Weak Lensing of CMB by Cosmic Strings and its Detectability

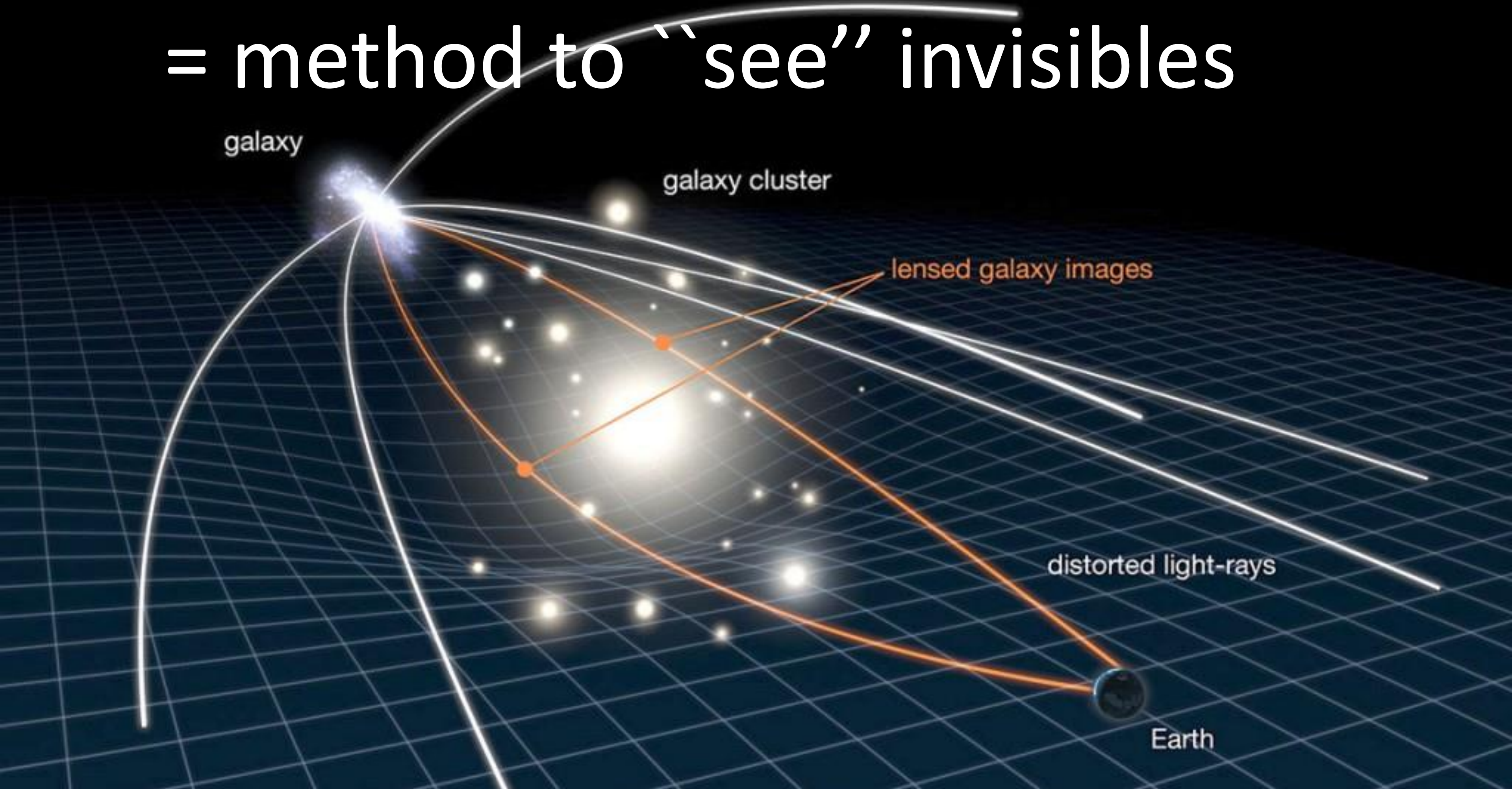
YAMAUCHI, Daisuke

Research Center for the Early Universe (RESCEU), U. Tokyo

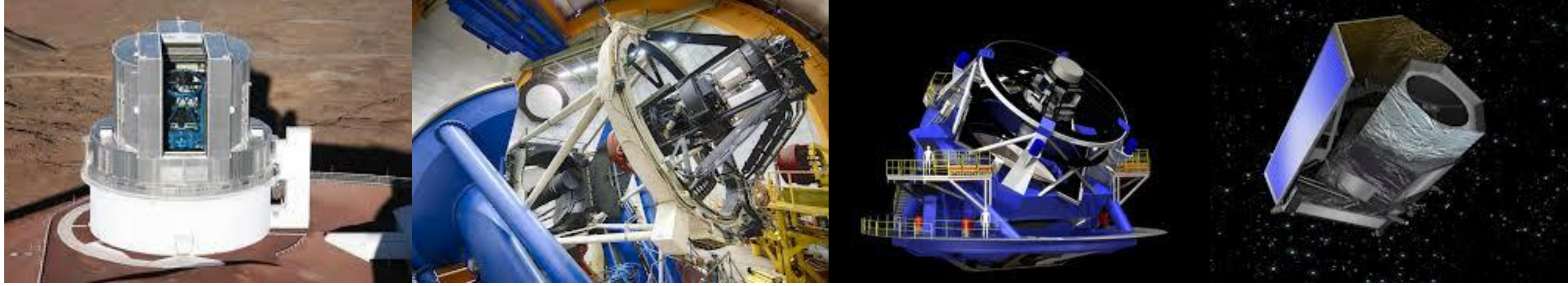
Based on the collaboration with T. Namikawa (Kyoto), A. Taruya (Kyoto), Y. Sendouda (Hirosaki), K. Takahashi (Kumamoto)

Gravitational Lensing
= method to ``see'' invisibles

NASA/ESA



WEAK LENSING observations can provide a direct evidence for the intervening matter distributions along a line of sight by measuring the spatial patterns of the deformation of the photon path.



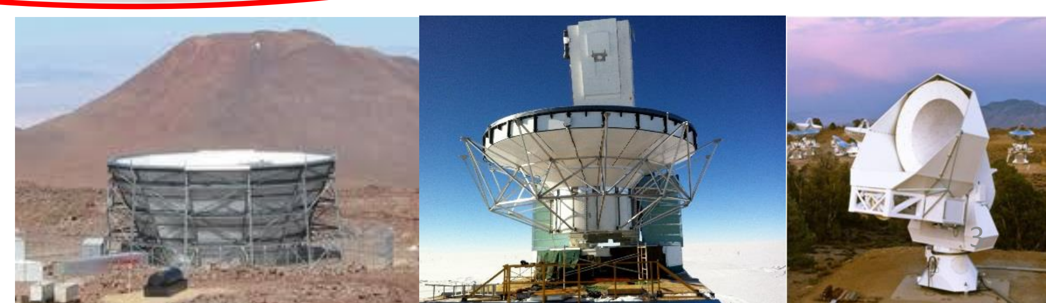
Imaging survey

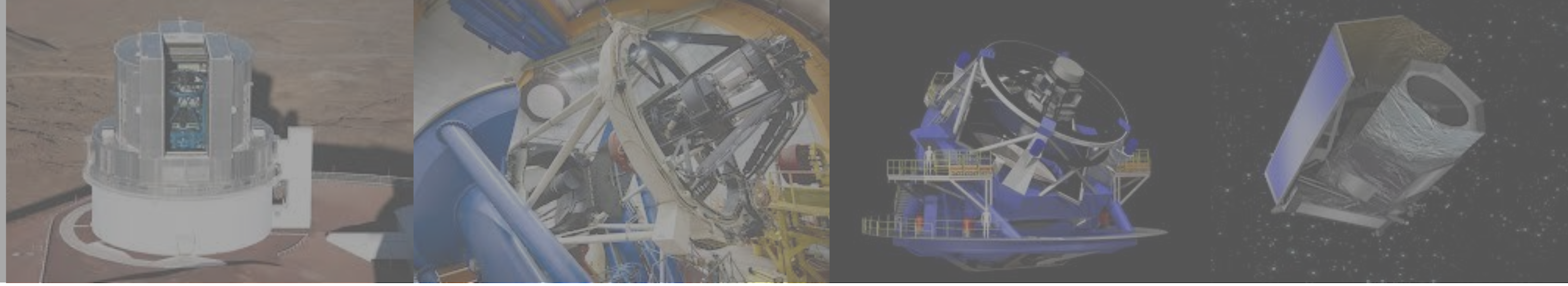
e.g. HSC, DES, LSST, Euclid…

Weak lensing measurement

CMB lensing

e.g. ACT, SPT, Planck, PolarBear,
ACTPol, SPTPol, COrE,…





Imaging survey

e.g. HSC, DES, LSST, Euclid…

Weak lensing measurement

CMB lensing

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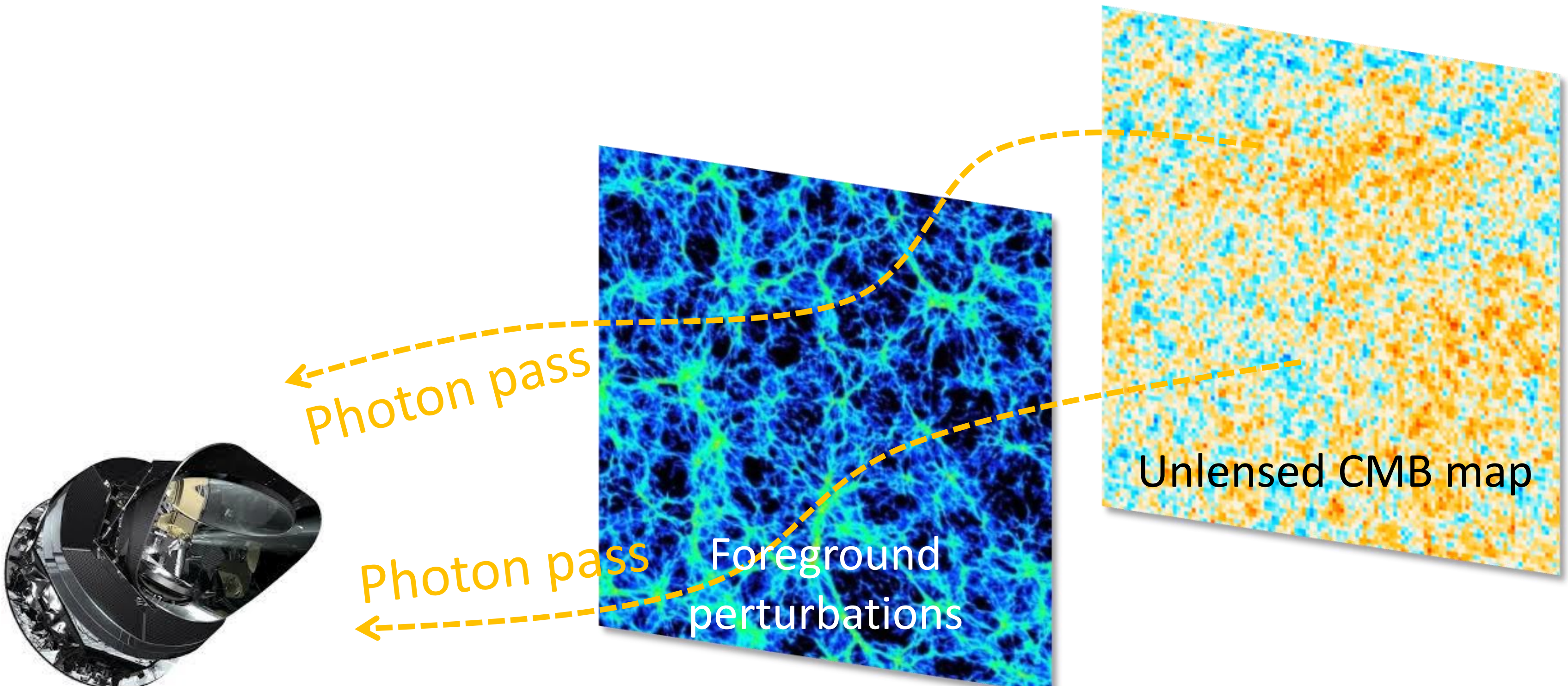
CMB lensing

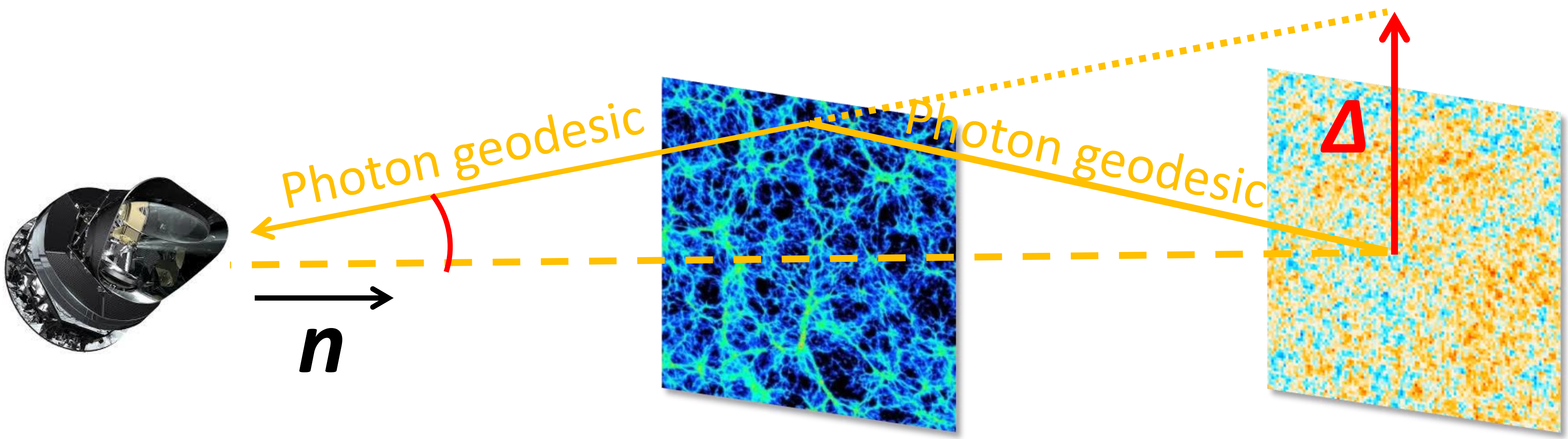
What we observe is a subtly distorted version of the primary CMB anisotropy.



Deflection field

The distortion effect of lensing on the primary CMB is expressed by a remapping with the deflection angle "***Δ***".

$$\tilde{\Theta}(\hat{\boldsymbol{n}}) = \Theta(\hat{\boldsymbol{n}} + \boldsymbol{\Delta})$$



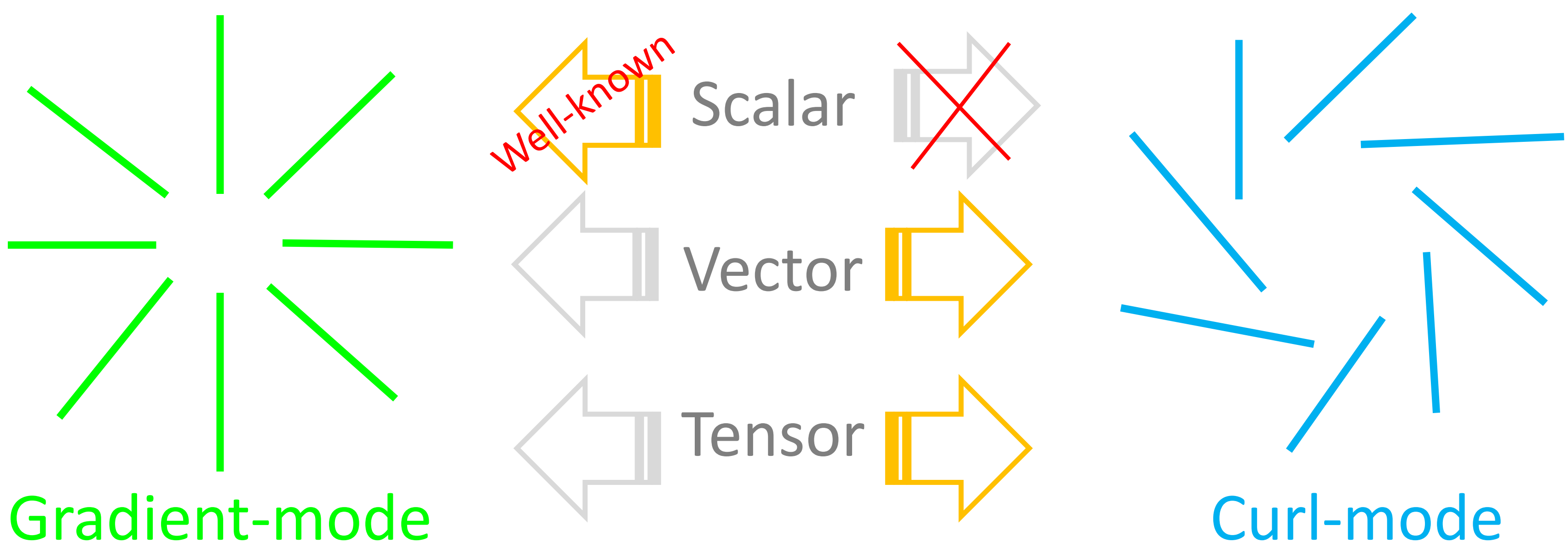
Observed: $\tilde{\Theta}$ Unlensed: Θ

The two dimensional distortion vector $\boldsymbol{\Delta}$ is decomposed into gradient-mode: $\nabla\phi$ and curl-mode: $(*\nabla)\varpi$.

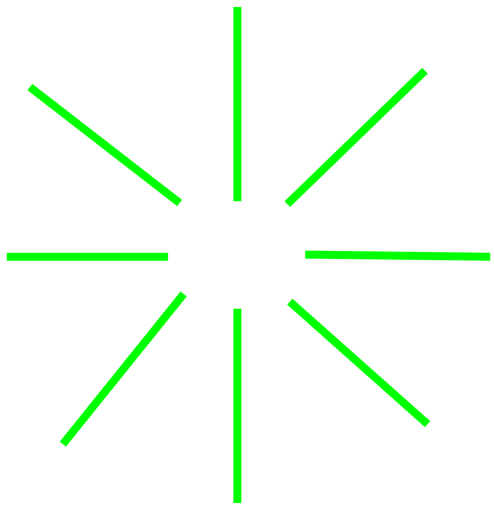
$$\boldsymbol{\Delta} = \nabla\phi + (*\nabla)\varpi$$

(For details, see [**DY**+Namikawa+Taruya 1305.3348])

✓ Scalar metric perturbations at linear order produce only the gradient-mode, and the curl-mode can be induced by vector and/or tensor perturbations:

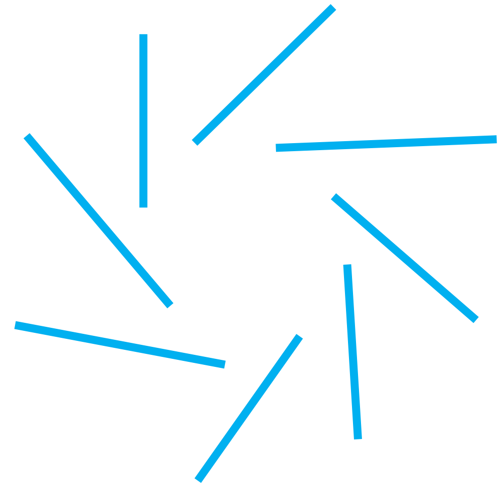


Two possible ways of detecting strings from weak lensing of CMB



Gradient-mode

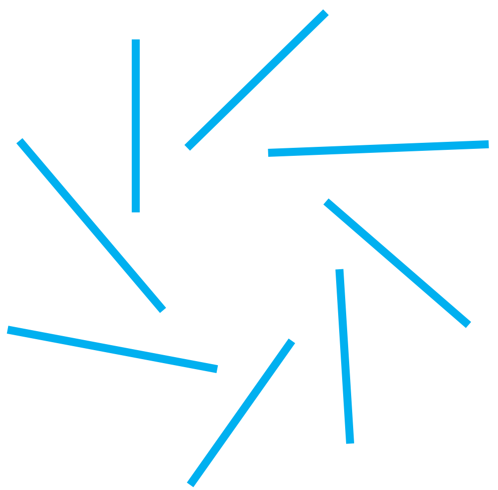
String-induced
ISW-lensing bispectrum



Curl-mode

New probe
for cosmic strings

CURL-MODE
FROM COSMIC STRINGS



Curl-mode

Vector/tensor perturbations from cosmic strings

Cosmic strings continuously generate vector and tensor metric perturbations even at late-time epoch, which induce the non-vanishing curl-mode signal at present time!

In order to compute the power spectrum analytically, we assume several idealizations:

- Velocity dependent one-scale model for a string network
  [Martins+Shellard(1996,2002), Avgoustidis+Shellard(2006),…]
- Analytic model to estimate correlations within string segments
  [Hindmarsh(1994), Vincent+Hindmarsh+Sakellariadou(1997), Albrecht+Battye+Robinson(1999),…]

Vector/tensor perturbations from cosmic strings

Cosmic strings continuously generate vector and tensor metric perturbations even at late-time epoch, which induce the non-vanishing curl-mode signal at present time!

Vector power spectrum

$$C_\ell^{\varpi\varpi,\mathrm{CS(V)}} = 4\pi \int_0^\infty \frac{\mathrm{d}k}{k} \left[\sqrt{\frac{(\ell-1)!}{(\ell+1)!}} \int_0^{\chi_\mathrm{S}} \frac{\mathrm{d}\chi}{\chi} \Delta_1(k,\chi)\, j_\ell(k\chi) \right]^2 ,$$

$$C_\ell^{\varpi\varpi,\mathrm{CS(T)}} = 4\pi \int_0^\infty \frac{\mathrm{d}k}{k} \left[\frac{1}{2} \frac{(\ell-1)!}{(\ell+1)!} \sqrt{\frac{(\ell+2)!}{(\ell-2)!}} \int_0^{\chi_\mathrm{S}} \mathrm{d}\chi \Delta_2(k,\chi) \frac{j_\ell(k\chi)}{k\chi^2} \right]^2$$

Tensor power spectrum

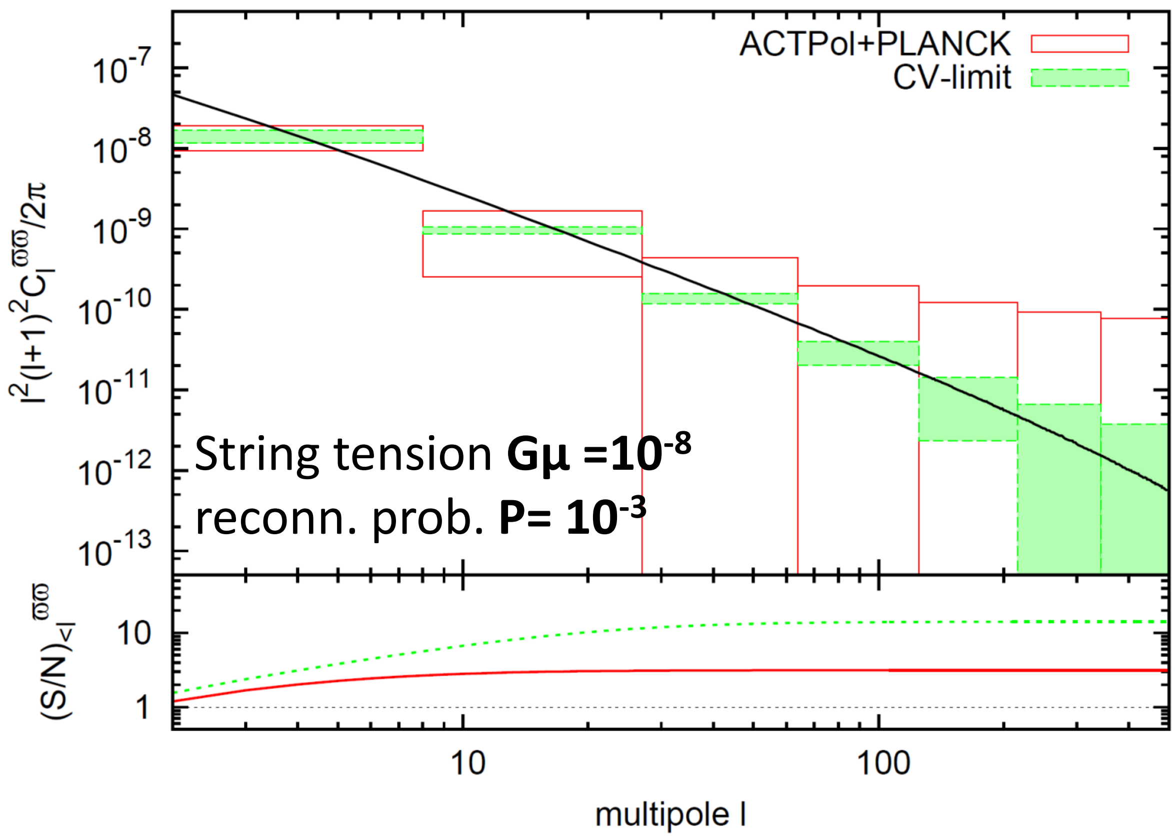
[**DY**+Namikawa+Taruya 1305.3348]

New !

(Full-sky curl-mode estimator [Namikawa+**DY**+Taruya 1110.1718])

Curl-deflection from cosmic strings

[**DY**+Namikawa+Taruya, 1205.2139, 1305.3348]



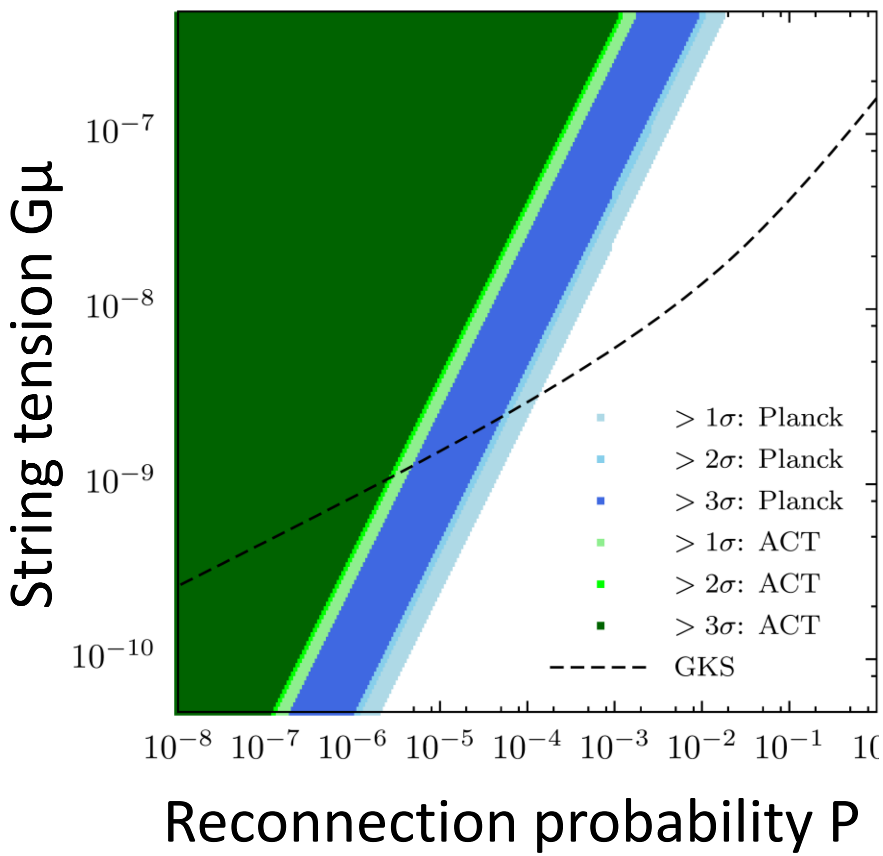
The curl-mode measurement would provide not only a direct probe of cosmic strings, but also a diagnosis helpful to check the systematics in the derived constraints from the CMB TT.

New !

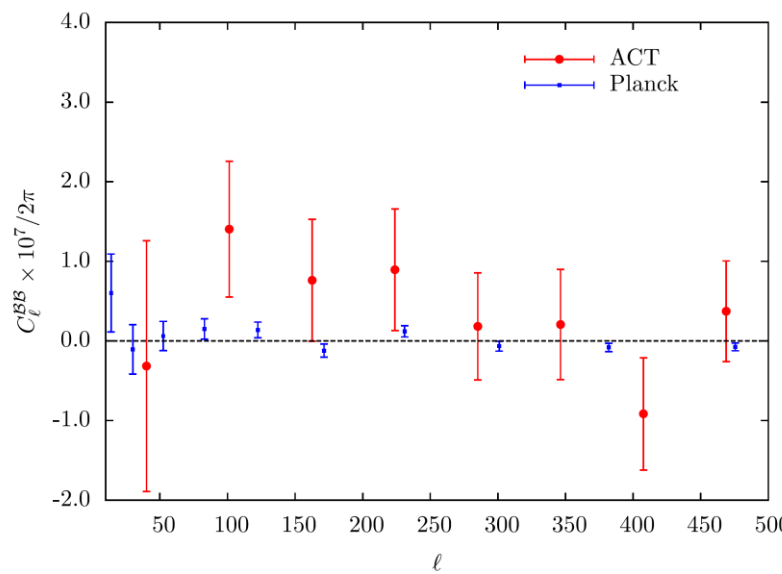
Constraint on string parameters from curl mode for Planck curl-mode

[Namikawa+**DY**+Taruya, 1308.6068]

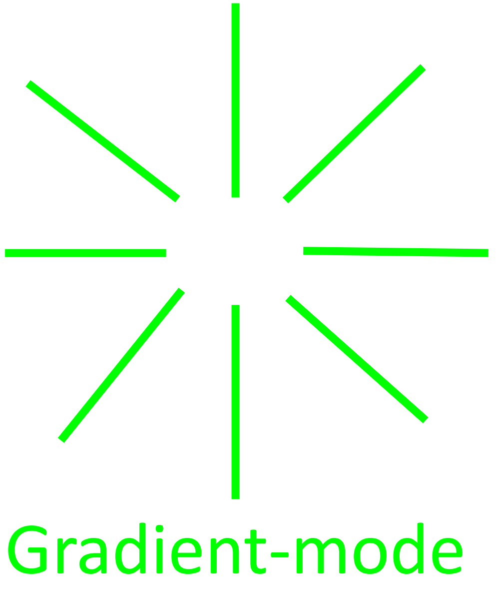
$$G\mu P^{-1} \leq 3.4 \times 10^{-5}$$ (95%CL, Planck curl-mode)



- For P=1, $G\mu < 6.6 \times 10^{-5}$
- Curl mode is more sensitive to small values of P compared to the power spectrum.



GRADIENT-MODE FROM COSMIC STRINGS



ISW-lensing bispectrum

- A lensed fluctuation is a nonlinear function of fields

$$\tilde{\Theta}(\boldsymbol{\theta}) = \Theta(\boldsymbol{\theta} + \nabla\phi)$$
$$= \Theta(\boldsymbol{\theta}) + \nabla\phi(\boldsymbol{\theta}) \cdot \nabla\Theta(\boldsymbol{\theta}) + \cdots$$

Lensing events lead to deviations from Gaussianity

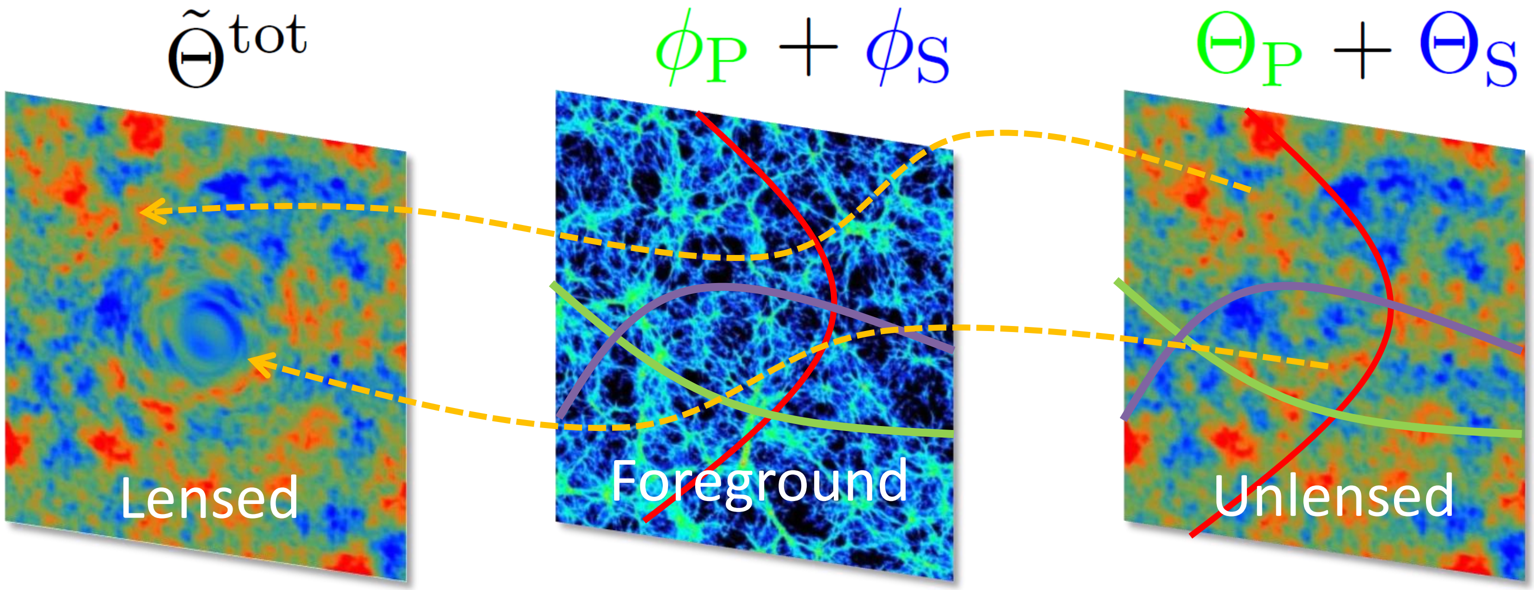
$$B^{\rm lens}(\ell_1, \ell_2, \ell_3) = -\boldsymbol{\ell}_1 \cdot \boldsymbol{\ell}_2 \, C_{\ell_1}^{\Theta\phi} C_{\ell_2}^{\Theta\Theta} + \cdots$$

✓ The cross-correlation due to the late-time evolution induces the *"ISW-lensing" bispectrum*.

CMB lensing from primordial perturbations (P) and cosmic strings (S)

In the case of the various independent gravitational sources, the observed CMB anisotropy can be regarded as a superposition of those due to each source.

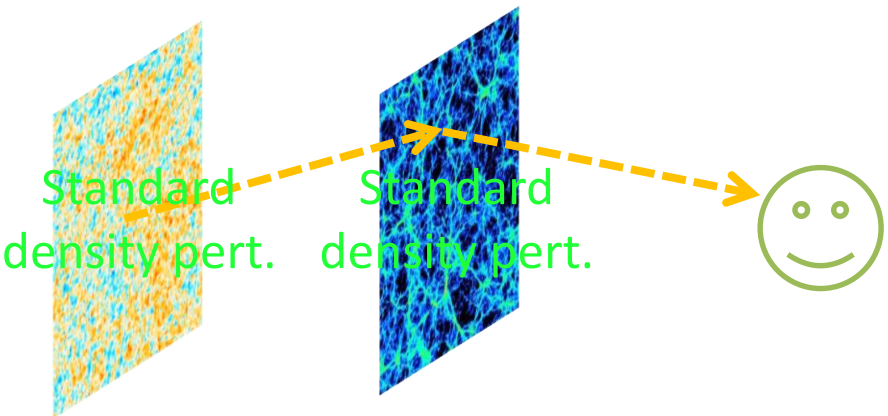
$$\tilde{\Theta}^{\rm tot}(\boldsymbol{\theta}) = \sum_{\alpha={\rm P,S}} \Theta_\alpha\Big(\boldsymbol{\theta} + \sum_{\beta={\rm P,S}} \nabla\phi_\beta\Big)$$



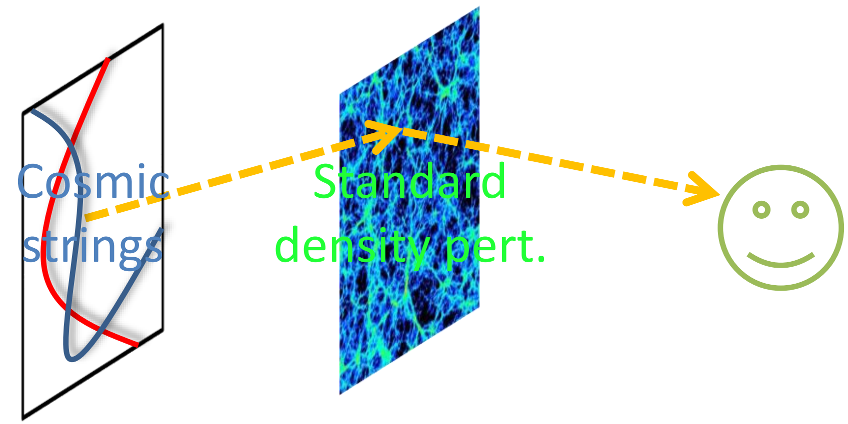
Various types of CMB lensing

"P" : Primordial density perturbations   "S" : Cosmic strings

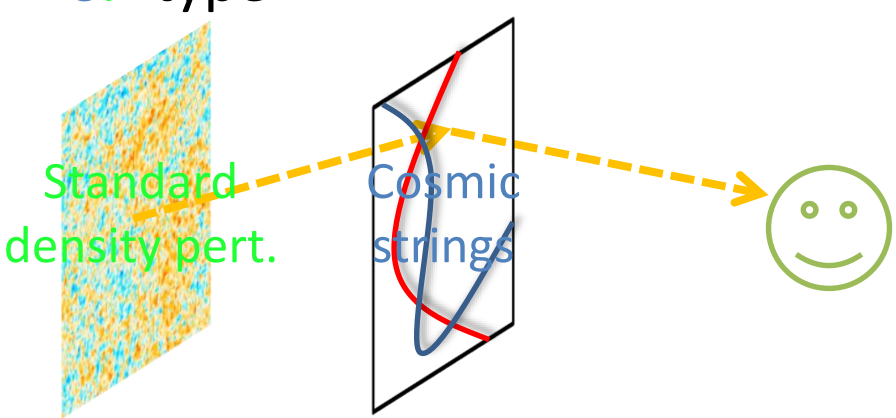
✓ PP-type (standard)



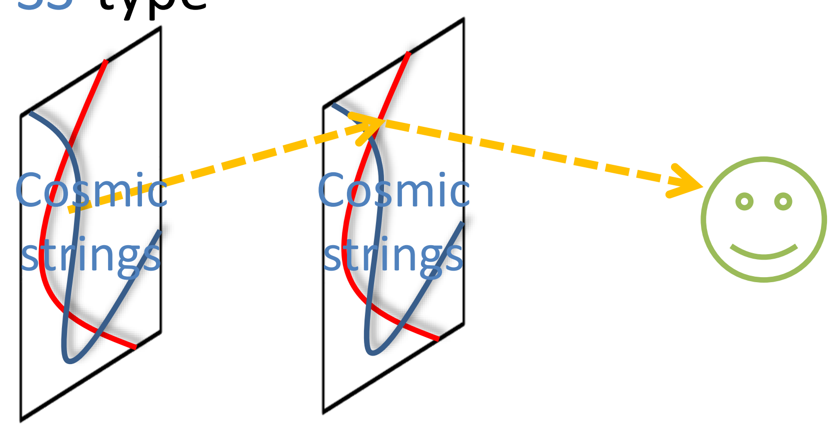
✓ PS-type



✓ SP-type



✓ SS-type



New !

[DY+Sendouda+Takahashi, 1309.5528]

αβ-type ISW-lensing bispectrum

$$B^{\alpha\beta}(\ell_1,\ell_2,\ell_3) = -\boldsymbol{\ell}_1\cdot\boldsymbol{\ell}_2\, C_{\ell_1}^{\Theta_\alpha\phi_\alpha} C_{\ell_2}^{\Theta_\beta\Theta_\beta} + \cdots$$

$B^{\rm tot} = B^{\rm PPP}$: Primordial bispectrum

$+\, B^{\rm PP}$: Primordial ISW-lensing [2σ detection, Planck19]

Cosmic strings

$+\, B^{\rm SSS}$: purely due to the GKS effect [Hindmarsh+(2009), Regan+Shellard(2010)]

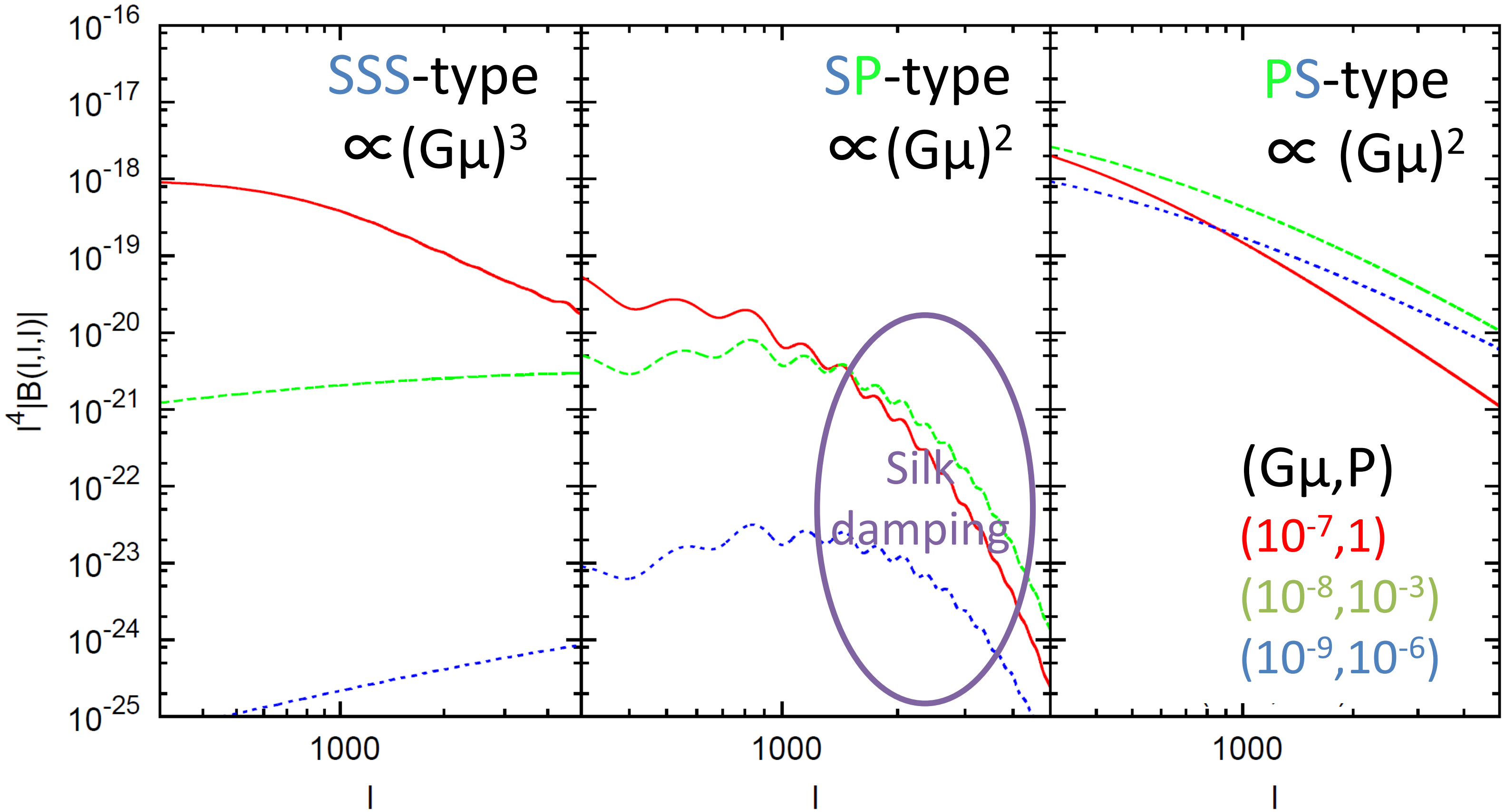
$+\, B^{\rm SP} + B^{\rm PS} + B^{\rm SS}$

: String-induced GKS-lensing

New !

[**DY**+Sendouda+Takahashi, 1309.5528]

Equilateral-shaped bispectra induced by cosmic strings



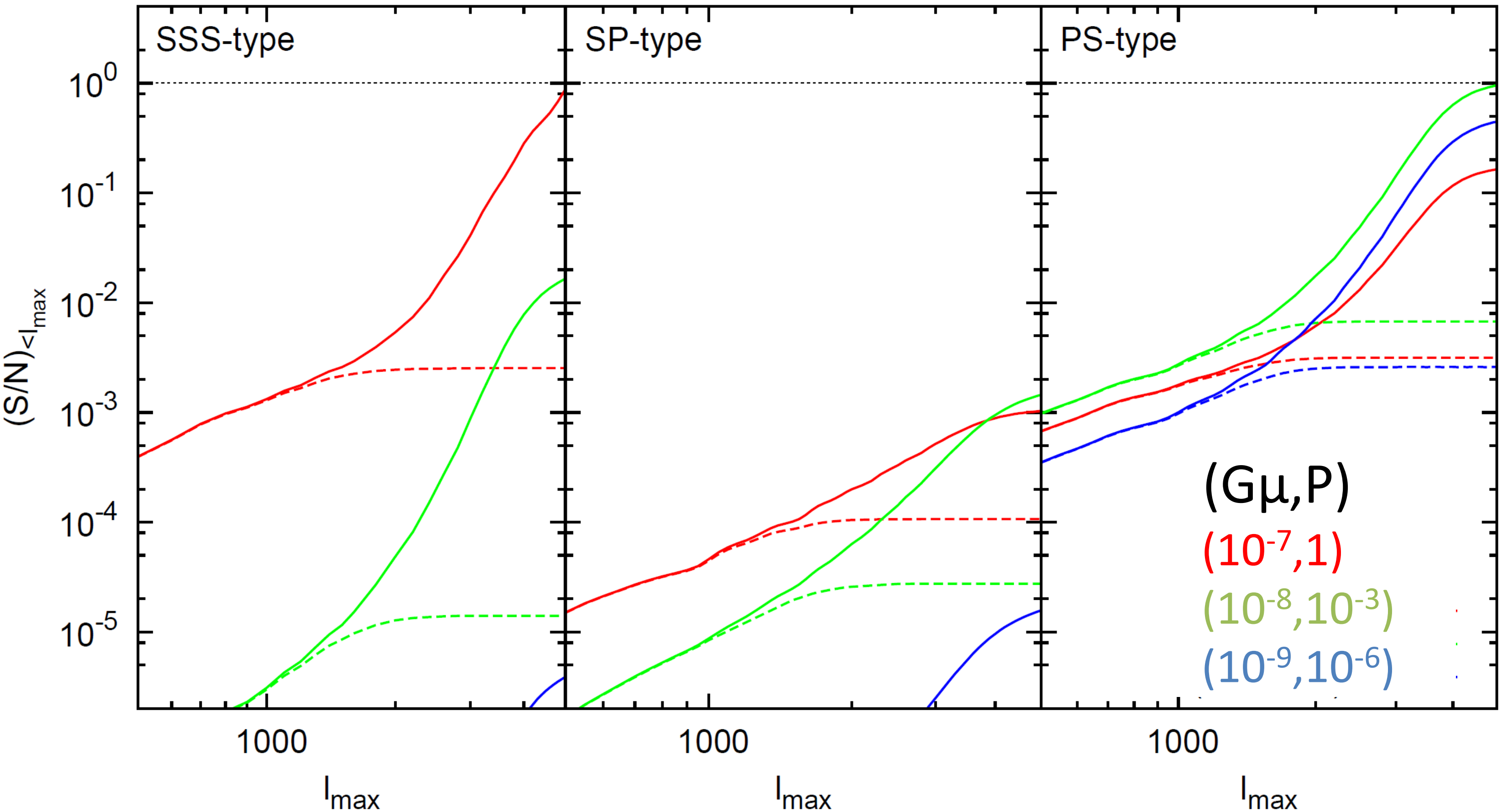
- The standard ISW-L (PP-type) and SP-type bispectra are particularly suppressed due to the Silk damping, so only the SSS- and PS-type bispectra are relevant at small scale.

New !

[DY+Sendouda+Takahashi, 1309.5528]

Cumulative signal-to-noise ratio

Solid : Planck+ACTPol–like noise, dashed : Planck-like noise



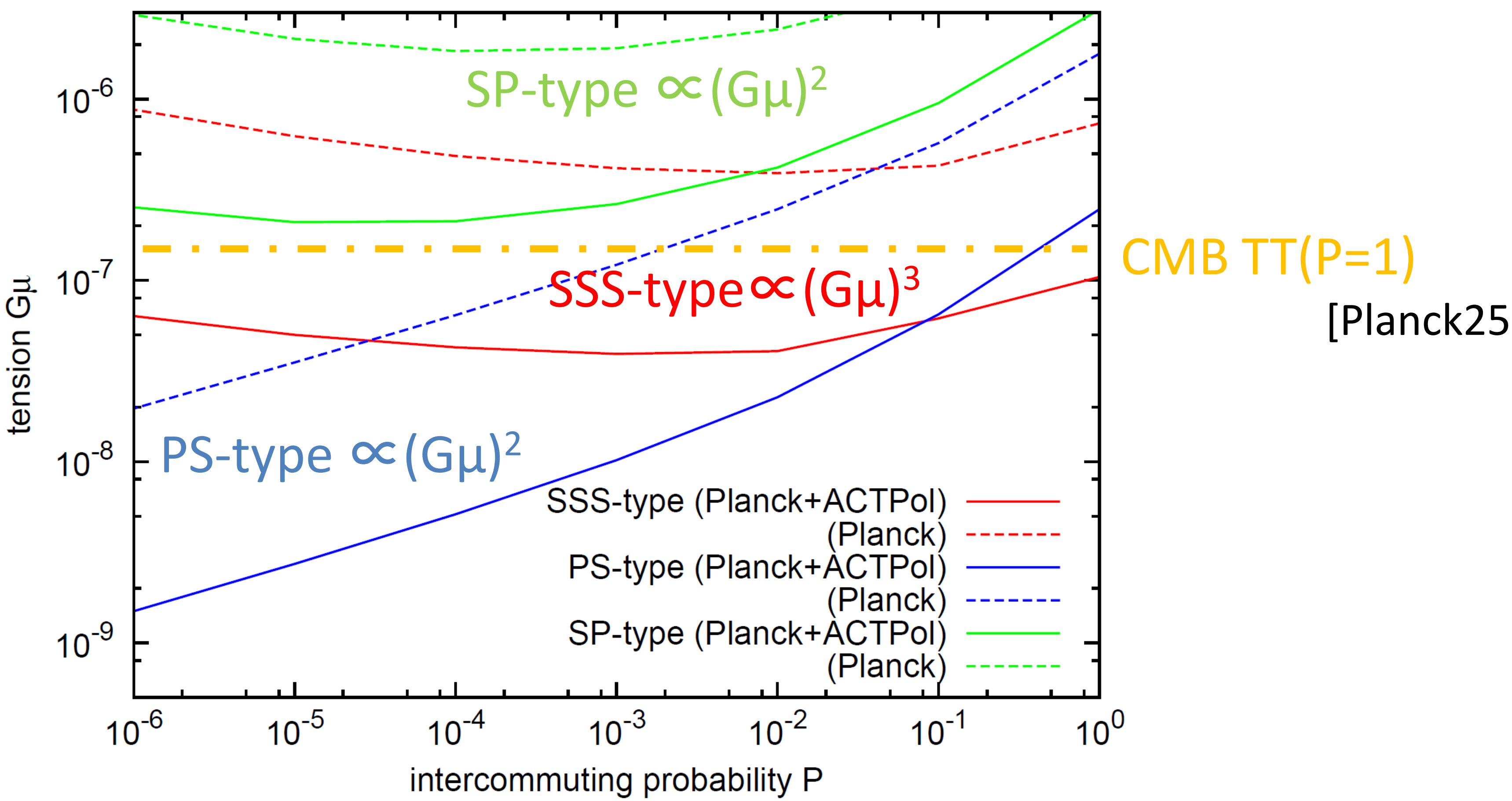
To estimate the feasibility to detect their signals, we quantify (S/N) in the current and future CMB observations. The SP-type is not relevant, as expected.

New !

[**DY**+Sendouda+Takahashi, 1309.5528]

Constraint in Gμ-P plane

Solid : Planck+ACTPol–like noise, dashed : Planck-like noise



For small P, the PS-type ISW-L bispectrum $\propto C_l^{\Theta\rho\phi\rho} C_l^{\Theta s\Theta s} \propto (G\mu)^2$ gives the tighter constraint on Gμ than the SSS-type bispectrum $\propto (G\mu)^3$.

Summary

- Vector and tensor perturbations from cosmic strings induce the non-vanishing *curl-mode* signal of the CMB lensing, which is potentially detectable for future observations.
- Cosmic strings are expected to cause weak lensing as well as the ISW effect, which are naturally produces the yet another kind of the CMB temp. bispectra, *string-induced ISW-lensing bispectra (SP-, PS-, SS-type).*

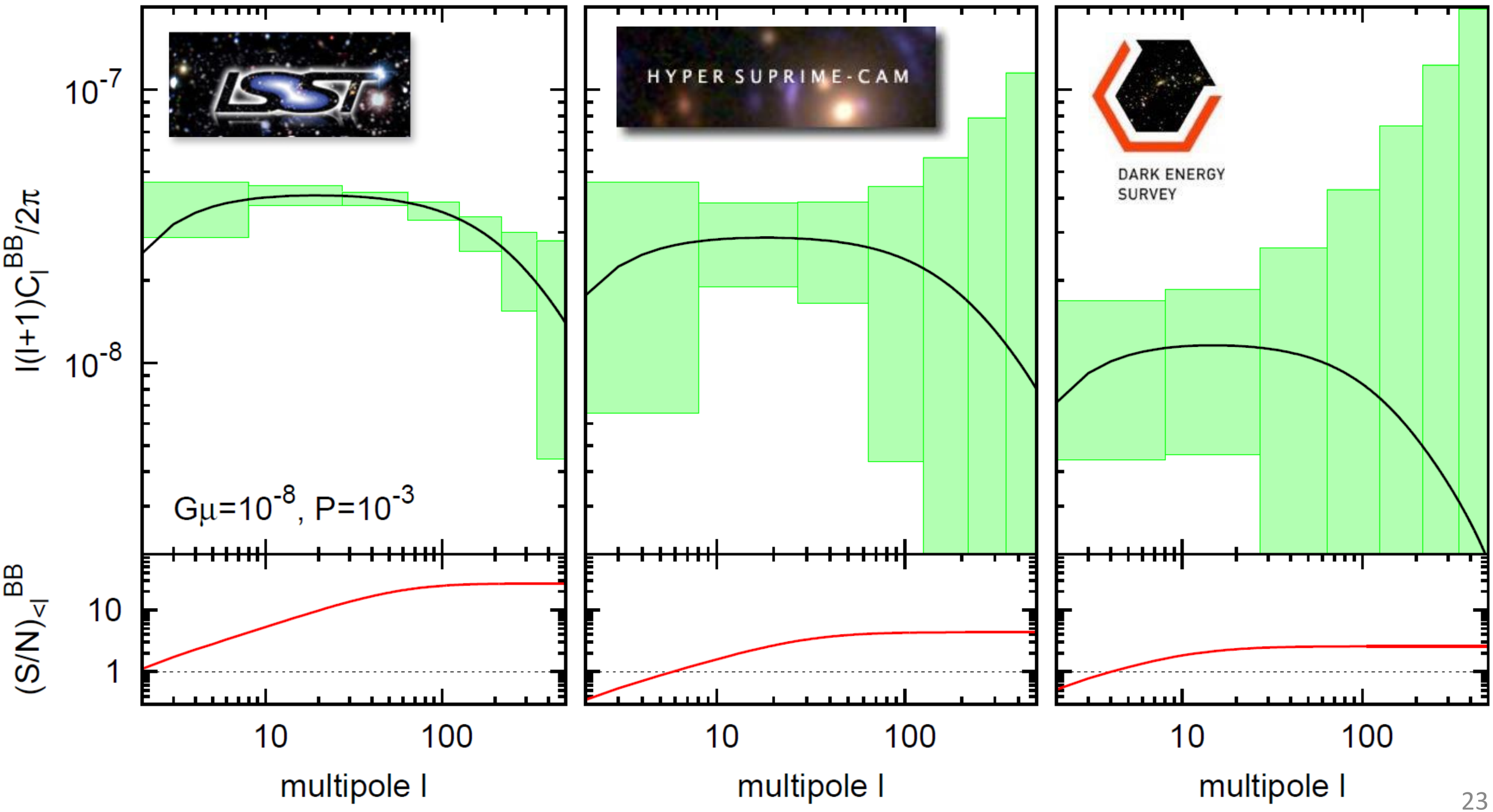
Thank you !

B-mode shear from cosmic strings

New !

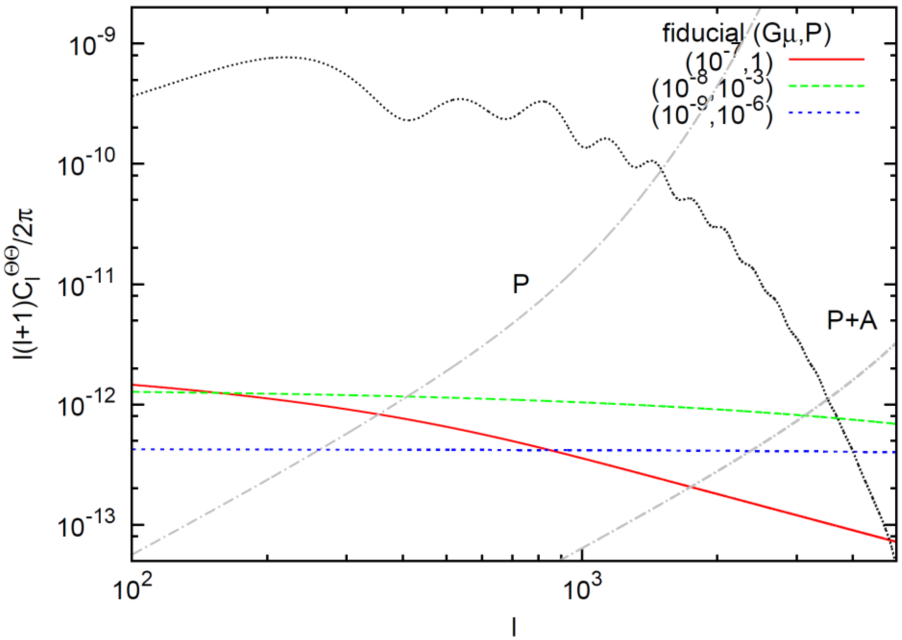
[**DY**+Namikawa+Taruya, 1205.2139, 1305.3348]

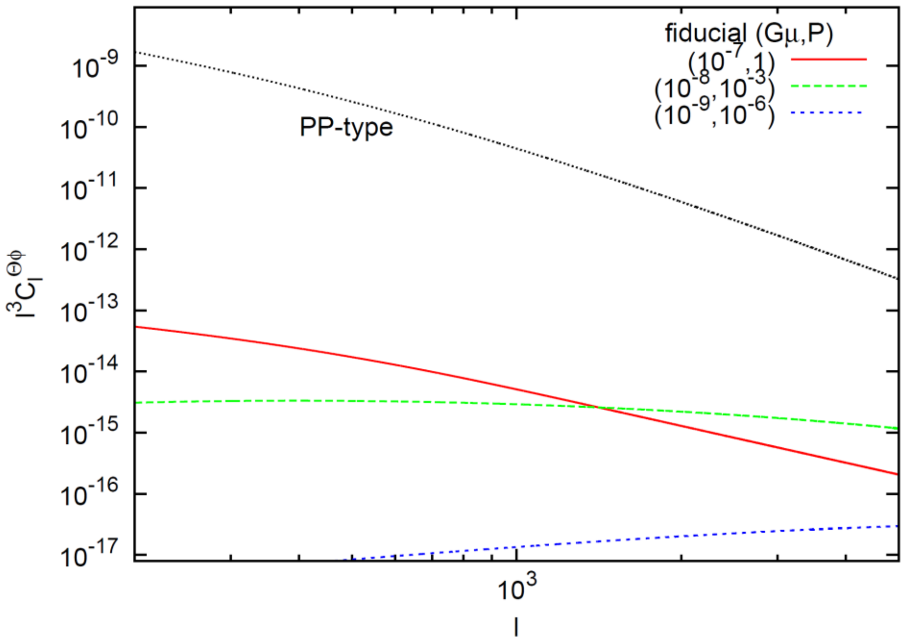
Fiducial string parameters : String tension **$G\mu = 10^{-8}$,** reconnection prob. **$P = 10^{-3}$**



APPENDIX

$C_l^{\Theta s\Theta s}$ and $C_l^{\Theta s\phi s}$





Gμ-P dependence

- GKS-induced power spectrum

$C_l^{GKS} \sim$ (GKS amplitude)^2 $\times$ (string number)

$\sim (G\mu)^2$ $\propto$ 1/(correlation length)^3

$\sim P^{-3/2}$

- Curl-mode power spectrum

$\sim (G\mu)^2$ $\sim P^{-3/2}$

$C_l^{curl} \sim$ (amplitude)^2 $\times$ (string number)

$\times$ (energy density per single segment)

$\propto$ 1/(correlation length)^2

$\sim P^{-1}$