Information content in the weak lensing bispectrum

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workshop gravitational lensing

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Cosmological context

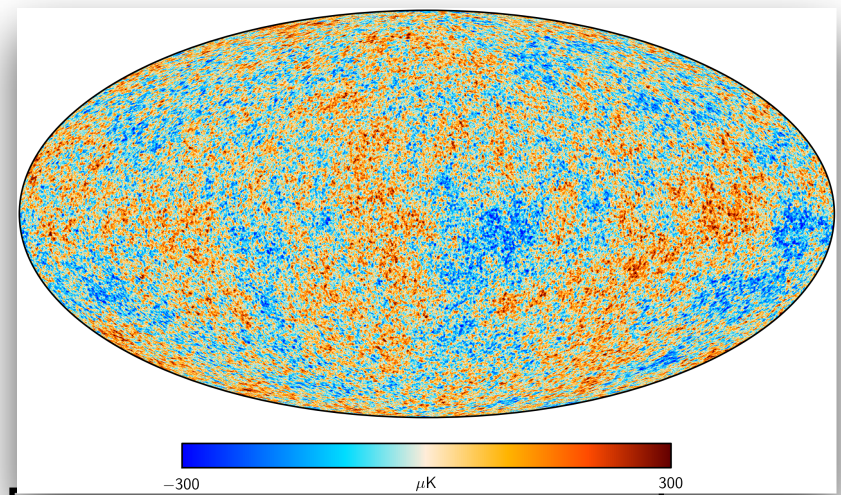
Non linear clustering

Gaussian Initial Conditions (Temperature Field-CMB)

Gravitational Collapse

Non linear coupling between different modes in the matter field

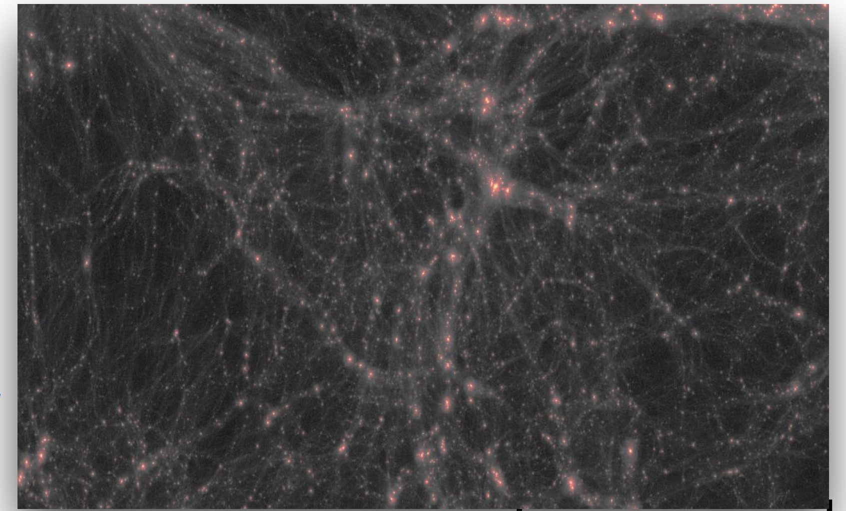
Final non Gaussian distribution of the matter field



Planck Collaboration 2015

Underlying cosmology

cosmological parameters

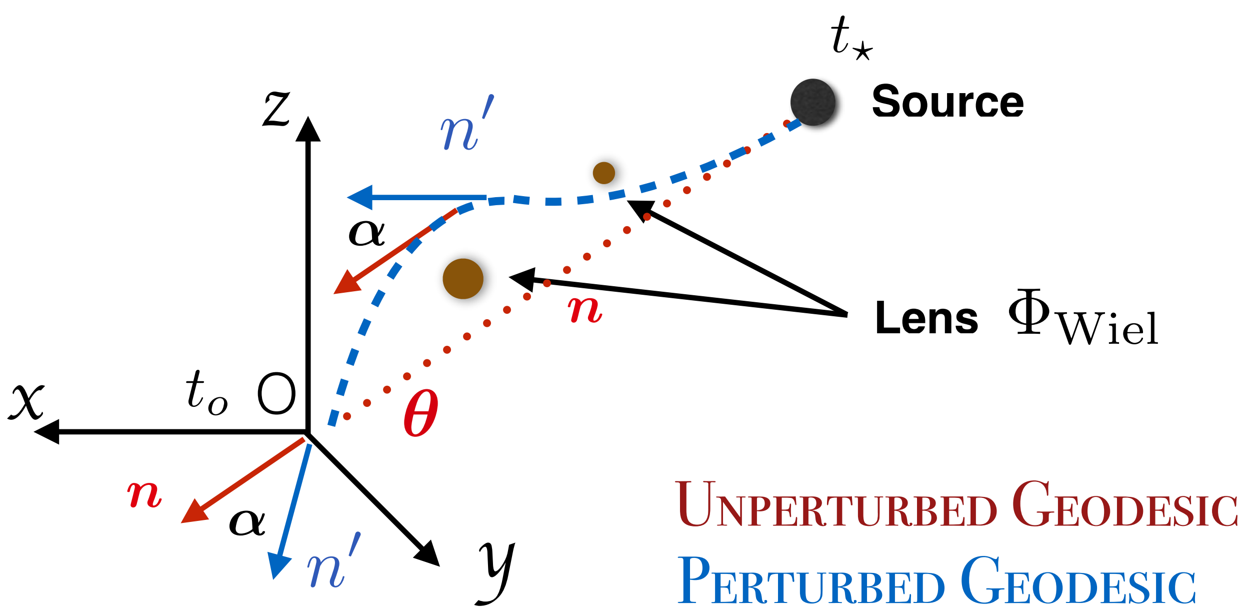


Horizon AGN

How to retrieve the information content in the observables?

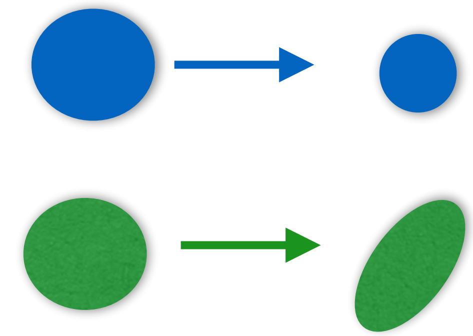
Tools to be used

Convergence field



Convergence field

Shear field

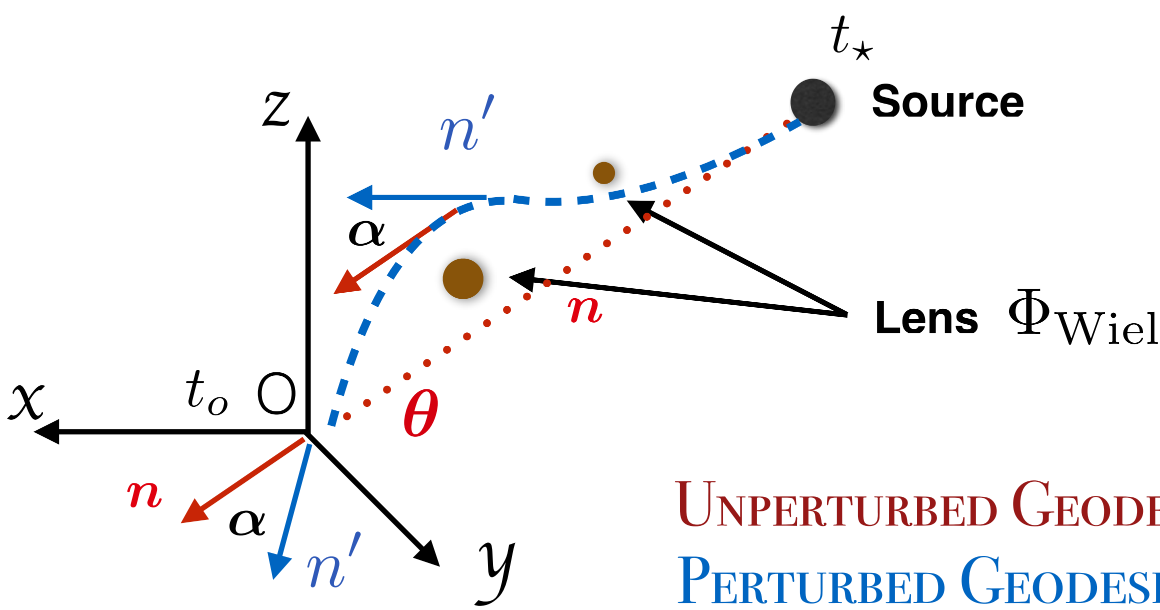


$$\kappa_{(i)}(\boldsymbol{\theta}) = \int_0^{\chi_\star} d\chi\ W_{(i)}(\chi)\, \delta_m\left[\chi, \chi\boldsymbol{\theta}\right]$$

Projection

TOOLS TO BE USED

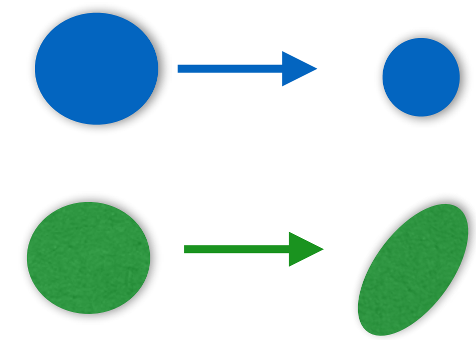
CONVERGENCE FIELD



UNPERTURBED GEODESIC
PERTURBED GEODESIC

CONVERGENCE FIELD

SHEAR FIELD



$$\kappa_{(i)}(\boldsymbol{\theta}) = \int_0^{\chi_\star} d\chi\, W_{(i)}(\chi)\, \delta_m[\chi, \chi\boldsymbol{\theta}]$$

← PROJECTION

FIELD STATISTICS

CONTRAST DENSITY FIELDS

$$\delta_f(\vec{x}, t) = \frac{f(\vec{x}, t) - f^o(t)}{f^o(t)} \longrightarrow$$

N-POINT CORRELATIONS FUNCTIONS (REAL SPACE)

$$\langle \delta_f(\mathbf{x}_1), \ldots, \delta_f(\mathbf{x}_n)\rangle_c \sim \mathcal{C}^{(n)}_{\mathcal{P}}(\mathbf{x}_1, \ldots, \mathbf{x}_n)$$

$$\mathcal{C}^{(2n)}_{\mathcal{P}_G}(\mathbf{x}_1, \ldots, \mathbf{x}_{2n}) \sim \mathcal{C}^{(2)}_{\mathcal{P}_G}(\mathbf{x}_i, \mathbf{x}_j)$$

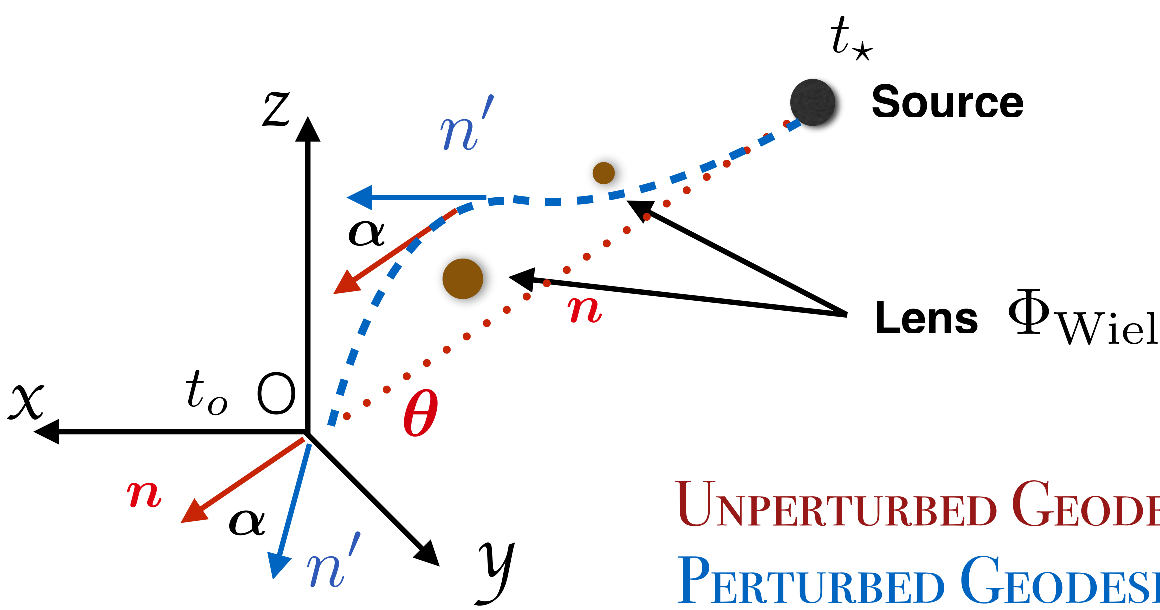
$$\mathcal{C}^{(2n+1)}_{\mathcal{P}_G}(\mathbf{x}_1, \ldots, \mathbf{x}_{2n+1}) = 0$$

$$\mathcal{C}^{(2n+1)}_{\mathcal{P}_{NG}}(\mathbf{x}_1, \ldots, \mathbf{x}_{2n+1}) \neq 0$$

Cosmological context

Tools to be used

Convergence field

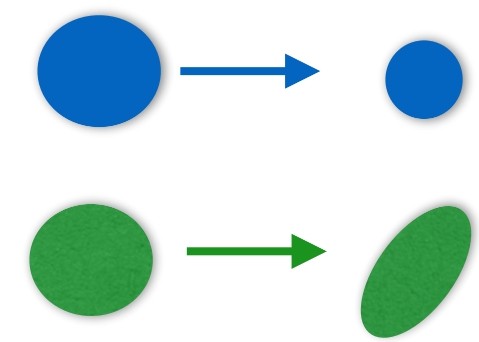


Unperturbed Geodesic

Perturbed Geodesic

Convergence field

Shear field



$$\kappa_{(i)}\left(\boldsymbol{\theta}\right) = \int_0^{\chi_\star} d\chi \; W_{(i)}(\chi)\, \delta_m\left[\chi, \chi\boldsymbol{\theta}\right]$$

Projection

Field statistics

Contrast density fields

Flat sky approx.

$\kappa_{(i)}\left(\boldsymbol{\theta}\right)$

$\kappa_{(i)}\left(\mathbf{l}\right)$

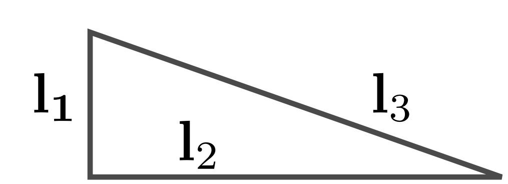
N-point correlations functions (Fourier space)

$$\langle \kappa_{(i)}\left(\mathbf{l_1}\right), \kappa_{(j)}\left(\mathbf{l_2}\right)\rangle \equiv (2\pi)^2\, P^{\kappa}_{(ij)}\left(\mathbf{l_1}\right) \delta\left(\mathbf{l}_1 + \mathbf{l}_2\right)$$

$$\langle \kappa_{(i)}\left(\mathbf{l_1}\right), \kappa_{(j)}\left(\mathbf{l_2}\right), \kappa_{(k)}\left(\mathbf{l_3}\right)\rangle_c \equiv$$

$$\equiv (2\pi)^2\, B^{\kappa}_{(ijk)}\left(\mathbf{l_1}, \mathbf{l_2}, \mathbf{l_3}\right) \delta\left(\mathbf{l}_1 + \mathbf{l}_2 + \mathbf{l}_3\right)$$

$$B^{\kappa}_{(ijk)}\left(\mathbf{l_1}, \mathbf{l_2}, \mathbf{l_3}\right) \approx$$



Tools to be used

Covariance matrices

- Vector of observables : $P^{\kappa}_{(ij)}(\mathbf{l_1})$ $B^{\kappa}_{(ijk)}(\mathbf{l_1}, \mathbf{l_2}, \mathbf{l_3})$
- Covariance of the observables :

$$\mathrm{Cov}\left[P_{ij}(\mathbf{l}), P_{i'j'}(\mathbf{l}')\right] = \mathrm{Cov}\left[P_{ij}(\mathbf{l}), P_{i'j'}(\mathbf{l}')\right]_{\mathrm{Gauss}} + \mathrm{Cov}\left[P_{ij}(\mathbf{l}), P_{i'j'}(\mathbf{l}')\right]_{\mathrm{NG}} + \\ + \mathrm{Cov}\left[P_{ij}(\mathbf{l}), P_{i'j'}(\mathbf{l}')\right]_{\mathrm{SSC}}$$

$$\mathrm{Cov}\left[B_{ijk}(\mathbf{l}_1, \mathbf{l}_2, \mathbf{l}_3), B_{i'j'k'}(\mathbf{l'}_1, \mathbf{l'}_2, \mathbf{l'}_3)\right] = \mathrm{Cov}\left[B_{ijk}(\mathbf{l}_1, \mathbf{l}_2, \mathbf{l}_3), B_{i'j'k'}(\mathbf{l'}_1, \mathbf{l'}_2, \mathbf{l'}_3)\right]_{\mathrm{phy}} + \\ + \mathrm{Cov}\left[B_{ijk}(\mathbf{l}_1, \mathbf{l}_2, \mathbf{l}_3), B_{i'j'k'}(\mathbf{l'}_1, \mathbf{l'}_2, \mathbf{l'}_3)\right]_{\mathrm{SSC}}$$

$$\mathrm{Cov}\left[P_{ij}(\mathbf{l}), B_{i'j'k'}(\mathbf{l}_1, \mathbf{l}_2, \mathbf{l}_3)\right] = \mathrm{Cov}\left[P_{ij}(\mathbf{l}), B_{i'j'k'}(\mathbf{l}_1, \mathbf{l}_2, \mathbf{l}_3)\right]_{\mathrm{phy}} + \\ + \mathrm{Cov}\left[P_{ij}(\mathbf{l}), B_{i'j'k'}(\mathbf{l}_1, \mathbf{l}_2, \mathbf{l}_3)\right]_{\mathrm{SSC}}$$

TOOLS TO BE USED

COVARIANCE MATRICES

- VECTOR OF OBSERVABLES : $P^{\kappa}_{(ij)}(\mathbf{l_1})$ $\quad B^{\kappa}_{(ijk)}(\mathbf{l_1},\mathbf{l_2},\mathbf{l_3})$
- COVARIANCE OF THE OBSERVABLES :

$$\mathrm{Cov}\left[P_{ij}(\mathbf{l}),P_{i'j'}(\mathbf{l}')\right] = \mathrm{Cov}\left[P_{ij}(\mathbf{l}),P_{i'j'}(\mathbf{l}')\right]_{\mathrm{Gauss}} + \mathrm{Cov}\left[P_{ij}(\mathbf{l}),P_{i'j'}(\mathbf{l}')\right]_{\mathrm{NG}} + \\ + \mathrm{Cov}\left[P_{ij}(\mathbf{l}),P_{i'j'}(\mathbf{l}')\right]_{\mathrm{SSC}}$$

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(E.G.) BAYESIAN INFERENCE BASED ON GAUSSIAN LIKELIHOOD

THEORY

$$\mathcal{L}\left(\vec{\theta}\mid\vec{p}\right) = \frac{1}{\sqrt{(2\pi)^n \det\left(C_D\right)}} \exp\left[-\frac{1}{2}\left(\vec{\theta}-\vec{D}\left(\vec{p}\right)\right)^t C_D^{-1}\left(\vec{\theta}-\vec{D}\left(\vec{p}\right)\right)\right]$$

DATA

Cosmological context

Tools to be used

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- Covariance of the observables :

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$$\mathrm{Cov}\left[B_{ijk}\left(\mathbf{l}_1,\mathbf{l}_2,\mathbf{l}_3\right),B_{i'j'k'}\left(\mathbf{l'}_1,\mathbf{l'}_2,\mathbf{l'}_3\right)\right]=\mathrm{Cov}\left[B_{ijk}\left(\mathbf{l}_1,\mathbf{l}_2,\mathbf{l}_3\right),B_{i'j'k'}\left(\mathbf{l'}_1,\mathbf{l'}_2,\mathbf{l'}_3\right)\right]_{\mathrm{phy}}+\mathrm{Cov}\left[B_{ijk}\left(\mathbf{l}_1,\mathbf{l}_2,\mathbf{l}_3\right),B_{i'j'k'}\left(\mathbf{l'}_1,\mathbf{l'}_2,\mathbf{l'}_3\right)\right]_{\mathrm{SSC}}$$

$$\mathrm{Cov}\left[P_{ij}\left(\mathbf{l}\right),B_{i'j'k'}\left(\mathbf{l}_1,\mathbf{l}_2,\mathbf{l}_3\right)\right]=\mathrm{Cov}\left[P_{ij}\left(\mathbf{l}\right),B_{i'j'k'}\left(\mathbf{l}_1,\mathbf{l}_2,\mathbf{l}_3\right)\right]_{\mathrm{phy}}+\mathrm{Cov}\left[P_{ij}\left(\mathbf{l}\right),B_{i'j'k'}\left(\mathbf{l}_1,\mathbf{l}_2,\mathbf{l}_3\right)\right]_{\mathrm{SSC}}$$

Approximated covariances?
Impact on the parameter forecast?
Efficiency of the inversion?
...

(e.g.) Bayesian inference based on Gaussian likelihood

THEORY

$$\mathcal{L}\left(\vec{\theta}\,|\,\vec{p}\right)=\frac{1}{\sqrt{(2\pi)^n\det\left(C_D\right)}}\exp\left[-\frac{1}{2}\left(\vec{\theta}-\vec{D}\left(\vec{p}\right)\right)^t C_D^{-1}\left(\vec{\theta}-\vec{D}\left(\vec{p}\right)\right)\right]$$

DATA

QUANTIFYING THE COSMOLOGICAL INFORMATION

SIGNAL TO NOISE RATIO: COMBINING BISPECTRUM AND POWER SPECTRUM

2013

Information content of weak lensing power spectrum and bispectrum: including the non-Gaussian error covariance matrix

Issha Kayo,[1★] Masahiro Takada[2] and Bhuvnesh Jain[3]

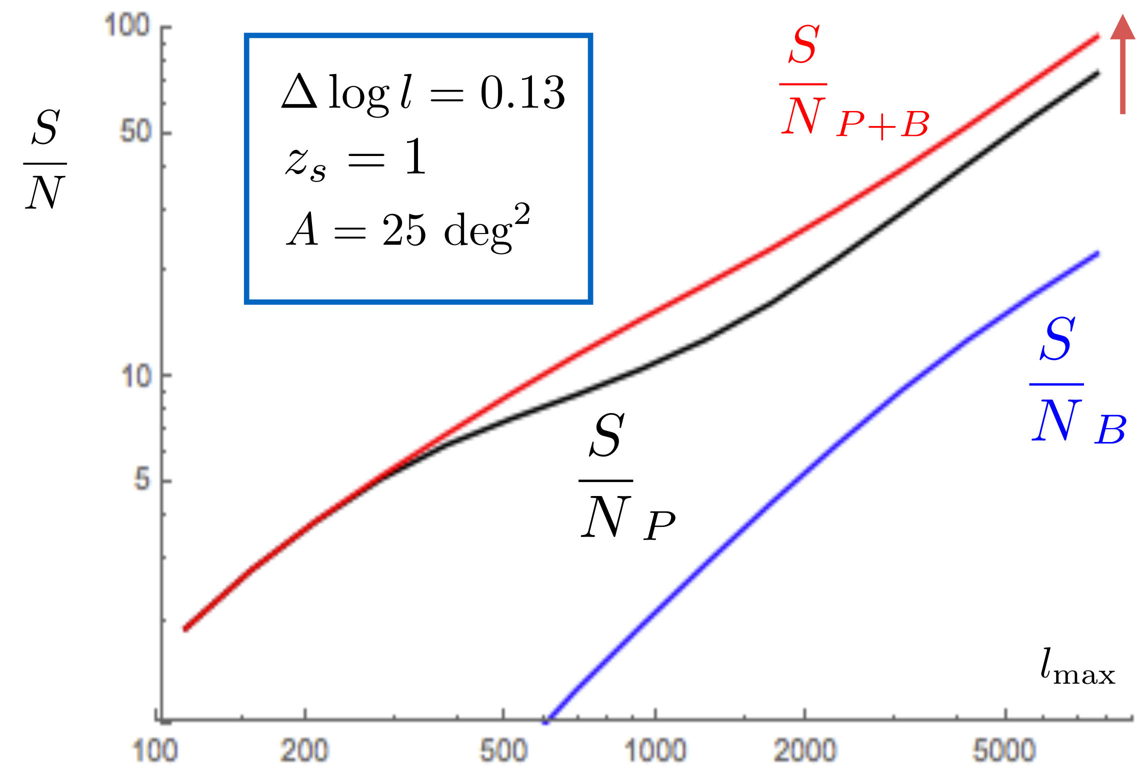
SOURCES: $i = j = k$

$$B^{\kappa}_{(ijk)}(\mathbf{l_1}, \mathbf{l_2}, \mathbf{l_3}) \sim B_{\kappa}(l_1, l_2, l_3)$$

$$C^{P+B} = \begin{bmatrix} C^P & C^{PB} \\ C^{PB} & C^B \end{bmatrix}$$

$$D = \{P_1, \ldots, P_{nb}, B_1, \ldots, B_{i_{\rm n\ conf}}\}$$

$$\left(\frac{S}{N}\right)^2_{P+B} = \sum_{i,j \le l_{max}} D_i \left[C^{P+B}\right]^{-1}_{ij} D_j$$



NO DOUBLE COUNTING

$l_1 \le l_2 \le l_3$

TRIANGULAR CONFIGURATIONS

$|l_j - l_k| \le l_i \le l_j + l_k$

16 BINS IN LN(L) → 204 CONFIGURATIONS

SURVEY'S PARAMETER

MODEL FOR NON LINEAR CLUSTERING

Getting things more complicated …

Including Tomographic Analysis

Different sources positions

$$\kappa_{(i)}(\boldsymbol{\theta}) = \int_0^{\chi_\star} d\chi \; W_{(i)}(\chi)\, \delta_m \left[\chi, \chi\boldsymbol{\theta}\right]$$

More Configuration to consider

$$\mathrm{Cov}\left[B^{\kappa}_{(i,j,k)}\left(l_1, l_2, l_3\right), B^{\kappa}_{(i',j',k')}\left(l'_1, l'_2, l'_3\right)\right]$$

$$\rightarrow \mathrm{Cov}\left[B^{\kappa}_{(I,L)}, B_{(I',L')}\right]$$

Survey related

$W_{(i)}(\chi) \approx$ Cosmology $\circ$ Survey related features

Survey related features ↑ Sources Distribution $\circ$ Binning $\circ$ Photometric Error

Getting things more complicated …

Including Tomographic Analysis

Different sources positions

$$\kappa_{(i)}(\boldsymbol{\theta}) = \int_0^{\chi_\star} d\chi\, W_{(i)}(\chi)\, \delta_m\left[\chi, \chi\boldsymbol{\theta}\right]$$

More Configuration to consider

$$\mathrm{Cov}\left[B^{\kappa}_{(i,j,k)}(l_1, l_2, l_3), B^{\kappa}_{(i',j',k')}(l'_1, l'_2, l'_3)\right]$$
$$\to \mathrm{Cov}\left[B^{\kappa}_{(I,L)}, B_{(I',L')}\right]$$

Survey related

$$W_{(i)}(\chi) \approx \boxed{\text{Cosmology}} \circ \boxed{\text{Survey related features}}$$

Survey related features ↑ [Sources Distribution ∘ Binning ∘ Photometric Error]

Indeces labelling Fourier Configurations

14 bins in ln(l) → 144 configurations ⟶ for each of them …

10 bins tomography (Euclid)

Vector of P : 770 Spectra

Vector of B : 73050 Spectra

Matrix of 10^10 elements

Index labelling Tomographic configurations

$\boxed{n_z^{\mathrm{Tomo}}}$

No symmetries : $\left(n_z^{\mathrm{Tomo}}\right)^3$

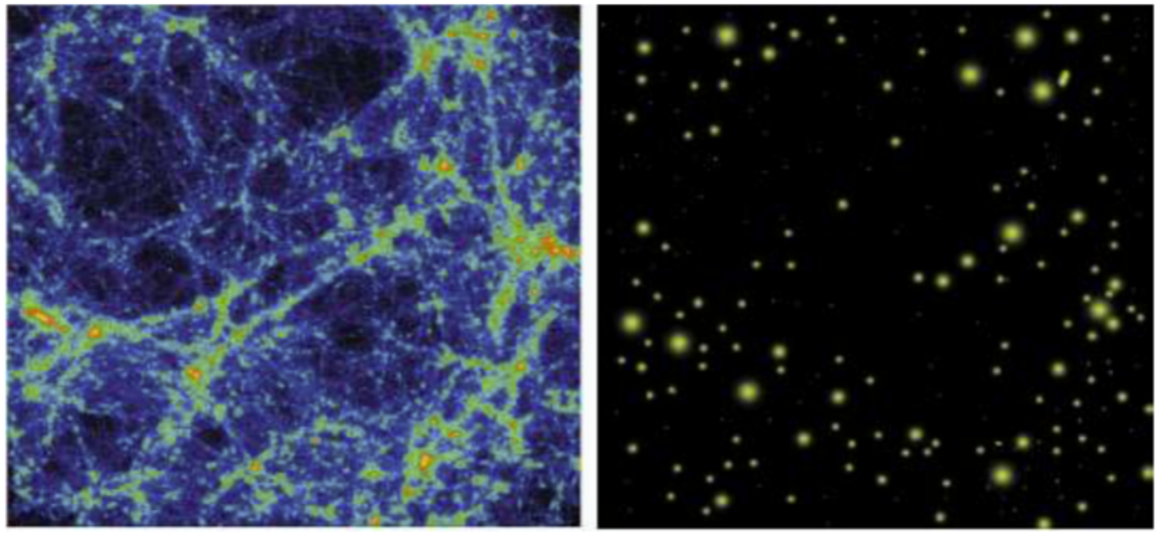
Isosceles conf. : $\left(n_z^{\mathrm{Tomo}}\right)^2\left(n_z^{\mathrm{Tomo}}+1\right)/2$

Equilateral conf. : $n_z^{\mathrm{Tomo}}\left(n_z^{\mathrm{Tomo}}+1\right)\left(n_z^{\mathrm{Tomo}}+2\right)/6$

Getting things more complicated …

Semi-analytical approach to non linear clustering: the halo model

- Dark matter distribution described as a distribution of dark matter halos with a given density profile



- Spherical collapse through a NFW profile

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

$$(\rho_s, r_s) \longrightarrow (m_v, c_v)$$

2 D.O.F

$$\frac{r_v}{r_s} \equiv c_v(m_v, z)$$

Concentration parameter

Getting things more complicated …

Semi-analytical approach to non linear clustering: the halo model

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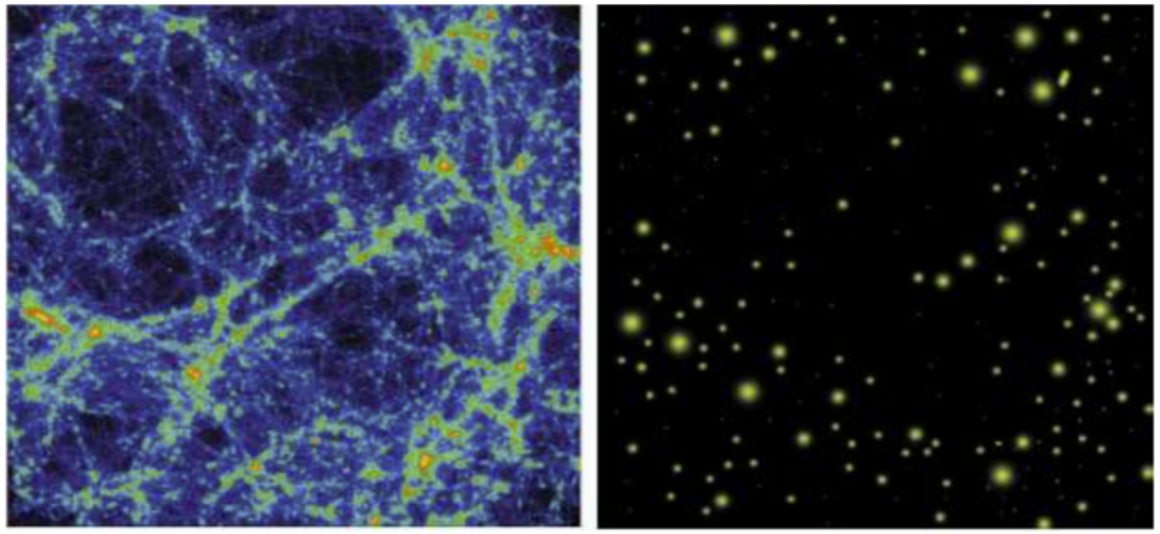

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2 D.O.F

$$\frac{r_v}{r_s} \equiv c_v(m_v, z)$$

Concentration parameter

- Concentration parameter c(z,m): Bullock et al. 2001

Spectra are modelled through the sum over all the possible realisations of halos distributions:

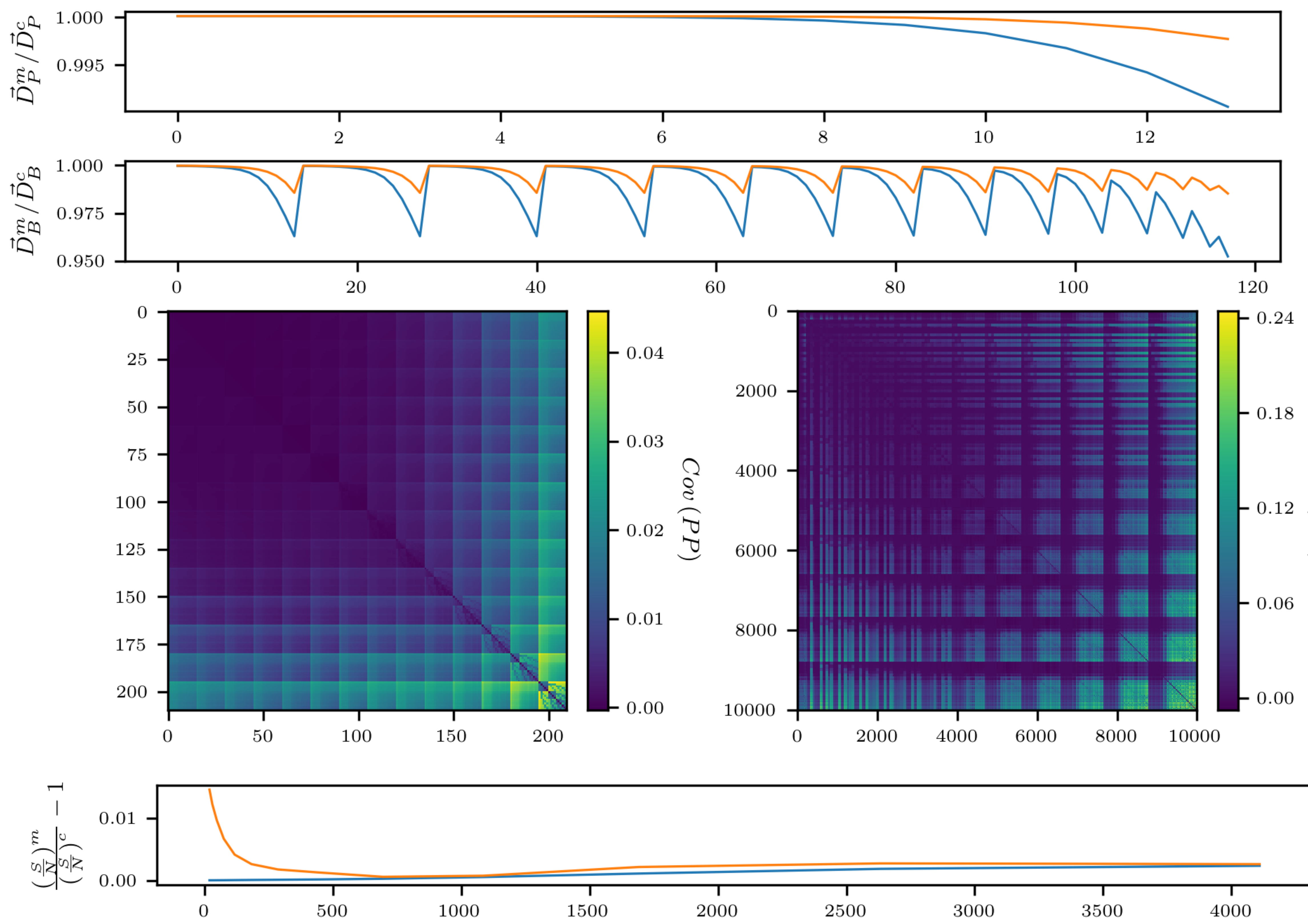
$$I^{\beta}_{\mu}(\mathbf{k}_1,\ldots,\mathbf{k}_\mu) = \int_{m_v^{\rm Min}}^{m_v^{\rm Max}} dm_v\; b_\beta(m)\,\frac{dn(m_v)}{dm_v}\left(\int_{c_v^{\rm Min}}^{c_v^{\rm Max}} dc_v\; p(c_v,m_v)\left[\prod_{i=1}^{\mu} u(m_v,c_v,\mathbf{k}_i)\right]\right)$$

$$p(c_v,m_v,z)\,\frac{dc_v}{d\log c_v} = \frac{1}{\sqrt{2\pi}\sigma_{\ln c_v}}\exp\left(-\frac{(\ln c_v - \ln\bar{c}_v(m_v,z))^2}{2\sigma^2_{\ln c_v}}\right)$$

$$\sigma_{\ln c} \approx 0.18$$

Results

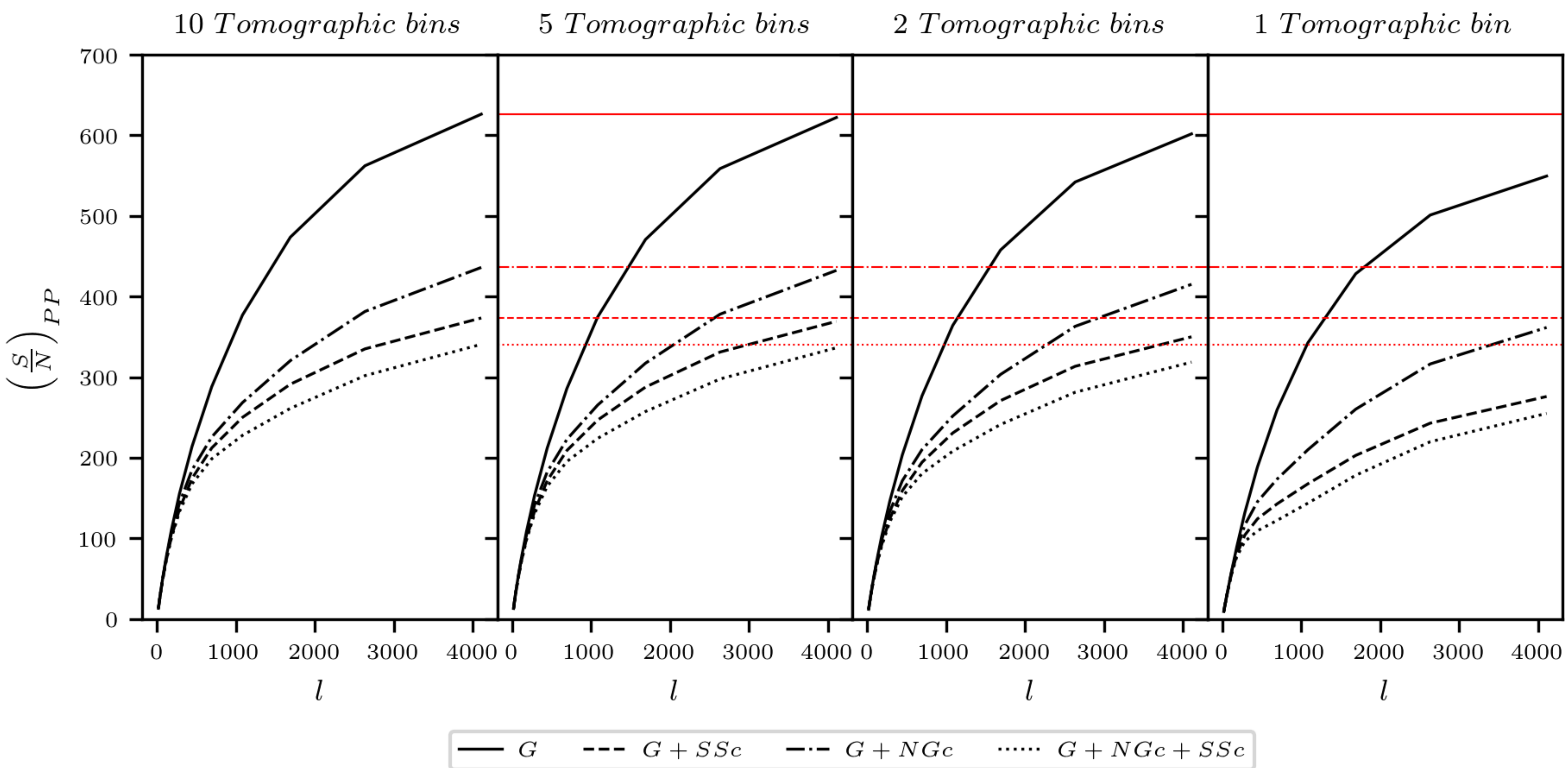
PROPAGATION OF THE MODEL UNCERTAINTIES



Matrix reduction: impact of the tomography

Photometric bins (redshift)

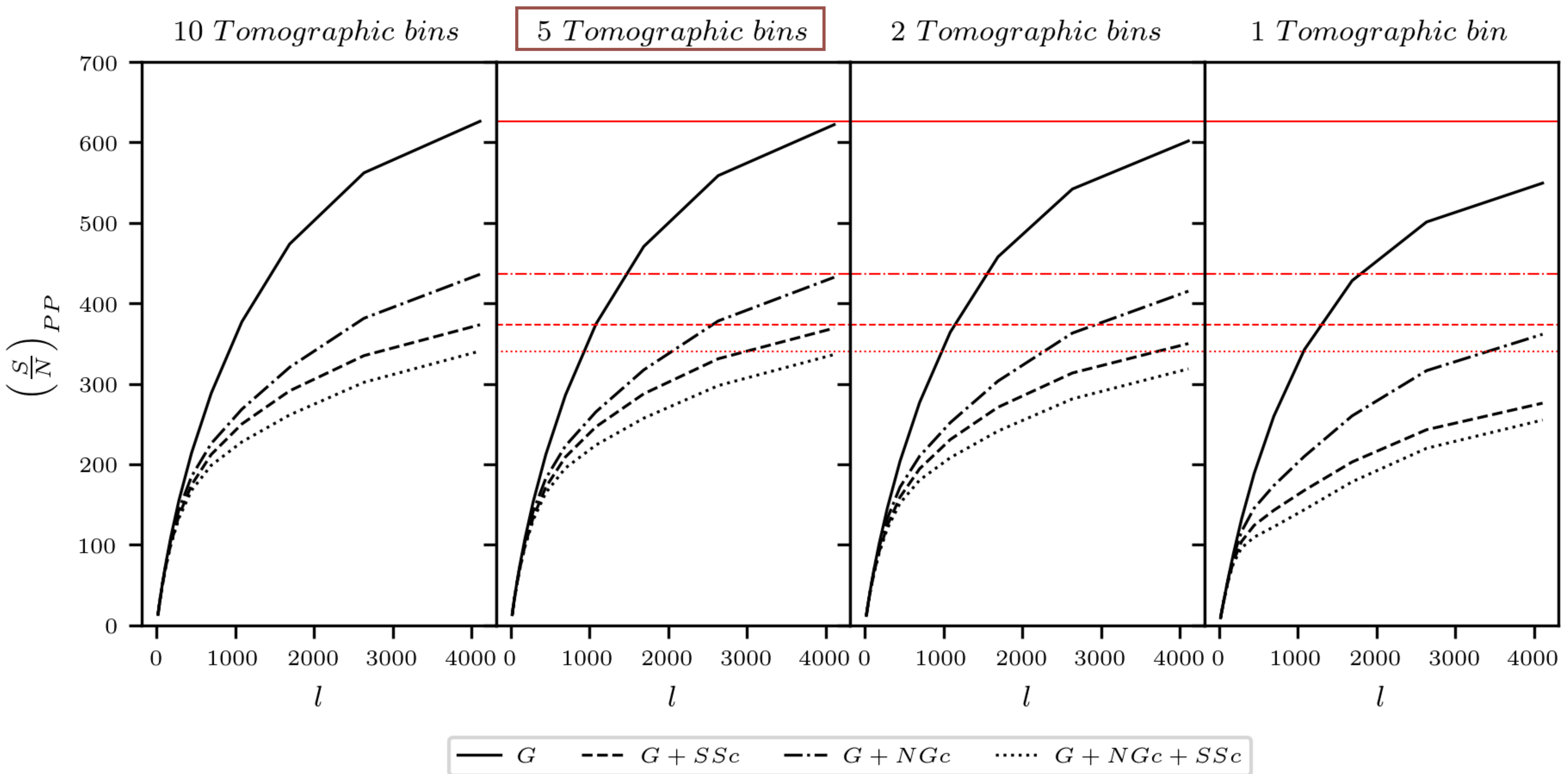
[0.001, 0.418, 0.560, 0.678, 0.789, 0.900, 1.019, 1.155, 1.324, 1.576, 2.500]



MATRIX REDUCTION: IMPACT OF THE TOMOGRAPHY

PHOTOMETRIC BINS (REDSHIFT)

[0.001, 0.418, 0.560, 0.678, 0.789, 0.900, 1.019, 1.155, 1.324, 1.576, 2.500]



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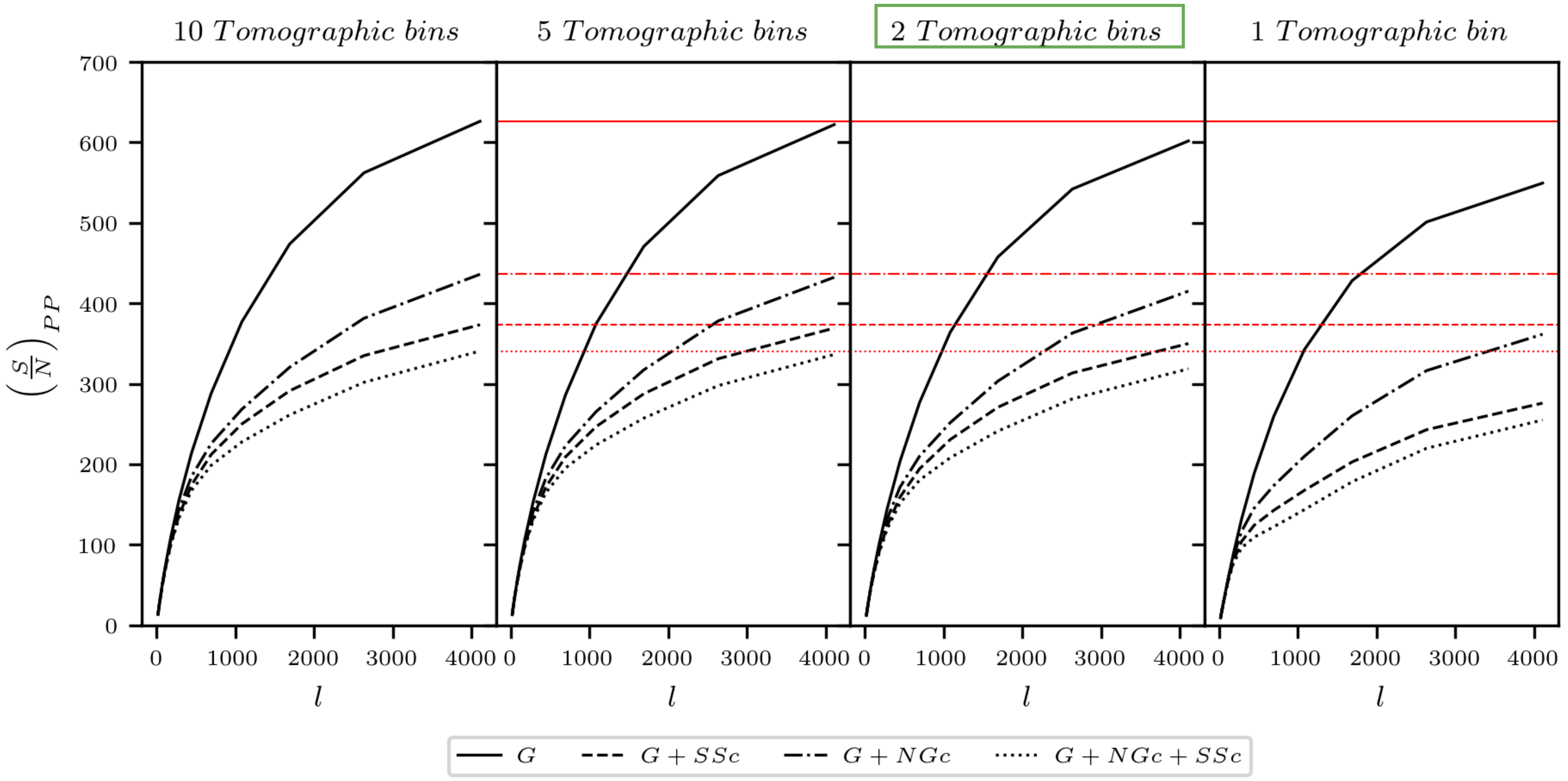

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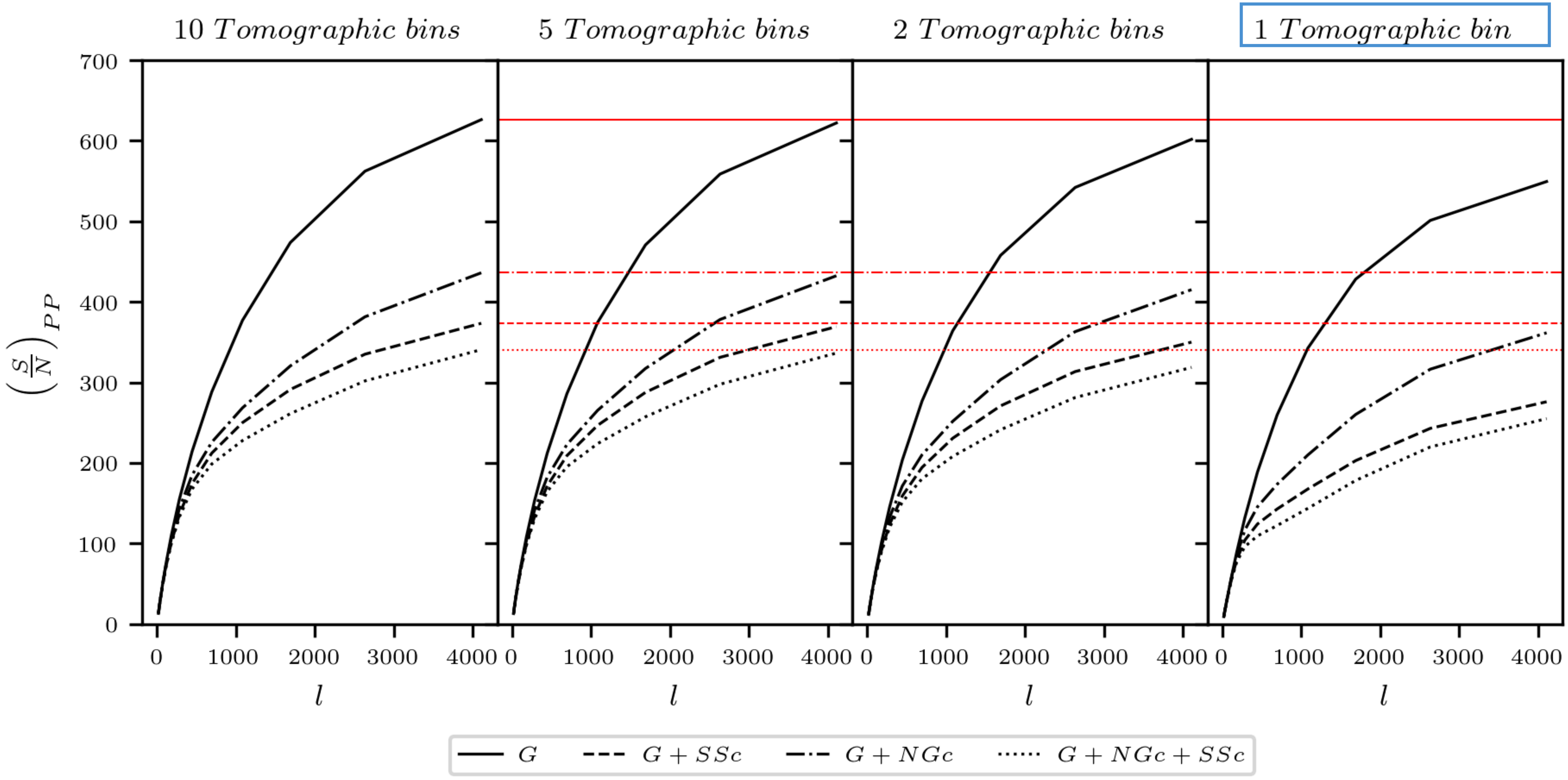
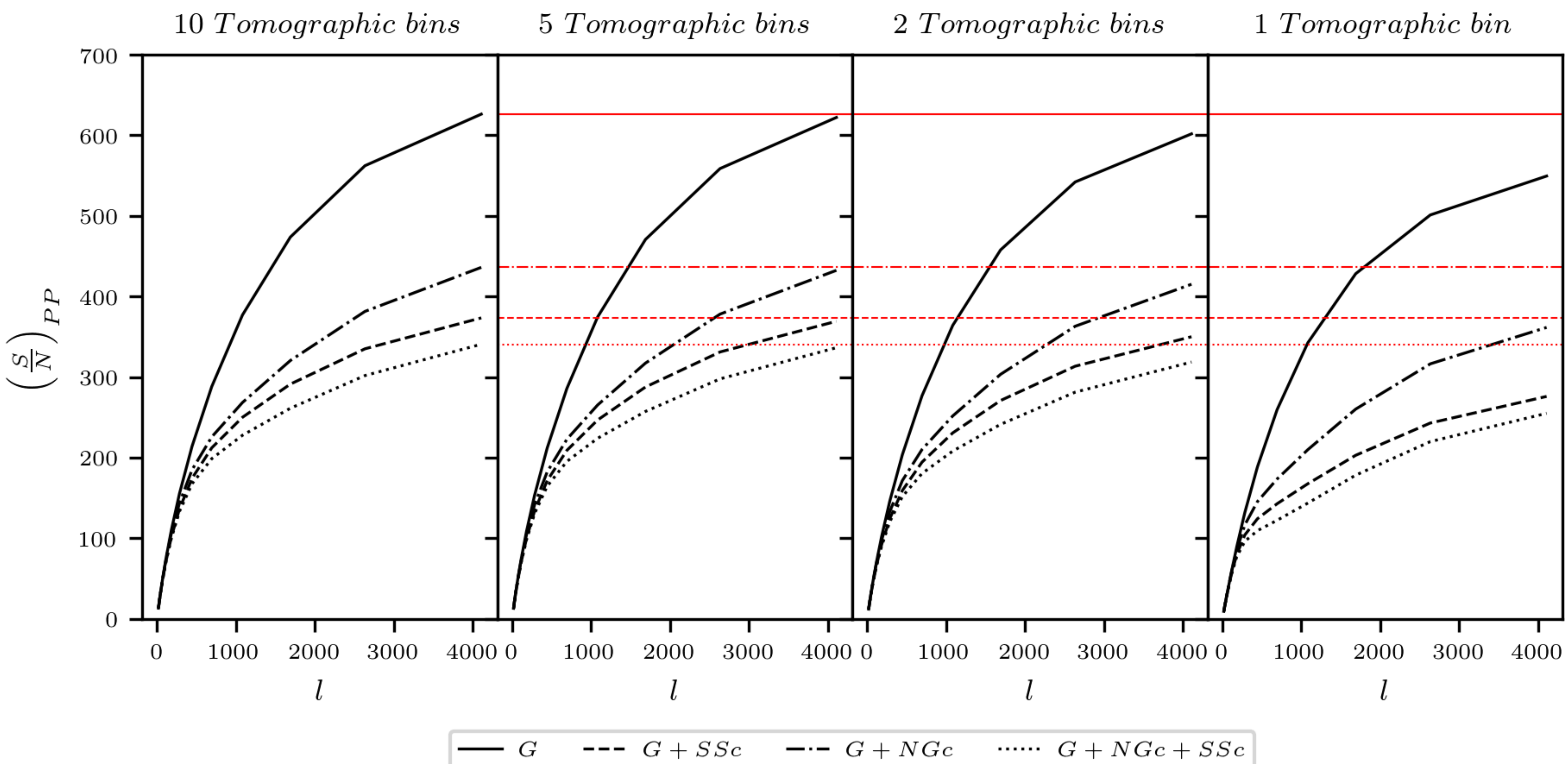


Results

<u>MATRIX REDUCTION: IMPACT OF THE TOMOGRAPHY</u>

Photometric bins (redshift)

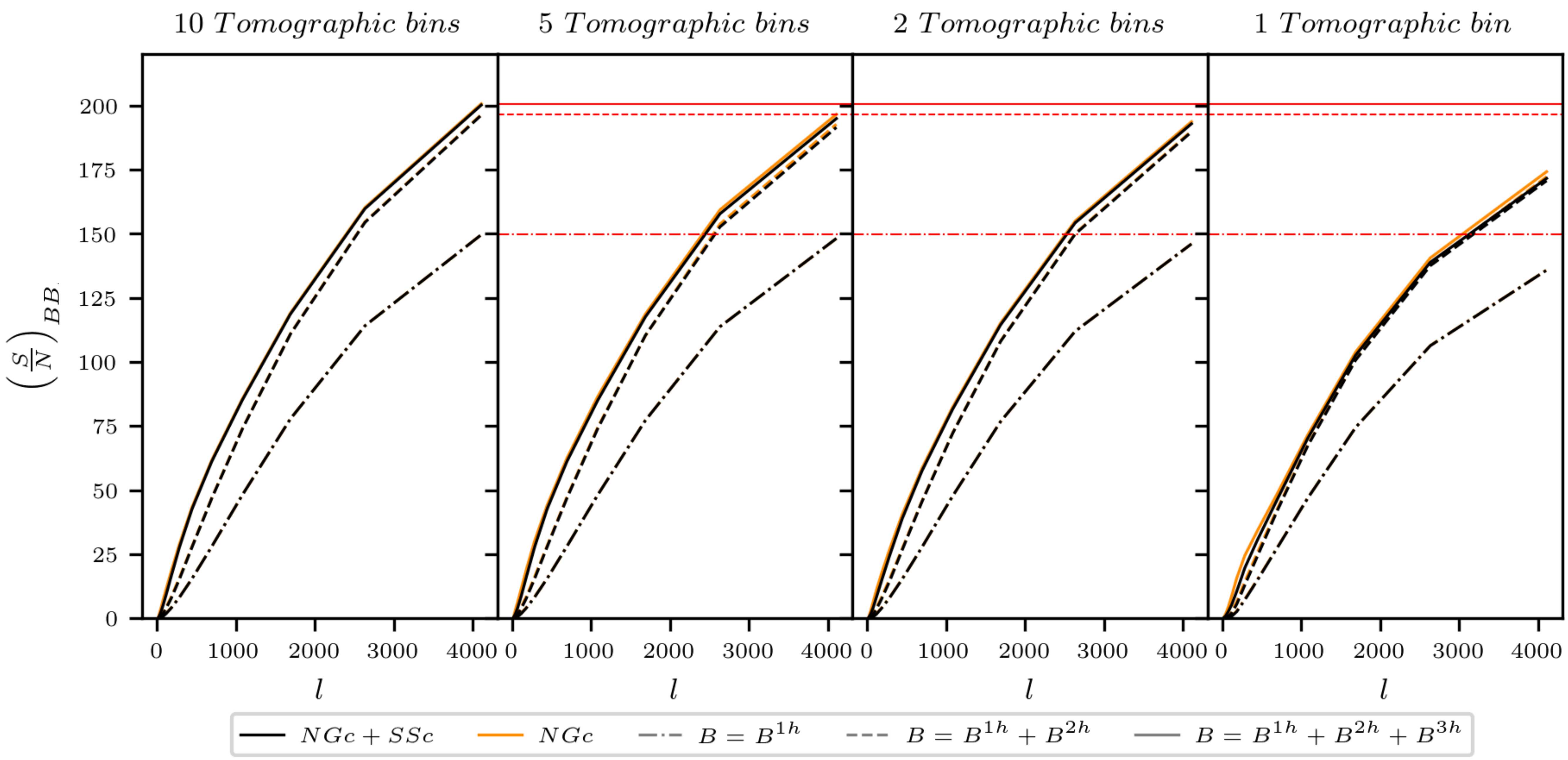
[0.001, 0.418, 0.560, 0.678, 0.789, 0.900, 1.019, 1.155, 1.324, 1.576, 2.500]



- 5 bin tomography statistics: maximum SN ratio underestimated by 1.2 %

Results

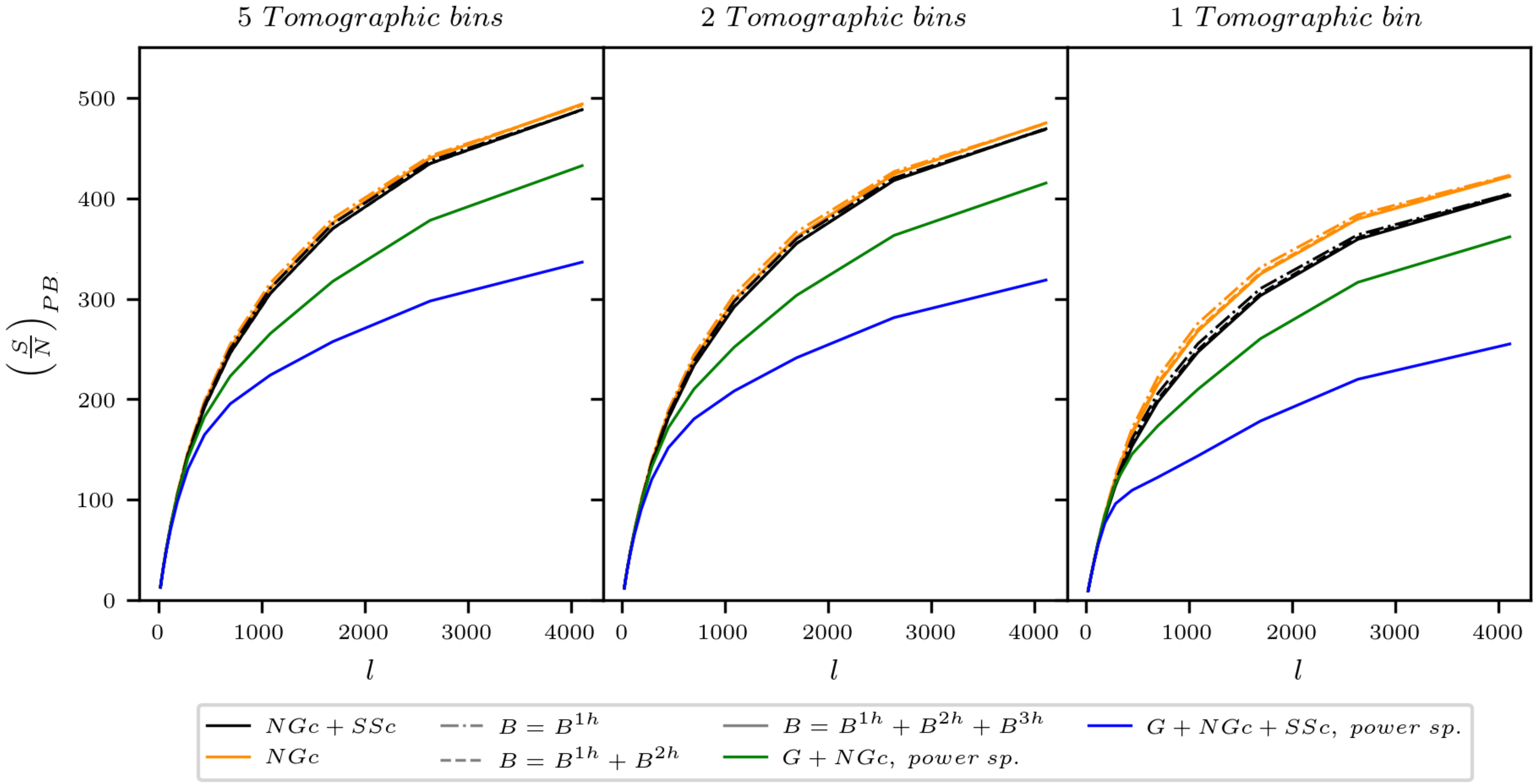
MATRIX REDUCTION: IMPACT OF THE TOMOGRAPHY



- 5 bin tomography statistics: maximum SN ratio underestimated by 2.5 %
- The 3 halo term lead to an improvement of 1.8 % compared to the 1 + 2 halo terms
- The impact of the SSC is negligible at all the scales

Results

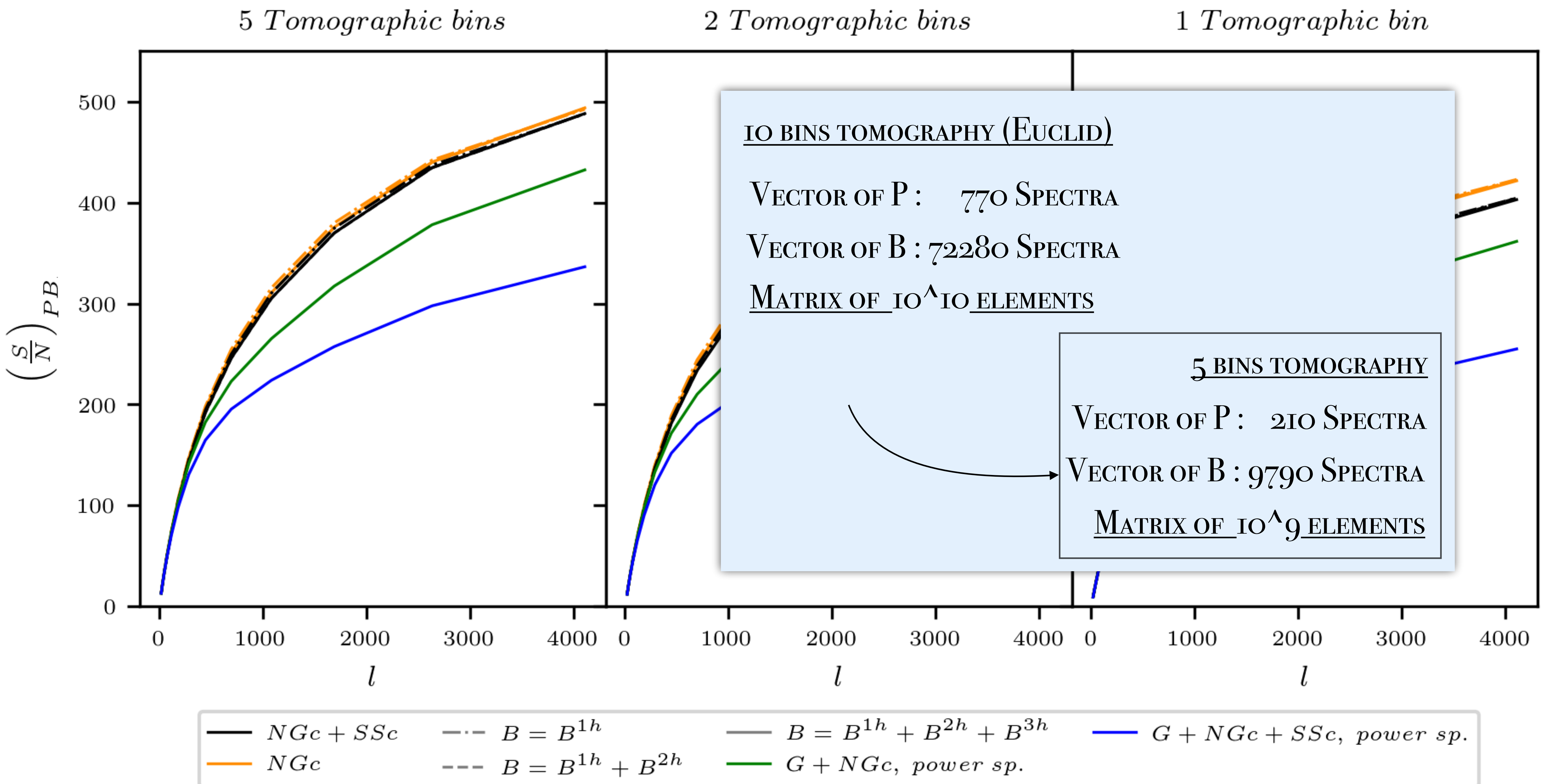
MATRIX REDUCTION: IMPACT OF THE TOMOGRAPHY



- The loss of information due to the SSC is recovered in the BP analysis
- The maximum SN ratio is increased of about 45 % in the BP analysis if compared to the PP analysis alone.

Results

Matrix reduction: impact of the tomography



10 bins tomography (Euclid)

Vector of P : 770 Spectra

Vector of B : 72280 Spectra

Matrix of 10^10 elements

5 bins tomography

Vector of P : 210 Spectra

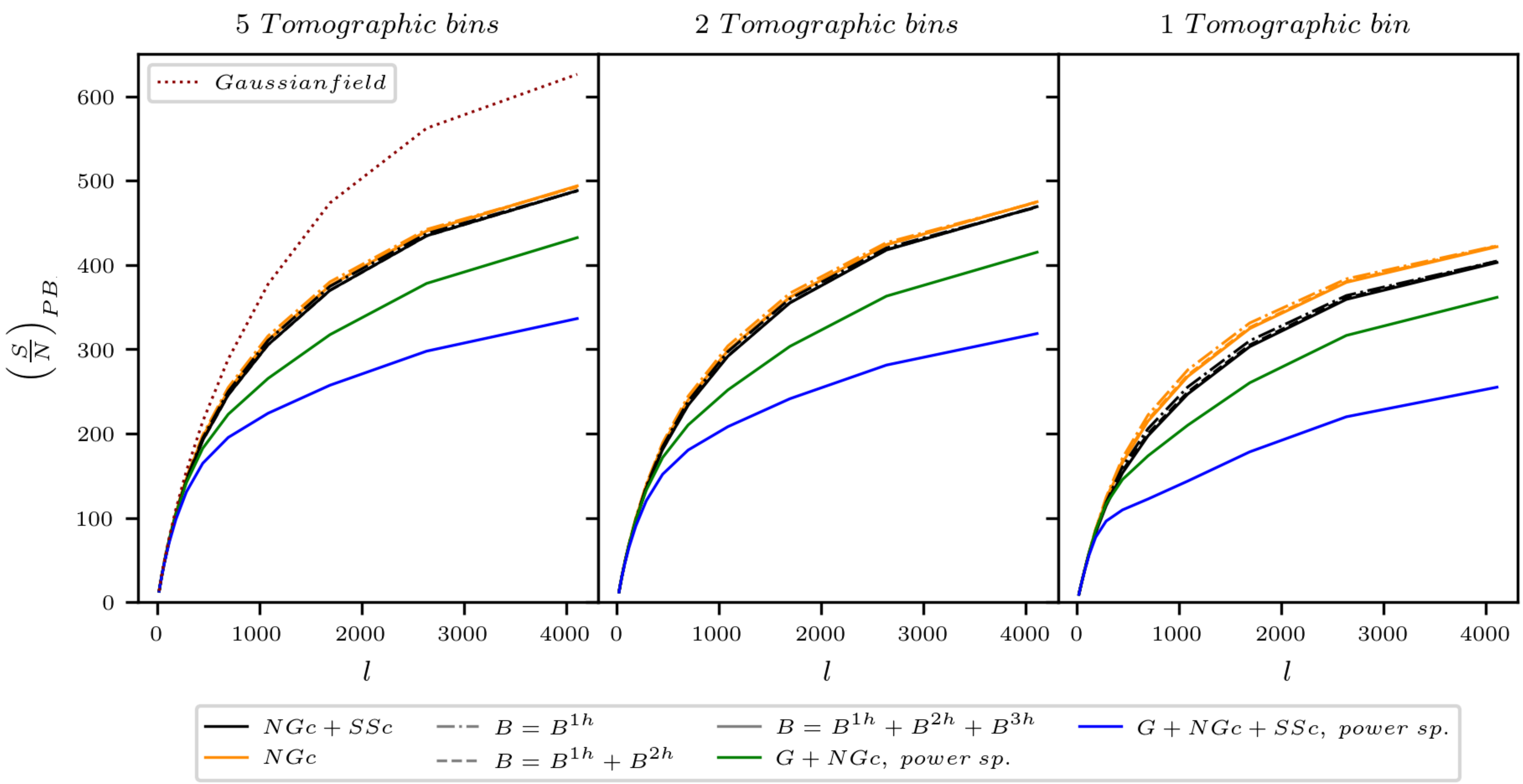
Vector of B : 9790 Spectra

Matrix of 10^9 elements

- The dimension of the full covariance matrix is reduce of 1 order of magnitude

Results

Matrix reduction: impact of the tomography



- We are still not capable to recover the 22 % of the information content (shot noise included)

Results

Principal Component Analysis (PCA): localising the information content

Orthonormal basis of eigenvectors:

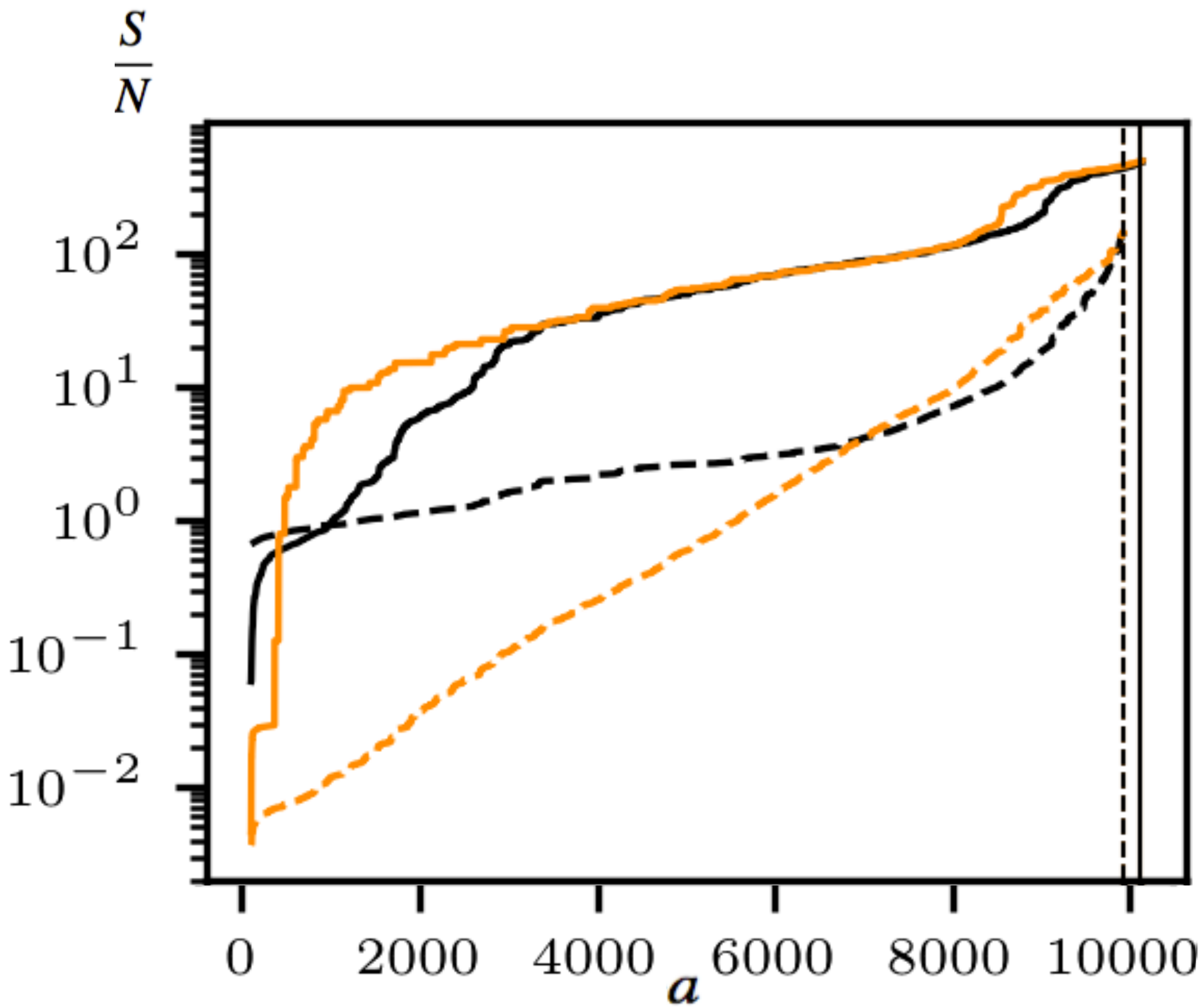
$$C^*_{ij} = \sum_a S^*_{ai} S^*_{aj} \lambda_a$$

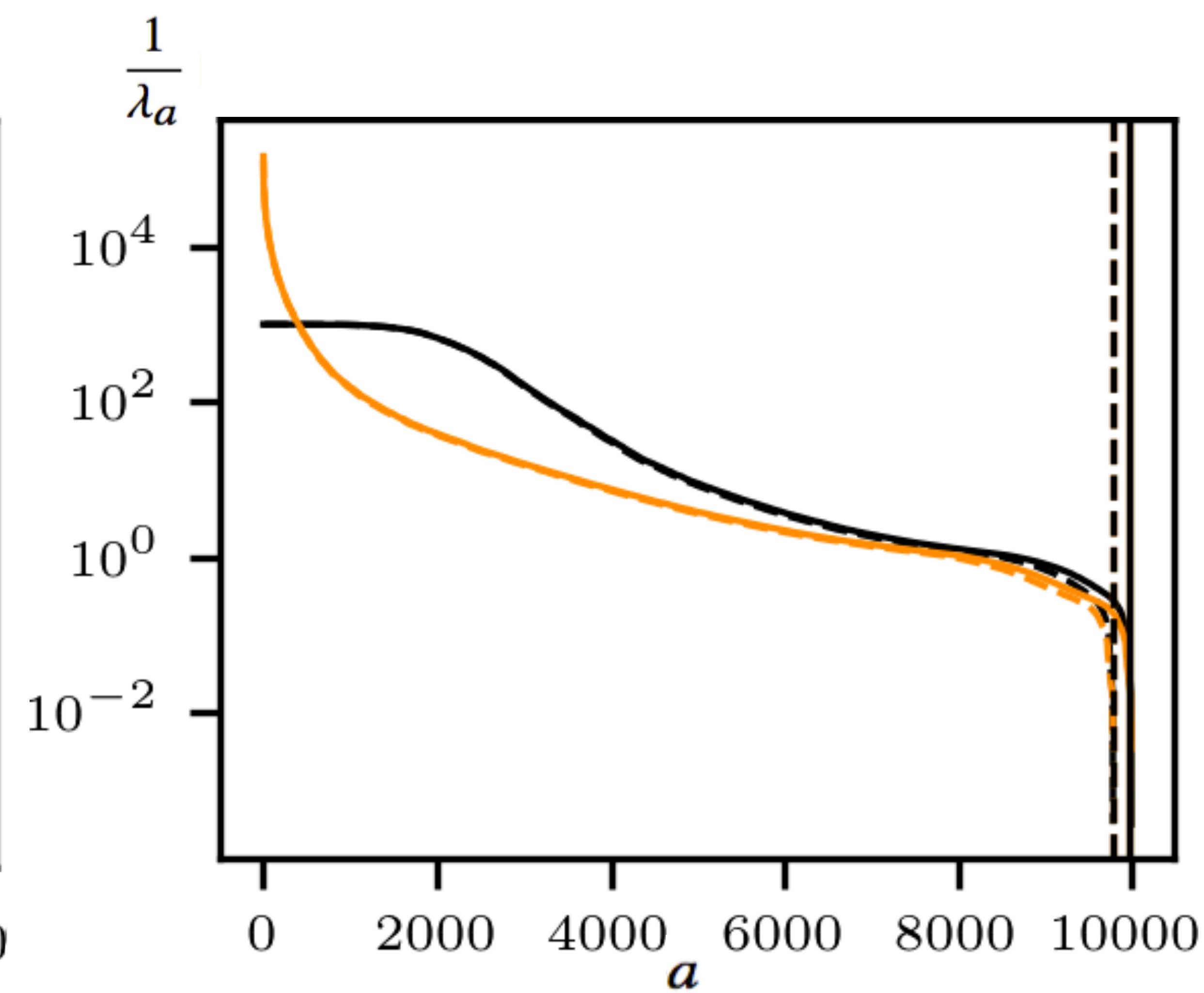
$$\left(\frac{S}{N}\right)^2_{P+B} = \sum_a \frac{1}{\lambda_a} \left(\sum_i S^X_{ai} X_i\right)^2$$

Pre-condition I for improved inversion

$$C^{\text{cr.}} = \text{Cr} \cdot C^{\text{D}} \cdot \text{Cr}, \qquad \text{Cr}_{ij} = \left(C^{\text{D}}_{ii}\right)^{-\frac{1}{2}} \delta^K_{ij},$$

$$\left(\frac{S}{N}\right)^2_{P+B} = \sum^{i,j}_{l(i),l(j)<l_{\max}} \frac{\text{D}_i \text{D}_j \left[C^{\text{Cr.}}\right]^{-1}_{ij}}{\text{Cr}_{ii}\text{Cr}_{jj}}.$$





B, NGc + SSc — B + P, NGc + SSc — B, NGc — B + P, NGc

Results

Principal Component Analysis (PCA): localising the information content

Orthonormal basis of eigenvectors:

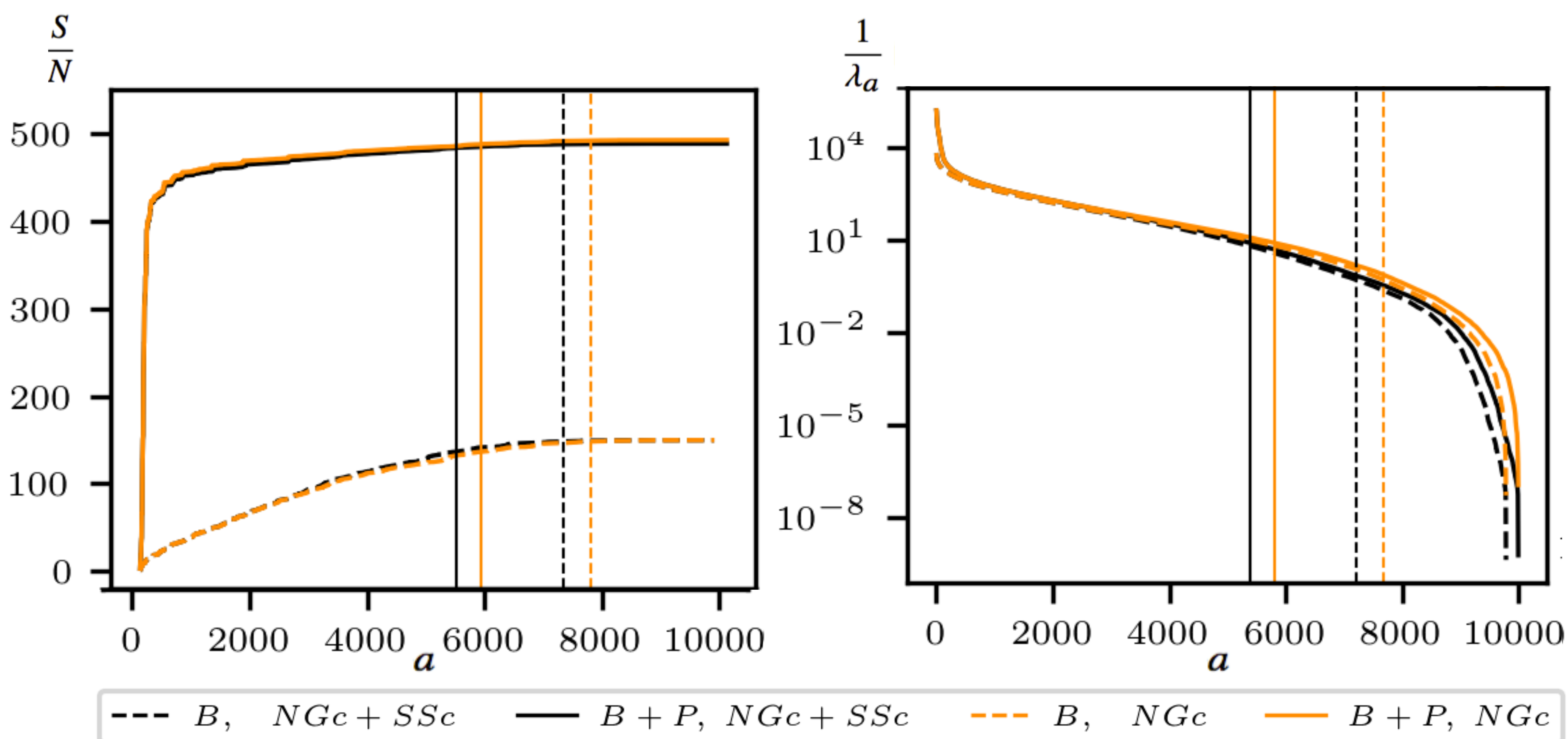
$$C^*_{ij} = \sum_a S^*_{ai} S^*_{aj} \lambda_a$$

$$\left(\frac{S}{N}\right)^2_{P+B} = \sum_a \frac{1}{\lambda_a} \left(\sum_i S^X_{ai} X_i\right)^2$$

Pre-condition 2 for improved inversion

$$C^P = P \cdot C^D \cdot P, \qquad P_{i,j} = D_i^{-1} \delta^K_{ij}.$$

$$\left(\frac{S}{N}\right)^2_{P+B} = \sum_{l(i),l(j)<l_{\max}}^{i,j} [C^P]^{-1}_{ij}$$



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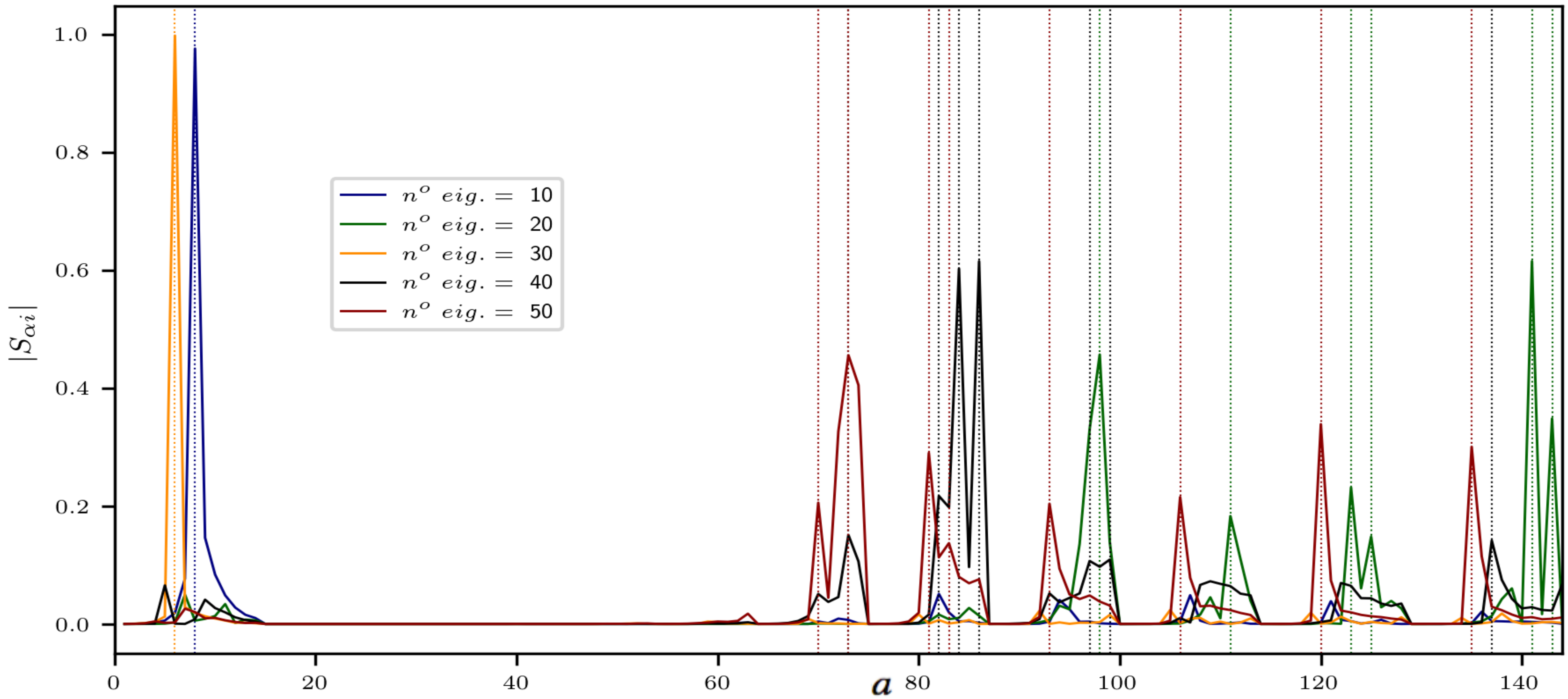

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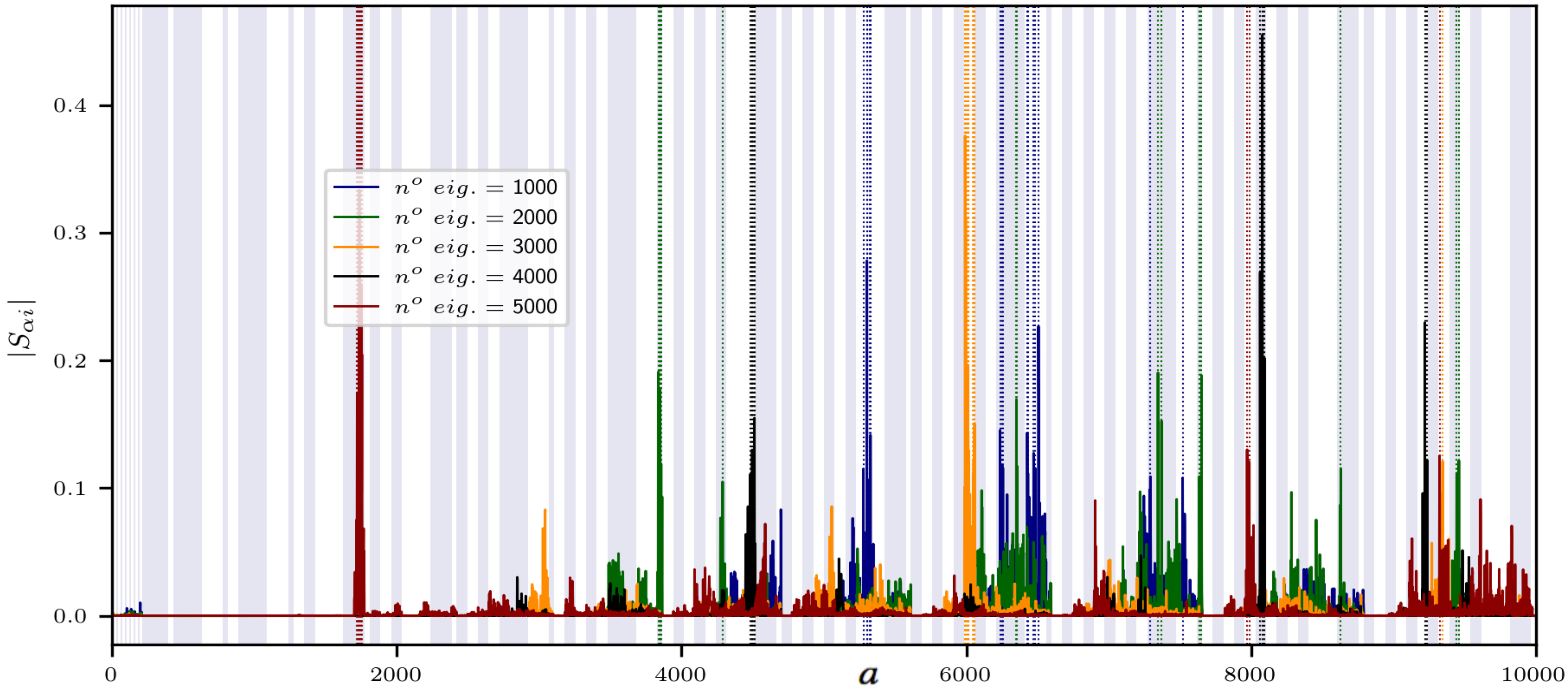
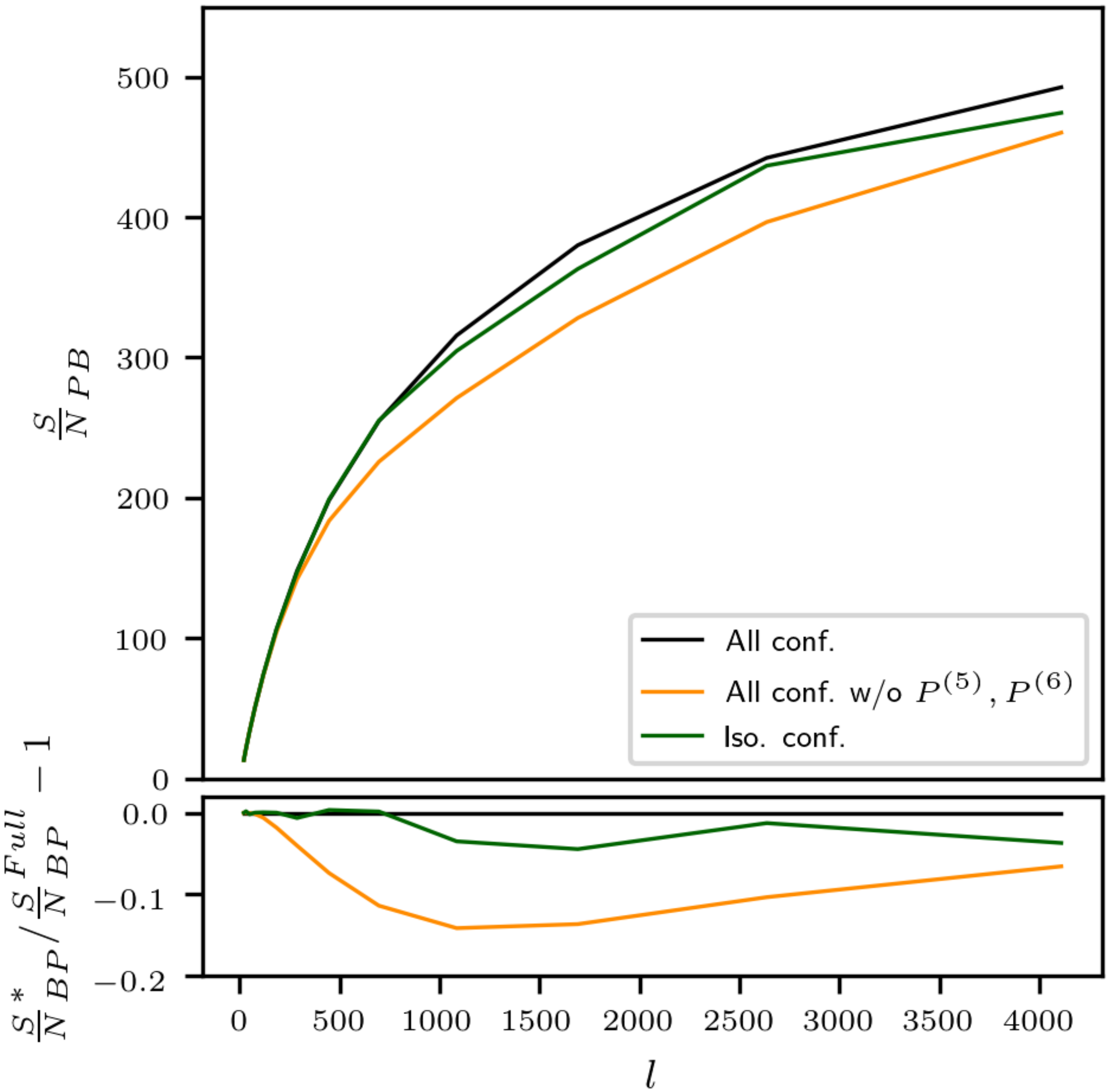
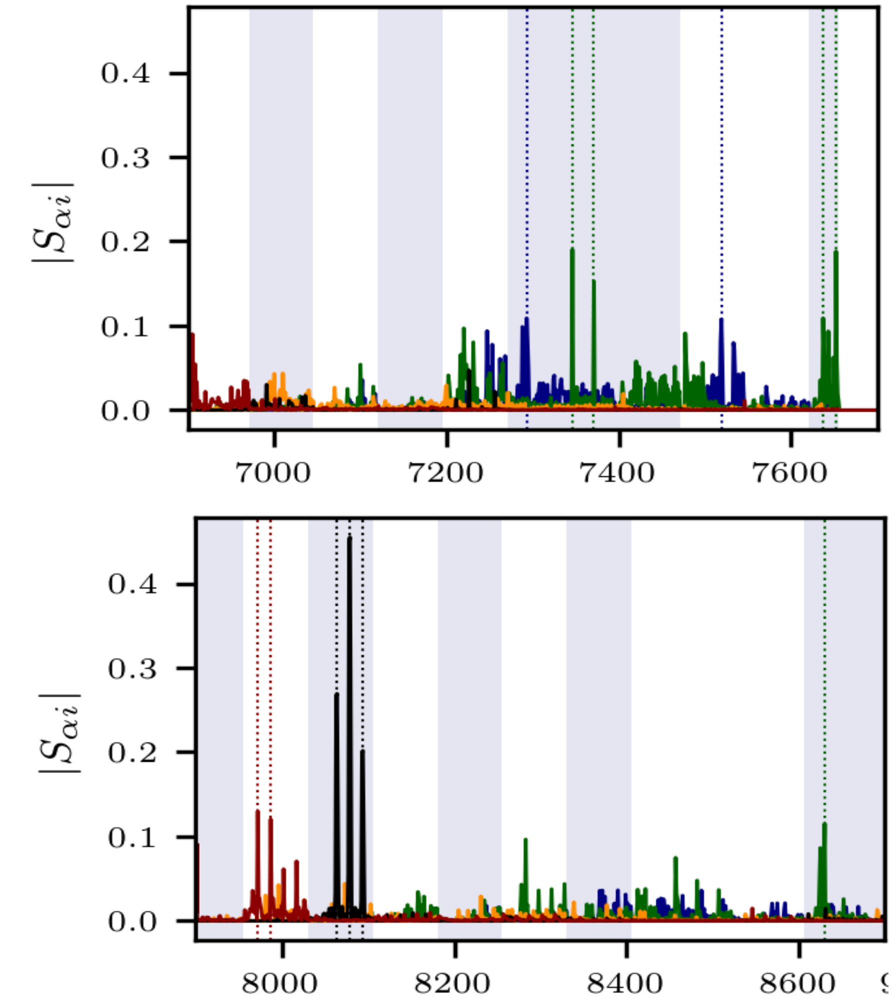


Results

Further reductions





For $|S_{ai}| > 0.1$

Configurations:	isosceles	equilateral	scalene
1 bin tomo.	653	84	57
2 bin tomo.	8340	528	1343
5 bin tomo.	143487	8250	31136

- Isosceles configurations alone carry the 96 % of the maximum information content
- Omitting the 5 and 6 point correlation functions bias the information content for about 8%

Conclusion

I have presented a thorough analysis of the information content in the bispectrum of the weak lensing convergence.

The tool developed can be applied to galaxy surveys like Euclid, DES or LSST.

The structure of the code allow the computation to be applied to Galaxy Clustering and to be based on different other models for the non linear growth structures.

With the present analysis we have proved :

- The only left uncertainty in the theoretical model does not effect our forecast.
- The loss of information due to the SSC is recovered in the joint analysis.
- The maximum SN ratio is increased of about 45 % in the joint analysis if compared to the power spectrum analysis alone.
- By applying the right preconditioning, we are capable to project the covariance matrix in a subspace of dimension 45 % smaller.

Thank you very much for the attention