How to measure a foreground mask from a galaxy redshift survey

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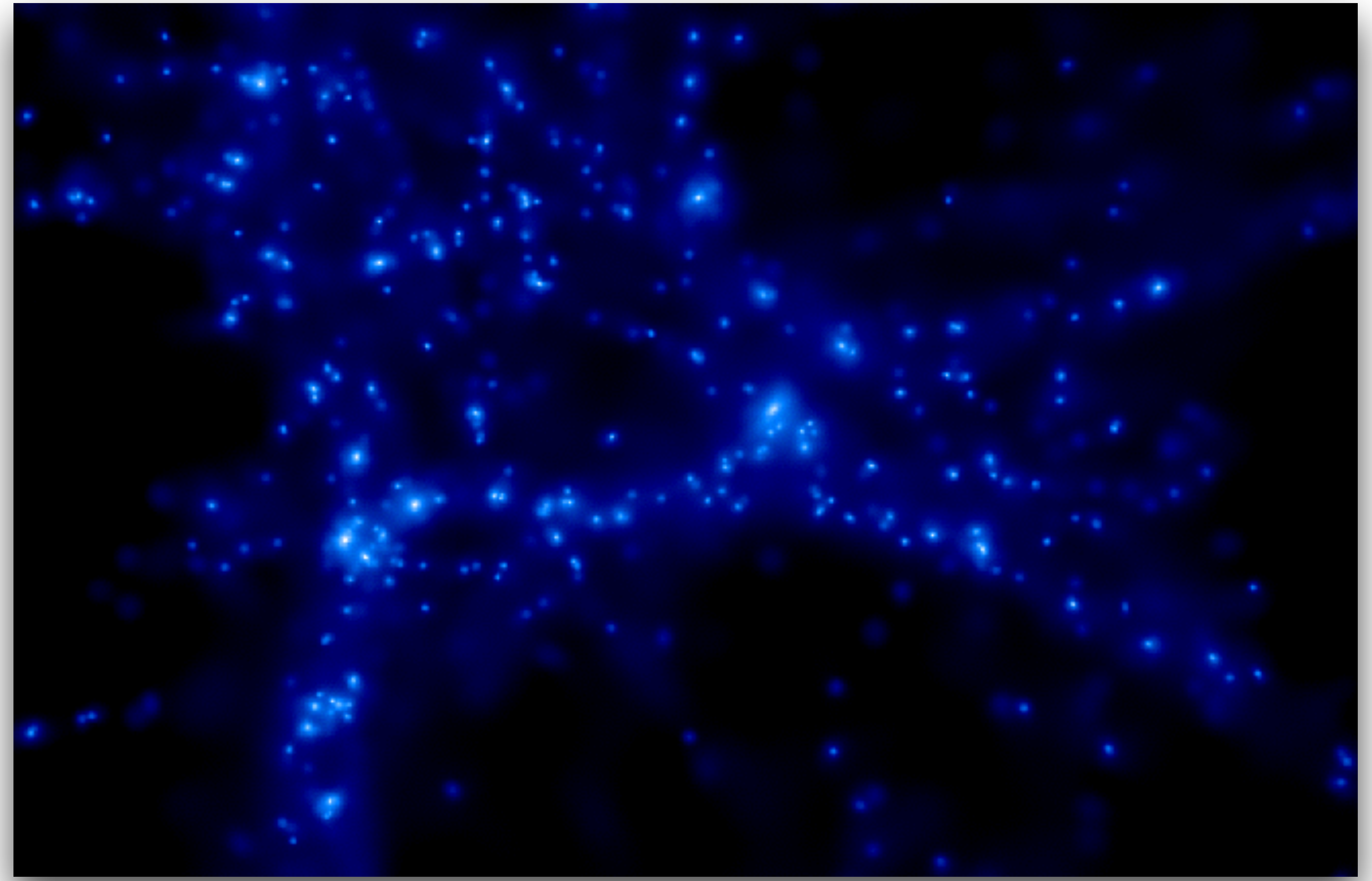

Paving the way for the next generation of cosmological surveys, Sesto, July 2018

- Foregrounds induce spurious power:

$$1+\delta_{obs} \simeq (1+\varepsilon)\,(1+\delta_{true})$$

$$\langle \delta_{obs,1}\delta_{obs,2}\rangle = \langle \delta_{true,1}\delta_{true,2}\rangle + \langle \varepsilon_1\varepsilon_2\rangle + \langle \delta_{true,1}\delta_{true,2}\rangle\langle \varepsilon_1\varepsilon_2\rangle$$

where $\varepsilon = \delta L/L_0$ is a modulation of the survey depth

- But if the true measure gives $\langle \delta_{true,1}\delta_{true,2}\rangle=0$, then one can measure the foreground from $\langle \delta_{obs,1}\delta_{obs,2}\rangle$

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Synergies vs Systematics

$$s^{\rm obs} = s + s^{\rm sys}$$

$$\langle s^{\rm obs} s^{\rm obs} \rangle = \langle ss \rangle + \cancel{2\langle s s^{\rm sys} \rangle} + \langle s^{\rm sys} s^{\rm sys} \rangle$$

$$\langle s^{\rm obs}_{(o)} s^{\rm obs}_{(r)} \rangle = \langle ss \rangle + \cancel{\langle s_{(r)} s^{\rm sys}_{(o)} \rangle} + \cancel{\langle s_{(o)} s^{\rm sys}_{(r)} \rangle} + \cancel{\langle s^{\rm sys}_{(o)} s^{\rm sys}_{(r)} \rangle}$$

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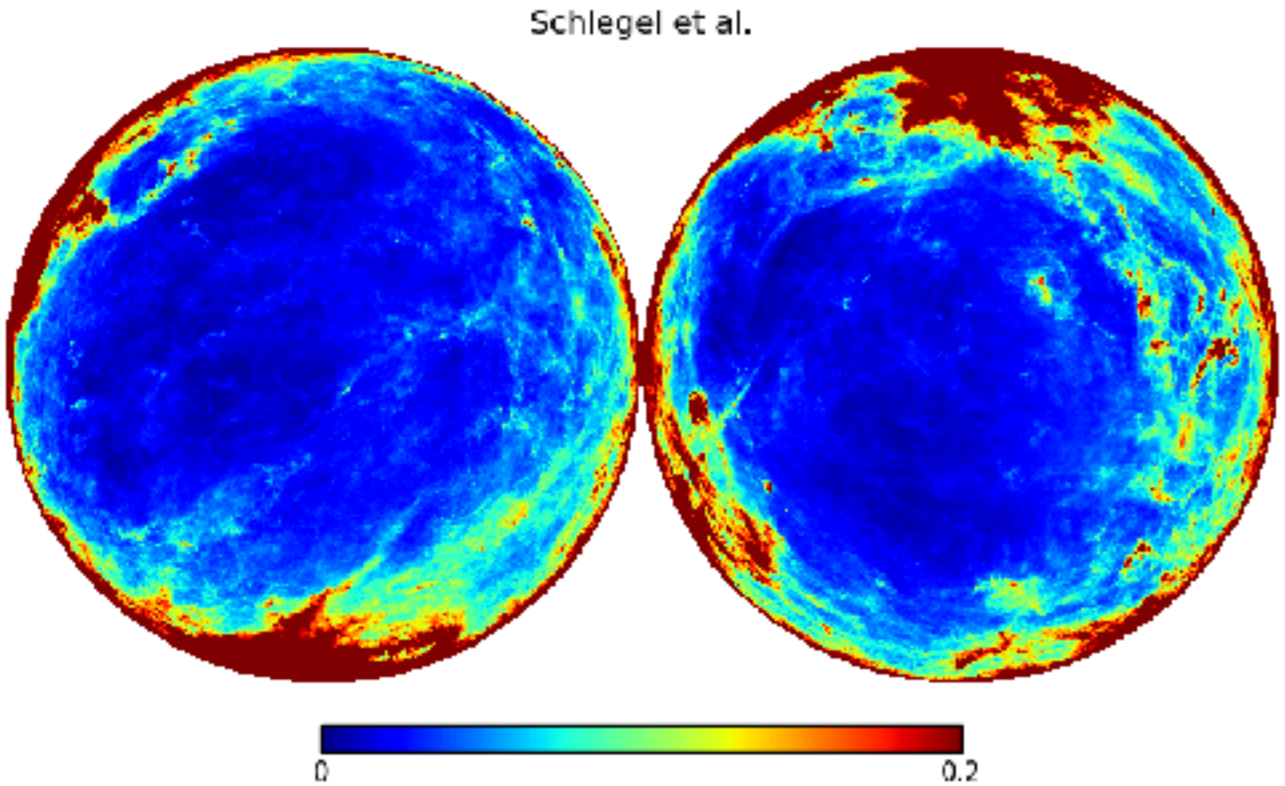
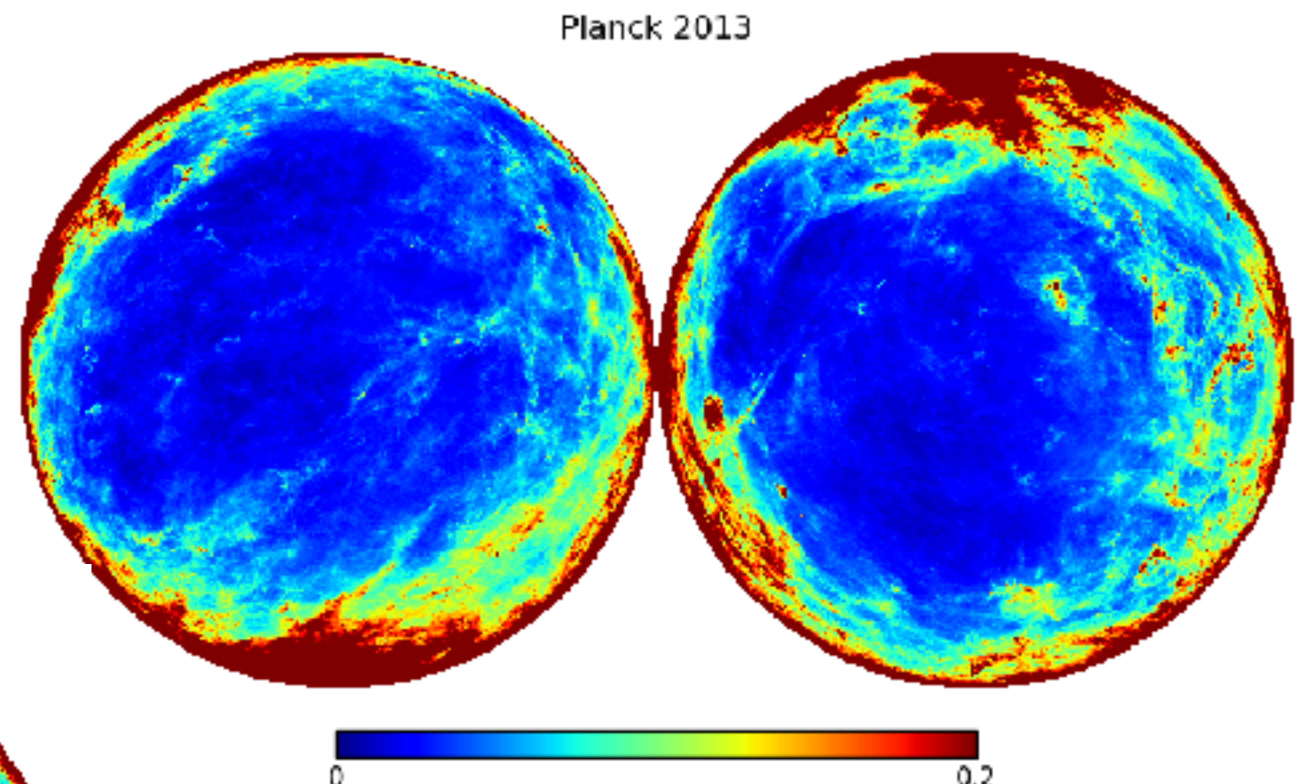
- Contribution to galaxy density cross-correlation:
    - vanishing correlations from large-scale structure
    - foreground contamination
    - gravitational lensing
    - catastrophic redshift errors

Prototypical foreground: Milky Way extinction

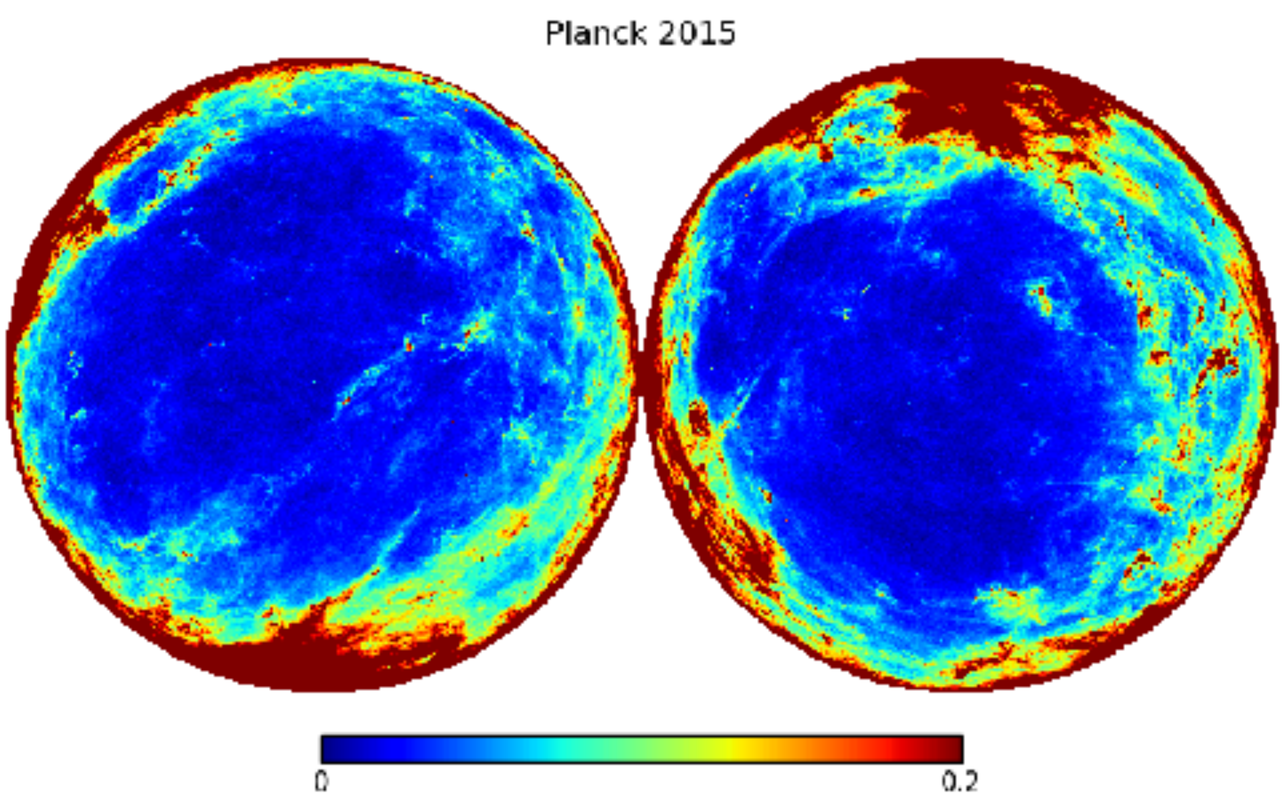
SFD



P13



P15

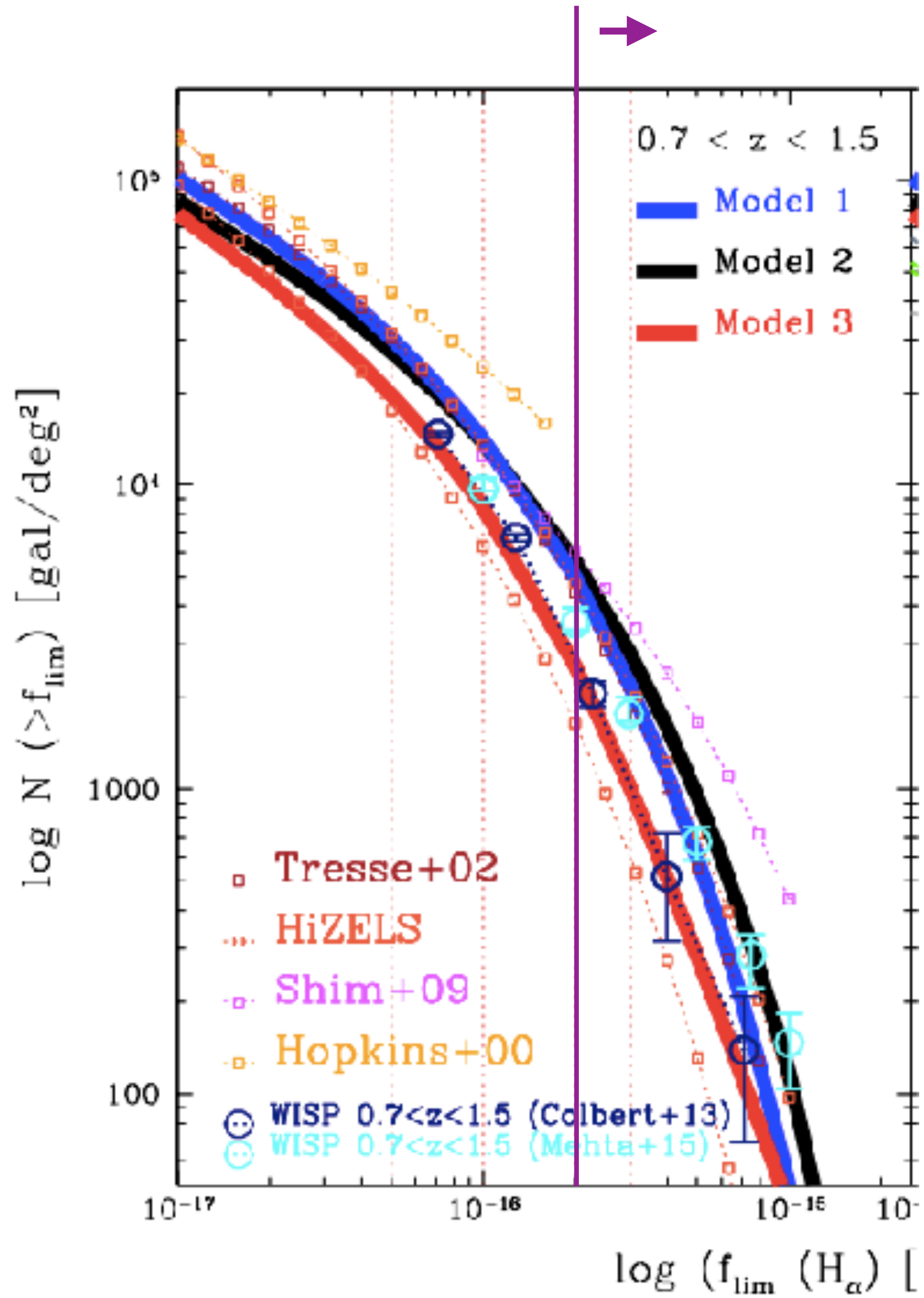


The observed number of galaxies:

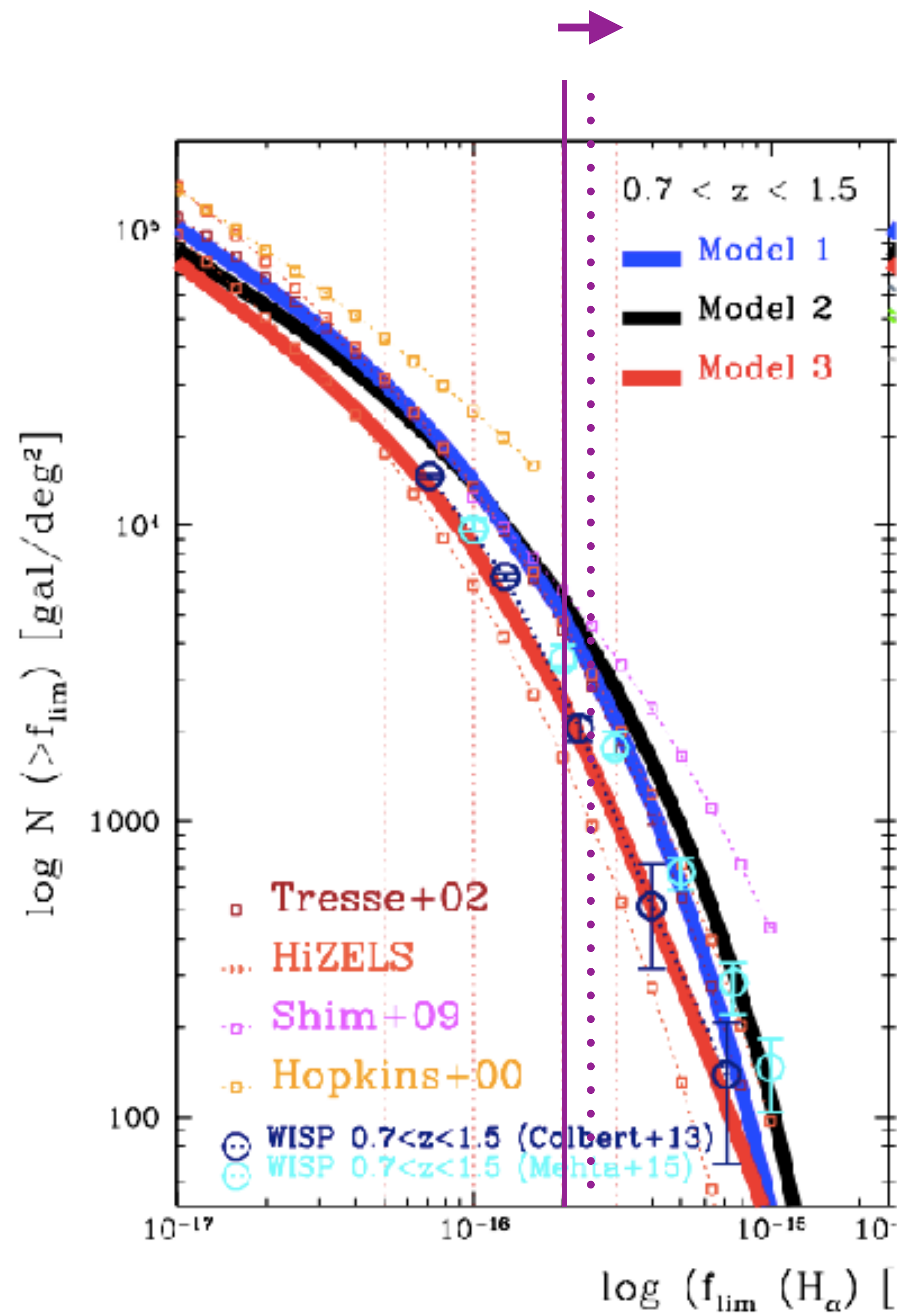
$$n_o(\mathbf{x}) = \int_{L_{\rm lim}}^{\infty} \Phi_{\rm local}(L|\mathbf{x}) dL$$

$$\Phi_{\rm local}(L|\mathbf{x}) = [1 + \delta_g(\mathbf{x})]\Phi(L|z)$$

under the assumption of a universal LF



Pozzetti et al. (2016)



The observed number of galaxies is subject to modulations of survey depth.

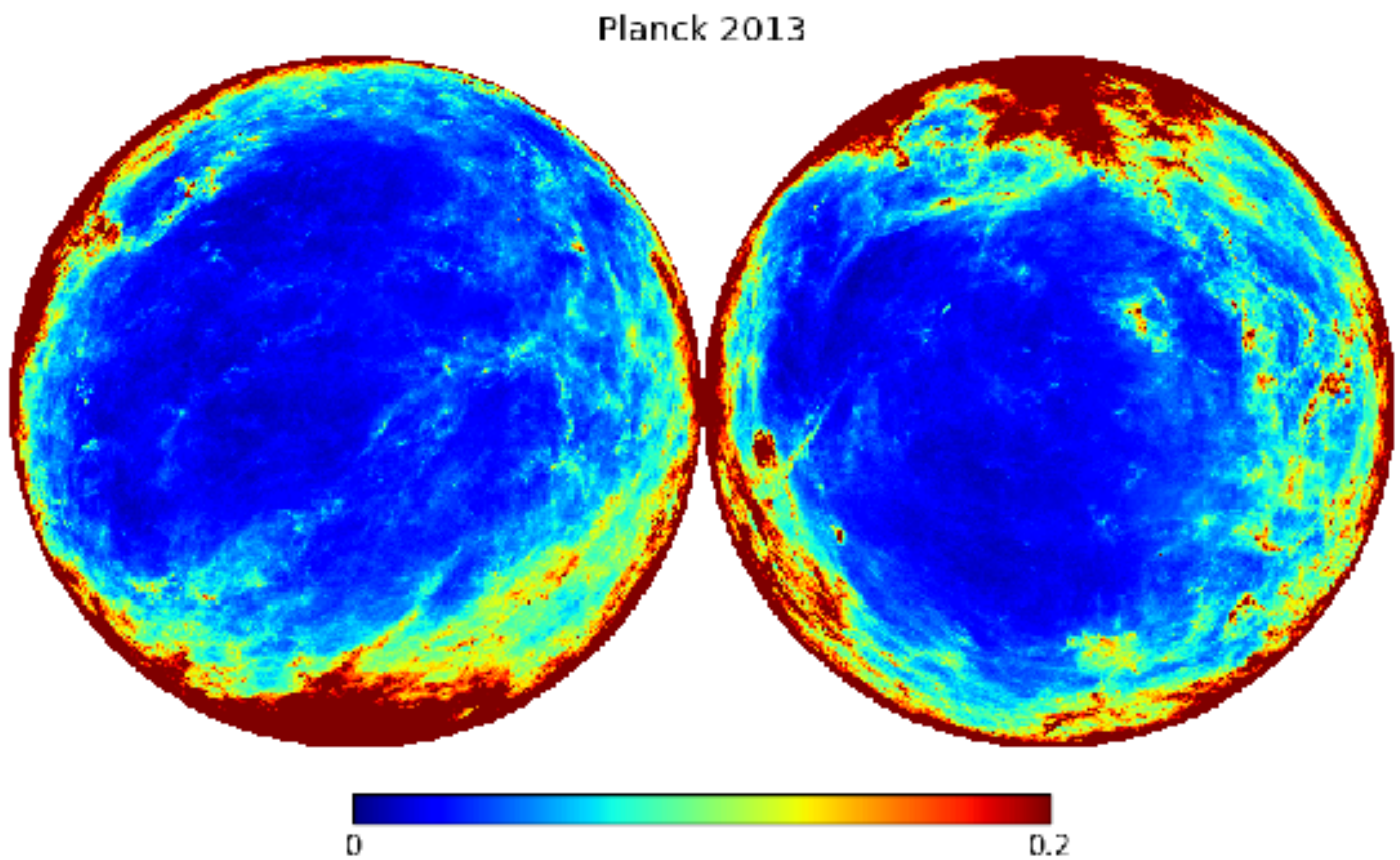
A second-order expansion in δL/L gives:

$$n_o(\mathbf{x}) = \int_{L_0+\delta L(\boldsymbol{\theta})}^{\infty} [1 + b_1(L)\delta(\mathbf{x})]\Phi(L)dL$$

$$\simeq \langle n\rangle[1 + \bar{b}_1(L_0)\delta(\mathbf{x})] - \boxed{\Phi(L_0)[1 + b_1(L_0)\delta(\mathbf{x})]\delta L} - \boxed{\frac{1}{2}\frac{d}{dL}[\Phi(L)(1 + b_1(L)\delta(\mathbf{x}))]_{L_0}(\delta L)^2}$$

This involves luminosity dependence of bias

$$\mathcal{M}(\boldsymbol{\theta}) = E(B-V)$$



Planck maps have been resampled to the same resolution of SFD

The (purely angular) mask has an impact that depends on redshift

$$\boxed{C(z) = 0.4 \ln 10\, R(z)}$$

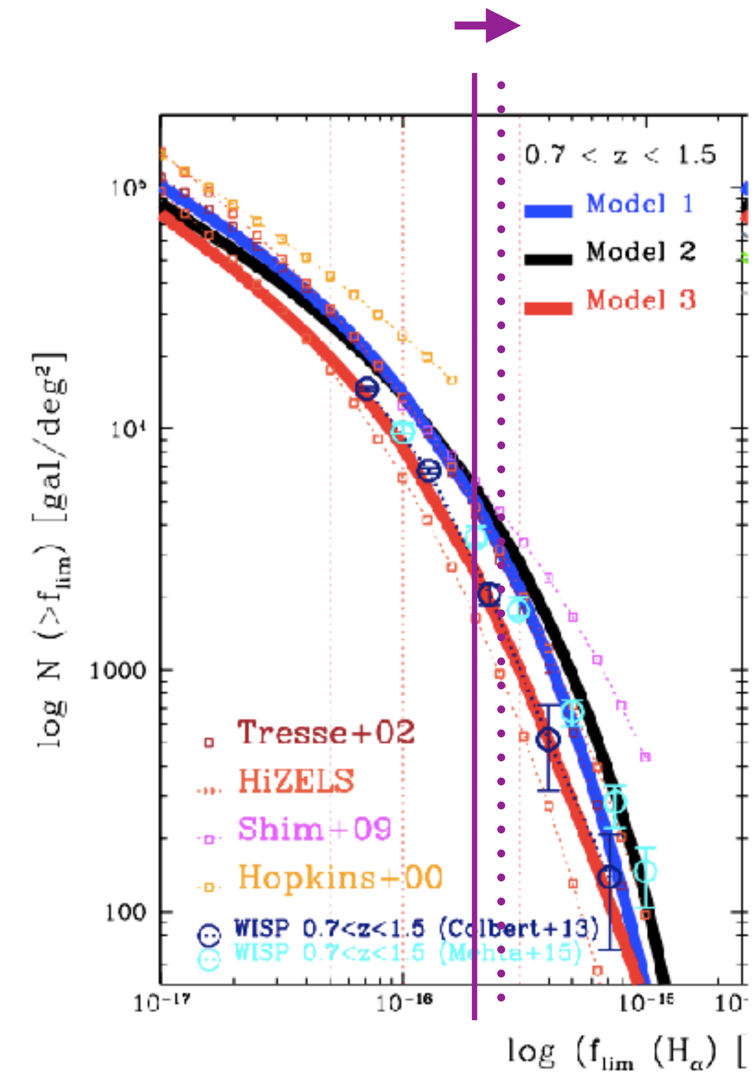
this is proportional to the extinction curve

$$\epsilon(\boldsymbol{\theta}) = \exp[C(z)\,\mathcal{M}(\boldsymbol{\theta})] - 1 \simeq C(z)\mathcal{M}(\boldsymbol{\theta}) + \frac{1}{2}C^2(z)\mathcal{M}^2(\boldsymbol{\theta})$$

But the mask changes the average density

$$\langle n\rangle(z) = B_1(z)\Phi(L_0|z)L_0(z) \qquad B_2(z) = \frac{d\Phi}{dL}(L_0|z)\frac{L_0(z)}{2\Phi(L_0|z)} + \frac{1}{2}$$

these functions depend on the shape of the luminosity function



$$\frac{\langle n_o\rangle}{\Phi L_0} = B_1 - \langle\epsilon\rangle - \left(B_2 - \frac{1}{2}\right)\langle\epsilon^2\rangle$$

$$\delta_o = \frac{n_o}{\langle n_o\rangle} - 1 \simeq \boxed{\frac{B_1\bar{b}_1 - C\mathcal{M}b_1 - B_2C^2\mathcal{M}^2b_1 - \left(B_2 - \frac{1}{2}\right)C^2\mathcal{M}^2b_1'\frac{\Phi}{\Phi'}}{B_1 - C\langle\mathcal{M}\rangle - B_2C^2\langle\mathcal{M}^2\rangle}} \times \delta$$

$$\boxed{-\frac{C\left(\mathcal{M} - \langle\mathcal{M}\rangle\right) + B_2C^2\left(\mathcal{M}^2 - \langle\mathcal{M}^2\rangle\right)}{B_1 - C\langle\mathcal{M}\rangle - B_2C^2\langle\mathcal{M}^2\rangle}}$$

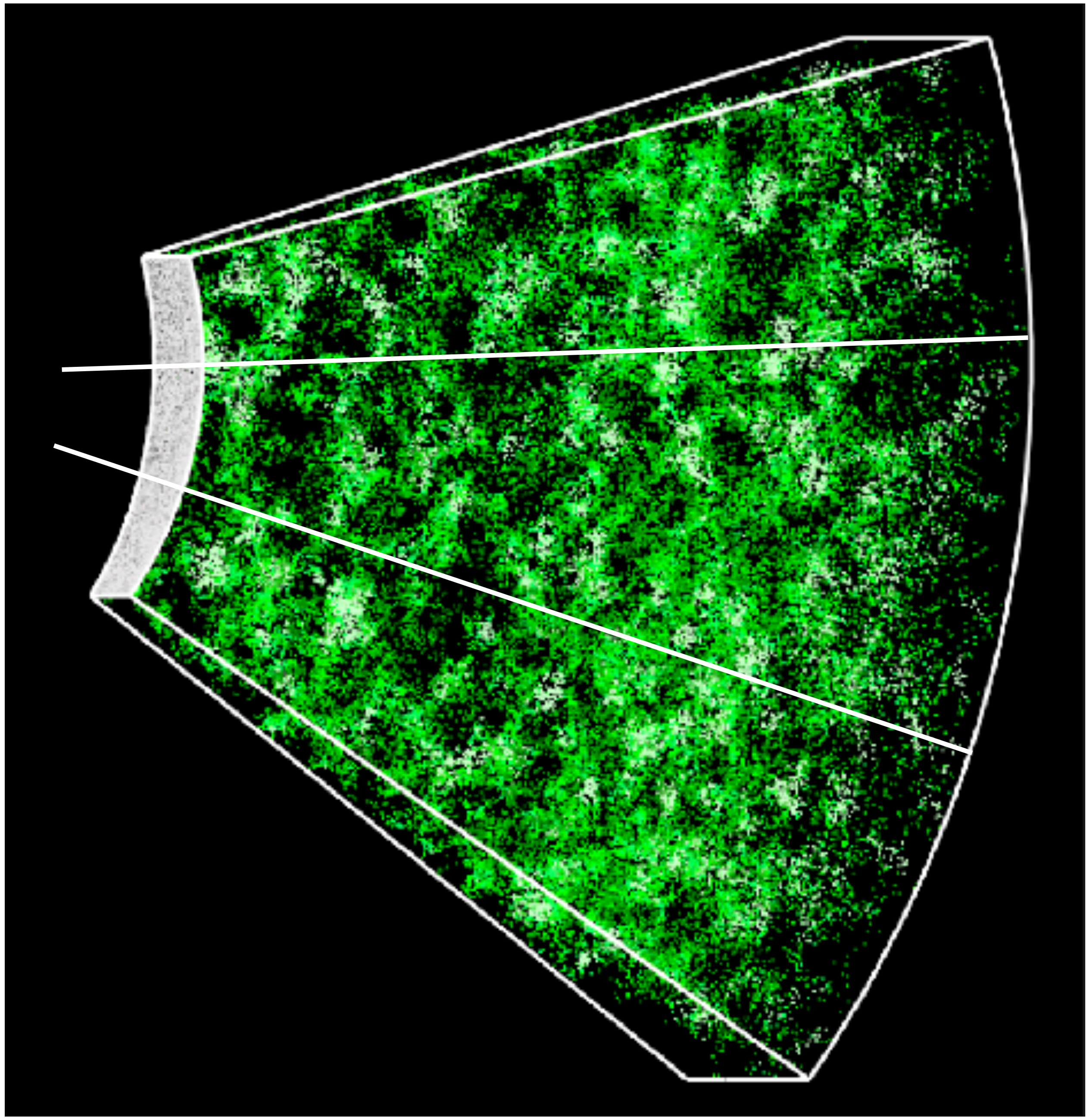
this is the cosmological signal
and it averages out for our estimators

this is the effect of the mask

Define estimators that are sensitive to the "mask" M:

$$Avz(\boldsymbol{\theta}) \equiv \frac{1}{N_z} \sum_i \delta_o([z_i, \boldsymbol{\theta}])$$

$$Ccz(\boldsymbol{\theta}) \equiv \frac{1}{N_p} \sum_i \sum_{j>i} \delta_o([z_i, \boldsymbol{\theta}])\delta_o([z_j, \boldsymbol{\theta}])$$



If prior knowledge of <M> and <M^2> is assumed:

$$\bar{\delta}_o = \frac{n_o}{\langle n \rangle} - 1 \simeq \frac{B_1 \bar{b}_1 - C\mathscr{M} b_1 - B_2 C^2 \mathscr{M}^2 b_1 + \left(B_2 - \frac{1}{2}\right) C^2 \mathscr{M}^2 b_1' \frac{\Phi}{\Phi'}}{B_1} \times \delta - \frac{C\mathscr{M} + B_2 C^2 \mathscr{M}^2}{B_1}$$

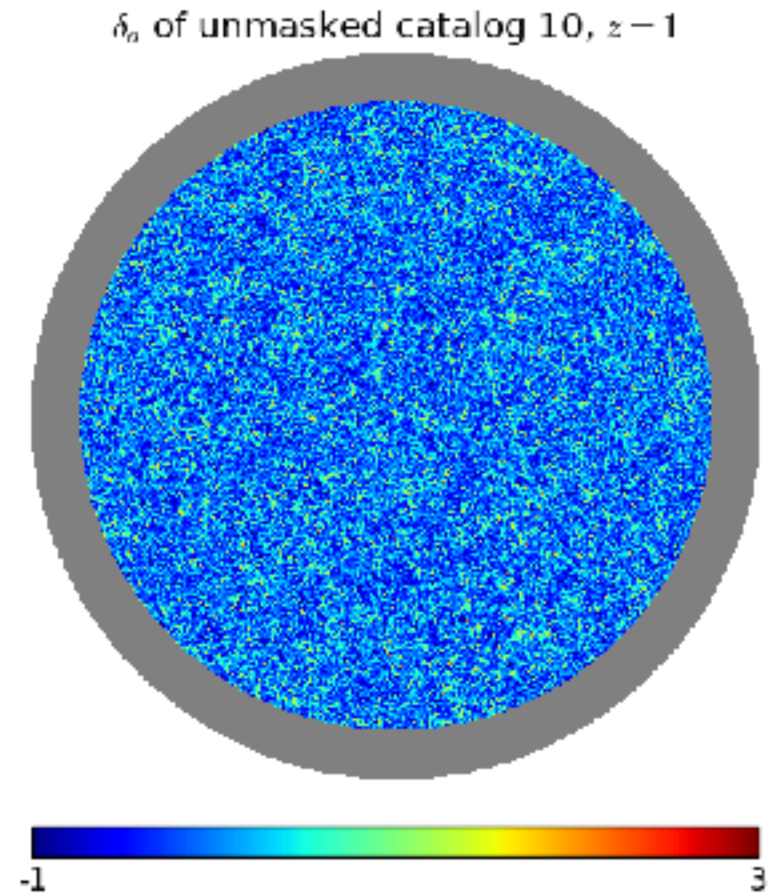
$$Avz(\boldsymbol{\theta}) \simeq \boxed{-\frac{1}{N_z} \sum_i \frac{C_i}{B_{1i}}} \mathscr{M} - \boxed{\frac{1}{N_z} \sum_i \frac{B_{2i} C_i^2}{B_{i1}}} \mathscr{M}^2 .$$

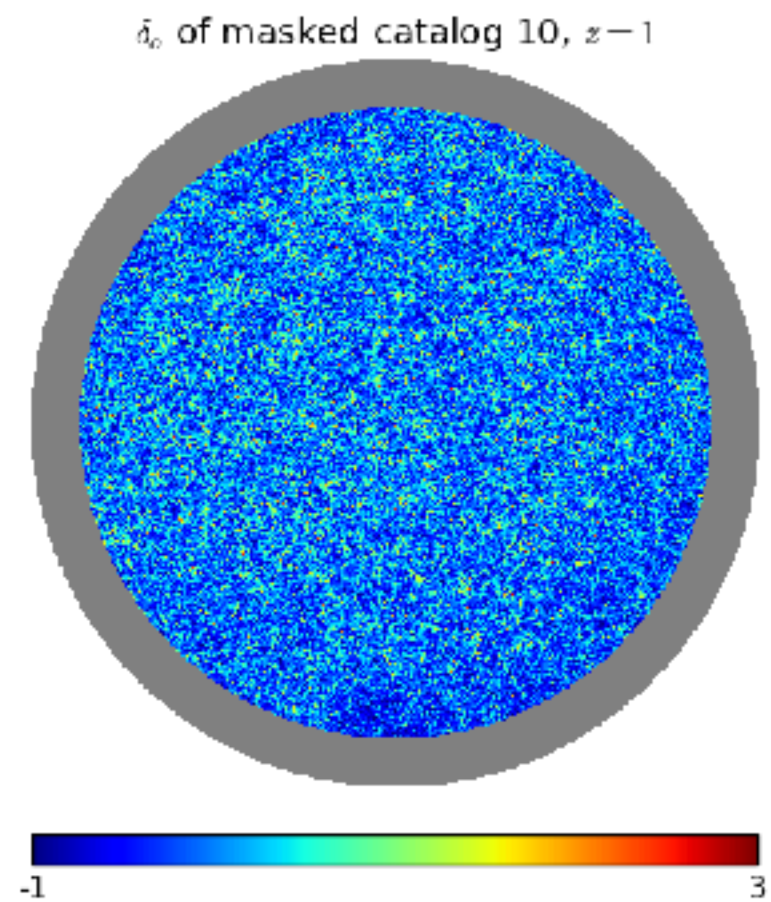
$$Ccz(\boldsymbol{\theta}) \simeq \boxed{\frac{1}{N_p} \sum_i \sum_{j>i} \frac{C_i C_j}{B_{1i} B_{1j}}} \mathscr{M}^2 + \boxed{\frac{1}{N_p} \sum_i \sum_{j>i} \frac{C_i C_j (B_{2i} C_i + B_{2j} C_j)}{B_{1i} B_{1j}}} \mathscr{M}^3 + \boxed{\frac{1}{N_p} \sum_i \sum_{j>i} \frac{B_{2i} B_{2j} C_i^2 C_j^2}{B_{1i} B_{1j}}} \mathscr{M}^4 .$$

these coefficients require knowledge
of the luminosity function
and of the redshift dependence of the mask impact

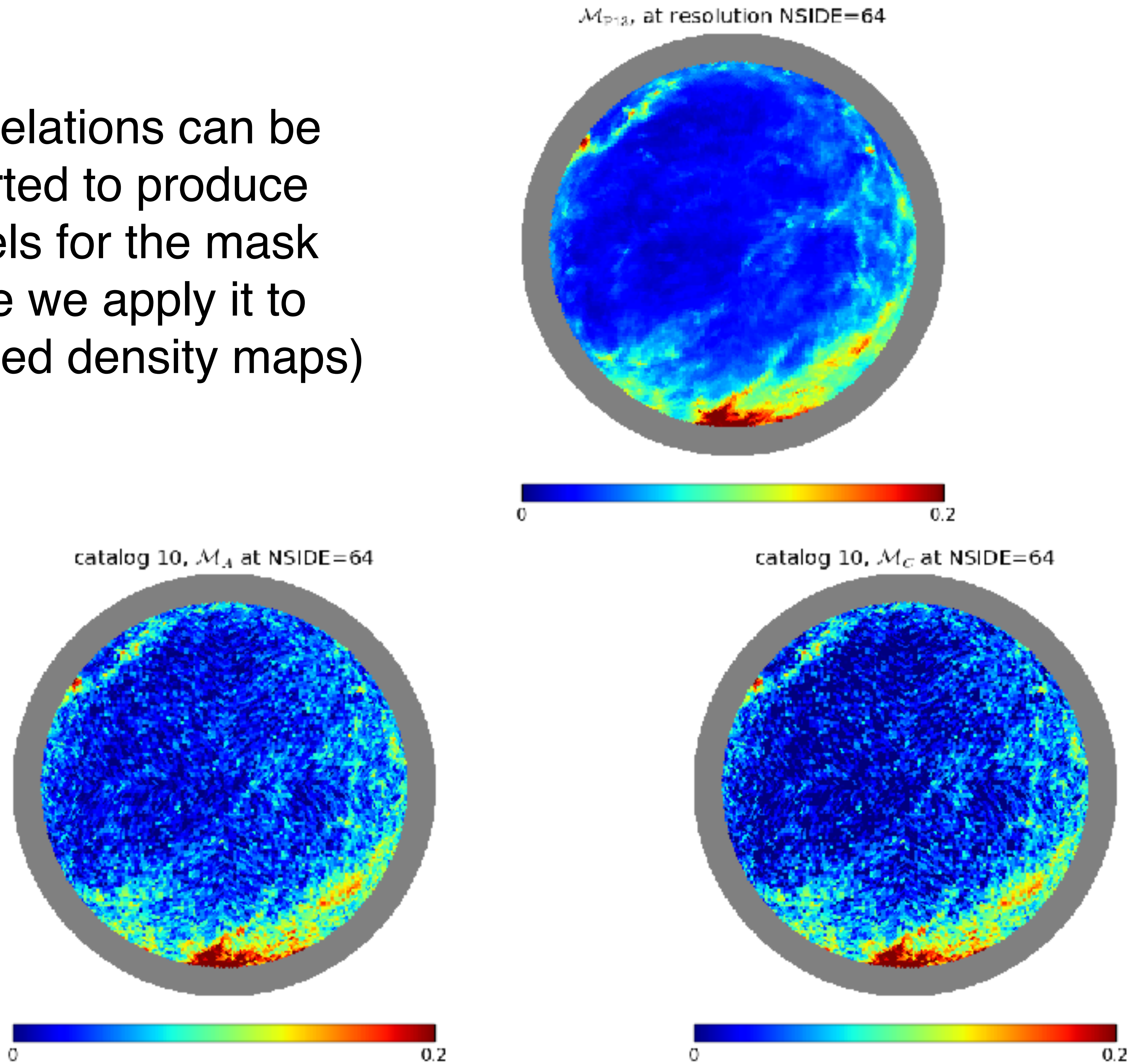
Mocks

- Generate 20 light cones with PINOCCHIO:
  - 3.2 Gpc/h box sampled with 4096^3 particles,
  - smallest halo 7.5 10^{11} M_{sun}/h (20 particles),
  - light cone from z=2.5 to z=0, covering 1/4 of the sky;
- abundance matching of halos with LF of Hα emitters, model 1 of Pozzetti et al. (2016);
- **“shuffled” masses** to **remove luminosity-dependent bias**;
- flux limit of 2 10^{-16} erg s^{-1} cm^{-2}, complete from z=0.8 to z=2.5;
- apply galactic extinction using P13 map;
- create density maps on the sky with healpy;
- redshift bins of delta z=0.1, no redshift error;





The relations can be inverted to produce models for the mask (here we apply it to smoothed density maps)



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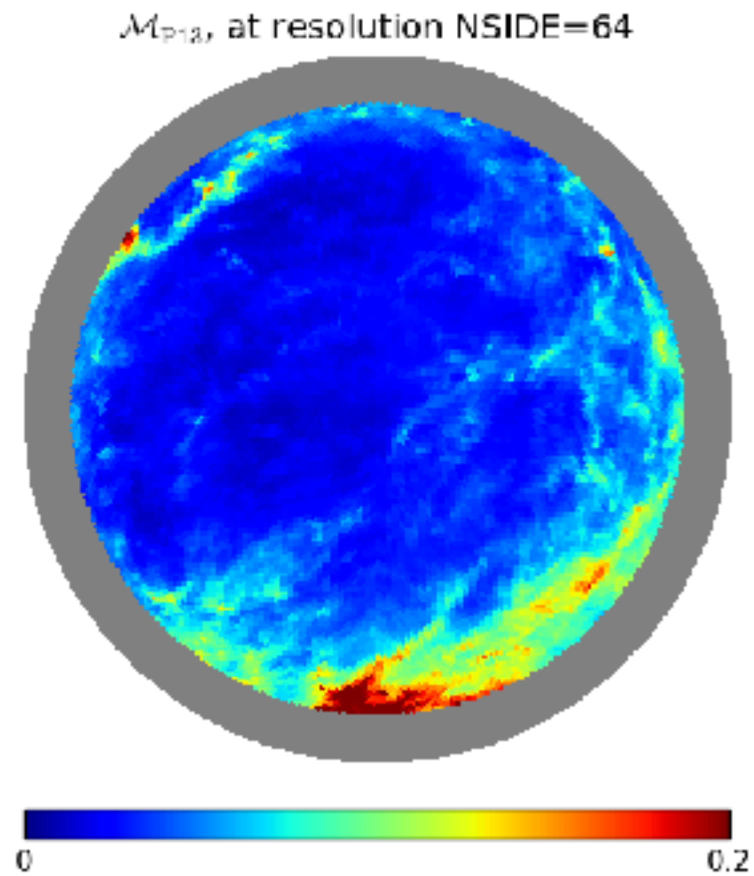
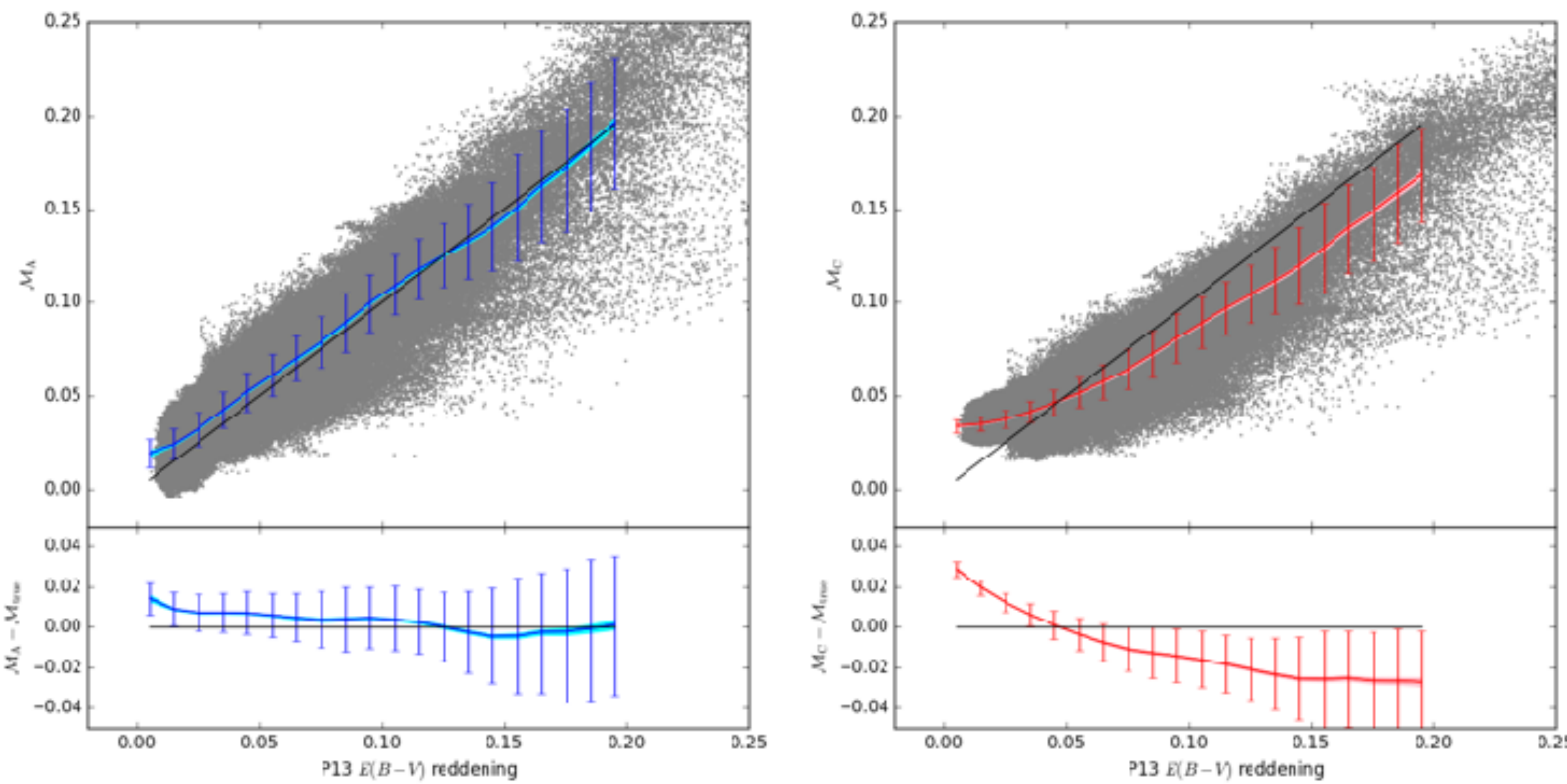
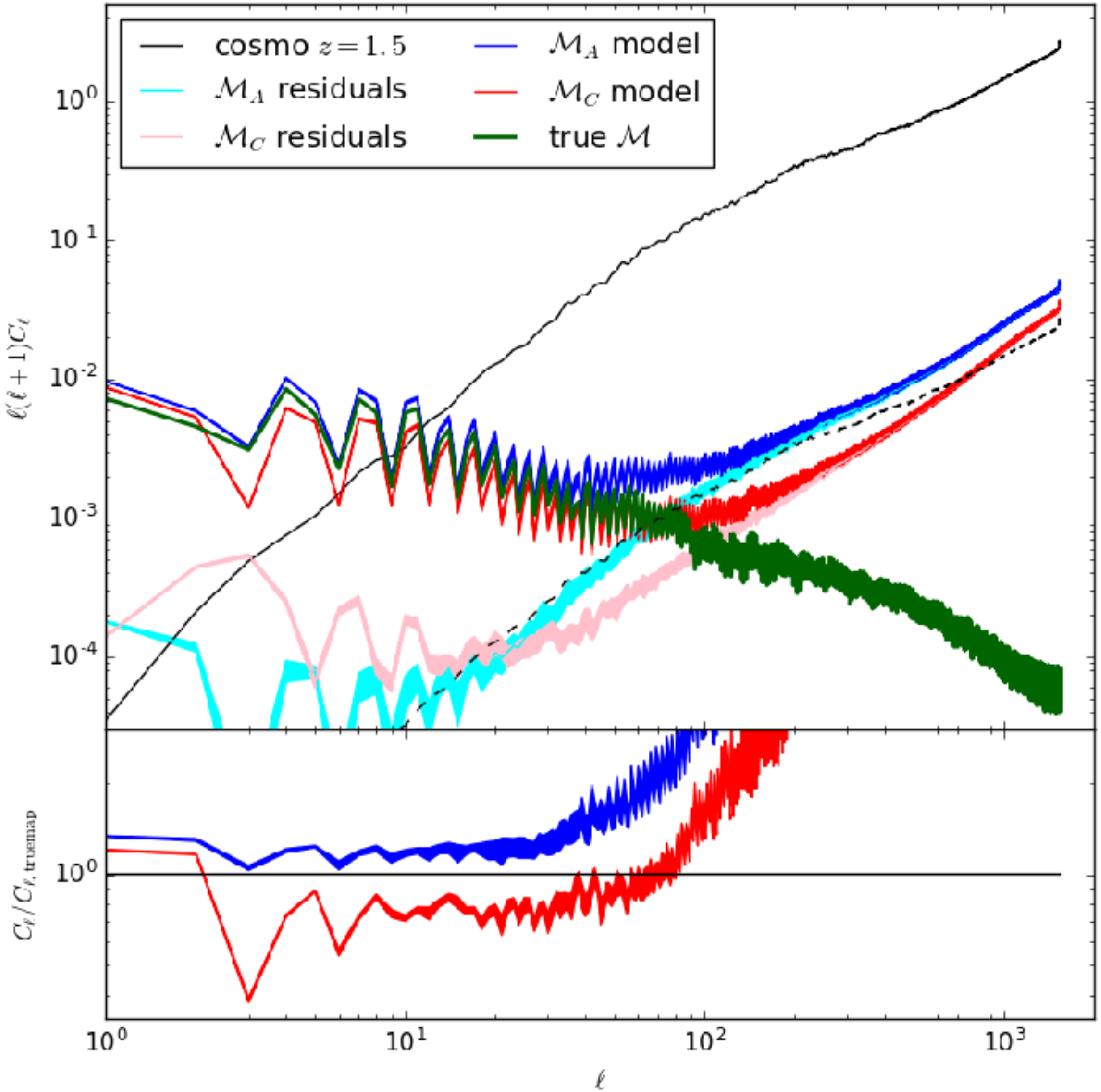




Here we compute M_A and M_C on the full resolution density maps

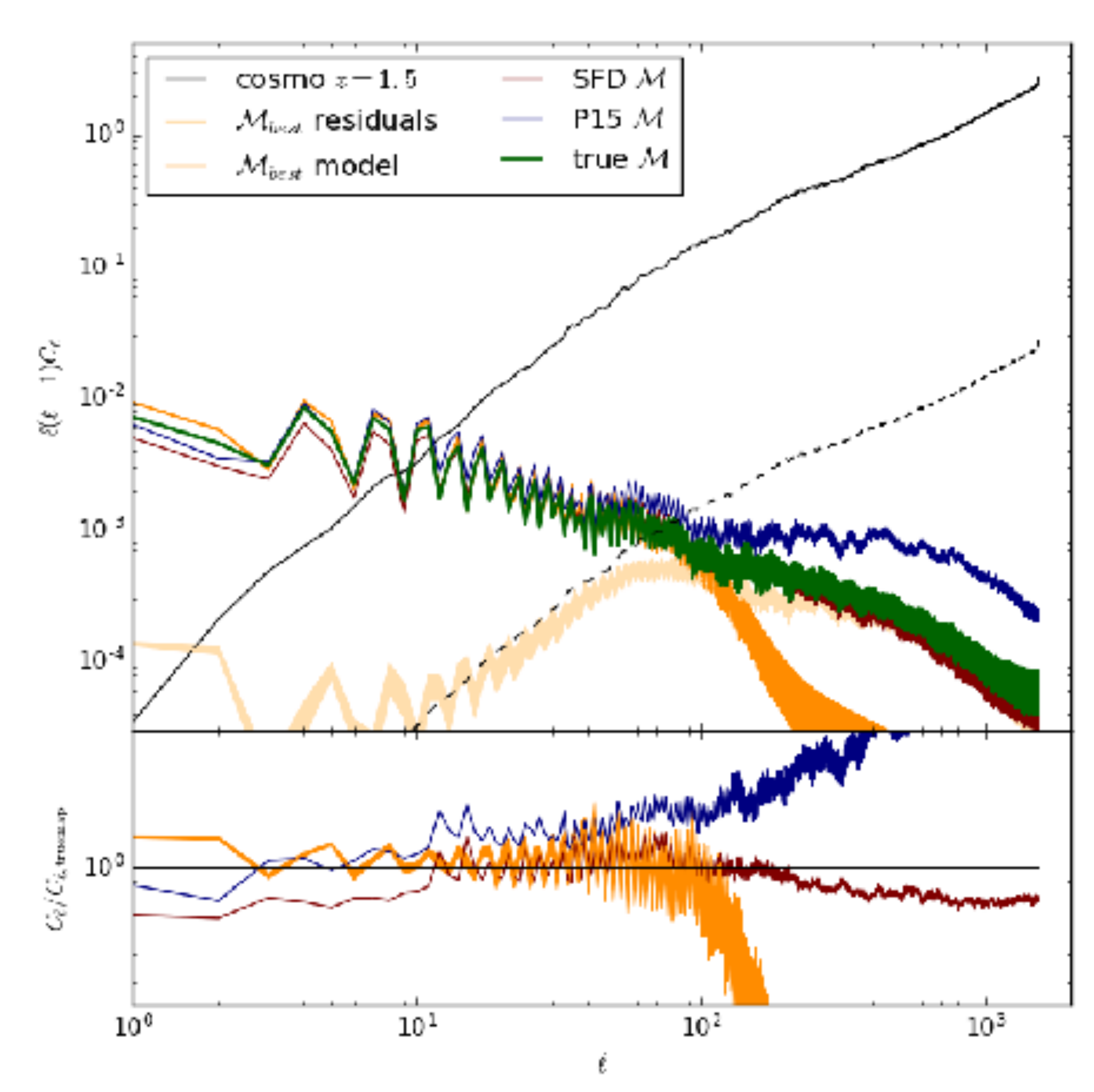
Residuals with respect to the true mask correlate with the cosmic signal

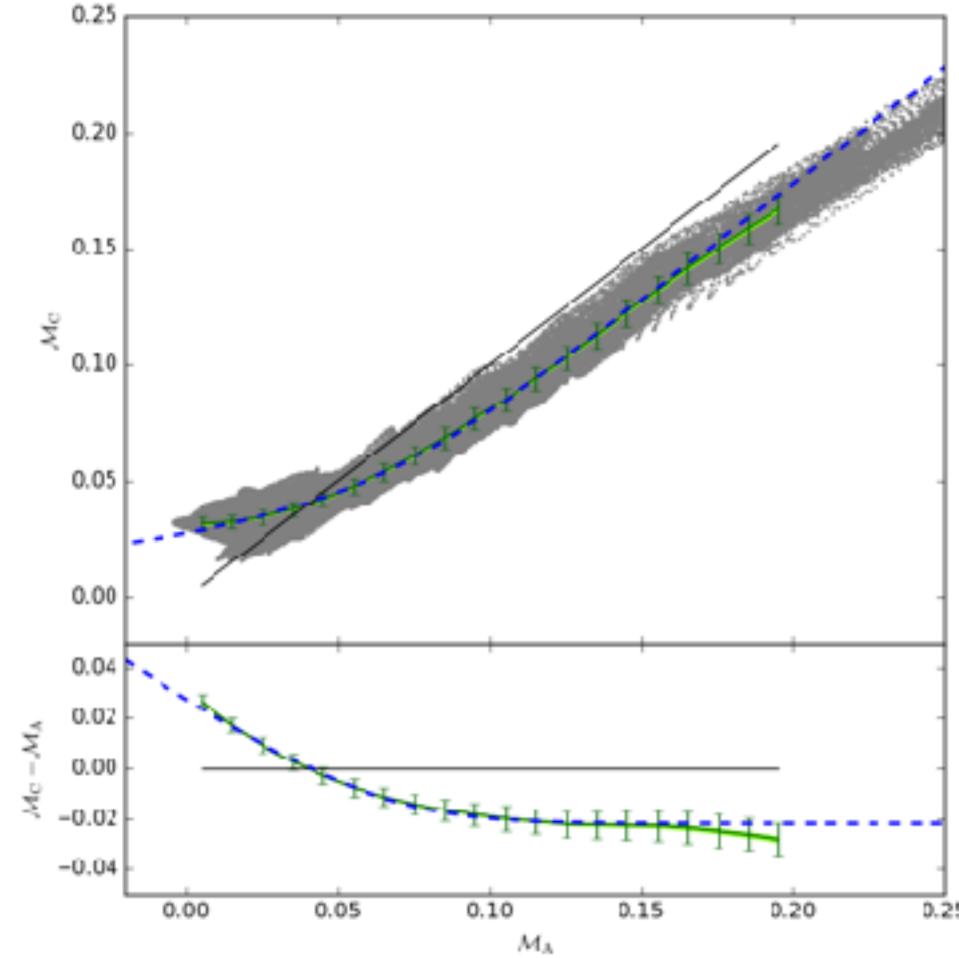
The model M_C based on Ccz has lower residuals

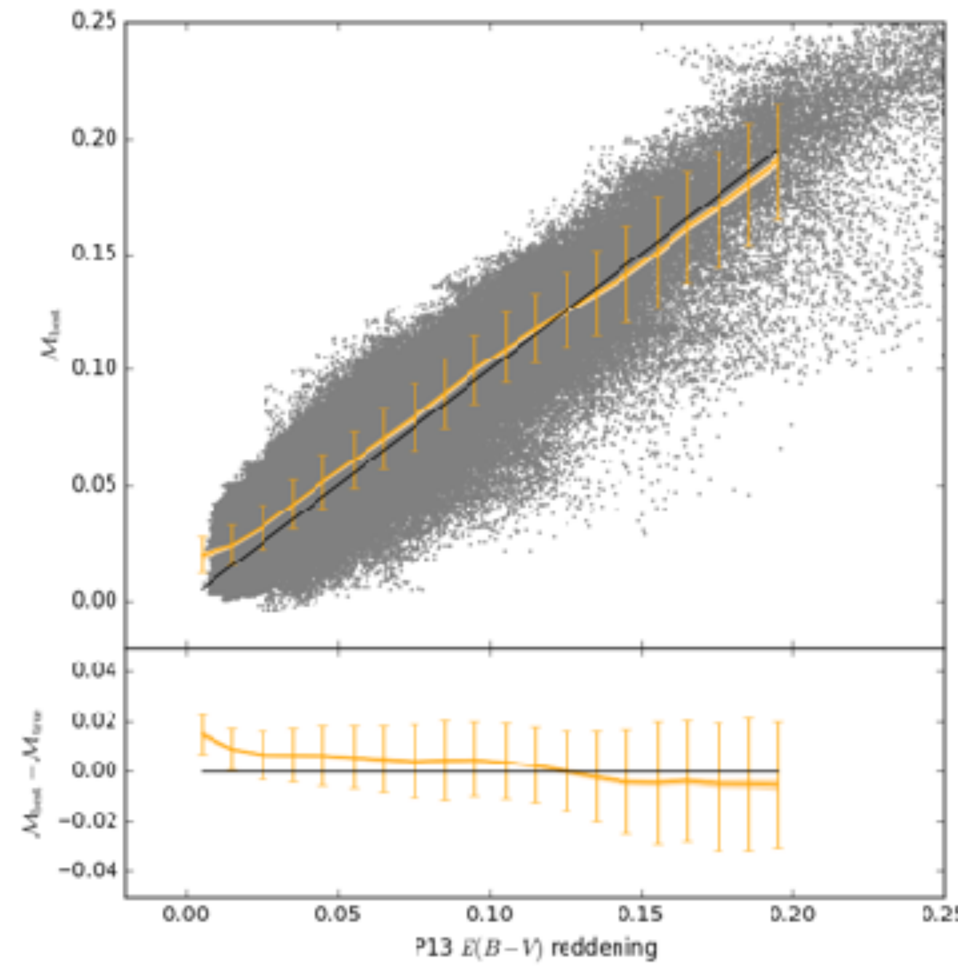


- smooth both models to fiter residuals out
- find the relation $f(M_A)$ between M_A and M_C
- combine them as:

$$\mathcal{M}_{\text{best}} = \mathcal{M}_C - (f(\mathcal{M}_A) - \mathcal{M}_A)$$







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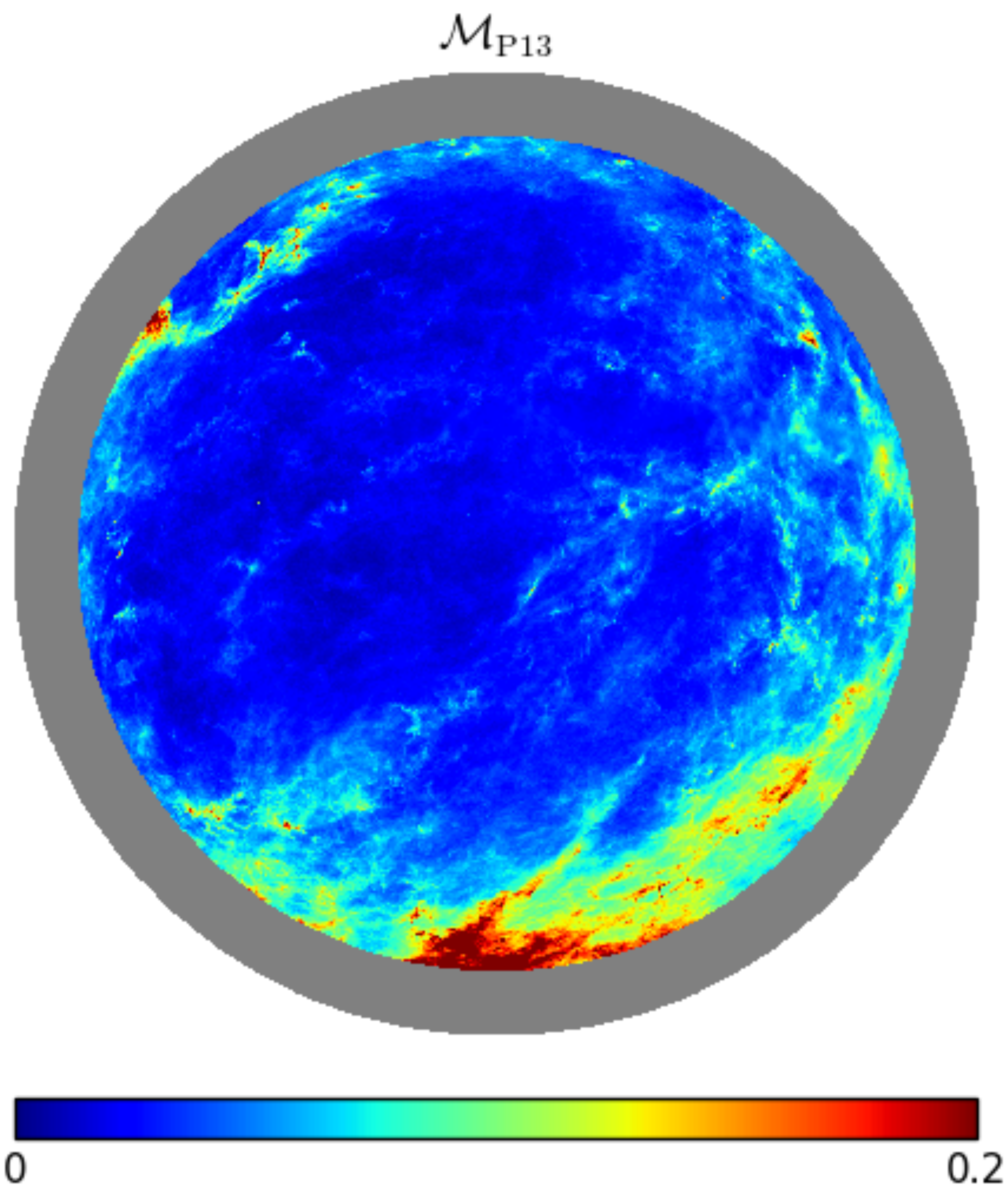
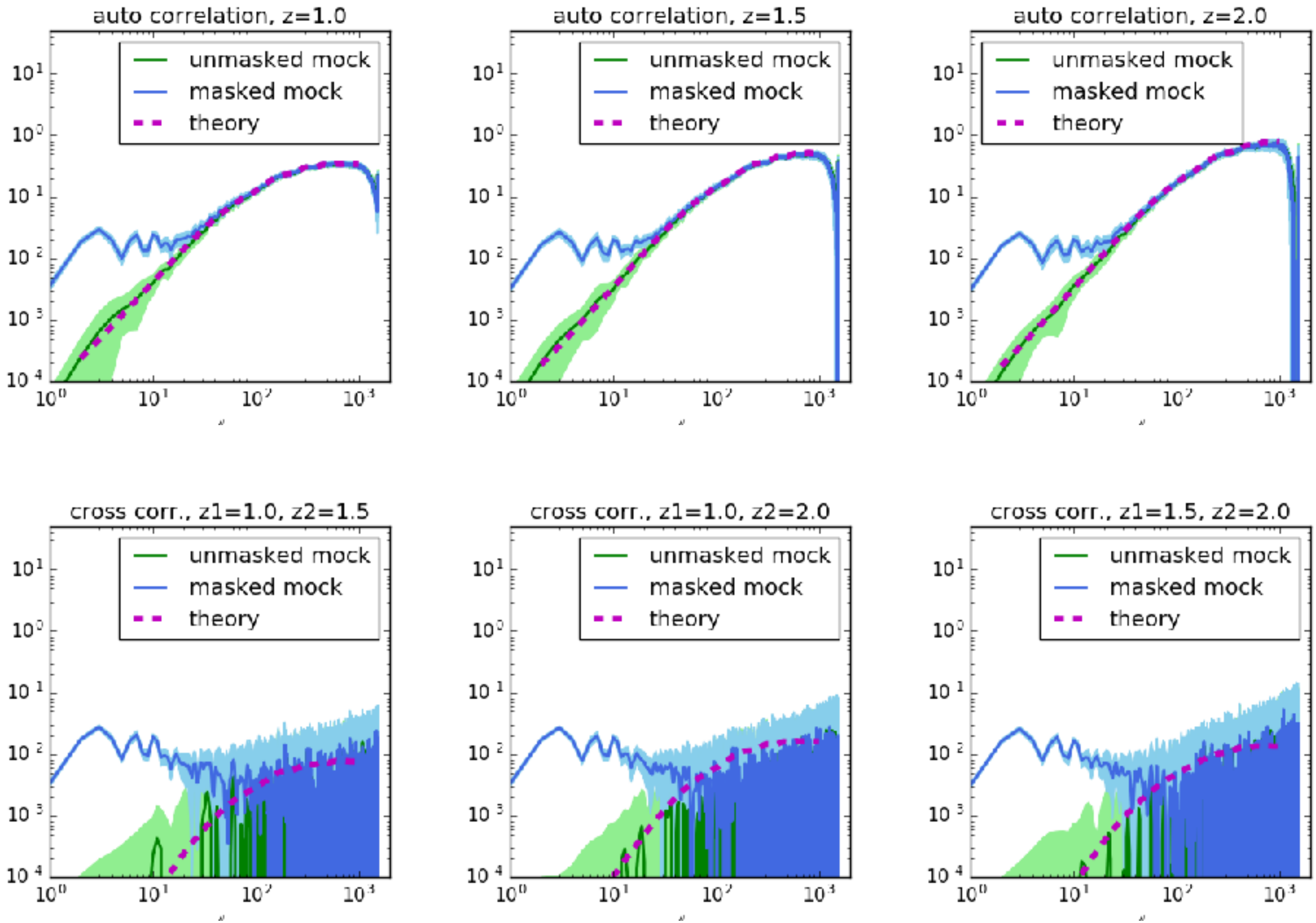
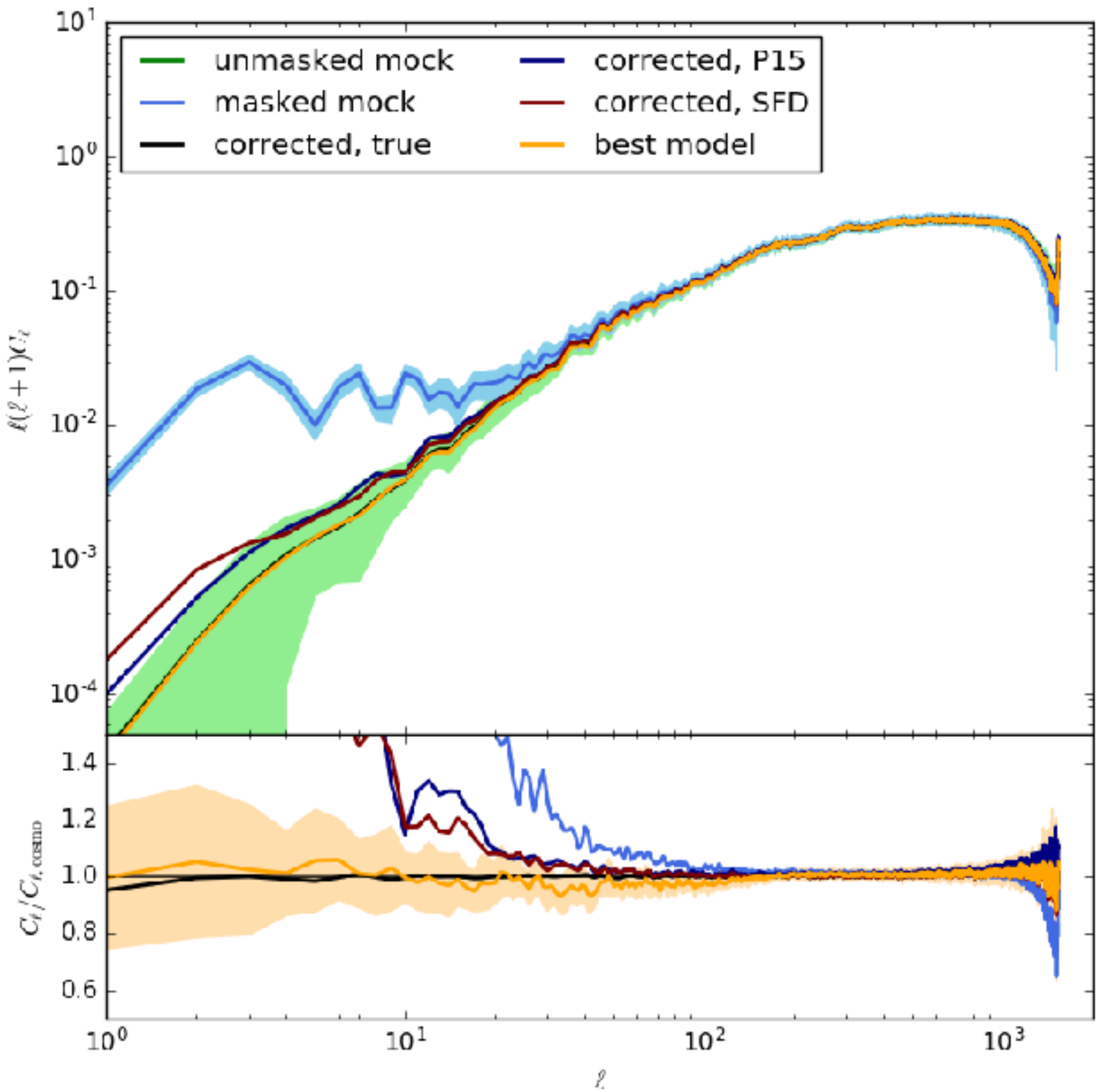
2018


$\mathcal{M}_{\rm P13}$
catalog 10, $\mathcal{M}_{\rm best}$
0
0.2
0
0.2

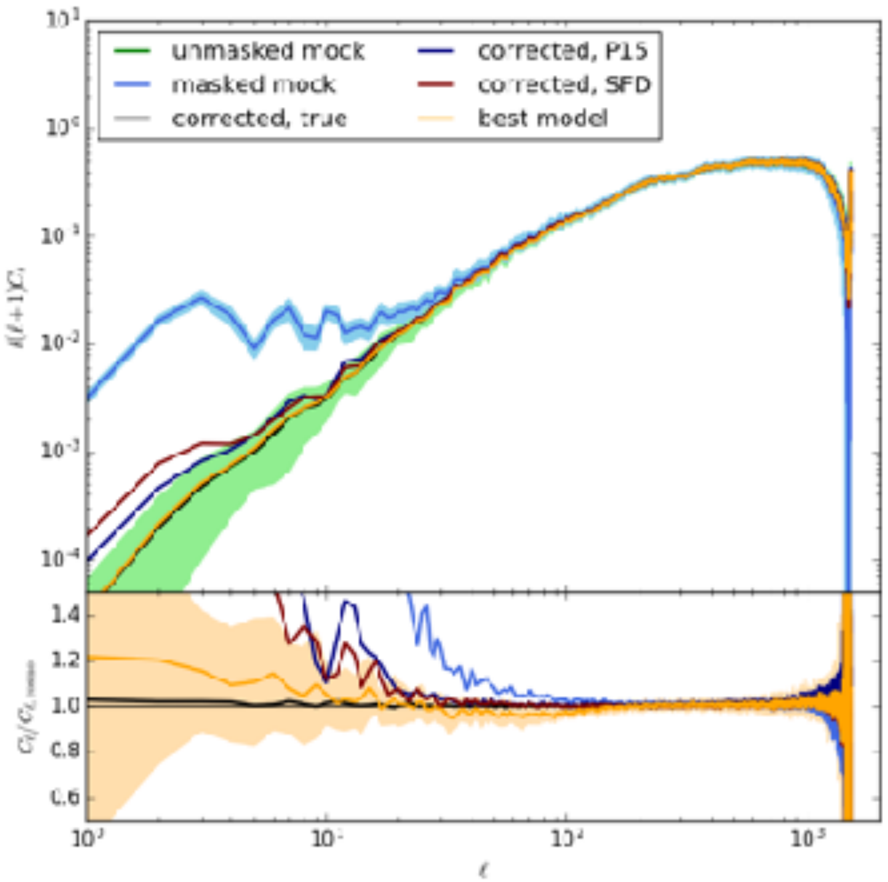

auto correlation, z=1.0
auto correlation, z=1.5
auto correlation, z=2.0
cross corr., z1=1.0, z2=1.5
cross corr., z1=1.0, z2=2.0
cross corr., z1=1.5, z2=2.0
unmasked mock
masked mock
theory

$$\delta_\mathrm{g} = \frac{\left(B_1 - C\langle \mathscr{M} \rangle - B_2 C^2 \langle \mathscr{M}^2 \rangle\right)\delta_\mathrm{o} + C(\mathscr{M} - \langle \mathscr{M} \rangle) + B_2 C^2 (\mathscr{M}^2 - \langle \mathscr{M}^2 \rangle)}{B_1 - C\mathscr{M} - B_2 C^2 \mathscr{M}^2}$$

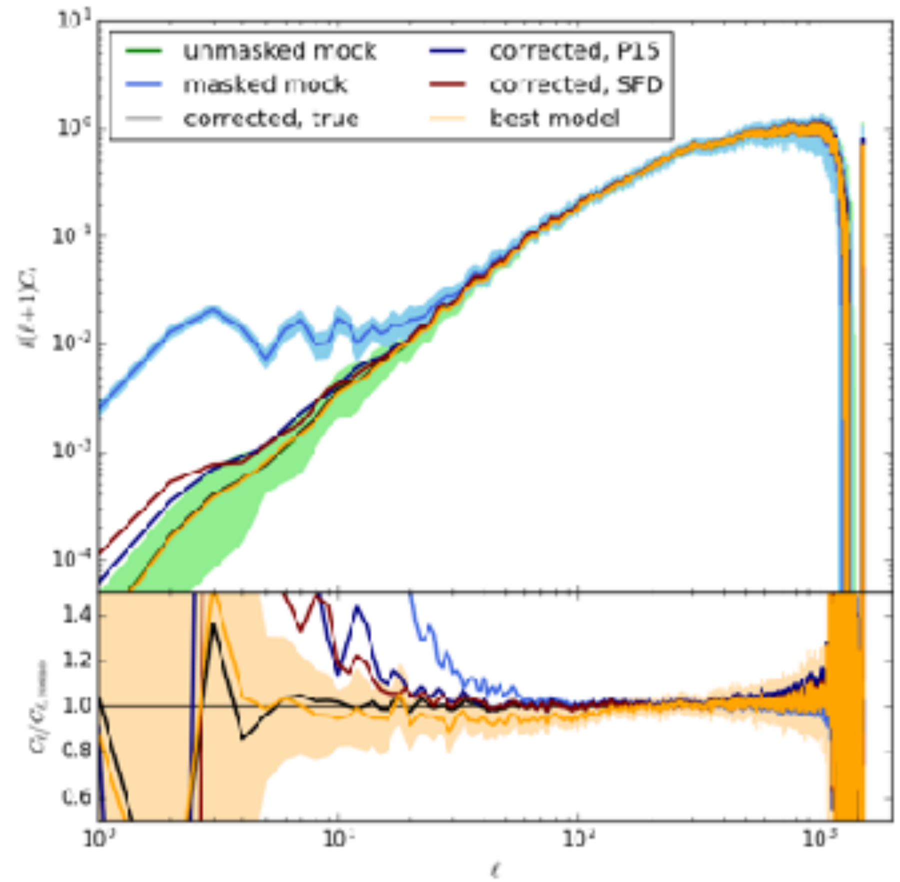
z=1



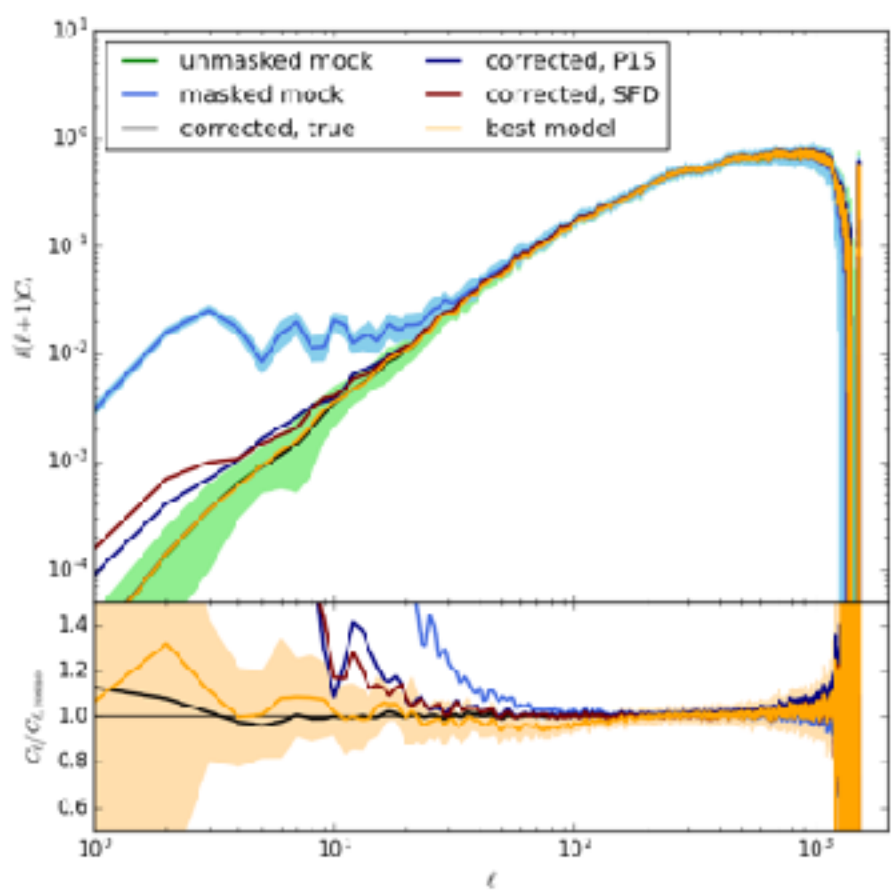
z=1.5

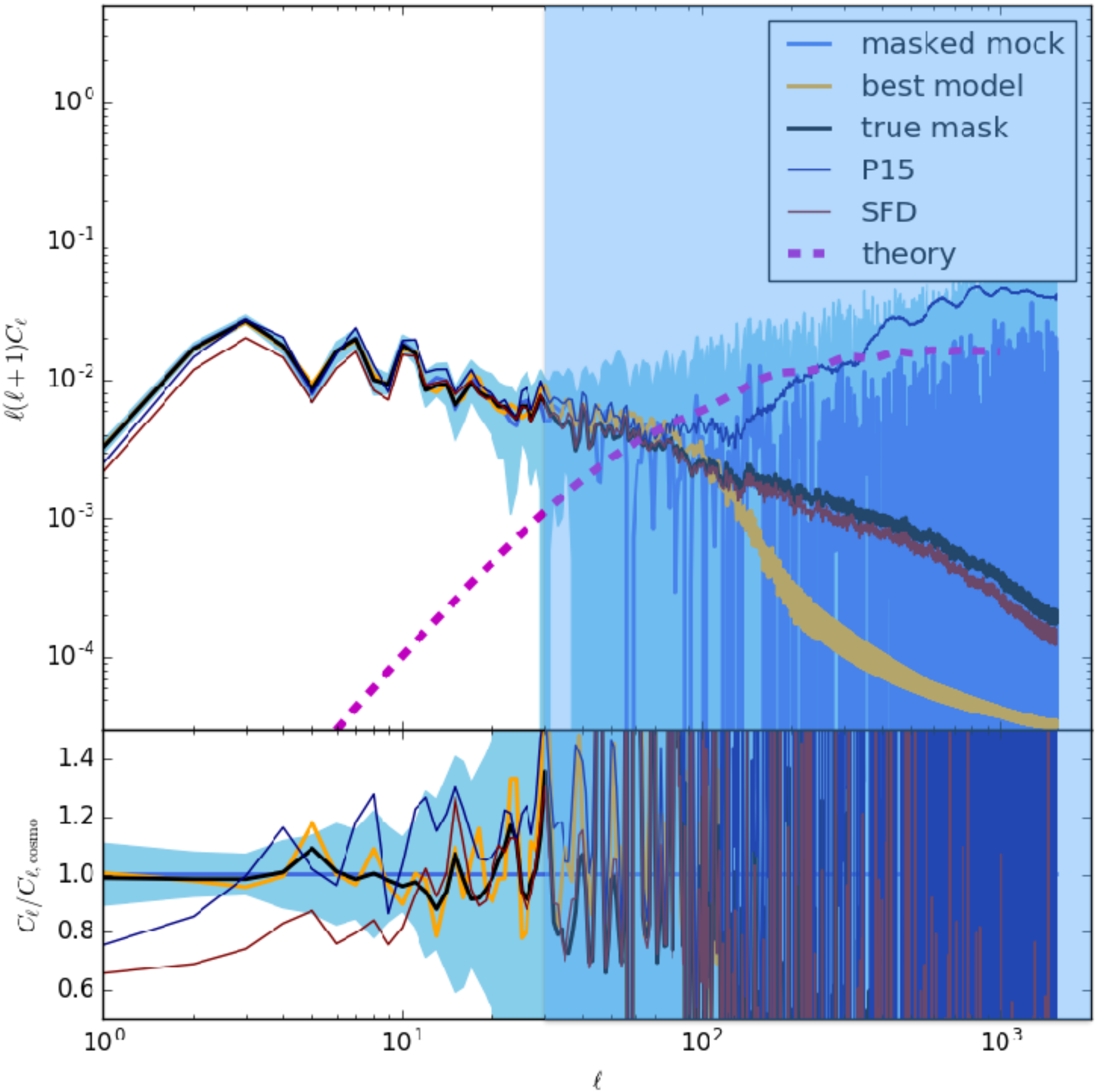

unmasked mock
masked mock
corrected, true
corrected, P15
corrected, SFD
best model

z=2.0


unmasked mock
masked mock
corrected, true
corrected, P15
corrected, SFD
best model

z=2.4


unmasked mock
masked mock
corrected, true
corrected, P15
corrected, SFD
best model

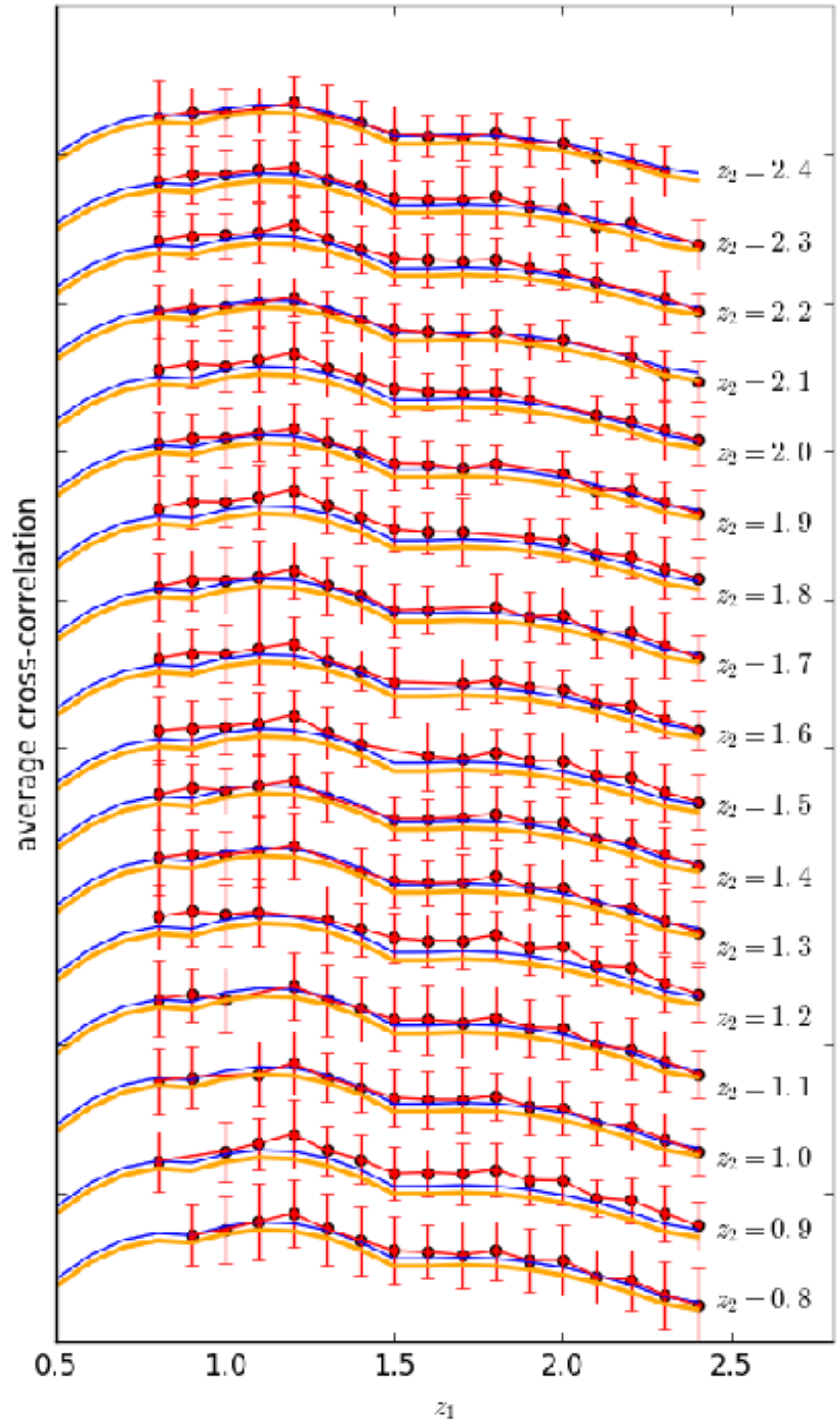

masked mock
best model
true mask
P15
SFD
theory
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\ell(\ell+1)C_\ell$
1.4
1.2
1.0
0.8
0.6
$C_\ell/C_{\ell,\,\mathrm{cosmo}}$
10^0
10^1
10^2
10^3
ℓ

$$\delta_o = \frac{n_o}{\langle n_o \rangle} - 1 \simeq$$

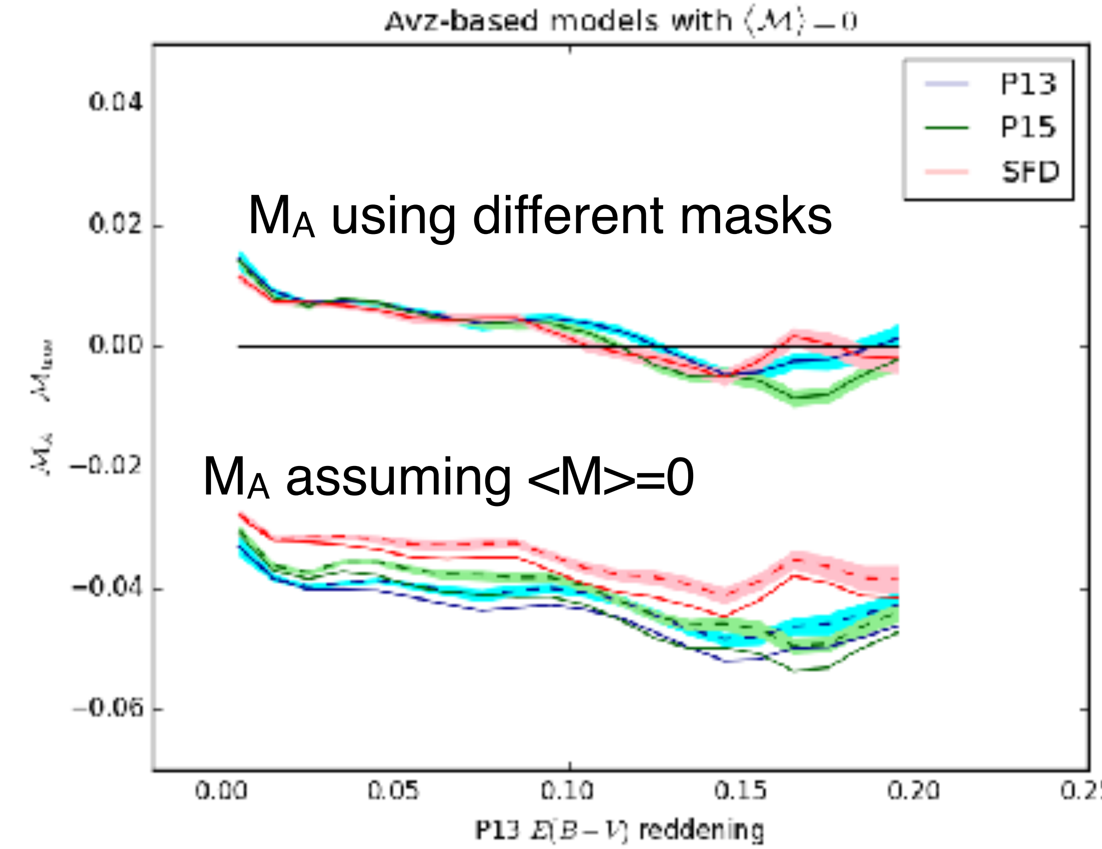
$$- \frac{C\left(\mathscr{M} - \langle \mathscr{M} \rangle\right) + B_2 C^2 \left(\mathscr{M}^2 - \langle \mathscr{M}^2 \rangle\right)}{B_1 - C\langle \mathscr{M} \rangle - B_2 C^2 \langle \mathscr{M}^2 \rangle}$$

average cross correlation as a function of redshift: a strong constraint to the mask model

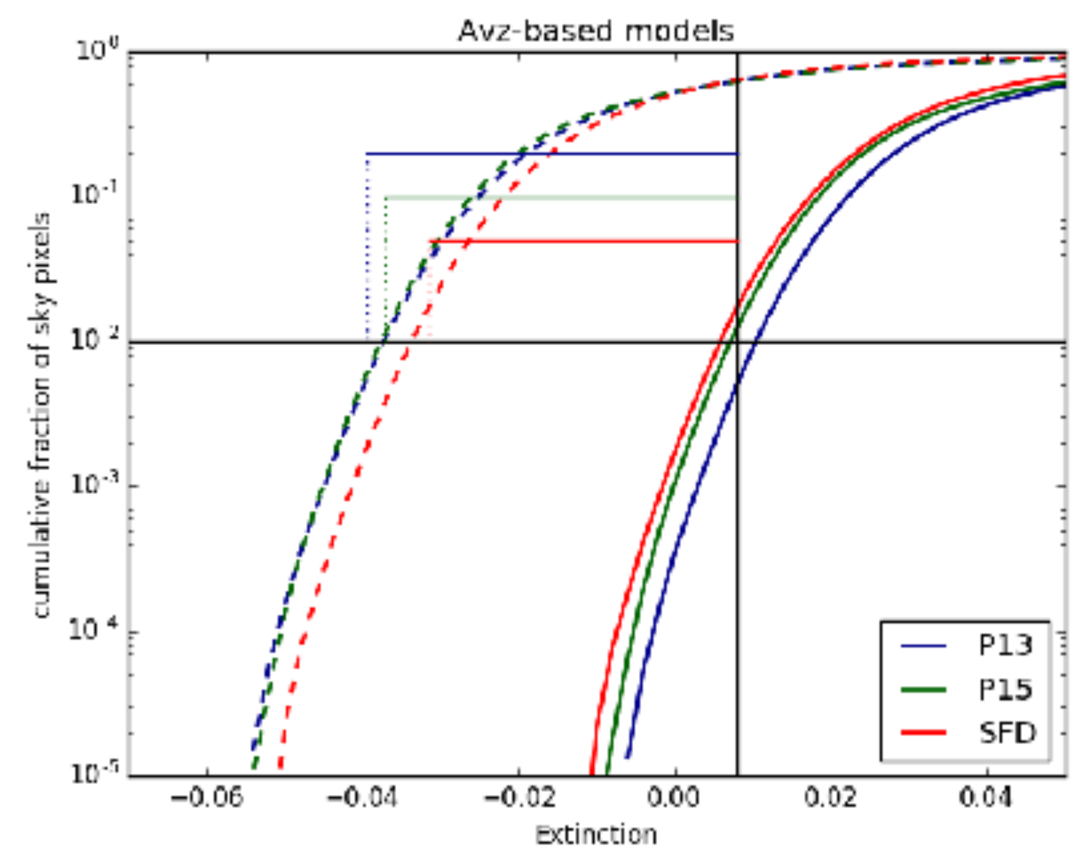
- points: measured mean Cl for masked mock
- errorbars: sample variance over the 20 mocks
- blue curve: predictions with true mask
- orange curve: prediction with best model



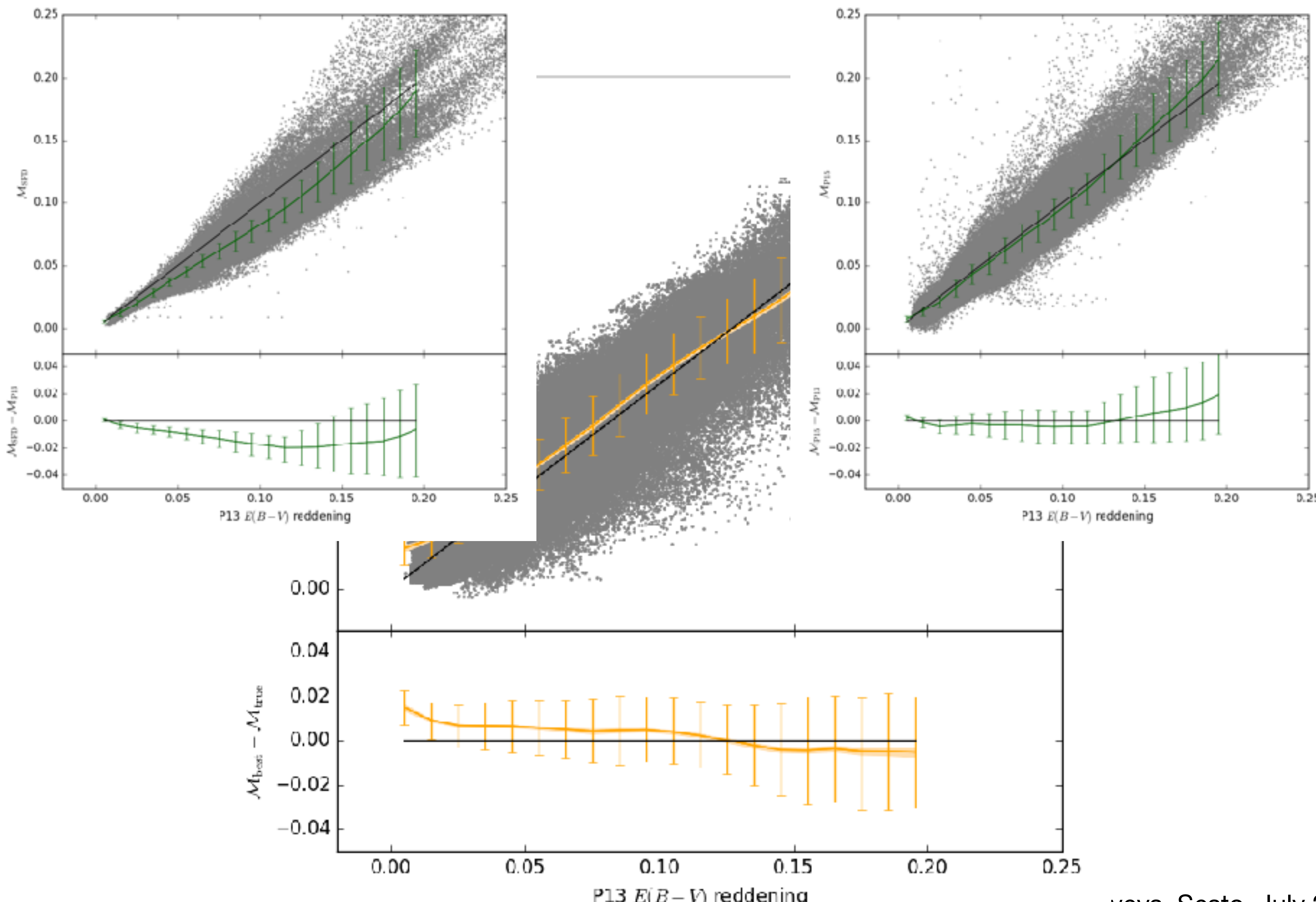
Can we assume we know <M> and <M²>?



- Using values from P15 and SFD gives very similar results
- <M> can be estimated by using M_A computed for <M>=0
- <M²> can be estimated as the mean of the square of the best model computed with <M²>=0
- In any case, one can calibrate <M> to reproduce the cross correlations



Can we distinguish between reddening models?



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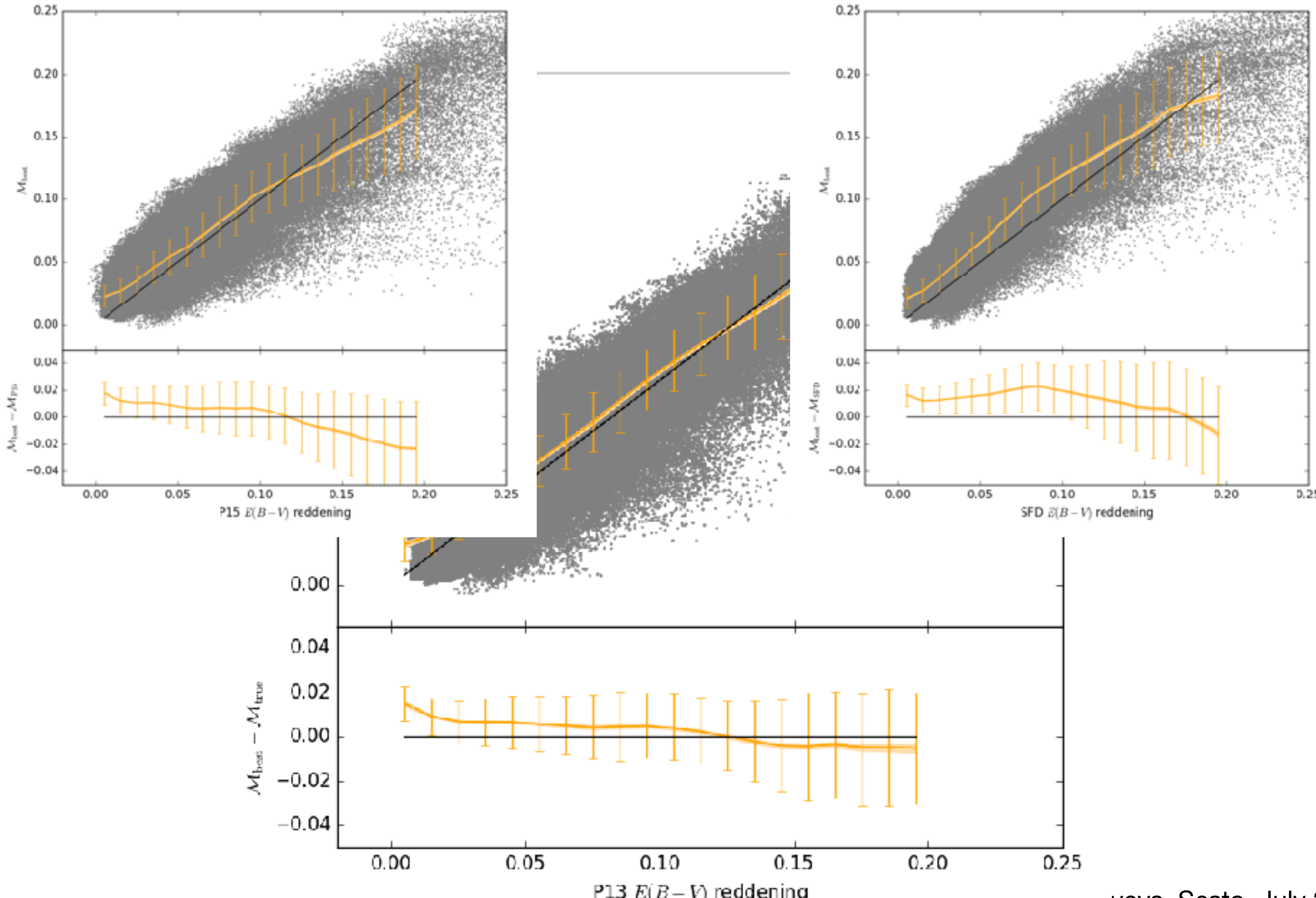

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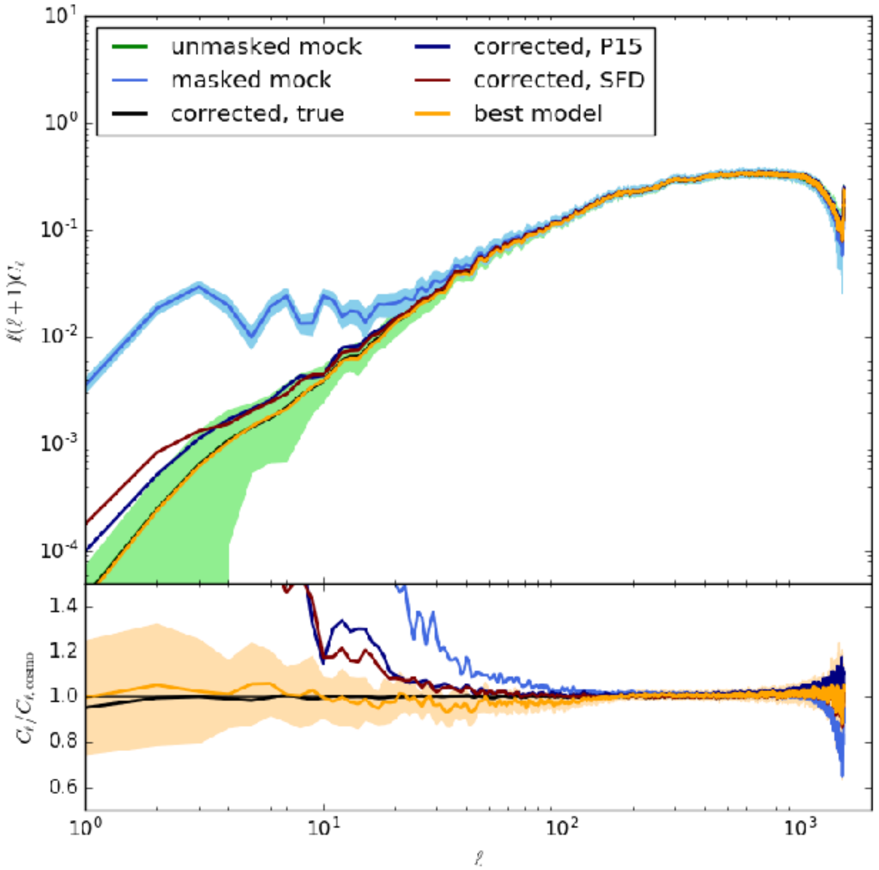

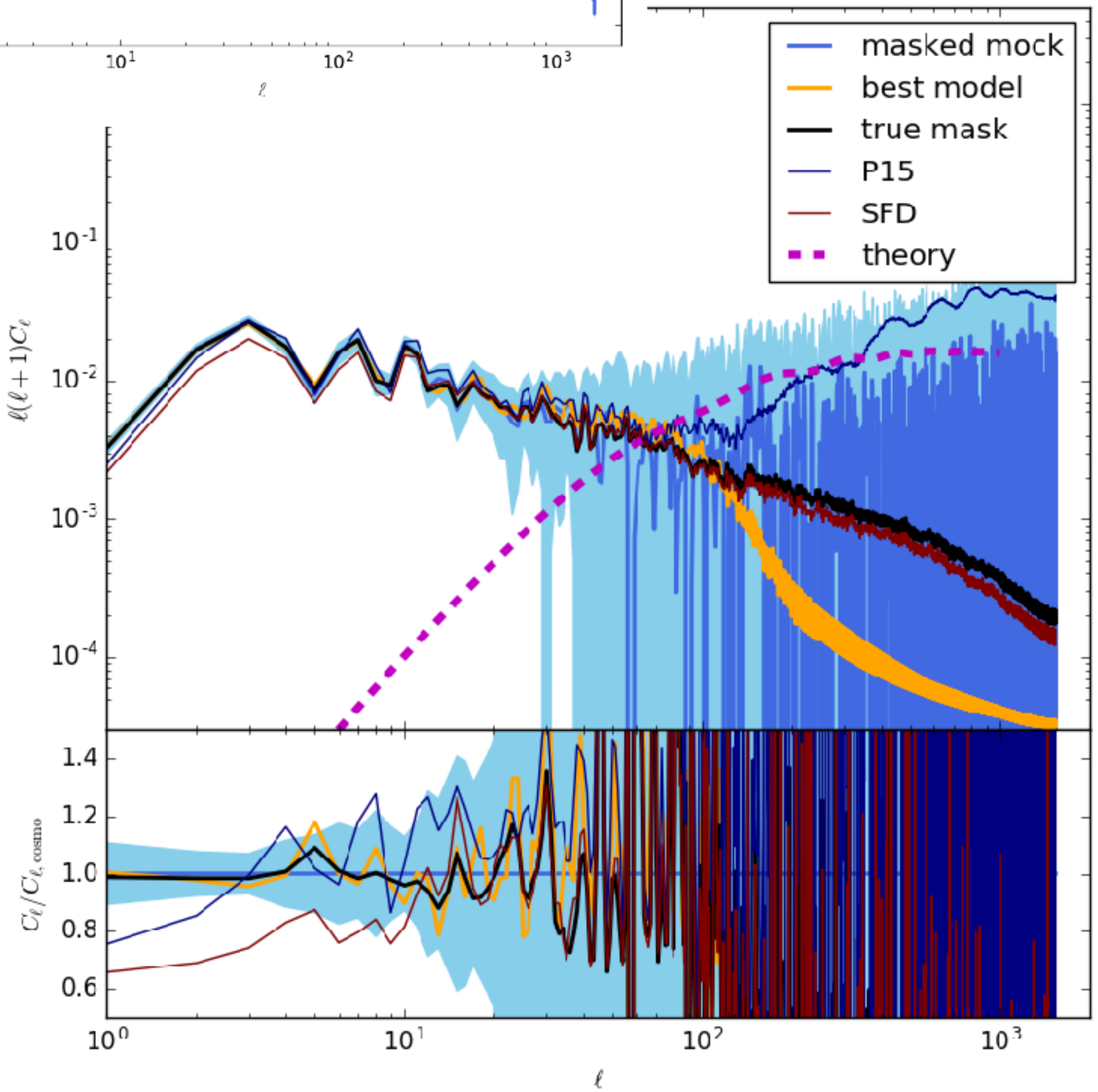

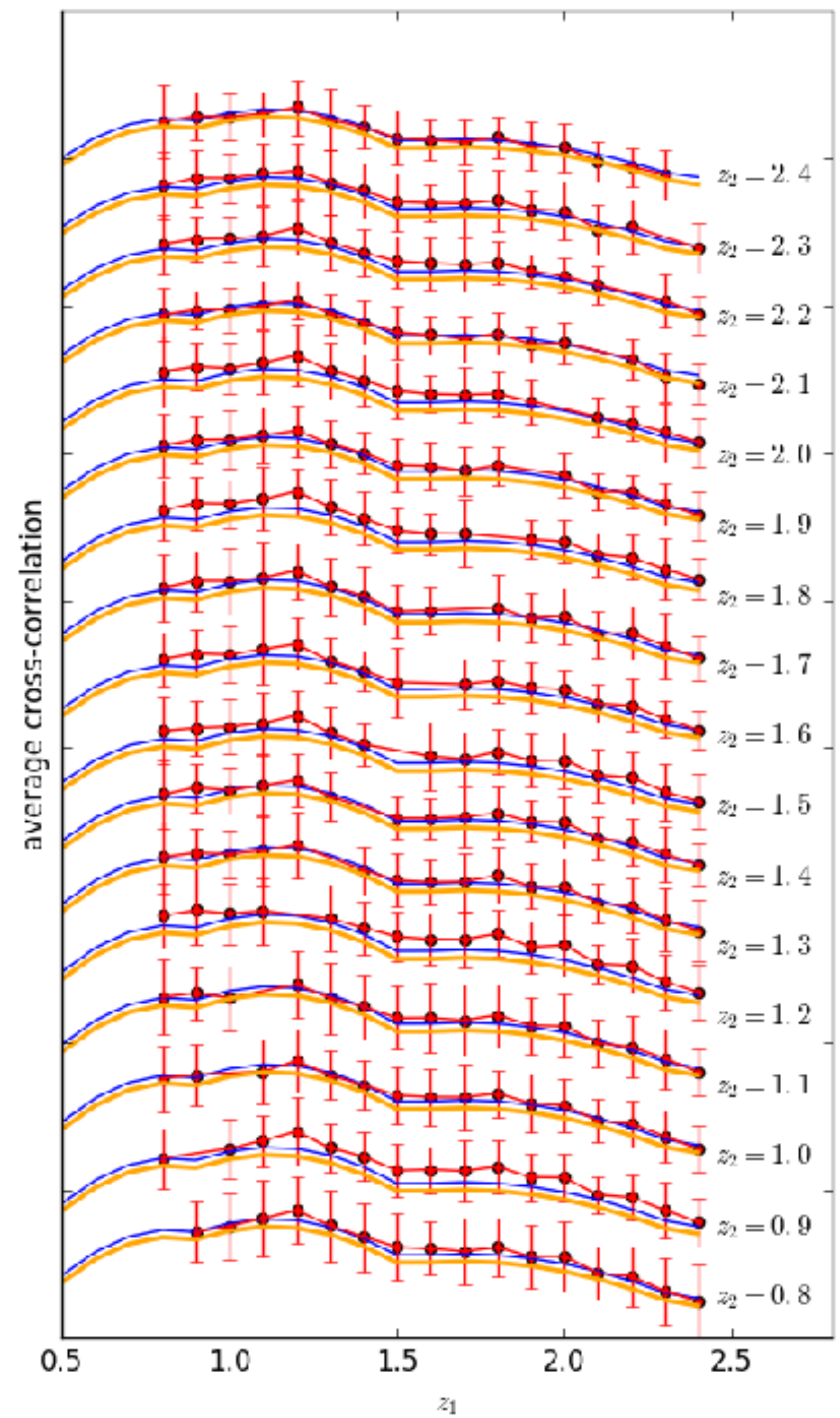

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Main uncertainties:

- every "foreground", including observing biases, will get into the mask - we need to model the sum of different foregrounds
- catastrophic redshift errors will create features in cross correlations
- we need to take lensing properly into account - easy to model
- we need to assume a universal galaxy LF, environmental dependence will result as an effective foreground term.
- $B_1(z)$ and $B_2(z)$: need to propagate uncertainties of the galaxy LF
- we must know luminosity-dependent bias and propagate its uncertainty

...a more sophisticated statistical approach?

Two possible strategies to use these results:

Use cross-correlations as a diagnostic for foreground contamination

or try a more aggressive program:

☞ apply some correction for MW extinction

☞ model residual foreground mask from cross correlations

☞ create a random

☞ use it to measure the 2D clustering

   ☞ compute covariances using many mock catalogues