

Is the CMB statistically anisotropic?

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I. Introduction

II. Conformal rolling scenario

III. Estimator for statistical anisotropy

IV. Implementation on CMB map

V. Conclusions and outlook

First three femtoseconds

- ▶ Era of precision cosmology: time to ask questions about the very beginning of the Universe
- ▶ CMB parameters sensitive to pre-RD evolution:
 - ▶ n_s – scalar spectral index
 - ▶ r – tensor-to-scalar ratio
 - ▶ non-Gaussianity
 - ▶ statistical anisotropy
 - ▶ isocurvature perturbations
 - ▶ n_T – tensor spectral index

First three femtoseconds

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 - ▶ non-Gaussianity
 - ▶ **statistical anisotropy**
 - ▶ isocurvature perturbations
 - ▶ n_T – tensor spectral index

- ▶ Statistical anisotropy: primordial power spectrum depends on wave vector direction.

$$\langle \zeta(\mathbf{k})\zeta^*(\mathbf{k}') \rangle = \frac{(2\pi)^6}{4\pi k^2} \delta(\mathbf{k} - \mathbf{k}') \frac{\mathcal{P}_\zeta(\mathbf{k})}{k}$$

$$\mathcal{P}_\zeta(\mathbf{k}) = \mathcal{P}_0(k) \left[1 + a(k) \sum_{LM} q_{LM} Y_{LM}(\hat{\mathbf{k}}) \right]$$

$$\hat{\mathbf{k}} \equiv \mathbf{k}/k$$

- ▶ $\{q_{LM}\}$ – parameters of statistical anisotropy
- ▶ correlation function is even \Rightarrow only even L
- ▶ What is an imprint on CMB map?

- ▶ Observed temperature map $\delta T(\Omega)$

$$\delta T(\Omega) = \sum_{lm} a_{lm} Y_{lm}(\Omega),$$

$$a_{lm} = 4\pi i^l \int \frac{d\mathbf{k}}{(2\pi)^3} \Delta_l(k) \zeta(\mathbf{k}) Y_{lm}^*(\hat{\mathbf{k}}),$$

$\Delta_l(k)$ – transfer function

$$S_{|m|'m'} \equiv \langle a_{lm} a_{l'm'}^* \rangle = C_l \delta_{ll'} \delta_{mm'} + \delta S_{|m|'m'}$$

$$S_{lm'l'm'} = 4\pi i^{l-l'} \int dk \frac{\mathcal{P}_\zeta(\mathbf{k})}{k^3} \Delta_l(k) \Delta_{l'}(k) Y_{lm}^*(\hat{\mathbf{k}}) Y_{l'm'}(\hat{\mathbf{k}})$$

remember $\mathcal{P}_\zeta(\mathbf{k}) = \mathcal{P}_0(k) \left[1 + a(k) \sum_{LM} q_{LM} Y_{LM}(\hat{\mathbf{k}}) \right]$

$$S_{lm'l'm'} = \delta_{ll'} \delta_{mm'} 4\pi \int \frac{dk}{k} \mathcal{P}_0(k) \Delta_l^2(k) \\ + i^{l-l'} q_{LM} \int d\Omega Y_{LM}(\hat{\mathbf{k}}) Y_{lm}^*(\hat{\mathbf{k}}) Y_{l'm'}(\hat{\mathbf{k}}) \\ \times 4\pi \int \frac{dk}{k} \mathcal{P}_0(k) a(k) \Delta_l(k) \Delta_{l'}(k)$$

$$= \delta_{ll'} \delta_{mm'} C_l + i^{l-l'} q_{LM} (-1)^{m'} \sqrt{\frac{(2l+1)(2l'+1)}{4\pi(2L+1)}} C_{l0l'0}^{L0} C_{lm;l'-m'}^{LM} \times C_{ll'}$$

- ▶ C_l and $C_{ll'}$ from CAMB
- ▶ $\delta S_{lm'l'm'} C_{lm;l'-m'}^{LM}$ – Clebsch-Gordan coefficients

$$S_{lm'l'm'} = 4\pi i^{l-l'} \int dk \frac{\mathcal{P}_\zeta(\mathbf{k})}{k^3} \Delta_l(k) \Delta_{l'}(k) Y_{lm}^*(\hat{\mathbf{k}}) Y_{l'm'}(\hat{\mathbf{k}})$$

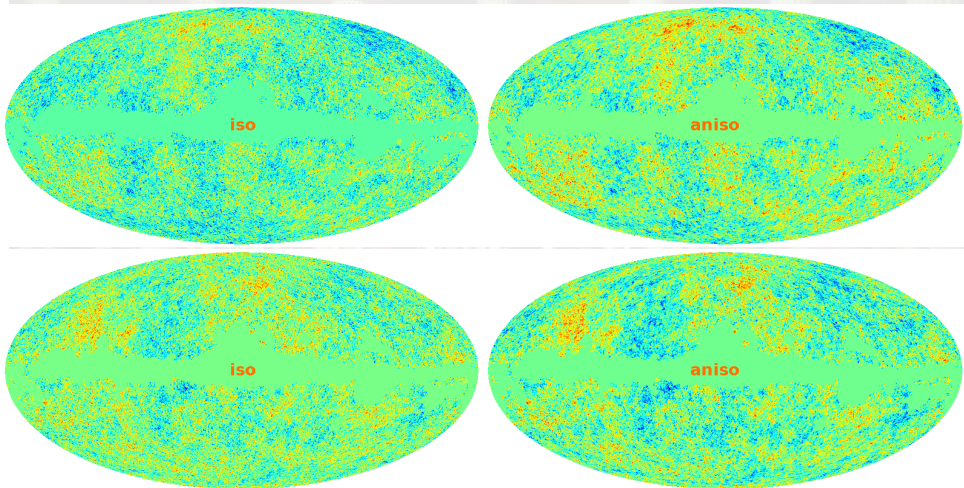
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$$\begin{aligned} S_{lm'l'm'} &= \delta_{ll'} \delta_{mm'} 4\pi \int \frac{dk}{k} \mathcal{P}_0(k) \Delta_l^2(k) \\ &\quad + i^{l-l'} q_{LM} \int d\Omega Y_{LM}(\hat{\mathbf{k}}) Y_{lm}^*(\hat{\mathbf{k}}) Y_{l'm'}(\hat{\mathbf{k}}) \\ &\quad \times 4\pi \int \frac{dk}{k} \mathcal{P}_0(k) a(k) \Delta_l(k) \Delta_{l'}(k) \end{aligned}$$

$$= \delta_{ll'} \delta_{mm'} C_l + i^{l-l'} q_{LM} (-1)^{m'} \sqrt{\frac{(2l+1)(2l'+1)}{4\pi(2L+1)}} C_{l0l'0}^{L0} C_{lm;l'-m'}^{LM} \times C_{ll'}$$

- ▶ Example: quadrupolar anisotropy $q_{2M} \neq 0$
- ▶ only $\delta S_{lm|+1m'}$ and $\delta S_{lm|+2m'} \neq 0$, $|m - m'| \leq 2$

Statistically isotropic and anisotropic CMB maps



- ▶ CMB map and statistical anisotropy generated randomly in ranges allowed by WMAP 7 yr limits

Statistically isotropic and anisotropic CMB maps



- ▶ Standard inflation – practically no statistical anisotropy
- ▶ Statistical anisotropy:
 - ▶ Inflation with vector fields or non-standard kinetic terms
for review, J. Soda, Class.Quant.Grav. 29 (2012) 083001
 - ▶ Nontrivial geometry or noncommutative field theory
A.E. Gumrukcuoglu et al. JCAP 0711 (2007) 005
E. Akofer et.al. JHEP 0805 (2008) 092
 - ▶ Conformal rolling scenario
V.A. Rubakov, JCAP 0909 (2009) 030
 - ▶ Galilean Genesis model
P.Creminelli, A.Nicolis, E.Trincherini, JCAP 1011 (2010) 021
 - ▶ General case of pseudo-conformal Universe
K. Hinterbichler, J. Khoury, JCAP 1204 (2012) 023
 - ▶ List is incomplete and growing

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 - ▶ **Conformal rolling scenario**
V.A. Rubakov, JCAP 0909 (2009) 030
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$$S = S_{G+M} + S_\phi$$

S_{G+M} - action of gravity and some dominating matter

$$S_\phi = \int d^4x \sqrt{-g} \left[g^{\mu\nu} \partial_\mu \phi^* \partial_\nu \phi + \frac{R}{6} \phi^* \phi + h^2 |\phi|^4 \right]$$

ϕ rolls down negative quartic potential from $|\phi| = 0$ till $|\phi| = f_0$
where conformal symmetry is broken

V.A. Rubakov, JCAP 0909 (2009) 030

$$\chi = a\phi$$

$$S_\chi = \int d^3x d\eta (\eta^{\mu\nu} \partial_\mu \chi^* \partial_\nu \chi + h^2 |\chi|^4)$$

$\eta^{\mu\nu}$ - Minkowski metric, η - conformal time

$$\text{Re } \chi = \chi_c + \delta\chi_1/\sqrt{2}$$

$$\text{Im } \chi = \delta\chi_2/\sqrt{2}$$

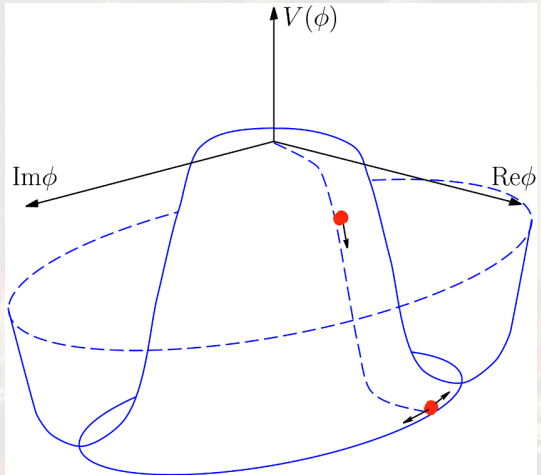
$$\chi_c(\eta) = \frac{1}{h(\eta_* - \eta)}$$

$$\theta \equiv \frac{\sqrt{2} \text{Im } \chi}{\text{Re } \chi} = \frac{\delta\chi_2}{\chi_c}$$

$$\frac{\partial}{\partial \eta} (\chi_c^2 \theta'(\eta)) = 0$$

⇒ evolution proceeds
along radial direction

- ▶ perturbations of phase are later converted into adiabatic perturbations (e.g. via curvaton mechanism)



Radial perturbations

$$(\delta\chi_1)'' - \partial_i\partial_i\delta\chi_1 - 6h^2\chi_c^2\delta\chi_1 = 0$$

$$(\delta\chi_1)'' - \partial_i\partial_i\delta\chi_1 - \frac{6}{(\eta_* - \eta)^2}\delta\chi_1 = 0$$

We require for beginning and end time of conformal rolling η_i, η_f :

$$k(\eta_* - \eta_i) \gg 1$$

$$k(\eta_* - \eta_f) \ll 1$$

$$\delta\chi_1^{(-)} = \frac{1}{4\pi} \sqrt{\frac{(\eta_* - \eta)}{2}} H_{5/2}^{(1)}[k(\eta_* - \eta)]$$

$$\delta\chi_2^{(-)} = \frac{1}{4\pi} \sqrt{\frac{(\eta_* - \eta)}{2}} H_{3/2}^{(1)}[k(\eta_* - \eta)]$$

At late times $k(\eta_* - \eta) \ll 1$:

$$\delta\chi_1^{(-)} = \frac{3}{4\pi^{3/2}} \frac{1}{k^{5/2}(\eta_* - \eta)^2}$$

$$\delta\chi_2^{(-)} = \frac{i}{2\pi^{3/2}} \frac{1}{k^{3/2}(\eta_* - \eta)}$$

$$\mathcal{P}_{\chi_1} = \frac{9}{4\pi^2 k^2 (\eta_* - \eta)^4}$$

$$\mathcal{P}_{\chi_2} = \frac{1}{4\pi^2 (\eta_* - \eta)^2}$$

Red spectrum

Flat spectrum

We have:

$$\mathcal{P}_{\chi_2} = \frac{1}{4\pi^2(\eta_* - \eta)^2}$$
$$\theta \equiv \frac{\sqrt{2} \operatorname{Im} \chi}{\operatorname{Re} \chi} = \frac{\delta\chi_2}{\chi_c}$$

$$\chi_c(\eta) = \frac{1}{h(\eta_* - \eta)}$$
$$\delta\chi_1 = \frac{3}{4\pi^{3/2}} \frac{1}{k^{5/2}(\eta_* - \eta)^2}$$

Therefore:

$$\mathcal{P}_\theta = \frac{h^2}{4\pi^2}$$

$$\mathcal{P}_\zeta \sim \mathcal{P}_\theta$$

flat perturbations

$$\chi_c + \delta\chi_1 = \frac{1}{h(\eta_* + \delta\eta_*(\mathbf{x}) - \eta)}$$

in the first approximation doesn't affect θ perturbation

in the next: *statistical anisotropy*

- ▶ conformal rolling predicts absence of tensor perturbation
- ▶ scalar tilt may be a result of conformal symmetry breaking

V. Rubakov, M. Osipov, JETP Lett. 93:52-55 (2011)

- ▶ statistical anisotropy is a result of radial perturbations
⇒ parameters q_{LM} are Gaussian random variables.

Two sub-scenarios of the conformal rolling:

Sub-scenario A. The modes of interest are superhorizon at the end of conformal rolling $k/a < H$.

M. Libanov, V. Rubakov, JCAP 1011 (2010) 045

Sub-scenario B. They are subhorizon and there exists an intermediate stage.

M. Libanov, S. Ramazanov, V. Rubakov, JCAP 1106 (2011) 010

Conformal rolling. Sub-scenario A

The power spectrum in linear and next-to-linear order on h is:

$$\mathcal{P}_\zeta(\mathbf{k}) = \mathcal{P}_0(k) (1 + Q_1(\mathbf{k}) + Q_2(\mathbf{k}))$$

$$Q_1(\mathbf{k}) = -\frac{\pi}{k} \hat{k}_i \hat{k}_j \left(\partial_i \partial_j \eta_* - \frac{1}{3} \delta_{ij} \partial_k \partial_k \eta_* \right)$$

$$Q_2(\mathbf{k}) = -\frac{3}{2} (\hat{\mathbf{k}}\mathbf{v})^2, \quad \text{where } v_i \equiv -\partial_i \eta_*(\mathbf{x})$$

- ▶ dominated by infrared modes; one may consider Q_1, Q_2 constant tensor throughout our part of the Universe
- ▶ linear order:

$$\langle q_{2M} q_{2M'}^* \rangle = \delta_{MM'} \frac{\pi h^2 H_0^2}{25}, \quad a(k) = k^{-1}$$

- ▶ next-to-linear order:

$$q_{2M} = -\frac{4\pi \mathbf{v}^2}{5} Y_{2M}^*(\hat{\mathbf{v}}), \quad a(k) = 1$$

$$\langle \mathbf{v}^2 \rangle = \frac{3h^2}{8\pi^2} \ln \frac{H_0}{\Lambda}$$

Conformal rolling. Sub-scenario A: extension

- ▶ One may consider “pseudo-Conformal Universe”, where conformal field drives the cosmological evolution.

K. Hinterbichler, J. Khoury, JCAP 1204 (2012) 023

- ▶ Evolution of the Universe is a slow contraction and the metric is close to Minkowski.
- ▶ Main properties of theory are determined by spontaneous breaking of conformal symmetry $so(4, 2)$ to de Sitter symmetry $so(4, 1)$.
- ▶ Statistical anisotropy prediction is the same up to reparametrization in different realization of pseudo-Conformal Universe
- ▶ Galilean Genesis and conformal rolling sub-scenario A may be considered as a special case of general pseudo-conformal Universe

$$\mathcal{S}_\pi = \int d^4x \sqrt{-g} \left[-f^2 e^{2\pi} (\partial\pi)^2 + \frac{f^3}{\Lambda^3} (\partial\pi)^2 \square\pi + \frac{f^3}{2\Lambda^3} (\partial\pi)^4 \right]$$

P. Creminelli, A. Nicolis, E. Trincherini, JCAP 1011 (2010) 021

- ▶ Conformal invariance is spontaneously broken by solution $e^\pi = \frac{1}{t^* - t}$.
- ▶ Statistical anisotropy is the same up to reparametrization

$$h^2 \leftrightarrow \frac{2\Lambda^3}{3f^3}$$

Conformal rolling. Sub-scenario B

- ▶ If conformal field is spectacular it's possible that the modes of interest are subhorizon at the end of conformal rolling $k/a > H$.
- ▶ We assume the intermediate stage is long $r \equiv \eta_1 - \eta_* \gg k^{-1}$
- ▶ To preserve flat spectrum the dynamics of θ must be nearly Minkowskian at the intermediate stage.
- ▶ Statistical anisotropy

$$\mathcal{P}_\zeta(\mathbf{k}) = \mathcal{P}_0(k) \left[1 + \hat{\mathbf{k}}\mathbf{v}(\mathbf{x} - r\hat{\mathbf{k}}) - \hat{\mathbf{k}}\mathbf{v}(\mathbf{x} - r\hat{\mathbf{k}}) \right]$$

$$a(k) = 1$$

$$\langle q_{LM} q_{L'M'}^* \rangle = \delta_{LM'} \delta_{MM'} \frac{3h^2}{\pi} \frac{1}{(L-1)(L+2)}$$

Anisotropic inflation

- ▶ Inflation with vector fields

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa^2} R - \frac{1}{2} (\partial_\mu \phi)^2 - V(\phi) - \frac{1}{4} f^2(\phi) F_{\mu\nu} F^{\mu\nu} \right]$$

M. Watanabe, S. Kanno, J. Soda Phys.Rev.Lett. 102 (2009) 191302

- ▶ Statistical anisotropy:

$$\mathcal{P}_\zeta(\mathbf{k}) = \mathcal{P}_0(k) [1 + g_s \sin^2 \theta], \quad \theta - \text{zenith angle}$$

$$g_s = 24N^2 l$$

N - e-folding number, l - anisotropy parameter; can be derived from parameters of the model.

J. Soda, Class.Quant.Grav. 29 (2012) 083001

$$\Rightarrow q_{20} = \frac{4}{3} \sqrt{\frac{\pi}{5}} g_s \quad (\text{in preferred coordinate frame})$$

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\hat{a}_{lm} – observed temperature map // $\delta \hat{T}(\Omega) = \sum \hat{a}_{lm} Y_{lm}(\Omega)$

- ▶ Estimator: $\hat{a}_{lm} \rightarrow \{q_{LM}\}$
- ▶ Maximum likelihood approach: $P(\hat{a}|\mathbf{q})$ is a probability density to observe \hat{a} given statistical anisotropy parameters equal to $\mathbf{q} = \{q_{LM}\}$
- ▶ CMB map is a Gaussian random:

$$\hat{C}_{|m|'m'} \equiv \langle \hat{a}_{lm} \hat{a}_{l'm'}^* \rangle = B_l B_{l'} (C_l \delta_{ll'} \delta_{mm'} + \delta S_{|m|'m'}(\mathbf{q})) + N_{|m|'m'}$$

B_l – beam transfer function, N – noise covariance.

$$P(\hat{a}|\mathbf{q}) = \frac{1}{\sqrt{\det \hat{C}}} \exp\left(-\frac{1}{2} \hat{a}^+ \hat{C}^{-1} \hat{a}\right)$$

$$-\mathcal{L}(\hat{a}|\mathbf{q}) \equiv -\ln P(\hat{a}|\mathbf{q}) = \frac{1}{2} \text{Tr} \ln \hat{C}(\mathbf{q}) + \frac{1}{2} \hat{a}^+ \hat{C}^{-1}(\mathbf{q}) \hat{a}$$

Quadratic Maximum Likelihood (QML)

$$\frac{\partial \mathcal{L}}{\partial \mathbf{q}^+} = 0$$

- ▶ \hat{C} is far from diagonal in both coordinate and harmonic spaces \Rightarrow computationally difficult to solve directly
- ▶ Let's expand log-likelihood up to quadratic order of \mathbf{q}

$$\frac{\partial \mathcal{L}}{\partial \mathbf{q}^+} = \left. \frac{\partial \mathcal{L}}{\partial \mathbf{q}^+} \right|_0 + \left. \frac{\partial^2 \mathcal{L}}{\partial \mathbf{q}^+ \partial \mathbf{q}} \right|_0 \mathbf{q}$$

D.Hanson and A.Lewis, Phys.Rev.D 80 (2009) 063004

- ▶ Replace the second derivative by it's expectation value

$$\left\langle \frac{\partial^2 \mathcal{L}}{\partial \mathbf{q}^+ \partial \mathbf{q}} \right\rangle = - \left\langle \frac{\partial \mathcal{L}}{\partial \mathbf{q}^+} \frac{\partial \mathcal{L}}{\partial \mathbf{q}} \right\rangle \equiv -\mathbf{F}$$

first equality follows from normalization $\int \exp(\mathcal{L}) d\hat{\mathbf{a}} = 1$

$$\left. \frac{\partial \mathcal{L}}{\partial \mathbf{q}^+} \right|_0 = \frac{1}{2} \hat{\mathbf{a}}^+ \hat{\mathbf{C}}_0^{-1} \frac{\partial \hat{\mathbf{C}}}{\partial \mathbf{q}^+} \hat{\mathbf{C}}_0^{-1} \hat{\mathbf{a}} - \frac{1}{2} \text{Tr} \left(\hat{\mathbf{C}}_0^{-1} \frac{\partial \hat{\mathbf{C}}}{\partial \mathbf{q}^+} \right)$$

Note: if \mathbf{x} - random with covariance \mathbf{C} , $\text{Tr} \mathbf{A} = \langle \mathbf{x}^+ \mathbf{A} \mathbf{C}^{-1} \mathbf{x} \rangle$

$$\mathbf{h} \equiv \frac{1}{2} \bar{\mathbf{a}}^+ \frac{\partial \hat{\mathbf{C}}}{\partial \mathbf{q}^+} \bar{\mathbf{a}}$$

$$\bar{\mathbf{a}} \equiv \hat{\mathbf{C}}_0^{-1} \hat{\mathbf{a}}$$

$$\left. \frac{\partial \mathcal{L}}{\partial \mathbf{q}^+} \right|_0 = \mathbf{h} - \langle \mathbf{h} \rangle_{iso}$$

where average is over statistically isotropic CMB realizations

$$\mathbf{q} = \mathbf{F}^{-1} (\mathbf{h} - \langle \mathbf{h} \rangle_{iso})$$

Inverse-variance filtering – most resource consuming operation. Performed by conjugate gradient technique with multigrid preconditioner

Estimator for h^2 for model with intermediate stage

- ▶ For a given h^2 , $\{q_{LM}\}$ are Gaussian randoms. Probability is defined as an integral over all realizations of \mathbf{q} .

$$P(a|h^2) = \int d\mathbf{q} P(a|\mathbf{q}) P(\mathbf{q}|h^2)$$

second term is Gaussian by the model, first – Gaussian in QML approximation.

- ▶ One may evaluate integral and construct h^2 estimator as:

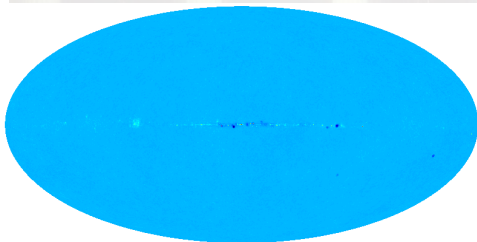
$$\frac{\partial \ln P(a|h^2)}{\partial h^2} = 0$$

S.Ramazanov, G.R. JCAP 05 (2012) 033

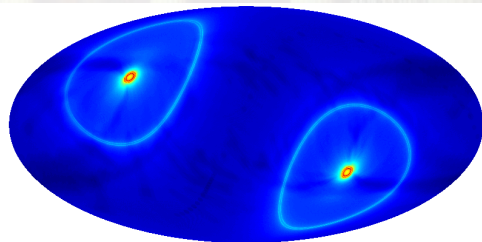
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WMAP 7 years map, W-band (94 GHz)

- ▶ get the map and noise inverse covariance (WMAP website)



-1.103E+04 +2.379E+04

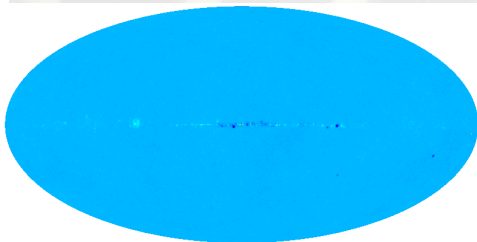


+1.011E-04 +1.238E-03

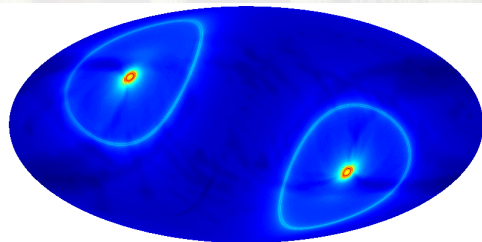


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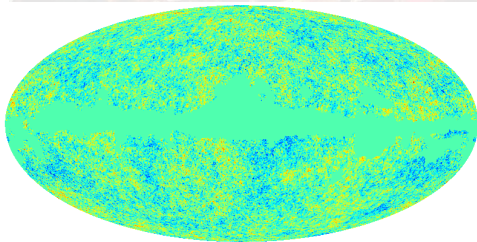


-1.103E+04  +2.379E+04

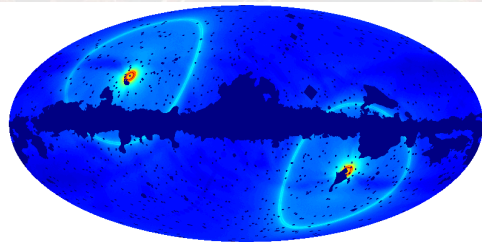


+1.011E-04  +1.238E-03

- ▶ apply the temperature analysis mask



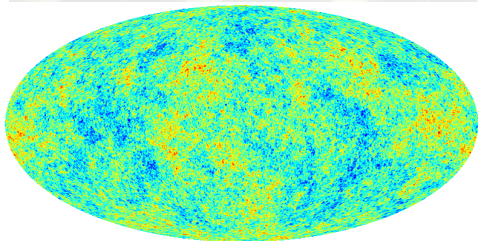
-541.  +606.



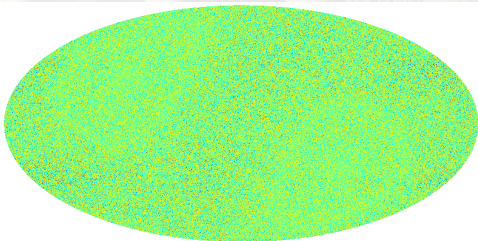
0.00  +1.238E-03

Statistically isotropic MC map

- ▶ C_l from CAMB; generate random $\{a_{lm}\}$ and noise



-390.  +420.

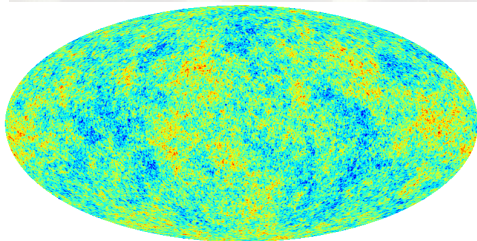


-360.  +326.

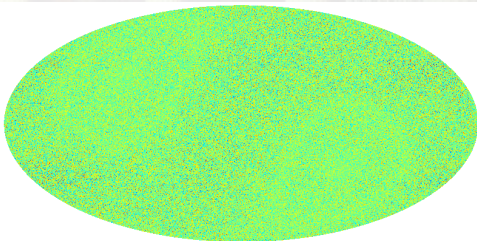


Statistically isotropic MC map

- ▶ C_l from CAMB; generate random $\{a_{lm}\}$ and noise

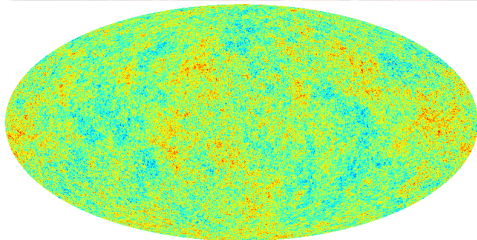


-390.  +428.

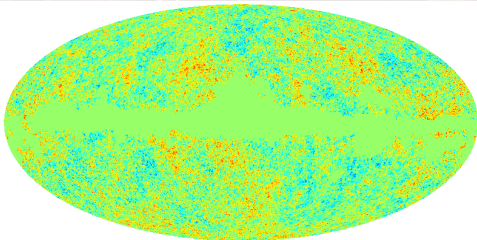


-368.  +326.

- ▶ add up signal and noise; apply mask



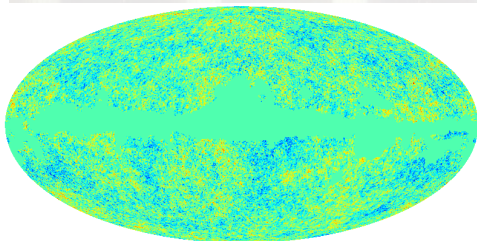
-607.  +511.



-607.  +511.

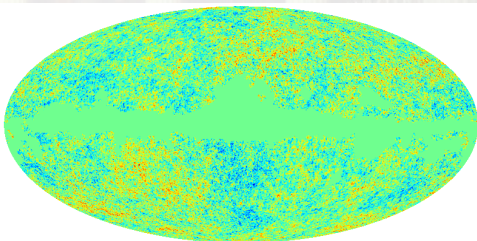
Data and isotropic MC

► data



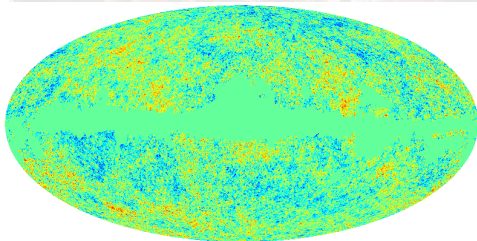
-541.  +606.

MC01



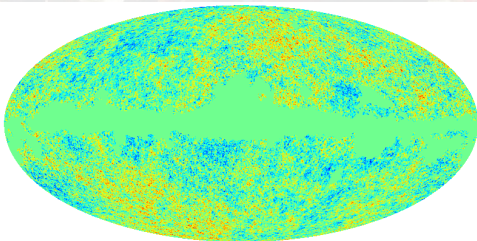
-527.  +519.

► MC02



-489.  +499.

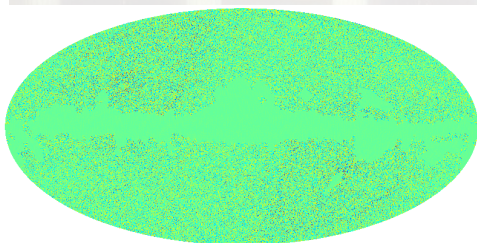
MC03



-518.  +523.

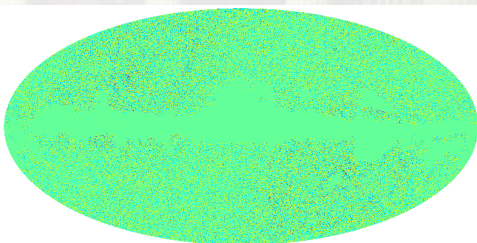
Inverse variance filtering (\bar{a} shown)

▶ data



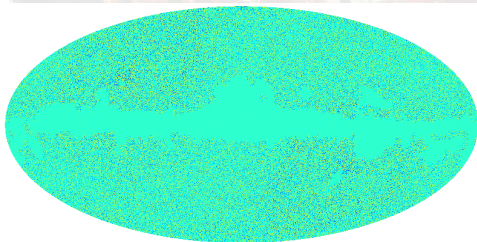
-2,006E+03 +2,075E+03

MC01



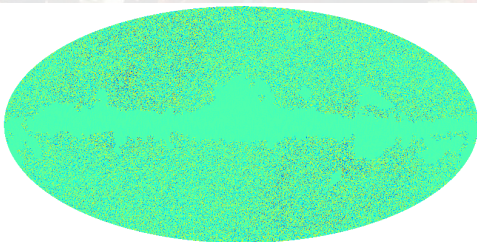
-2,921E+03 +3,028E+03

▶ MC02



-2,750E+03 +3,526E+03

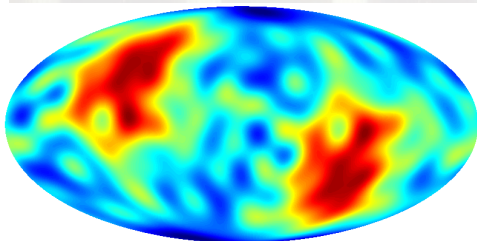
MC03



-2,730E+03 +3,114E+03

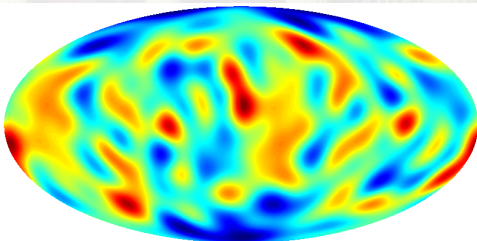
QML estimator (\mathbf{h}_{LM} shown), $a(k) = 1$

▶ data



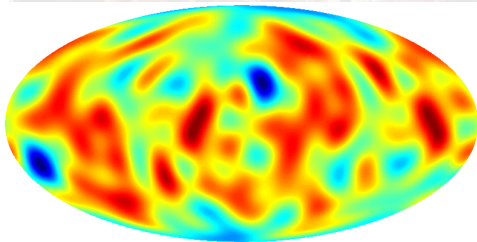
+4.012E+03 +4.754E+03

MC01



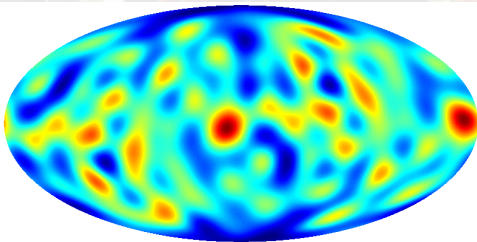
+4.139E+03 +4.526E+03

▶ MC02



+4.045E+03 +4.509E+03

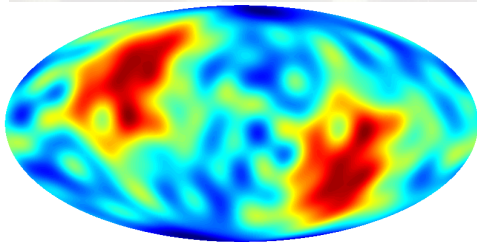
MC03



+4.169E+03 +4.572E+03

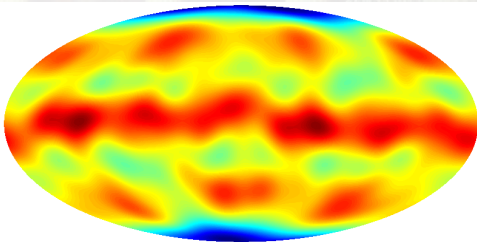
QML estimator

▶ data h_{lm}



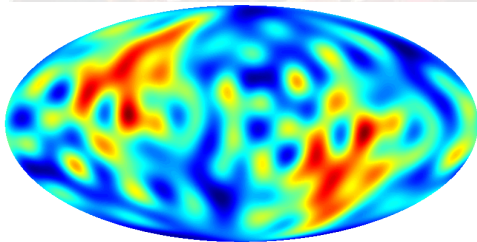
+4,012E+03  +4,754E+03

average over 100 MC $\langle h_{lm} \rangle$



+4,314E+03  +4,542E+03

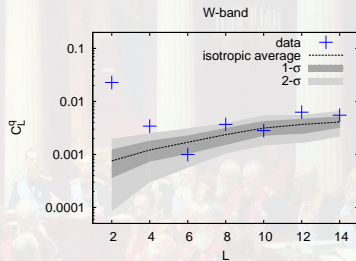
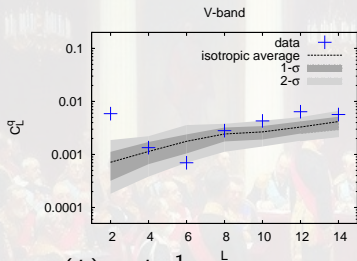
▶ $h_{lm} - \langle h_{lm} \rangle$



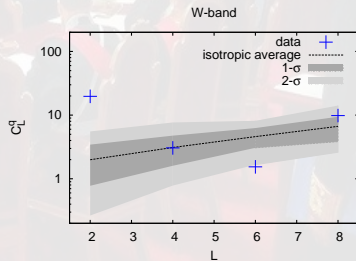
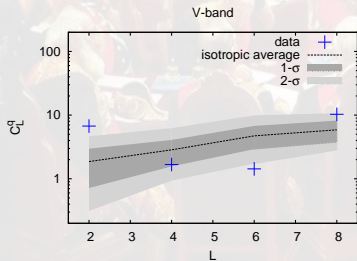
-102.  +310.

WMAP 7yr results for $C_L^q = \sum_M q_{LM}^* q_{LM} / (2L + 1)$

▶ $a(k) = 1$



▶ $a(k) = k^{-1}$



- ▶ Sub-scenario B (with intermediate stage)

$$h^2 < 0.045$$

- ▶ Sub-scenario A

$$h^2 < 190$$

The limit is so weak that next-to-linear order terms start playing role:

M. Libanov, V. Rubakov, JCAP 1011 (2010) 045

$$h^2 \ln \frac{H_0}{\Lambda_0} < 7$$

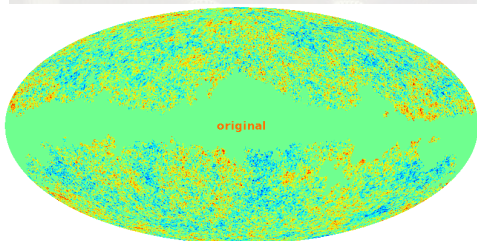
Λ_0 – unknown infrared scale

S. Ramazanov, G.R. JCAP 05 (2012) 033

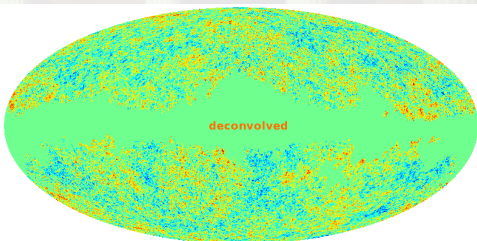
WMAP 7yr statistical anisotropy discussion

- ▶ Magnitude of quadrupole is different in V and W bands
- ▶ Direction coincides with ecliptic pole (orientation of the satellite axis)
- ▶ D.Hanson, A.Lewis and A.Challinor suggested that anisotropy may result from WMAP beam asymmetry.
- ▶ Elliptical beam effectively convolve map with quadrupole asymmetric function. *D.Hanson et al. Phys.Rev.D 80 (2009)*
- ▶ Two possible solutions:
 1. Deconvolve a map to compensate for beam asymmetry.
WMAP 9yrs deconvolved maps
C.L. Bennett et al [WMAP] arXiv:1212.5225
 2. Simulate statistically isotropic MC maps with realistic beam
Planck FFP6 product (not yet public)
Planck collaboration, arXiv:1303.5083

WMAP 9yrs new product: deconvolved maps

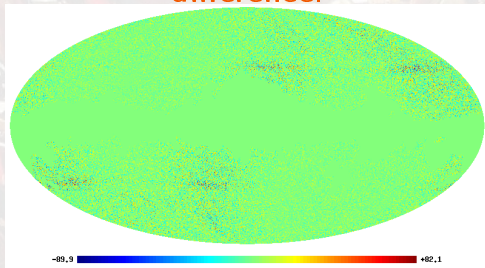


-450. +450.



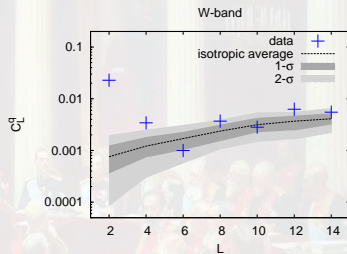
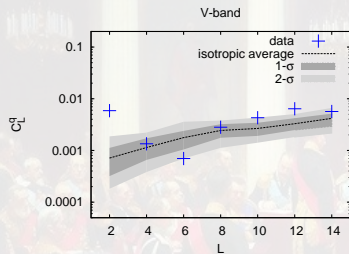
-450. +450.

difference:

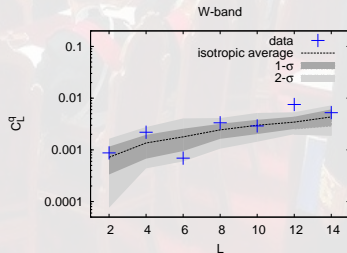
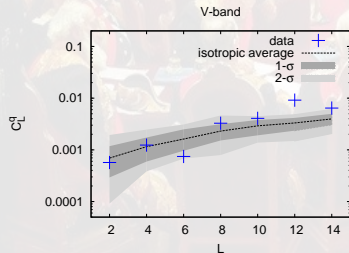


WMAP 7yr/9yr results for $C_L^q = \sum_M q_{LM}^* q_{LM} / (2L + 1)$

- ▶ WMAP 7yr, $a(k) = 1$



- ▶ WMAP 9yr, $a(k) = 1$, deconvolved map



WMAP 9yr constraints on early Universe models

	WMAP 7yr	WMAP 9yr
Sub-scenario A (LO)	$h^2 < 190$	$h^2 < 11$
Sub-scenario A (NLO)	$h^2 \ln \frac{H_0}{\Lambda_0} < 7$	$h^2 \ln \frac{H_0}{\Lambda_0} < 1.2$
Galilean Genesis	$\frac{\Lambda^3}{f^3} \ln \frac{H_0}{\Lambda_0} < 11$	$\frac{\Lambda^3}{f^3} \ln \frac{H_0}{\Lambda_0} < 1.8$
Sub-scenario B	$h^2 < 0.045$	$h^2 < 0.006$
Anisotropic inflation	$N^2 I < 0.013$	$N^2 I < 0.003$

Conclusions and outlook

- ▶ CMB is sensitive to the dynamics of the earliest Universe
- ▶ No evidence for primordial power anisotropy in WMAP data
- ▶ Parameter space is constrained for variety of models: conformal rolling, Galilean Genesis, inflation with vector fields
- ▶ The Planck has a power to exclude or discover early evolution scenarios