Title: Large-scale homogeneity vs. small-scale inhomogeneity: testing Î›CDM with large scale structure

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Abstract: The most fundamental assumption of the standard cosmological model (LambdaCDM) is that the Universe is homogeneous on large scales. This is not true on small scales, and some studies suggest that galaxies follow a fractal distribution up to very large scales (~200 h⁻¹ Mpc or more), whereas Î›CDM predicts homogeneity at ~100 h⁻¹ Mpc. We have tested this using the WiggleZ Dark Energy Survey, a UV-selected spectroscopic survey of ~200,000 luminous blue galaxies up to z=1, with the Anglo-Australian Telescope. The large volume and depth of WiggleZ allows us to probe the transition of the galaxy distribution to homogeneity on large scales, and see if this is consistent with a Î›CDM prediction. Conversely, the properties of small-scale inhomogeneities are an important probe of cosmology. The growth of primordial density perturbations to the large-scale structures present in the Universe today depends on the interplay between cosmic expansion and gravitational interaction. We measure the "bulk flow", or dipole of the velocity field, using the 6dF Galaxy Survey, and show how this can be used as an independent probe of cosmology.

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Large-scale homogeneity vs. small-scale inhomogeneity: testing ΛCDM with large scale structure

Perimeter Institute, 22 April 2014

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Outline

Big picture: Testing ΛCDM with large-scale structure

1. Testing large-scale cosmic homogeneity with the WiggleZ Dark Energy Survey
2. Cosmology with Peculiar Velocity Surveys: Measuring the Bulk Flow with the 6dF Galaxy Survey

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Large-scale Cosmic Homogeneity

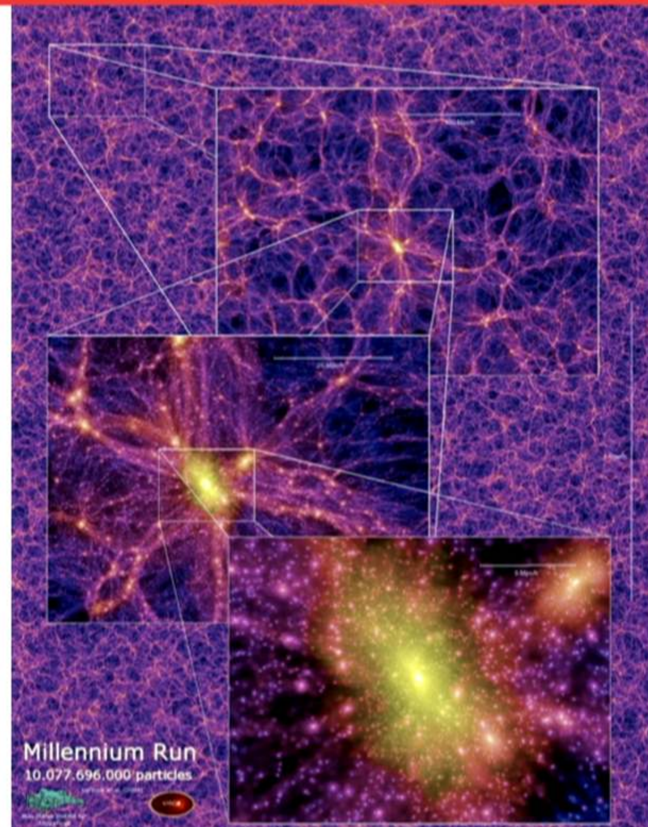
Cosmological principle: Universe is homogeneous and isotropic

- **Homogeneous**: different regions of the Universe have the same mean density
- **Isotropic**: looks the same in all directions

Allows use of Friedmann-Robertson-Walker (FRW) spacetime metric

Need FRW to convert redshifts to distances, via Friedmann eqn:

$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

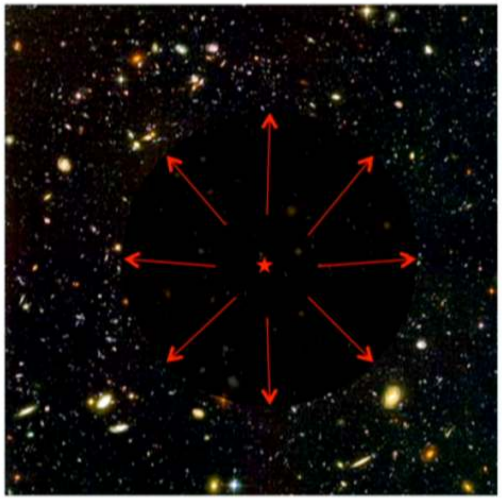


Springel et al. (2005)

Inhomogeneity: alternative to Dark Energy?

- Is 'perturbed FRW' a valid description?
- Large inhomogeneities → problem for FRW?
  - **Light paths distorted**: distances inferred from redshifts are wrong (e.g. Wiltshire 2010)
  - **"Averaging problem" and backreaction**: different-density regions evolve differently, can have global accelerated expansion **without** Dark Energy (e.g. Buchert 2007, Li & Schwarz 2009, Räsänen 2011)
  - **Void models**, e.g. Lemaître-Tolman-Bondi model

Image: hubblesite.org



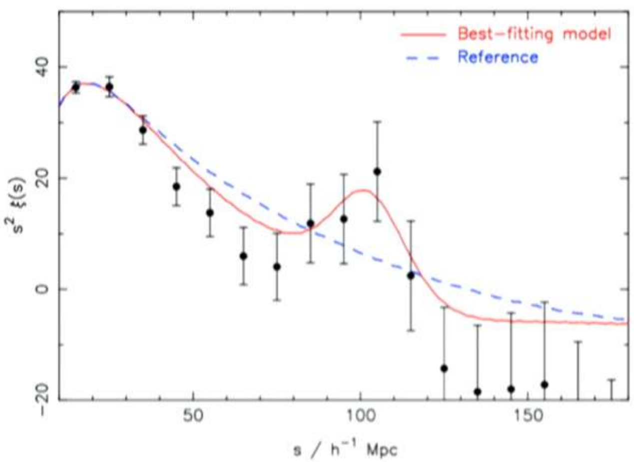
Even if we have large-scale homogeneity…

- Statistical tools used to test cosmology (Power Spectrum, Correlation Function) require homogeneity on scale of survey
  - Their definition and calculation requires mean density (from largest scales in survey):

$$P(r) = \bar{\rho}^2 \left[1 + \xi(r)\right] dV_1 dV_2$$

  - Mean density undefined below scale of homogeneity → results can be misleading
  - Important to know scale of transition to homogeneity

WiggleZ correlation function at z=0.6



Blake et al. (2010)

The WiggleZ Dark Energy Survey

- Large (~1Gpc^3), deep (z<1) spectroscopic redshift survey at AAT
- ~200,000 UV-selected blue emission-line galaxies
- ~1000 deg^2 in 7 regions
- Deep – allows us to measure the scale of homogeneity over several epochs:

$0.1 < z < 0.3$ $0.5 < z < 0.7$

$0.3 < z < 0.5$ $0.7 < z < 0.9$

- Volumes ~ 500 x 300 x 400 (h^{-1} Mpc)^3

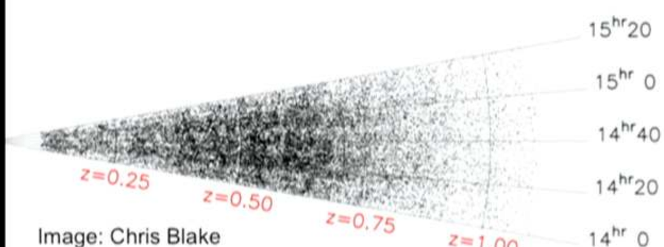
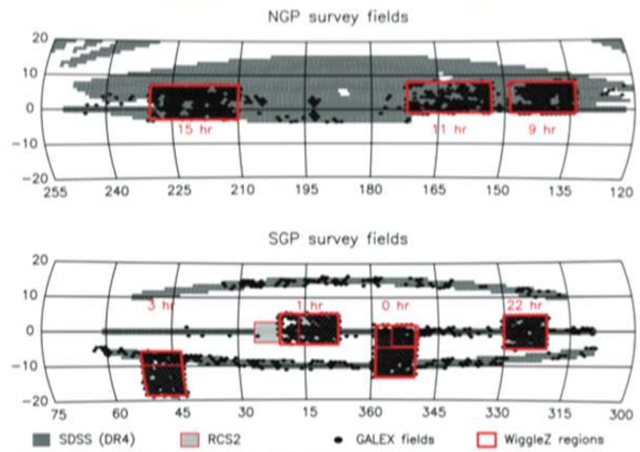


Image: Chris Blake



Drinkwater et al. (2010)

Fractal (correlation) dimension $D_2(r)$

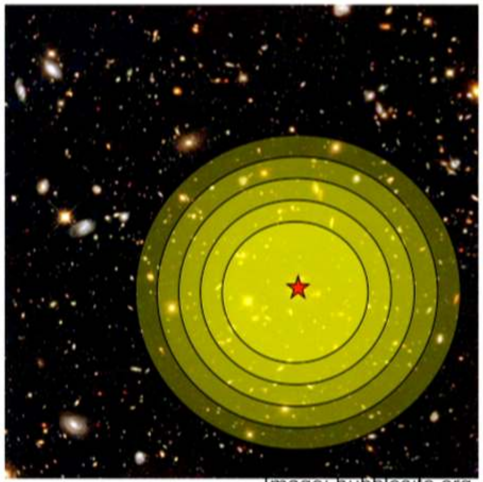
- Fractal dimensions quantify clustering
- Correlation dimension $D_2(r)$: related to 2-point correlation function. Based on the mean value N(<r) of the number of galaxies within distance r of a galaxy:

$$N(<r) \propto r^{D_2}$$

- D_2 is defined:

$$D_2(r) \equiv \frac{d \ln N(<r)}{d \ln r}$$

D_2=3 for a homogeneous distribution



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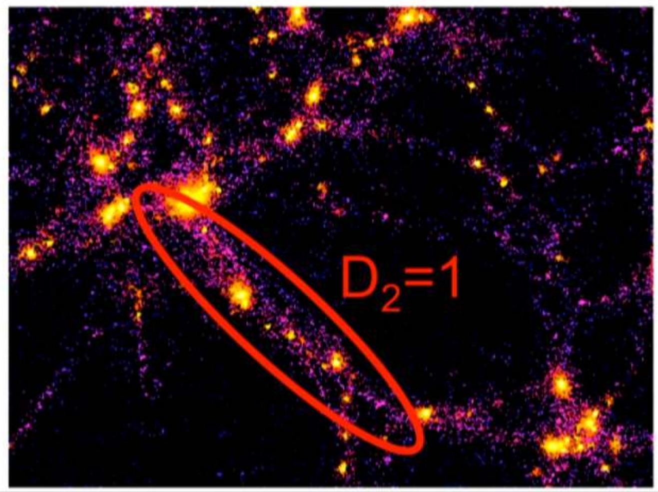
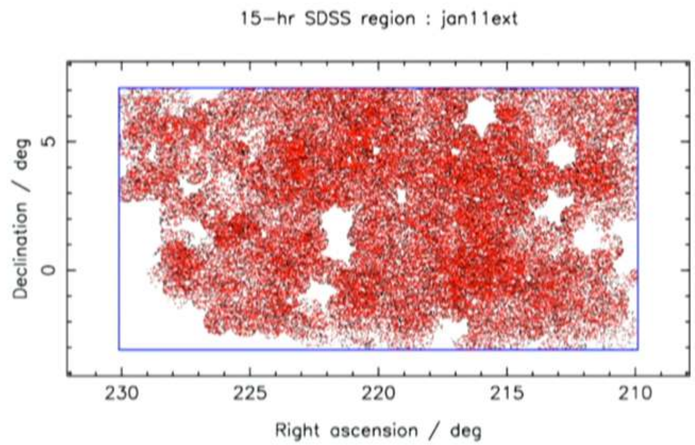


Selection Function Correction

- Ideally, want a complete, volume-limited sample
- In WiggleZ: must correct for selection function using random catalogues

$$N(<r) = \left\langle \frac{N_{gal}(<r)}{< N_{rand}(<r) >} \right\rangle$$

- Takes into account angular and redshift incompleteness



Blake et al. (2010)

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Model N(<r) & $D_2(r)$

- Simple relation to correlation function:

$$P(r) = \bar{\rho}^2 [1 + \xi(r)] dV_1 dV_2$$

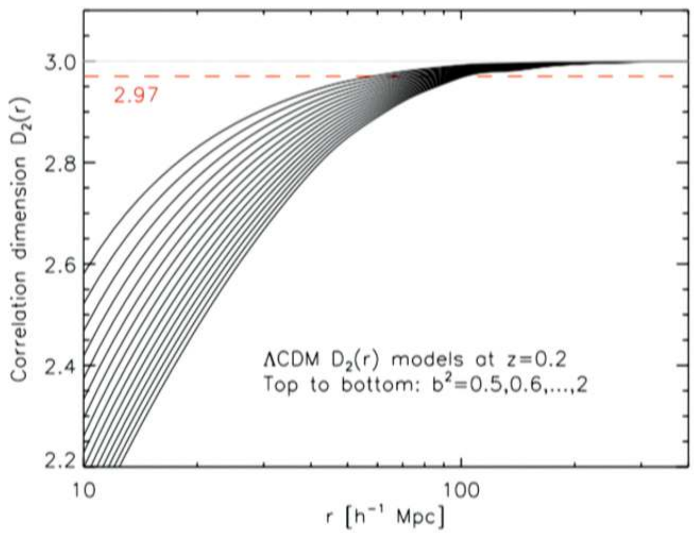
- Number of neighbours is integral of correlation function over volume:

$$N(r) = \bar{\rho} \int_0^r [1 + b^2 \xi(s)] 4\pi s^2 ds$$

- Divide by expected number for ξ=0, ρV:

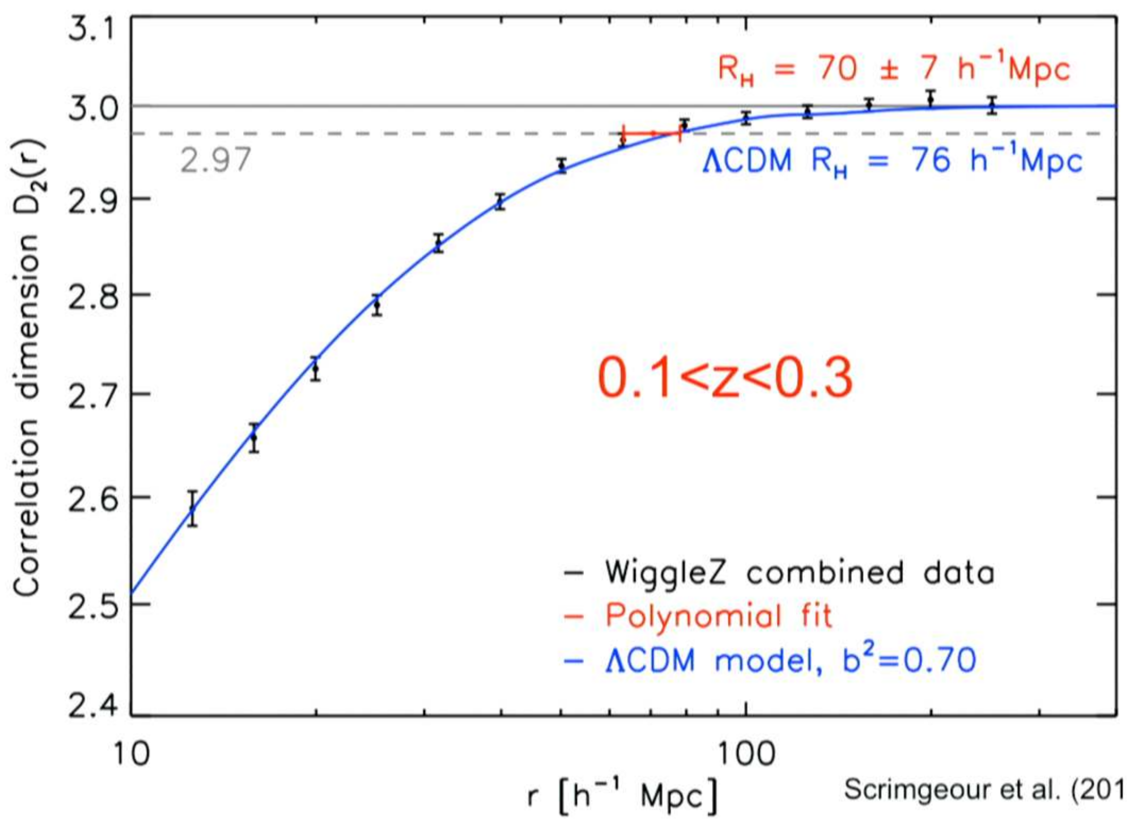
$$N(r) = \frac{3}{4\pi r^3} \int_0^r [1 + b^2 \xi(s)] 4\pi s^2 ds$$

Scrimgeour et al. (2012)



$$D_2(r) \equiv \frac{d \ln N(<r)}{d \ln r}$$

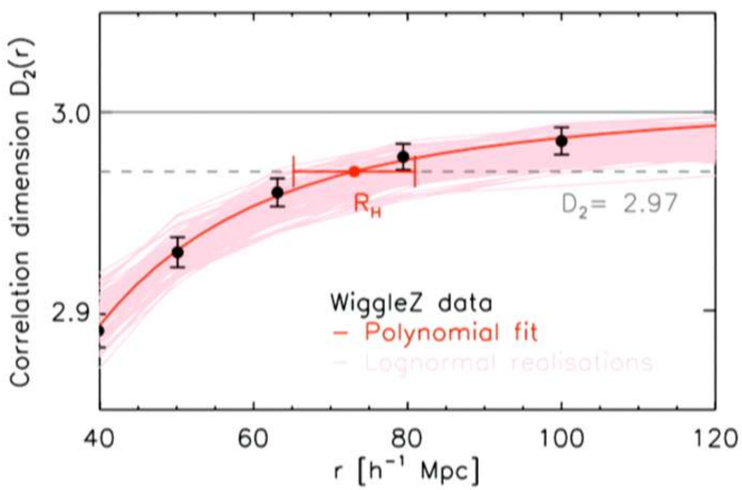
$D_2(r)$ Results 1



Scrimgeour et al. (2012)

How do we define the "homogeneity scale" R_H?

- Past measurements: see where data comes within 1-sigma of homogeneity
- Our method: Fit polynomial to data, take intercept with chosen value close to homogeneity
- Uncertainties from 100 lognormal realisations



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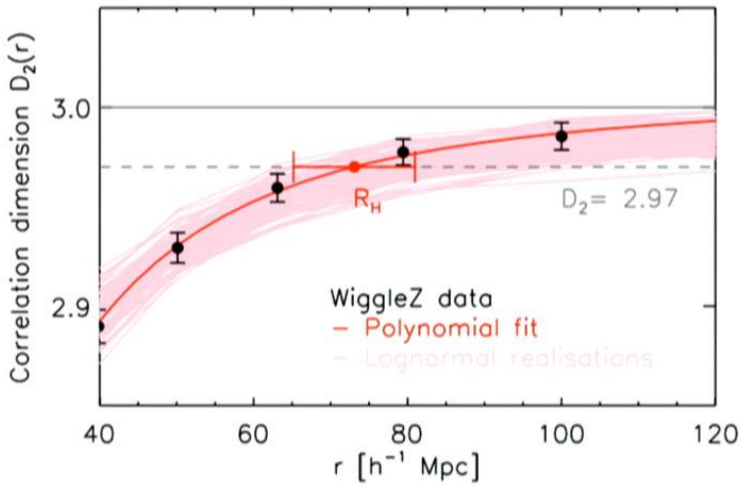

Scrimgeour et al. (2012)

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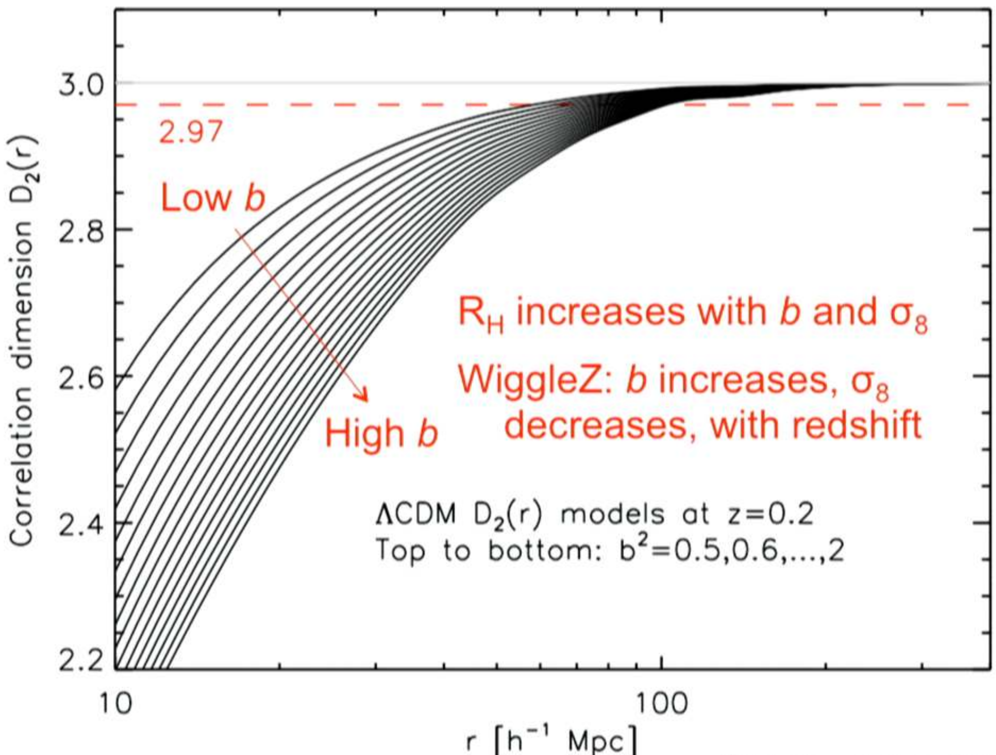
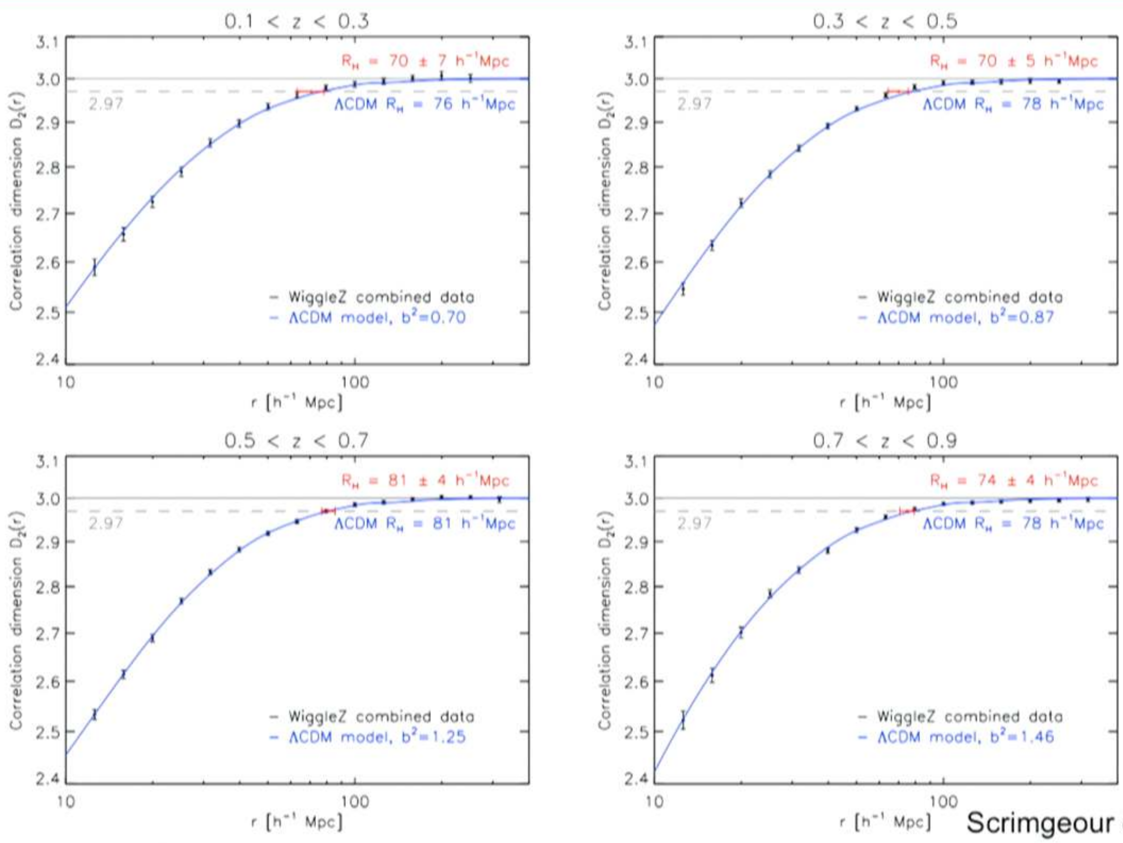
ΛCDM $D_2(r)$ model: effect of bias



Scrimgeour et al. (2012)

$D_2(r)$: All results



Scrimgeour et al. (2012)

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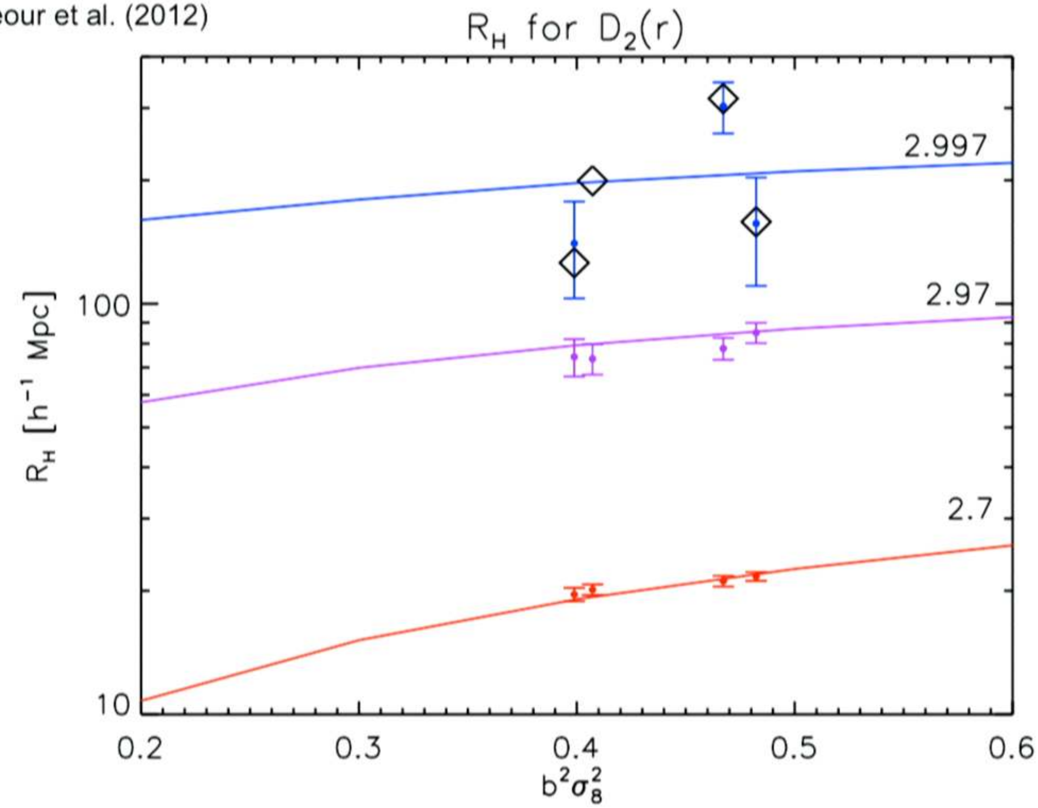
R_H as a function of $b^2\sigma_8^2$

Scrimgeour et al. (2012)



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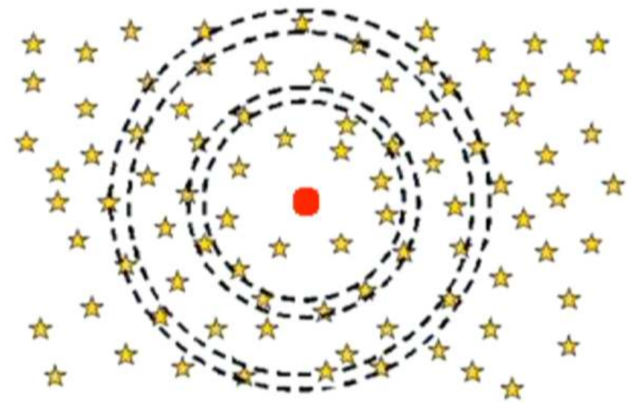
Homogeneity Discussion

- WiggleZ measurement of homogeneity scale: R_H = [71±8, 70±5, 81±5, 75±4] h^{-1} Mpc for z~[0.2, 0.4, 0.6, 0.8].
- Results indicate Universe is not a fractal, **does** transition to homogeneity



- Find strong **consistency** with a FRW-based ΛCDM model
- Complication for all homogeneity analyses: only observe galaxies on past light cone
  - Must assume FRW to convert redshifts to distances.
  - Isotropy measurement in *z*-shells? → Future work

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Cosmology with Peculiar Velocity Surveys: Measuring the Bulk Flow with the 6dF Galaxy Survey

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What are peculiar velocities?

- **Peculiar velocity**: the velocity of a galaxy separate from the Hubble flow
- Due to gravitational interaction with nearby galaxies / overdensities

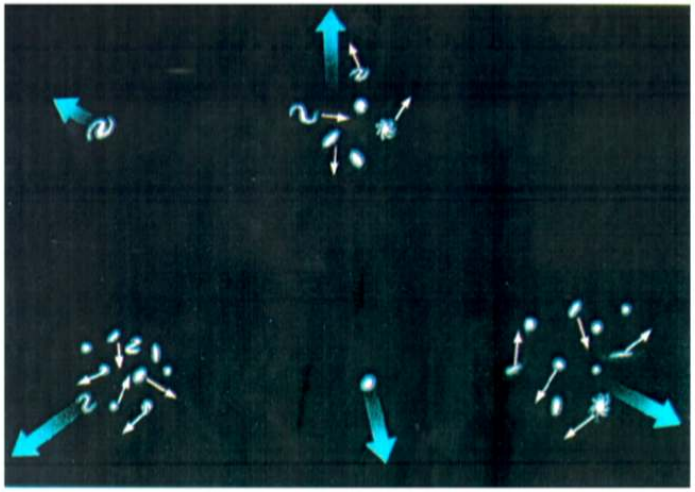

Image: University of Oregon

Peculiar velocities: tracers of matter

- Provide map of underlying matter field
- Velocity field related to density field via (assuming linear approximation):

$$\mathbf{v}(\mathbf{r}) = \frac{fH}{4\pi} \int d^3\mathbf{r}' \frac{\mathbf{r}' - \mathbf{r}}{|\mathbf{r}' - \mathbf{r}|^3} \delta_{\mathrm{mass}}(\mathbf{r}')$$

where $f(a) = \frac{d \ln D}{d \ln a} \simeq \Omega_m^\gamma$

  – D: linear growth factor
  – γ: growth index
- Unbiased (unlike galaxies)

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Measuring Peculiar Velocities

$$V_{pec} = cz - H_0 D$$

redshift (cz)   Hubble flow ($H_0 D$)

Need known distance indicator

- Tully-Fisher: $L \propto v^4$ (~20% error)
- Fundamental Plane (~30% error)
- SN Ia (5-10% error)

Bulk flows and dark flows: a problem for ΛCDM?

"Bulk flow": the average velocity over some volume

$$\boldsymbol{u} = (u_1\hat{\boldsymbol{x}}_1, u_2\hat{\boldsymbol{x}}_2, u_3\hat{\boldsymbol{x}}_3)$$

Kashlinsky et al. (2008): kSZ effect in clusters,
600-1000 km/s at z~0.3 toward l=283°±14°, b=12°±14° **(since disproven?)**

Watkins et al. (2009): peculiar velocity surveys,
407±81 km/s in ~50 h^{-1}Mpc radius toward l=287°±9°, b=8°±6°

ΛCDM linear theory: ~190 km/s

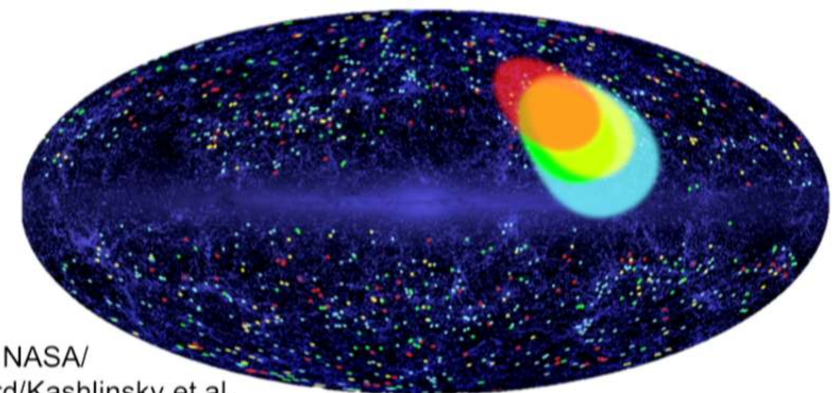

Image: NASA/
Goddard/Kashlinsky et al.

Conflicting σ_8 constraints

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Measurements of σ_8 from Bulk Flow measurements

	σ_8
Feldman et al. (2003)	$1.13^{+0.22}_{-0.23}$
Watkins et al. (2009)	$1.7^{+?}_{-0.59}(95\%)$
Nusser & Davis (2011)	0.86 ± 0.11
Ma & Scott (2013)	$0.65^{+0.47}_{-0.35}$

- Feldman et al. (2003): use pairwise velocities from Mark III, SFI, ENEAR
- Watkins et al. (2009): COMPOSITE sample, Minimum Variance bulk flow weighting scheme
- Nusser & Davis (2011): SFI++ Tully Fisher survey, ACSE bulk flow estimation (constrained realisation method)
- Ma & Scott (2013): reanalysis of COMPOSITE

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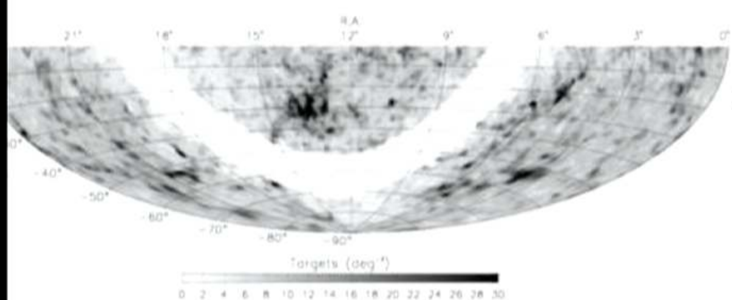
Problems for Bulk flow measurements

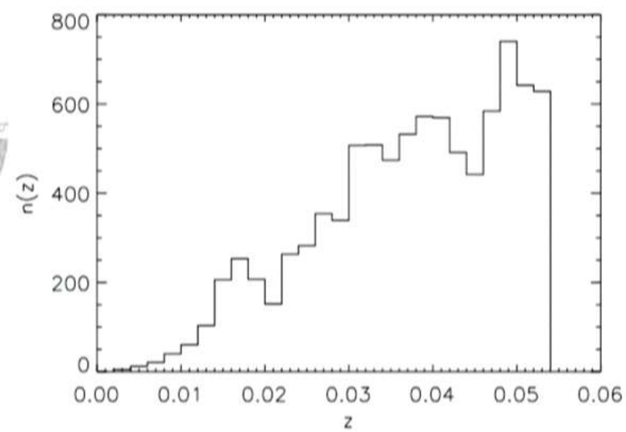
Several potential systematics:

- Velocity samples difficult to compare
  - Shallow & dense vs. deep & sparse
  - Distance indicators: SNe, FP, TF
- Partial sky can induce systematic error
- Logarithmic distance errors
- Difficult to compare velocities with density field
- Need all-sky, deeper peculiar velocity surveys
- Homogeneous selection
- Accurate modelling of systematics

6dFGS Peculiar Velocities

- Spectroscopic survey of southern sky (17,000 deg^2)
- Primary sample from 2MASS with K_{tot} < 12.75, also secondary samples with H < 13.0, J < 13.75, *r* < 15.6, *b* < 16.75
- 125,000 redshifts, 9000 FP peculiar velocities
- Largest combined redshift *and* peculiar velocity survey by a factor of 2
- Max *z* ~ 0.15





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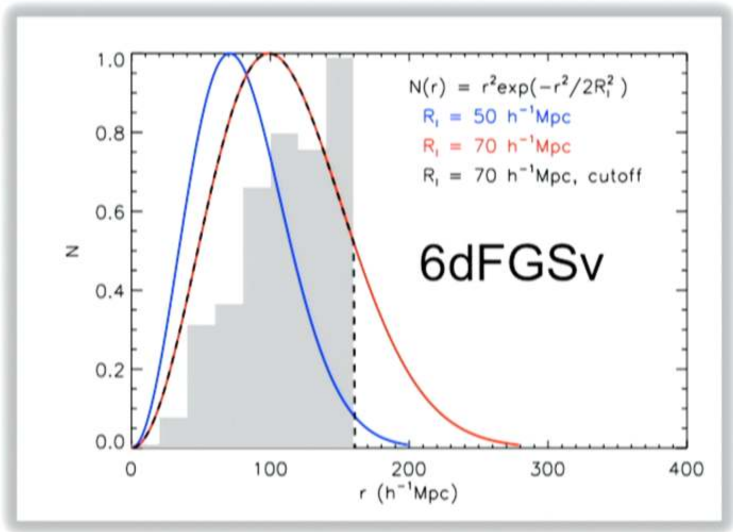
Bulk Flows: Minimum Variance Weights

- Bulk flow: $$\mathbf{U}(r) = \frac{3}{4\pi r^3} \int_{x=0}^{r} \mathbf{v}(\mathbf{x}) d^3 x$$
- Estimator: $$u_i = \sum_n w_{i,n} v_n$$
- Different surveys difficult to compare
  - Different volumes, geometry, sparseness
- Calculate weights to mimic 'ideal' survey geometry
  - Minimise variance between measured and 'ideal' bulk flow



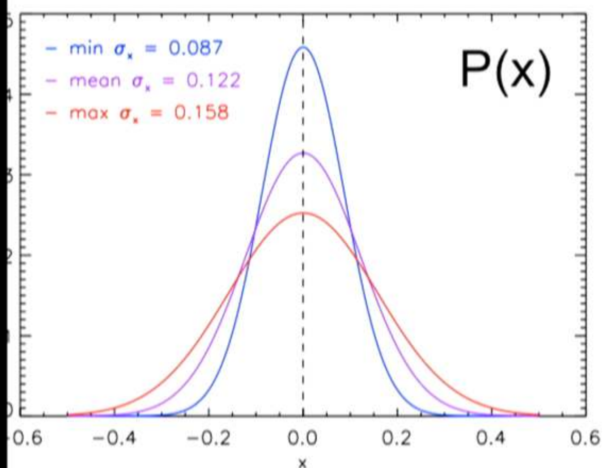
6dFGSv Peculiar Velocity Probability Distributions

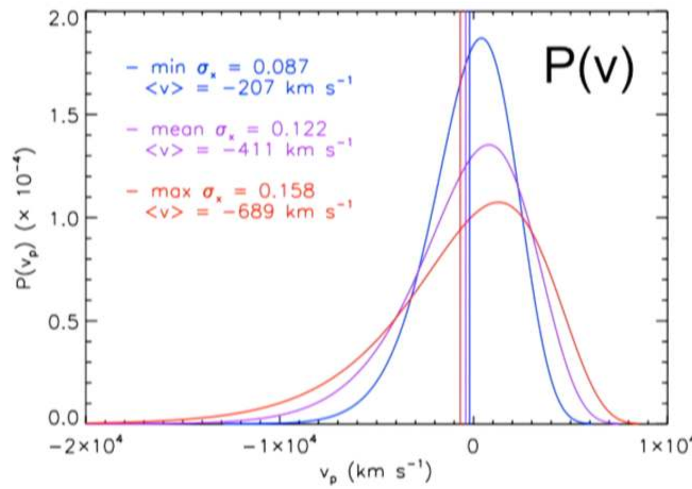
- Output of Fundamental Plane for 6dFGSv is a probability distribution of

$$x = \log_{10}(D_z/D_r)$$

- Convert *x* to velocity via

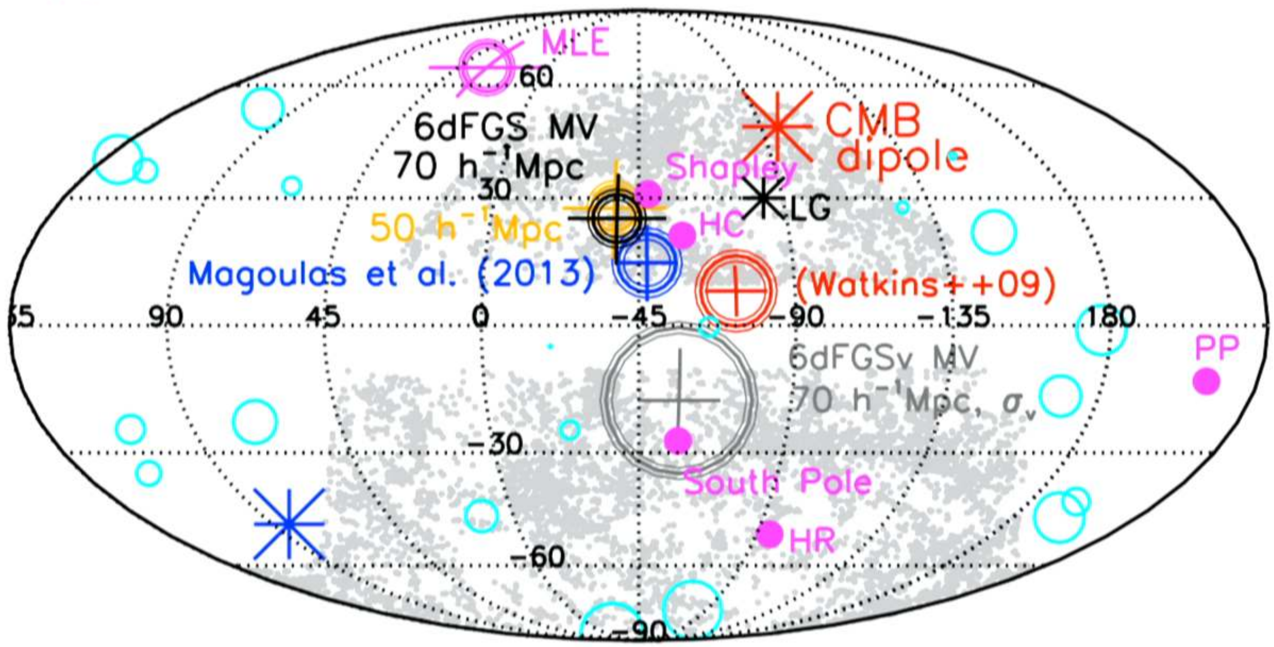
$$P(v) = P(x)\frac{1}{D_r \ln(10)}\frac{dD_r}{dz_r}\frac{(1+z_r)^2}{c(1+z)}$$





6dFGS Bulk Flow Results

- $|u|$ = 257 ± 56 km/s



(Scrimgeour et al. 2014, in prep)

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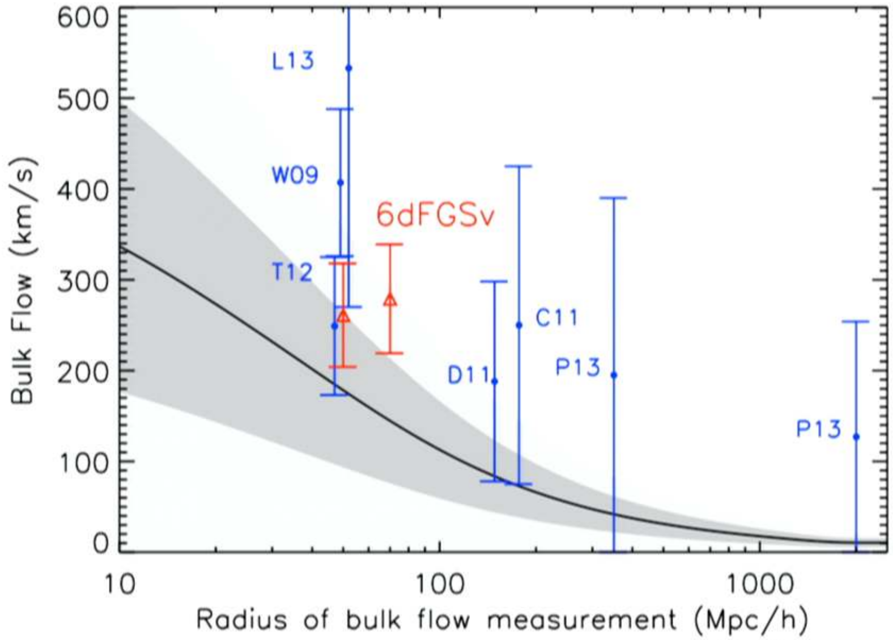
3D Bulk flow amplitude: comparison with theory

$$\langle V(R)^2 \rangle = \frac{H_0^2 f^2}{2\pi^2} \int_{k=0}^{\infty} dk P(k) \widetilde{W}(k;R)^2$$



(Scrimgeour et al. 2014, in prep)

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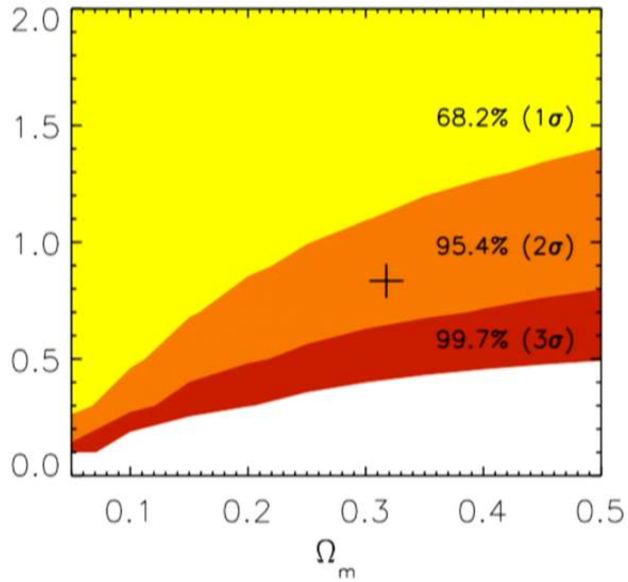
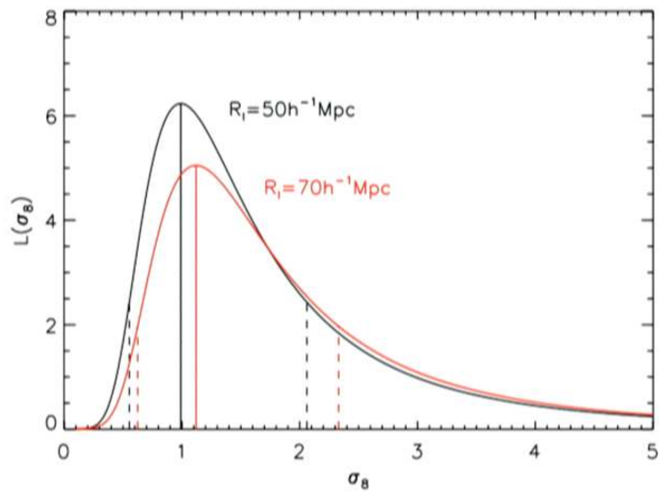
1D Bulk Flow components: Ω_m and σ_8 constraints

$$\chi^2 = \sum_{i,j} u_i R_{ij}^{-1} u_j$$

$$R_{ij} = \sum_n w_{i,n} w_{j,n} (\sigma_n^2 + \sigma_*^2) + \frac{f^2 H_0^2}{2\pi^2} \int_0^\infty dk \mathcal{W}_{ij}^2(k) P(k)$$





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Summary

Homogeneity in the WiggleZ Survey

- WiggleZ measurement of homogeneity scale:
  R_H = [71±8, 70±5, 81±5, 75±4] h^{-1} Mpc for z~[0.2, 0.4, 0.6, 0.8].
- Strong consistency with FRW-based ΛCDM

Meauring the Bulk Flow with the 6dF Galaxy Survey

- Have tested the findings of Watkins et al. 2009
- 6dFGS bulk flow large, but appears consistent with ΛCDM
- Need to further develop ways to analyse data and deal with systematics…