A Reassessment of Hemispherical Power Asymmetry in CMB Temperature Data from Planck PR4

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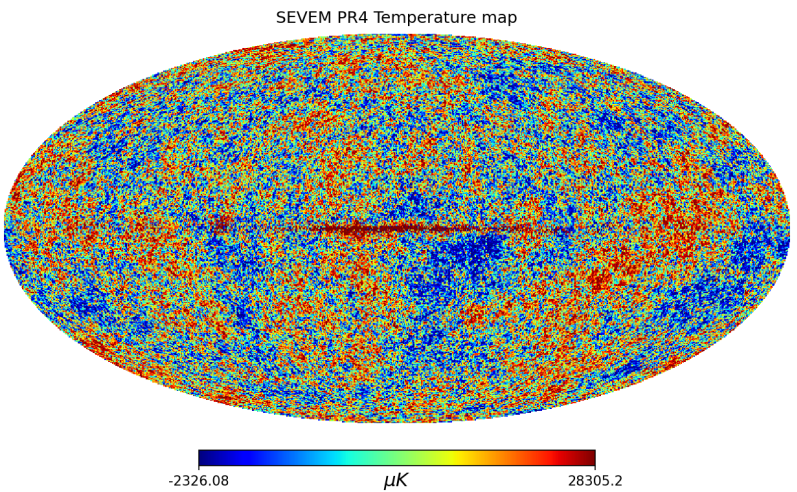
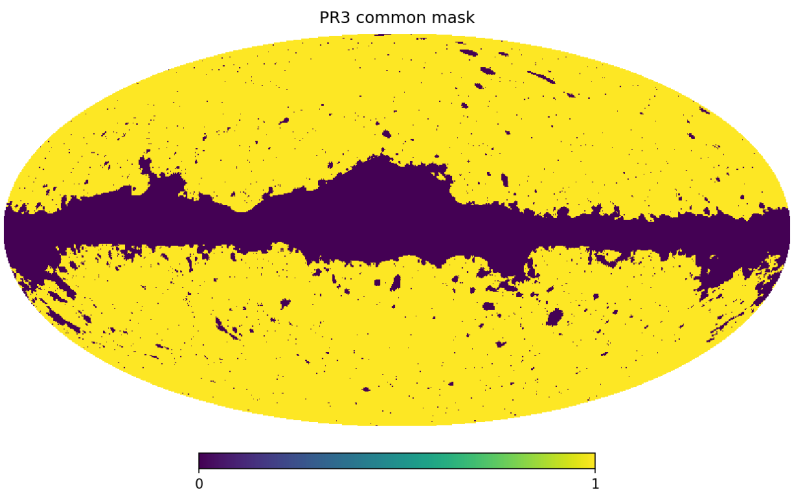
CMBR : Cosmic Microwave Background Radiation

- Relic from the early universe (z ~ 1080)
- Almost uniform in all direction (fluctuations ~ 10 ppm)
- Measured with utmost precision (COBE, WMAP, Planck)



Full sky “cleaned” (using SEVEM method) CMB map from Planck 2020 data release



Mask prescribed for use with Planck 2020 CMB data to avoid residual foreground contamination

HPA : Hemispherical Power Asymmetry

- Power in one hemisphere is larger than the other

  (Eriksen et.al,2004.)

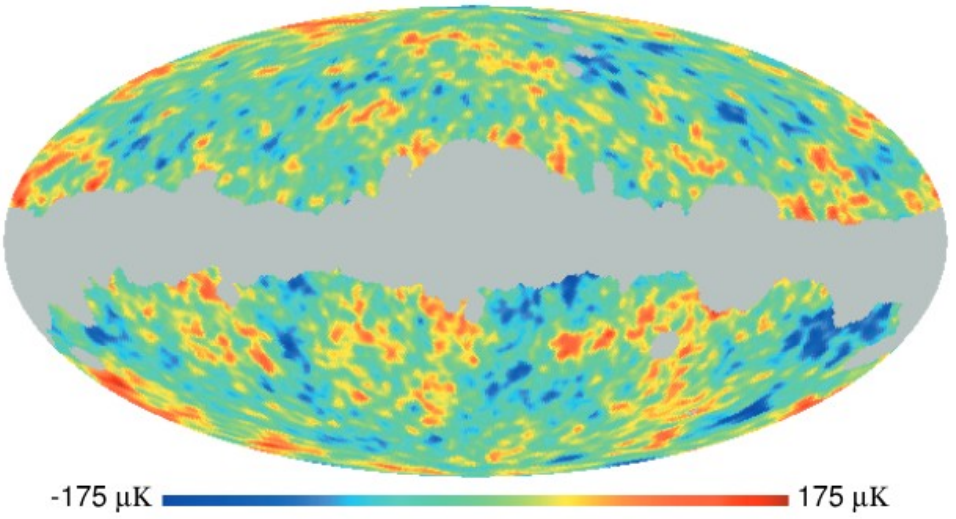
- Gordon et.al, 2005 suggested a dipole modulation model to explain HPA

$$\Delta T_{\rm obs}(\hat{n}) \equiv \Delta T_{\rm mod}(\hat{n}) = [1 + M(\hat{n})]\Delta T_{\rm iso}(\hat{n}) = (1 + \vec{d} \cdot \hat{n})\Delta T_{\rm iso}(\hat{n})$$

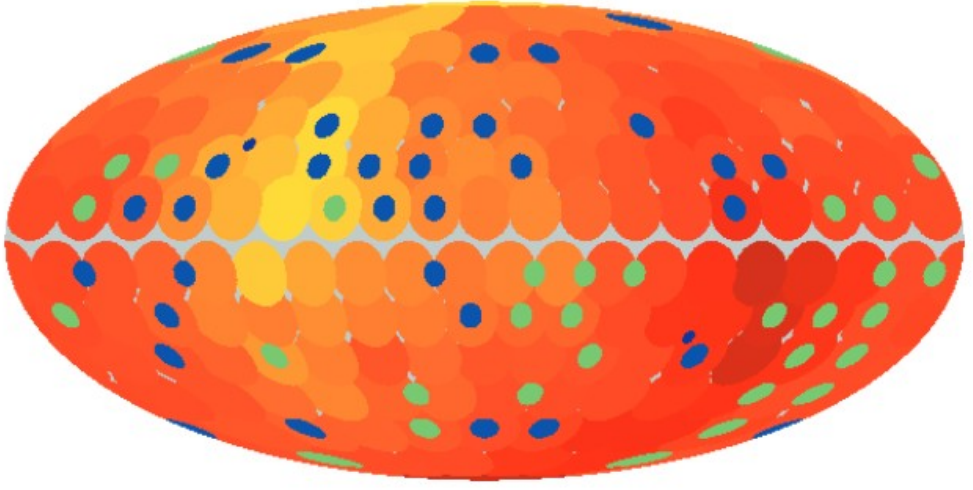
- Hoftuft et.al, 2009 : A = 0.072 , (l , b) = (224^{o}, -22^{o}) in Galactic coordinates

HPA / Eriksen et al., 2004

The low-resolution Q, V, and W band co-added WMAP map, to which the extended Kp0 mask has been applied.



Results from the local power Spectrum analysis



HEALPix :

Hierarchical, Equal Area, and iso-Latitude Pixelation of the sphere

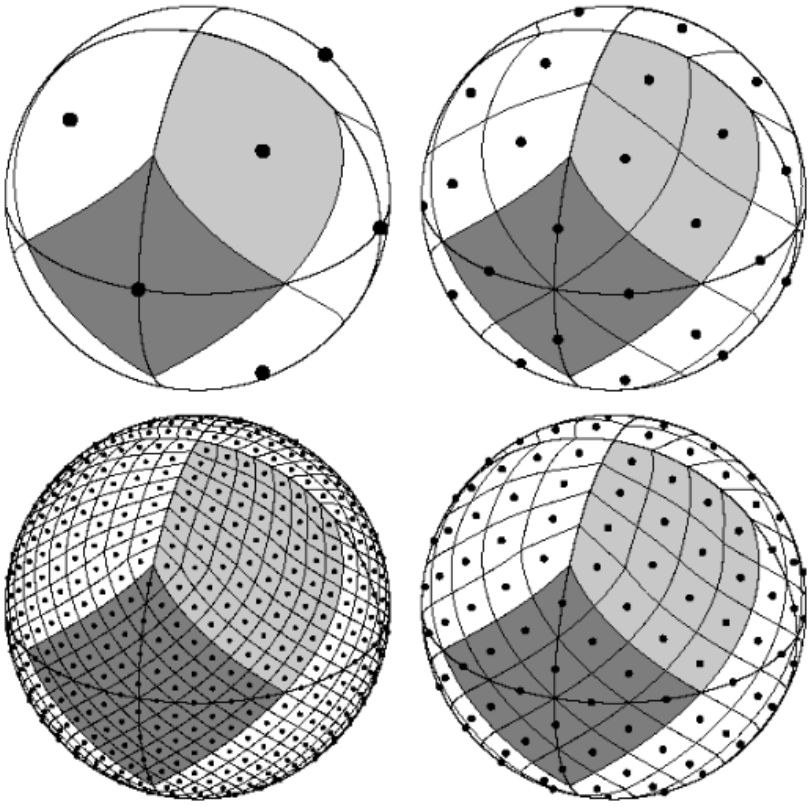


Fig ref. https://healpix.sourceforge.io

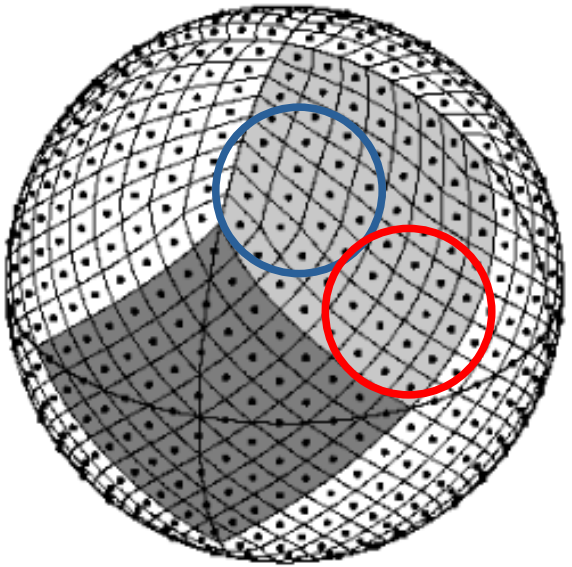
CMB is a signal on a sphere,
Digitized using HEALPix grid.

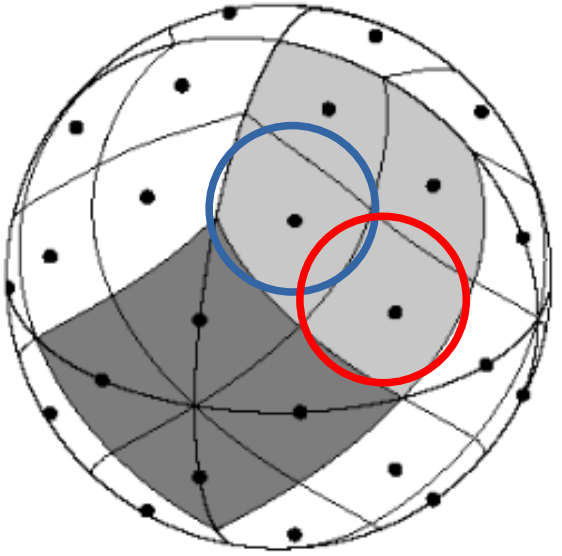
Nside	Npix=12*Nside^2
1	12
2	48
4	192
8	768
512	3 million
2048	50 million

LVE : Local Variance Estimator

$$\sigma_r^2(\hat{N}) = \frac{1}{N_p} \sum_{p \in r@\hat{N}} (T(p) - \bar{T}_r)^2 \,, \qquad \xi(\hat{N}) = \frac{\sigma^2_{\rm obs}(\hat{N}) - \langle \sigma^2_{\rm iso}(\hat{N}) \rangle}{\langle \sigma^2_{\rm iso}(\hat{N}) \rangle}$$

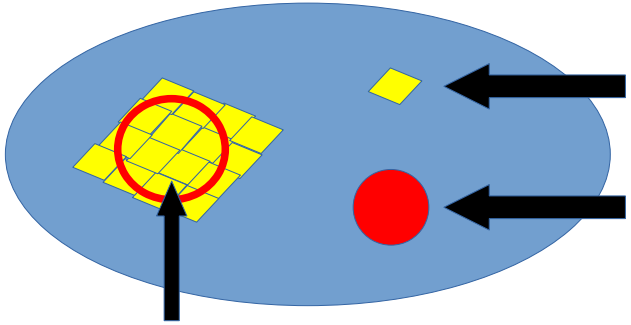
$$\sigma^2_{\rm obs}(\hat{N}) \approx \sigma^2_{\rm iso}(\hat{N})(1 + 2A\hat{\lambda} \cdot \hat{N}) \,. \qquad \xi(\hat{N}) \equiv 2A\hat{\lambda} \cdot \hat{N}$$





LVE : Local Variance Estimator

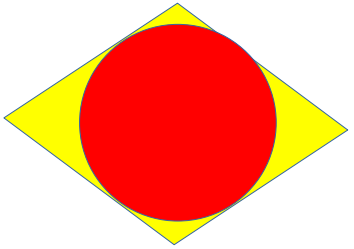
Input CMB Map at Nside = 2048



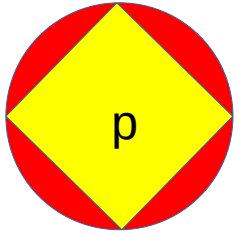
Quad shape pixel with size ~ 0.03°

Circulr disc of radius ‘r’

Pixels inside circular disc



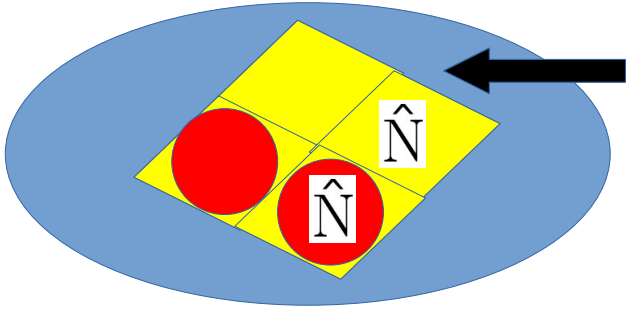
Inscribe



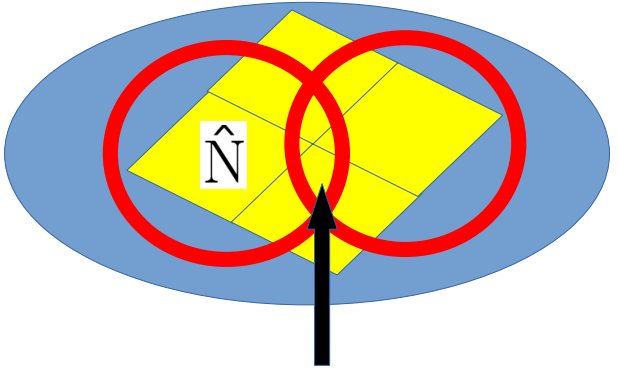
Circumscribe

$$\sigma_r^2(\hat{N}) = \frac{1}{N_p} \sum_{p \in r@\hat{N}} (T(p) - \bar{T}_r)^2 ,$$

LV Map at Nside = 16, 8, 4, 2



ps ~ 3.66°
Nside = 16



Overlapping information leading to correlation among the LV Map pixels

Reassessment : With varying nside

- LVE was first proposed by Akrami et.al, 2014 with fixed Nside
- Matching the disc radius with the LV helapix grid pixel size.

Disc Radius (r)	Nside	Pixel Size, PS	√2 x PS
1°	32	1.83°	2.59°
2°	16	3.66°	5.18°
4°, 6°	8	7.33°	10.36°
8°, 10°, 12°, 14°	4	14.66°	20.73°
16°, 18°, 20°, 24°, 28°, 32°, 36°, 40°, 50°, 60°, 70°, 80°, 90°	2	29.32°	41.46°

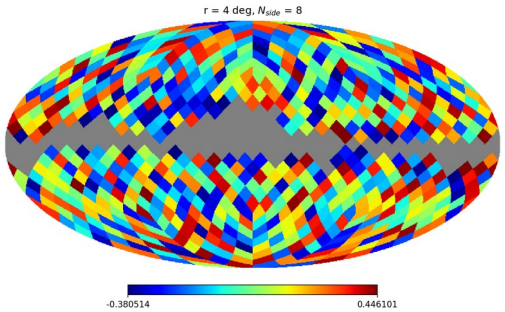
- We choose to limit using upto Nside = 2 (48 pixels) instead Nside = 1 (12 pixels and high coarse graining)

Normalized Variance Maps

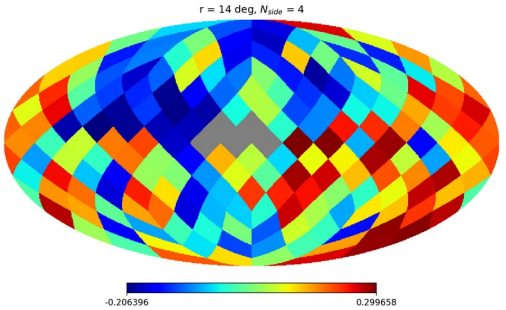
$$\xi(\hat{N}) = \frac{\sigma^2_{\rm obs}(\hat{N}) - \langle \sigma^2_{\rm iso}(\hat{N}) \rangle}{\langle \sigma^2_{\rm iso}(\hat{N}) \rangle}$$

$$\xi(\hat{N}) \equiv 2A\hat{\lambda} \cdot \hat{N}$$

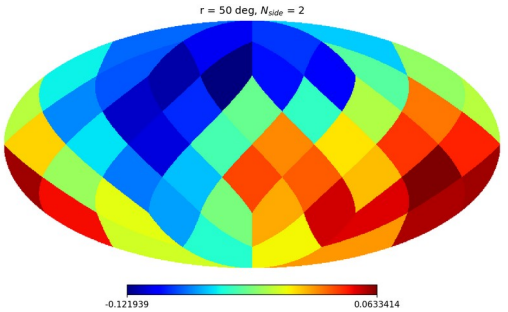
r = 4°, Nside = 8



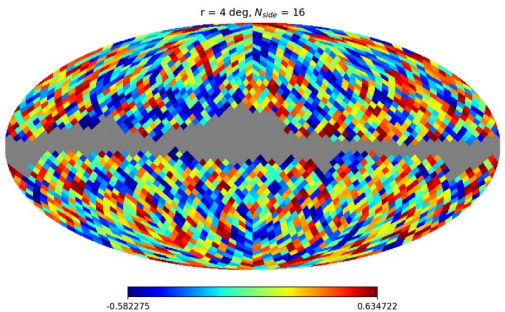
r = 14°, Nside = 4

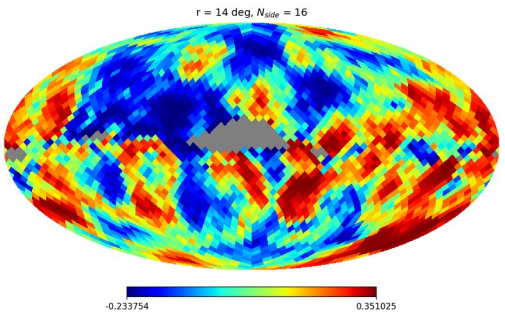


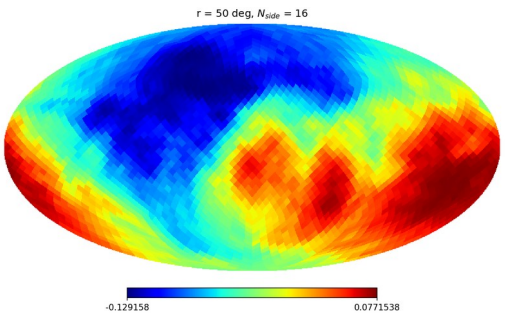
r = 50°, Nside = 2



Varying Nside





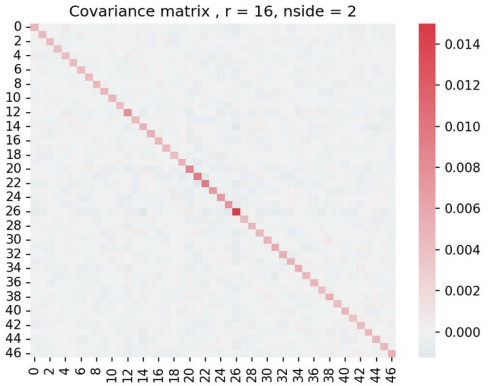


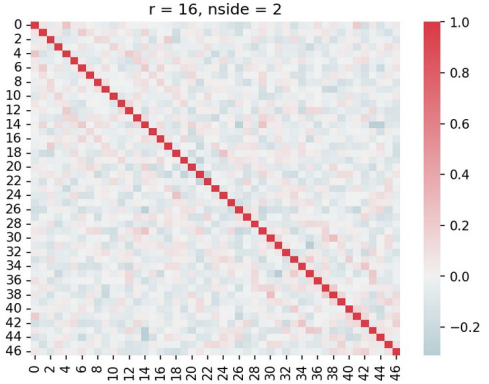
Fixed Nside=16

Covariance/Correlation matrices

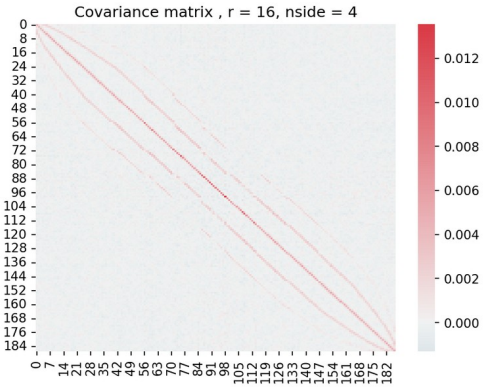
- For a fixed radius, r = 16°, but different Nside grid choices

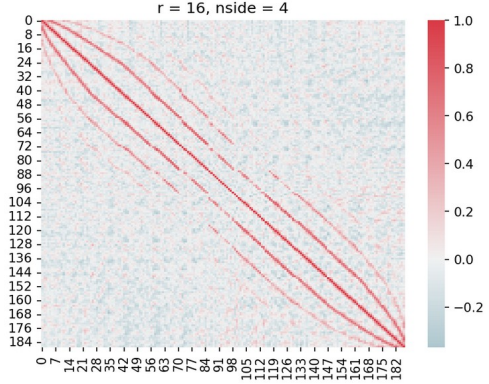
Nside = 2, ps ~ 30°



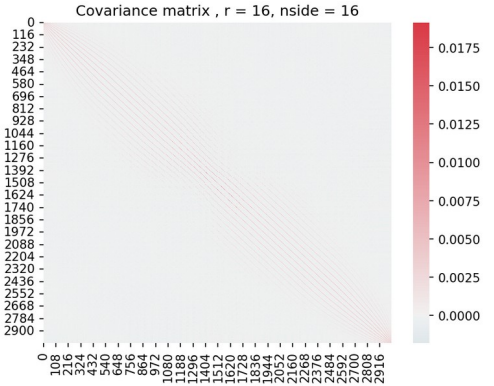


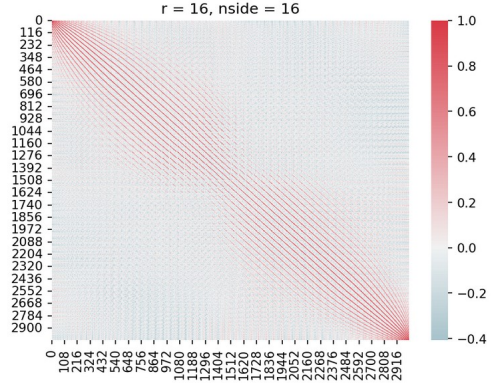
Nside = 4, ps ~ 15°



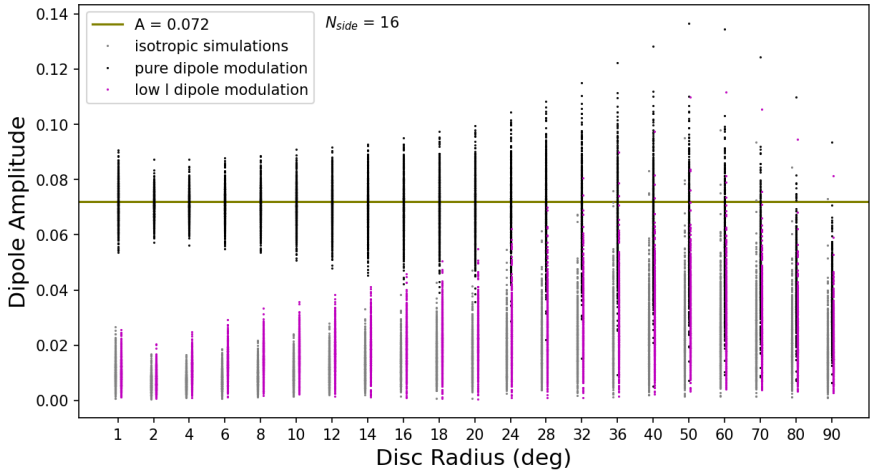


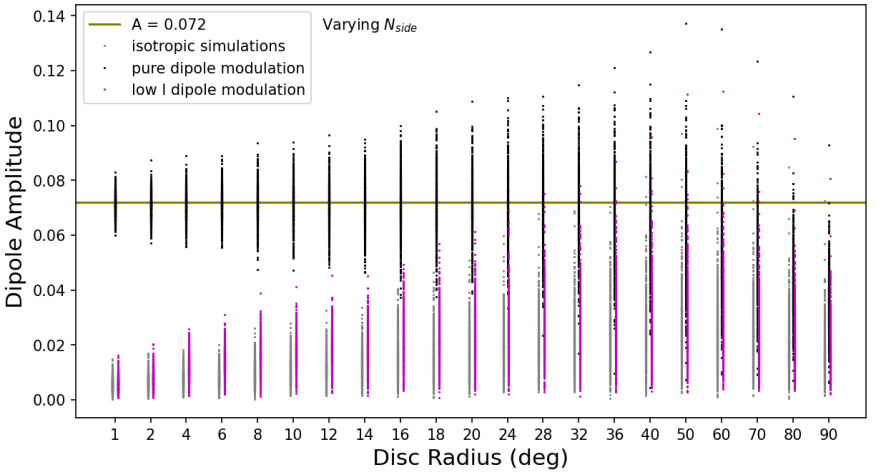
Nside = 16, ps ~ 4°





Validation of method and comparison of the two case



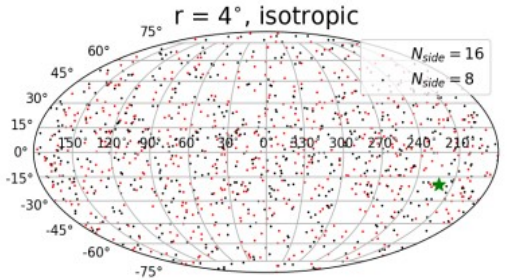


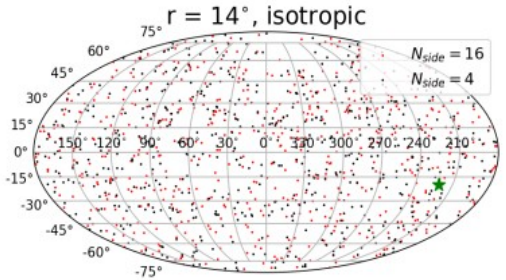
- 3 sets of simulation : isotropic, pure dipole modulated, low multipole only (l ~ 60) dipole modulated
- Similar results are found in both cases of Nside choices for r >= 2°. Perhaps due to high SNR of CMB temperature data

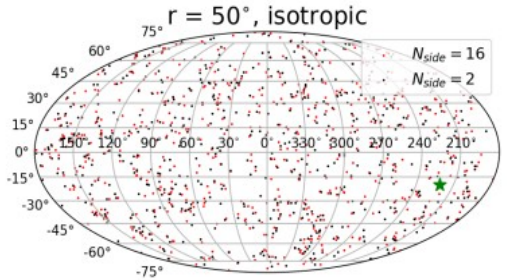
Dipole directions recovered from two case

- Statistically they look similar, due to high SNR

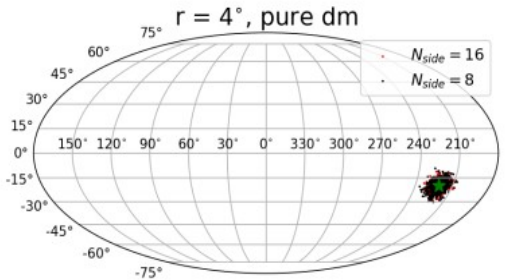
Isotopic sim.

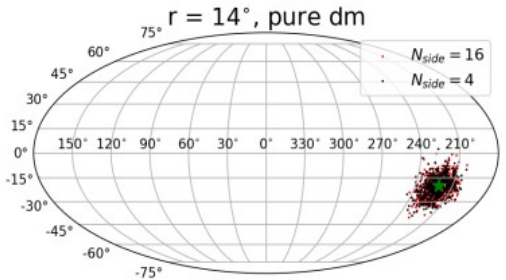


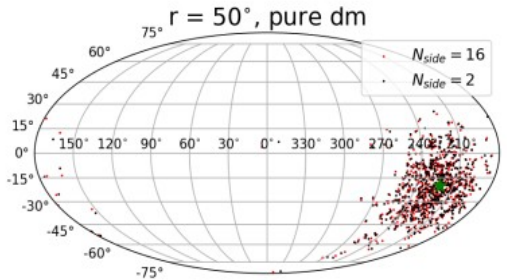




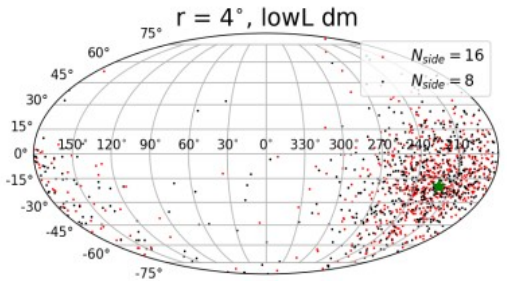
Pure-dm sim.

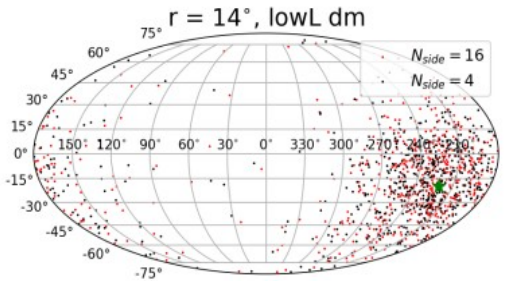


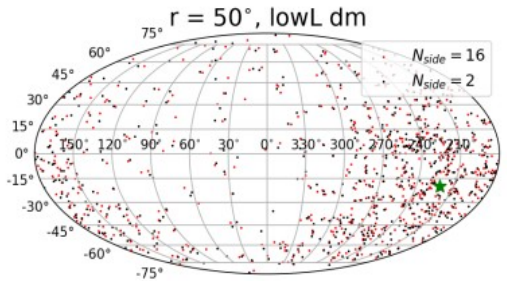




low-l-dm sim.

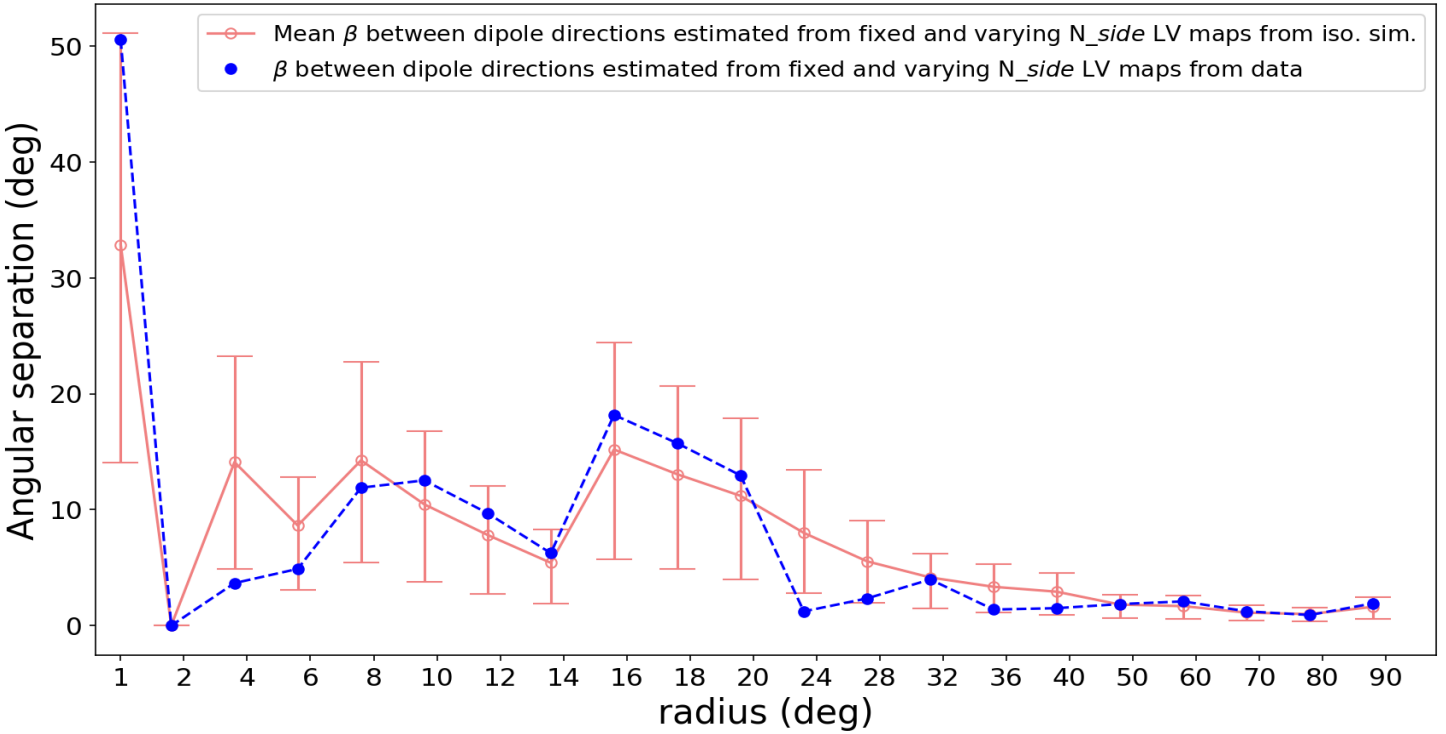






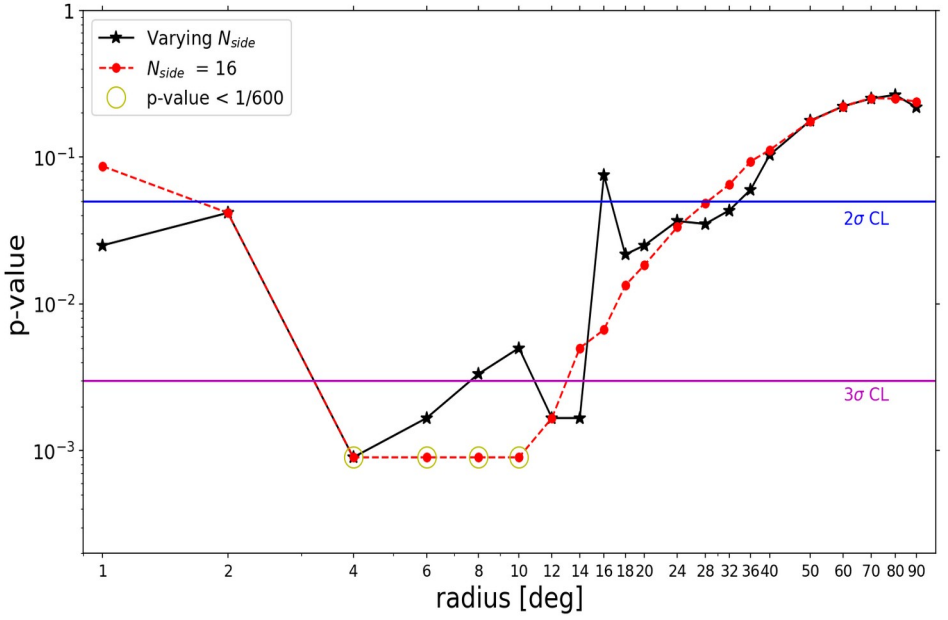
Angular separation vs disc size

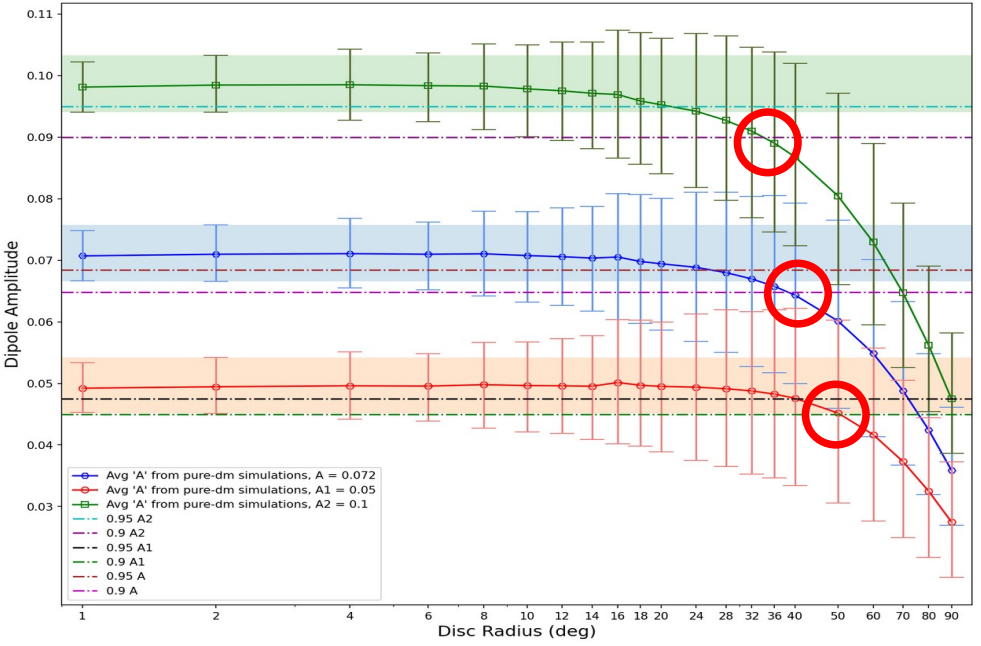
- Angular separation b/w dipole directions as recovered from Fixed Nside=16 and Varying Nside LV maps as a function of disc radius.
- If both methods were good, the angular separation b/w them should be ~ 0°



Significance & Range of Reliability of LVE method

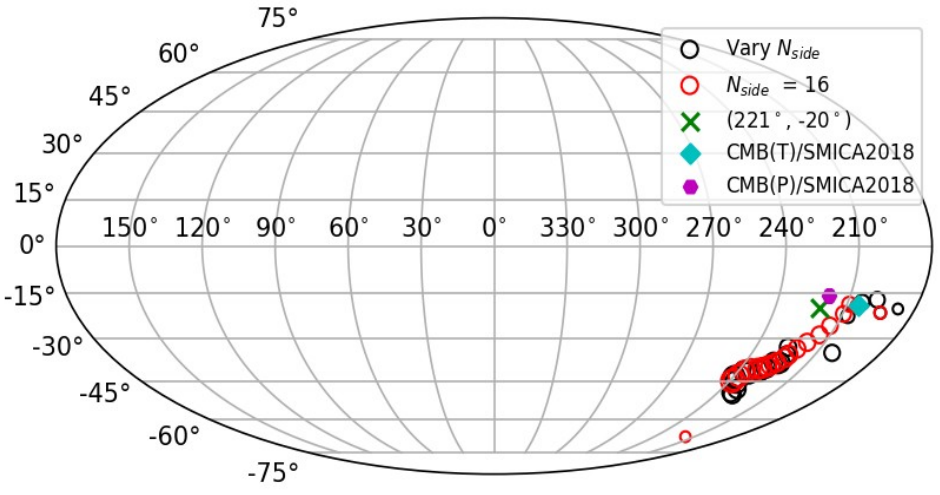
- Scales of anomalies around r ~ 4° to 14° with ~ 3σ significance
- Reliability of LVE method is found to depend on the amplitude of strength of the underlying isotropy violating signal
- Our claim of anomalous isotropy violation i.e, dipole modulation lies in reliable region of LVE method (r <= 40°)

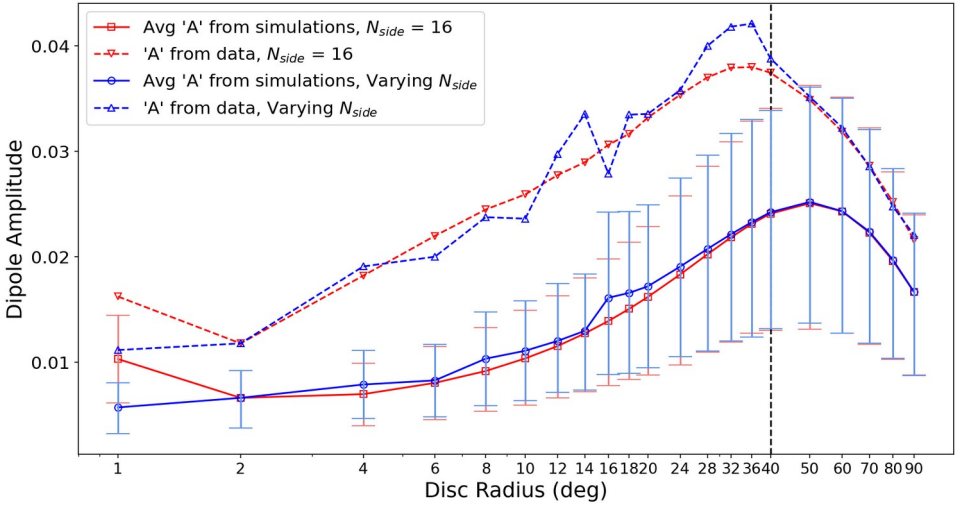




Dipole amplitude and direction from PR4 temperature data

- Dipole directions moving away from galactic plane with increase in disc size
- Outcomes are in conformity with earlier reported ones.
- We can rely on the results upto r ~ 40°





Conclusion

- HPA Anomaly is robust and present on large angular scales.
- Size of circular disc choice is matched with a suitable healpix grid size to get LV maps, where correlation between LV map pixels are none or minimal.
- LVE works well upto r ~ 40°.
- LVE with varying nside is computationaly cost effective.

Thank You

Dipole Amplitude estimated from dipole modulated simulations for fixed Nside and Varying Nside case