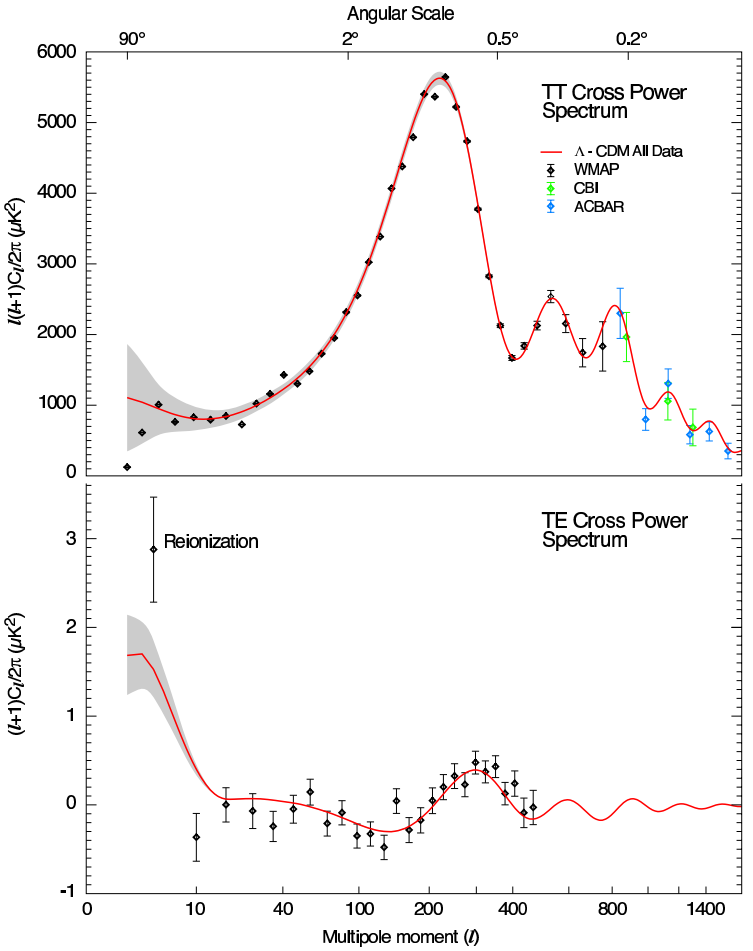
$0.98 < \Omega < 1.08$ (95%CL)

WMAPext & SN & HST & $\tau < 0.3$:

$\Omega = 1.02 \pm 0.02$

Bennett et al. 2003, Spergel et al. 2003

consistent with cosmological inflation and ΛCDM

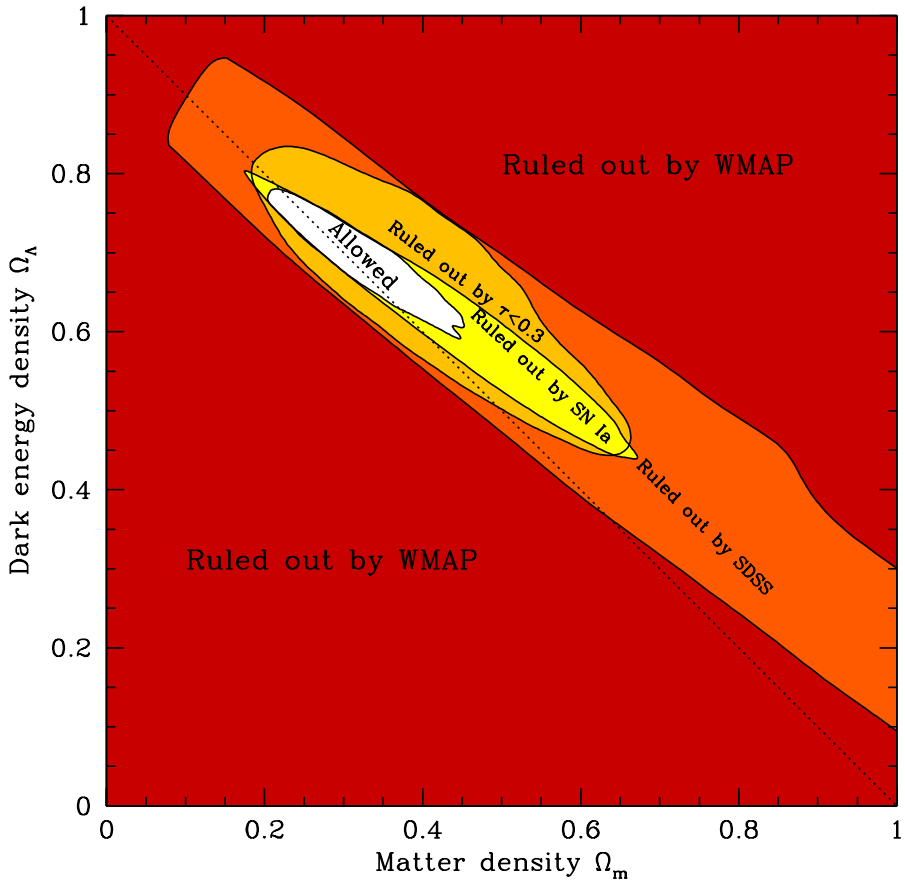


How to measure Ω_Λ?

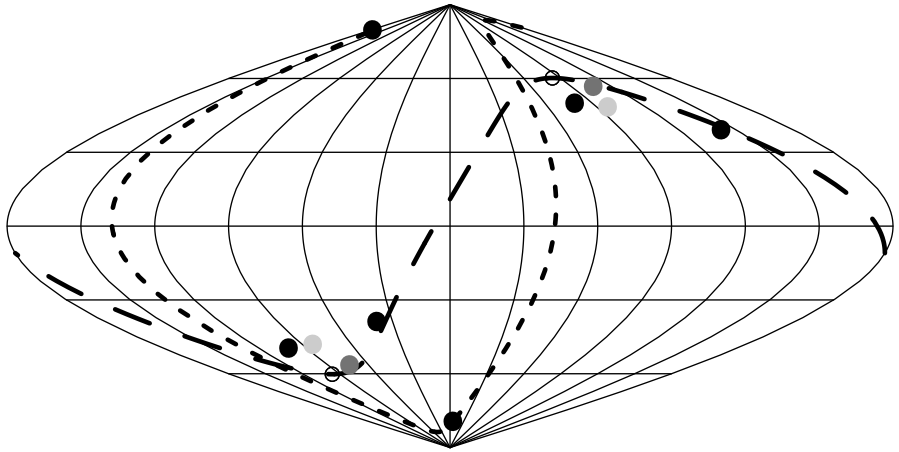
WMAP & SDSS:

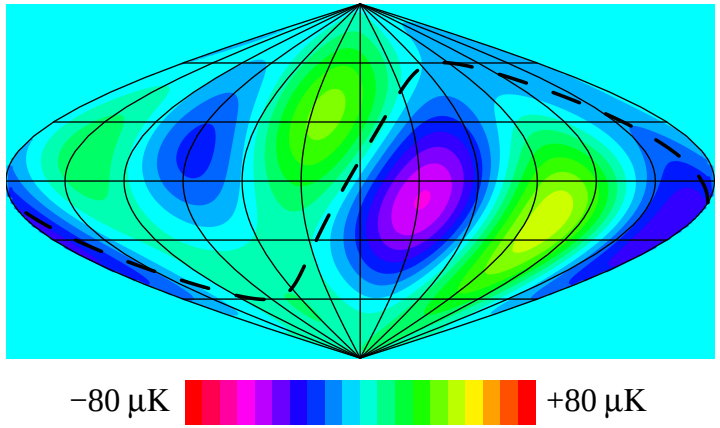
$\Omega = 1.06 \pm 0.04$
$\Omega_\Lambda = 0.65 \pm 0.08$

Tegmark et al. 2003



Low-l anomalies of the CMB?





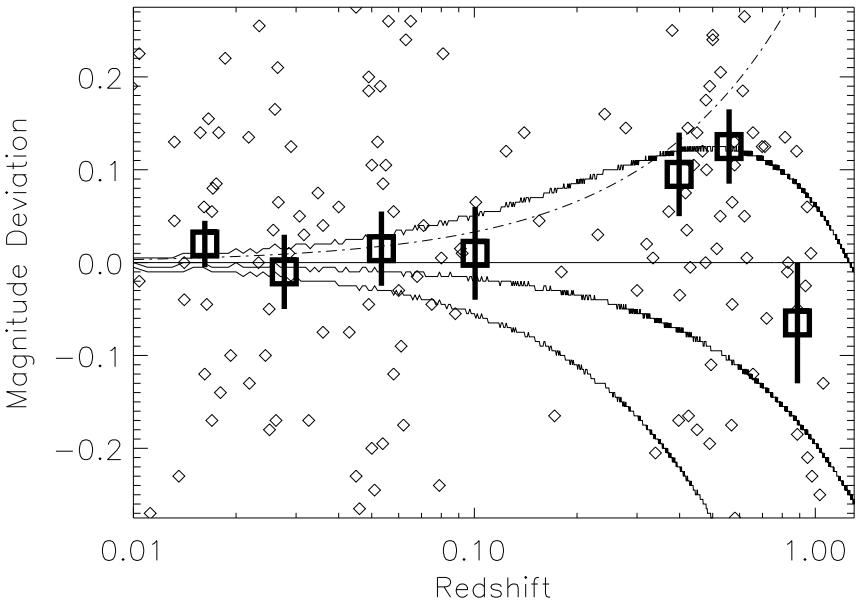
quadrupole and octopole show unexpected correlations ($>$ 99% C.L.) with the local Universe

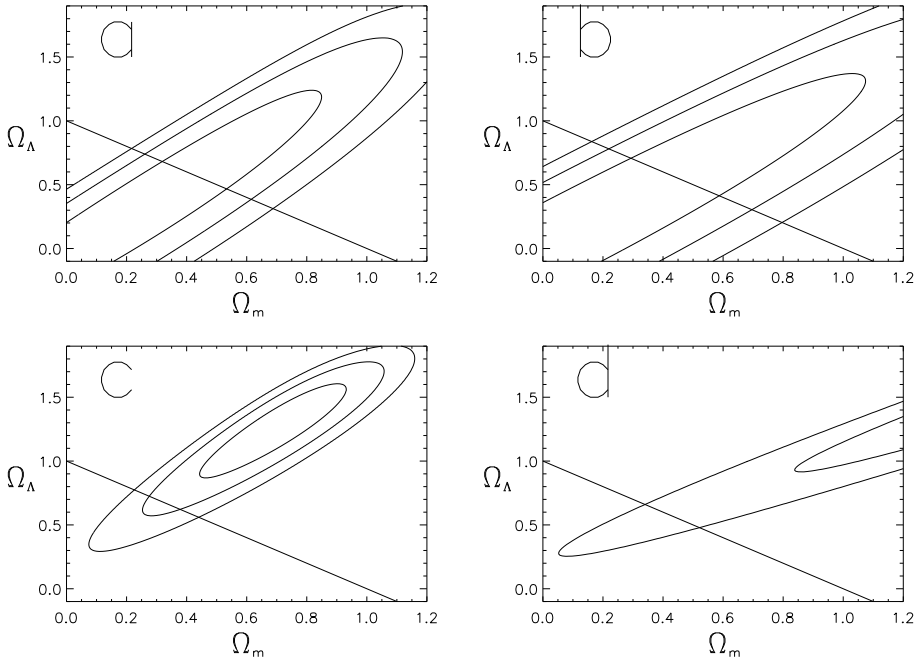
here based on Tegmark et al. 2003 map

Schwarz et al. 2004

Supernovae type Ia

$$\Delta(m - M) = 5 \log \left[d_L / d_L^{\text{empty}} \right]$$



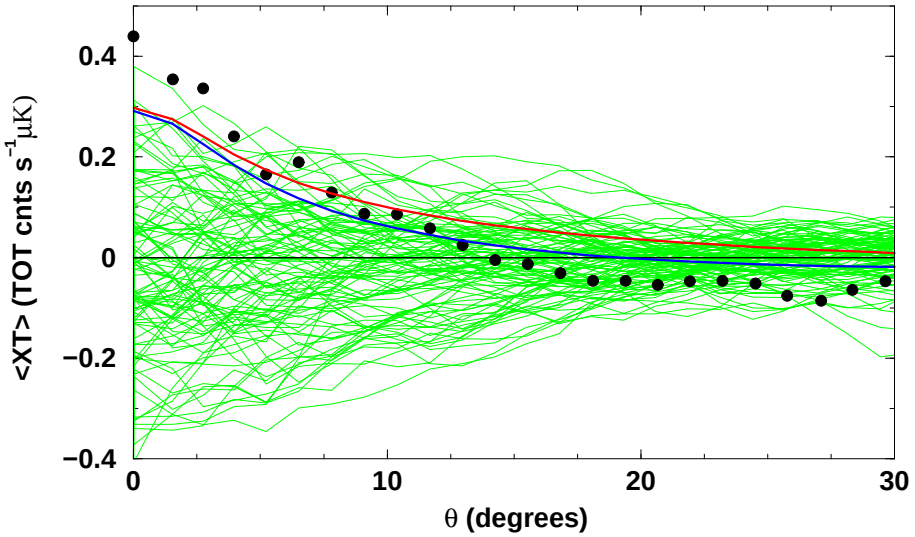


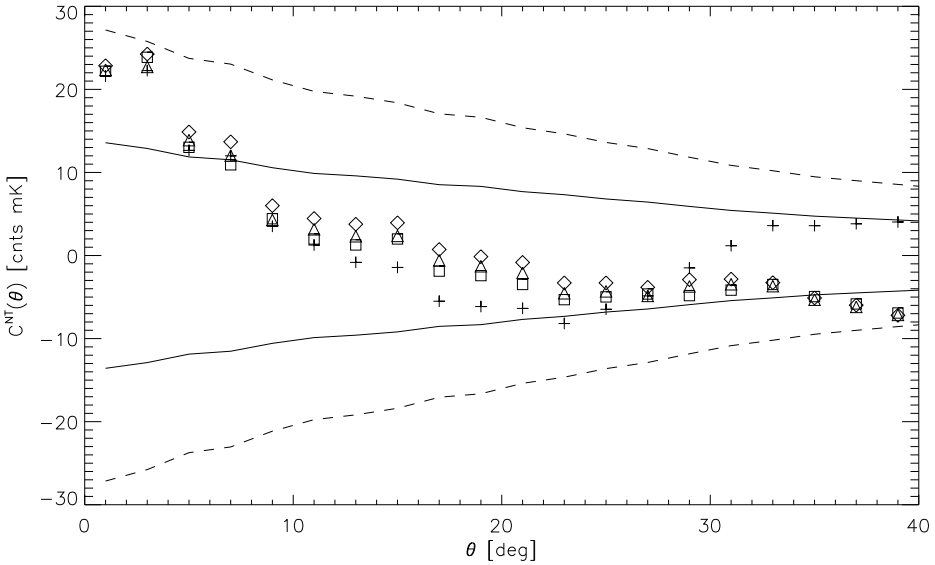
23 SN plus 230 SN from Tonry et al. 2003

consistent with Knop et al. 2003

Barris et al. 2003

CMB(WMAP)-LSS correlations (ISW)





hard X-ray sky (HEAO-A1)

Boughn & Crittenden 2004

radio galaxies (NRAO VLA Sky Survey)

Nolta et al. 2004

see also SDSS Scranton et al. 2003 and others

Untested parts of the ΛCDM model?

- Λ or some form of dark energy $\Omega_{\rm de}, w_{\rm de}(z)$
- general relativity at the largest scales — Dvali and Turner 2003
- shape of primordial power spectrum — Blanchard et al. 2003
- largest scale properties of CDM — Schwarz 2002

Are structure formation and dark energy linked phenomena?

Imperfect CDM?

isotropic fluid $\neq$ perfect fluid

$P = p + \Pi$ (equilibrium part + non-equilibrium part)

◇ covariant conservation of energy density and baryon number ($\epsilon_{\rm B} \ll \epsilon$)

$$\dot{\epsilon} + 3H(\epsilon + P) = 0 \qquad \dot{n}_B + 3Hn_B = 0$$

◇ entropy per baryon σ

$$T\mathrm{d}\sigma = \mathrm{d}\frac{\epsilon}{n_{\rm B}} + p\,\mathrm{d}\frac{1}{n_{\rm B}} \qquad \Rightarrow \qquad n_{\rm B}T\dot{\sigma} = -3H\Pi$$

◇ 2nd law of thermodynamics

$$\Rightarrow \Pi \leq 0, \quad \text{for } p = 0 \Rightarrow P \leq 0$$

negative CDM bulk pressure possible Schwarz 2002

non-linear structure formation IS dissipative

Structure formation and cosmic expansion

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

dust, comoving gauge, average $\langle Q\rangle = 1/V \int Q \mathrm{d}V$

$$\bar{G}^a_b = 8\pi G \bar{T}^a_b - \langle G^a_b - \bar{G}^a_b\rangle \qquad \langle T^a_b\rangle = \bar{T}^a_b (\text{Friedmann})$$

effective energy-momentum tensor or modified Friedmann equation

Geshnizjani & Brandenberger 2002: measure average expansion in proper time!

Buchert & Carfora 2003: existence of effect, no estimate of magnitude

Wetterich 2003: 2nd order estimate, harmonic, no time derivatives, 10^{-5} effect

Bene, Czinner & Vasuth 2003: 2nd order, synchronous, effect large?

Räsänen 2003: 2nd order estimate, longitudinal, large effect from surface terms?

Räsänen 2004: exact toy model, which averaging procedure, which clock?

Kolb et al. 2004: 2nd order (incomplete), synchronous, surface terms vanish for ensemble average, mean 10^{-5}, variance 10^{-2}, UV cut-off, IR divergence?

Effective cosmic forces

Are cosmic forces consistent with the cosmological principle?

CMB defines comoving observer u^μ

test particle with momentum $p^\mu = Eu^\mu + pe^\mu$ $(p^\mu p_\mu = -m^2)$

force on test particle $F^\mu = \frac{\mathrm{D}p^\mu}{\mathrm{d}\tau}$, $p_\mu F^\mu = 0$

◇ isotropy and homogeneity

$$\Rightarrow \qquad F^\mu = B(-\frac{E}{m}p^\mu + mu^\mu) \quad \text{or} \quad \vec{F} \approx -B(m,t)m\vec{v} \quad \text{(Newtonian limit)}$$

effective (anti)frictional forces allowed

kinetic theory for non-relativistic gas

$$P = \frac{B}{H}\epsilon < 0 \quad \text{for} \quad B < 0$$

Could structure formation give rise to effective antifriction? Zimdahl et al. 2001

Antifriction from non-linear structure formation

toy model: longitudinal gauge, no tensor and vector perturbations

$$\mathrm{d}s^2 = -(1+2\phi)\mathrm{d}t^2 + a^2(1+2\psi)\mathrm{d}l^2$$

equation of motion for a non-relativistic particle ($p \ll m$):

$$\dot{\mathbf{p}} = -H\mathbf{p} - \frac{\nabla\phi}{1+2\phi}m - \frac{2\dot{\psi}}{1+2\psi}\mathbf{p}$$

initially $\mathbf{p} \approx 0 \Rightarrow \mathbf{p} \approx -\nabla\phi(\mathbf{x})\, m\, t \Rightarrow B \approx -1/t$

$\mathbf{F} \approx (-H + 1/t)\mathbf{p} \approx \mathbf{p}/(3t)$ before collapse, effective antifriction!

last term not included in N-body simulations

Cosmological evolution with antifriction

equation of state and deceleration

$$w(z) = \frac{P(z)}{\epsilon(z)} = \frac{B(z)}{H(z)} \qquad q(z) = \frac{1}{2}[1 + 3w(z)]$$

accelerated expansion for $B < -H/3$

toy model: $B \approx -1/t \approx -2H/3 \Rightarrow w \approx -3/2$ violation of NEC!

phenomenological "Ansätze"

(a) $B(z) = -\nu H_0^2/H(z) \Rightarrow w(z) = -\nu[H_0/H(z)]^2$

(b) $B(z) = -\nu H_0^4/[H(z)]^3 \Rightarrow w(z) = -\nu[H_0/H(z)]^4$

(a) equivalent to ΛCDM since $P \propto \epsilon/H^2 = \text{const}$

(b) equivalent to Chaplygin gas $P = -A/\epsilon, c_s^2 = A/\epsilon^2 > 0$

Zimdahl et al. 2001, Balakin et al. 2003

No conclusion

- link between structure formation and accelerated expansion?

THE scale of hierarchical structure formation: $k_{\rm eq}$; coincidence $z_{\rm acc} \sim z_{\rm nl}(k_{\rm eq})$?

- averaging/backreaction/fitting problem waits for definite answer

- need to study non-linear regime $\Rightarrow$ non-perturbative methods

- imperfect CDM with time (and perhaps scale) dependent P possible

might be dynamically equivalent to ΛCDM

- effective cosmic antifriction?

$B_0 \sim H_0$ suggests gravitational effect, violation of NEC possible