Cosmological constraints from cosmic flows based on distance data

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Outline

- Context:
    - Distance tracers, relation to H_0
    - Biases in cosmic flows: homogeneous Malmquist, inhomogeneous Malmquist
    - A warning on non-linearities
    - Velocity field statistics
    - A short history of distance surveys

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  - A short history of distance surveys
- Cosmological information: derivation, tensions
- Modernization: the Bayesian inverse problem for velocity field
  - Formulation
  - Test on mock data
  - Application to SNe & TF data.
  - Updates on cosmology and the bulk flow

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- Conclusion & the way forward

Context

Why peculiar velocities from distance surveys?

- Study nearby cosmology / cosmography
  - observe supernovae, galaxies with Tully-Fisher relation, fundamental plane
  - high sampling rate of galaxies in spectroscopic sample

- Tightly constraining $f\,\sigma_8$ **(Hudson, Turnbull 2012; Boruah et al. 2020; ...)**

- Dark Matter distribution

- Test anistropic Dark Energy:
  - cf controversial claims: **(Colin+11, Rubin&Hayden 16, Raman+21)**

Not H_0, but residuals

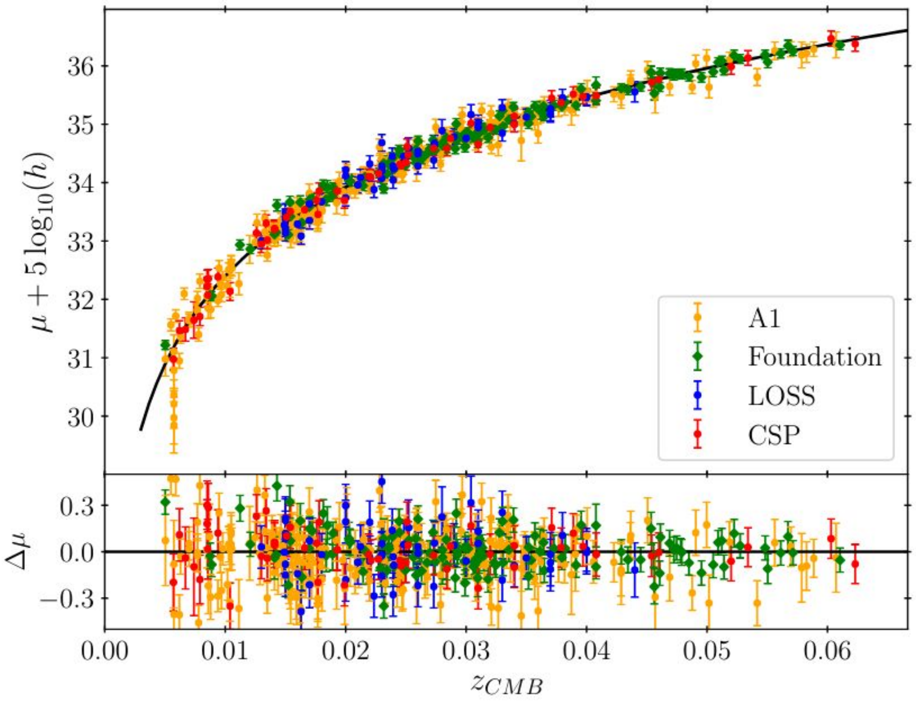
- First order:

$$cz = H_0 d + v_r$$

- If zero-point calibration unknown:

$$\tilde{H}\tilde{d} = H_0 d \times 10^{0.4\,\Delta}$$

- Get peculiar velocities even without zero point!



Two kinds of major bias

- Malmquist biases:
  - “Malmquist bias is not fundamentally related to a flux limit or any other selection criteria. It occurs because the true distance of a galaxy cannot be estimated from DI information alone, but requires knowledge of the actual line of sight density distribution as well.” (Strauss & Willick 1995)

Cosmic distance

$$P(r,\mu(d)) = \int_{-\infty}^{\infty} \mathrm{d}\eta \int_{-\infty}^{\infty} \mathrm{d}m\, P(r,m,\eta) \times \delta\left(m - [M(\eta) + \mu(d)]\right)$$
$$\propto r^2 n(r) \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left(-\frac{(\mu(r) - \mu(d))^2}{2\sigma^2}\right) S(d) \, .$$

Estimated distance

!

Works only if the original selection is $S(m, \eta)$

Strauss & Willick (1995)

Two kinds of major bias

- Homogeneous Malmquist bias:
  - model the distribution as homogeneous and only a radial selection

$$\frac{n'}{n} \ll (d\sigma)^{-1} \quad \Longrightarrow \quad \langle r \rangle_{|d} = d\,\boxed{\exp(\alpha\sigma^2)}$$

≠1

- Inhomogeneous Malmquist bias:
  - includes galaxy clustering in the model, i.e. we may not neglect the radial derivative
  - tracers are staying **in** *large scale structures*

Strauss & Willick (1995)

Velocity from galaxy surveys: linear velocity model

$$\vec{v} = aHf\vec{\nabla}\Delta^{-1}\delta_{\mathrm{m}}$$

Hubble constant

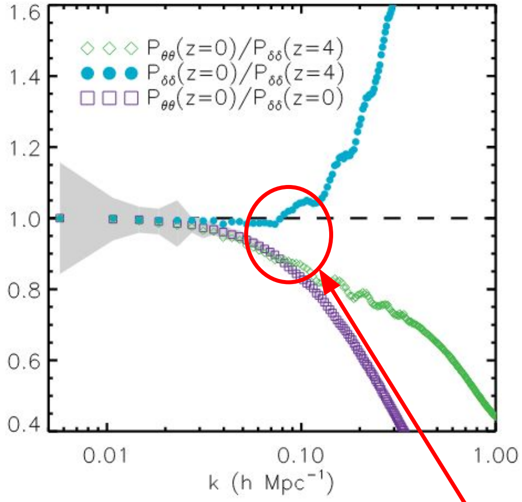
Linear growth rate

Matter density contrast

Linear or non-linear ? Velocity field statistics

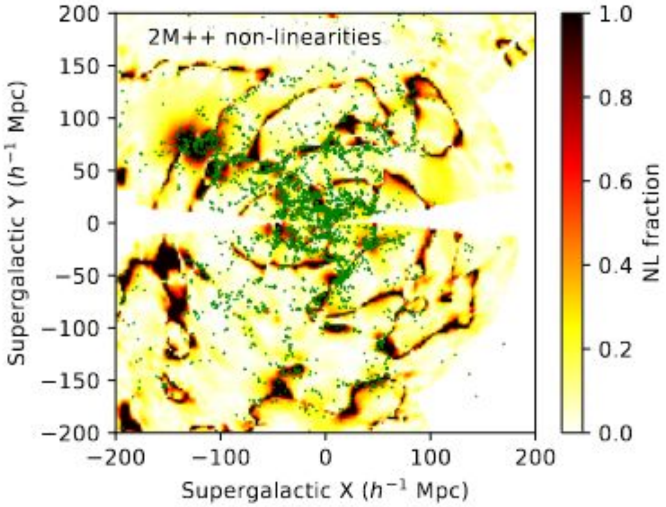
$$\vec{\nabla}.\vec{v} = \theta$$

2 point statistics



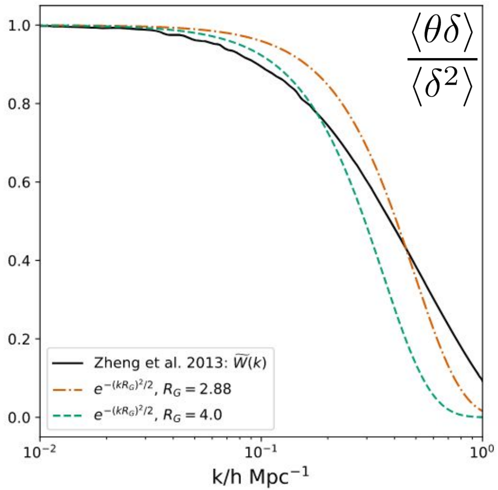
Jennings (2012)

Relative local importance



Mukherjee et al. (2021)

Cross-corr. on halo velocities



Hollinger & Hudson (2021)

θ more "nonlinear" than δ

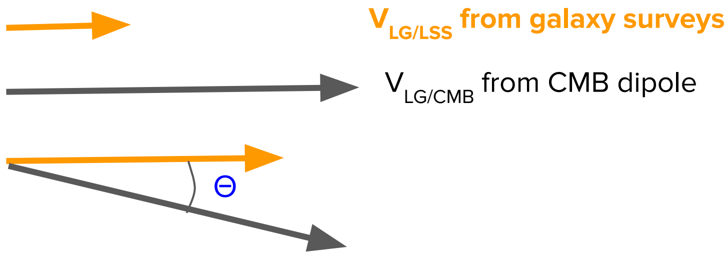
Distance/Redshift data

- Tully-Fisher based samples:
  - Mark III (Willick et al. 1996)
  - CF3 (Tully et al. 2013, 2016), CF4 (Kourkchi et al 2020, ApJ)
  - 2MTF (Masters et al. 2006, Hong et al. 2019)
  - SFI++ (Masters et al. 2006, Springob et al. 2007)
- Fundamental plane samples:
  - 6dFv (Campbell et al. 2014, Magoulas et al.)
- Supernovae samples:
  - CfA (Hicken et al 2009), CSP-DR3 (Krisciunas et al. 2017), Lick LOSS (Ganeshalingam et al. 2013), Foundation (Jones et al. 2019), …
  - Future with ZTF, LSST

Tensions on cosmological parameters

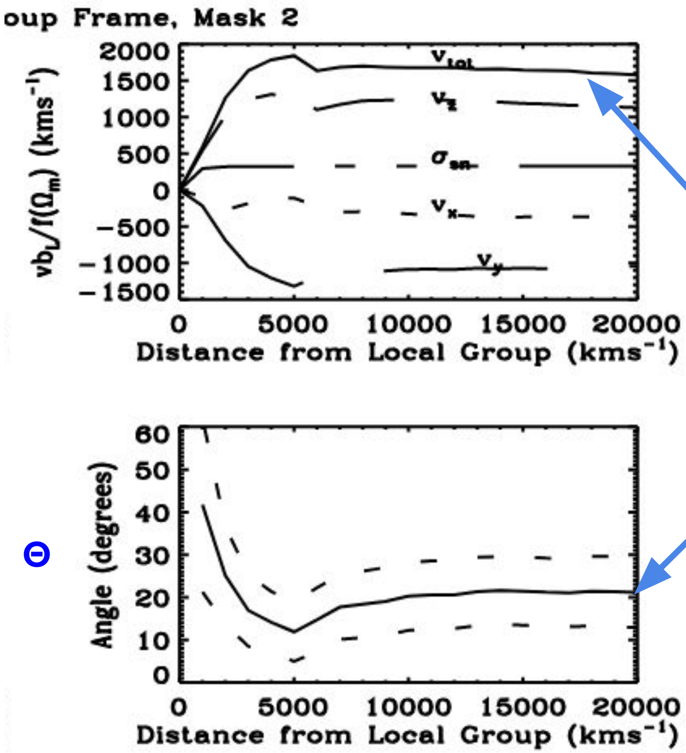
Bulk flow

- Mean velocity within a sphere of radius R
- Function of R ⇒ probe cosmology **(Juszkiewiecz et al 1990)**
- Very difficult to do with pure distances:
    - Attempted with **full-sky** spectroscopic surveys (PSCz, 2MRS)
        - However, needs fixing of the linear galaxy bias
    - Some early computations with only distance data
        - Results not necessarily consistents
- Two relevant quantities:
    - Amplitude
    - Mis-alignment angle



Probe cosmology w/ velocity spatial correlations!

Early example of bulk flow from 2MRS spec sample



Θ

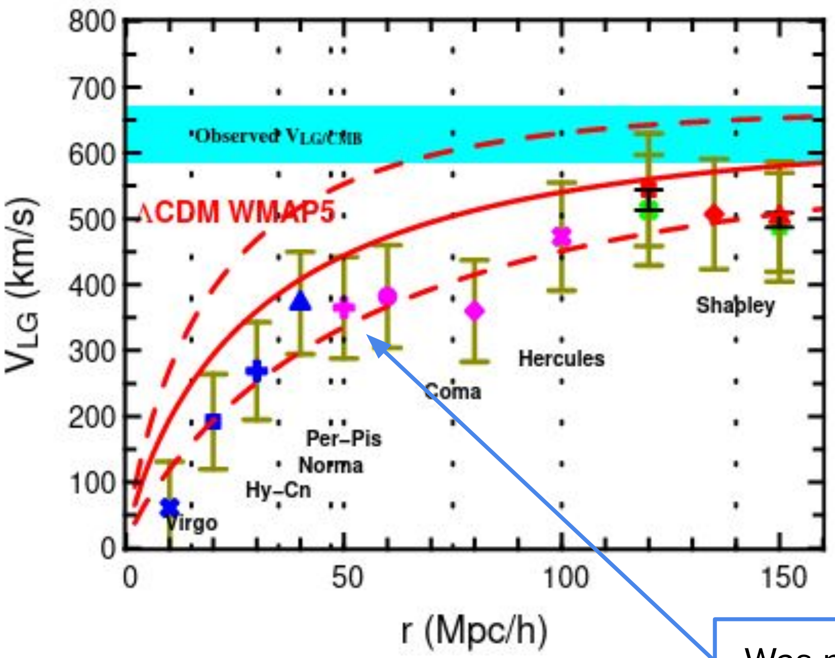
Convergence? Not?

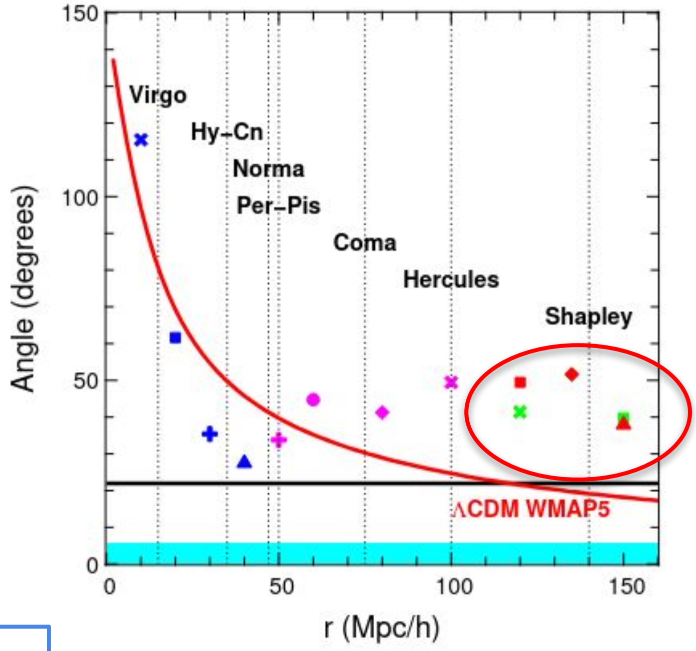
Linear bias value not measured

Erdogdu et al (2005)

The question of convergence

Same sample, non-linear model and other weighting scheme





Lavaux et al (2008)

Was not a convergence!

Some oddity

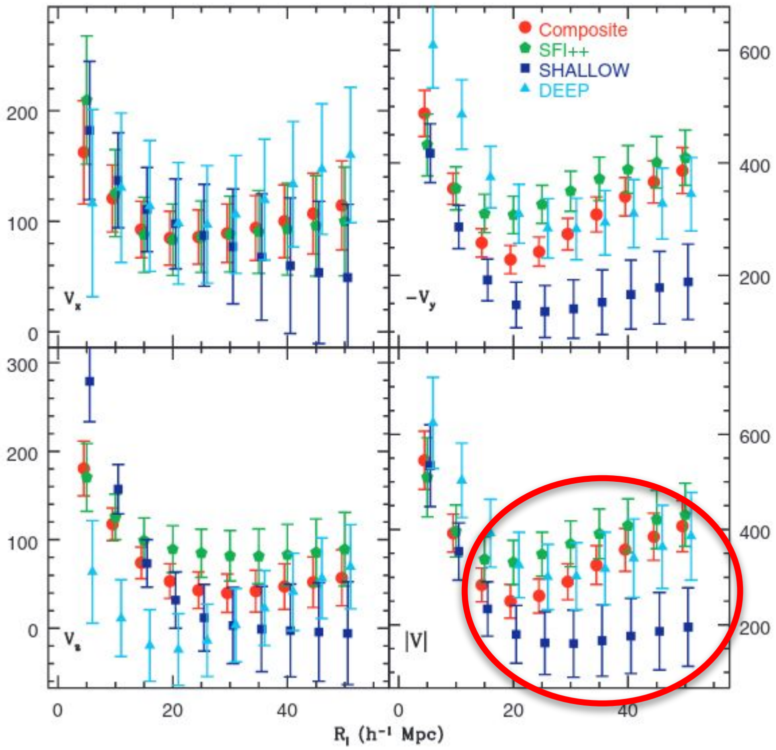
More confusion: bulk flow from distance data only

Pick standard max. likelihood estimator & reweight

Estimator of bulk flow w/ weighted observations:

$$v_a = \sum_n w_{a,n}(cz_n - H_0 d_n)$$

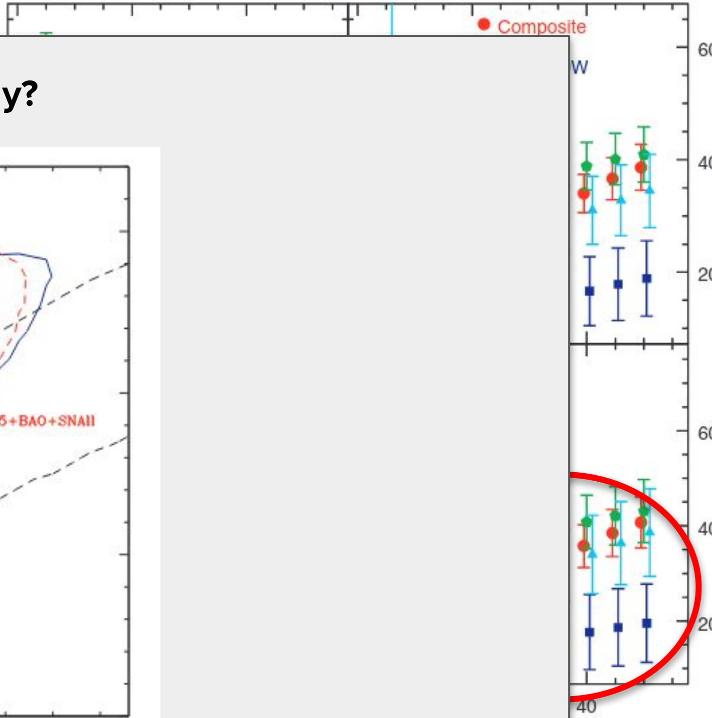
Determined by position & cosmology



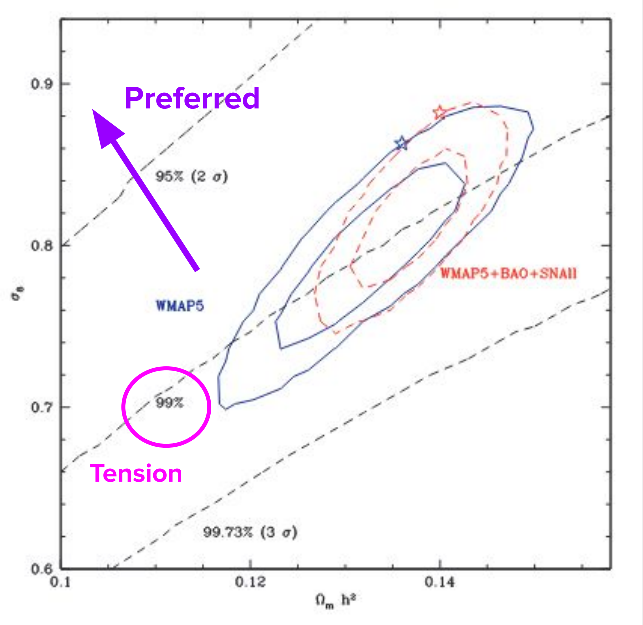
More confusion: bulk flow from distance data only

Pick stand

Estimator

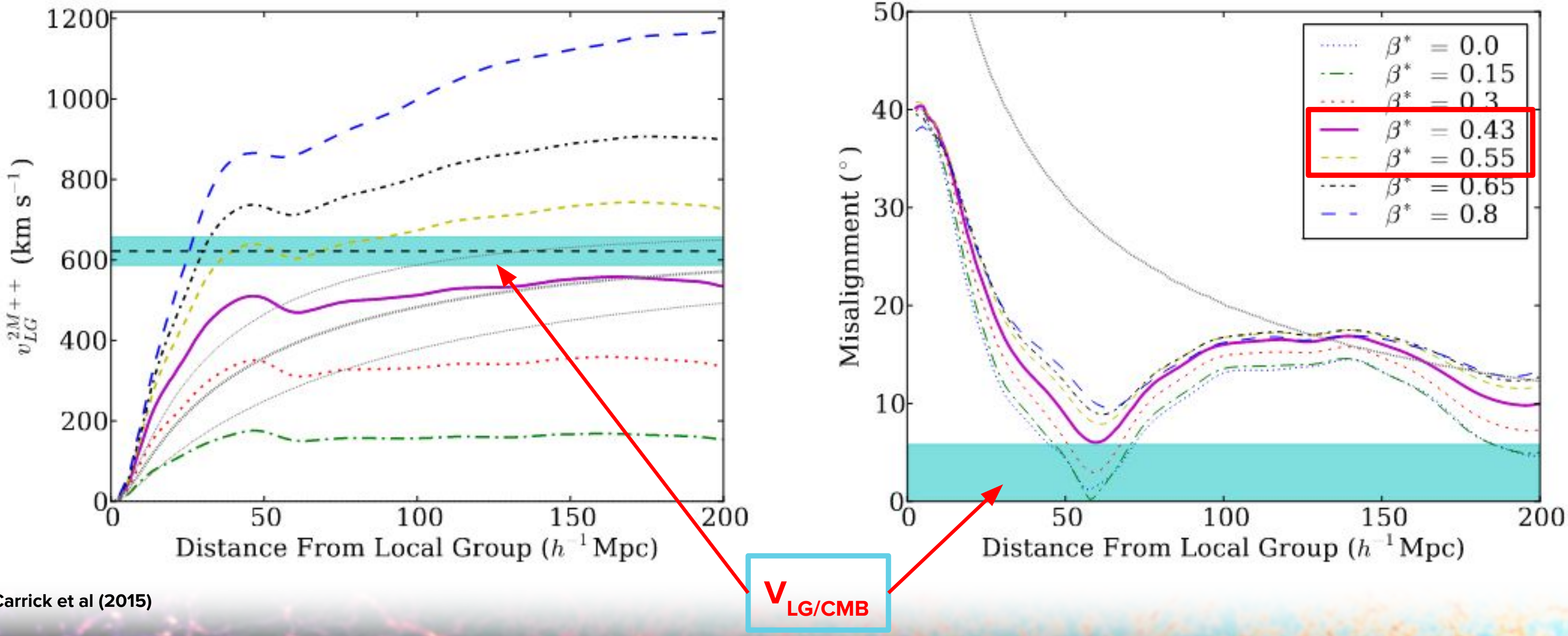


Impact for cosmology?



Bulk flow: deeper sample & N-body checks

Using **2M++** (≃ full sky), linear modeling, N-body tests for optimality



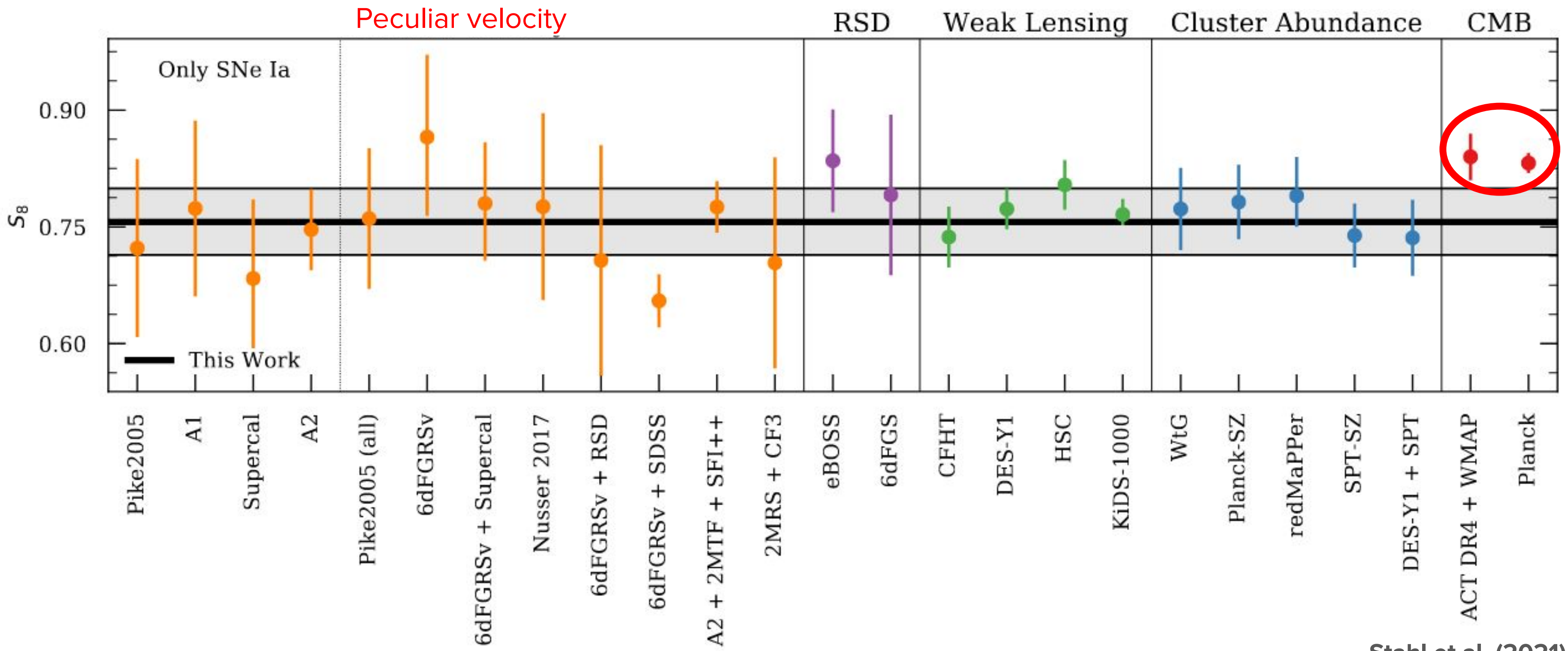
Carrick et al (2015)

Cross-analyzed with distance data

	β^*	$\chi^2/(\text{D.O.F.})$
Forward Likelihood (LW)		
A1	0.440 ± 0.023	-
SFI++ Galaxy Groups	0.429 ± 0.022	-
SFI++ Field Galaxies	0.423 ± 0.045	-
All	$\mathbf{0.431 \pm 0.021}$	-
Forward Likelihood (NW)	0.439 ± 0.020	-
Inverse VELMOD (LW)	0.387 ± 0.048	-
χ^2 (LW)	0.444 ± 0.026	2194/2899
χ^2 (NW)	0.442 ± 0.028	2200/2899

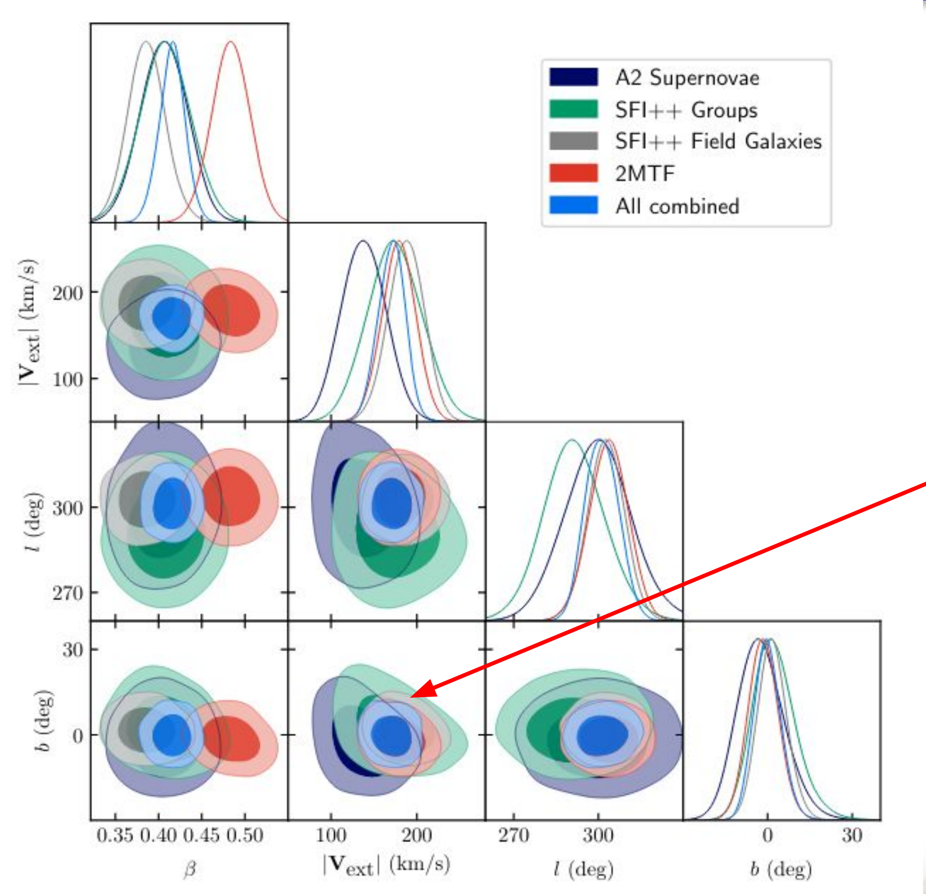
Carrick et al (2015)

Constraints translated in $S_8 = \sigma_8 (\Omega_m/0.3)^{0.55}$



Stahl et al. (2021)

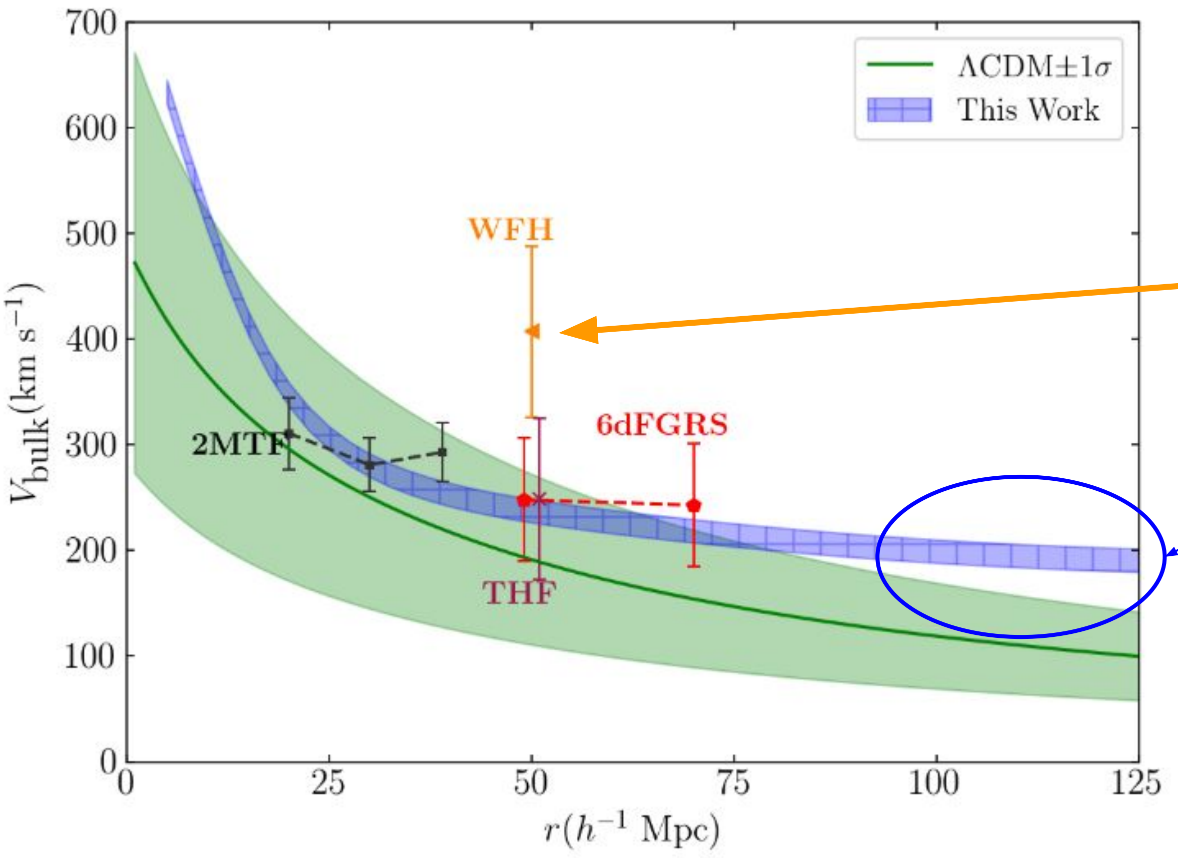
Synthetic joint constraints on residuals and cosmology



External unmodelled flow

Boruah et al. (2021)

New bulk flow measurement



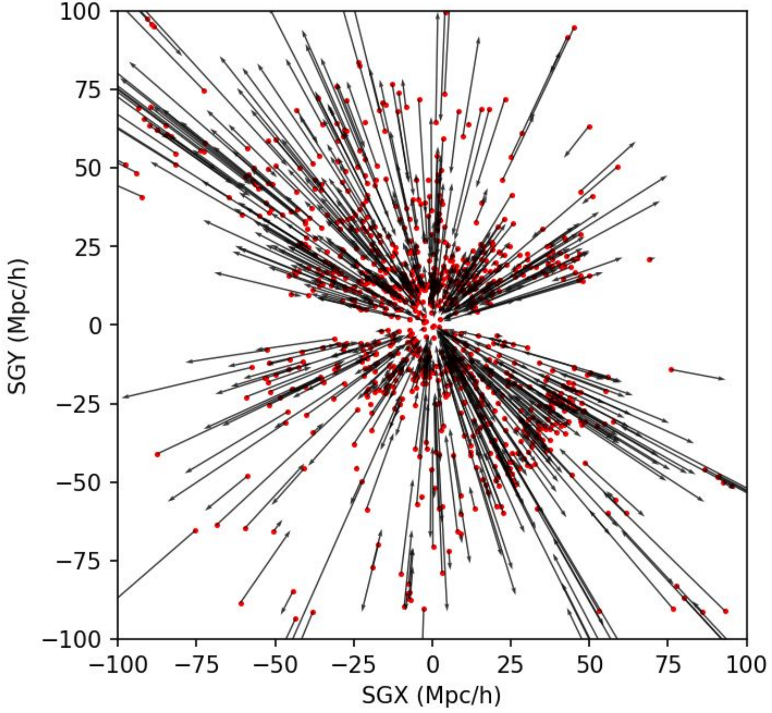
Previous constraints from weights

Tension? No tension?
Boundary effect?

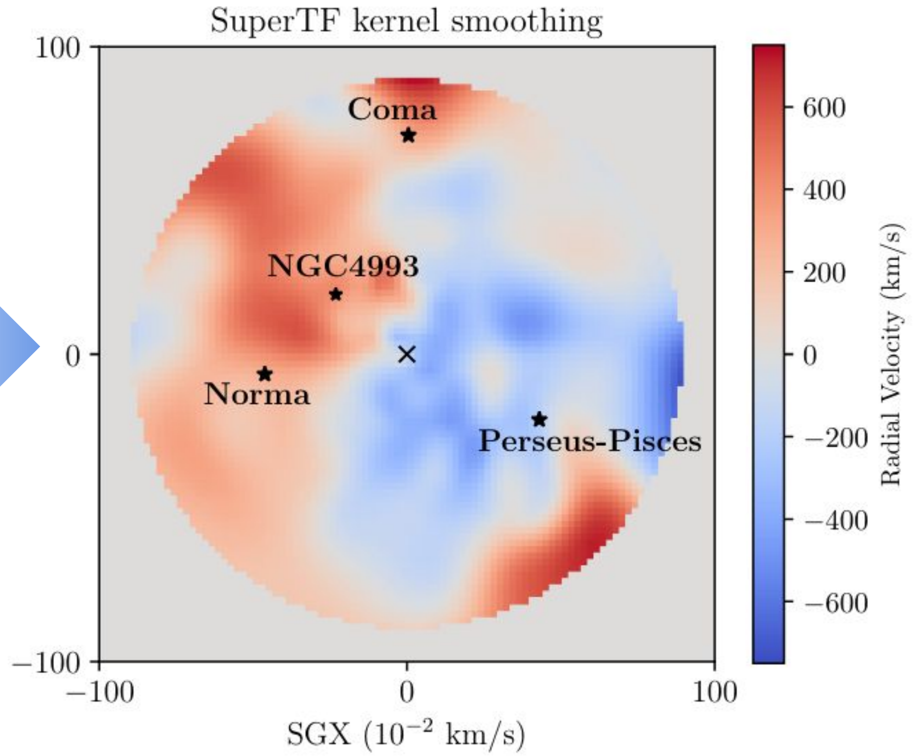
Boruah et al. (2021)

The Bayesian inverse problem

The concept



Noisy set of tracers w/ “bad” distances



Well behaving cosmic velocity field

Some history

- POTENT: Reconstruction assuming a scalar potential (Bertschinger et al 1990)

$$\vec{v} = \vec{\nabla}\phi$$

Some history

- POTENT: Reconstruction assuming a scalar potential (Bertschinger et al 1990)

- Simple adaptive filters

$$v_r(\vec{r}) = \sum_i W(\vec{r} - \vec{x}_i)(cz_i - H_0 d_i)$$

Some history

- POTENT: Reconstruction assuming a scalar potential (Bertschinger et al 1990)
- Simple adaptive filters
- Wiener reconstruction / Gaussian model (Zaroubi et al. 1999)

$$\vec{v} = \vec{\nabla}\phi \qquad v_r(\vec{r}) = \sum_i W(\vec{r} - \vec{x}_i)(cz_i - H_0 d_i)$$

$$\phi \sim \mathcal{G}(0, \mathbf{C})$$

Some history

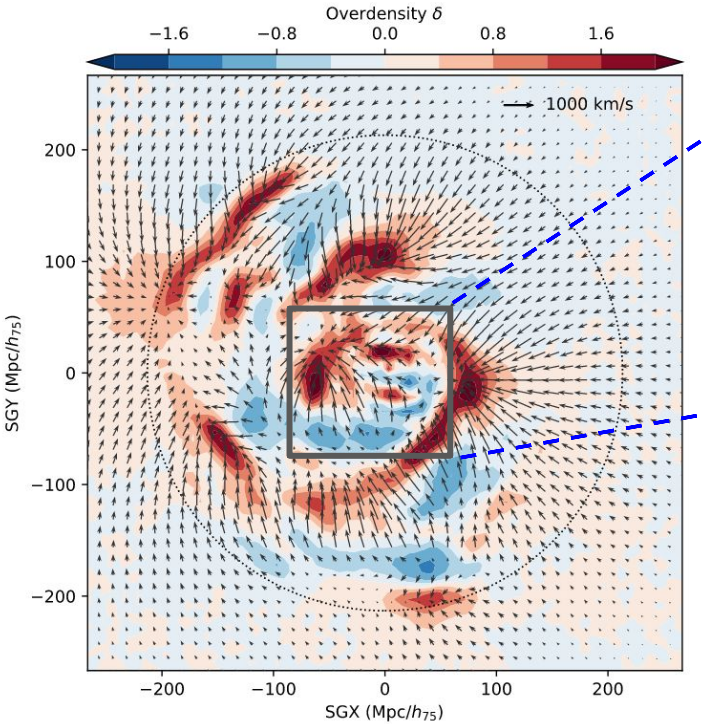
- POTENT: Reconstruction assuming a scalar potential **(Bertschinger et al 1990)**
- Simple adaptive filters
- Wiener reconstruction / Gaussian model **(Zaroubi et al. 1999)**
- VIRBIUS: Gaussian model+Homogeneous Malmquist **(Lavaux 2016)**
- "VIRBIUS+": Gaussian model+Inhomogeneous Malmquist **(Boruah et al. 2021)**

Non-linear distance mapping

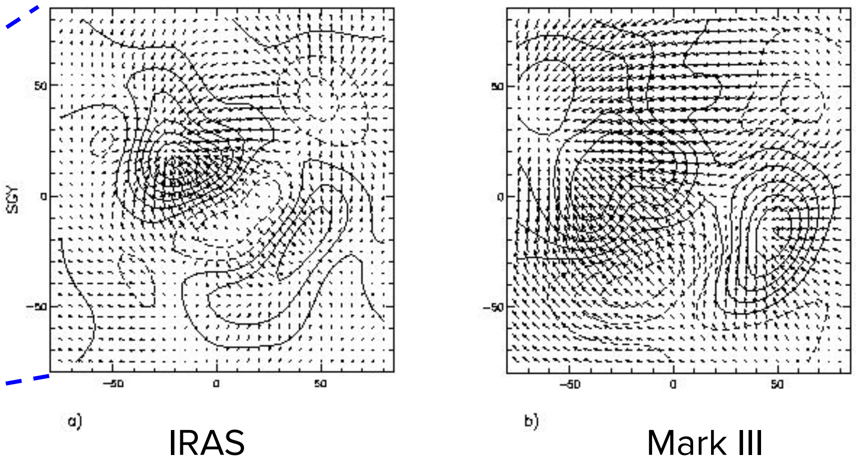
Why more developments?

- Systematics
- Data generation
- Cross-validation
- Composite data sets (clustering, lensing, …)

Earlier application to data



Graziani et al. (2019)

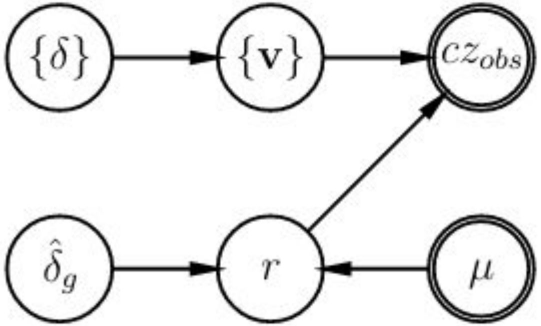


Zaroubi et al. (1999)

A schematic view of the Bayesian model

Density field

Prior galaxy density



Observed redshifts

Observed distance moduli

In practice... equations for the inference

Prior: $$P(\{\delta\}) = \mathcal{G}_{0,C}(\{\delta\})$$
$$C \sim P(k)$$

Linear modeling of velocity field:
$$\vec{v} \propto \vec{\nabla}\Delta^{-1}\delta$$

Redshift likelihood:
$$P(cz_{\mathrm{obs}}|\mu_{\mathrm{obs}}, \{\delta\}, \{\delta_g\}) = \int_0^{+\infty} \mathrm{d}r P(cz_{\mathrm{obs}}|r, \{\delta\}) P(r|\mu_{\mathrm{obs}}, \{\delta_g\})$$

Distance probability:
$$P(r|\mu_{\mathrm{obs}}, \{\delta_g\}) \propto r^2(1+\delta_g(r)) \exp\left(-\frac{[\mu_{\mathrm{obs}} - \mu(r)]}{2\sigma_\mu^2}\right)$$

Tests on mock catalog

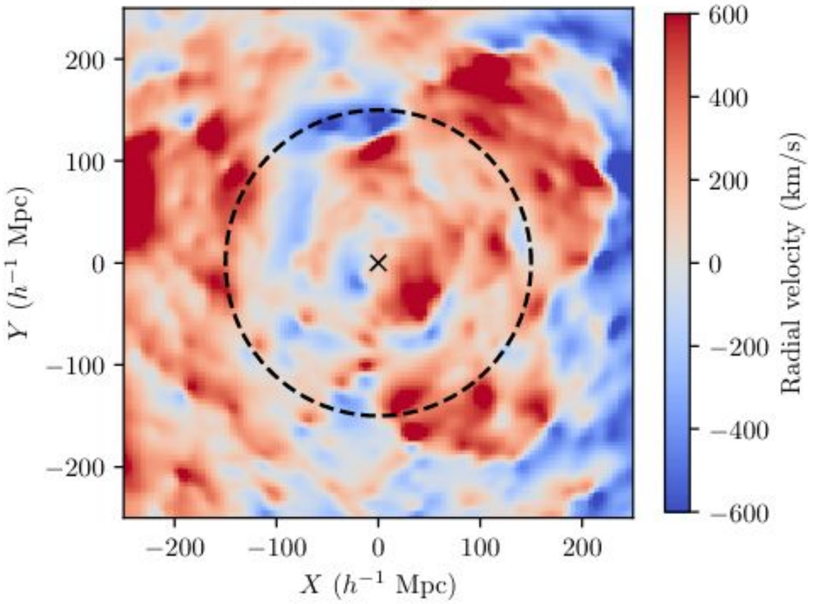
Mock catalog: the VELMASS suite

- A suite of 2048^3 / 2000 Mpc/h, pure N-body simulation
- Initial condition with MUSIC (Hahn et al.…), Eisenstein & Hu power-spectrum
- Perturbations in Ω_m, Ω_b, H, σ_8, …
- First used in **Lavaux (2016)**
- Resolve halos with mass ~10^{12} $M_\odot$

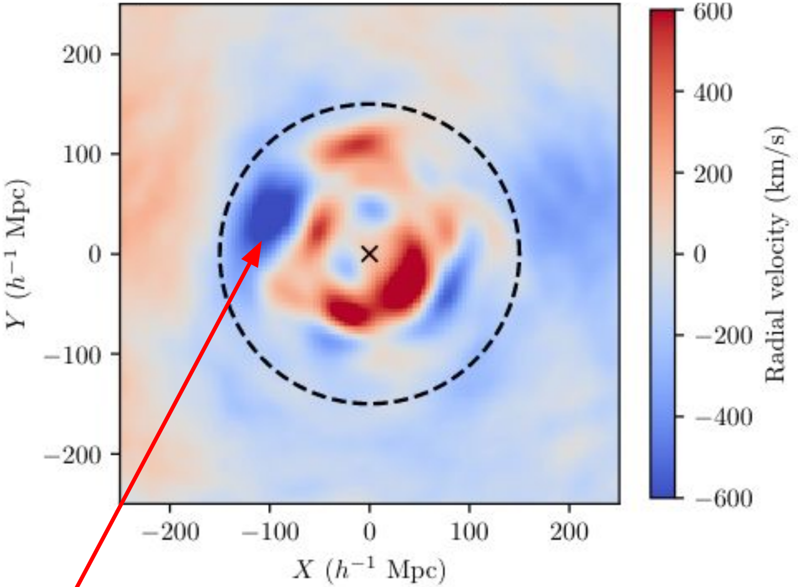
- Apply a selection to mimic 2MTF / SNe, add noise, and infer the fields

Test on mock data: global reliability (Tully-Fisher-like error)

Velocity field of simulation



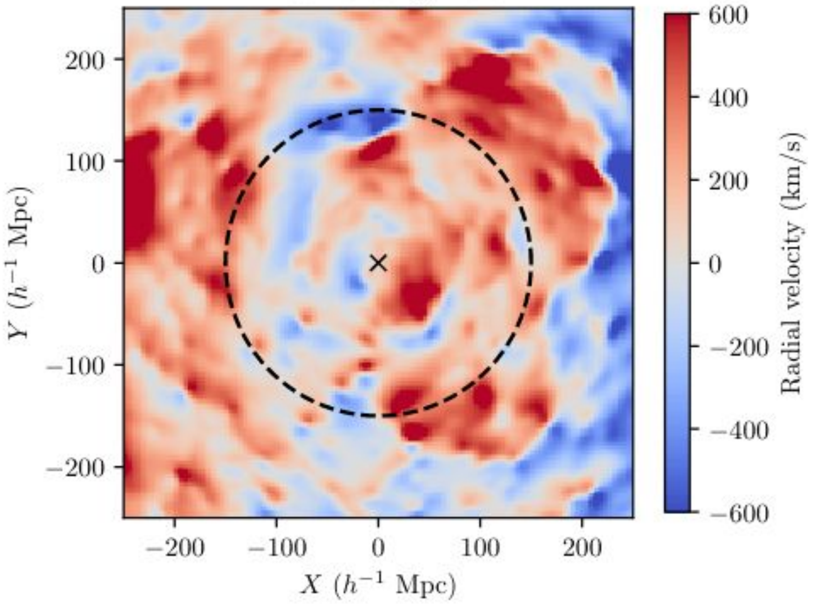
Inferred radial component of velocity field
(IHM not modeled)



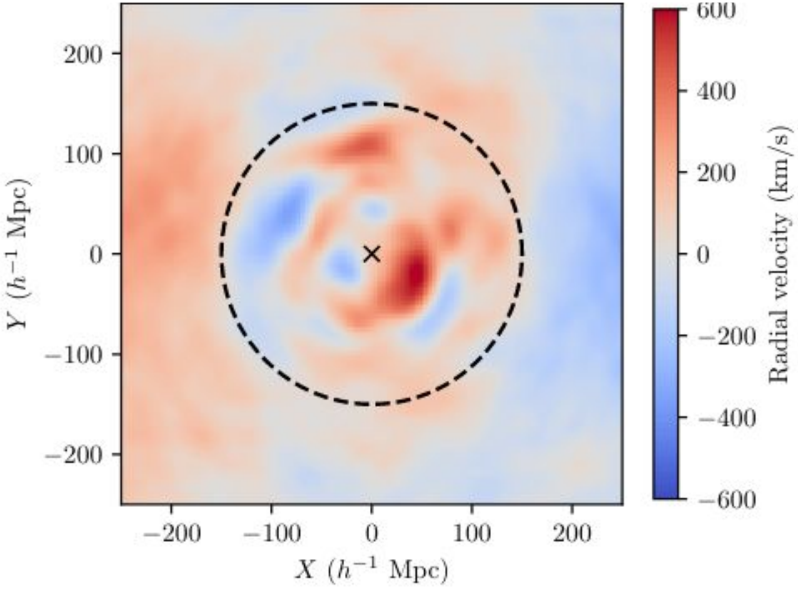
Spurious flows

Test on mock data: global reliability (Tully-Fisher-like error)

Velocity field of simulation

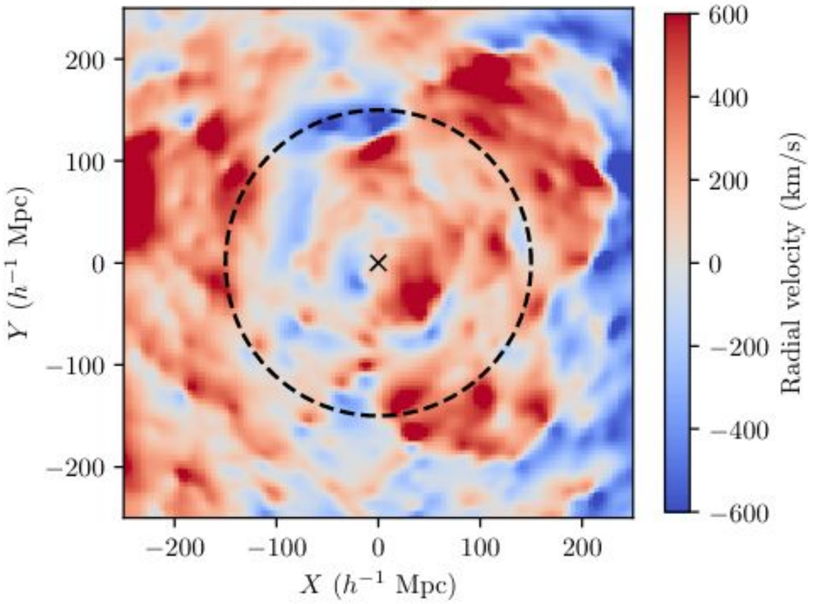


Inferred radial component of velocity field (IHM modeled)

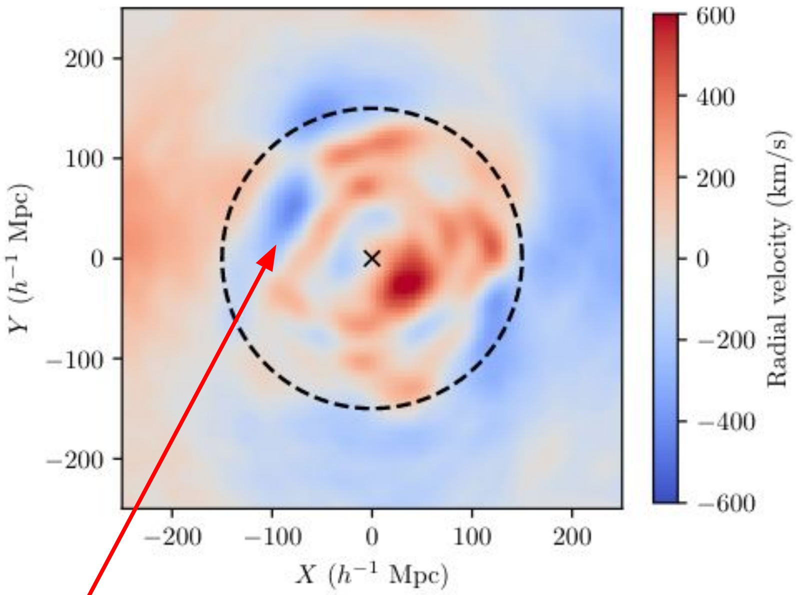


Test on mock data: global reliability (SNe-like error)

Velocity field of simulation



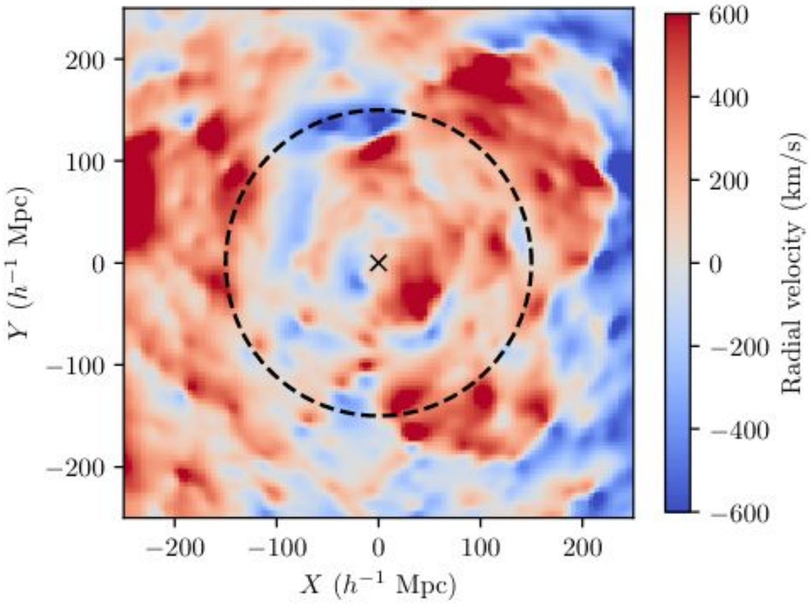
Inferred radial component of velocity field (IHM not modeled)



Spurious flows less prominent

Test on mock data: global reliability (SNe-like error)

Velocity field of simulation



Inferred radial component of velocity field
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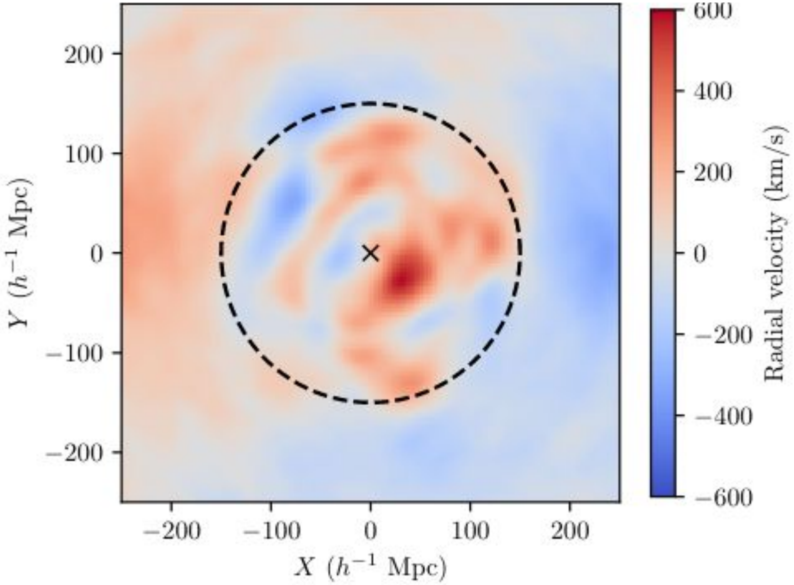
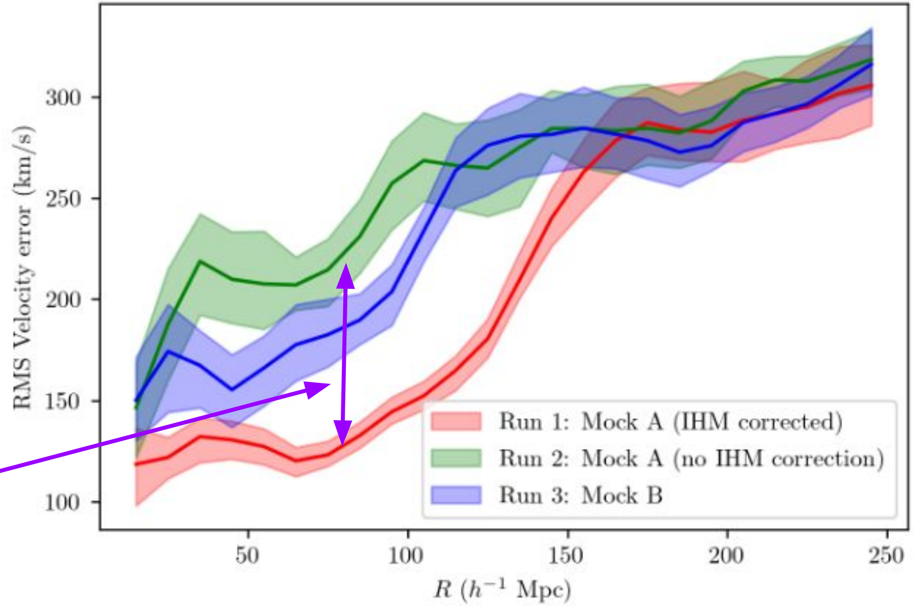


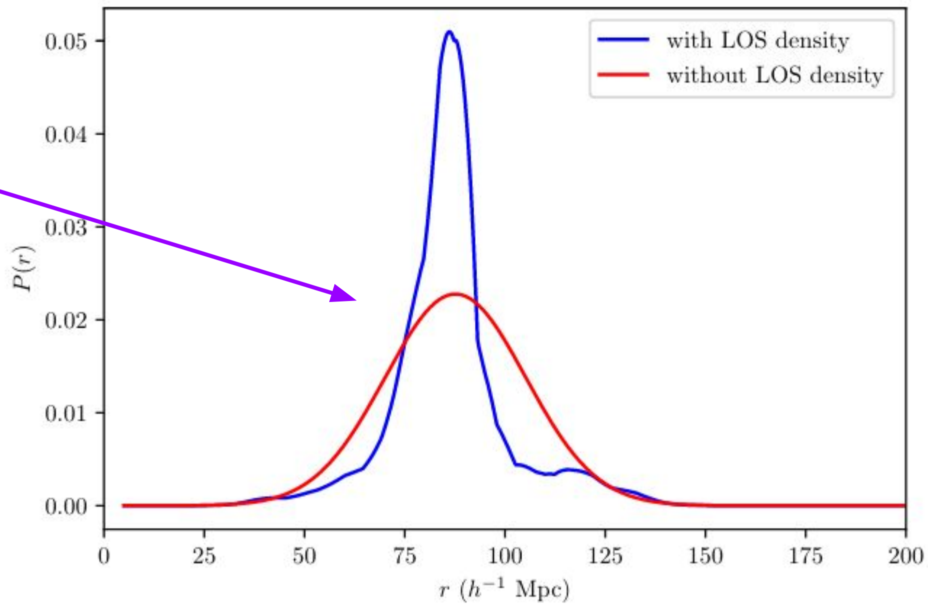
Test on mock data: surprise "grouping" effect

- Including Inhomogeneous Malmquist Bias
  ⇒ additional benefits **reduce noise**
- Three tests:
  - **self consistent mock catalog with homogeneous tracer distribution**
  - **halo mock catalog, skipping IHM modeling**
  - **halo mock catalog, including IHM modeling**
- Compute RMS between
  - **inferred** velocity field
  - **simulation** velocity field
- Reduction of error budget with IHM model



Test on mock data: surprise "grouping" effect

- Source of the improvement?
  - Implicit grouping with IHM model
  - No more average systematic bias
- Example of distance probability with/without IHM model

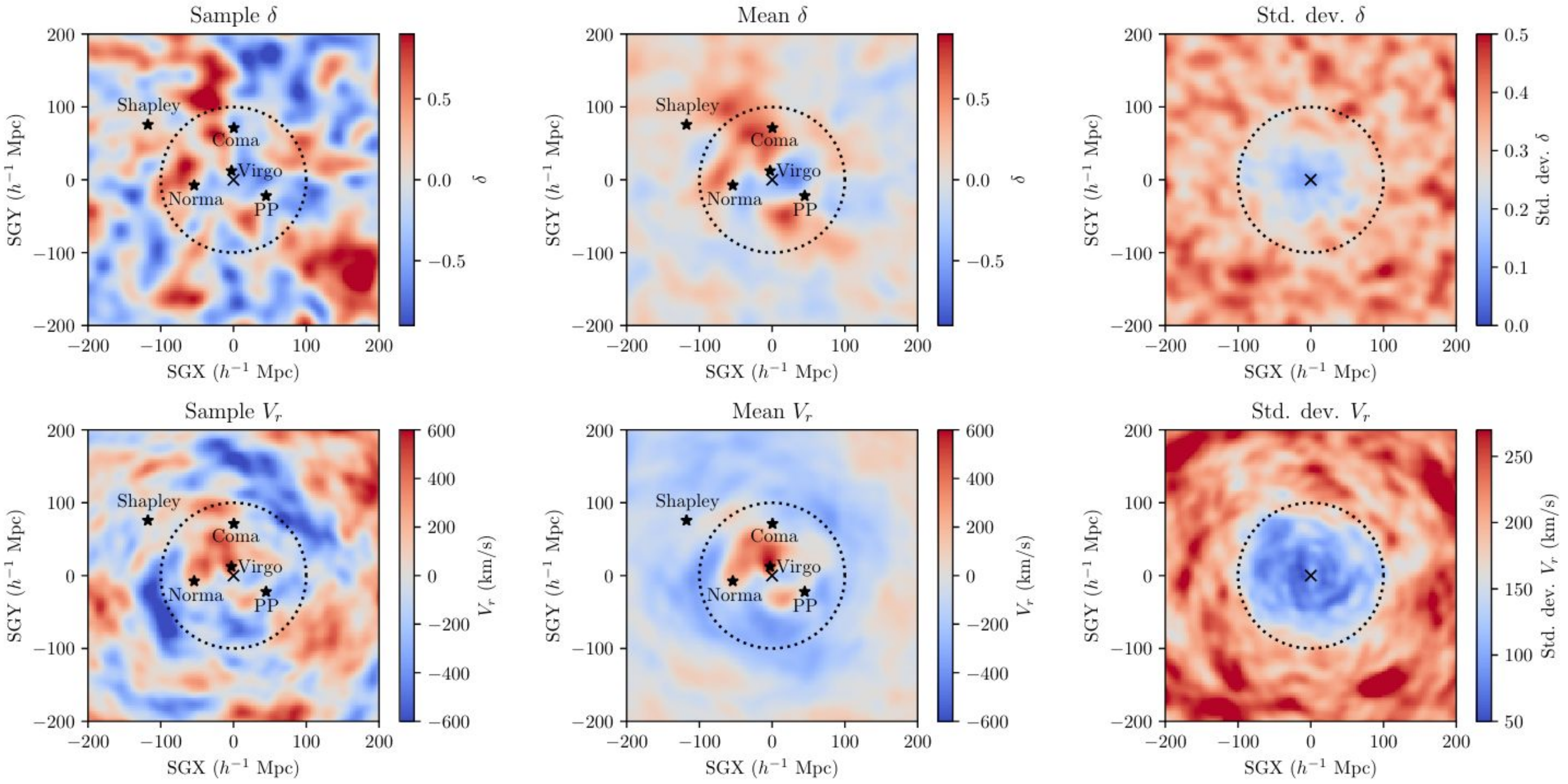


Application to data

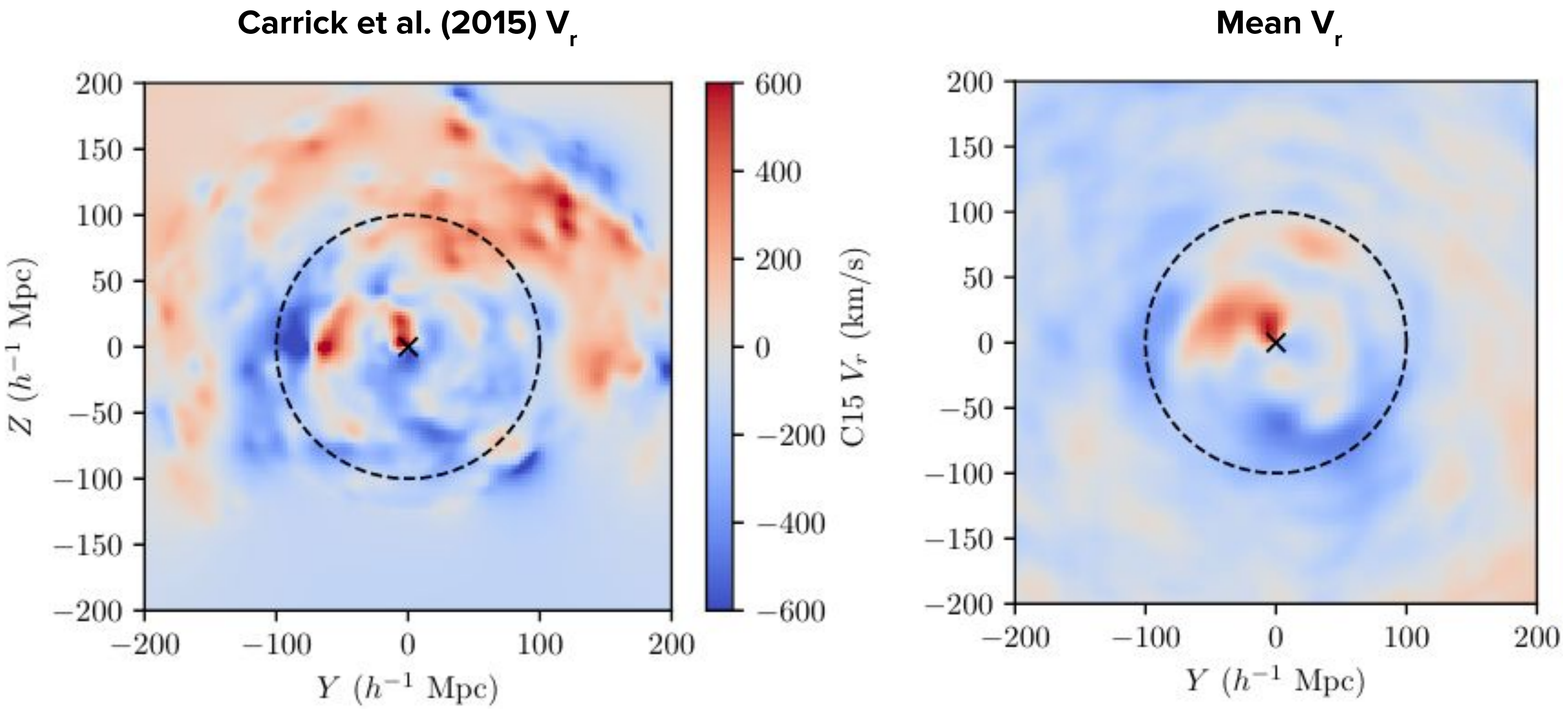
Application to 2MTF & Pantheon SNe: inferred fields

10 Mpc/h smoothed density contrast

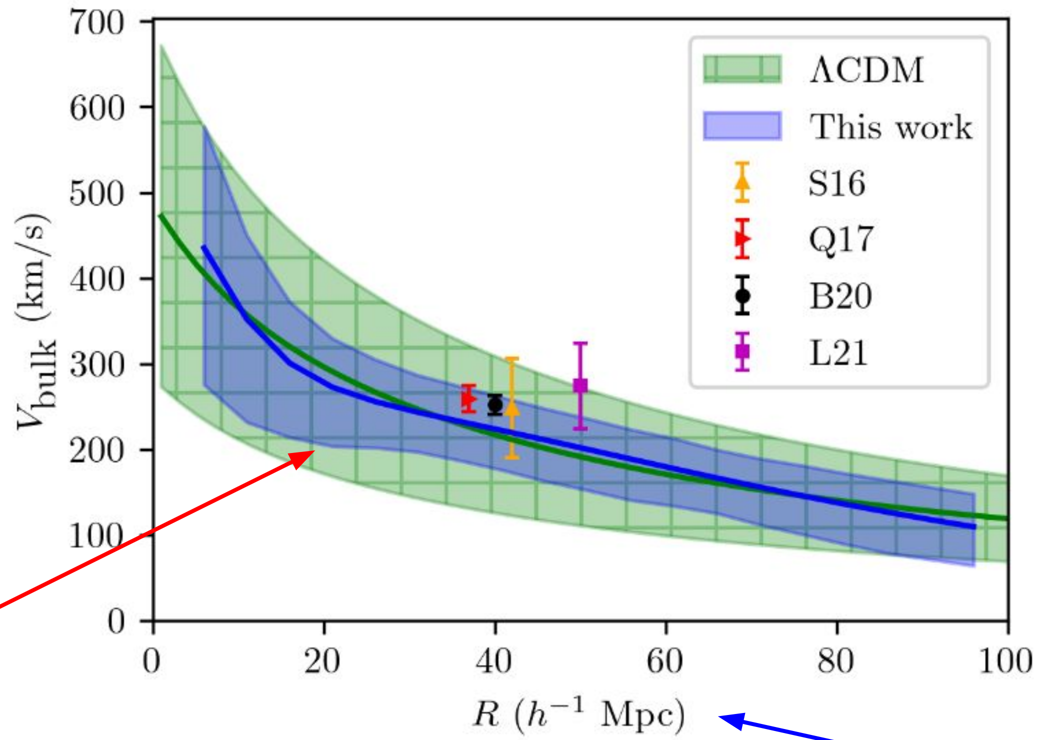
Radial component of velocity field



Comparison to 2M++ fields



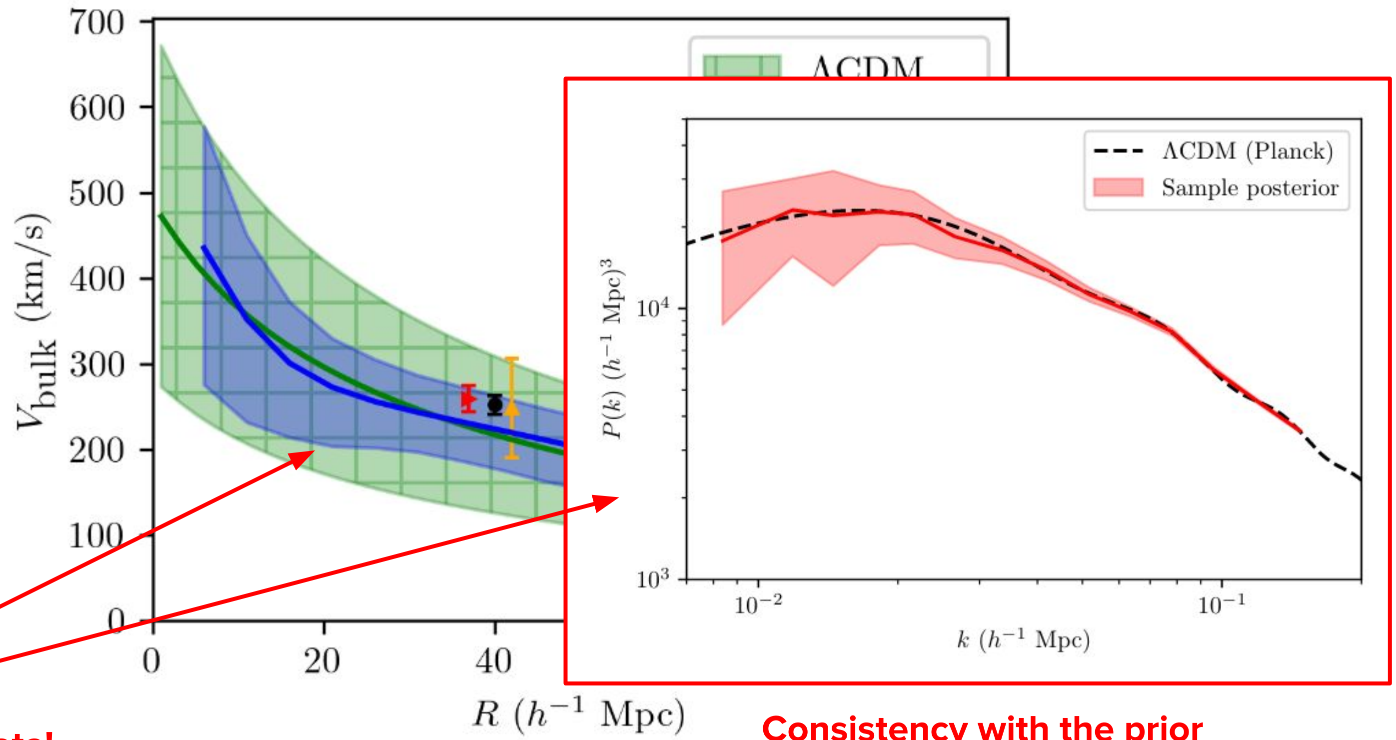
New bulk flow measurements: amplitude



ΛCDM explains data!

Radius of the sphere

New bulk flow measurements: amplitude

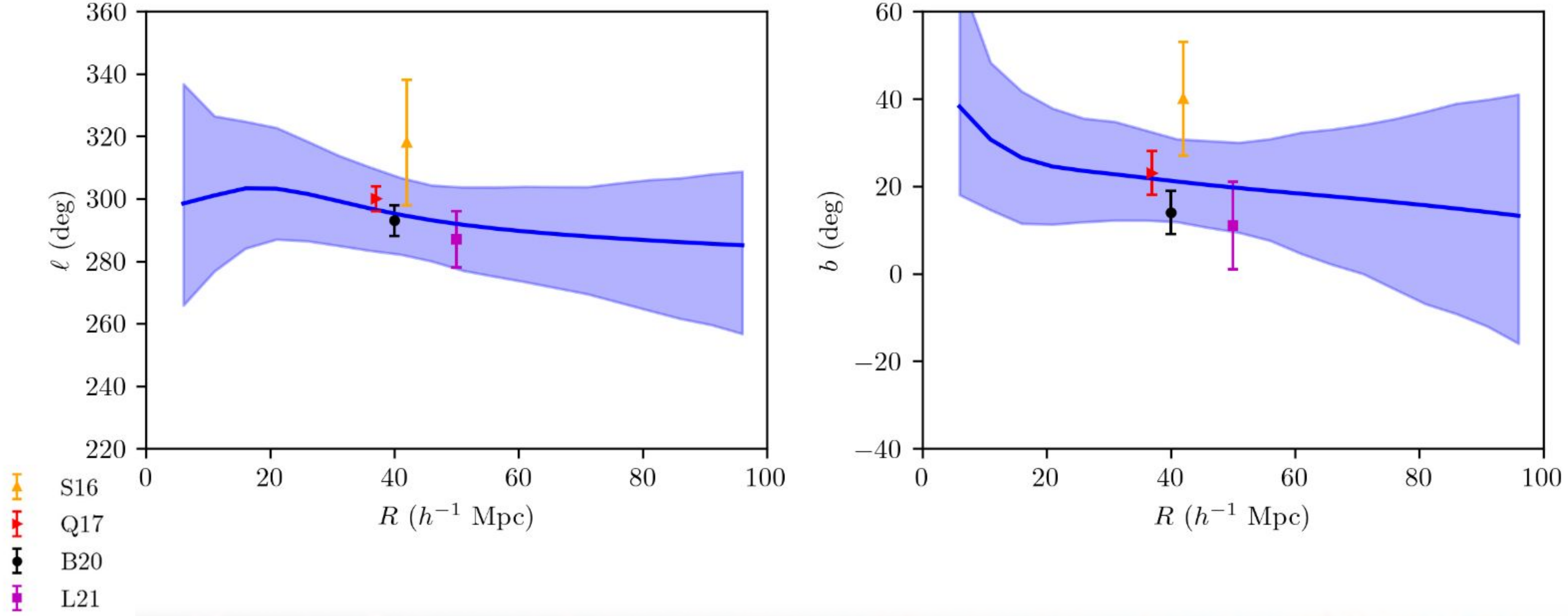


ΛCDM really explains data!

Consistency with the prior

New bulk flow measurements: direction

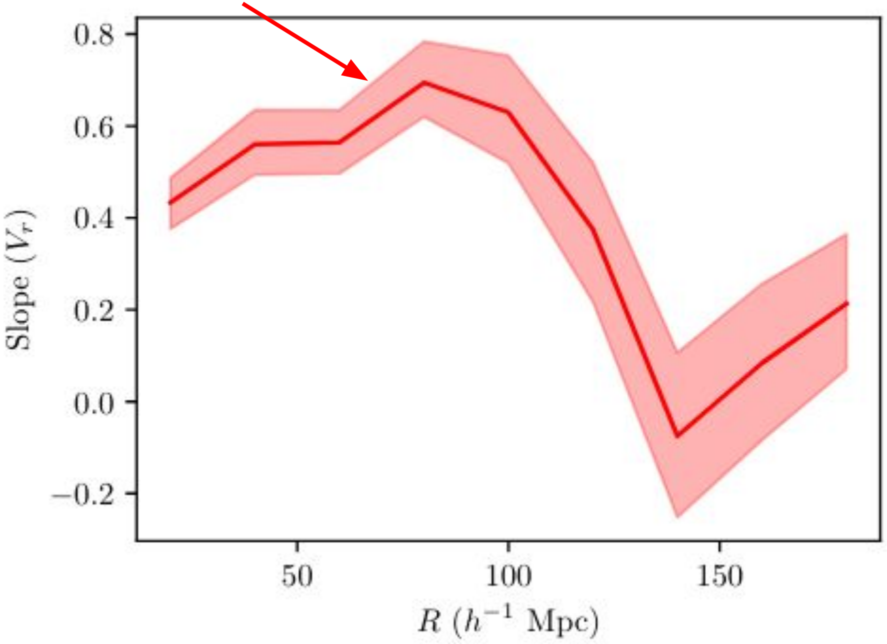
Galactic coordinates



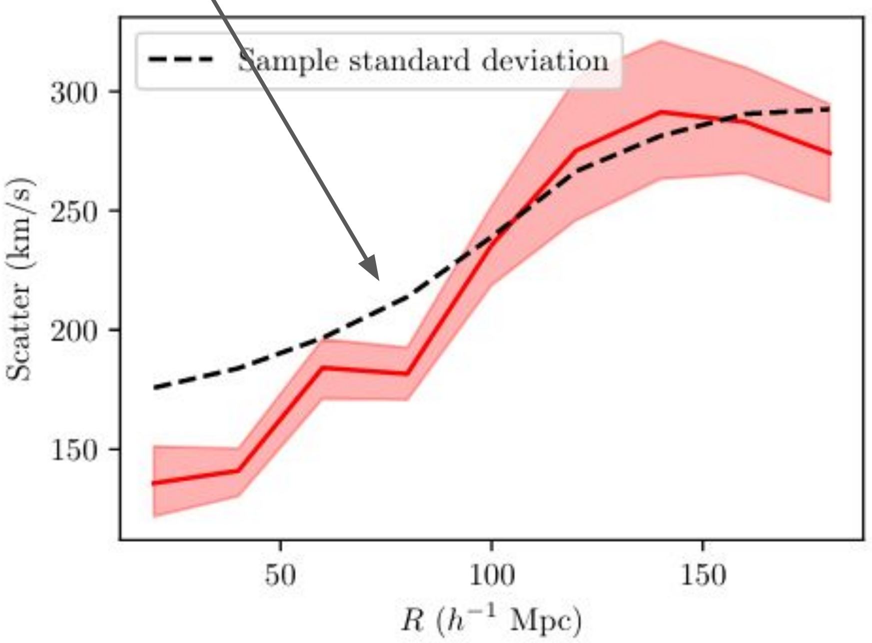
Cross-validation with Carrick+15 model

Want as close to "1" as possible

MCMC scatter + halo stochastic scatter



Field-field linear alignment



Field-field stochasticity

Conclusion

Conclusions

- **Reviewed a short history of bulk flow & cosmo constraints**
  (a lot more, check Marc Davis, Adi Nusser, Mike Hudson, Roya Mohayaee, ...)

- **Getting unbiased / concording results with distance catalogs**

- **Confirmation through 2 methods**

- **Future development:**
  - use nonlinear model of structure formations **(see Prideaux-Ghee et al., in prep.)**
  - joint inference density reconstruction and flow reconstruction w/ BORG
  - scale to LSST