1st RESCEU International Symposium

The Cosmological Constant and the Evolution of the Universe

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22 August, 1995

Dr. Kin-Wang Ng
Institute of Physics
Academia Sinica
Taipei, Taiwan 11529
Republic of China

Dear Dr. Ng:

We are planning to organize the 1st RESCEU International Symposium on "the Cosmological Constant and the Evolution of the Universe" on November 7-10, 1995 in Tokyo. The purpose of the symposium is to bring together the observational data and theoretical ideas concerning the cosmological constant.

On behalf of the organizing committee, I have a pleasure to invite you to be an active participant in our symposium. I would like you to present a talk regarding your current research related to the topic of our conference.

I look forward to your participation in our conference. It should be an interesting and stimulating experience.

Sincerely yours,

K. Sato

Katsuhiko Sato,
Chairman of the organizing committee

榮休

Congratulations to
Prof. Sato
from Colleagues
@ CosPA Center

三十而立、
四十而不惑、
五十而知天命、
六十而耳順、
七十而従心所欲

Cosmic Microwave Background Polarization

from a theorist's point of view

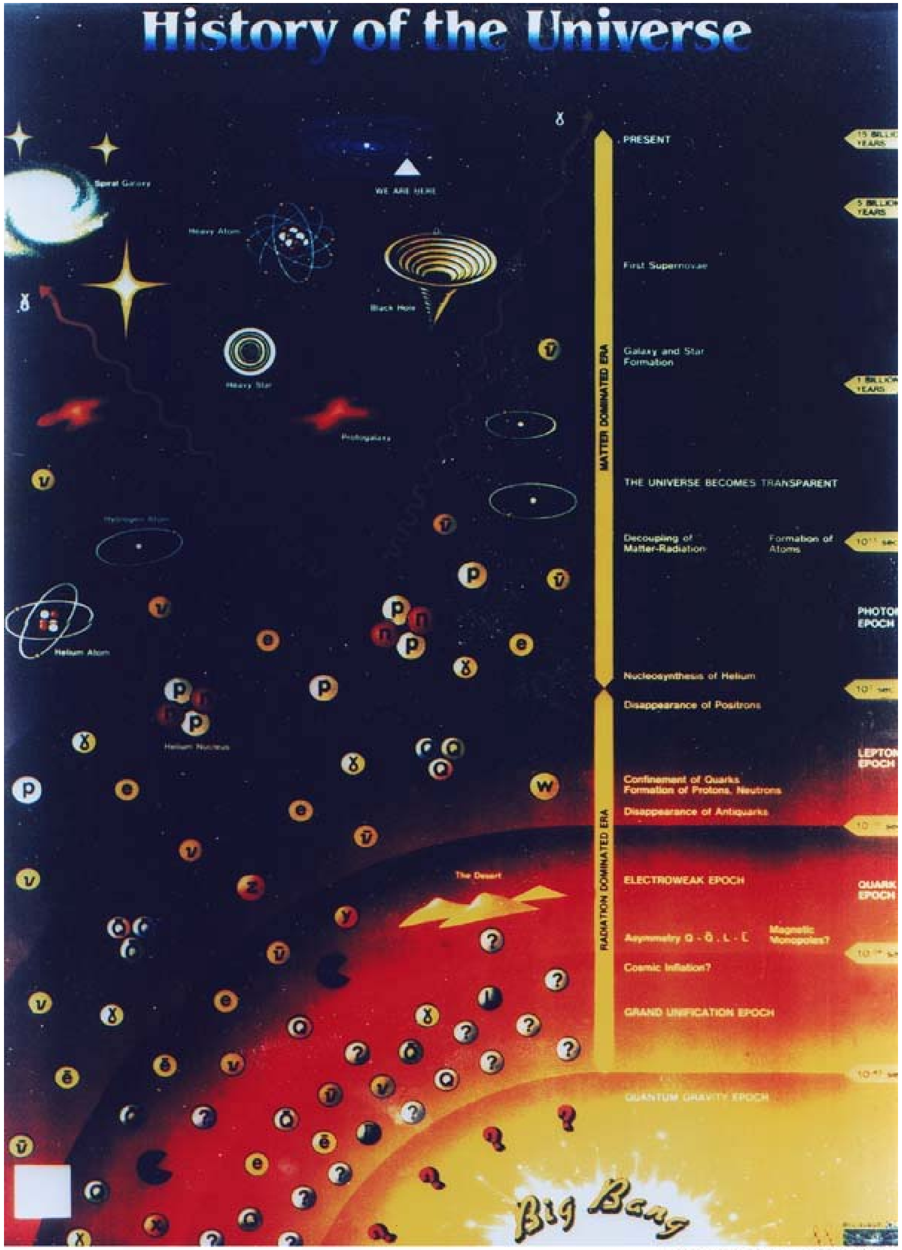
Kin-Wang Ng (吳建宏)

Academia Sinica & KIPAC

7th RESCEU Nov 11-14, 2008

Outline

- The 3K cosmic microwave background
  - the relic photons of Hot Big Bang
- CMB anisotropy and polarization
- How to probe the early Universe and measure the cosmological parameters
- Current status and future directions



Fermilab Image 01-582D

Cosmic Microwave Background

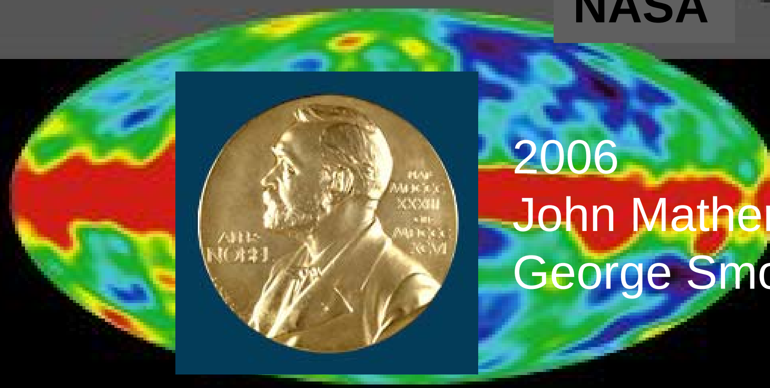
- Relic photons of hot big bang
- First observed in 1965
- Black body radiation of temperature about 3K
- Coming from last scatterings with electrons at redshift of about 1100 or 400,000 yrs after the big bang (age of the Universe is about 14 Gyrs)
- Slightly anisotropic (10 μK) and linearly polarized (μK)

CMB Milestones

1965 | AT&T Bell | Penzias and Wilson

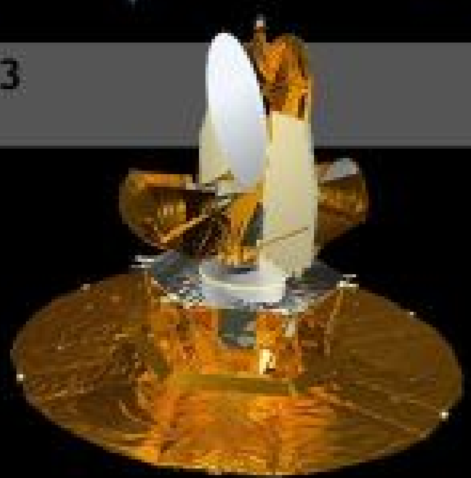
1978
Arno Penzias
Robert Wilson

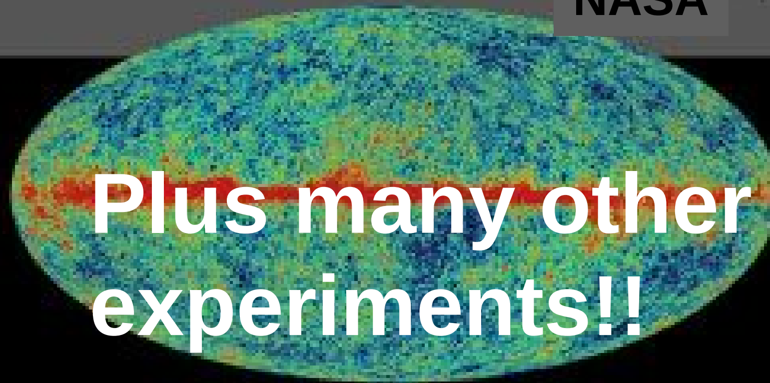
1992 | NASA | COBE



2006
John Mather
George Smoot

2003 | NASA | WMAP

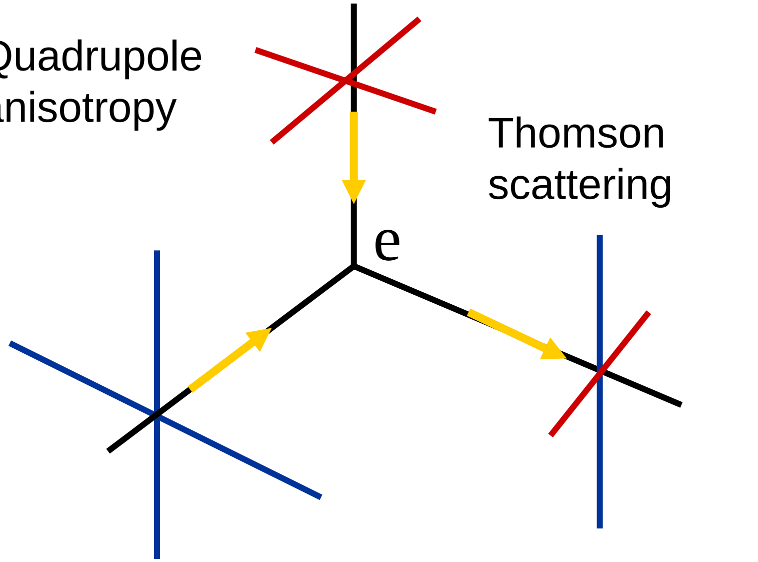


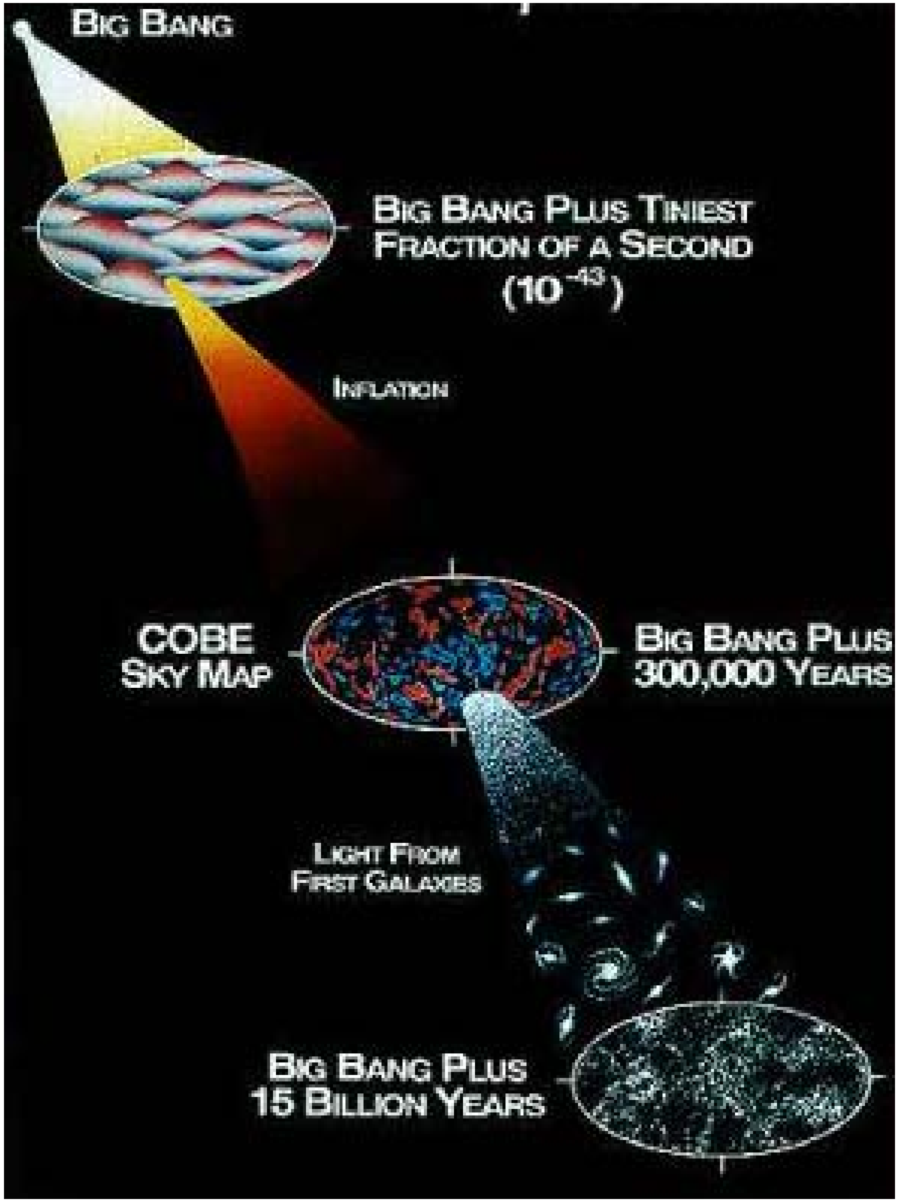


Plus many other experiments!!

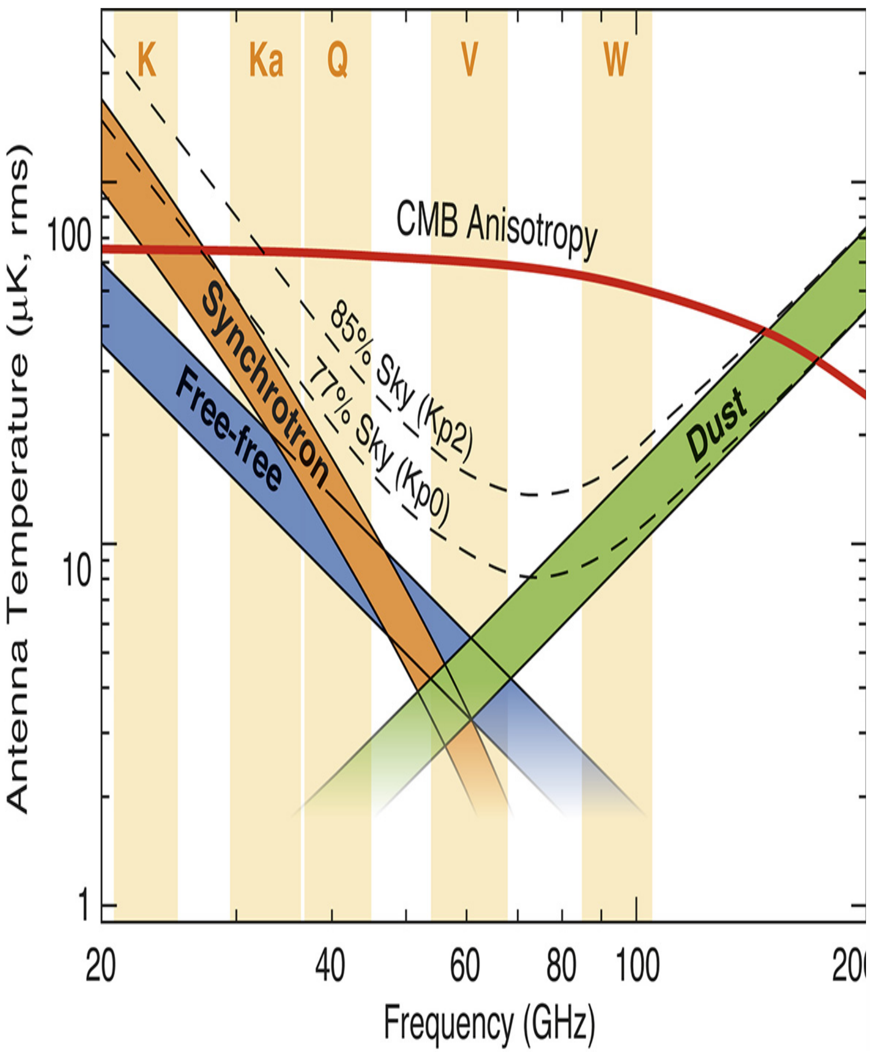
CMB Anisotropy and Polarization

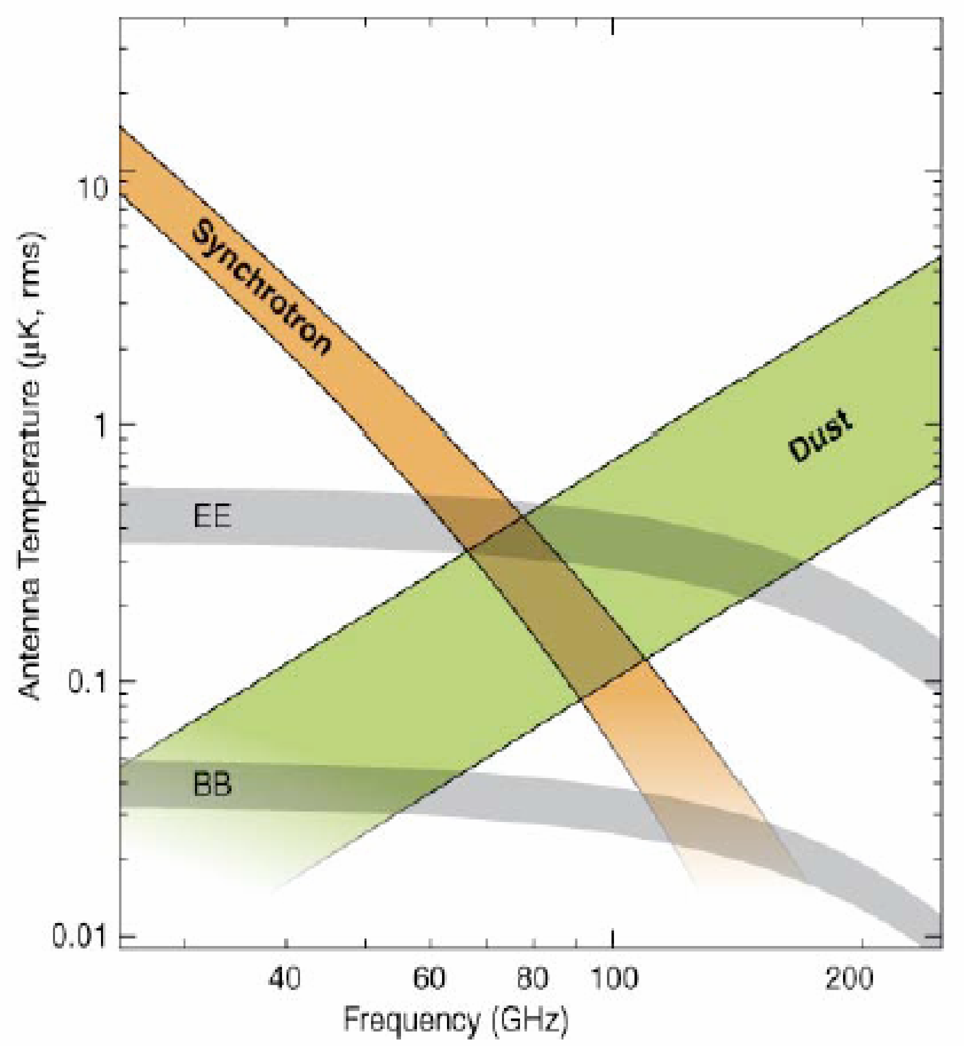
- On large angular scales, matter imhomogeneities generate gravitational redshifts
- On small angular scales, acoustic oscillations in plasma on last scattering surface generate Doppler shifts
- Thomson scatterings with electrons generate polarization





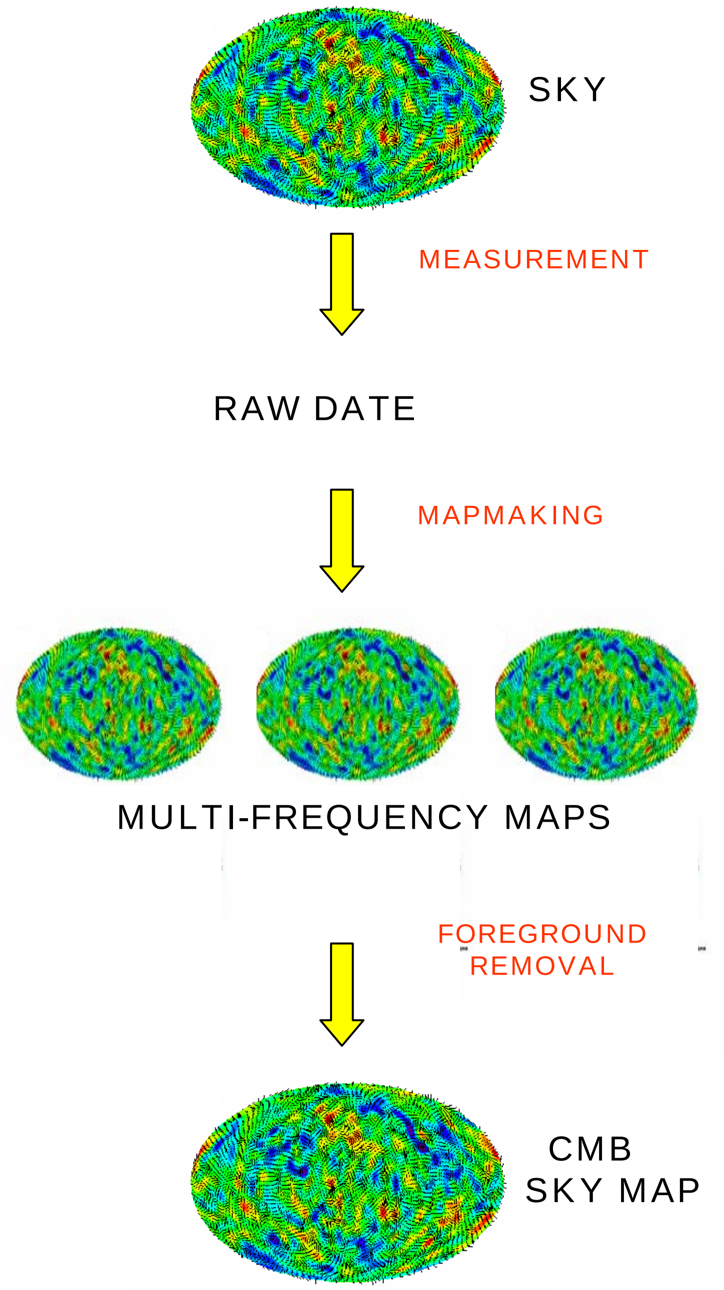
CMB Foreground





CMB Measurements

- Point the telescope to the sky
- Measure CMB Stokes parameters:
  $T = T_{CMB} - T_{mean}$,
  $Q = T_{EW} - T_{NS}$, $U = T_{SE\text{-}NW} - T_{SW\text{-}NE}$
- Scan the sky and make a sky map
- Sky map contains CMB signal, system noise, and foreground contamination including polarized galactic and extra-galactic emissions
- Remove foreground contamination by multi-frequency subtraction scheme
- Obtain the CMB sky map



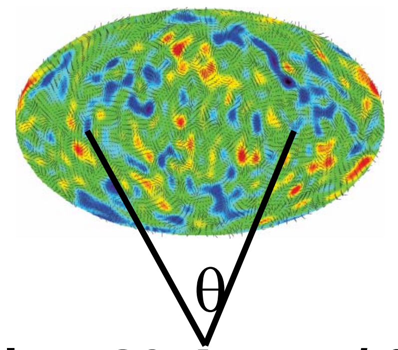
CMB Anisotropy and Polarization Angular Power Spectra

Decompose the CMB sky into a sum of spherical harmonics:

$$T(\theta,\varphi) = \Sigma_{lm}\, a_{lm}\, Y_{lm}(\theta,\varphi)$$

$$(Q - iU)(\theta,\varphi) = \Sigma_{lm}\, a_{2,lm}\ {}_{2}Y_{lm}(\theta,\varphi)$$

$$(Q + iU)(\theta,\varphi) = \Sigma_{lm}\, a_{-2,lm}\ {}_{-2}Y_{lm}(\theta,\varphi)$$



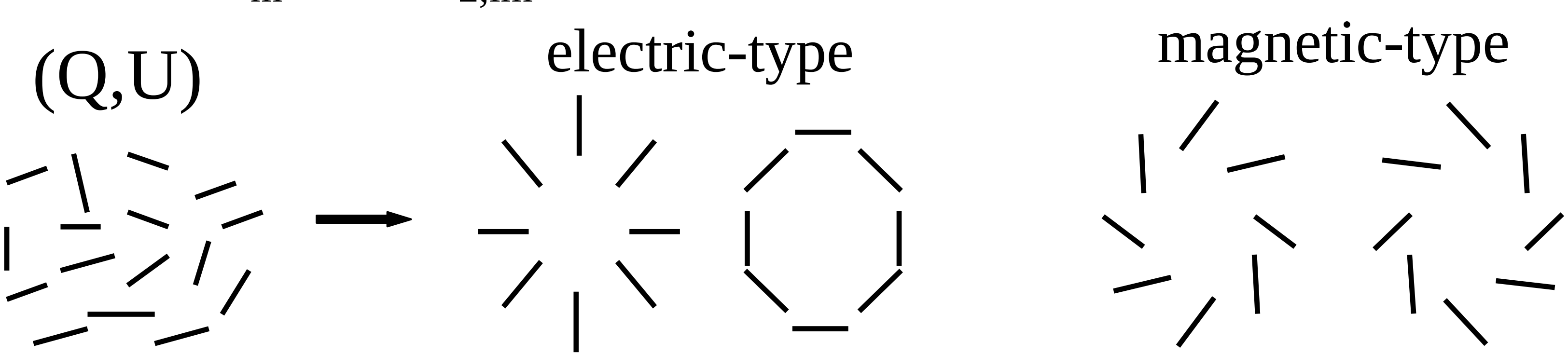
l = 180 degrees/ θ

$C^{T}_{l} = \Sigma_{m} (a^*_{lm}\, a_{lm})$ anisotropy power spectrum

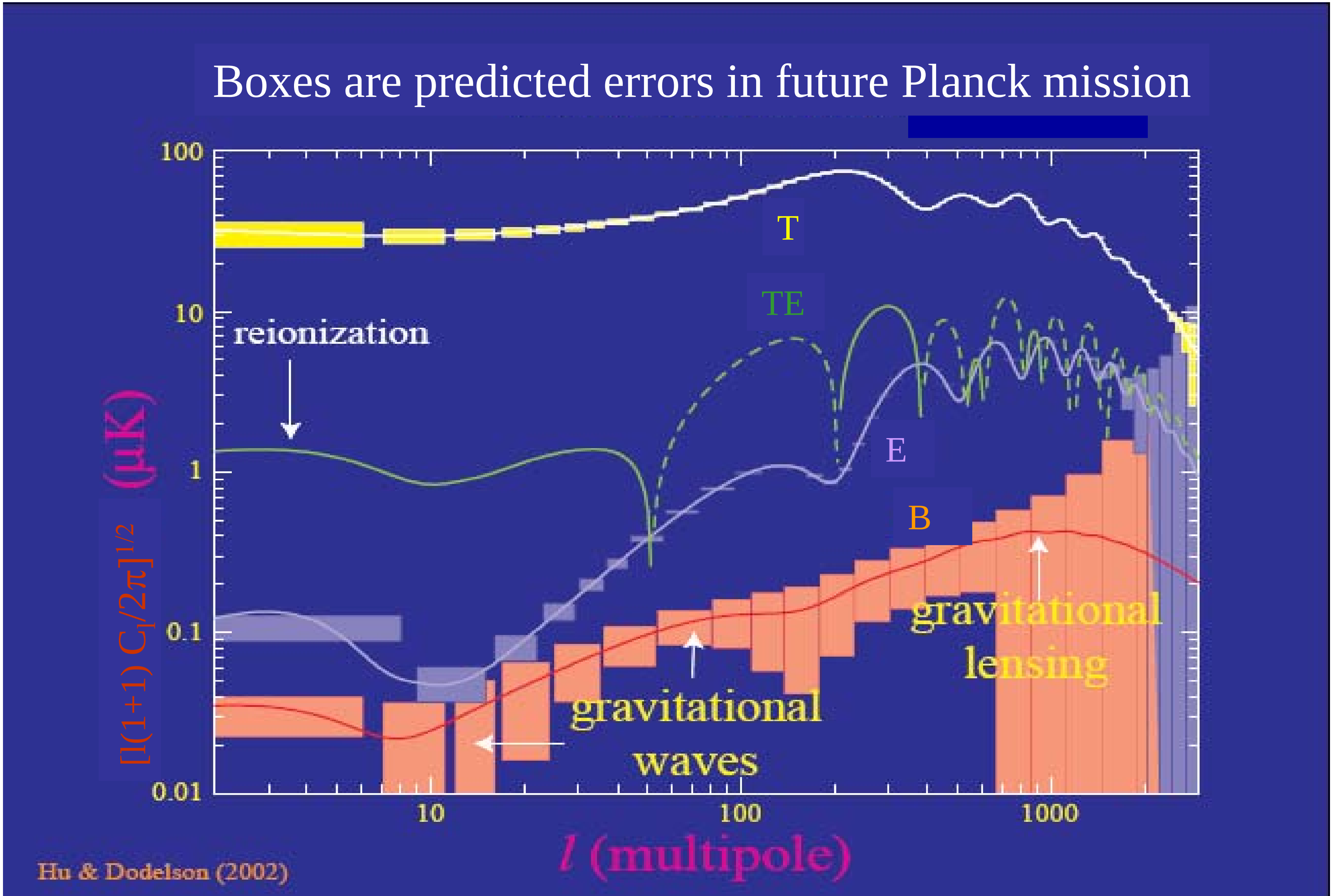
$C^{E}_{l} = \Sigma_{m} (a^*_{2,lm}\, a_{2,lm} + a^*_{2,lm}\, a_{-2,lm})$ E-polarization power spectrum

$C^{B}_{l} = \Sigma_{m} (a^*_{2,lm}\, a_{2,lm} - a^*_{2,lm}\, a_{-2,lm})$ B-polarization power

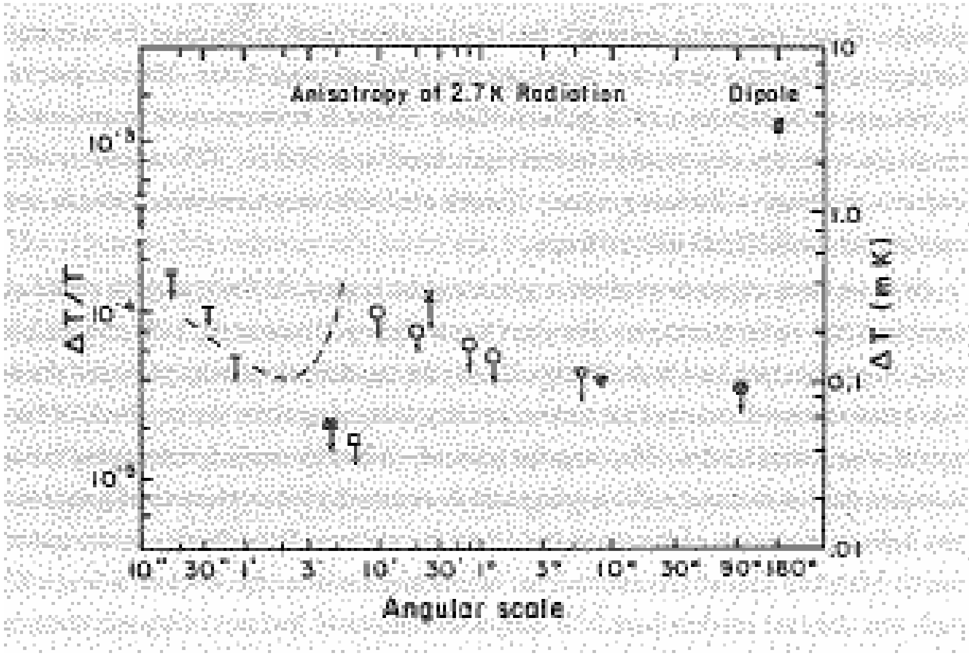
$C^{TE}_{l} = - \Sigma_{m} (a^*_{lm}\, a_{2,lm})$ TE correlation power spectrum



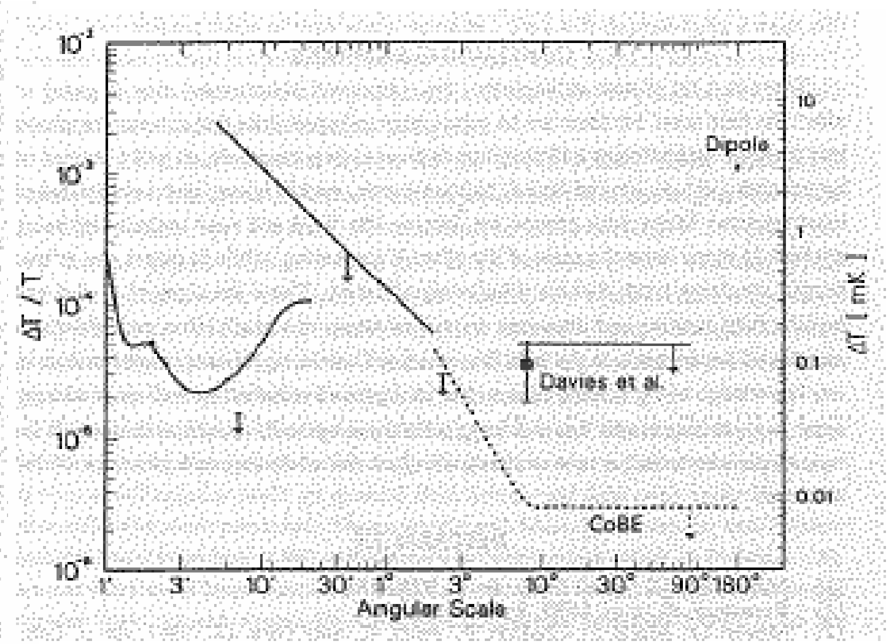
Theoretical Predictions for CMB Power Spectra



Before COBE (1965-1990)



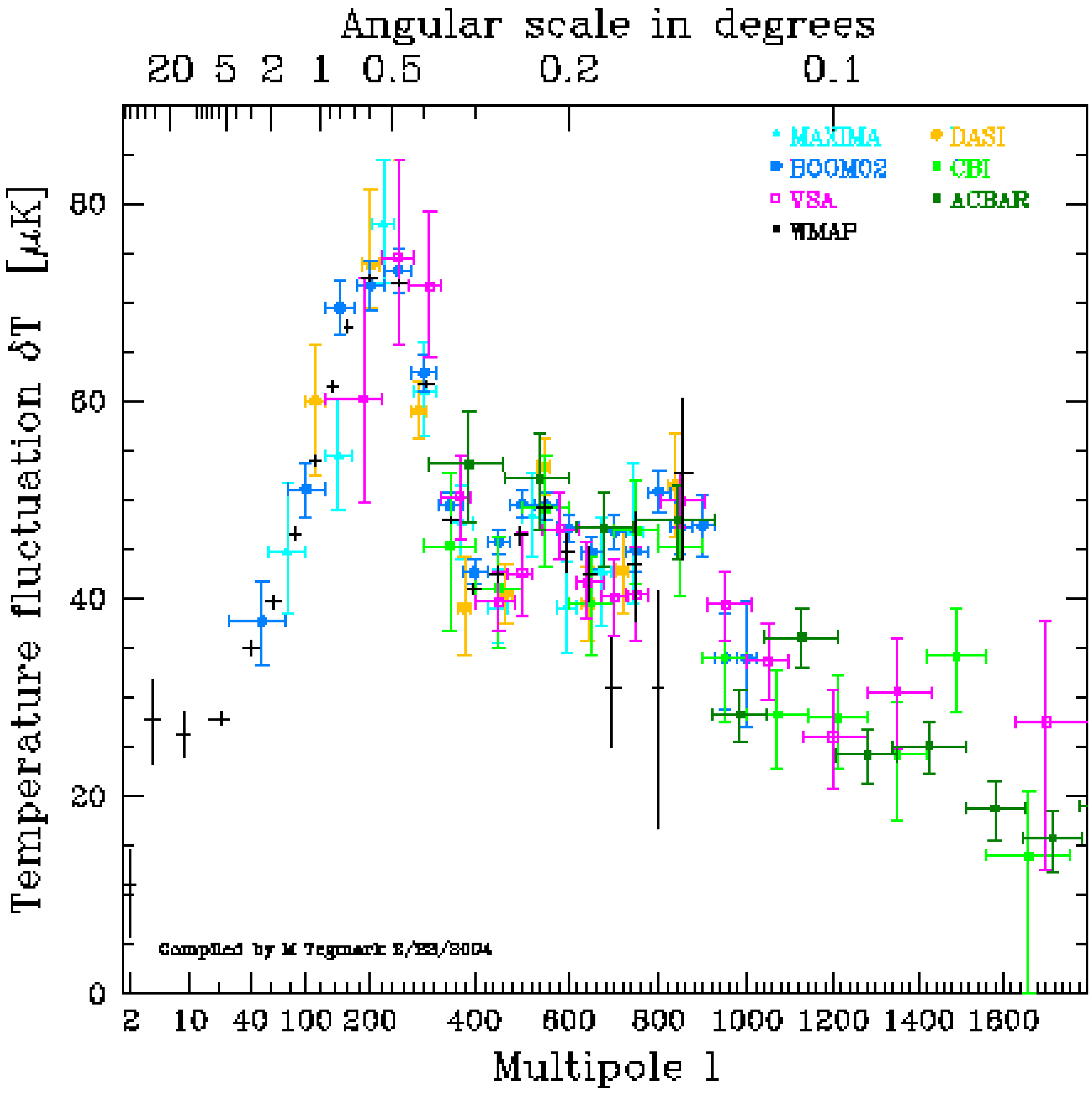
David Wilkinson @ Princeton



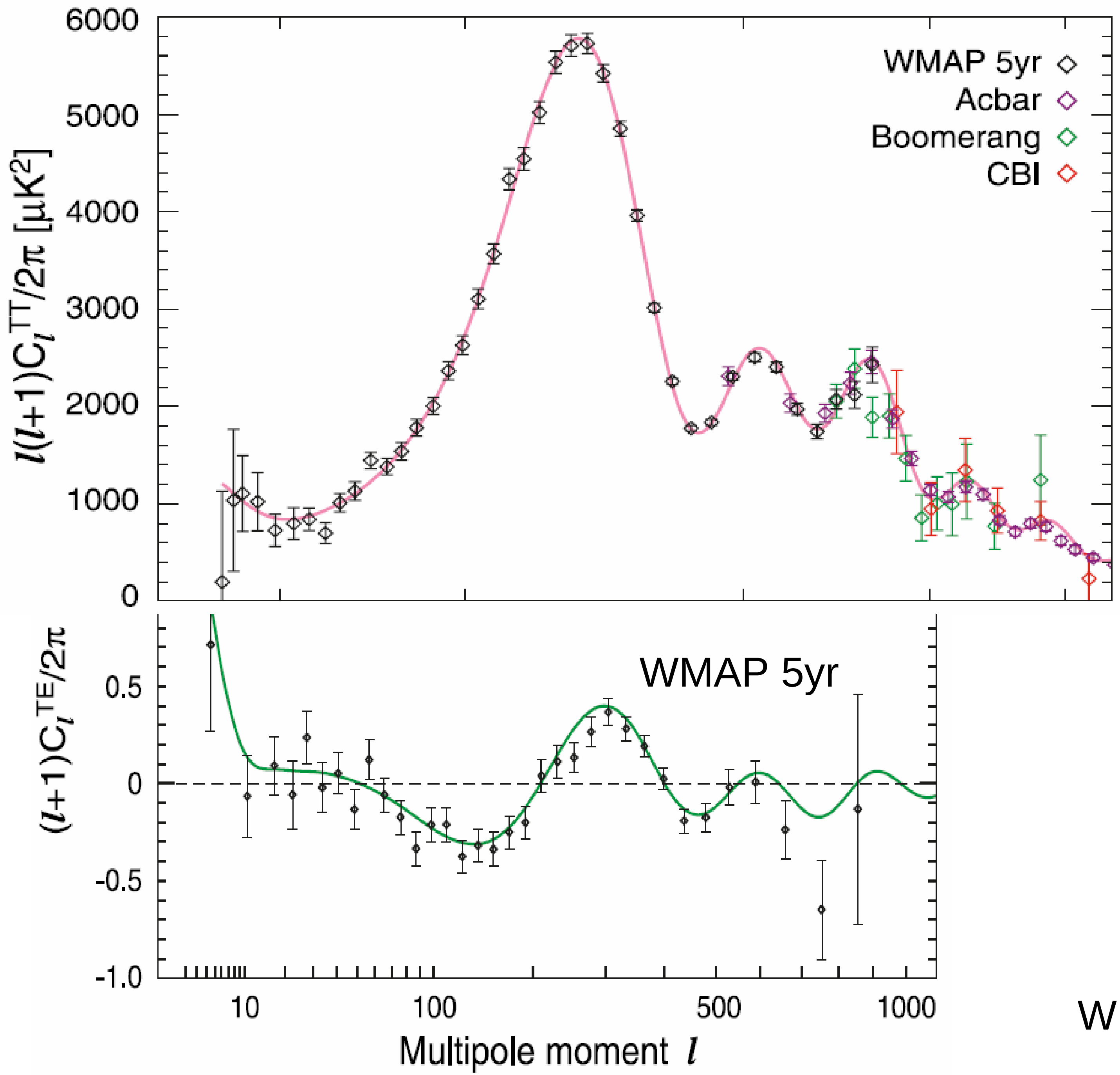
George Smoot @ Berkeley

In Proceedings of the Workshop on
Particle Astrophysics: Forefront Experimental Issues
December 1988, Berkeley, California
(1st CfPA meeting)

Post COBE



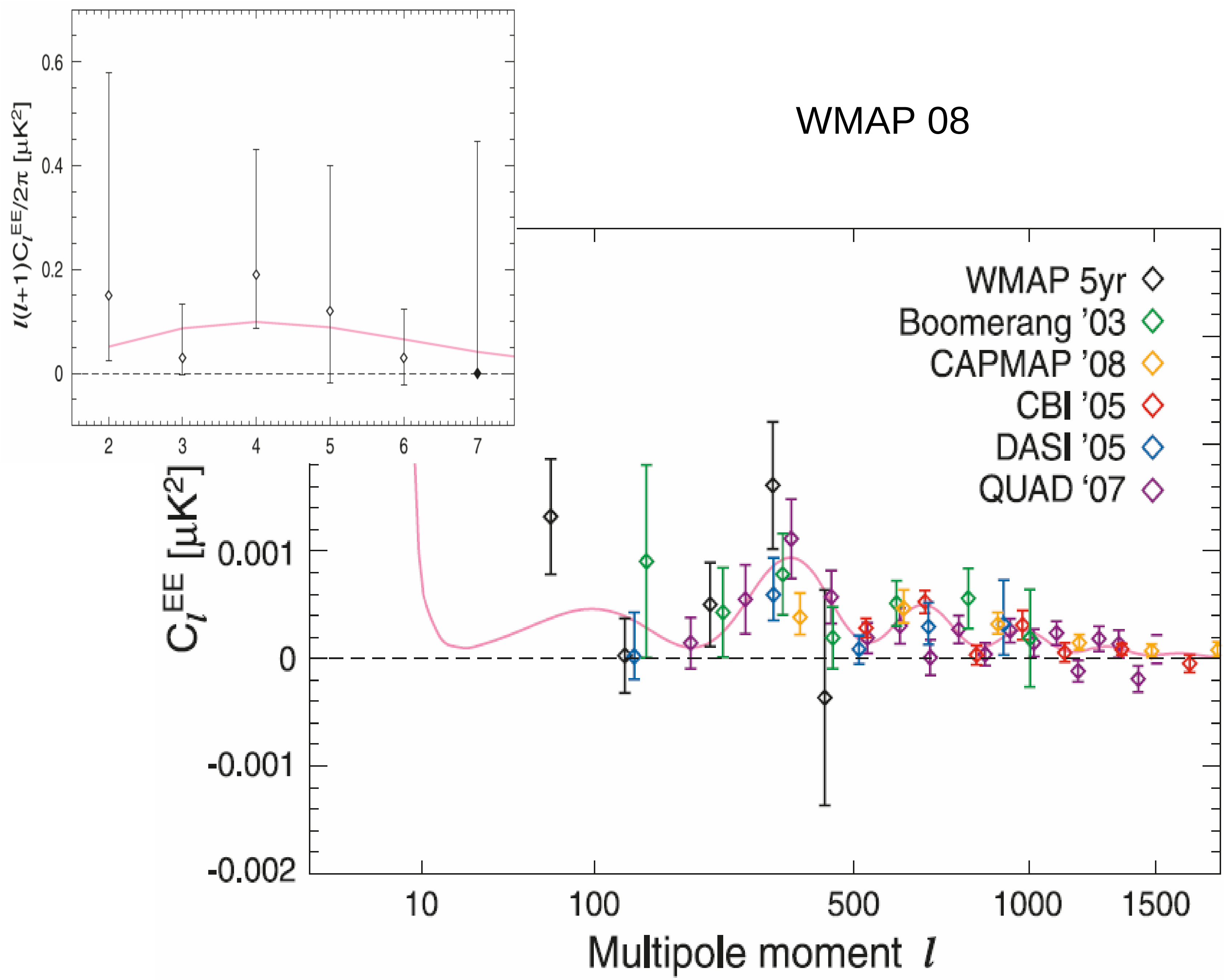
Angular scale in degrees
20 5 2 1 0.5 0.2 0.1
MAXIMA
BOOM02
VSA
WMAP
DASI
CBI
ACBAR
Temperature fluctuation δT [μK]
0
20
40
60
80
2 10 40 100 200 400 600 800 1000 1200 1400 1600
Multipole l
Compiled by M Tegmark 2/23/2004



6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l^{TT}/2\pi$ [μK²]
WMAP 5yr
Acbar
Boomerang
CBI
0.5
0
-0.5
-1.0
$(l+1)C_l^{TE}/2\pi$
WMAP 5yr
10
100
500
1000
Multipole moment l

WMAP 08

WMAP 08



$l(l+1)C_l^{EE}/2\pi$ [μK^2]
0.6
0.4
0.2
0
2
3
4
5
6
7
WMAP 5yr
Boomerang '03
CAPMAP '08
CBI '05
DASI '05
QUAD '07
C_l^{EE} [μK^2]
0.001
0
-0.001
-0.002
10
100
500
1000
1500
Multipole moment l

WMAP Cosmological Parameters

Model: lcdm+sz+lens

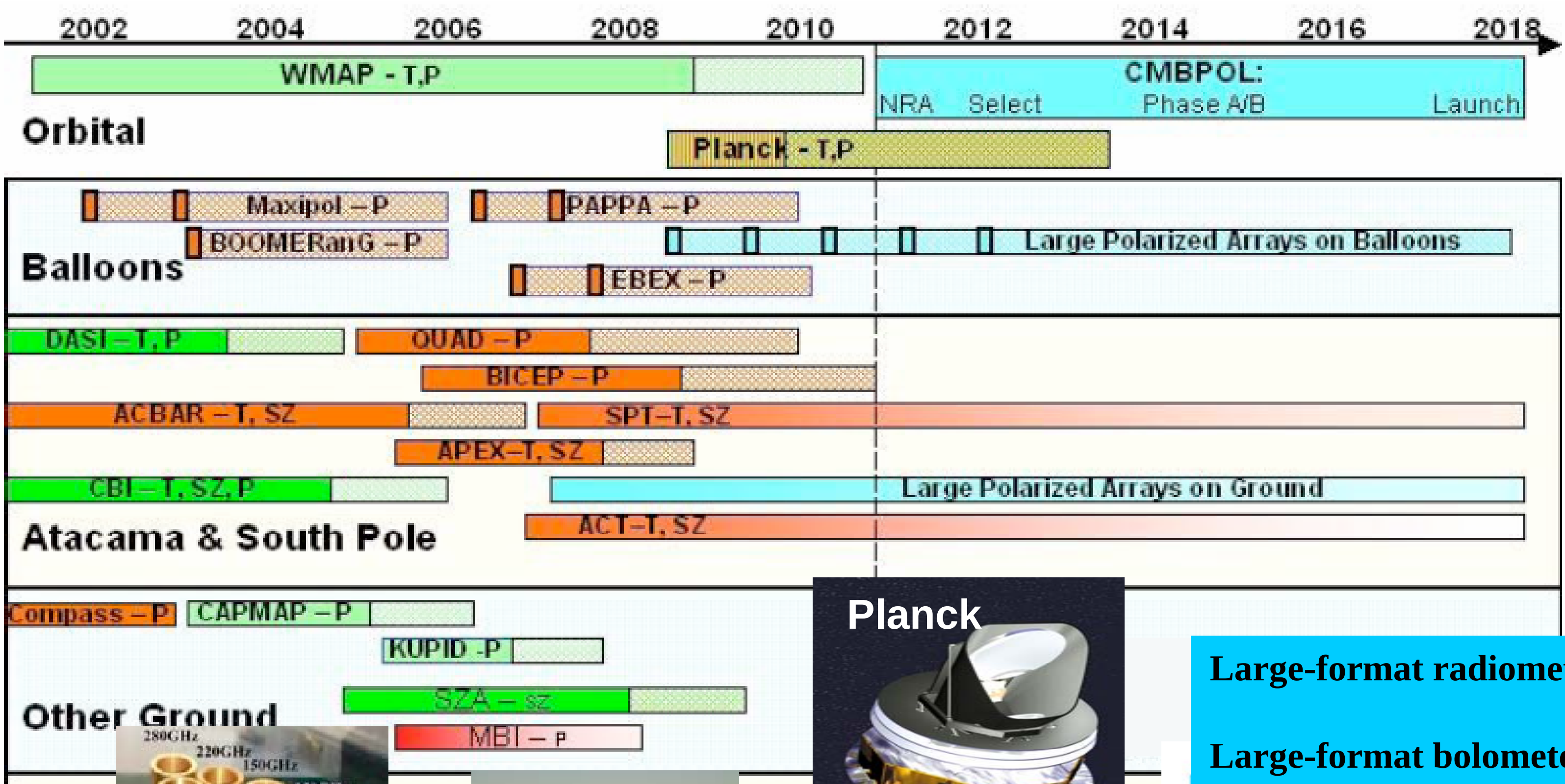
Data: wmap5+cmb

$10^2\Omega_b h^2$	2.250 ± 0.061	$1-n_s$	0.040 ± 0.014
$1-n_s$	$0.013 < 1-n_s < 0.067$ (95% CL)	$A_{BAO}(z=0.35)$	0.451 ± 0.021
C_{220}	5755^{+19}_{-11}	$d_A(z_{eq})$	14301^{+140}_{-141} Mpc
$d_A(z_*)$	14166^{+105}_{-103} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.41 \pm 0.11) \times 10^{-9}$
h	$0.725^{+0.026}_{-0.027}$	H_0	$72.5^{+2.6}_{-2.7}$ km/s/Mpc
k_{eq}	0.00952 ± 0.00045	ℓ_{eq}	135.0 ± 4.7
ℓ_*	$302.14^{+0.81}_{-0.80}$	n_s	0.960 ± 0.014
Ω_b	$0.0430^{+0.0026}_{-0.0027}$	$\Omega_b h^2$	0.02250 ± 0.00061
Ω_c	$0.207^{+0.023}_{-0.023}$	$\Omega_c h^2$	$0.1079^{+0.0061}_{-0.0060}$
Ω_Λ	$0.750^{+0.029}_{-0.034}$	Ω_m	$0.250^{+0.026}_{-0.027}$
$\Omega_m h^2$	0.1304 ± 0.0061	$r_{hor}(z_{dec})$	287.2 ± 3.4 Mpc
$r_s(z_d)$	$154.2^{+2.4}_{-1.8}$ Mpc	$r_s(z_d)/D_v(z=0.2)$	$0.1900^{+0.0070}_{-0.0070}$
$r_s(z_d)/D_v(z=0.35)$	0.1179 ± 0.0042	$r_s(z_*)$	$147.5^{+1.6}_{-1.7}$ Mpc
R	1.708 ± 0.020	σ_8	0.763 ± 0.035
A_{SZ}	$0.66^{+0.57}_{-0.63}$	t_0	$13.70^{+0.14}_{-0.13}$ Gyr
τ	$0.090^{+0.017}_{-0.016}$	θ_*	0.010398 ± 0.000029
θ_*	$0.5958^{+0.0016}_{-0.0017}$ °	t_*	382028^{+5738}_{-5751} yr
z_{dec}	1087.9 ± 1.2	z_d	1019.6 ± 1.5
z_{eq}	3122 ± 147	z_{reion}	10.9 ± 1.4
z_*	1090.62 ± 0.95		

CMB Polarization

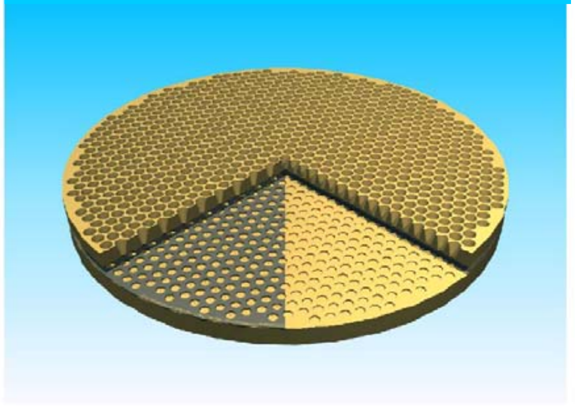
- CMB temperature anisotropy has been well measured for $l < 1000$; fine-scale anisotropy needed for tracing baryons
- CMB polarization will be the primary goal
- E-mode to break the degeneracy of determining cosmological parameters
- Sensitive to ionization history of the Universe: last scattering surface and reionization epoch
- Lensing B-mode and large scale structure
- Gravity-wave induced B-mode to test inflation models (r=Tensor/Scalar in Koyama's talk)

Recent, On-going, and Future CMB Space Missions and Experiments

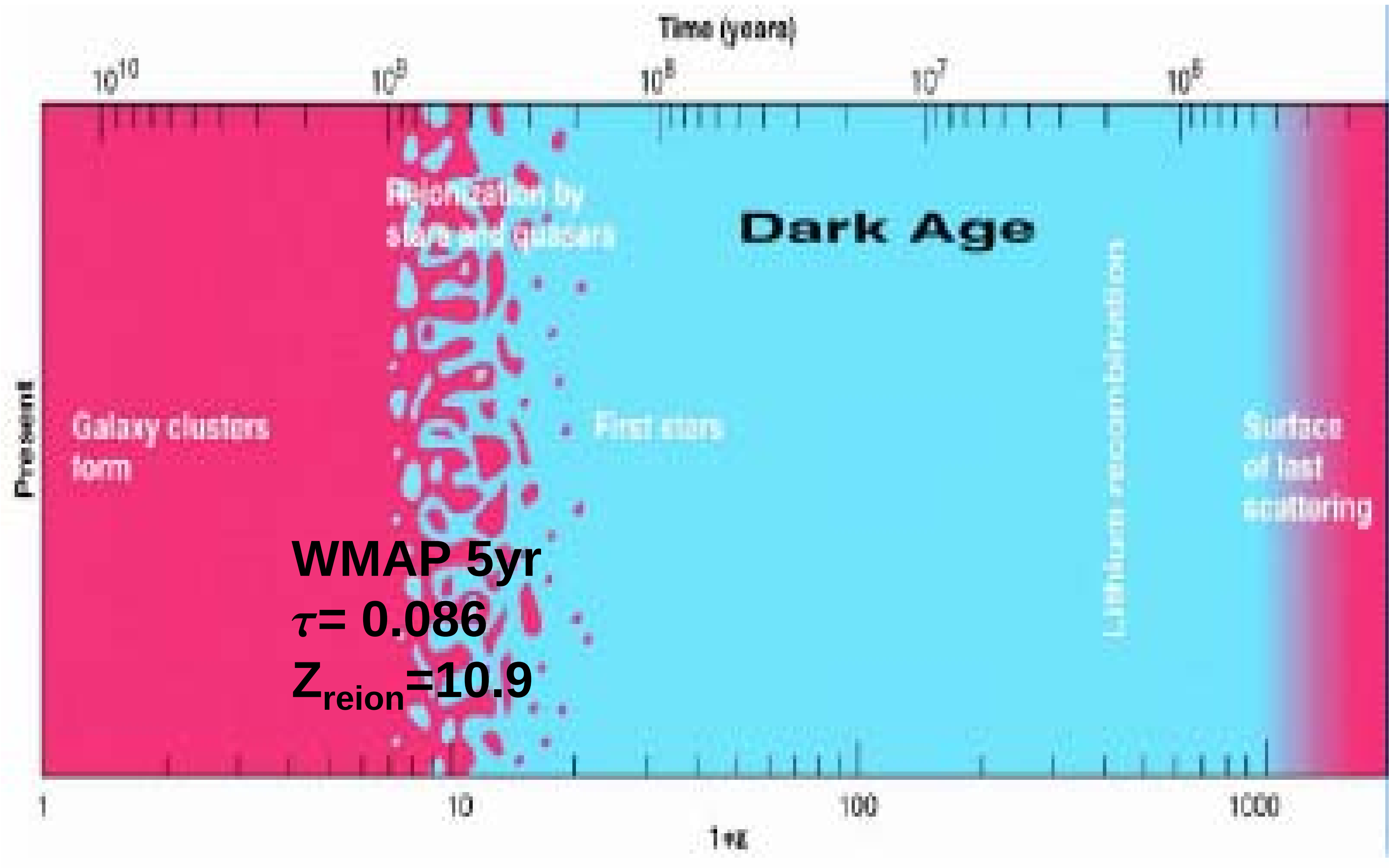


Large-format radiometer arrays

Large-format bolometer arrays

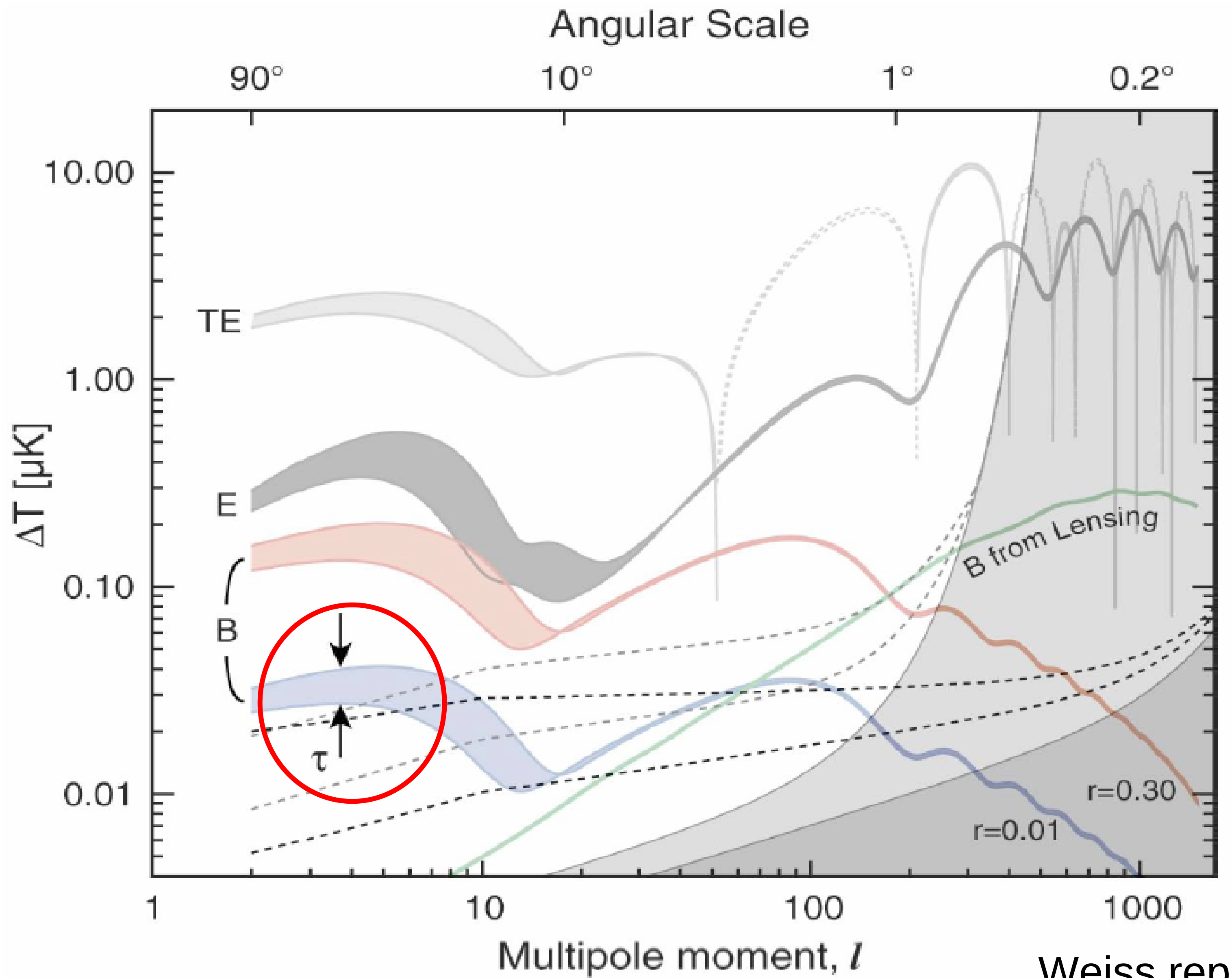


Large-scale CMB Polarization and Reionization of the Universe



WMAP 5yr
τ= 0.086
Z_{reion}=10.9

Uncertainty about the epoch of reionization



Weiss report 05

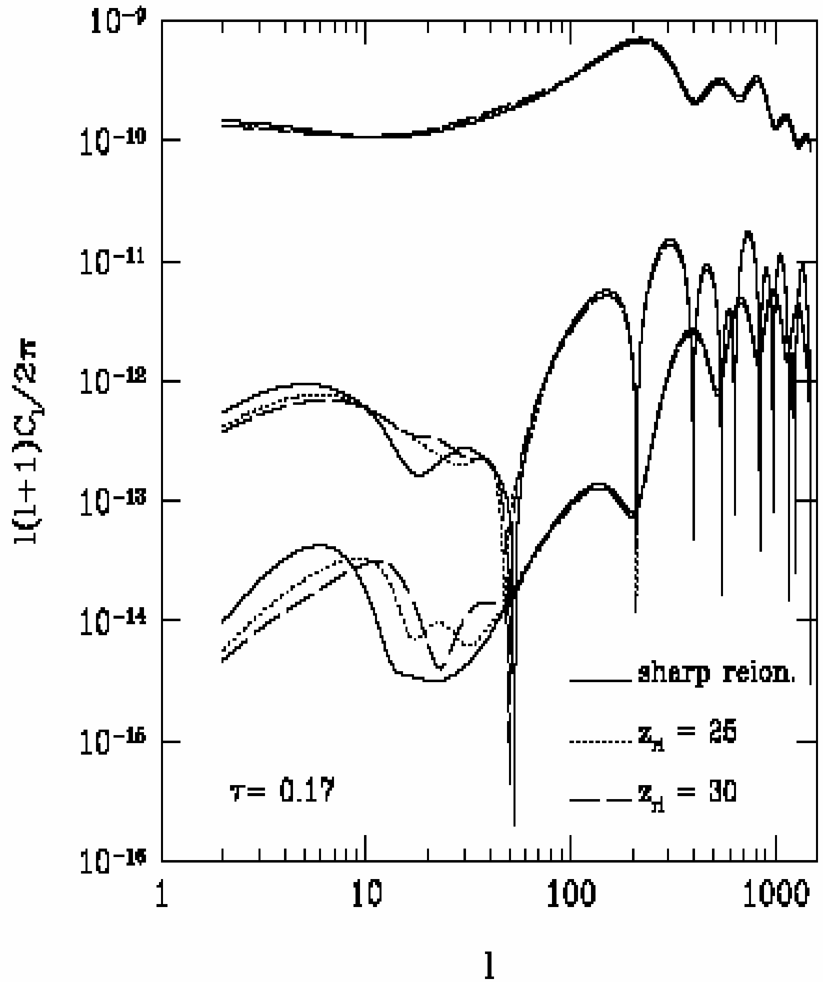


Fig. 2. Dependence of angular power spectra (in K^2) on model reionization histories.

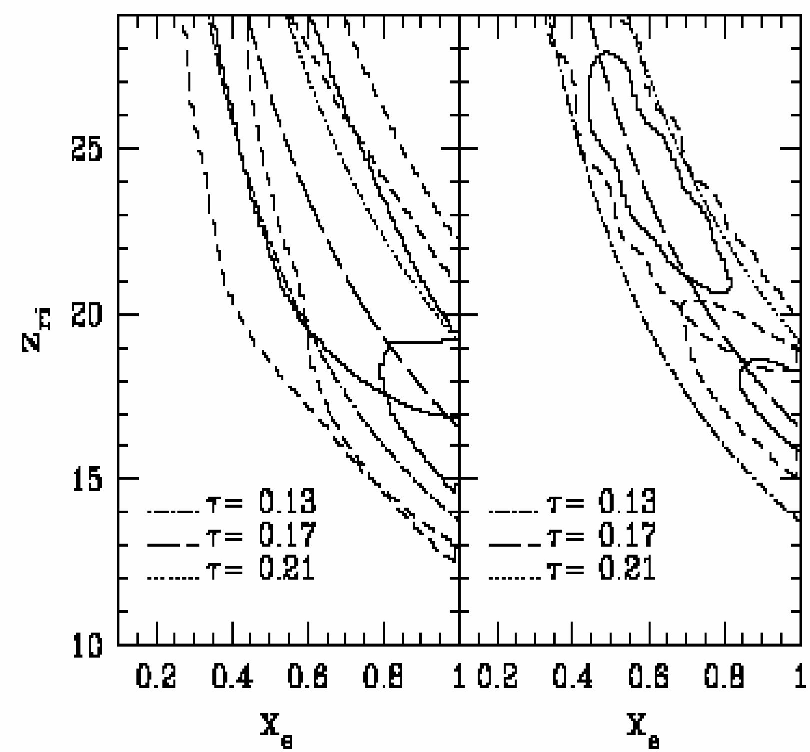
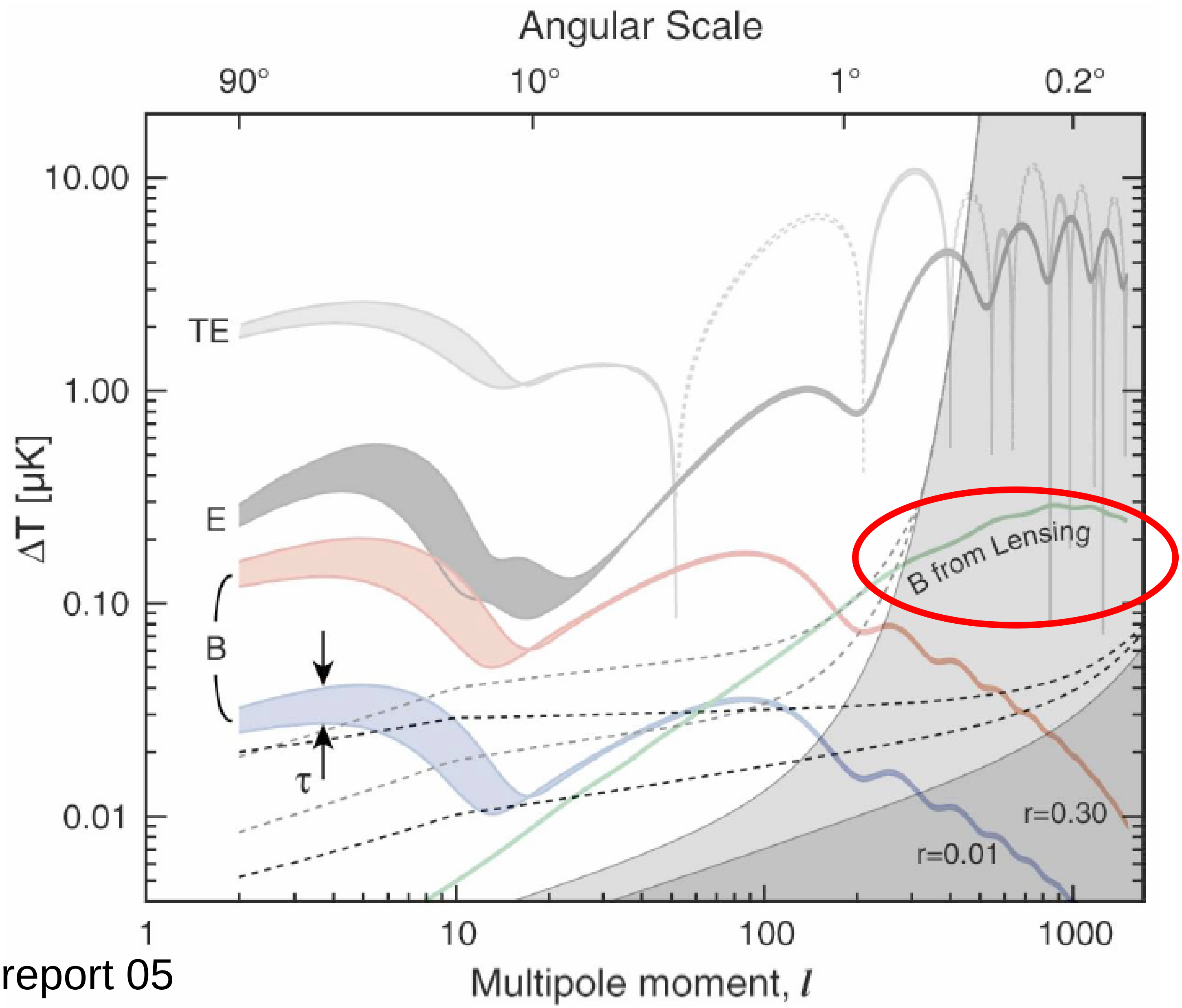


Fig. 3. Likelihood distributions for the simultaneous determination of reionization redshift z_{ri} and ionization rate x_e in models with fixed $\tau = 0.17$; the left (right) panel corresponds to a 7°-pixel noise $\sigma_{pix} = 2$ μK (0.5 μK).

E converted into B by weak lensing

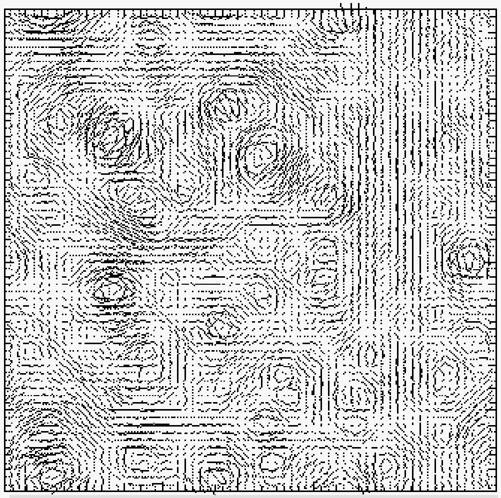


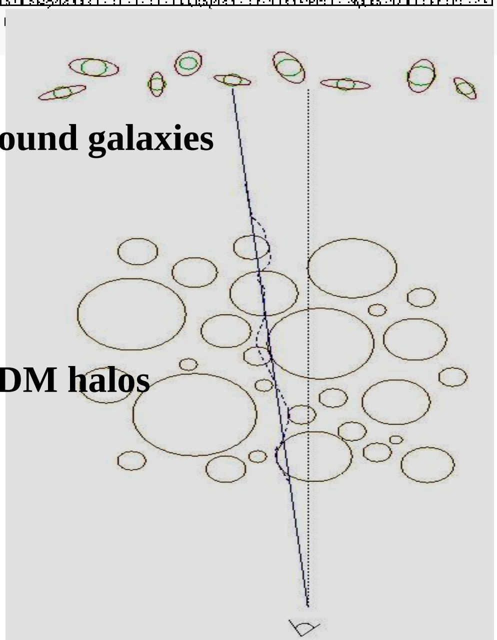
Weiss report 05

Weak Lensing by Large-Scale Structure

Jain et al. 1997
1x1 deg

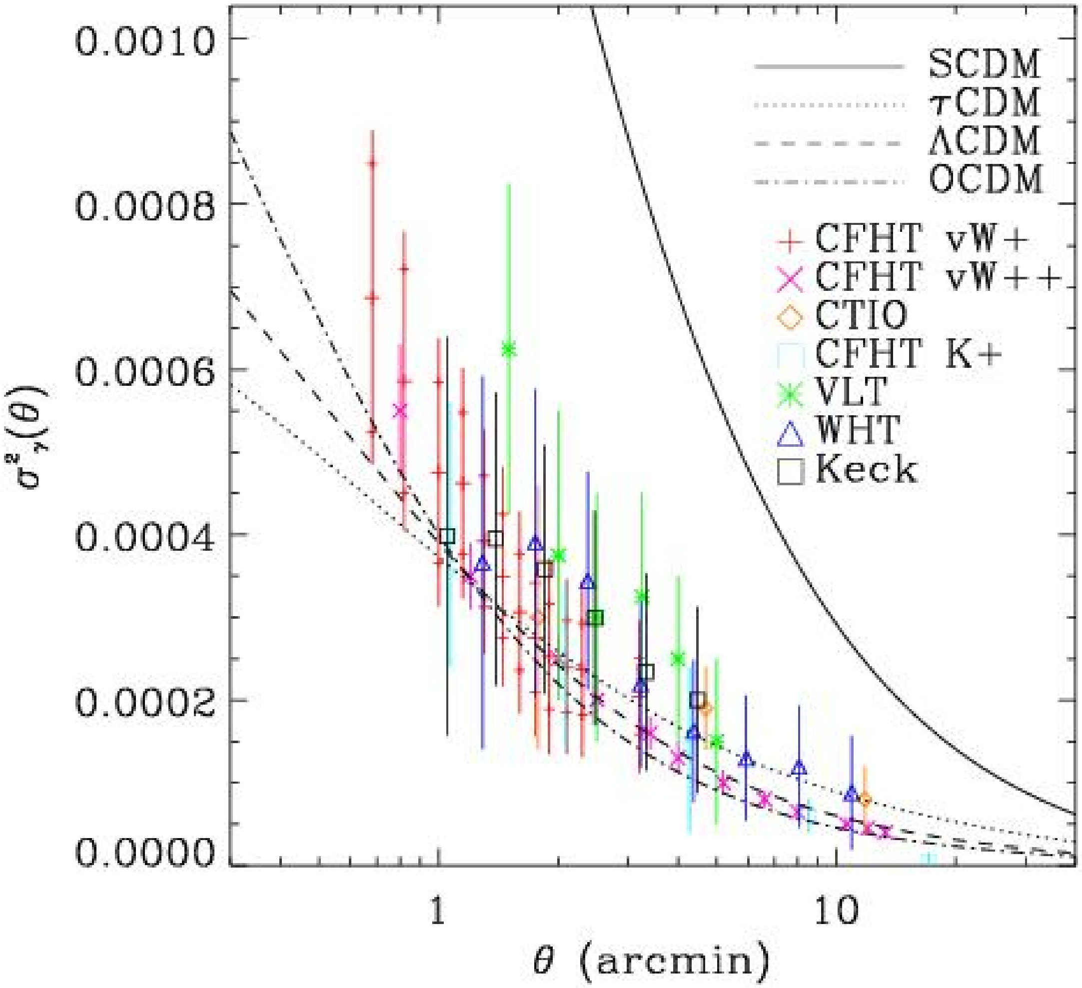
Cosmic Shear γ





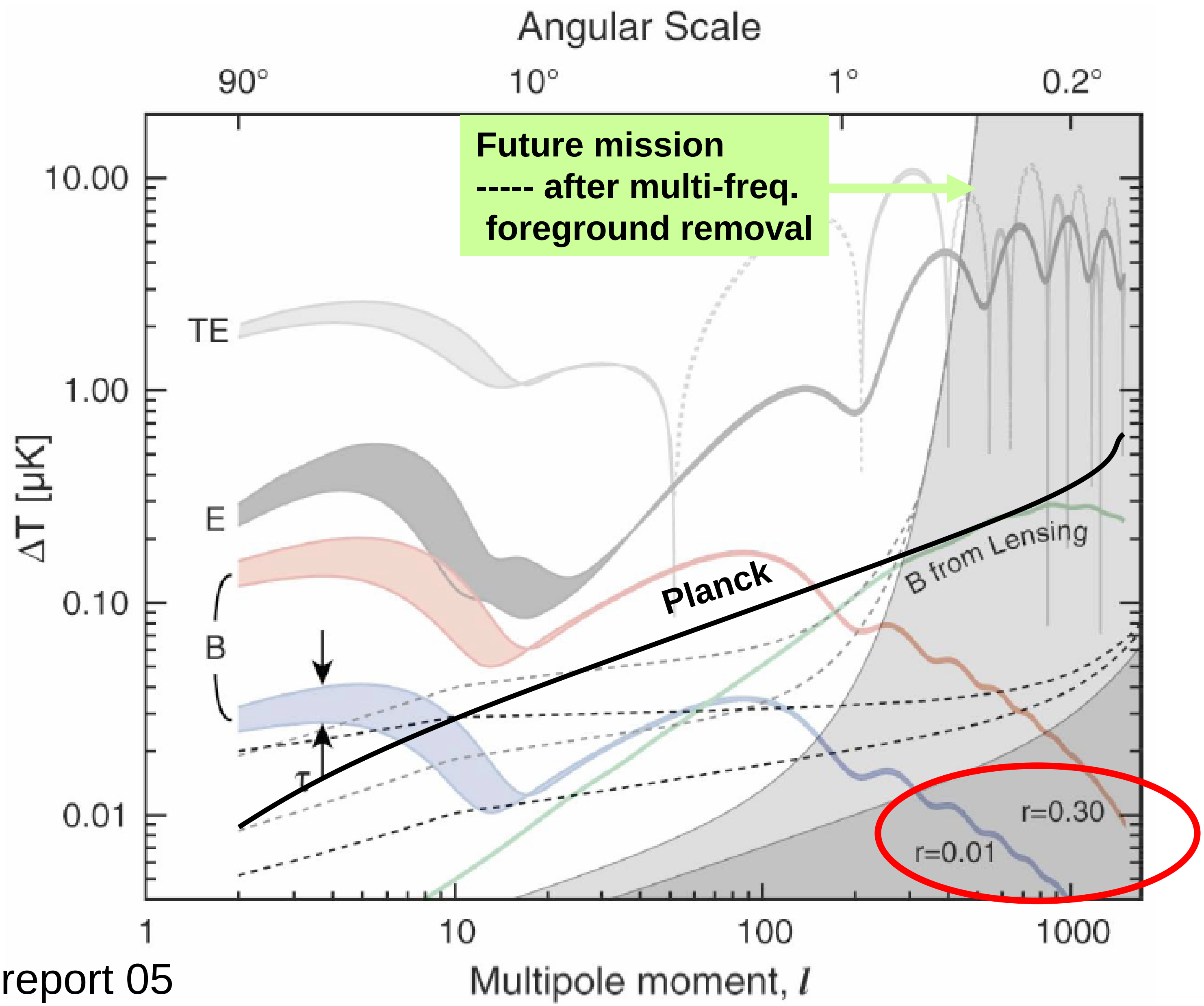
Shear Variance in circular cells with size θ

$$\sigma^2_\gamma(\theta) = \langle \gamma^2 \rangle$$



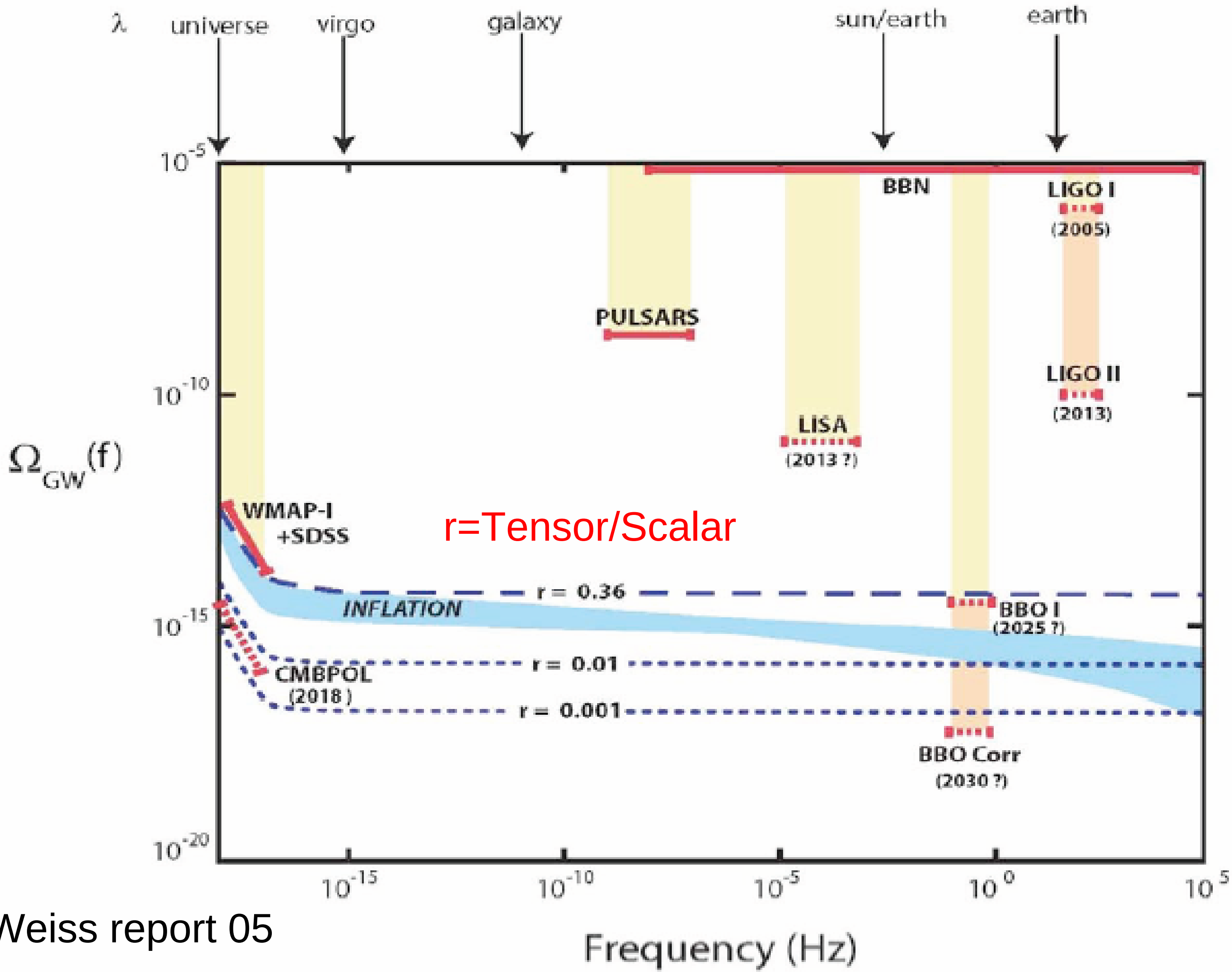
Ellis et al. 02

Gravity-wave induced B-mode



Weiss report 05

Primordial gravitational waves



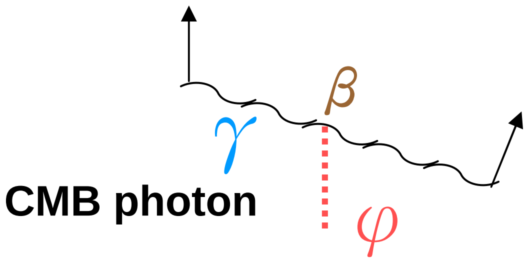
Weiss report 05

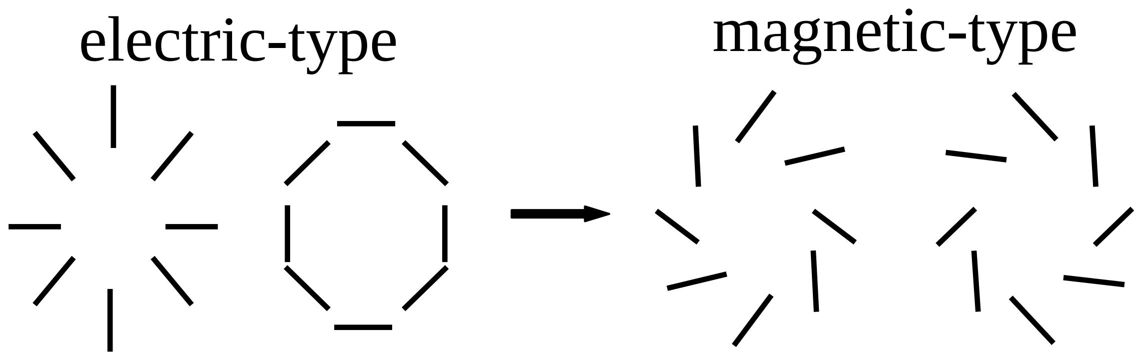
Some Issues before Detection of Genuine B-mode

- Other B-mode Sources?
- E and B modes mixing in real measurements
- Systematics, e.g., asymmetric beam
- Data analysis, e.g., large-scale coverage by interferometric observations

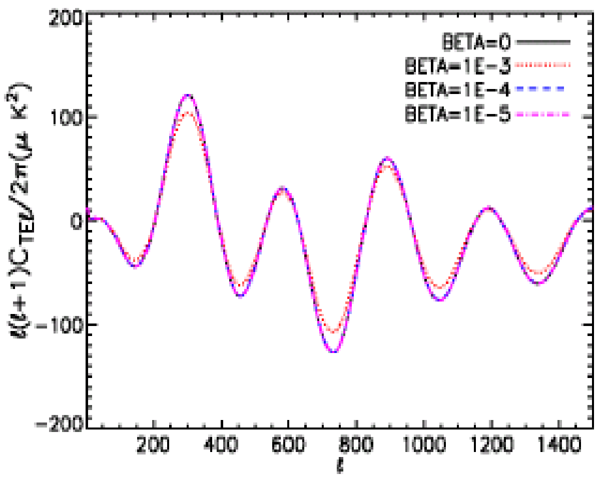
Vacuum birefringence inducing freq.-indep. rotation of CMB polarization

Lue et al. 99
Feng et al. 06
Liu,Lee,Ng 06
Komatsu et al 08
Wu et al. 08

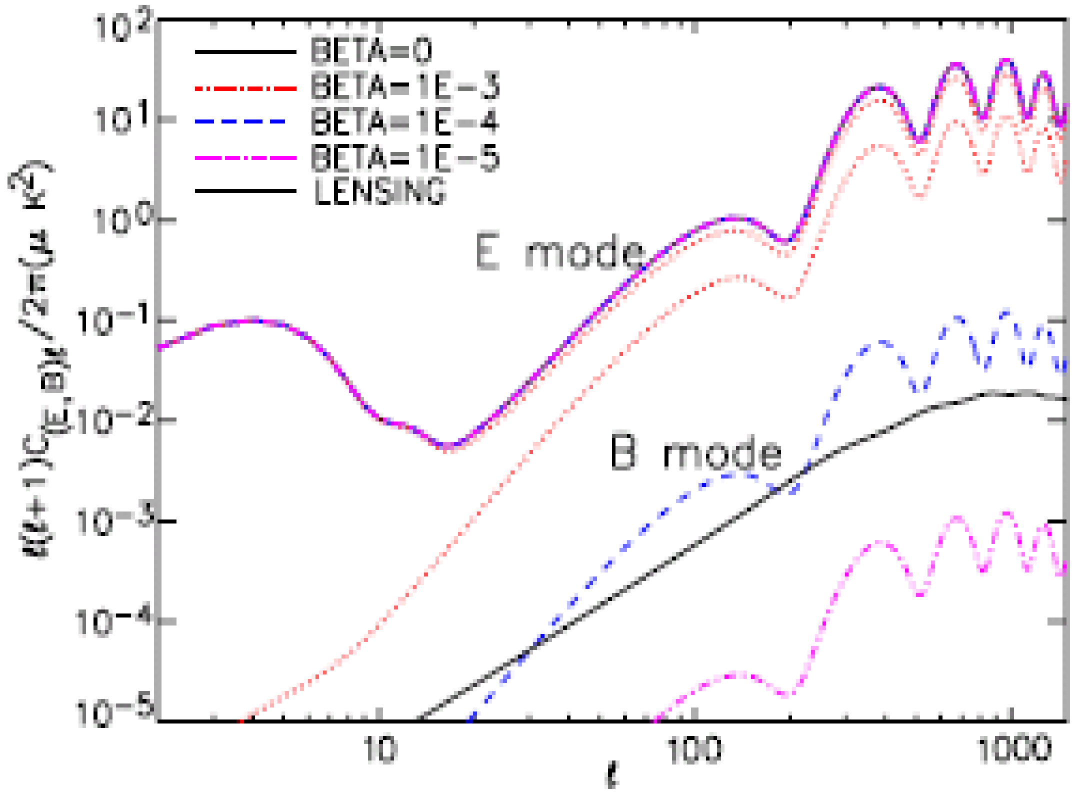




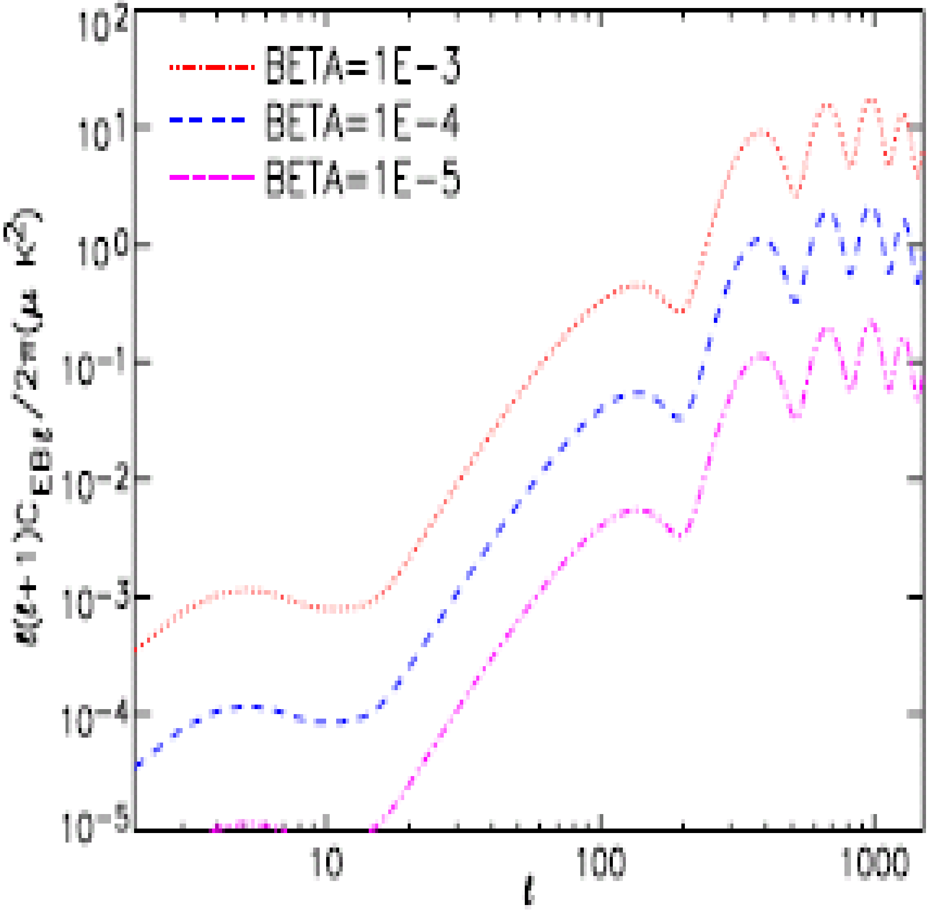
e.g. Dark energy induced
Liu, Lee, Ng 06

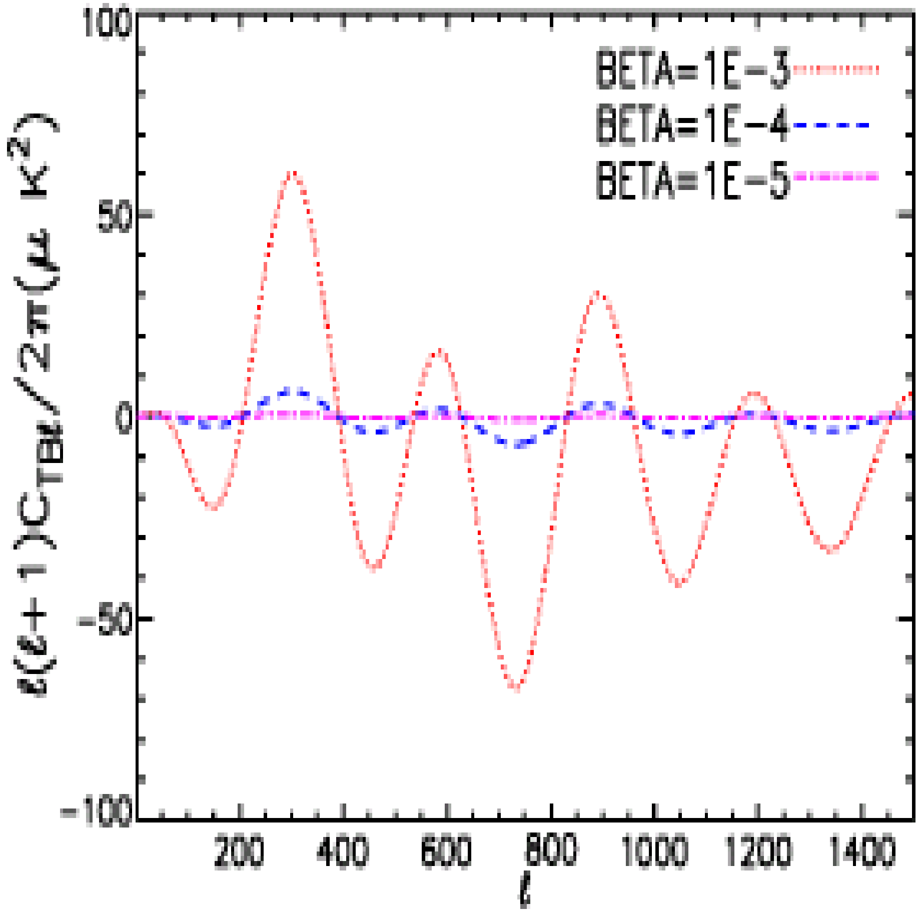


TE spectrum



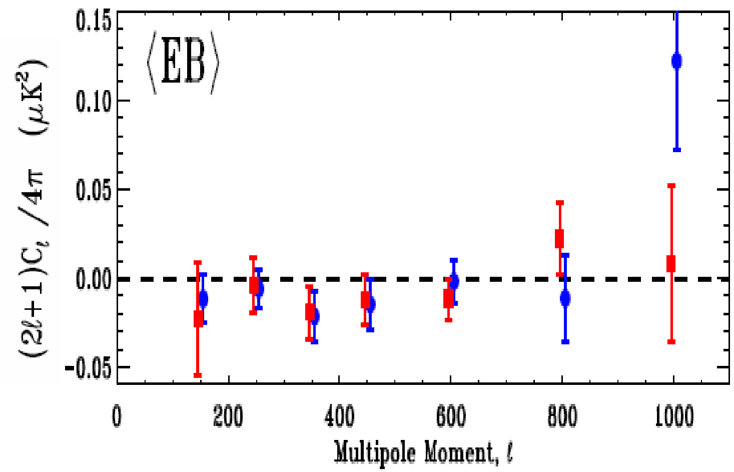
Parity violating EB,TB cross power spectra

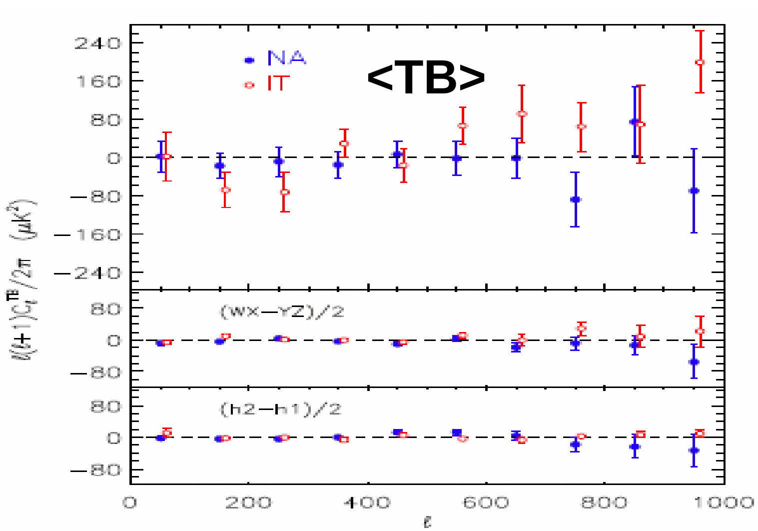




Constraining β by CMB polarization data

2003 Flight of BOOMERANG

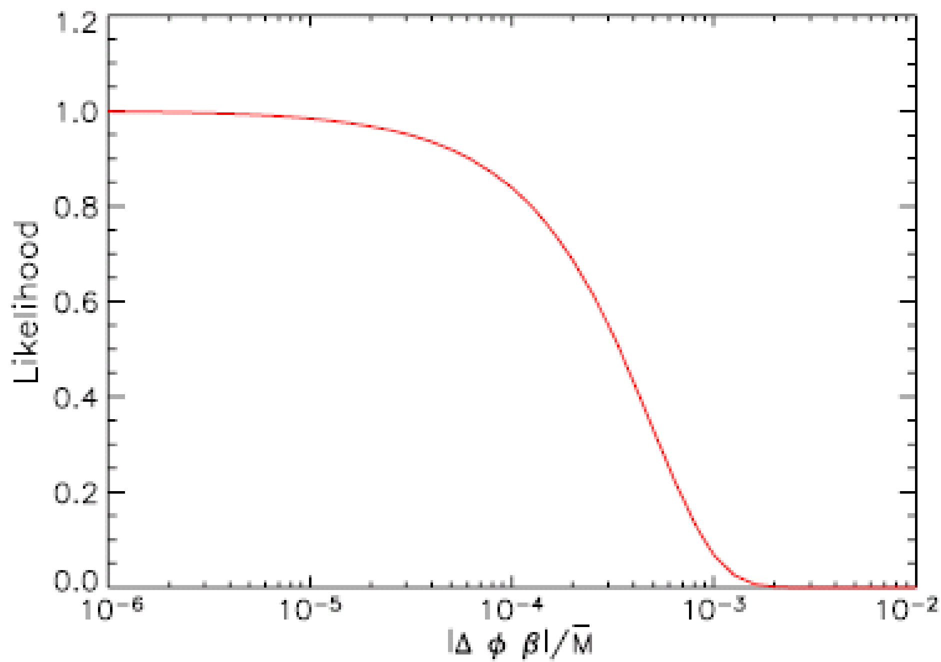




Likelihood analysis assuming reasonable quintessence models

$V(\phi) = V_0 \exp(\lambda\phi^2/2\bar{M}^2)$ $\quad$ $V(\phi) = V_0 \cosh(\lambda\phi/\bar{M})$

$\bar{M}$ reduced Planck mass



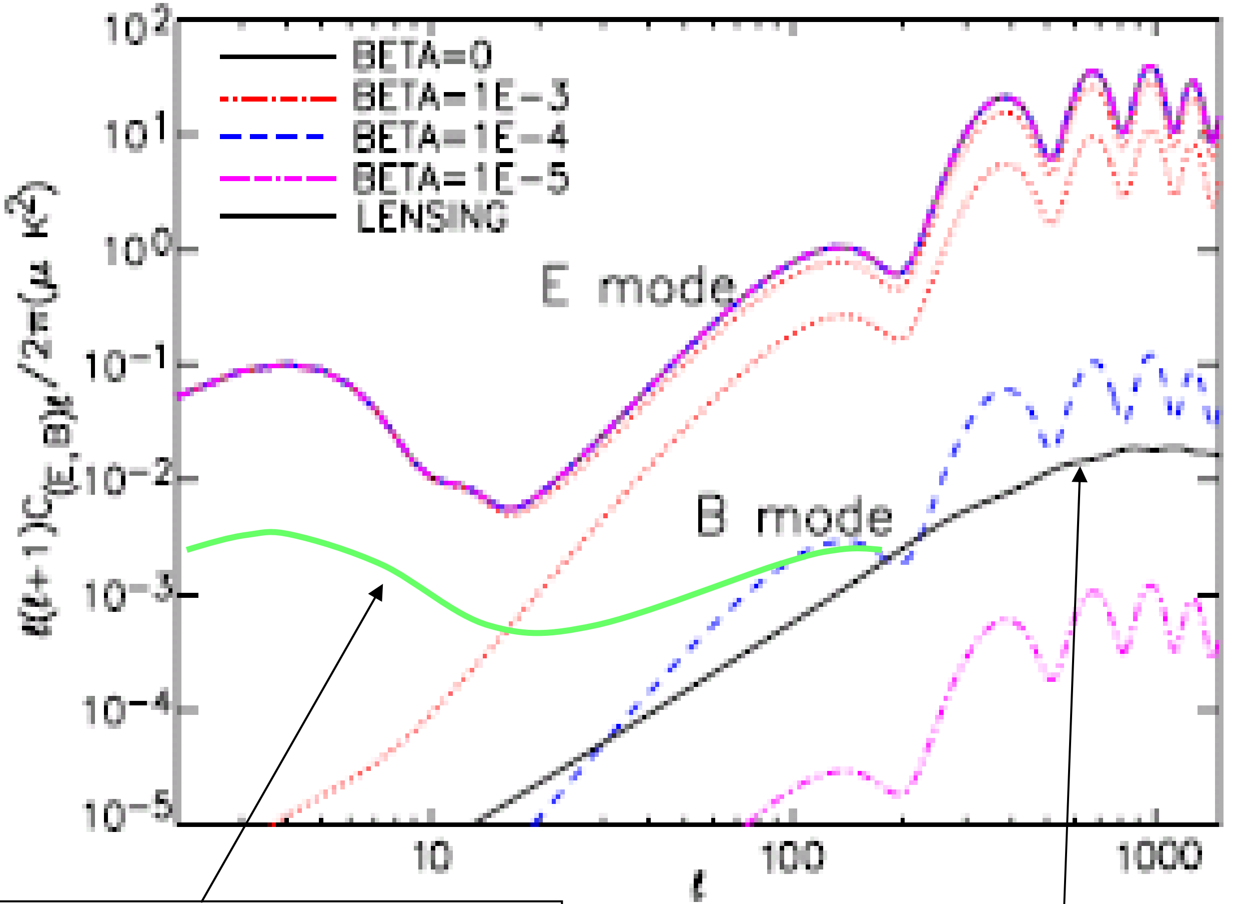
$|\beta_{FF}\Delta\phi|/\bar{M} < 8.32\times10^{-4}$ at 95% **c.l.**

where $\Delta\phi$ is the total change of ϕ until today.

Komatsu et al 08 – WMAP 5 yr data

Wu et al. 08 – QUAD 06-07 data

Future search for B mode

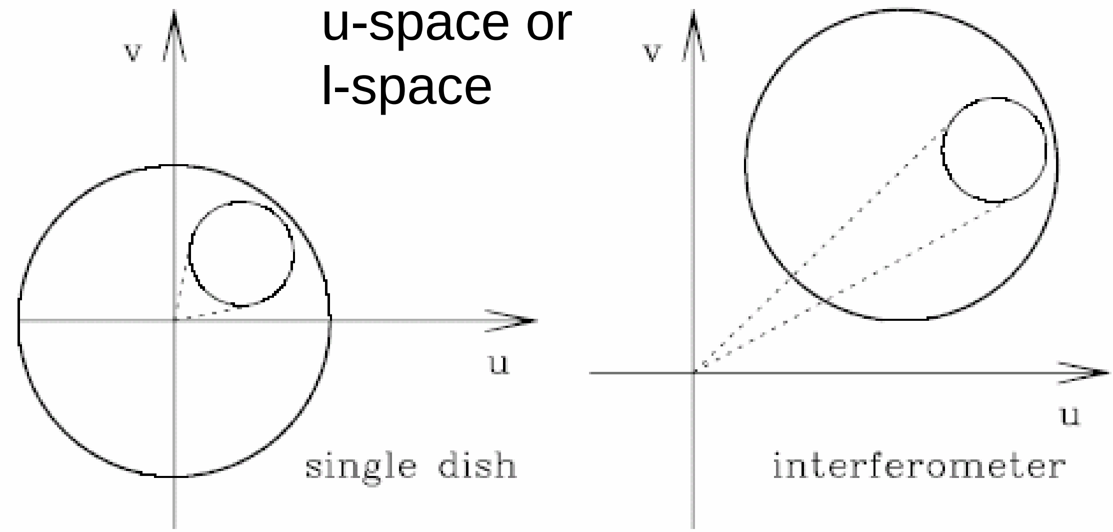


Gravity-wave B mode mimicked by late-time quintessence evoution (z<10)

Lensing B mode mimicked by early quintessence evolution

Origin of E and B modes mixing

u-space or
l-space



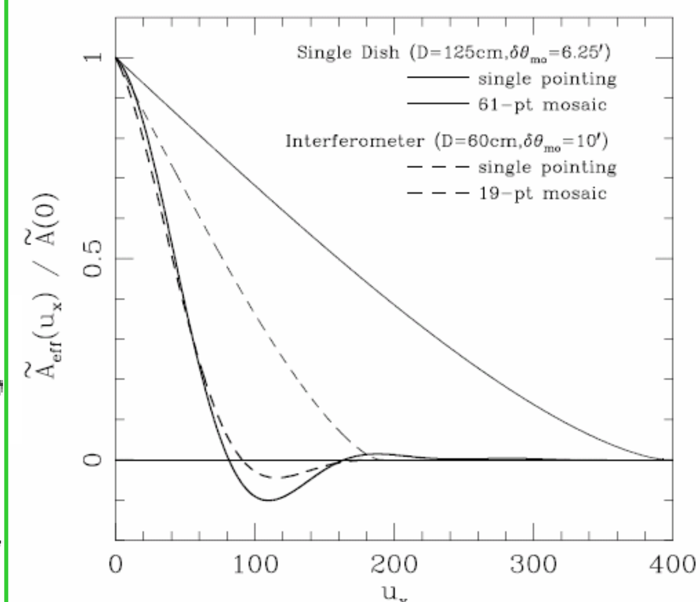
$$V_{\mathbf{y}}^{X}(\mathbf{u}) = b_\nu \int d\mathbf{x} A(\mathbf{x}-\mathbf{y}) X(\mathbf{x}) e^{2\pi i \mathbf{u}\cdot\mathbf{x}},$$

$$X(\mathbf{x}) = Q(\mathbf{x}) \pm iU(\mathbf{x}) = \int d\mathbf{u} \left[\widetilde{E}(\mathbf{u}) \pm i\widetilde{B}(\mathbf{u})\right] e^{\pm i2\phi_{\mathbf{u}}} e^{-2\pi i \mathbf{u}\cdot\mathbf{x}},$$

$$V^{\pm}_{\mathbf{y}=0}(\mathbf{u}) = b_\nu \int d\mathbf{w} \widetilde{A}(\mathbf{u}-\mathbf{w}) \left[\widetilde{E}(\mathbf{w}) \pm i\widetilde{B}(\mathbf{w})\right] e^{\pm i2\phi_{\mathbf{w}}}$$

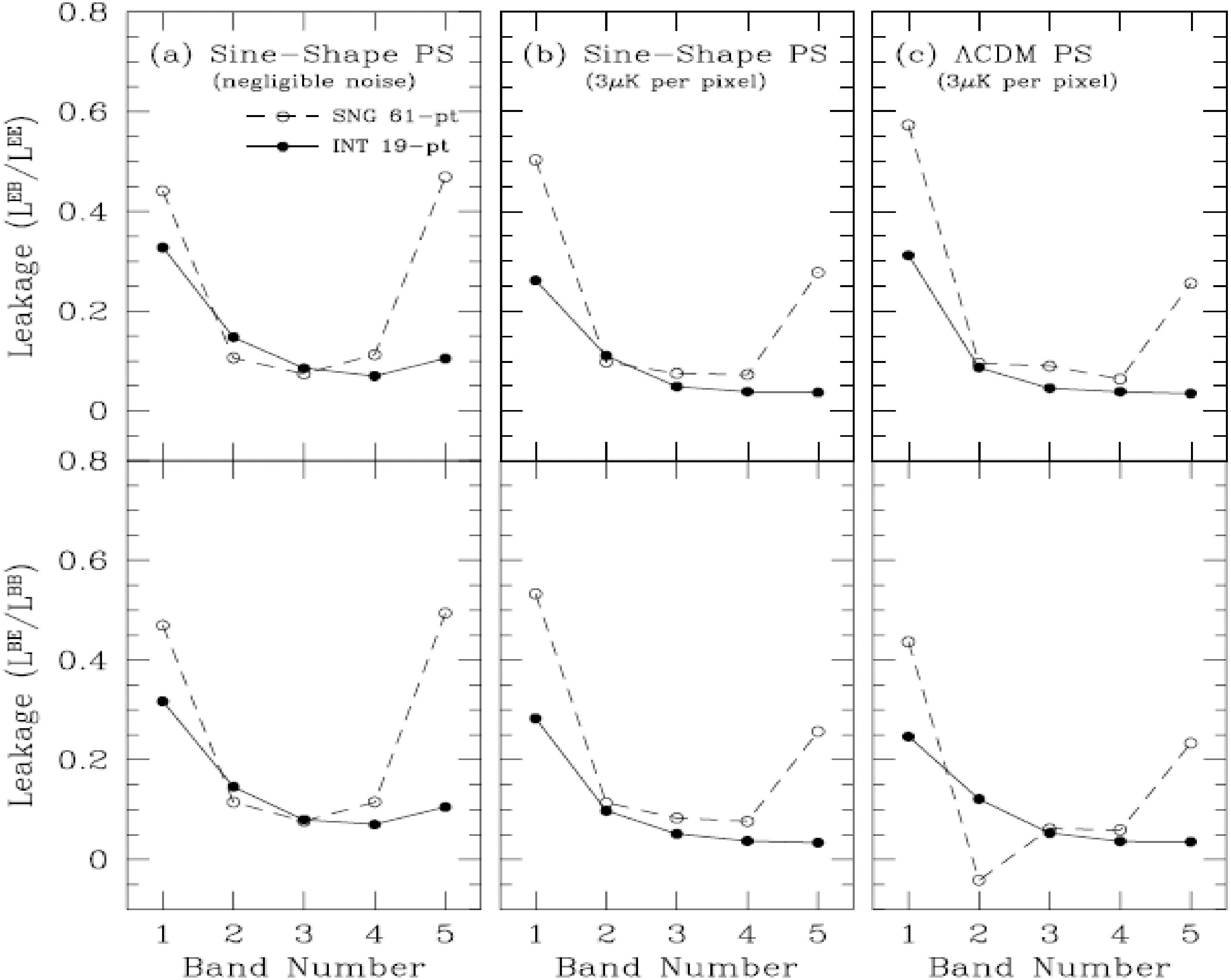
Big circle:
- single-pointing resolution or primary beam *A(x)*

Small circle:
- mosaicking or finite-sky coverage



E/B leakage

Park, Ng 04



Two-point correlation functions

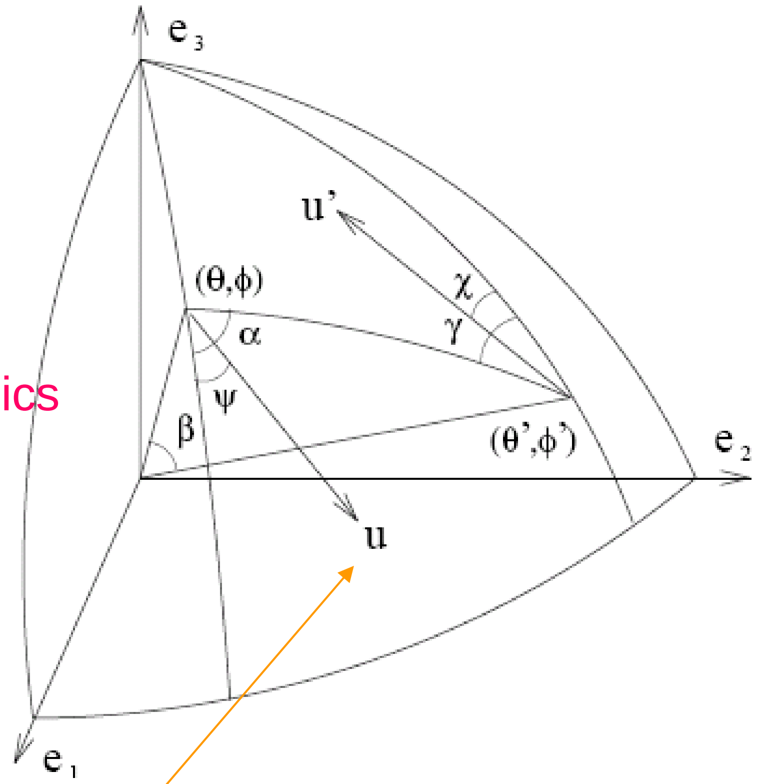
$$\langle T^*(\hat{e}')T(\hat{e})\rangle = \sum_l \frac{2l+1}{4\pi} C_{Tl} P_l(\cos\beta),$$

$$\langle T^*(\hat{e}')\left[Q(\hat{e})+iU(\hat{e})\right]\rangle = -\sum_l \frac{2l+1}{4\pi}\sqrt{\frac{(l-2)!}{(l+2)!}} C_{Cl} P_l^2(\cos\beta) e^{-2i\alpha},$$

Spin-2 spherical harmonics

$$\left\langle \left[Q(\hat{e}')+iU(\hat{e}')\right]^* \left[Q(\hat{e})+iU(\hat{e})\right]\right\rangle = \sum_l \sqrt{\frac{2l+1}{4\pi}} (C_{El}+C_{Bl})\, {}_2Y_{l-2}(\beta,0) e^{-2i(\alpha-\gamma)},$$

$$\left\langle \left[Q(\hat{e}')-iU(\hat{e}')\right]^* \left[Q(\hat{e})+iU(\hat{e})\right]\right\rangle = \sum_l \sqrt{\frac{2l+1}{4\pi}} (C_{El}-C_{Bl})\, {}_2Y_{l2}(\beta,0) e^{-2i(\alpha+\gamma)},$$



$$X_s^{\rm map}(\hat{e},\hat{u}) = \int d\hat{e}'\, R(\hat{e}';\hat{e},\hat{u}) X_s(\hat{e}'),$$

$X_0 = T$, $X_{\pm 2} = Q \mp iU$, and $R(\hat{e}';\hat{e},\hat{u})$ denotes the response function.

With asymmetric beam

$$X_s^{\rm map}(\theta,\phi,\psi) = e^{is\psi} \sum_{lmm'} a_{s,lm} D^{l*}_{mm'}(\phi,\theta,\psi)\sqrt{\frac{2l+1}{4\pi}}\, {}_s b_{lm'},$$

$${}_s b_{lm'} = \sqrt{\frac{4\pi}{2l+1}} \int \sin\beta\, d\beta d\alpha\, R(\beta,\alpha)\, {}_s Y_{lm'}(\beta,\alpha)\, e^{is\alpha}.$$

Wigner D-functions $D^l_{m'm}$

$D^l_{m'm}(\psi,\theta,\phi) = e^{-im'\psi} d^l_{m'm}(\theta) e^{-im\phi}$, where ${}_s Y_{lm}(\theta,0) = (-1)^{s+m}\sqrt{\frac{2l+1}{4\pi}} d^l_{-sm}(\theta)$

$$\left\langle \bar{X}_{s'}^{\rm map\,*}(\vec{r}\,')\bar{X}_s^{\rm map}(\vec{r})\right\rangle = \sum_{lm'm} \frac{2l+1}{4\pi} C_{s's,l}(-1)^{m'} D^l_{mm'}(\bar{\alpha},\beta,-\bar{\gamma})\, {}_{s'}b^*_{lm'}\, {}_s b_{lm}.$$

$\vec{r} = (\hat{e},\hat{u}) = (\theta,\phi,\psi)$, $\bar{X}_s^{\rm map}(\vec{r}) = e^{-is\psi} X_s^{\rm map}(\vec{r})$, $\bar{\alpha} = \alpha - \psi$, and

$\bar{\gamma} = \gamma - \chi$ where $\psi' = \pi + \chi$.

Elliptical Gaussian Beam

$$R^{EG}(\beta,\alpha) = \frac{1}{2\pi\sigma_x\sigma_y}\exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right),$$

$$\begin{aligned} {}_s b_{lm}^{EG} \simeq\ & \frac{1}{2}\left[1+(-1)^{s+m}\right]\exp\left[-l^2(\sigma_x^2+\sigma_y^2)/4\right] I_{(s+m)/2}\left(l^2(\sigma_x^2-\sigma_y^2)/4\right) \\ & \text{for} \quad s+m > -1 \quad \text{and} \quad 1 > (\sigma_x^2-\sigma_y^2)/\sigma_x^2, \end{aligned}$$

where $I_n(x)$ are modified Bessel functions.

Interferometric Gaussian Beam

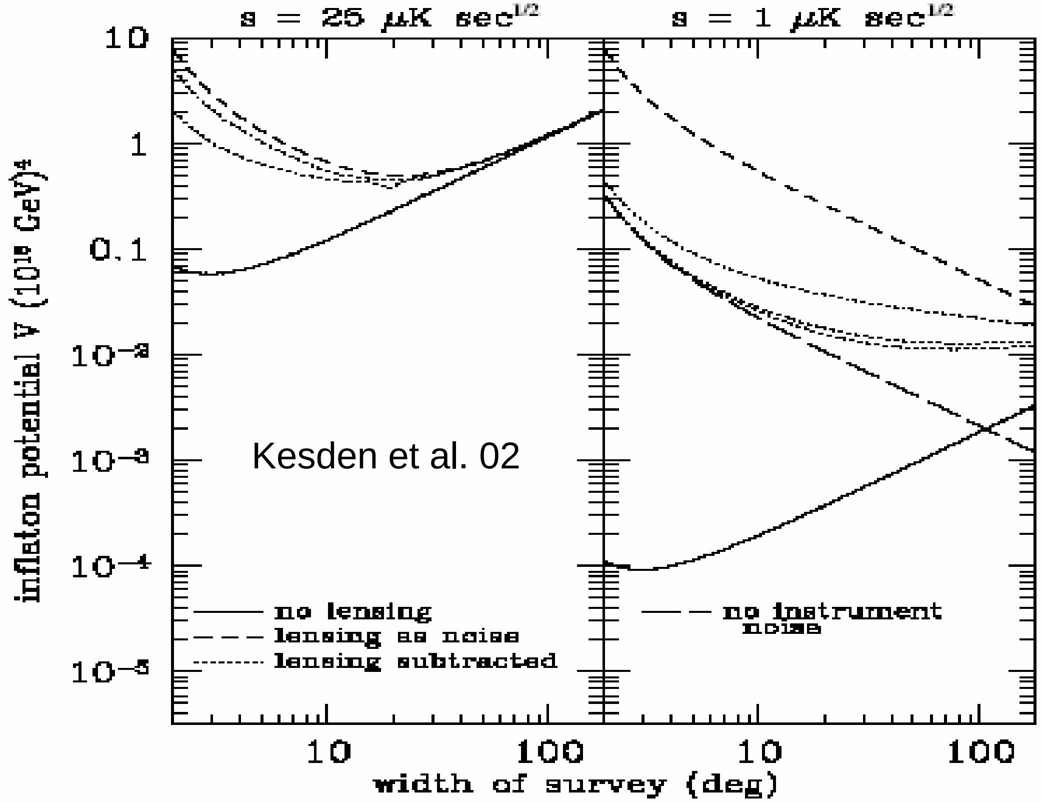
$$R^{IG}(\beta,\alpha) = A(\beta,\alpha)e^{i2\pi u\beta\cos\alpha} \qquad A(\beta,\alpha) = \exp\left(-\frac{\beta^2}{2\sigma_b^2}\right)$$

$\vec{u}$ is the separation vector (baseline) of the two antennae

$${}_s b_{lm}^{IG} \simeq i^{s+m} 2\pi\sigma_b^2 \exp\left[-\sigma_b^2(l^2+l_u^2)/2\right] I_{s+m}(l l_u \sigma_b^2),\ l_u = 2\pi u$$

To measure the genuine B-mode, we will need to do:

- De-lensing
  Kesden et al. 02
  Hu, Okamota 01
  Hirata, Seljak 04
  Reconstruction of lensing potential



- De-rotation

  Kamionkowski, Ng 08
  TB, EB

- E/B separation
  Bunn et al. 03; Park, Ng 04; Smith, Zaldarriaga 07; …

Summary

- Cosmic microwave background is a powerful tool for unveiling the initial conditions of the early Universe
- Anisotropy power spectrum has been well measured
- Combined with other observations such as supernova, large-scale structure formation, gravitational lensing, cosmological parameters have been measured at 10% accuracy
- Polarization signal is a sensitive probe of the formation of first stars and reionization history
- B-mode polarization is a clean signal of primordial gravitational waves and inflation
- Future and next-generation observations will lead us to an era of high-precision cosmology