Could enhanced structure formation ease large-scale cosmological tensions?

By Alfie Russell

Supervisors: Hongsheng Zhao & Indranil Banik
Summer student: Oscar Cray

University of St Andrews

Introduction

- Large-scale tensions in cosmology
- My simulations
- H_0 and q_0 within a Local Hole
- Local bulk flows and bulk flow reversal

Large-scale tensions in cosmology

Enhanced structure formation

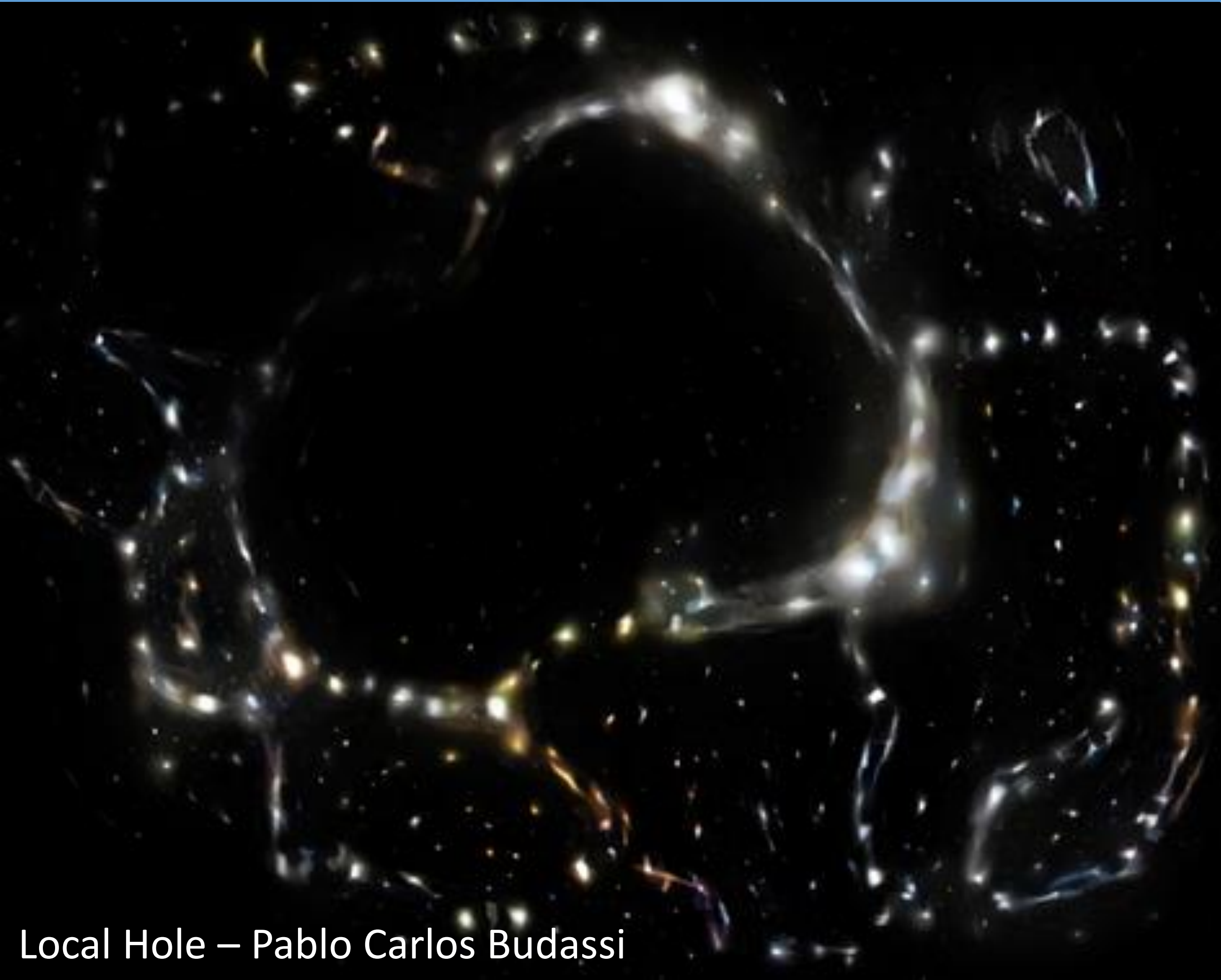
El Gordo cluster - ESO

High local bulk flows (Watkins+ 2023)

High velocity cluster mergers (Asencio+ 2023)

High redshift galaxies (Robertson+ 2023)

Supervoids and the Local Hole



Local Hole – Pablo Carlos Budassi

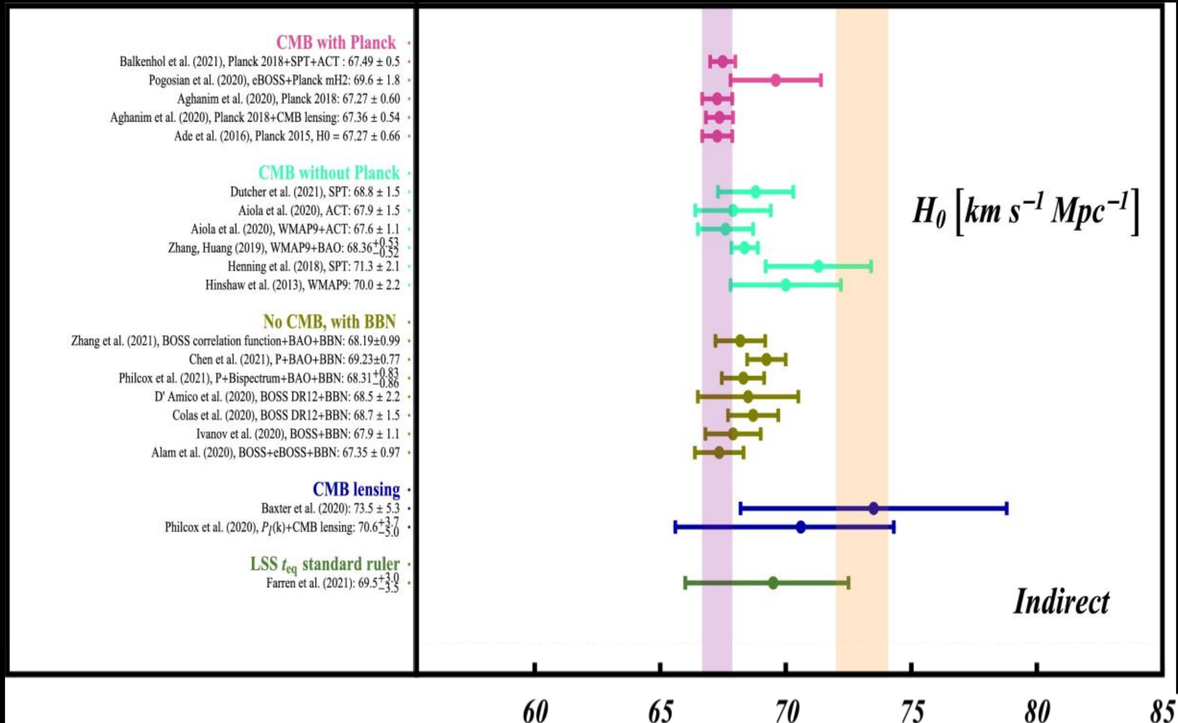
"Local Hole" with 120 Mpc radius observed in near-IR, X-ray and radio (Wong+ 2022; Böhringer+ 2015; Rubart+ 2014)

$\delta = -0.20 \pm 0.02$ (Wong+ 2022)

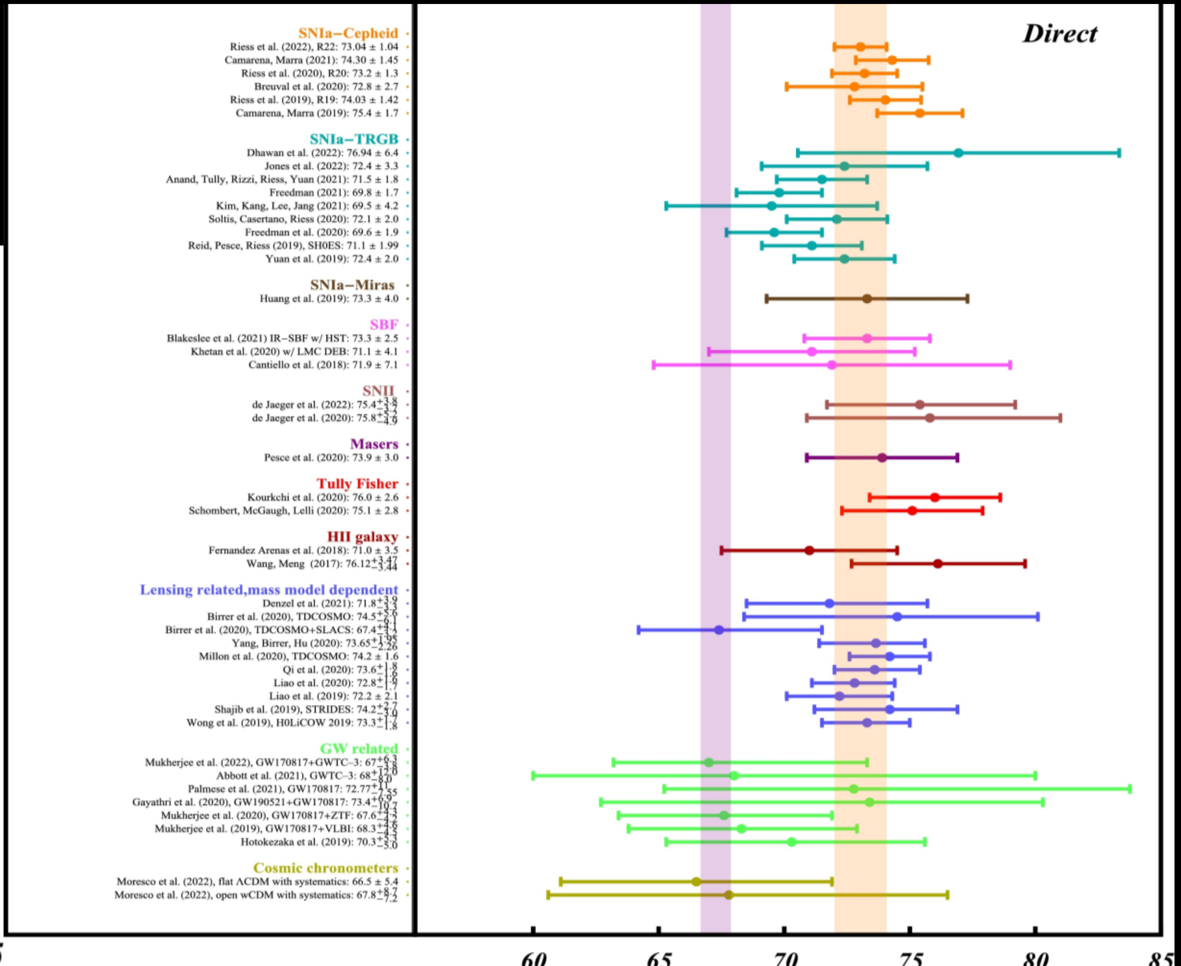
Overproduction of ~100 Mpc voids inferred from Integrated Sachs-Wolfe effect (Kovács+ 2019; Kovács+ 2022)

The Hubble Tension

Early-time and late-time measurements of H_0 disagree!
Related to the Local Hole?



Cosmology Intertwined 2021



How to simulate enhanced structure formation?

Simulating enhanced structure formation

Use the “νHDM” model to simulate enhanced structure formation (Angus 2009)

Self-consistently produces 100s Mpc scale supervoids (Angus+ 2013)

Not a perfect model!

- e.g., does not reproduce observed cumulative halo mass function

Components of νHDM

The ν is the MOND interpolation function, ν(y):

$$\nu\left(\frac{g_N}{a_0}\right) = \frac{1}{2} + \sqrt{\frac{1}{4} + \frac{a_0}{g_N}} \quad \rightarrow \quad g_{tot} = \nu\left(\frac{g_N}{a_0}\right) g_N$$

$$a_0 = 1.2 \times 10^{-10} ms^{-2}$$

The HDM is Hot Dark Matter (11eV sterile neutrinos)

Assume FRLW background metric and use Planck 2018 parameters

Comparisons and vantage points

Useful to know how changing the model changes results, so run comparison simulations

- ΛCDM – Newtonian gravity + Cold Dark Matter initial conditions
- ΛHDM – Newtonian gravity + Hot Dark Matter initial conditions
- νCDM – MONDian gravity + Cold Dark Matter initial conditions

Use "Vantage points" to probe observables

- Split simulation box into 25^3 smaller chunks
- Search for a reference particle in each chunk to measure observables from
- Particles roughly correlate with where galaxies should be

Simulation parameters

Cosmological collisionless N-body simulations using "Phantom of Ramses" code (Teyssier 2002; Lüghausen 2014)

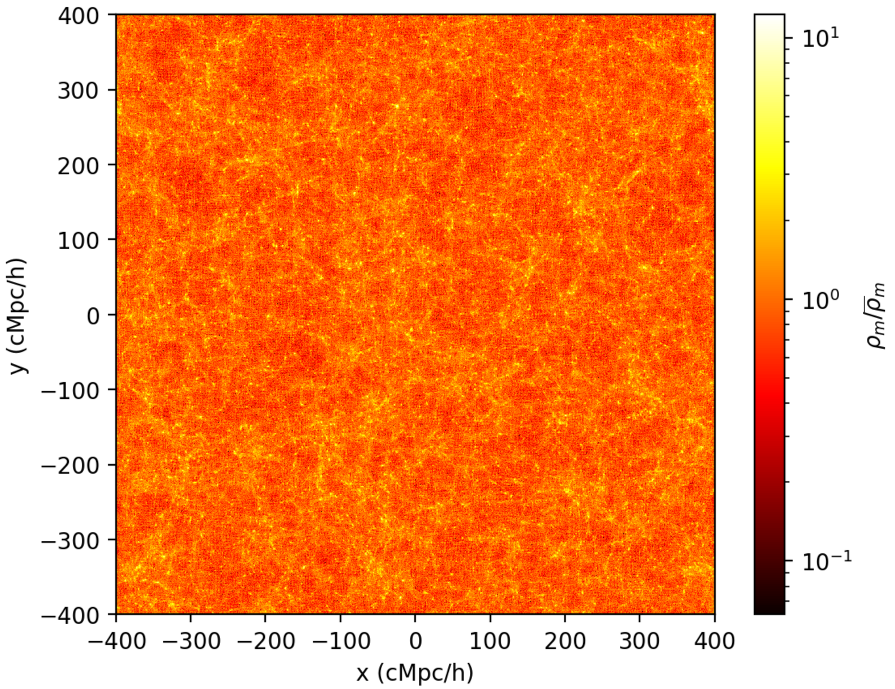
$$\nabla \cdot \overrightarrow{g_{tot}} = \nabla \cdot \left[\nu \left(\frac{g_N}{a_0} \right) \overrightarrow{g_N} \right]$$

800 cMpc/h box length and 256^3 particles

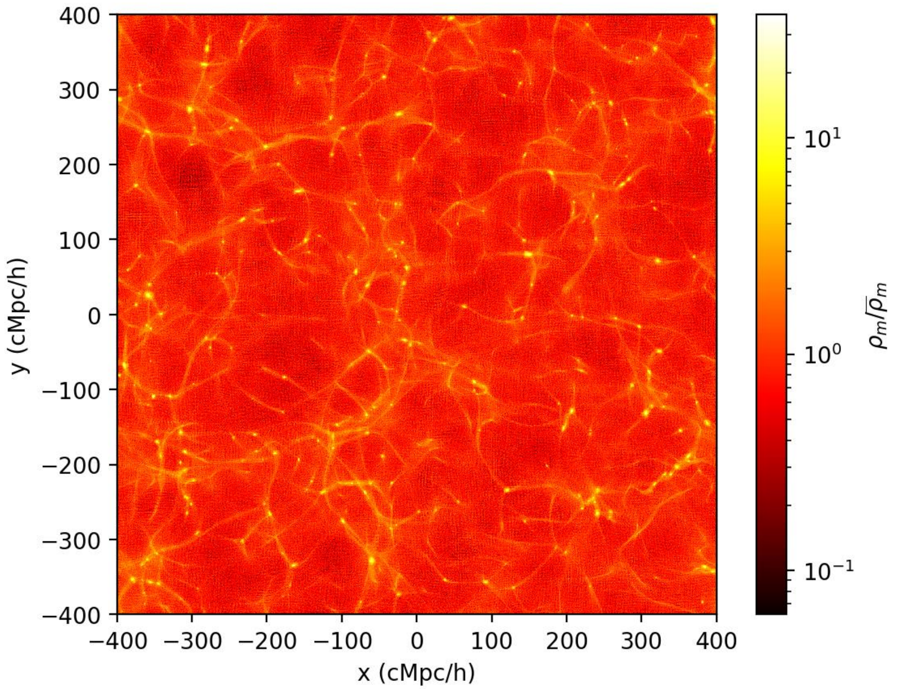
Initialised at z=199 and initial conditions produced with CAMB and MUSIC (https://bitbucket.org/SrikanthTN/bonnpor/src/master/)

For smaller scale hydrodynamical simulations of vHDM see Wittenburg+ 2023

ΛCDM



ΛHDM



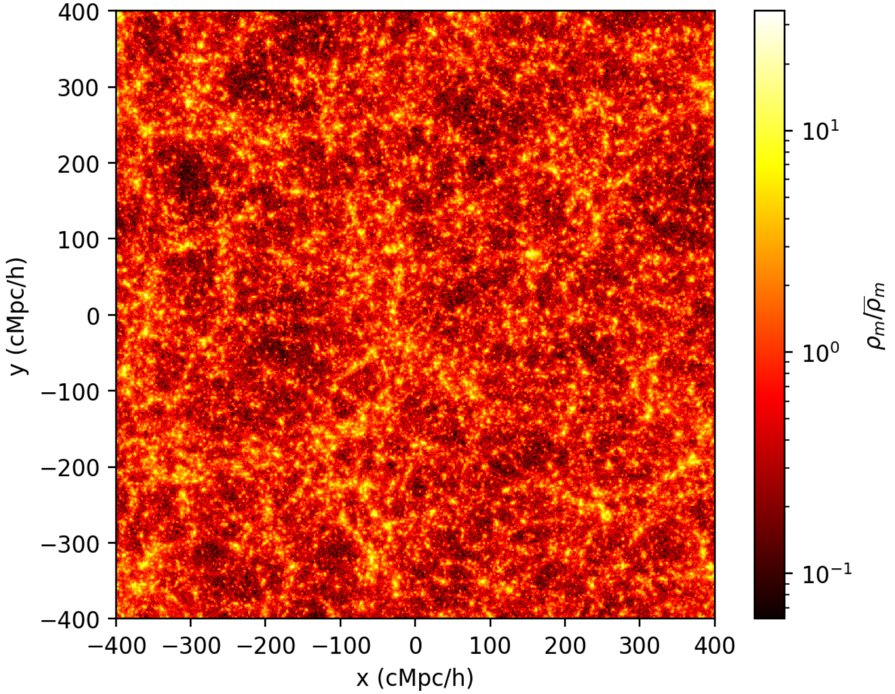
Density maps

Projected through whole box at $z = 0$

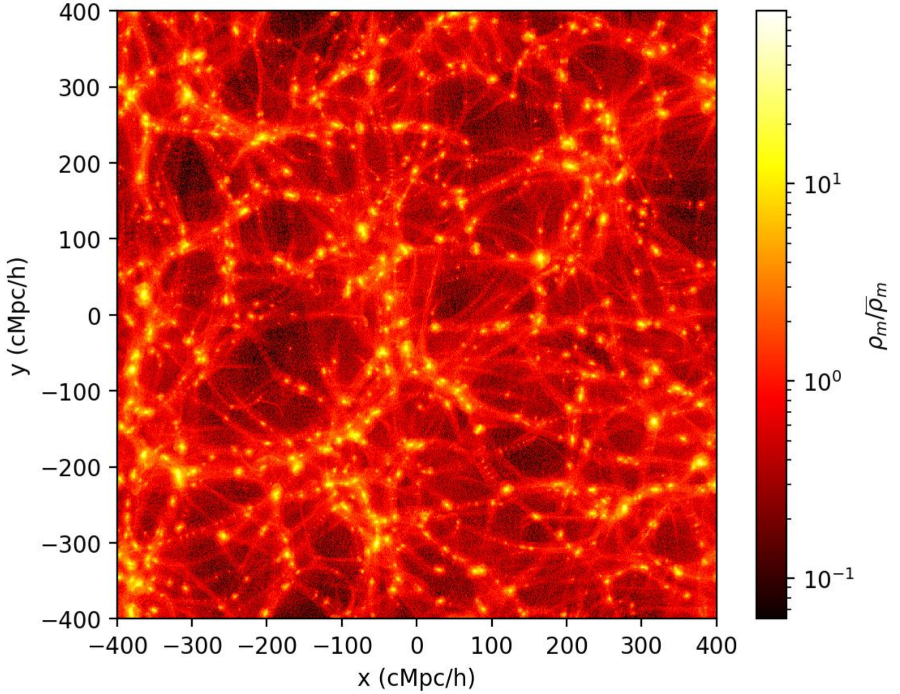
Large-scale structure enhanced by HDM

All structure enhanced by MOND gravity

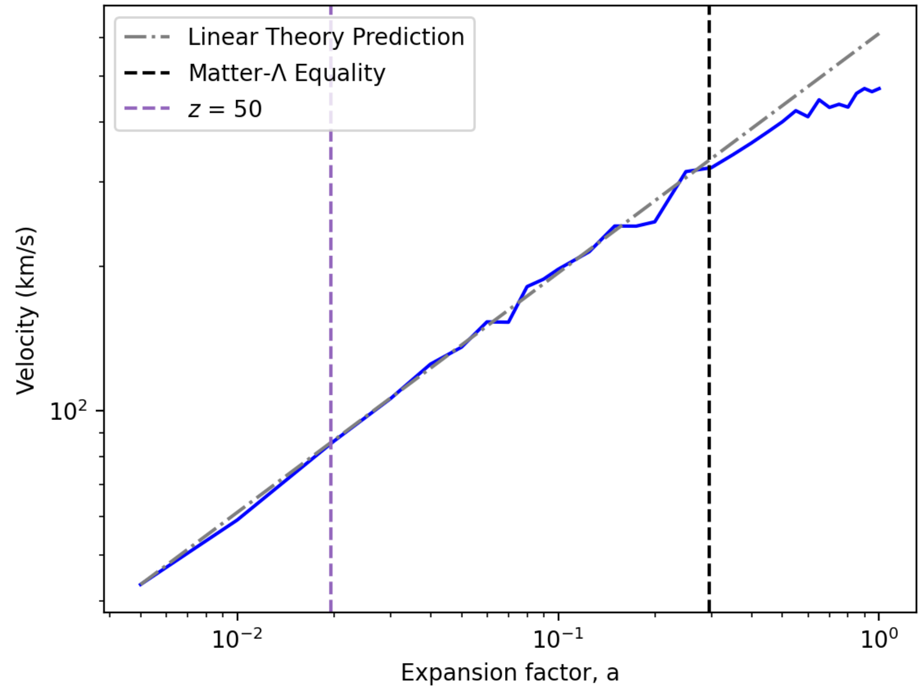
νCDM



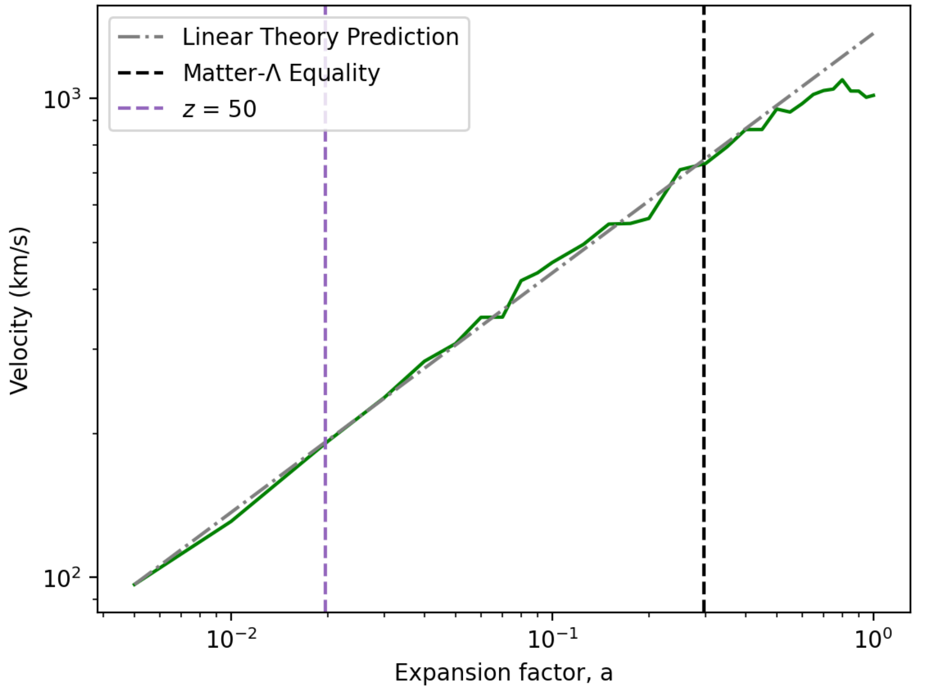
νHDM



ΛCDM



ΛHDM

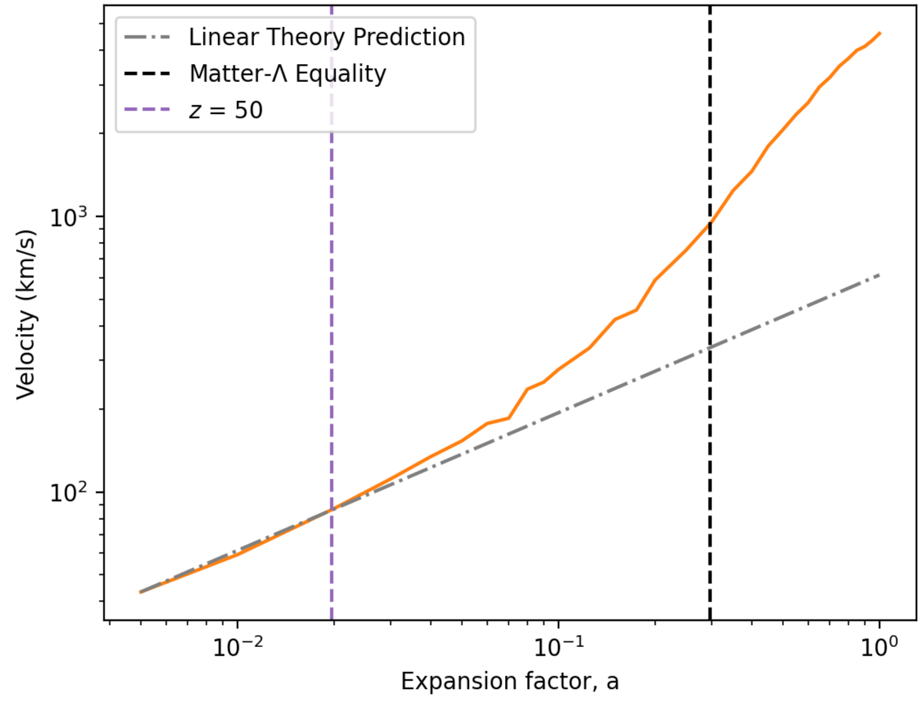


Median peculiar velocity growth

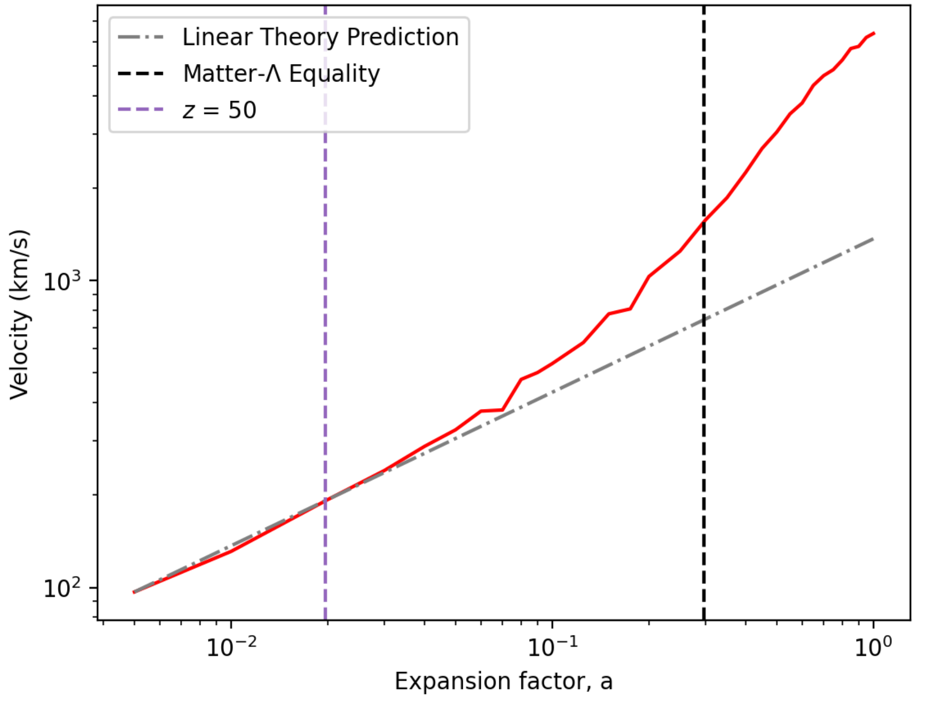
All follow Newtonian linear theory at early-times

MOND enhancement begins once background density low enough (z = 50)

νCDM

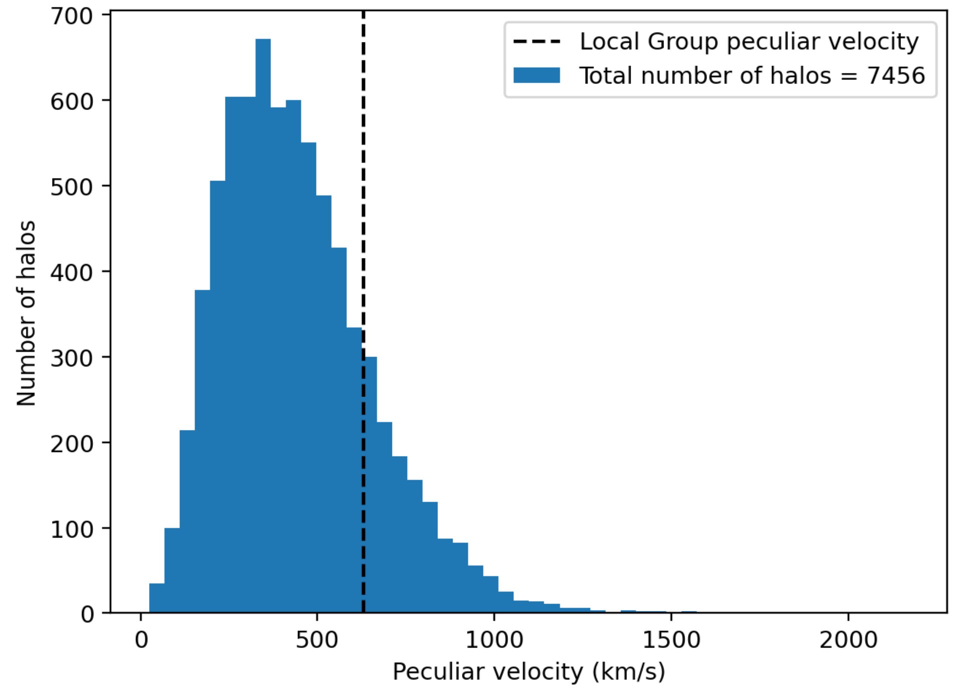


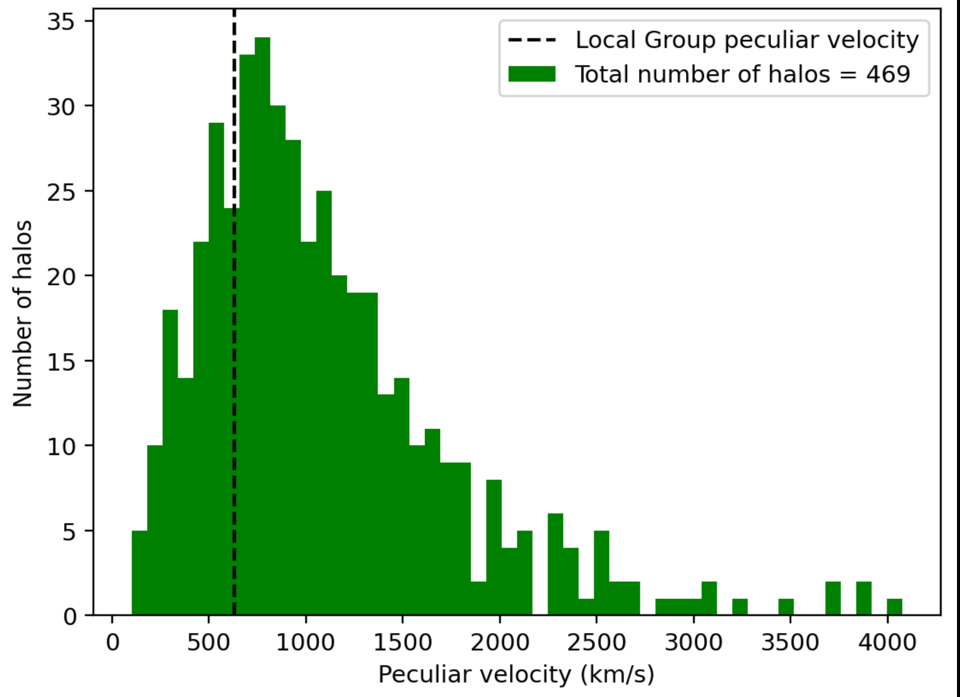
νHDM



ΛCDM ΛHDM

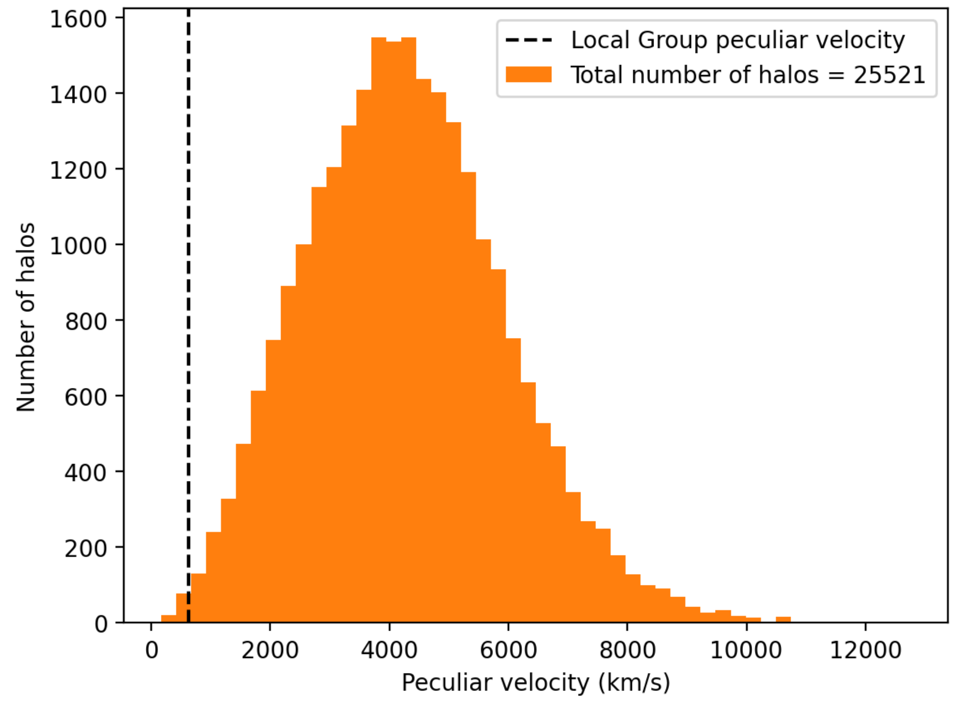
Peculiar velocity distributions ($z = 0$)

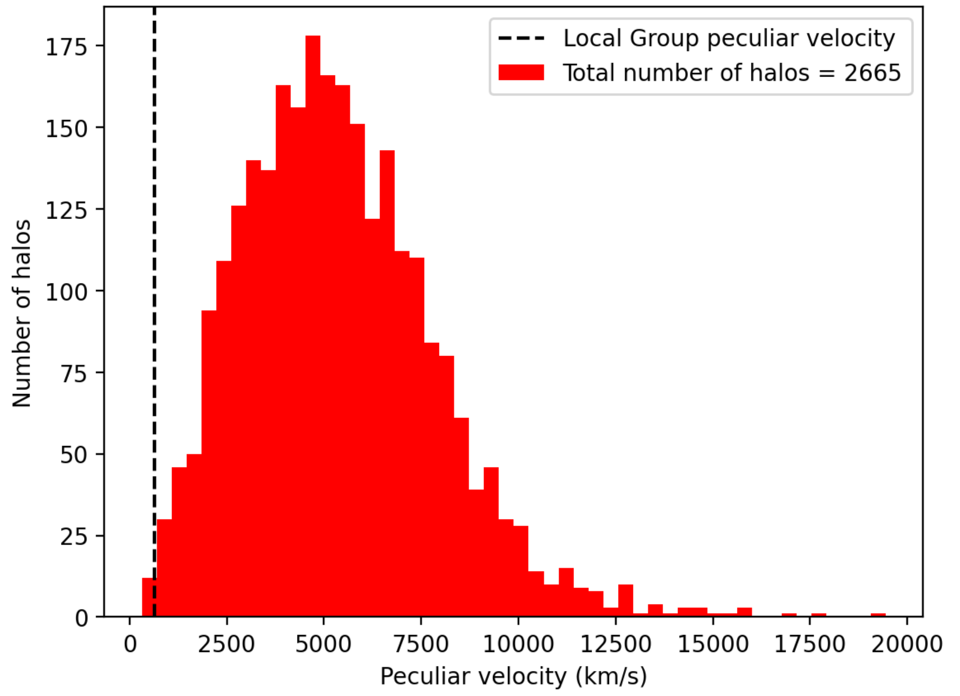




Slight enhancement due to HDM initial conditions

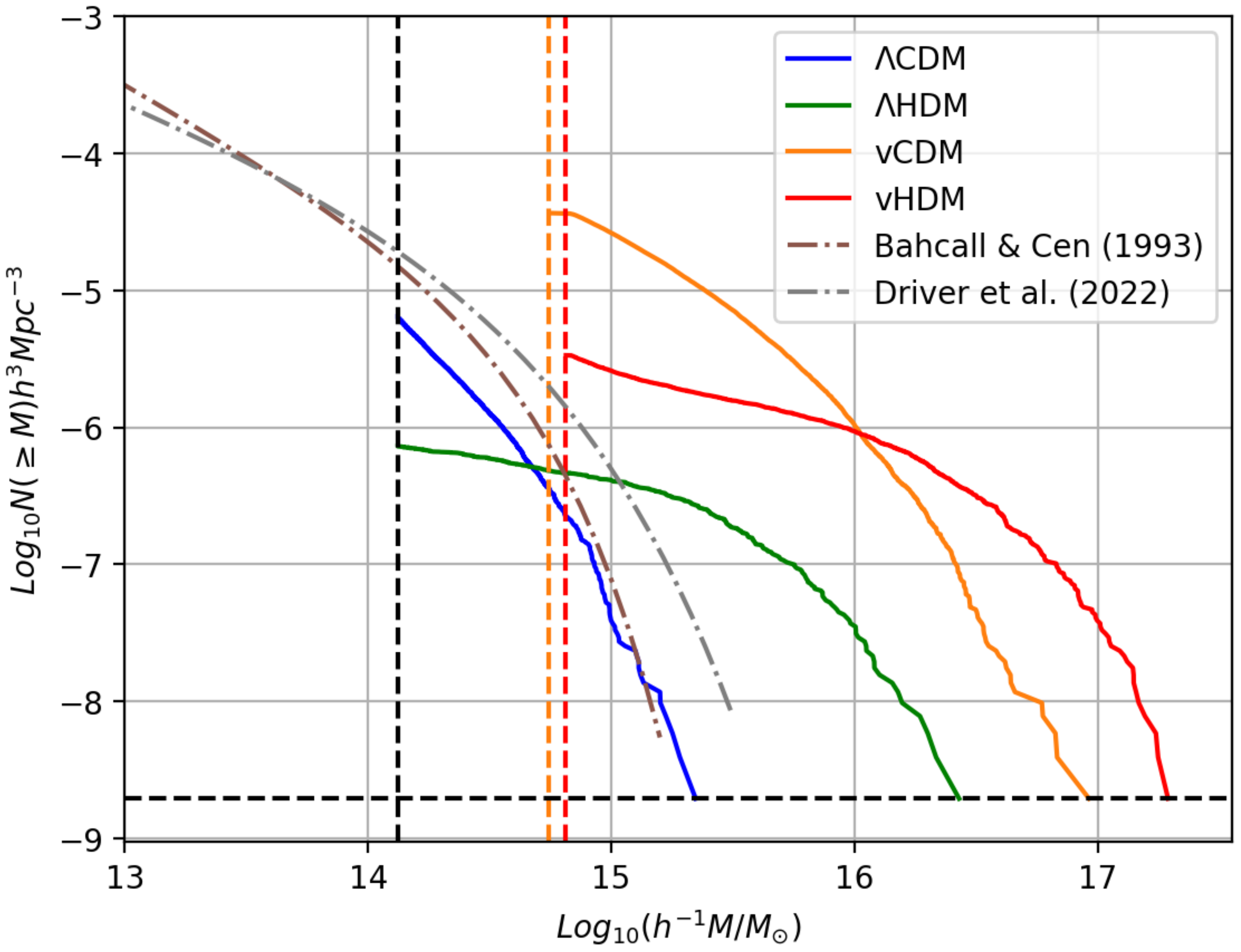
Major enhancement due to MOND gravity





νCDM νHDM

Cumulative Halo Mass Function



$$M_{180} \equiv 180\rho_{crit}\left(\frac{4}{3}\pi R_{180}^3\right)$$

$$M_N = v\left(\frac{g_N}{a_0}\right)M_{180}$$

Scaling relations preserved when changing gravity law, normalisation is modified

H_0 and q_0 within a Local Hole

The local deceleration parameter: an oddity

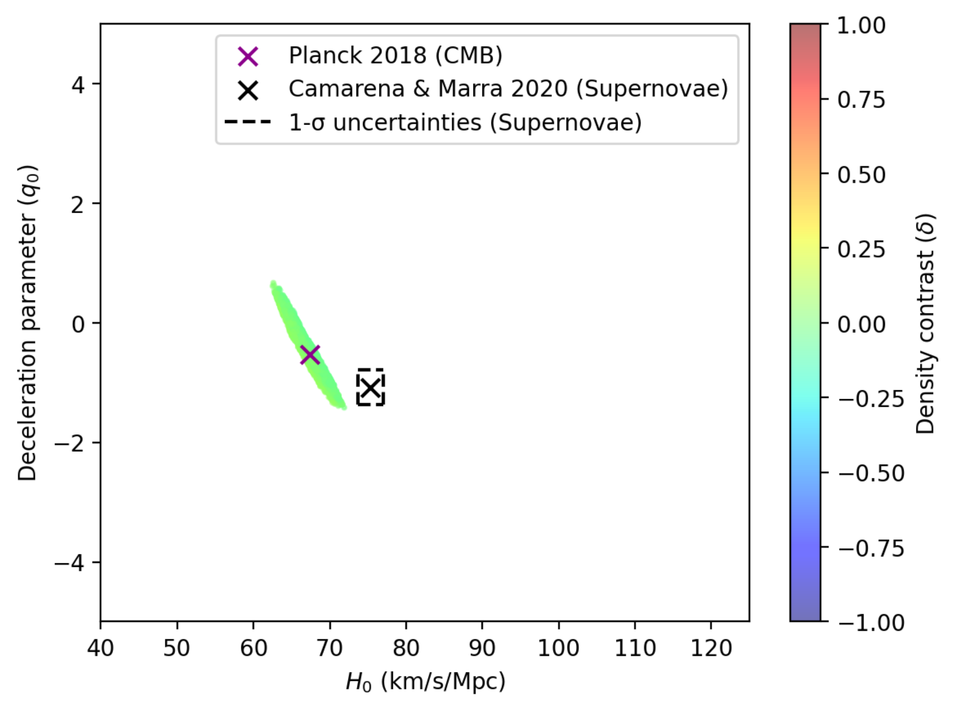
Deceleration parameter is defined as $q \equiv -\frac{\ddot{a}a}{\dot{a}^2}$

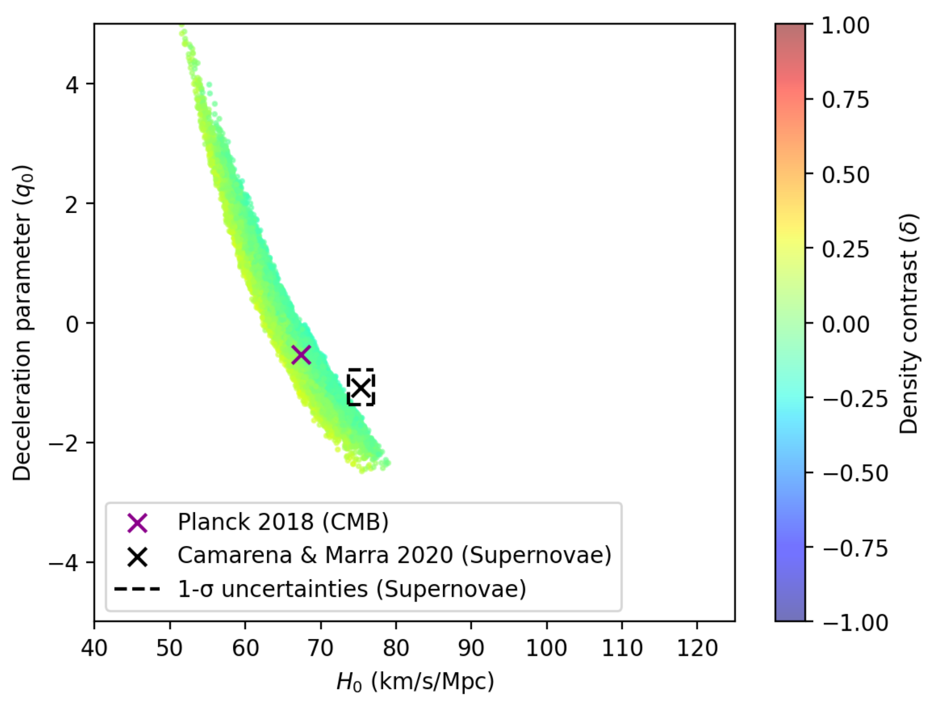
Should find $q_0 = \frac{1}{2}\Omega_m - \Omega_\Lambda \rightarrow q_0 = -0.53$ with Planck 2018

Local measurements with supernovae find $q_0 = -1.08 \pm 0.29$ (Camarena & Marra 2020)

ΛCDM ΛHDM

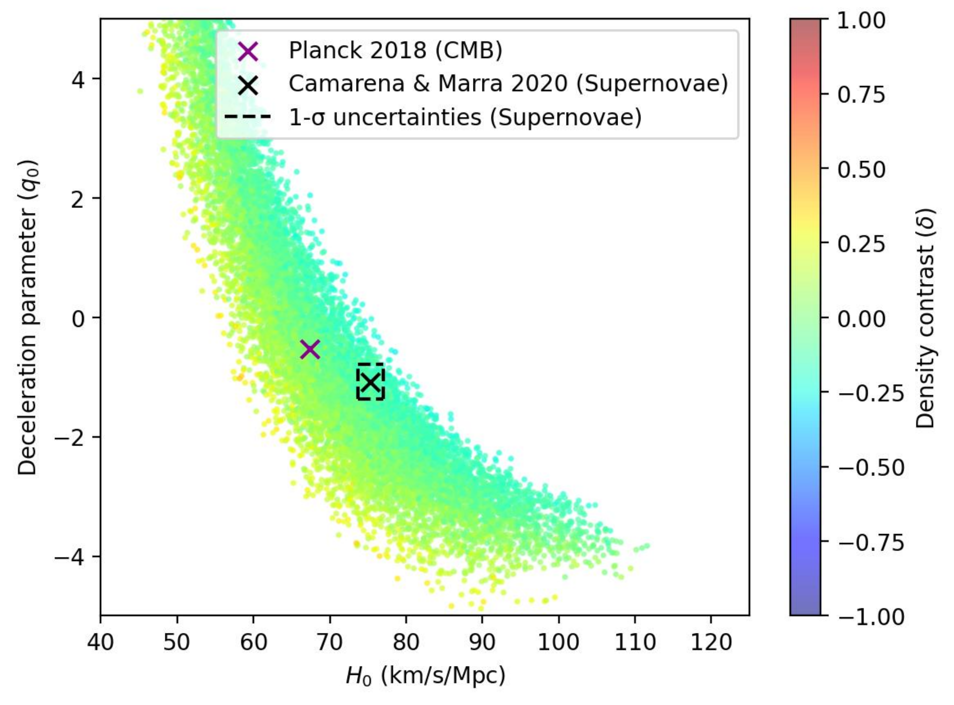
q_0 vs H_0

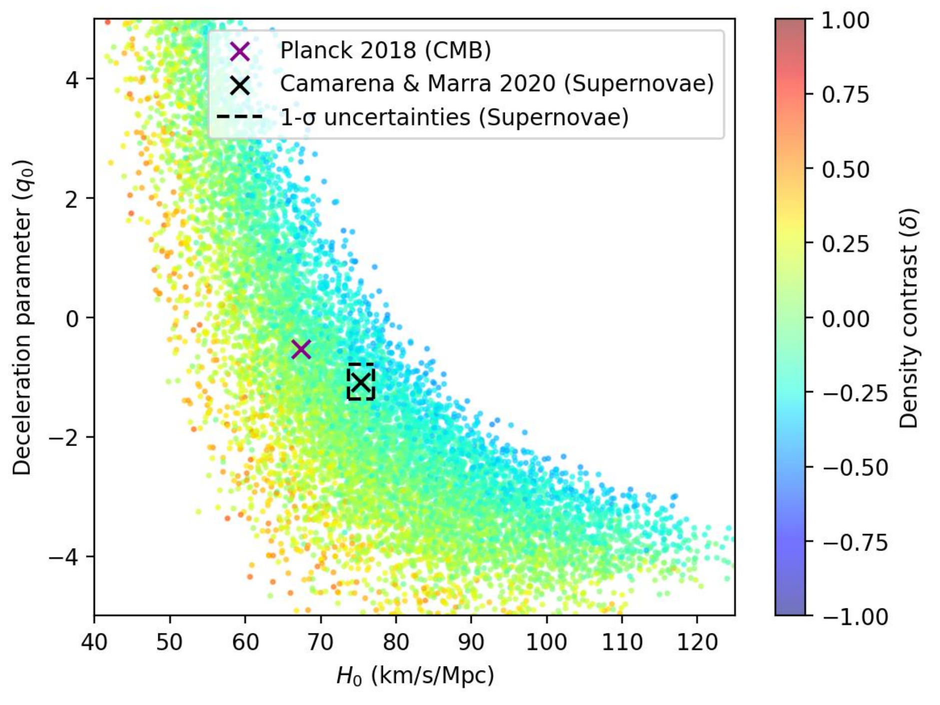




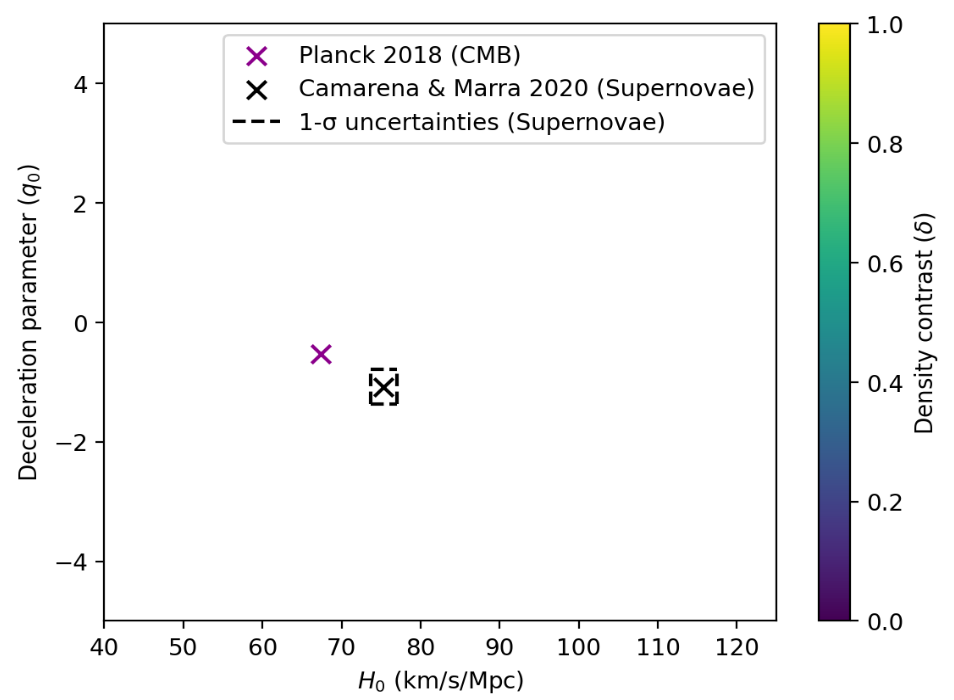
Colour shows local density contrast

"Bands" of density contrasts visible

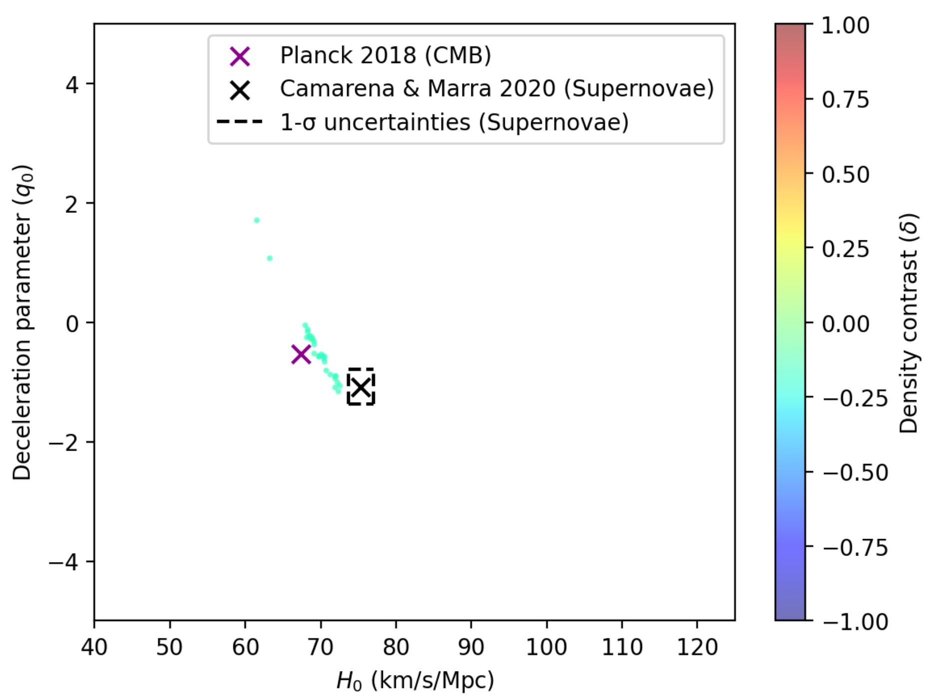




νCDM νHDM



ΛCDM ΛHDM



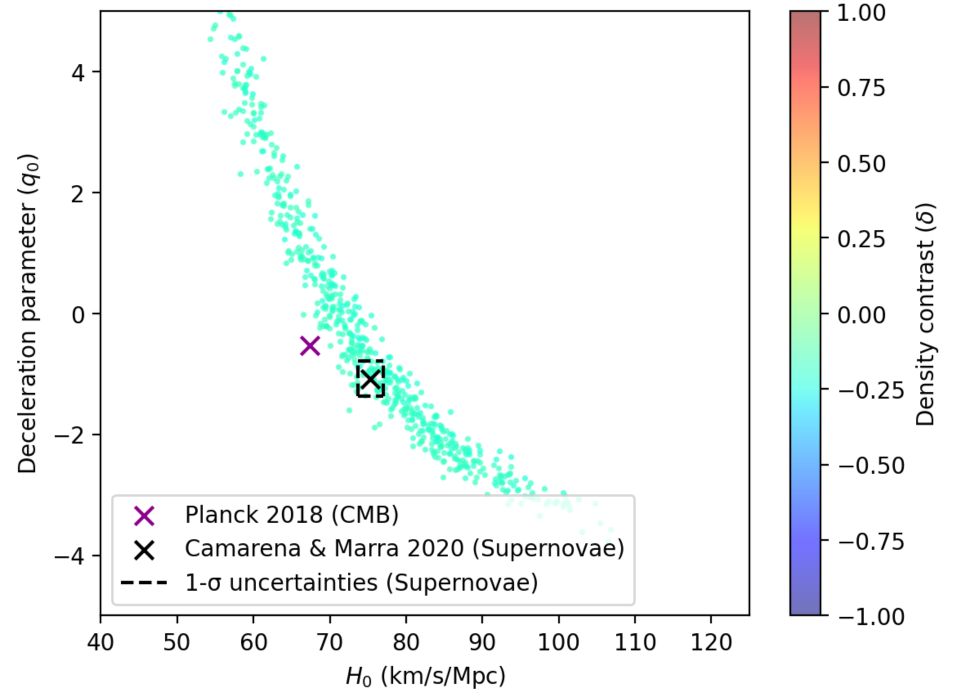
q_0 vs H_0
$(-0.24 < \delta < -0.16)$

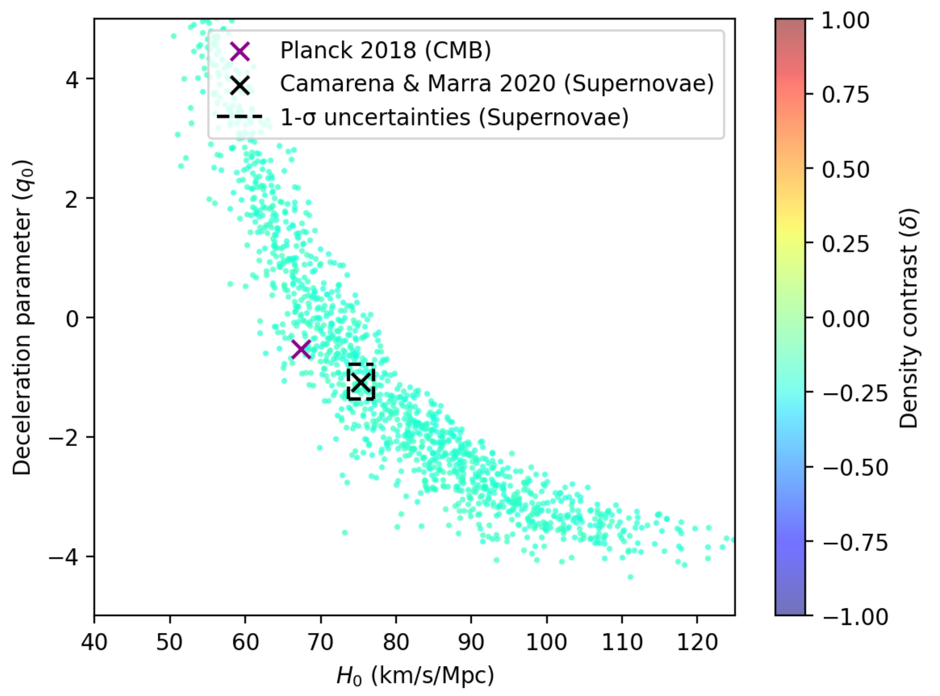
Limit to Local Hole density contrast

δ-band passes straight through observed point

Seems to be link here – Local Hole analogues with H_0 also recover the local q_0

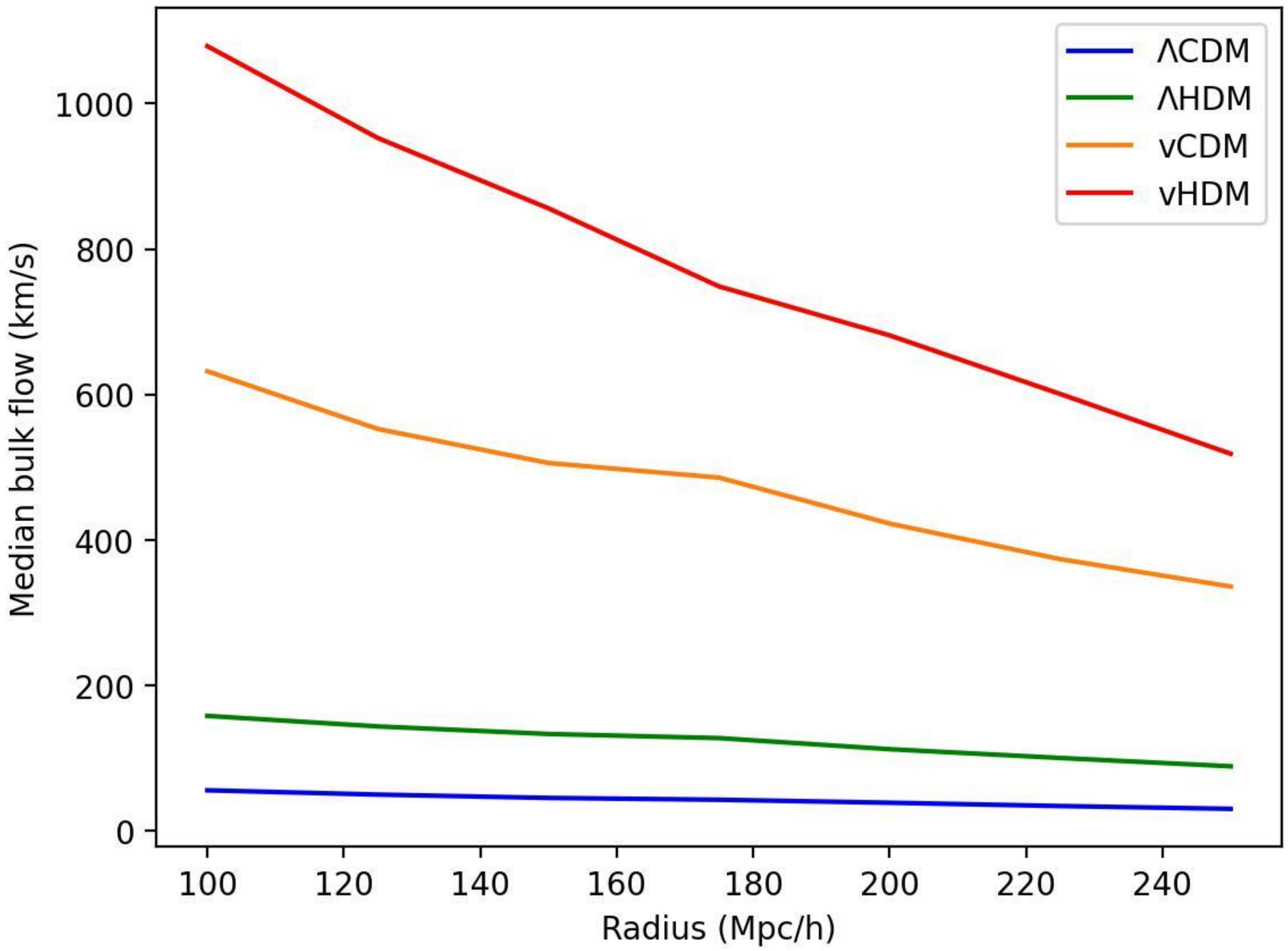
νCDM νHDM





Bulk flows

The local bulk flows



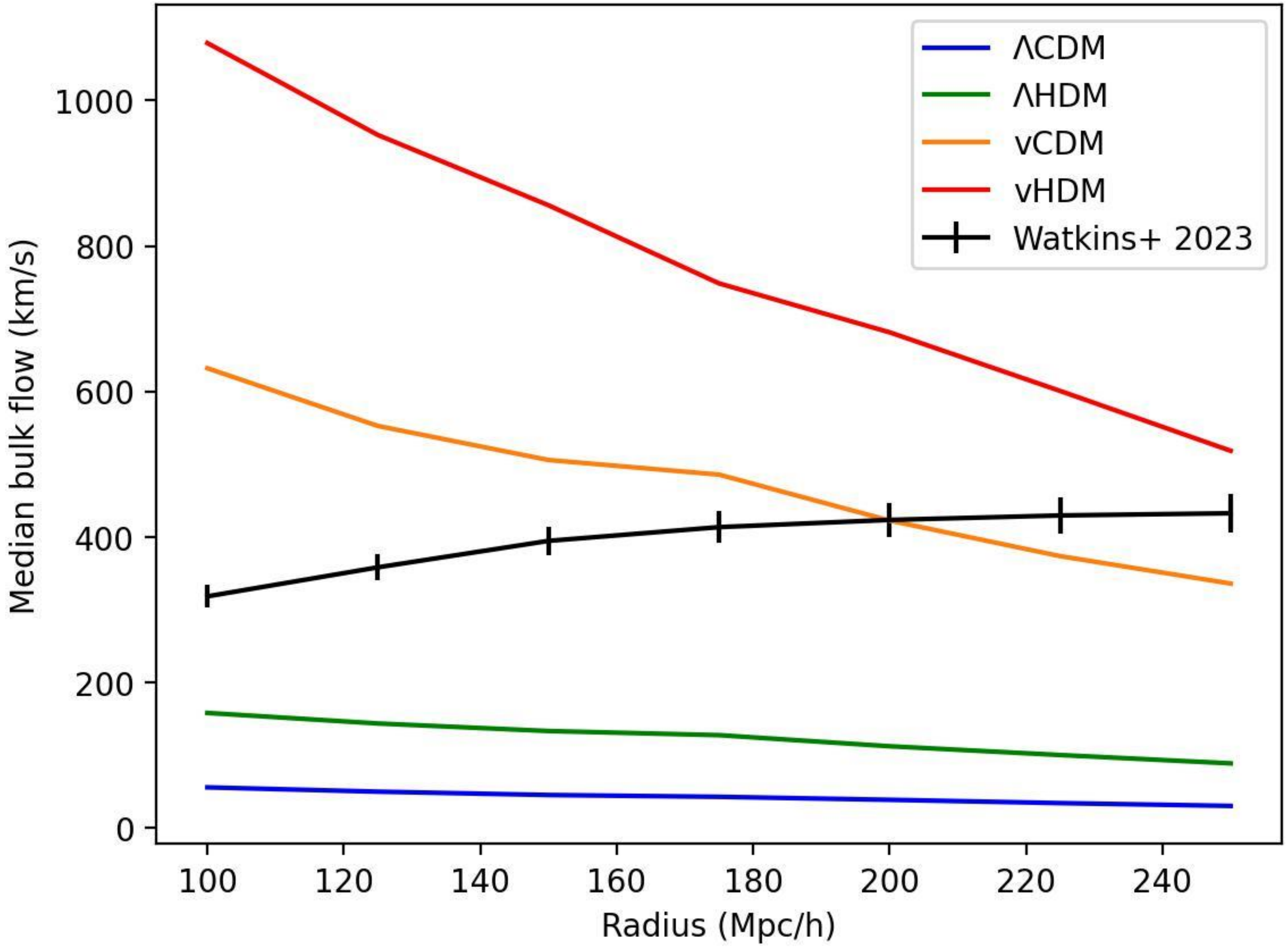
Bulk flows are average velocity of matter within a sphere around us

Measured with line-of-sight velocities

$$U_i = \frac{1}{V} \int_V \hat{r}_i \, v_{los} \, w(r) \, d^3x$$

Expect to fall at larger radii due to homogeneity and isotropy

The local bulk flows



Observed to rise, not fall as we expect

430 km/s peak!!!!

Watkins+ 2023 report a 4.8σ tension with ΛCDM expectations (at 200 Mpc/h)

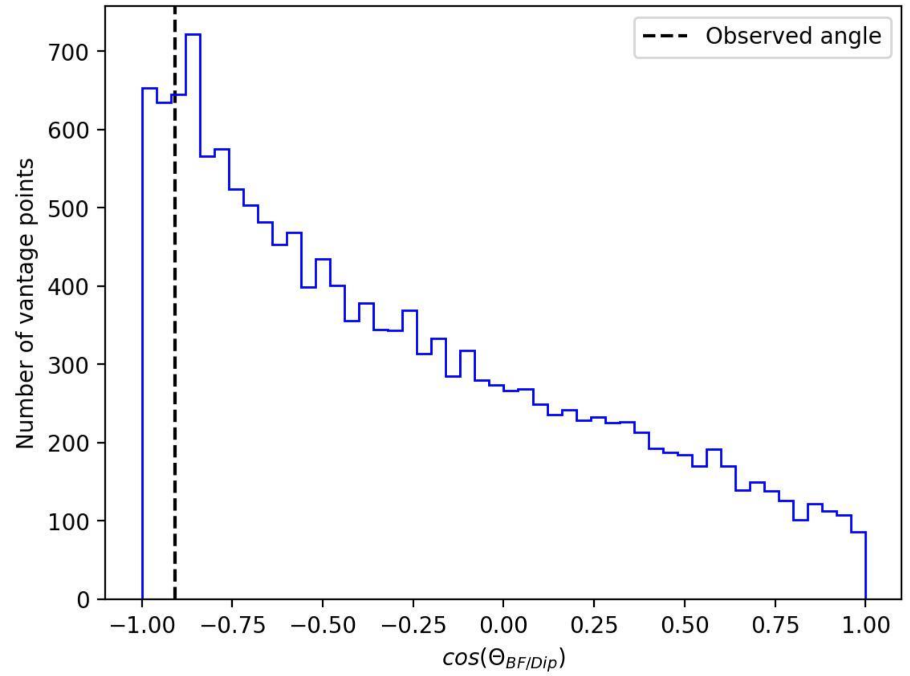
Reversing bulk flows?

Watkins+ 2023

- Measure bulk flow up to 250 Mpc/h
- Rises to 430 km/s
- Direction: $l = 298°$, $b = -8°$

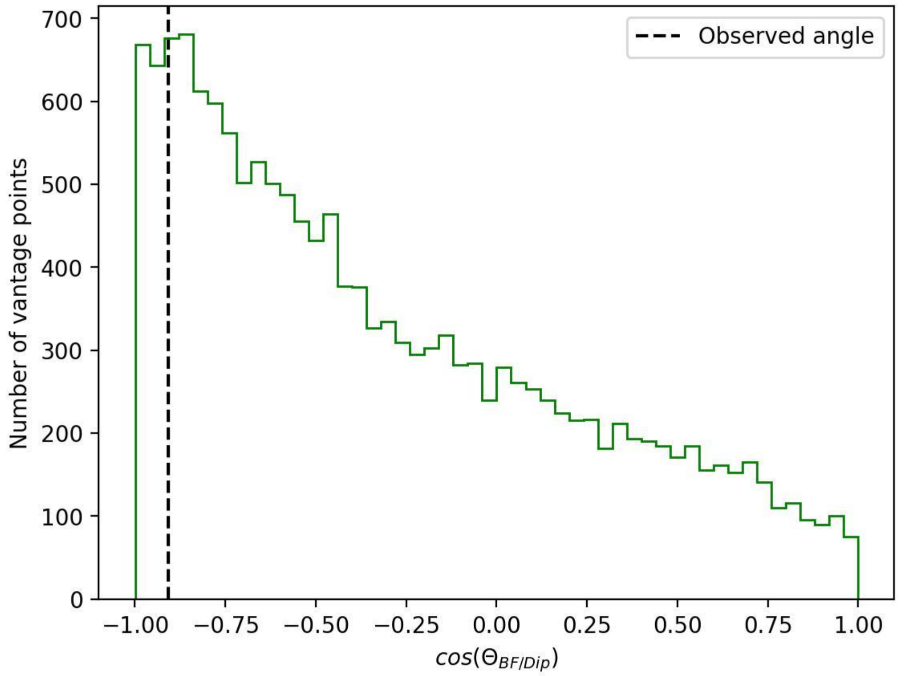
Migkas+ 2021

- Measured 9% H_0 dipole at 500 Mpc/h with clusters
- If caused by a bulk flow has magnitude of 900 km/s!!!
- Direction: $l = 93°$, $b = 11°$, almost opposite to Watkins+ 2023



ΛCDM

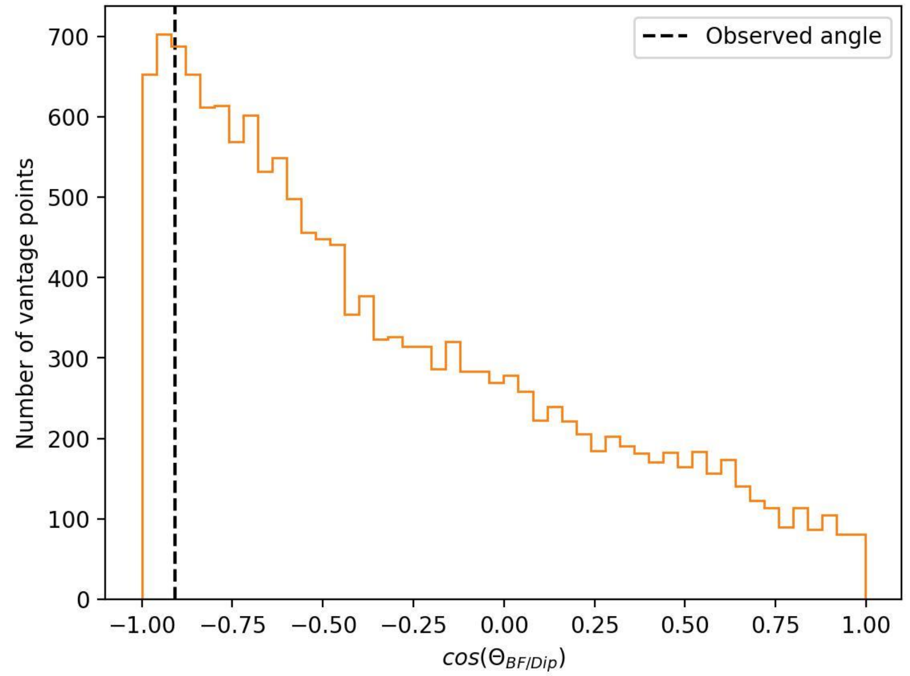
ΛHDM



Frequency of bulk flow reversal

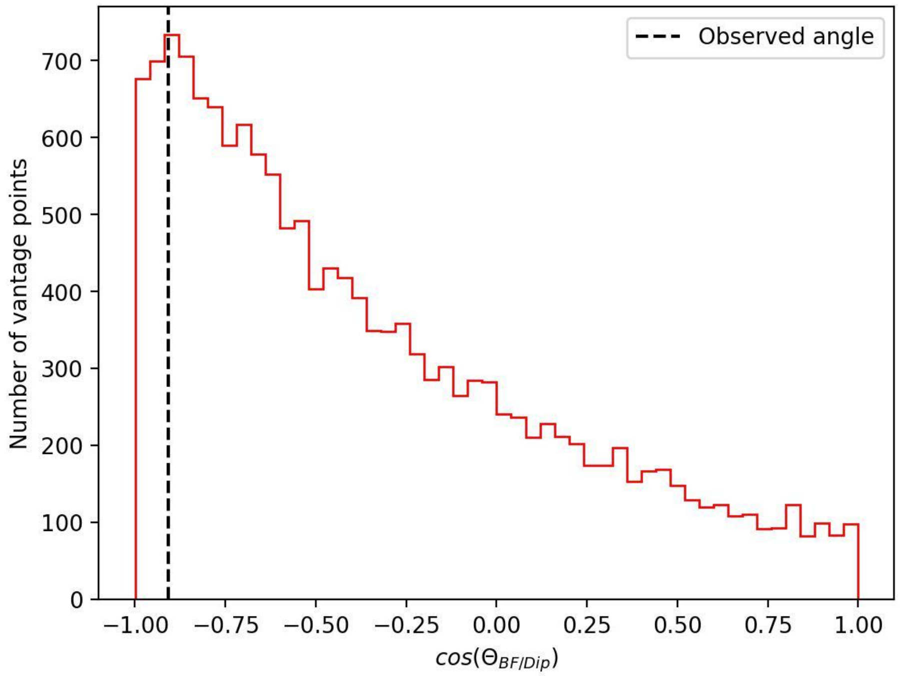
Angle found by dot product of bulk flow directions at 200 Mpc/h and 500 Mpc/h

Bulk flow reversal is common in all simulations!



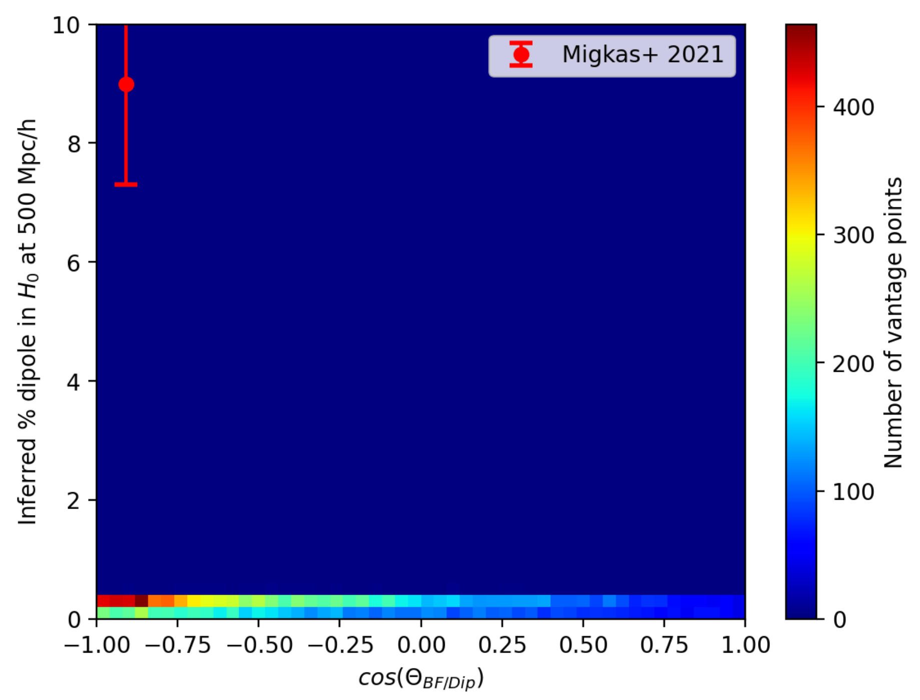
νCDM

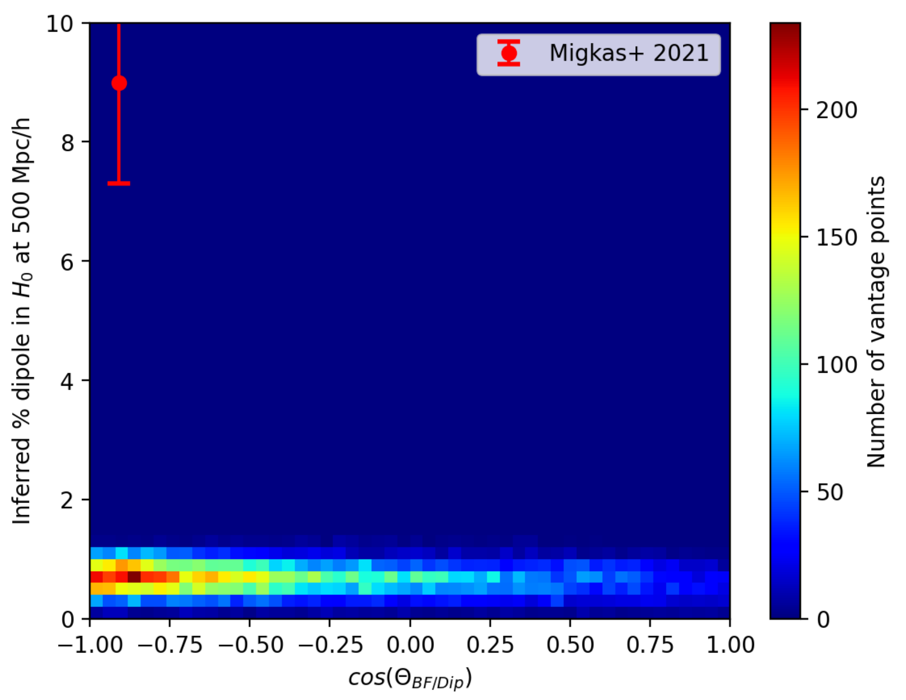
νHDM



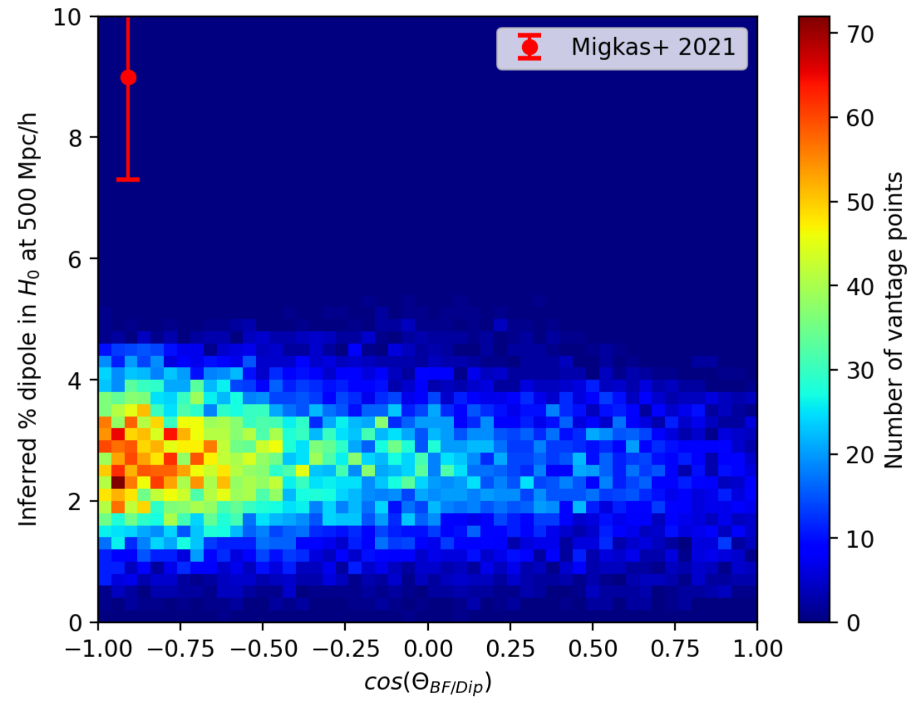
ΛCDM ΛHDM

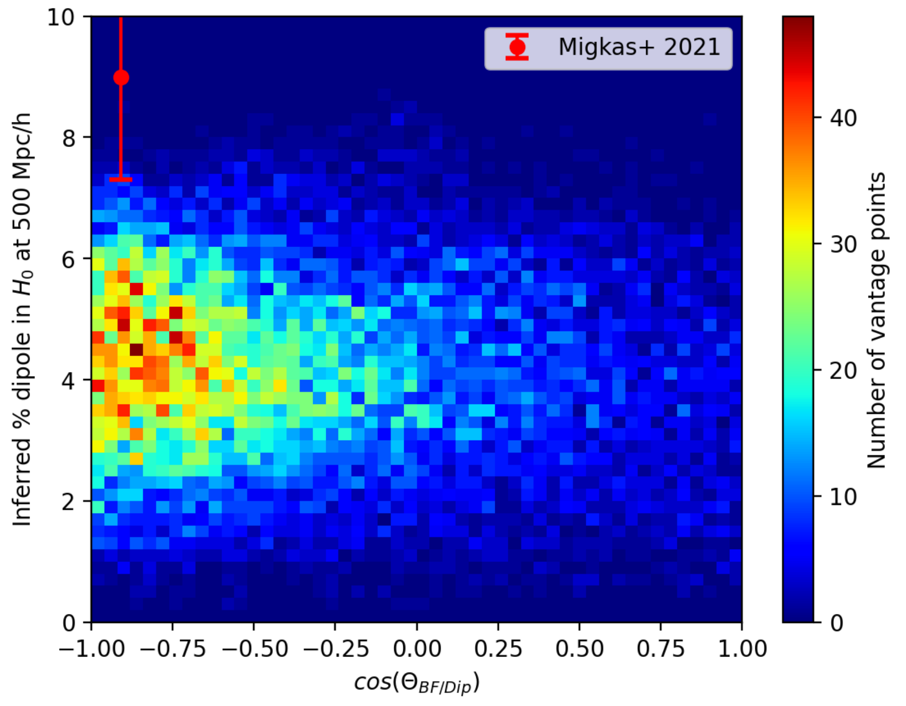
Inferred Hubble dipole and bulk flow reversal



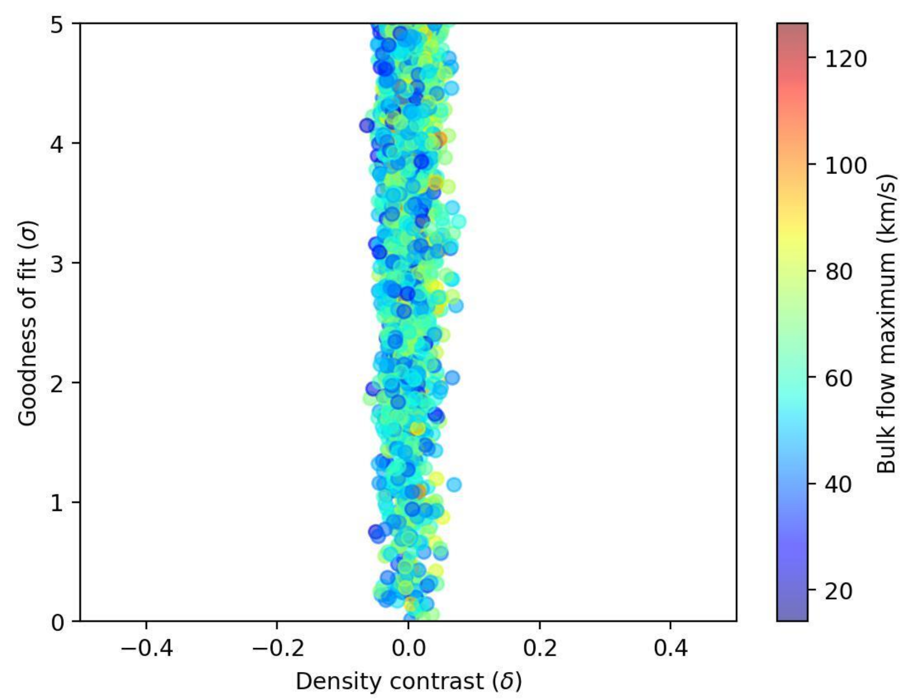


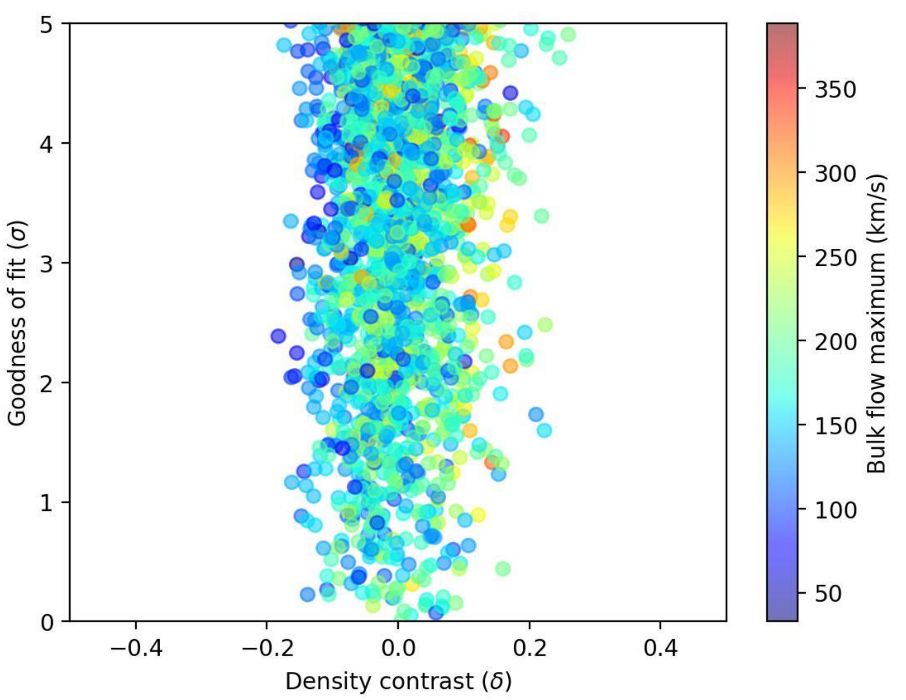
Bulk flows alone struggle to explain observed Hubble dipole in all simulations





νCDM νHDM





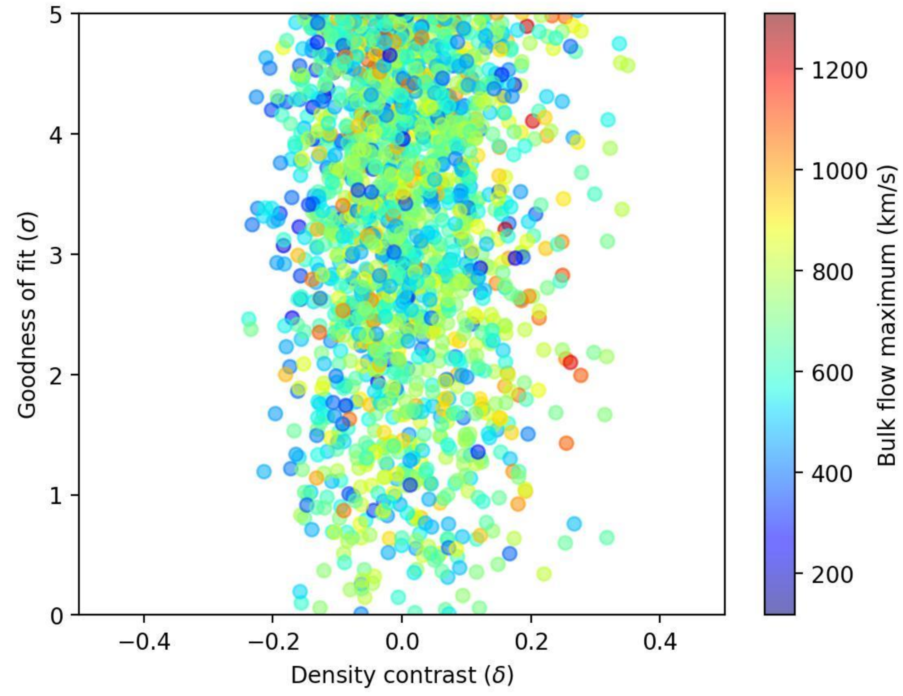
ΛCDM ΛHDM

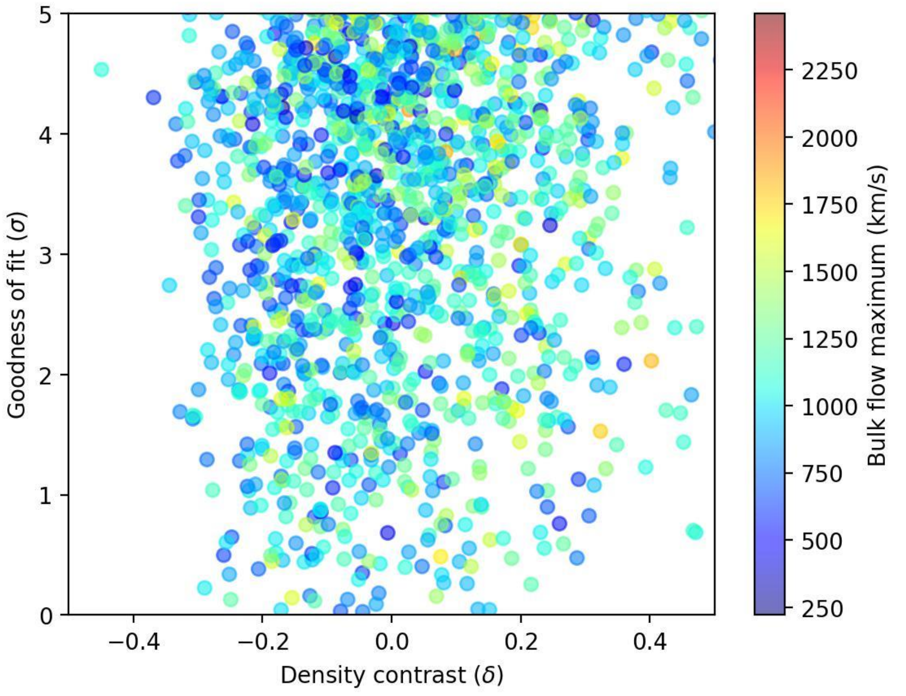
Shape of the local bulk flow curve

Find lower maximum bulk flow in underdensities → observed local bulk flow would be at lower end of spectrum!

Better than 2σ fit to observed shape for 2% of vantage points (up to 200 Mpc/h)

νCDM νHDM





What next?

Creating complete mock observations

- How do anisotropies in galaxy catalogue affect bulk flow measurements?

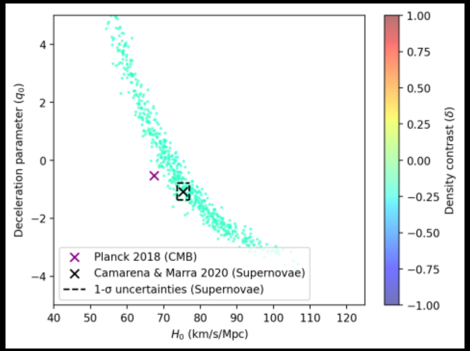
Tuning enhancement to gravity

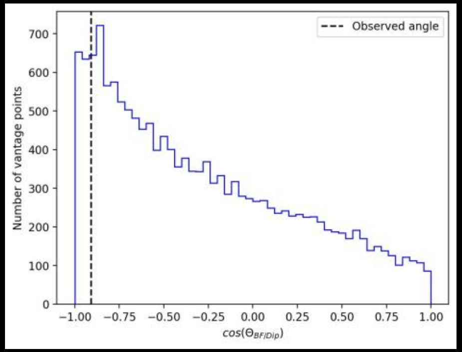
- Will many observations be accurately reproduced if enhancement is tuned to fit just one?

Exploring other theories

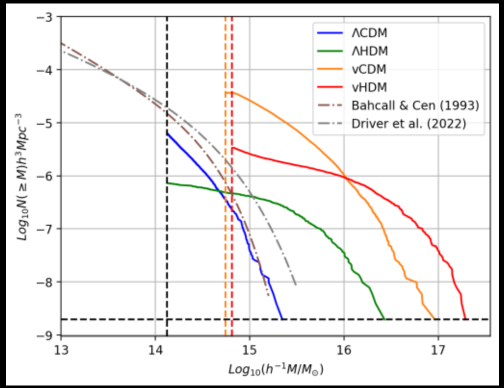
Conclusions

Possible link between H_0, q_0 and Local Hole underdensity





Bulk flows commonly flip direction at large radii in all simulations considered

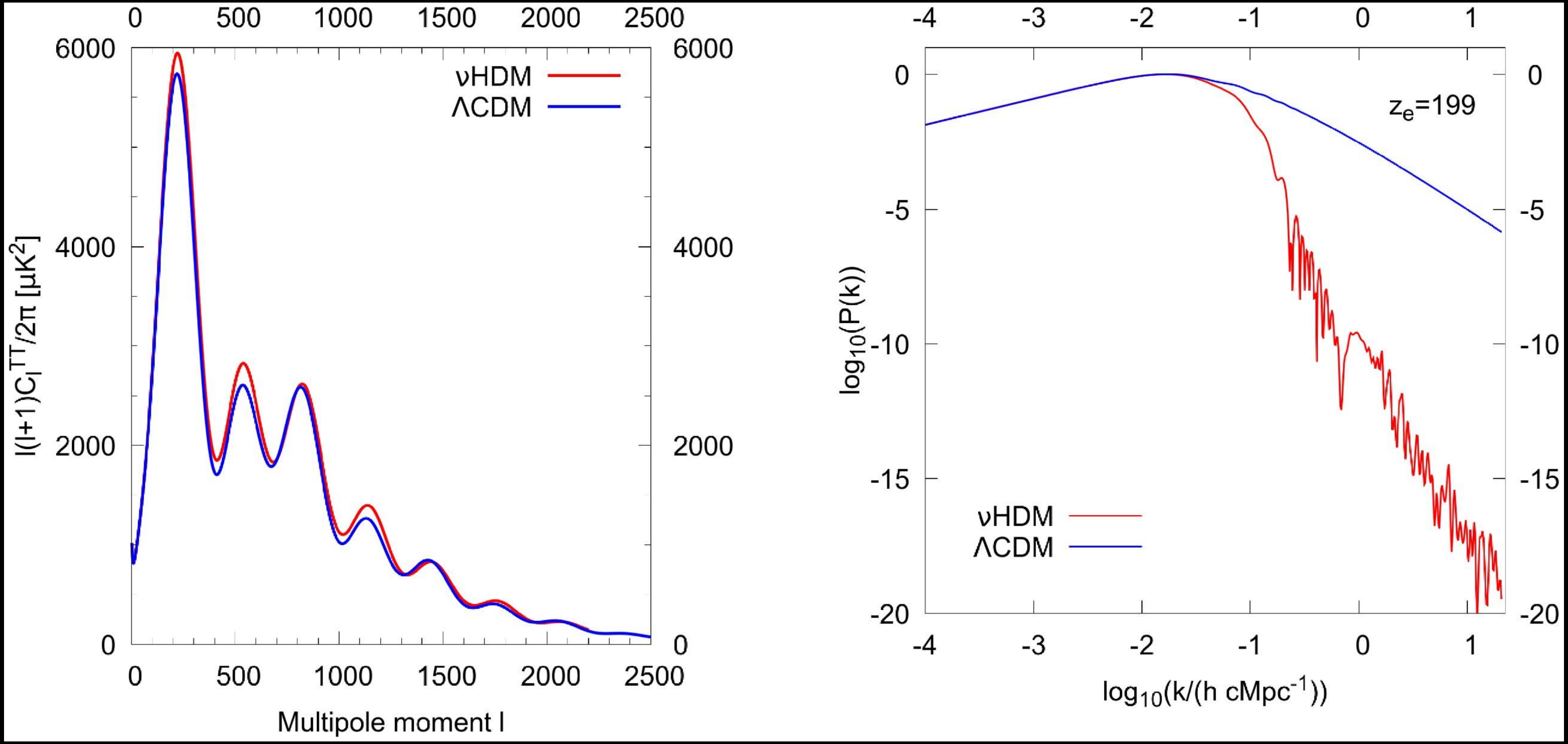


A scale-invariant theory is likely not the answer; enhancement to large-scale structure overproduces small scale structure

Is a local solution to the Hubble Tension preferable or not?

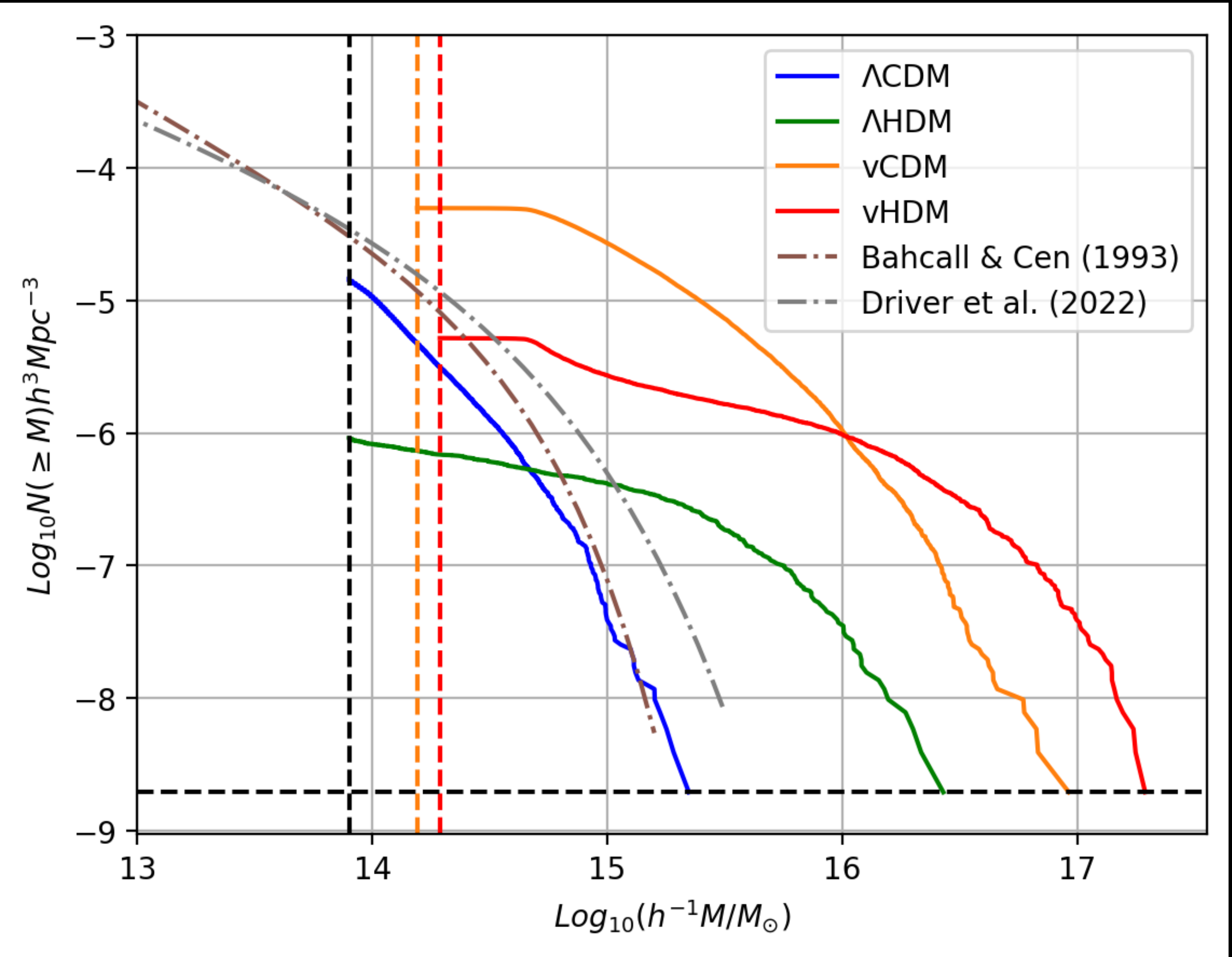
Appendix slides

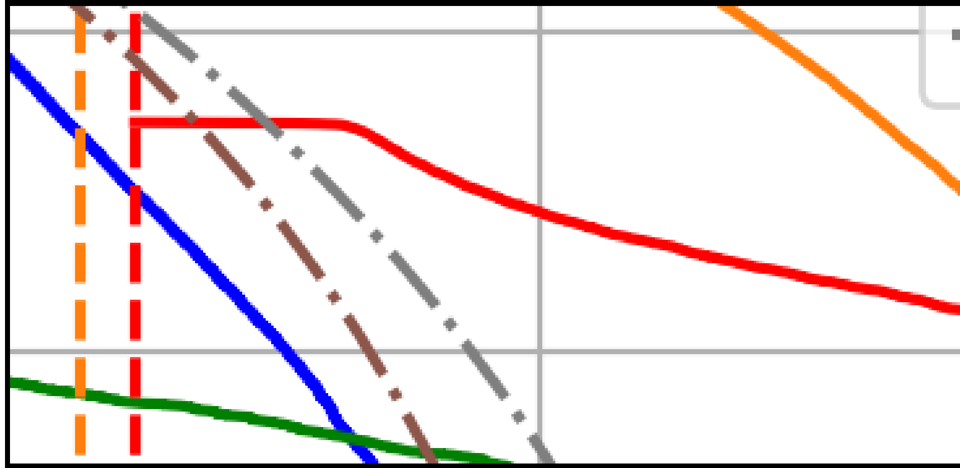
Power spectrum and Transfer function



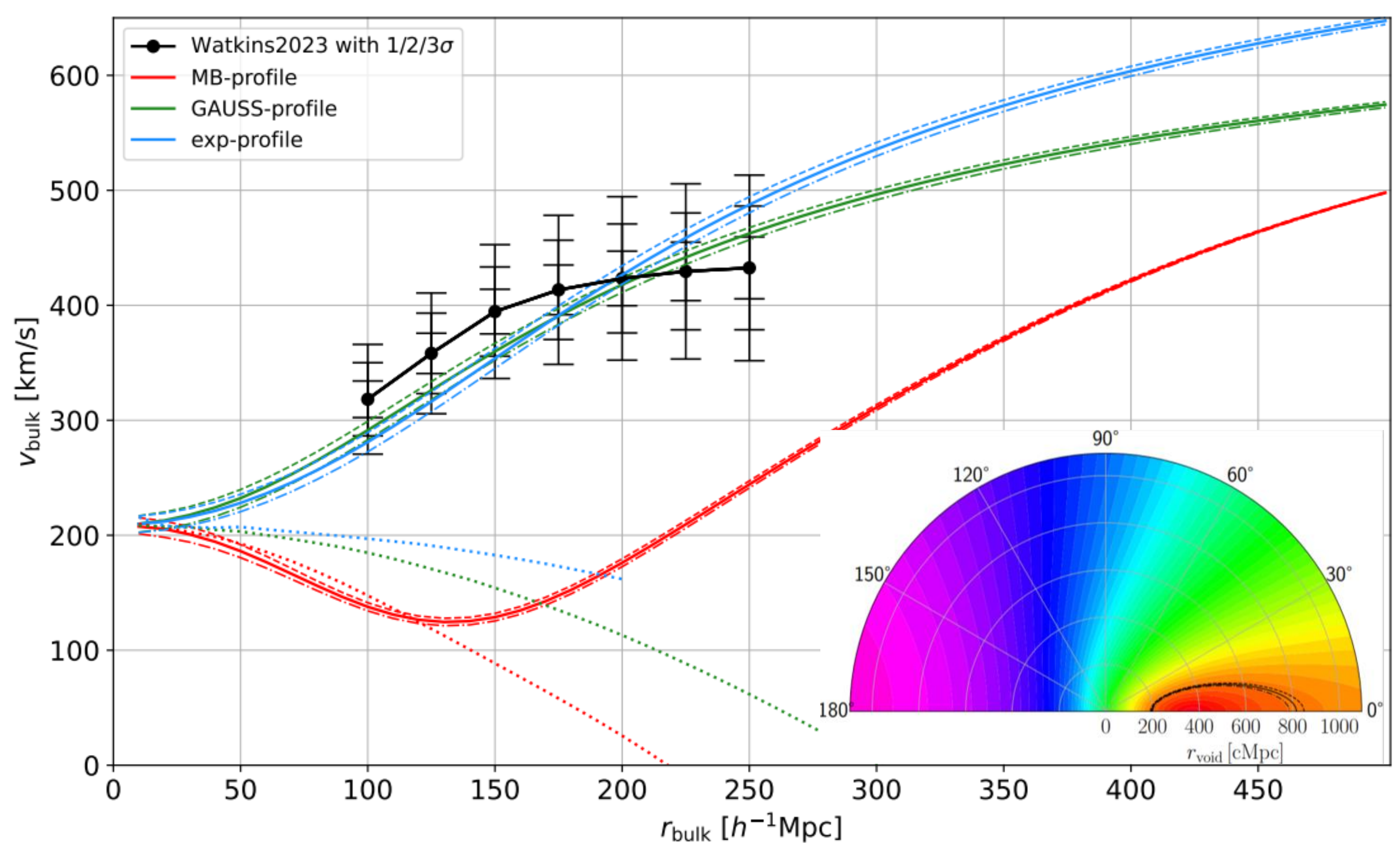
Wittenburg+ 2023, Figure 4

Spurious haloes





Semi-analytic bulk flow curve (Mazurenko+, submitted)



Semi-analytic model of Haslbauer+ 2020 was designed to fit KBC void density profile and solve the Hubble tension with outflows from the void + bulk motion. Local Group (LG) location in void is constrained by its peculiar velocity (black curve on inset). 3 void profiles x 2 LG locations considered (along symmetry axis). Bulk flow predictions for 2/3 density profiles match observed for the inner (left) vantage point. Bulk flow prediction is a priori, the semi-analytic model was created **before** Watkins+ 2023 and has not been altered to better fit the bulk flows in this work.