# CMB Sky at Large Scales:
## Imprints of New Physics (?)

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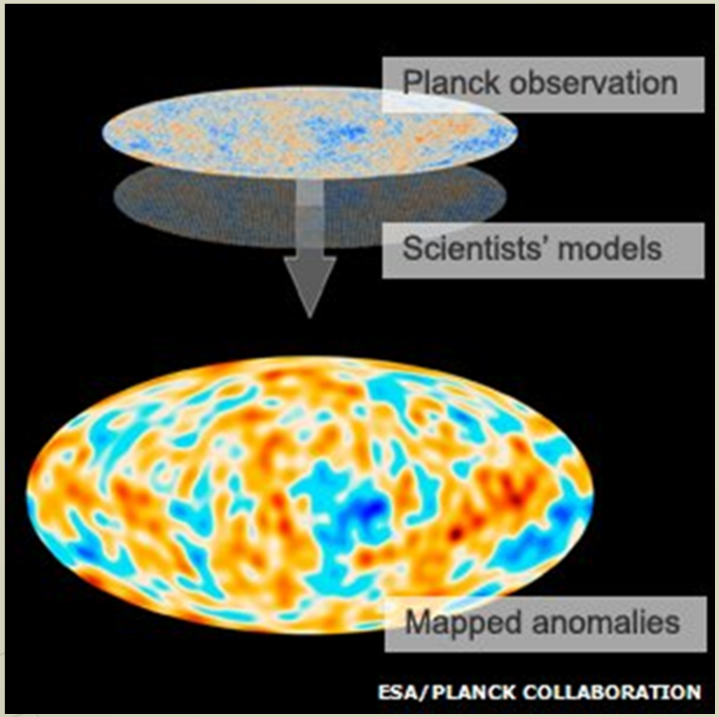
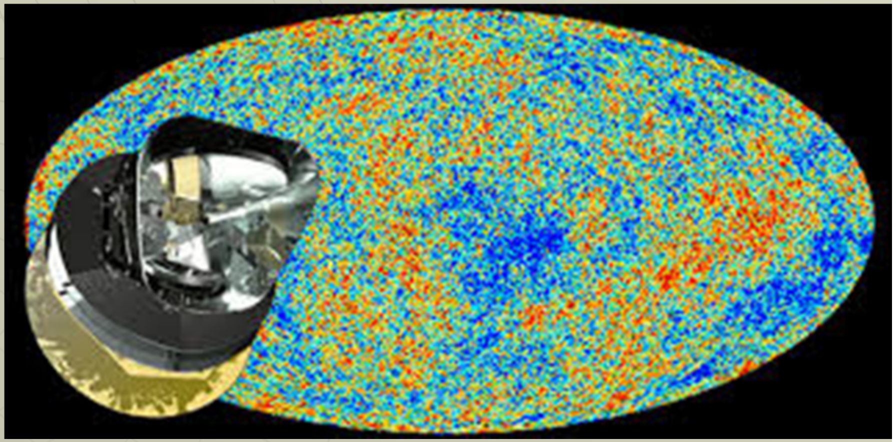
**New Light in Cosmology from the CMB**
**ICTP, August 1, 2013**

# Outline

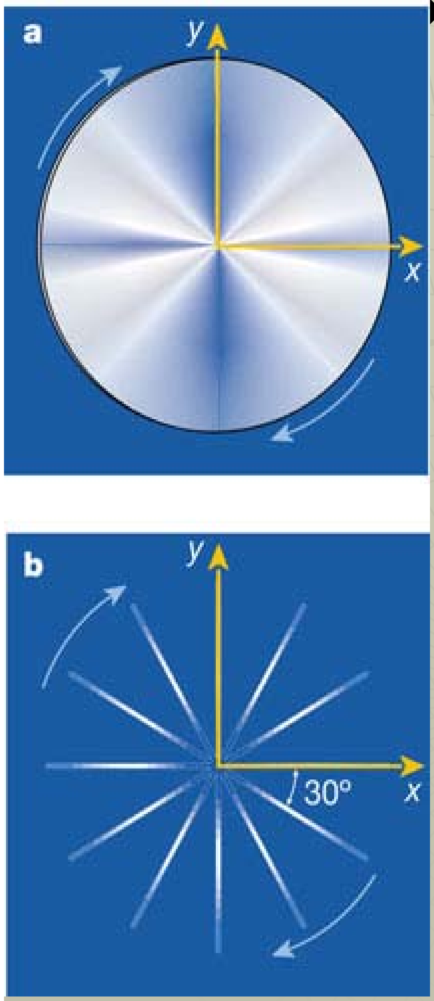
- PLANCK Results: Puzzles
  - Low Multipole Anomalies
  - Cold Spot
  - North South Asymmetry
  - Large Scale Power Suppression
- Possible explanation?
  - Primordial Magnetic Field
  - Massive Gravity (dRGT)

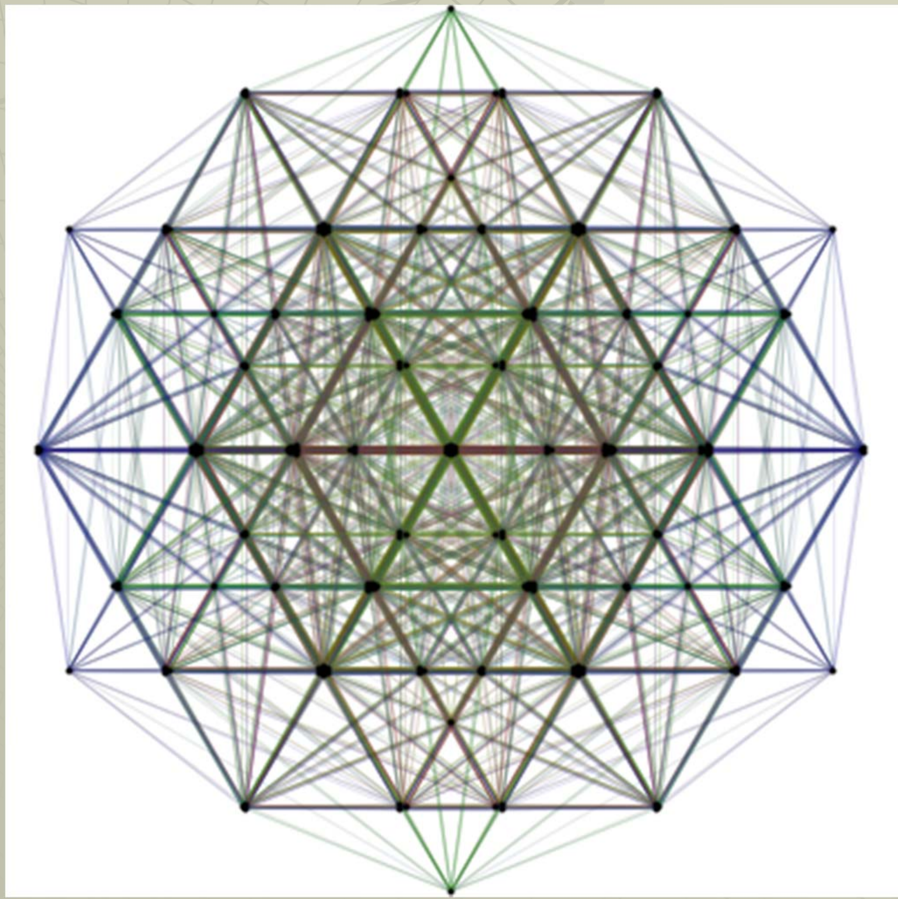


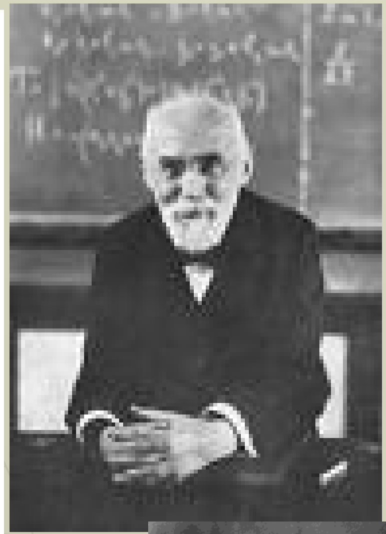



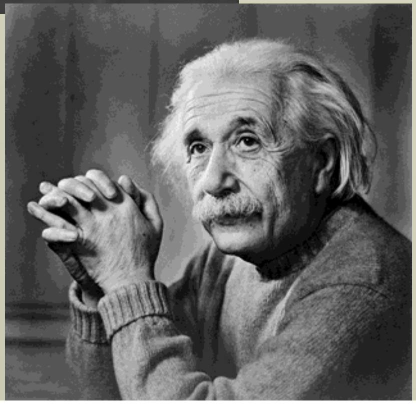
# The beauty of symmetry…

- Space-time in the Einstein model has no preferred or distinguishable direction (frame) ***Isotropy of the Universe***





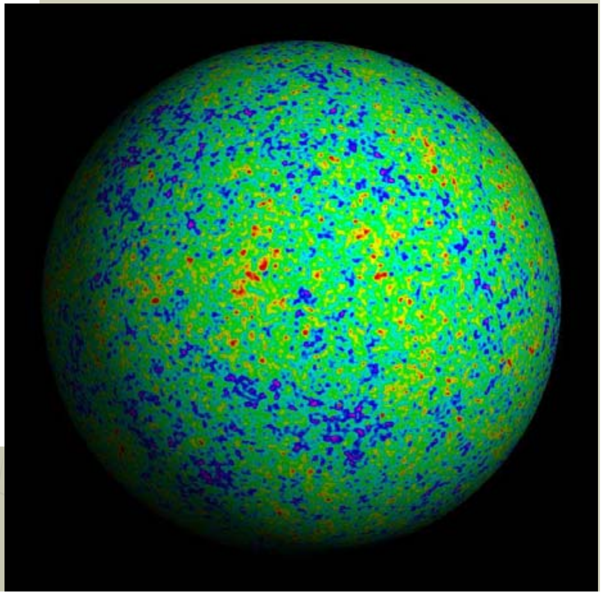


# Is the CMB sky isotropic?

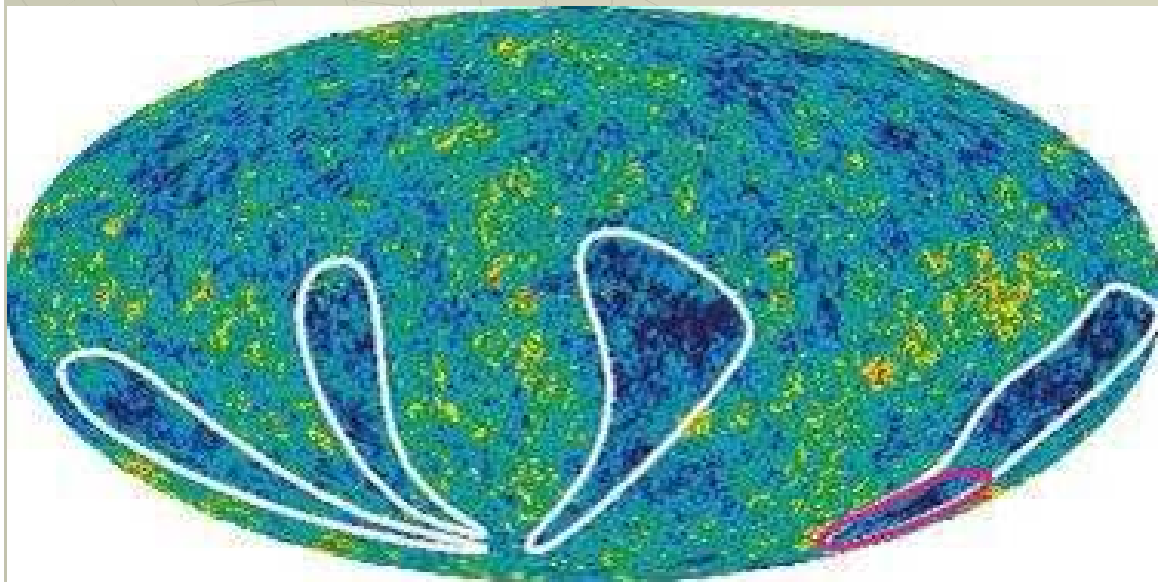
## *Planck* 2013 results. XXIII. Isotropy and statistics of the CMB

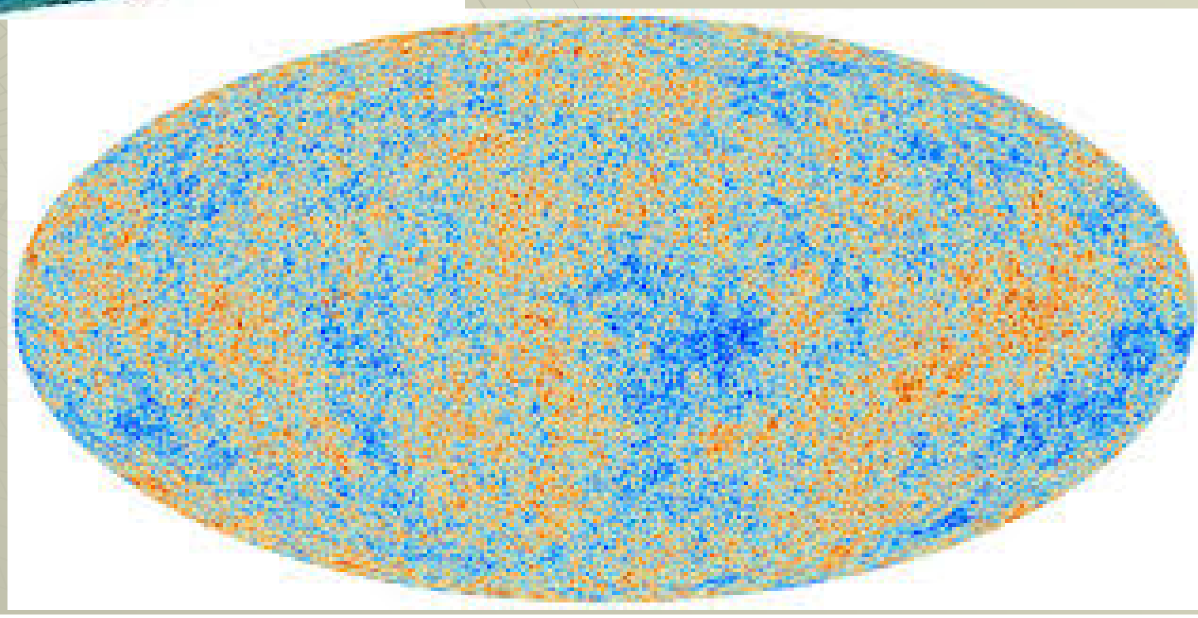
Planck Collaboration: P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, ...

(Affiliations can be found after the references)



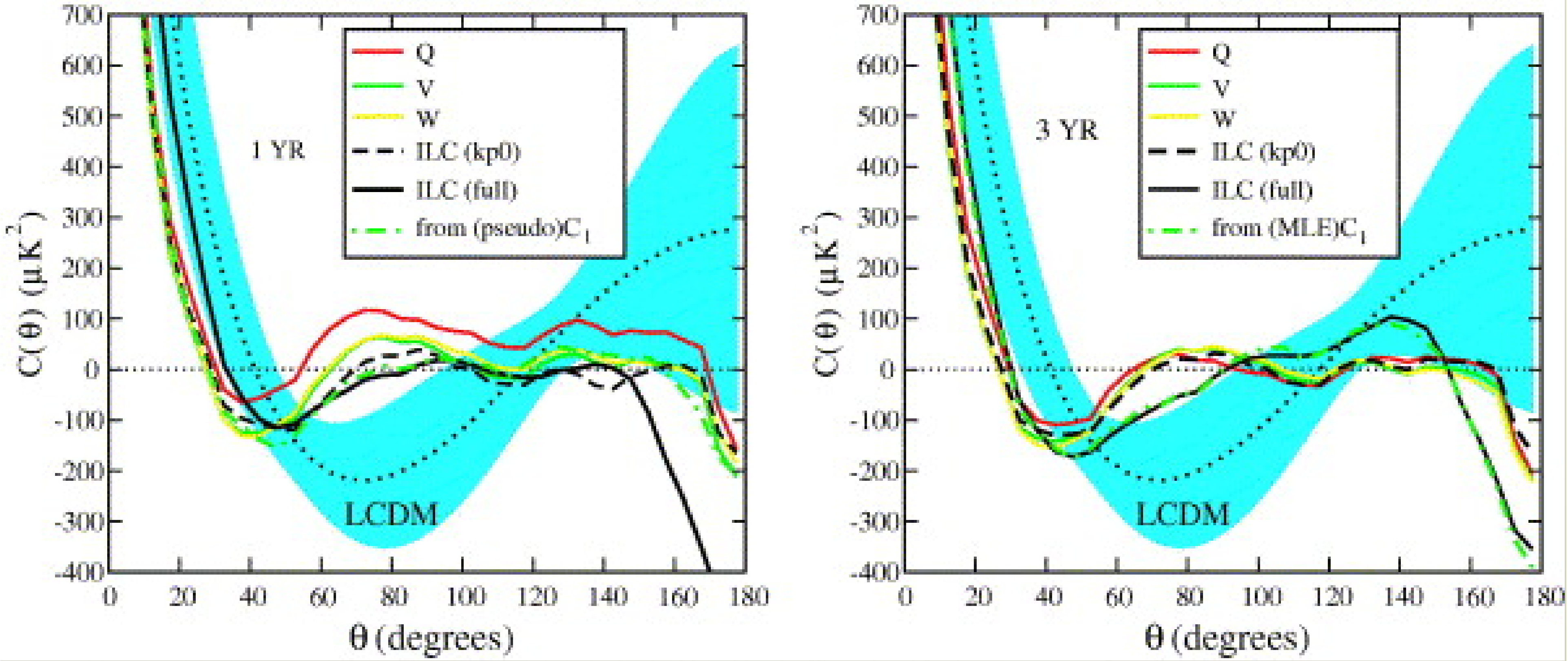
# North-South Asymmetry





# Two Point Correlation Function

*Copi,. Huterer, Schwarz & Starkman, 2008*




See also Yoho talk, July 29

# Low Multipoles Alignments

- Possibly related to two point correlations power suppression at large angular scales

  *Copi, Huterer, Schwarz & Starkman, 2008*

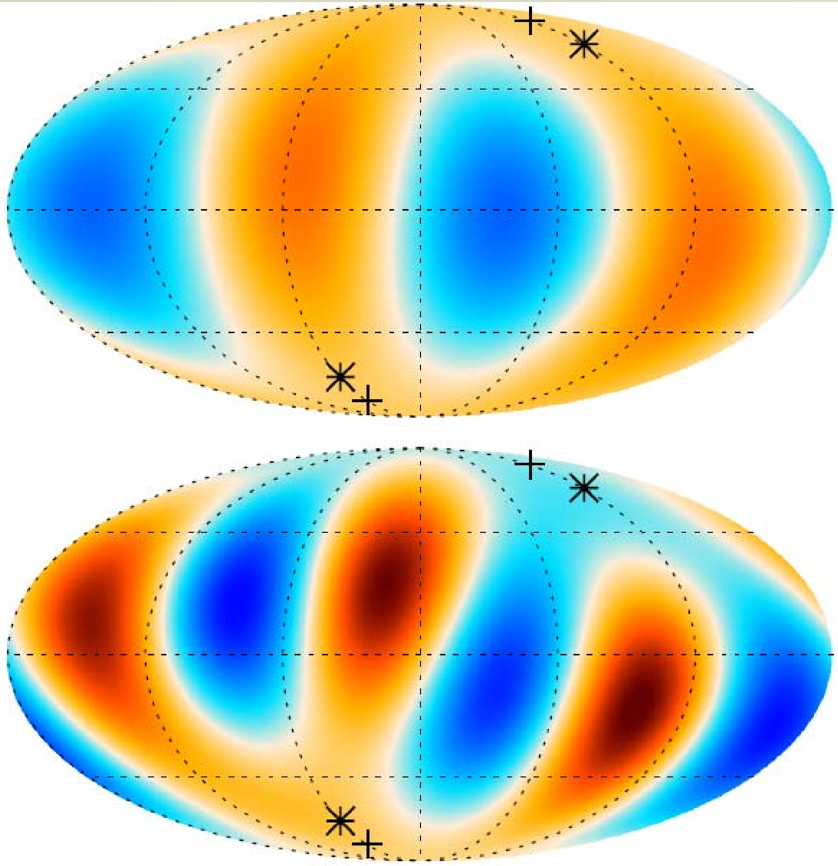
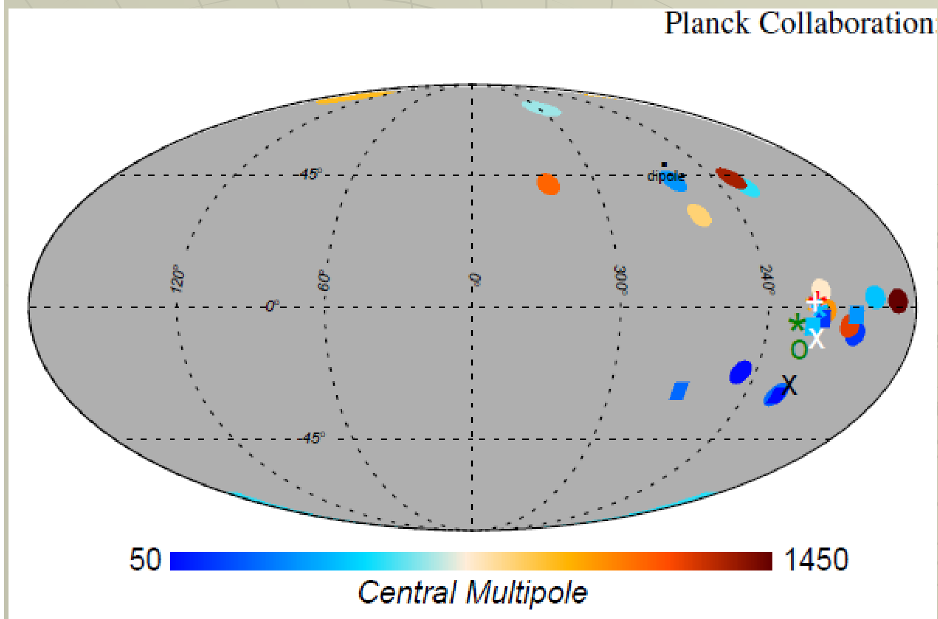
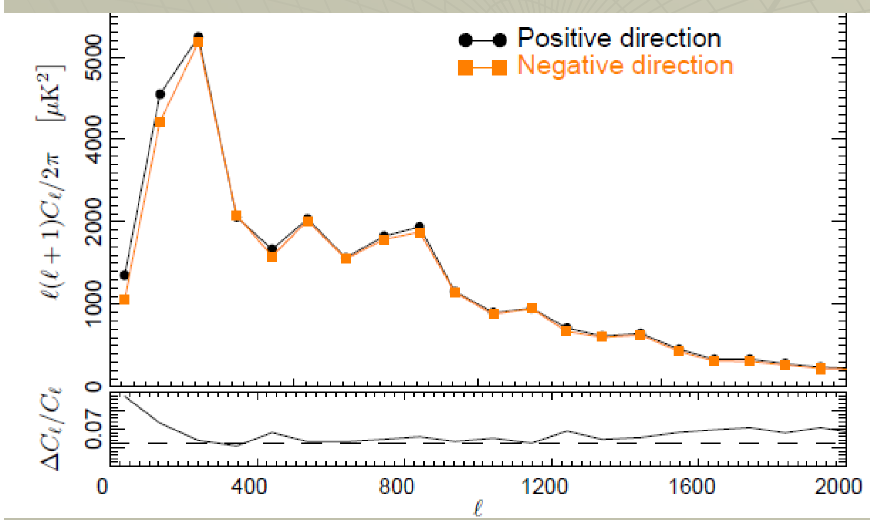


**Fig. 20.** Upper: The Wiener filtered SMICA CMB sky (temperature range ± 400 $\mu$K). Middle: the derived quadrupole (temperature range ± 35 $\mu$K). Lower: the derived octopole (temperature range ± 35 $\mu$K). Cross and star signs indicate axes of the quadrupole and octopole, respectively, around which the angular momentum dispersion is maximized.

*Planck 2013 results XXIII*

# PLANCK 2013 Results XXIII
# CMB Asymmetry



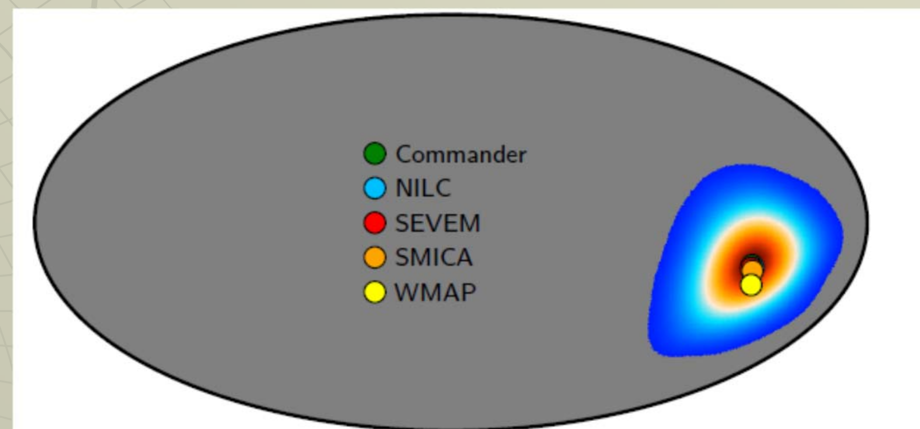




**Fig. 30.** Consistency between component separation algorithms as measured by the dipole modulation likelihood. The top panel shows the marginal power spectrum amplitude for the 5° smoothing scale, the middle panel shows dipole modulation amplitude, and the bottom panel shows the preferred dipole directions. The coloured area indicates the 95% confidence region for the `Commander` solution, while the dots shows the maximum-posterior directions for the other codes.

# Courtesy of Jaiseung Kim
# CMB Asymmetry (Rough Estimates)

The sky masked by the Union73 is split into the northen and southern hemisphere, where the southern pole concides with $(\theta, \phi) = (110°, 237°)$ in Galactic co-latitutde and longitude.

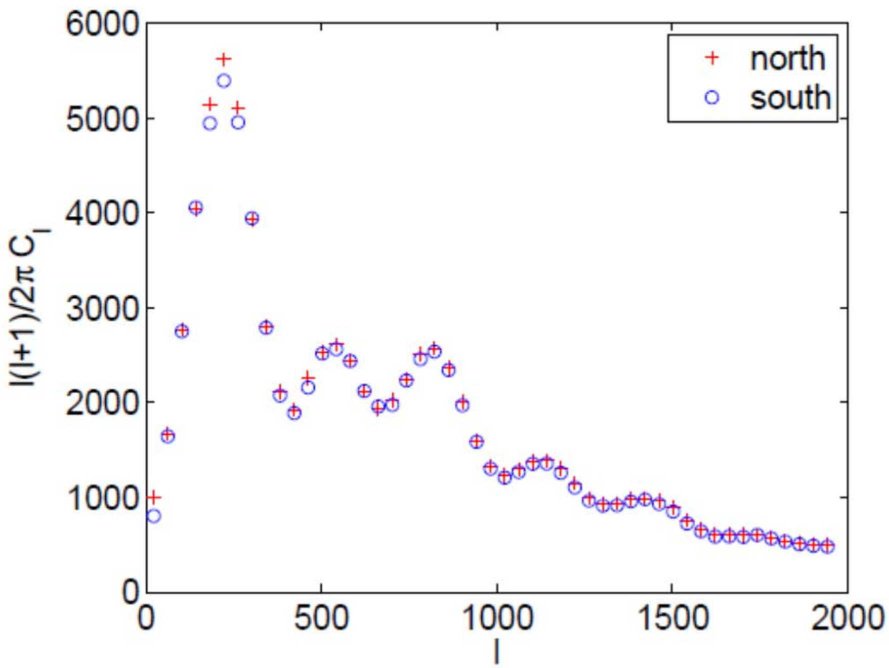



FIG. 3: The angular power spectrum estimated from each hemisphere: the figure at the bottom is plotted, after binned with $\Delta l = 40$.

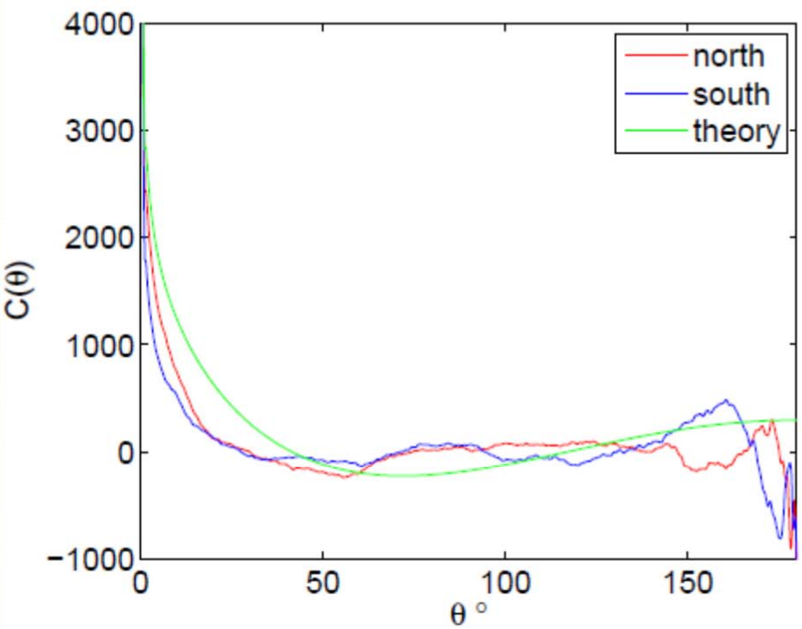



FIG. 5: The angular correlation

# Dipole Modulation

- *Gordon et al 2005*:

$$\mathbf{d} = (1 + A\, p \cdot n)\mathbf{s}_{\rm iso} + \mathbf{n} \equiv \mathbf{M}\mathbf{s}_{\rm iso} + \mathbf{n}$$

See also Firouzjahi talk July 29

- A- dipole amplitude, ***p*** – dipole direction. **n** – noise, $\mathbf{s}_{\rm iso}$ – an isotropic CMB field
- A=const and scale independent simple phenomenological model – tension with observations of asymmetry at small scales – works for l<100

# Possible explanations: WMAP

The Astrophysical Journal Supplement Series, 192:17 (19pp), 2011 February 1 doi:10.1088/0067-0049/192/2/17


SEVEN-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP**) OBSERVATIONS: ARE THERE COSMIC MICROWAVE BACKGROUND ANOMALIES?

C. L. Bennett[1], R. S. Hill[2], G. Hinshaw[3], D. Larson[1], K. M. Smith[4], J. Dunkley[5], B. Gold[1], M. Halpern[6], N. Jarosik[7], A. Kogut[3], E. Komatsu[8], M. Limon[9], S. S. Meyer[10], M. R. Nolta[11], N. Odegard[2], L. Page[7], D. N. Spergel[4,12], G. S. Tucker[13], J. L. Weiland[2], E. Wollack[3], and E. L. Wright[14]

**NO ANOMALIES**

Evidence has been reported for a significant quadrupolar power asymmetry that does not appear to be cosmological in origin and most likely results from an incomplete propagation of beam asymmetries. A careful analysis will be a subject of future work.

ABSTRACT

A simple six-parameter ΛCDM model provides a successful fit to *WMAP* data. This holds both when the *WMAP* data are analyzed alone or in combination with other cosmological data. Even so, it is appropriate to examine the data carefully to search for hints of deviations from the now standard model of cosmology, which includes inflation, dark energy, dark matter, baryons, and neutrinos. The cosmological community has subjected the *WMAP* data to extensive and varied analyses. While there is widespread agreement as to the overall success of the six-parameter ΛCDM model, various "anomalies" have been reported relative to that model. In this paper we examine potential anomalies and present analyses and assessments of their significance. In most cases we find that claimed anomalies depend on posterior selection of some aspect or subset of the data. Compared with sky simulations based on the best-fit model, one can select for low probability features of the *WMAP* data. Low probability features are expected, but it is not usually straightforward to determine whether any particular low probability feature is the result of the a posteriori selection or non-standard cosmology. Hypothesis testing could, of course, always reveal an alternative model that is statistically favored, but there is currently no model that is more compelling. We find that two cold spots in the map are statistically consistent with random cosmic microwave background (CMB) fluctuations. We also find that the amplitude of the quadrupole is well within the expected 95% confidence range and therefore is not anomalously low. We find no significant anomaly with a lack of large angular scale CMB power for the best-fit ΛCDM model. We examine in detail the properties of the power spectrum data with respect to the ΛCDM model and find no significant anomalies. The quadrupole and octupole components of the CMB sky are remarkably aligned, but we find that this is not due to any single map feature; it results from the statistical combination of the full-sky anisotropy fluctuations. It may be due, in part, to chance alignments between the primary and secondary anisotropy, but this only shifts the coincidence from within the last scattering surface to between it and the local matter density distribution. While this alignment appears to be remarkable, there was no model that predicted it, nor has there been a model that provides a compelling retrodiction. We examine claims of a hemispherical or dipole power asymmetry across the sky and find that the evidence for these claims is not statistically significant. We confirm the claim of a strong quadrupolar power asymmetry effect, but there is considerable evidence that the effect is not cosmological. The likely explanation is an insufficient handling of beam asymmetries. We conclude that there is no compelling evidence for deviations from the ΛCDM model, which is generally an acceptable statistical fit to *WMAP* and other cosmological data.

# Possible explanations

PHYSICAL REVIEW D **75**, 123517 (2007)

## Extensions of the standard cosmological model: Anisotropy, rotation, and the magnetic field

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(Received 14 February 2007; published 26 June 2007)

We show that the difference between the theoretically expected and measured by WMAP amplitude of the quadrupole fluctuations of the cosmic microwave background (CMB) can be related to the impact of the anisotropic curvature of the homogeneous universe dominated by dark energy. In such a universe the matter expansion becomes practically isotropic just after the period of inflation, and only at small redshifts is the anisotropic expansion generated again by the small curvature $\Omega_K = 1 - \Omega_m - \Omega_\Lambda \leq 10^{-4}$. For such models the possible deviations from the parameters derived for the standard cosmological model are evidently negligible but the correlations of large scale perturbations and distortions of their Gaussianity are possible. Such models are also compatible with the existence of a homogeneous magnetic field and matter rotation which contribute to the low $\ell$ anisotropy and can be considered as "hidden parameters" of the model. Their influence can be observed as, for example, special correlations of small scale fluctuations and the Faraday rotation of the CMB and radiation of the farthest quasars. However, both the magnetic field and matter rotation also require modifications of the simple models of isotropic inflation, and they change the evolutionary history of the early Universe.

# Possible (Cosmological) Explanations Planck XXIII: Anisotropic Models

Of more interest to us is that the anomalies are genuinely cosmological in origin. In that context, obvious candidate models include those with simply or multi-connected topology. In a companion paper (Planck Collaboration XXVI 2013), a subset of such models are considered and the signatures of their specific correlation structures on the sky are searched for. However, no detections are found, but rather the scale of topology is limited to be of order the diameter of the last-scattering surface or greater. More interestingly, they reconsider Bianchi $VII_h$ models that were previously demonstrated to show statistical correlation with the *WMAP* data (Jaffe et al. 2005, 2006; Bridges et al. 2007; McEwen et al. 2013), albeit with parameters inconsistent with standard cosmological parameters. In this new analysis, the Bianchi parameters are physically coupled to the cosmological ones, yielding no evidence for a Bianchi $VII_h$ cosmology. However, as before, when treated simply as a template for

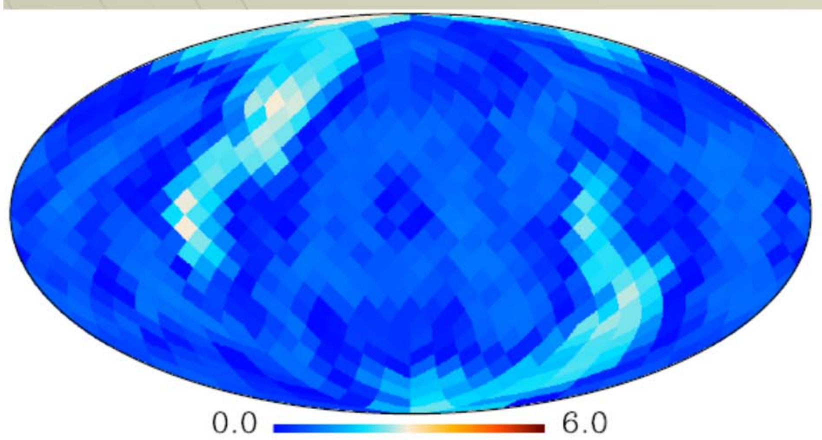
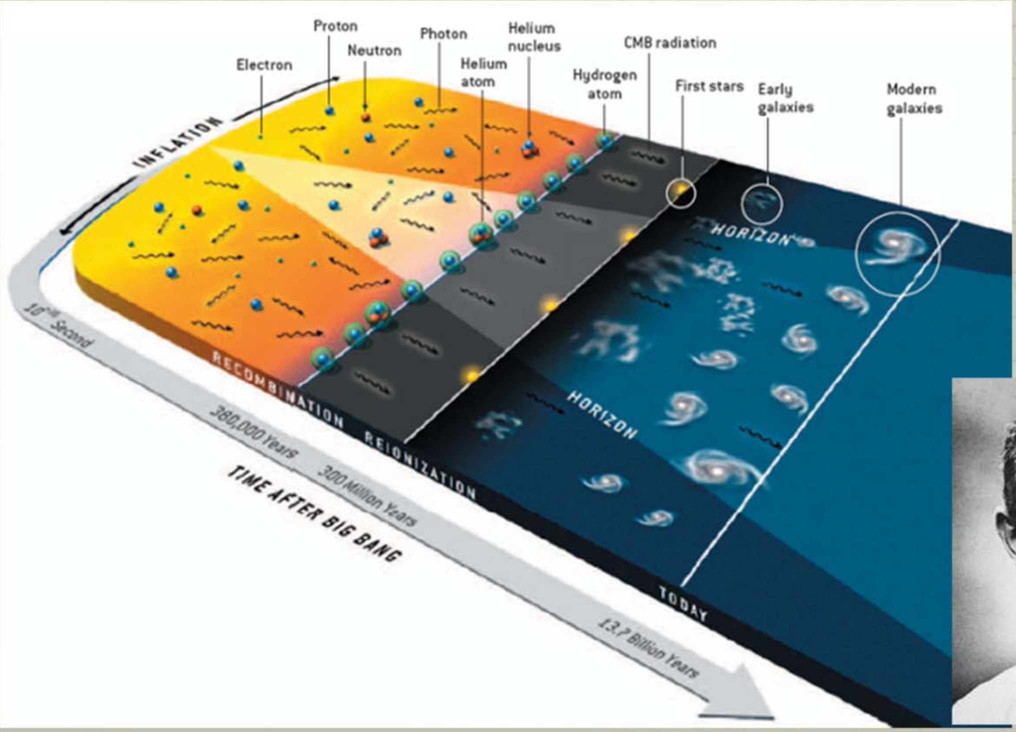



**Fig. 38.** Same as Fig. 24 but with the best fit Bianchi template subtracted from the SMICA map.

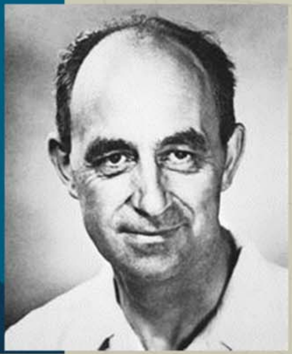
# Possible (Cosmological) Explanations
# Planck XXIII: Magnetic Field

The presence of primordial magnetic fields (PMFs) due to either pre- or post-recombination mechanisms could also provide a physical basis for some of the anomalies discussed in this paper. Specifically, PMFs with coherence scales comparable to the present day horizon could result in Alfvén waves in the early Universe that generate specific signatures on the sky

**F. Hoyle in Proc. "*La structure et l'evolution de l'Universe*" (1958)**




**E. Fermi "On the origin of the cosmic radiation", PRD, 75, 1169 (1949)**



- Inflation
- Phase transitions
- Supersymmetry
- String Cosmology
- Topological defects

# Cosmological Magnetic Field Sourced Perturbations

- Scalar mode (fast and slow magnetosound waves)
- Vector mode (Alfven waves)
- Tensor mode (gravitational waves)

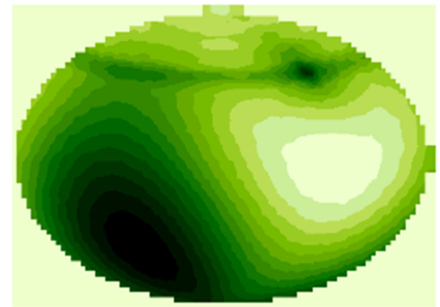
$$G_{ik} = 8\pi G T_{ik}$$

- If present before recombination primordial magnetic field might leave imprints on CMB fluctuations

# Alfven waves (vector mode)

*Durrer, Kahniashvili & Yates 1998*

*Kahniashvili, Lavrelashvili & Ratra 2008*



- Euler equations for photons and baryons (Lorentz force L(x))

$$\begin{aligned} \dot{\boldsymbol{\Omega}}_\gamma + \dot{\tau}(\mathbf{v}_\gamma - \mathbf{v}_b) &= 0, \\ \dot{\boldsymbol{\Omega}}_b + \frac{\dot{a}}{a}\boldsymbol{\Omega}_b - \frac{\dot{\tau}}{R}(\mathbf{v}_\gamma - \mathbf{v}_b) &= \frac{\mathbf{L}^{(V)}(\mathbf{x})}{a^4(\rho_b + p_b)}, \end{aligned}$$

$\Omega=\Omega_0 \sin(k\mu\, v_A\eta)$

$$(1+R)\dot{\boldsymbol{\Omega}} + R\frac{\dot{a}}{a}\boldsymbol{\Omega} = \frac{\mathbf{L}^{(V)}(\mathbf{x})}{a^4(\rho_\gamma + p_\gamma)}.$$

- Alfven wave equation (tight coupling $v_\gamma=v_b$)

$$\langle a^\star_{l-1,m} a_{l+1,m'} \rangle = D^{(m,m')}_{l-1,l+1}(\Theta_B, \phi_B),$$

# Homogeneous Magnetic Field CMB Signatures

*Kahniashvili et al. 2008*

$$\frac{\Delta T}{T}(\eta_0, \mathbf{n}) \simeq \mathbf{v}(\eta_{\rm dec}) \cdot \mathbf{n} - \mathbf{V}(\eta_{\rm dec}) \cdot \mathbf{n} = \mathbf{\Omega}_0 \cdot \mathbf{n}$$

$$\begin{aligned}\left\langle \frac{\Delta T}{T}(\mathbf{n}) \frac{\Delta T}{T}(\mathbf{n}') \right\rangle &= \frac{1}{2} \sum_{l,l'} \sum_{m,m'} [\langle a^\star_{lm} a_{l'm'} \rangle Y^\star_{lm}(\mathbf{n}) Y_{l'm'}(\mathbf{n}') + \langle a_{lm} a^\star_{l',m'} \rangle Y_{lm}(\mathbf{n}) Y^\star_{l'm'}(\mathbf{n}')] \\ &= \left\langle \frac{\Delta T}{T}(\mathbf{n}) \frac{\Delta T}{T}(\mathbf{n}') \right\rangle \Bigg|^{l=l'} + \left\langle \frac{\Delta T}{T}(\mathbf{n}) \frac{\Delta T}{T}(\mathbf{n}') \right\rangle \Bigg|^{l=l' \pm 2},\end{aligned}$$

$$\begin{aligned}\left\langle \frac{\Delta T}{T}(\mathbf{n}) \frac{\Delta T}{T}(\mathbf{n}') \right\rangle \Bigg|^{l=l' \pm 2} &= \frac{1}{4\pi} \sum_l \frac{2(l+2)(l-1)}{2l+1} \\ &\times \left\{ 2(\mathbf{b}\cdot\mathbf{n})(\mathbf{b}\cdot\mathbf{n}')P''_l - \frac{1}{2}[(\mathbf{b}\cdot\mathbf{n})^2 + (\mathbf{b}\cdot\mathbf{n}')^2][3P'_l(x) + 2(\mathbf{n}\cdot\mathbf{n}')P''_l] + P'_l \right\} I_d^{(l-1,l+1)},\end{aligned}$$

# CMB Anomalies vs. Magnetic Fields

Mon. Not. R. Astron. Soc. **389,** 1453–1460 (2008) doi:10.1111/j.1365-2966.2008.13683.x

## Can a primordial magnetic field originate large-scale anomalies in *WMAP* data?

A. Bernui[1★] and W. S. Hipólito-Ricaldi[2★]

[1] *Instituto Nacional de Pesquisas Espaciais, Divisão de Astrofísica, Av. dos Astronautas 1758, 12227-010*
[2] *Universidade Federal do Espírito Santo, Departamento de Física, 29060-900 – Vitória, ES, Brazil*



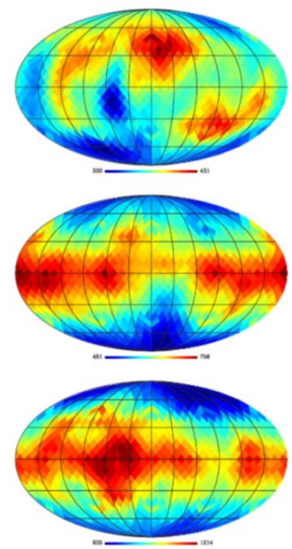


**Figure 2.** These sky maps, in Galactic coordinates and from top to bottom panel, represent the mean of 100 $\sigma$-maps–MC obtained from a similar number of MC computed considering three cases: $B_0 = 0$, 10, and 30 nG, respectively, and with the magnetic field pointing in the SGP–NGP direction, which means that the equator is the preferred plane. Note that for $B_0 \neq 0$, the region around the equator concentrates strong angular correlations, here

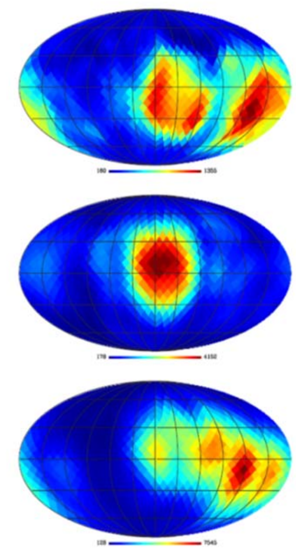
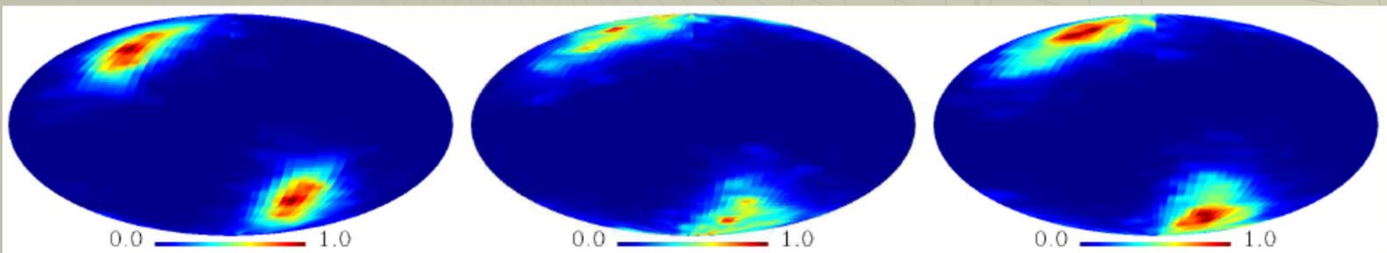


**Figure 3.** For illustration, we show three $\sigma$-maps: the $\sigma$-map–*WMAP* from the ILC-5 yr CMB map (top panel), and two $\sigma$-maps–MC having large dipole term $S_1$ one obtained from a MC map with $B_0 = 10$ nG (middle panel) and the other obtained from a MC map with $B_0 = 30$ nG (bottom panel).

## Cosmological Alfvén waves in the recent CMB data, and the observational bound on the primordial vector perturbation

Jaiseung Kim and Pavel Naselsky



# Magnetic Fields Characteristic Signatures

- Off-diagonal cross correlations
  - l’= l +/- 2
  - m’=m or m’=m +/-1

- An homogeneous magnetic field
- Stochastic magnetic field preserves isotropy and cannot be responsible for the CMB asymmetries

**Table A.1.** *Planck* constraints on the Alfvén wave amplitude $A_v v_A^2$.

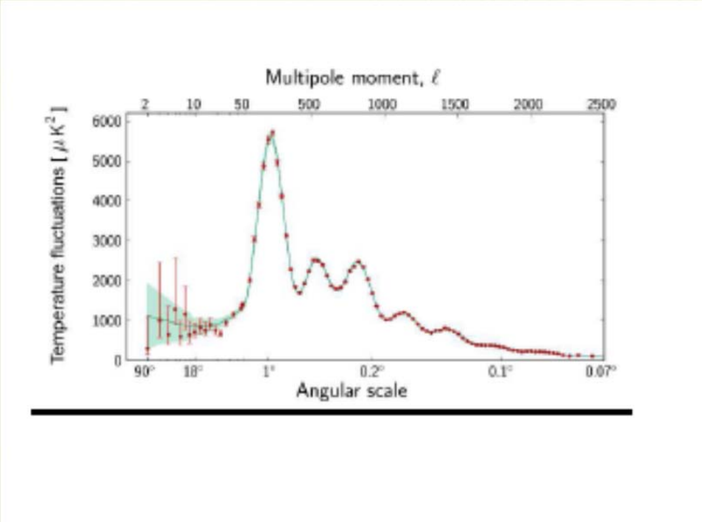
| Confidence Level | 68% | 95% | 99.7% |
|---|---|---|---|
| C-R .......... | $< 0.48 \times 10^{-9}$ | $< 1.01 \times 10^{-9}$ | $< 1.57 \times 10^{-9}$ |
| NILC .......... | $< 0.49 \times 10^{-9}$ | $< 1.00 \times 10^{-9}$ | $< 1.56 \times 10^{-9}$ |
| SEVEM ........ | $< 0.54 \times 10^{-9}$ | $< 1.13 \times 10^{-9}$ | $< 1.73 \times 10^{-9}$ |
| SMICA ........ | $< 0.47 \times 10^{-9}$ | $< 0.87 \times 10^{-9}$ | $< 1.29 \times 10^{-9}$ |

**No detection of l'=l+/-2 off diagonal cross correlations…**

**No significant magnetic field which might be responsible for the large scale anomalies**

# Naïve Consideration

- It seems that the CMB sky looks anomalous at large scales, while at small scales is in a very good agreement with the “standard” cosmological model




- Deviation from the standard scenario at large scales (order of Hubble horizon today)

- Recovering the standard cosmology at small scales

# Scale Dependent Dipole Modulation

- *Gordon et al 2005*:

$$\mathbf{d} = (1 + A\, p \cdot n)\mathbf{s}_{\text{iso}} + \mathbf{n} \equiv \mathbf{M}\mathbf{s}_{\text{iso}} + \mathbf{n}$$

- A(l)–scale dependent: *Hoftuft et al. 2009; Moss et al. 2011*
- Scale dependent off –diagonal cross correlations l'=l+/- 1
  - Best fit from data
  - Theoretical motivation?

**FLRW – SMALL SCALES**
**ANISOTROPIC MODEL – LARGE SCALES**

# Massive Gravity

- **Motivation:** Alternative explanation of accelerated expansion of the Universe
  - Massive graviton spin0 mode mimics the presence of Dark Energy

- **Theory (dRGT):**

*deRham, Gabadadze, Tolley, 2010 (1011.1232)*

- **Massive Cosmologies**

*D'Amico, de Rham, Dubovsky,Gabadadze, Pirtskhalava, Tolley, 2011 (1108.5231)*

# Massive Gravity (brief overview)

- ***Fierz & Pauli, 1939***
  - Non-zero graviton mass
- ***van Dam & Veltman, 1970; Zakharov, 1970***
  - vDVZ discontinuity (GR is not recovered in m->0 limit)
- ***Vainstein 1972***
  - vDVZ discontinuity disappears if we take into account non-linear interactions of the scalar mode
- ***Boulware & Deser, 1972***
  - Sixth degree of freedom - ghost

# Ghost-Free Massive Gravity (dRGT) Massive Cosmologies

- **dRGT** – 4D covariant, nonlinear, ghost free at decoupling limit at all orders
  - **m ~ $H_0$**
- **Vainstein radius**

$$r_* = \left(\frac{r_g}{m^2}\right)^{1/3} = \left(\frac{\rho}{3M_{\rm Pl}^2 m^2}\right)^{1/3} R,$$

- **Cross-over density**

$$\rho_{\rm co} \equiv 3M_{\rm Pl}^2 m^2.$$

- **Two limits of the Universe expansion**

  *D'Amico et al. 2011 (1108.5231)*
  - high densities
    - Isotropic FLRW
  - low densities
    - Non-isotropic

# Massive Cosmologies

- **Two metrics**
  - Physical (Einstein-Hilbert action)

$$I = I_{EH,\Lambda}[g] + I_{\mathrm{matter}}[g,\, \psi] + I_{\mathrm{mass}}[g^{-1} f]$$

$$I_{RH,\Lambda}[g] = \frac{M_{Pl}}{2} \int d^4 \sqrt{-g}\, (R - 2\,\Lambda)$$

  - Fiducial Stuckelberg fields

$$f_{\mu\nu} \equiv \bar{f}_{AB}(\phi^C)\, \partial_\mu \phi^A\, \partial_\nu \phi^B$$

$$I_{\mathrm{mass}}[g^{-1} f] = M_p^2\, m_g^2 \int d^4x\, \sqrt{-g}\, (\mathcal{L}_2 + \alpha_3\, \mathcal{L}_3 + \alpha_4\, \mathcal{L}_4)$$

- **Background:**
  - after the Hubble length scale order of 1/m – anisotropic metric solutions
- **Stability of perturbations**
  - Vanishing or negative sign kinetic terms

# Massive Cosmologies: Perturbations

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

**Nonlinear stability of cosmological solutions in massive gravity**

Antonio De Felice,[a,b] A. Emir Gümrükçüoğlu,[c] Chunshan Lin[c] and Shinji Mukohyama[c]

- 5 healthy modes recovered when the isotropy has been broken in the physical metric.

$$g^{(0)}_{\mu\nu}\, dx^\mu\, dx^\nu = -N^2(t)dt^2 + a^2(t)\left(e^{4\,\sigma(t)}\, dx^2 + e^{-2\,\sigma(t)}\,\delta_{ij}\, dy^i\, dy^j\right) .$$

- *De Felice et al. 2013 (1303.4154)*

  - Bianchi I model
  - Fiducial - FLRW

$$f_{\mu\nu} = -n^2(\phi^0)\partial_\mu\phi^0\partial_\nu\phi^0 + \alpha^2(\phi^0)\left(\partial_\mu\phi^1\partial_\nu\phi^1 + \delta_{ij}\partial_\mu\phi^i\partial_\nu\phi^j\right)$$

# Massive Cosmologies: Perturbations

*De Felice et al. 2013 (1303.4154)*

## 4 Perturbations

In this section, we calculate the action quadratic in perturbations around the metric (3.2). The most general set of perturbations around the axisymmetric Bianchi type-I are given by [30]

$$g^{(1)}_{\mu\nu} = \begin{pmatrix} -2\,N^2\,\Phi & a\,e^{2\,\sigma}\,N\,\partial_x\chi & a\,e^{-\sigma}\,N\,(\partial_i B + v_i) \\ & a^2\,e^{4\,\sigma}\psi & a^2\,e^{\sigma}\,\partial_x\,(\partial_i\beta + \lambda_i) \\ & & a^2\,e^{-2\,\sigma}\left[\tau\,\delta_{ij} + \partial_i\partial_j E + \partial_{(i}h_{j)}\right] \end{pmatrix}\,, \tag{4.1}$$

where $\partial_{(i}h_{j)} \equiv (\partial_i h_j + \partial_i h_j)/2$ and $\partial^i v_i = \partial^i\lambda_i = \partial^i h_i = 0$. Note that, since the $y$–$z$ plane is Euclidean, the indices $i, j$ are raised and lowered with $\delta^{ij}$ and $\delta_{ij}$. Similarly, we decompose the perturbations of the Stückelberg fields (3.3) as

$$\pi^A = \left(\pi^0,\ \partial_1\pi^1,\ \partial^i\pi + \pi^i\right)\,, \tag{4.2}$$

Nevertheless, the anisotropic FLRW solution studied here is the first calculable example of a stable cosmology in the dRGT theory of nonlinear massive gravity. One of technical advantages of this solution is that the spatial homogeneity and the SO(2) invariance of the axisymmetric background allows decoupling between even and odd sectors at the linear order.

# Some Extensions of dRGT

*De Felice et al. (1304.0484)*

- Existence of isotropic (for physical metric) solutions?
  - Anisotropy is accommodated within the fiducial metric (can be tested only through perturbations)

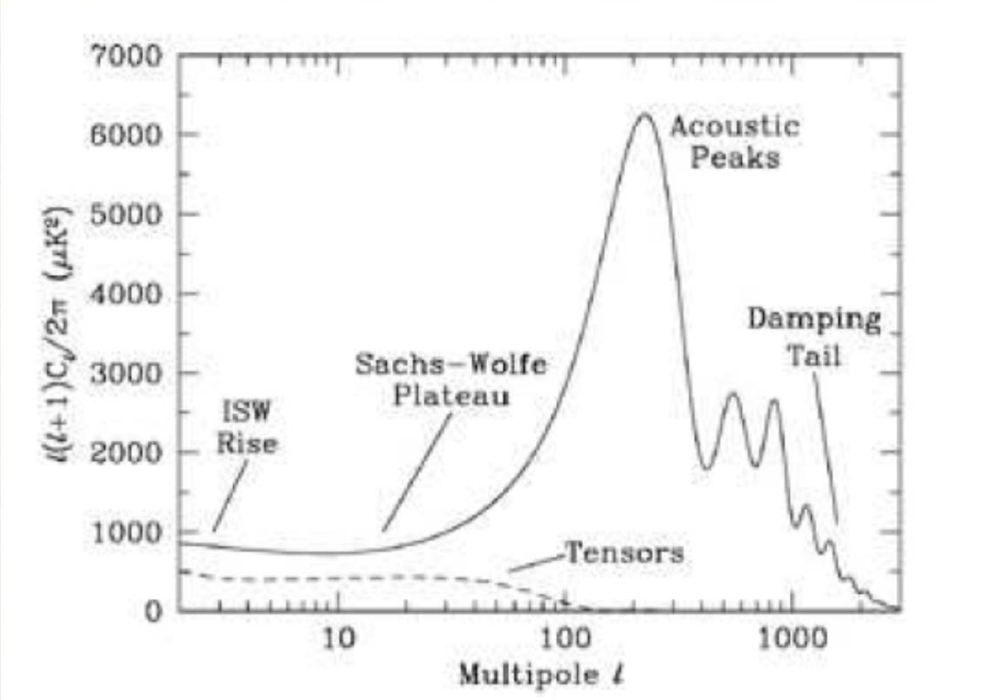
- Quasi-Dilaton
  - *D'Amico, Gabadadze, Hui, Pirtskhalava, 2012 (1206.4253)*

- Mass varying theory
  - *Huang, Piao, Zhou, 2012 (1206.5678)*

# Massive Gravity: Imprints on CMB?

- At high densities GR is recovered and perturbations look like as LCDM
- Late time evolution –ISW
- Suppression exp(-mR)?

- Anisotropic Bianchi model(s) ONLY at large scales




$$\frac{\Delta T}{T}(\vec{n}) \approx \phi_e(\vec{n}) + \int_e^o \frac{\partial \phi}{\partial t} dt + \vec{n}\cdot(\vec{v}_o - \vec{v}_e) + \left(\frac{\Delta T}{T}(\vec{n})\right)_e$$

# Conclusions

- Are large scale anomalies physical?
  - Cosmological origin?
- If yes do we see new physics at large scales?
  - Early Universe
  - Late time

- Magnetic field explanation – problematic
  - Non-gaussianity
  - Non observations of l'=l+/- 2 signal
- Massive gravity manifestation?
  - CMB fluctuations formation
  - CMB Polarization

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