Distinguishing the large-scale anisotropic imprint from the super-sample anisotropy

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based on Phys. Rev. D 95, 083522(2017)
and Phys. Rev. D 97, 063527(2018) and in prep.

PTchat, April 9@YITP, Kyoto

Introduction : a variety of anisotropies

- **3D isotropy can be violated through**
  - Redshift-space distortion : peculiar velocity of galaxies
  - Alcock-Paczynski effect : (mis)translation of distances

$$P(k) \to P(k, \mu)$$

  - Initial imprint : vector field during the inflation

$\hat{p}$: preferred direction

$$P(k) \to P(\mathbf{k}) = P(k)\left[1 + \sum_M g_{2M} f(k) Y_{2M}(\hat{k})\right] = P(k)\left[1 + g_* \bar{f}(k)(\hat{k}\cdot\hat{p})^2\right]$$

  - *Super-sample effect : non-linear evolution by gravity*

$$P(k) \to P(\mathbf{k}) = P(k)\left[1 + \frac{\partial \ln P(k)}{\partial \delta_\mathrm{b}}\delta_\mathrm{b} + \frac{\partial \ln P(\mathbf{k})}{\partial \tau_{ij}}\tau_{ij}\right]$$

$\delta_\mathrm{b},\ \tau_{ij}$: super-sample mode

- **Can we distinguish these anisotropic signals from the super-sample effect?**

Super-sample modes

- **Super-sample modes:**

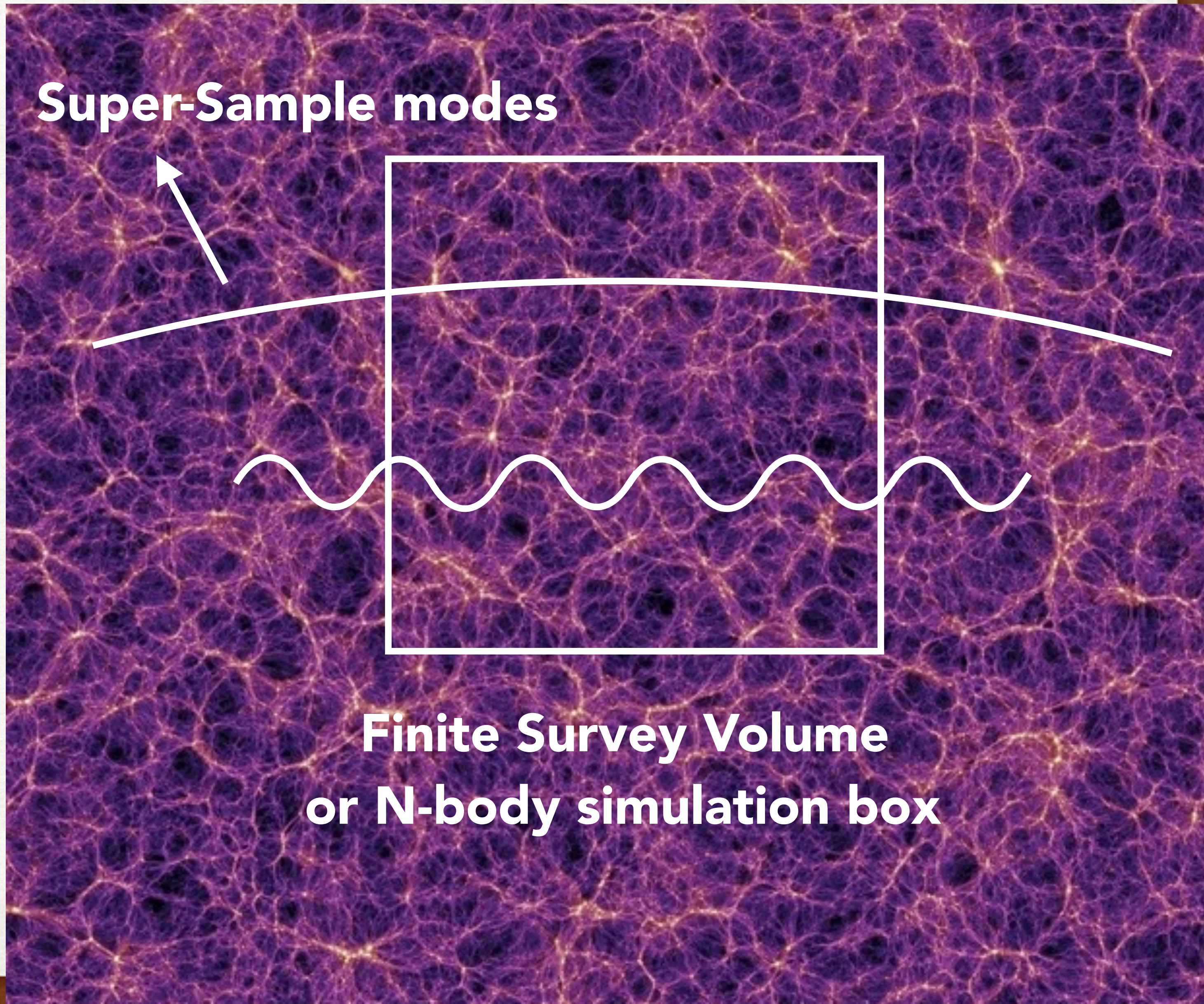
  Large-scale perturbations beyond a finite survey volume

- **Observations: finite volume**
  - not directly observable

- **Theory: N-body simulations**
  - periodic boundary

- **The super-sample modes affect observables via nonlinear mode-coupling (Super-sample effects)**

  Hamilton+'06, Baldauf+'11, de Putter+'12, Sherwin&Zaldarriaga'12, Takada&Hu'13,Li+'14ab



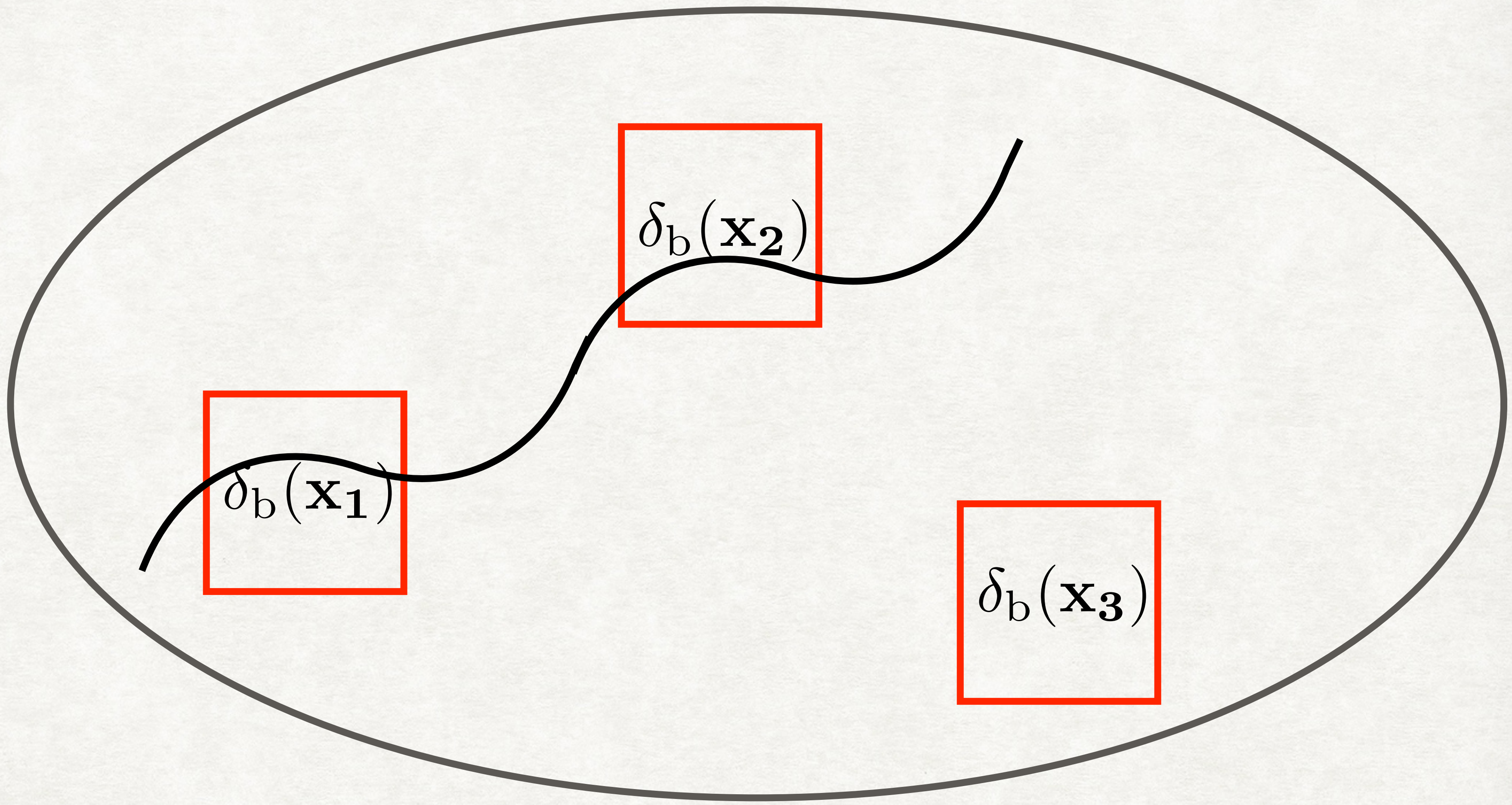
Effect of the Super-sample modes in observations

- **physical effects <- second derivatives of the potential**
  - **density field**

    $\delta_{\rm b}$

  - **tidal field**

    τ_{ij}



- **observed power spectrum has a dependence of a position due to the presence of the super-sample modes** $\delta_{\rm b},\ \tau_{ij}$

$$P\left(\mathbf{k};\delta_{\rm b}(\mathbf{x}),\tau_{ij}(\mathbf{x})\right)=P(k)\left[1+\underbrace{\frac{\partial\ln P(k)}{\partial\delta_{\rm b}}}_{\text{response}}\delta_{\rm b}(\mathbf{x})+\underbrace{\frac{\partial\ln P(k)}{\partial\tau_{ij}}}_{\text{response}}\tau_{ij}(\mathbf{x})\right]$$

Power Spectrum Response in redshift space

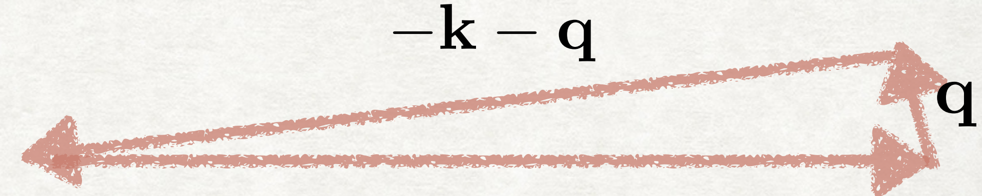
KA&Takada'18, Li+'18

- **Consistency relation: The squeezed bispectrum is related to the power spectrum responses to the long-mode.**

$$\lim_{q\to 0} B_{ssm}(\mathbf{k}, -\mathbf{k}-\mathbf{q}, \mathbf{q}) = P_{\rm lin}(q)\left[\frac{\partial P_s(\mathbf{k})}{\partial \delta_{\rm b}} + \left(\hat{q}_i\hat{q}_j - \frac{\delta^K_{ij}}{3}\right)\frac{\partial P_s(\mathbf{k})}{\partial \tau_{ij}}\right]$$

with $\langle \delta_s(\mathbf{k_1})\delta_s(\mathbf{k_2})\delta_{mL}(\mathbf{q})\rangle \equiv B_{ssm}(\mathbf{k_1}, \mathbf{k_2}, \mathbf{q})(2\pi)^3\delta^3_D(\mathbf{k_1}+\mathbf{k_2}+\mathbf{q})$

- **Standard Perturbation theory:**



$$\begin{aligned}\frac{\partial P_g(\mathbf{k},\hat{n})}{\partial \tau_{ij}} = &\left[\frac{8}{7}b_1 + 2b_{s^2} - b_1\frac{d\ln P_{\rm lin}(k)}{d\ln k}\right]\hat{k}_i\hat{k}_j b_1 P_{\rm lin}(k)\\ &+\left[b_1^2\hat{n}_i\hat{n}_j + \frac{24}{7}b_1\mu^2\hat{k}_i\hat{k}_j + 2b_{s^2}\mu^2\hat{k}_i\hat{k}_j - b_1\mu\left(2\mu\hat{k}_i\hat{k}_j + b_1\hat{k}_i\hat{n}_j\right)\frac{d\ln P_{\rm lin}(k)}{d\ln k}\right] f P_{\rm lin}(k)\\ &+\left[\frac{16}{7}\mu\hat{k}_i\hat{k}_j + 4b_1\hat{k}_i\hat{n}_j - \left(\mu\hat{k}_i\hat{k}_j + 2b_1\hat{k}_i\hat{n}_j\right)\frac{d\ln P_{\rm lin}(k)}{d\ln k}\right]\mu^3 f^2 P_{\rm lin}(k)\\ &+\left[\left(4\mu\hat{k}_i\hat{n}_j - \hat{n}_i\hat{n}_j\right) - \mu\hat{k}_i\hat{n}_j\frac{d\ln P_{\rm lin}(k)}{d\ln k}\right]\mu^4 f^3 P_{\rm lin}(k),\end{aligned}$$

- **The response to τ_{ij} has angular dependence like** $\tau_{ij}\hat{k}_i\hat{k}_j,\ \tau_{ij}\hat{k}_i\hat{n}_j,\ \tau_{ij}\hat{n}_i\hat{n}_j$
  - **affect the cosmological distortion measurements (RSD&AP)**

Fisher Forecast in 2D power spectrum

KA&Takada'18

- **degeneracy between the super-sample mode** $\tau_{33} = \tau_{ij}\hat{n}_i\hat{n}_j = \tau_{ij}\hat{z}_i\hat{z}_j$ **and cosmological distortion parameters**

$(D_A, H(z), \beta)$

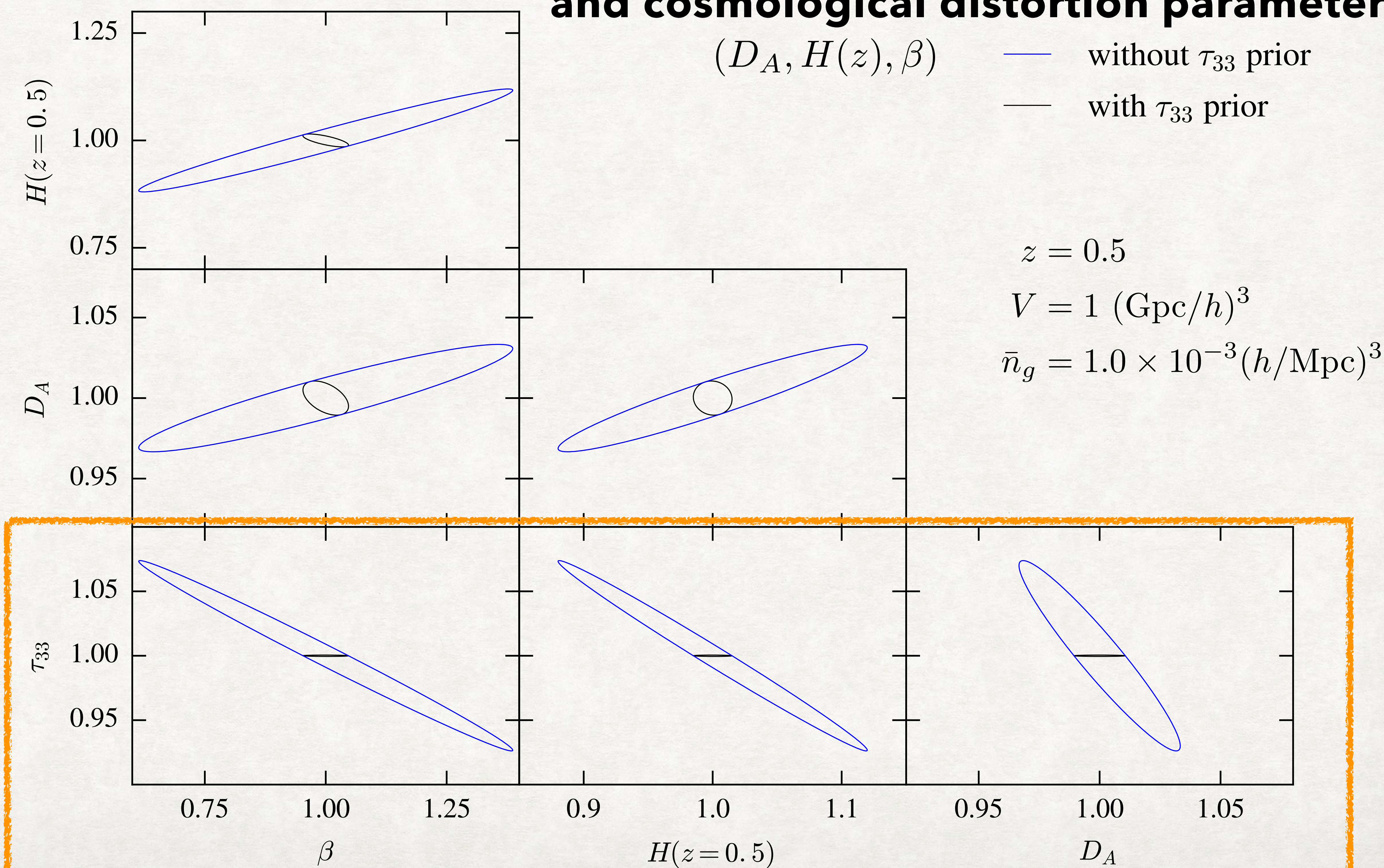
without τ_{33} prior

with τ_{33} prior

$z = 0.5$

$V = 1\ (\mathrm{Gpc}/h)^3$

$\bar{n}_g = 1.0 \times 10^{-3}(h/\mathrm{Mpc})^3$



SSS in the Bipolar Spherical Harmonics expansion

(KA, Sugiyama&Shiraishi in prep.)

- **To distinguish the cosmological anisotropy from the super-sample anisotropy**

  →Bipolar Spherical Harmonics(BipoSH) expansion

$$P^s(\mathbf{k}, \hat{n}; \tau_{ij}) = \sum_{LM\ell\ell'} P^{LM}_{\ell\ell'}(k; \tau_{ij})[X^{LM}_{\ell\ell'}]^*(\hat{k}, \hat{n}),$$

$$X^{LM}_{\ell\ell'}(\hat{k}, \hat{n}) = \{Y_\ell(\hat{k}) \otimes Y_{\ell'}(\hat{n})\}_{LM} = \sum_{mm'} \mathcal{C}^{LM}_{\ell m \ell' m'} Y_{\ell m}(\hat{k}) Y_{\ell' m'}(\hat{n})$$

- **cf. Legendre expansion**

$$P^s(k, \hat{k}\cdot\hat{n}; \tau_{ij}) = \sum_\ell P^s_\ell(k; \tau_{ij}) \mathcal{L}_\ell(\hat{k}\cdot\hat{n})$$

- **The BipoSH separate the SS anisotropic signal from the RSD/AP**

$$P^{L=0\ M=0}_{\ell=\ell'}(k) = P_\ell(k) + R^{\delta_{\rm b}}_\ell(k)\delta_{\rm b}$$

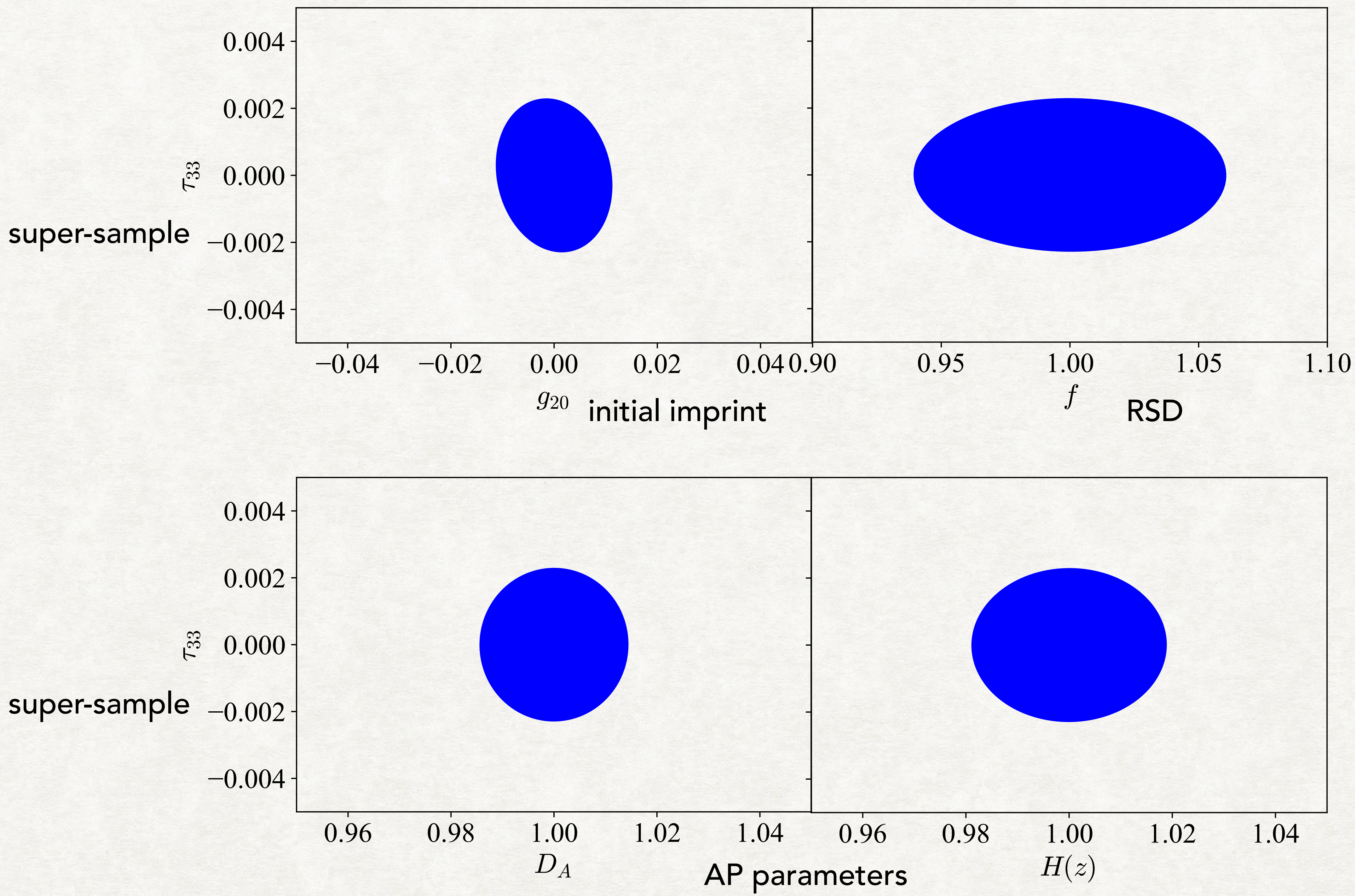
$$P^{L=2\ M=0}_{\ell\ell'}(k) = R^\tau_{\ell\ell'}(k)\tau_{33}$$

$$P^{L=2\ M=\pm1}_{\ell\ell'}(k) = R^\tau_{\ell\ell'}(k)(\mp\tau_{13} + i\tau_{23})$$

$$P^{L=2\ M=\pm2}_{\ell\ell'}(k) = R^\tau_{\ell\ell'}(k)(\tau_{11} - \tau_{22} \mp i\tau_{12})$$

Fisher Forecast in the BiPoSH expansion

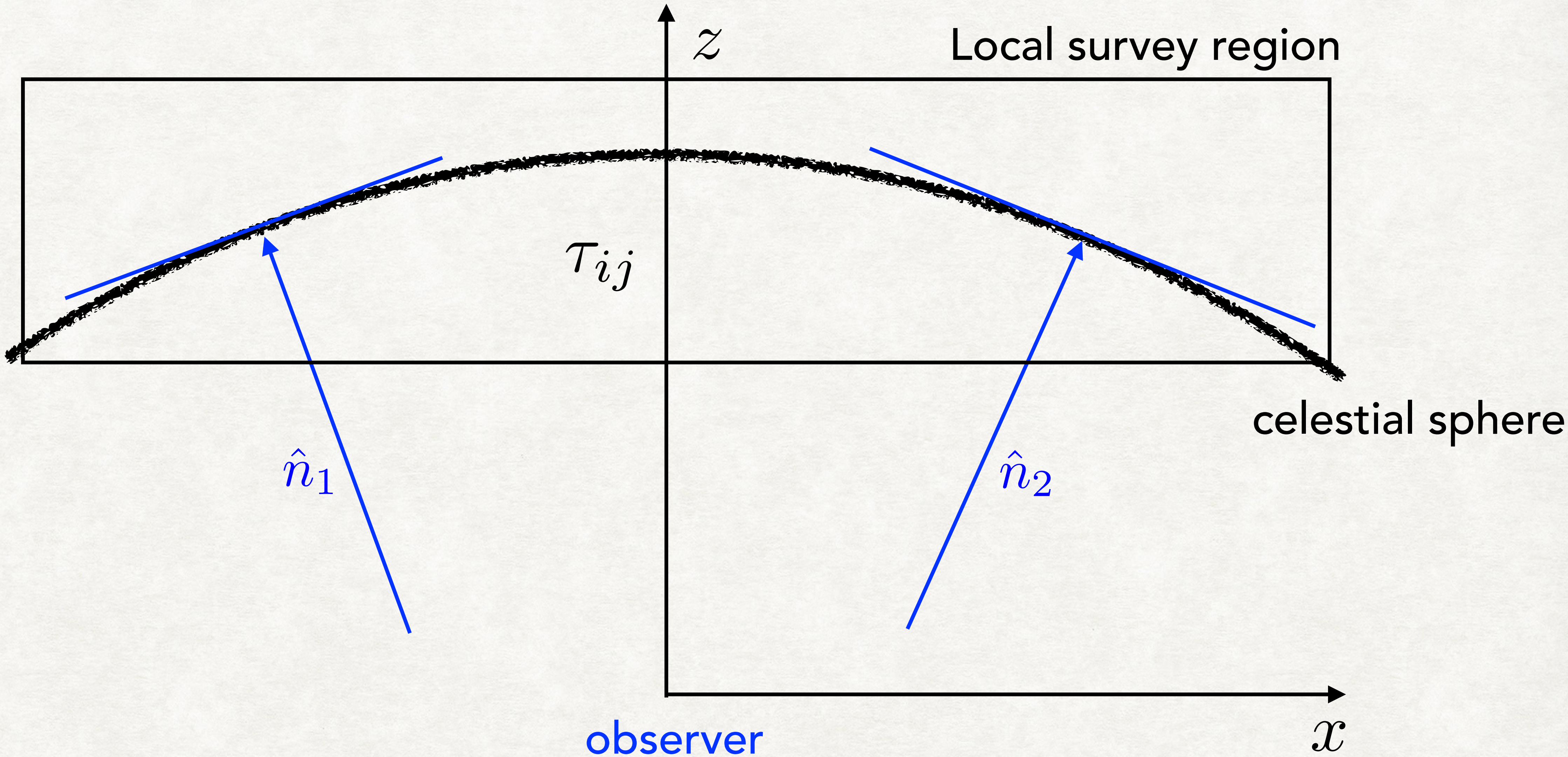
(KA, Sugiyama&Shiraishi in prep.)



- **Almost no correlation between AP/RSD/initial imprint and the super-sample mode.**

Origin of decomposition: Sky curvature

- $\tau_{33} = \tau_{ij}\hat{z}_i\hat{z}_j \neq \tau_{ij}\hat{n}_i\hat{n}_j$



- τ_{ij} **violates the rotational symmetry in the plane perp. to the LOS.**
  - **can be extracted by making use of the BipoSH**
- **Rotational symmetry around the observer is also violated.**

Comparison with initial anisotropic imprint

- **Anisotropic (quadrupolar) imprint on the initial condition (e.g. vector field / super-curvature fluctuation)**

$\hat{p}$: preferred direction

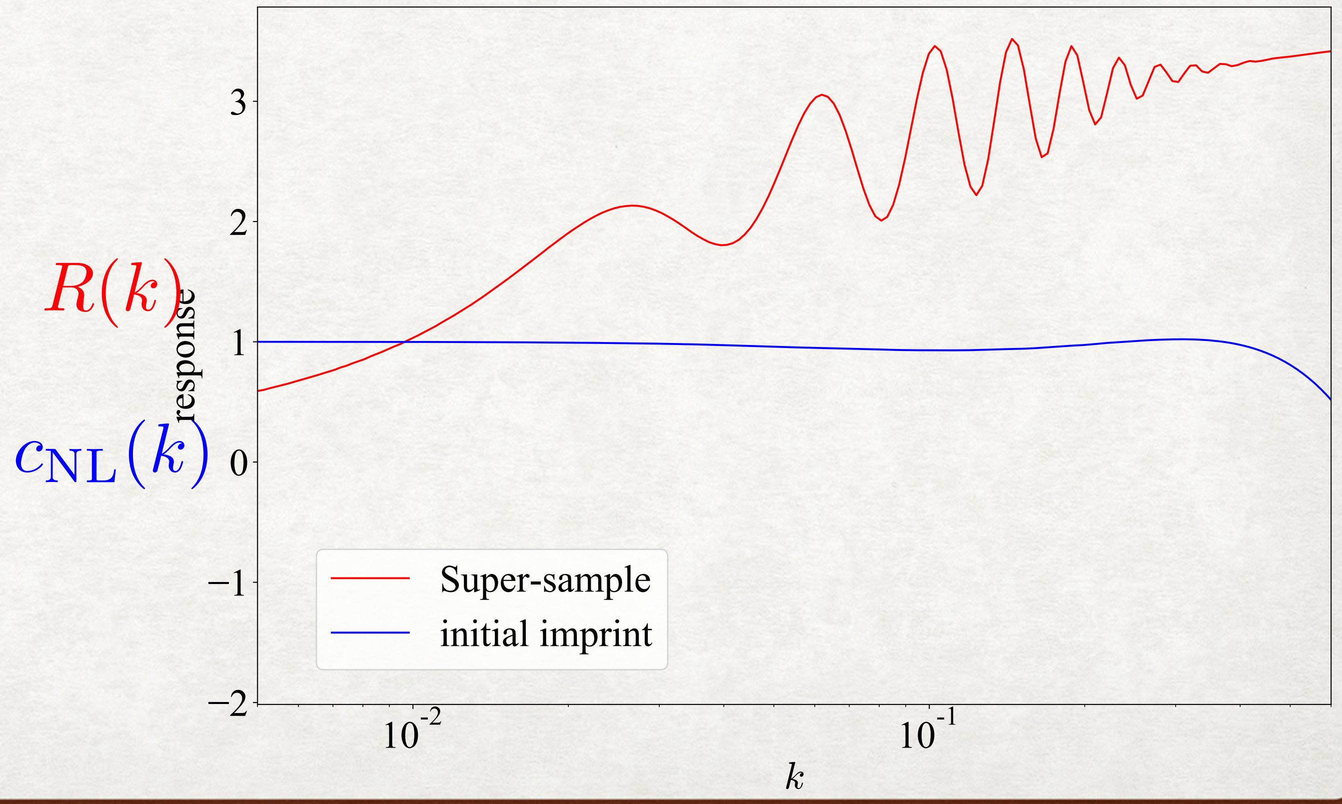
$$P(\mathbf{k}) = P^{\rm iso}(k)\left[1+\sum_M g_{2M} f(k) Y_{2M}(\hat{k})\right] = P^{\rm iso}(k)\left[1+g_* \bar{f}(k)(\hat{k}\cdot\hat{p})^2\right]$$

- **different angular couplings in redshift space**
  - Initial imprint: $\hat{p}_i\hat{p}_j\hat{k}_i\hat{k}_j$
  - Super-sample mode: $\tau_{ij}\hat{k}_i\hat{k}_j$, $\tau_{ij}\hat{k}_i\hat{n}_j$, $\tau_{ij}\hat{n}_i\hat{n}_j$

- **different scale dependence**

$$P(\mathbf{k}) = P(k)\left[1+R(k)\tau_{ij}\hat{k}_i\hat{k}_j\right]$$

$$P(\mathbf{k}) = P(k)\left[1+f(k)c_{\rm NL}(k)(\hat{p}\cdot\hat{k})^2\right]$$



Summary

- **Super-Sample modes : long-mode beyond the survey area**
  - affect the short-mode observables via mode-coupling
- **In redshift space, the SS mode generates the new anisotropy**
  - degrade the cosmological parameter estimation (new error)
  - prior of the SSS or the BiPoSH helps to restore the degradation
  - BipoSH expansion is useful to extract the anisotropic SSS
  - can distinguish initial anisotropic imprints from anisotropic SSS
- **Future works**
  - Super-sample mode with the wide-angle effect in redshift space
  - response with N-body ("anisotropic separate universe simulation")