Model independent constraints on clustering and growth of cosmic structures from intensity mapping

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Cosmic structures

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- Projecting onto a sphere

$$\Delta(\boldsymbol{r}) = \sum_{\ell m} a_{\ell m}(z)Y_{\ell m}(\hat{\boldsymbol{r}})$$

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- physical form of the perturbation variable [1]

$$\Delta(\boldsymbol{r}) = b(z)\delta(\hat{\boldsymbol{r}}) + \frac{1}{\mathcal{H}(z)}\partial_r(\boldsymbol{V}(\boldsymbol{r})\cdot\hat{\boldsymbol{r}}) + ...$$

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- Power spectrum

$$P_{\Delta\Delta}(k,\mu,z) \simeq [b(z)\sigma_8 + f(z)\sigma_8\mu^2]^2 D^2(z)\frac{P_{lin}(k)}{\sigma_8}. \quad (1)$$

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- Harmonic power spectrum

$$C^{gg}_{ij,\ell} = b\sigma^i_8 b\sigma^j_8 C^{\delta\delta}_{ij,\ell} + f\sigma^i_8 f\sigma^j_8 C^{VV}_{ij,\ell} + 2b\sigma^{(i}_8 f\sigma^{j)}_8 C^{\delta V}_{ij,\ell}$$

$$b\sigma_8(z) := b(z)D(z)\sigma_8; \quad f\sigma_8(z) := -\frac{\mathrm{d}\ln D(z)}{\mathrm{d}\ln(1+z)}D(z)\sigma_8$$

21cm HI emission line

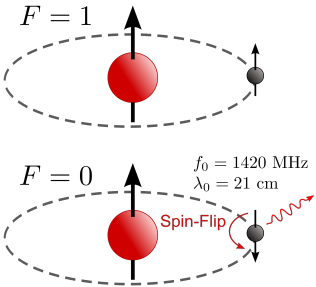


Figure: HI 21cm spin-flip transition between hyperfine states

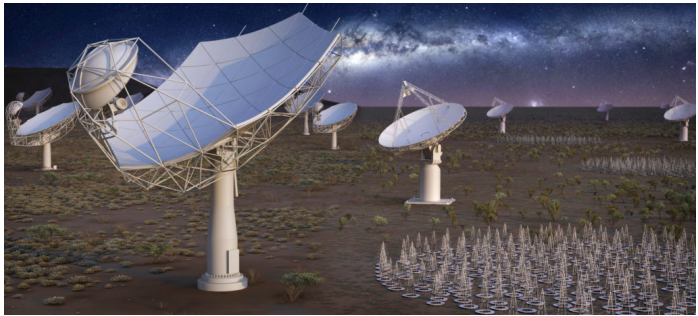


Figure: Square Kilometer Array

$$\frac{\mathrm{d}L}{\mathrm{d}\Omega \mathrm{d}\nu} \propto N_H$$

After reionization HI survives only in **high density regions**.

$\Longrightarrow$

Good DM halos tracer.

Intensity mapping

Integrating over large volume elements

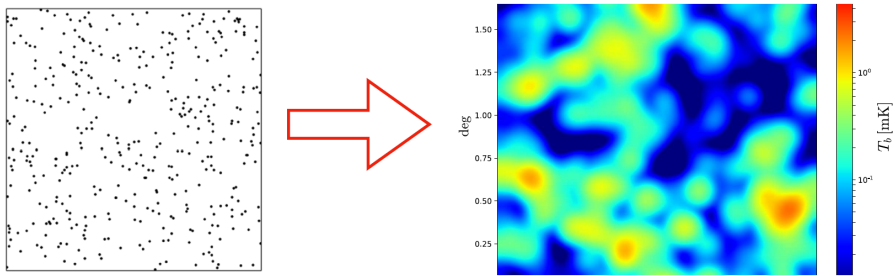


Figure: Galaxies become a temperature map

- **time-effective**
- **excellent redshift resolution**
- **astrophysical foregrounds**
- **instrumental systematics**

IM simulation

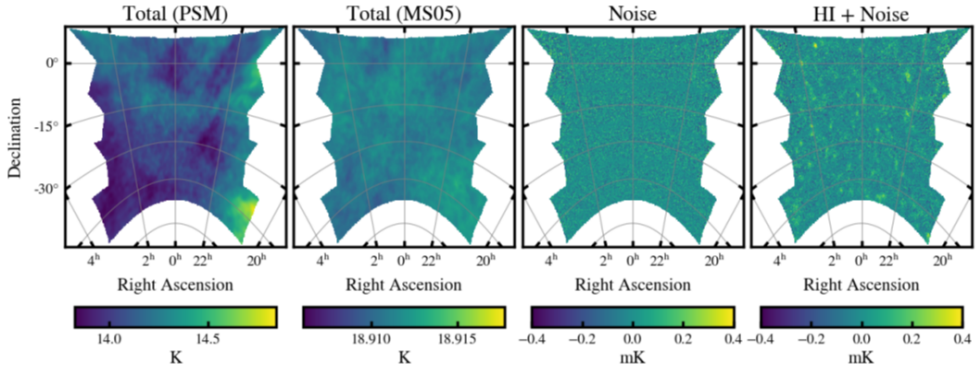


Figure: Maps of the contributing components to the final simulation

Binning the simulation

Top hat(s) functions

$$w_{HI}^{i}(z) = \frac{1}{2}\Big[1 - \tanh\Big(\frac{2|z - \overline{z}_i| - \Delta z_i}{\sigma \Delta z_i}\Big)\Big]$$

$$\sigma = 0.01$$

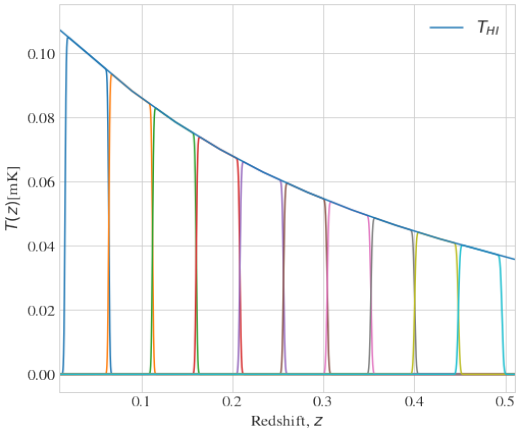
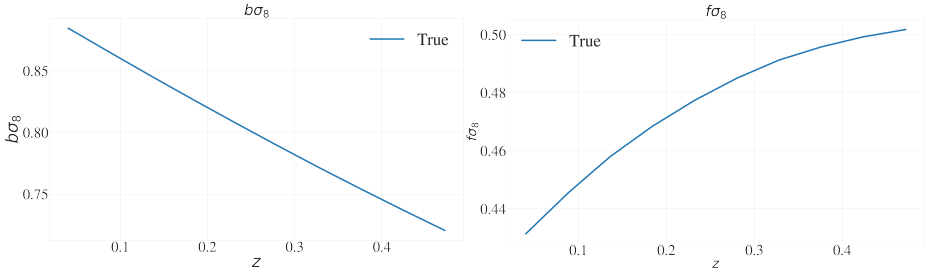
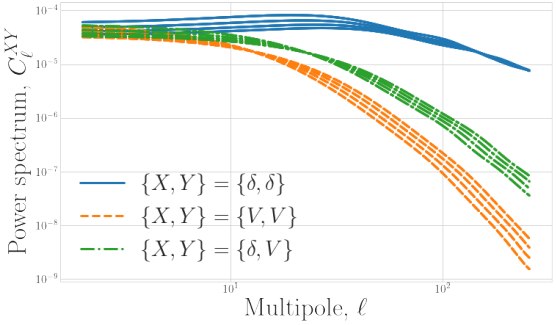


Figure: Bins description

CAMB - Theoretical **predictions** for cosmological observables





Template fitting

- Likelihood

$$\ln L(\boldsymbol{\theta}; \boldsymbol{d}) \propto [\boldsymbol{d} - \boldsymbol{m}(\boldsymbol{\theta})]^{\mathsf{T}} \, \Sigma^{-1} \, [\boldsymbol{d} - \boldsymbol{m}(\boldsymbol{\theta})]$$

Template fitting

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$$\ln L(\boldsymbol{\theta}; \boldsymbol{d}) \propto [\boldsymbol{d} - \boldsymbol{m}(\boldsymbol{\theta})]^{\mathsf{T}} \, \Sigma^{-1} \, [\boldsymbol{d} - \boldsymbol{m}(\boldsymbol{\theta})]$$

- Model

$$m_{\ell}^{ij}(\boldsymbol{\theta}) = b\sigma_8^i b\sigma_8^j C_{ij,\ell}^{\delta\delta} + f\sigma_8^i f\sigma_8^j C_{ij,\ell}^{VV} + b\sigma_8^i f\sigma_8^j C_{ij,\ell}^{\delta V} + b\sigma_8^j f\sigma_8^i C_{ji,\ell}^{\delta V}$$

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$$\boldsymbol{\theta} = \{b\sigma_8^i\} \cup \{f\sigma_8^i\}$$

Template fitting

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- Parameters

$$\boldsymbol{\theta} = \{b\sigma_8^i\} \cup \{f\sigma_8^i\}$$

- Covariance

$$\Sigma_{\ell\ell'}^{ij,nk} = \frac{C_\ell^{in} C_\ell^{jk} + C_\ell^{ik} C_\ell^{jn}}{(2\ell+1)\Delta\ell f_{\rm sky}} \delta_{\ell\ell'}^{\rm K}$$

Pipeline test I

$$m^i_\ell(\boldsymbol{\theta}) = b\sigma^i_8 b\sigma^i_8 C^{\delta\delta}_{ii,\ell} + f\sigma^i_8 f\sigma^i_8 C^{VV}_{ii,\ell} + 2b\sigma^i_8 f\sigma^i_8 C^{\delta V}_{ii,\ell}; \qquad d^i_\ell = C^{HIHI,Th}_\ell$$

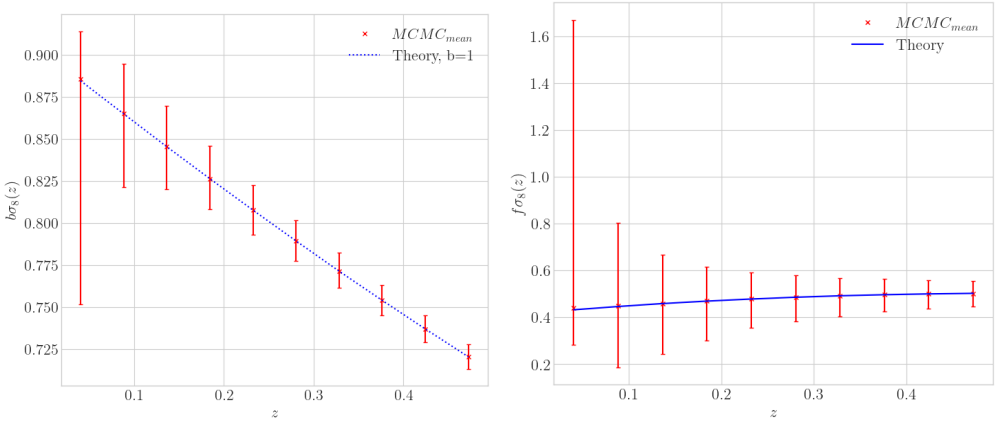
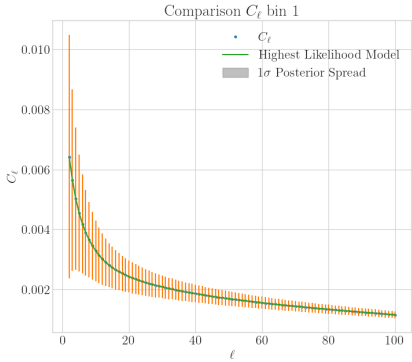


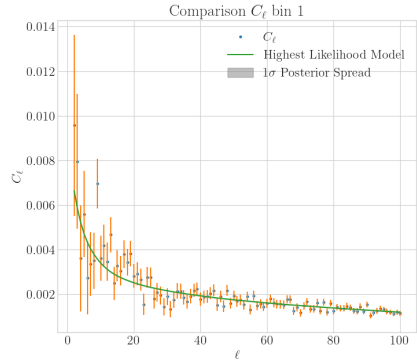
Figure: Estimation of artificial parameters

Pipeline test II

$$C_\ell \sim \mathcal{N}(C_\ell, \Sigma_\ell)$$



(a) Template



(b) Gaussian scattered data

Pipeline test III

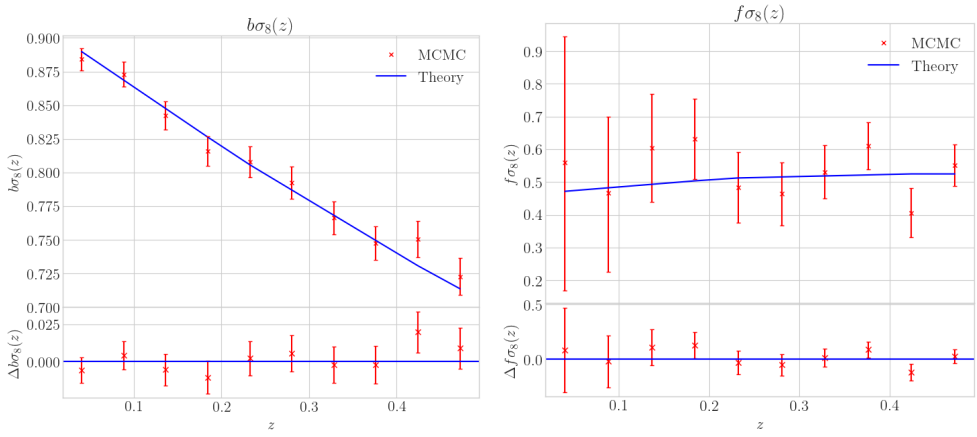


Figure: Estimation of artificial parameters

Intensity map

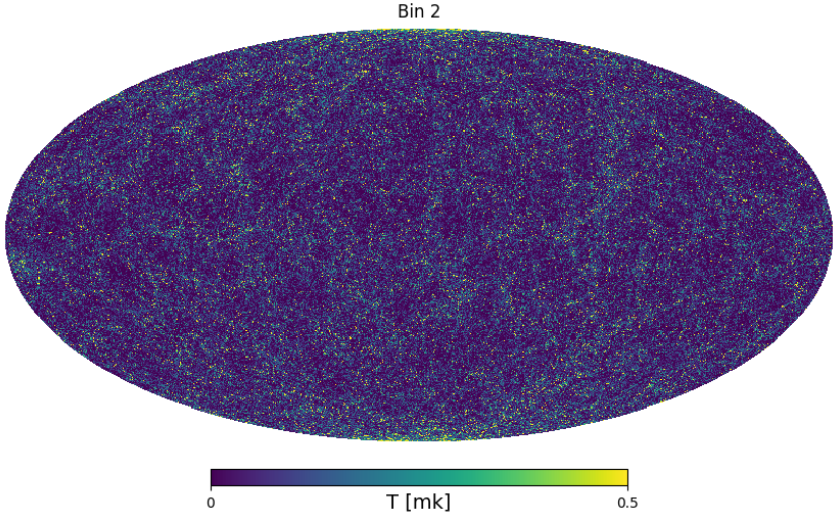


Figure: Intensity map at $z = 0.424$

$b\sigma_8$ and $f\sigma_8$ measure

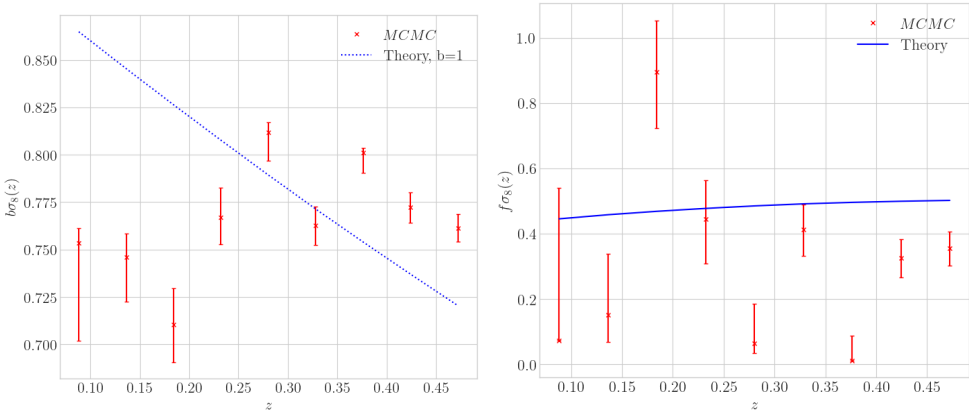


Figure: Estimation of maps parameters

Data

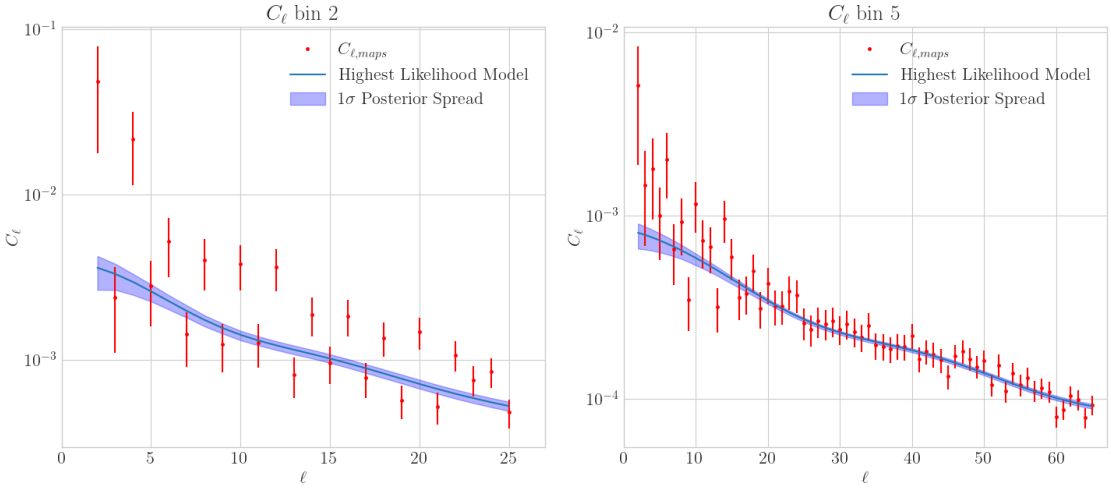


Figure: Data of bin 2 and 5

Shot Noise

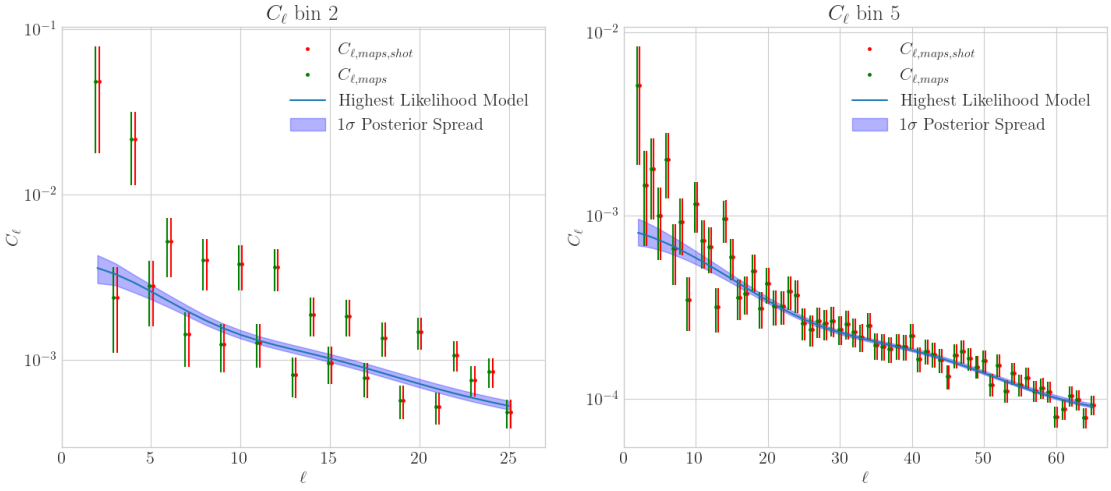


Figure: Data of bin 2 and 5

Noise as a free parameter

$$\Sigma^{ii}_{\ell\ell'} = \frac{2(C^{ii}_\ell + N^{ii})^2}{(2\ell+1)\Delta\ell f_{\rm sky}}\delta^{\rm K}_{\ell\ell'}$$

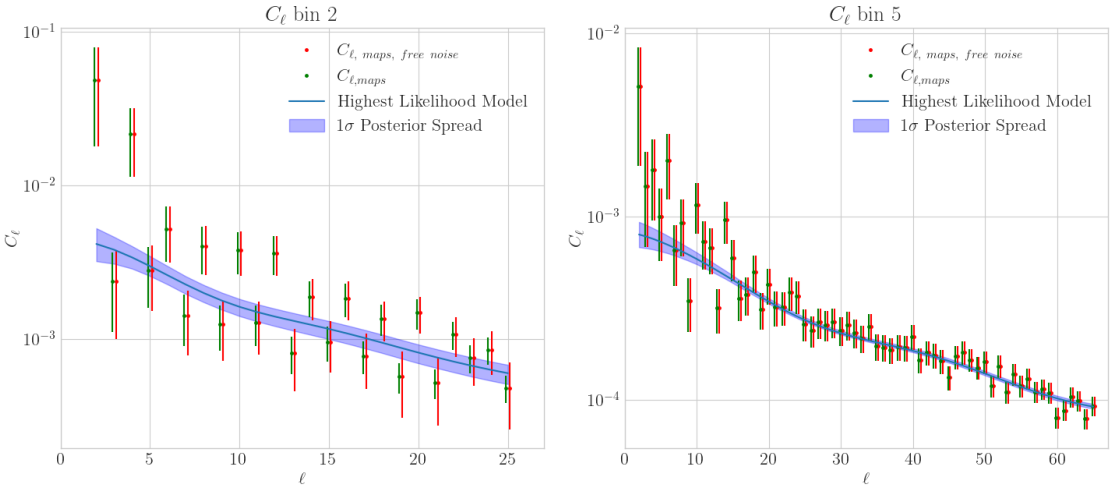


Figure: Data with noise of bin 2 and 5

Noise as a free parameter - Results

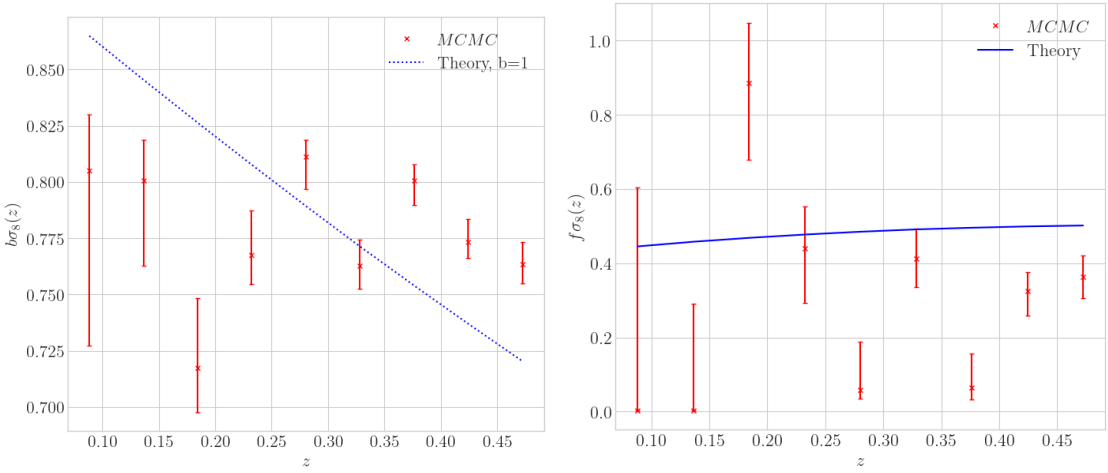
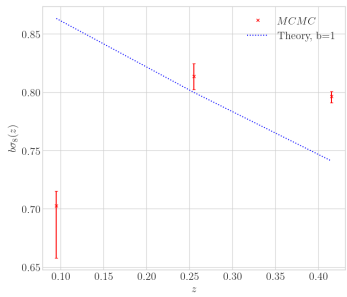
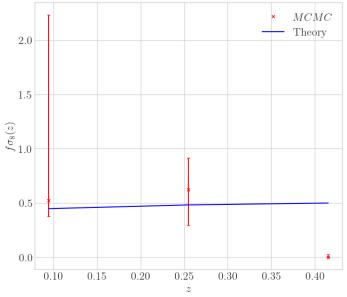
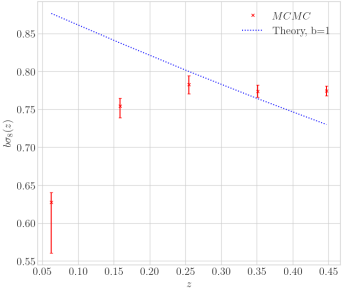


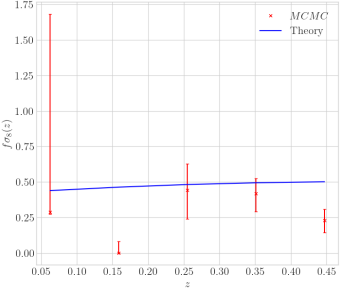
Figure: Estimation of parameters with noise

Other binning I









Other binning II

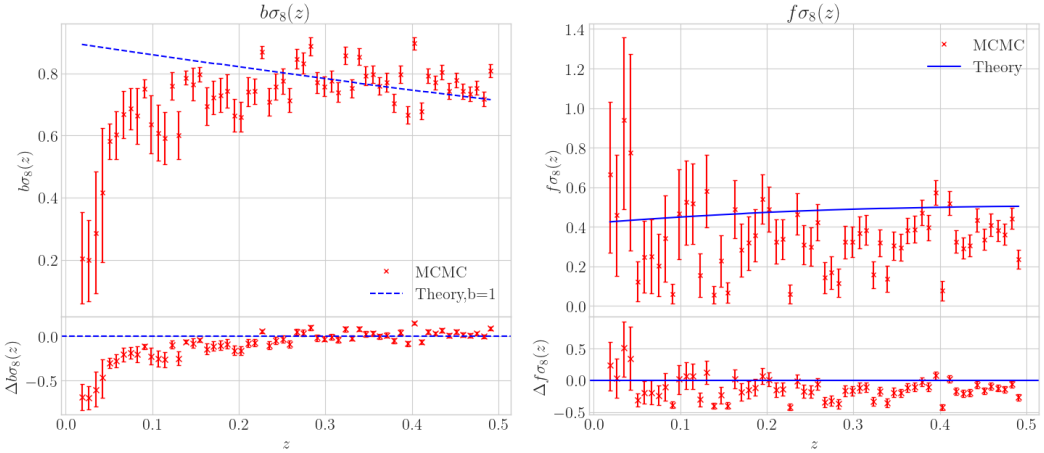


Figure: Estimation of parameters, 60 bins

Next steps

Template

Next steps

Template

↓

Pipeline validation

Next steps

Template

↓

Pipeline validation

↓

Attemps of measuring $b\sigma_8$ and $f\sigma_8$

Next steps

Template

↓

Pipeline validation

↓

Attemps of measuring $b\sigma_8$ and $f\sigma_8$

↓

Not understood trend of the results

Next steps

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↓

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↓

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↓

Not understood trend of the results

- The **technique** behaviour is **validated**
- The work is continuing

Next steps

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↓

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↓

Attemps of measuring $b\sigma_8$ and $f\sigma_8$

↓

Not understood trend of the results

- The **technique** behaviour is **validated**
- The work is continuing

$\Longrightarrow$

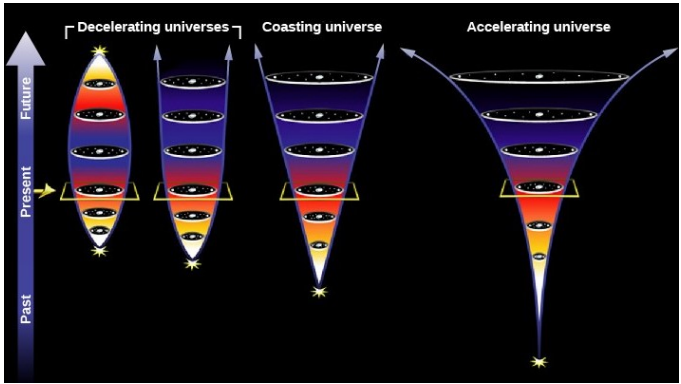
Rendering IM a reliable tool to provide new fresh data

Thanks for the attention!

Backup slides

ΛCDM Model

$$\Omega_b,\ \Omega_{CDM},\ H_0,\ A_s,\ n_s,\ \tau$$



$$\Omega_k = 0 \quad \Omega_{CDM} \simeq 27\% \quad \Omega_\Lambda \simeq 70\%$$

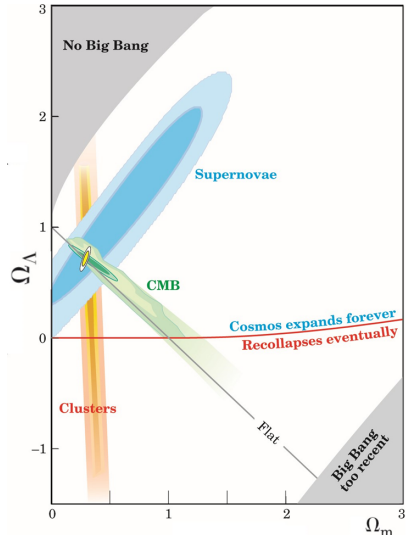


Figure: Cosmological parameters constraints [2–4]

Structures

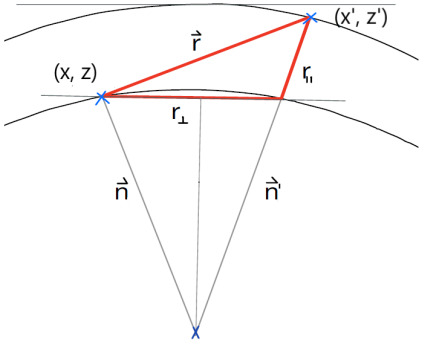
$$\delta(\boldsymbol{r}) = \frac{\rho(\boldsymbol{r}) - \overline{\rho}}{\overline{\rho}}$$

Using $\boldsymbol{r} = \boldsymbol{r}(z)$, where $\boldsymbol{r} = r\hat{\boldsymbol{r}}$. In general

$$\delta(t) = D(t)\delta_i$$

Gaussian distribution

$$\langle \delta(\boldsymbol{r}), \delta(\boldsymbol{r}') \rangle \equiv \xi(|\boldsymbol{r} - \boldsymbol{r}'|)$$



Power spectrum

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

$$P_i(k) = A_s k^{-n_s}$$

Spherical harmonics decomposition

The observer sees the perturbation variable projected onto a sphere

$$\Delta(\boldsymbol{r}) = \sum_{\ell m} a_{\ell m}(z)\, Y_{\ell m}(\hat{\boldsymbol{r}}) \qquad a_{\ell m}(z) = \int \mathrm{d}^2\hat{\boldsymbol{r}}\, Y^*_{\ell m}(\hat{\boldsymbol{r}})\Delta(\boldsymbol{r})$$

Here $\boldsymbol{r} = \boldsymbol{r}(z)$, where $\boldsymbol{r} = r\hat{\boldsymbol{r}}$.

$$\langle \Delta(\boldsymbol{r}), \Delta(\boldsymbol{r}')\rangle = \sum_{\ell=0}^{\infty} C_\ell(z, z') \sum_{m=-\ell}^{\ell} Y_{\ell m}(\hat{\boldsymbol{r}})\, Y^*_{\ell m}(\hat{\boldsymbol{r}'}) \tag{2}$$

Using the definition of Fourier transform $\Delta(\boldsymbol{r}) = \frac{1}{(2\pi)^3}\int \mathrm{d}^3\boldsymbol{k}\Delta(\boldsymbol{k})e^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}}$ in equation 2

$$= \frac{1}{(2\pi)^6}\int \mathrm{d}^3\boldsymbol{k}\mathrm{d}^3\boldsymbol{k}'\Delta(\boldsymbol{k})e^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}}\Delta^*(\boldsymbol{k}')e^{-\mathrm{i}\boldsymbol{k}'\cdot\boldsymbol{r}'}$$

We moreover make use of the plane-wave expansion

$$\mathrm{e}^{\mathrm{i}\,\boldsymbol{k}\cdot\boldsymbol{r}} = 4\pi \sum_{\ell=0}^{\infty} \mathrm{i}^\ell\, j_\ell(k\, r) \sum_{m=-\ell}^{\ell} Y_{\ell m}(\hat{\boldsymbol{k}})\; Y^*_{\ell m}(\hat{\boldsymbol{r}})$$

Using physical form of the perturbation variable [1]

$$\Delta(\boldsymbol{r}) = b(z)\delta(\hat{\boldsymbol{r}}) + \frac{1}{\mathcal{H}(z)}\partial_r(\boldsymbol{V}(\boldsymbol{r})\cdot\hat{\boldsymbol{r}}) + ...$$

$$\delta(\hat{\boldsymbol{r}}) = \frac{1}{(2\pi)^3}\int \mathrm{d}^3\boldsymbol{k}\delta(\hat{\boldsymbol{k}})e^{i\boldsymbol{k}\cdot\boldsymbol{r}} \quad \frac{\partial}{\partial r}(\boldsymbol{V}(\boldsymbol{r})\cdot\hat{\boldsymbol{r}}) = \frac{1}{(2\pi)^3}\int \mathrm{d}^3\boldsymbol{k}\frac{V(\boldsymbol{k})}{k}\frac{\partial^2}{\partial r^2}(e^{i\boldsymbol{k}\cdot\boldsymbol{r}})$$

Data are grouped in $i, j = 1, ..., N_b$ redshift bins containing $n^i(z)dz$ source per steradiant

$$\Delta^i(\hat{\boldsymbol{r}}) = \int_{z_-}^{z_+} \mathrm{d}z\ n^i(z)\Delta(\boldsymbol{r})$$

$$C^{gg}_{ij,\ell} = b\sigma^i_8 b\sigma^j_b C^{\delta\delta}_{ij,\ell} + f\sigma^i_8 f\sigma^j_8 C^{VV}_{ij,\ell} - 2b\sigma^{(i}_8 f\sigma^{j)}_8 C^{\delta V}_{ij,\ell}$$

$$b\sigma_8(z) := b(z)D(z)\sigma_8; \quad f\sigma_8(z) := \frac{\mathrm{d}D(z)}{\mathrm{d}\ln(1+z)}\sigma_8$$

Structures

Growth factor [5]

$$D(a) = \frac{5\Omega_m}{2}\frac{H(a)}{a}\int_0^a \frac{\mathrm{d}a'}{a'^3 H(a')}$$

Factorized C_ℓ expressions [6]

$$C_{ij,\ell}^{\delta\delta} = \frac{2}{\pi}\int \mathrm{d}k\mathrm{d}r\mathrm{d}r' k^2 \frac{P_{lin}(k)}{\sigma_8^2} n^i(r) n^j(r') j_\ell(kr) j_\ell(kr'),$$

$$C_{ij,\ell}^{VV} = \frac{2}{\pi}\int \mathrm{d}k\mathrm{d}r\mathrm{d}r' k^2 \frac{P_{lin}(k)}{\sigma_8^2} n^i(r) n^j(r') j_\ell''(kr) j_\ell''(kr'),$$

$$C_{ij,\ell}^{\delta\delta} = \frac{2}{\pi}\int \mathrm{d}k\mathrm{d}r\mathrm{d}r' k^2 \frac{P_{lin}(k)}{\sigma_8^2} n^{(i}(r) n^{j)}(r') j_\ell(kr) j_\ell''(kr').$$

Redshift and distances

$$d_c = \int_{t_e}^{t_0} c \frac{\mathrm{d}t}{a(t)} \qquad d = a(t) d_c$$

$$H(z) \equiv \frac{\mathrm{d}a}{\mathrm{d}t}\frac{1}{a} = \frac{\mathrm{d}a}{\mathrm{d}z}\frac{\mathrm{d}z}{\mathrm{d}t}(1+z); \qquad \mathrm{d}a = -\frac{\mathrm{d}z}{(1+z)^2}$$

$$\mathrm{d}t = -\frac{\mathrm{d}z}{(1+z)}$$

using Friedman equation

$$d_c = \frac{c}{H_0}\int_0^z \frac{\mathrm{d}z'}{\sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda}}$$

Brightness temperature

Given the Plank function for a black body

$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1} \qquad \left[\frac{W}{m^2 s^{-1}}\right]$$

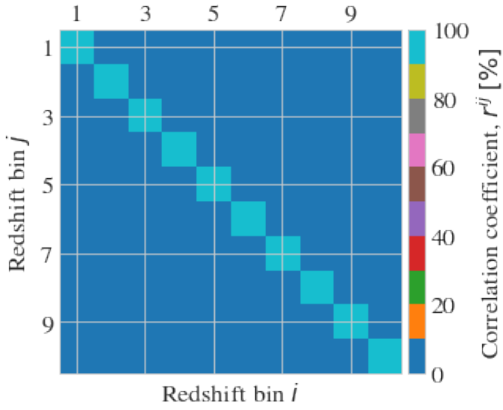
in the limit $h\nu \ll kT$ one che invert the relation obtaining

$$T_b = \frac{I_\nu c^2}{2k\nu^2}$$

Evaluating the cross correlations

Correlation coefficient

$$r^{ij} = \frac{\sum_{\ell}^{N_\ell} \frac{C_\ell^{ij}}{\sqrt{C_\ell^{ii} C_\ell^{jj}}}}{N_\ell}$$



Shot noise

$$C_\ell^{shot} = T_{HI}^2(z)/\overline{N}(z), \tag{3}$$

$$\overline{N}(z) = n_0 c \int \frac{r^2(z)}{H(z)} \mathrm{d}z. \tag{4}$$

Comoving number density of sources $n_0 = 0.03 h^3 Mpc^{-3}$

i	1	2	3	4	5	6	7	8	9	10
$C_{\ell,min}^{ii}$	1.7×10^{-3}	4.8×10^{-4}	1.7×10^{-4}	1.1×10^{-4}	7.9×10^{-5}	6.5×10^{-5}	4.7×10^{-5}	3.7×10^{-5}	3.0×10^{-5}	2.6×10^{-5}
$C_\ell^{shot,ii}$	1.3×10^{-5}	3.4×10^{-6}	1.5×10^{-6}	8.9×10^{-7}	5.9×10^{-7}	4.3×10^{-7}	3.3×10^{-7}	2.7×10^{-7}	2.2×10^{-7}	1.9×10^{-7}

Covariance

$$
\begin{aligned}
\Sigma_{\ell\ell'}^{ij,nk} =& Cov\left(C_\ell^{ij}, C_{\ell'}^{nk}\right) \\
=& \left\langle C_\ell^{ij} C_{\ell'}^{nk} \right\rangle - \left\langle C_\ell^{ij} \right\rangle \left\langle C_{\ell'}^{nk} \right\rangle \\
=& \left\langle a_{\ell m}^{i} a_{\ell m}^{j} a_{\ell' m'}^{n} a_{\ell' m'}^{k} \right\rangle - C_\ell^{ij} C_{\ell'}^{nk} \\
=& \left\langle a_{lm}^{i} a_{lm}^{j} \right\rangle \left\langle a_{l' m'}^{n} a_{l' m'}^{k} \right\rangle + \left\langle a_{lm}^{i} a_{l' m'}^{n} \right\rangle \left\langle a_{lm}^{j} a_{l' m'}^{k} \right\rangle + \\
& \left\langle a_{lm}^{i} a_{l' m'}^{k} \right\rangle \left\langle a_{l' m'}^{n} a_{lm}^{j} \right\rangle + C_\ell^{ij} C_{\ell'}^{nk} + o(a^3) \\
=& C_\ell^{ij} C_{\ell'}^{nk} + C_\ell^{in} C_{\ell'}^{jk} \delta_{\ell\ell'}^{K} \delta_{mm'}^{K} + C_\ell^{ik} C_{\ell'}^{nj} \delta_{\ell\ell'}^{K} \delta_{mm'}^{K} - C_\ell^{ij} C_{\ell'}^{nk} \\
=& \frac{C_\ell^{in} C_\ell^{jk} + C_\ell^{ik} C_\ell^{jn}}{(2\ell+1)} \delta_{\ell\ell'}^{\mathrm{K}}
\end{aligned}
\tag{5}
$$

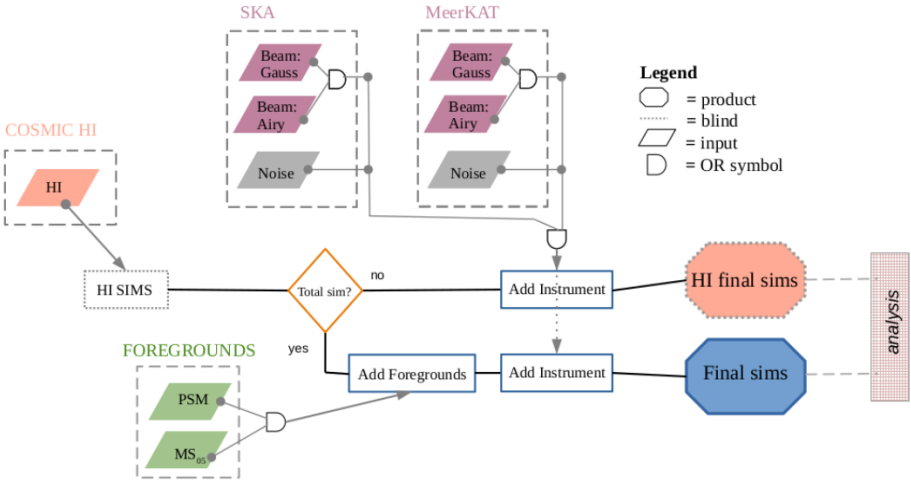


Figure: Foreground modelling and instrumental effects simulation. [7]

Other binning III

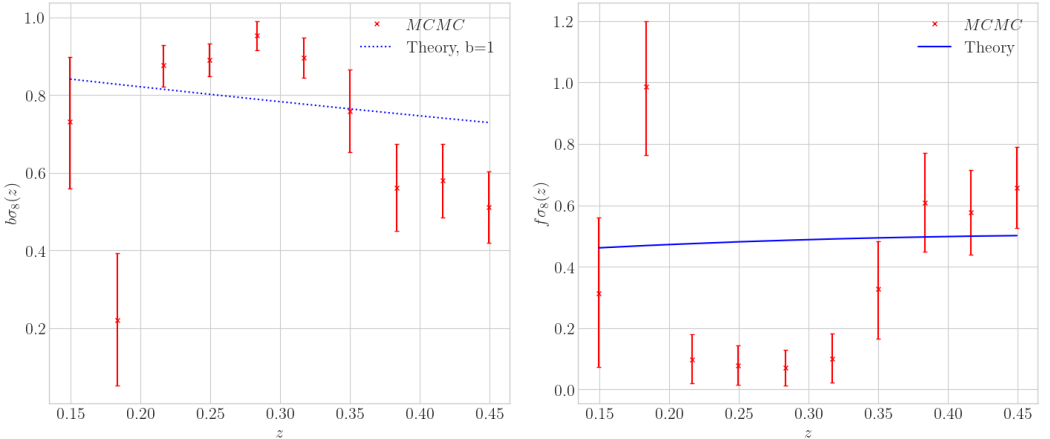


Figure: Estimation of parameters, 10 of the 512 original bins

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