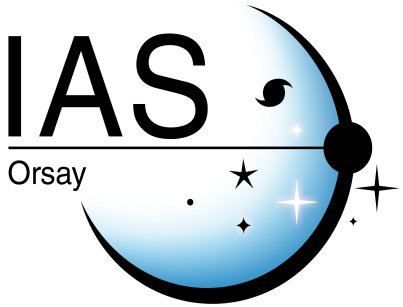


Pseudo-spectrum methods to estimate CMB B-modes

Agnès Ferté

Julien Grain (@ IAS Orsay), Radek Stompor (@APC Paris), Matthieu Tristram (@LAL Orsay)

June 24th 2013

Pseudo-spectrum methods to estimate CMB B-modes power spectrum

1. The challenge of B-modes detection

   E/B leakage

2. Pseudo-spectrum methods

   Handle E-to-B leakage

3. Numerical results

   The surprising problematic of full sky experiment

   Small sky experiment

B-modes to explore inflation period

Polarized anisotropies in the CMB produced by

- Density perturbations
- Gravitational waves

Generate B-modes

→ B-modes give the energy scale of inflation.

The CMB polarization can be described by E- and B-modes

Spin-2

$$P_{\pm 2} = Q \pm iU$$

Harmonic space

Pixel space

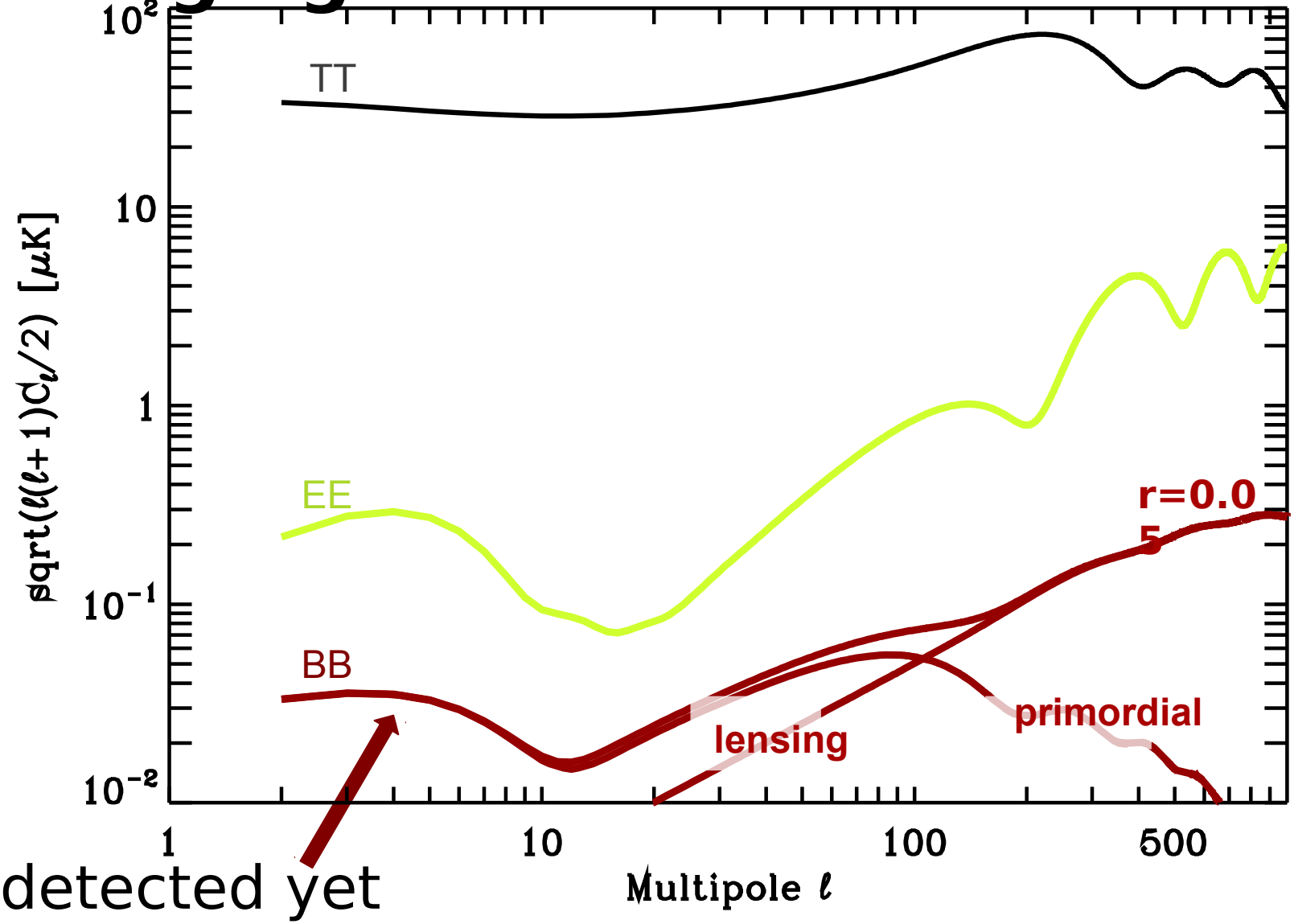
Spin-0

$$\begin{cases} a^E_{\ell m} = -\frac{1}{2}\int \left[P_{2\,2} Y^*_{\ell m} + P_{-2\,-2} Y^*_{\ell m} \right] \\ a^B_{\ell m} = \frac{i}{2}\int \left[P_{2\,2} Y^*_{\ell m} - P_{-2\,-2} Y^*_{\ell m} \right] \end{cases}$$

$$\begin{cases} \chi^E = -\frac{1}{2}\left[\bar{\partial}\bar{\partial} P_2 + \partial\partial P_{-2} \right] \\ \chi^B = \frac{i}{2}\left[\bar{\partial}\bar{\partial} P_2 - \partial\partial P_{-2} \right] \end{cases}$$

$$\chi^B = \sum_{\ell m} a^B_{\ell m} Y_{\ell m}$$

B-modes detection is challenging

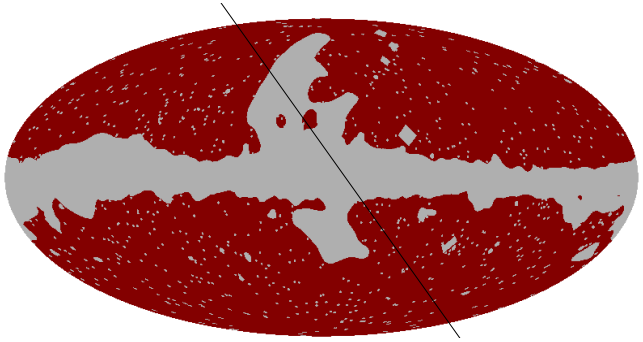


Not detected yet

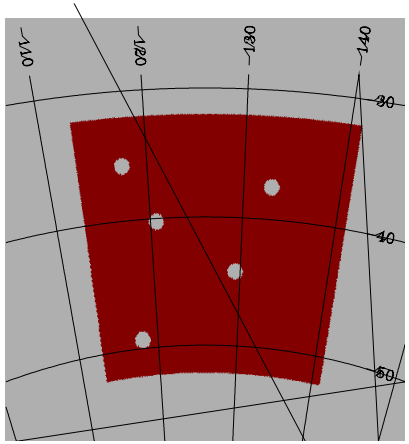
A major systematic effect: E/B leakage

Observation of a partial part of the celestial sphere.

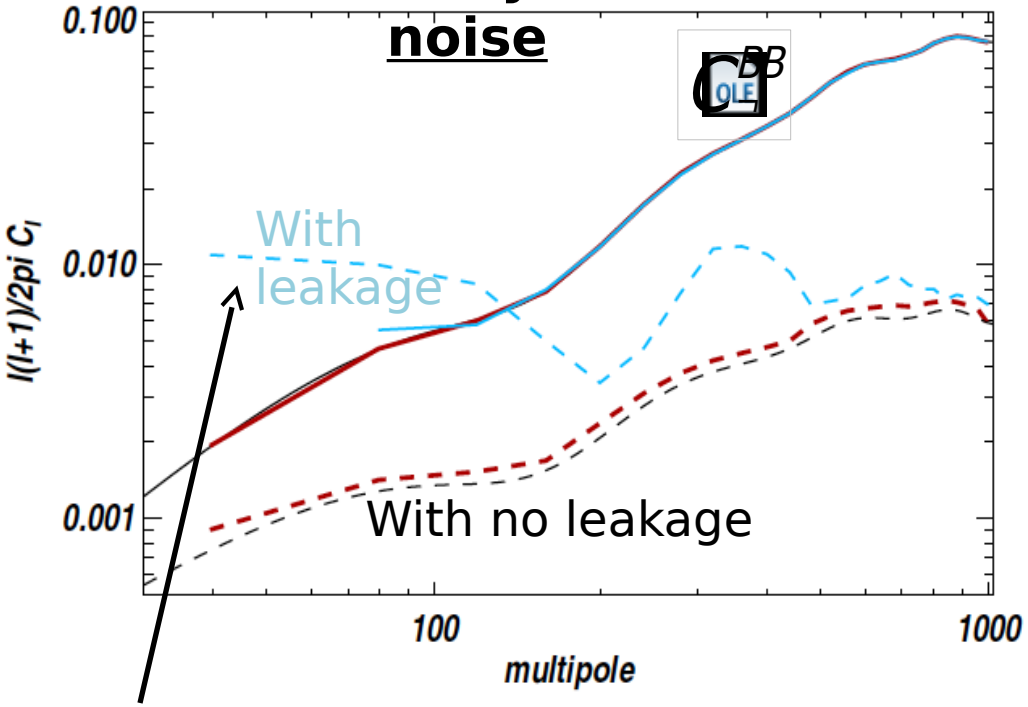
ffsky = 71%



ffsky = 1%



ffsky = 1%, no noise



Sampling variance higher than the signal it self!

Picture from Grain et al. (2009)

Pseudo-spectrum methods to estimate CMB B-modes power spectrum

1. The challenge of B-modes detection

   E/B leakage

2. Pseudo-spectrum methods

   Handle E-to-B leakage

3. Numerical results

   The surprising problematic of full sky experiment

   Small sky experiment

Pseudo multipoles are the multipoles of the masked field

$$\begin{cases} a^{E}_{\ell m} = \sum_{\ell' m'} \left[H^{(+)}_{\ell m, \ell' m'} a^{E}_{\ell' m'} + i H^{(-)}_{\ell m, \ell' m'} a^{B}_{\ell' m'} \right] \\ a^{B}_{\ell m} = \sum_{\ell' m'} \left[-i K^{(-)}_{\ell m, \ell' m'} a^{E}_{\ell' m'} + K^{(+)}_{\ell m, \ell' m'} a^{B}_{\ell' m'} \right] \end{cases}$$

Kernels depending on the applied mask W to the (Q,U) map.

We want the modes mixing kernels to vanish.

SZ-method: defining pure pseudo multipoles

$$a^B_{\neg m} = \frac{1}{\alpha_{\neg}} \int \left[P_2 (\partial\partial W Y_{\neg m})^* - P_{-2} (\bar{\partial}\bar{\partial} W Y_{\neg m})^* \right]$$

$$a^B_{\neg m} = \frac{1}{\alpha_{\neg}} \chi^B_{\neg m} \frac{1}{\alpha_{\neg}} \int \chi^B W Y^*_{\neg m}$$

Contains only B-modes.

About the window function W:

- must satisfy W and δW = 0 at the contour
- Is optimized to give the smallest error bars on

Based on:

Smith K., Pseudo-Cl estimators which do not mix E and B modes, Phys.Rev.D**74**, 083002 (2006)

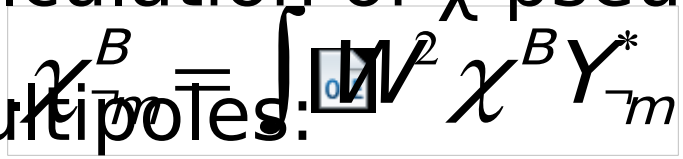
Smith K., Zaldarriaga M., *A general solution to the E-B mixing problem*, Phys.Rev.D**76**, 043001 (2007)

Grain J., Tristram M., Stompor R. *Polarized CMB power spectrum estimation using the pure*

ZB-method: calculating the masked χ field in the pixel space

- Multiple differentiations of masked (Q,U) maps to obtain:

- Calculation of χ pseudo-multipoles:



<u>About the window function W:</u>

Use the same as in the SZ-method.

Based on:
Zhao W., Baskaran D., *Separating E and B types of polarization on an incomplete sky*, Phys.Rev.D**82**, 023001 (2010)

KN-method: removing aliased pixels

- Computation of the pseudo χ-field:

$$\chi^B = \frac{i}{2}\left[\bar{\partial}\bar{\partial}(W_2 P_2) - \partial\partial(W_{-2} P_{-2})\right]$$

- Calculation of B-modes pseudo-multipoles:

$$a^B_{\ell m} = \int d\Omega\, \chi^B\, Y^*_{\ell m}$$

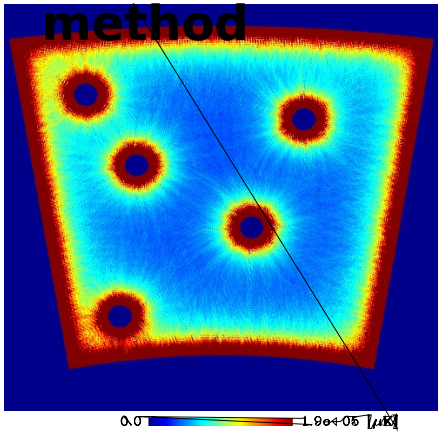
About the masks:

- Apodization of (Q,U) maps to have pseudo-χB field
- Masking aliased pixels

Based on:
Kim J., Naselsky D., *CMB E/B decomposition of incomplete sky : a pixel a space approach*, A&A, 519 A104 (2011)
Kim J., *How to make a clean separation between CMB E and B modes with proper foreground*

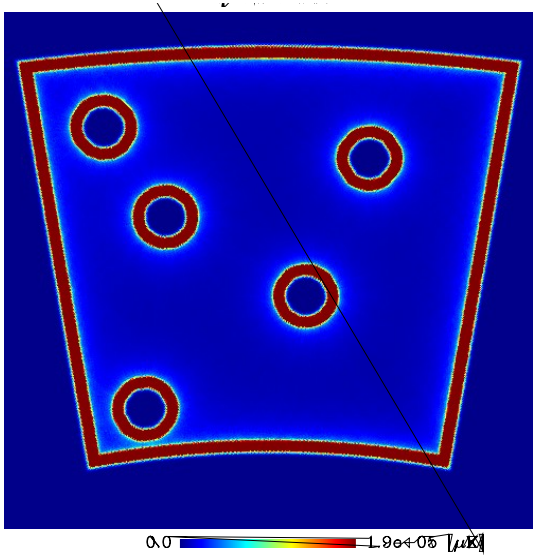
Maps of the E/B leakage

Standard method

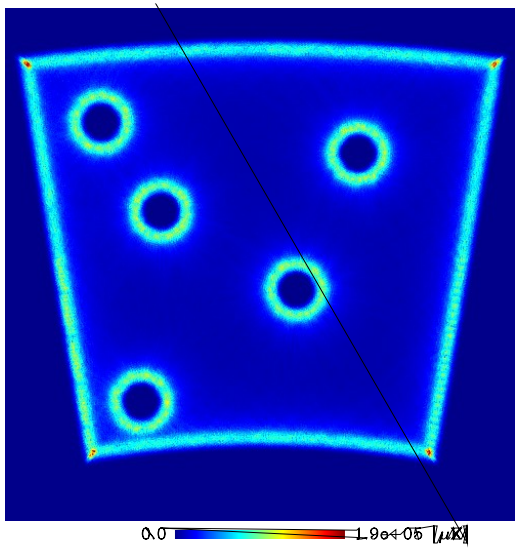


B-modes maps with **no** intial B-modes!

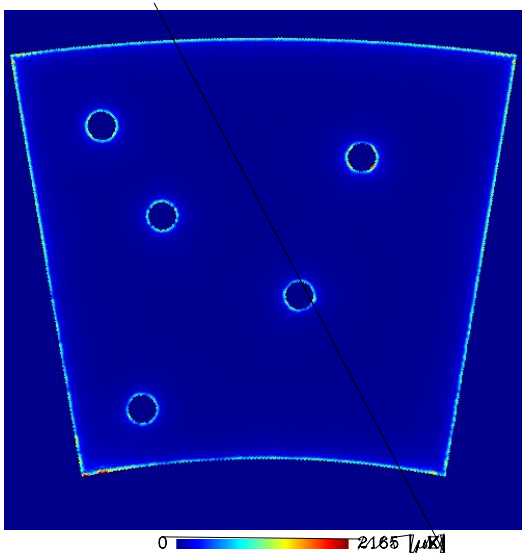
KN method



ZB method



SZ method



Pseudo-spectrum methods to estimate CMB B-modes power spectrum

1. The challenge of B-modes detection

   E/B leakage

2. Pseudo-spectrum methods

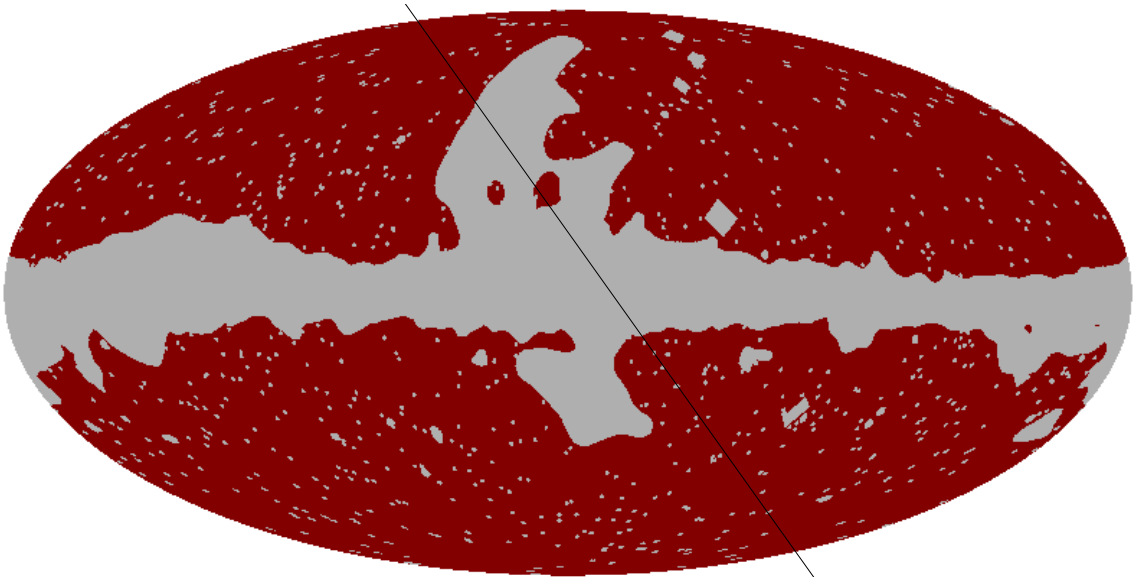
   Handle E-to-B leakage

3. Numerical results

   The surprising problematic of full sky experiment

   Small sky experiment

The case of satellite experiment

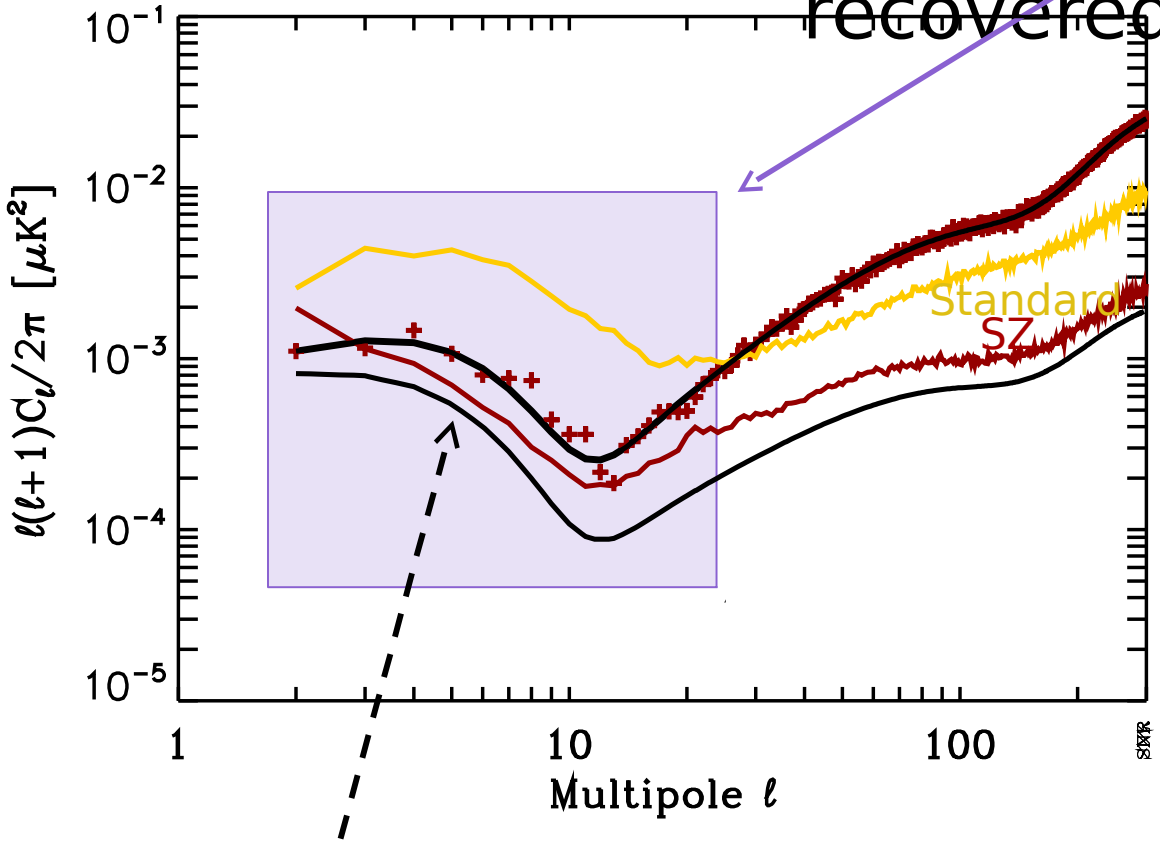


Like PRISM,
EPIC,
LiteBIRD…

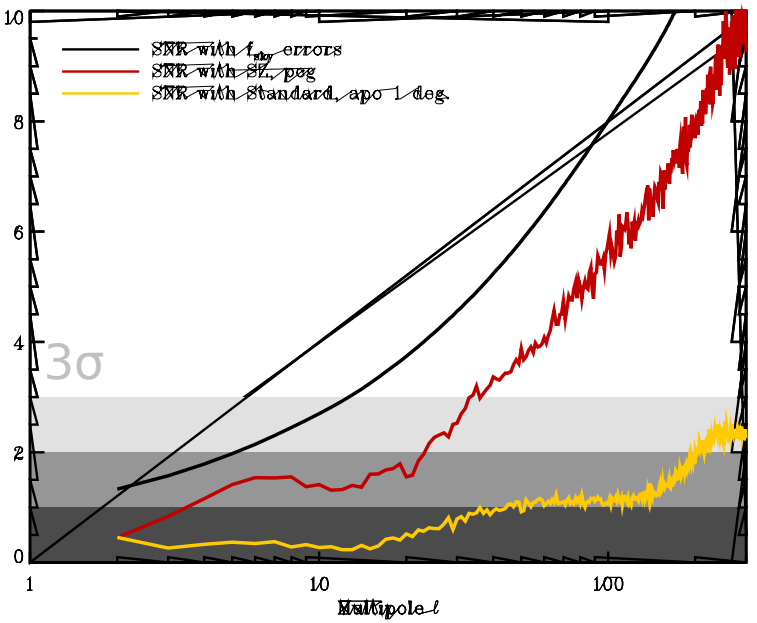
Observed sky fraction
= 71%
Noise = 2.2μK-arcmin
Beam = 8 arcmin

This case is surprisingly not trivial

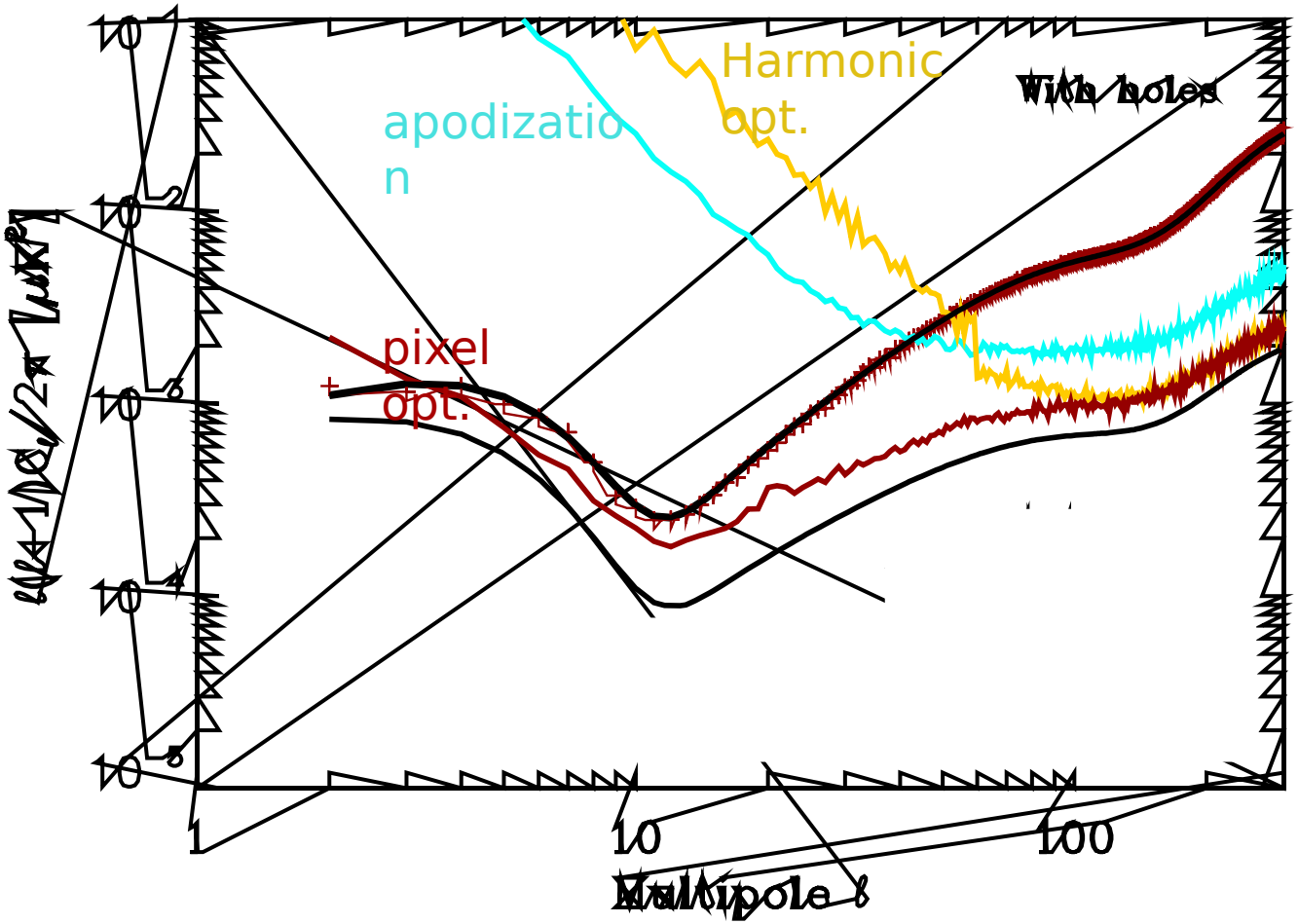
B-modes can not be recovered



The smallest reachable variances
only accounting for the sky fraction



Choosing the appropriate window function is crucial

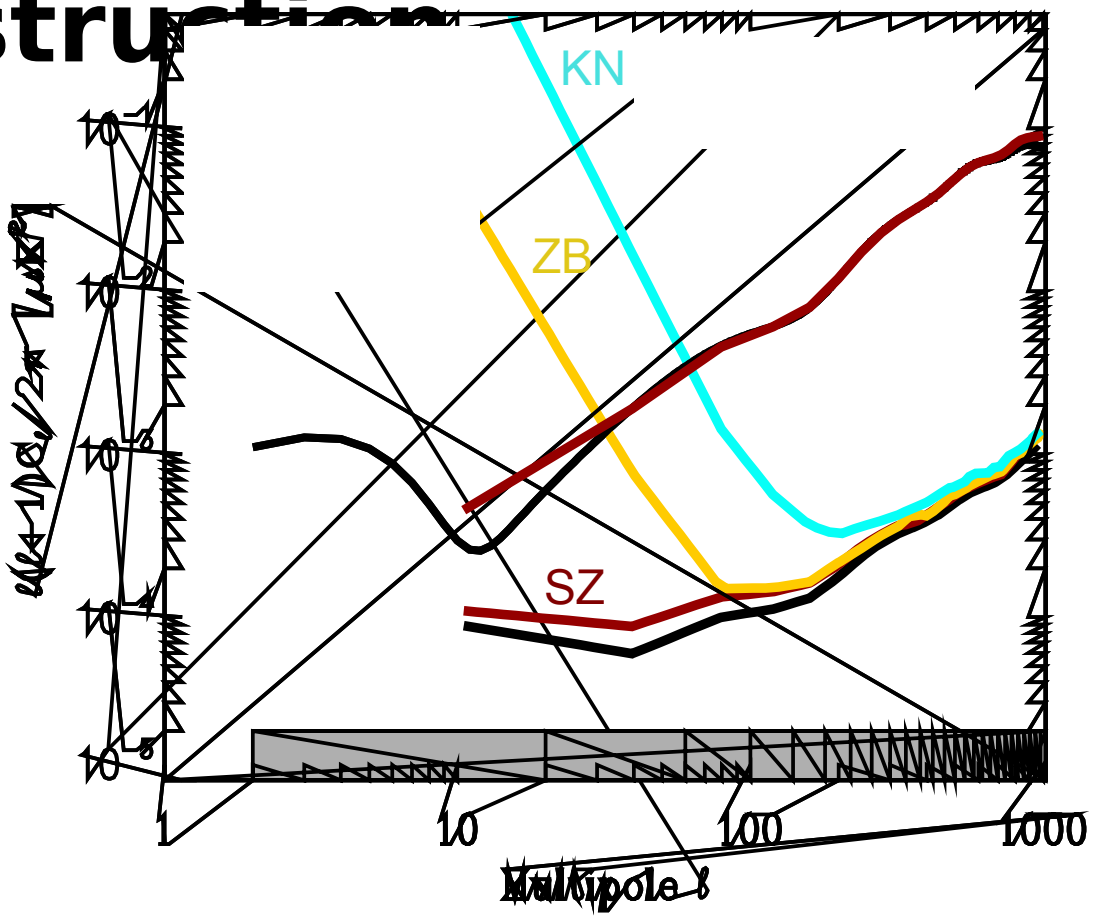


→ SZ-method is sensitive to the

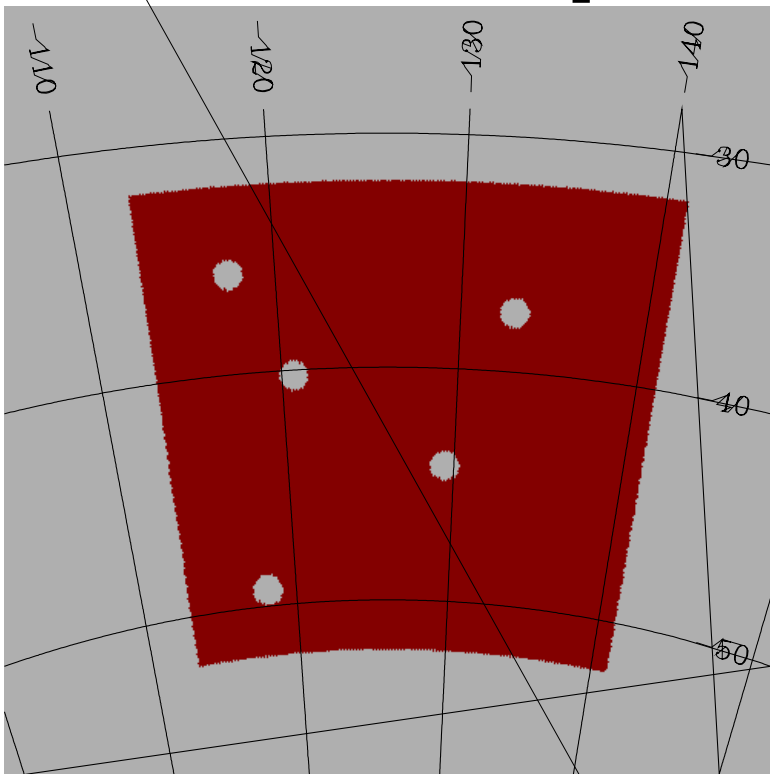
SZ-method gives the smallest error bars on B-modes reconstruction

B-modes detection:

- SZ: all multipoles
- ZB: l > 20
- KN: l > 60



The case of ground based and balloon borne experiments



Like POLARBEAR, EBEX, SPTPOL…

Observed sky fraction = 1%

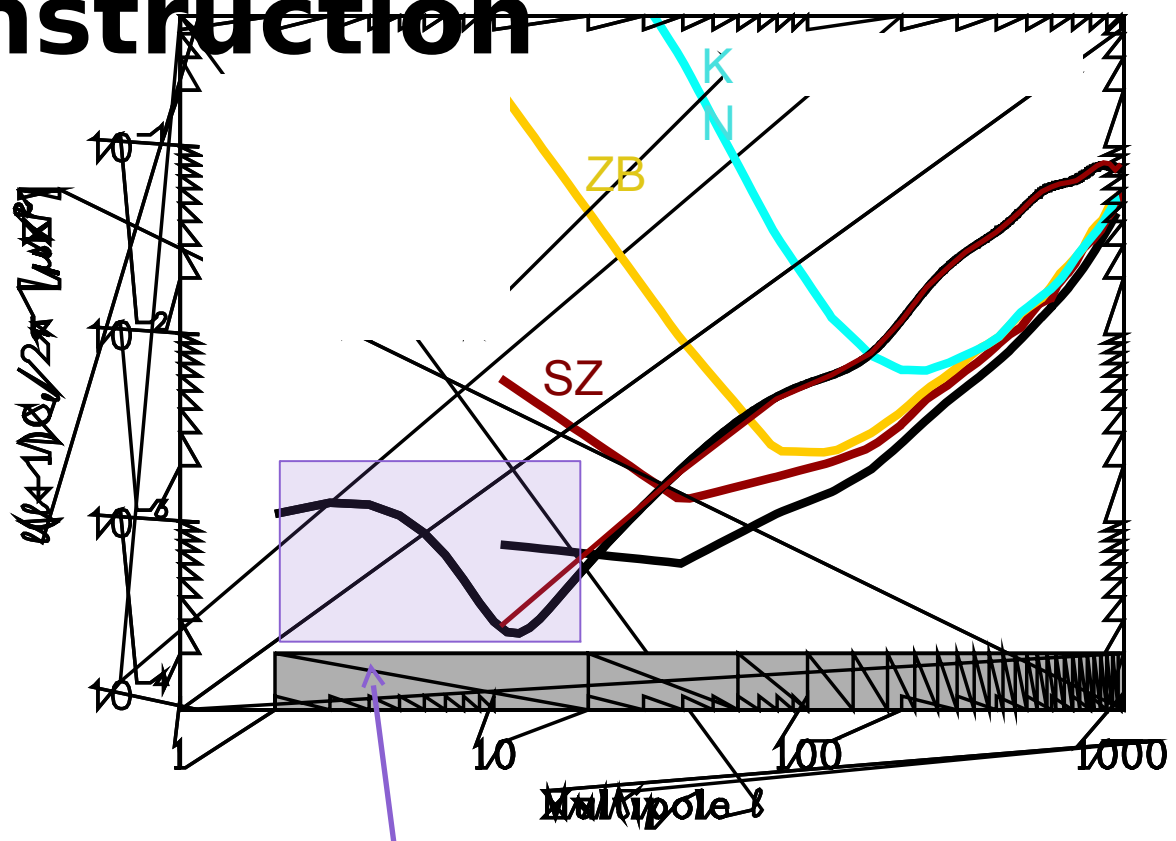
Noise = 5.75μK-arcmin

Beam = 8 arcmin

SZ-method gives the smallest error bars on B-modes reconstruction

B-modes detection:

- SZ: l > 20
- ZB: l > 60
- KN: l > 100



Impossible to recover B-modes because of sky coverage

To take away

- The E/B leakage has to be corrected for even in the case of a large scale survey.
- In the way we implement these methods, the SZ-methods give the smallest error bars.
- Computation of W is crucial.

More information in: Ferté et al., *Efficiency of pseudo-spectrum methods for estimation of Cosmic Microwave Background B-modes power spectrum*, accepted for publication in Phys. Rev. D, **arXiv:1305.7441**

Thank you!

IAS Orsay