Anticorrelating Void and Peak Galaxies with Marked CF to Pin Down Modified Gravity

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Modified Gravity (MG) - Why?

- ΛCDM paradigm seems to be most accurate model… up to now
- Accelerated expansion is modelled by a huge unknown energy contribution dubbed 'dark energy'
- Not flawless in every regard: H_0-tension, fine tuning problem,.. → MG comes to the rescue!
- To comply with GR in the solar system/high densities MG theories need to exhibit a *screening effect* → fundamental effect of environment

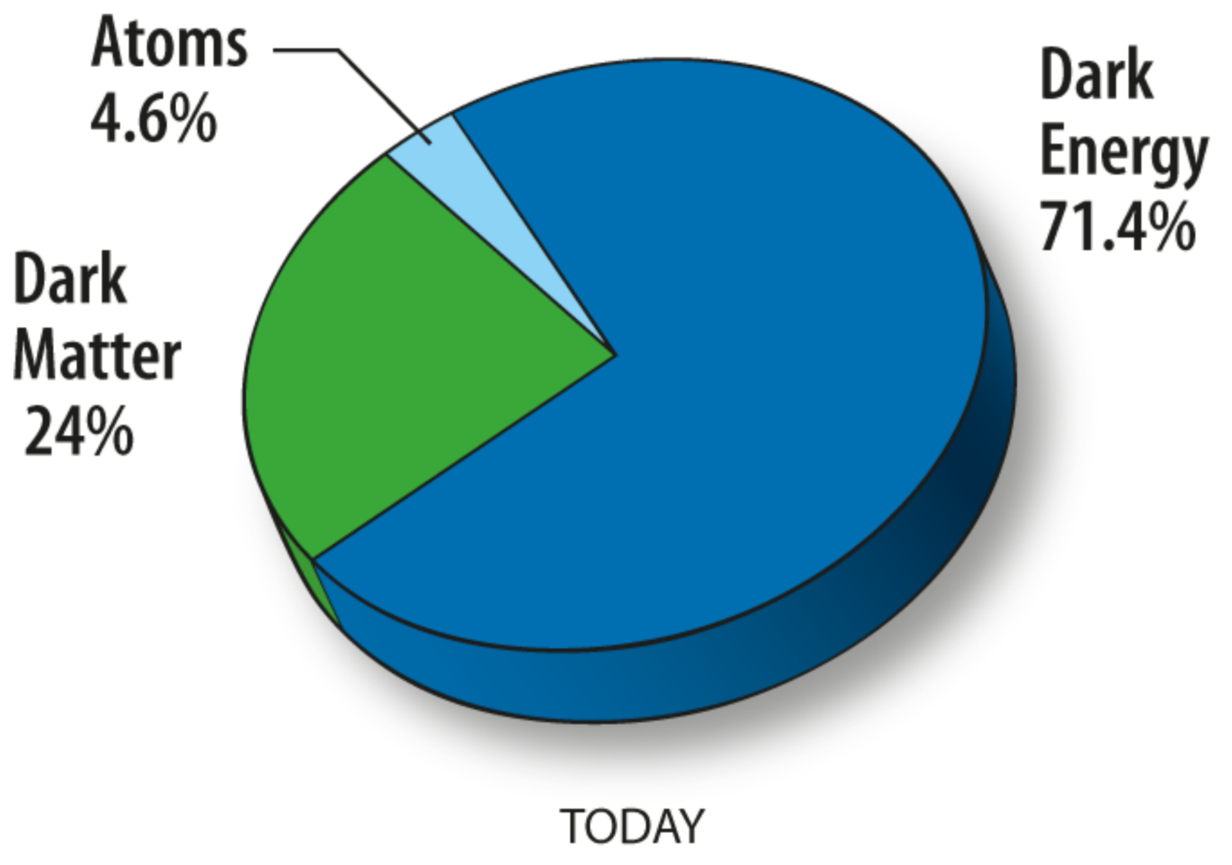
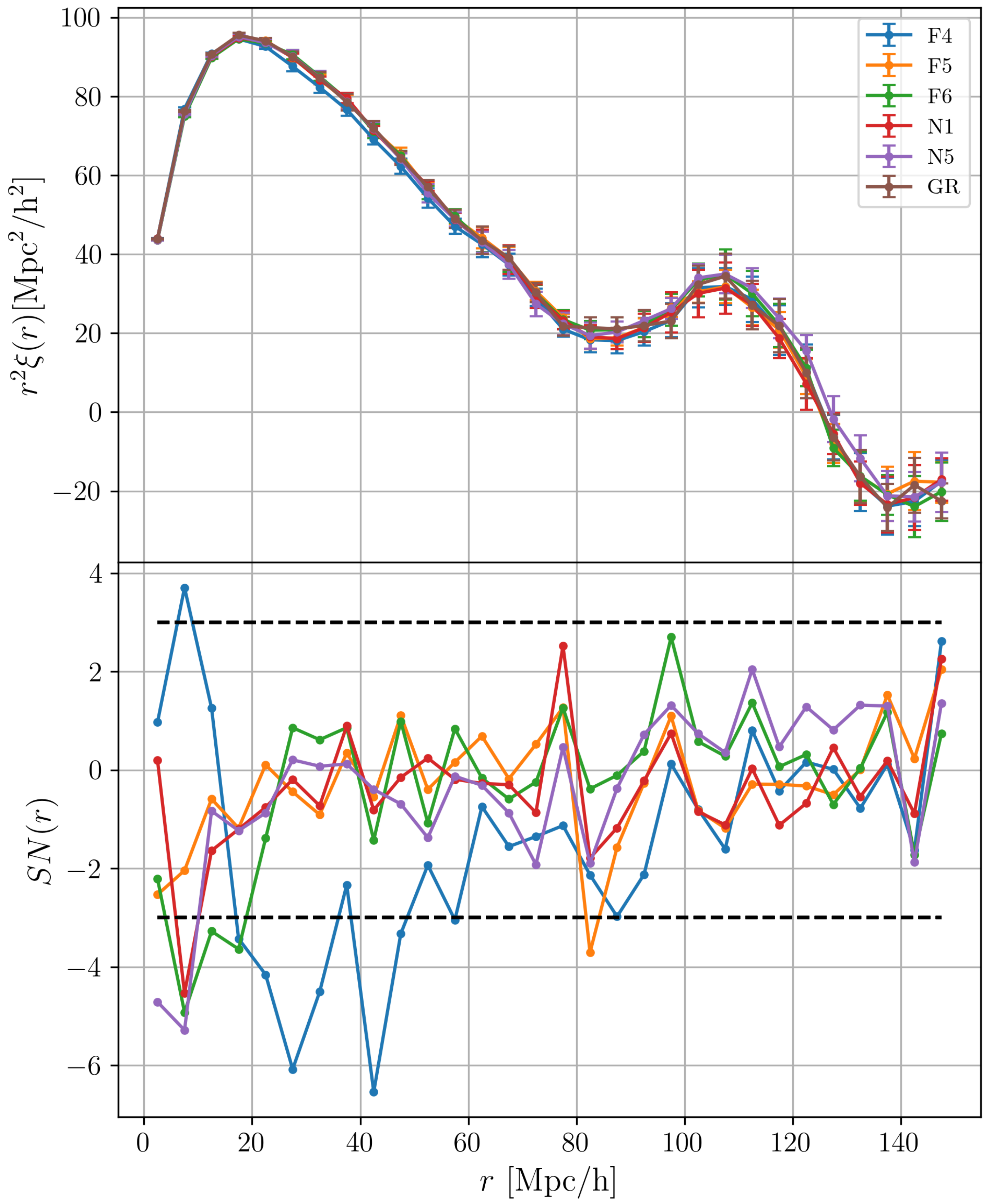


Image Credit: WMAP

Goal: Use this environmental dependency to better detect MG

Setup - ELEPHANT Simulations

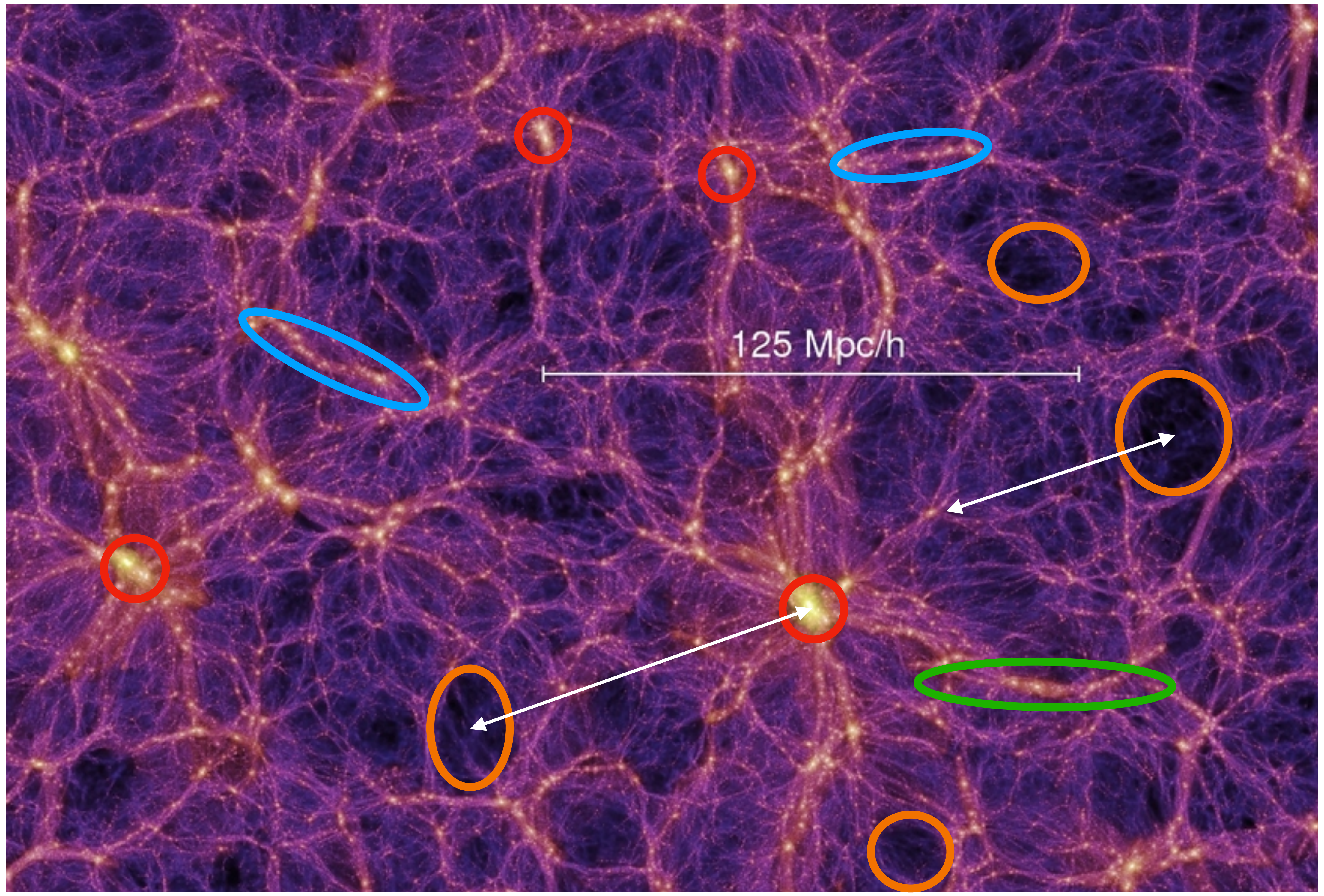


Kärcher et al. in prep.

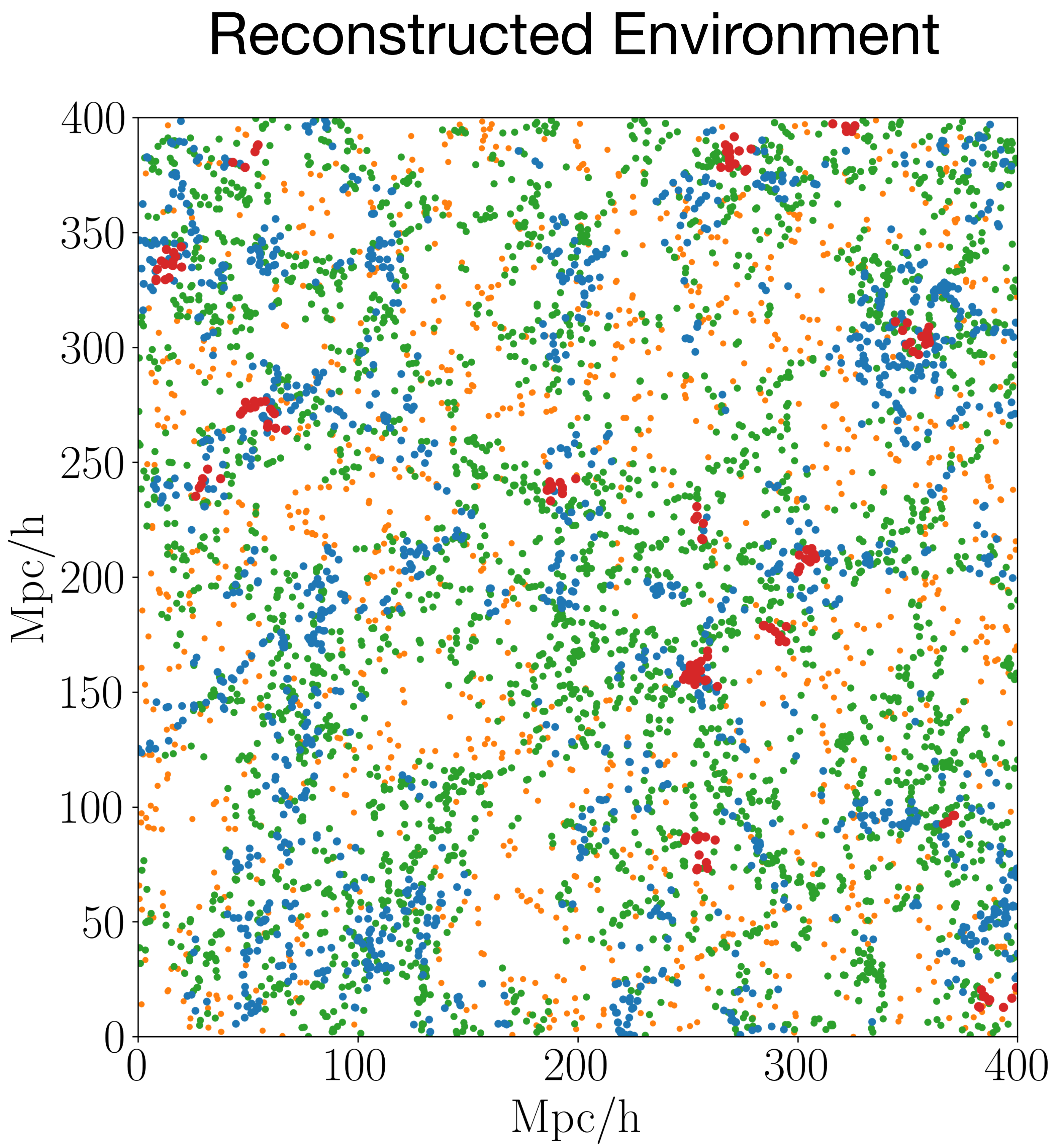
- Box side length: $L = 1024\,\mathrm{h}^{-1}\mathrm{Mpc}$
- Galaxy density: $\bar{n} \sim 3 \times 10^{-4}\,\mathrm{h}^3\mathrm{Mpc}^{-3}$
- 5 realisations of GR, f(R)(3x) and nDGP(2x) gravity
- Rockstar halos, HOD (5-parameter) galaxies
- Matching projected 2PCF $w_p(r_p)$ by tuning HOD parameters

$$SN(r) = \frac{\overline{\Delta\xi(r)}}{\sigma_{\mathrm{avg}}(r)}$$

Simulated Cosmic Web



Original plot from
Millenium simulation



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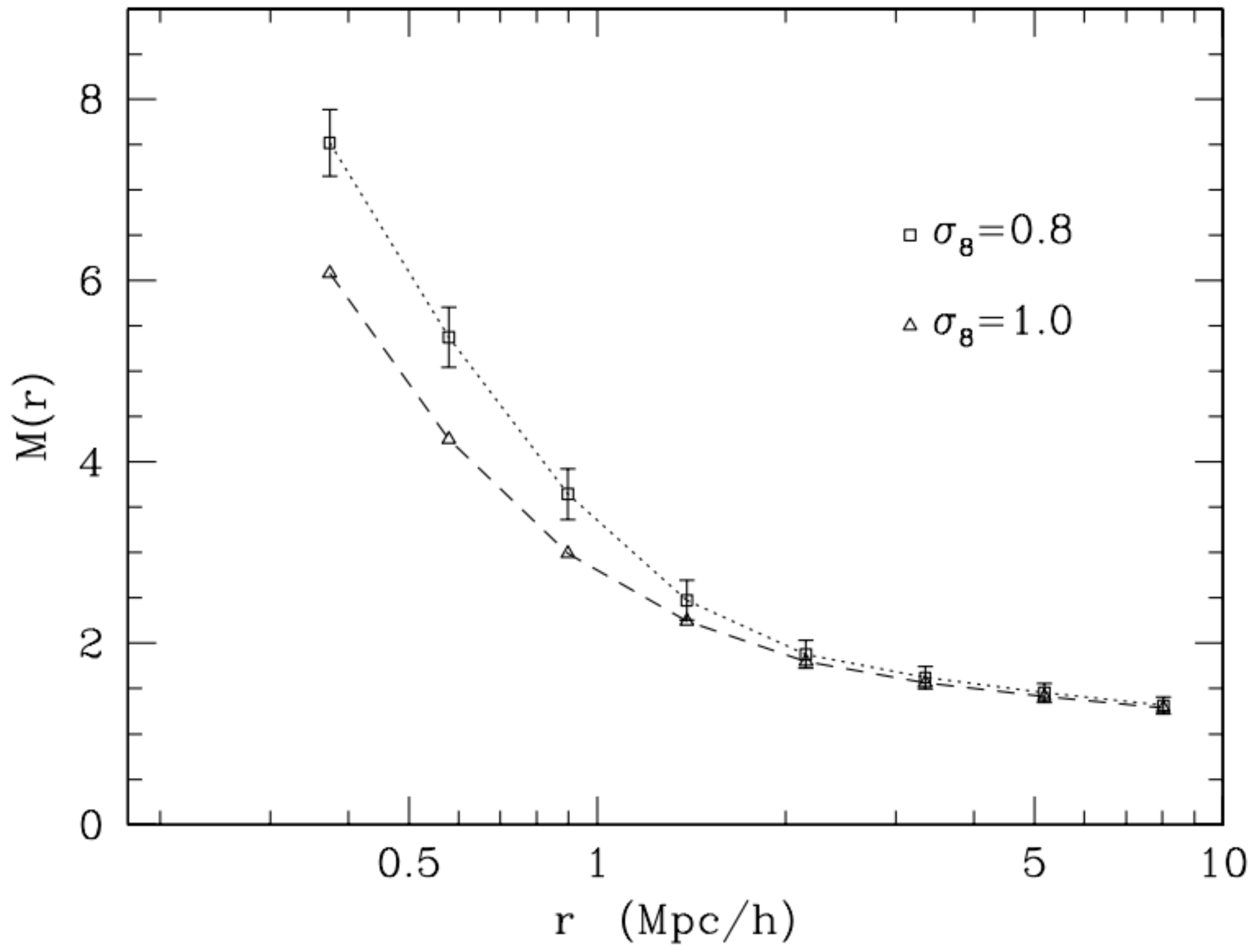
Marked Correlation Functions (mCF)

$$W(\mathbf{r}) = \langle m(\mathbf{x})\delta(\mathbf{x})m(\mathbf{x}+\mathbf{r})\delta(\mathbf{x}+\mathbf{r})\rangle$$

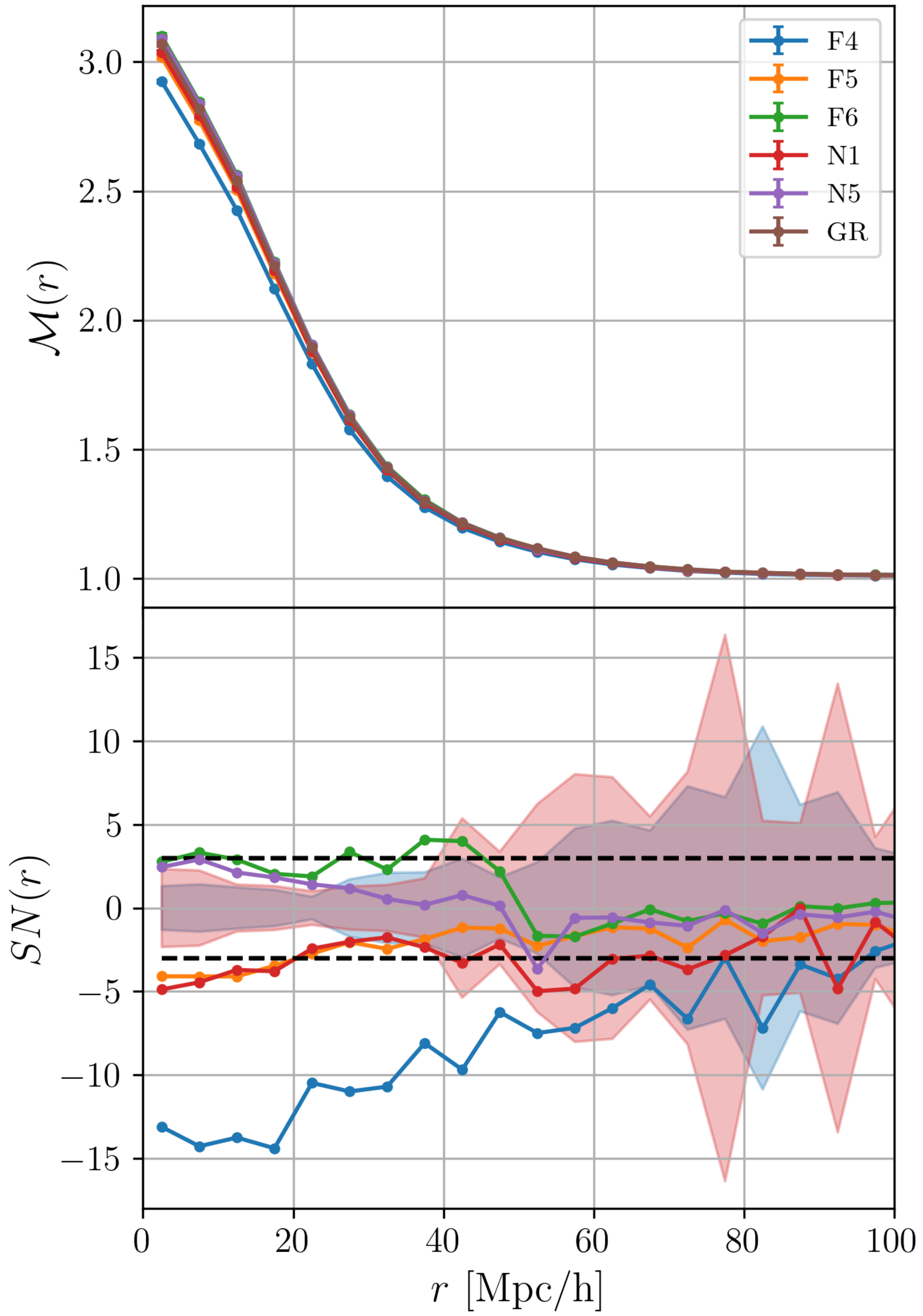
$$\mathcal{M}(r) \equiv \frac{1+W(r)}{1+\xi(r)}$$

- mCF originally developed to investigate correlation of galaxy properties
- Free choice for mark $m(\delta(\mathbf{x}))$, $m(T_{ij}(\mathbf{x}))$ or $m(E)$
- General idea: up-weigh galaxies for which MG effects are more pronounced
- What if mark is allowed to switch signs?
  $\Rightarrow$ Correlation and anticorrelation



White & Padmanabhan (2009)

Results - Negative Void Mark

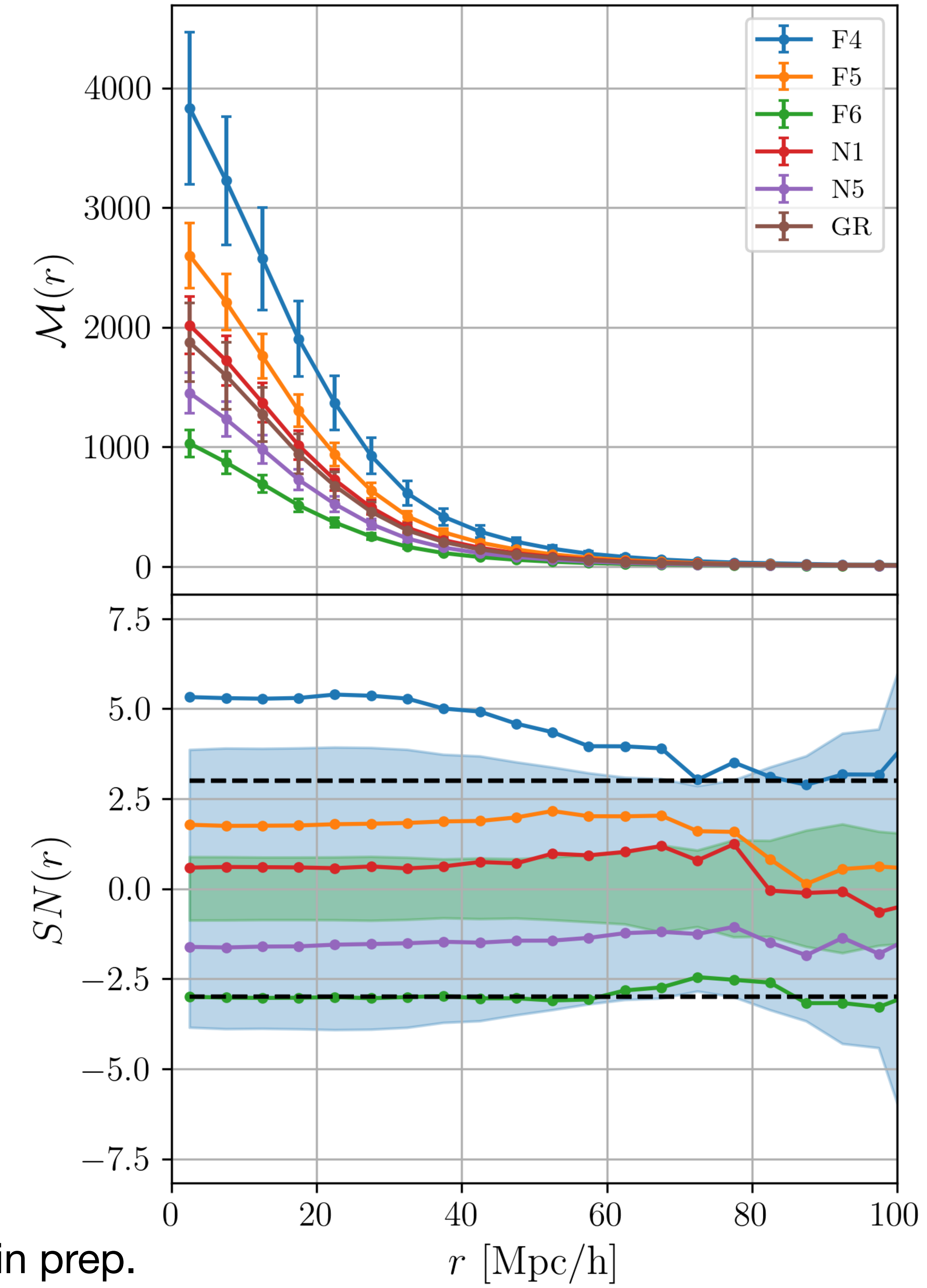


$$m(\mathbf{x}) = \begin{cases} -1 & \text{if void} \\ 1 & \text{else} \end{cases}$$

- Anticorrelating galaxies in voids with remaining ones → Increase anticorrelation
- High SN particularly for F4 and N1
- Difficult to model perturbatively for real application

Kärcher et al. in prep.

Results - Tanh Mark

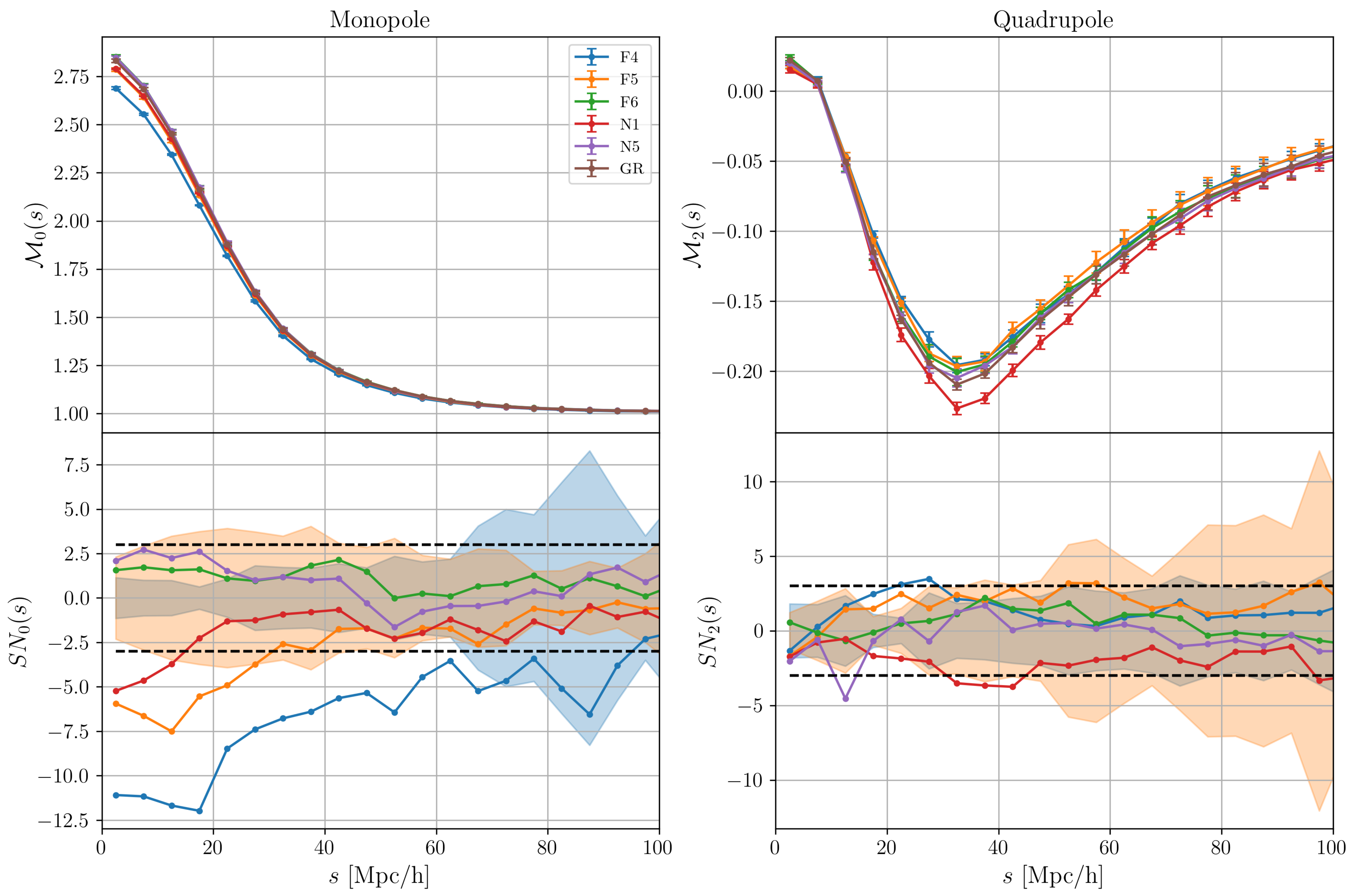


Kärcher et al. in prep.

$m[\delta(\mathbf{x})] = \tanh(a(\delta(\mathbf{x}) + b)$ with $a = 2.5$ and $b = -0.7$

- Try to reproduce performance of negative void mark but based on density
- Very stable SN up to scales of 60-80Mpc/h
- F6 even significantly detectable in single simulation (given the limited statistics we have)

Results - What About Redshift Space?



⇒ Similar performance in the monopole

⇒ Apparently no propagation into quadrupole

⇒Behaviour differs for different marks

Kärcher et al. in prep.

Negative void mark

Conclusion/Outlook

- Creating anticorrelation yields significant differences at intermediate scales of 40-80Mpc/h
- Differences seem to propagate into monopole in redshift space but not into quadrupole
- Particularly $\tanh$ mark promising due to straightforward perturbative expansion
- Future:
    - mCF in redshift space via a Gaussian streaming approach within LPT
    - Compute mCF on real data for proposed marks

mCF - How to Compute?

Weighted pair counts $WW(r) = \frac{1}{c} \sum_{i \neq j} m_i m_j$

Normalisation $c = \left(\sum m_i \right)^2 - \sum m_i^2$

Marked correlation function: $\mathcal{M}(r) \equiv \frac{1 + W(r)}{1 + \xi(r)} = \frac{WW(r)}{DD(r)}$

- If totally uncorrelated or mark=const then $WW(r) \rightarrow DD(r)$
- $\mathcal{M}(r)$ will approach 1 on large scales
- $\mathcal{M}(r)$ measures correlation of marks

nDGP Gravity

- Action has 5D bulk with a 4D brane embedded in it

$$S = M_5^3 \int \mathrm{d}^5x \sqrt{-g_5} R_5 + \int \mathrm{d}^4x \sqrt{-g_4} \left\{ -2M_5^3 K + \frac{M_4^2}{2} R_4 - \sigma + \mathscr{L}_m \right\}$$

- Additional scalar degree of freedom (brane bending mode) φ

$$\nabla^2 \Phi = 4\pi G a^2 (\rho - \bar{\rho}) \boxed{+ \frac{1}{2} \nabla^2 \varphi}$$

$$\nabla^2 \varphi + \frac{r_c}{3\beta a^2} \left((\nabla^2 \varphi)^2 - (\nabla_i \nabla_j \varphi)^2 \right) = \frac{8\pi G a^2}{3\beta} (\rho - \bar{\rho})$$

- Screening effect, involving derivative-terms of φ, gives rise to Vainshtein radius r_V

$$r_V \approx (r_s r_c^2)^{1/3}$$

Example of MG: f(R) Gravity

- Allowing for general function $f(R)$ of Ricci scalar

$$S = \int \mathrm{d}^4x\sqrt{-g}\left\{\frac{R + f(R)}{16\pi G} + \mathscr{L}_m\right\}$$

- Fifth force is arising due to an additional scalar degree of freedom (scalaron)

$$\nabla^2\Phi = 4a^2\pi G\delta\rho \boxed{-\frac{1}{2}\nabla^2 f_R} \qquad \nabla^2 f_R = -\frac{a^2}{3}\delta R - \frac{8\pi G}{3}a^2\delta\rho$$

- Additional force suppressed on small distance from massive object

→ Large scales see modifications (clustering), small scales see GR (solar system)

Can we Actually Model the mCF?

- ‘Straightforward’ as long as we can expand the mark function in density contrast…

$$1 + W(r) = \frac{1}{\bar{m}^2} \int \frac{d^3q\, e^{-\frac{1}{2}(\mathbf{r}-\mathbf{q})^T \mathbf{A}_L^{-1}(\mathbf{r}-\mathbf{q})}}{(2\pi)^{3/2}|\mathbf{A}_L|^{1/2}} \int \frac{d^3Q\, e^{-\frac{1}{2}(\mathbf{R}-\mathbf{Q})^T \mathbf{C}^{-1}(\mathbf{R}-\mathbf{Q})}}{(2\pi)^{3/2}|\mathbf{C}|^{1/2}} \left(1 + \mathcal{I}\right)$$

Aviles+ (2020)

- Based on CLPT for unmarked correlation function

- Treat mark function as a bias function, define renormalized mark parameters

- Double convolution of I-function containing all bias and mark contributions up to specific order

How to Infer Environment?

$$\rho(\mathbf{x}) = \frac{\bar{\rho}}{(1 - D(t)\lambda_1)(1 - D(t)\lambda_2)(1 - D(t)\lambda_3)}$$

Derived from LPT for the linear displacement field

$$\begin{cases} \lambda_1 > 0 \quad \Rightarrow \quad \lambda_2 > 0,\ \lambda_3 > 0 & \text{then cluster} \\ \lambda_1 < 0,\ \lambda_2 > 0 \quad \Rightarrow \quad \lambda_3 > 0 & \text{then filament} \\ \lambda_1 < 0,\ \lambda_2 < 0,\ \lambda_3 > 0 & \text{then wall} \\ \lambda_3 < 0 \quad \Rightarrow \quad \lambda_2 < 0,\ \lambda_3 < 0 & \text{then void} \end{cases}$$

- Assume that $D(t)$ is growing mode of growth factor
- Eigenvalues λ_i of the tidal tensor $T_{ij} = \partial_i \partial_j \phi$
- Problems arise if some Eigenvalues are very small compared to others
- Environmental signatures account for this problem
- Largest signature defines environment

$$\mathcal{S} = \begin{cases} |\lambda_1|\theta(\lambda_1)|\frac{\lambda_1}{\lambda_3}| & \text{cluster} \\ |\lambda_2|\theta(\lambda_2)|\frac{\lambda_2}{\lambda_3}|\left(1 - |\frac{\lambda_1}{\lambda_3}|\right)\theta\left(1 - |\frac{\lambda_1}{\lambda_3}|\right) & \text{filament} \\ |\lambda_3|\theta(\lambda_3)\left(1 - |\frac{\lambda_2}{\lambda_3}|\right)\theta\left(1 - |\frac{\lambda_2}{\lambda_3}|\right)\left(1 - |\frac{\lambda_1}{\lambda_3}|\right)\theta\left(1 - |\frac{\lambda_1}{\lambda_3}|\right) & \text{wall} \end{cases}$$

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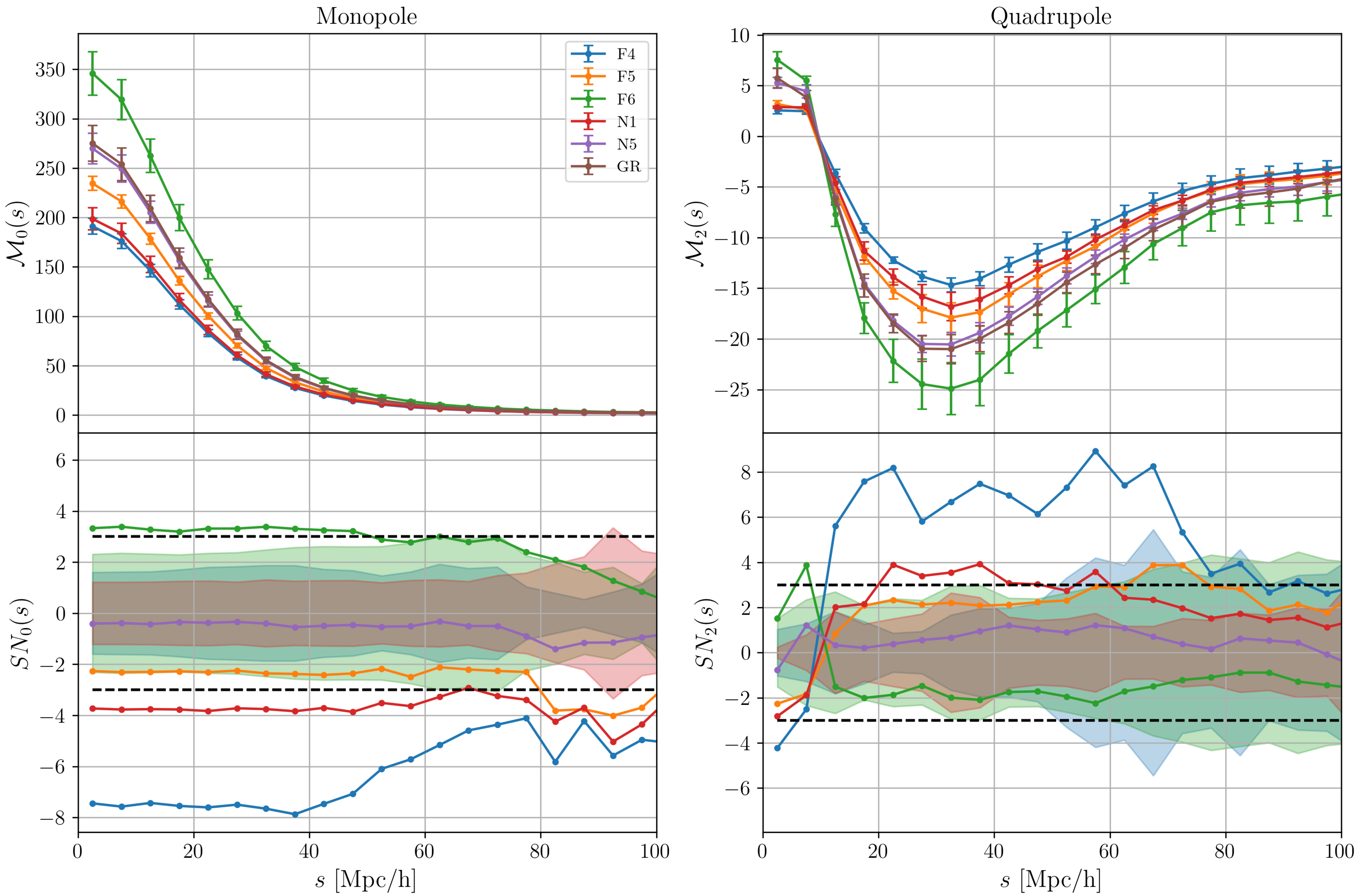

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tanh mark