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Weak lensing of CMB from cosmic (super-)strings

Daisuke Yamauchi

ICRR, U. Tokyo

With A. Taruya, T. Namikawa, K. Takahashi, Y. Sendouda, C.M. Yoo, M. Sasaki

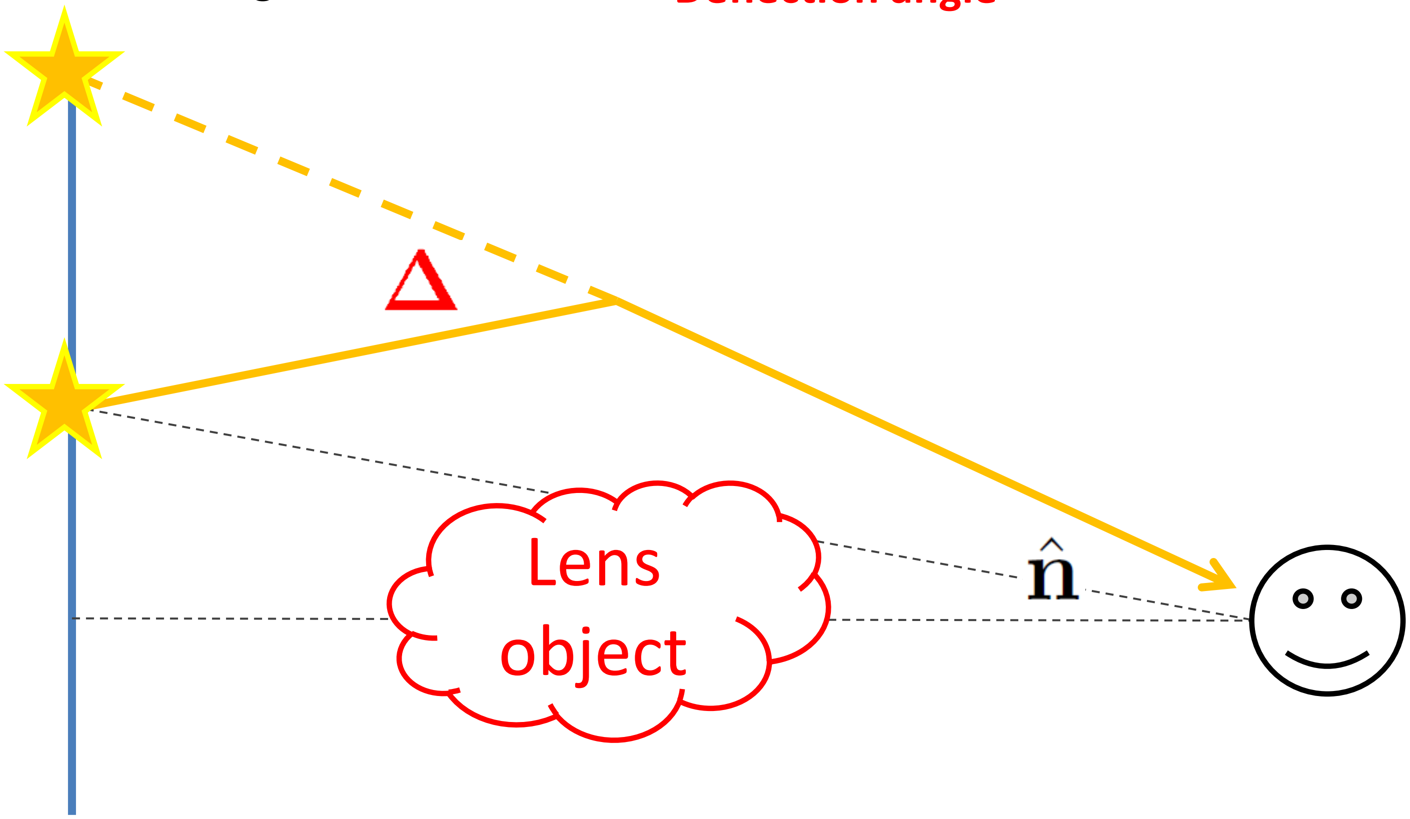
Introduction

Lensing effect on the CMB can be treated as a mapping of the intrinsic temperature/polarization fields :

$$\hat{n} \rightarrow \hat{n} + \Delta(\hat{n})$$

Line-of-sight vector

Deflection angle



Introduction

Lensing effect on the CMB can be treated as a mapping of the intrinsic temperature/polarization fields :

$$\hat{\boldsymbol{n}} \to \hat{\boldsymbol{n}} + \boldsymbol{\Delta}(\hat{\boldsymbol{n}})$$

Line-of-sight vector **Deflection angle**

- In the case of scalar perturbations, the deflection at linear order can be described by the angular gradient of the lensing weighted projected potential:

$$\boldsymbol{\Delta} = \nabla_{\hat{\boldsymbol{n}}} \phi^{\oplus}(\hat{\boldsymbol{n}})$$

where $\phi^{\oplus}(\hat{\boldsymbol{n}}) = \int_0^{\chi_S} d\chi \frac{\chi_S - \chi}{\chi_S \chi} \Phi(\chi\hat{\boldsymbol{n}}, \eta_0 - \chi)$

geometry matter potential

Subdominant, but may be helpful for early universe !

- In general, vector/tensor perturbations lead to a new contribution to the deflection angle, **curly deflection**:

90 deg rotation operator

$$\Delta = \underbrace{\nabla_{\hat{n}}\,\phi^{\oplus}(\hat{n})}_{\text{Gradient part}} + \underbrace{(*\nabla_{\hat{n}})\,\phi^{\otimes}(\hat{n})}_{\text{Curly part}}$$

Gradient part ↑ Scalar/Vector/Tensor perturbations

Curly part ↑ Vector/Tensor perturbations

Cosmic strings as a possible source producing scalar/vector/tensor perturbations

Gradient part

Curly part

- ✓ It is natural to expect that topological defects, appearing as solutions to the field equation in many particle physics models, have formed during phase transitions in the early universe.
- ✓ Various new types of cosmic strings, so-called cosmic superstrings, may be formed at the end of stringy inflation.

⇨ Remnants of unified theory

Cosmic strings as a possible source producing scalar/vector/tensor perturbations

Gradient part

Curly part

- ✓ It is natural to expect that topological defects, appearing as solutions to the field equation in many particle physics models, have formed during phase transitions in the early universe
- ✓ Var… ay be t…

Intercommutation process provides a mechanism for a string network to lose its energy and approach to an attractor sol.

→ P is strongly related to the string number density !

Intercommuting probability P (clue to detect superstrings !)

- ➢ Conventional cosmic strings : P=1
- ➢ Cosmic superstrings : $P \sim 10^{-3} \ll 1$

Gradient part of deflection

$$\boldsymbol{\Delta} = \nabla_{\hat{\boldsymbol{n}}}\,\phi^{\oplus}(\hat{\boldsymbol{n}}) + (*\nabla_{\hat{\boldsymbol{n}}})\;\phi^{\otimes}(\hat{\boldsymbol{n}})$$

Gradient part is directly related to convergence field κ as usual :

$$\nabla^2_{\hat{\boldsymbol{n}}}\,\phi^{\oplus}(\hat{\boldsymbol{n}}) = \nabla_{\hat{\boldsymbol{n}}}\cdot\boldsymbol{\Delta}(\hat{\boldsymbol{n}}) = 2\,\kappa(\hat{\boldsymbol{n}})$$

The observed sky map of the convergence due to strings appears as a superposition of those due to each segment:

$$\kappa(\hat{\boldsymbol{n}}) = \sum_{(i)\in\mathrm{all\,strings}} \kappa^{(i)}(\hat{\boldsymbol{n}})$$

where $\kappa^{(i)}(\hat{\boldsymbol{n}}) = 4\pi G\int_0^{\chi_{\rm S}} \mathrm{d}\chi\,\frac{(\chi_{\rm S}-\chi)\chi}{2\chi_{\rm S}}\,\delta T^{(i)}_{\mu\nu}(\chi\hat{\boldsymbol{n}},\eta_0-\chi)\bar{K}^{\mu}\bar{K}^{\nu}$

: lensing weighted projected energy density

$$\kappa(\hat{\boldsymbol{n}}) = \sum_{(i)\in \text{all strings}} \kappa^{(i)}(\hat{\boldsymbol{n}})$$

The string segments are distributed randomly.
→ No correlations between two different segments!

$$C_\ell^{\kappa\kappa} = \frac{1}{2\ell+1}\sum_m \left\langle \left|\kappa_{\ell m}\right|^2 \right\rangle$$

$$= \frac{1}{2\ell+1}\sum_m \left[\left\langle \sum_{(i)\in \text{strings}} \left|\kappa_{\ell m}^{(i)}\right|^2 \right\rangle + \left\langle \sum_{(i)\neq(j)} \kappa_{\ell m}^{(i)} \kappa_{\ell m}^{(j)\,*} \right\rangle \right]$$

1-segment contribution

segment-segment correlations

For strings, ensemble average can be replaced by averaging over the parameter space

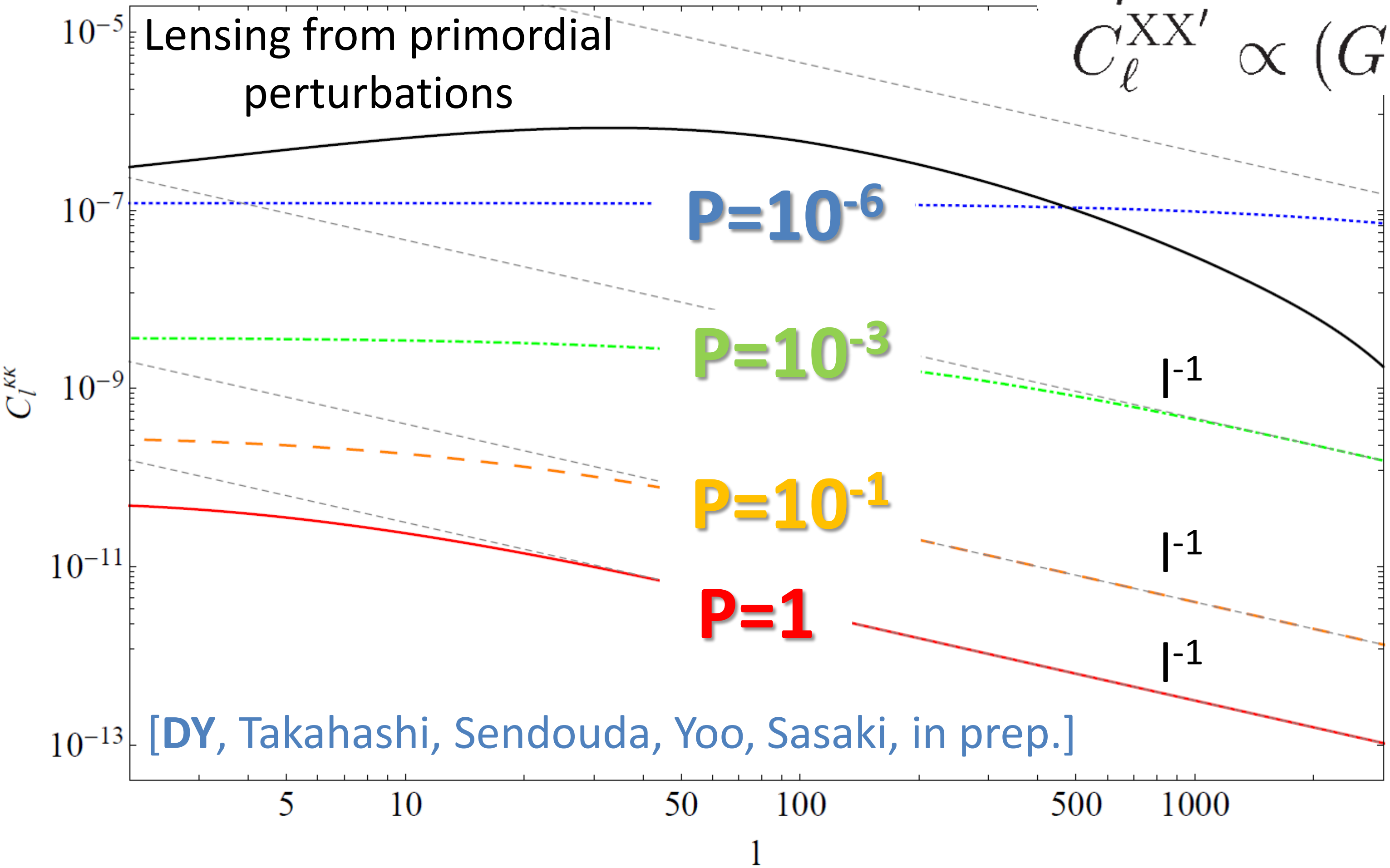
$$\approx \int_0^{z_{\rm LSS}} dz \frac{dV}{dz} \int d\boldsymbol{\Theta}_{\rm L} \cdot \frac{dn}{d\boldsymbol{\Theta}_{\rm L}} \frac{1}{2\ell+1} \sum_m \left|\kappa_{\ell m}^{(*)}\right|^2$$

Averaging over redshift space

Averaging over the velocity/direction

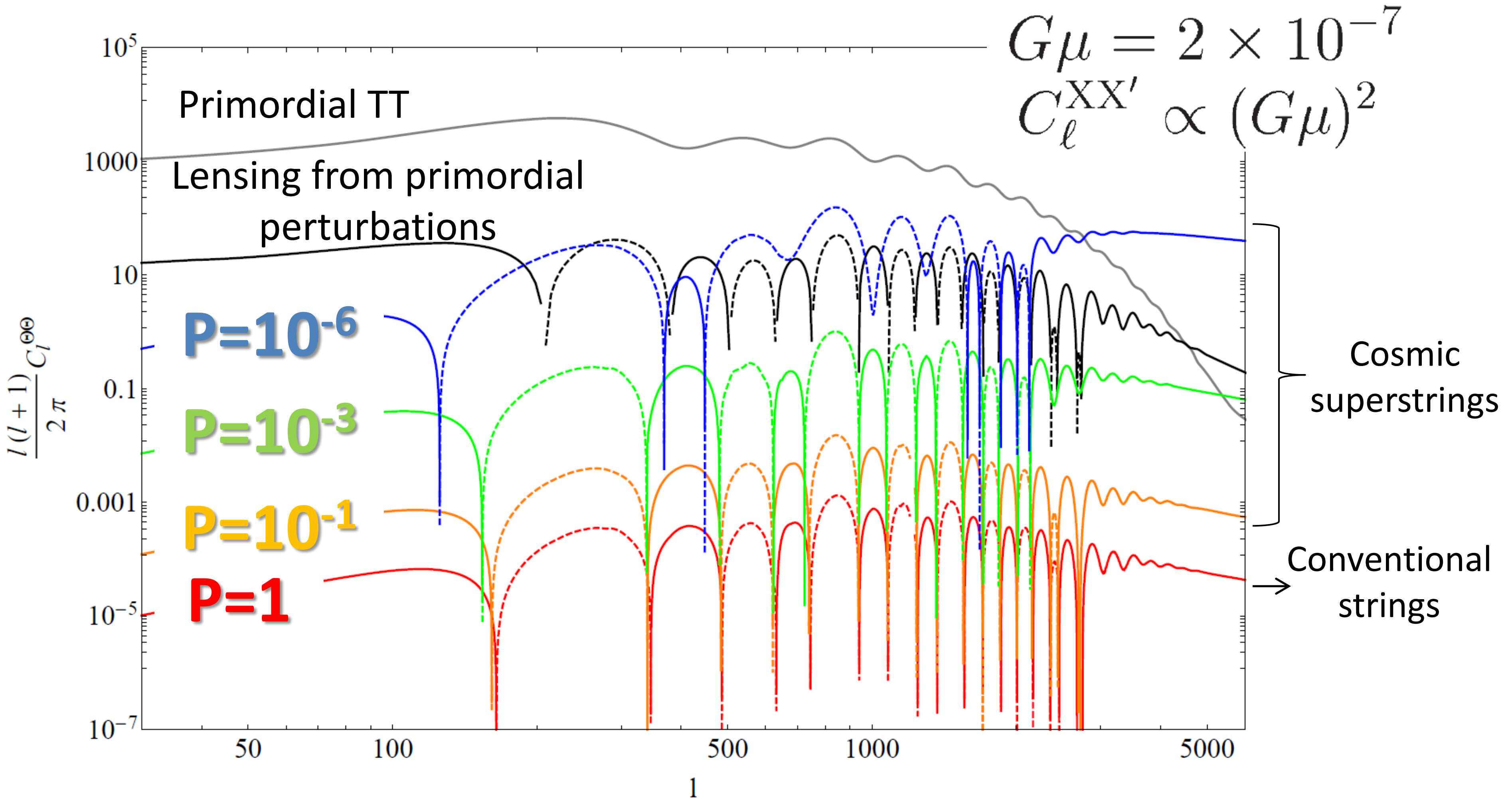
Power spectrum for convergence κ

$$G\mu = 2\times 10^{-7}$$
$$C_\ell^{XX'} \propto (G\mu)^2$$



- ✓ The spectrum for large l behaves as inverse power law.
- ✓ As P degreases, the overall amplitude increases and the spectrum becomes broader.
- ✓ Lensing events from low multipole modes of the convergence are essential for lensed spectra even at high l in CMB.

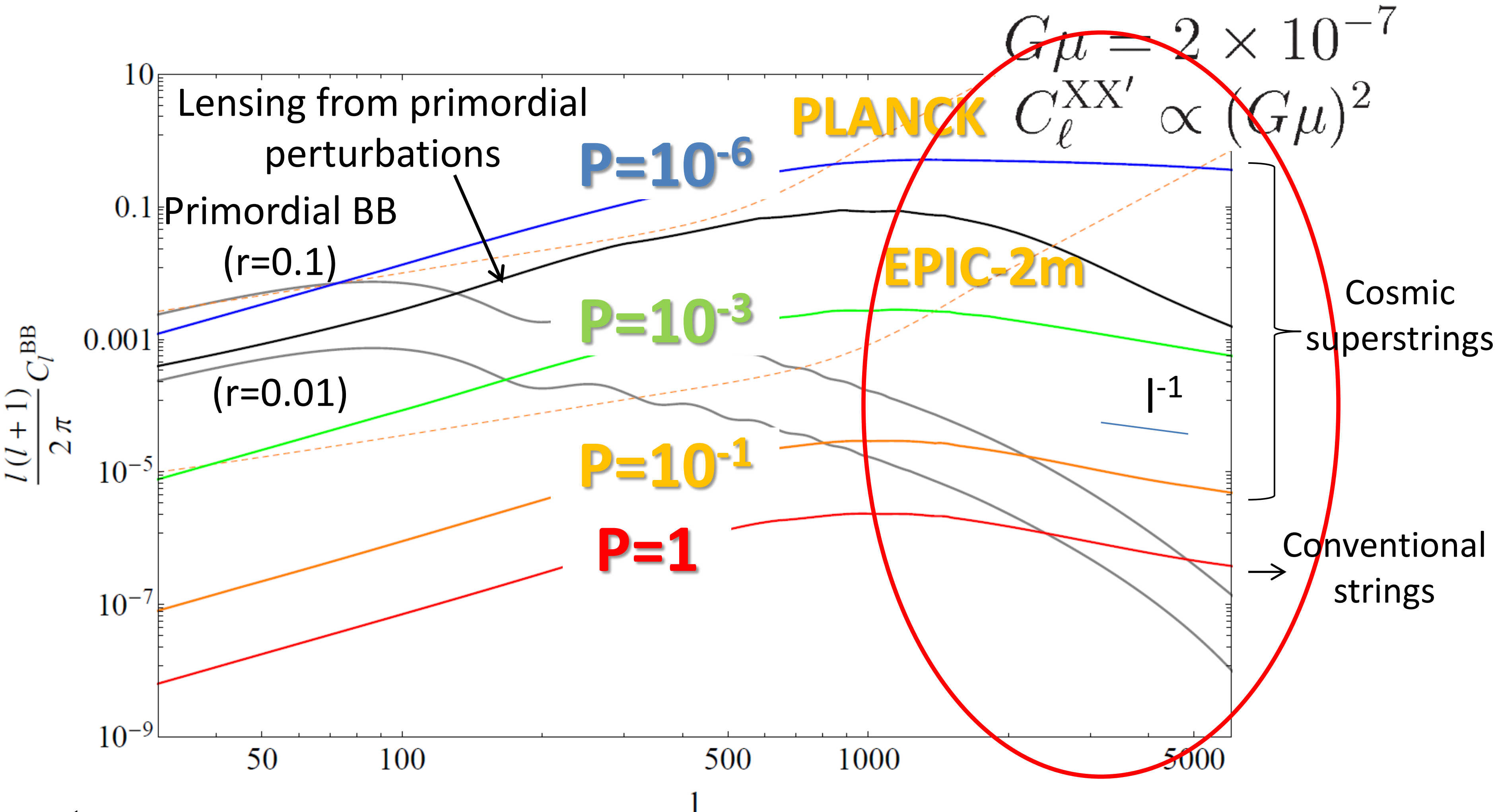
Lensed TT spectrum from gradient deflection



✓ The difference between the lensed and unlensed spectrum have the feature of the oscillation around zero, which is similar to that due to the primordial scalar perturbations.

[**DY**, Takahashi, Sendouda, Yoo, Sasaki, in prep.]

Lensed BB spectrum from gradient deflection



- ✓ In large scale, the spectrum are similar to that due to the primordial perturbations.
- ✓ In small scale limit, the spectrum decays slowly proportion to the inverse power law, compared with the those due to primordial scalar perturbations.

[**DY**, Takahashi, Sendouda, Yoo, Sasaki, in prep.]

Curly part of deflection

[**DY**, Namikawa, Taruya, in prep.]

- We focus on the contribution from **the vector perturbations due to strings**.

→ **CURLY DEFLECTION !!**

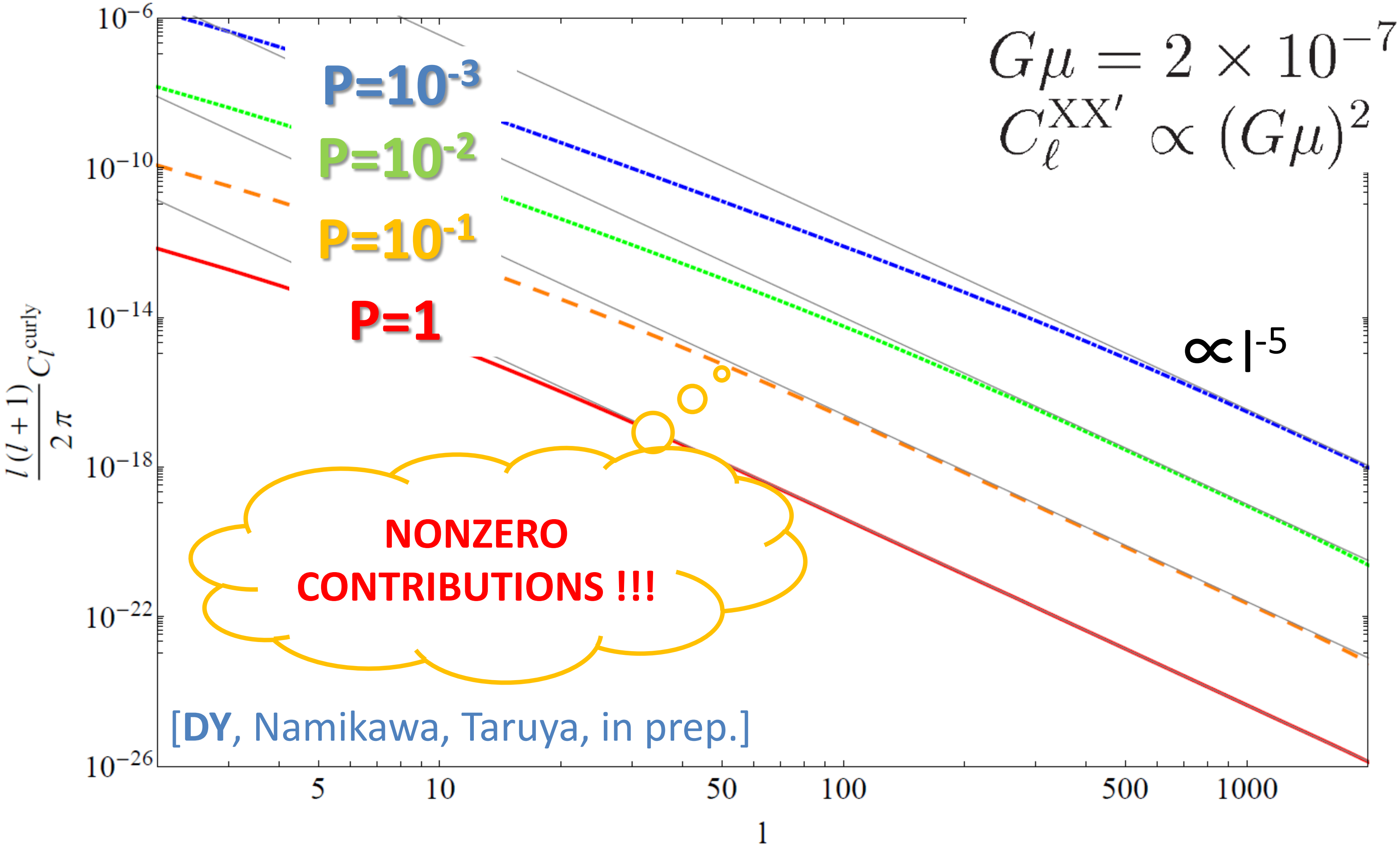
$$\boldsymbol{\Delta} = \nabla_{\hat{\boldsymbol{n}}}\,\phi^{\oplus}(\hat{\boldsymbol{n}}) + (*\nabla_{\hat{\boldsymbol{n}}})\,\phi^{\otimes}(\hat{\boldsymbol{n}})$$

$$C_\ell^{\otimes} = \frac{\ell(\ell+1)}{2\pi}\int k^2 \mathrm{d}k \int_0^{\chi_S}\frac{\mathrm{d}\chi_1}{\chi_1}\int_0^{\chi_S}\frac{\mathrm{d}\chi_2}{\chi_2} j_\ell(k\chi_1) j_\ell(k\chi_2) P_{\mathrm{vector}}(k,\chi_1,\chi_2)$$

With the same method as the convergence, we can derive the power spectrum for the vector perturbations due to a string network!

N.B. In the case of pure scalar perturbations, the curly deflection is exactly zero at linear order !

Power spectrum for curly deflection



- As we expected, cosmic (super-)strings can produce the curly deflection !
- Curly mode gives a new constraint of properties of a cosmic (super-)string network !

Summary

- ✓ The deflection angle can be decomposed into 2 part : gradient + curly.
- ✓ Topological defects can produce not only scalar but also vector/tensor perturbations, which lead to the curly part of the deflection.

$$\Delta = \underbrace{\nabla_{\hat{n}}\, \phi^{\oplus}(\hat{n})}_{\text{Scalar/Vector/Tensor perturbations}} + \underbrace{(*\nabla_{\hat{n}})\ \phi^{\otimes}(\hat{n})}_{\text{Vector/Tensor perturbations}}$$

- ✓ We present calculations of cosmic (super-)string contributions to the deflection angles such as
  - Gradient deflections due to arbitrary perturbations
  - Curly deflections due to vector perturbations

Thank you !