Developing a unified pipeline for Large Scale Structure Data Analysis: The effect of correcting terms on galaxy clustering with angular power spectra

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What is galaxy number counts or galaxy clustering?

- Distribution of galaxies studied with the 3D galaxy Fourier PS: Fourier mode of the 3D separation between pairs of galaxies in the sky at a given z:

$$P_g(k,z) = b^2 P_m(k,z)$$

- Here use 2D or tomographic angular power spectrum : 2D angular separation of galaxies in different z slices
- Approximate sky as flat in small patches-Limber approximation and consider only linear scales

$$C^{g}_{\ell\gg1}(z_i, z_j) = \int d\chi \, \frac{W^i(\chi)W^j(\chi)}{\chi^2} P_{\rm lin}\left(k = \frac{\ell + 1/2}{\chi}\right)$$

$$W^i(\chi) = n^i(\chi)b(\chi)D(\chi)$$

How to study galaxy clustering?

- With density fluctuations by computing galaxy bias.

$$\delta_g(\vec{n}, z) = b_g(z) \cdot \delta_m(\vec{n}, z)$$

There are also correcting terms such as RSD and magnification bias

$$\delta_g(\vec{n}, z) = b_g(z) \cdot \delta_m(\vec{n}, z) \quad + \quad ? \quad + \quad ?$$

What are these correcting terms?

What is redshift-space distortions (RSD)?

- The background galaxies recede: expanding universe

- Galaxies also have their own peculiar velocities whose contributions are added to the main component of cosmological recession

- Result: Distribution of the galaxies in the redshift space is squashed and deformed

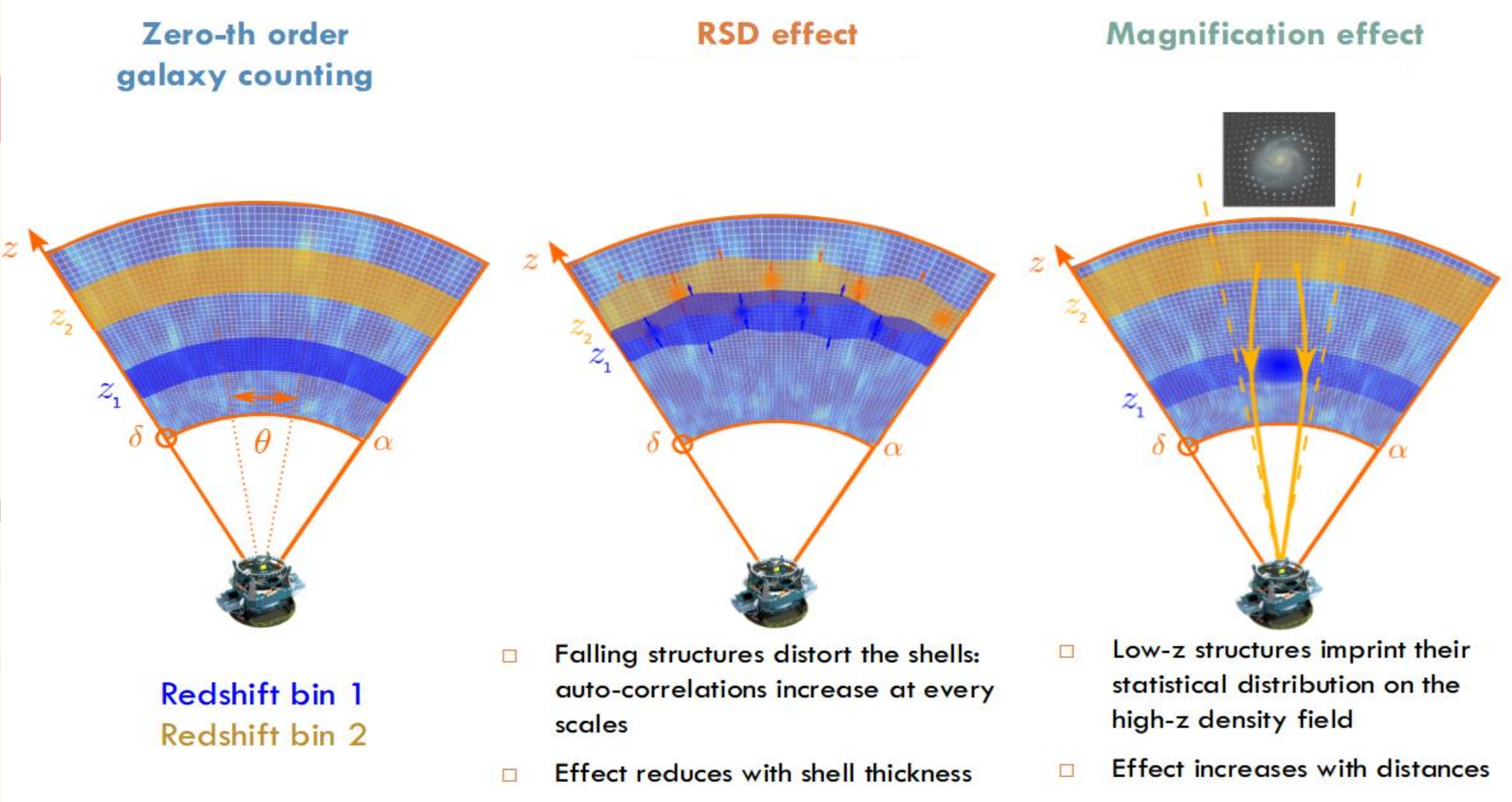
$$\delta_g(\vec{n}, z) = b_g(z) \cdot \delta_m(\vec{n}, z) + \frac{1}{\mathcal{H}(z)} \partial_r(\vec{v} \cdot \vec{n}) + \ ?$$

What is magnification bias?

- It is well known that light-rays experience deflections by the underlying matter distribution lying in the l.o.s direction, inducing distortions in the images of the distant sources.

- This weak lensing contribution induces a modulation in the clustering signal across redshift bins, correlating background and foreground sources: The foreground sources act as 'lenses' for the 'sources' in the background

$$\delta_g(\vec{n}, z) = b_g(z) \cdot \delta_m(\vec{n}, z) + \frac{1}{\mathcal{H}(z)} \partial_r(\vec{v} \cdot \vec{n}) + 2(Q-1)k$$



Credit image: courtesy of Jérémy Neveu

Limber approximated angular power spectra: Galaxy clustering and correcting terms

$$C^{\mathrm{g}}_{\ell\gg 1}(z_i, z_j) = \int \mathrm{d}\chi \, \frac{W^i(\chi) W^j(\chi)}{\chi^2} P_{\mathrm{lin}}\left(k = \frac{\ell + 1/2}{\chi}\right)$$

Density fluctuations → $W^i_{\mathrm{g,den}}(\chi) = n^i(\chi) b(\chi) D(\chi)$

RSD → $f \equiv -(1+z)\mathrm{d}\ln D/\mathrm{d}z$

↓

$$\begin{aligned} W^i_{\mathrm{g,RSD}}(\chi) = & \frac{2\ell^2 + 2\ell - 1}{(2\ell - 1)(2\ell + 3)} \left[n^i f D\right](\chi) \\ & - \frac{(\ell - 1)\ell}{(2\ell - 1)\sqrt{(2\ell - 3)(2\ell + 1)}} \left[n^i f D\right]\left(\frac{2\ell - 3}{2\ell + 1}\chi\right) \\ & - \frac{(\ell + 1)(\ell + 2)}{(2\ell + 3)\sqrt{(2\ell + 1)(2\ell + 5)}} \left[n^i f D\right]\left(\frac{2\ell + 5}{2\ell + 1}\chi\right); \end{aligned}$$

Limber approximated angular power spectra: Galaxy clustering and correcting terms

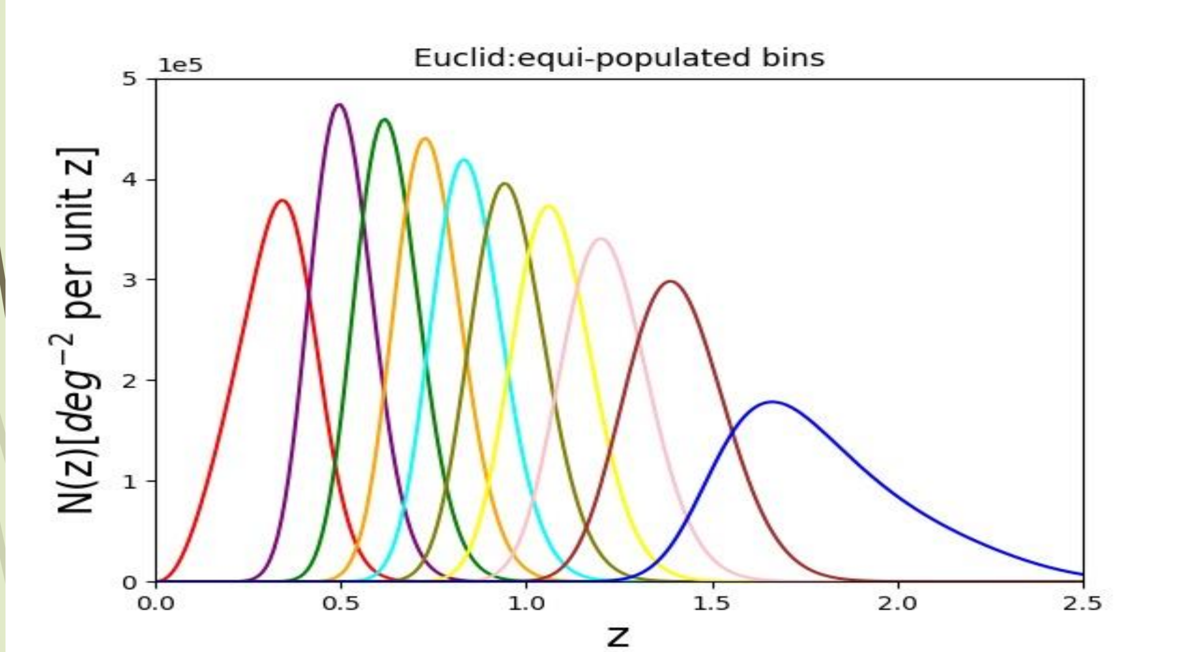
Magnification bias →

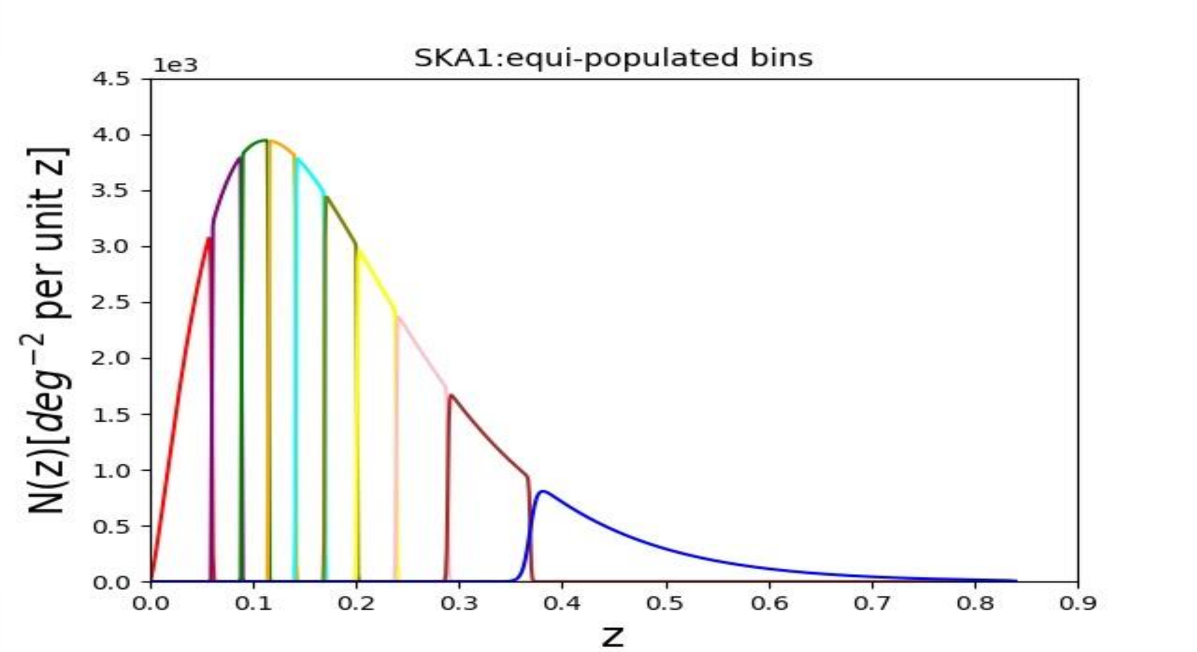
$$W^i_{\mathrm{g,mag}}(\chi) = \frac{3\ell(\ell+1)}{(\ell+1/2)^2}\Omega_{\mathrm{m}} H_0^2 \left[1+z(\chi)\right] \chi^2 \tilde{n}^i(\chi) \left[\mathcal{Q}(\chi)-1\right] D(\chi)$$

$$\tilde{n}^i(\chi) = \int_\chi^\infty \mathrm{d}\chi' \, \frac{\chi'-\chi}{\chi'\chi} n^i(\chi')$$

$$W_{\mathrm{g}}(\chi) = W^i_{\mathrm{g,den}}(\chi) + W^i_{\mathrm{g,RSD}}(\chi) + W^i_{\mathrm{g,mag}}(\chi)$$

- Equi-populated bins : The same number of galaxies in each bin
- Euclid NIR/optical $15000\ deg^2$ and SKA1 HI galaxy radio $5000\ deg^2$





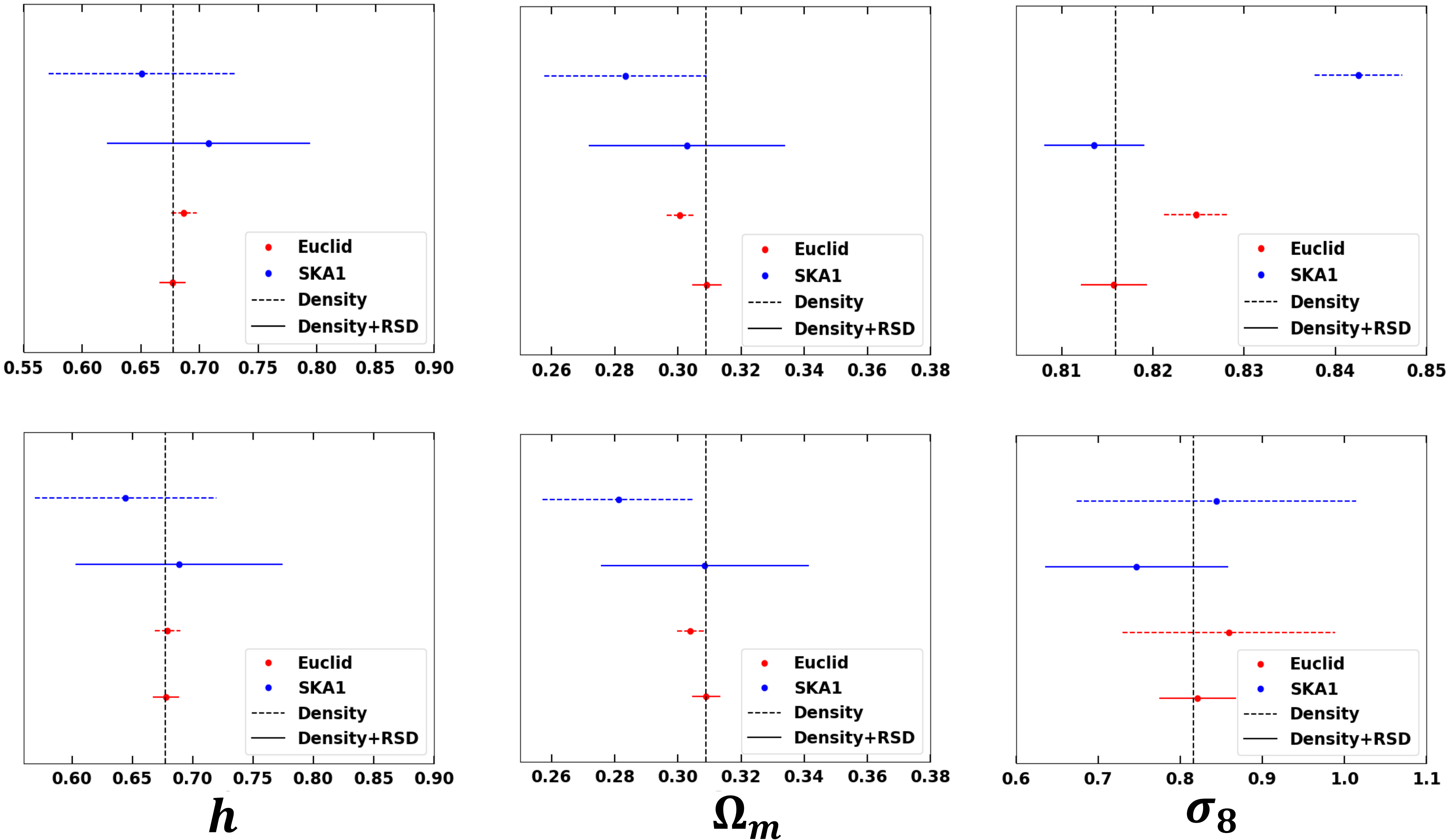
- For each bin, proxy, calculate the angular power spectra
- Want to see how the information based on the RSD on top of the density fluctuations change the results. In order to do so:
- Construct mock observables assuming perfect knowledge of the density fluctuation and RSD
- Then fit these data with 2 models:
  - Keep the same information
  - Neglect RSD

- Constrain 3 cosmological parameters: $\Omega_{\mathrm{m}}, h0, \sigma_8$, being the current matter fraction in the Universe, the Hubble constant today Ho/100 km/s/Mpc and the rms variance of matter in spheres of radius 8 Mpc/h today

Three scenarios based on our knowledge of the galaxy bias

- Assume perfect knowledge of the galaxy bias
- An overall normalization and power-law unknown parameters at all redshifts
- Unknown evolution of the galaxy bias with one parameter per z bin

Results: Euclid, SKA1

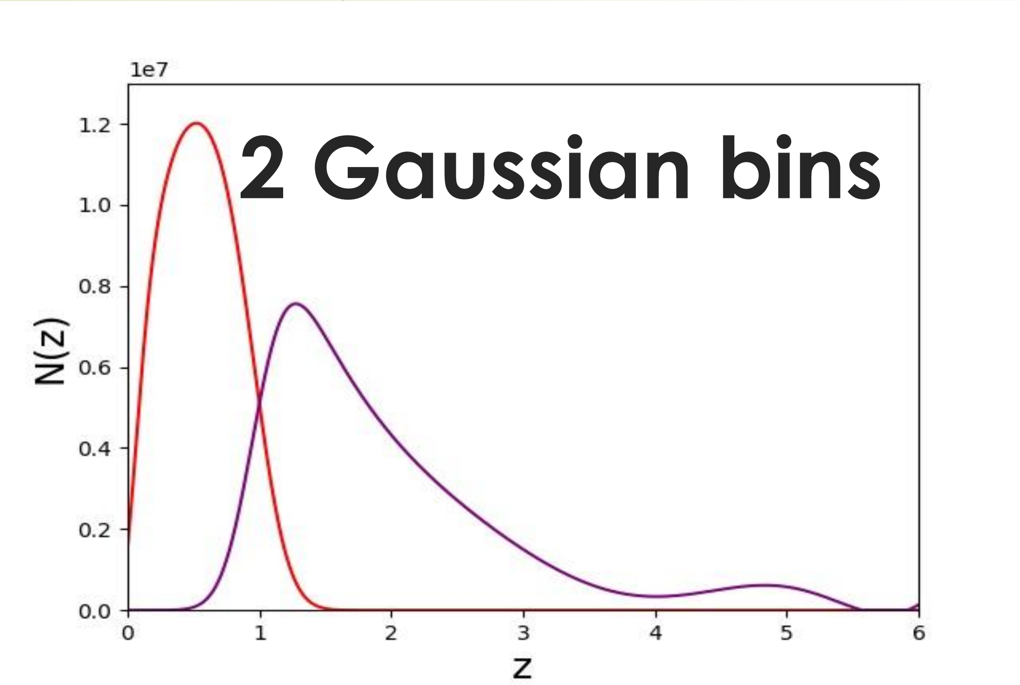


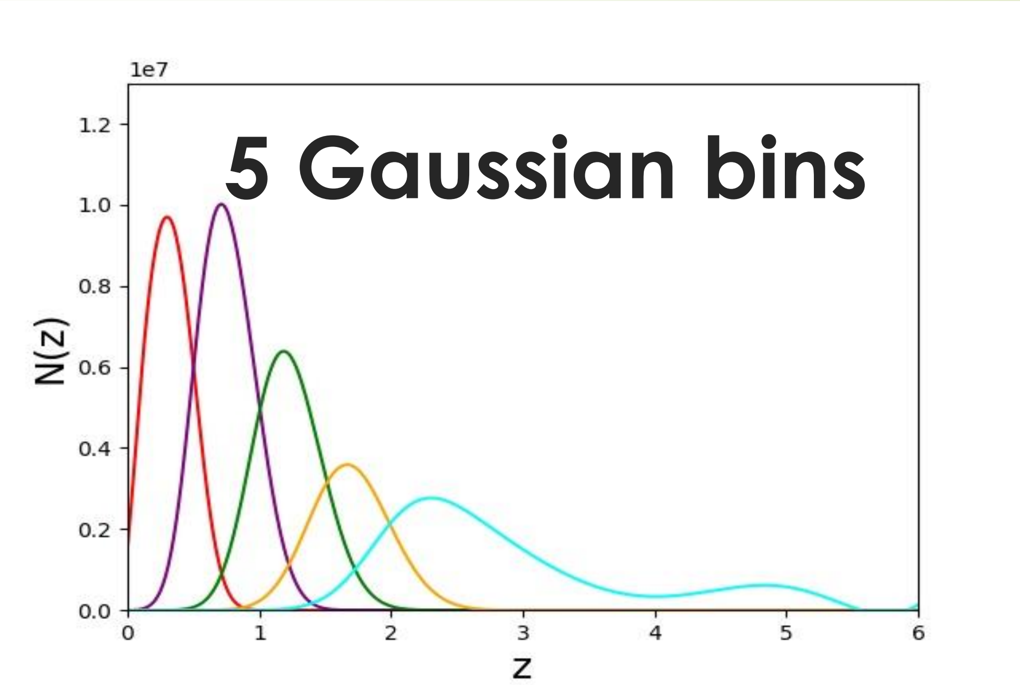
ideal

conservative

Evolutionary Map of the Universe (EMU)

- Its unrivalled depth makes it ideal for the study of the magnification bias, and the large scale structure over the very large volume will be ideal to investigate extensions to the $\Lambda\mathrm{CDM}$ model.
- Deep radio continuum nearly full sky survey (detect extragalactic objects in the southern sky up to $\delta = +30^o$)
- Sky coverage $30,000\ deg^2$, with a sensitivity $10\mu Jy$ per beam rms, and a resolution of $\approx 10\ arcsec$ over the frequency range 800-1400 MHz


1e7
2 Gaussian bins
N(z)
z


1e7
5 Gaussian bins
N(z)
z

- For each bin and binning configuration calculate the angular power spectra

- Want to see how the information based on the magnification on top of the density fluctuations change the results. In order to do so:

- Construct mock observables assuming perfect knowledge of the density fluctuation and magnification bias
  - Then fit these data with 2 models:
    - Keep the same information
    - Neglect magnification bias

Cosmological models

- ΛCDM model: $\boldsymbol{\theta}_{\{\Lambda\mathrm{CDM}\}} = \{\Omega_{\mathrm{m}}, \mathrm{h0}, \sigma_8\}$
- Dark Energy: Model where the dark energy equation of state varies with redshift such that:

$$w(z) = w_0 + w_\alpha \cdot\ z/(1+z)$$

$$\theta_{\{DE\}} = \theta_{\{\Lambda\mathrm{CDM}\}} \cup \{w_0, w_\alpha\}$$

- Modified Gravity: $\nabla^2\Phi = 4\pi QGa^2\,\bar{\rho}\delta$, and the ratio of the two potentials can be different : $R = \Psi/\Phi$. R and Q are degenerate so we define $\Sigma_0 = Q_0(1 + R_0)/2$

$$\theta_{\{MG\}} = \theta_{\{\Lambda\mathrm{CDM}\}} \cup \{\Sigma_0, Q_0\}$$

Three scenarios based on our knowledge of the galaxy bias

- Assume perfect knowledge of the galaxy bias

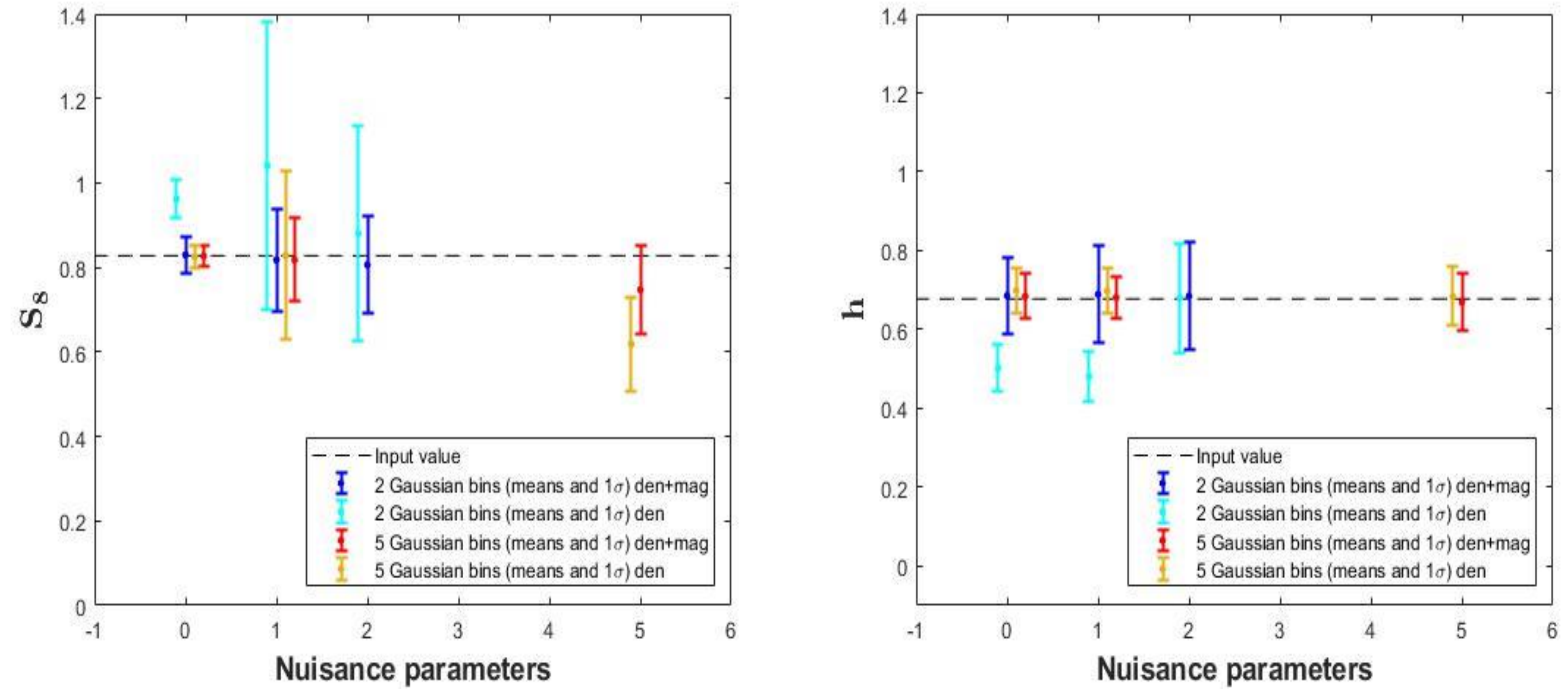
- An overall normalization nuisance parameter at all redshifts

- Unknown evolution of the galaxy bias with one parameter per z bin

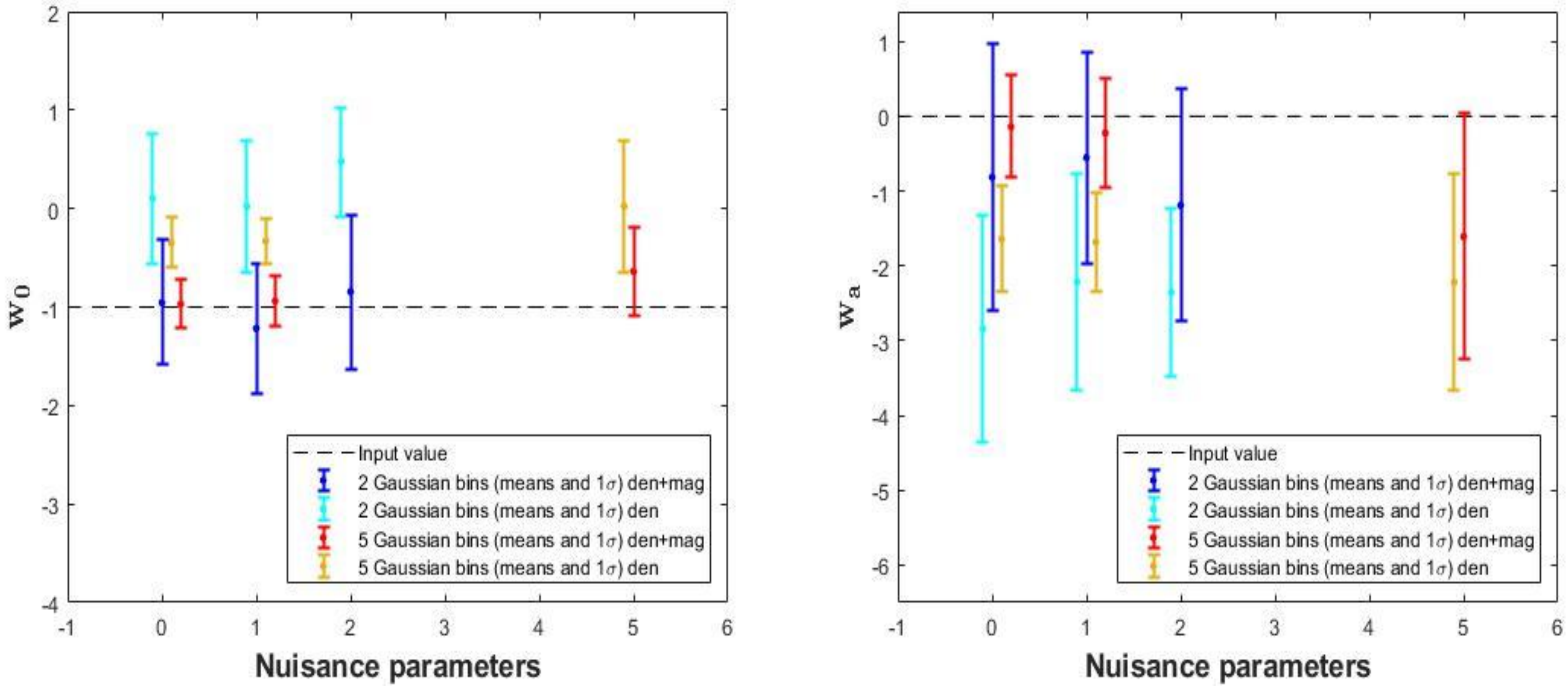
In all cases keep the magnification bias is fixed to the fiducial value

1σ Results Gaussian bins: ΛCDM model.

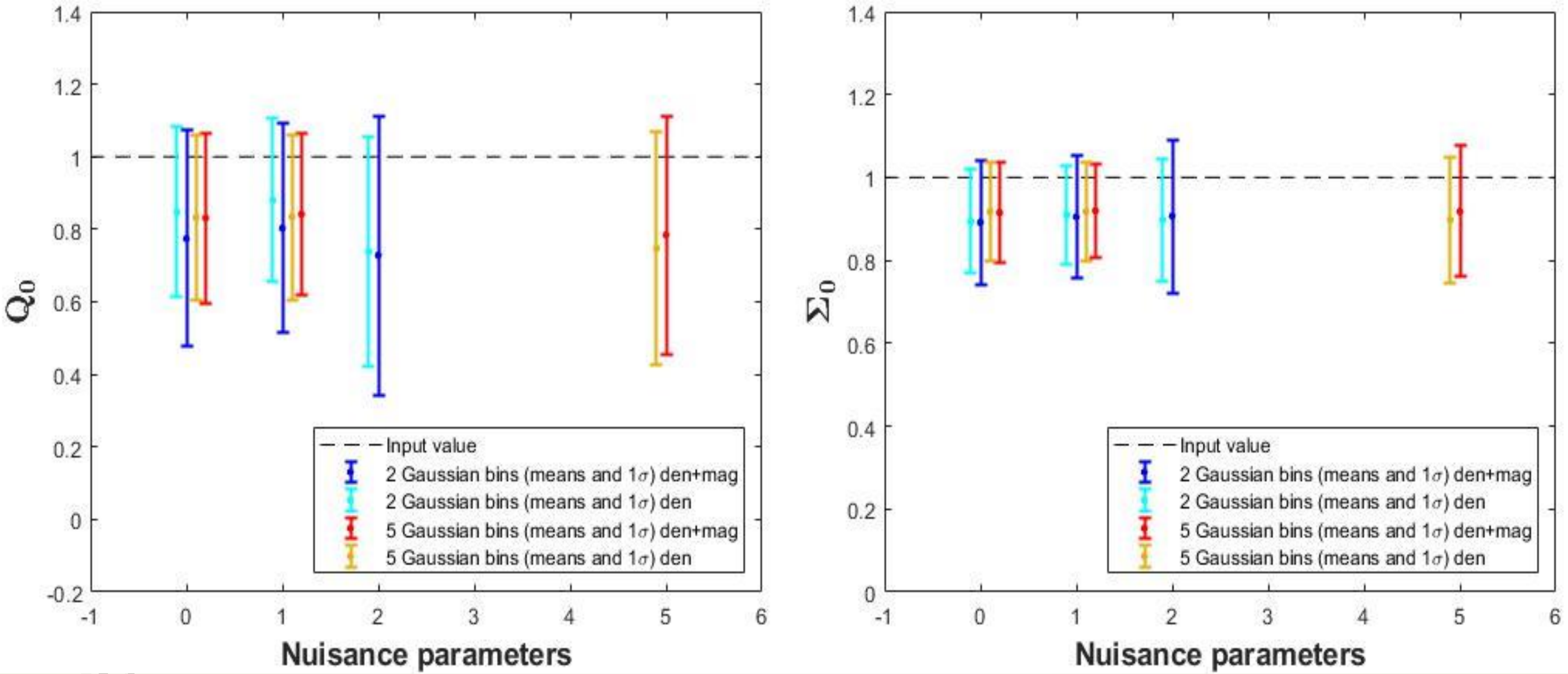
Constraints shown on $S_8 = \sigma_8\sqrt{\frac{\Omega_m}{0.3}}$, because it is better constrained than σ_8 and is not correlated with Ω_{m}



1σ Results Gaussian bins: DE model.



1σ Results Gaussian bins: MG model.



Conclusions 1/3 Euclid-SKA1 [arXiv: 1902.07226]

- Bias if RSD neglected on $\{\Omega_m, \sigma_8\}$ for all cases
- Break degeneracy on σ_8 with RSD in the realistic cases
- SKA1 is not as informative as Euclid due to the lower SNR

Conclusions 2/3 EMU [arXiv:1909.10539]

➨ ΛCDM :

- Bias if magnification neglected on $\{S_8, h\}$ for wide bins

- Break degeneracy on S_8 with magnification in the realistic cases. True also for all cosmological models examined

- Narrower binning better precision on the PS. Underestimate S_8 for conservative case .

Conclusions 3/3 EMU [arXiv:1909.10539]

➨ DE :

- Bias only for 5-bin on h in the pessimistic scenario and S_8 in the conservative.

- $\{w_0, w_\alpha\}$, always biased. More pronounced with wide bins

➨ MG:

- Bias only for 5-bin on S_8 in the conservative.

- Not seen on $\{\Sigma_0, Q_0\}$, Cut on the very large scales sensitive to the extension of the GR. (?)

The inclusion of the RSD not important in the case of radio continuum surveys, due to the dilution of the effect in very wide bins

Future Steps

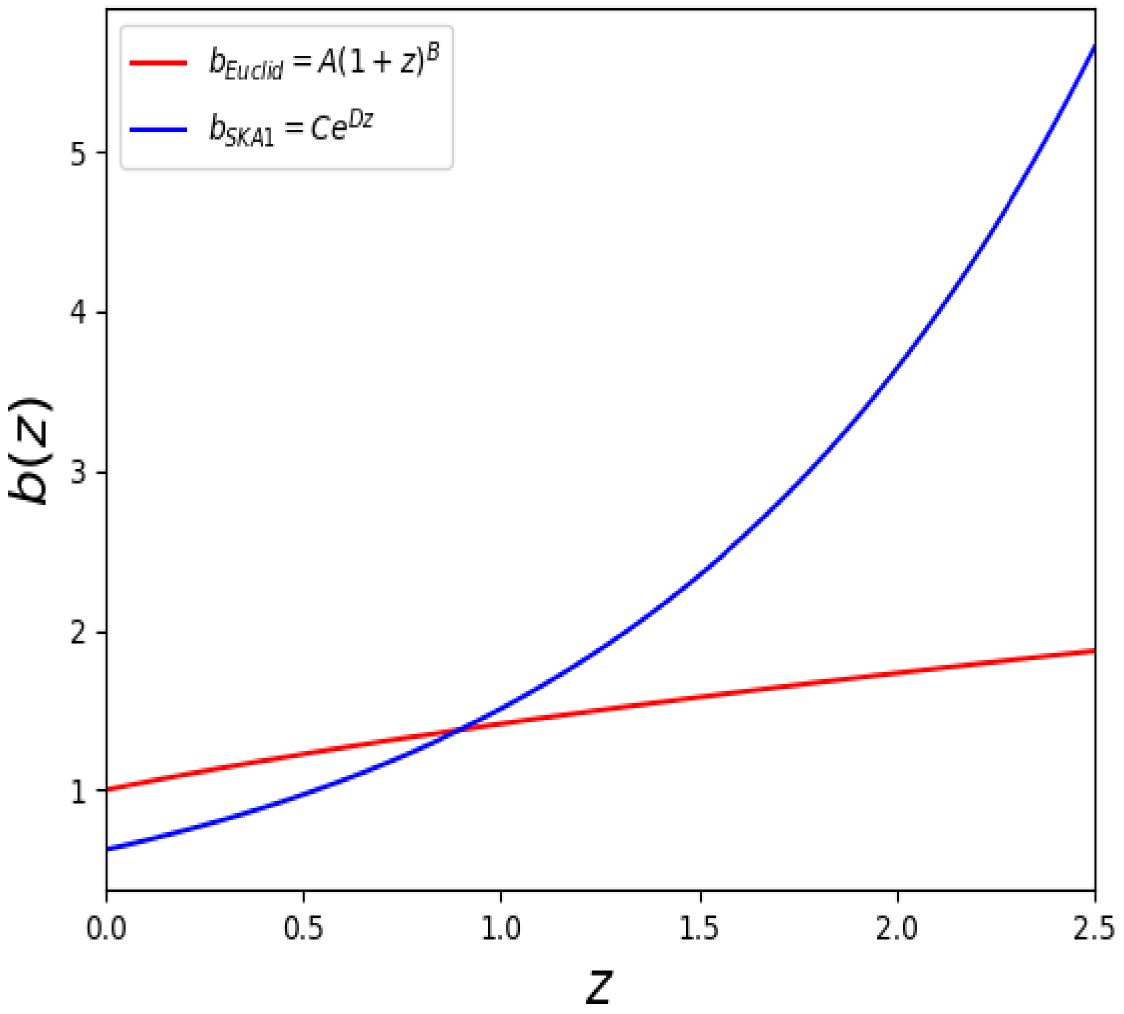
- Explore the multi-tracer technique (get rid of systematics and cosmic variance) with the Dark Energy Spectroscopic Instrument to study the neutrino mass with RSD at the linear and non linear regime

- Directly probe the growth rate of structure with the full spherical harmonic power spectra with CMASS galaxy clustering data

Thank you for your attention!

Extra slides

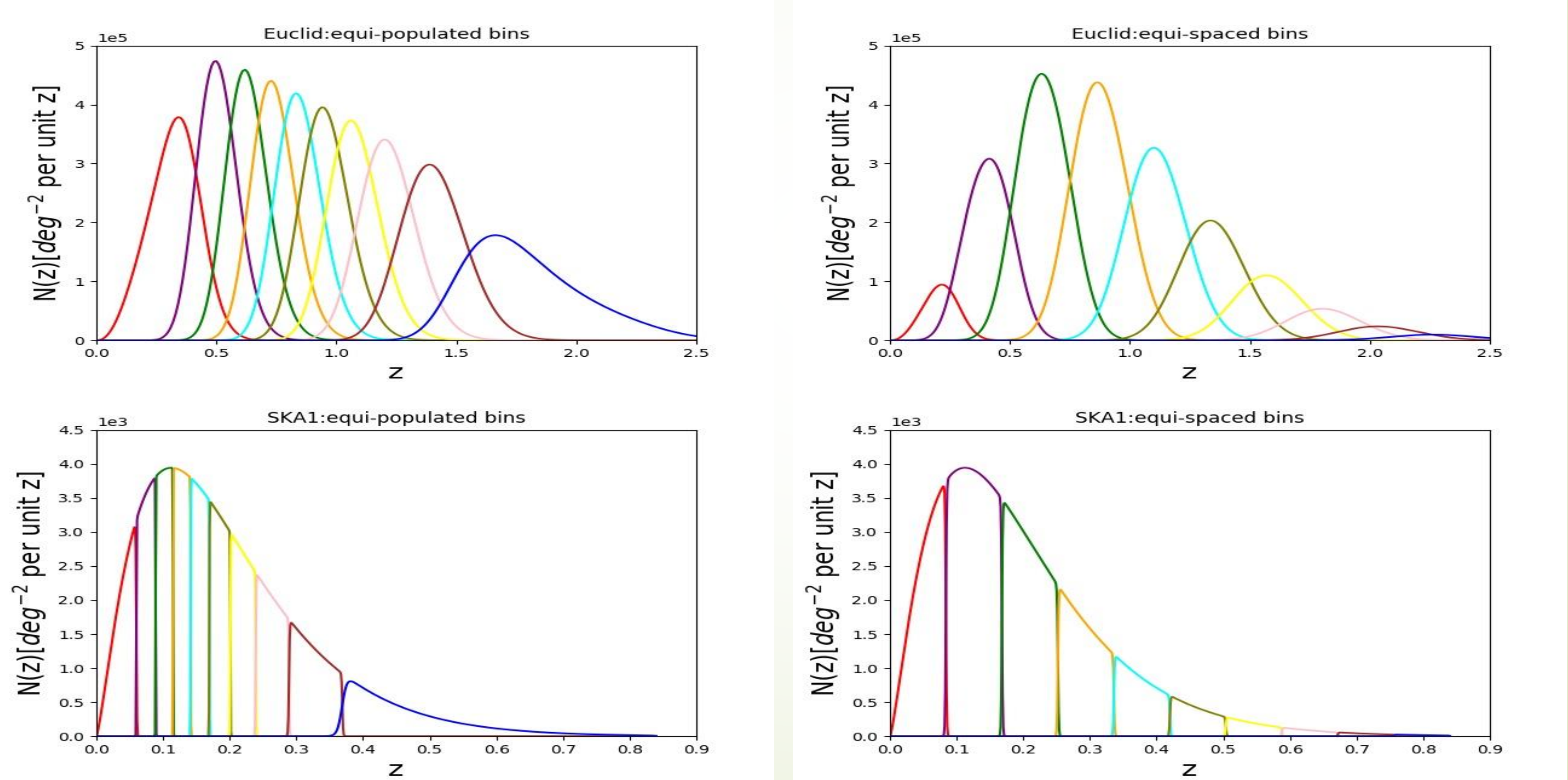
- In order to study galaxy clustering we make forecasts based on proxies with real experiment specifications:



- **Euclid** telescope in optical/NIR detecting a large number of galaxies and measuring their photometric redshifts
  - Sky coverage: $15000\ deg^2$
  - Scale independent galaxy bias with A=1.0 and B=0.5

- Square Kilometre Array phase 1 (**SKA1**) which is an HI galaxy survey in radio. Therefore, the redshift estimation is made with spectroscopy.
  - Sky coverage: $5000\ deg^2$
  - Scale independent galaxy bias with C=0.625 and D=0.881

- We choose 2 binning configurations for each proxy
- Equi-populated bins : The same number of galaxies in each bin
- Equi-spaced bins: Bins of equal size in redshift range



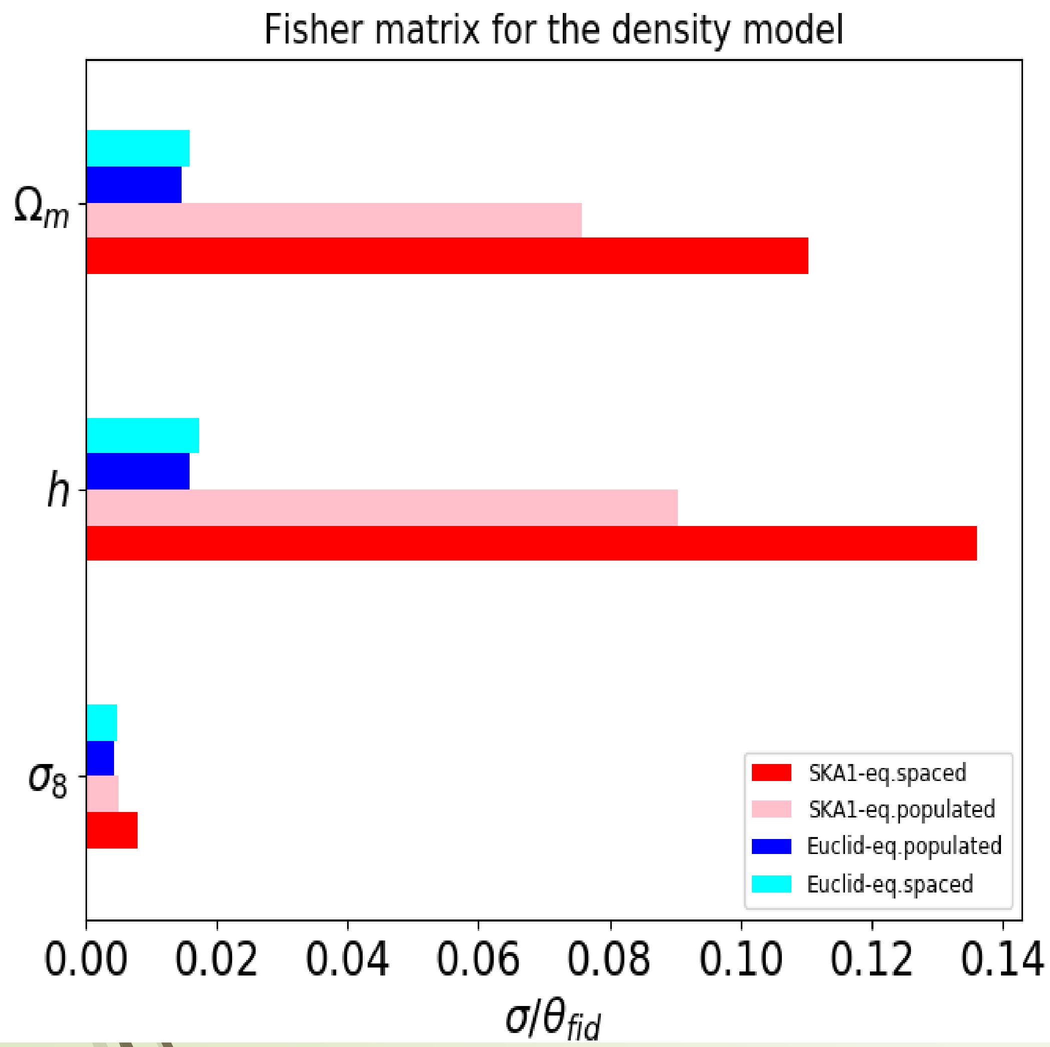
Multipole Range

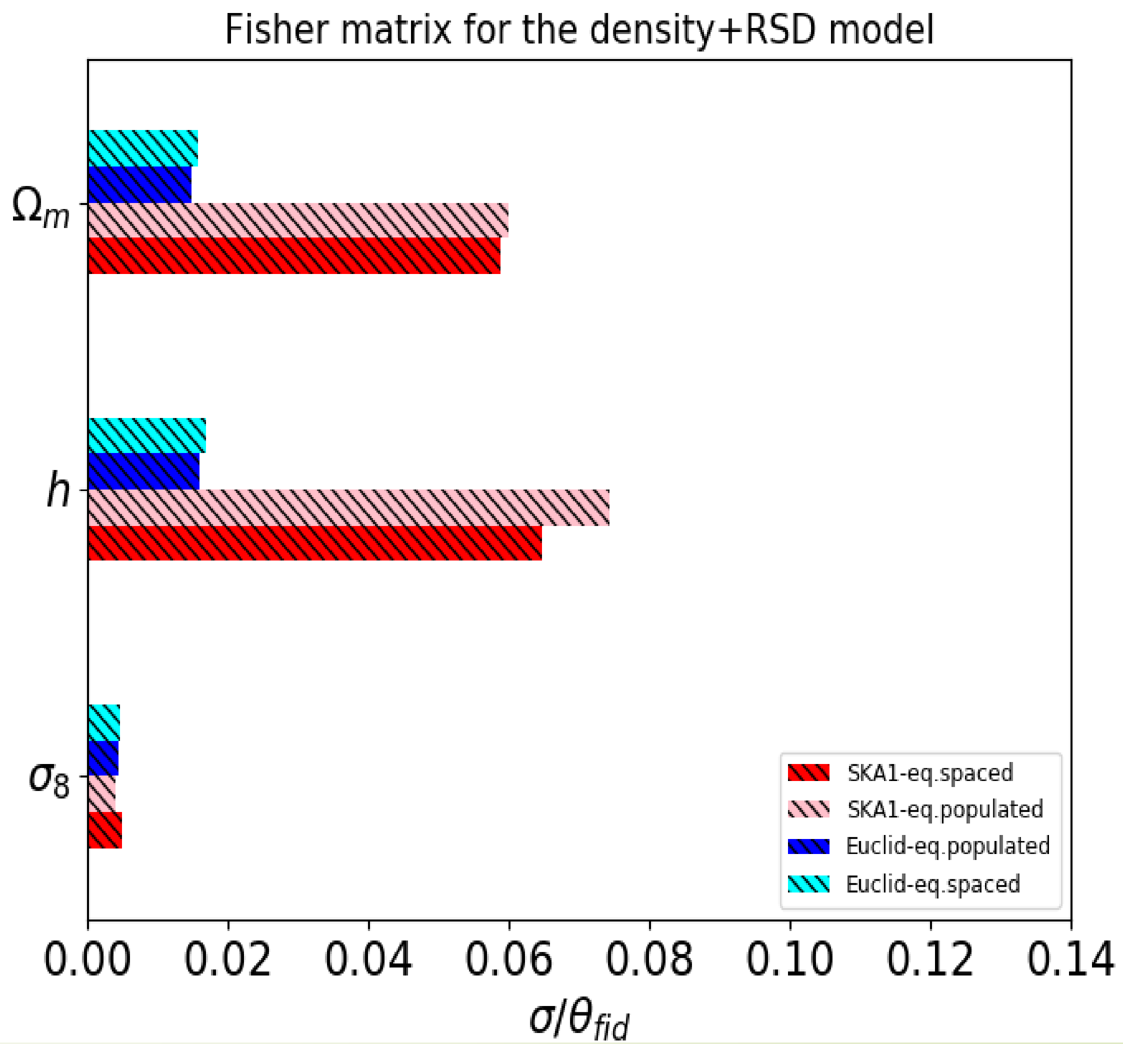
Table 1. Mininum and maximum multipoles for the two binning strategies. The former are set so that the relative error between angular spectra computed with `CosmoSIS` and `CLASS` is below 5%. The latter follow $\ell_{\max} = \chi(\bar{z}_i)k_{\max}$ in redshift bin i centred on $\bar{z}_i$.

Equi-spaced bins						Equi-populated bins					
Euclid			SKA1			*Euclid*			SKA1		
$\ell_{\min}$		$\ell_{\max}$	$\ell_{\min}$		$\ell_{\max}$	$\ell_{\min}$		$\ell_{\max}$	$\ell_{\min}$		$\ell_{\max}$
den	den+RSD		den	den+RSD		den	den+RSD		den	den+RSD	
2	2	133	3	13	45	4	3	348	2	7	32
8	6	373	1	13	134	10	7	480	7	30	80
12	9	581	14	26	218	12	9	576	11	78	109
16	11	759	29	40	299	15	10	659	13	77	136
22	13	913	33	60	375	17	12	733	15	80	164
28	17	1046	43	70	448	18	13	806	19	80	194
32	20	1162	63	73	518	20	14	880	22	91	228
36	22	1265	60	101	584	22	15	957	26	82	270
40	25	1356	70	110	647	24	17	1054	30	65	331
50	30	1437	80	120	707	25	19	1181	11	44	564

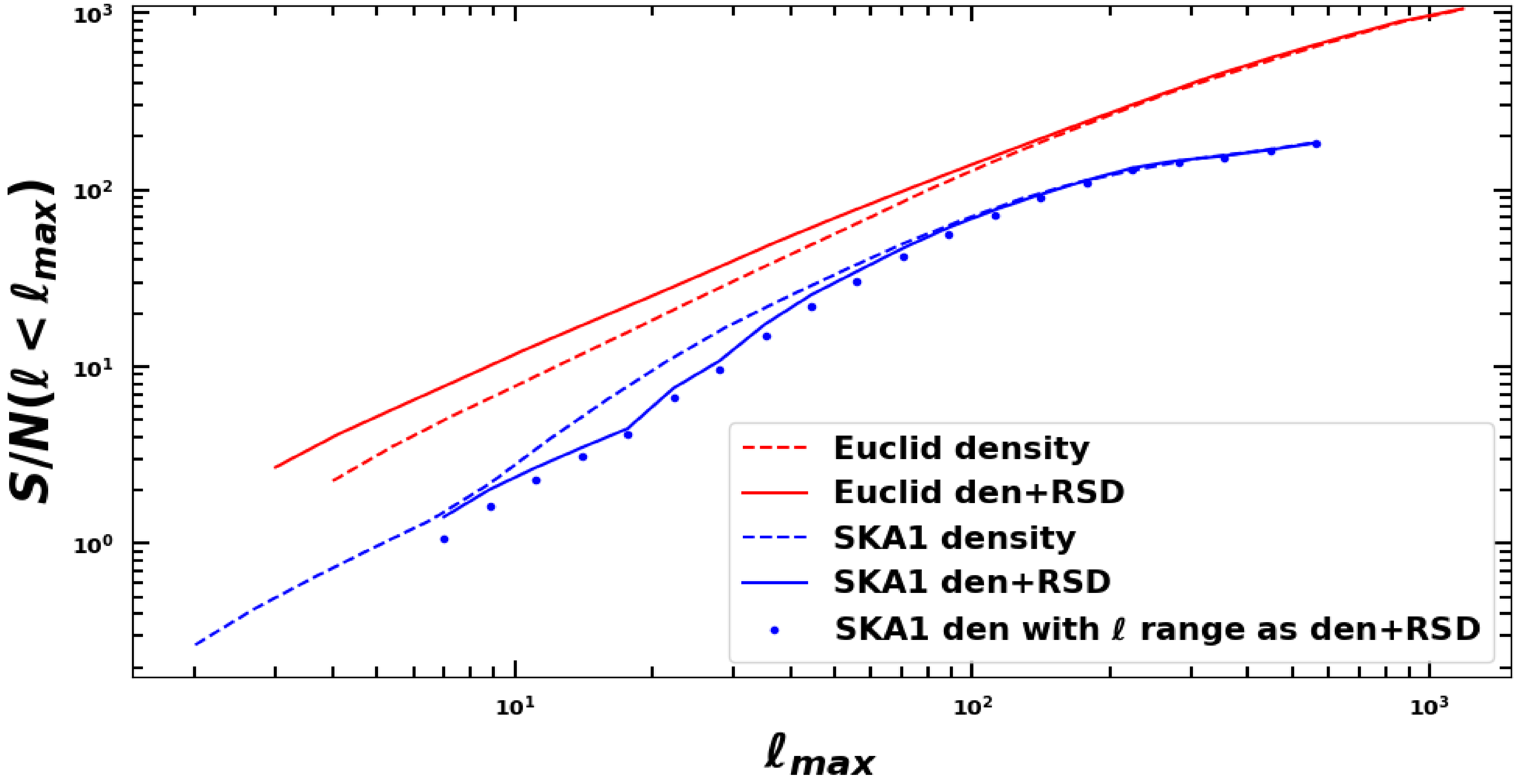
Fisher test: likelihood behaviour near the peak

- **Which binning configuration is optimal**





Signal-Noise-Ratio



Results: Euclid, SKA1

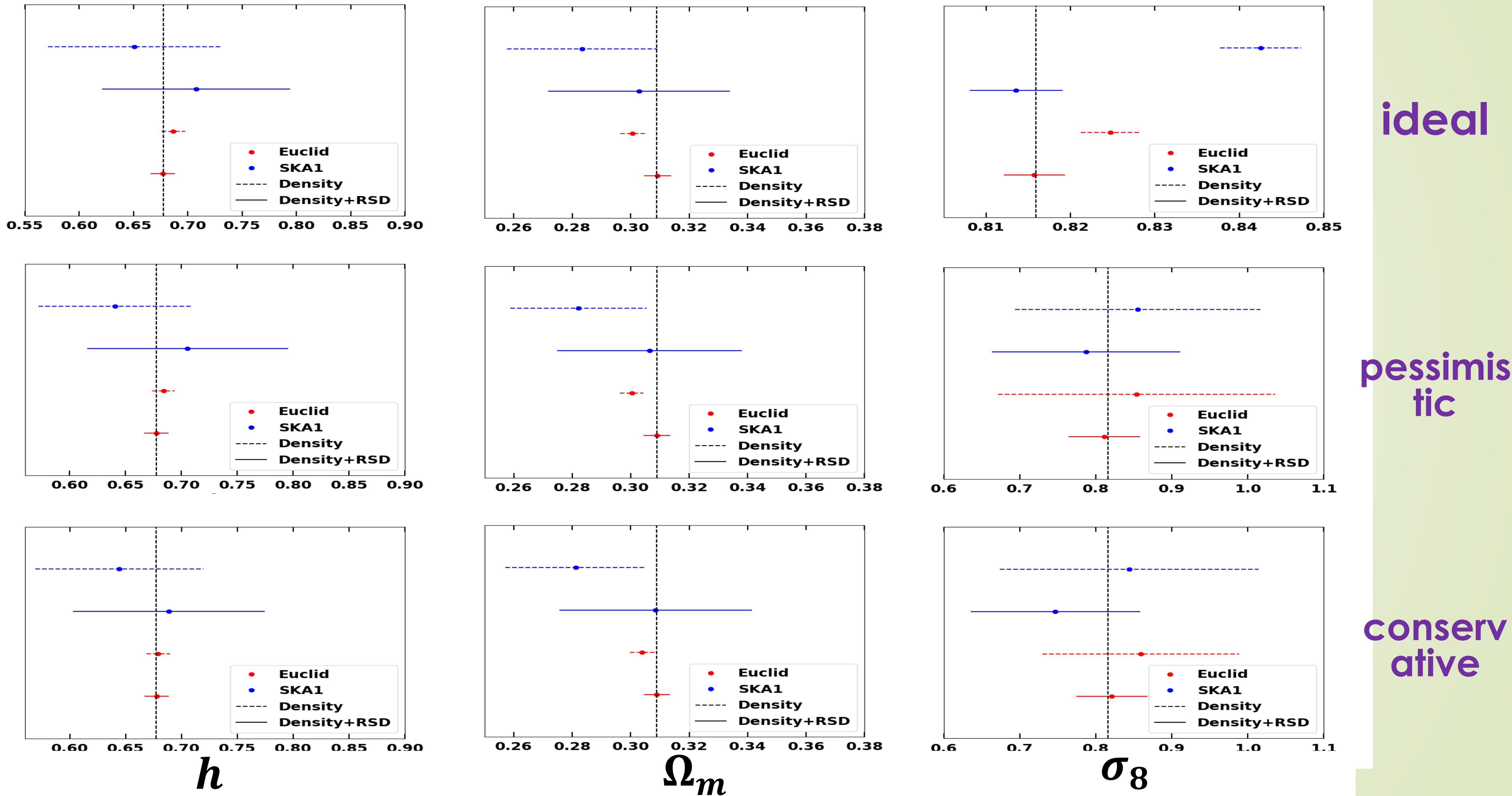
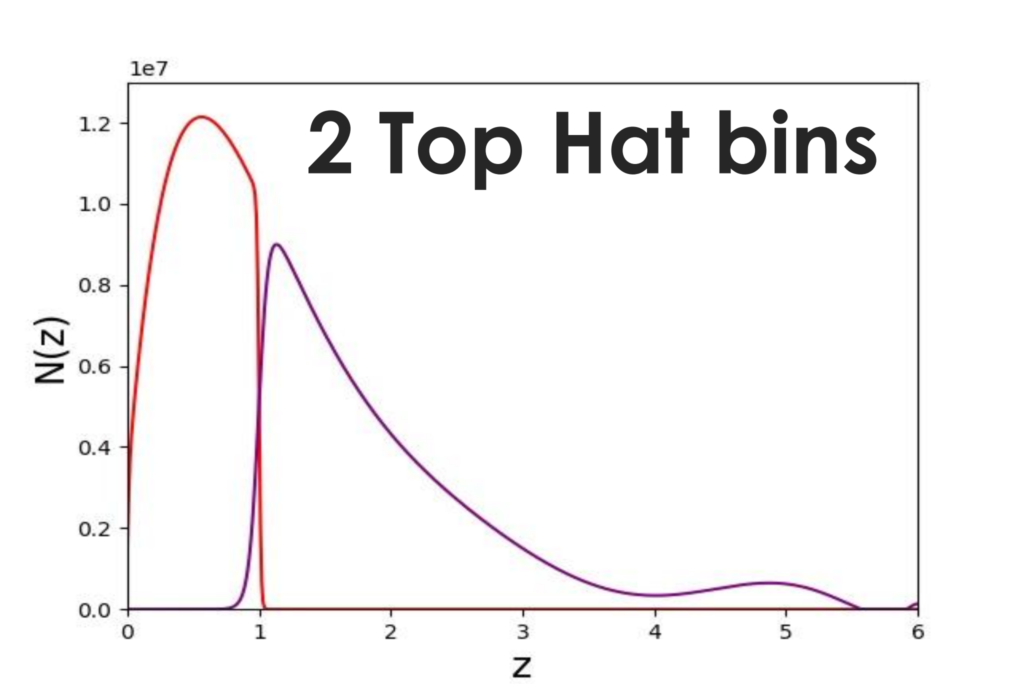


Table 1. Estimated number densities, galaxy bias, and magnification bias for EMU sources grouped in 2 redshift bins.

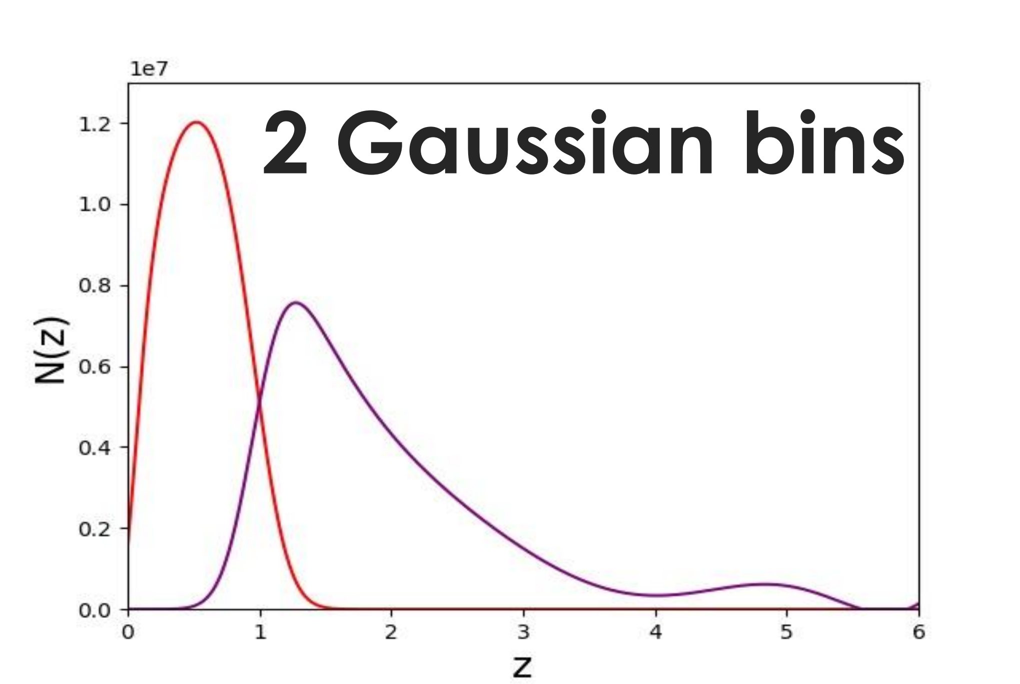
Bin	$z_{\rm min}$	$z_{\rm max}$	# of gal. ($\times 10^6$)	bias	mag. bias
1	0.0	1.0	10.68	0.833	1.050
2	1.0	6.0	11.58	2.270	1.298

Table 2. Same as Table 1, but for EMU sources grouped in 5 redshift bins.

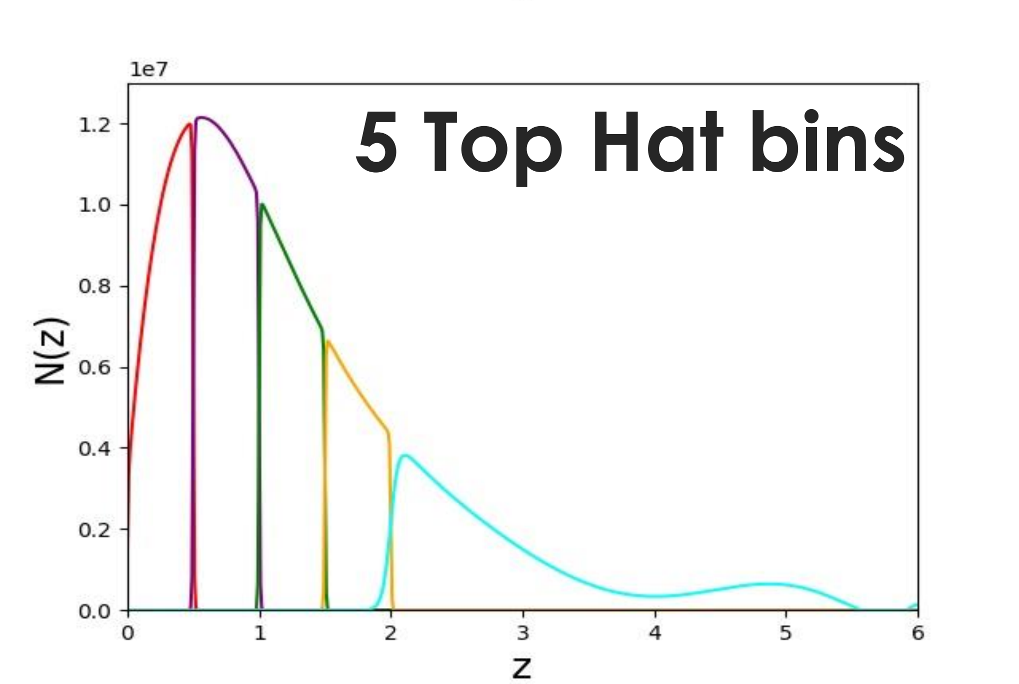
Bin	$z_{\rm min}$	$z_{\rm max}$	# of gal. ($\times 10^6$)	bias	mag. bias
1	0.0	0.5	5.55	1.000	0.953
2	0.5	1.0	5.13	1.124	1.273
3	1.0	1.5	4.43	1.920	1.569
4	1.5	2.0	2.70	3.250	1.176
5	2.0	6.0	4.05	4.046	0.964



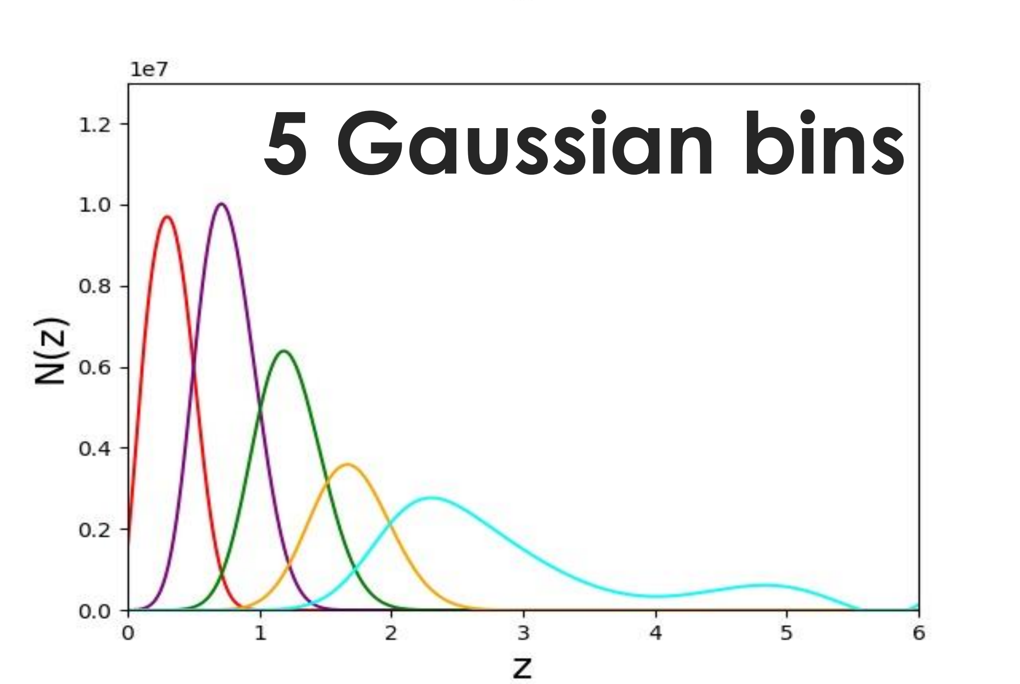
2 Top Hat bins
1e7
N(z)
z



2 Gaussian bins
1e7
N(z)
z



5 Top Hat bins
1e7
N(z)
z



5 Gaussian bins
1e7
N(z)
z

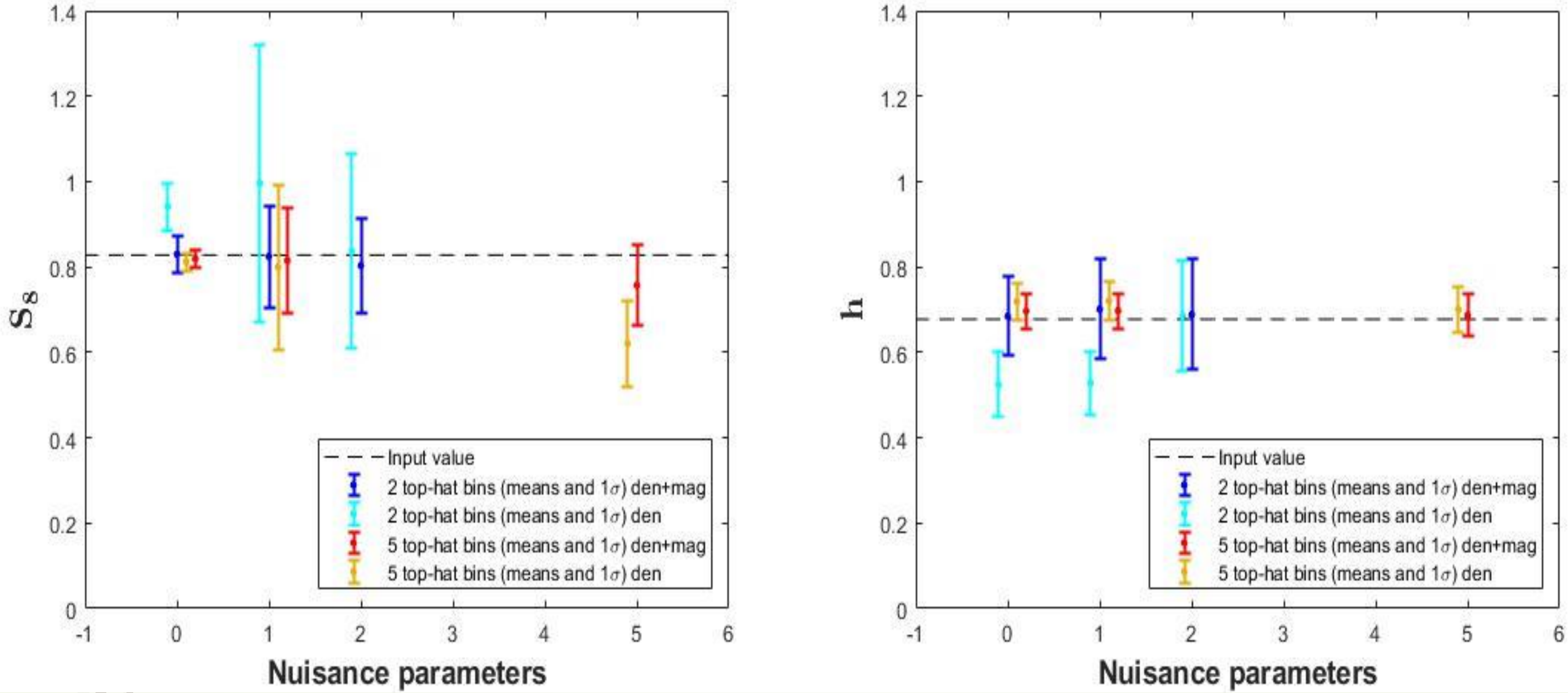
Multipole Range

Table 4. The $\ell_{\min}$ and $\ell_{\max}$ values for all the EMU bin configurations. The former is specified as the point where the relative error between `CosmoSIS` and `CLASS` angular power spectra measurements is below 5%, while the latter in the limit where $\ell_{\max} = k_{\max}\chi(\bar{z}_i)$ with $\bar{z}_i$ the centre of the ith bin.

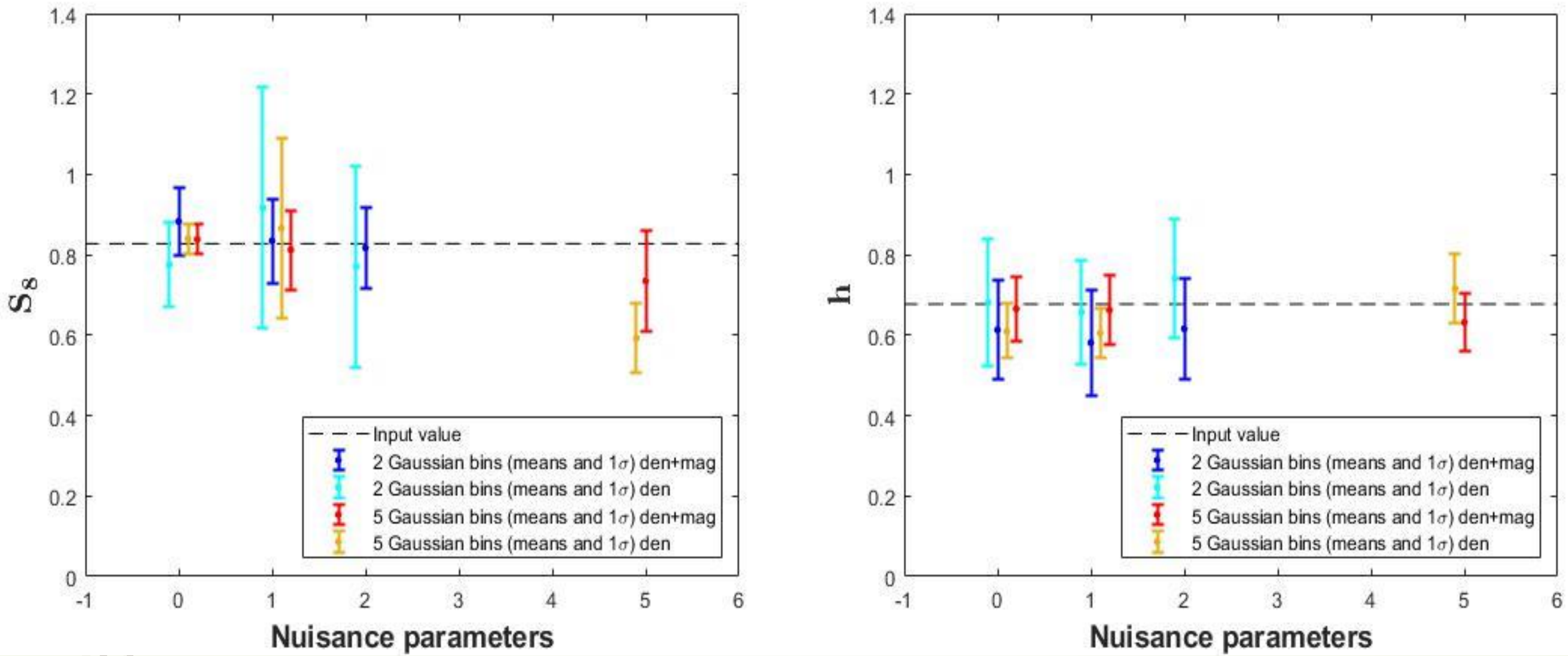
2 redshift bins					5 redshift bins				
$\ell_{\min}$				$\ell_{\max}$	$\ell_{\min}$				$\ell_{\max}$
Top-hat		Gaussian			Top-hat		Gaussian		
w/o mag	w/ mag	w/o mag	w/ mag		w/o mag	w/ mag	w/o mag	w/ mag	
3	2	2	2	480	2	2	2	2	257
10	12	10	10	1718	6	6	8	8	673
–	–	–	–	–	17	18	11	11	982
–	–	–	–	–	24	25	10	10	1215
–	–	–	–	–	24	25	9	9	1813

1σ Results Top Hat bins: ΛCDM model.

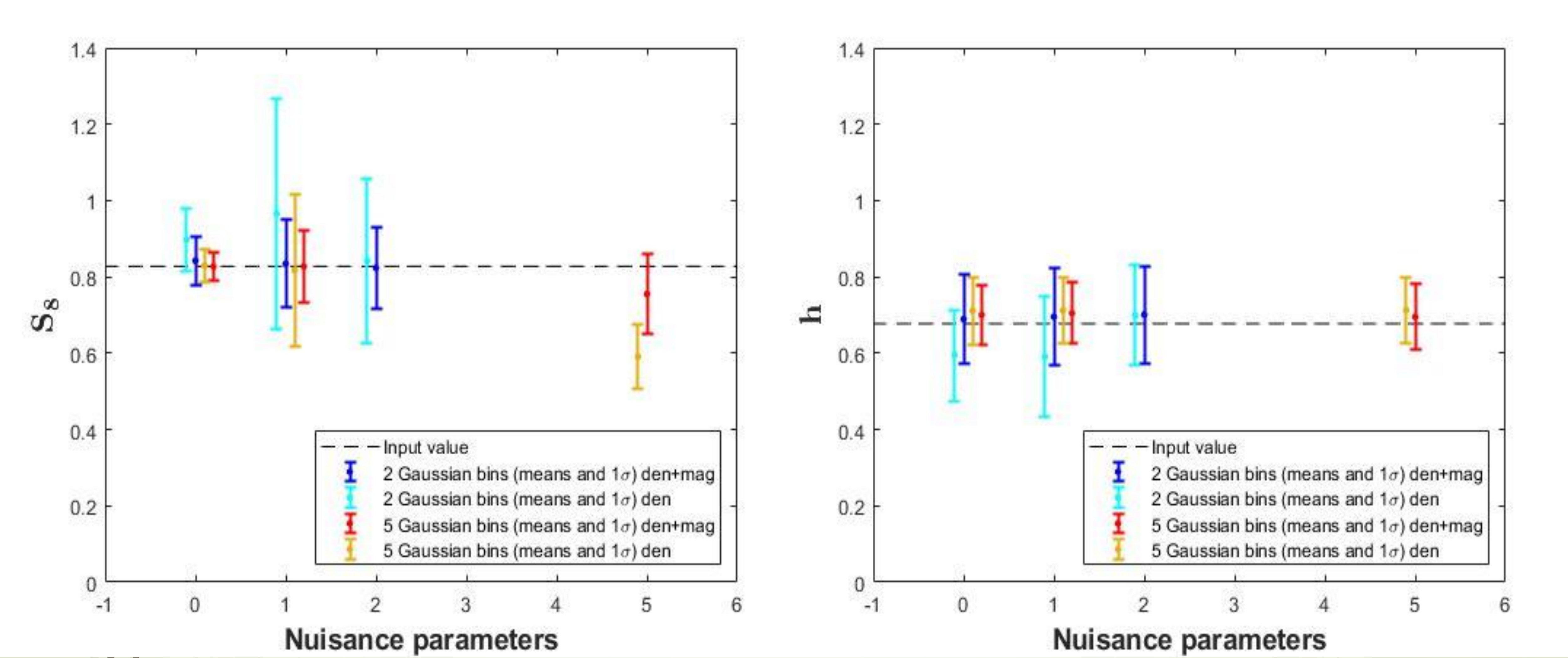
Constraints shown on $S_8 = \sigma_8\sqrt{\frac{\Omega_m}{0.3}}$, because it is better constrained than σ_8 and is not correlated with Ω_{m}



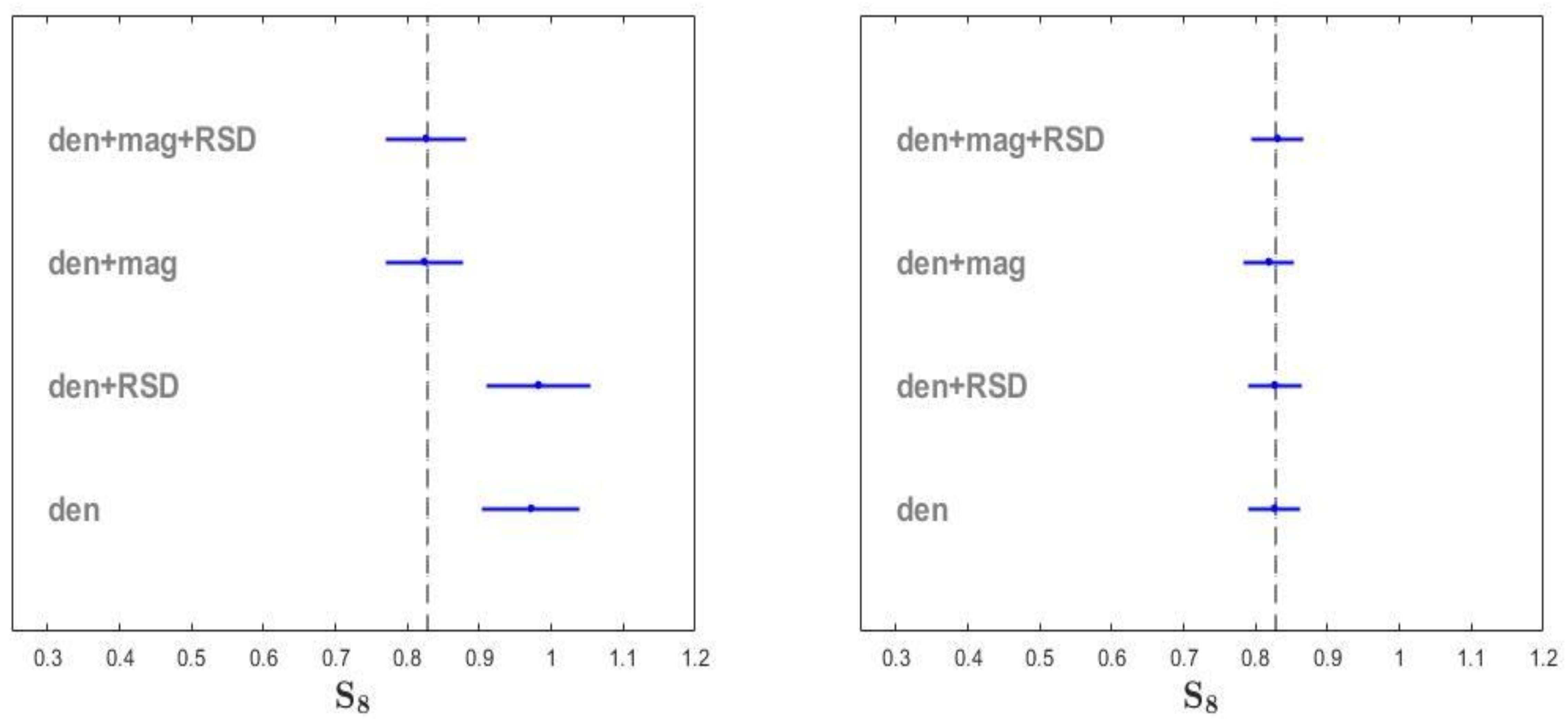
1σ Results Gaussian bins: DE model.



1σ Results Gaussian bins: MG model.



Investigating RSD - ΛCDM (2 and 5 bins)



Investigating RSD - ΛCDM (2 and 5 bins)