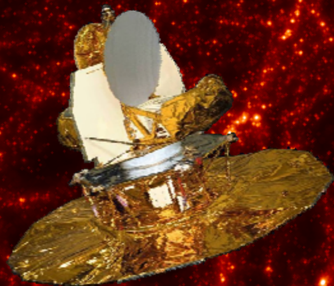
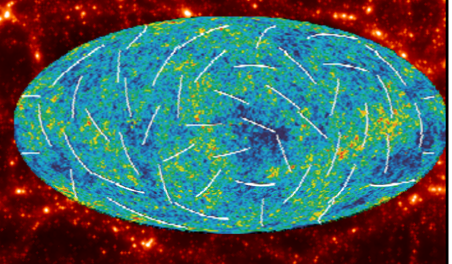
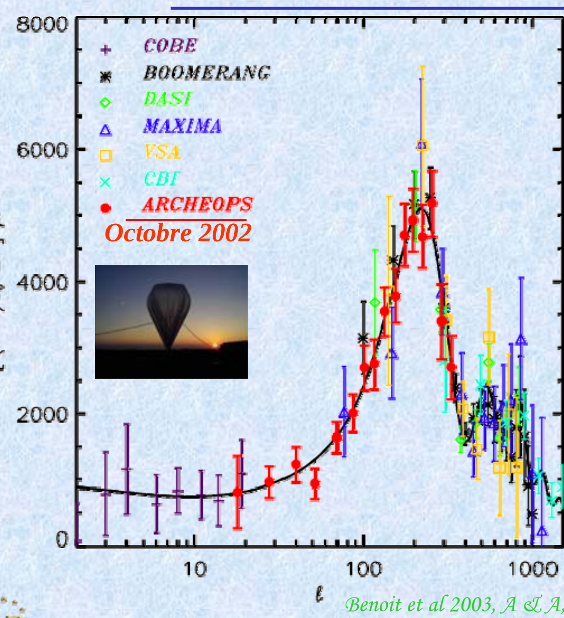
CMB ANISOTROPIES: CURRENT STATUS & PERSPECTIVES

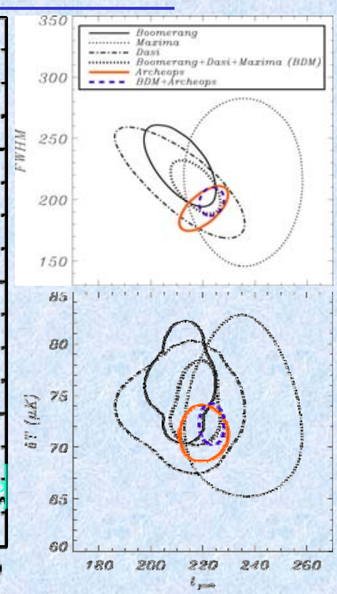




F. R. BOUCHET
INSTITUT D'ASTROPHYSIQUE DE PARIS, CNRS
IAP, PARIS, MAY 5TH 2006

PRE-WMAP (END OF 2002) STATUS…

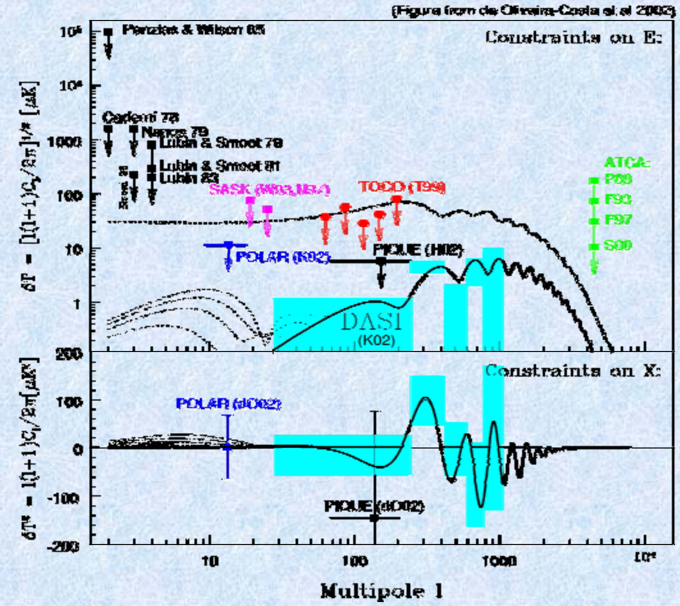




Benoit et al 2003, A &A, 399, L25

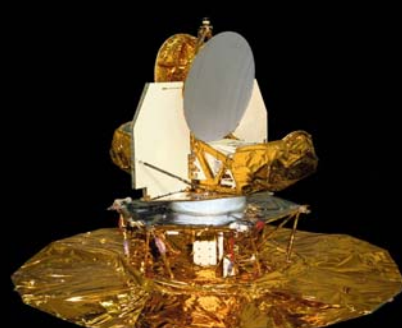
PRE-WMAP POLARISATION KNOWLEDGE

(Figure from de Oliveira-Costa et al 2002)



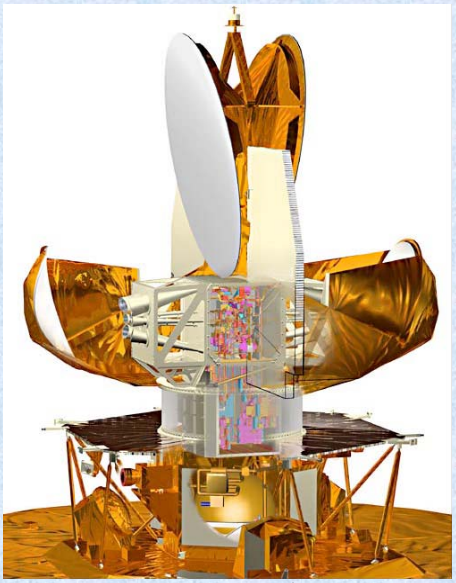
WMAP

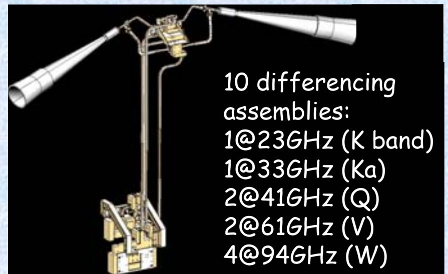
Wilkinson Microwave Anisotropy Probe

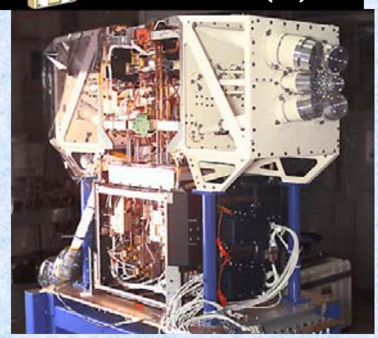


Launched on June 30, 2001

HEMT based differential measures



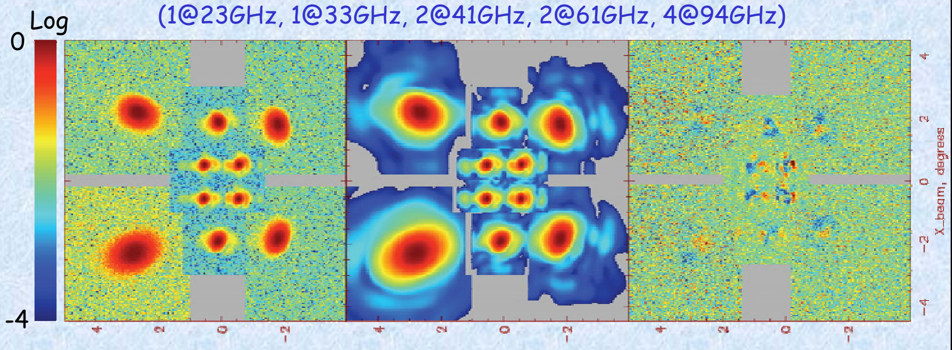




2 back-to-back telescopes

Beams, A-side optics

(1@23GHz, 1@33GHz, 2@41GHz, 2@61GHz, 4@94GHz)

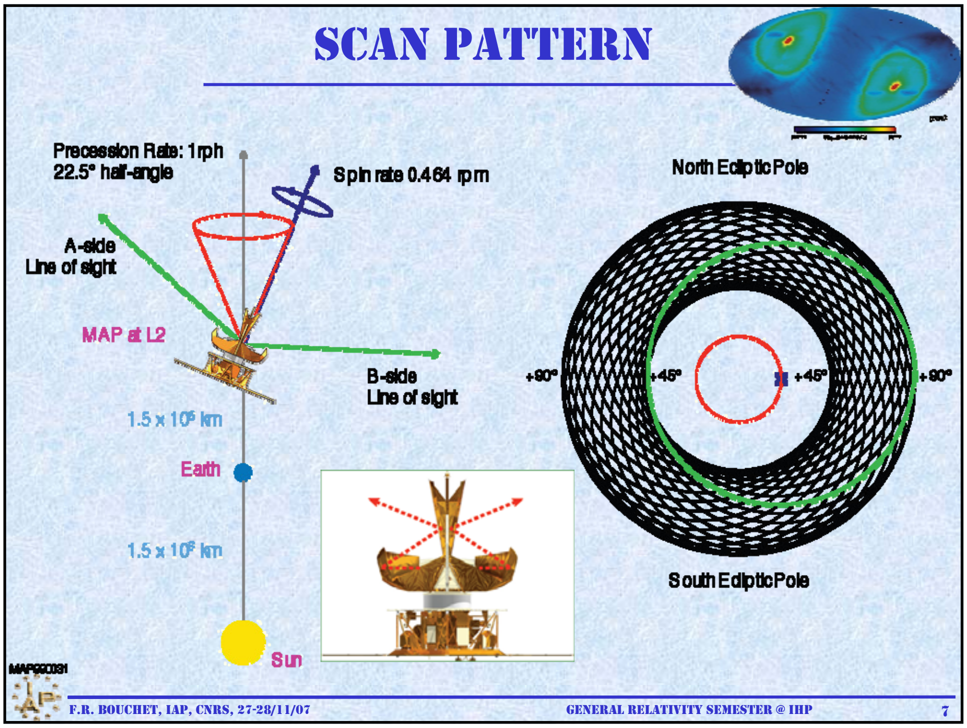


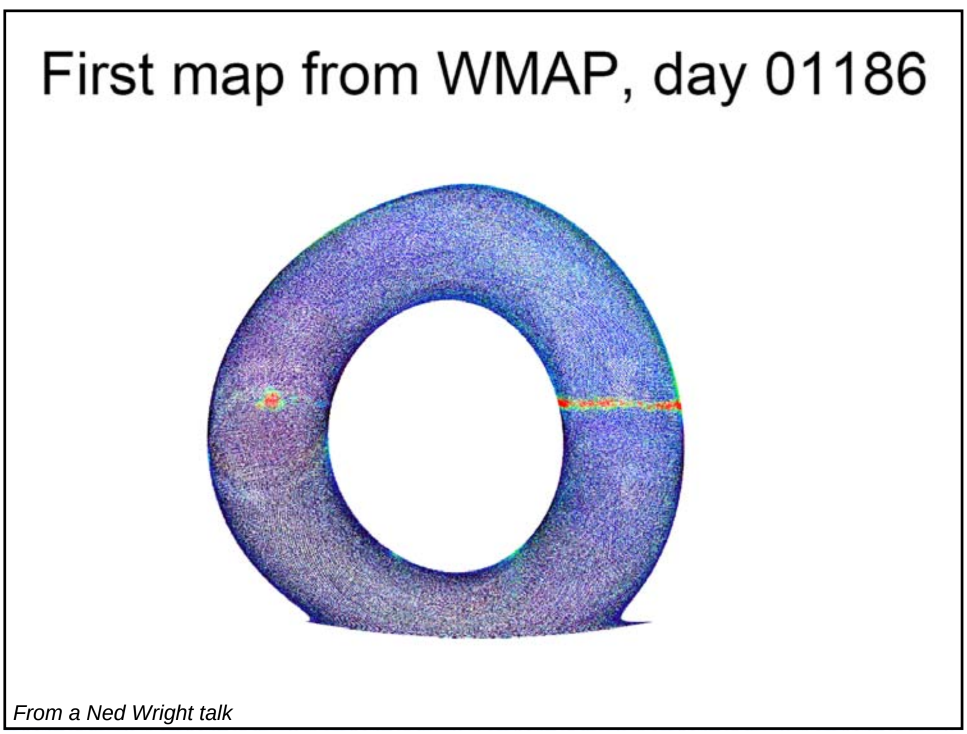
In-flight beam maps from Jupiter obs.

Model beam response

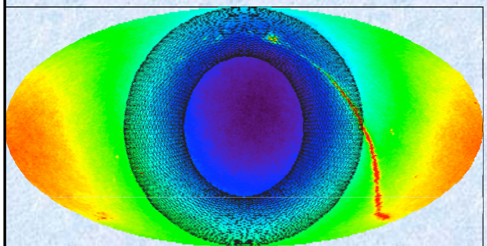
Residuals (linear scales, 10%-2.5%, depending on DA)

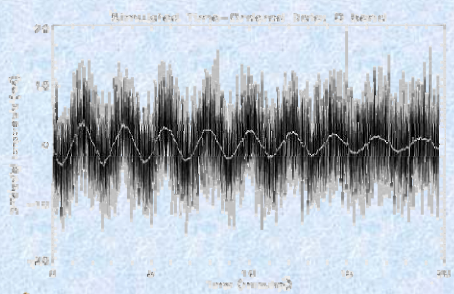
Hybrid beam response constructed from Jupiter data (high S/N) and model (low S/N). Results in ~1% larger solid angle than first-year.


SCAN PATTERN
Precession Rate: 1rph
22.5° half-angle
Spin rate 0.464 rpm
A-side
Line of sight
MAP at L2
B-side
Line of sight
1.5 x 10⁶ km
Earth
1.5 x 10⁸ km
Sun
North Ecliptic Pole
+90°
+45°
+45°
+90°
South Ecliptic Pole
MAP990031
F.R. BOUCHET, IAP, CNRS, 27-28/11/07
GENERAL RELATIVITY SEMESTER @ IHP
7

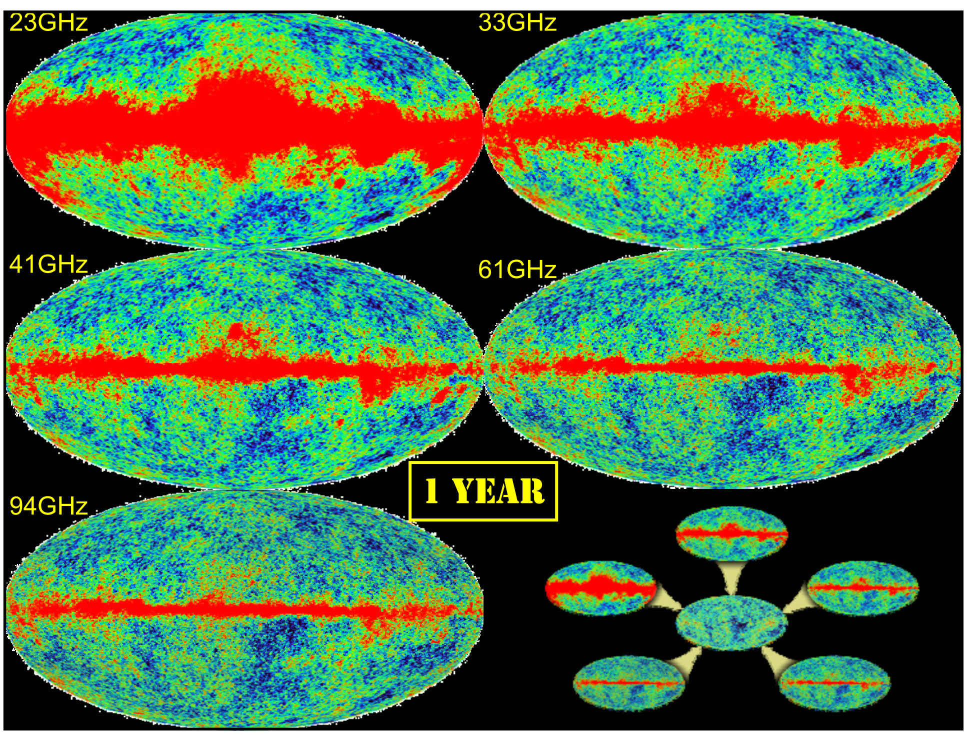

First map from WMAP, day 01186
From a Ned Wright talk

Continuous calibration from dipole

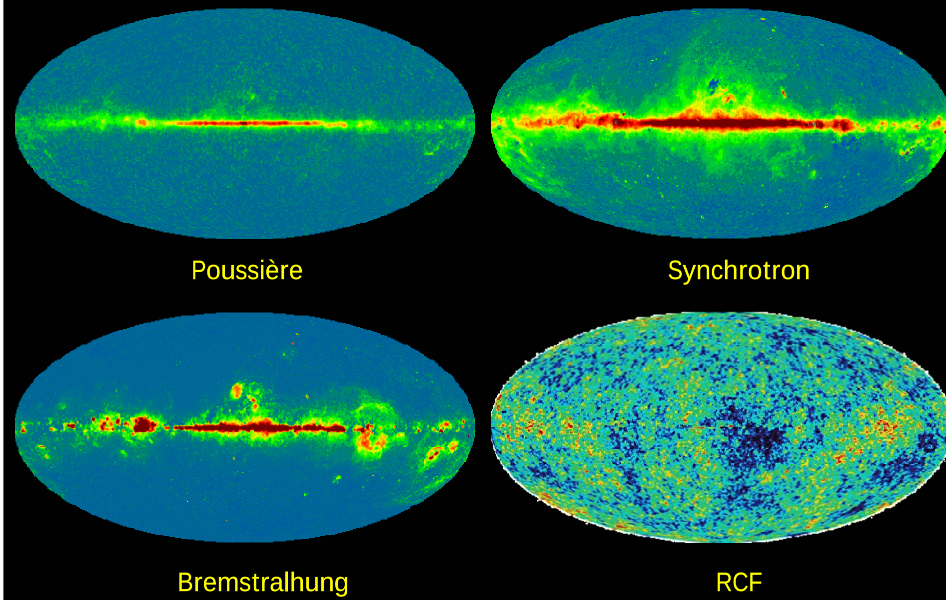




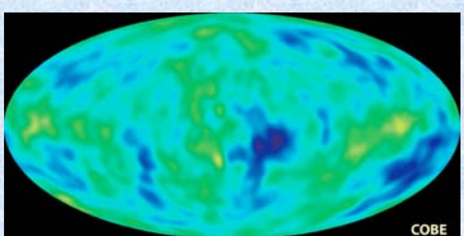
- Gain calibration based on known dipole modulation due to motion of WMAP around the Sun.
- CMB dipole provides short term transfer standard.
- Baseline (or offset) determination based on sky signal changing sign every half-spin.

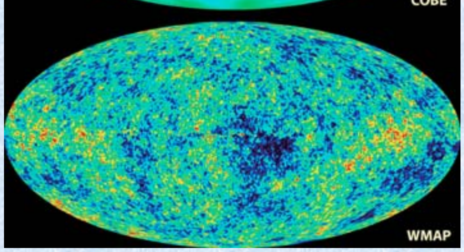


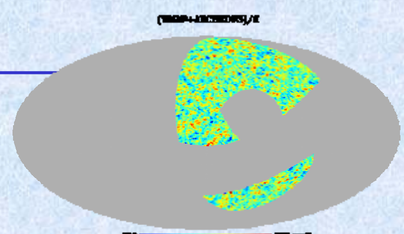
Cartes d'émission Déduites

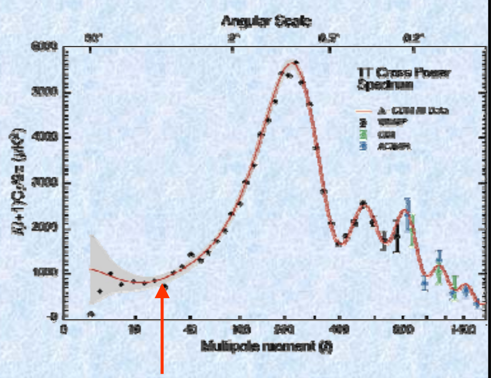


CARTE & SPECTRE DU RCF PAR WMAP-1





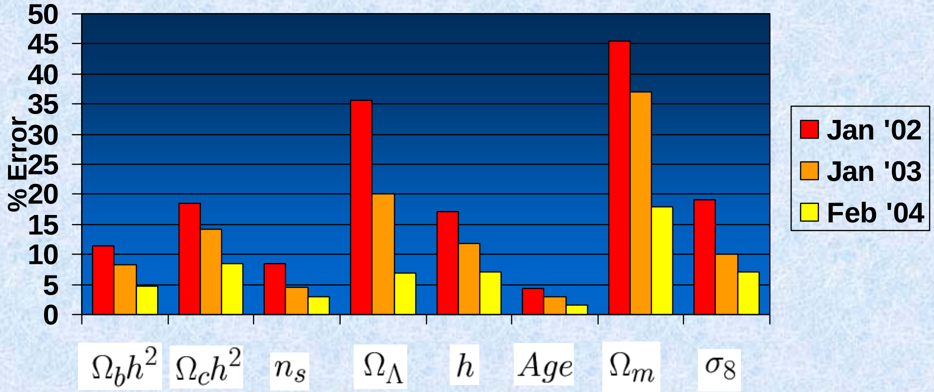




Courbe rouge = Théorie pour un univers avec 5% d'atomes, 25% de matière sombre, 70% d'énergie sombre

PRE-WMAP1 ⇔ POST-WMAP1

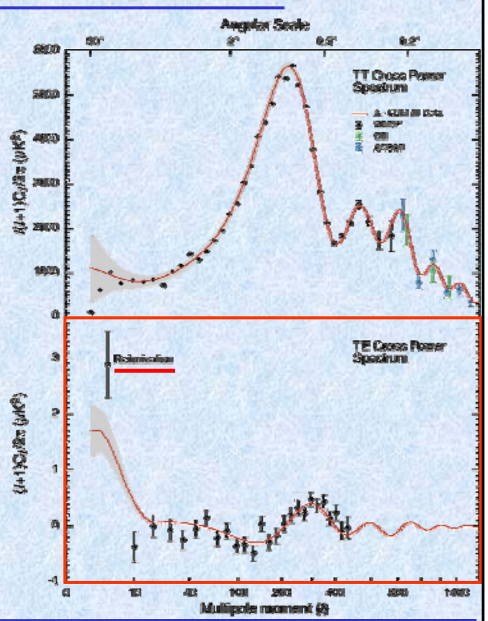
Parameters very similar. Precision +



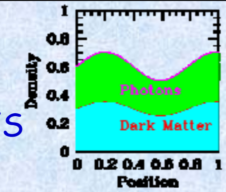
[Bond, Contaldi & Pogosyan astro-ph/0310735]

WMAP & POLARISATION

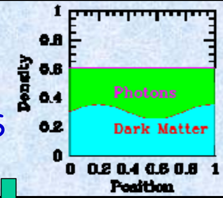
- 1st measure of polarisation spectrum (temperature correlated part, TE)
- Oscillations/comparaison with same theoretical model (red curve): additional consolidation of paradigm
- Peak at low l (large scales) is very high: Reionisation earlier than anticipated. Strong constraints on the end of the dark ages, IF CONFIRMED
- Large scale TT vs TE anti-correlation:
  - Signature of superhorizon fluctuations at decoupling and
  - Adiabaticity of primordial fluctuations (phases TT/TE)
  - An indication of apparently acausal physics, calling for a period of accelerated expansion (Spergel & Zaldariaga 97)

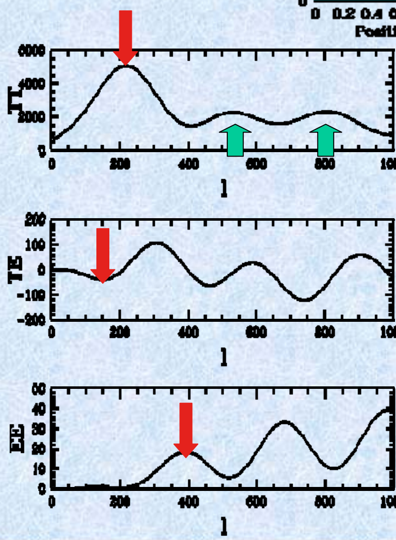


Fluctuations
de densité
ADIABATIQUES

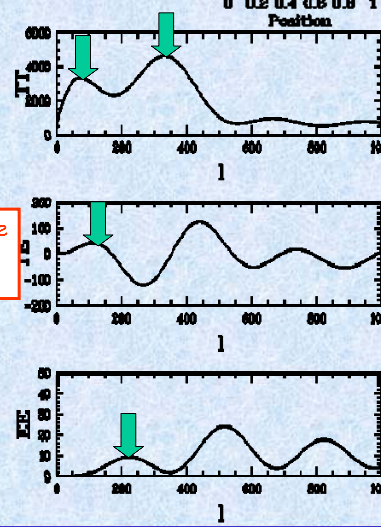


Fluctuations
D'entropie
ISOCOURBES





Différence
de signe
à l ~100

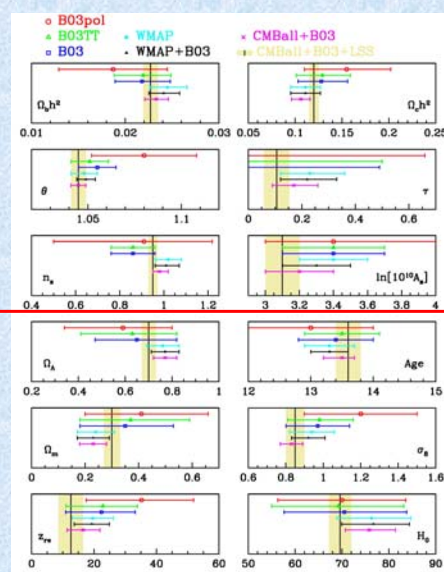


CONSISTENCY

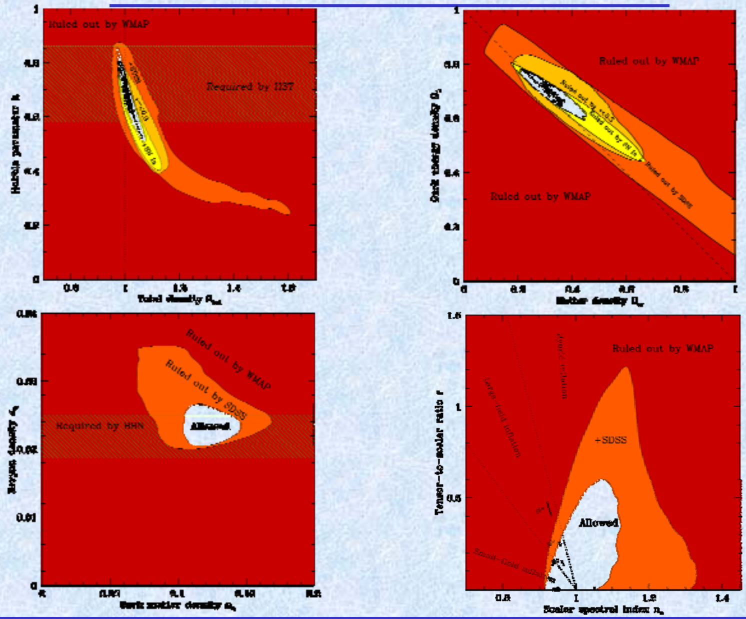
- A Minimal Model fits well (2+4 pars)
- Boomerang Polarization data taken alone (B03Pol) agrees with temperature data (B03TT)
- CMBdata alone (CMBall+B03) gives by itself rather tight error bars
- Can be further tightened with LSS data (vertical band)
- Note the use of "weak" priors

$$\begin{cases} 0.5 \le n_s \le 1.5 \\ 2.7 \le \ln(10^{10}A_s) \le 4.0 \\ 0.005 \le \Omega_b h^2 \le 0.1 \\ 0.01 \le \Omega_c h^2 \le 0.99 \\ 0.5 \le \theta \le 10.0 \\ 0.01 \le \tau \le 0.8 \end{cases}$$

- But also priors on age and expansion rate:
  10 Gyr ≤ Age ≤ 20 Gyr
  45 ≤ H_0 ≤ 90 km/s/Mpc.

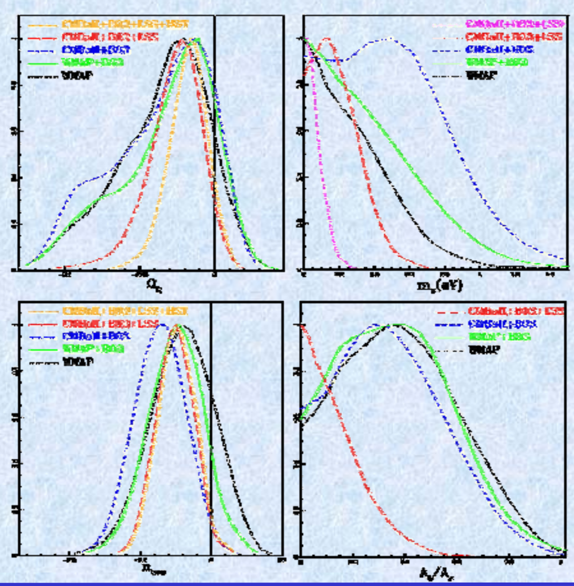


CONSISTENCY / COMPLEMENTARITY



FURTHER CONSTRAINTS?

Curvature ?

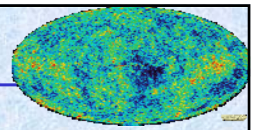


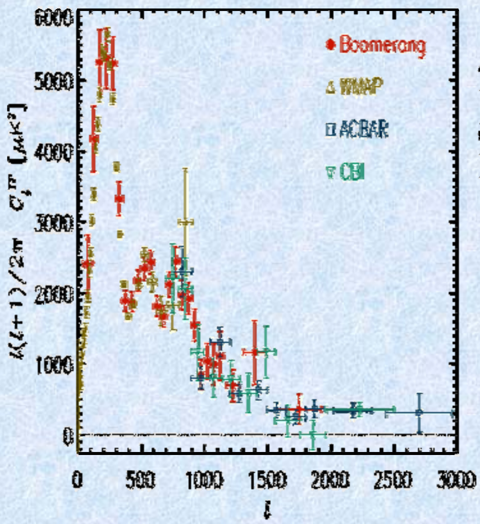
Non-zero Neutrinos masses ?

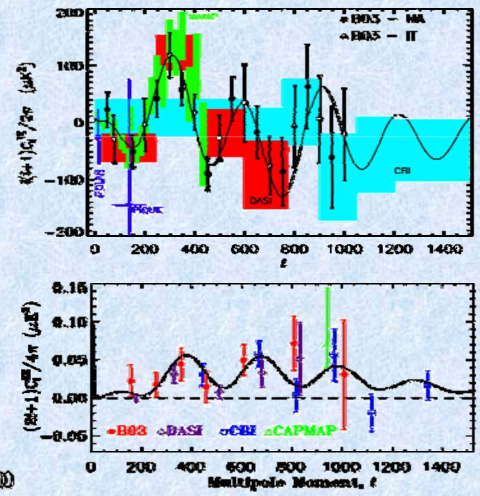
Logarithmic correction to IC scale invariance ?

Tensor modes ?

PRE-WMAP3 STATUS



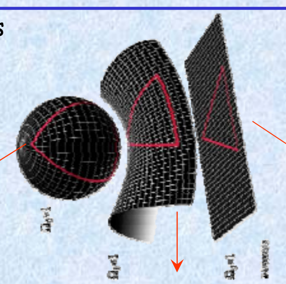


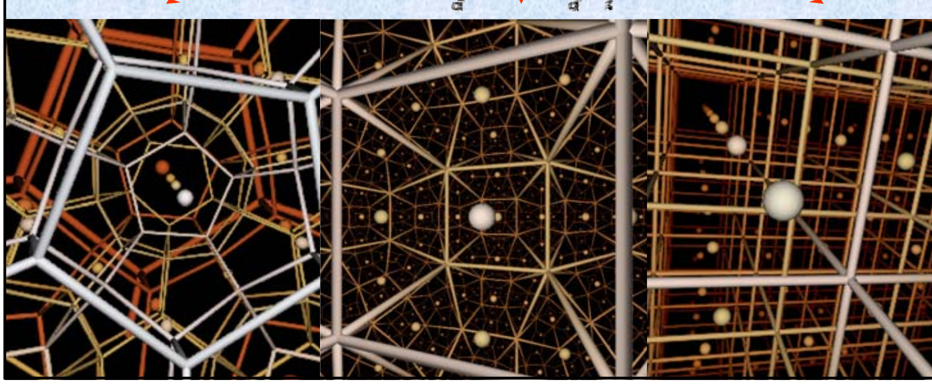


RÉPLICATIONS DANS DIVERS ESPACES

NB1: il existe de multiples manière de paver un espace avec divers volume élémentaires et identifications

NB2: si réplication il y a, elle est à une distance inaccessible ($V > V_{SSD}$)

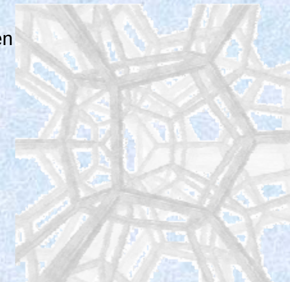


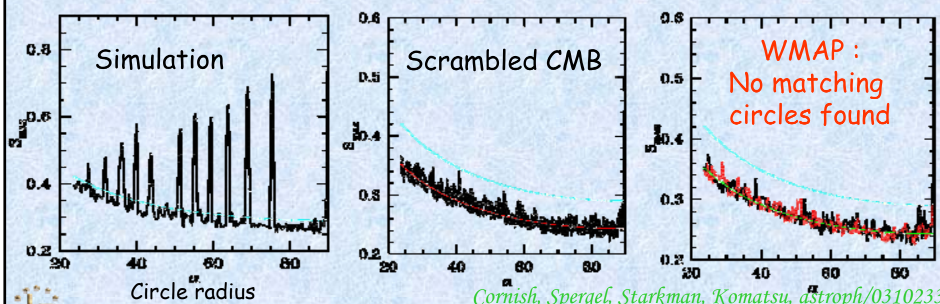


NON-TRIVIAL TOPOLOGY ?

- Based on the WMAP confirmation of low low-l power spectrum, it has been suggested that our space could be dodecahedral (shaped like a soccer ball)
- This model is slightly closed and positively curved, $\Omega = 1.013$

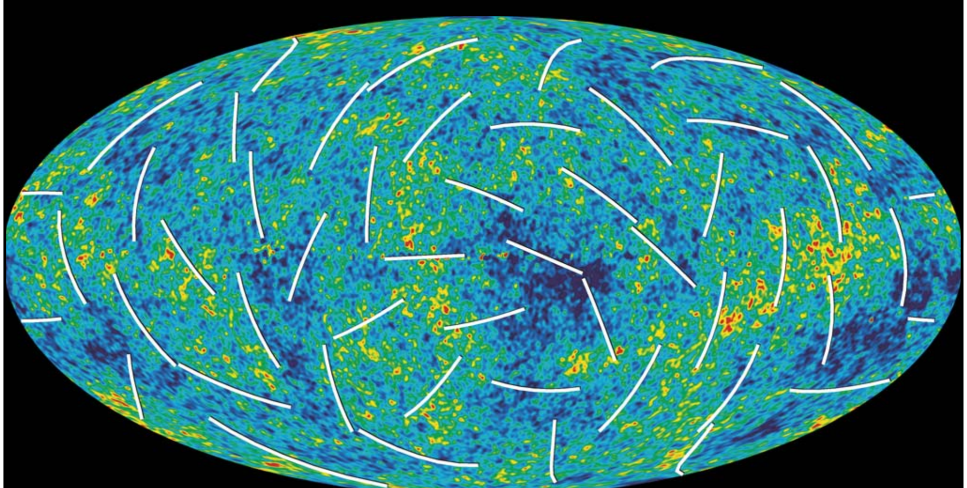
Luminet et al. 2003.





Cornish, Spergel, Starkman, Komatsu, astroph/0310233

WMAP 3 YEARS



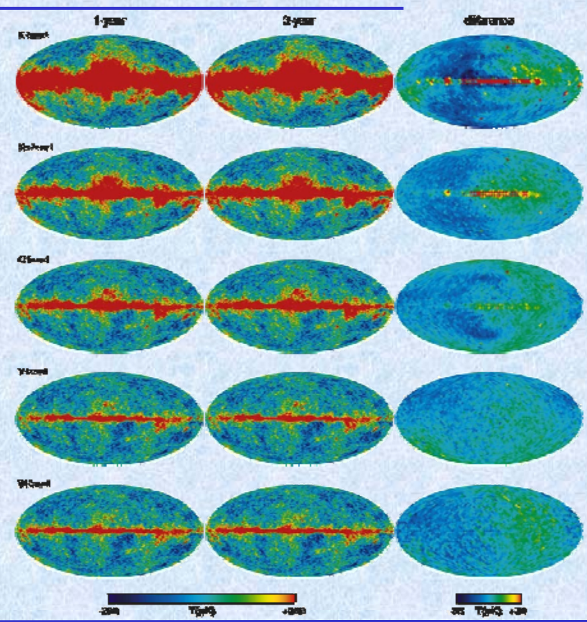
astro-ph/0603449 to astro-ph/0603452

Highlights

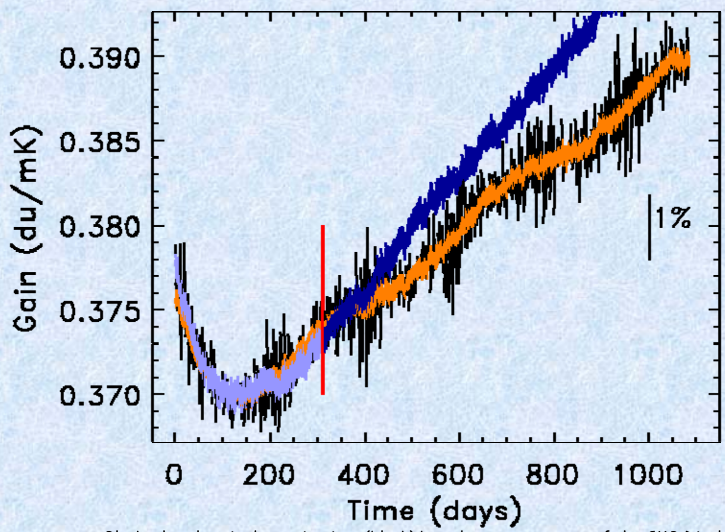
- Full sky polarisation measurements
  - Galactic foregrounds knowledge
  - Simple synchrotron emission model works well
- Minimal model - power-law CDM – with 6 parameters still fits well.
- χ2eff (TT)/dof = 1.068 (1.09 yr 1) & χ2eff (all)/dof = 1.04 (1.04 yr 1)
- Improvements in the constraints on parameters $\{\Omega_b h^2, \Omega_m h^2, h, \tau, n_s, A_s\}$
  - lower σ_8 and Ω_m (⇒ tension with lensing & Ly$_a$),
  - lower n_s and τ (⇒ hint on inflation, removes tension with Galaxy formation)
- Results from <u>much</u> 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



Gain Model Improvement



Black = hourly gain determinations (black) based on measurement of the CMB Dipole.
Blue = First year version of the radiometer gain model (light & extrapolation in dark).
Orange = new form gain model fit to all three years of data.
NB: difference between the models contains a component roughly linear in time.

Temperature Foreground Analysis - MEM

Synchrotron prior:

Haslam 408 MHz, index: $\beta_s = -2.9$

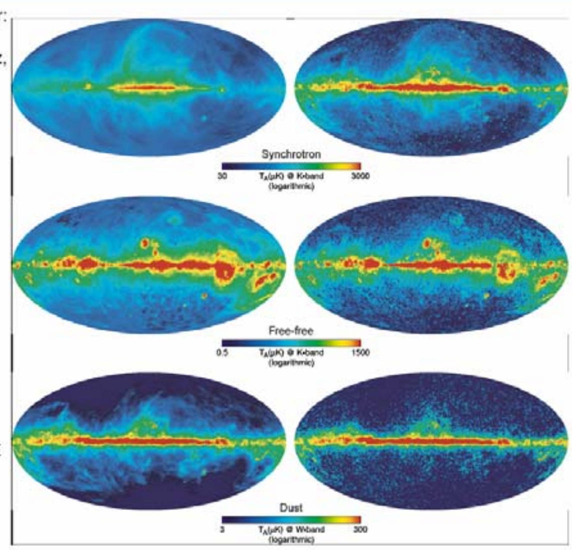
Free-free prior:

Finkbeiner Hα compilation*, 11.4 μK R^{-1}.

Dust prior:

FDS "Model 8", 2-component fit to IRAS/COBE

*WHAM, VTSS SHASSA



Synchrotron output:

Much brighter in outer plane. Anomalous dust emission?

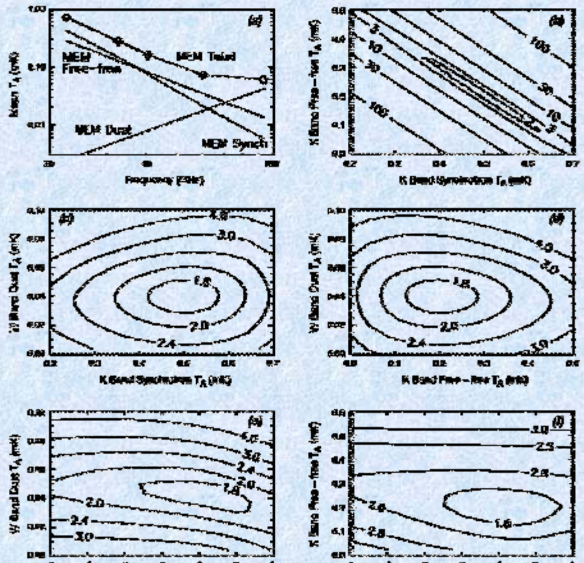
Free-free output:

Fainter than expected, ~8 μK R^{-1} Needs study.

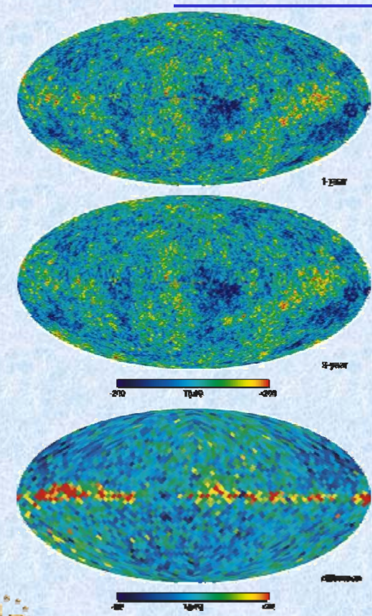
Dust output:

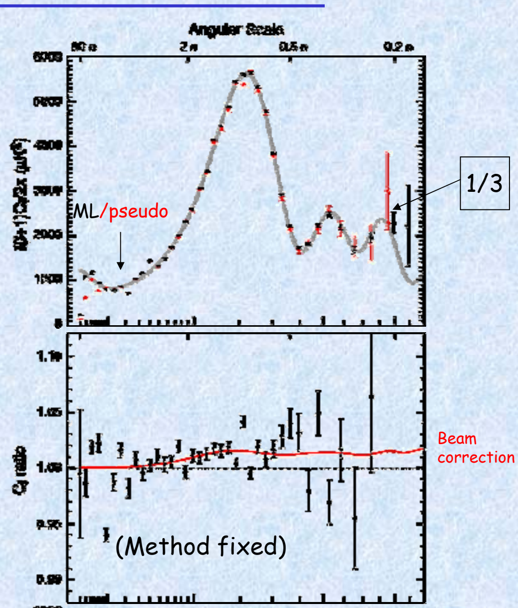
Excellent agreement with FDS "Model 8" prediction.

MEM FOREGROUND DEGENERACY ANALYSIS



WMAP 1 > WMAP 3



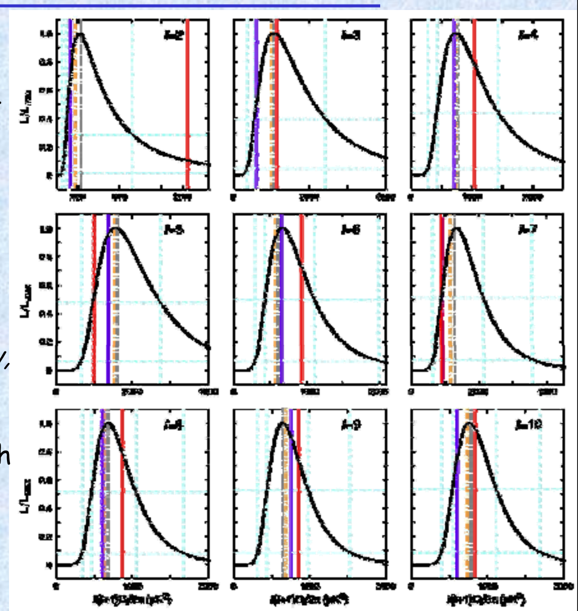


Low Quadrupole Power

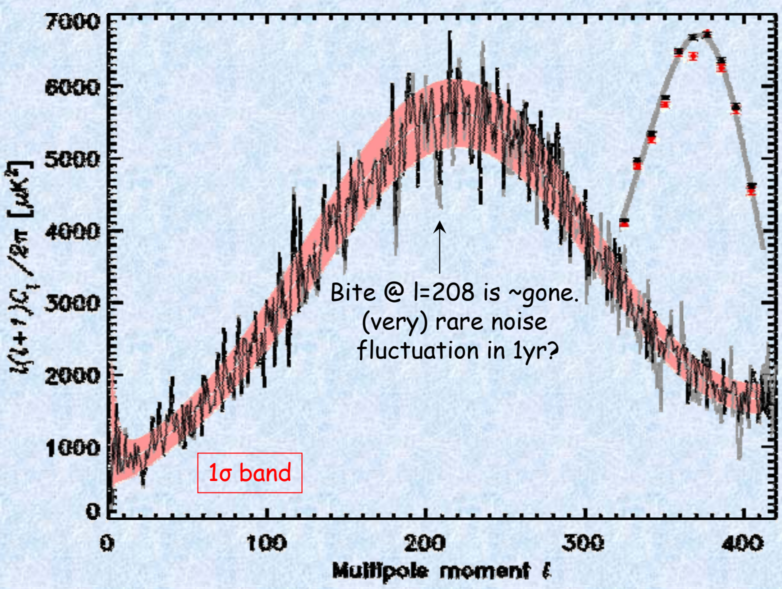
- Expected (mean) values for selected best-fit LCDM models -
  - Pure power-law, WMAP+CBI+ACBAR: 1221 mK^2*
  - Running index, WMAP+CBI+ACBAR: 870 mK^2
  - Power-law, CMB+2dF+Ly-a: 1107 mK^2
- Measured value(s) of quadrupole -
  - Quadratic estimator, V+W band, galaxy template & cut: 123 mK^2
    (Hinshaw, 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

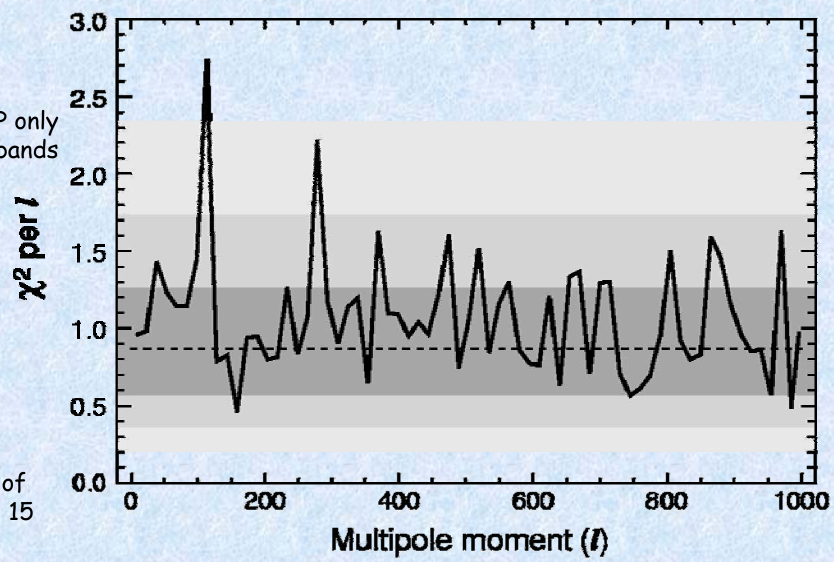


"LOOKS" OK?



χ2 VS. L /BEST-FIT LCDM MODEL

WMAP only
1,2,3 s bands



l bands of
width 15

"FEATURES" IN THE DATA

- low power, especially in the quadrupole moment;
- various "ringing" features, "glitches", and/or "bites" in the power spectrum.

- alignment of modes, particularly along an "axis of evil";
- unequal fluctuation power in the northern and southern sky;
- a surprisingly low three-point correlation function in the northern sky;
- an unusually deep/large cold spot in the southern sky;

- Usual Problem of a posteriori analyses in the absence of a theory

SUMMARY OF IMPROVEMENTS IN THE POLARIZATION ANALYSIS

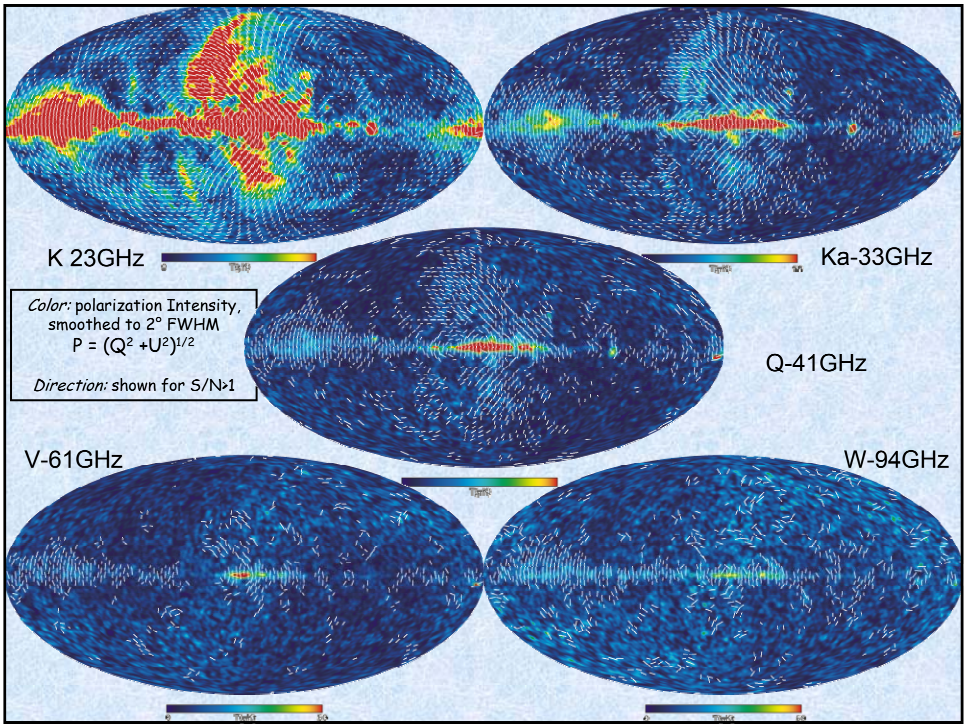
First Year (TE)

- 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)

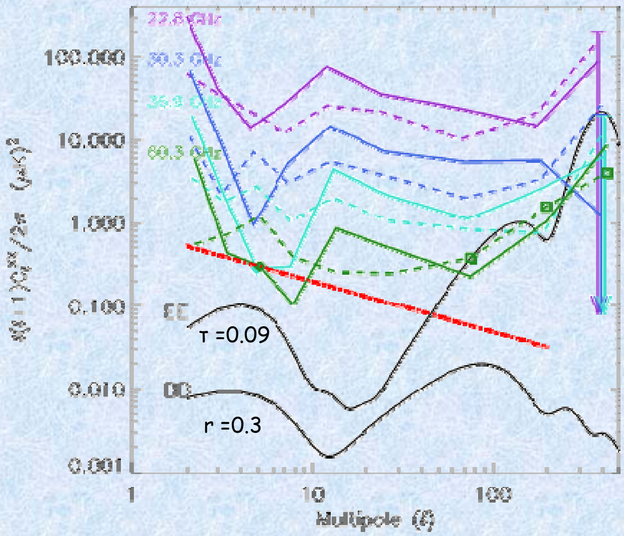


Polarised Foregrounds

- WMAP Polarization maps are foreground dominated at all frequencies.
- Emission can be interpreted in terms of a simple model of Galactic magnetic field and interstellar electron density.
- Improved foreground polarisation knowledge maybe the most important WMAP3 result for the future.

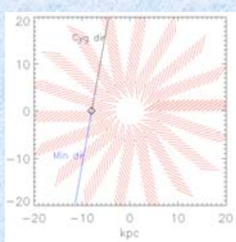
Polarised Foregrounds (outside P06)

- 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

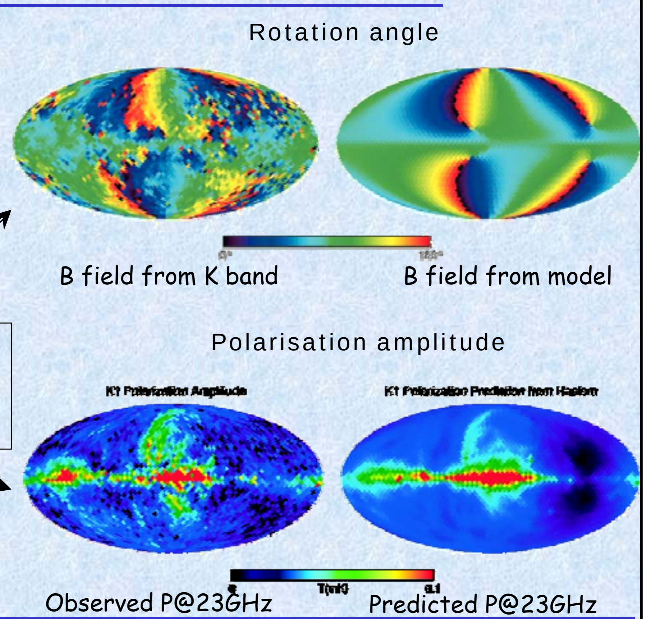


Must be cleaned…

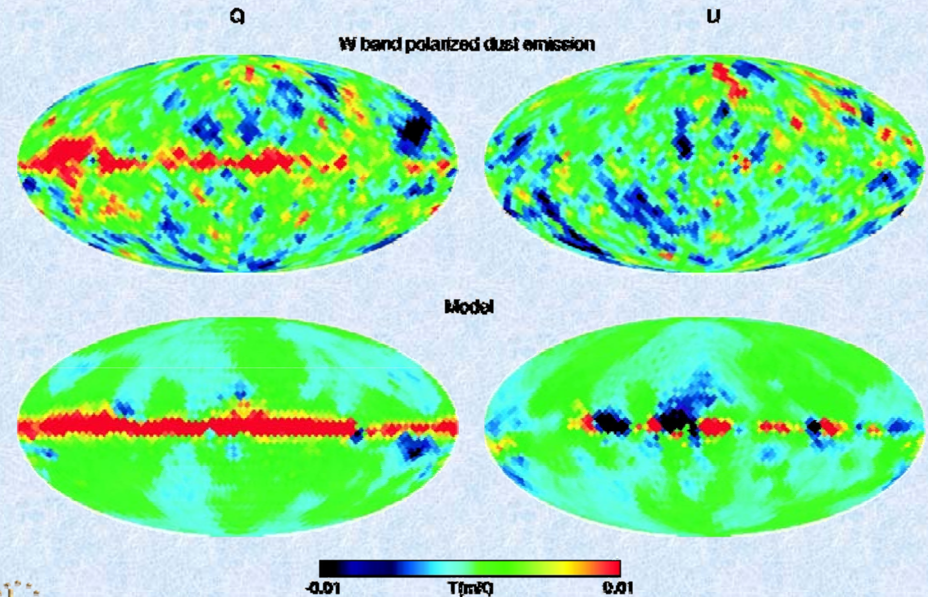
Synchrotron Emission



Bisymmetric Spiral Magnetic Field Model + electron distribution: $n_e = n_0 \exp(-r_5) \sec h^2(z)$

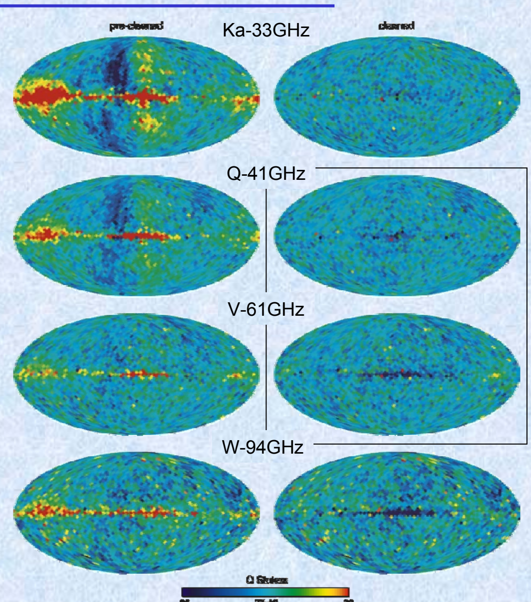


EXPECT PROGRESS IN DUST MODELLING

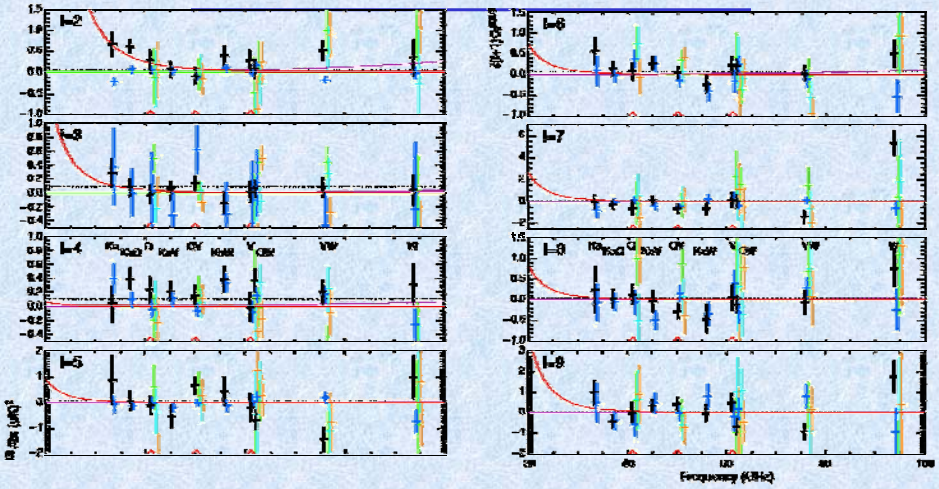


POLARISED FOREGROUNDS SUBTRACTION

- 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



Frequency dependence of (cleaned) L-modes

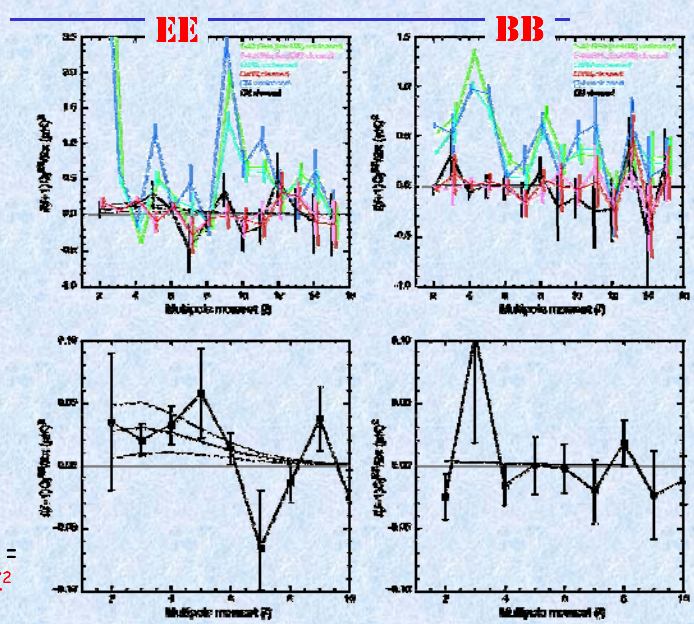


Black=EE, blue=BB; + null tests :green, cyan, and orange show the EE year_i – year_j spectra (the BB ones are similar).
Dotted black line = predicted EE for τ = 0.09.

For cosmological analysis, only the QQ, QV, and VV frequency channels are used (red triangles on the bottom of each panel).
(red line = 15% of raw synchrotron @ Kband; brown line = 5% polarized dust).
Note: all frequency combinations above 40 GHz (excluding KW), BB is clearly consistent with zero.

Low-L polarisation spectra

What the cleaning does...

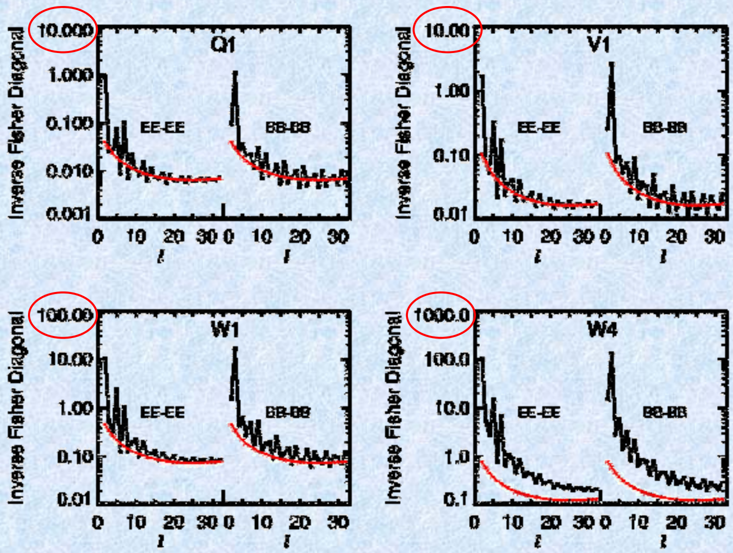


About all reionisation information comes from that bump...

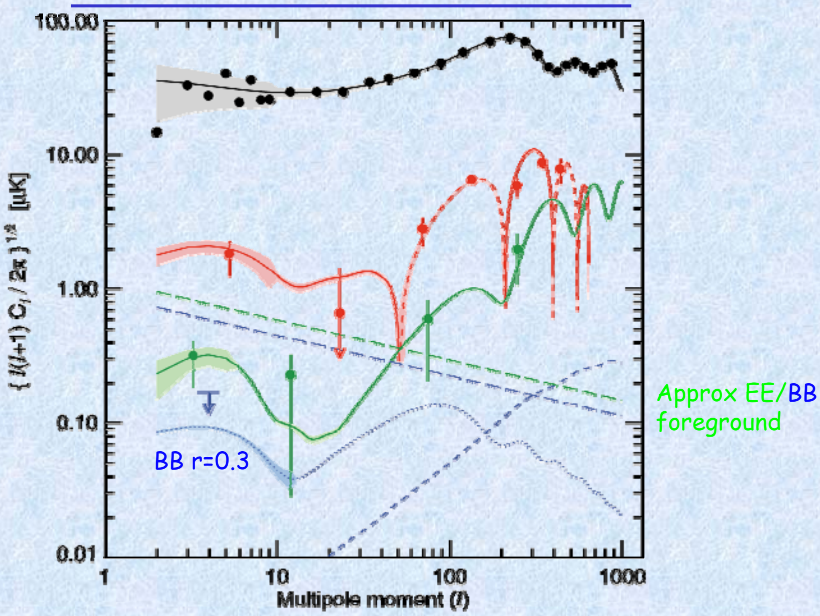
$l^2C^E\langle 2\text{-}6\rangle/2\pi$ =
0.09+-0.03μK^2

PREDICTED C(L) ERRORS (IN μK^4)

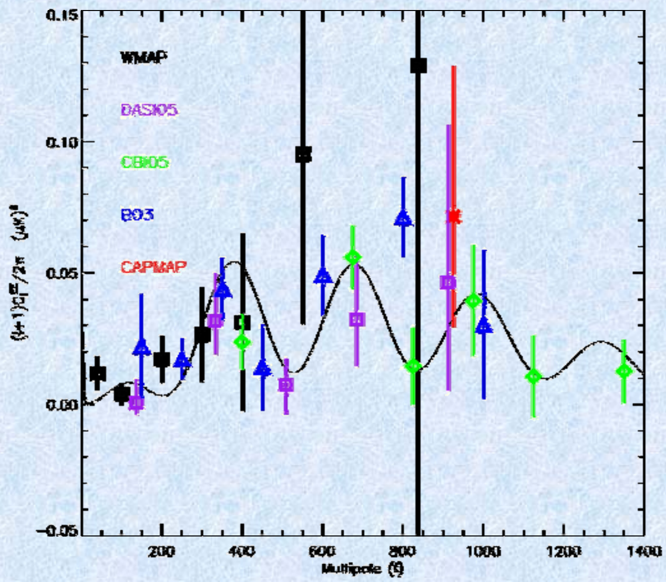
- variations in the N^{-1} weighting are due to the scan pattern combined with the sky cut.
- W data 3 years still not good enough at l=5,7!



WMAP3 SPECTRA



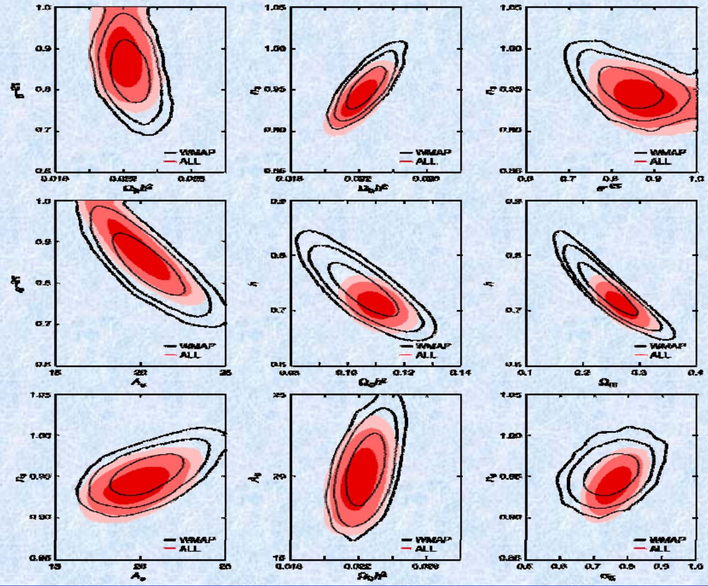
EE spectrum at ℓ > 40 (all today)



3 years results

WMAP3 ONLY/ALL

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



CONSISTENCY WITH LSS

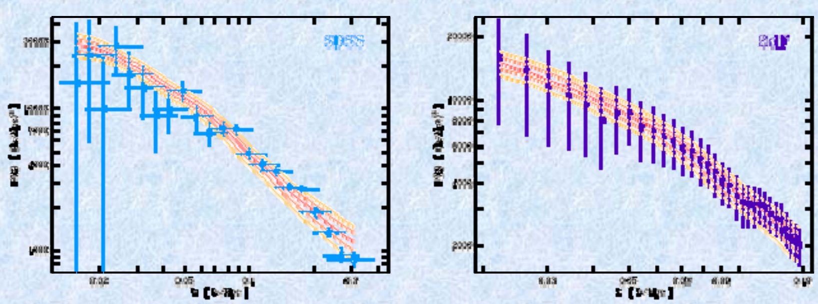
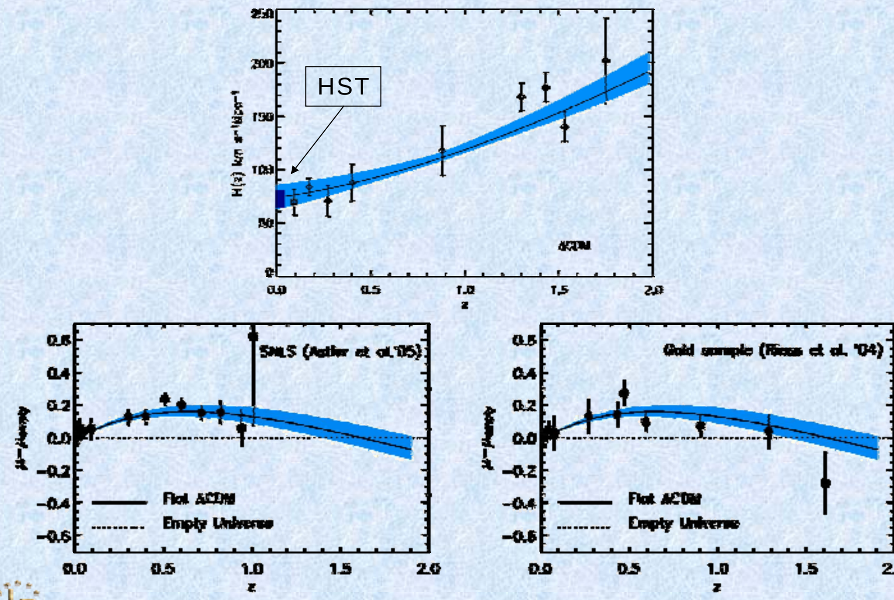
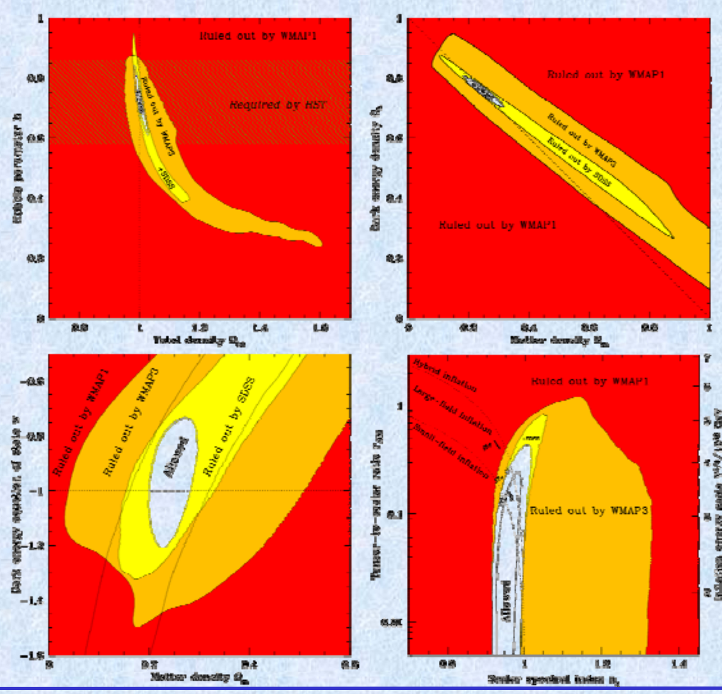


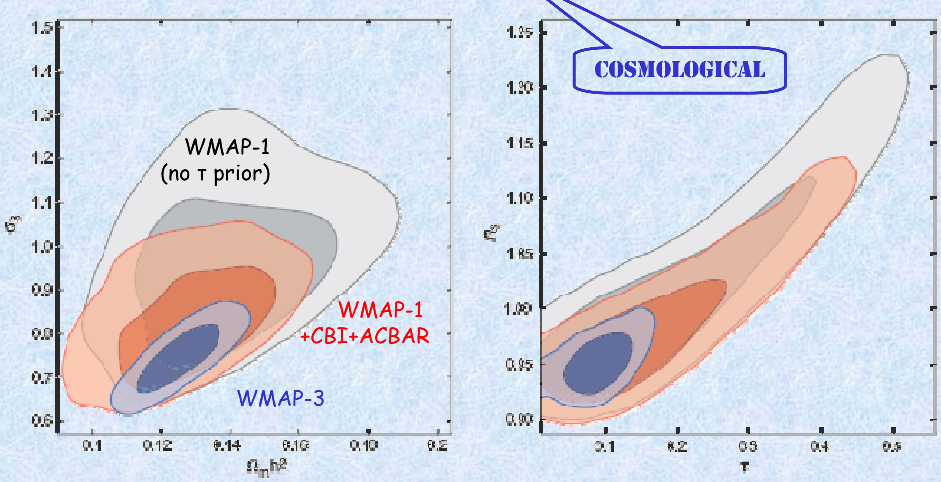
Fig. 6.— The prediction for the mass fluctuations measured by galaxy surveys from the ΛCDM model fit to the WMAP data only. (*Left*) The predicted power spectrum (based on the range of parameters consistent with the WMAP-only parameters) is compared to the mass power spectrum inferred from the SDSS galaxy 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





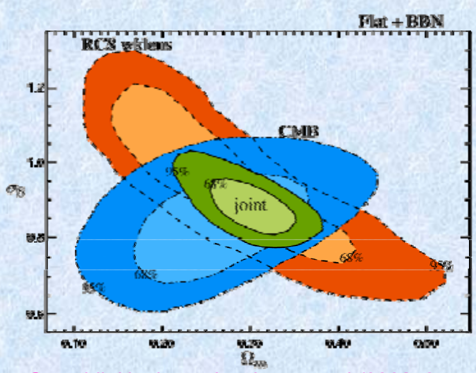
WMAP MAIN RESULTS



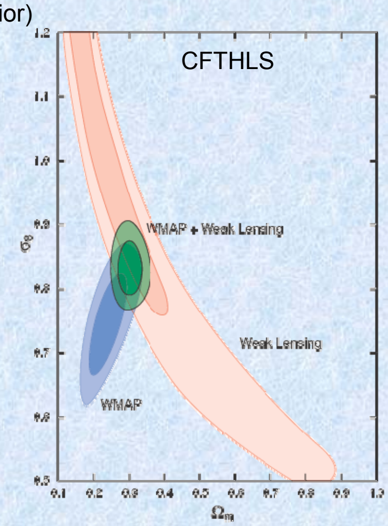
Improvement in parameter constraints for the power-law CDM model (6 pars).
$\{\Omega_b h^2, \Omega_m h^2, h, \tau, n_s, A_s\}$
χ2eff (TT)/dof = 1.068 (1.09 yr 1) & χ2eff (all)/dof = 1.04 (1.04 yr 1)

A_S-Ω_M

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



Contaldi, Hoekstra, Lewis: astro-ph/0302435



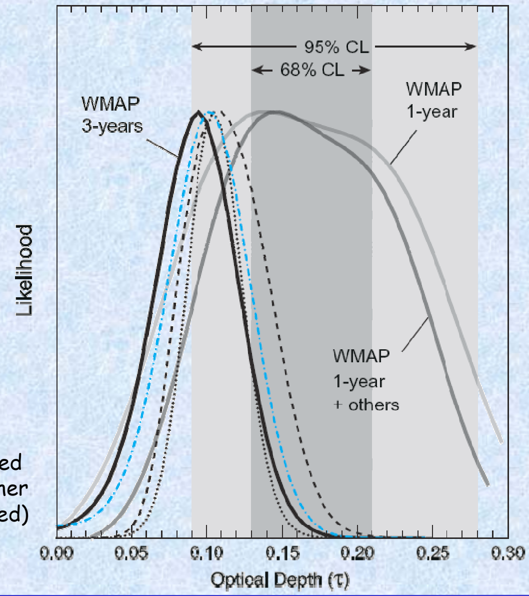
NB: σ_8 and A_S are just different normalisation of the (scalar) power spectrum

Spergel et al 2006

OPTICAL DEPTH

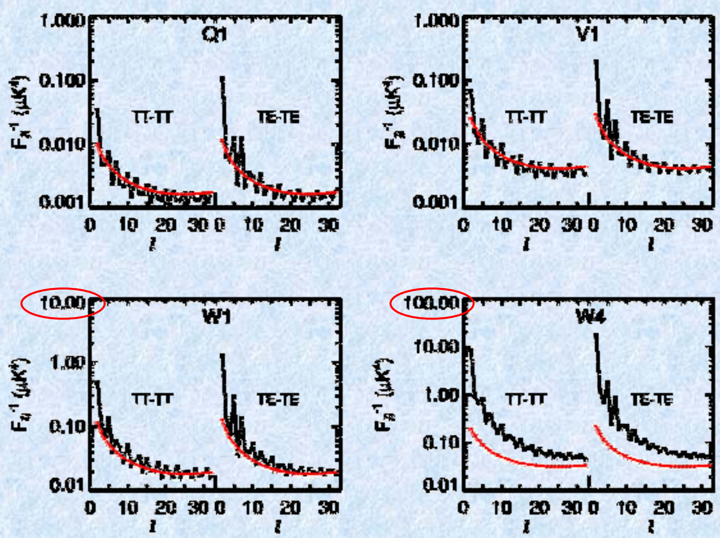
- TE-3 years contributes very little
- Alone would be an upper limit on tau
- New noise estimation is the reason
- tau from (EE-) 3yr is compatible at 2σ level with 1 yr data

(likelihood plotted keeping all other parameters fixed)

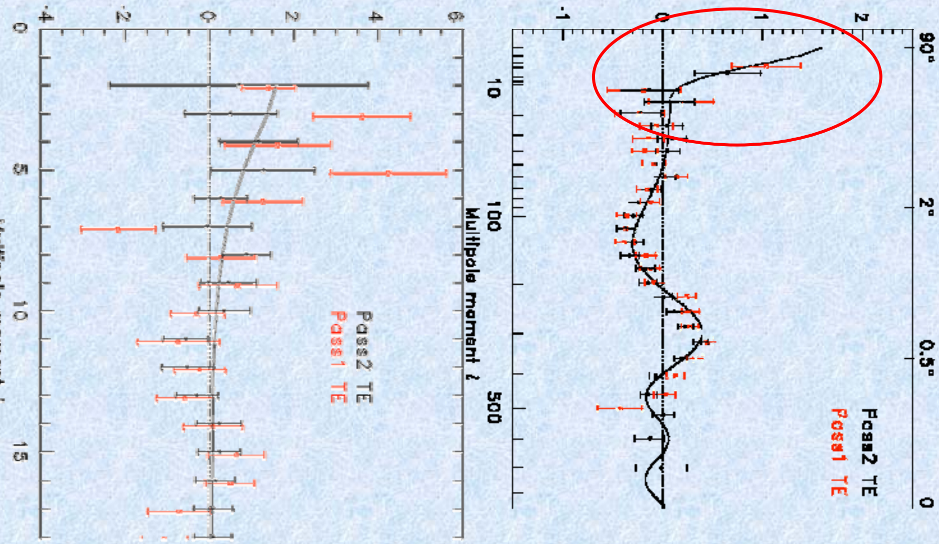


PREDICTED CL UNCERTAINTY AT LOW L

- 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

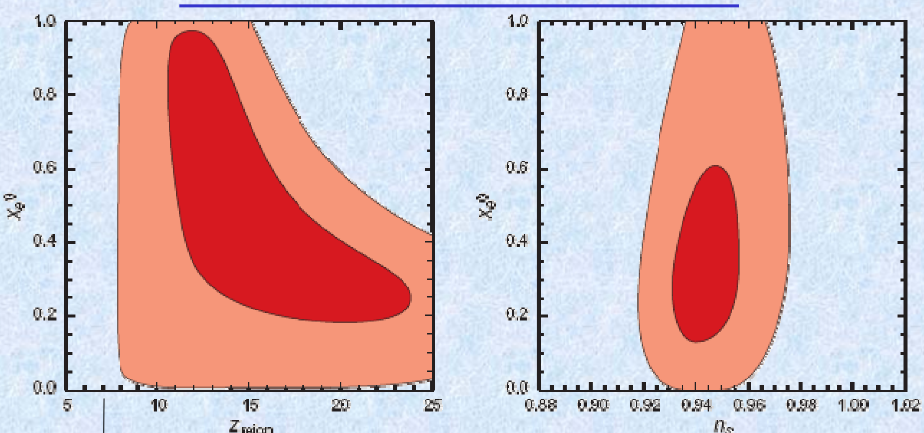


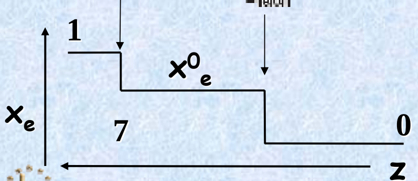
TE COMPARISON 1 VS 3 YEARS



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

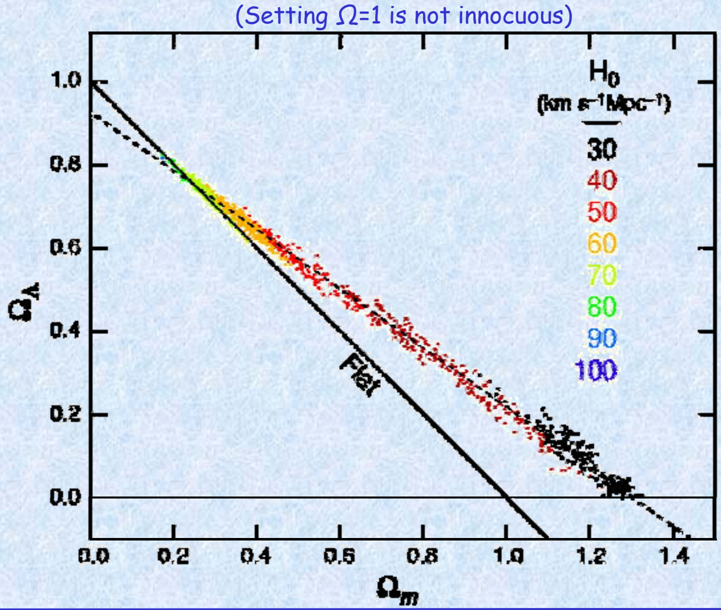
WHAT'S NEEDED!

	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:

Ω/H DEGENERACY TRACK

(Setting Ω=1 is not innocuous)



CONSTRAINING IC

Epsilon, eta et ksi correspond to successive derivatives of the inflation potential

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

Measurement of the amplitude of tensor modes fixes Hubble parameter H during inflation when relevant scales are leaving horizon; alternatively, fixes scalar field potential and first derivative.

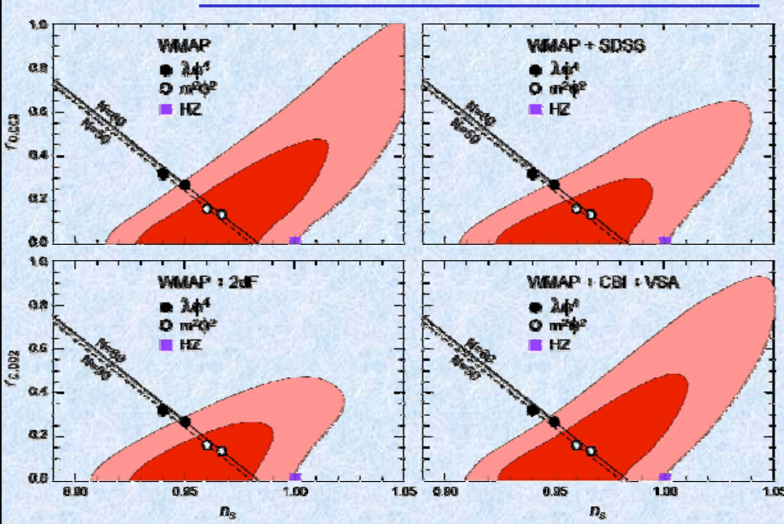
e.g. Liddle & Lyth (1993), Copeland et al. (1993), Liddle (1994)

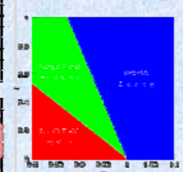
$$H \equiv \dot{a}/a \approx \frac{1}{M_{Pl}}\sqrt{\frac{V}{3}}$$

$$r = \frac{2V}{3\pi^2 M_{Pl}^4 \Delta_R^2(k_0)} = 8M_{Pl}^2\left(\frac{V'}{V}\right)^2$$

$$V^{1/4} \leq 3.3\times10^{16}\, r^{1/4}\ \text{GeV}$$

IMPLICATIONS (FOR INFLATION)





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

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

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

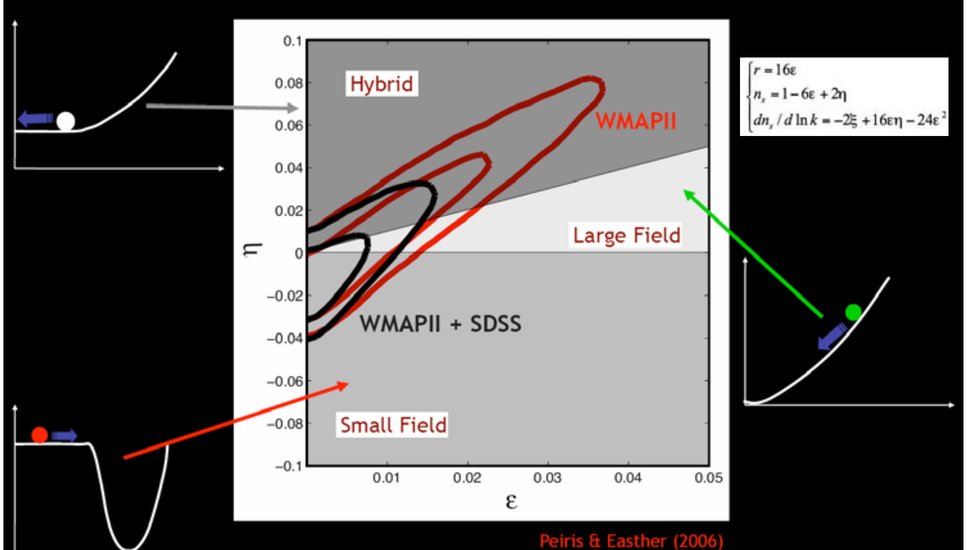
LIMITS ON TENSOR-TO-SCALAR RATIO

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)

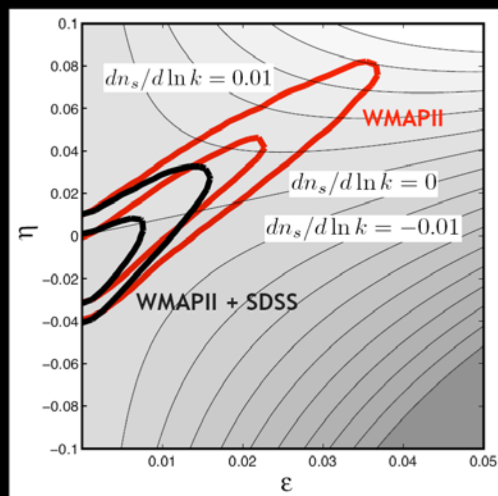
The Inflationary Zoo



Peiris & Easther (2006)

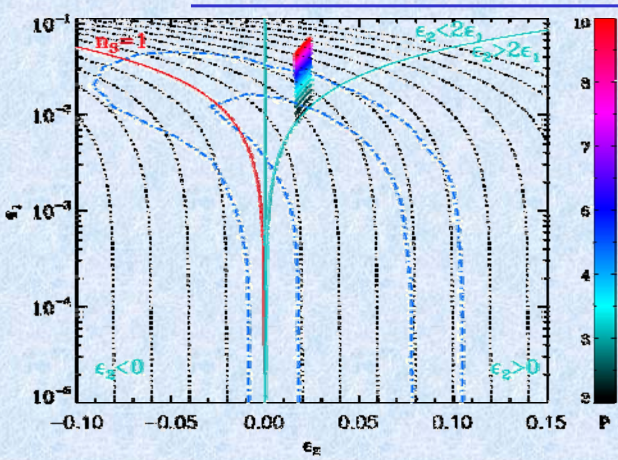
Constraints on first two HSR parameters at k=0.002 Mpc^{-1}

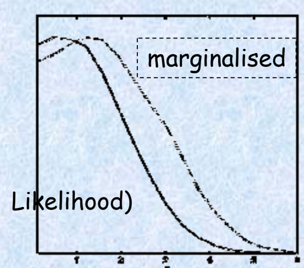
Inflation and a running spectral index?



Peiris & Easther (2006)

Constraints on Large-Field Models



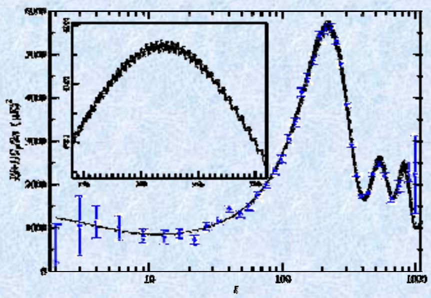


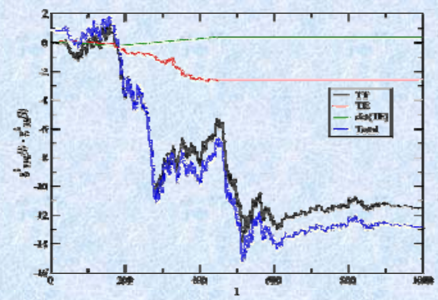
- Models $V \propto \Phi^p$
- Dotted = constant spectral index lines
- P>4 are in trouble (one start constraining the potential shape)

Martin & Ringeval 2006 (to be submitted to JCAP)

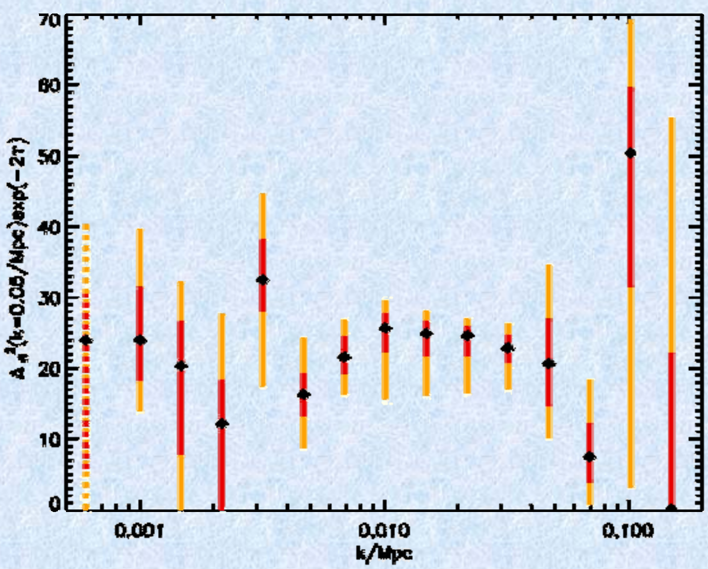
A sign of trans-Planckian physics?

- Probleme theorique trans-Planckien J. Martin and R. Brandenberger, PRD 63 123501, 2001 (hep-h/0005209)
- WMAP et les oscillations :
  - J. Martin & C. Ringeval, PRD 69 064406, 2004 (astro-ph/ 0310382);
  - J. Martin & C. Ringeval, PRD 69 127303, 2004 (astro-ph/ 0402609);
  - J. Martin & C. Ringeval, JCAP 0501 007, 2004 (astro-ph/0405249)
- Ongoing discussions with WMAP team, stay tuned…



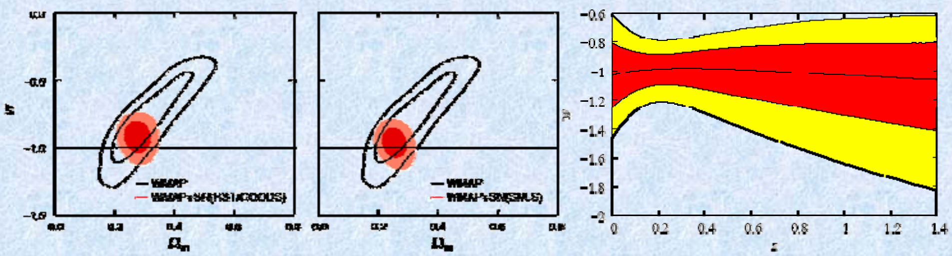


Reconstructed shape of P_S



INVESTIGATING DARK ENERGY

- The equation of state parameter w(z) = p/ρ
  - w = -1
  - w = const ≠ -1
  - w(z)



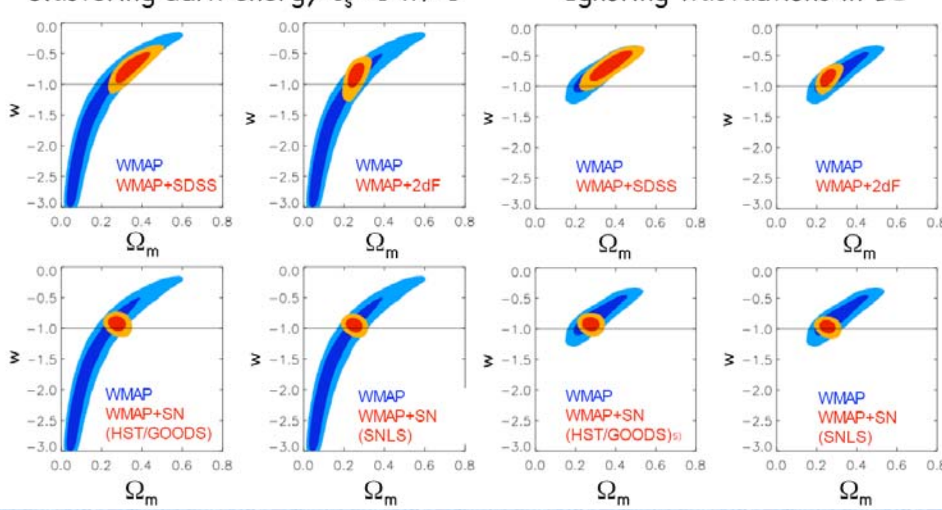
Spergel et al 2006

Seljak et al 2005

DARK ENERGY

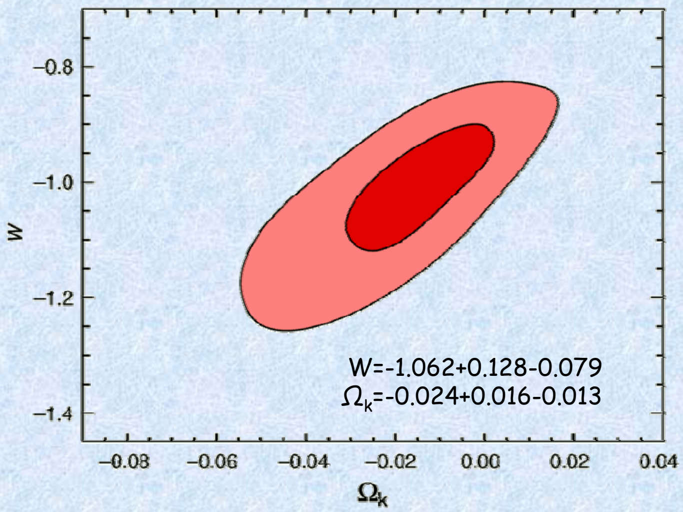
Clustering dark energy c_s^2=1 w≠-1

Ignoring fluctuations in DE



Equation of State & Curvature

Interesting constraints are beginning to emerge

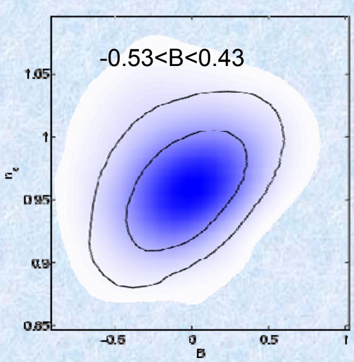


WMAP+CMB+2dFGRS+SDSS+SN

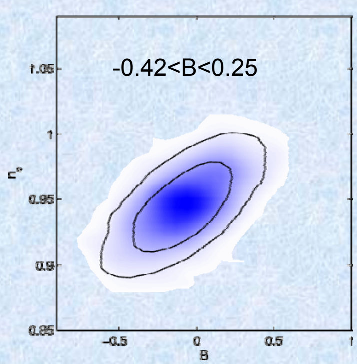
Matter Isocurvature Modes

- Possible in two-field inflation models, e.g. 'curvaton' scenario
- Curvaton model gives adiabatic + correlated CDM or baryon isocurvature, no tensors
- CDM, baryon isocurvature indistinguishable – differ only by cancelling matter mode

Constrain B = ratio of matter isocurvature to adiabatic



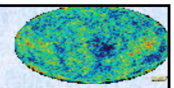
WMAP1+2df+CMB+BBN+HST

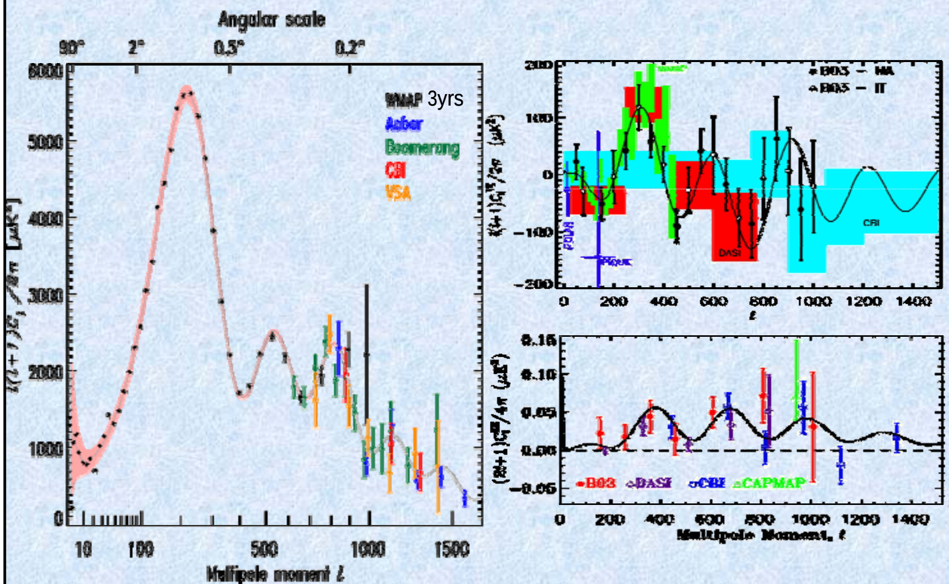


WMAP3+2df+CMB

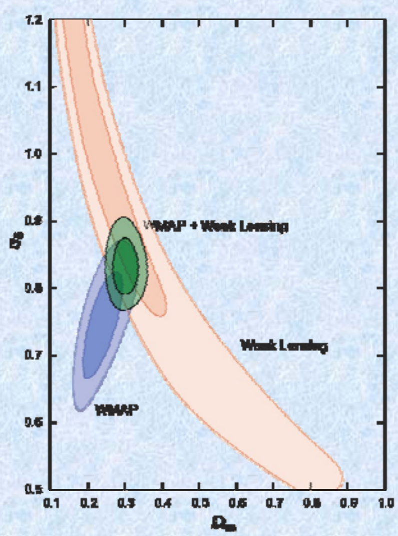
Gordon, Lewis: astro-ph/0212248 Lewis @ Moriond-march06

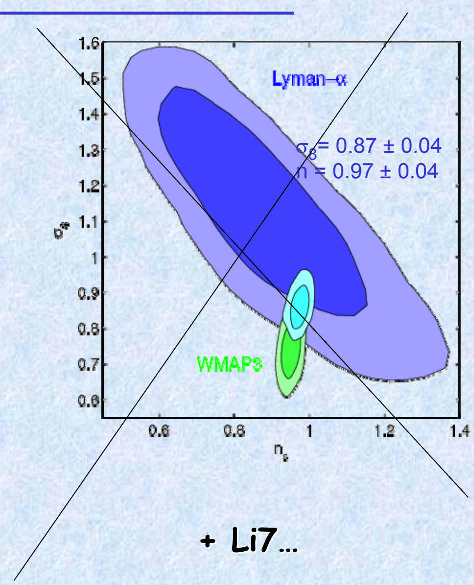
What we now know





With some interesting tensions...

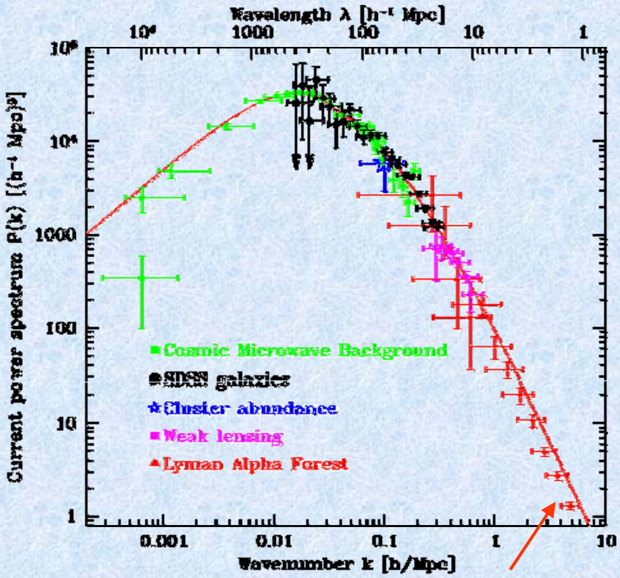




La cosmologie a un modèle cohérent

RCF en accord avec :

- estimation BBN de la densité baryonique
- Mesures HST du taux d'expansion
- Mesures de distance par les Supernova
- Ages stellaires tirés de la théorie de l'évolution stellaire
- Estimations des fluctuations de densité
  - Déflections Gravitationnelles
  - Amas
  - Grandes structures
  - Forêt Lyman α



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

Non-Gaussianity in WMAP?

- Initial analyses indicated that the WMAP results were consistent with Gaussianity:
  1) Three point tests are consistent up to known point source contribution (Komatsu et al., Gaztanaga & Wagg)
  2) Apparent non-Gaussianities in COBE bispectrum do not appear in WMAP (Magueijo & Madeiros)
  3) Topological tests (Minkowski functionals, genus) also consistent (Komatsu et al., Colley & Gott)
- Limits not sufficient yet to probe the levels predicted by inflation models
- But recent analyses point to possible inconsistencies:
  1) Evidence that north ecliptic hemisphere has less large scale power than southern (Eriksen et al.)
  2) A wavelet analysis shows evidence for non-Gaussianity in the southern Galactic hemisphere (Vielva et al.)
  3) Asymmetry between some genus statistics for north and south Galactic hemispheres (Park)
  4) Some strange alignments seen in the quadrupole and octupole moments (Tegmark et al.)
  5) Multipole vector analysis indicates unexpected alignments at low l (Copi et al.)
  6) Evidence for strange phase correlations at l=16 (Coles et al.) and at very high l (Chiang et al.)
- Is it significant?
  - Most authors argue against foreground being responsible, but it is not impossible
  - Possibly a problem with *a posteriori* statistics, but many seem to be pointing to similar problems
  - Could it be similar to COBE problems, where some of the data was contaminated? This seems unlikely for the large scale problems.
- The jury is still out, and more investigation is needed!

Maps of Power Spectrum Modes L = 2 − 8