UNIVERSITÀ DI TORINO
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Istituto Nazionale di Fisica Nucleare
Sezione di Torino
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Detecting Relativistic Doppler in Galaxy Clustering by Multi-tracing a Single Galaxy Population

[F. Montano & S. Camera, PDU 46 (2024) 101570, arXiv:2309.12400]
[F. Montano & S. Camera, PDU 46 (2024) 101634, arXiv:2407.06284]

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Relativistic galaxy number counts

The leading local contributions to the number density contrast of galaxies are [Yoo (2010); Bonvin & Durrer (2011); Challinor & Lewis (2011)]:

$$\Delta(\vec{x}) = b\delta(\vec{x}) - \frac{1}{\mathcal{H}}\partial_r v_r(\vec{x}) - \alpha v_r(\vec{x}) \, ,$$

with:

- $\alpha = -\mathcal{E} + 2Q - 2\frac{Q-1}{r\mathcal{H}} + \frac{\mathcal{H}'}{\mathcal{H}^2}$,
- r = comoving radial distance,
- b = linear galaxy bias,
- $\delta = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$ = matter density contrast,
- $\mathcal{H}$ = conformal Hubble factor,
- v = velocity field,
- Q = magnification bias,
- $\mathcal{E}$ = evolution bias.

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Sample-dependent quantities

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Auto- and cross-correlation measurements

- $<\delta_X(\vec{k})\delta_Y(\vec{k'})> \propto \delta^D(\vec{k}+\vec{k'})P_{XY}(k)$

$$P_{XY}(z,k,\mu) =$$

$$= \left[(b_X + f\mu^2)(b_Y + f\mu^2) + \left(\frac{\mathcal{H}f\mu}{k}\right)^2 \alpha_X\alpha_Y + i\frac{\mathcal{H}f\mu}{k}\left(\alpha_X(b_Y + f\mu^2) - \alpha_Y(b_X + f\mu^2)\right)\right] P_m(k)$$

- $X = Y \rightarrow$ auto-correlation
- $X \neq Y \rightarrow$ cross-correlation

Auto- and cross-correlation measurements

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Auto- and cross-correlation measurements

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$$P_{XY}(z,k,\mu) = $$
$$= \left[(b_X + f\mu^2)(b_Y + f\mu^2) + \left(\frac{\mathcal{H}f\mu}{k}\right)^2 \alpha_X\alpha_Y \right.$$
$$\left. + i\frac{\mathcal{H}f\mu}{k}\left(\alpha_X(b_Y + f\mu^2) - \alpha_Y(b_X + f\mu^2)\right) \right] P_m(k)$$

- $P_{XY}(z,k,\mu) = P^*_{YX}(z,k,\mu) \rightarrow P_{XY}(z,k,\mu) = P_{YX}(z,k,-\mu)$
- The Doppler contribution is proportional to k^{-1} in the imaginary part of the cross-power spectrum [McDonald (2009)].

Multi-tracer power spectrum

We can put together information given by auto- and cross-power spectra to obtain tighter constrains [Percival et al. (2004); Fonseca *et al*. (2015)].

- We have now:

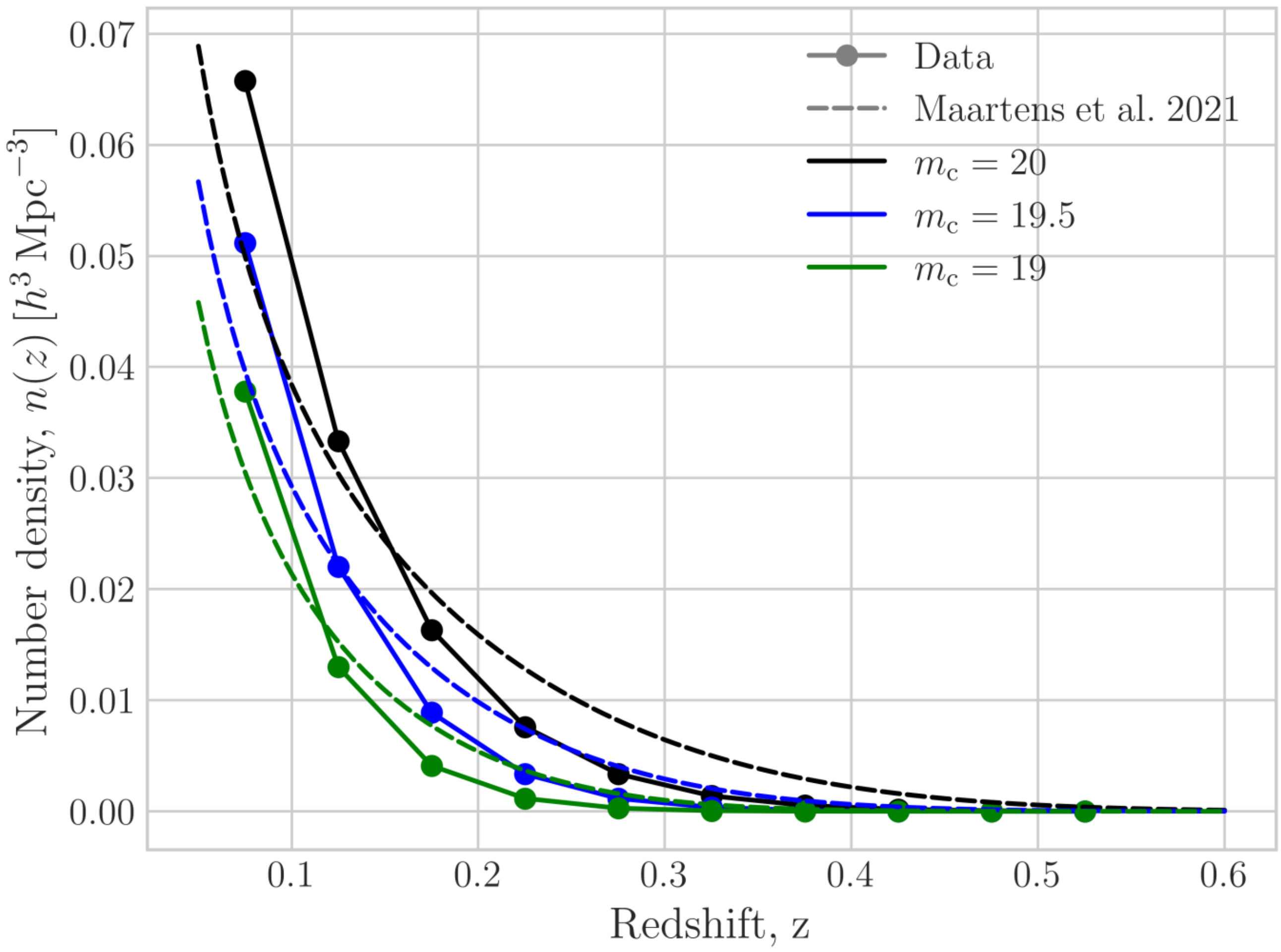
$$P = \begin{pmatrix} P_{XX} \\ P_{XY} \\ P_{YY} \end{pmatrix}, \qquad \Gamma = \frac{2}{N_{modes}} \begin{pmatrix} \tilde{P}_{XX}^2 & \tilde{P}_{XX}\tilde{P}_{XY} & \tilde{P}_{XY}^2 \\ \tilde{P}_{XX}\tilde{P}_{YX} & \dfrac{\tilde{P}_{XX}\tilde{P}_{YY} + \tilde{P}_{XY}\tilde{P}_{YX}}{2} & \tilde{P}_{XY}\tilde{P}_{YY} \\ \tilde{P}_{YX}^2 & \tilde{P}_{YX}\tilde{P}_{YY} & \tilde{P}_{YY}^2 \end{pmatrix}$$

- Multi-tracer power spectrum with P_{FF}, P_{FB}, P_{BB} [Montano & Camera (2024)].

The Doppler contribution is sample-dependent

We use:

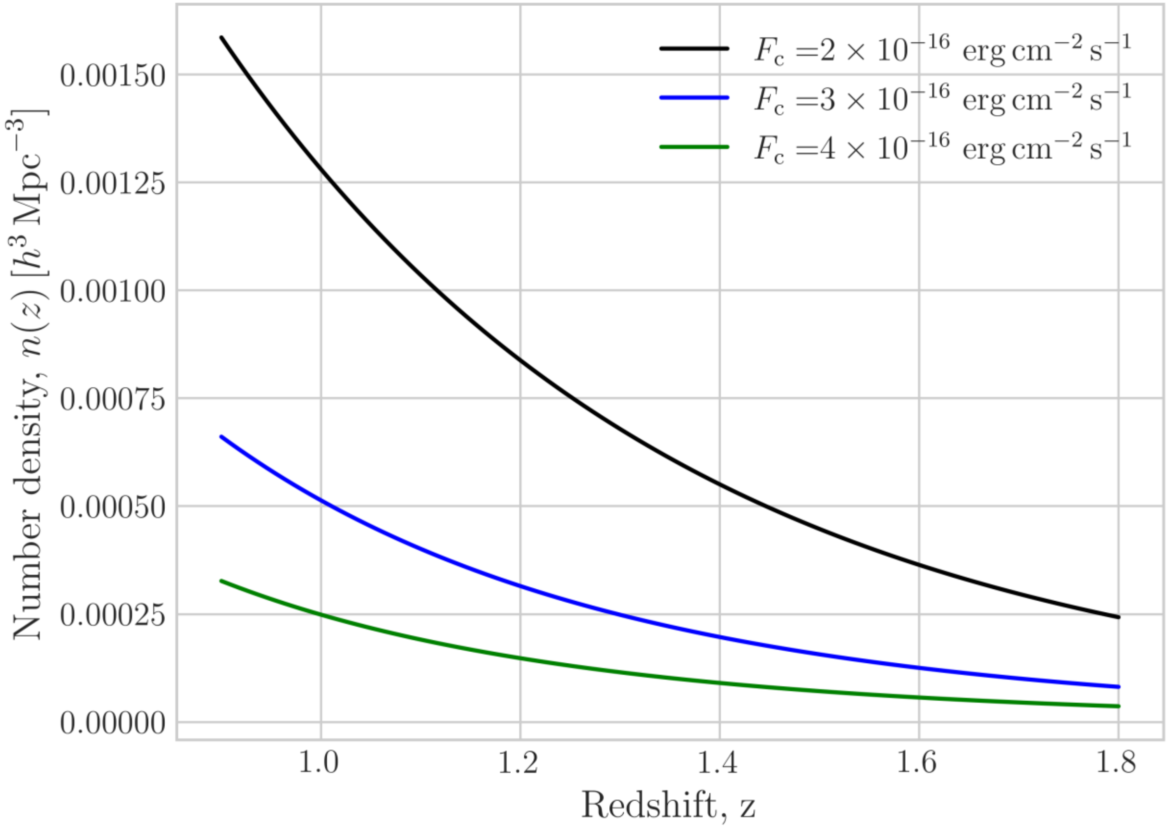
- A low-redshift DESI-like Bright Galaxy Sample (BGS) [Smith et al. (2023)];



The Doppler contribution is sample-dependent

We use:

- A low-redshift DESI-like Bright Galaxy Sample (BGS) [Smith et al. (2023)];
- A population of Hα galaxies observed by a *Euclid*-like survey [Maartens et al. (2021)].



Luminosity cut technique

[Bonvin et al. (2014, 2016, 2023); Gaztanaga et al. (2017)]

- Complete sample (T): all the galaxies that are observed with a flux density F higher than a fixed minimum flux

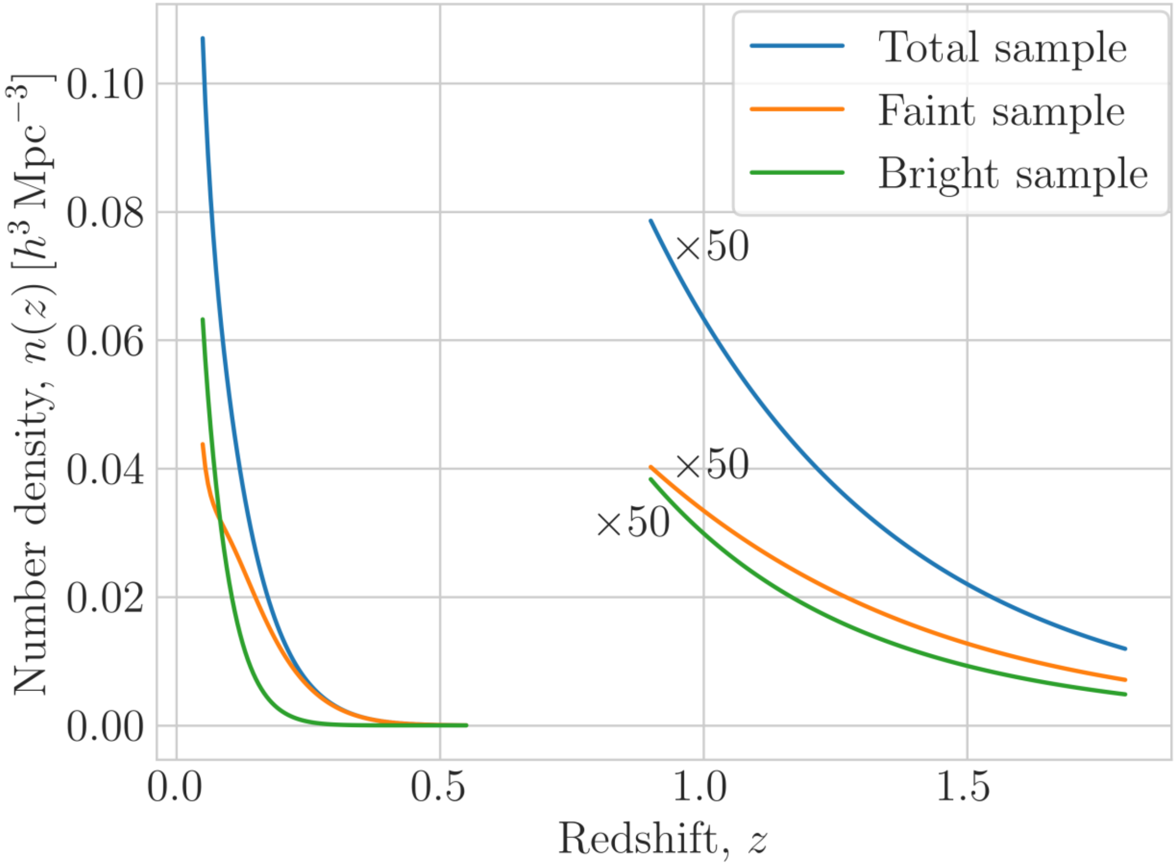
$$F > F_c$$

- Faint sample (F): all the galaxies with

$$F_c < F < F_s$$

- Bright sample (B): all the galaxies with

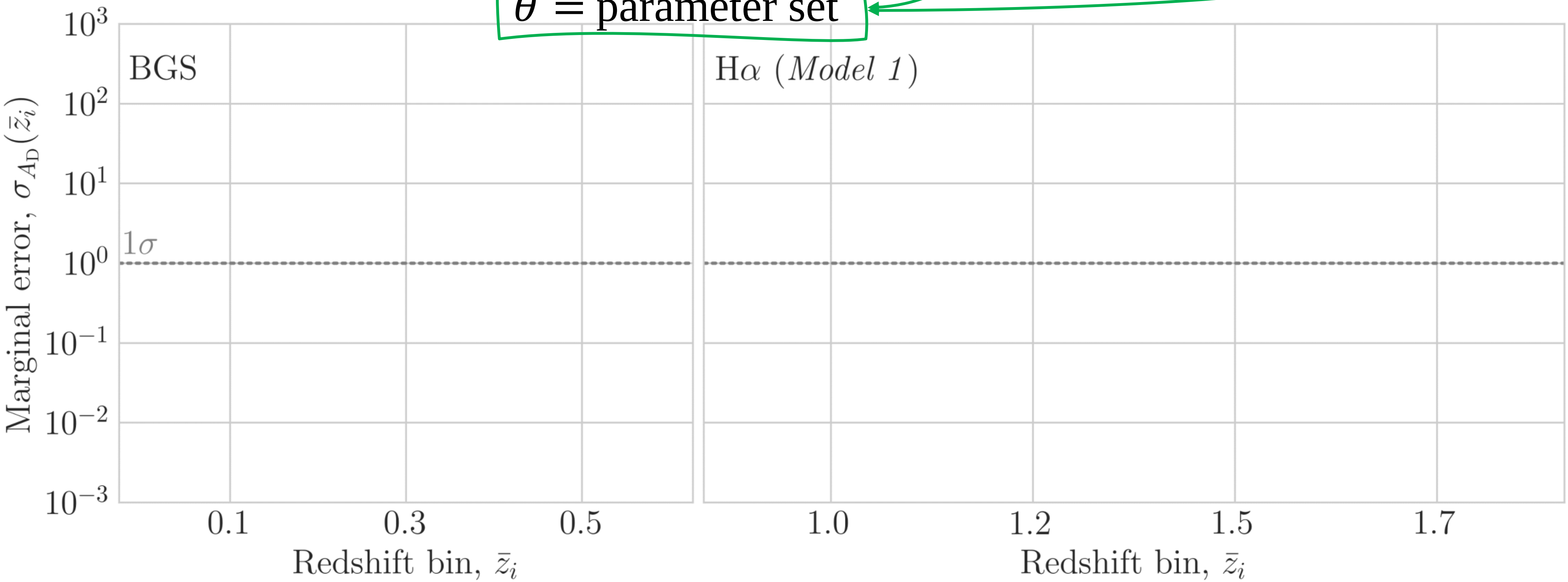
$$F > F_s$$



Information matrix analysis

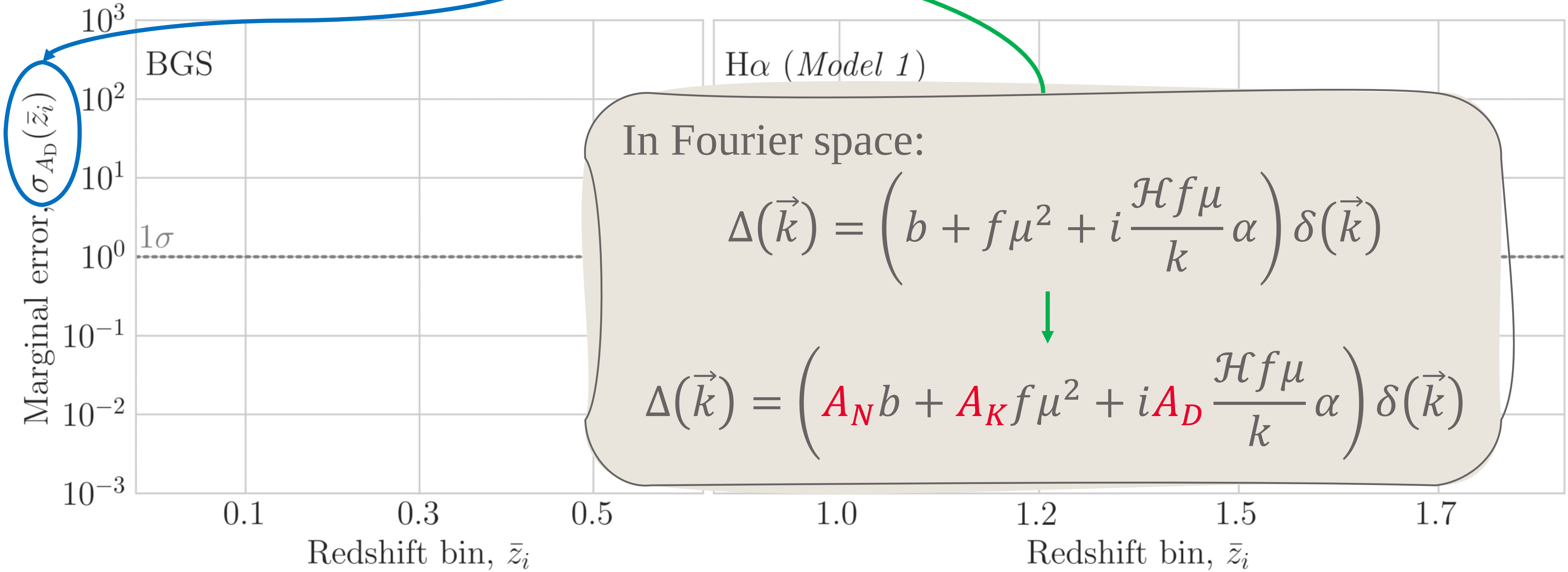
$$P = \begin{pmatrix} P_{FF} \\ P_{FB} \\ P_{BB} \end{pmatrix}, \quad I_{\alpha\beta}(z_i) = \sum_{m,n} \frac{\partial P(z_i,\mu_m,k_n)^H}{\partial \theta_{(\alpha}} \Gamma^{-1} \frac{\partial P(z_i,\mu_n,k_m)}{\partial \theta_{\beta)}}$$

θ = parameter set



- Hα emitters, *Model 3* luminosity function [Pozzetti et al. (2016)]:
  - $F_c = 2 \times 10^{-16}$ erg cm^{-2} s^{-1}
  - $\Delta z \sim 0.23$
- BGS:
  - $m_c = 20.175$
  - $\Delta z \sim 0.17$
- $f_{sky} = 0.36$

$$\boldsymbol{\theta_\alpha = \{A_N, A_K, A_D\}}$$



In Fourier space:

$$\Delta(\vec{k}) = \left(b + f\mu^2 + i\frac{\mathcal{H} f \mu}{k}\alpha\right)\delta(\vec{k})$$

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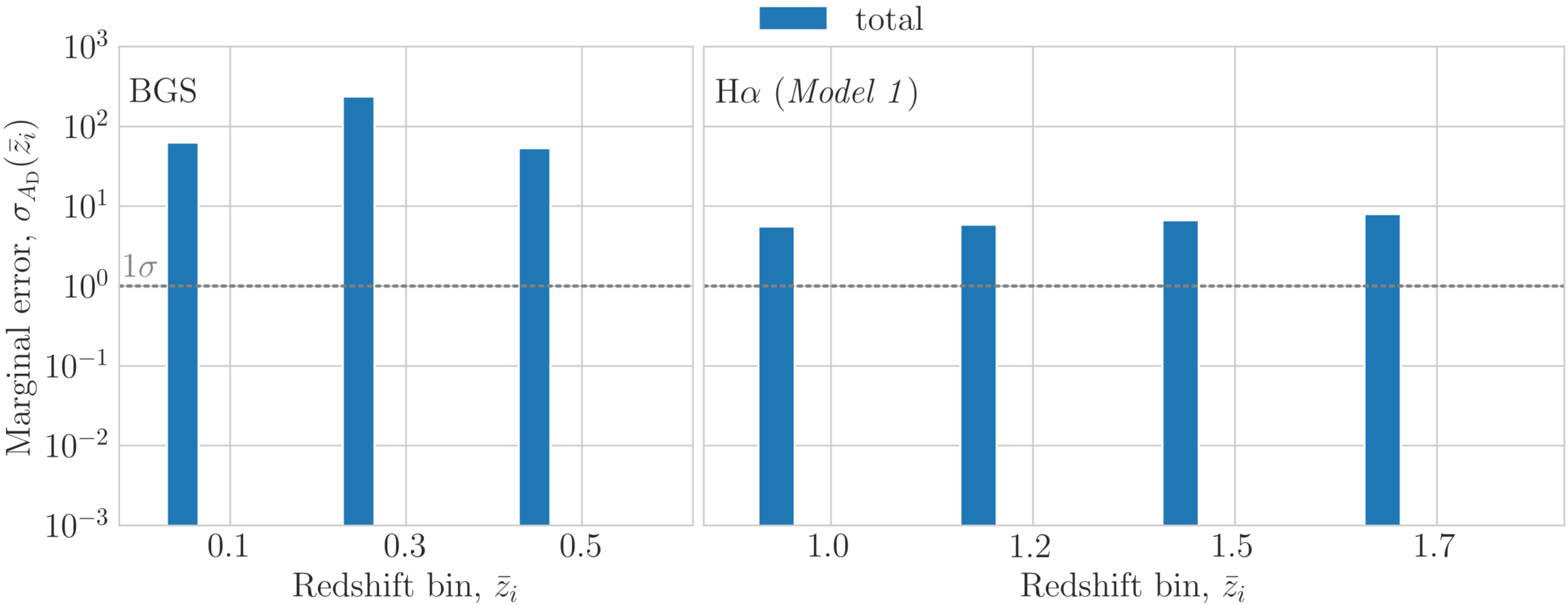

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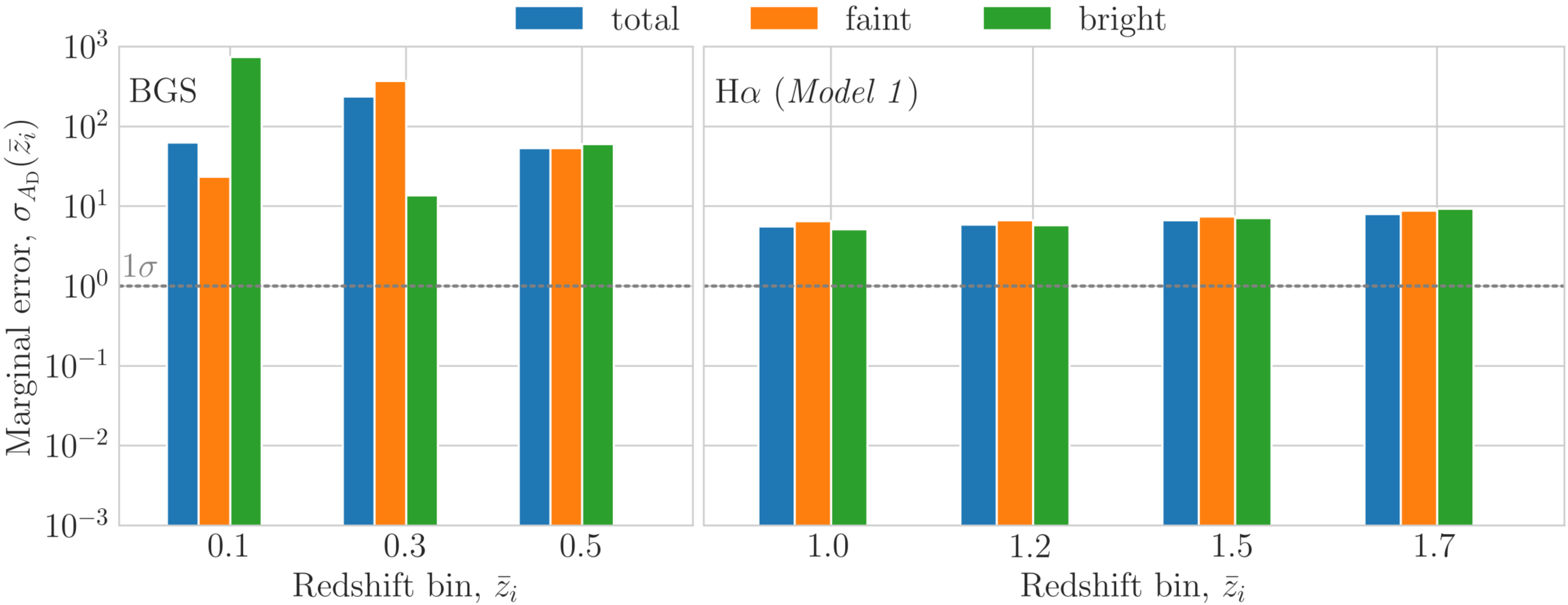

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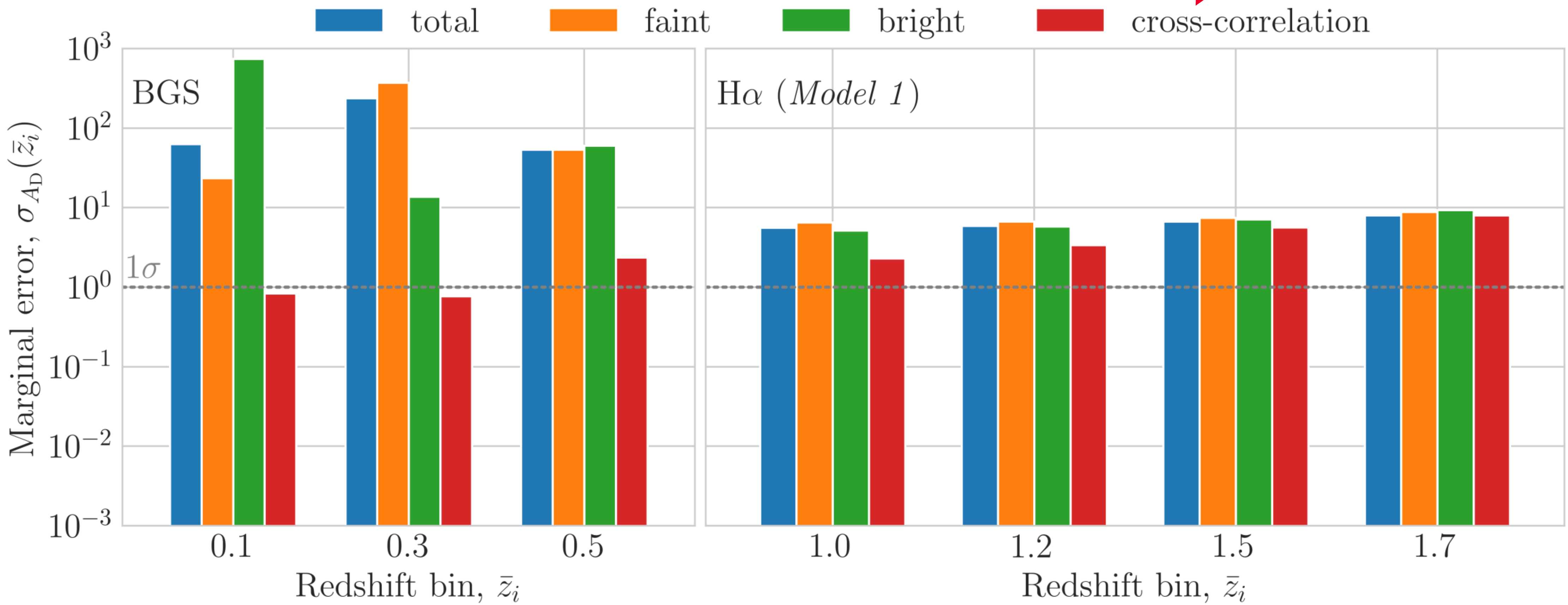

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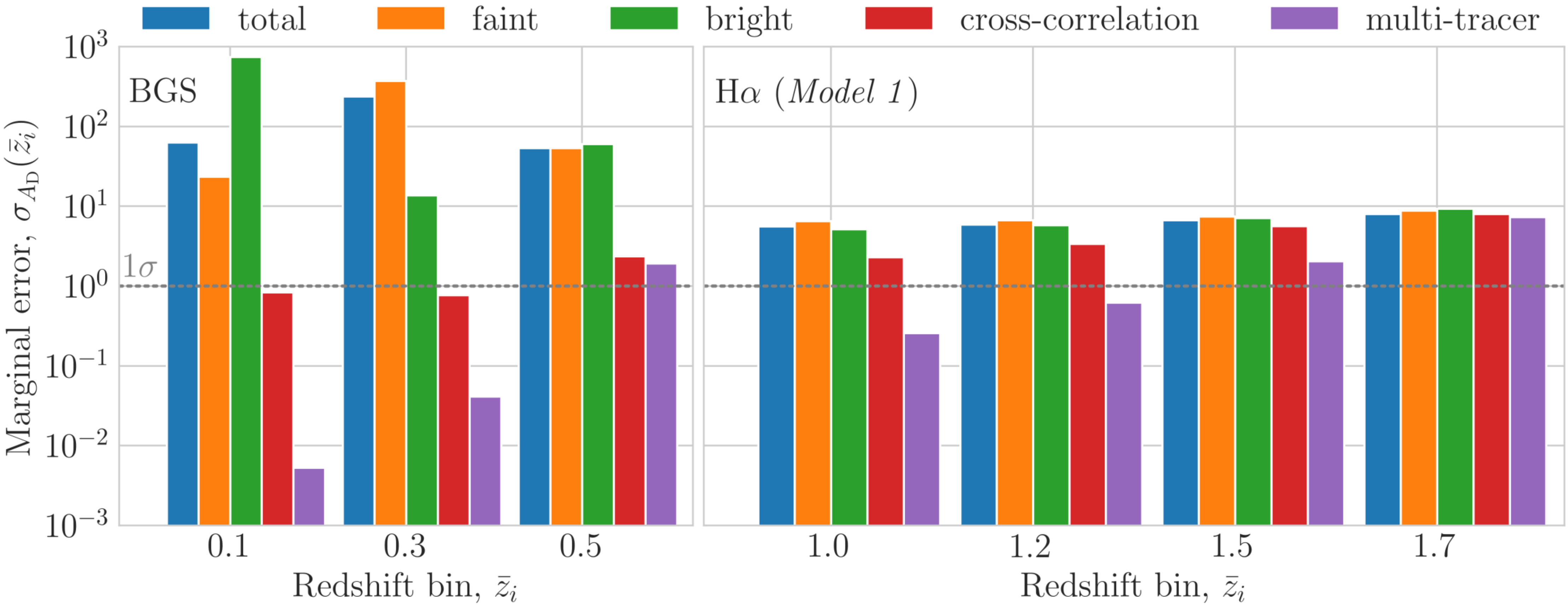
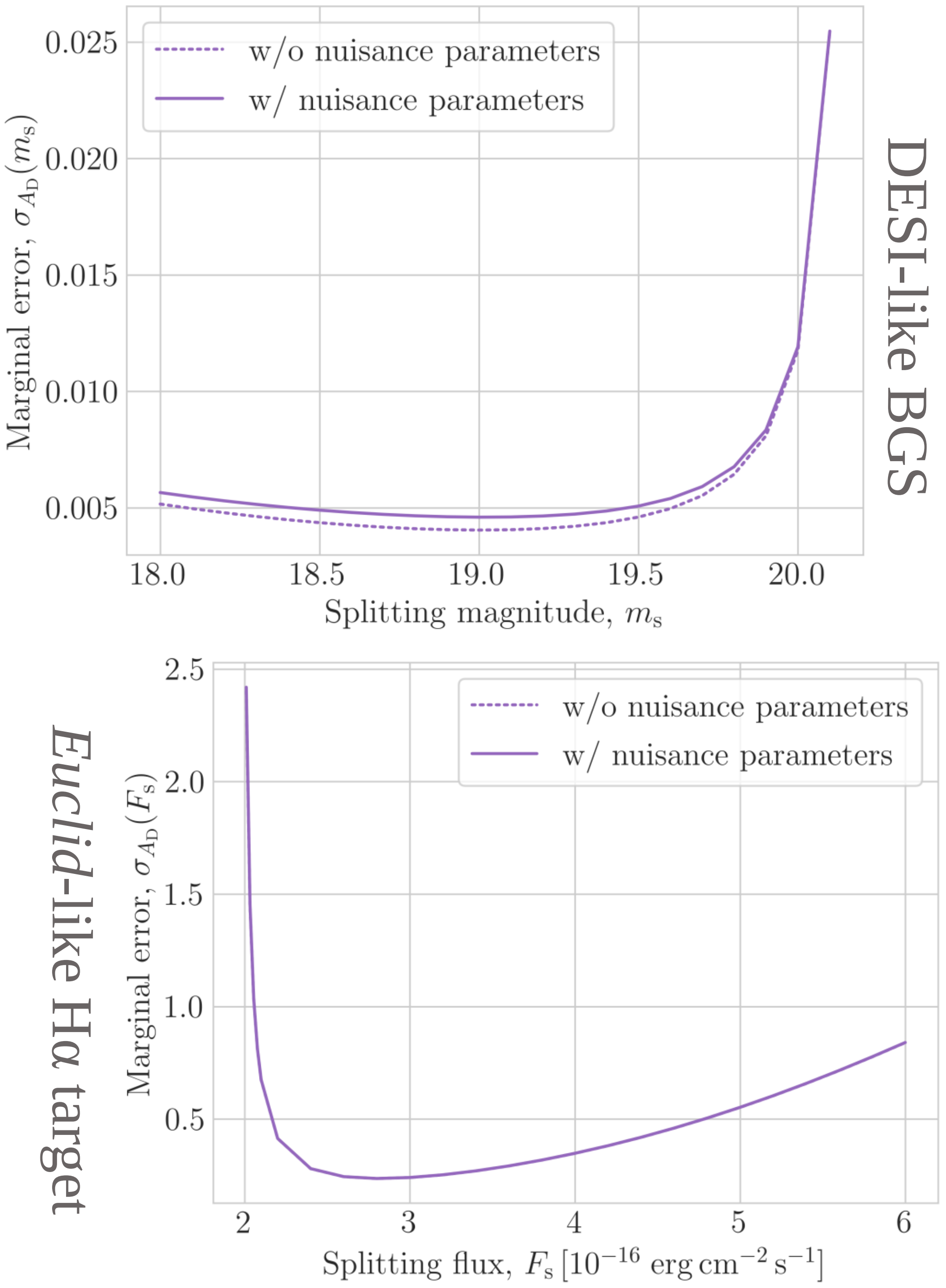
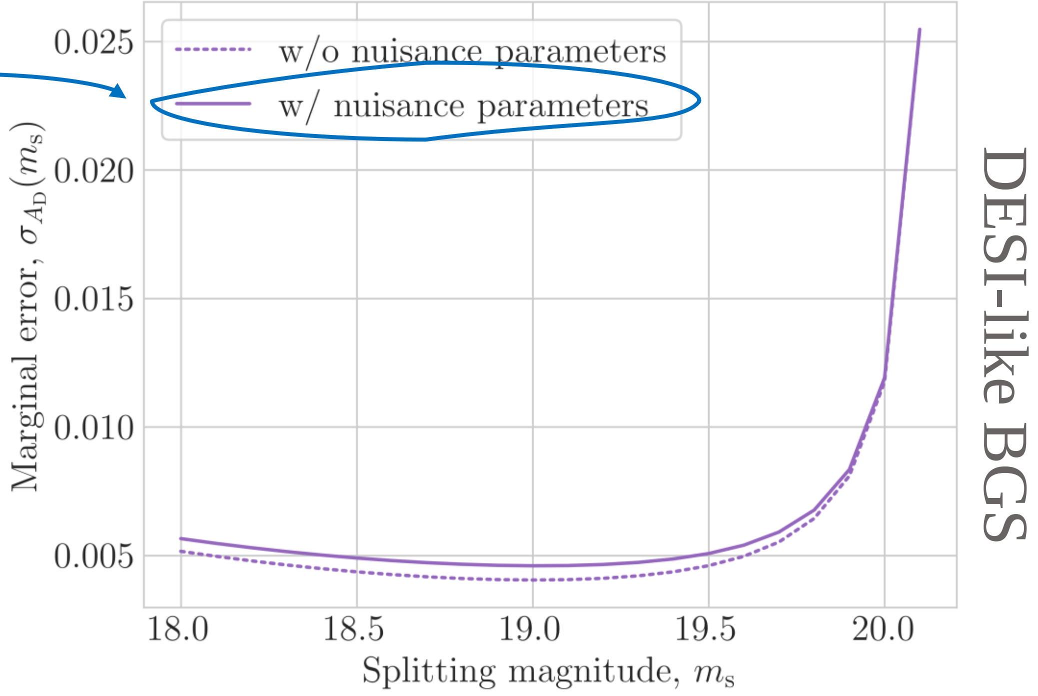


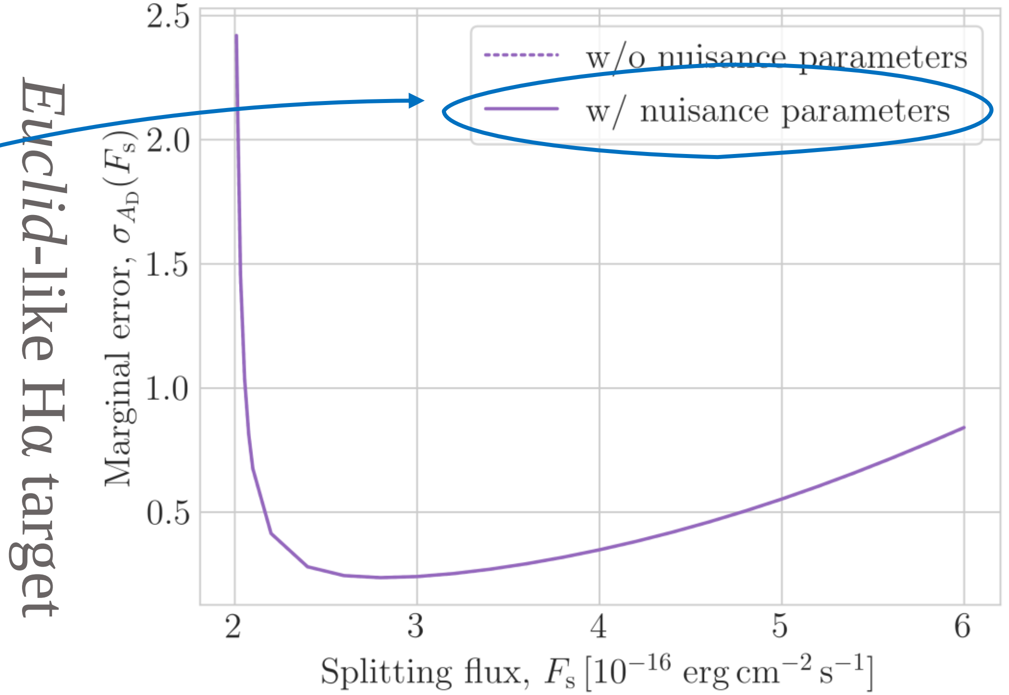
We can study how the probability of detecting a relativistic contribution depends upon the splitting flux adopted.



We can study how the probability of detecting a relativistic contribution depends upon the splitting flux adopted.

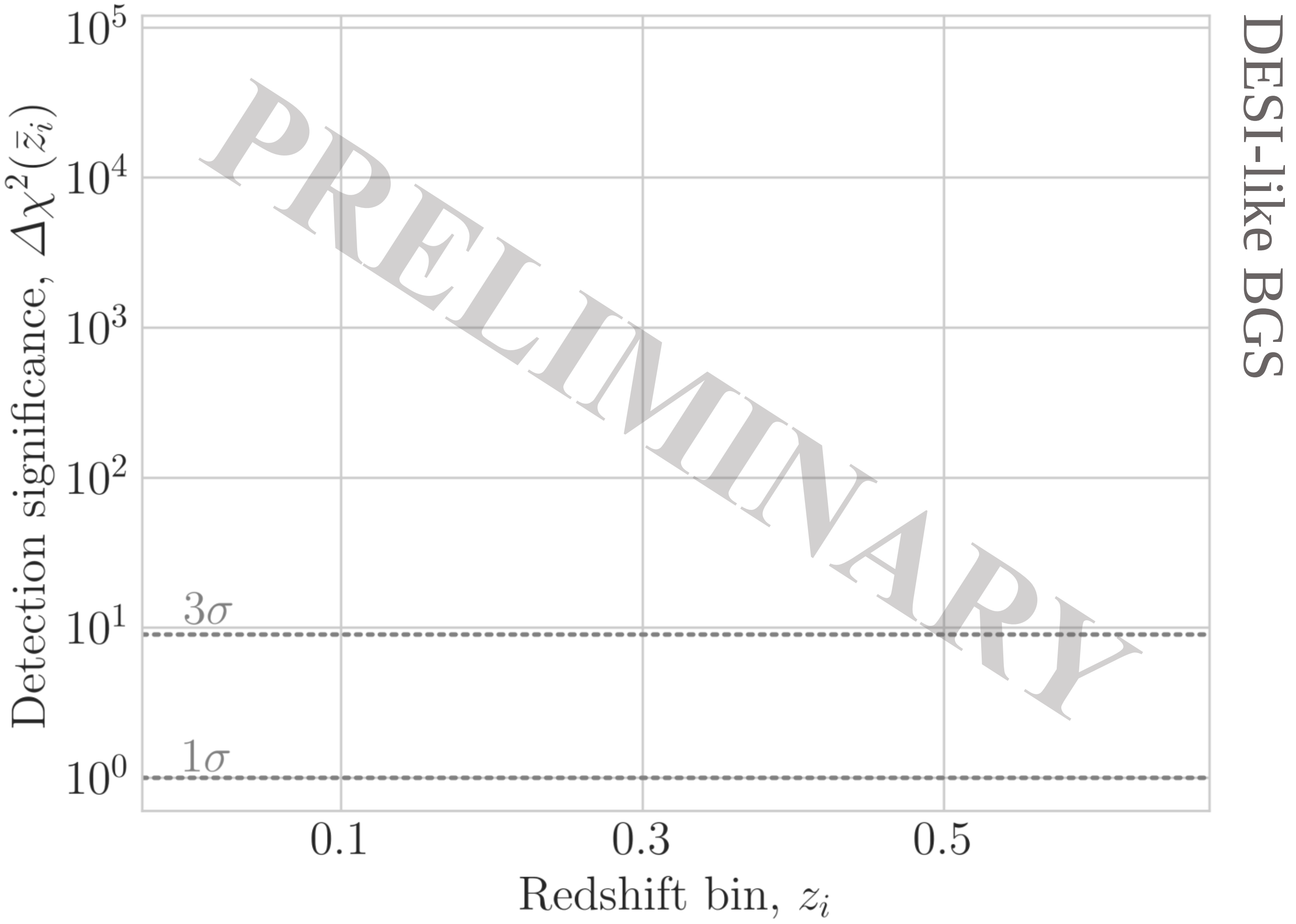
$$\theta_\alpha = \left\{A_N, A_K, A_D, \left\{N_{FF}^{(i)}\right\}, \left\{N_{FB}^{(i)}\right\}, \left\{N_{BB}^{(i)}\right\}\right\}$$





What about multiple splits?

Can we further increase the signal by considering more than 2 sub-samples?



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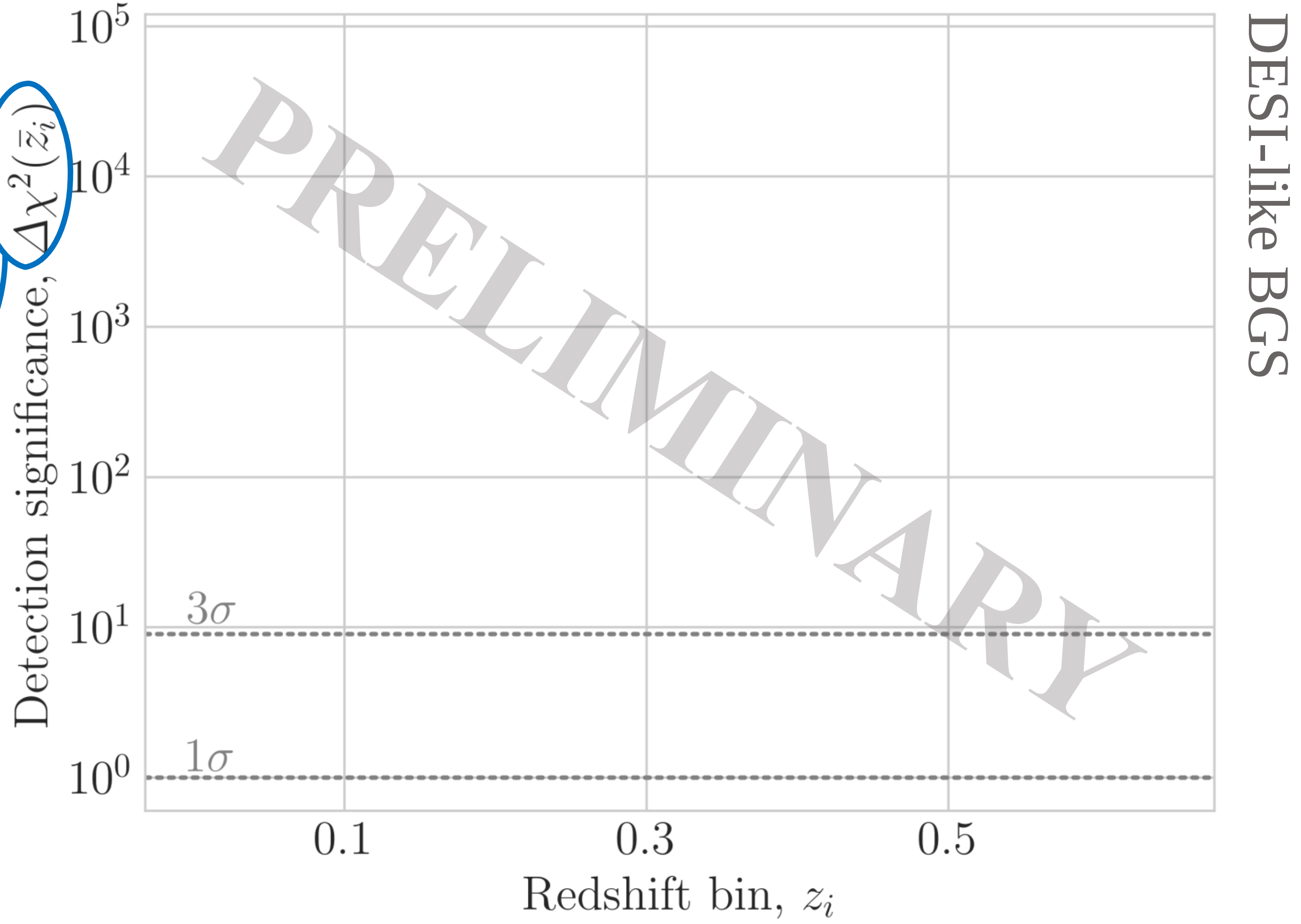
Detection significance analysis

Can we further increase the signal by considering more than 2 sub-samples?

$$\Delta\chi^2(\bar{z}_i) = \sum_{k,\mu} \boldsymbol{\Delta P}^H \, \Gamma^{-1} \, \boldsymbol{\Delta P}$$

$\boldsymbol{\Delta P}$ computed with a null-hypothesis of no Doppler



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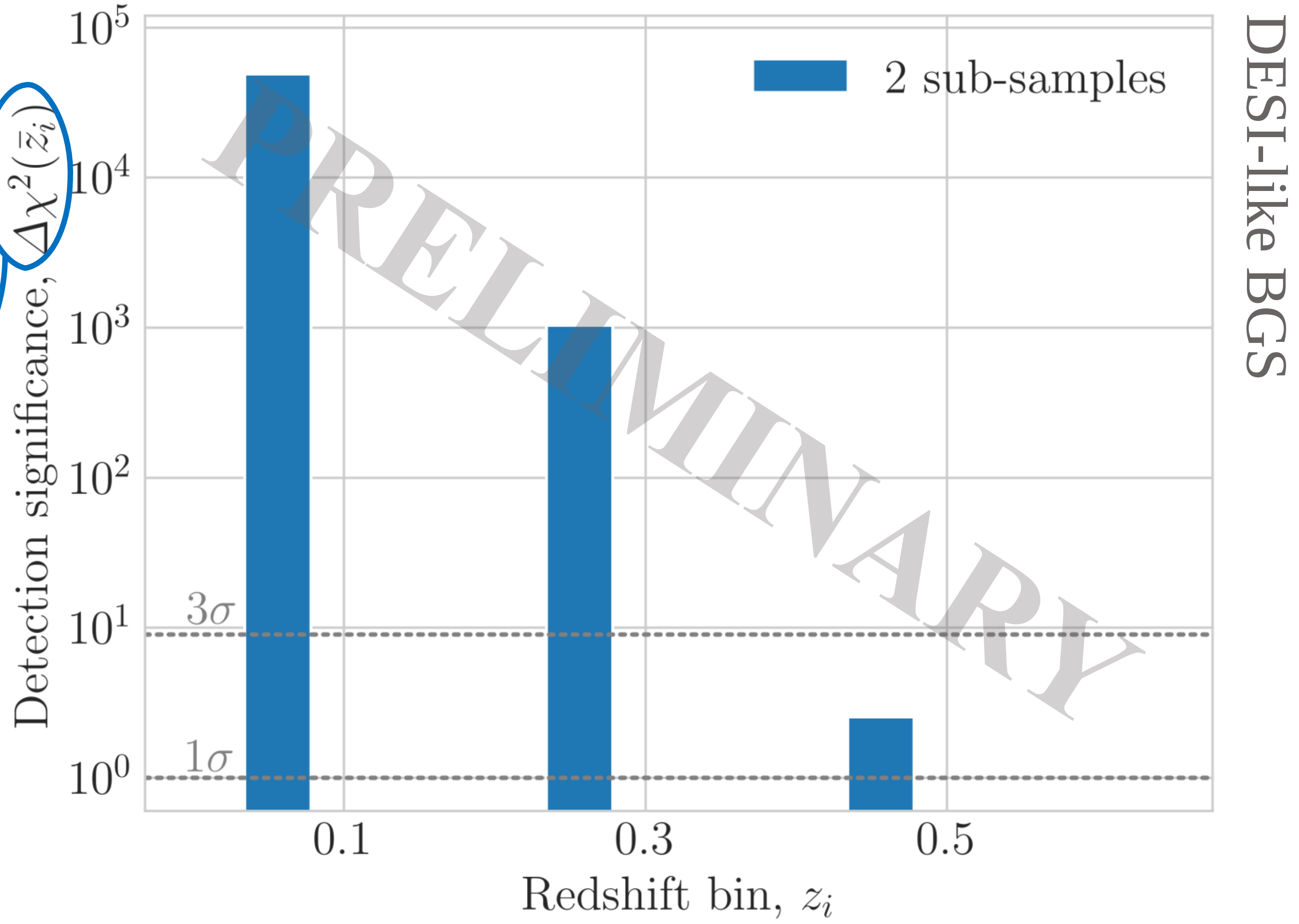

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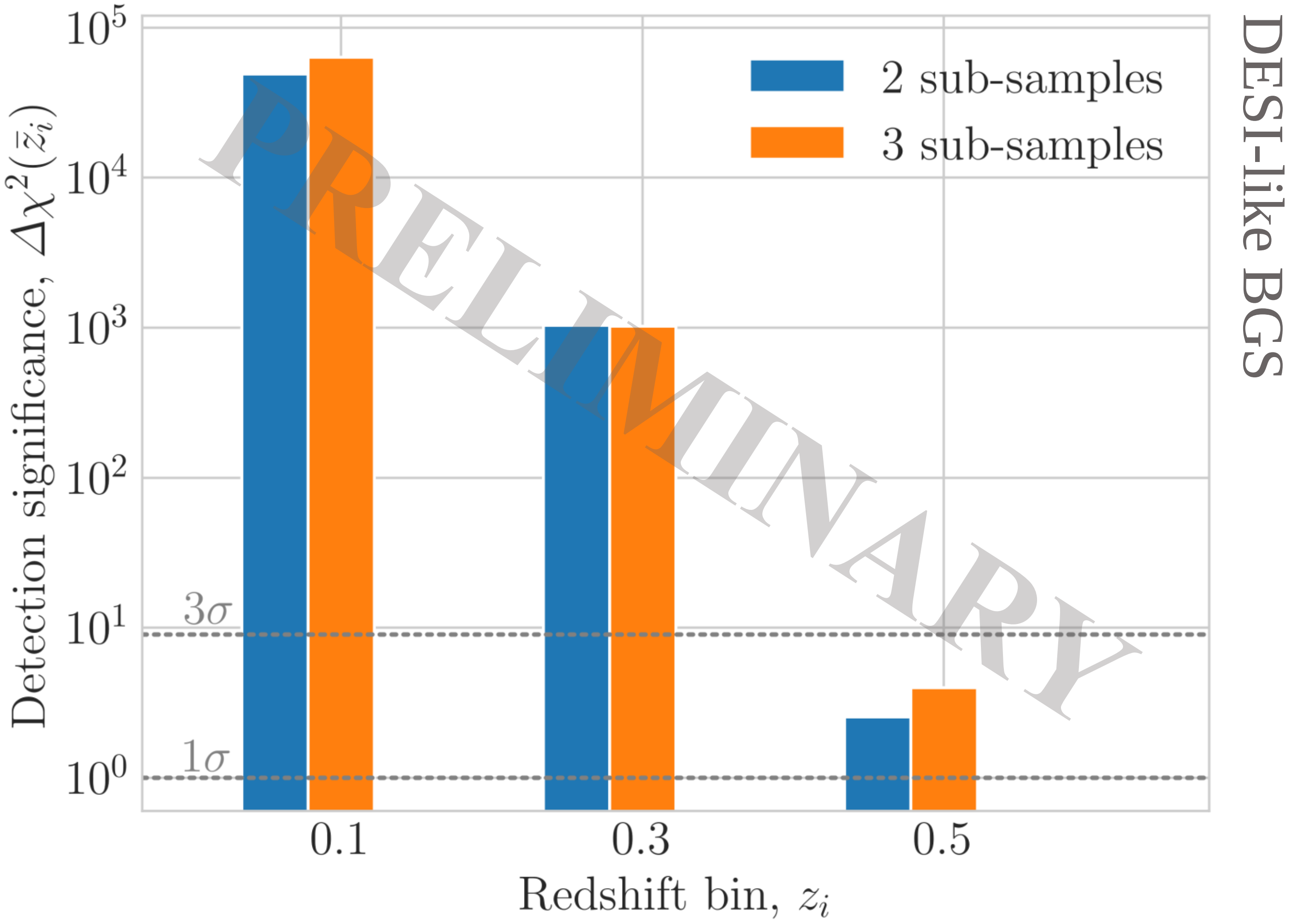

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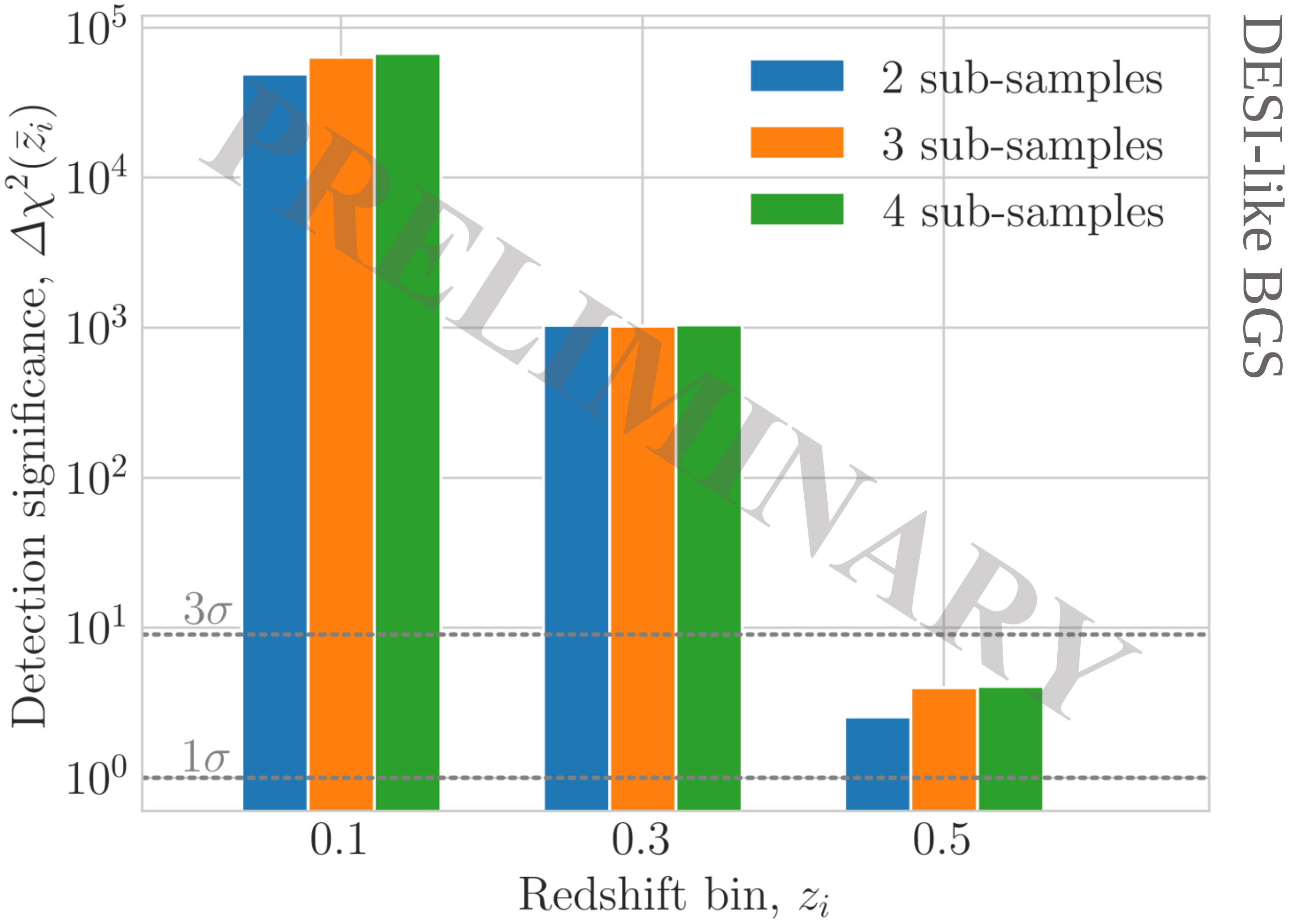

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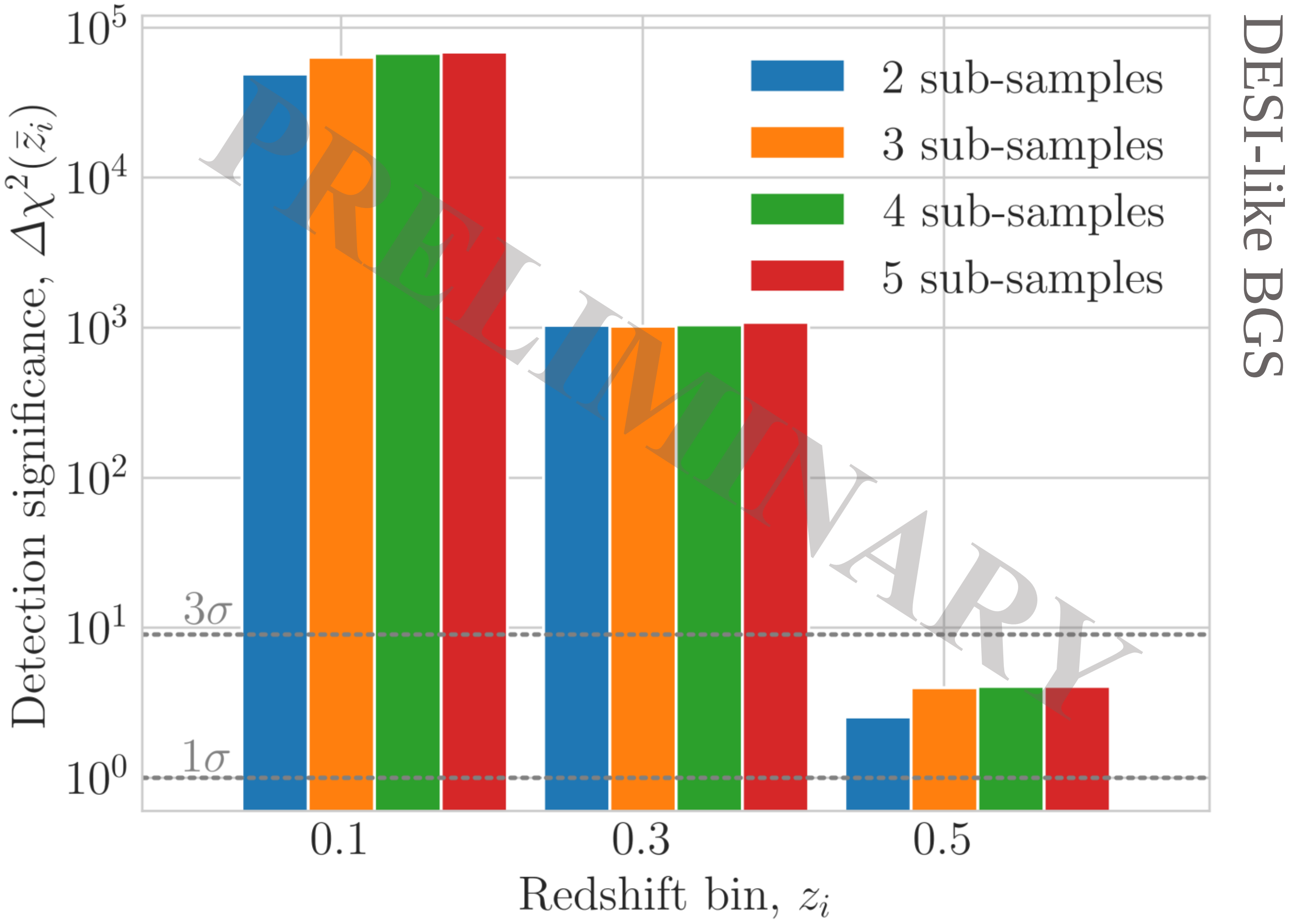
Can we further increase the signal by considering more than 2 sub-samples?

We seem to be going towards a saturation of the information we can extract from a single galaxy population



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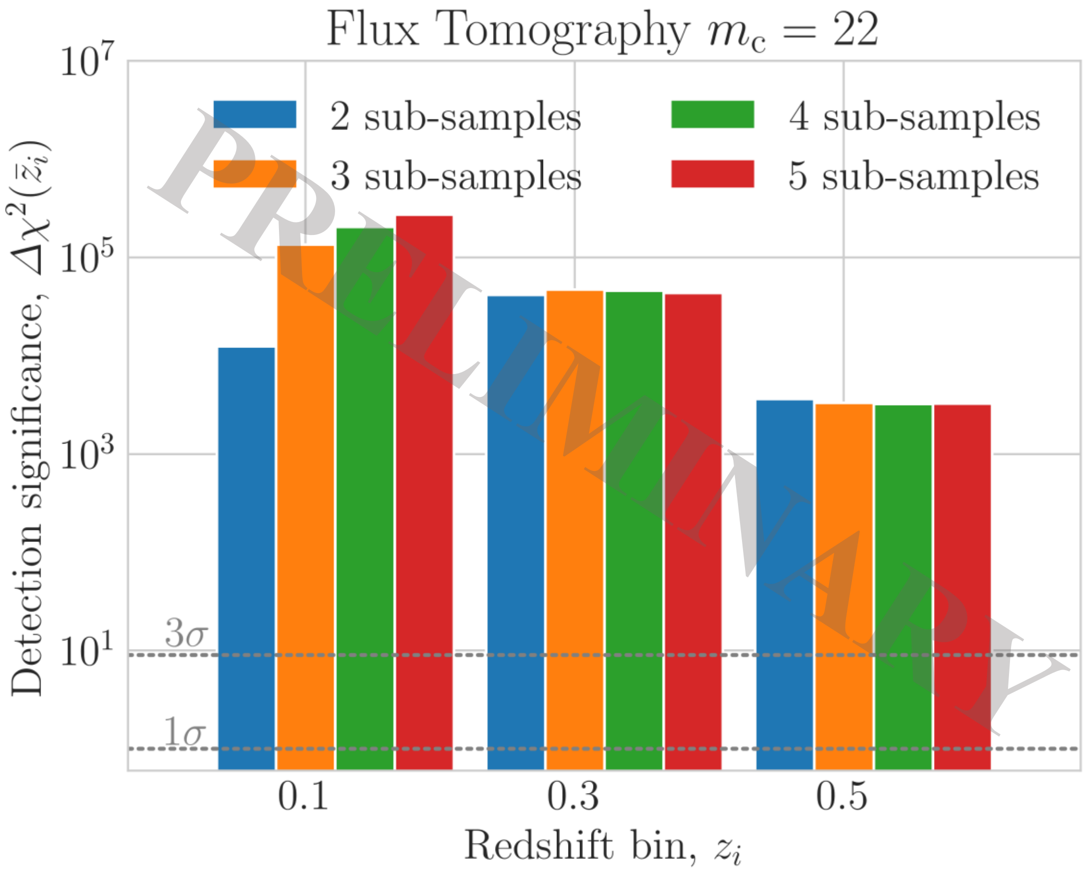
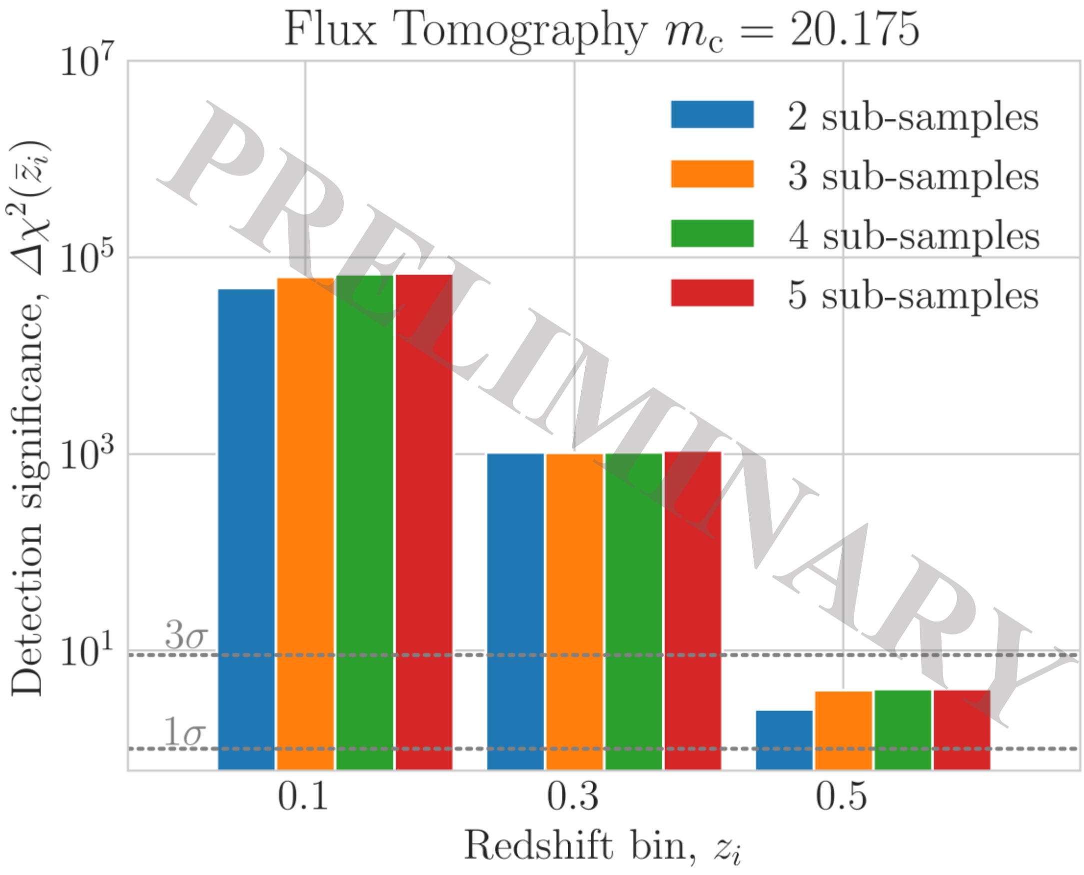




DESI-like BGS

What about integrated effects?

[**Marco Novara**, FM & S. Camera, (2024 TBS)]

Effects included in the angular power spectrum analysis

$$\Delta_l = \Delta_l^{N} + \Delta_l^{Doppler} + \Delta_l^{lensing} + \Delta_l^{GR}$$

[Castorina & Di Dio (2022)]

$$\begin{aligned}
\Delta(\mathbf{n}, z) = {} & b_1 D_m + \mathcal{H}^{-1}\partial_r v_{||} \\
& + \frac{5s_b - 2}{2}\int_0^r dr' \frac{r - r'}{rr'} \Delta_\Omega (\Psi + \Phi) \\
& + \mathcal{R}\left(v_{||} - v_{||_o}\right) - (2 - 5s_b)\, v_{||_o} \\
& + \left\{ \left(\mathcal{R} - \frac{2 - 5s_b}{\mathcal{H}_0 r}\right) \mathcal{H}_0 V_o + (\mathcal{R} + 1)\,\Psi - \mathcal{R}\Psi_o + (5s_b - 2)\,\Phi + \dot{\Phi}\mathcal{H}^{-1} \right. \\
& \quad \left. + \left(f_{\mathrm{evo}} - 3\right) \mathcal{H} V \right\} \\
& + \frac{2 - 5s_b}{r}\int_\tau^{\tau_o} (\Psi + \Phi)\, d\tau' + \mathcal{R}\int_\tau^{\tau_o} \left(\dot{\Psi} + \dot{\Phi}\right) d\tau' ,
\end{aligned}$$

where we have introduced the redshift dependent parameter

$$\mathcal{R} = 5s_b + \frac{2 - 5s_b}{\mathcal{H}r} + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - f_{\mathrm{evo}} .$$

What about integrated effects?

[**Marco Novara**, FM & S. Camera, (2024 TBS)]

Effects included in the angular power spectrum analysis [Di Dio *et al.* 2016)]

$$\Delta_l = \Delta_l^N + \Delta_l^{Doppler} + \Delta_l^{lensing} + \Delta_l^{GR}$$

Study of the relevance of the Doppler, local and integrated potential terms in a faint-bright multi-tracer angular power spectrum.

$$\Delta\chi^2 = \sum_l \mathrm{tr}[S\,\Gamma^{-1}\,S\,\Gamma^{-1}]$$

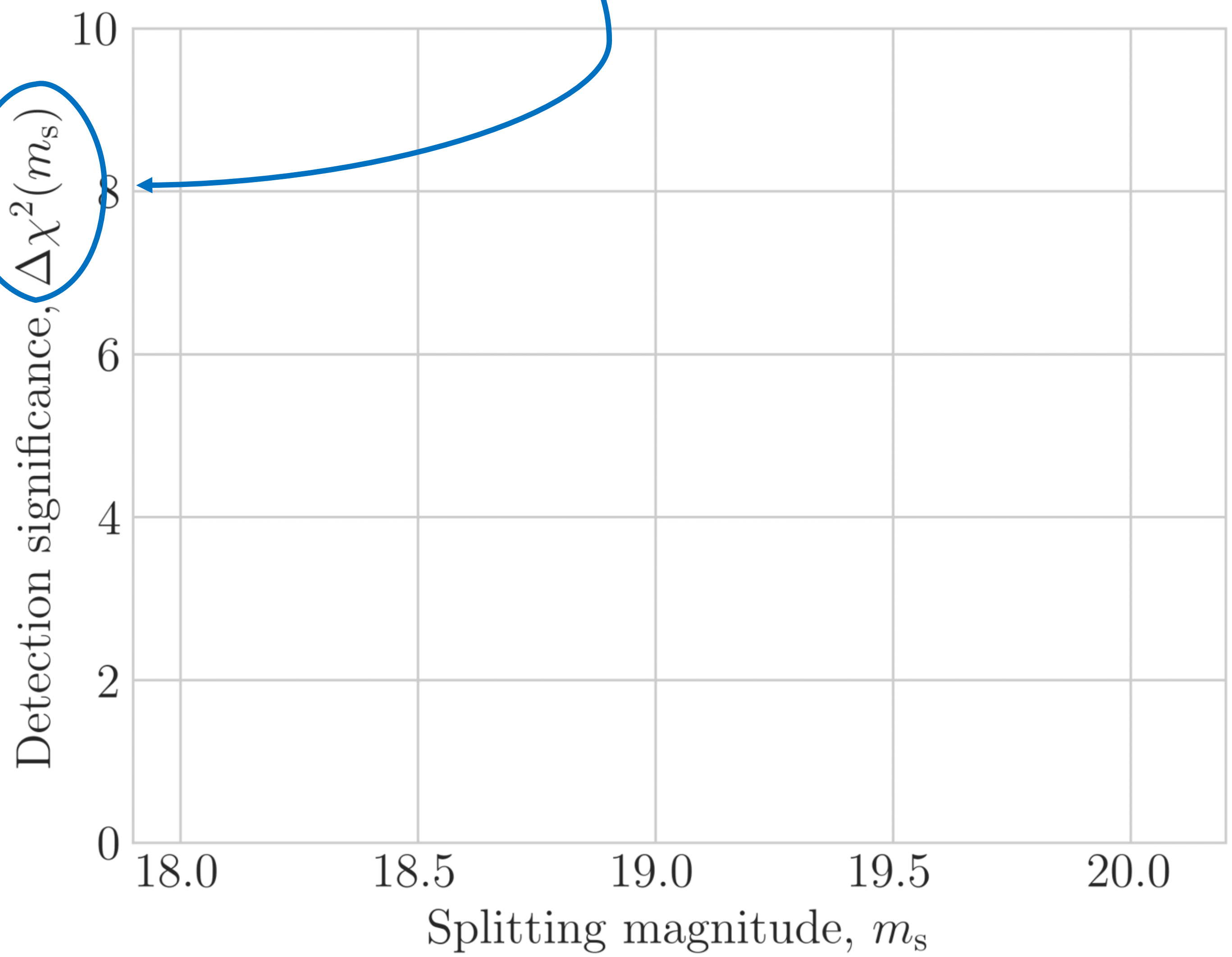
$S = (d - m)$

Γ = Covariance

Null-hypothesis: $\Delta_l^{Doppler} = \Delta_l^{GR} = 0$

DESI-like BGS

Also in harmonic space we can study how the statistical significance of the relativistic contribution depends upon the splitting flux adopted.



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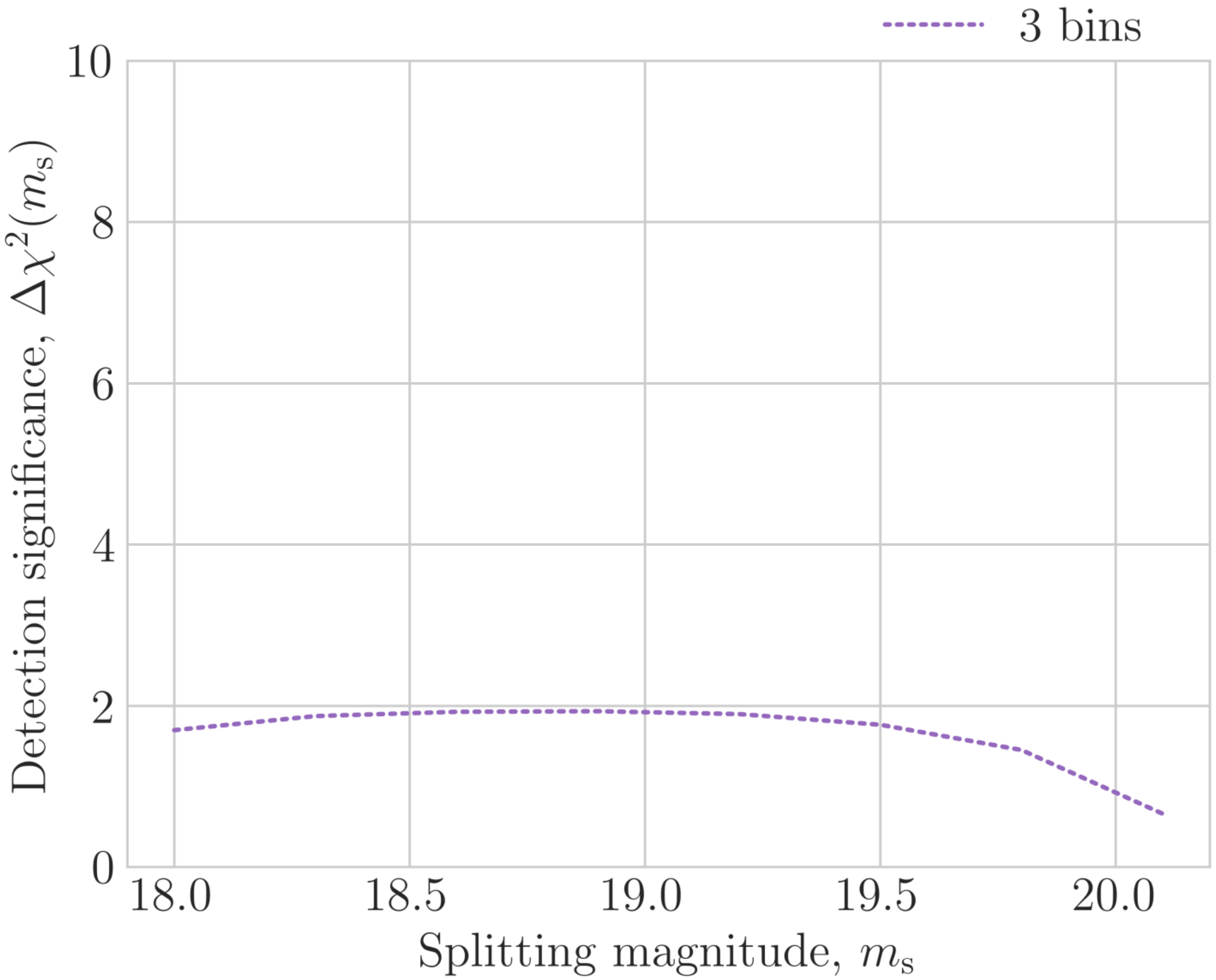

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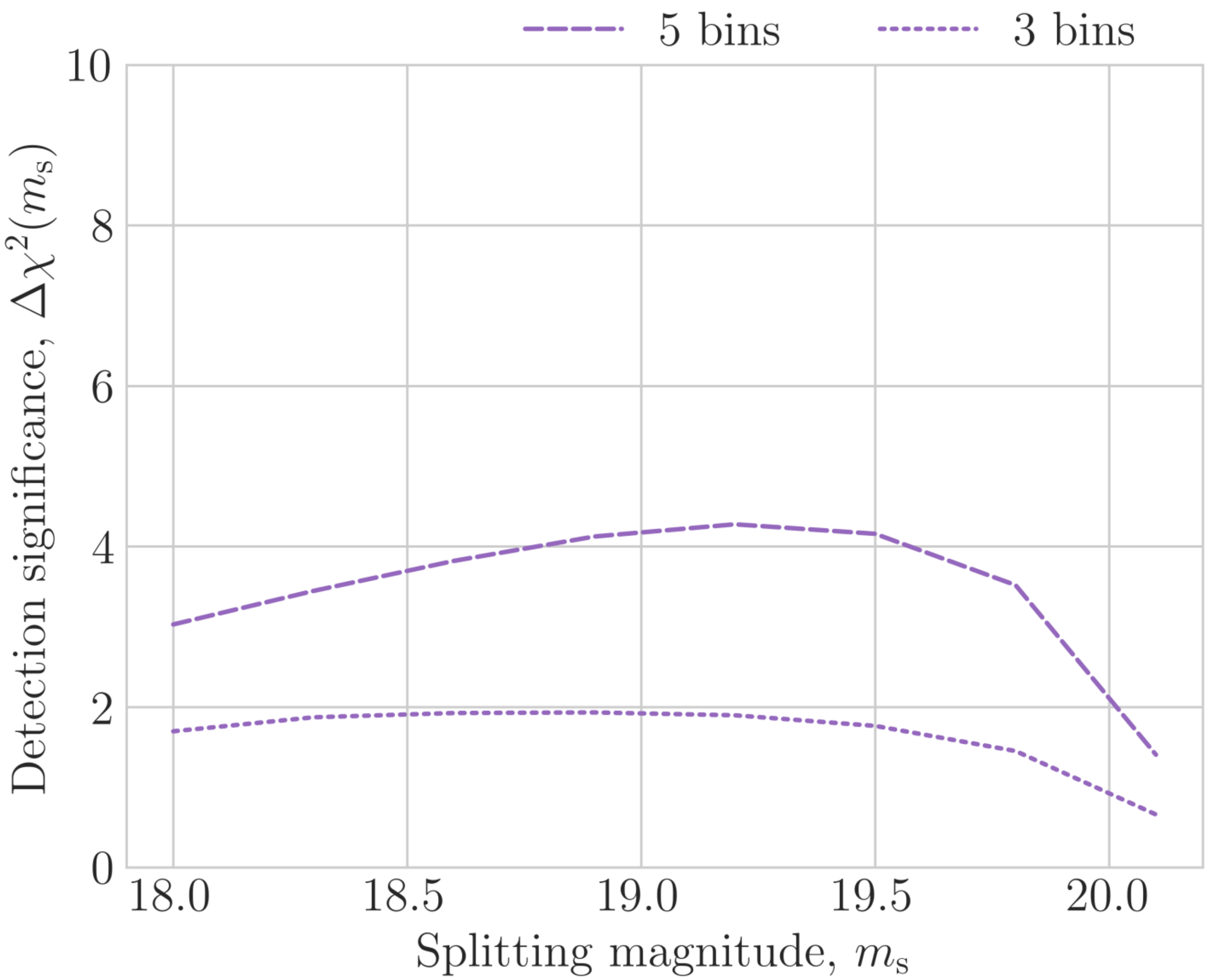

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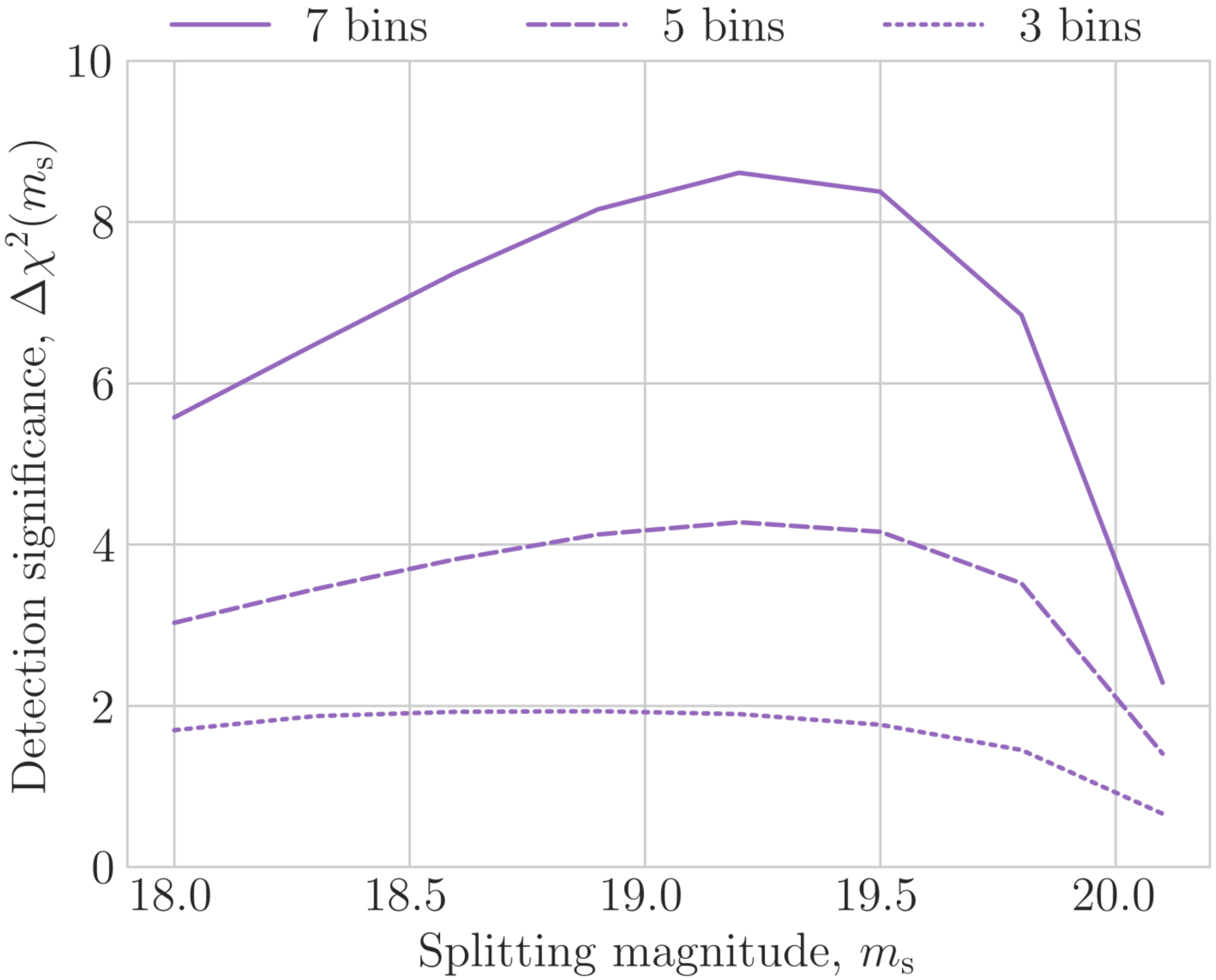
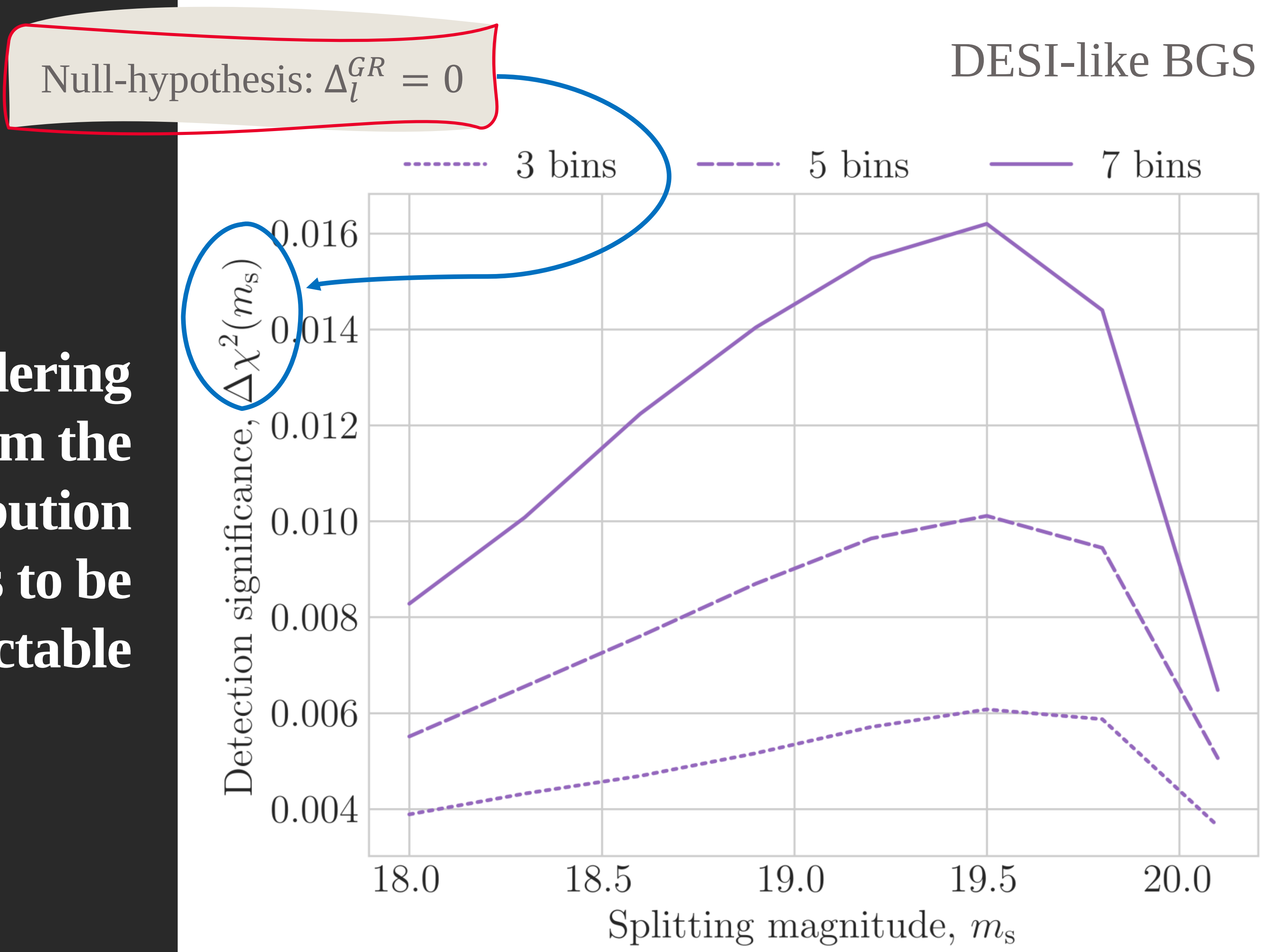


[Novara *et al.* (2024 TBS)]

Without considering the Doppler term the GR contribution seems to be undetectable



[Novara *et al.* (2024 TBS)]

Future work

- An analysis of the performance of the luminosity cut technique using simulated data will demonstrate its reliability.
- Including wide-angle effects.

Take-home messages

- A multi-tracer approach is able to beat cosmic variance, even within a single dataset.
- Thanks to the increased sensitivity and the enhanced volume the upcoming galaxy surveys will shed light on the largest scales of the universe.

Thanks for your attention!

Backup slides

Relativistic galaxy number counts

In Fourier space, our assumptions give us:

$$\Delta(\vec{k}) = \mathcal{Z}^{(1)}(\vec{k})\delta(\vec{k})$$

$$\mathcal{Z}_N^{(1)}(k,\mu) = b + f\mu^2$$

$$\mathcal{Z}_{GR}^{(1)}(k,\mu) = i\frac{\mathcal{H}}{\mathrm{k}}\alpha f\mu$$

[Castorina & Di Dio (2022)]

$$\begin{aligned}
\Delta(\mathbf{n}, z) = {} & b_1 D_m + \mathcal{H}^{-1}\partial_r v_{||} \\
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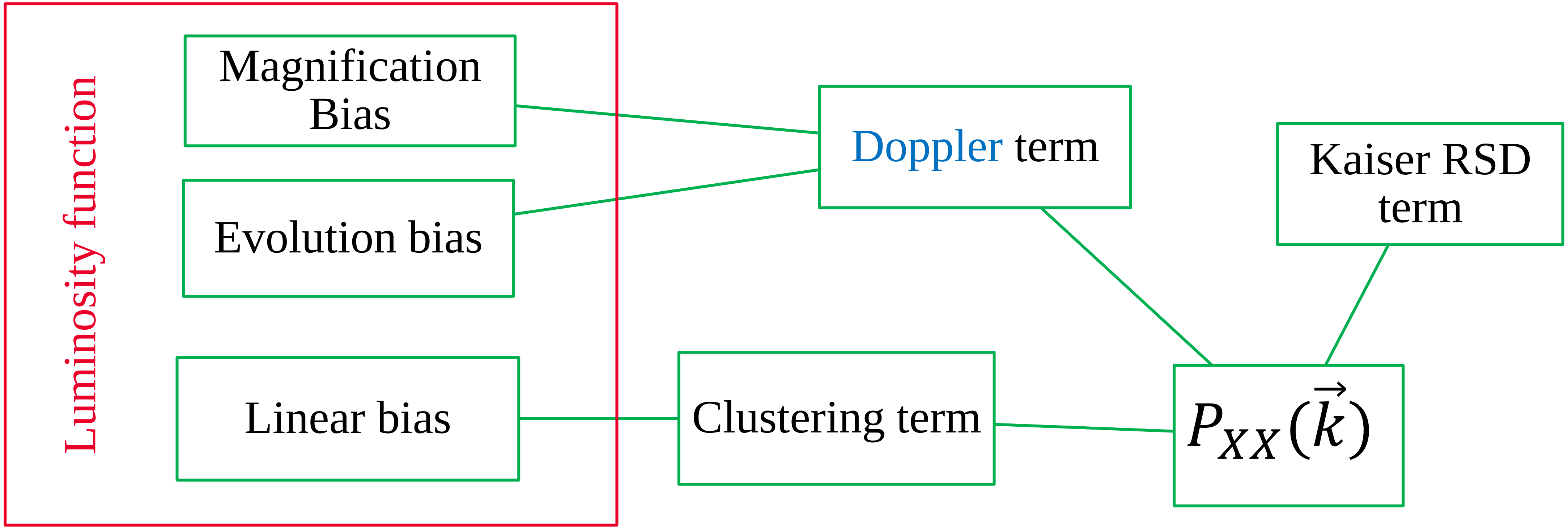
\end{aligned}$$

where we have introduced the redshift dependent parameter

$$\mathcal{R} = 5s_b + \frac{2 - 5s_b}{\mathcal{H}r} + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - f_{\rm evo}.$$

Relativistic Doppler in galaxy power spectra

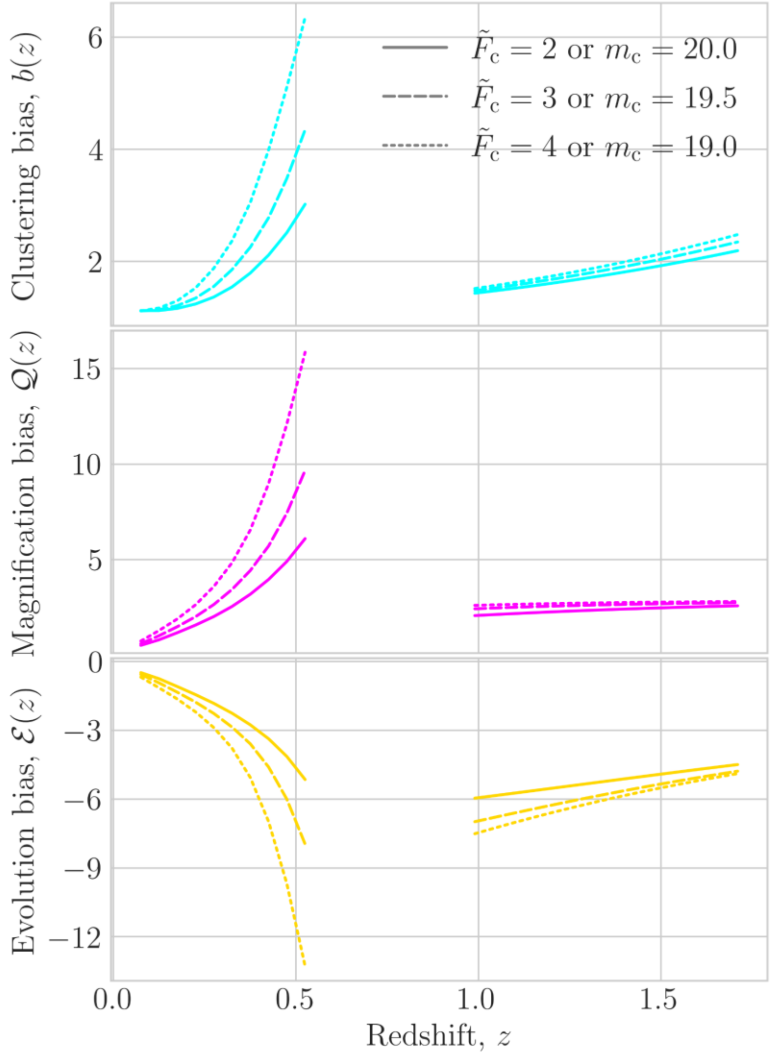


A sample optimisation work is required.

Linear bias in the case of multiple targets

The clustering bias for the faint population can be written as [Ferrmacho *et al*. (2014)]:

$$b_F = \frac{n_T b_T - n_B b_B}{n_F}$$



Magnification ed evolution biases for the sub-samples

Biases for the bright sample can be easily obtained from those of the total sample by substituting $F_c \to F_s$.

$$\mathcal{Q}_B = -\frac{\partial \ln(n_B)}{\partial \ln(L_s)}$$

$$\mathcal{E}_B = -\frac{\partial \ln(n_B)}{\partial \ln(1+z)}$$

In the case of the faint sample, we have instead to consider the upper cut [Bonvin et al. (2023)].

$$\mathcal{Q}_F = -\frac{\partial \ln(n_F)}{\partial \ln(L_c)} + \frac{\partial \ln(n_F)}{\partial \ln(L_s)}$$

$$\mathcal{E}_F = -\frac{\partial \ln(n_F)}{\partial \ln(1+z)}$$

Information matrix analysis

$$I_{\alpha\beta}(z_i) = \sum_{m,n} \frac{\partial P(z_i, \mu_m, k_n)^H}{\partial \theta_{(\alpha}} \Gamma^{-1} \frac{\partial P(z_i, \mu_n, k_m)}{\partial \theta_{\beta)}}$$

- Covariance:

$$\Gamma(, \mu, k) = \frac{\widetilde{P_{XX}}(z,\mu,k)\widetilde{P_{YY}}(z,\mu,k) + \widetilde{P_{XY}}(z,\mu,k)\widetilde{P_{YX}}(z,\mu,k)}{N_{modes}(z,k,\mu)}$$

$$\widetilde{P_{XY}} = P_{XY} + \frac{\delta_X^Y}{n_X}$$

$$N_{modes}(z,k,\mu) = \frac{V(z,\Delta z)}{(2\pi)^3} 2\pi k^2 \Delta k \Delta \mu$$

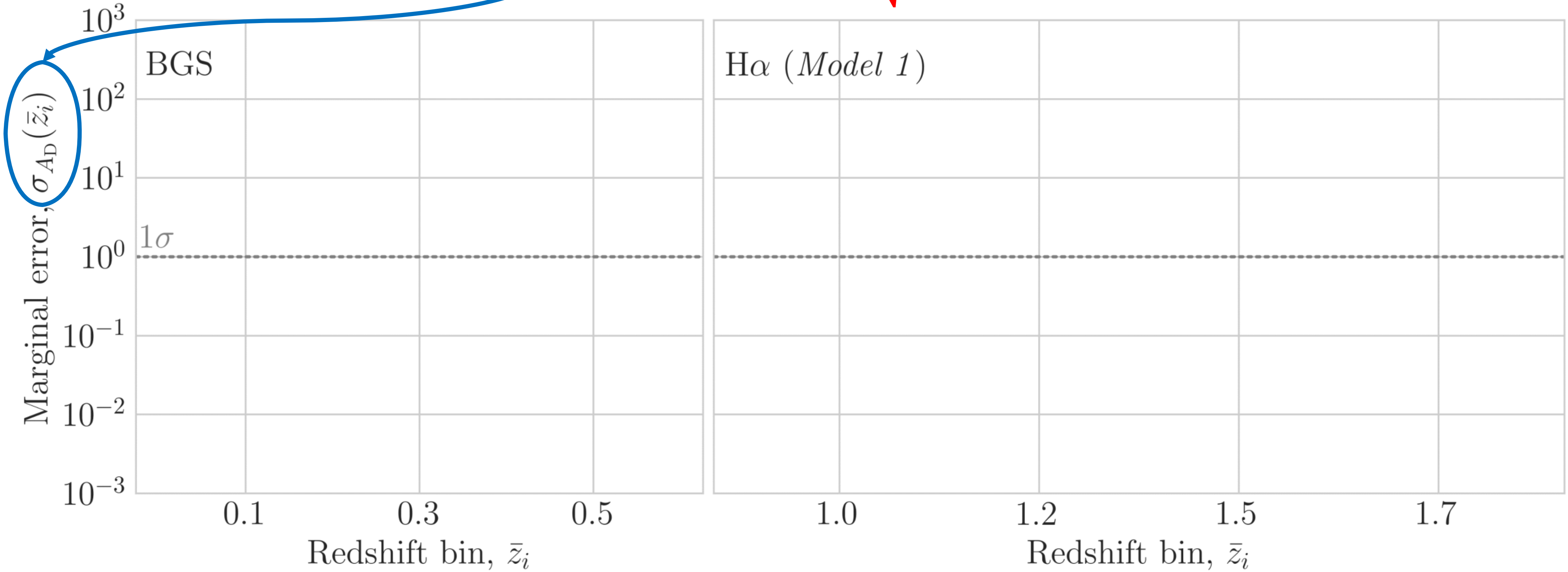
$$V(z,\Delta z) = \frac{4\pi f_{sky}}{3}\left[r^3\left(z + \frac{\Delta z}{2}\right) - r^3\left(z - \frac{\Delta z}{2}\right)\right]$$

- Lowest and highest scale:

$$k_{min} = \frac{2\pi}{\sqrt[3]{V(z,\Delta z)}}, \qquad k_{max} = 0.2\ h\ \mathrm{Mpc}^{-1}$$

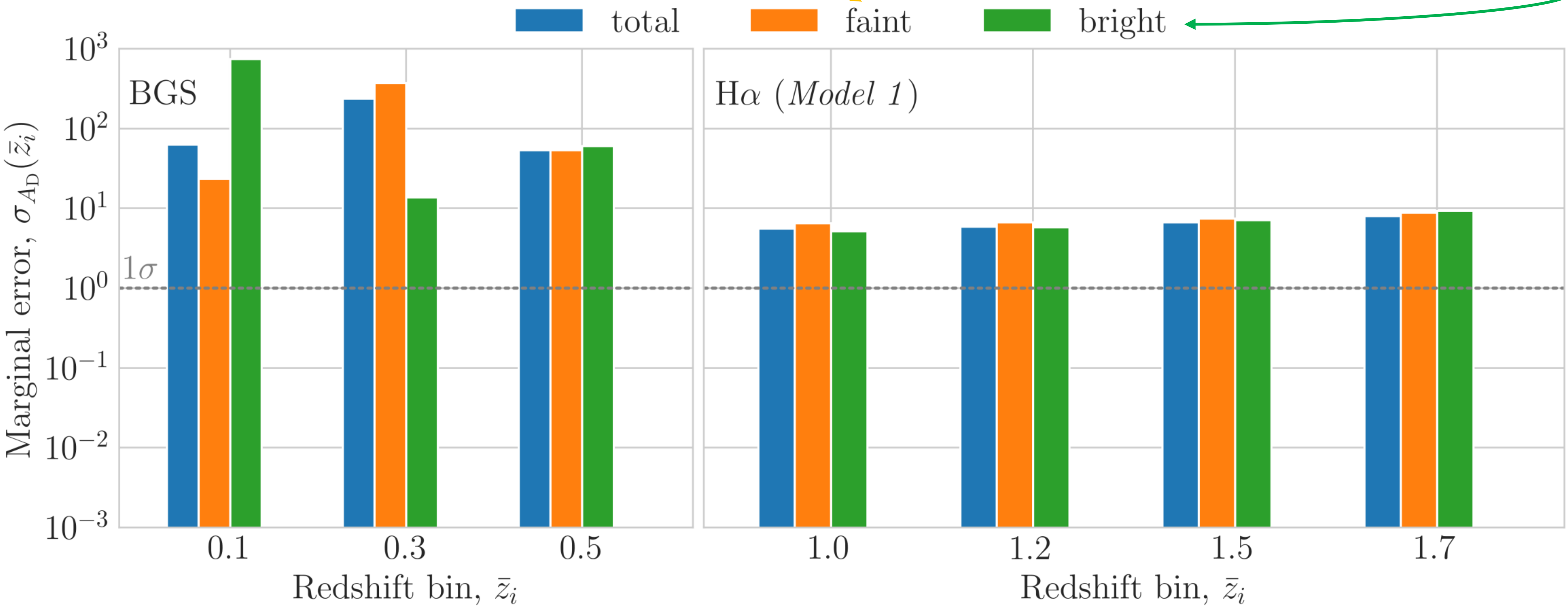
- Hα emitters, *Model 3* luminosity function [Pozzetti et al. (2016)]:
  - $F_c = 2 \times 10^{-16}$ erg cm^{-2} s^{-1}
  - $\Delta z \sim 0.23$
- BGS:
  - $m_c = 20.175$
  - $\Delta z \sim 0.17$
- $f_{sky} = 0.36$

$$\boldsymbol{\theta_\alpha = \{A_N, A_K, A_D\} \to \sigma_{\theta_\alpha} = \sqrt{(I_{\alpha\alpha})^{-1}}}$$

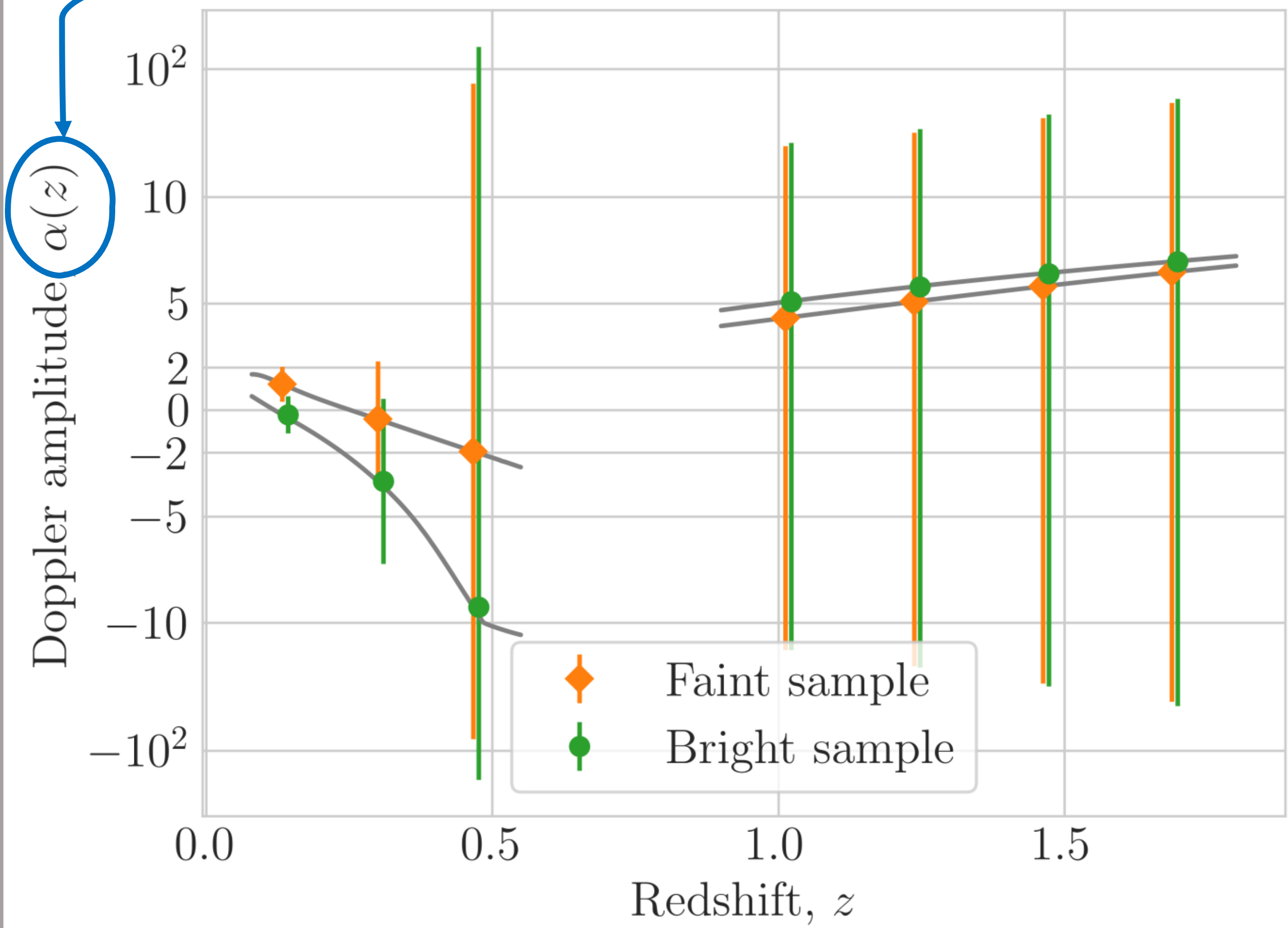


- Hα emitters, *Model 3* luminosity function [Pozzetti et al. (2016)]:
  - $F_c = 2 \times 10^{-16}$ erg cm^{-2} s^{-1}
  - $F_s = 2.8 \times 10^{-16}$ erg cm^{-2} s^{-1}
  - $\Delta z \sim 0.23$
- BGS:
  - $m_c = 20.175$
  - m_s
  - Δz
  - f_{sky} =

$$\Gamma = \frac{2}{N_{modes}} \begin{pmatrix} \tilde{P}_{XX}^2 & \tilde{P}_{XX}\tilde{P}_{XY} & \tilde{P}_{XY}^2 \\ \tilde{P}_{XX}\tilde{P}_{YX} & \frac{\tilde{P}_{XX}\tilde{P}_{YY} + \tilde{P}_{XY}\tilde{P}_{YX}}{2} & \tilde{P}_{XY}\tilde{P}_{YY} \\ \tilde{P}_{YX}^2 & \tilde{P}_{YX}\tilde{P}_{YY} & \tilde{P}_{YY}^2 \end{pmatrix}$$



$$\boldsymbol{\theta_\alpha = \{b_F\sigma_8, b_B\sigma_8, f\sigma_8, \alpha_F, \alpha_B\}}$$



- Hα emitters, *Model 3* luminosity function [Pozzetti et al. (2016)]:
  - $F_c = 2 \times 10^{-16}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$
  - $F_s = 2.8 \times 10^{-16}\mathrm{erg\ cm^{-2}\ s^{-1}}$
  - $\Delta z \sim 0.23$
- BGS:
  - $m_c = 20.175$
  - $m_s = 19$
  - $\Delta z \sim 0.17$
- $f_{sky} = 0.36$