PhD Thesis: Modified Gravity from Cosmic Web Environment-Dependent Galaxy Clustering and Weak Lensing

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Going Beyond ΛCDM

- ΛCDM fits observations very well but still problem of fine tuning, H_0 -tension, σ_8-tension…

$$R^{\mu\nu} - \frac{1}{2} g^{\mu\nu} \mathscr{R} = 8\pi G T^{\mu\nu} - \Lambda g^{\mu\nu}$$

- Accelerated expansion via modified gravity $\rightarrow f(\mathscr{R})$, DGP-gravity with screening mechanism
- Modified gravity is modelled to act on large scales $\rightarrow$ Affects clustering in low-density regions
- Marked correlation functions offer a tool to give these regions more impact in clustering analysis

Marked Correlation Functions

- Defined via ratio of unweighted and weighted correlation function $\xi(r)$ and $W(r)$
- Weight galaxy pairs by a product of marks
- Aim for high S/N ratio and enhancement of signal
- Division by $\xi(r)$ cancels effect of clustering itself
- Marks based on δ or T_{ij} appear promising

→**Need robust reconstruction from galaxy catalog**

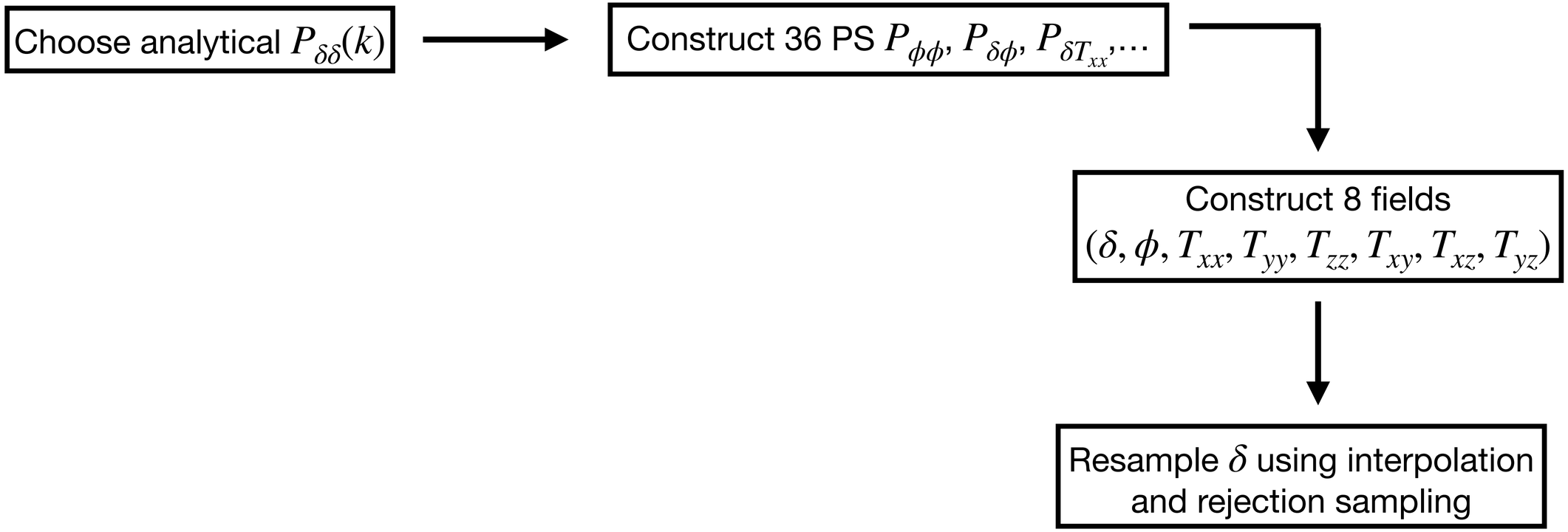
$$WW(r) = \frac{\sum_{ij} m_i m_j}{\bar{m}^2 N(N-1)}$$

$$\mathscr{M}(r) \equiv \frac{1 + W(r)}{1 + \xi(r)}$$

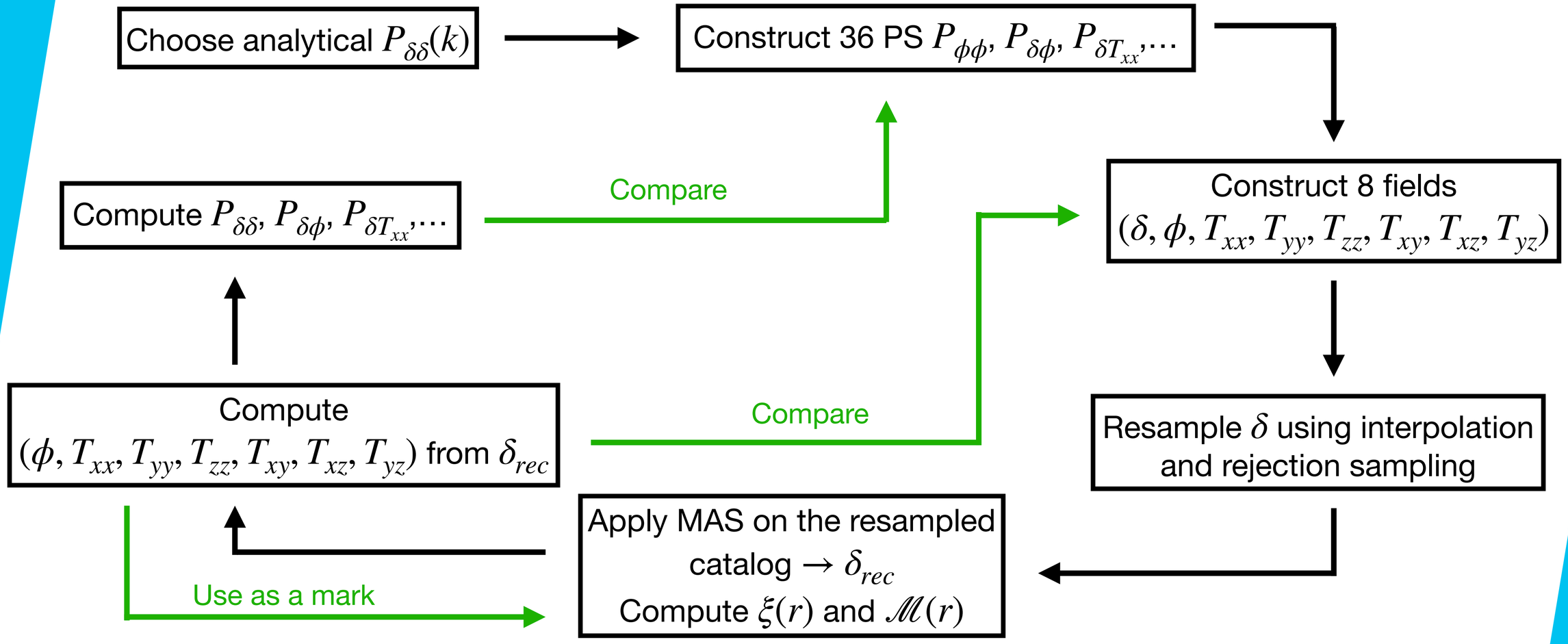
$$m = \left(\frac{\rho_\star + 1}{\rho_\star + \rho} \right)^p$$

Mark proposed in White (2016)

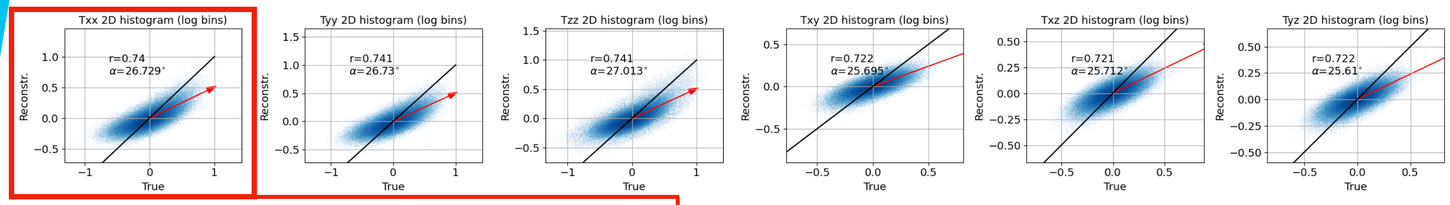
From a Galaxy Catalog to δ on a Grid and Beyond



From a Galaxy Catalog to δ on a Grid and Beyond

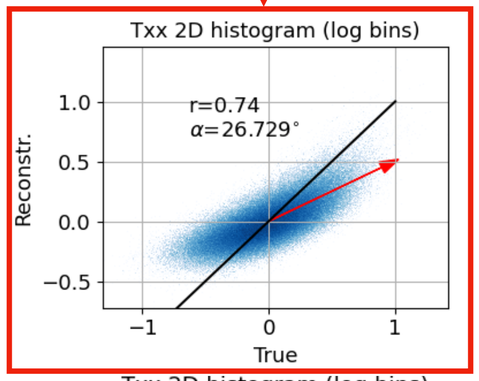


Reconstruction of T_{ij}

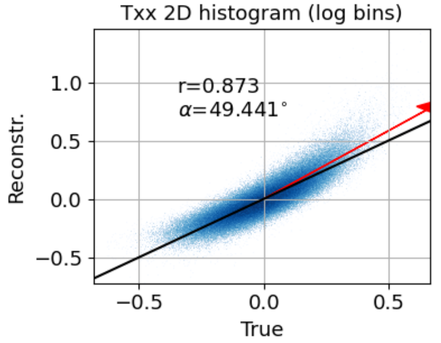


PCS MAS

$\sigma_{eff} \approx 9$ Mpc/h

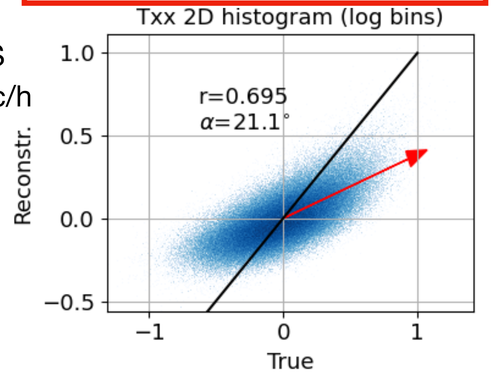


Convolve true field



Quintic MAS

$\sigma_{eff} \approx 11$ Mpc/h



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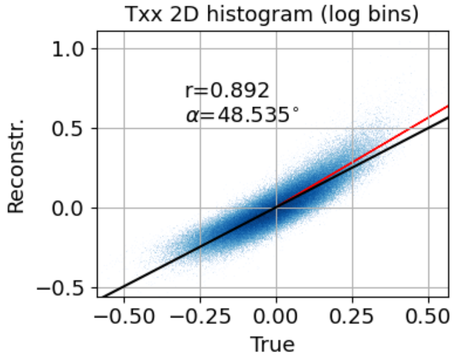
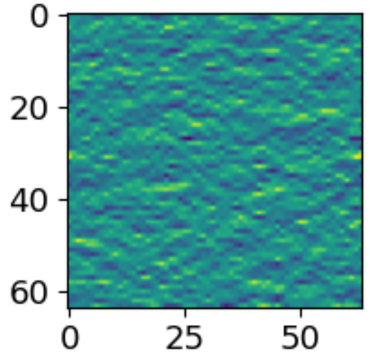


<u>Settings:</u>

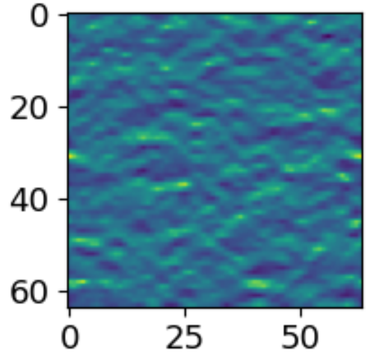
- N=64
- L=1000Mpc/h
- a=15.625Mpc/h
- R=8Mpc/h
- Log-Normal Field
- $N_p \approx 1.3 \times 10^6$

$\rightarrow \approx$ 5 points/cell

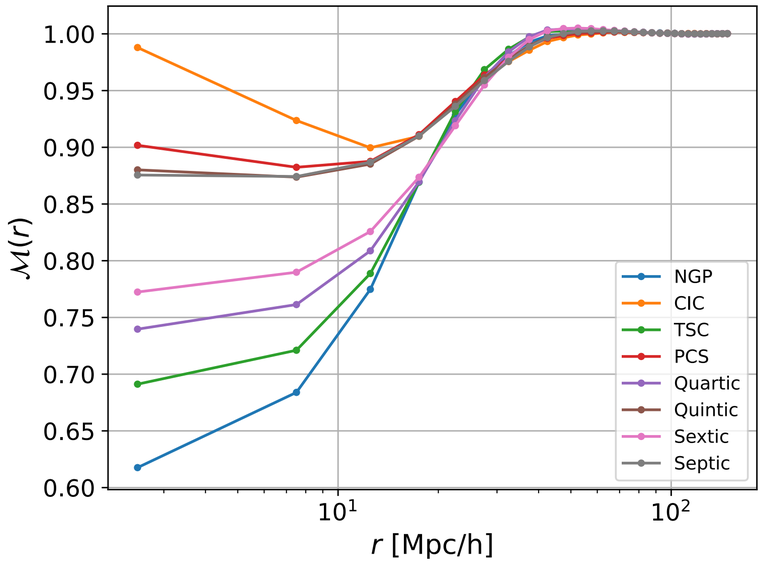
True



Reconstructed

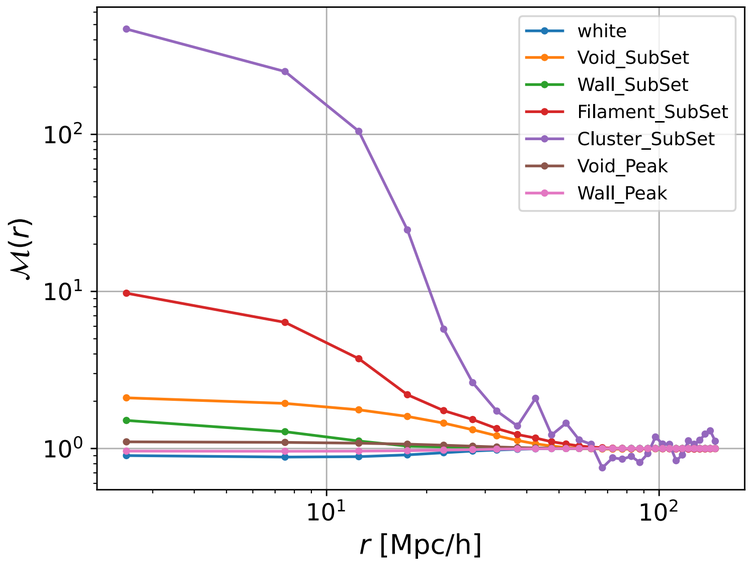


Marked Correlation Functions - Reconstructed Fields



"White Mark" with $\rho_\star = 4$ and $p = 10$, different MAS

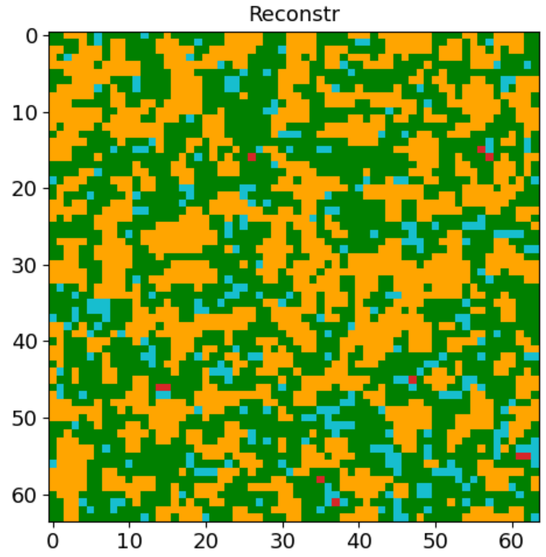
$$m = \left(\frac{\rho_\star + 1}{\rho_\star + \rho} \right)^p$$



PCS MAS, different marks

Void_Subset: Set mark to 1 for voids and 0 otherwise

Void_Peak: Set mark to 4 for voids and
walls: 3
filaments: 2
clusters: 1



Red: cluster
Blue: Filament
Green: Wall
Orange: Void

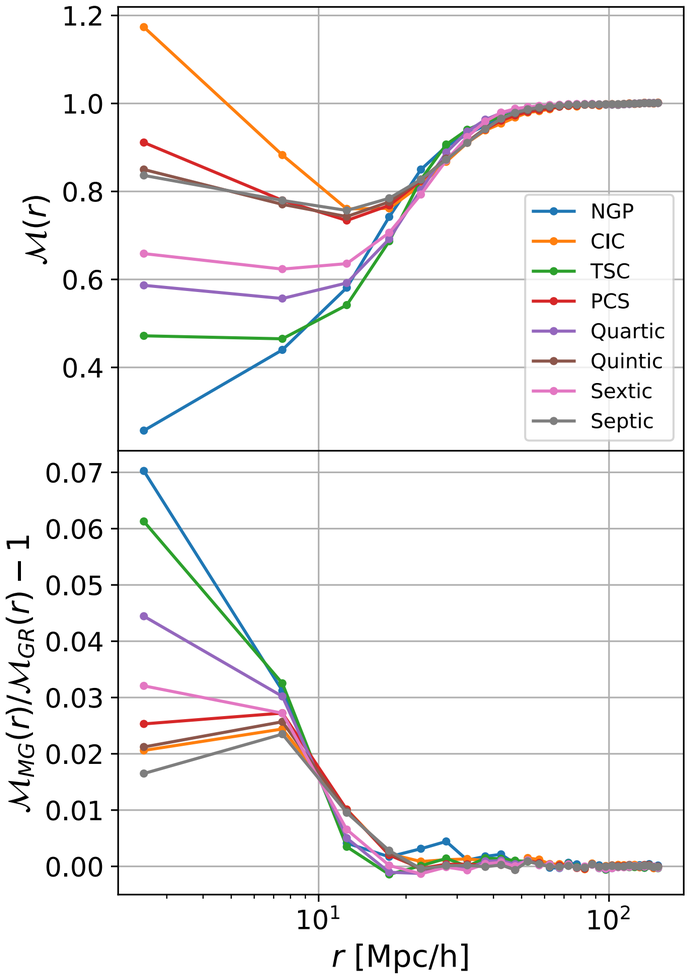
Marked Correlation Functions - Simulations

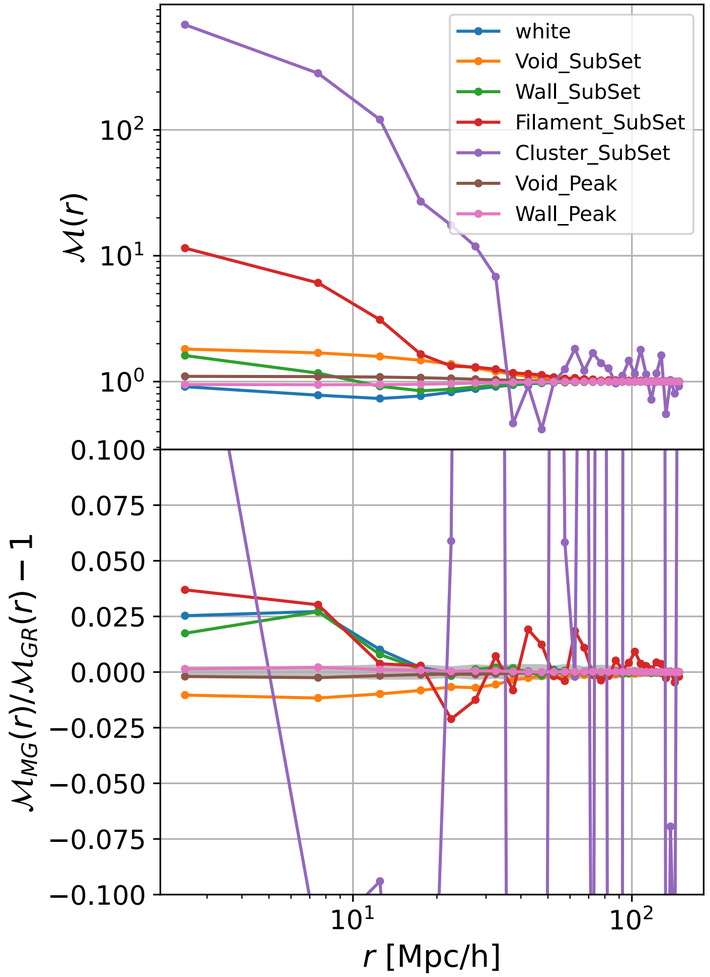
ELEPHANT simulation:

- L=1024Mpc/h
- GR and $f(\mathscr{R})$
- $|f_{\mathscr{R}0}| = 10^{-4}$
- ~ 340000 galaxies

MAS applied on N=64
$\rightarrow \approx 1.3$ points per cell

Simulation used in e.g. Hernández-Aguayo et al. (2018) or Alam et al. (2021)





Summary and Outlook

- Marked correlation functions able to enhance difference between MG and GR
- MAS impacts quality of reconstruction and marked correlation function
    - Introduces smoothing scale → trade between quality of reconstruction and smoothing scale
    - Higher order MAS reducing difference between MG and GR for “White Mark”
- Environmental classification used as marks produce reasonable $\mathscr{M}(r)$ in first test

→ Explore tidal tensor directly as mark, theoretical modelling needed

Thank you for your attention!

Reconstruction of δ

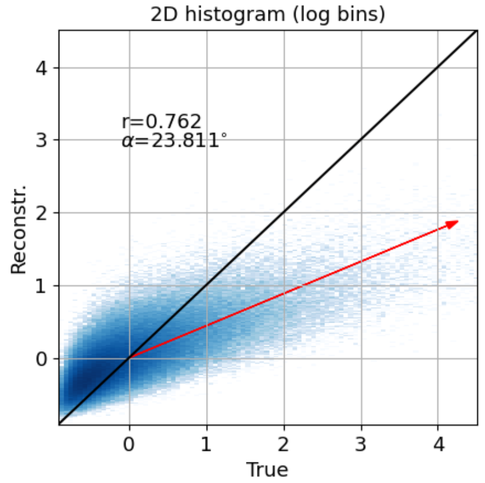
<u>Settings:</u>

- N=64
- L=1000Mpc/h
- a=15.625Mpc/h
- R=8Mpc/h
- Log-Normal Field
- $N_p \approx 1.3 \times 10^6$

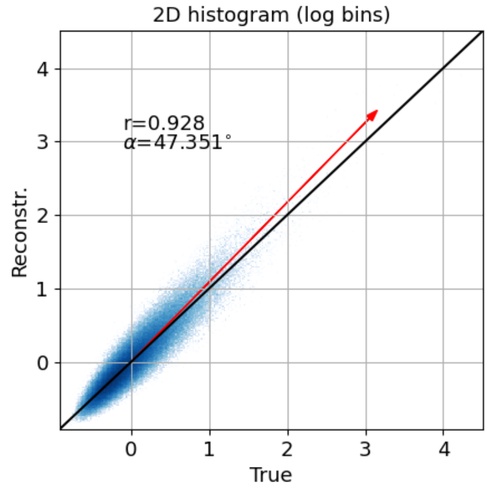
$\rightarrow \approx$ 5 points/cell

PCS MAS

$\sigma_{eff} \approx 9$ Mpc/h

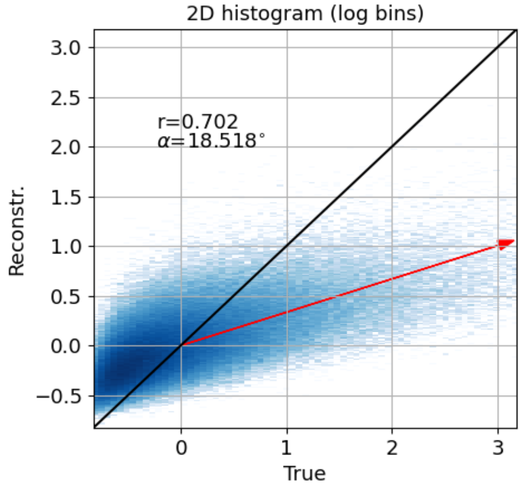


Convolve true field

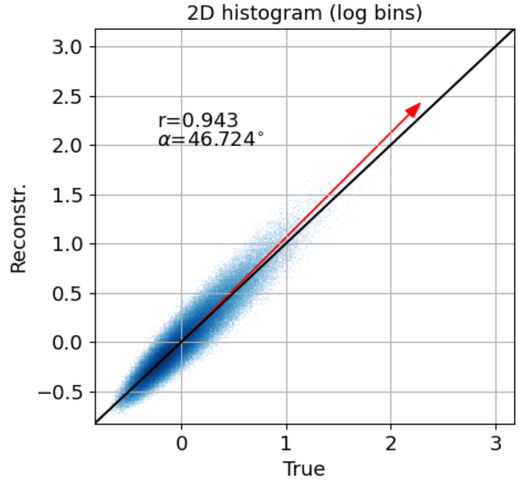


Quintic MAS

$\sigma_{eff} \approx 11$ Mpc/h



Convolve true field



Impact of Points per Grid-Cell

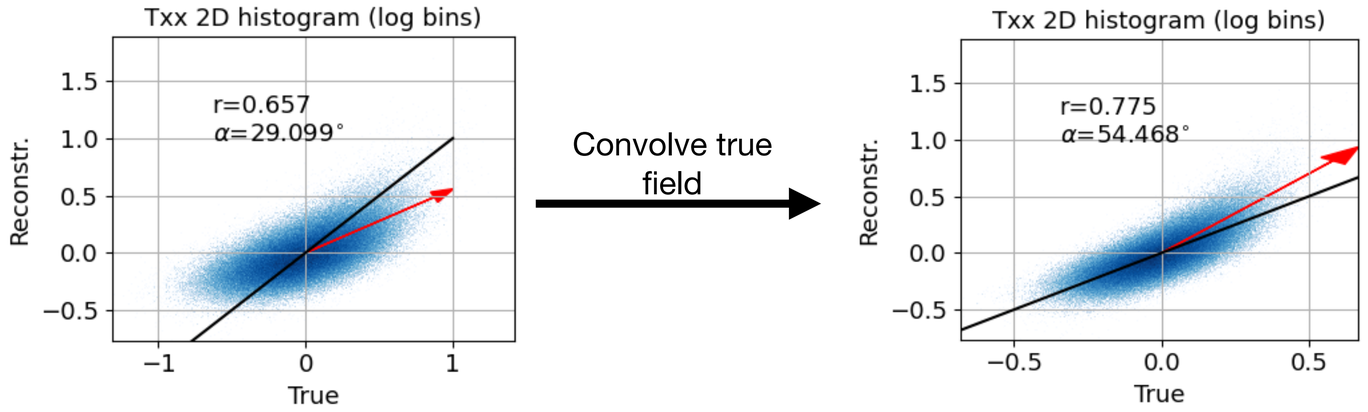
Settings:

- N=64
- L=1000Mpc/h
- a=15.625Mpc/h
- R=8Mpc/h
- Log-Normal Field
- $N_p \approx 434000$

$\rightarrow \approx$ 1.66 points/cell

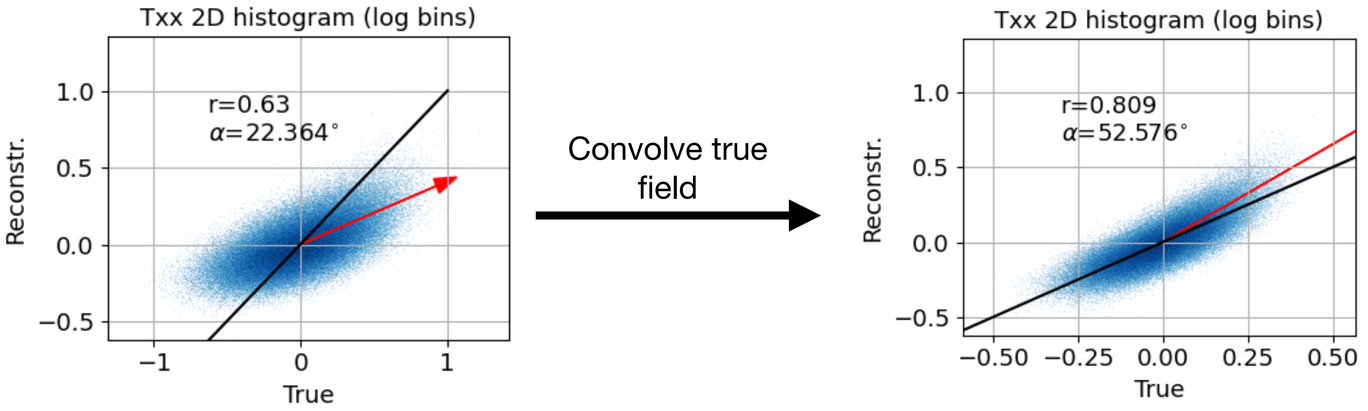
PCS MAS

$\sigma_{eff} \approx 9$ Mpc/h



Quintic MAS

$\sigma_{eff} \approx 11$ Mpc/h



Impact of Points per Grid-Cell

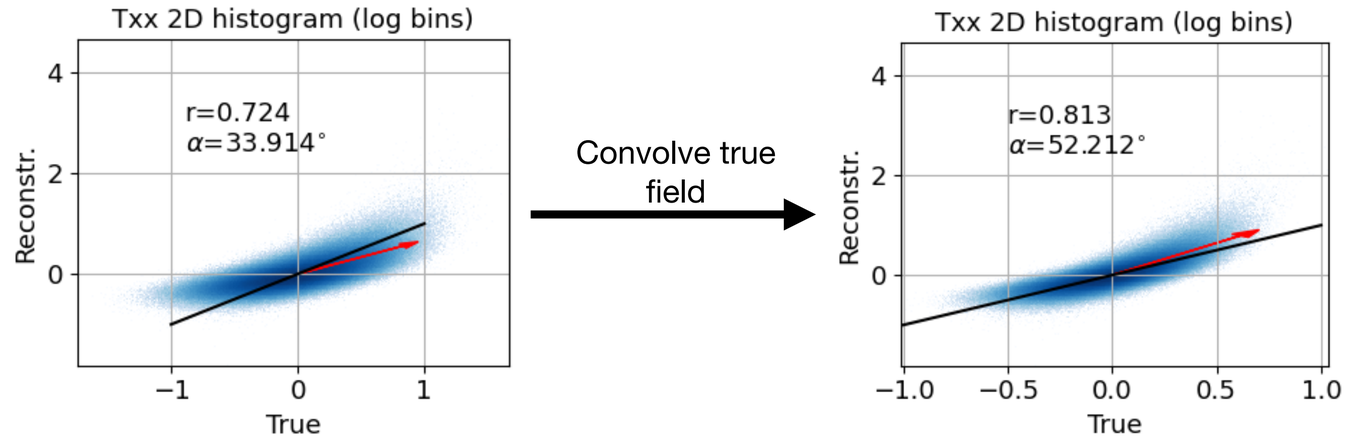
Settings:

- N=128
- L=1400Mpc/h
- a=10.9375Mpc/h
- R=8Mpc/h
- Log-Normal Field
- $N_p \approx 3.1 \times 10^6$

$\rightarrow \approx$ 1.5 points/cell

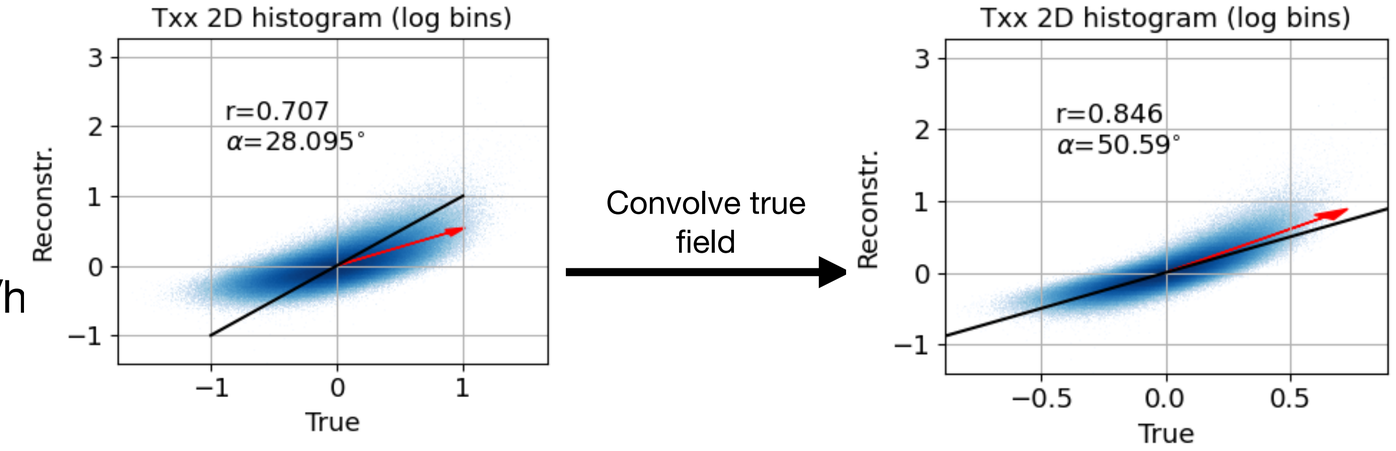
PCS MAS

$\sigma_{eff} \approx 6.3$ Mpc/h



Quintic MAS

$\sigma_{eff} \approx 7.7$ Mpc/h



Some Formulas

Analytical power spectrum approximation

$$P_{\delta\delta}(k) = (2\pi)^6 W_{R,th}^2(k) \frac{k}{\left(1 + \left(\frac{k}{0.05}\right)^2\right)^{3/2}} \quad \text{with} \quad W_{R,th}(k) = 3\frac{(\sin(kR) - kR\cos(kR))}{(2\pi)^3 (kR)^3}$$

Computation of ϕ and T_{ij} from δ:

$$\phi = -4\pi G \frac{\delta}{k^2} \qquad T_{ij} = -k_i k_j \phi = 4\pi G k_i k_j \frac{\delta}{k^2}$$

Kernels

Configuration space 1D

$$W_{Cubic}(s) = \begin{cases} \frac{3}{2}|s|^3 - \frac{5}{2}|s|^2 + 1 & \text{for} \quad |s| \leq 1 \\ -\frac{1}{2}|s|^3 + \frac{5}{2}|s|^2 - 4|s| + 2 & \text{for} \quad 1 < |s| \leq 2 \\ 0 \quad \text{for} \quad |s| > 2. \end{cases}$$

$$W_{PCS}(s) = \begin{cases} \frac{1}{6}(4 - 6|s|^2 + 3|s|^3) & \text{for} \quad |s| \leq 1 \\ \frac{1}{6}(2 - |s|)^3 & \text{for} \quad 1 < |s| \leq 2 \\ 0 \quad \text{for} \quad |s| > 2. \end{cases}$$

Fourier Space 1D

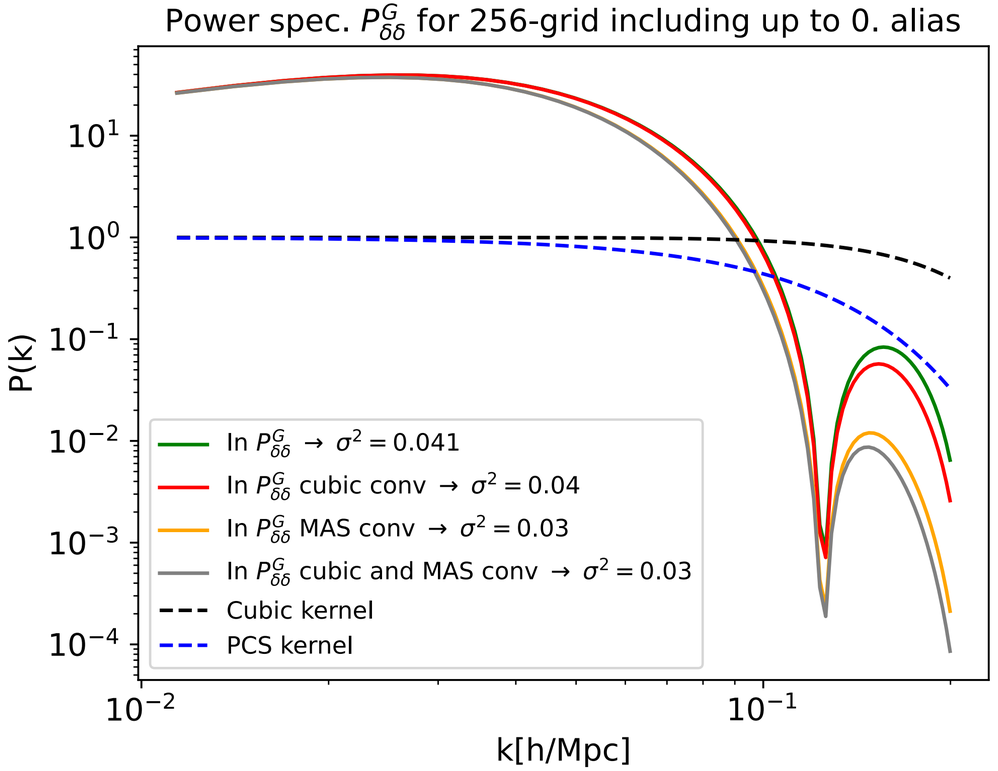
$$W_{Cubic}(ak) = -\frac{1}{2\pi}\frac{16(ak\cos(\frac{ak}{2}) - 3\sin(\frac{ak}{2}))\sin^3(\frac{ak}{2})}{(ak)^4}$$

$$W_{PCS}(ak) = \frac{1}{2\pi}16\frac{\sin^4\left(\frac{ak}{2}\right)}{(ak)^4}$$

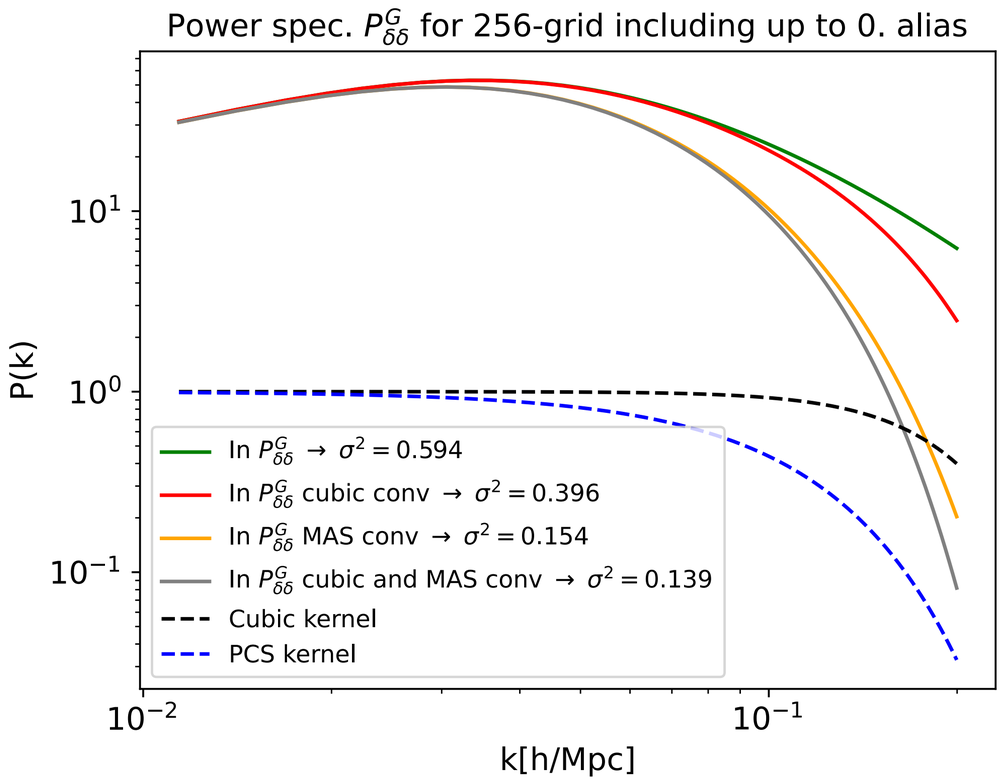
$a = \frac{L}{N}$ size of one grid-cell

Impact of Interpolation and MAS Kernels

N=256, L=4000Mpc/h → $k_N = \pi/a \approx 0.2$ with $a = 15.625$ Mpc/h



R=36Mpc/h for top-hat filter → used for Gaussian fields



R=8Mpc/h for top-hat filter → used for LN fields