# Primordial Magnetic Fields and CMB Anomalies

(work in progress)

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# Outline

1. CMB anomalies.

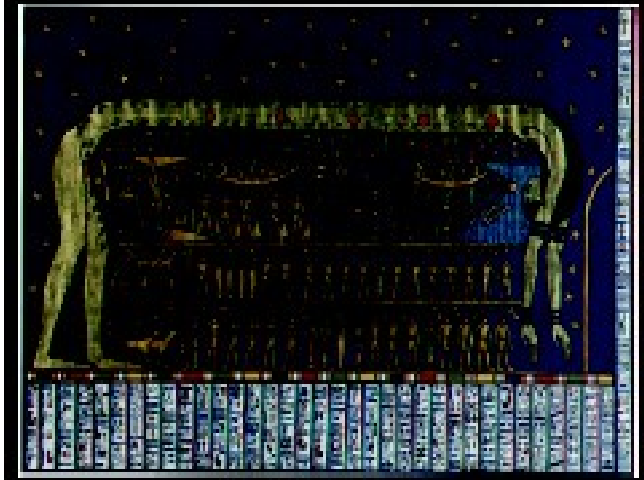
2. Possible causes.

3. Effects of Primordial Magnetic Fields on CMB.

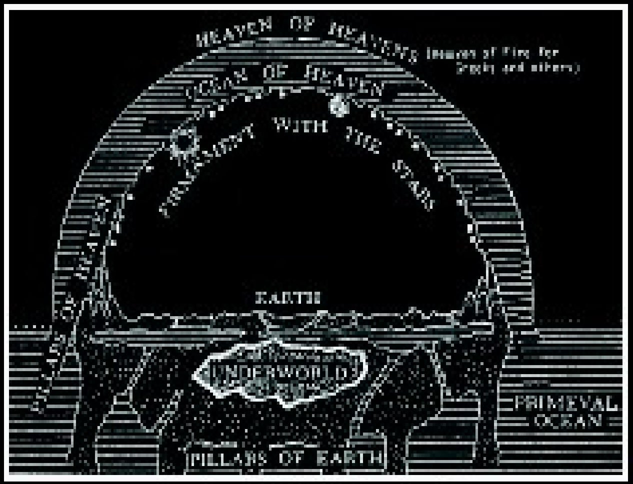
4. Preliminary results.

5. Conclusions.

# Old cosmological Models



Ancient Egypt




Ancient Middle East

1998-2020

ΛCDM model (?)

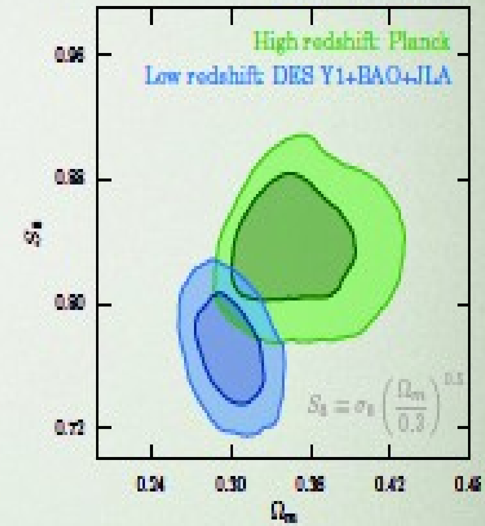
Dark Ages (and Kansas today)

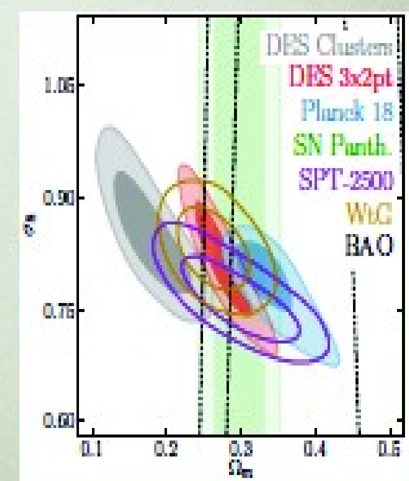

Ancient South Asia

# Tensions in the ΛCDM model

- high- vs low-$z$ $\sigma_8$-$\Omega_m$ constraints: clusters, weak lensing
- CMB anomalies: low-$\ell$, hem. anisotropies, …
- small scale CDM problems: cusps, too big to…
- **high- vs low-$z$ $H_0$ measurements**

DES 1708.01530



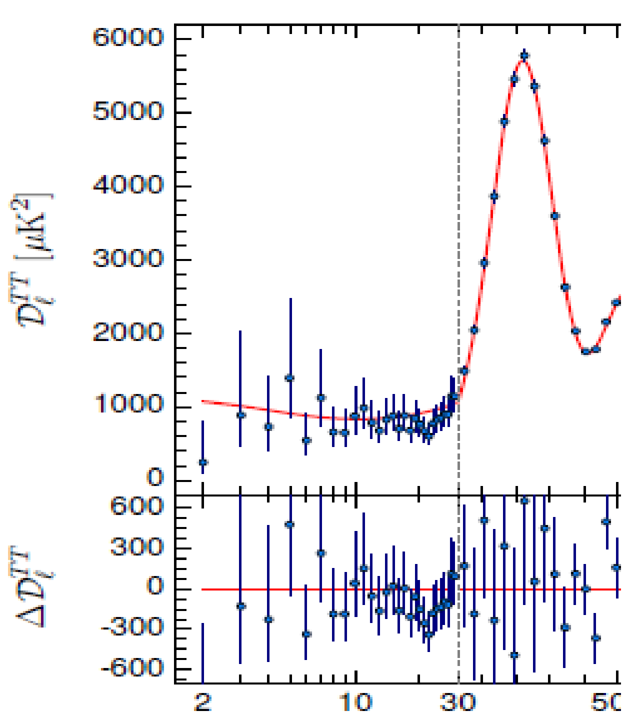



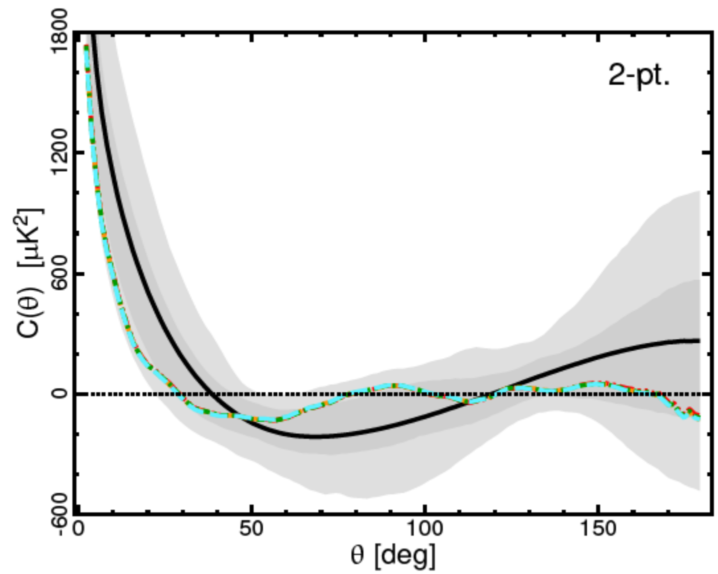

DES 2002.11124

# 1. CMB Anomalies

- Several unexpected features were observed in CMB data at large angular scales (WMAP, Planck, COBE).

**Low variance and lack of correlation on large angular scales**




Planck2018 (1906.02552)

$$C(\theta) = \frac{1}{4\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\cos\theta)$$

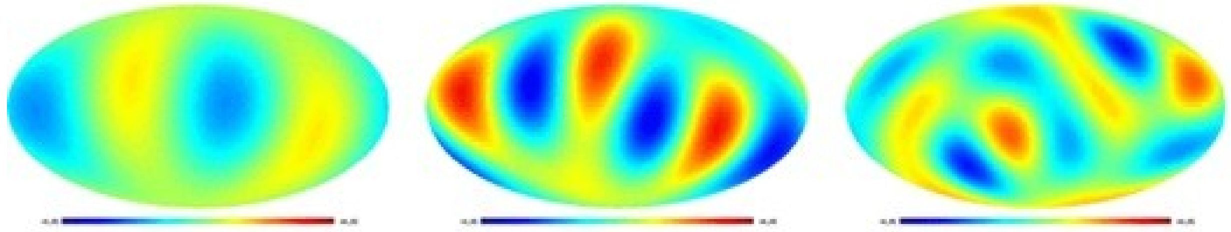
- Variance, skewness and kurtosis (Planck)

- < 0.5 % p-value

## Planarity and Alignment of the lowest multipole moments.

- In LCDM temperature anisotropies have random phases

- In harmonic space, orientations and shapes of the multipole moments are uncorrelated.

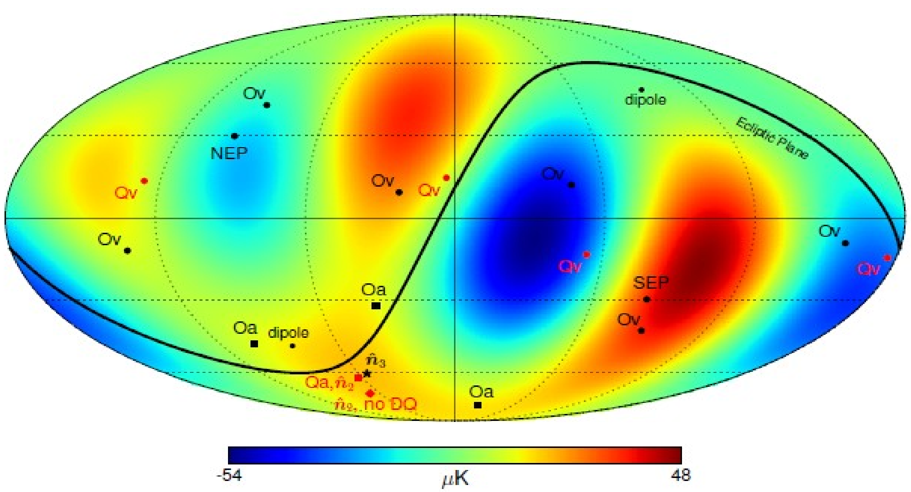


$\ell = 2$ $\ell = 3$ $\ell = 4$

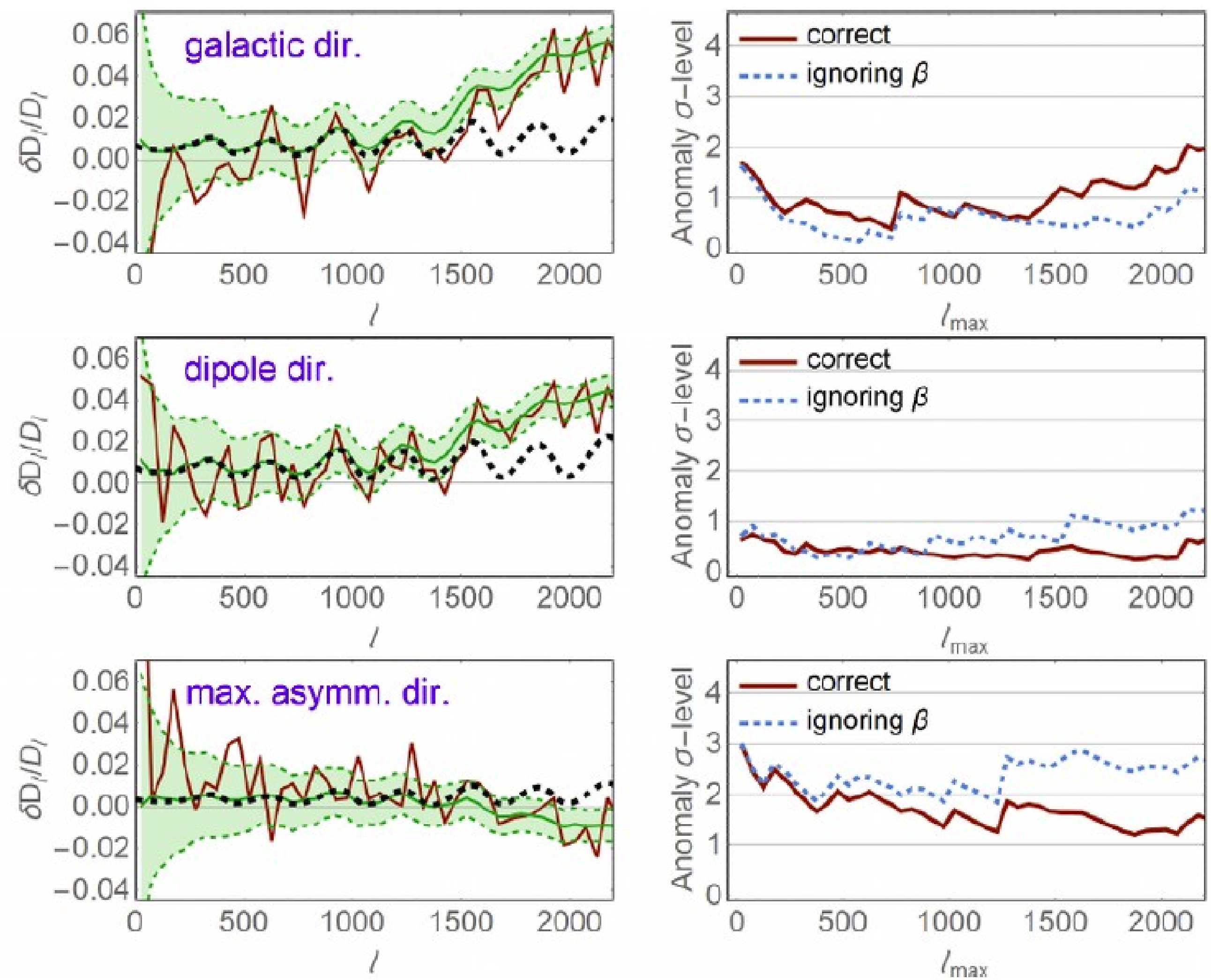
- The octupole is somewhat planar, $p < 5\%$.

- The normal to the quadrupole plane is aligned to the normal to the octupole plane, $p < 1{,}5\%$

- Quadrupole and octupole plane Is ortogonal to the Ecliptic plane, $2\% < p < 4\%$



## Hemispherical power asymmetry




$$(l, b) = (230°, -16°) \pm 24°$$

- p-value < 1%

- Preference for odd parity modes (p-value < 1%),  large could spot in the southern hemisphere (p-value < 1,8%)

Dominik J. Schwarz, Craig J. Copi, Dragan Huterer,
Glenn D. Starkman, Class.Quant.Grav. 33 (2016) no.18, 184001

| feature | p-value | data | reference |
|---|---|---|---|
| in angular space | | | |
| low variance ($N_{\rm side} = 16$) | $\leq 0.5\%$ | Planck 15 | Tab. 12 [7] |
| 2-pt correlation $\chi^2(\theta > 60^\circ)$ | $\leq 3.2\%$ | Planck 15 | Tab. 14 [7] |
| 2-pt correlation $S_{1/2}$ | $\leq 0.5\%$ | Planck 15 | Tab. 13 [7] |
| 2-pt correlation $S_{1/2}$ | $\leq 0.3\%$ | Planck 13 & | |
| | | WMAP 9yr | Tab. 2 [31] |
| 2-pt correlation $S_{1/2}$ (larger masks) | $\leq 0.1\%$ | Planck13 | Tab. 2 [31] |
| | $\leq 0.1\%$ | WMAP 9yr | [31, 32] |
| hemispherical variance asymmetry | $\leq 0.1\%$ | Planck 15 | Tab. 20 [7] |
| cold spot | $\leq 1.0\%$ | Planck 15 | Tab. 19 [7] |
| in harmonic space | | | |
| quadrupole-octopole alignment | $\leq 0.5\%$ | Planck 13 | Tab. 7 [33] |
| $\ell = 1, 2, 3$ alignment | $\leq 0.2\%$ | Planck 13 | Tab. 7 [33] |
| odd parity preference $\ell_{\max} = 28$ | $< 0.3\%$ | Planck 15 | Fig. 20 [7] |
| odd parity preference $\ell_{\max} < 50$ (LEE) | $< 2\%$ | Planck 15 | Text [7] |
| dipolar modulation for $\ell = 2 - 67$ | $\leq 1\%$ | Planck 15 | Text [7] |

- Do the anomalies are independent? Maybe 3 of them (p $\sim 10^{-5}$ )

# Breaking Statistical Isotropy

- In LCDM, CMB is supossed to be Gaussian and Statisically isotropic. i.e multipolar coefficients are statistically independent (correlation matrix is diagonal)

$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_\ell$$

- All information is in the power spectrum and 2PCF.

$$P(\mathrm{a}) = \frac{1}{\sqrt{(2\pi)^{3(l_{max}+1)^2} det(\mathrm{M})}} e^{-\frac{1}{2}\mathrm{a}^\dagger \mathrm{M}^{-1} \mathrm{a}} \qquad \mathbf{a} = \begin{pmatrix} a^T_{lm} \\ a^E_{lm} \\ a^B_{lm} \end{pmatrix}$$

- Anomalies are related to Violation of Statistical Isotropy (correlation matrix is not diagonal anymore)

- Are necessary more estimators.

## 2. Possible Causes for Violation of Statistical Isotropy

- Residual Foregrounds:
  - Solar System emissions
  - Milky Way emissions
  - Contamination by Sunyaev-Zeldovich effect
- Cosmological:
  - Kinetic effects ( Earth's motion with respect to CMB)
  - Local large scale structure
  - Broken scale invariance
  - Broken isotropy in Early Universe
  - Topology
  - Primdordial Magnetic Fields....

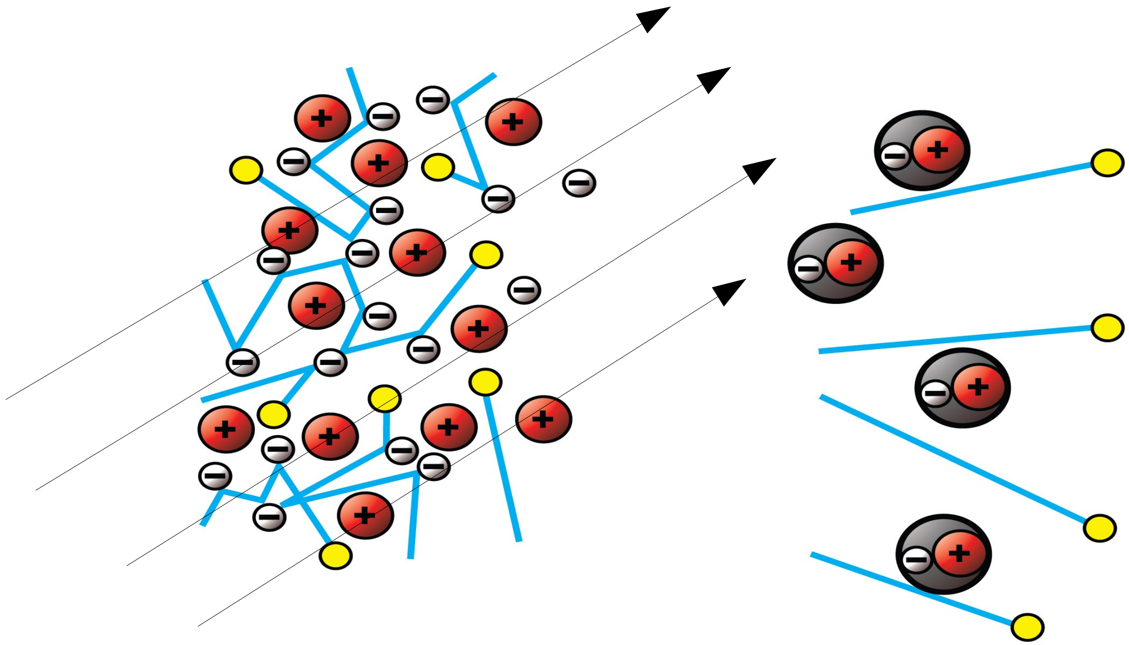
**Why Primordial Magnetic Fields?**

- There is observational evidence for the presence of large-scale intergalactic magnetic Fiels, within clusters of galaxies ( $\mu G$ )

- Amplification of Primordial Magnetic Fields (nG) appeared in early times?

- Assumption: There exists a primordial homogeneous magnetic field (nG)

- Recombination epoch



# 3. Effects of the Magnetic Fields in CMB

- Speed of sound and Acoustic Oscillations:

$$c_s^2 \longrightarrow c_s^2 + v_{\mathrm{A}}^2 \cos^2\theta \qquad v_{\mathrm{A}}^2 = \frac{B_0^2}{4\pi(\rho+p)}$$

Adams J., Danielsson U. H., Grasso D., Rubinstein H., 1996, Phys. Lett. B, 253, 388

- Induced vector perturbations and Sachs Wolfe effect corrections

$$\frac{\delta T}{T}^{\mathbf{B}}(\hat{n},k) \approx \hat{n}\cdot\vec{v}_0\, v_A\, k\, t_{\mathrm{dec}} \cos\theta\,.$$

Chen G., Mukherjee P., Kahniashvili T., Ratra B., Wang Y., 2004, ApJ, 611, 655

- In harmonic space

$$\langle a_{\ell m} a^*_{\ell' m'}\rangle = \langle a_{\ell m} a^*_{\ell' m'}\rangle^{\Lambda\mathrm{CDM}} + \langle a_{\ell m} a^*_{\ell' m'}\rangle^{\mathbf{B}}$$

$$\langle a_{\ell m} a^*_{\ell' m'}\rangle^{\Lambda\mathrm{CDM}} = C_\ell^{\Lambda\mathrm{CDM}}\,\delta_{mm'}\,\delta_{\ell\ell'}$$

$$\langle a_{\ell m} a^*_{\ell' m'}\rangle^{\mathbf{B}} = \delta_{mm'}[\delta_{\ell\ell'} C^{\mathbf{B}}_{\ell m} + (\delta_{\ell+1,\ell'-1} + \delta_{\ell-1,\ell'+1}) D^{\mathbf{B}}_{\ell m}],$$

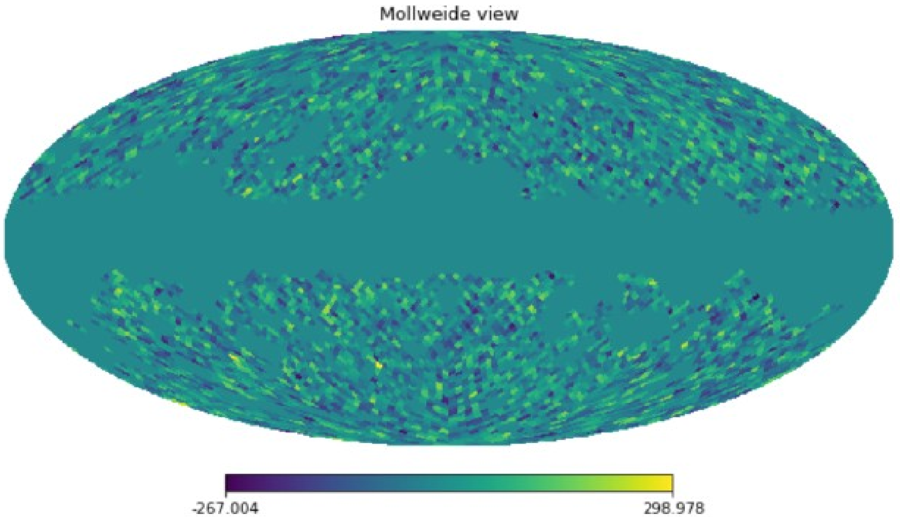
$$C^{\mathbf{B}}_{\ell m} = 27.12\times 10^{-16}\left(\frac{B_0}{1\,nG}\right)^4 \times \frac{2\ell^4 + 4\ell^3 - \ell^2 - 3\ell + 6m^2 - 2\ell m^2 - 2\ell^2 m^2}{(\ell+2)(\ell+1)\ell(\ell-1)(2\ell-1)(2\ell+3)}$$

$$\frac{D^{\mathbf{B}}_{\ell m}}{C^{\mathbf{B}}_{\ell m}} = \frac{9\pi}{32}\frac{\sqrt{(\ell+m+1)(\ell-m+1)(\ell+m)(\ell-m)}}{2\ell^4+4\ell^3-\ell^2-3\ell+6m^2-2\ell m^2-2\ell^2 m^2} \quad \frac{\sqrt{(2\ell-1)(2\ell+3)}(\ell-1)(\ell+2)}{(2\ell+1)}$$

# Simulated maps (Masked with U73)

- LCDM maps (Statistically isotropic)

$$P(\mathbf{a}) = \frac{1}{\sqrt{(2\pi)^{3(l_{max}+1)^2} det(\mathrm{M})}} e^{-\frac{1}{2}\mathrm{a}^{\dagger}\mathrm{M}^{-1}\mathrm{a}}$$




- Maps with B = 10 nG

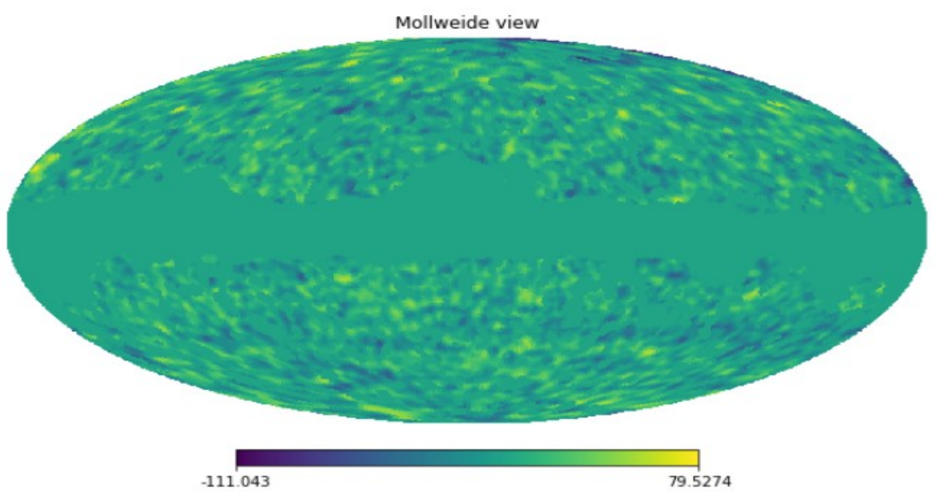
Cholesky decomposition

$$\mathbf{M} = \mathbf{L}^{\dagger}\,\mathbf{L}\,,$$

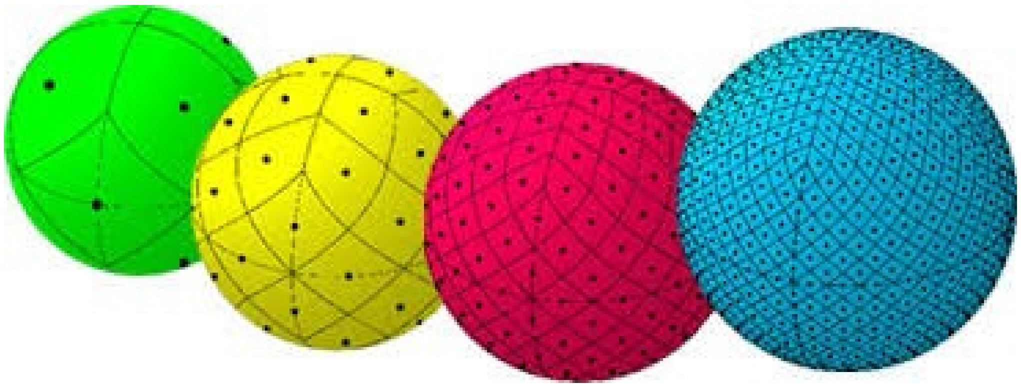
$$\mathbf{a} = \mathbf{L}\,\mathbf{z}$$

$$P(\mathbf{z}) = \frac{1}{\sqrt{(2\pi)^{3(l_{max}+1)^2}|det(\mathbf{L})|}} e^{-\frac{1}{2}\mathbf{z}^{\dagger}\mathbf{z}}\,,$$

B=10nG



## Robustness of low variance (in context of LCDM, Planck 2018)



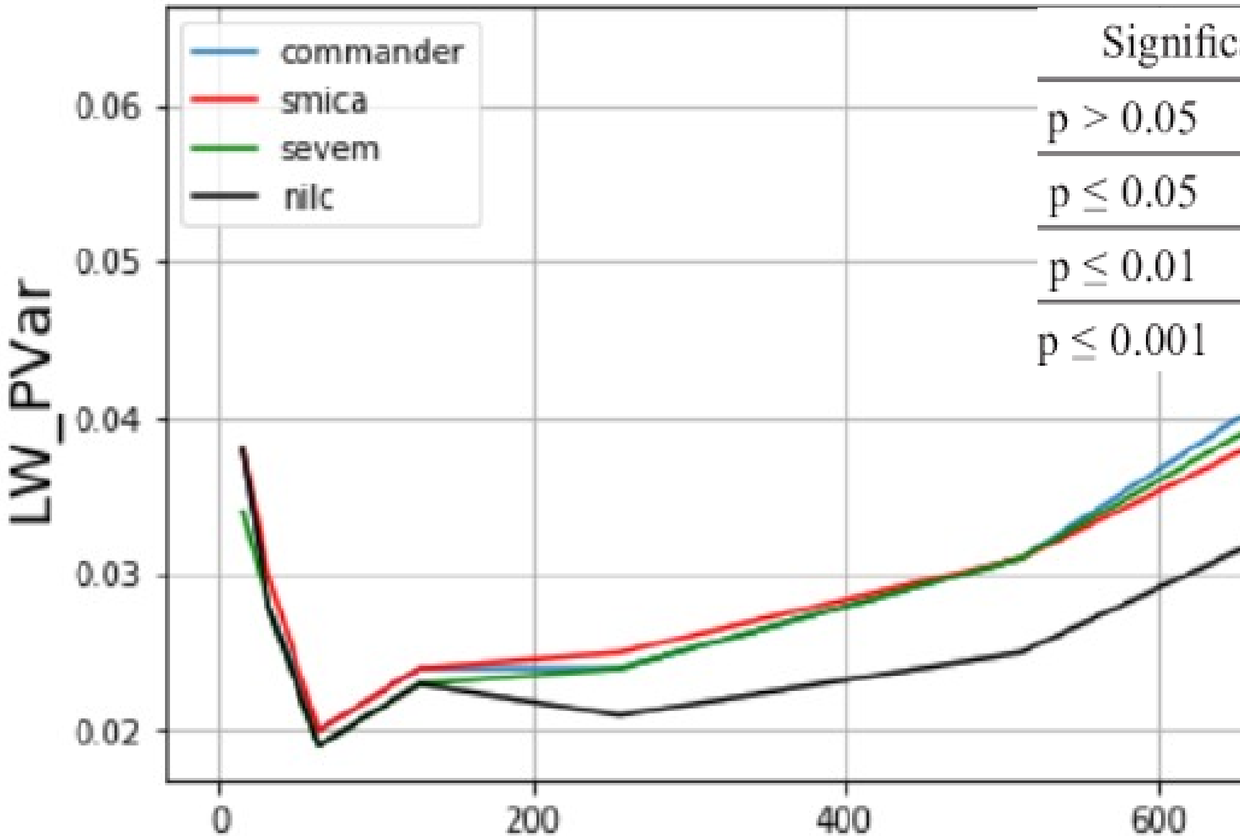
$N_{side} = 512$:

| Probability | | | |
|---|---|---|---|
| Method | Variance | Skewness | Kurtosis |
| Commander | 0.031 | 0.246 | 0.311 |
| Smica | 0.031 | 0.26 | 0.256 |
| SEVEM | 0.031 | 0.304 | 0.304 |
| NILC | 0.025 | 0.261 | 0.22 |

$N_{side} = 16$:

| Probability | | | |
|---|---|---|---|
| Method | Variance | Skewness | Kurtosis |
| Commander | 0.038 | 0.173 | 0.758 |
| Smica | 0.038 | 0.178 | 0.755 |
| SEVEM | 0.034 | 0.195 | 0.775 |
| NILC | 0.038 | 0.175 | 0.749 |

# Robustness of low variance (in context of LCDM)




| Significance Level | | Specification |
|---|---|---|
| $p > 0.05$ | | not significant |
| $p \leq 0.05$ | (5%) | significant |
| $p \leq 0.01$ | (1%) | very significant |
| $p \leq 0.001$ | (0.1%) | highly significant |

- $2\ \% < p < 4\ \%$

Consistent with Planck 2018

## What about CMB maps with Magnetic Fields?

# Conclusions

- There are unexpected features in CMB highly unlikely in context of LCDM. At least 3 of them independents.

- Those unexpected features are caused by broken of statistical isotropy

- There are several scenarios to violation of the statistical isotropy

- Primordial magnetic fields changes the speed of sound and acoustic oscillations, they induced vector perturbations <u>and Sachs Wolfe effect corrections.</u>

- In harmonic space, a magnetic field will induce correlations between different multipolar moments.

- 2019 Planck data present a low variance, 2%<p<4%. this results are robust