Probing structure growth with constrained realizations from 2MRS

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Cosmology from Home

The local universe as a cosmological probe

- Structure formation often investigated via statistics, e.g.
  - Matter power spectrum
  - Halo mass function
- But also probed by local distribution and flow of matter

$$-\frac{1}{H}\vec{\nabla}_r \cdot \vec{v}^{(\mathrm{lin})} = f\,\delta \qquad\qquad f \approx \Omega_{\mathrm{m}}^{0.55}$$

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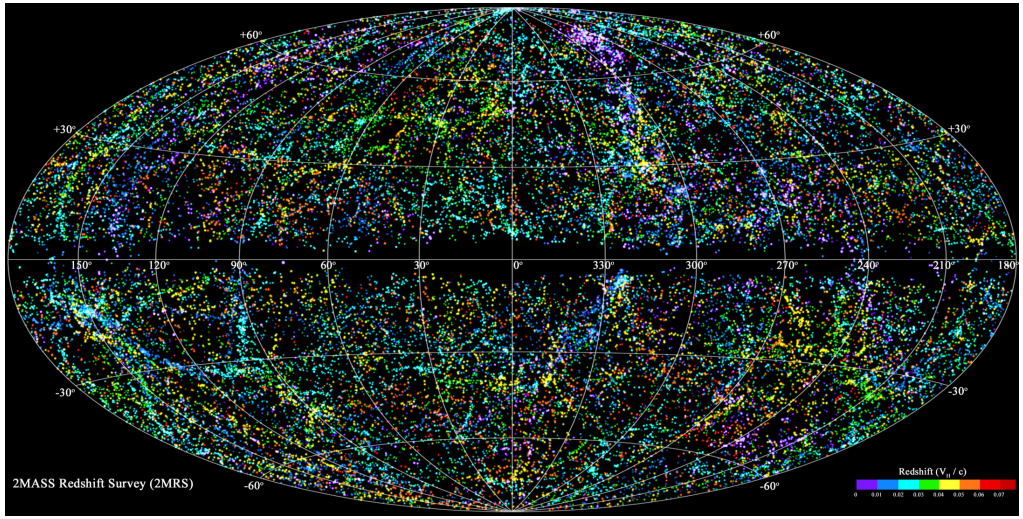
$\Rightarrow$ Constrain normalized growth rate $f\sigma_8$ in two steps

1. Reconstruct peculiar velocities from redshift survey
2. Compare with independent peculiar velocity survey

2MASS Redshift Survey (2MRS)

- Redshifts and angular positions of ≈ 45.000 galaxies
- Covering 91% of the sky with effective depth of $z = 0.05$
- Full completeness within flux limit $K_s < 11.75\,\mathrm{mag}$

$\Longrightarrow$ Input for reconstruction out to 200 h^{-1} Mpc



2MRS

Reconstruction à la Fisher+95

- Linearly correct for redshift-space distortions

$$\vec{r} = \vec{s} - \frac{v_r}{H}\frac{\vec{r}}{r}$$

$$\hat{\delta}(\vec{r}) \approx \hat{\delta}(\vec{s}) - \frac{\mathrm{d}\hat{\delta}(\vec{s})}{\mathrm{d}s}\frac{v_r}{H}$$

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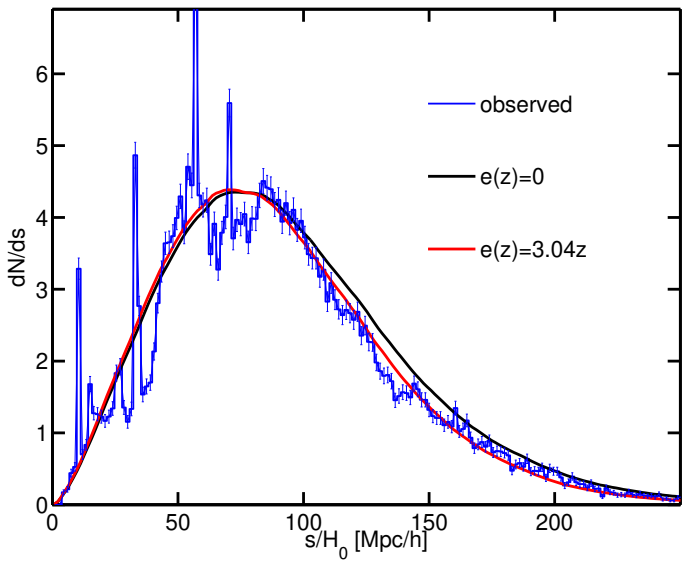
- Suppress shot noise in observed galaxy density via Wiener filter

$$\mathrm{Wiener}(D_{\mathrm{2MRS}}) = \langle SD \rangle \langle DD \rangle^{-1} D_{\mathrm{2MRS}}$$

$\Longrightarrow$ Minimum-variance estimator of density and velocity fields

Reconstruction à la Fisher+95

- Shot noise radially increasing, due to flux-limited survey
- RSDs only affect radial direction



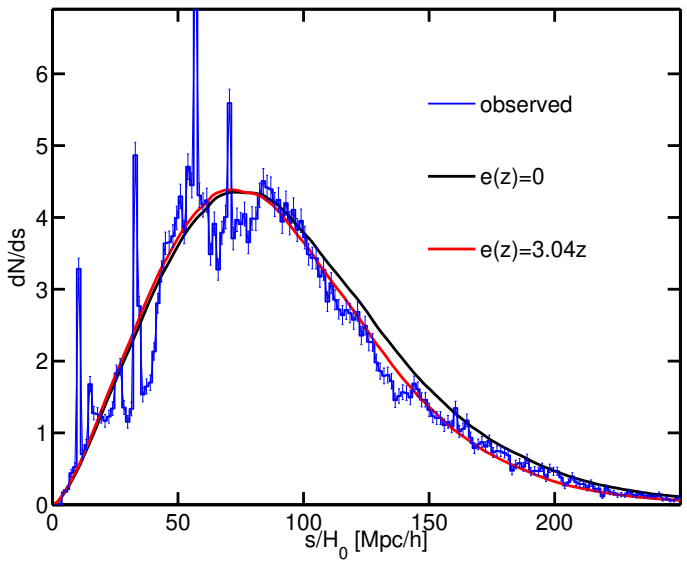
Branchini+ MNRAS 424 (2012) 472

Reconstruction à la Fisher+95

- Shot noise radially increasing, due to flux-limited survey
- RSDs only affect radial direction

$\Longrightarrow$ Filter maximally diagonal in spherical Fourier-Bessel (SFB) space

$$\hat{\delta}(\vec{r}) = \sum_{lmn} C_{ln}\, \hat{\delta}_{lmn}\, j_l(k_{ln} r)\, Y_{lm}(\vartheta, \varphi)$$



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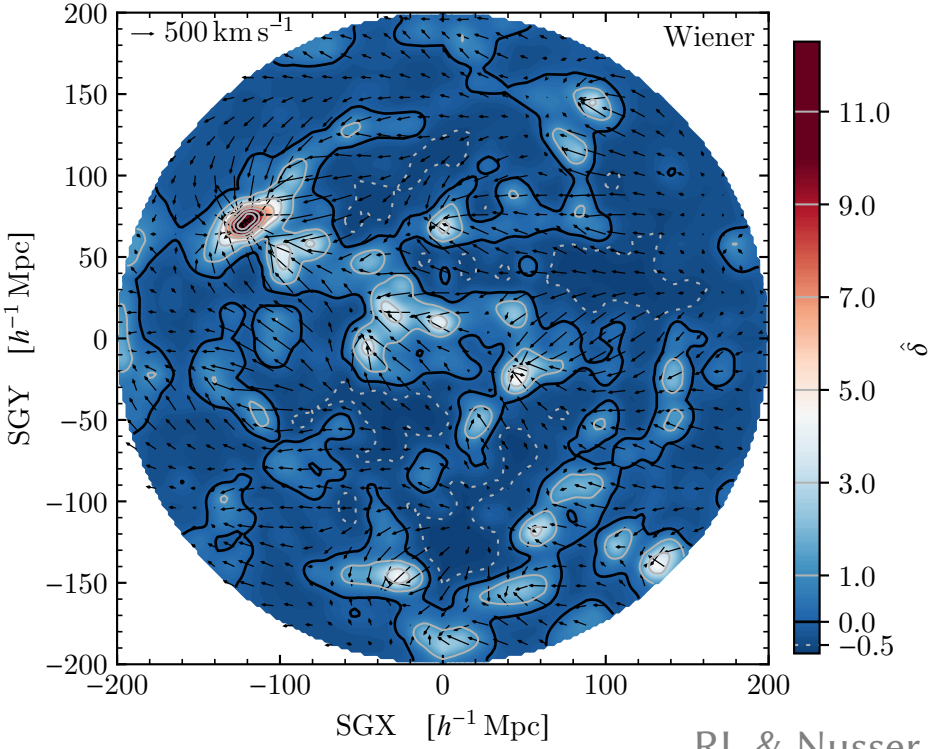
$\Longrightarrow$ More efficient and scalable than real-space reconstruction

Constrained realizations à la Hoffman & Ribak 91

$$S|_{2\mathrm{MRS}} = \mathrm{Wiener}(D_{2\mathrm{MRS}})$$



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Constrained realizations à la Hoffman & Ribak 91

- Generate log-normally distributed random signal S_{random}
- Poisson-sample galaxy data D_{random} from S_{random}

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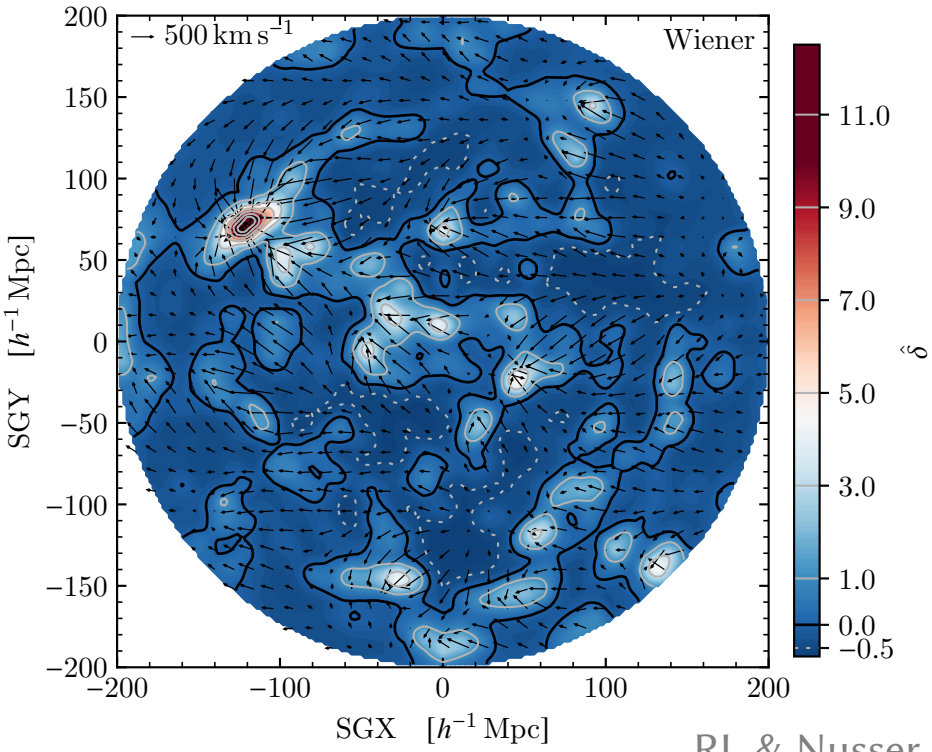

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Constrained realizations à la Hoffman & Ribak 91

- Generate log-normally distributed random signal S_{random}
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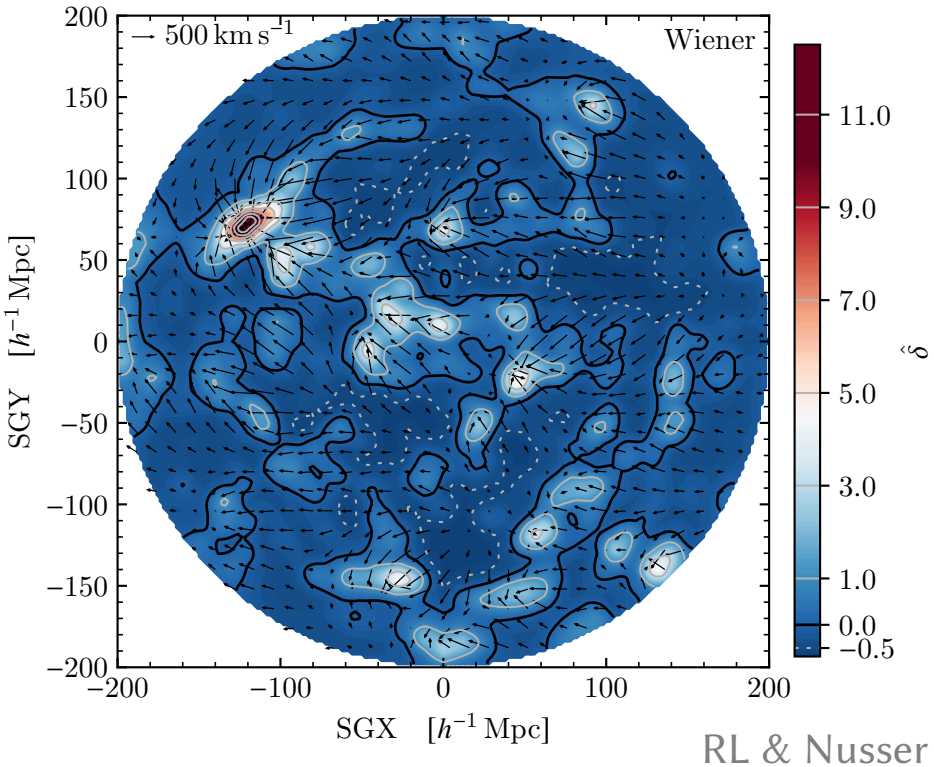
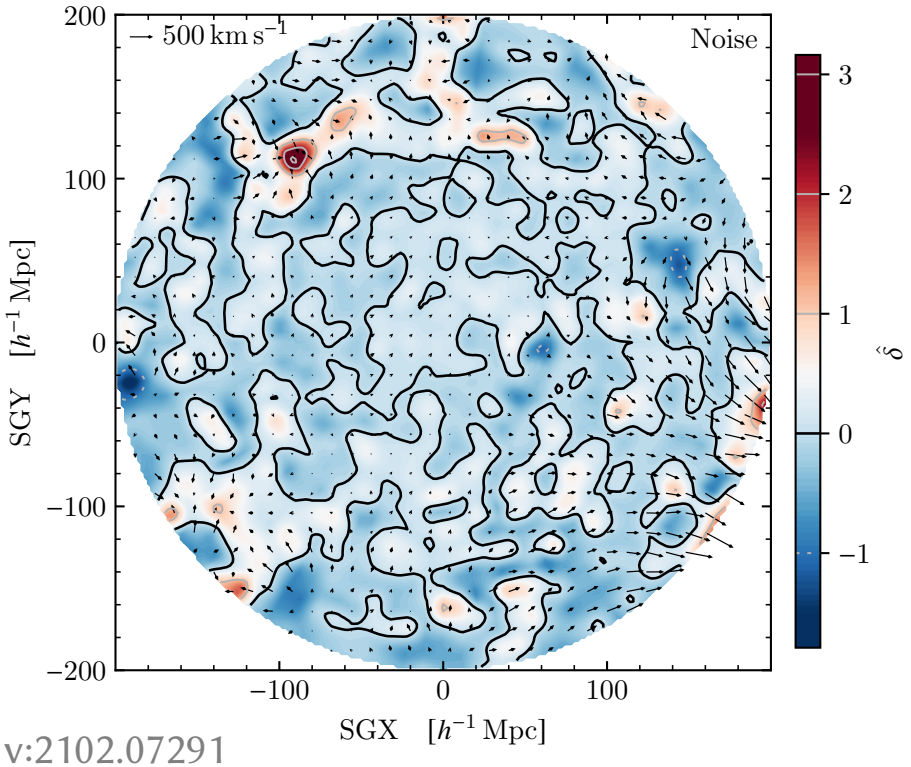
$\Longrightarrow$ Minimum-variance constrained realizations (CRs)

$$S|_{\text{2MRS}} = \text{Wiener}(D_{\text{2MRS}}) + S_{\text{random}} - \text{Wiener}(D_{\text{random}})$$





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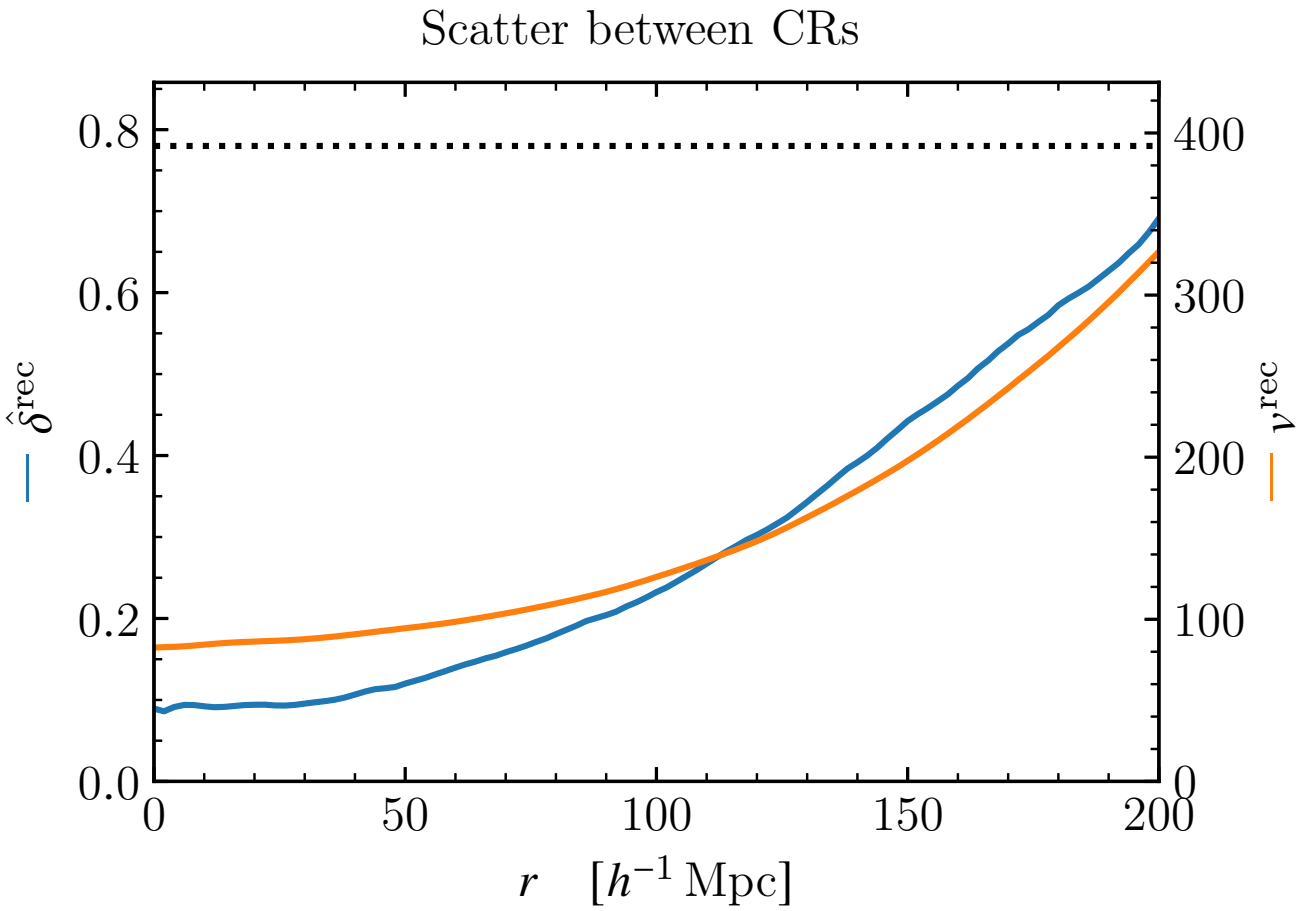
Reconstruction uncertainty

- Scatter between CRs (dotted line: cosmic variance)



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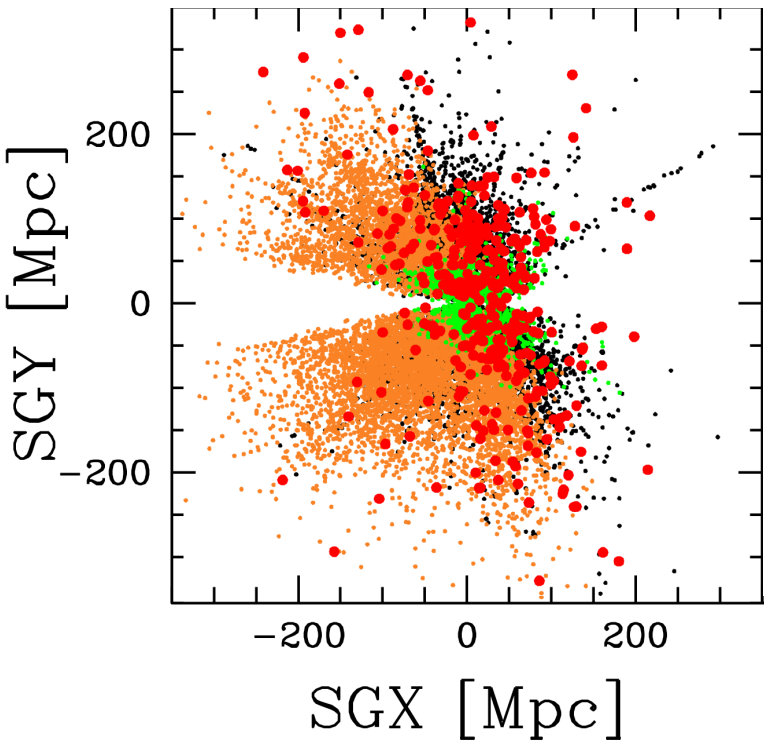
Cosmicflows-3 (CF3)

- Compilation of galaxy distances, e.g. via
  - Tully-Fisher relation
  - Fundamental plane
  - Type Ia supernovae
- Contains ≈ 18 000 galaxies, distributed over ≈ 11 500 groups



Tully+ AJ 152 (2016) 50

⟹ Compare inferred observed velocities to reconstruction

Parameter estimation

- Allow for bulk velocity contribution from sources beyond 2MRS

$$\vec{v}|_{2\mathrm{MRS}} \longrightarrow \vec{v}|_{2\mathrm{MRS}} + \vec{B}^{\mathrm{ext}}$$

- Simultaneously fit $f\sigma_8$, $\vec{B}^{\mathrm{ext}}$ and H_0^{CF3} via χ^2-minimization of

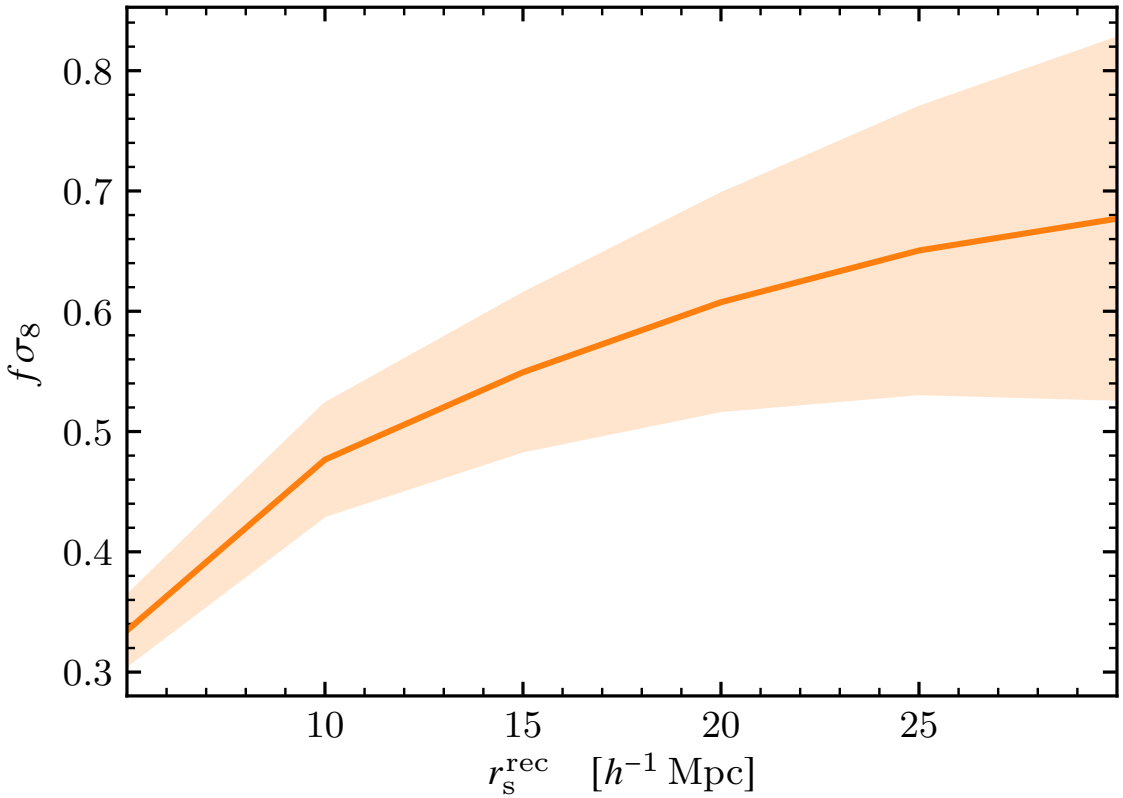
$$\Delta\mu = \mu^{\mathrm{CF3}} - \mu^{\mathrm{exp}}\left(cz^{\mathrm{CF3}} - v_r|_{2\mathrm{MRS}}(f\sigma_8) - B_r^{\mathrm{ext}};\ H_0^{\mathrm{CF3}}\right)$$

$\Longrightarrow$ Average best-fit values over CRs

$\Longrightarrow$ Error due to scatter in $v_r|_{2\mathrm{MRS}}$ and average χ^2-fit error

Constraint on growth rate

- Inferred $f\sigma_8$ as function of smoothing scale



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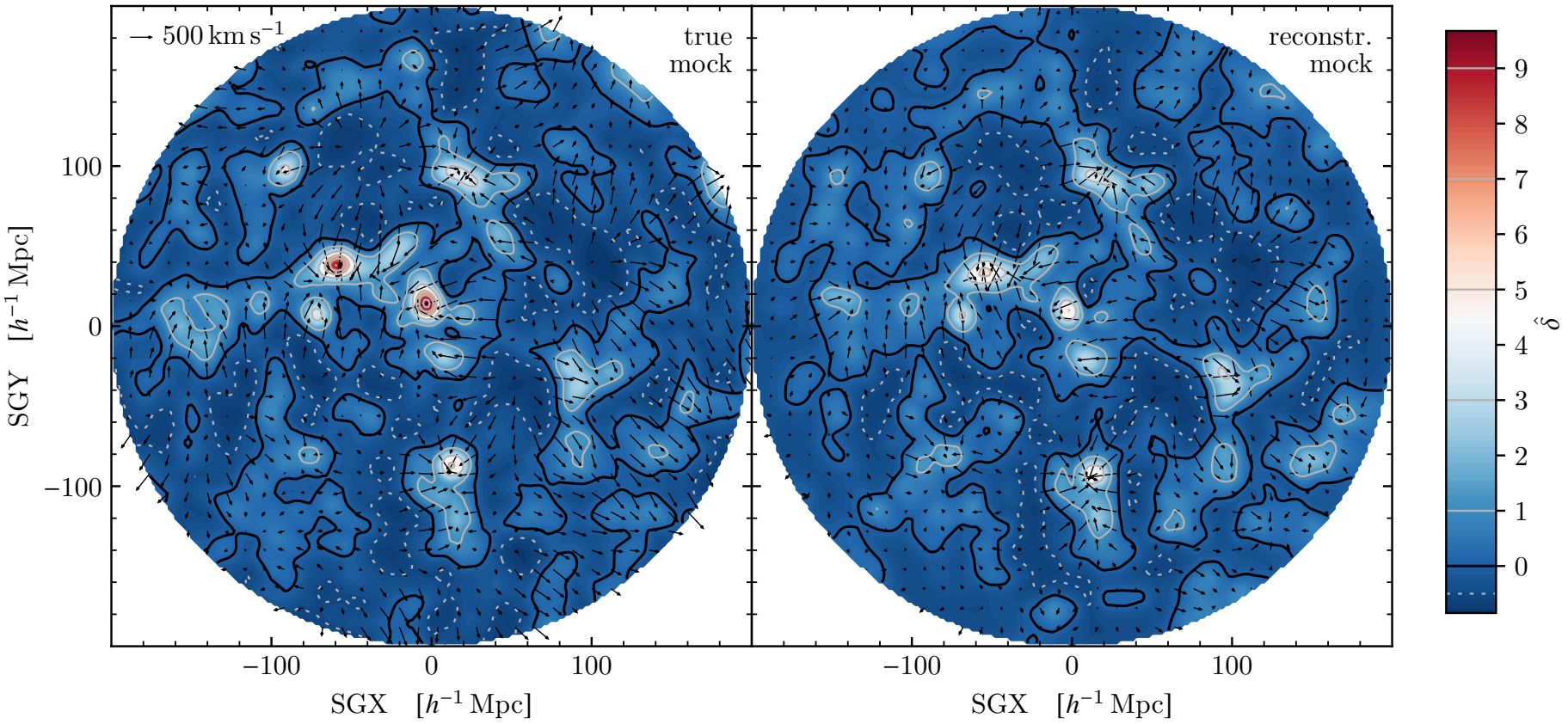
$\Longrightarrow$ Smoothing scale-dependent bias

Constraint on growth rate

- Generate 17 mock 2MRS and CF3 catalogs from semi-analytic galaxy catalog of MultiDark simulation run MDPL2
- Selected to closely represent LG environment, including Virgo



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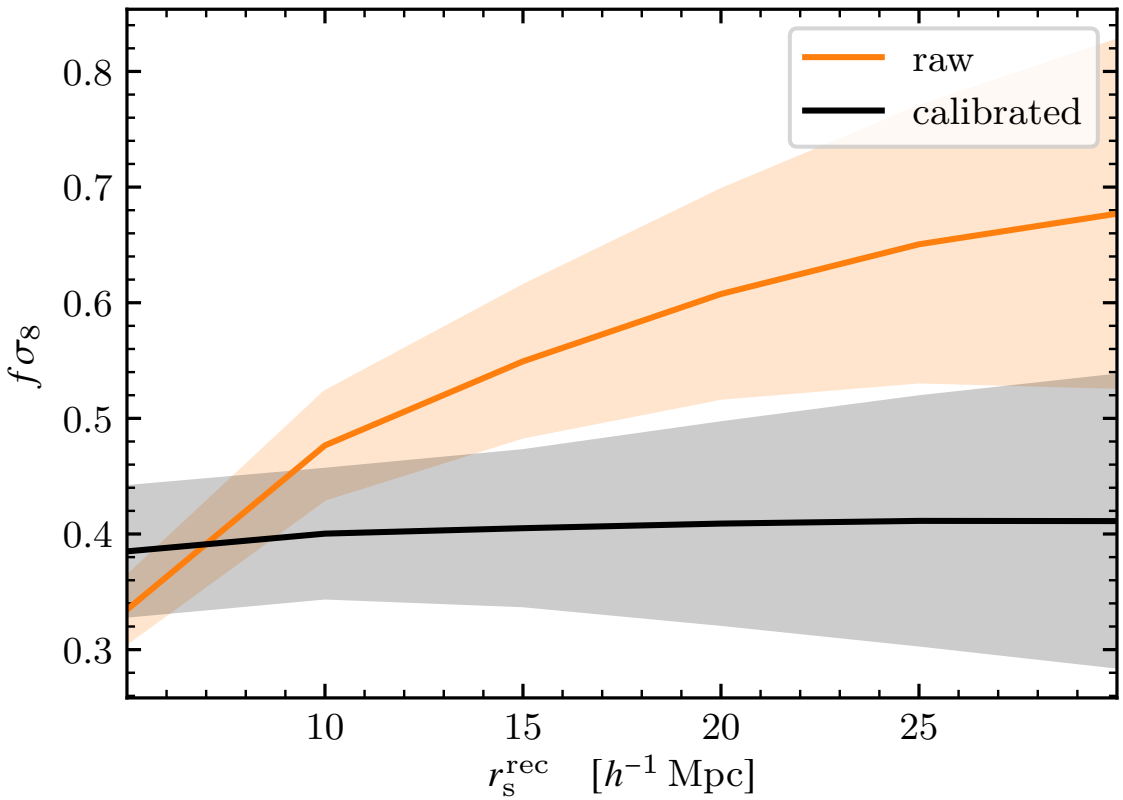
Constraint on growth rate

- Calibrate growth rate estimate

$$f\sigma_8^{\text{cal}} = f\sigma_8^{\text{raw}} \frac{f\sigma_8^{\text{mock, true}}}{\left\langle f\sigma_8^{\text{mock, raw}} \right\rangle}$$



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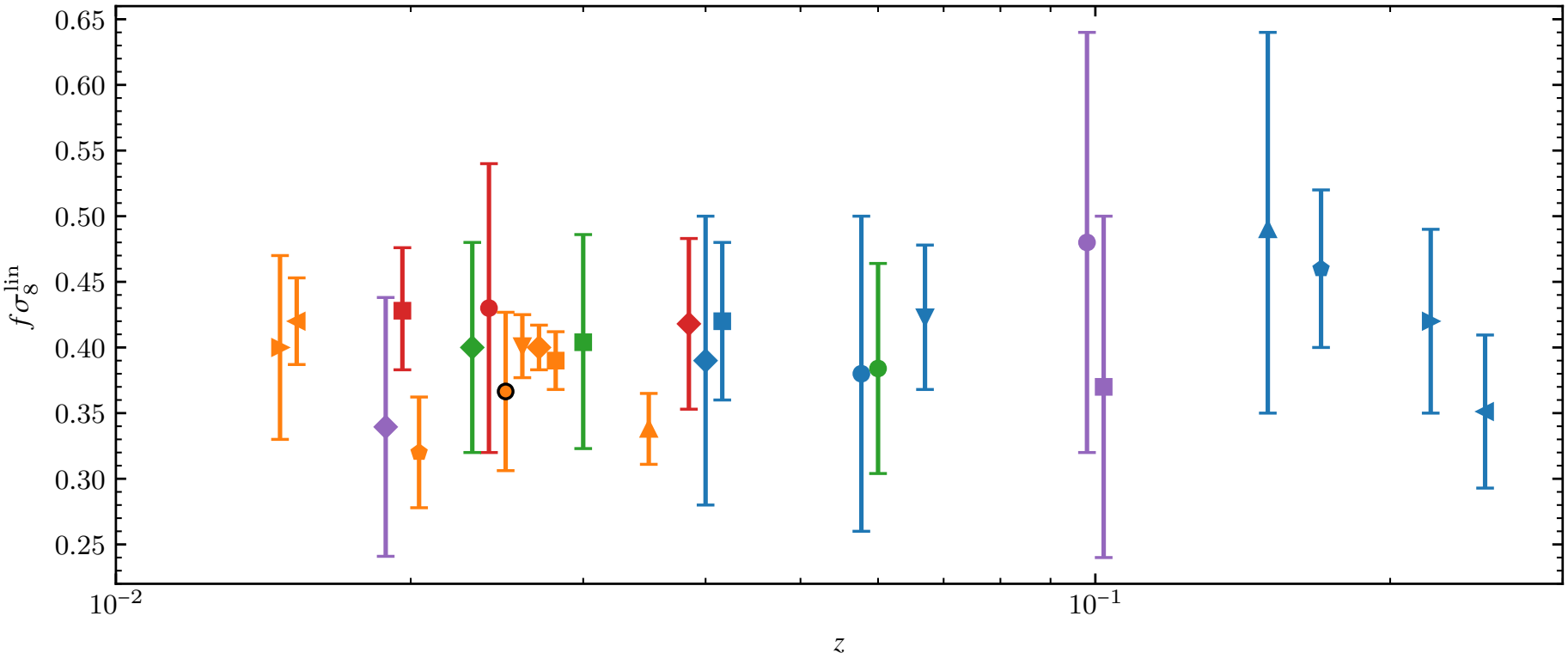
Constraint on growth rate

- Multiply with $\sigma_8^{\rm lin}/\sigma_8$ to obtain linear normalized growth rate

$$f\sigma_8^{\rm lin} = 0.367 \pm 0.060$$



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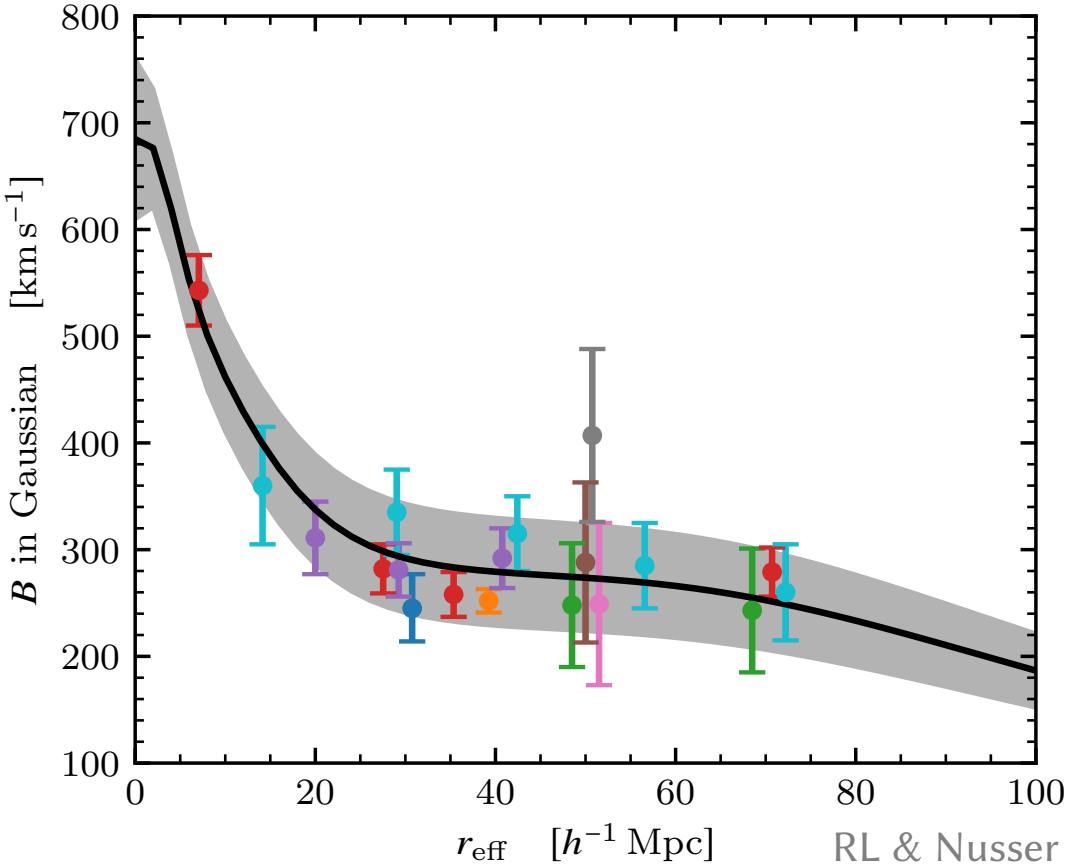
Constraints on bulk flow

- External bulk flow contribution

$$B^{\mathrm{ext}} = 199 \pm 68 \ \mathrm{km\,s^{-1}}$$

- Total bulk flow in Gaussian windows



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Conclusion

Summary

- Wiener filter-based CRs from 2MRS provide field reconstructions with faithful statistical error estimation
- Calibration on realistic mocks crucial to account for systematic errors
- Combination with CF3 yields competitive constraints on growth rate and bulk flow
- Code CORAS and reconstructed fields publicly available

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Outlook

- Account for photometric redshift errors
- Directly include observed peculiar velocities in Wiener filter
- Prepare for future all-sky survey SPHEREx ($\sim$ 450 million galaxies up to $z > 1$)