Angular Clustering in the 2MPZ galaxy sample

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In collaboration with
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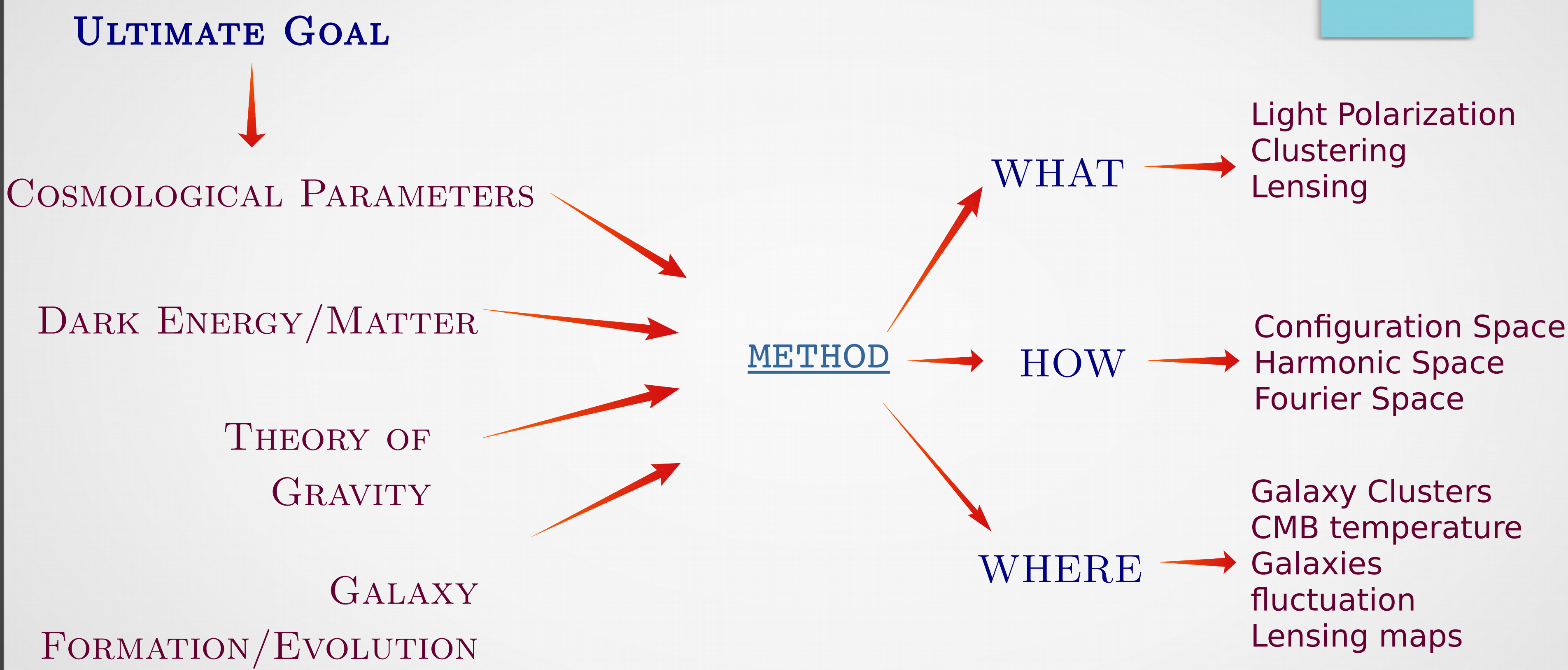
Motivation

- Combination of different probes (e.g., galaxy clustering) and methods
- (e.g, N-point statistics) to break degeneracies among parameters and study models/theories of gravity/galaxy formation

- Need to combine "all forms of struggle"

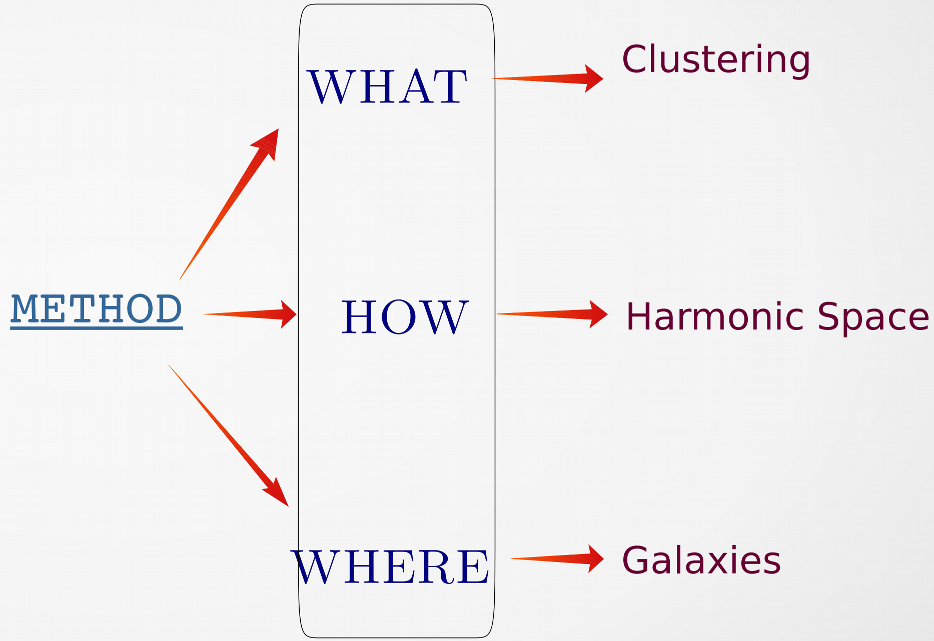
EXPERIMENTAL COSMOLOGY



EXPERIMENTAL COSMOLOGY

This talk / work

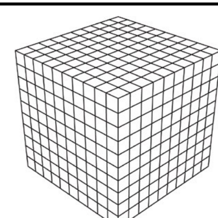
Cosmological parameters (validate sample and methods)

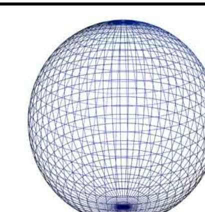


HOW

2-PT STATISTICS OF THE OBSERVED GALAXY DISTRIBUTION

Name	Symbol	Plane waves	Spherical Harmonics	Fourier-Bessel
Base	$\lvert \mathbf{p}\rangle$	$\lvert \mathbf{k}\rangle$	$\lvert \boldsymbol{\ell}\rangle$	$\lvert \mathbf{f}\rangle$
Eigenvectors	$\mathbf{p}$	$\mathbf{k} = (k_x, k_y, k_z)$	$\boldsymbol{\ell} = (\ell, m)$	$\mathbf{f} = (k_{\ell n}, \ell, m)$
Eigenfunctions	$\langle \mathbf{p} \lvert \boldsymbol{s}\rangle$	$\mathrm{e}^{i\mathbf{k}\cdot\boldsymbol{s}}$	$Y^*_{\ell m}(\hat{\boldsymbol{s}})$	$j_\ell(k_{\ell n} s) Y^*_{\ell m}(\hat{\boldsymbol{s}})$
Completness relation	$\langle \mathbf{p} \lvert \mathbf{p}\rangle$	$\delta^K_{\mathbf{k},\mathbf{k}'}$	$\delta^K_{\ell\ell'}\delta^K_{mm}$	$\delta^K_{\ell\ell'}\delta^K_{mm}\delta^K_{nn}$
Transition matrix	$\mathcal{U}^i_{\mathbf{pp}'}$	$W_i(\mathbf{k}-\mathbf{k}')$	$\int \mathrm{d}\boldsymbol{s} \langle \boldsymbol{\ell} \lvert \boldsymbol{s}\rangle\, W_i(\boldsymbol{s}) \langle \boldsymbol{s} \lvert \mathbf{k}\rangle$	$\int \mathrm{d}\boldsymbol{s} \langle \mathbf{f} \lvert \boldsymbol{s}\rangle W_i(\boldsymbol{s}) \langle \boldsymbol{s} \lvert \mathbf{f}\rangle$
Shot noise	$S^i_{\mathbf{pp}'}$	$\int \mathrm{d}\boldsymbol{s}\, \bar{n}_i(\boldsymbol{s}) w_i^2(\boldsymbol{s})$	$\int \mathrm{d}\boldsymbol{s} \langle \boldsymbol{\ell} \lvert \boldsymbol{s}\rangle \bar{n}_i(\boldsymbol{s}) w_i^2(\boldsymbol{s}) \langle \boldsymbol{s} \lvert \boldsymbol{\ell}\rangle$	$\int \mathrm{d}\boldsymbol{s} \langle \mathbf{f} \lvert \boldsymbol{s}\rangle \bar{n}_i(\boldsymbol{s}) w_i^2(\boldsymbol{s}) \langle \boldsymbol{s} \lvert \mathbf{f}\rangle$
Power Spectrum		$P(k_r)$	C_ℓ	$C_\ell(k_{\ell n})$
Angular average	$\langle\cdot\rangle_{\mathbf{p}}$	$N^{-1}_{k_r} \sum_{\mathbf{k}\in k_r}$	$\sum_{\ell\in\ell_r} \sum_{m=-\ell}^{+\ell}$	$N^{-1}_{k_r} \sum_{\mathbf{k}\in k_r} (2\ell+1)^{-1} \sum_{m=-\ell}^{+\ell}$
Estimator				





Angular power spectrum

Angular Correlation function
(see Will P. and Martin C. talks)

Power Spectrum

$$w(\tilde{\theta}) \equiv \langle \delta(\hat{\mathbf{r}}_1)\delta(\hat{\mathbf{r}}_2)\rangle = \sum_{\ell m}\sum_{\ell' m'}\langle a_{\ell m}a^*_{\ell' m'}\rangle Y_{\ell m}(\hat{\mathbf{r}}_1)Y_{\ell m}(\hat{\mathbf{r}}_2) = \frac{1}{4\pi}\sum_{\ell}(2\ell+1)\boxed{C_\ell}P_\ell(\cos\tilde{\theta}),$$

Legendre Transform

Angular cross power spectrum

$$a_{\ell m}^{i,(s)} = \int \delta_{\rm gal}^{(i)}(\hat{\Omega}) Y_{\ell m}^{*}(\hat{\Omega})\, {\rm d}\hat{\Omega} = \int {\rm d}^3 s\, \phi_i(\mathbf{s}) \delta_{\rm gal}(\mathbf{s}) Y_{\ell m}^{*}(\hat{\Omega})$$

$$\tilde{C}_{\ell}^{ij} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \langle a_{\ell m}^{i(s)} a_{\ell m}^{j(s)*} \rangle = \sum_{\ell'} R_{\ell\ell'} C_{\ell'}^{ij}$$

$$C_{\ell}^{ij} = b_i b_j \int_0^{\infty} \mathcal{P}(k) k^2 F_{\ell}^{i}(k) F_{\ell}^{j}(k)\, {\rm d}k$$

$$R_{\ell\ell'} = \frac{(2\ell'+1)}{4\pi} \sum_{\ell''} (2\ell''+1) W_{\ell''} \begin{pmatrix} \ell & \ell' & \ell'' \\ 0 & 0 & 0 \end{pmatrix}^2$$

Angular cross power spectrum

Galaxy surface overdensity

Selection Function

Redshift bin

$$a_{\ell m}^{i,(s)} = \int \delta_{\rm gal}^{(i)}(\hat{\Omega}) Y_{\ell m}^{*}(\hat{\Omega})\,\mathrm{d}\hat{\Omega} = \int \mathrm{d}^3 s\, \phi_i(\mathbf{s}) \delta_{\rm gal}(\mathbf{s}) Y_{\ell m}^{*}(\hat{\Omega})$$

$$\left(\frac{\mathrm{d}N}{\mathrm{d}z_{\rm s}}\right)_i = \int_0^\infty W_i(z_{\rm p}) \frac{\mathrm{d}N}{\mathrm{d}z_{\rm p}} P(z_{\rm s}|z_{\rm p})\,\mathrm{d}z_{\rm p}$$

Redshift bins

Photo-z errors

Angular cross power spectrum

$$a_{\ell m}^{i,(s)} = \int \delta_{\rm gal}^{(i)}(\hat{\Omega}) Y_{\ell m}^{*}(\hat{\Omega})\, {\rm d}\hat{\Omega} = \int {\rm d}^3 s\, \phi_i(\mathbf{s}) \delta_{\rm gal}(\mathbf{s}) Y_{\ell m}^{*}(\hat{\Omega})$$

$$\boxed{C_\ell^{ij}} = b_i b_j \int_0^\infty \mathcal{P}(k) k^2 F_\ell^i(k) F_\ell^j(k)\, {\rm d}k$$

Underlying cross angular power spectrum

$$\boxed{\tilde{C}_\ell^{ij}} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \langle a_{\ell m}^{i(s)} a_{\ell m}^{j(s)*} \rangle = \sum_{\ell'} R_{\ell\ell'} C_{\ell'}^{ij}$$

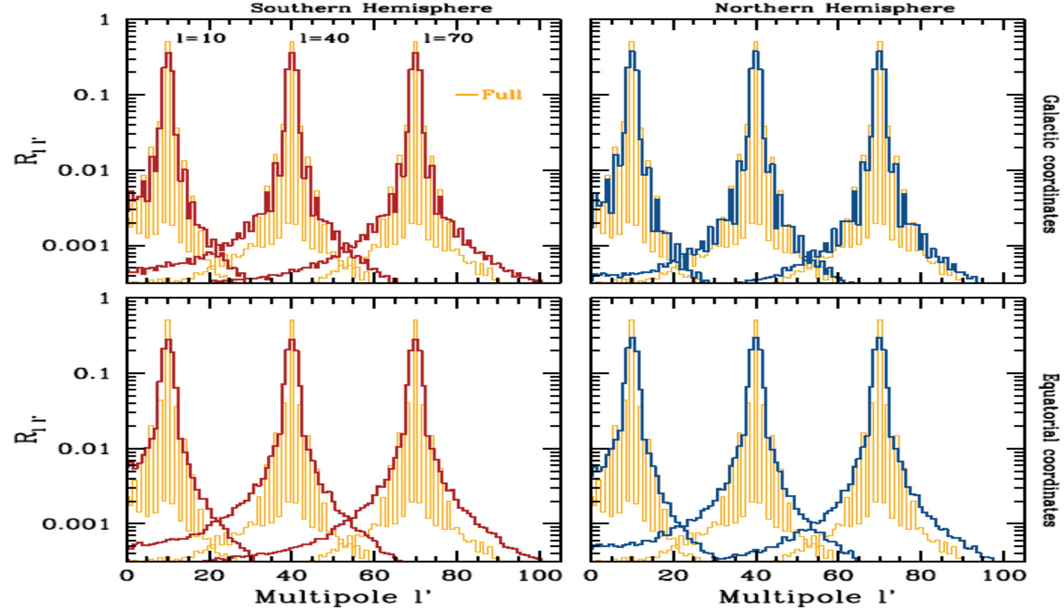
$$\boxed{R_{\ell\ell'}} = \frac{(2\ell'+1)}{4\pi} \sum_{\ell''} (2\ell''+1) \boxed{W_{\ell''}} \begin{pmatrix} \ell & \ell' & \ell'' \\ 0 & 0 & 0 \end{pmatrix}^2$$

Expected cross angular power spectrum

Mixing matrix

Angular cross power spectrum

$$a^{i,(s)}_{\ell m} = \int \delta^{(i)}_{\rm gal}(\hat\Omega) Y^*_{\ell m}(\hat\Omega)\,{\rm d}\hat\Omega$$



$$\tilde C^{ij}_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}\langle a^{i(s)}_{\ell m} a^{j(s)*}_{\ell m}\rangle = \sum_{\ell'} R_{\ell\ell'} C^{ij}_{\ell'}$$

$$R_{\ell\ell'} = \frac{(2\ell'+1)}{4\pi}\sum_{\ell''}(2\ell''+1) W_{\ell''} \begin{pmatrix} \ell & \ell' & \ell'' \\ 0 & 0 & 0 \end{pmatrix}^2$$

Mixing matrix

Angular cross power spectrum

3D galaxy overdensity

$$a_{\ell m}^{i,(s)} = \int \delta_{\rm gal}^{(i)}(\hat{\Omega}) Y_{\ell m}^{*}(\hat{\Omega})\,\mathrm{d}\hat{\Omega} = \int \mathrm{d}^3 s\, \phi_i(\mathbf{s}) \delta_{\rm gal}(\mathbf{s}) Y_{\ell m}^{*}(\hat{\Omega})$$

Projection kernels

Linear Gal-DM bias

$$C_\ell^{ij} = b_i b_j \int_0^\infty \mathcal{P}(k) k^2 F_\ell^i(k) F_\ell^j(k)\,\mathrm{d}k$$

$$\tilde{C}_\ell^{ij} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \langle a_{\ell m}^{i(s)} a_{\ell m}^{j(s)*} \rangle = \sum_{\ell'} R_{\ell\ell'} C_{\ell'}^{ij}$$

Underlying cross angular power spectrum

Primordial DM Power Spectrum

Expected cross angular power spectrum

Angular cross power spectrum

$$a_{\ell m}^{i,(s)} = \int \delta_{\rm gal}^{(i)}(\hat{\Omega}) Y_{\ell m}^{*}(\hat{\Omega})\, \mathrm{d}\hat{\Omega} = \int \mathrm{d}^3 s\, \phi_i(\mathbf{s}) \boxed{\delta_{\rm gal}(\mathbf{s})} Y_{\ell m}^{*}(\hat{\Omega})$$

$$C_\ell^{ij} = b_i b_j \int_0^\infty \mathcal{P}(k) k^2 F_\ell^i(k) F_\ell^j(k)\, \mathrm{d}k$$

$$\tilde{C}_\ell^{ij} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \langle a_{\ell m}^{i(s)} a_{\ell m}^{j(s)*} \rangle = \sum_{\ell'} R_{\ell\ell'} C_{\ell'}^{ij}$$

Limber approximation

$$C_\ell^{ij} \approx b_i b_j \int_0^\infty \frac{\mathrm{d}N_i}{\mathrm{d}z} \frac{\mathrm{d}N_j}{\mathrm{d}z} P_{\rm mat}\left(\frac{\ell}{r(z)}, z\right) \frac{H(z)}{r^2(z)}\, \mathrm{d}z,$$

Angular cross power spectrum

$$a_{\ell m}^{i,(s)} = \int \delta_{\rm gal}^{(i)}(\hat{\Omega}) Y_{\ell m}^{*}(\hat{\Omega})\, {\rm d}\hat{\Omega} = \int {\rm d}^3 s\, \phi_i(\mathbf{s}) \delta_{\rm gal}(\mathbf{s}) Y_{\ell m}^{*}(\hat{\Omega})$$

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Projection kernels

Linear Gal-DM bias

$$C_\ell^{ij} = b_i b_j \int_0^\infty \mathcal{P}(k) k^2 F_\ell^i(k) F_\ell^j(k)\, {\rm d}k$$

RSD parameter

$$F_\ell^i(k) = \sqrt{\frac{2}{\pi}} \int_0^\infty {\rm d}r r^2 \phi_i(r) \left[\tilde{j}_\ell(k,r) + \beta_i \Psi_\ell(k) \right]$$

$$\tilde{j}_\ell(k,r) \equiv \sqrt{D(k,z)}\, j_\ell(kr)$$

Transfer function

Angular cross power spectrum

$$a_{\ell m}^{i,(s)} = \int \delta_{\rm gal}^{(i)}(\hat{\Omega}) Y_{\ell m}^{*}(\hat{\Omega})\,{\rm d}\hat{\Omega} = \int {\rm d}^3 s\, \phi_i(\mathbf{s}) \delta_{\rm gal}(\mathbf{s}) Y_{\ell m}^{*}(\hat{\Omega})$$

Projection kernels

Linear Gal-DM bias

$$C_\ell^{ij} = b_i b_j \int_0^\infty \mathcal{P}(k) k^2 F_\ell^i(k) F_\ell^j(k)\,{\rm d}k$$

$$\Psi_\ell(k) = \left[\frac{2\ell^2 + 2\ell - 1}{(2\ell-1)(2\ell+3)} \tilde{j}_\ell(k,r) - \frac{\ell(\ell-1)}{(2\ell+1)(2\ell-1)} \tilde{j}_{\ell-2}(k,r) - \frac{(\ell+1)(\ell+2)}{(2\ell+1)(2\ell+3)} \tilde{j}_{\ell+2}(k,r) \right].$$

$$F_\ell^i(k) = \sqrt{\frac{2}{\pi}} \int_0^\infty {\rm d}r\, r^2 \phi_i(r) \left[\tilde{j}_\ell(k,r) + \beta_i \Psi_\ell(k) \right]$$

Kaiser boost-factor in harmonic space

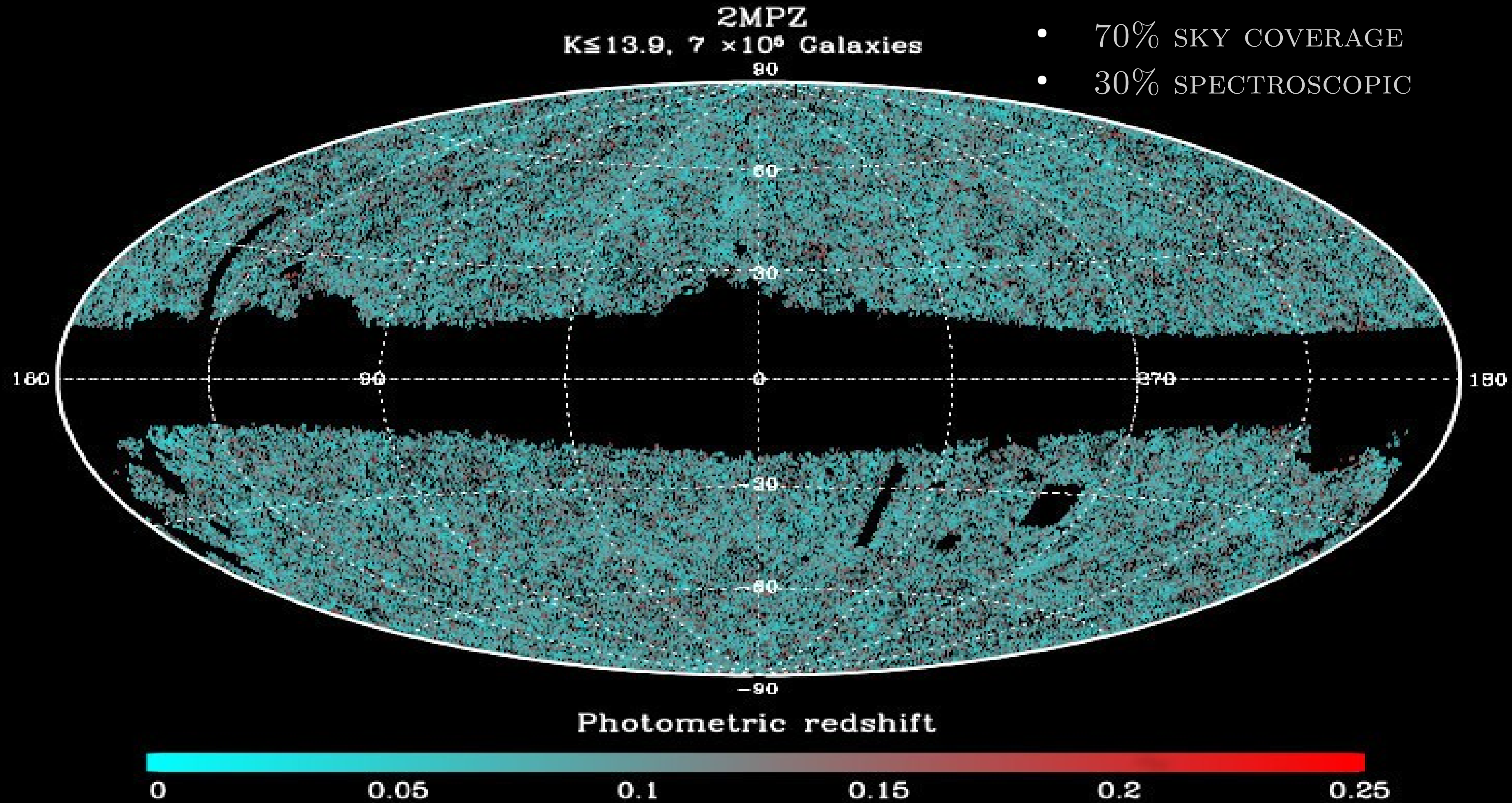
WHERE

The 2MRS Photometric redshift catalog (2MPZ)

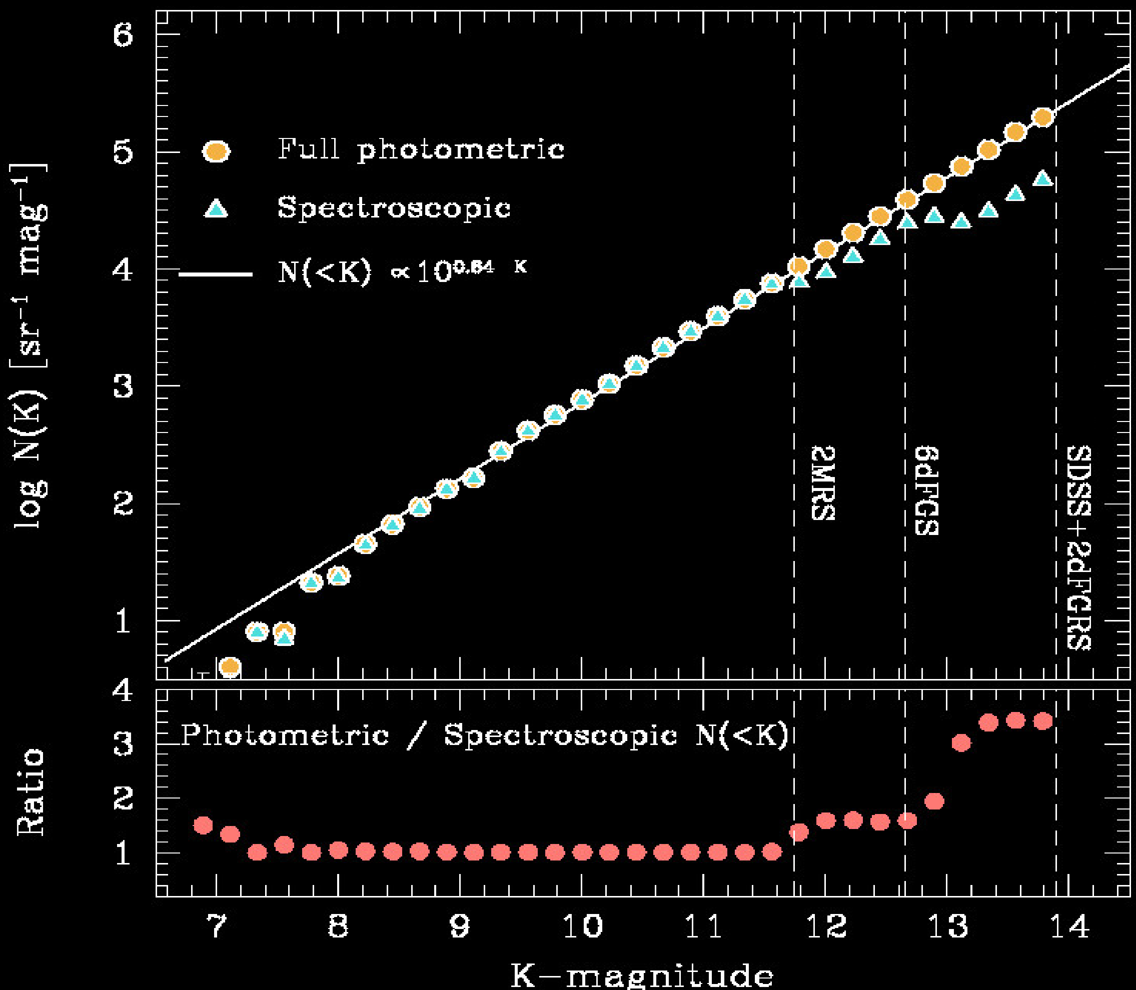
TWO MICRON ALL SKY SURVEY PHOTOMETRIC REDSHIFT CATALOG: A COMPREHENSIVE THREE-DIMENSIONAL CENSUS OF THE WHOLE SKY

Maciej Bilicki[1,2], Thomas H. Jarrett[1], John A. Peacock[3], Michelle E. Cluver[1,4], and Louise Steward[1]

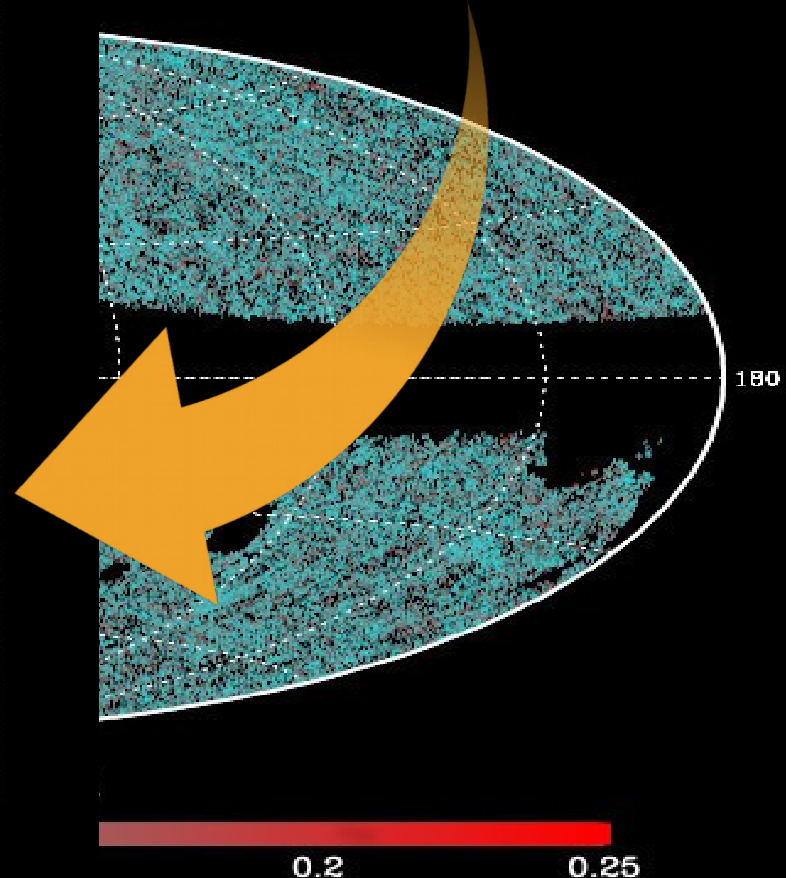
- Nearly 1M galaxies
- 70% sky coverage
- 30% spectroscopic



The 2MRS Photometric redshift catalog (2MPZ)



Correlation of 2MRS with other all-sky surveys (e.g SuperCOSMOS, WISE) and calibration with SDSS 6dFGRS



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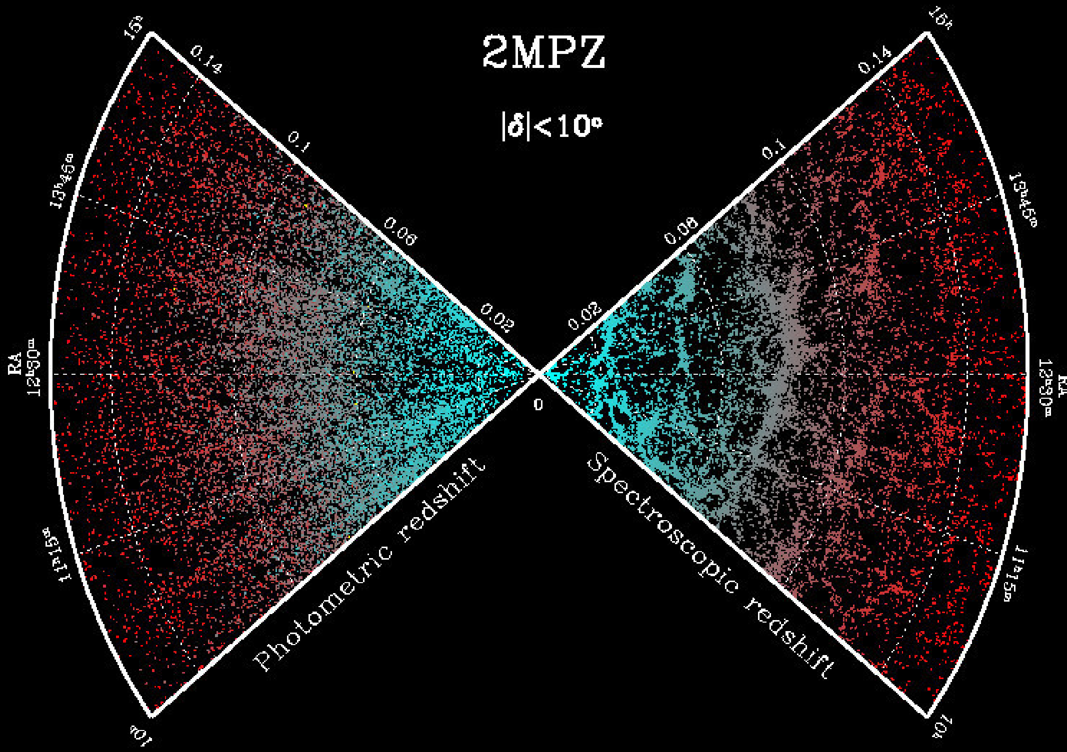
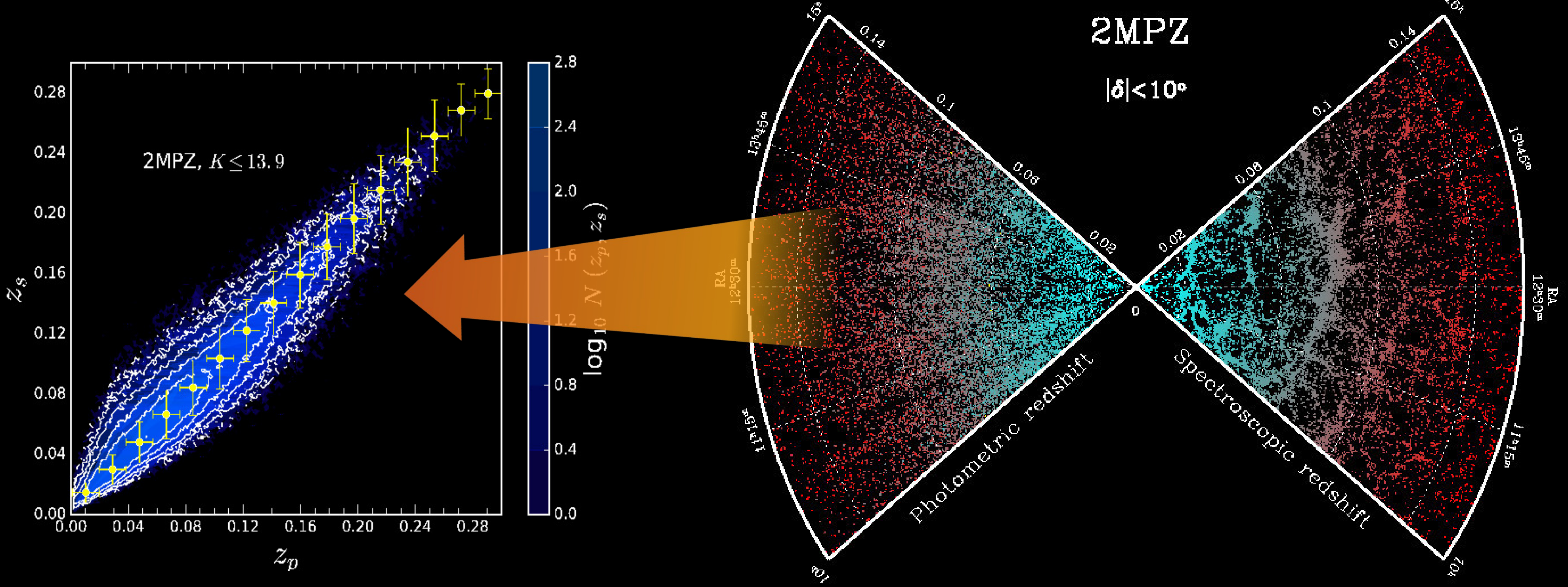


Typical displacement of 50 Mph/h

The 2MRS Photometric redshift catalog (2MPZ)



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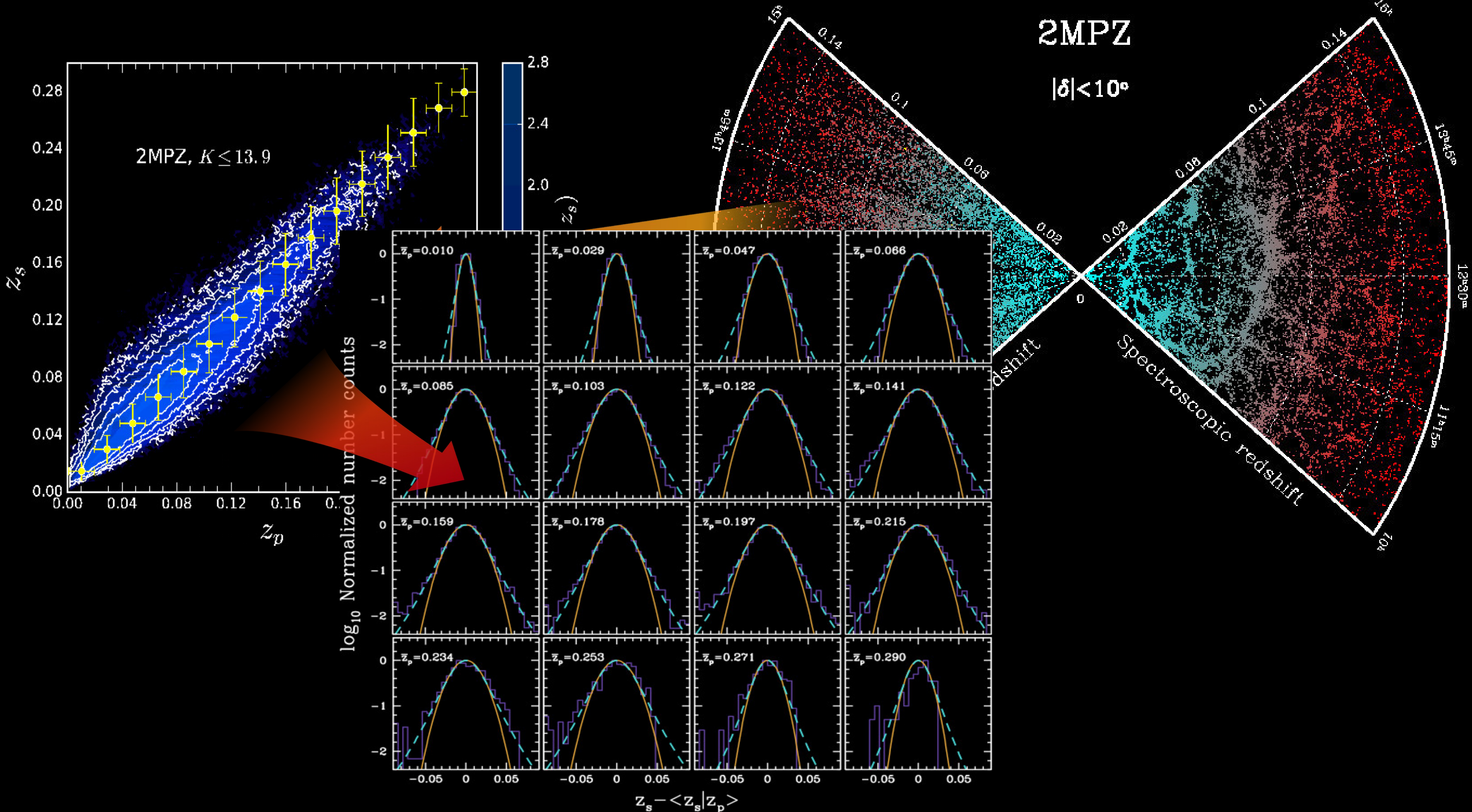

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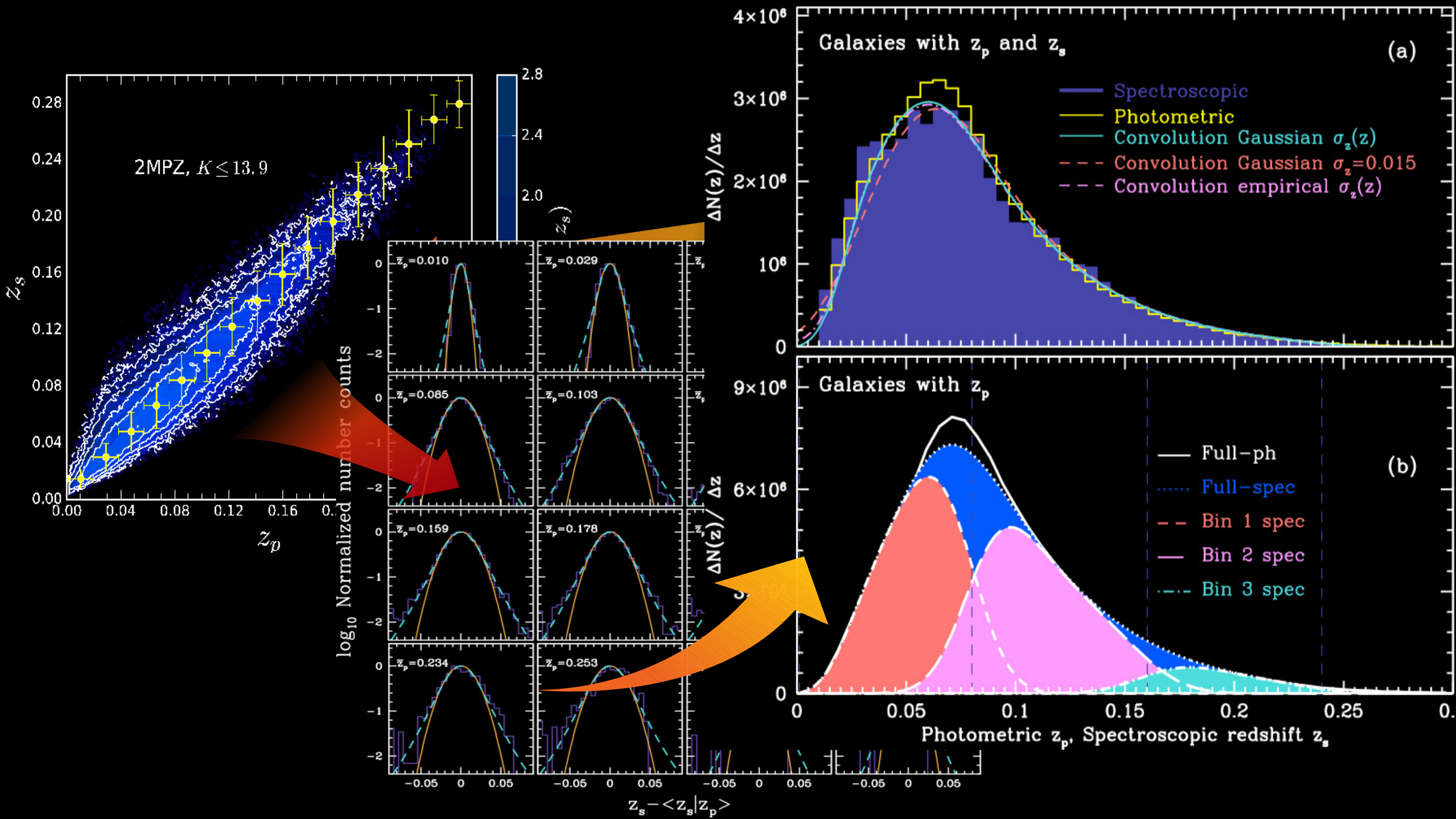


Angular cross power spectrum

Redshift bin

Galaxy surface overdensity

Selection Function

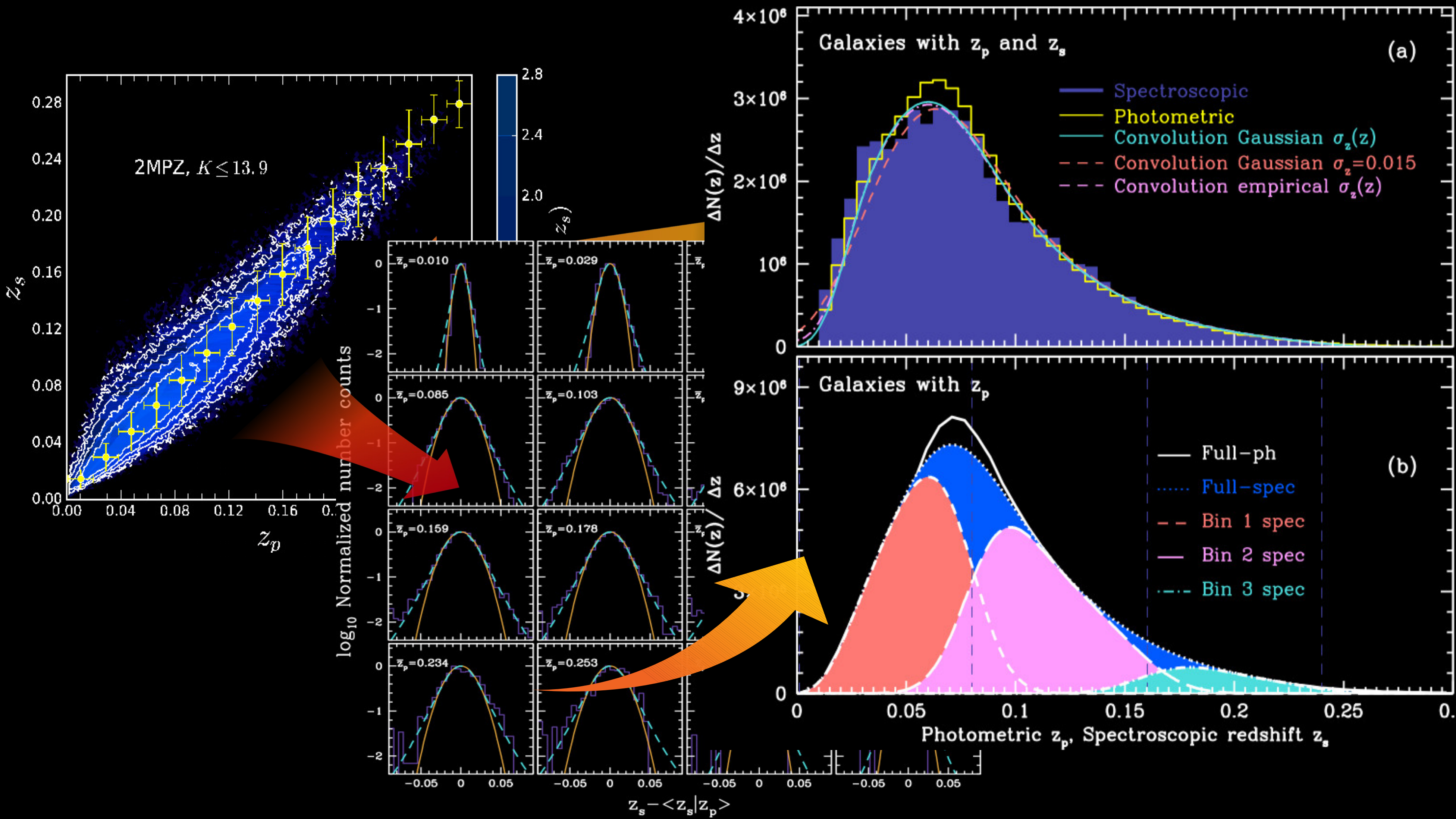
$$a_{\ell m}^{i,(s)} = \int \delta_{\rm gal}^{(i)}(\hat{\Omega}) Y_{\ell m}^{*}(\hat{\Omega})\, {\rm d}\hat{\Omega} = \int {\rm d}^3 s\, \phi_i(\mathbf{s}) \delta_{\rm gal}(\mathbf{s}) Y_{\ell m}^{*}(\hat{\Omega})$$

$$\left(\frac{{\rm d}N}{{\rm d}z_{\rm s}}\right)_i = \int_0^{\infty} W_i(z_{\rm p}) \frac{{\rm d}N}{{\rm d}z_{\rm p}} P(z_{\rm s}|z_{\rm p})\, {\rm d}z_{\rm p}$$

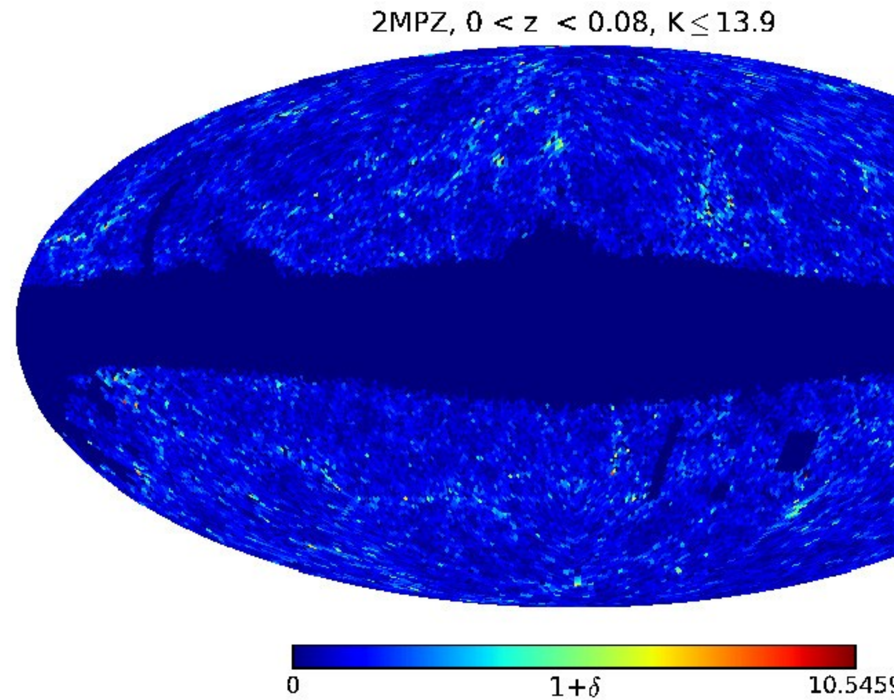
Redshift bins

Photo-z errors

Tomographic analysis Photometric redshifts

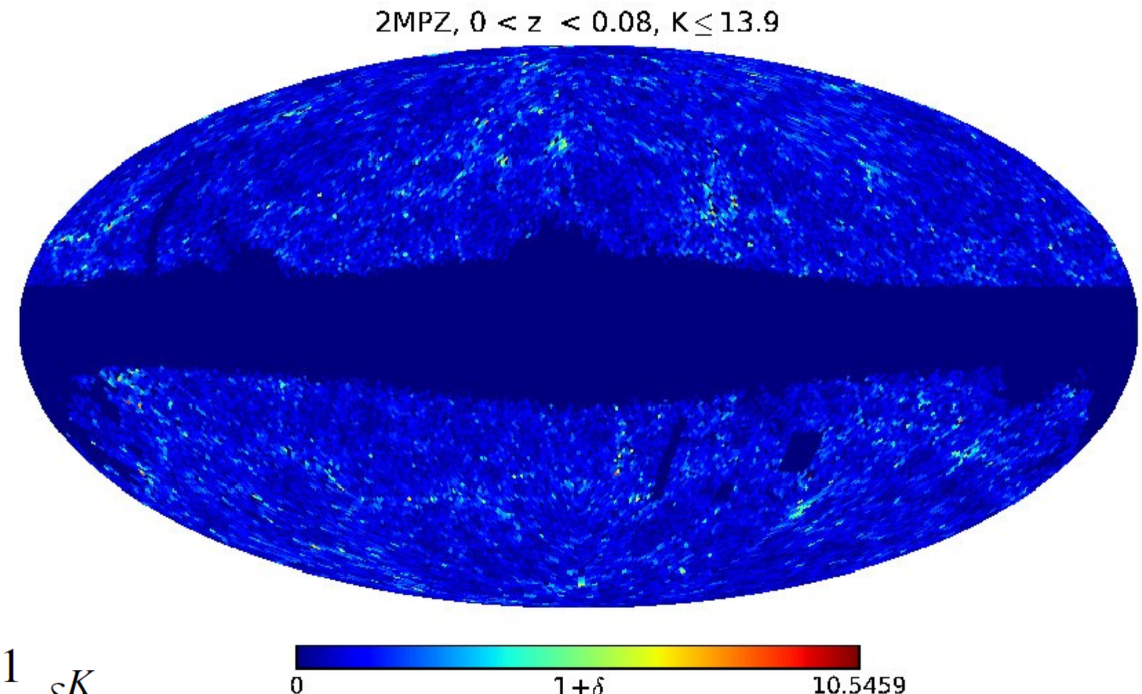


Measuring cross angular power spectrum



Measuring cross angular power spectrum

$$\hat{a}^i_{\ell m} = \Delta\Omega_p \sum_{k=1}^{N_{\rm pix}} \left(\frac{\mathcal{N}_{ik} - \bar{\mathcal{N}}_i}{\bar{\mathcal{N}}_i} \right) Y^*_{\ell m}(\hat{\Omega})$$



$$\hat{K}^{ij}_\ell = \frac{1}{f_{\rm sky}(2\ell+1)} \sum_{m=-\ell}^{m=+\ell} |\hat{a}^i_{\ell m} \hat{a}^{*j}_{\ell m}| - \frac{1}{\bar{\sigma}_i} \delta^K_{ij}.$$

CODE
AVAILABLE

$$\langle \hat{K}^{ij}_\ell \rangle = \frac{1}{f_{\rm sky}} \sum_{\ell'} R_{\ell\ell'} C^{ij}_{\ell'}.$$

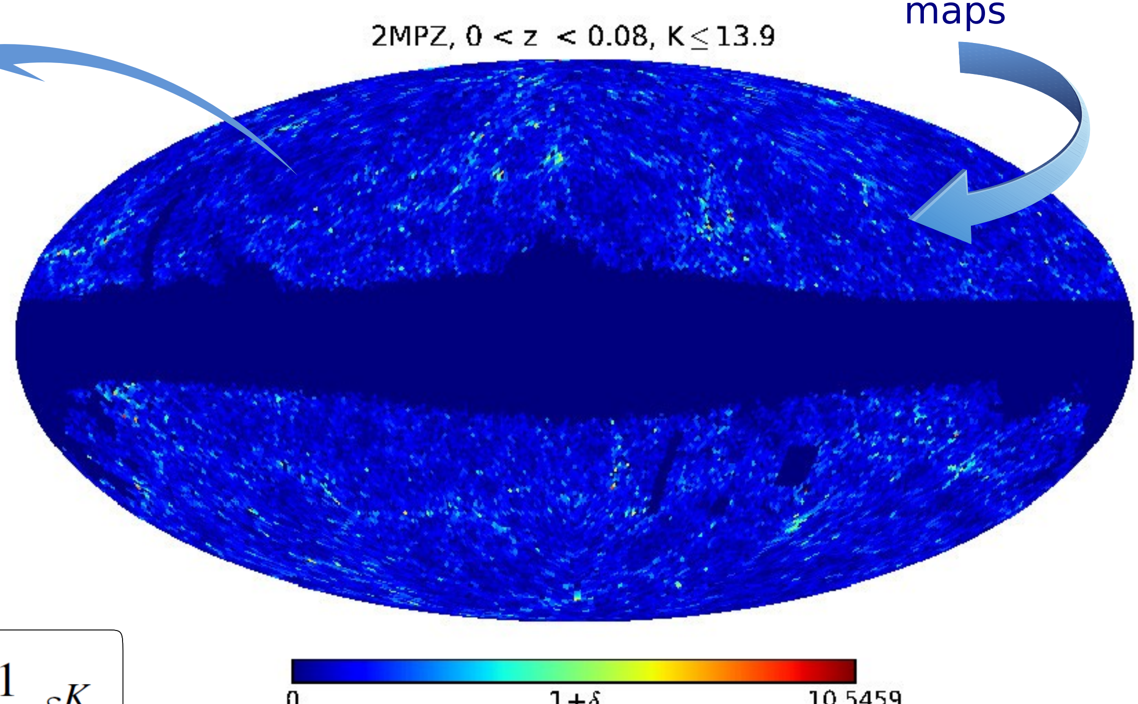
Measuring cross angular power spectrum

Number of galaxies in pixels

$$\hat{a}^{i}_{\ell m} = \boxed{\Delta\Omega_p} \sum_{k=1}^{N_{\rm pix}} \left(\frac{\boxed{\mathcal{N}_{ik}} - \bar{\mathcal{N}}_i}{\bar{\mathcal{N}}_i} \right) Y^{*}_{\ell m}(\hat{\Omega})$$

Area Pixel

HealPix maps



$$\boxed{\hat{K}^{ij}_{\ell}} = \frac{1}{f_{\rm sky}(2\ell+1)} \sum_{m=-\ell}^{m=+\ell} |\hat{a}^{i}_{\ell m}\hat{a}^{*j}_{\ell m}| - \boxed{\frac{1}{\bar{\sigma}_i}\delta^{K}_{ij}.}$$

Estimator

Shot noise

Ensemble average

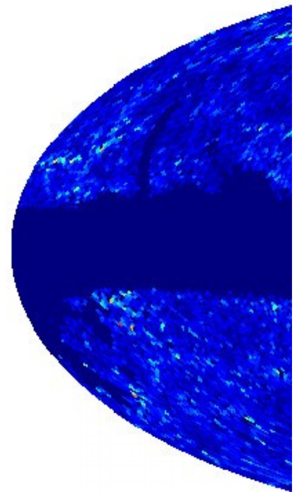
$$\langle \hat{K}^{ij}_{\ell} \rangle = \frac{1}{f_{\rm sky}} \sum_{\ell'} R_{\ell\ell'} C^{ij}_{\ell'}.$$

CODE AVAILABLE

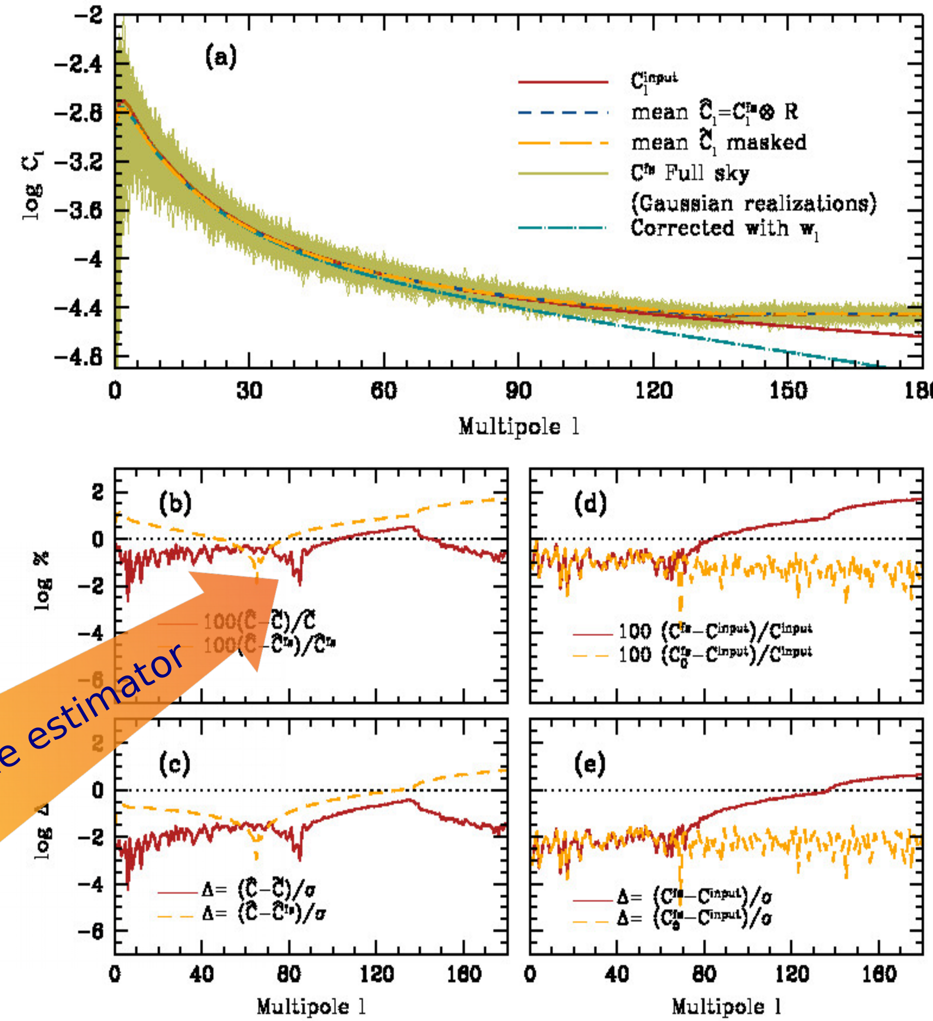
Measuring cross angular power spectrum

$$\hat{a}^{i}_{\ell m} = \Delta\Omega_p \sum_{k=1}^{N_{\rm pix}} \left(\frac{\mathcal{N}_{ik} - \bar{\mathcal{N}}_i}{\bar{\mathcal{N}}_i} \right) Y^{*}_{\ell m}(\hat{\Omega})$$

$$\hat{K}^{ij}_{\ell} = \frac{1}{f_{\rm sky}(2\ell+1)} \sum_{m=-\ell}^{m=+\ell} |\hat{a}^{i}_{\ell m}\hat{a}^{*j}_{\ell m}| - \frac{1}{\bar{\sigma}_i}\delta^{K}_{ij}.$$



Validate the estimator



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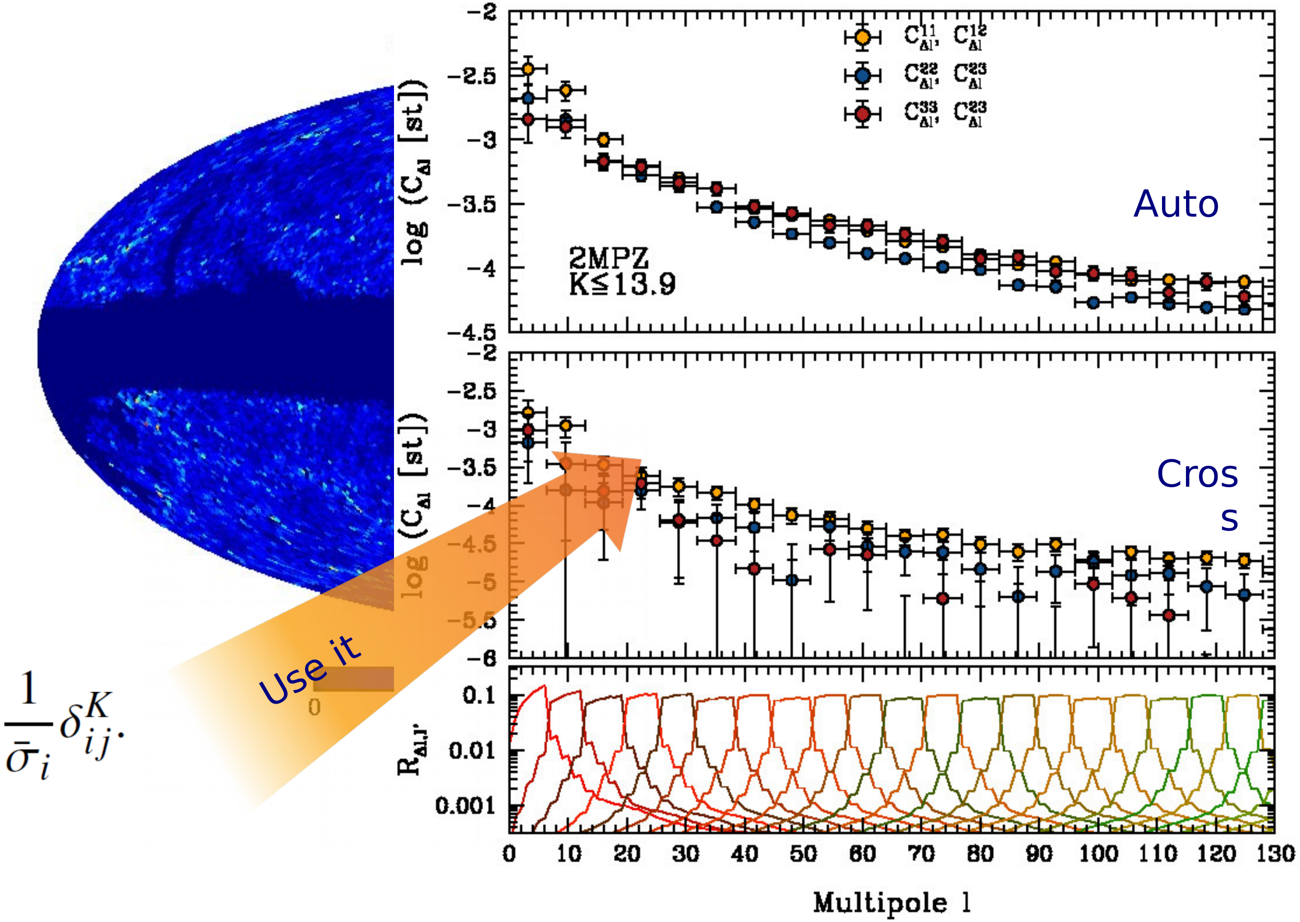
Measuring cross angular power spectrum

$$\hat{a}^{i}_{\ell m} = \Delta\Omega_p \sum_{k=1}^{N_{\rm pix}} \left(\frac{\mathcal{N}_{ik} - \bar{\mathcal{N}}_i}{\bar{\mathcal{N}}_i} \right) Y^{*}_{\ell m}(\hat{\Omega})$$

$$\hat{K}^{ij}_{\ell} = \frac{1}{f_{\rm sky}(2\ell+1)} \sum_{m=-\ell}^{m=+\ell} |\hat{a}^{i}_{\ell m}\hat{a}^{*j}_{\ell m}| - \frac{1}{\bar{\sigma}_i}\delta^{K}_{ij}.$$



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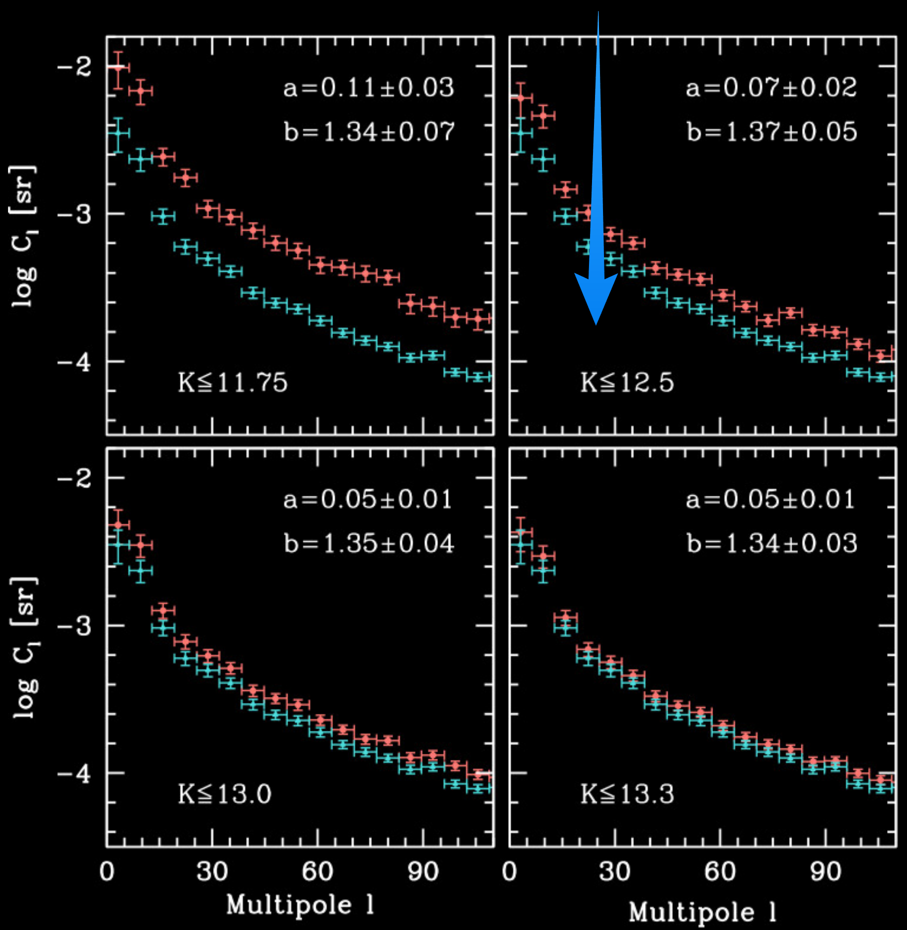
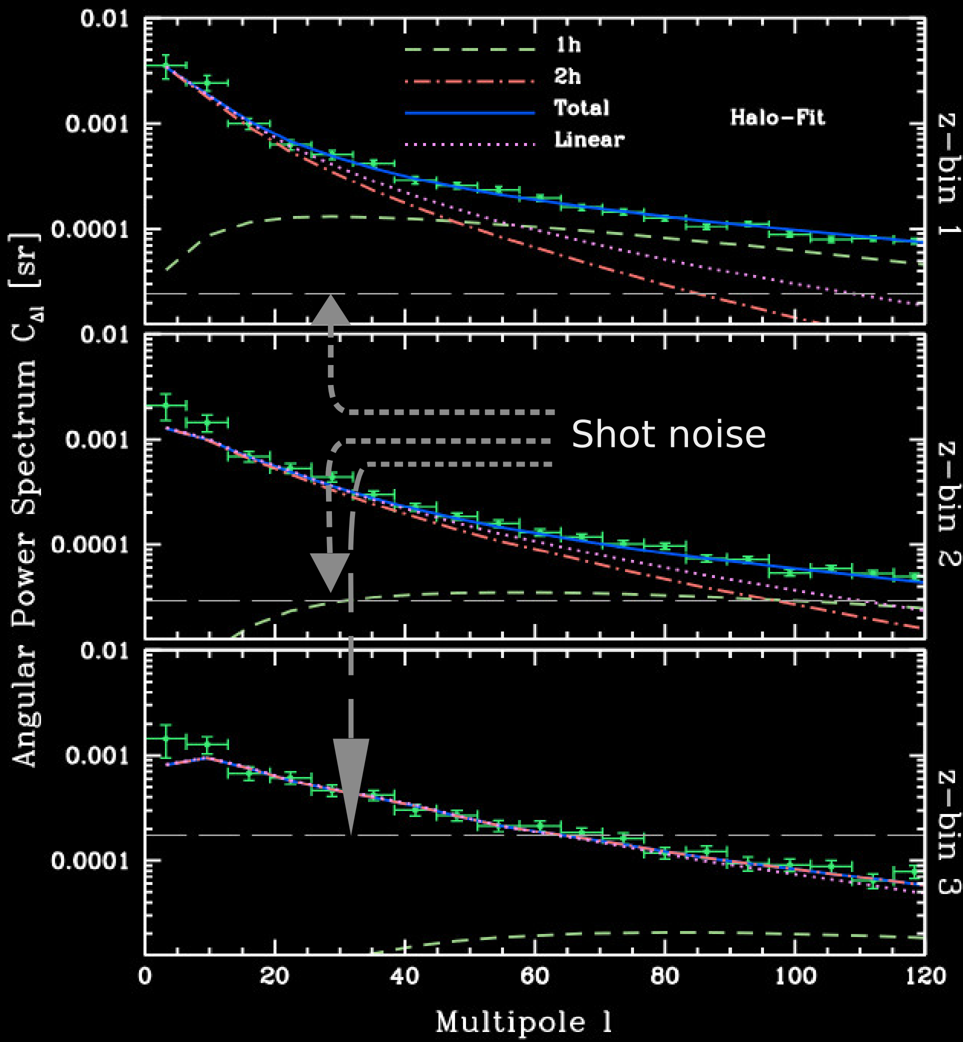
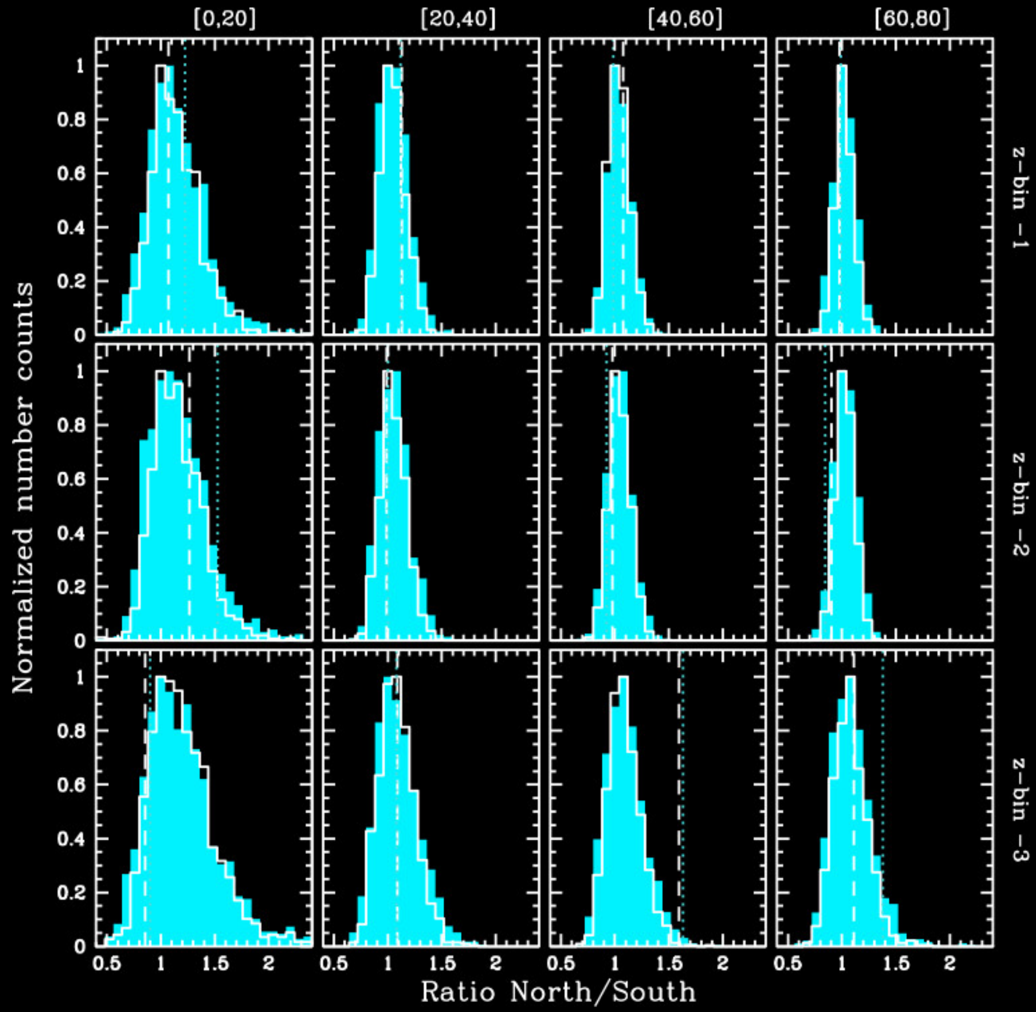
Measuring cross angular power spectrum

As a function of K-band magnitud

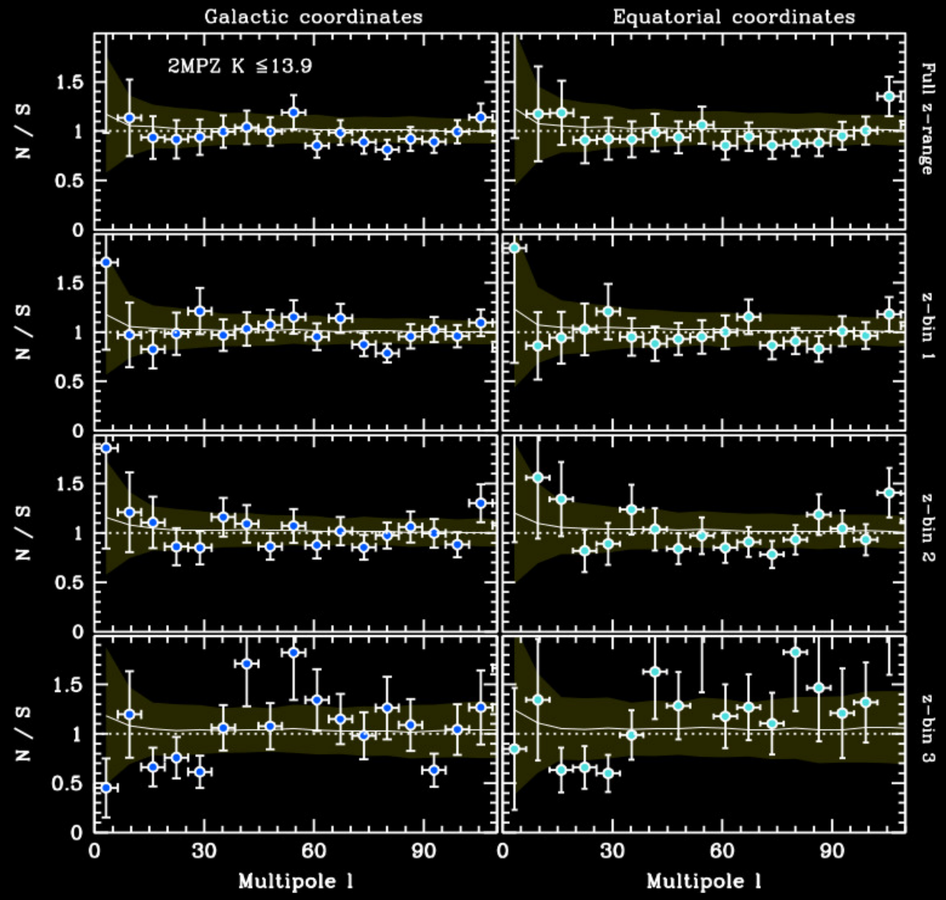




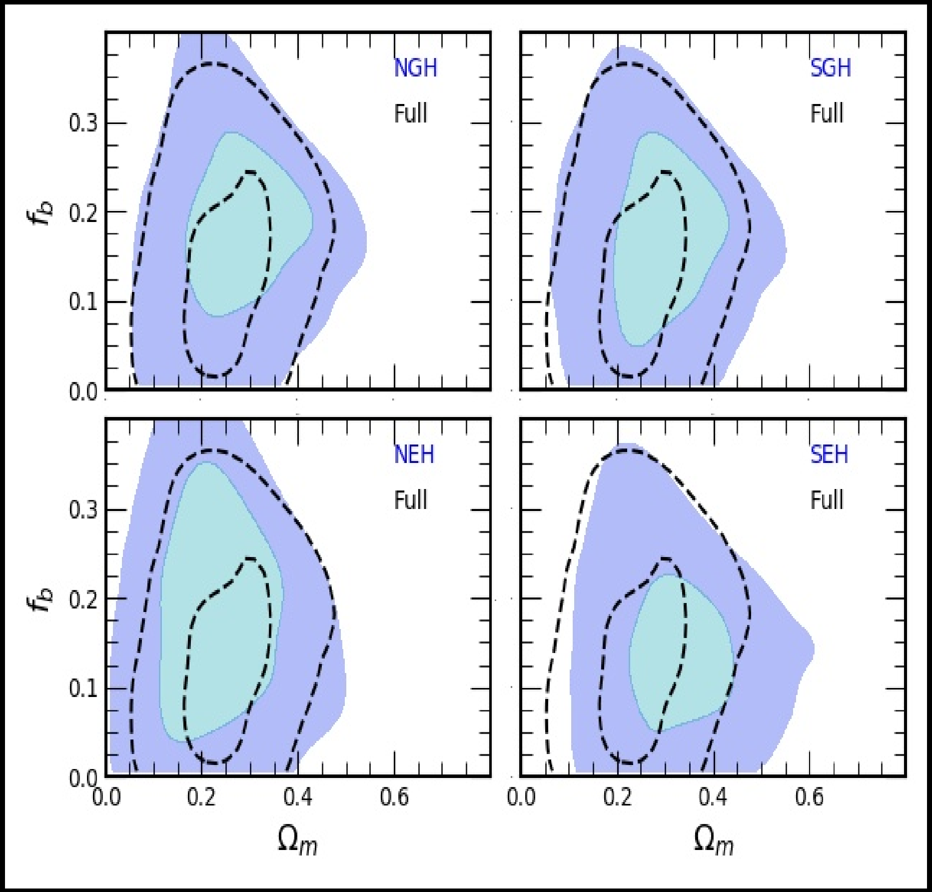
Measuring cross angular power spectrum



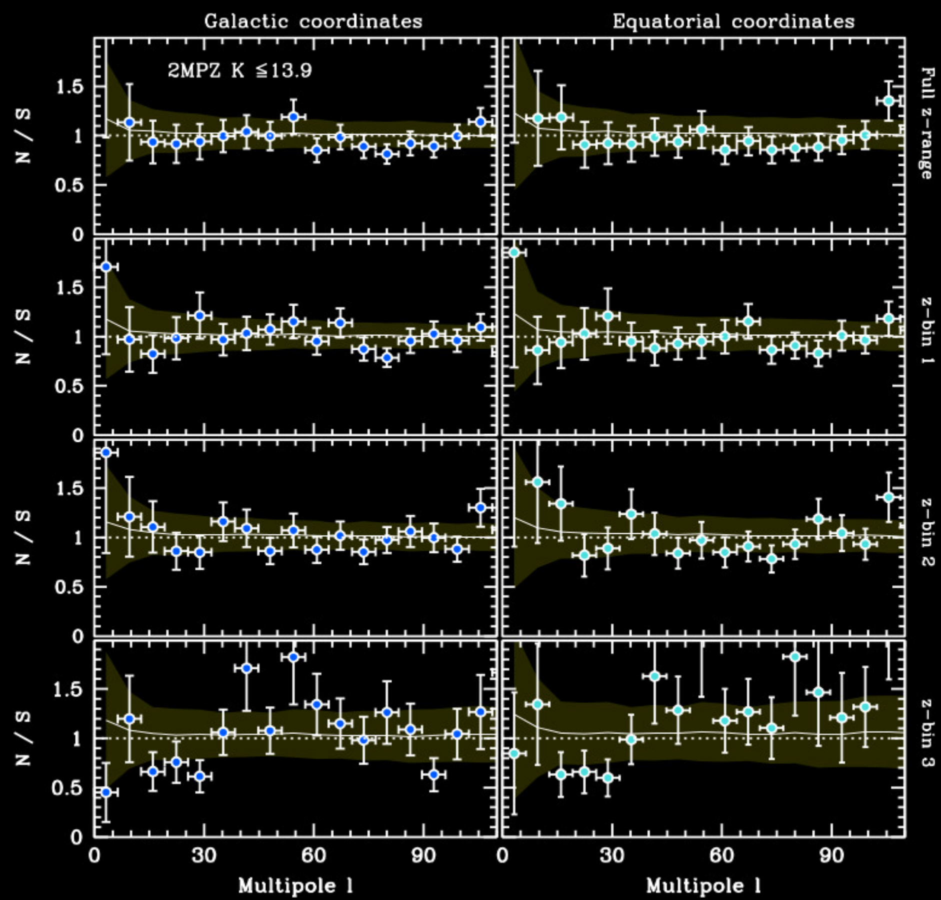
Hemispherical anomaly



Measuring cross angular power spectrum



Hemispherical anomaly



Error estimates

- Gaussian approximation
- Mock Catalogs
- Jack-Knife resampling

These are just some examples: also

Bayesian analysis

N-body based mock catalogs (Physical mode coupling)

Error estimates

- Gaussian approximation (e.g Dodelson 2006, White et al. 2009):
  Diagonal covariance (no mode coupling) matrix with diagonal given by

$$\sigma_\ell^{(i)} = \sqrt{\frac{2}{(2\ell+1)f_{\rm sky}}}\left(C_\ell^{(i)} + S_i\right)$$

Sample variance

Shot Noise (Poisson)

Sky coverage

Number of independent modes

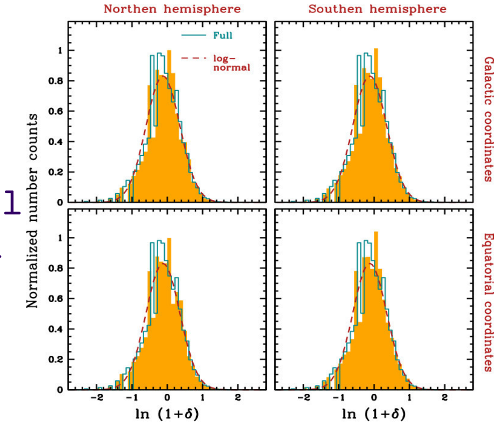
Error estimates

- Gaussian approximation
- Mock Catalogs

$C_\ell^{\rm input}$

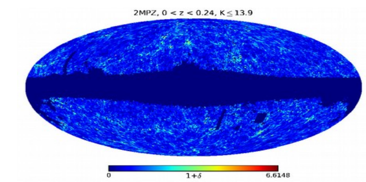
Gaussian distributed $a_{\ell m}$ with variance $(C_\ell^{\rm input})^{1/2}$

Get pixelized map



Log-normal transform

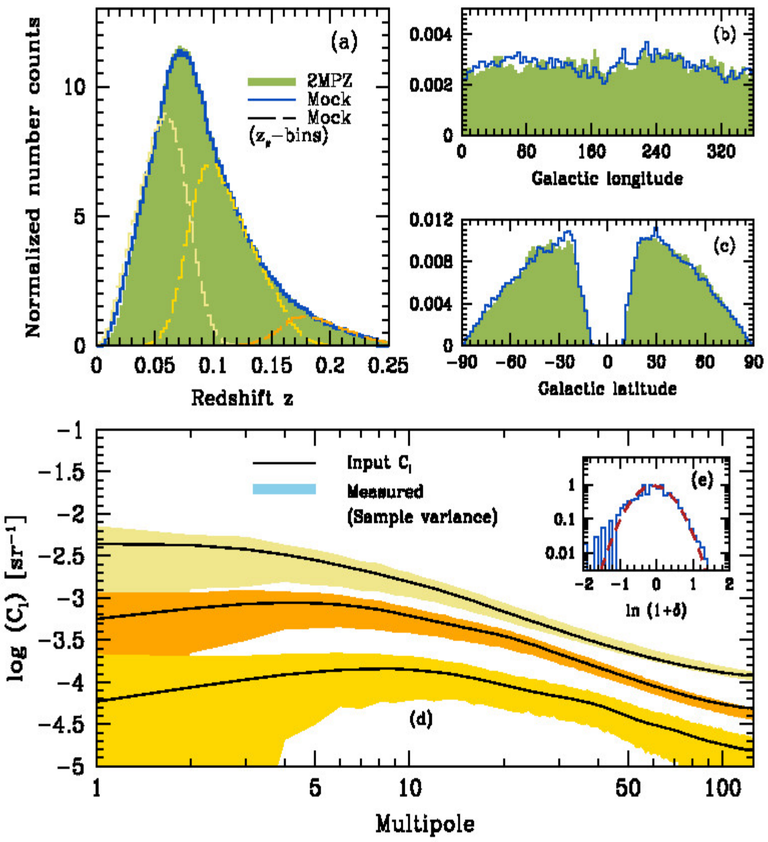
Impose 2MPZ Mask



Poisson sample: Assign photo-z using $\frac{dN}{dz_p}$ and spec-z using $P(z_s|z_p)$

Catalog with RA,Dec, zs, zp with 2MPZ angular clustering

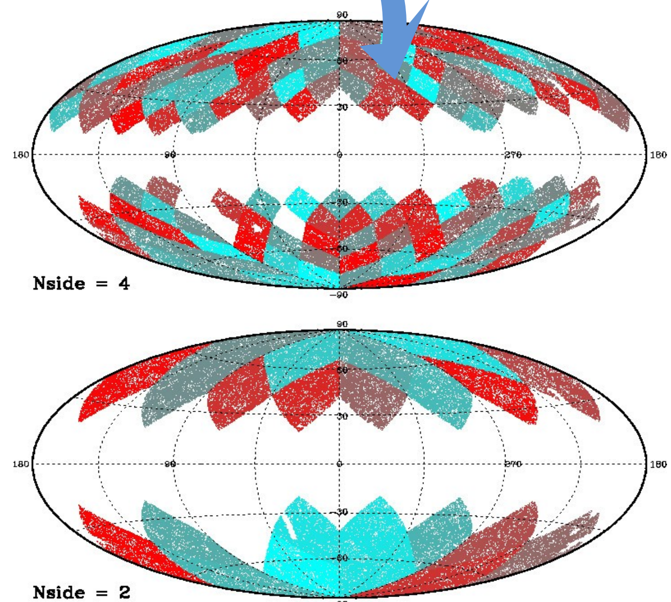
Mode coupling only through the mask

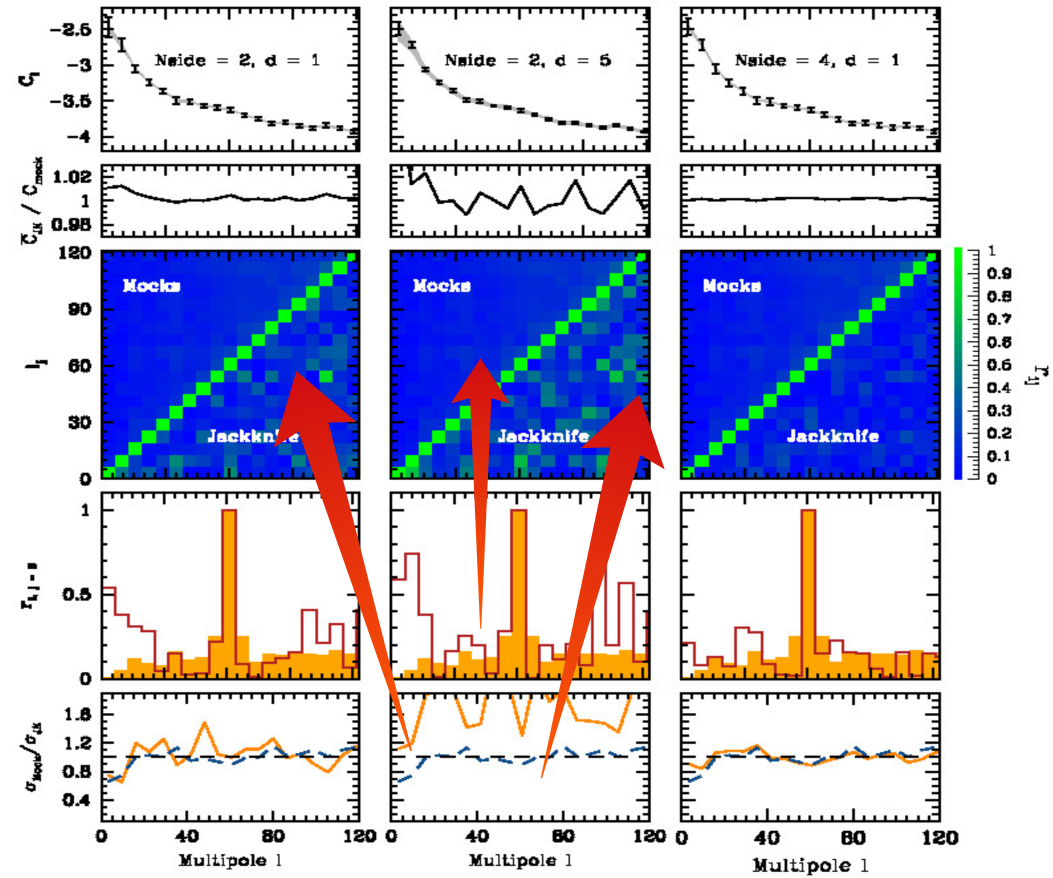


Error estimates

- Gaussian approximation
- Mock Catalogs
- Jack-Knife resampling

Divide the observed area in N patches of (approximately) equal area.

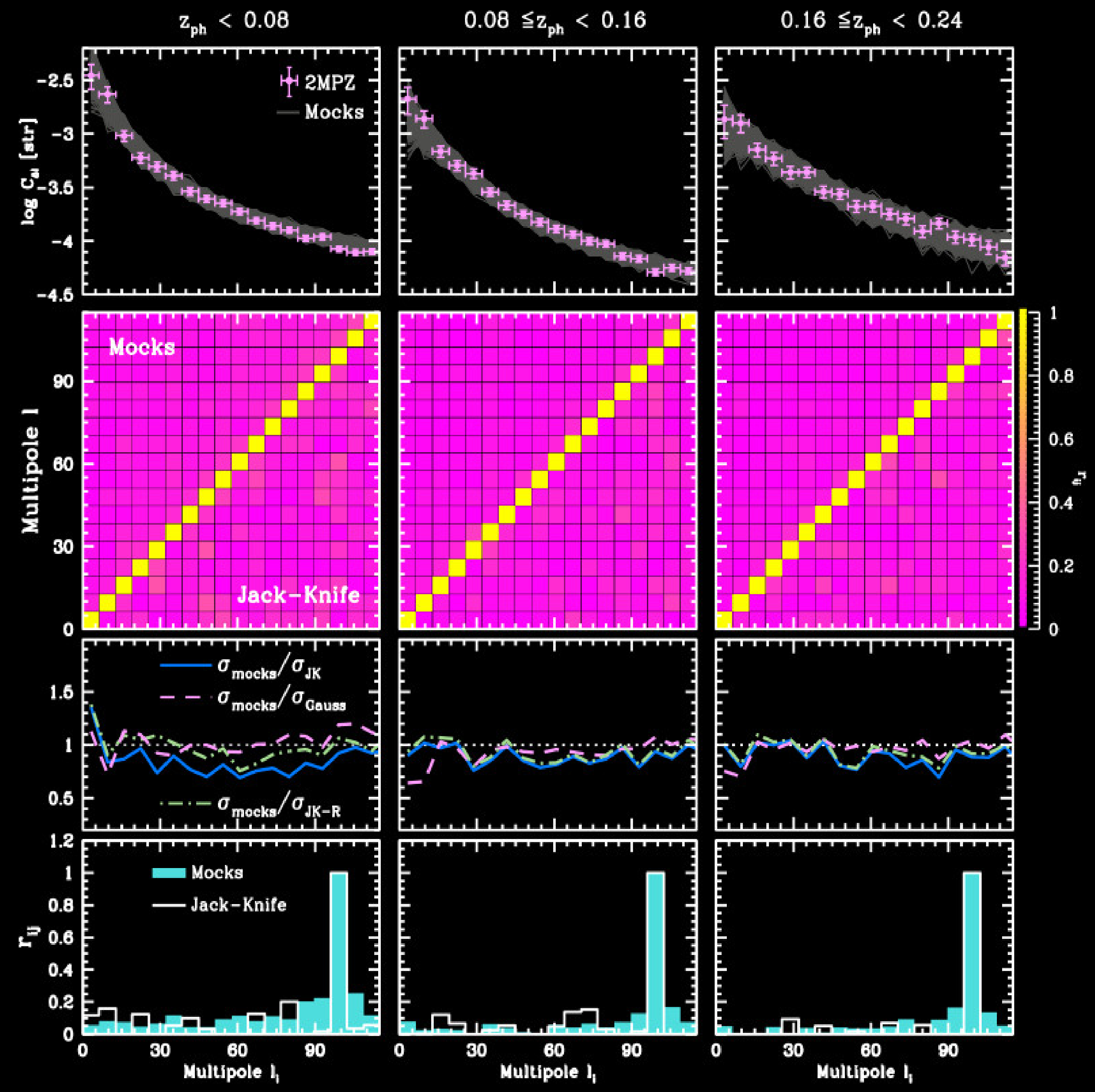




How many sub-patches? Apply it to a mock, for which we know the covariance matrix

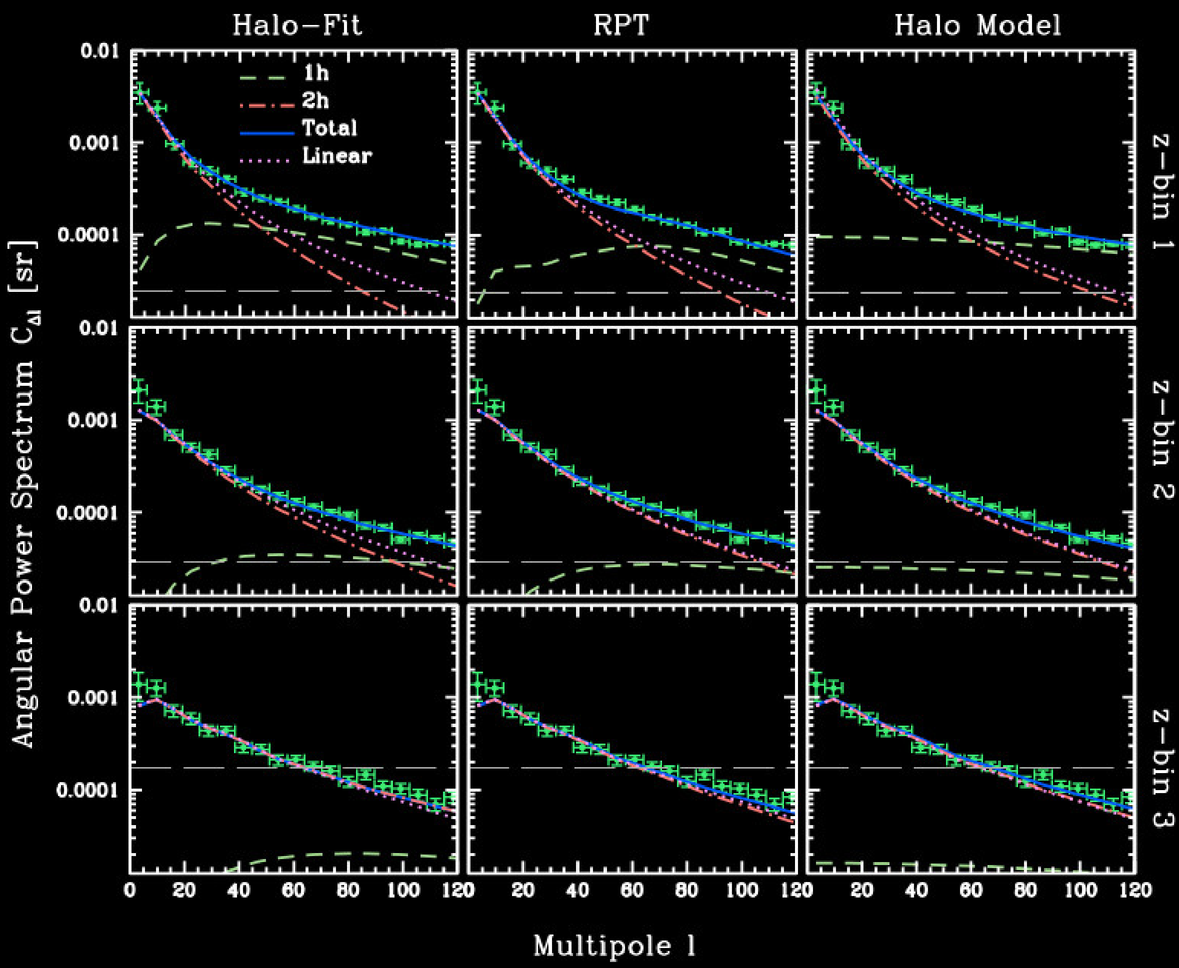
Covariance matrix

- Power
- Covariance
- Variance
- Correlation



Interpretation of angular clustering signal

- COSMOLOGICAL: HALO-FIT
- PHENOMENOLOGICAL: RPT
- ASTROPHYSICAL: HALO-MODEL



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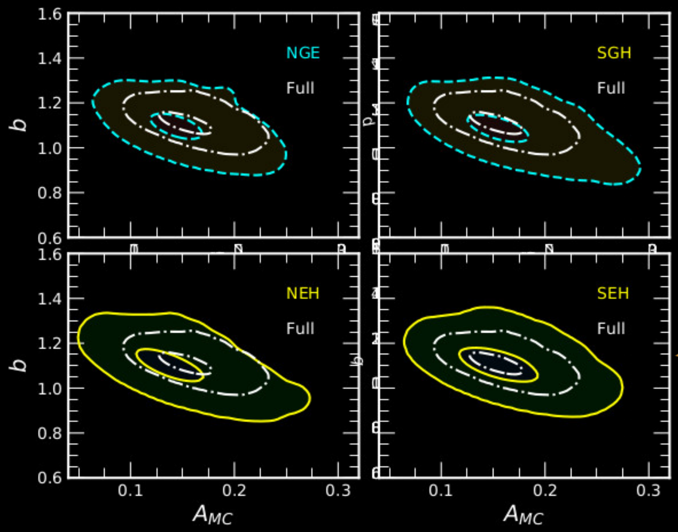
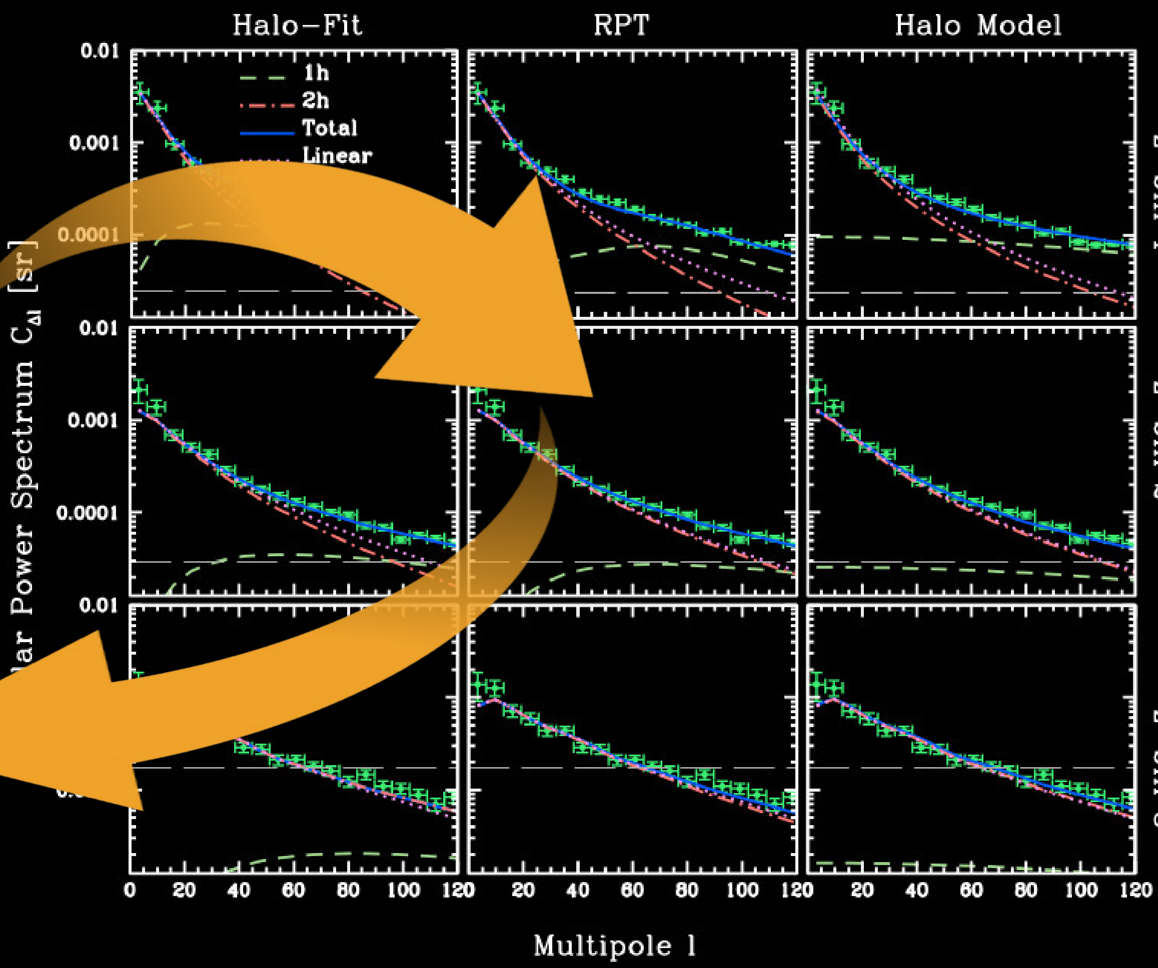
$$P_{\rm gal}(k,z) = b^2\left(e^{-k^2/2k_\star^2} P_{\rm lin}(k,z) + A_{MC} P_{MC}(k,z)\right)$$

Crocce M., Scoccimarro R., 2006, Phys. Rev. D, 73, 063519





Interpretation of angular clustering signal

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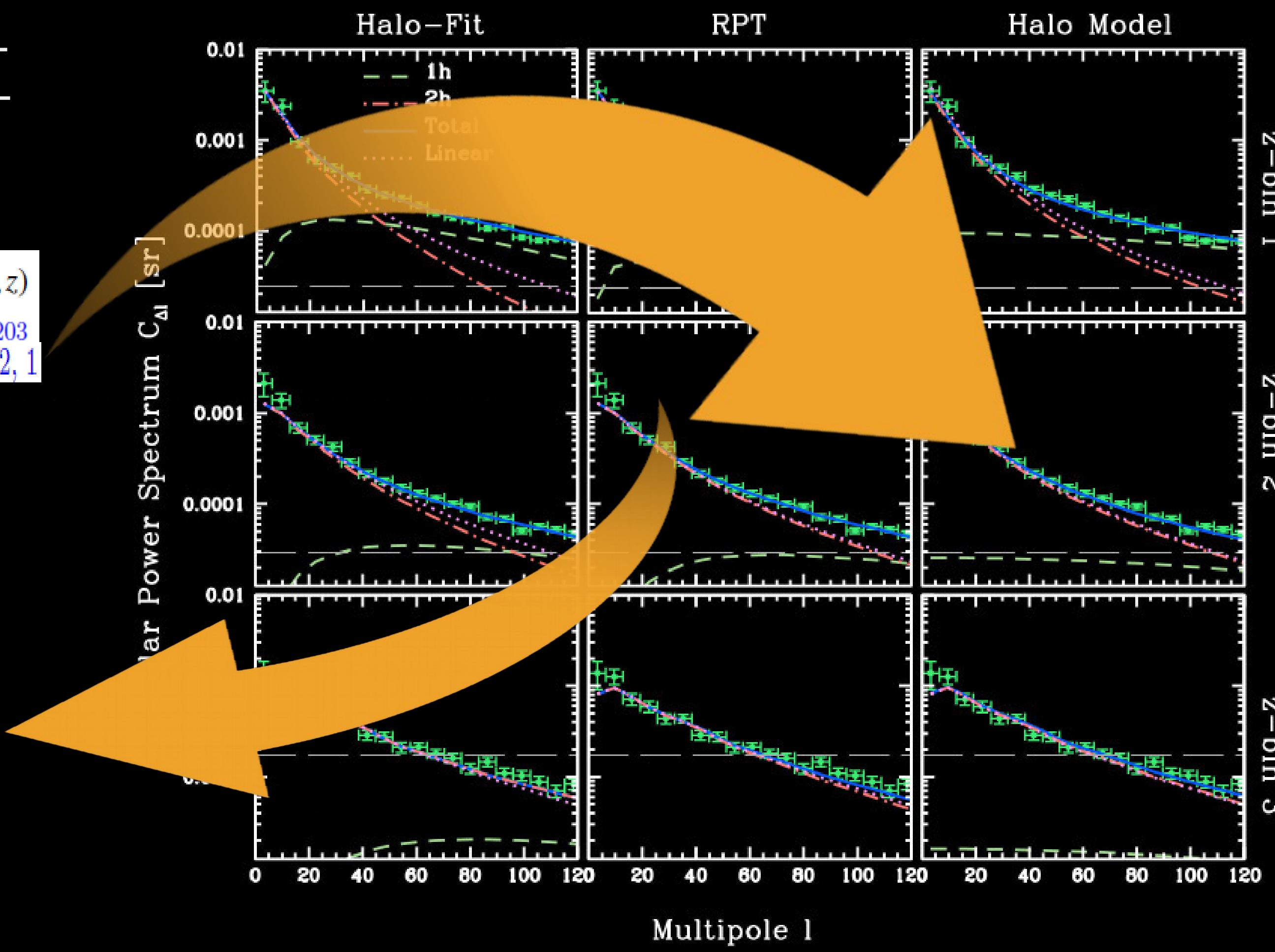
$$P_{\rm gal}(k,z) = b^2(k,z)P_{\rm lin}(k,z) + P_{cs}(k,z) + P_{ss}(k,z)$$

Seljak U., 2000, MNRAS, 318, 203

Cooray A., Sheth R., 2002, Phys. Rep., 372, 1



Interpretation of angular clustering signal

- COSMOLOGICAL: HALO-FIT
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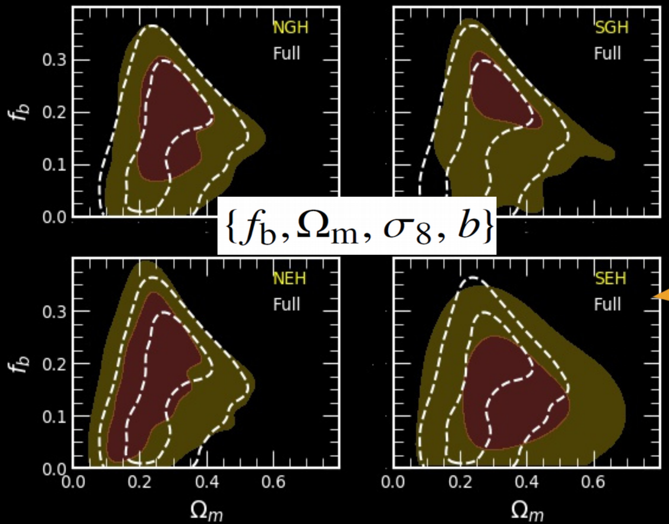
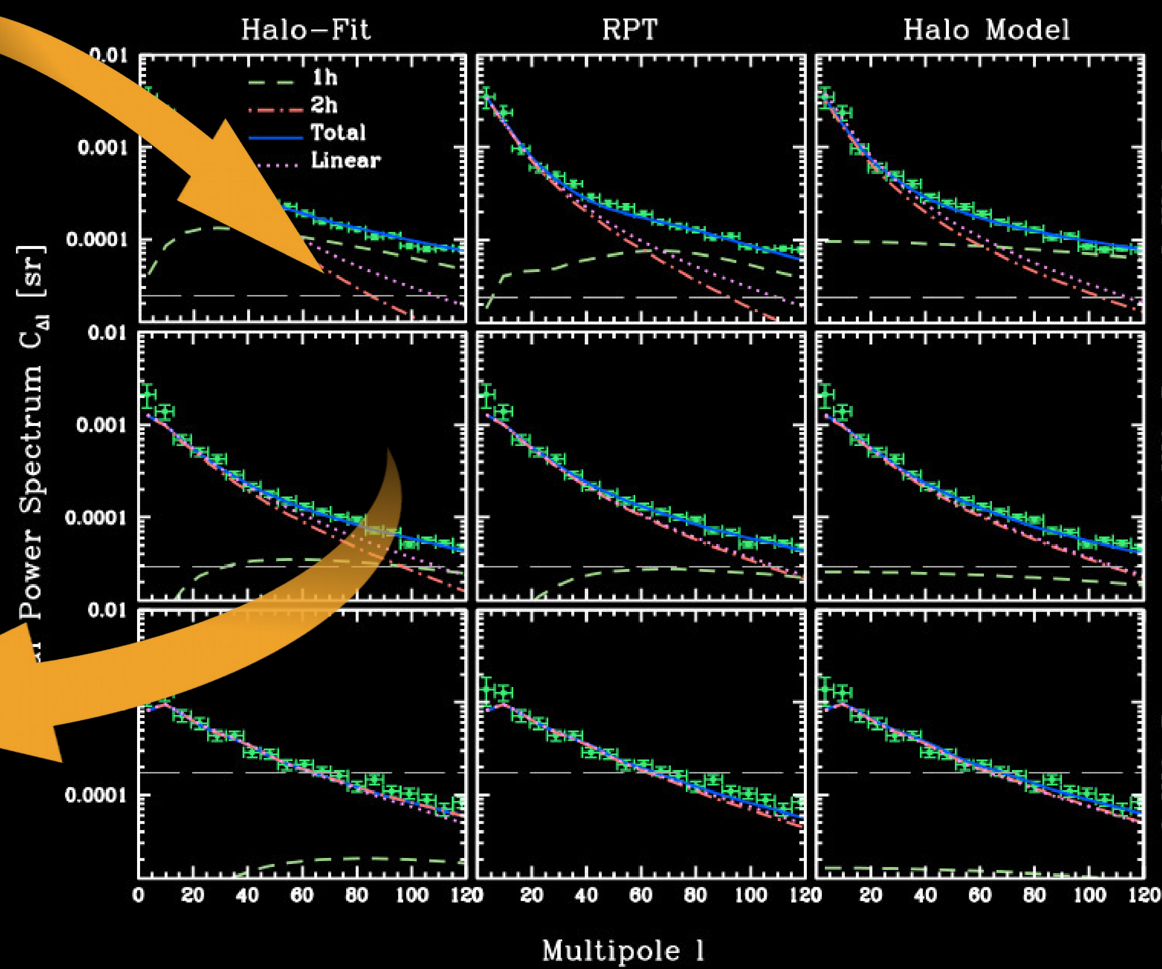
Di Dio E., Montanari F., Lesgourgues J., Durrer R., 2013
Lesgourgues J., 2011, preprint, (arXiv:1104.2932)

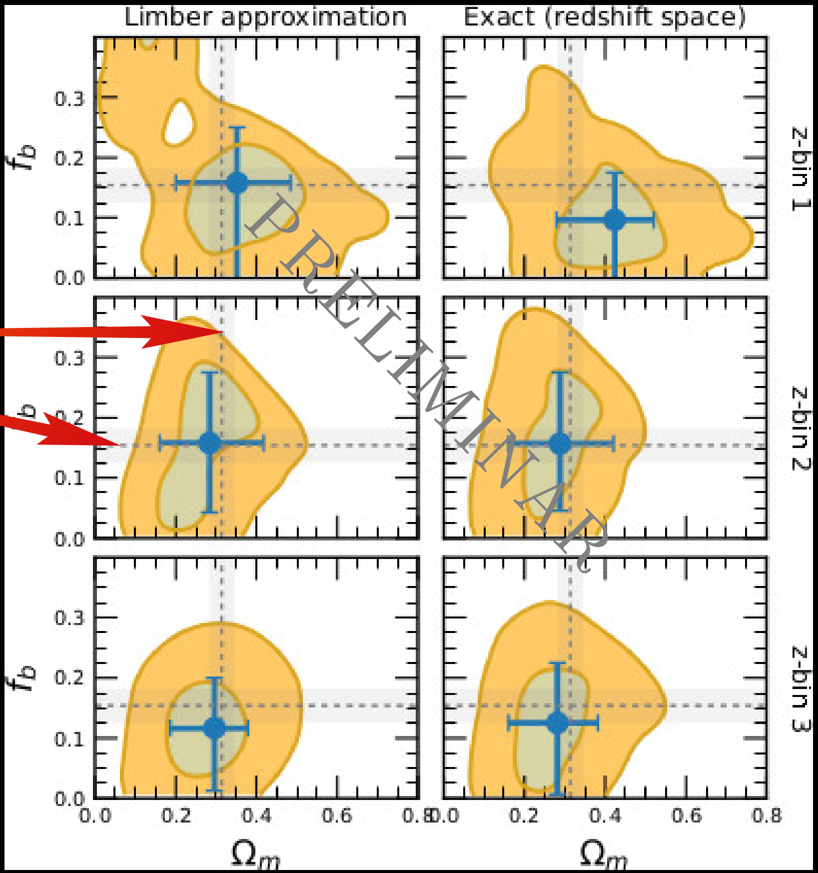


$\{f_{\rm b}, \Omega_{\rm m}, \sigma_8, b\}$



Interpretation of angular clustering signal

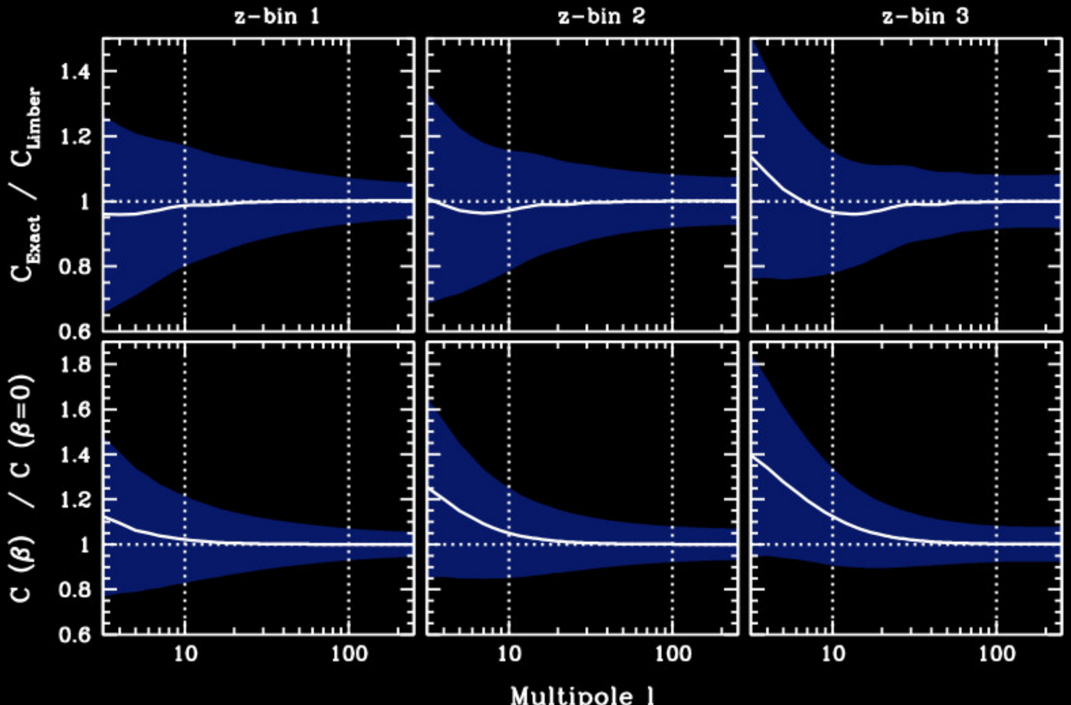
PLANCK values + error bars

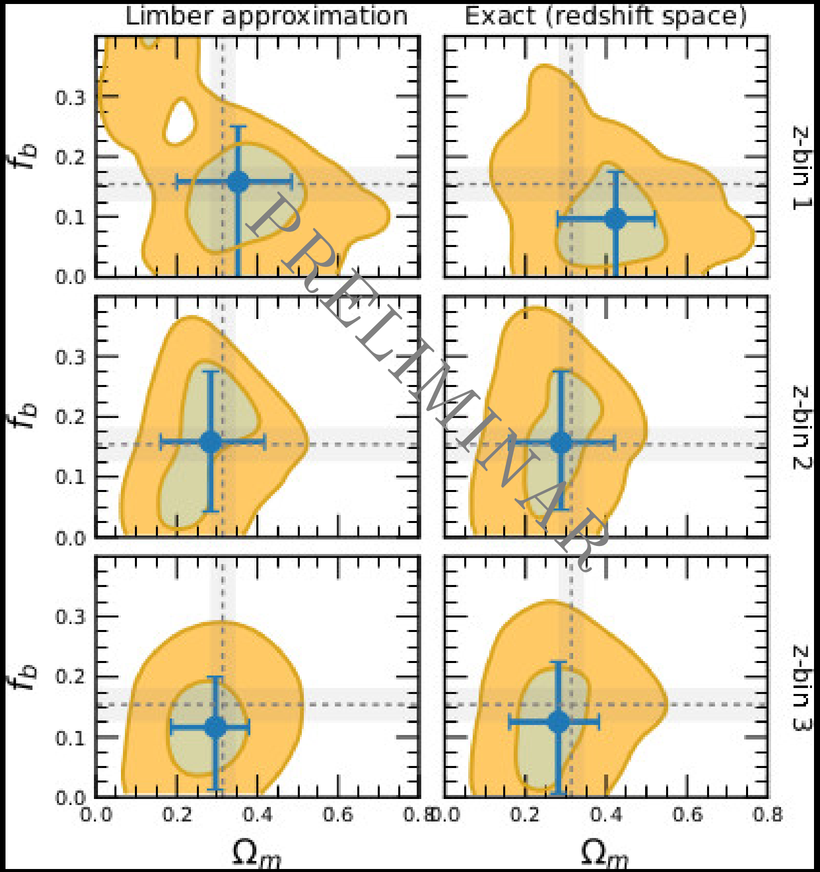


Interpretation of angular clustering signal

(No) Redshift space distortions

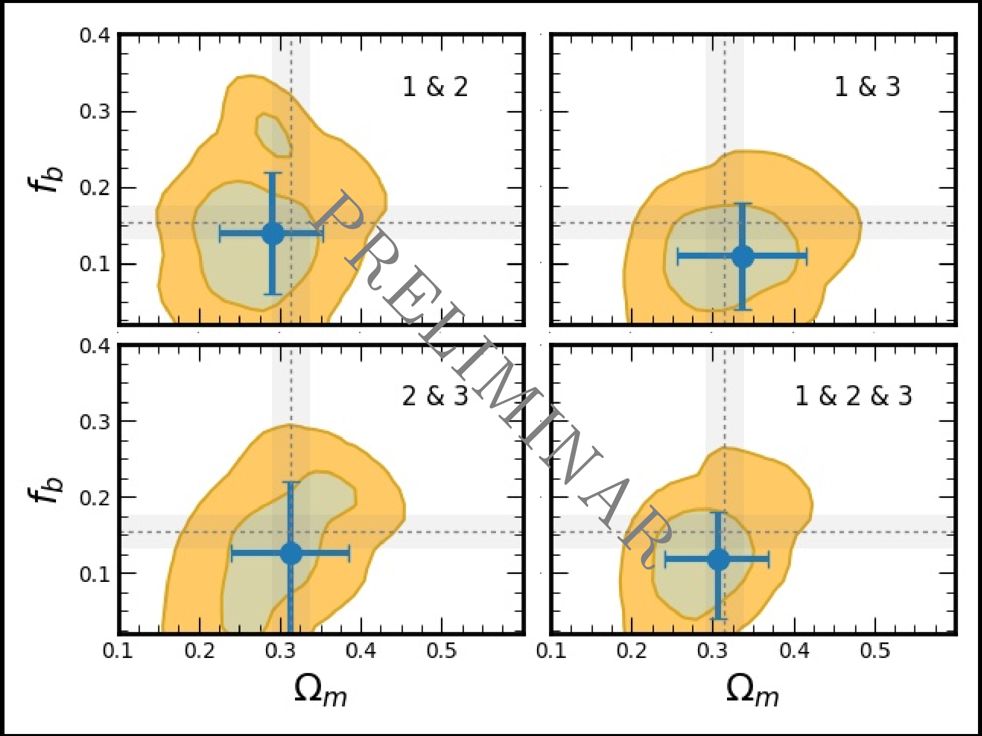
Compare model with RSD vs model without, in terms of expected error bars



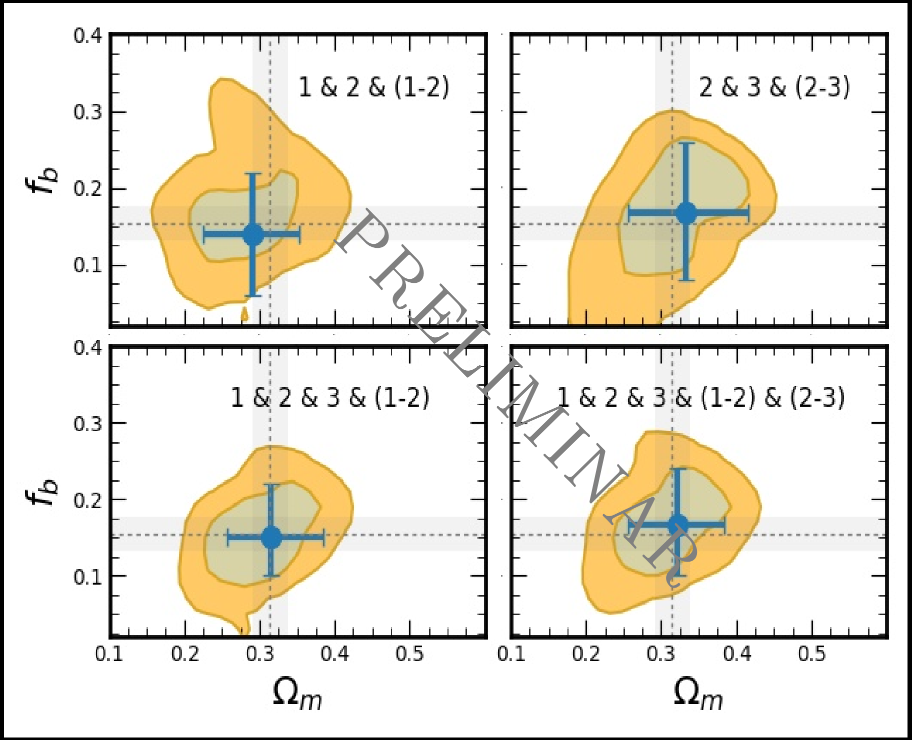


Interpretation of angular clustering signal

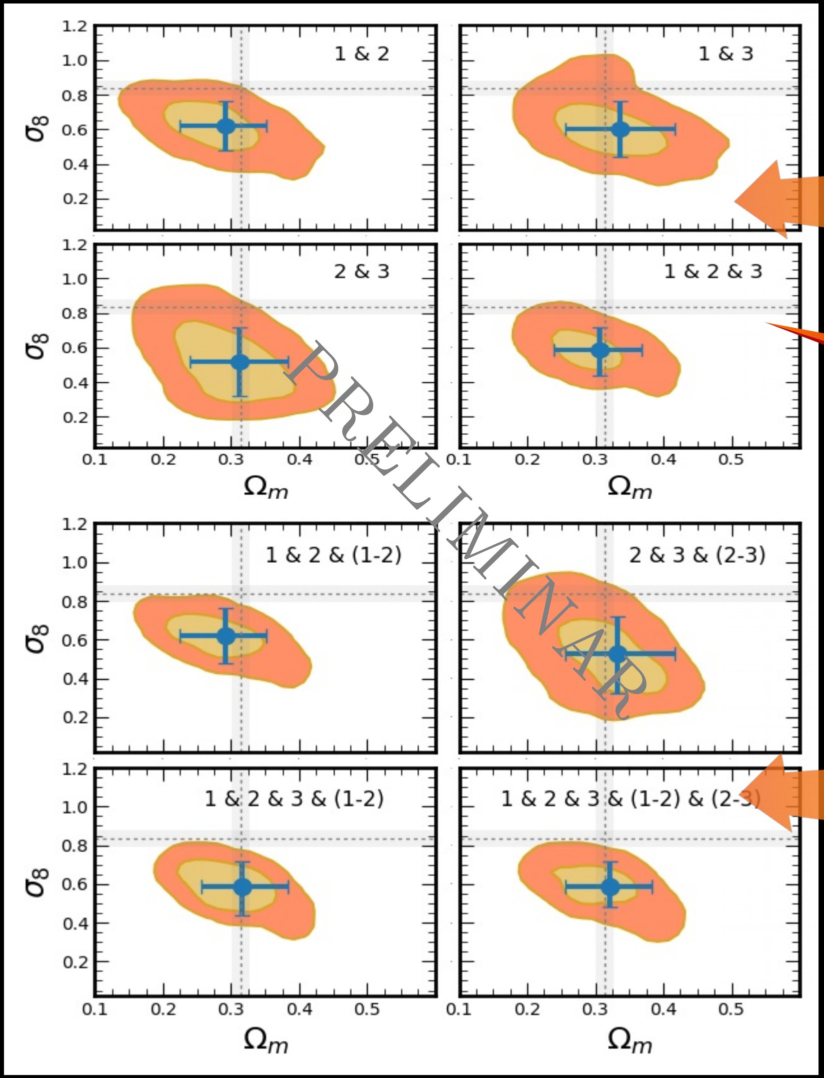
Combine clustering from different bins



Include cross-power spectra



Interpretation of angular clustering signal

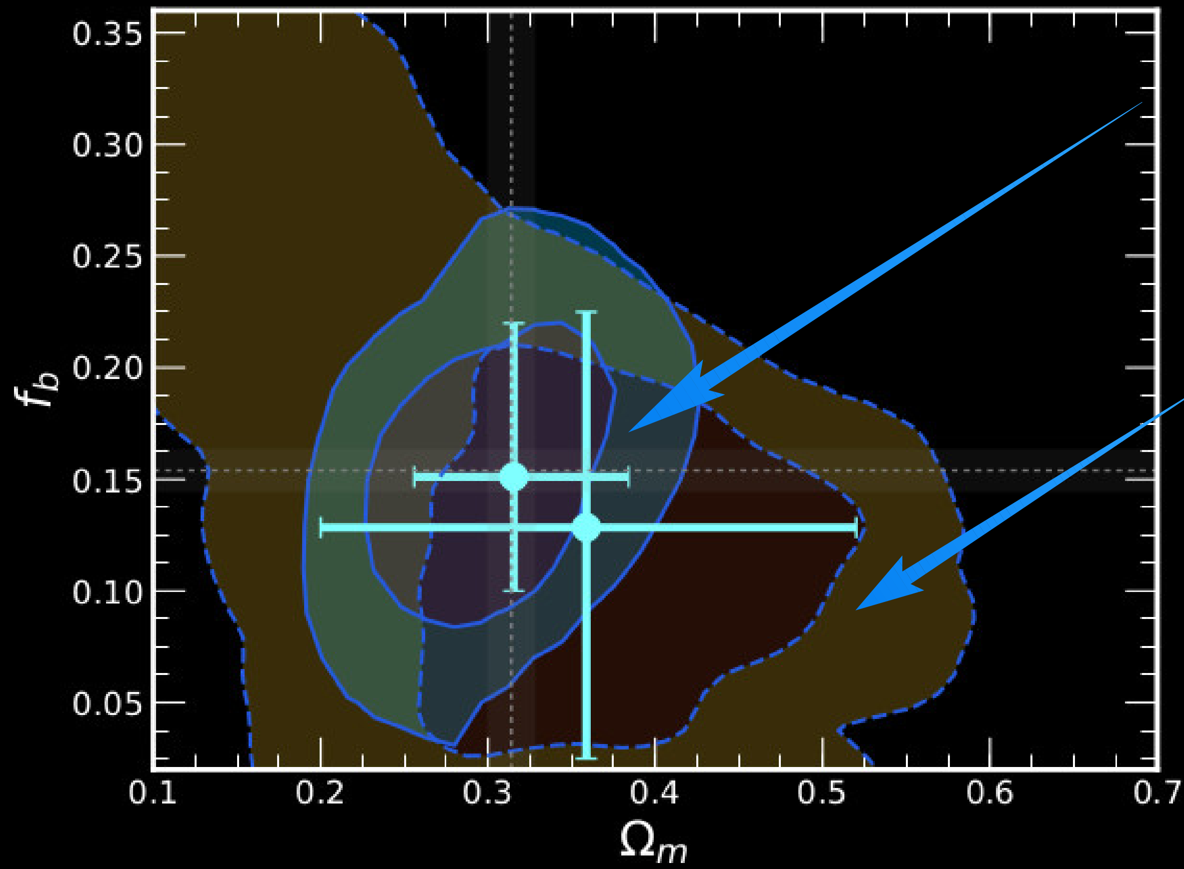


Combine clustering from different bins

Systematics?

Include cross-power spectra

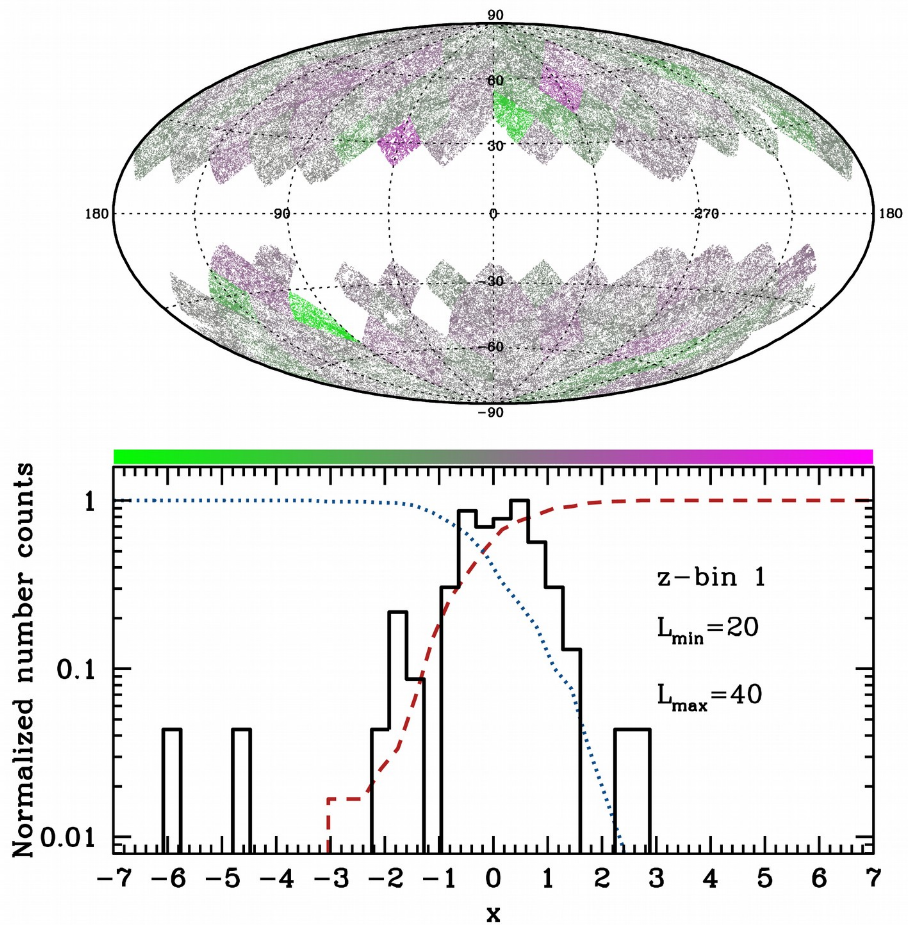
Take home message



Using clustering from different redshift bins

Using the full redshift range

THERE IS MUCH MORE ...



- ENVIRONMENTAL DEPENDENCIES OF CLUSTERING
- MARK STATISTICS

Conclusions / Comments

All forms of struggle

Tomographic Analysis including cross power spectrum for photometric samples

Astrophysical information in the clustering signal