UNIVERSITÀ DI TORINO

INFN TORINO
Istituto Nazionale di Fisica Nucleare
Sezione di Torino

Funded by
the European Union
NextGenerationEU

Detecting Relativistic Doppler 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]

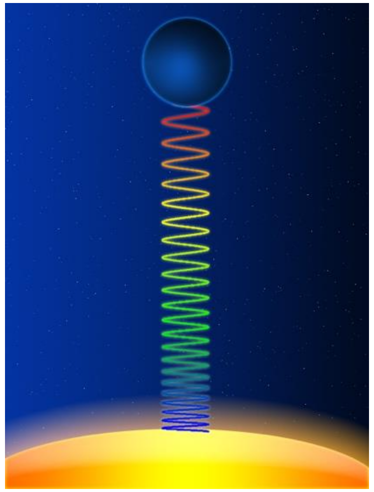
Federico Montano (federico.montano@unito.it)

COLOURS – Institut Pascal – 10th June 2025

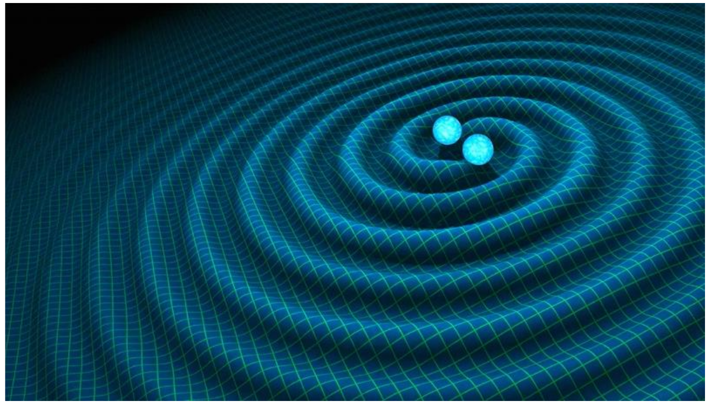
Detecting relativistic effects: why?

Are there any confirmations of GR on scales far from the strong-gravity regime?

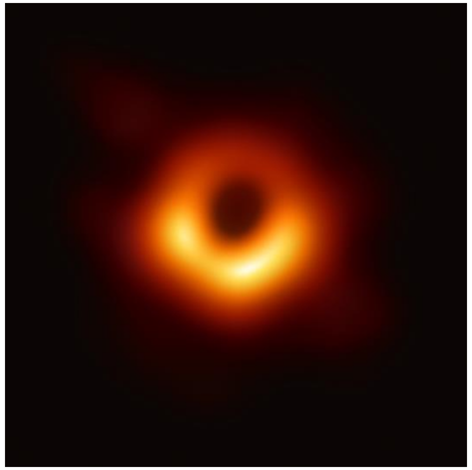
[from wikipedia.org]



[LIGO Collaboration]



[NASA/ESA Hubble Space Telescope]



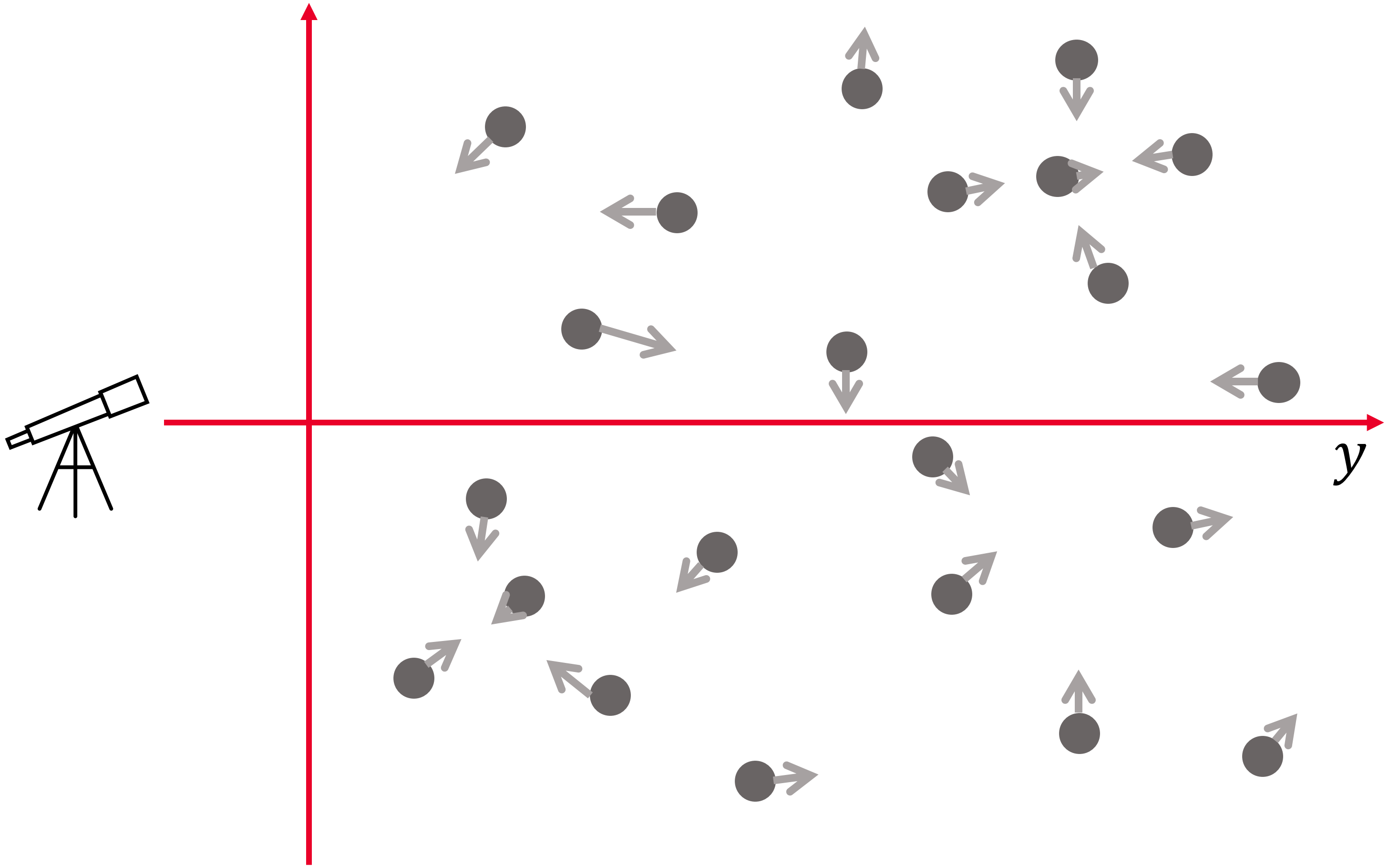
[Event Horizon Telescope]

Relativistic galaxy number counts

[Yoo (2010); Bonvin & Durrer (2011); Challinor & Lewis (2011)]

Galaxy surveys observe the galaxy distribution

- in redshift space
- on the past light-cone



Relativistic galaxy number counts

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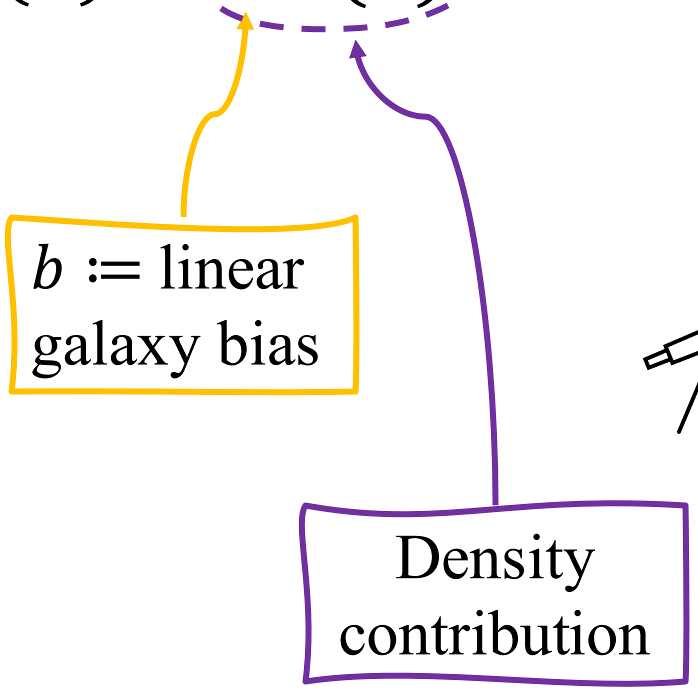
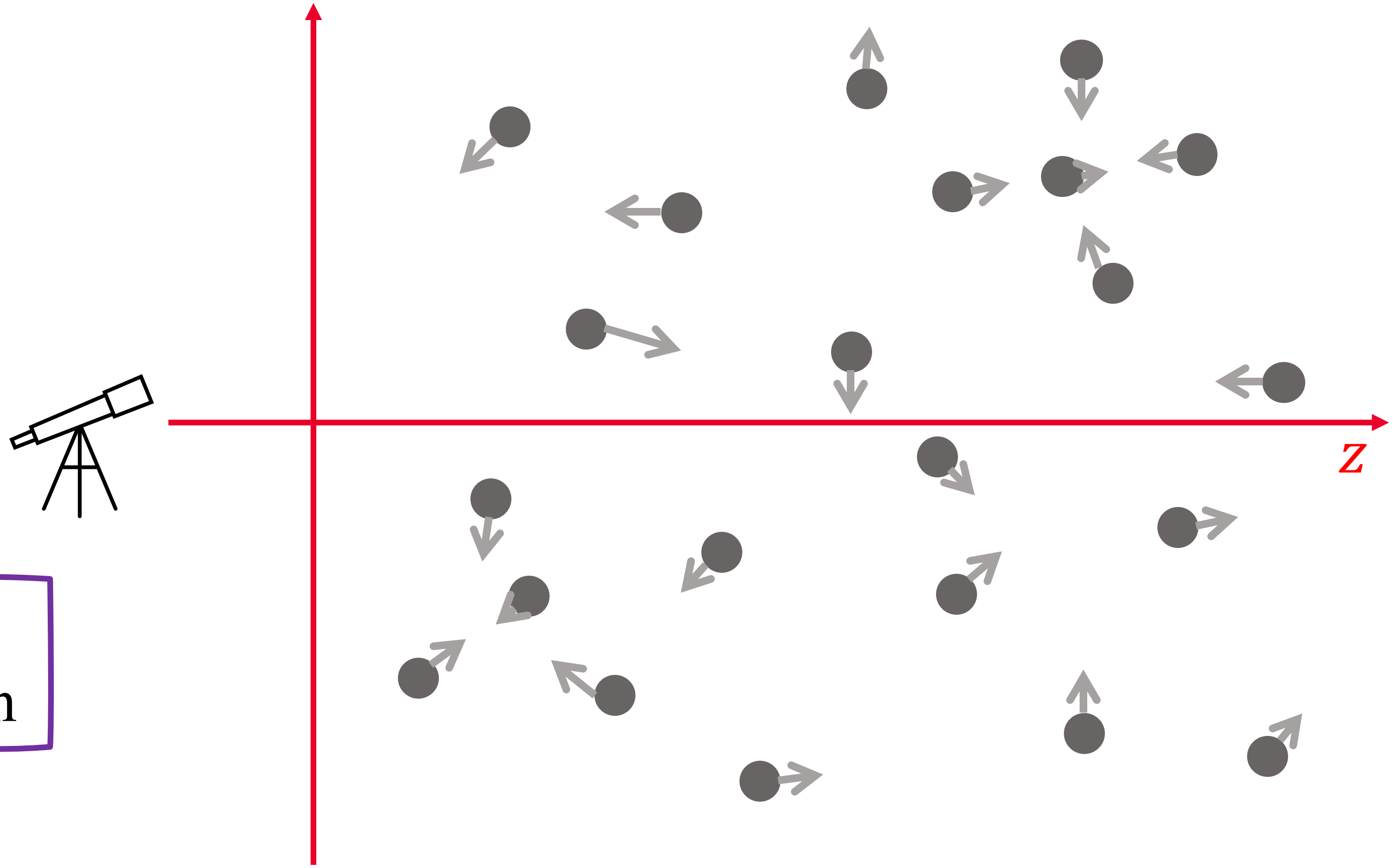
$$\Delta(\vec{x}) = b\delta(\vec{x})$$



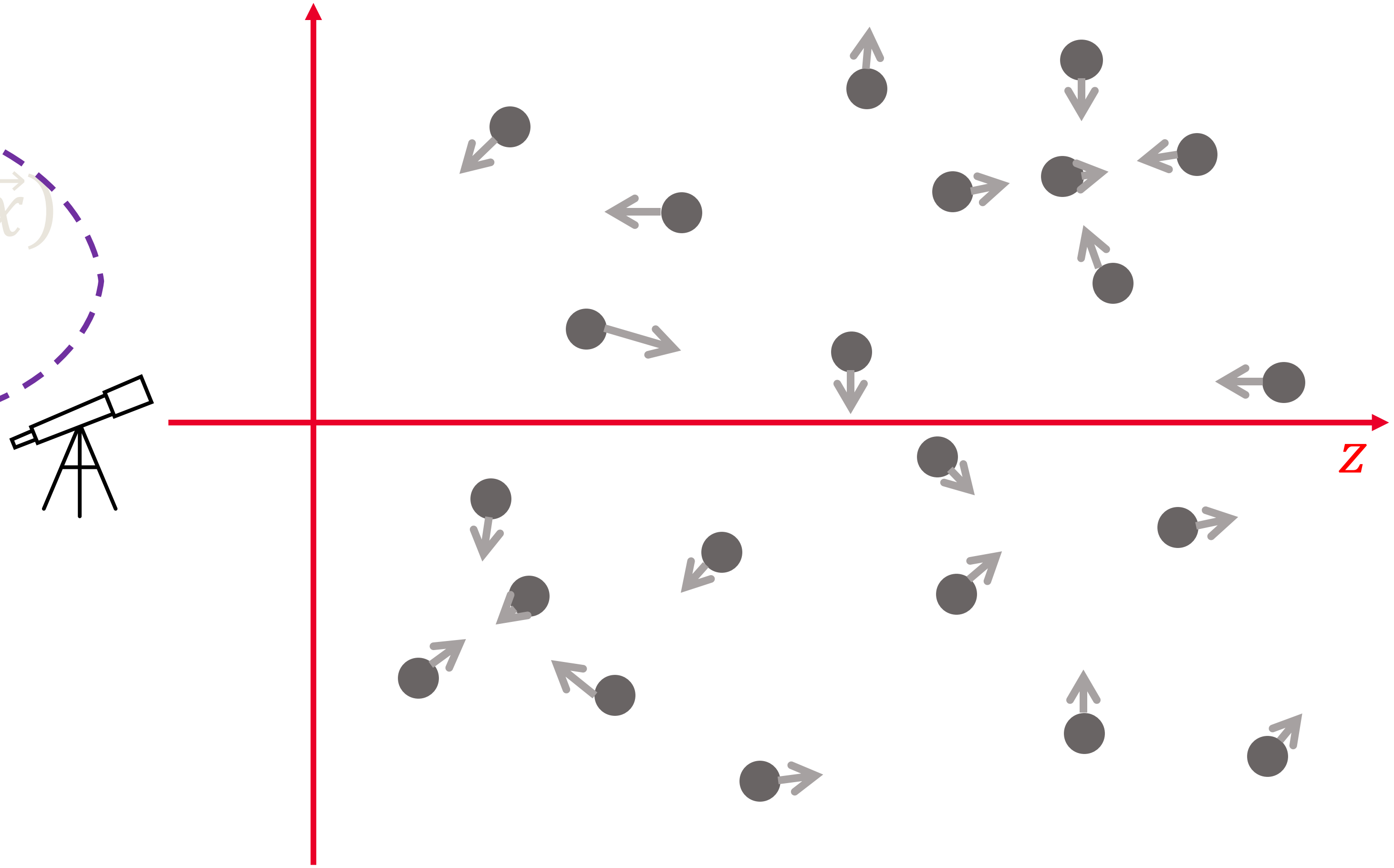


Relativistic galaxy number counts

[Yoo (2010); Bonvin & Durrer (2011); Challinor & Lewis (2011)]

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

Velocity contributions



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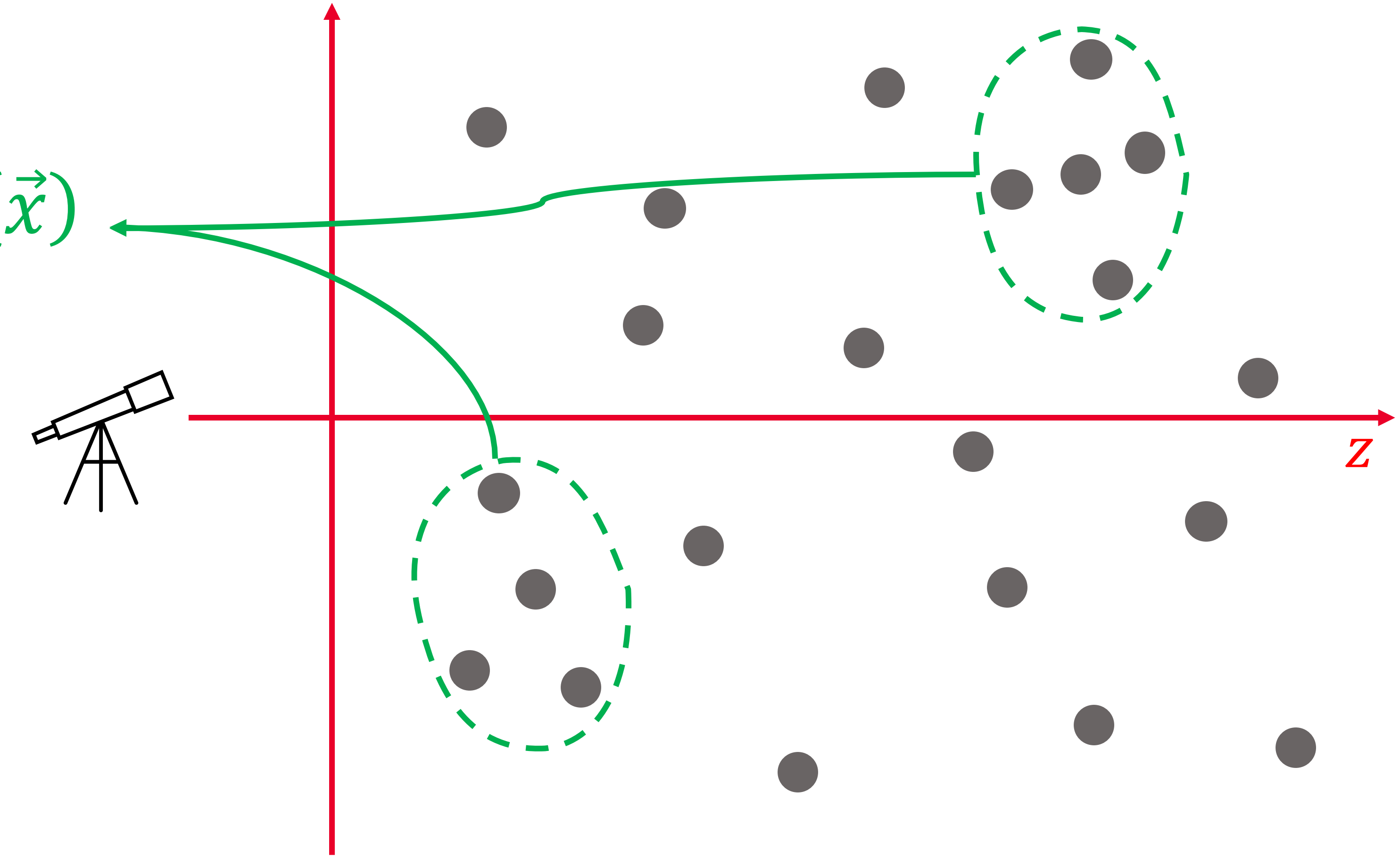

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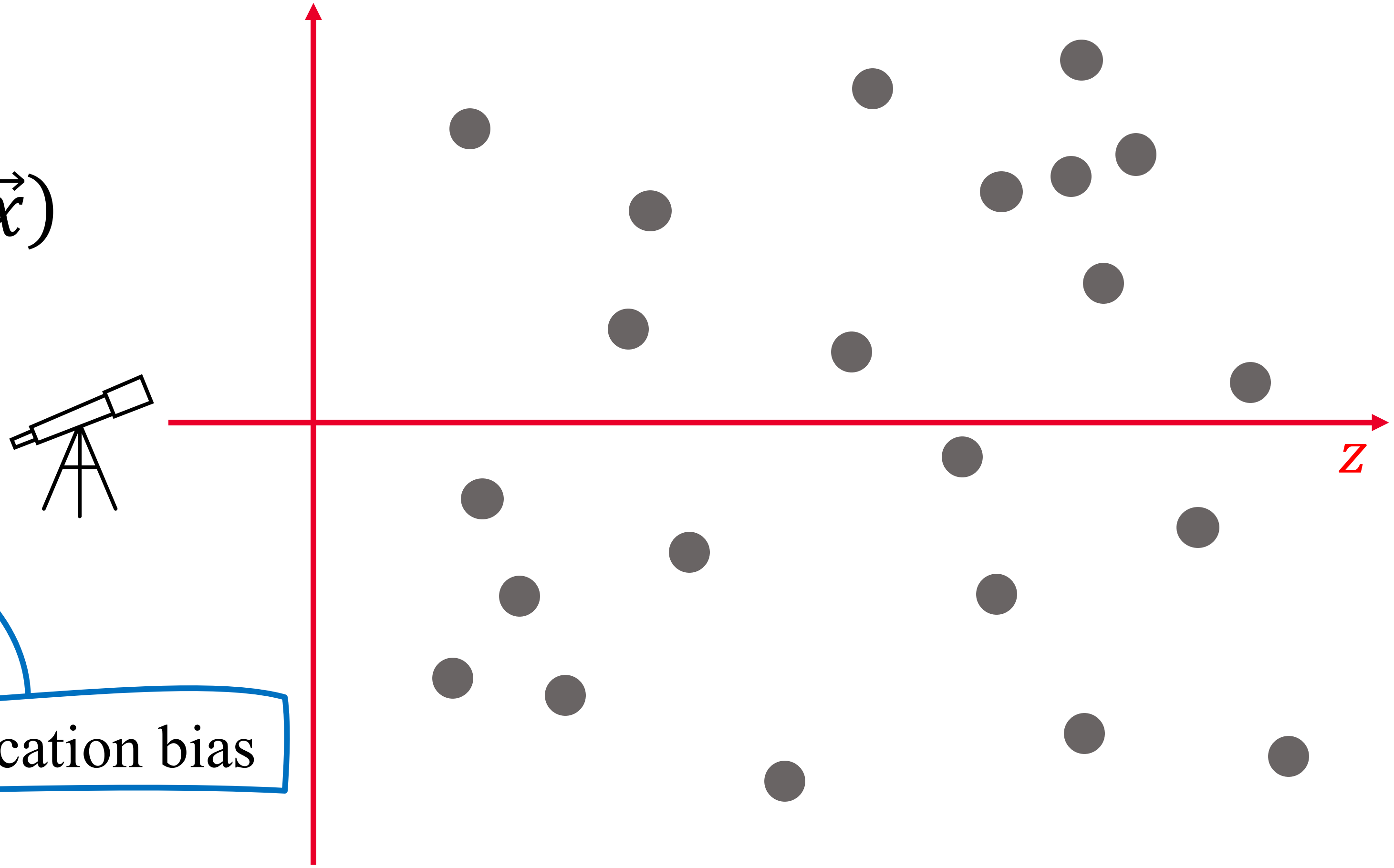
$$\Delta(\vec{x}) = b\delta(\vec{x}) - \frac{1}{\mathcal{H}}\partial_r v_r(\vec{x}) - \alpha v_r(\vec{x})$$

Relativistic Doppler term

Magnification bias

Evolution bias



Relativistic galaxy number counts

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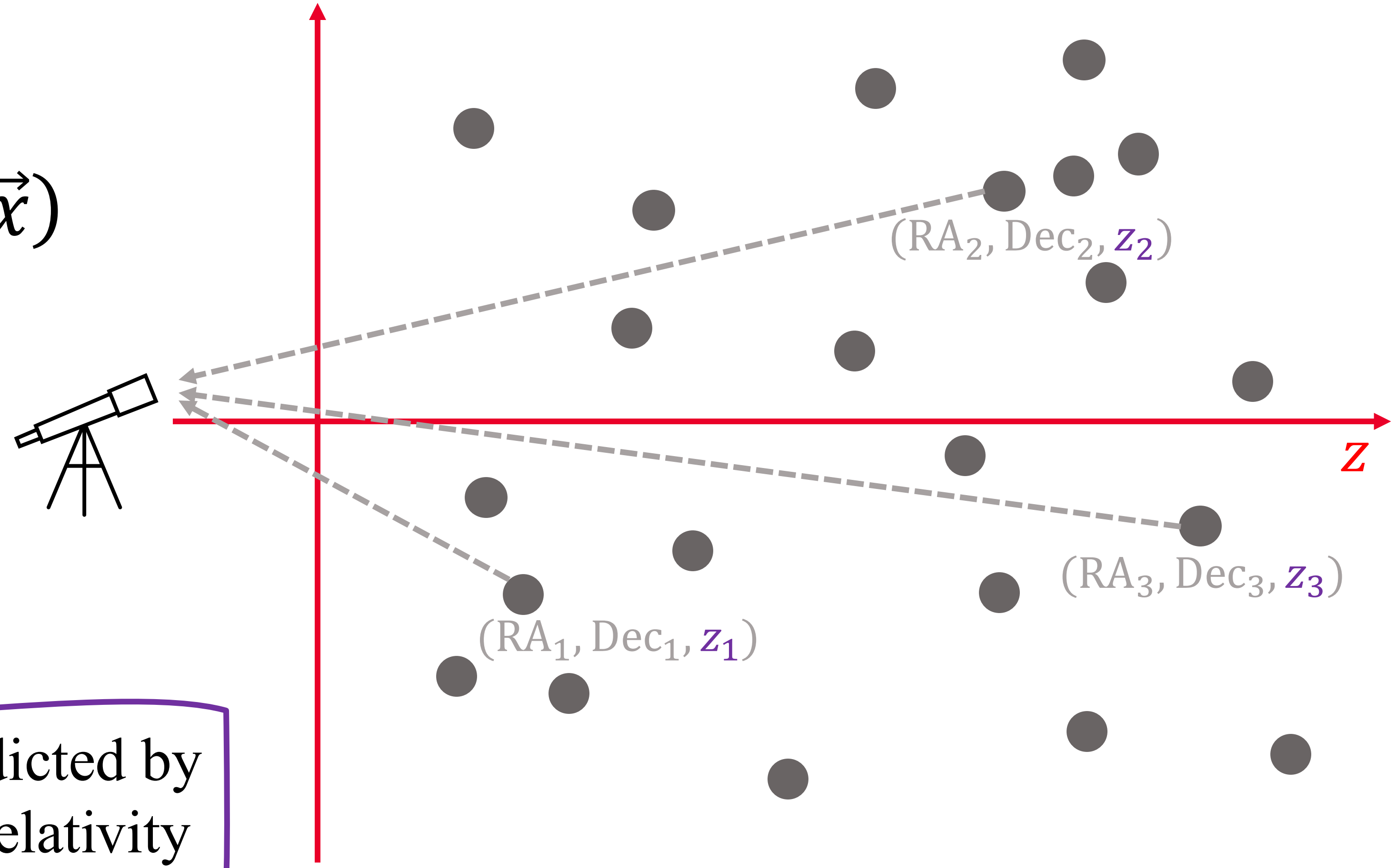
$$\Delta(\vec{x}) = b\delta(\vec{x}) - \frac{1}{\mathcal{H}}\partial_r v_r(\vec{x}) - \alpha v_r(\vec{x}) + \dots$$

Relativistic Doppler term

Terms predicted by General Relativity



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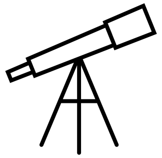
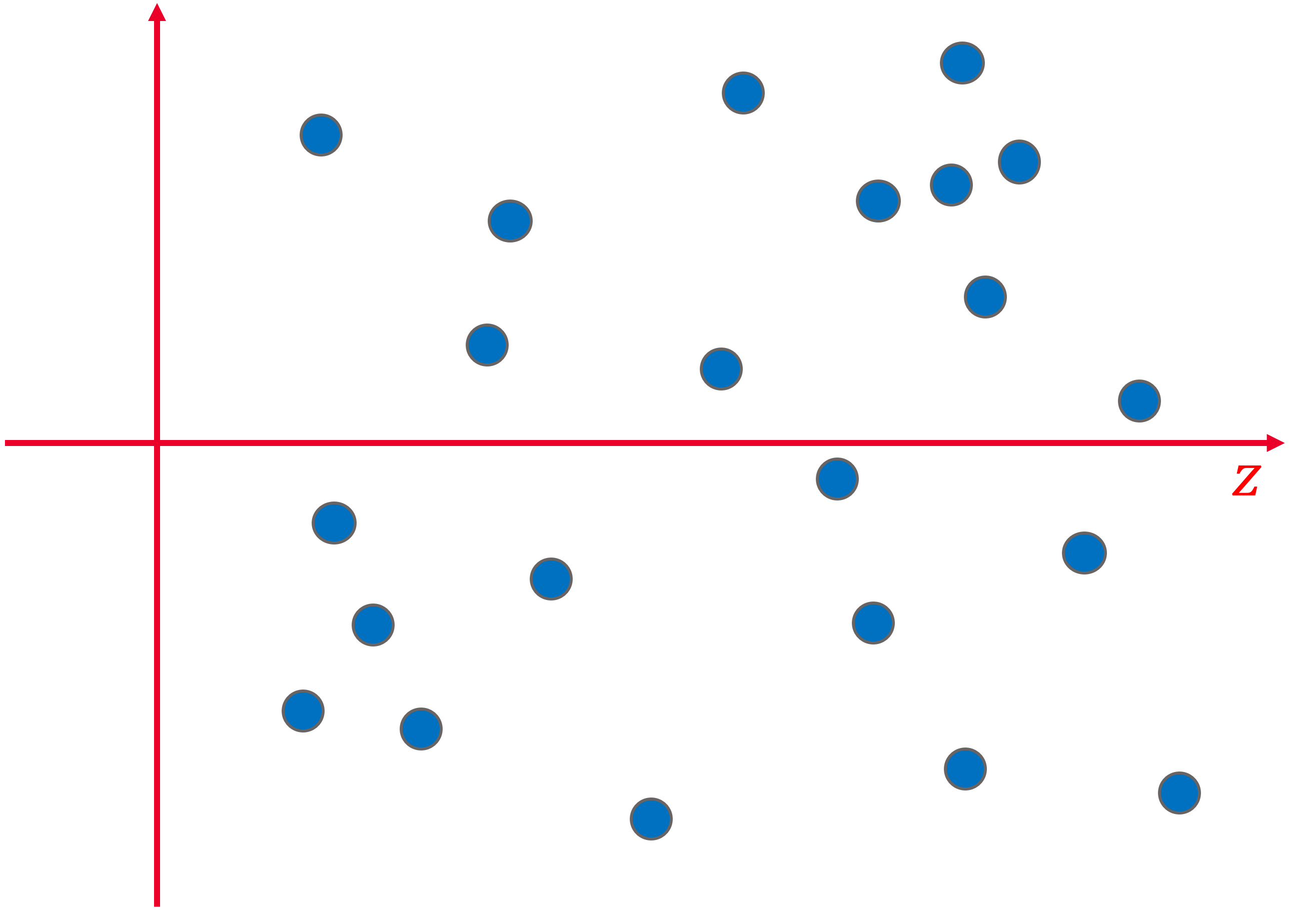
Sample-dependent quantities





Auto- and cross-correlation measurements

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

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

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

Auto- and cross-correlation measurements

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

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Auto- and cross-correlation measurements

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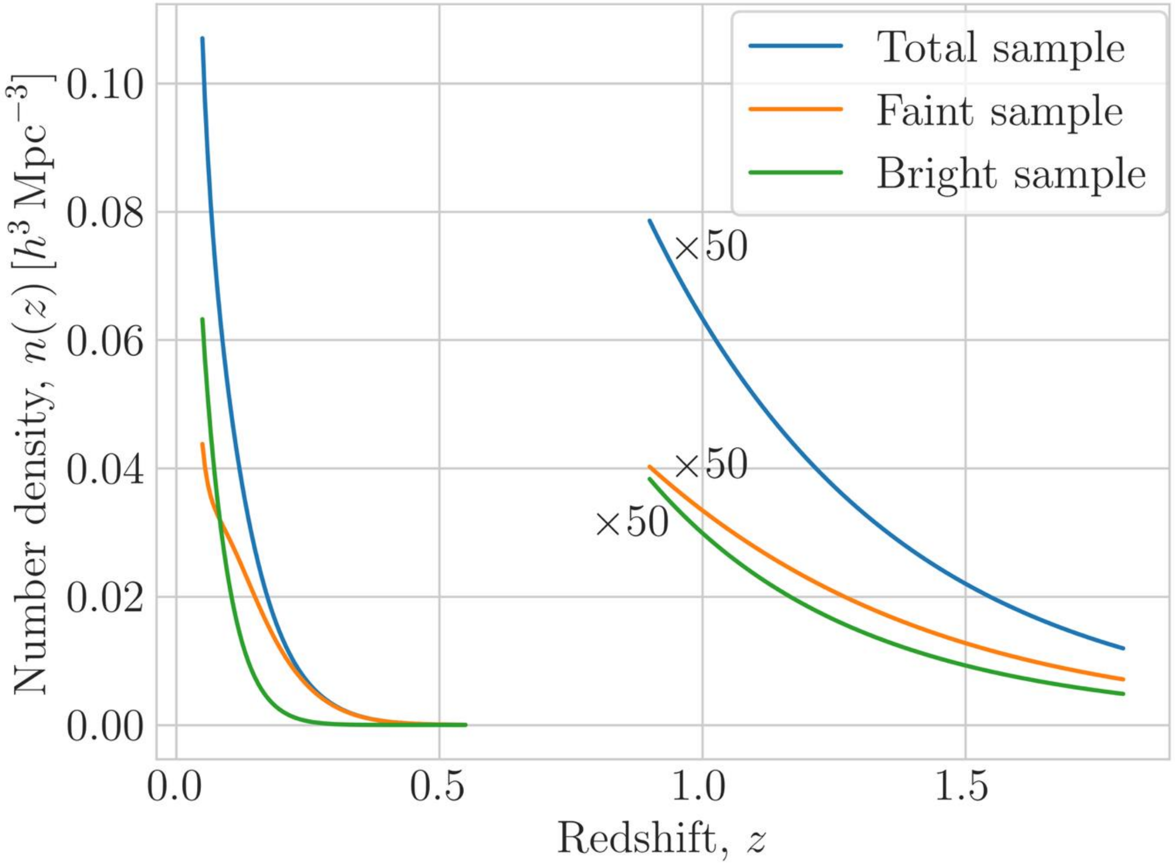
- $P_{XY}(z,k,\mu)=P^*_{YX}(z,k,\mu)\rightarrow P_{XY}(z,k,\mu)=P_{YX}(z,k,-\mu)$
- The Doppler contribution is proportional to k^{-1} in the imaginary part of the cross-power spectrum [McDonald (2009)].

Luminosity cut technique

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

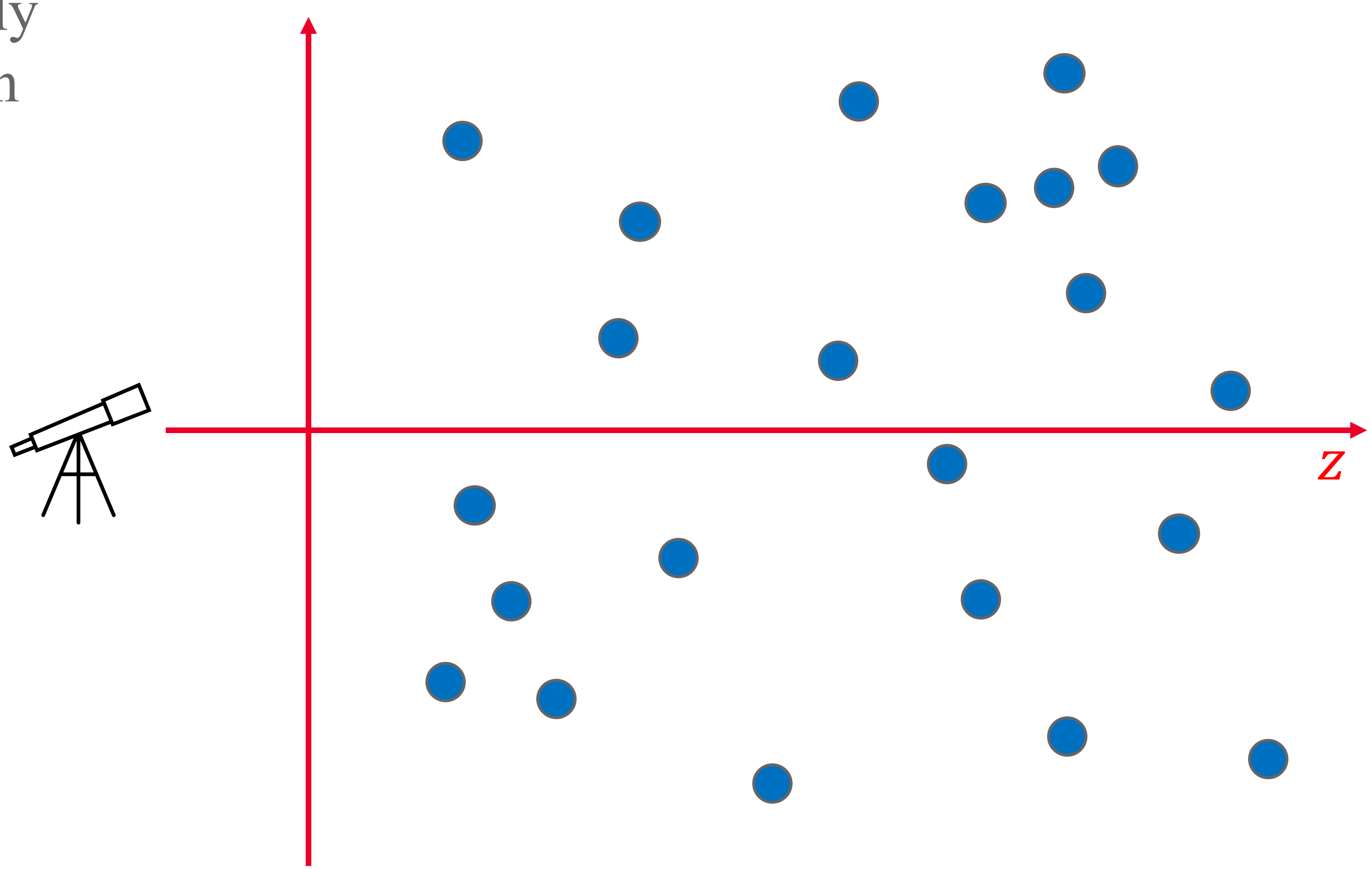
- Complete sample (T): all the galaxies that are observed with a flux density F higher than a fixed minimum flux
$$F > F_c$$
- Faint sample (F): all the galaxies with
$$F_c < F < F_s$$
- Bright sample (B): all the galaxies with
$$F > F_s$$



Multi-tracer power spectrum

[McDonald & Seljak (2009); Seljak (2009); Abramo & Leonard (2013); Fonseca *et al.* (2015)]

With one tracer, we can only measure its auto-correlation power spectrum.



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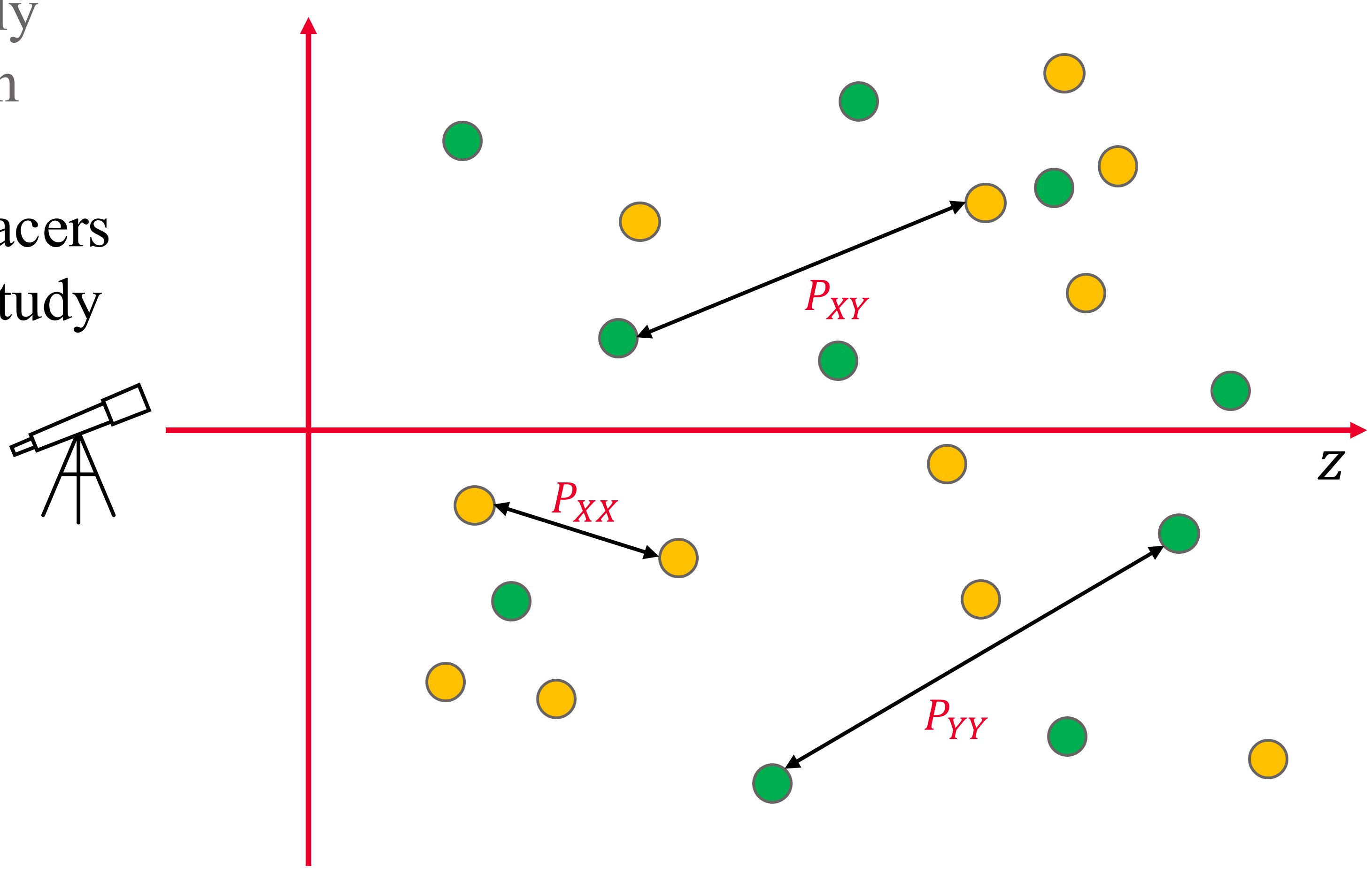
Looking at two different tracers of the LSS we are able to study P_{XX}, P_{YY}, P_{XY}



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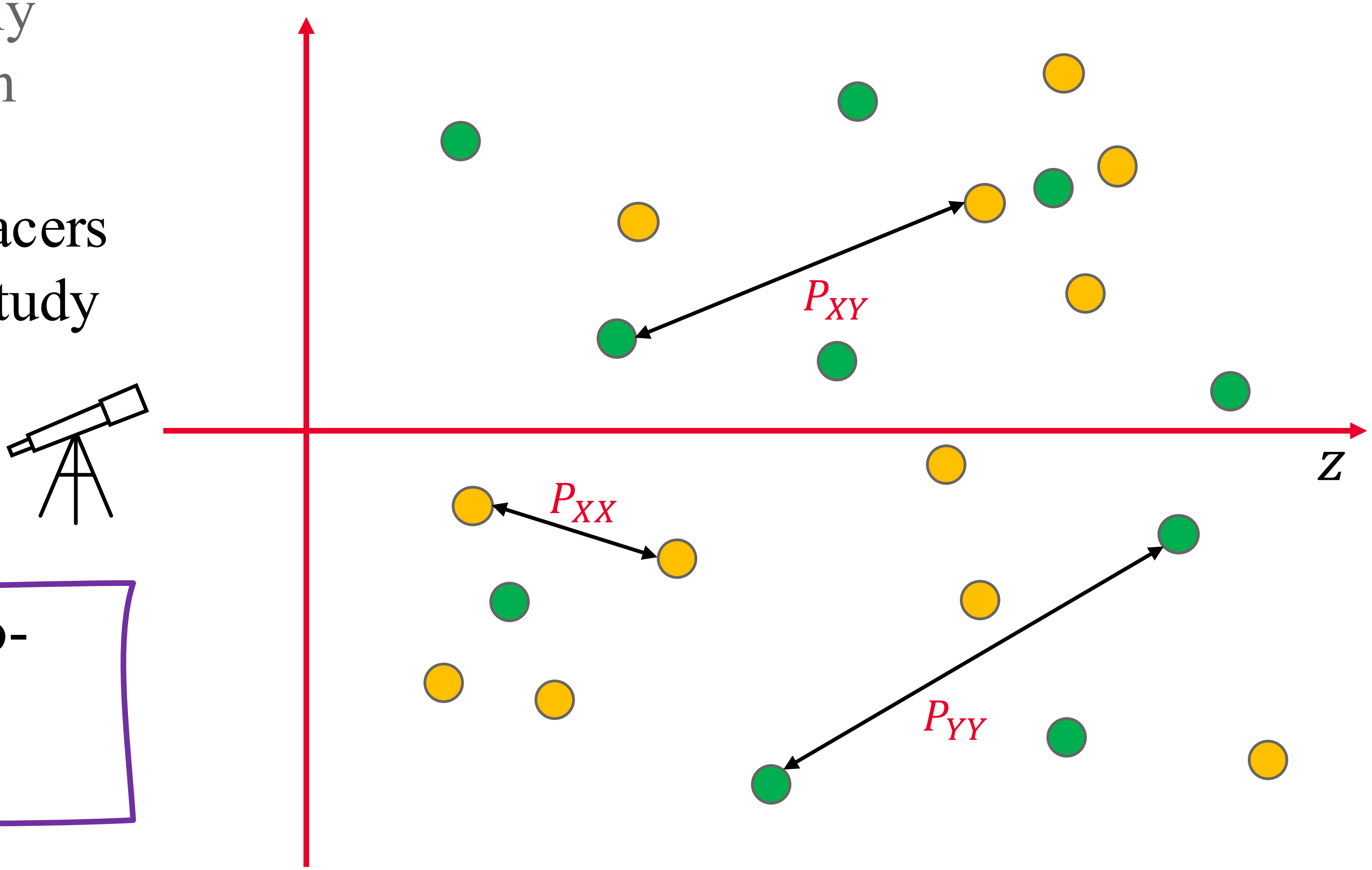


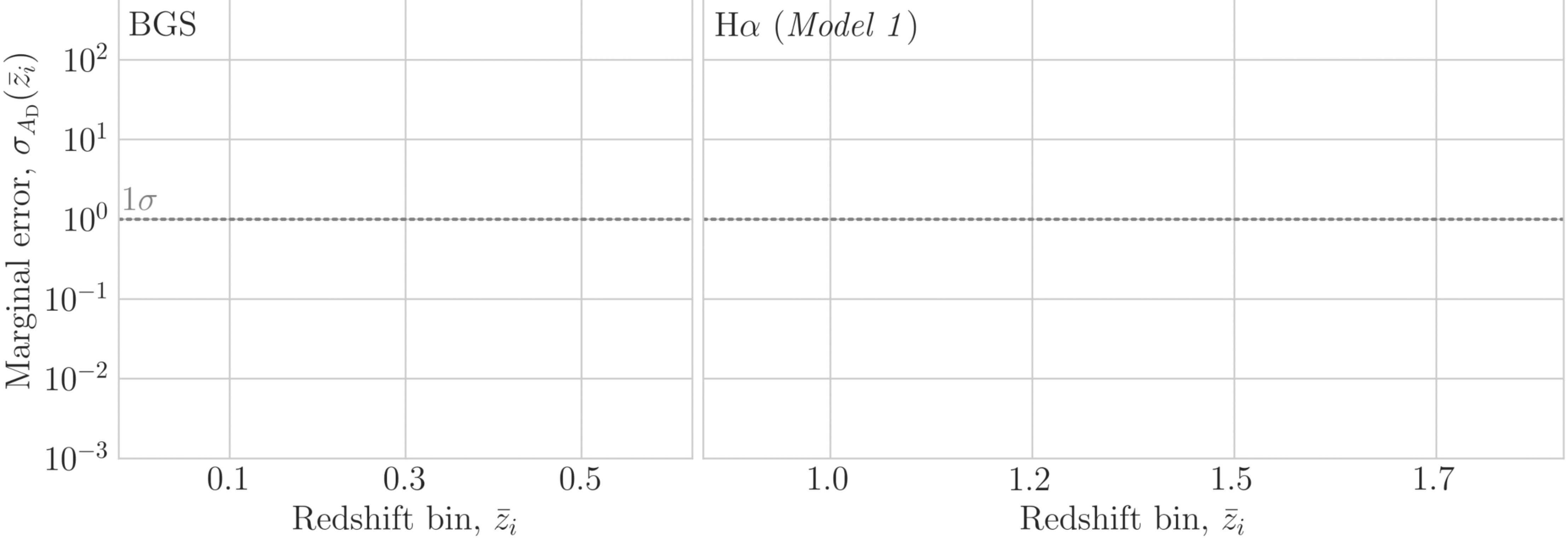
We can jointly analyse auto- and cross-power spectra to obtain tighter constrains

Faint-bright multi-tracer

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

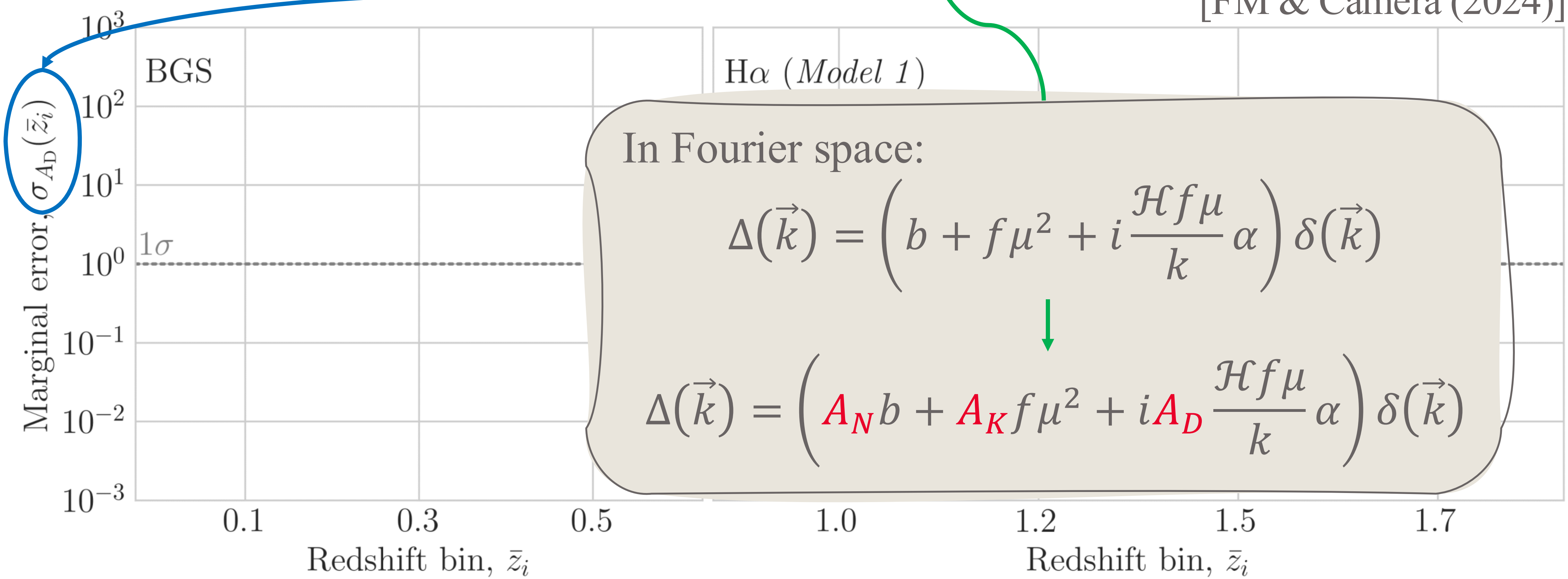


Faint-bright multi-tracer

Information matrix analysis

$$P = \begin{pmatrix} P_{FF} \\ P_{FB} \\ P_{BB} \end{pmatrix} \qquad \boldsymbol{\theta_\alpha} = \{A_N, A_K, A_D\} \rightarrow \boldsymbol{\sigma_{\theta_\alpha}} = \sqrt{(\boldsymbol{I_{\alpha\alpha}})^{-1}}$$

[FM & Camera (2024)]



In Fourier space:

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

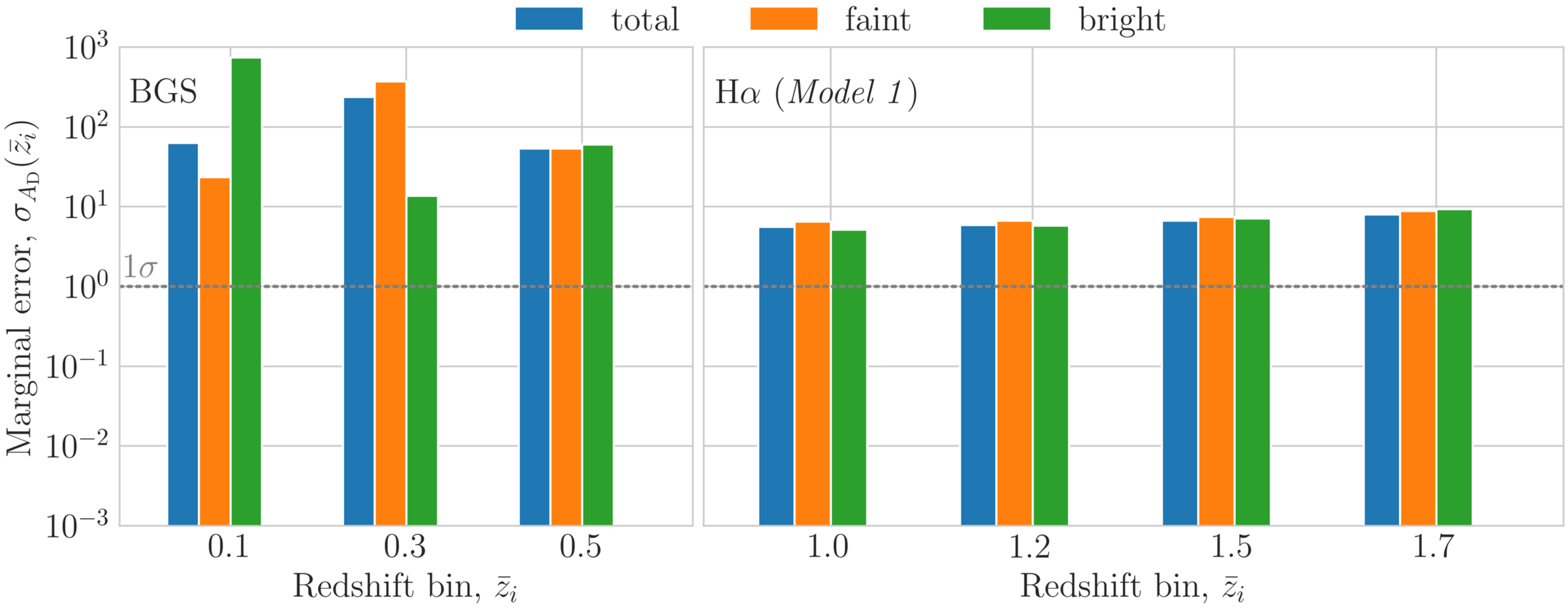
$$\downarrow$$

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

Faint-bright multi-tracer

Information matrix analysis

[FM & Camera (2024)]



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$$P = \begin{pmatrix} P_{FF} \\ P_{FB} \\ P_{BB} \end{pmatrix}$$

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

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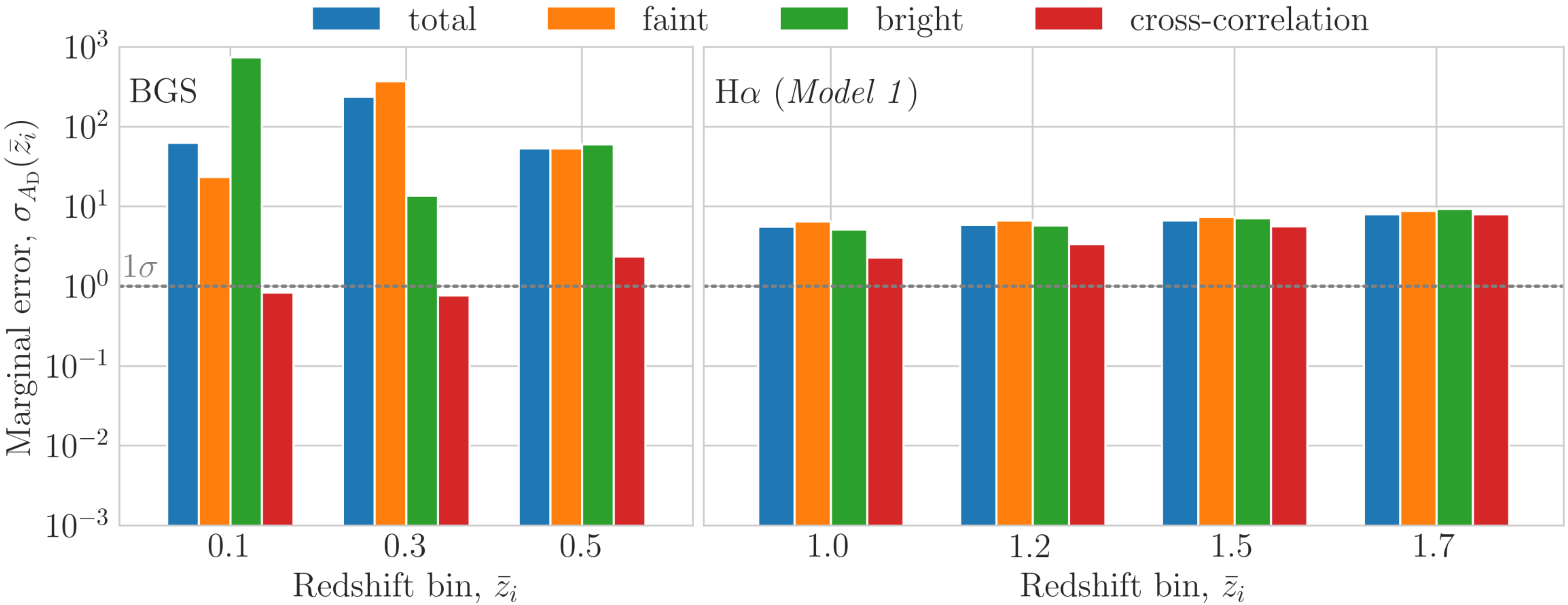

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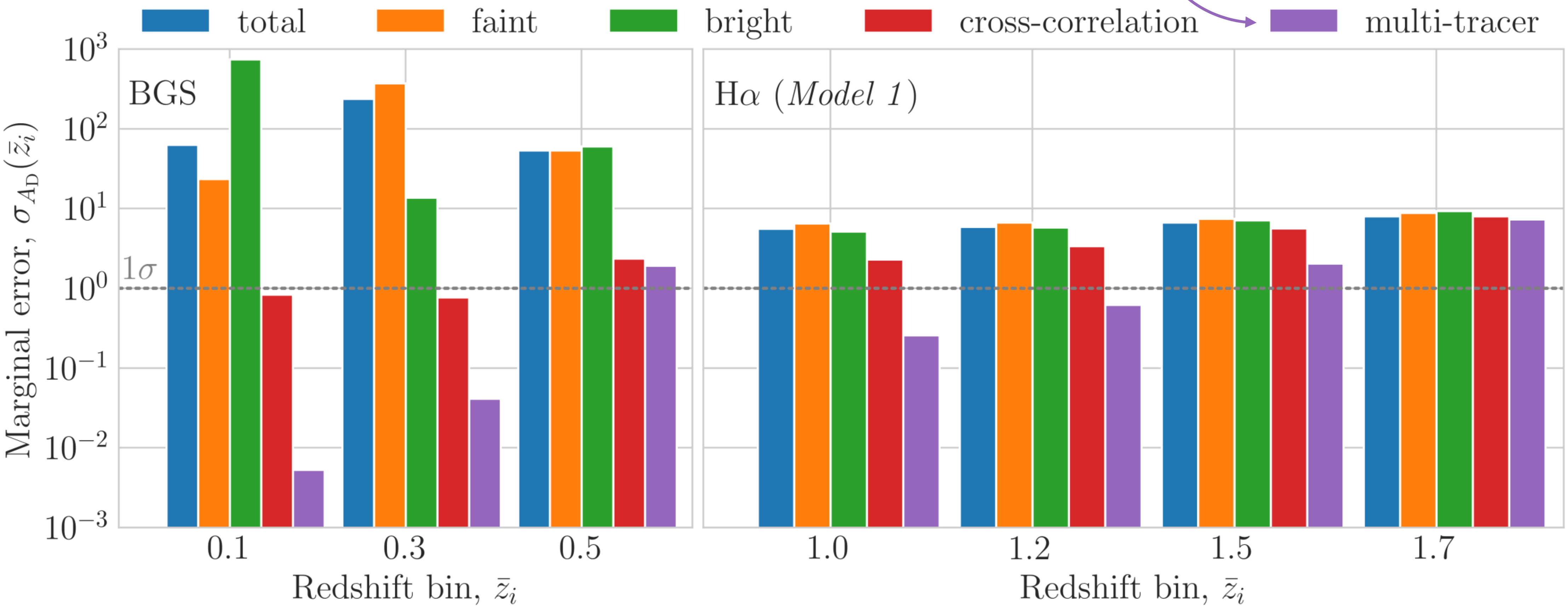
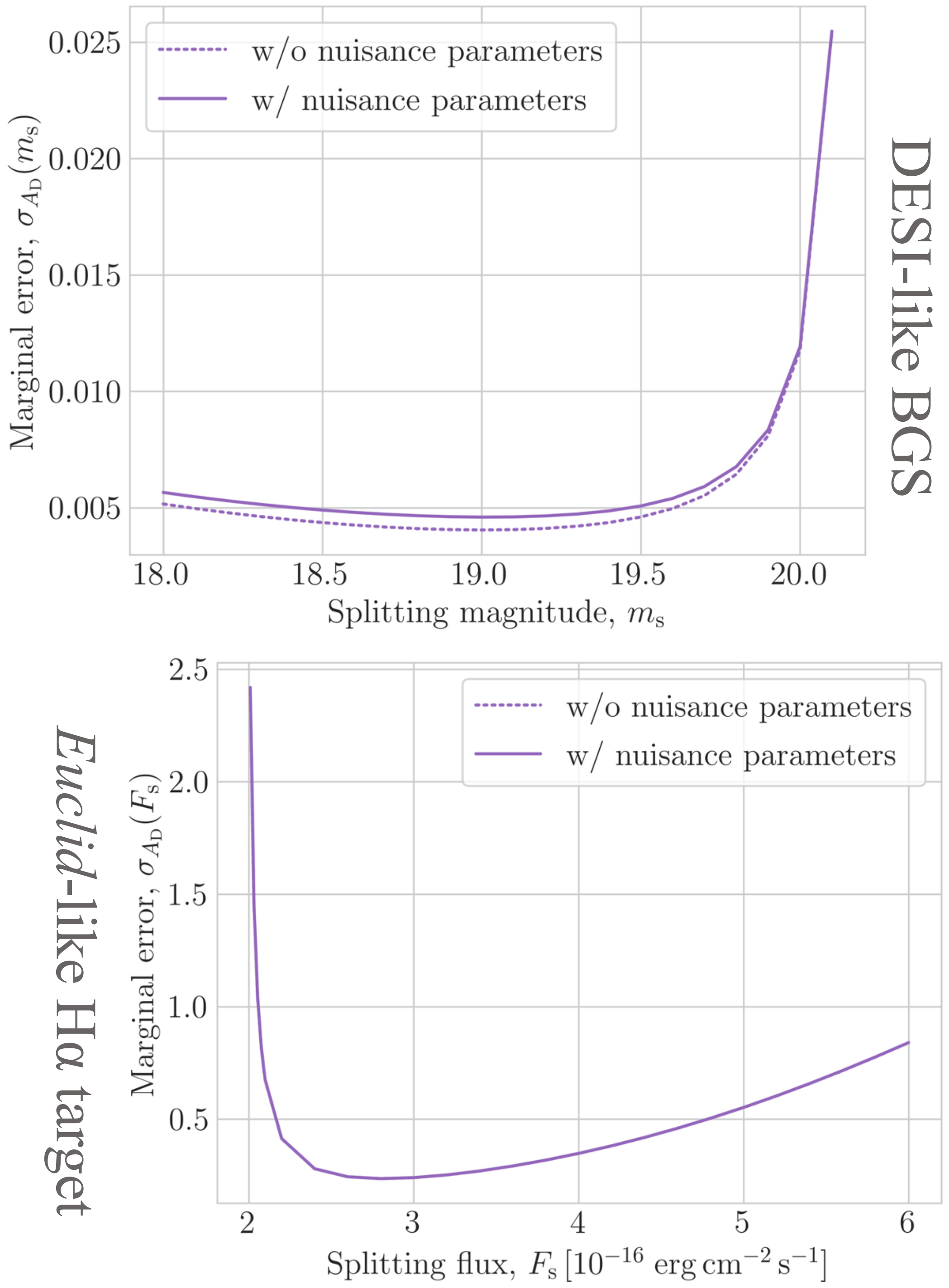
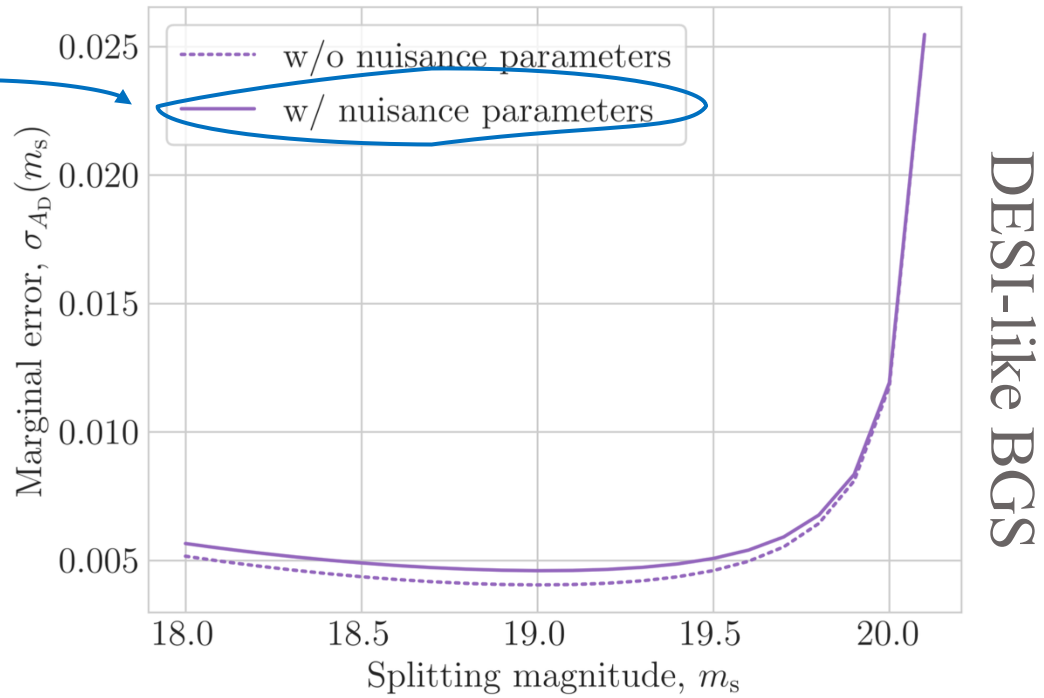


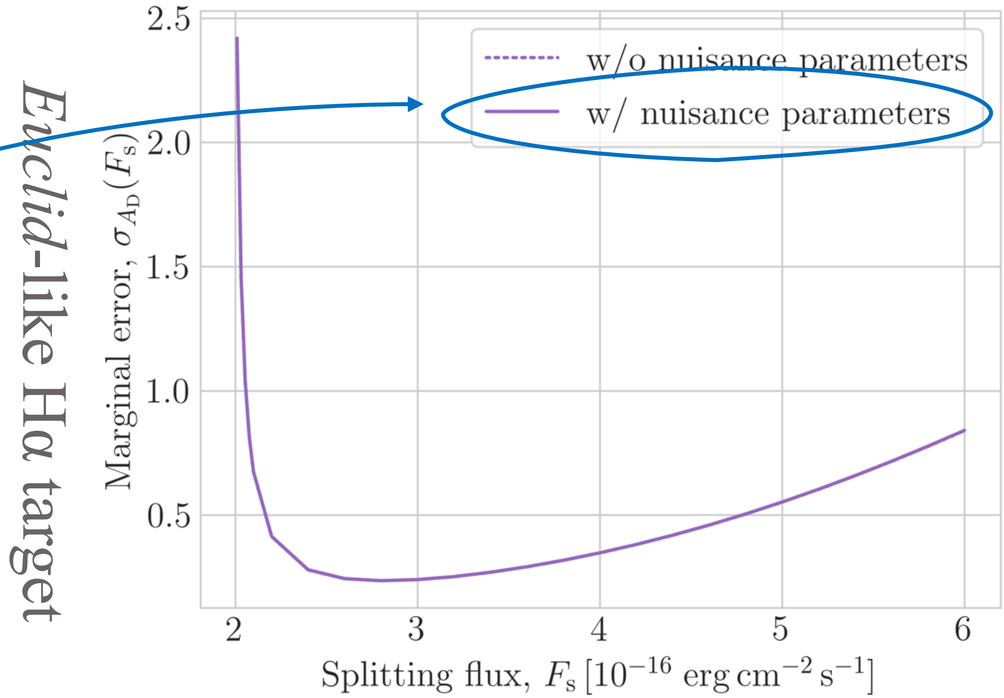
We can study how the probability of detecting a relativistic contribution depends upon the splitting flux adopted.



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

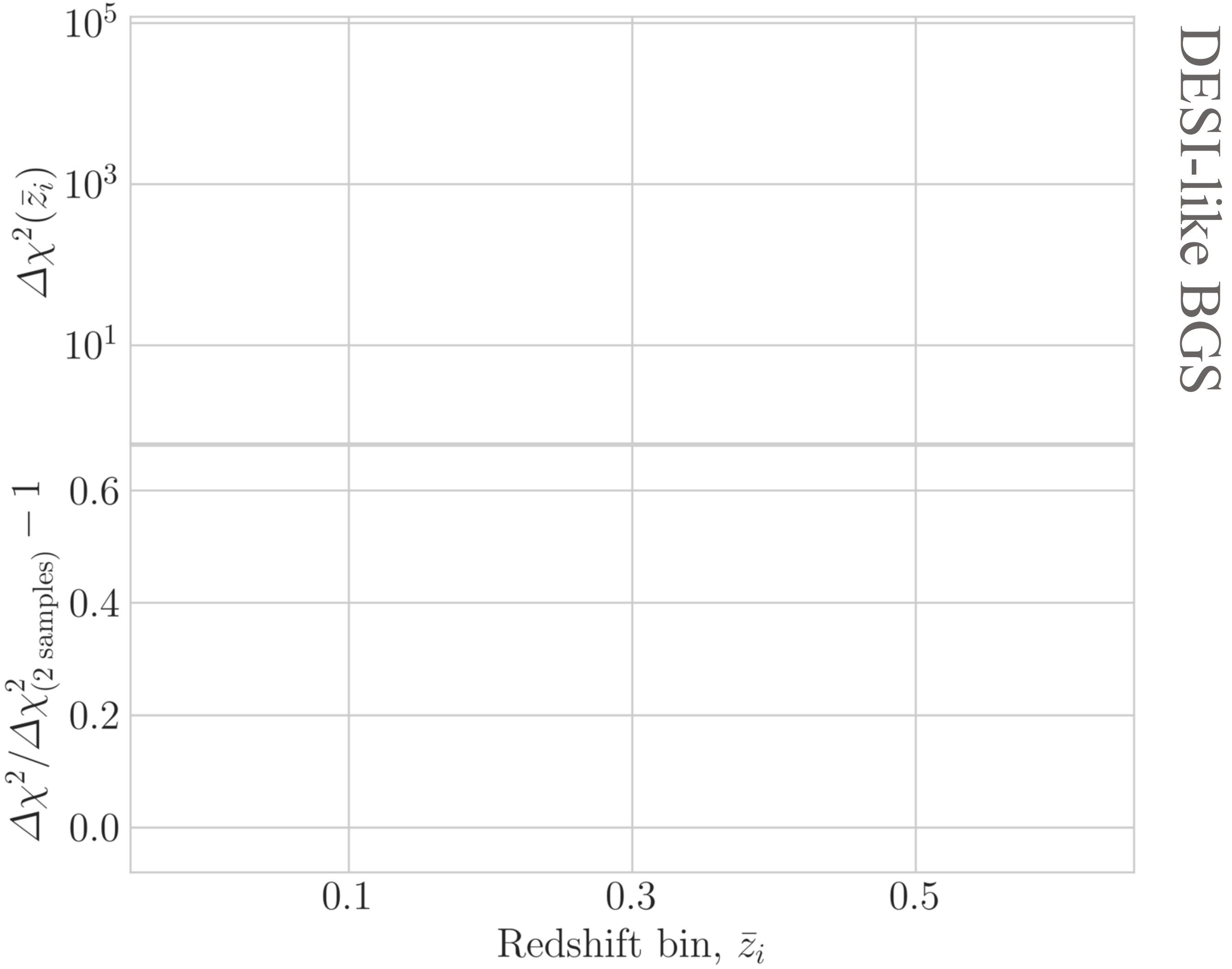
$$\theta_\alpha = \left\{A_N, A_K, A_D, \left\{N_{FF}^{(i)}\right\}, \left\{N_{FB}^{(i)}\right\}, \left\{N_{BB}^{(i)}\right\}\right\}$$





What about multiple splits?

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



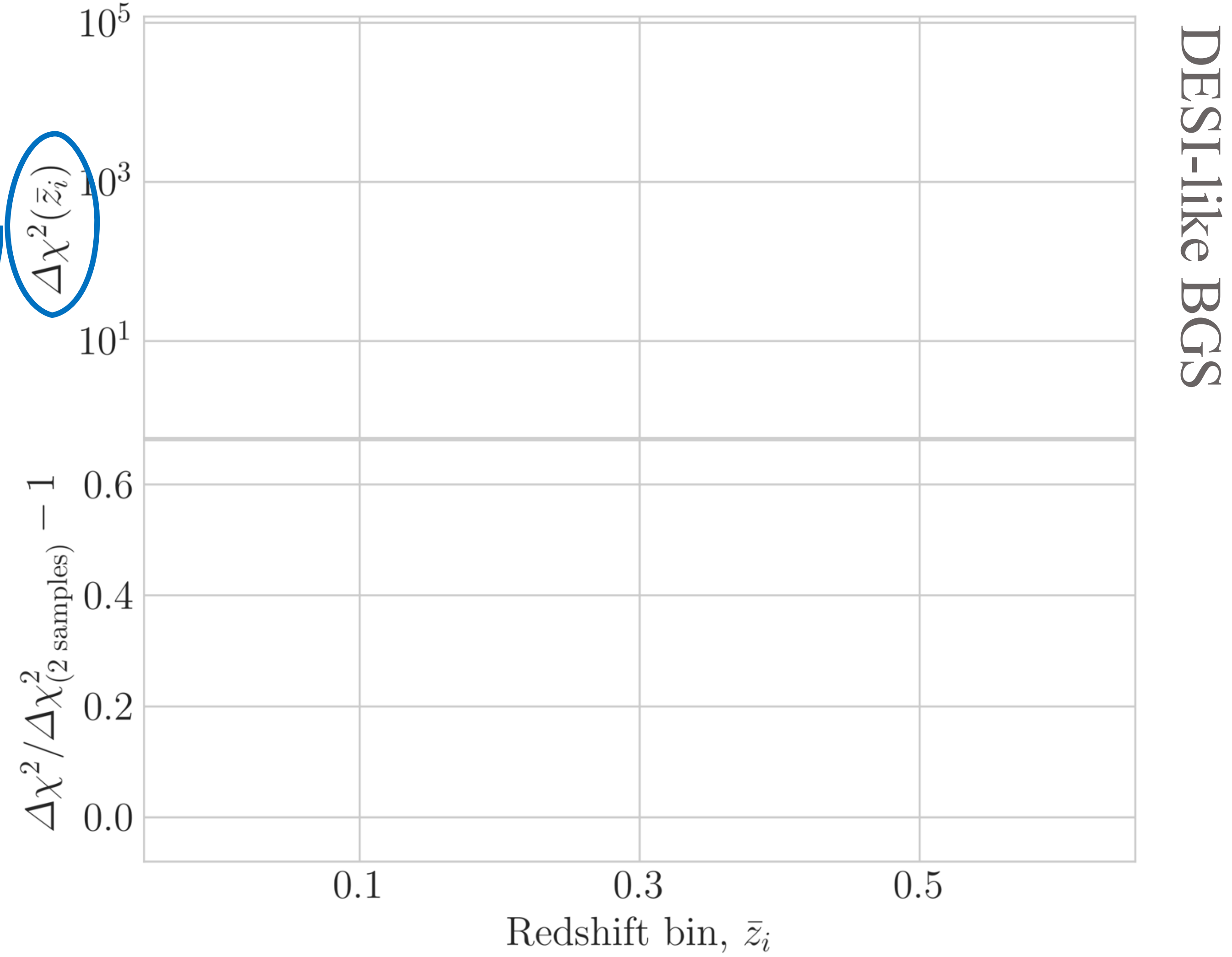
What about multiple splits?

Detection significance analysis

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

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

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



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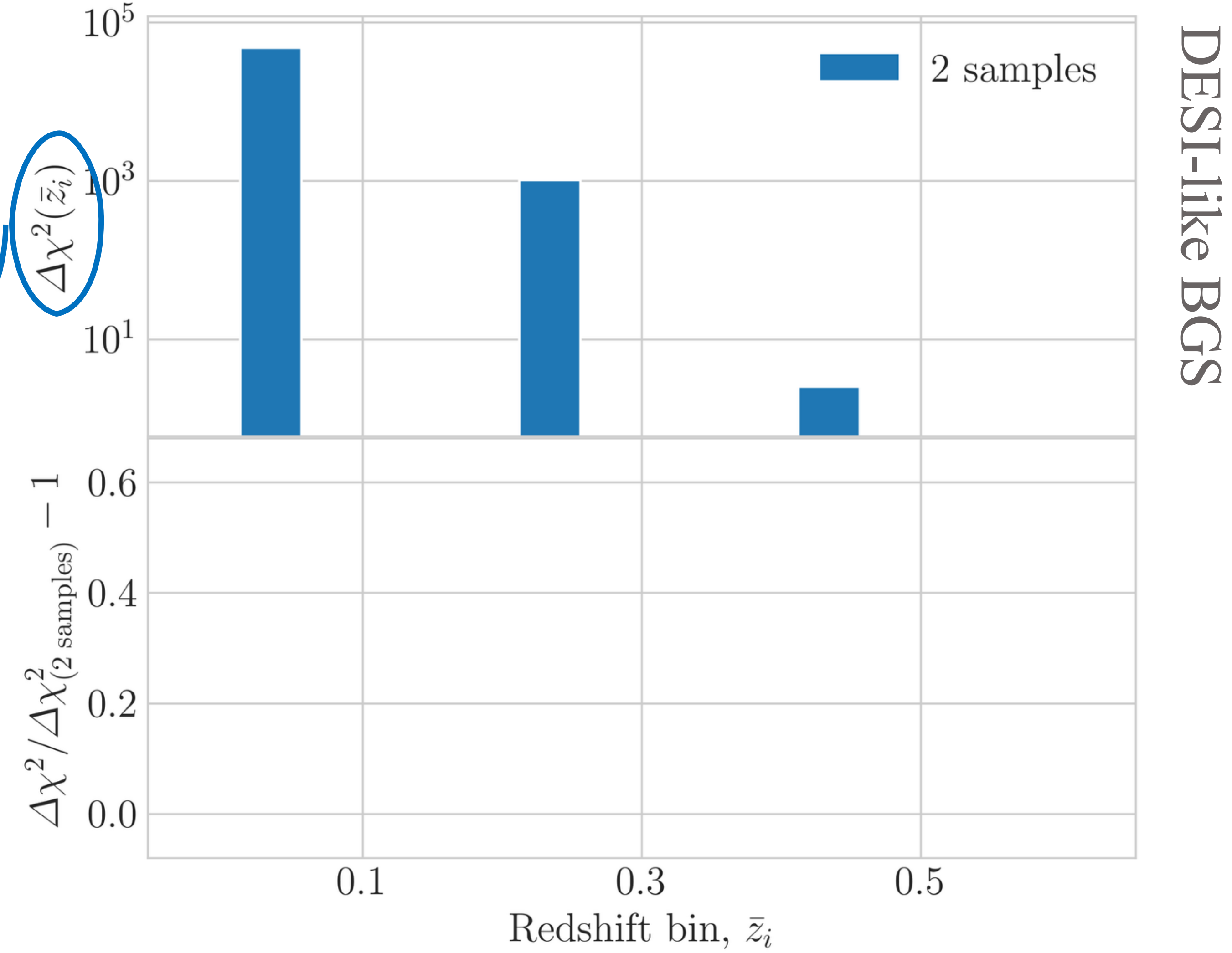

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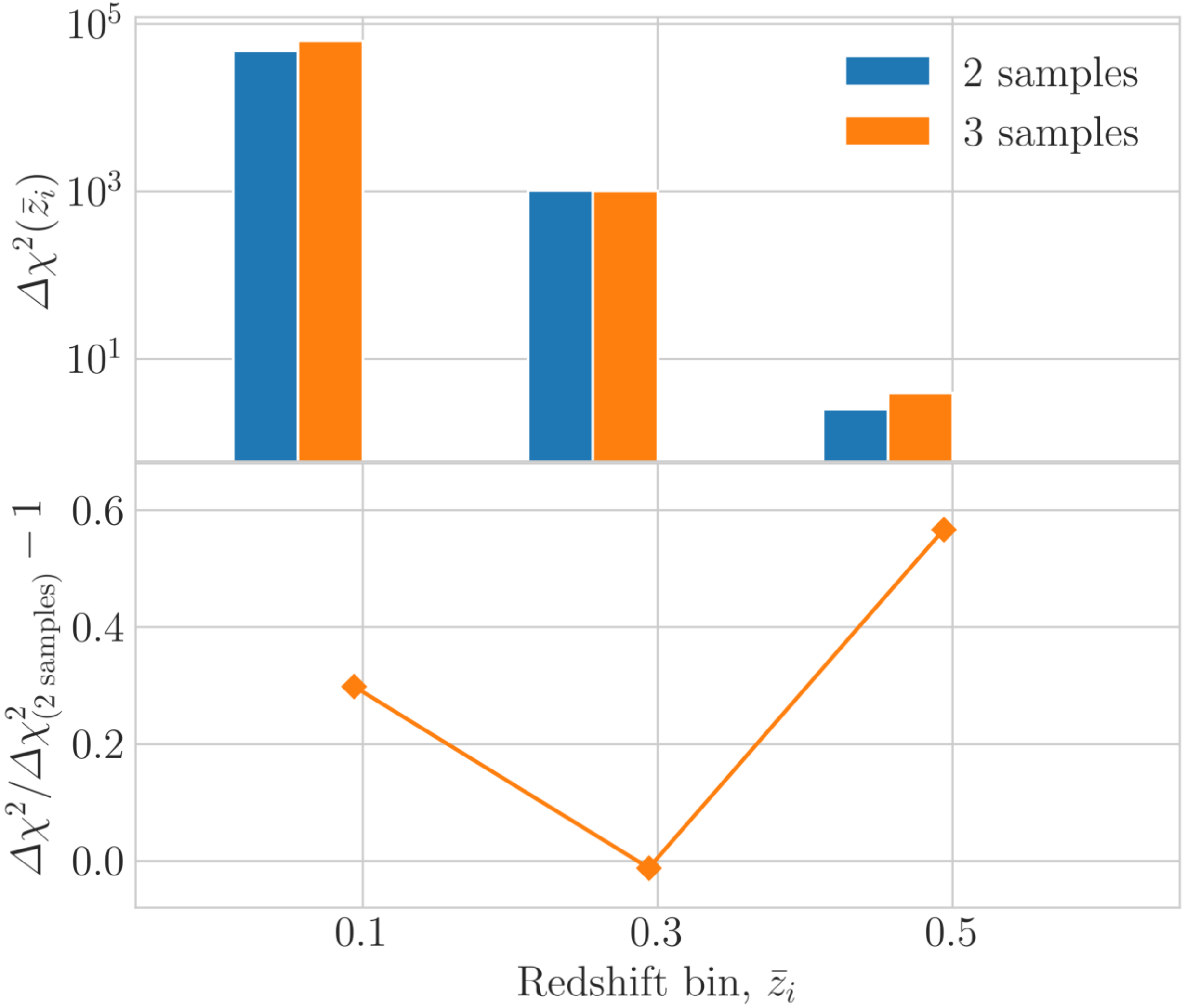

DESI-like BGS

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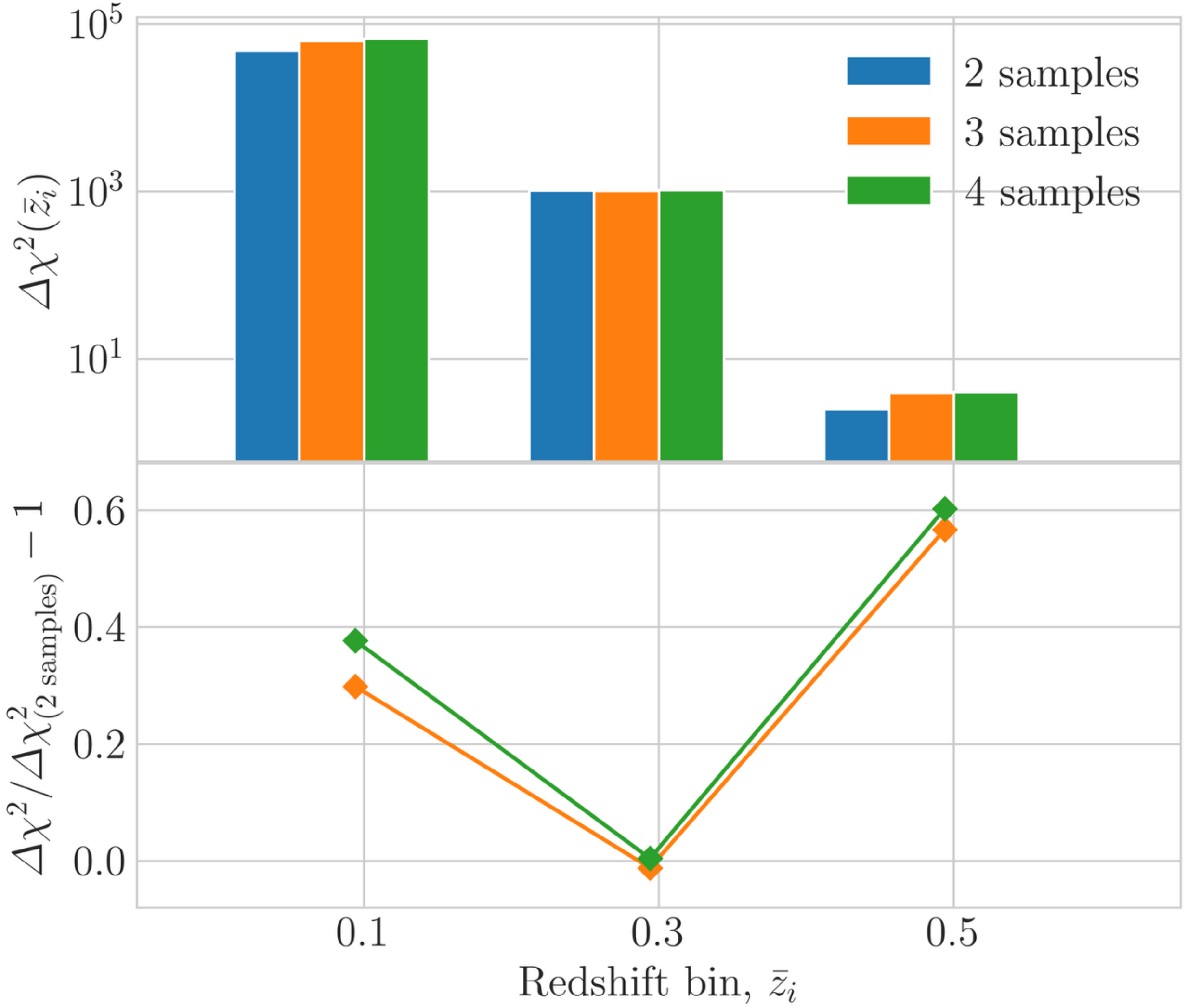

DESI-like BGS

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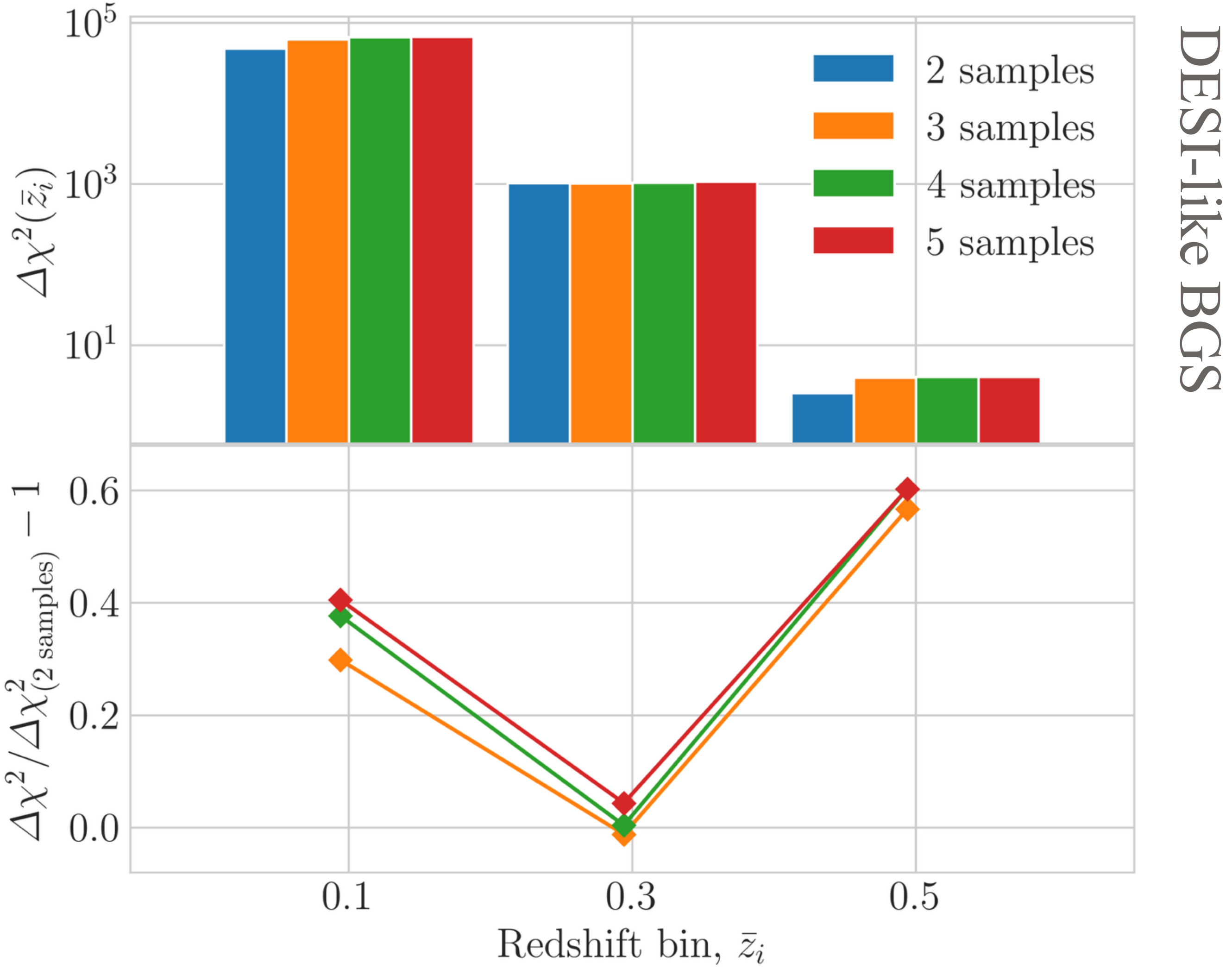
Detection significance analysis

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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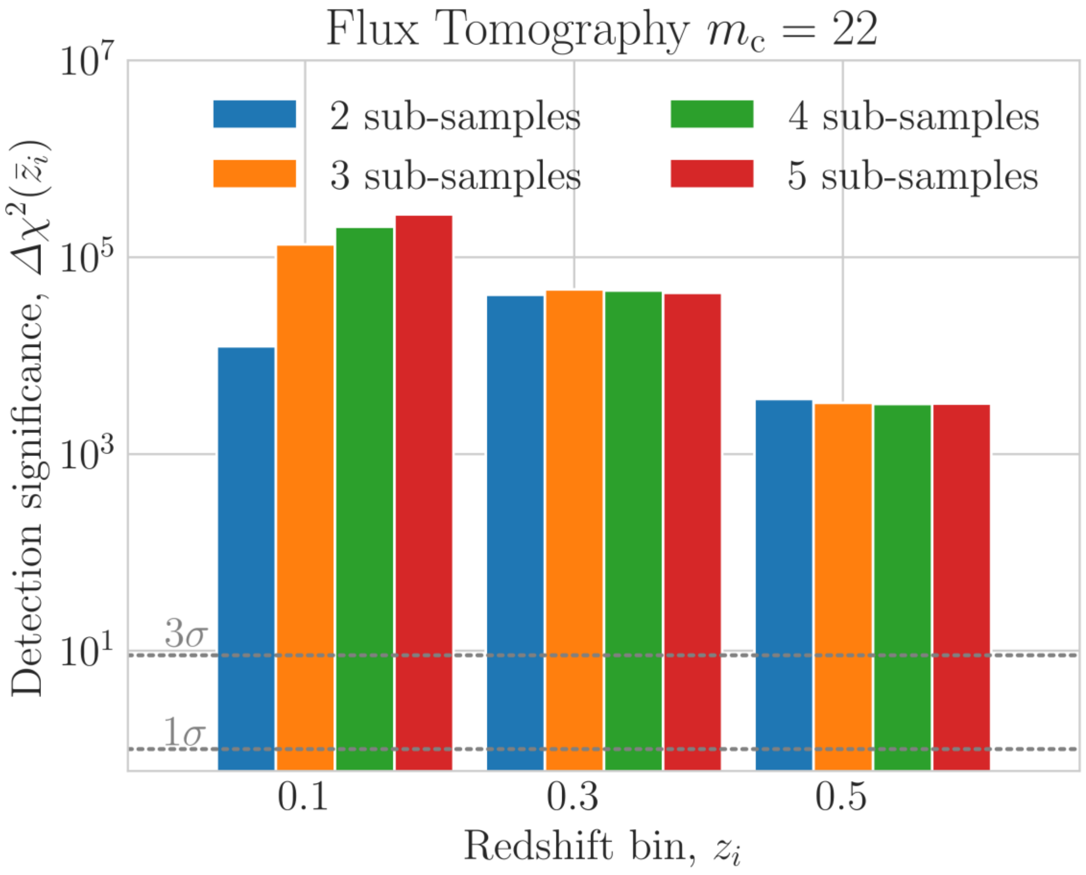

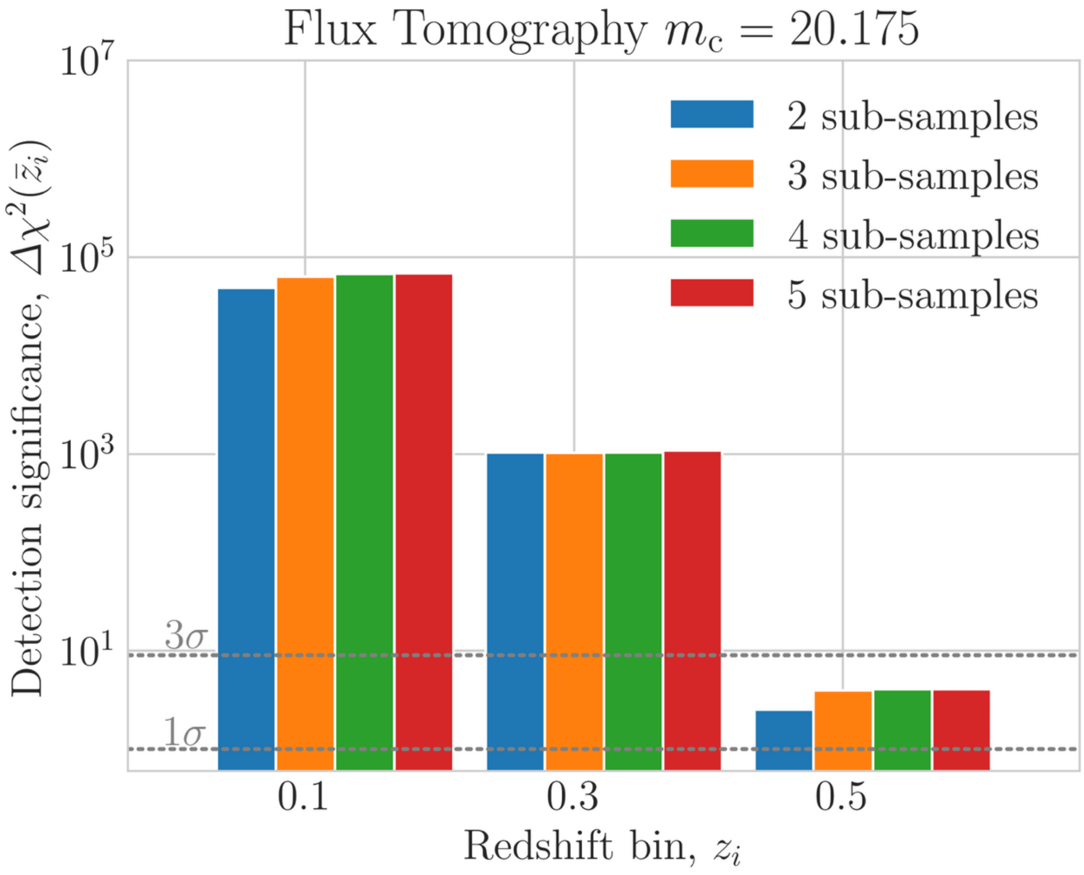

DESI-like BGS

Ongoing work

- An analysis of the performance of the luminosity cut technique using simulated data will demonstrate its reliability
  - With M. Y. Elkhashab, J. Salvalaggio & P. Monaco
- Including wide-angle effects
- Convolution with window function

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Take-home messages

- A first detection of relativistic Doppler could confirm the validity of general relativity on cosmological scales
- A multi-tracer approach is able to overcome cosmic variance, even within a single dataset.

Thanks for your attention!