# CMB studies with Planck

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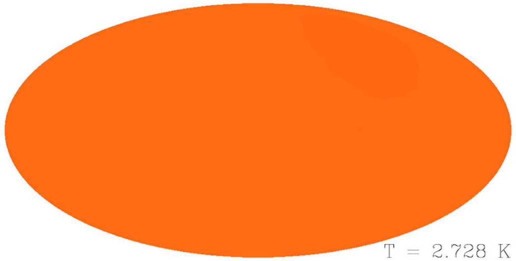
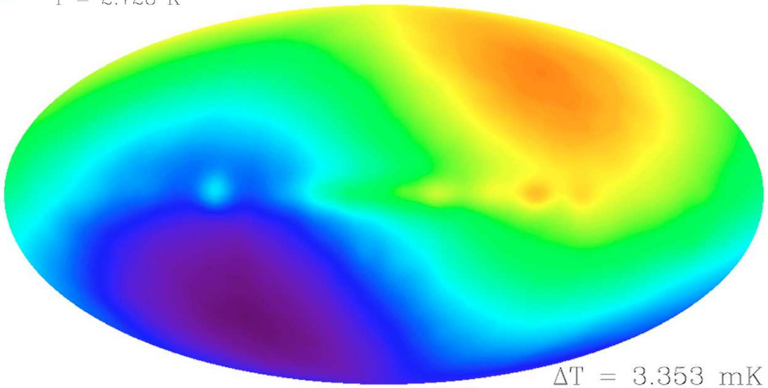
Thanks to Anthony Challinor & Anthony Lasenby for a few slides

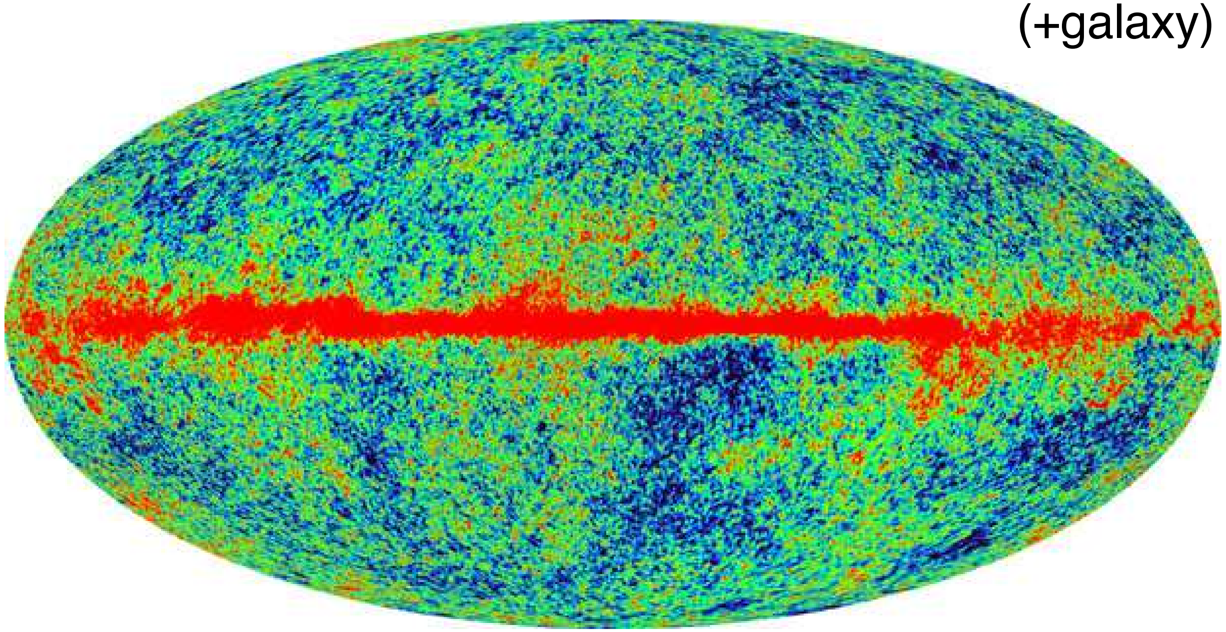


(almost) uniform 2.726K blackbody




Dipole (local motion)

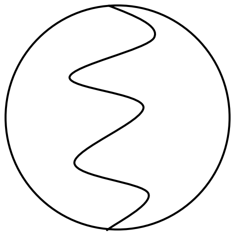
$O(10^{-5})$ perturbations
(+galaxy)



# Observations: the microwave sky today

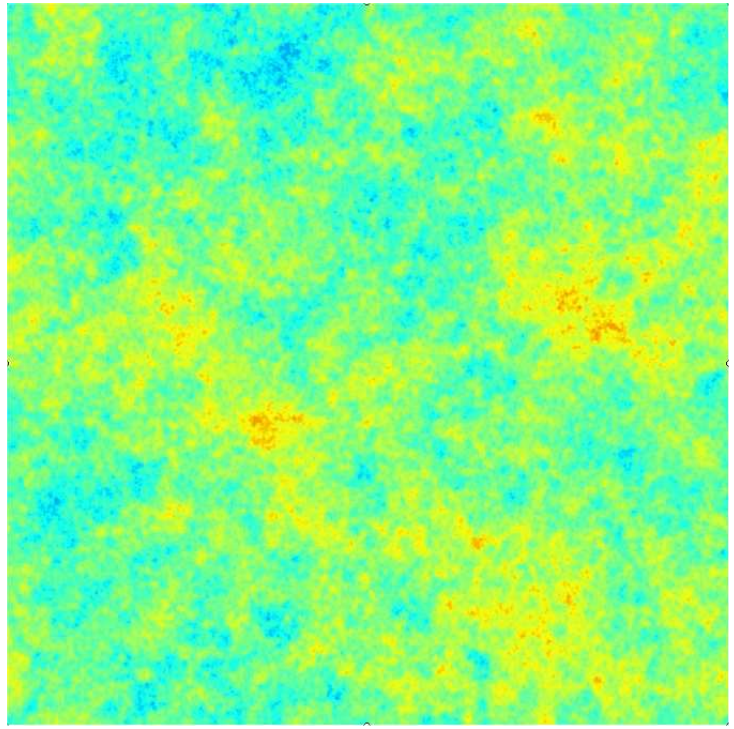
Source: NASA/WMAP Science Team

# Where do the perturbations come from?



**Quantum Mechanics**
“waves in a box”

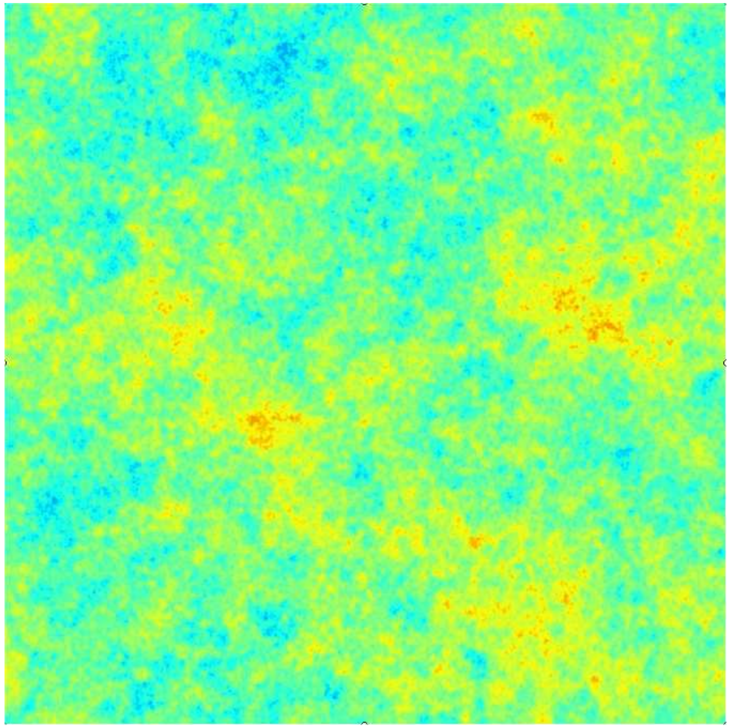
**Inflation**
make $>10^{30}$ times bigger



**After inflation**
Huge size, amplitude $\sim 10^{-5}$

# CMB temperature

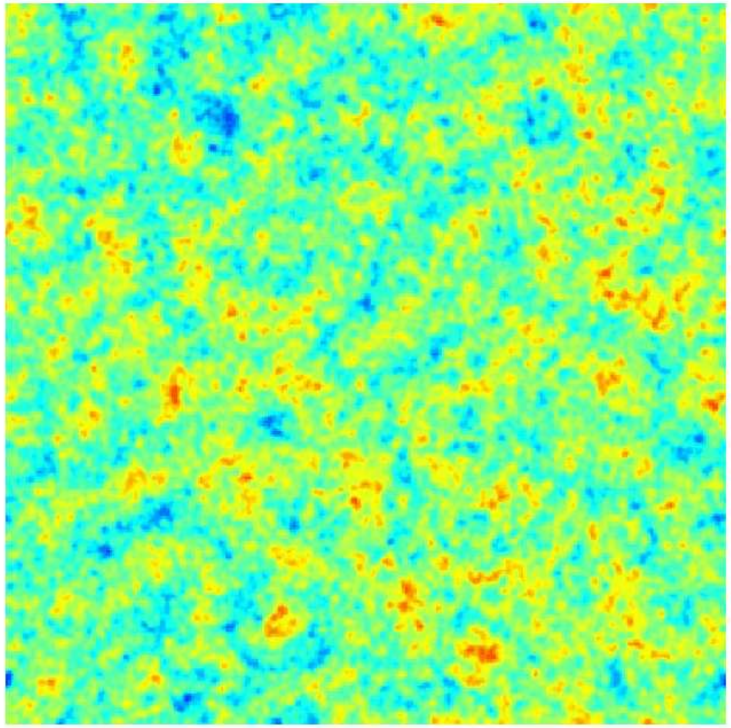
End of inflation

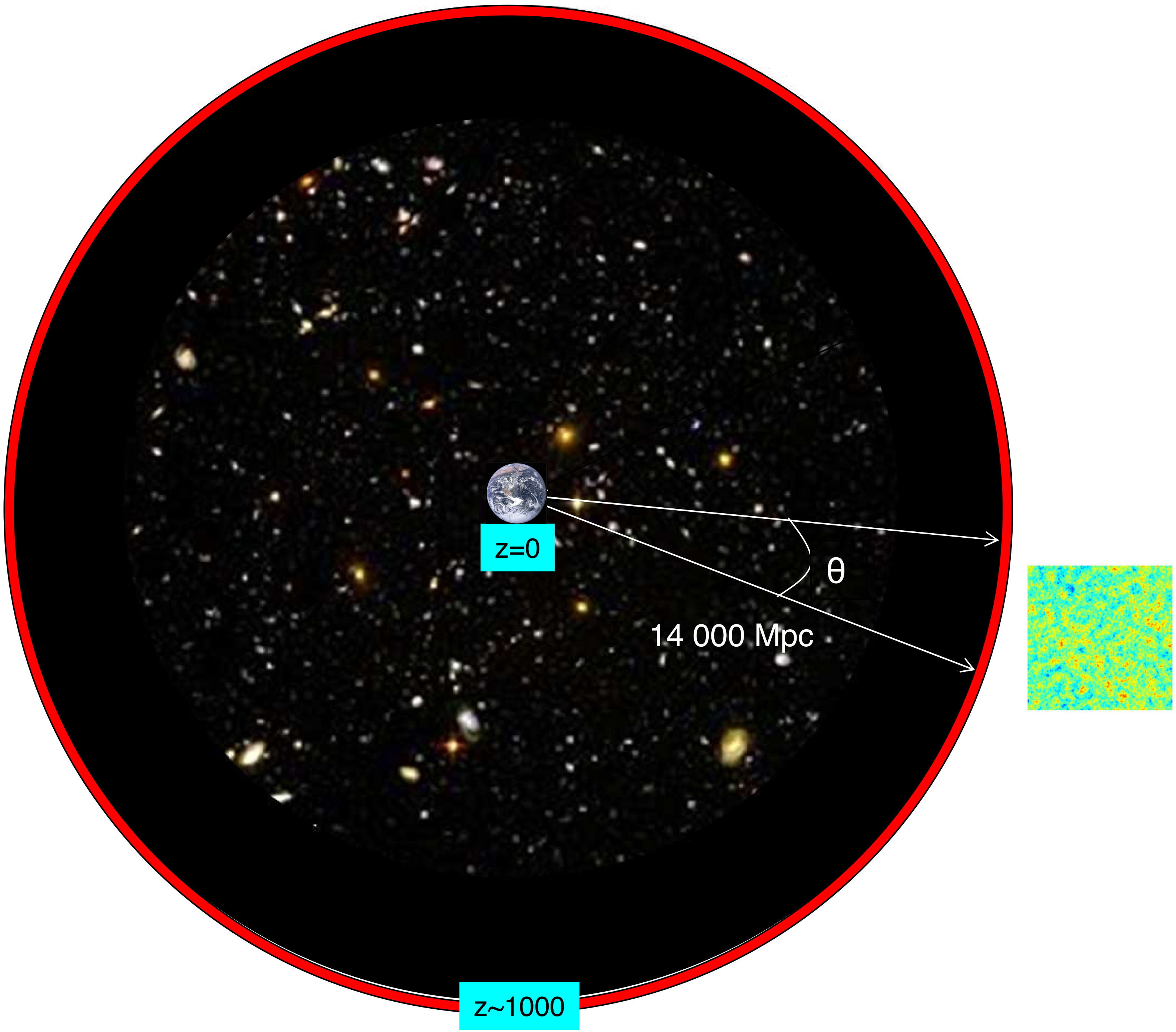


gravity+
pressure+
diffusion

→

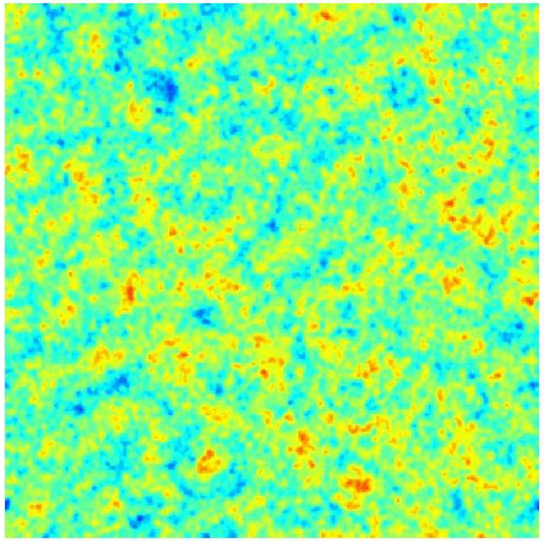
Last scattering surface

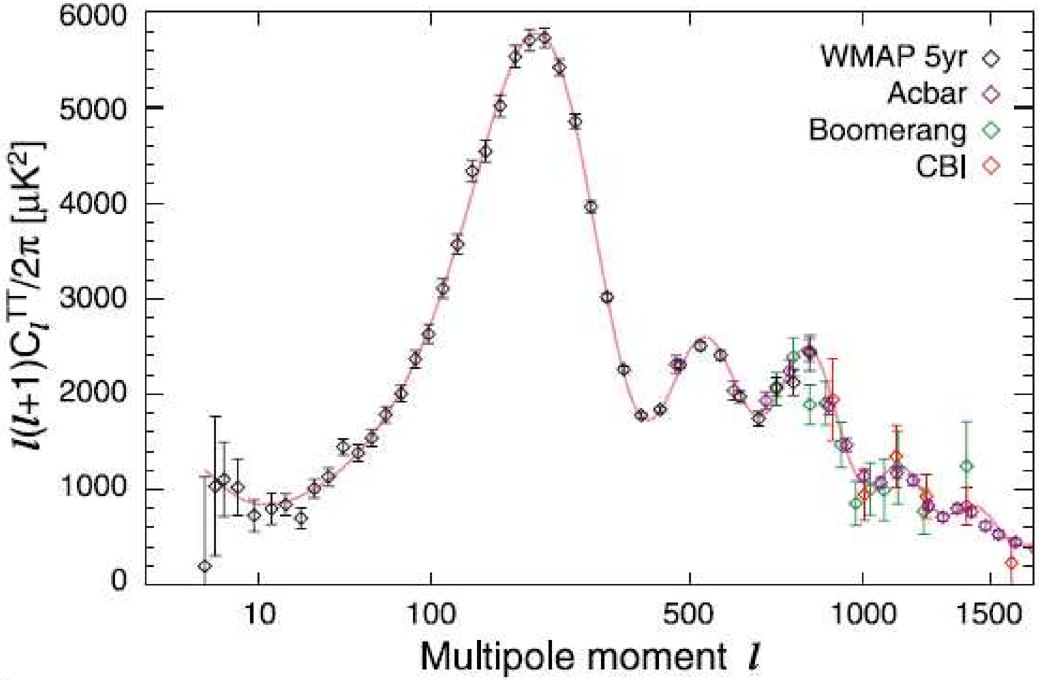



z=0
θ
14 000 Mpc
z~1000

# Observed CMB temperature power spectrum

**Primordial perturbations + known physics with unknown parameters**

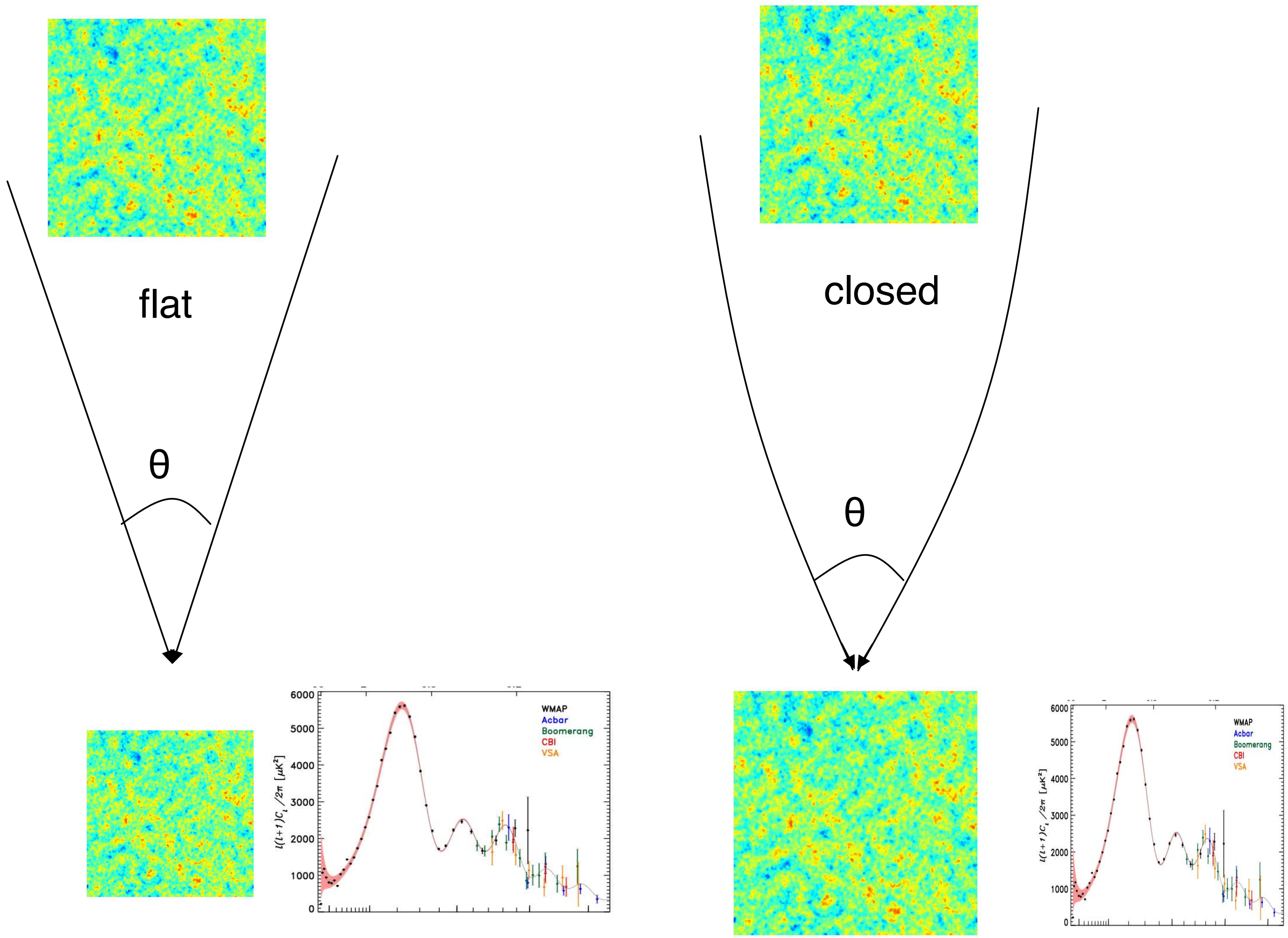





Nolta et al.

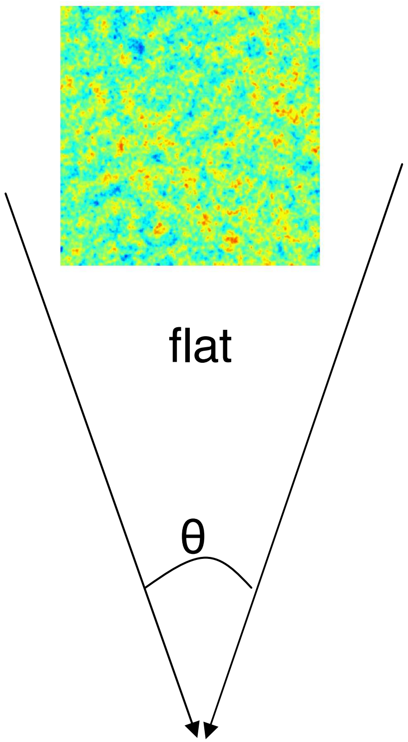
**Observations** → **Constrain theory of early universe + evolution parameters and geometry**

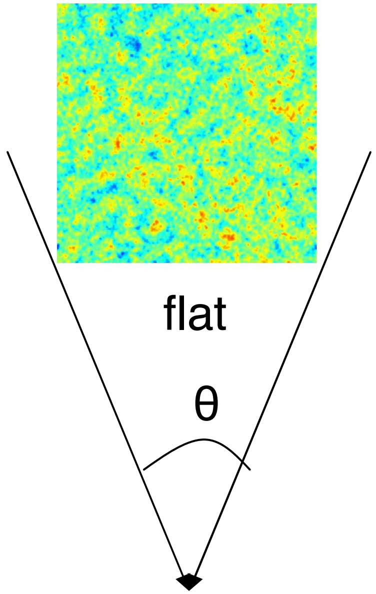
# e.g. Geometry: curvature



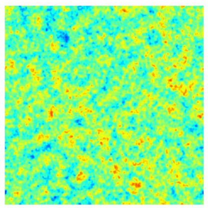

We see:

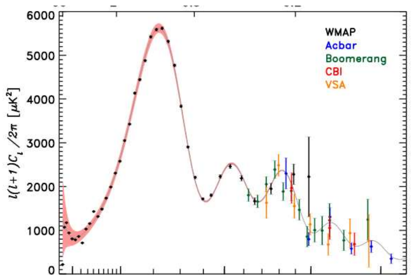
or is it just closer??

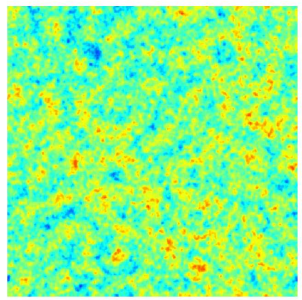


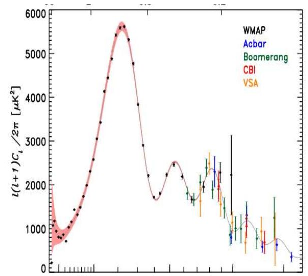




We see:



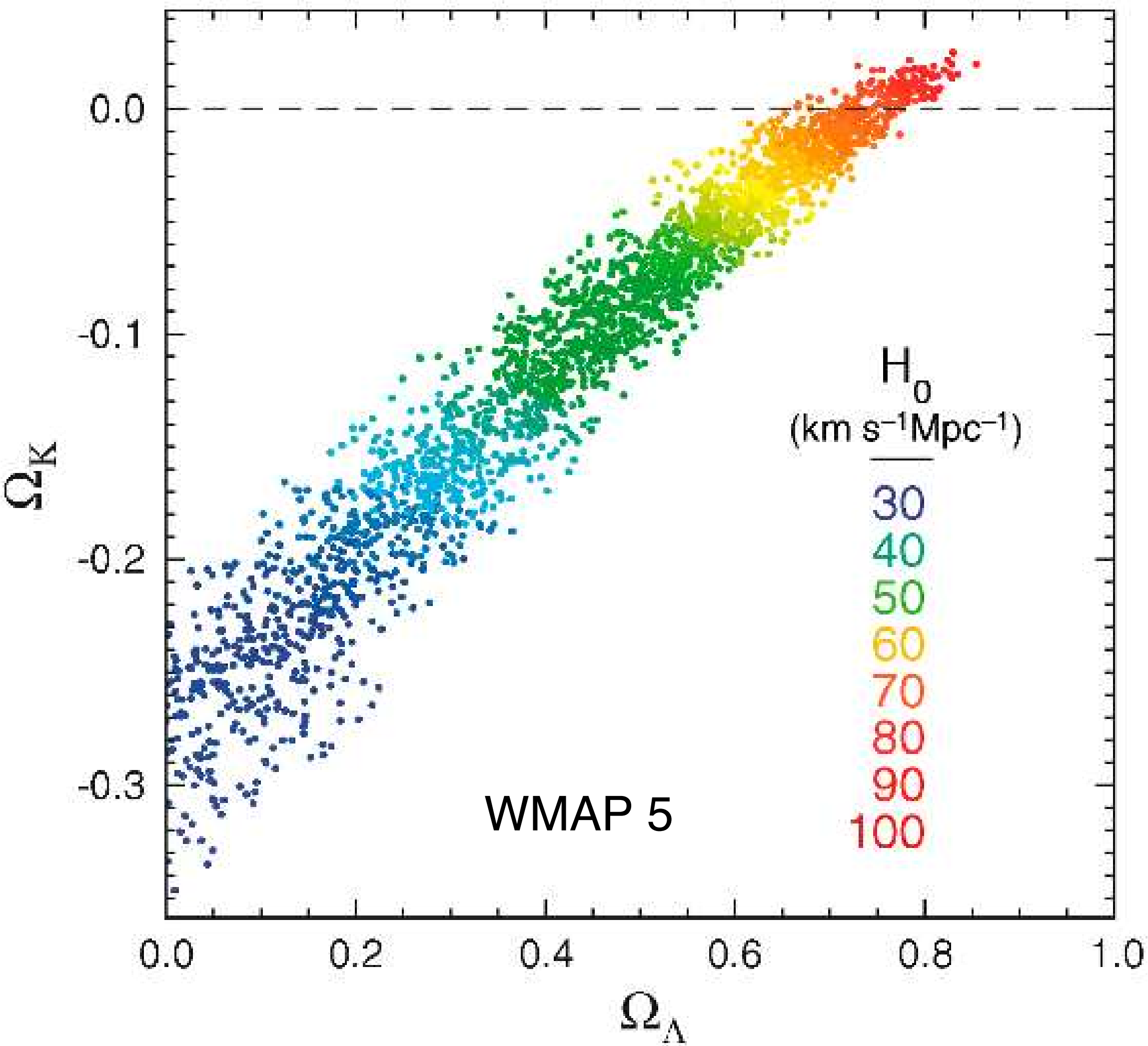


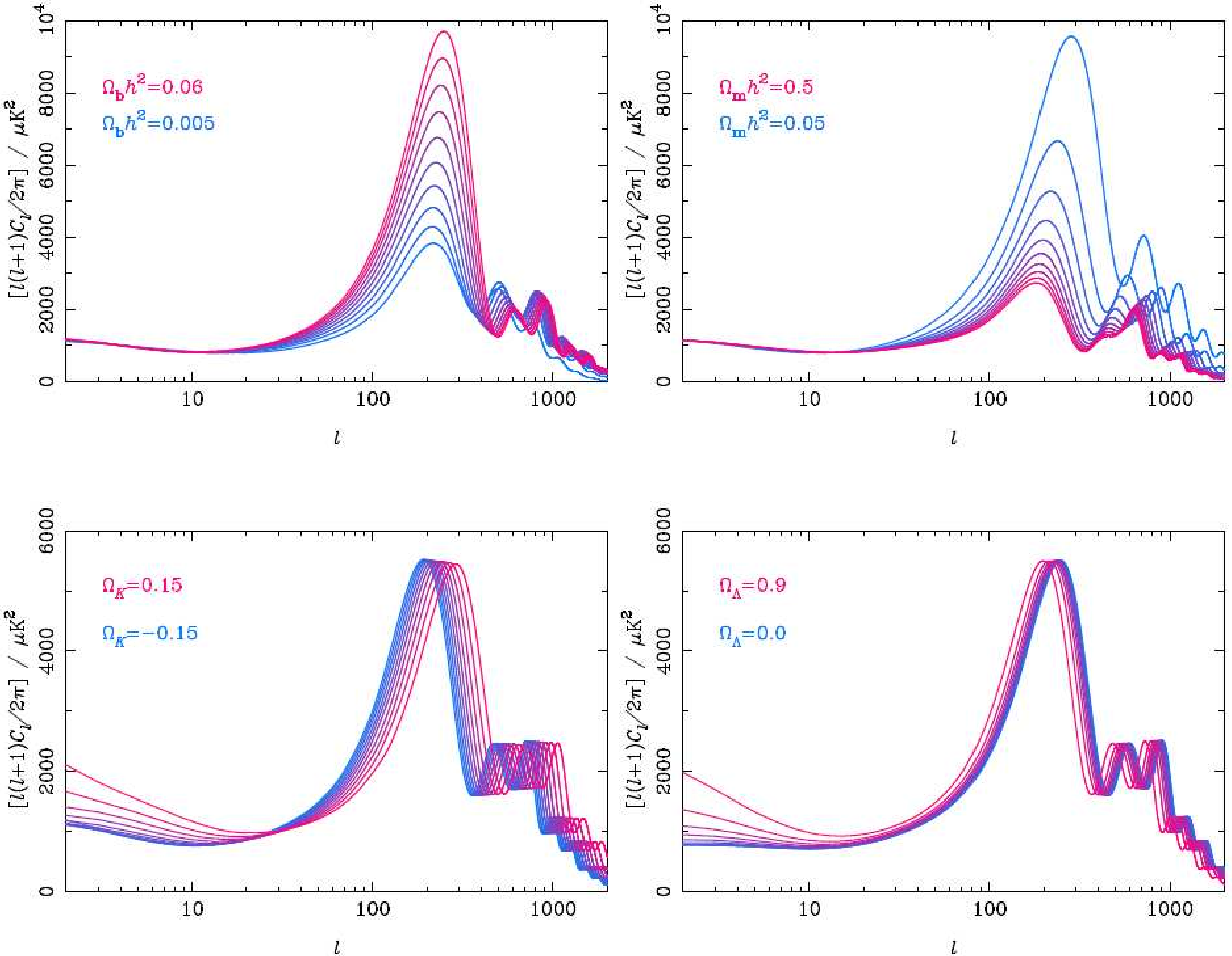



Degeneracies between parameters

Dunkley et al. 2009

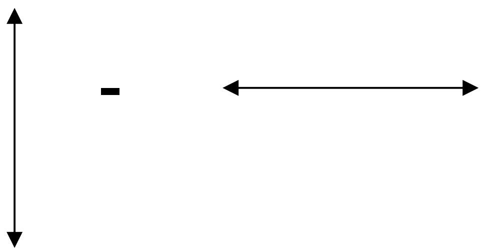



Use other data to break remaining degeneracies

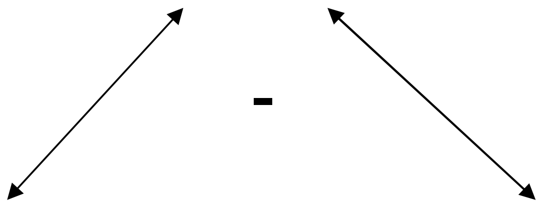



Credit: Anthony Challinor

# Polarization: Stokes' Parameters



Q

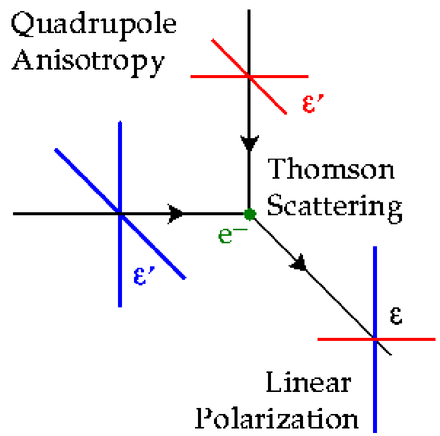


U

Q → -Q, U → -U under 90 degree rotation

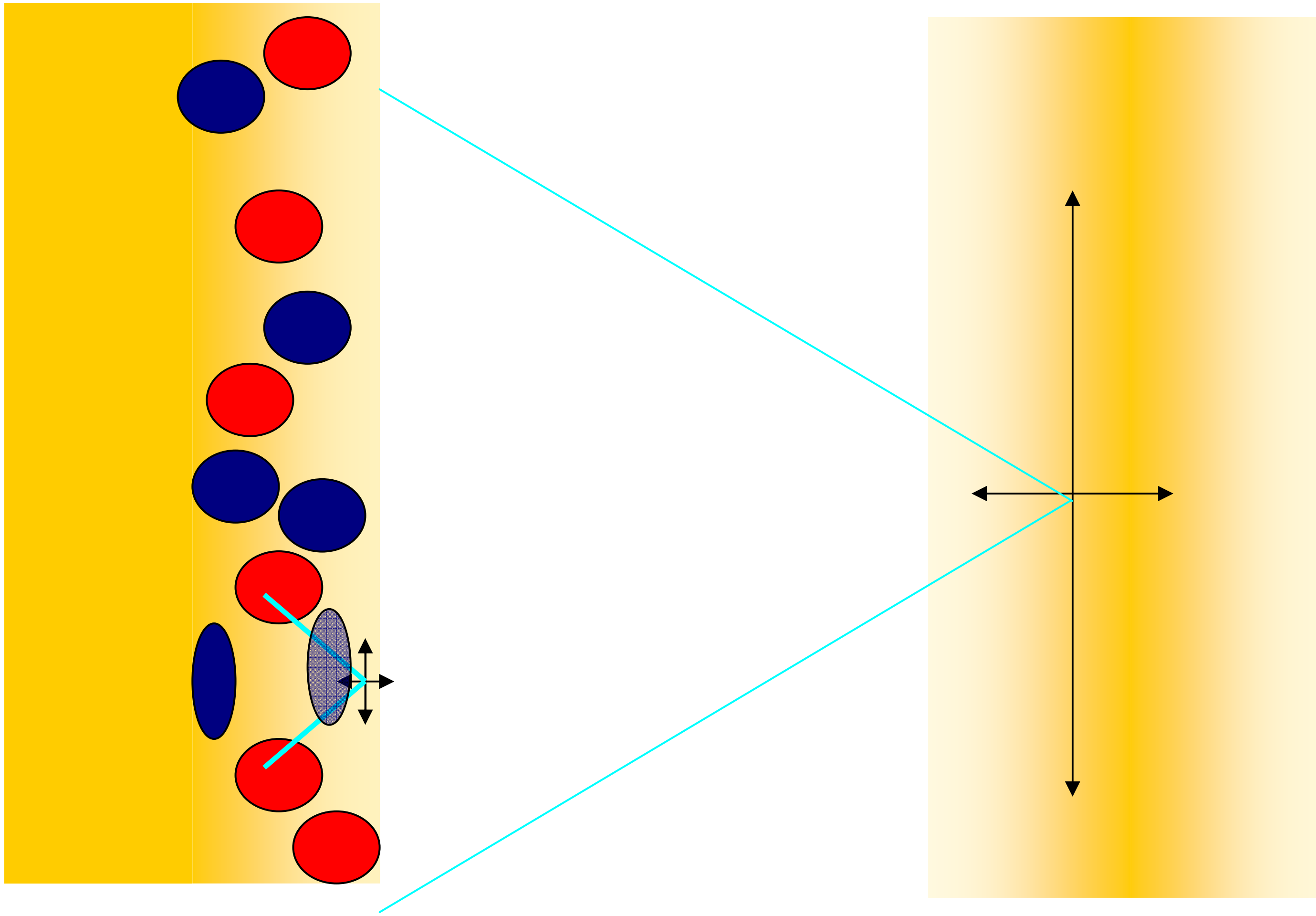
Q → U, U → -Q under 45 degree rotation

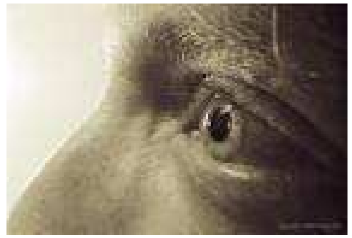
Generated by Thomson scattering of anisotropic unpolarized light




Hu astro-ph/9706147

$$n_e \sim x_e\,(1+z)^3\,n_0$$





Local quadrupole at end of recombination

Large-scale quadrupole scatters at reionization

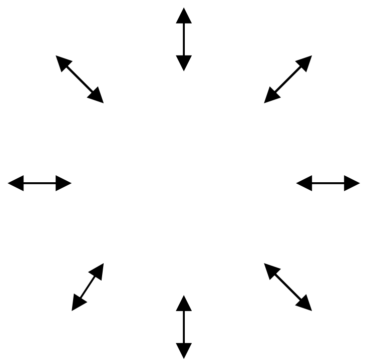
Scale of acoustic peaks

Large-scale
(coherent over horizon scale at reionization)

# CMB polarization: E and B modes

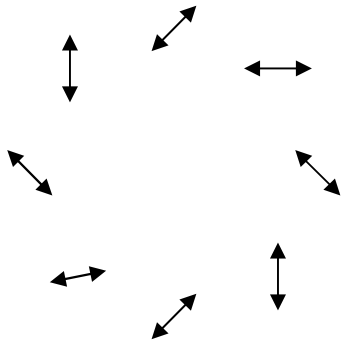
“gradient” modes
E polarization

e.g.

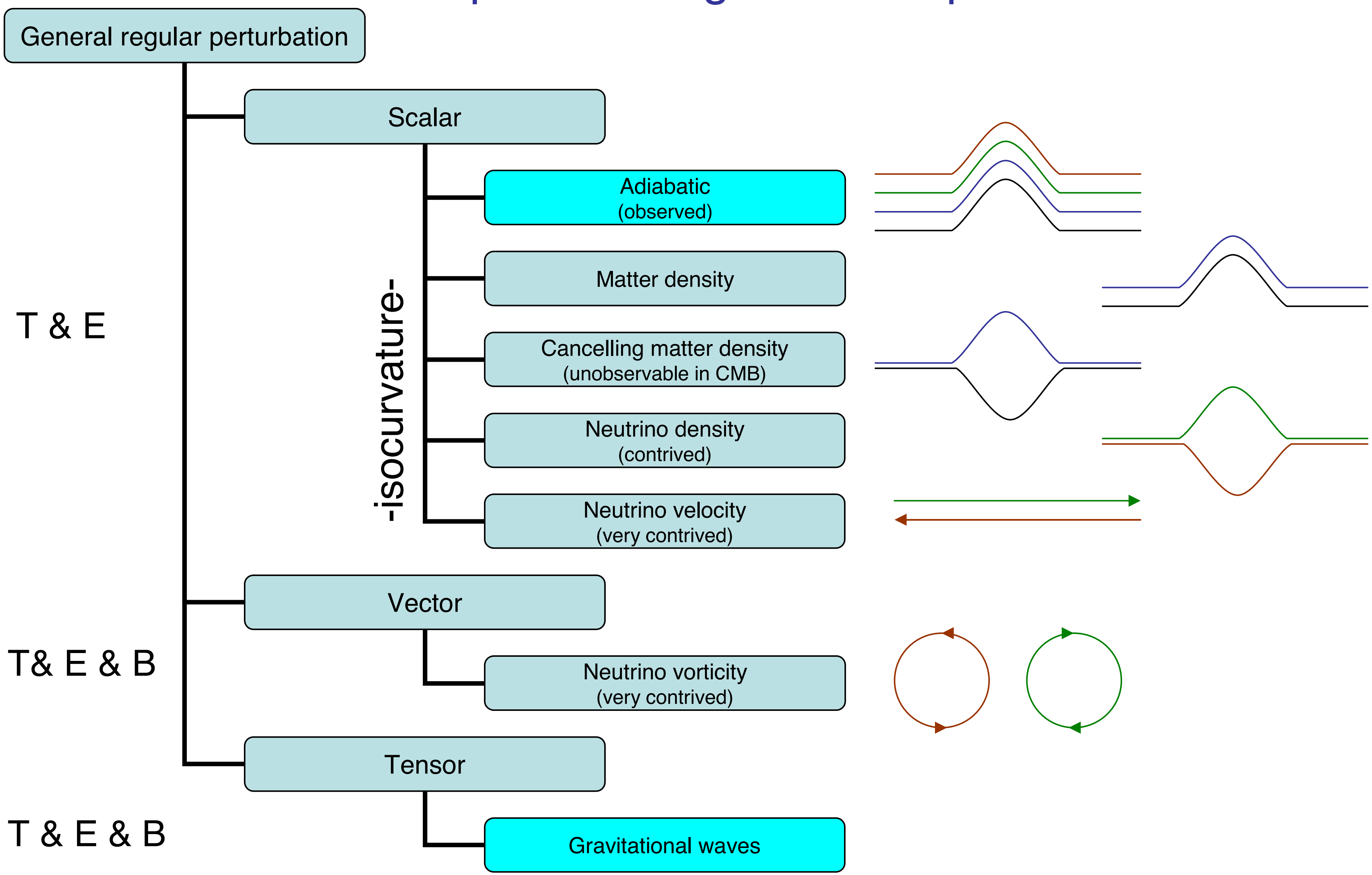


e.g. cold spot

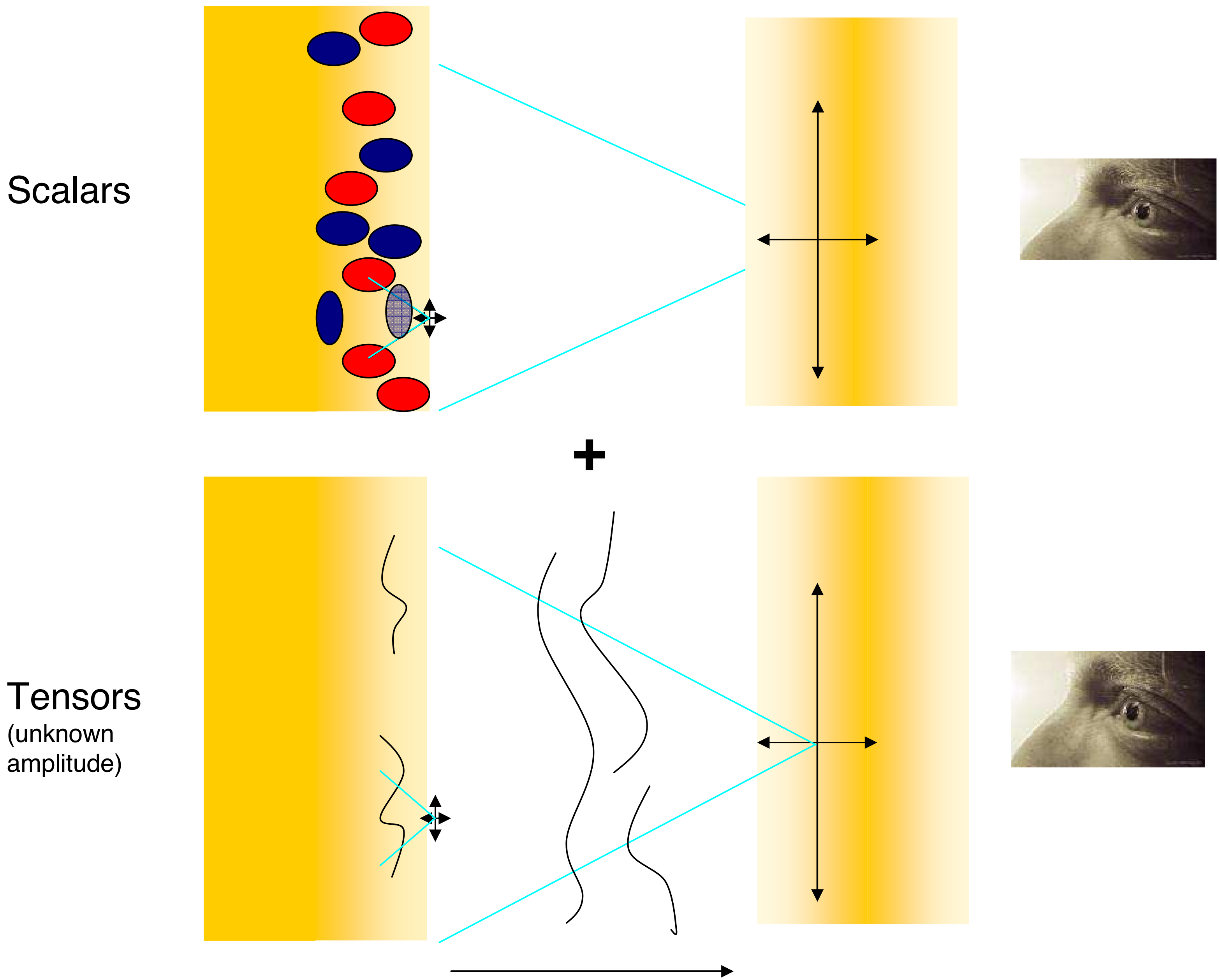
“curl” modes
B polarization



# What are the possible regular initial perturbations?



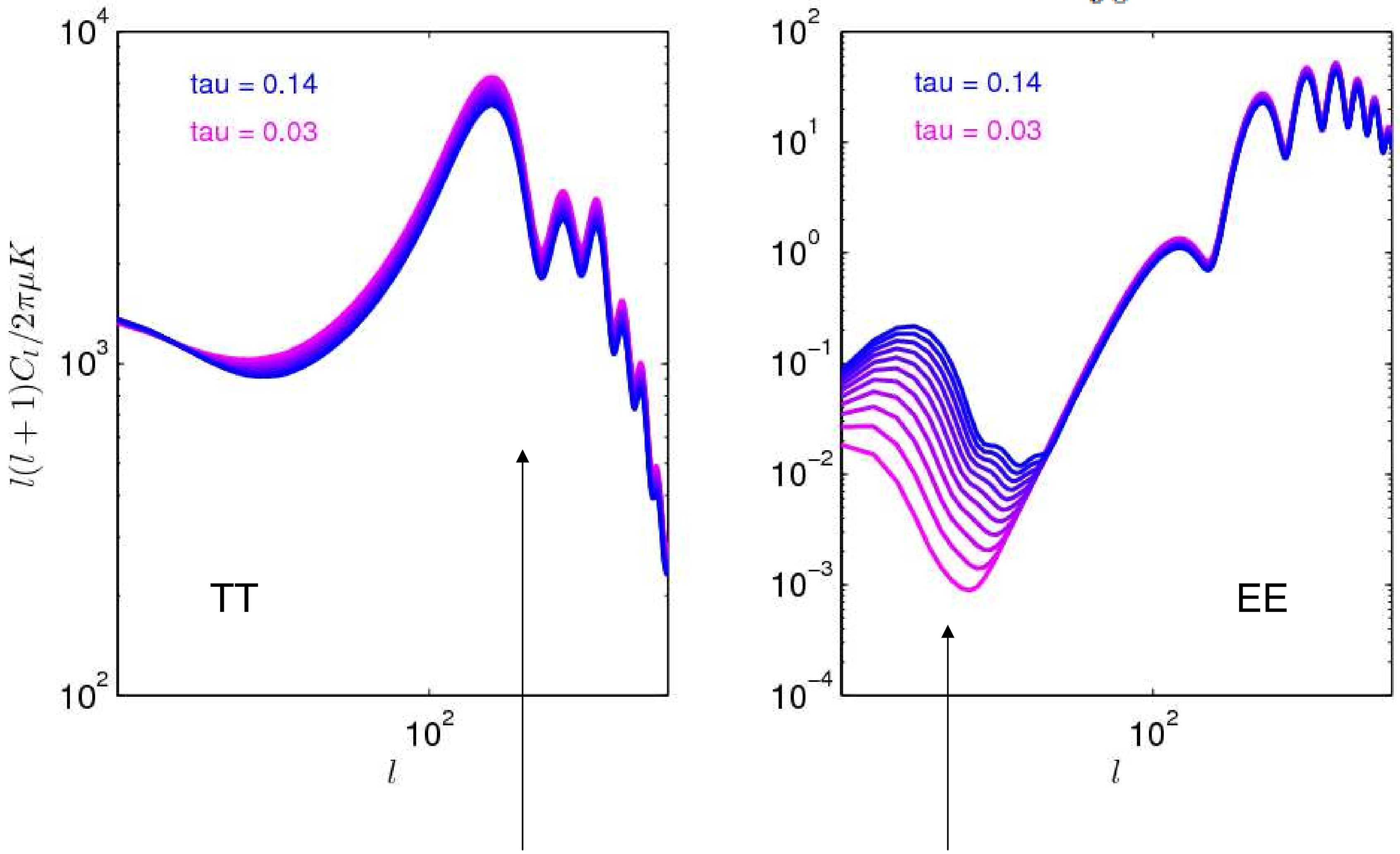

**B modes only expected from gravitational waves and CMB lensing**




Quadrupole generated by anisotropic redshifting of LSS monopole
by gravitational waves along the line of sight

Scalar modes

faction ~tau of photons scatter at reionization $\tau = \int_0^{\eta_0} \mathrm{d}\eta \, a n_e^{\mathrm{reion}} \sigma_T$

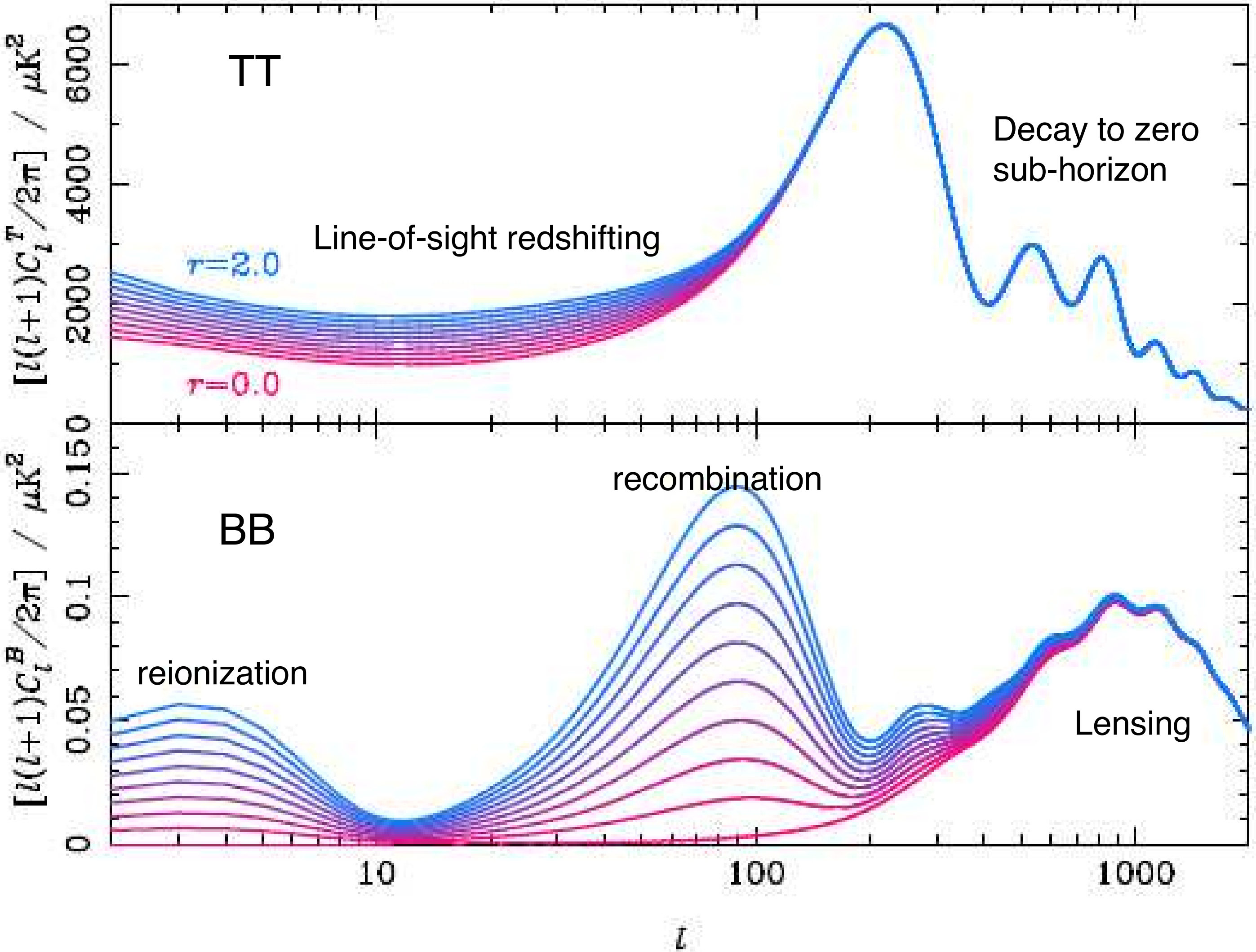



(also TE)

$e^{-2\,\mathrm{tau}}$ suppression

Quadrupole scattering at reionization ~ $\mathrm{tau}^2$

# Effect of primordial gravitational waves




Current: $r < 0.43$ from WMAP5 $\Delta T$ and $E$ ($r < 0.2$ with BAO + SN)

Thanks: Anthony Challinor

# WMAP: Polarization breaks large temperature-only degeneracies

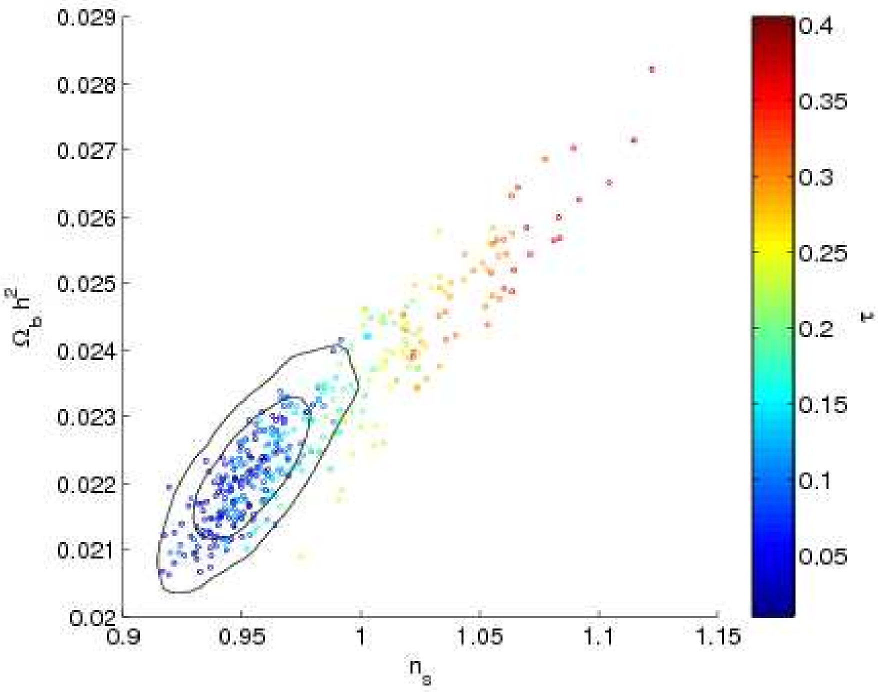
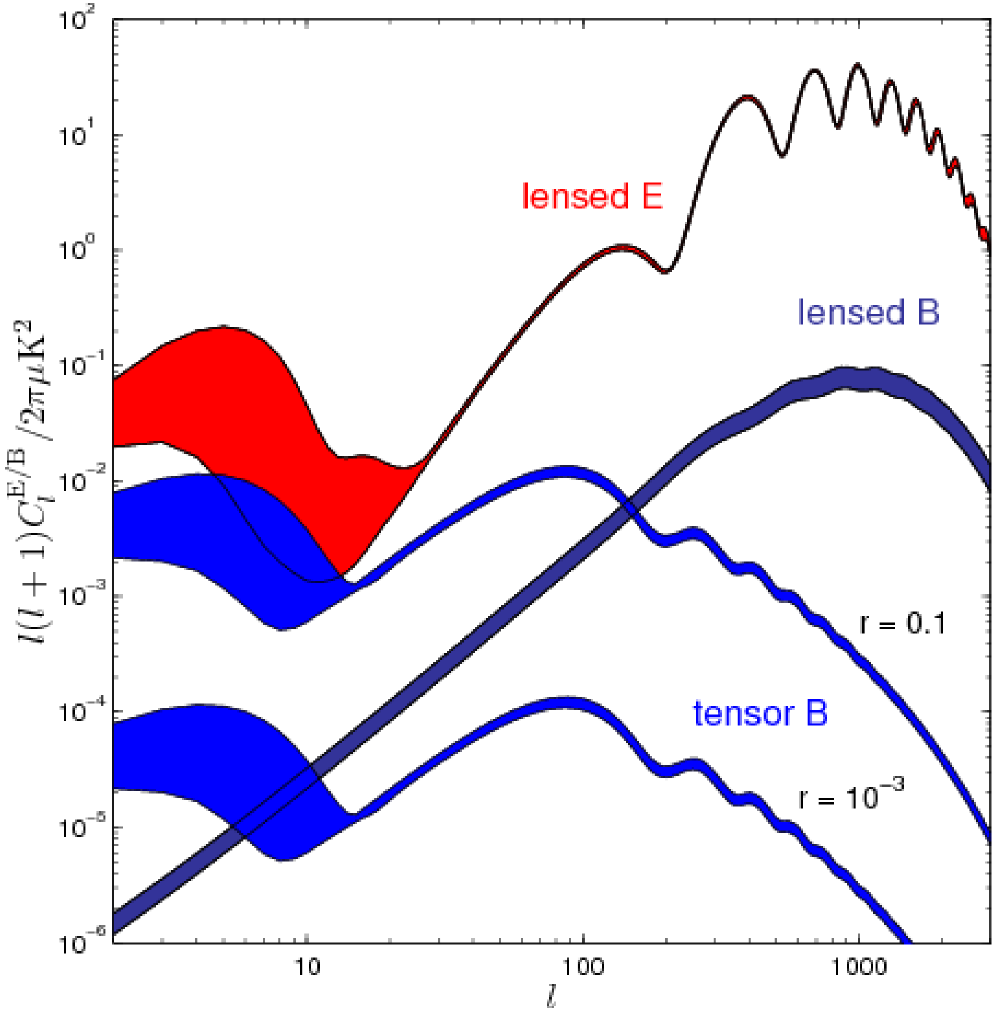



FIG. 1: Constraints from WMAP 3-year temperature (points) and joint with polarization (68% and 95% contours) for a basic six parameter ΛCDM model (no tensors). The points represent samples from the posterior distribution, and are coloured by the value of the optical depth $\tau$. Polarization constrains the optical depth, breaking the main flat-model degeneracy and suggesting $n_s < 1$.

Lewis: astro-ph/0603753

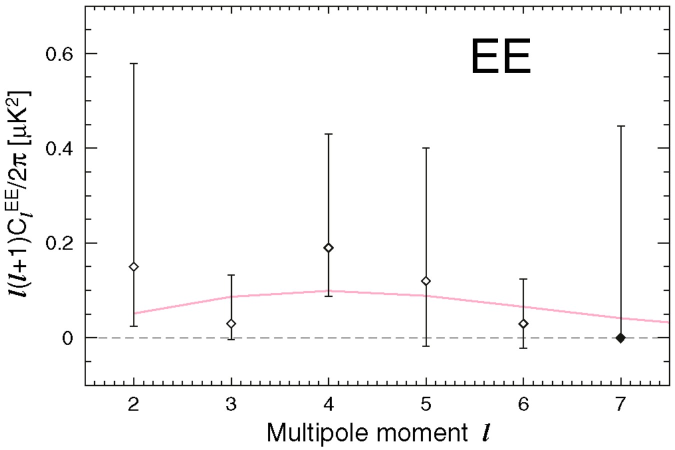
# CMB Polarization Predictions

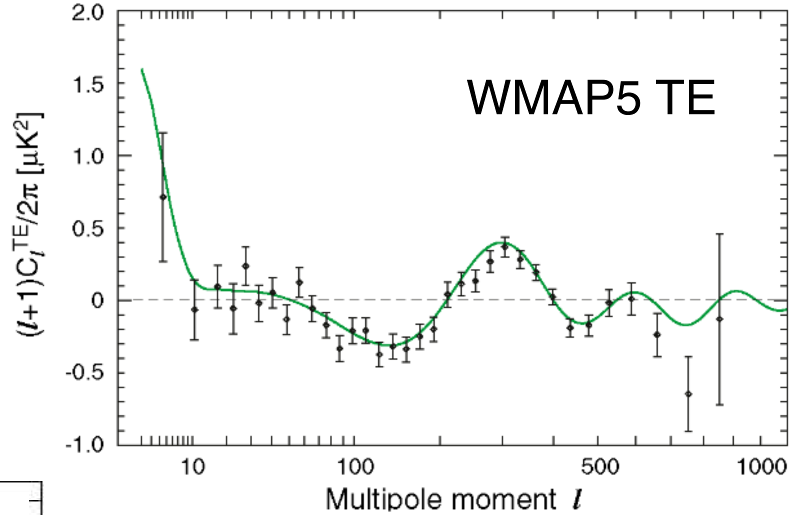
95% indirect limits for LCDM given WMAP+2dF+HST+$z_{re}$>6

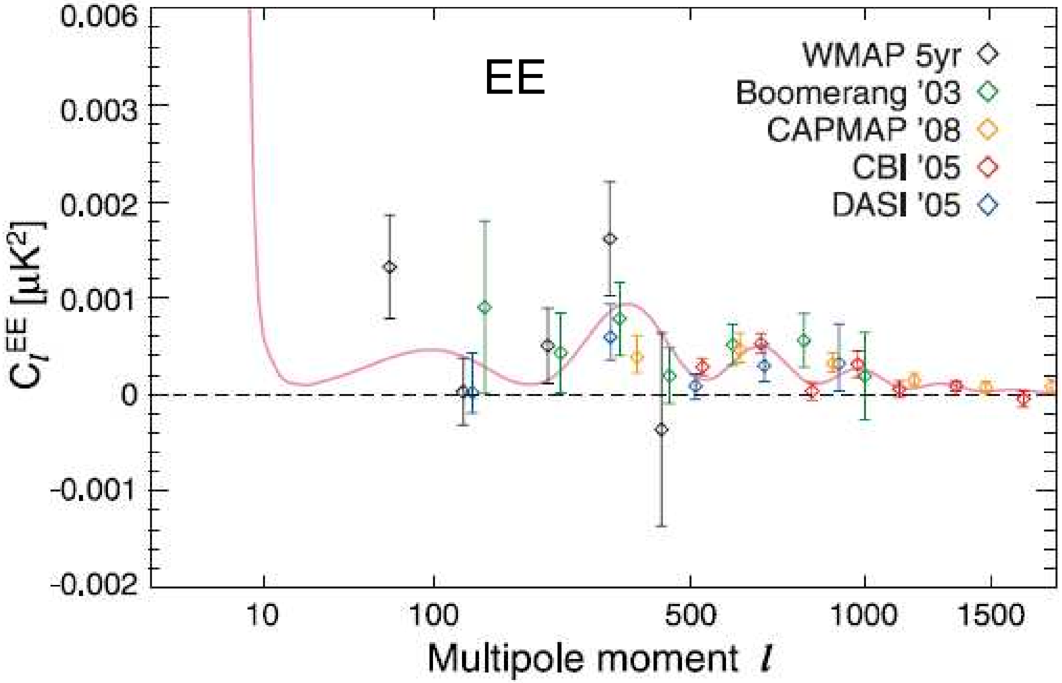



WMAP3ext

Lewis, Challinor : astro-ph/0601594



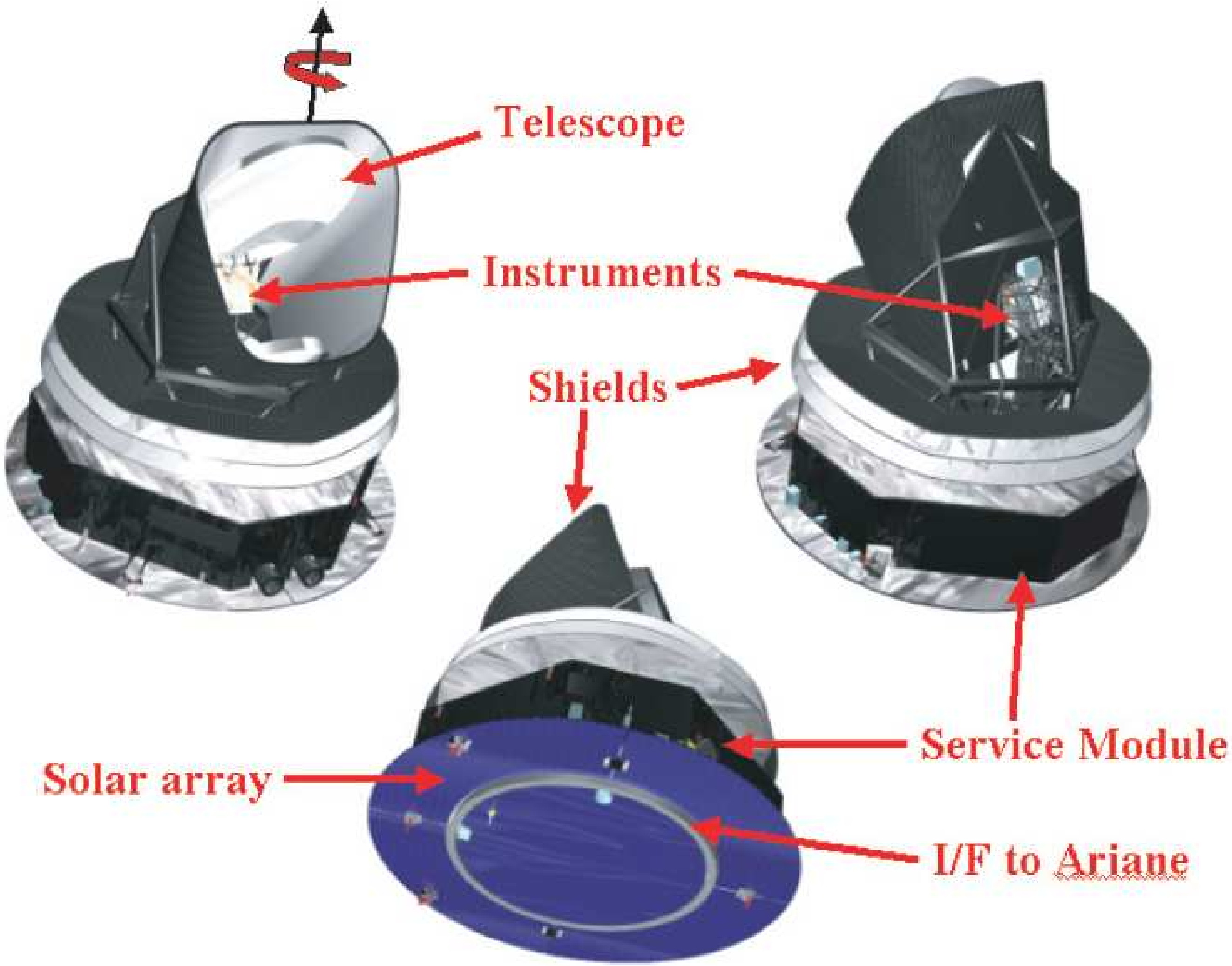

Nolta et al.

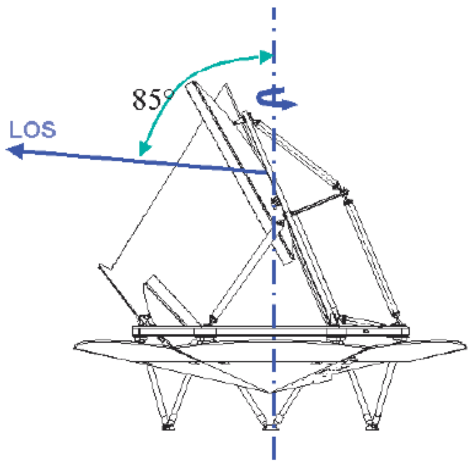
Currently only large scales useful for parameters

(+ consistency check on small scales)

# PLANCK

- Third-generation CMB
- Measure linear temperature anisotropies to cosmic variance
- Polarization
- Launched 14th May 2009 (Ariane 5, from Kourou, French Guiana)
- Two instruments:
  - LFI – Reno Mandolesi
  - HFI – Jean-Loup Puget


Telescope
Instruments
Shields
Service Module
Solar array
I/F to Ariane

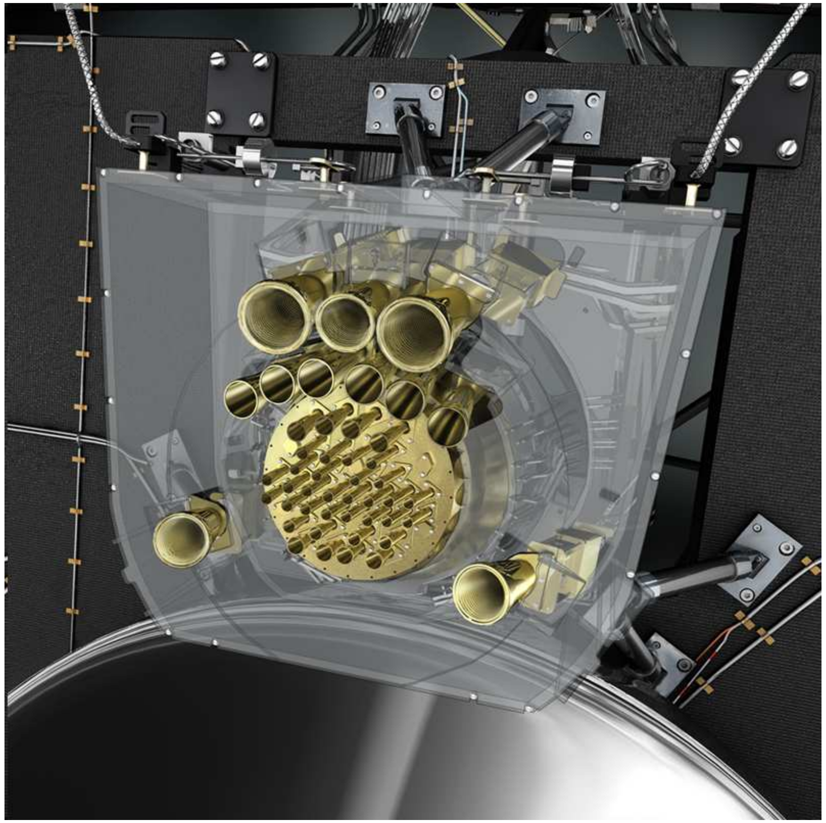

LOS
85°

Blue book

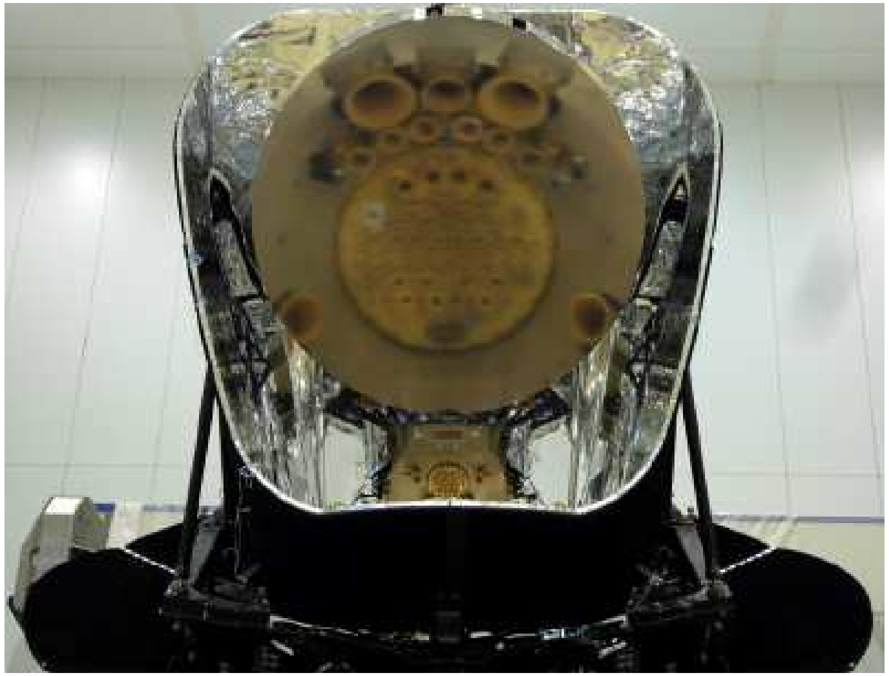
| Instrument Characteristic | LFI | | | HFI | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Detector Technology | HEMT arrays | | | Bolometer arrays | | | | | |
| Center Frequency [GHz] | 30 | 44 | 70 | 100 | 143 | 217 | 353 | 545 | 857 |
| Bandwidth ($\Delta\nu/\nu$) | 0.2 | 0.2 | 0.2 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 |
| Angular Resolution (arcmin) | 33 | 24 | 14 | 10 | 7.1 | 5.0 | 5.0 | 5.0 | 5.0 |
| $\Delta T/T$ per pixel (Stokes $I$)[a] | 2.0 | 2.7 | 4.7 | 2.5 | 2.2 | 4.8 | 14.7 | 147 | 6700 |
| $\Delta T/T$ per pixel (Stokes $Q$ & $U$)[a] | 2.8 | 3.9 | 6.7 | 4.0 | 4.2 | 9.8 | 29.8 | ... | ... |

[a] Goal ($\mu$K/K, 1$\sigma$), 14 months integration, square pixels whose sides are given in the row "Angular Resolution".

~ SZ null



Planck focal plane

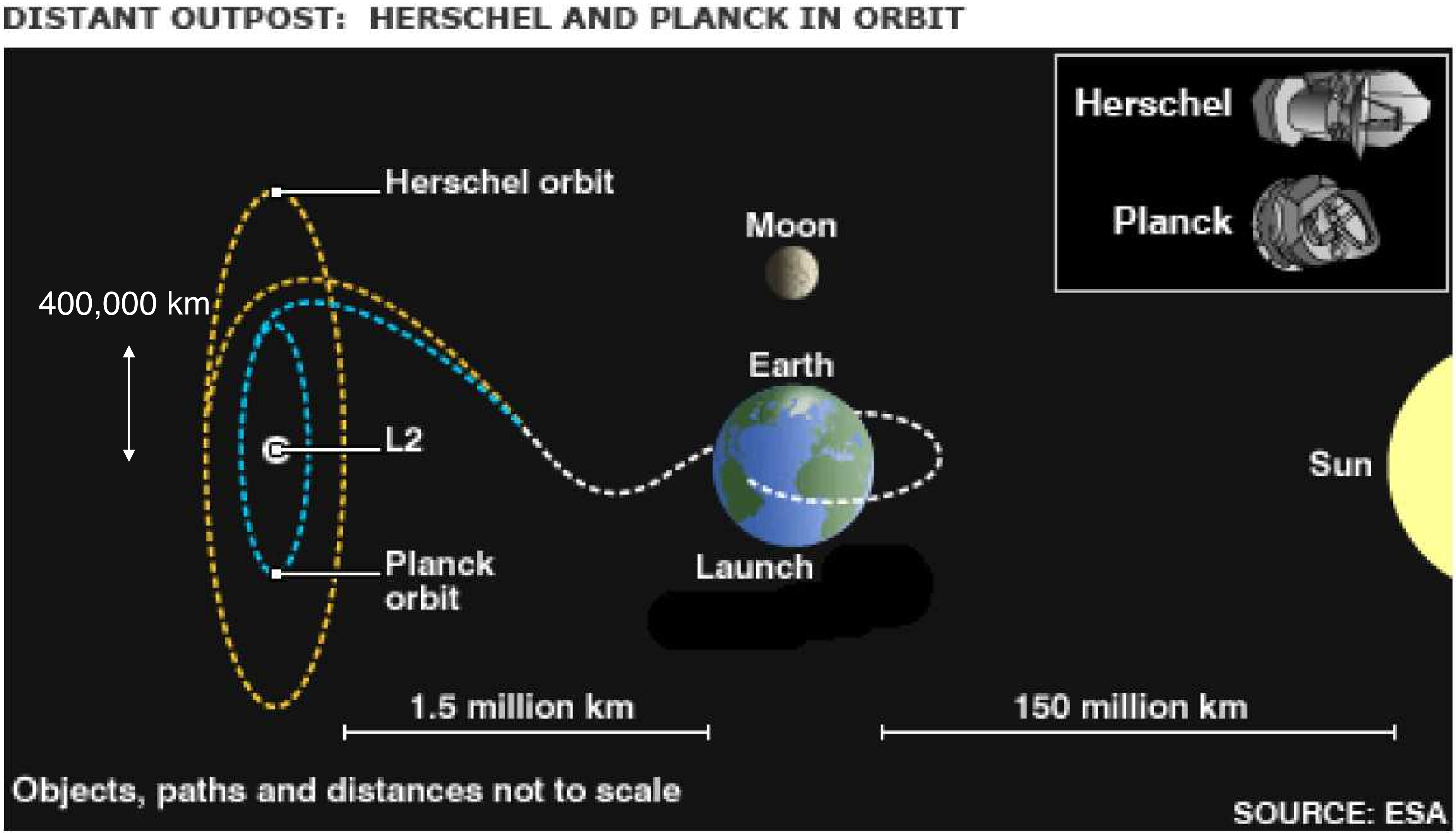


ESA/AOES Medialab

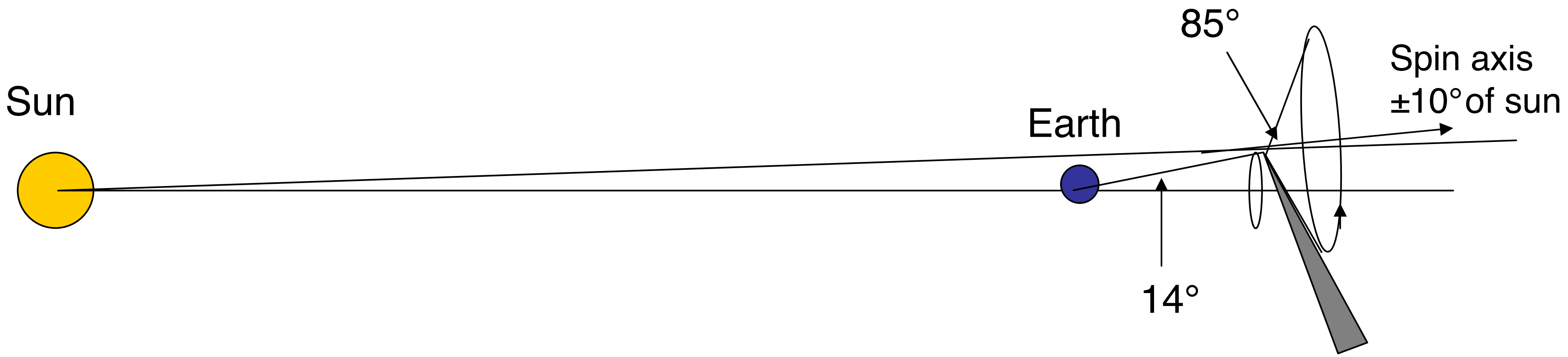
ESA

Images: ESA

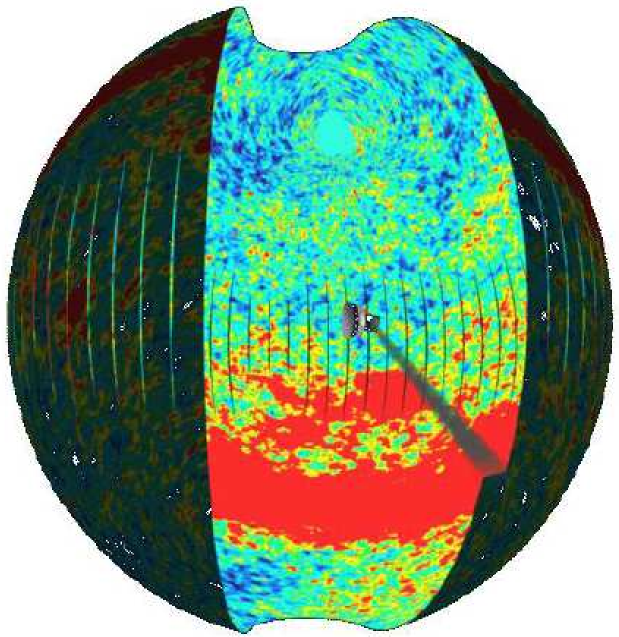
14 May 2009




Corrections to stay in Lissajous L2 orbit every 30 days




- Spacecraft rotates at 1 rpm
- Optic axis at 85° traces large circles on the CMB
(small precession to cover whole sky)
- Re-points every hour



Full sky every 6-7 months: first 2, then hopefully 4 full scans

# Current Status

- Orbiting L2; HFI detectors at operational temperature ~ 0.1K (coolest known objects in space!)
- LFI and HFI declared to be fully and optimally tuned; meet predicted performance
- 13$^{th}$ August: First Light Survey (2 weeks) calibration running into first sky survey (starting 27$^{th}$ August)
  - dipole measurement in 1 degree strip

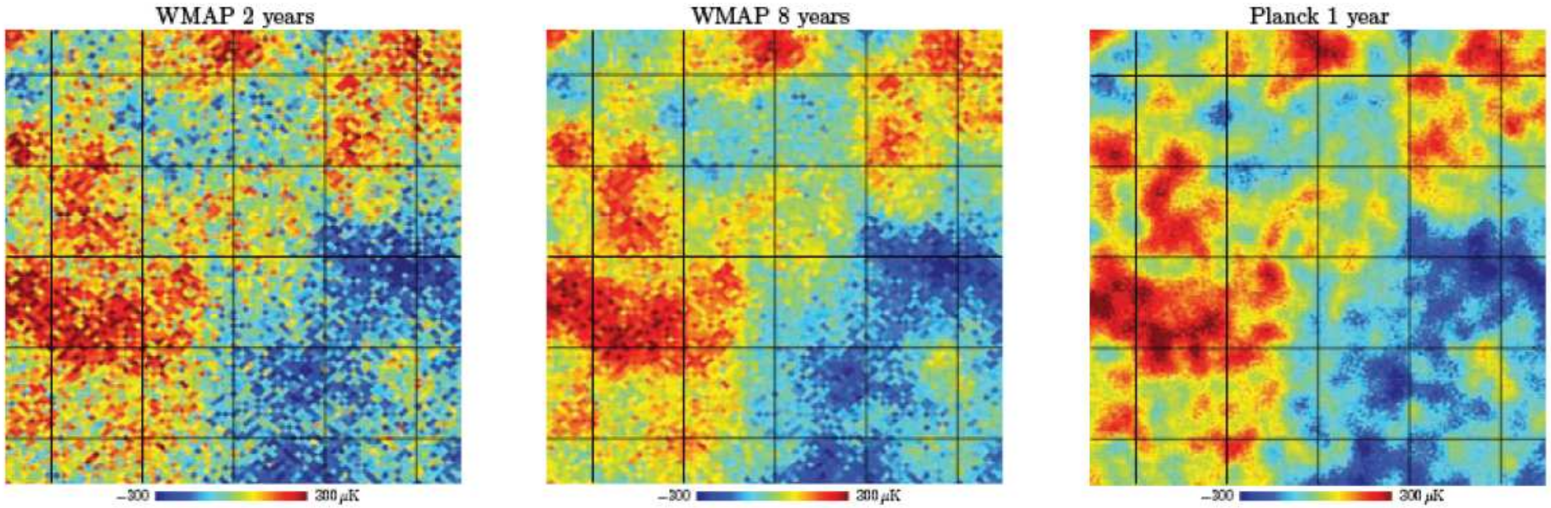
So far, so good!

## Timetable

| | Duration (months) | Date |
|---|---|---|
| Launch | 0 | 5/2009 |
| Cruise, cooldown, checkout | 3 | 7/2009 |
| First sky survey | 6 | 1/2010 |
| Second sky survey | 6 | 7/2010 |
| ERCSC (based on first survey) | | 7/2010 |
| Analyse first-year data | 24 | |
| First-year results released | | 7/2012 |
| Extended mission | TBD | |

**(Early Release Compact Source Catalogue)**

# Planck vs WMAP




30–857 GHz cf 23–94 GHz (WMAP)

$3\times$ resolution

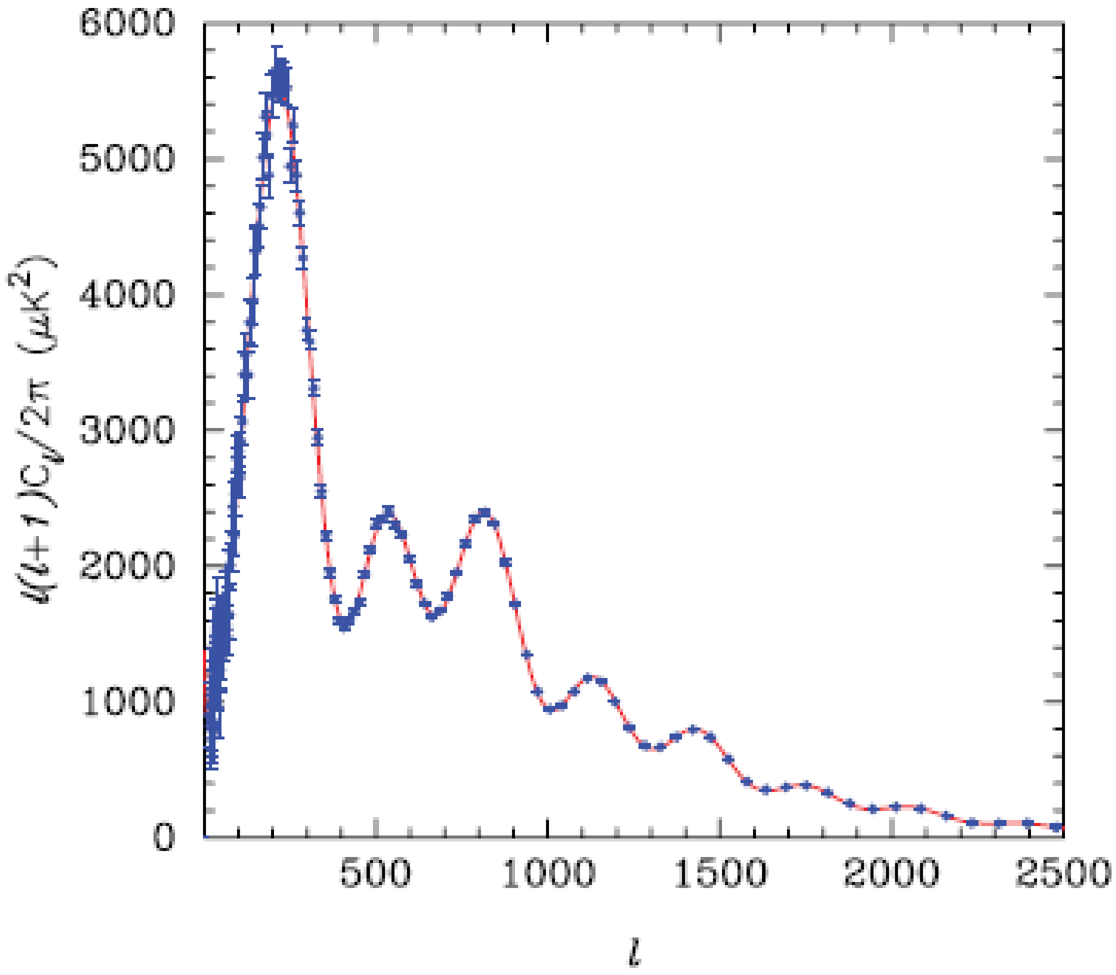
$\sim 20\times$ instantaneous sensitivity

- Nominal Planck survey $7\times$ sensitivity of WMAP8

$\Delta T$ cosmic-variance limited to $l \sim 2000$

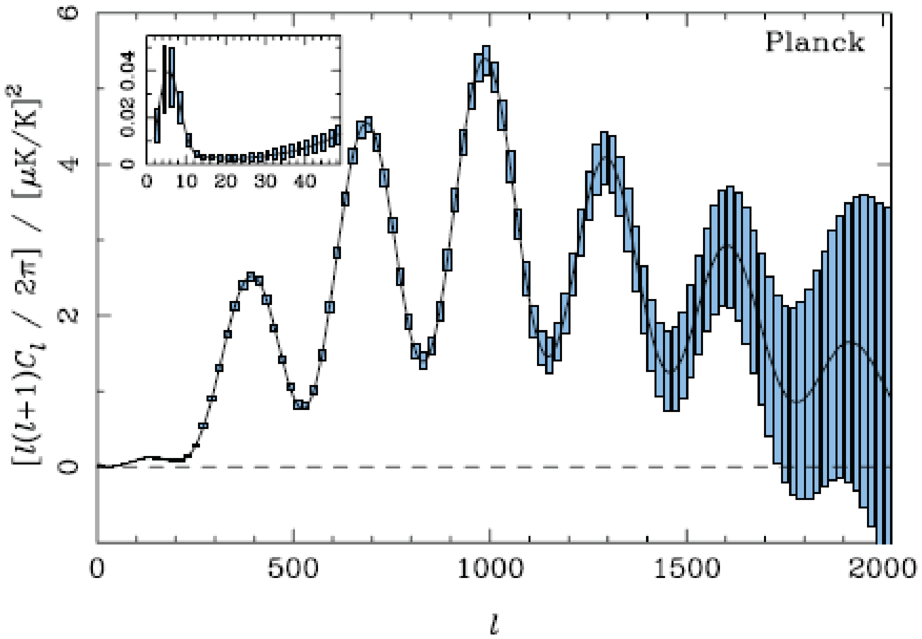
Temperature almost cosmic variance limited until secondaries dominate

'Blue book' forecast

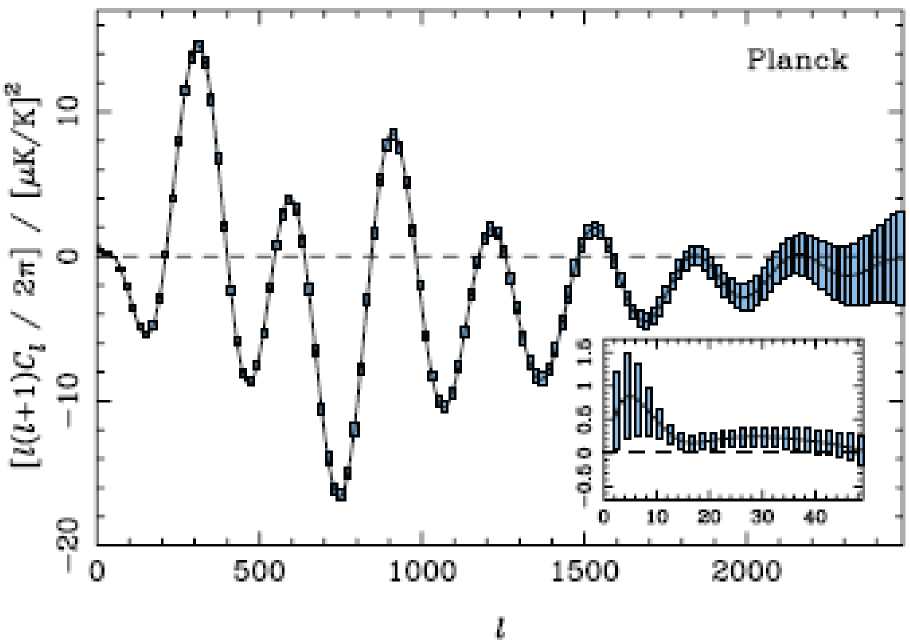


Planck blue book

EE




TE




- small scales only slight help with parameters
- but allows important consistency cross-checks (less SZ in EE)
- Large scales crucial for optical depth constraint

## Parameters. WMAP4 vs Planck

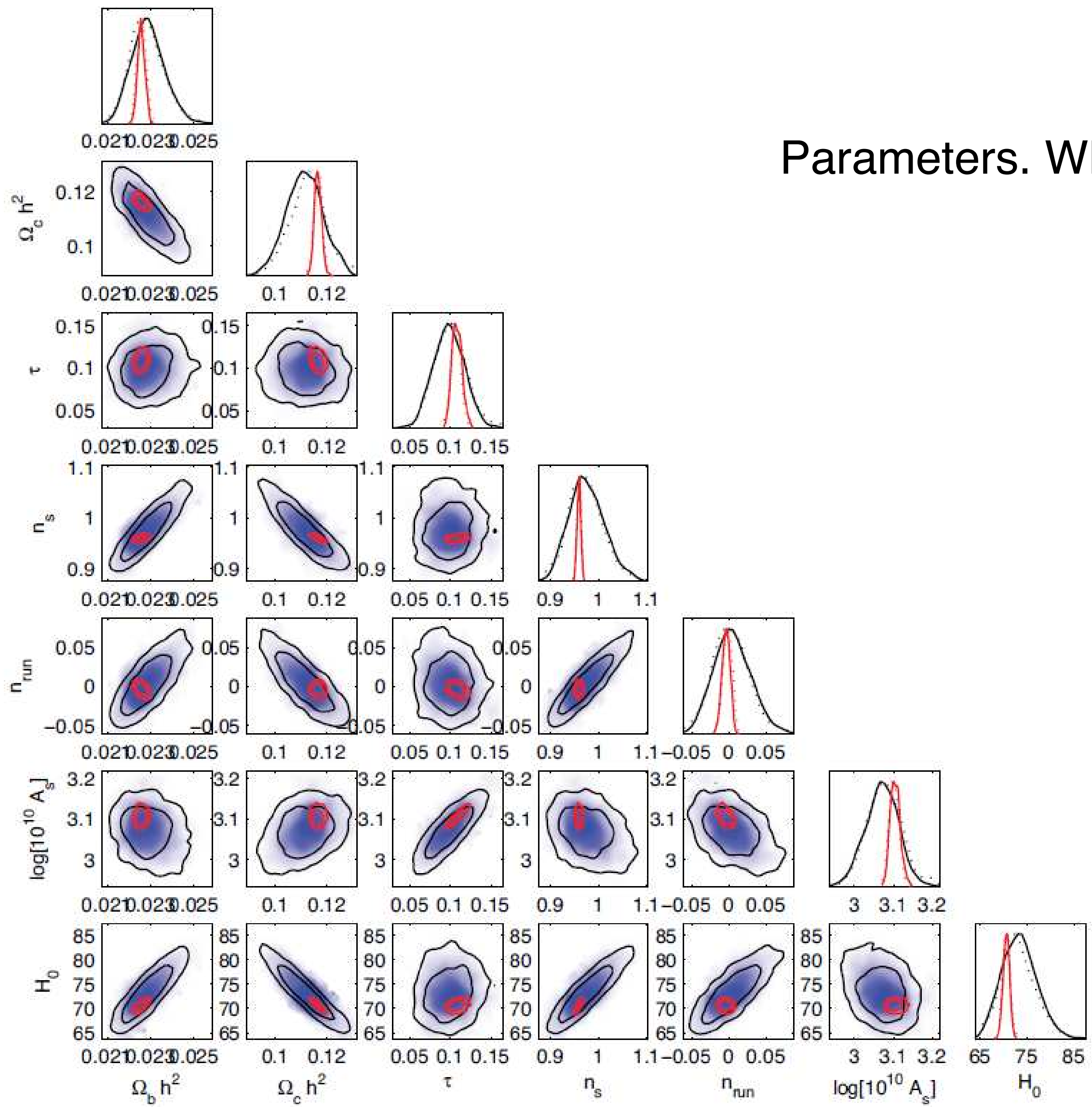
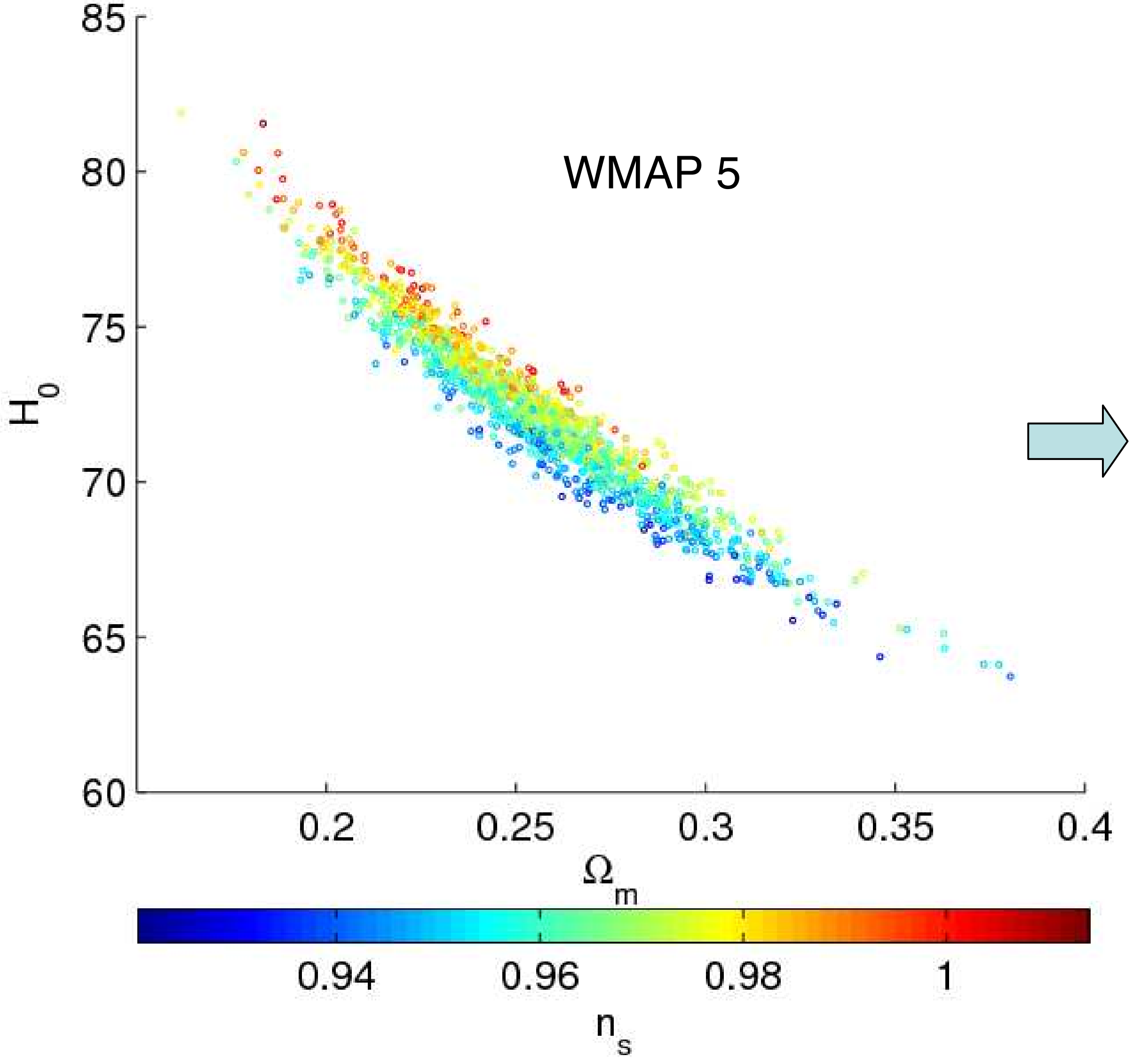
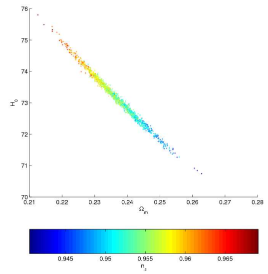



FIG 2.18.—Forecasts of 1 and 2$\sigma$ contour regions for various cosmological parameters when the spectral index is allowed to run. Blue contours show forecasts for *WMAP* after 4 years of observation and red contours show results for *Planck* after 1 year of observations. The curves show marginalized posterior distributions for each parameter.

Degeneracies with other parameters – still benefit from combining with other data



Planck forecast

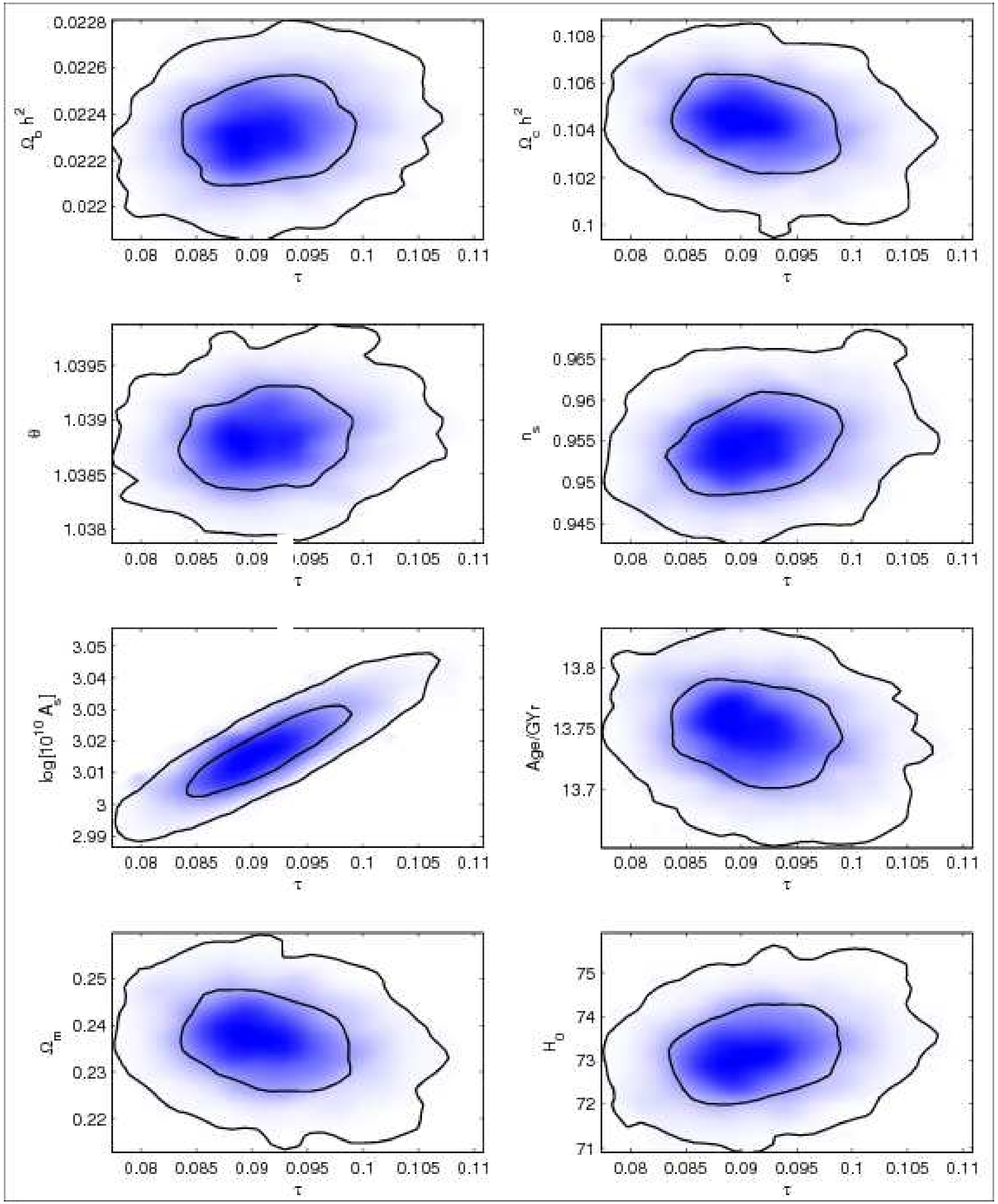
(assume Flat, w=-1)

# Planck optical depth constraints

Marginalized:
tau ~ X ± 0.005

c.f. WMAP
tau ~ 0.09 ± 0.017 ± 0.01

Small scale $C_l \sim A_s e^{-2\,\mathrm{tau}}$



# Default reionization ($x_e$) parameterization

$$\tau = \int_0^{\eta_0} d\eta\, a n_e^{\text{reion}} \sigma_T$$

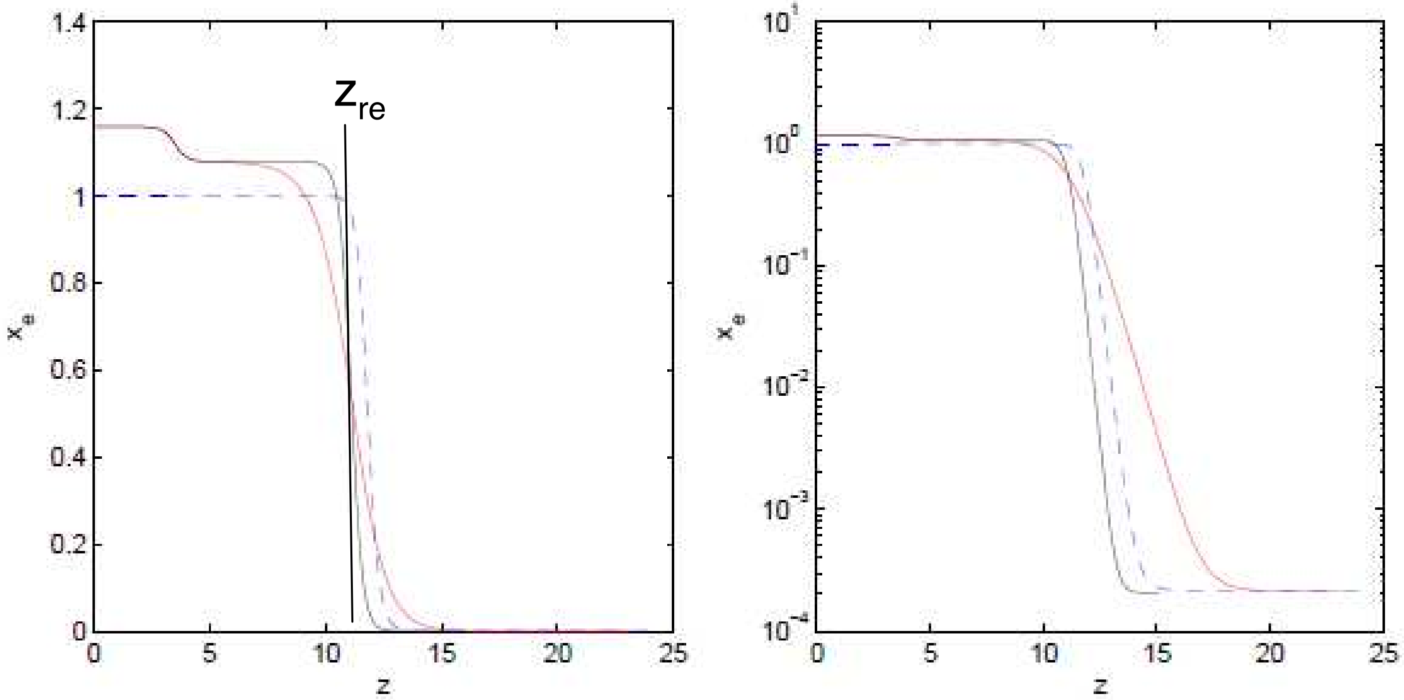



FIG. 6: Three recombination histories all with $\tau = 0.09$. The dashed line is the model typically used by CMBFAST and CAMB prior to March 2008 with $f = 1$. The black line is the new model with $\Delta_z = 0.5$, the red line with $\Delta_z = 1.5$.

$$x_e(y) = \frac{f}{2}\left[1 + \tanh\left(\frac{y - y(z_{re})}{\Delta_y}\right)\right]$$

CAMB's default parameterization as of March 2008: http://camb.info/

$$y(z_{re}) = (1 + z_{re})^{3/2} \qquad f = 1 + f_{He}$$

Lewis 0804.3865

History may matter too…

Potentially bias tau, hence $A_s$ (hence $\sigma_8$) if we assume the wrong reionization history

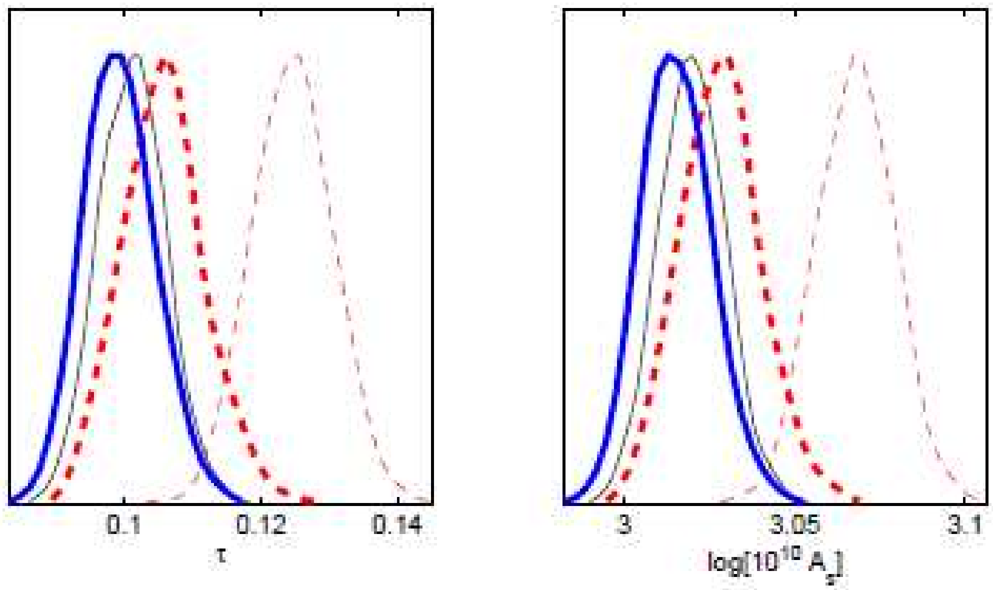
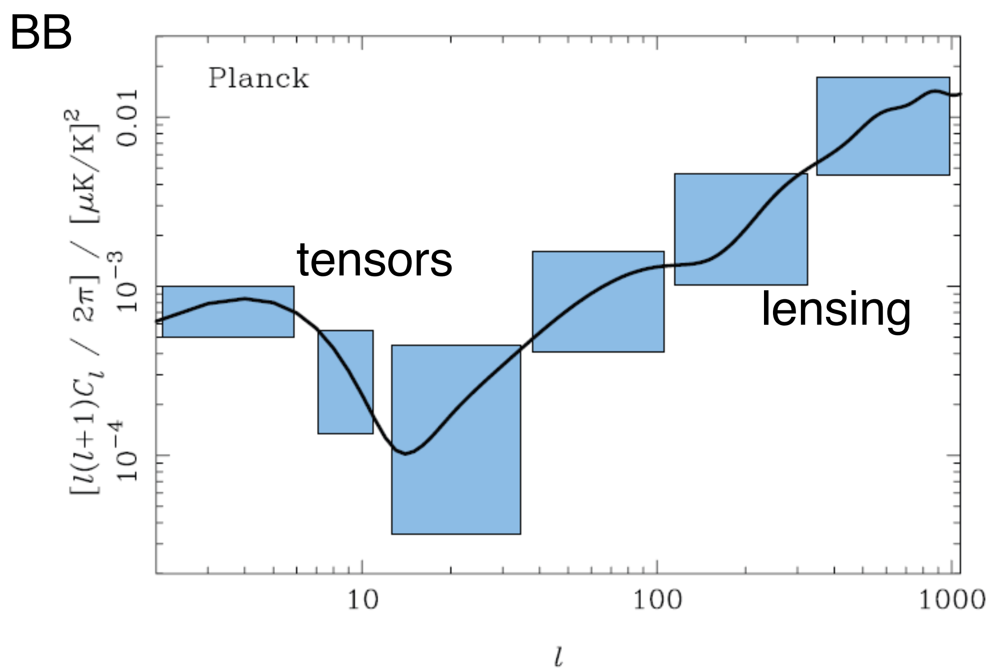



**Figure 6.** PLANCK optical depth and amplitude constraints from the sharp model analysed using the sharp model (thin solid), the incorrect result from analysing a double reionization model using a sharp model (thin dashed), and the consistent result from the double reionization (thick dashed) and sharp (thick solid) models using a binned reconstruction.

Lewis,Weller,Battye
astro-ph/0606552

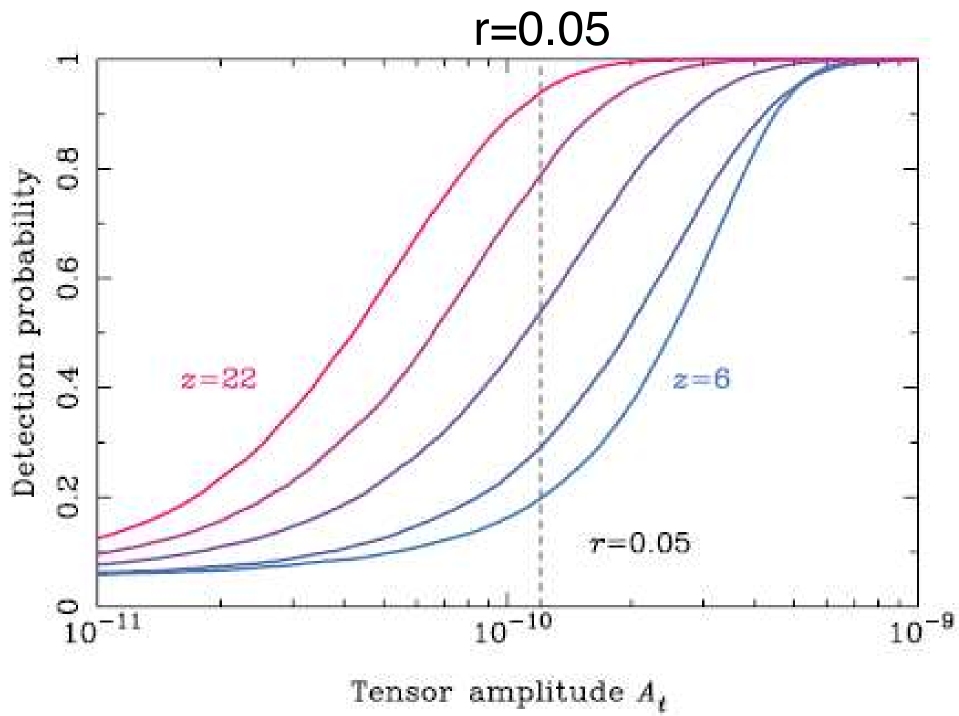
- good physically-motivated parameterizations useful!

See Jochen's talk..

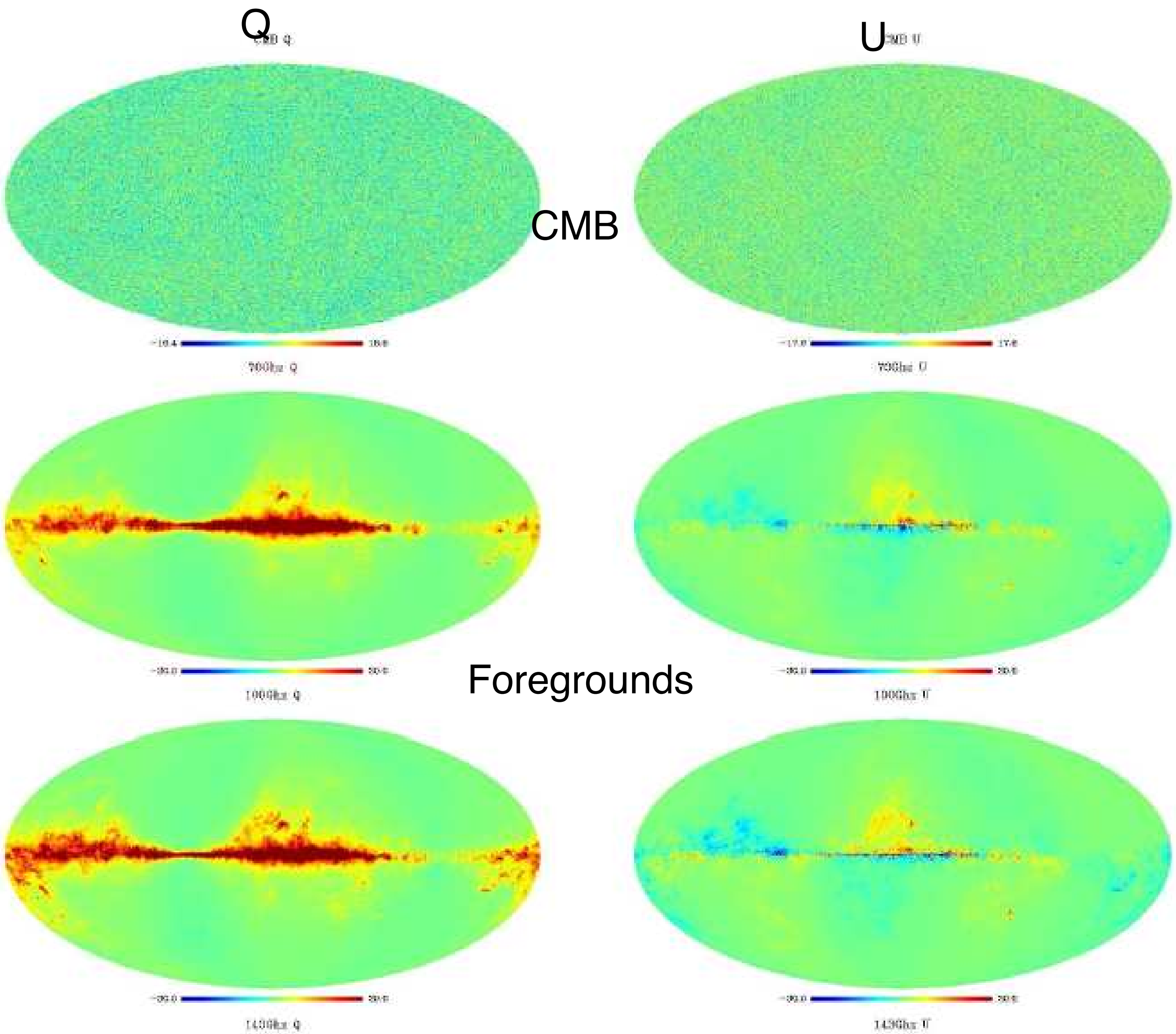



- Some constraints from lensing
- Chance to detect primordial gravitational waves
- Also all gravitational wave signal detectable by Planck is from reionization

Reionization optical depth effects primordial tensor amplitude that can be detected



BUT: Big foregrounds on large scales

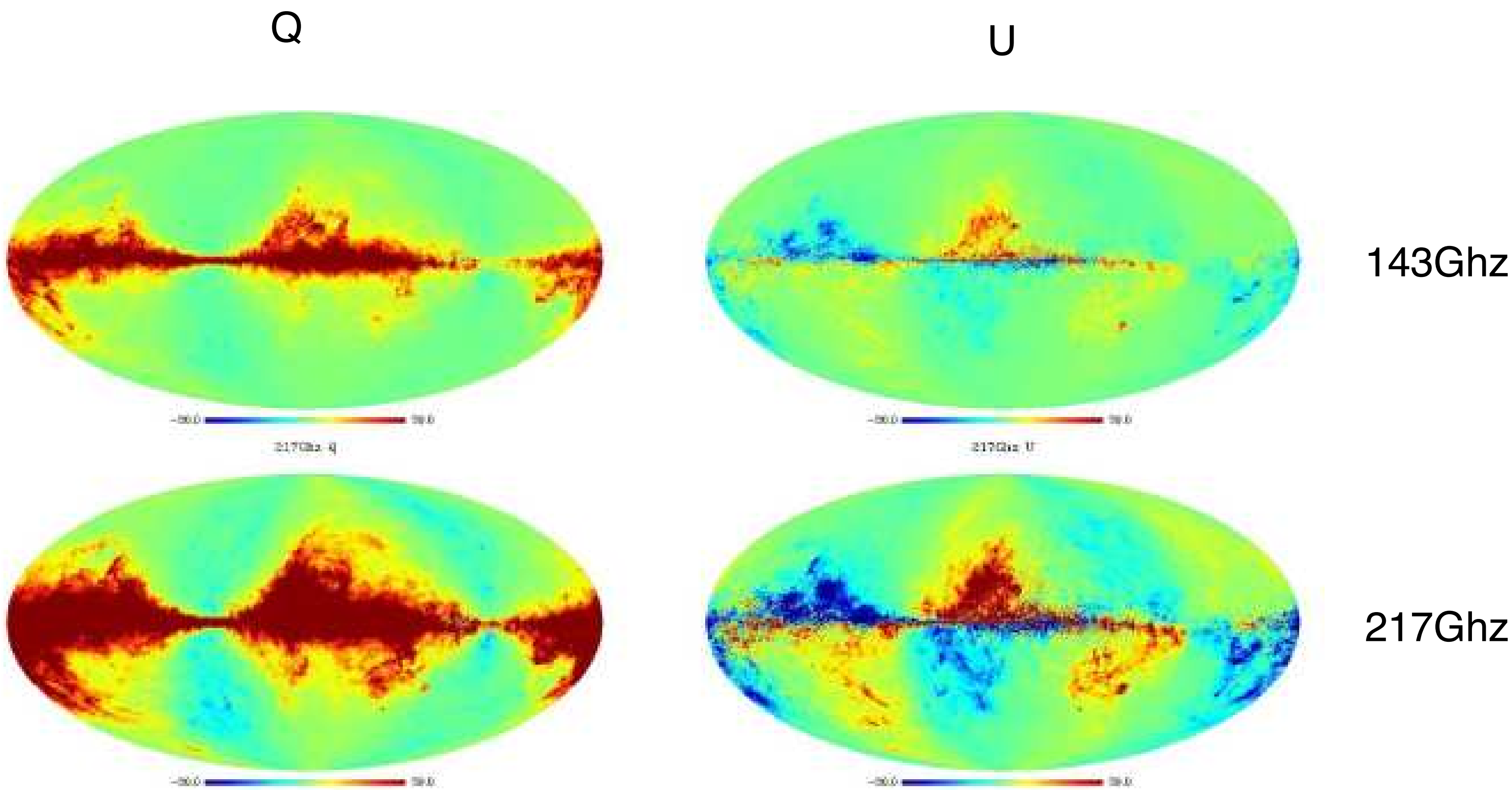



Pure-CMB Simulation

70GHz

100Ghz

Efstathiou et al 2009


Q
U
143Ghz
217Ghz

Efstathiou et al 2009

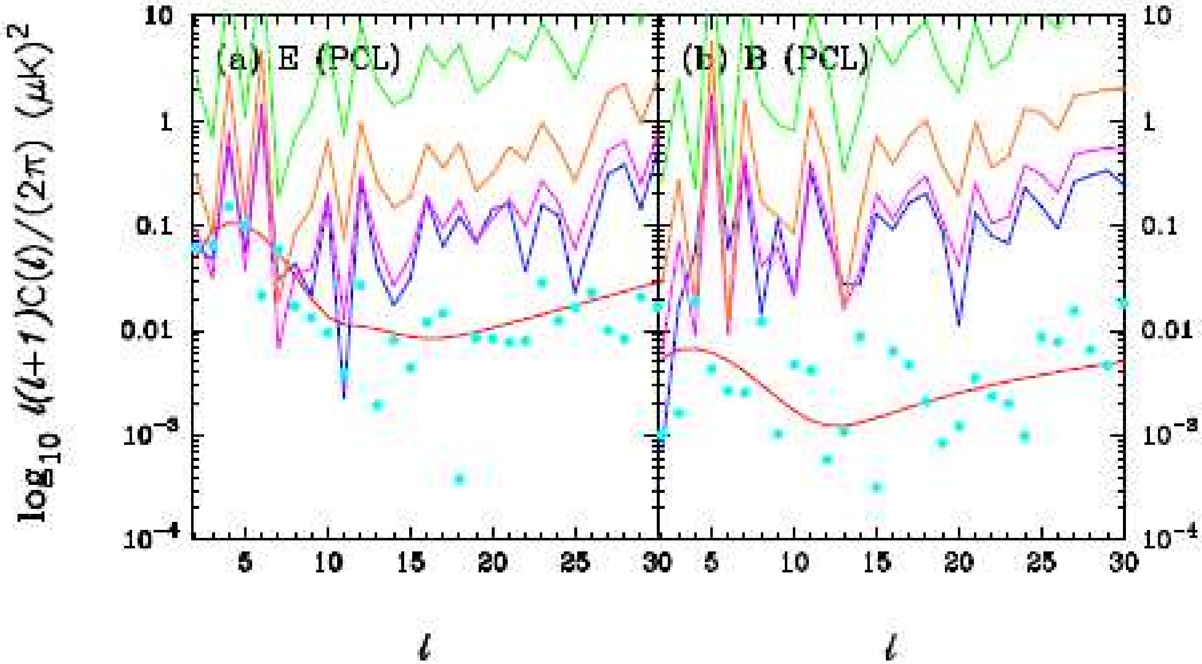
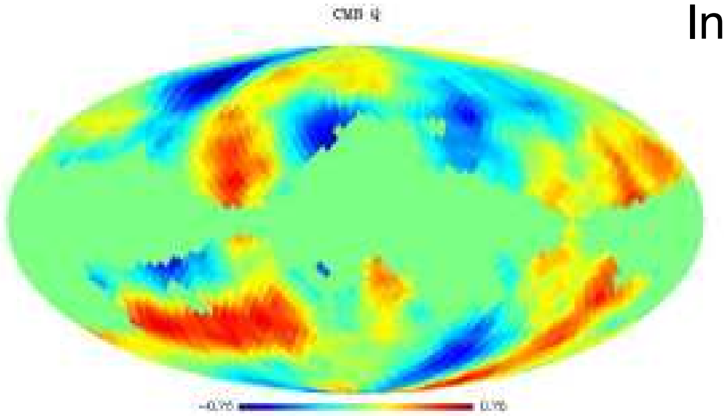


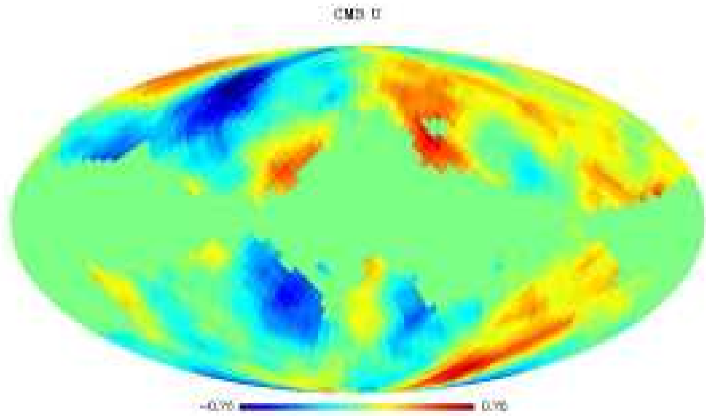

**Figure 4.** PCL $E$ and $B$-mode power spectrum estimates computed for the CMB simulations and foreground components of Figure 1. The power spectra are computed for the region of the sky outside the internal mask. No instrumental noise has been added to the simulations. The blue points show the power spectrum estimates for the CMB. The red lines show the theoretical input CMB spectra. The foreground power spectra are as follows: 70 GHz (dark blue); 100 GHz (purple); 143 GHz (orange); 217 GHz (green).

<u>Foregrounds very important for reionization and tensor mode studies</u>

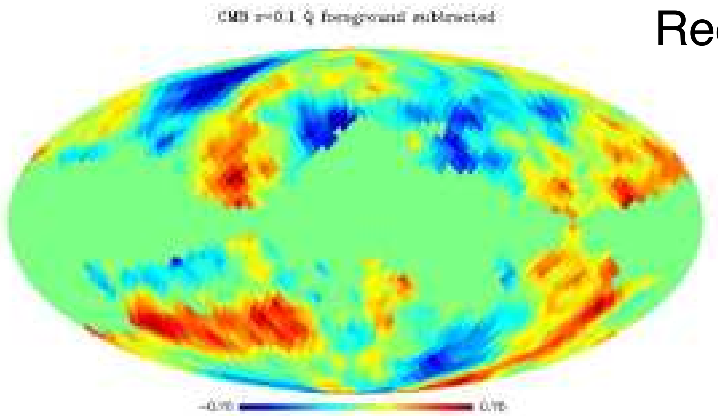
- Use assumed blackbody spectrum to subtract foregrounds

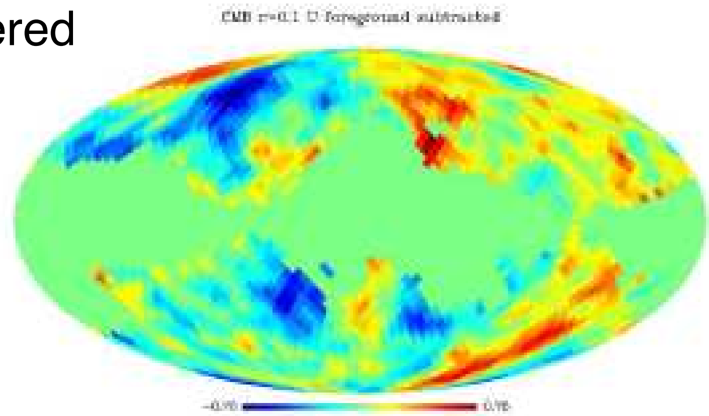
Input




Recovered



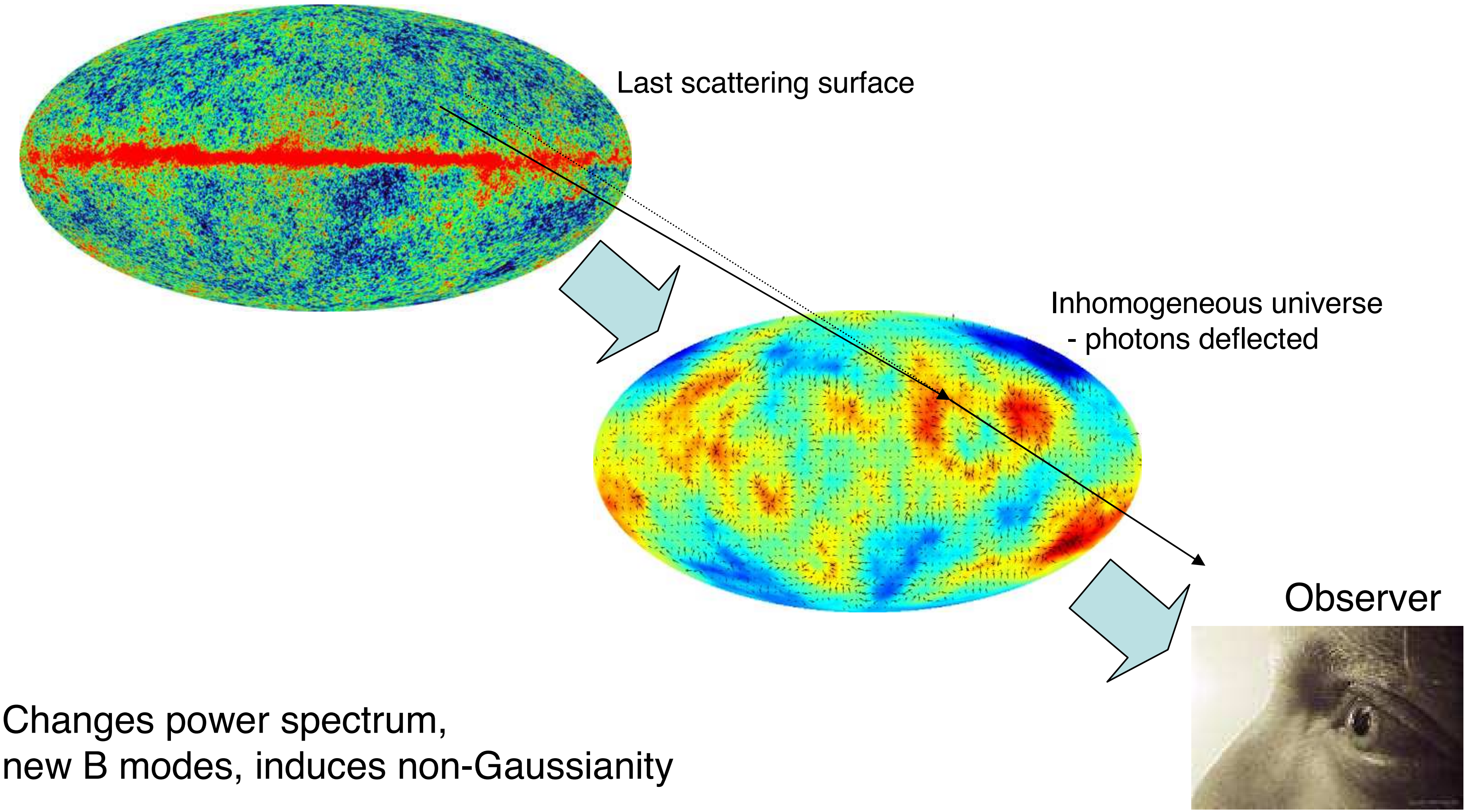

B-mode constraint

r ~ 0.1 in 14 months
r ~ 0.05 if 28 months (Efstathiou, Gratton 09)

If it can be done for B-modes, E-mode reionization should also be OK

# Beyond linear order

Weak lensing to break CMB degeneracies

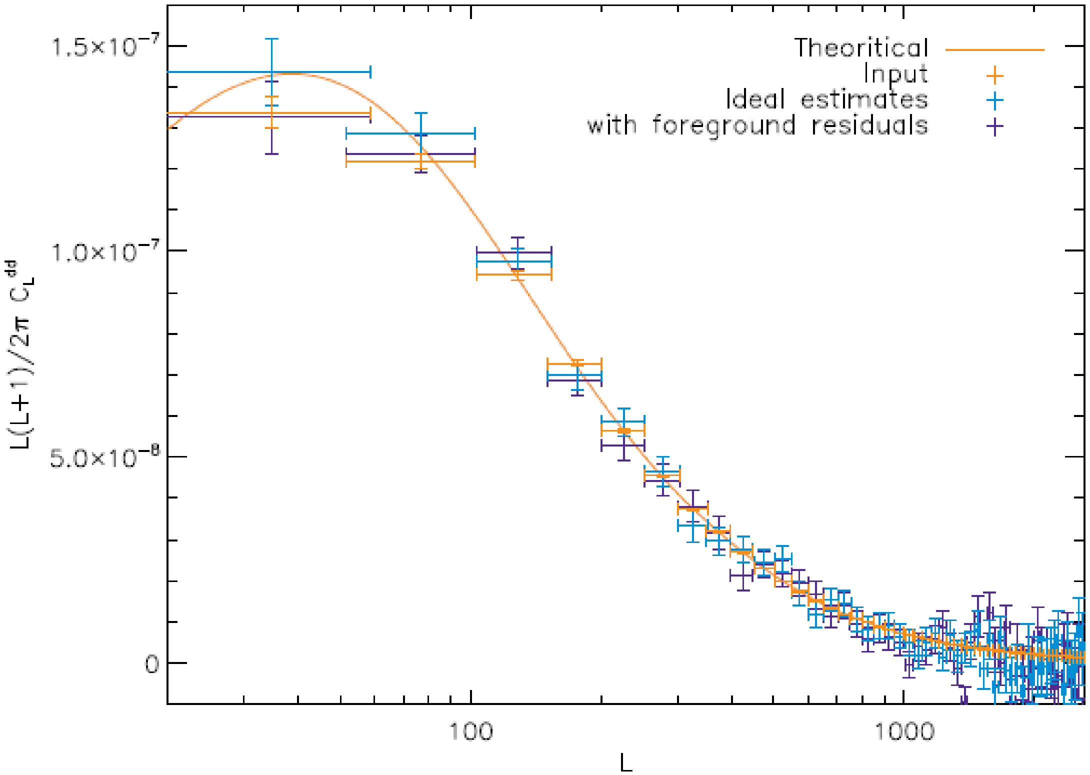



Changes power spectrum,
new B modes, induces non-Gaussianity

Review: Lewis & Challinor *Phys. Rept . 429, 1-65 (2006)*: astro-ph/0601594

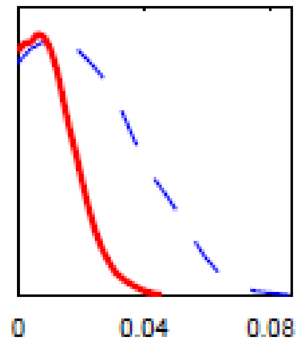
Probe 0.5<~ z <~ 6: depends on geometry and matter power spectrum

Already helps with Planck




Perotto et al. 2009

Neutrino mass fraction with and without lensing (Planck only)




Perotto et al. 2006

Also kSZ² x Lensing signal (Dore et al. 2004)

# Conclusions

- Looking good!
- Precision cosmology parameters
- Maybe B-mode from gravitational wave temperature quadrupole scattering at reionization
- Good constraint on optical depth
- Physical reionization models useful for extracting other parameters
- See  Blue Book for other areas of science case
- Next talks for SZ/kSZ/reionization reconstruction…