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Cosmological information in the redshift-space bispectrum

with Cristiano Porciani

Yankelevich & Porciani arXiv:1807.07076

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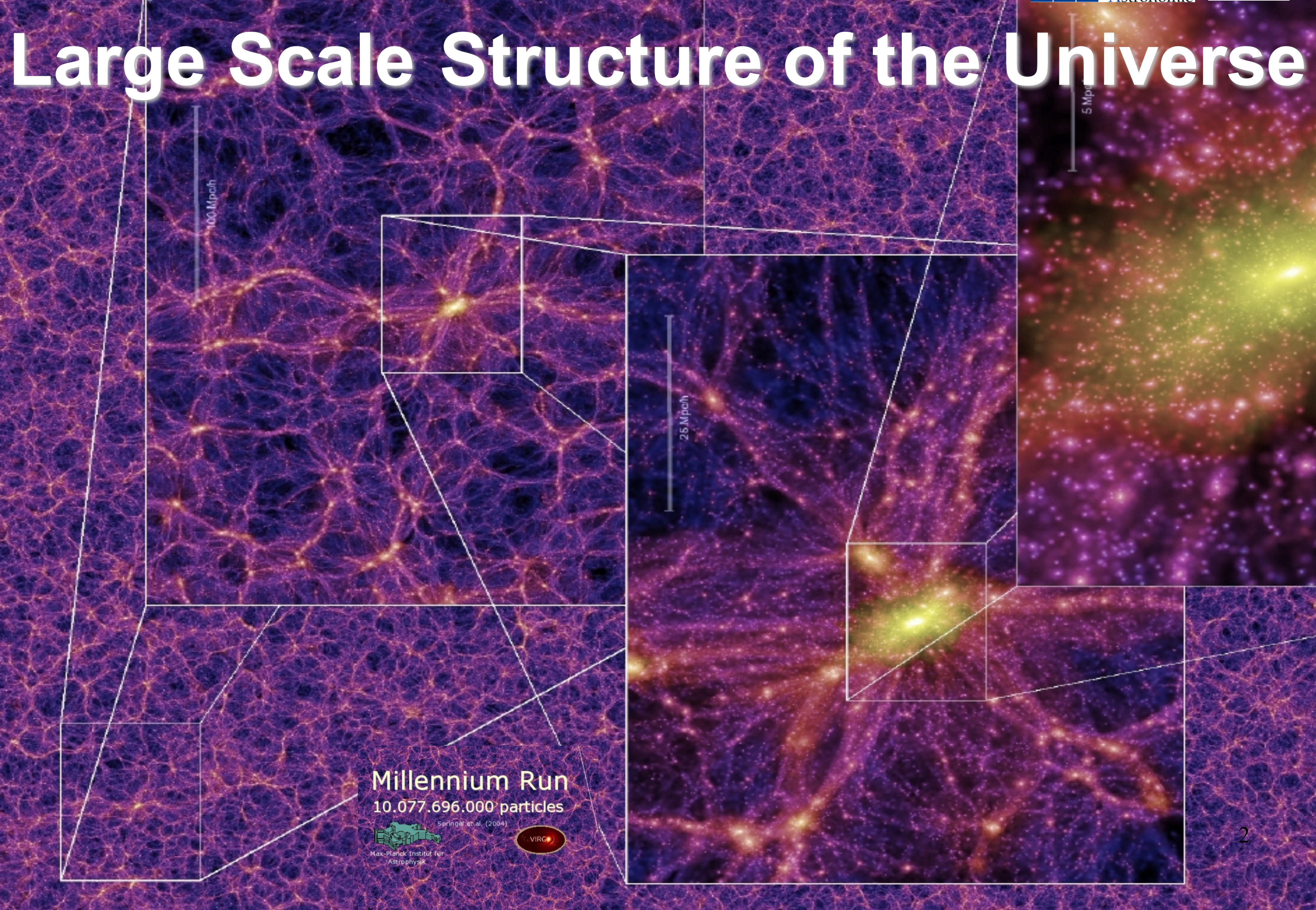
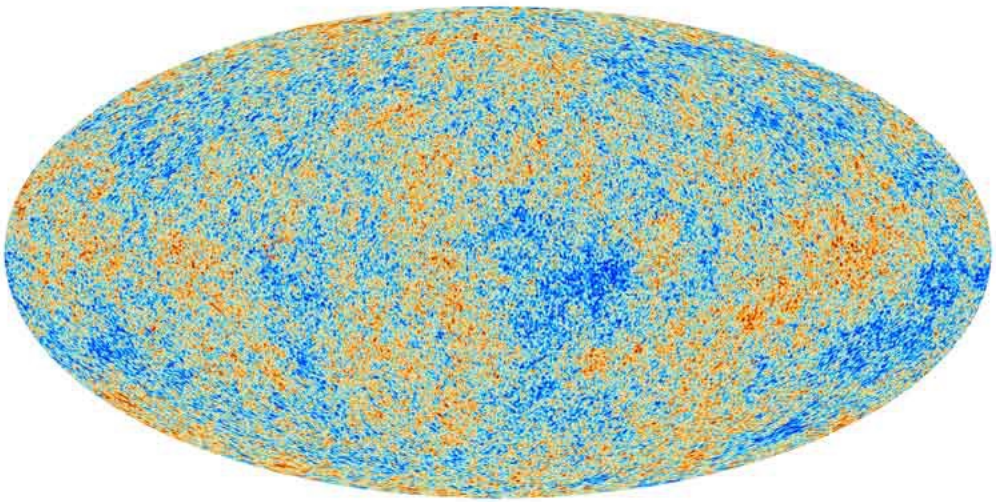
Large Scale Structure of the Universe



Large Scale Structure of the Universe

Cosmic Microwave Background (CMB)



$$\left|\frac{\Delta\rho}{\rho}\right| \leq 10^{-5}$$

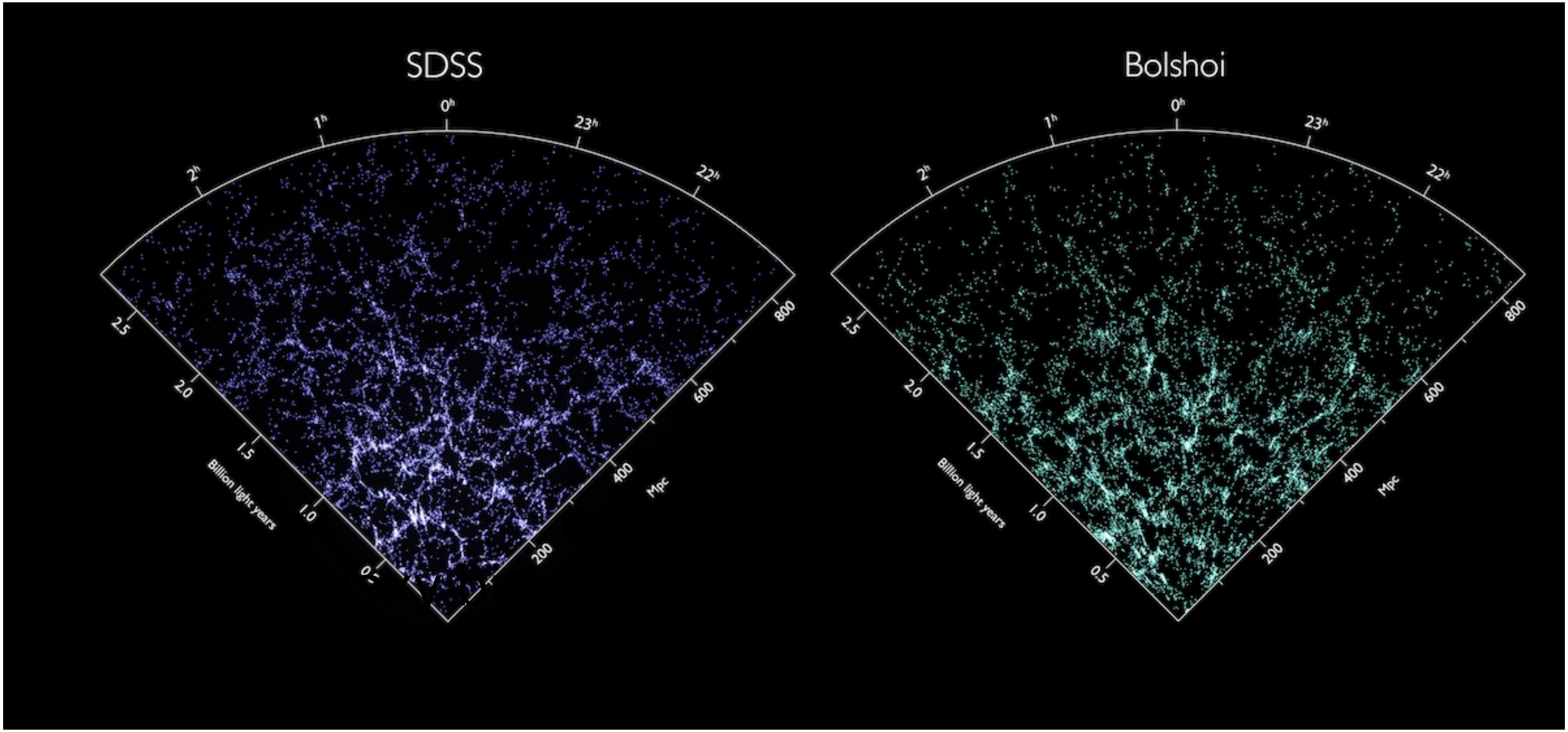
Galaxy

$$\left|\frac{\Delta\rho}{\rho}\right| \geq 200$$

Initial conditions ?

Galaxy bias

b_1 – linear, b_2 non – linear, b_{s^2} – tidal biases



Power spectrum

$$\delta(\vec{x},\tau)=\frac{\rho(\vec{x},\tau)-\bar{\rho}(\tau)}{\bar{\rho}(\tau)}$$

density contrast

$$\tilde{\delta}(\mathbf{k})=\int d^3\mathbf{x}\,\delta(\mathbf{x})e^{i\mathbf{k}\cdot\mathbf{x}}$$

Fourier transform

$$\left\langle\tilde{\delta}(\mathbf{k})\tilde{\delta}(\mathbf{k}')\right\rangle=(2\pi)^3\,\delta^D(\mathbf{k}+\mathbf{k}')\mathrm{P}(\mathrm{k})$$

$$\mathrm{P}(\mathbf{k})\sim\left\langle\left|\tilde{\delta}(\mathbf{k})\right|^2\right\rangle$$

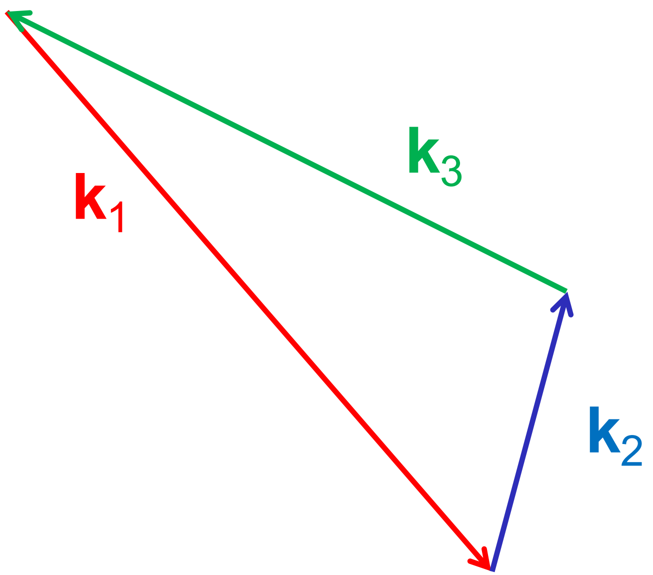
loosing phase

Bispectrum

$$\left\langle \delta_{\mathbf{x}_1} \delta_{\mathbf{x}_2} \delta_{\mathbf{x}_3} \right\rangle = \xi\left(\mathbf{r}_{12}, \mathbf{r}_{23}, \mathbf{r}_{31}\right)$$

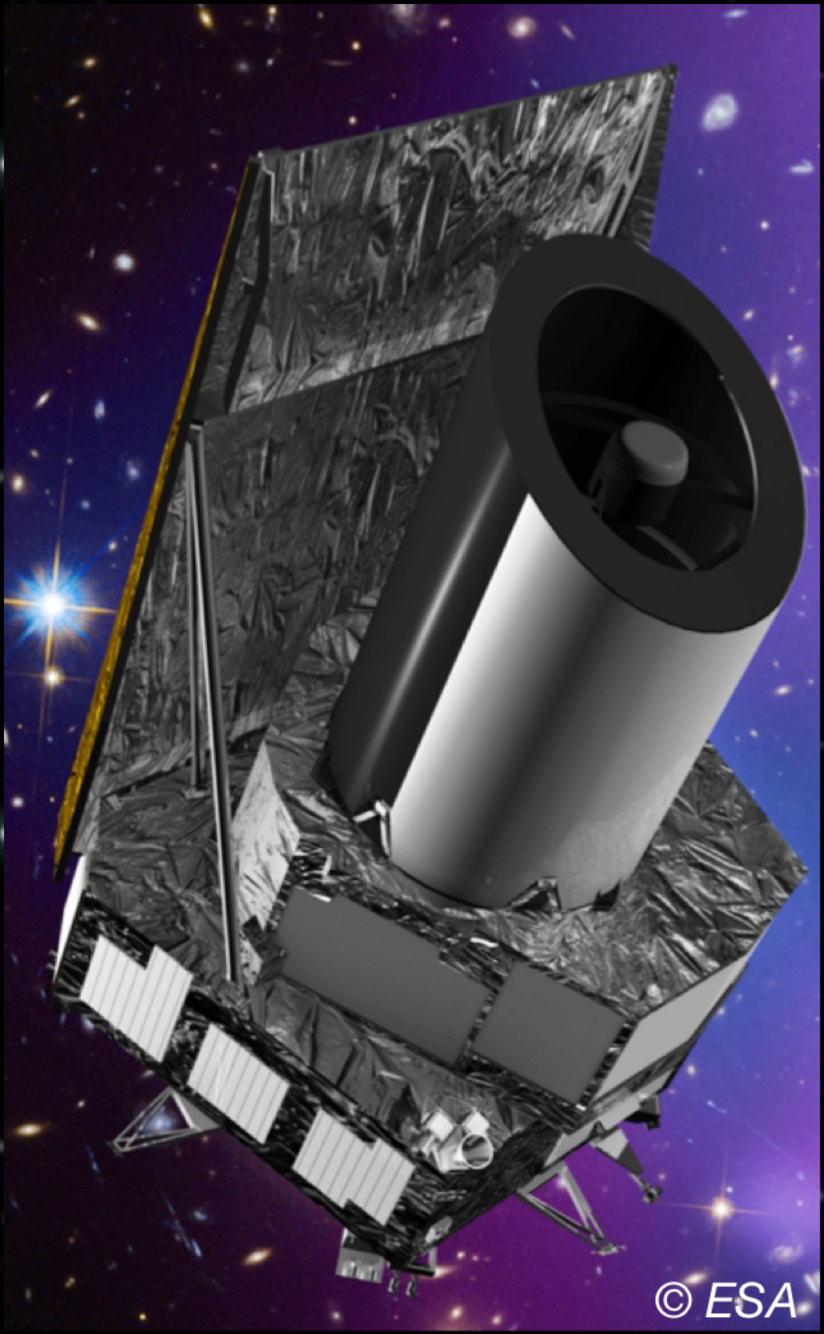
3-point correlation function

$$\left\langle \tilde{\delta}(\mathbf{k}_1)\tilde{\delta}(\mathbf{k}_2)\tilde{\delta}(\mathbf{k}_3)\right\rangle = (2\pi)^3 \delta^D(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) B(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)$$



$$\mathbf{r}_{ij} = \left|\mathbf{x}_i - \mathbf{x}_j\right|$$

ESA's Euclid mission



Year 2021

The nature of dark energy and dark matter

Galaxies and clusters of galaxies out to z~2

Visible and near-infrared wavelength

Aim of the work

Make forecasts for the cosmological parameters for *Euclid*-like survey

$$\Lambda\text{CDM model}: \ \Omega_m, \Omega_b, \ n, \ h, \ A, \sigma_p, b_1, b_2, b_{s^2}$$

$$\text{wCDM model}: \ w, \Omega_m, \Omega_b, \ n, \ h, \ A, \sigma_p, b_1, b_2, b_{s^2}$$

$$w_0 w_a\text{CDM model}: \ w_0, w_a, \Omega_m, \Omega_b, \ n, \ h, \ A, \sigma_p, b_1, b_2, b_{s^2}$$

Perturbation theory (leading order)

Advantages of the combination of the power spectrum and the bispectrum in comparison with a single probe

IMPRS astronomy & astrophysics Bonn and Cologne · Euclid consortium · TR 33 The Dark Universe Bonn München Heidelberg · Argelander-Institut für Astronomie · bcgs Bonn-Cologne Graduate School of Physics and Astronomy

Power Spectrum

$$\left\langle \tilde{\delta}(\mathbf{k})\tilde{\delta}(\mathbf{k}')\right\rangle = (2\pi)^3 \delta^D(\mathbf{k}+\mathbf{k}')\mathrm{P}(\mathrm{k})$$

$$\mathrm{P}(\mathbf{k},\mu) = \mathrm{Z}_1^2(\mathbf{k},\mu)\mathrm{P}_0(\mathrm{k})e^{-\frac{(\mathrm{k}\mu\sigma_p)^2}{2}}, \quad \mathrm{P}_0(\mathrm{k}) -- \text{ from CAMB}$$

$$\mathrm{Z}_1(\mathbf{k},\mu) = \mathrm{b}_1 + \mathrm{f}\mu^2, \quad \mathrm{b}_1 -- \text{Linear galaxy bias parameter}$$

$$\mathrm{f} = [\Omega_\mathrm{m}(\mathrm{z})]^{0.55}, \quad \text{Growth of structure parameter}$$

$$\mu = \frac{\mathrm{k}_\mathrm{z}}{\mathbf{k}}, \quad \text{Cosine between vector and line of sight}$$

k, μ separate bins for k and μ

$$e^{-\frac{(\mathrm{k}\mu\sigma_p)^2}{2}} -- \text{ FoG effect,} \qquad \sigma_p^2 = 2\sigma_v^2 = \frac{f^2}{6\pi^2}\int_0^\infty \mathrm{P}_0(\mathrm{k})d\mathrm{k}$$

Bispectrum

$$\left\langle \tilde{\delta}(\mathbf{k}_1)\tilde{\delta}(\mathbf{k}_2)\tilde{\delta}(\mathbf{k}_3)\right\rangle = (2\pi)^3 \delta^D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)\mathrm{B}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

Perturbation theory (leading order)

$$\mathrm{B}(\mathrm{k}_1,\mathrm{k}_2,\mathrm{k}_3,\mu_1,\varphi) =$$

$$2\left[Z_2(\mathbf{k}_1,\mathbf{k}_2)Z_1(\mathrm{k}_1,\mu_1)Z_1(\mathrm{k}_2,\mu_2)\mathrm{P}_0(\mathrm{k}_1)\mathrm{P}_0(\mathrm{k}_2)+\mathrm{cyc.}\right]\cdot$$

$$\cdot\exp\left[-\left(\mathrm{k}_1^2\mu_1^2+\mathrm{k}_2^2\mu_2^2+\mathrm{k}_3^2\mu_3^2\right)\frac{\sigma_p^2}{2}\right]$$

Galaxy bias parameters:

b_1 – linear, b_2 non–linear, b_{s^2} – tidal bias

Fisher Matrix

$$F_{\alpha\beta} = \sum_{\mathbf{k}}^{\mathbf{k}_{max}} \sum_{\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3}^{\mathbf{k}_{max}} \frac{\partial^t \mathbf{S}}{\partial x_\alpha} C^{-1} \frac{\partial \mathbf{S}}{\partial x_\beta} \qquad \mathbf{S} = \begin{pmatrix} P(\mathbf{k}) \\ B(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) \end{pmatrix}$$

$$\alpha,\beta : \Omega_m, \Omega_b, \text{ n}, \text{ h}, \text{ A}, \sigma_p, b_1, b_2, b_{s^2}, w, w_0, w_a$$

C_{PP} $\qquad$ C_{BB}

$$\mathbf{C}(\text{diag}) = \begin{pmatrix} C_{PP} & 0 \\ 0 & C_{BB} \end{pmatrix} \qquad \mathbf{C} = \begin{pmatrix} C_{PP} & C_{PB} \\ C_{BP} & C_{BB} \end{pmatrix}$$

Covariance matrix

$$C_{PP}=\frac{2\tilde{P}^2(k)}{N_p}$$

$$\tilde{P}(k)=Z_1^2(k,\mu)P(k)e^{-\frac{(k\mu\sigma_p)^2}{2}}+n_g^{-1}$$

$$C_{BB}=s_B\frac{V_s\tilde{P}(k_1)\tilde{P}(k_2)\tilde{P}(k_3)}{N_B}$$

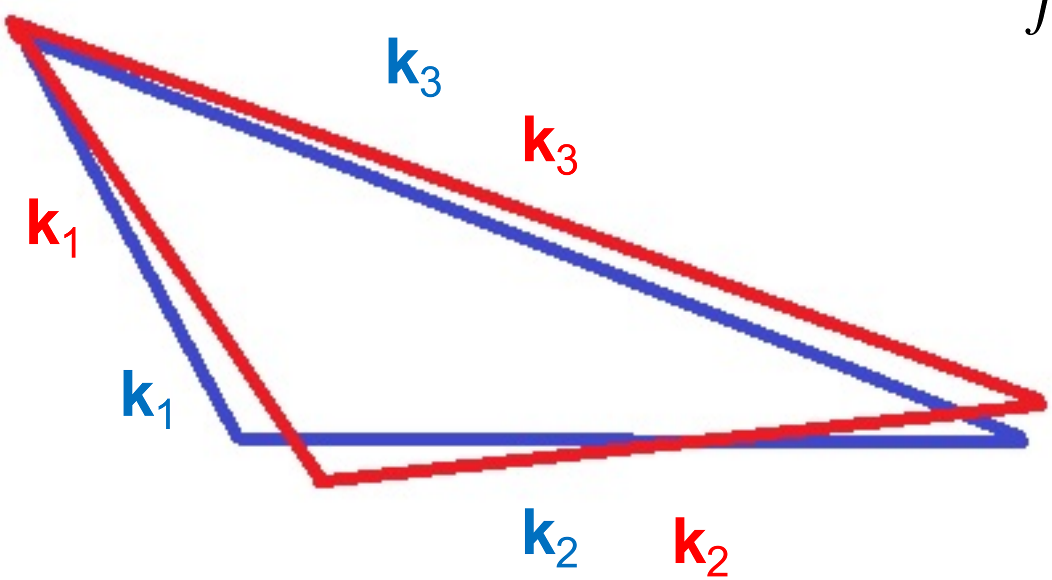
$$C_{PB}=2s_{PB}\frac{\tilde{P}_i(k)\tilde{B}_j(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)}{N_pN_B}\left(I_{ij_1}+I_{ij_2}+I_{ij3}\right)$$

$$\tilde{B}=B+\left[P(k_1)+P(k_2)+P(k_3)\right]/n_g+n_g^{-2}$$

Features=Challenges

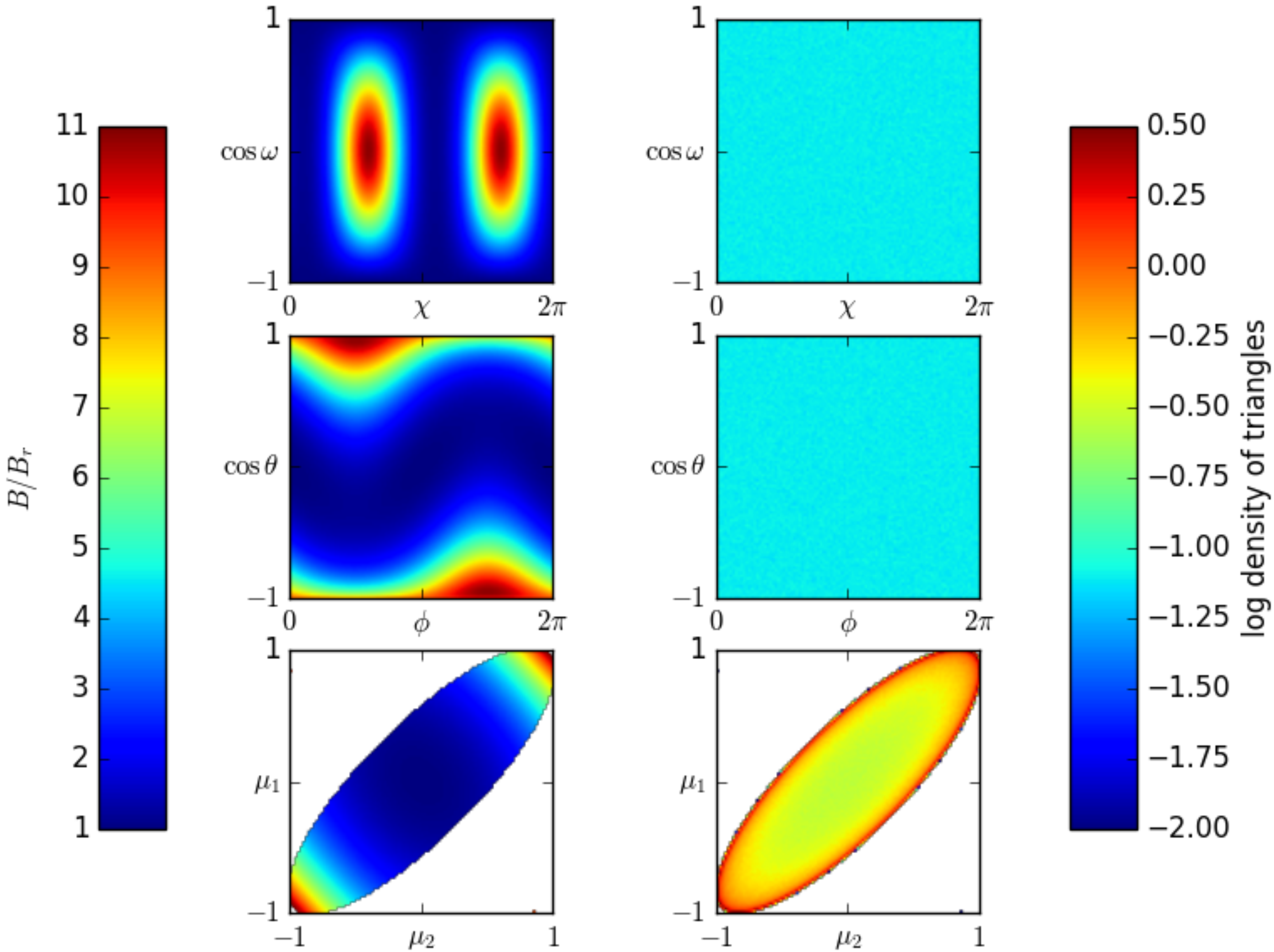
Compressing the information

$$n \cdot k_f \le \begin{matrix} k_3 \\ k_3 \end{matrix} < (n+1) \cdot k_f$$

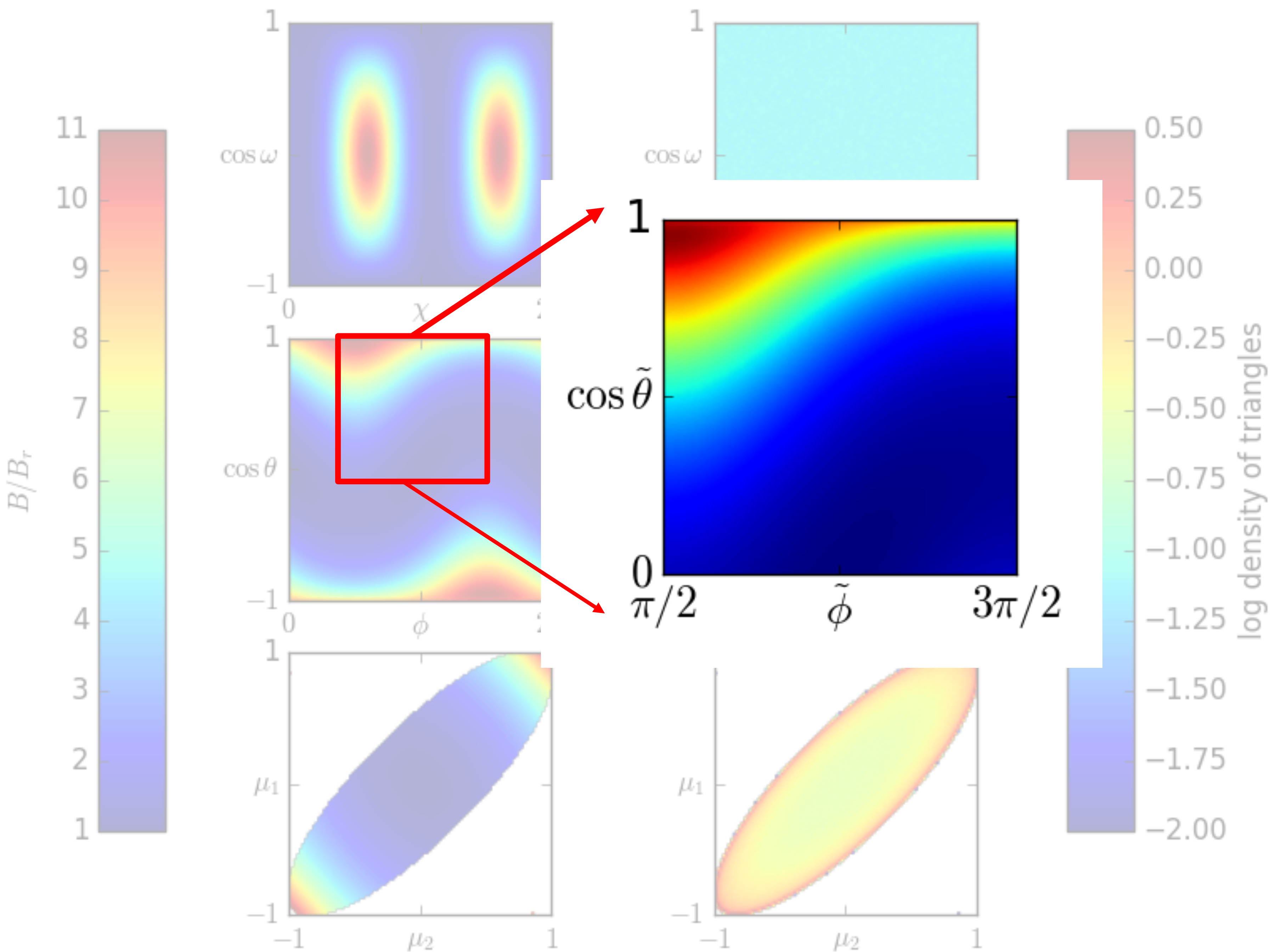


The same bin!!!

Bispectrum symmetry



Bispectrum symmetry



Results:

$$\mathbf{k}_{max} = 0.15\ h\,\mathrm{Mpc}^{-1}$$

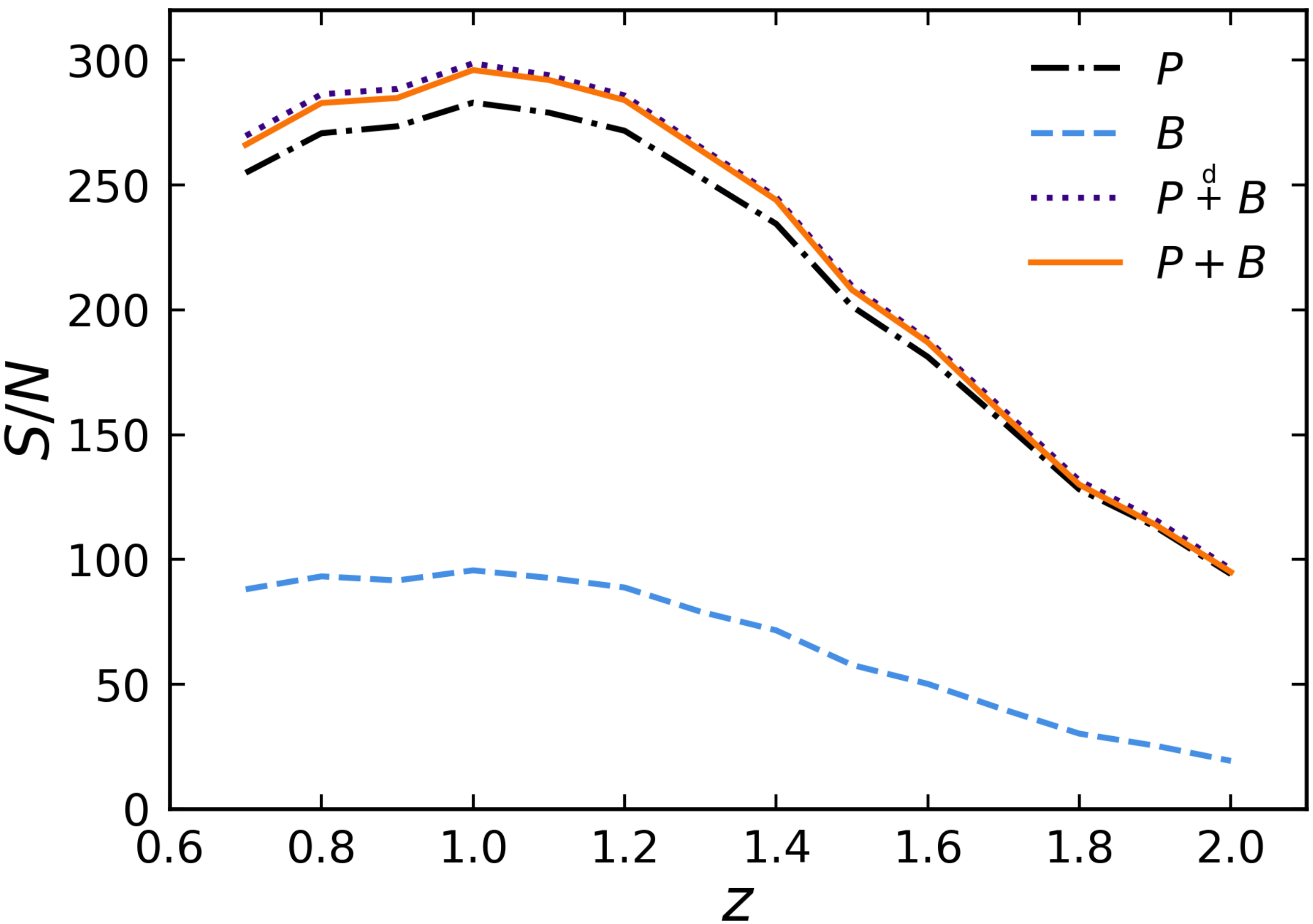
$$k_F = \frac{2\pi}{\sqrt[3]{V_s}}$$

$$\Delta k = k_F$$

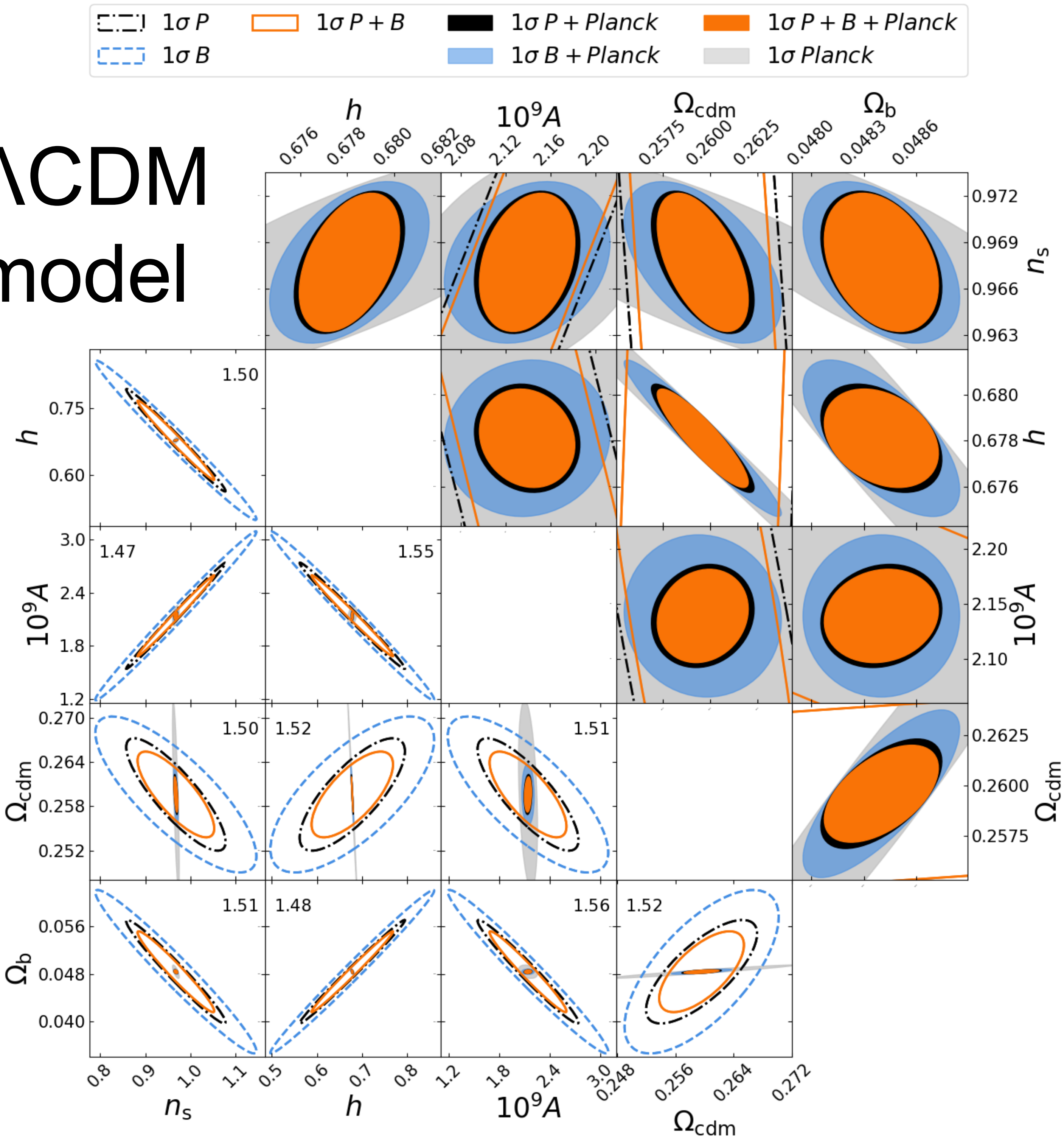
$$N_\mu = 4$$

$$N_{\tilde{\varphi}} = 2$$

Signal-to-Noise



ΛCDM model



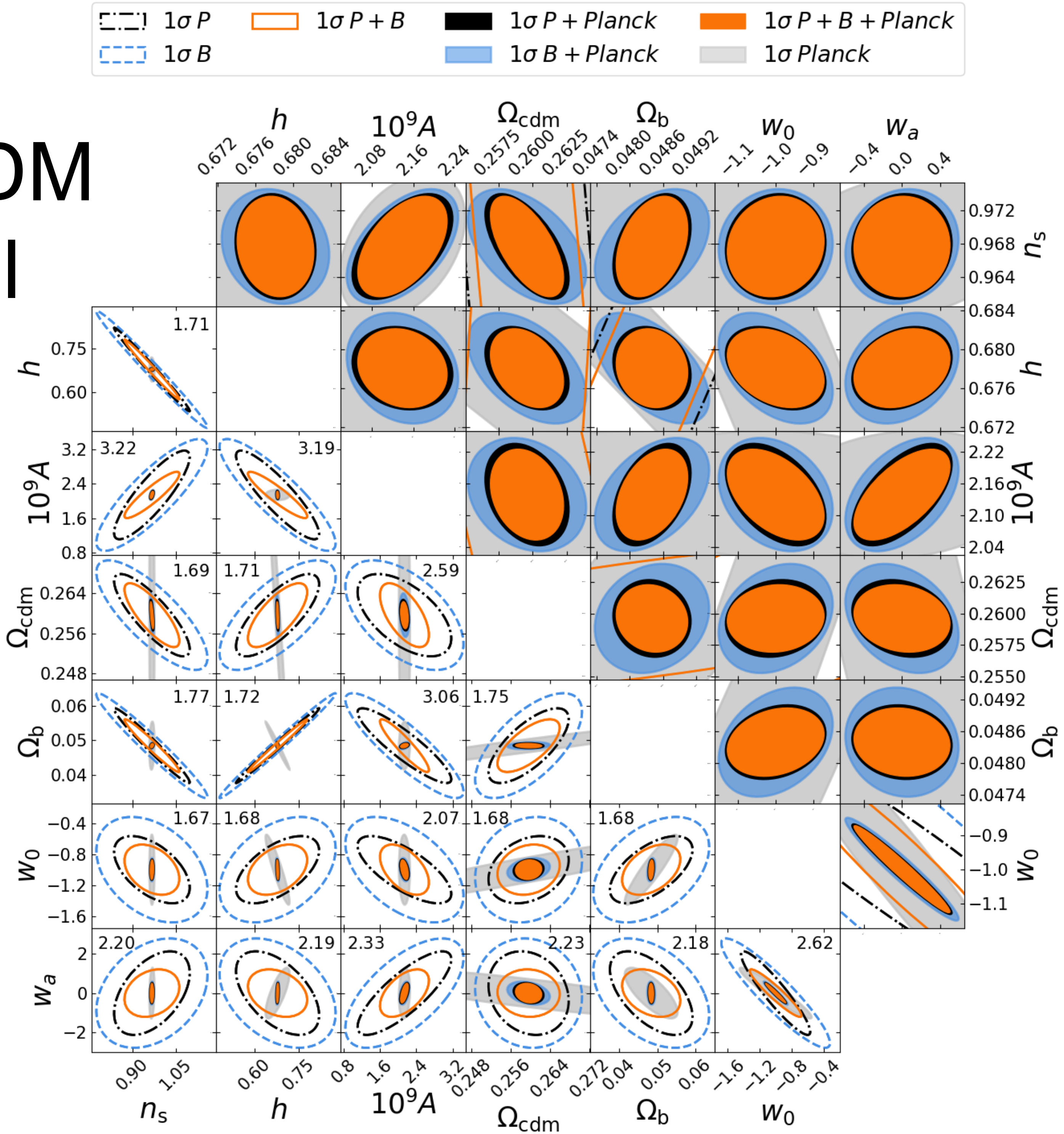
$1\sigma\left(10^3\Omega_{cdm}\right)$

P 5.01
B 6.84
P+B 3.81

with *Planck*

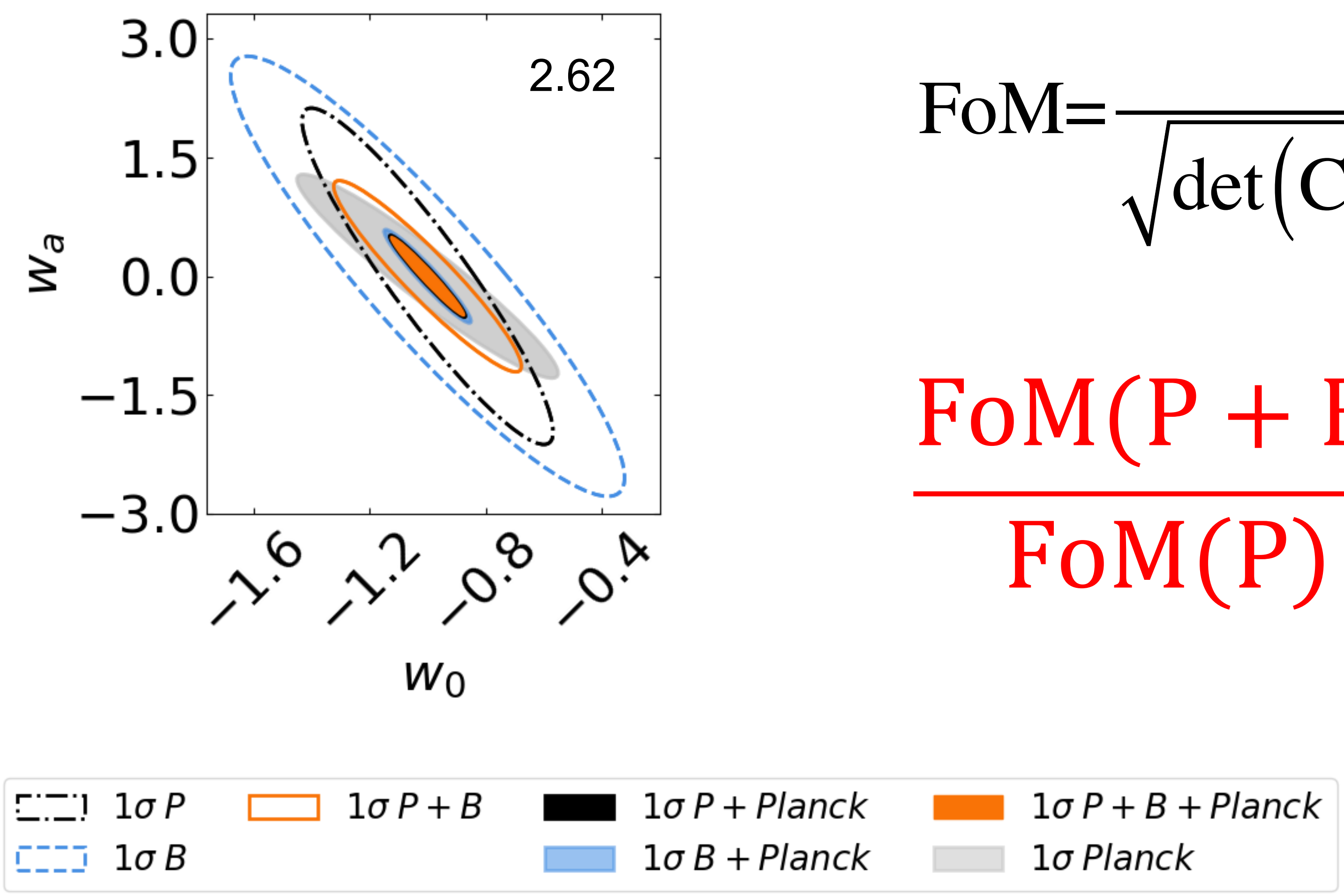
P 1.78
B 2.69
P+B 1.57

$w_0 w_a$CDM model



$w_0 w_a$CDM model

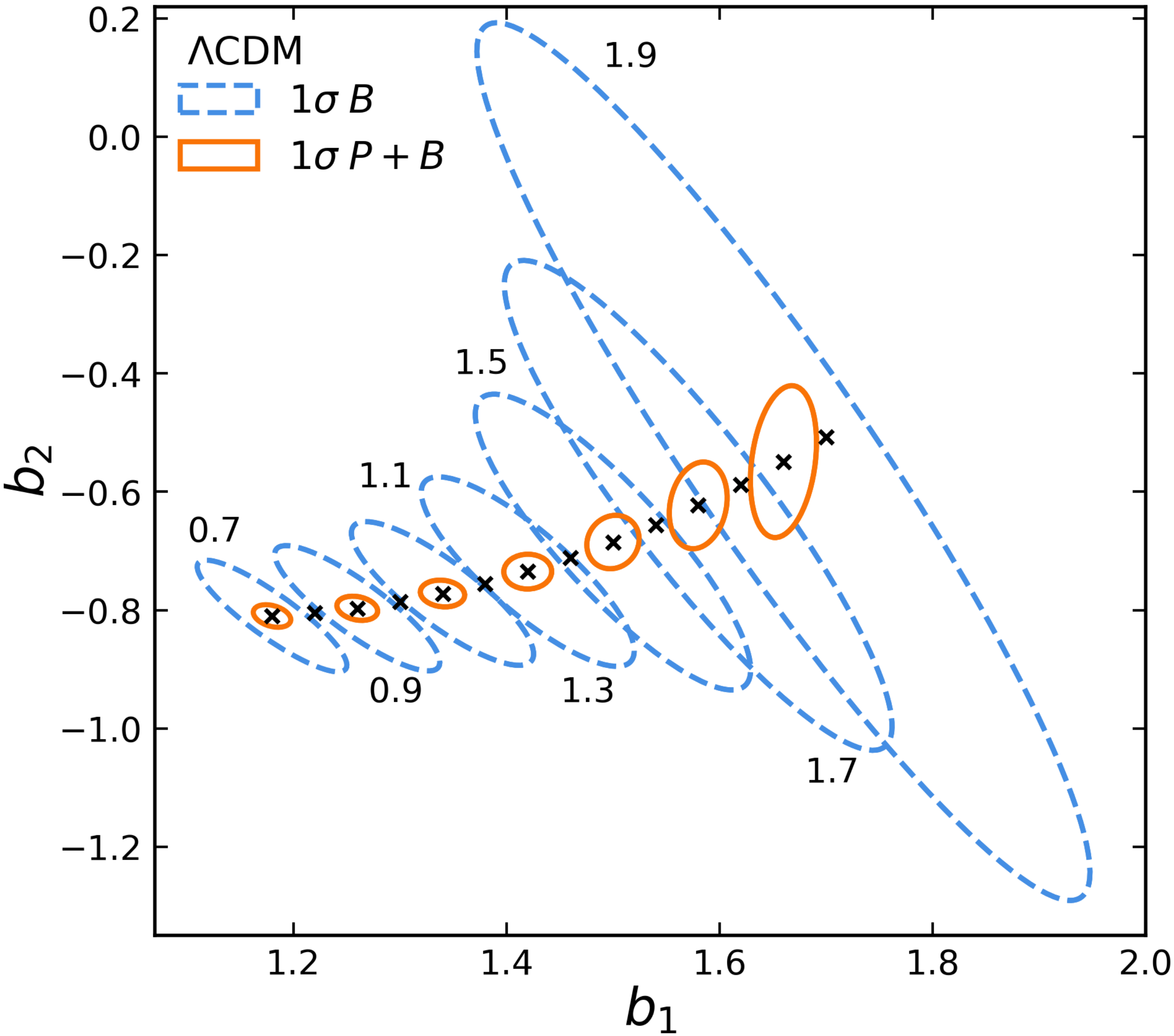
P	B	P + B	P + Planck	B + Planck	P+B + Planck
6.66	3.03	17.43	147.06	93.32	162.49



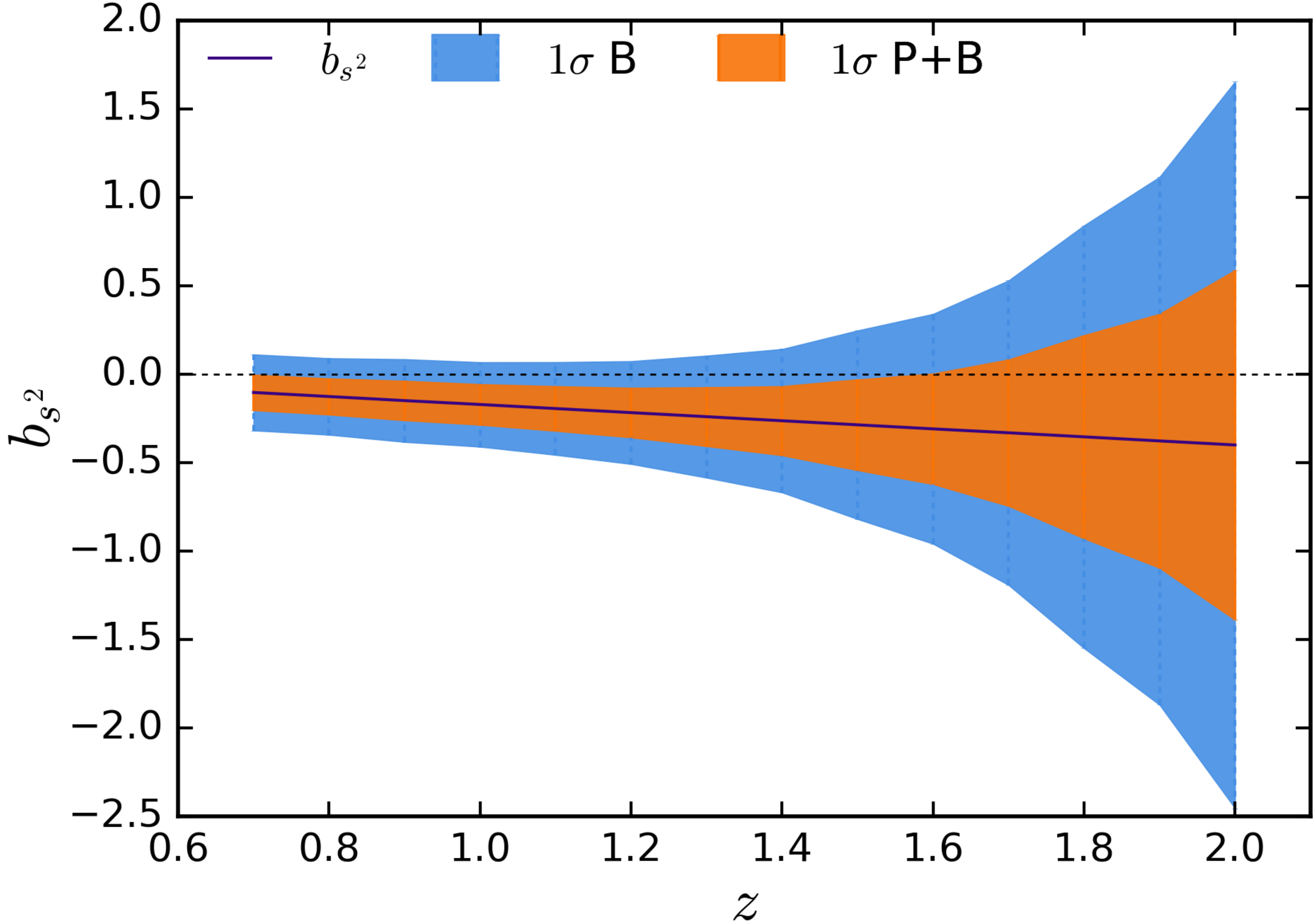
$$\mathrm{FoM} = \frac{1}{\sqrt{\det\left(\mathrm{Cov}\left(w_0 w_a\right)\right)}}$$

$$\frac{\mathrm{FoM}(\mathrm{P}+\mathrm{B})}{\mathrm{FoM}(\mathrm{P})} = 2.62$$

Galaxy bias b_1 b_2

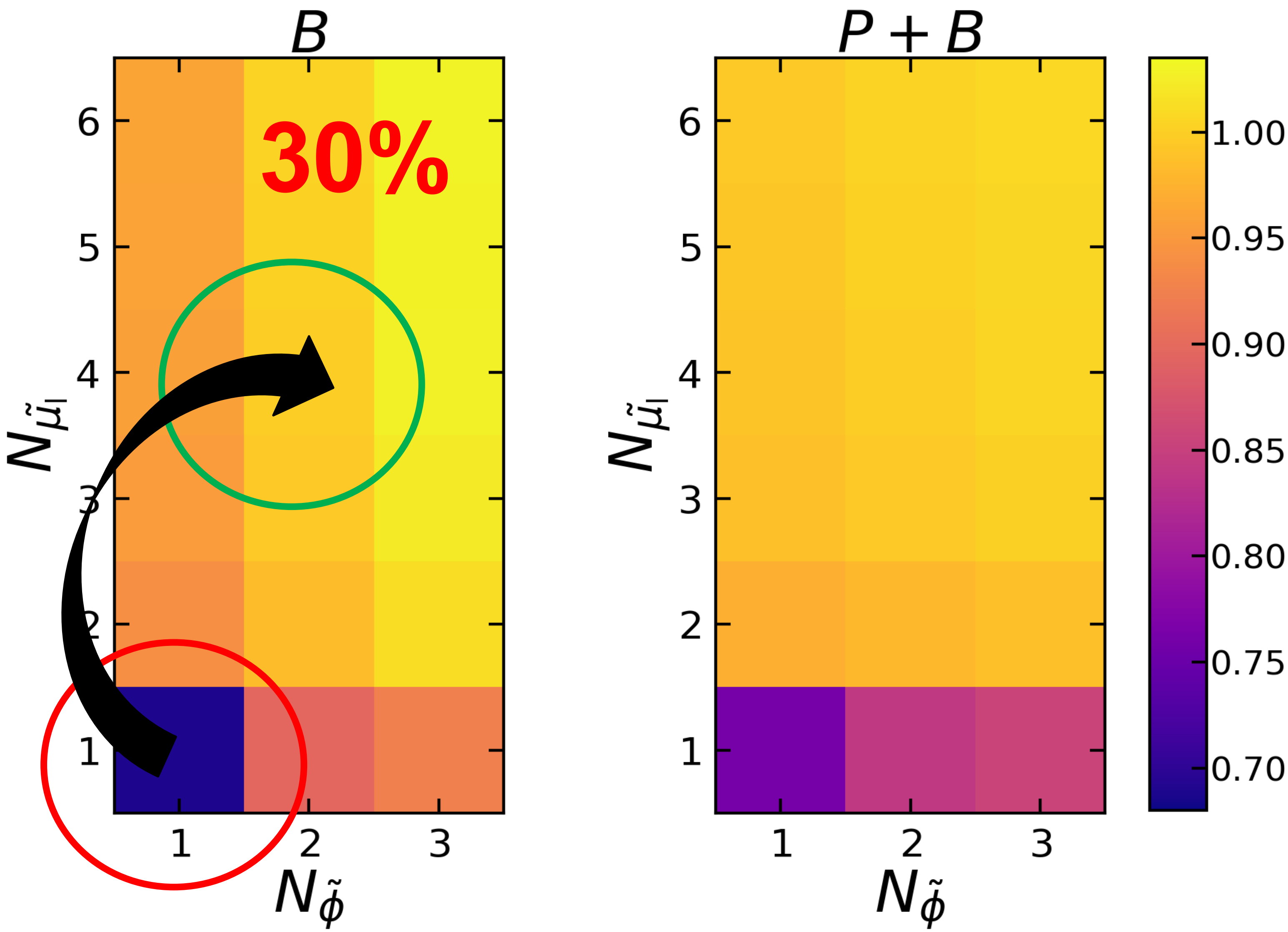


Galaxy bias b_{s2}

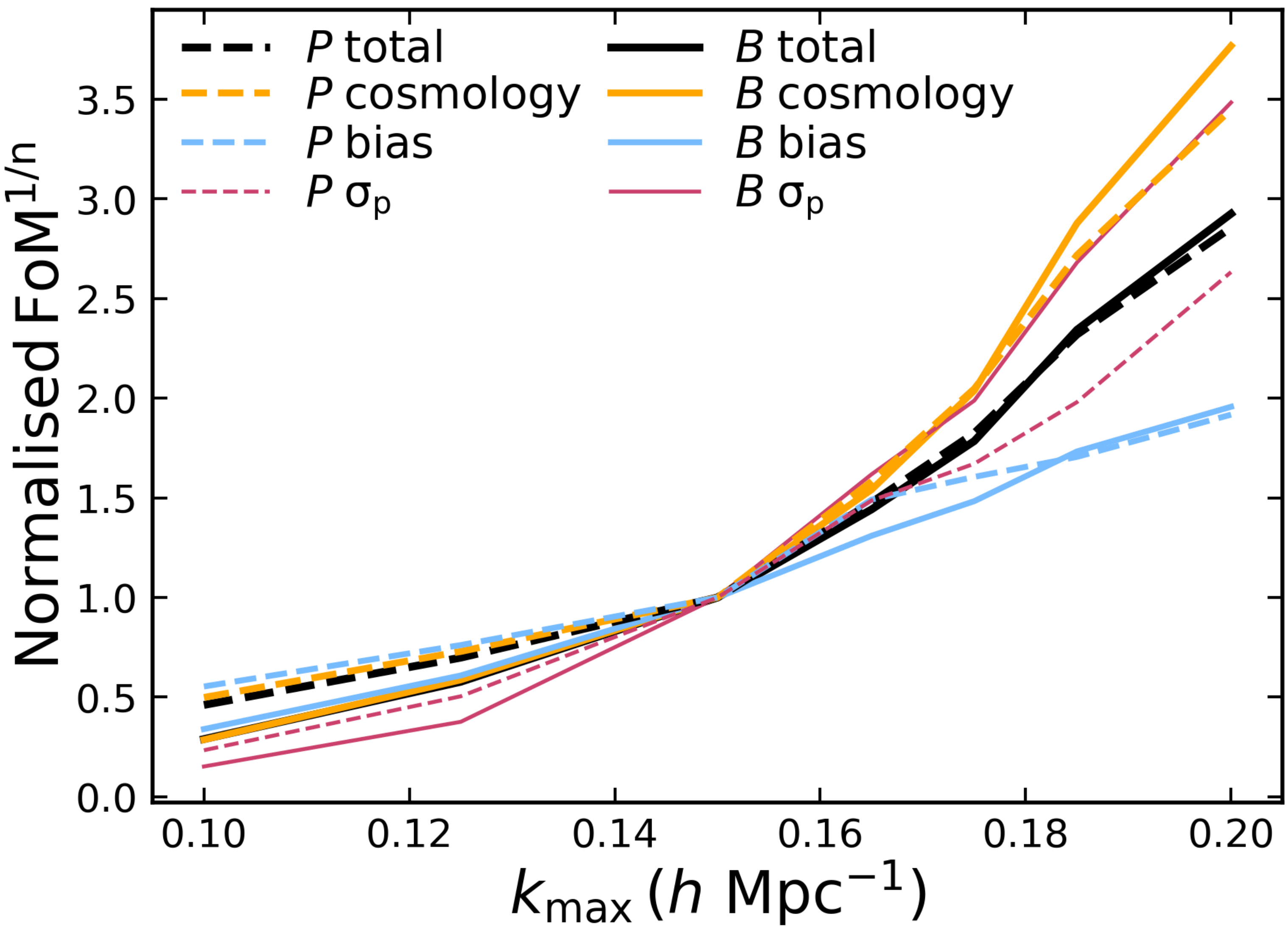


Dependence on orientation binning

$\mathrm{FoM}^{1/n}$



Dependence on k_{max}



Conclusions

Forecast for *Euclid*-like survey (including Planck):

$$\Lambda\text{CDM}, \text{wCDM}, \text{w}_0\text{w}_a\text{CDM models}$$

$$+$$

$$\text{Galaxy bias } b_1, b_2, b_{s^2}$$

Combination of the power spectrum and the bispectrum provides much more accurate results than single probes (2-3 times better!)

Considering only monopole leads to non-negligible loss of information (up to 30%)

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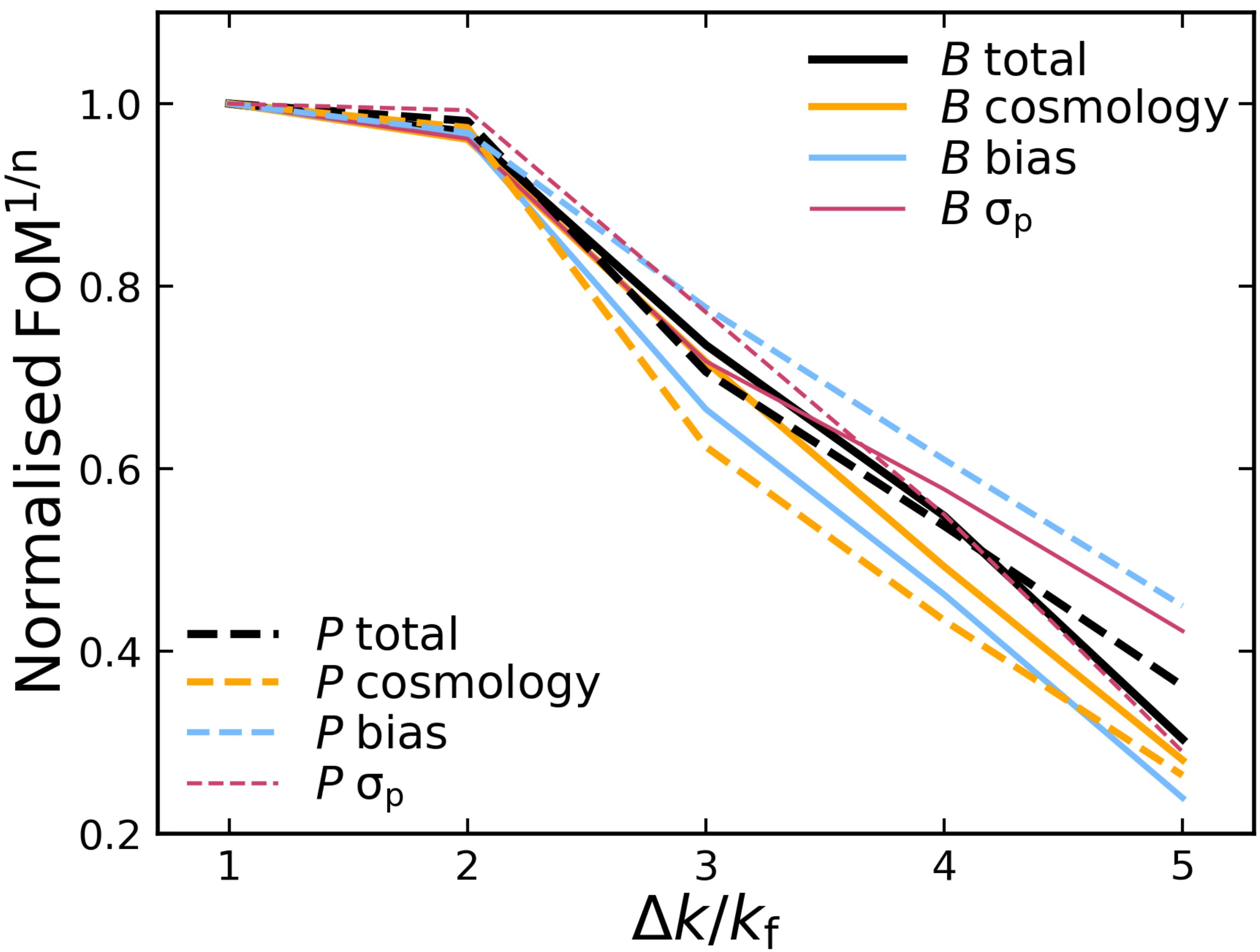
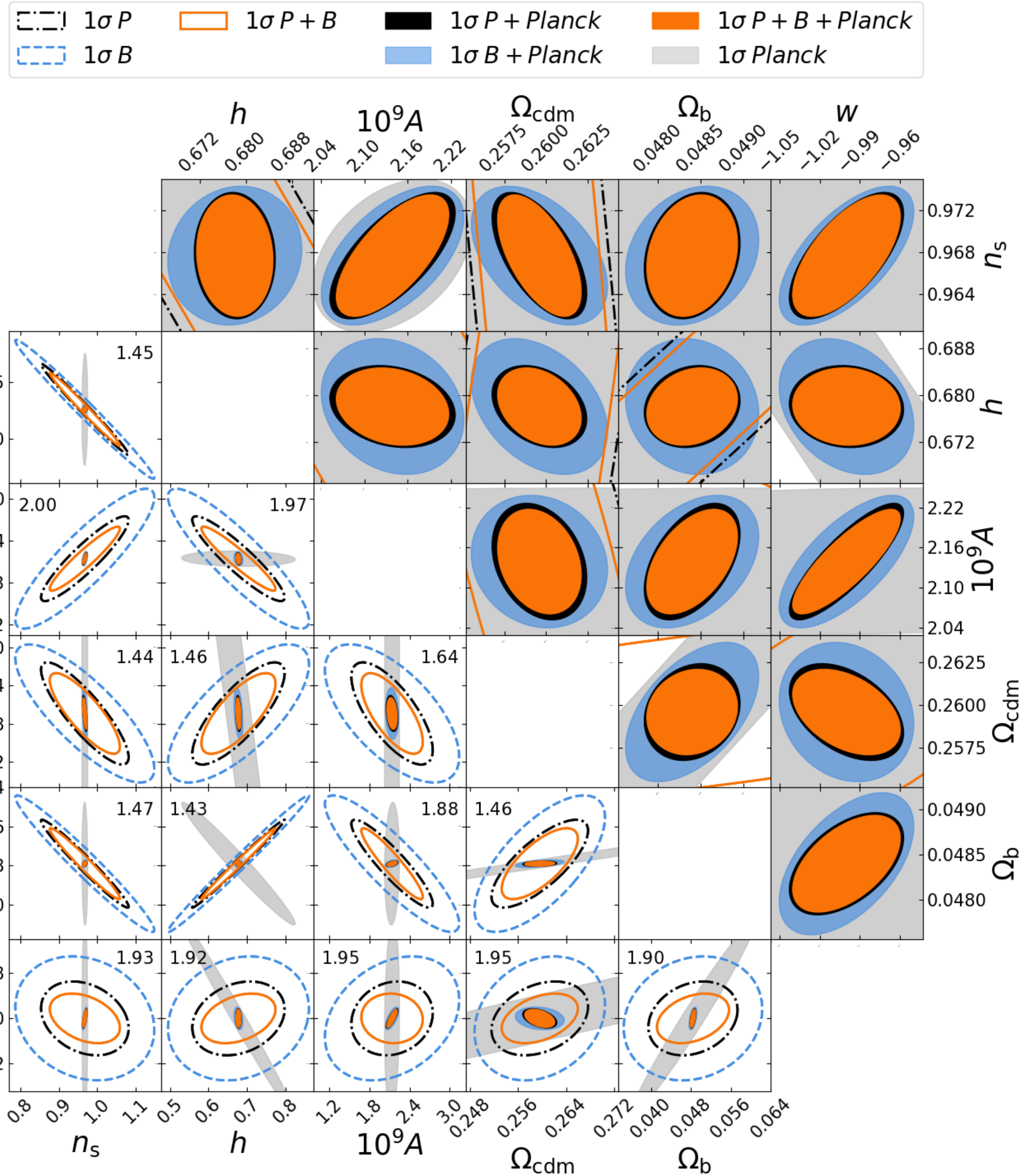
New frontiers of cosmology
is not far away

Thank you
for your attention

Dependence on bin width



wCDM model



1σ P
1σ P + B
1σ P + Planck
1σ P + B + Planck
1σ B
1σ B + Planck
1σ Planck
n_s
h
$10^9 A$
Ω_{cdm}
Ω_b
w
1.45
2.00
1.97
1.44
1.46
1.64
1.47
1.43
1.88
1.46
1.93
1.92
1.95
1.95
1.90

Covariance matrix

$$\mathbf{C} = \begin{pmatrix} C_{PP} & C_{PB} \\ C_{BP} & C_{BB} \end{pmatrix} \qquad \mathbf{C}(\mathrm{diag}) = \begin{pmatrix} C_{PP} & 0 \\ 0 & C_{BB} \end{pmatrix}$$

$$\mathbf{C}^{-1} = \begin{pmatrix} M & -MC_{PB}C_{BB}^{-1} \\ -C_{BB}^{-1}C_{BP}M & C_{BB}^{-1} + C_{BB}^{-1}C_{BP}MC_{PB}C_{BB}^{-1} \end{pmatrix}$$

$$M = \left(C_{PP} - C_{PB}C_{BB}^{-1}C_{BP}\right)^{-1}$$

Bispectrum

$$Z_2(\mathbf{k}_i,\mathbf{k}_j) = \frac{b_{s^2}}{2} S_2(\mathbf{k}_i,\mathbf{k}_j) + \frac{b_2}{2} + b_1 F_2(\mathbf{k}_i,\mathbf{k}_j) + f\mu_{ij}^2 G_2(\mathbf{k}_i,\mathbf{k}_j) +$$

$$+\frac{f\mu_{ij}k_{ij}}{2}\left[\frac{\mu_i}{k_i}\left(b_1 + f\mu_j^2\right) + \frac{\mu_j}{k_j}\left(b_1 + f\mu_i^2\right)\right], \qquad \mathbf{k}_{ij} = \mathbf{k}_i + \mathbf{k}_j$$

$$F_2(\mathbf{k}_i,\mathbf{k}_j) = \frac{5}{7} + \frac{x_{ij}}{2}\left(\frac{k_i}{k_j} + \frac{k_j}{k_i}\right) + \frac{2}{7}x_{ij}^2, \qquad x_{ij} = \frac{\mathbf{k}_i \cdot \mathbf{k}_j}{k_i k_j}, \; \mu_{ij} = \frac{\mathbf{k}_{ij} \cdot \mathbf{z}}{k_{ij}}$$

$$G_2(\mathbf{k}_i,\mathbf{k}_j) = \frac{3}{7} + \frac{x_{ij}}{2}\left(\frac{k_i}{k_j} + \frac{k_j}{k_i}\right) + \frac{4}{7}x_{ij}^2, \qquad S_2(\mathbf{k}_i,\mathbf{k}_j) = \frac{(\mathbf{k}_i \cdot \mathbf{k}_j)^2}{(k_i k_j)^2} - \frac{1}{3}$$

Galaxy bias b_1