A TRIPTYCH AROUND CMB B-MODES

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- ***An example of theoretical predictions*** : bouncing cosmology induced by LQC
  Collaborateurs: *Mielczarek (Cracaw), Barrau, Gorecki & Cailleteau (Grenoble)*

- ***Power spectrum estimation :*** pure pseudo-spectrum
  Collaborateurs: *Stompor (APC-Paris) & Tristram (LAL-Orsay)*

- ***Component Separation :*** parametric approach
  Collaborateurs: *Stivoli (INRIA-Orsay), Tristram (LAL-Orsay), Leach & Baccigalupi (SISSA-Trieste), Stompor (APC-Paris)*

POLARIZED ANISOTROPIES OF THE CMB

CMB plays a *keyrole* in setting cosmology in the ages of *precise science*
(geometry of the Universe, matter content, neutrinos total mass)

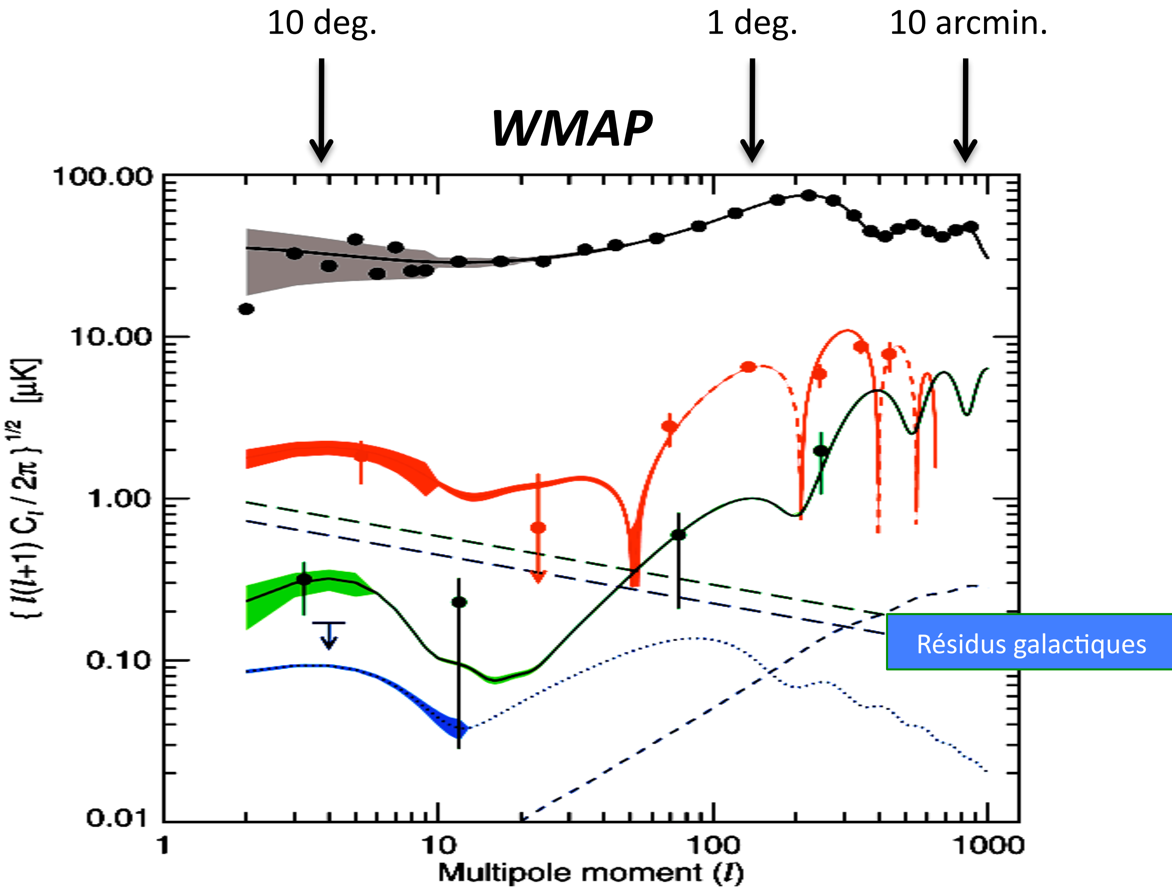
- **Statistics of its anisotropies**

  Temperature **T** (scalar & tensor)
  Polarization **E** (scalar & tensor)
  Polarization **B** (tensor)

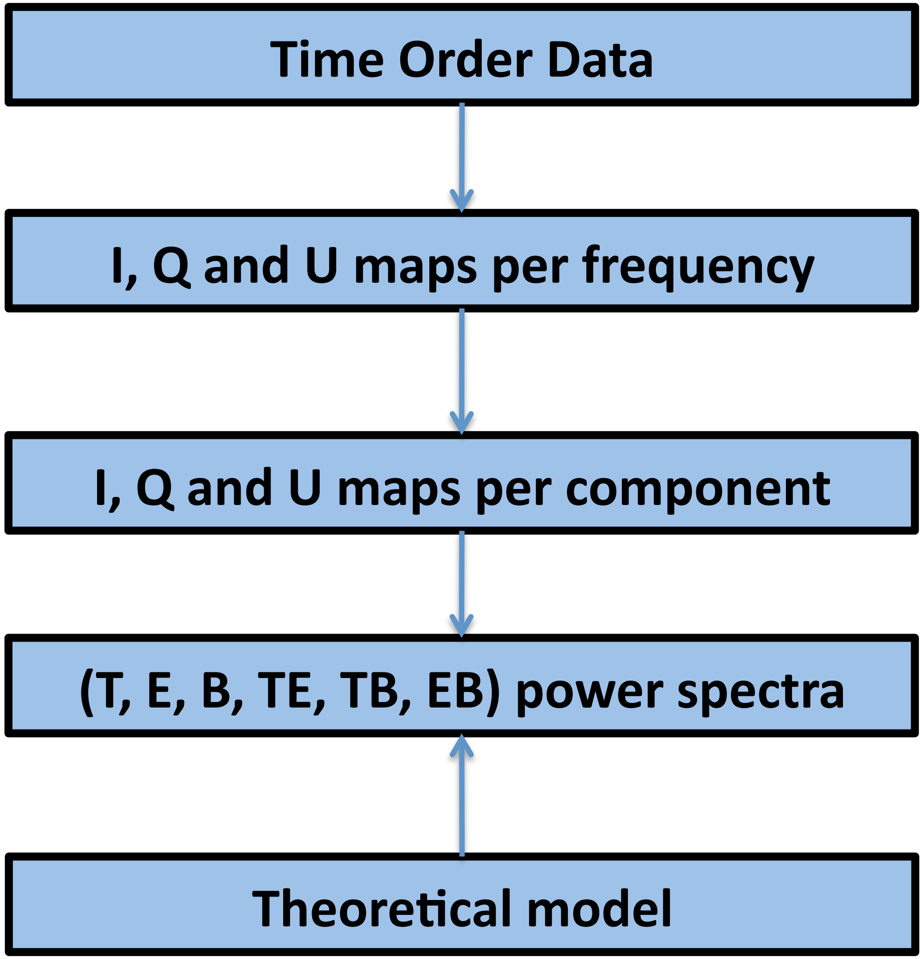
- **B-mode**

Open window on inflation/alternatives/new theories

Gravitational lensing



CMB DATA ANALYSIS



Time Order Data

I, Q and U maps per frequency

I, Q and U maps per component

(T, E, B, TE, TB, EB) power spectra

Theoretical model

A RAPID SKETCH OF LOOP QUANTUM GRAVITY (LQG)

« Can we construct a quantum theory of spacetime based only on the experimentally well confirmed principles of general relativity and quantum mechanics ? » L. Smolin, hep-th/0408048

GR classically re-written with Ashtekar variables :

densitized triad $E_i^a \equiv \left|\det(e_j^b)\right|^{-1} e_i^a$

Ashtekar connection $A_a^i = \Gamma_a^i + \gamma K_a^i$

Quantization by use of holonomies and fluxes (background independence)

$$F(E) \propto \int_S \tau^i E_i^a n_a d^2 s$$

$$h(A) \propto \exp\left(\int_C \tau_i A_a^i u^a d\lambda \right)$$

- **The area, volume and length operators have a discrete sectrum**
- **The horizon entropy is completely explained.**
- **Singularities are eliminated.**
- **Ultraviolet divergences of QFT are not present.**
- **Loop quantum cosmology is on the way….**

LQG IN THE COSMOLOGICAL FRAMEWORK : BACKGROUND

FLRW-reduced formulation of LQG : Loop Quantum Cosmology (LQC)

$$ds^2 = a^2(\eta)\left(d\eta^2 - \delta_{ij}dx^i dx^j\right)$$

Background equation : classical results

$$H^2 = \frac{8\pi G}{3}\rho$$

$$\ddot{\Phi} + 3H\dot{\Phi} + \frac{\delta V}{\delta \Phi} = 0$$

See works of: Ashtekar, Bojowald, Lewandowski, Pawlowski, Singh, Corichi, Mielczarek, Vandersloot, etc.

For a review, see: Calcagni & Hossain, Adv. Sci. Lett. 2, 184 (2009)

Background equation : quantum corrected results

$$H^2 = \frac{8\pi G}{3}\rho\left[1 - \frac{\rho}{\rho_c}\right]$$

$$\ddot{\Phi} + 3H\dot{\Phi} + \frac{\delta V}{\delta \Phi} = 0$$

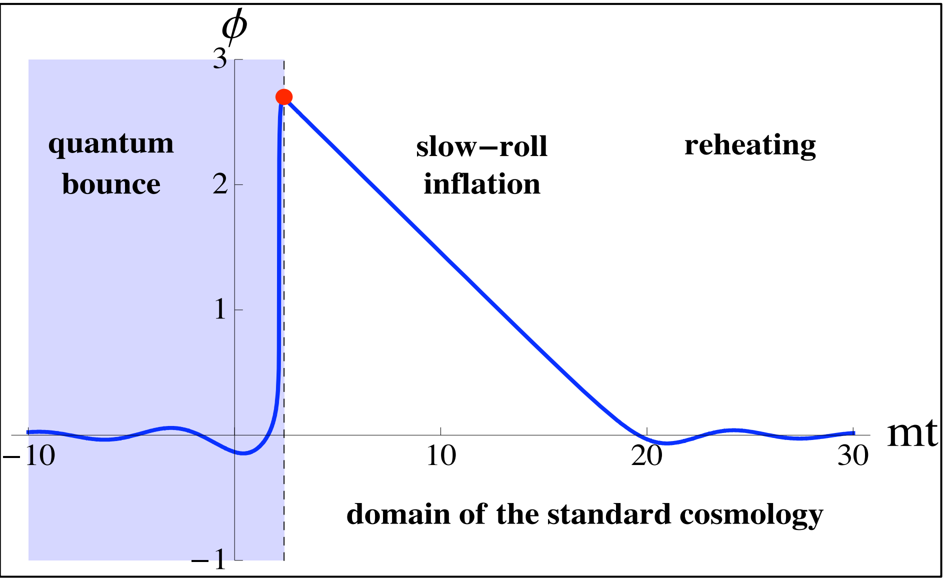
→ bouncing cosmology

BACKGROUND WITH HOLONOMIES

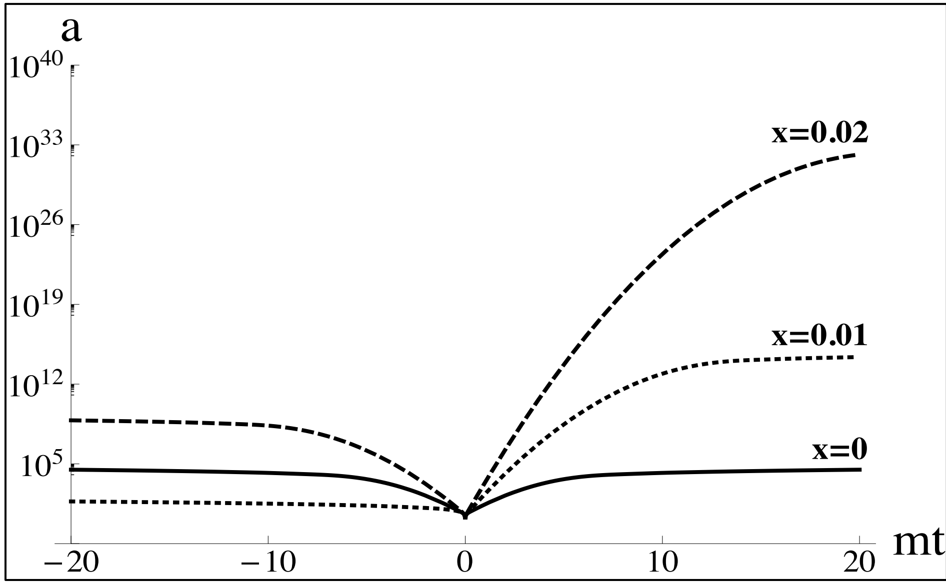
$$H^2 = \frac{8\pi G}{3}\rho \times \left[1 - \frac{\rho}{\rho_c}\right]$$

$$\ddot{\Phi} + 3H\dot{\Phi} + m_\Phi^2 \Phi = 0$$

Scalar field



Scale factor



- ✓ A sufficient amount of e-folds: $\underline{\rho_c = m_{Pl}^4}$:

  for $m_\Phi = 10^{-6} m_{Pl}$, $x = 0$: $\Phi_{\max} \approx 2.1 m_{Pl}$ and $N \approx 28$

  for $m_\Phi = 10^{-3} m_{Pl}$, $x = 0.01$: $\Phi_{\max} \approx 3 m_{Pl}$ and $N \approx 60$

- ✓ A maximum amount of e-folds: $N_{\max} = \frac{4\pi\rho_c}{m_\Phi^2 m_{Pl}^2}\left(\approx 4\pi \frac{m_{Pl}^2}{m_\Phi^2} \text{ for } \rho_c \approx m_{Pl}^4\right)$

J. MIELCZAREK, PHYS. REV. D 81 063593 (2010)
J. MIELCZAREK, T. CAILLETEAU, ***J. GRAIN*** & A. BARRAU, SUBMITTED TO PHYS. REV. D

LQG IN THE COSMOLOGICAL FRAMEWORK : TENSOR PERTURBATIONS

Perturbed FLRW metric

$$ds^2 = a^2(\eta)\left(d\eta^2 - \left(\delta_{ij} + h_{ij}\right)dx^i dx^j\right)$$

Gravity waves equation : classical results

$$\frac{d^2\phi_k}{d\eta^2} + \left(k^2 - \frac{a''}{a}\right)\phi = 0 \quad \text{with} \quad \phi_\mathrm{k} \equiv a(\eta)h_{ij}^{(k)}$$

Gravity waves equation : quantum corrected results

$$\frac{d^2\phi_k}{d\eta^2} + \left(k^2 - \frac{a''}{a} - V_{holo}(a,\rho_c)\right)\phi_k = 0 \quad \text{with} \quad \phi_\mathrm{k} \equiv a(\eta)h_{ij}^{(k)}$$

- **Modified background**
- **Modified «Dispersion relation»**

FOR THE EQUATION: BOJOWALD & HOSSAIN, PHYS. REV. D 77 023508 (2008)

APPLIED TO INFLATION:
J. Grain, A. Barrau , Phys. Rev. Lett. **102** 081301 (2009)
J. Grain, A. Barrau & A. Gorecki, Phys. Rev. D **79** 084015 (2009)
J. Grain, T. Cailleteau, A. Barrau & A. Gorecki, Phys. Rev. D **81** 024040 (2010)

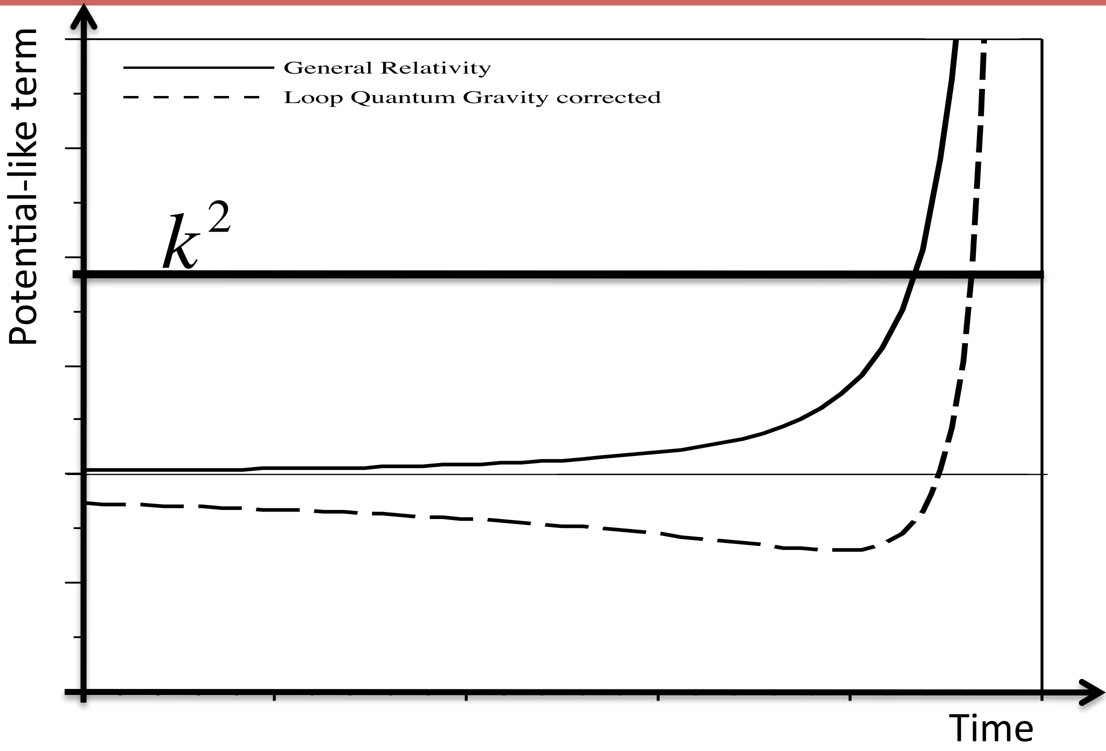
AND WORKS OF: MIELCZAREK, COPELAND, NUNES, MULRYNE, ETC.

TENSOR PERTURBATIONS : POWER SPECTRA AND IMPACT ON B-MODES

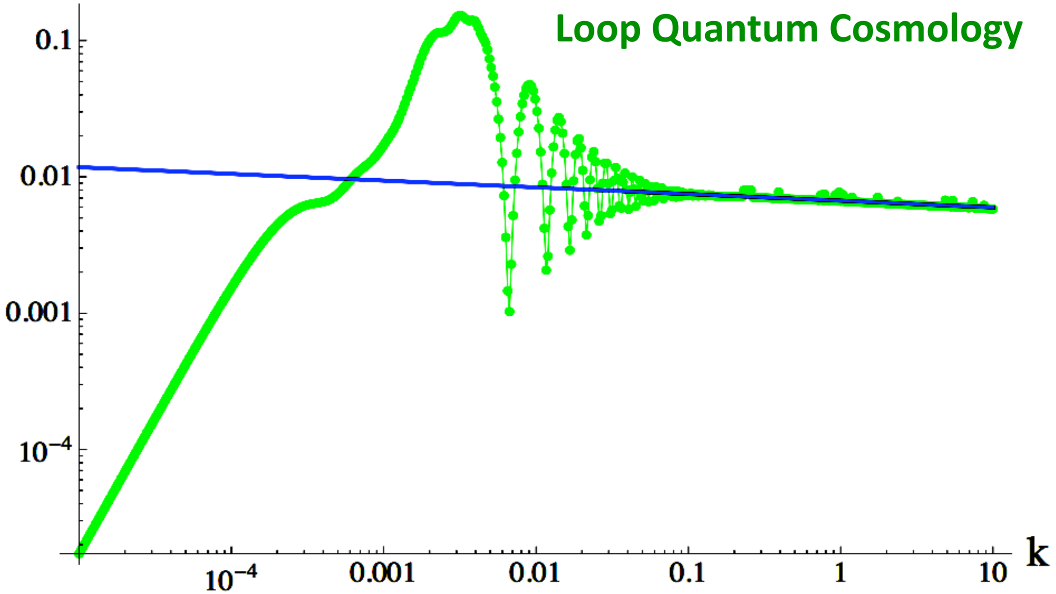
J. MIELCZAREK, T. CAILLETEAU, ***J. GRAIN*** & A. BARRAU, SUBMITTED TO PHYS. REV. D

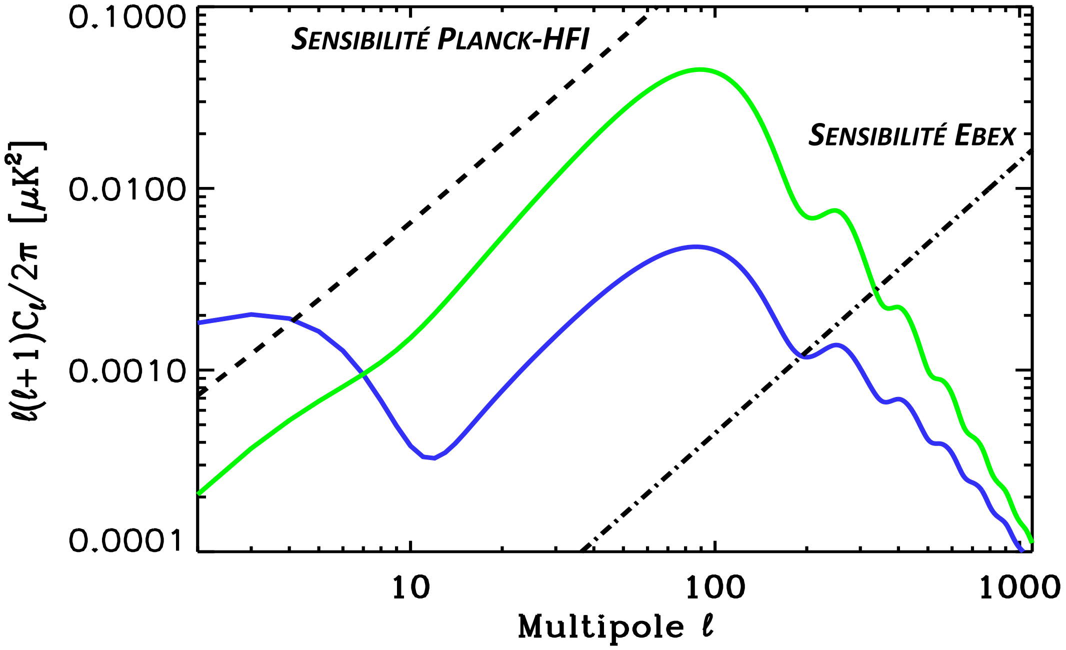
$$\frac{d^2\phi_k}{d\eta^2} + \left[k^2 - V(\eta)\right]\phi_k = 0$$

$$\text{with } V_{GR}(\eta) = V_{LQC}(\eta) = 4\pi G a^2\left(\frac{\rho_\Phi}{3} - p_\Phi\right)$$



Tensor perturbations
power spectra





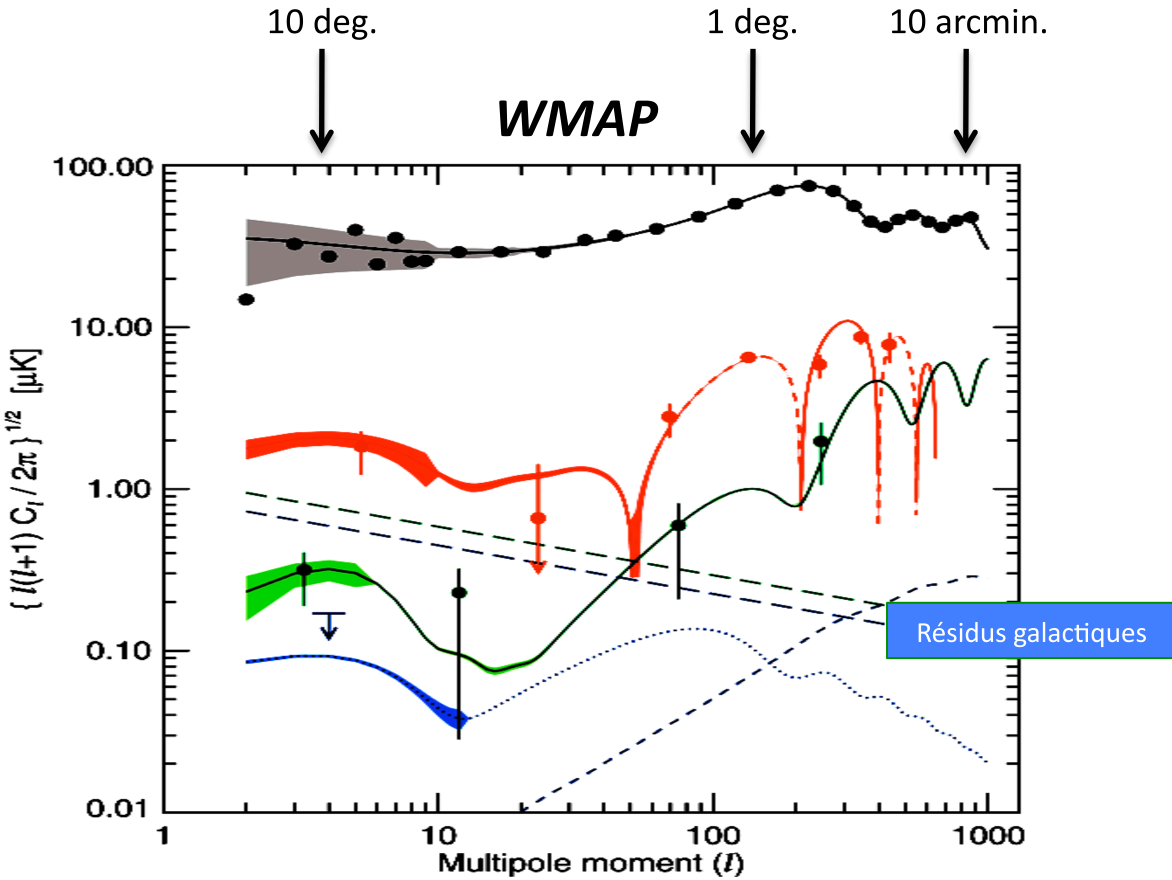
POLARIZED ANISOTROPIES OF THE CMB

- **Statistics of its anisotropies**

Temperature **T** (scalar & tensor)
Polarization **E** (scalar & tensor)
Polarization **B** (tensor)

- **B-mode**

Open window on inflation
Gravitational lensing
Open window on tentative new theories



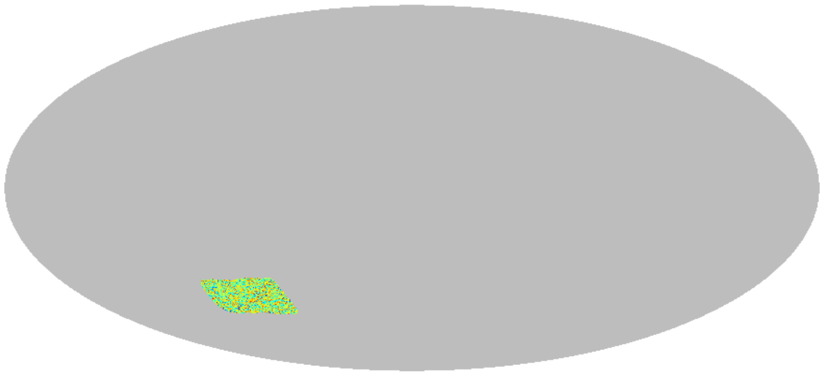
Résidus galactiques

Observational challenges
➔**instrumental sensitivity**
➔**systematic effects**
➔***FOREGROUNDS >> CMB :* component separation**
➔***E >> B :* E-to-B leakages to be corrected**

POLARIZED POWER SPECTRUM ESTIMATION WITH *PURE* PSEUDO SPECTRUM

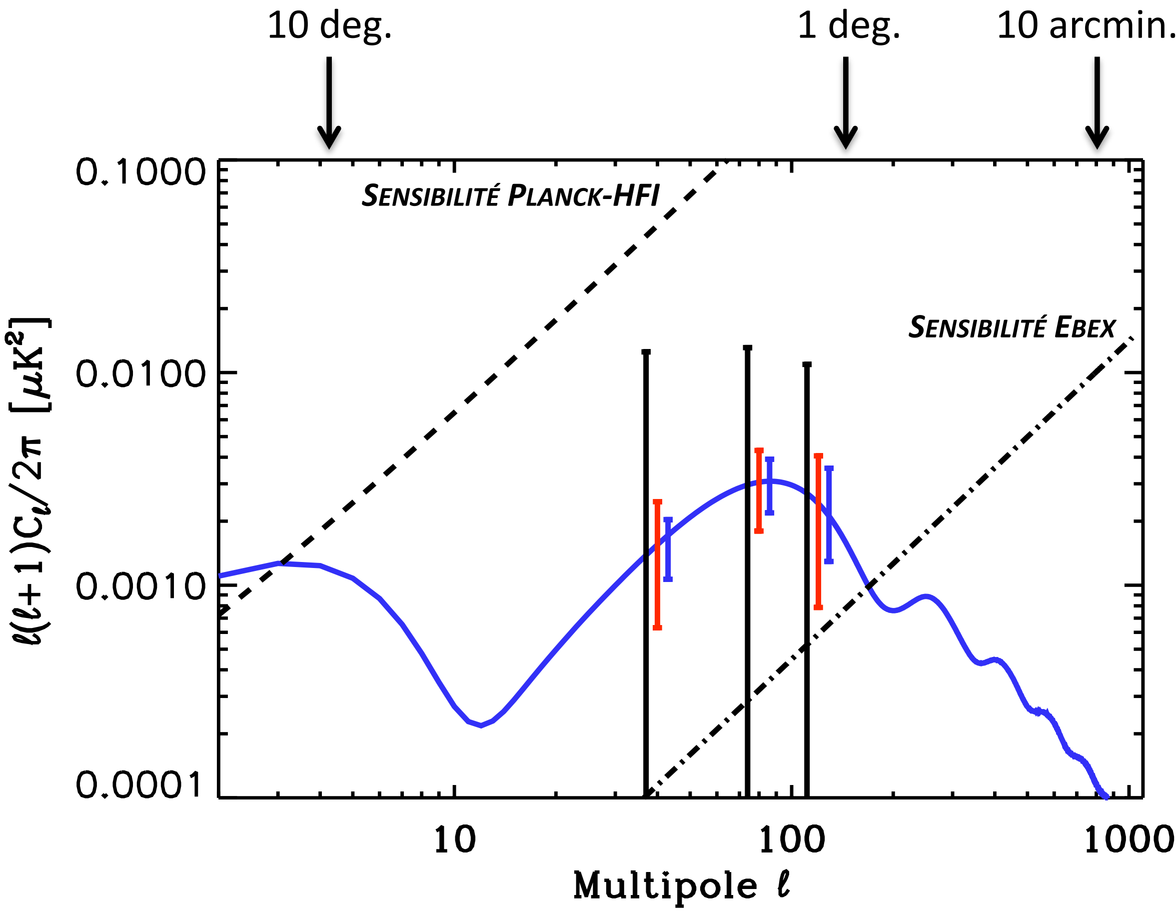
J. Grain, M. Tristram & R. Stompor, Phys. Rev. D 79, 123515 (2009)

Q and *U* maps



EBEX (balloon)
$f_{sky} \approx 1$ %

B-mode power spectrum



REMOVING E-MODES LEAKING INTO B-MODES

$$\begin{pmatrix} Q(\vec{n}) \\ U(\vec{n}) \end{pmatrix} = \mathbf{D^E} E(\vec{n}) + \mathbf{D^B} B(\vec{n}) \text{ with } \mathbf{D^E}\cdot\mathbf{D^B} = \mathbf{D^B}\cdot\mathbf{D^E} = 0$$

The *standard* way

$$a^B_{\ell m} = \int_{4\pi} (Q,U)\cdot \mathbf{D^B} Y_{\ell m} \times M$$

T. Bunn, M. Zaldarriaga, M. Tegmark & A. de Oliveira-Costa, Phys. Rev. D 67 023501 (2003)
K. Smith, Phys. Rev. D 74 083002 (2006)
K. Smith & M. Zaldarriaga, Phys. Rev. D 76 043001 (2007)

$$a^B_{\ell m} = \boxed{\int_{S<4\pi} \mathbf{D^B}\cdot(Q,U)\times Y_{\ell m}} + \boxed{\oint_{C_S}(Q,U)\partial Y_{\ell m} + \oint_{C_S}\partial(Q,U) Y_{\ell m}}$$

B-modes only

B-modes and E-modes

E-to-B mixing and L-to-L' mixing ←

$$\begin{pmatrix}\tilde E_{\ell m}\\ \tilde B_{\ell m}\end{pmatrix} = \sum_{\ell' m'}\begin{pmatrix} W^+_{\ell m,\ell' m'} & iW^-_{\ell m,\ell' m'} \\ -iW^-_{\ell m,\ell' m'} & W^+_{\ell m,\ell' m'}\end{pmatrix}\begin{pmatrix} a^E_{\ell' m'} \\ a^B_{\ell' m'}\end{pmatrix}$$

✓**E-B and L-L' separation on average**

BUT

✓for any realization : **E variance leaks into B variance** ←

$$\begin{pmatrix}\langle\tilde C^E_\ell\rangle\\ \langle\tilde C^B_\ell\rangle\end{pmatrix} = \frac{1}{2\ell+1}\sum_m \begin{pmatrix}\left\langle\left|\tilde E_{\ell m}\right|^2\right\rangle \\ \left\langle\left|\tilde B_{\ell m}\right|^2\right\rangle\end{pmatrix} = \sum_{\ell'}\begin{pmatrix} M^+_{\ell,\ell'} & M^-_{\ell,\ell'}\\ M^-_{\ell,\ell'} & M^+_{\ell,\ell'}\end{pmatrix}\begin{pmatrix}C^E_{\ell'}\\ C^B_{\ell'}\end{pmatrix}$$

REMOVING E-MODES LEAKING INTO B-MODES

$$\begin{pmatrix} Q(\vec{n}) \\ U(\vec{n}) \end{pmatrix} = \mathbf{D^E} E(\vec{n}) + \mathbf{D^B} B(\vec{n}) \text{ with } \mathbf{D^E}\cdot\mathbf{D^B} = \mathbf{D^B}\cdot\mathbf{D^E} = 0$$

The *standard* way

$$a^B_{\ell m} = \int_{4\pi} (Q,U)\cdot\mathbf{D^B} Y_{\ell m} \times M$$

$$a^B_{\ell m} = \boxed{\int_{S<4\pi} \mathbf{D^B}\cdot(Q,U)\times Y_{\ell m}} + \boxed{\oint_{C_S} (Q,U)\partial Y_{\ell m} + \oint_{C_S} \partial(Q,U) Y_{\ell m}}$$

B-modes only

B-modes and E-modes

The *pure* way

$$a^B_{\ell m} = \int_{4\pi} (Q,U)\cdot\mathbf{D^B}(W Y_{\ell m})$$

$$a^B_{\ell m} = \boxed{\int_{S<4\pi} \mathbf{D^B}\cdot(Q,U)\times W Y_{\ell m}} + \boxed{\oint_{C_S} (Q,U)\partial(W Y_{\ell m}) + \oint_{C_S} \partial(Q,U)\times W Y_{\ell m}}$$

B-modes only

Vanish if *W=0* and *dW=0* on C_S

REMOVING E-MODES LEAKING INTO B-MODES

$$\begin{pmatrix} Q(\vec{n}) \\ U(\vec{n}) \end{pmatrix} = \mathbf{D}^{\mathbf{E}} E(\vec{n}) + \mathbf{D}^{\mathbf{B}} B(\vec{n}) \text{ with } \mathbf{D}^{\mathbf{E}} \cdot \mathbf{D}^{\mathbf{B}} = \mathbf{D}^{\mathbf{B}} \cdot \mathbf{D}^{\mathbf{E}} = 0$$

The *pure* way

$$a^B_{\ell m} = \int_{4\pi} (Q,U) \cdot \mathbf{D}^{\mathbf{B}} (WY_{\ell m})$$

$$a^B_{\ell m} = \boxed{\int_{S<4\pi} \mathbf{D}^{\mathbf{B}} \cdot (Q,U) \times WY_{\ell m}} + \boxed{\oint_{C_S} (Q,U) \partial (WY_{\ell m}) + \oint_{C_S} \partial (Q,U) \times WY_{\ell m}}$$

B-modes only

Vanish if *W=0* and *dW=0* on C_S

$$\begin{pmatrix} \tilde{E}_{\ell m} \\ \tilde{B}_{\ell m} \end{pmatrix} = \sum_{\ell' m'} \begin{pmatrix} W^{+}_{\ell m, \ell' m'} & 0 \\ 0 & W^{+}_{\ell m, \ell' m'} \end{pmatrix} \begin{pmatrix} a^E_{\ell' m'} \\ a^B_{\ell' m'} \end{pmatrix}$$

ONLY L-to-L' mixing

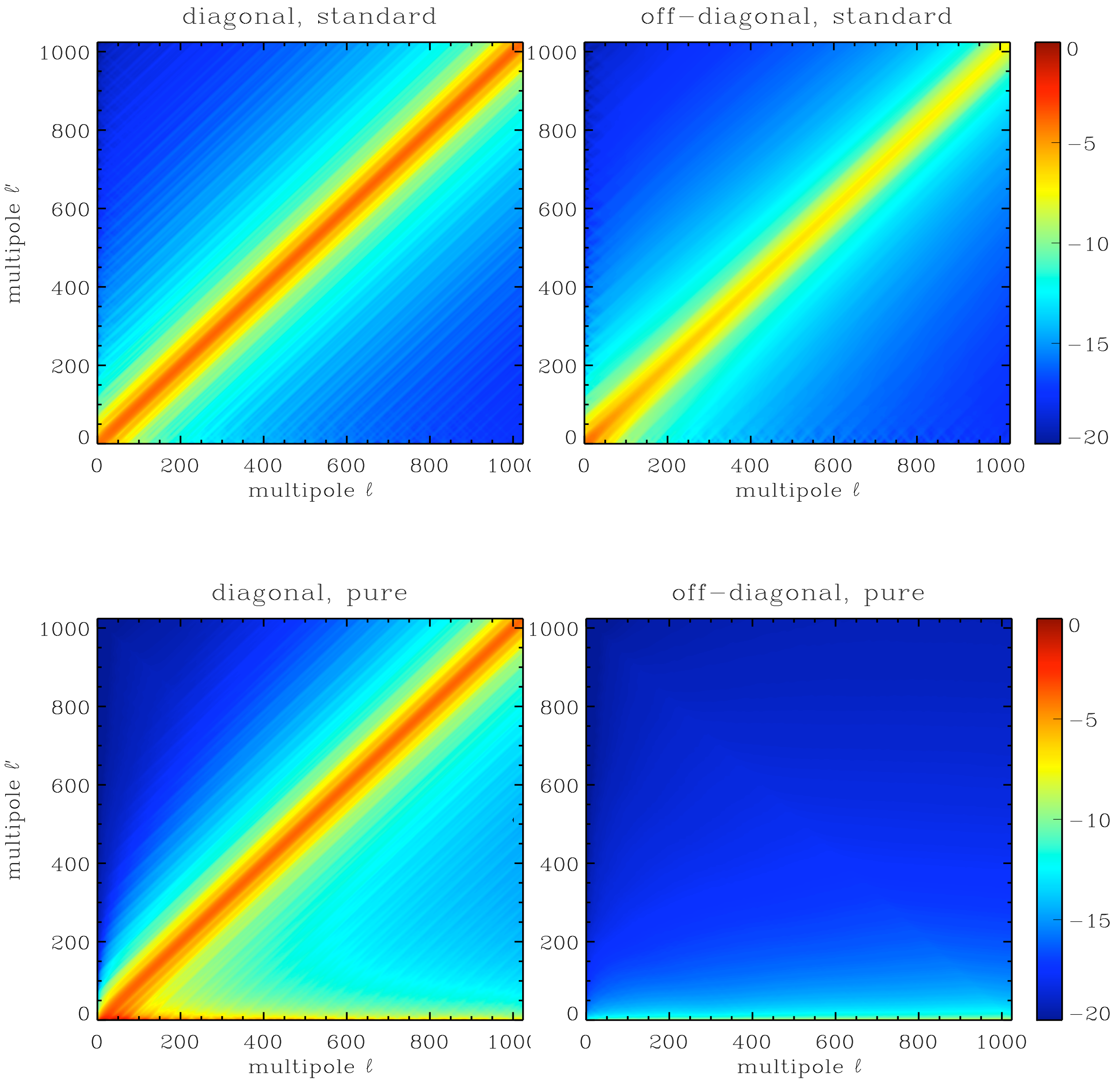
$$\begin{pmatrix} \langle \tilde{C}^E_\ell \rangle \\ \langle \tilde{C}^B_\ell \rangle \end{pmatrix} = \frac{1}{2\ell+1} \sum_m \begin{pmatrix} \langle |\tilde{E}_{\ell m}|^2 \rangle \\ \langle |\tilde{B}_{\ell m}|^2 \rangle \end{pmatrix} = \sum_{\ell'} \begin{pmatrix} M^{+}_{\ell,\ell'} & 0 \\ 0 & M^{+}_{\ell,\ell'} \end{pmatrix} \begin{pmatrix} C^E_{\ell'} \\ C^B_{\ell'} \end{pmatrix}$$

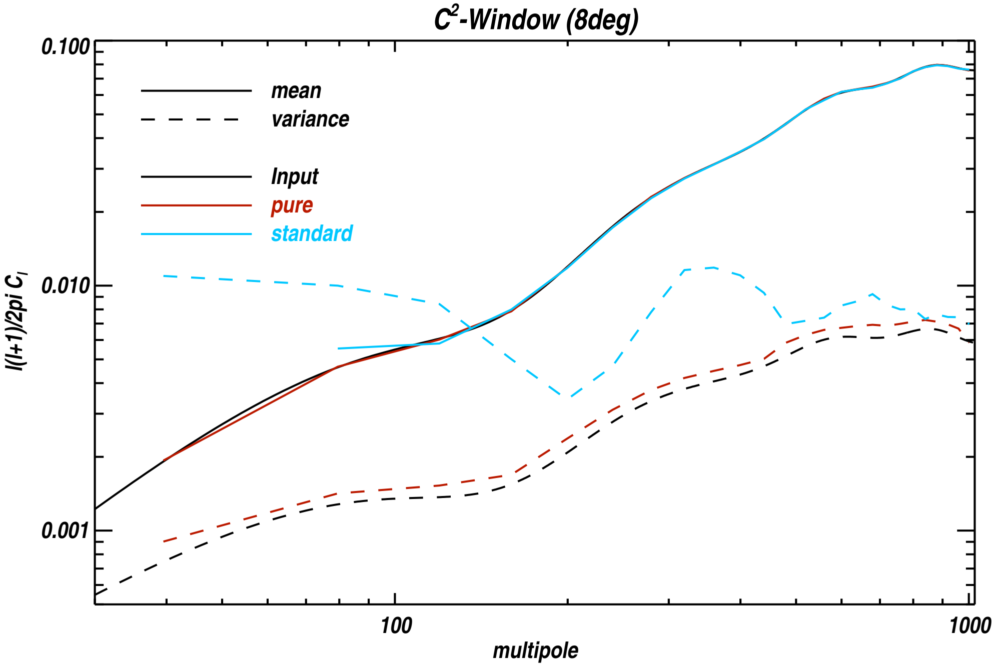
✓ E-B separation for any realizations :

E variance DOES leaks into B variance

✓ **L-L' separation on average**

INDEED, THE LEAKAGE IS UNDER CONTROL



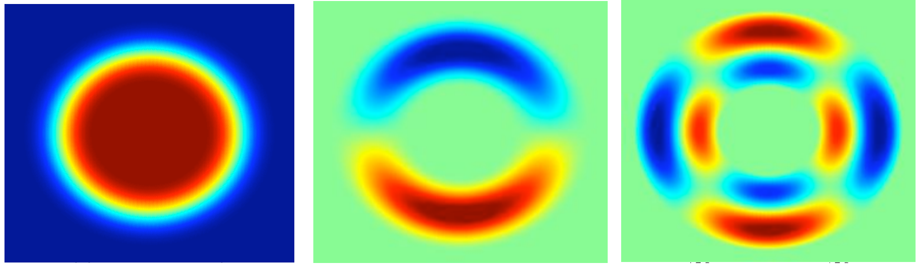


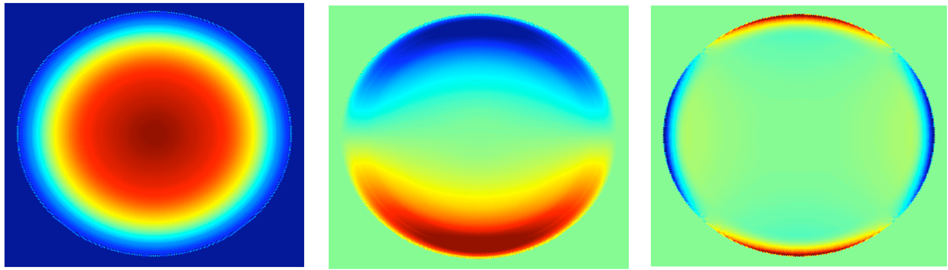
POWER SPECTRA UNCERTAINTIES : IDEAL CASE

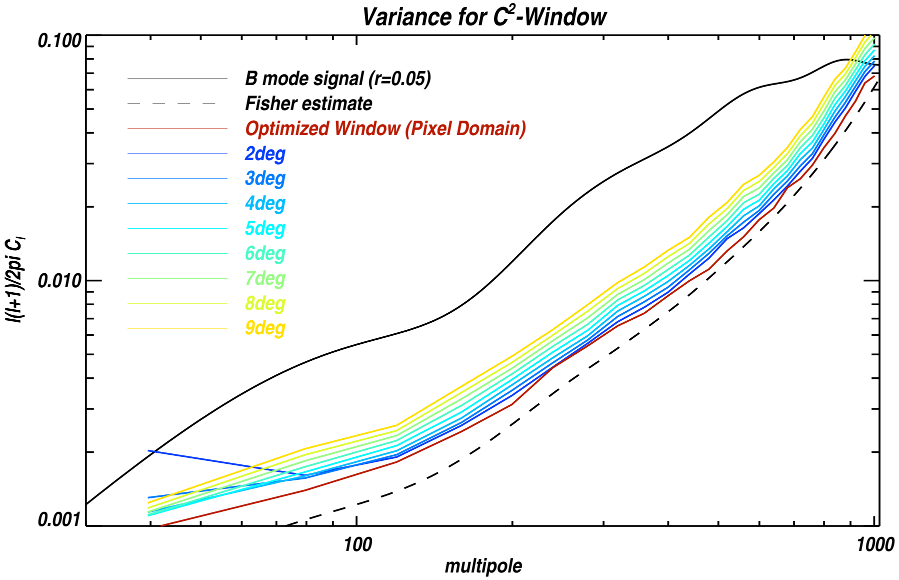
f_{sky}=1 % and σ=5,75 μK-arcmin.

Analytic weighting

Optimal weighting







Optimization is reached

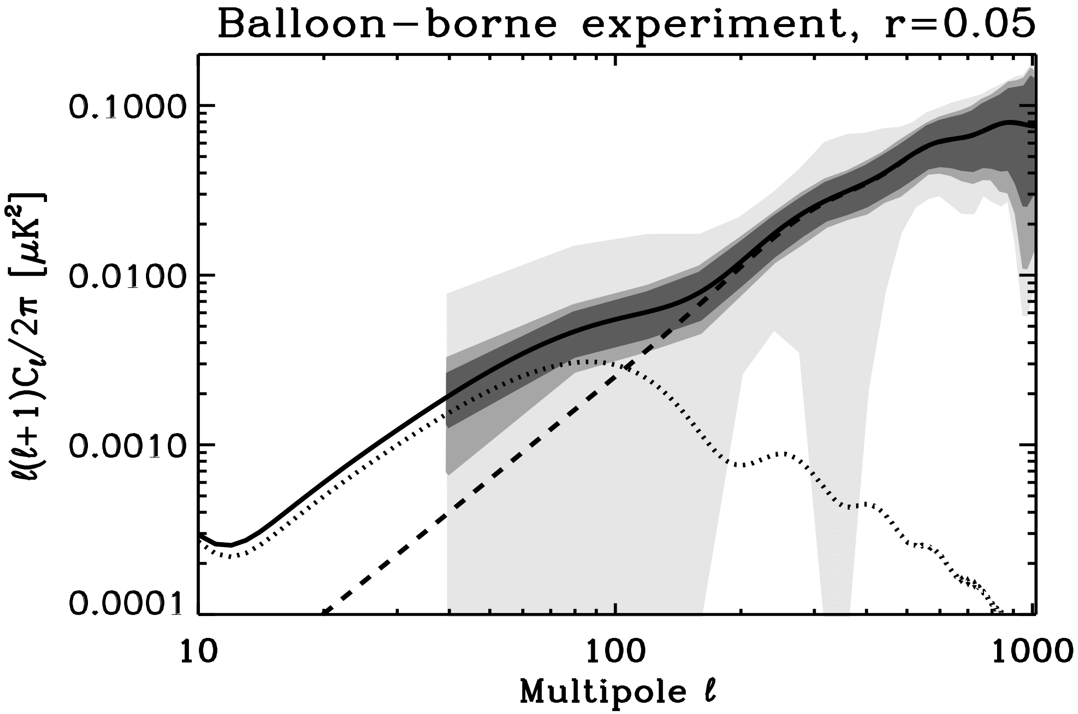
➔needed for **all** type of weighting

TO RECAP…

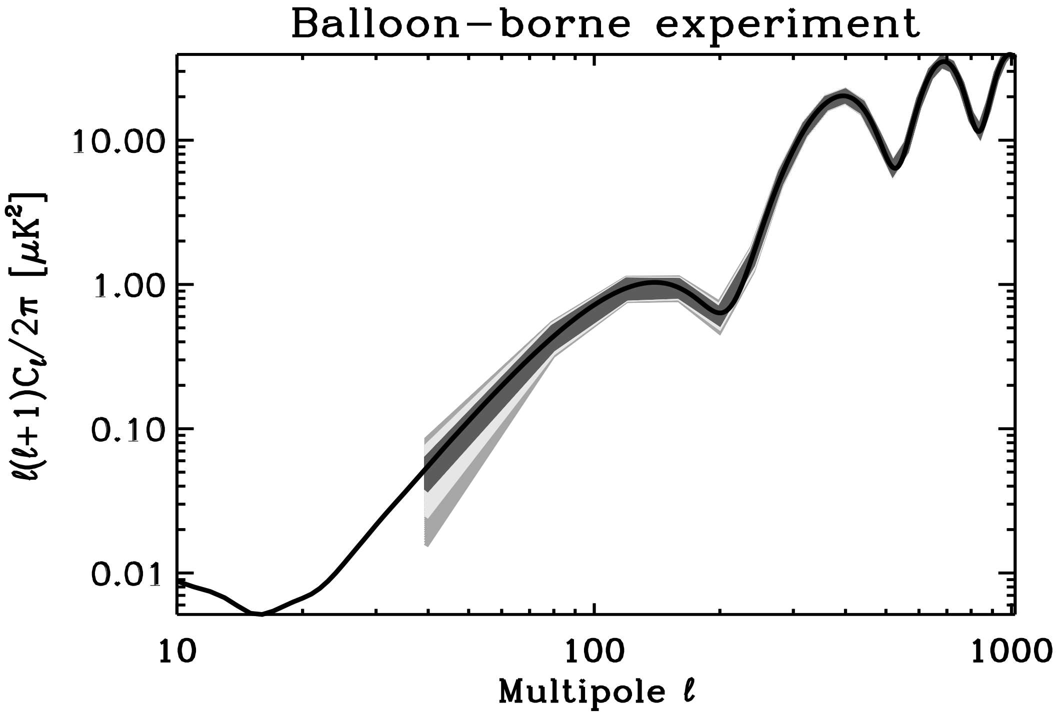
- **Fast** approach: $(N_{pix})^{3/2}$ au lieu de $(N_{pix})^3$
- **Precise** approach : $Var(C_\ell^B) \approx 2 \times Var_{optimal}(C_\ell^B)$

➔**Efficient alternative to optimal methods and a Monte-Carlo tool**

B-mode



E-mode



FOREGROUND CLEANING

Performances of parametric ML component separation method for B-mode detection

STOMPOR, LEACH, STIVOLI, BACCIGALUPI, MNRAS 392, 216 (2009)

Comparison : foreground residual vs. CMB

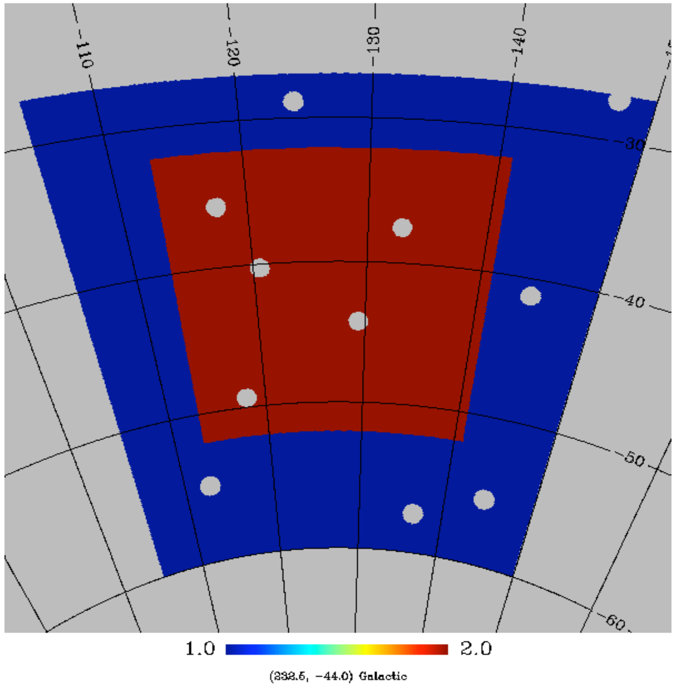
- **Pixel space :** B<<E for CMB (Q, U maps dominated by E) and E~B for foregrounds residuals
  ➔ $(Q,U)_{CMB} >> (Q,U)_{residuals}$ implies $E_{CMB} >> E_{residual}$ (eventually $E_{CMB} >> E_{residual} \sim B_{residual} >> B_{CMB}$)
- **E/B harmonic space :** $C_{\ell,E}^{(CMB)} >> C_{\ell,E}^{(residual)}$ and $C_{\ell,B}^{(CMB)} >> C_{\ell,B}^{(residual)}$

Balloon-borne experiment

- Frequencies : *150, 250 & 410 GHz*
- Sky coverage : *~1 %*
- Homogeneous noise : *~5.75 μK-arcmin*

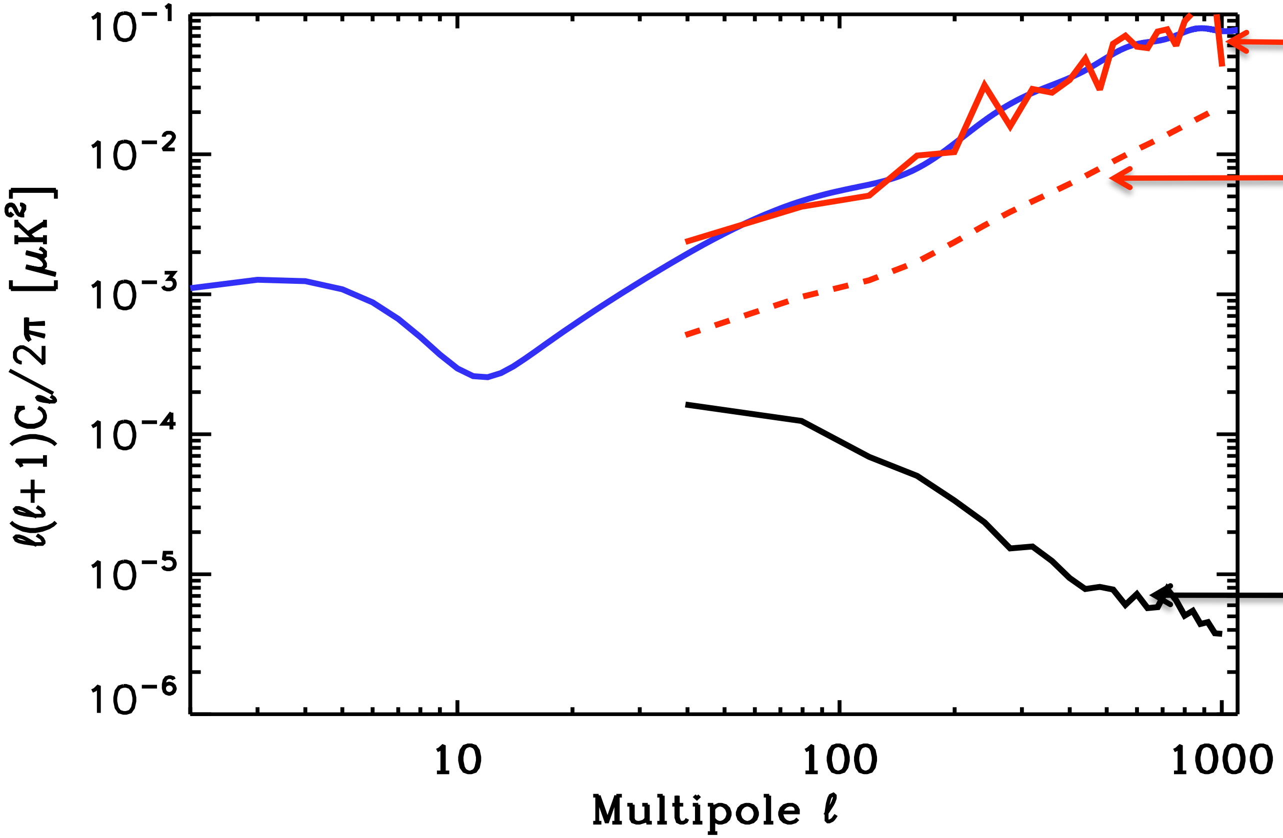
Ground-based experiment

- Frequencies : *90, 150 & 220 GHz*
- Sky coverage : *~2 %*
- Homogeneous noise : *~10 μK-arcmin*



FOREGROUND CLEANING : RESULTS FOR BALLOON-BORNE EXPERIMENT

- Simulated sky : **CMB + synchrotron + dust** (different frequency scaling,different spatial scaling)
-
- Component Separation : **MIRAMARE** Stompor, Leach, Stivoli, Baccigalupi, MNRAS 392, 216 (2009)
- Power spectrum : **Xpure** Grain, Tristram, Stompor, PRD 79, 123515 (2009)



Reconstructed CMB

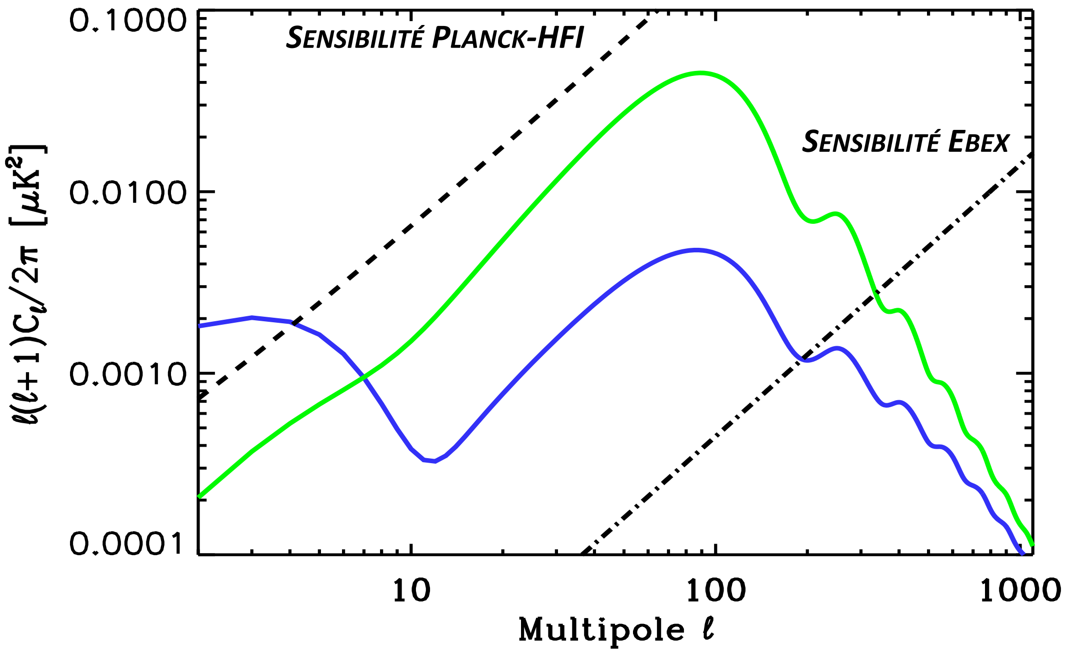
Statistical uncertainties

Foreground residuals

F. Stivoli, ***J. Grain***, S. Leach, M. Tristram, C. Baccigalupi & R. Stompor, in prep. for MNRAS

PLANCK-HFI, EBEX AND B-MODE

Planck-HFI



EBEX

- ✓ **Angular scale coverage:**
  constraints on B-mode
- ✓ **EM frequency coverage:**
  understanding of the foreground

Planck-HFI

- ✓ **Estimation de $C_l^{E/B}$**
- ✓ **Fluctuations du CIB**
- ✓ **Contraintes sur 'l'inflation'**

EBEX

- ✓ **Estimation de $C_l^{E/B}$**
- ✓ **Soustraction des avant-plans**
- ✓ **Effets systematiques**