Relativistic effects in galaxy clustering with the DESI Bright Galaxy Survey

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THE UNIVERSITY of EDINBURGH

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Underlying matter distribution

ESA/Euclid/Euclid Consortium/NASA

Matter power spectrum

$$\delta(z) = \frac{\rho(z) - \bar{\rho}(\bar{z})}{\bar{\rho}(\bar{z})}$$

background

$$\langle \delta(\boldsymbol{k}) \delta^*(\boldsymbol{k}') \rangle = (2\pi)^3 \delta_D(\boldsymbol{k} - \boldsymbol{k}') P_m(k)$$

what we actually observe

$$\Delta_{\rm obs}(\hat{\boldsymbol{n}}, z) = \frac{N(\hat{\boldsymbol{n}}, z) - \widetilde{N}(z)}{\widetilde{N}(z)}$$

Average over all directions

$$\langle \Delta(\boldsymbol{k}) \Delta^*(\boldsymbol{k}') \rangle = (2\pi)^3 \delta_D(\boldsymbol{k} - \boldsymbol{k}') P(k)$$

Not the the real picture

ESA/Euclid/Euclid Consortium/NASA

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$$\Delta_{\rm obs} \neq \Delta_{\rm real}$$

- In 1987, using Newtonian dynamics, Kaiser derived

$$\Delta_{obs} = \underbrace{\Delta_{real}}_{} - \frac{1}{\mathcal{H}}\partial_r v_\parallel - \frac{2}{\mathcal{H}r}v_\parallel$$

$$= b\,\delta$$

Galaxies are biased tracers

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$$1 + z_{obs} = (1 + z_{cos})(1 + v_\parallel)$$

Standard Redshift Space Distortions

Kaiser + Doppler terms

$$\Delta_{\text{obs}} \neq \Delta_{\text{real}}$$

- For a perturbed FLRW spacetime, at linear order in perturbation theory up to order k^{-1} and neglecting gravitational lensing

$$\Delta_{obs} = \Delta_{real} - \frac{1}{\mathcal{H}}\partial_r v_{\parallel} - \left(\frac{2}{\mathcal{H}r} + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - 1\right)v_{\parallel} + \frac{1}{\mathcal{H}}\dot{v}_{\parallel} + \frac{1}{\mathcal{H}}\partial_r \psi$$

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Relativistic Doppler

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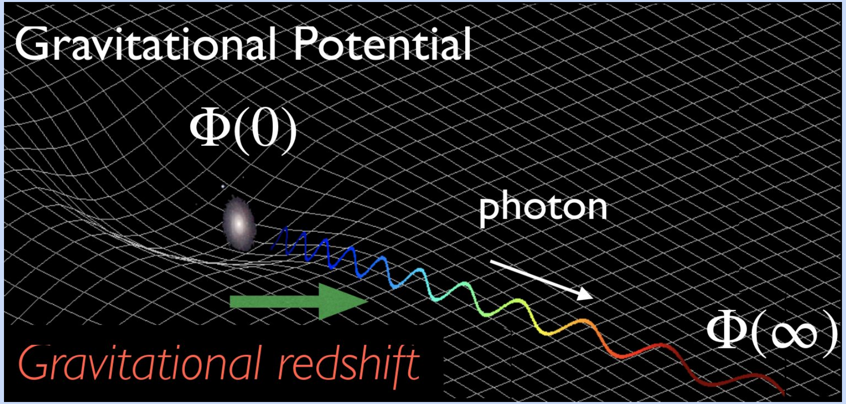

Taruya (2021)

$$+\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}-1\Big)v_\parallel+\frac{1}{\mathcal{H}}\dot{v}_\parallel+\frac{1}{\mathcal{H}}\partial_r\psi$$

Gravitational redshift

$$1+z_{obs}=(1+z_{cos})(1+v_\parallel-\psi)$$

$\Delta_{\rm obs} \neq \Delta_{\rm real}$

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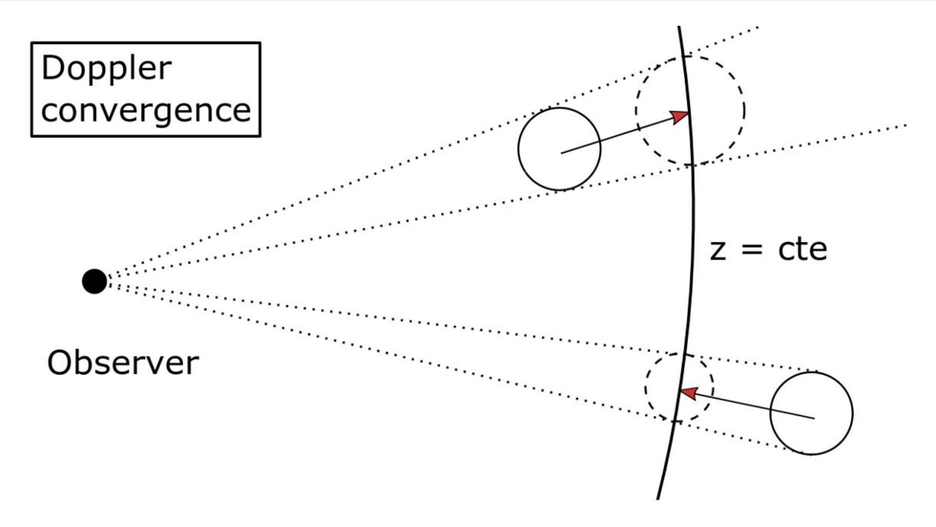
$$\Delta_{\rm obs} \neq \Delta_{\rm real}$$

- In the case of **General Relativity**, matter obeys Euler's equation

$$\dot{v}_{\|} + \mathcal{H}v_{\|} + \partial_r\psi = 0$$

$$\Delta_{obs} = \Delta_{real} - \frac{1}{\mathcal{H}}\partial_r v_{\|} - \left(\frac{2}{\mathcal{H}r} + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)v_{\|}$$

Selection effects - Magnitude limited survey



Breton (2018)

Doppler lensing

$$\tilde{m} \simeq m + 5\log(1-\kappa)$$

$$\kappa = \left(\frac{1}{\mathcal{H}r} - 1\right) v_{\parallel}$$

$$\Delta = 5s\kappa$$

Magnification bias

$$s = \left.\frac{\partial \log_{10} N(<m)}{\partial m}\right|_{m_{lim}}$$

New window to **probe general relativity** on cosmological scales!

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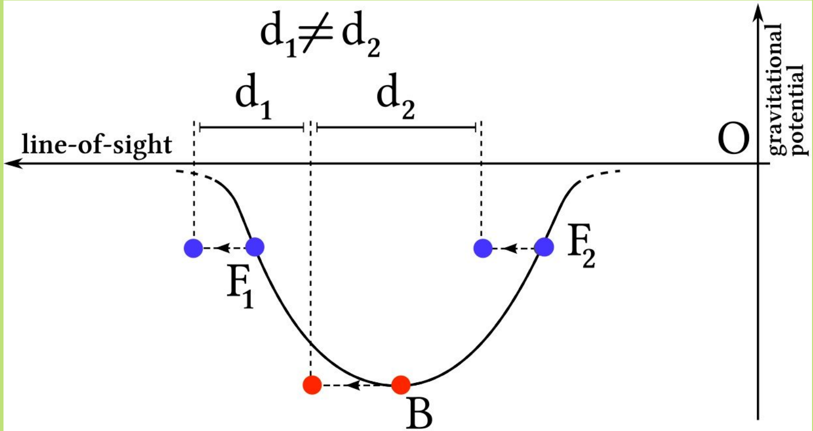
Relativistic effects generate **asymmetric** distortions along the line of sight



Bonvin, Hui, Gaztañaga (2014)

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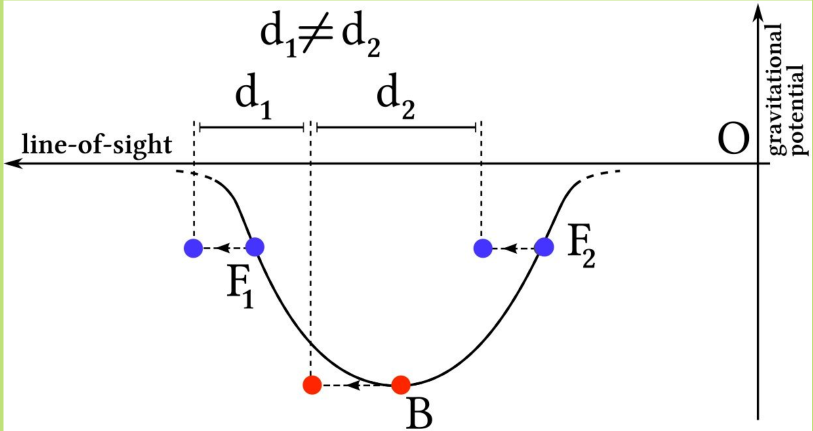


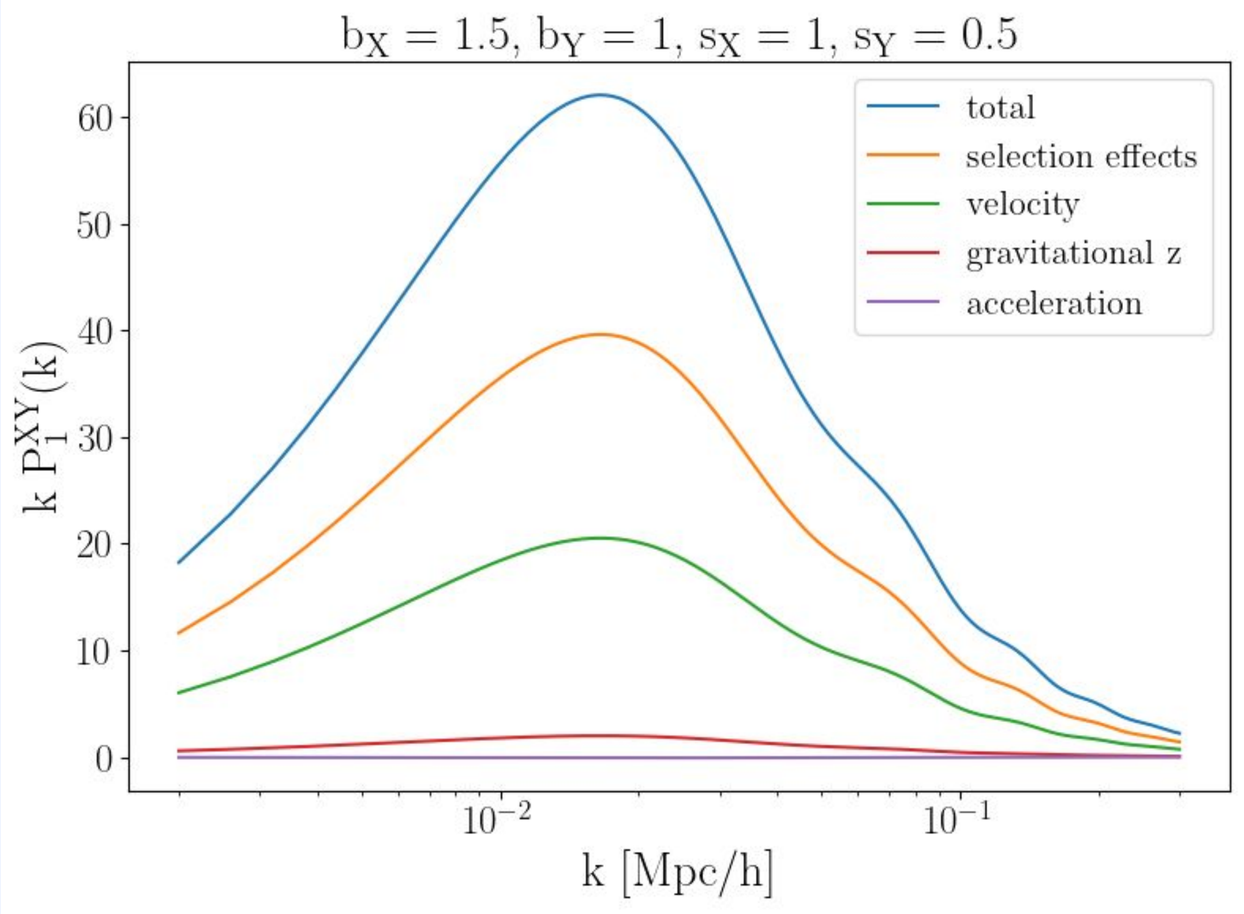
Bonvin, Hui, Gaztañaga (2014)

Non-vanishing **dipole** in the cross-power spectrum of **two different biased tracers**

$$P_1^{\mathrm{BF}}(k) = \frac{3}{2}\int_{-1}^{1} P^{\mathrm{BF}}(k,\mu)\mu\,\mathrm{d}\mu$$

$$\mu = \hat{\boldsymbol{k}} \cdot \hat{\boldsymbol{n}}$$

Dipole model



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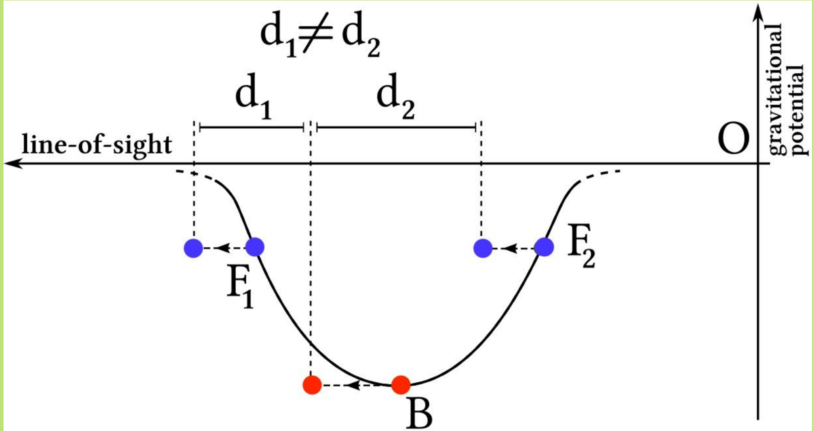

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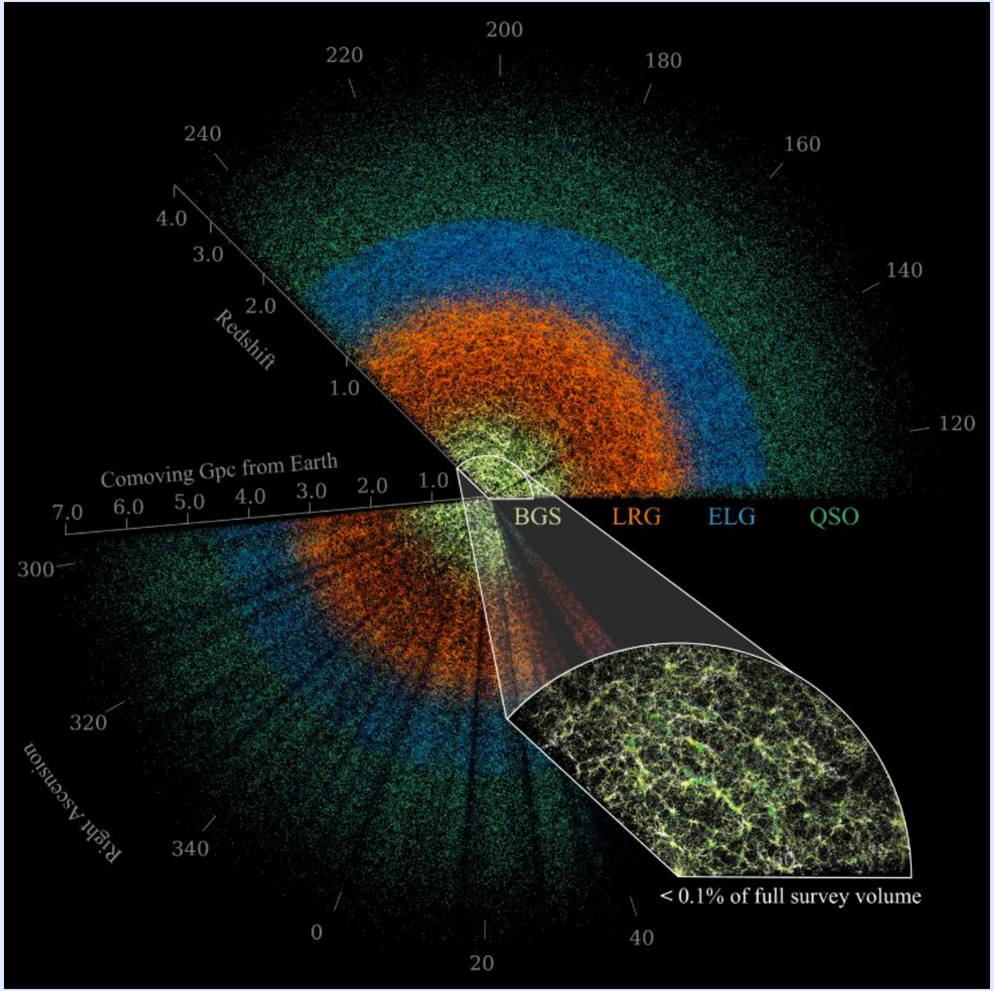
$$\mu = \hat{\boldsymbol{k}} \cdot \hat{\boldsymbol{n}}$$

We need a lot of statistical power!

DESI **Bright Galaxy Survey (BGS)** is very promising

- redshift range $0 < z < 0.6$
- magnitude-limited sample ($m < 19.5$)
- measure redshifts of more than 10 million galaxies spanning 14,000 deg^2
- produce the most detailed map of the universe during the dark-energy-dominated epoch



DESI collaboration

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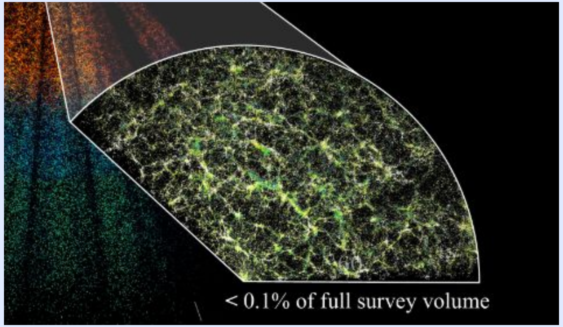

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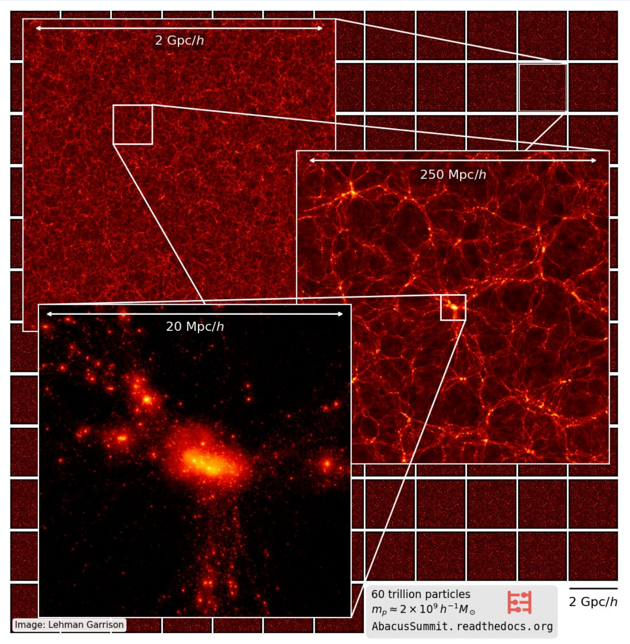


To study the dipole, we use **BGS mocks** created from large, high-accuracy cosmological N-body simulations (AbacusSummit)

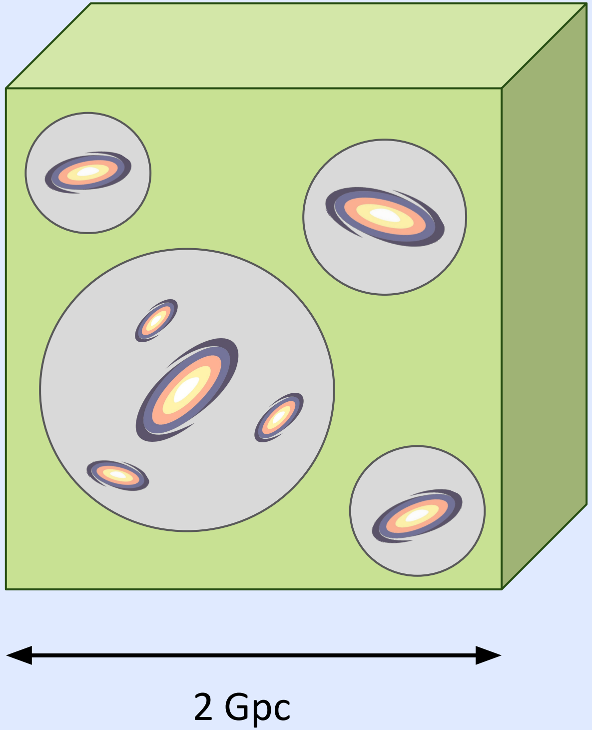
BGS Cut-sky mocks

A **Halo Occupation Distribution** (HOD) model varying with absolute magnitude is used to populate the halos with central and satellite galaxies

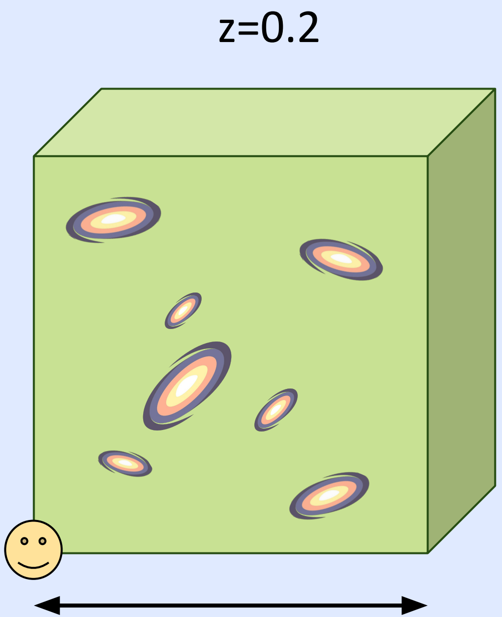
$$\langle N_{\rm cen}(>L \mid M)\rangle = \frac{1}{2}\left[1 + F\left(\frac{\log M - \log M_{\rm min}(L)}{\sigma_{\log M}(L)}\right)\right]$$

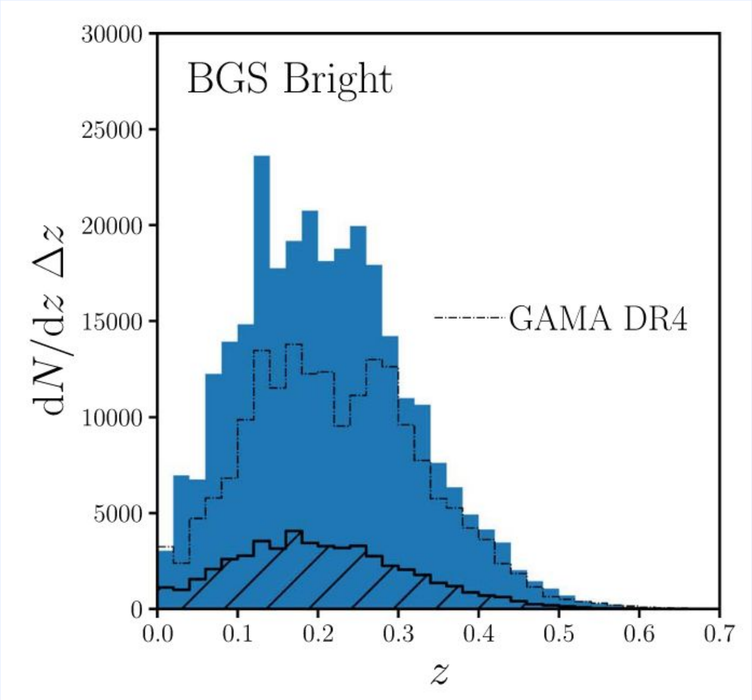
$$\langle N_{\rm sat}(>L \mid M)\rangle = \langle N_{\rm cen}(>L \mid M)\rangle \left(\frac{M - M_0(L)}{M_1'(L)}\right)^{\alpha(L)}$$

Smith et al. (2023)



BGS Cut-sky mocks





Hahn et al. (2023)

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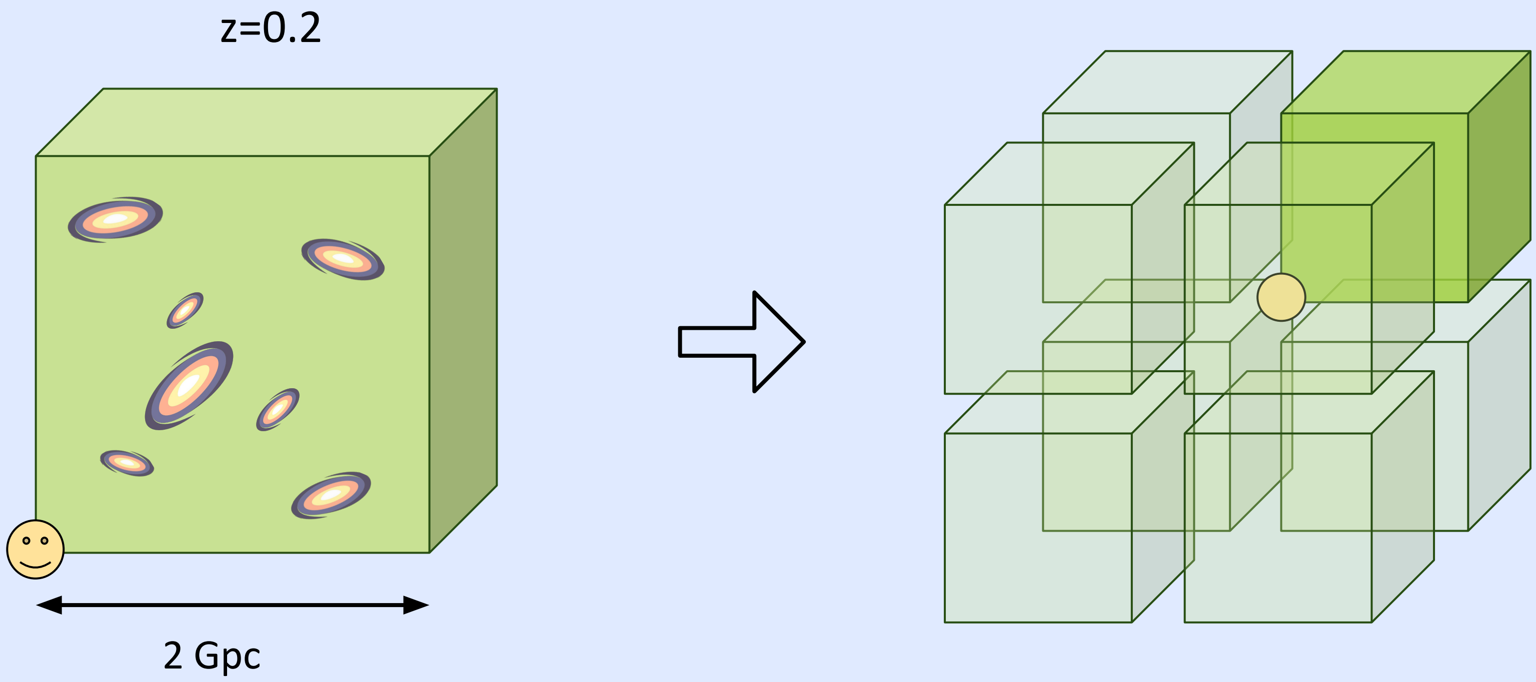

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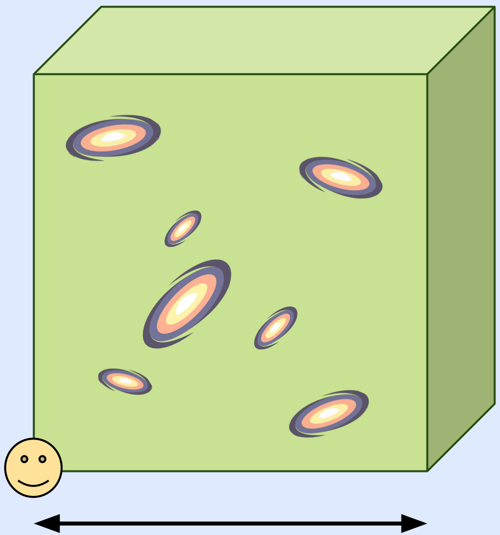
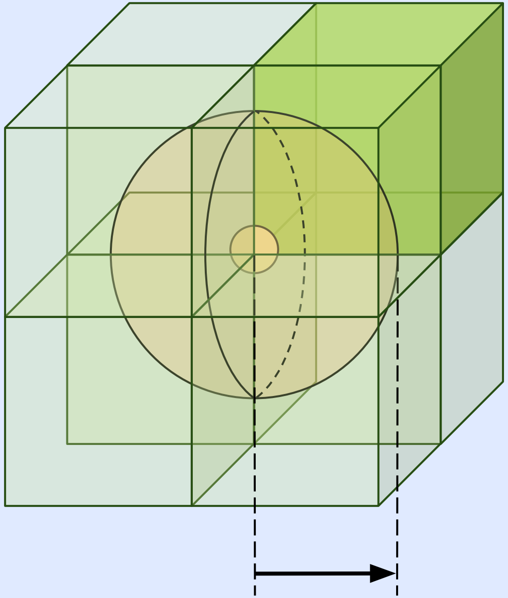
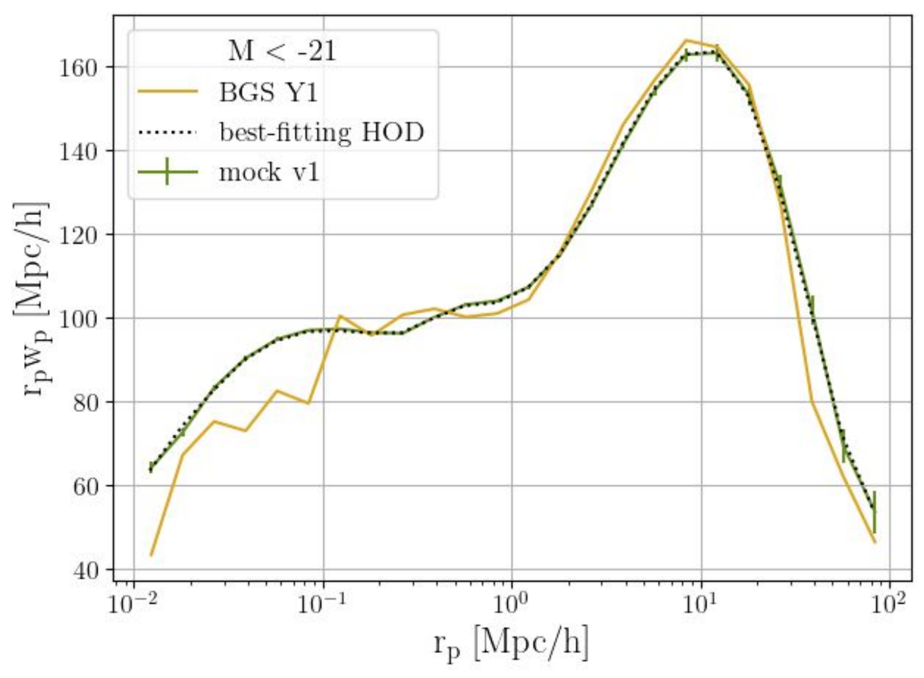
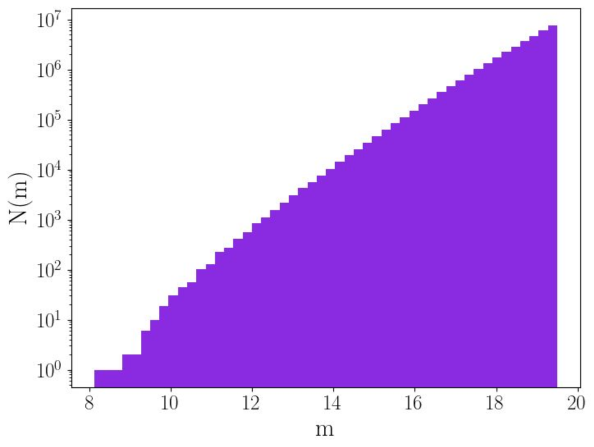


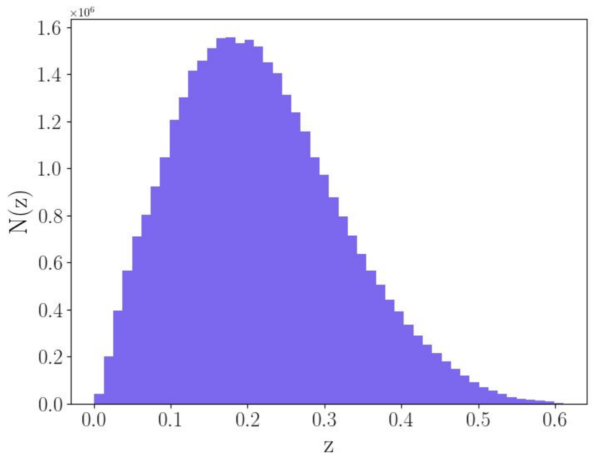


+ redshift evolution applied to magnitudes

BGS Cut-sky mocks







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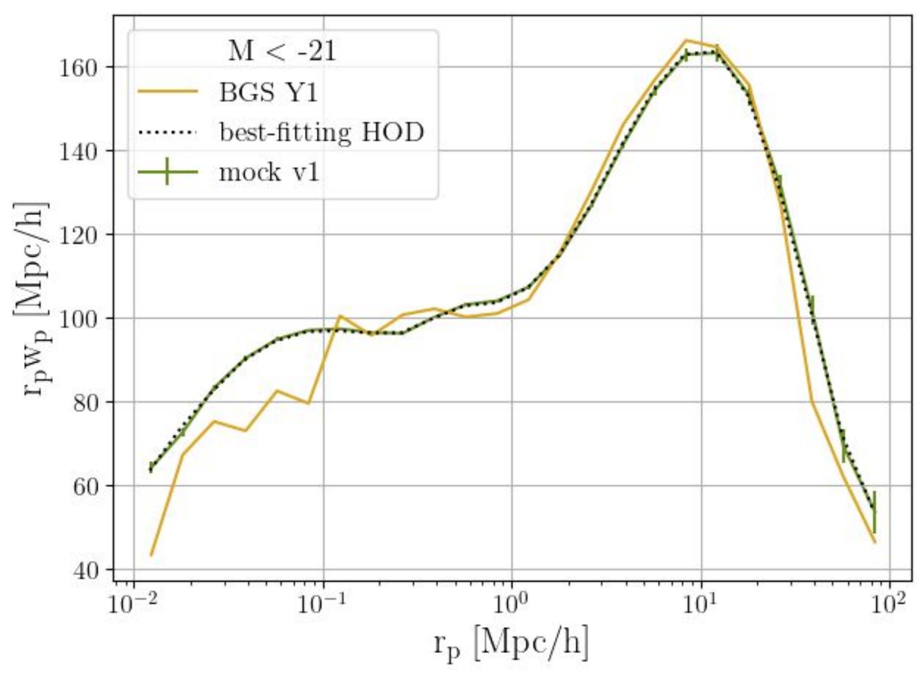

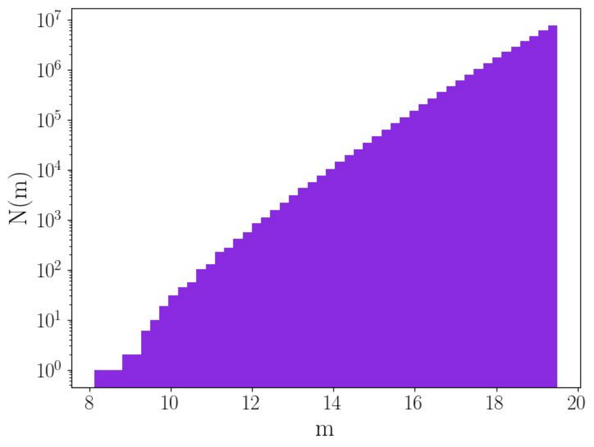

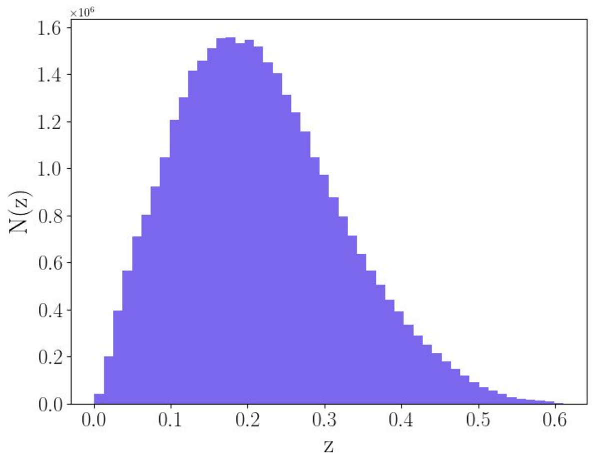

How do we select our **tracers**?

The dipole is sensitive to Δb and Δs

Magnification bias

$$s(z) = \frac{\partial \log_{10} N(< m, z)}{\partial m}\bigg|_{m=m_{lim}}$$

Split galaxies into **bright** and **faint** tracers

Doppler lensing

$$\tilde{m} \simeq m + 5\log(1-\kappa)$$

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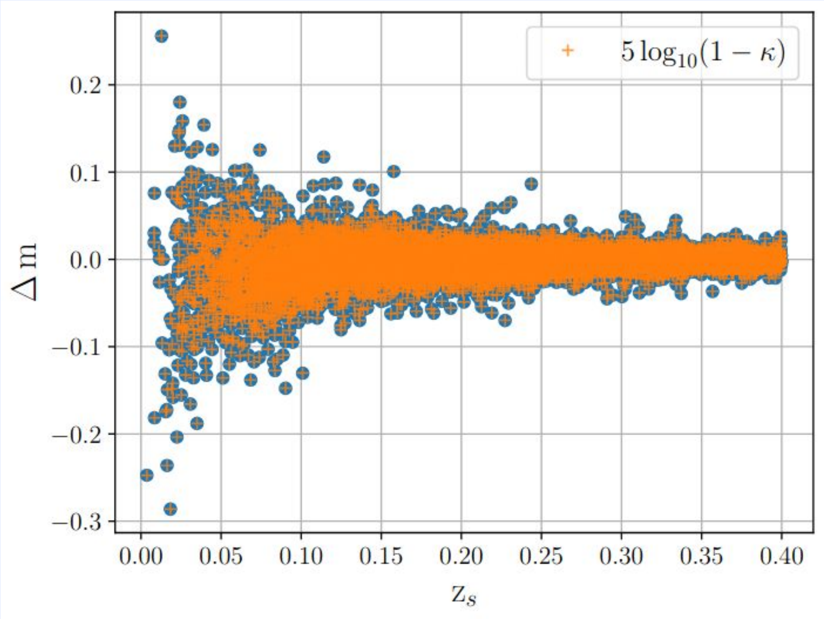


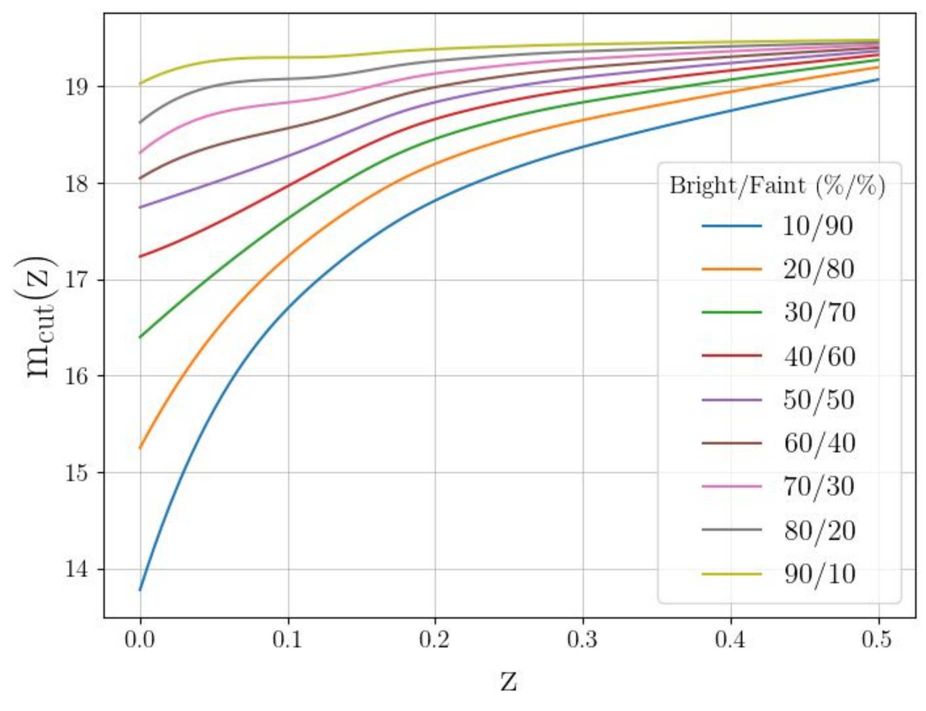
Magnification bias

$$s(z) = \left. \frac{\partial \log_{10} N(< m, z)}{\partial m} \right|_{m=m_{lim}}$$

$$s_B(z) = \left. \frac{\partial \log_{10} N(< m, z)}{\partial m} \right|_{m=m_{cut}}$$

$$s_F(z) = s(z)\frac{N(z)}{N_F(z)} - s_B(z)\frac{N_B(z)}{N_F(z)}$$

Magnitude cuts



Effective magnification bias

$$s_{\text{eff}} = \frac{\sum N_i s(z_i)}{\sum N_i}$$

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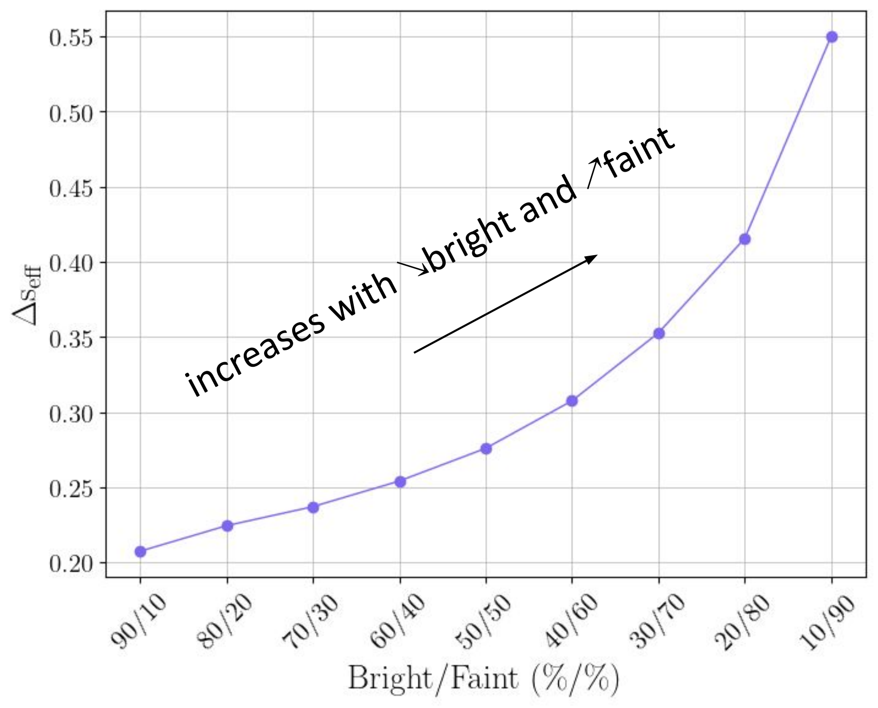
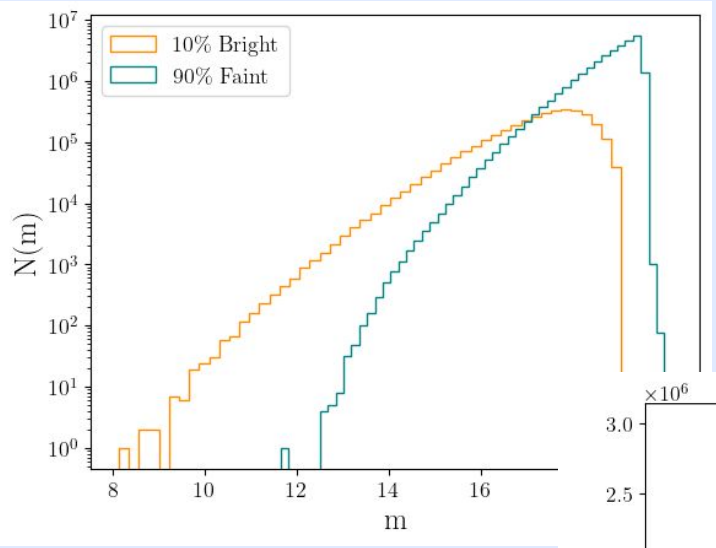
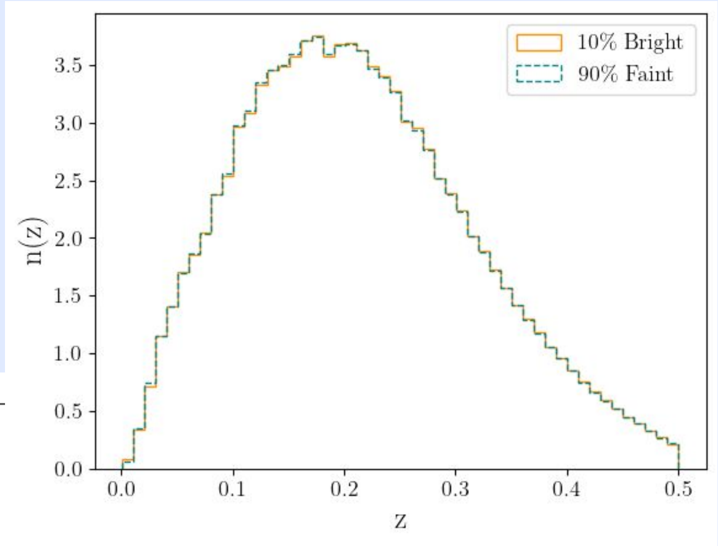
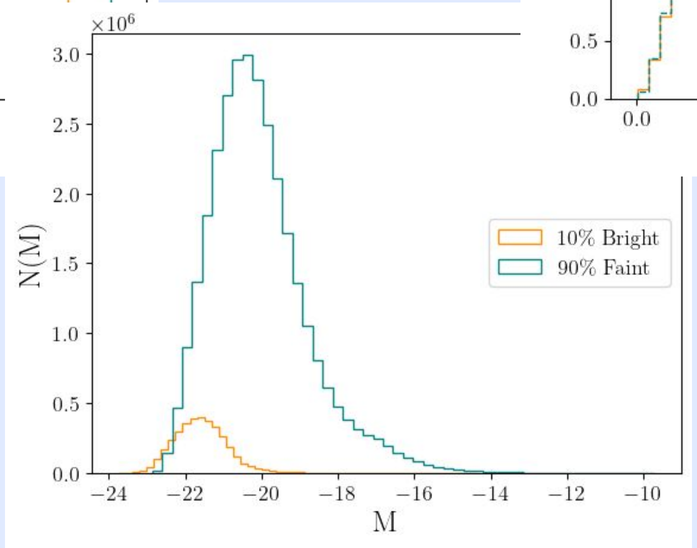
Effective magnification bias difference



10% Bright / 90% Faint samples

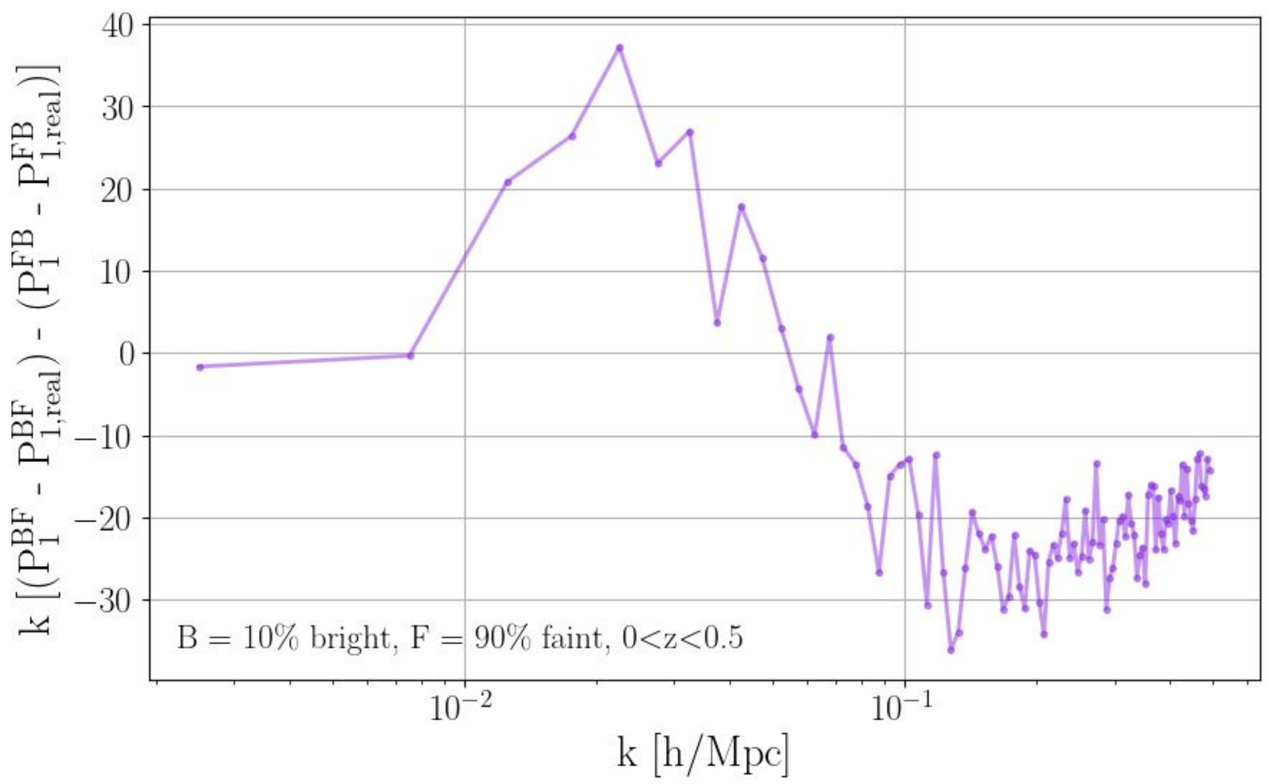




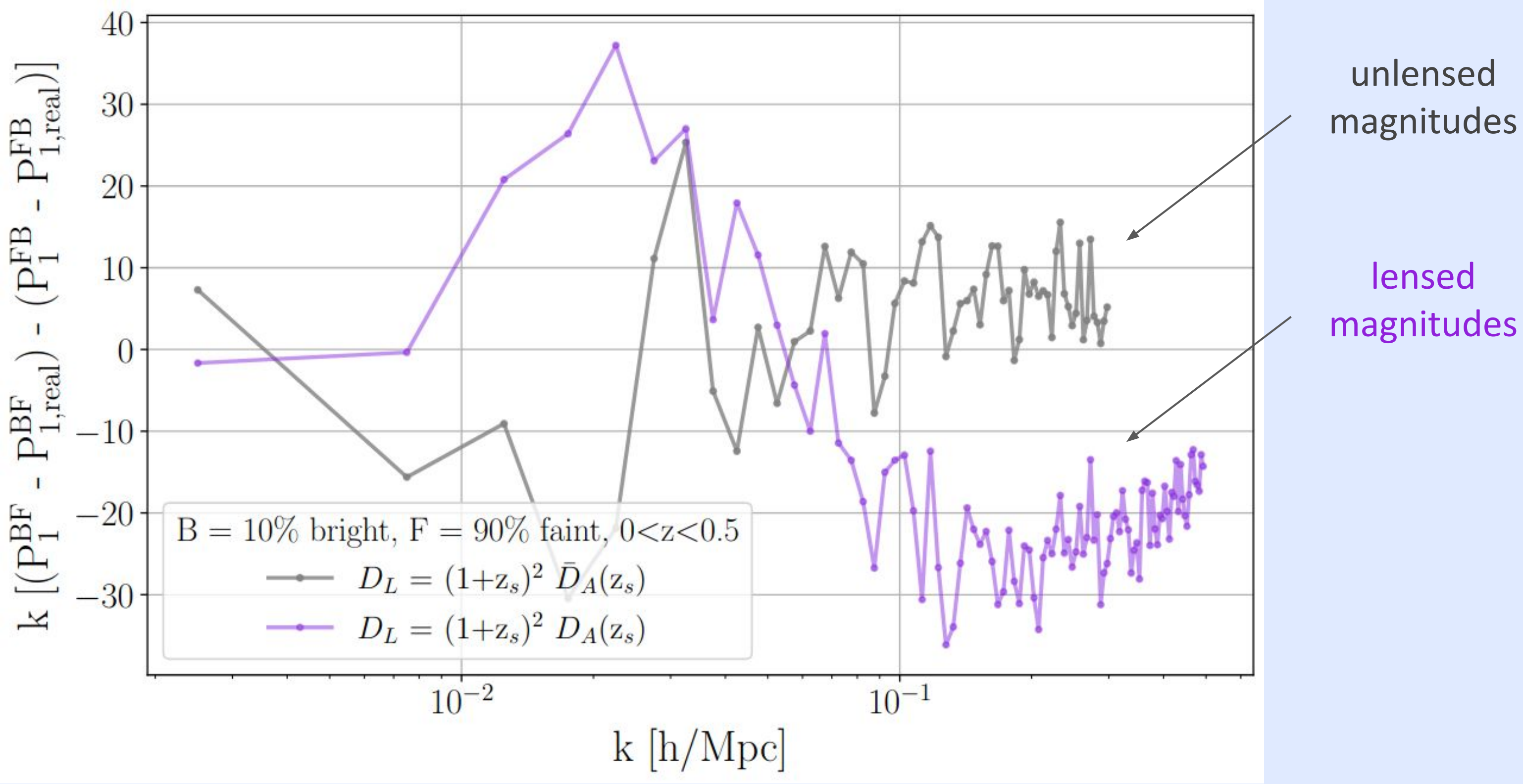


Effective dipole

$$(P_1^{BF} - P_{1,real}^{BF}) - (P_1^{FB} - P_{1,real}^{FB})$$



Selection effect - Doppler lensing



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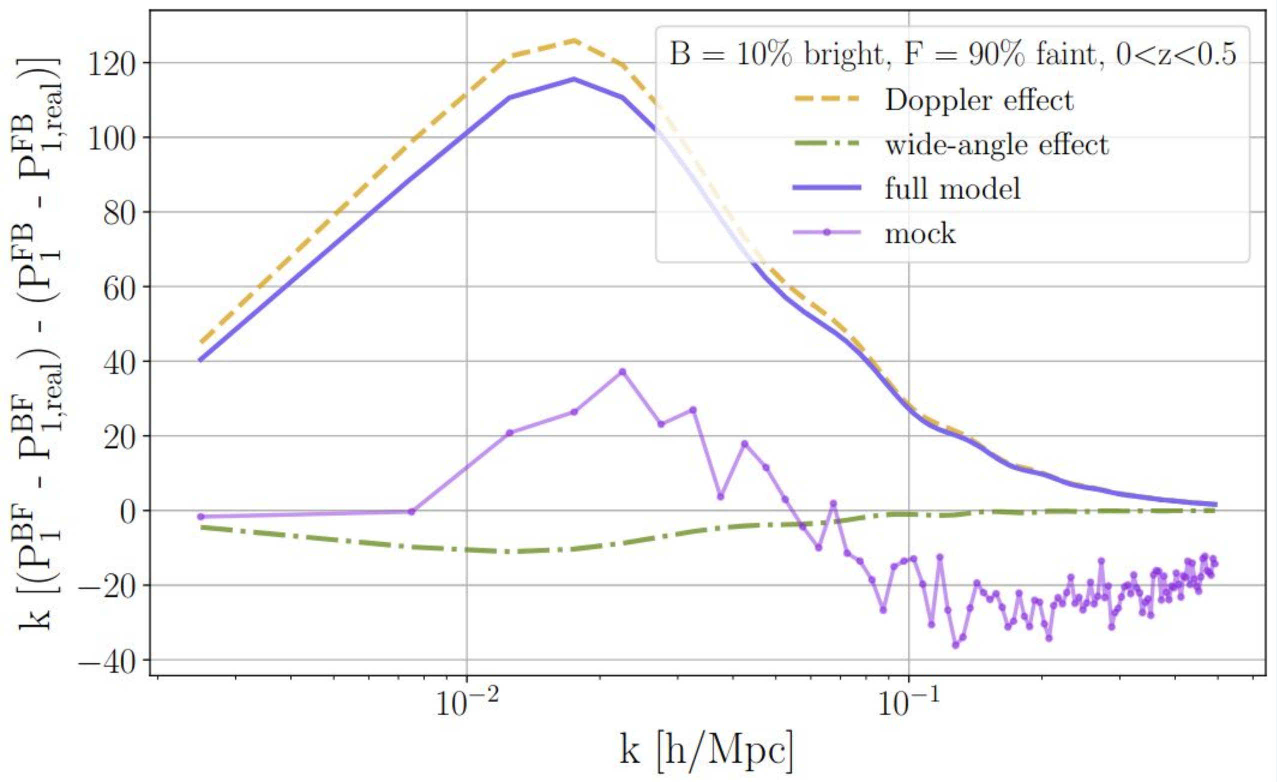
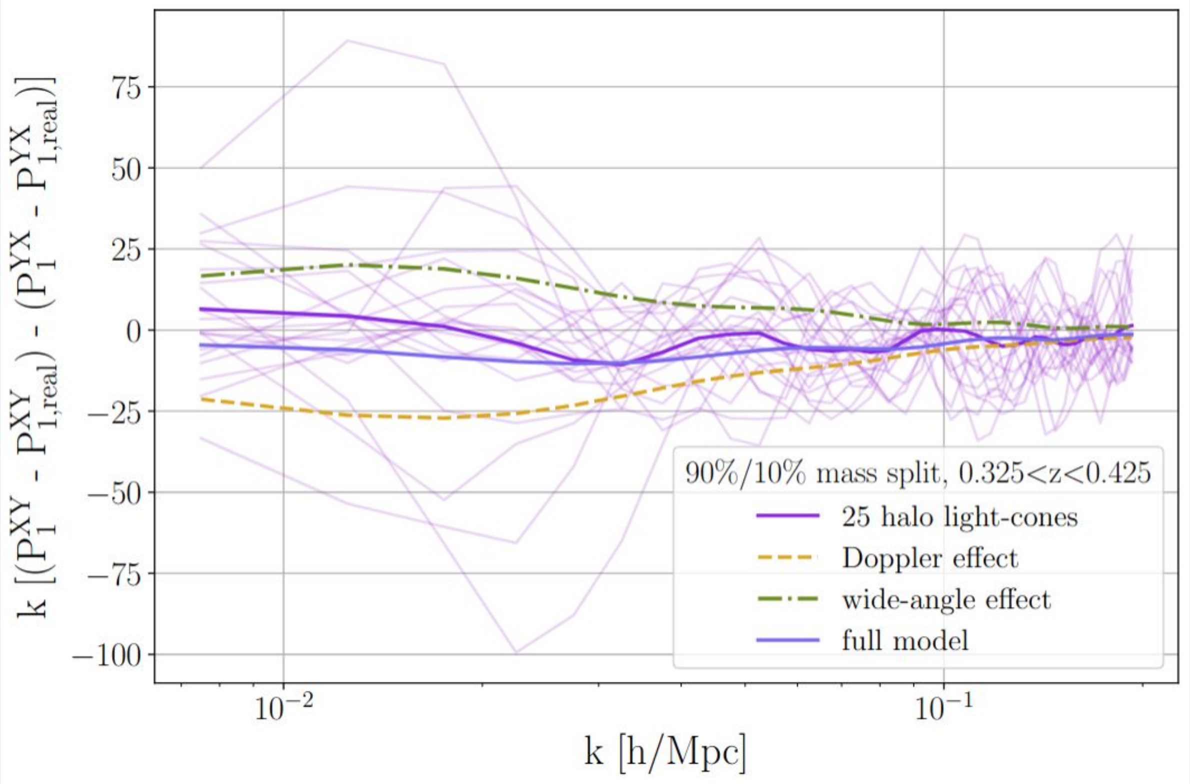


Problem: No redshift evolution in cut-sky mocks ⇨

- Apply linear velocity evolution
- Use interpolated lightcones mocks

Requires redshift evolution of the HOD



Summary

- The galaxy number overdensity has relativistic corrections
- Relativistic effects can be isolated from standard contributions as they generate a dipole in the cross-power spectrum of two different biased tracers
- We can use several properties to split galaxies into different tracers such as apparent magnitude

Next steps

- Further investigate how to optimise the dipole, apply velocity evolution to cutsky mocks
- Extend the post-processing of the mocks to include all relativistic effects such as the gravitational redshift
- Produce realistic light-cones mocks
- Process all 25 mocks and compute the covariance matrix
- Compute the dipole of the correlation function (configuration space)