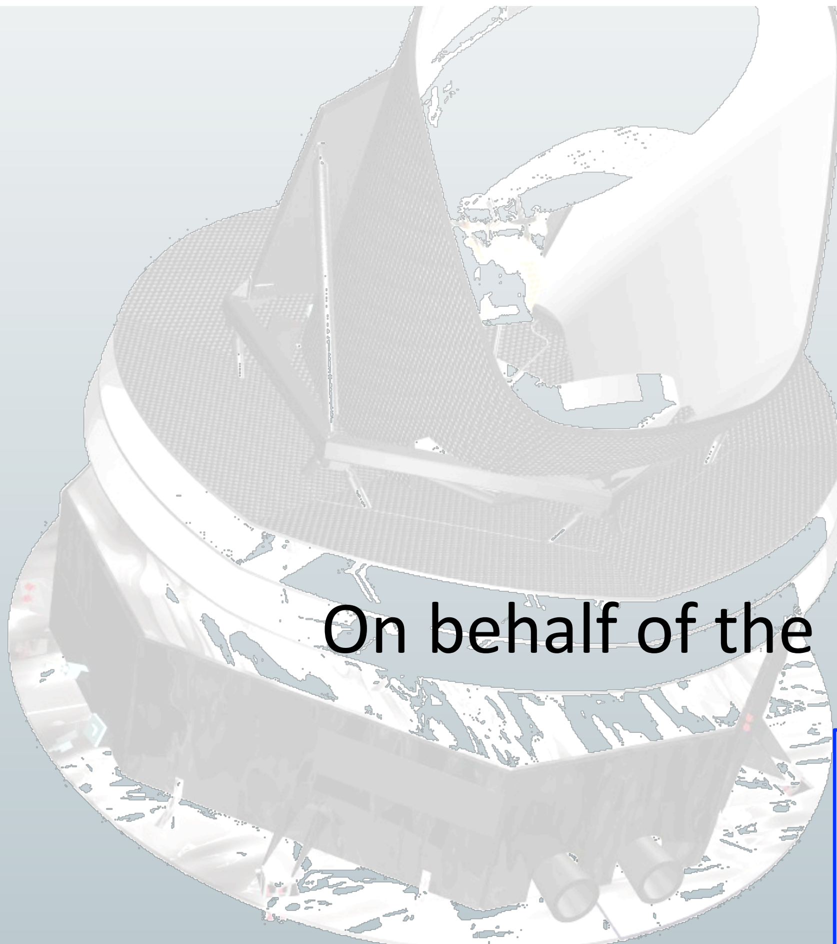
Statistical anisotropies
(Power asymmetry in BipoSH representation)



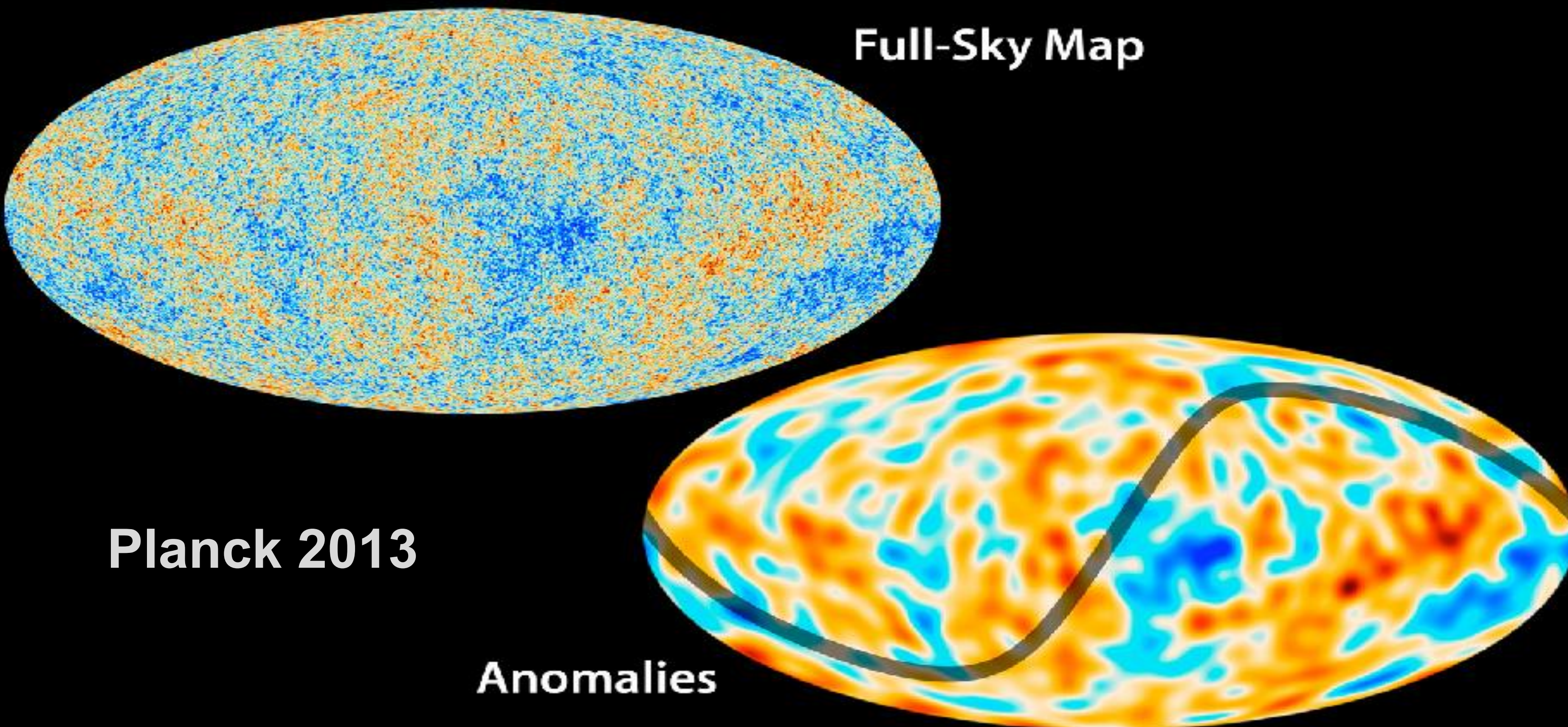
Tarun Souradeep

IUCAA, India

On behalf of the Planck collaboration

Primordial Universe after Planck
30th IAP Colloquium
Paris
Dec 15-19, 2014

Hemispherical power asymmetry

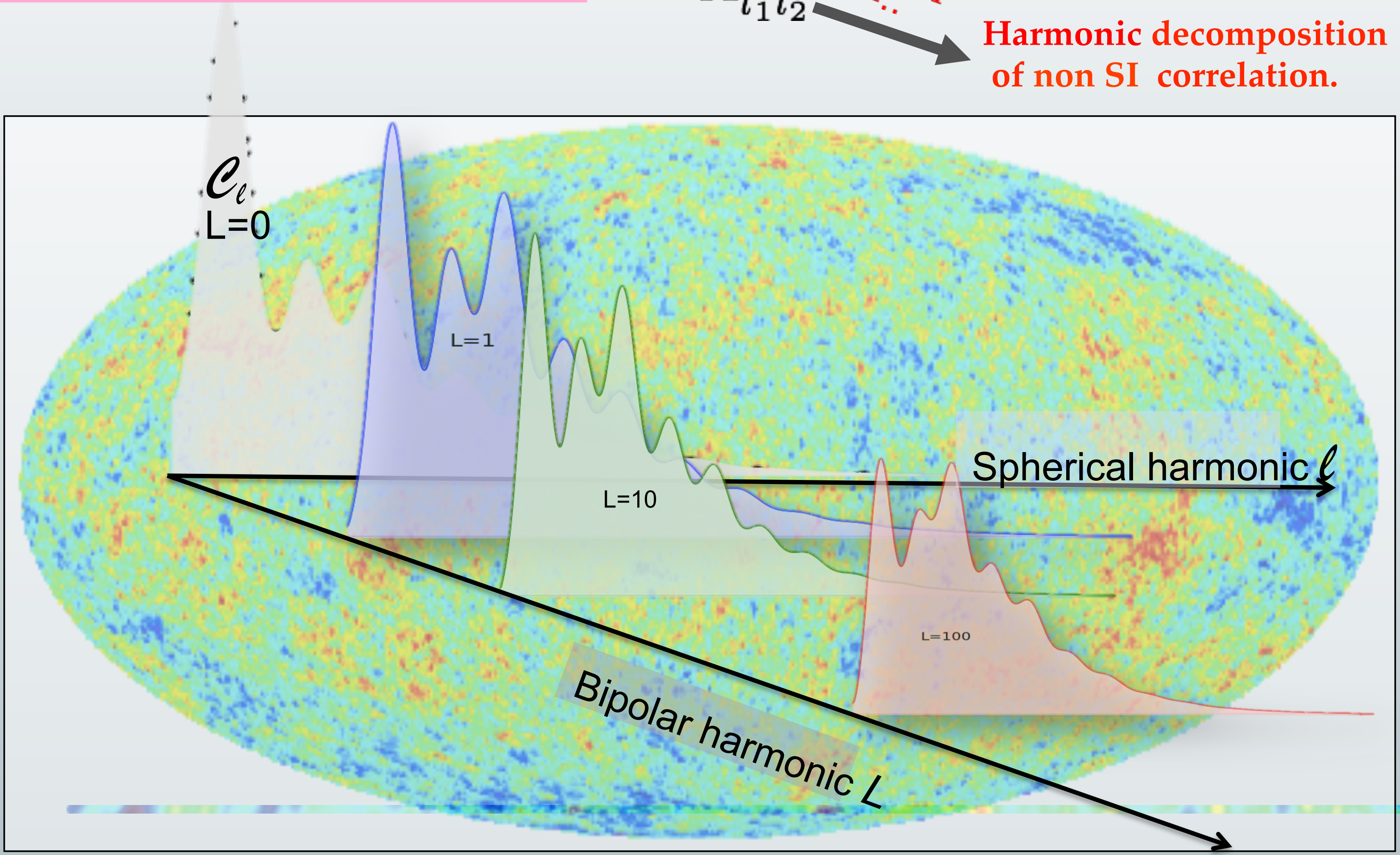


BipoSH Spectra : *Natural* generalization of C_ℓ

$$\tilde{A}^{LM}_{l_1 l_2} = \sum_m \left\langle a^*_{l_1 m} a_{l_2 m+M} \right\rangle \; C^{LM}_{l_1 m l_2 m+M}$$

$A^{LM}_{l_1 l_2}$ → $A^{\cdot\cdot}_{l_1 l_2}$ → **Harmonic decomposition of map (temp, Pol)**

$A^{LM}_{l_1 l_2}$ → $A^{LM}_{\cdot\cdot}$ → **Harmonic decomposition of non SI correlation.**



BipoSH: Natural generalization of C_ℓ

Bipolar Spherical Harmonic representation

Amir Hajian & Souradeep 2003

Stat Iso Correlation

$$C(n_1 \bullet n_2) = \sum \frac{2l+1}{4\pi} C_l P_l(n_1 \bullet n_2)$$

Non SI Correlation

$$C(\hat{n}_1, \hat{n}_2) = \sum_{l_1 l_2 LM} \tilde{A}^{LM}_{l_1 l_2} \{Y_{l_1}(\hat{n}_1) \otimes Y_{l_2}(\hat{n}_2)\}_{LM}$$

Bipolar spherical harmonics.

BipoSH Spectra

$$A^{LM}_{\ell\ell+d} = \tilde{A}^{LM}_{\ell\ell+d} \frac{\Pi_L}{\Pi_{\ell(\ell+d)} \mathcal{C}^{L0}_{\ell 0 (\ell+d) 0}}, \quad (0 \le d \le L),$$

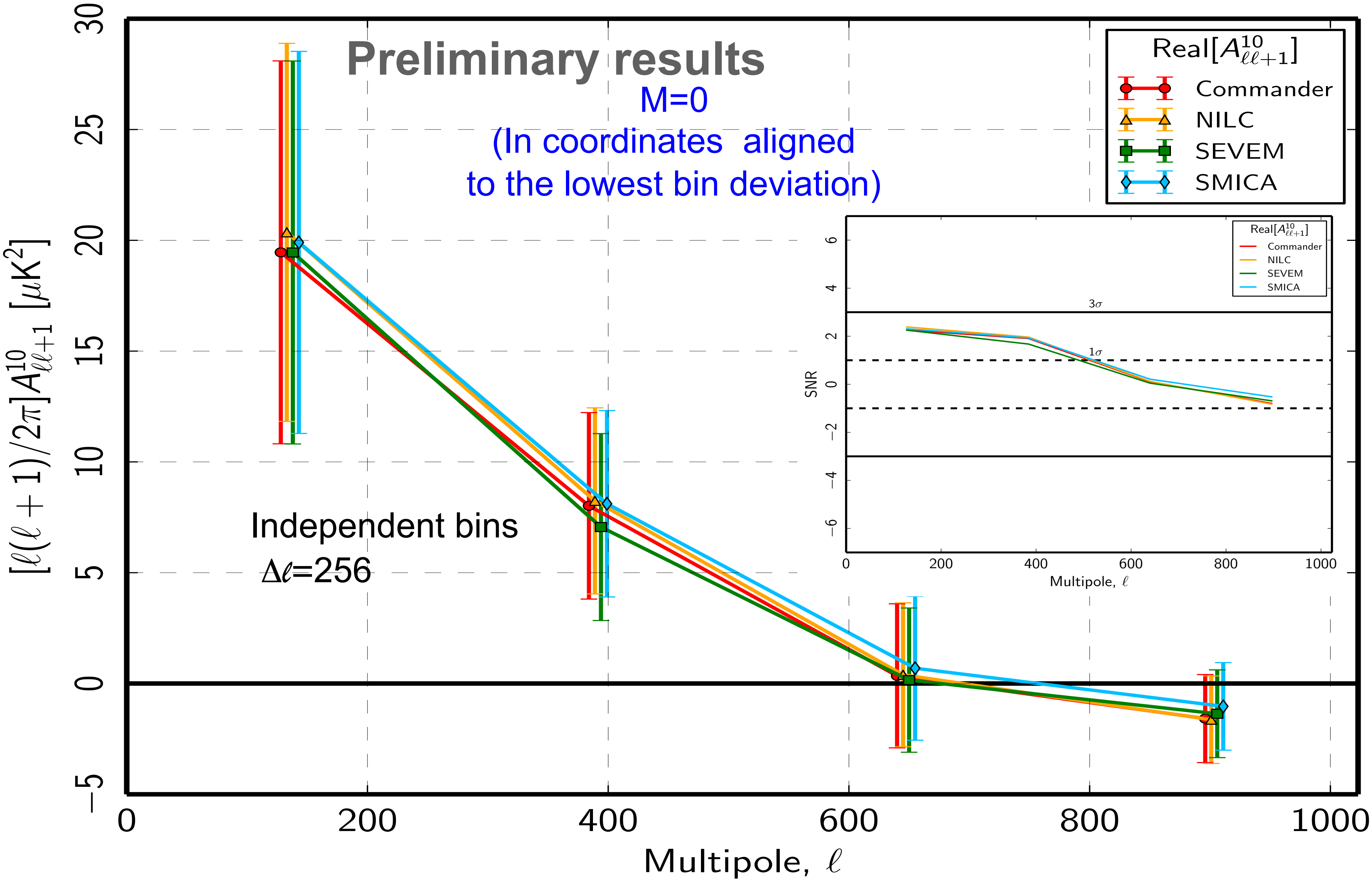
BipoSH spectrum L=0, d=0: Angular power spectrum C_ℓ $\quad C_\ell = \langle a_{\ell m} a^*_{\ell m} \rangle$

Linear combination of off-diagonal elements
BipoSH provide complete representation of SH space correlation matrix

Planck 2014 Data used

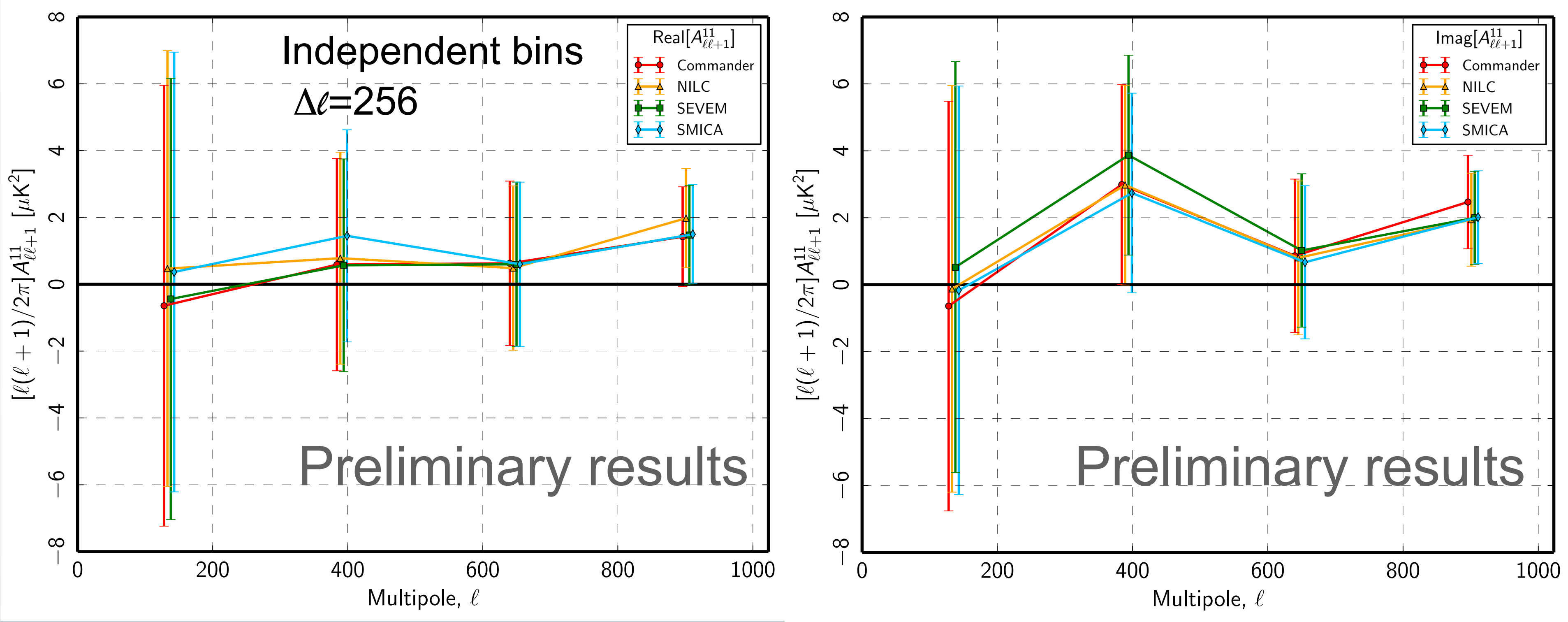
- Frequency maps have been processed by 4 different component separation methods [NILC,SEVEM,SMICA] to obtain 4 CMB maps, in order to test the robustness of results wrt foreground cleaning.
- SEVEM multi-frequency maps : 100 , 143 and 227 GHz used
- A common mask is used including both Galactic plane and point source masking. The corresponding fsky is ~77% at full resolution.
- Appropriate companion sets of realistic simulations has been produced and analyzed in the same way as the real data.
- In order to assess significance we use the p-value, defined as the probability to obtain a value for a test statistics from a set of simulations as extreme as for the real data.

BipoSH spectra [L=1]

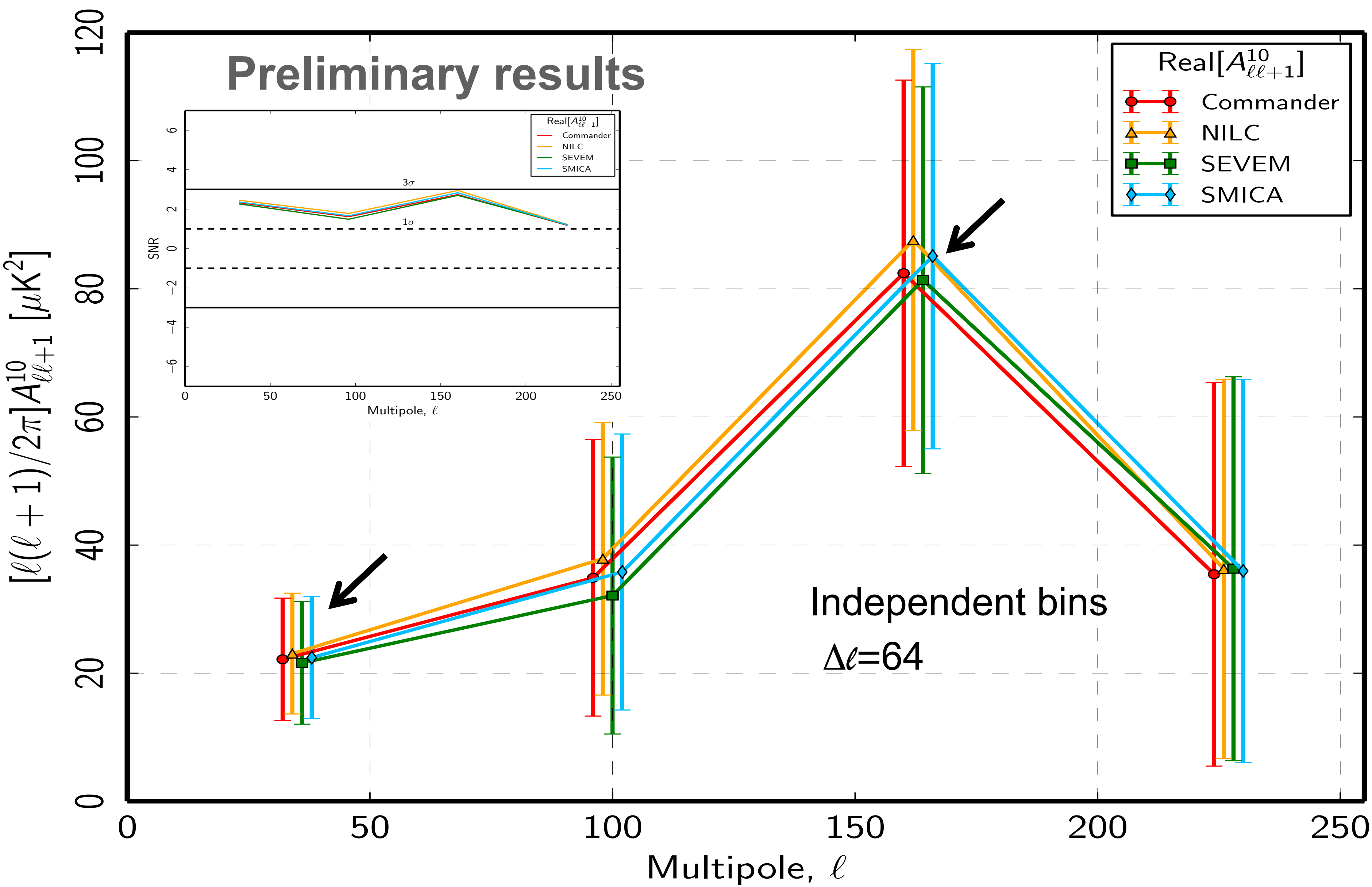


BipoSH spectra [L=1]

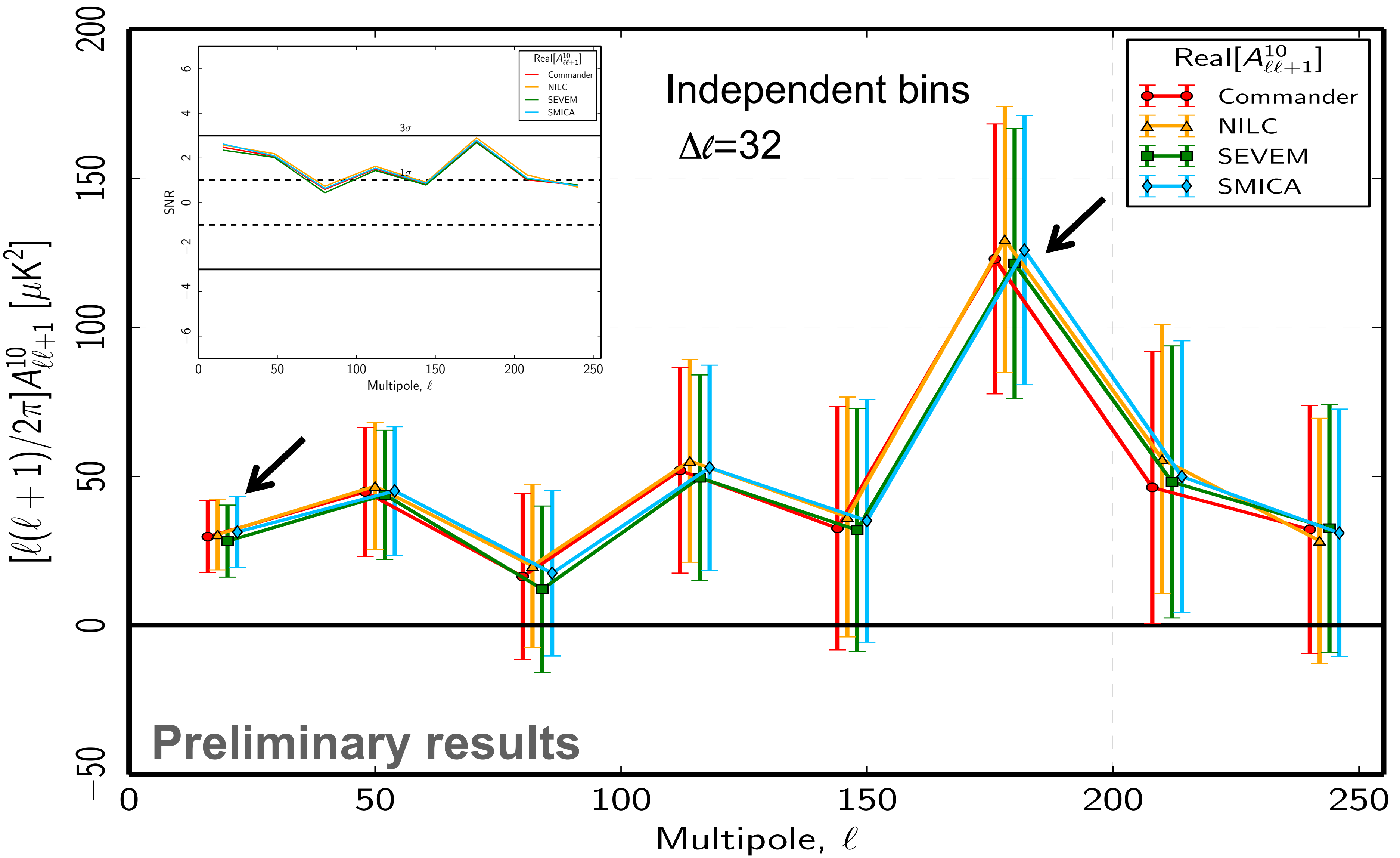
M=1 modes are consistent with zero by design
coordinates aligned
to the lowest bin deviation



BipoSH spectra : zoomed



BipoSH spectra : zoomed



BipoSH: *Natural* generalization of C_ℓ

Bipolar Spherical Harmonic representation

A *complete* representation of two-point correlation

- Modulation of CMB map:

$$\Delta T(\hat{n}) = [1 + M(\hat{n})]\Delta T^{\mathrm{SI}}(\hat{n})$$

Amir Hajian & Souradeep 2003

$$\begin{aligned} A^{LM}_{\ell_1\ell_2} &= \bar{A}^{LM}_{\ell_1\ell_2} + m_{LM} G^L_{\ell_1\ell_2}\,; \\ G^L_{\ell_1\ell_2} &= \frac{C_{\ell_1}+C_{\ell_2}}{\sqrt{4\pi}} \sqrt{\frac{(2\ell_1+1)(2\ell_2+1)}{(2L+1)}}\, \mathcal{C}^{L0}_{\ell_1 0 \ell_2 0} \end{aligned}$$

- Modulation of variance

$$\langle \Delta T(\hat{n})^2 \rangle = \mathcal{R}(\hat{n}) = \sum_{LM} \mathcal{R}_{LM} Y_{LM}(\hat{n})$$

$$\mathcal{R}_{LM} = \sum_{l_1 l_2} \mathcal{A}^{LM}_{l_1 l_2} \frac{\Pi_{l_1}\Pi_{l_2}}{\sqrt{4\pi}\Pi_L} \mathcal{C}^{L0}_{l_1 0 l_2 0}$$

(cumulative BipoSH spectra)

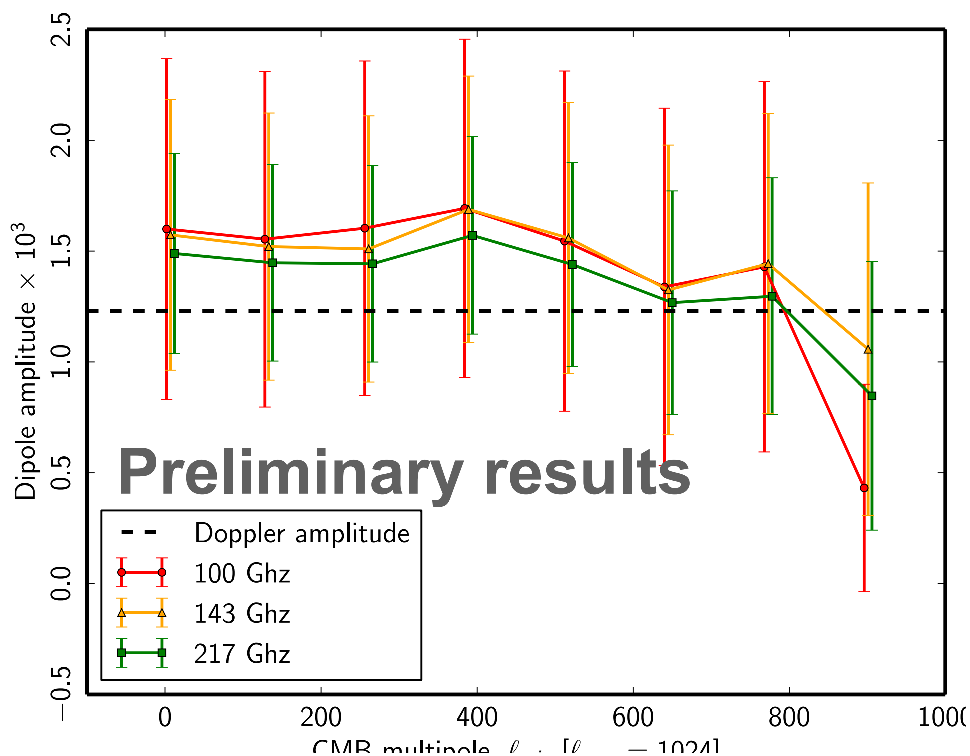
- Doppler boost:

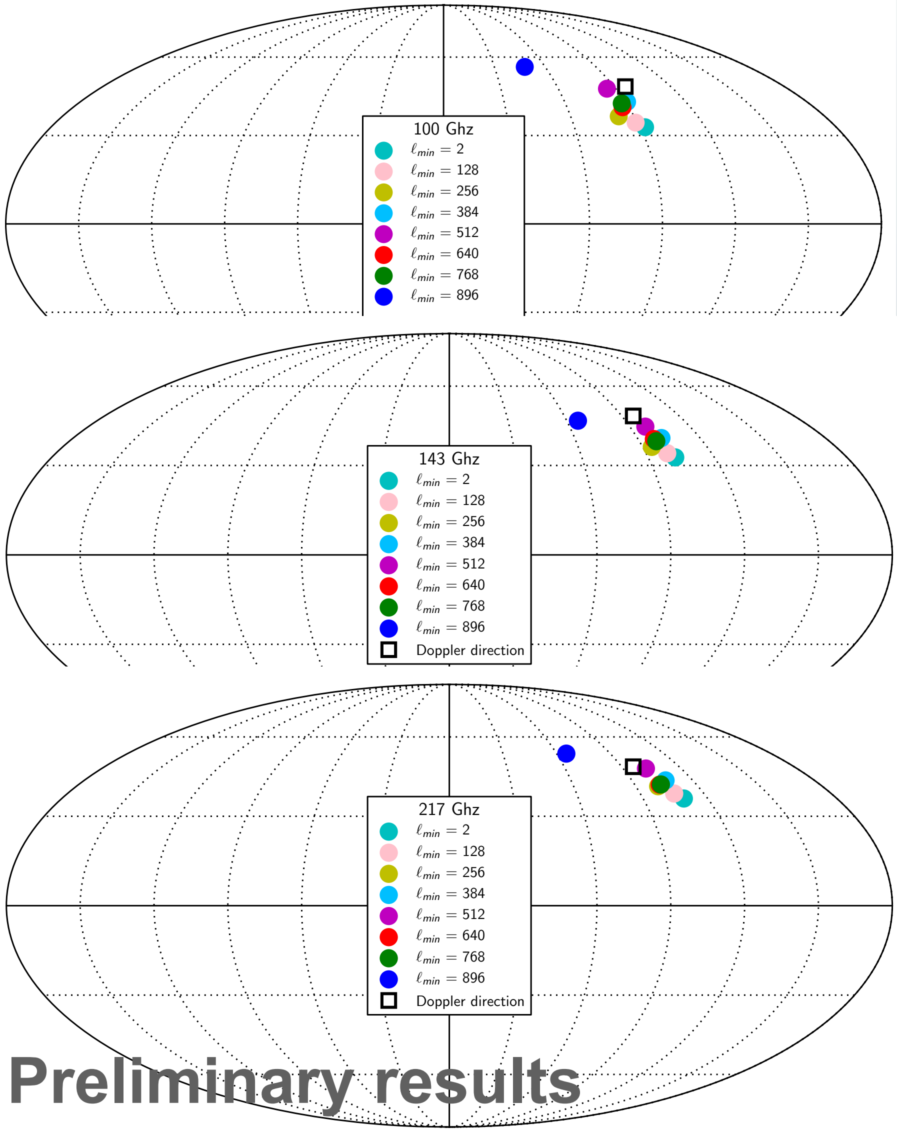
(known guaranteed signal)

$$\begin{aligned} A^{1M}_{\ell_1\ell_2} &= \bar{A}^{1M}_{\ell_1\ell_2} + \beta_{1M} G^1_{\ell_1\ell_2}\,, \\ G^1_{\ell_1\ell_2} &= \left\{ b_\nu [G^1_{\ell_1\ell_2}]^{\mathcal{M}} - [G^1_{\ell_1\ell_2}]^{\phi} \right\} \times \\ &\quad \sqrt{\frac{(2\ell_1+1)(2\ell_2+1)}{12\pi}}\, \mathcal{C}^{10}_{\ell_1 0 \ell_2 0}\,, \\ [G^1_{\ell_1\ell_2}]^{\mathcal{M}} &= [C_{\ell_1} + C_{\ell_2}]\,, \\ [G^1_{\ell_1\ell_2}]^{\phi} &= [C_{\ell_1} + C_{\ell_2}] \\ &\quad + [C_{\ell_1} - C_{\ell_2}]\,[\ell_1(\ell_1+1) - \ell_2(\ell_2+1)]\,/2 \end{aligned}$$

Doppler boost recovery

Test of the BipoSH apparatus with a known L=1 signal





- Expected signal due to Doppler boosting of the CMB sky has been detected.

- Test of method for robustness to masked sky analysis up to high multipoles

(Masked shape function formalism)

Modulation model of SI violation

$$\Delta T(\hat{n}) = [1 + M(\hat{n})]\Delta T^{\mathrm{SI}}(\hat{n})$$

M(n) : modulation field searched $M(\hat{n}) = \sum_{LM} m_{LM} Y_{LM}(\hat{n})$

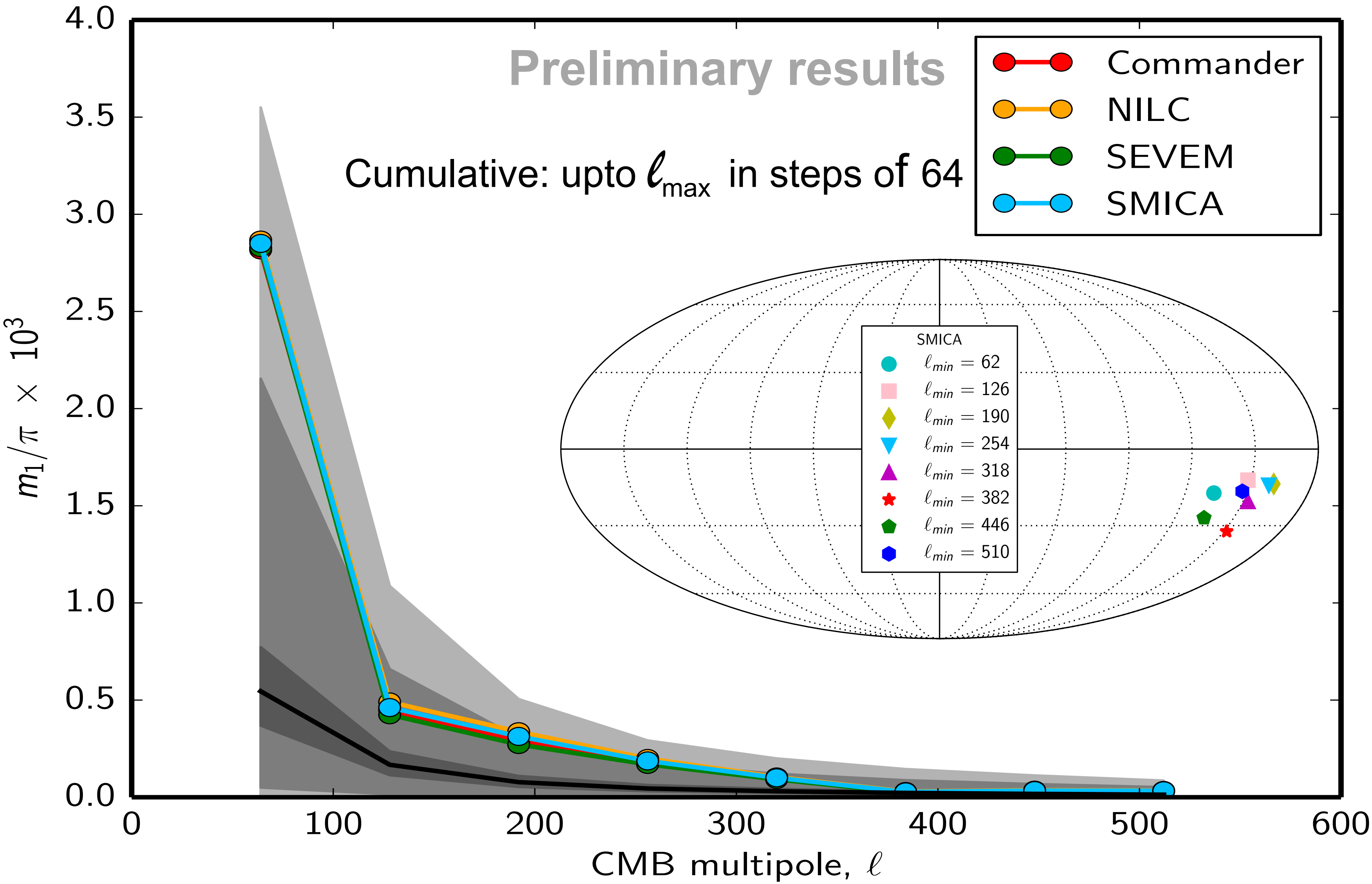
Focus only on L=1 Dipole Modulation in 2014

$$\Delta T(\hat{n}) = [1 + A\ (\hat{p}.\hat{n})]\ \Delta T^{\mathrm{SI}}(\hat{n})$$

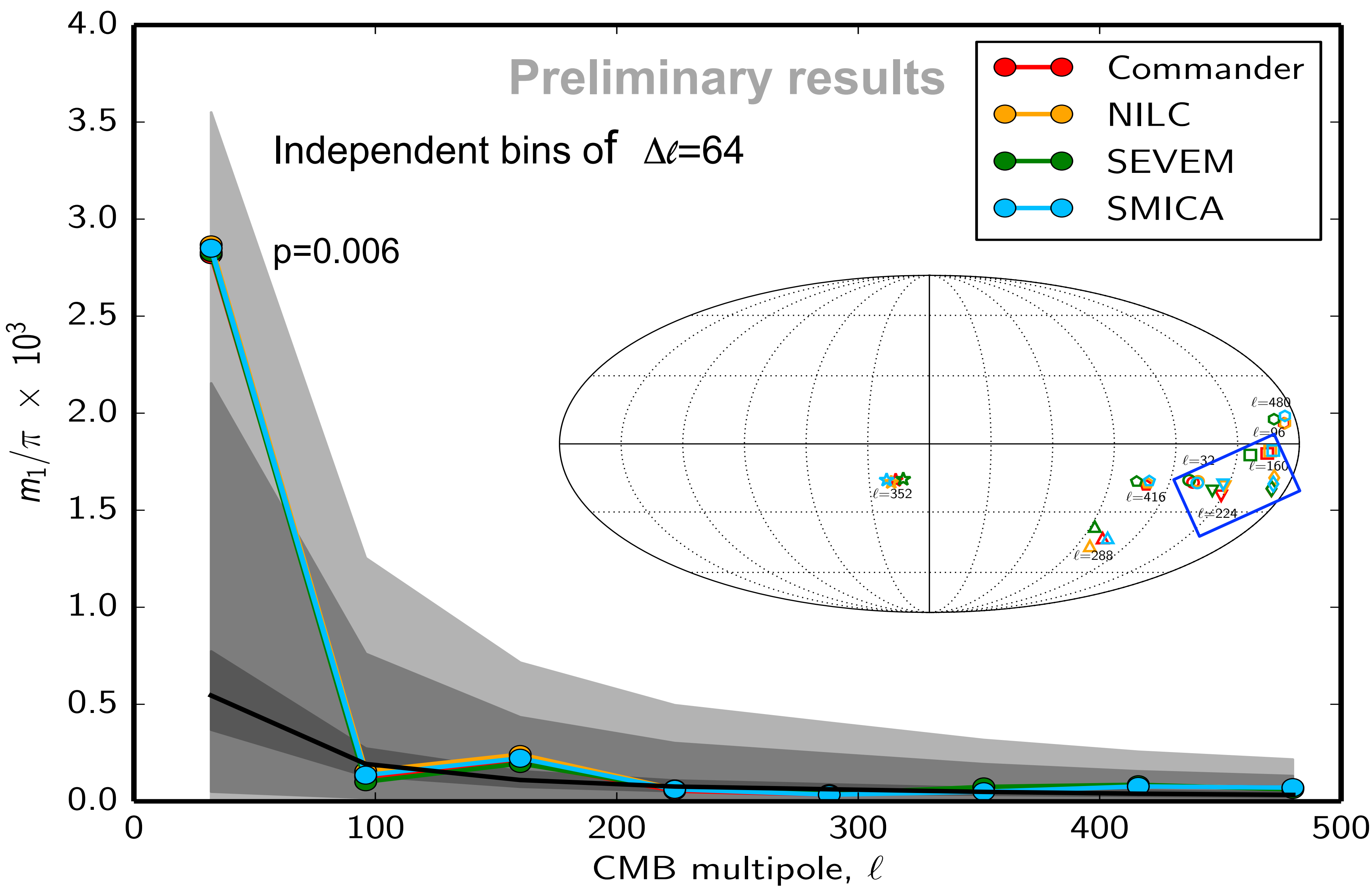
$$A = 1.5\sqrt{\frac{m_1}{\pi}}$$

$$m_1 = \frac{|m_{10}|^2 + |m_{11}|^2 + |m_{1-1}|^2}{3}$$

Dipole modulation

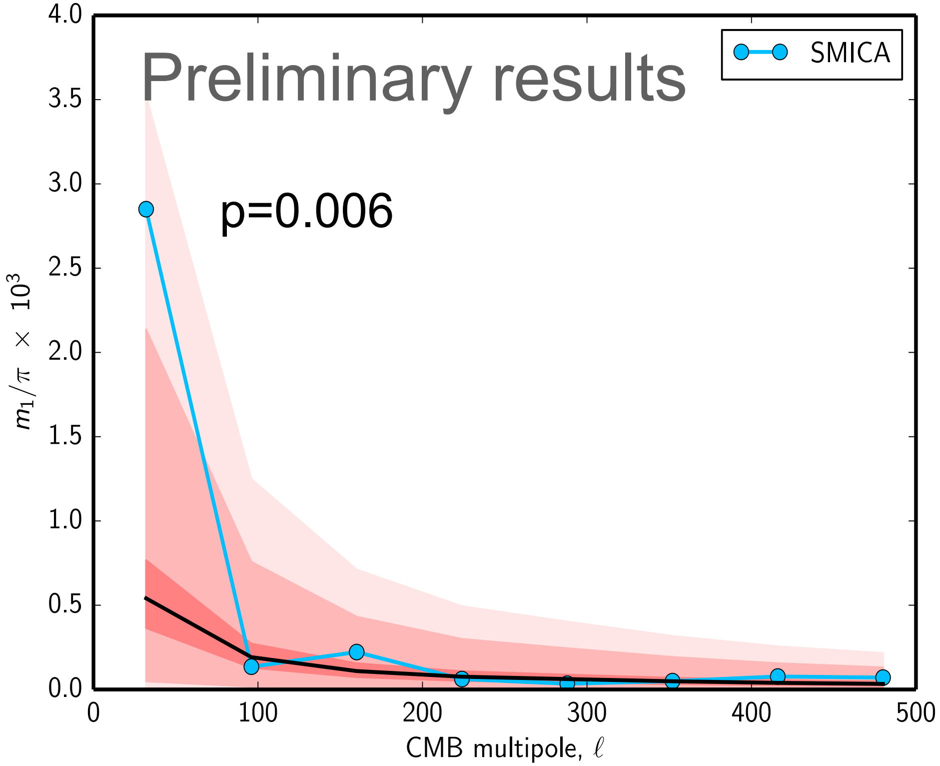


Dipole modulation

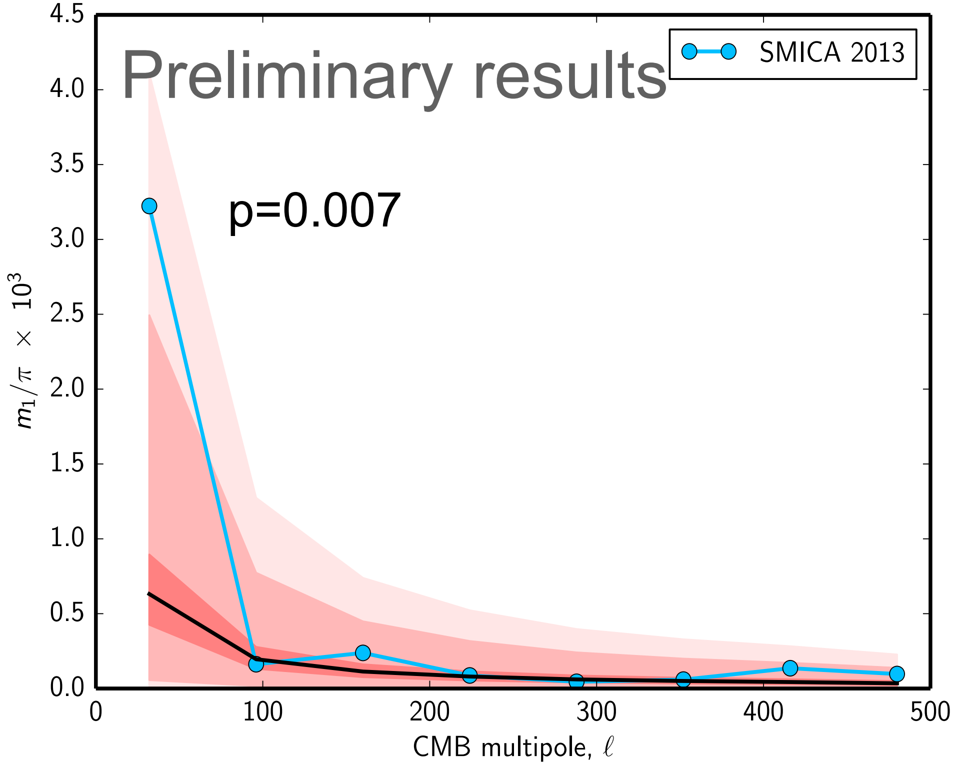


Dipole modulation: Scale Dependence

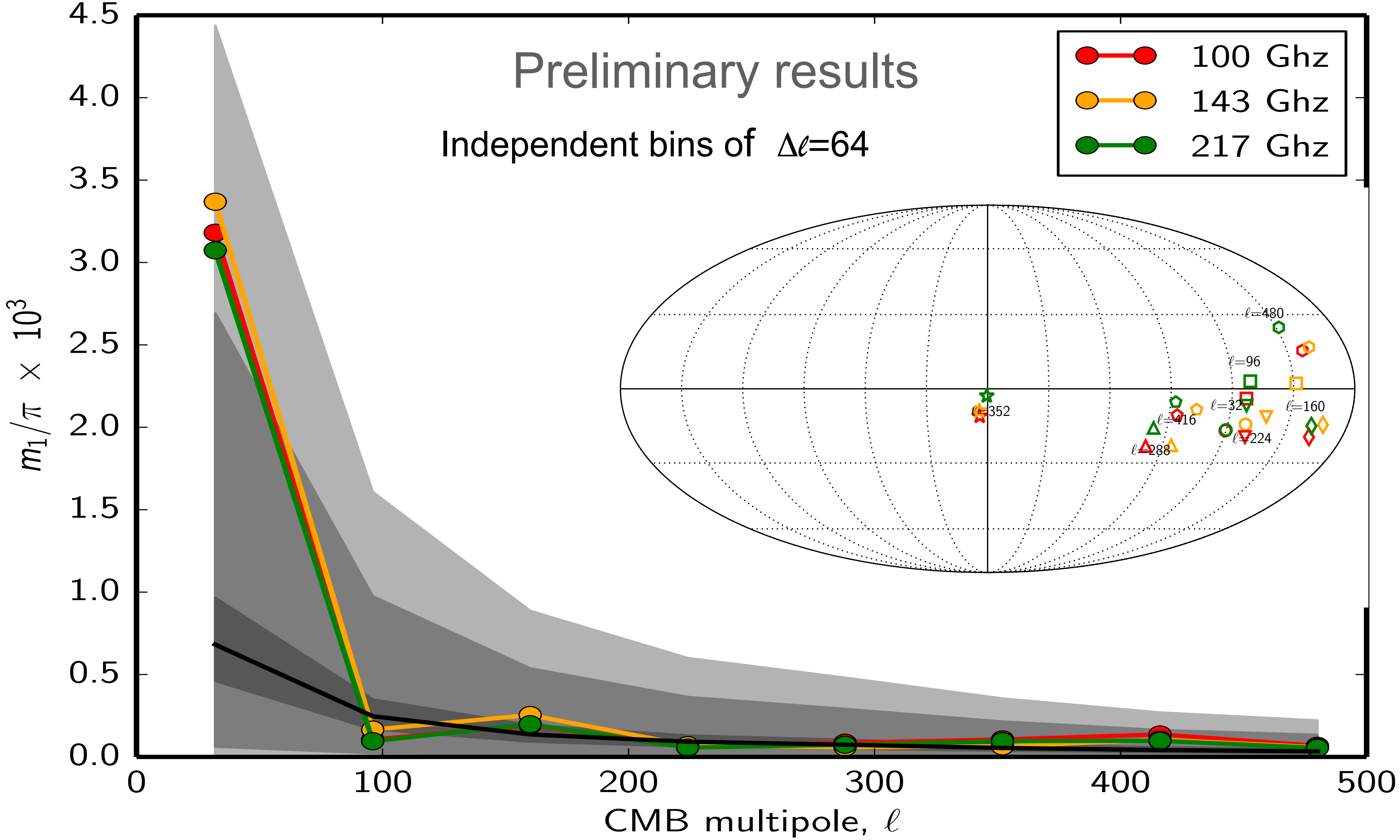
Planck 2014 SMICA



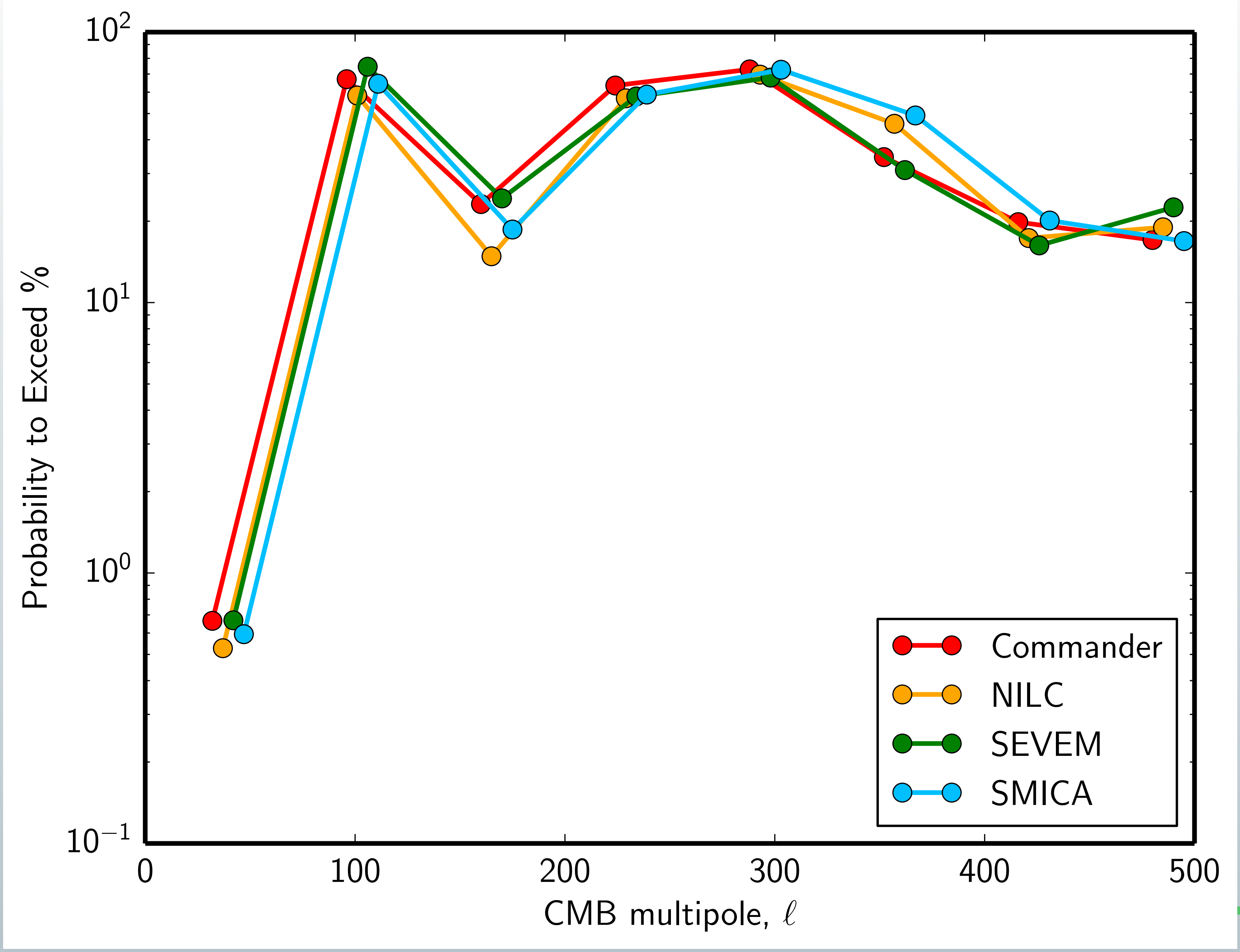
Planck 2013 SMICA



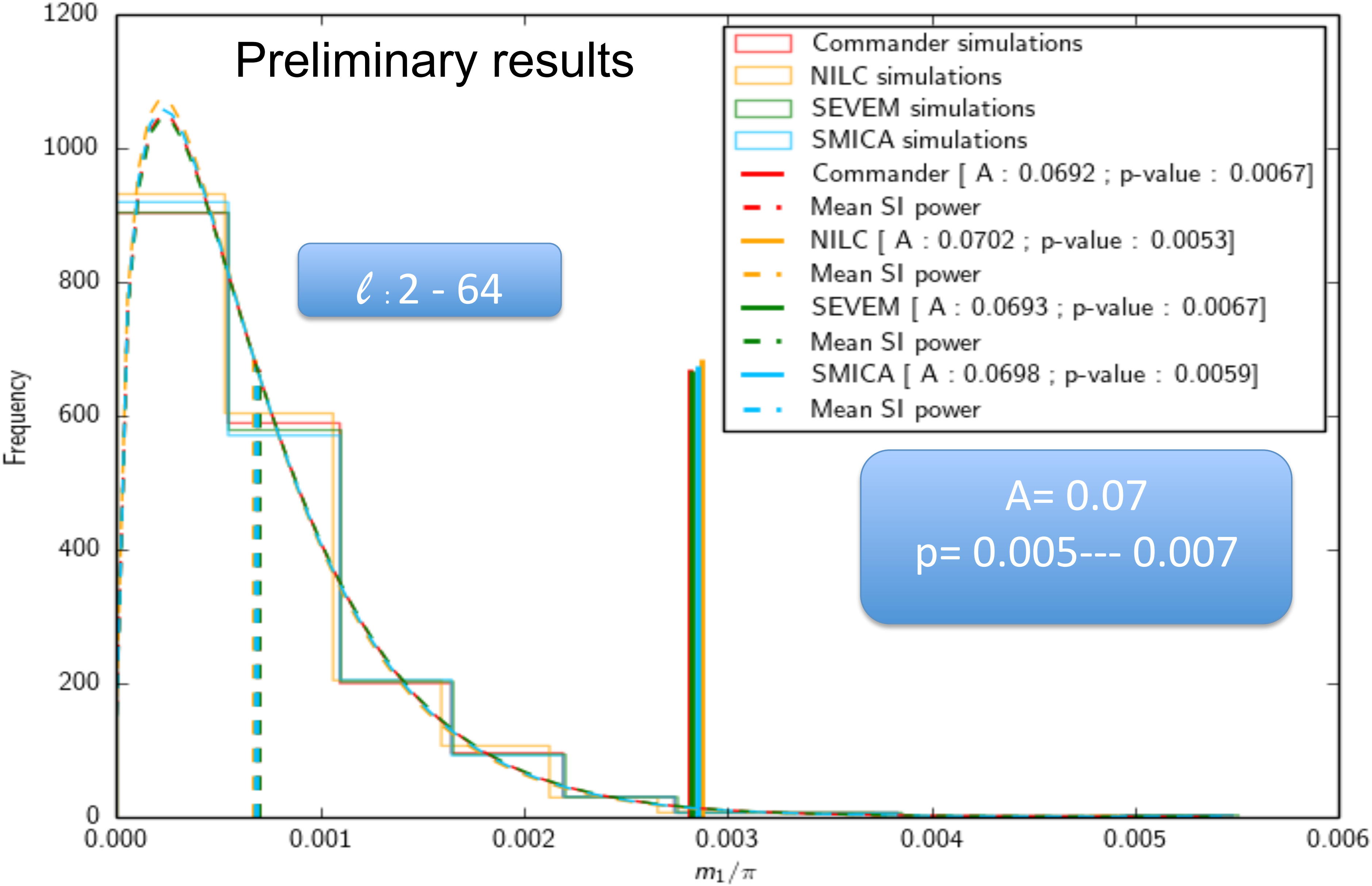
Dipole modulation : Frequency dependence



Dipole modulation: PTE

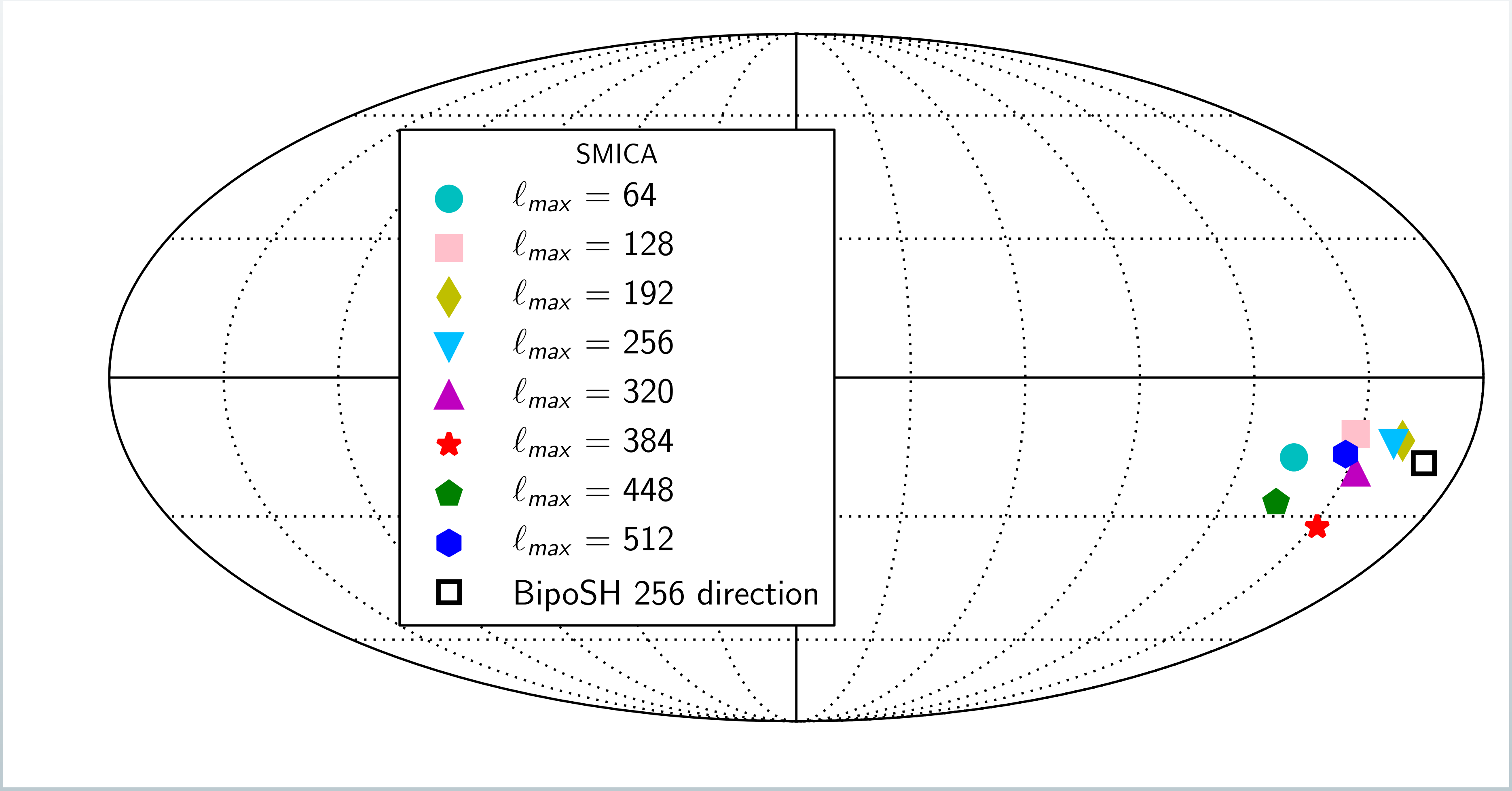


Dipole modulation power statistics

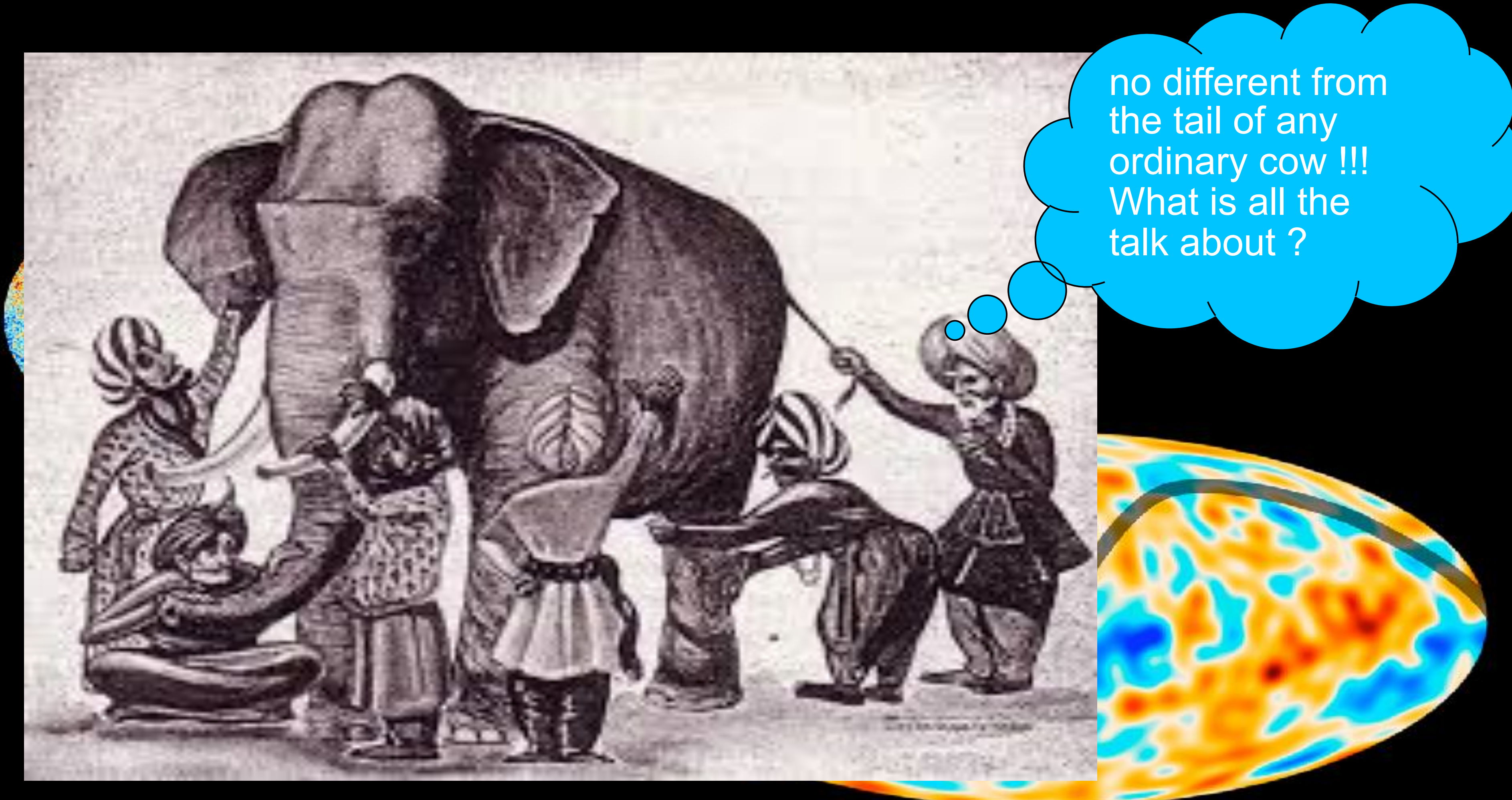


Inferred Directions

Consistent between BipoSH spectra and Dipole modulation inferred



Hemispherical power asymmetry



Summary

- Excess seen in 'natural' L=1 BipoSH spectra
  - *Not a 'designer statistics' for specific signal (analog of flat band power C_ℓ)*
  - *Gaussian statistics of flat band power estimates*
  - *Analysis up to high multipoles ($\ell < 1024$) ; zoom in with finer resolution bands*
  - *non zero BipoSH spectra within low multipole band [2-256] at 2 to 3σ*

- Dipolar modulation in Planck in 2014 persists (A~0.07 at p=0.006)
  - *Consistent with 2013 results of scale dependent amplitude*
  - *Analysis extended to higher multipoles up to 1024 [2014]*
  - *absence of significant power in the multipole bins $\ell > 64$* [2014]
  - *Frequency independent --100, 143, 217 GHz SEVEM maps* [2014]

There persists evidence of an interesting effect that may signal new physics and merits continued attention

Should explore estimating BipoSH spectra simultaneously with C_ℓ

Paolo Natoli's talk yesterday

- More specific searches: ML search for Dipolar modulation

(results consistent with 2013, Polarization does not provide extra info yet)

- `Look elsewhere' effect can be invoked. Including it the PTE will be reduced slightly However, implementation & interpretation is open to discussion.

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Thank you!!!

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.