# Distribution of Local Matter on BAO Scale

Nao Suzuki & Friends

# Hubble's Law

$$v = H_0 d$$

$v$ = recession velocity in km/sec

$d$ = distance in Mpc

$H_0$ = expansion rate today (*Hubble Parameter*)

In words:

The more *distant* a galaxy, the *faster* its recession velocity.

# General Relativity Metric

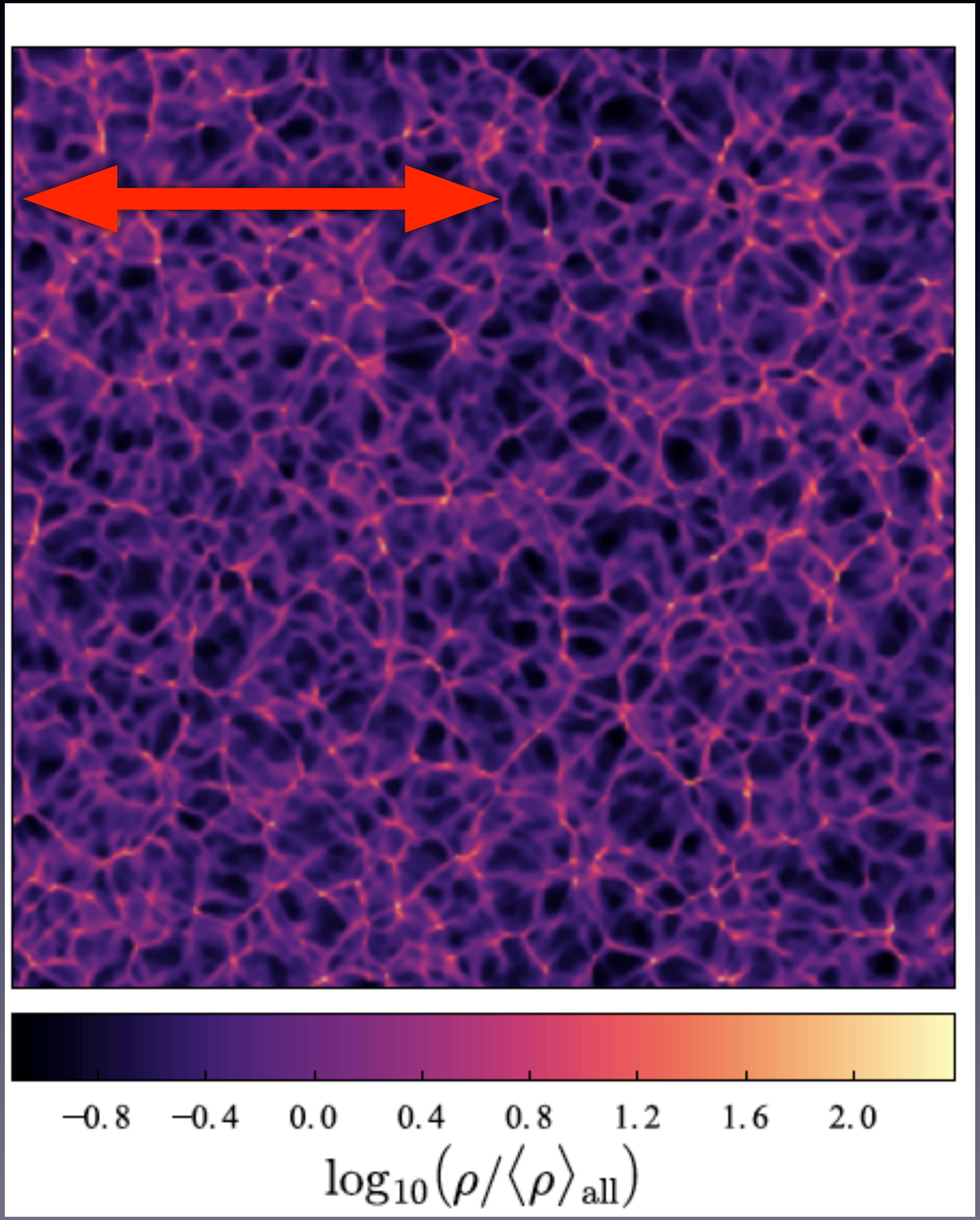
## Robertson-Walker Metric

$$ds^2 = dt^2 - \frac{R^2(t)}{c^2}\left[\frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 sin^2\theta d\phi^2\right]$$

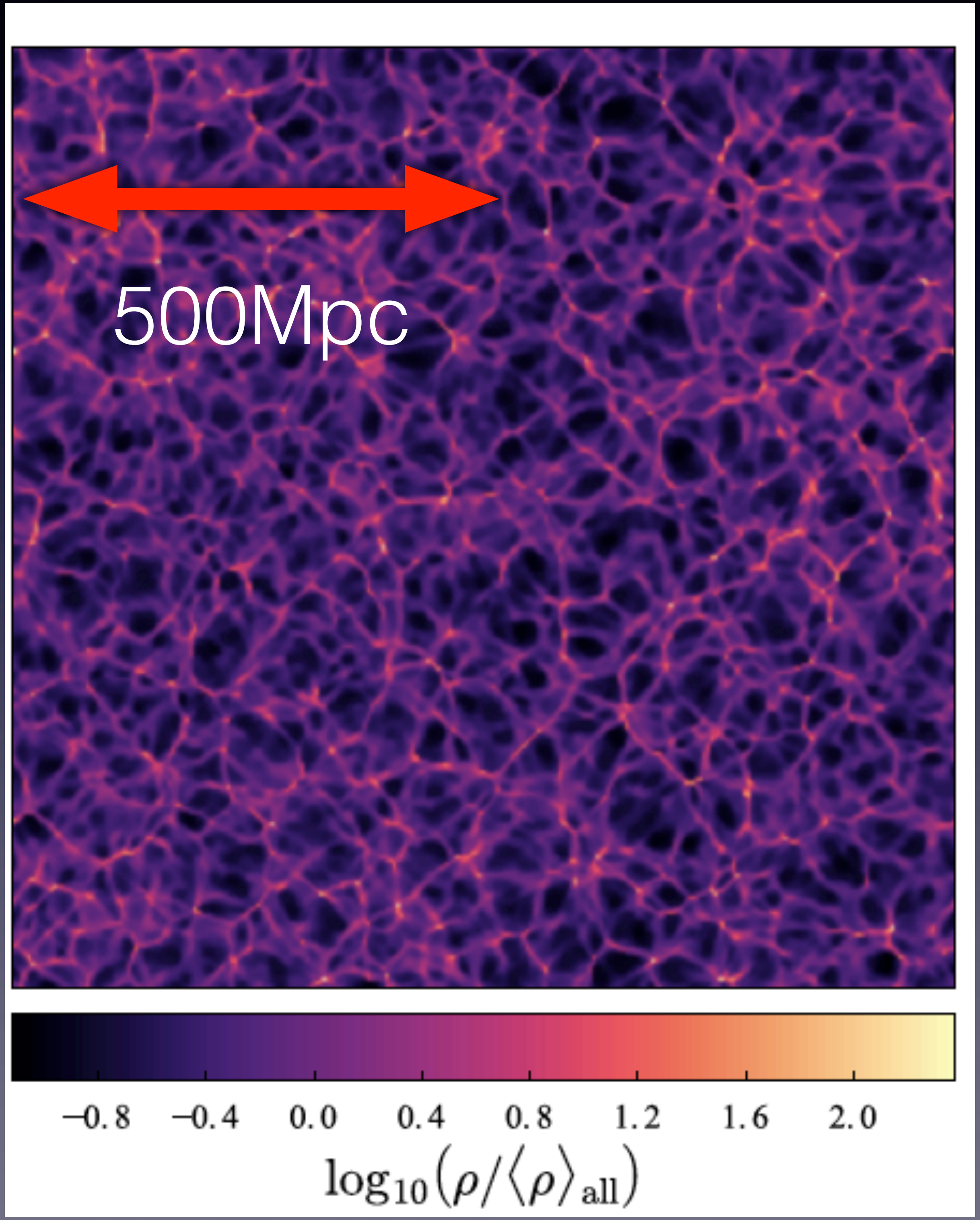
## Schwartzschild Metric

$$ds^2 = \left(1 - \frac{2m}{r}\right) dt^2 - \frac{dr^2}{1 - \frac{2m}{r}} - r^2 d\theta^2 - r^2 \sin^2\theta\, d\varphi^2$$

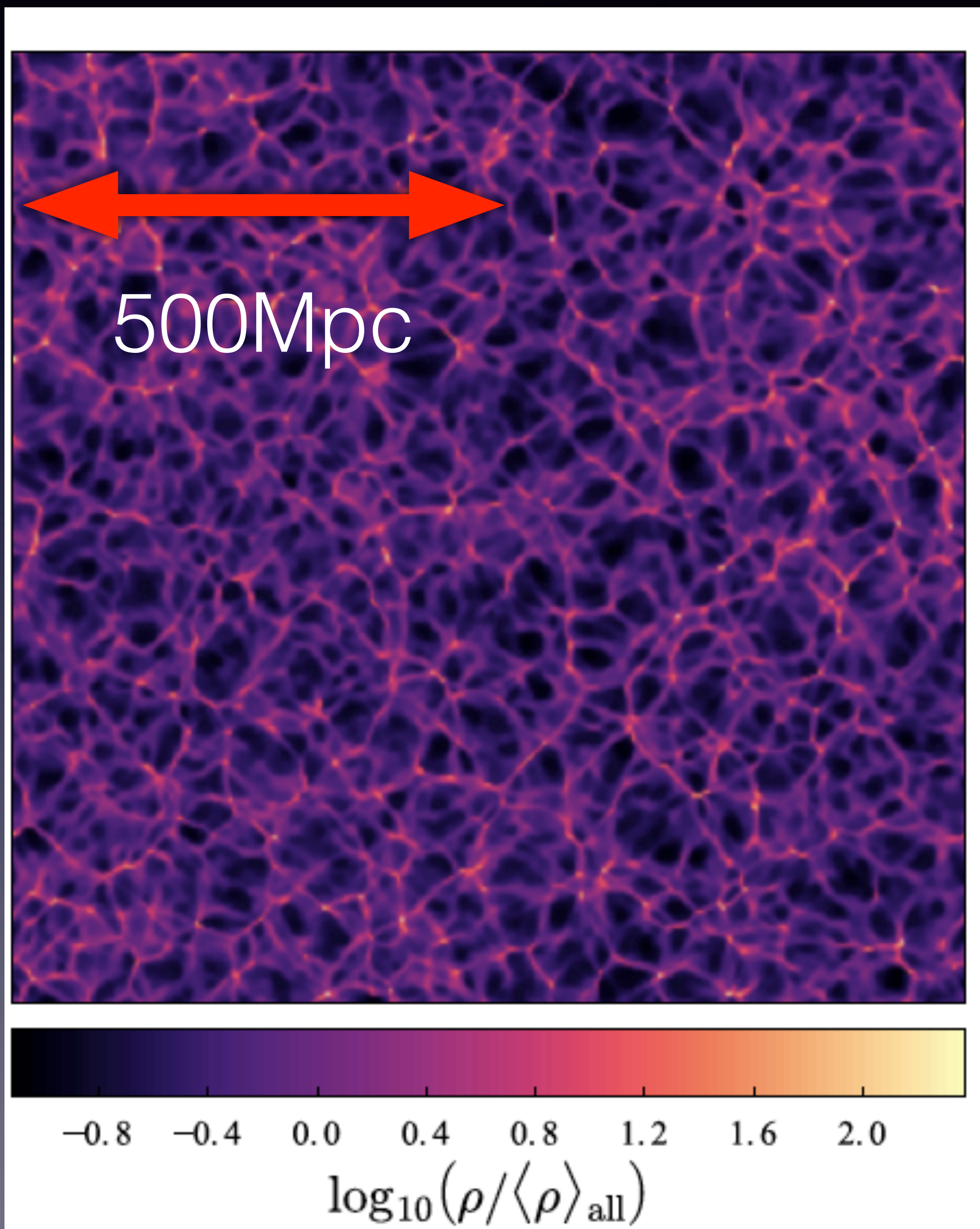
# Density Field at z=0

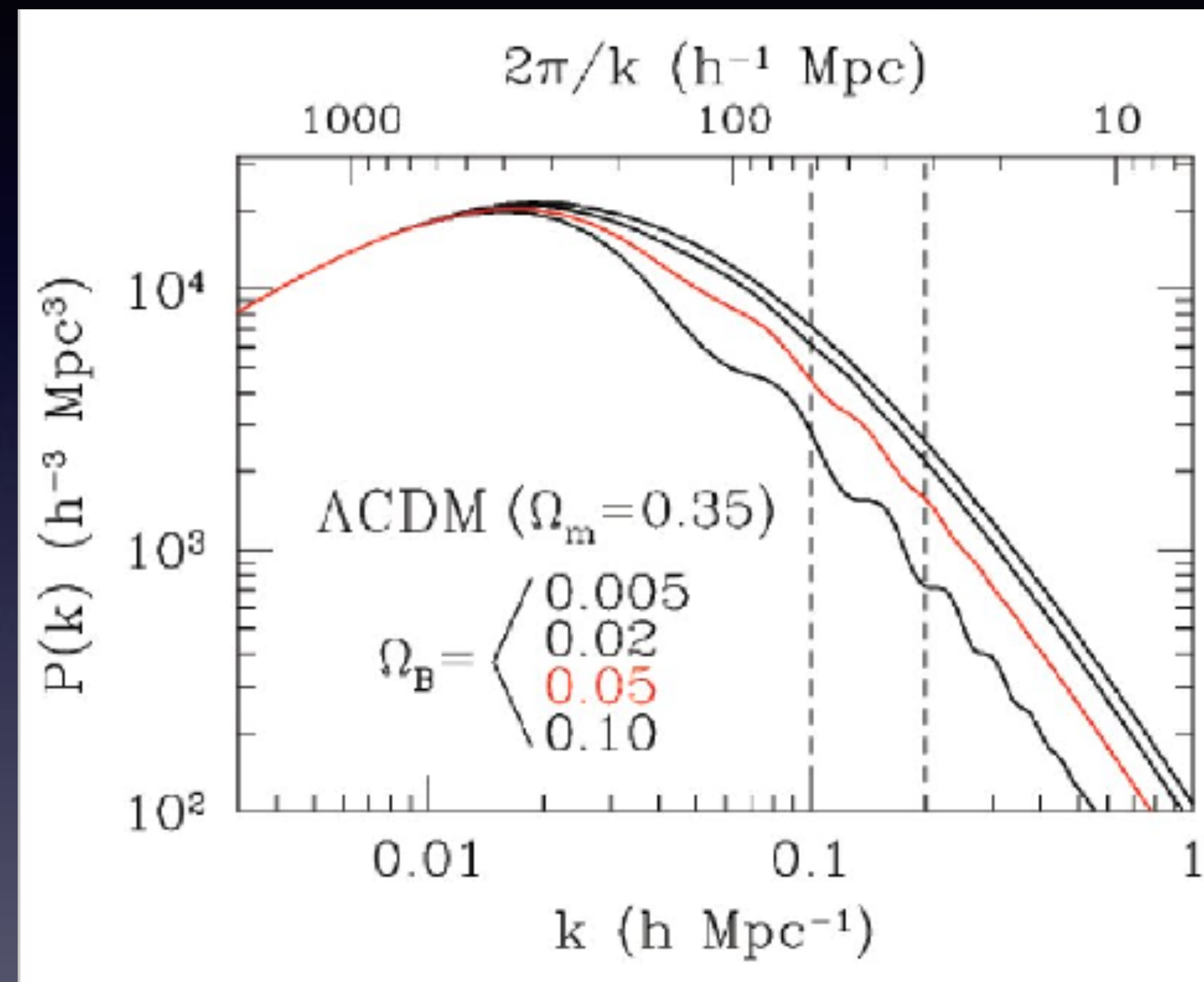


# Density Field at z=0



# How to quantify density fluctuation?

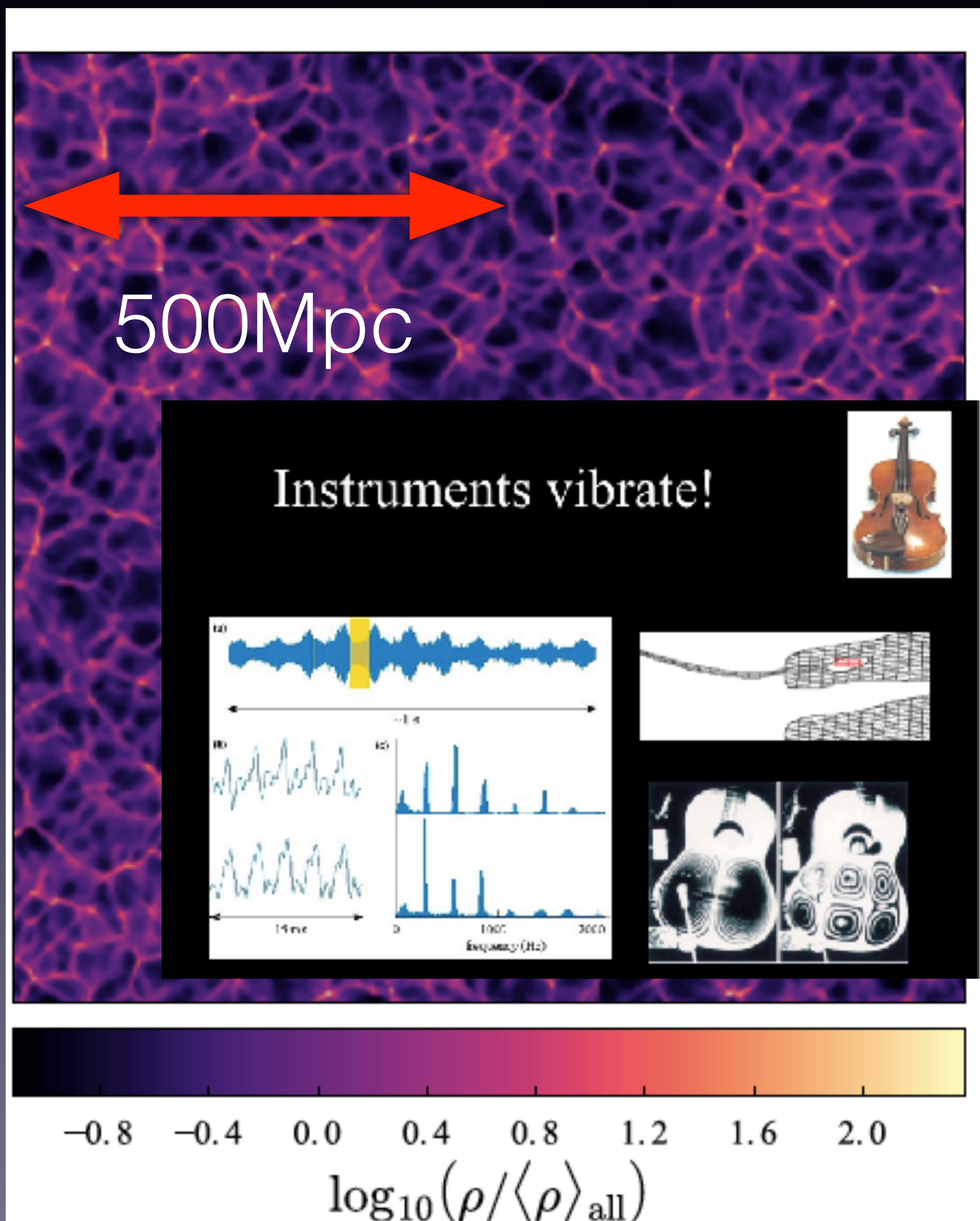


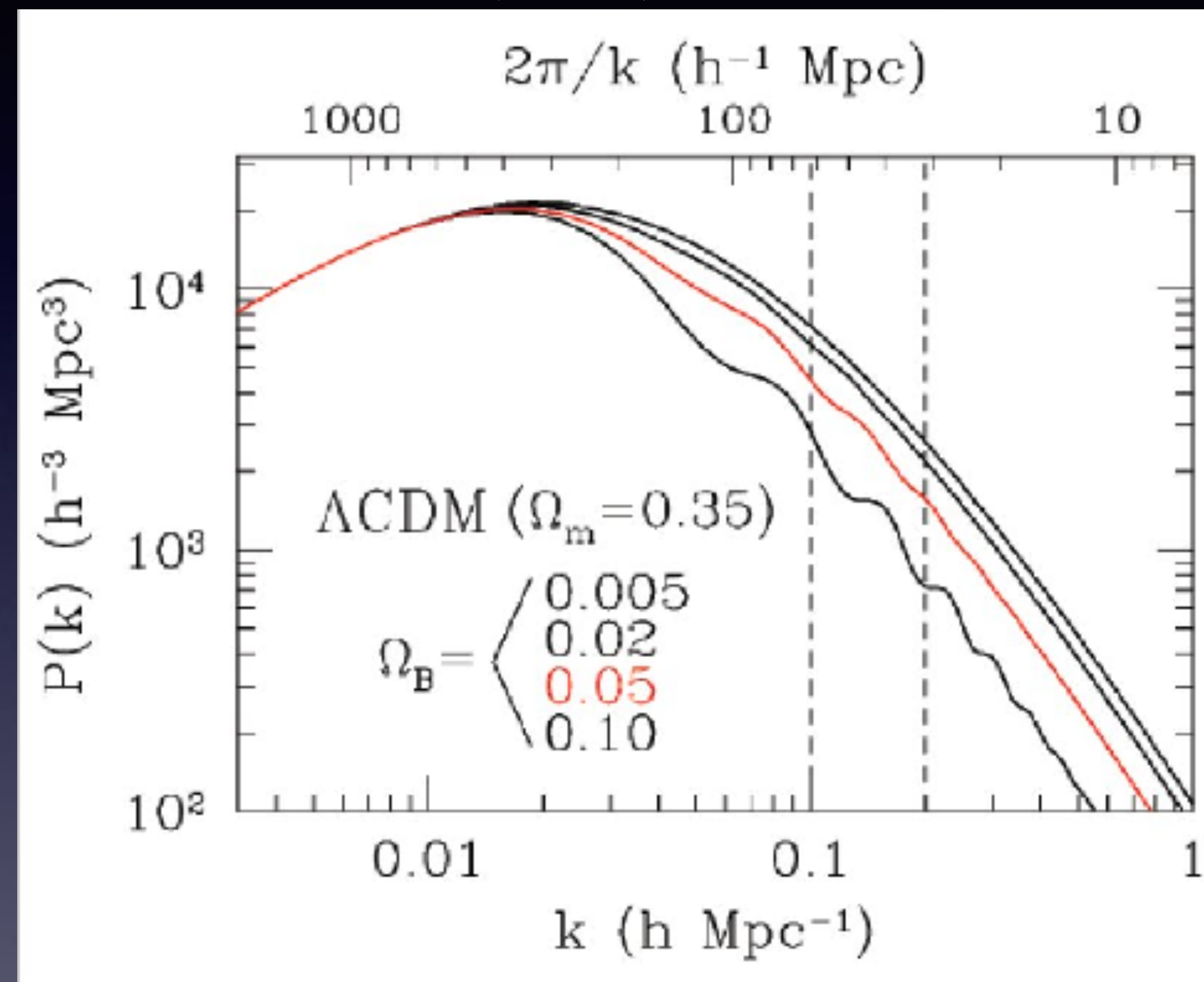




Einj said: ↑

*Thanks a lot! Does that simply mean $\sigma_8 = \mathcal{P}(k = 1/8\,h/Mpc)$? Where $\mathcal{P}$ is the power spectrum.*

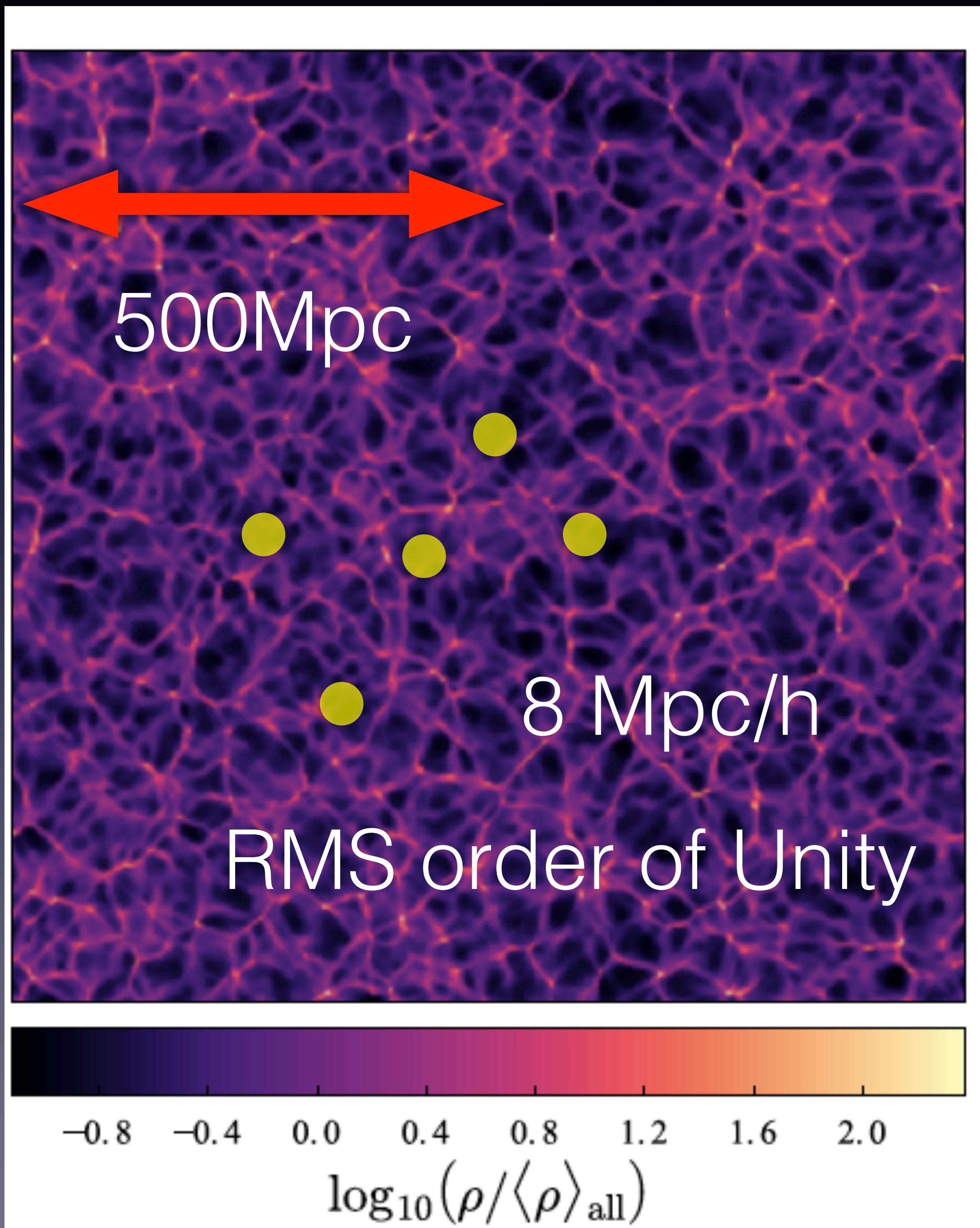
# Harmonics has to be counted
# Window Function W(kR)

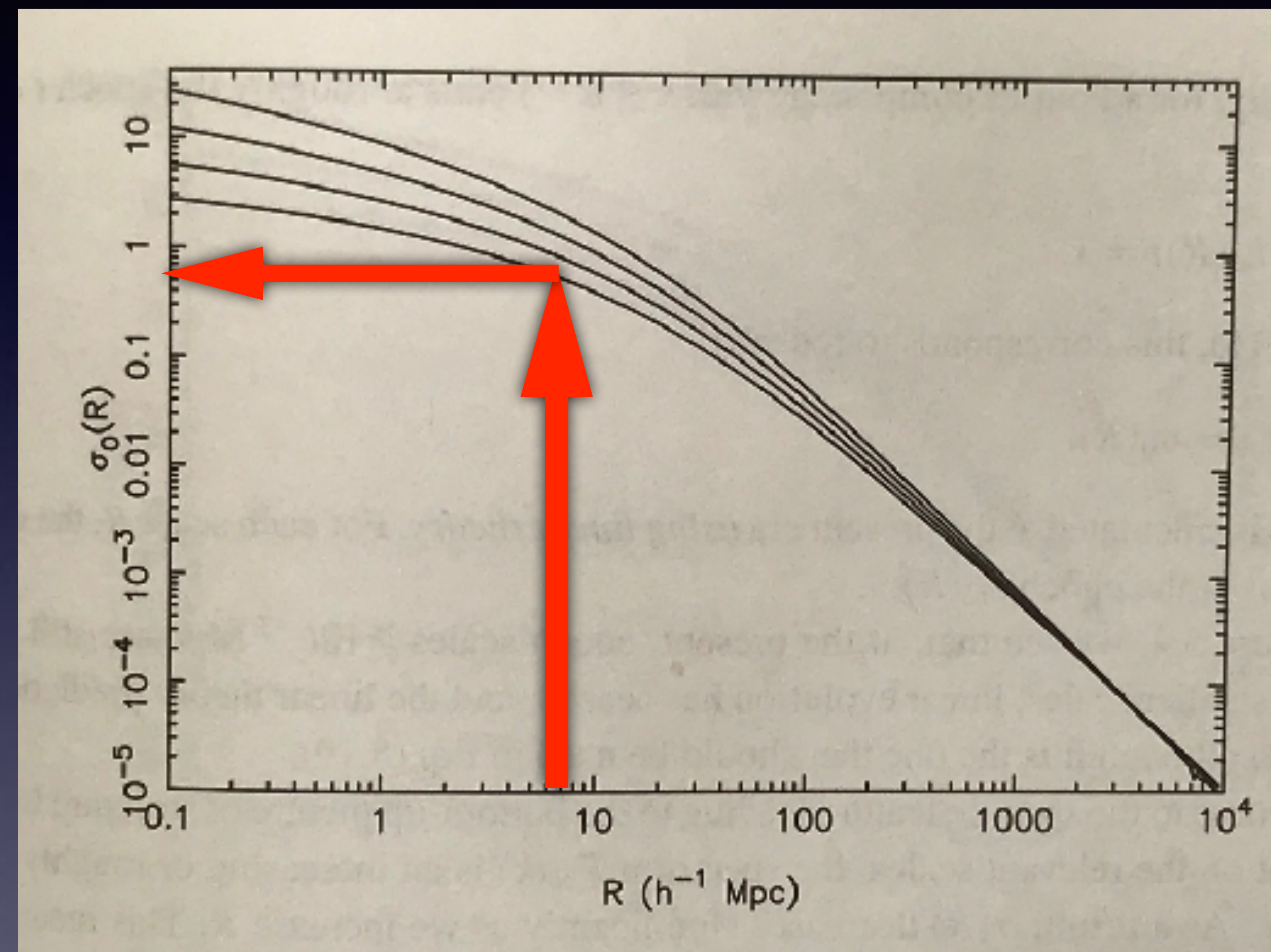



$$\sigma_0^2(R) = \int_0^\infty W^2(kR)\left(\frac{k}{a_0 H_0}\right)^4 T^2(k)\,\delta_{\rm H}^2(k)\frac{dk}{k}.$$

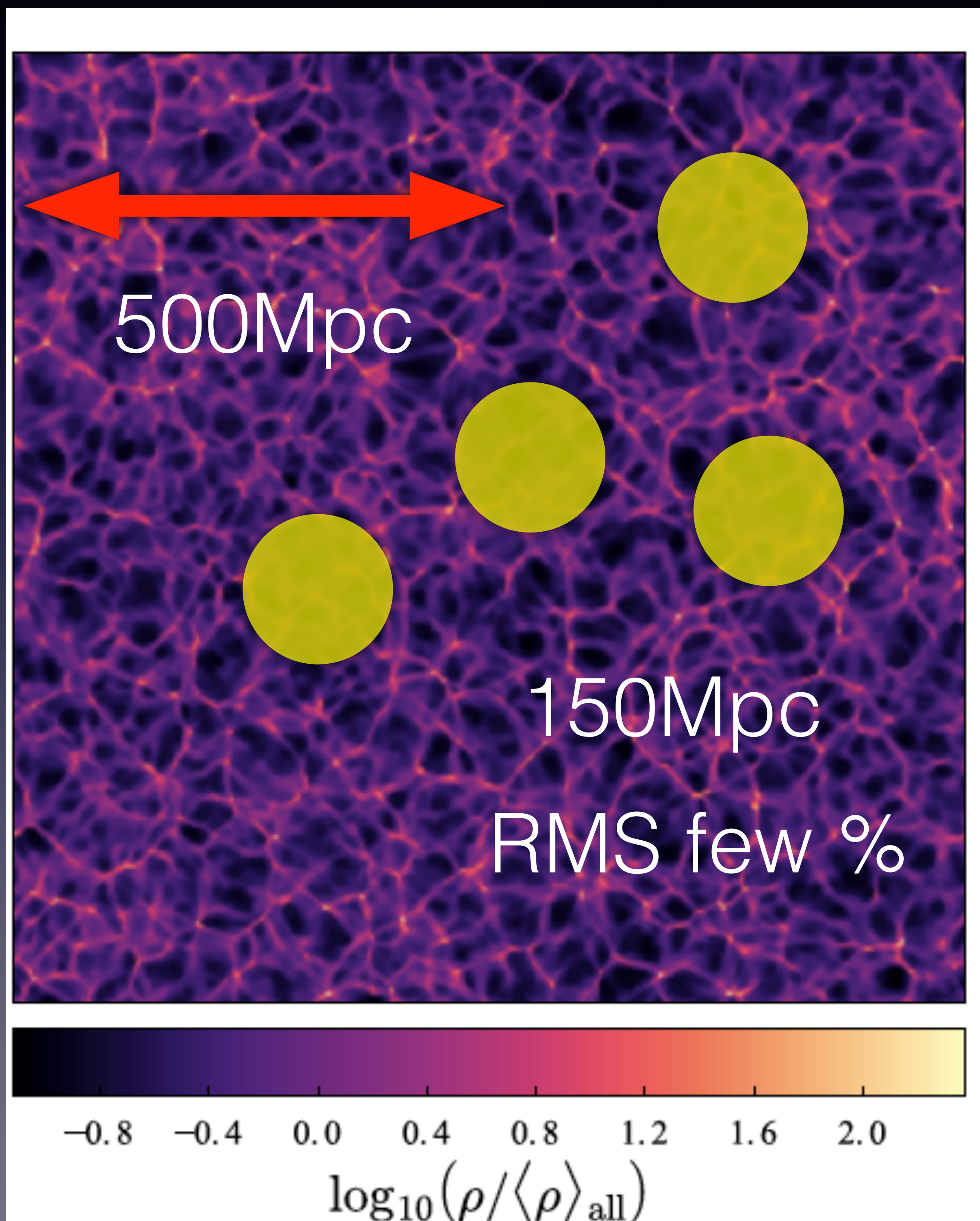
# 8 Mpc/h : RMS is Unity (0.8-ish)

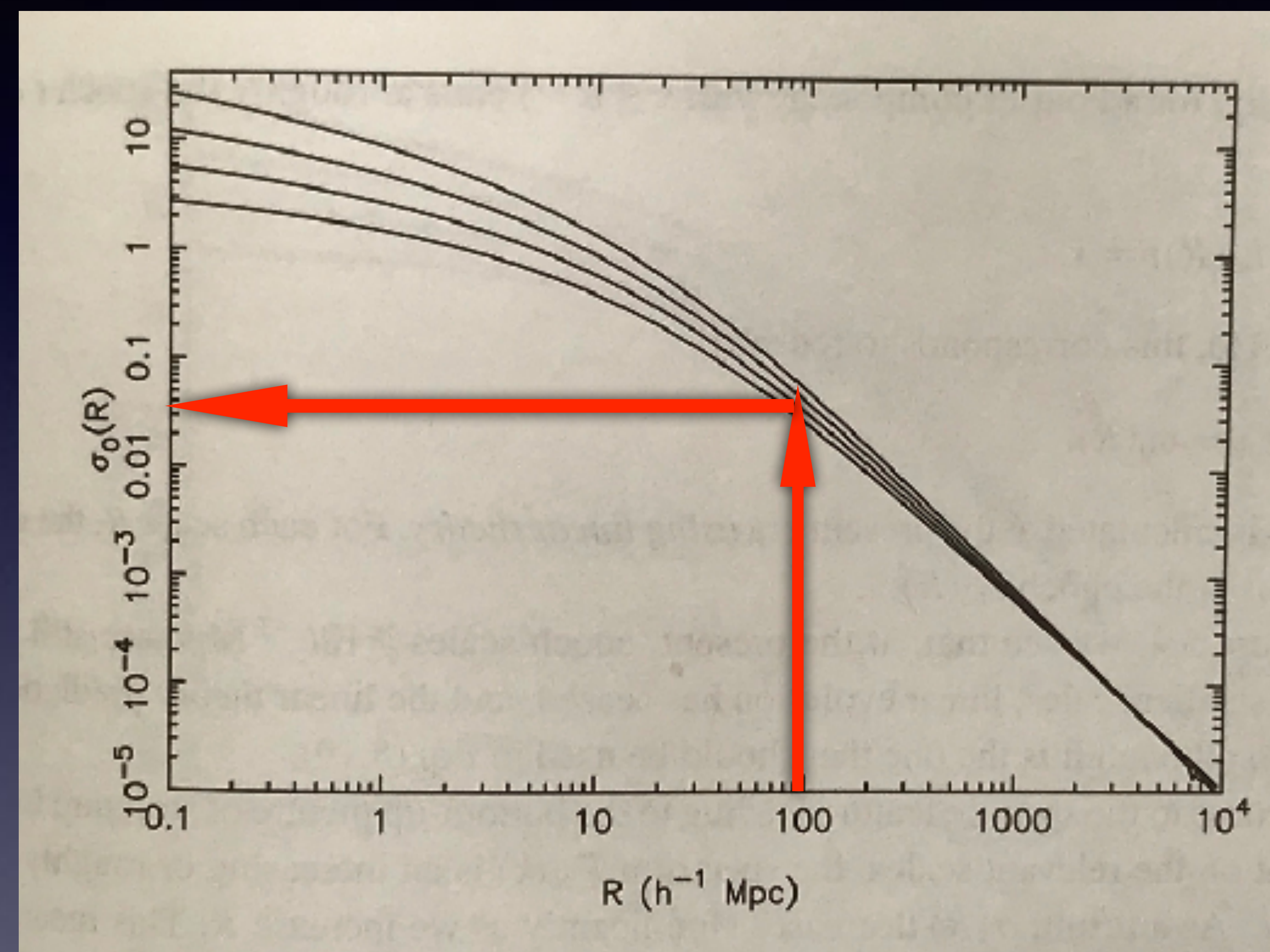



$$\sigma_0^2(R) = \int_0^\infty W^2(kR)\left(\frac{k}{a_0 H_0}\right)^4 T^2(k)\,\delta_{\rm H}^2(k)\frac{dk}{k}.$$

# 150Mpc represents the Universe




$$\sigma_0^2(R) = \int_0^\infty W^2(kR)\left(\frac{k}{a_0 H_0}\right)^4 T^2(k)\,\delta_{\rm H}^2(k)\frac{dk}{k}.$$

Q What is the area to study for 150Mpc?

Q1 : $z=2$

Q2 : $z=0$

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# Local gravity versus local velocity: solutions for $\beta$ and non-linear bias

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## 2.2 TF sample

20 yr ago, the mis-calibration of full sky Tully–Fisher (TF) data was the problem that led to very discrepant results for the determination of $\beta \equiv \Omega/b$, with $\beta = 0.5 \pm 0.2$ (DNW96) and $\beta = 1.0 \pm 0.2$ (e.g. Dekel et al. 1993). The mistaken TF calibration led to a large-scale flow that confused both analyses, but in the end, it was a calibration error in the southern sky which made a false large-scale flow (Willick et al. 1997). In one analysis, this led to a higher $\chi^2$ than was acceptable, and in the other it led to a biased result.

$$v_g(r) = \frac{2f(\Omega)}{3H_0\Omega}\, g(r).$$

## 3.2 Peculiar velocities from the inverse Tully–Fisher relation

Given a sample of galaxies with measured circular velocity parameters, $\eta_i = \log\omega_i$, linewidth $\omega_i$, apparent magnitudes $m_i$ and redshifts $z_i$, the goal is to derive an estimate for the smooth underlying peculiar velocity field. We assume that the circular velocity parameter, $\eta$, of a galaxy is, up to a random scatter, related to its absolute magnitude, $M$, by means of a linear ITF relation, i.e.

$$\eta = \gamma M + \eta_0. \qquad (8)$$

One of the main advantages of inverse TF methods is that samples selected by magnitude, as most are, will be minimally plagued by Malmquist bias effects when analysed in the inverse direction (Schechter 1980; Aaronson et al. 1982). We write the absolute magnitude of a galaxy,

$$M_i = M_{0i} + P_i \qquad (9)$$

where

$$M_{0i} = m_i + 5\log(z_i) - 15 \qquad (10)$$

and

$$P_i = 5\log(1 - u_i/z_i), \qquad (11)$$

where $m_i$ is the apparent magnitude of the galaxy, $z_i$ is its redshift in units of km s$^{-1}$ and $u_i$ is its radial peculiar velocity in the LG frame.

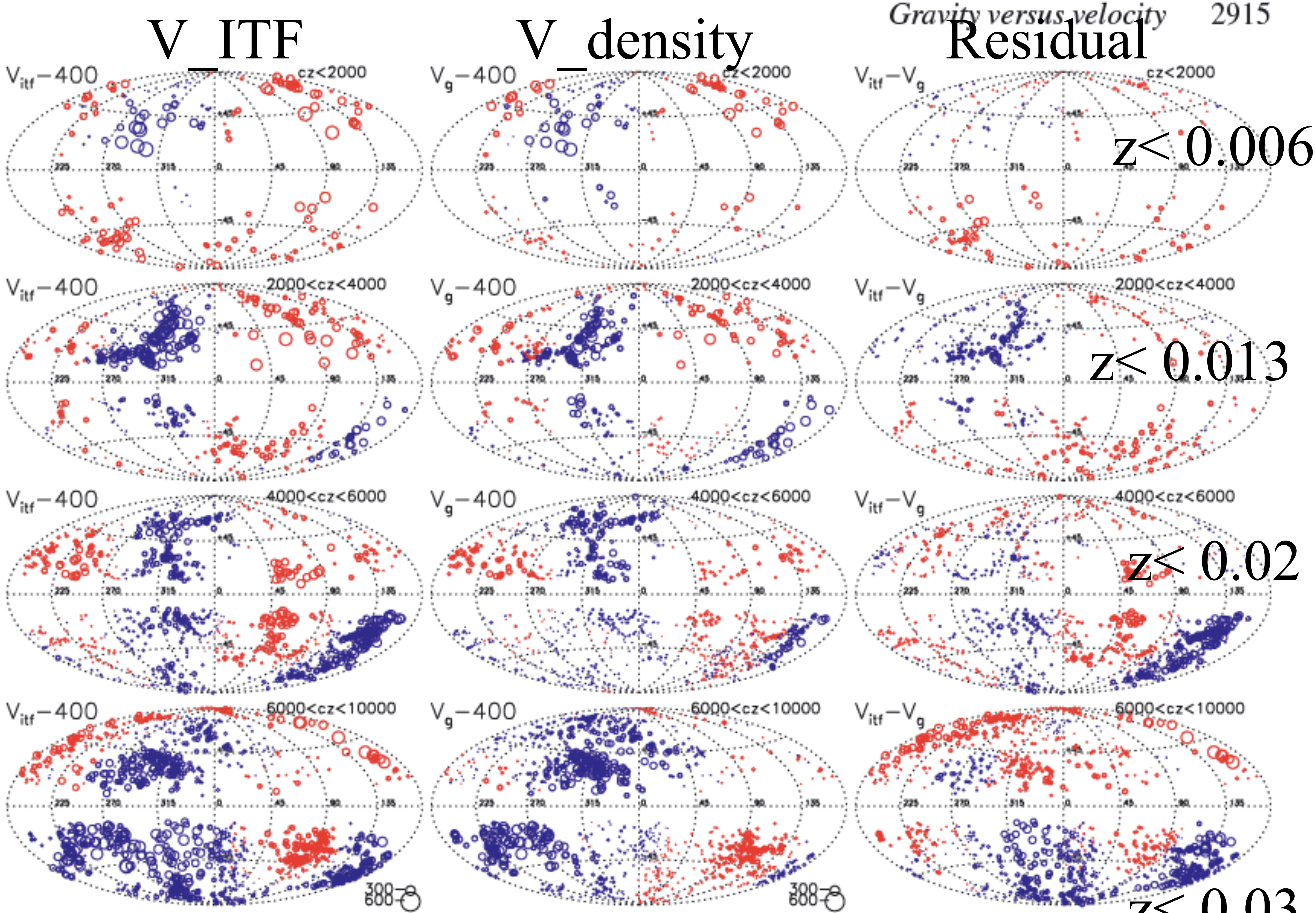
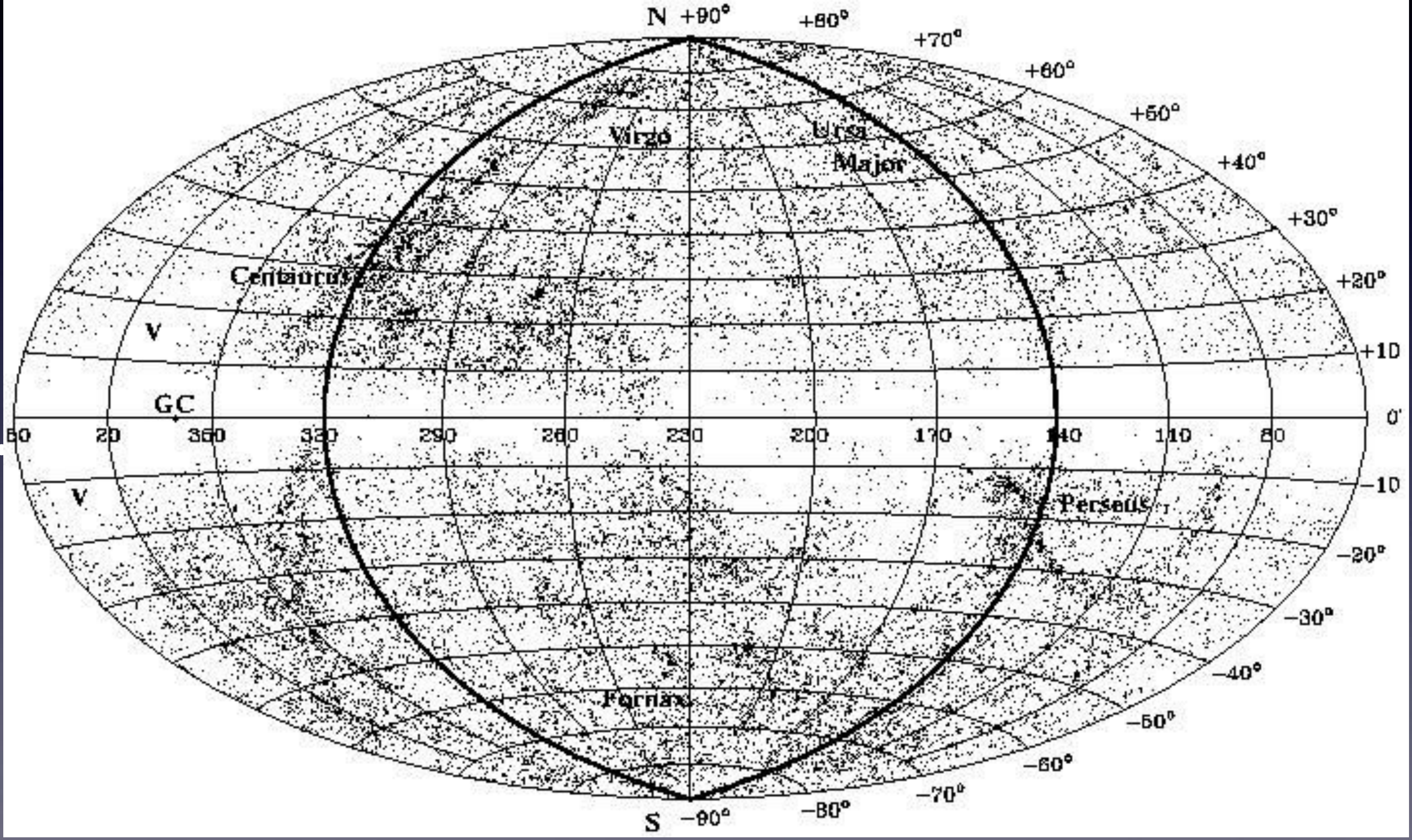



**Figure 5.** The derived peculiar velocities $v_{\rm ITF}$, $v_g$ and $v_{\rm ITF} - v_g$ of galaxies on aitoff projections on the sky in galactic coordinates. The rows correspond to galaxies with $cz < 2000$, $2000 < cz < 4000$, $4000 < cz < 6000\,\mathrm{km\,s^{-1}}$ and $6000 < cz < 10\,000\,\mathrm{km\,s^{-1}}$, respectively. The size of the symbols is linearly proportional to the velocity amplitude (see key to the size of the symbols given at the bottom of the figure). In order to better see the differences, a $400\,\mathrm{km\,s^{-1}}$ dipole, in the direction of the CMB dipole, has been subtracted from the $v_{\rm ITF}$ and $v_g$ velocities. Note that $v_{\rm ITF} - v_g$ is considerably smaller than $v_{\rm ITF}$ or $v_g$, even for the most distant galaxies.

Davis et al. 2011

# Supergalactic Plane
# 14650 Bright Galaxies  T. Kolatt, O. Lahav.



# Supergalactic Plane Coordinates

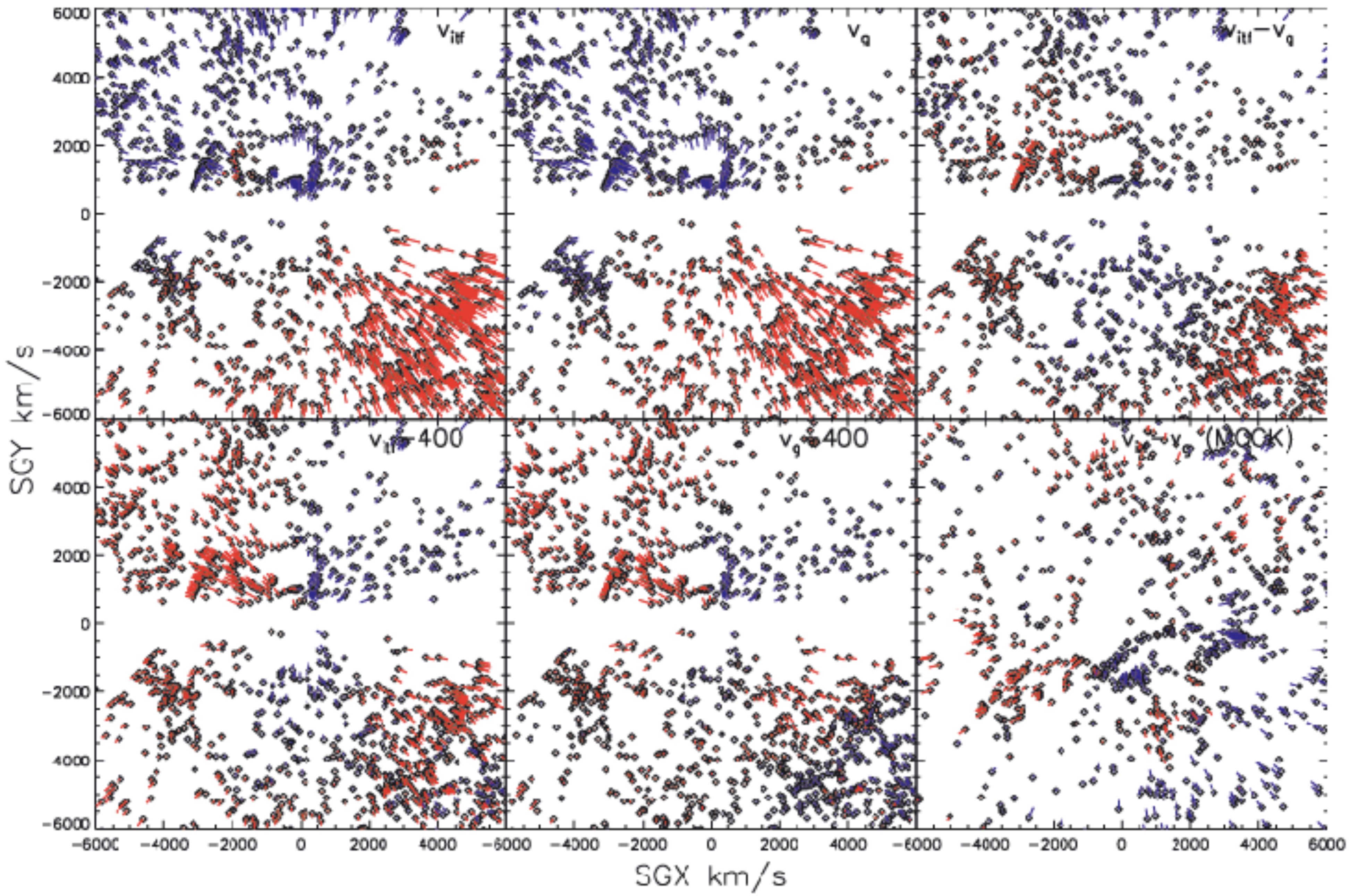



**Figure 8.** Supergalactic plane projection, $|SGB| < 30$, of the derived flows. To better see the differences in the plots, a dipole of 400 km s$^{-1}$ towards the CMB pole has been subtracted from the fields, and is shown in the bottom left and bottom centre. A quadruple velocity is now visible in the plots. The points are drawn at the estimated distance of an SFI++ galaxy, and the line, blue or red, is drawn to the galaxy's redshift. In other words, the length of the arrow is the peculiar velocity. The lower-right plot shows $v_{\rm ITF} - v_g$ for a mock catalogue, and the upper right shows $v_{\rm ITF} - v_g$ for the data. They have very similar degrees of coherence.

Davis et al. 2011

# SNIa Supernova (z<0.05)
# Feindt et al 2013 : SN Factory



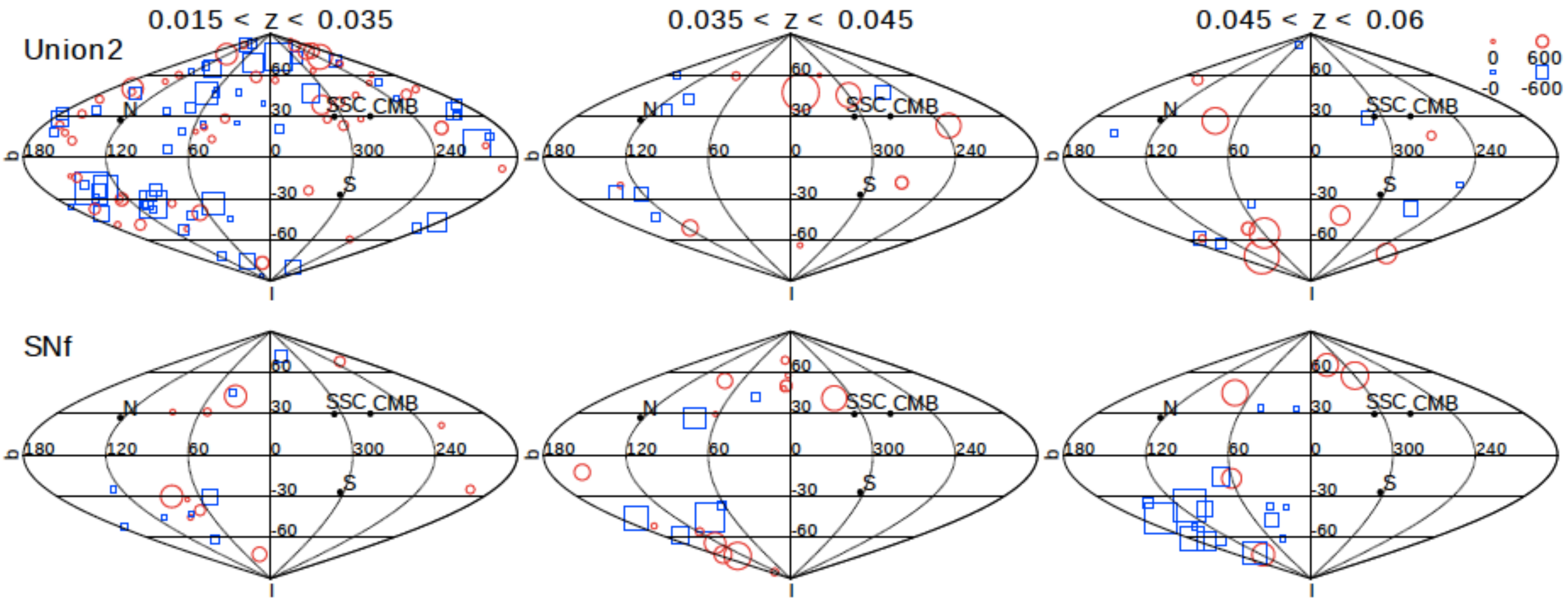
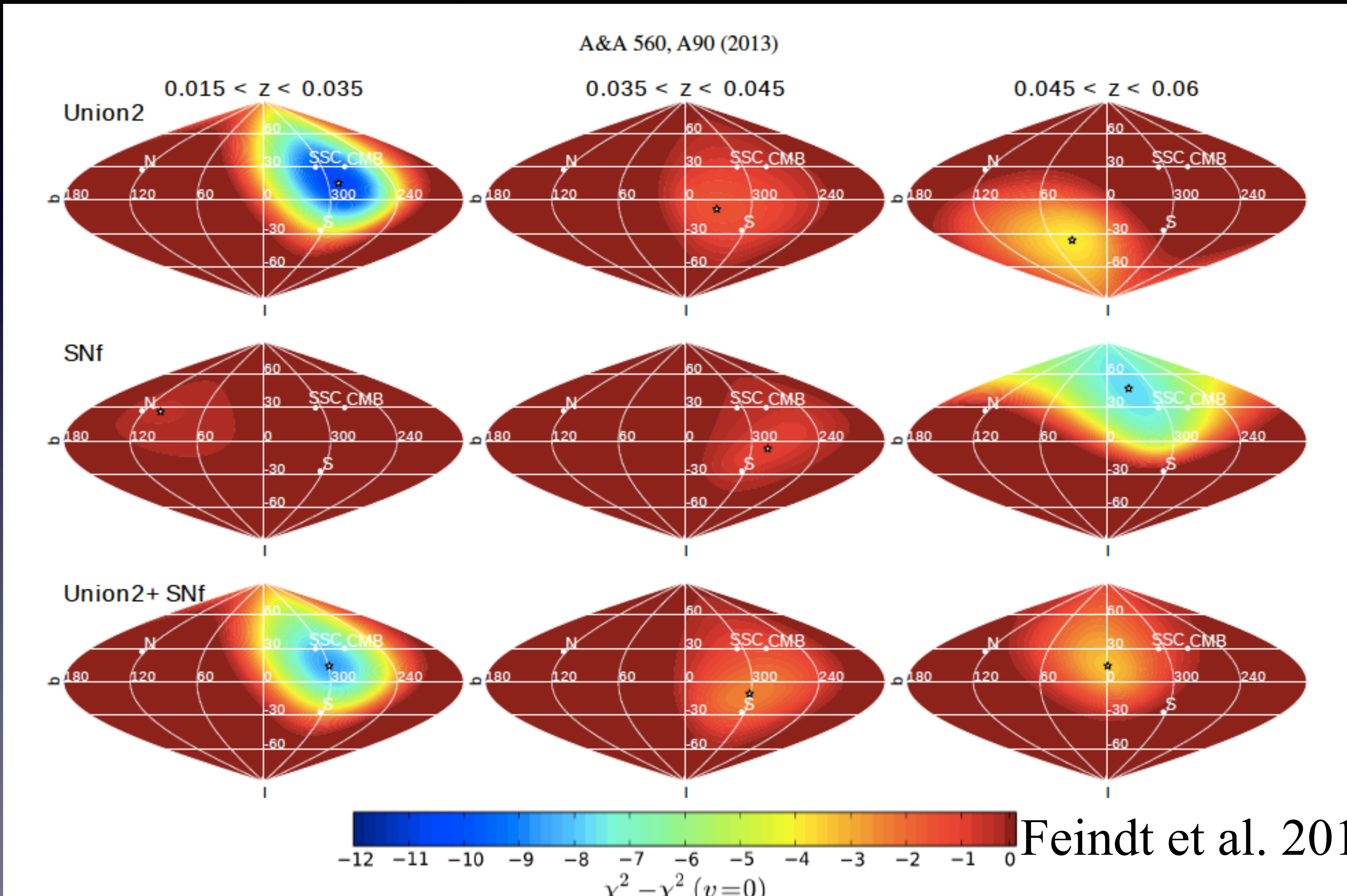



**Fig. 1.** Peculiar velocities of individual SNe determined from their distance moduli, $\mu_i$, by solving Eq. (2) for $v_{\mathrm{DF}}$. The plots show the Union2 (*top row*) and SNFACTORY (*bottom row*) datasets in the redshift bins $0.015 < z < 0.035$ (*left column*), $0.035 < z < 0.045$ (*middle column*) and $0.045 < z < 0.06$ (*right column*). The marker diameter of each SN is proportional to the absolute value of the velocity plus an offset (see the scale at the top right), with red circles corresponding to positive velocities and blue squares corresponding to negative ones. For reference, the directions of the CMB dipole and the Shapley supercluster (SSC) are shown.

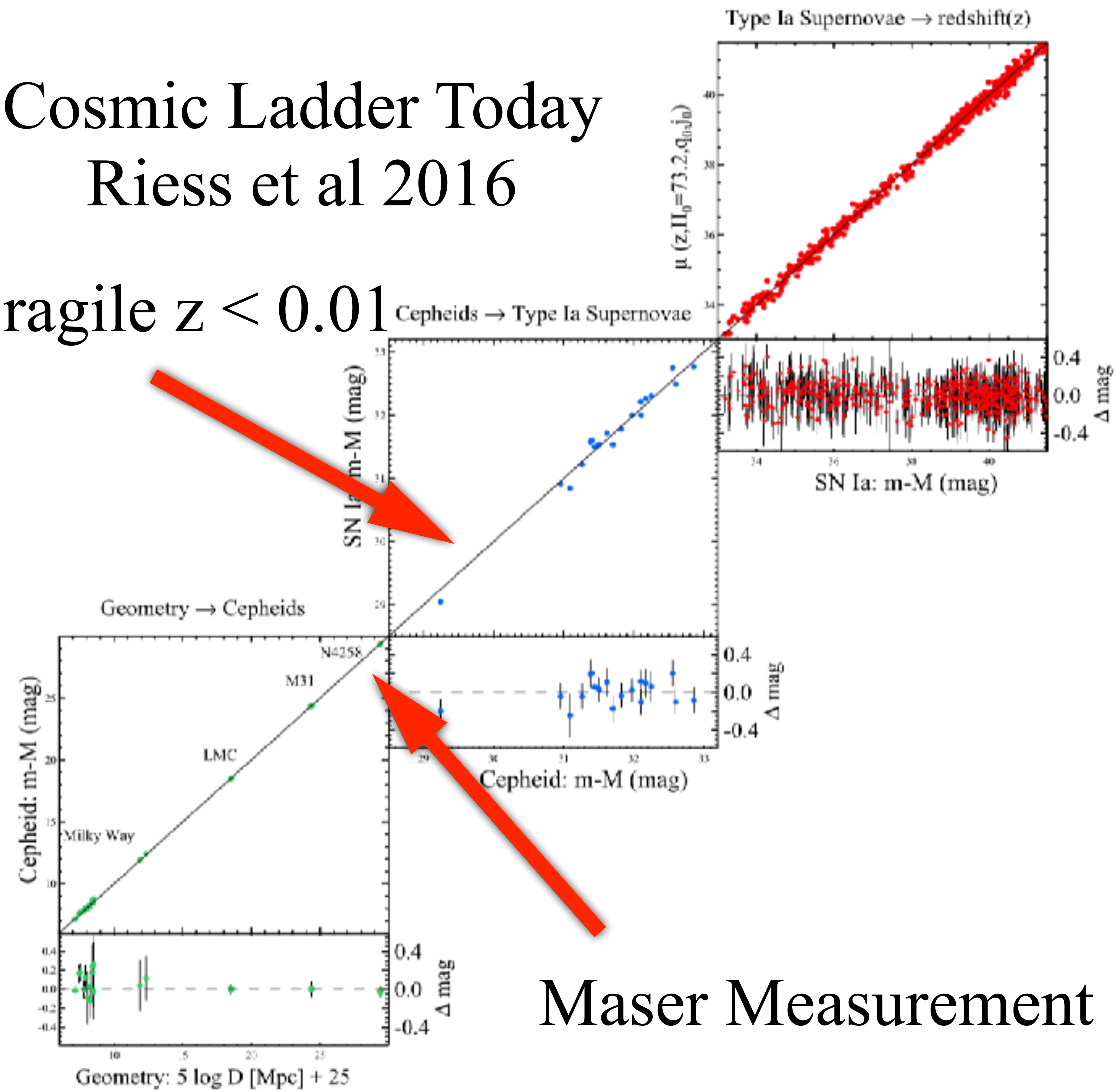
# CMB Dipole is seen by SNIa




Feindt et al. 2011

# Cosmic Ladder Today
# Riess et al 2016

Fragile z < 0.01




Maser Measurement

# Inhomogeneous Expansion of the Universe

The trouble with Hubble: Local versus global expansion rates in inhomogeneous cosmological simulations with numerical relativity

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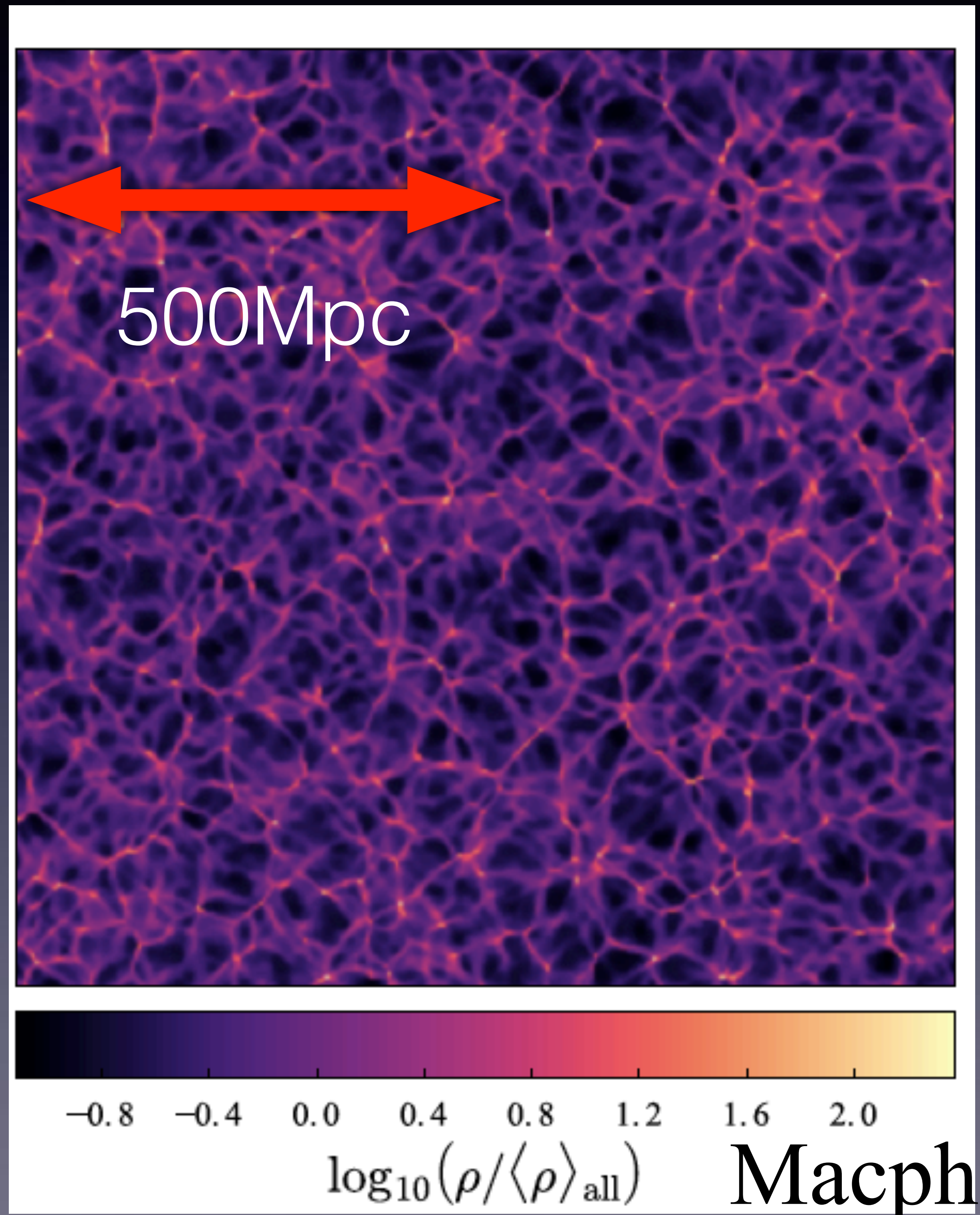
Submitted to ApJ

Macpherson et al 2018

ABSTRACT

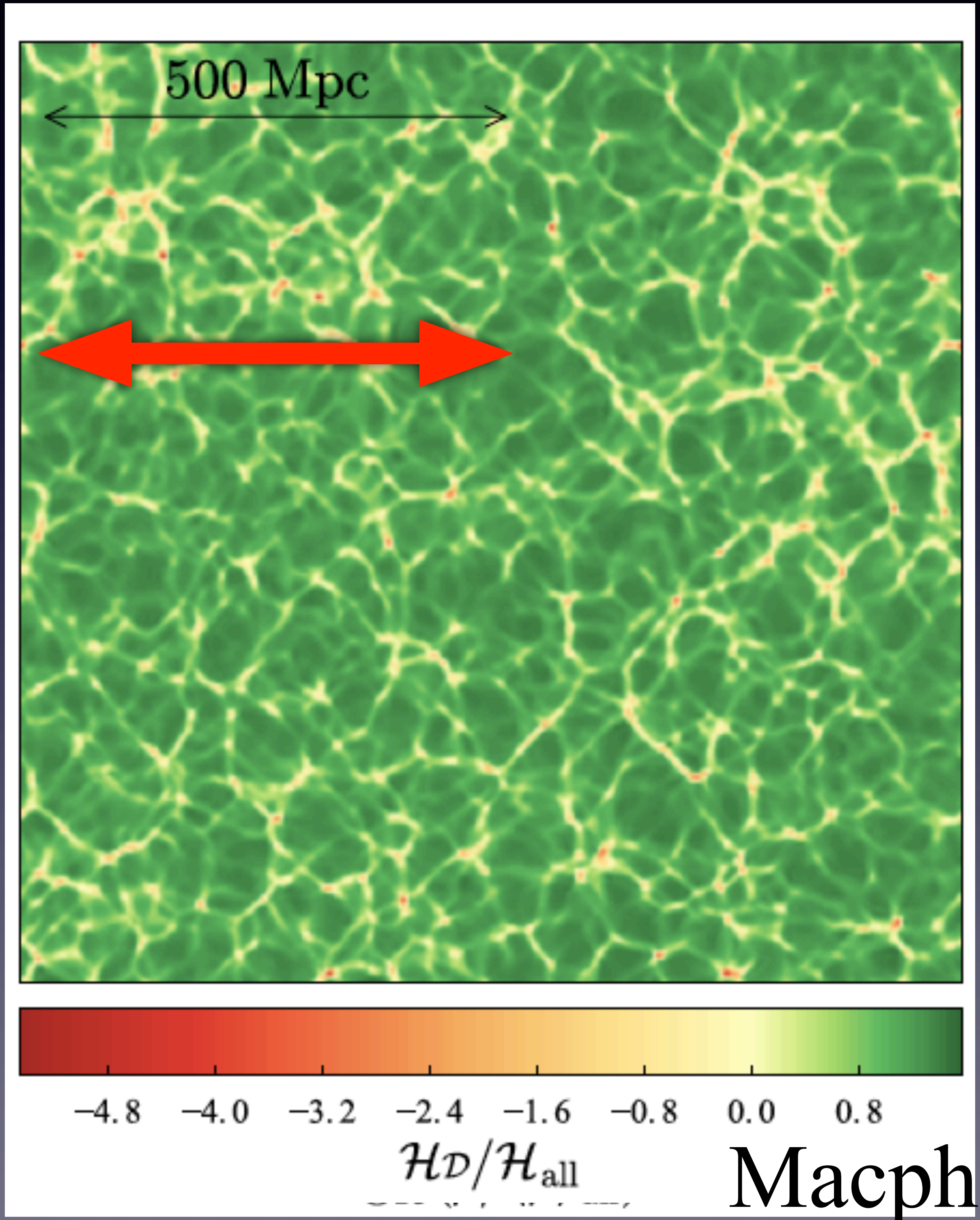
In a fully inhomogeneous, anisotropic cosmological simulation performed by solving Einstein's equations with numerical relativity, we find a local measurement of the effective Hubble parameter differs by less than 1% compared to the global value. This variance is consistent with predictions from Newtonian gravity. We analyse the averaged local expansion rate on scales comparable to Type 1a supernova surveys, and find that local variance cannot resolve the tension between the Riess et al. (2018a) and Planck Collaboration et al. (2018) measurements.

# Density Field at z=0




Macpherson et al 2018

# Expansion Rate at z=0 (normalized by global) Inhomogeneous Expansion of the Universe

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# Hubble Flow vs SNIa Cosmology

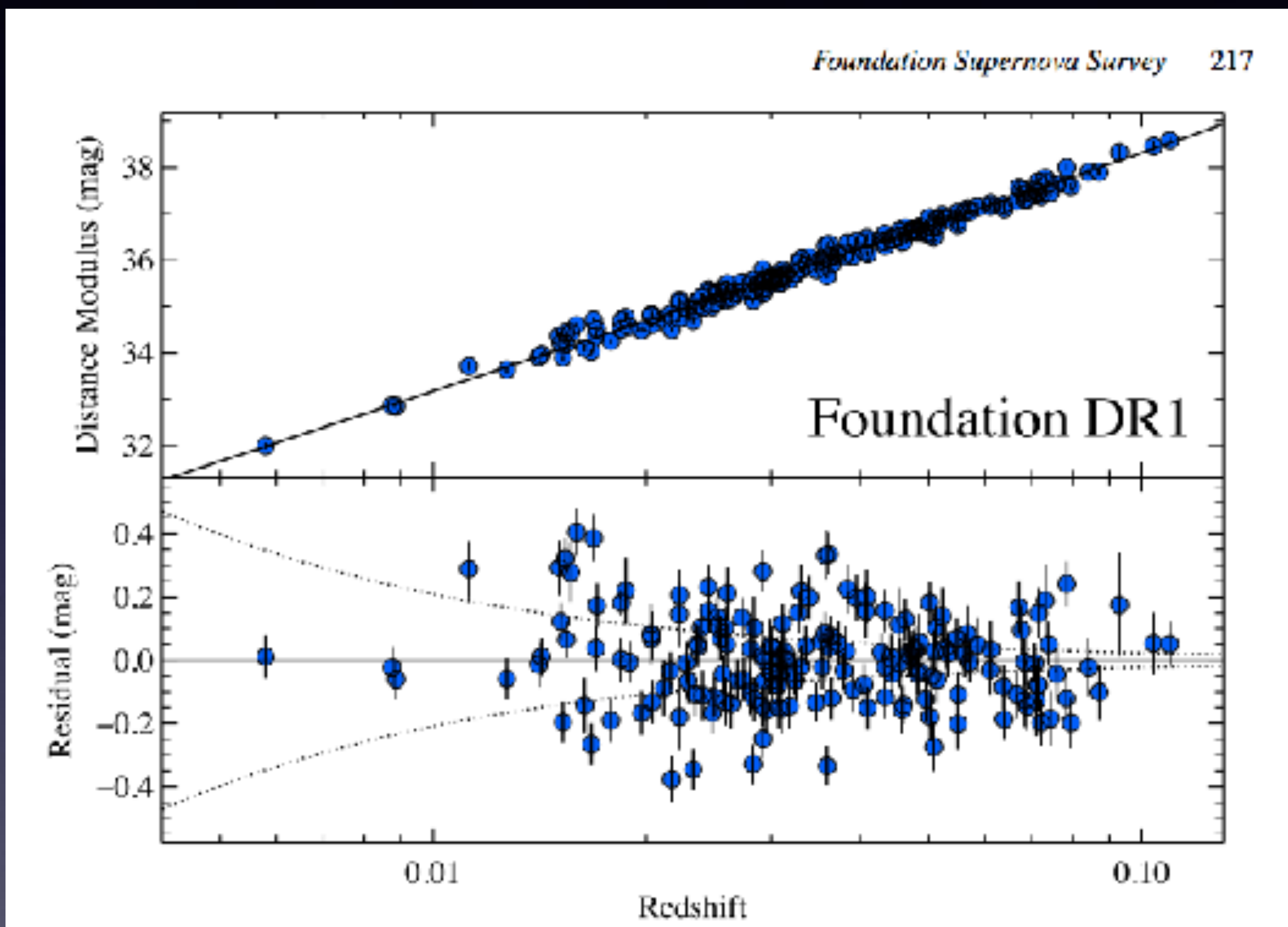
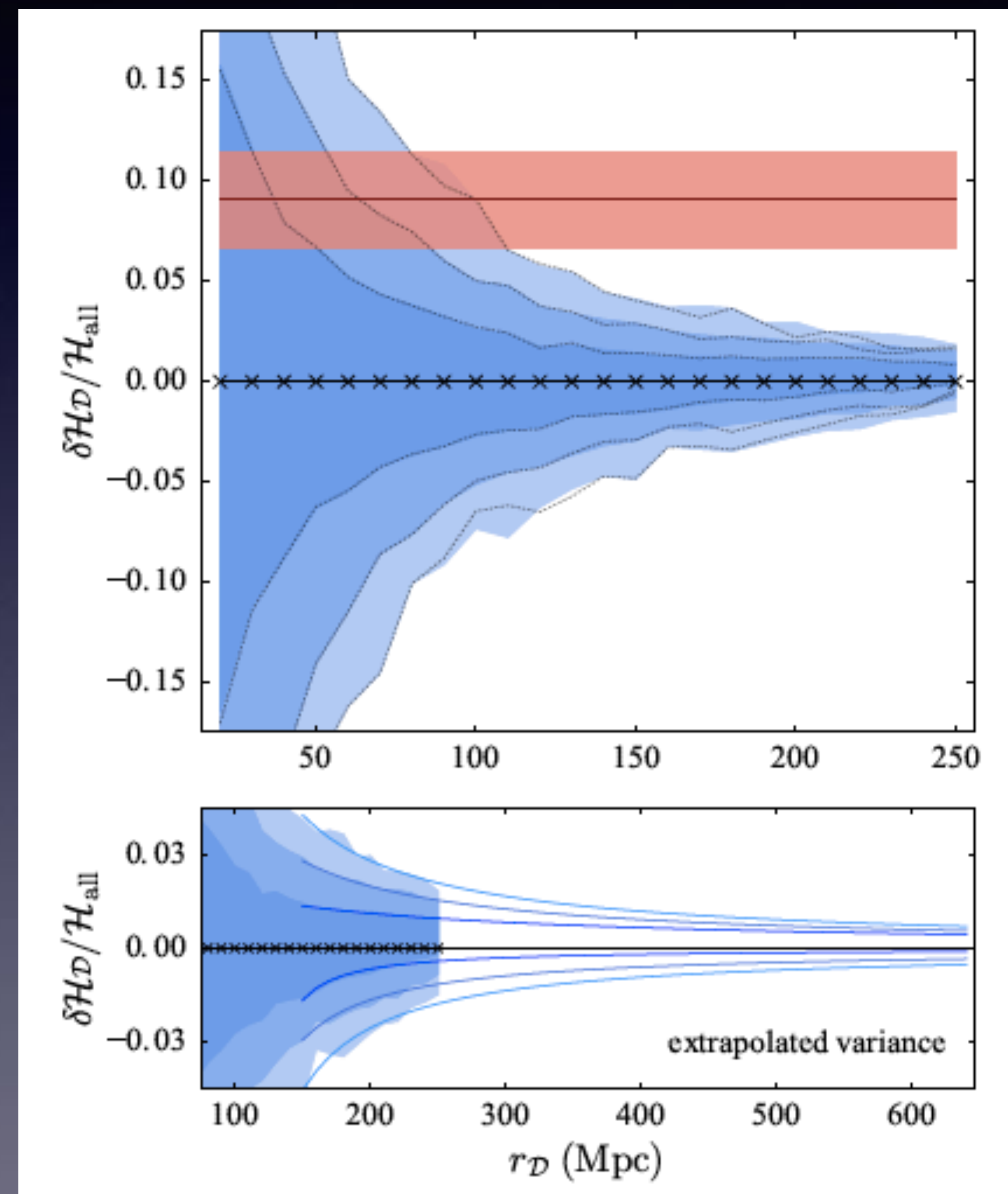



Figure 8. Hubble diagram for the Foundation DR1 sample and residuals to a fiducial ΛCDM model (lower panel). Error bars do not include uncertainties related to peculiar velocities (which are represented by the dotted curves in the lower panel) and redshift uncertainties.

Foley et al 2018




Macpherson et al 2018

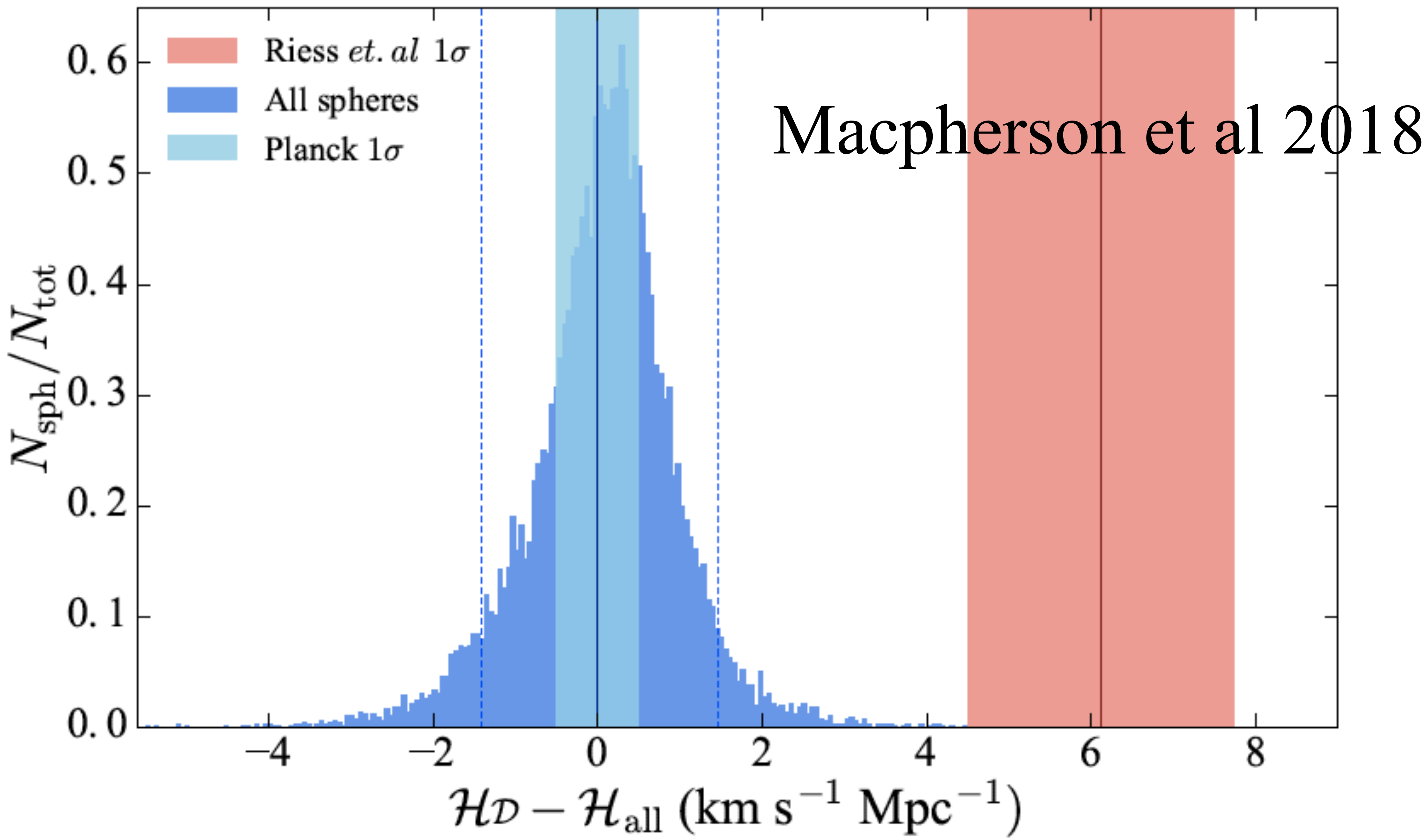



**Figure 3.** Local deviations in the Hubble parameter due to inhomogeneities. We show the full distribution of all spheres in the range $75 < r_\mathcal{D} < 180\,h^{-1}$ Mpc in blue. The dashed blue lines represent the $1\sigma$ deviation of the inhomogeneous distribution. The blue shaded region represents the $1\sigma$ uncertainties on the Planck Collaboration et al. (2016) measurement, while the solid red line and shaded region represent the mean and $1\sigma$ deviation in the Riess et al. (2018a) measurement, respectively.

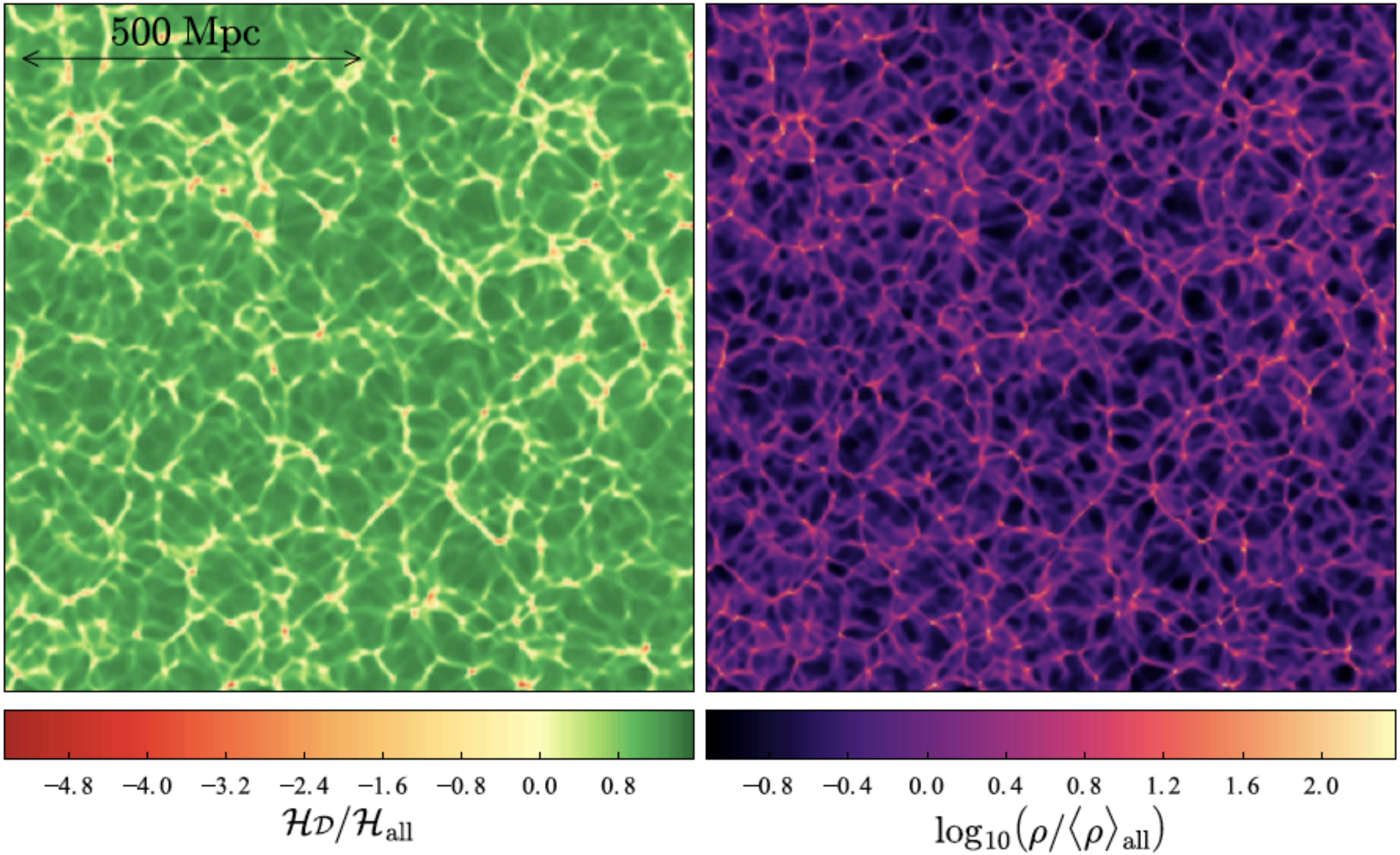



**Figure 1.** Expansion rate and density of an inhomogeneous, anisotropic universe. Left panel shows the deviation in the Hubble parameter relative to the global mean $\mathcal{H}_{\rm all}$. Right panel shows the density distribution relative to the global average, $\langle\rho\rangle_{\rm all}$. Both panels show a slice through the midplane of a $256^3$ resolution simulation with $L = 1$ Gpc.

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# Summary : Fact Sheet

- 150Mpc (BAO scale) represents the local universe
- All Sky Survey is needed
- $\sigma 8$ is the measure of fluctuation amplitude, $\sigma 100$ is about 2%
- Redshift is a sum of peculiar velocity + Hubble Flow
- By using SNIa, we can extract peculiar velocity to prove local density fluctuations
- With 100 SNeIa, CMB Dipole is seen
- $z<0.05$ SNeIa were threw away in the past for SNIa cosmology business

# Discussion ($z<0.05$ Science)

- Peculiar Velocity = Local Density Field
- Local Density Field can be modeled
- Supergalactic Plane can be mapped
- Are we in a void?
- Local Density Map can be drawn from 10,000 SNeIa
- How do we get SNIa Spectra?
- Southern Hemisphere Facilities are needed
- Inhomogeneous Expansion of the Universe should be detectable