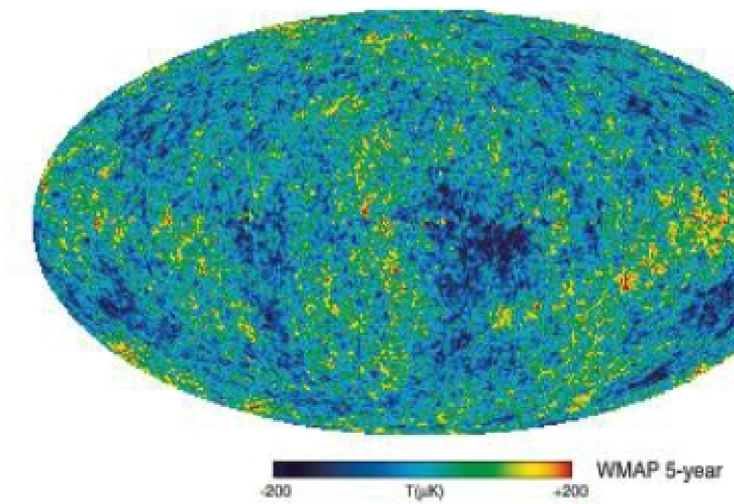
Preparation to the CMB Planck analysis: contamination due to the polarized galactic emission



L. Fauvet, J.F. Macías-Pérez

Polarized foregrounds

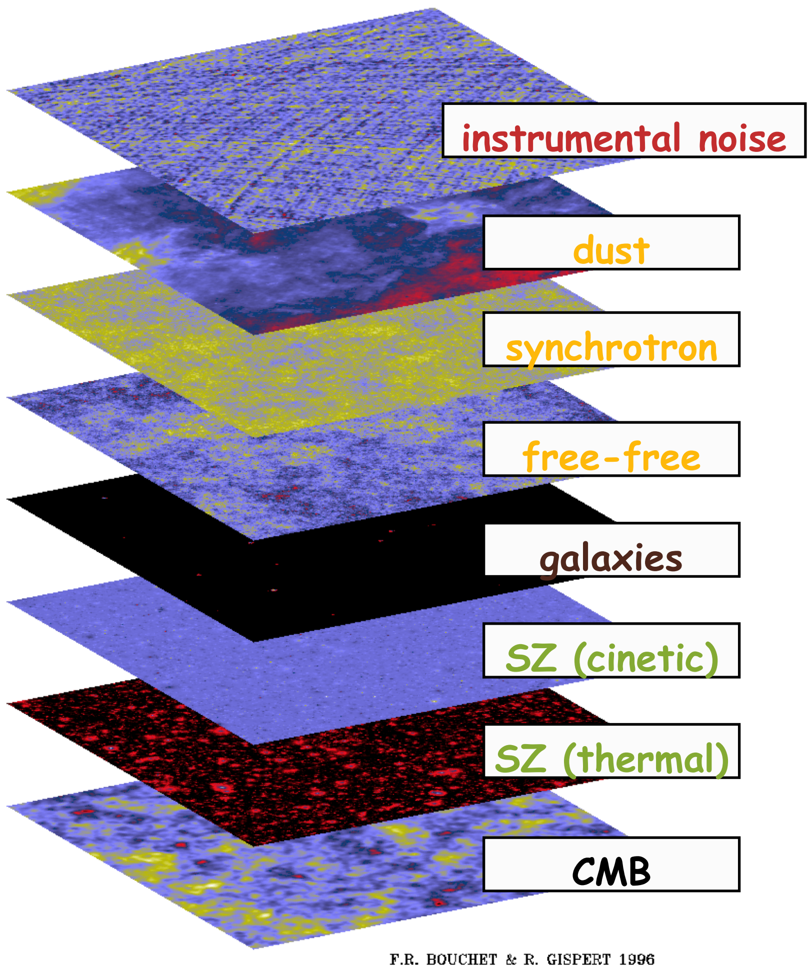
3D model of the galaxy: optimization

Expected constraints with Planck simulations

Contamination of the CMB data

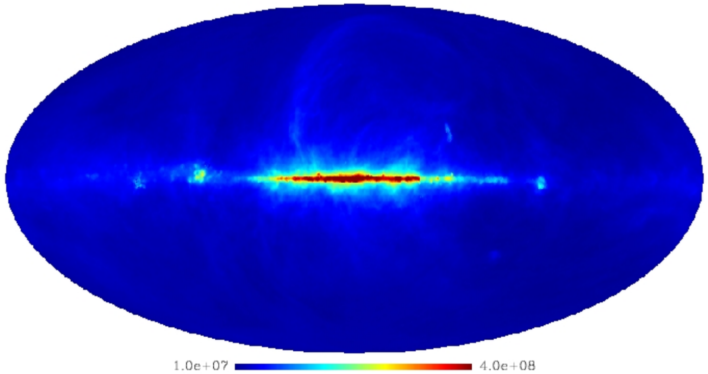
[LF, Macías-Pérez et al, submitted to A&A, astro-ph: *1003.4405*]

polarized foregrounds

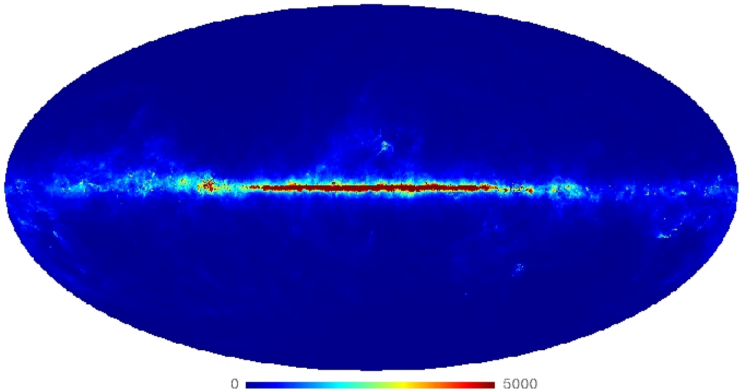


synchrotron dominates at $\nu < 70$ GHz
thermal dust dominates at $\nu > 70$ GHz

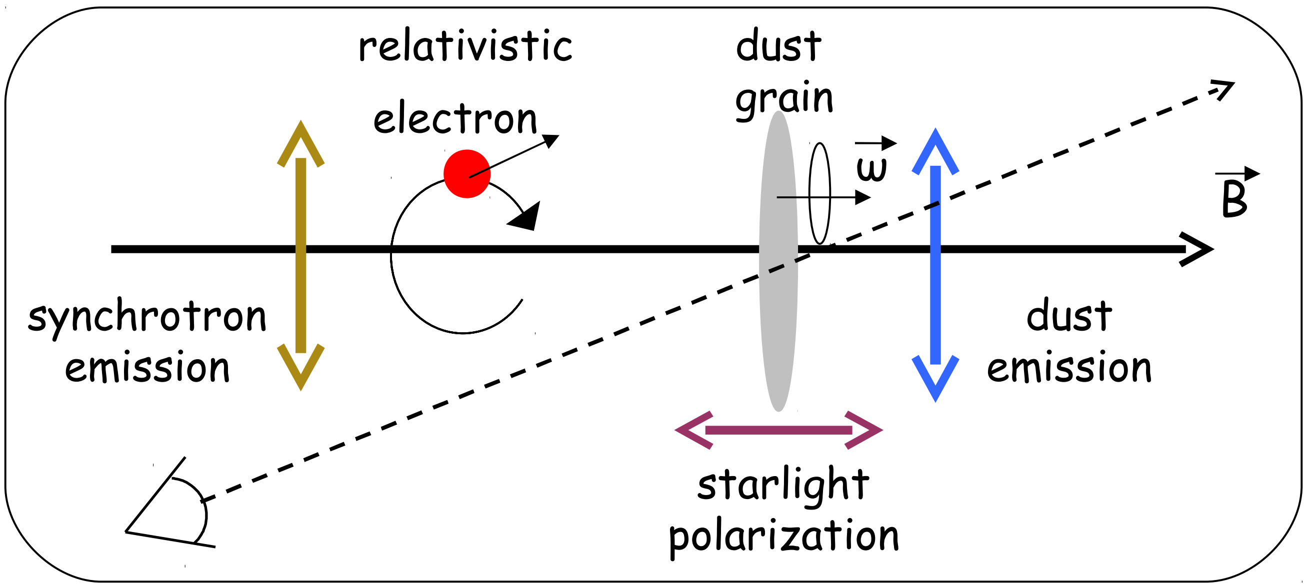
Galactic polarized foregrounds



synchrotron emission (408 MHz)
[Haslam et al, 1982]



thermal dust emission (353 GHz)
[Finkbeiner et al, 1999]



3D model of the Galaxy

physical model of polarized foreground emissions depends on:

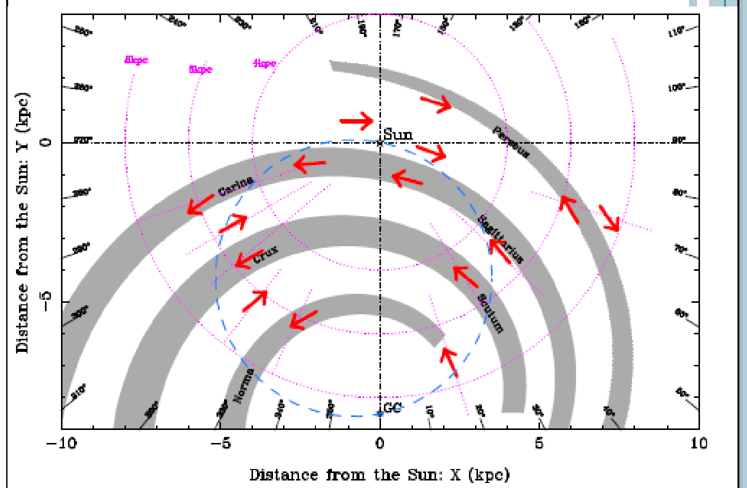
- the shape of the galactic magnetic field :

⟶ regular component : MLS or ASS

free parameter : pitch angle *[Han et al, 2006]*

⟶ non regular component *[Han et al, 2004]*

free parameter: A_{turb}



[Han et al, 2006]

- the distribution of relativistic electrons , free parameter: h_r

[Page et al, 2007; Sun et al, 2008]

- the distribution of dust grains

[Page et al, 2007; Paladini et al, 2007]

3D model of the Galaxy

- integrating along the line of sight

synchrotron emission

$$I = \int dI = \int n_e \left(B_l^2 + B_t^2\right)$$
$$Q_{ms} = \int dI \cos(2\gamma) p_s$$
$$U_{ms} = \int dI \sin(2\gamma) p_s$$

with:

$$p_s = \frac{s+1}{s+7/3}$$

polarization fraction related to the cosmic ray energy dimension slope s : p_s = 0.75

$$\gamma = \frac{1}{2} \arctan\left(\frac{2B_l \cdot B_t}{B_l^2 - B_t^2}\right)$$

idem for thermal dust

- extrapolation at various μ : β_s

thermal dust emission

$$I_{md} = \int n_d \cdot ds$$
$$Q_{md} = \int dI \cos(2\gamma) \sin^2(\alpha) f_{\rm norm} p_d$$
$$U_{md} = \int dI \sin(2\gamma) \sin^2(\alpha) f_{\rm norm} p_d$$

p_d: the polarization fraction = 0.1
[Ponthieu et al, 2005]

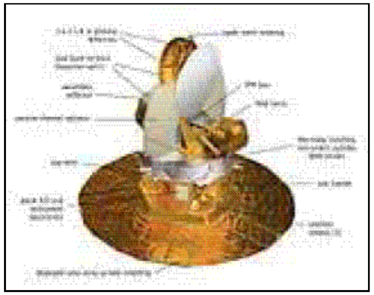
$$\sin^2(\alpha) = \sqrt{\frac{1 - B_t^2}{B_{\rm norm}}}$$

- extrapolation at various μ : β_d

3D model of the Galaxy : optimisation

- 408 MHz all-sky continuum survey *[Haslam et al, 1982]*

- 5 years of WMAP data *[Hinshaw et al, 2009]*
  - NASA satellite currently flying
  - 5 polarized channels between 23 and 94 GHz

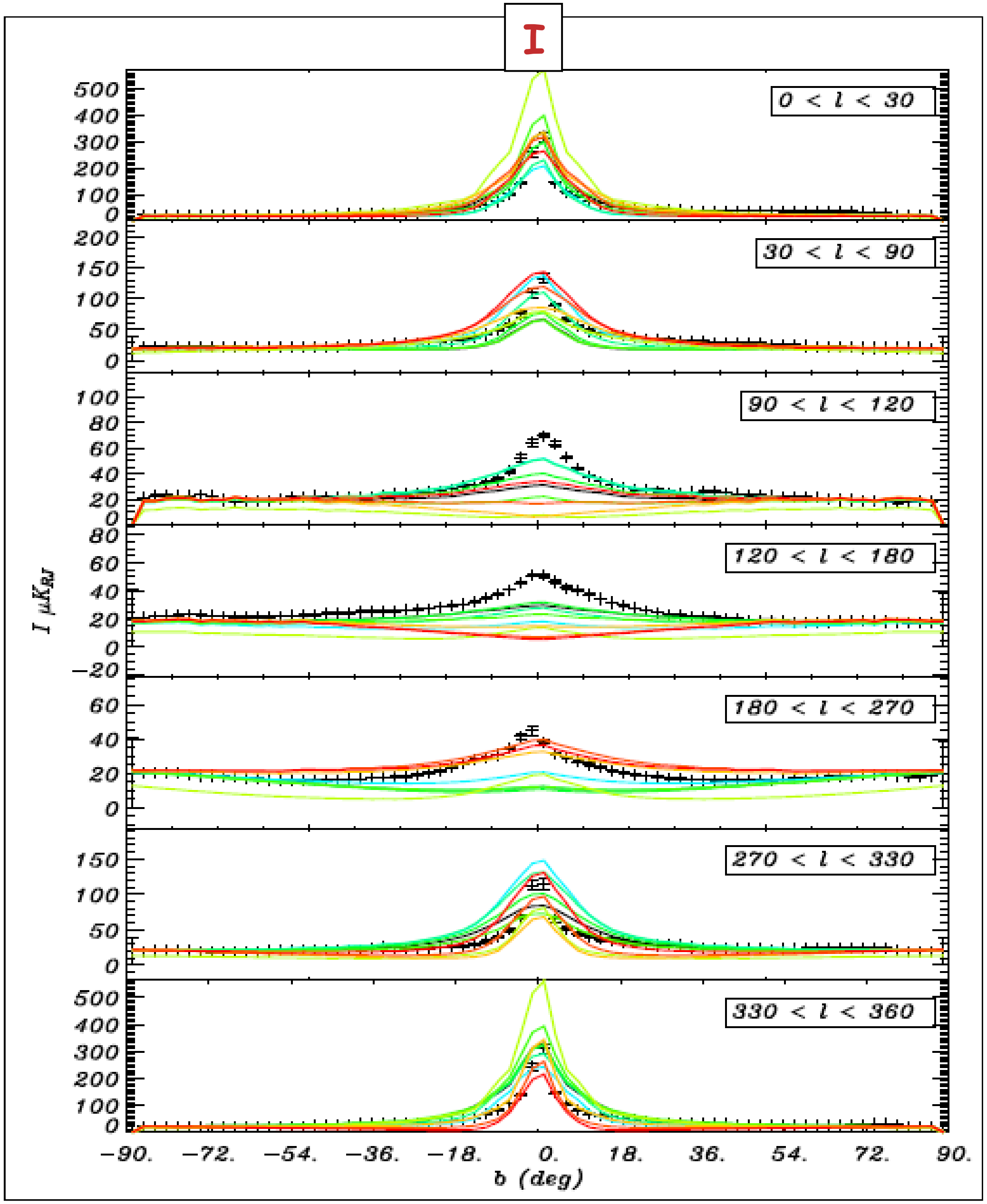


→ optimisation of the synchrotron emission model

- ARCHEOPS *[Benoit et al, 2003]*
  - ballon experiment, flew in 2002
  - 1 polarized channel at 353 GHz

→ optimisation of the thermal dust emission model

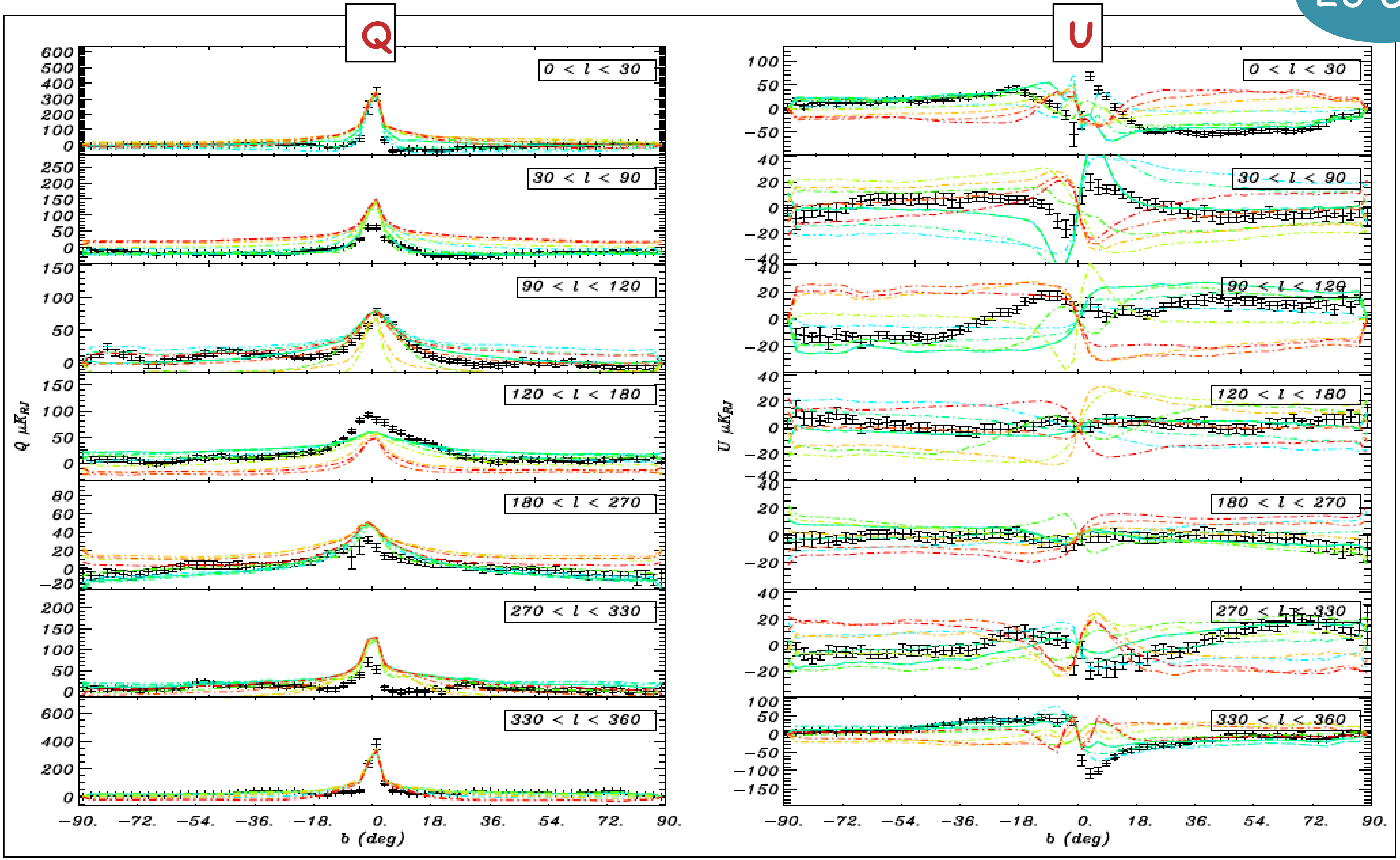
3D model of the Galaxy: optimisation



Haslam data, MLS field for different values of A_{turb}

3D model of the Galaxy : optimisation

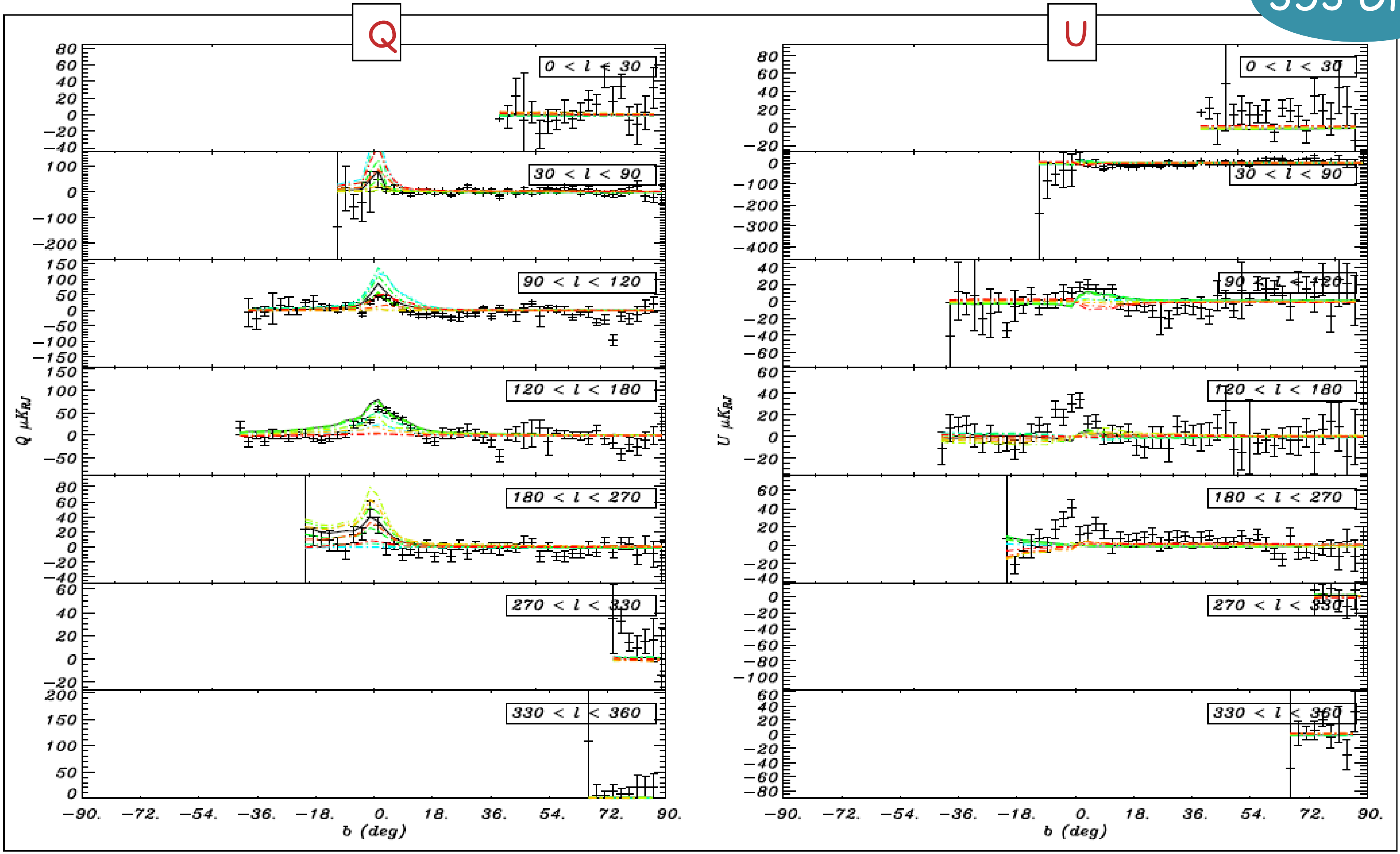
23 GHz



WMAP 5 years data +
synchrotron emission *(from green to red)* (MLS model of magnetic field and exponnential distribution of relativistic electrons)

3D model of the Galaxy : optimisation

353 GHz



galactic profiles for various values of the latitudes the ARCHEOPS data and our model of thermal dust emission (MLS model of magnetic field and exponential distribution of dust grains)

3D model of the Galaxy : best fit model

MLS field

- for the synchrotron emission

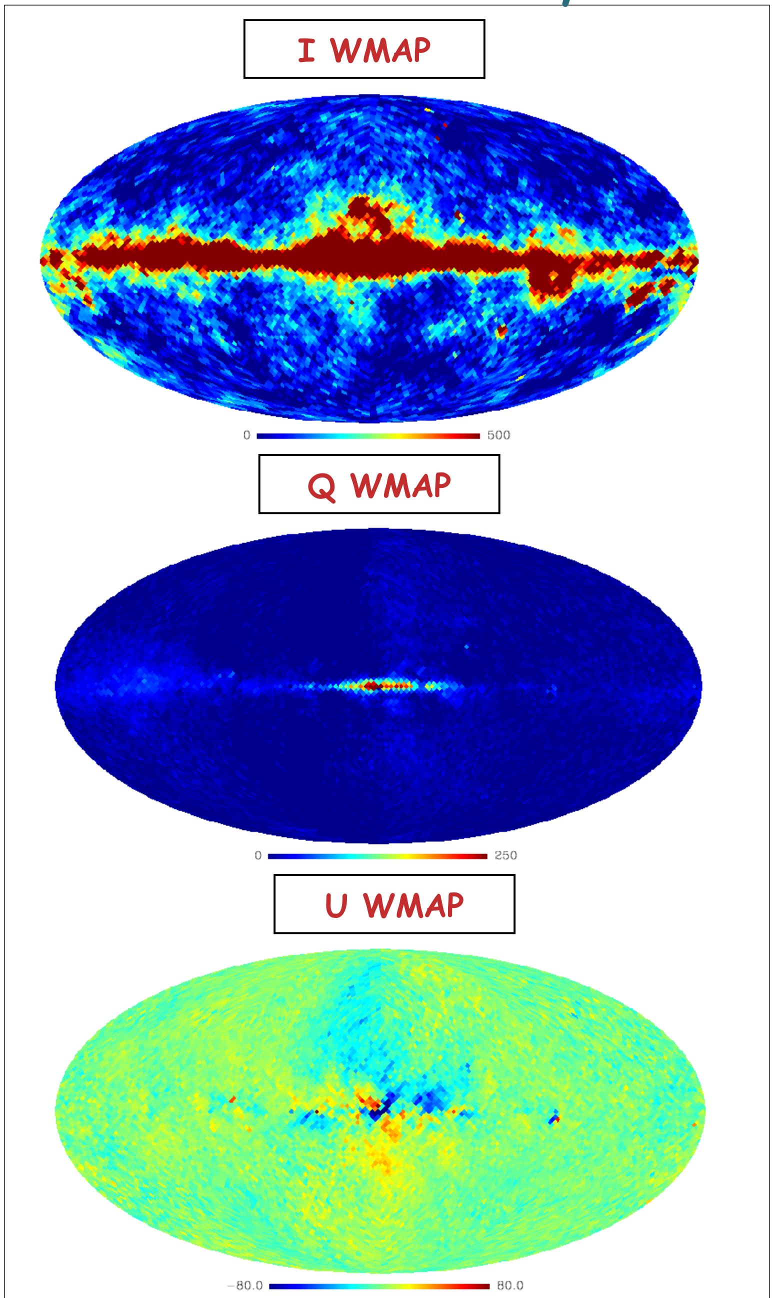
$A_{turb} < 0.25\ B_{reg}$
$p = -30 \pm 20$ deg
$h_r < 15$ kpc
$\beta_s = -3.3 \pm 0.1$

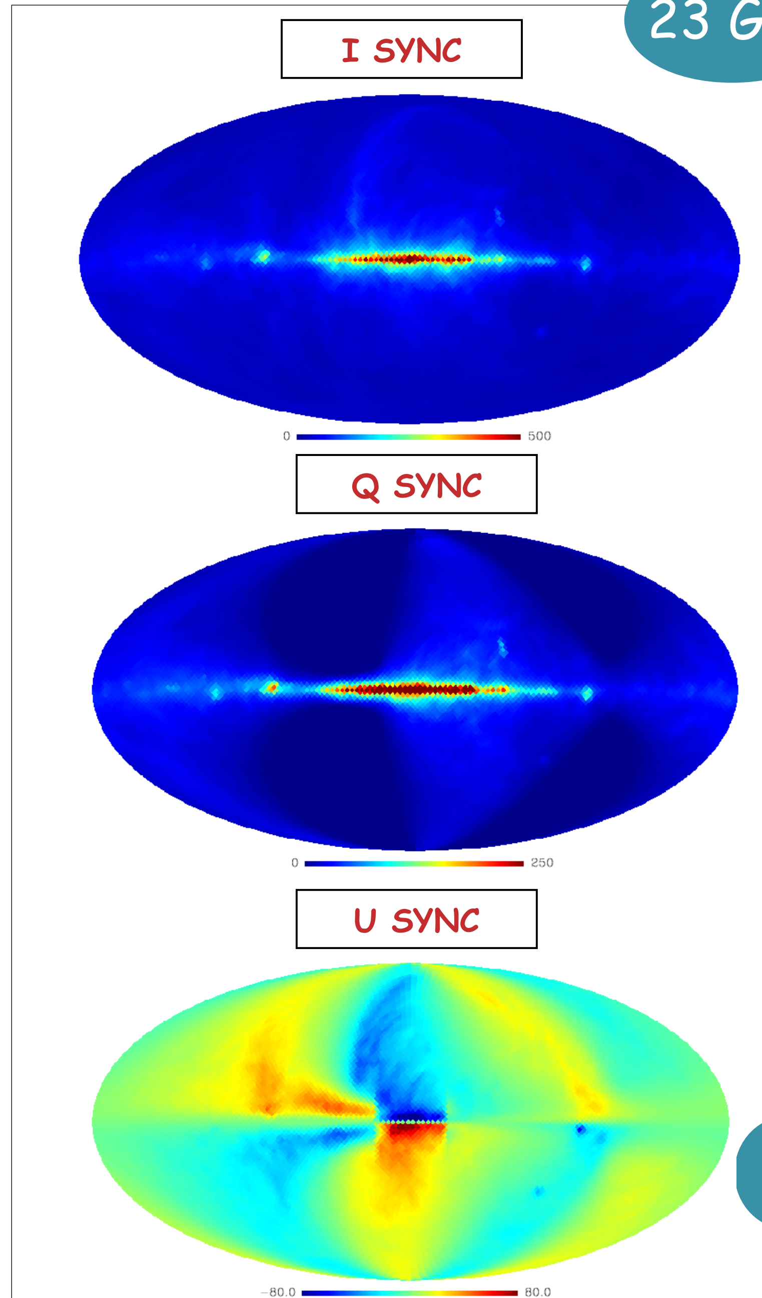
- for the dust thermal emission

$A_{turb} < 0.25\ B_{reg}$
$p = -20 \pm 10$ deg

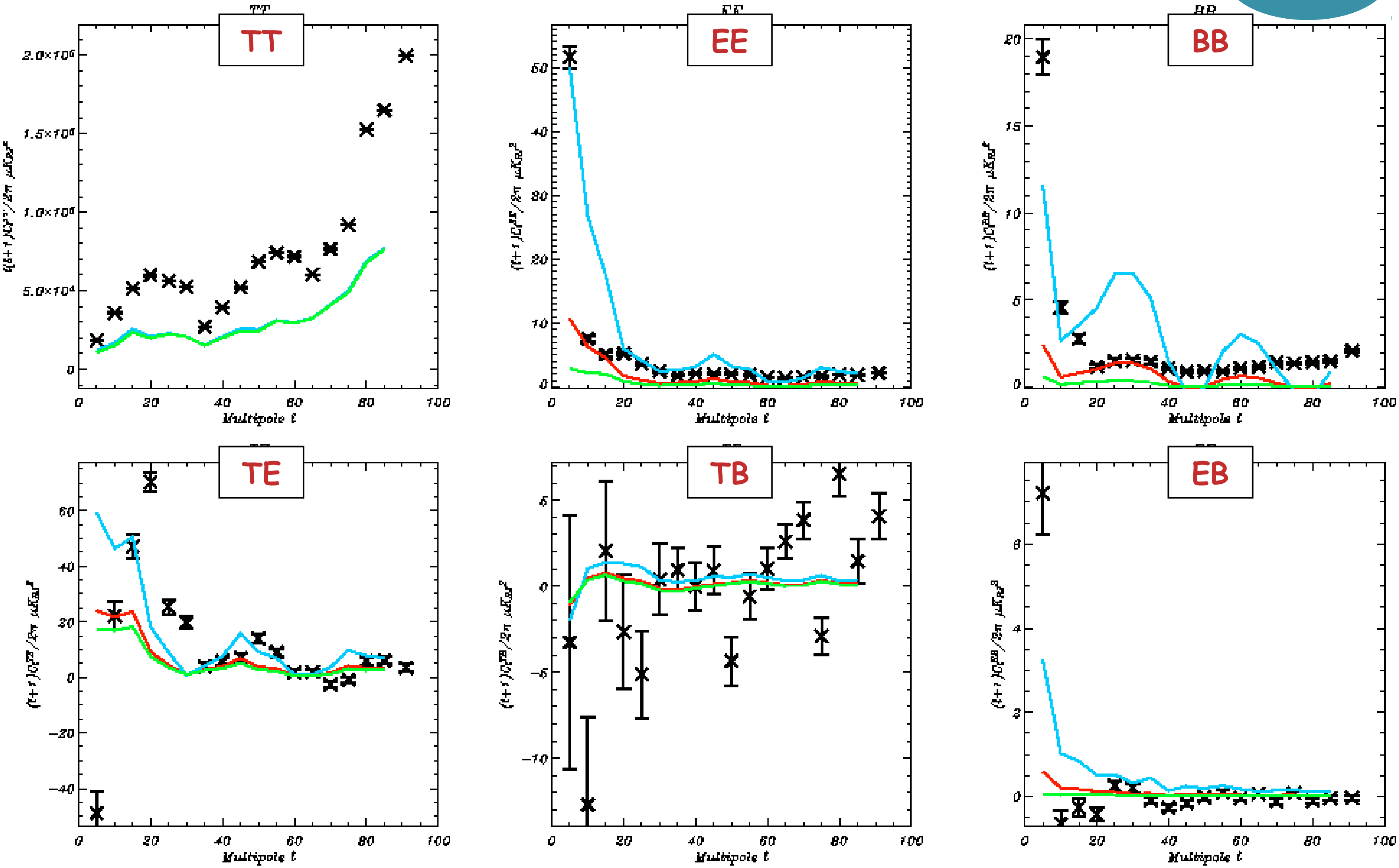
3D model of the Galaxy : best fit model

23 GHz



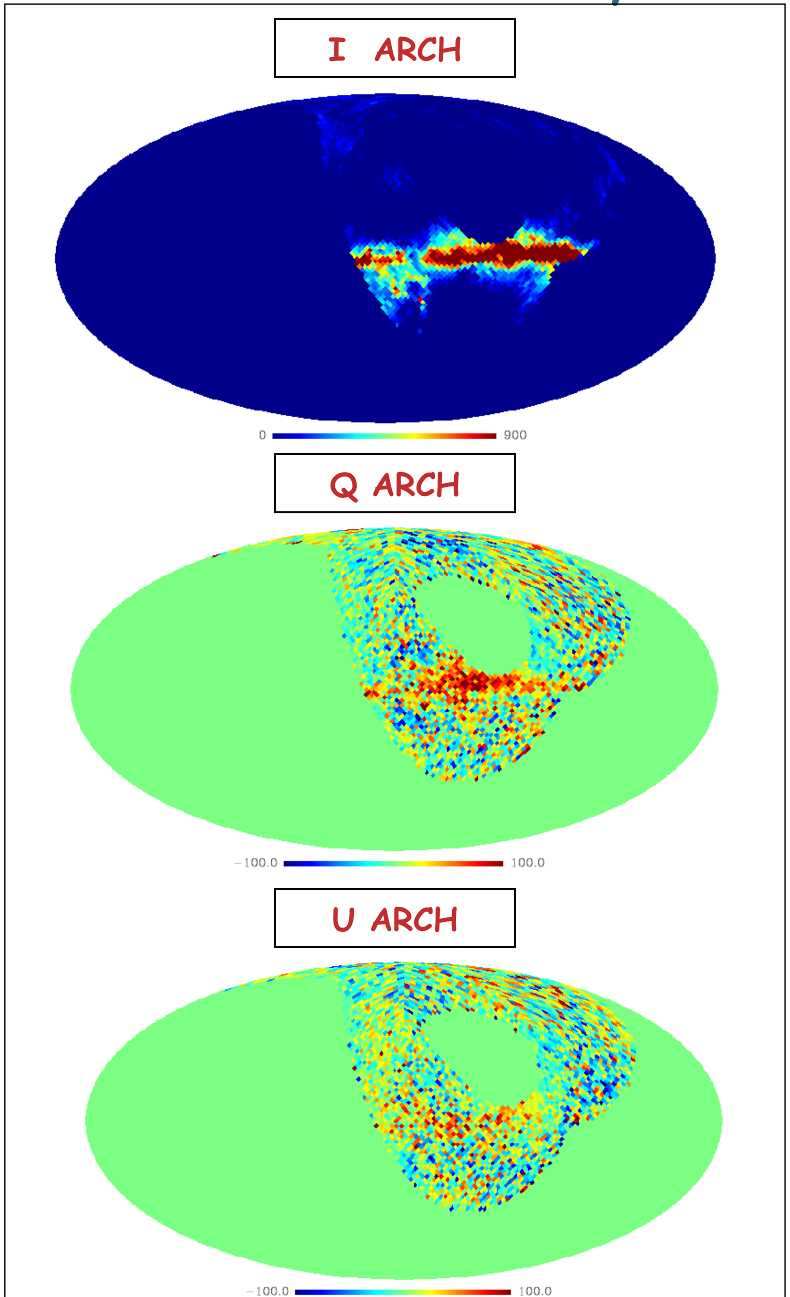


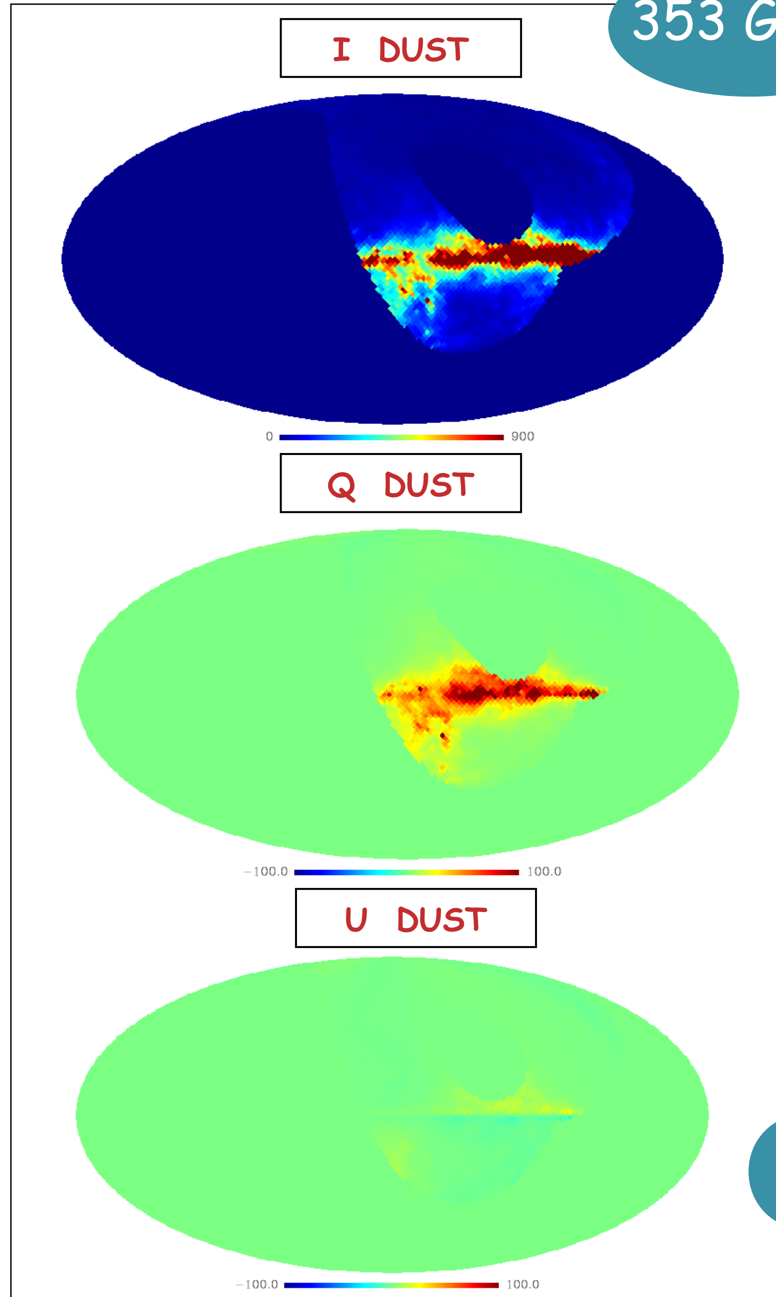
3D model of the Galaxy : best fit model



3D model of the Galaxy : best fit model

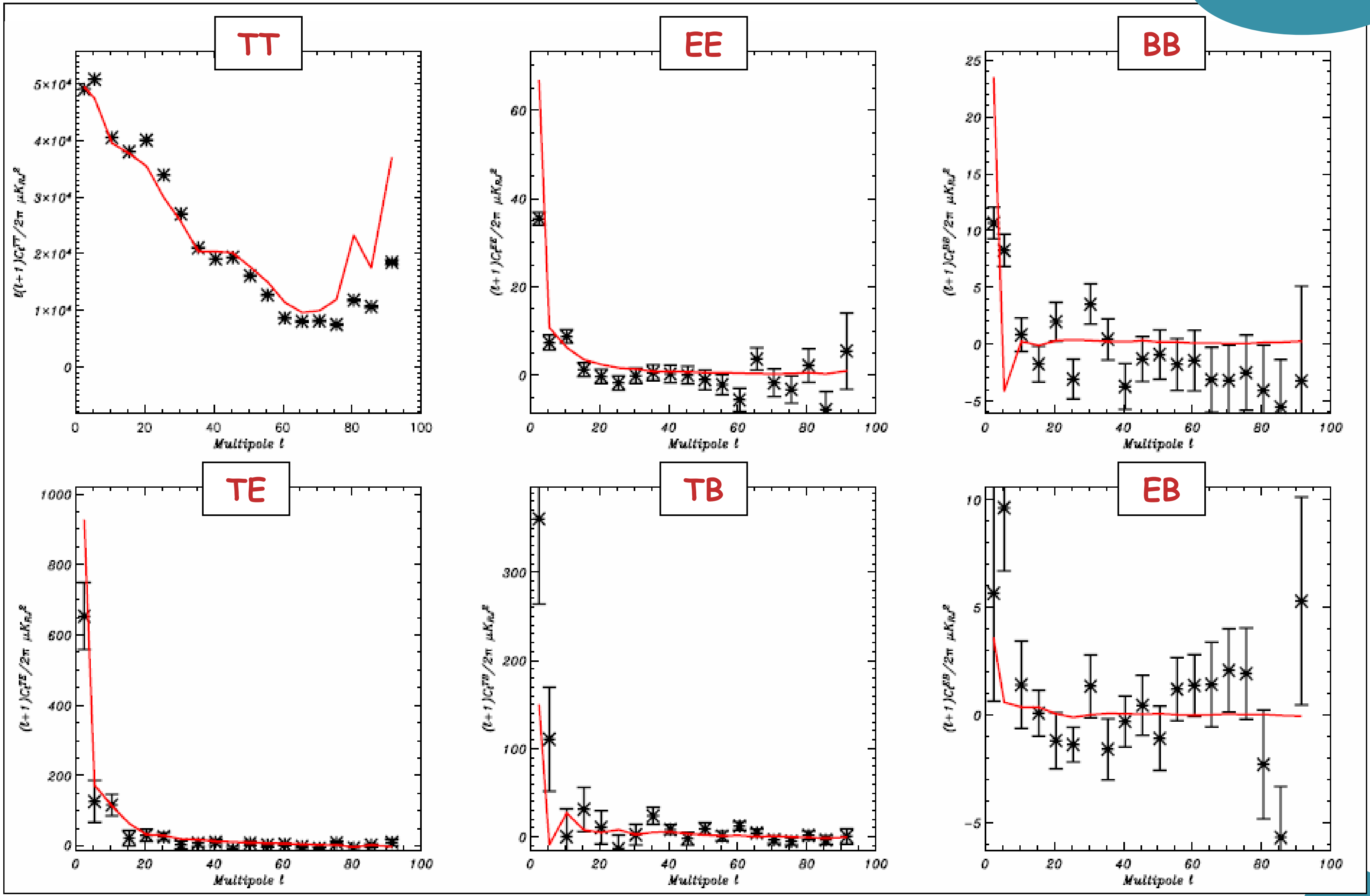
353 GHz





3D model of the Galaxy : best fit model

353 GHz



Expected constraints on the galactic magnetic field with Planck

[LF, Macías-Pérez et al, to be submitted to A&A]

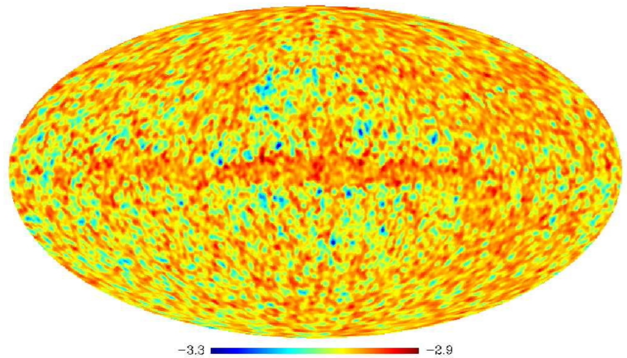
Expected constraints with Planck

- simulations of Q and U map of Planck and WMAP 8-years data for all polarized channels :

$$\begin{pmatrix} Q^\nu \\ U^\nu \end{pmatrix} = \begin{pmatrix} Q^\nu_d \\ U^\nu_d \end{pmatrix} + \begin{pmatrix} Q^\nu_s \\ U^\nu_s \end{pmatrix} + \begin{pmatrix} Q^\nu_N \\ U^\nu_N \end{pmatrix} + C$$

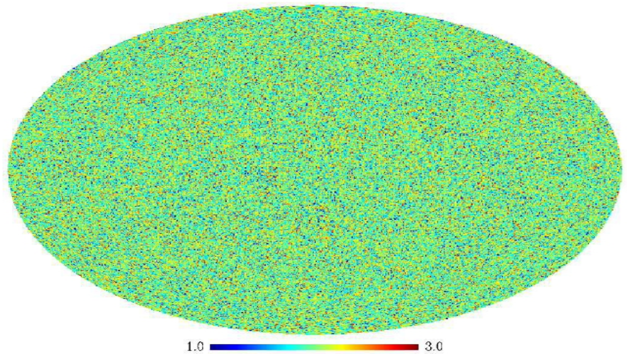
- 4 types of simulations :
  - -> with or without turbulent component of the magnetic fields (A_{turb} = 0.25)
  - -> with spectral index spatialy constants (β_s = -3.0, β_d = 1.4) or variables

- noise : gaussian random *[Planck Bluebook, 2004; Hinshaw et al, 2010]*
- CMB : model ΛCDM *[Komatsu et al, 2010]*



$-3.5 < \beta_s < -2.8$

[Gold et al, 2010]

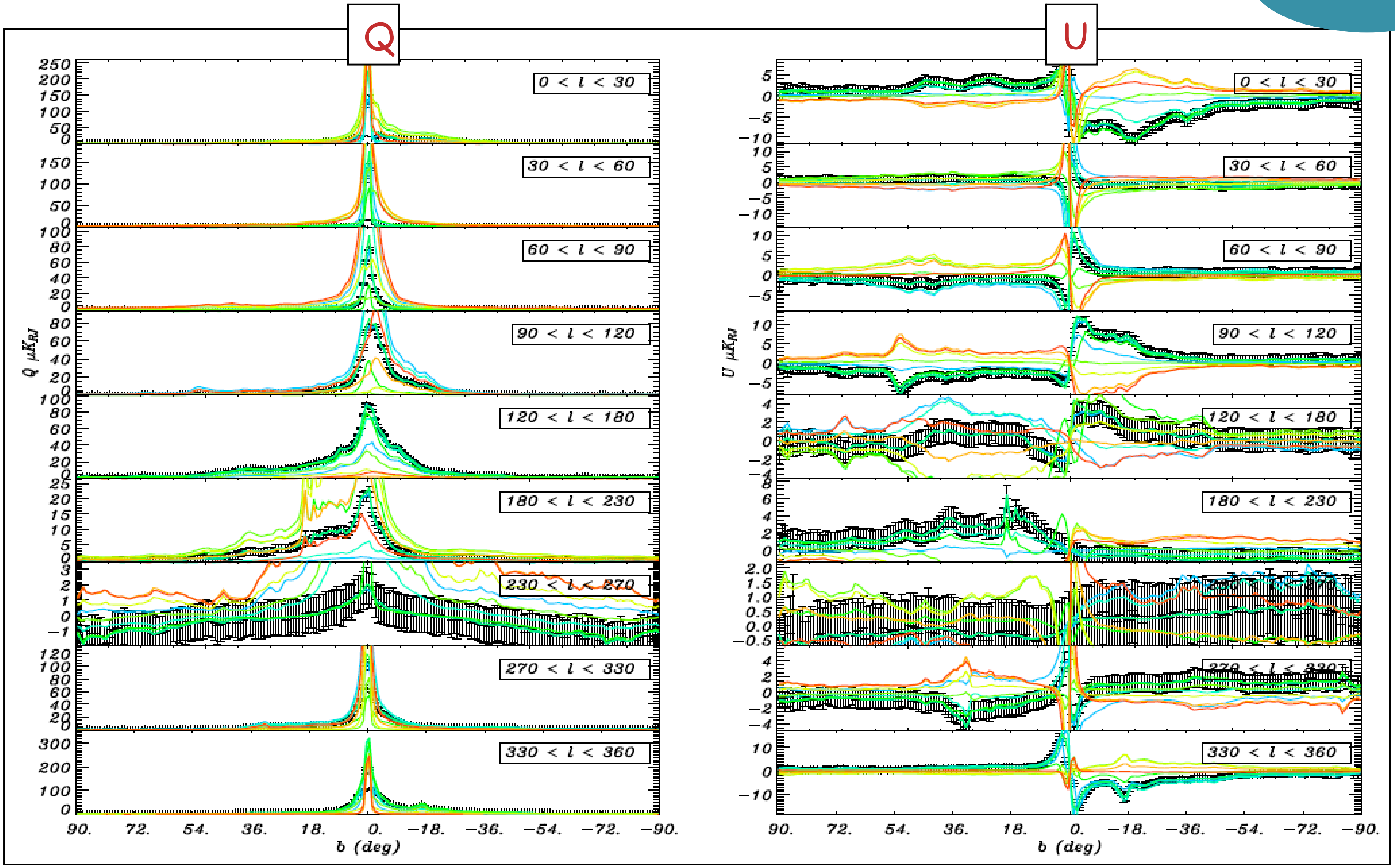


$\beta_d = 1.4 \pm 0.3$

[Macias-Pérez, LF et al, in preparation]

Expected constraints with Planck

353 GHz



MLS field for different values of p

Expected constraints with Planck

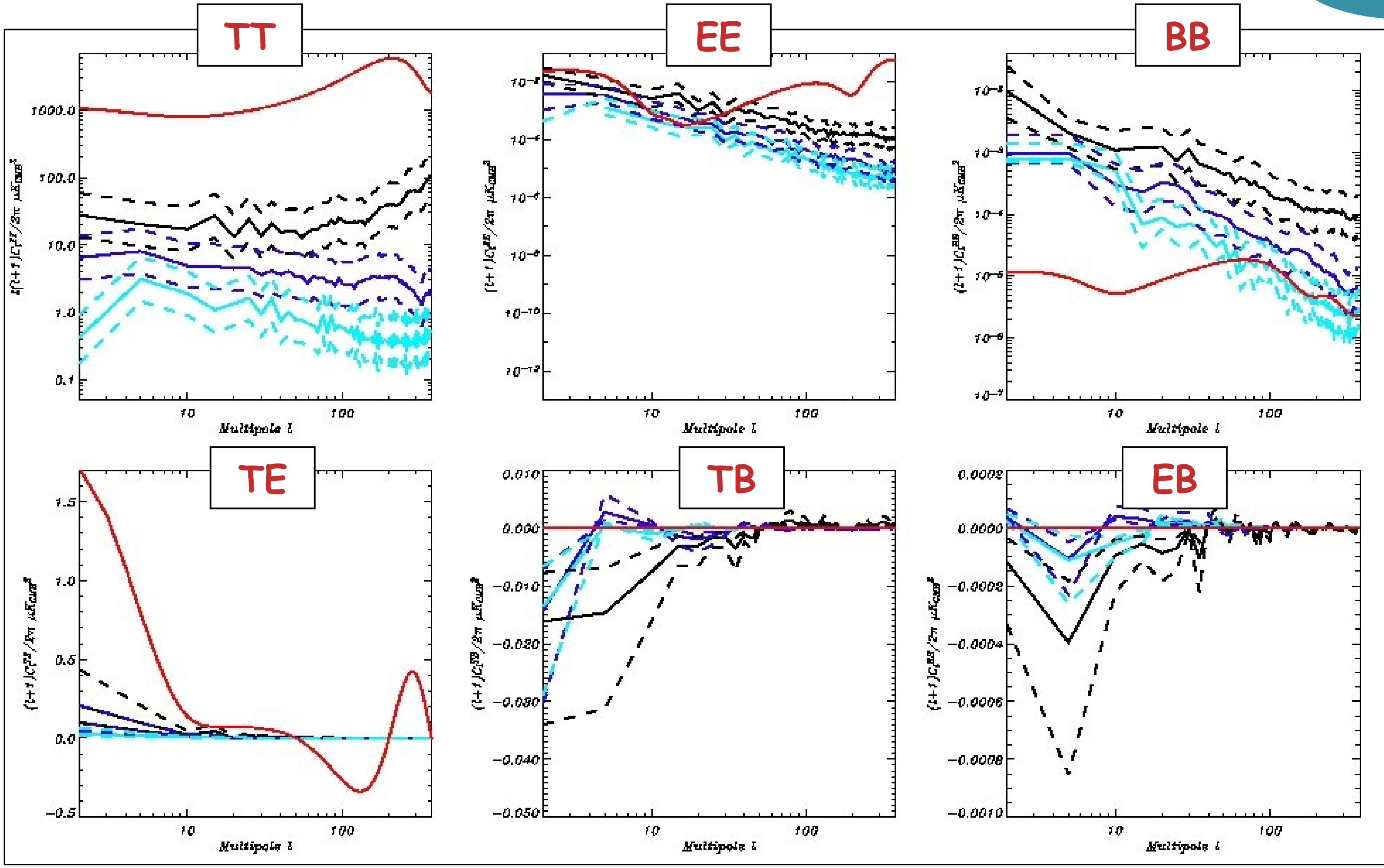
simulation	component	β_{simu}	A_{turb}	$p(deg)$	h_r^e	h_r^d	β_s	β_d
simu 1	P	cst	< 0.25	-30^{+10}_{-20}	< 17	< 15	$-3.0^{+0.1}_{-0.2}$	$1.4^{+0.6}_{-0.3}$
		var	< 0.25	-30^{+10}_{-20}	< 17	< 17	$-3.0^{+0.1}_{-0.2}$	$1.3^{+0.7}_{-0.2}$
	P+W	cst	< 0.125	-30 ± 10	< 2	< 17	-3.0 ± 0.1	$1.4^{+0.7}_{-0.2}$
		var	< 0.125	-30 ± 10	< 2	< 17	-3.0 ± 0.1	$1.4^{+0.7}_{-0.2}$
simu 2	P	cst	$0.125^{+0.875}_{-0.125}$	-30^{+20}_{-30}	< 17	< 17	$-3.1^{+0.1}_{-0.8}$	$1.5^{+1}_{-0.2}$
		var	$0.125^{+0.750}_{-0.125}$	-30^{+20}_{-30}	< 17	< 17	$-3.1^{+0.1}_{-0.8}$	$1.4^{+1.0}_{-0.2}$
	P+W	cst	0.25 ± 0.125	-30 ± 10	< 2	< 17	-3.0 ± 0.1	$1.4^{+0.9}_{-0.2}$
		var	0.25 ± 0.125	-30 ± 10	< 2	< 17	-3.0 ± 0.1	$1.4^{+0.98}_{-0.2}$

- strong constraints expected on p, β_s and β_d
- no constraints expected on h^e_r and h^d_r
- adding WMAP data improve the constraints

Contamination of the CMB data

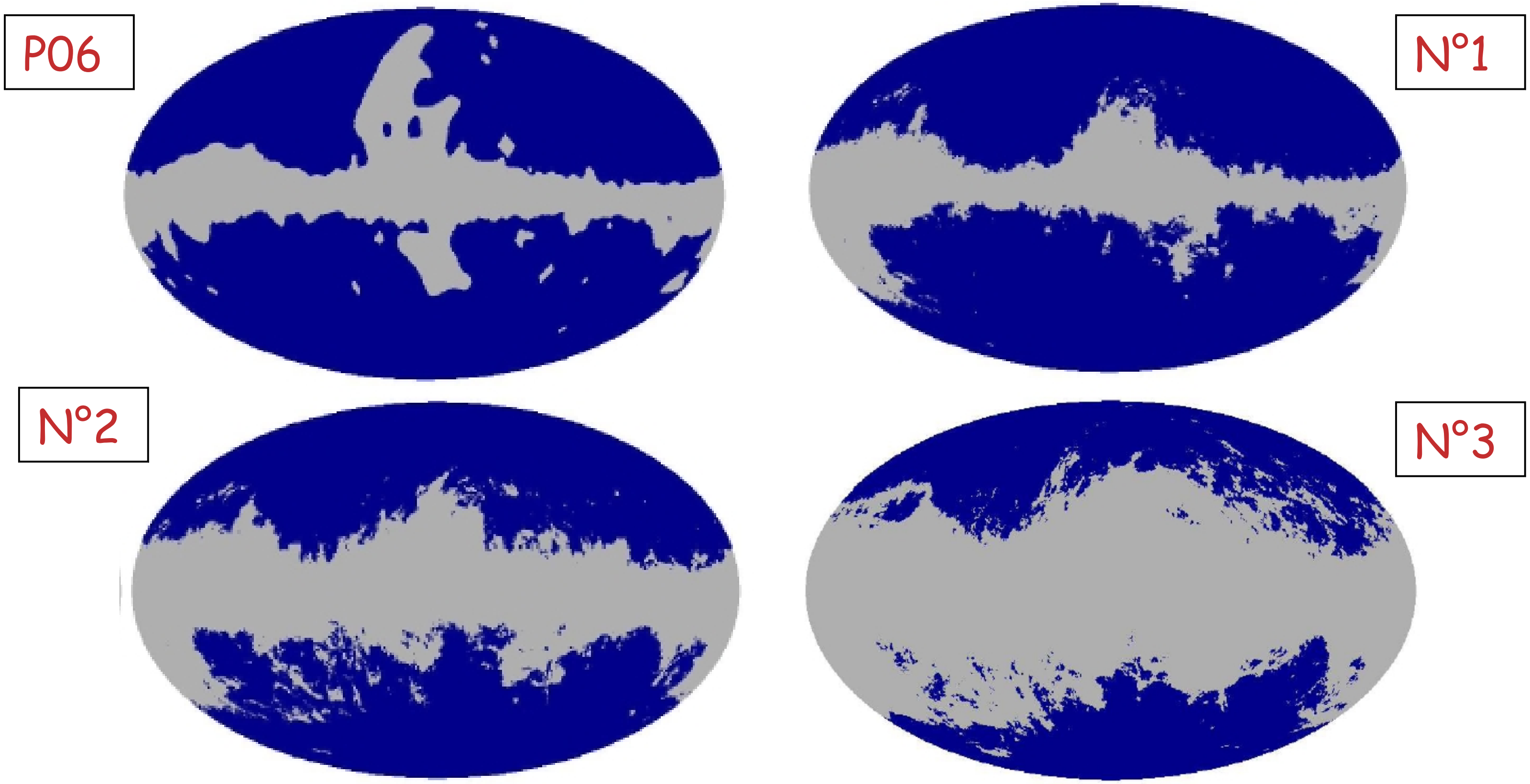
Contamination of the CMB data: galactic cut

100 GHz



from blue to black: model of galactic emission for |b| > 15, 30, 40 deg
red : CMB simulations, r=0.1, ΛCDM *[Komatsu et al, 2010]*

Contamination of the CMB data: dust masks

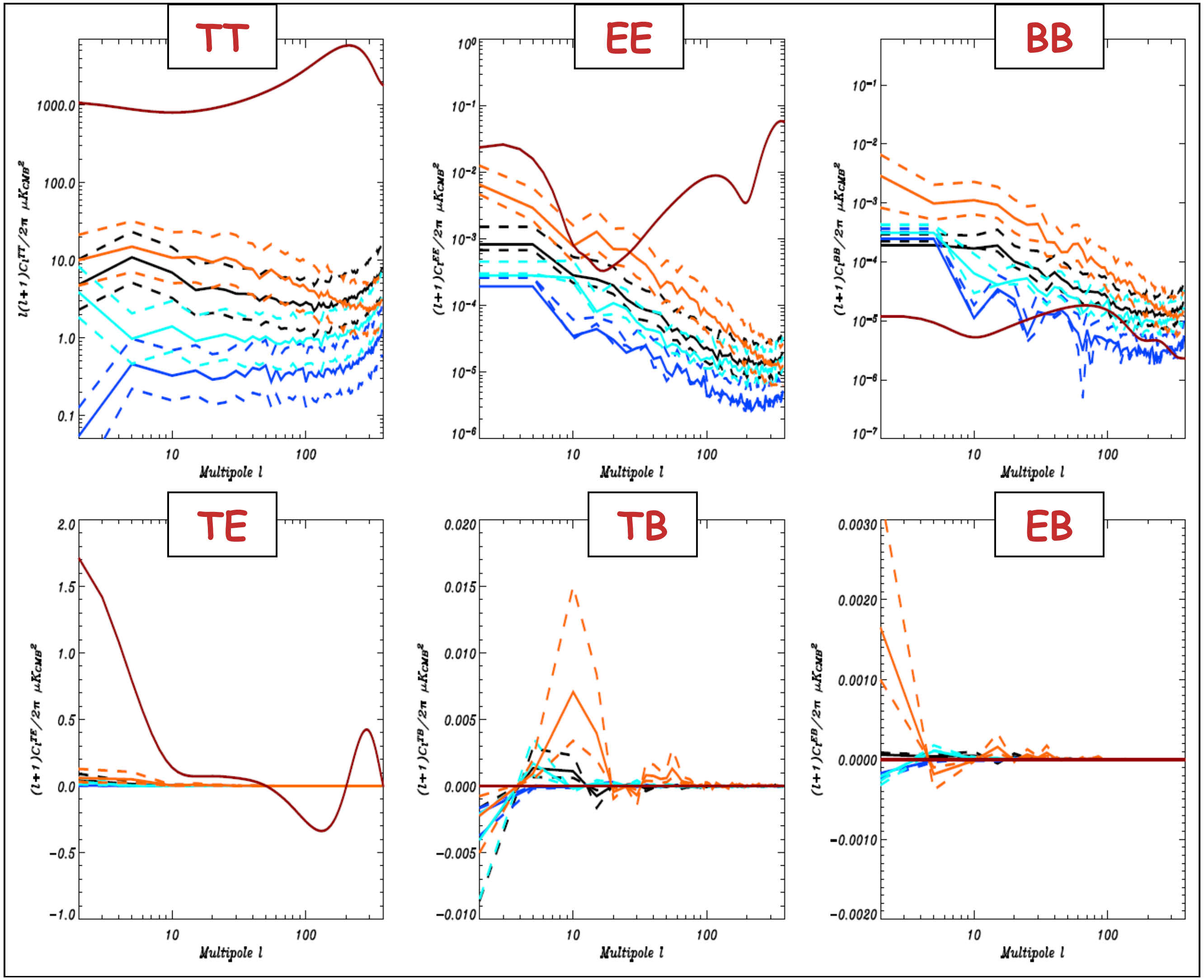


N°1 : cut for Q > 50 μKRJ or I > 500 μKRJ (f_{sky} = 27 %)
N°2 : cut for Q > 100 μKRJ or I > 1000 μKRJ (f_{sky} = 59 %)
N°3 : cut for Q > 300 μKRJ or I > 3000 μKRJ (f_{sky} = 63 %)
P06 : using WMAP data at 23 and 94 GHz *[Gold et al, 2010]*

	P06	N°1	N°2	N°3
$\Delta C_\ell^{sampling} / \Delta C_\ell^{cosmic}$	1.37	1.37	1.7	2.7

Contamination of the CMB data

100 GHz



from black to blue : model of galactic emission using masks N°1, N°2, N°3
Orange : using P06 mask
red : simulation of CMB, r=0.1, ΛCDM *[Komastu et al, 2010]*

Conclusions

- coherent models for the diffuse polarized galactic emissions

- compared to existing data

- used the best fit model to estimate the foregrounds contamination to the CMB Planck data

- implemented a method to constraint the models of diffuse galactic emissions using Planck data.

- masks to minimize the dust emission in the final power spectra.

The PLANCK mission

Planck : ESA mission dedicated to the CMB anisotropies measurement

- large frequency range :

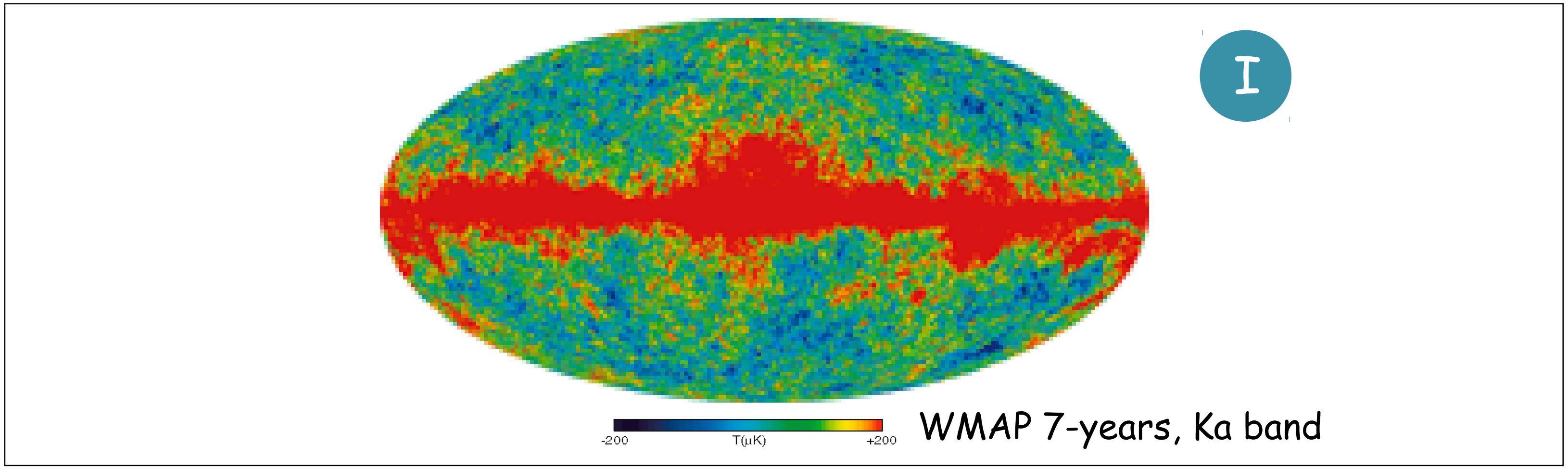
  LFI : 30, 44, 70 GHz

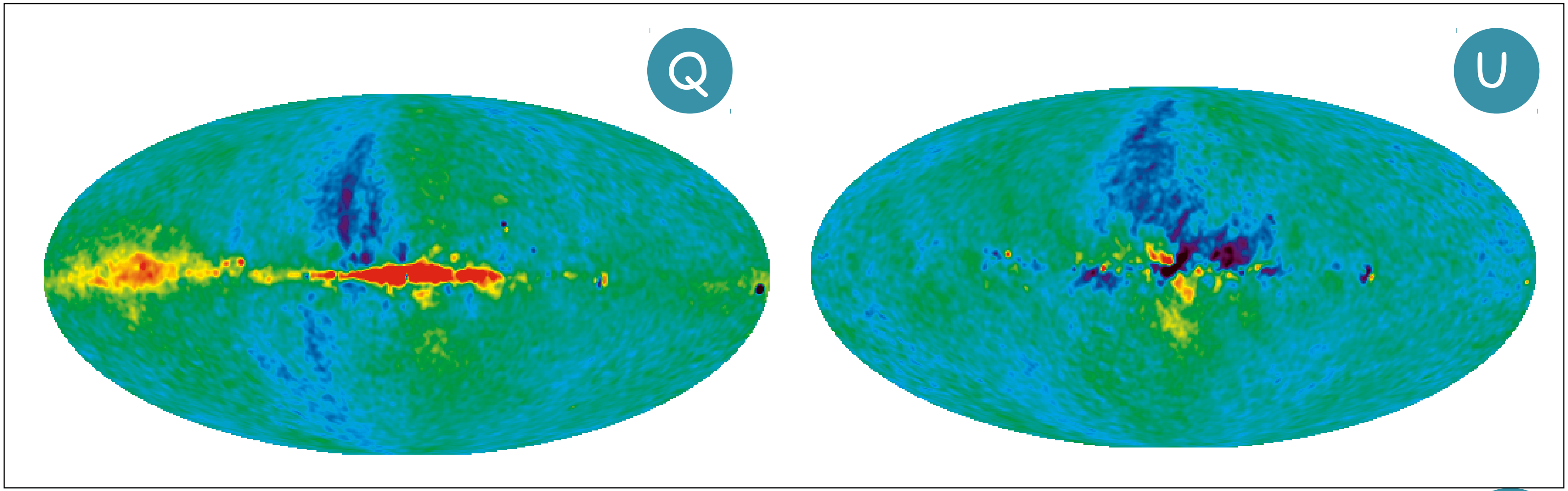
  HFI : 100, 143, 217, 353, 545, 857 GHz

- full-sky coverage and angular resolution of 5′
- sensitivity limited by the ability to subtract astrophysical foregrounds ~ 2.10^{-6}K

- Ultimate measurement of the CMB temperature anisotropies
- Best possible measurement of polarization with currently available technologies

polarized foregrounds

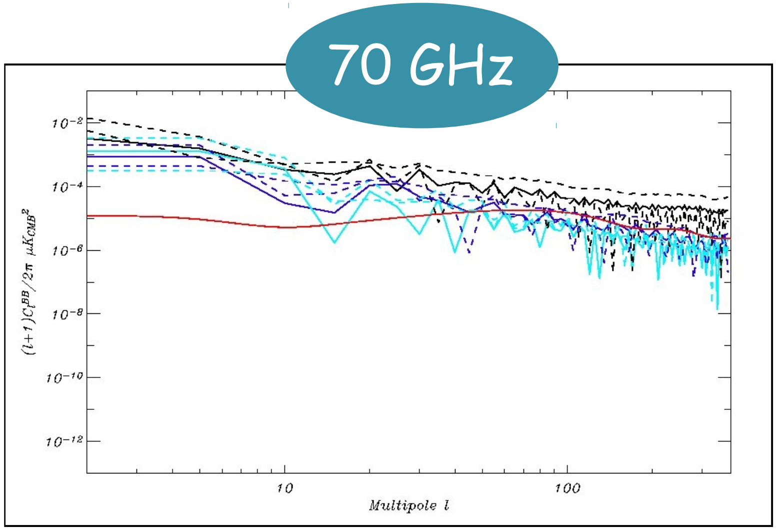


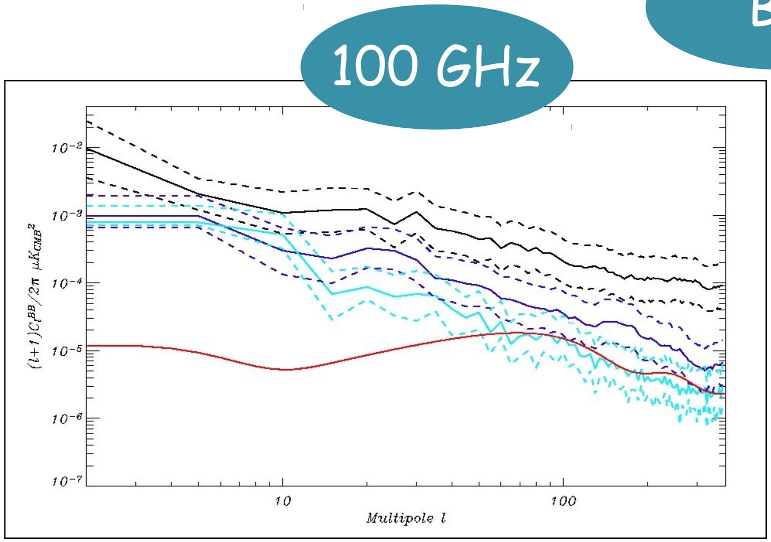


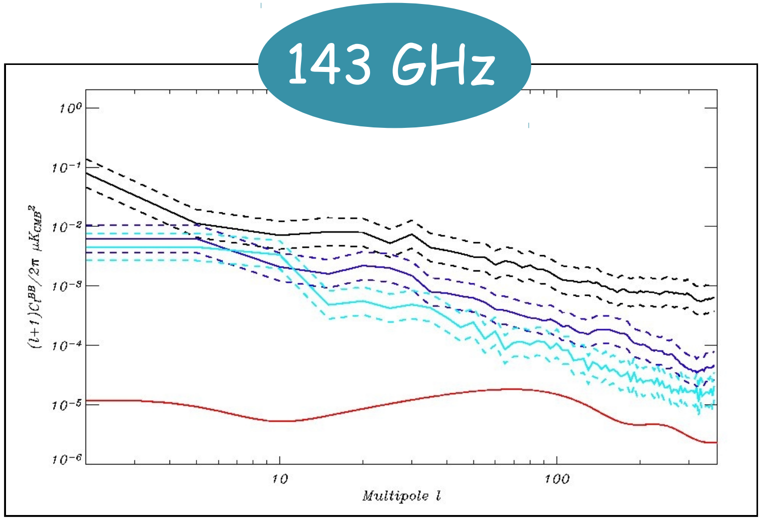
[Gold et al, 2010]

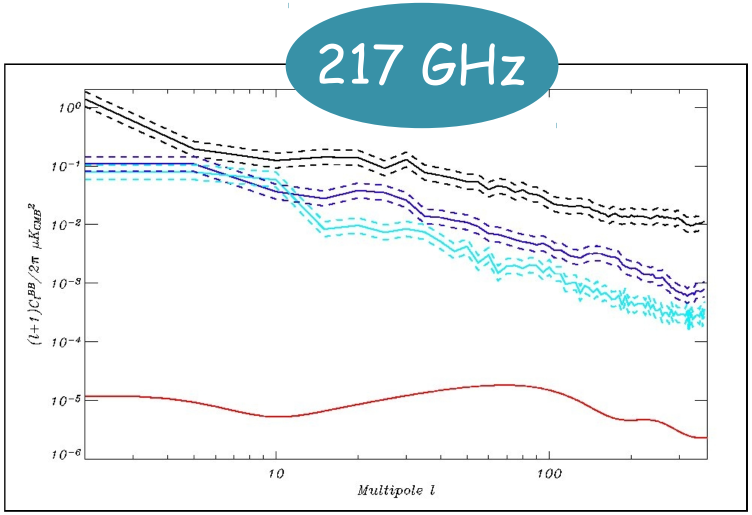
contamination of the CMB data

BB







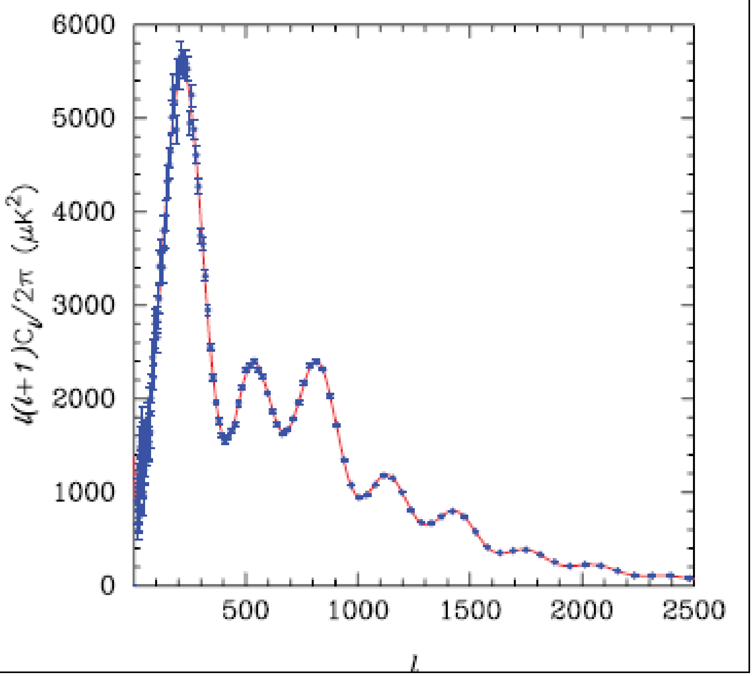


from blue to black: model of galactic emission for |b| > 15, 30, 40 deg
red : simulation of CMB, r=0.1

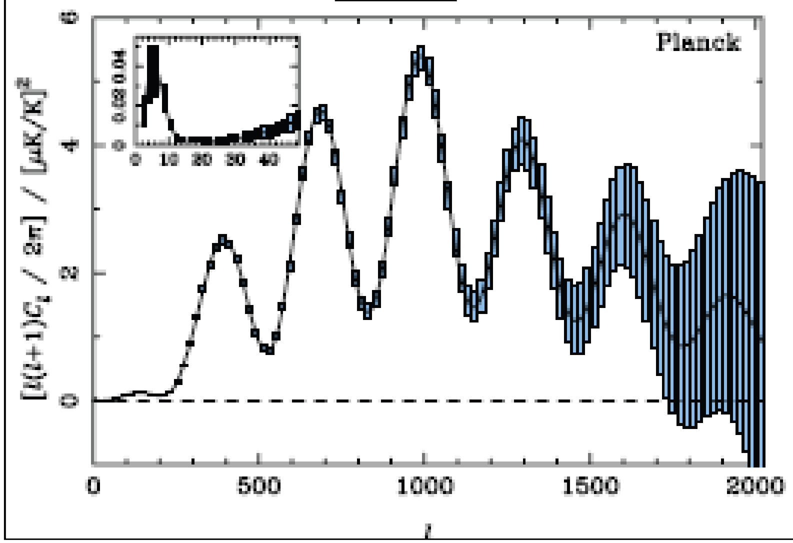
L. Fauvet

expected CMB measurements with Planck

TT



EE



[PLANCK Bluebook,,the PLANCK collaboration, 2005]

for the synchrotron :

$$\mathrm{d}I_\nu^{sync} = \epsilon^{sync}(\nu) \;\; n_{\mathrm{CRE}}(\mathbf{n},z)$$
$$.\left(B_l(\mathbf{n},z)^2 + B_t(\mathbf{n},z)^2\right)^{(s+1)/4} dz$$

$$\begin{aligned} I_\nu^{sync}(\mathbf{n}) &= \int \mathrm{d}I_\nu^{sync}, \\ Q_\nu^{sync}(\mathbf{n}) &= \int \mathrm{d}I_\nu^{sync} \cos(2\gamma(\mathbf{n},z))\; p^{sync}, \\ U_\nu^{sync}(\mathbf{n}) &= \int \mathrm{d}I_\nu^{sync} \sin(2\gamma(\mathbf{n},z))\; p^{sync}. \end{aligned}$$

$$p^{sync} = \frac{s+1}{s+7/3}$$

for the thermal dust

$$\mathrm{d}I_\nu^{dust}(\mathbf{n}) = \epsilon^{dust}(\nu) \;\; n_{dust}(\mathbf{n},z)\; dz$$

$$\begin{aligned} I_\nu^{dust}(\mathbf{n}) &= \int \mathrm{d}I_\nu^{dust}, \\ Q_\nu^{dust}(\mathbf{n}) &= \int \mathrm{d}I_\nu^{dust} p^{dust} \cos(2\gamma(\mathbf{n},\mathrm{z})) \\ &\quad .f_{\mathrm{g}}(\mathbf{n},z) f_{\mathrm{ma}}(\mathbf{n},z), \\ U_\nu^{dust}(\mathbf{n}) &= \int \mathrm{d}I_\nu^{dust} p^{dust} \sin(2\gamma(\mathbf{n},z)) \\ &\quad .f_{\mathrm{g}}(\mathbf{n},z) f_{\mathrm{ma}}(\mathbf{n},z). \end{aligned}$$

local angle of polarization:

$$\gamma(\mathbf{n},s) \;=\; \frac{1}{2}\arctan\left(\frac{2B_l(\mathbf{n},z)\cdot B_t(\mathbf{n},z)}{B_l^2(\mathbf{n},z) - B_t^2(\mathbf{n},z)}\right)$$

$$\begin{aligned} Q_s &= I_{\mathrm{Has}} \left(\frac{\nu}{0.408}\right)^{\beta_s} \frac{Q_\nu^{sync}}{I_\nu^{sync}}, \\ U_s &= I_{\mathrm{Has}} \left(\frac{\nu}{0.408}\right)^{\beta_s} \frac{U_\nu^{sync}}{I_\nu^{sync}}, \end{aligned}$$

$$\begin{aligned} Q_d &= I_{sfd} \frac{Q_\nu^{dust}}{I_\nu^{dust}}, \\ U_d &= I_{sfd} \frac{U_\nu^{dust}}{I_\nu^{dust}}, \end{aligned}$$

MLS

$$\mathbf{B}(\mathbf{r}) = B_{reg}(\mathbf{r})[\cos(\phi+\beta)\ln\left(\frac{r}{r_0}\right)\sin(p)\cos(\chi)\cdot\mathbf{u_r} - \cos(\phi+\beta)\ln\left(\frac{r}{r_0}\right)\cos(p)\cos(\chi)\cdot\mathbf{u}_\phi + sin(\chi)\cdot\mathbf{u_z}],$$

$$\beta = 1/\tan(p)$$

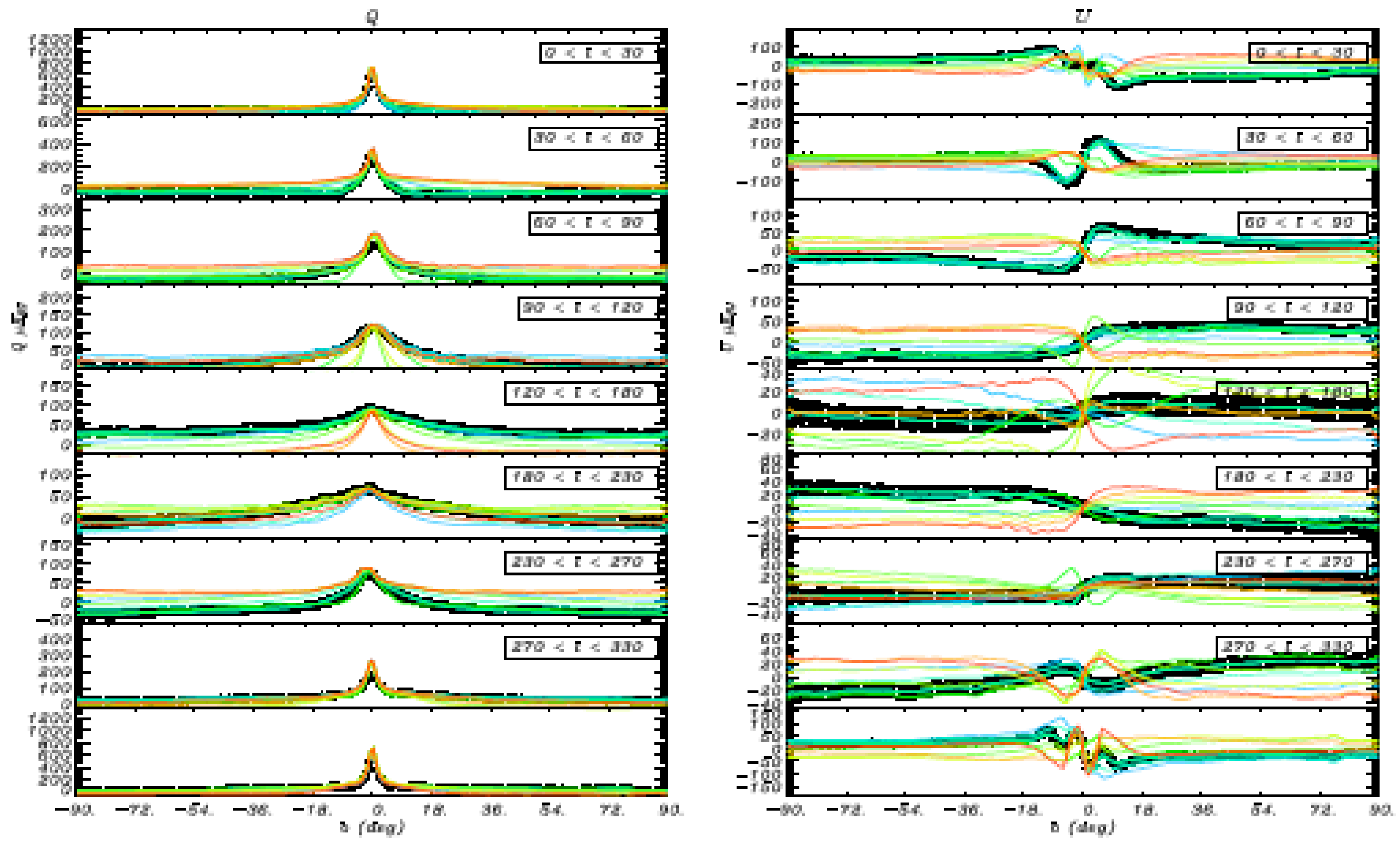
ASS [Sun et al, 2008]

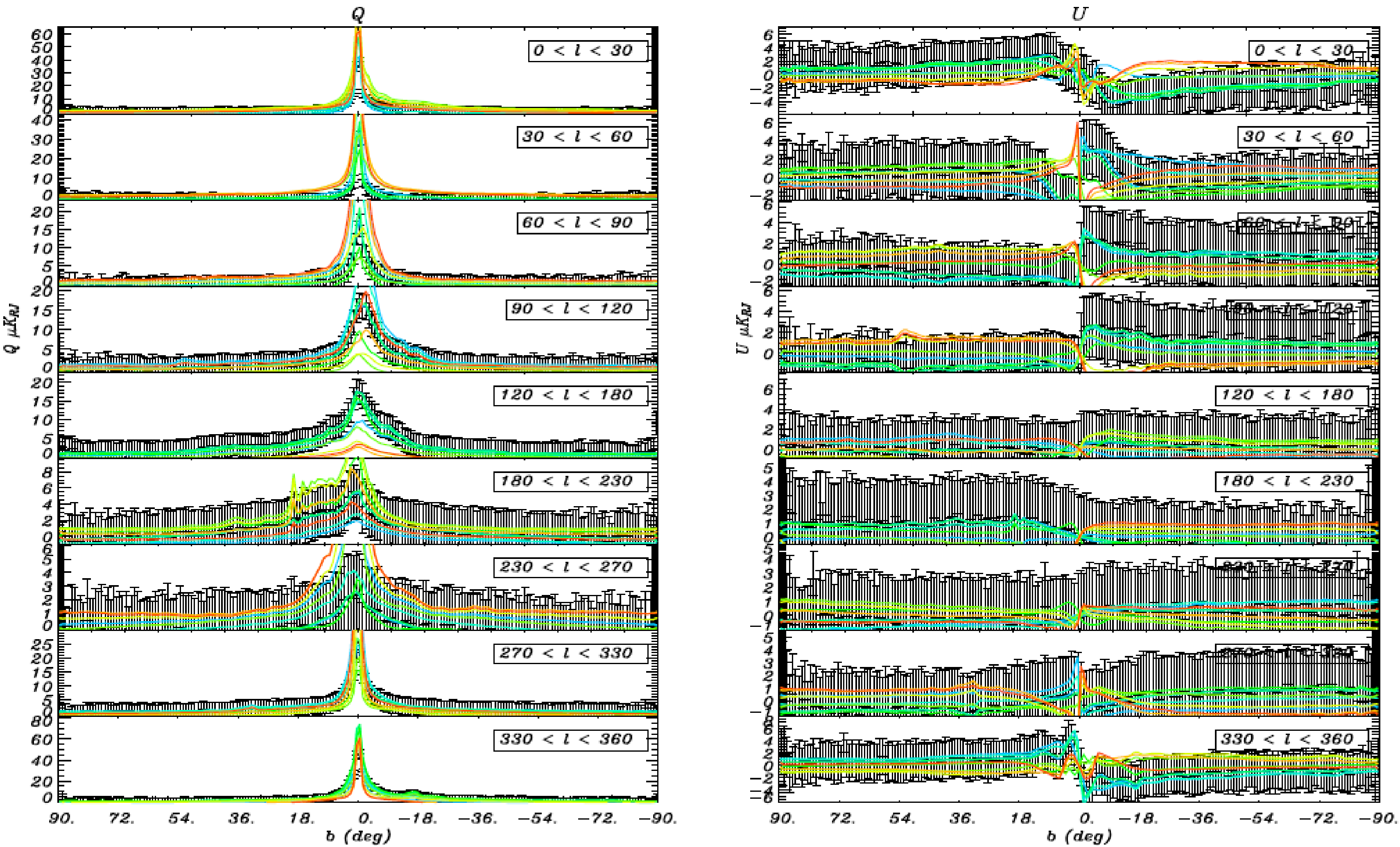
$$B_r^D = D_1(r,\Phi,z)D_2(r,\Phi,z)sin(p)$$
$$B_\Phi^D = -D_1(r,\Phi,z)D_2(r,\Phi,z)cos(p)$$
$$B_z^D = 0$$

$$D_1(r,z) = \begin{cases} B_0\, exp(\frac{r-R_\odot}{R_0} - \frac{|z|}{z_0}) & r > R_c \\ B_c & r \leq R_c \end{cases}$$

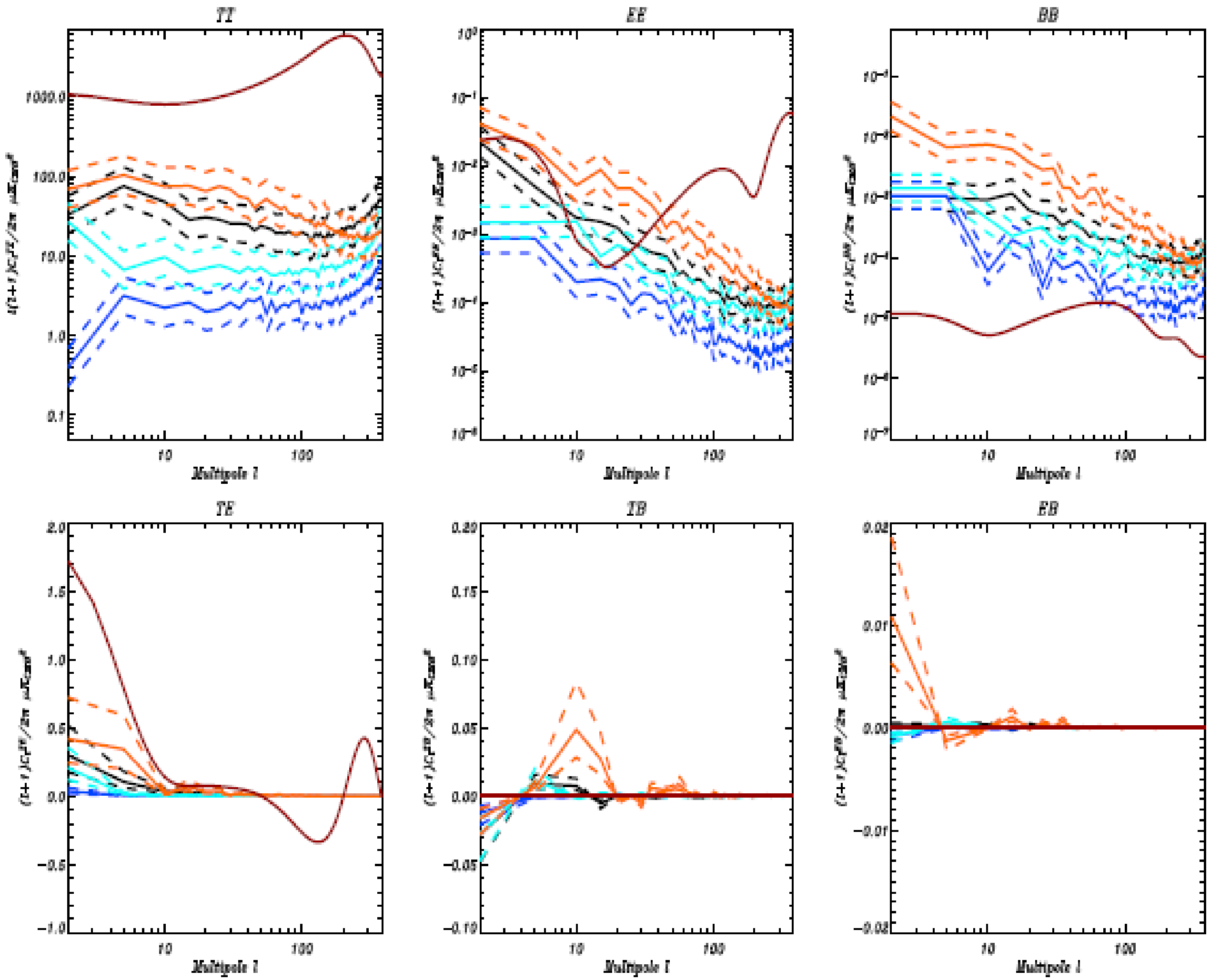
$$D_2(r) = \begin{cases} +1 & r > 7.5 \\ -1 & 6 < r \leq 7.5 \\ +1 & 5 < r \leq 6 \\ -1 & r < 5 \end{cases}$$

expected constraints with Planck




Q
U
0 < l < 30
30 < l < 60
60 < l < 90
90 < l < 120
120 < l < 180
180 < l < 230
230 < l < 270
270 < l < 330
330 < l < 360
Q μK_RJ
U μK_RJ
90. 72. 54. 36. 18. 0. −18. −36. −54. −72. −90.
b (deg)

143 GHz


TT
EE
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Multipole l
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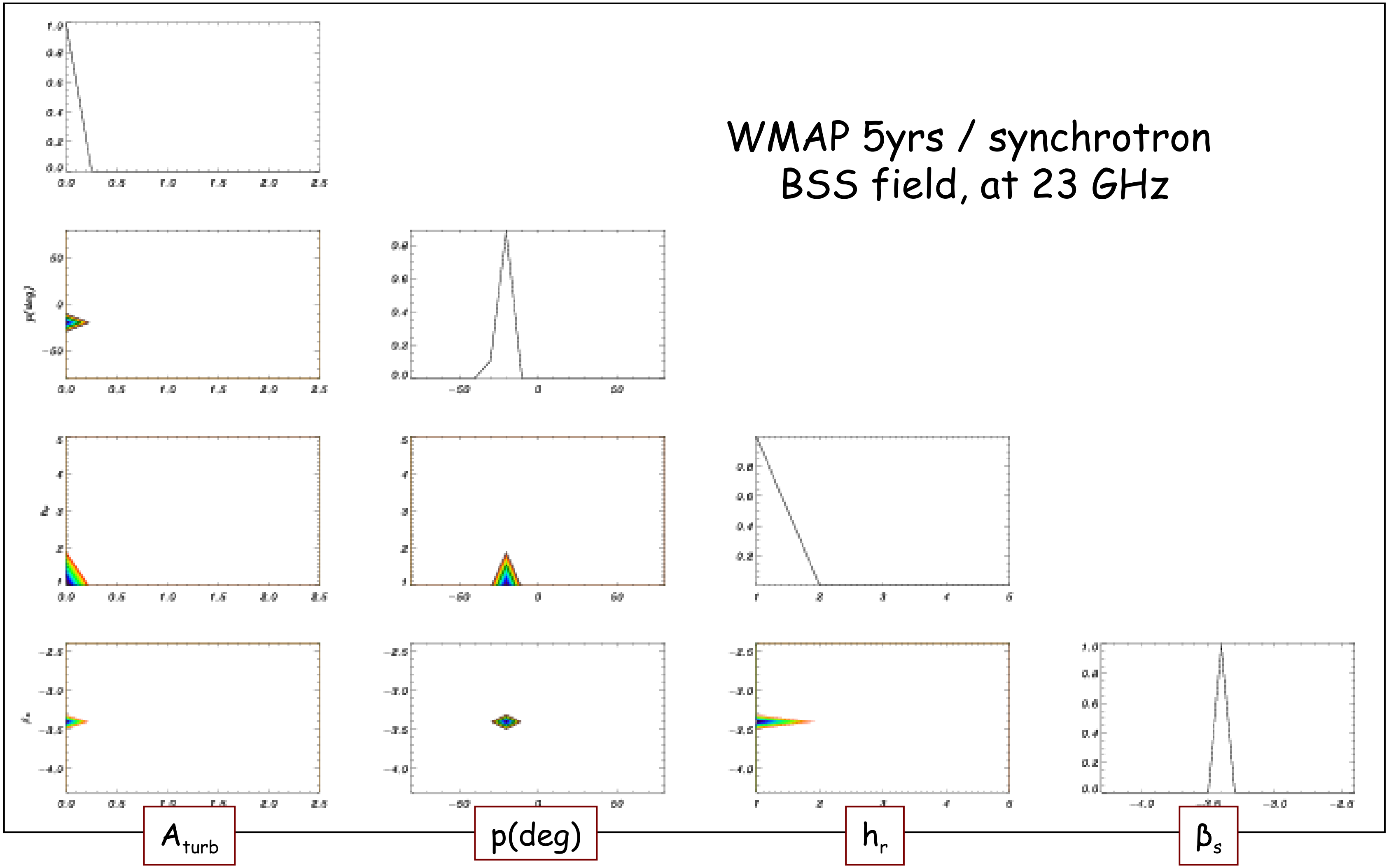
Multipole l
Multipole l
Multipole l

Data	Magnetic field model	$p(deg)$	A_{turb}	$n_{\mathrm{CRE},r}$	β_s	χ^2_{min}
408 MHz	MLS	$-20.0^{+60.0}_{-50.0}$	< 1.00 (95.4 % CL)	4^{+16}_{-3}	$\emptyset$	3.58
	ASS	$-10.0^{+80.0}_{-70.0}$	< 1.0 (95.4 % CL)	5^{+15}_{-3}	$\emptyset$	4.65
WMAP 23 GHz	MLS	$-30.0^{+40.0}_{-30.0}$	< 1.25 (95.4 % CL)	< 20 (95.4 % CL)	$-3.4^{+0.1}_{-0.8}$	5.72
	ASS	$-40.0^{+60.0}_{-30.0}$	< 1.5 (95.4 % CL)	3^{+17}_{-2}(95.4% CL)	$-3.4^{+0.1}_{-0.8}$	7.62
Archeops 353 GHz	MLS	-20^{+80}_{-50}	$< 2.25(95.4\%CL)$	$\emptyset$	$\emptyset$	1.98
	ASS	60.0^{+20}_{-40}	$0.25^{+2.0}_{-0.25}$	$\emptyset$	$\emptyset$	1.72
All	MLS	-20^{+80}_{-50}	$< 2.25(95.4\%CL)$	$\emptyset$	$\emptyset$	1.98
	ASS	60.0^{+20}_{-40}	$0.25^{+2.0}_{-0.25}$	$\emptyset$	$\emptyset$	1.72

Best fit parameters



$A_{turb} < 0.25$, $p = -20 \pm 10$ deg
$h_r < 15$kpc, $\beta_s = -3.4 \pm 0.1$

3D model of the galaxy

→ turbulente component

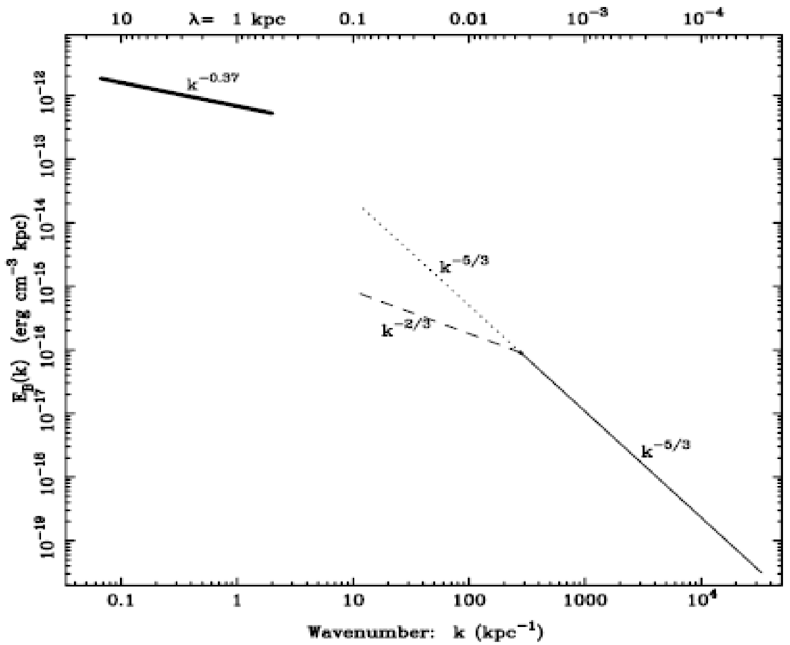
- non regular field at all scales
- same intensity as the regular component
- Kolmogorov spectrum *[Han et al, 2006]*

$$B_{tot} = B_{reg}(r) + A_{turb}B_{turb}(r)$$

$B_{turb} = (8\mu_0 E_B)^{1/2}$ with $\mu_0 = 4\pi.10^{-7}H.m^{-1}$

A_{turb} (dimensionless) : normalisation of the turbulent component

- 3D gaussian simulation with used a power spectrum

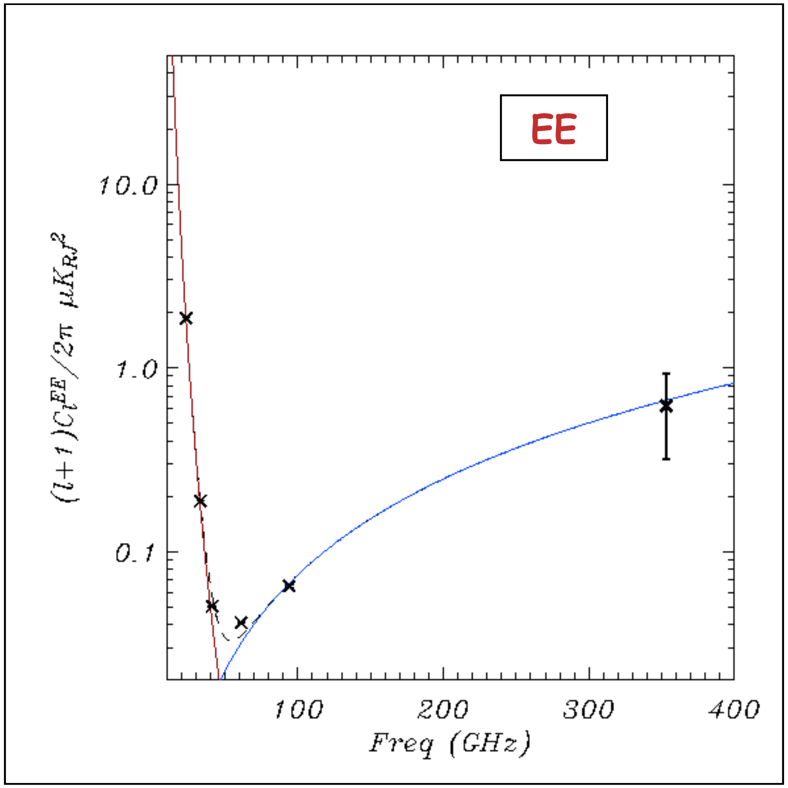


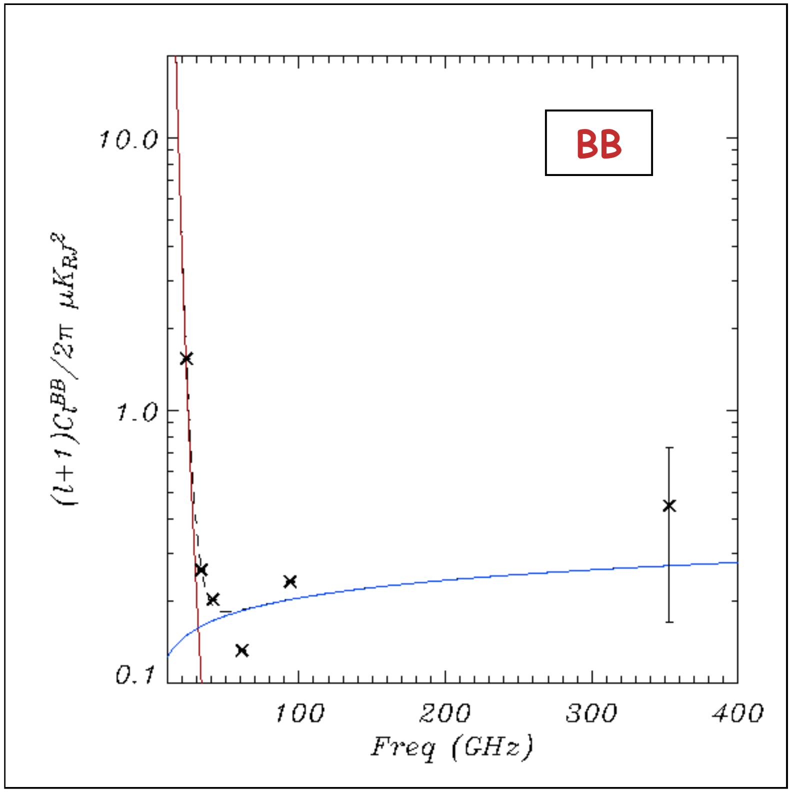
$$E_B(k) = C\left(\frac{k}{k_0}\right)^{\alpha}$$

- 1/k > 15 kpc :
  - $C = (9.5 \pm 0.3)*10^{-13}$erg.cm^{-3}.kpc
  - $\alpha = -5/3$
- 0.5 < 1/k < 15 kpc :
  - $C = (6.8 \pm 0.3)*10^{-13}$erg.cm^{-3}.kpc
  - $\alpha = -0.37$

[Han et al, 2006]

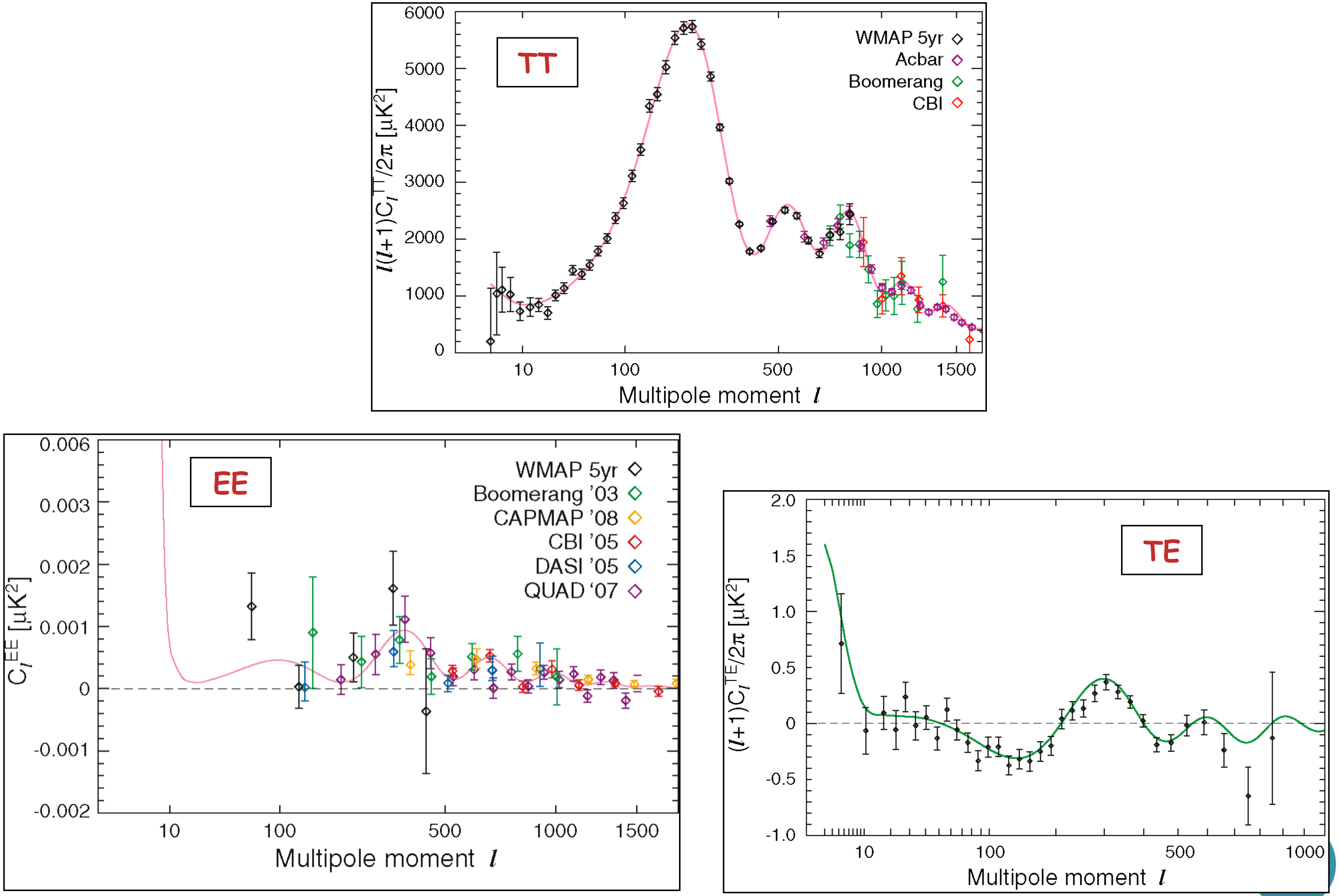
impact on the CMB data





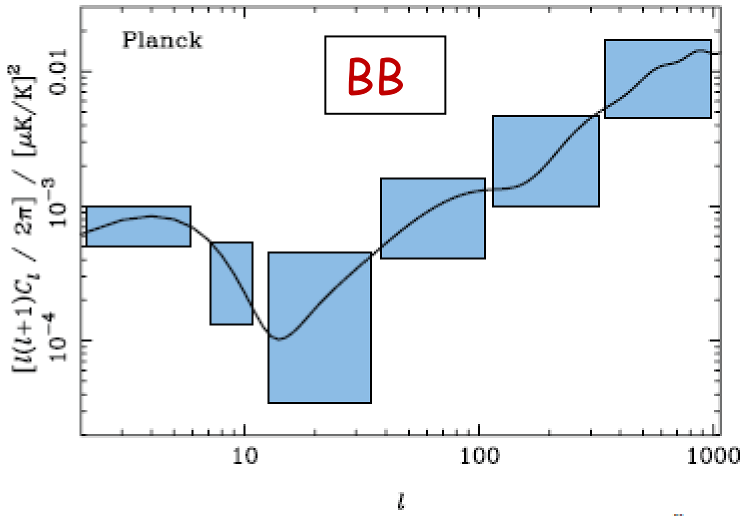
red : synchrotron emission model
blue : thermal dust emission model
black: 3 years of WMAP and ARCHEOPS data

The CMB : current results

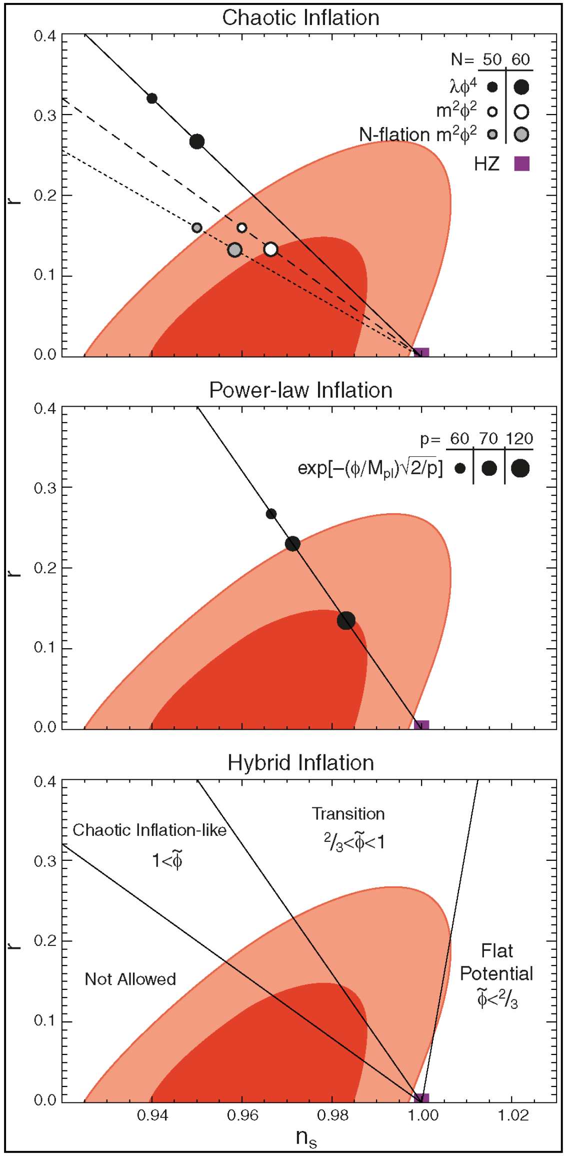


[Nolta et al, 2008]

the CMB : Planck perspectives



[Planck Bluebook, the Planck collaboration 2005]



[Komatsu et al, 2008]

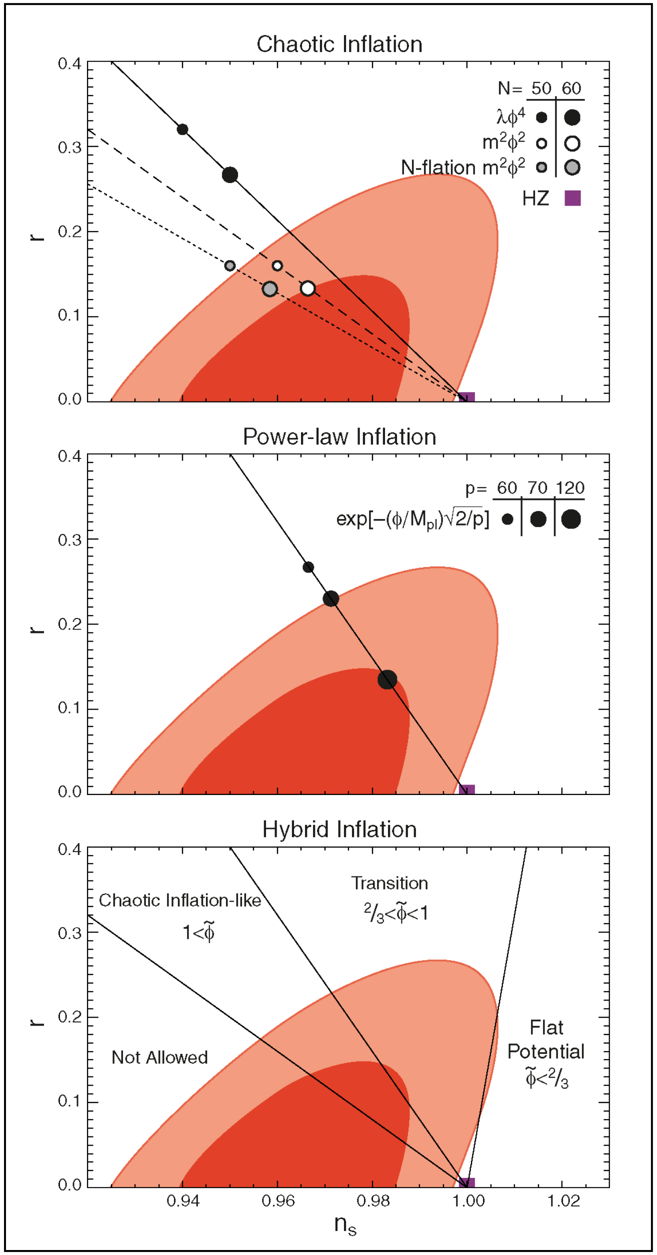
- upper limit of r ≤ 0.05 if no primordial tensor modes
- detect tensor mode if r ~ 0.03

  [Efstathiou et al, 2009]

- constraints : n_s ~ 0.1 & r ~ 0.05

  → discriminate inflation models and other models

The CMB : current results



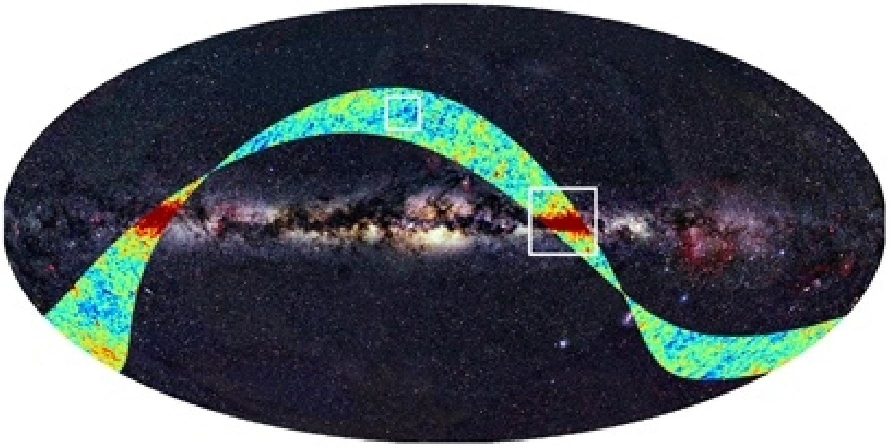
[Komatsu et al, 2008]

The PLANCK schedule

- launched the 14th of May 2009 from Kourou
- travelled to L2 point and cooling until end of June 2009
- final checks until 15th of August

NOW : 14 months of operations for 2 all-sky surveys

First light of Planck



2012 : First public data release by ESA

≥ 2013 : Potential second data surveys (He)

[Bouchet, 2009]

The Planck mission : scientific objectifs

- Primary anisotropies:
  - cosmological parameters
  - physics of the Early Universe
  - non-gaussianity
- Secondary anisotropies
  - ISW
  - gravitational lensing
  - reionisation
  - galaxy clusters
- Extragalactic sources :
  - radio sources
  - dusty galaxies and their contaminants
- Galactic & Solar systems :
  - galactic magnetic field & ISM
  - planets and asteroides …

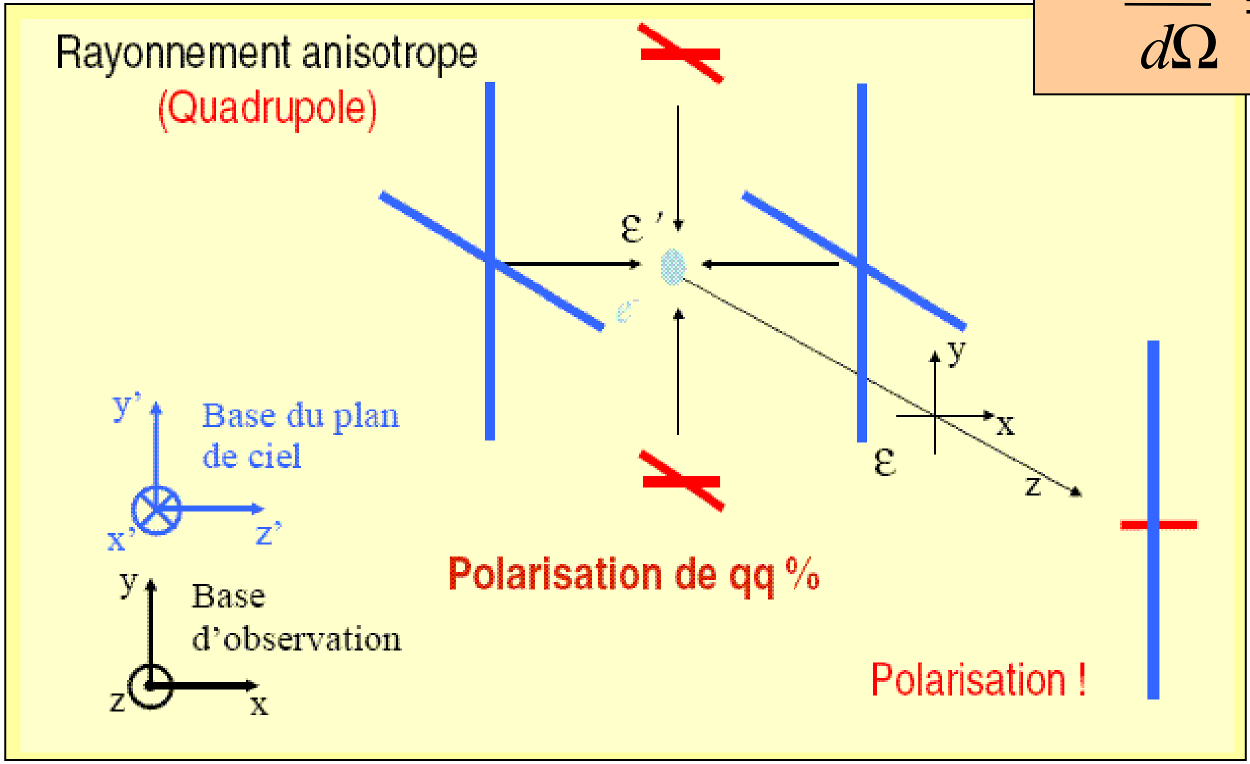
["Planck bluebook", the Planck collaboration, 2005]

Formation de la polarisation

Diffusion Thomson des photons sur les électrons:

Section efficace

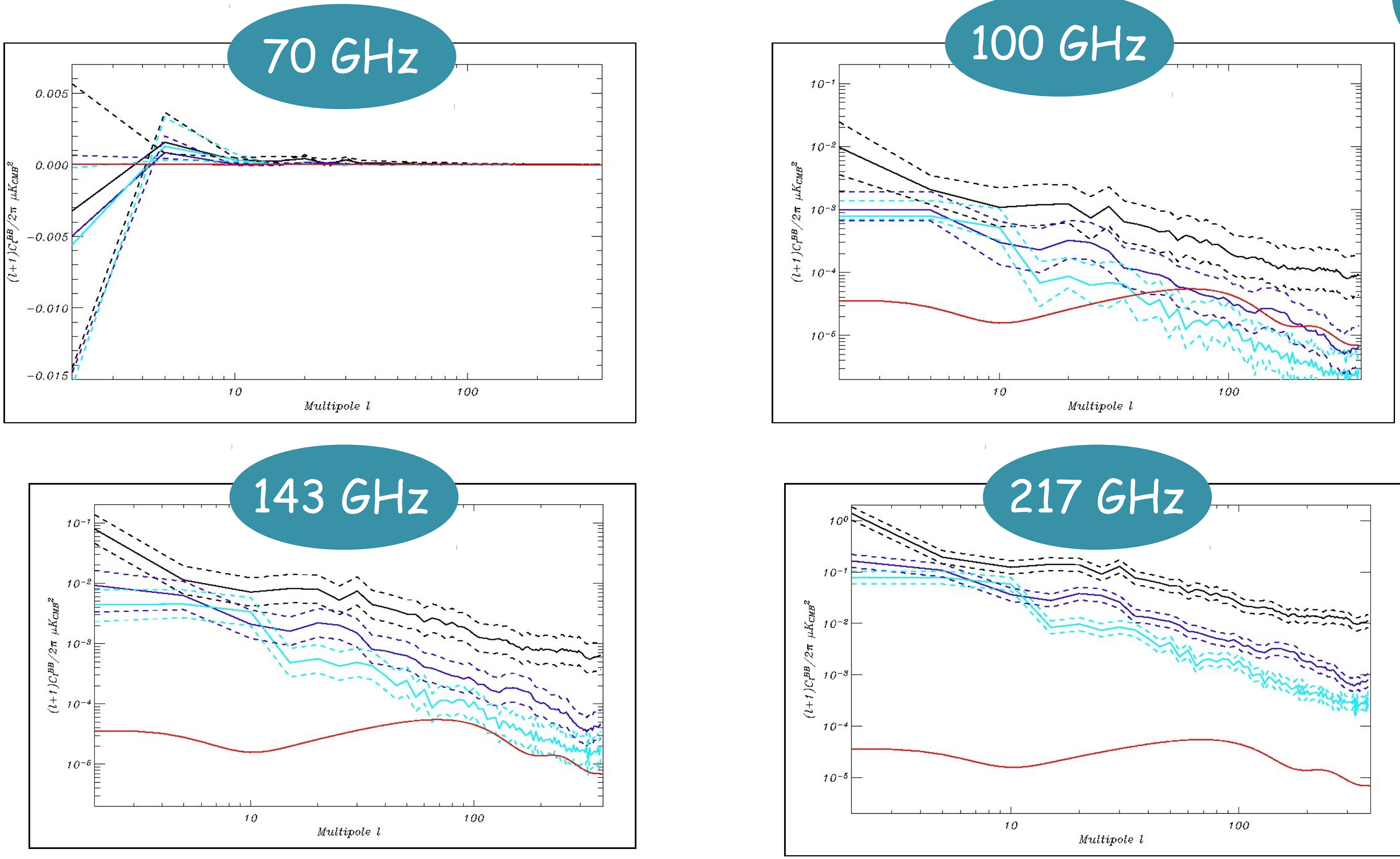
$$\frac{d\sigma}{d\Omega} = |\varepsilon.\varepsilon'|$$



Anisotropies quadrupolaires responsables de la polarisation du CMB

(Kosowsky et al (1994))

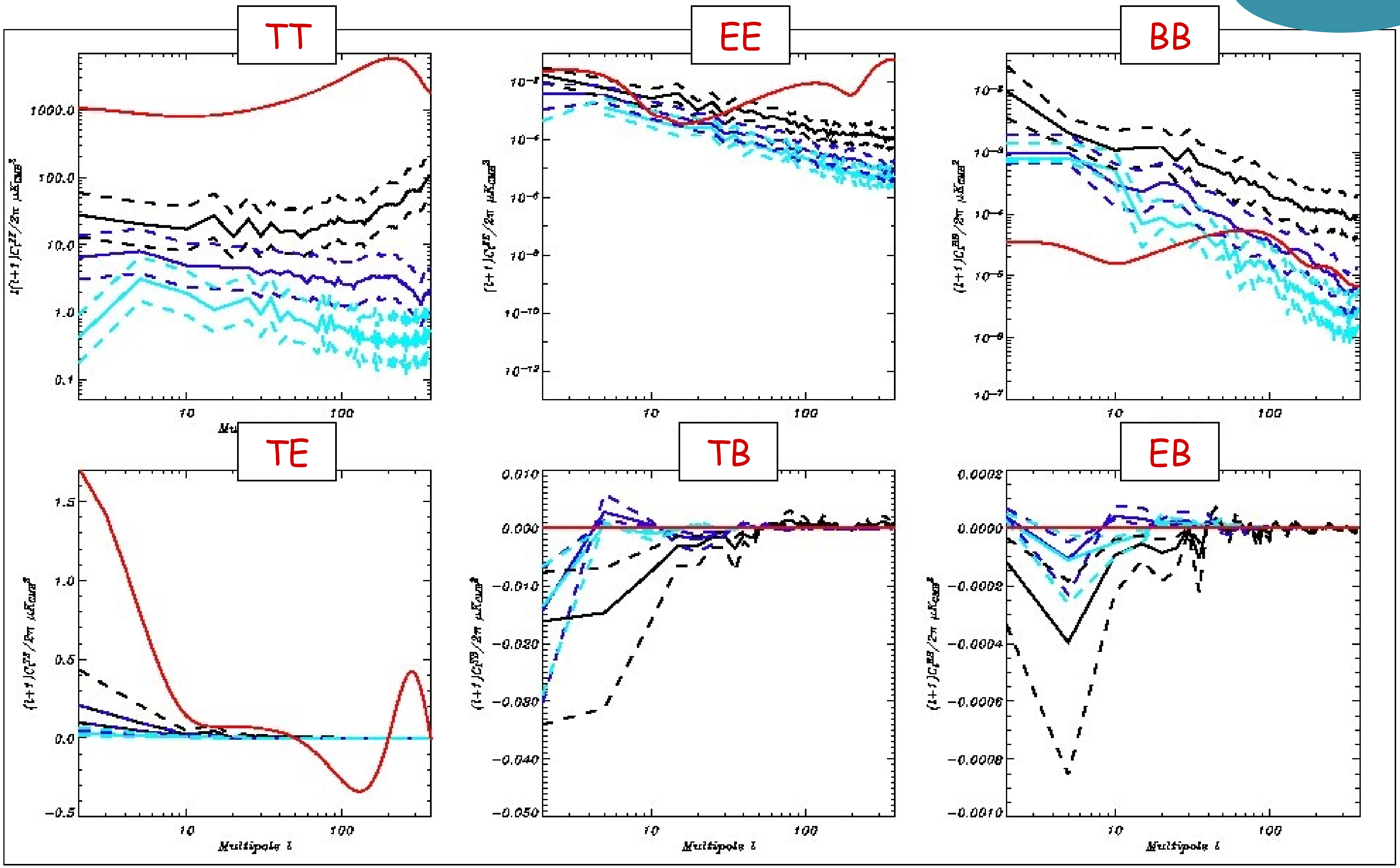
contamination of the CMB data



from blue to black: model of galactic emission for |b| > 15, 30, 40 deg
red : simulation of CMB, r=0.3

contamination of the CMB data

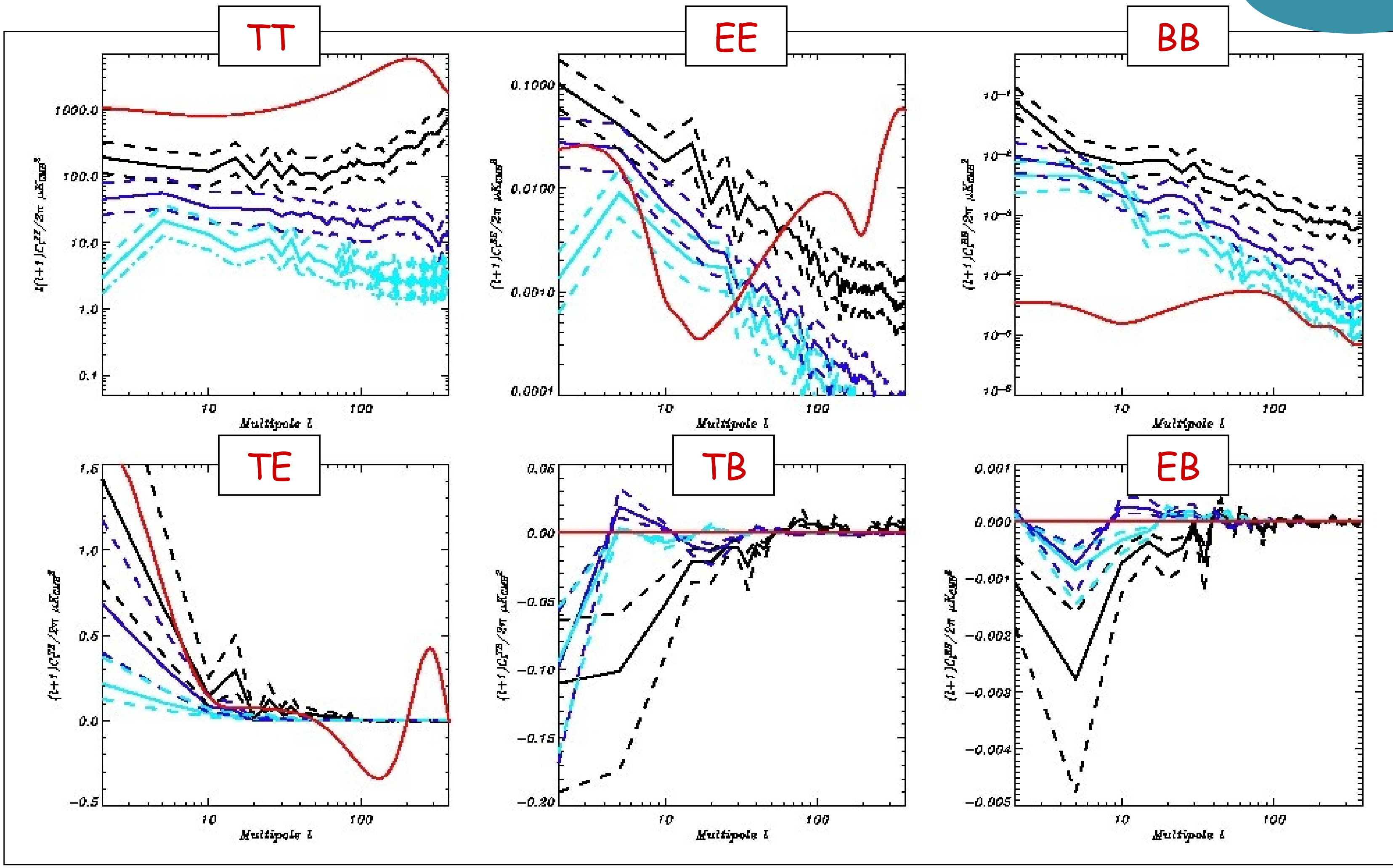
100 GHz



from blue to black: model of galactic emission for |b| > 15, 30, 40 deg
red : simulation of CMB, r=0.3

contamination of the CMB data

143 GHz



from blue to black: model of galactic emission for |b| > 15, 30, 40 deg
red : simulation of CMB, r=0.3

Paramètres de Stokes

I : intensité

Q,U : polarisation linéaire (dépendants du choix du référentiel).

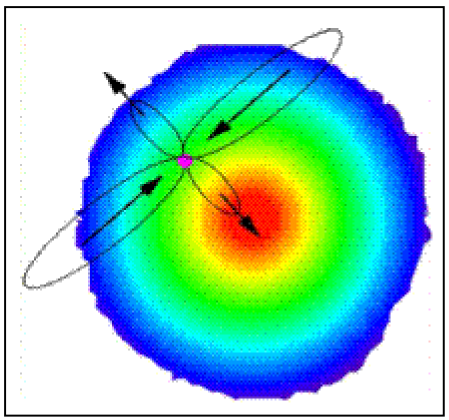
V : polarisation circulaire (absente du CMB).

Décomposition en harmoniques sphériques → **T**

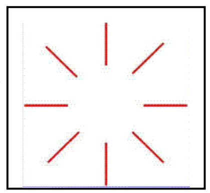
Décomposition en harmoniques sphériques spinnées → **E**, **B**

Perturbations

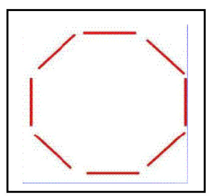
►Perturbations scalaires



Sur densité



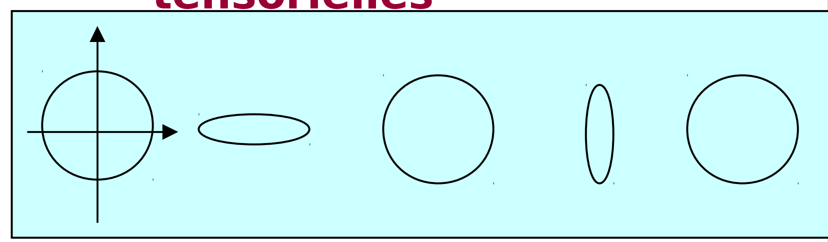
Sous densité



- Gradient de vitesse non nul dans le repère de l'e⁻ → quadrupôle.

Produit du mode E

►Perturbations tensorielles



- Passage d'une onde gravitationnelle.

Génère des modes E et B

(Hu et al (1997))

(Zaldarriaga et al (1998))

The Planck mission

$$\varphi = \varphi_L + f_{NL}\varphi_L^2$$

φ~ : gaussian, linear curvature perturbation on the matter dominating era

[Salopek & Bond, 1990]

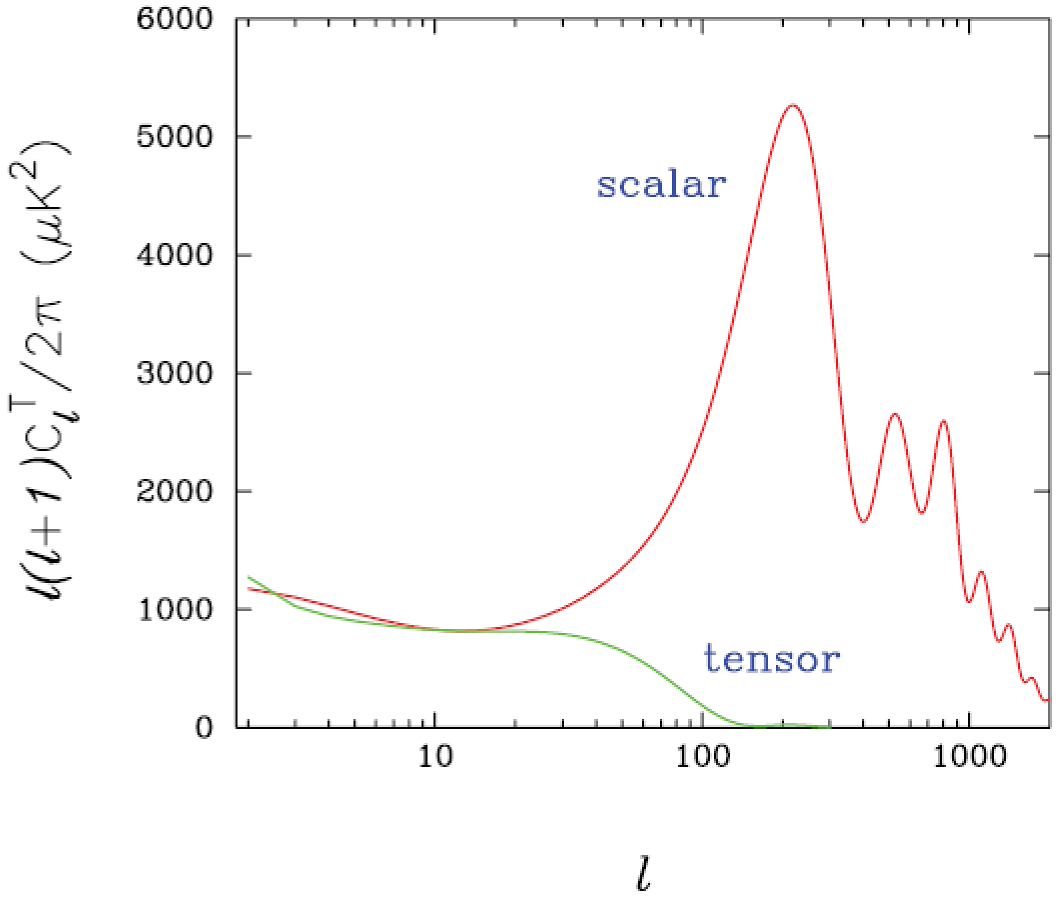
f_{NL} ~ 0.05 canonical inflation [Maldacena,2003 ; Acquaviva et al, 2003]

f_{NL} ~ 0.1-100 higher order derivatives (biblio …)

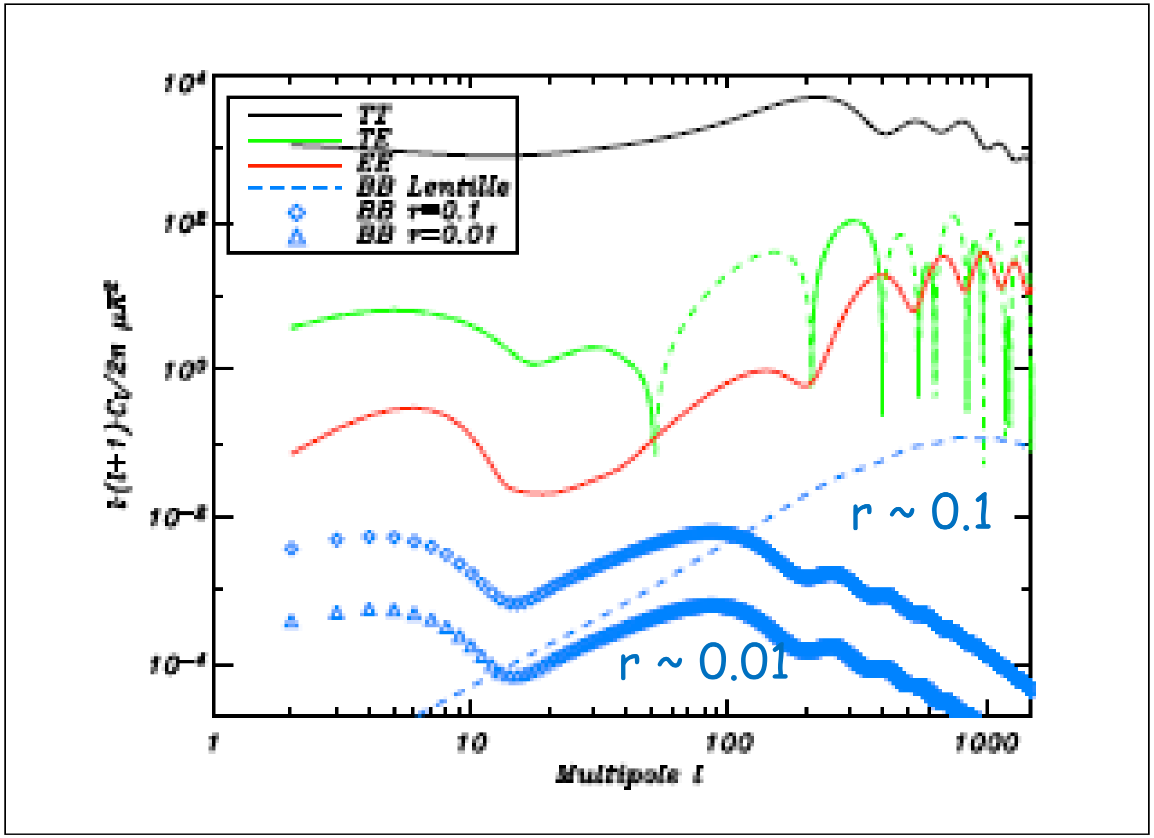
f_{NL} > 10 curvaton models [Lyth, Ungarelly et Wands, 2003]

f_{NL} ~ 100 : ghost inflation [Arkani-Hamed et al, 2004]

…


6000
5000
4000
3000
2000
1000
0
10
100
1000
$l(l+1)C_l^T/2\pi$ (μK^2)
scalar
tensor
l

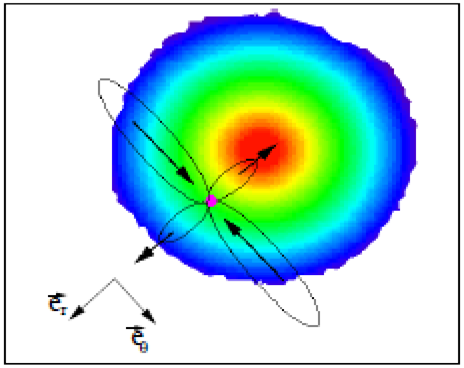
Stokes parameters I,Q & U → C_l^{TT} C_l^{TE} C_l^{EE} C_l^{BB}



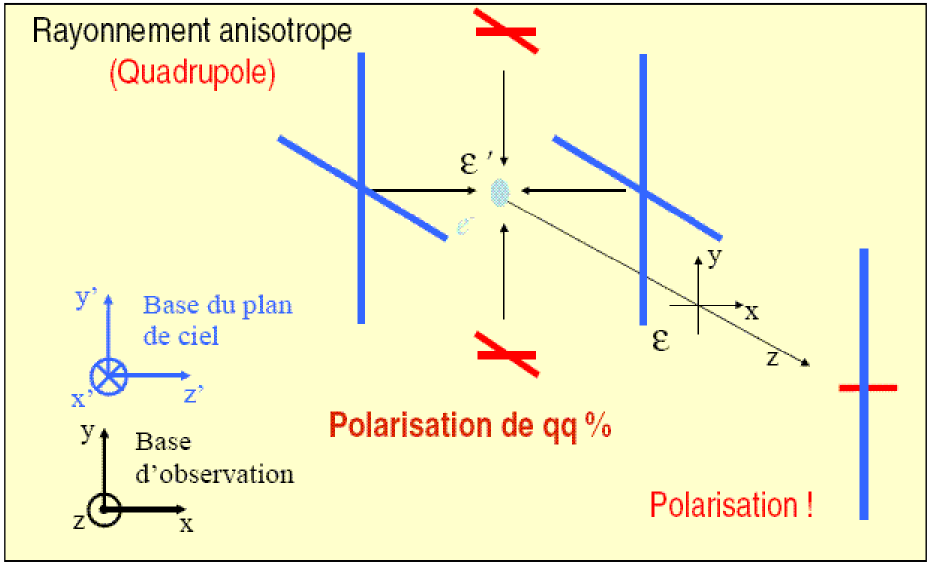
$$\left.\frac{\ell(\ell+1)}{2\pi}C_\ell^{BB}\right|_{\ell=\ell_{\rm pic}} \simeq 0.024^2\left(\frac{E_{\rm Inf}}{10^{16}}\right)^4 \mu K^2$$

[Zaldarriaga , 2002]

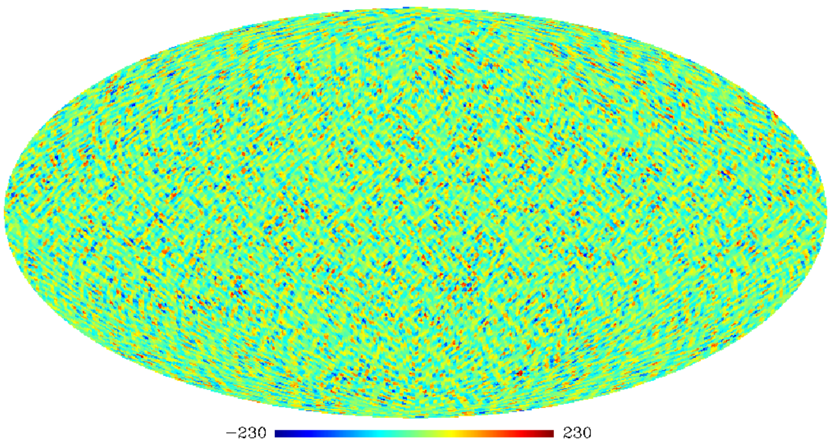
the CMB: polarization



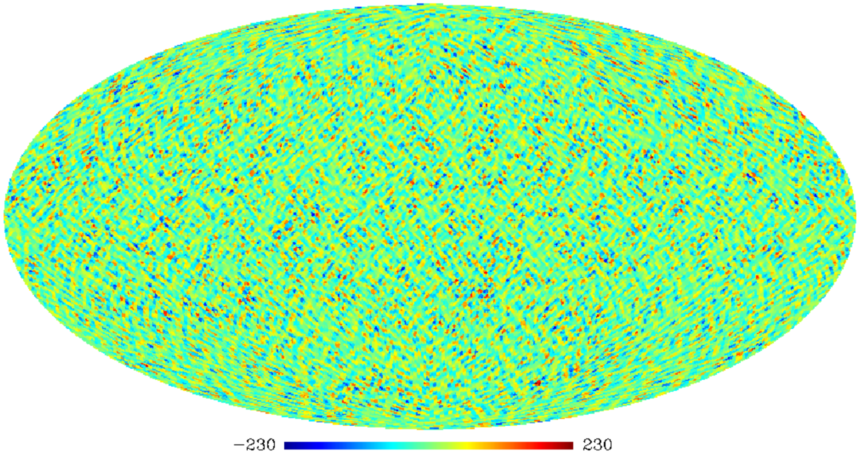
[Kosowsky, 1992]



Q



U



3D model of the galaxy

→ turbulente component

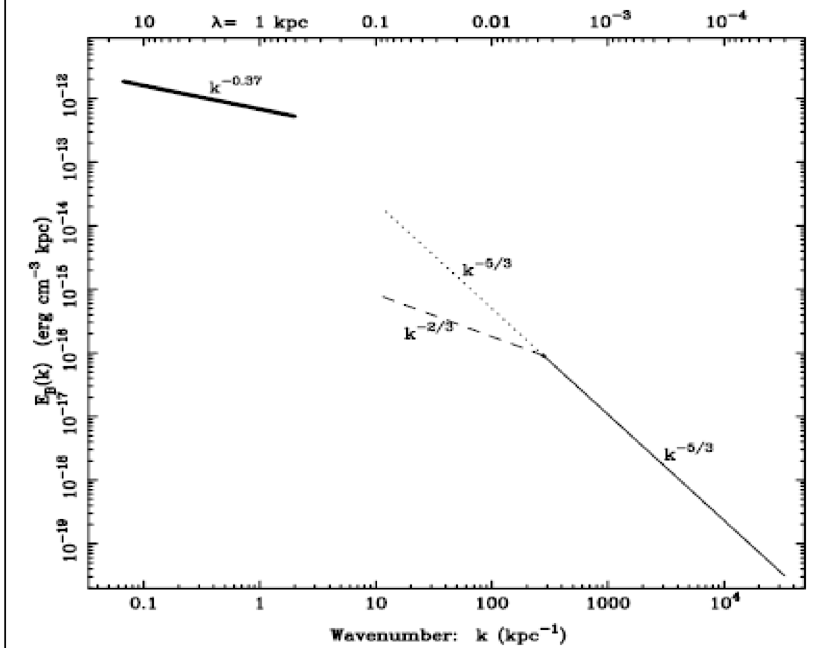
- non regular field at all scales
- same intensity as the regular component
- Kolmogorov spectrum *[Han et al, 2006]*

$$B_{tot} = B_{reg}(r) + A_{turb} B_{turb}(r)$$

$B_{turb} = (8\mu_0 E_B)^{1/2}$ with $\mu_0 = 4\pi.10^{-7} H.m^{-1}$

A_{turb} (dimensionless) : normalisation of the turbulent component

- 3D gaussian simulation with used a power spectrum



$$E_B(k) = C\left(\frac{k}{k_0}\right)^{\alpha}$$

- 1/k > 15 kpc :

  $C = (9.5 \pm 0.3) * 10^{-13} erg.cm^{-3}.kpc$

  $\alpha = -5/3$

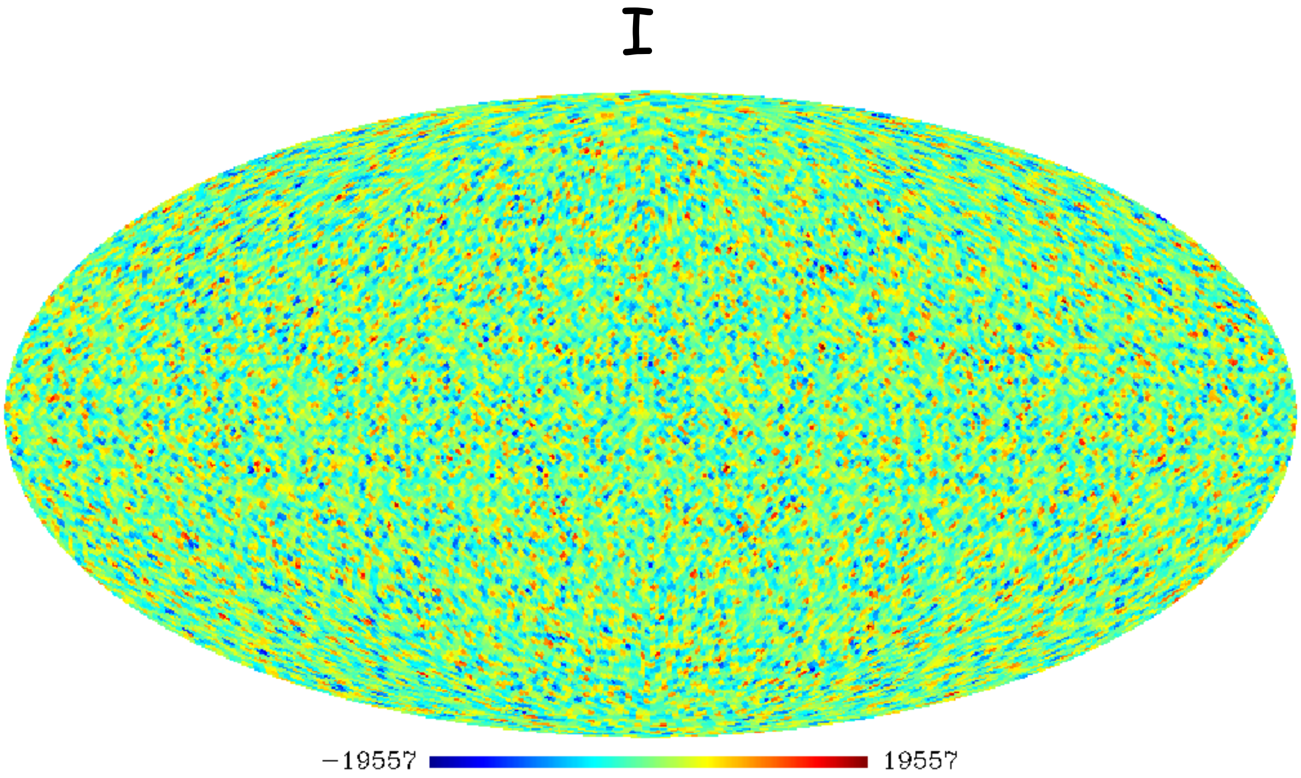
- 0.5 < 1/k < 15 kpc :

  $C = (6.8 \pm 0.3) * 10^{-13} erg.cm^{-3}.kpc$

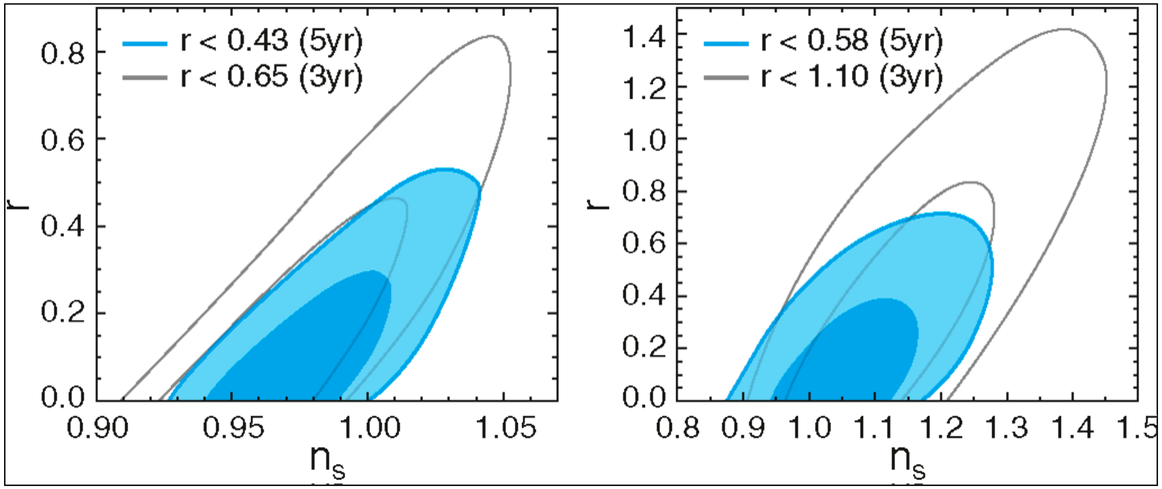
  $\alpha = -0.37$

[Han et al, 2006]

the CMB



Cosmological parameters



tensor-scalar ratio constraint by WMAP 5 and 3 years (at 95% et 68% C.L)

The Planck mission

Simplified analysis (isotropic noise, using 70, 100, 143 and 217 GHz Planck data) : r=0.05 and uper limit at r = 0.03 95%C.L. for lower values

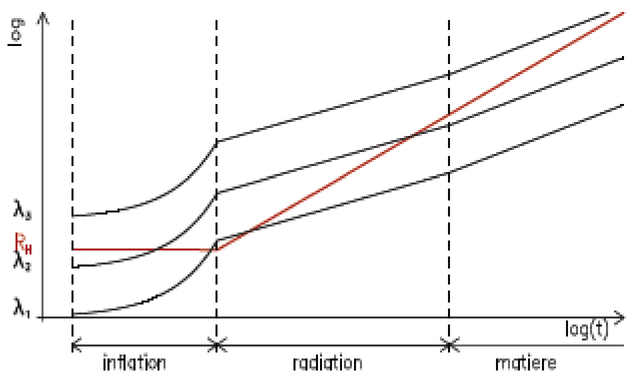
Upper limit of $r \leq 0.05$ if no primordial tensor mode
Detect tensor mode if $r \sim 0.1$
G.Efstathiou ...

$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{(\nabla\phi)^2}{2a^2} + V(\phi),$$
$$p = \frac{1}{2}\dot{\phi}^2 - \frac{(\nabla\phi)^2}{6a^2} - V(\phi).$$

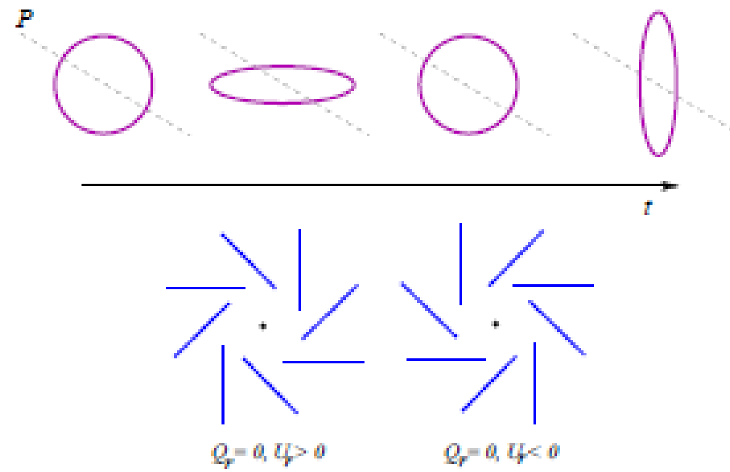
$$H^2 = \frac{8\pi G}{3}\rho \qquad \text{(équation de Friedmann)}$$
$$\ddot{\phi} + 3H\dot{\phi} + \frac{\nabla^2\phi}{a^2} + V' = 0 \qquad \text{(équation de Klein-Gordon)}$$

slow-roll

$$\begin{cases} H^2 \simeq \frac{8\pi G}{3}V(\phi) & \frac{1}{2}\dot{\phi}^2 \ll V \\ 3H\dot{\phi} + V' \simeq 0 & \ddot{\phi} \ll 3H\phi \end{cases}$$



$$(Q \pm iU)(\mathbf{n}) = \sum_{\ell,m} a_{\pm 2\ell m} \cdot {}_{\pm 2} Y_{\ell m}(\mathbf{n})$$



$$a^E_{\ell m} \equiv -\frac{a_{2\ell m} + a_{-2\ell m}}{2}$$

$$a^E_{\ell m} \equiv i\frac{a_{2\ell m} - a_{-2\ell m}}{2}$$

$$E(\mathbf{n}) \equiv \sum_{\ell,m} a^E_{\ell m} Y_{\ell m}$$

$$B(\mathbf{n}) \equiv \sum_{\ell,m} a^B_{\ell m} Y_{\ell m}$$

$$\hat{C}_\ell^{XX'} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a^X_{\ell m} a^{X'*}_{\ell m},$$

The Planck mission: cooling chain

- 1.5 m telescope
- LFI HEMTS to 18K
- HFI bolometers to 0.1K

40K : radiative cooling

18K : H_2 sorption cooler (J-T)

4K : He mechanical pump (J-T)

["Planck bluebook", the Planck collaboration, 2005]

1.6K : J-T expansion

0.1K : $^3He/^4He$ dilution