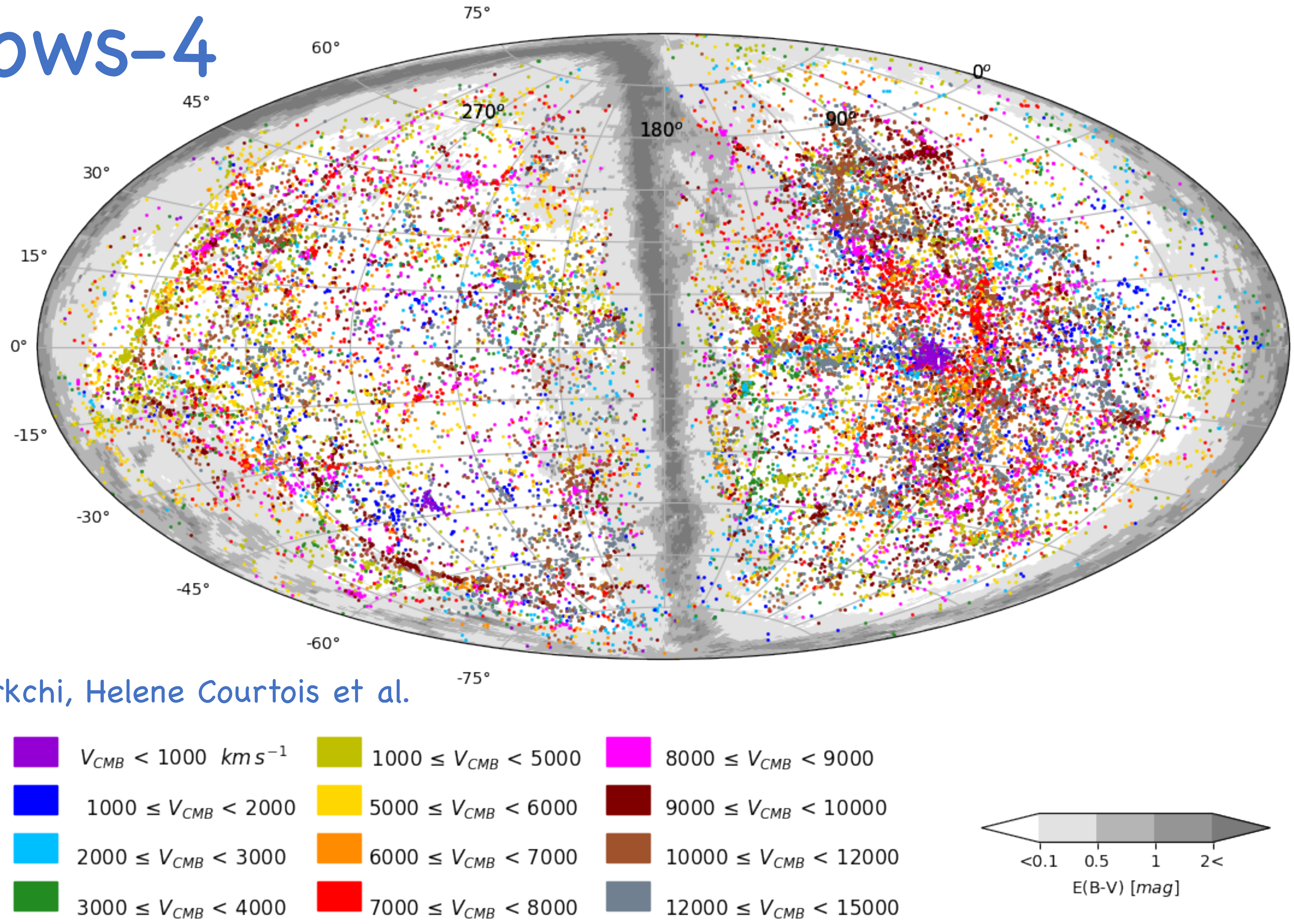
Cosmicflows-4



Brent Tully, Ehsan Kourkchi, Helene Courtois et al.

Cosmicflows-1
Tully et al. 2008, ApJ, 676, 184
1,791 galaxies in 743 groups

Cosmicflows-2
Tully, Courtois et al. 2013, AJ, 146, 86
8,315 galaxies in 5,224 groups

Cosmicflows-3
Tully, Courtois & Sorce 2017, AJ, 152, 50
17,669 galaxies in 11,508 groups

Cosmicflows-4
Tully, Kourkchi et al. 2022, ApJ, 000, 000
55,877 galaxies in 38,065 groups

Methodologies

Foundations:
Parallaxes, RR Lyrae, Horizontal Branch, Eclipsing Binary, Maser

First Step:
Cepheids, Tip of the Red Giant Branch

Wide coverage, high density:
Fundamental Plane, Luminosity-Linewidth (Tully-Fisher)

Accurate at substantial distances:
Surface Brightness Fluctuations, Supernovae Ia & II

Catalogs available:

Within 3,500 km/s
Kourkchi & Tully 2017, ApJ, 843, 16

Roughly 3,000 km/s to 15,000 km/s
Tully 2015, AJ, 149, 171

>15,000 km/s in SDSS footprint
Temple at al. 2017, A&A, 602, A100

The Importance of Grouping

1. Cross referencing between methodologies
2. Weighted averaging of distances and velocities
3. Identification of anomalous data

Scaling relations:
correlations between
=> group **Mass** (~ K luminosity)
=> velocity dispersion ($\boldsymbol{\sigma_p}$)
=> radius of 2nd turnaround ($\mathbf{R_{2t}}$)

Group
=
Cluster
=
Halo

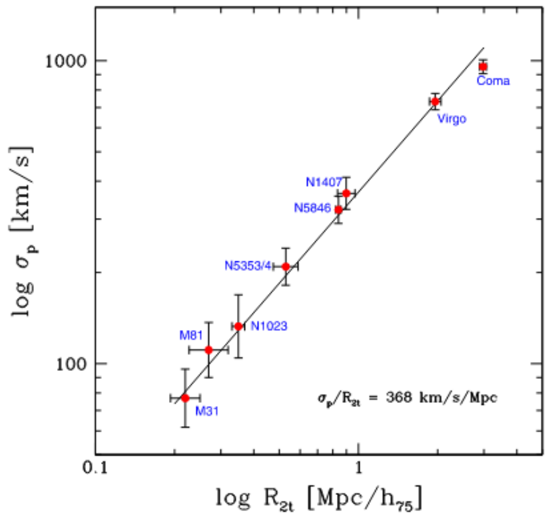


Figure 21. Correlation between projected second turnaround radius R_{2t} and the radial velocity dispersion of galaxies within this radius σ_p.

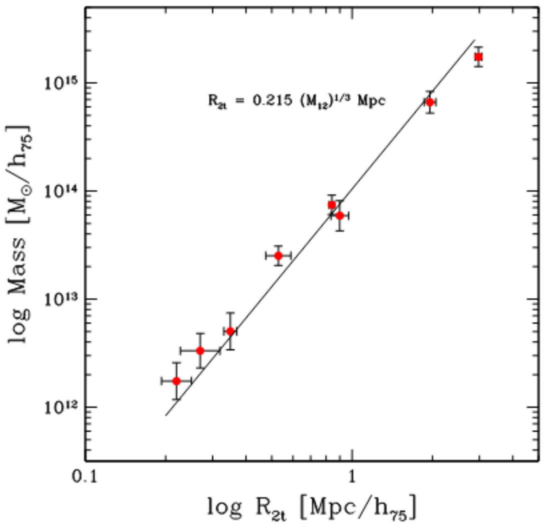


Figure 22. Correlation between the projected second turnaround radius R_{2t} and the virial mass calculated for galaxies within this radius M_v.

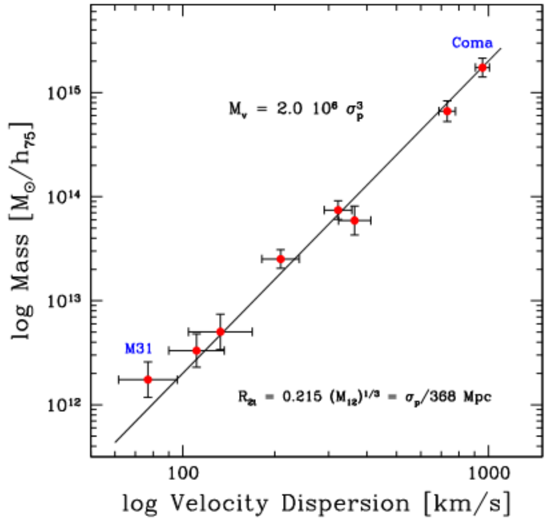
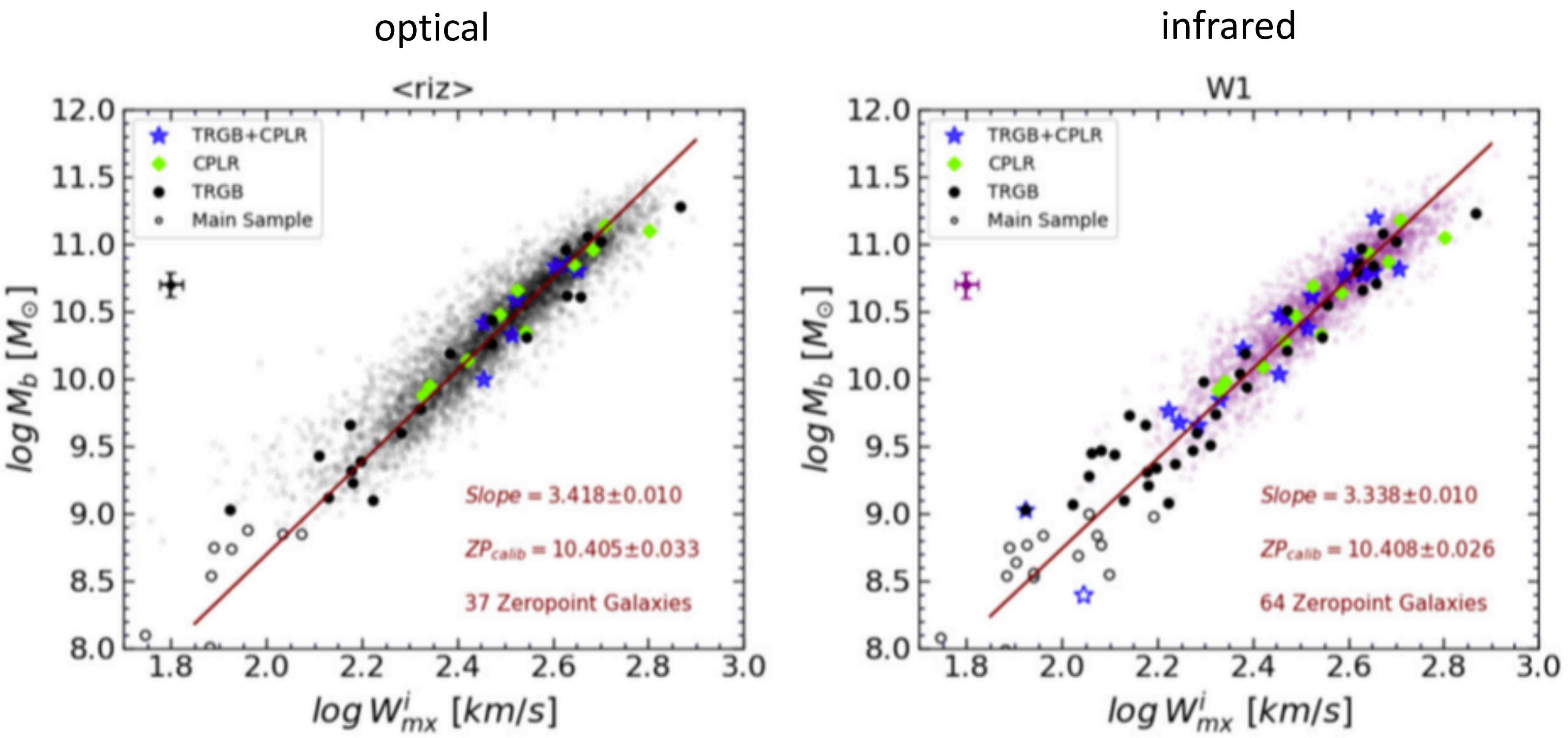


Figure 23. Correlation between the virial mass and the velocity dispersion of galaxies within r_{2t}.

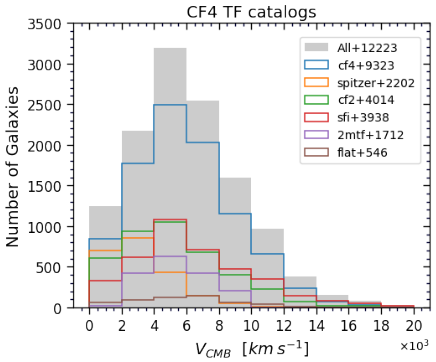
Baryonic TF Relation

Kourkchi et al. 2022, MNRAS, 511, 6160

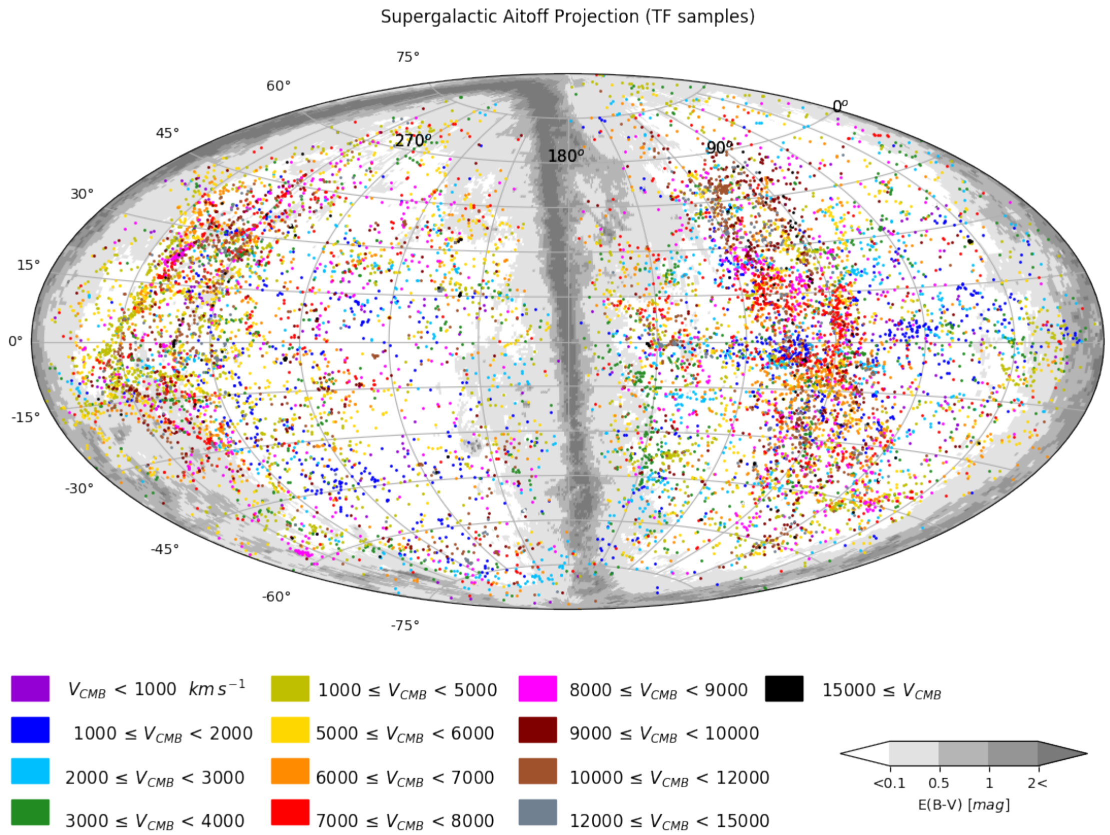


10148 BTF distances

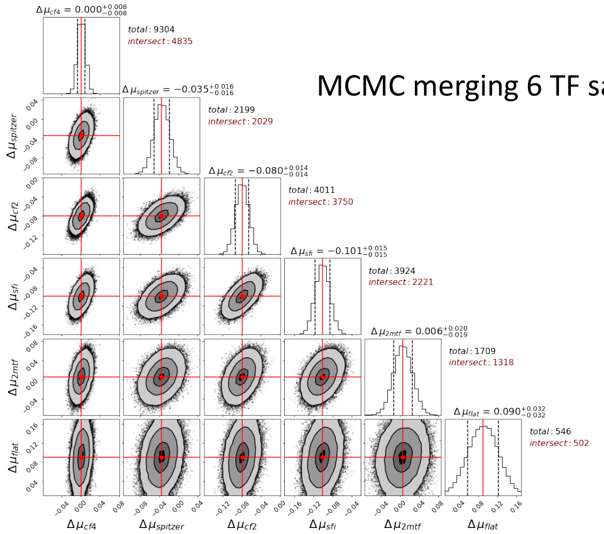
12395 TF Distances



Redshift distribution



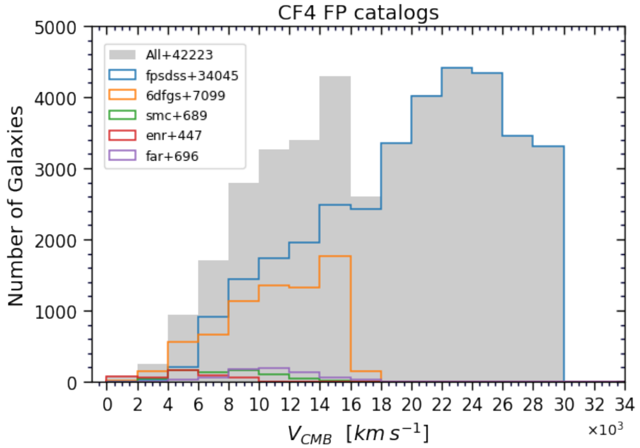
Sky distribution – supergalactic coordinates



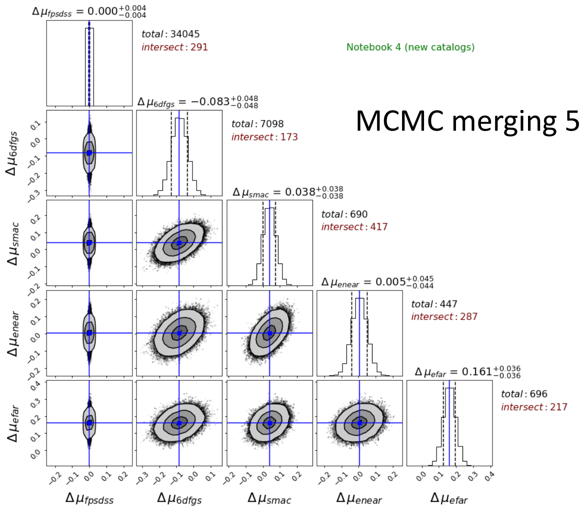
MCMC merging 6 TF samples

42253 Fundamental Plane distances

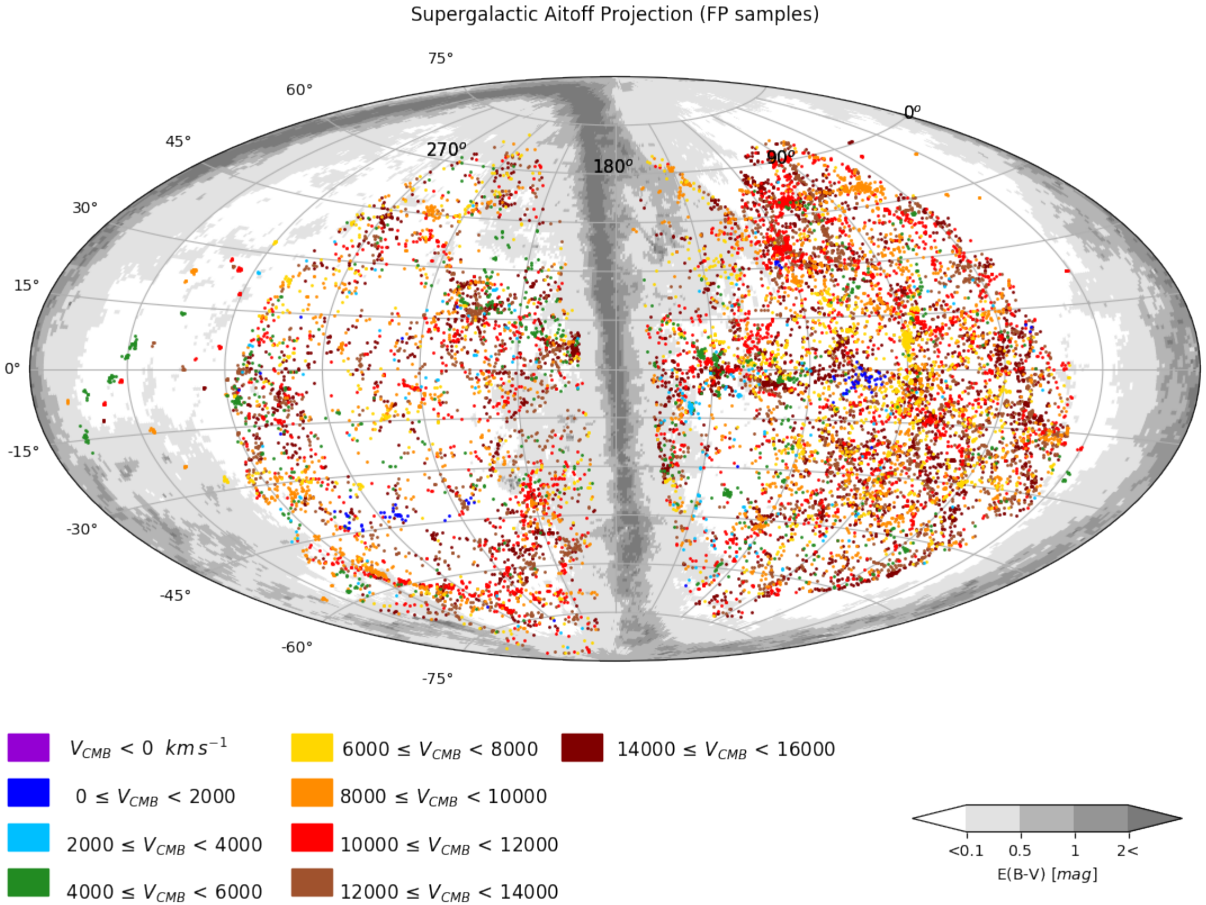
SDSS sample:
Howlett et al. 2022, MNRAS 515, 953



Redshift distribution

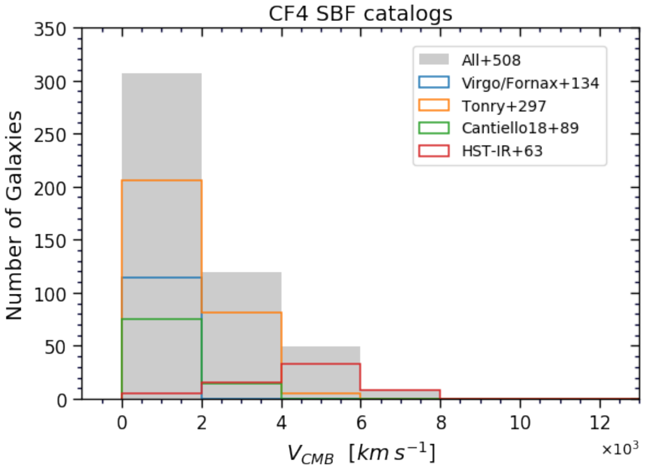


MCMC merging 5 FP samples

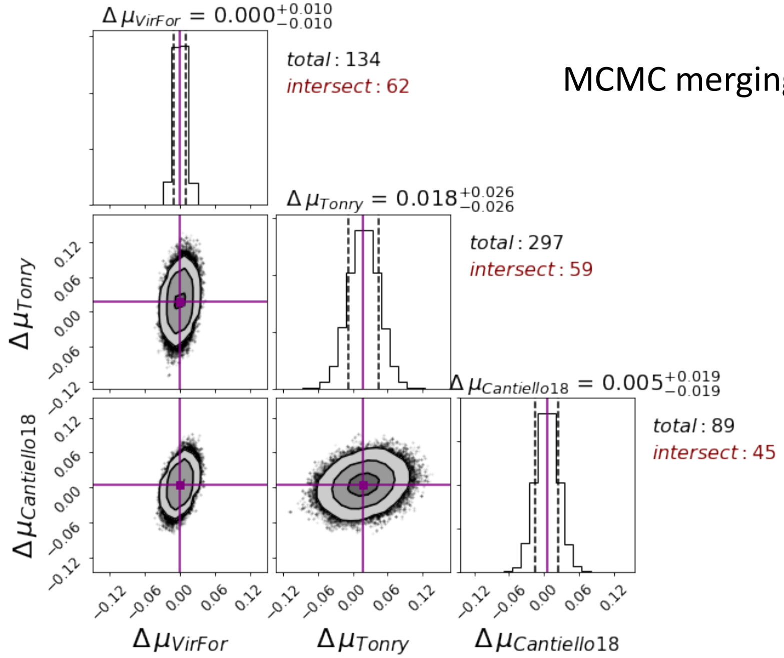


Sky distribution supergalactic coordinates

488 Surface Brightness Fluctuation distances



Redshift distribution

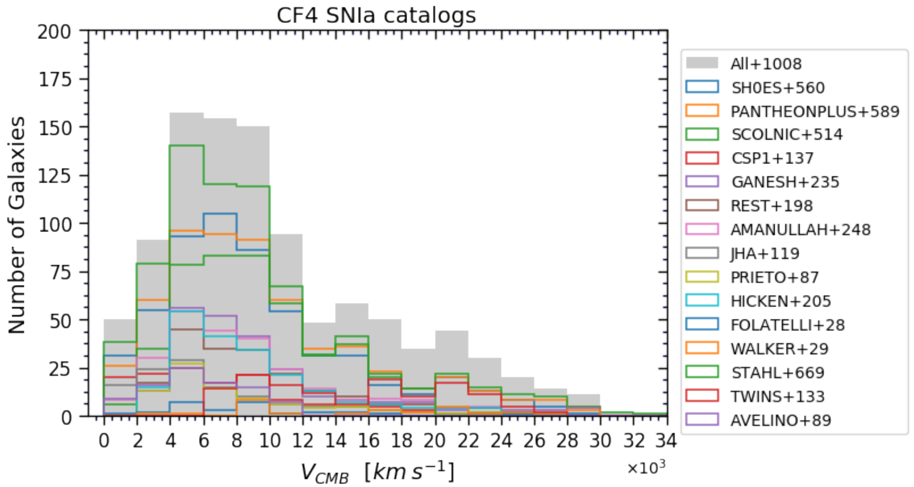


MCMC merging 3 SBF samples

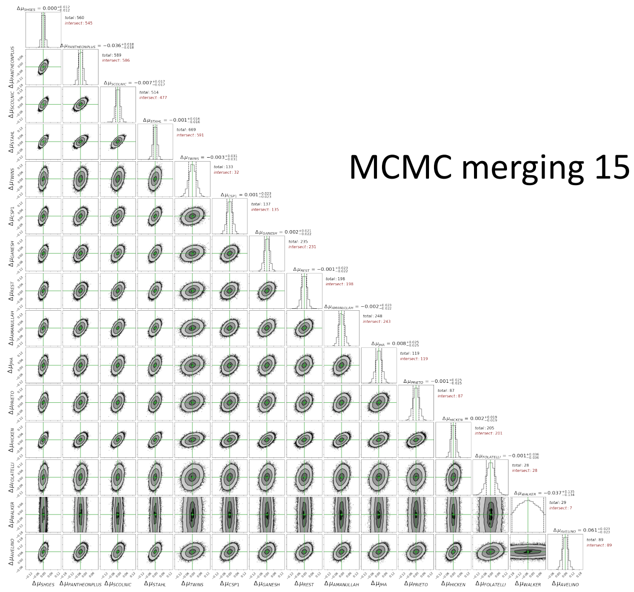
94 Supernova Type II distances

de Jaeger et al. 2020, MNRAS 496, 3402

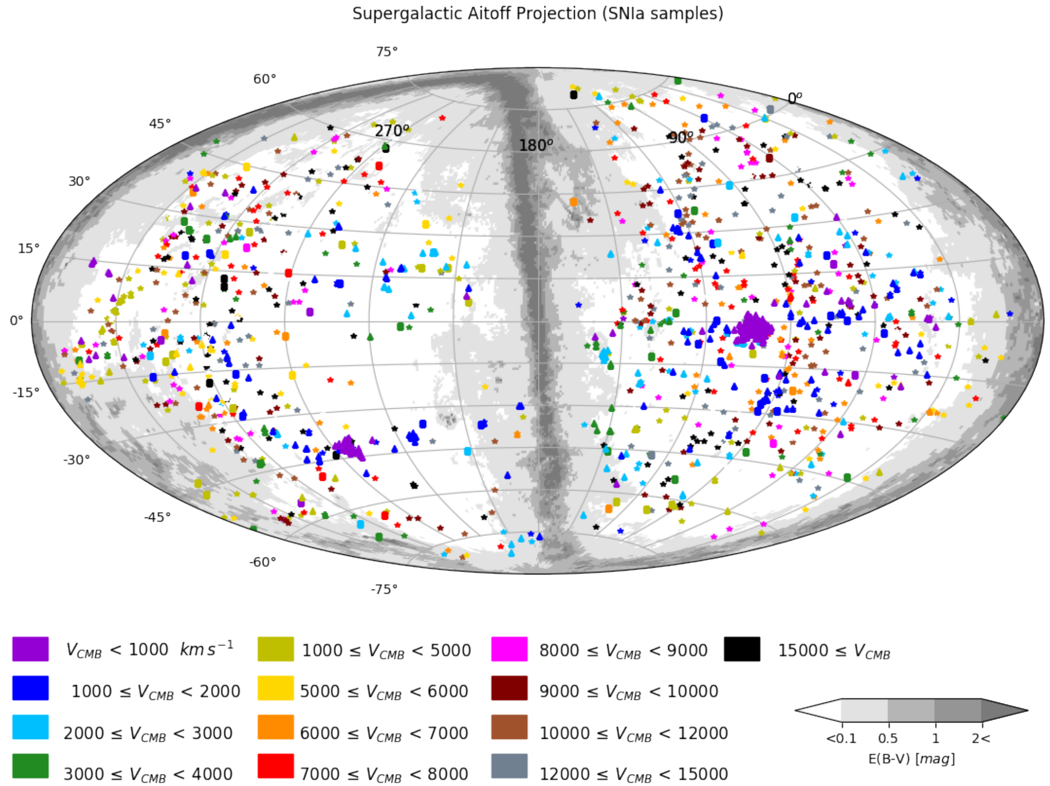
1008 Supernova Type Ia distances



Redshift distribution



MCMC merging 15 SNIa samples



Sky distribution: SNIa, SNII, SBF

Merging SNIa, SNII, SBF, TF, FP through group affiliations

Coma (Abell 1656)

209 FP, 50 TF, 7 SNIa, 2 SNII

Leo (Abell 1367)

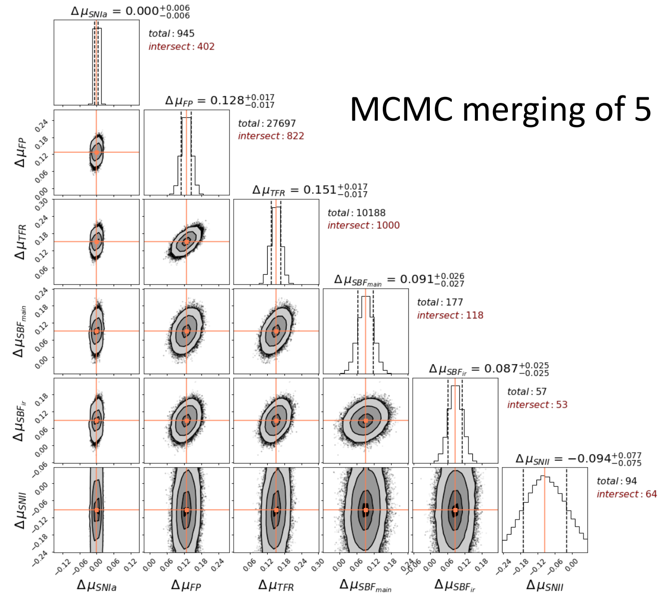
66 FP, 49 TF, 2 SNIa, 1 SNII

Hercules (Abell 2147/51)

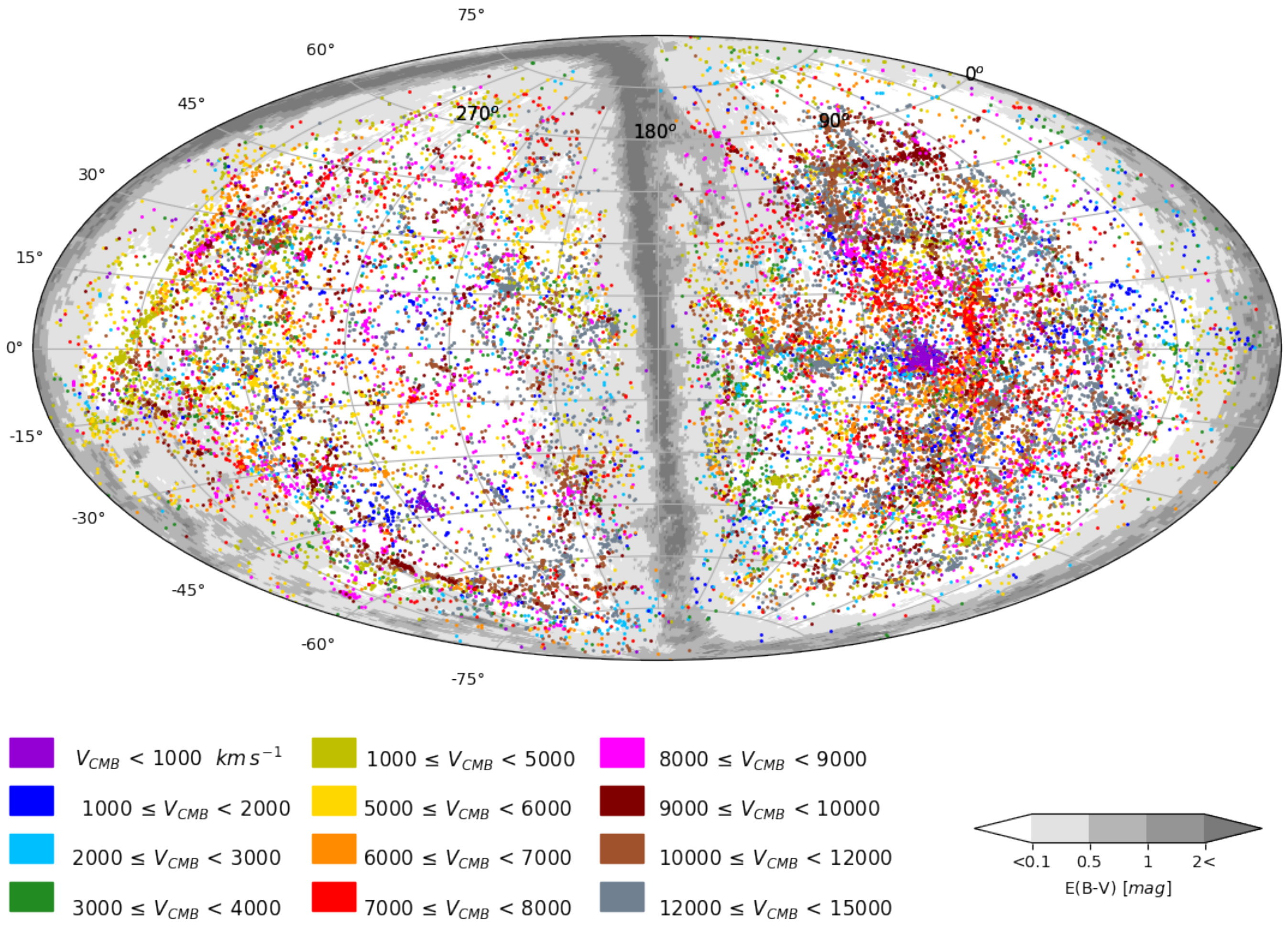
193 FP, 60 TF, 2 SNIa

Virgo

32 FP, 49 TF, 132 SBF, 4 SNIa



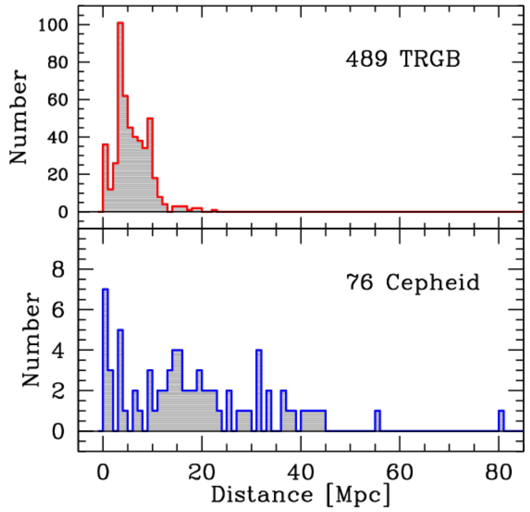
MCMC merging of 5 methodologies



Sky distribution, combined sample, supergalactic coordinates

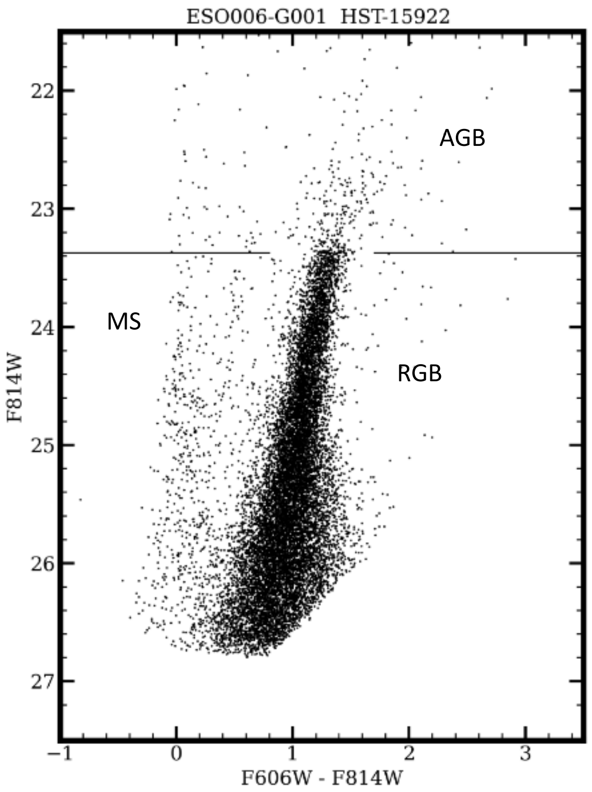
489 Tip of the Red Giant Branch
76 Cepheid distances

Anand et al. 2021, AJ 162, 80
Riess et al. 2022, ApJL 934, L7



Pop II

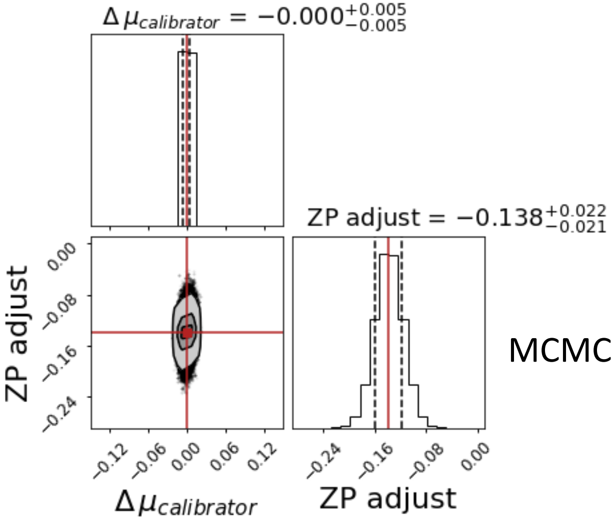
Pop I



TRGB example: ESO 006-001

Cepheids on ZP scale of Riess et al. (2022)

TRGB closer by 0.05 mag from Rizzi et al. (2007) ZP based on preliminary Gaia eDR3 parallaxes



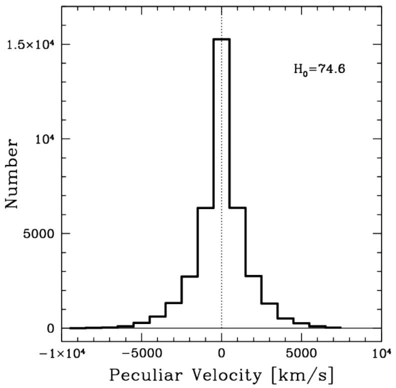
MCMC linkage of SNIa, SNII, SBF, TF, FP with zero point calibrators

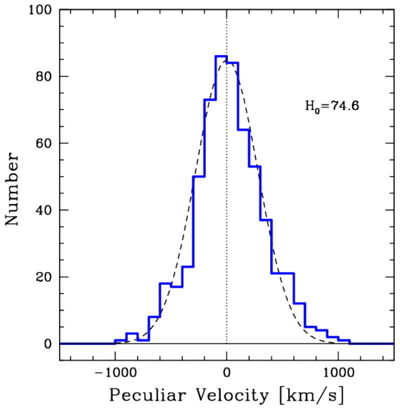
Hubble Constant

H_0=74.6+-0.08 (stat.) km/s/Mpc

35,000 groups

Gaussian 280 km/s

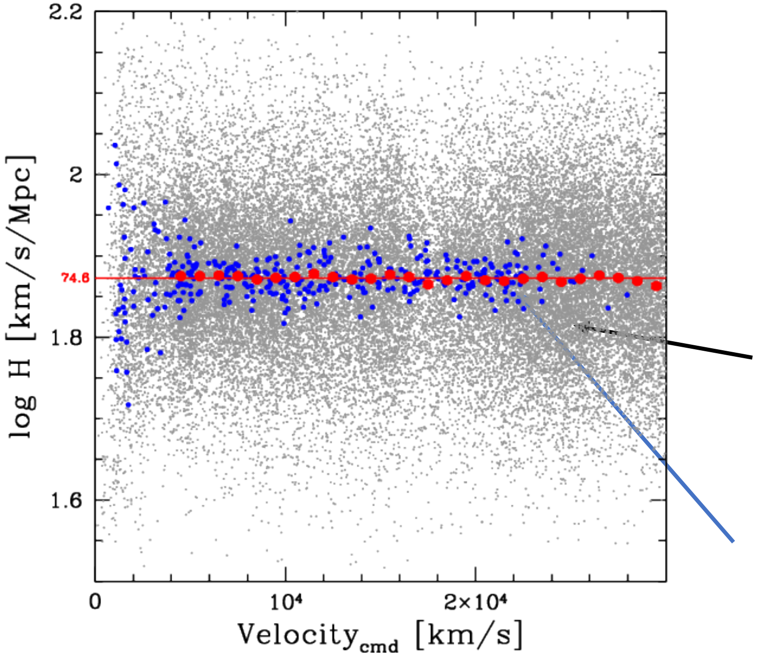




all groups

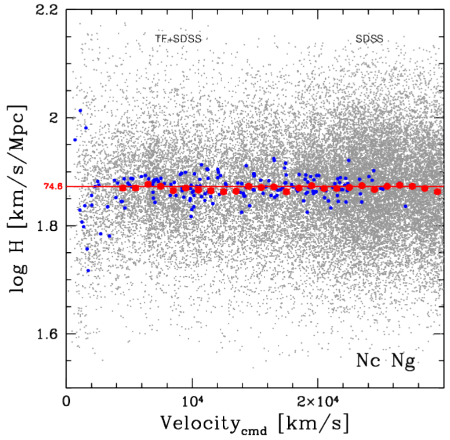
errors 5% or better

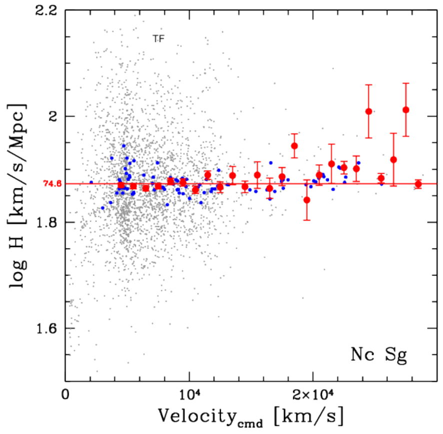
peculiar velocities assuming H_0=74.6 km/s/Mpc

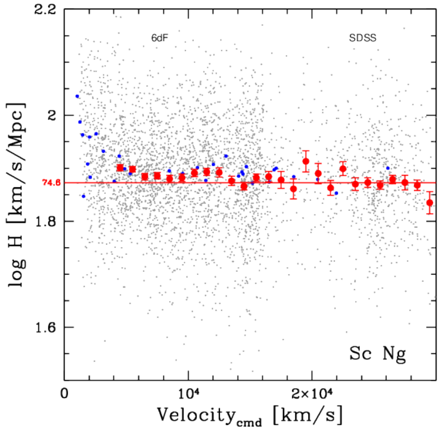


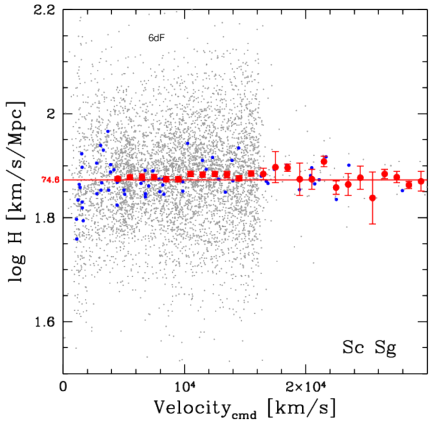
all groups

errors 5% or better









Hubble parameter values by redshift and sector

Systematic uncertainty issues

Path giving H_0=74.6 km/s/Mpc

- 1008 SNIa are merged with FP, TF, SBF, and SNII on an arbitrary zero point scale
- This ensemble is merged with 128 galaxies with cepheid, TRGB, maser distances

Path giving H_0=72.1 km/s/Mpc

- 44 SNIa with cepheid, TRGB, maser distances set SNIa scale (as per Riess et al. 2022: H_0=73.0+-1.0)
- This zero point scaling is accepted for the ensemble

Possible explanations of the difference:

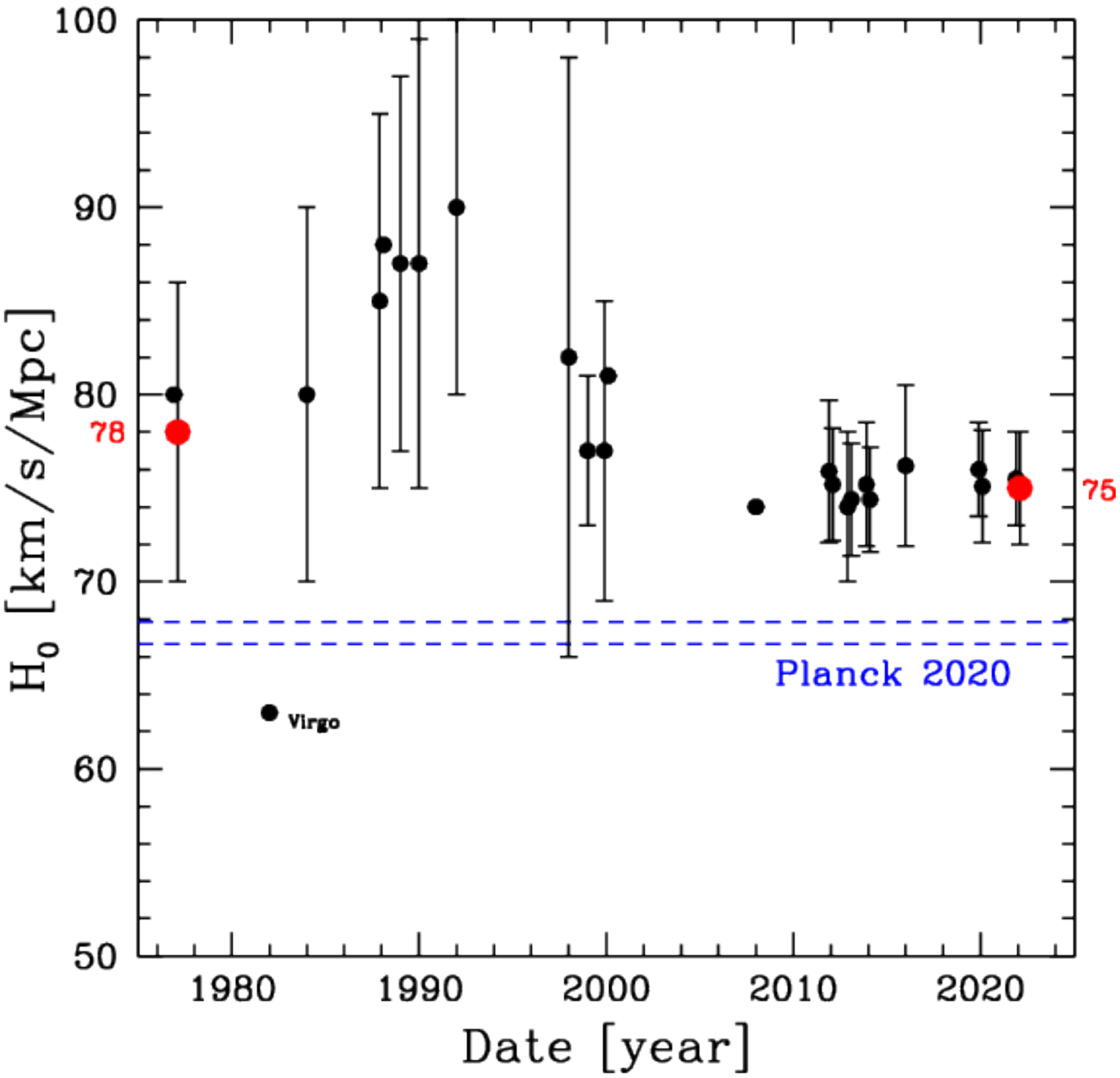
- small number statistics?
- systematic differences between SNIa in galaxies with cepheids and SNIa in random samples?

Alert: systematics in H_0 at the level of 4% possible !

H_0 from literature; same methodologies

TRGB	69.8+-0.8+-1.7	Freedman et al. (2019)	15
	71.5+-1.8	Anand et al. (2022)	13
	73.2	revised ZP	
Ceph+SNIa	73.0+-1.0	Riess et al. (2022)	42
Ceph+CF4	72.2	Tully et al. (2022)	44
SNII	75.8+-5.1	de Jaeger (2020)	94
SBF	73.3+-0.7+-2.4	Blakeslee et al. (2021).	62
FP	75. +-2	Howlett et al. (2022)	34k
TF	75.5+-2.5.	Kourkchi et al. (2022)	10k

Personal measurements of the Hubble Constant



Doing better in the future

1. Absolute zero point scale:

-- **Gaia parallaxes** (eDR3 and beyond) of Galactic cepheids, RR Lyrae, Horizontal Branch and Red Giant Branch stars
-- direct calibration of TRGB, including metallicity dependencies, with samples of 10^3-10^4 stars
-- direct transfer to Local Group galaxies

2. Distances beyond the realm of peculiar velocity concerns:

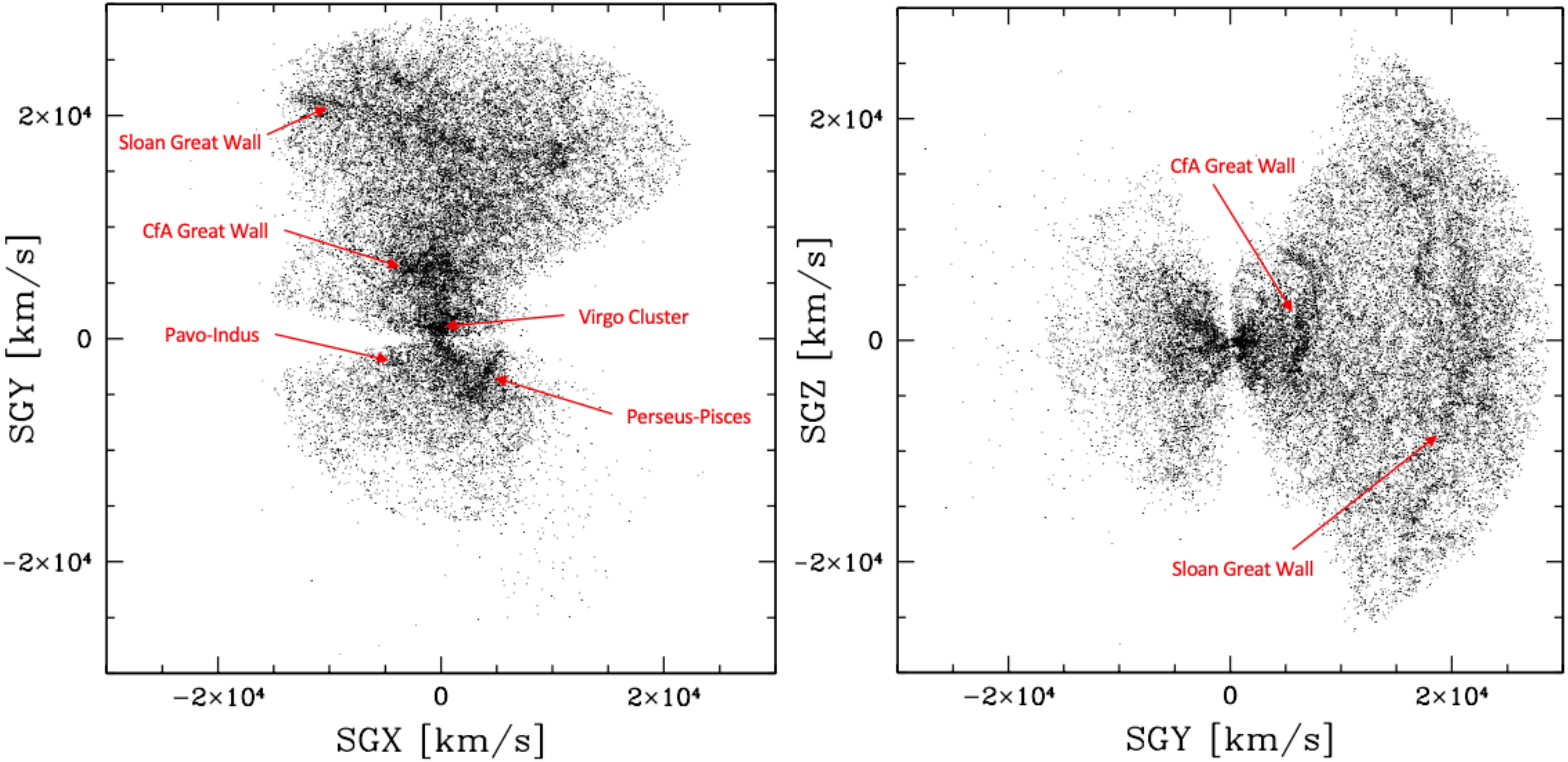
-- currently depending on TF and FP methods with 20-25% uncertainties per target
-- **Hawaii Supernova Flows** campaign to acquire ~10^4 SNIa
-- current uncertainties 7% potentially reduced to 4-5% with multiband photometry, spectra, and "twinning"

3. Local – far field connection:

-- currently cepheids -> SNIa; problem small samples with little growth possible
-- alternative **TRGB -> SBF**; offers larger samples with comparable accuracy per target

Cosmography with Cosmicflows-4

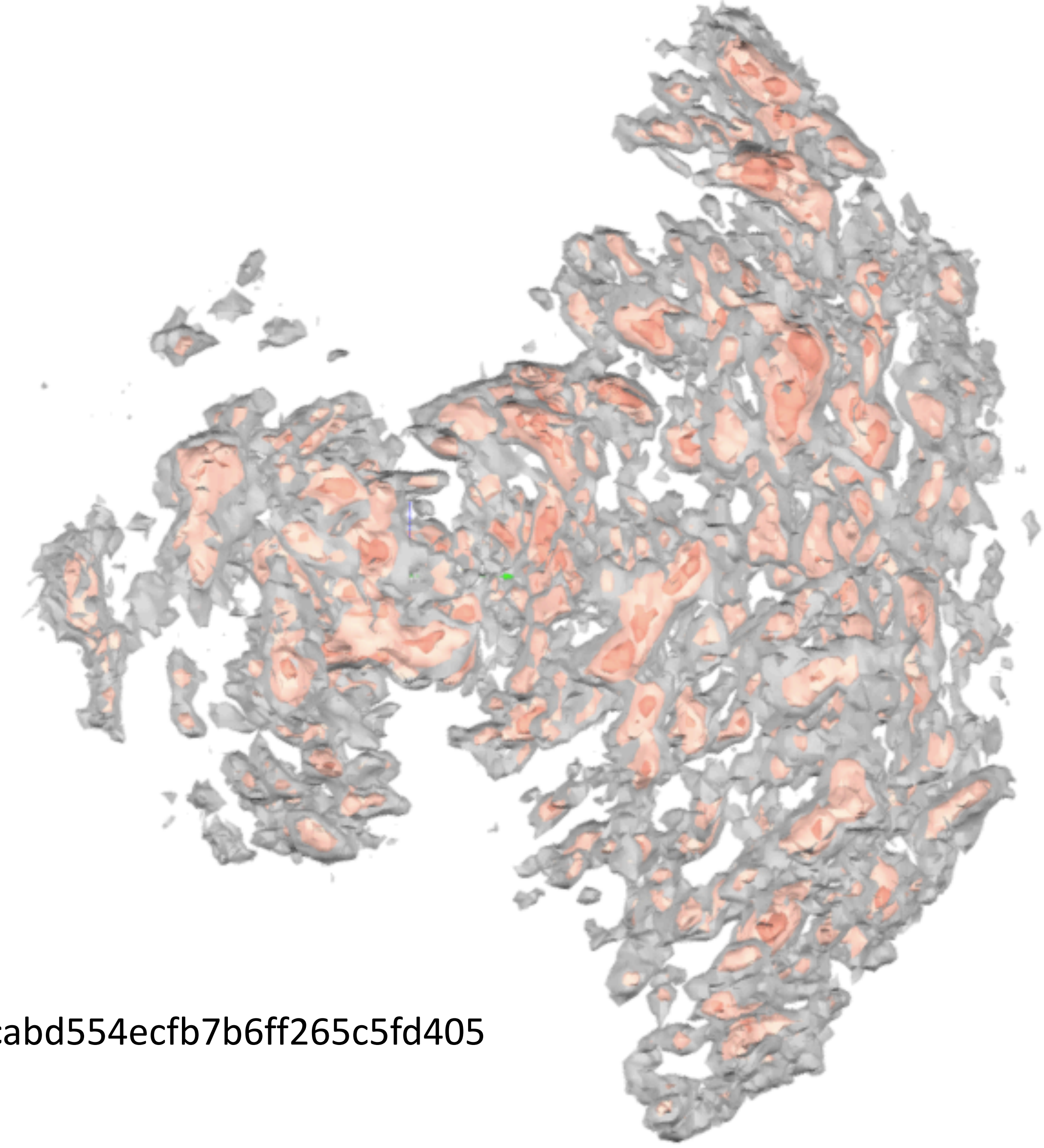
38,053 galaxy groups



supergalactic coordinates

A preliminary look at structure from a model derived from CF4 peculiar velocities

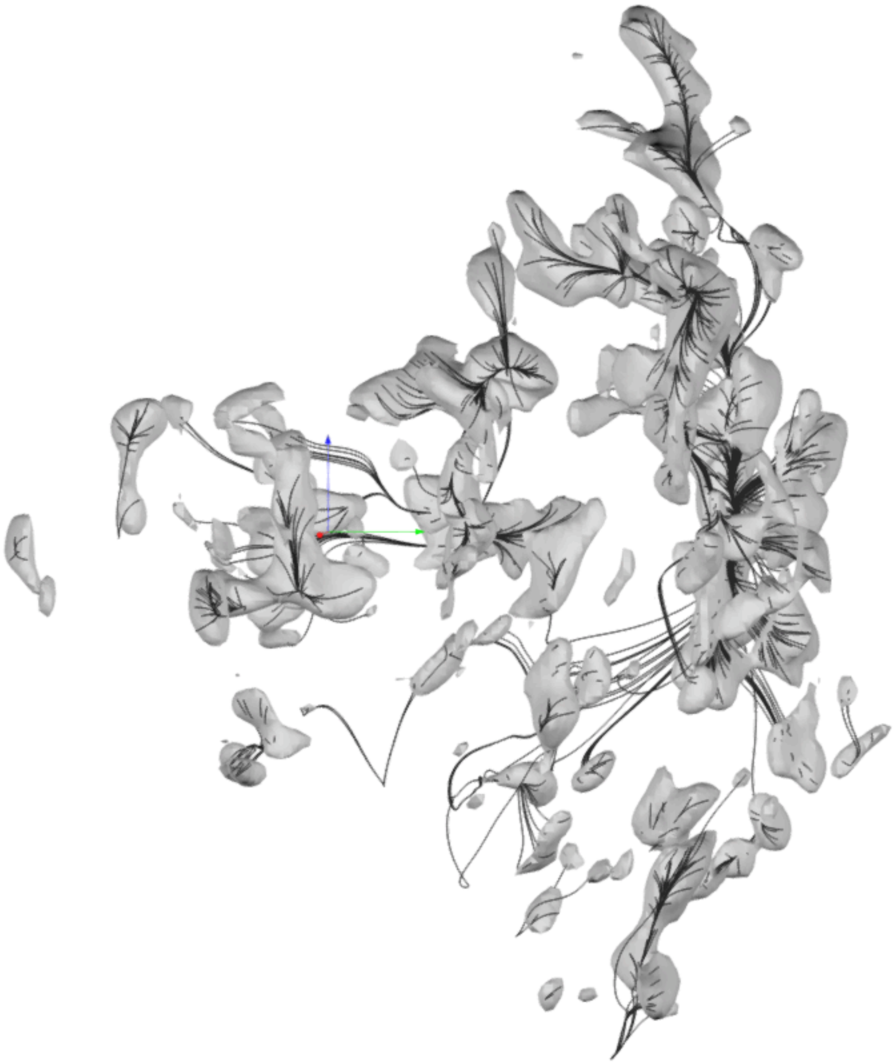
(Aurelien Valade et al., in preparation)



https://sketchfab.com/3d-models/cf4-hamlet-isos-f4e768cabd554ecfb7b6ff265c5fd405

A preliminary look at flow lines seeded from high density regions.

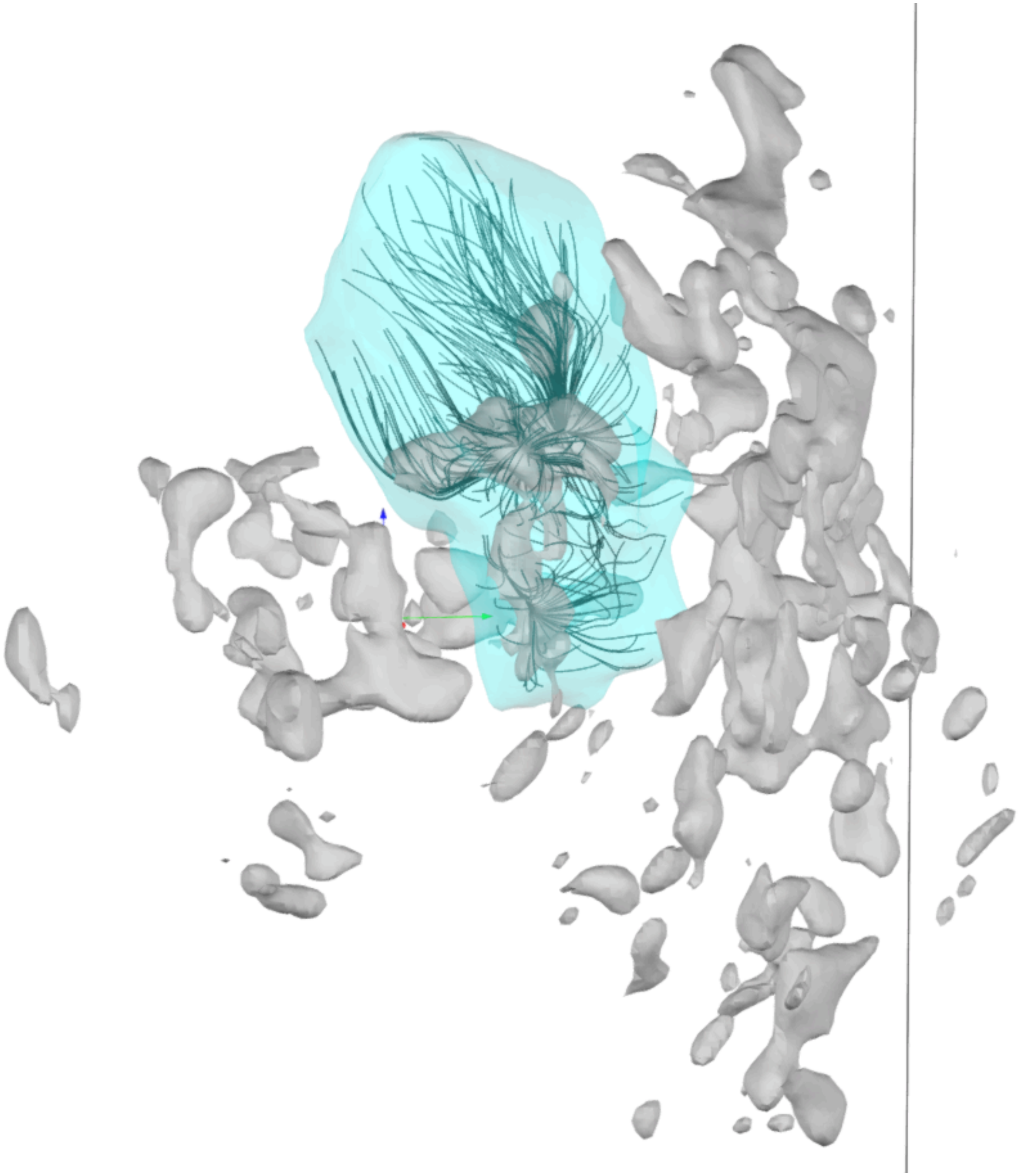
(Aurelien Valade et al., in preparation)



https://sketchfab.com/3d-models/cf4gp-cor-hamlet-g5-final-flowlines-highdenseeds-78d8264aaa65474aa6ab3bc2e9016cf9

A preliminary look at flow lines reaching the Hercules basin of attraction.

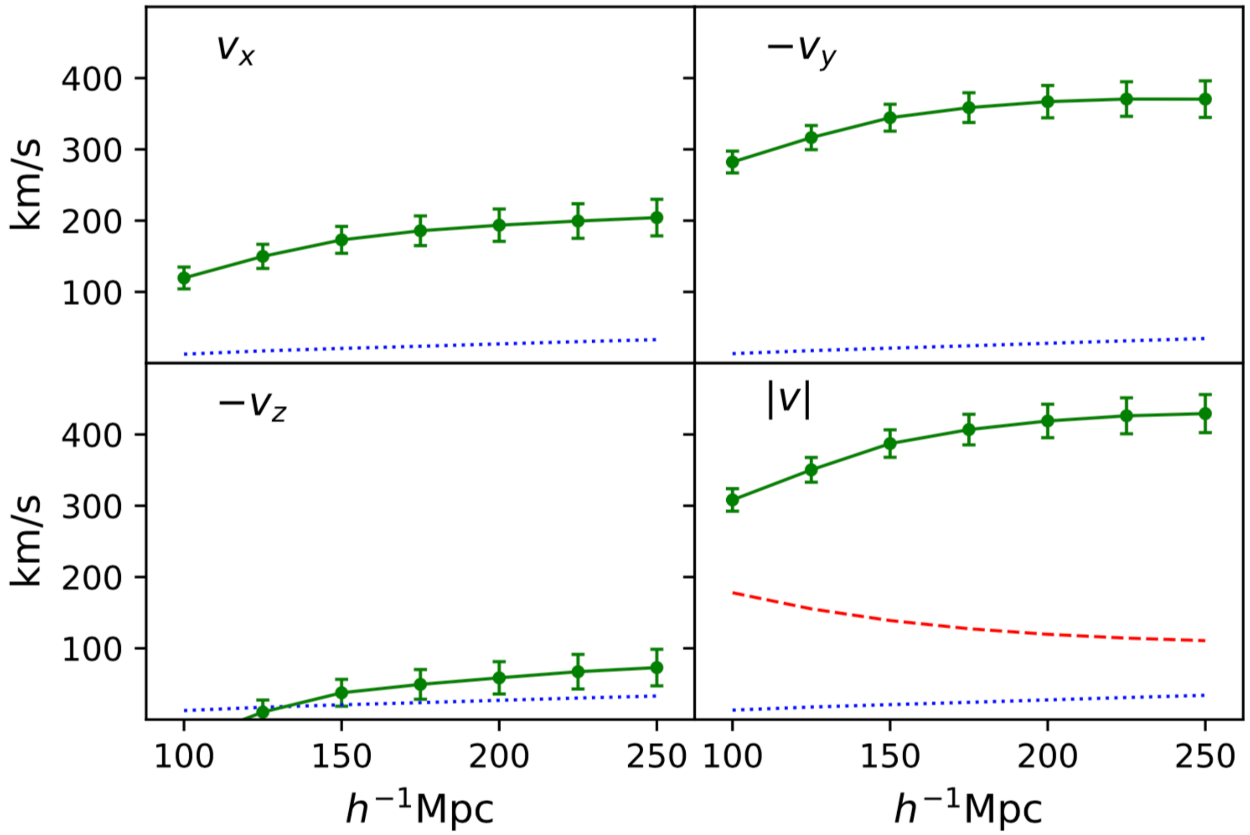
(Aurelien Valade et al., in preparation)



https://sketchfab.com/3d-models/cf4-boa-hercules-48f8dd6f404b4dc9a1651e18bb249bef

Bulk flow

Rick Watkins, Hume Feldman et al.
submitted to MNRAS

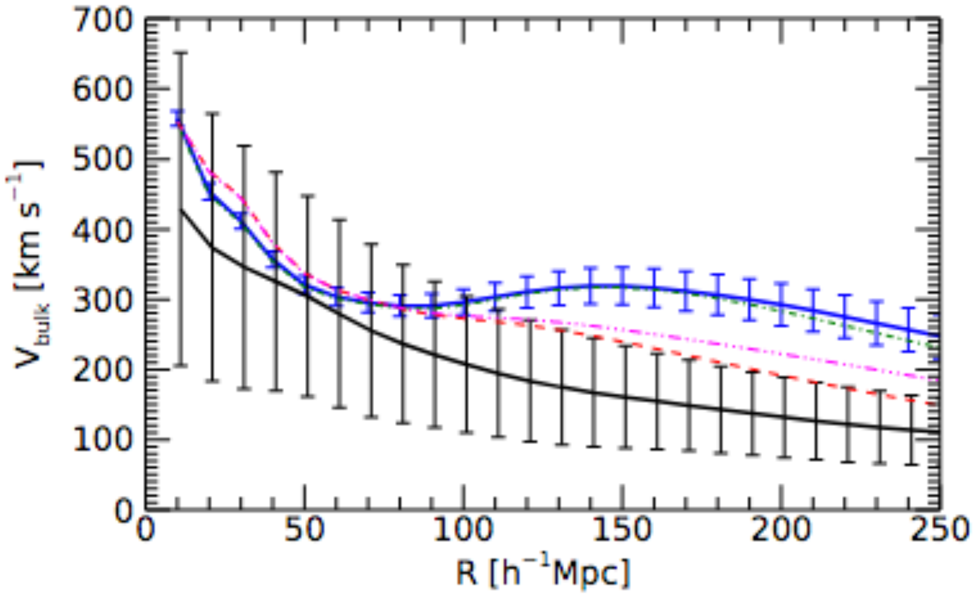


Bulk flow derived using Minimum Variance method

	$R = 150h^{-1}$Mpc	$R = 200h^{-1}$Mpc
Expectation (km/s)	139	120
Bulk Flow (km/s)	387 ± 28	419 ± 36
Direction	$l = 297° \pm 4°$	$l = 298° \pm 5°$
	$b = -6° \pm 3°$	$b = -8° \pm 4°$
χ^2 with 3 d.o.f.	19.34	29.13
Probability	0.023%	0.00021%

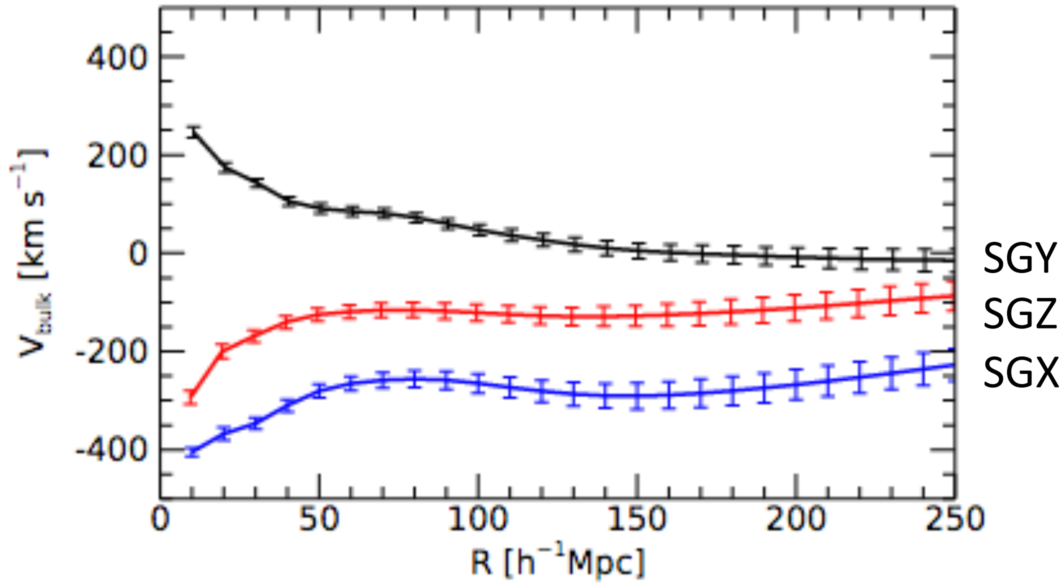
Bulk flow (confidential)

Hoffman et al. in preparation



* Bias Gaussian corrections give peculiar velocities

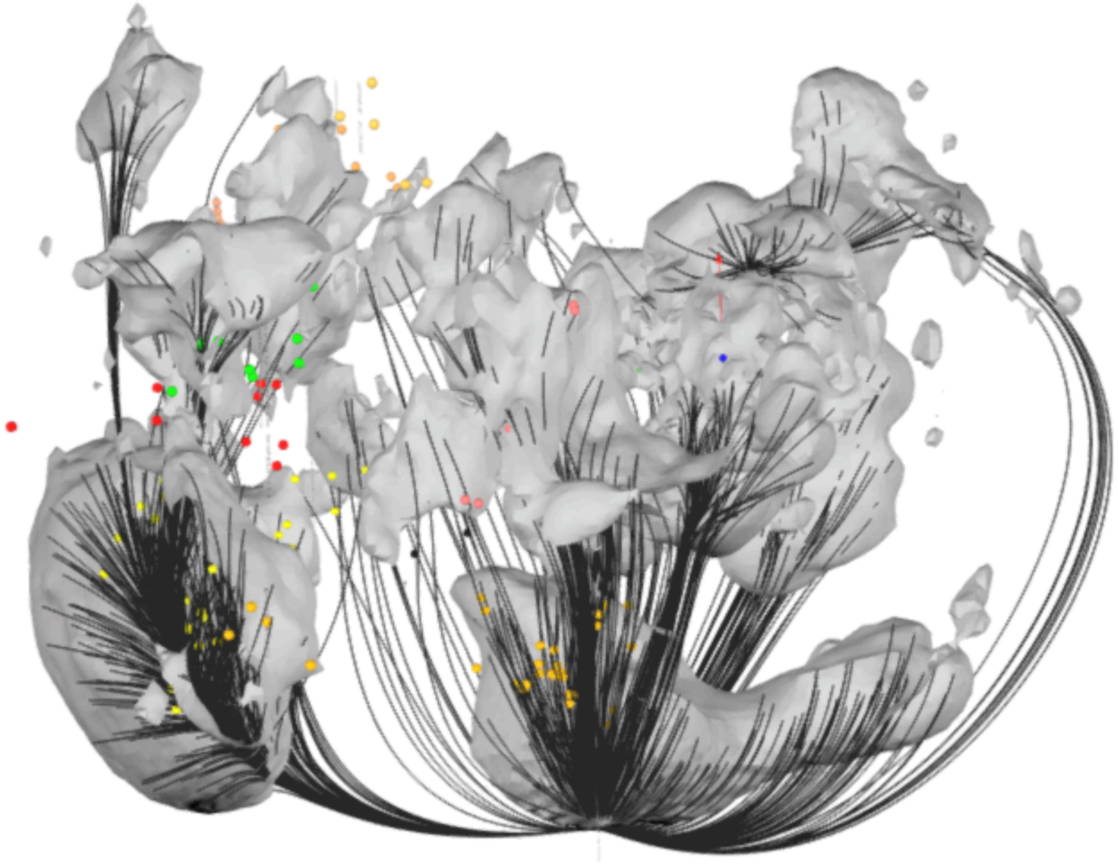
* Linear theory reconstruction of velocities and densities with Wiener filter/Constrained realizations



Bias Gaussian Corrected Wiener Filter Constrained Realization density-velocity reconstruction:

flow lines seeded in high density regions

Hoffman et al. in preparation



https://sketchfab.com/3d-models/cf4r-bgc-flowlines-highdenseeds-superclusters-5e96eebe3a9f488a8d733616d84730c8