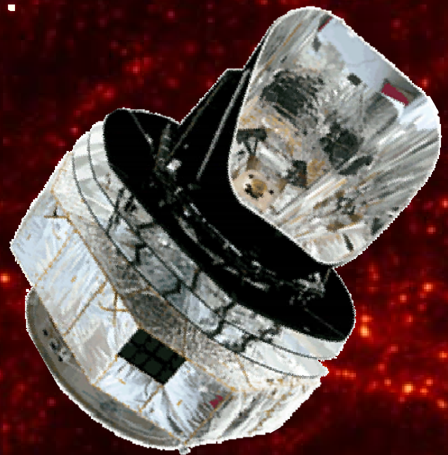
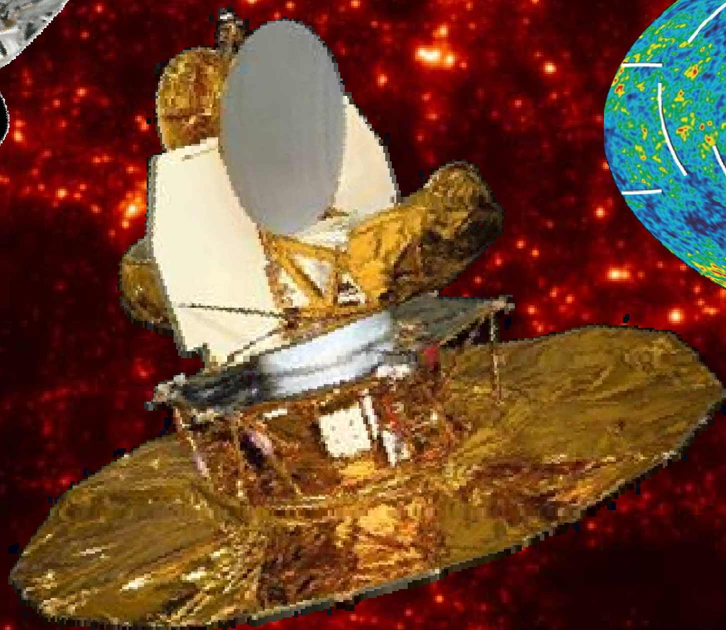
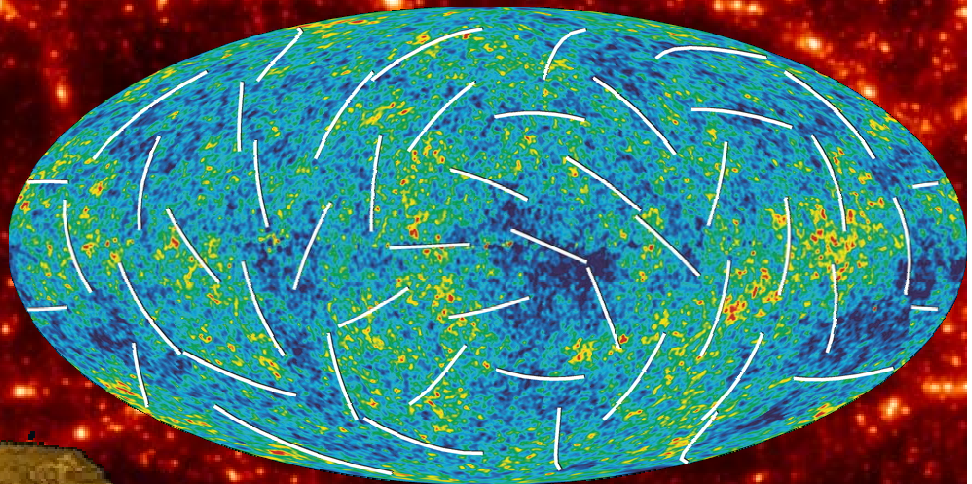
ANALYSE STATISTIQUE *EN ACTION* : ANISOTROPIES DU RCF







F. R. BOUCHET
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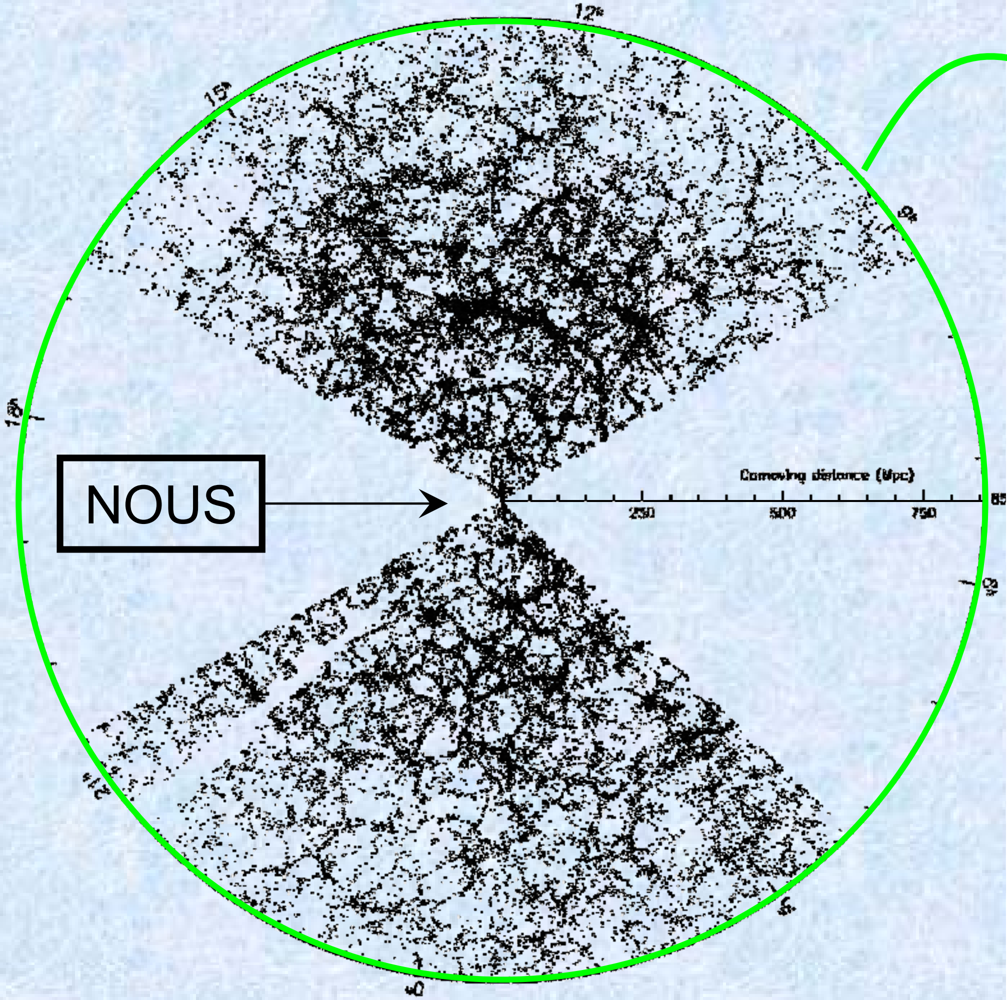
@ CARGÈSE, AOUT 2006

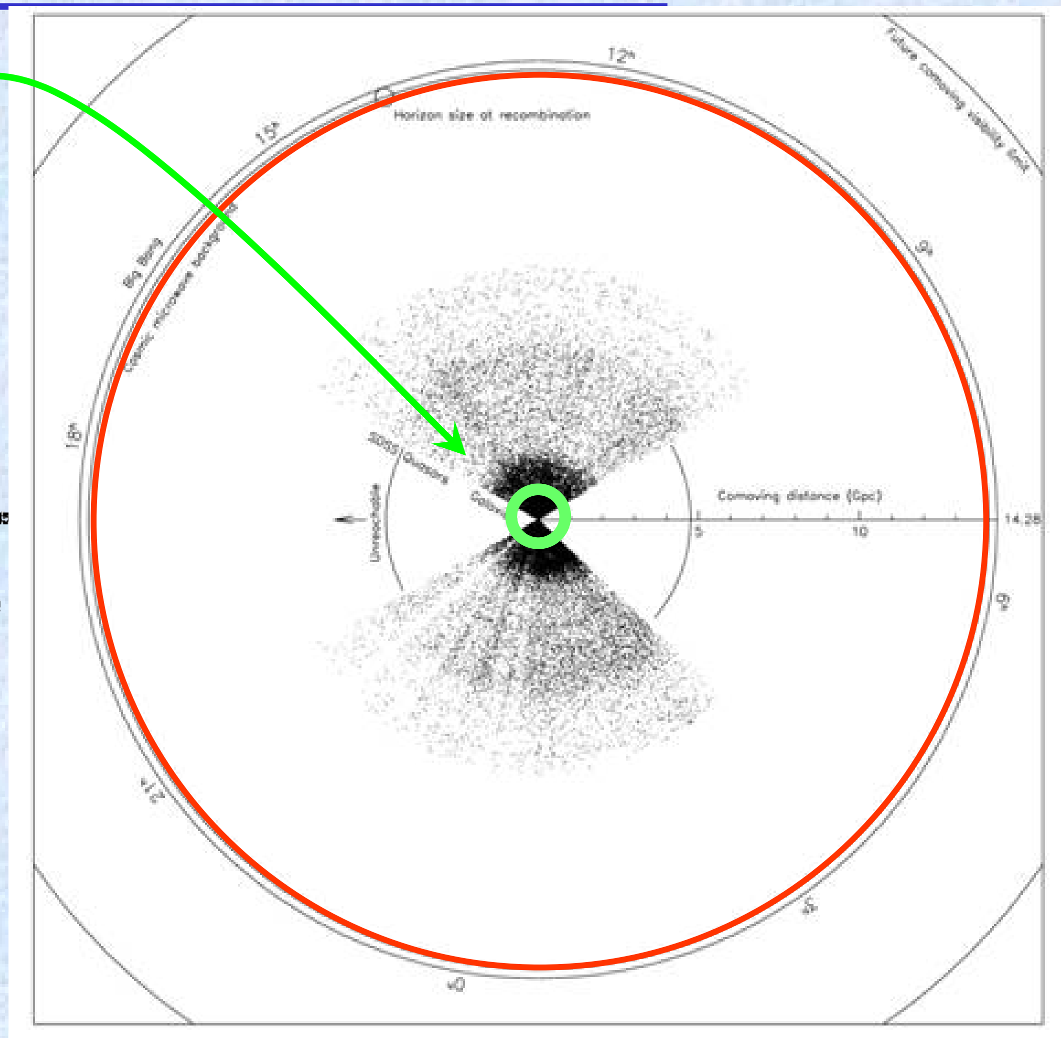
Liste de paramètres, wanted!

- Description du contenu (qui contrôle l'évolution et croissance gravitationnelle)
  - Ω, ou $\Omega_K = 1 - \Omega_{CDM} - \Omega_B - \Omega_{\Lambda,}$ ($\Omega_X = \rho_x / \rho_c = 8\pi G \rho_x/(3H^2)$, $H=1/a\, da/dt$)
  - Ω_{CDM}
  - Ω_B
  - H
  - (τ)

- Description des conditions initiales, *supposées* Gaussiennes, Adiabatiques, invariantes d'échelle
  - n_s
  - As (ou $C_{2,}$ ou σ_8)
  - (n_T)
  - (A_T or $r = A_S/A_T$)

VOIR LOIN, C'EST VOIR LE PASSÉ LOINTAIN !



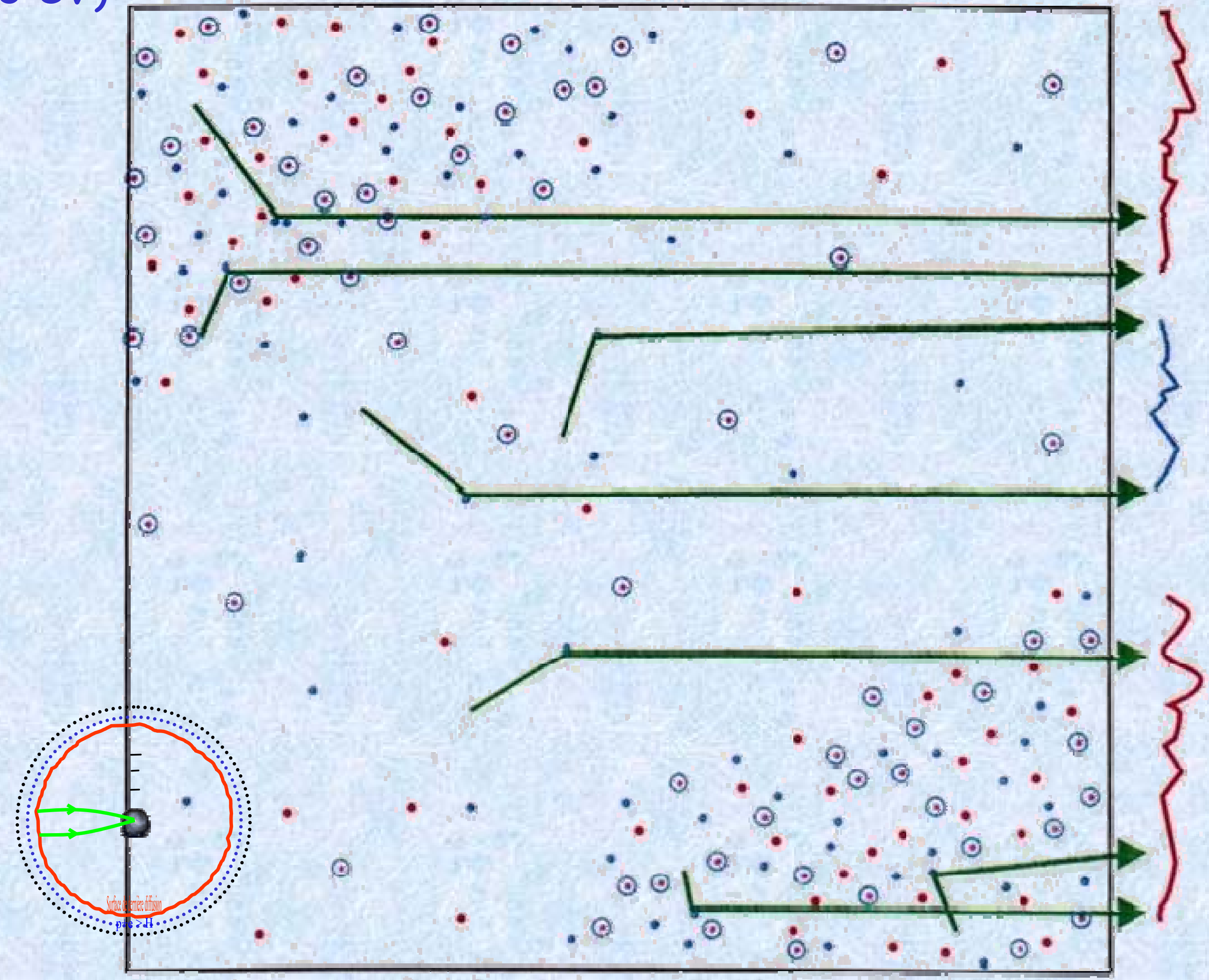


Chaque point est une galaxie comme la Notre. La plus proche, M31, est à ~2,5 Mal. Il faut 2,7 milliards d'années à la lumière d'une galaxie sur le cercle vert pour qu'elle nous parvienne.

La lumière **millimétrique** a mis environ 1[illegible] milliards d'années pour nous parvenir (cercle rouge).
C'est la trace intacte (comme fossilisée) de la fournaise primordiale, 400 000 ans après le Bang, quand l'Univers est devenu Transparent.

QUAND L'UNIVERS DEVIENT TRANSPARENT…

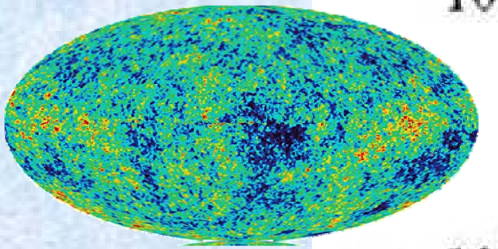
(at ~1/3 eV)



+ ISW…

Θ+ψ
& v

« COSMOMÉTRIE »: SPECTRE DE PUISSANCE ANGULAIRE DES ANISOTROPIES DE TEMPÉRATURE



Hauteur des vagues / longueur d'onde l

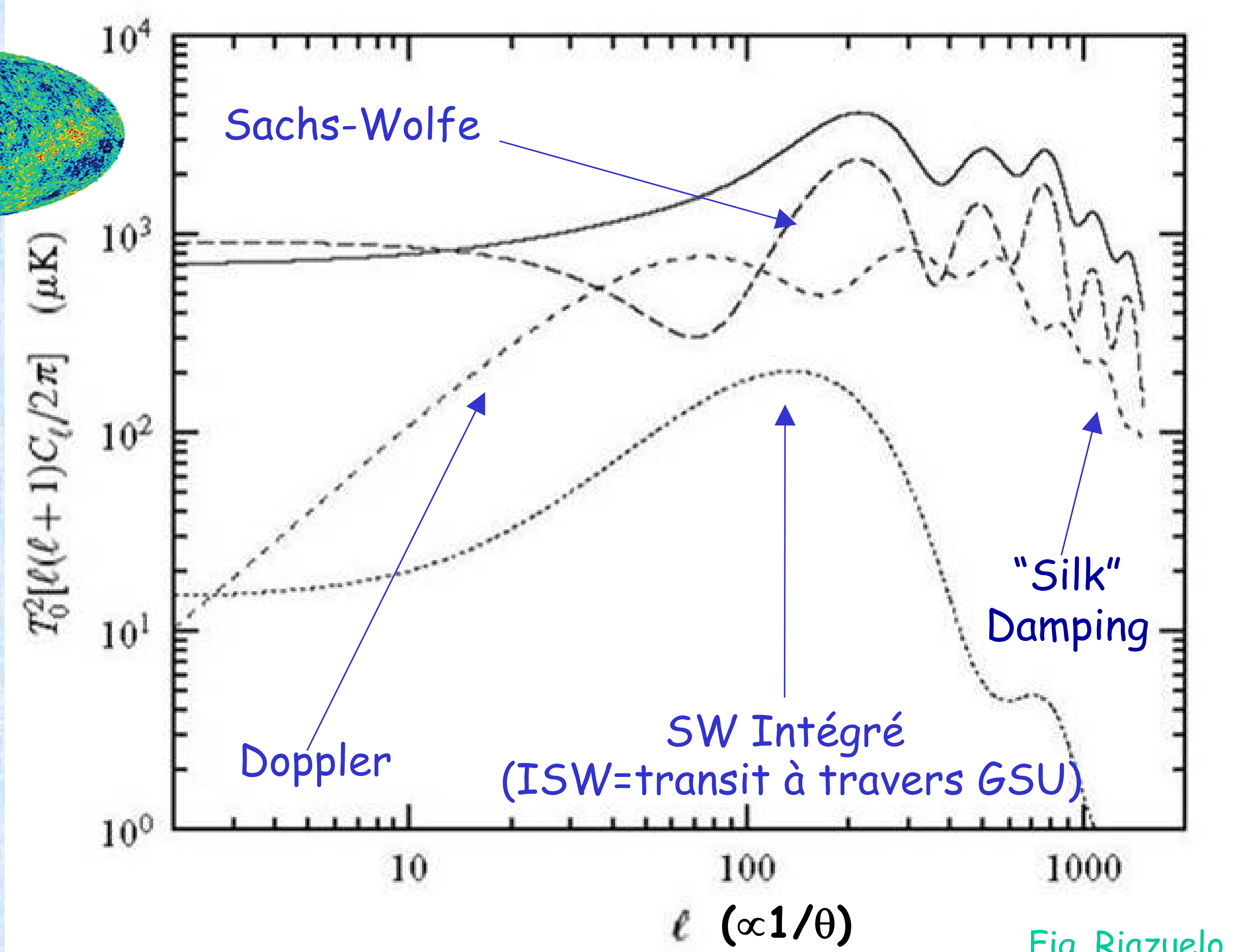
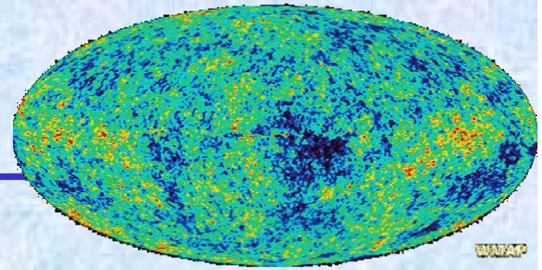
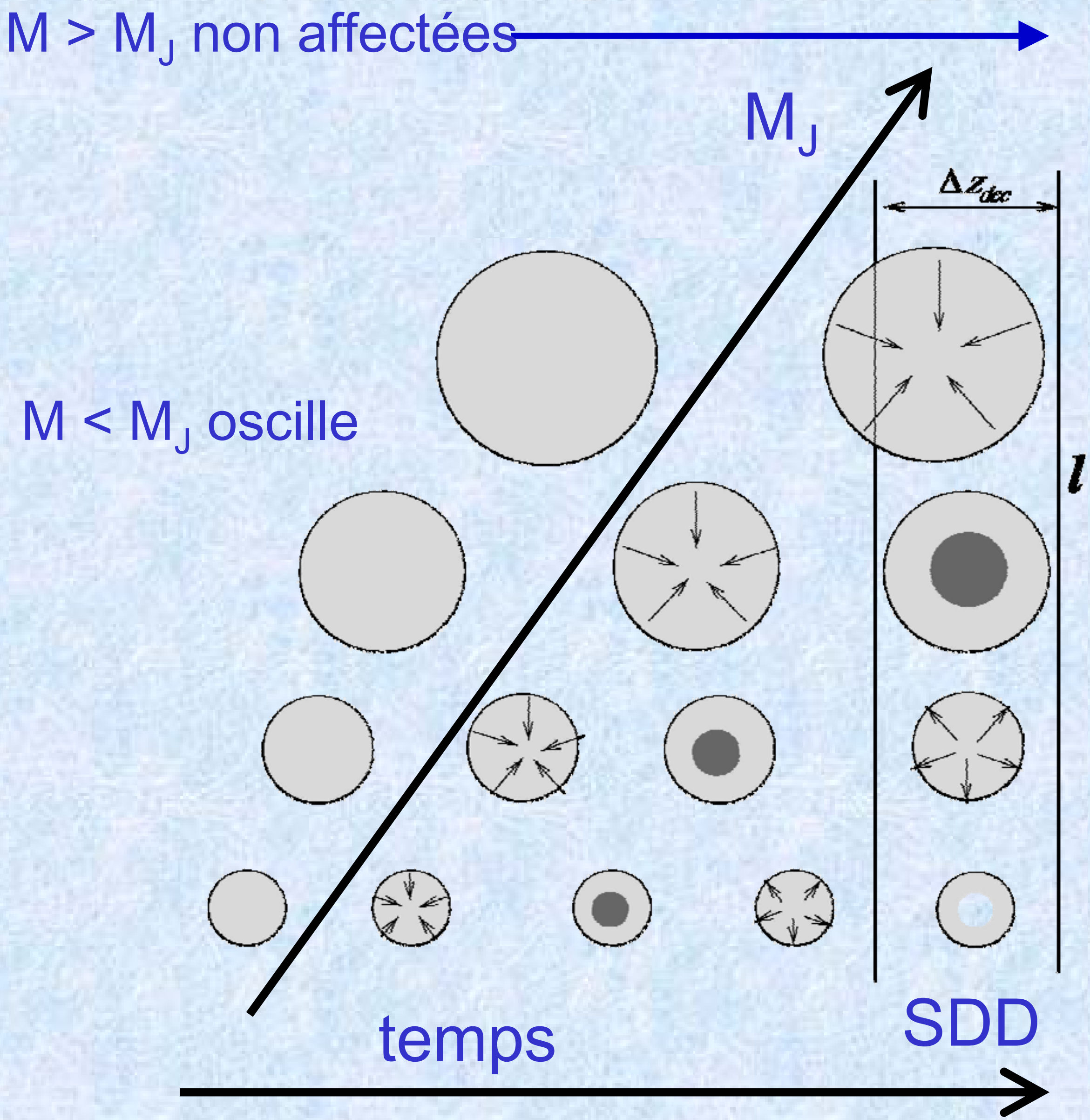


Fig. Riazuelo

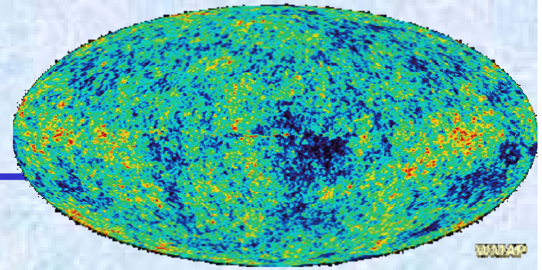
NB1 : Ici, cas restreint de fluctuations Scalaires uniquement (sinon il existe un terme additionnel)
NB2 : SW & ISW sont anti-corrélés

OSCILLATIONS ACOUSTIQUES





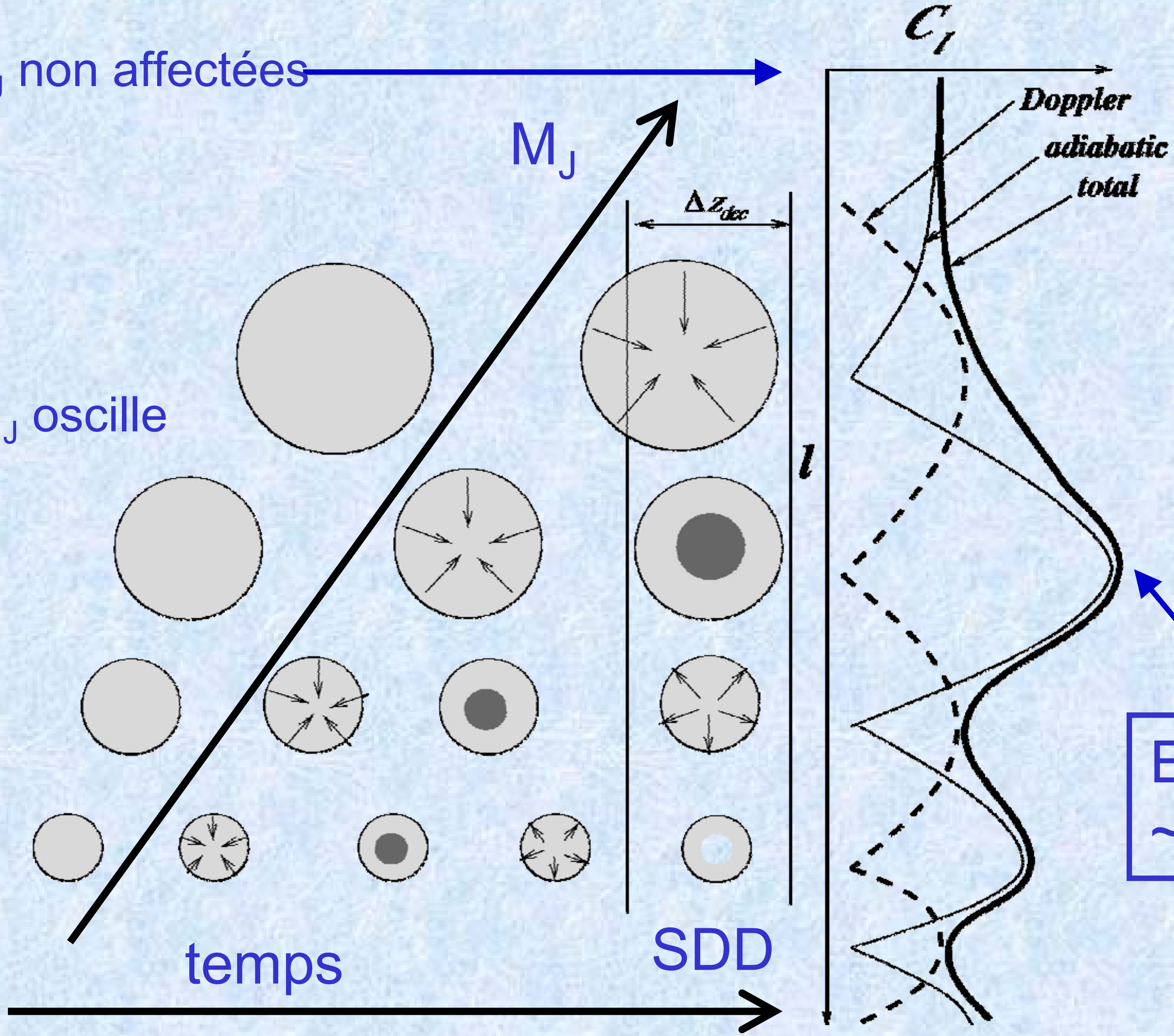
OSCILLATIONS ACOUSTIQUES



M > M_J non affectées

M < M_J oscille

M_J

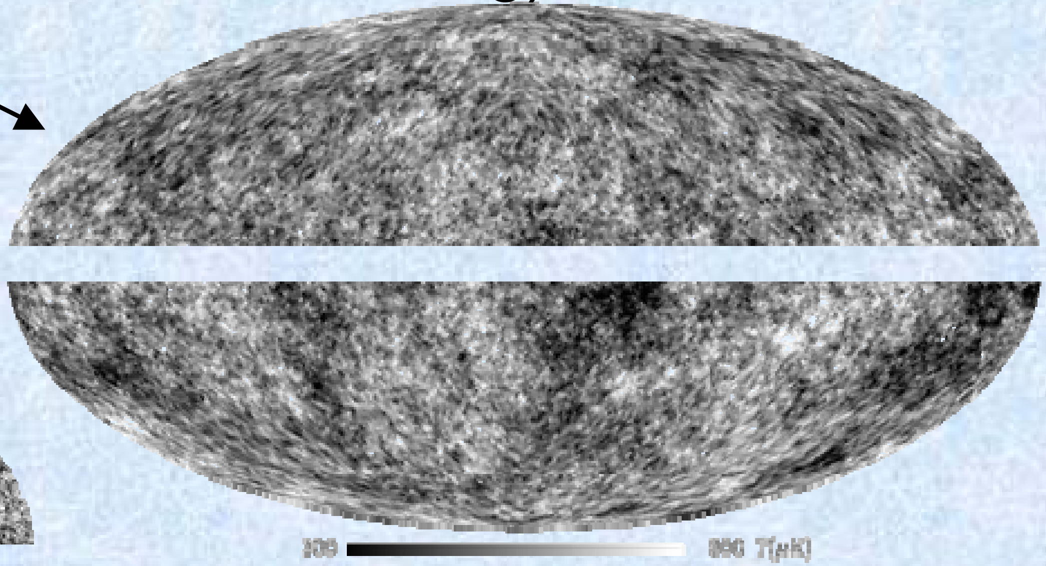


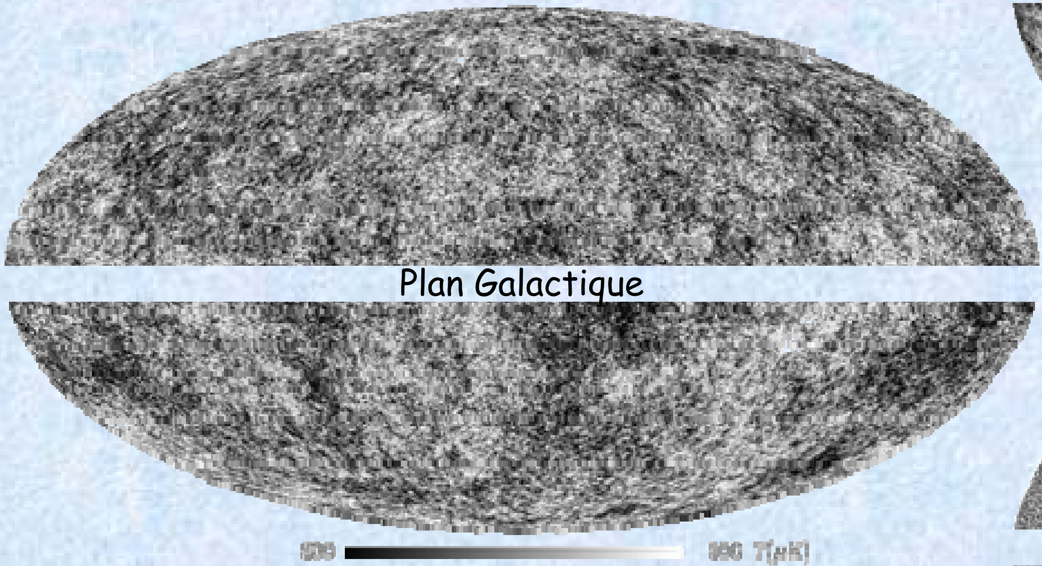
Echelle de ~ 1 degré

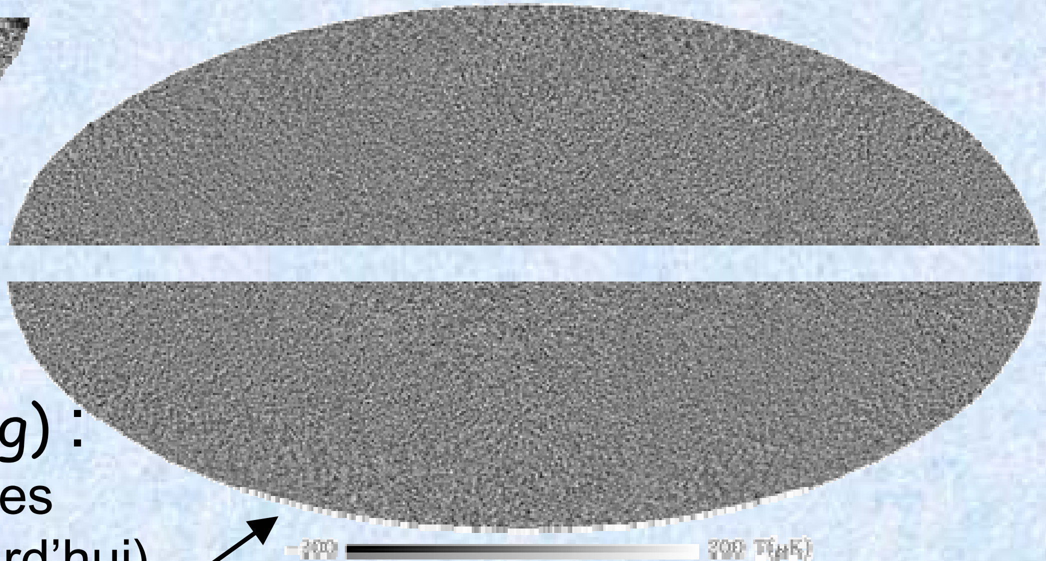
CE QU'ON OBSERVE

Carte lissée (suppression des échelles θ < 1 deg) :

Fluctuations Quantiques imprimées quand l'age de l'Univers était dans l'intervalle [10^{-43}, 10^{-12}] seconds





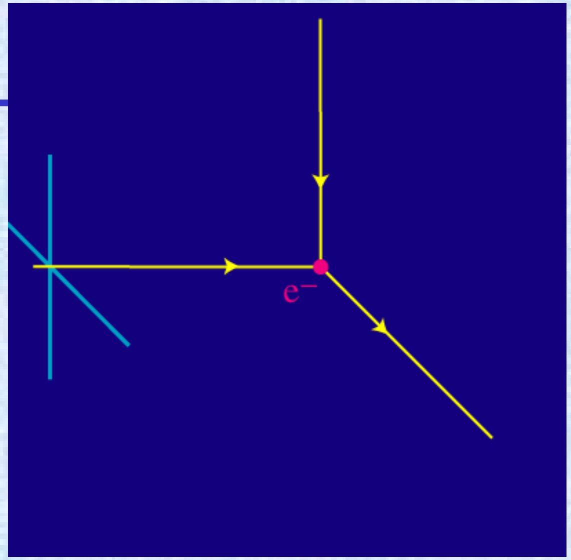


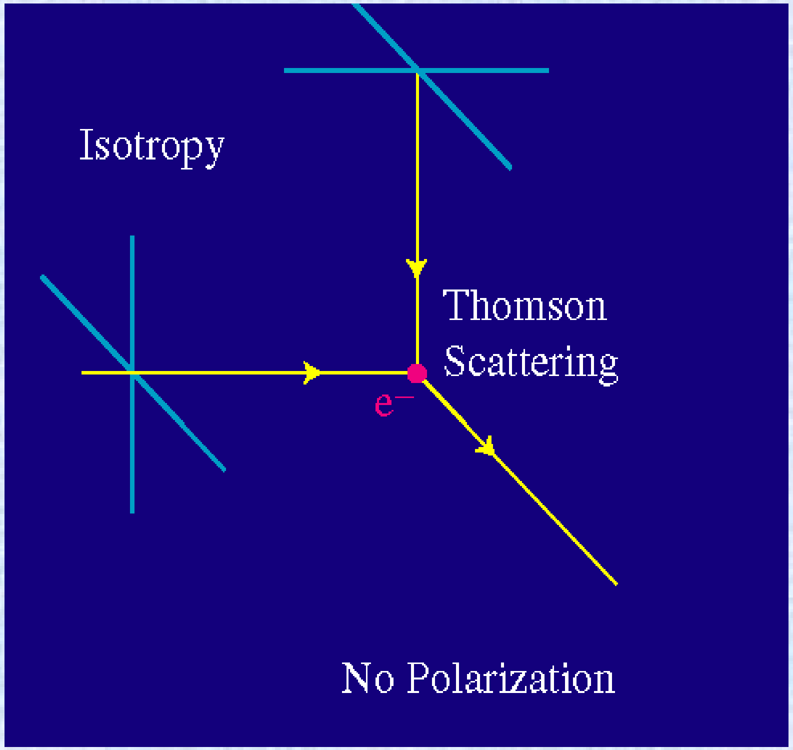
Carte différence (*échelles θ < 1 deg*) :

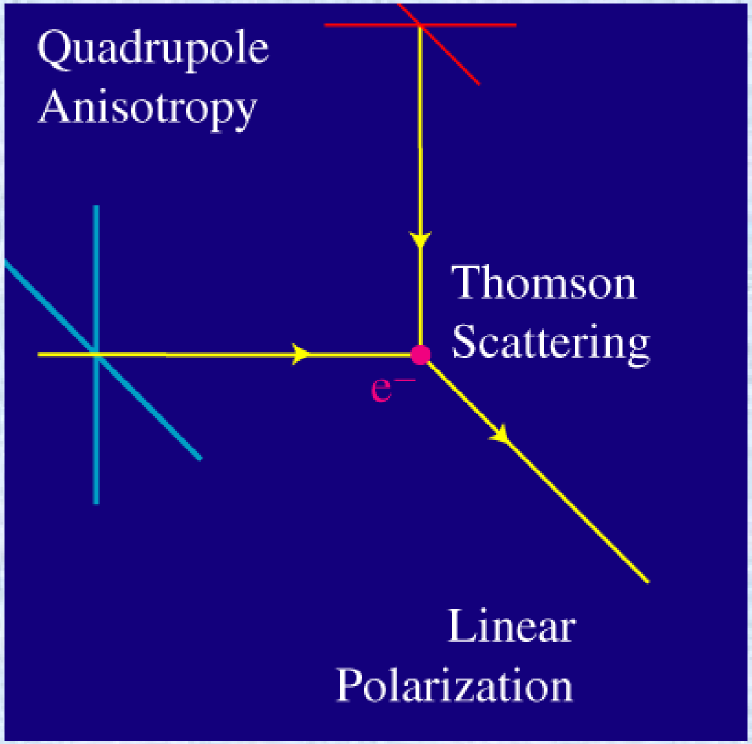
Oscillations acoustiques aux petites échelles < ct quand t=370 000 ans (~150Mpc aujourd'hui).

Permet de recenser le contenu

LES DIFFUSIONS THOMSON SONT POLARISÉES

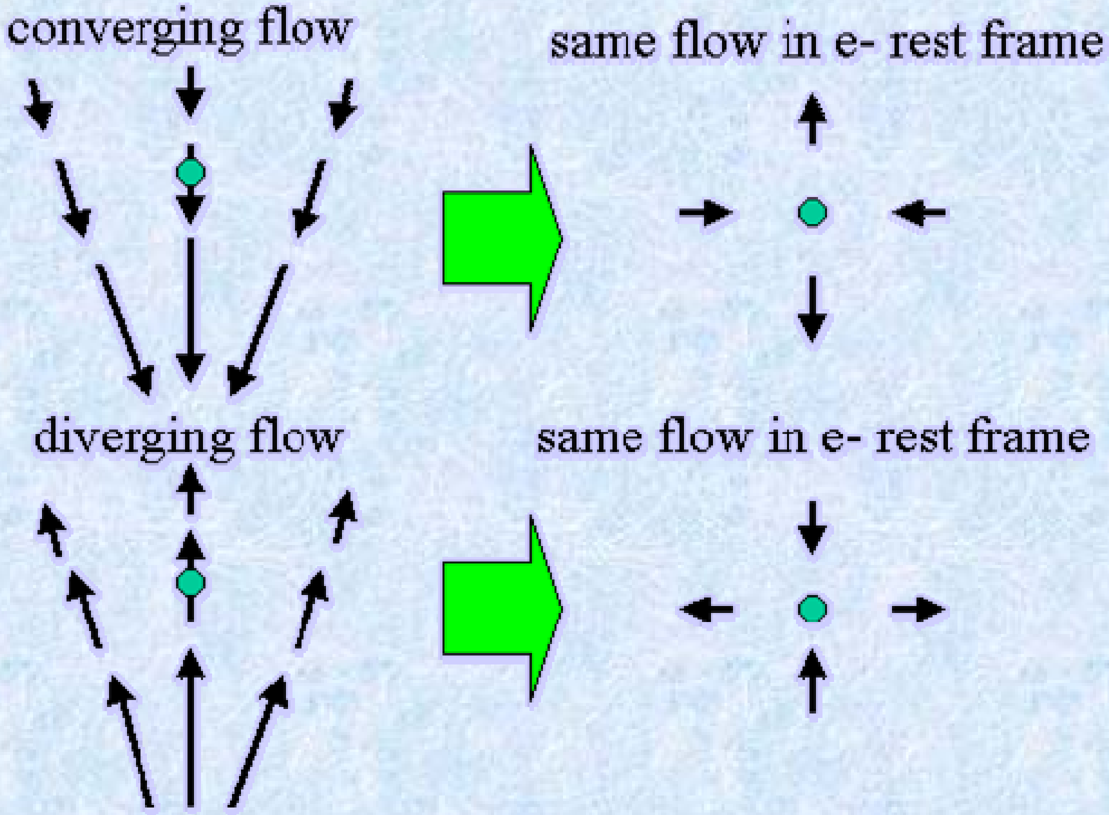






POLARISATION

- Before recombination, successive scatterings destroy polarization and the radiation arrives at recombination unpolarized
- During recombination, Gradients in the velocity field can produce a quadrupole in the rest frame of the scattering electron



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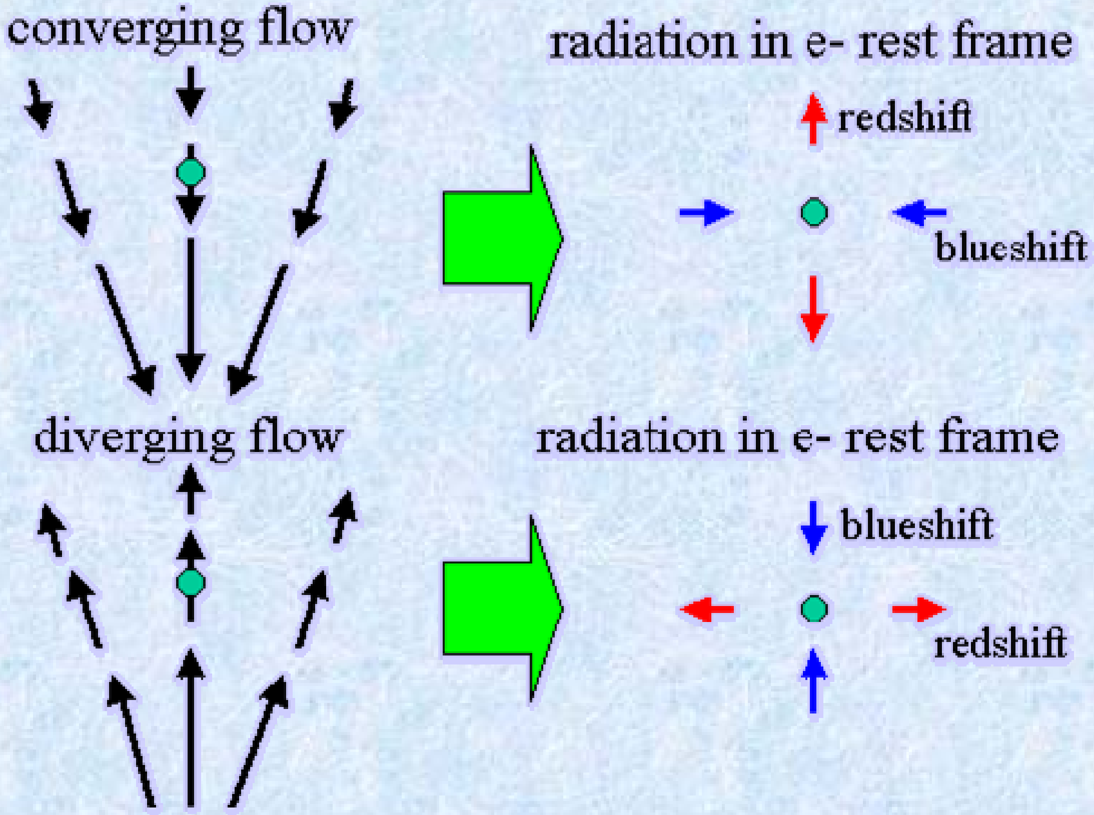

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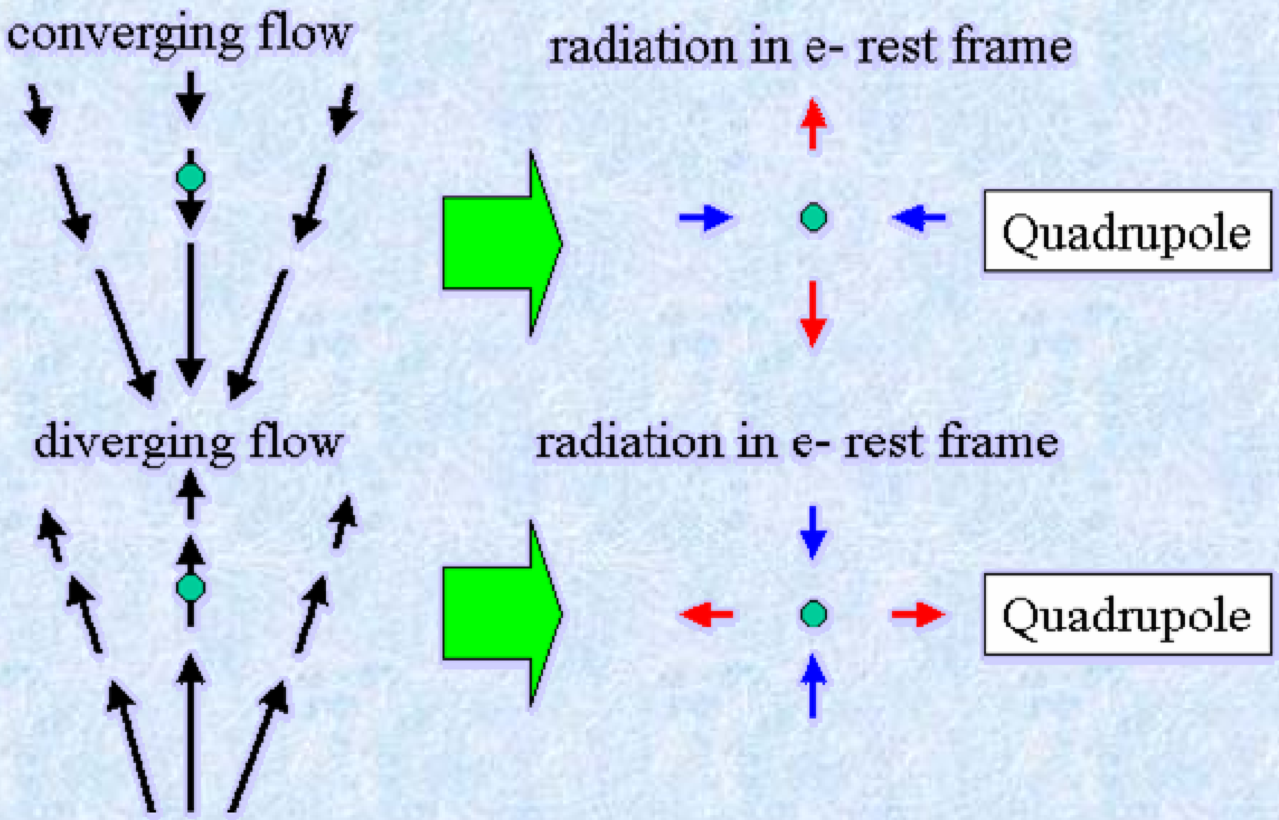

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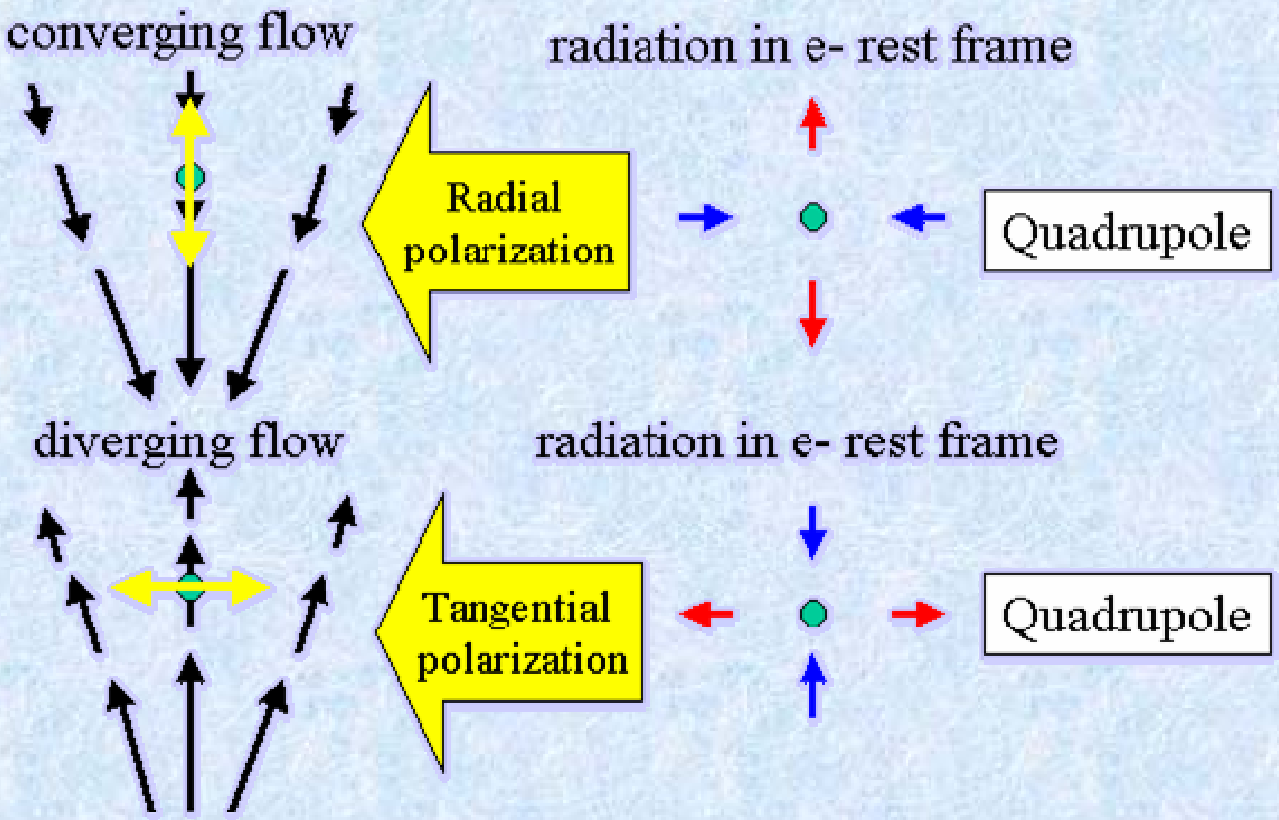
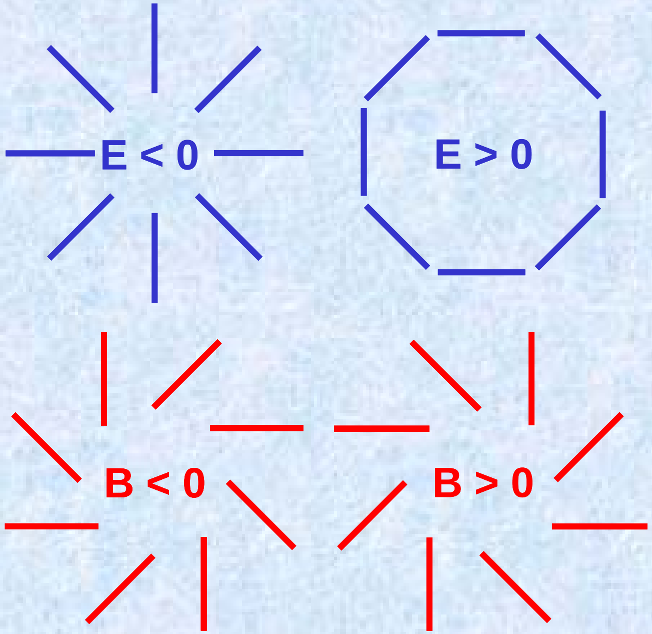
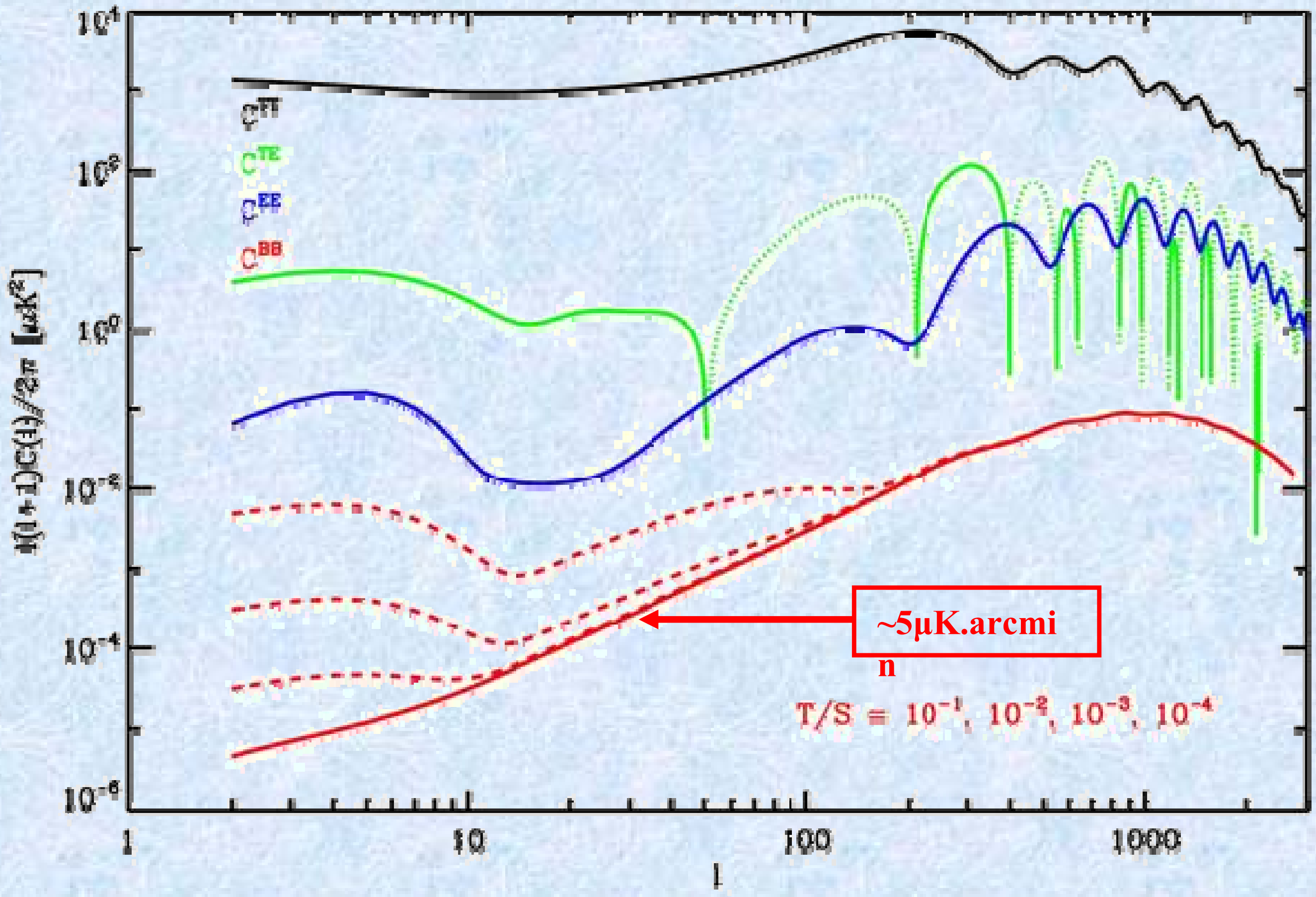


SPECTRES DE PUISSANCE DU RCF

- 3 observables : T, E, B

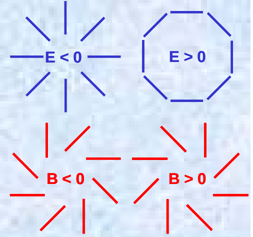


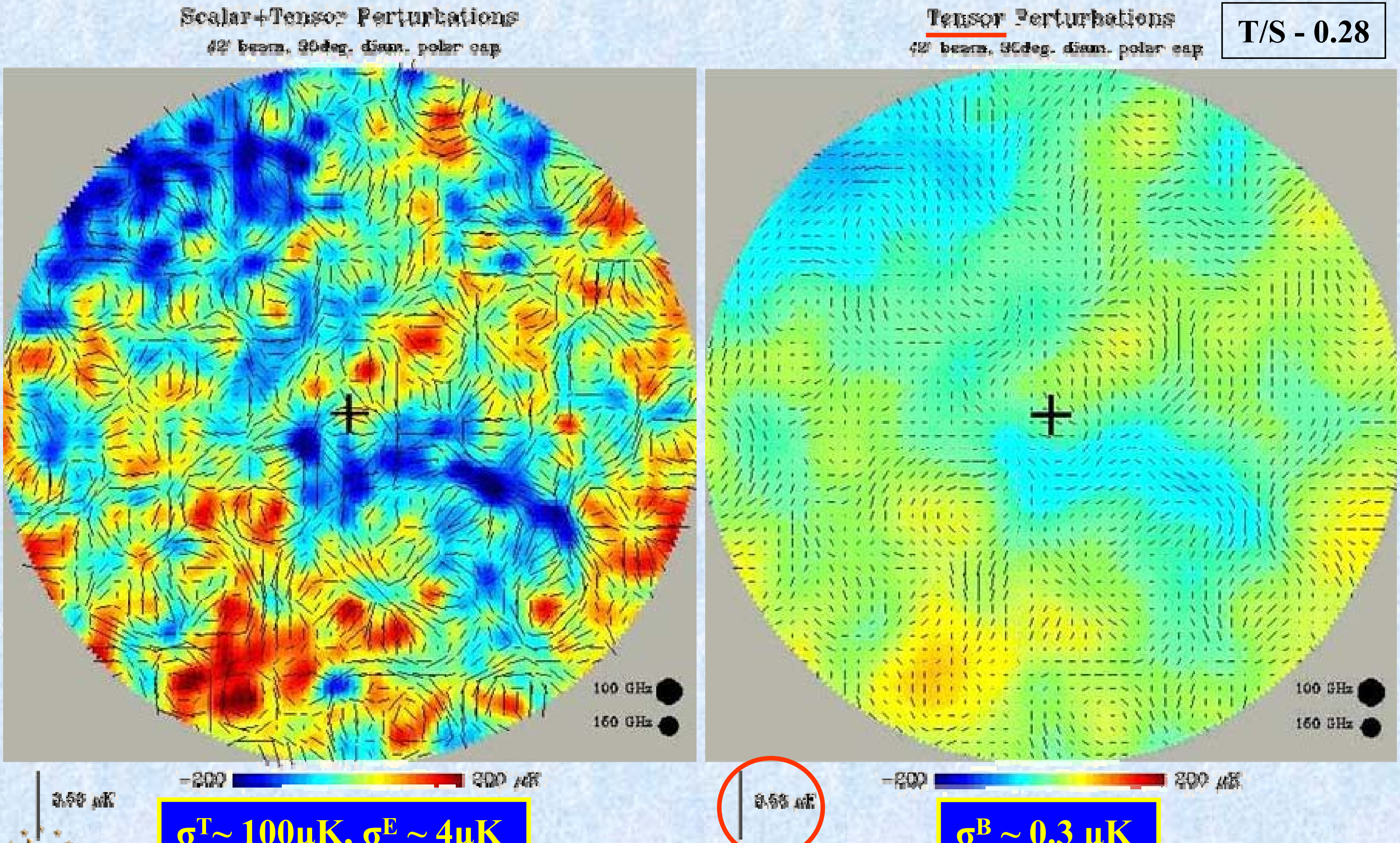
- Les modes B **ne peuvent pas** être générés par des fluctuations primordiales scalaires
  mais « lentillage » par les grandes structures transforme du E en B



($\propto 1/\theta$)

MOTIFS POLARISÉS ATTENDUS





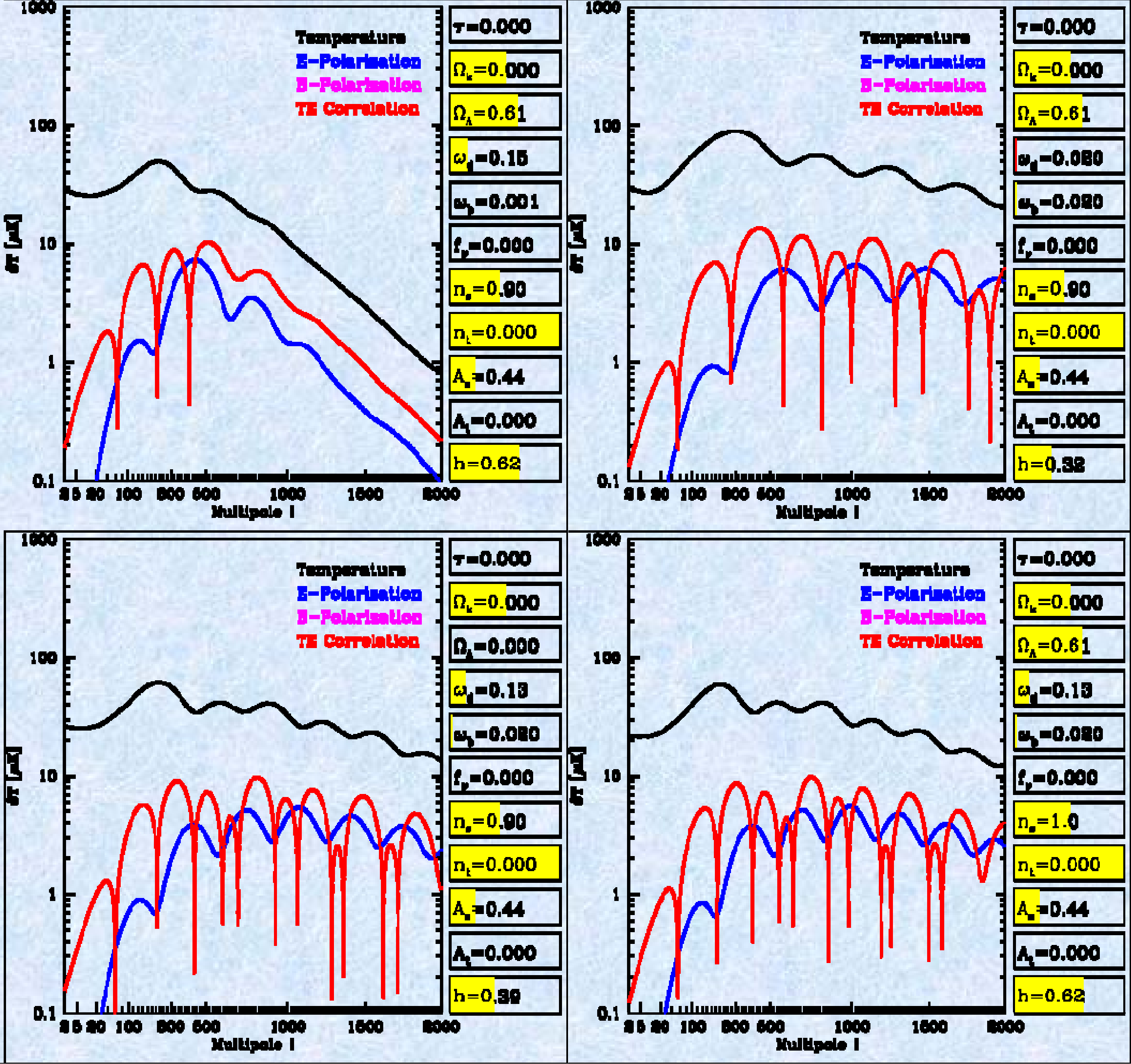
$\sigma^T \sim 100\mu K$, $\sigma^E \sim 4\mu K$

$\sigma^B \sim 0.3\ \mu K$

www.astro.caltech.edu/~lgg/bicep_front.htm

Ω_B (D/H)

Ω_Λ

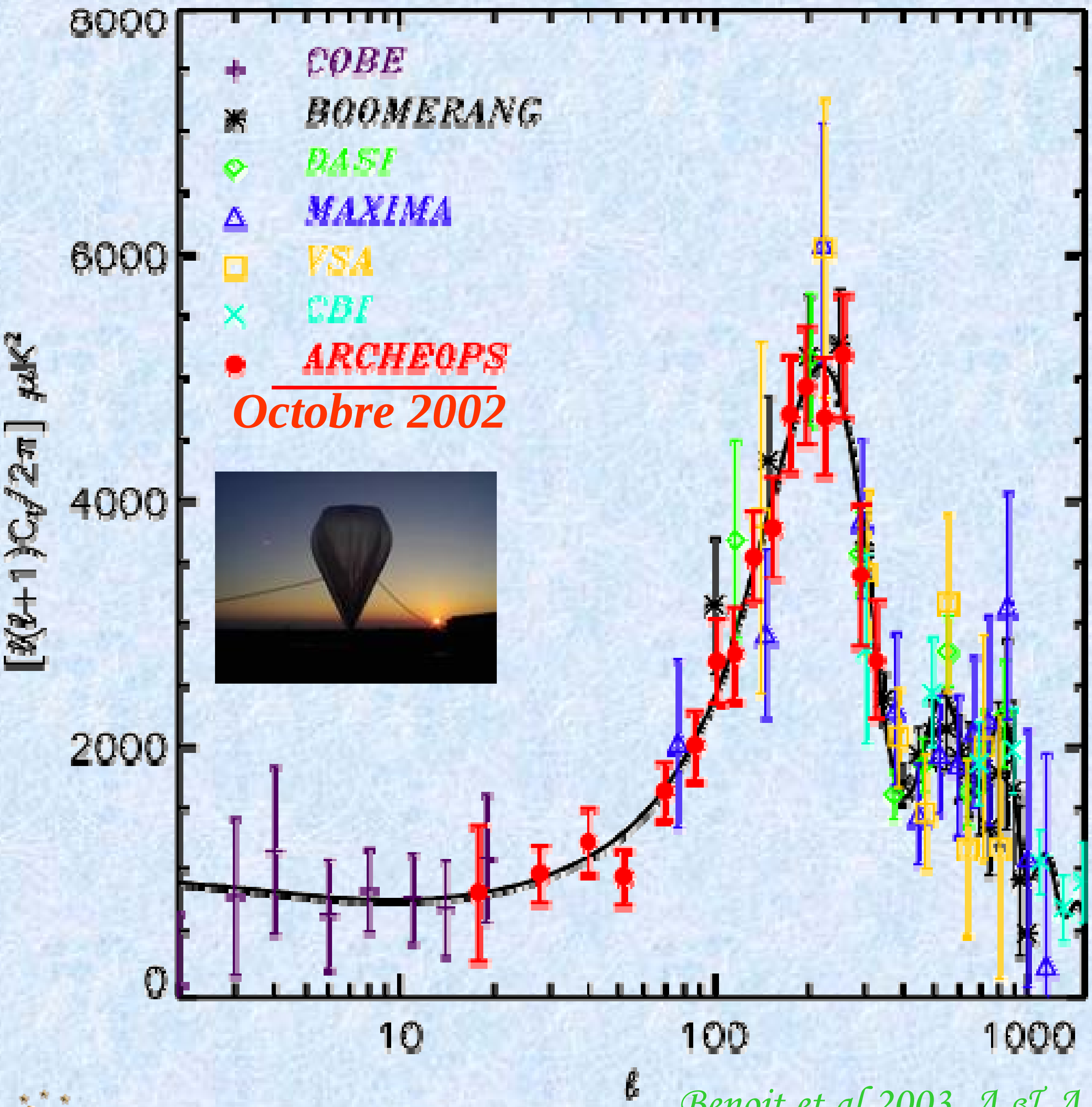


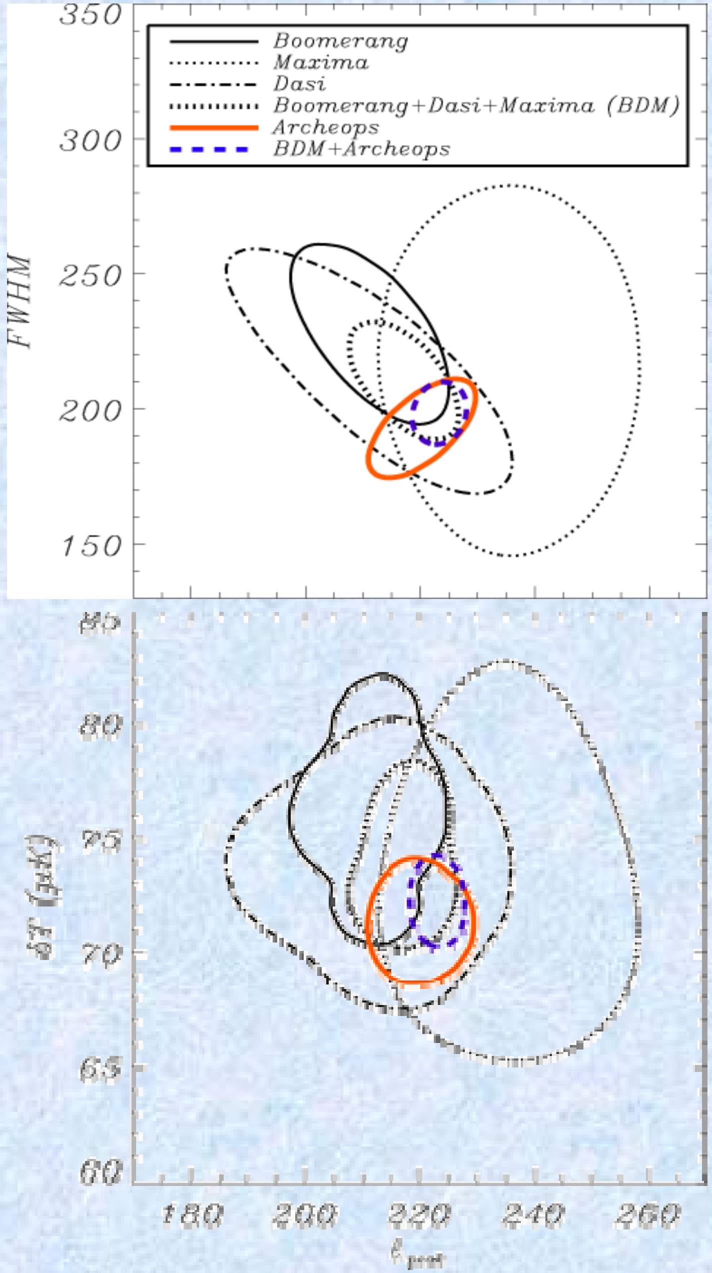
Ω_M (LSS, WL)

$f_\nu = \frac{\Omega_\nu}{\Omega_M}$

Tegmark's web site

END OF 2002 STATUS…

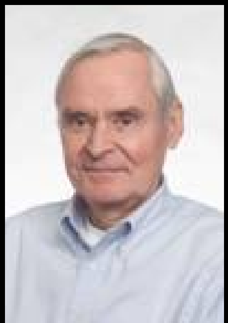


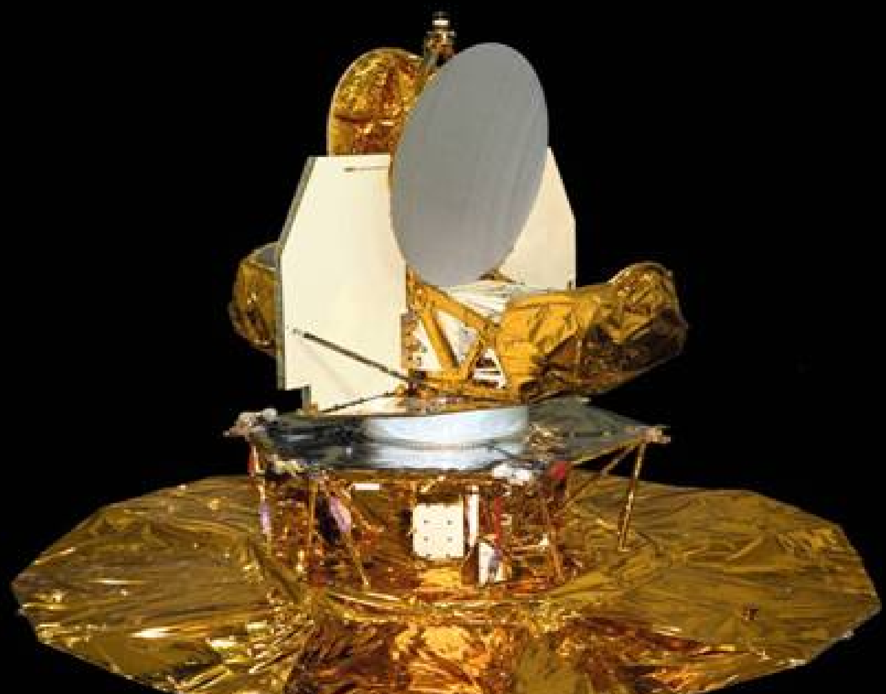


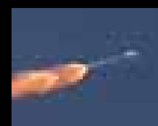
Benoit et al 2003, A & A, 399, L25

WMAP

Wilkinson Microwave Anisotropy Probe

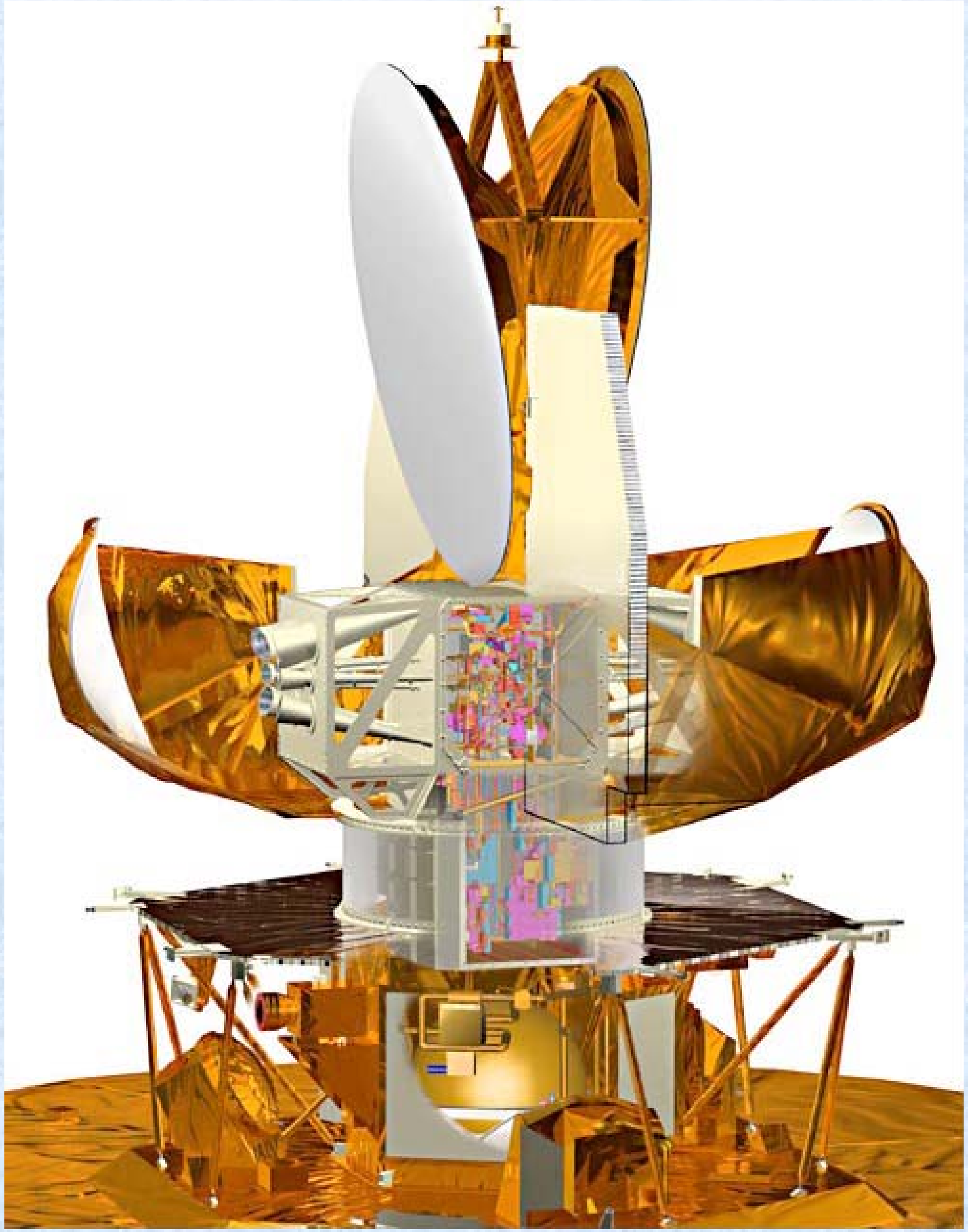




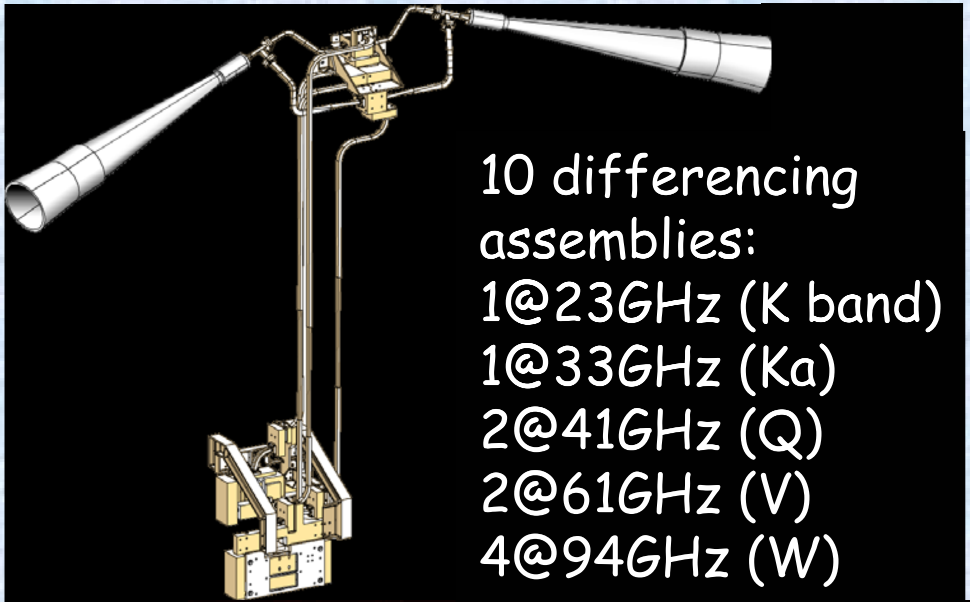


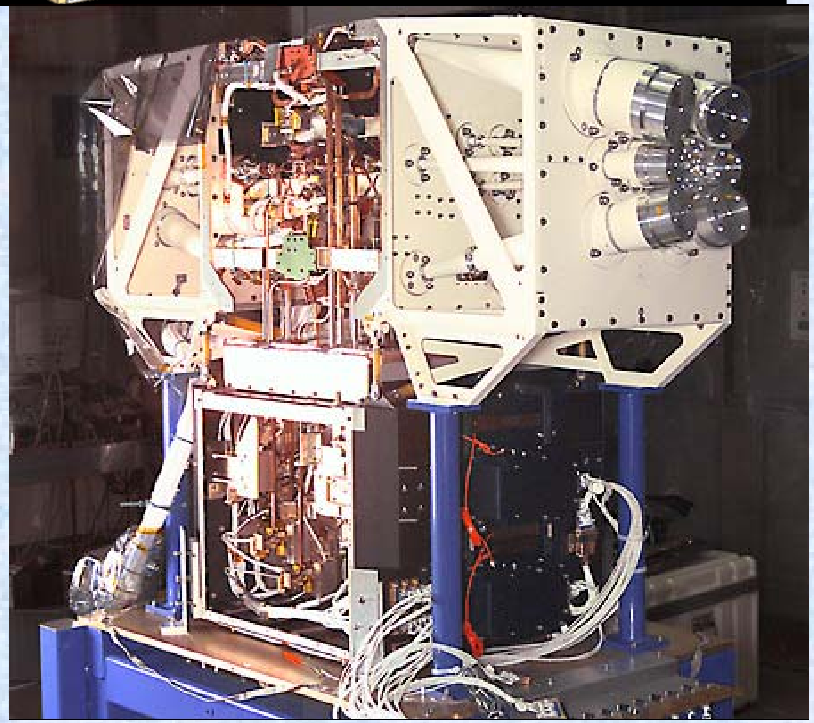
Launched on
June 30, 2001

HEMT BASED DIFFERENTIAL MEASURES

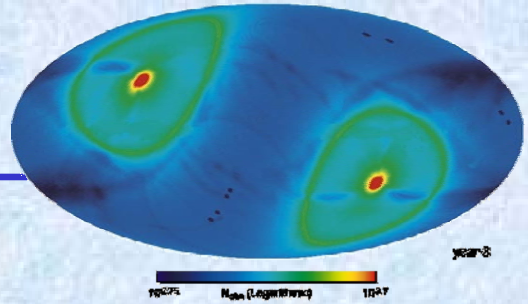


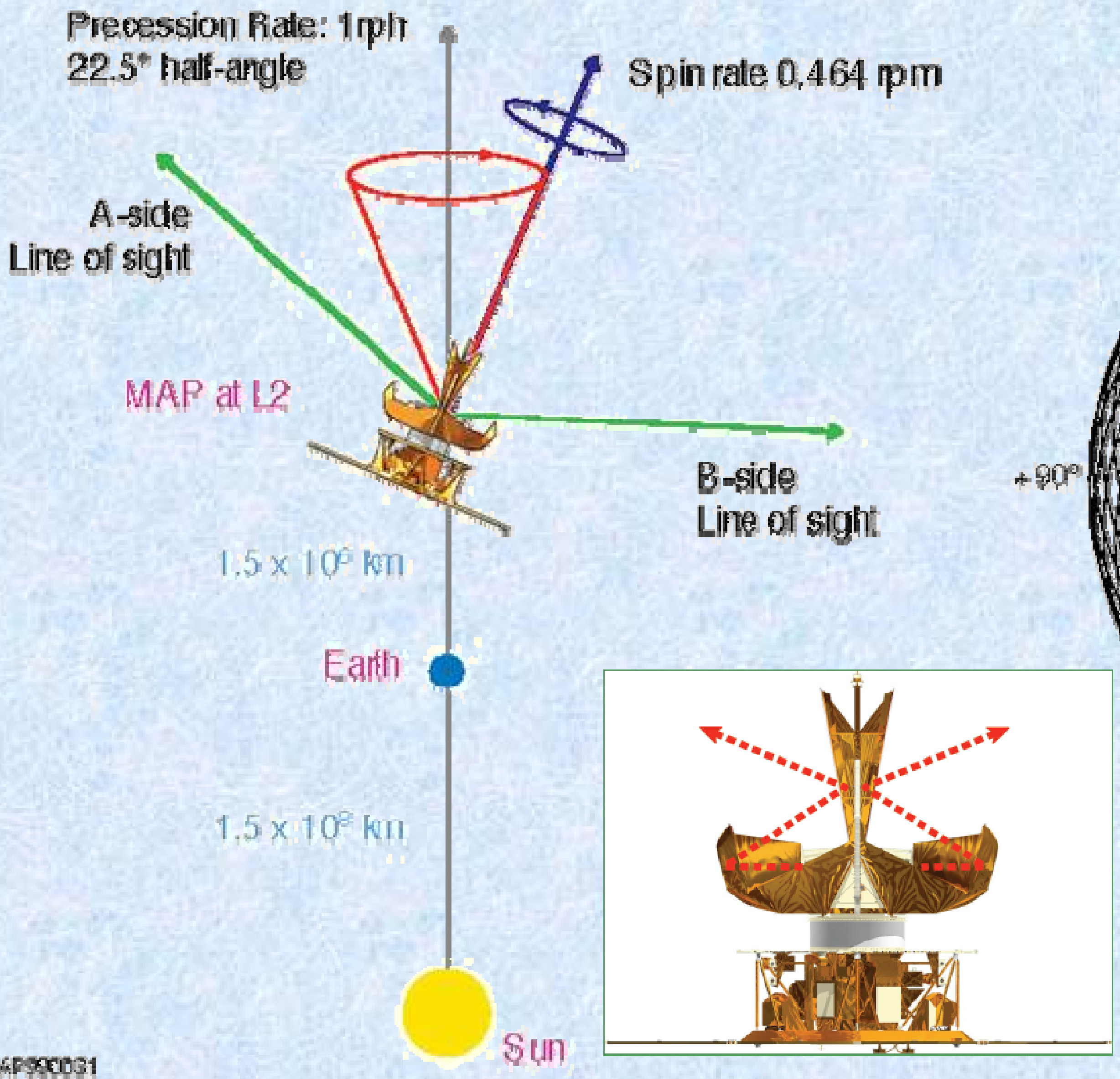
2 back-to-back telescopes

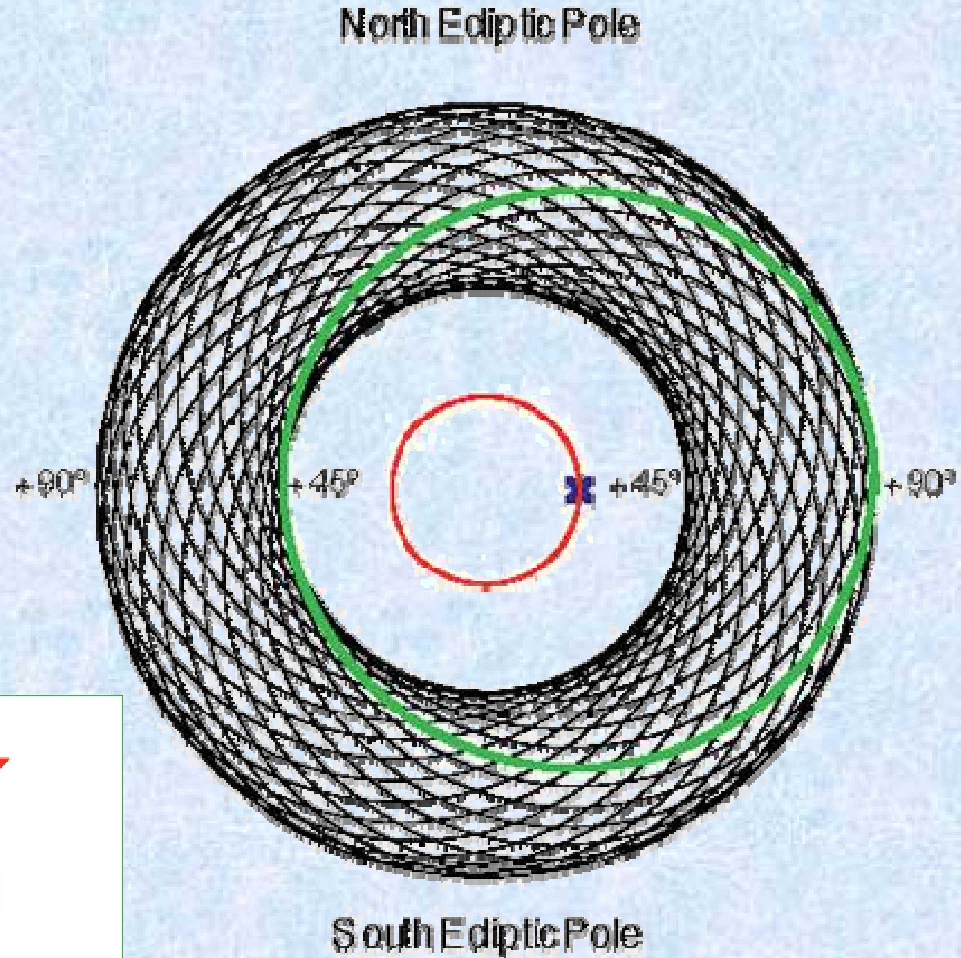




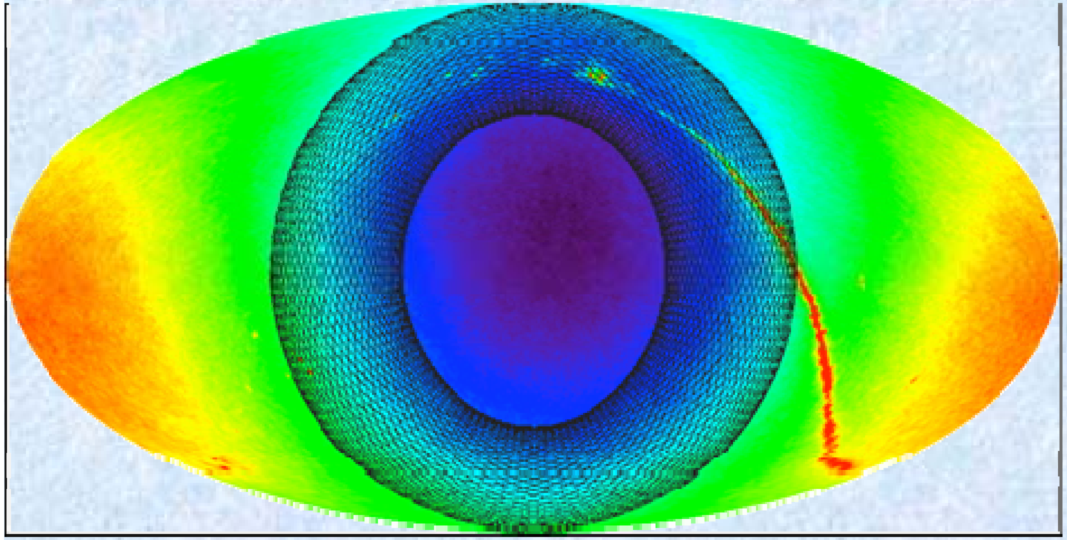
SCAN PATTERN

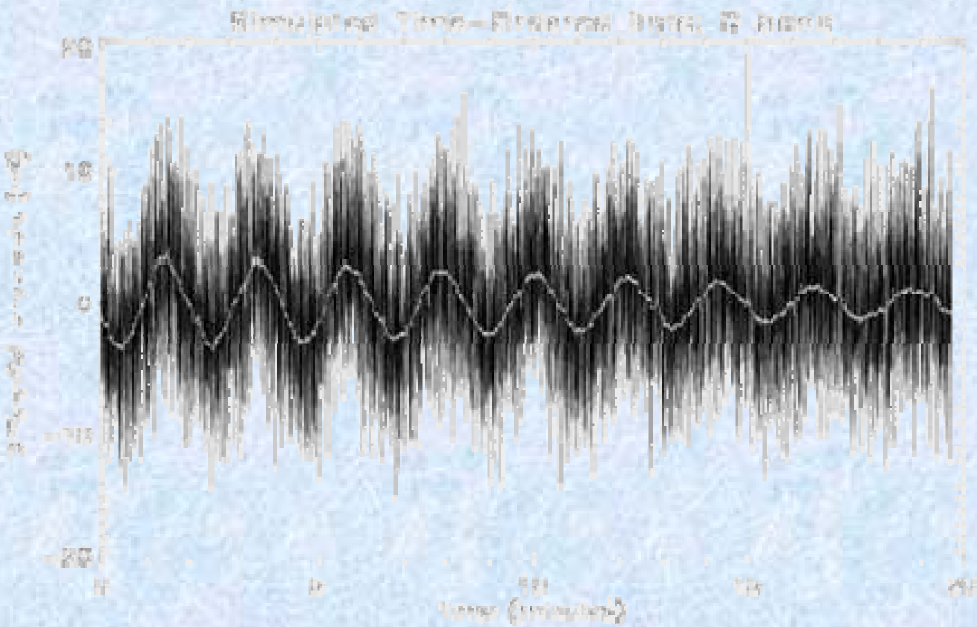




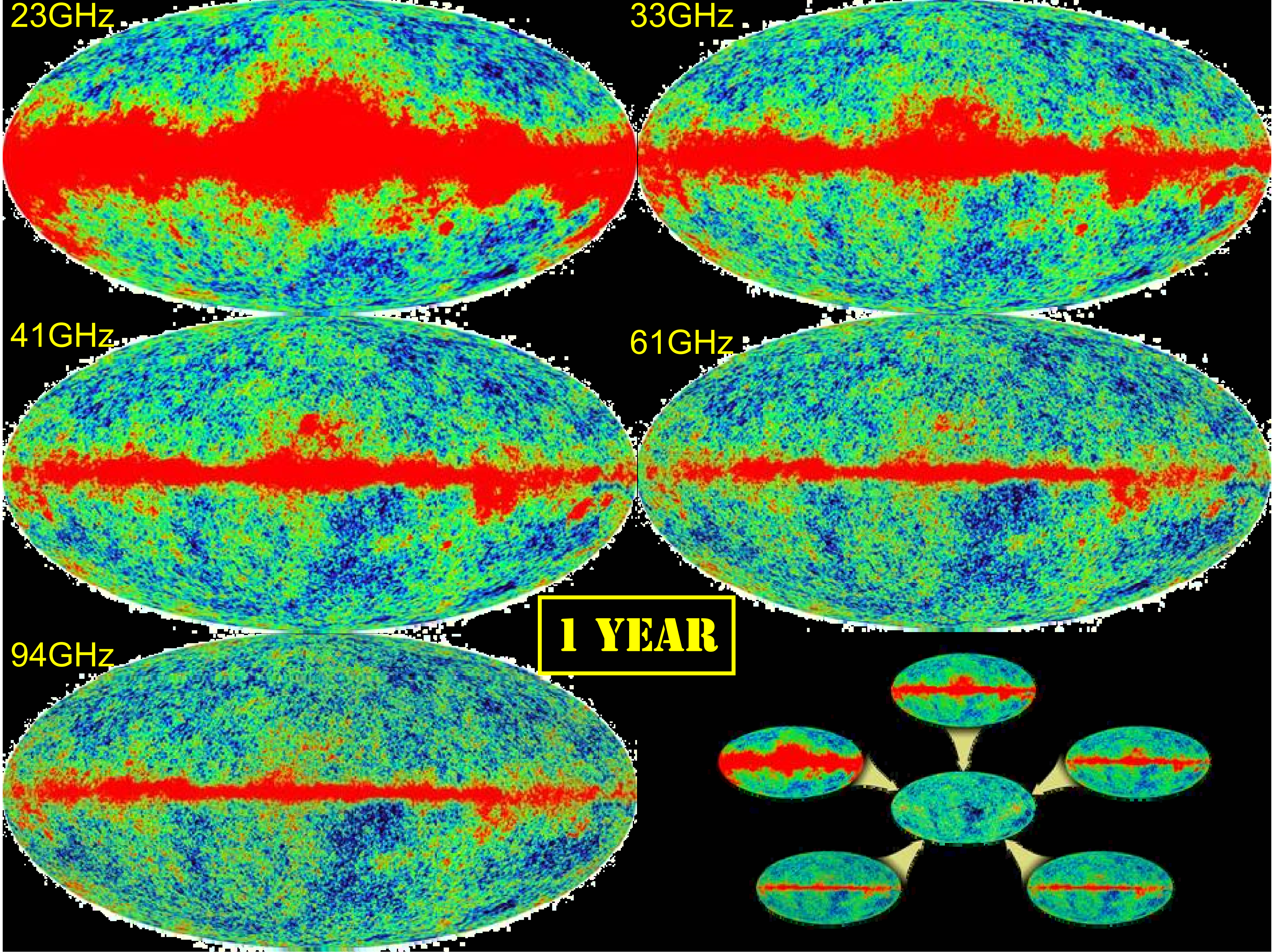


CONTINUOUS CALIBRATION FROM DIPOLE





- Gain calibration based on known dipole modulation due to motion of WMAP around the Sun.
- CMB dipole provides short term transfer standard.
- Baseline (or offset) determination based on sky signal changing sign every half-spin.


23GHz
33GHz
41GHz
61GHz
94GHz
1 YEAR

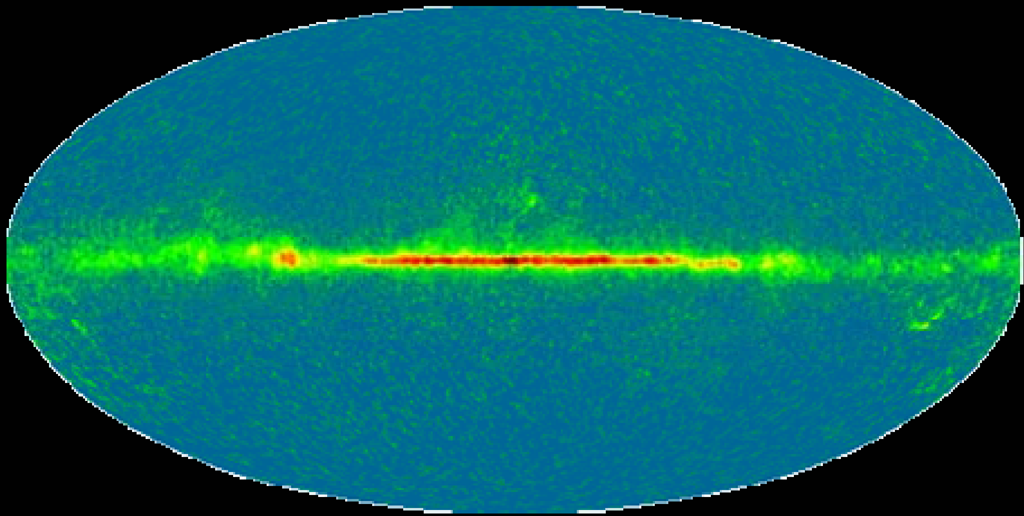
FABRICATION DES CARTES

- $y = A\,x + b$
  - y = vecteur des données ordonnées en temps
  - b = vecteur du bruit détecteur ordonné en temps
  - X = vecteur des pixels du ciel
  - A matrice de pointage
- Pb bien posé:
  - On minimise e.g. $< |x - \hat{x}|^2 >$
  - Matrice de covariance du bruit $N = \langle b\, b^T \rangle$

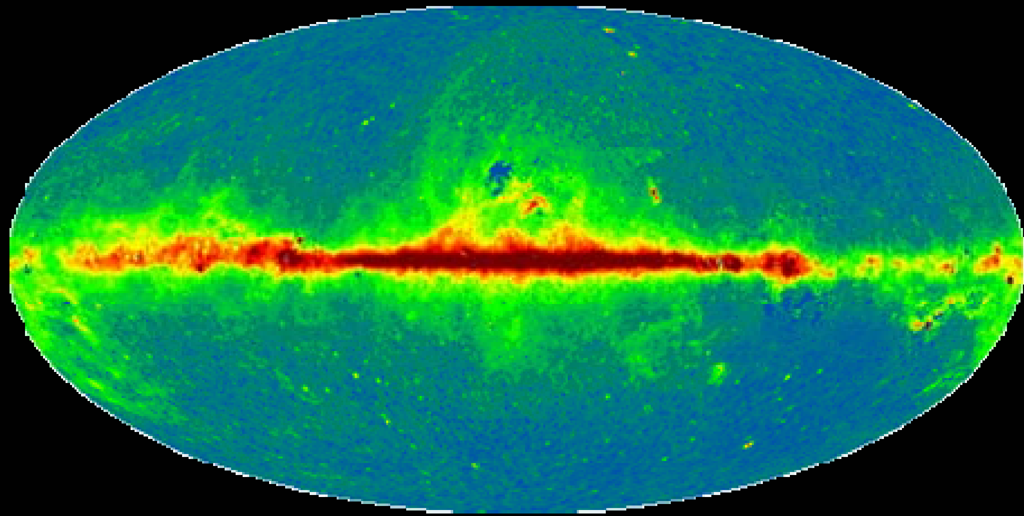
$$\Longrightarrow \quad \hat{x} = [A^T N^{-1} A]^{-1} A^T N^{-1} \; Y$$

- NB:
  - si $Npix = O(10^9)$, $Ndat = O(10^{12})$, il faut se pencher sur l'implémentation ☺.
  - Il peut y avoir un problème mal contraint…

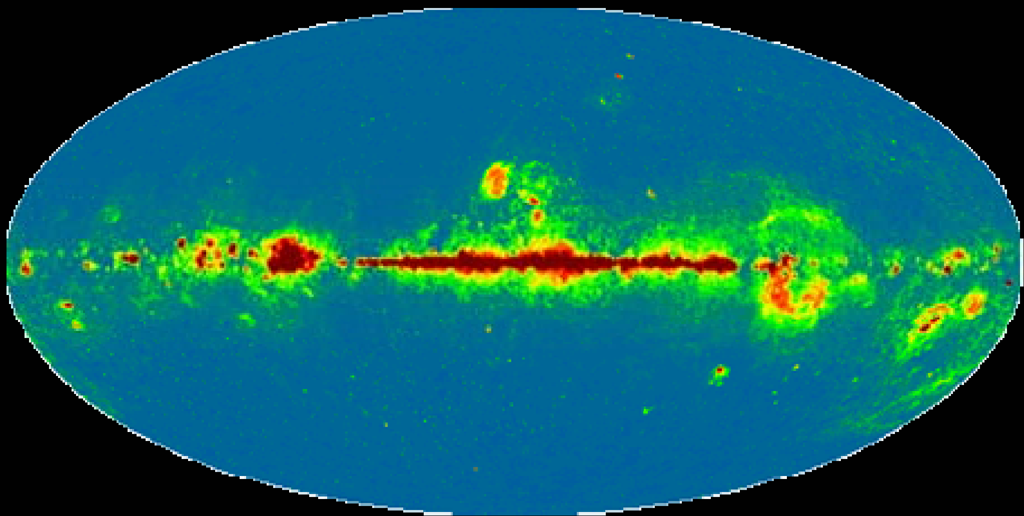
Cartes d'émission Déduites



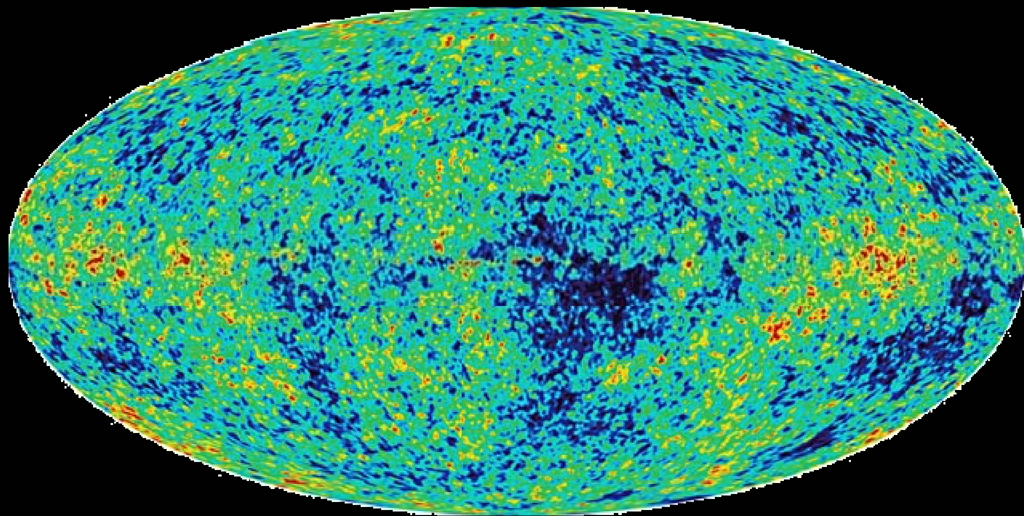
Poussière



Synchrotron



Bremstralhung

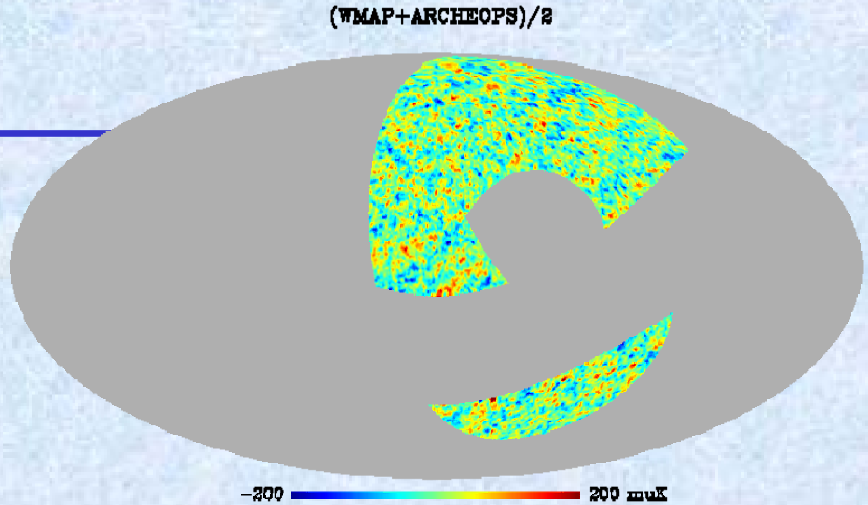


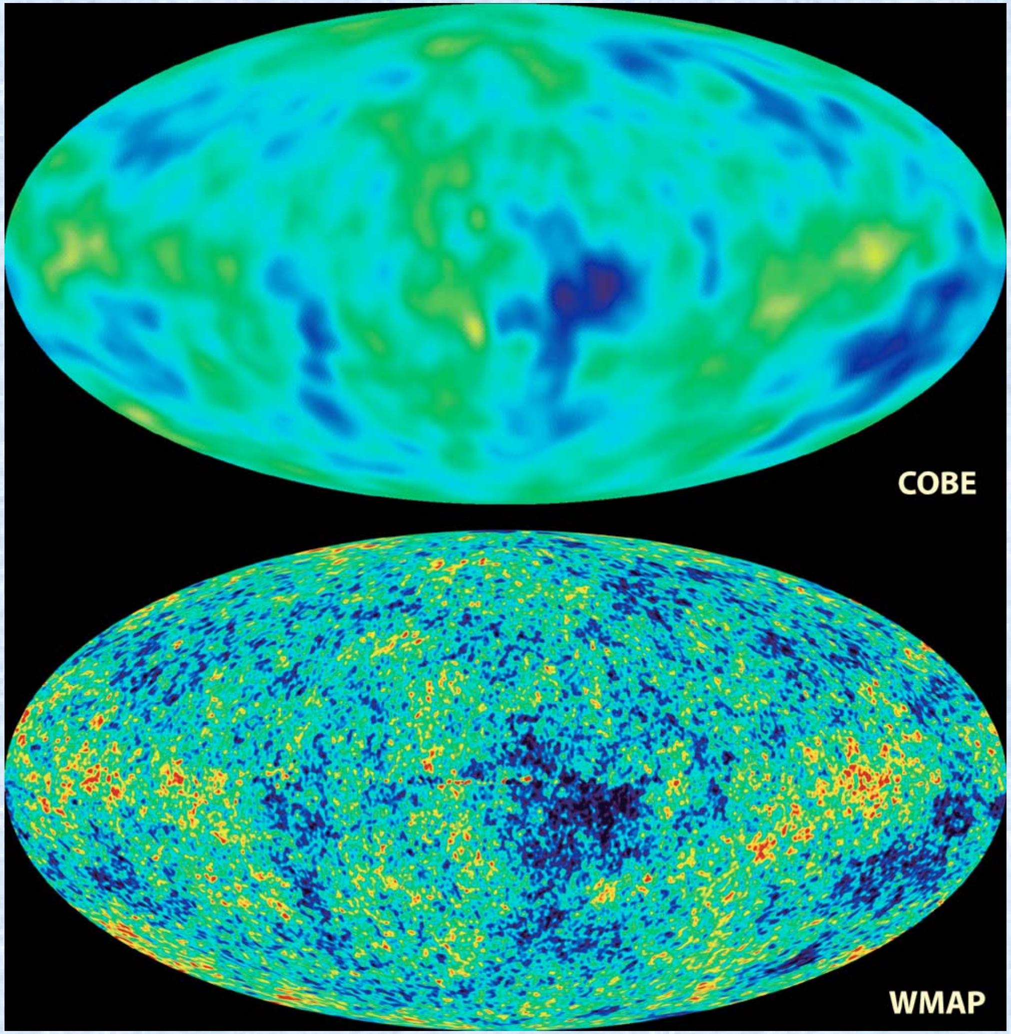
RCF

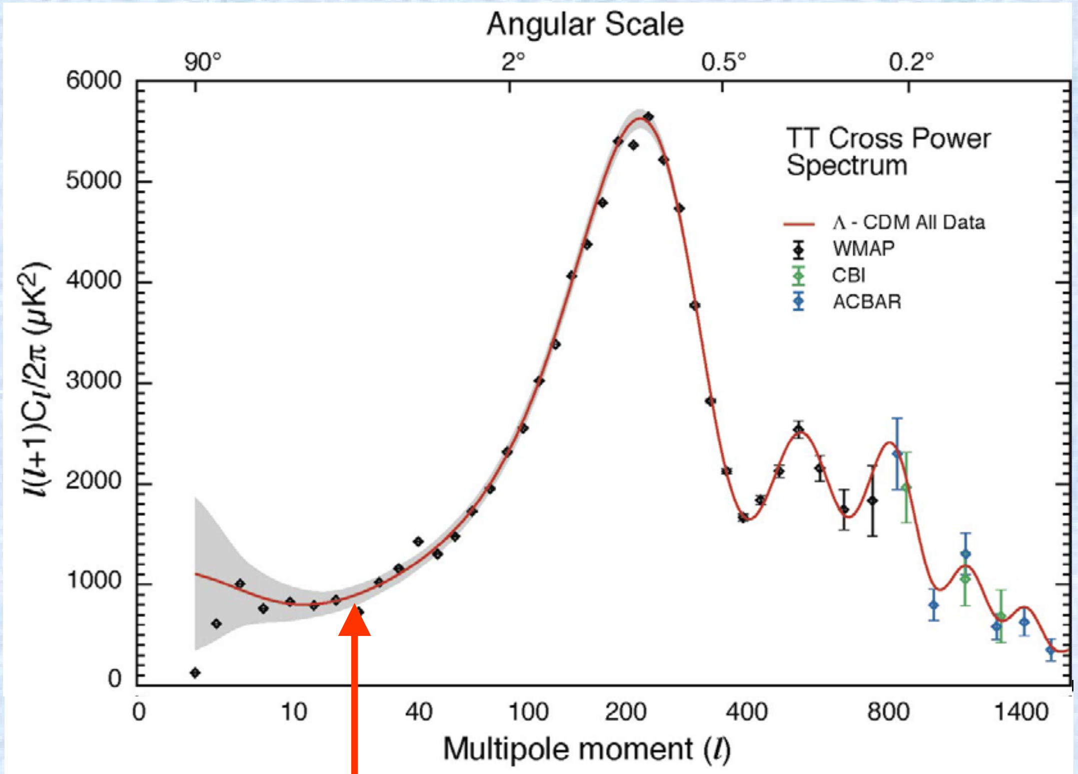
SEPARATION DES COMPOSANTES

- $y = A\,x + b$
  - y = vecteur des pixels des cartes en fréquence
  - b = vecteur du bruit détecteur dans les pixels observés vecteur des pixels du ciel
  - A matrice de mélange
  - x = vecteur des pixels des cartes des composantes astrophysiques
- NB:
  - Le modèle est peut être plus incertain que dans le cas de la fabrication des cartes
  - Il peut y avoir un problème mal contraint…diverse régularisations possibles…

Carte & Spectre du RCF par WMAP-1



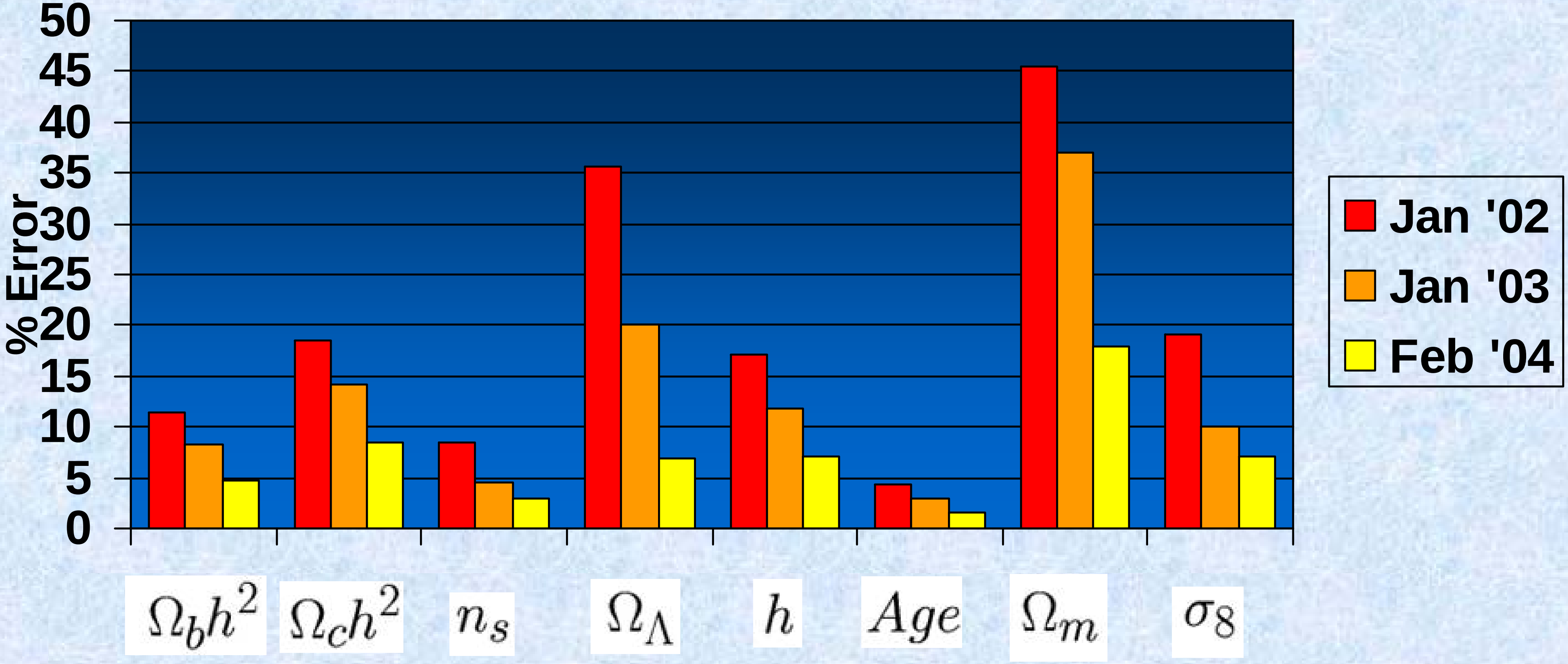




Courbe rouge =Théorie pour un univers avec 5% d'atomes, 25% de matière sombre, 70% d'énergie sombre

PRE-WMAP1 ⇔ POST-WMAP1

Parameters very similar. Precision +



[Bond, Contaldi & Pogosyan astro-ph/0310735]

ESTIMATION DU SPECTRE, CONTRAINTES

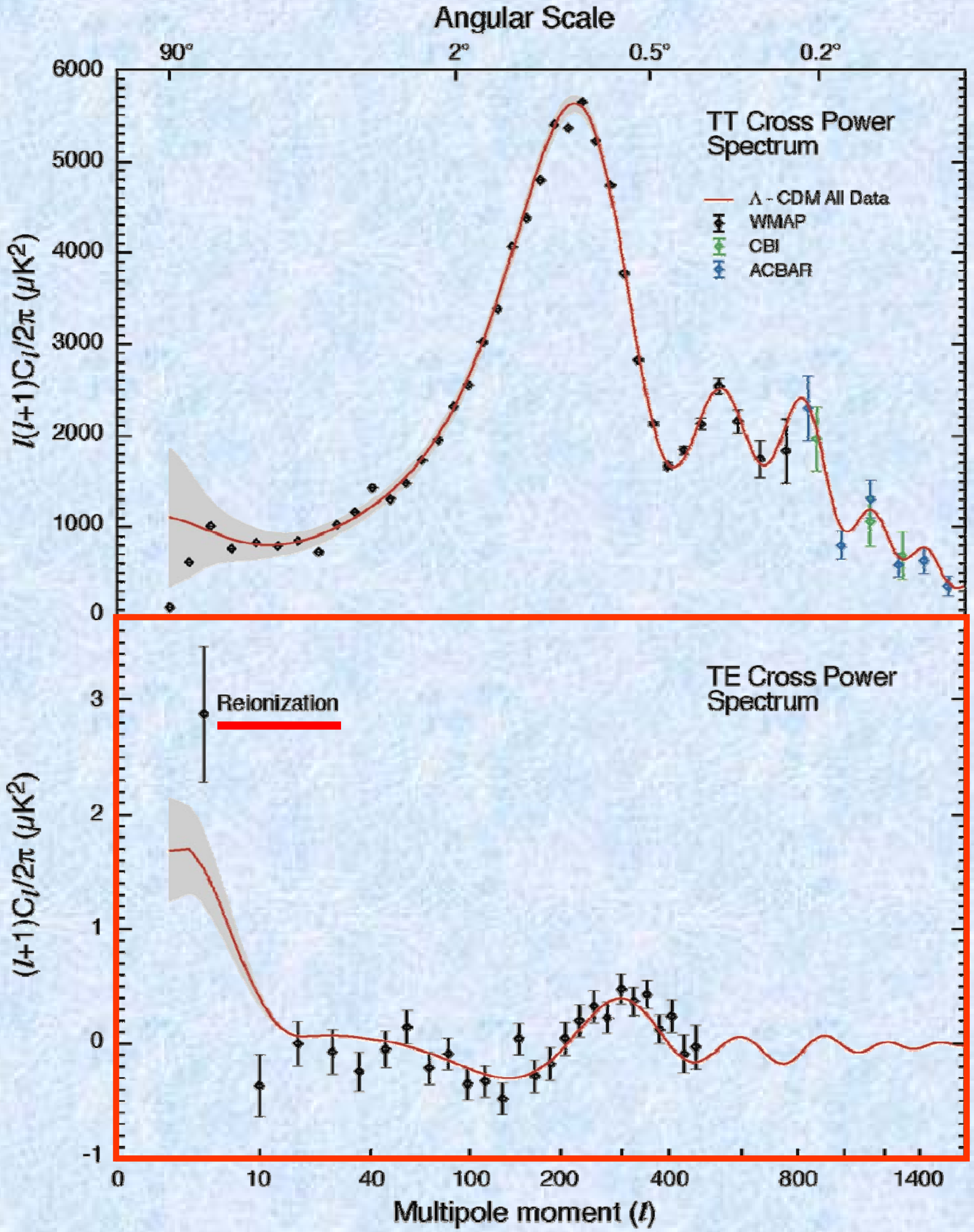
- $C(l) = \langle | a_{lm} |^2 \rangle$; \hat C et \hat Cov entre bins?

- L(d|p) \propto exp(-a^{lm} C^{-1}(l|p) a^{lm})
  - avec P(p |d) \propto L(d | p) P(p)
  - Problématique du choix de modèle (eg évidence bayesienne)

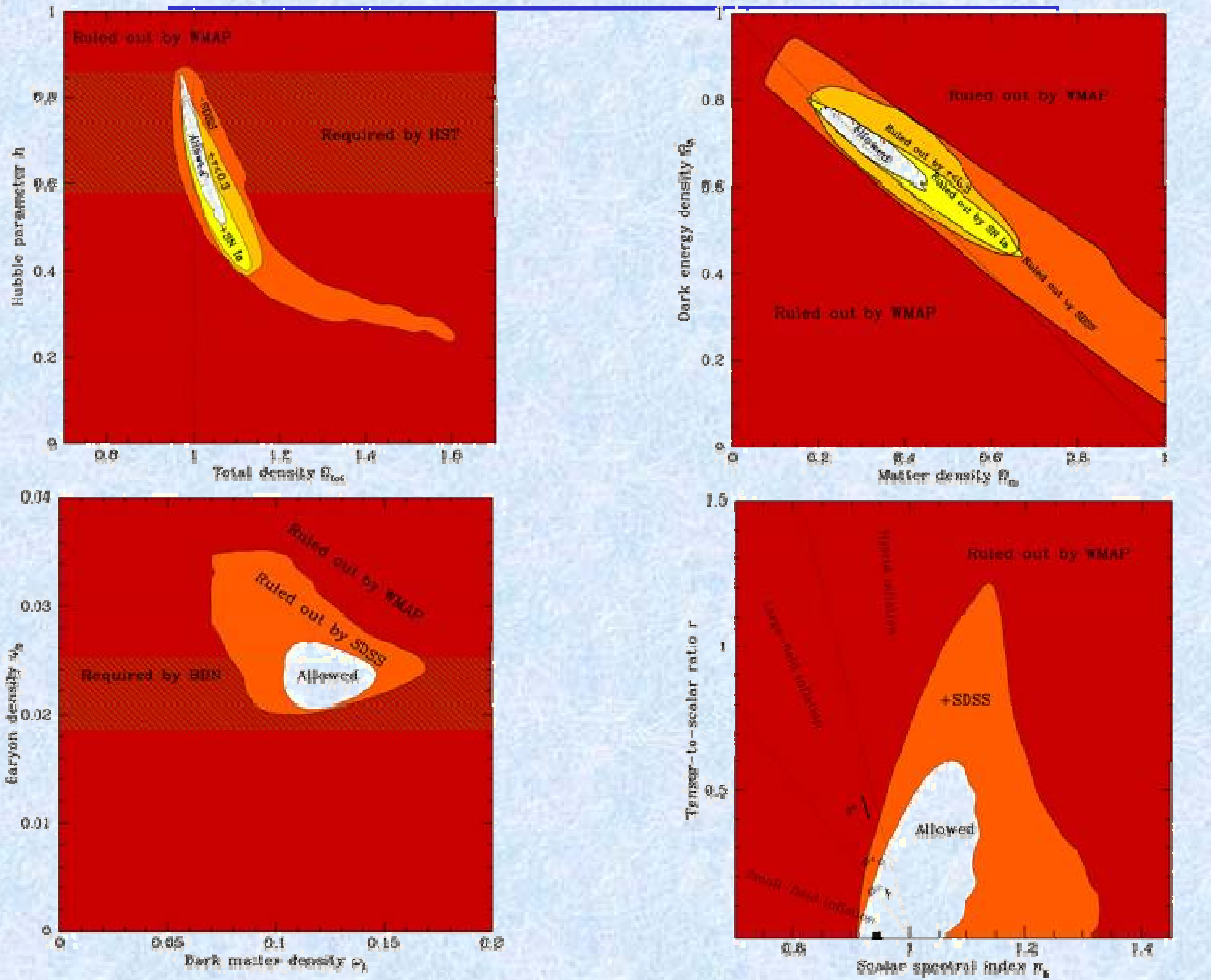
- NB: Pb du temps d'évaluation de la vraisemblance L, quand on veut échantillonner un modèle à Npar =O(10) (il y a quelque années, faire tourner un code de Boltzmann pour chaque vecteur p, puis CMBFAST, mais quand même…)

WMAP-1 & LA POLARISATION

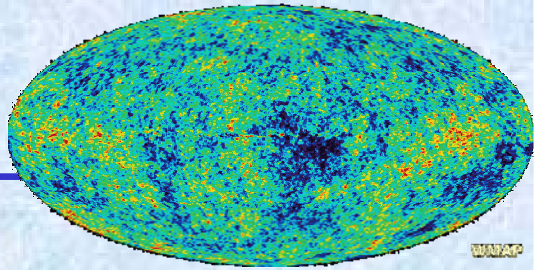
- 1ere mesure du spectre de la polarisation (partie corrélée avec la Température, dite TE)
- Oscillations / comparaison au même modèle théorique (courbe rouge): consolidation supplémentaire du paradigme
- Le pic à bas l (grandes échelles) est très haut : Réionisation de l'Univers plus tôt que prévu. Fortes contraintes sur la sortie de l'age sombre si confirmé
- Adiabaticité des fluctuations primordiales (phases TT/TE)

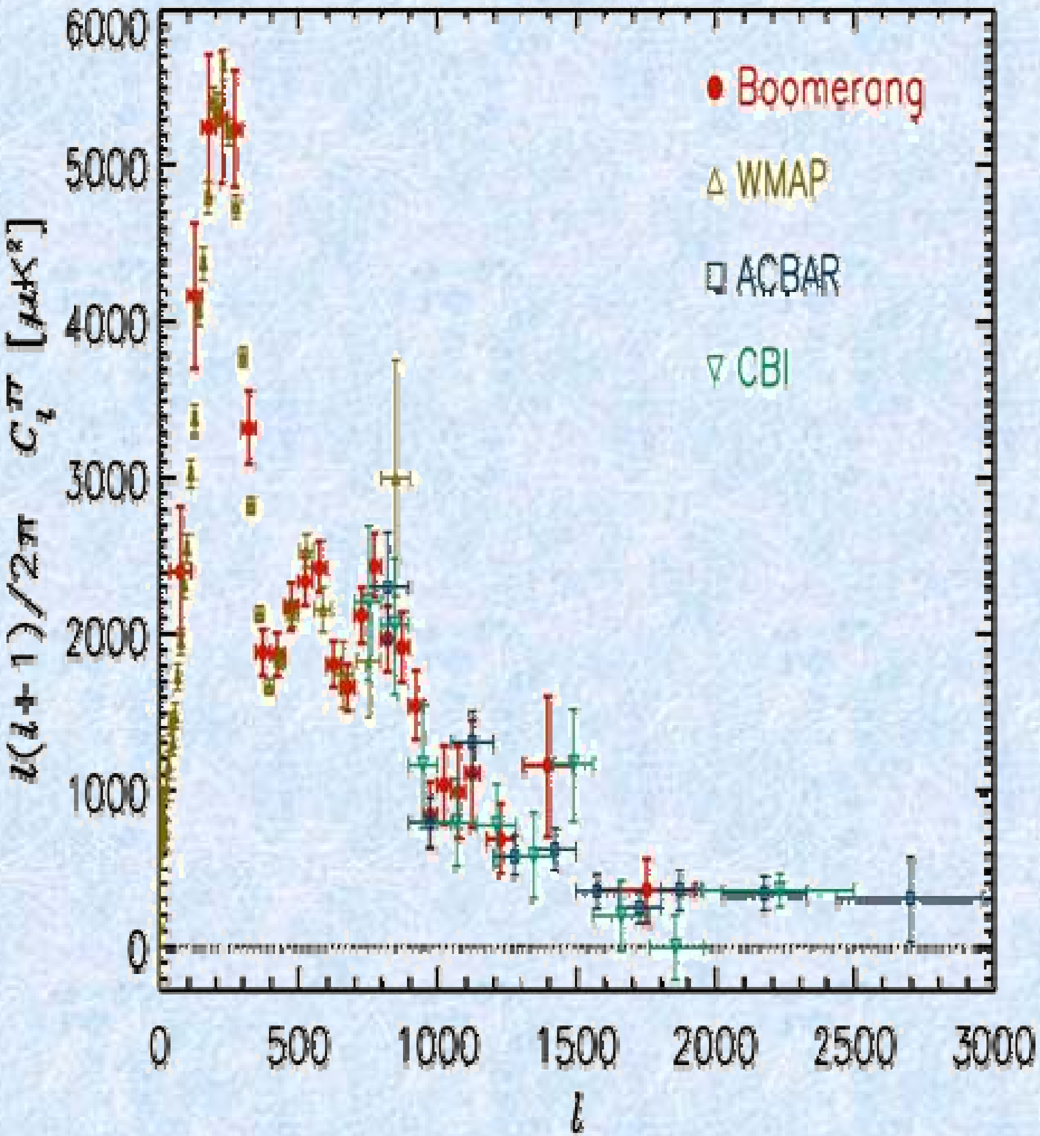


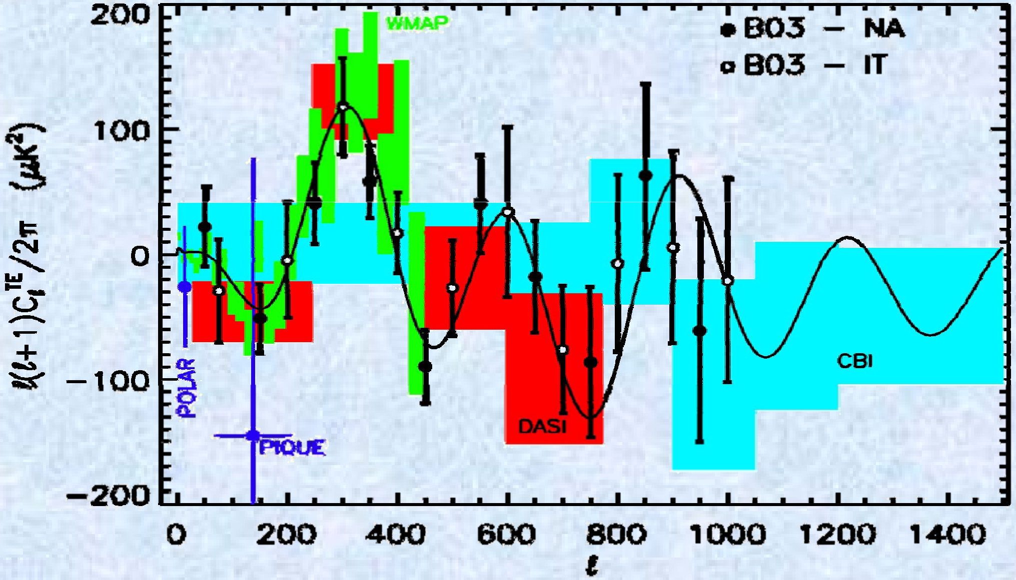
CONSISTENCY / COMPLEMENTARITY

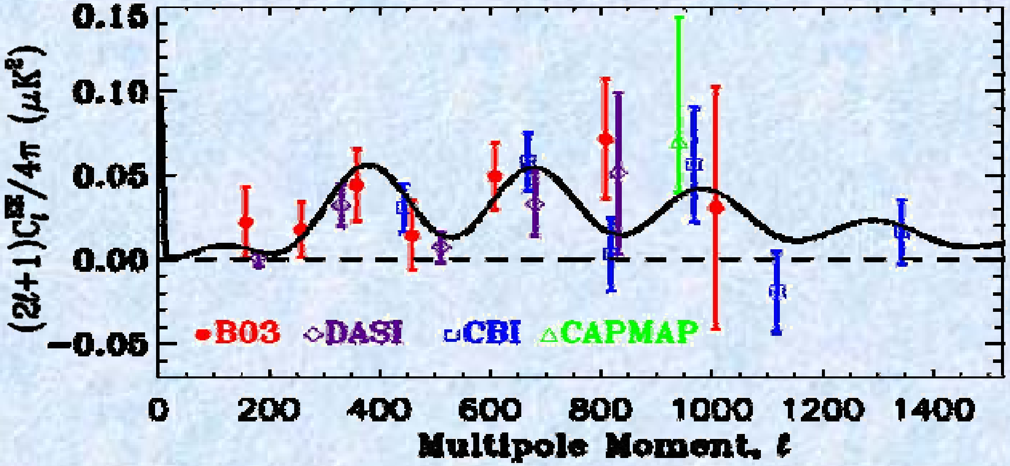


Pre-WMAP3 Status

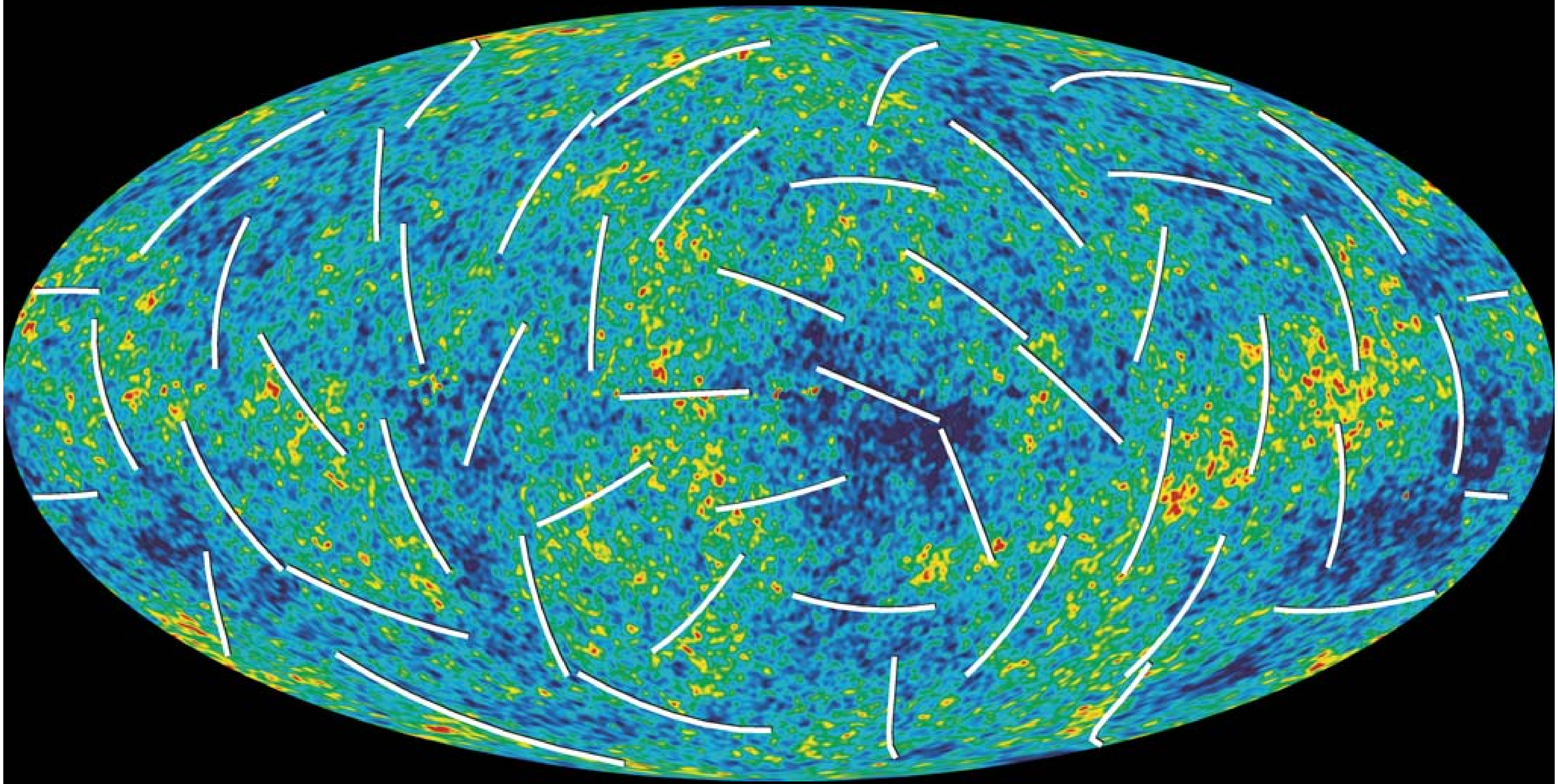








WMAP 3 YEARS



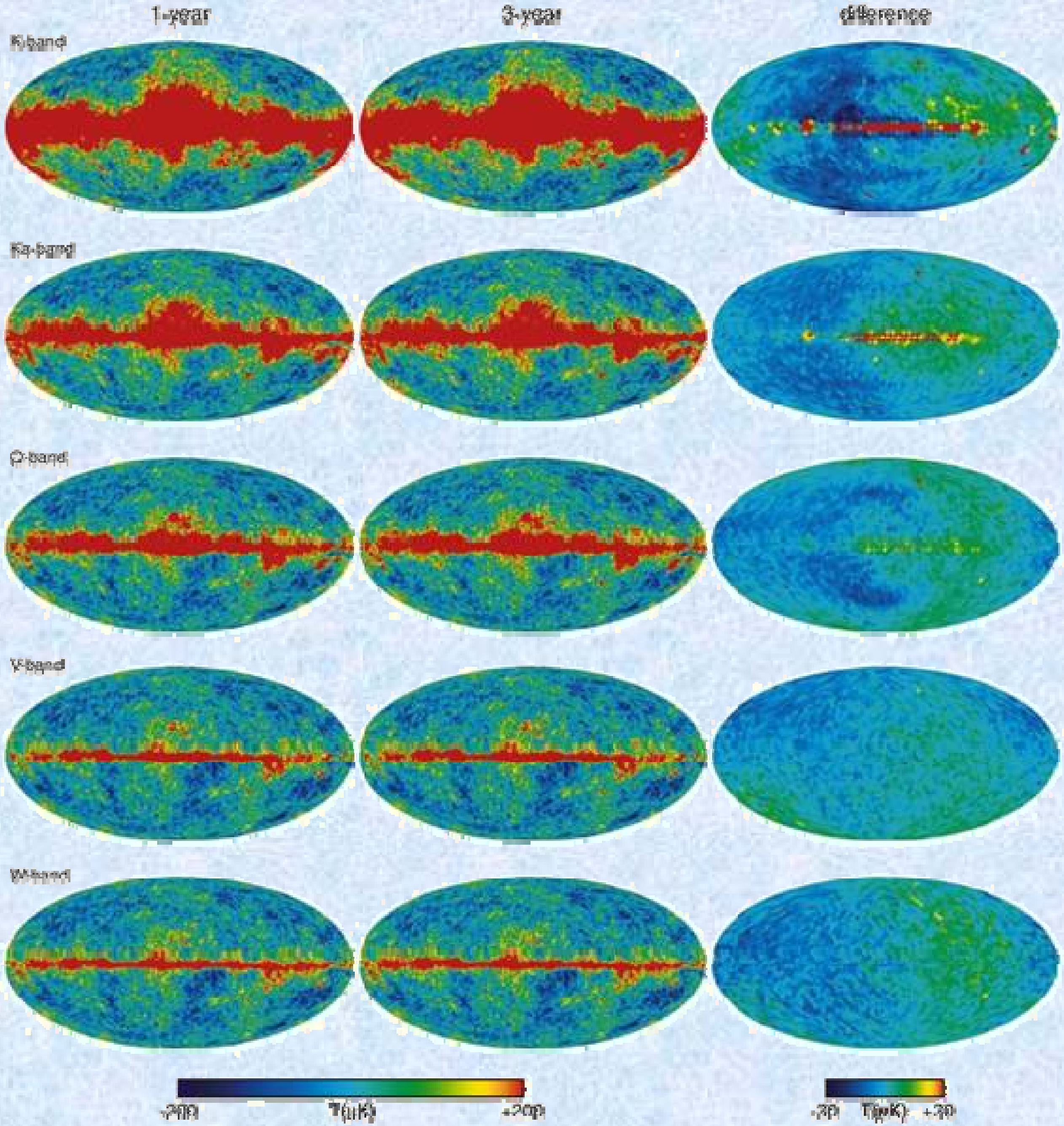
HIGHLIGHTS

- Full sky polarisation measurements
  - Galactic foregrounds knowledge
  - Simple synchrotron emission model works well
- Minimal model - power-law CDM – with 6 parameters still fits well.
- χ^2eff (TT)/dof = 1.068 (1.09 for yr 1) & χ^2eff (all)/dof = 1.04 (1.04 for yr 1)
- Improvements in the constraints on parameters $\{\Omega_b h2, \Omega_m h2, h, \tau, n_s, A_s\}$
  - lower σ_8 and Ω_m ($\Rightarrow$ tension with lensing & Ly_α),
  - lower n_s and τ ($\Rightarrow$ hint on inflation, removes tension with Galaxy formation)

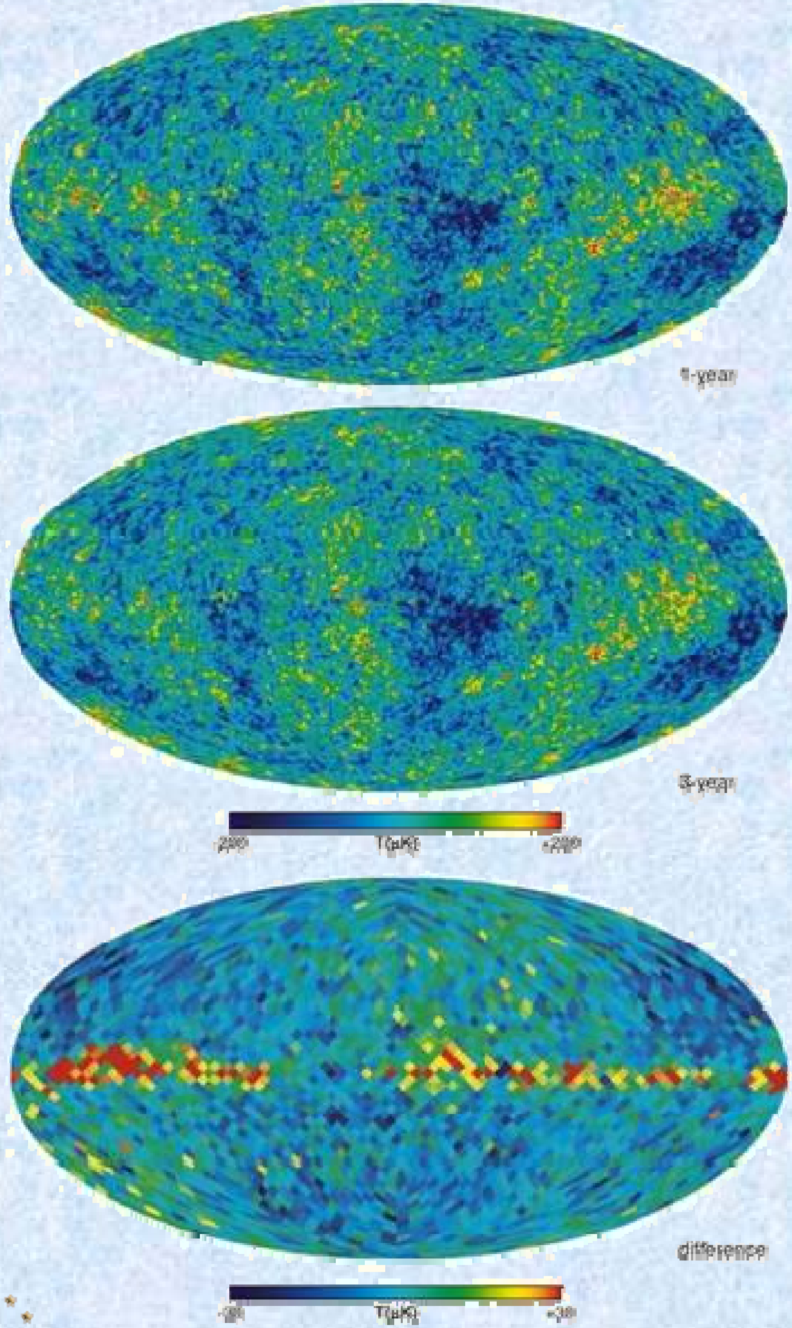
- Results from much more sophisticated data analysis

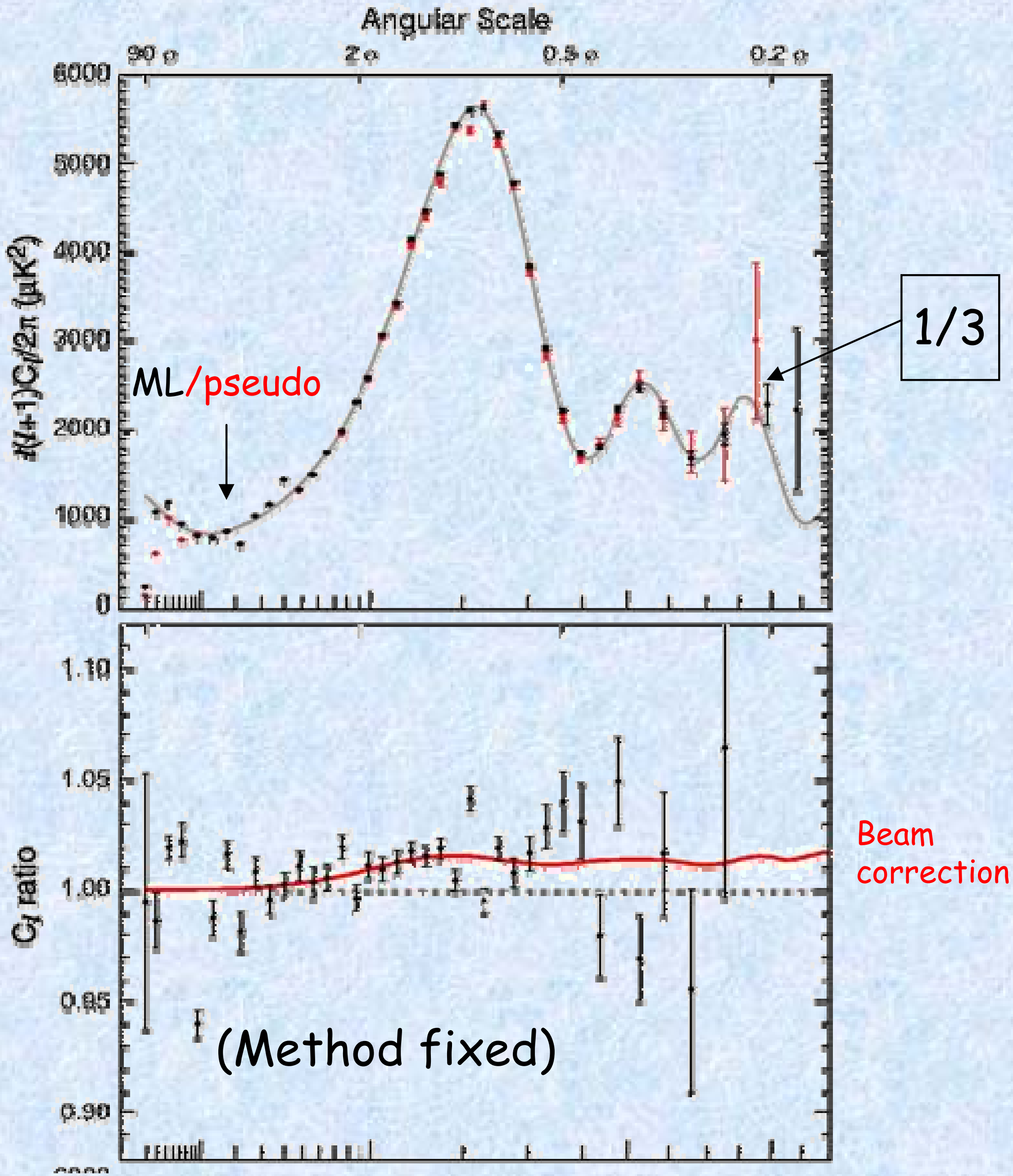
1 YEAR VERSUS 3 YEARS COMPARISON

- Data smoothed to 1° resolution, scaled to ±200 μK
- The difference maps (right) degraded to pixel resolution 4 (~3.7°) & scaled to ±20 μK.
- Small difference in low-l power, mostly due to improvements in the gain model vs. t



WMAP 1 > WMAP 3


1-year
3-year
T(μK)
difference
T(μK)


Angular Scale
90°
2°
0.5°
0.2°
l(l+1)C_l/2π (μK²)
C_l ratio
ML/pseudo
1/3
Beam correction
(Method fixed)

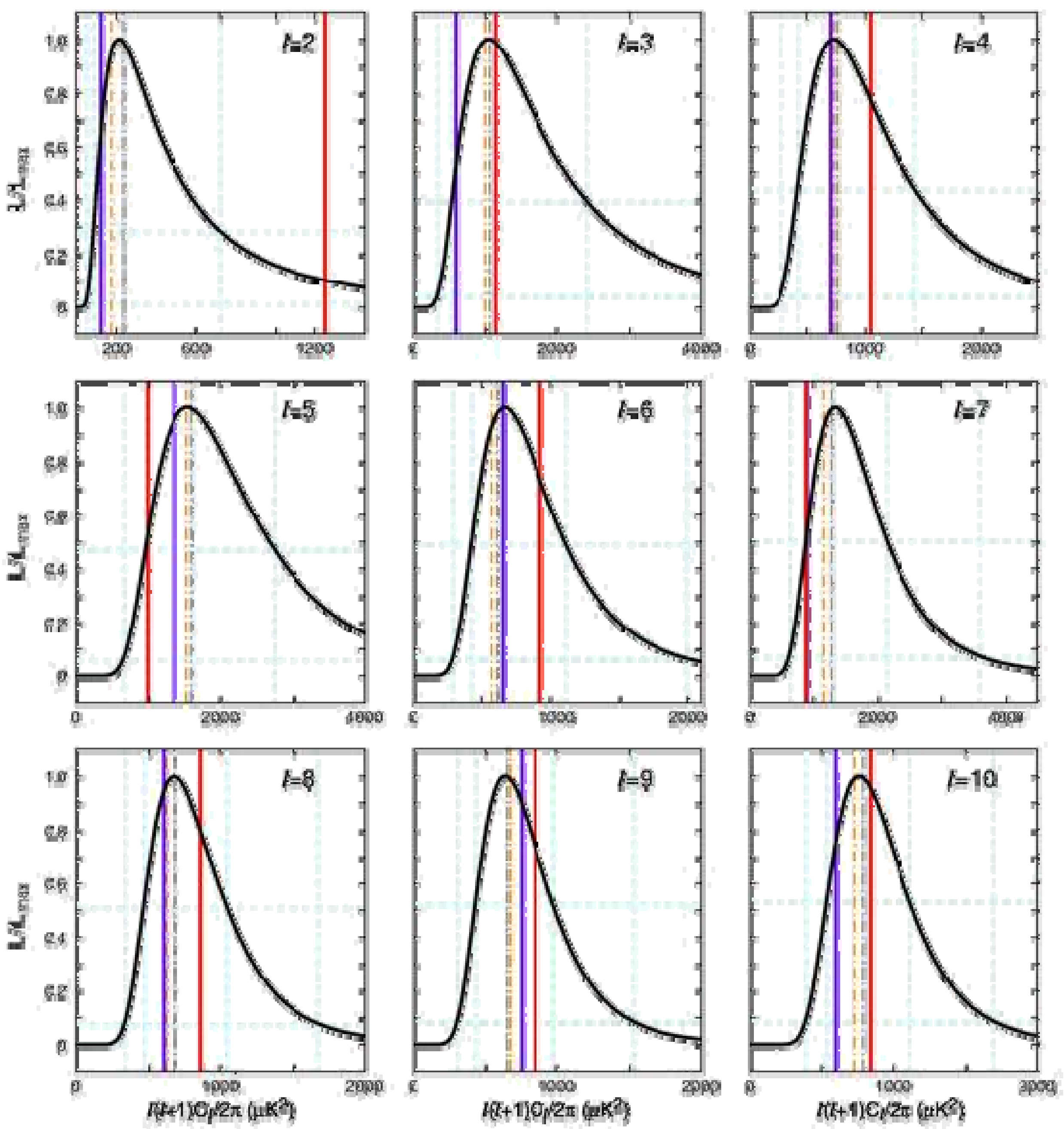
LOW QUADRUPOLE POWER

- Expected (mean) values for selected best-fit LCDM models -
  - Pure power-law, WMAP+CBI+ACBAR: 1221 mK^{2*}
  - Running index, WMAP+CBI+ACBAR: 870 mK^2
  - Power-law, CMB+2dF+Ly-a: 1107 mK^2
- Measured value(s) of quadrupole -
  - Quadratic estimator, V+W band, galaxy template & cut: 123 mK^2
    (Hinshaw, et al., ApJS, 148, 135, 2003)
  - Full-sky estimate, Galaxy-cleaned map: 184 mK^2
    (Tegmark et al, astro-ph/0302496)
  - Full-sky estimate, Linear Combination map: 154 ± 70 mK^2
    Error based on spread of values by galaxy cut and frequency
    (Bennett, et al., ApJS, 148, 1, 2003)
  - Max. likelihood estimate, Galaxy-cleaned map(s): 176-250 mK^2
    (Efstathiou, astro-ph/0310207)
  - Max. likelihood estimate, Galaxy template marginalization: < 300 mK^2
  - (Bielewicz, astro-ph/0405007; Slosar & Seljak, astro-ph/04??)
- Likelihood of low quadrupole given power-law LCDM model –
  ~2% - 10%
- Fine print: estimates of significance depend on
  1) quadrupole estimation method,
  2) handling of foreground errors,
  3) handling of cosmic variance errors,
  4) handling of cosmological parameter errors.

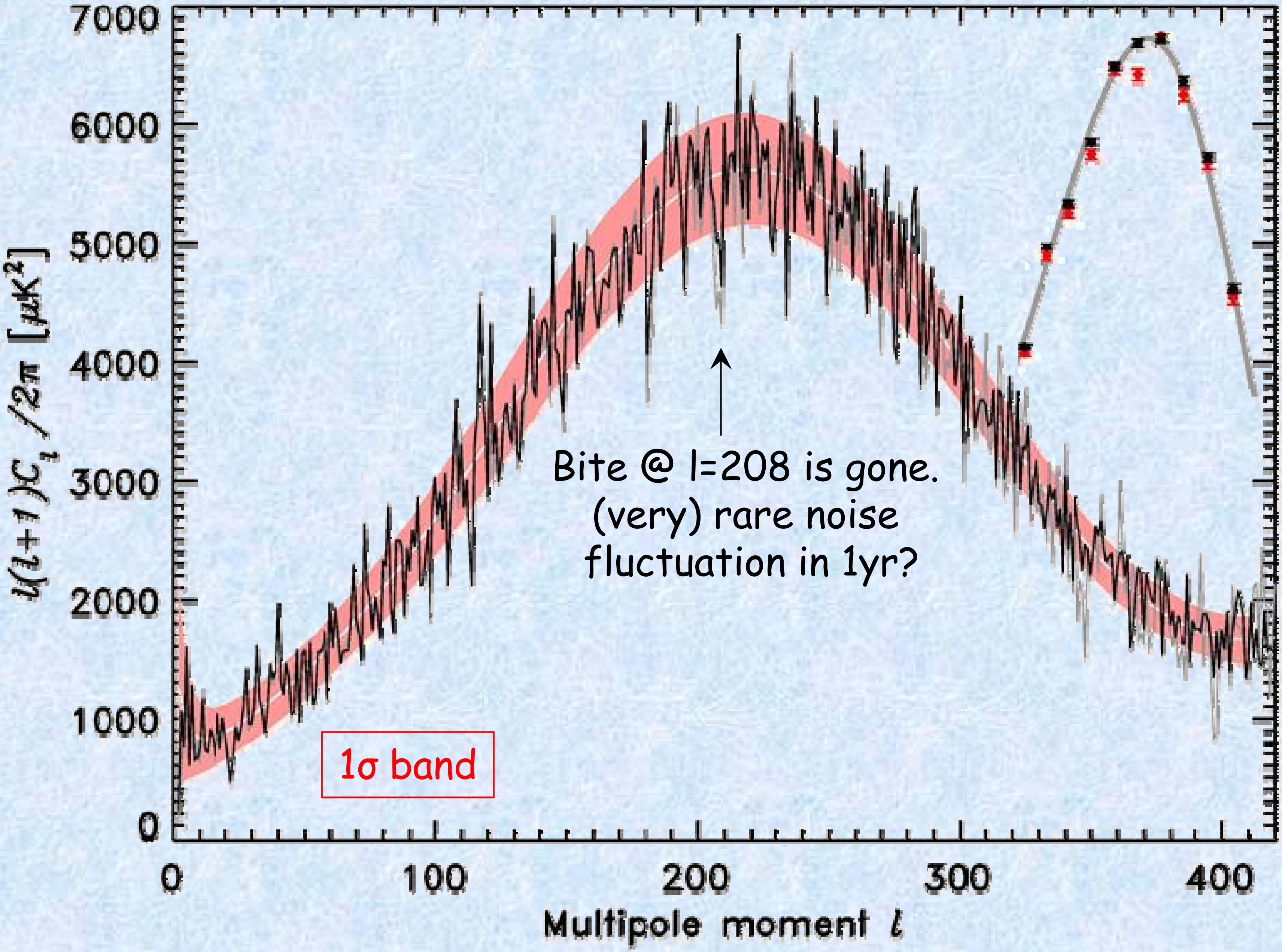
LOW-L (NEW, ML) ANALYSIS

- Black= posterior distribution of l(l + 1)Cl/2π from the ILC map outside the Kp2 sky cut
- Vertical red = Mean for best fit CDM to WMAP
- Purple=pseudo-C(l) estimate, tend to be lower than peak at l = 2, 3, 7
- *Quadrupole still rather low, but now the only one*

- NB: Vertical black dot-dash =maximum with no sky cut; orange – with Kp2 V-band only



"LOOKS" OK?



7000
6000
5000
4000
3000
2000
1000
0
0
100
200
300
400
$l(l+1)C_l\ /2\pi\ [\mu K^2]$
Multipole moment l
Bite @ l=208 is gone.
(very) rare noise
fluctuation in 1yr?
1σ band

Summary of Improvements in the Polarization Analysis

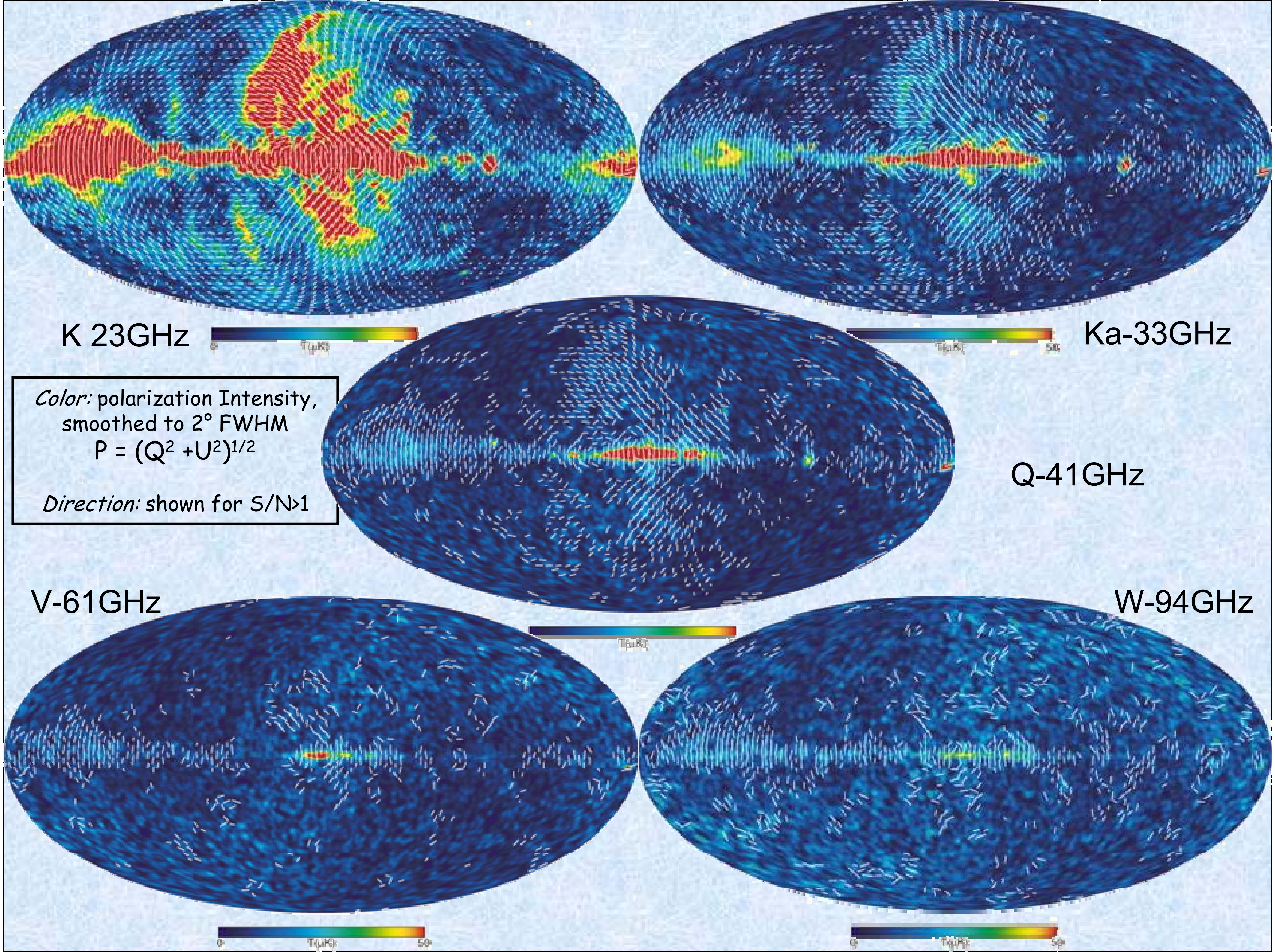
First Year (TE)

- Foreground Removal
  - Done in harmonic space
- Null Tests
  - Only TB
- Data Combination
  - Ka, Q, V, W are used
- Data Weighting
  - Diagonal weighting
- Likelihood Form
  - Gaussian for *Cl*
  - *Cl* estimated by MASTER

Three Years (TE,EE,BB)

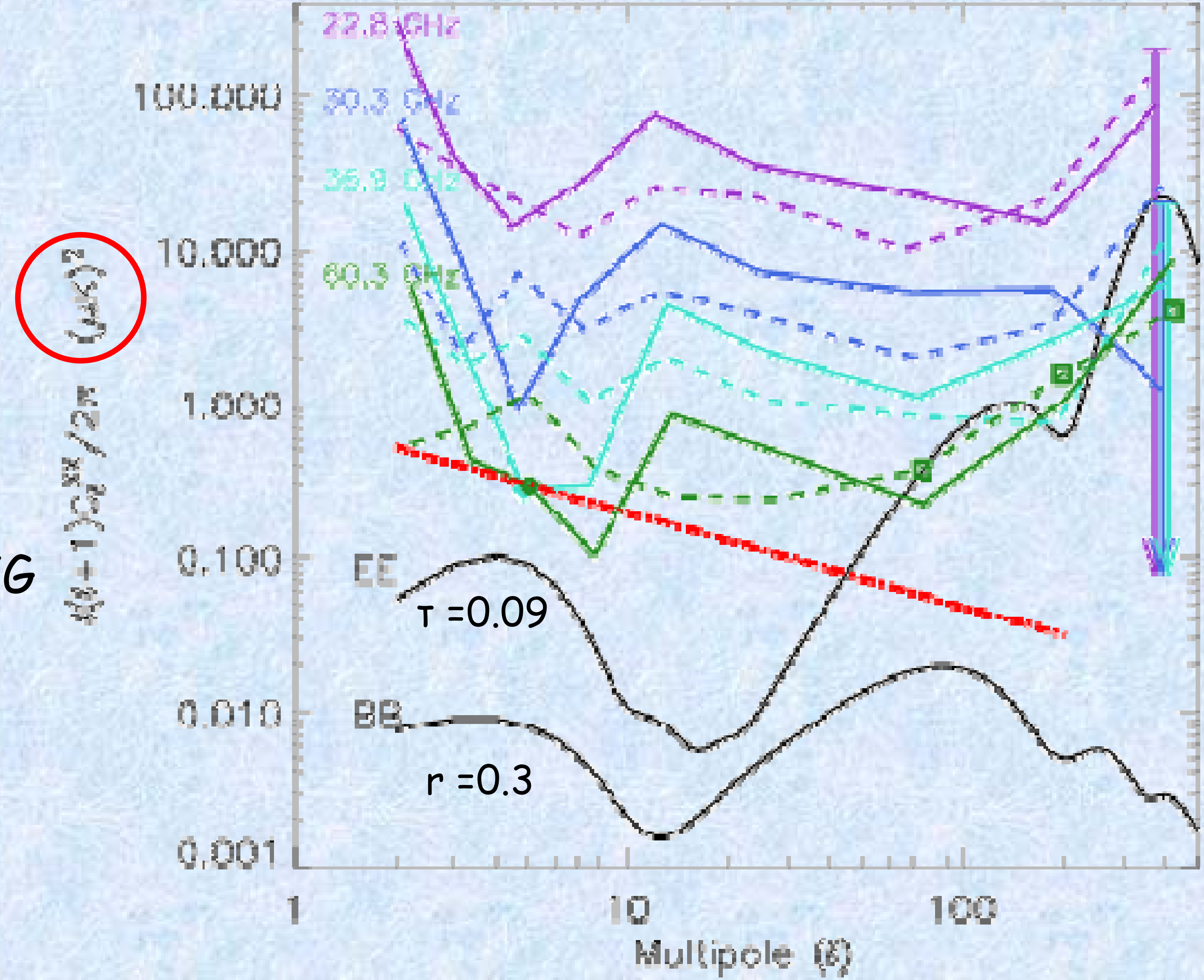
- Foreground Removal
  - Done in pixel space
- Null Tests
  - l Year Difference & TB, EB, BB
- Data Combination
  - Only Q and V are used
- Data Weighting
  - Optimal weighting (C^{-1})
- Likelihood Form
  - Gaussian for the pixel data
  - *Cl* not used at *l*<23

These are improvements only in the analysis techniques: there are also various improvements in the polarization map-making algorithm. See Jarosik et al. (2006)


K 23GHz
Ka-33GHz
Q-41GHz
V-61GHz
W-94GHz
Color: polarization Intensity, smoothed to 2° FWHM
P = (Q² +U²)^1/2
Direction: shown for S/N>1
T(μK)
0
50

POLARISED FOREGROUNDS (OUTSIDE P06)

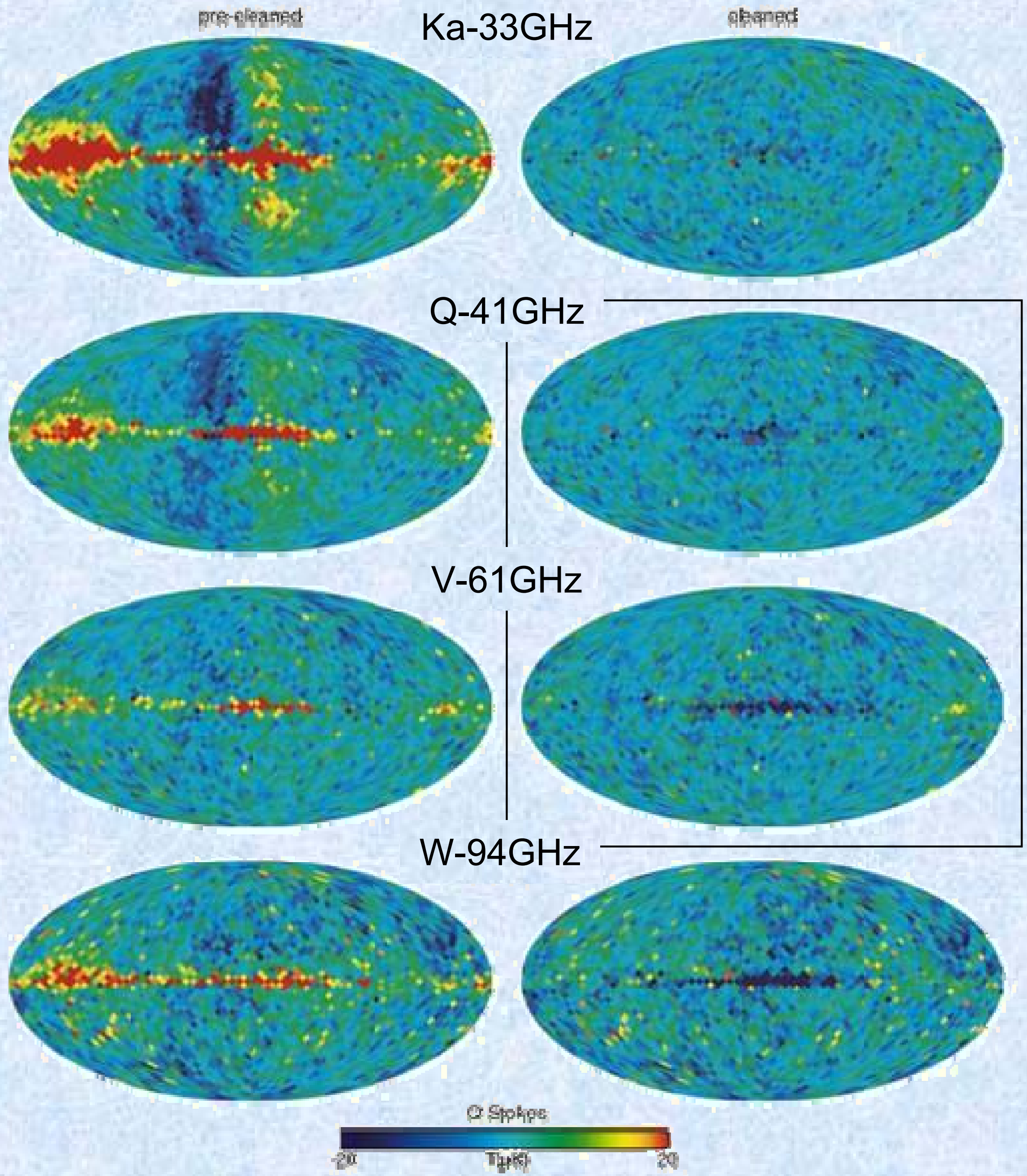
- EE Solid
- BB Dashed
- Frequency = geometric mean of data used for the spectra
- Red = estimate of FG level for BB at 60 GHz
- High-l rise <> noise



MUST BE CLEANED...

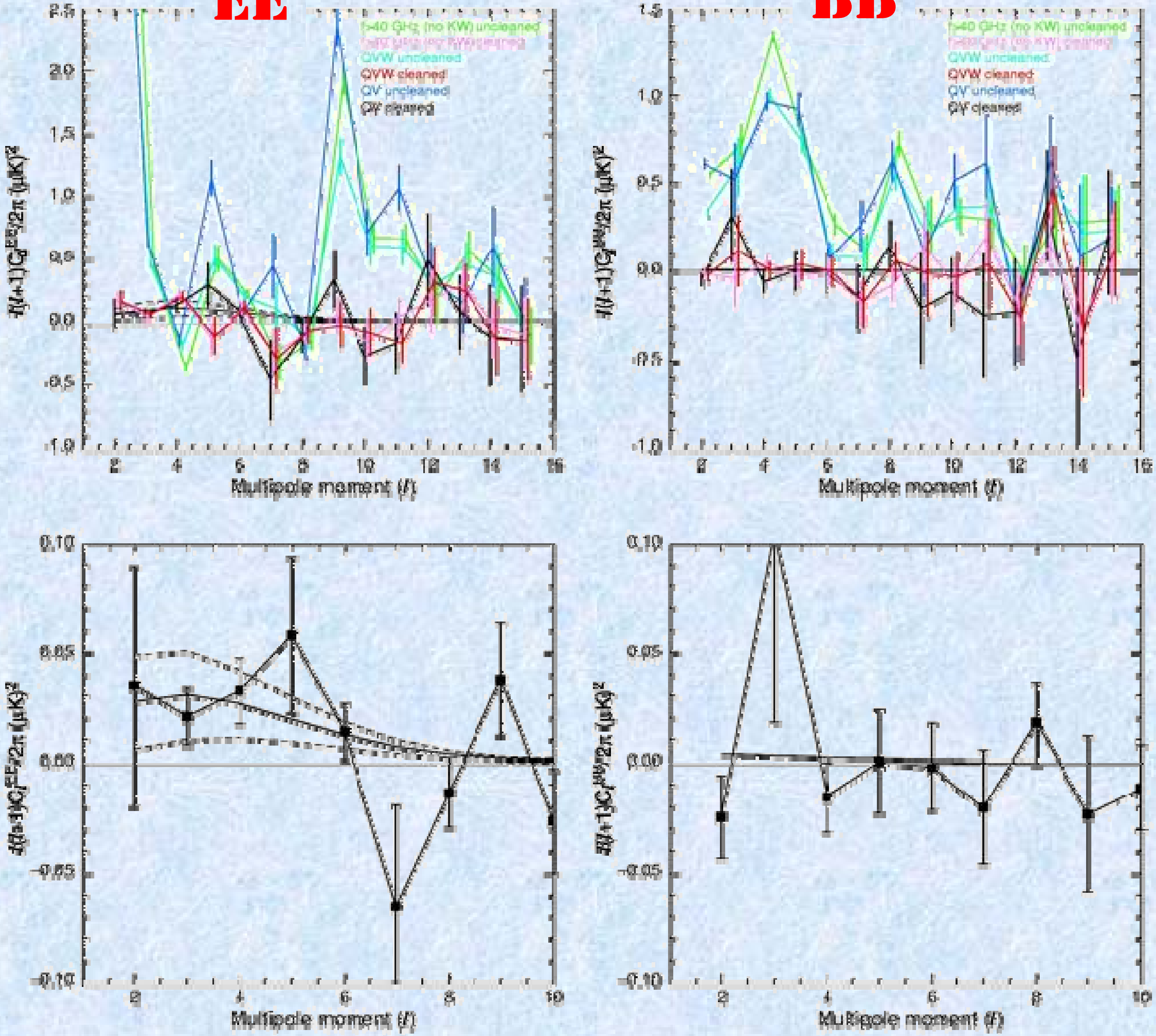
POLARISED FOREGROUNDS SUBTRACTION

- Fit & subtract 2 spatial templates of Galactic emission (Q is shown)
- Synchotron: 23 GHz Q & U
- Dust: Intensity COBE/IRAS-FDS plus Sparse polarisation angle data from starlight absorption



LOW-L POLARISATION SPECTRA

EE BB



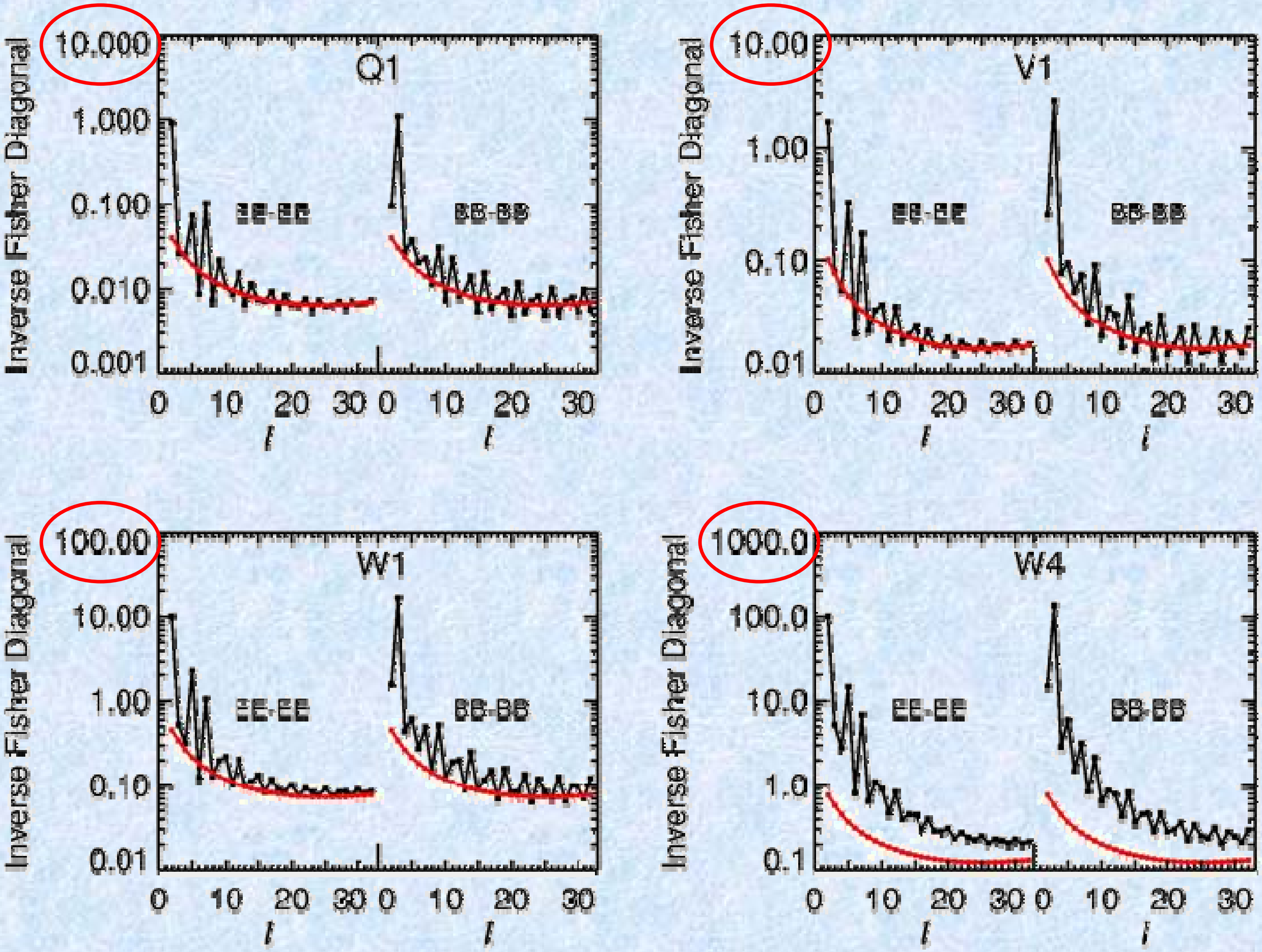
What the cleaning does…

About all reionisation information comes from that bump…

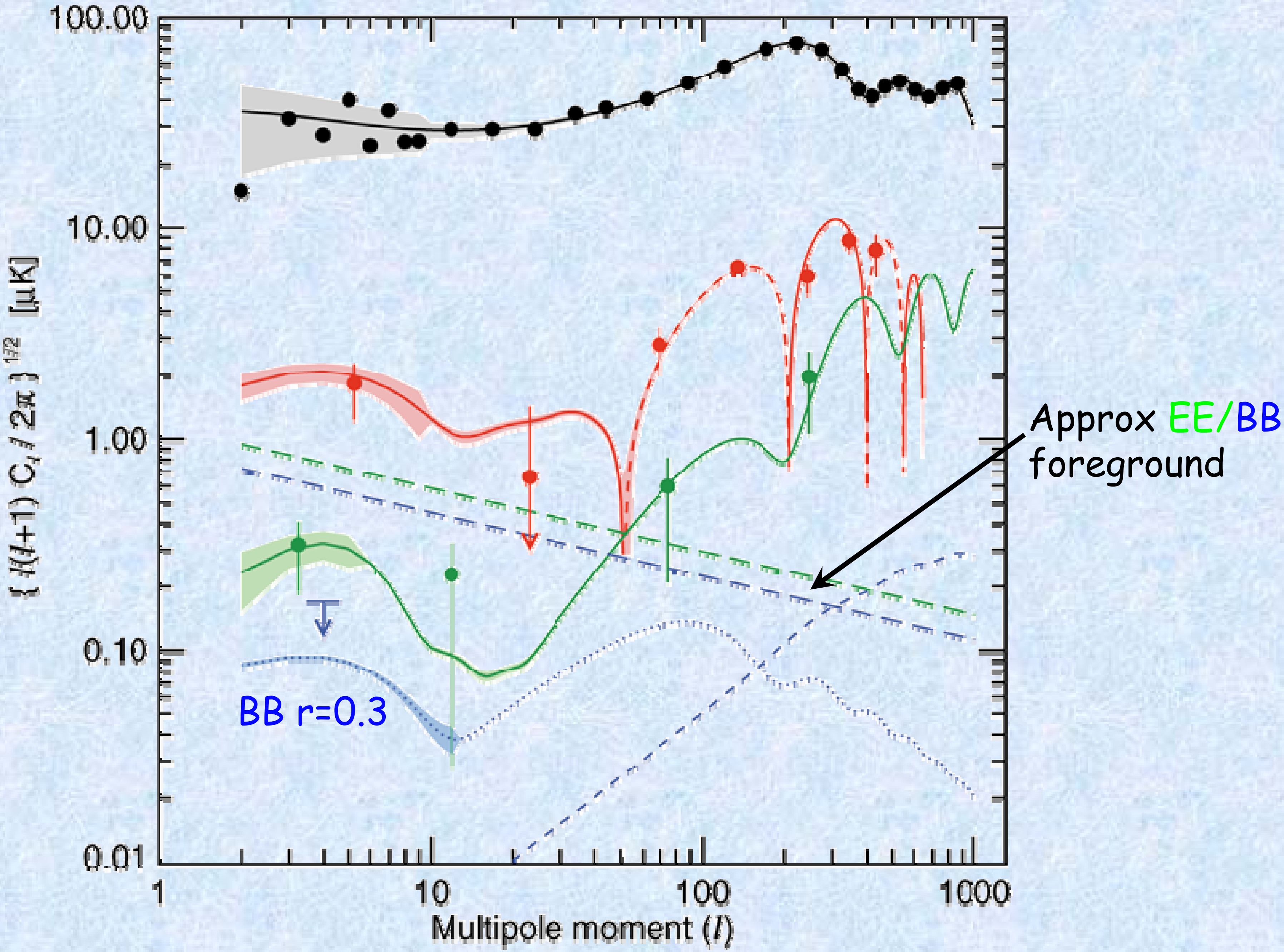
l^2C^E<2-6>/2pi =
0.09+-0.03μK^2

PREDICTED C(L) ERRORS (IN μK^4)

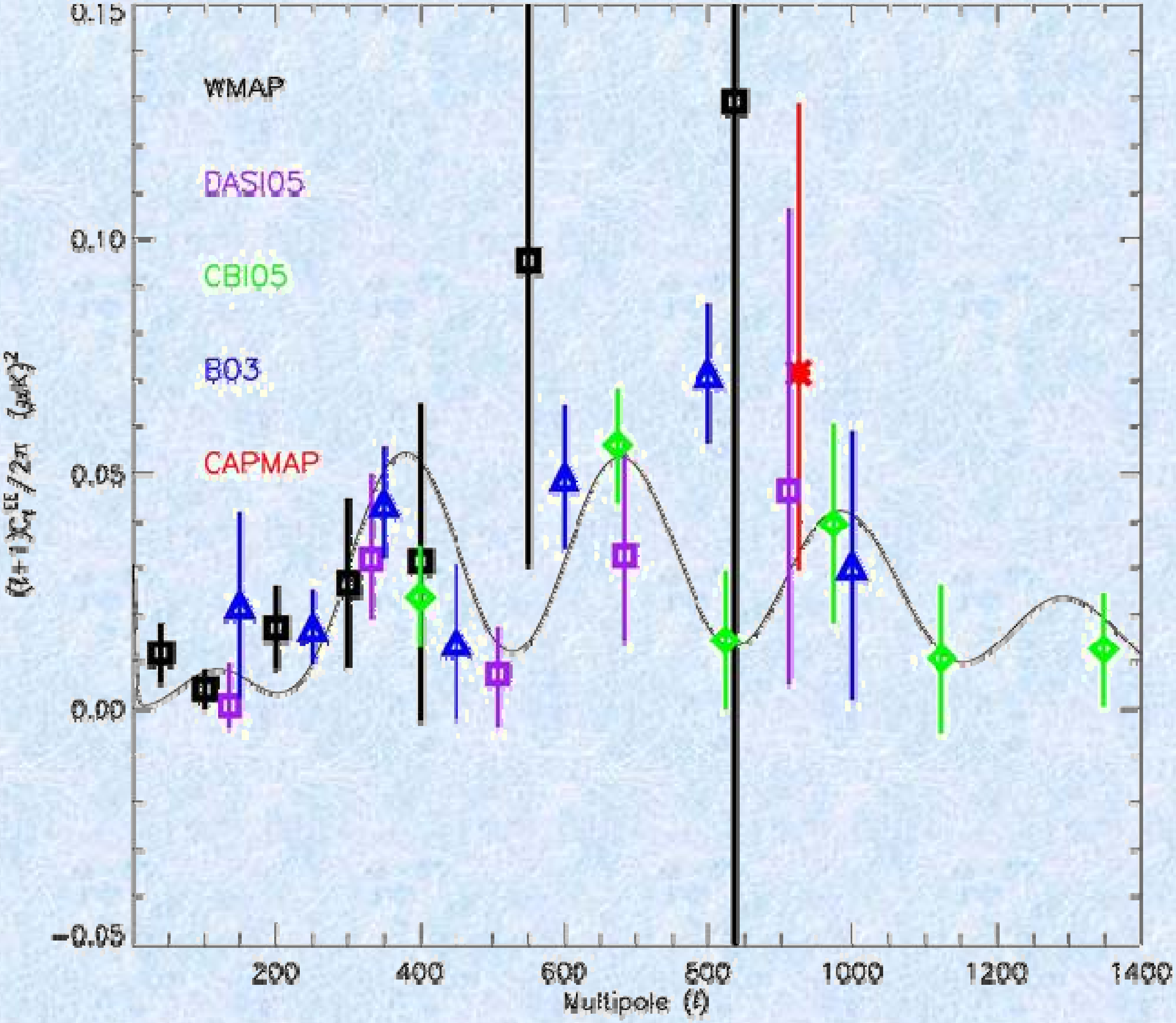
- variations in the N^{-1} weighting are due to the scan pattern combined with the sky cut.
- W data 3 years still not good enough at l=5,7!



WMAP3 SPECTRA



EE spectrum at $\ell > 40$ (all today)

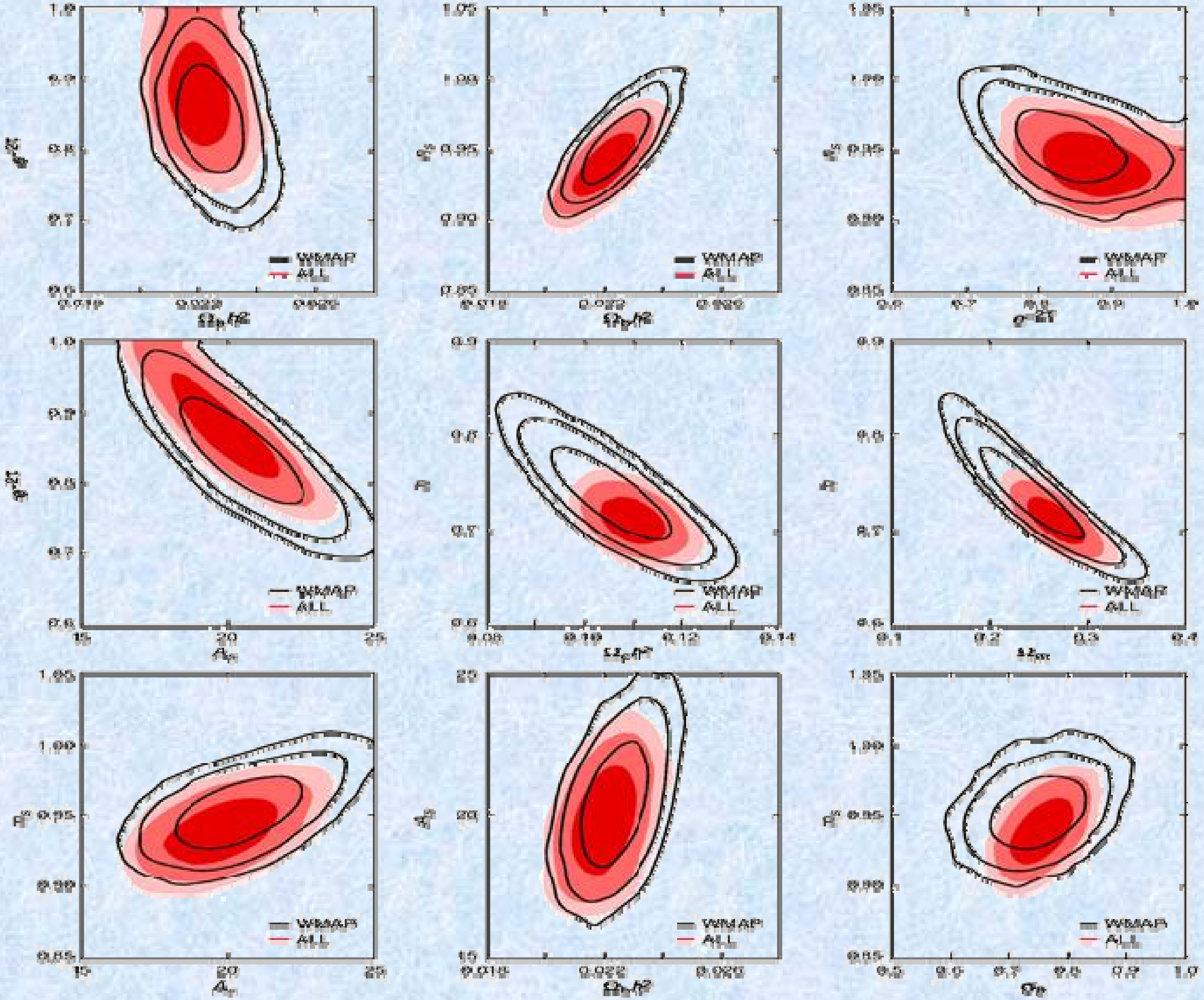


3 YEARS RESULTS

WMAP3 ONLY/ALL

ALL=WMAP+2dFGRS+SDSS+ACBAR+BOOMERanG+CBI+VSA+SN(HST/GOODS)+SN(SNLS)

Joint two-dimensional marginalized contours (68%, and 95% confidence levels)



Consistency with LSS

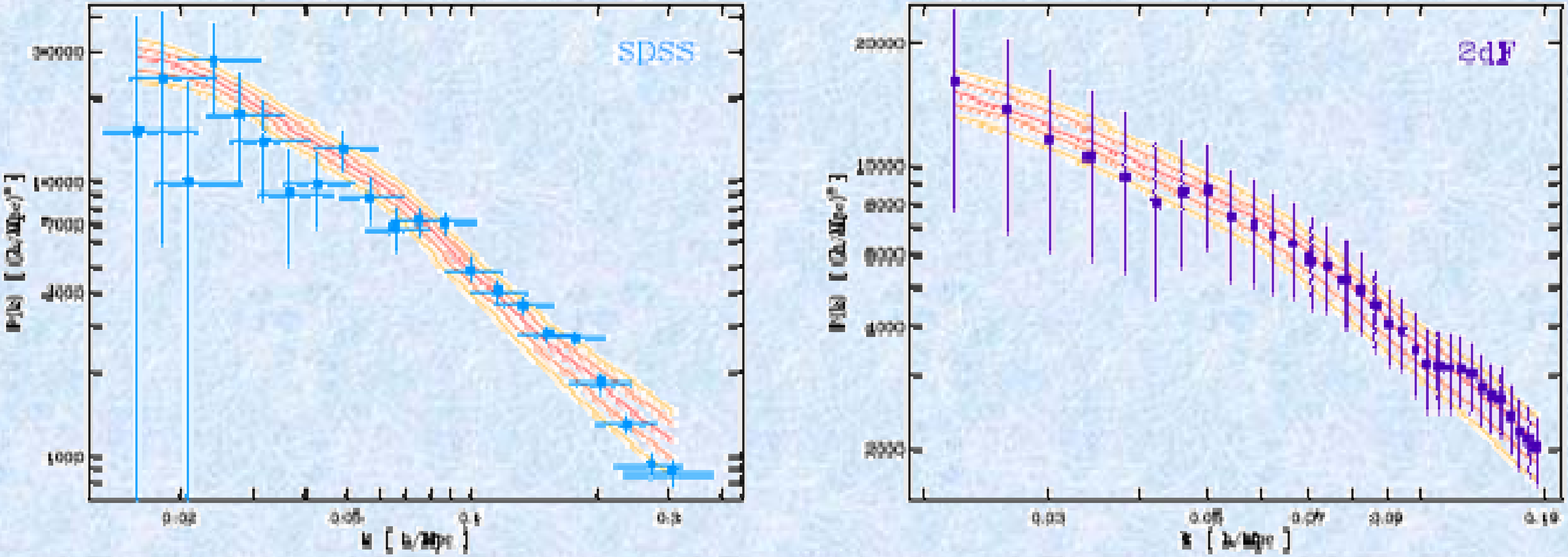
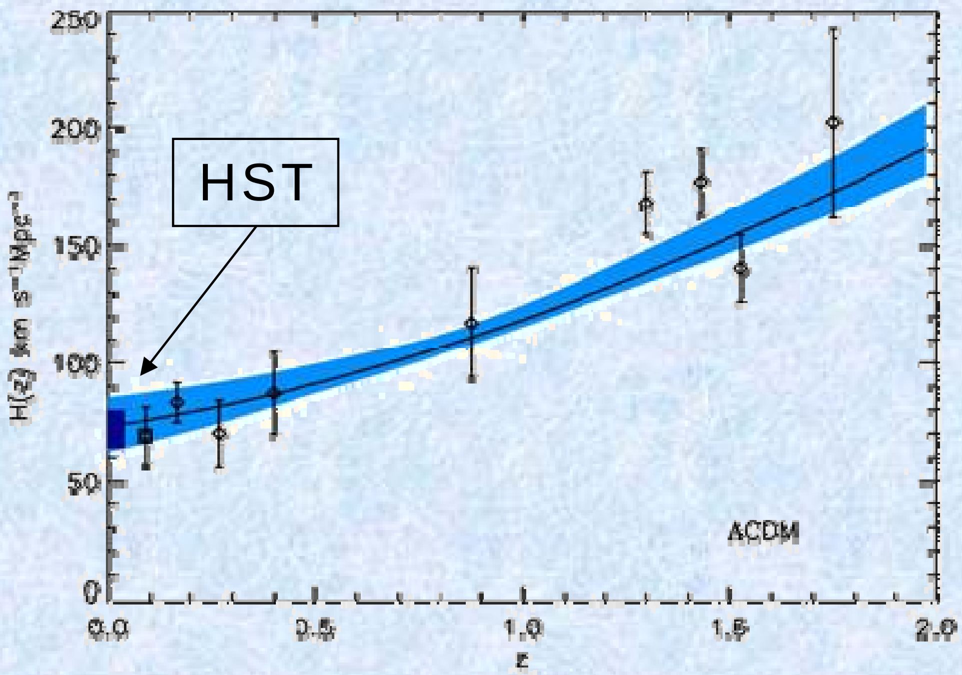
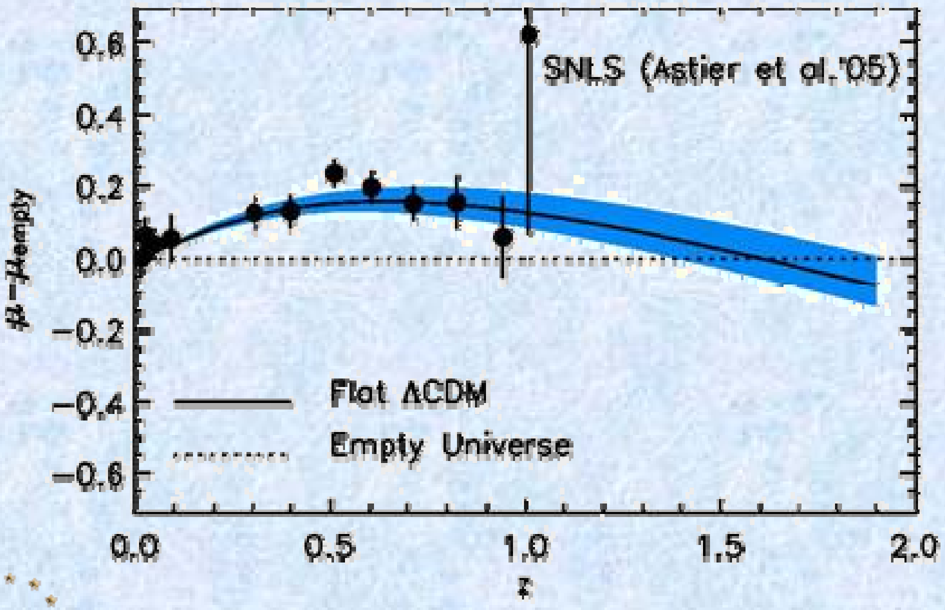
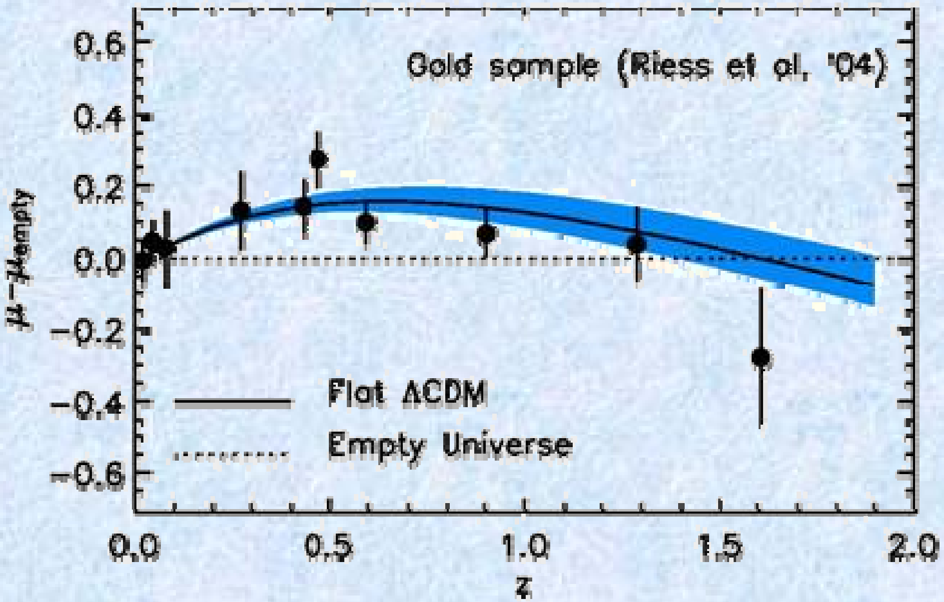


Fig. 6.— The prediction for the mass fluctuations measured by galaxy surveys from the ΛCDM model fit to the WMAP data only. (*Left*) The predicted power spectrum (based on the range of parameters consistent with the WMAP-only parameters) is compared to the mass power spectrum inferred from the SDSS galaxy power spectrum (Tegmark et al. 2004b) and normalized by weak lensing measurements (Seljak et al. 2005b). (*Right*) The predicted power spectrum is compared to the mass power spectrum inferred from the 2dFGRS galaxy power spectrum(Cole et al. 2005) with the best fit value for b_{2dFGRS} based on the fit to the WMAP model. Note that the data points shown are correlated.

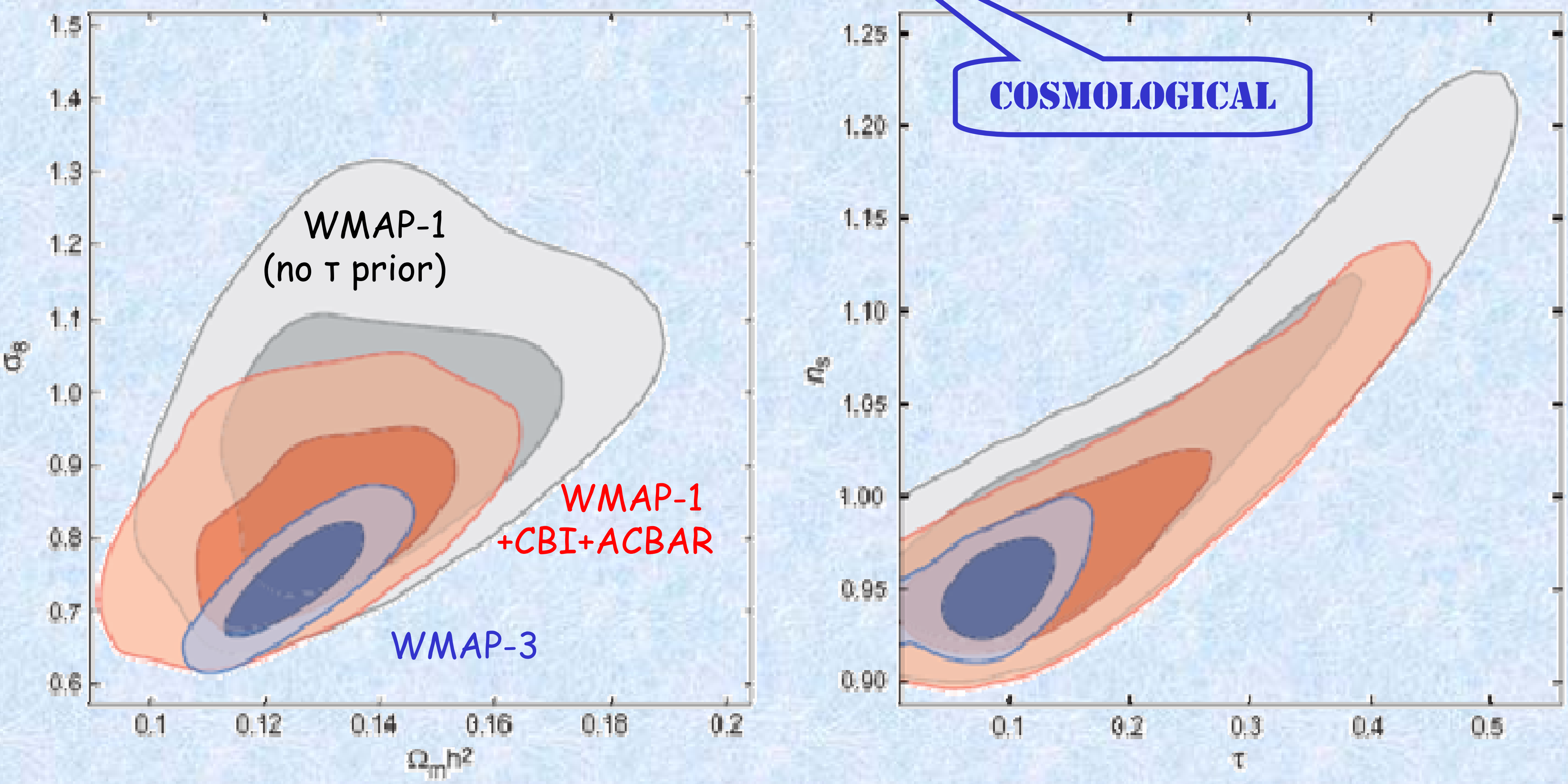
Further predictions







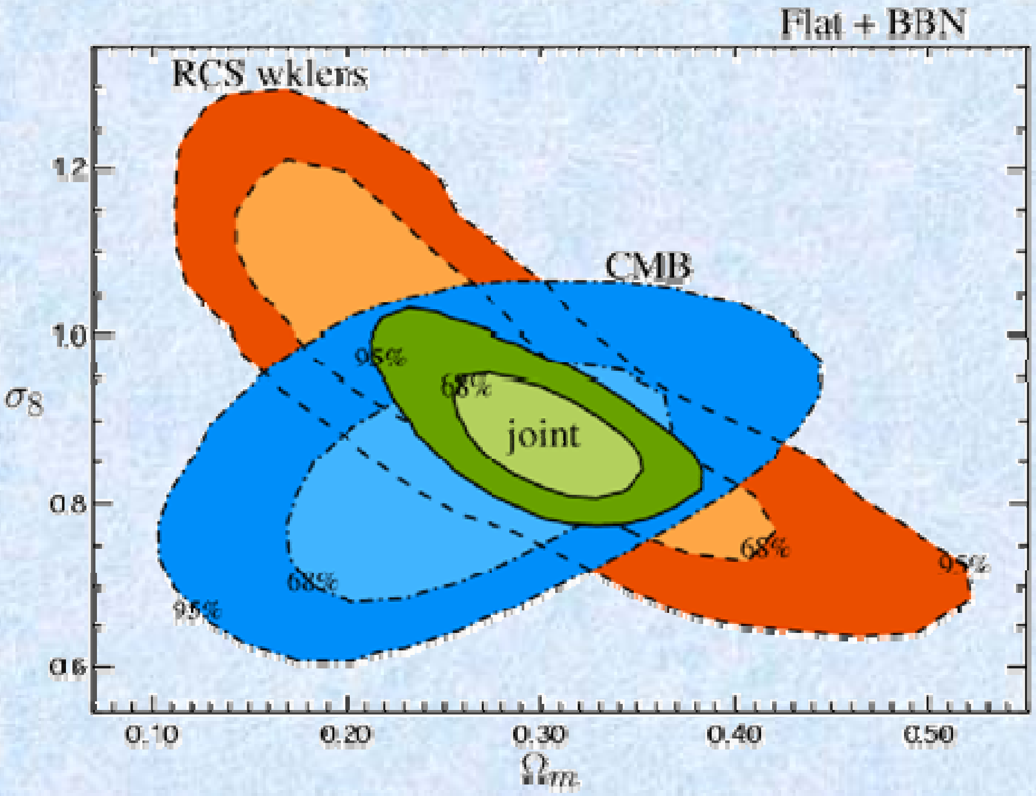
WMAP MAIN RESULTS



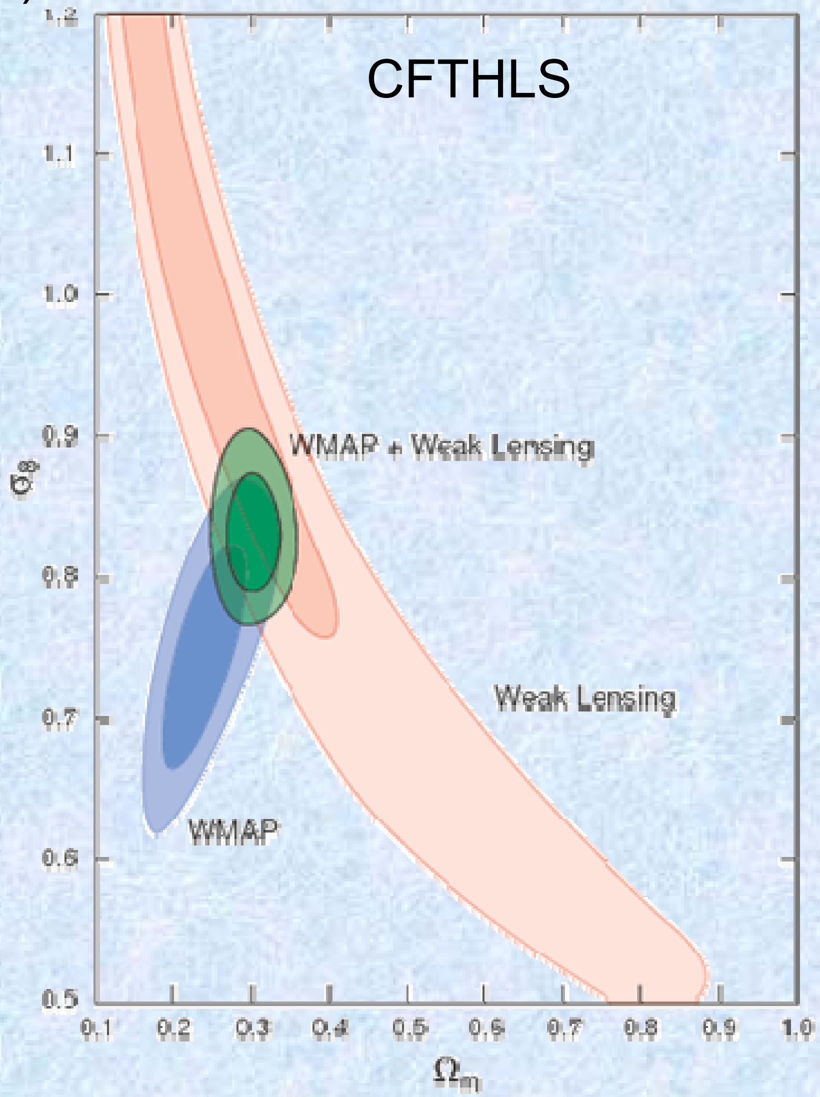
Improvement in parameter constraints for the power-law CDM model (6 pars).
$\{\Omega_b h^2, \Omega_m h^2, h, \tau, n_s, A_s\}$
χ2eff (TT)/dof = 1.068 (1.09 yr 1) & χ2eff (all)/dof = 1.04 (1.04 yr 1)

A_S-Ω_M

CMB (WMAP1ext) with galaxy lensing (+BBN prior)



Contaldi, Hoekstra, Lewis: astro-ph/0302435

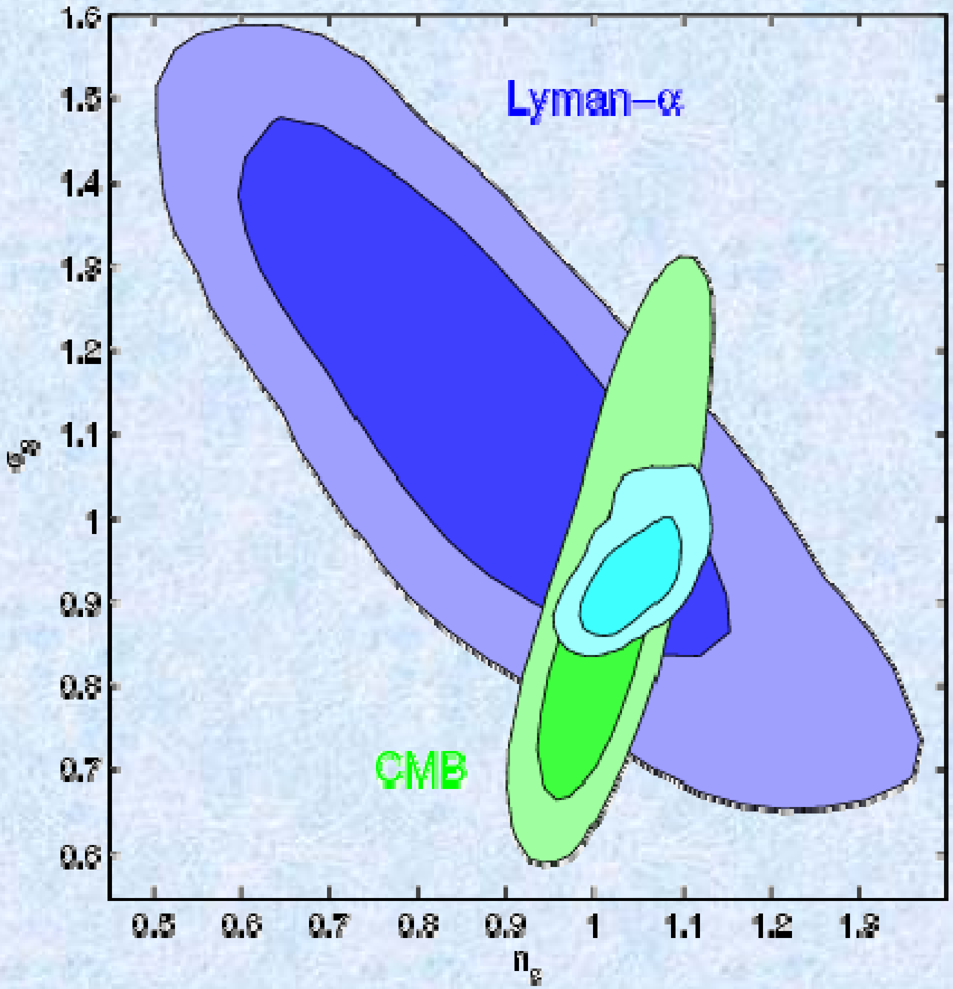


Spergel et al 2006

NB: σ_8 and A_S are just different normalisation of the (scalar) power spectrum

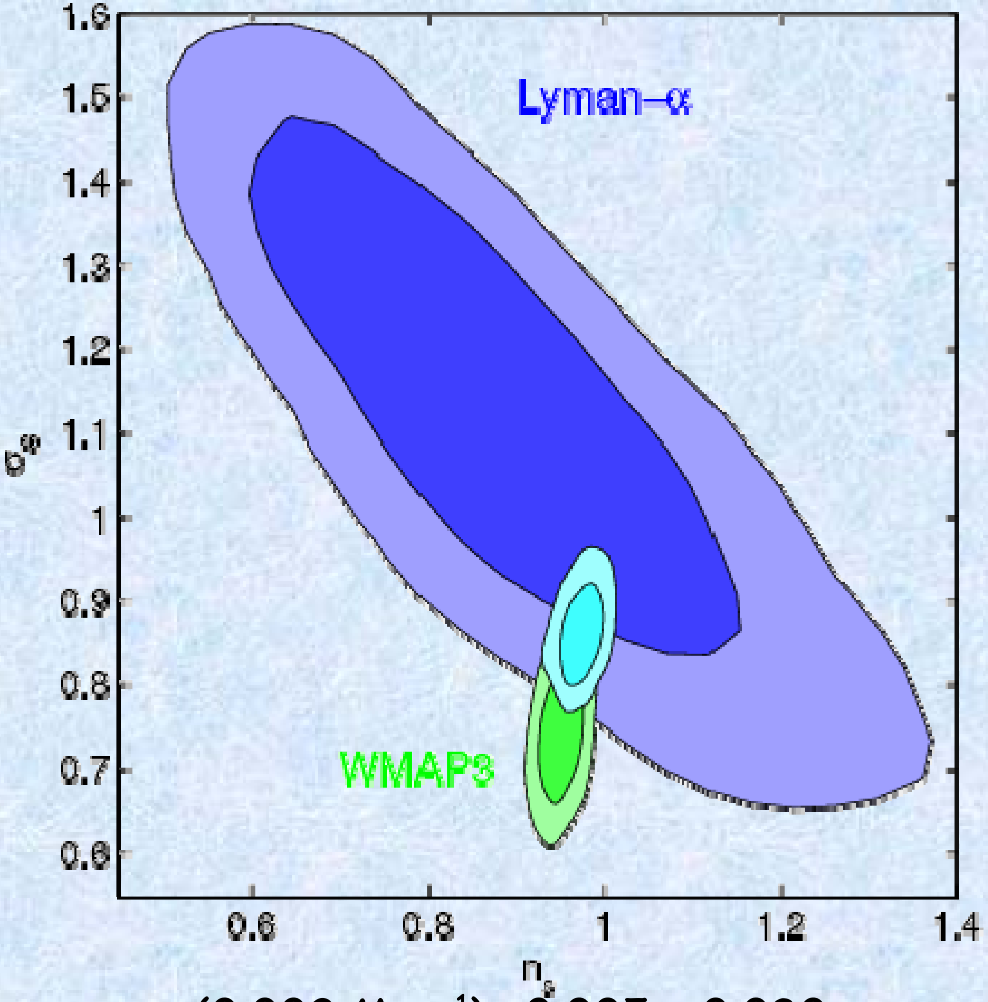
LYMAN ALPHA + WMAP

WMAP 1



(both +HST)

WMAP 3 bfp: n_s=0.97, s_8=0.88



n_{run} (0.002 Mpc^{-1})= 0.005 ± 0.030

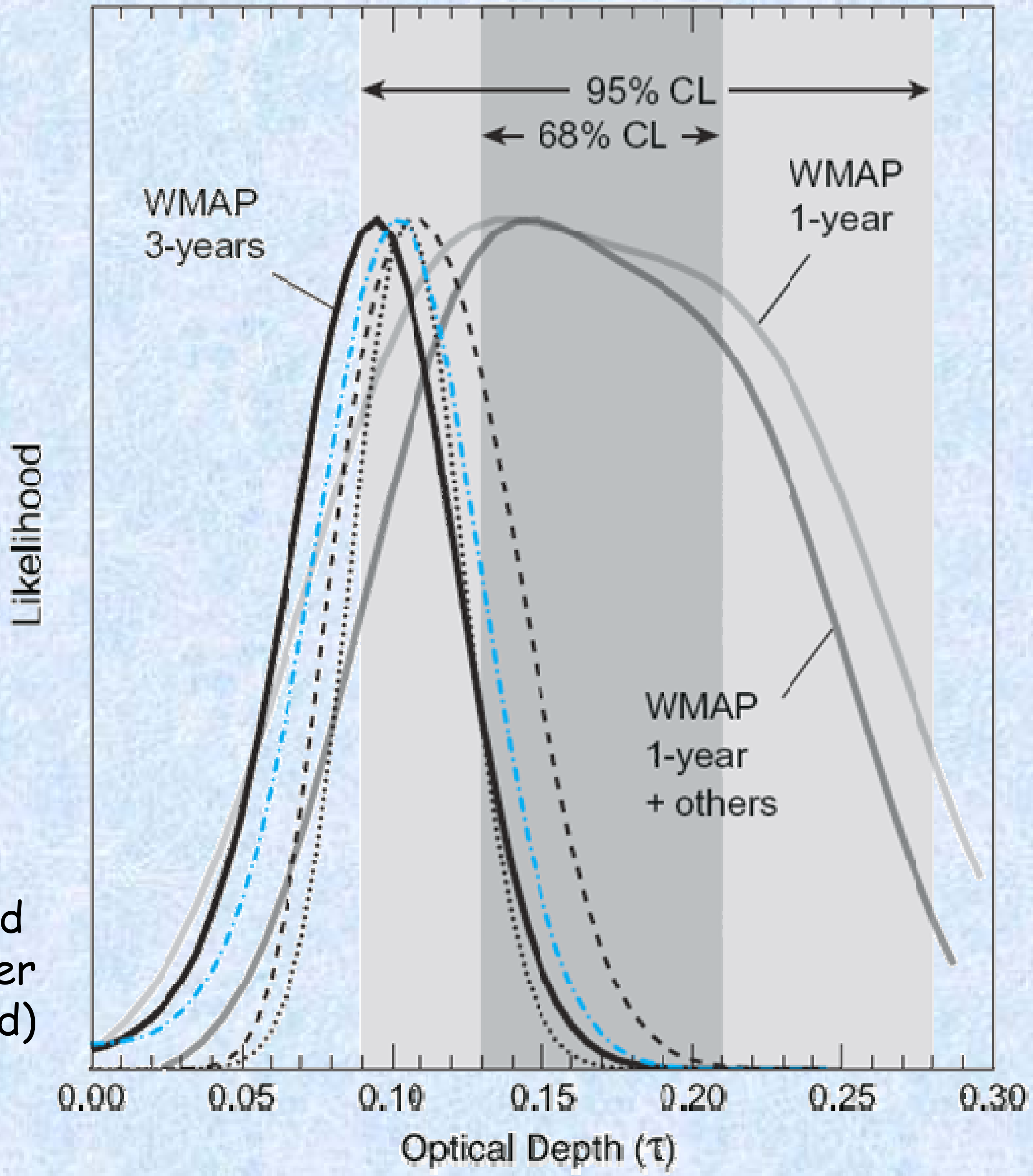
Does not favour running: 0.005 ± 0.03

Ly-alpha: Viel Matteo, Haehnelt Martin G., Springel Volker, 2004, MNRAS, 354, 684

OPTICAL DEPTH

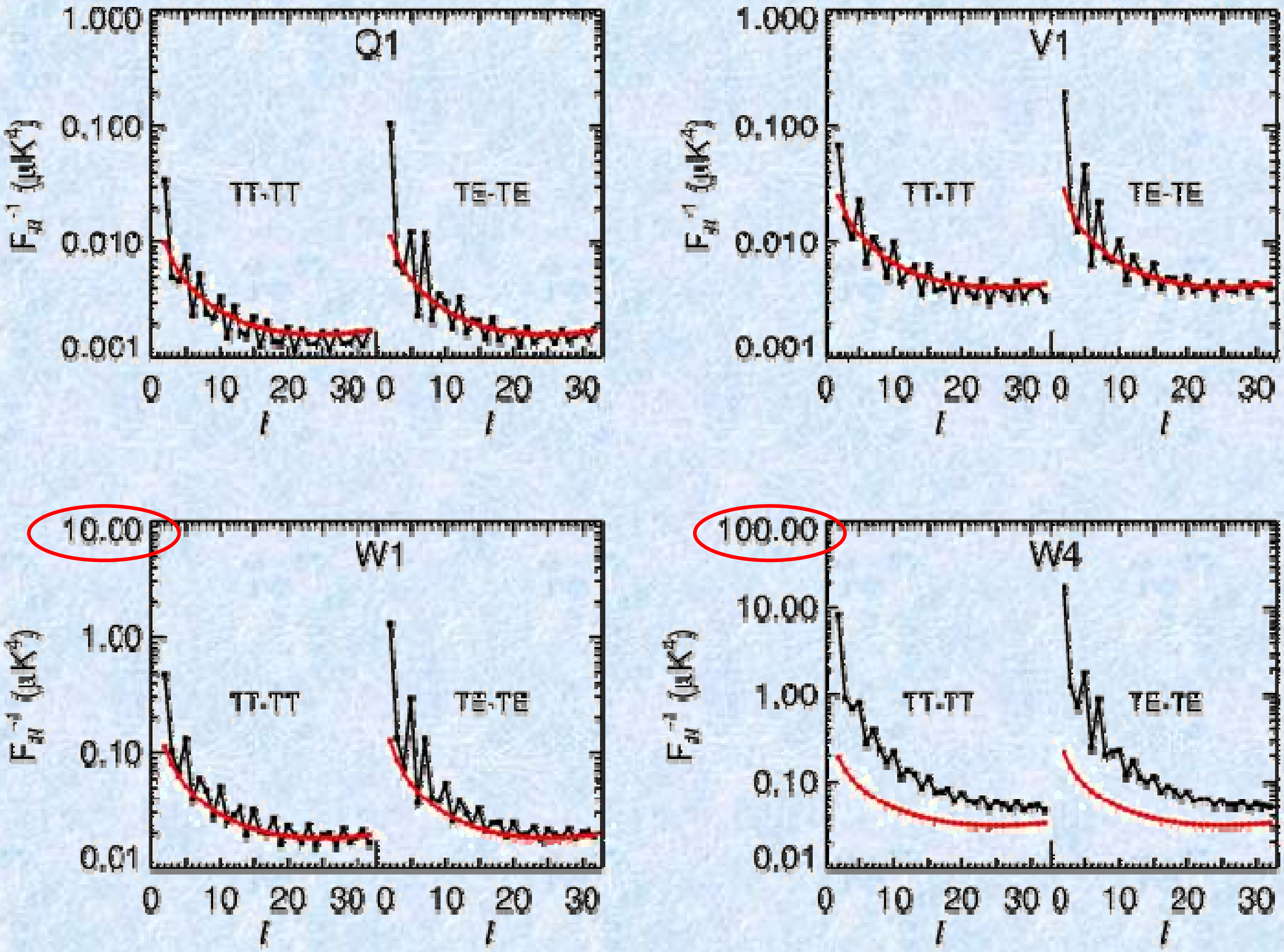
- TE-3 years contributes very little
- Alone would be an upper limit on tau
- New noise estimation is the reason
- tau from (EE-) 3yr is compatible at 2σ level with 1 yr data

(likelihood plotted keeping all other parameters fixed)



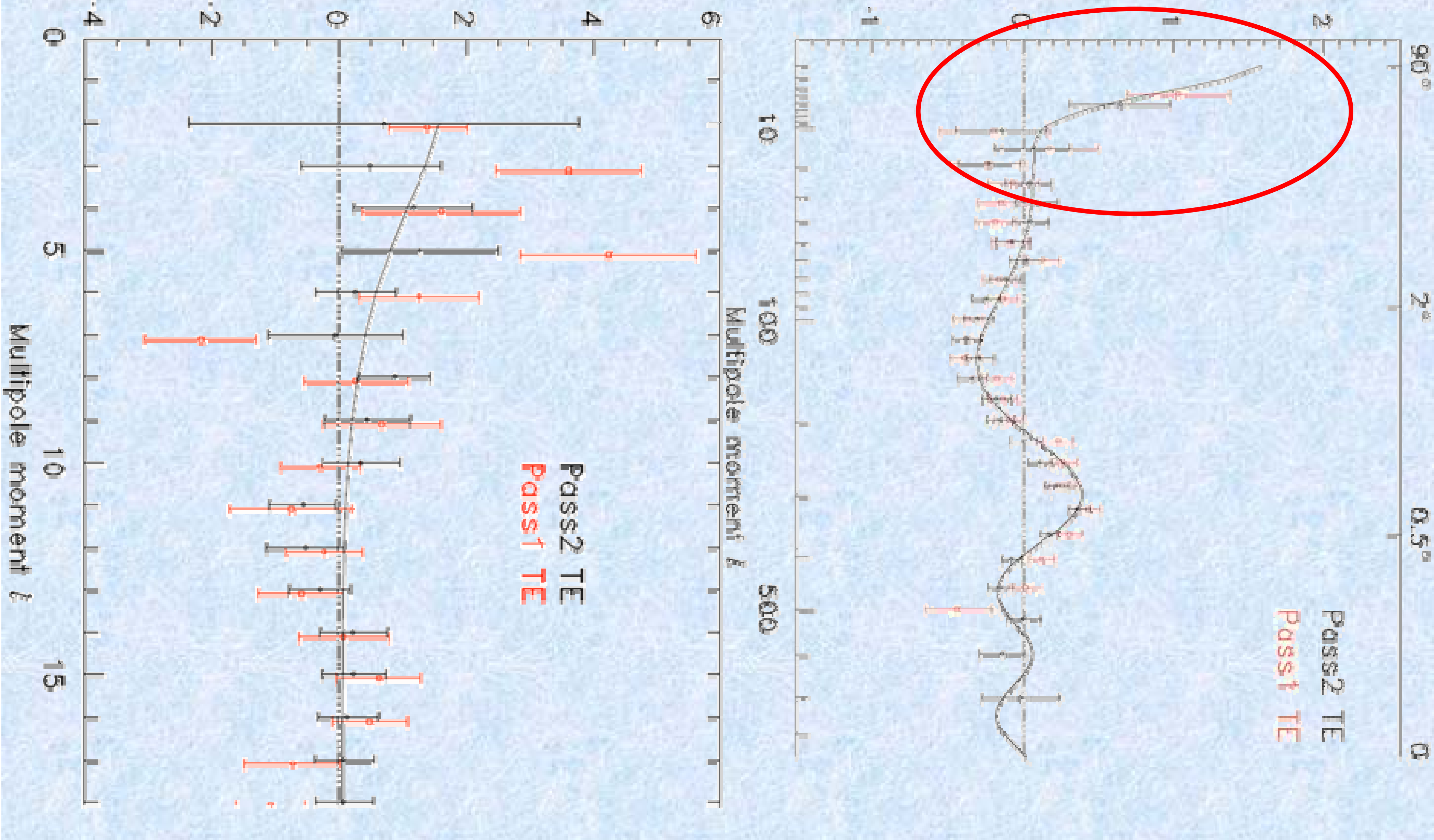
PREDICTED CL UNCERTAINTY AT LOW L

- Black = inverse Fisher Matrix
- Red = pixel-pixel noise correlations (after map-making) are ignored
- Low-l rise from 1/f noise (in time)



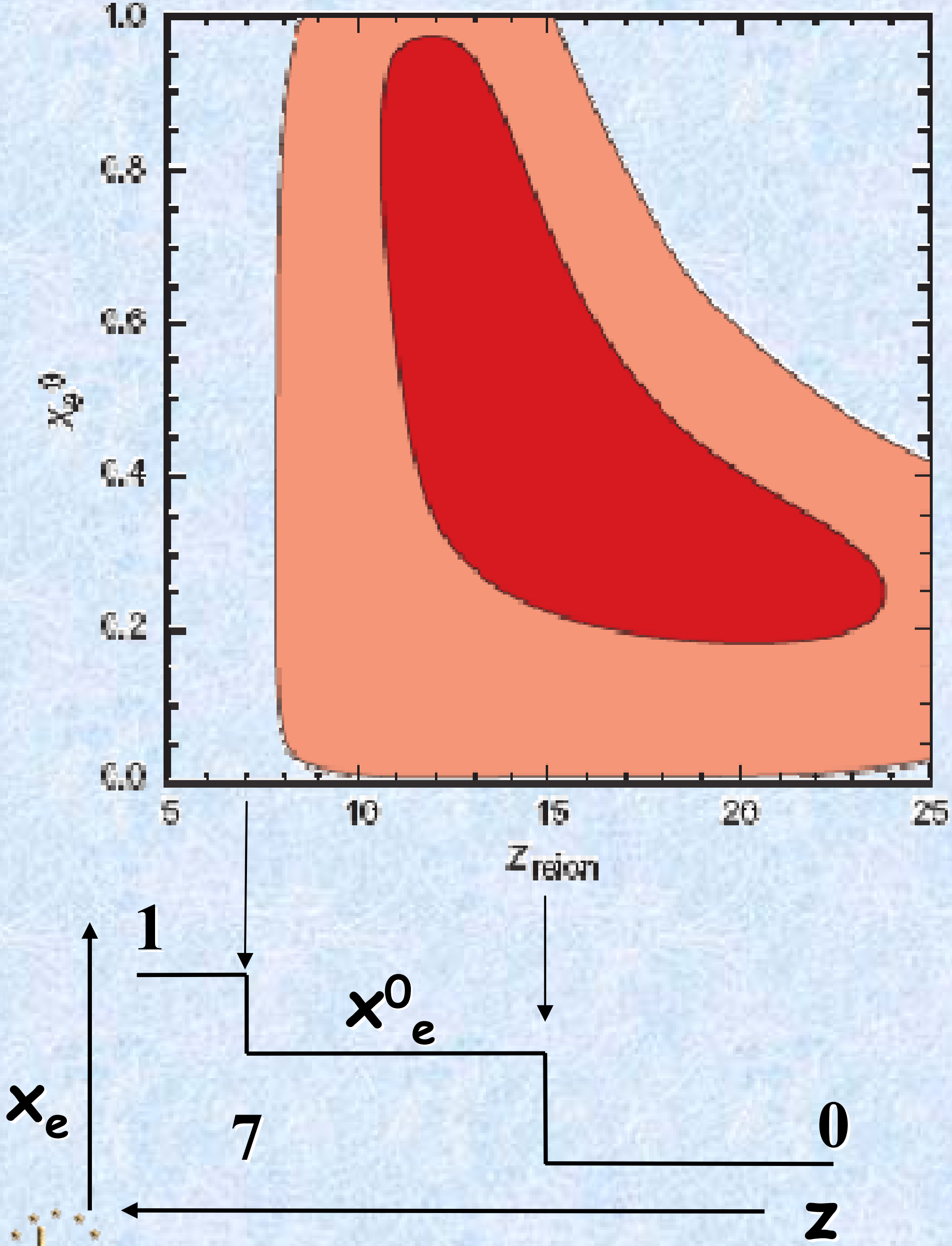
- NB: Noise negligible / signal for TT, but TE analysis must take the structure into account

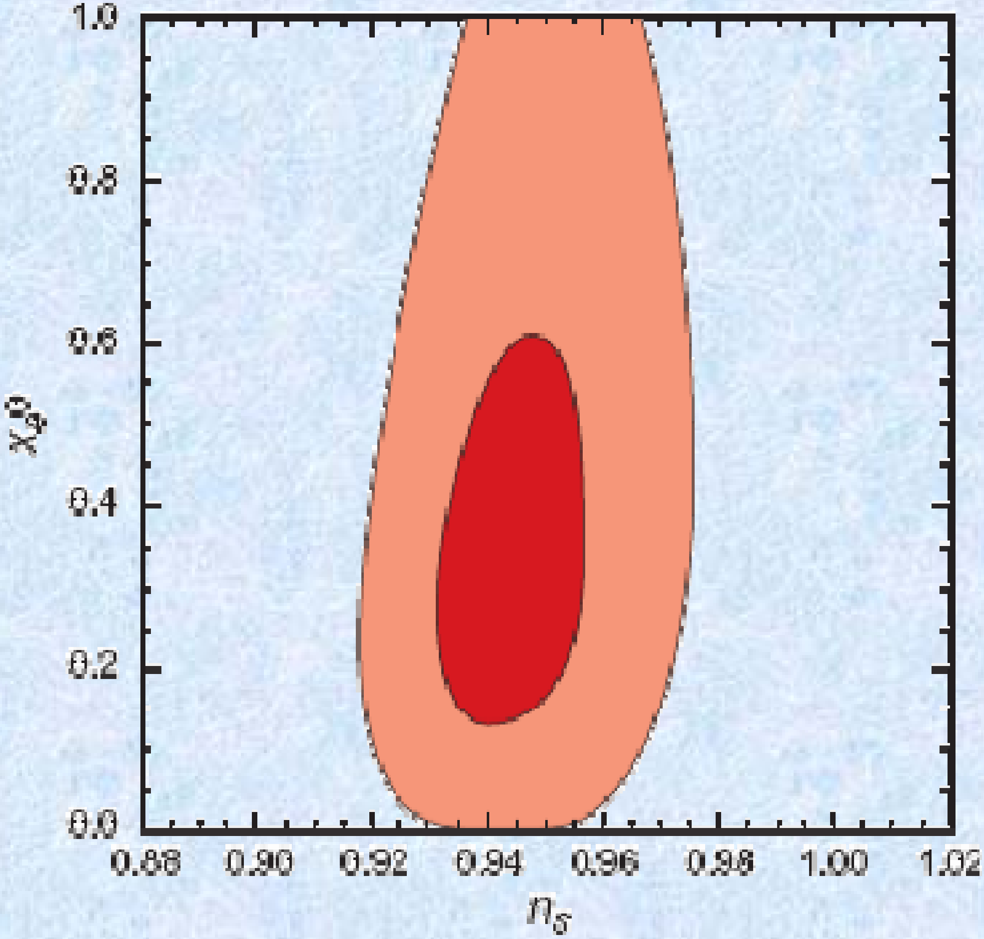
TE Comparison 1 vs 3 years



From Hinshaw @ Irvine Conference

WMAP3 CONSTRAINTS ON REIONISATION

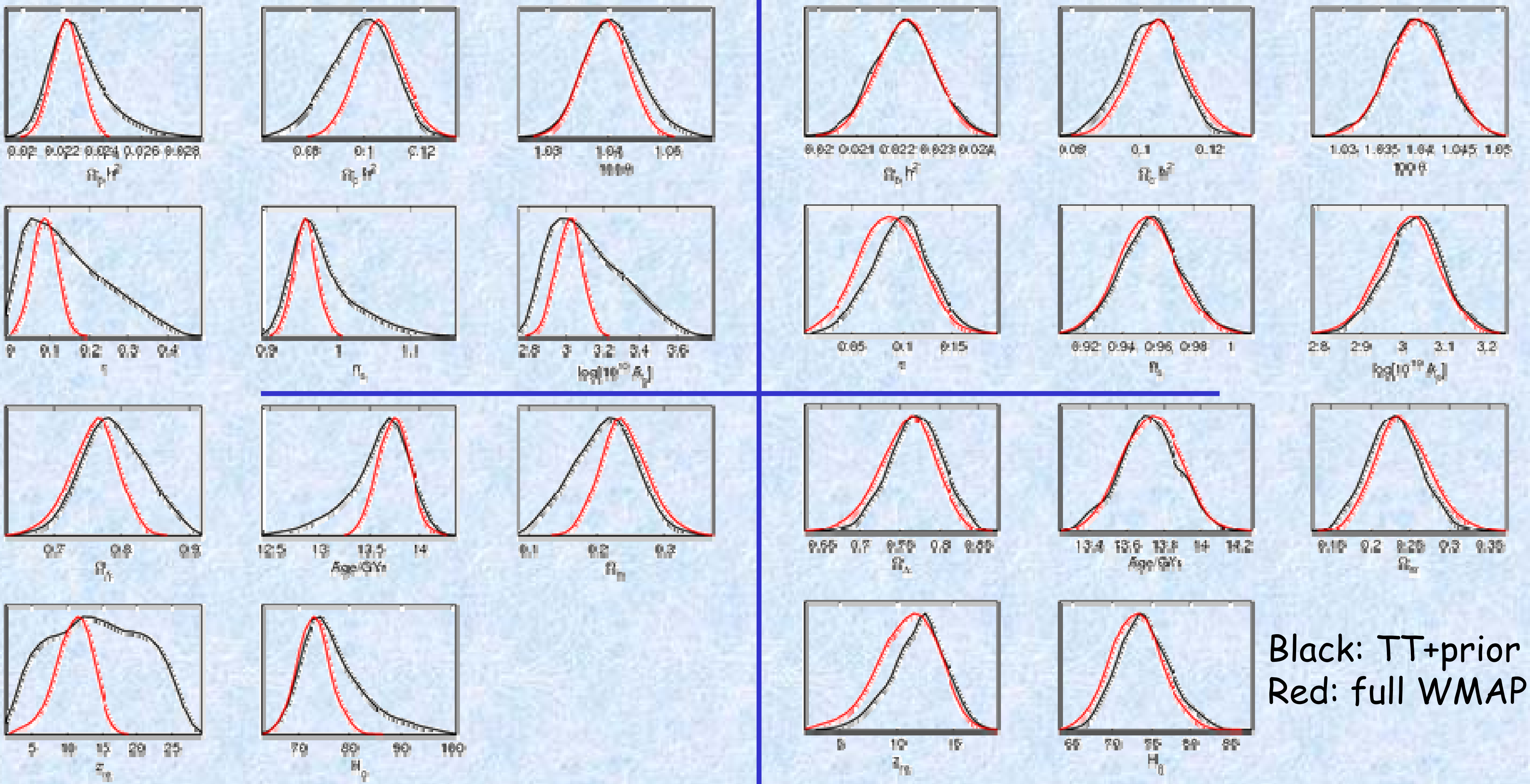




68% and 95% joint 2-d marginalized confidence level contours for x0e – zreion for a power law LCDM

NB: If instantaneous, z_r=10.9 +2.7-2.3

WMAP3 PARAMETER UPDATES RELY MUCH ON EE POLARIZATION



Slide content from A. Lewis

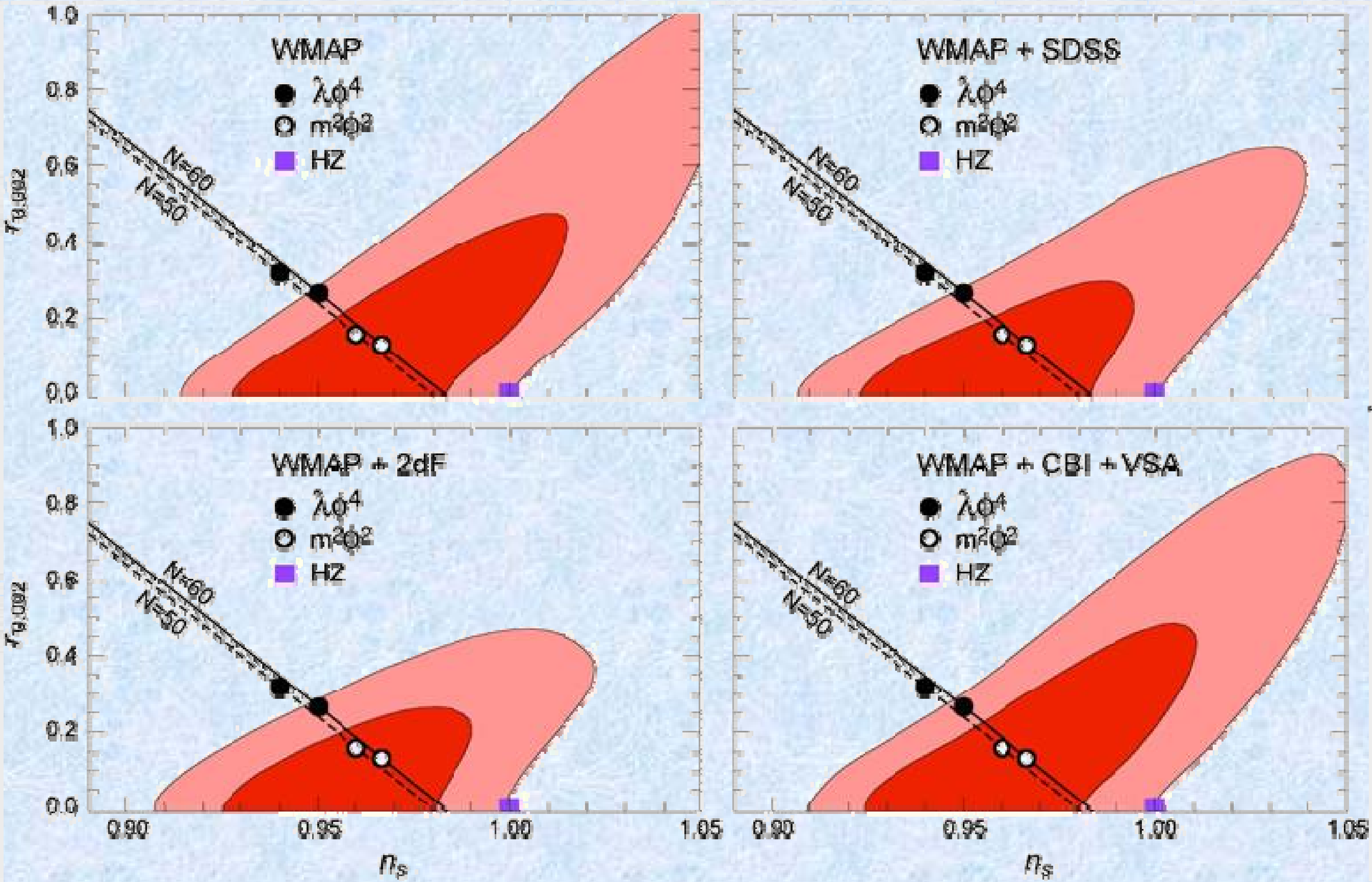
WMAP3 TT with τ = 0.10 ± 0.03 prior (equiv to WMAP EE)

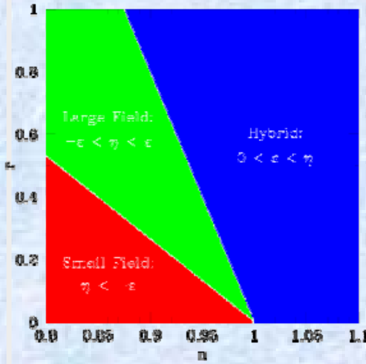
WHAT'S NEEDED!

	Model	$-\Delta(2\ln\mathcal{L})$	N_{par}
M1	Scale Invariant Fluctuations ($n_s = 1$)	8	5
M2	No Reionization ($\tau = 0$)	8	5
M3	No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)	248	6
M4	No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)	0	6
M5	**Power Law ΛCDM**	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive Neutrino ($m_\nu > 0$)	0	7
M8	Tensor Modes ($r > 0$)	0	7
M9	Running Spectral Index ($dn_s/d\ln k \neq 0$)	−3	7
M10	Non-flat Universe ($\Omega_k \neq 0$)	−6	7
M11	Running Spectral Index & Tensor Modes	−3	8
M12	Sharp cutoff	−1	7
M13	Binned $\Delta^2_\mathcal{R}(k)$	−22	20

WMAP Collaboration (Spergel & al), 2006:

Implications (for inflation)





$\lambda\varphi^4$ is out, but a simple $m^2\varphi^2$ is still in…

*NB: this is **not** the astroph plot*

Tendencies:
ns < 1
or τ is high
or there are tensors
or the model is wrong
or we are quite unlucky…

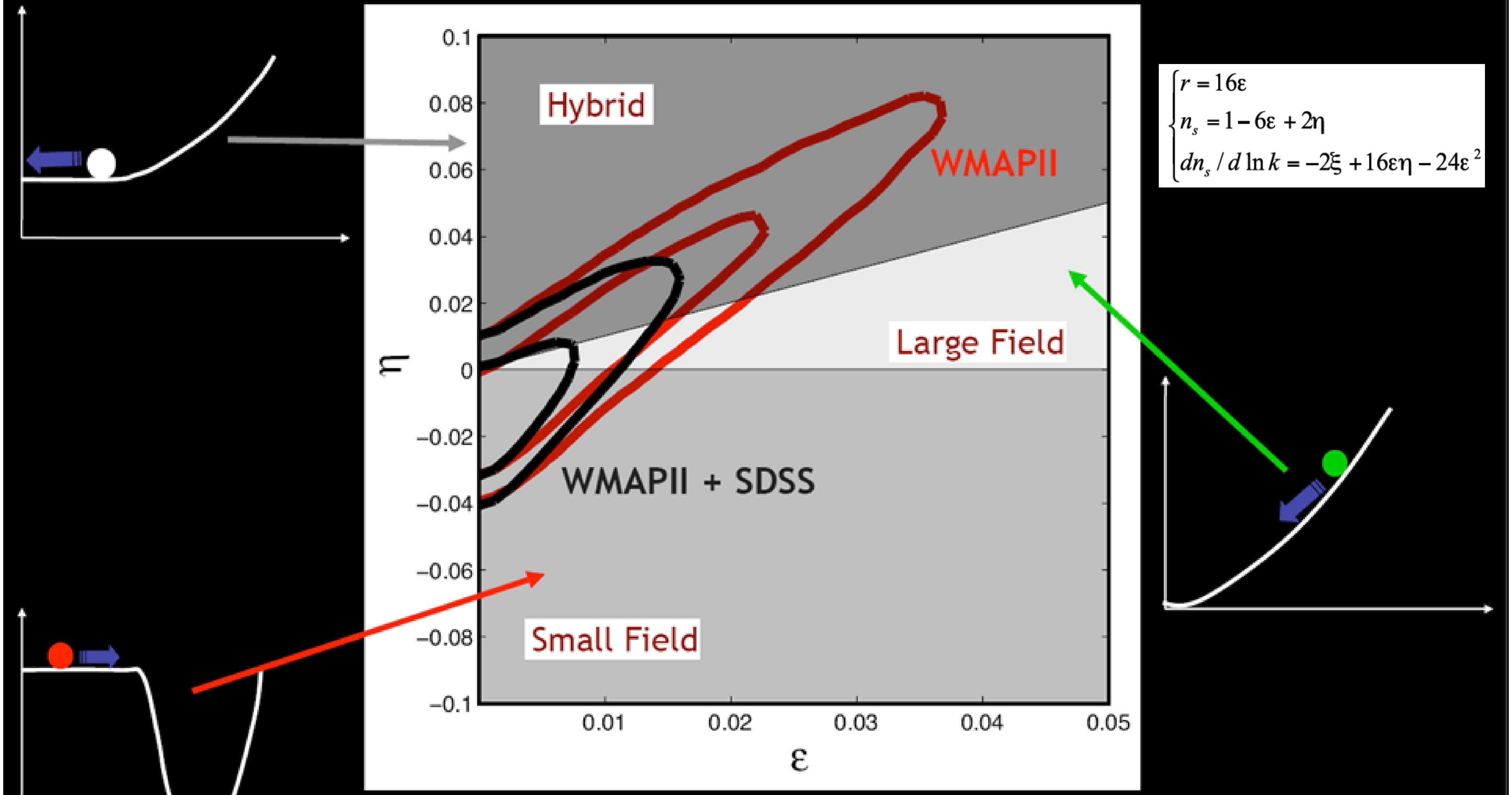
LIMITS ON TENSOR-TO-SCALAR RATIO

Table 8: Constraints on r, Ratio of Amplitude of Tensor Fluctuations to Scalar Fluctuations (at $k = 0.002$ Mpc^{-1})

Data Set	r (no running)	r (with running)
WMAP	0.55 (95% CL)	1.5 (95% CL)
WMAP+BOOM+ACBAR	0.63 (95% CL)	1.4 (95% CL)
WMAP+CBI+VSA	0.55 (95% CL)	1.1 (95% CL)
WMAP+2df	0.30 (95% CL)	1.0 (95% CL)
WMAP+SDSS	0.28 (95% CL)	0.67 (95% CL)

$r < 0.55$ @ 95% CL $\Rightarrow$ $\Omega_{GW}h^2 < 1.\ 10^{-12}$ (@95% CL)

The Inflationary Zoo

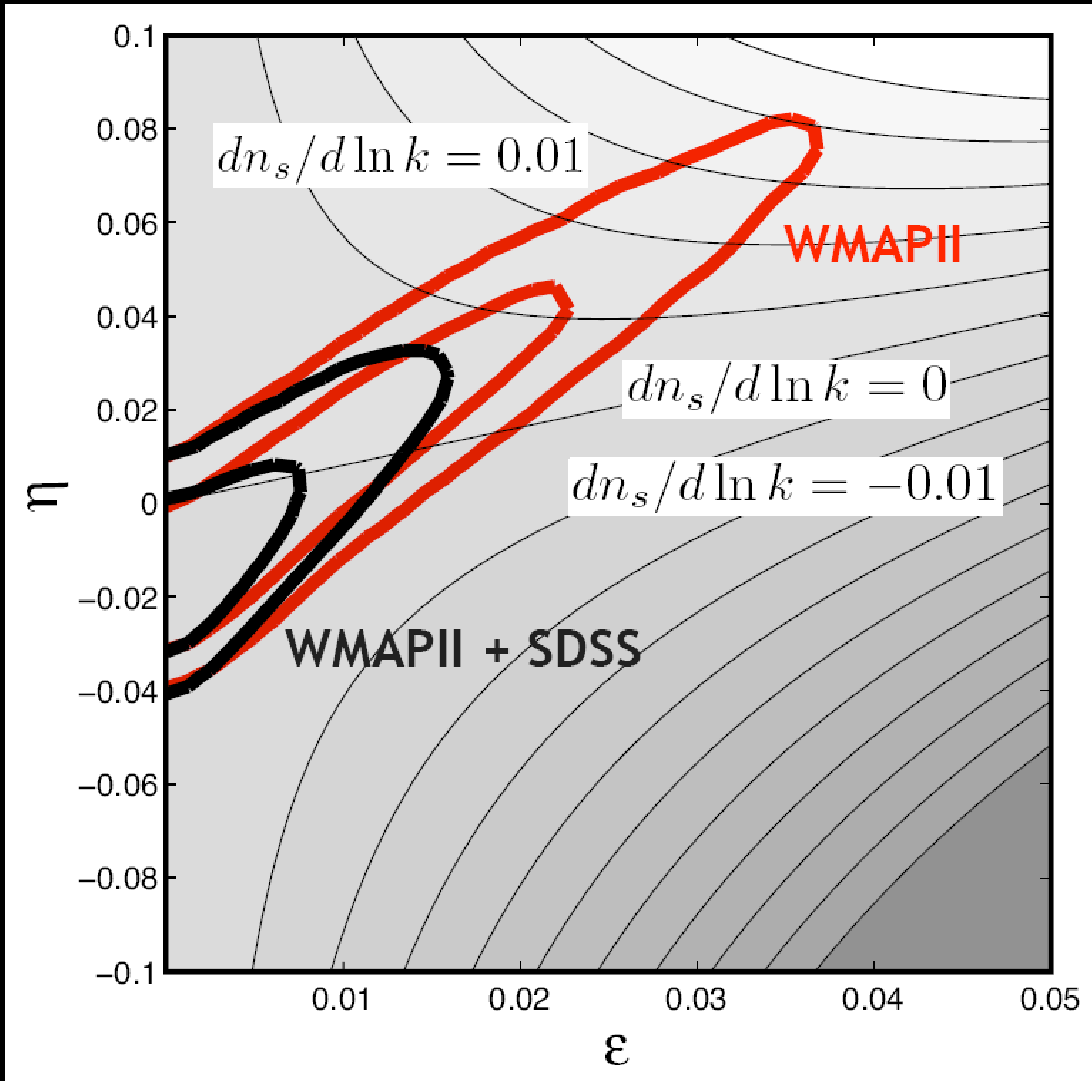


$$\begin{cases} r = 16\varepsilon \\ n_s = 1 - 6\varepsilon + 2\eta \\ dn_s / d\ln k = -2\xi + 16\varepsilon\eta - 24\varepsilon^2 \end{cases}$$

Peiris & Easther (2006)

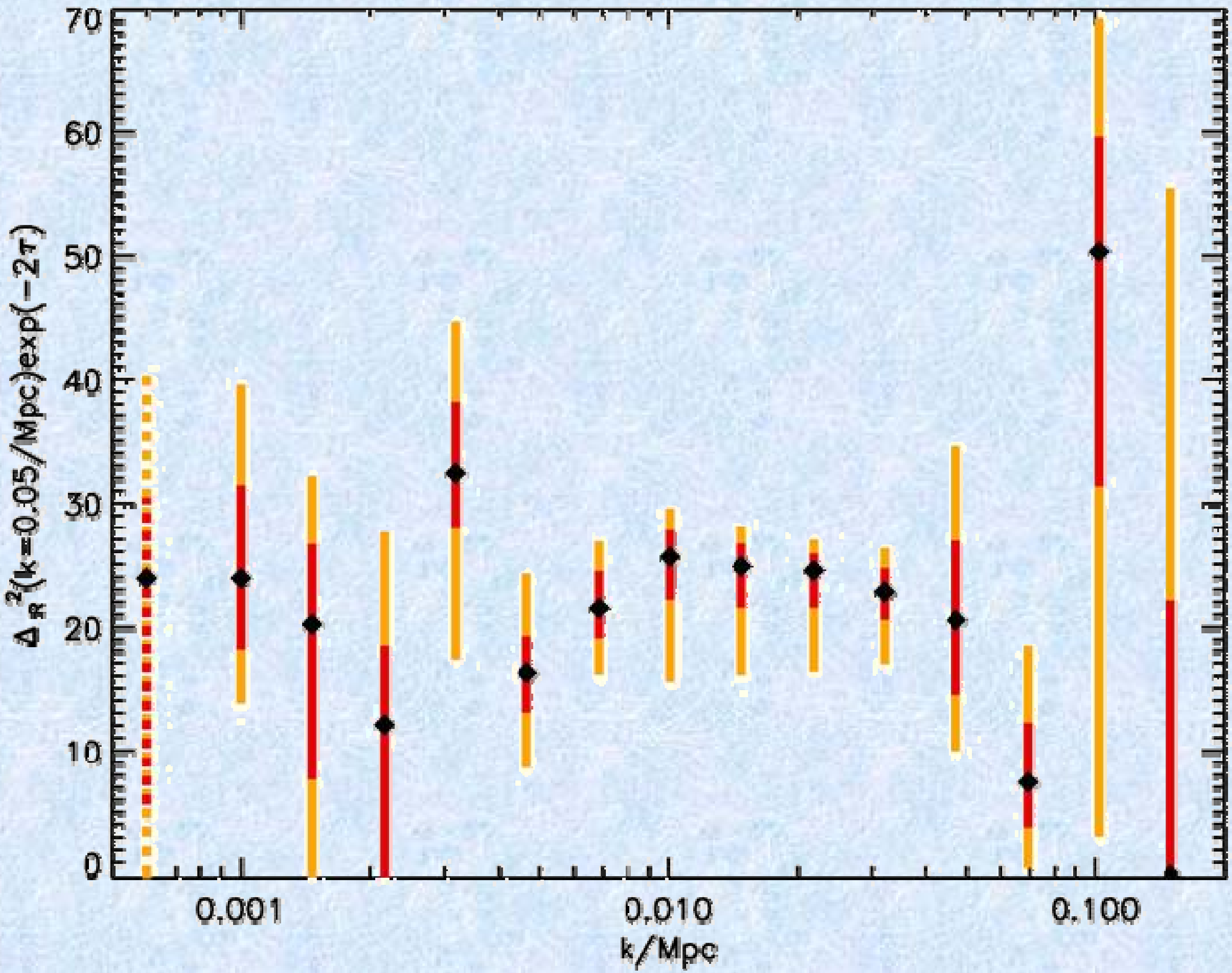
Constraints on first two HSR parameters at k=0.002 Mpc^{-1}

Inflation and a running spectral index?

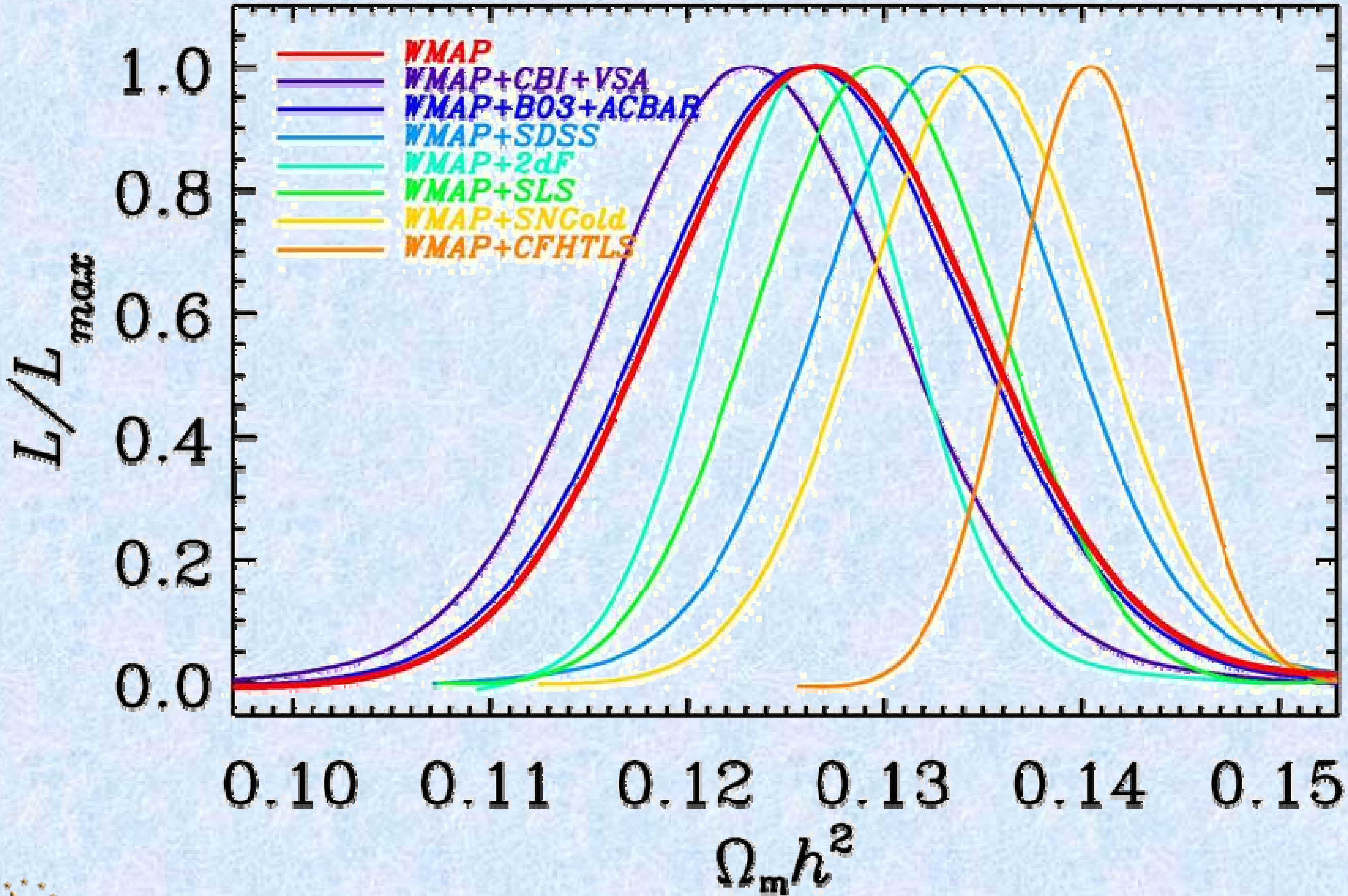


Peiris & Easther (2006)

Reconstructed shape of P_s



1D MARGINALIZED DISTRIBUTION OF $\Omega_M h^2$



CMB DATA SET SIZE

	Samples	Pixels
COBE (1989)	$2x10^9$	$6x10^3$
Boomerang (1998)	$3x10^8$	$5x10^5$
WMAP (2001)	$7x10^{10}$	$4x10^7$
Planck (2008)	$5x10^{11}$	$6x10^8$
Polar Bear (2007)	$8x10^{12}$	$6x10^6$
SAMPAN	$7x10^{13}$!	$4x10^5$

CONCLUSIONS

- From Hinshaw :
- WMAP three-year data includes full-sky polarization maps
- Analysis of EE + BB power spectra
- Improved measurements of many degenerate parameter pairs, especially (τ, *ns*)
- New limits on dark energy eq. of state, flatness.
- Spacecraft continues to function well.

- NB: many indications of non-gaussianity and/or anisotropies at large scale. Much work, but nothing has changed much after WMAP3 yet (large scales are already well known)