Anisotropy of the Hubble Flow

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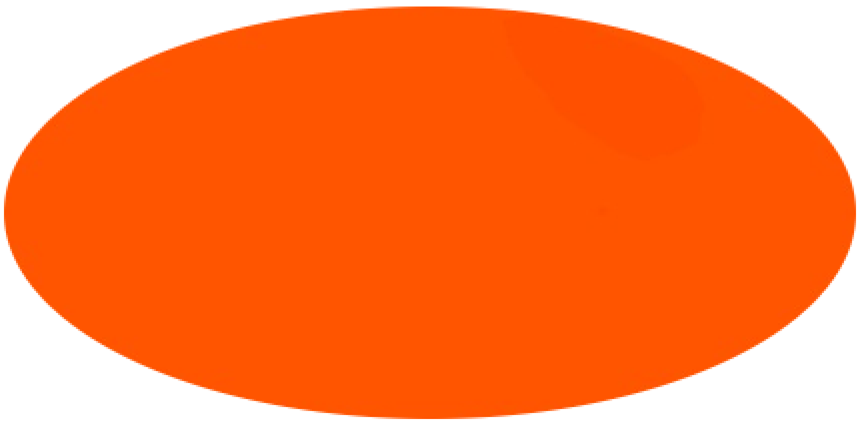
THE UNIVERSITY OF SYDNEY

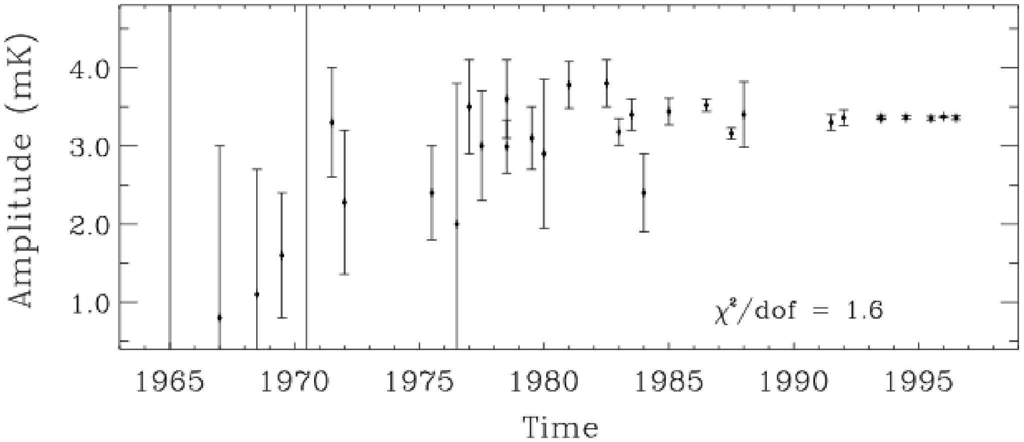
Australian Government
Australian Research Council

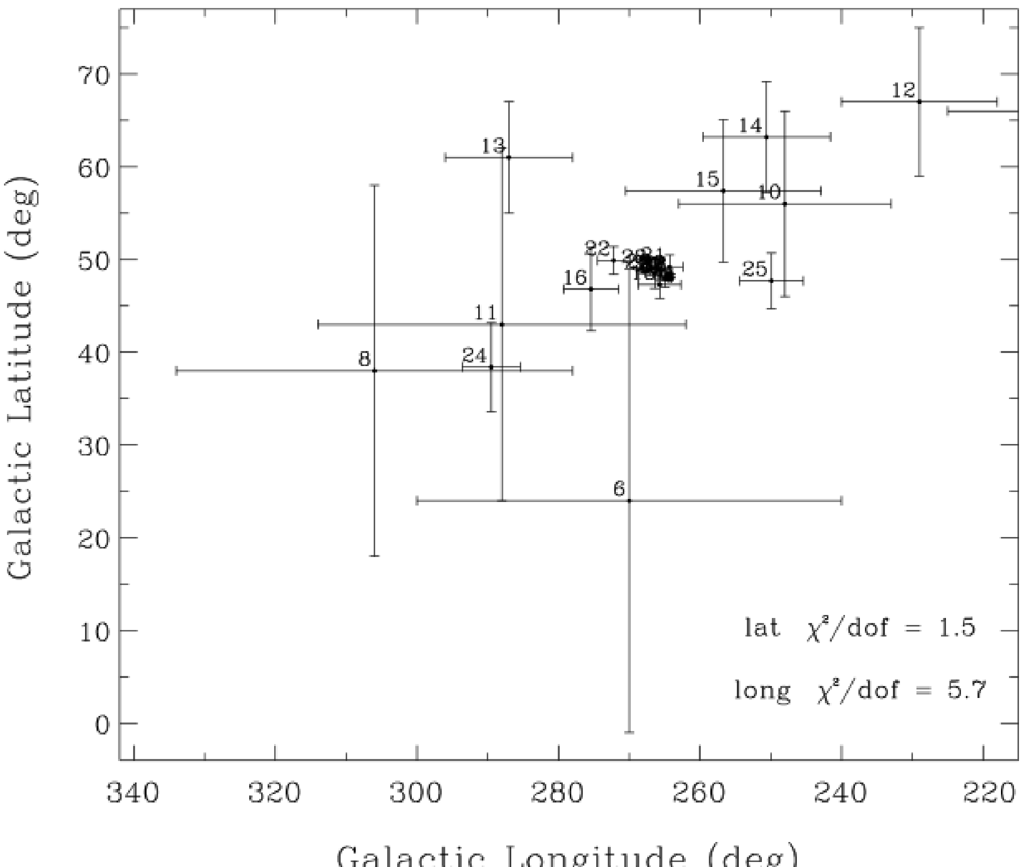
ANITA
Australian National Institute for Theoretical Astrophysics

20 July 2016, Cairns

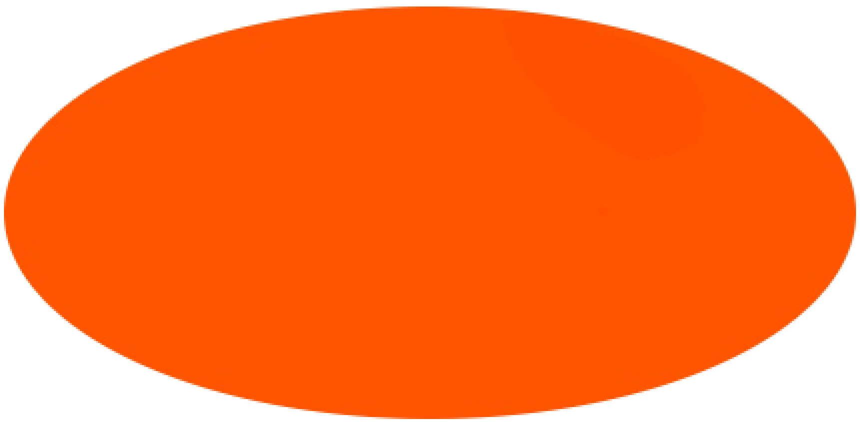
Diving into the Dark: Bridging Cosmological Theory and Observation

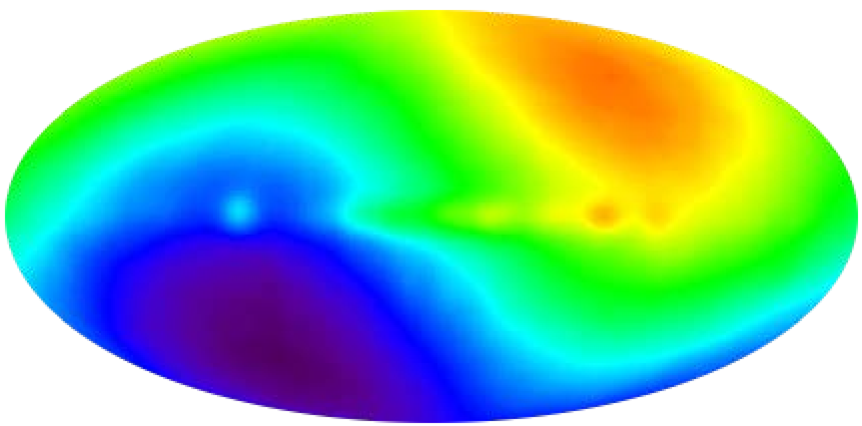


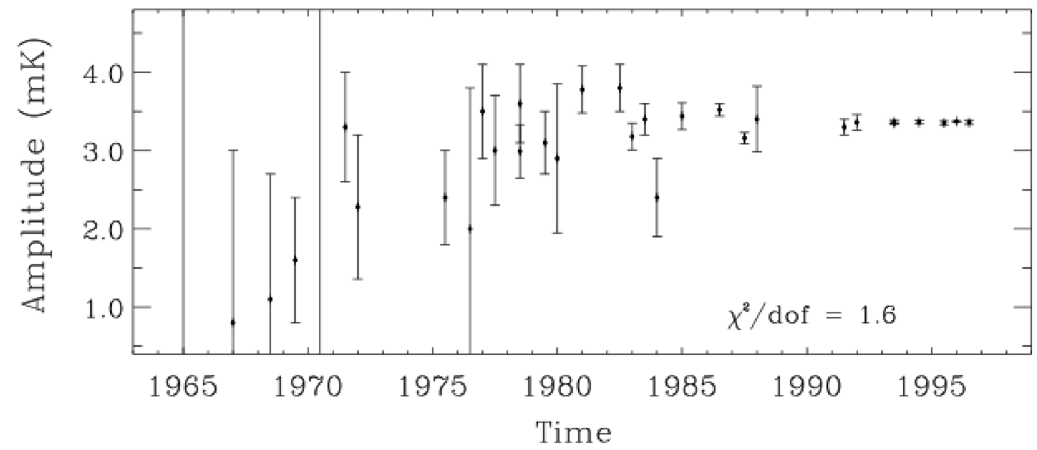


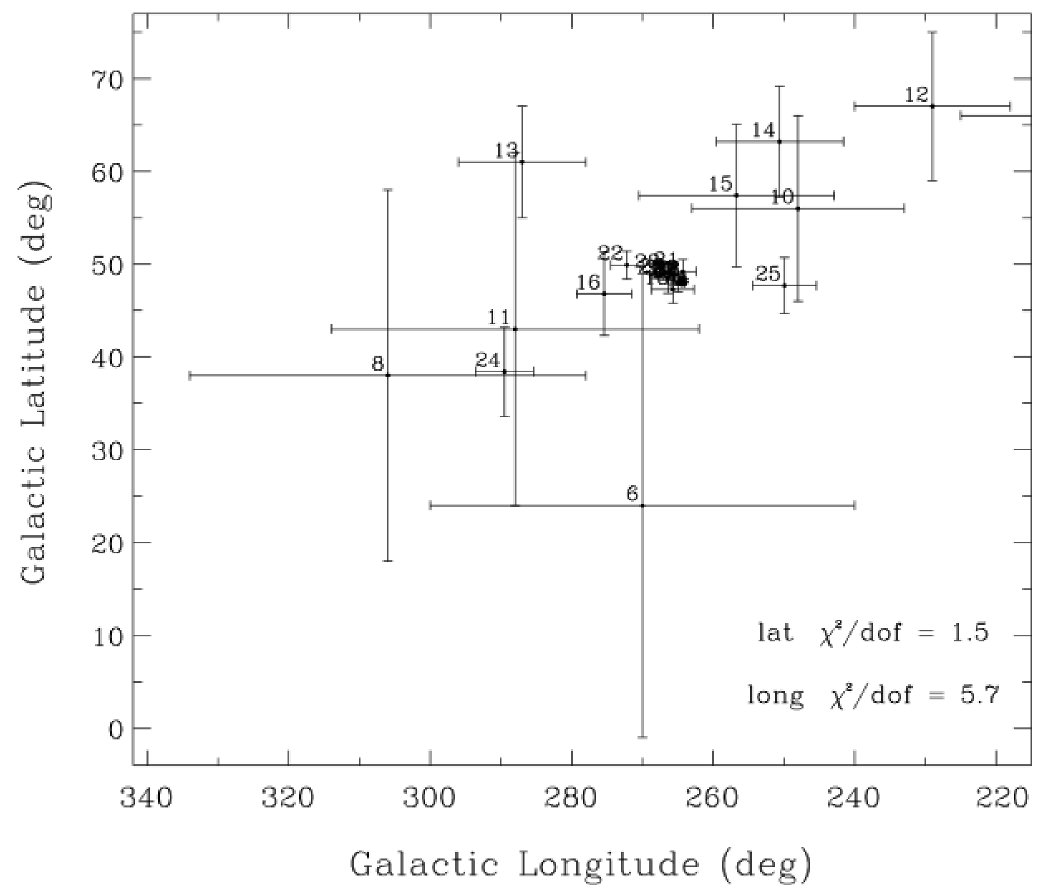


Lineweaver (1996)









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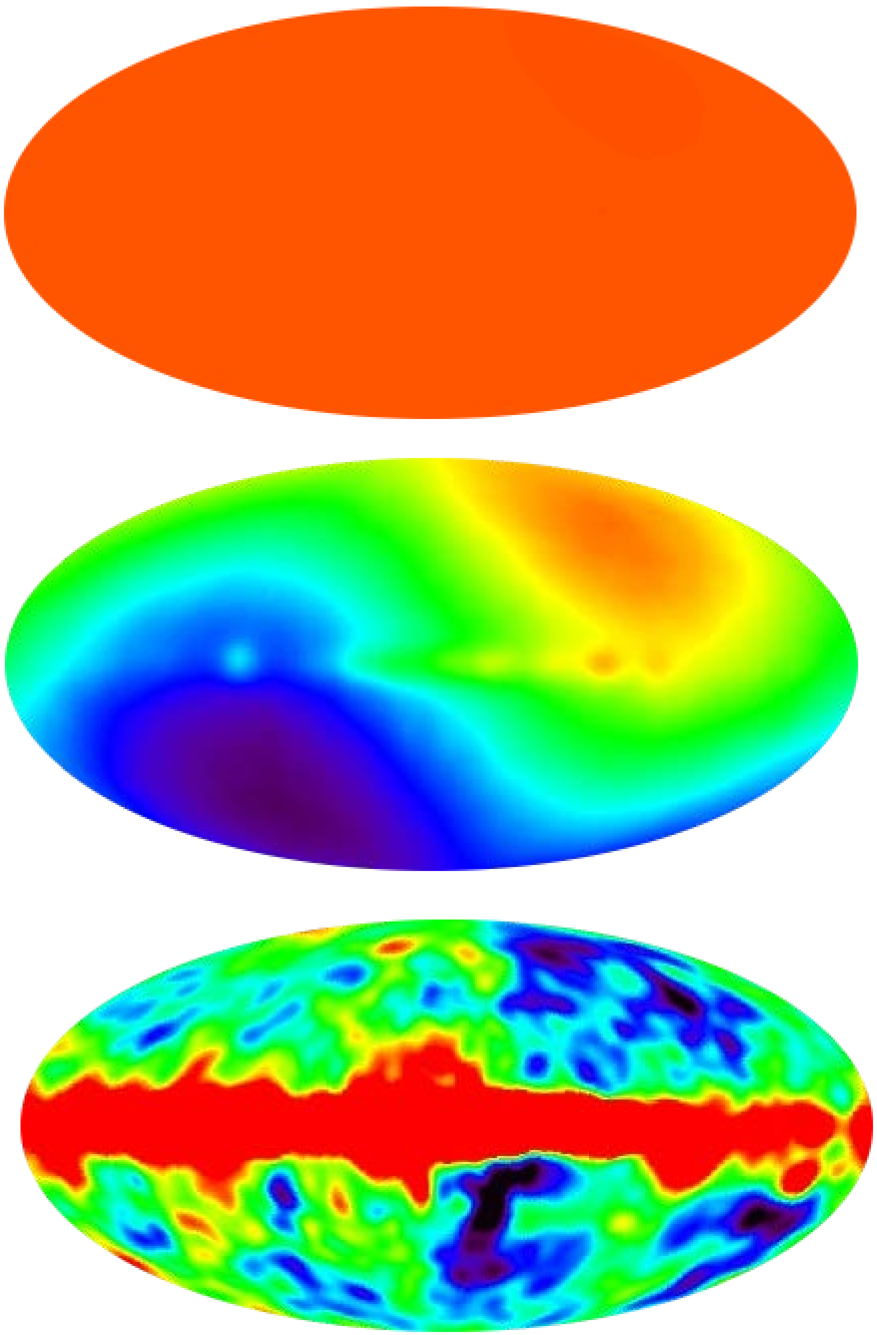

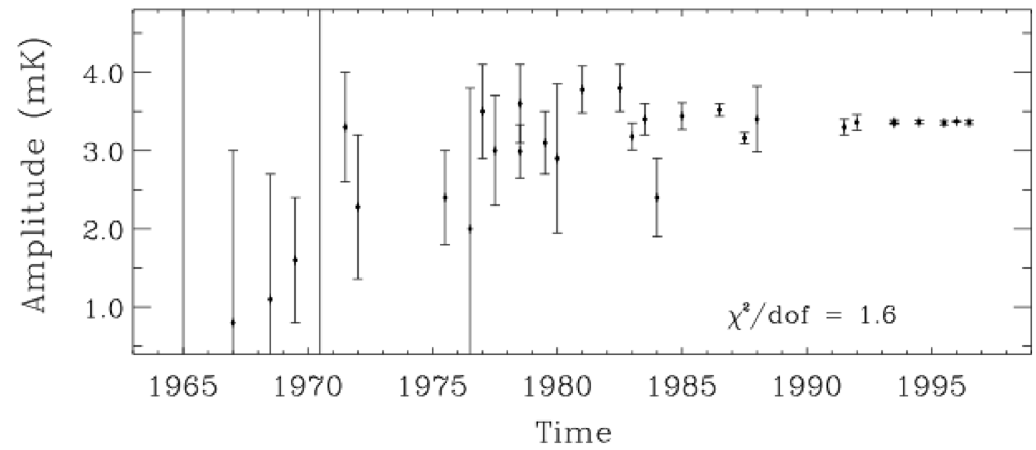

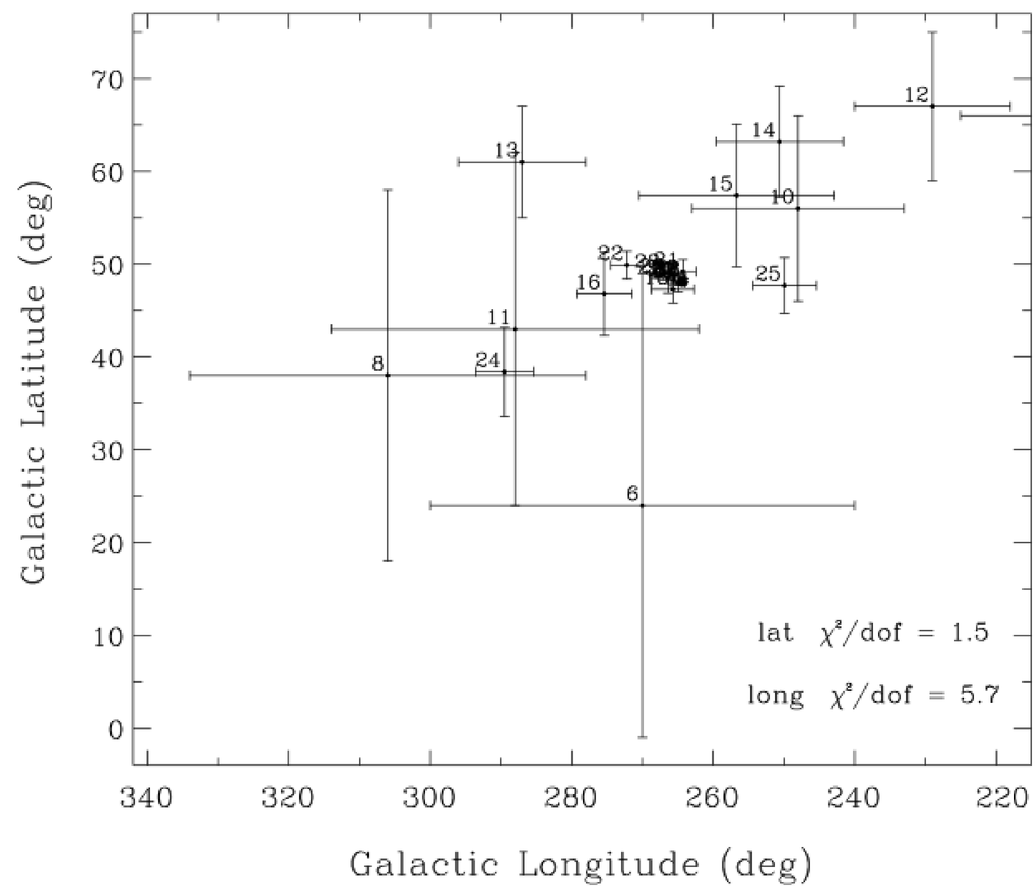

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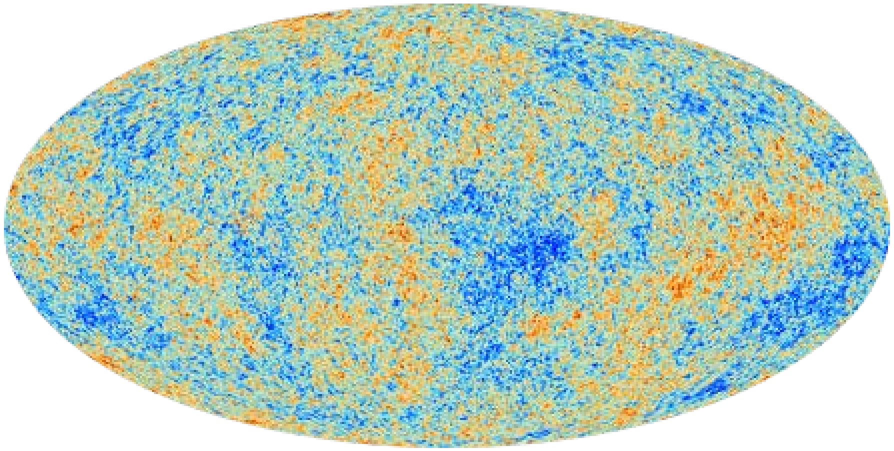

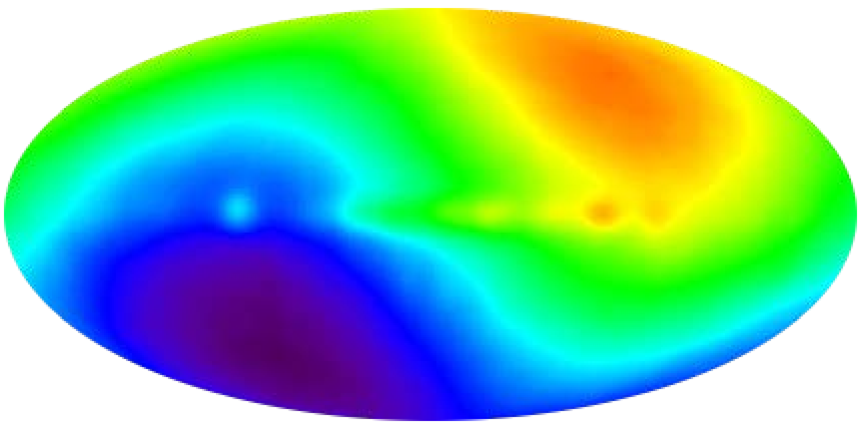

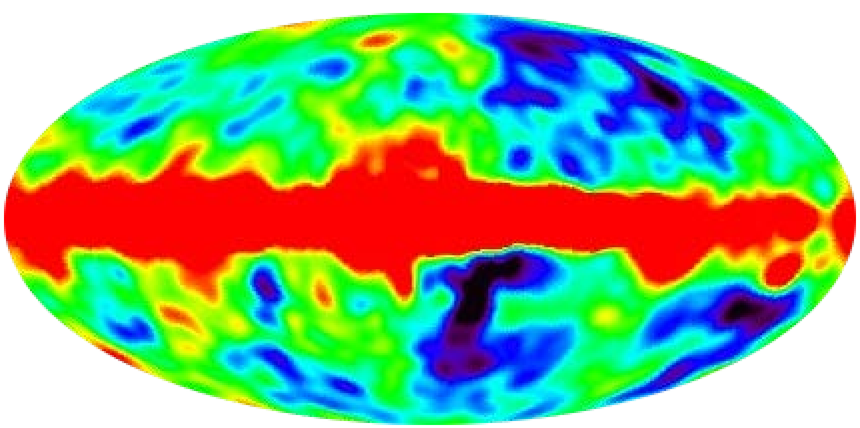

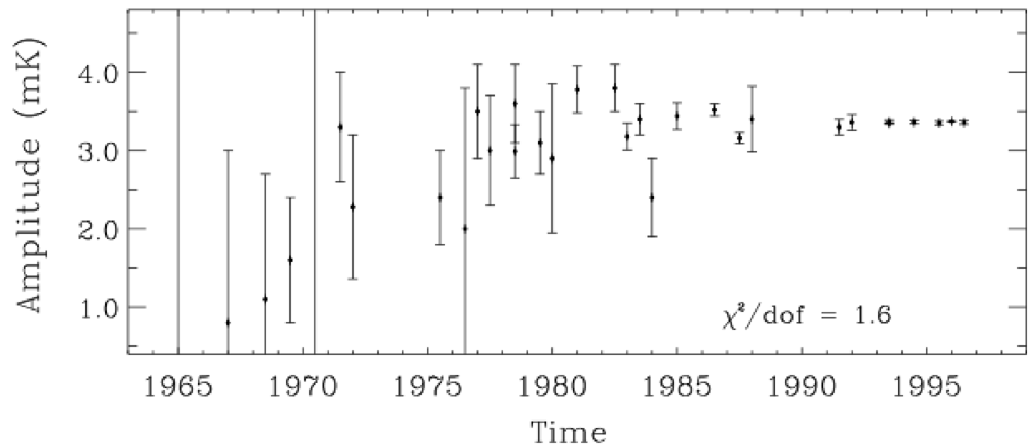

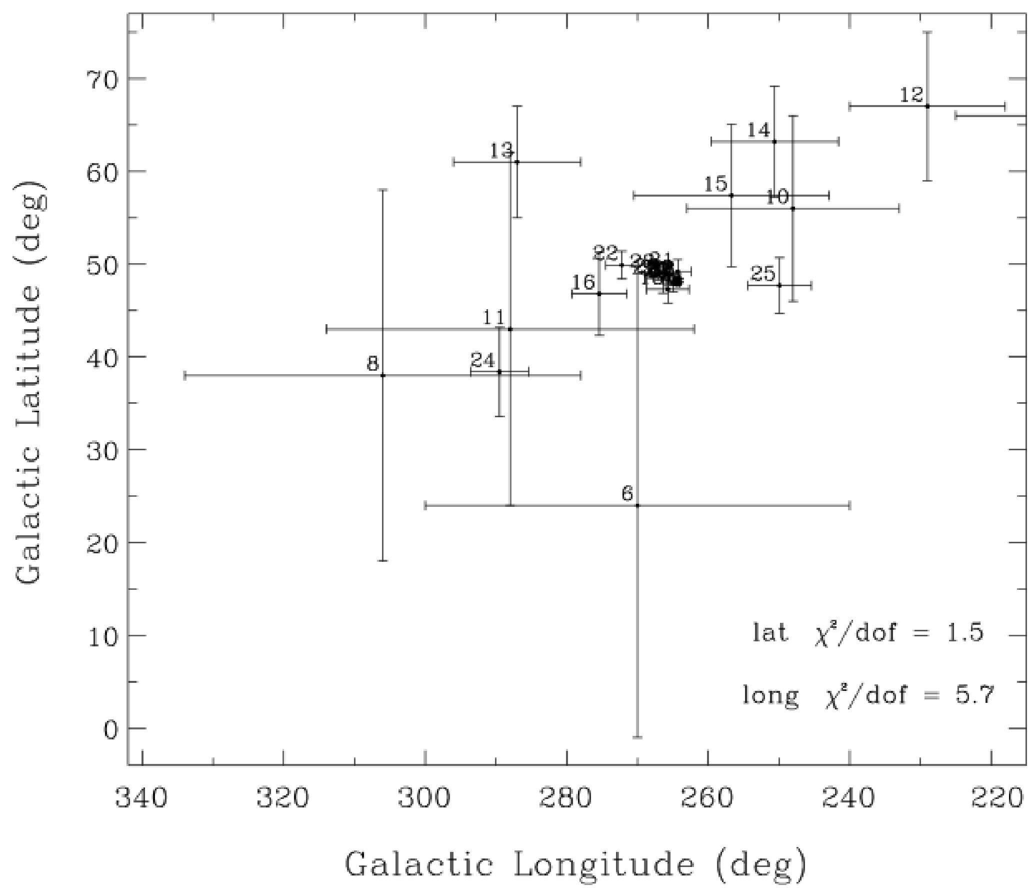

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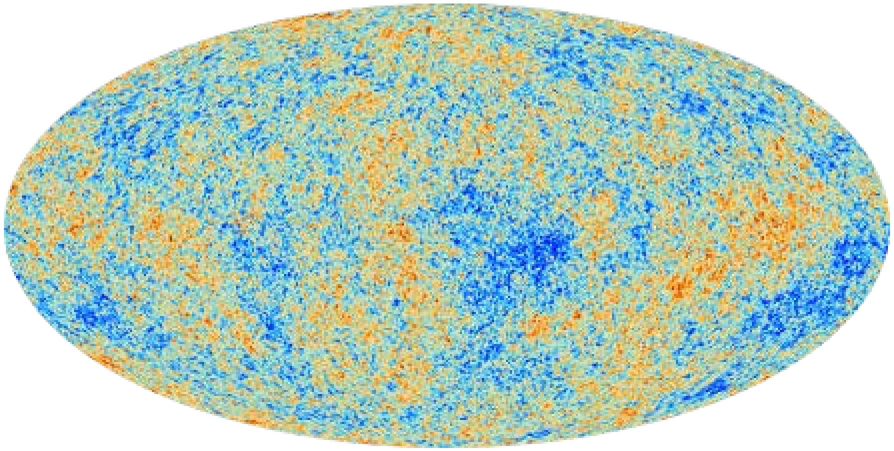
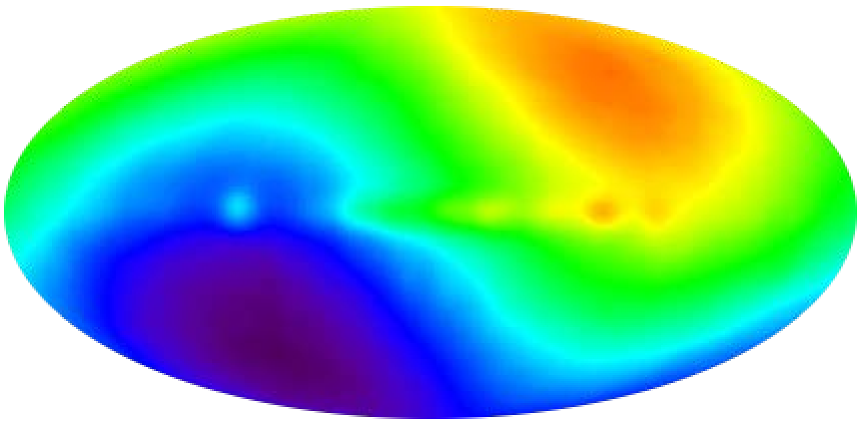
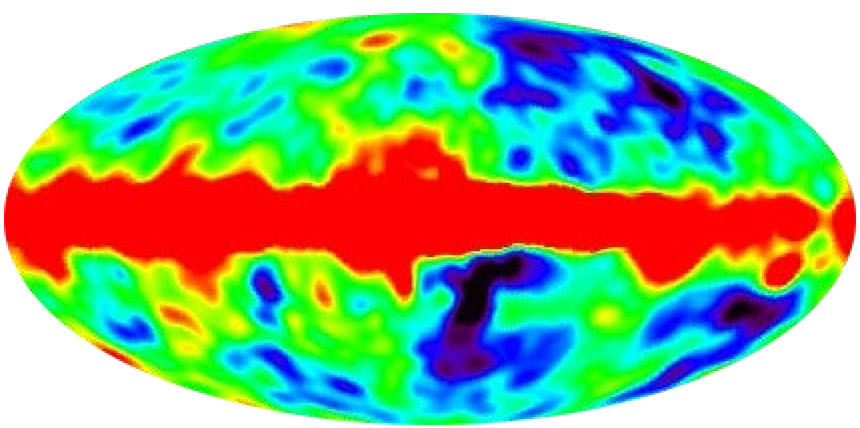
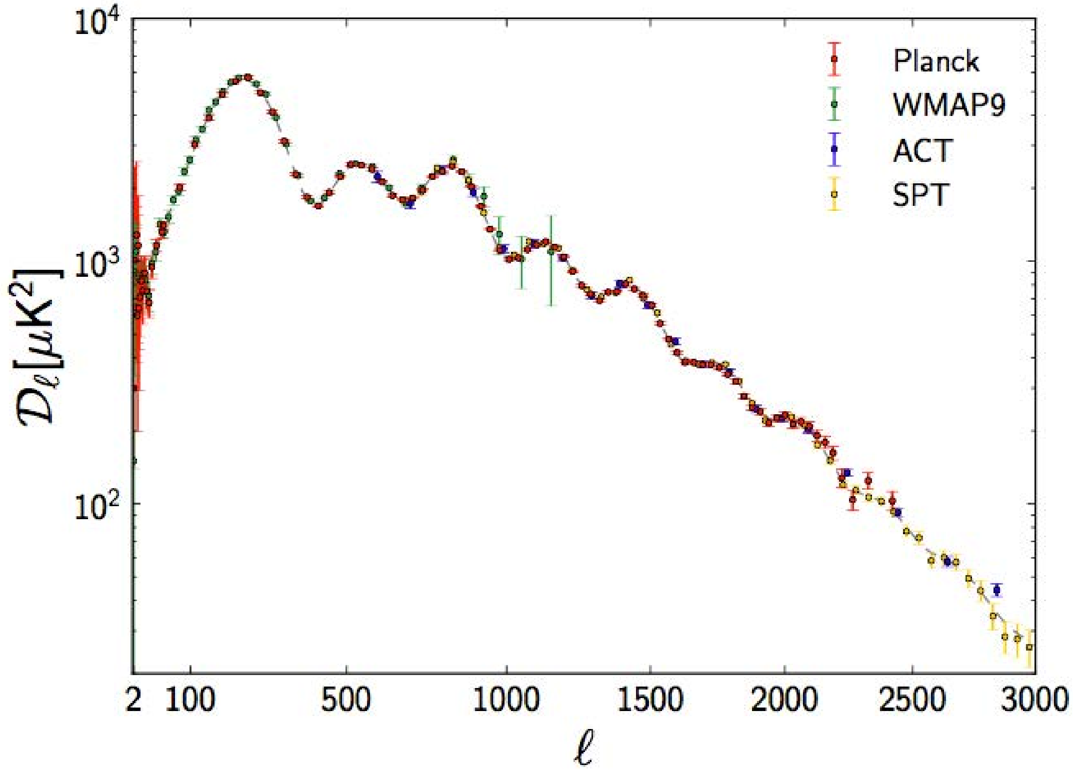
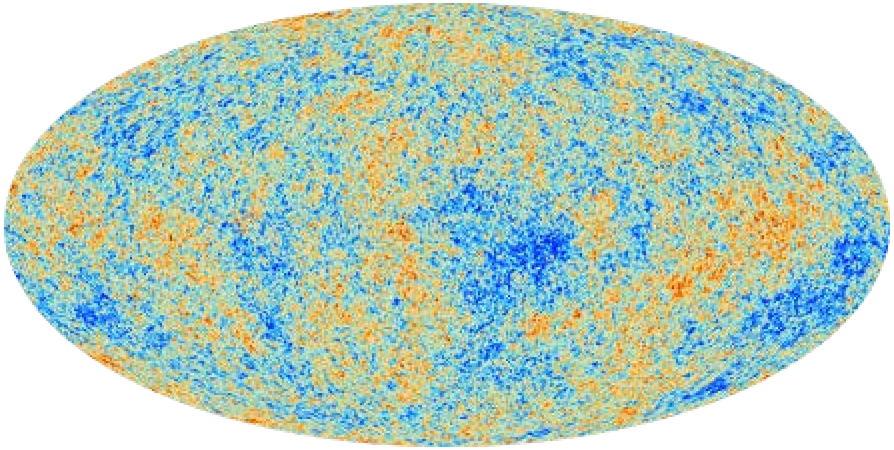
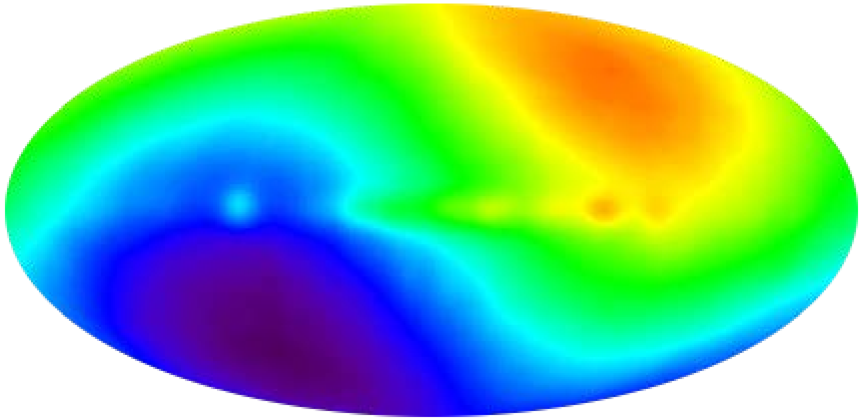


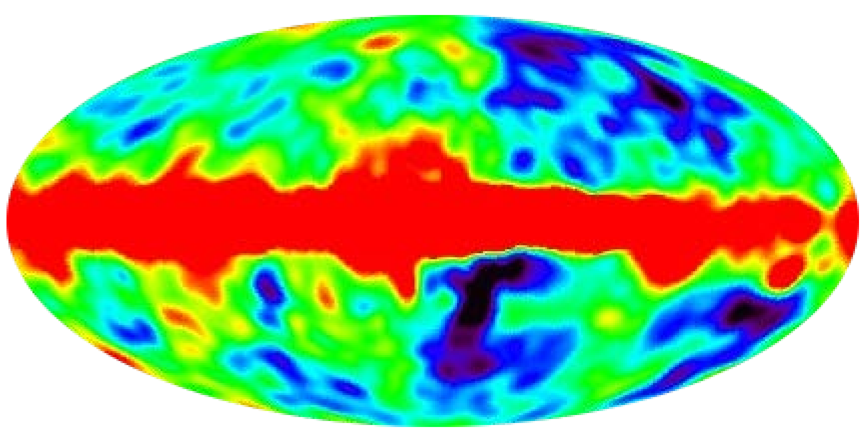


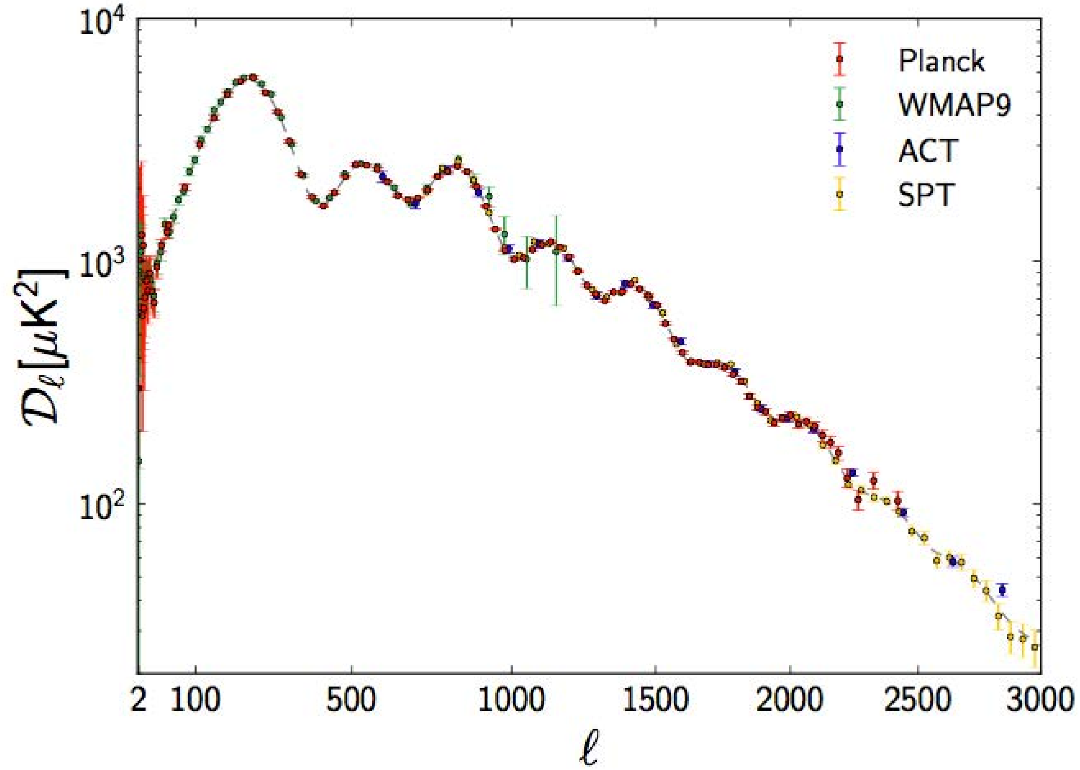



Planck
WMAP9
ACT
SPT
$\mathcal{D}_\ell[\mu K^2]$
10^4
10^3
10^2
2 100 500 1000 1500 2000 2500 3000
ℓ



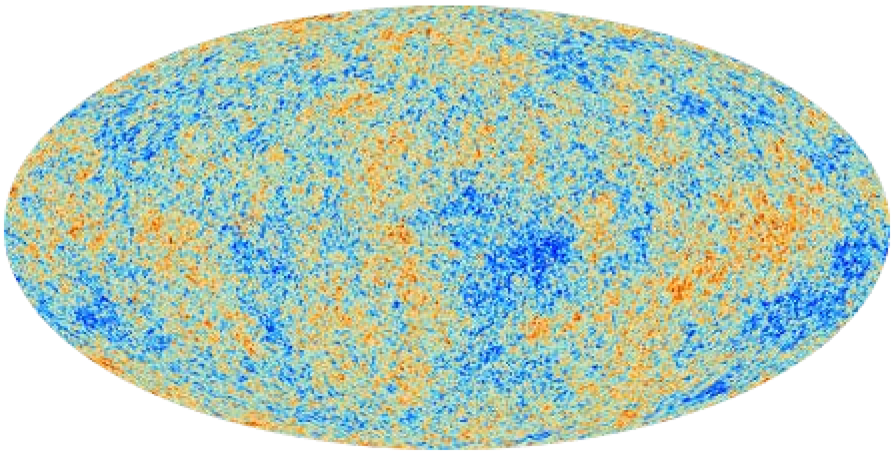


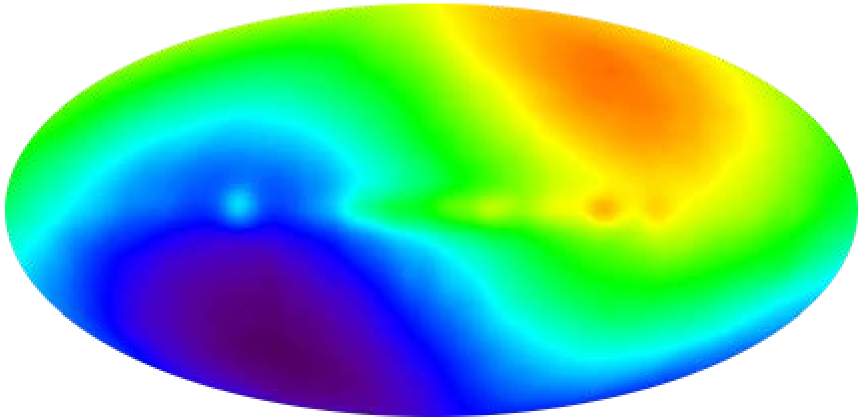


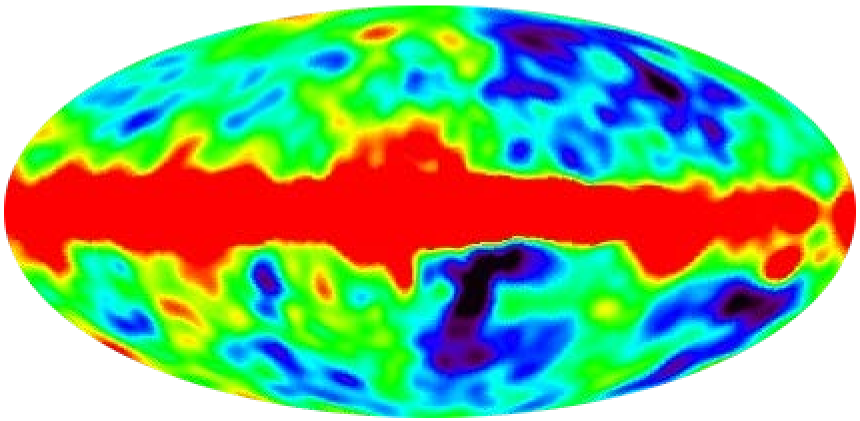


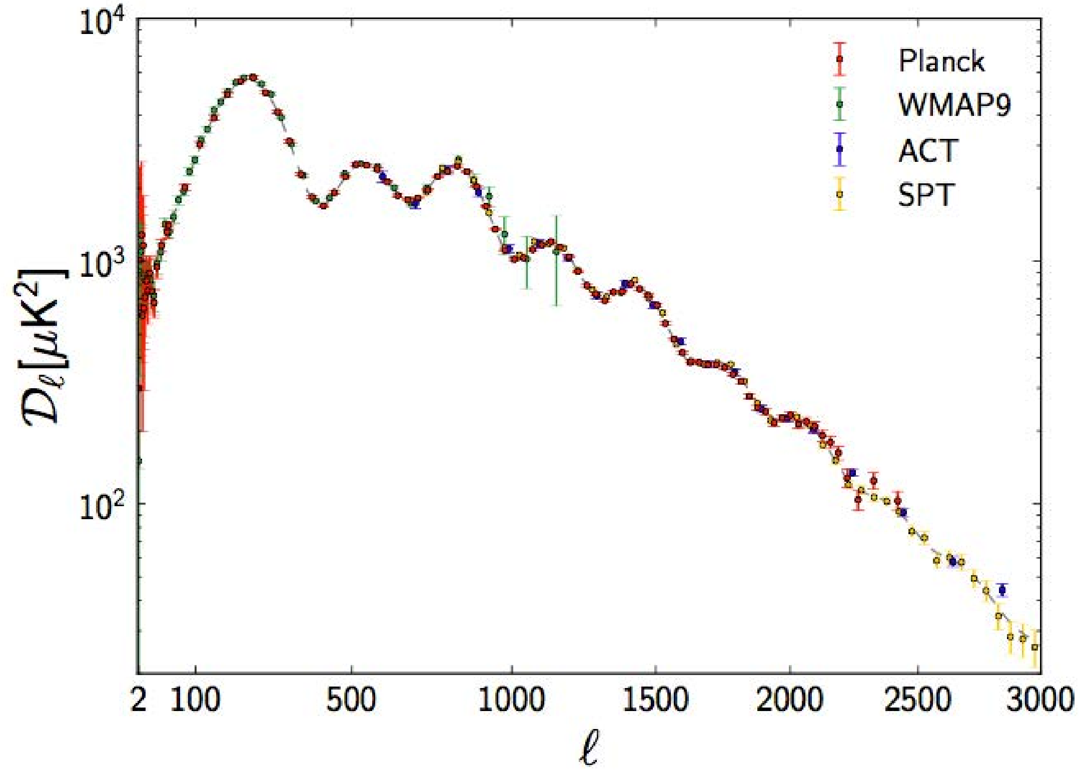
Exquisite tool but…

it is sensitive to *mostly* to physics of the early Universe.









Exquisite tool but…

it is sensitive to *mostly* to physics of the <u>early Universe.</u>

<u>Late Universe</u>:

- modified gravity
- modified geometry
- evolving curvature...

Anisotropy of the Hubble Flow

Hubble Flow

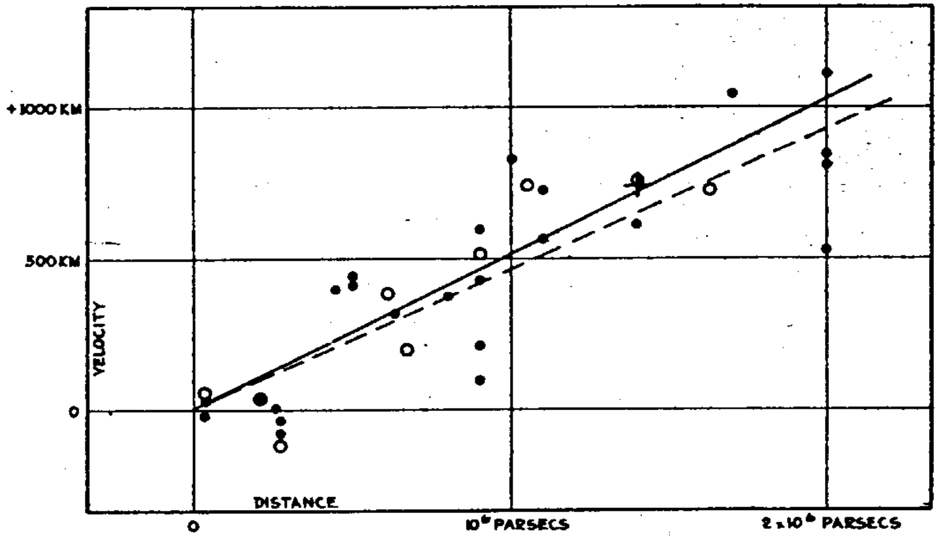
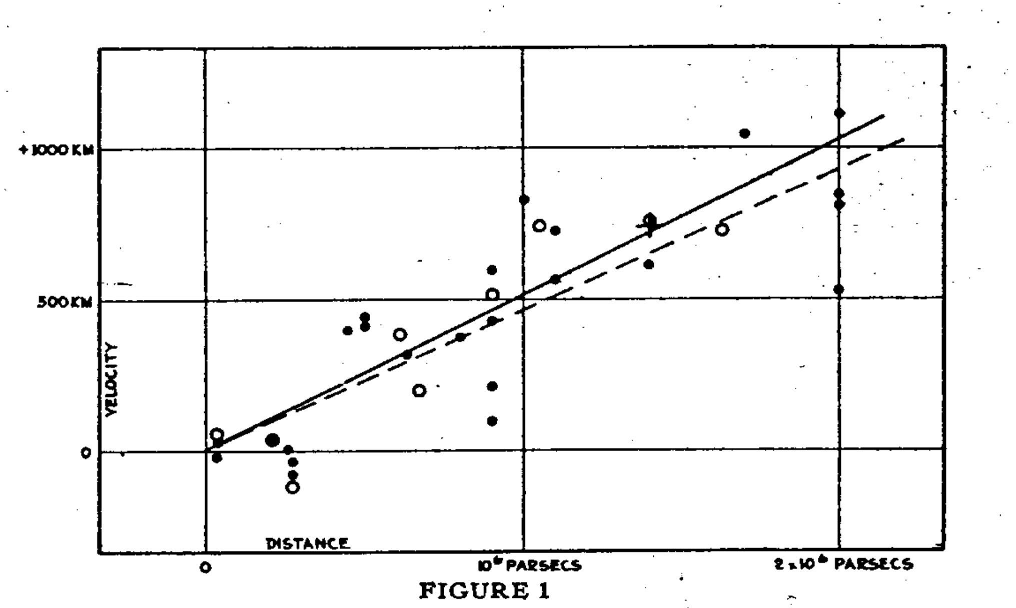


FIGURE 1

Hubble (1929)

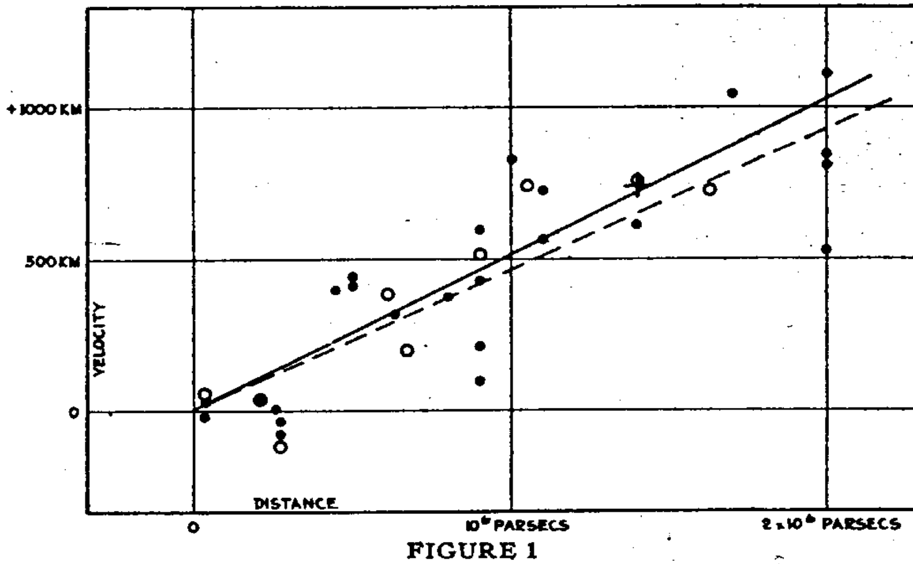
Hubble Flow



Hubble (1929)

$$cz = H_0 d$$

Hubble Flow

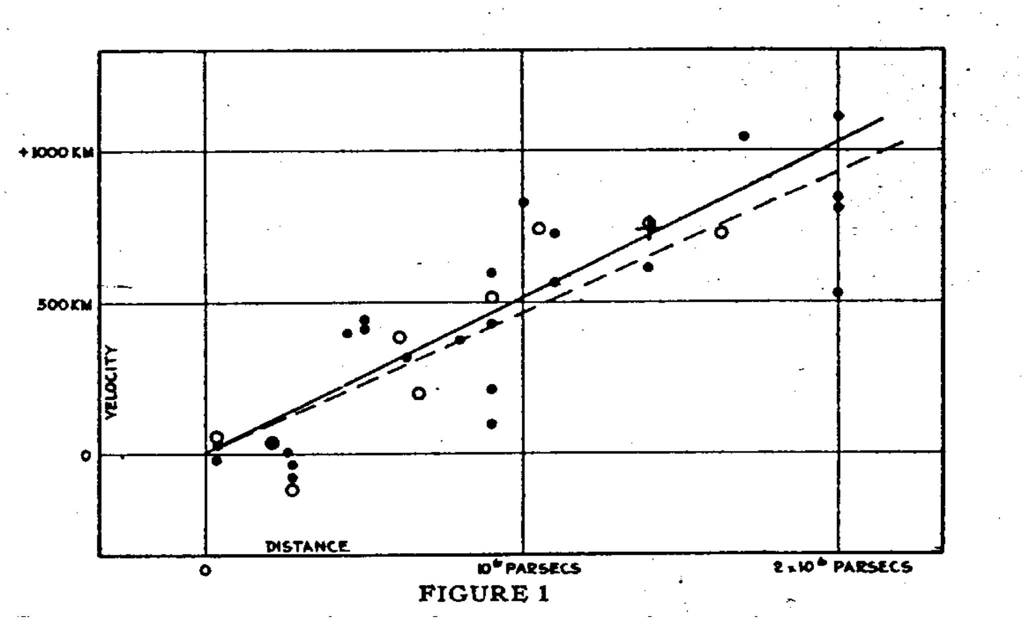


Hubble (1929)

$$cz = H_0 d$$

$$H_0 = \frac{cz}{d}$$

Hubble Flow



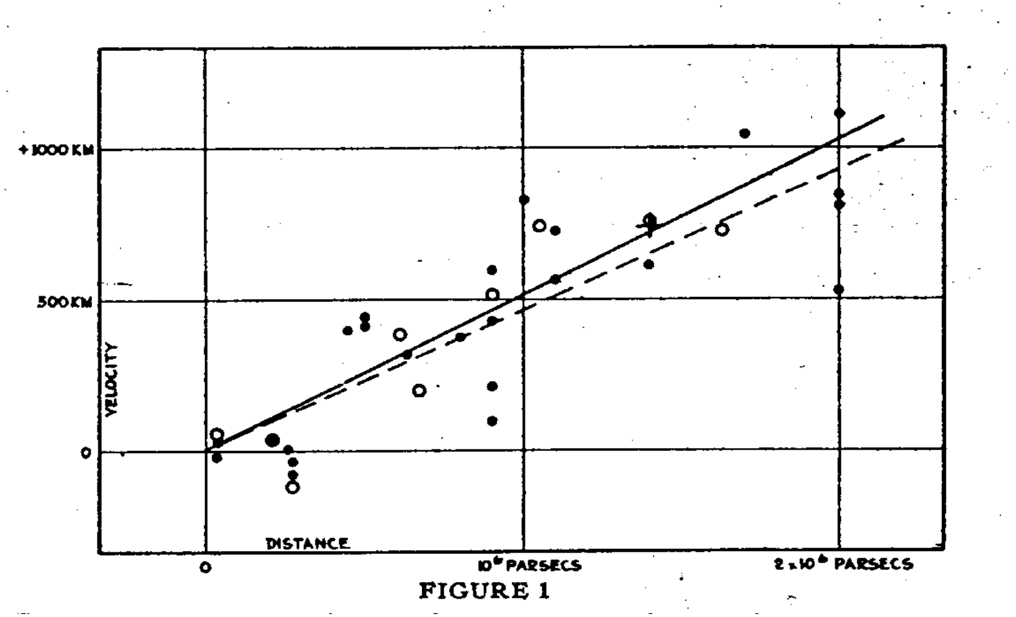
Hubble (1929)

$$cz = H_0 d$$

$$H_0 = \frac{cz}{d}$$

$$H_0 = \frac{c}{d}\left[z + \frac{1}{2}(1 - q_0) z^2 - \frac{1}{6}(1 - q_0 - 3q_0^2 + j_0) z^3\right]$$

Hubble Flow



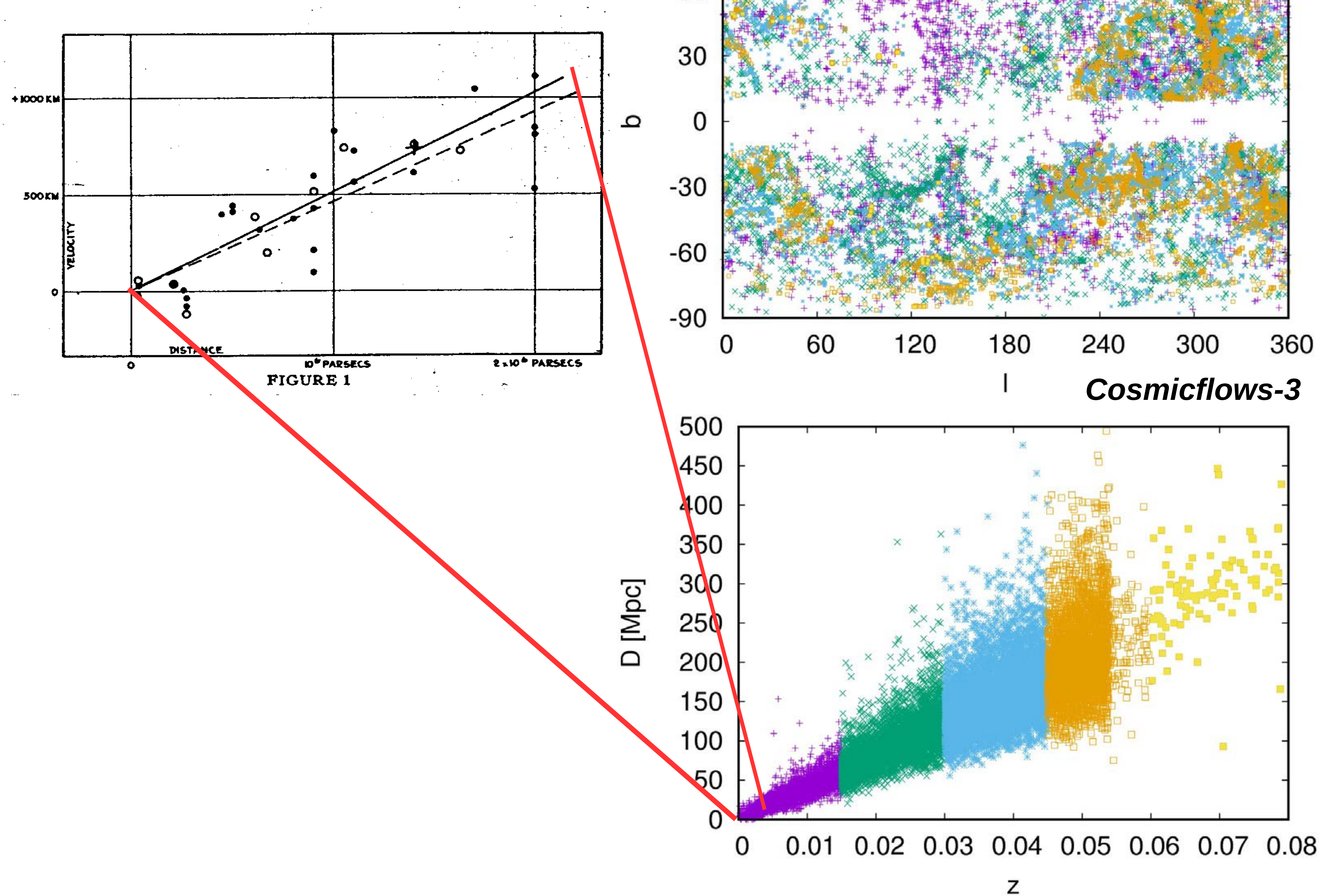
Hubble (1929)

$$cz = H_0 d$$

$$H_0 = \frac{cz}{d}$$

$$H_0 = \frac{c}{d}\left[z + \frac{1}{2}(1 - q_0) z^2 - \frac{1}{6}(1 - q_0 - 3q_0^2 + j_0) z^3 \right]$$

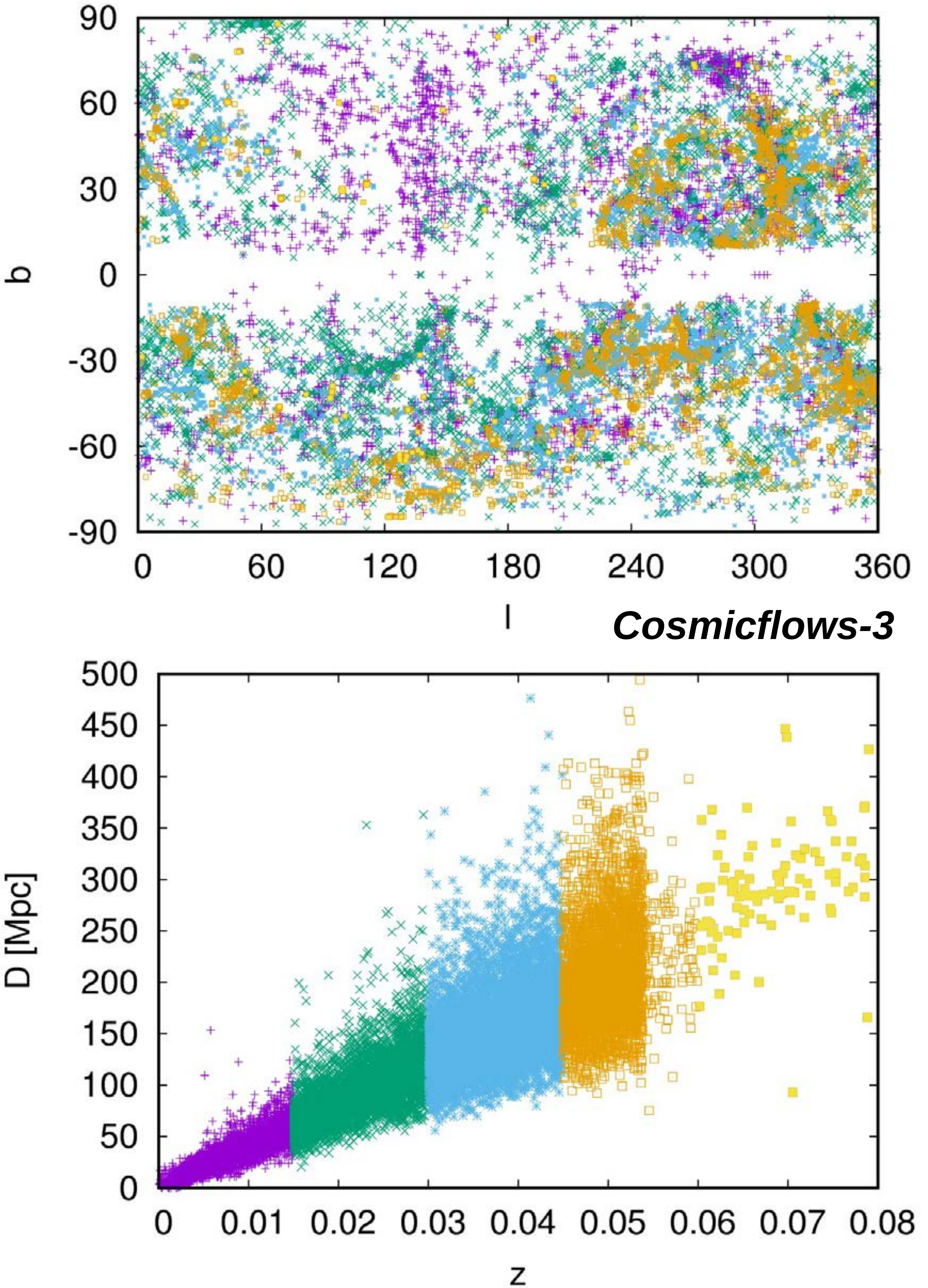
Hubble Flow



+1000 KM
500 KM
0
VELOCITY
DISTANCE
0
10^6 PARSECS
2×10^6 PARSECS
FIGURE 1
b
90
60
30
0
-30
-60
-90
0
60
120
180
240
300
360
l
Cosmicflows-3
D [Mpc]
500
450
400
350
300
250
200
150
100
50
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
z

Hubble Flow

$$H_0 = H_0(\vartheta, \varphi)$$

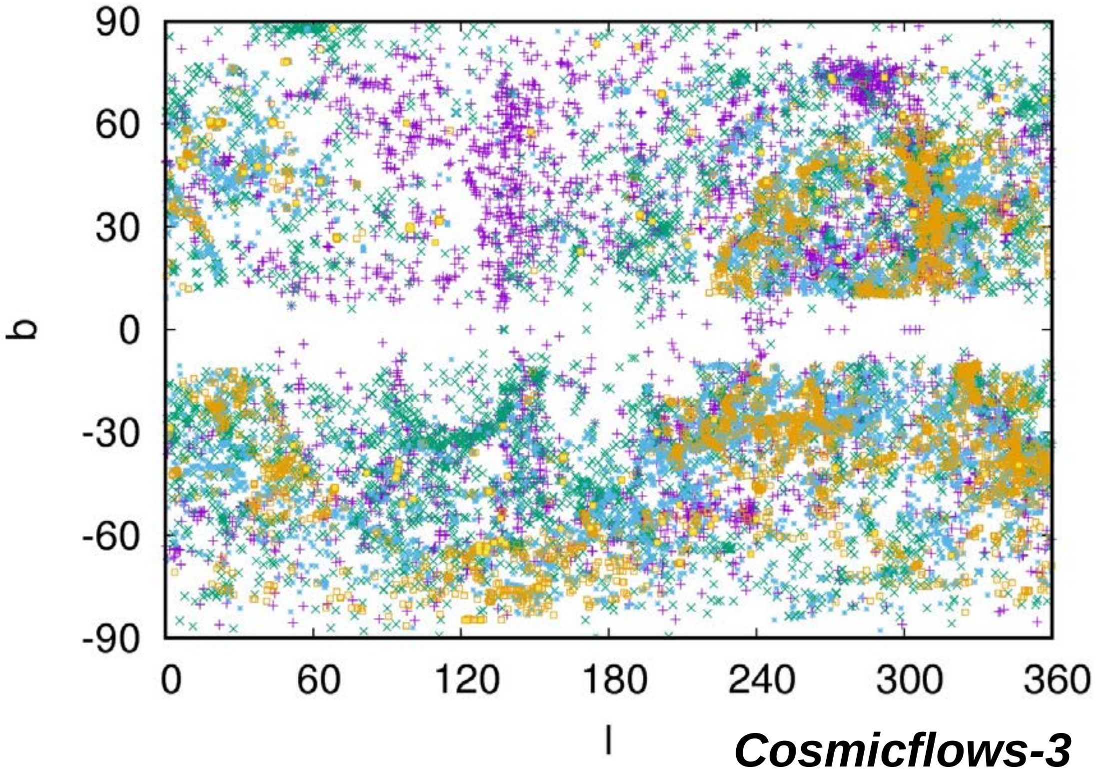


Cosmicflows-3

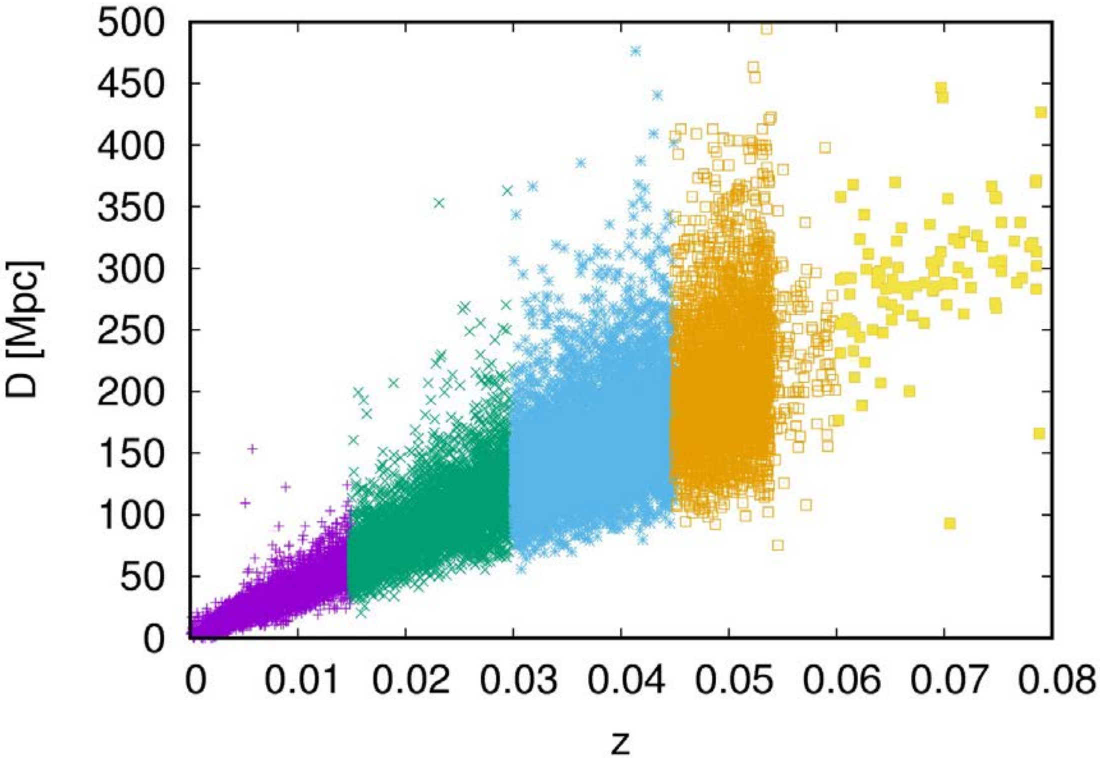
Hubble Flow

$$H_0 = H_0(\vartheta, \varphi)$$

$$H_0 = \sum_{l,m} a_{lm} Y_{lm}$$



Cosmicflows-3

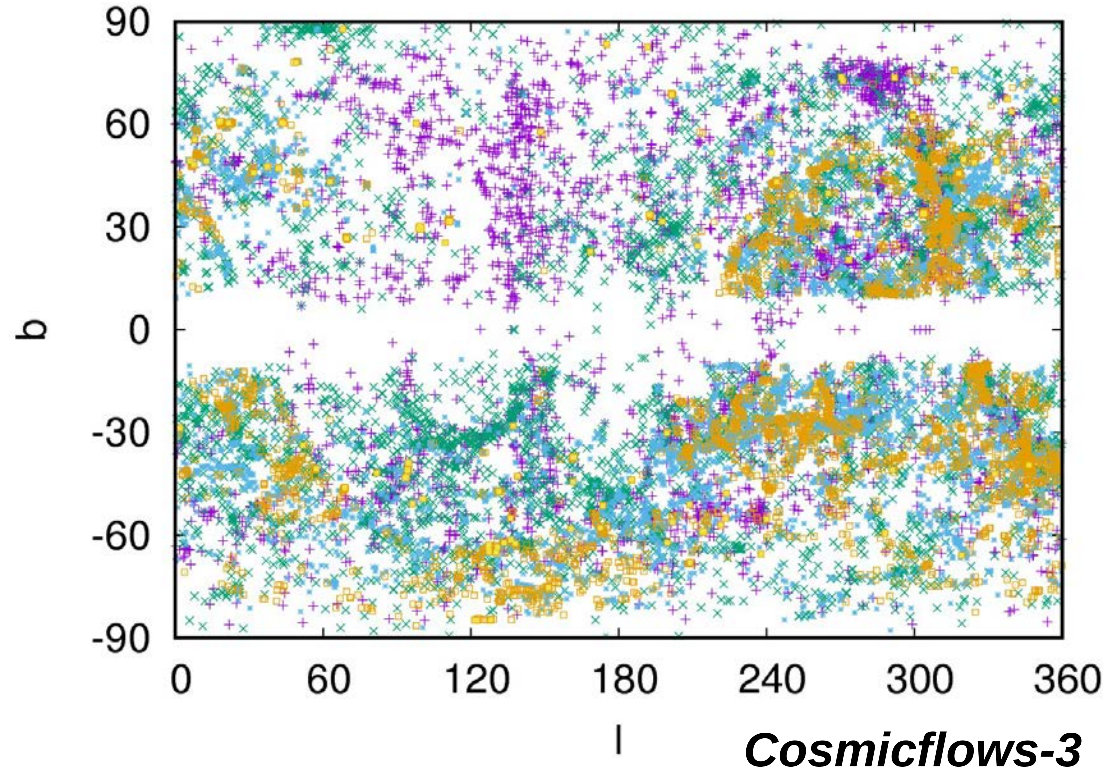


Hubble Flow

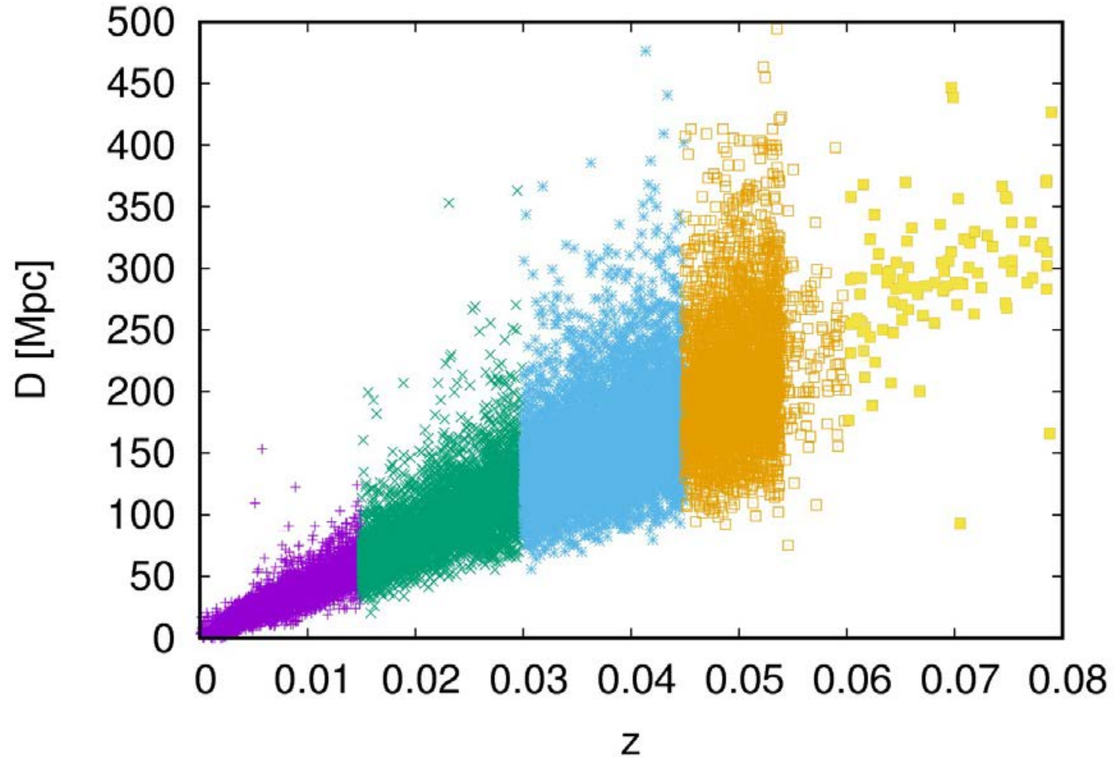
$$H_0 = H_0(\vartheta, \varphi)$$

$$H_0 = \sum_{l,m} a_{lm} Y_{lm}$$

$$C_l = \frac{1}{2l+1} \sum_m |a_{lm}|^2$$



Cosmicflows-3



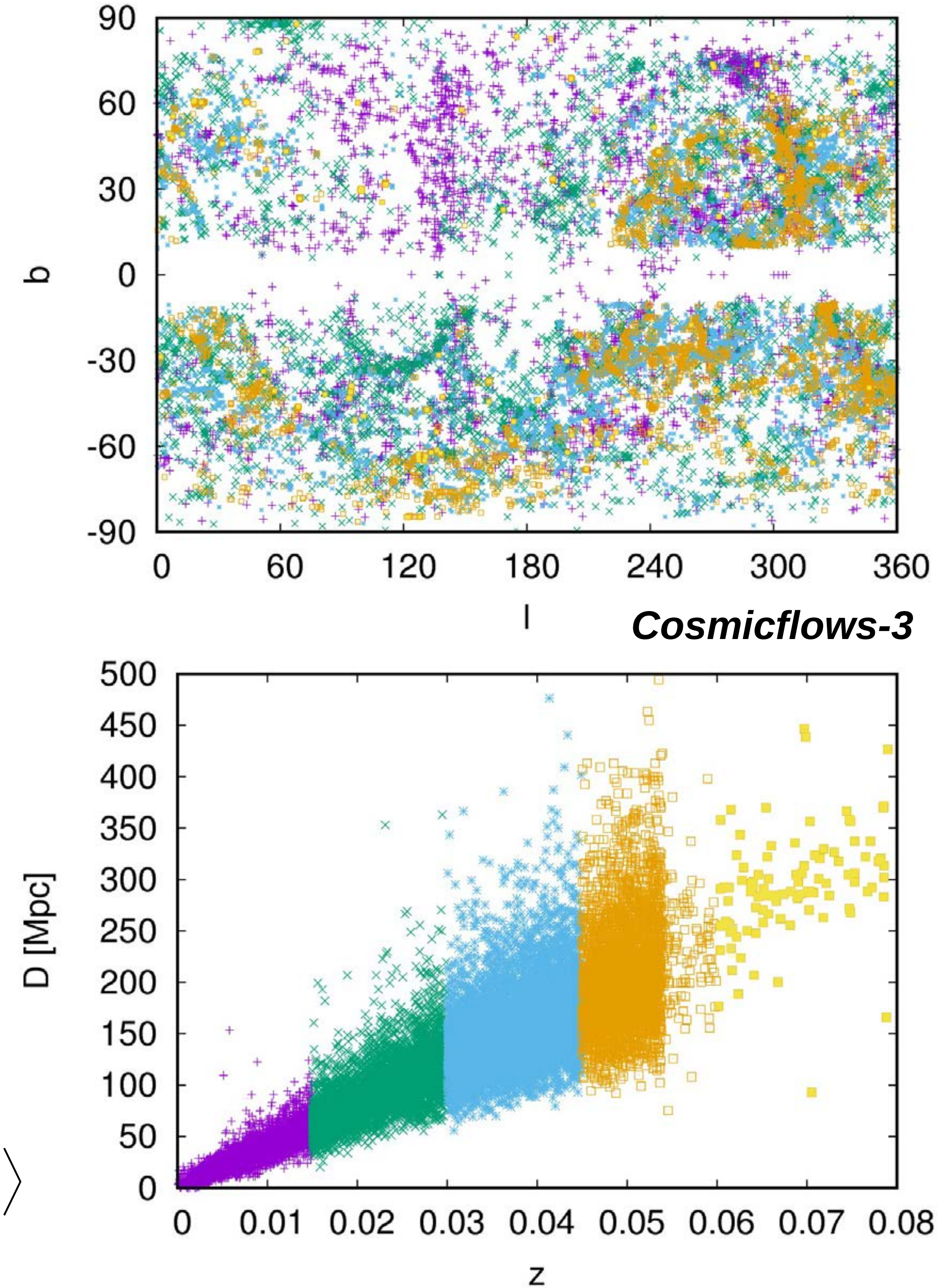
Hubble Flow

$$H_0 = H_0(\vartheta, \varphi)$$

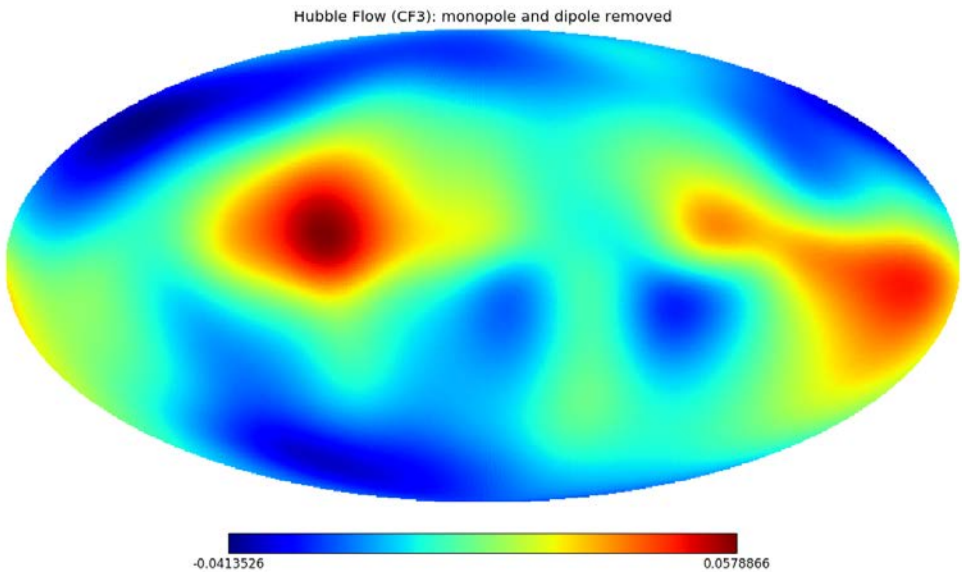
$$H_0 = \sum_{l,m} a_{lm} Y_{lm}$$

$$C_l = \frac{1}{2l+1} \sum_m |a_{lm}|^2$$

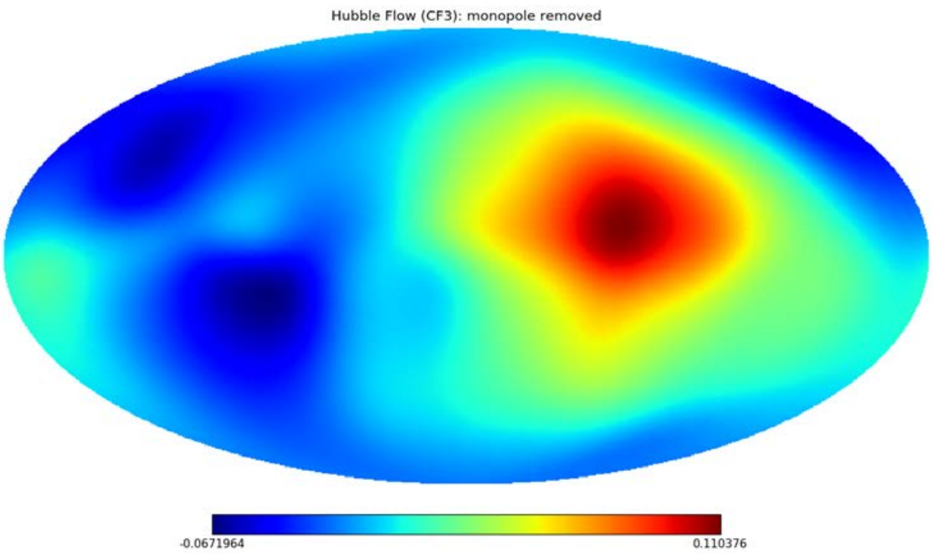
$$\langle \widetilde{C}_l \rangle = \sum_{l'} M_{ll'} B_{l'}^2 \langle C_{l'} \rangle + \langle N_l \rangle$$



Anisotropy of the Hubble Flow



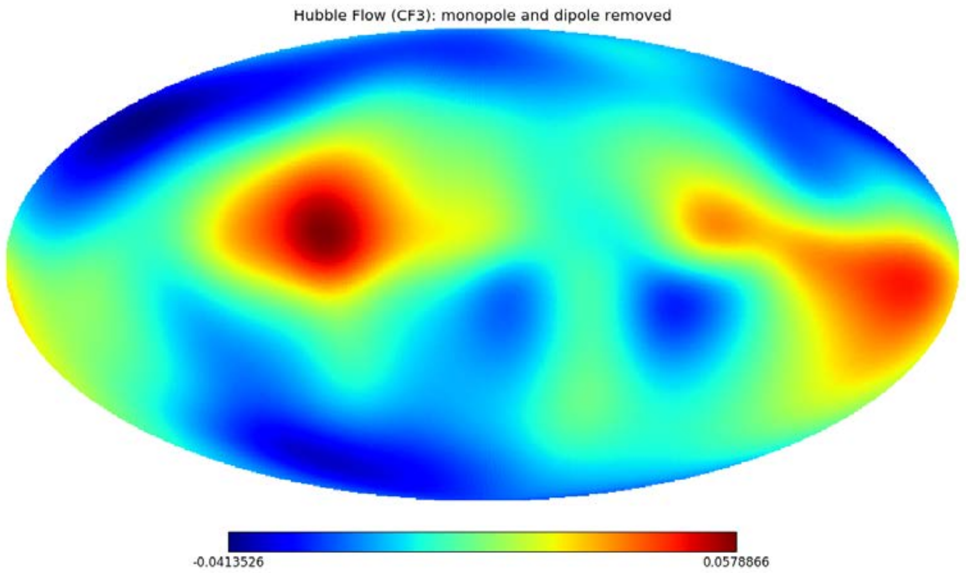
monopole and dipole removed



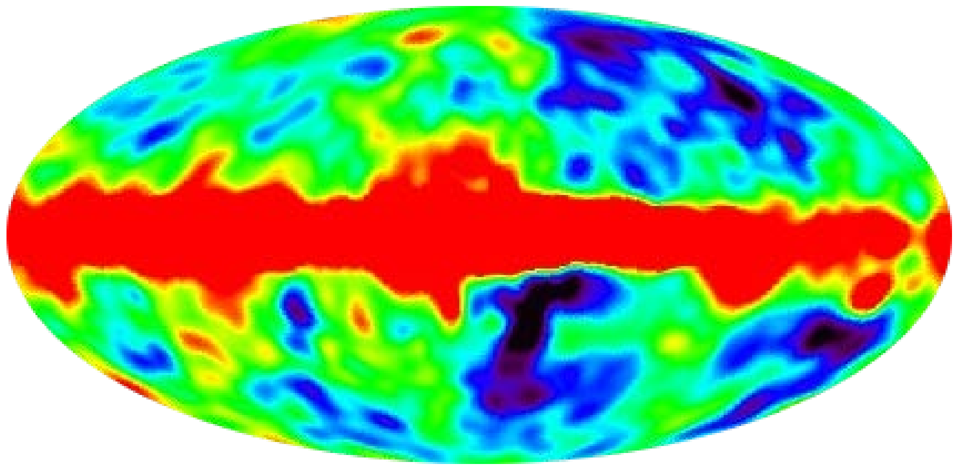
monopole removed

Data: *Cosmicflows-3*
Angular smoothing: *15º*

Anisotropy of the Hubble Flow

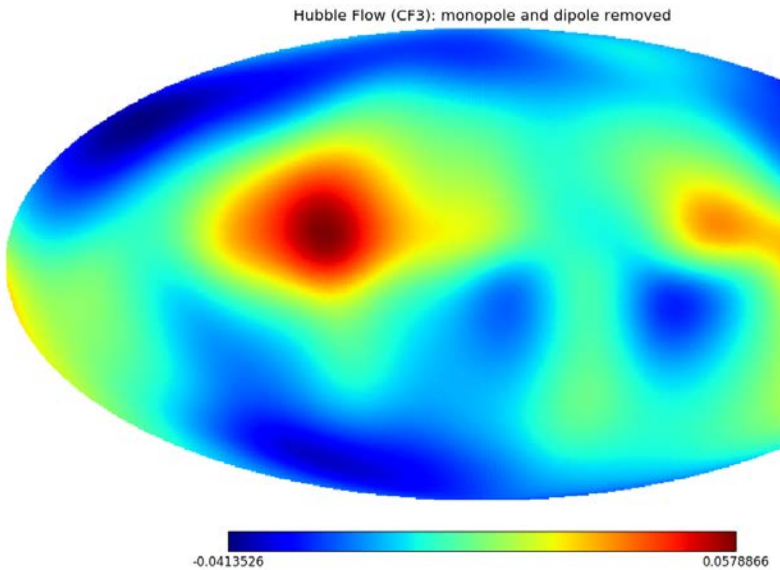


Hubble Flow

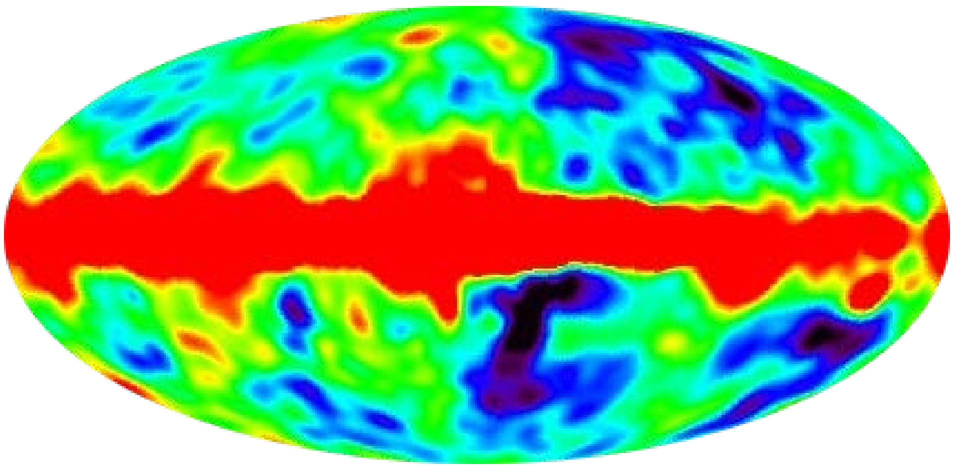


CMB

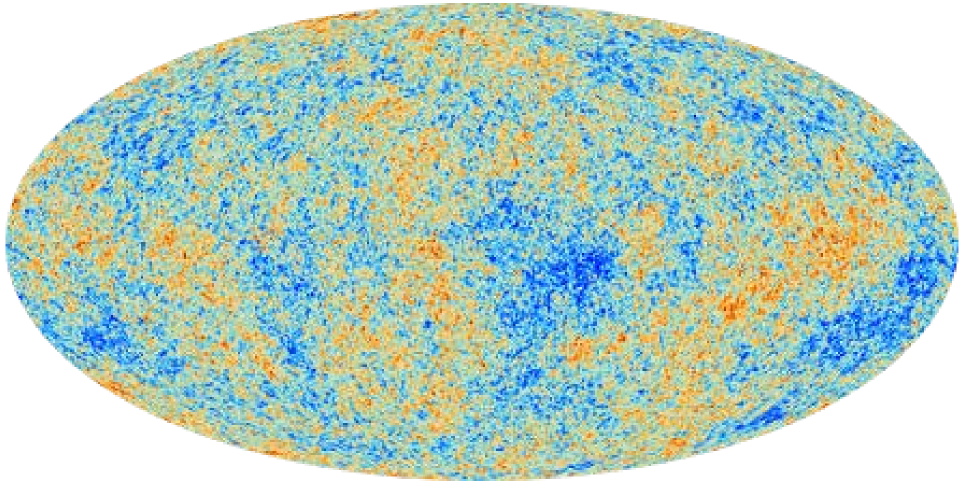
Anisotropy of the Hubble Flow



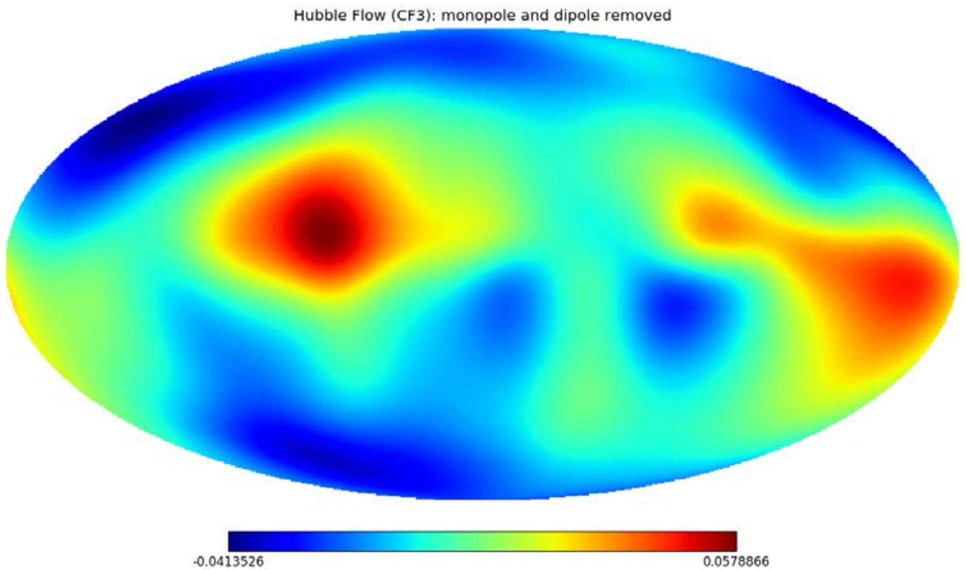
Hubble Flow

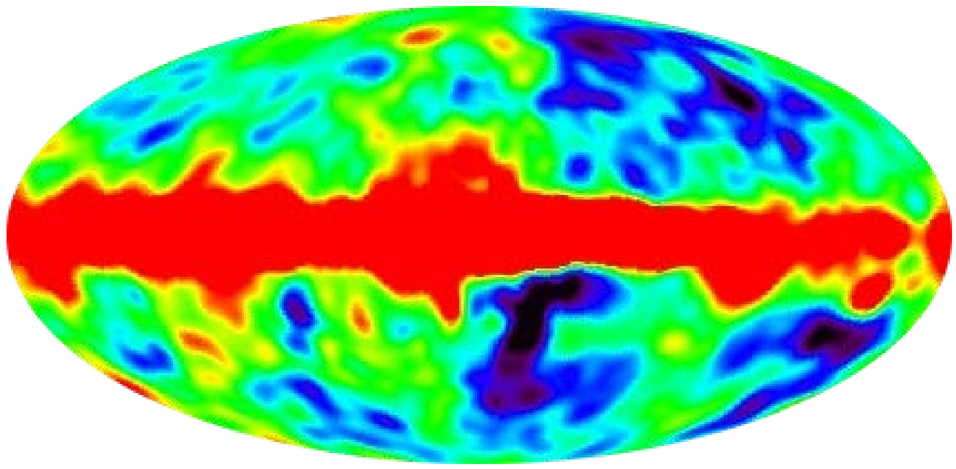


CMB



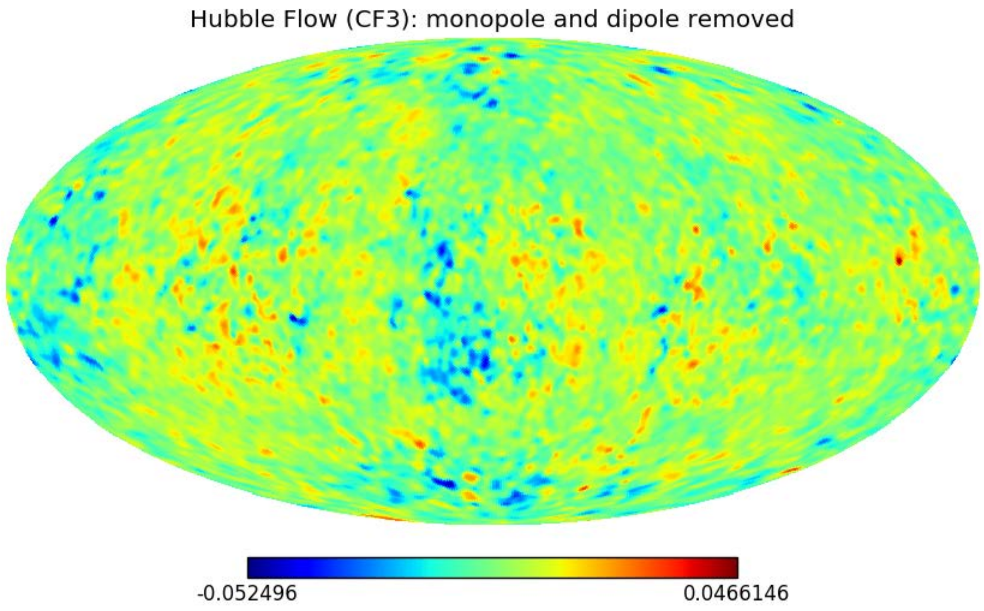
Anisotropy of the Hubble Flow

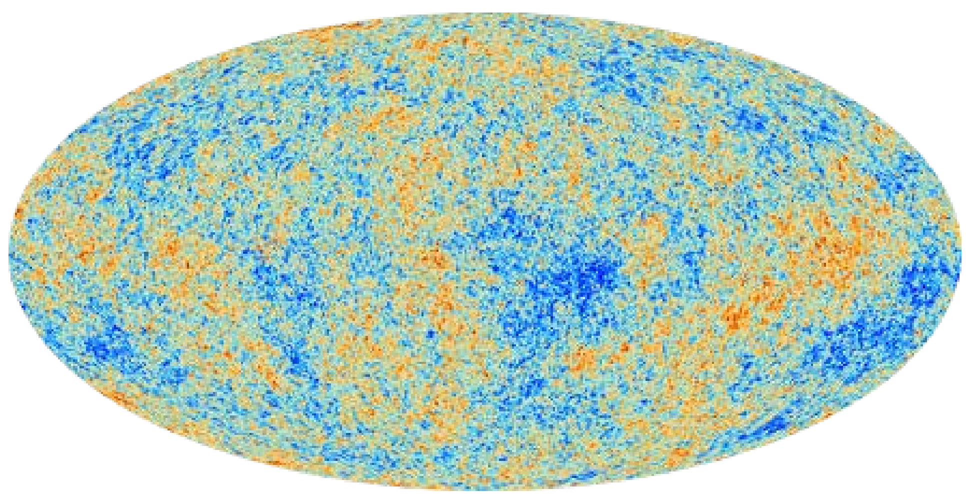




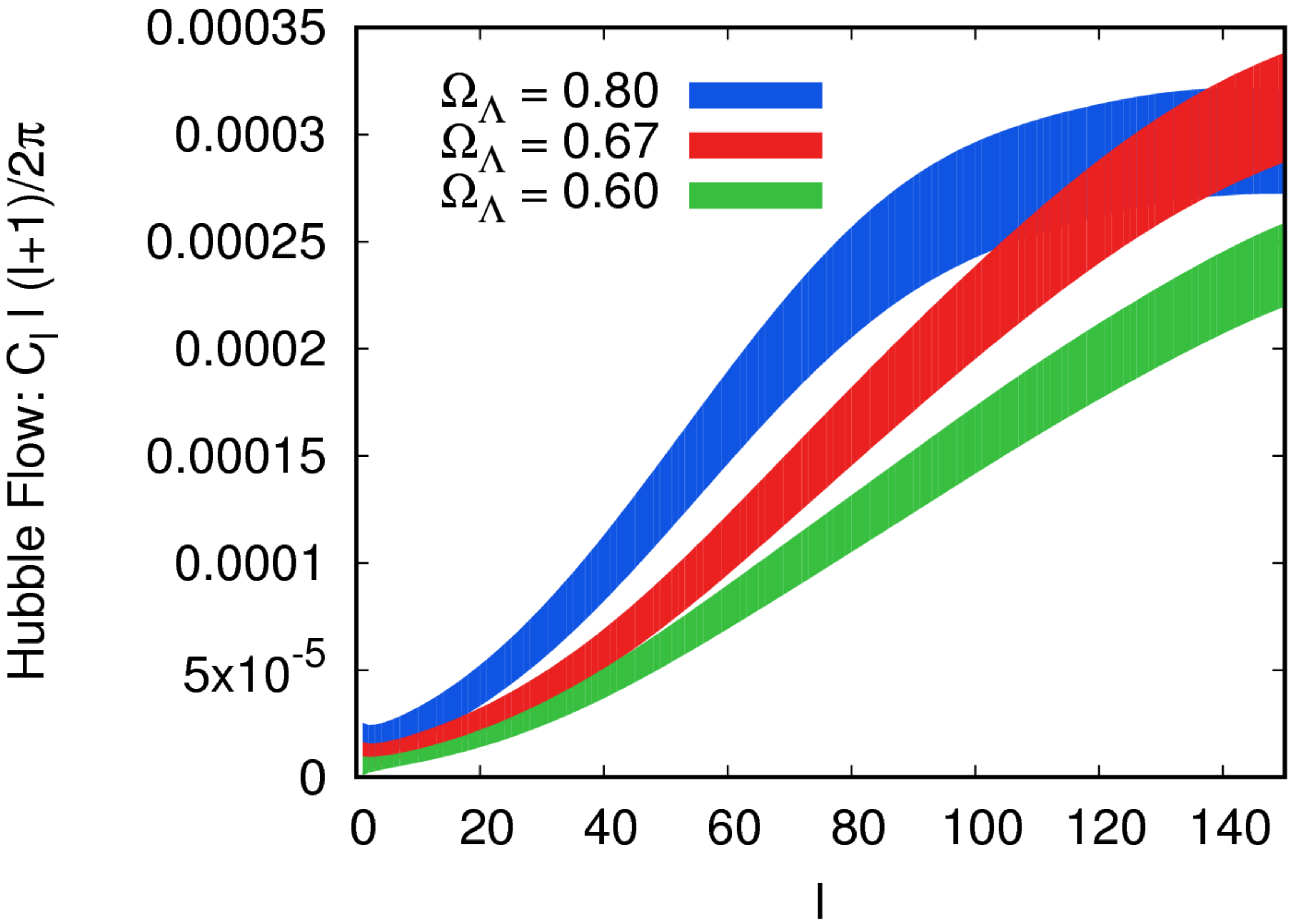
Hubble Flow

CMB



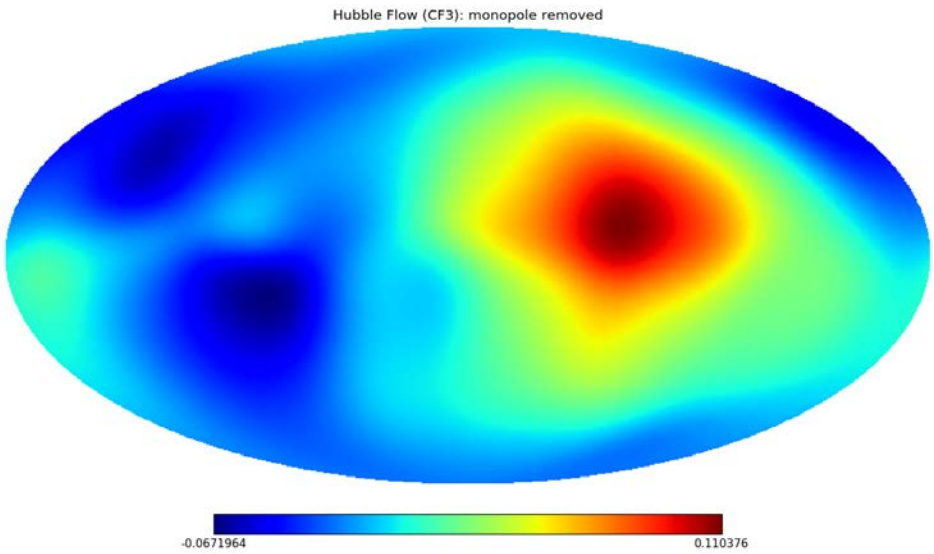


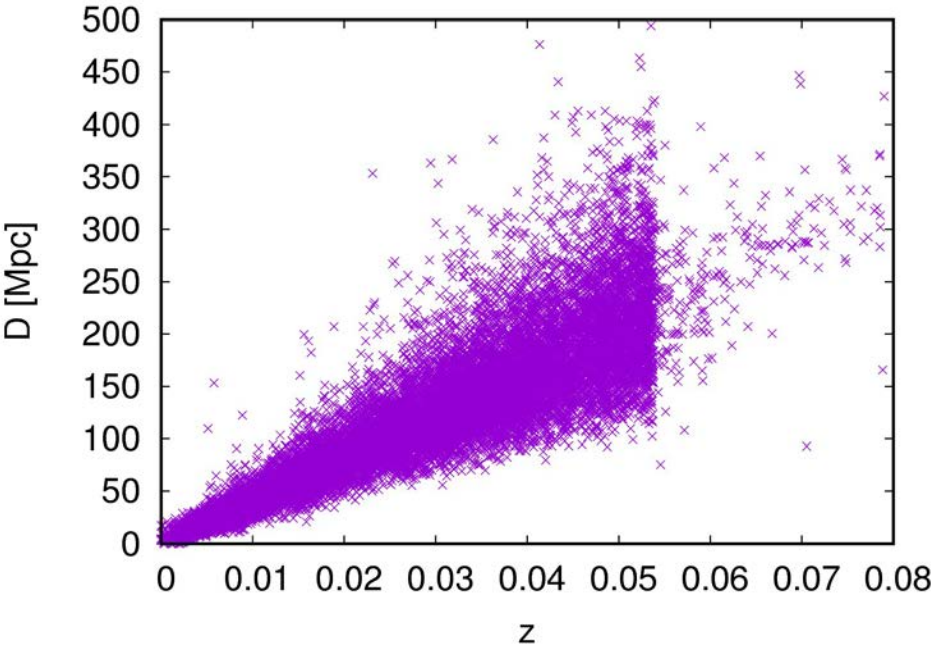
Constrining the Universe using the anisotropy of the Hubble Flow



Origin of the dipole

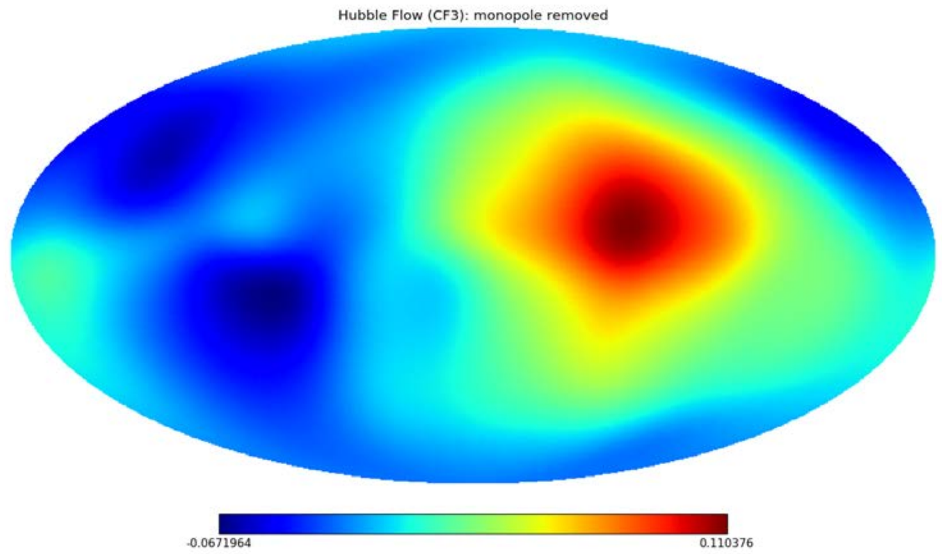
Hubble Flow:





Origin of the dipole

Hubble Flow:



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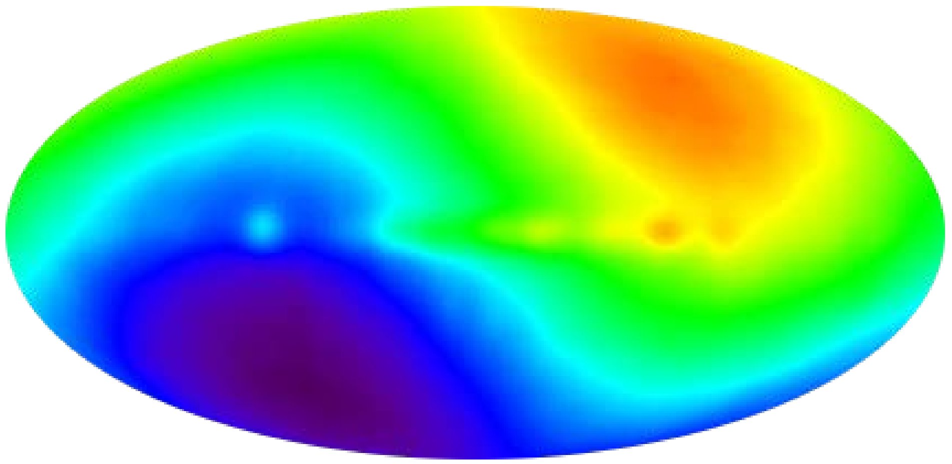
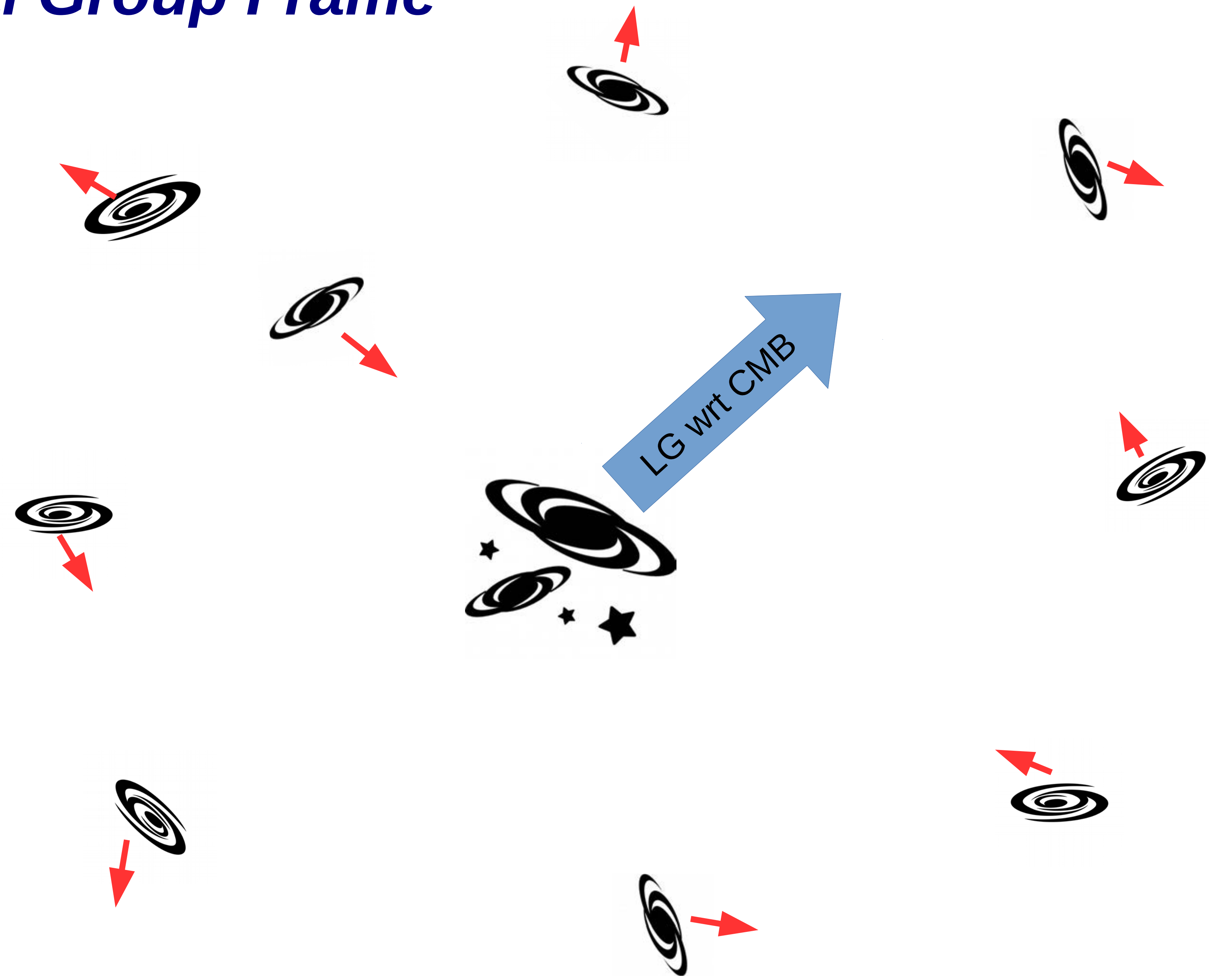
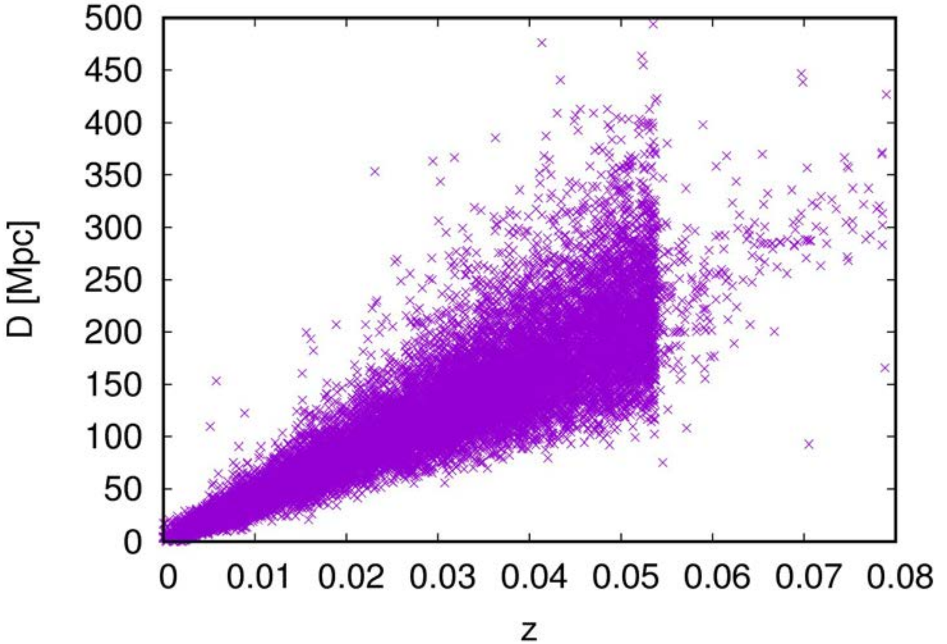
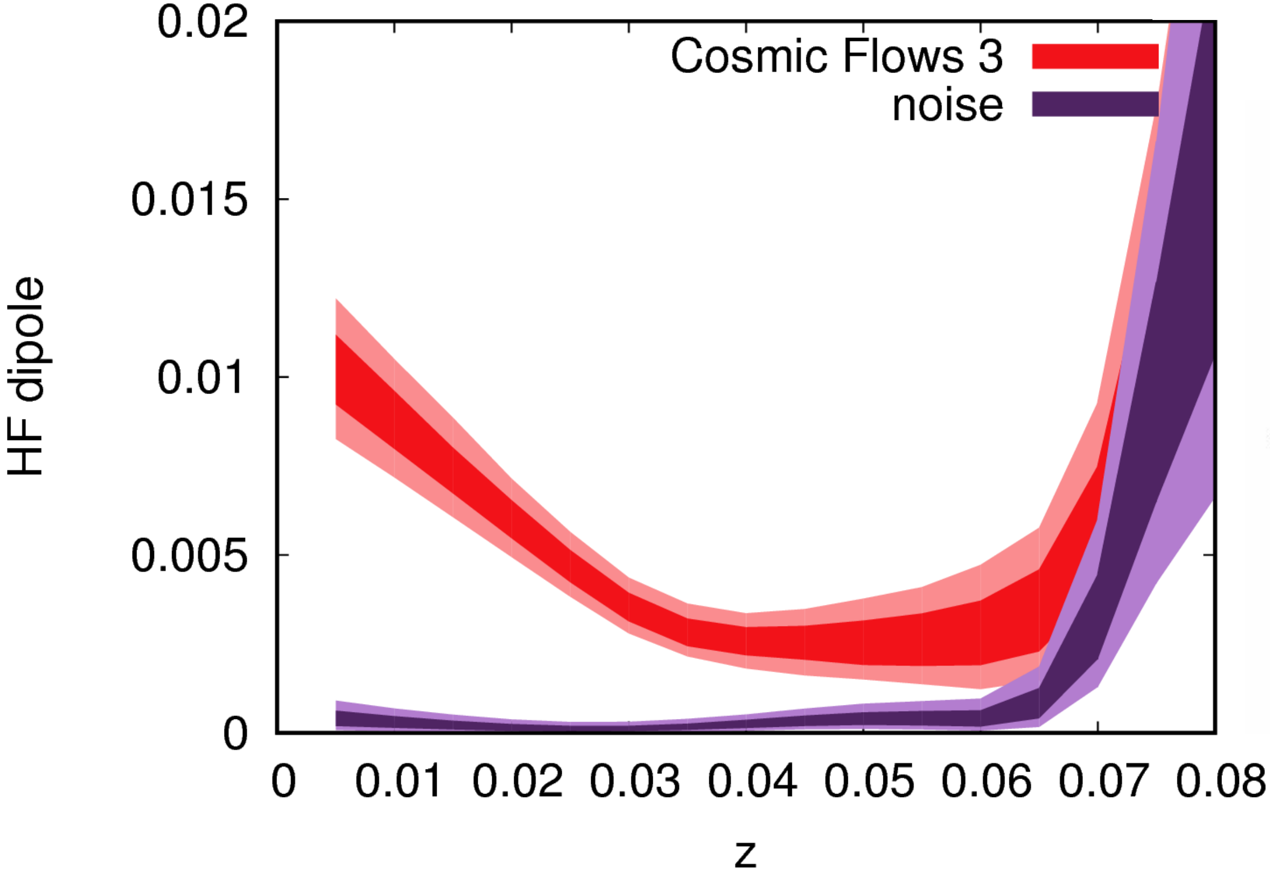


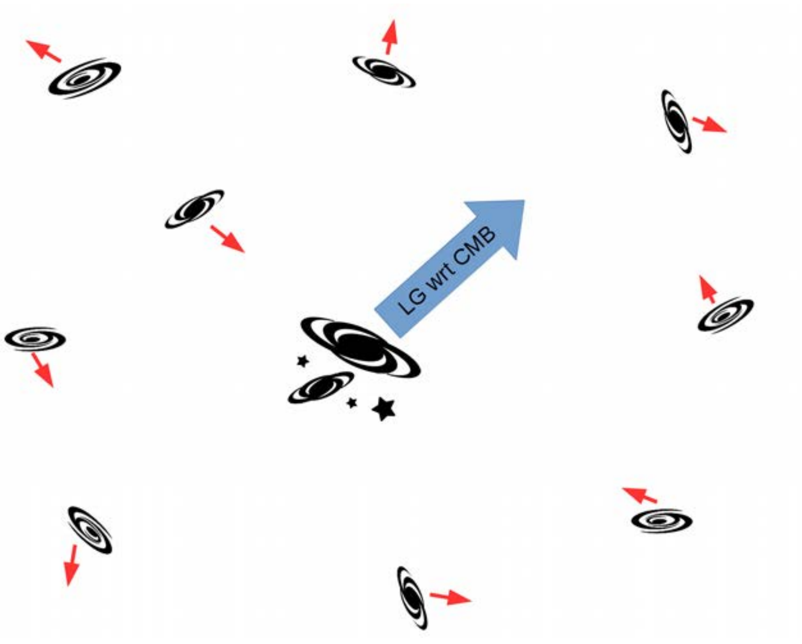
Local Group Frame



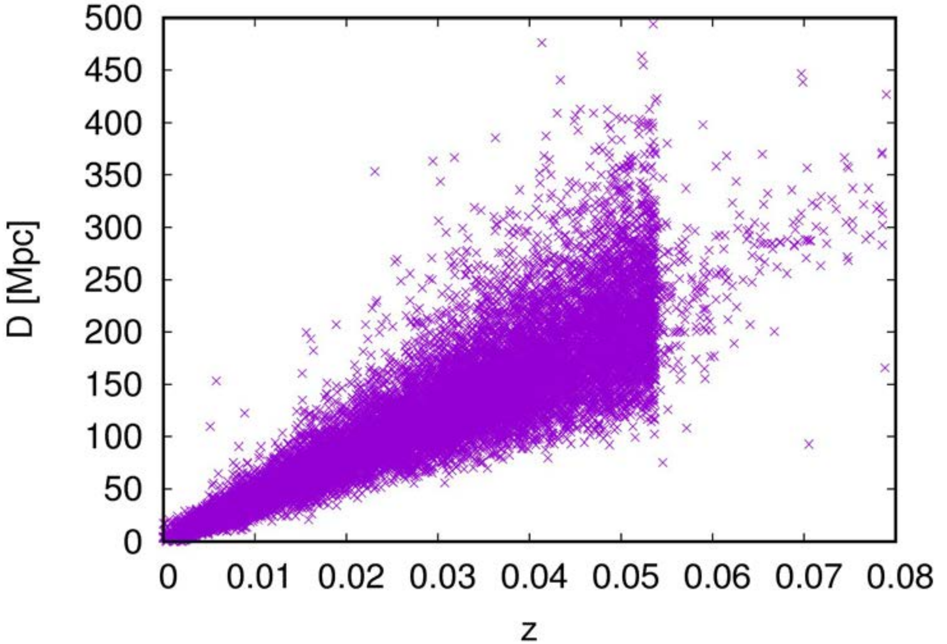
Hubble Flow dipole due to LG's boost

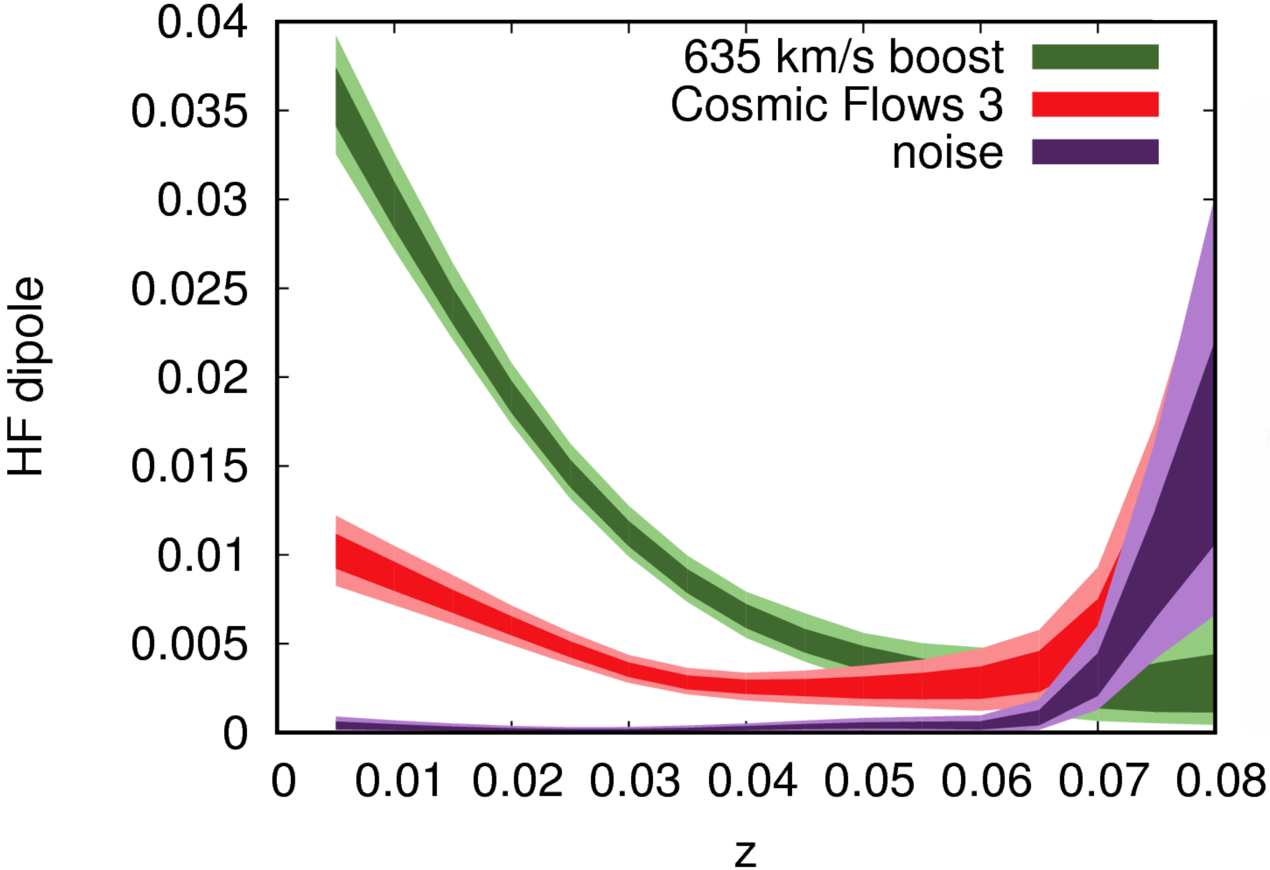


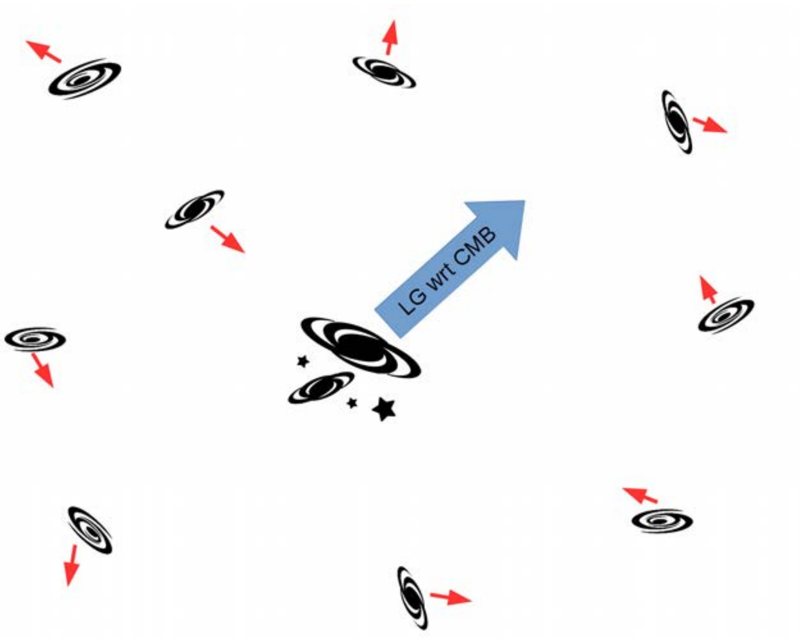




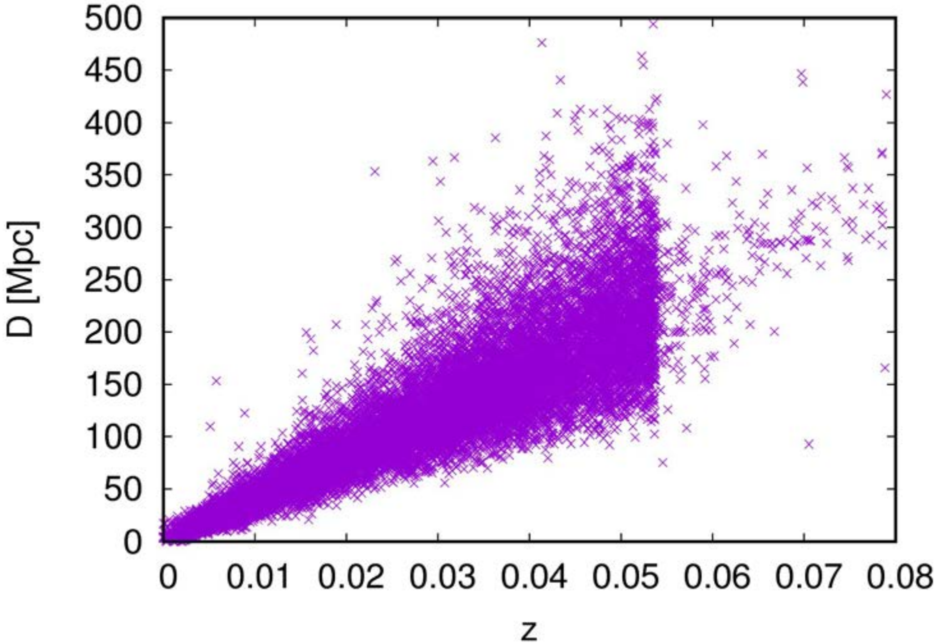
Hubble Flow dipole due to LG's boost

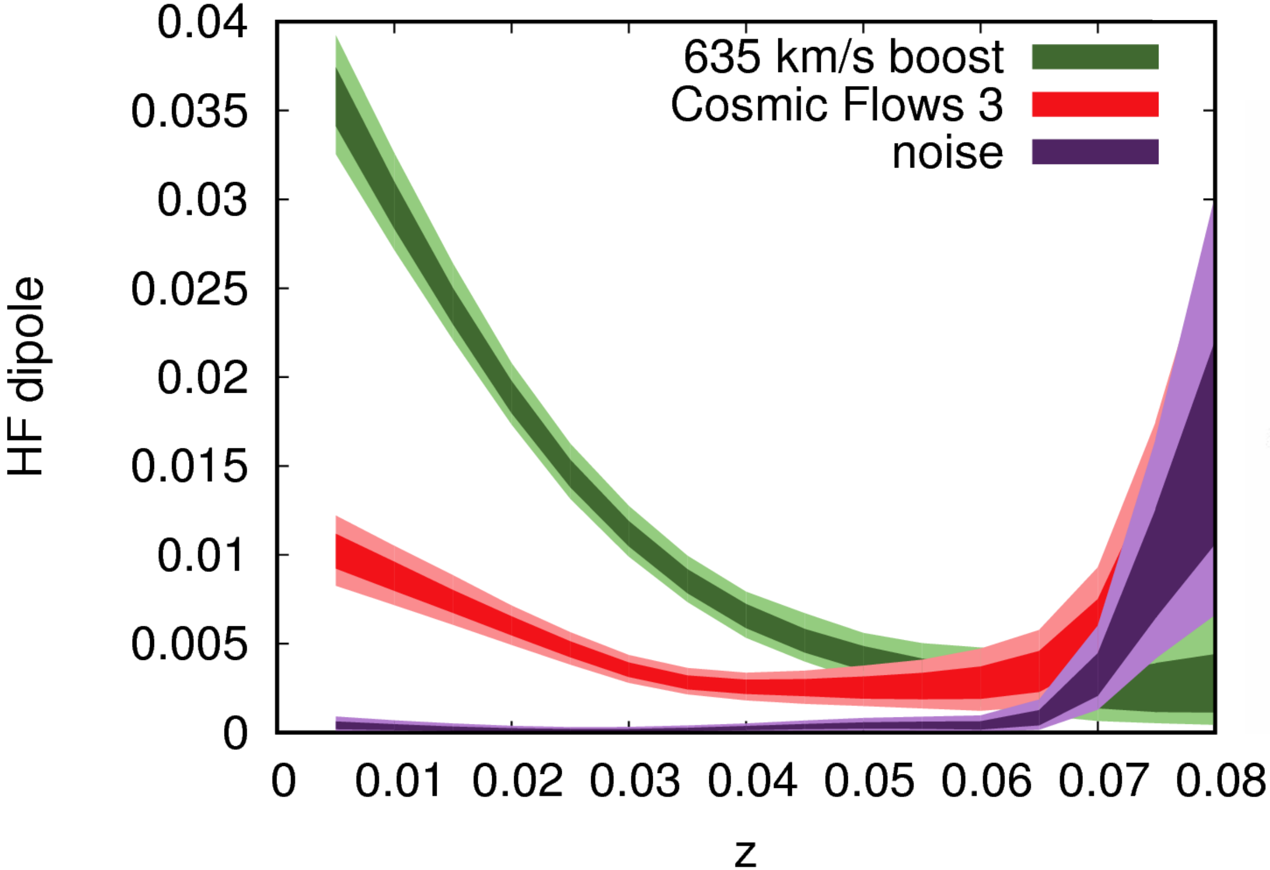


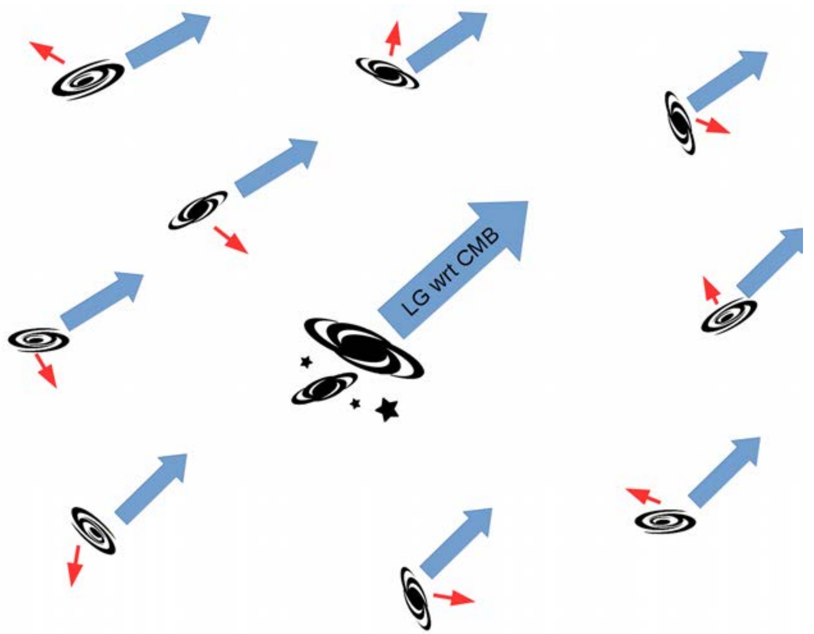




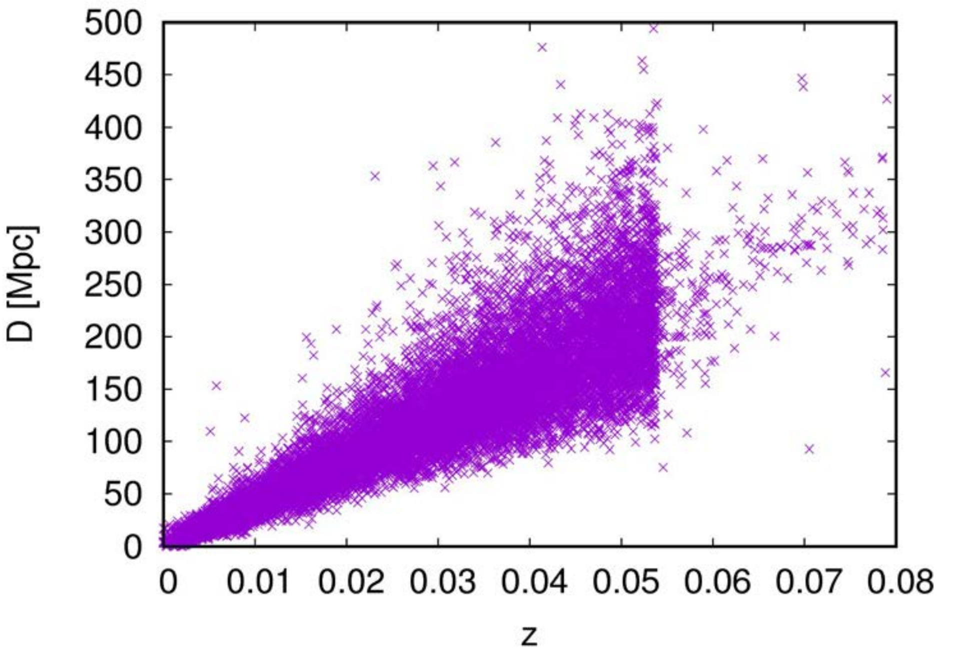
Hubble Flow dipole due to LG's boost and bulk flow

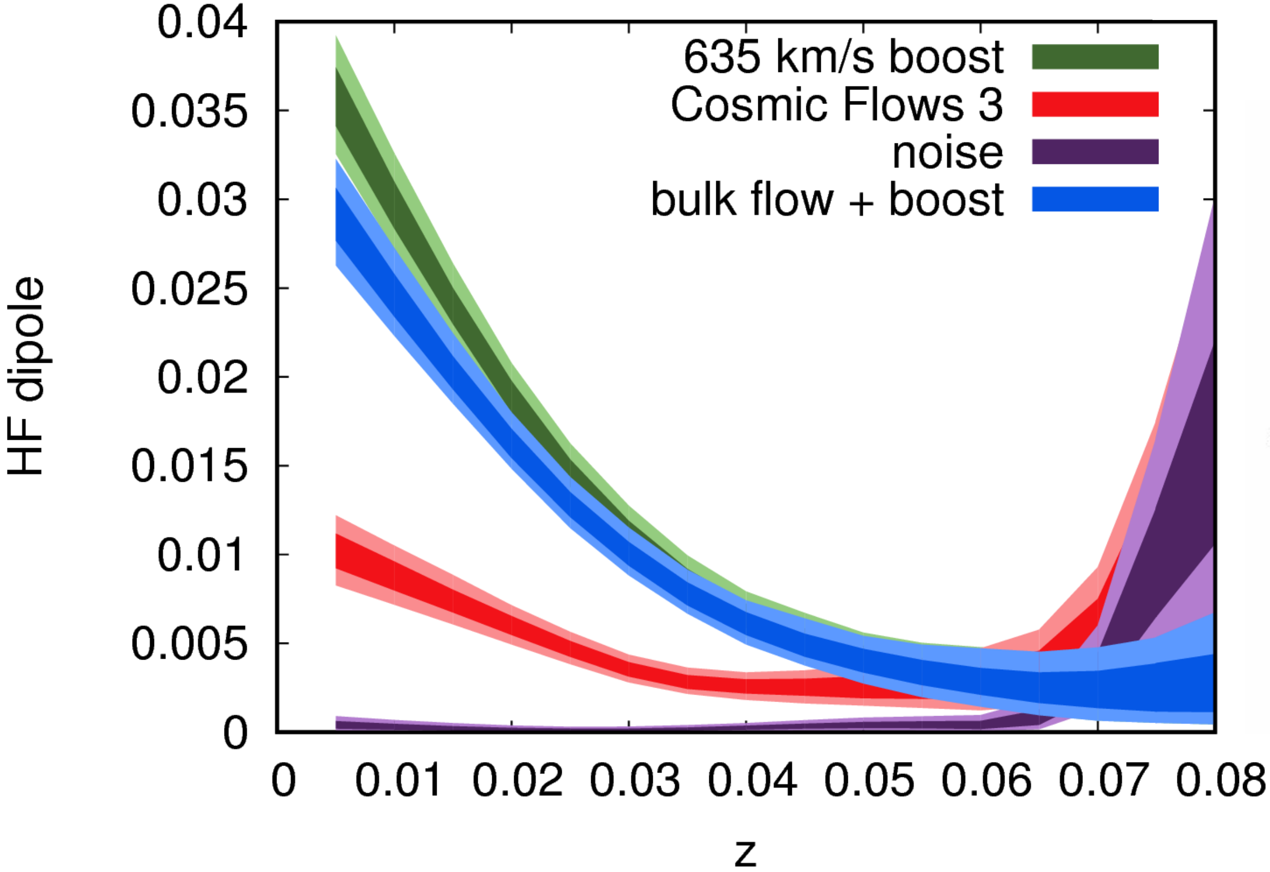


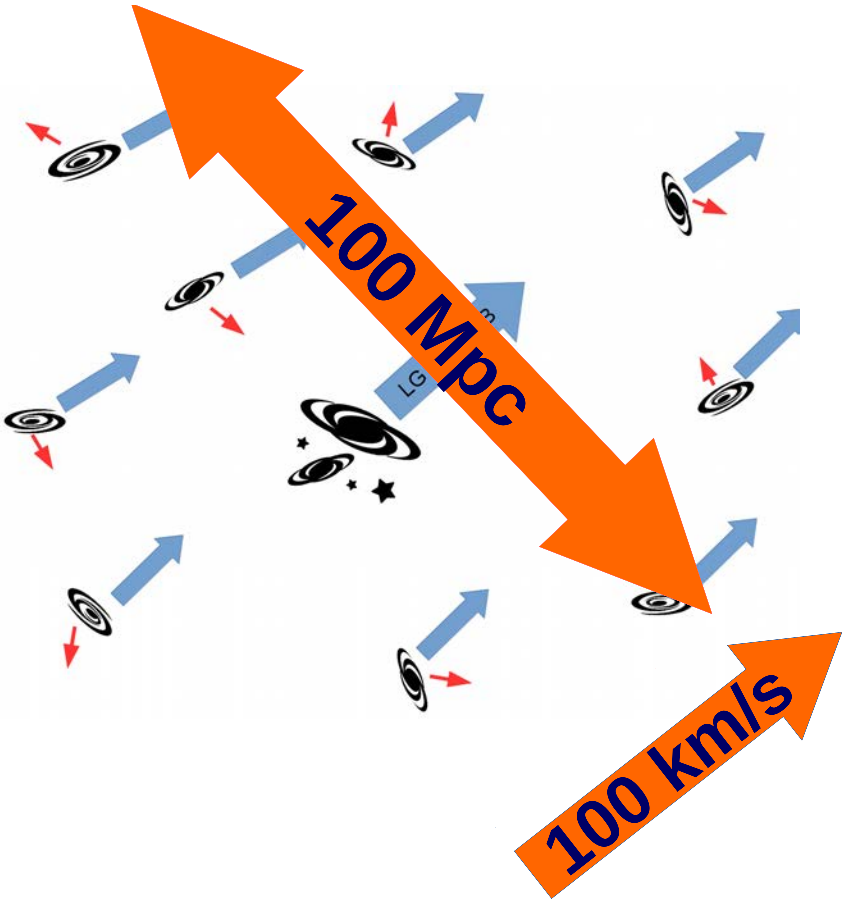




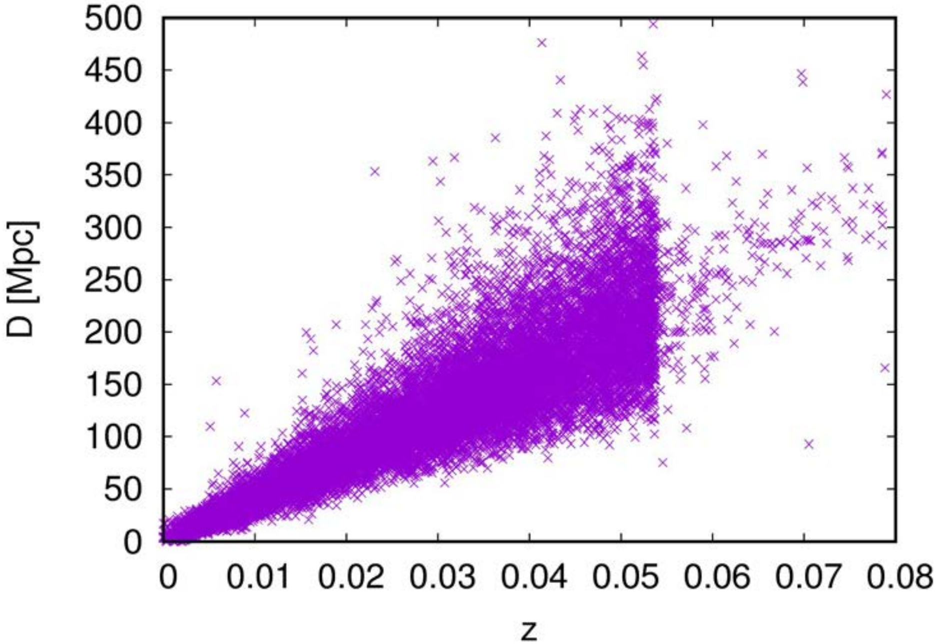
Hubble Flow dipole due to LG's boost and bulk flow

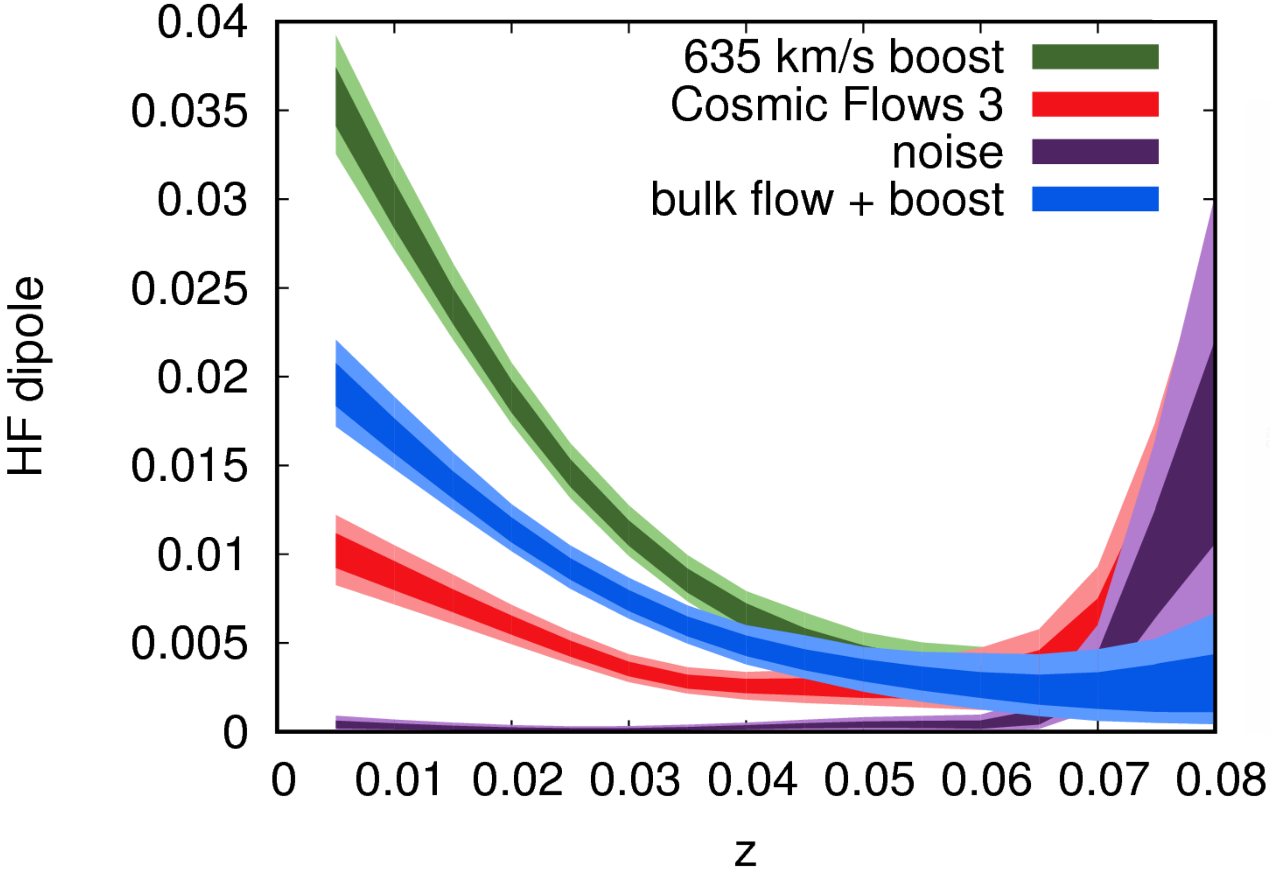


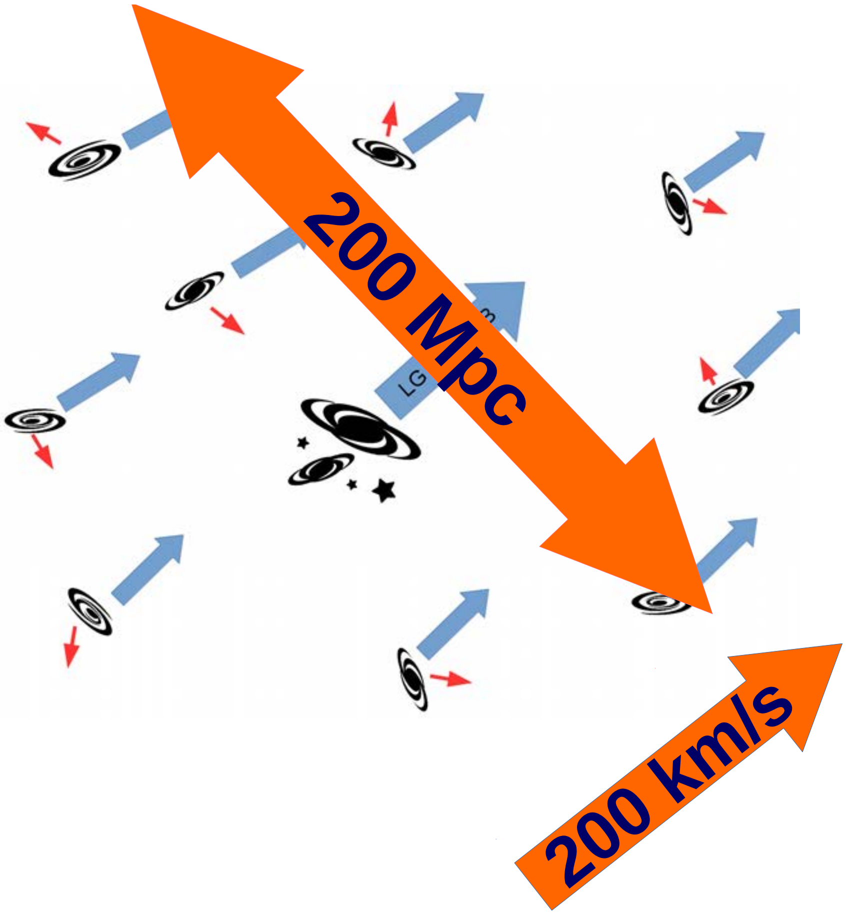




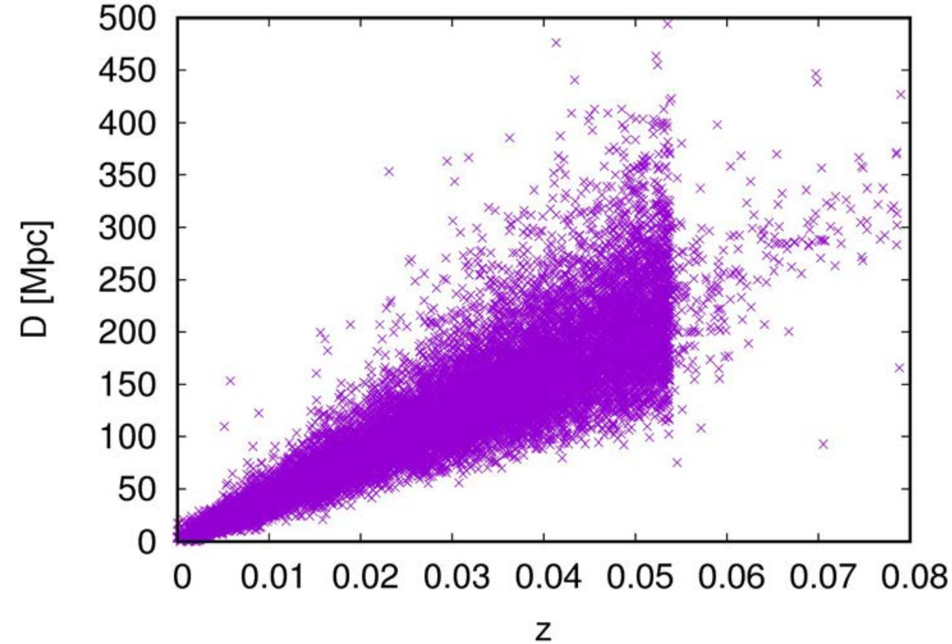
Hubble Flow dipole due to LG's boost and bulk flow

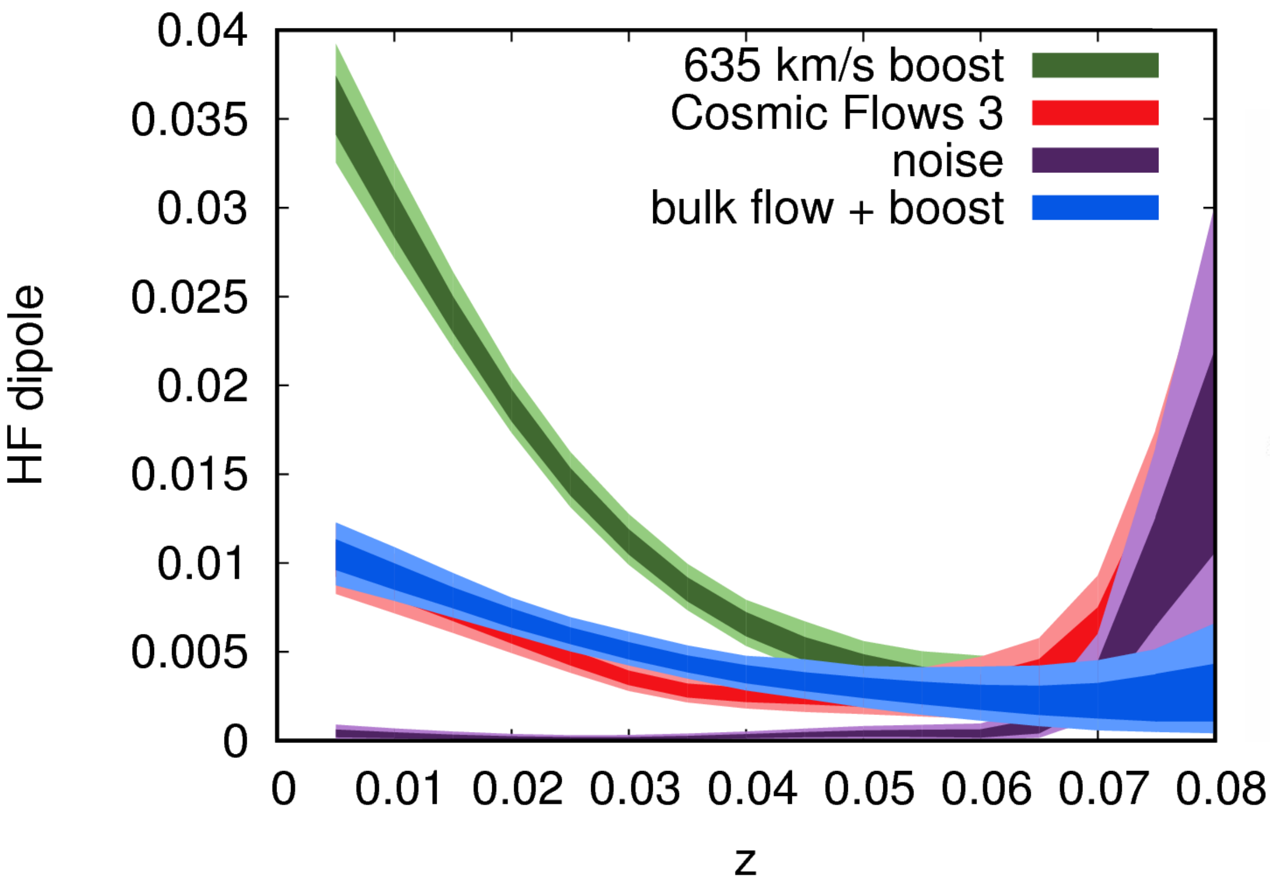


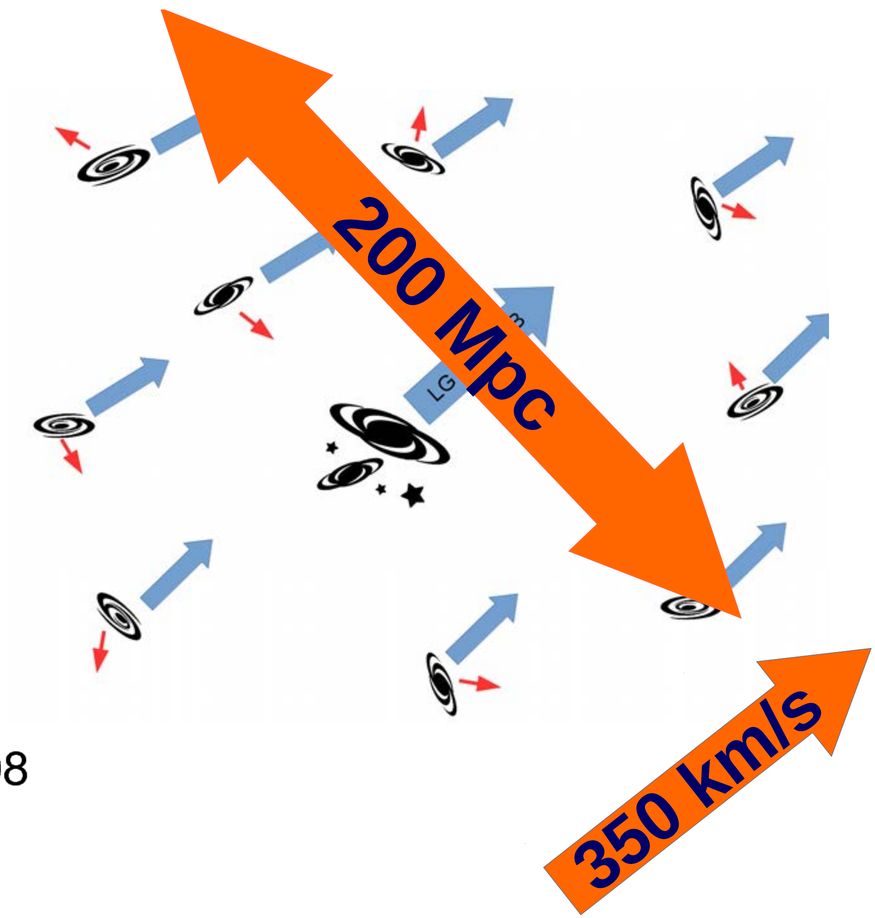




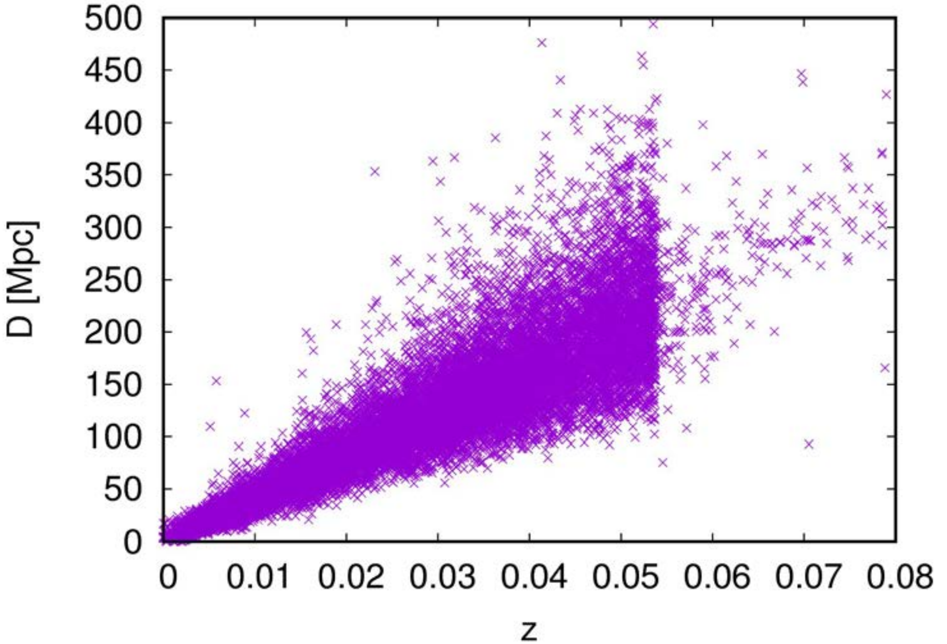
Hubble Flow dipole due to LG's boost and bulk flow

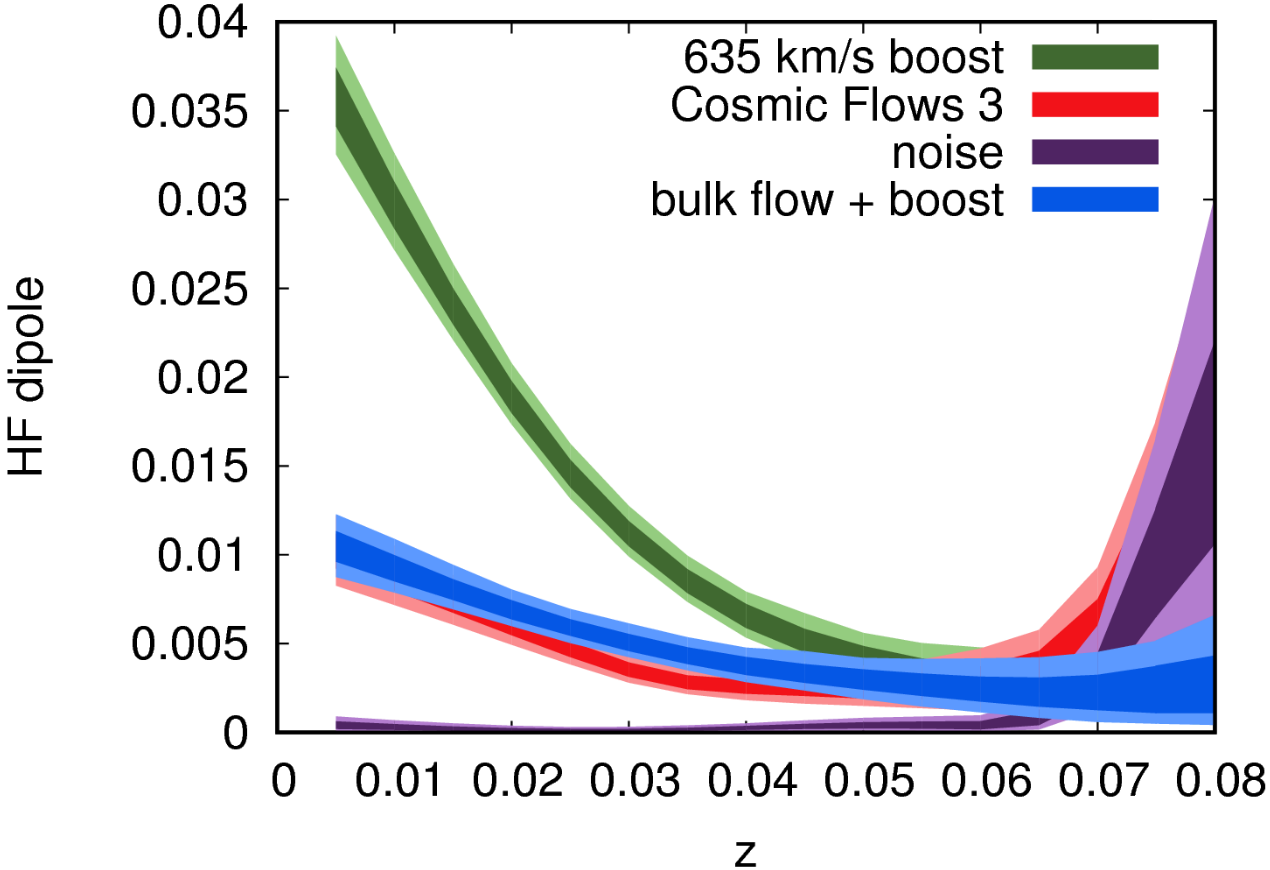


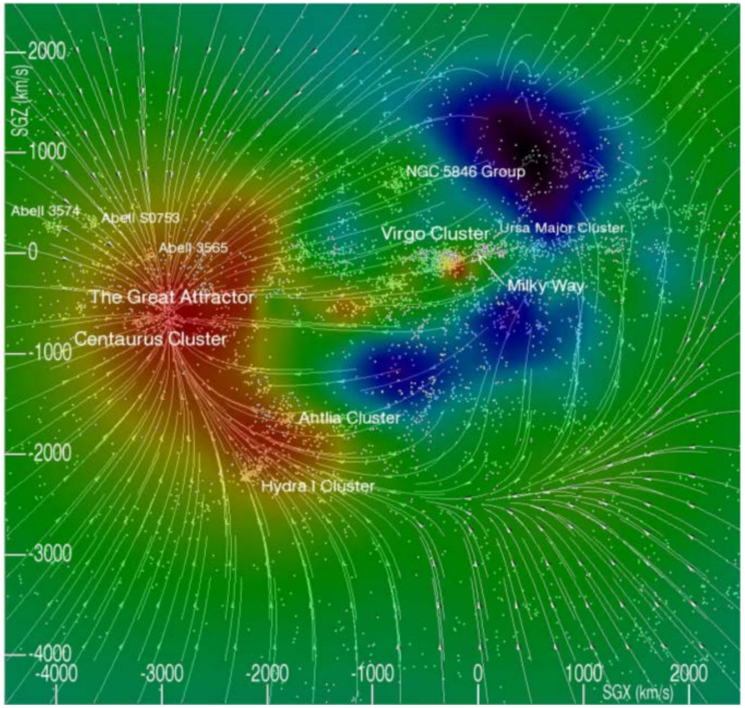




Hubble Flow dipole and cosmic environment

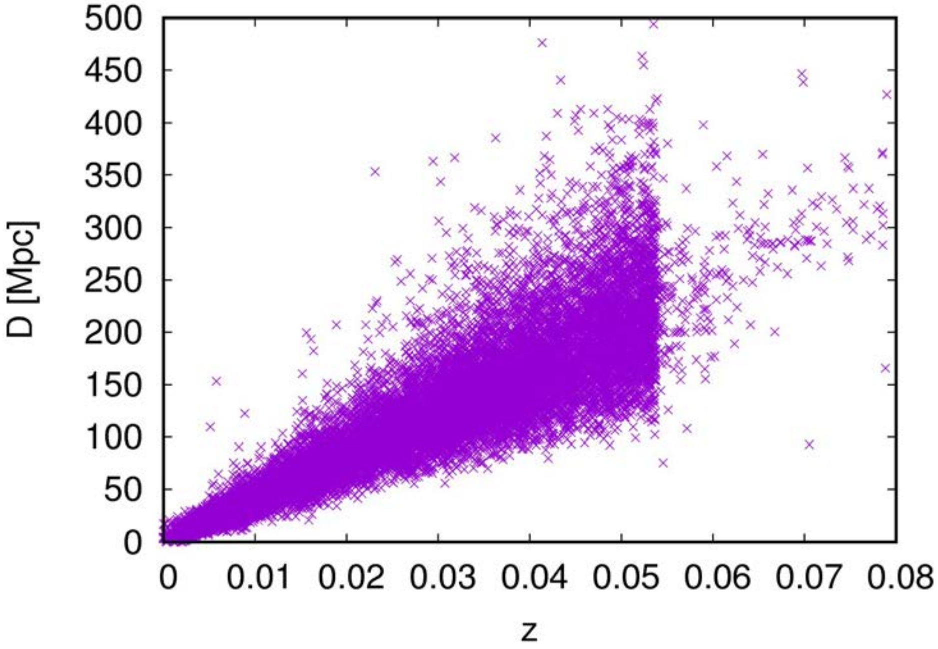


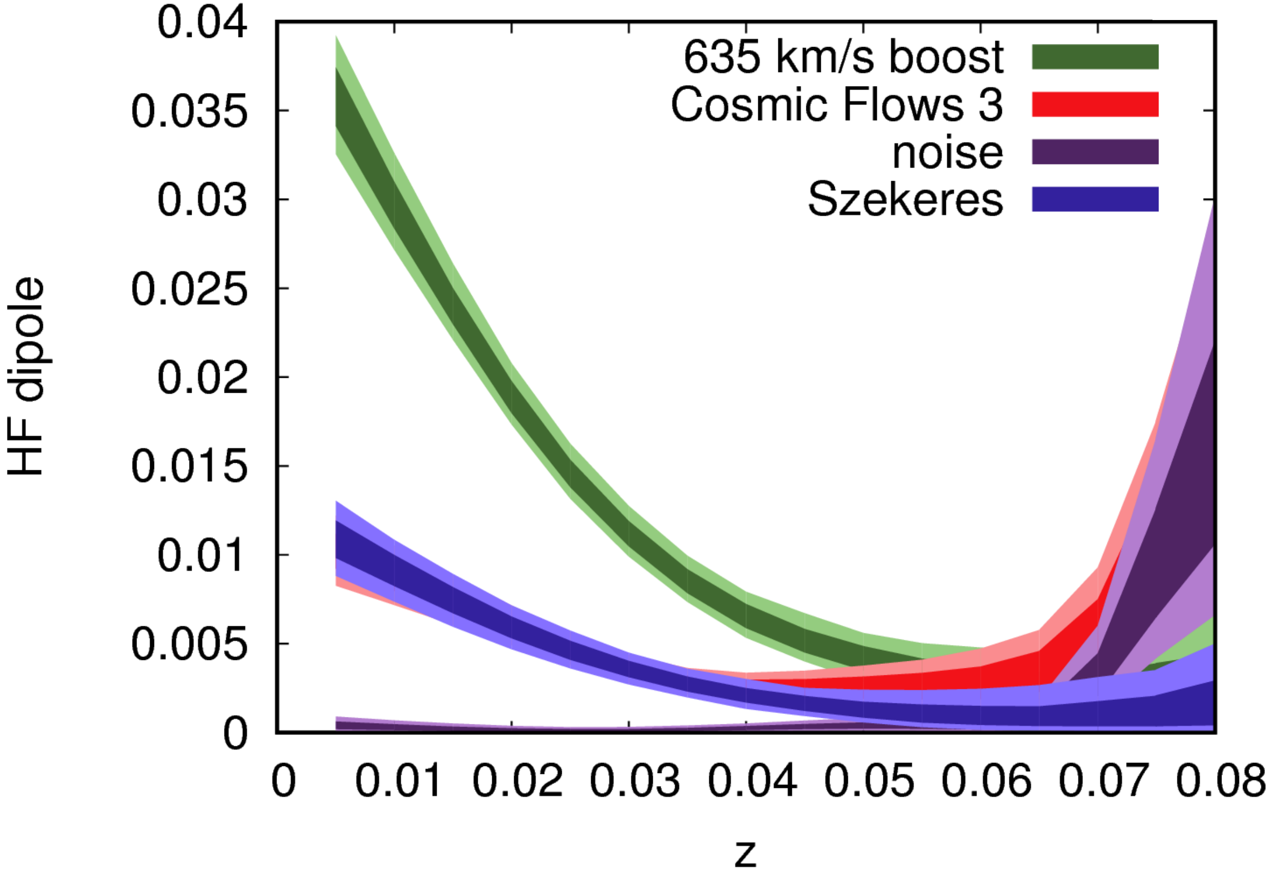


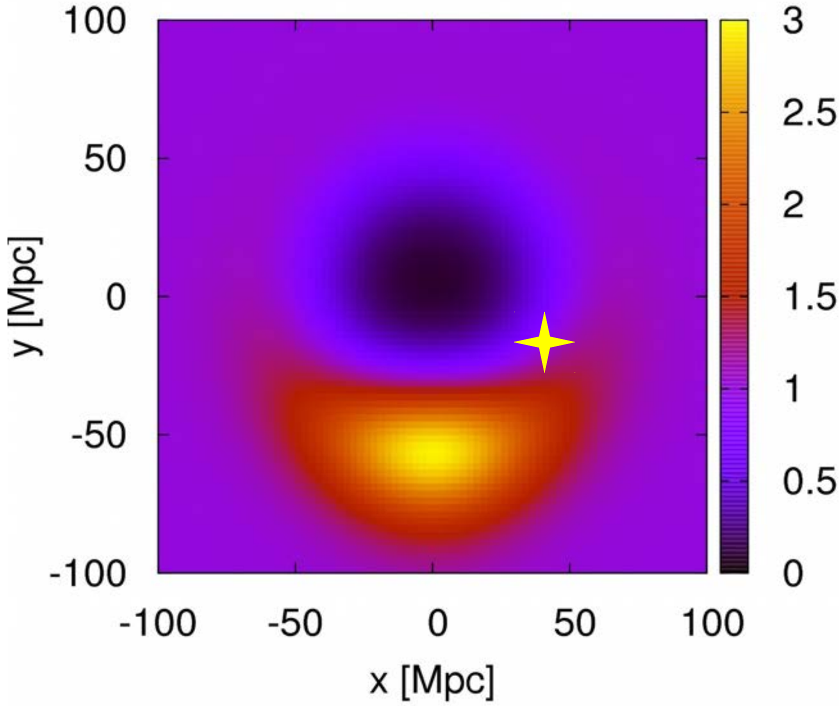


Courtois et al. (2015)

Hubble Flow dipole within full GR treatment







Bolejko et al. (JCAP, 06, 035, 2016)

Summary

- New tool sensitive to late time cosmology:
  - Cosmological parameters
  - Modified gravity (?)
  - Modified geometry (?)

- Useful tool to understand local cosmological environment:
  - Test the Bulk Flow hypothesis