Recent Progress and Future Prospects of CMB Lensing

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Dark Matter, Dark Energy and Matter-Antimatter Asymmetry @ **Taiwan, Dec. 28-31, 2012**

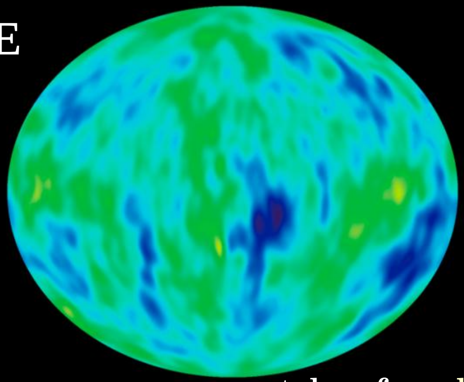
Contents

1. Introduction

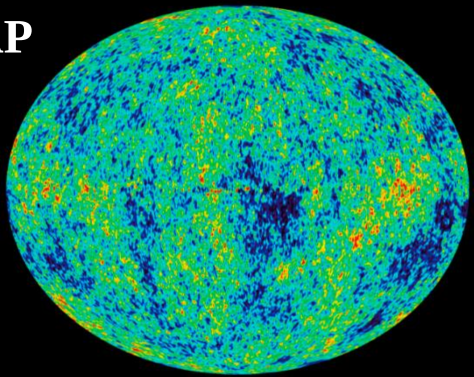
Cosmic Microwave Background (CMB)

- **Precise measurements of CMB fluctuations**

COBE



WMAP



taken from http://lambda.gsfc.nasa.gov/

✓ The energy components of Universe is well described by flat ΛCDM model

- **Cosmology can now focus on more advanced and fundamental issues !**

✓ dark energy
✓ dark matter
✓ mass of neutrinos
✓ primordial gravitational waves
✓ cosmic strings
✓ primordial non-Gaussianity

⋮

Cosmological probes

- **Observations**
  - ✓ CMB temperature/ polarizations
  - ✓ Type-Ia Super Novae
  - ✓ Baryon Acoustic Oscillations
  - ✓ Cluster abundance
  - ✓ 21cm brightness temperature
  - ✓ Weak Lensing

⋮

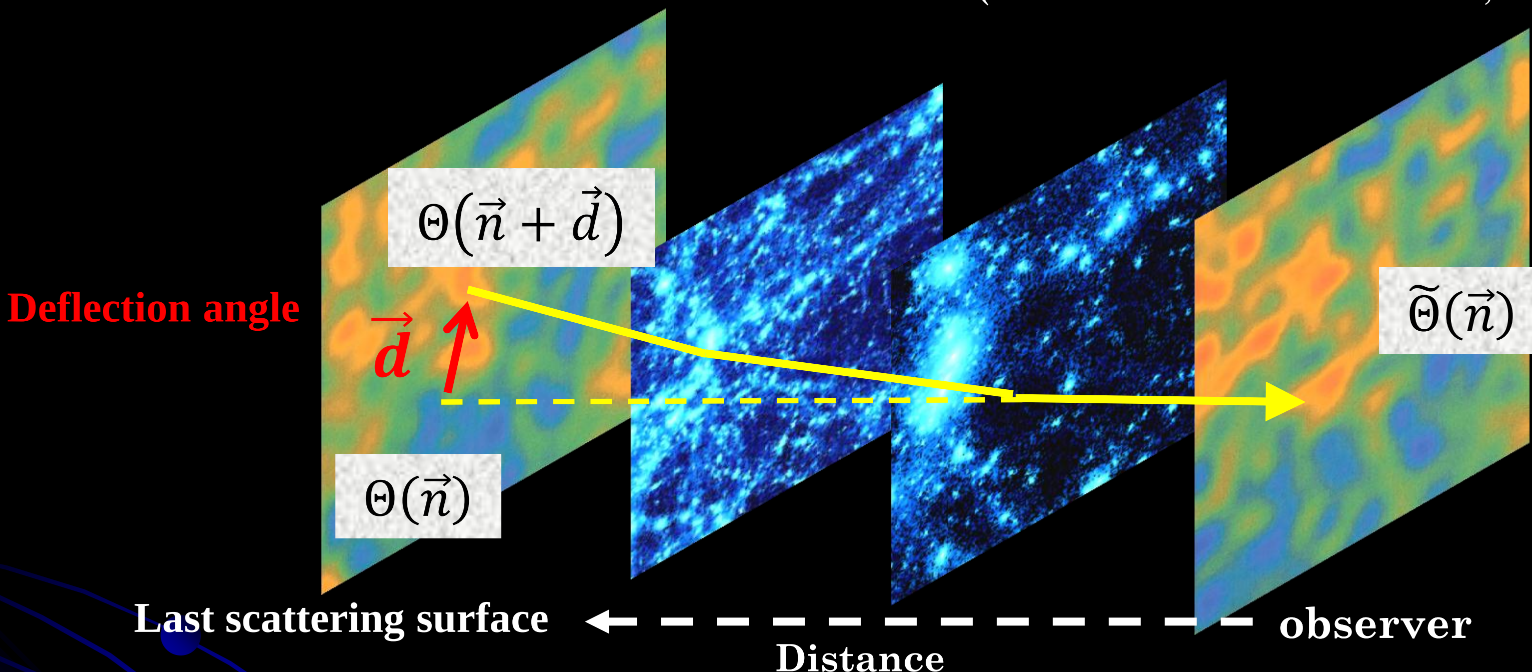
→ **Compared to other observables, weak lensing is …**

- ✓ sensitive to both geometry and density fluctuations
- ✓ free from galaxy bias ← (Important for "accurate" cosmology)
- ✓ for CMB lensing, the properties of source (CMB) is well known

CMB Lensing

- **CMB Lensing = distortion of spatial pattern of CMB anisotropies**

(Reviews : Lewis&Challinor'06, Hanson+'10)



- **Lensed anisotropies**

$$\tilde{\Theta}(\vec{n}) = \Theta\left(\vec{n} + \vec{d}(\vec{n})\right)$$

Lensing potential

Gravitational potential

$$\vec{d}(\vec{n}) = \nabla\left(-2\int_0^{\chi_s} d\chi \frac{\chi_s - \chi}{\chi\chi_s} \psi(\eta_0 - \chi, \chi\vec{n})\right)$$

Lensed temperature anisotropies

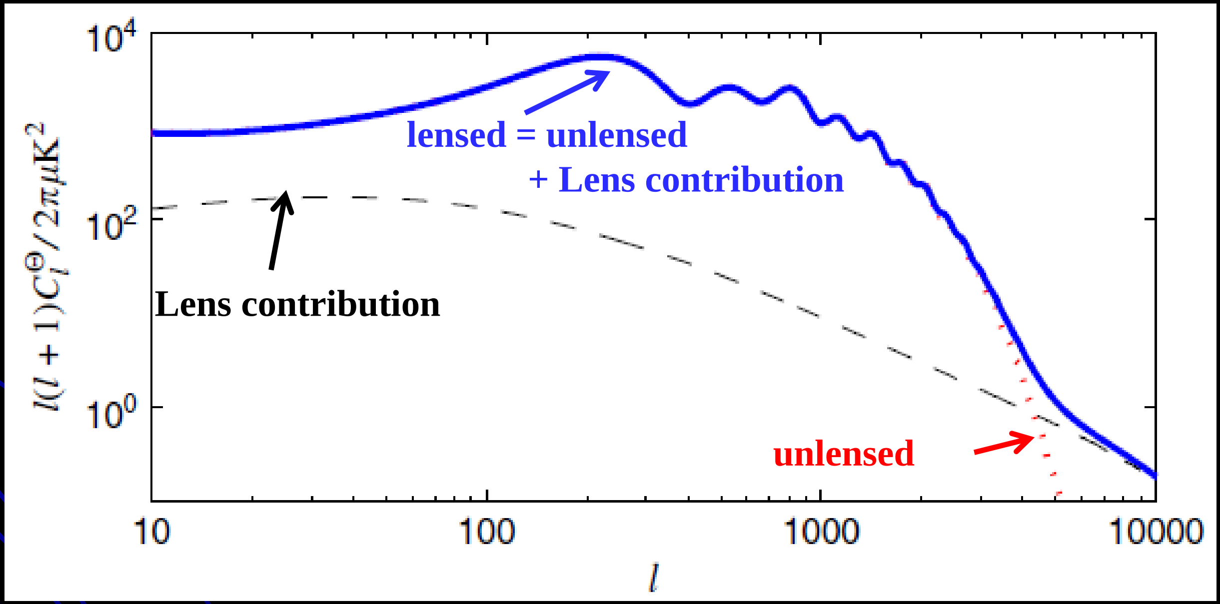
- **Angular power spectrum**

$$\widetilde{\Theta}(\vec{n}) \;\Rightarrow\; \widetilde{\Theta}_{\ell m} = \int d\vec{n}\, Y^{*}_{\ell m}(\vec{n})\widetilde{\Theta}\,(\vec{n}) \;\Rightarrow\; \langle \widetilde{\Theta}_{\ell m}\widetilde{\Theta}^{*}_{\ell' m'}\rangle = \delta_{\ell\ell'}\delta_{mm'}\tilde{C}^{\Theta\Theta}_{\ell}$$

Harmonics space   **Angular power spectrum**

- **Lensed angular power spectrum**

(Lewis&Challinor'06)

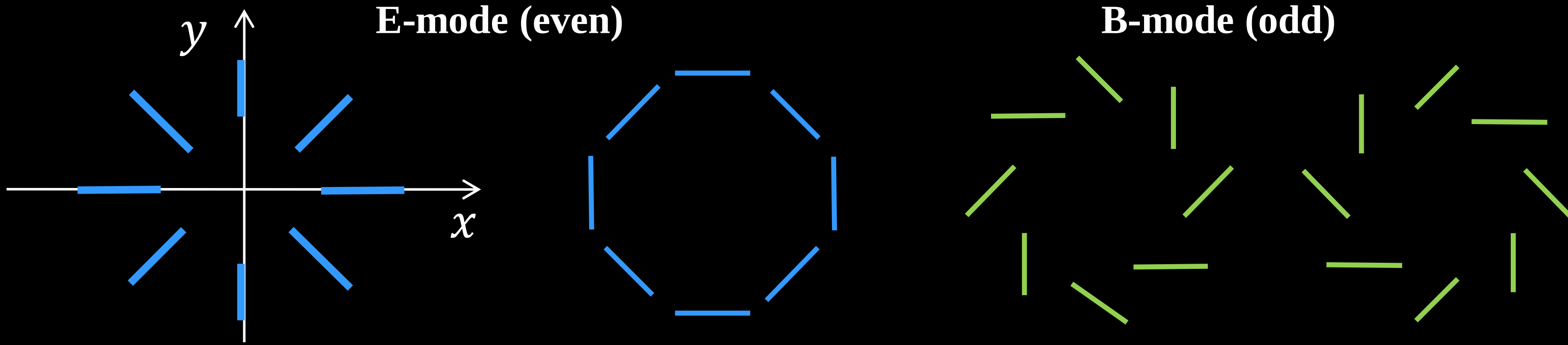


Lensing effect becomes dominate at Silk damping scale: $\ell > 2000$ (~ few arcmin)

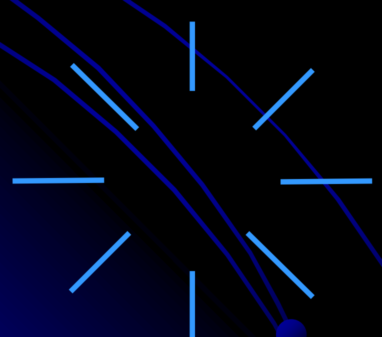
→ **High angular resolution is required**

Lensed polarizations anisotropies

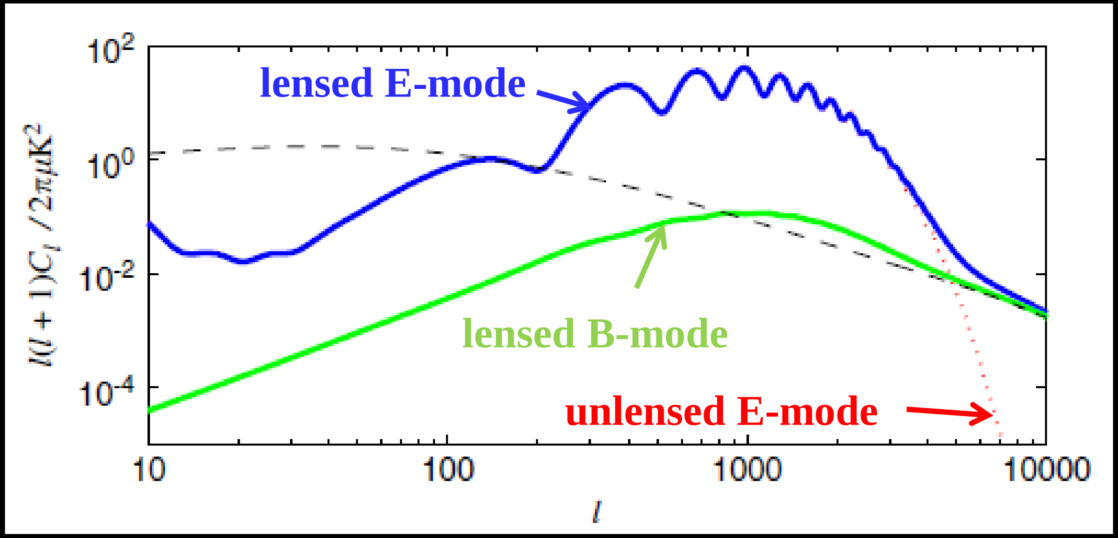
- **CMB polarizations**
  - **Decomposition with parity** (patterns of E/B-modes)



- **Lensed E/B-modes angular power spectra**
  - **B-mode from lensing**



(Lewis&Challinor'06)



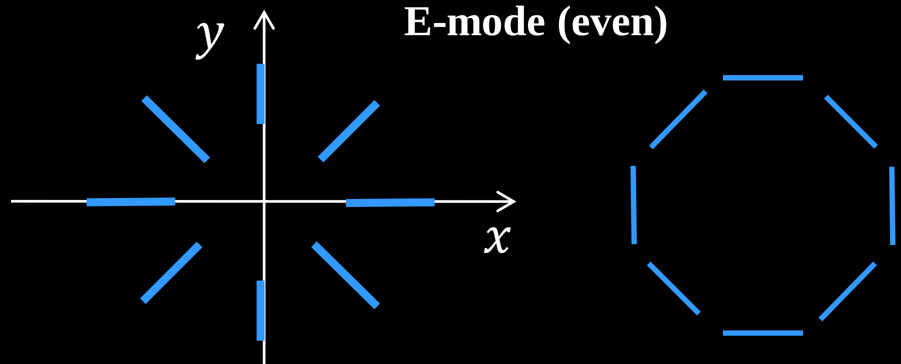
Lensed polarizations anisotropies

➢ CMB polarizations

- Decomposition with parity

(patterns of E/B-modes)

E-mode (even)

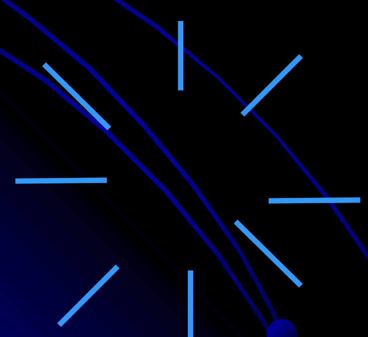


B-mode (odd)

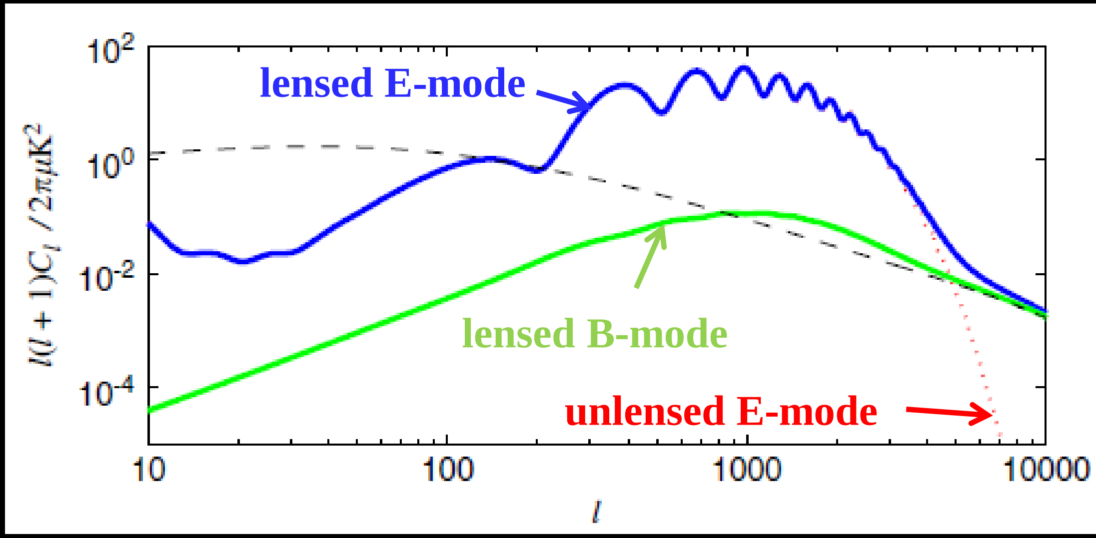
➢ Lensed E/B-modes angular power spectra

(Lewis&Challinor’06)

- B-mode from lensing



E/B-modes are mixed



2. CMB lensing as a cosmological probe

Gradient / Curl

- **Deflection angle**

$$\vec{d}(\vec{n}) = \nabla\phi(\vec{n})$$

gradient

$$+(\star\,\nabla)\omega(\vec{n})$$

curl

rotation in 2D

scalar

linear density fluctuations

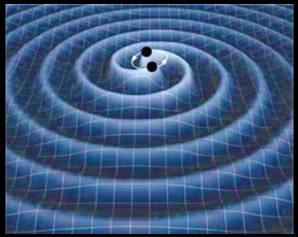
vector, tensor

magnetic fields

from ESO

cosmic strings

gravitational waves



from NASA

- **Application of curl-mode reconstruction**
  - Probing, e.g., cosmic strings, GWs, magnetic fields …
  - Check for systematics

Dark energy/ Massive Neutrinos

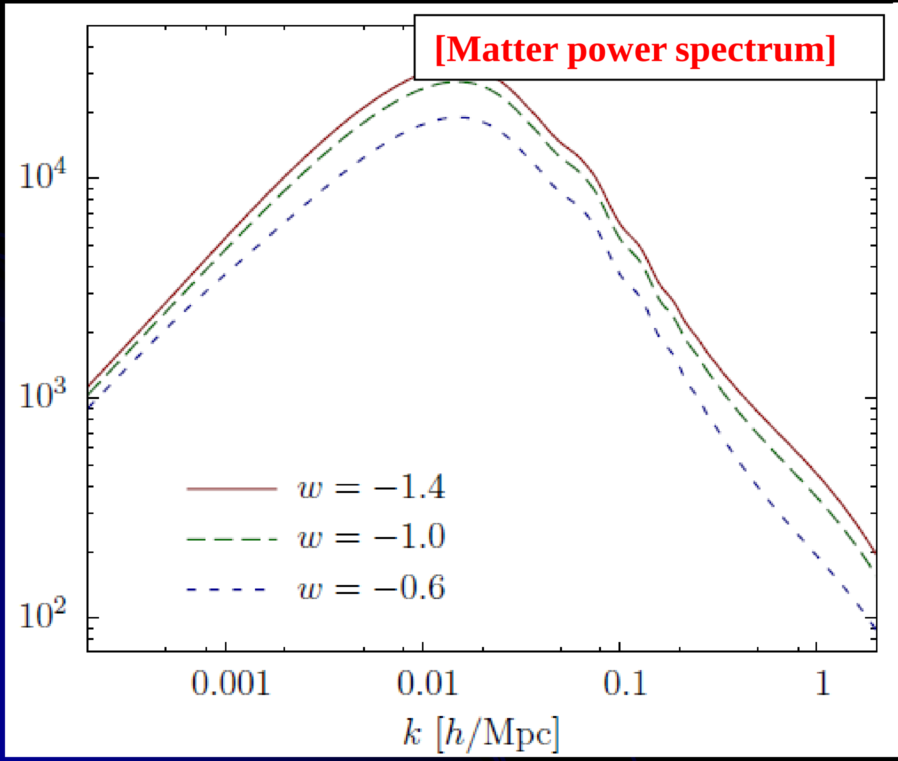
Dark energy, massive neutrinos (see, e.g., Hu'01, Lesgourgues&Pastor'06)

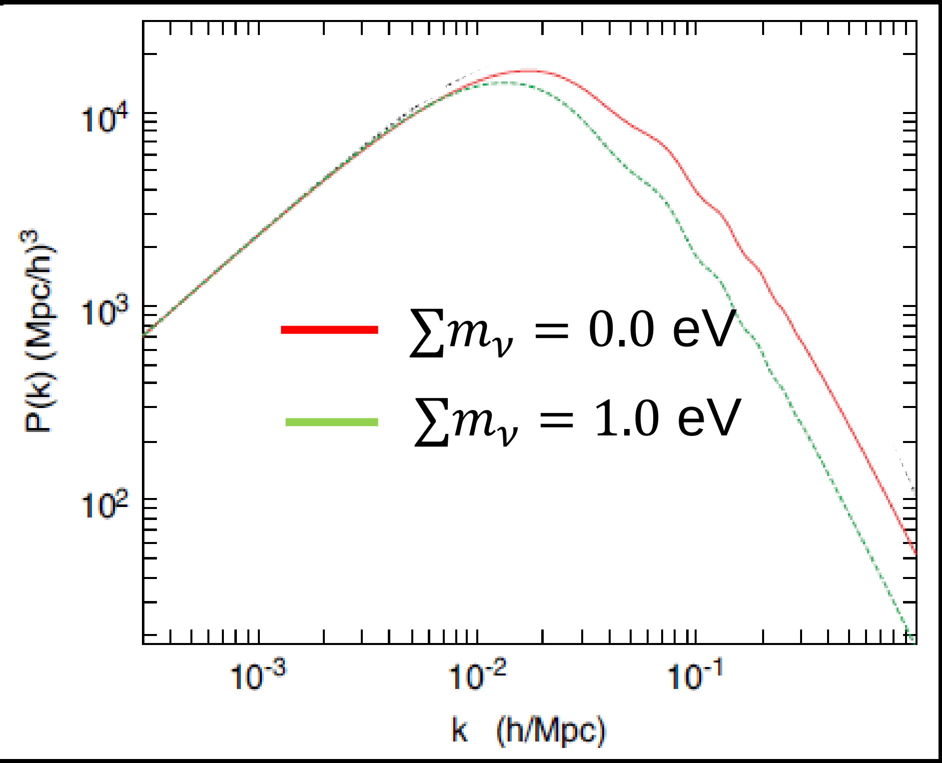
→ **Density perturbations** → **Gravitational potential** → $\phi(\vec{n})$

gradient mode

Dark energy

Massive neutrinos



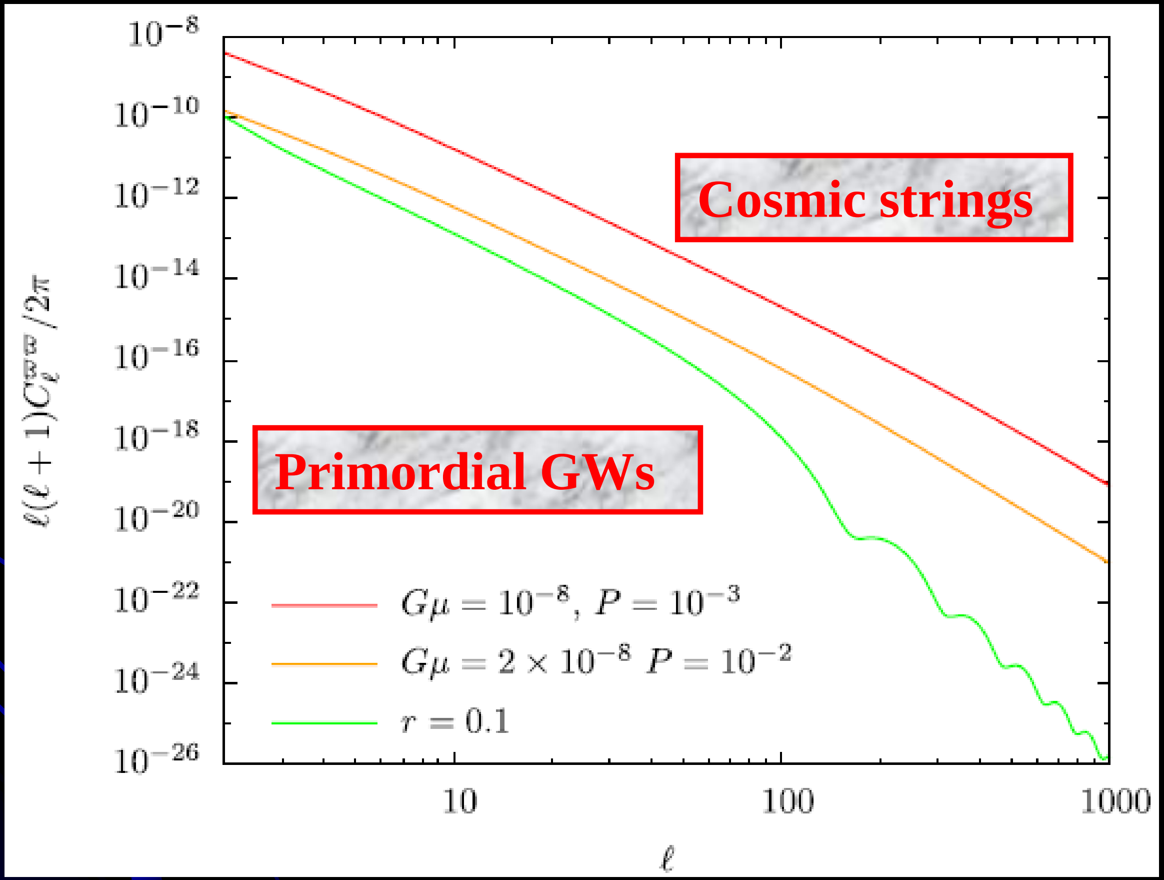


Primordial GWs/ Cosmic strings

GWs, magnetic fields, cosmic strings (see, e.g., Li&Cooray'06,Yamauchi,TN,Taruya'12)

→ **vector, tensor perturbations** → $\varpi(\vec{n})$

curl mode

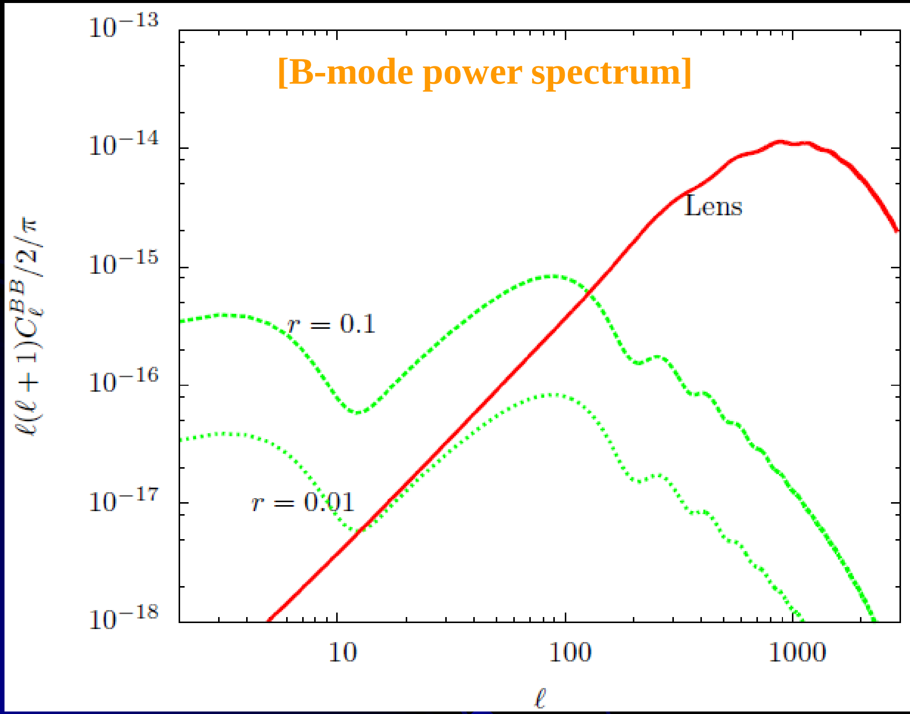


Other motivations to measure CMB lensing

✓ **CMB Lensing generates B-mode and secondary non-Gaussianity**

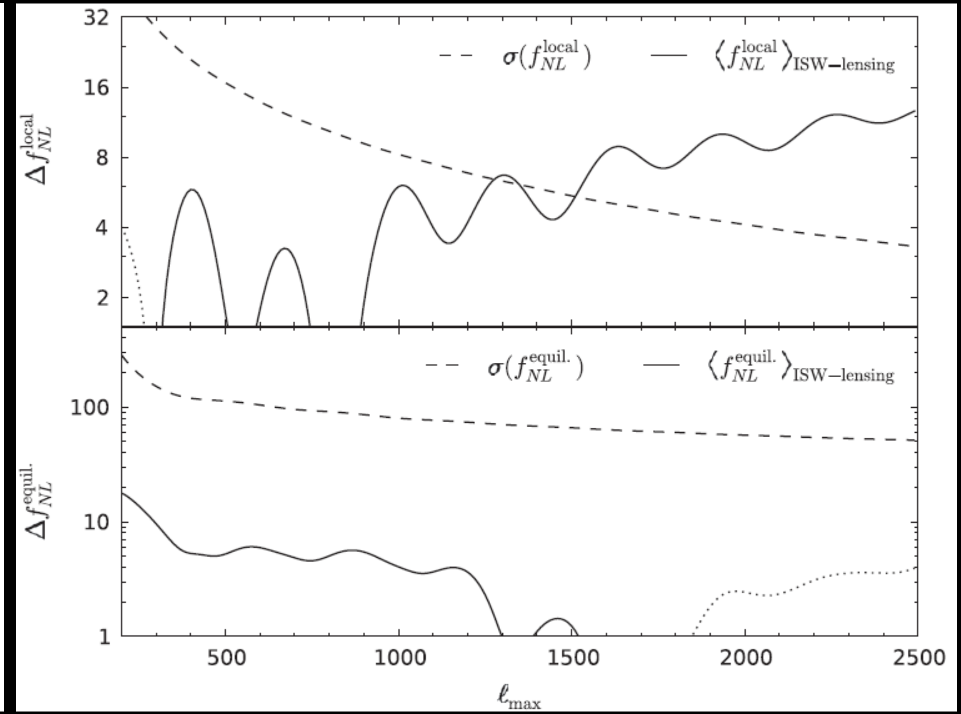
noise for primordial GWs detection | **noise for primordial non-Gaussianity**

Primordial GWs



e.g., Knox+'02, Kesden+'02, Smith+'09

Primordial non-Gaussianity



Hanson+'09

3. How to measure lensing effect

How to measure lensing effect

- **Angular power spectrum**
  - ✓ **useful to see whether the observed CMB anisotropies are lensed or not**
- **CMB lensing reconstruction = estimate lensing potentials**
  - ✓ **useful for cross-correlation studies with, e.g., cosmic shear, galaxy clustering, etc**
- **Minkowski Functionals (e.g., Schmalzingr+'00) may be another possible method to measure lensing effect**

CMB lensing reconstruction

- **Essence of lensing reconstruction** (Review: Hanson+'10)
  - ✓ **Lensing induces mode coupling in the temperature anisotropies**

$$\widetilde{\Theta}_{\vec{\ell}} = \Theta_{\vec{\ell}} - \int d^2L\,(\vec{\ell}\cdot\vec{L})\underline{\phi_{\vec{L}-\vec{\ell}}}\,\Theta_{\vec{L}} - \int d^2L\,(\star\vec{\ell}\cdot\vec{L})\underline{\varpi_{\vec{L}-\vec{\ell}}}\,\Theta_{\vec{L}}$$

  - ✓ **Lensing potentials would be estimated from mode coupling** $\widetilde{\Theta}_{\ell}\widetilde{\Theta}_{\vec{L}}$ $(\ell \neq L)$

- **(Maximum-Likelihood) Estimator** (e.g., Hu&Okamoto'02; Hirata&Seljak'03a,b; Hanson+'09)

$$\hat{\phi}_L^{(C)} = \hat{\phi}_L^{(S)} - \langle \hat{\phi}_L^{(S)} \rangle$$

→ **Mean-field bias: induced by non-lensing effect (mask, inhomogeneous noise, beam asymmetry, …)**

$$\hat{\phi}_L^{(S)} = \int d^2\ell\ F^{\phi}_{\ell,L}\,\overline{\Theta}_{\ell}\overline{\Theta}_{\vec{L}-\vec{\ell}}$$

$\left(\textbf{For idealistic case: } \overline{\Theta}_{\ell} = \frac{\widetilde{\Theta}_L}{C_L^{\Theta\Theta}}\right)$

weight function for unbiased estimator and for minimizing contributions from primary CMB
(more robust estimator is proposed in TN+'12)

Lensing effect is estimated through mode coupling of lensed CMB

Estimating lensing power spectrum

- ✓ For cosmology, we are interested in $C_\ell^{\phi\phi}$ and $C_\ell^{\varpi\varpi}$ rather than ϕ and ϖ

- ✓ Currently, $C_\ell^{\phi\phi}$ and $C_\ell^{\varpi\varpi}$ are estimated from $\hat{\phi}$ and $\hat{\varpi}$ (e.g., Kesden+'03, Hanson+'11)

$$\hat{x}_L = \int d\vec{\ell}\ F^x_{\ell,L}\ \overline{\Theta}_\ell \overline{\Theta}_{\vec{L}-\vec{\ell}}$$

$$\langle|\hat{x}_L|^2\rangle = \int d\vec{\ell}_1 \int d\vec{\ell}_2\, F^x_{L,\ell_1} F^x_{L,\ell_2} \langle \overline{\Theta}^*_{\ell_1} \overline{\Theta}^*_{\vec{L}-\vec{\ell}_1} \overline{\Theta}_{\ell_2} \overline{\Theta}_{\vec{L}-\vec{\ell}_2}\rangle$$

decomposed into disconnected/connected part

$$\langle|\hat{x}_L|^2\rangle = N_\ell^{x,(0)} + C_\ell^{xx} + N_\ell^{x,(1)} + N_\ell^{x,(2)} + \cdots$$

connected part

disconnected part (Gaussian bias)

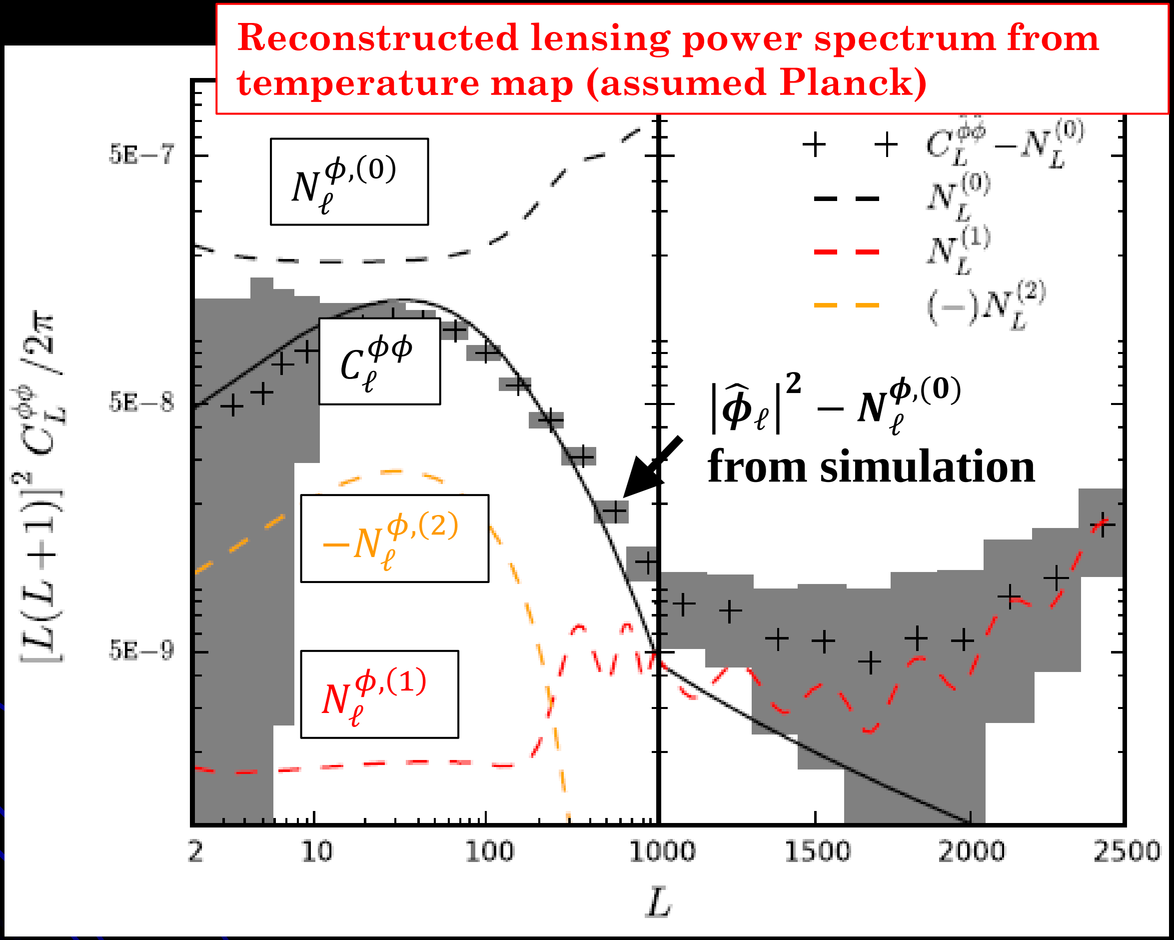
$O(C_\ell^{xx})$ $O([C_\ell^{xx}]^2)$

(more robust estimator is proposed in TN+'12)

Lensing power spectrum is estimated through trispectrum of lensed CMB

Estimating lensing power spectrum

- **Bias contributions**
  (Hanson+'11)



✓ **In practical cases, the bias terms should be robustly estimated**

Short summary of lensing reconstruction

➢ History

- **Reconstruction technique**

  - Basic ideas for quadratic estimator

  (e.g., Seljak'97; Seljak&Zaldarriaga'98; Hu&Okamoto'02; Okamoto & Hu'03; Lewis+'11)

  - Maximum-likelihood estimator (Hirata&Seljak'03a,b; Hanson+'09)

  - Curl mode estimator (Cooray+'05; TN,Yamauchi & Taruya+'12)

- **Estimating lensing power spectrum, C_ℓ^{xx}**

  (e.g., Kesden&Cooray'03; Cooray&Kesden'04; Hanson+'10; TN,Hanson&Takahashi'+12)

- **Method in practical cases (masking, inhomogeneous noise, etc.)**

  (e.g., Carvalho&Tereno'11; Hanson+'11; TN, Hanson & Takahashi+'12)

➢ Future

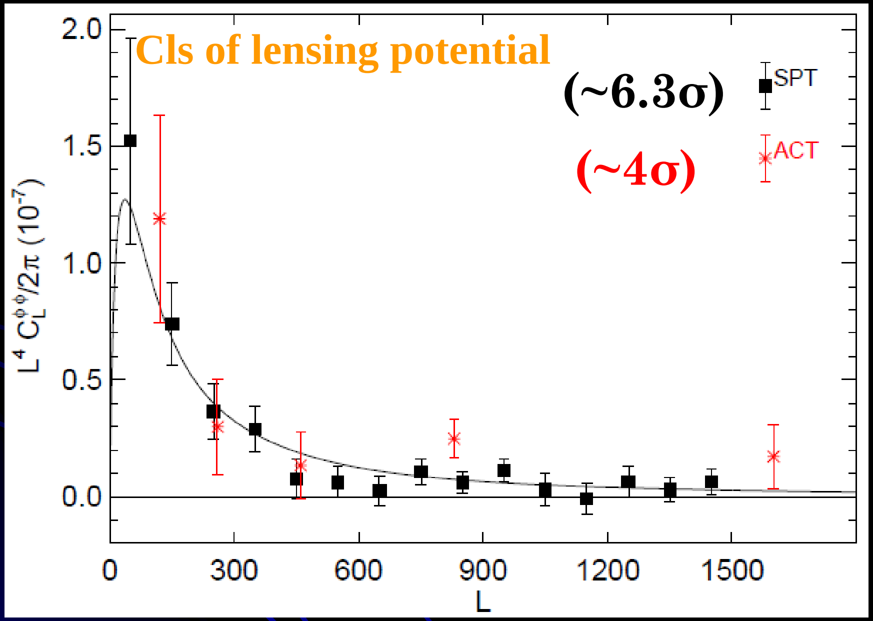
- **Method in practical cases for polarization**

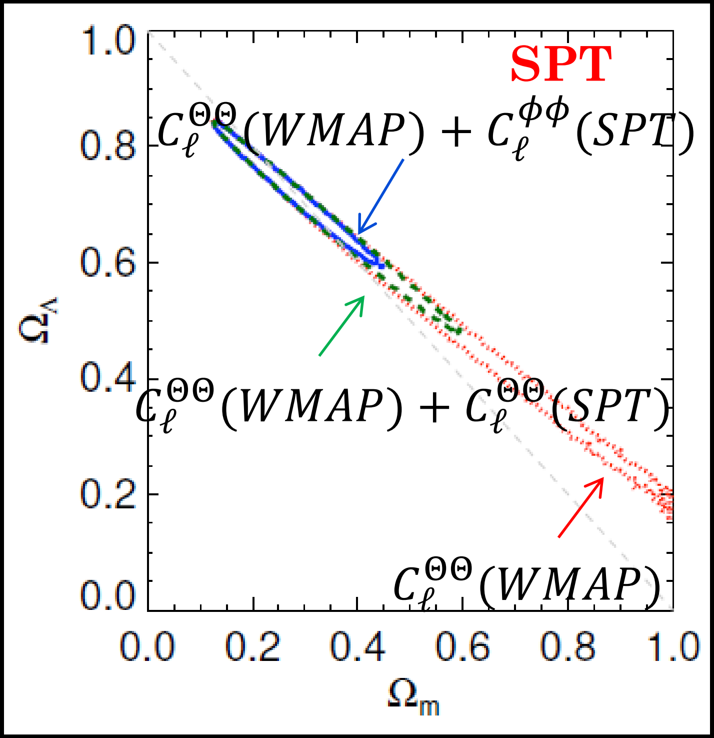
- **Importance of higher-order statistics**

4. Recent Progress and Future Prospects

Current status (gradient mode)

- **Recent works detect lensing signals from CMB maps alone**
  - ✓ WMAP + Atacama Cosmology Telescope (ACT) (Das+'11)
  - ✓ WMAP + South Pole Telescope (SPT) (van Engelen+'12)





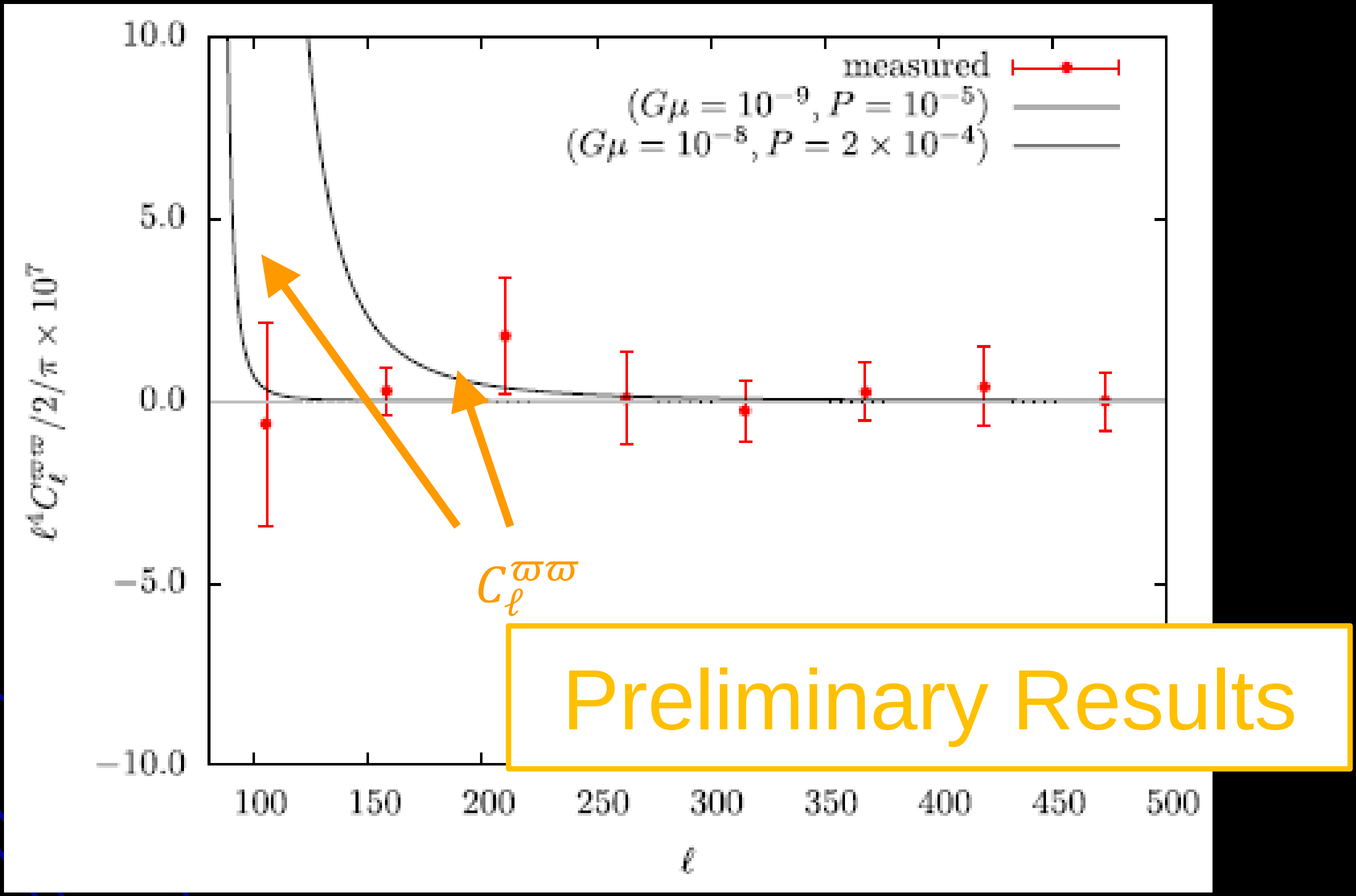
(van Engelen+'12)

- **Cross correlations with galaxies/quasars are also detected**

Smith+'07, Hirata+'08, Bleem+'12, Sherwin+'12

Current status (curl mode)

- **An example of cosmological implications from curl mode**

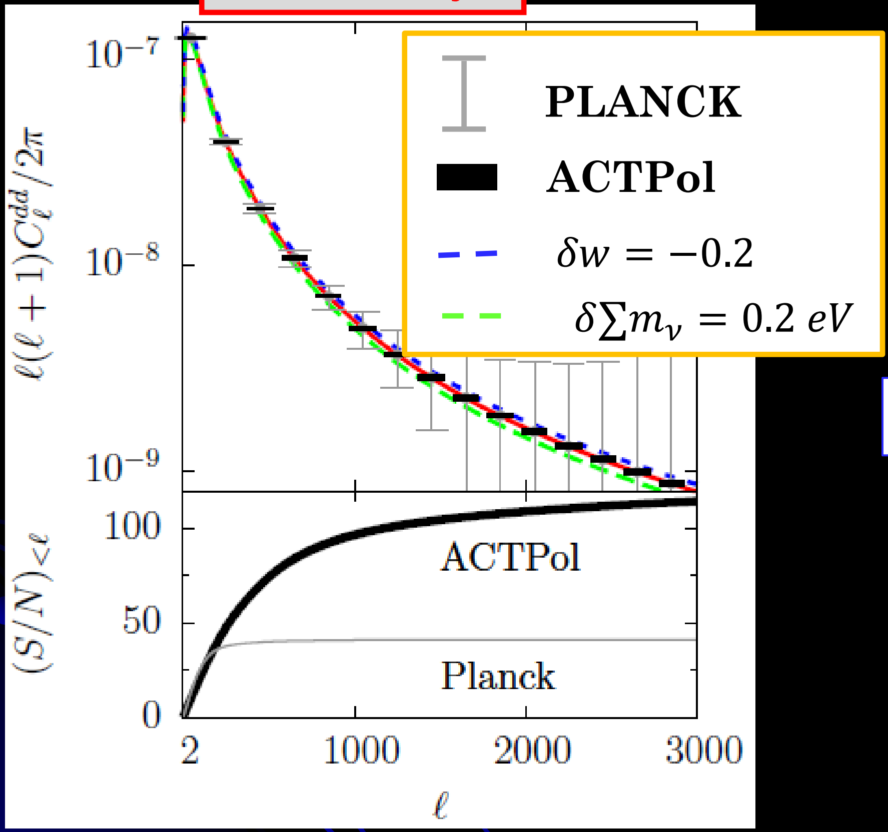


✓ **With ACT data, parameter regions which is not ruled out from $C_\ell^{\Theta\Theta}$, e.g., $G\mu \sim 10^{-9}$ with P $\sim 10^{-5}$, seems to be ruled out**

Future prospects

➢ **CMB experiments** **Planck, LiteBird, SPTpol, PolarBear, ACTPol, Polar, CMBPol…**

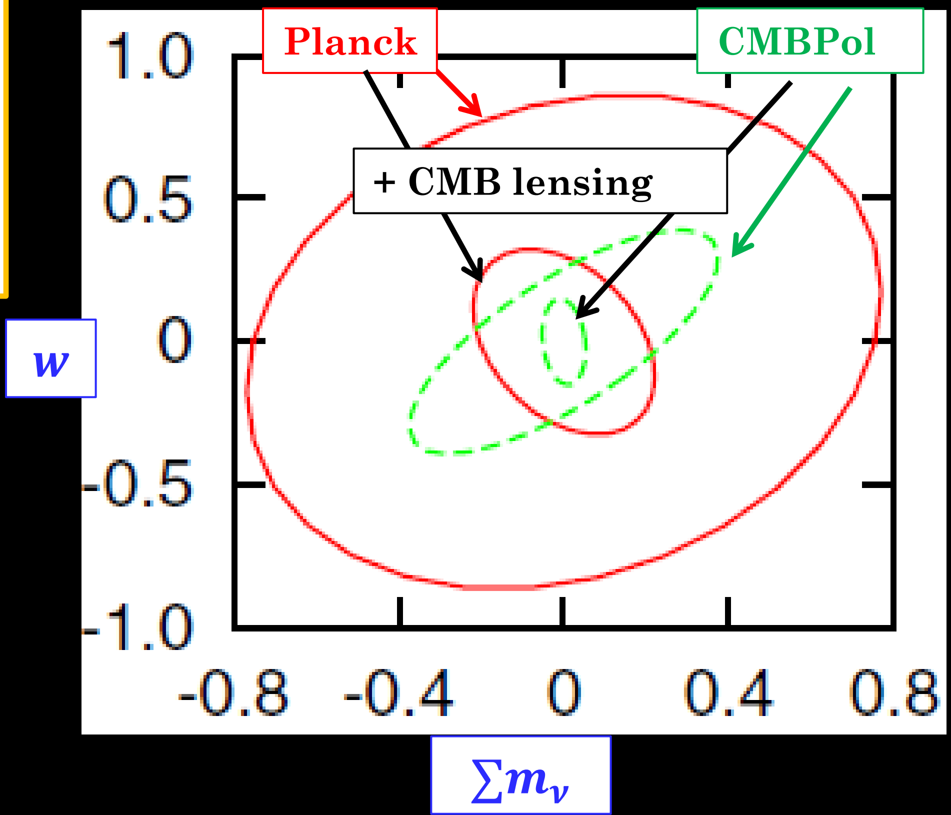
detectability



TN+'10

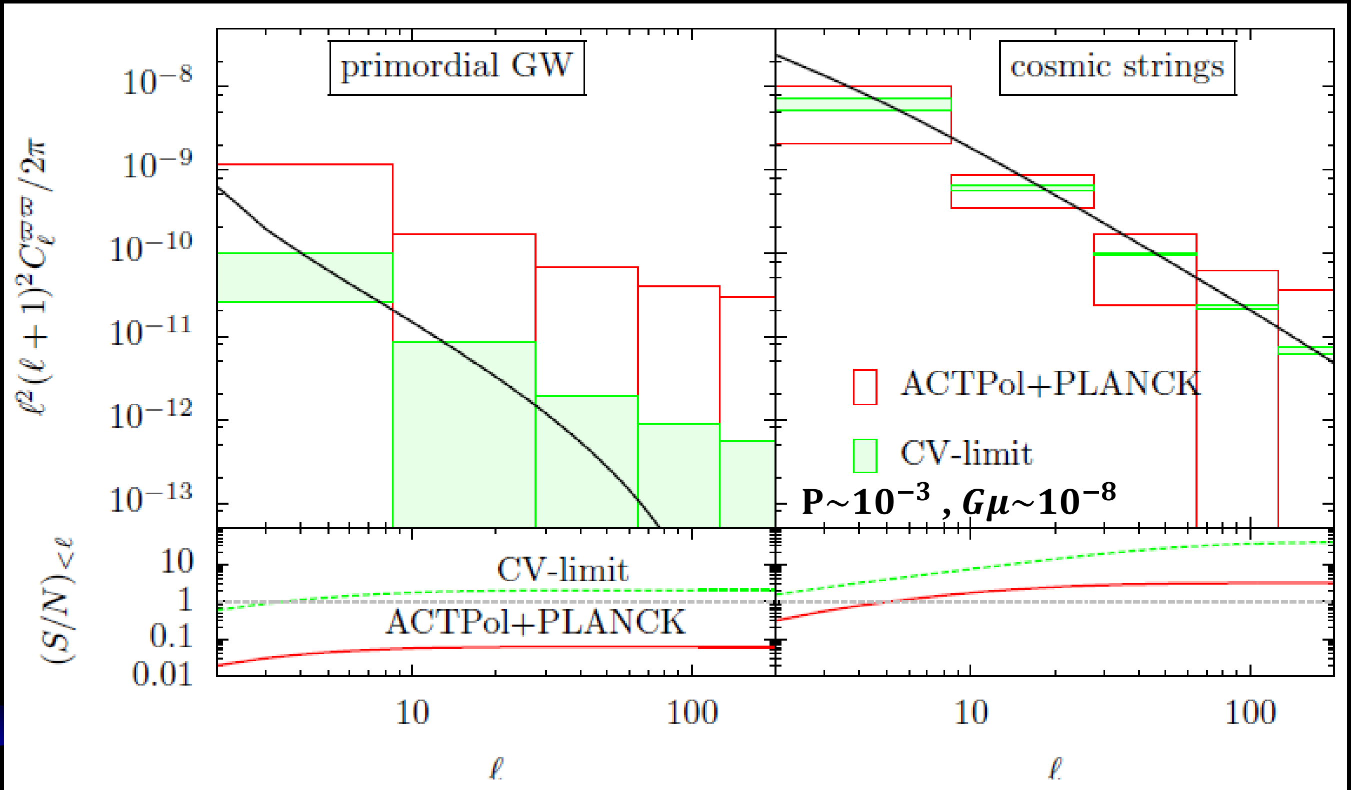
expected 1σ-constraints

Lesgourgues+'06



✓ **Lensing signals would be measured with enough precision to probe, e.g., dark energy and massive neutrinos**

Cosmological applications of curl mode



TN+'12

- ✓ Primordial GWs --- even r=0.1 would be difficult to detect.
- ✓ Cosmic strings --- can be explored with upcoming experiments

(This would be a new probe of cosmic strings from CMB)

Summary

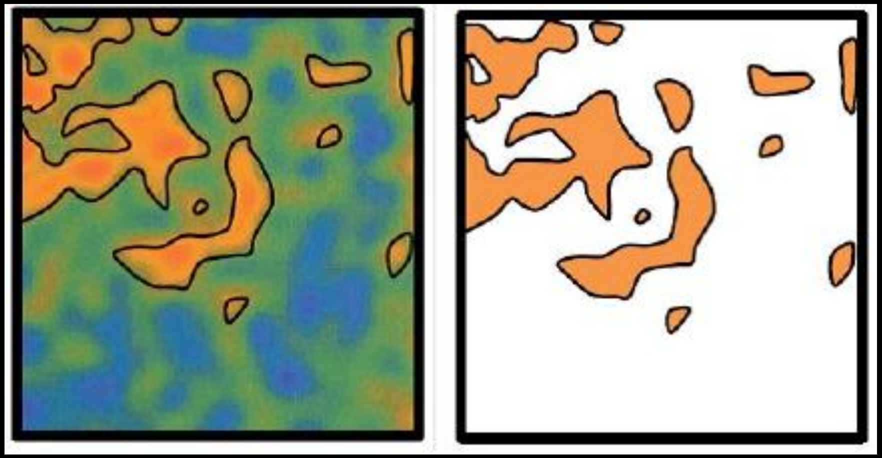
- **CMB lensing as a cosmological probe**
  - ✓ **CMB lensing has sensitivity to probe massive neutrinos, dark energy, etc.**
  - ✓ **Measurement of CMB lensing is also important to probe primordial GWs and non-Gaussianity**
- **How to measure lensing effect**
  - ✓ **Lensing effect can be measured from mode coupling induced by lensing**
  - ✓ **Lensing power spectrum can be also measured from lensing estimator**
- **Near future**
  - ✓ **Recent CMB lensing detection is from temperature maps, but polarization data from upcoming experiments would significantly improve the current constraints from CMB lensing**
  - ✓ **Practical methods of lensing measurement for polarization are required in near future**

Minkowski Functionals

- **Minkowski Functionals**

Topological information on two-dimensional sphere is characterized by the following three quantities (Minkowski Functionals)

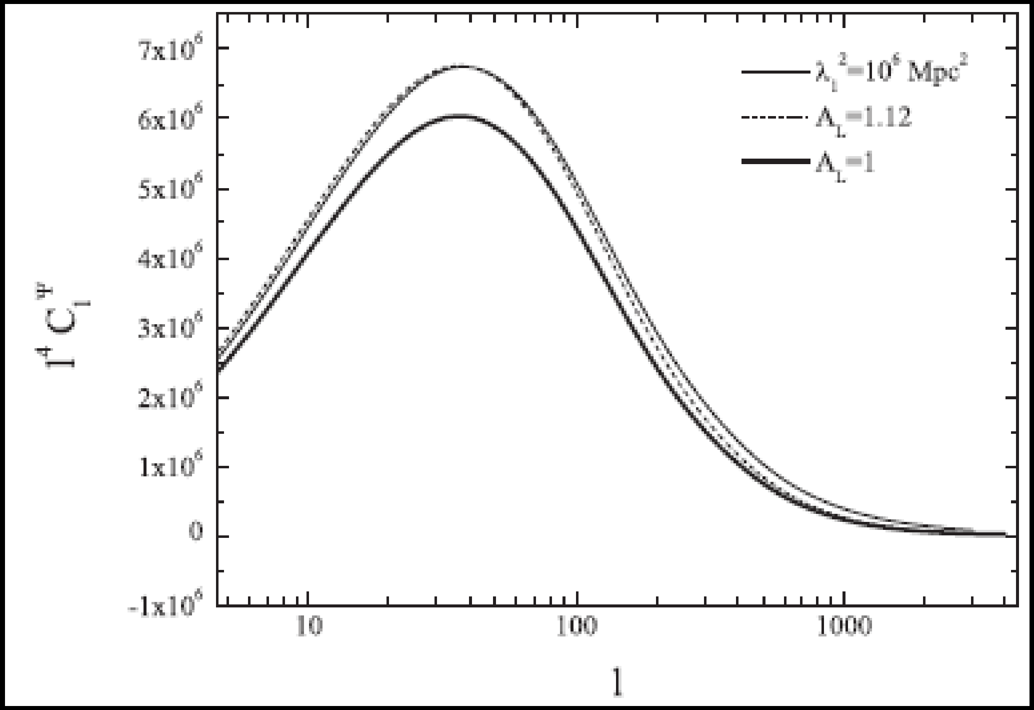
- ✓ **total area**
- ✓ **total length**
- ✓ **Euler number**



Minkowski Functionals include contributions from higher-order correlations (skewness, kurtosis…)

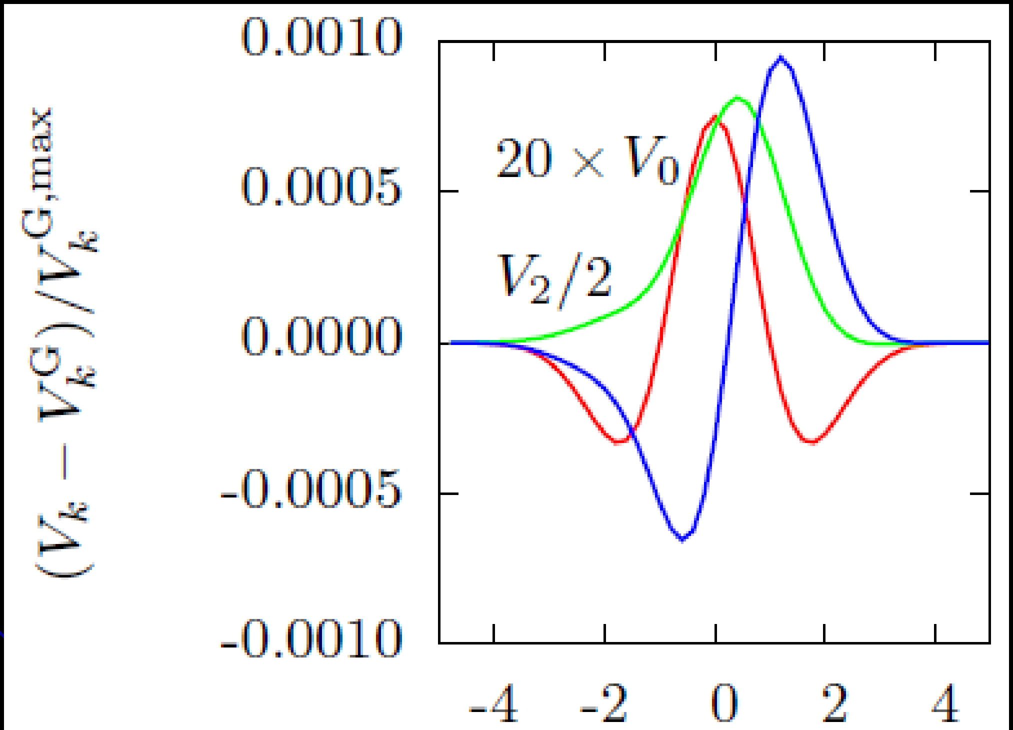
Future prospects

- **Test for modified gravity** **e.g., Calabrese+'09**



Minkowski Functionals

Preliminary Results



Bias-hardened estimators (1)

- **mean-field bias**

Consider distortion by an arbitrary function, $\epsilon(n)$, in the following form

$$\widetilde{\Theta}^{obs}(\vec{n}) = (1-\epsilon(\vec{n}))\widetilde{\Theta}(\vec{n}) \quad (\epsilon_\ell \ll 1)$$

We first propose a lensing estimator which is free from uncertainty in $\epsilon(n)$

(1) define ϵ estimator: $\hat{\epsilon}$

(2) $\hat{\epsilon}$ estimator also includes a mean-field bias, so we define a quantity by combining $\hat{\epsilon}$ and $\hat{\phi}$ so that mean-field bias vanishes

$$\hat{\phi}_L^{(BR)} = \frac{\hat{\phi}_L^{(S)} - R_L^{\phi\epsilon}\hat{\epsilon}_L^{(S)}}{1 - R_L^{\phi\epsilon}R_L^{\epsilon\phi}}$$

The above estimator reduces mean-field bias from ϵ_ℓ, but there are still other possible sources of mean-field bias, e.g., uncertainty in Cl's

This estimator would be useful as a cross-check of the standard method

Bias-hardened estimators (2)

- **Gaussian bias**

  ✓ **Current methods**

  vanishing the bias by cross-correlating different multipoles

  (Hu'01; Das&Sherwin'11)

  ✓ **Our method**

$$\langle|\hat{x}_L|^2\rangle_D = 2\int d\vec{\ell}_1 \int d\vec{\ell}_2\, F^x_{L,\ell_1} F^x_{L,\ell_2} \bar{C}_{\ell_1,\ell-\ell_2} \bar{C}_{\ell-\ell_1,\ell_2} \qquad (\bar{C}_{L_1,L_2} \equiv \overline{\Theta}_{L_1}\overline{\Theta}_{L_2})$$

↓

$$\langle|\hat{x}_L|^2\rangle_D = 2\int d\vec{\ell}_1 \int d\vec{\ell}_2\, F^x_{L,\ell_1} F^x_{L,\ell_2} [2\bar{C}_{\ell_1,\ell-\ell_2} \overline{\Theta}_{\ell-\ell_1} \overline{\Theta}_{\ell_2} - \bar{C}_{\ell_1,\ell-\ell_2} \bar{C}_{\ell-\ell_1,\ell_2}]$$

- **The above estimator is derived with maximum likelihood approach**
- **Less sensitive to the bias in** $\bar{C}_{L_1,L_2}$

e.g., $\bar{C}_{L_1,L_2} \rightarrow \bar{C}_{L_1,L_2} + \Sigma_{L_1,L_2}$

Bias-reduced estimator

(2) improve "standard" estimator to remove "mean field"

$$\langle \hat{\phi}_{\vec{\ell}} \rangle = R_\ell^{\phi M} M_\ell \quad \longrightarrow \quad \langle \hat{\phi}_{\vec{\ell}}^{BR} \rangle = 0$$

We consider "lensing" and "mask" estimators:

$$\widehat{M}_\ell = N_\ell^{MM} \int d\vec{L} \, \frac{f_{\ell,L}^{\phi} f_{\ell,L}^{M}}{2\tilde{C}_\ell^{\Theta\Theta} \tilde{C}_L^{\Theta\Theta}}$$

$$f_{\ell,L}^{\phi} = \vec{\ell} \cdot \vec{L} \tilde{C}_L^{\Theta\Theta} + \vec{\ell} \cdot (\vec{\ell} - \vec{L}) \tilde{C}_{|\vec{\ell}-\vec{L}|}^{\Theta\Theta}$$

$$f_{\ell,L}^{M} = [\tilde{C}_L^{\Theta\Theta} + \tilde{C}_{|\vec{\ell}-\vec{L}|}^{\Theta\Theta}]$$

$$R_\ell^{ab} = N_\ell^{aa} \int d\vec{L} \, \frac{f_{\ell,L}^{a} f_{\ell,L}^{b}}{2\tilde{C}_\ell^{\Theta\Theta} \tilde{C}_L^{\Theta\Theta}}$$

$$[N_\ell^{aa}]^{-1} = \int d\vec{L} \, \frac{f_{\ell,L}^{a} f_{\ell,L}^{a}}{2\tilde{C}_\ell^{\Theta\Theta} \tilde{C}_L^{\Theta\Theta}}$$

Since

$$\langle \hat{\phi}_\ell \rangle_{CMB} = \phi_\ell + R_\ell^{\phi M} M_\ell$$

$$\langle \widehat{M}_\ell \rangle_{CMB} = R_\ell^{M\phi} \phi_\ell + M_\ell$$

we define a new estimator

$$\hat{\phi}_\ell^{BR} = \frac{\hat{\phi}_\ell - R_\ell^{\phi M} \widehat{M}_\ell}{1 - R_\ell^{\phi M} R_\ell^{M\phi}}$$

Appendix: Filter functions

- **"standard" quadratic estimator**

$$F^{a}_{\vec{\ell},\vec{L}} = -N^{aa}_{\ell} f^{a}_{\ell,L}$$

$$f^{\phi}_{\ell,L} = \vec{\ell}\cdot\vec{L}C^{\Theta\Theta}_{L} + \vec{\ell}\cdot(\vec{\ell}-\vec{L})C^{\Theta\Theta}_{|\vec{\ell}-\vec{L}|}$$

$$f^{\varpi}_{\ell,L} = (\star\,\vec{\ell})\cdot\vec{L}C^{\Theta\Theta}_{L} + (\star\,\vec{\ell})\cdot(\vec{\ell}-\vec{L})C^{\Theta\Theta}_{|\vec{\ell}-\vec{L}|}$$

$$[N^{aa}_{\ell}]^{-1} = \int d\vec{L}\,\frac{f^{a}_{\ell,L}f^{a}_{\ell,L}}{2\tilde{C}^{\Theta\Theta}_{\ell}\tilde{C}^{\Theta\Theta}_{L}}$$

- **Our "bias-reduced" estimator**

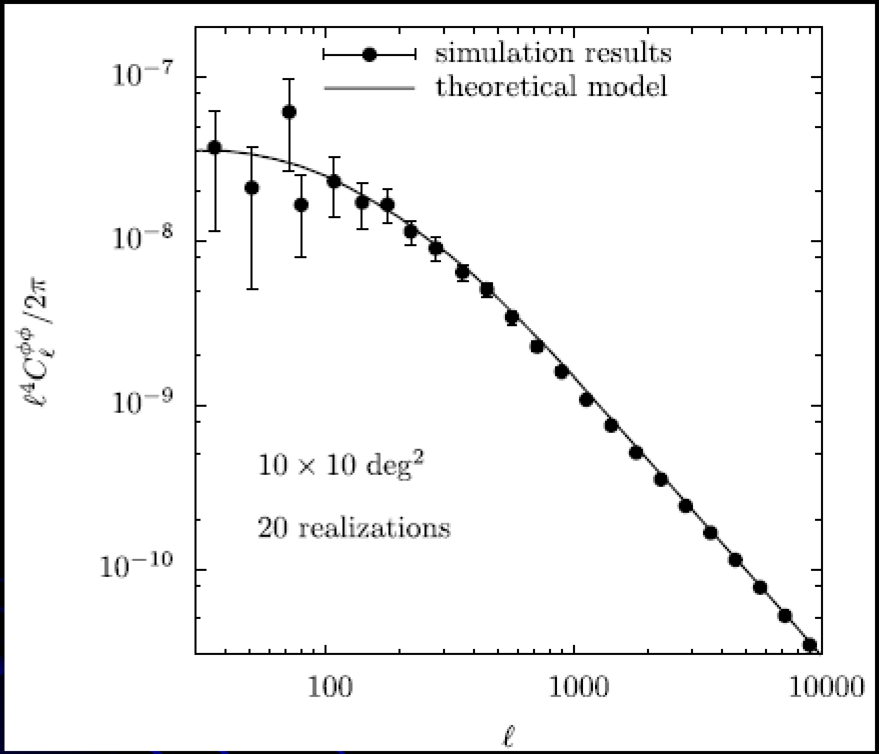
$$F'^{\,\phi}_{\vec{\ell},\vec{L}} = \frac{F^{\phi}_{\ell,L} - R^{\phi M}F^{M}_{\ell,L}}{1 - R^{\phi M}R^{M\phi}}$$

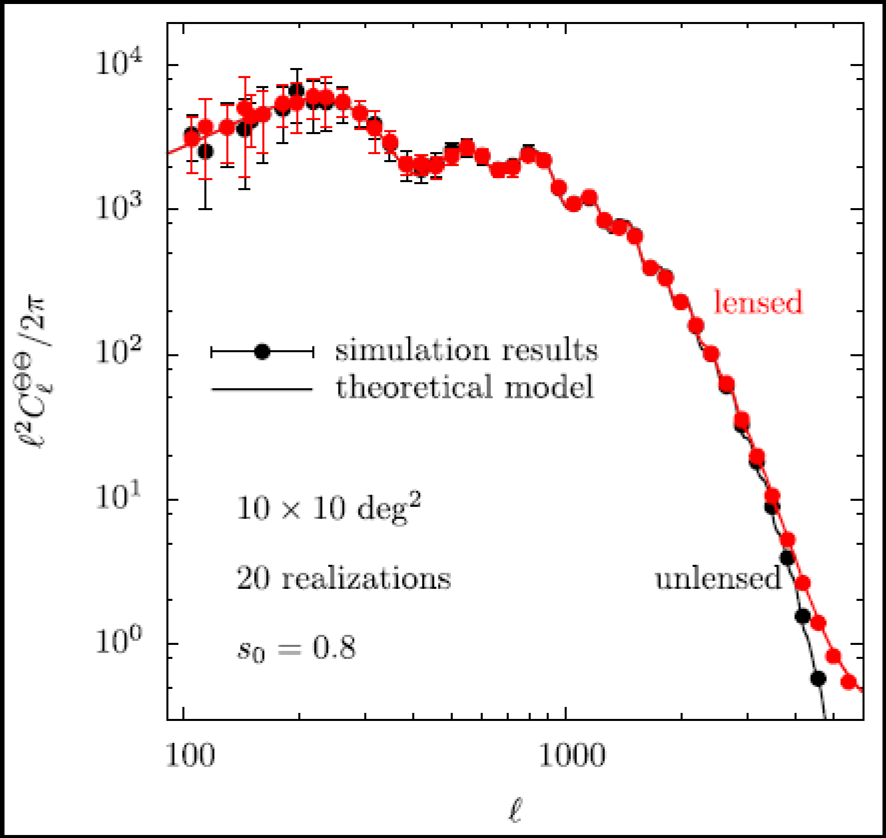
$$f^{\phi}_{\ell,L} = \vec{\ell}\cdot\vec{L}\tilde{C}^{\Theta\Theta}_{L} + \vec{\ell}\cdot(\vec{\ell}-\vec{L})\tilde{C}^{\Theta\Theta}_{|\vec{\ell}-\vec{L}|}$$

$$f^{\varpi}_{\ell,L} = (\star\,\vec{\ell})\cdot\vec{L}\tilde{C}^{\Theta\Theta}_{L} + (\star\,\vec{\ell})\cdot(\vec{\ell}-\vec{L})\tilde{C}^{\Theta\Theta}_{|\vec{\ell}-\vec{L}|}$$

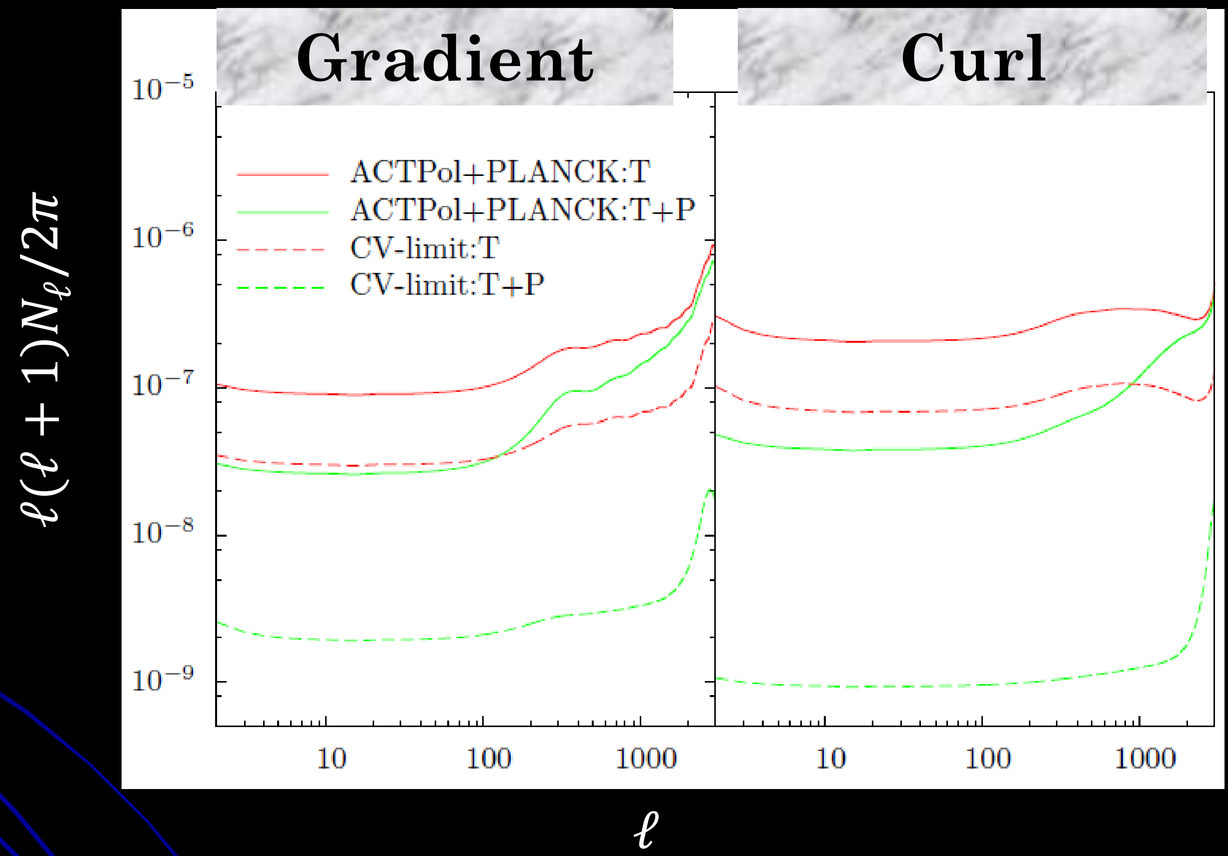
$$f^{M}_{\ell,L} = [\tilde{C}^{\Theta\Theta}_{L} + \tilde{C}^{\Theta\Theta}_{|\vec{\ell}-\vec{L}|}]$$

$$R^{ab}_{\ell} = N^{aa}_{\ell}\int d\vec{L}\,\frac{f^{a}_{\ell,L}f^{b}_{\ell,L}}{2\tilde{C}^{\Theta\Theta}_{\ell}\tilde{C}^{\Theta\Theta}_{L}}$$


simulation results
theoretical model
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$\ell^4 C_\ell^{\phi\phi}/2\pi$
10×10 deg^2
20 realizations
100
1000
10000
ℓ


10^4
10^3
10^2
10^1
10^0
$\ell^2 C_\ell^{\Theta\Theta}/2\pi$
lensed
simulation results
theoretical model
10×10 deg^2
20 realizations
unlensed
$s_0 = 0.8$
100
1000
ℓ

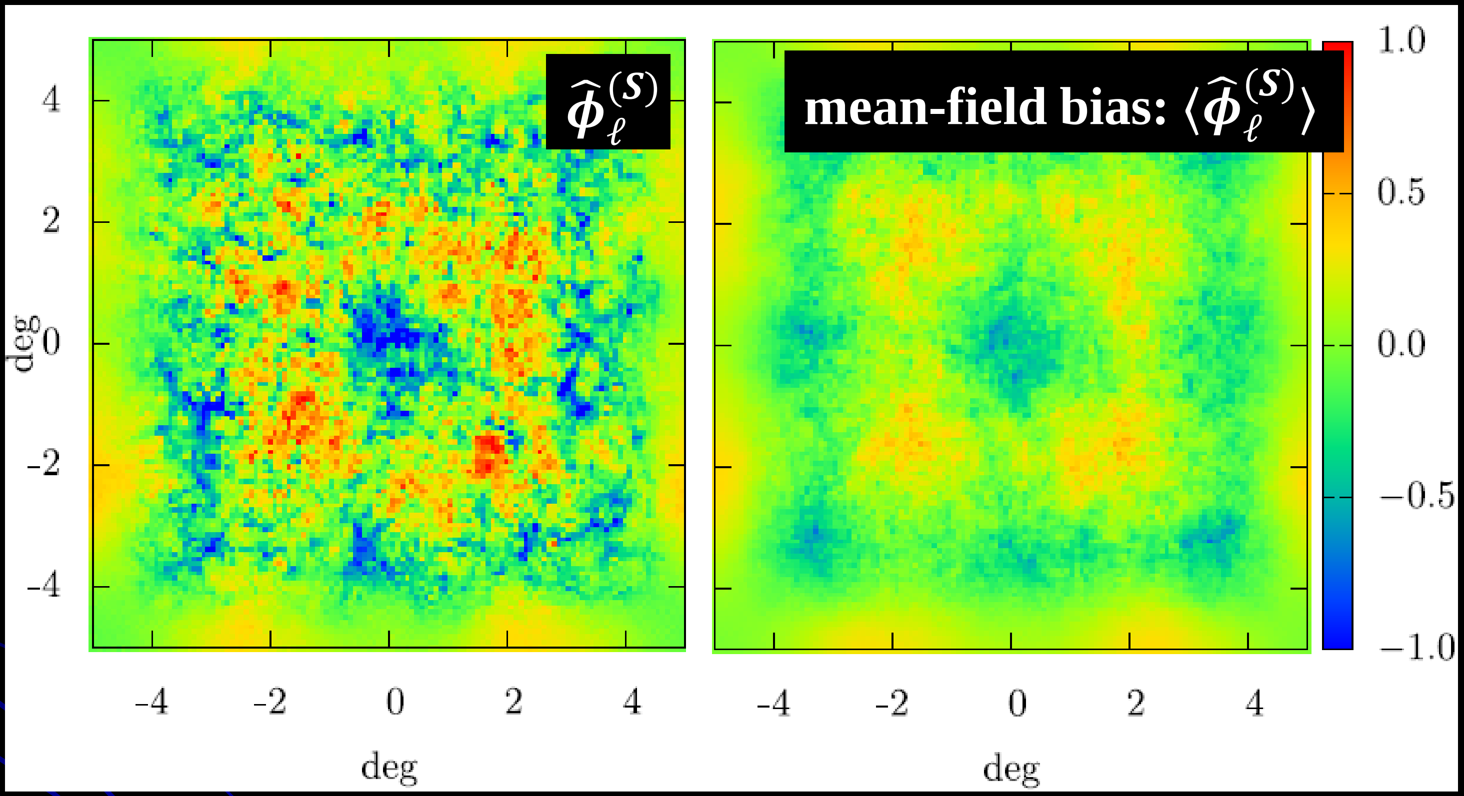
Noise spectrum (Gaussian bias)



- **The variance of curl-mode estimator is similar to that of gradient-mode**

Mean-Field Bias

- **An example of mean-field bias**



- ✓ **Mean-field bias is usually estimated with Monte Carlo, but the underlying fluctuations should be perfectly known**

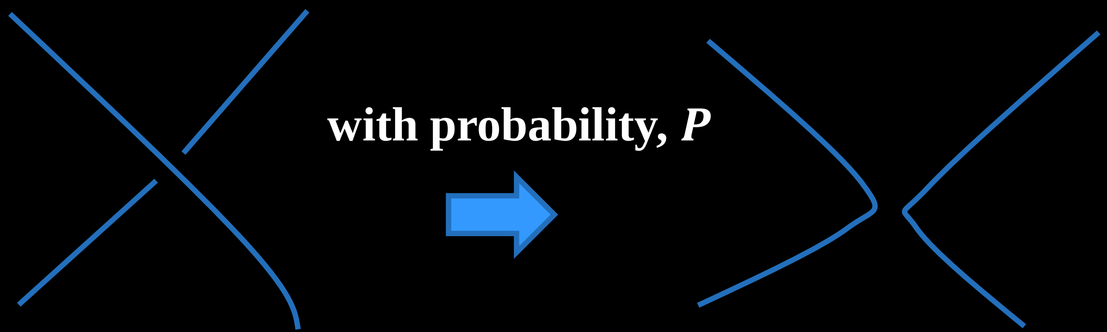
- ✓ **We first define an estimator for mask field $\hat{\epsilon}$, and then propose an estimator by combining $\widehat{\phi}$ with $\hat{\epsilon}$ so that mean-field bias vanishes**

Application of curl mode

We consider two sources of curl mode: primordial GWs and cosmic strings

See Yamauchi, *TN* & Taruya '12 for details of our model

- **We consider straight string, randomly oriented**
- **Motion of strings is determined by velocity-dependent one scale model which depends on string tension, $G\mu$ and intercommuting probability, P**

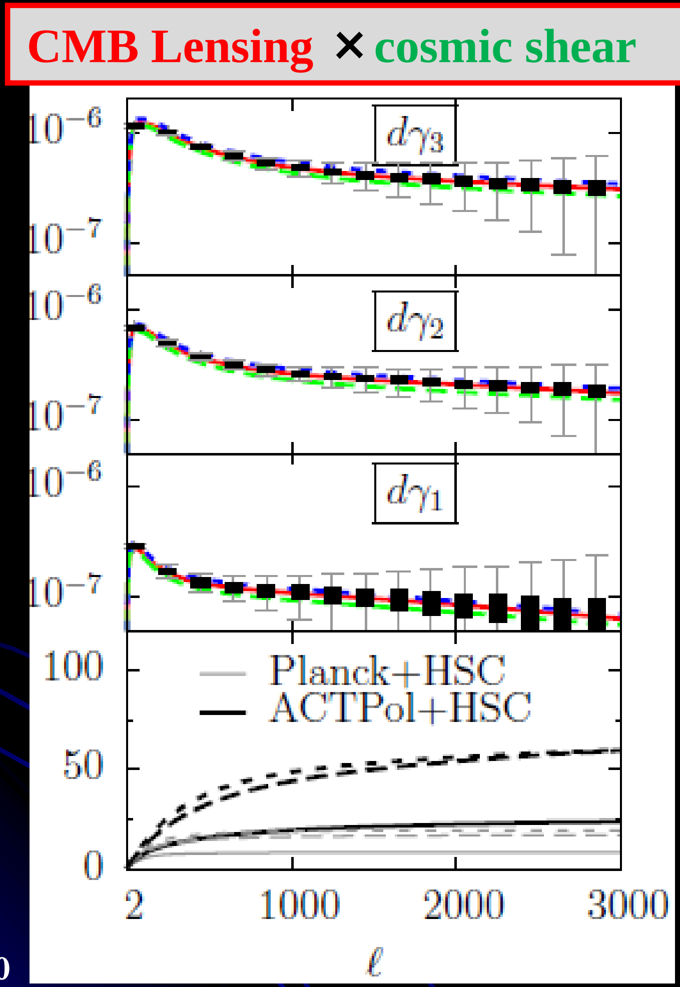


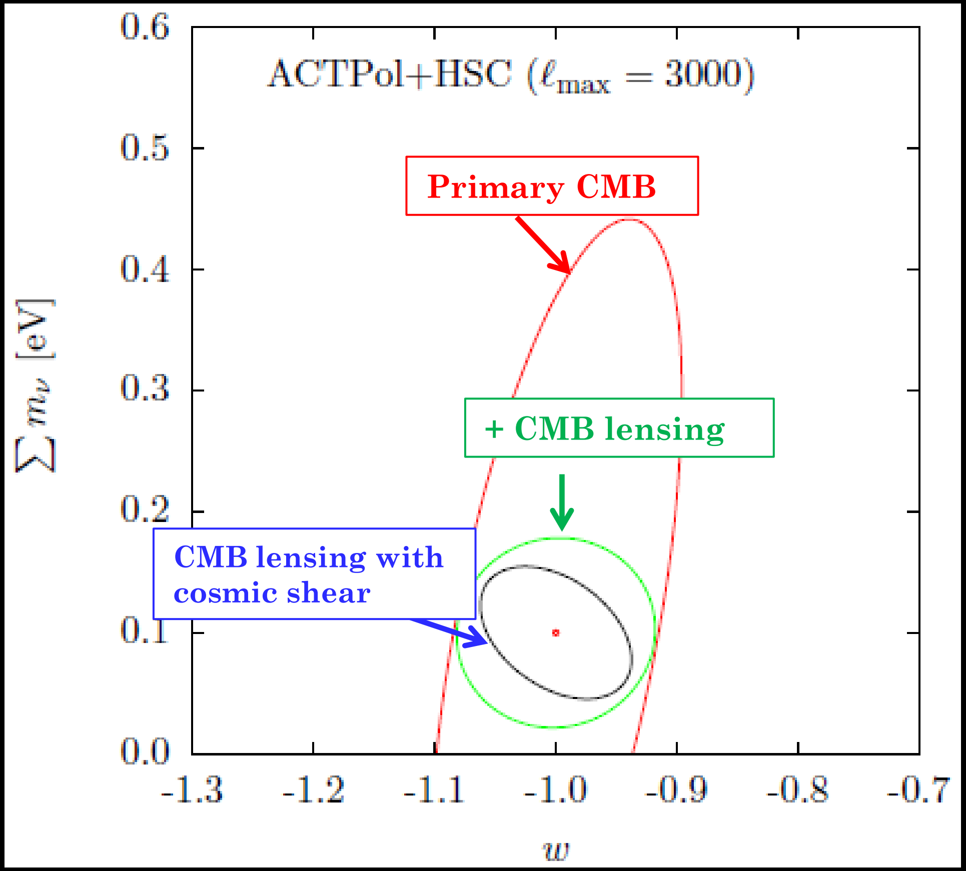
if $P \ll 1$, cosmic strings would not be generated by field theoretic inflation

- **Lensing is induced by metric perturbations from strings in our line-of-sight**

Future prospects (cross correlation)

- Expected 1σ constraints on dark energy and massive neutrinos





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✓ Cross-correlation signals with other probes (e.g., cosmic shear) would be powerful for robust constraints