Recent Progress in CMB lensing

Toshiya Namikawa, January 20, 2014

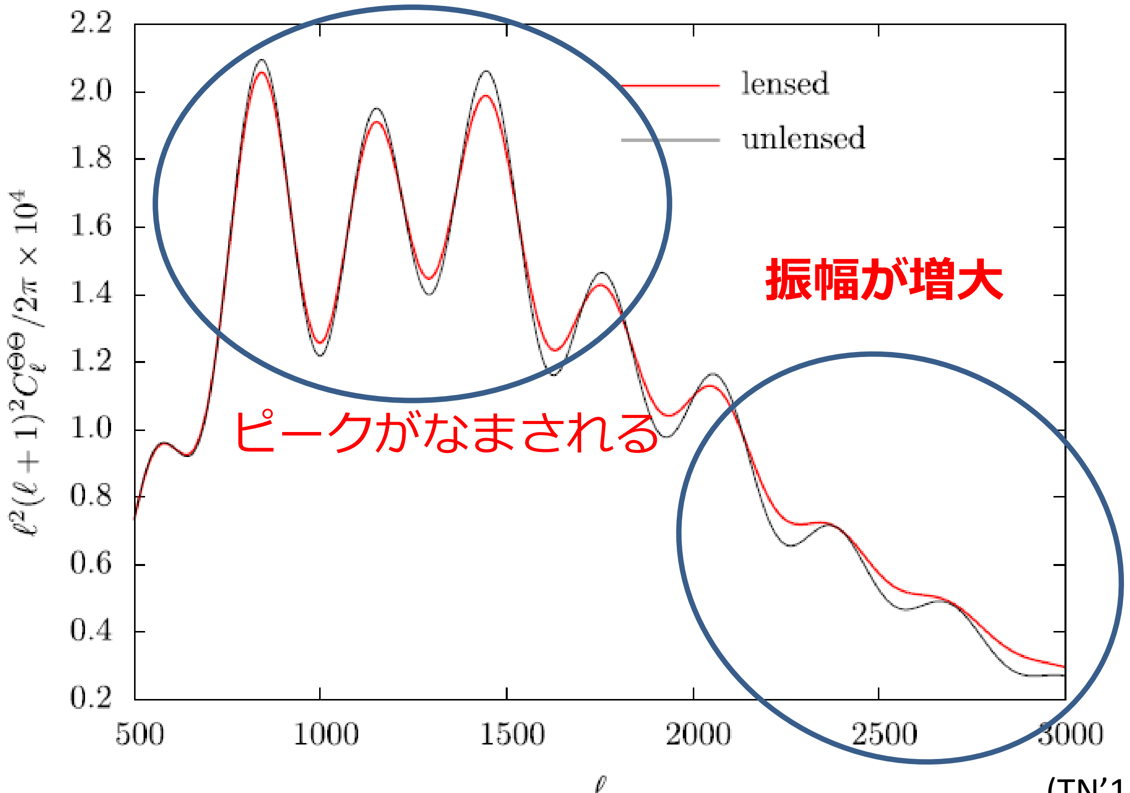
@ YITP observational cosmology lunch meeting

CMBの重力レンズ(CMB lensing)に対する研究を簡単に振り返ってみる

1) 重力レンズを受けたCMB揺らぎの（統計的）性質

温度揺らぎの2点統計 (correlation function, angular power spectrum)

(e.g., Blanchard&Schneider'87, Sasaki'89,Seljak'96)



(TN'14)

偏光揺らぎの2点統計　(Zaldarriaga & Seljak'98)

B-mode偏光が生成される

2) CMB揺らぎから重力レンズの情報を引き出す方法

A) 揺らぎの2点統計量

- 重力レンズ曲がり角のパワースペクトルの見積もりなど

B) レンズ再構築　(e.g., Zaldarriaga & Seljak’99, Hirata & Seljak’03a,b)

- 重力レンズが作る統計的非等方性を利用して重力レンズの曲がり角を測り、その統計量を調べる

- 他の観測量との相関をとったりできる

- 統計的には、Lensed CMB （＋他の観測量）の高次統計を考えることに帰着（2点推定の場合、auto-correlation=4点, Cross-correlation=3点）

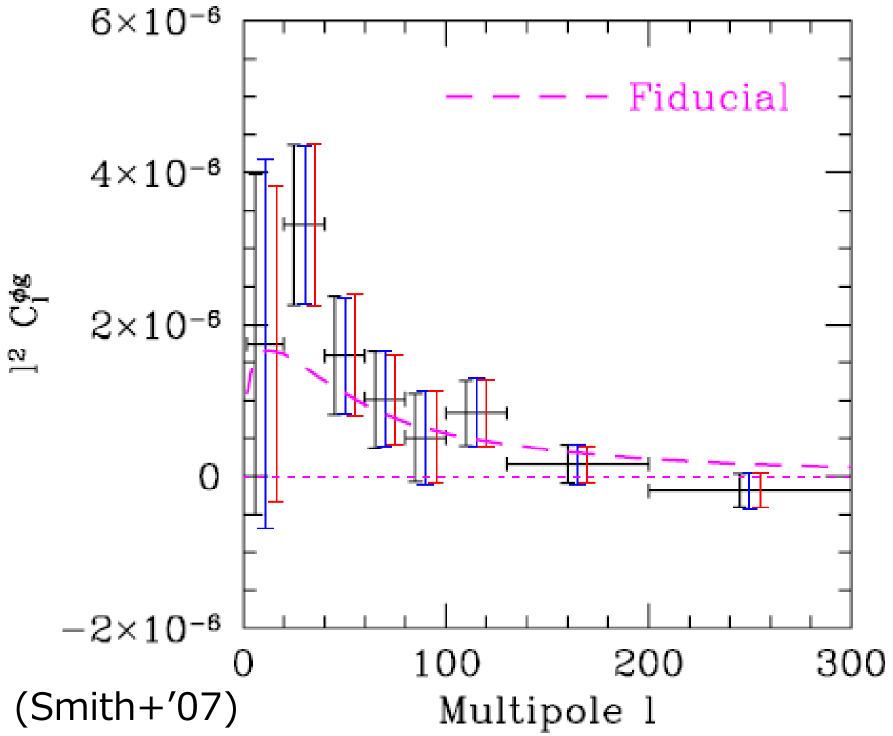
3) 観測

- 2004年、 WMAPと銀河サーベイのデータを使って、相関量（Lensed CMB ×2 と matter density の3点）の検出が試みられるが、検出には至らなかった

  (Hirata+’04)

- 2007-2008年、 Updateされた WMAPと銀河サーベイのデータを使って、相関量の検出に成功

  (Smith+’07, Hirata+’08)



(Smith+’07)

FIG. 5 (color online). Detection of CMB lensing via the cross power spectrum $C_\ell^{\phi g}$ between the reconstructed potential and galaxy counts. The three 1σ error bars on each bandpower represent different Monte Carlo methods: WMAP simulations vs NVSS simulations (left/black); WMAP data vs NVSS simulations (middle/blue); and WMAP simulations vs NVSS data (right/red). These error bars represent statistical errors only; the result with systematic errors included will be shown in Fig. 19.

3) 観測

- 2008年、ACBARの実験チームは、CMB Lensing を3σ 以上で検出したと報告

the dipole-calibrated WMAP3 experiment. The measured power spectrum is consistent with a spatially flat, ΛCDM cosmological model. We see evidence for weak gravitational lensing of the CMB at $> 3\sigma$ significance by comparing the likelihood for the best-fit lensed/unlensed models to the ACBAR+WMAP3 data. On fine angular scales, there is weak evidence (1.7σ) for excess power above the level expected from primary anisotropies. The source of this power cannot be constrained by the ACBAR 150 GHz

(arXiv:0801.1491v1)

- 一方、Calabrese+'08の解析では、$C_\ell^{\phi\phi} \to AC_\ell^{\phi\phi}$ として制限したAは1を2σ以上で棄却

(Calabrese+'08)

- その後、ACBARの実験チームがreviseした論文

with that of the dipole-calibrated WMAP5 experiment. The measured power spectrum is consistent with a spatially flat, ΛCDM cosmological model. We include the effects of weak lensing in the power spectrum model computations and find that this significantly improves the fits of the models to the combined ACBAR+WMAP5 power spectrum. The preferred strength of the lensing is consistent with theoretical expectations. On fine angular scales, there is weak evidence (1.1σ) for excess power above the level expected from primary anisotropies. We expect any excess power to be dominated by the

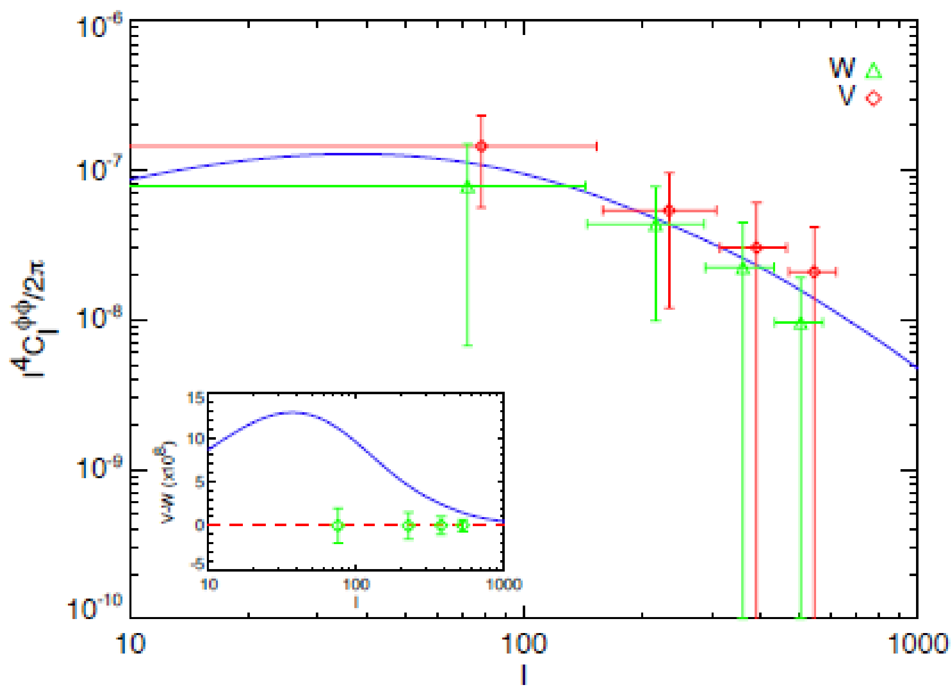
(arXiv:0801.1491v3)

- その脚注

[17] Calabrese et al. (2008) also undertook a lensing analysis of ACBAR temperature power spectrum, but, instead of $q_{\rm lens}$ as defined here, they used a multiplier $A_{\rm L}$ of the lensing potential power spectrum, defined to be unity for normal lensing; they found $A_{\rm L} = 3.0^{+0.9}_{-0.9}$ for WMAP5+ACBAR. Repeating our analysis with this parameterization, we find lower values, $A_{\rm L} = 1.60^{+0.55(+1.79)}_{-0.26(-0.99)}$.

3) 観測

- 2010年末、Smidt+’10は、WMAP7yrのデータを使ってCMB Lensing のパワースペクトル（Lensing-induced trispectrum）を測定したと主張

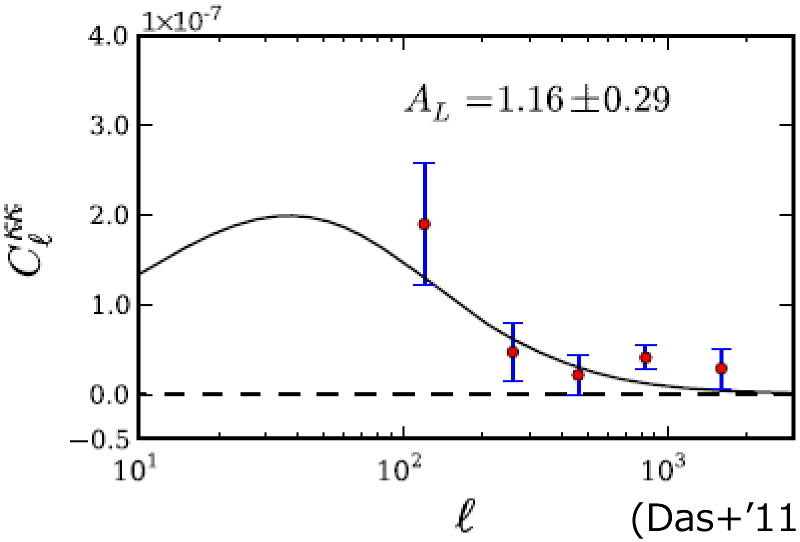


(Smidt+’10)

FIG. 2.— The constraints on $C_l^{\phi\phi}$ using the $\mathcal{K}^{(2,2)}$ estimator. In the larger plot, the red squares are the constraints by the V-band and the green circles are for the W-Band. The result of the null test is given in the smaller plot. These error bars represent 1σ errors.

3) 観測

- 2011年、Das+’11は、ACTのデータを使って”初めて”CMB lensing のパワースペクトルを測定したと報告



(Das+’11)

FIG. 2 (color online). Convergence power spectrum (red points) measured from ACT equatorial sky patches. The solid line is the power spectrum from the best-fit WMAP + ACT cosmological model with amplitude $A_L = 1$, which is consistent with the measured points. The error bars are from the Monte Carlo simulation results displayed in Fig. 1. The best-fit lensing power spectrum amplitude to our data is $A_L = 1.16 \pm 0.29$.

- その４カ月前に出ていたSmidt+’10の解析についてコメント

difficult, and can lead to large discrepancies. Smidt *et al.* [14] use this standard approach for an analysis of the WMAP data, and report a detection significance larger than expected from Fisher information theory. An alterna-

- 銀河サーベイとのCross-correlationにも応用されている(Sherwin+’12)

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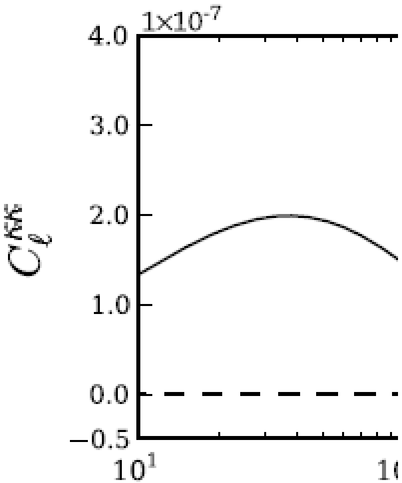
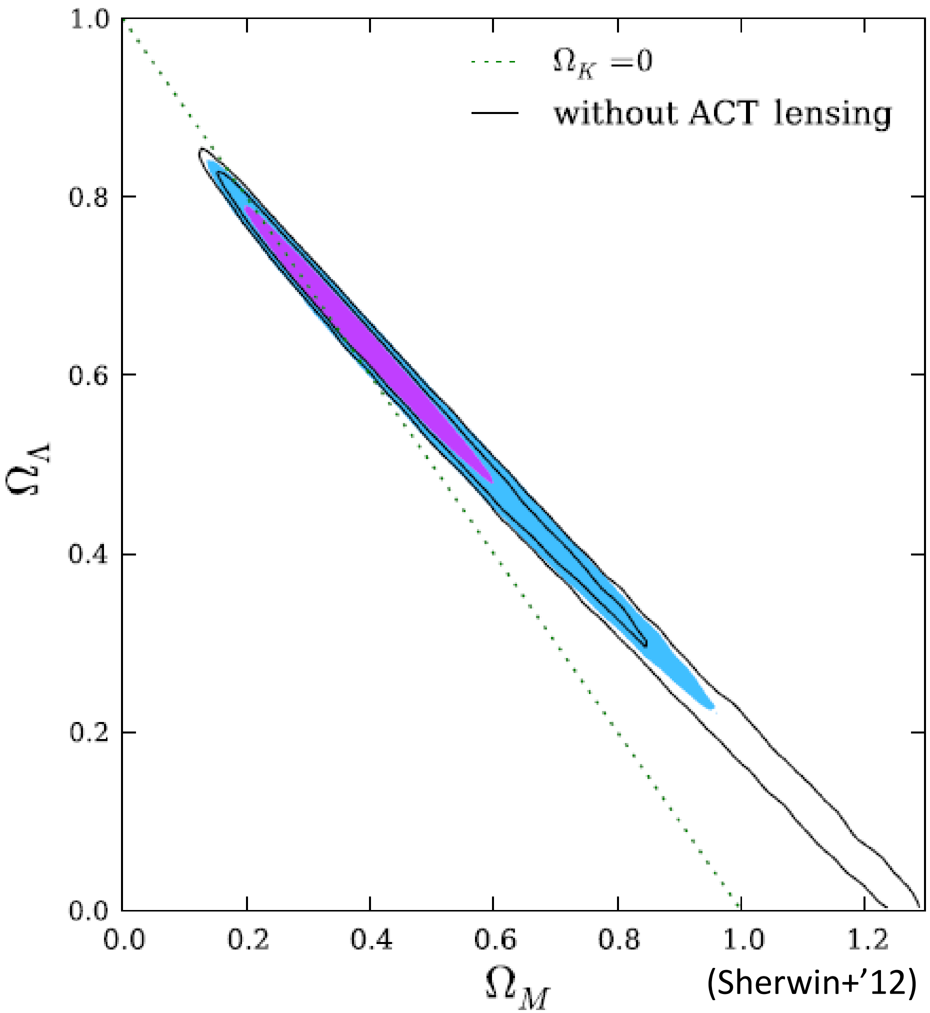




(Sherwin+’12)

gence power spectrum (red quatorial sky patches. The from the best-fit WMAP + amplitude $A_L = 1$, which is nts. The error bars are from lts displayed in Fig. 1. The amplitude to our data is

- その４カ月前に ... ト
- 銀河サーベイと ... herwin+’12)

3) 観測

- 2012年、van Engelen+’12も、SPTのデータを使ってCMB lensing のパワースペクトルを測定したと報告

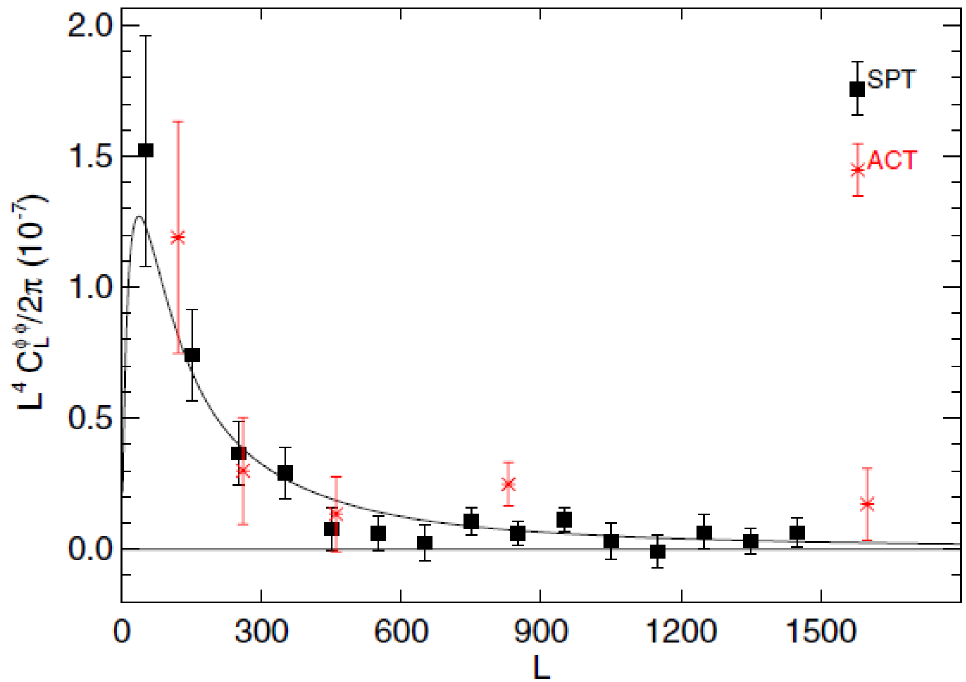


Figure 6. Comparison of the derived lensing bandpowers from SPT and ACT (Das et al. 2011b). Although we show the lowest-L data point, centered at $L = 50$, we do not use this point in our fits due to the possible interaction with the subtraction of the apodization feature (Section 4.1.2) on this large scale. The solid curve is not a fit to the data; rather, it is the lensing power spectrum in our fiducial ΛCDM cosmology, corresponding to $A^0_{\rm lens} = 1$.

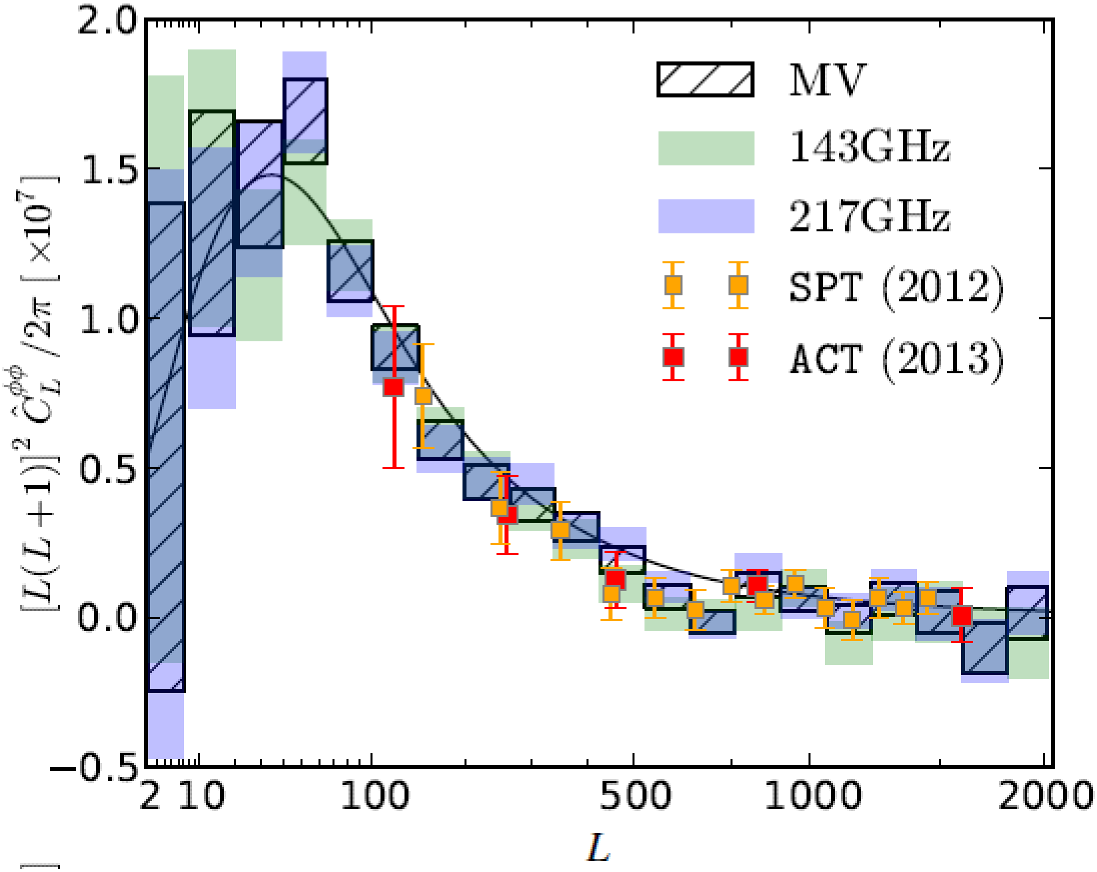
(van Engelen+’12)

- 銀河サーベイとのCross-correlationにも応用されている

(Bleem+’12)

3) 観測

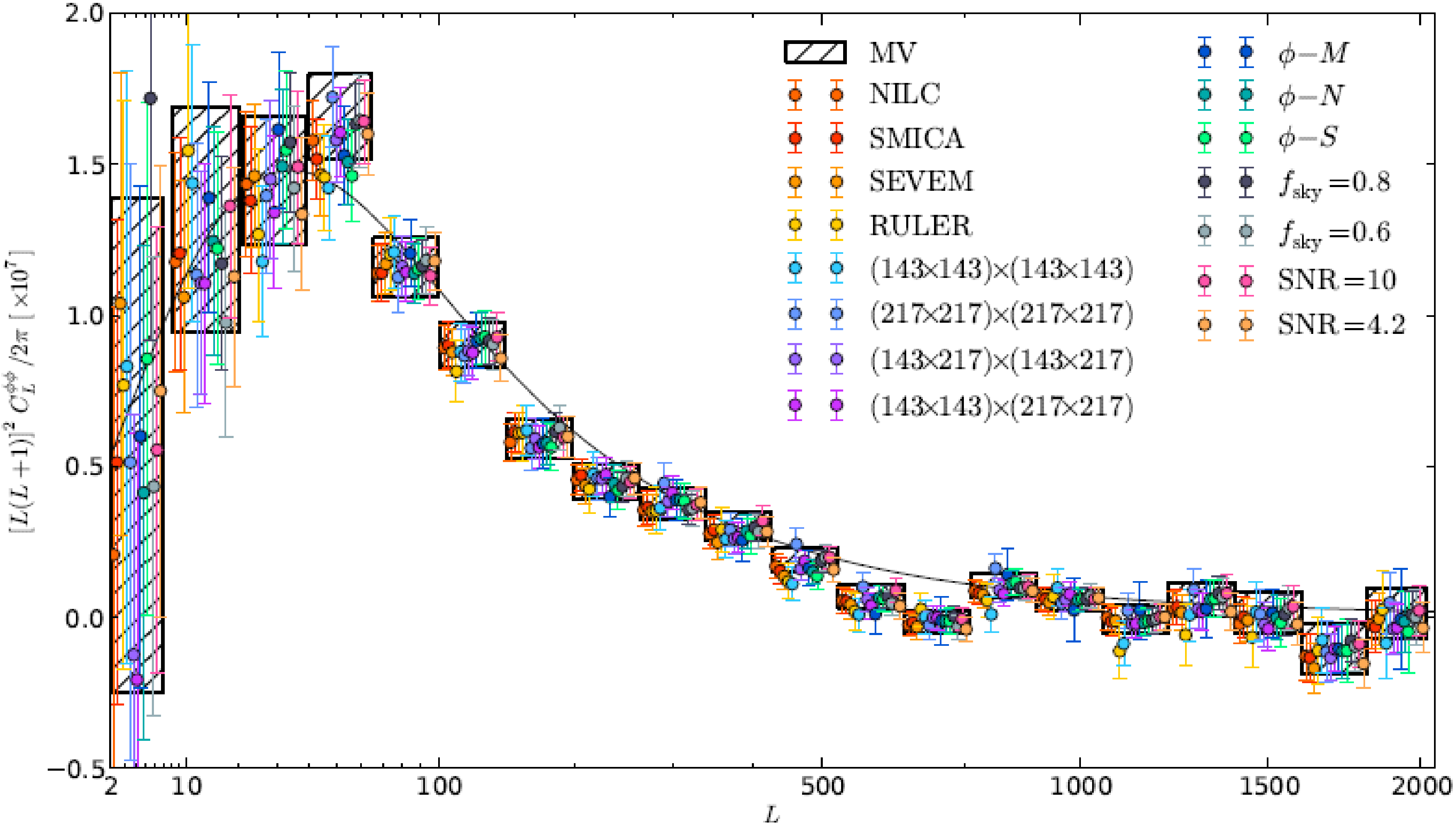
- 2013年、Planckの結果が出る



(Planck Collaboration’13)

3) 観測

- さまざまな解析方法



(Planck Collaboration’13)

3) 観測

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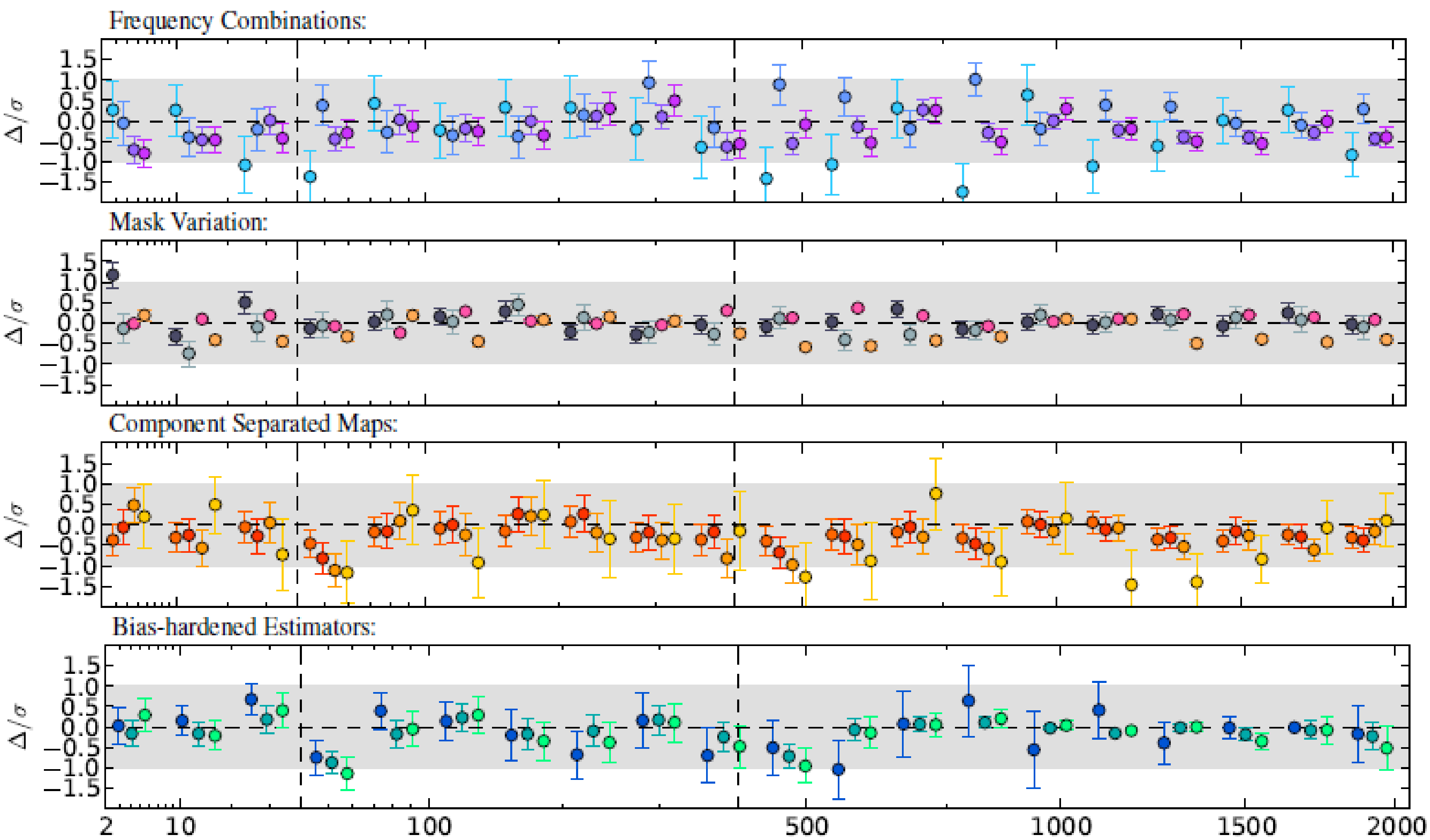
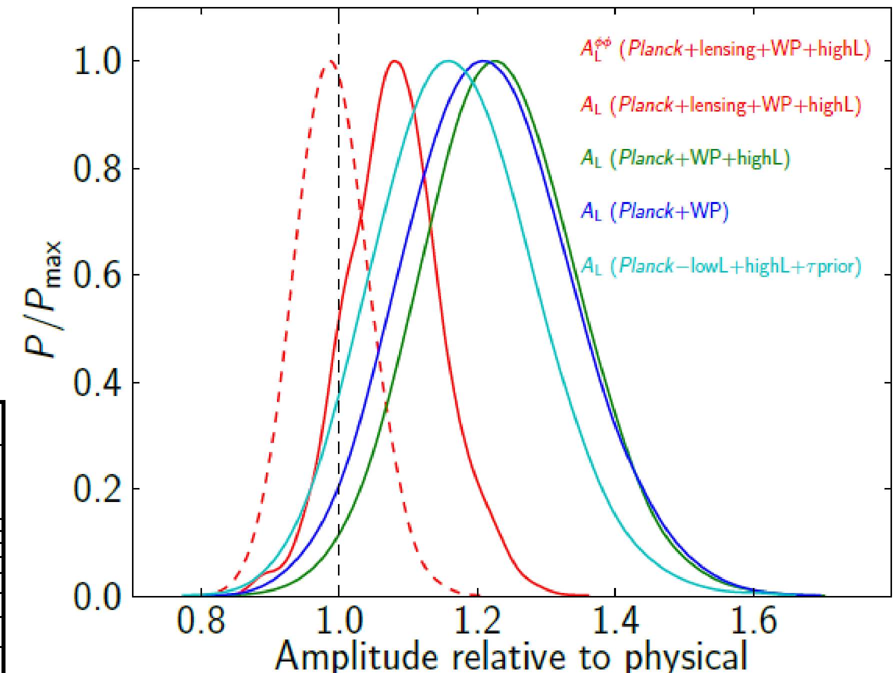


(Planck Collaboration'13)

3) 観測

- ただし、いくつか原因のよく分からない点も…

(Planck Collaboration’13)

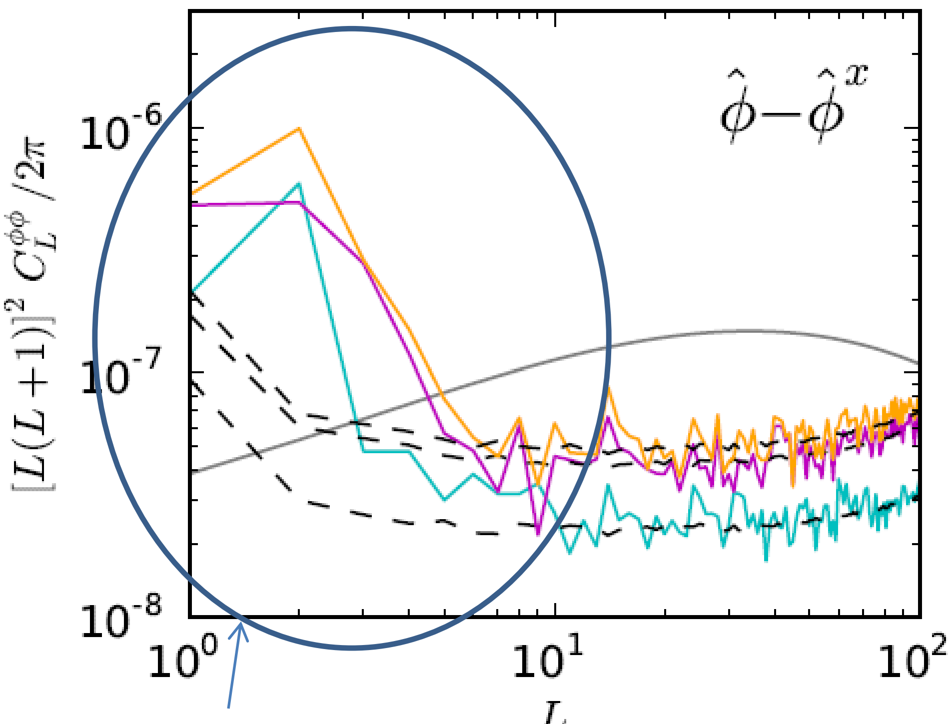


trum. Figure 13 reveals a preference for $A_L > 1$ from the *Planck* temperature power spectrum (plus *WMAP* polarization). This is most significant when combining with the high-ℓ experiments for which we find

$$A_L = 1.23 \pm 0.11 \quad (68\%; \textit{Planck}+\text{WP}+\text{highL}), \qquad (44)$$

i.e., a $2\,\sigma$ preference for $A_L > 1$. Including the lensing measurements, the posterior narrows but shifts to lower A_L, becoming consistent with $A_L = 1$ at the $1\,\sigma$ level as expected from the $A_L^{\phi\phi}$ results.

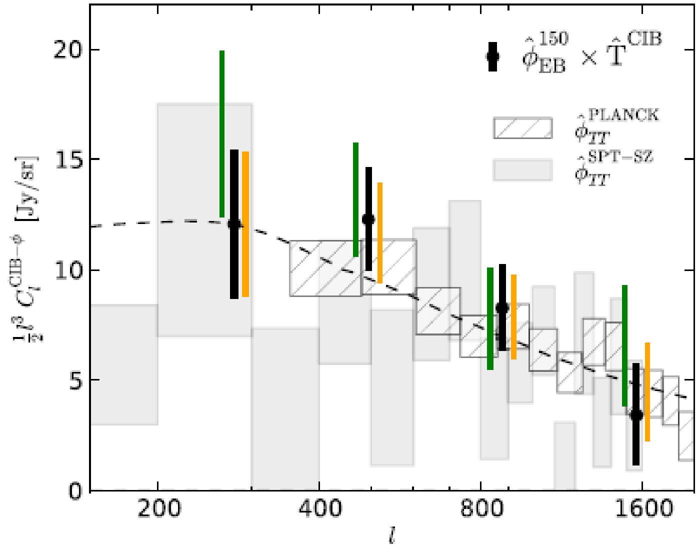
(Planck Collaboration’13)



異なる推定法の差分が残っている（予期していないバイアスが残っている可能性）

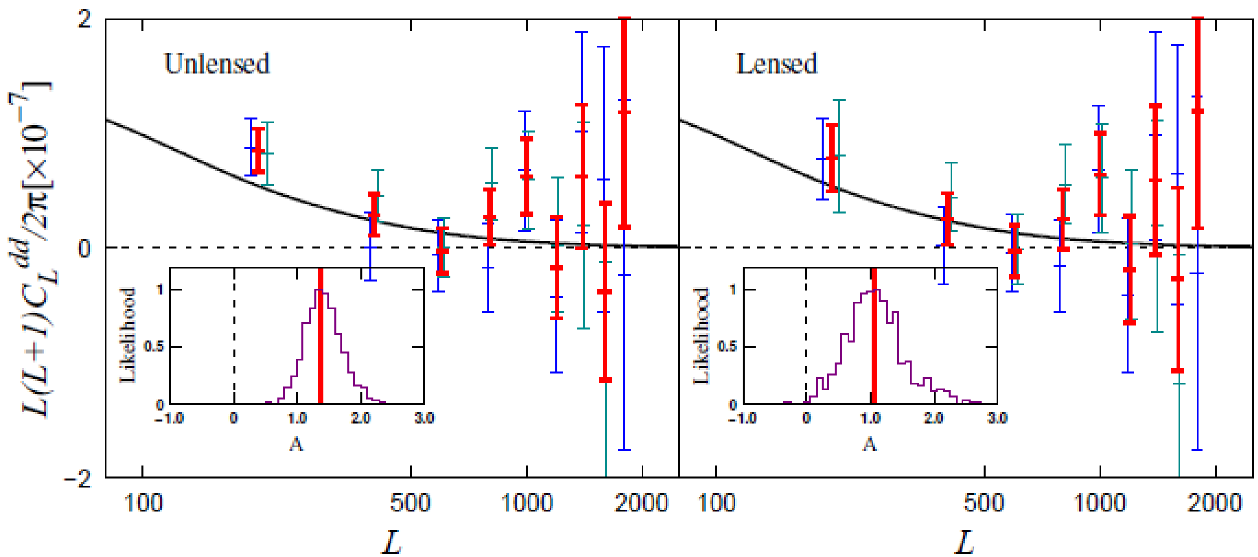
2) 観測

- 2013年、さらに偏光データを使ったCMB lensing の解析が行われた



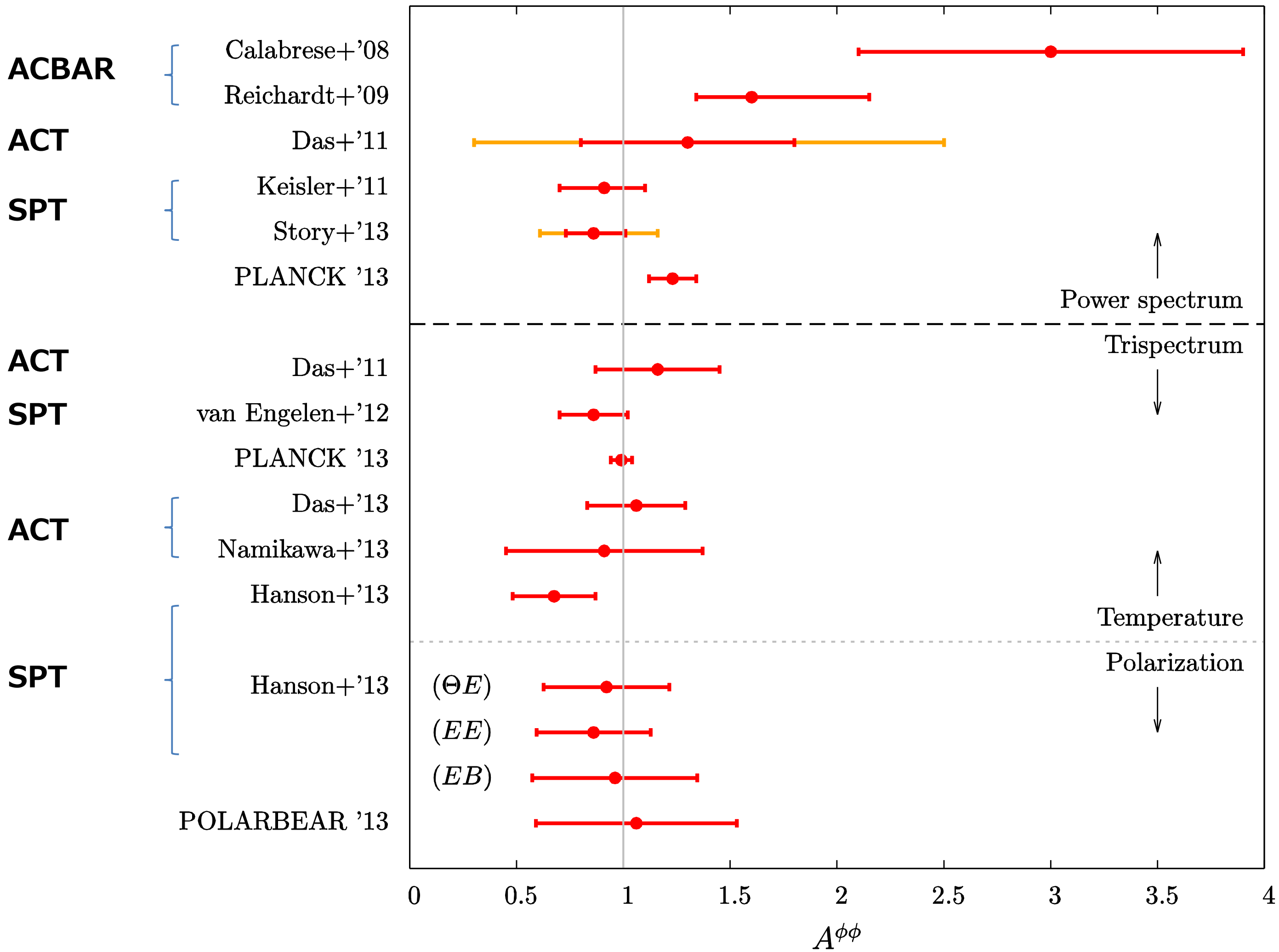
(Hanson+'13)

(PolarBear collaboration+'13)



(PolarBearは日本人の貢献も大きい)

Constrains on lensing amplitudes



＊ すべて 1σ エラー（オレンジは2σ）

2) 観測

- また、Planckの結果が出たことで数多くの相関解析が可能に

	auto correlation		cross correlation		
	$\tilde{C}_\ell$	$C_\ell^{\phi\phi}$	$\times$G	$\times$CIB	$\times$ other probes
ACT	$2.8\,\sigma$ [28]	$4\,\sigma$ [29] $4.6\,\sigma$ [30]	$3.8\,\sigma$ [101]	—	$3.2\,\sigma$ [44] ($\times\gamma$)
Planck	— [a]	$26\,\sigma$ [18]	$7\,\sigma$ - $20\,\sigma$ [18]	$42\,\sigma$ [19] [b]	$2.5\,\sigma$ [16] ($\times$ISW) $6.2\,\sigma$ [52] ($\times$tSZ)
PolarBear	—	$\sim 2\,\sigma$ [23]	—	$4.0\,\sigma$ [22]	—
SPT	$\sim 5\,\sigma$ [67] $8.1\,\sigma$ [112]	$6.3\,\sigma$ [121]	4.2 - $5.3\,\sigma$ [9] $\sim 7\,\sigma$ [39]	$8.8\,\sigma$ [57]	— —
(+pol)	—	— [c]	—	$7.7\,\sigma$ [48]	—
WMAP	—	— [d]	$\sim 3\,\sigma$ [36, 54, 107] [e]	—	— [f]

[a] Ref. [17] shows constraints on the lensing amplitude A by replacing $C_\ell^{\phi\phi} \to AC_\ell^{\phi\phi}$ in computing the lensed temperature power spectrum, and find that $A > 1$ is favored at $2\,\sigma$.
[b] Statistical significance at 545 GHz
[c] Ref. [48], however, gives constraints on the lensing amplitude as a test of systematics test.
[d] Ref. [37] shows that the significance is $\lesssim 1\,\sigma$.
[e] The measurement of the cross-correlation was first attempted by Ref. [53], but the signals are not detected.
[f] Statistical significance of cross-correlation with the sum of SZ and ISW is at $\lesssim 1\sigma$ [13]

(TN'14)

まとめ

- 今後は偏光データがとれるので、重力レンズの測定精度は今後数年でかなり向上する(Planckで 50σ?, ACTPol , SPTpol, PolarBear (Stage-IIIクラス)で 100σ以上?)

- 他の宇宙論観測と比べて系統誤差が少ないと考えられているため、相関を使った銀河バイアスの測定、CIBを使ったアストロへの応用など、**いろいろできる**

- CMB lensing を使った宇宙論は、少なくとも以下の点で今後重要になるはず：

  ✓ シグナルの精度が上がるので、ニュートリノ質量、暗黒絵エネルギー、暗黒物質、宇宙ひもその他の宇宙論的検証に使えるようになる

  ✓ 原始重力波探査における重力レンズB-modeの除去も重要課題

- **CMBに限らず、今後も観測に立脚した宇宙論研究が重要**