Peculiar Velocities
Important probe in Cosmology

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What are peculiar velocities?

- Deviations in the motion of the galaxies from the Hubble flow
- Valuable tool which probe the underlying distribution of the dark matter
- Used to estimate □ which itself is Cosmology dependent
  - Peculiar velocity analysis provides a direct means of testing cosmological predictions

Velocity fields in the linear perturbation theory

- A quantity that is usually coupled with density perturbations.

$$r(t) = a(t)x(t) \qquad u = \frac{dr}{dt} = V_H(x,t) + V(x,t)$$

- The relation between peculiar velocity and galaxy density:

  Peculiar Gravitational Acceleration: $g = -\frac{\nabla\Phi}{a}$

  Induced velocity flow in linear regime is given by:

$$\nabla . V = -a\nabla . \frac{\delta}{\delta t}\left(\frac{\nabla\Phi}{4\pi G\rho_u a^2}\right) \qquad \nabla . V = -a\nabla . \frac{\delta}{\delta t}\left(\frac{g}{4\pi G\rho_u a}\right)$$

  g and V are gradients of potential : $V = a\frac{\delta}{\delta t}\left(\frac{g}{4\pi G\rho_u a}\right)$

In linear regime, *g* grows with a Universal gravity growth factor D_g,

$$g(t) \propto D_g(t) \propto \frac{D}{a(t)^2} \qquad \frac{g}{4\pi G\rho_u a} \propto D(t)$$

D(t) = linear density growth factor

=> $$V = \frac{1}{D}\frac{dD}{dt}\left(\frac{g}{4\pi G\rho_u}\right)$$ => $$V \propto g$$

Peculiar velocity is directly and linearly proportional to peculiar acceleration.

Let f : Dimensionless linear velocity growth factor $$\frac{1}{t}\frac{dD}{dt} = Hf$$

=> $$V = \frac{2f}{3H\Omega} g$$

Linear bias: Density fluctuations in the galaxy distribution do form a biased reflection of underlying matter density fluctuations: $\delta_{gal}(x) = b\delta_m(x)$ $\quad \beta = \frac{f(\Omega_m)}{b}$

$$\mathbf{V}(x,t) = \frac{Hf(\Omega_M)a}{4\pi b} \int dx' \delta_{gal}(x', t) \frac{(x' - x)}{|x' - x|^3}$$

Ways to measure peculiar velocities

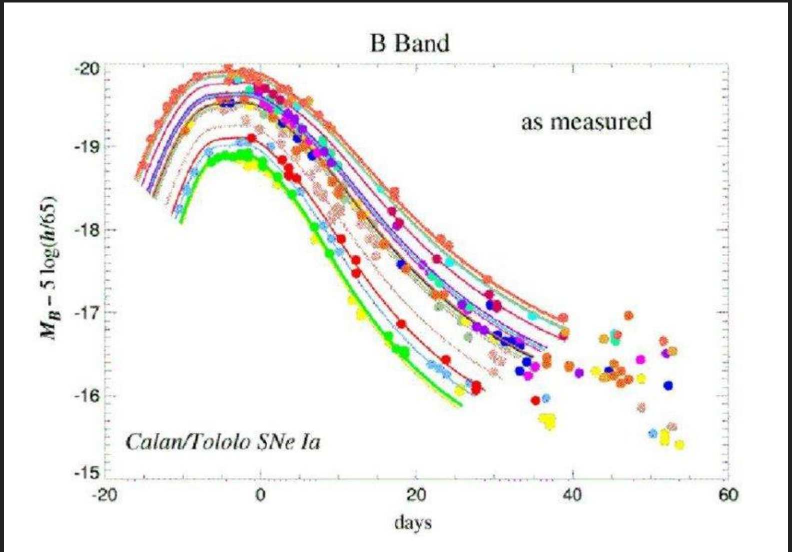
1. Tully Fisher Relation for Spiral Galaxies

$$L \propto \sigma^3$$

2. Faber-Jackson Relation for Elliptical Galaxies

$$L \propto \sigma'^4$$

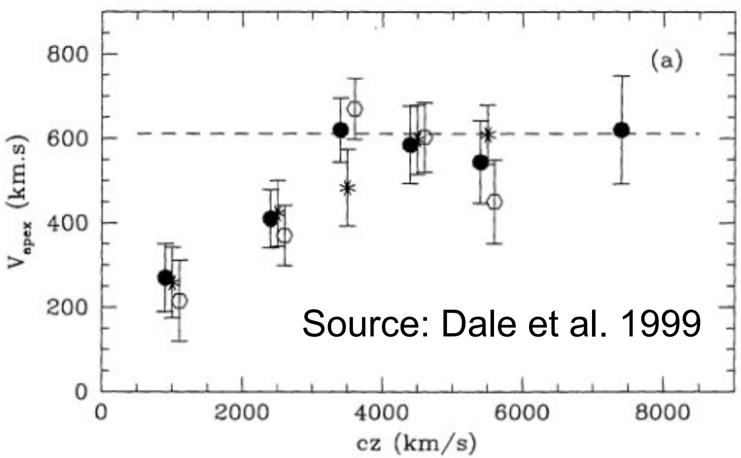
3. Supernova type Ia:
Luminosity Distance from light-curve



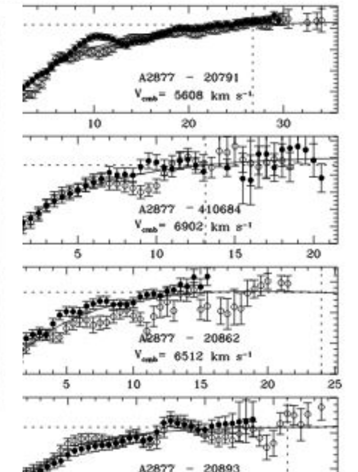
4. Gravitational Waves: Distance from amplitude of detected signal

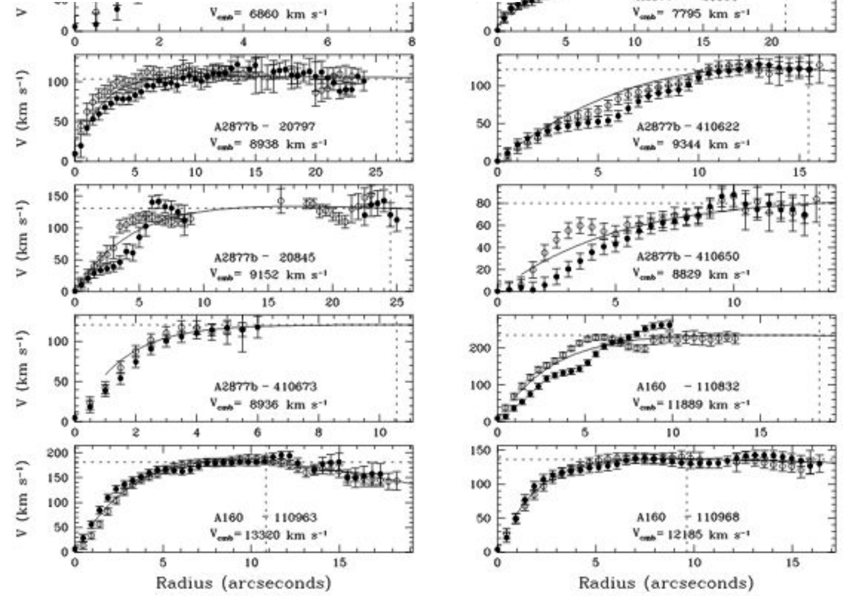
Velocities

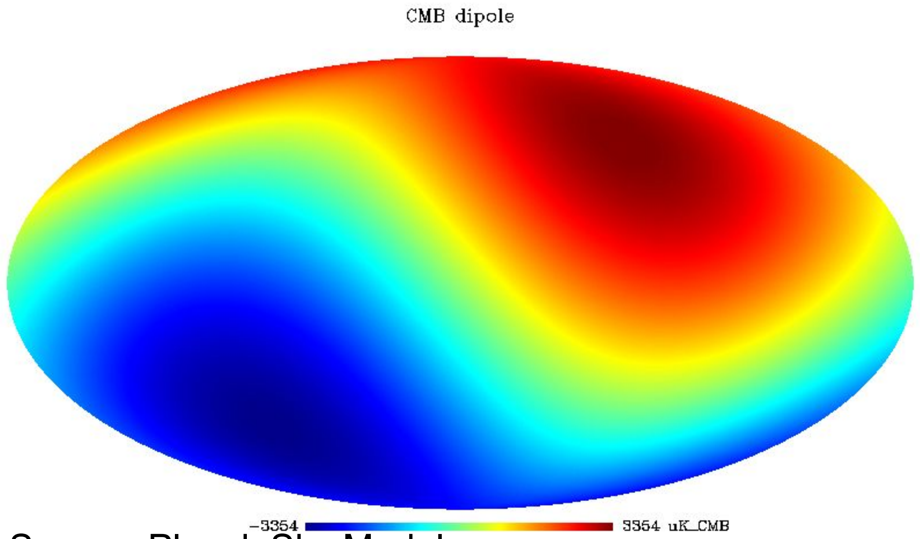
- Local Group Motion
- Motion of galaxy groups/clusters
- Bulk Flows



Source: Dale et al. 1999



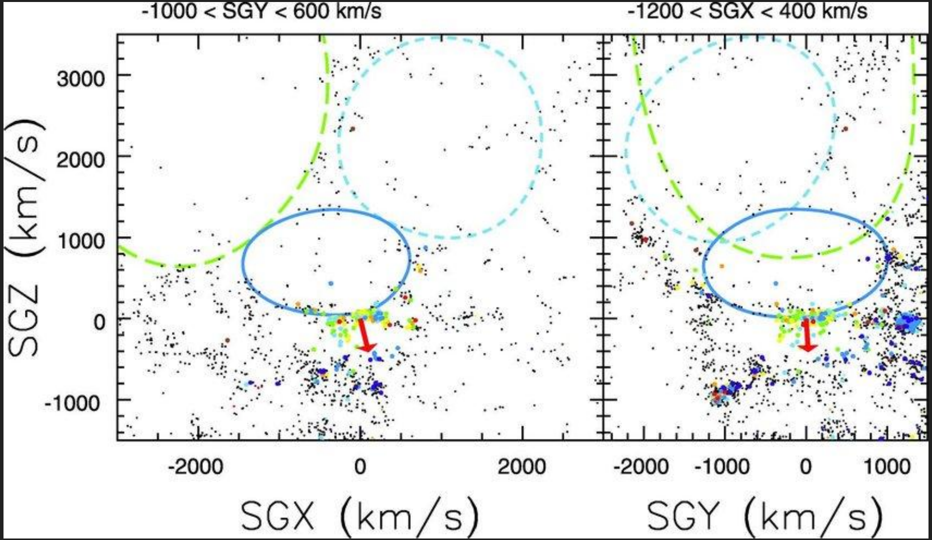




Source: Planck Sky Model

Velocities

Local Void / Hubble Bubble



Source: Billicki 2012

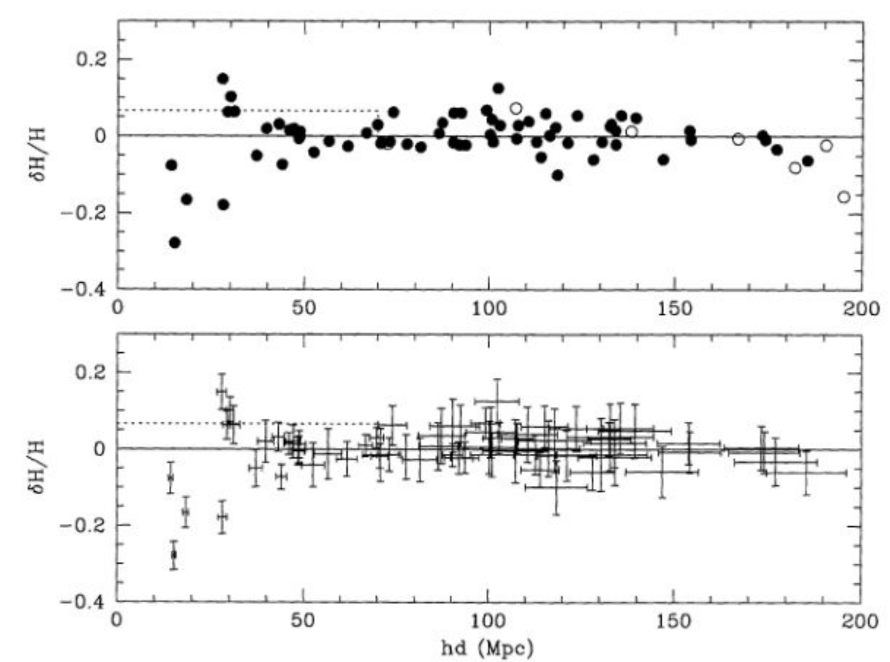


Figure 8. No Hubble Bubble in the local Universe. $\delta H/H = 0$ line identifies null deviation from Hubble flow. The dotted line is the effect of the Hubble bubble proposed by Zehavi et al. (1998). The lower panel shows the error bars associated with the filled data points shown above.

Source: Dale et al. 2000

Chi-squared estimator

- Reflex motion of the observer V_D follows from chi^2 minimization

$$\chi^2 = \sum_{i=1}^{n} \frac{1}{s_i}\left(\frac{V_i - \hat{r}_i.\mathbf{V_D}}{\epsilon_i}\right)^2 \qquad (V_D) = (V_{DX}, V_{DY}, V_{DZ})$$

- Widths of V_D components: (-1000:1000) km/sec
- Best combination of above 3 gives minimum chi^2
- Resolution
  - For resolution 1 km/sec : 1000 x 2000^3
  - For resolution 0.1 km/sec : 1000 x 20000^3
  - Steps of resolutions:
  - 50 km/sec, 10 km/sec, 1 km/sec, 0.1 km/sec: 4 x 1000 x 40^3

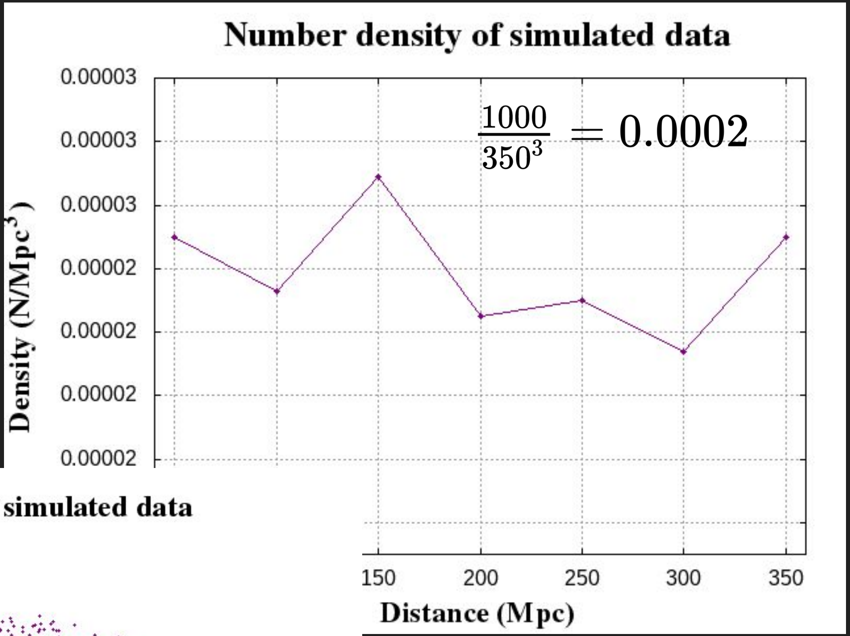
$$\Delta\chi^2_{min} = \chi^2_{Dipole} - \chi^2_{null}$$

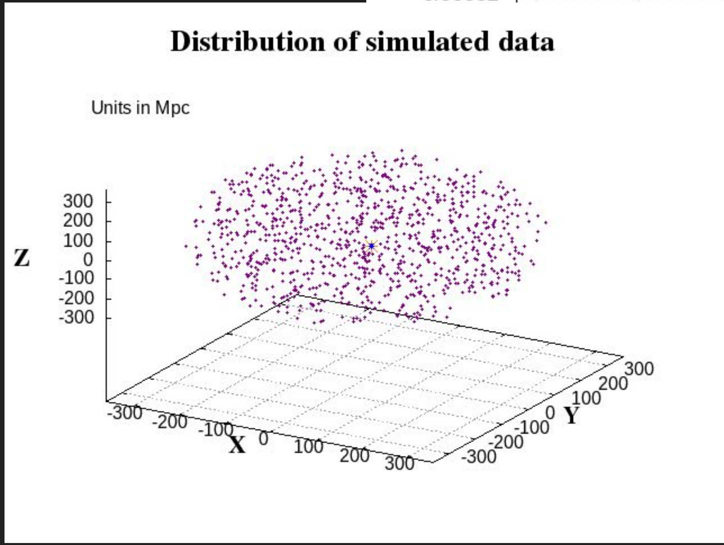
Chi-squared estimator

- Selection Function (Si) :
  Fundamentally, it relates observed catalog properties to relevant intrinsic characteristics of the source population under study.
  - Flux Limited Surveys
  - Sky Limited Surveys
    - ZoA
- Weighting observer’s sky in terms of theta, phi and distance
- In our data, distribution of galaxies is homogeneous and isotropic i.e. “Si = 1”

Testing chi2 estimator

- 1000 galaxies in a sphere of radius 350 Mpc
  - 200 realizations
- Random positions
  - no clustering, no biased distribution
  - Constant Number Density
- Selecting an observer
  - Within distance of 10% of box size from center
  - Velocity > 250 km/sec



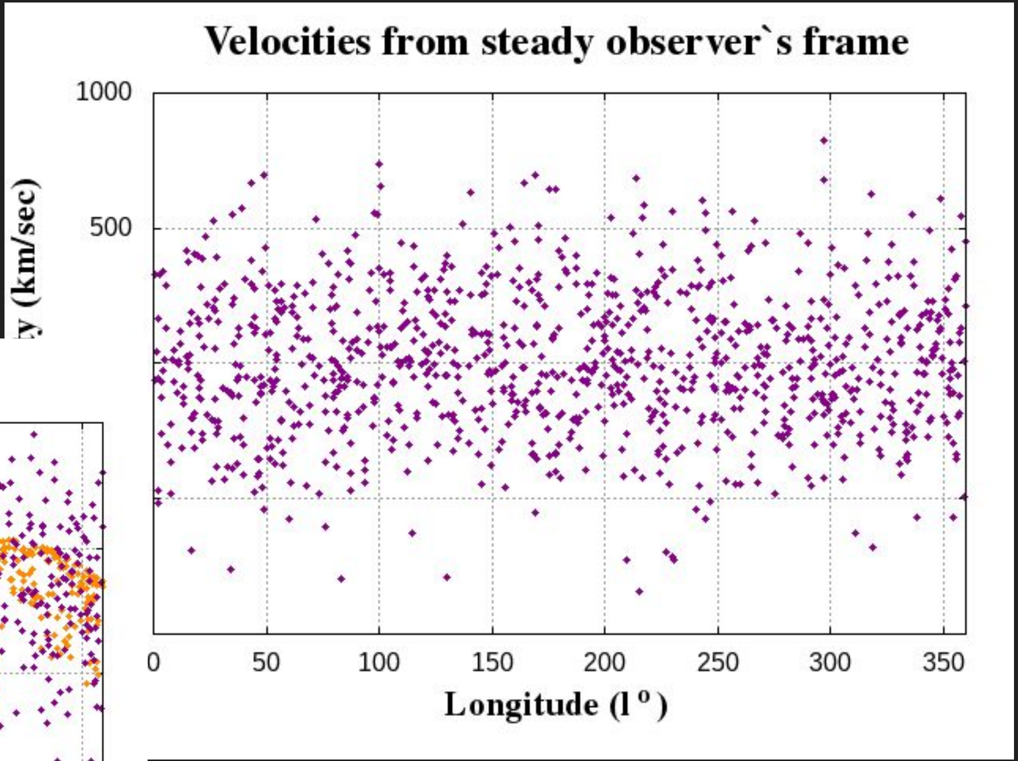


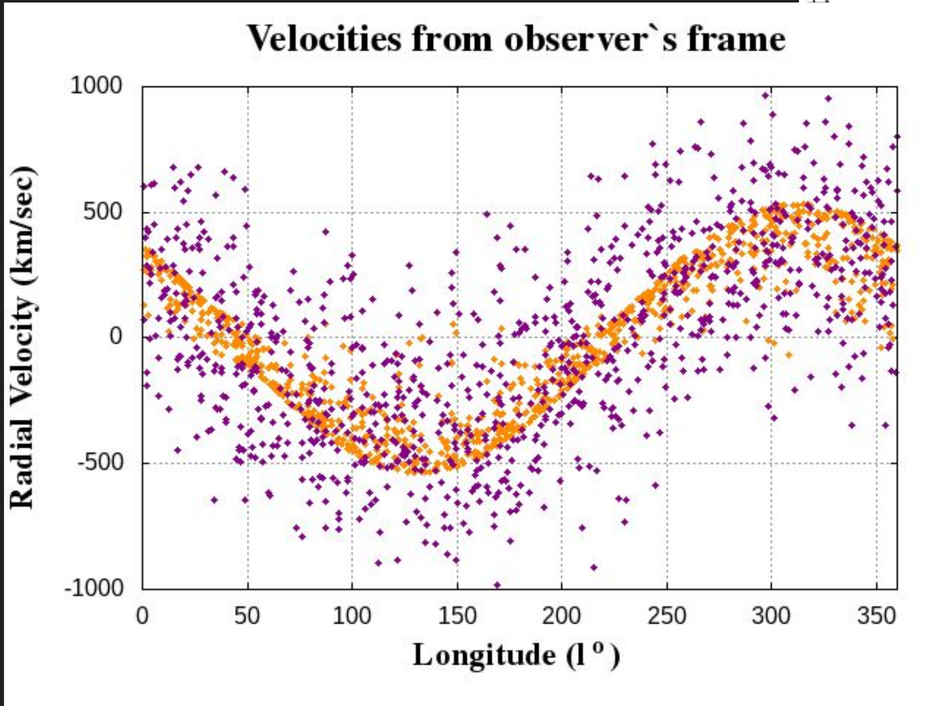
Testing chi-squared estimator

- Random Velocities following Maxwellian distribution
  - Cartesian Components follows Gaussian
  - Box-Muller transformation
  - μ = 0 km/sec; σ = 250 km/sec
- Same mass - No velocity fields, no bulk flows

$$x = \mu + \sigma\sqrt{-2\ln(U_1)}\cos(2\pi U_2)$$

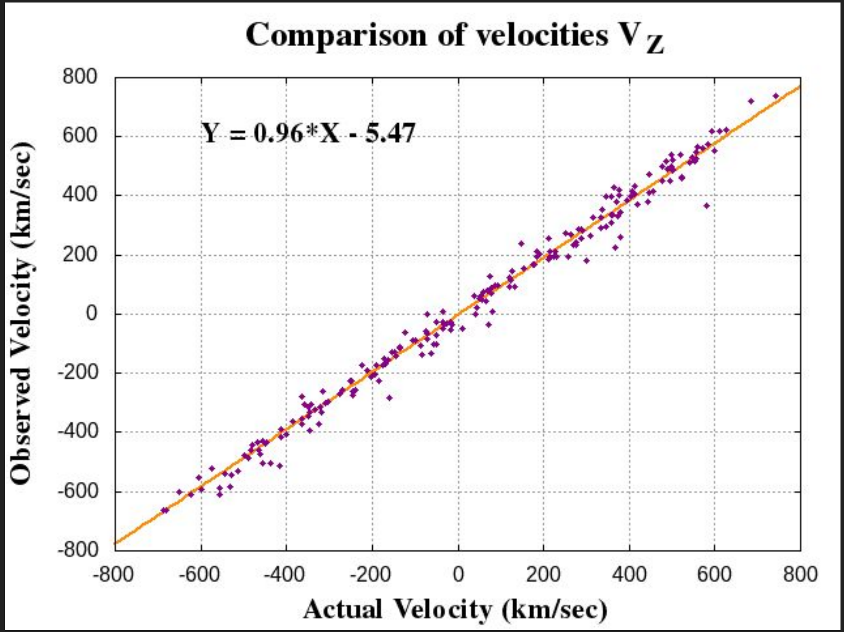
Gaussianity Check				
	Kurtosis	Skewness	Std Dev	Mean
Vx	-0.09	0.01	257.02	-6.99
Vy	0.17	0.06	250.66	-9.52
Vz	-0.12	-0.07	254.89	-7.73


Velocities from steady observer`s frame
1000
500
0
50
100
150
200
250
300
350
Longitude (l º)


Velocities from observer`s frame
Radial Velocity (km/sec)
1000
500
0
-500
-1000
0
50
100
150
200
250
300
350
Longitude (l º)

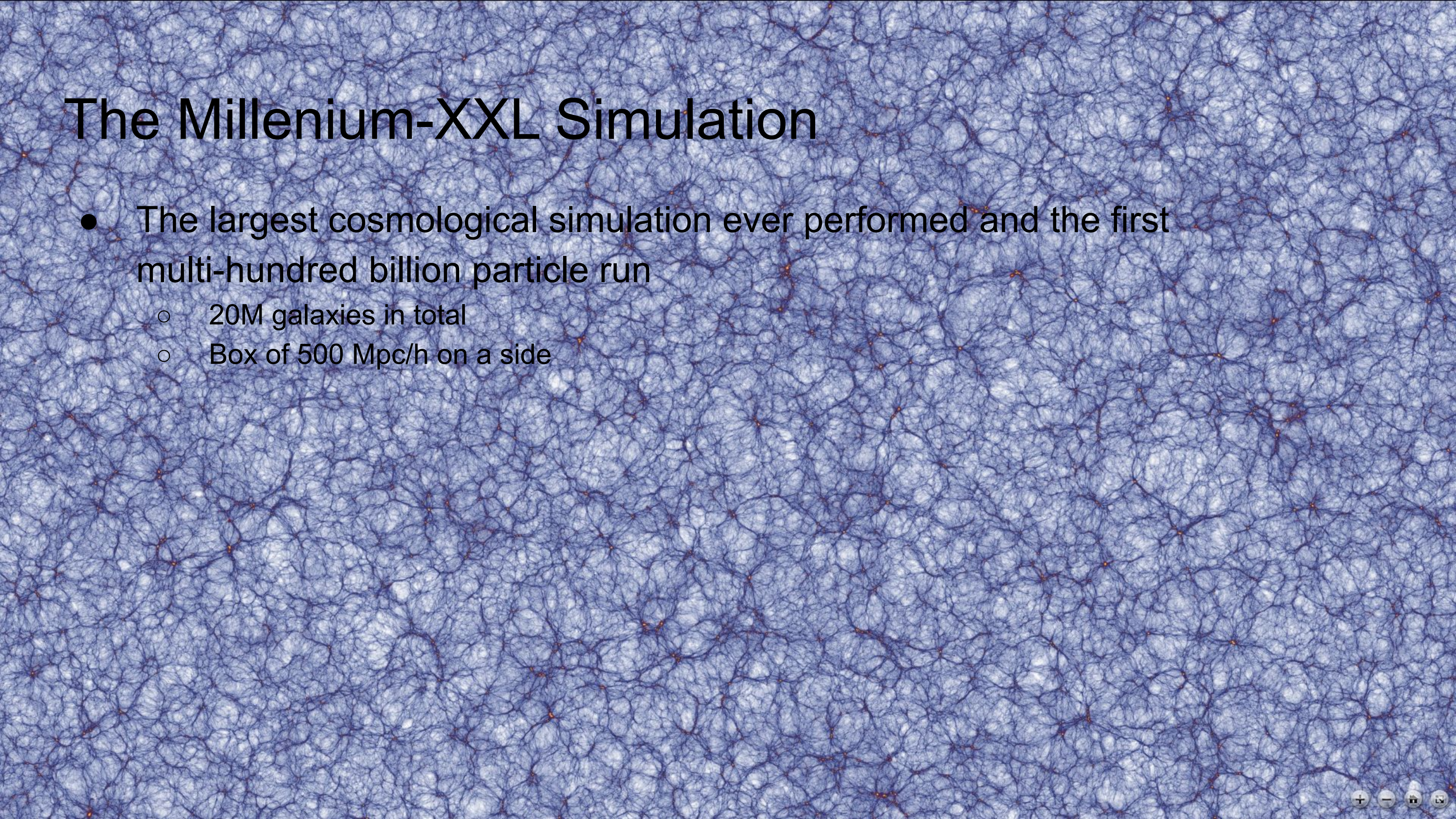
Test results

Component	Slope	Intercept
Vx	0.98	2.76
Vy	0.97	-1.64
Vz	0.96	-5.47
I	1.02	-2.30
b	0.99	-0.56



The Millenium-XXL Simulation

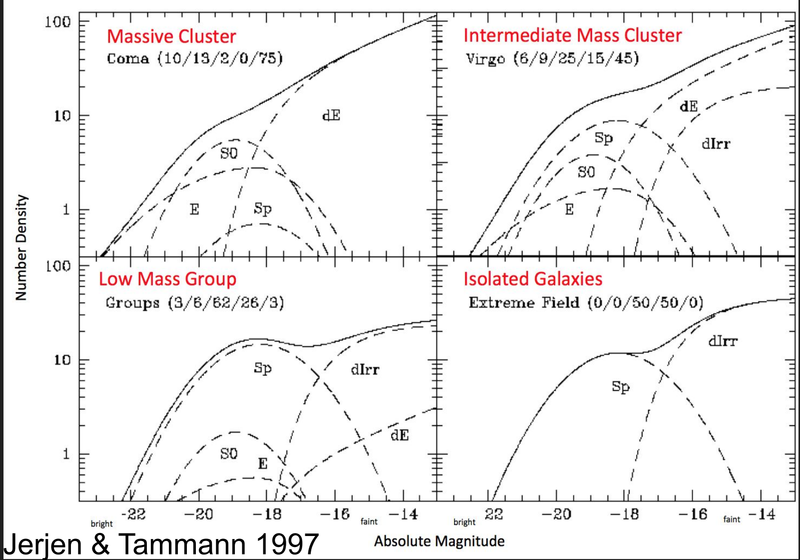
- The largest cosmological simulation ever performed and the first multi-hundred billion particle run
  - 20M galaxies in total
  - Box of 500 Mpc/h on a side



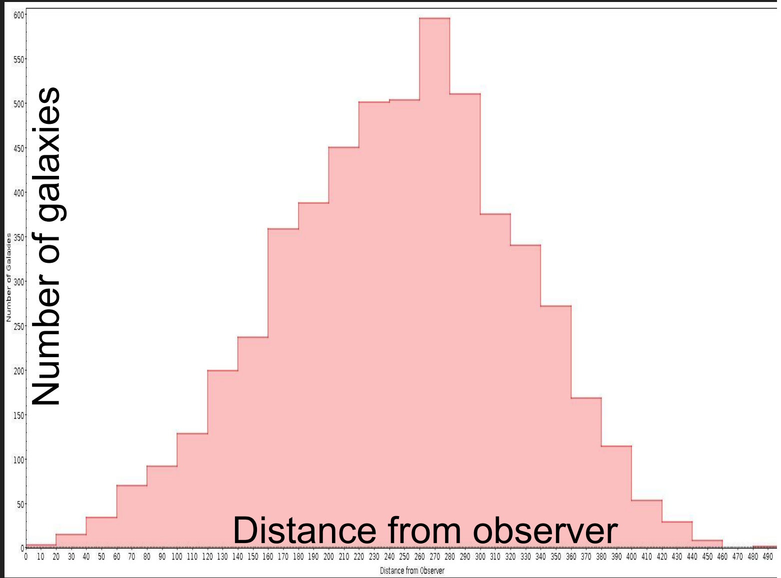
Modified MXXL data

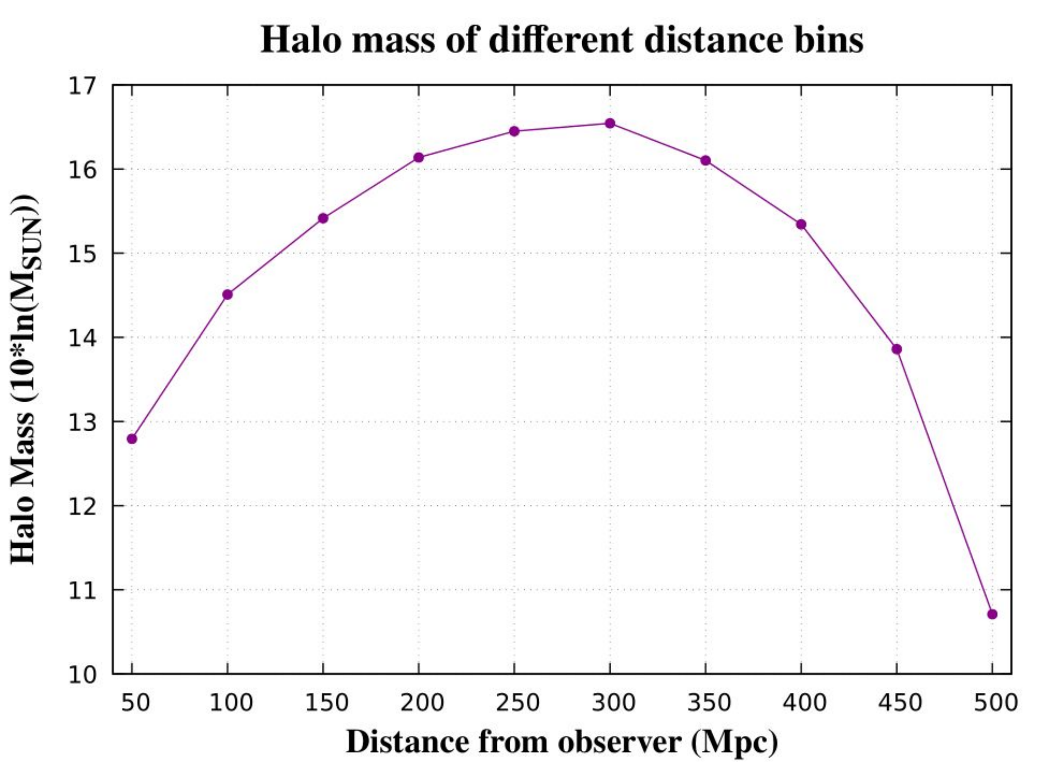
- After initial constraints on M_B, data reduced to ~3.6M galaxies
  - -26 < M_B < -18
- Massive ellipticals are Better tracers of LSS (Marc Postman 1998)
- Their velocities traces cluster velocity better
- To identify cD and gE in our data

  We apply further constraints:
  - -21 < M_B < -18
  - Halo Mass > 5 x 10^(13) Solar mass
  - ~6000 galaxies



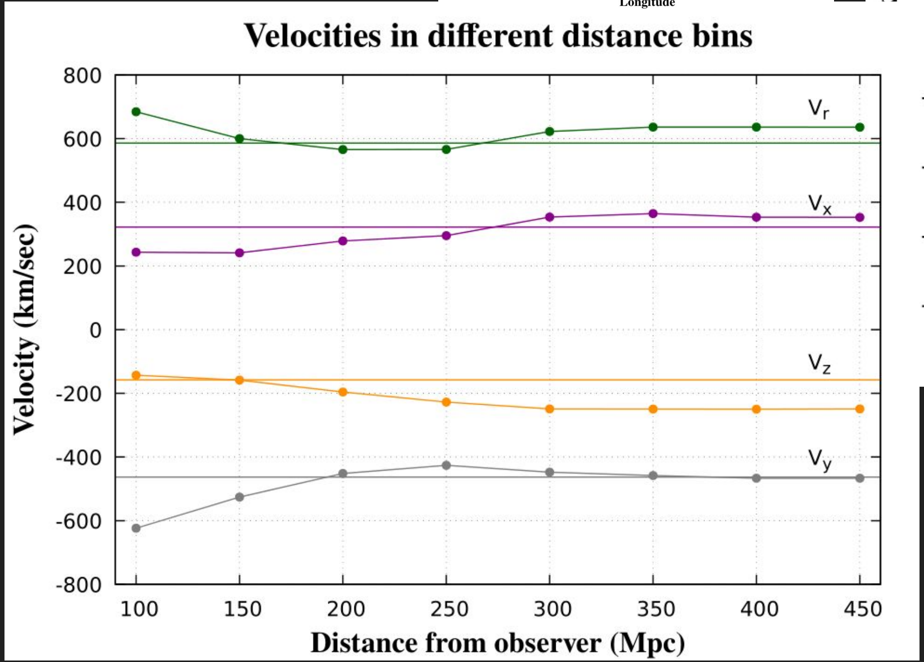
Jerjen & Tammann 1997

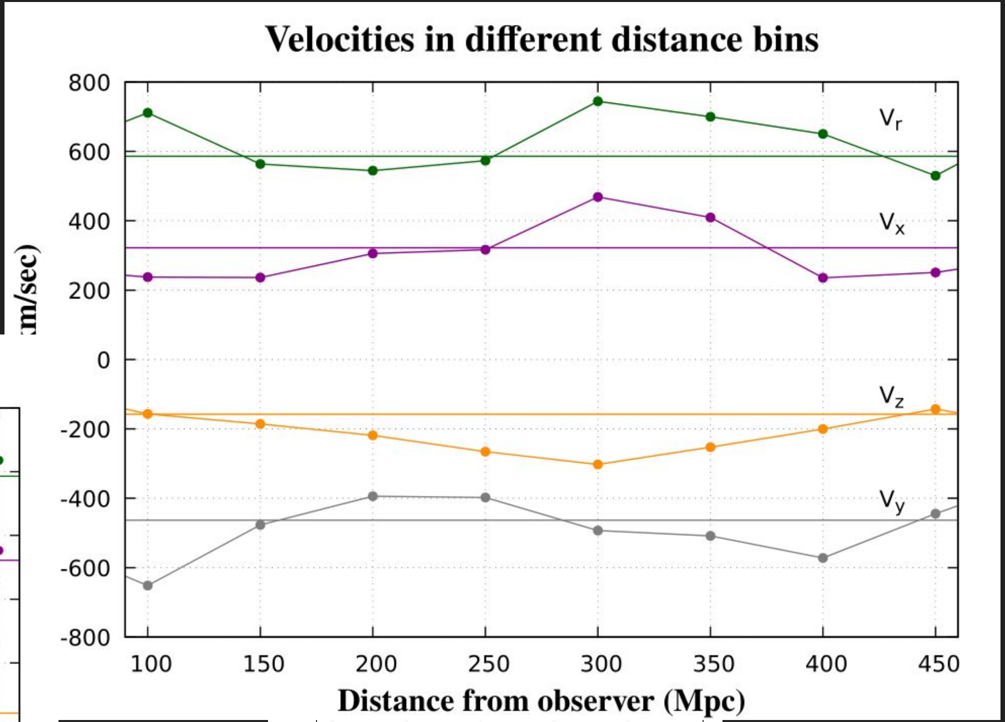

Number of galaxies
Distance from observer
Number of Galaxies
Distance from Observer

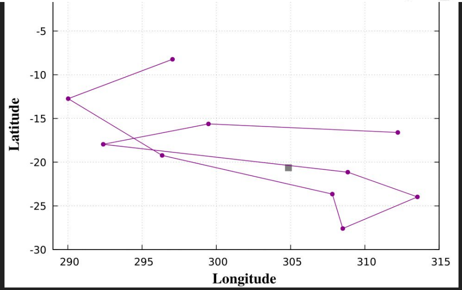

Halo mass of different distance bins
Halo Mass (10*ln(M_SUN))
Distance from observer (Mpc)
17
16
15
14
13
12
11
10
50
100
150
200
250
300
350
400
450
500

Bulk Flow?

Cumulative bins







Isolated bins

What next?

- Add isolated galaxies which are not necessarily massive ellipticals
  - They are also good tracers of velocity fields
- Use groups instead of ellipticals
- Make data more realistic by adding flux limits and sky limits
  - adding zone of avoidance and apparent magnitudes (by considering distance) instead of absolute magnitudes
- Use selection function to avoid any biasing due to these changes
- Use real observations to study bulk flows in the Local Universe

Thank you