Latest results of the POLARBEAR experiment

Giulio Fabbian (SISSA)

on behalf of the POLARBEAR collaboration

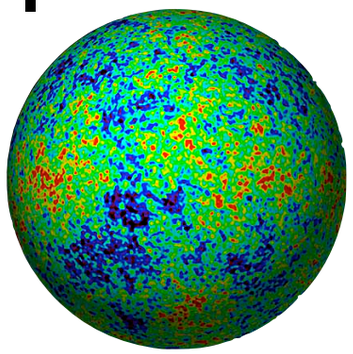
TAUP, Turin, 7th September 2015

Outline

- Few words on:
  - CMB anisotropies and B-modes science
- POLARBEAR 1 first season results:
  - Multiple evidence for B-modes of CMB polarization
- Conclusions

The universe of the CMB

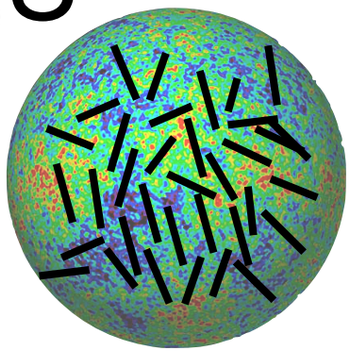
I



$$= \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a^T_{\ell m} Y^m_\ell(\theta, \phi)$$

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

Q,U



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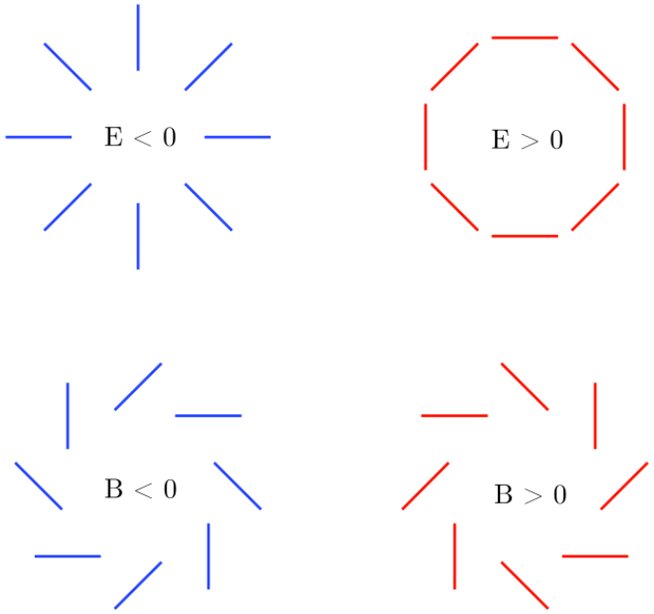
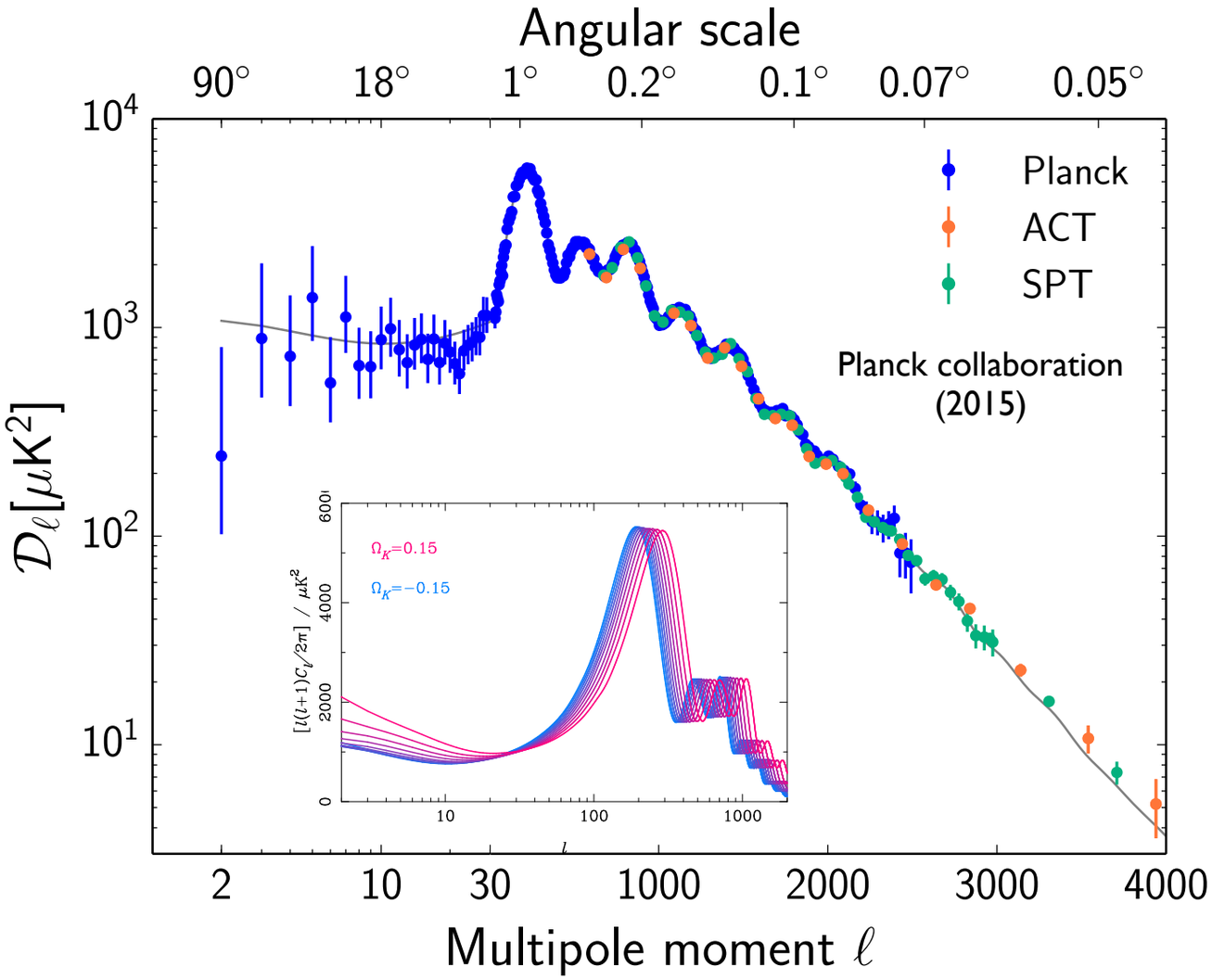
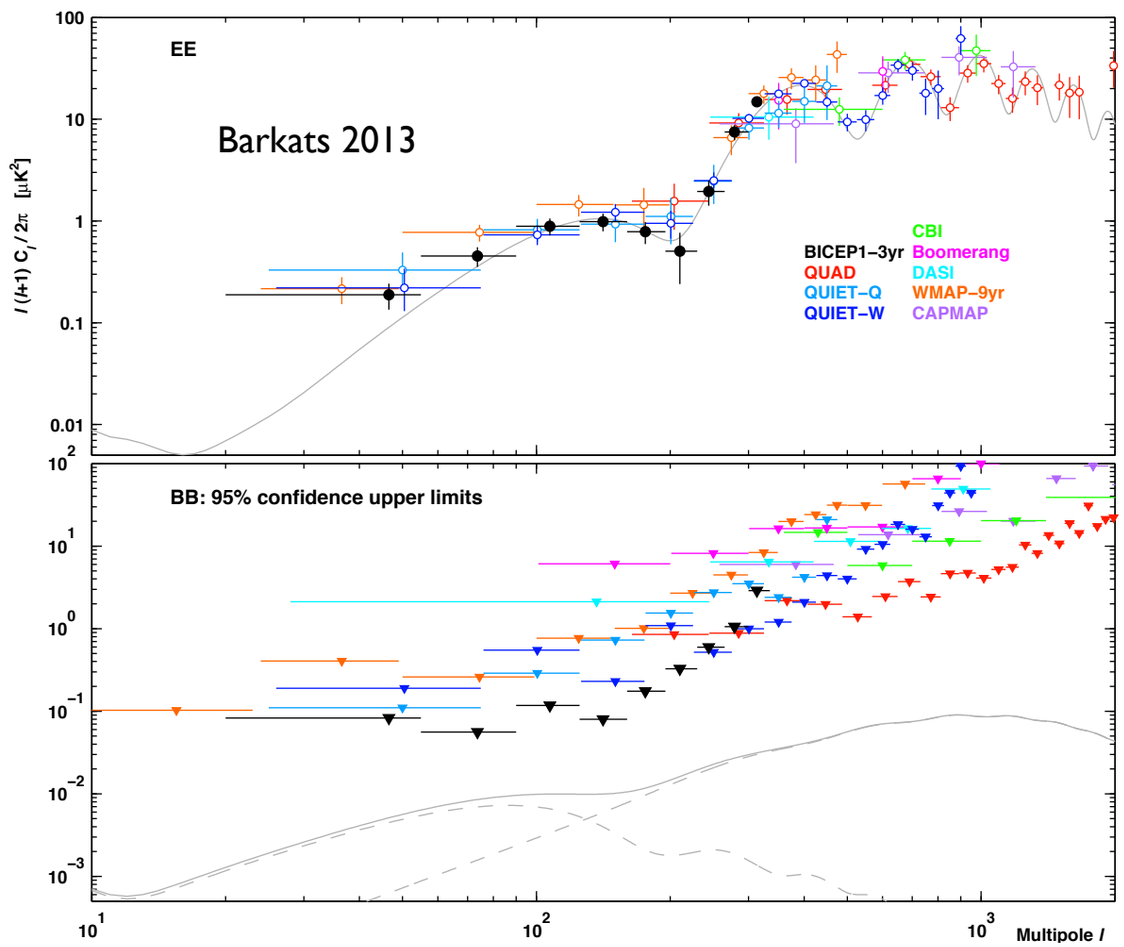




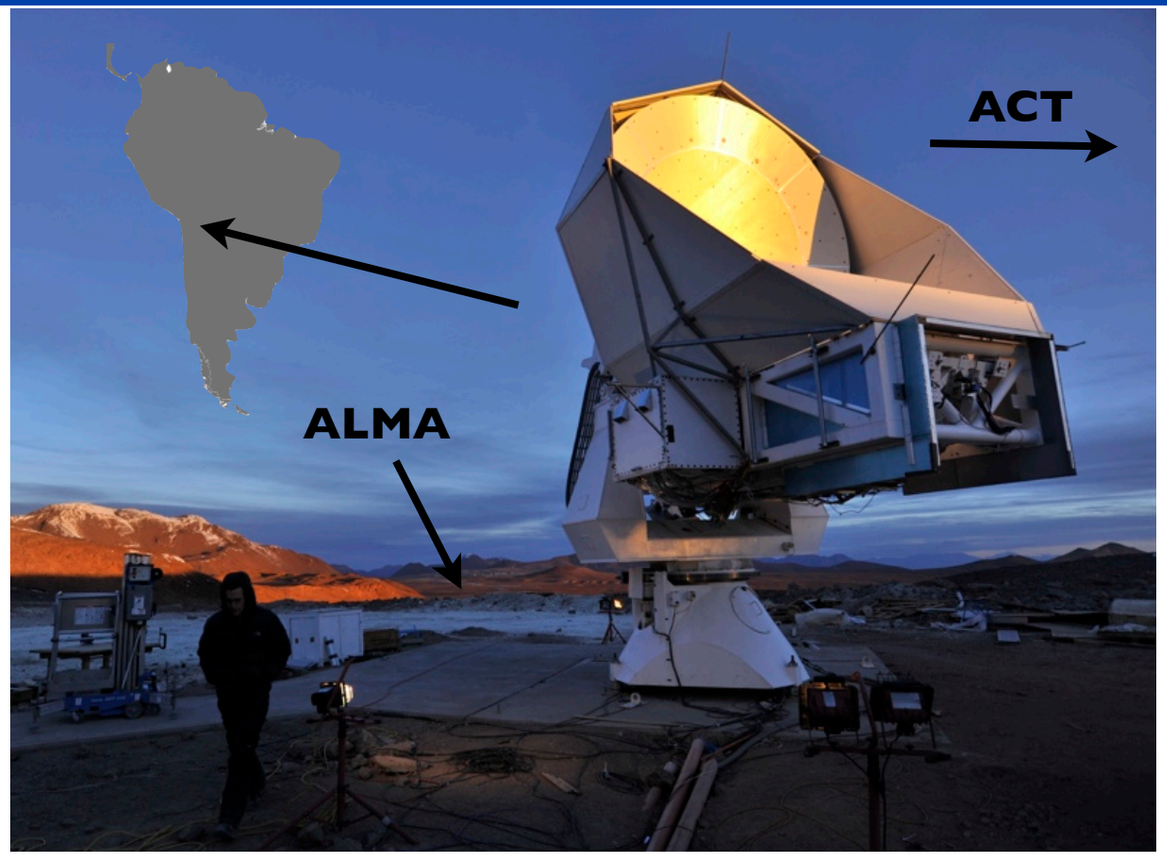


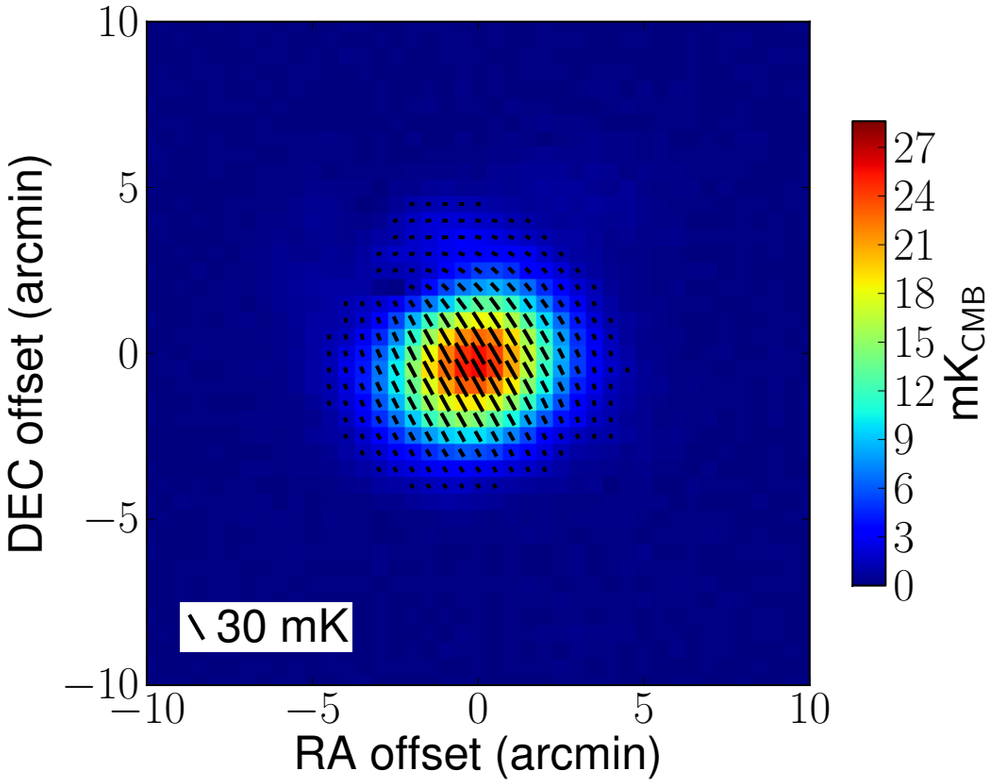
The POLARBEAR collaboration

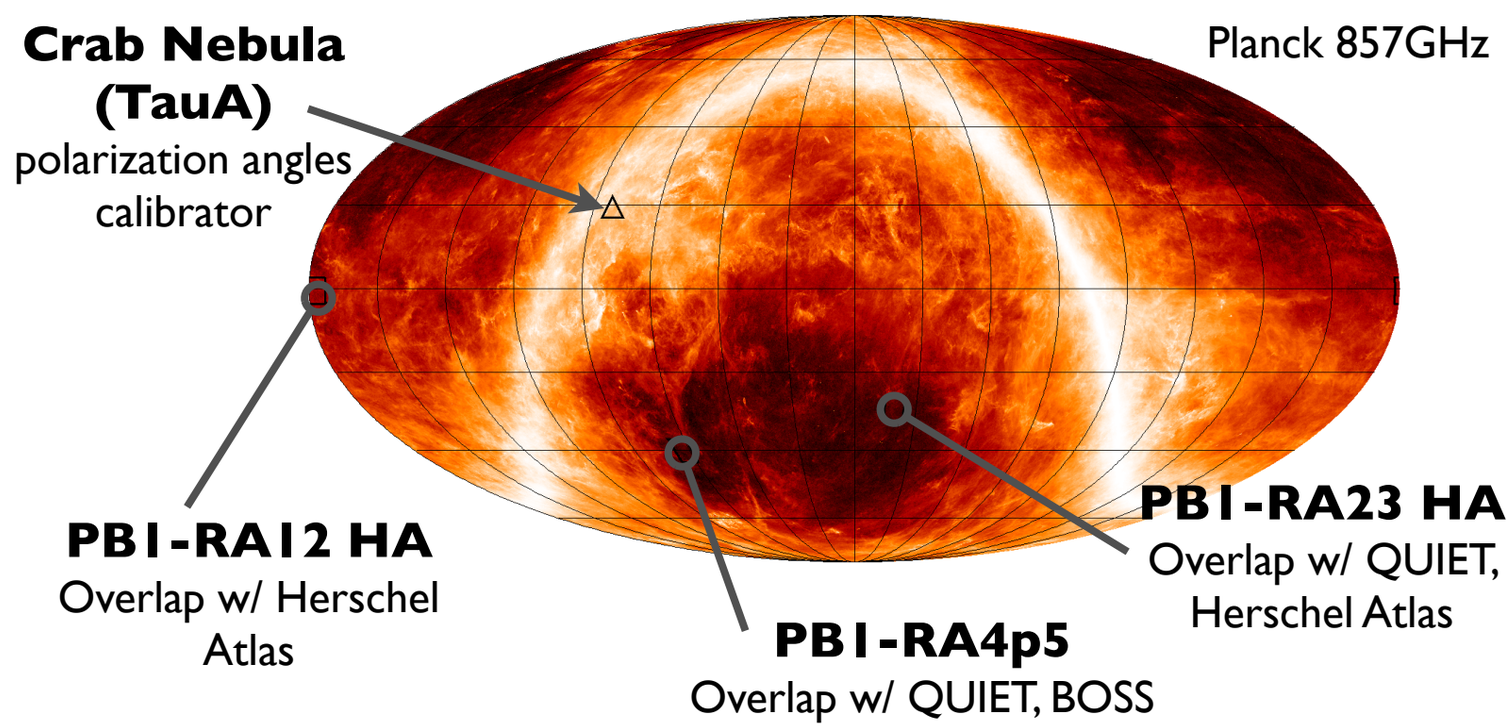
CONICYT Ministerio de Educación Gobierno de Chile · NSF · NASA · MEXT · KAVLI IPMU · SISSA · SIMONS FOUNDATION Advancing Research in Basic Science and Mathematics · BERKELEY LAB · UNIVERSITY OF COLORADO 1876 · JAXA · CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD · NIFS

The POLARBEAR experiment

- CMB polarization dedicated experiment in Atacama Desert
- Targeting both large and small scales
- 80% of the sky with *el* > 30 accessible
- 1st & 2nd season: deep 5x5 patches integration for sub-degree signal

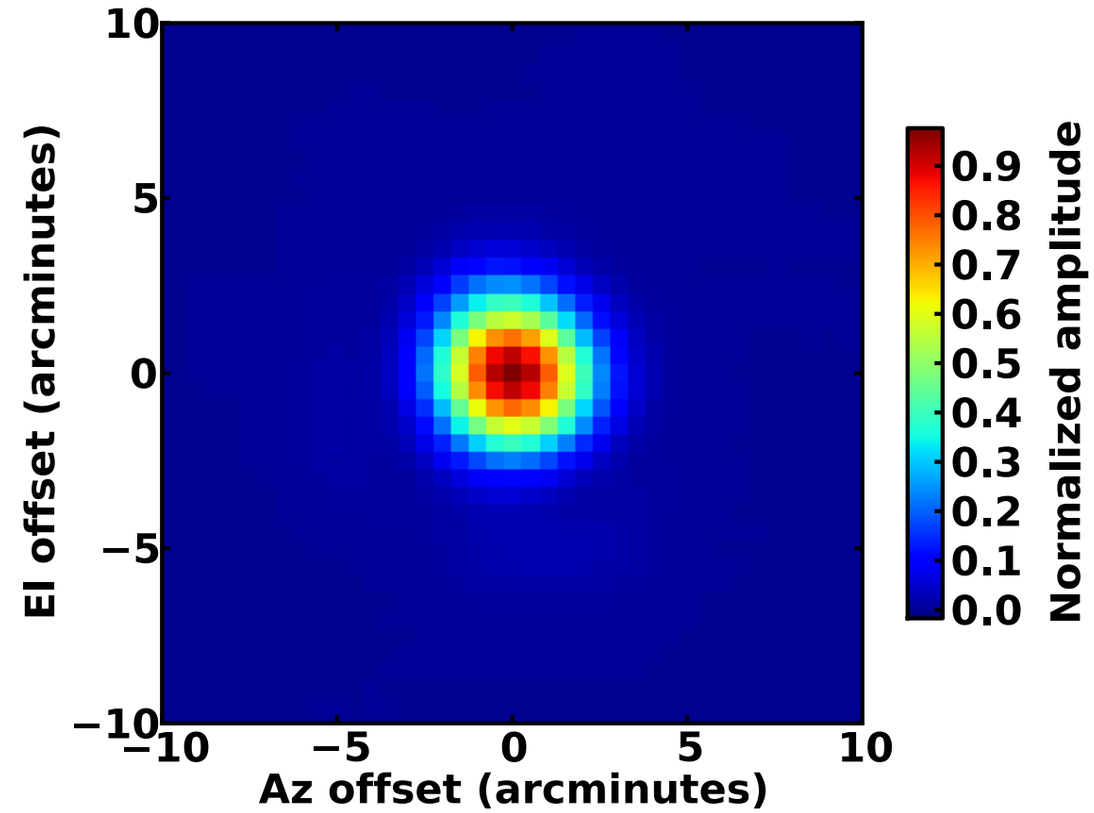


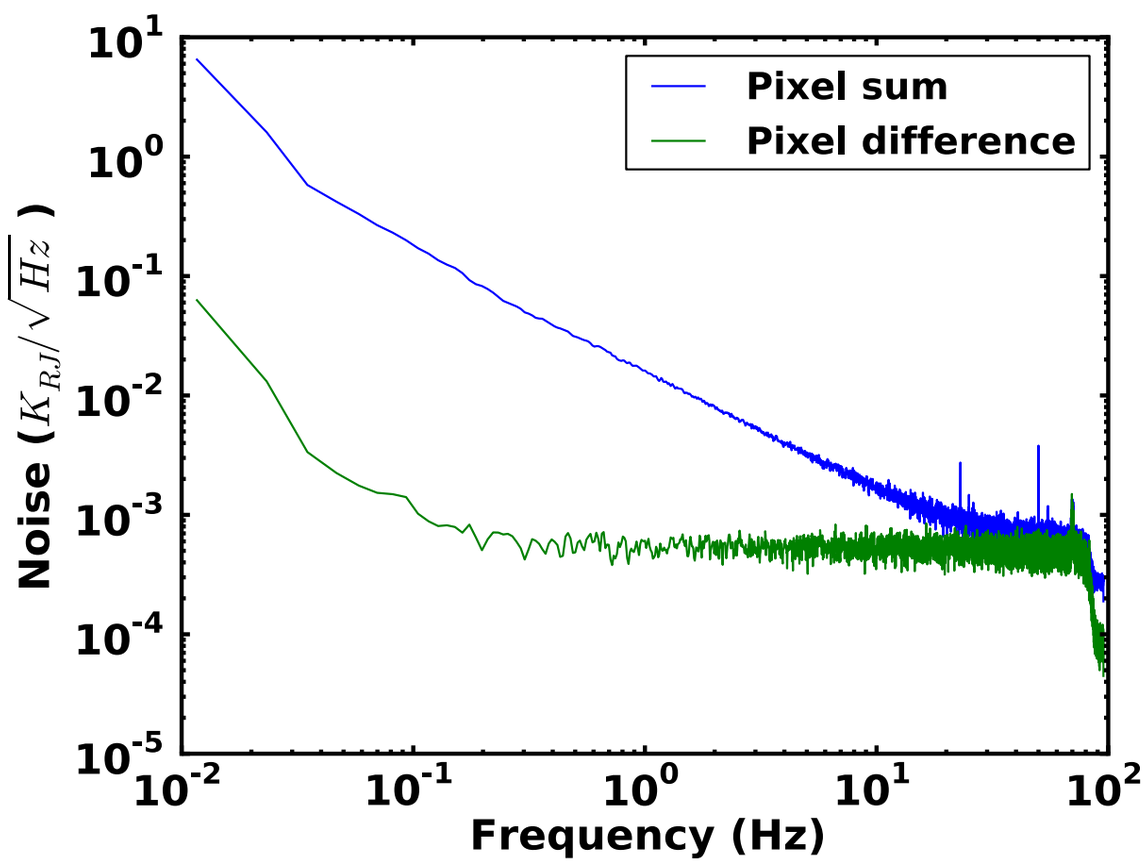


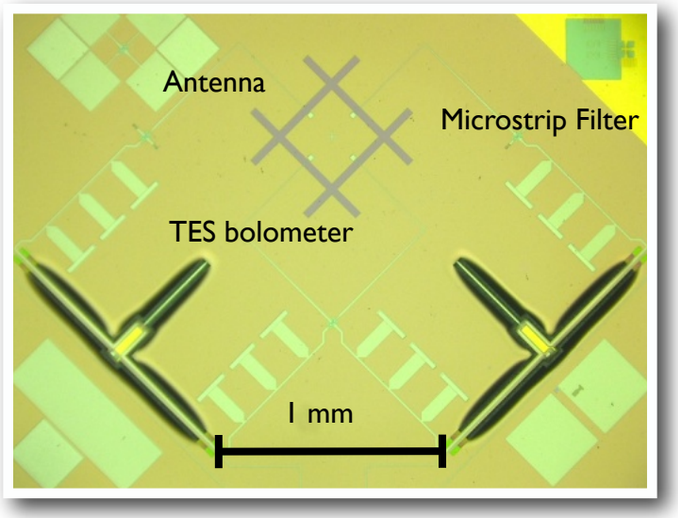


Instrument characterization

- Good availability of on-sky calibrators
- 3.5 arcmin beam FWHM
- Ellipticity < 5%, differential ellipticity 1%
- Array NET $25\mu K/\sqrt{Hz}$



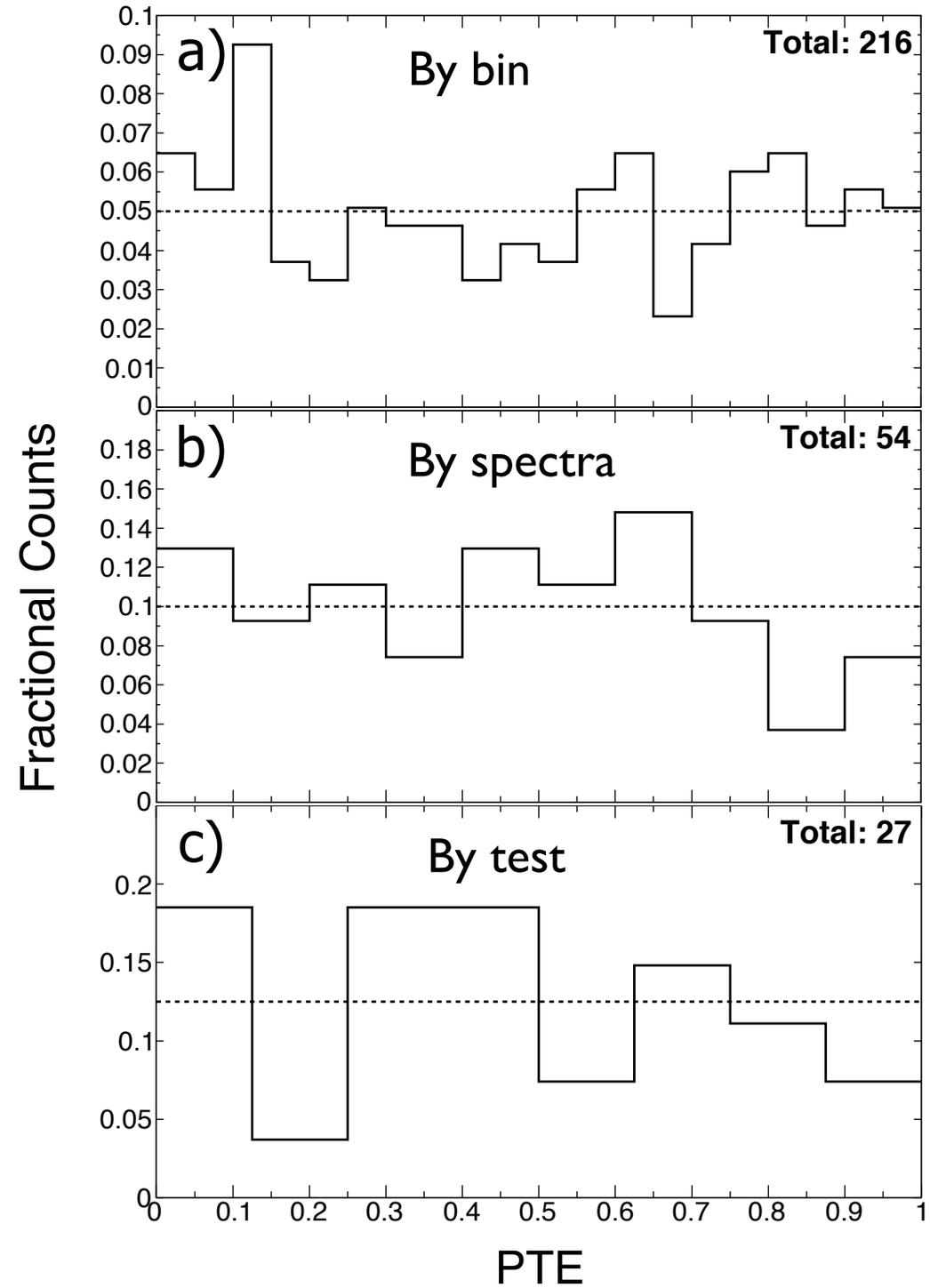




$$
\begin{aligned}
d^t(t) &= g_{top}\,[I(\hat{n}(t)) + Q(\hat{n}(t))\cos(2\psi(t)) + U(\hat{n}(t))\sin(2\psi(t))] \\
d^b(t) &= g_{bot}\,[I(\hat{n}(t)) - Q(\hat{n}(t))\cos(2\psi(t)) - U(\hat{n}(t))\sin(2\psi(t))]
\end{aligned}
$$

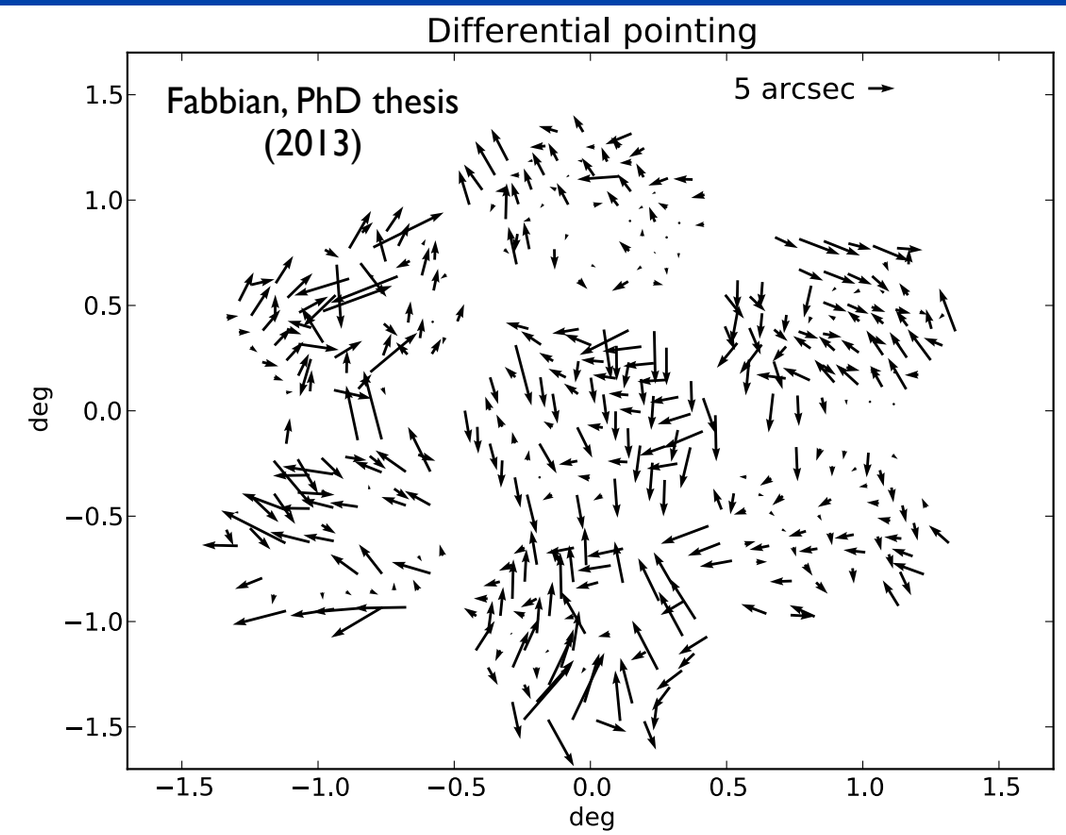
Instrumental systematics and data selection

- Blind-analysis policy: assess data selection and quality without looking at the scientific products
- Null-test suite:
  - temporal
  - scan properties
  - weather
  - calibration
  - detector selection
  - bright sources distance
- Kolmogorov-Smirnov test consistent with uniform probability PTEs distribution
- No significant outliers found!



Systematics error modeling

- *Ab initio* high-resolution instrumental systematics simulation pipeline
- 12 effects different effects analyzed
- Propagation of systematics error through science pipeline
- Sky-rotation helps mitigating systematics!



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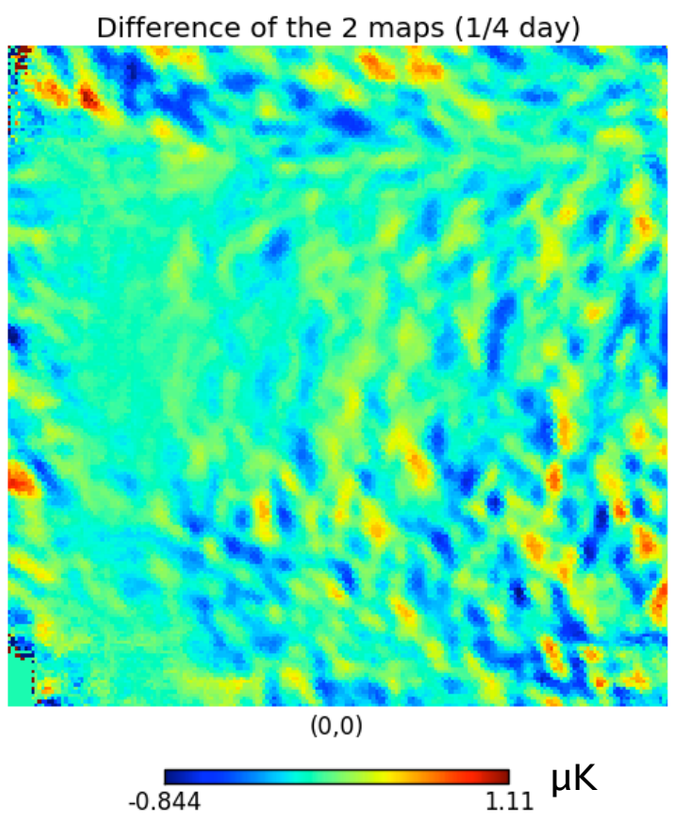

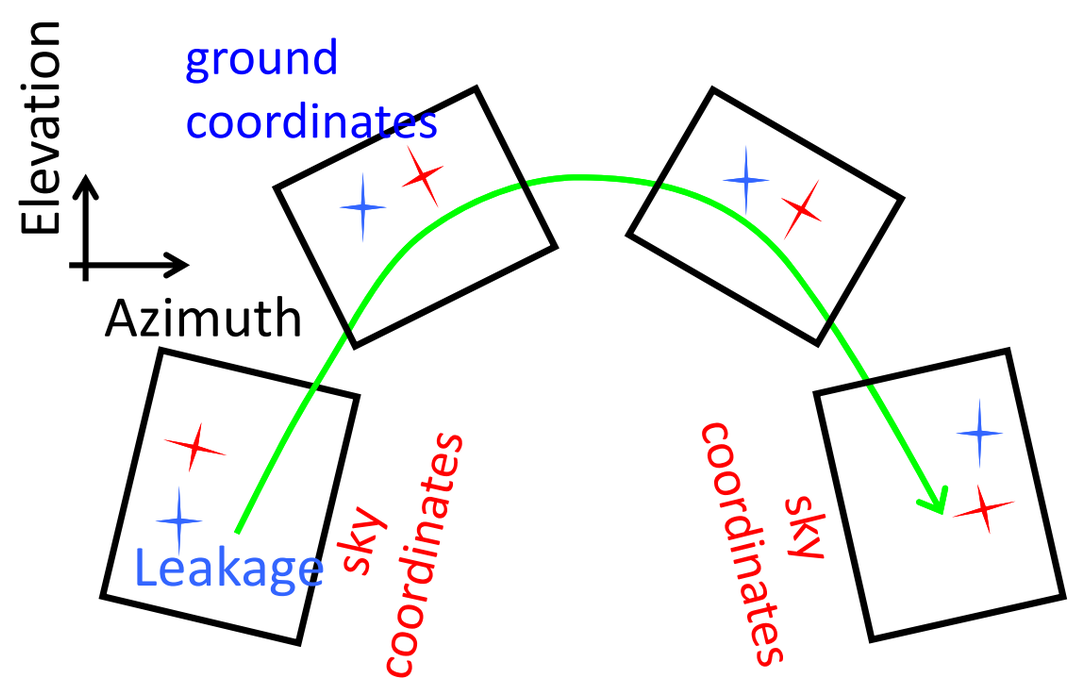

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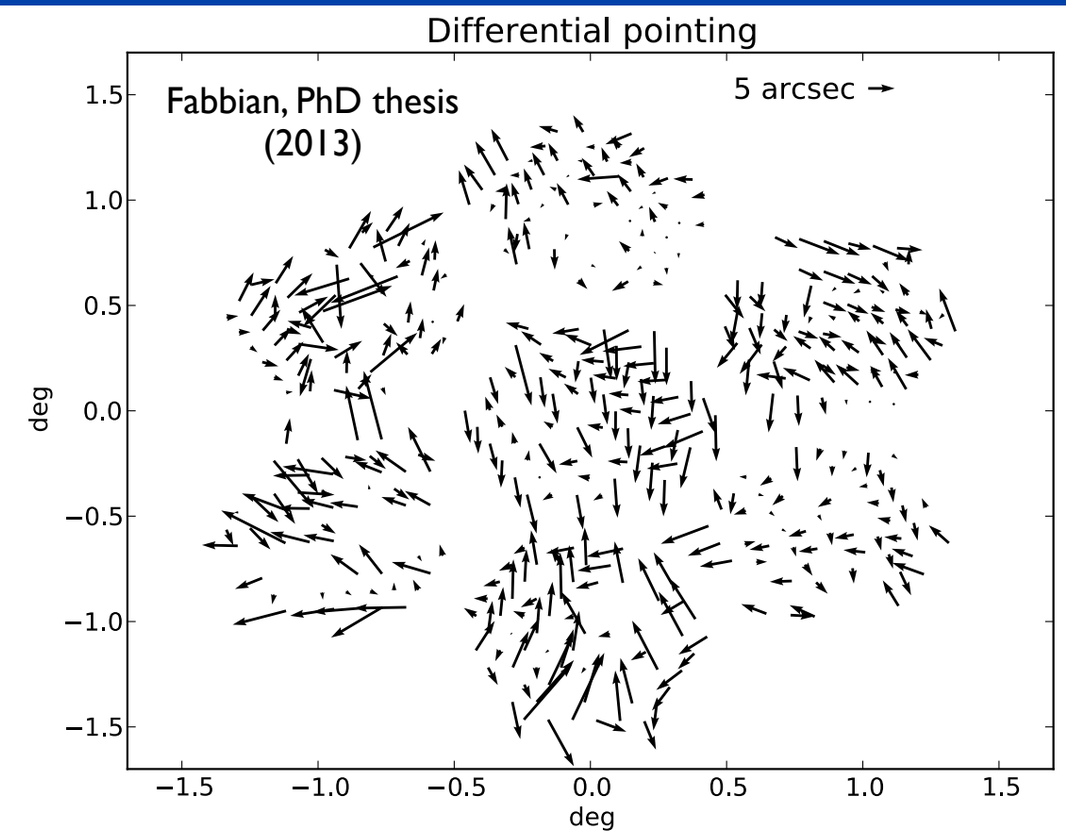

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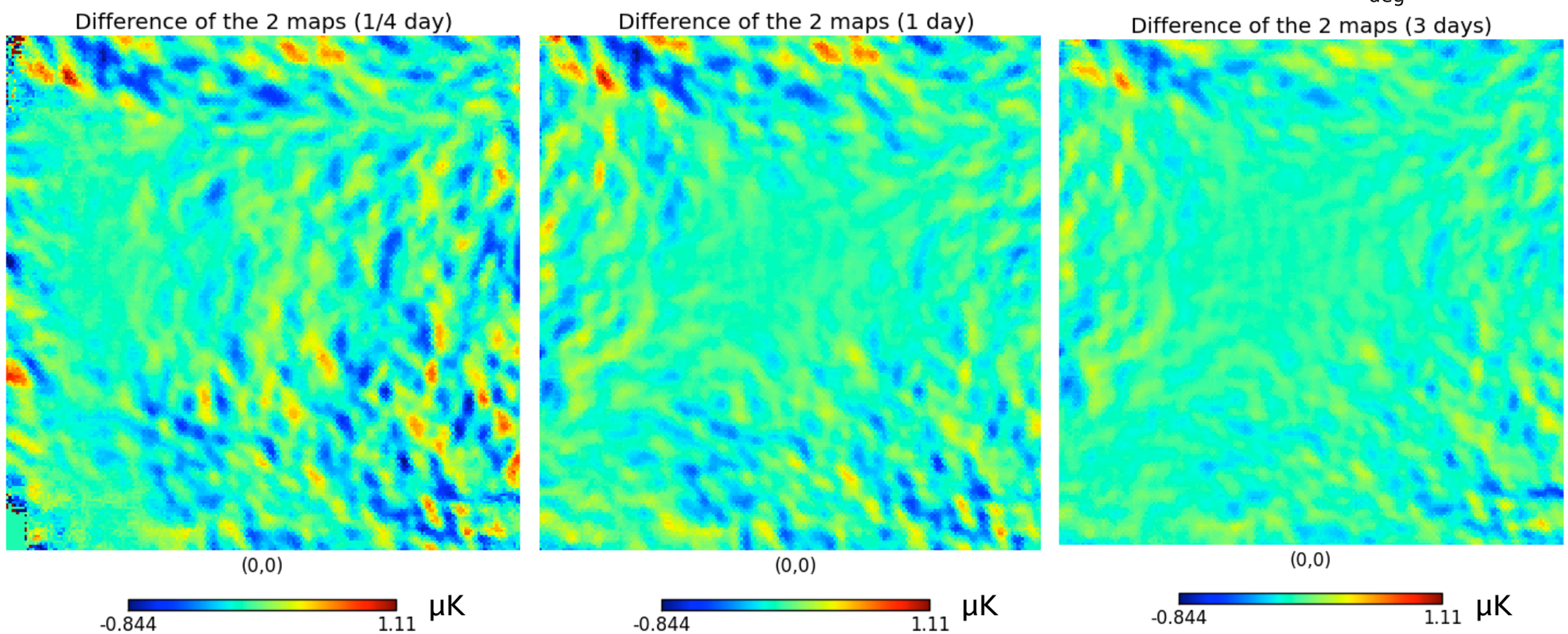
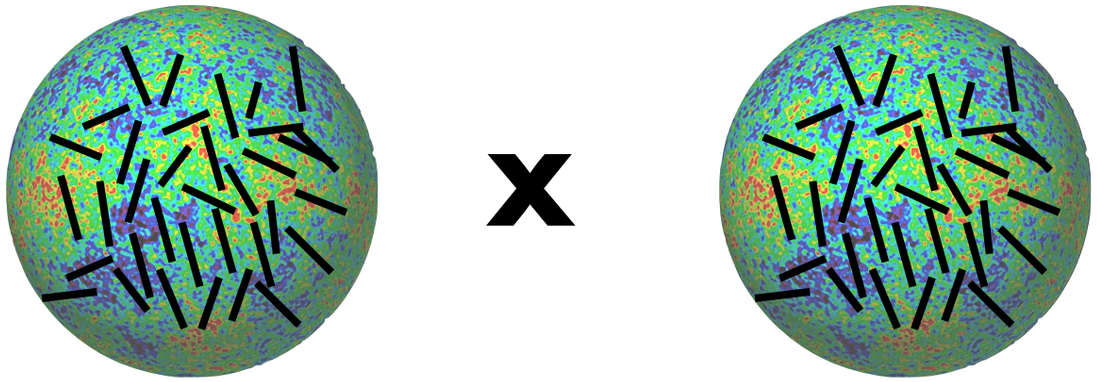


Which evidence for B-modes?

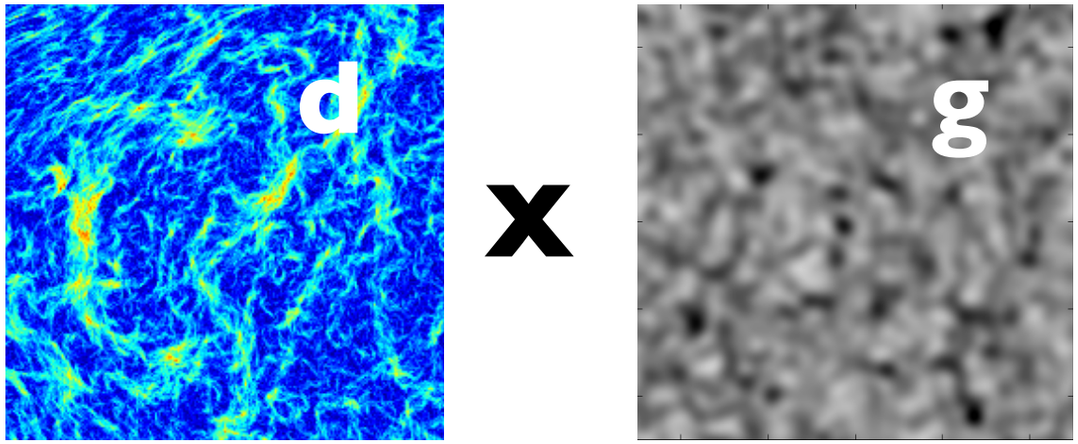
- 2-point correlation:
  CMB power spectrum

  arXiv:1403.2369 ApJ 2014. 794, 71



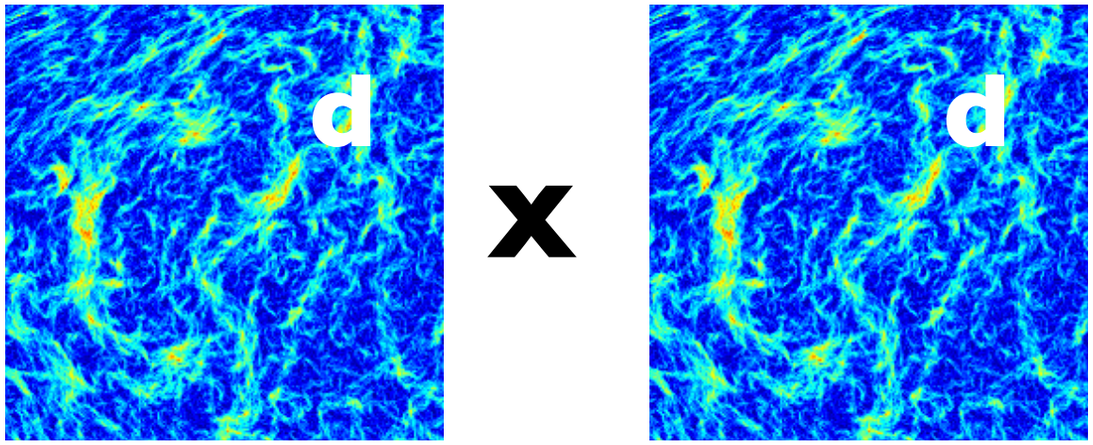
- 3-point correlation:
  CMB cross correlation with biased tracers of dark matter halos

  arXiv:1312.6646 PRL.112.131302



- 4-point correlation: lensing reconstruction with polarization

  arXiv:1312.6645 PRL.13.021301



Lensing reconstruction with polarization data

- Clean reconstruction of the deflection field from CMB polarization

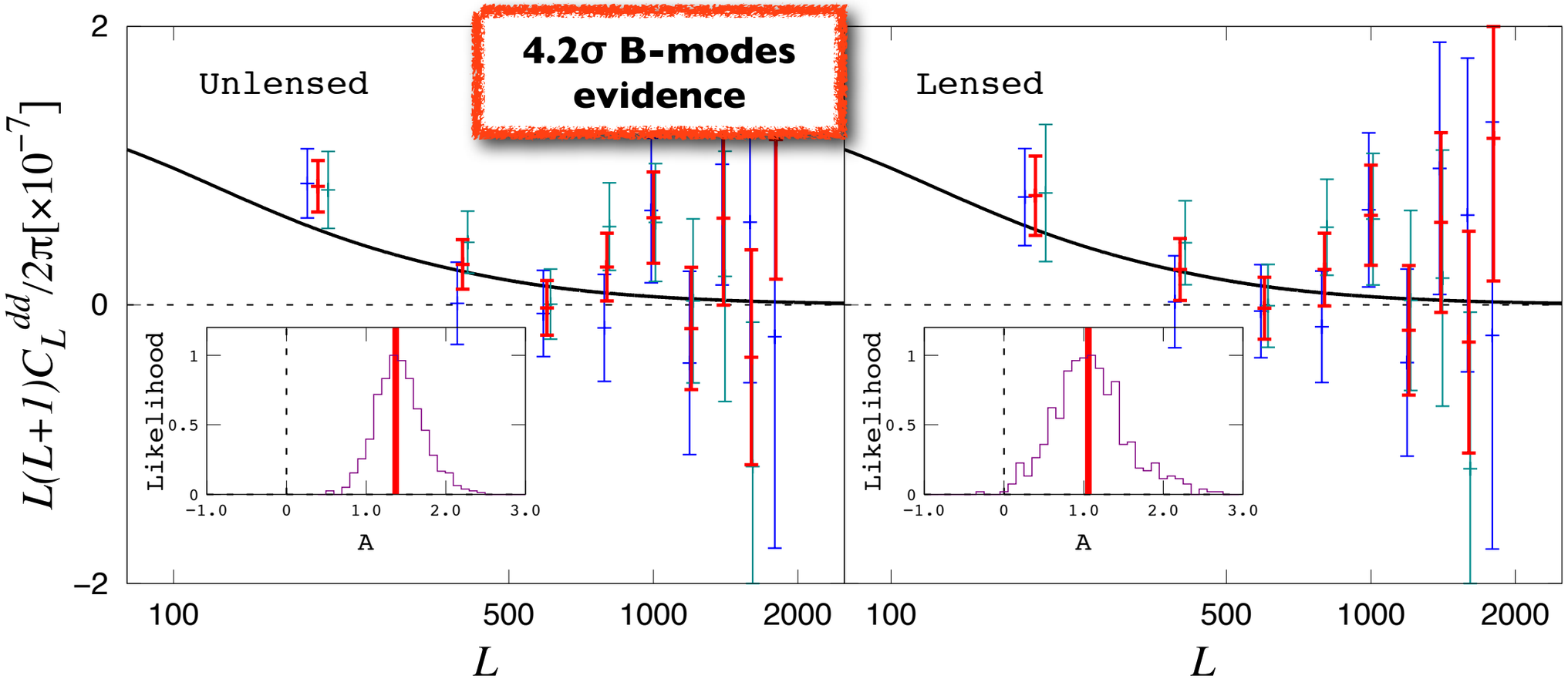
$$\boldsymbol{d} = \nabla\phi$$

$$d_{EB}(\mathbf{L}) = \frac{A_{EB}(L)}{L}\int \frac{d^2\mathbf{l}}{(2\pi)^2} E(\mathbf{l})B(\mathbf{l}')\frac{\tilde{C}_l^{EE}\mathbf{L}\cdot\mathbf{l}}{C_l^{EE}C_{l'}^{BB}}\sin 2\phi_{\mathbf{ll}'}$$

$$d_{EE}(\mathbf{L}) = \frac{A_{EE}(L)}{L}\int \frac{d^2\mathbf{l}}{(2\pi)^2} E(\mathbf{l})E(\mathbf{l}')\frac{\tilde{C}_l^{EE}\mathbf{L}\cdot\mathbf{l}}{C_l^{EE}C_{l'}^{EE}}\cos 2\phi_{\mathbf{ll}'}$$

$$\longrightarrow \mathcal{A}/\Delta\mathcal{A}$$

- Detection of lensing of CMB polarization from CMB alone



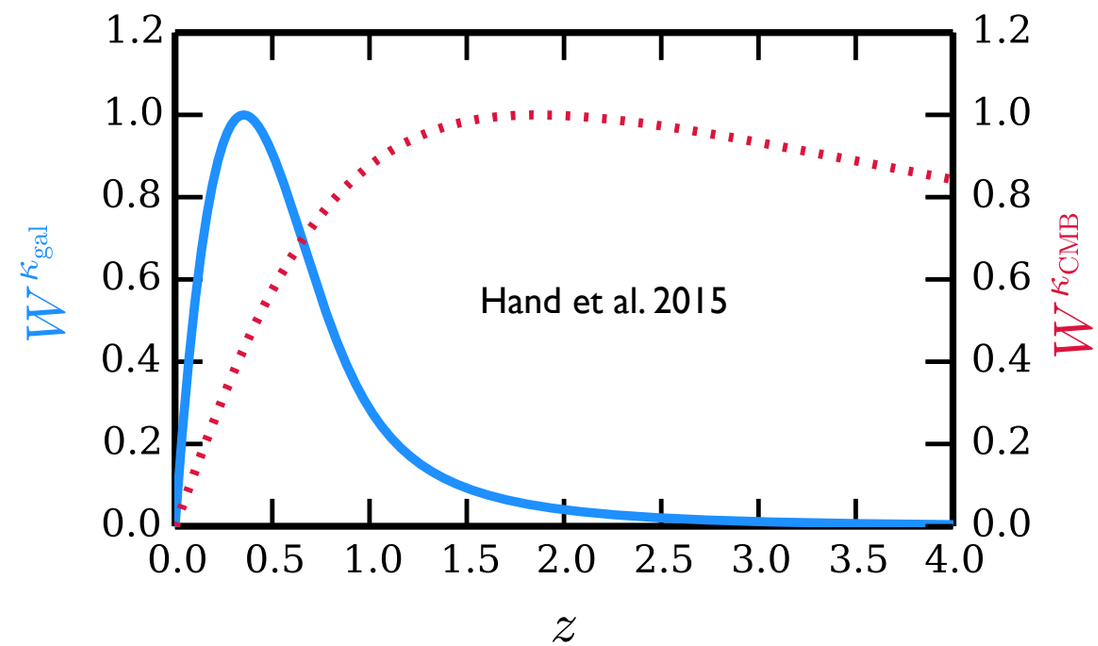
POLARBEAR/HERSCHEL cross-correlation

- CMB lensing convergence $\kappa = -\frac{1}{2}\nabla \cdot \mathbf{d}$ and large scale structures trace the same dark matter distribution

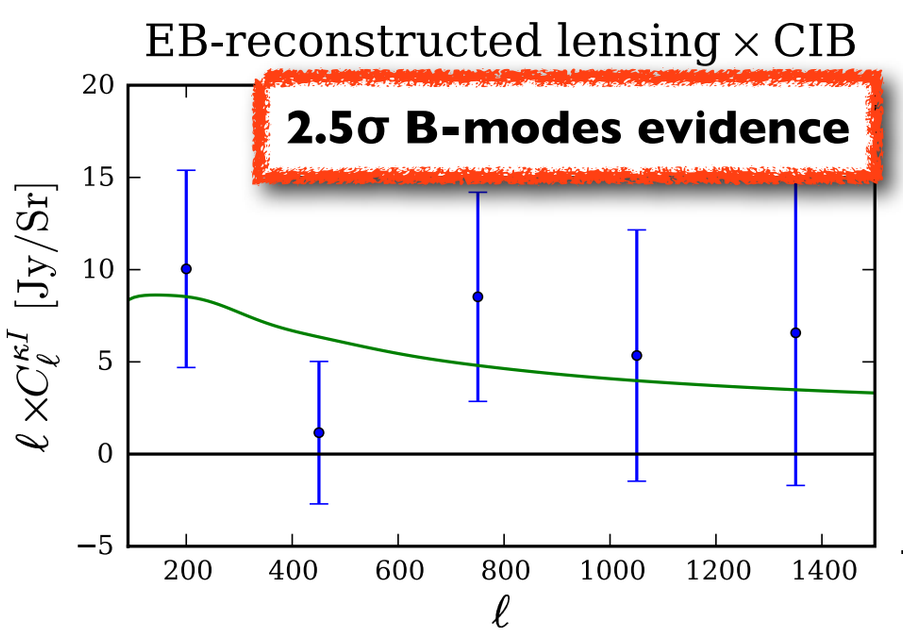
$$W^{\kappa}(z) = \frac{3}{2H(z)}\Omega_0 H_0^2 (1+z)\eta(z)\frac{(\eta^* - \eta(z))}{\eta^*}$$

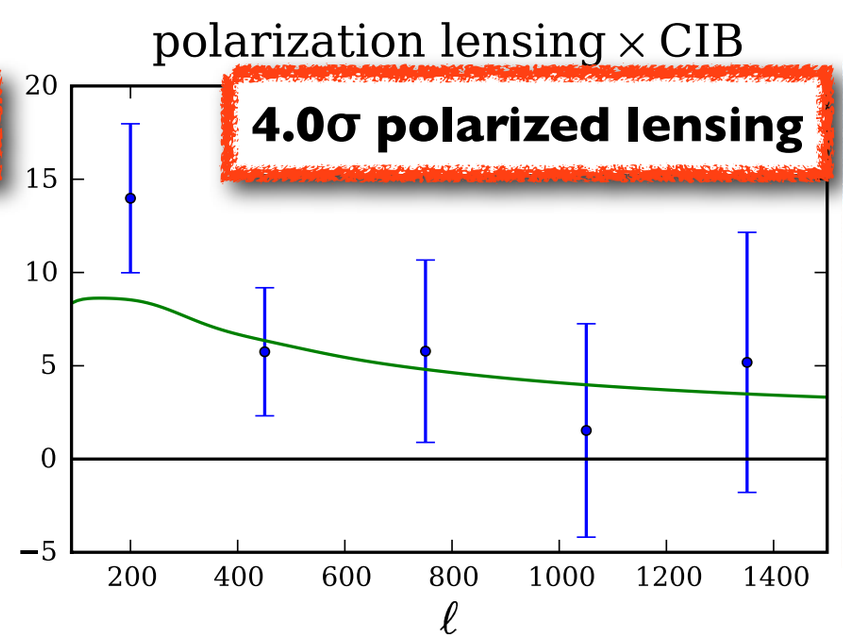
$$W^{I}(z) = \frac{3}{2}\Omega_m H_0^2 \frac{(1+z)}{H(z)}\frac{\eta(z)}{c}\int_z^{\infty} dz' \frac{dN^I}{dz'}\frac{\eta(z') - \eta(z)}{\eta(z')}$$

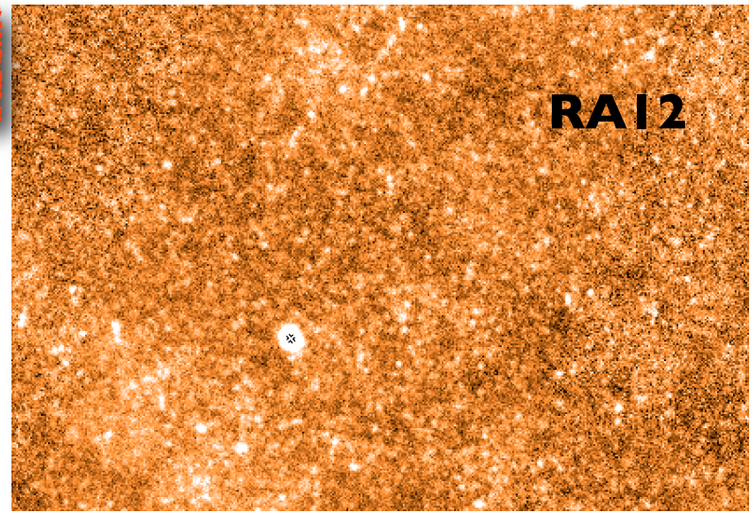
$$C_\ell^{\kappa I} = \int \frac{dz H(z)}{\eta^2(z)} W^{\kappa}(z) W^{I}(z) P(k = \ell/\eta(z), z)$$



- HERSCHEL/SPIRE H-ATLAS data and POLARBEAR convergence





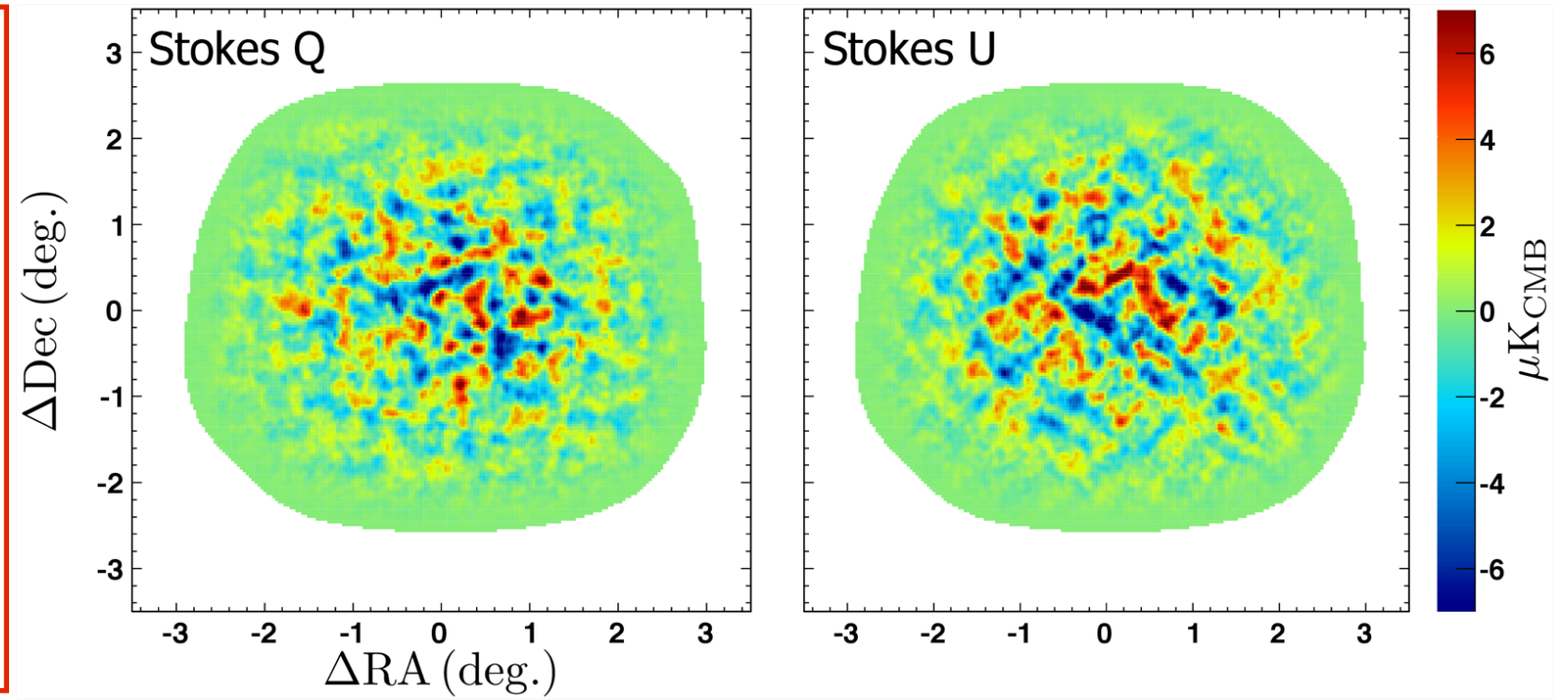


Data analysis framework

- Filtered mapmaking

$$\hat{s} = (A^T N^{-1} A)^{-1} A^T N^{-1} F d$$

- Flat-sky MASTER power spectrum estimation with daily cross-spectra

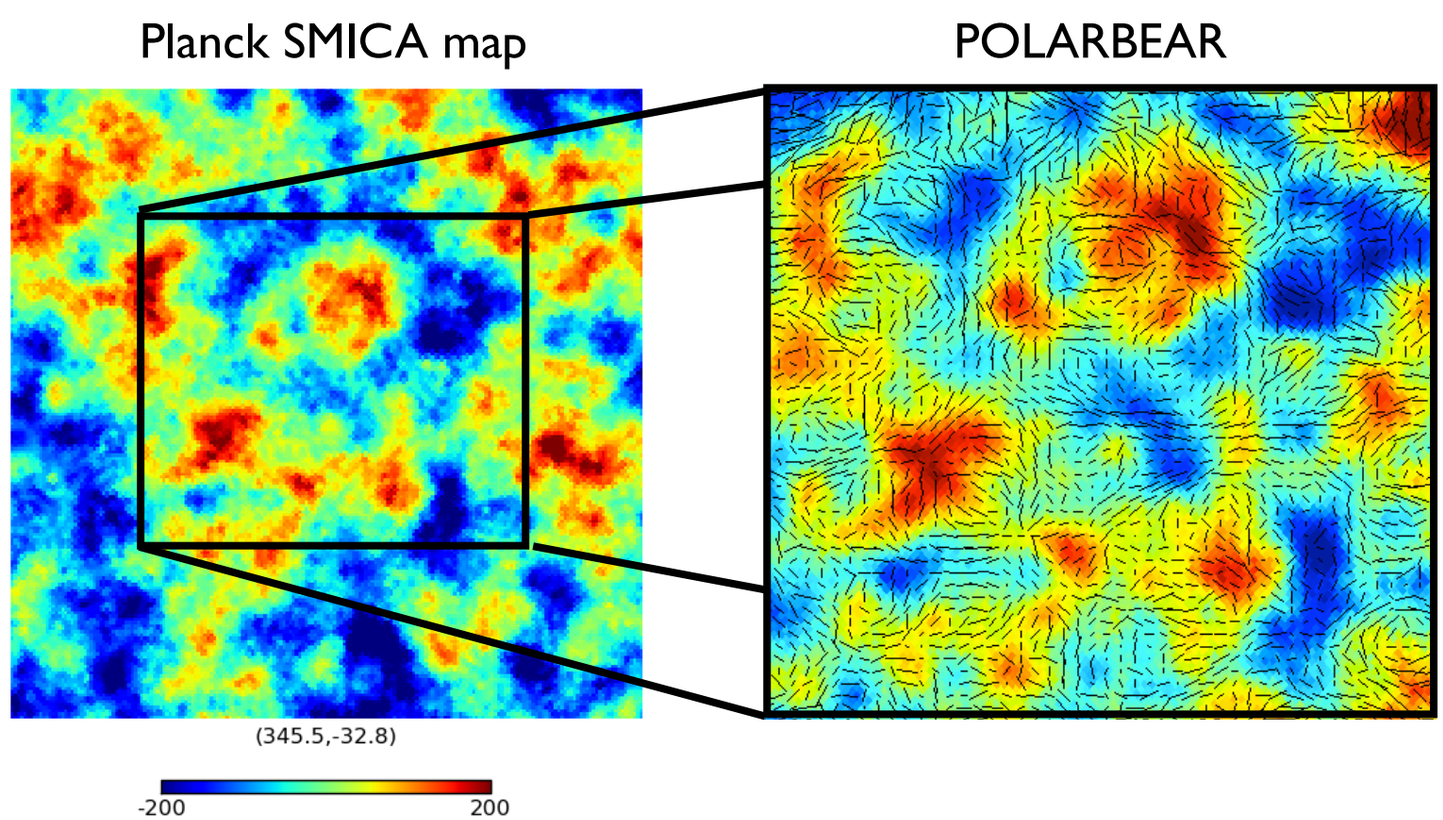


Cross check and validation

- Unbiased mapmaking

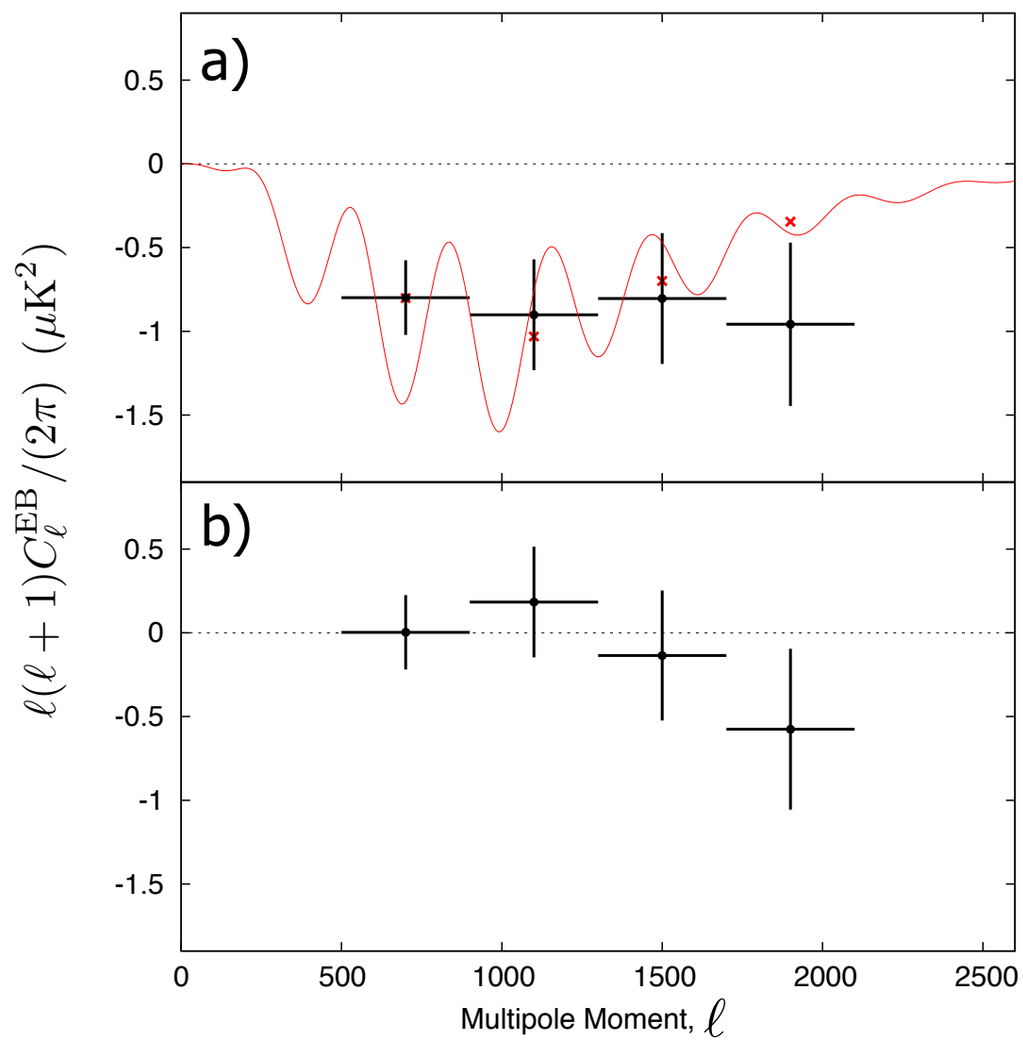
$$(A^T F A)\hat{s}_{ith} = A^T F d$$

- Curved sky pure-pseudo power spectrum estimation

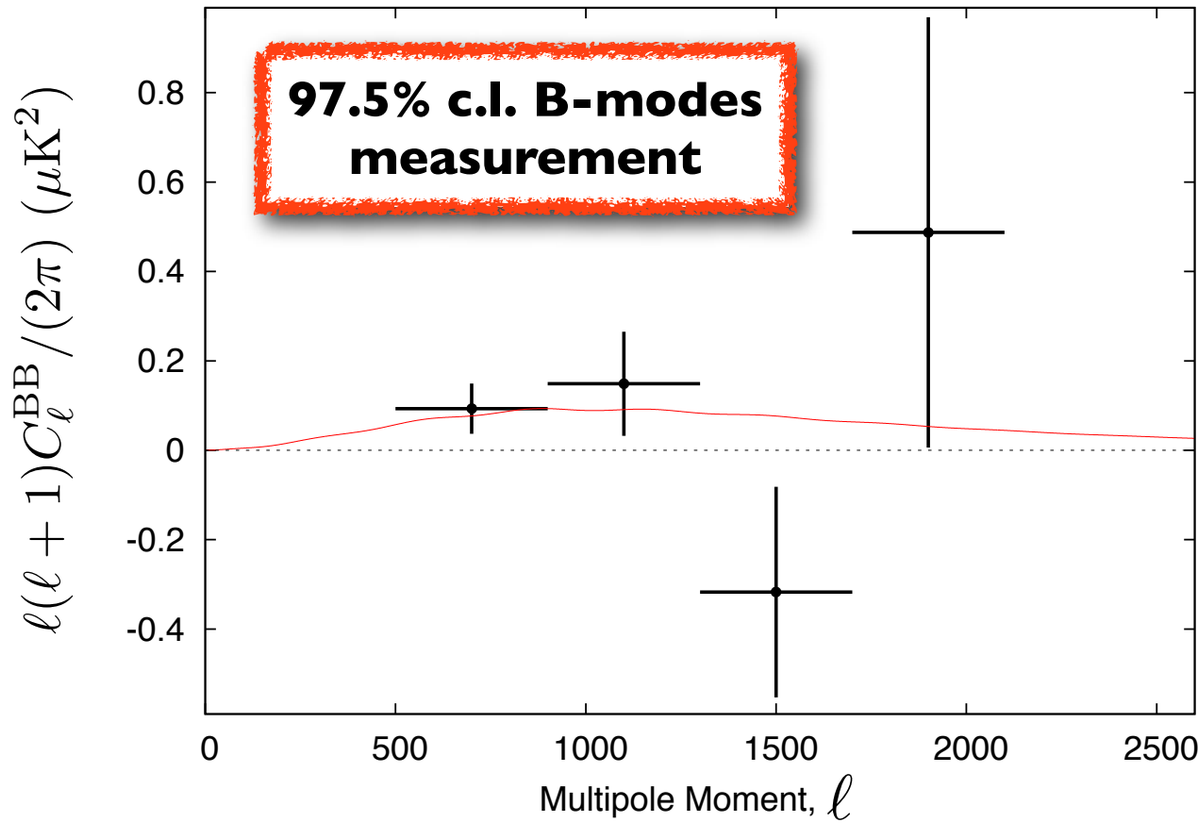


B-modes power spectrum measurement

- Polarization angle self-calibration from detected EB power (~1deg)
- Negligible contamination from diffuse astrophysical foregrounds with conservative assumptions
- First direct evidence of lensing B-modes

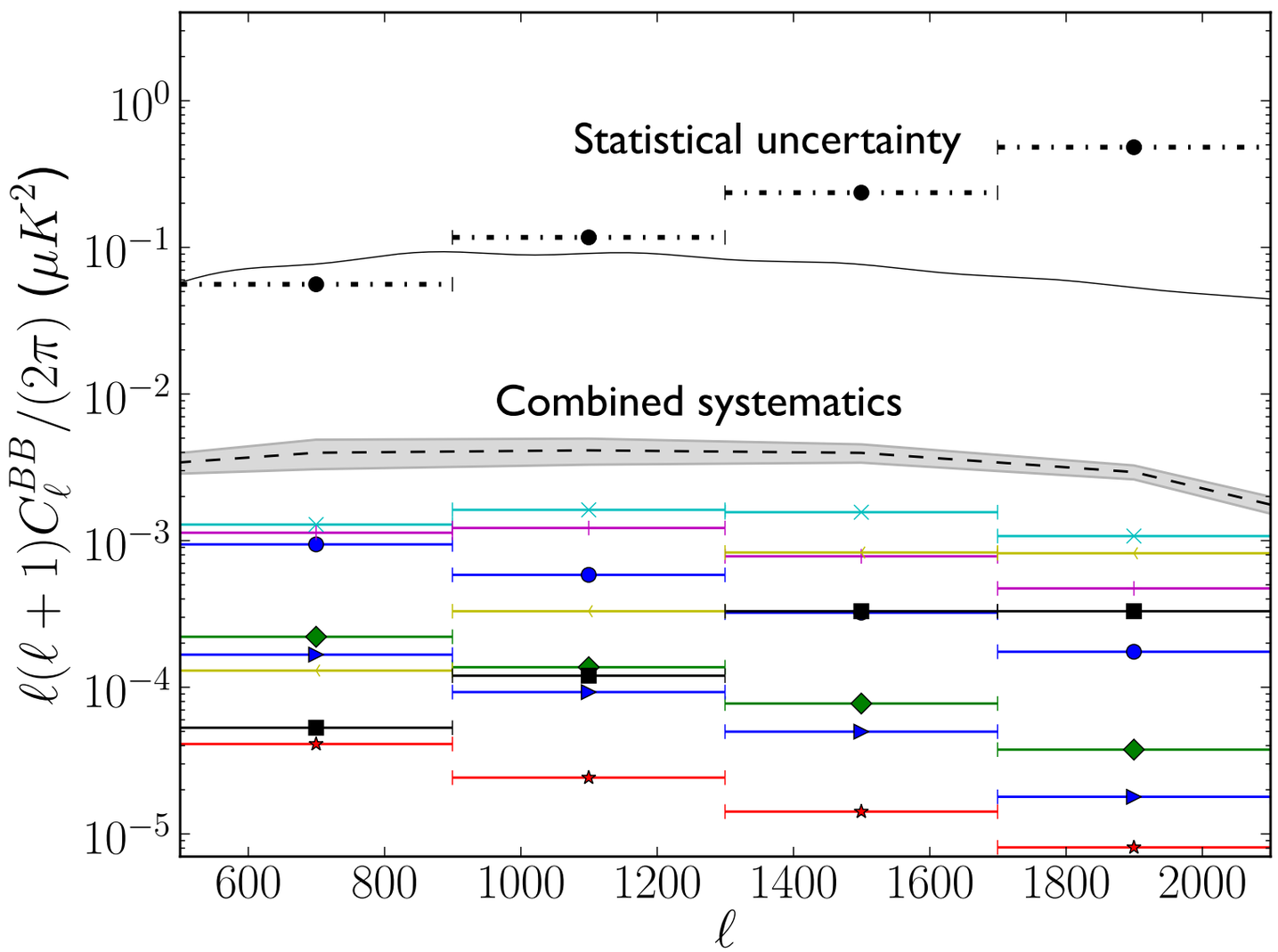


$$A_{BB} = 1.12 \pm 0.61({\rm stat})^{+0.04}_{-0.10}({\rm sys}) \pm 0.07({\rm multi})$$



Control of instrumental systematics

- No temperature-polarization correlation detected on map level
- Result robust to systematics marginalization for different type of leakages
- Careful instrumental systematics uncertainties propagation: negligible!



Most notably:

Boresight and differential pointing

Differential beam size

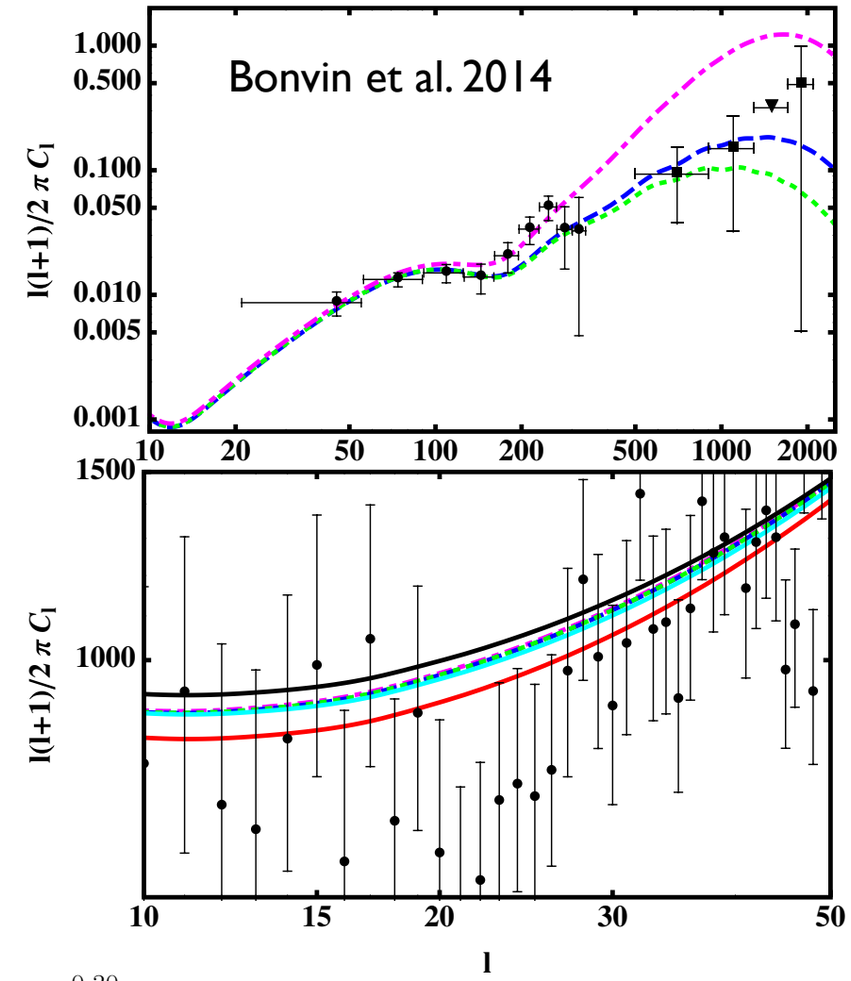
Polarization angle

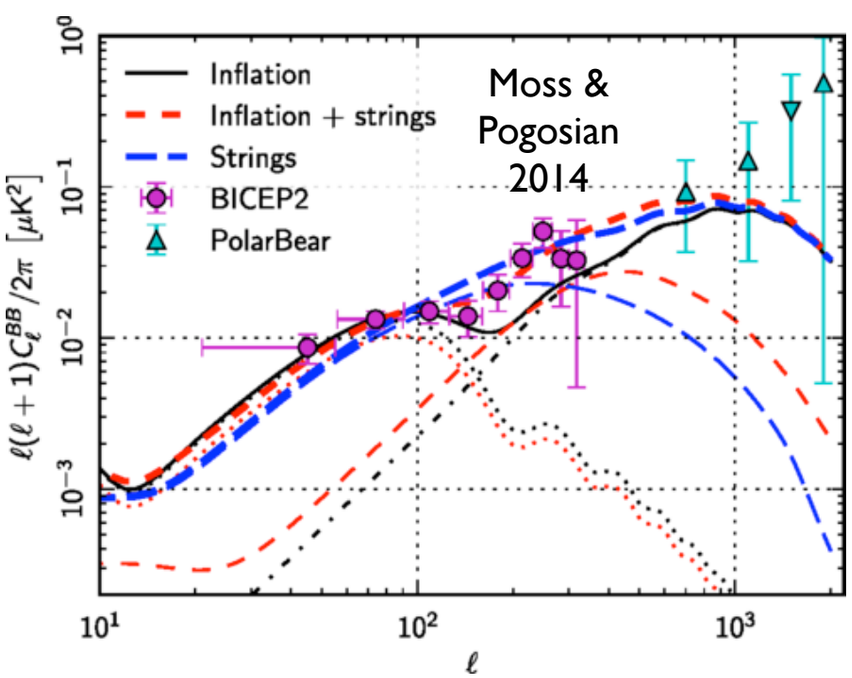
Differential beam ellipticity

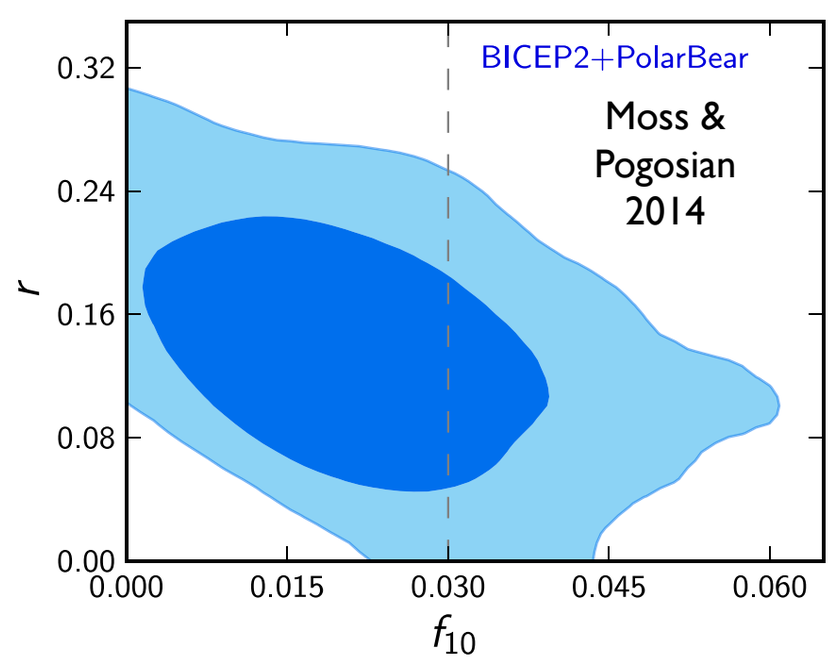
HWP dependent gain

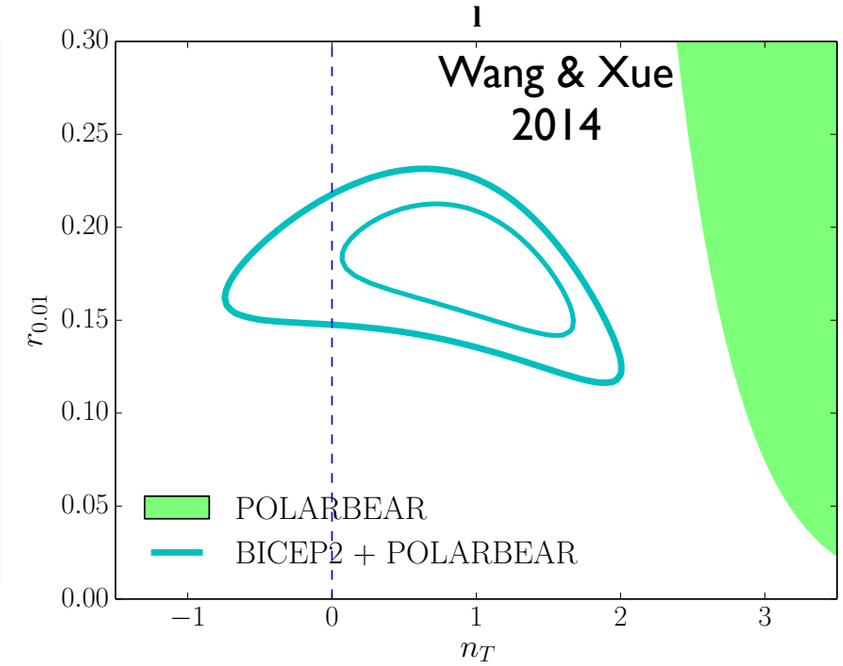
Cosmological constraints with POLARBEAR

- Constraints on inflationary magnetogenesis: compatible with lower r and blue tensor spectra
- Cosmic defects / vector plus tensor modes can explain data but rule out local strings
- Alternatives to inflation can be tightly constrained:
  - string gas cosmology with blue tensor spectrum
  - slow roll or null energy condition violation



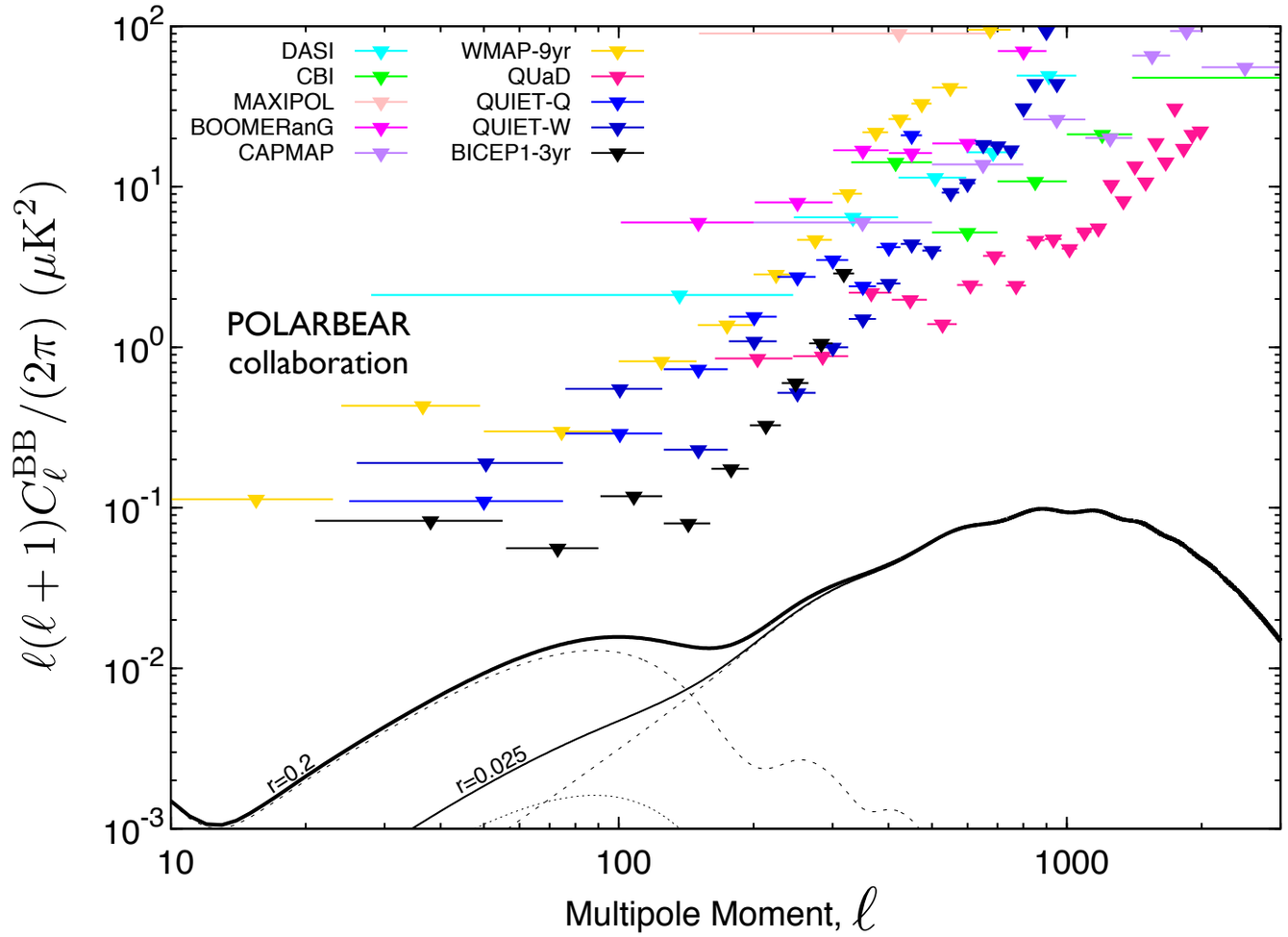




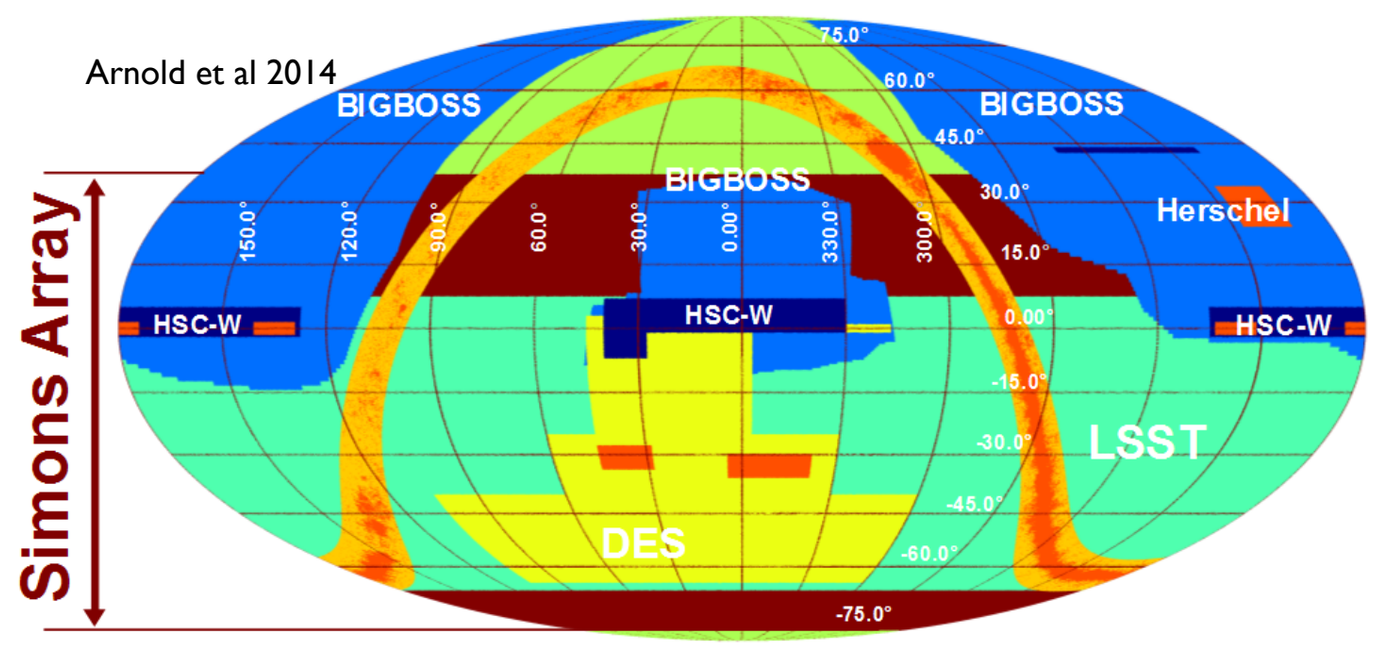


Conclusions

- B-modes era has begun and accuracy is rapidly increasing!
- POLARBEAR season 1:
  - Multiple probes for a combined evidence of 4.7σ
  - Systematics under control
- Future: high sensitivity and foreground rejection with POLARBEAR2 and Simons Array
- Data analysis of 2nd season ongoing, results coming soon!



Arnold et al 2014



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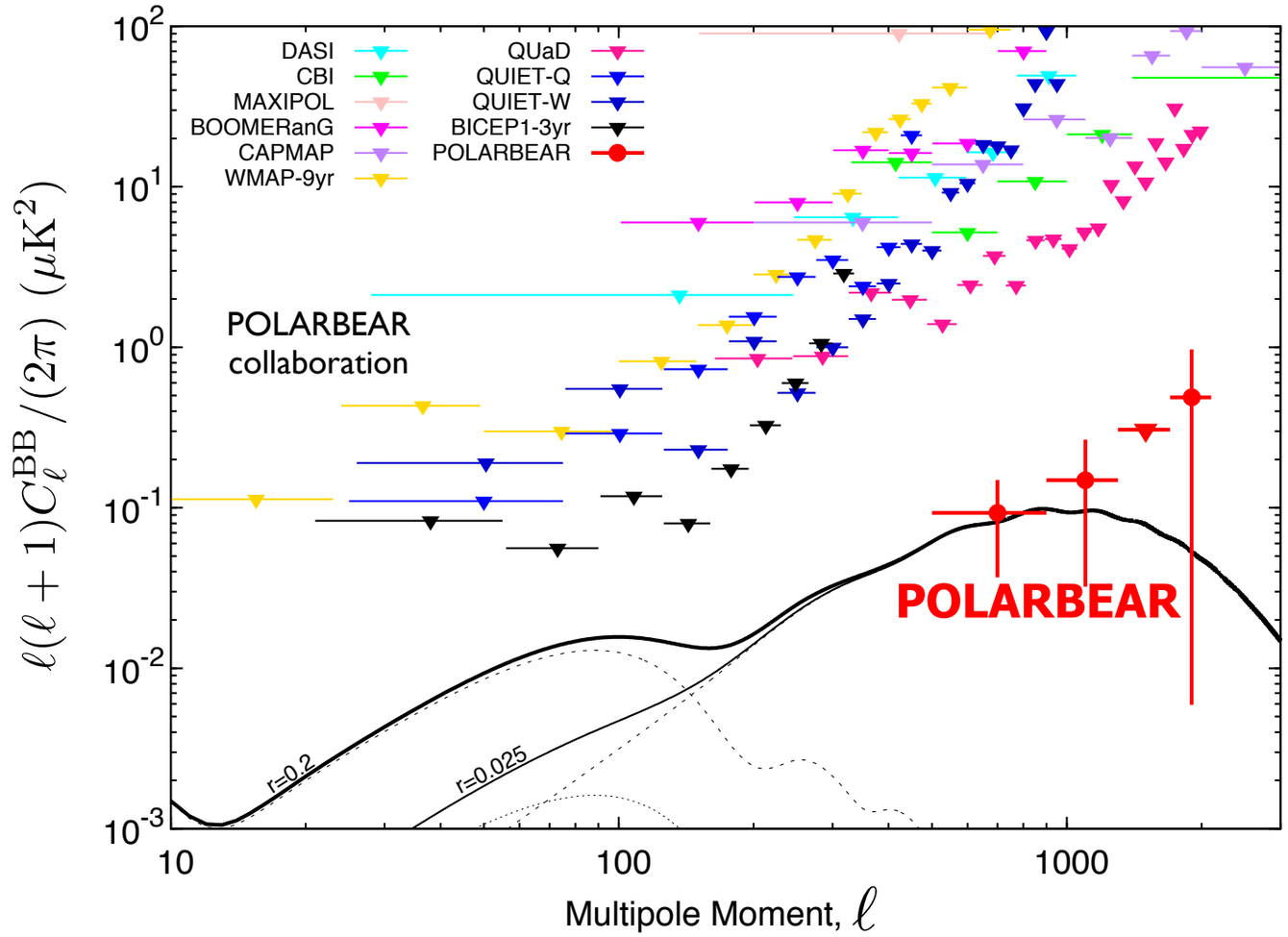

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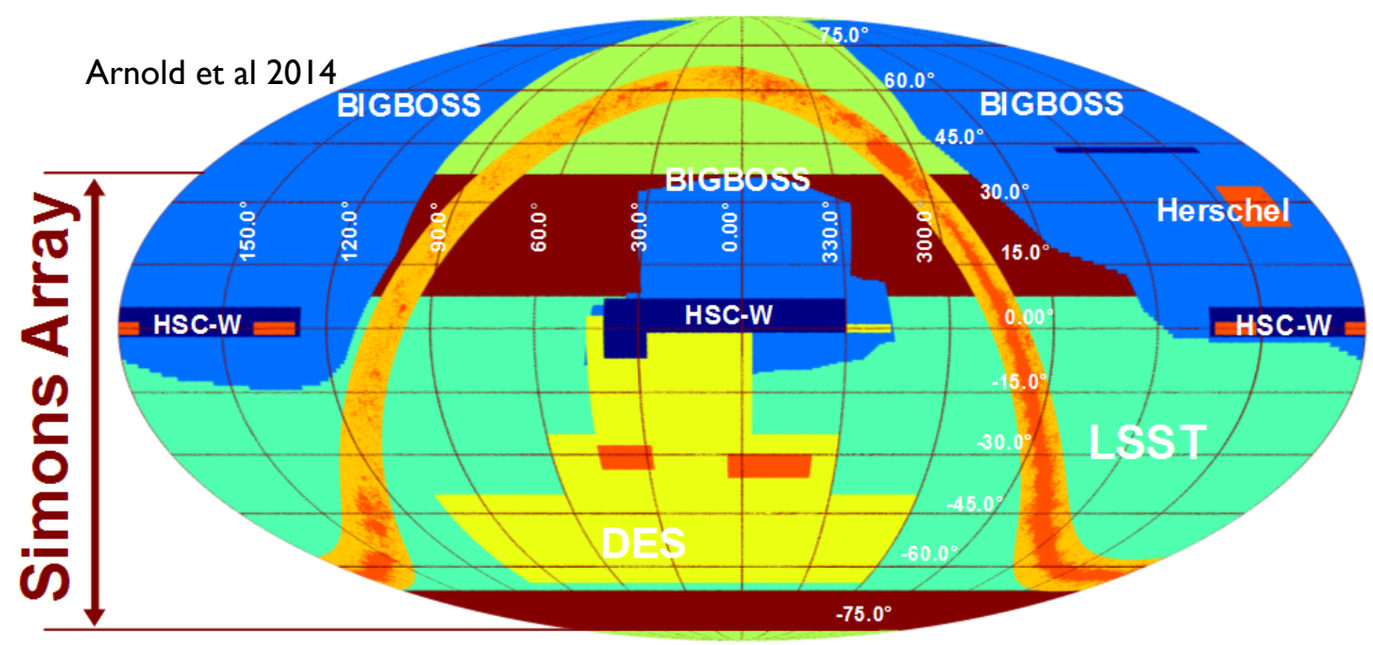

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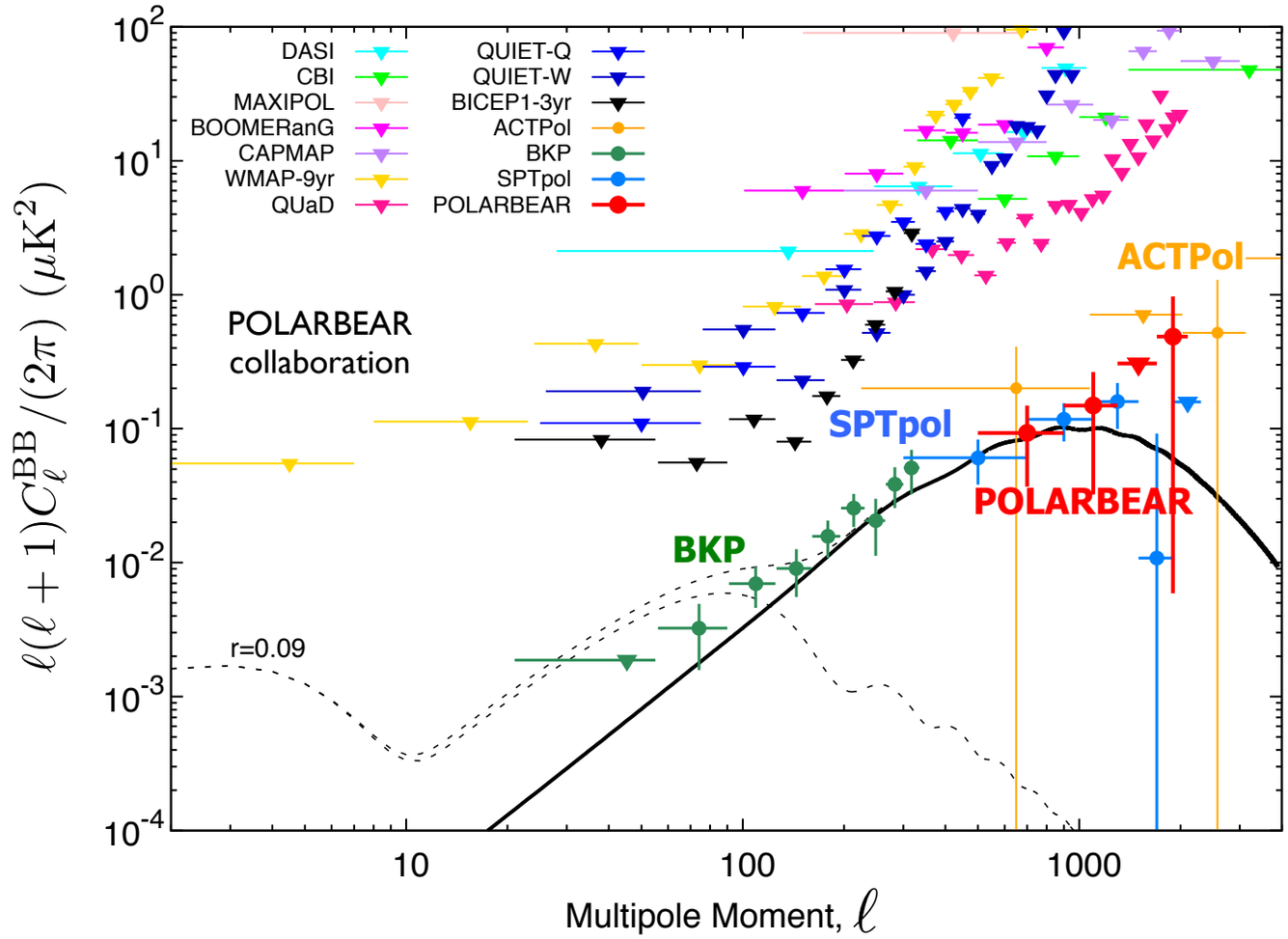

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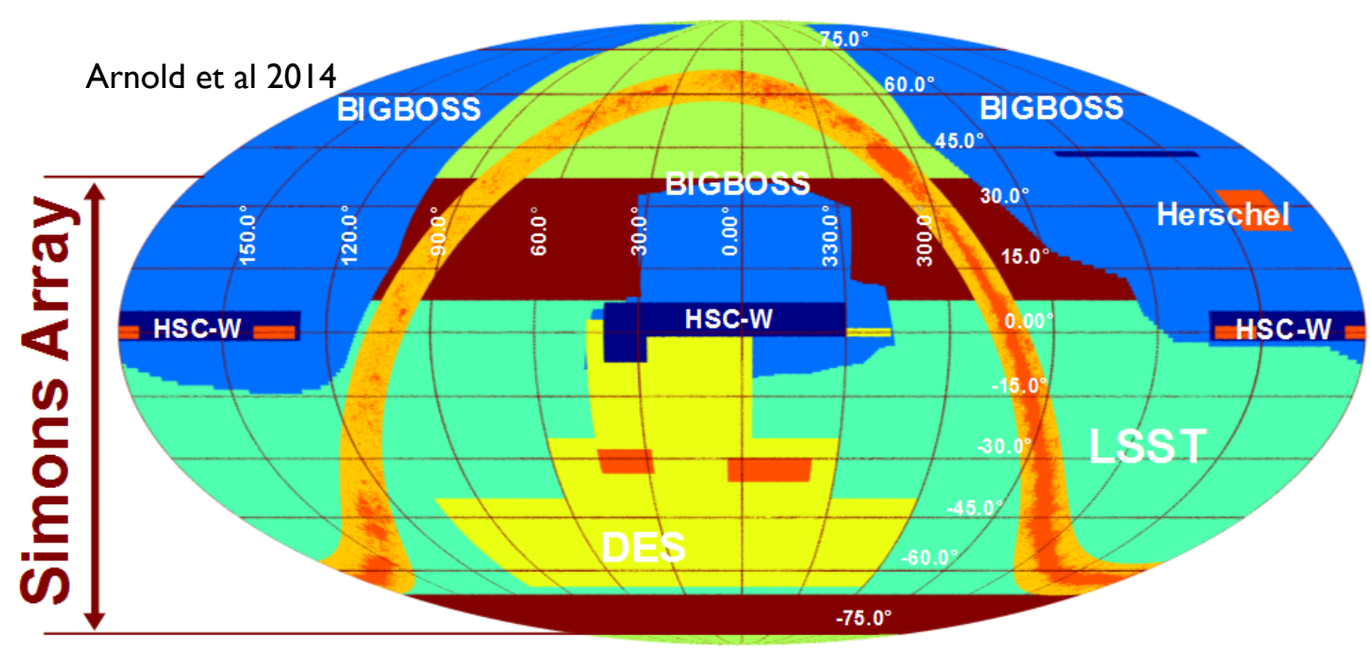

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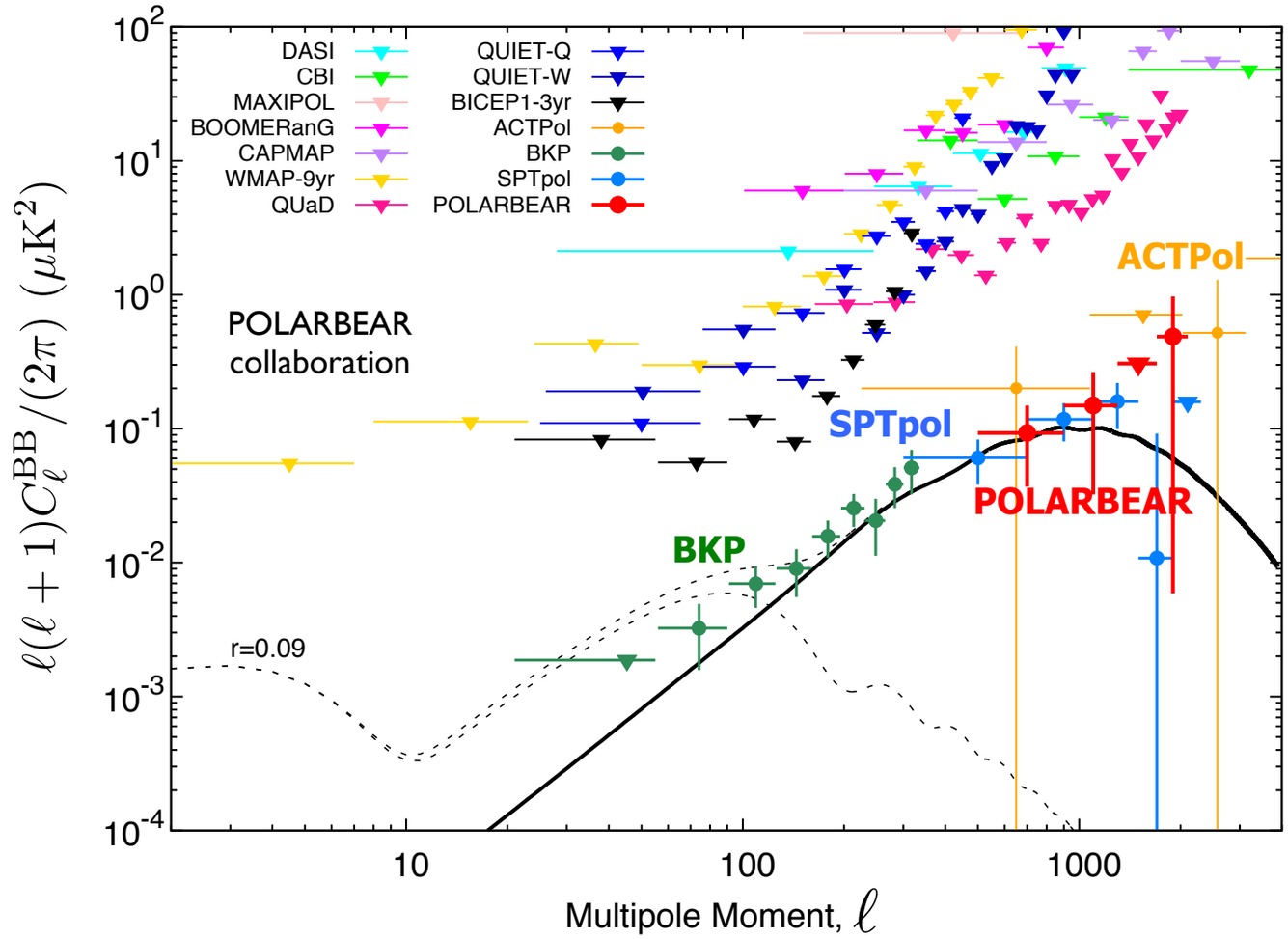


THANK
YOU
GRACIAS
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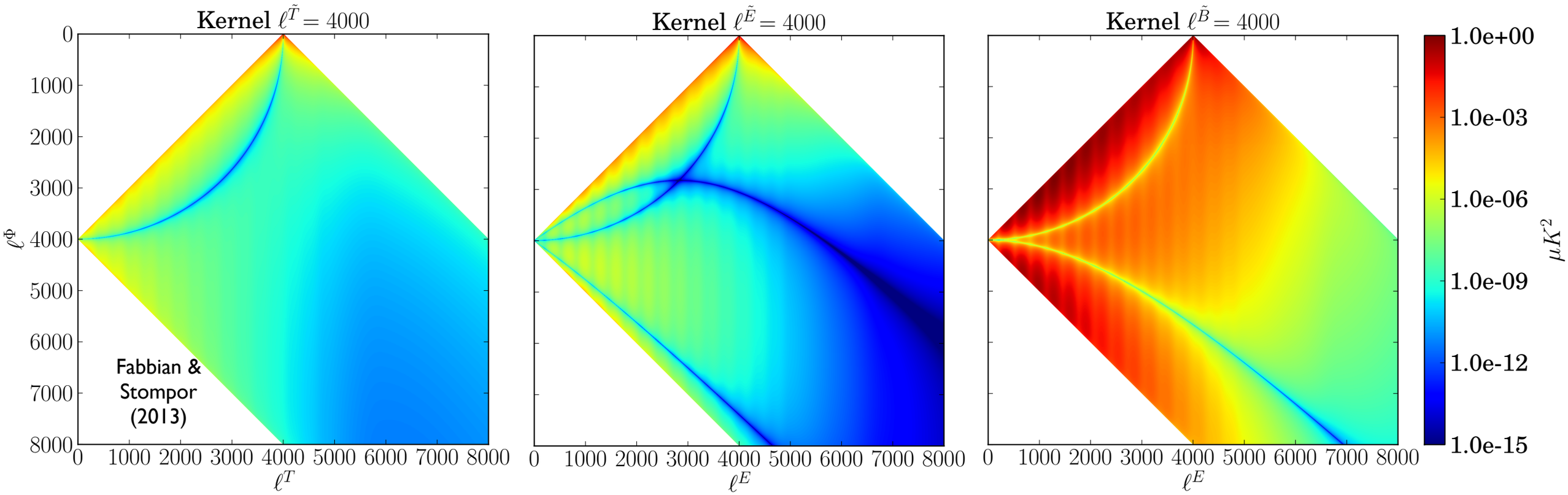
BOLZÏN
MERCI
DANKSCHEEN
BÏYAN
SHUKRIA
TINGKI
YAQHANYELAY
TASHAKKUR ATU
SUKSAMA
EKHMET
GRAZIE
MEHRBANI
MAAKE
SUMNIDA
KOMAP
PALDIES
GOZAIMASHITA
EFCHARISTO
JUSPAXAR

Two words on lensing reconstruction

- Lensing act as a convolution in harmonic domain

$$\tilde{C}^{BB}_{\tilde{\ell}^B} = \frac{1}{2}\sum_{\ell^\Phi \ell^E} \frac{|{}_2F_{\tilde{\ell}^B \ell^\Phi \ell^E}|^2}{2\tilde{\ell}^B + 1} C^{\Phi\Phi}_{\ell^\Phi} C^{EE}_{\ell^E}(1-(-1)^L)$$

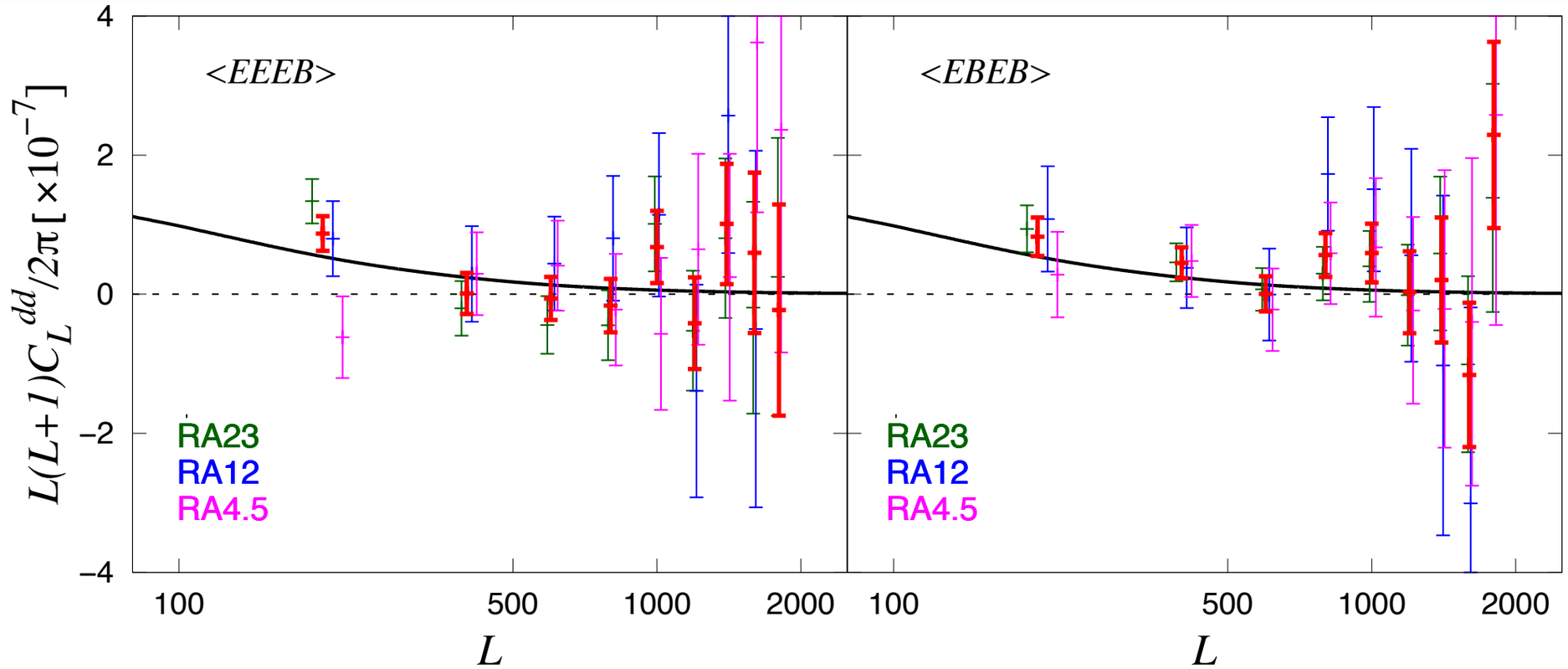
Temperature | E-modes | B-modes



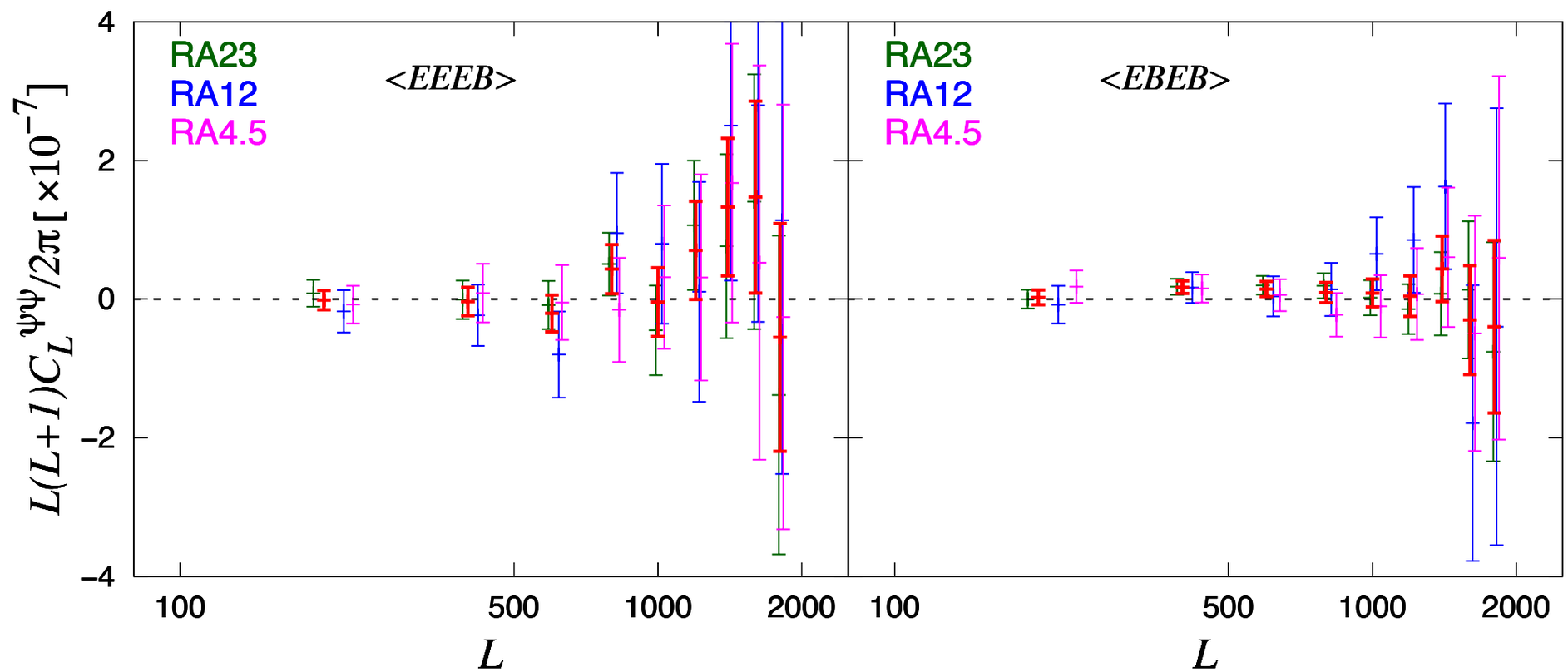
- B-modes are the most powerful observable for CMB lensing science

Lensing reconstruction robustness

- Single channel and patch combined



- Swap-patch, channel, curl-mode null-tests passed



Lensing and cross-correlation systematics estimate

- Lensing systematics:

Systematics	$\Delta\mathcal{A}$
Pol. point sources	±0.08 (±0.14)
0.5% T→{Q,U}	±0.10 (±0.13)
Beam uncert.	$^{+0.19}_{-0.16}$
Calibration	$^{+0.22}_{-0.18}$
Total	±0.13 ($^{+0.32}_{-0.27}$)

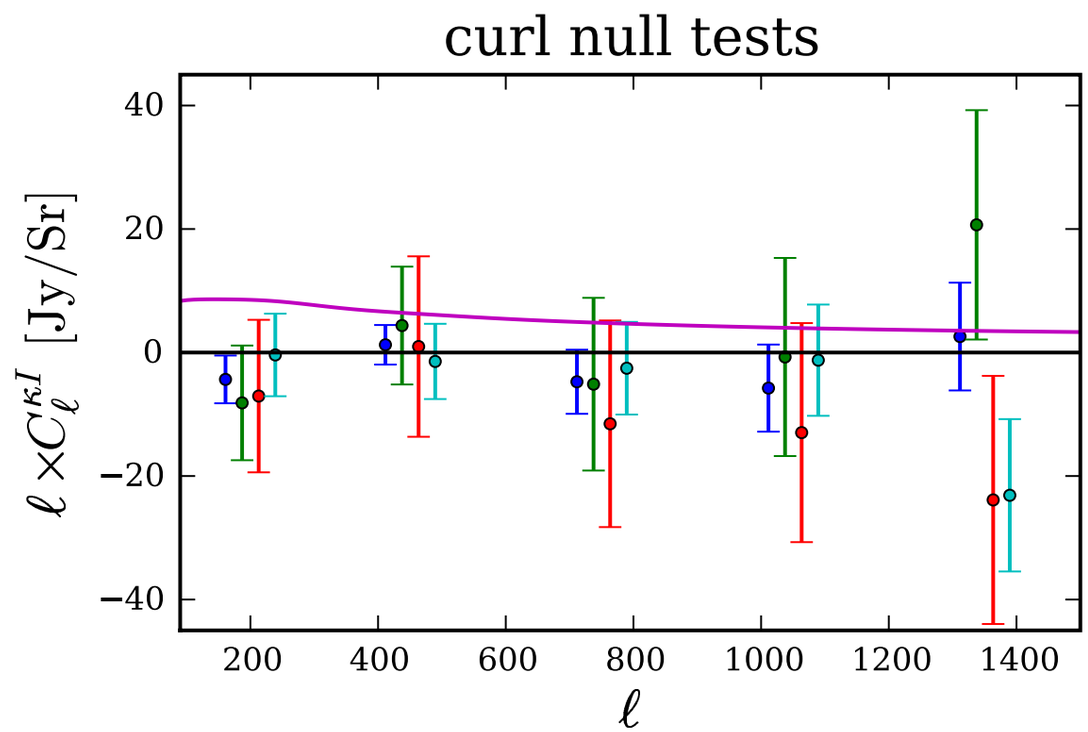
- Cross-correlation is insensitive to systematics

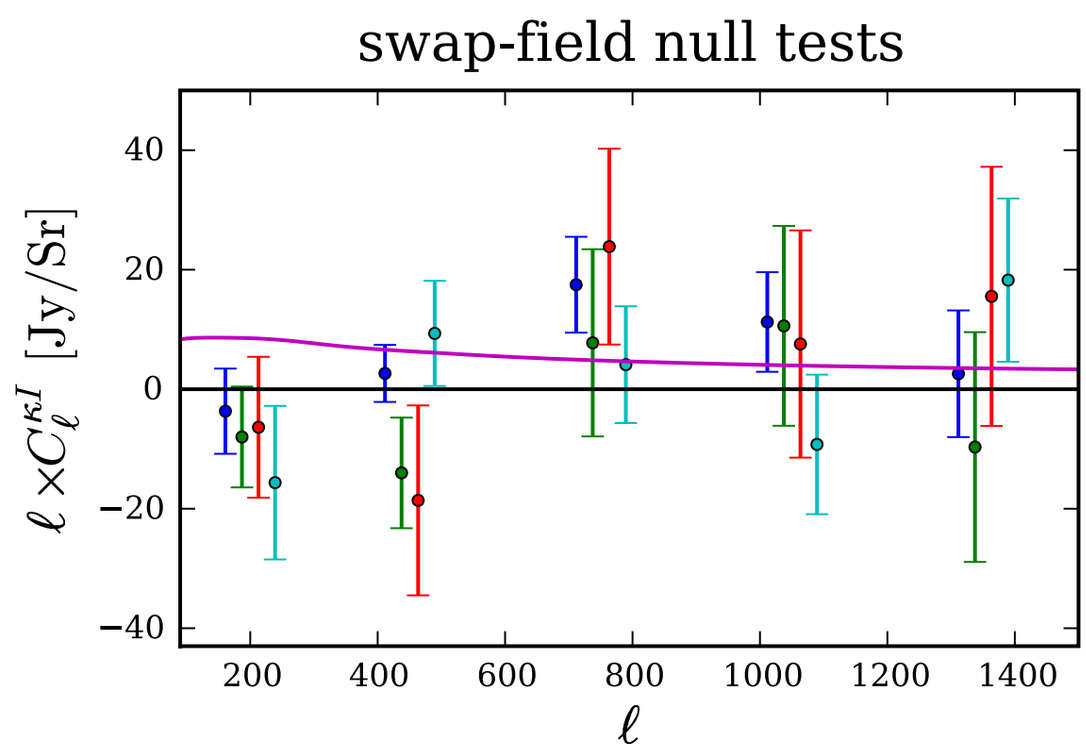
- Robust to polarized PS masking of ATCA catalogue (0.2σ difference)

- 1% T leakage, 10% QU leakage do not bias the estimate at 1% level

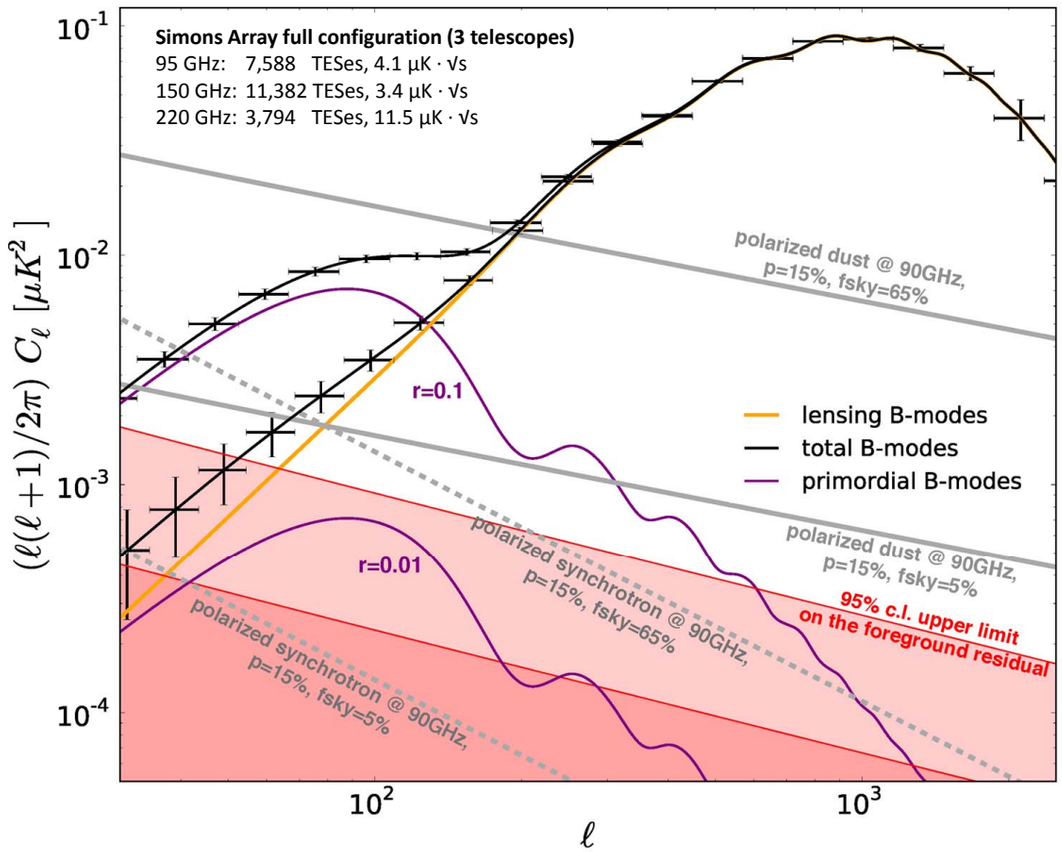
- Beams and pol. angle systematics change significance of 0.2σ level

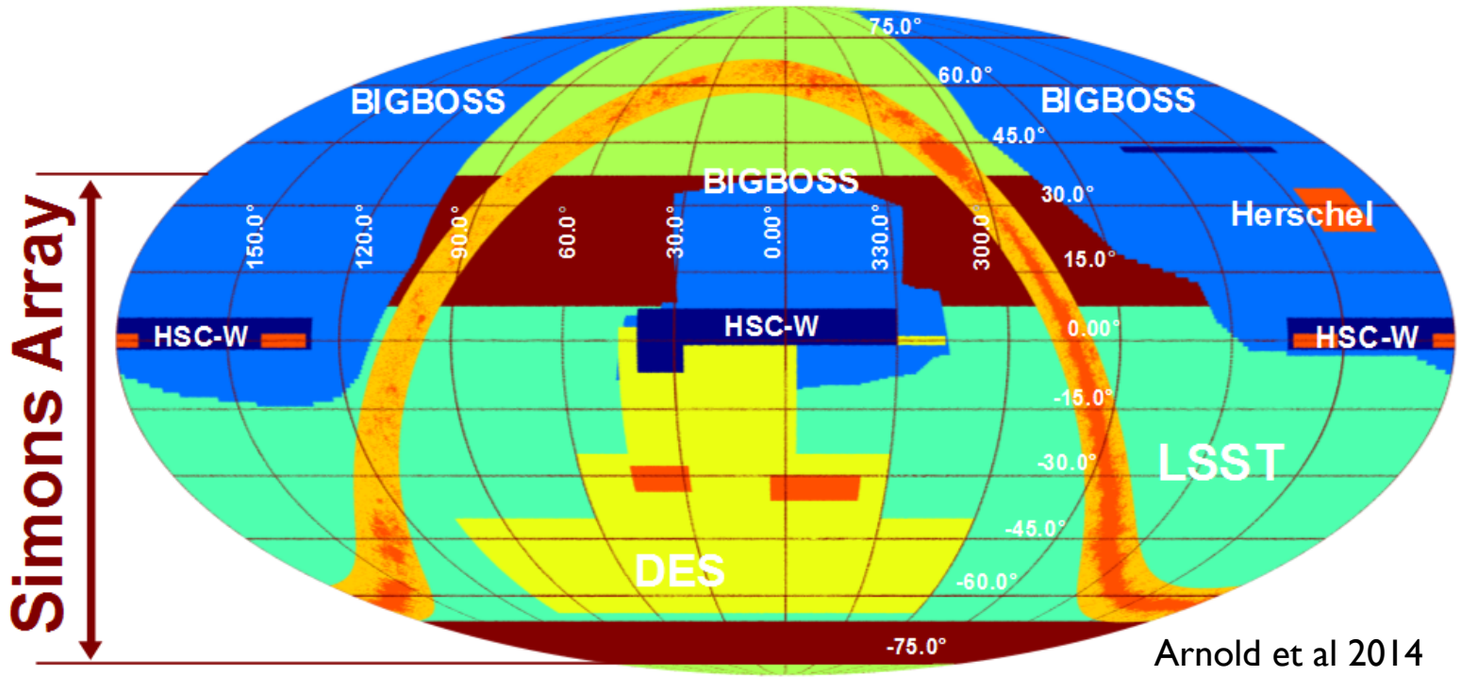
- Curl and swap-field null tests with excellent PTEs (>50%)





Simons Array performances





Arnold et al 2014

- Large sky, overlap with other astrophysical surveys for cross-correlation studies
- Cosmological constraints, in combination with Planck, CBASS, DASI BAO (3years):
  - Inflation $\sigma(r=0.1) = 4\cdot 10^{-3}(\mathrm{stat})$ / $6\cdot 10^{-3}(\mathrm{stat}+\mathrm{FC})$ $\quad \sigma(n_s) = 10^{-3}$
  - Neutrino mass $\sigma\left(\sum m_\nu\right) = 19\mathrm{meV}(\mathrm{stat})$ / $40\mathrm{meV}(\mathrm{stat}+\mathrm{FC})$
  - Primordial magnetic field to micro-Gauss scale