A case study for magnification bias and radio continuum surveys

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The matter power spectrum

- Let a dimensionless quantity be the matter overdensity: $$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$$

  with $\bar{\rho}$ the mean matter density

  - The autocorrelation function reads ξ :

$$\xi(r) = \langle \delta(\mathbf{x})\delta(\mathbf{x}') \rangle = \frac{1}{V}\int d^3\mathbf{x}\, \delta(\mathbf{x})\delta(\mathbf{x}-\mathbf{r})$$

$$\mathbf{r} = \mathbf{x} - \mathbf{x}'$$

- And its Fourier transform is the matter power spectrum $P(\mathbf{k})$ defined as: $$\xi(r) = \int \frac{d^3k}{(2\pi)^3} P(k) e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')}$$

- The following average over the Fourier space gives the power spectrum:

$$\langle \tilde{\delta}(\mathbf{k})\tilde{\delta}(\mathbf{k}') \rangle = (2\pi)^3 P(k) \delta^3(\mathbf{k}-\mathbf{k}')$$

denoting now $\tilde{\delta}(\mathbf{k})$ as the Fourier transform of the overdensity $\delta(\mathbf{x})$

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

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

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

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

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

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

↓

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

Limber approximated angular power spectra: Galaxy clustering and correcting terms

Magnification bias →

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

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

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

Evolutionary Map of the Universe

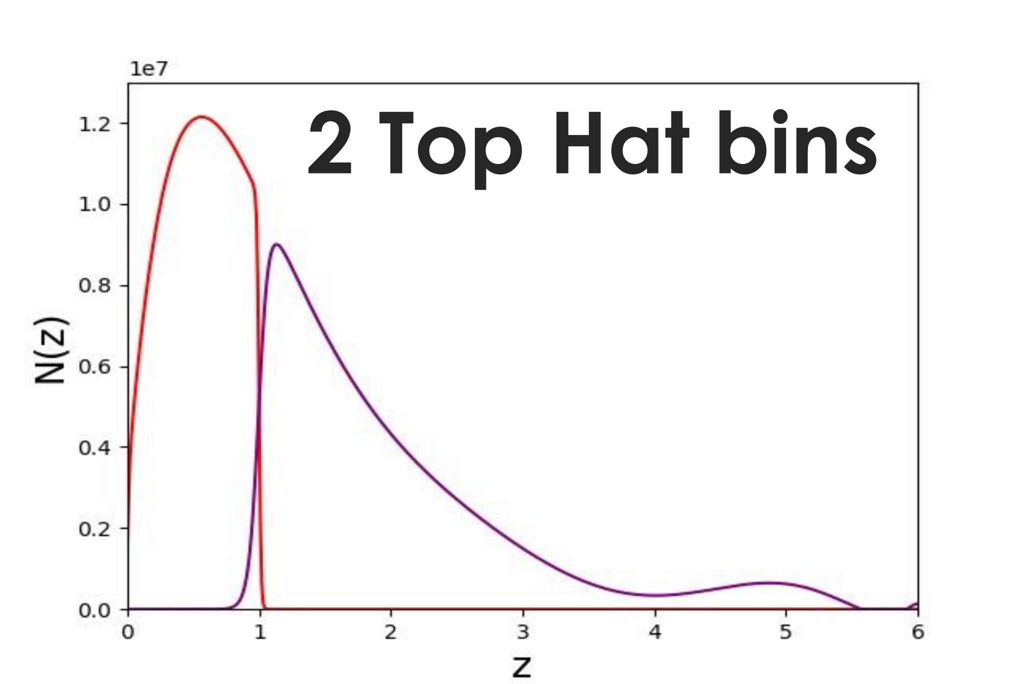
- Its unrivalled depth makes it ideal for the study of the magnification bias, and the large scale structure over the very large volume will be ideal to investigate extensions to the $\Lambda\mathrm{CDM}$ model.
- Deep radio continuum nearly full sky survey (detect extragalactic objects in the southern 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
- For the redshift distribution n(z) a 10σ detection limit of $100\mu Jy$ is assumed for AGN and SF galaxies
- The galaxies are sampled from the mock catalogues generated by SKA Simulated Skies (S-cubed) simulations up to that limit. The distributions of redshifts and magnitudes of these mocks are used to estimate the n(z), the galaxy bias b(z), and the magnification bias Q(z)

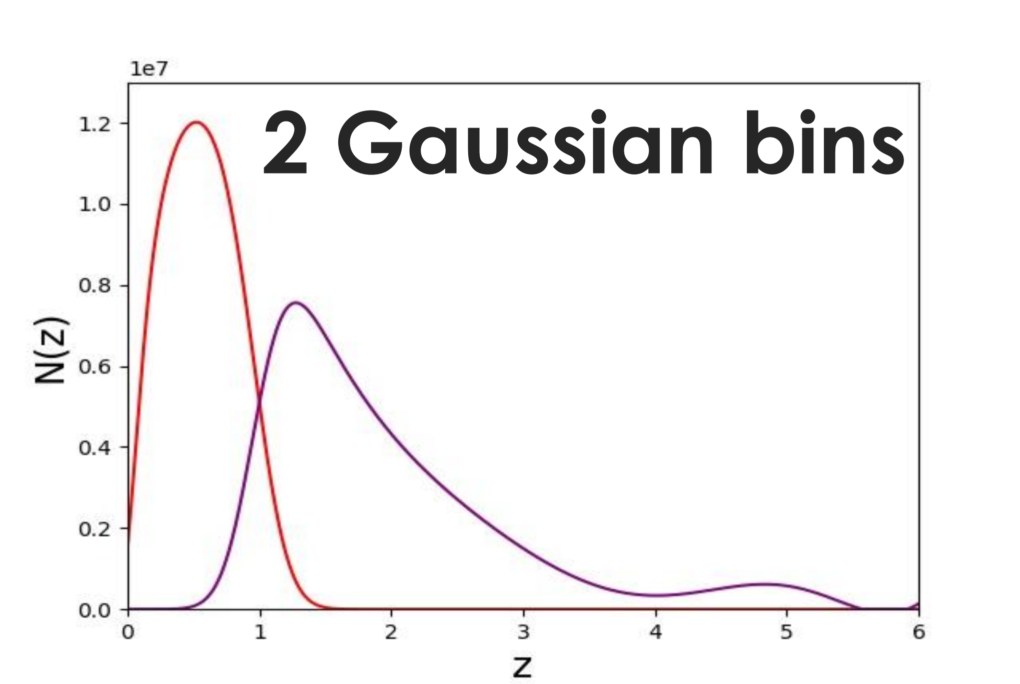
Table 1. Estimated number densities, galaxy bias, and magnification bias for EMU sources grouped in 2 redshift bins.

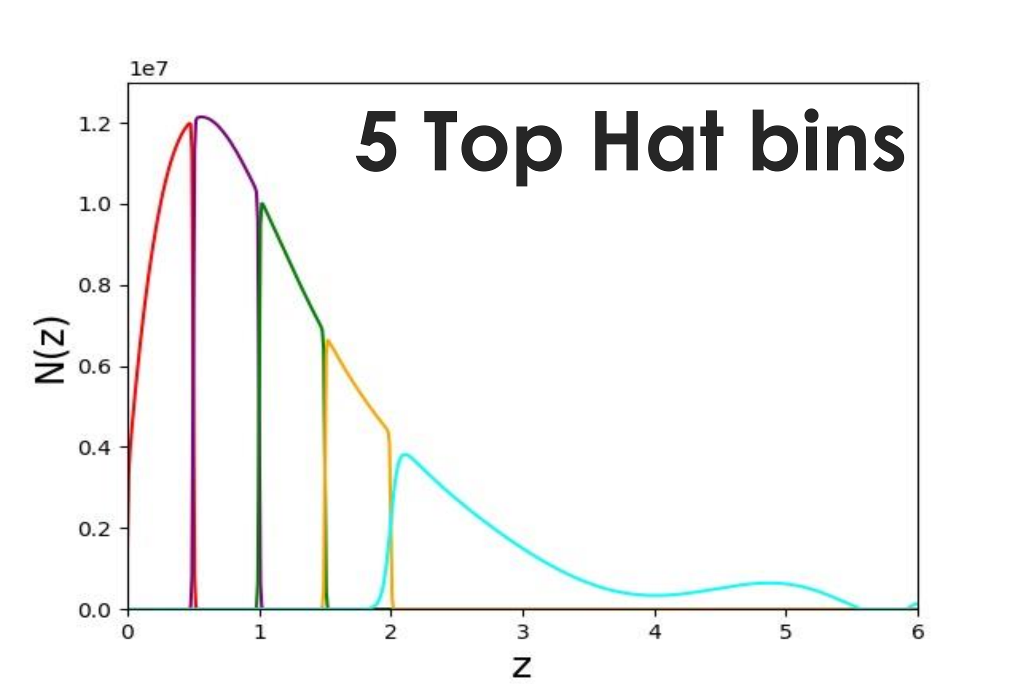
Bin	$z_{\rm min}$	$z_{\rm max}$	# of gal. ($\times 10^6$)	bias	mag. bias
1	0.0	1.0	10.68	0.833	1.050
2	1.0	6.0	11.58	2.270	1.298

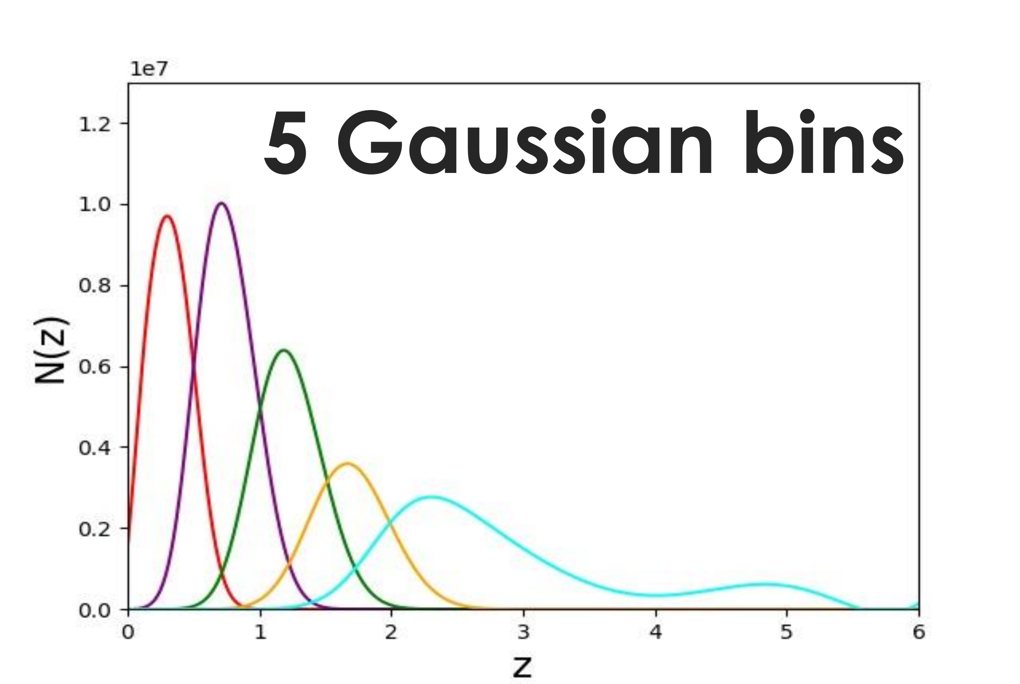
Table 2. Same as Table 1, but for EMU sources grouped in 5 redshift bins.

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
1.2
1.0
0.8
0.6
0.4
0.2
0.0
N(z)
0
1
2
3
4
5
6
z


2 Gaussian bins
1e7
1.2
1.0
0.8
0.6
0.4
0.2
0.0
N(z)
0
1
2
3
4
5
6
z


5 Top Hat bins
1e7
1.2
1.0
0.8
0.6
0.4
0.2
0.0
N(z)
0
1
2
3
4
5
6
z


5 Gaussian bins
1e7
1.2
1.0
0.8
0.6
0.4
0.2
0.0
N(z)
0
1
2
3
4
5
6
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

Multipole Range

Table 4. The $\ell_{\rm min}$ and $\ell_{\rm max}$ 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 $\ell_{\rm max} = k_{\rm max}\chi(\bar{z}_i)$ with $\bar{z}_i$ the centre of the ith bin.

2 redshift bins					5 redshift bins				
$\ell_{\rm min}$				$\ell_{\rm max}$	$\ell_{\rm min}$				$\ell_{\rm max}$
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

Cosmological models

- ΛCDM model: $\theta_{\{\Lambda\mathrm{CDM}\}} = \{\Omega_{\mathrm{m}}, \mathrm{h0}, \sigma_8\}$ 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

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

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

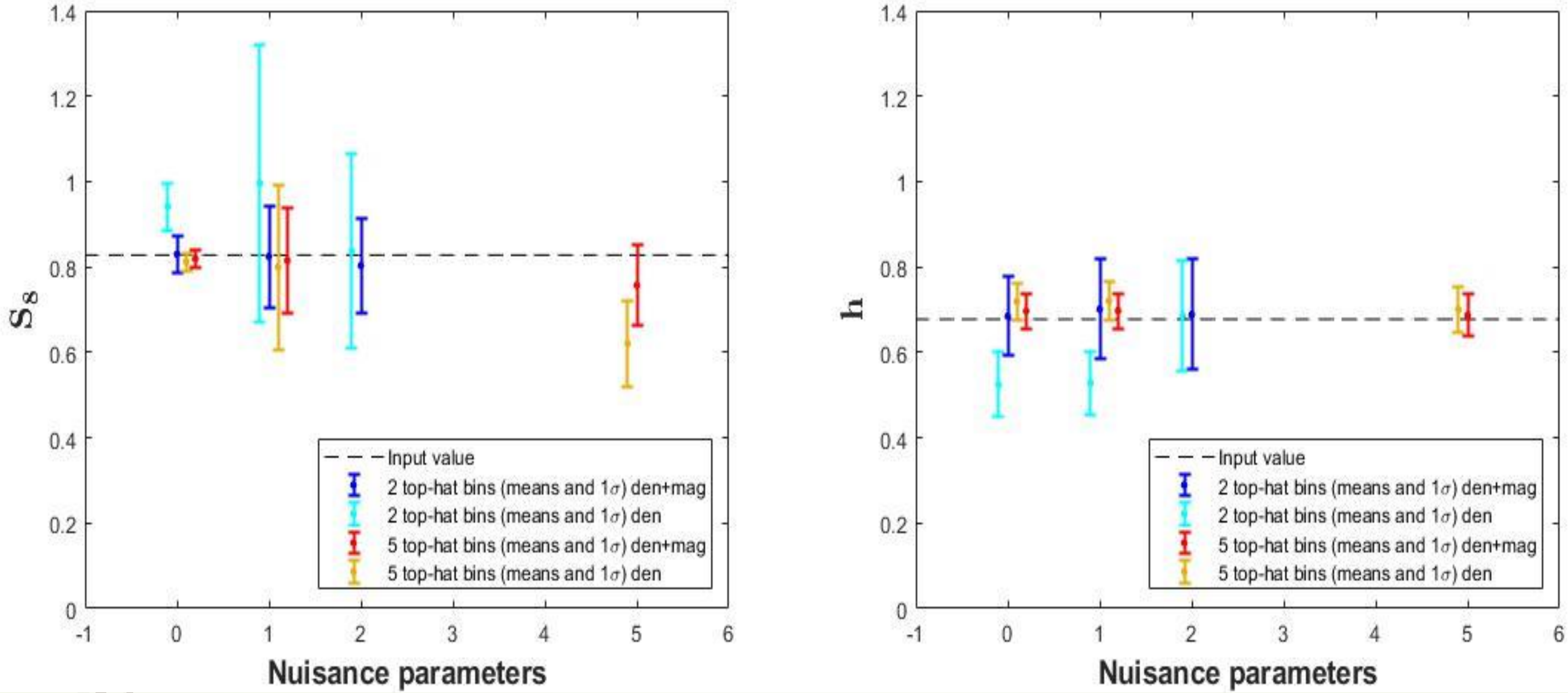
Three scenarios based on our knowledge of the galaxy bias

- 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

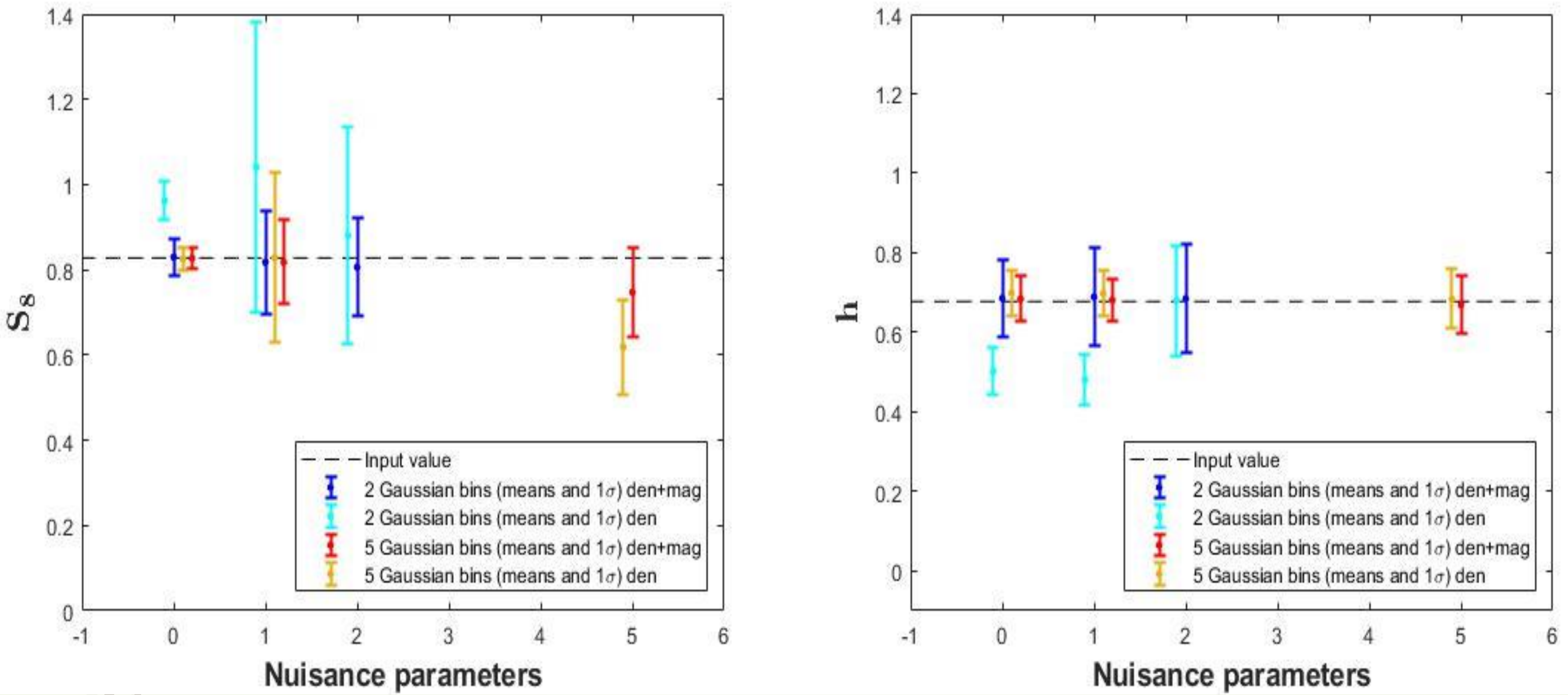
In all cases keep the magnification bias is fixed to the fiducial value

1σ Results Top Hat bins: ΛCDM model.

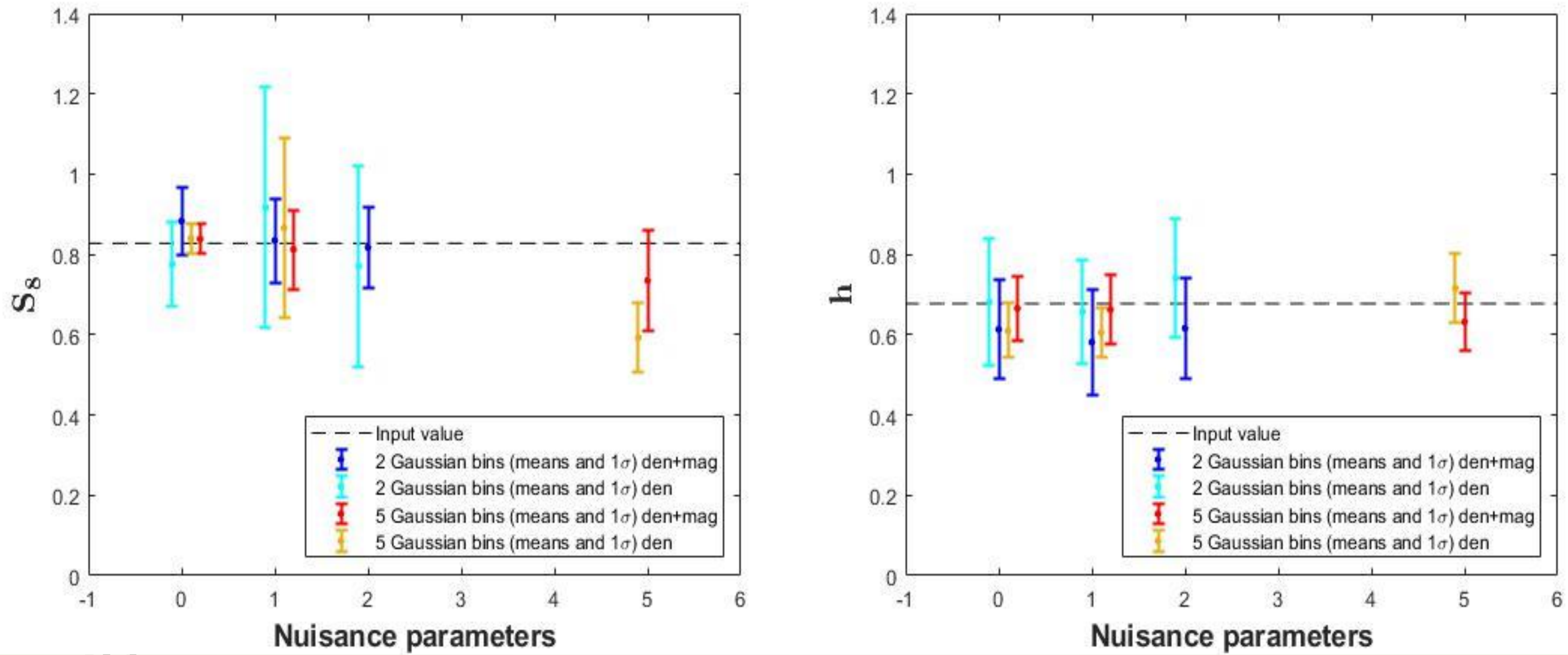
Constraints shown on $S_8 = \sigma_8\sqrt{\frac{\Omega_m}{0.3}}$, because it is better constrained than σ_8 and is not correlated with Ω_m



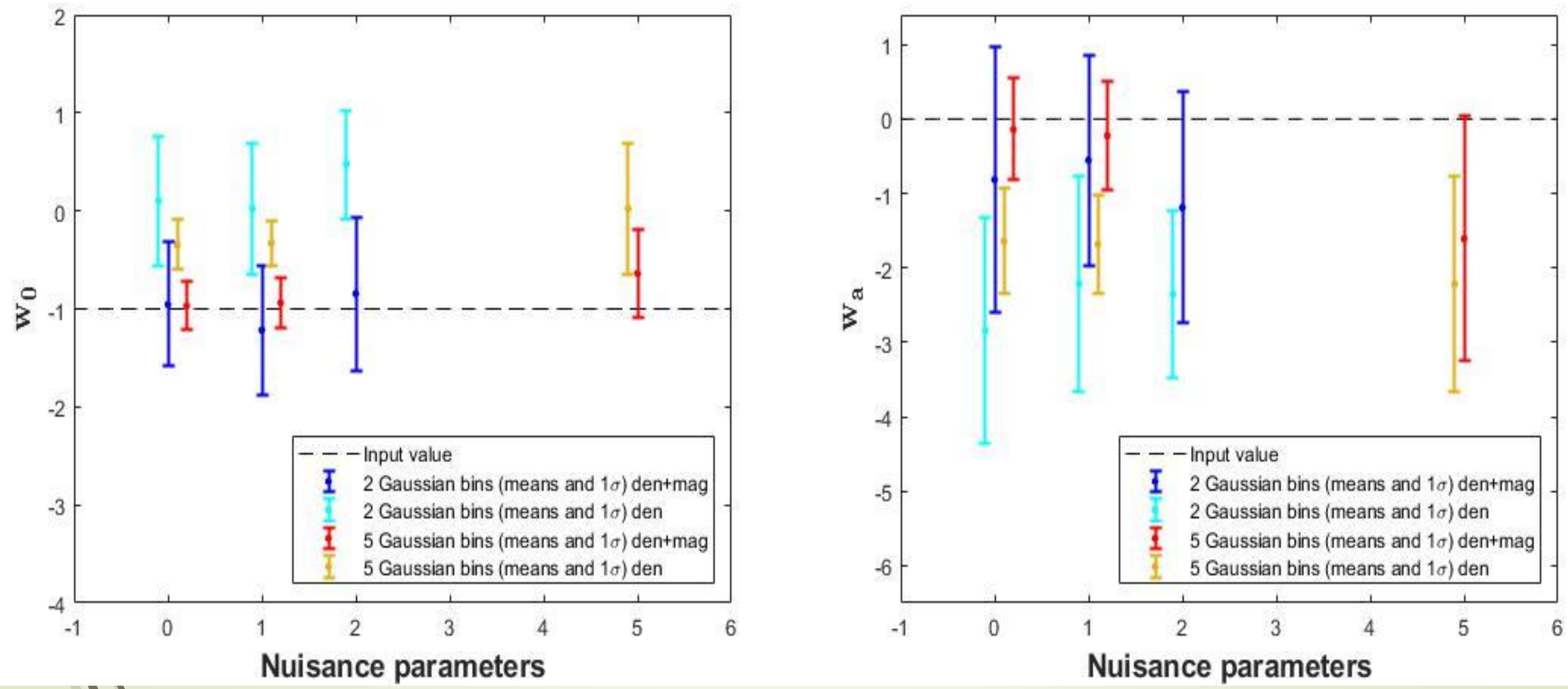
1σ Results Gaussian bins: ΛCDM model.



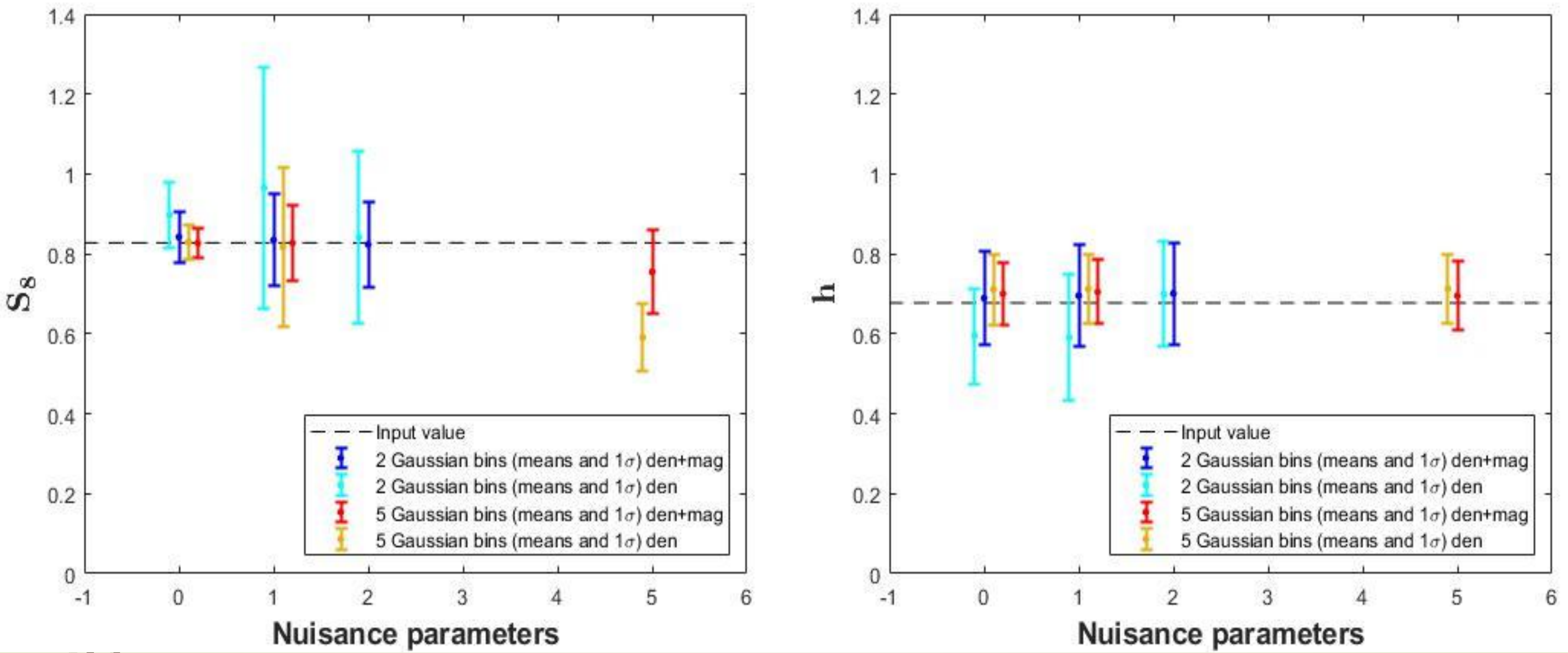
1σ Results Gaussian bins: DE model.



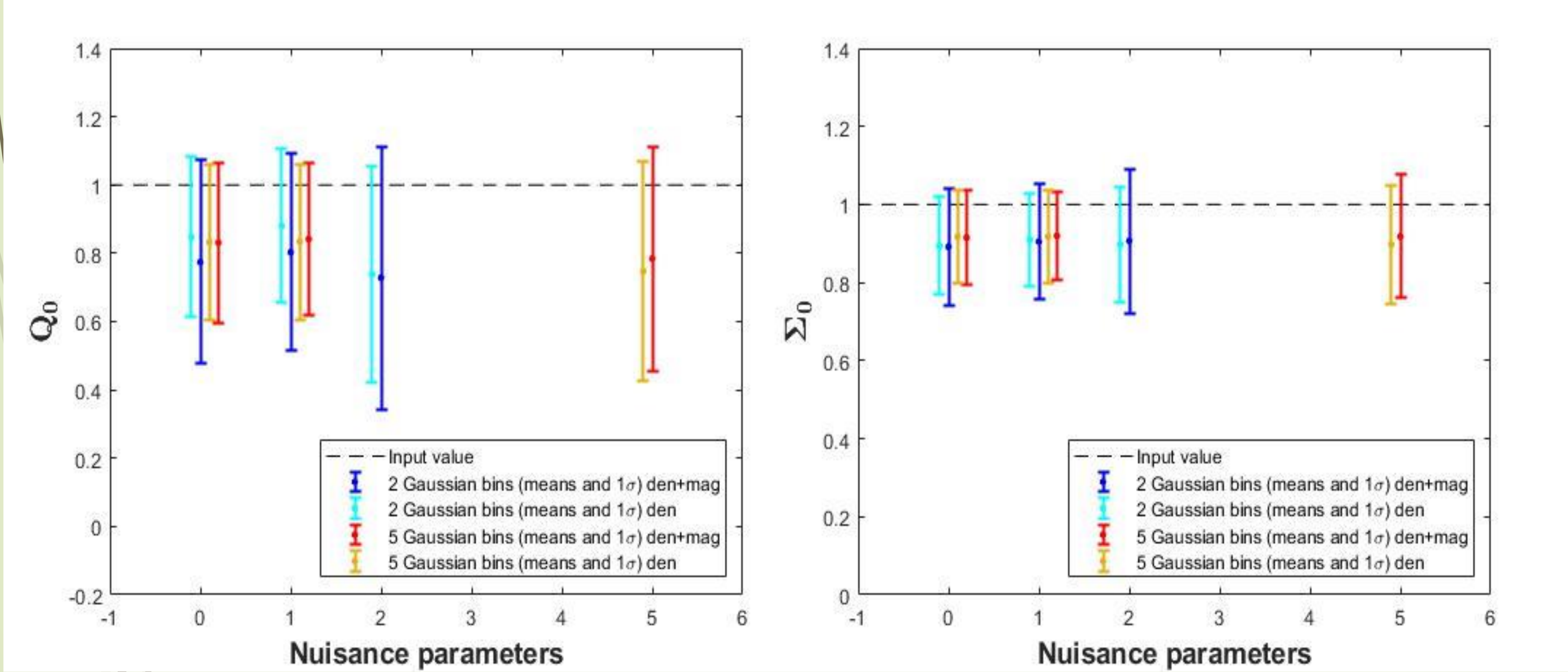
1σ Results Gaussian bins: DE model.



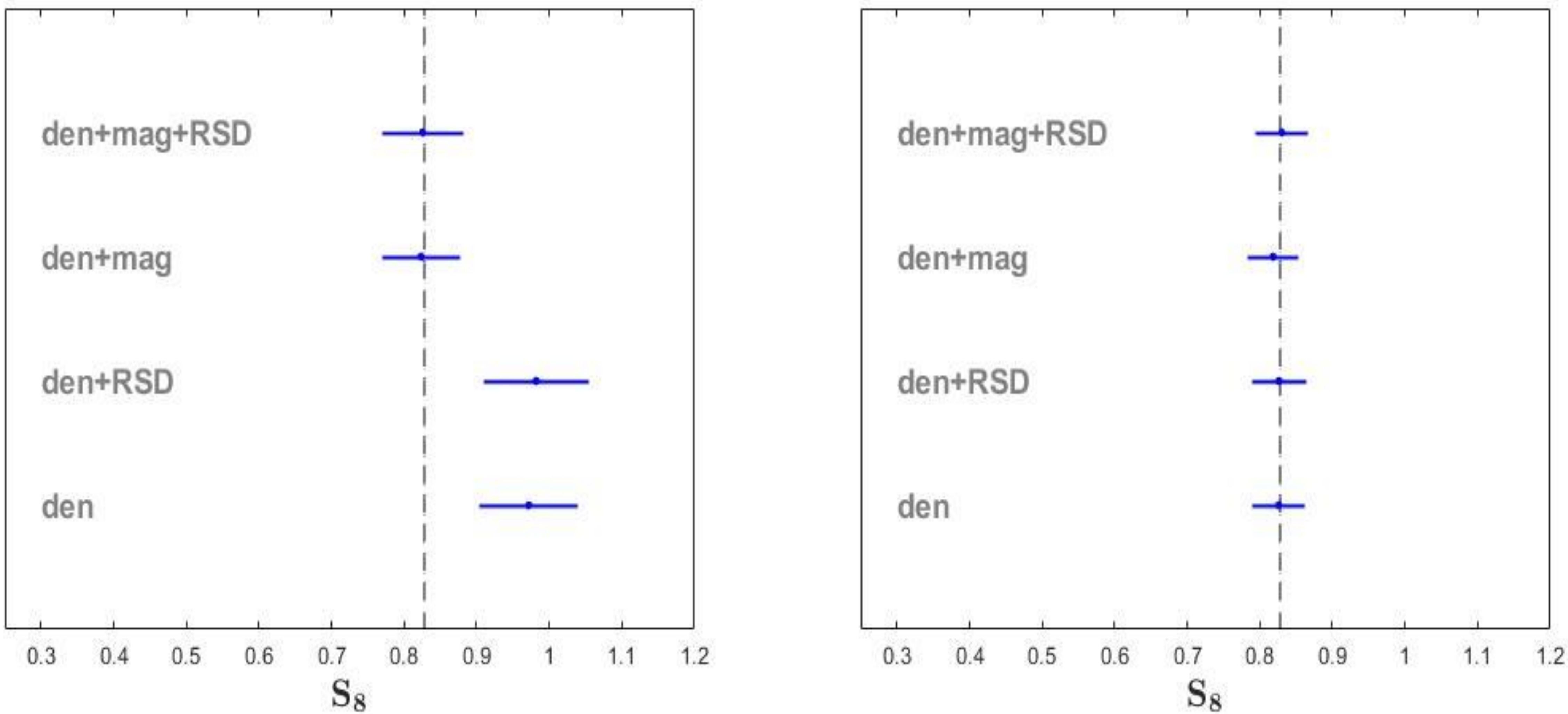
1σ Results Gaussian bins: MG model.



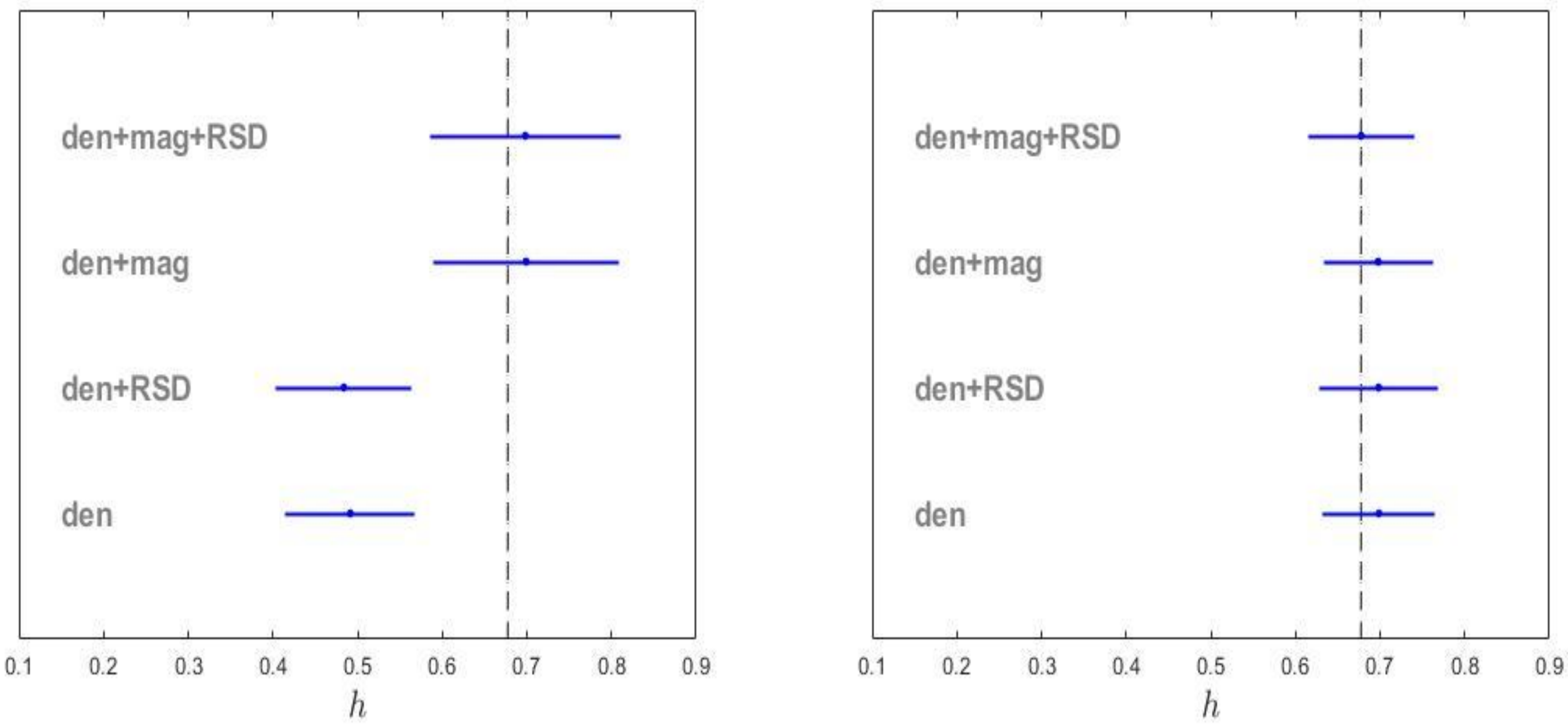
1σ Results Gaussian bins: MG model.



Investigating RSD - ΛCDM (2 and 5 bins)



Investigating RSD - ΛCDM (2 and 5 bins)



Conclusions 1/2

ΛCDM :

- Both binning configurations (TH/Gaussian) give comparable results since the bins are always wide enough. The discrepancy on the estimated cosmological parameters mean values $\{S_8, h\}$ between an analysis with and without magnification is statistically significant for the ideal scenario and the wide bins.
- This bias is not seen in the realistic scenarios. However, the purely density model yields very degenerate results on S_8 since it is the normalization of the PS. Partially broken when adding magnification bias which are insensitive to the galaxy bias
- When narrower binning is chosen, the parameters are more constrained due to the better precision on the PS. There is also biased estimate on S_8 for the incomplete model and the conservative case owing to the overestimate of the nuisance galaxy parameters. This is also true for the rest of the cosmological models examined

Conclusions 2/2

- DE:

- No bias in the wide bin case with the wrong vector. Only seen in the 5-bin case on h in the pessimistic scenario and on S_8 in the conservative. Again we have better constraints with the 5-bin and the degeneracy on S_8 is alleviated with the inclusion of magnification flux in the realistic scenarios. As for $\{w_0, w_\alpha\}$, we always have biased estimates with the incomplete model. The bias is more pronounced with the wide bins, since the magnification flux is a lensing effect and becomes more important

- MG:

- Results on $\{S_8, h\}$ similar to the DE. Only bias in the 5-bin conservative. No bias at all on $\{\Sigma_0, Q_0\}$, probably due to the cut on the very large scales which are sensitive to the extension of the GR.

The inclusion of the RSD important in the case of radio continuum surveys, due to the dilution of the effect in very wide bins

Thank you for your attention!