Anisotropic cosmology?

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Minimal model and its limitations
Origin of (an)isotropy
Observational tests: CMB and SNIa

2nd Bethe Center Workshop, Bad Honnef 2010

The minimal cosmological model

relies on

◇ comological inflation:

isotropy, homogeity and spatial flatness

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

◇ the Einstein equation with a cosmological constant H_0, Λ

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

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

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

The cosmic energy budget (WMAP 7yr + H_0 + BAO)

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

72% dark energy

23% cold dark matter

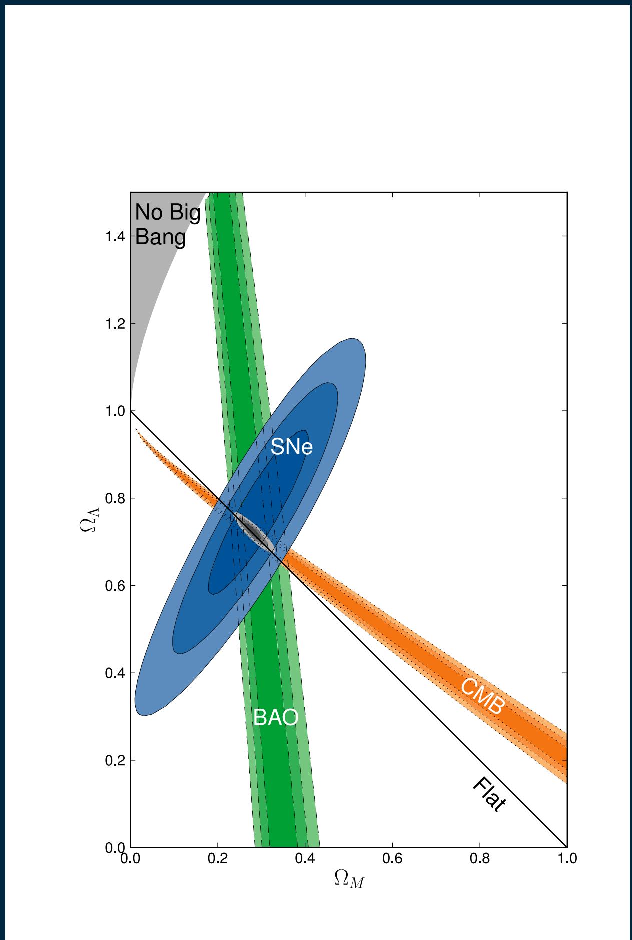
5% atoms

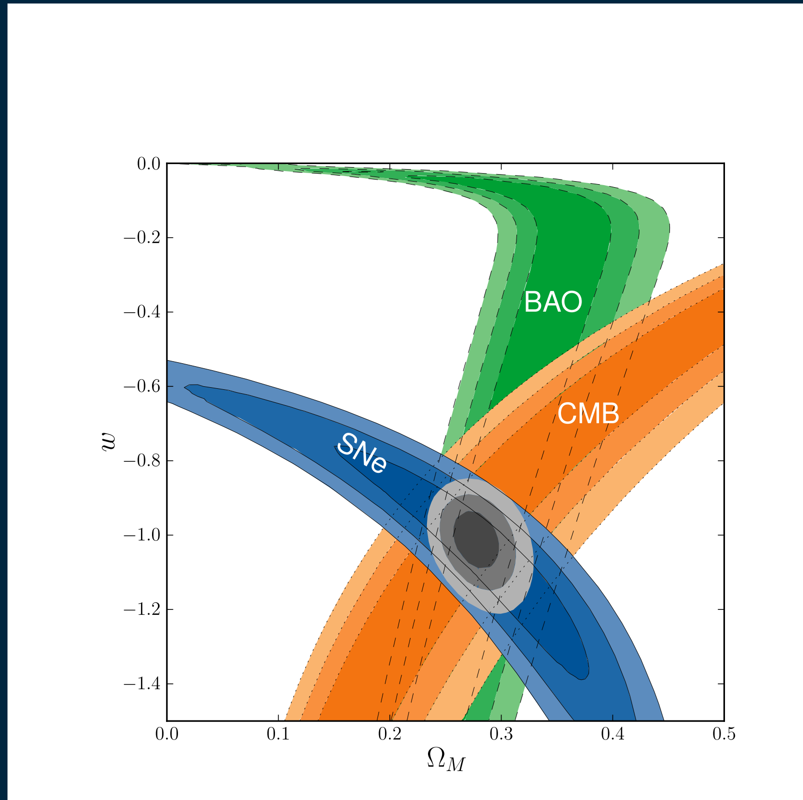
$<$ 1% neutrinos

all $\pm 1\%$ Komatsu et al. 2010

95% dark physics

Supernovae Ia





Union2: Amanullah et al. 2010

flatness and $w \approx -1$ agrees also with SN Ia, LSS, clusters

Conceptual limitations of the minimal model

◇ 95% dark physics

◇ cosmological constant problem: $|\Lambda|\kappa < 10^{-120}$

◇ coincidence problems:

Why is $\Omega_\Lambda \sim \Omega_{\rm m} \sim \Omega_{\rm b}$?

Why is $z_{\rm nl}(\lambda_{\rm eq}) \sim z_{\rm acc}$?

◇ origin of cosmological inflation

◇ origin of isotropy and homogeneity

here: focus on aspects related to isotropy

Cosmological principle(s)

problem: initial conditions of the Universe

perfect cosmological principle: maximally symmetric space-time ×

steady state model, de Sitter model

cosmological principle: exact isotropy & homogeneity ×

Friedmann-Lemaître model; symmetry implies cosmic time; no LSS

statistical cosmological principle: statistical isotropy & homogeneity

perturbed FL; statistically isotropic and homogeneous perturbations

Does cosmological inflation predict a CP?

eternal inflation: CP not on global scale (multiverse)

observable universe:
inflation pushes pre-inflationary anisotropies and inhomogeneities far beyond apparent horizon,
if number of e-foldings (N) large and start from smooth Hubble patch

Bianchi space-times, except Bianchi IX, isotropise; CP temporarily
e.g. Turner & Widrow 1986, Rothmann & Ellis 1986

general inhomogeneous models, perturbation theory:
$\zeta \equiv \frac{\delta\epsilon}{3(\epsilon+p)} - \psi$ constant for $k_{\rm ph} \ll H$; What if $\zeta(t < t_{\rm infl}) \sim 1$?

What if N just ~ 60? Pre-inflationary structure observable!

Initial conditions at $\mu \sim M_{\mathsf{P}}$

chaotic inflation:
inflaton field $\dot{\varphi}^2 \sim V(\varphi) \sim M_{\mathsf{P}}^4$ initially
geometry $H^2 \sim k/a^2 \sim M_{\mathsf{P}}^2$ initially

while geometric and kinetic terms describe space-time and inertia, the effective potential V encodes all information on interactions

without potential, the single fundamental scale would be M_{P}

interactions introduce new scales, e.g. G_{F} or Λ_{QCD}

What if the inflaton potential is limited to $V \sim M^4 \ll M_{\mathsf{P}}^4$?

Example: effective Higgs potential

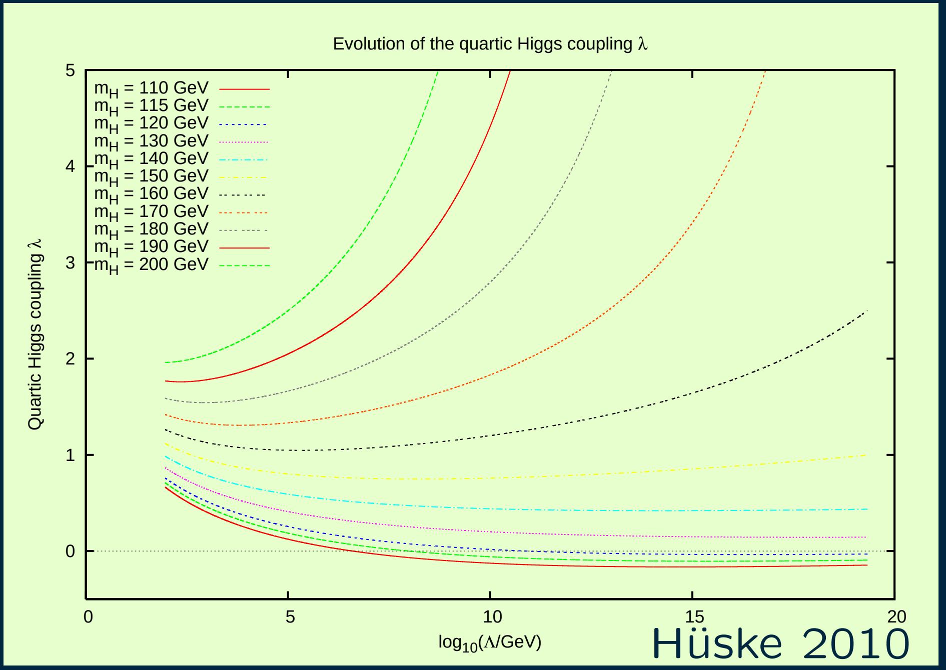
$$V \simeq \frac{\lambda}{24}\phi^4 + \frac{1}{16\pi^2}\left[\frac{1}{4}H^2\left(\ln\frac{H}{\mu^2} - \frac{3}{2}\right) + \ldots\right], \qquad H \simeq \frac{1}{2}\lambda\phi^2, \qquad \text{at } \mu \gg m_Z$$

Ford et al. 1993

running of λ can lead to $\lambda < 0$
at $\mu > M$

$\Rightarrow V$ complex at $\phi \sim \mu > M$

complex inflaton potential
would imply inflaton decay
and no inflation



Hüske 2010

Initial conditions with two fundamental scales

modification of chaotic initial condition: $V \sim M^4 \ll \dot{\varphi}^2 \sim M_\mathsf{P}^4$

kinetic energy dominates initially, i.e.,

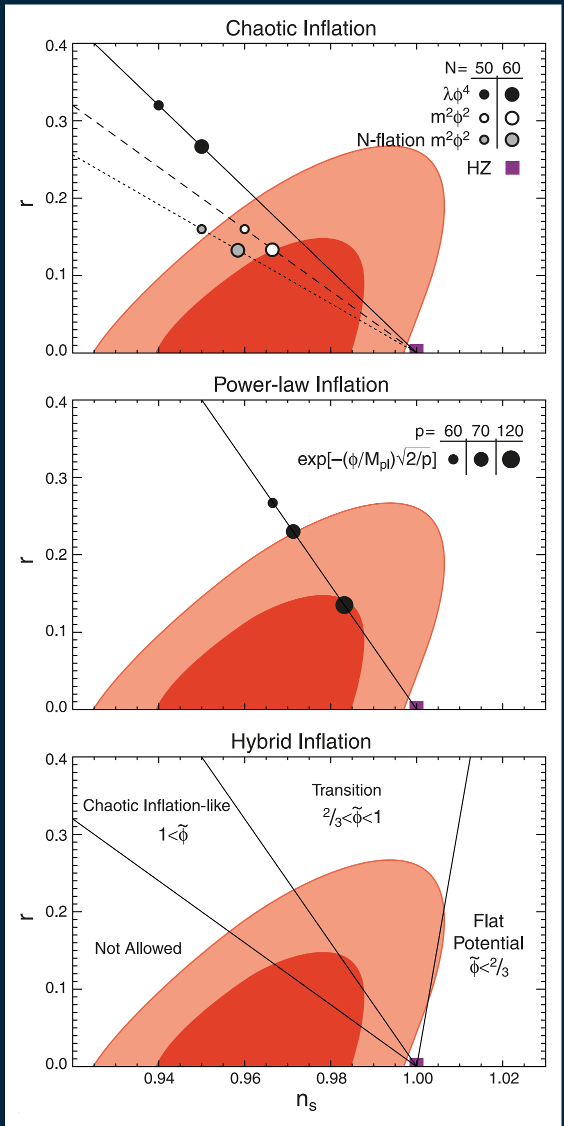
$$\epsilon_1 \equiv \dot{d}_H = 3 \frac{\dot{\varphi}^2/2}{\dot{\varphi}^2/2 + V} \approx 3$$

nevertheless, as $\dot{\varphi} \propto a^{-3}$, inflation starts when $\epsilon_1 < 1$

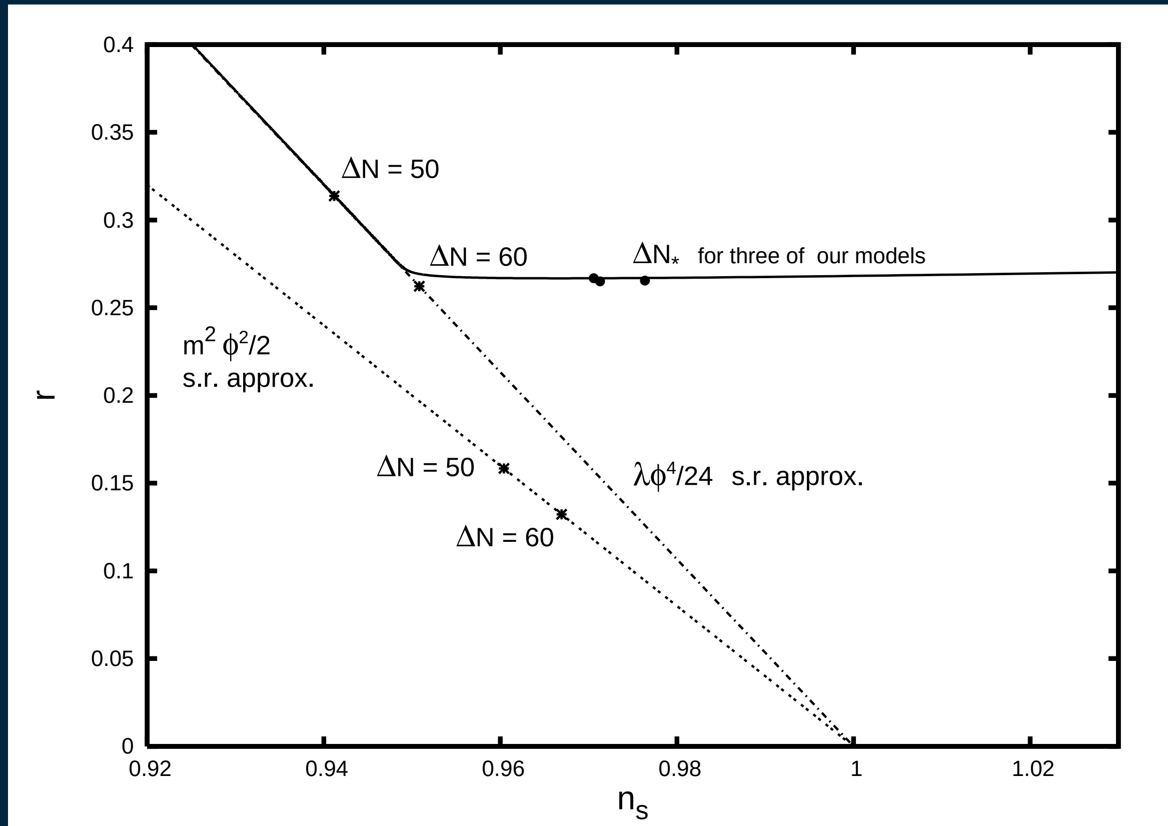
slow-roll after a few e-foldings, iff $\varphi_\mathsf{i} > 3M_P$

for $M \sim M_\mathsf{gut}$: $\varphi_\mathsf{i} \sim 20 M_\mathsf{P}$ and $N \sim 60$

Observational constraints



Komatsu et al. 2009



Ramirez & Schwarz 2009

$N \sim 60$ is motivated and could fit CMB

Motivations for testing isotropy

◇ check the minimal model

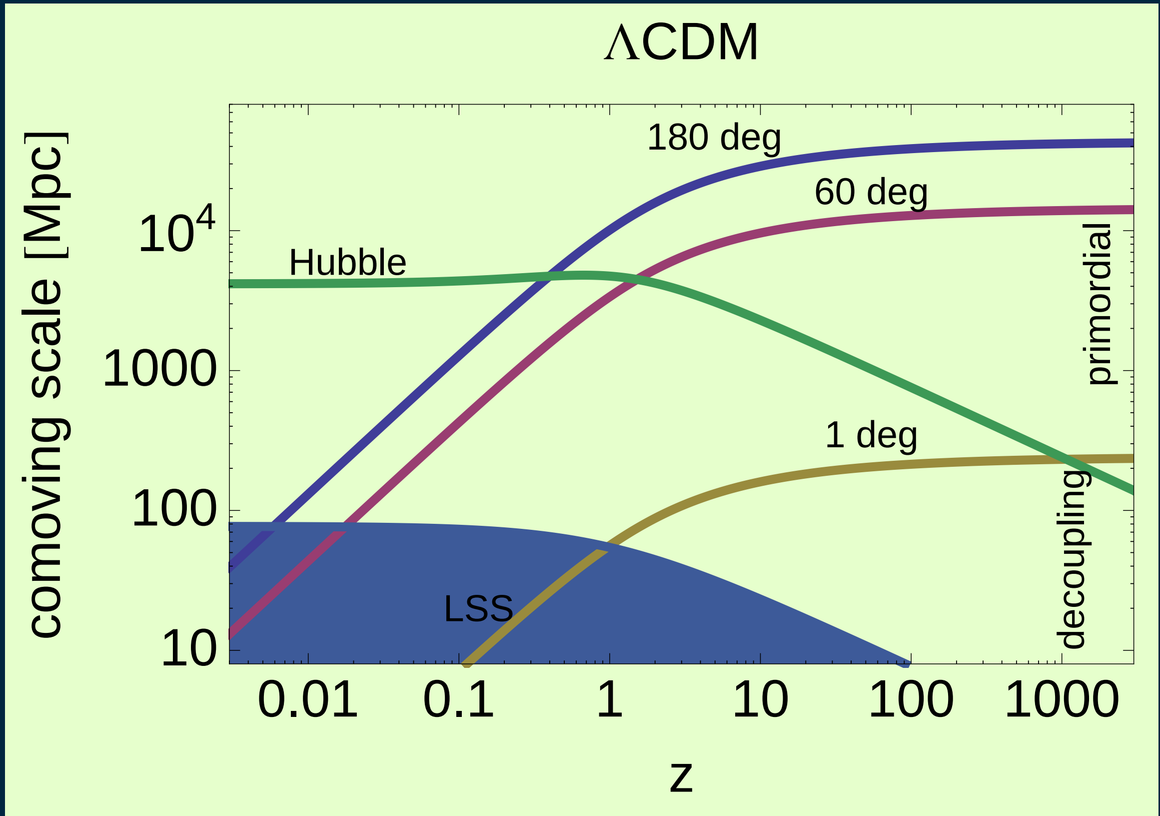
◇ pre-inflationary perturbations (if $N \sim 60$ or less)

◇ investigate the nearby LSS; do we live in a large void?

◇ discover systematic errors

here: CMB at large angular scales and SN Ia Hubble diagram

Why are large angular scales interesting?



$$s(z) = \theta \, d_{\mathrm{C}}(z)$$

Cosmological inflation — Generic CMB predictions I

temperature fluctuations:

$\delta T(\mathbf{e}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\mathbf{e})$; $2\ell + 1$ degrees of freedom for each ℓ

statistical isotropy:

$\langle \delta T(\mathrm{R}\mathbf{e}_1) \ldots \delta T(\mathrm{R}\mathbf{e}_n) \rangle = \langle \delta T(\mathbf{e}_1) \ldots \delta T(\mathbf{e}_n) \rangle$, $\quad \forall \mathrm{R} \in \mathrm{SO}(3)$, $\forall n > 0$

- $\langle \delta T(\mathbf{e}) \rangle = 0$ and $\langle a_{\ell m} \rangle = 0$
- $\langle \delta T(\mathbf{e}_1) \delta T(\mathbf{e}_2) \rangle = f(\mathbf{e}_1 \cdot \mathbf{e}_2) = \frac{1}{4\pi} \sum_\ell (2\ell + 1) C_\ell P_\ell(\cos\theta)$, $\quad \cos\theta \equiv \mathbf{e}_1 \cdot \mathbf{e}_2$ with $\langle a_{\ell m} a^*_{\ell' m'} \rangle = C_\ell \delta_{\ell\ell'} \delta_{mm'}$, C_ℓ angular power spectrum

gaussianity: no extra information in higher correlation functions

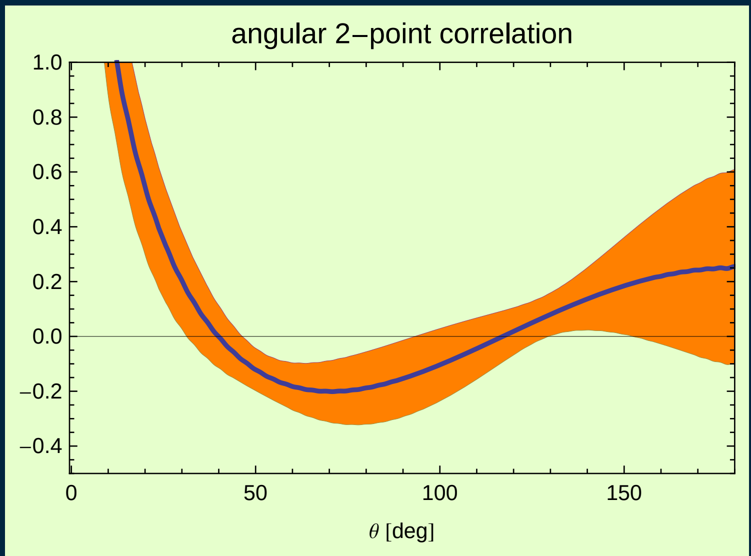
(best) estimator: $\hat{C}_\ell = 1/(2\ell + 1) \sum_m |a_{\ell m}|^2$ (assumes statistical isotropy)

cosmic variance: $\mathrm{Var}(\hat{C}_\ell) = 2C_\ell^2/(2\ell + 1)$ (assumes gaussianity)

Cosmological Inflation — Generic CMB predictions II

scale invariance, $n \approx 1$:

$C_\ell \approx 2\pi A/[\ell(\ell+1)]$, at the largest scales $\qquad A \approx 1000 \mu K^2$ (obs.)



$C(\theta)$ without dipole (arbitrary units)

What can we test?

◇ statistical isotropy

◇ gaussianity

◇ approximate scale invariance

violations may be due to secondary effects (e.g. ISW, Rees-Sciama), foregrounds, instrument, . . .

no influence of secondaries between $z_{\text{1st h.c.}}$ and $z \sim 1$ for $\theta > 60$ deg

A test of statistical isotropy — Multipole vectors

alternative representation of multipoles

Maxwell 1891, Copi, Huterer & Starkman 2003

one (real) amplitude A_ℓ and ℓ headless (unit) vectors:

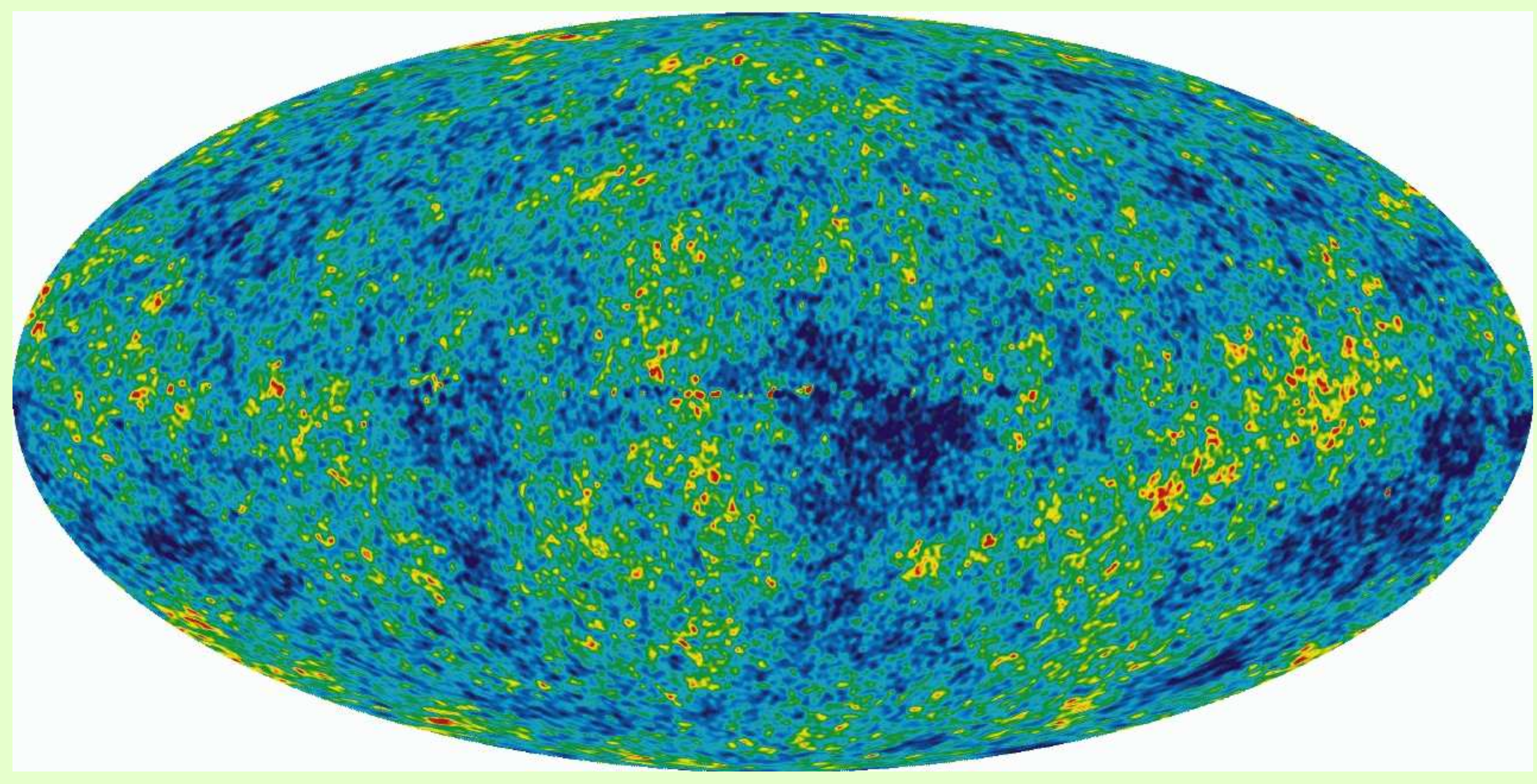
$2\ell + 1$ degrees of freedom

$$T_\ell(\mathbf{e}) = \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{e}) = A_\ell [\mathbf{v}^{(\ell,1)} \ldots \mathbf{v}^{(\ell,\ell)}]_{i_1 \ldots i_\ell} [\mathbf{e} \cdots \mathbf{e}]^{i_1 \ldots i_\ell}$$

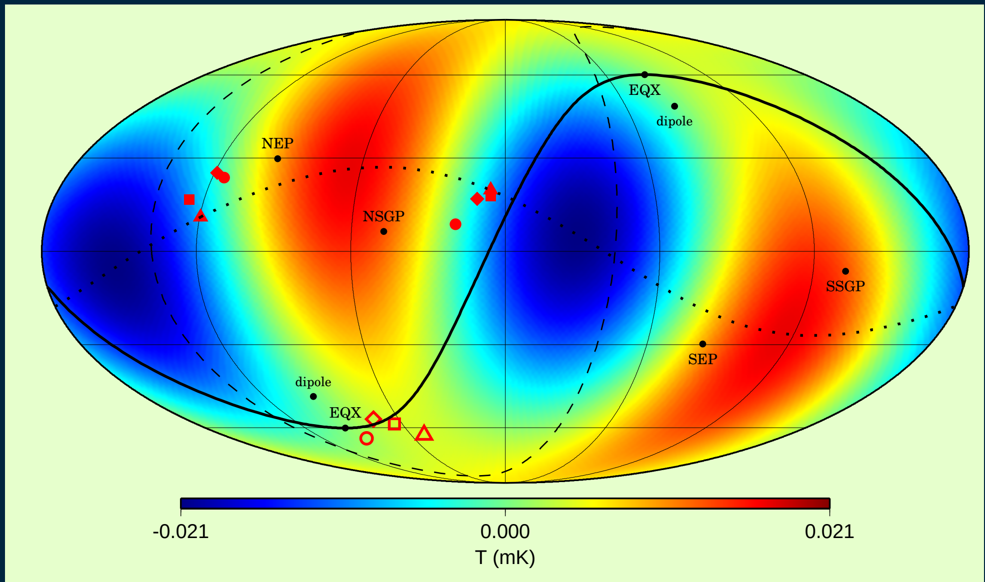
$[\ldots]$ . . . symmetric, traceless tensor product

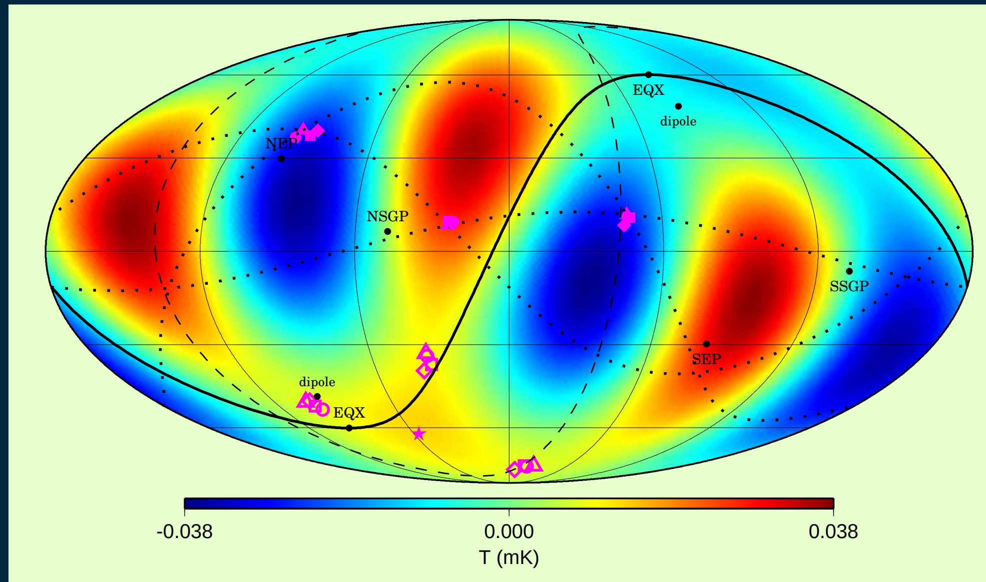
e.g. quadrupole: $T_2(\mathbf{e}) = A_2[(\mathbf{v}^{(2,1)} \cdot \mathbf{e})(\mathbf{v}^{(2,2)} \cdot \mathbf{e}) - \frac{1}{3}\mathbf{v}^{(2,1)} \cdot \mathbf{v}^{(2,2)}]$

Cosmic microwave background radiation



WMAP quadrupole and octopole



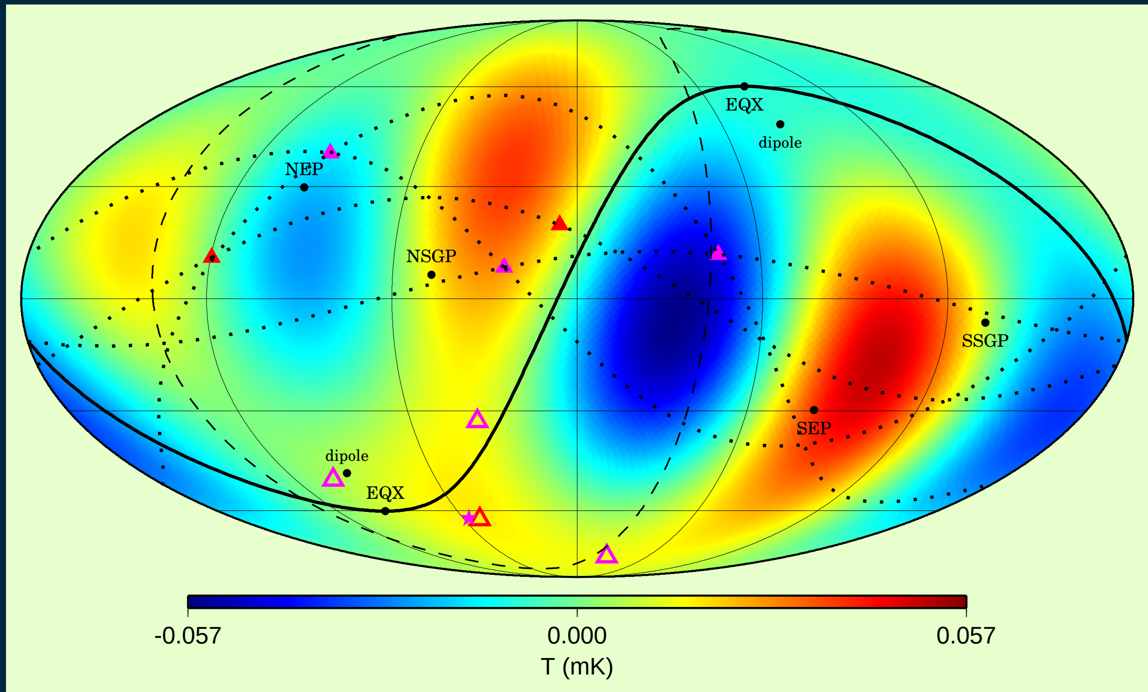


3 great circles defined by multipole vectors are nearly normal to ecliptic

1 great circle nearly normal to supergalactic plane

Schwarz et al. 2004, Copi et al. 2007

WMAP quadrupole plus octopole



ecliptic is close to nodal line — Schwarz et al. 2004, Copi et al. 2007

power asymmetry for [2,3] and [6,7] — Schwarz et al. 2004, Freeman et al. 2006

Internal and external correlations of quadrupole and octopole

– quadrupole-octopole (qo) alignment at 99.6%C.L.

– dipole-qo alignement at 99.7%C.L.

– ecliptic-qo alignment at 95%C.L.

– ecliptic North-South asymmetry

– ecliptic is close to nodal line Copi et al. 2007

full-sky maps violate statistical isotropy at large angular scales

Angular two-point correlation

$\widehat{C}_{\text{pixel}}(\theta) \equiv \sum_{\mathbf{e}_1\mathbf{e}_2=\cos\theta} T(\mathbf{e_1})T(\mathbf{e_2})$ or

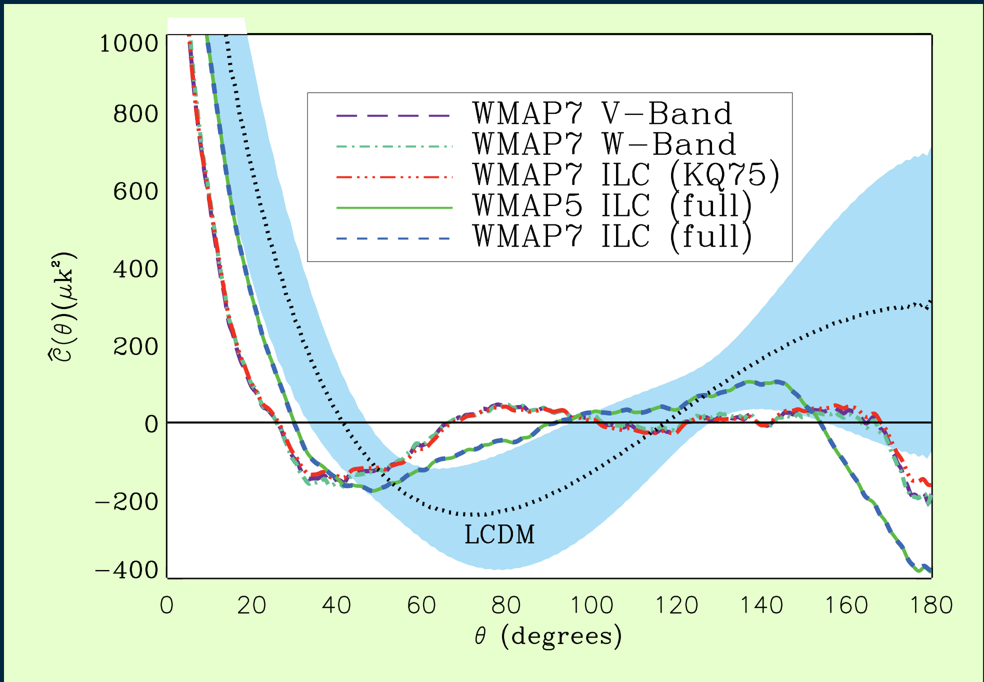
$\widehat{C}_{\text{power}}(\theta) \equiv 1/(2\pi) \sum_\ell (2\ell+1)\widehat{C}_\ell P_\ell(\cos\theta)$

full sky: $\widehat{C}_{\text{pixel}}(\theta) = \widehat{C}_{\text{power}}(\theta)$

cut sky: $\widehat{C}_{\text{pixel}}(\theta) \neq \widehat{C}_{\text{power}}(\theta)$ with
$\langle\widehat{C}_{\text{pixel}}(\theta)\rangle = \langle\widehat{C}_{\text{power}}(\theta)\rangle$, iff statistically isotropic

similar for angular power spectrum estimators
e.g. pseudo-C_ℓ vs. maximal likelihood estimator

WMAP angular correlation function



Sakar et al. 2010

$\widehat{C}(\theta) \equiv \sum_{\text{Pixel}(ij)} T_i T_j$, with $\mathbf{e}_i \cdot \mathbf{e}_j = \cos\theta = \mu$

estimator $\widehat{C}$ does not assume statistical isotropy

compare to 10^5 MC cut sky maps

$S_\alpha = \int_{-1}^{\alpha} \mathrm{d}\mu \, C^2(\mu)$

$P(S_{1/2}^{\text{cut sky}}) < 0.1\%$

Status of CMB large angle anomalies

Copi et al. 2010

observed microwave radiation at > 60 deg disagrees with prediction

vanishing 2-point correlation is inconsistent at 99.9%CL

quadrupole and octopole
aligned with each other at $> 99\%$CL
correlated with equinox/dipole at $> 99\%$CL
correlated with ecliptic at $> 95\%$CL
alignments extend up to multipoles $\ell \sim 10$ Land & Magueijo 2005

systematics or unexpected physics?
Solar system dust, large scale structure, cosmology, . . .

How to find the origin of disagreement

some ideas:

◇ cosmological explanation:

$N \sim 60$ could explain lack of correlation

d-q-o alignment could be pre-inflationary

ecliptic alignment would be fluke

◇ nearby LSS ($z < 0.1$):

Rees-Sciama effect of 100 Mpc structures gives alignment

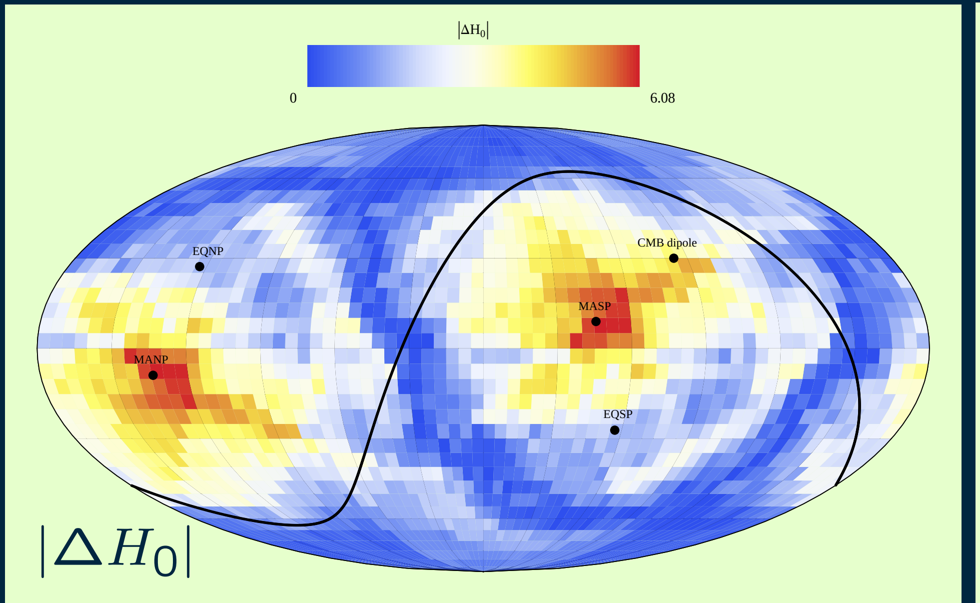
lack of correlation hard to explain, e.g. systematic

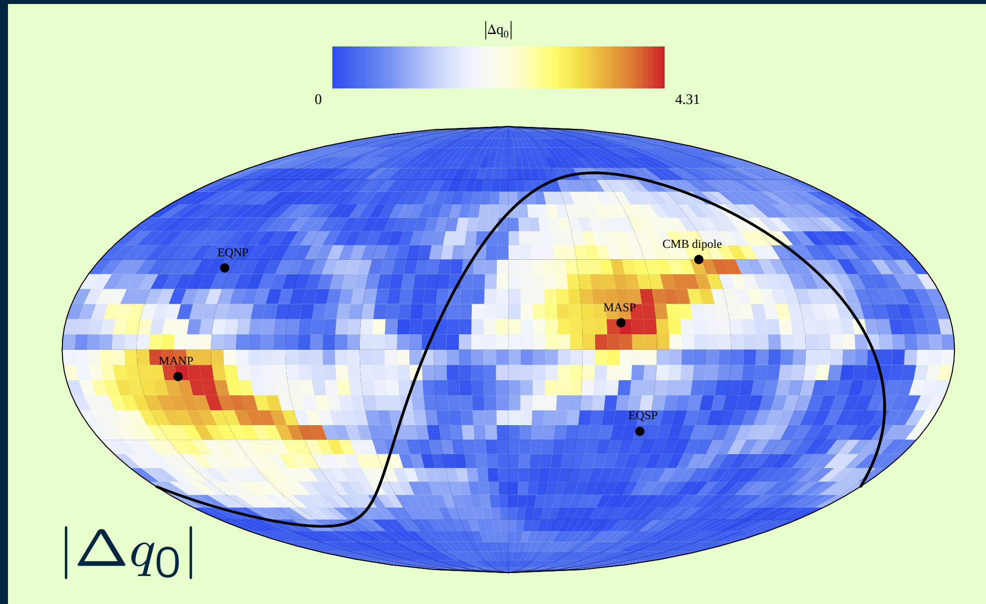
...

look at other cosmological probes, e.g. SN Ia

(An)isotropy of the low z Hubble diagram

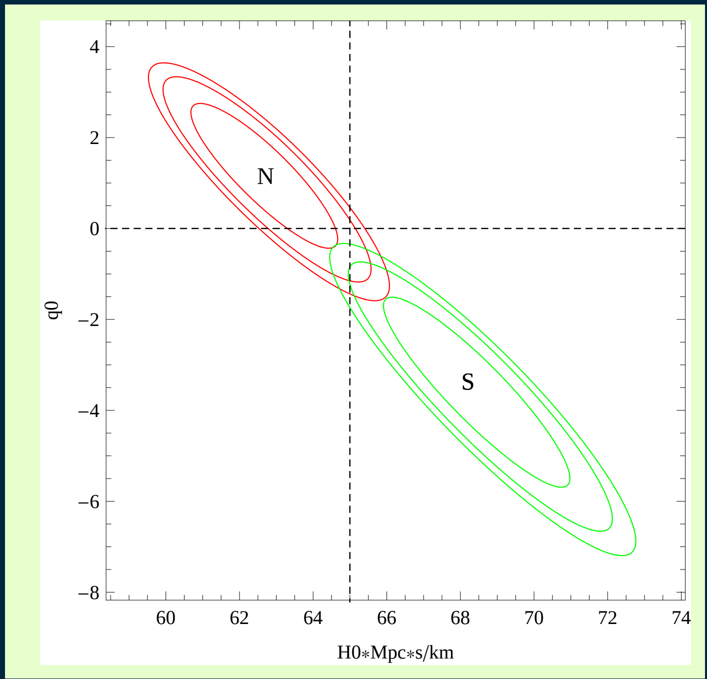
Hubble diagrams from opposite hemispheres Schwarz & Weinhorst 2007
Constitution set (SALT2) Hicken et al 2009 at $z < 0.2$





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

(An)isotropy of the low z Hubble diagram



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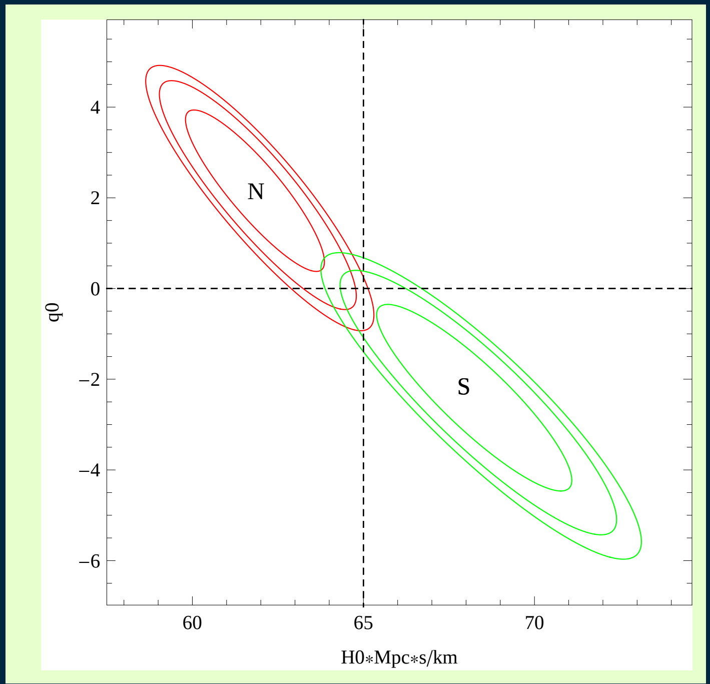
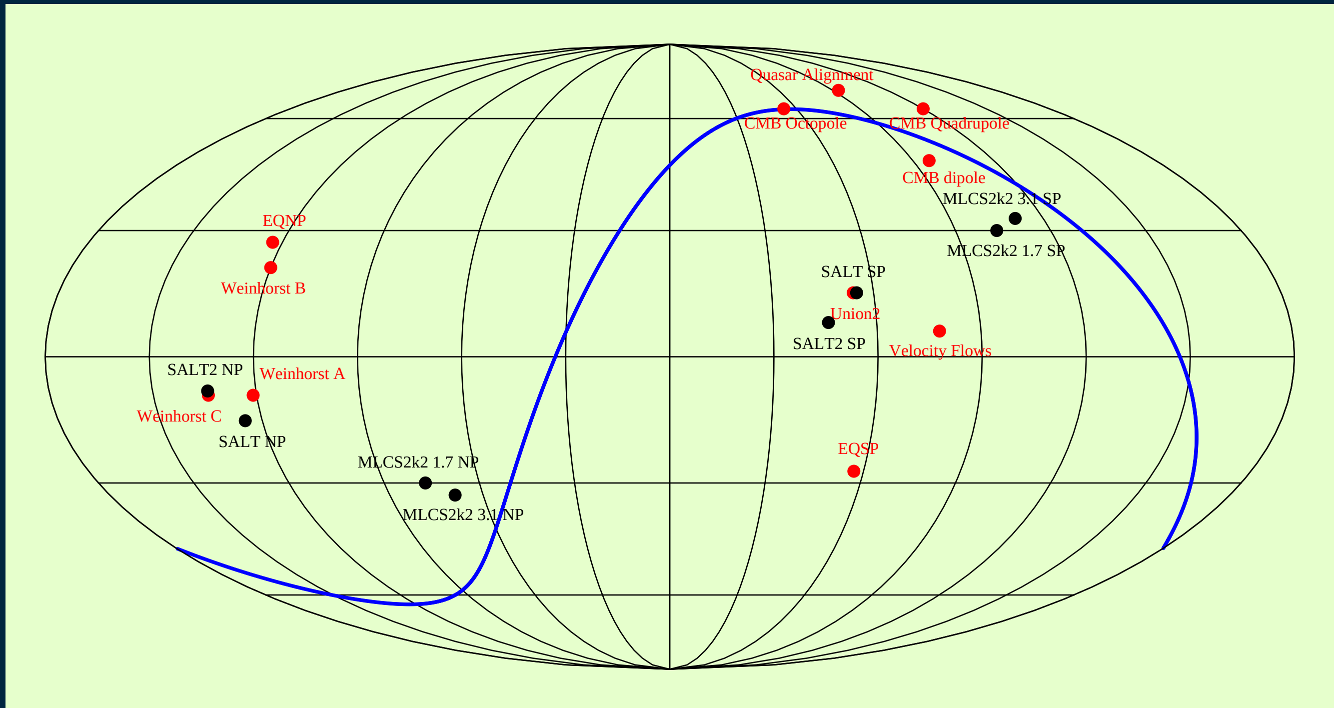


SALT2

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

Comparison to other directions on sky



Schwarz & Weinhorst 2007, Kalus & Schwarz (in prep.)

Conclusions

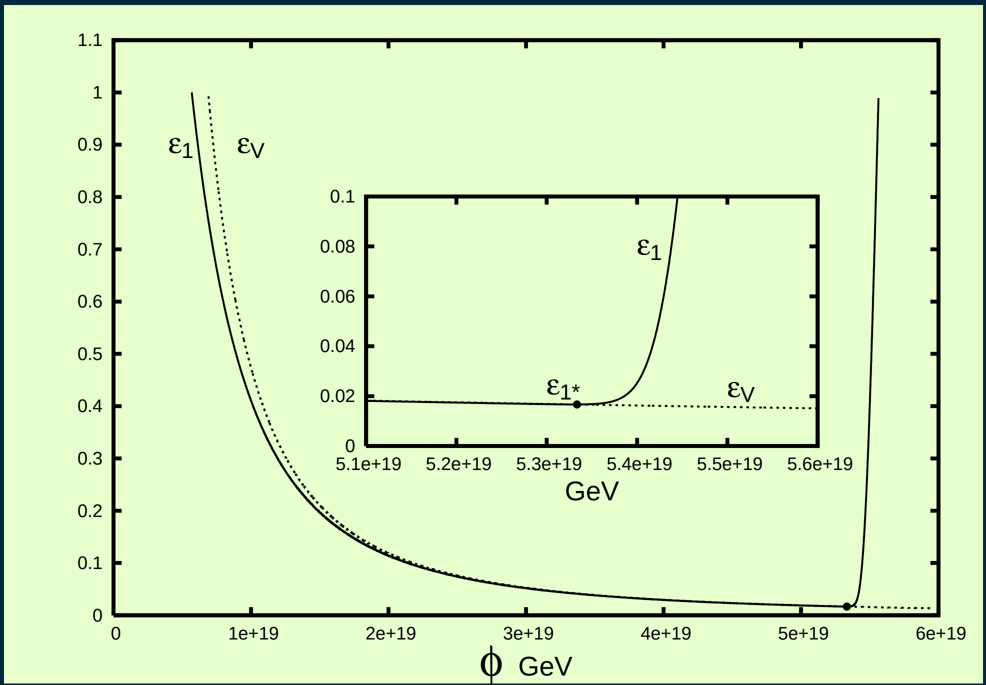
- ◇ cosmological inflation does not predict global isotropy
- ◇ if $N \sim 60$ or less, observable anisotropy
- ◇ CMB shows several anomalies on largest angular scales
- ◇ Hubble diagram at $z < 0.2$ anisotropic, could be systematic effect

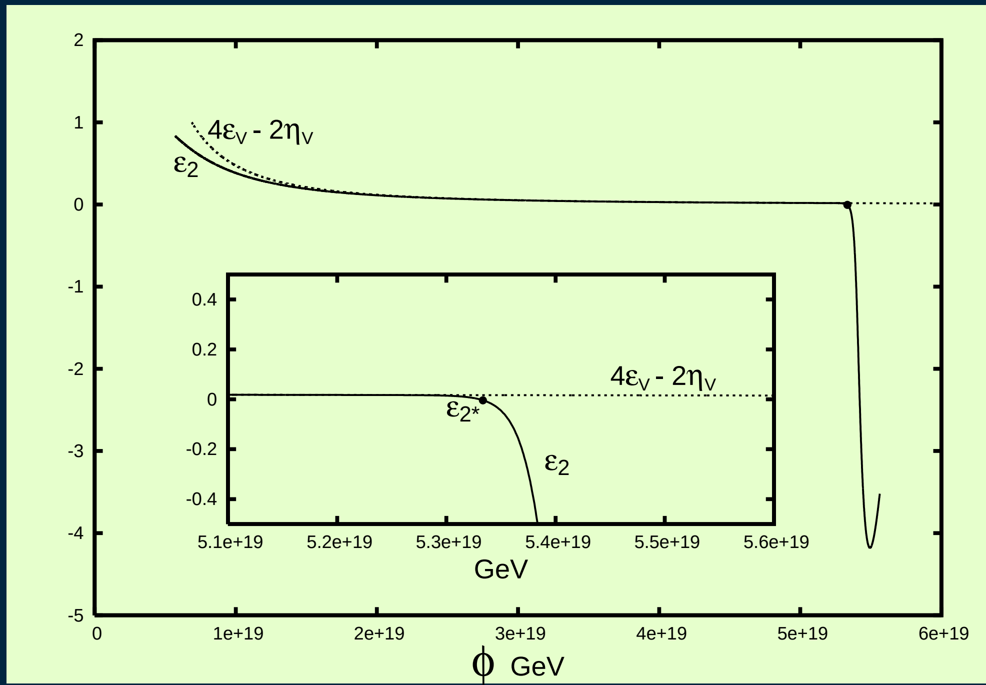
  deviations correspond to 0.1 mag

  effect of acceleration is 0.2 mag, compared to a $q_0 = 0$ model

back up slides

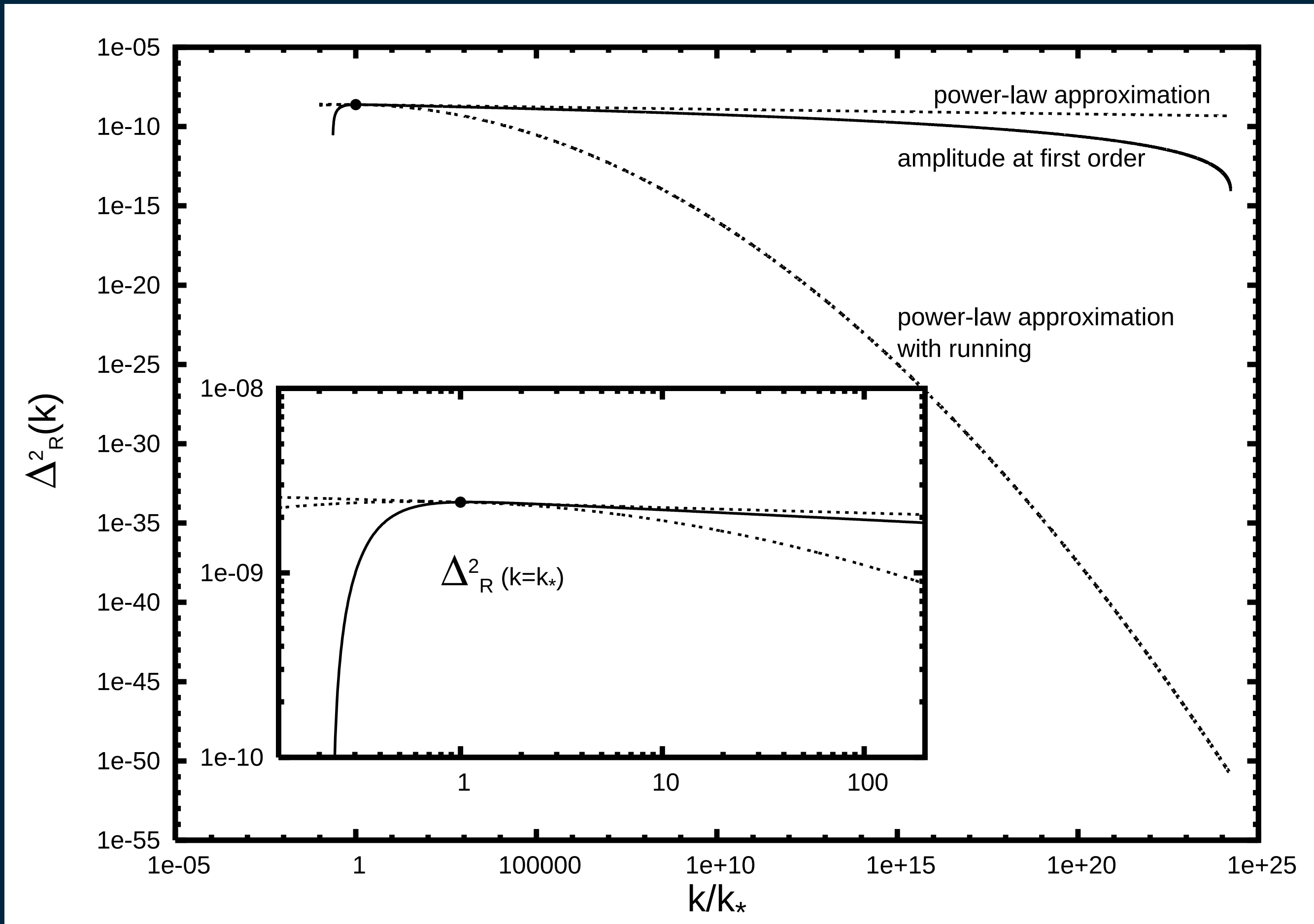
Just enough inflation ($\lambda\varphi^4$)





$\epsilon_{n+1} \equiv \mathrm{d} \ln \epsilon_n / \mathrm{d}N$, $\epsilon_1 = \dot{d}_{\mathrm{H}}$, inflation $\Leftrightarrow \epsilon_1 < 1$ Ramirez & Schwarz 2009

Primordial fluctuations



Ramirez & Schwarz 2009

Physical interpretation of multipole vectors

monopole: no vector

dipole: trivial $\mathbf{d} = \mathbf{v}^{(1,1)}$

quadrupole:

the two vectors define a plane, extrema at $\pm(\mathbf{v}^{(2,1)} \pm \mathbf{v}^{(2,2)})/\sqrt{2}$

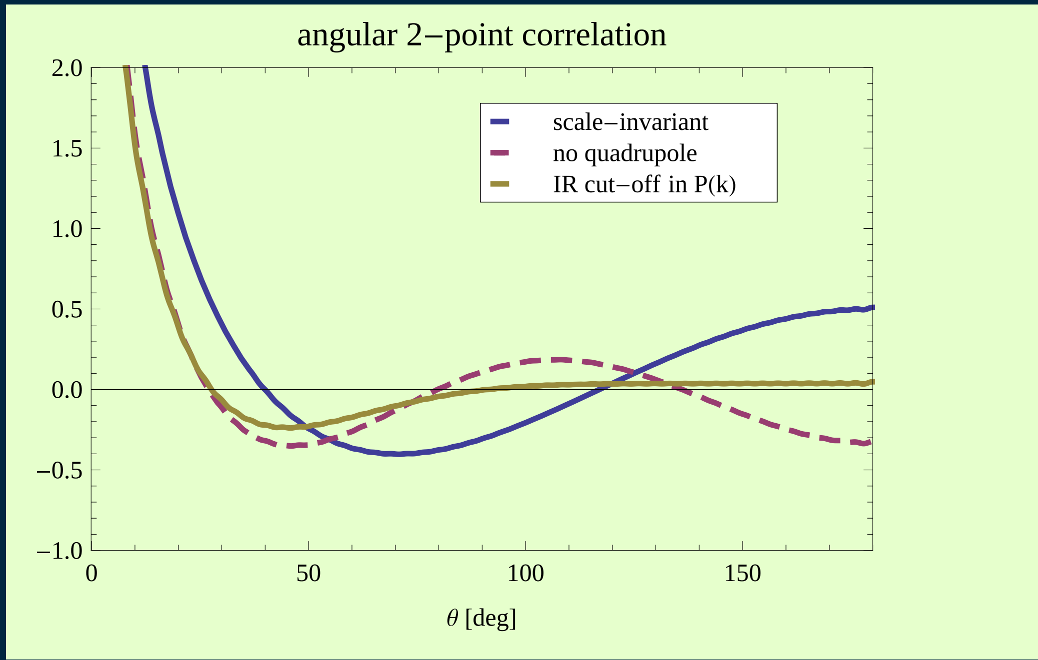
natural to define "oriented area": $\mathbf{w}^{(2;1,2)} = \pm(\mathbf{v}^{(2,1)} \times \mathbf{v}^{(2,2)})$

general multipole:

real and imaginary parts of spherical harmonic function $Y_{\ell m}$ have

$\ell - |m|$ vectors equal $\pm\mathbf{z}$, $|m|$ vectors in $\mathbf{x}$-$\mathbf{y}$ plane

Attempts of cosmological explanations for lack of correlation



cosmic topology — Aurich, Lustig, Then & Steiner 200n

IR cut-off in $P(k)$, but ISW regenerates IR power — Ramirez & Schwarz 2009

How to resolve the issue?

– more data and better systematics from WMAP

– Planck has different systematics (e.g. scan strategy, one beam on sky)

– Planck adds information in Wien regime (e.g. solar system dust?!)

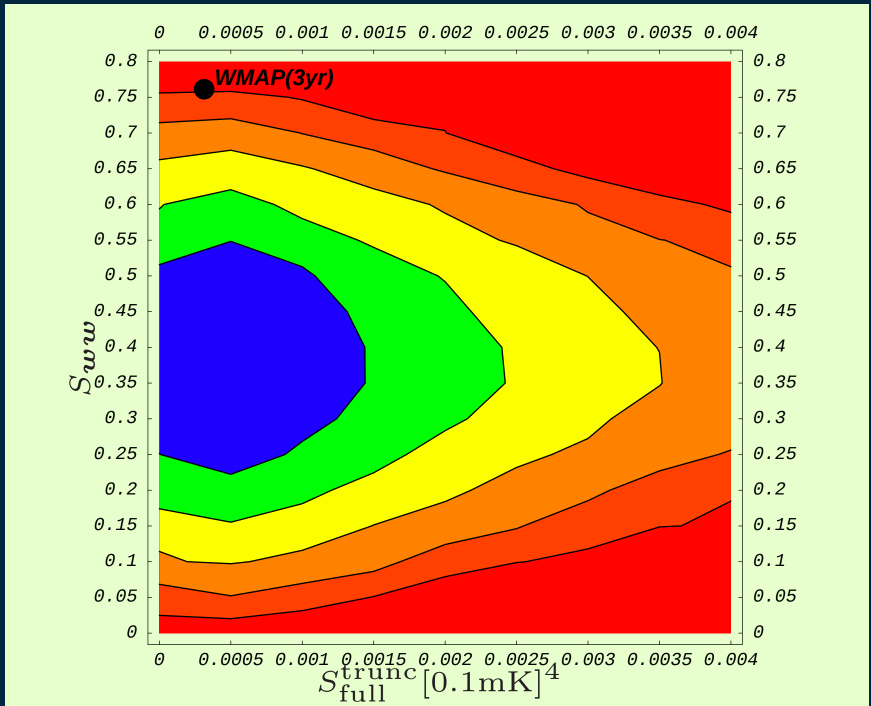
– exploit frequency, time and polarisation information

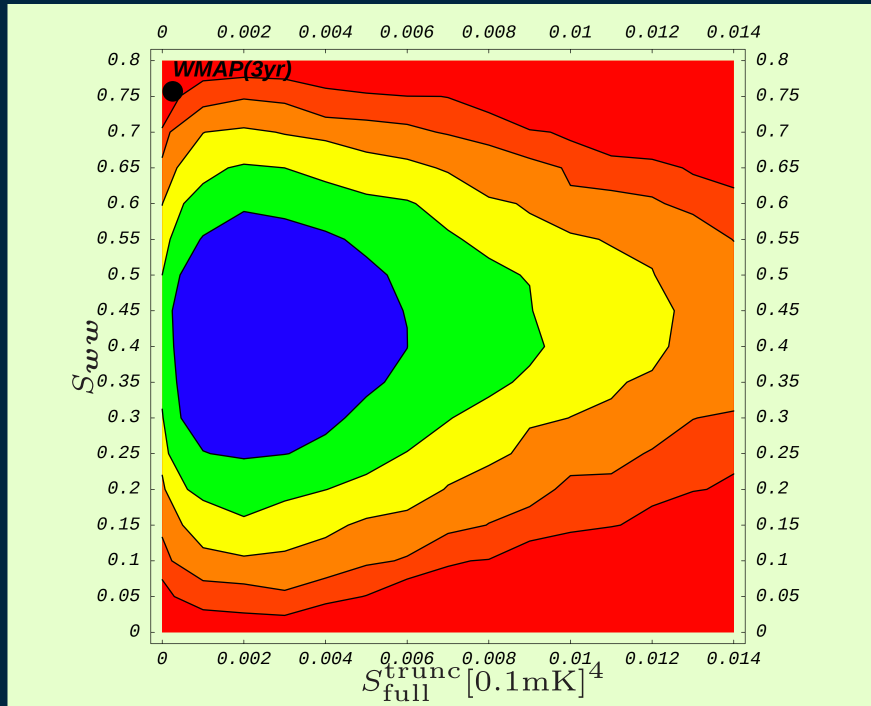
– correlation with non-CMB probes (e.g. radio galaxies, clusters)

make progress by exclusion of wrong possibilities

e.g. additive axial effect is excluded Rakić & Schwarz 2007

Main problem: additive extra foreground conflicts with low power





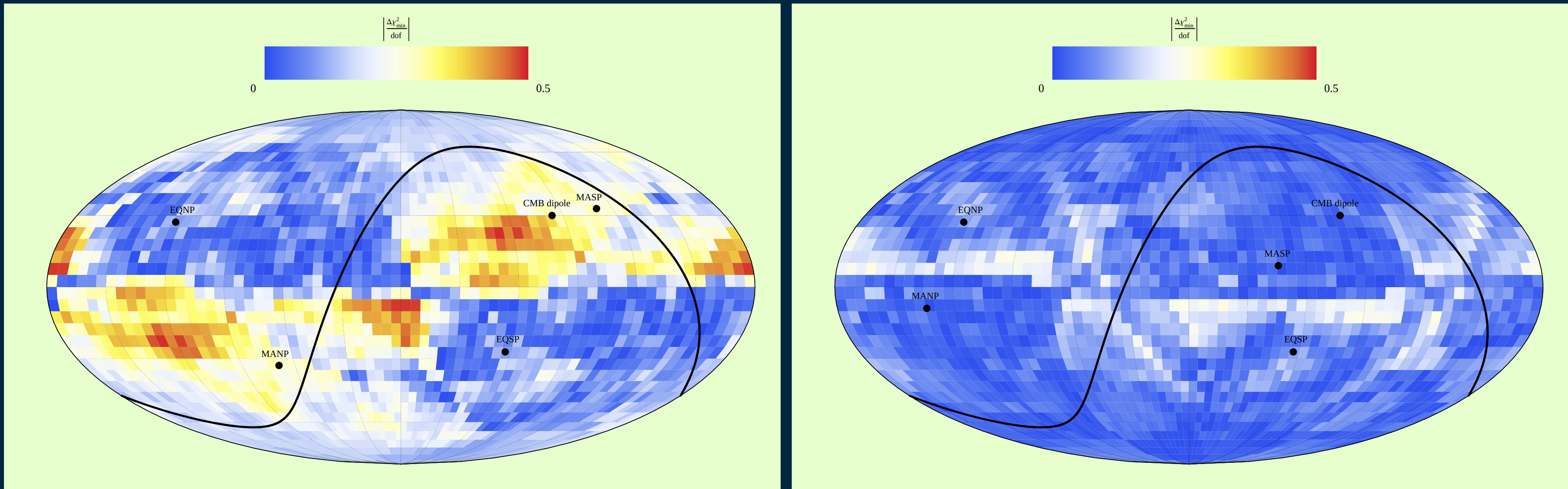
left: CMB only, right: additional axial effect

Rakić & Schwarz 2007

(An)isotropy of the low z Hubble diagram

Hubble diagrams from opposite hemispheres Schwarz & Weinhorst 2007

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



MLCS31 SALT2