# Towards the analysis of the redshift-space bispectrum

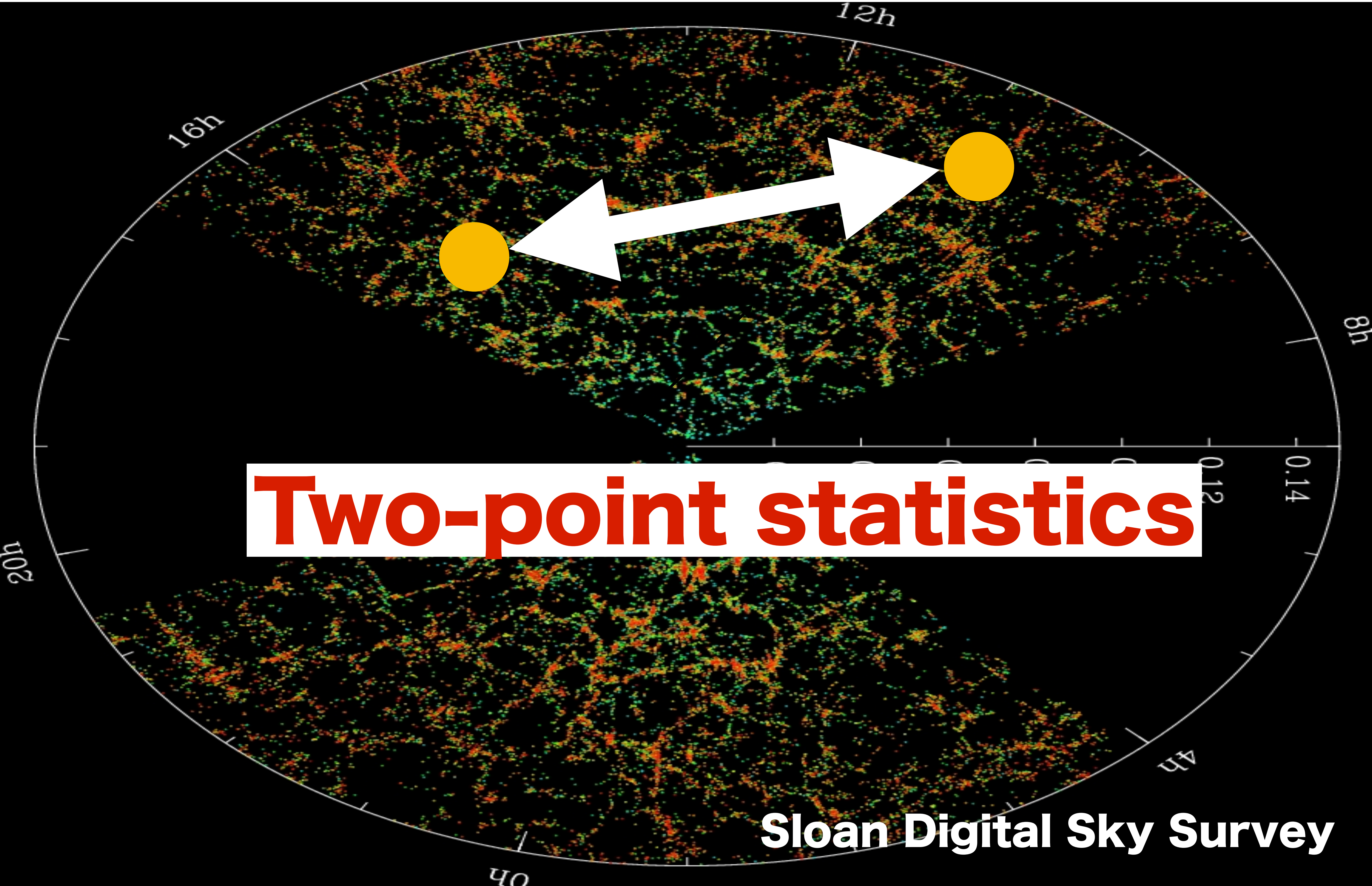
**Naonori Sugiyama**

**Collaborators: Shun Saito, Florian Beutler and Hee-Jong Seo**

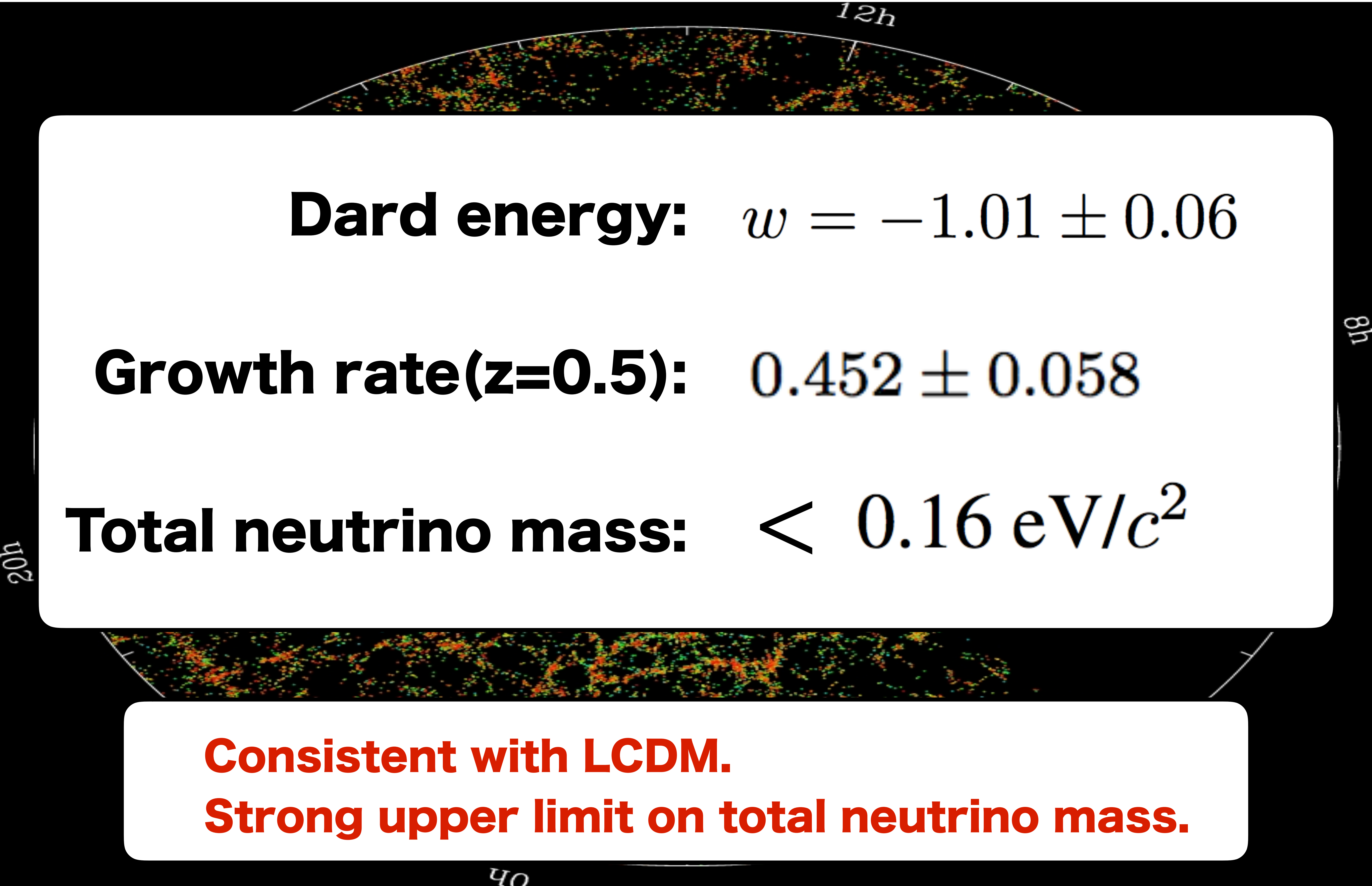
国立天文台
NAOJ
National Astronomical Observatory of Japan

**PTchat @ Yukawa Institute (April 8-12, 2019)**

# 3D galaxy map



# SDSS DR12 BOSS (2016)



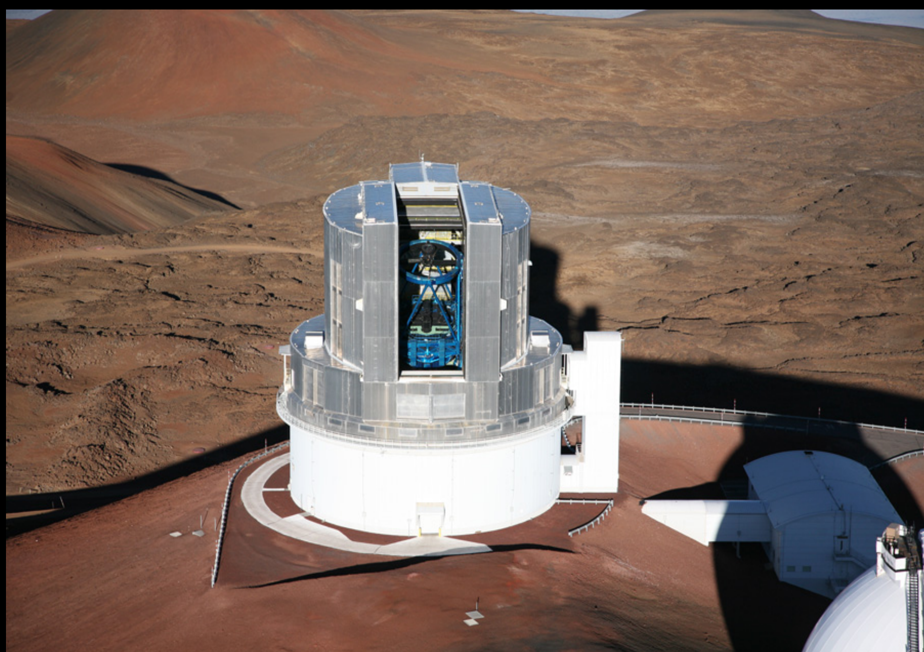

**Dard energy:** $w = -1.01 \pm 0.06$

**Growth rate(z=0.5):** $0.452 \pm 0.058$

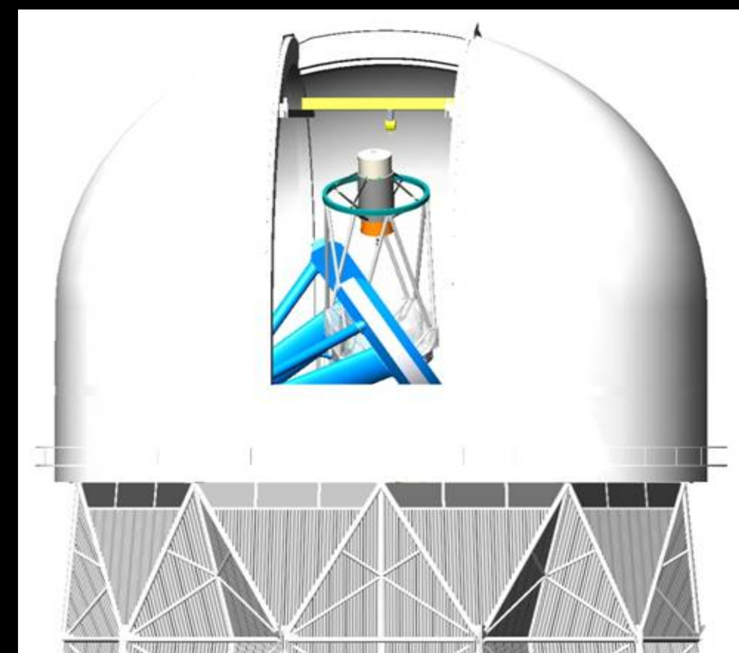
**Total neutrino mass:** $< \ 0.16 \, \mathrm{eV}/c^2$

**Consistent with LCDM.**
**Strong upper limit on total neutrino mass.**

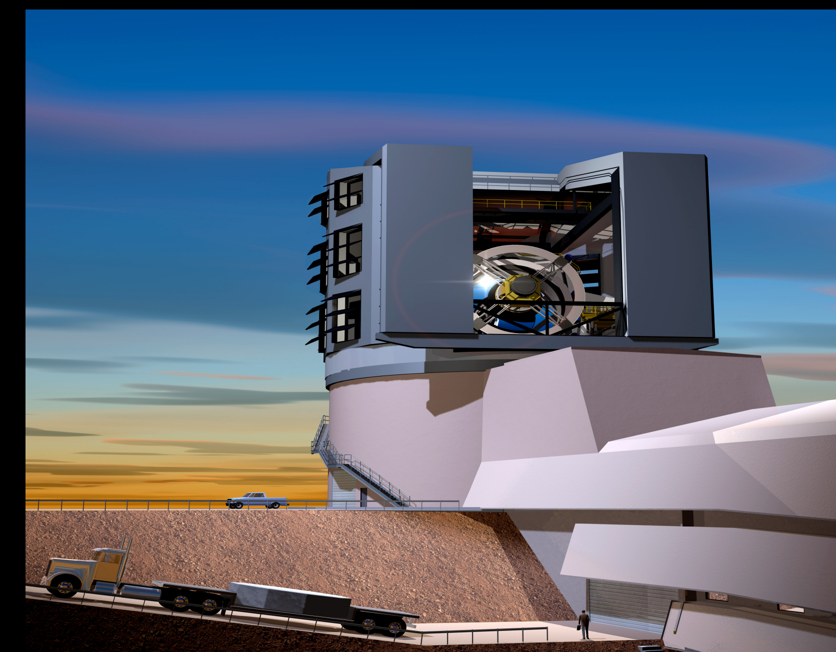
# Next Generation Galaxy Surveys



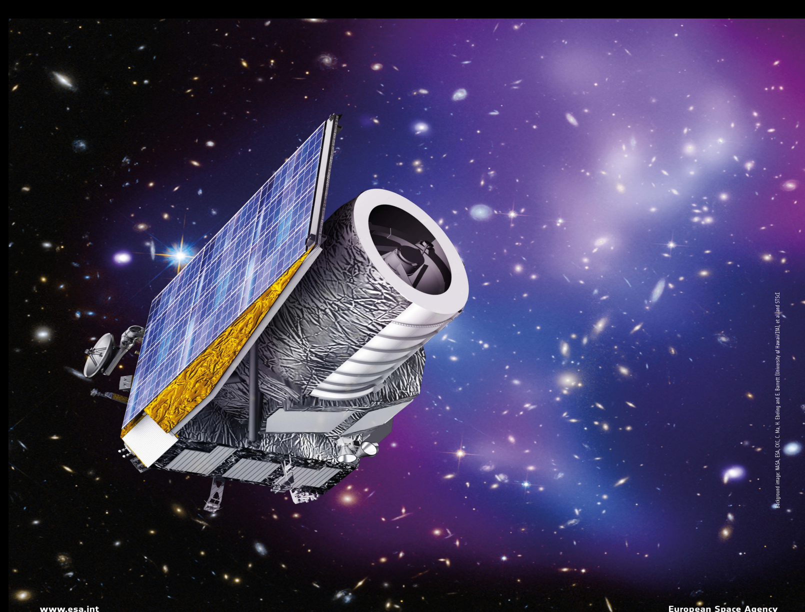
SuMIRe HSC/PFS (2015-25)



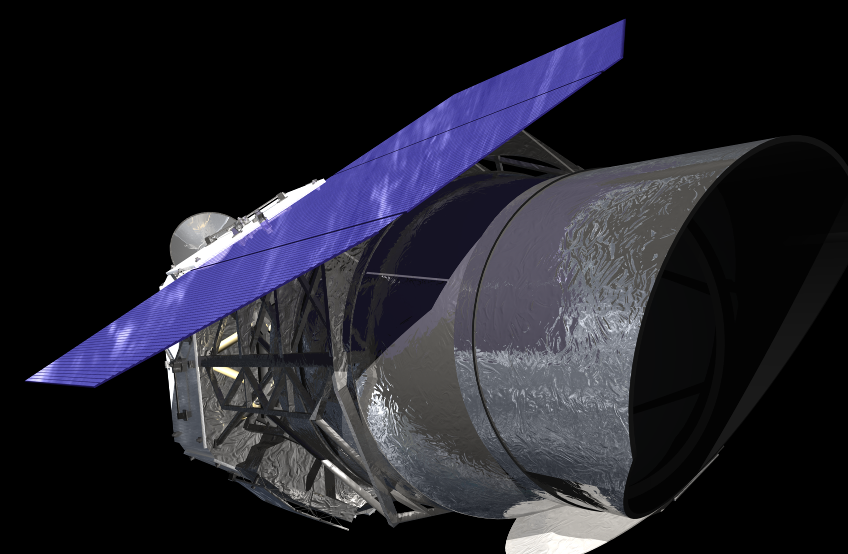
DESI (4m, LBL, 2020-)



LSST (6.5m, SLAC,2022-)

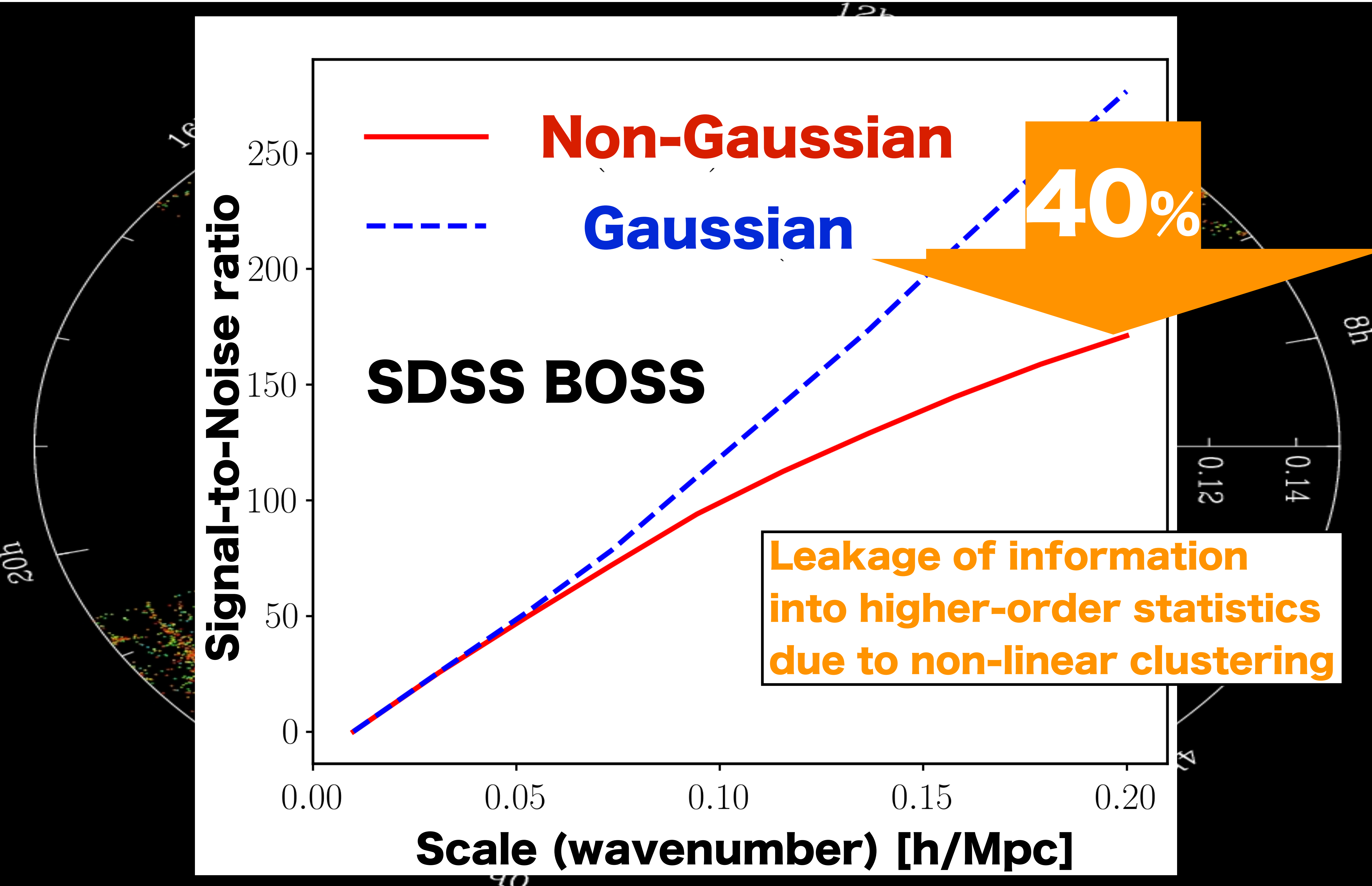



Euclid (ESA, 2022-)

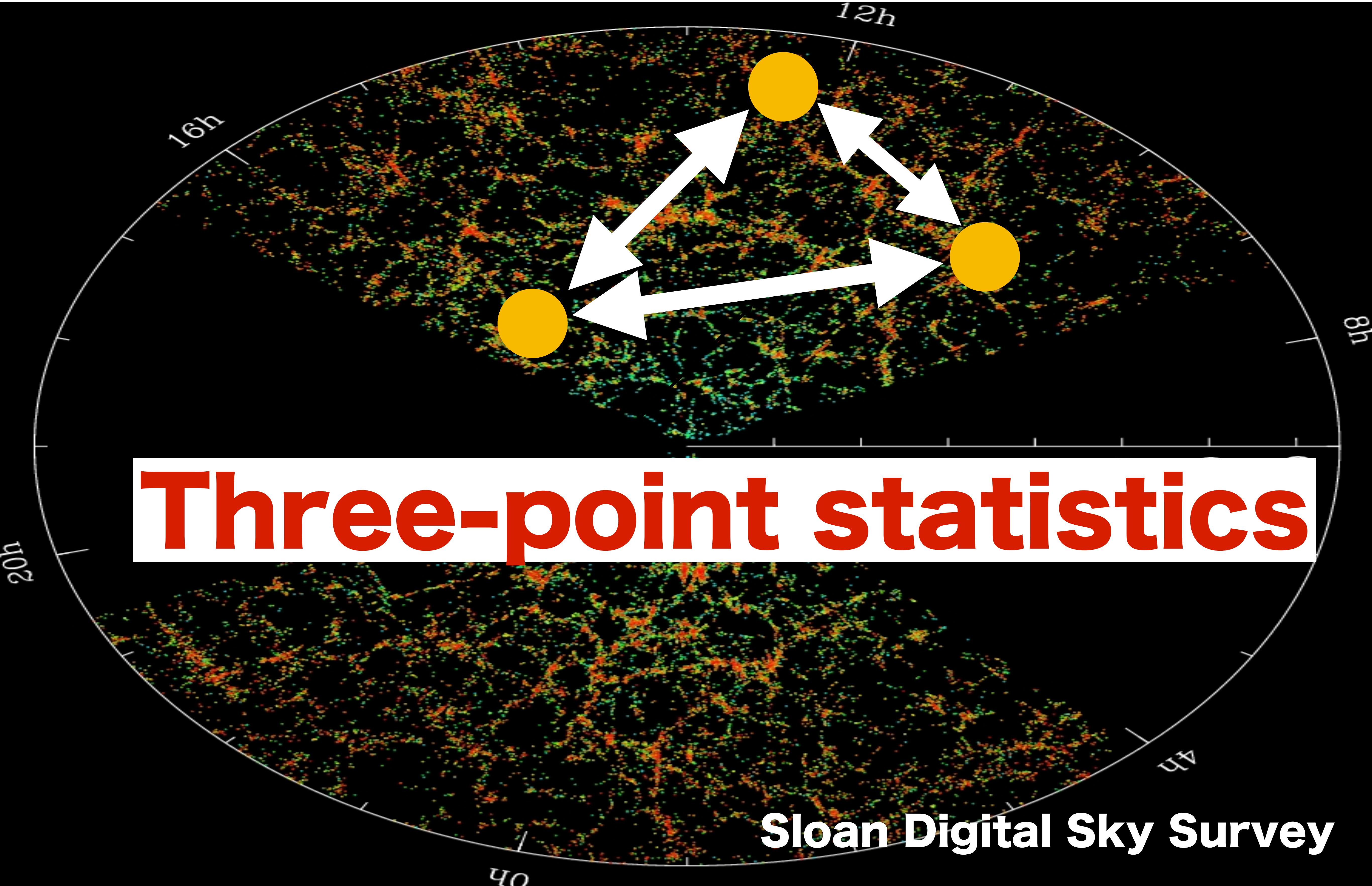


WFIRST (NASA,2025-)

# Limitation of two-point statistics



# Towards full information extraction



# History

## Angular catalogues:

## Peebles & Groth (1975)

Groth & Peebles (1977);
Fry & Slender (1982)

## Spectroscopic surveys in configuration-space

Kayo et al. (2004);
Jing & Boerner (2004);
Wang et al. (2004);
Gaztanaga et al. (2005);
Nichol et al. (2006);
Kulkarni et al. (2007);
Gaztanaga et al. (2009);
McBride et al. (2011a, b);
Marin (2011);
Marin et al. (2013);
Guo et al. (2013);
Slepian et al. (2017a,b);

## Spectroscopic surveys in Fourier-space

Scoccimarro et al. 2001;
Feldman et al. 2001;
Verde et al. 2002;
Gil-Marin et al. 2015a,b;

## Gil-Marin et al. 2017 (SDSS BOSS analysis)

Pearson & Samushia 2017;

**Joint analysis of P + B will become the standard method for future galaxy surveys.**

**Is there anything else we should do?**

**Anisotropic bispectrum analysis has not been done yet.**

# Bispectrum Project

## [1] NS, Saito, Beutler and Seo 2018

- A new decomposition formalism
- Detection of the quadrupole bispectrum ($14\sigma$)

## [2] In progress

- Modeling the bispectrum
- Modeling the bispectrum covariance
- Fisher analysis

## [3] Future works

- Analysis using BOSS data

## Final goal

- Application to future galaxy survey,
  PFS, DESI and Euclid.

# Decomposition formalism

$$B(\boldsymbol{k}_1, \boldsymbol{k}_2, \hat{n})$$

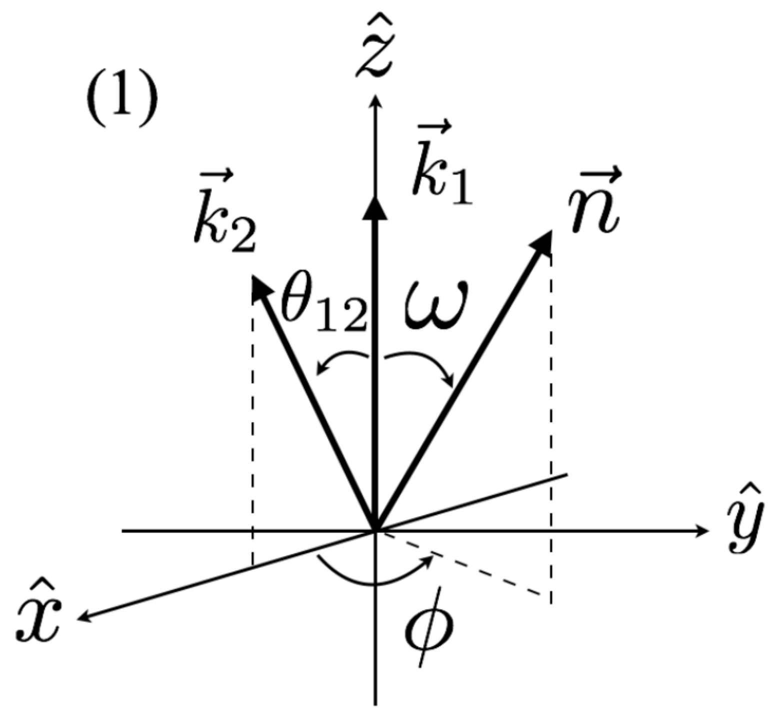
**Wavevectors** **Line-of-sight**

**k1 is the z-axis**

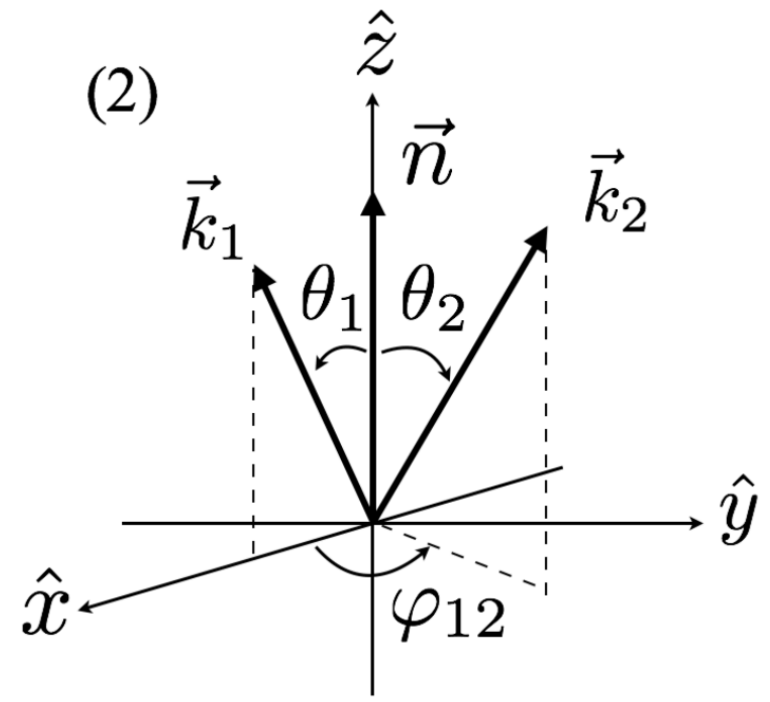
$$B = B_{LM}\, Y_{LM}(\hat{n})$$

**LOS is the z-axis**

$$B = B^{m}_{\ell_1 \ell_2}\, Y^{m}_{\ell_1}(\hat{k}_1)\, Y^{m*}_{\ell_2}(\hat{k}_2)$$




**Scoccimarro et al. (1999)**




**Slepian et al. (2017)**

# New decomposition formalism not depending on coordinate systems

**1)Expand the bispectrum in three spherical harmonics**

$$B^{m_1 m_2 M}_{\ell_1 \ell_2 L}(k_1, k_2) = N_{\ell_1 \ell_2 L} \int \frac{d^2\hat{k}_1}{4\pi} \int \frac{d^2\hat{k}_2}{4\pi} \int \frac{d^2\hat{n}}{4\pi} \times \quad y^{m_1 *}_{\ell_1}(\hat{k}_1) y^{m_2 *}_{\ell_2}(\hat{k}_2) y^{M *}_{L}(\hat{n}) B(\boldsymbol{k}_1, \boldsymbol{k}_2, \hat{n}),$$

**2) Sum up over all m-modeswith wigner 3j symbol.**

$$B_{\ell_1 \ell_2 L}(k_1, k_2) \propto \sum_{m_1 m_2 m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} B^{m_1 m_2 M}_{\ell_1 \ell_2 L}(k_1, k_2)$$

**3) Restrict the allowed multipoles to l1+l2+L=even**

# New Bispectrum Multipoles

**Three multipole indexes**

**Two wavenumber**

$$B_{\ell_1 \ell_2 L}(k_1, k_2)$$

**k1, k2** **LOS**

1) Translational symmetry
   (triangle condition)
2) Rotational symmetry
3) Parity symmetry

# New Bispectrum Multipoles

**Three multipole indexes**

**Two wavenumber**

$$B_{\underline{\ell_1 \ell_2} \underline{L}}(k_1, k_2)$$

k1, k2

LOS

**L = 0: monopole**

**L = 2: quadrupole**

# Advantages (1)

**For example,**

$$\underbrace{B_{\ell_1\ell_2 L}(k_1,k_2)}_{\text{Ours}} \propto \int \frac{d\cos\theta}{2} \sum_M \begin{pmatrix} \ell_1 & \ell_2 & L \\ 0 & -M & M \end{pmatrix} \times \mathcal{L}_{\ell_2}^{-M}(\cos\theta)\, B_{LM}(k_1,k_2,\theta)$$

Scoccimarro et al. (1999)

**Independent of the choice of the coordinate axis.**

# Advantages (2)

**Following Scoccimarro 2015:**

$$\widehat{B}_{\ell_1\ell_2 L}(k_1,k_2) = H_{\ell_1\ell_2 L} \sum_{m_1 m_2 M} \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & M \end{pmatrix} \times \frac{N_{\ell_1\ell_2 L}}{I} \int d^3x\, F_{\ell_1}^{m_1}(\boldsymbol{x};k_1)\, F_{\ell_2}^{m_2}(\boldsymbol{x};k_2)\, G_L^M(\boldsymbol{x}),$$

$$F_\ell^m(\boldsymbol{x};k) = \int \frac{d^2\hat{k}}{4\pi}\, \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}\, y_\ell^{m*}(\hat{k})\, \frac{\delta n|_{\mathrm{FFT}}(\boldsymbol{k})}{W_{\mathrm{mass}}(\boldsymbol{k})}$$

$$G_L^M(\boldsymbol{x}) = \int \frac{d^3k}{(2\pi)^3}\, \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}\, \frac{\delta n_L^M|_{\mathrm{FFT}}(\boldsymbol{k})}{W_{\mathrm{mass}}(\boldsymbol{k})}.$$

**Requires only FFT processes.**

# Advantages (3)

## Double Hankel transform

$$B_{\ell_1\ell_2L}(k_1,k_2) \propto \int dr_1 r_1^2 \int dr_2 r_2^2 j_{\ell_1}(k_1r_1) j_{\ell_1}(k_2r_2) \zeta_{\ell_1\ell_2L}(r_1,r_2)$$

**Bispec.** **3PCF**

$$\begin{aligned}\zeta^{\rm masked}_{000}(r_1,r_2) &= Q_{000}(r_1,r_2)\zeta^{\rm theory}_{000}(r_1,r_2)\\ &+ Q_{110}(r_1,r_2)\zeta^{\rm theory}_{110}(r_1,r_2)\\ &+ \cdots\end{aligned}$$

**Masked 3PCF**

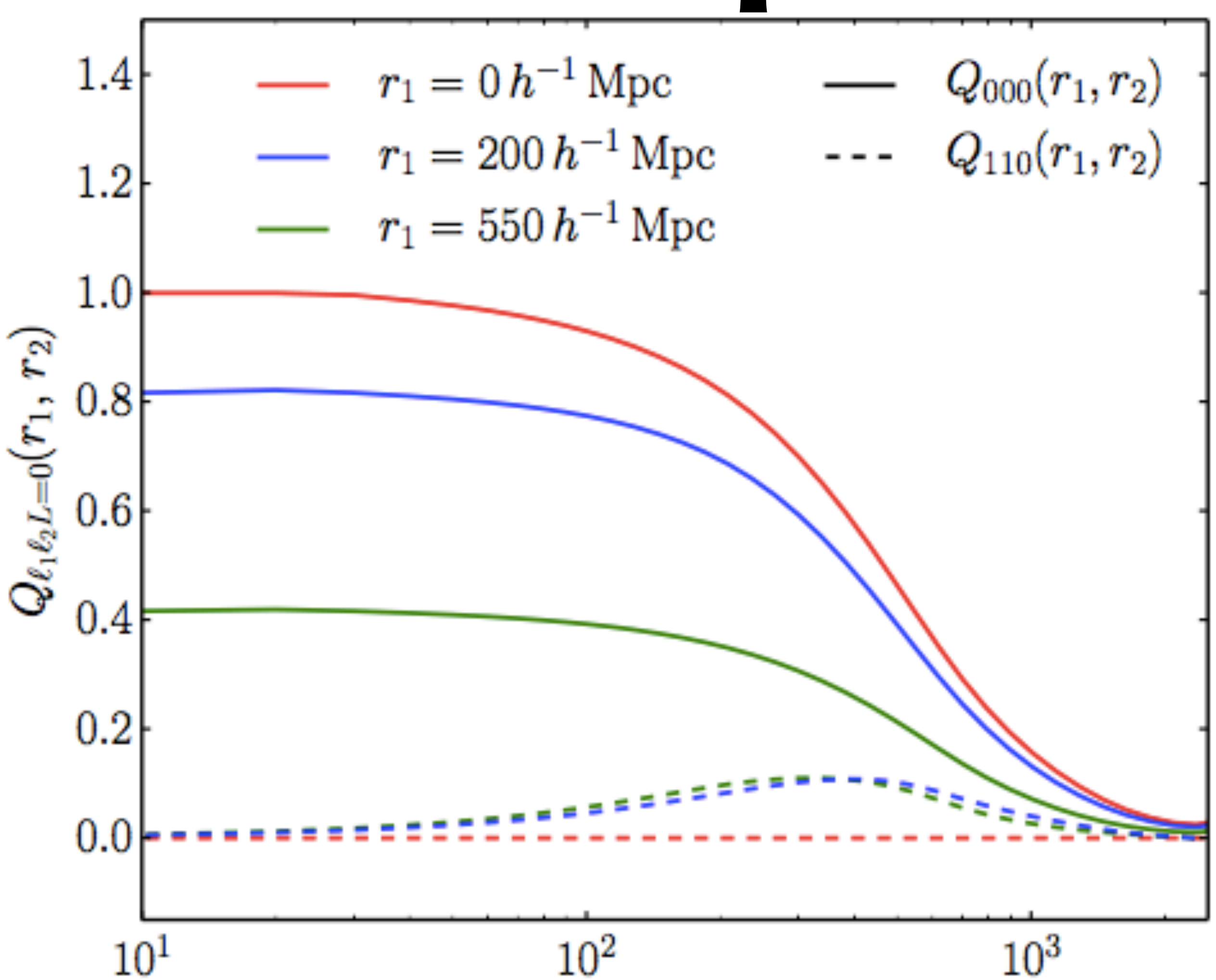
**Window function**

**Gives a simple expression to correct for survey geometry**

# Three-point window function multipoles

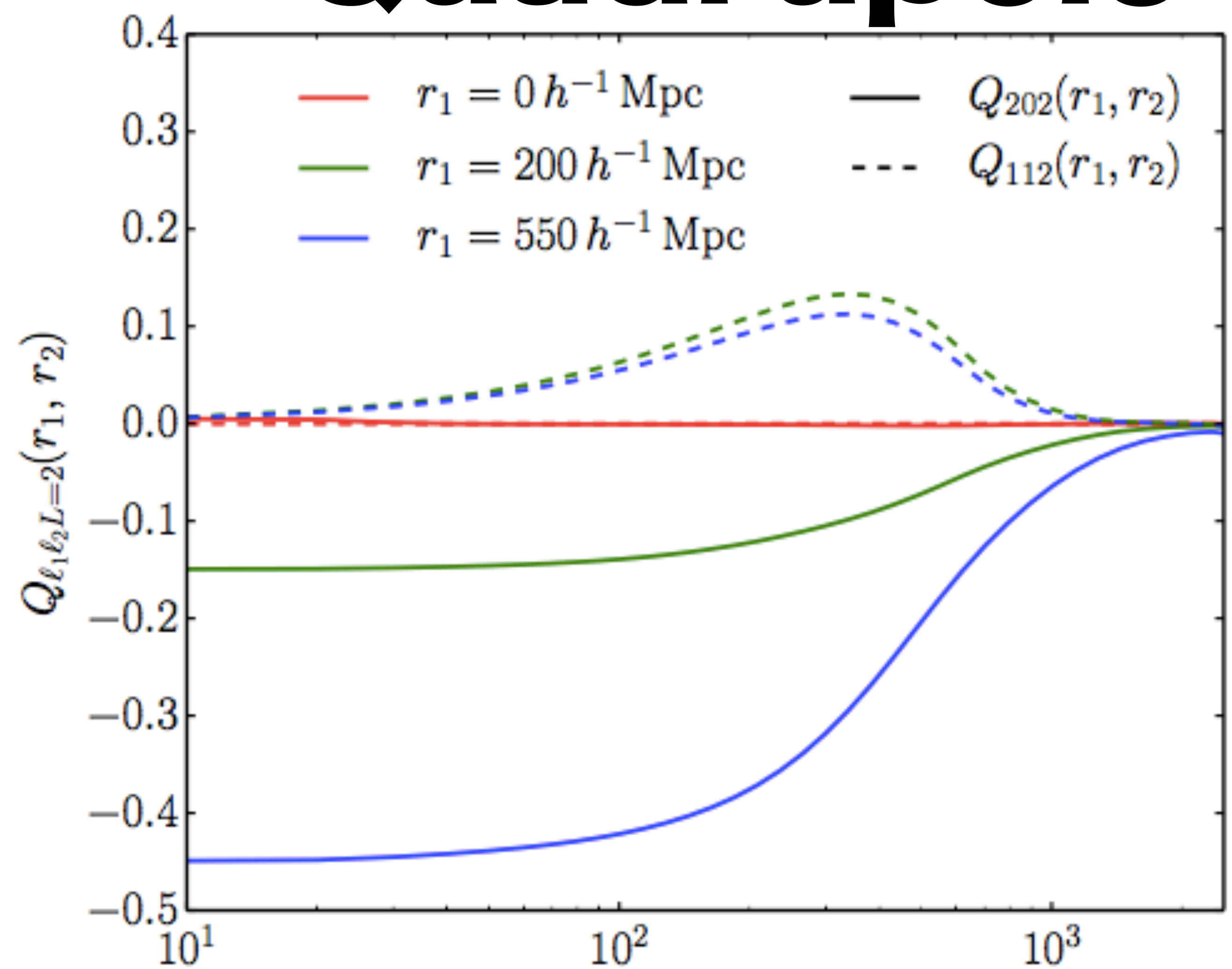
$$Q_{\ell_1 \ell_2 L}(r_1, r_2)$$

## Monopole



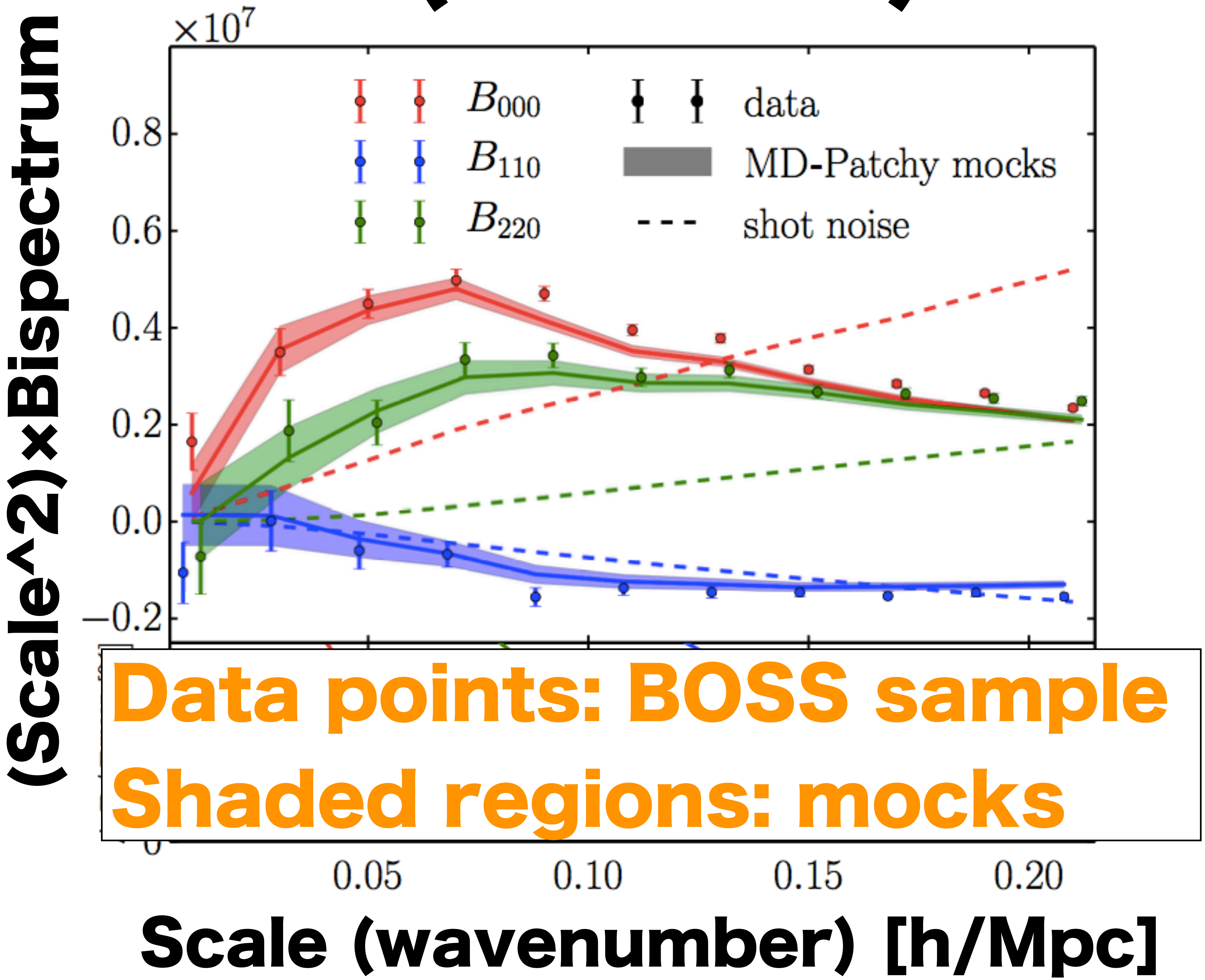

Scale [r_2]

## Quadrupole

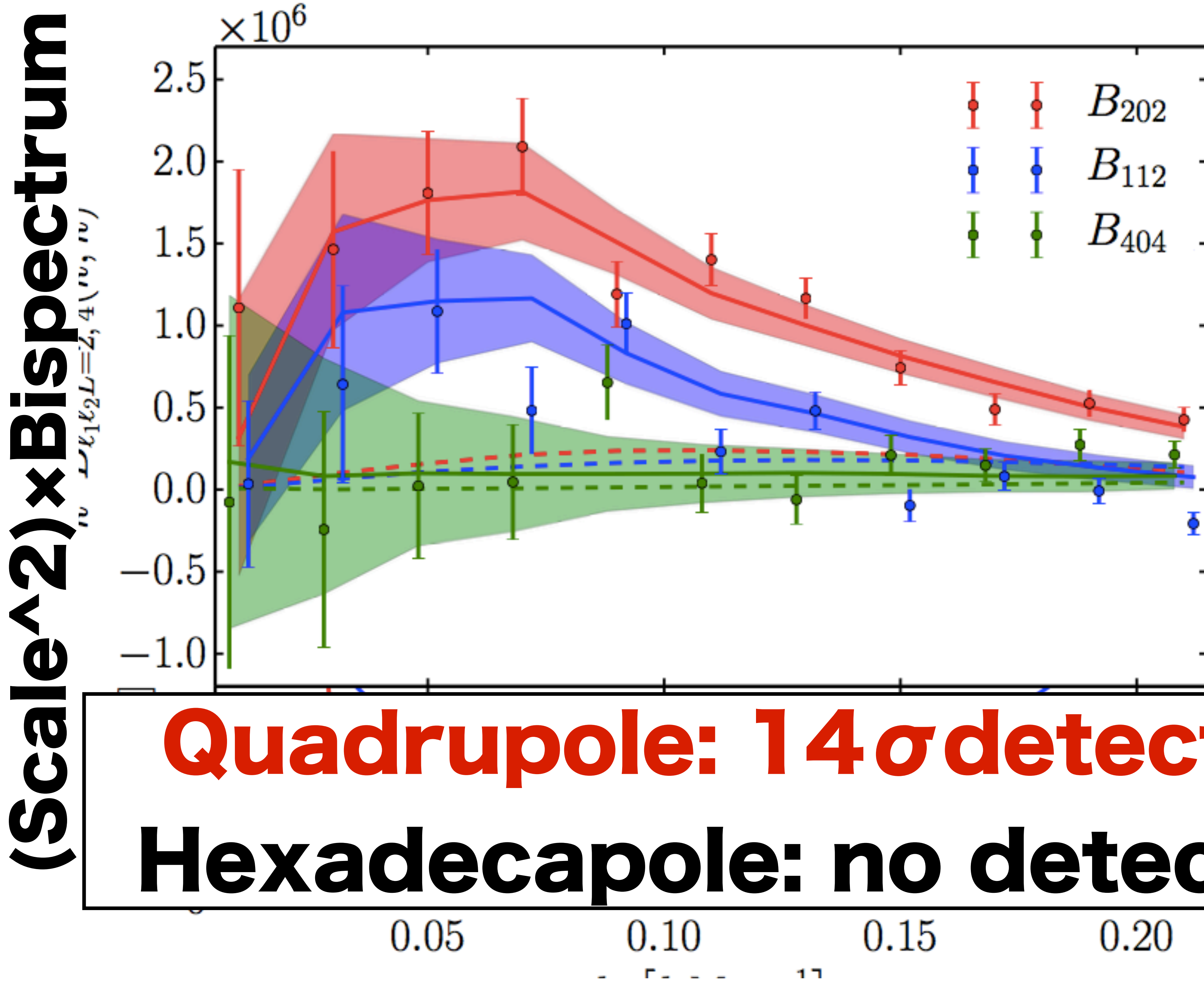



Scale [r_2]

# Measurements of Monopole (L=0)
# (k1 = k2)



# Quadrupole (L=2) and Hexadecapole (L=4)




**Quadrupole: 14σ detection**

**Hexadecapole: no detection**

# Strategy

1) Focus only on k1=k2 elements of the bispectrum multipoles.

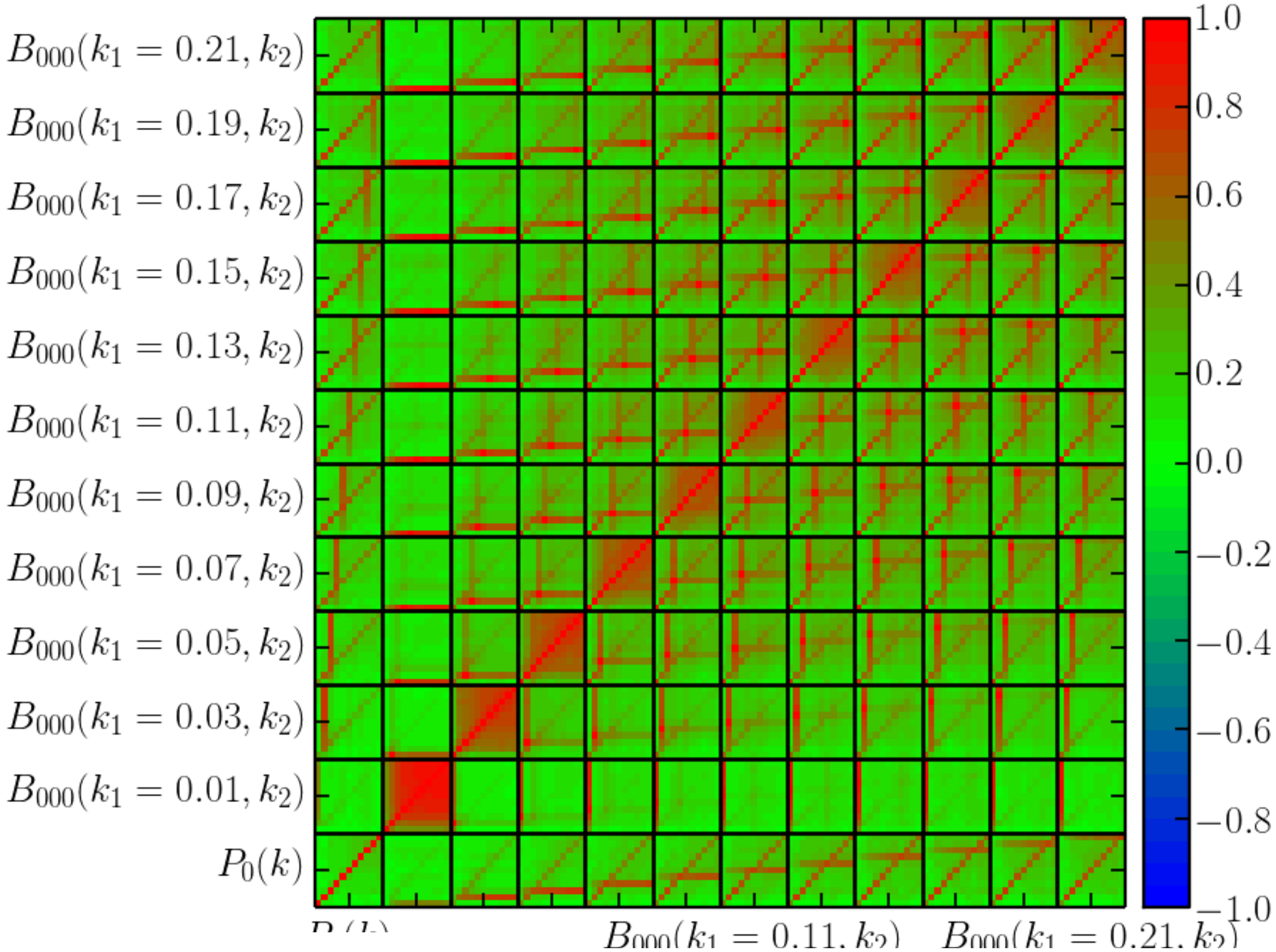
⇒ • Decreases the number of bins

⇒ • Smaller number of mocks
• Fast measurements
• Fast analysis

2) Full bispectrum analysis.

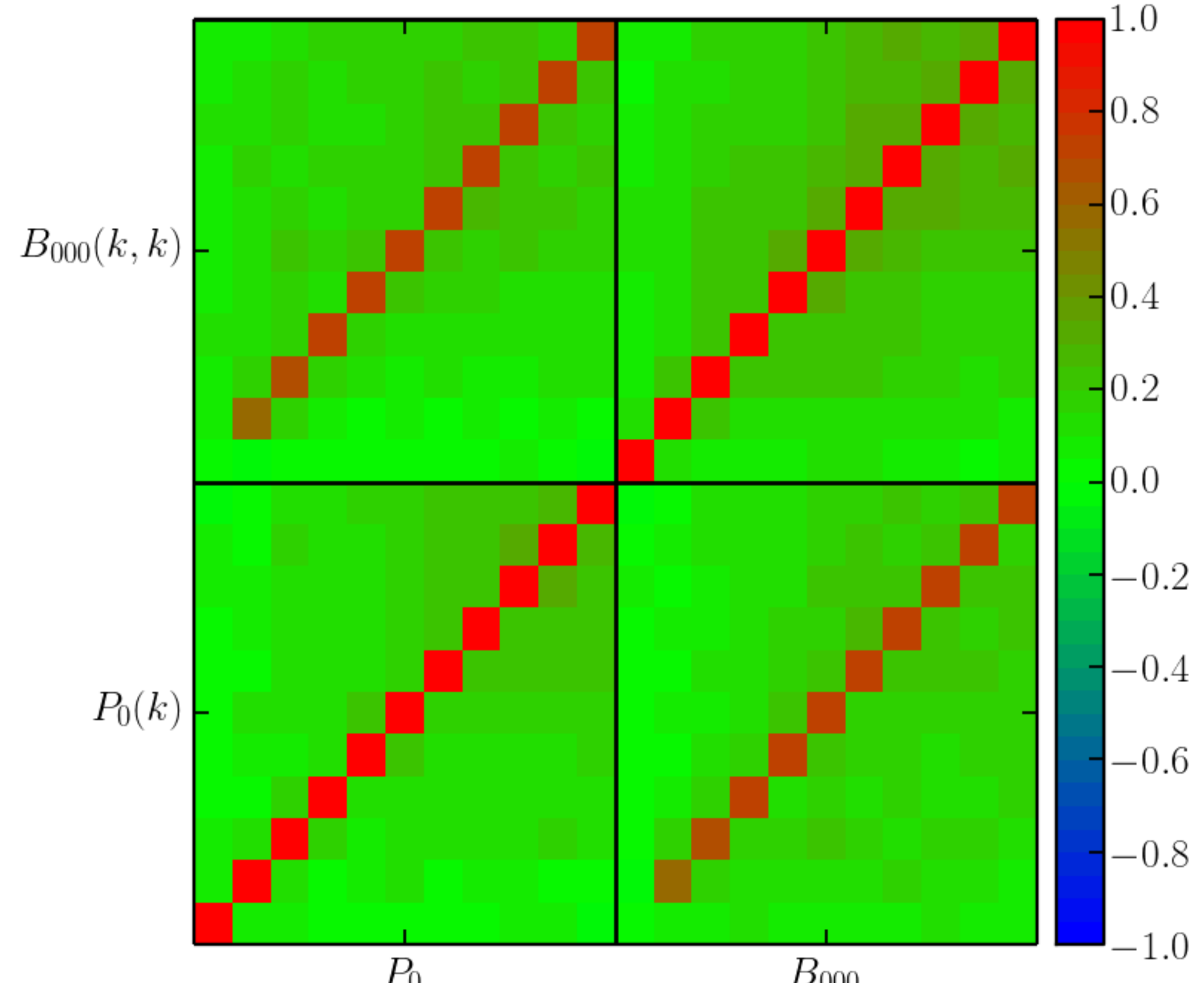
# B000

## Full(k1, k2)



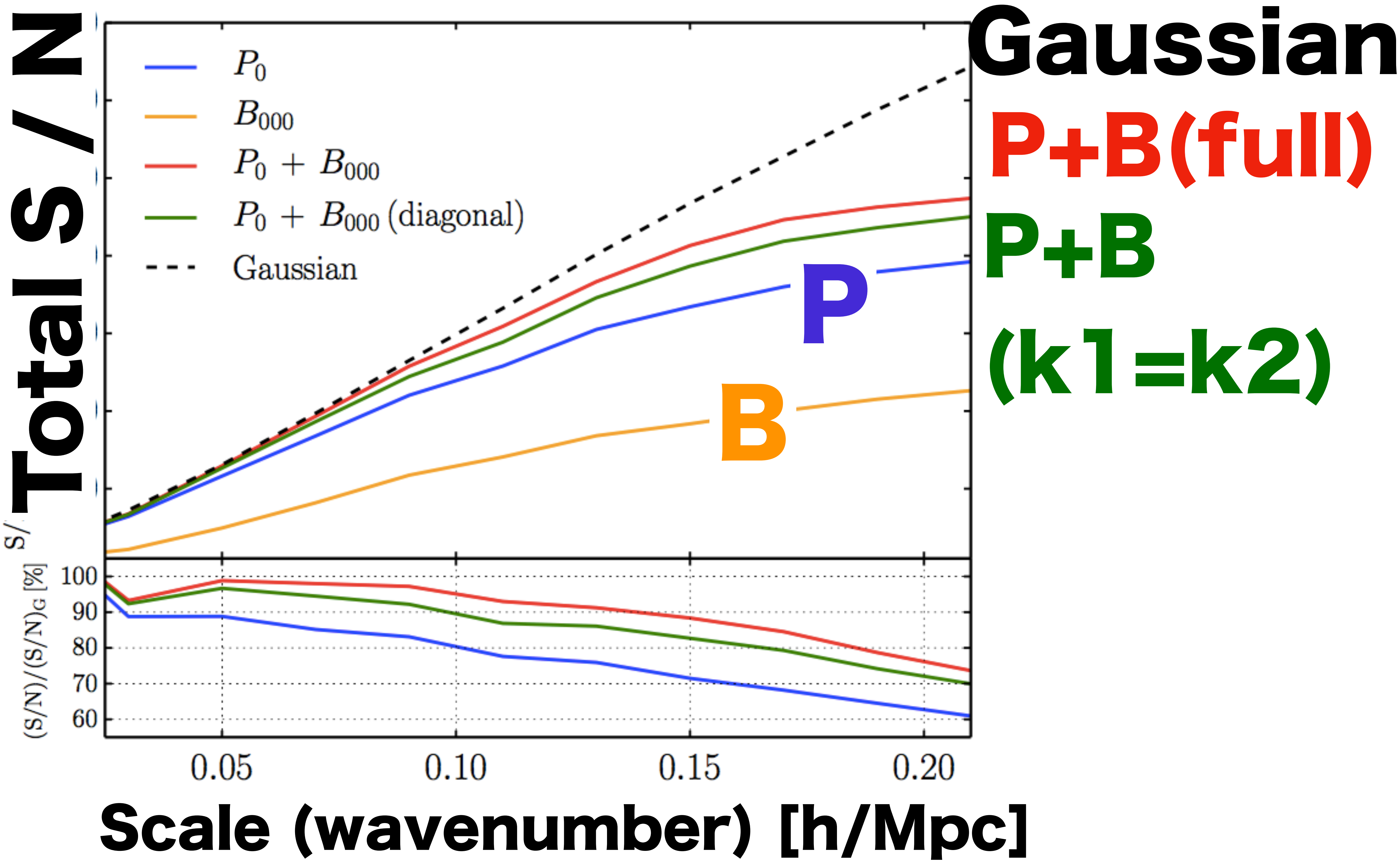

**P B(k1=fixed, k2)**

## k1 = k2




**P(k) B(k,k)**

# Cumulative S/N:
# CMASS North



# How do anisotropic bispectrum measurements improve constraints on cosmological parameters?

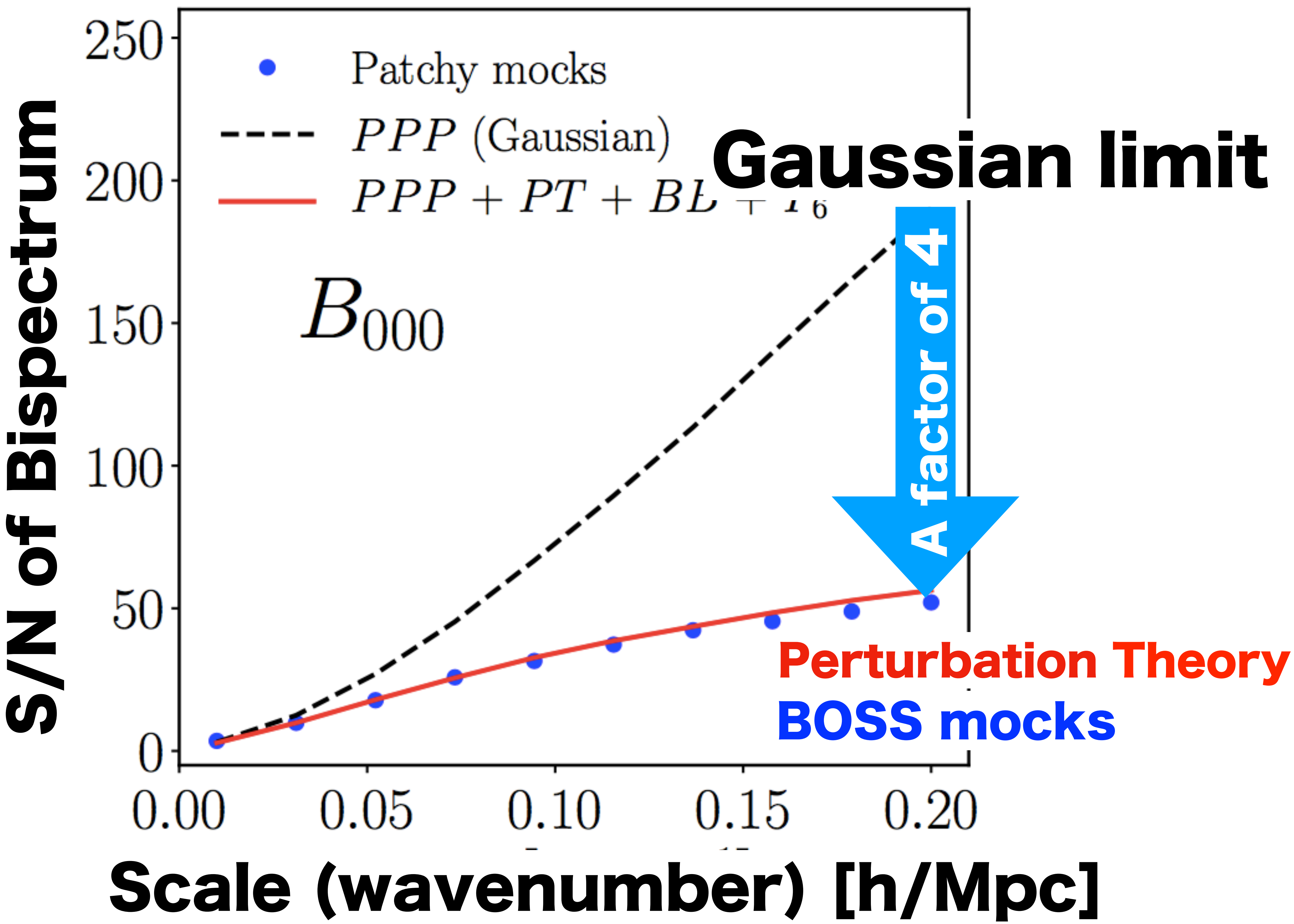
# (Preliminary results)

# Fisher analysis

**Correct error estimates**
**[non-Gaussian covariance]**

**Correct theoretical model**

# Importance of Non-Gaussian errors



# Non-Gaussian covariance

P-P covariance -> tri-spectrum

P-B covariance -> 5-point spectrum

B-B covariance -> 6-point spectrum

RSD + linear bias (b1) + shot noise

# Shot-noise subtraction effect

$$\mathrm{Cov}\left(|\delta(\mathbf{k})|^2, |\delta(\mathbf{k})|^2\right)$$

$$\neq$$

$$\mathrm{Cov}\left(P(\mathbf{k}), P(\mathbf{k})\right)$$

$$P = |\delta(\mathbf{k})|^2 - \frac{1}{\bar{n}}$$

$$N_{\mathrm{obs}} = N_{\mathrm{true}}\left(1 + \delta_{\mathrm{b}}\right)$$

# Before shot-noise subtraction

# Cov [P, P]

$$
\begin{aligned}
= \quad & \frac{1}{V}\Big\{T(\boldsymbol{k}, -\boldsymbol{k}, \boldsymbol{k}', -\boldsymbol{k}') \\
+ \quad & (1/\bar{n})[B(\boldsymbol{k}, -\boldsymbol{k}, \boldsymbol{0}) + B(\boldsymbol{k}', -\boldsymbol{k}', \boldsymbol{0}) \\
& \quad + B(\boldsymbol{k}, \boldsymbol{k}', -\boldsymbol{k} - \boldsymbol{k}') + B(\boldsymbol{k}, -\boldsymbol{k}, -\boldsymbol{k} + \boldsymbol{k}') + B(-\boldsymbol{k}, \boldsymbol{k}', \boldsymbol{k} - \boldsymbol{k}') + B(-\boldsymbol{k}, -\boldsymbol{k}', \boldsymbol{k} + \boldsymbol{k}')] \\
+ \quad & (1/\bar{n}^2)[2P(\boldsymbol{k}) + 2P(\boldsymbol{k}') + P(\boldsymbol{0}) + P(\boldsymbol{k} + \boldsymbol{k}') + P(\boldsymbol{k} - \boldsymbol{k}')] \\
+ \quad & (1/\bar{n}^3)\Big\}.
\end{aligned}
$$

# After shot-noise subtraction

# Cov [P, P]

$$
\begin{aligned}
= \quad & \frac{1}{V}\Big\{T(\boldsymbol{k}, -\boldsymbol{k}, \boldsymbol{k}', -\boldsymbol{k}') \\
+ \quad & (1/\bar{n})[B(\boldsymbol{k}, -\boldsymbol{k}, \boldsymbol{0}) + B(\boldsymbol{k}', -\boldsymbol{k}', \boldsymbol{0}) \\
& \quad + B(\boldsymbol{k}, \boldsymbol{k}', -\boldsymbol{k} - \boldsymbol{k}') + B(\boldsymbol{k}, -\boldsymbol{k}, -\boldsymbol{k} + \boldsymbol{k}') + B(-\boldsymbol{k}, \boldsymbol{k}', \boldsymbol{k} - \boldsymbol{k}') + B(-\boldsymbol{k}, -\boldsymbol{k}', \boldsymbol{k} + \boldsymbol{k}')] \\
+ \quad & (1/\bar{n}^2)[2P(\boldsymbol{k}) + 2P(\boldsymbol{k}') + P(\boldsymbol{0}) + P(\boldsymbol{k} + \boldsymbol{k}') + P(\boldsymbol{k} - \boldsymbol{k}')] \\
+ \quad & (1/\bar{n}^3)\Big\}.
\end{aligned}
$$

# Shot-noise subtraction effect

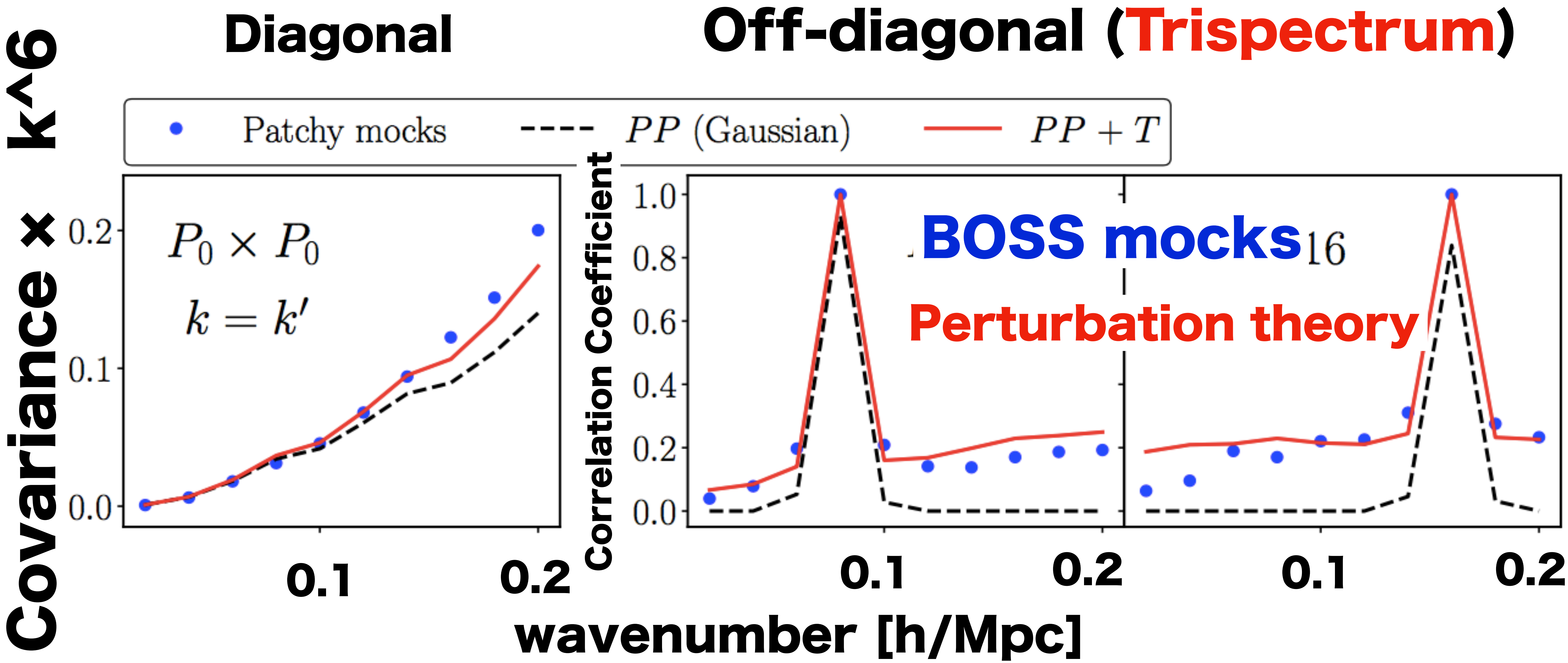
$$\mathrm{Cov}\left(B, B\right)$$

$$\neq$$

$$\mathrm{Cov}\left(\delta^3, \delta^3\right)$$

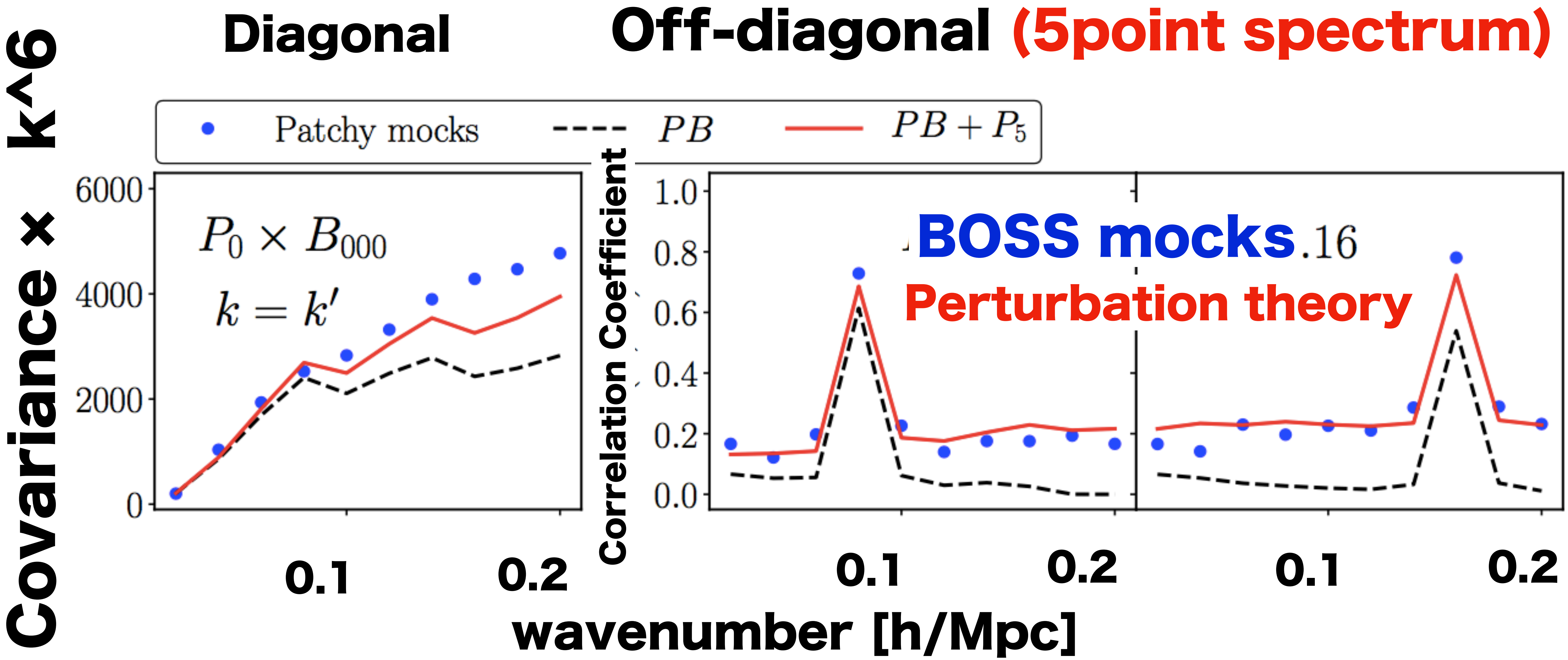
$$B = \delta^3 - \frac{1}{\bar{n}}P - \frac{1}{\bar{n}^2}$$

# Cov [P0, P0]



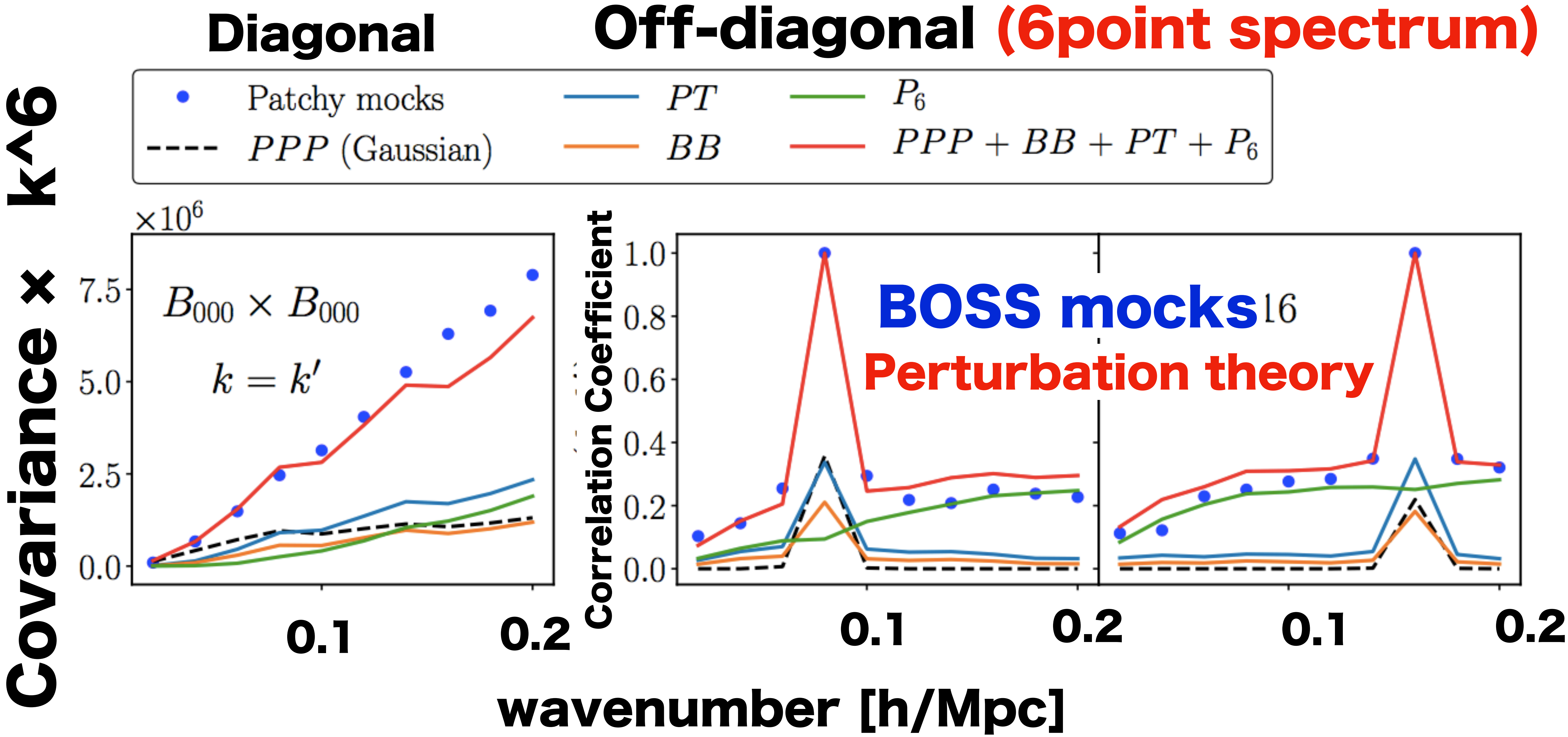

**Cov[P,P] = PP + T**

# Cov [P0, B000]



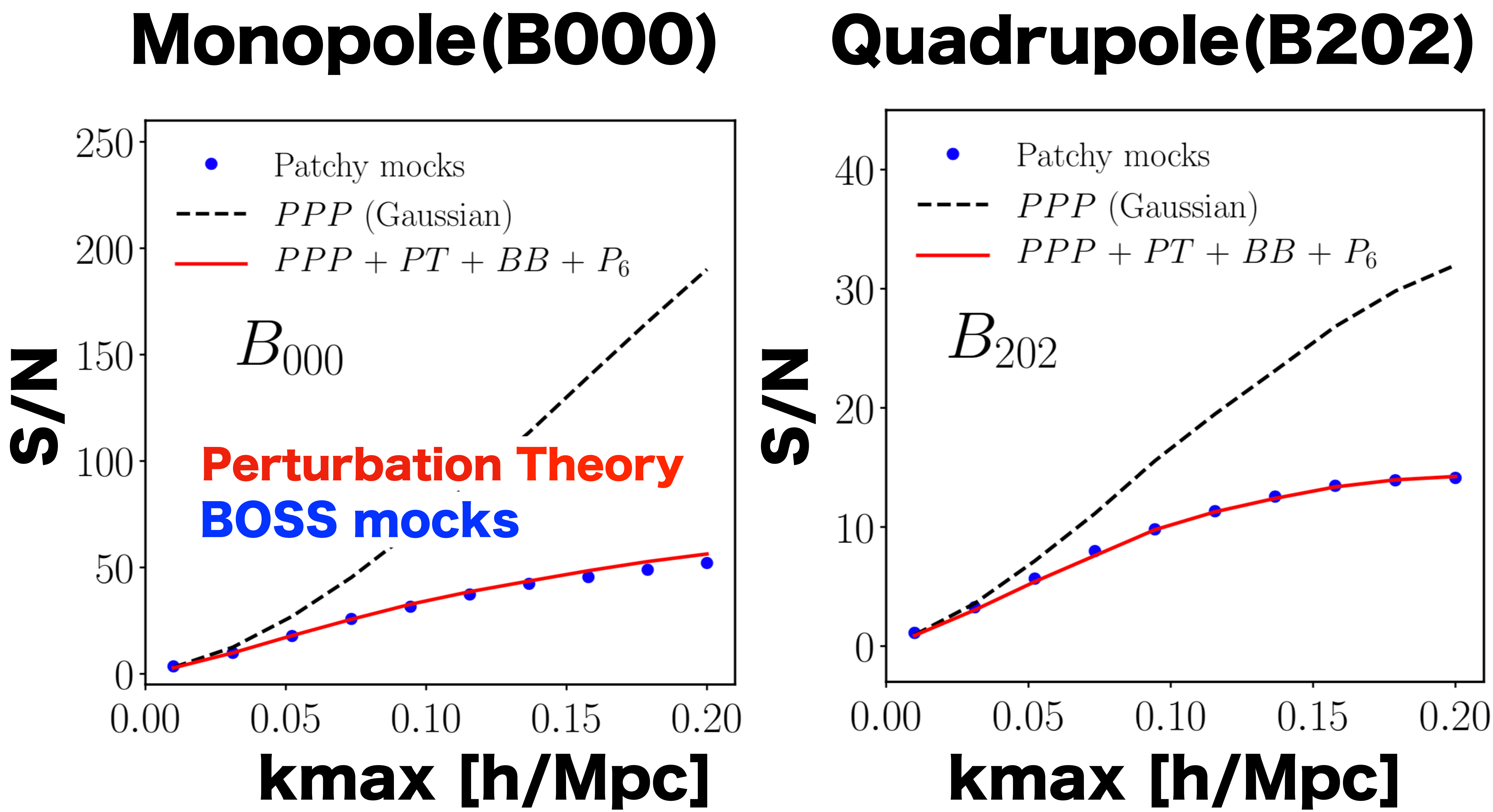

# Cov[P,B] = PB + P5

# Cov [B000, B000]




**Cov[B,B] = PPP + PT + BB + P6**

# S / N




**The same signal is used for both the mock and PT.**

# Bispectrum model

**We need a model that explains the anisotropic galaxy power spectrum and bispectrum simultaneously.**

1) Non-linear clustering
2) Non-linear RSDs
3) Non-linear bias

# Bispectrum model

We need a model that explains the anisotropic galaxy power spectrum and bispectrum simultaneously.

1) Non-linear clustering
2) Non-linear RSDs
3) Non-linear bias

# Bispectrum model describing the BAO damping

**In the power spectrum case (Eisenstein+2007):**

$$P(\boldsymbol{k},\hat{n}) = \left[Z^{[1]}(\boldsymbol{k},\hat{n})\right]^2 \left[\mathcal{D}^2(\boldsymbol{k},\hat{n})\, P_{\rm BAO}(k) + P_{\rm nw}(k)\right]$$

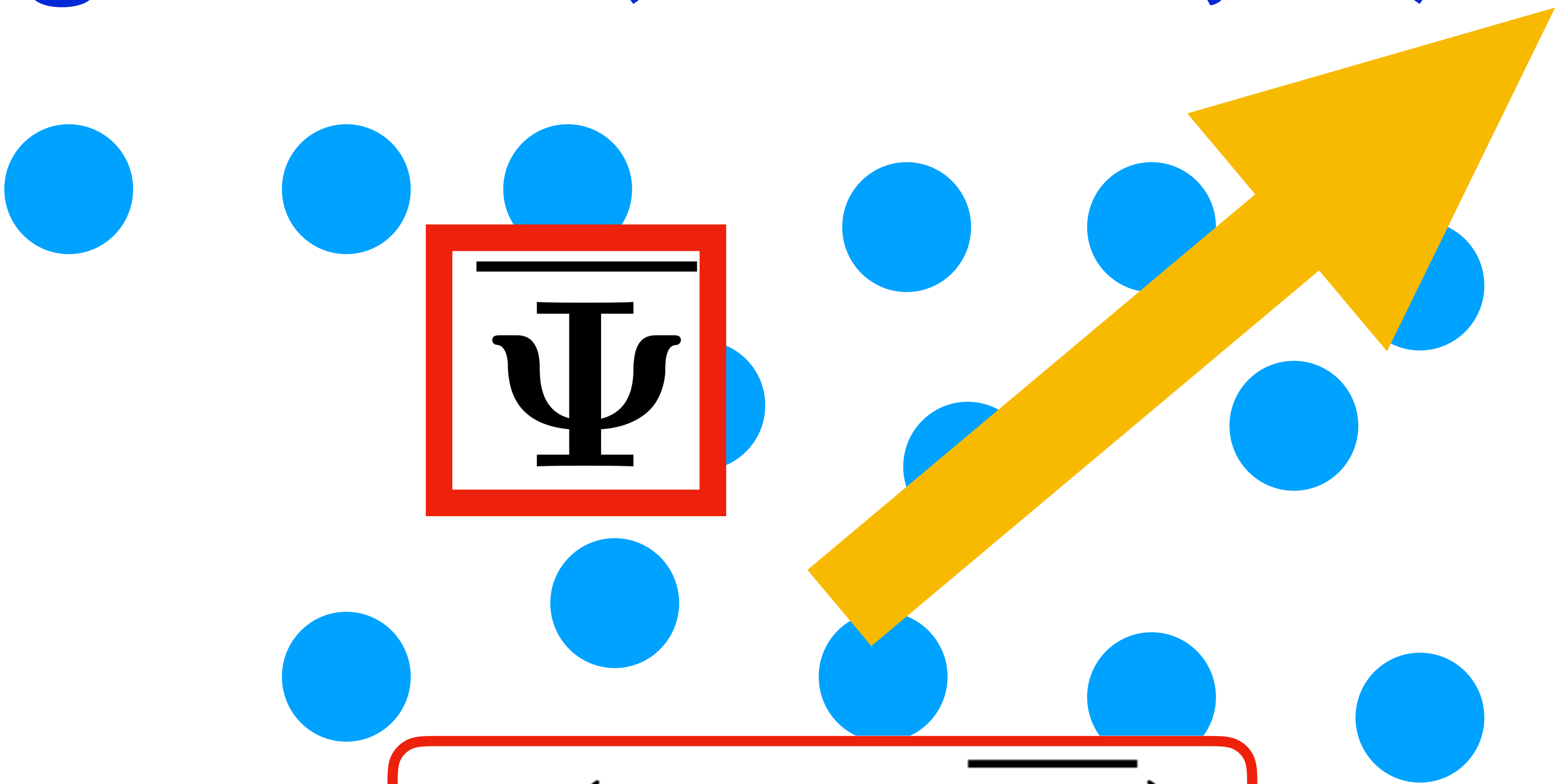
BAO

Power spec. without BAO

$$\mathcal{D}(\boldsymbol{k},\hat{n}) = \exp\left(-\frac{k^2\mu^2\Sigma_\parallel^2 + k^2\left(1-\mu^2\right)\Sigma_\perp^2}{4}\right)$$

$$P_{\rm BAO}(k) = P_{\rm lin}(k) - P_{\rm nw}(k)$$

# Large scale (infrared, IR) flow



$$\delta\left(\boldsymbol{x} - \overline{\boldsymbol{\Psi}}\right)$$

$$e^{-i\boldsymbol{k}\cdot\overline{\boldsymbol{\Psi}}}\,\widetilde{\delta}(\boldsymbol{k})$$

# IR cancellation

**Assuming that the IR flow is NOT correlated with the density field:**

$$\langle \delta(x - \overline{\Psi})\delta(y - \overline{\Psi}) \rangle = \langle \delta(x)\delta(y) \rangle = \xi(x - y)$$

**The effect from the IR flow completely cancels out because of translational symmetry (Galilean invariance)**

# IR cancellation

**Assuming that the IR flow is NOT correlated with the density field:**

$$
\begin{aligned}
& \langle e^{-i\boldsymbol{k}_1\cdot\overline{\boldsymbol{\Psi}}}\widetilde{\delta}(\boldsymbol{k}_1)e^{-i\boldsymbol{k}_2\cdot\overline{\boldsymbol{\Psi}}}\widetilde{\delta}(\boldsymbol{k}_2)\rangle \\
= \quad & \langle e^{-i\boldsymbol{k}_1\cdot\overline{\boldsymbol{\Psi}}}e^{-i\boldsymbol{k}_2\cdot\overline{\boldsymbol{\Psi}}}\rangle\langle\widetilde{\delta}(\boldsymbol{k}_1)\widetilde{\delta}(\boldsymbol{k}_2)\rangle \\
= \quad & (2\pi)^3\delta_{\mathrm{D}}\left(\boldsymbol{k}_1+\boldsymbol{k}_2\right)\ P(\boldsymbol{k}_1)
\end{aligned}
$$

**The effect from the IR flow completely cancels out because of translational symmetry (Galilean invariance)**

# IR (high-k limit) cancellation

$$e^{-i\boldsymbol{k}\cdot\overline{\boldsymbol{\Psi}}_{\rm lin}}\, Z^{[1]}(\boldsymbol{k})\,\widetilde{\delta}_{\rm lin}(\boldsymbol{k})$$

$$P_{22} = \int \frac{d^3p_1}{(2\pi)^3}\int\frac{d^3p_2}{(2\pi)^3} \times (2\pi)^3\delta_{\rm D}\left(\mathbf{k}-\mathbf{p}_1-\mathbf{p}_2\right) F^2(\mathbf{p}_1,\mathbf{p}_2)P_{\rm lin}(p_1)P_{\rm lin}(p_2)$$

$$p_1 \gg p_2$$

Shift

$$\rightarrow \quad k^2\sigma^2 P_{\rm lin}(k)$$

$$P_{13}+P_{22}\rightarrow 0$$

# IR (high-k limit) cancellation

## Gamma-expansion (all orders)

$$P(\boldsymbol{k}) = G^2(\boldsymbol{k})\, P_{\rm lin}(k) + P_{\rm MC}(\boldsymbol{k})$$

$$\mathcal{D}^2(\mathbf{k})[Z^{[1]}(\mathbf{k})]^2 P_{\rm lin}(k)$$

$$\left[1 - \mathcal{D}^2(\boldsymbol{k})\right]\left[Z^{[1]}(\boldsymbol{k})\right]^2 P_{\rm lin}(k)$$

$$\to \left[Z^{[1]}(\boldsymbol{k})\right]^2 P_{\rm lin}(k)$$

# The IR flow never affects the power spectrum??

**To extract physical effects from the IR flow, the breaking of the IR cancellation should be considered.**

# Breaking of the IR (high-k limit) cancellation

$$P_{22} = \int \frac{d^3p_1}{(2\pi)^3} \int \frac{d^3p_2}{(2\pi)^3} \times (2\pi)^3 \delta_{\rm D}\left(\mathbf{k} - \mathbf{p}_1 - \mathbf{p}_2\right) F^2(\mathbf{p}_1, \mathbf{p}_2) P_{\rm lin}(p_1) P_{\rm lin}(p_2)$$

$$p_1 \gg p_2$$

Too strong

$$\to \quad k^2\sigma^2 P_{\rm lin}(k)$$

# Breaking of the IR (high-k limit) cancellation

$$P_{22} = \int \frac{d^3p_1}{(2\pi)^3} \int \frac{d^3p_2}{(2\pi)^3} \times (2\pi)^3 \delta_{\rm D}(\mathbf{k} - \mathbf{p}_1 - \mathbf{p}_2) F^2(\mathbf{p}_1, \mathbf{p}_2) P_{\rm lin}(p_1) P_{\rm lin}(p_2)$$

$$p_1 \gg p_2$$

Too strong

$$\rightarrow \quad k^2\sigma^2 P_{\rm nw}(k)$$

# Eisenstein's template

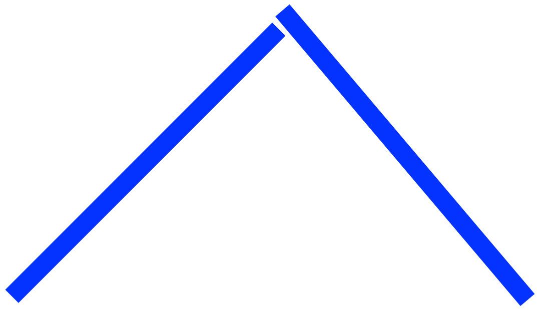
$$P(\boldsymbol{k}) = G^2(\boldsymbol{k})\, P_{\rm lin}(k) + P_{\rm MC}(\boldsymbol{k})$$

$$\mathcal{D}^2(\mathbf{k})[Z^{[1]}(\mathbf{k})]^2 P_{\rm lin}(k)$$

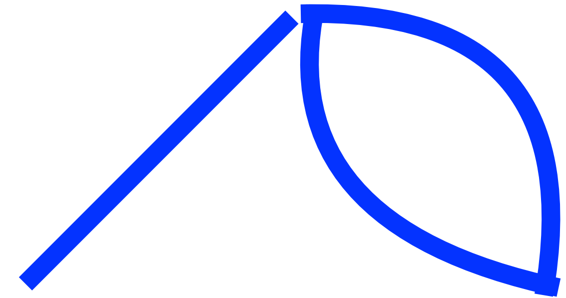
$$\left[1 - \mathcal{D}^2(\boldsymbol{k})\right] \left[Z^{[1]}(\boldsymbol{k})\right]^2 P_{\rm nw}(k)$$

$$P(\boldsymbol{k},\hat{n}) = \left[Z^{[1]}(\boldsymbol{k},\hat{n})\right]^2 \left[\mathcal{D}^2(\boldsymbol{k},\hat{n})\, P_{\rm BAO}(k) + P_{\rm nw}(k)\right]$$

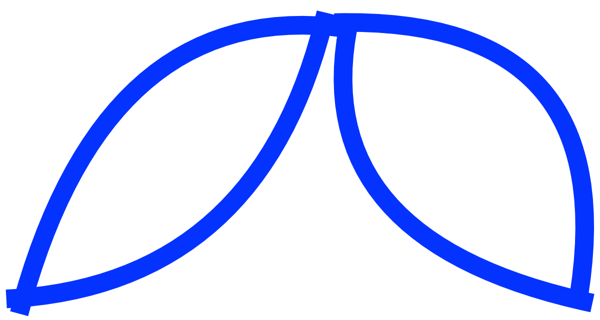
# Bispectrum case



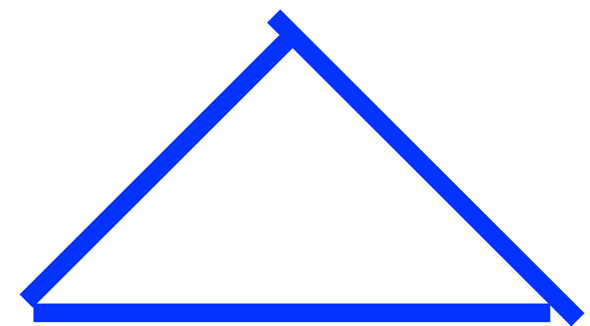
$$\mathcal{D}(\boldsymbol{k}_1)\mathcal{D}(\boldsymbol{k}_2)\mathcal{D}(\boldsymbol{k}_{12})B_{\rm tree}(\boldsymbol{k}_1,\boldsymbol{k}_2)$$



$$\left(\mathcal{D}^2(\boldsymbol{k}_1)-\mathcal{D}(\boldsymbol{k}_1)\mathcal{D}(\boldsymbol{k}_2)\mathcal{D}(\boldsymbol{k}_{12})\right)B_{\rm tree}(\boldsymbol{k}_1,\boldsymbol{k}_2)$$



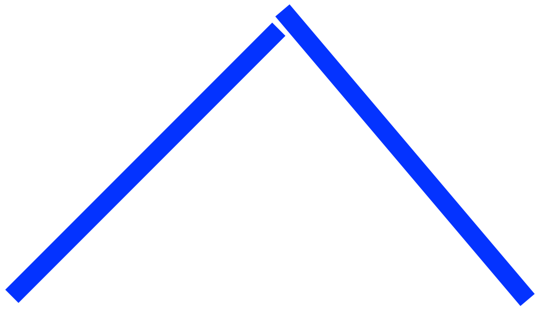
$$\Big(\mathcal{D}(\boldsymbol{k}_1)\mathcal{D}(\boldsymbol{k}_2)\mathcal{D}^{-1}(\boldsymbol{k}_{12})-\mathcal{D}^2(\boldsymbol{k}_1)-\mathcal{D}^2(\boldsymbol{k}_2)$$
$$+\mathcal{D}(\boldsymbol{k}_1)\mathcal{D}(\boldsymbol{k}_2)\mathcal{D}(\boldsymbol{k}_{12})\Big)B_{\rm tree}(\boldsymbol{k}_1,\boldsymbol{k}_2)$$



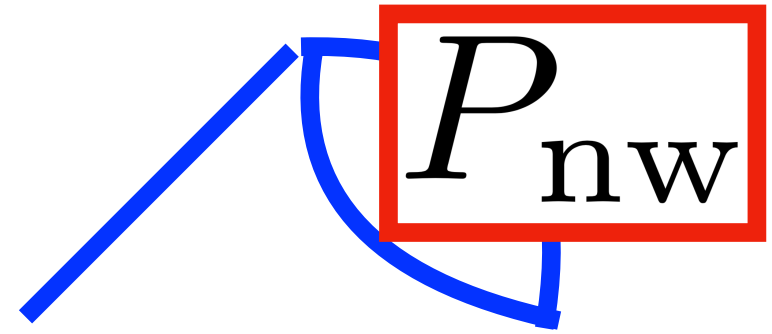
$$\left(1-\mathcal{D}(\boldsymbol{k}_1)\mathcal{D}(\boldsymbol{k}_2)\mathcal{D}^{-1}(\boldsymbol{k}_{12})\right)B_{\rm tree}(\boldsymbol{k}_1,\boldsymbol{k}_2)$$

➡ **Tree-level solution**

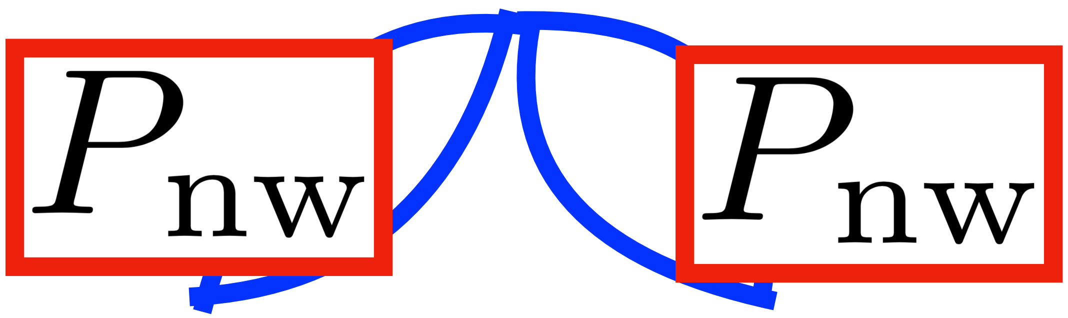
# Bispectrum case



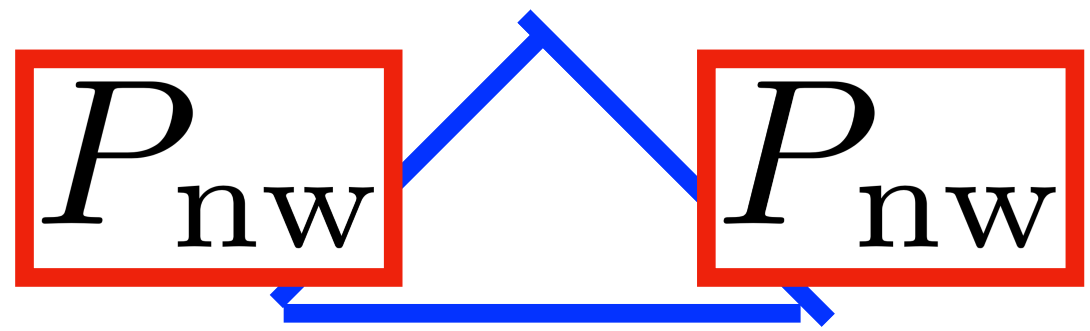
$$\mathcal{D}(\boldsymbol{k}_1)\mathcal{D}(\boldsymbol{k}_2)\mathcal{D}(\boldsymbol{k}_{12})B_{\rm tree}(\boldsymbol{k}_1,\boldsymbol{k}_2)$$




$$\left(\mathcal{D}^2(\boldsymbol{k}_1)-\mathcal{D}(\boldsymbol{k}_1)\mathcal{D}(\boldsymbol{k}_2)\mathcal{D}(\boldsymbol{k}_{12})\right)B_{\rm tree}(\boldsymbol{k}_1,\boldsymbol{k}_2)$$




$$\Big(\mathcal{D}(\boldsymbol{k}_1)\mathcal{D}(\boldsymbol{k}_2)\mathcal{D}^{-1}(\boldsymbol{k}_{12})-\mathcal{D}^2(\boldsymbol{k}_1)-\mathcal{D}^2(\boldsymbol{k}_2)$$
$$+\mathcal{D}(\boldsymbol{k}_1)\mathcal{D}(\boldsymbol{k}_2)\mathcal{D}(\boldsymbol{k}_{12})\Big)B_{\rm tree}(\boldsymbol{k}_1,\boldsymbol{k}_2)$$




$$\Big(1-\mathcal{D}(\boldsymbol{k}_1)\mathcal{D}(\boldsymbol{k}_2)\mathcal{D}^{-1}(\boldsymbol{k}_{12})\Big)B_{\rm tree}(\boldsymbol{k}_1,\boldsymbol{k}_2)$$

# Model

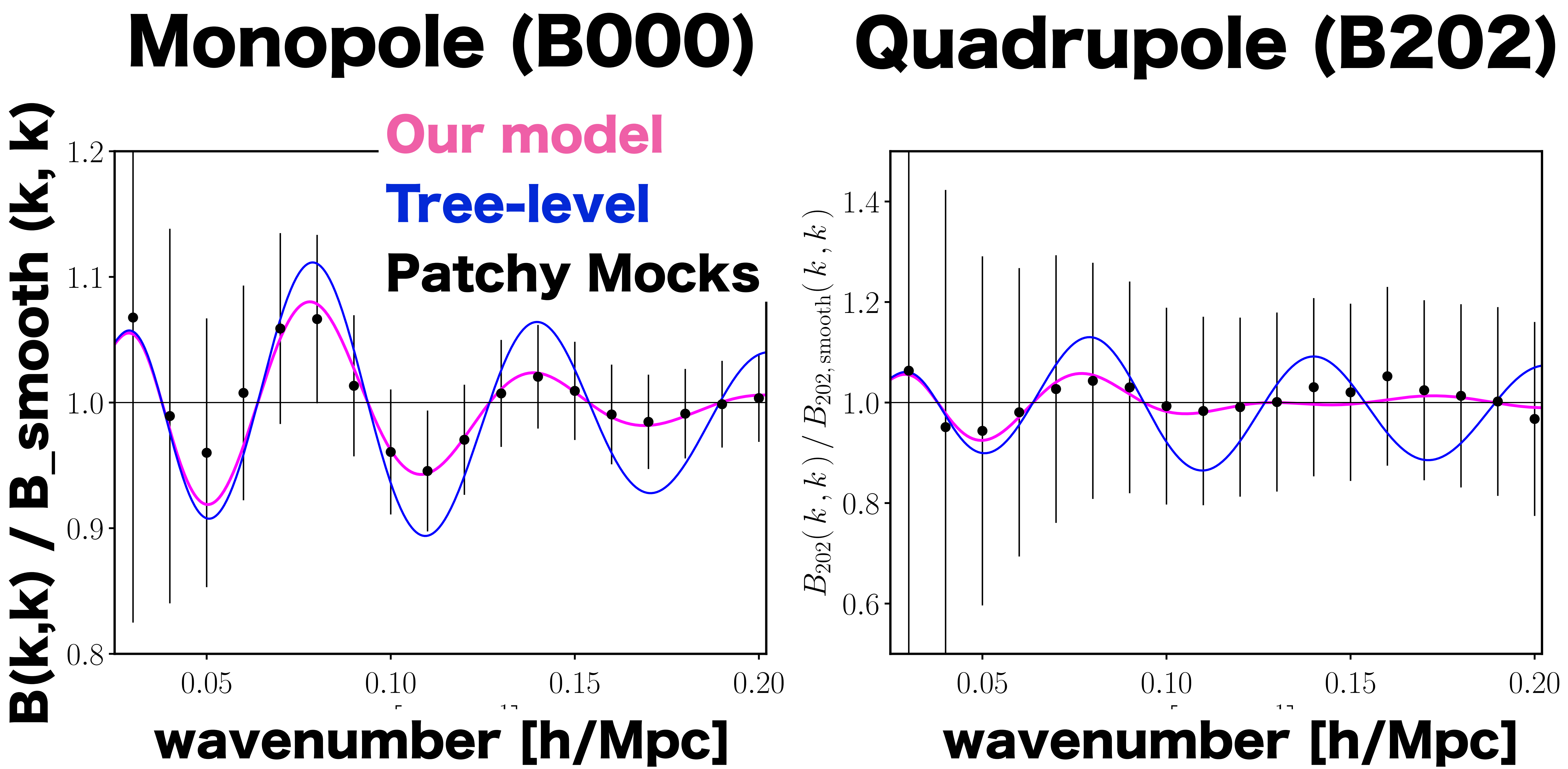
$$B(\boldsymbol{k}_1, \boldsymbol{k}_2)$$
$$= 2\, Z^{[1]}(\boldsymbol{k}_1) Z^{[1]}(\boldsymbol{k}_2) Z^{[2]}(\boldsymbol{k}_1, \boldsymbol{k}_2)$$
$$\times \Big\{ \mathcal{D}(\boldsymbol{k}_1)\mathcal{D}(\boldsymbol{k}_2)\mathcal{D}(\boldsymbol{k}_{12}) \underline{P_{\rm BAO}(k_1) P_{\rm BAO}(k_2)}$$
$$+\mathcal{D}^2(\boldsymbol{k}_1) P_{\rm BAO}(k_1) P_{\rm nw}(k_2) + \mathcal{D}^2(\boldsymbol{k}_2) \underline{P_{\rm nw}(k_1) P_{\rm BAO}(k_2)}$$
$$\underline{+P_{\rm nw}(k_1) P_{\rm nw}(k_2)} \Big\} + 2 \text{ cyc..}$$

$$\mathcal{D}(\boldsymbol{k}, \hat{n}) = \exp\left( -\frac{k^2 \mu^2 \Sigma_\parallel^2 + k^2 \left(1-\mu^2\right) \Sigma_\perp^2}{4} \right)$$

$$P_{\rm BAO}(k) = P_{\rm lin}(k) - P_{\rm nw}(k)$$

# BAO damping

$$B_{000}(k,k) = B_{\mathrm{BAO},\,000}(k,k) + B_{\mathrm{nw},\,000}(k,k)\left[ak + bk^2 + ck^3\right]$$



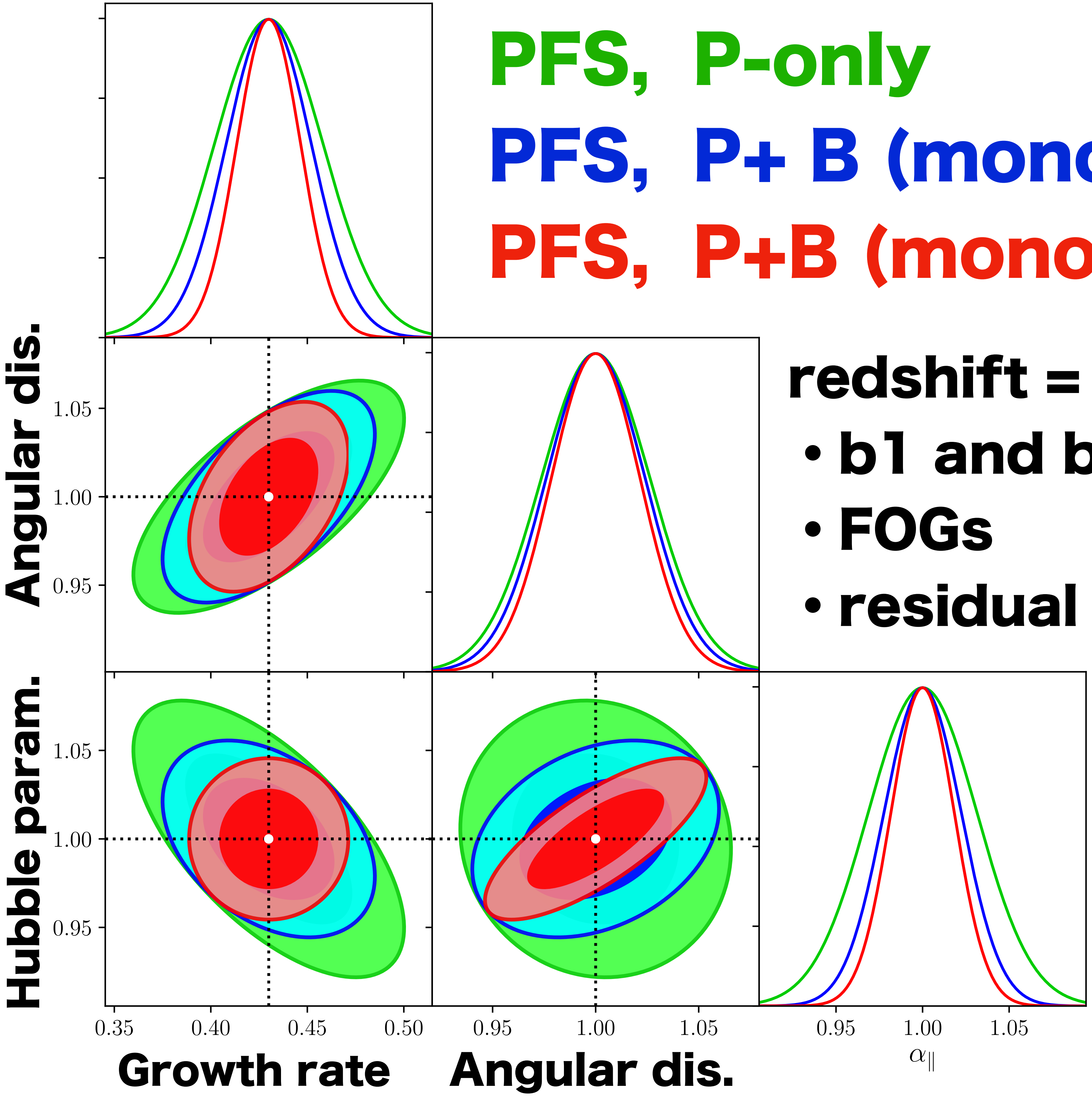
# Bispectrum model for the fisher analysis

**Power spectrum and bispectrum:**

Tree-level

+ non-linear BAO damping
+ Gaussian FOG ← non-linear RSD
+ local bias (b1, b2) ← non-linear bias
+ residual shot-noise terms

# Fisher analysis for PFS

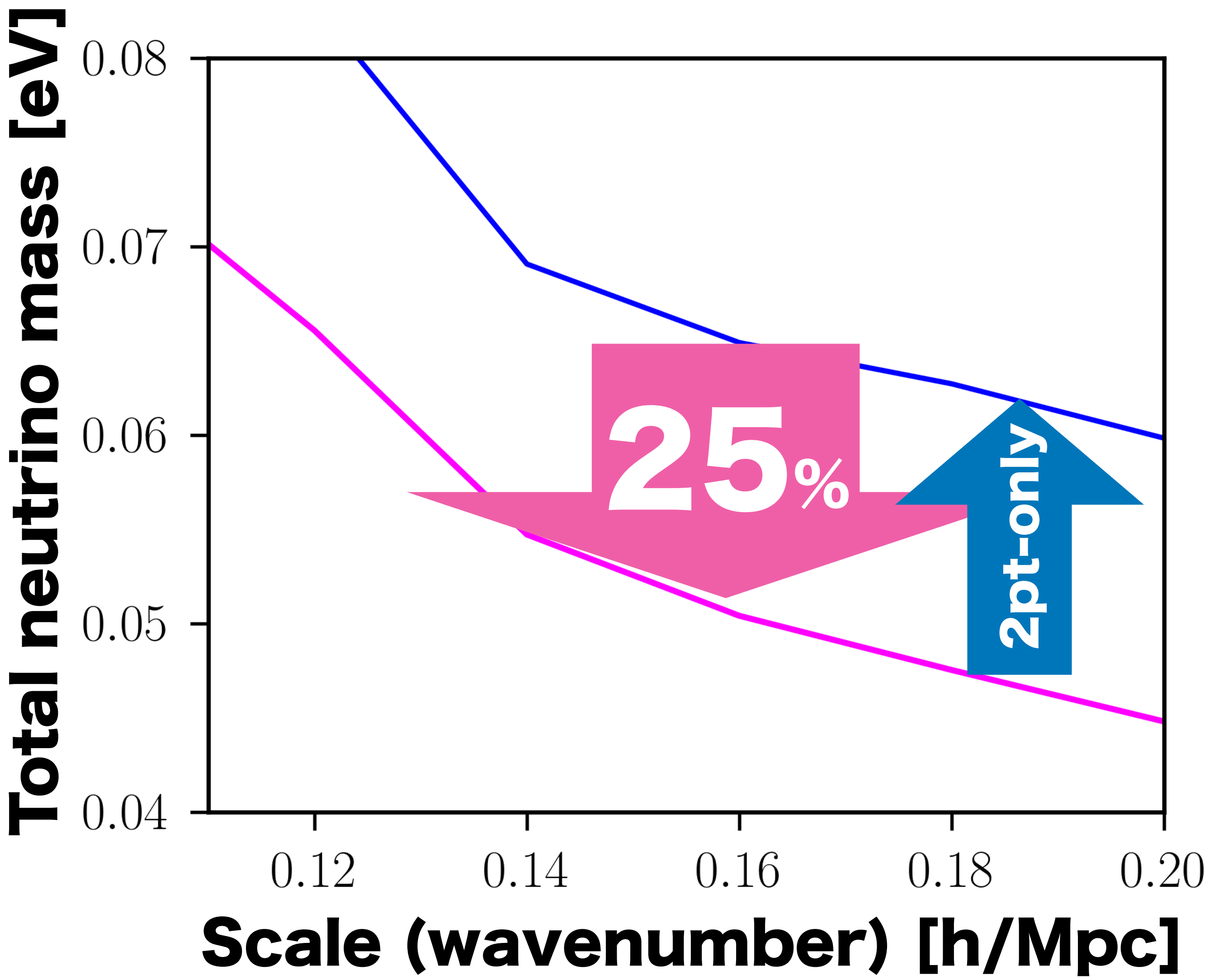



redshift = 1.1

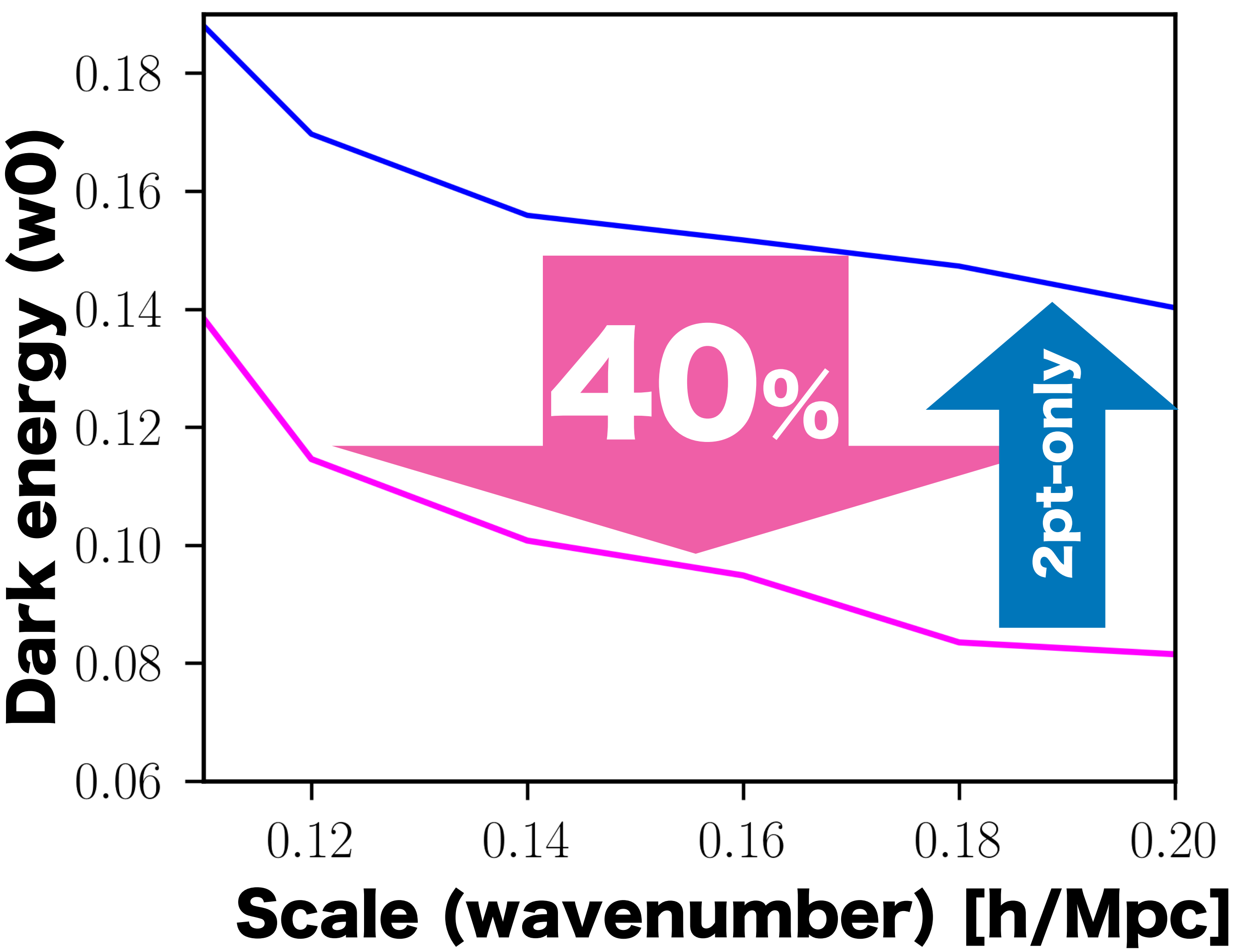
- b1 and b2
- FOGs
- residual shot noises

# PFS Project
# (0.6 < z < 2.2)

## Total neutrino mass




## Dark energy



# Bispectrum Project

## [1] NS, Saito, Beutler and Seo 2018

- A new decomposition formalism
- Detection of the quadrupole bispectrum (14$\sigma$)

## [2] In progress

This talk

- Modeling the bispectrum covariance
- Fisher analysis
- Modeling the anisotropic bispectrum

## [3] Future works

- Analysis using BOSS data

## Final goal

- Application to future galaxy survey, PFS, DESI and Euclid.