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CAASTRO ALL-SKY ASTROPHYSICS

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

Lawrence Berkeley National Laboratory, 18 January 2013

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Outline

Big picture: What is the nature of dark energy?

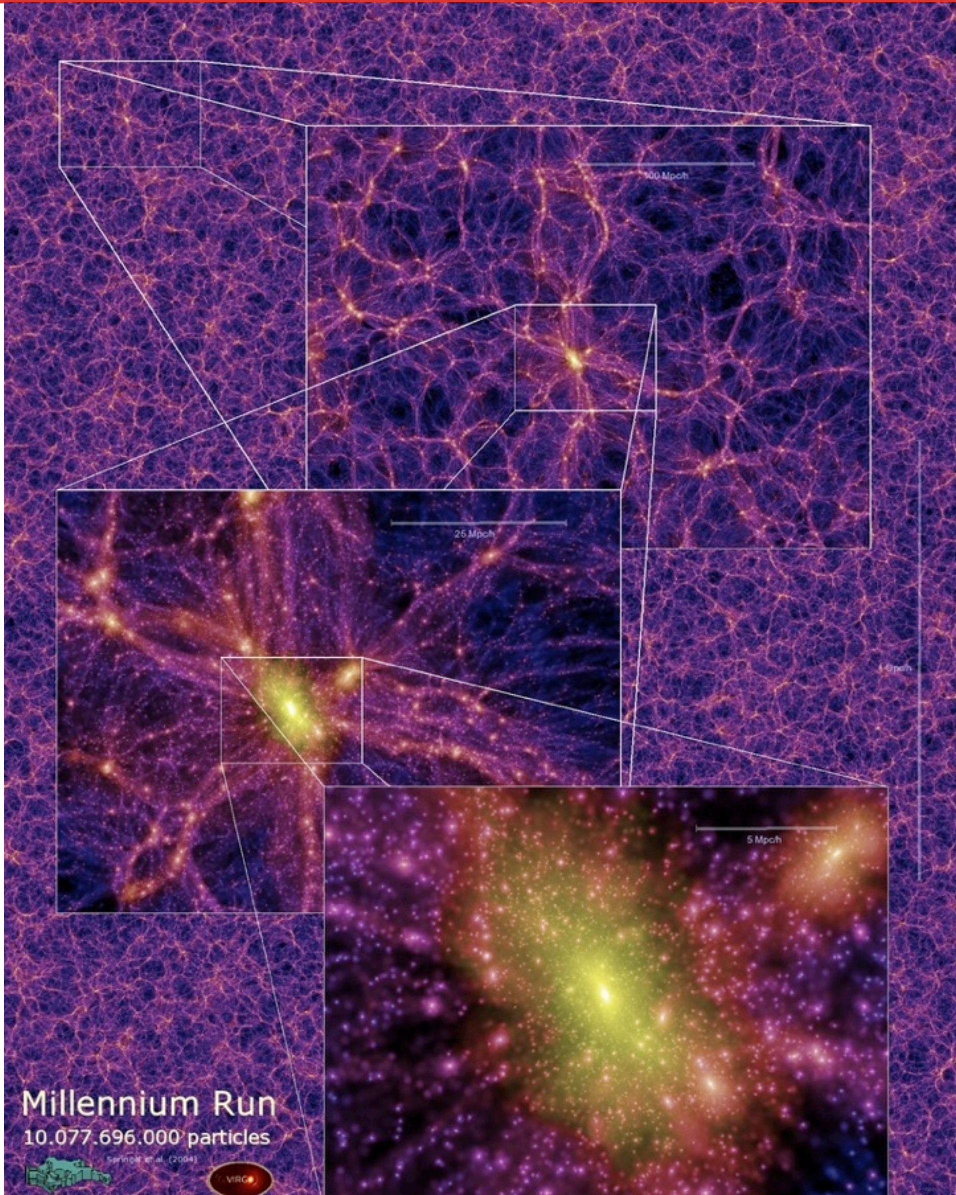
1. Testing large-scale cosmic homogeneity with the WiggleZ Dark Energy Survey
2. Cosmology with Peculiar Velocity Surveys

Testing large-scale cosmic homogeneity with the WiggleZ Dark Energy Survey

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:

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

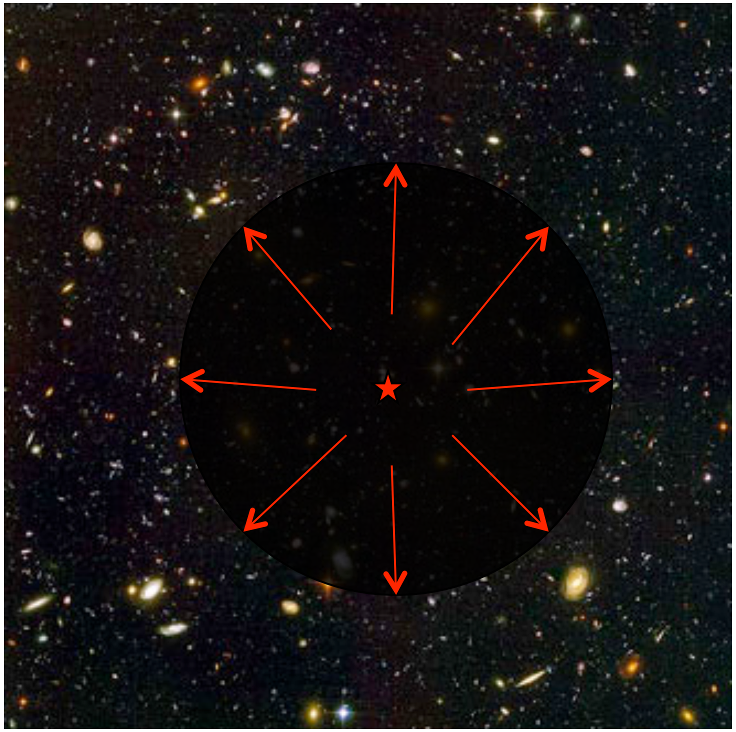


Springel et al. (2005)

Inhomogeneity: alternative to Dark Energy?

- Is ‘perturbed FRW’ a valid description?
- Large inhomogeneities → breakdown of 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



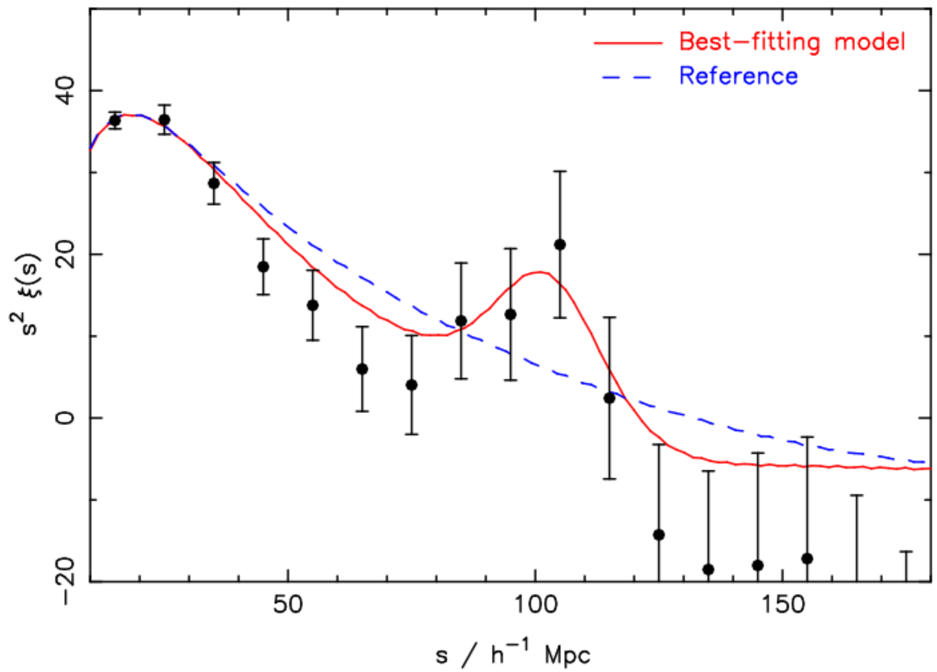
Even if we have large-scale homogeneity…

- 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

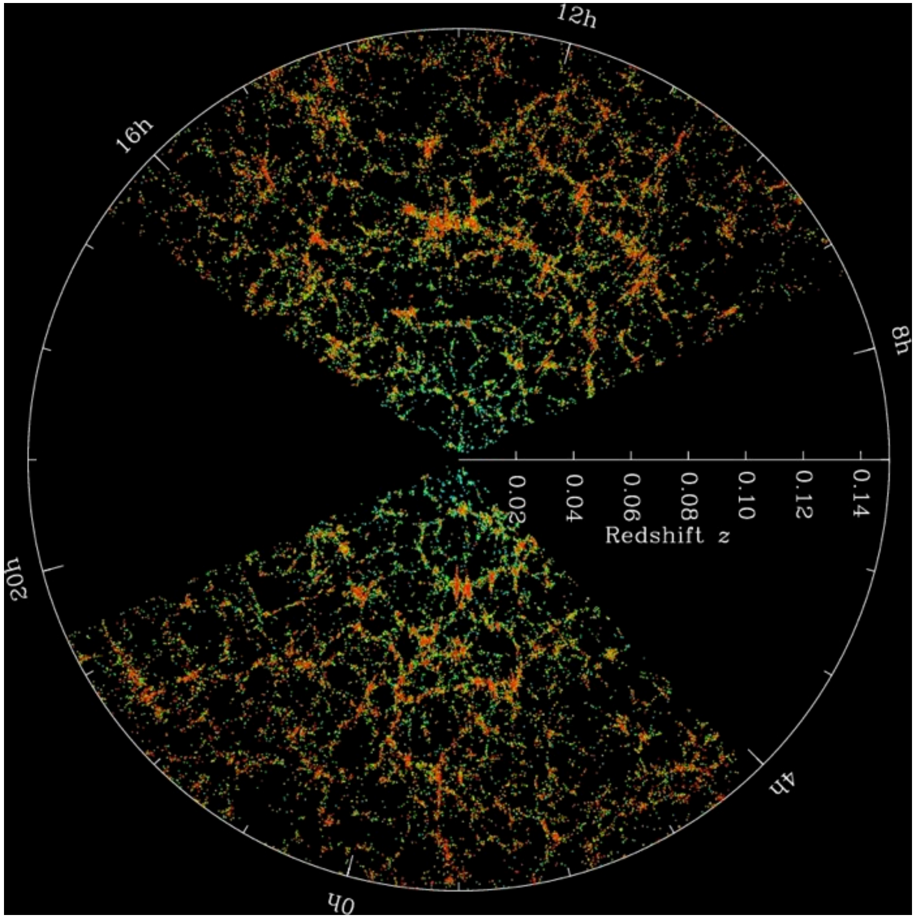


Blake et al. (2010)

Homogeneity in Galaxy Surveys

Image: M.Blanton and the SDSS collaboration

- So far, results are conflicting!
- Homogeneity ~ 70 h^{-1} Mpc: SDSS LRGs (Hogg et al. 2005), SDSS DR1 (Yadav et al. 2005), SDSS DR6 (Sarkar et al. 2009)
- But several works find fractal structure up to scales >100 h^{-1} Mpc - no transition to homogeneity (e.g. Joyce et al. 1999, Sylos Labini et al. 2009)



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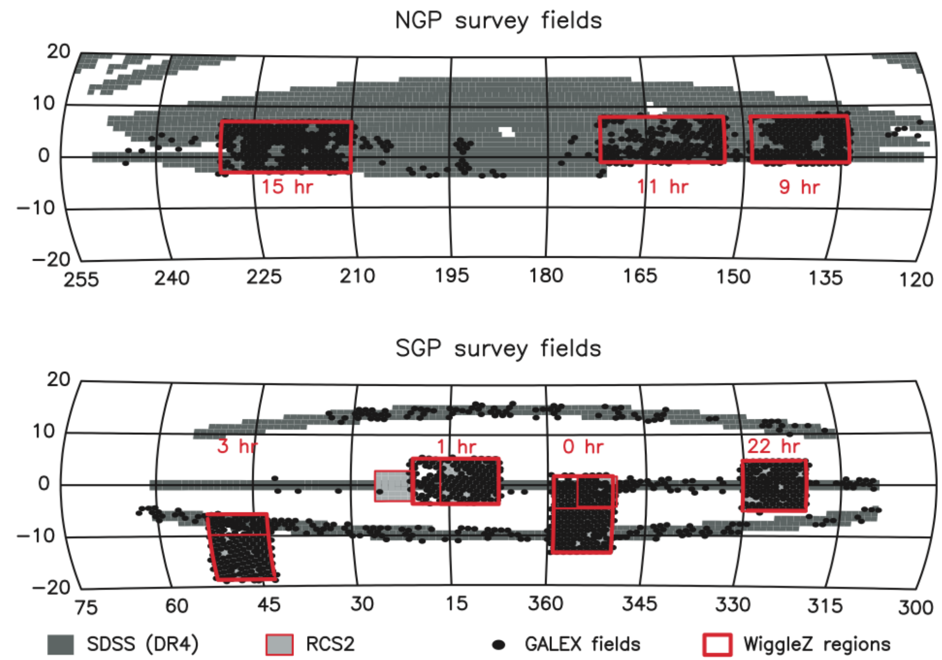
The WiggleZ Dark Energy Survey

- 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



Drinkwater et al. (2010)

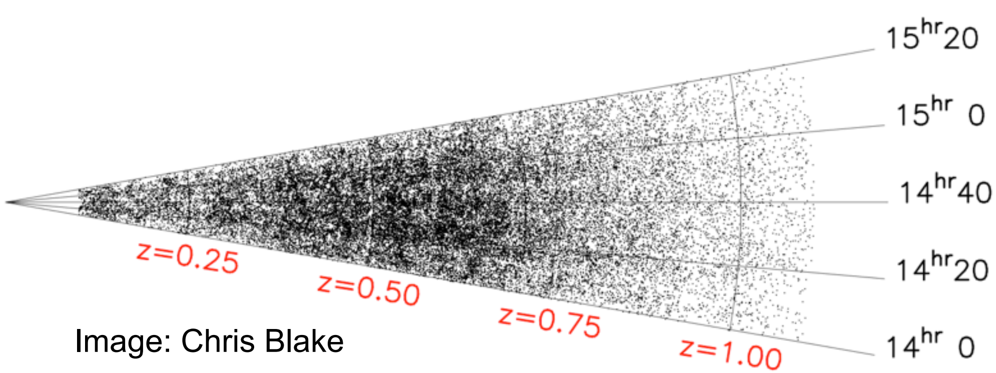


Image: Chris Blake

Fractal (correlation) dimension $D_2(r)$

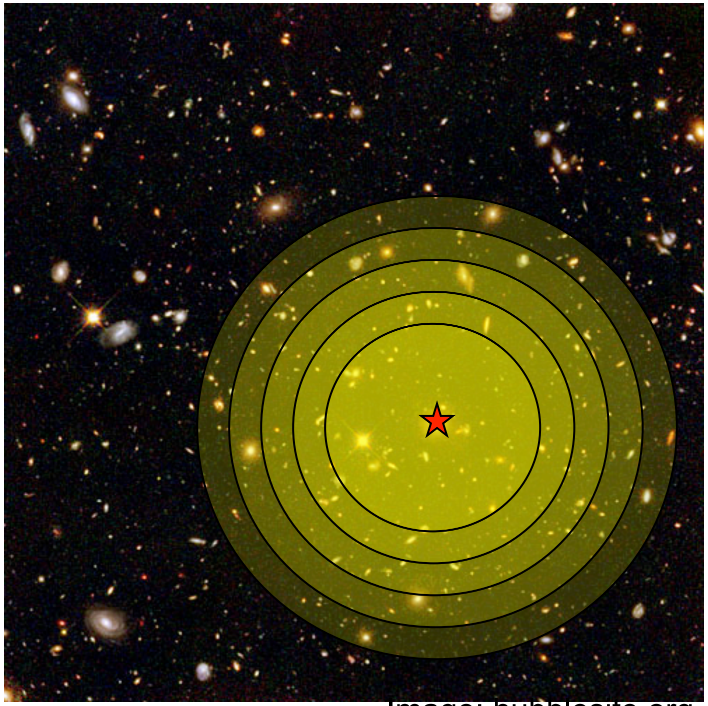
- Fractal dimensions quantify clustering
- Correlation dimension $D_2(r)$: related to 2-point correlation function. Based on the mean value $N(<r)$ of the number of galaxies within distance r of a galaxy:

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

- 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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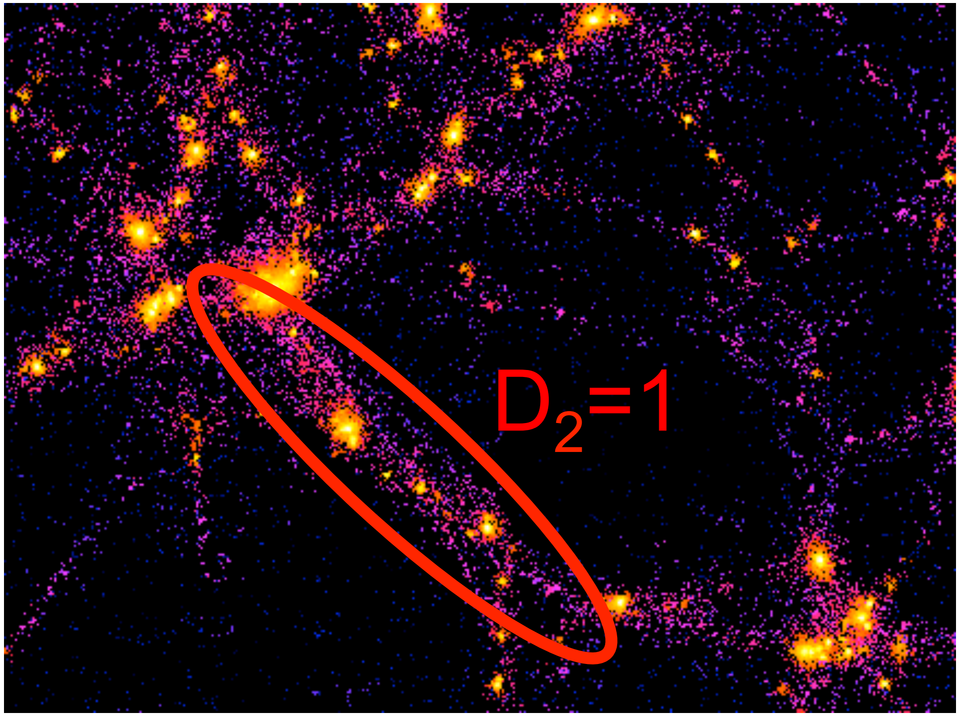
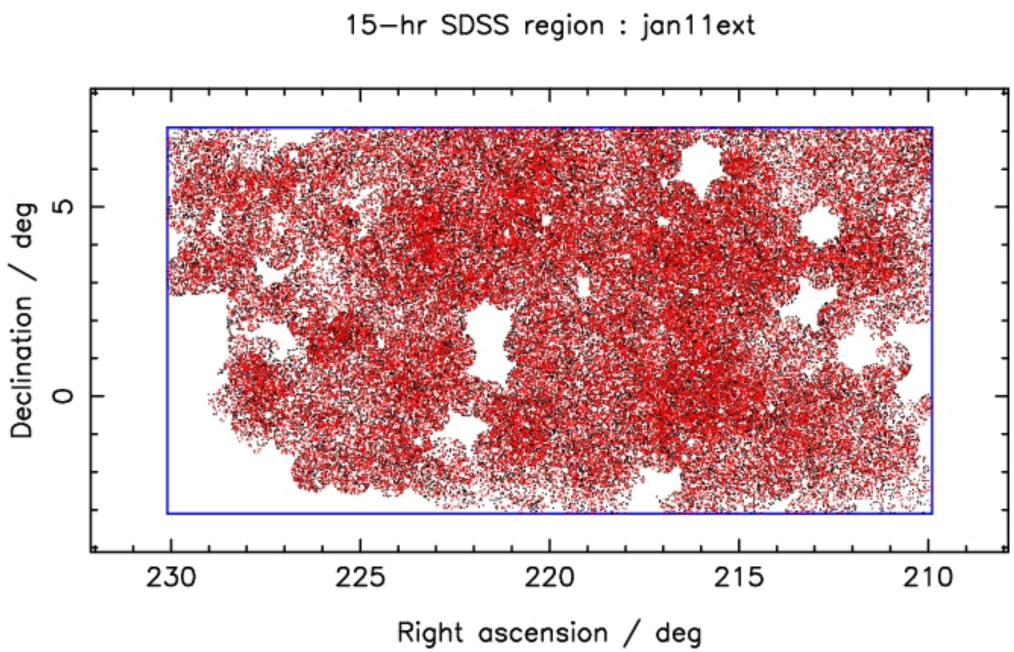


Selection Function Correction

- 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)

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

Scrimgeour et al. (2012)

- Simple relation to correlation function:

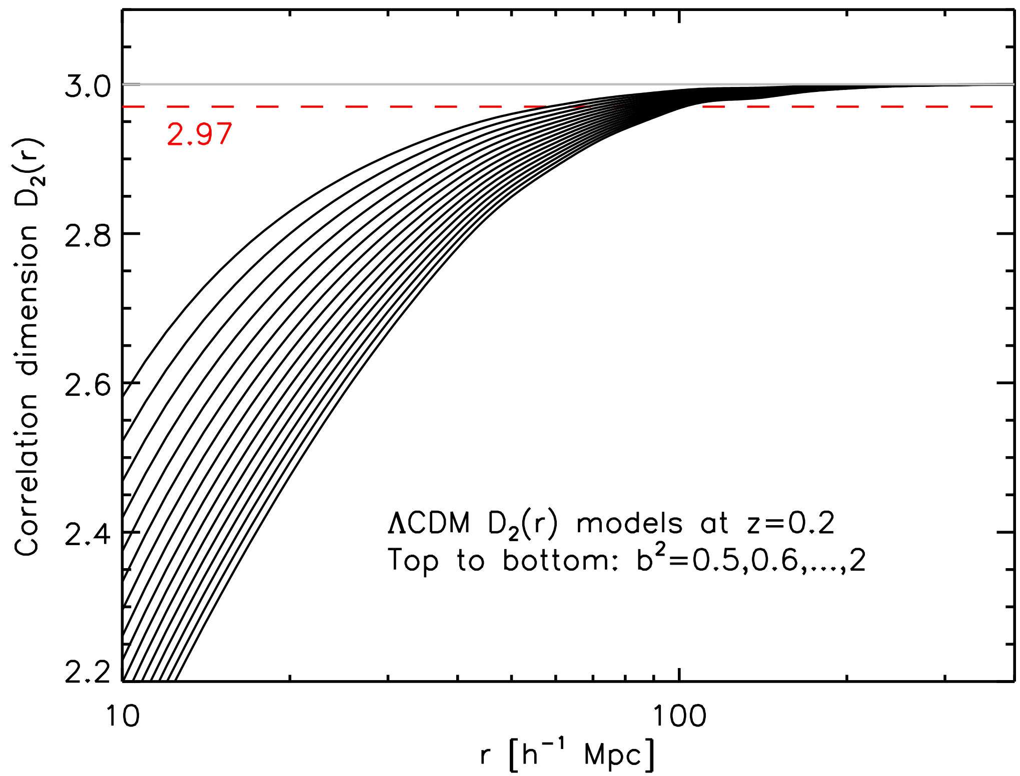
$$P(r) = \bar{\rho}^2[1+\xi(r)]dV_1 dV_2$$

- 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:

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



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

$D_2(r)$ measurements so far…

- In ΛCDM expect:
  - Small scales: fractal-like structure
  - >100 h^{-1} Mpc: homogeneous
- Some D_2 measures: 1.2 – 2.2 on small scales, close to 3 above ~ 70 h^{-1} Mpc (Wu et al. 1999, Yadav et al. 2005)
- But 'fractal proponents' have found D_2~2 for scales up to 150 h^{-1} Mpc (Sylos Labini et al. 1998, Joyce et al. 1999)
- So is the Universe a fractal?

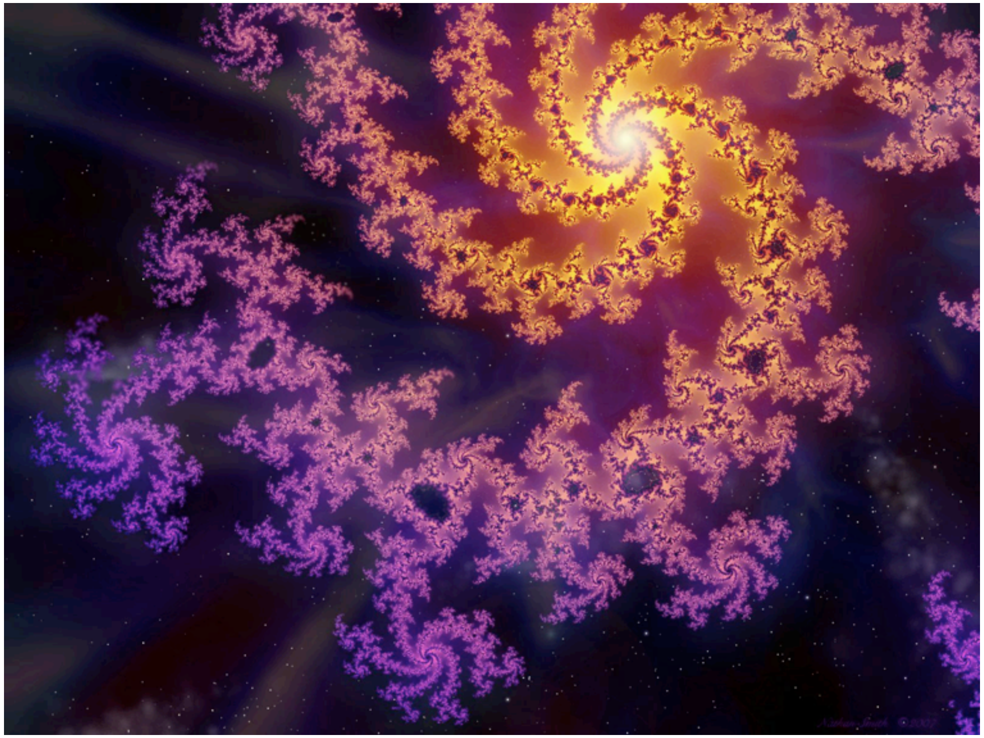
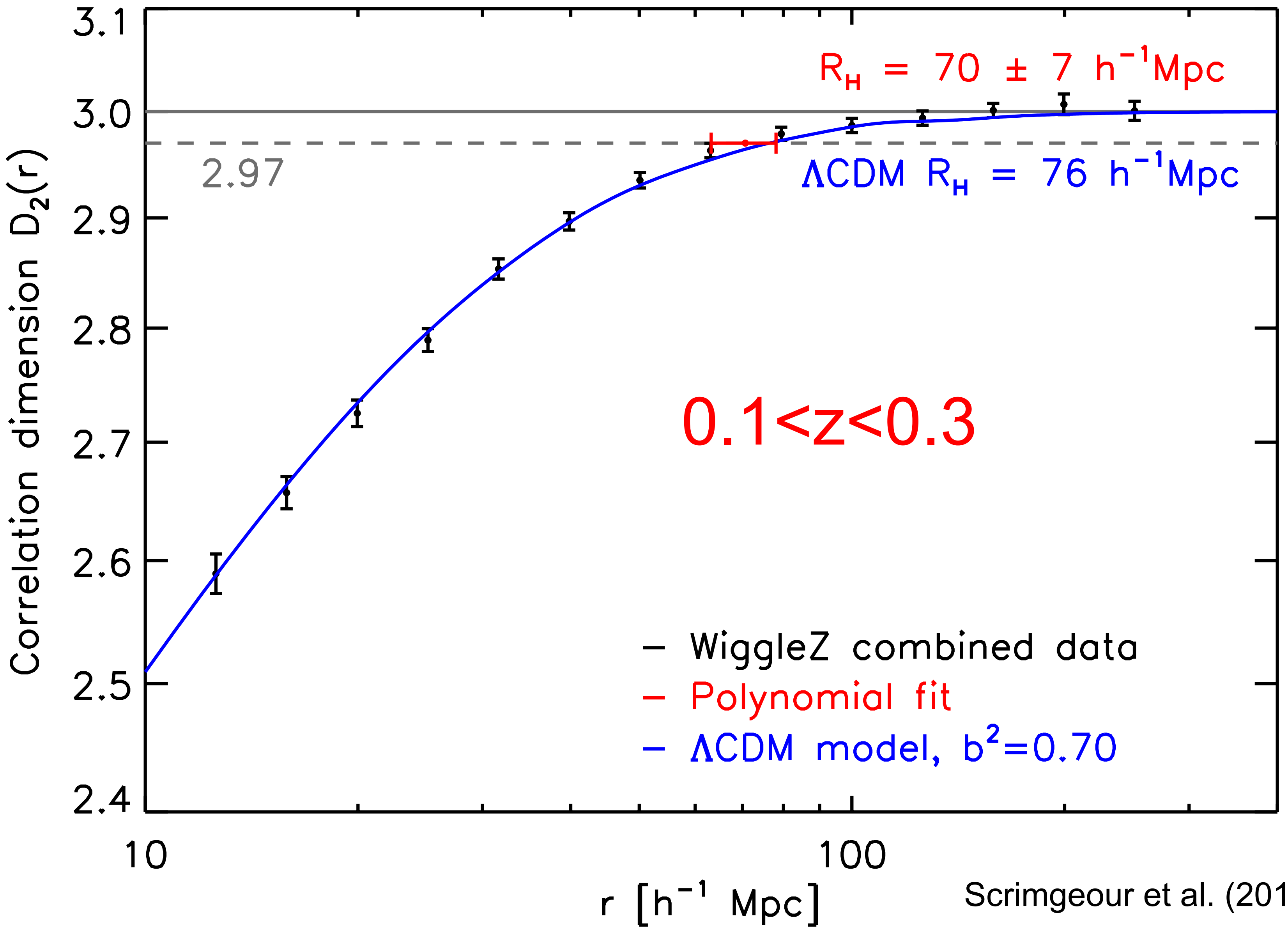


Image: www.presidiacreative.com

$D_2(r)$ Results 1



Scrimgeour et al. (2012)

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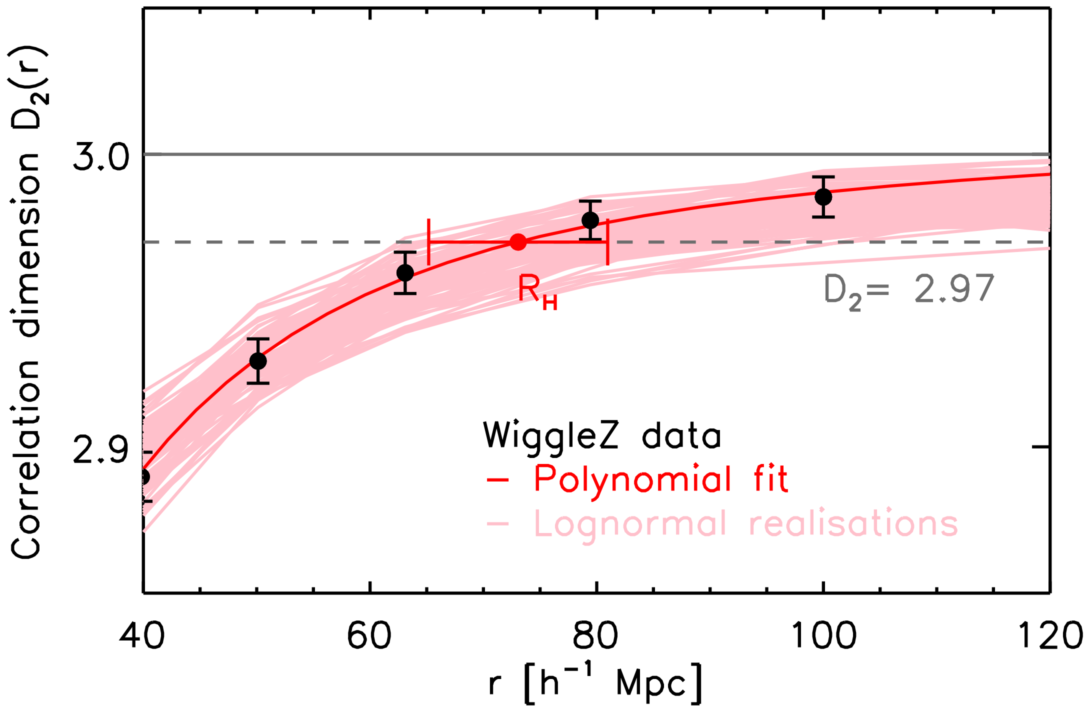
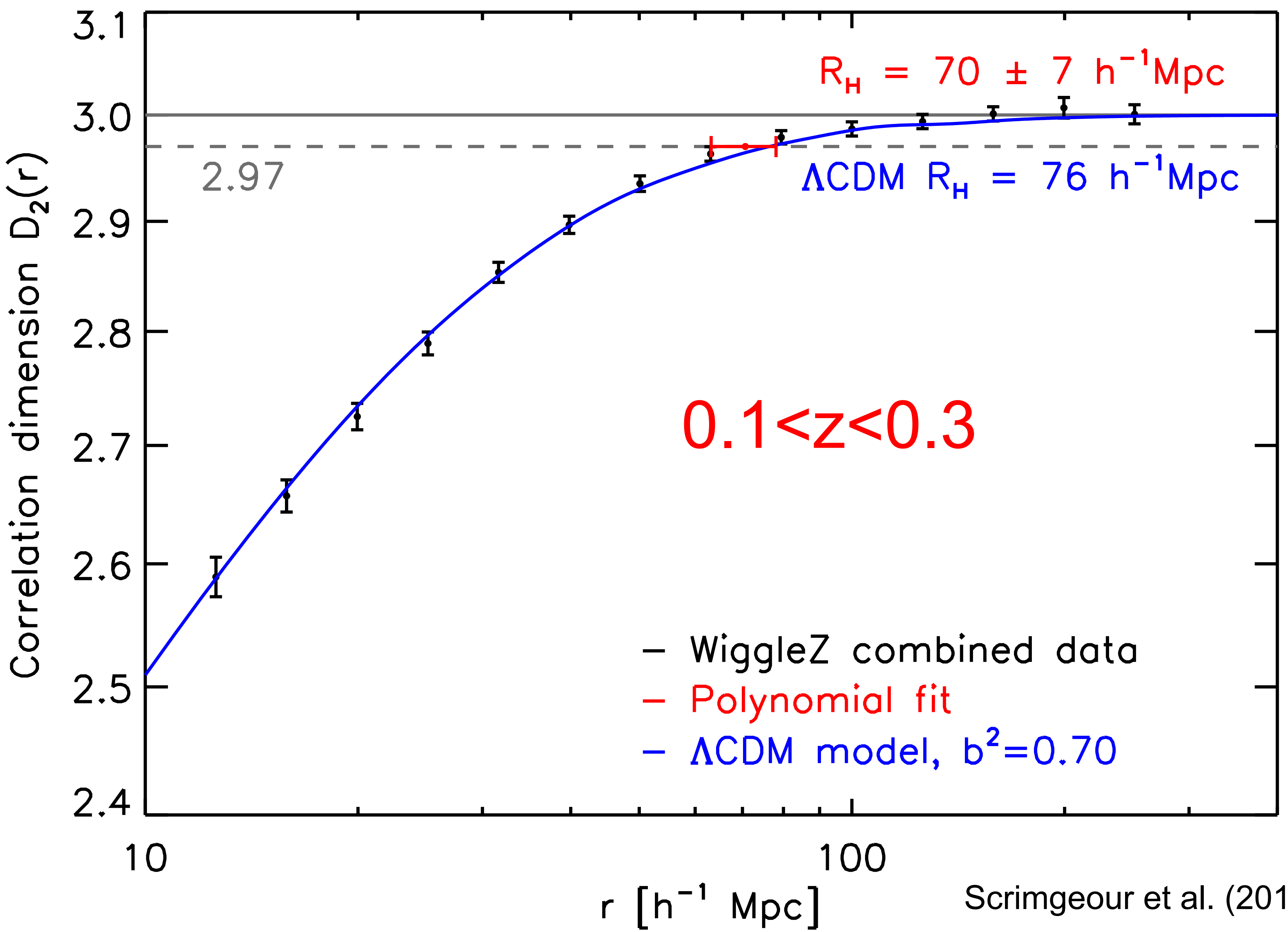
How do we define the "homogeneity scale" R_H?

- 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



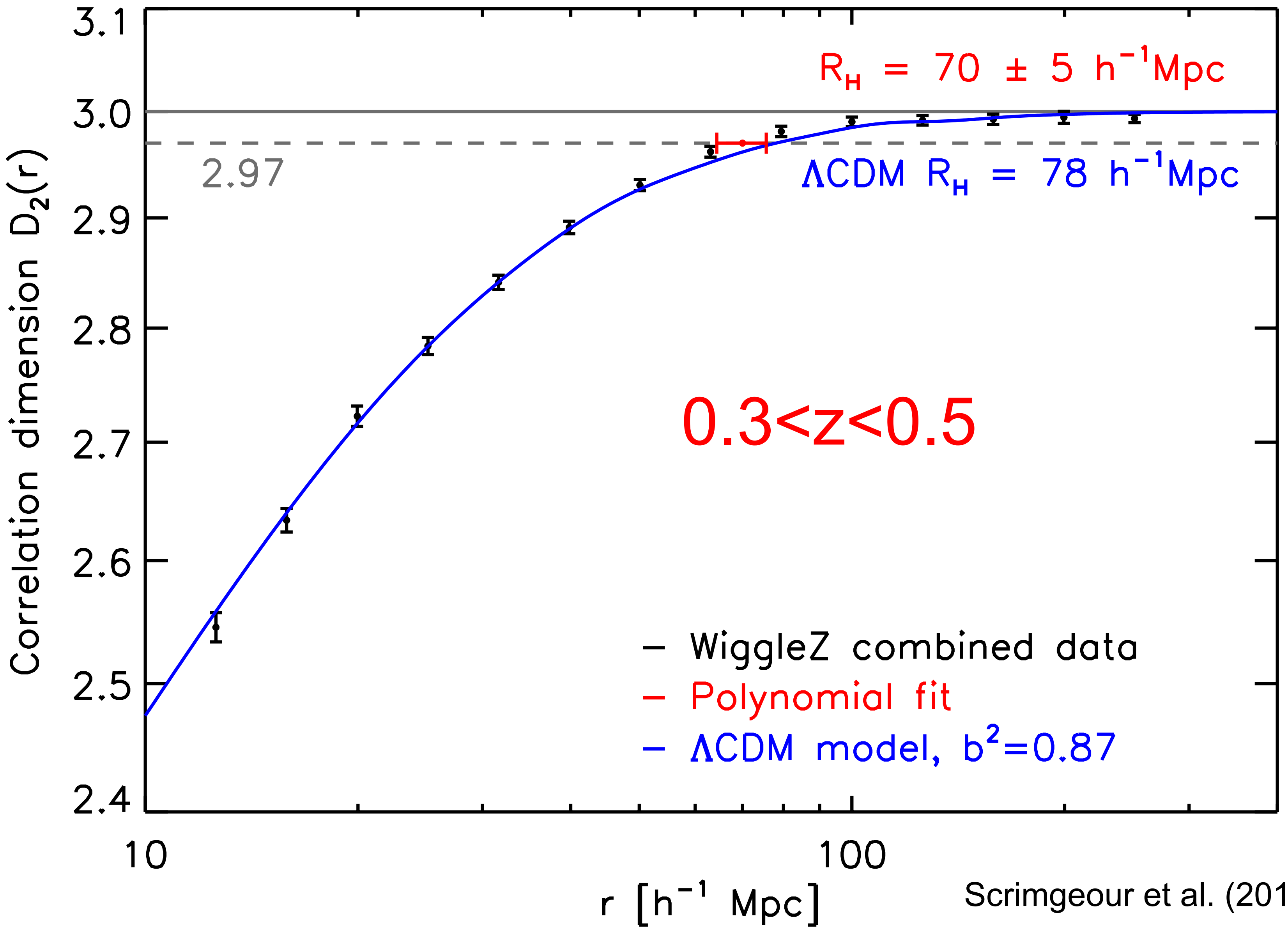
Scrimgeour et al. (2012)

$D_2(r)$ Results 1



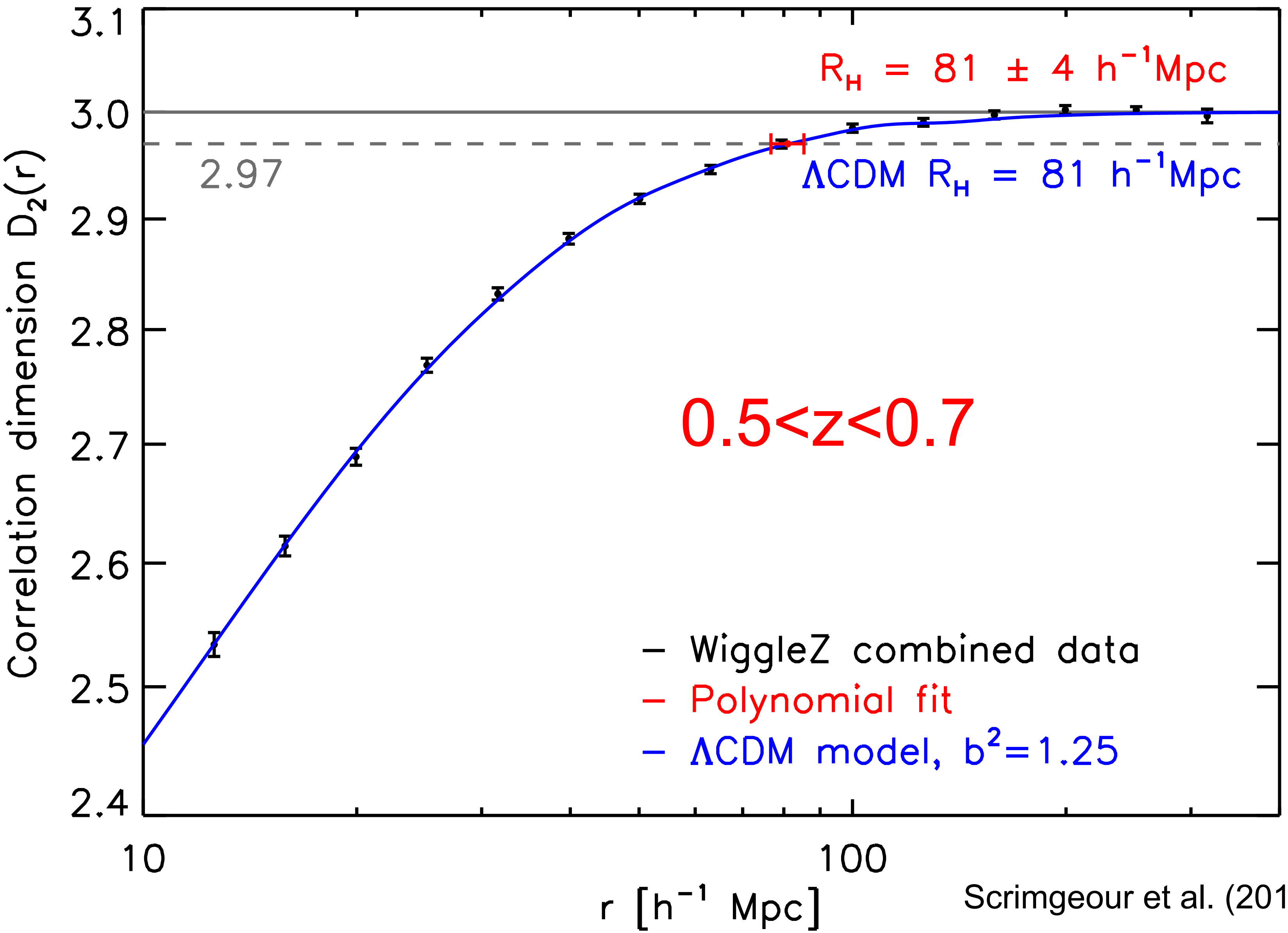
Scrimgeour et al. (2012)

$D_2(r)$ Results 2



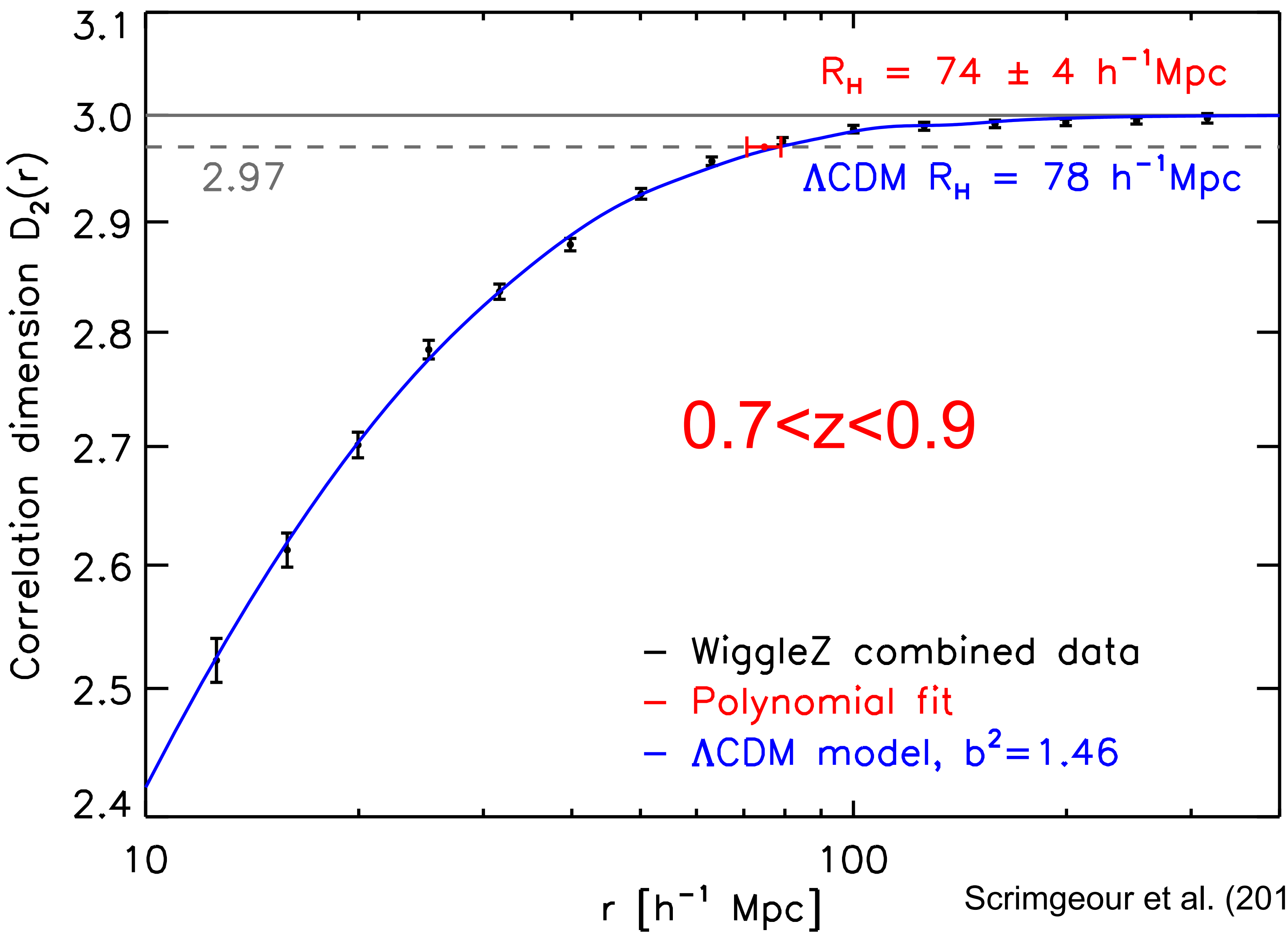
Scrimgeour et al. (2012)

$D_2(r)$ Results 3



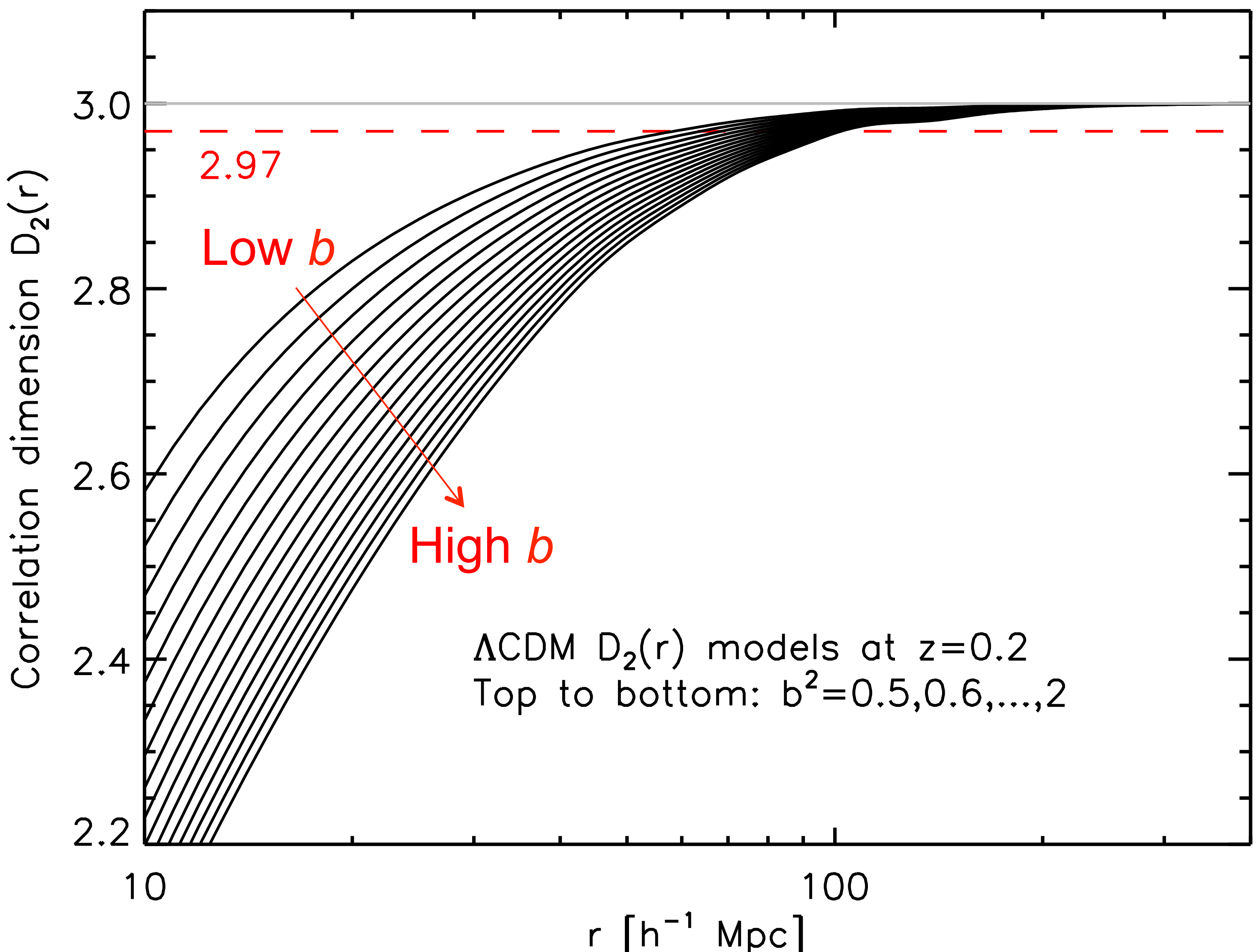
Scrimgeour et al. (2012)

$D_2(r)$ Results 4



Scrimgeour et al. (2012)

ΛCDM $D_2(r)$ model: effect of bias



Scrimgeour et al. (2012)

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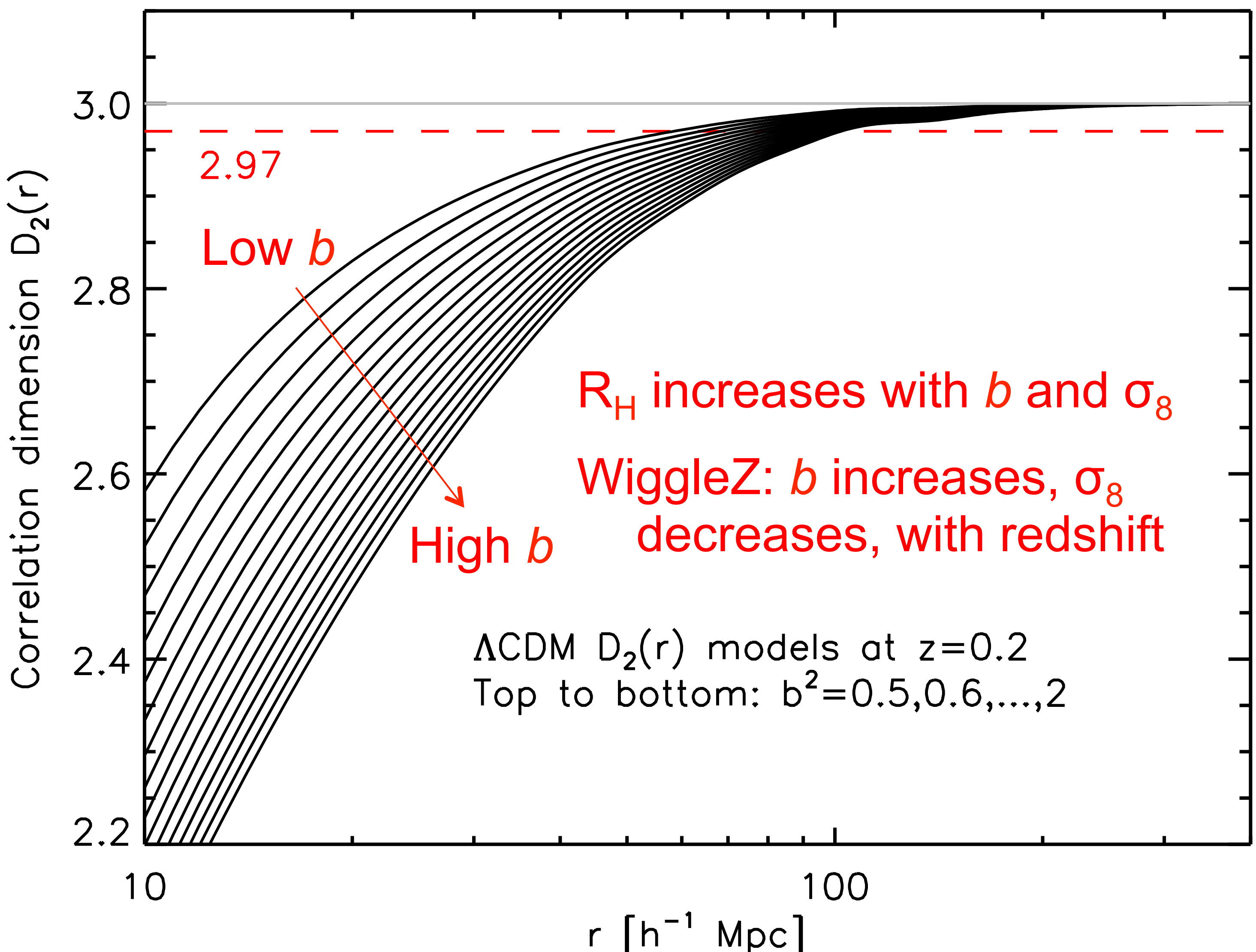
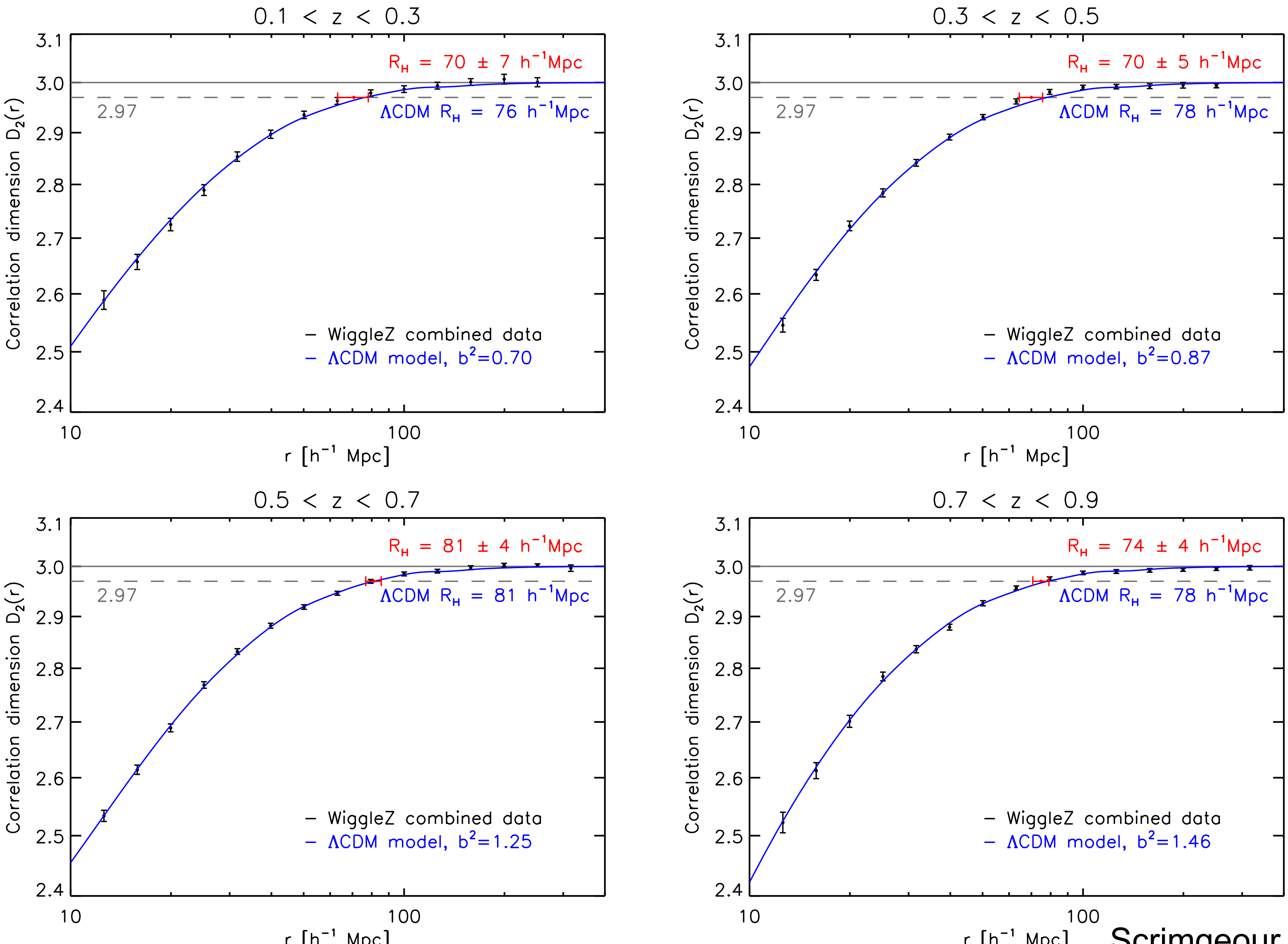


Scrimgeour et al. (2012)

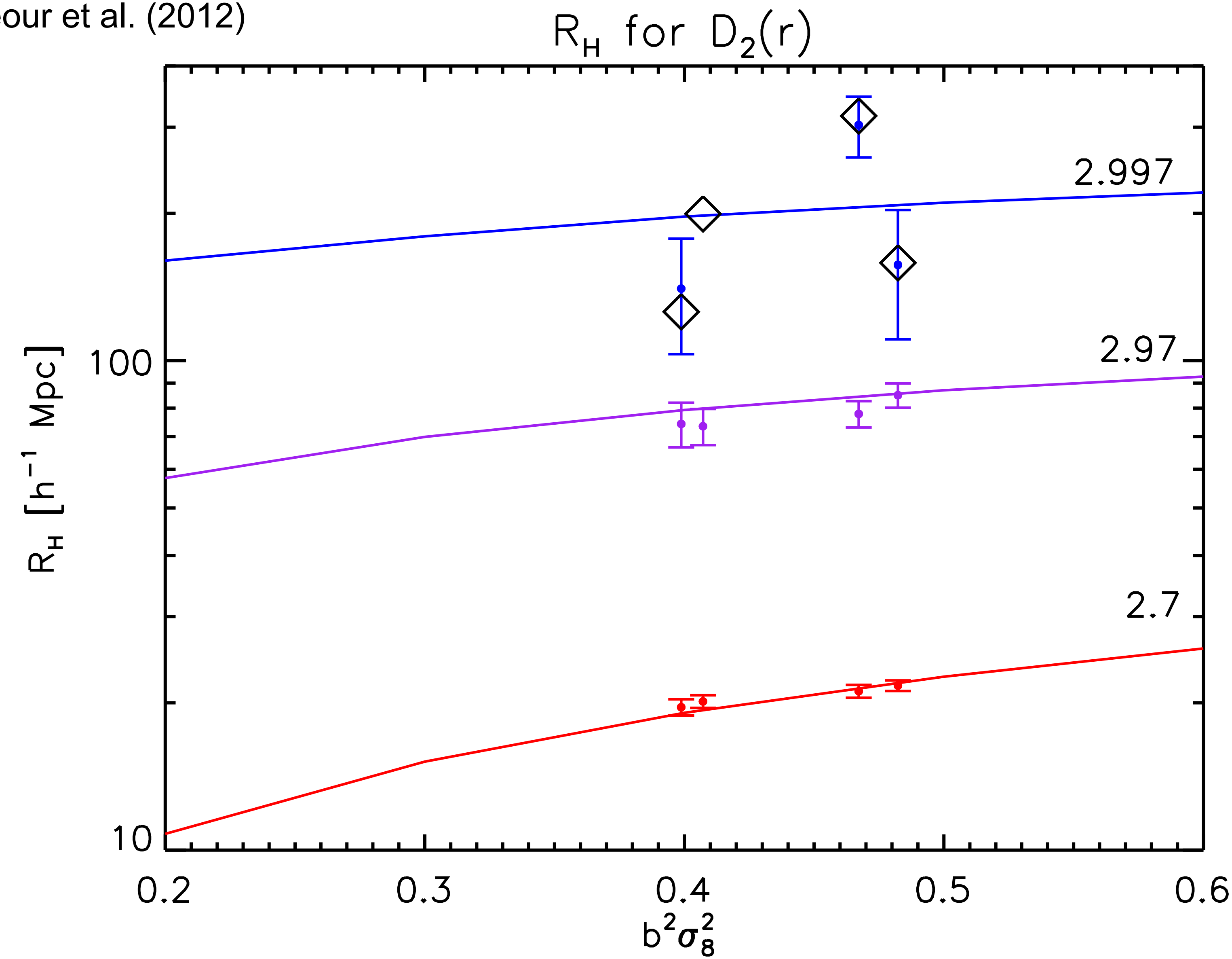
$D_2(r)$: All results



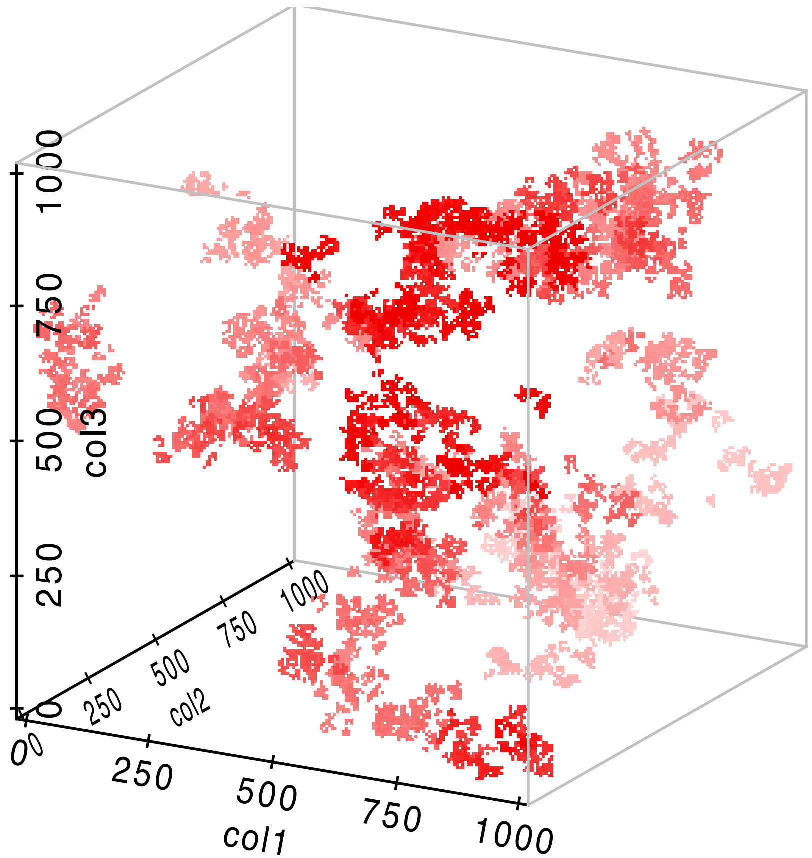
Scrimgeour et al. (2012)

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

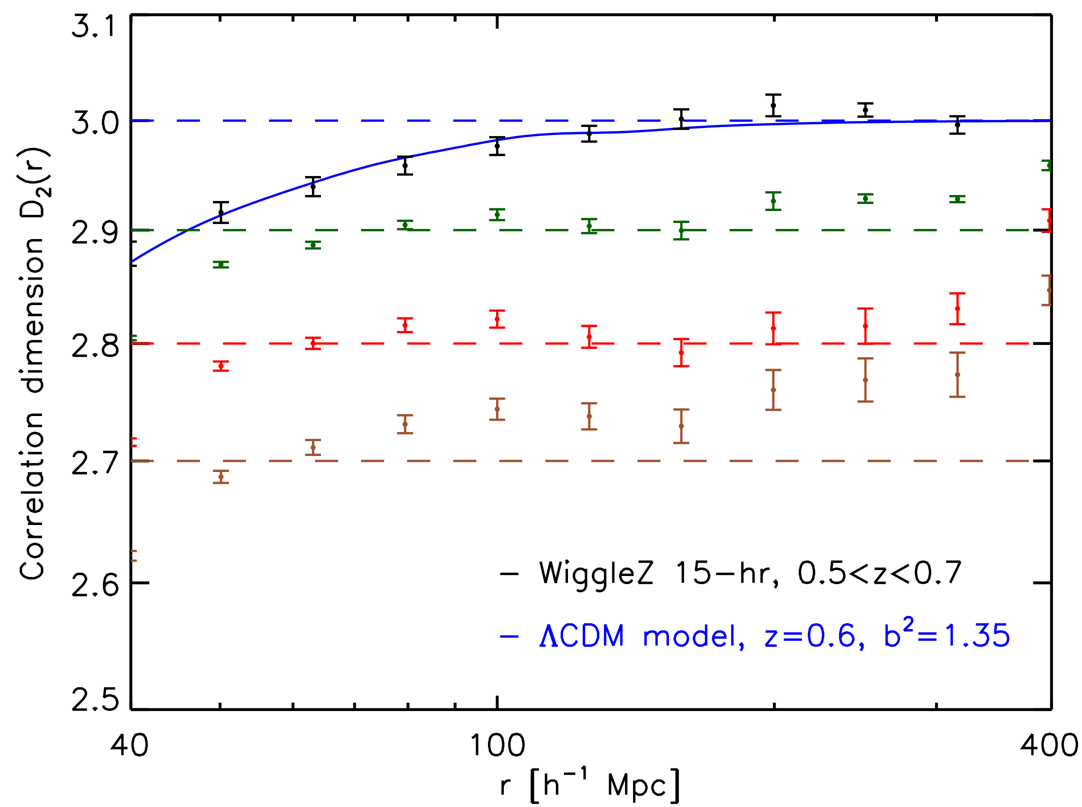
Scrimgeour et al. (2012)



Selection function and boundary condition tests with fractal models

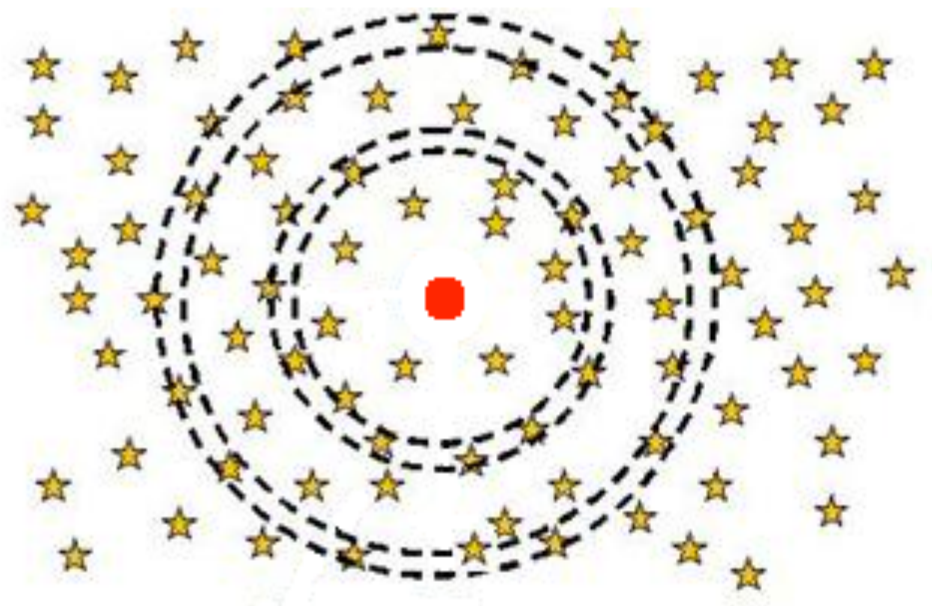


Scrimgeour et al. (2012)



- Generated 100 fractal distributions with D_2=2.7, 2.8, 2.9
- Sampled with WiggleZ selection function
- Find measured D_2 consistent with input D_2 up to at least 200 h^{-1} Mpc

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

Cosmology with Peculiar Velocity Surveys

What are peculiar velocities?

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

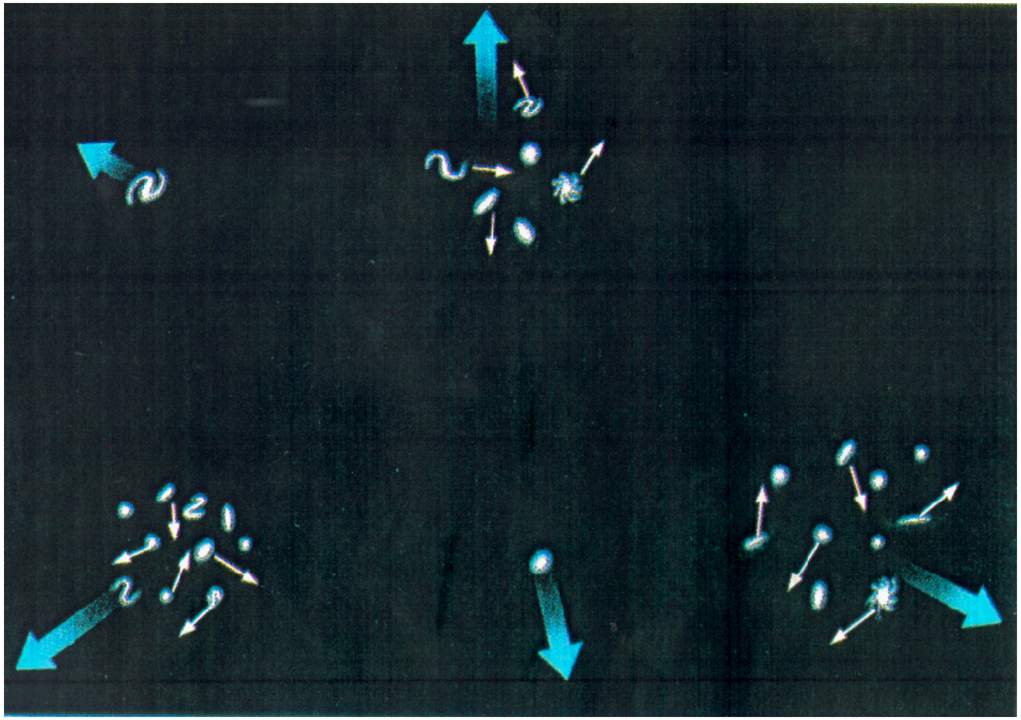
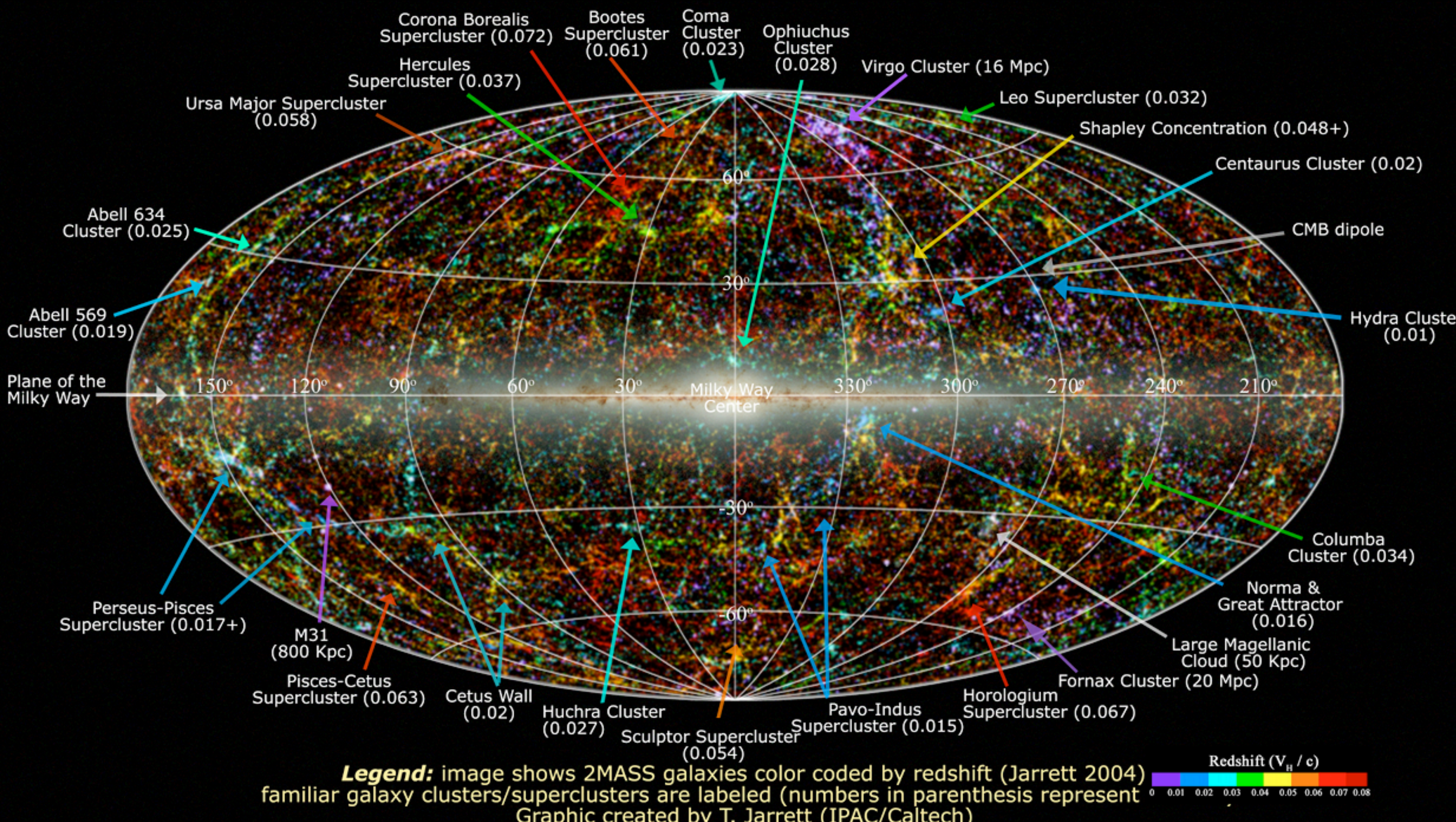
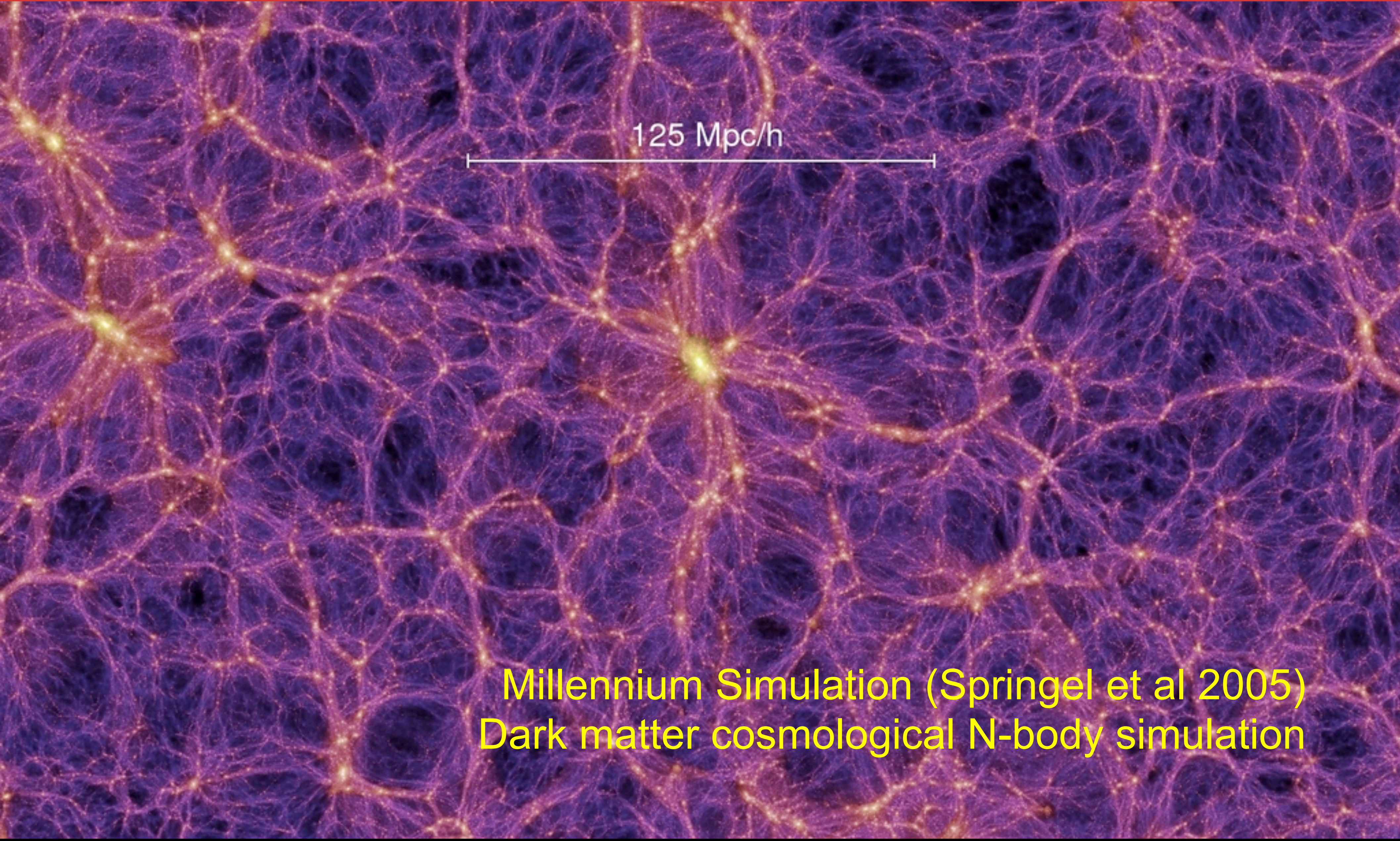


Image: University of Oregon

Large Scale Structure in the Local Universe



Large-scale Dark Matter field



Millennium Simulation (Springel et al 2005)
Dark matter cosmological N-body simulation

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 $f \sim \Omega_m^\gamma$

  - f: growth rate
  - γ: growth index
- Unbiased (unlike galaxies)

Measuring Peculiar Velocities

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

redshift   Hubble flow

Need known distance indicator

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

Peculiar Velocities as a cosmology probe I

- Nature of dark energy
  - Expansion history H(z)
  - Growth of structure $f=\Omega_m(z)^\gamma$
- PVs are direct probe of gravity
  - Can test General Relativity, modified gravity
  - $\beta=f/b$: redshift- space distortion parameter, from combination of velocity & density
- Nature of dark matter
  - Particle nature
  - Nature & evolution of structure
- σ_8 , Ω_m constraints
- Tests of backreaction

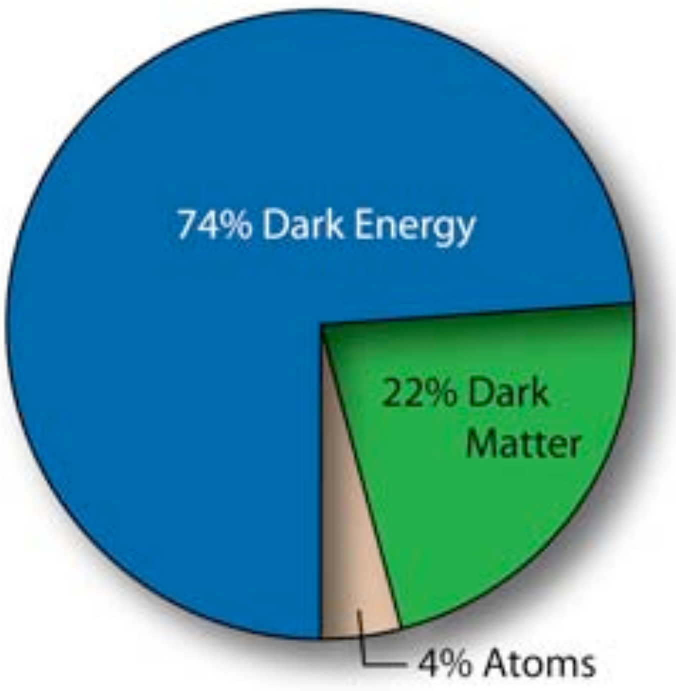


Image: NASA/WMAP Science team

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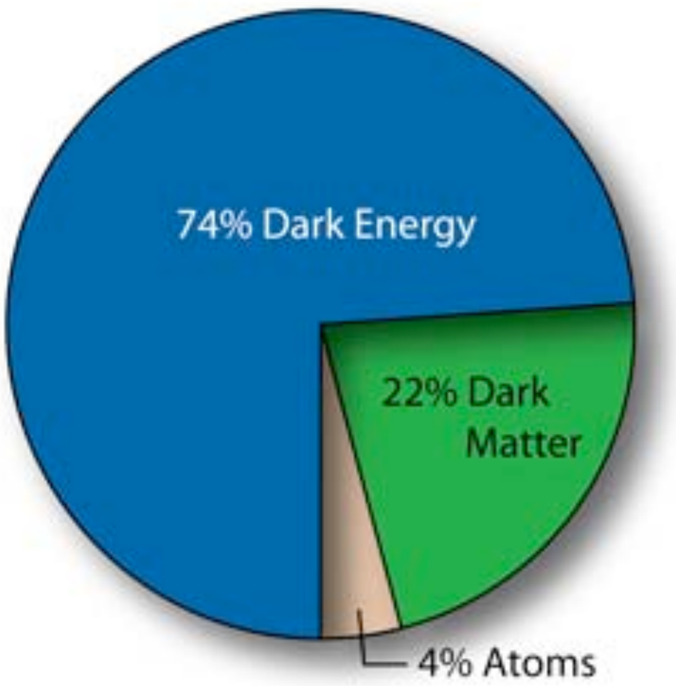

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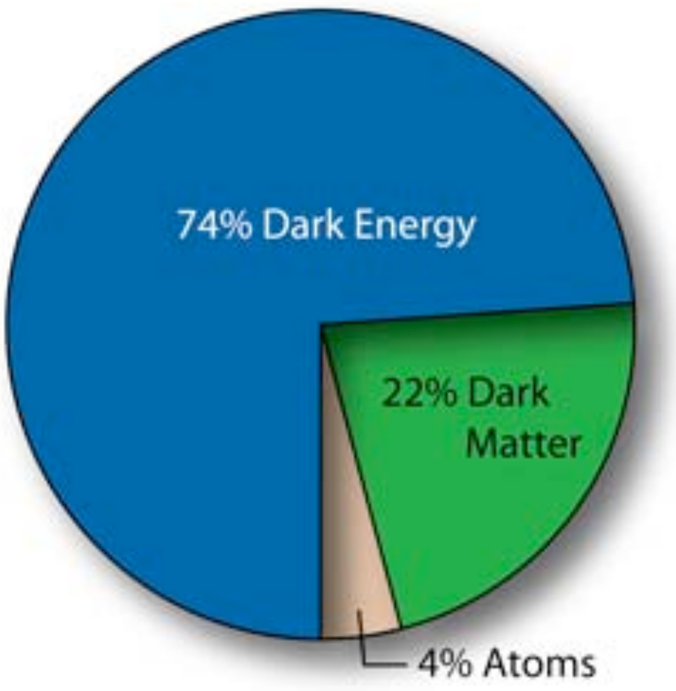

Image: NASA/WMAP Science team

Peculiar Velocities as a Cosmology Probe II

Advantages

- Trace underlying matter field (incl. Dark Matter)
- Independent of galaxy bias
- Complementary to RSDs
- Sensitive to large-scale modes

Disadvantages

- Large distance errors
- Low redshift only
- Possible systematics
  - Malmquist bias

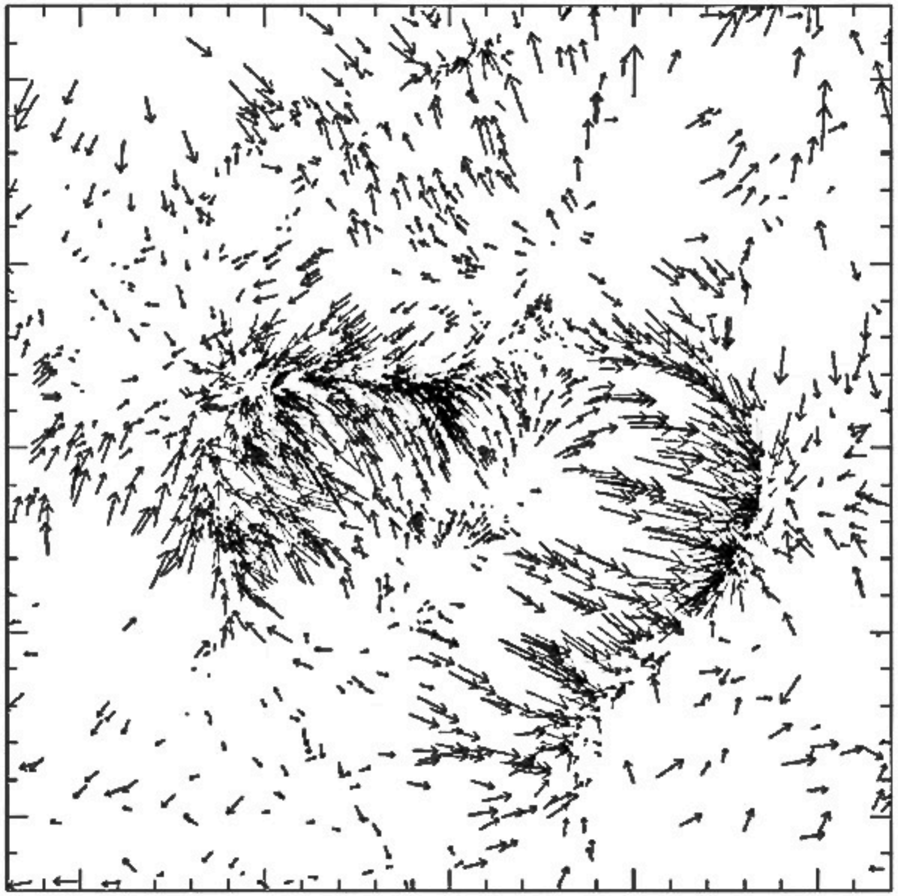

Image: The Cosmic Perspective (1998)

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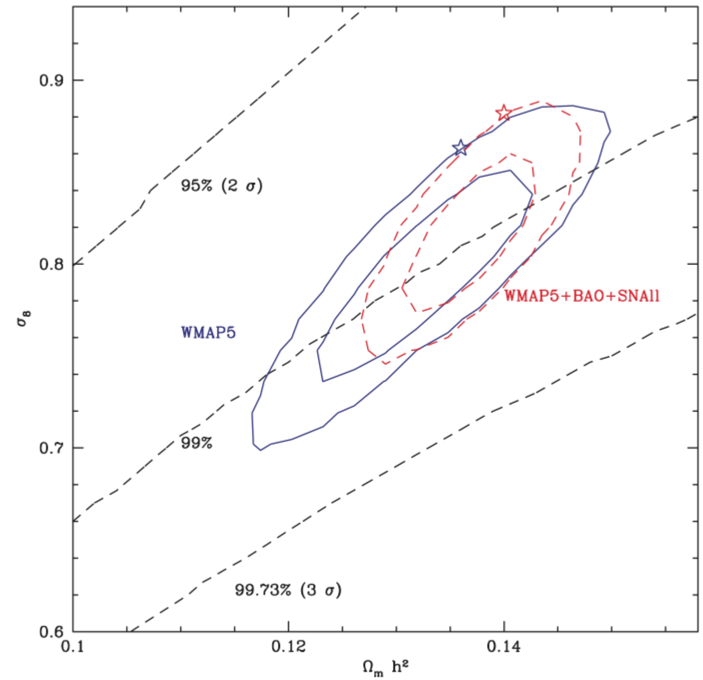
Velocity field statistics I

- Bulk Flow / dipole (Watkins et al. 2009, Nusser & Davis 2011): (σ_8, Ω_m)

$$\mathbf{u} = \sum_{n=1}^{N} w_n v_n$$

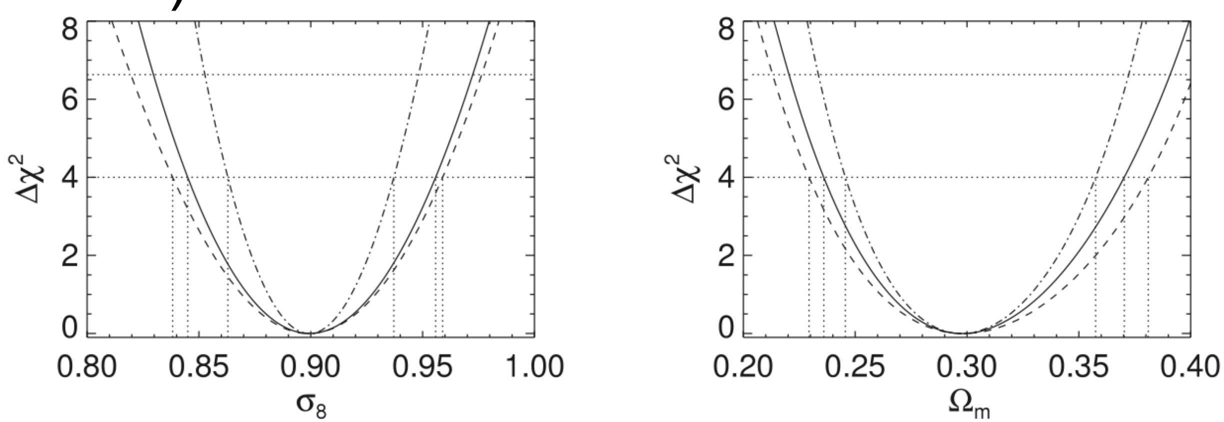
- Angular power spectrum / spherical harmonics of velocity field (Haugbølle et al. 2007, Hannestad et al. 2008) (σ_8, Ω_m, Γ)

$$v_r = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}$$



Watkins et al. (2009)

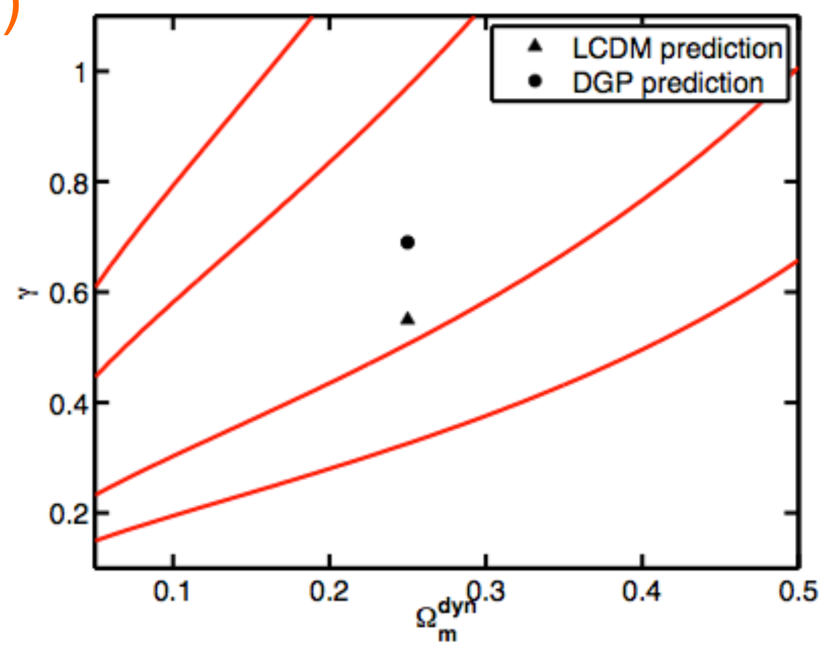
Hannestad et al. (2008)



Velocity Field Statistics II

- Velocity correlation function ξ_{vv} (Gordon et al. 2007, Abate & Lahav 2008) (σ_8, $\Omega_{m,}$ γ, H_0?)

$$\xi(\mathbf{r_i}, \mathbf{r_j}) \equiv \langle (\mathbf{v}(\mathbf{r}_i) \cdot \hat{\mathbf{r}}_i)(\mathbf{v}(\mathbf{r}_j) \cdot \hat{\mathbf{r}}_j) \rangle .$$



Abate & Lahav (2008)

- 3D velocity power spectrum (Burkey & Taylor 2004)

$$P_{u'u'}(\mathbf{k}) = \mu^4 H^2 f^2 P_{mm}(k)$$

- Comparison with redshift surveys: δ-δ vs. v-v ($\beta = f/b$, γ)
  - Can cancel cosmic variance (e.g. McDonald & Seljak 2009)

Bulk flows and dark flows: a problem for ΛCDM?

- "Bulk flow": the average velocity over some volume
- 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 on ~100 h^{-1}Mpc scales toward l=287˚±9˚, b=8˚±6˚
- ΛCDM linear theory: ~190 km/s

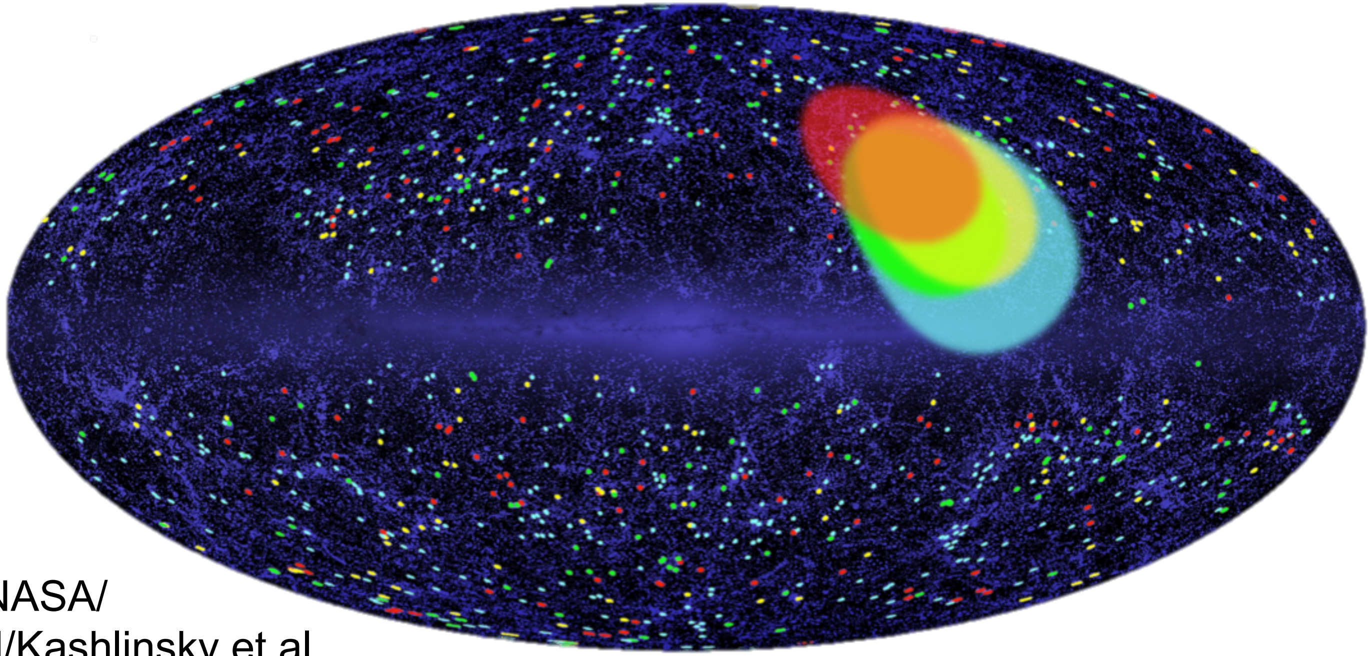
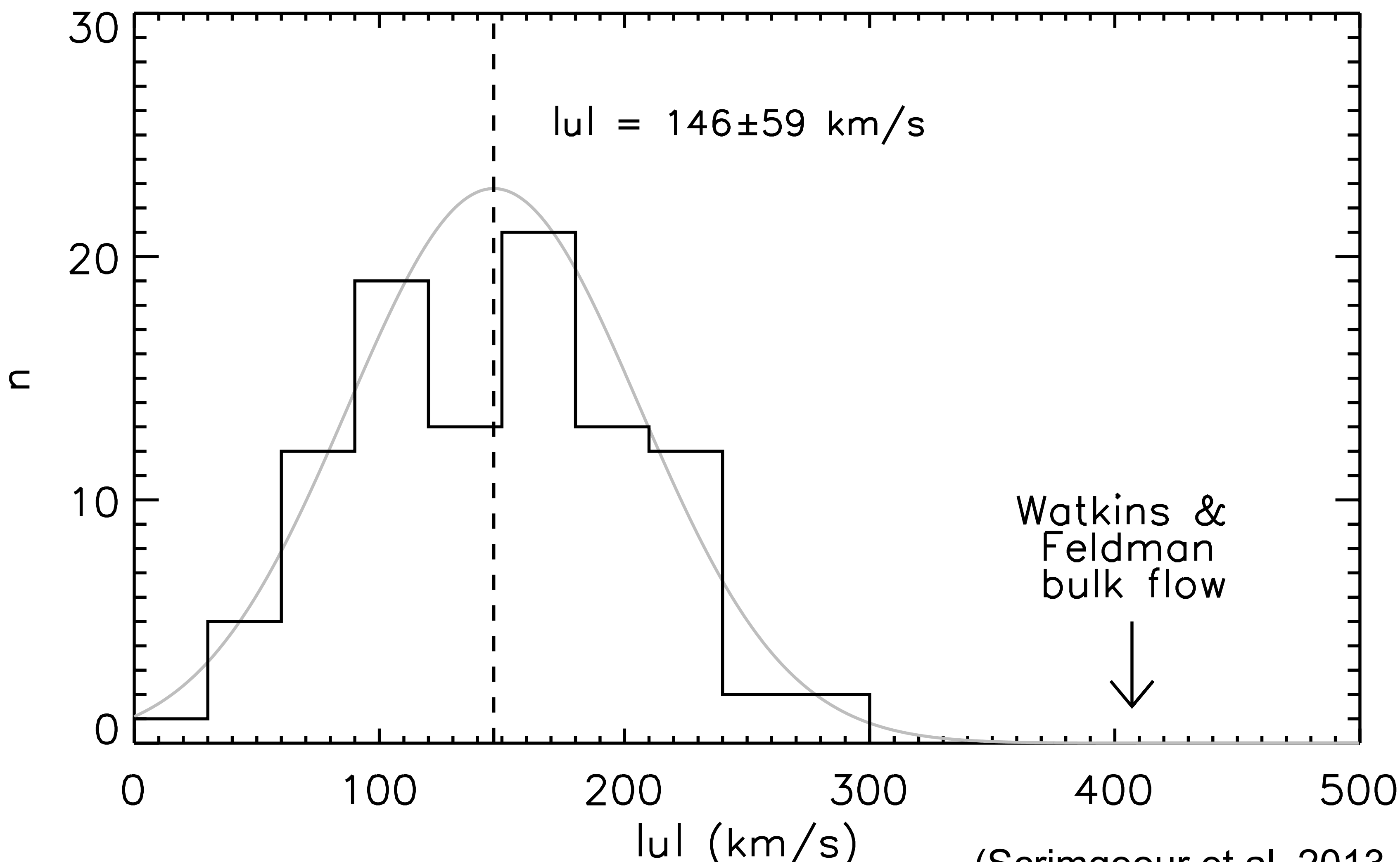


Image: NASA/
Goddard/Kashlinsky et al.

Millennium Simulation ΛCDM Bulk Flow prediction

- Bulk flow magnitude in 100 Gaussian spheres of radius 50 h^{-1} Mpc



(Scrimgeour et al. 2013, in prep)

Conflicting σ_8 constraints

Measurements of σ_8 from Peculiar Velocities

	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)	$0.65^{+0.47}_{-0.35}$

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

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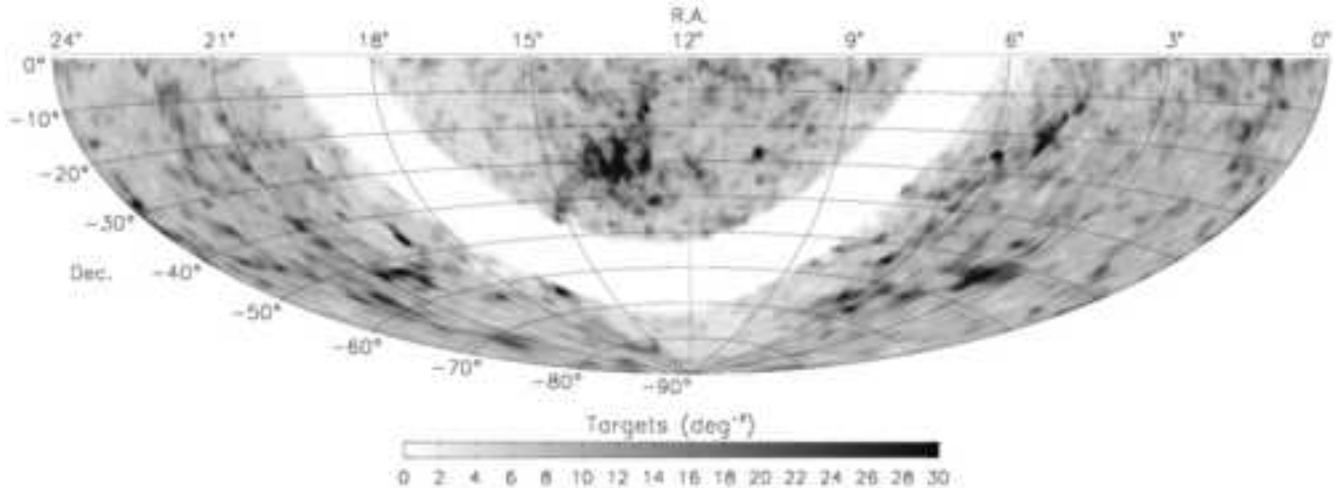
- Need all-sky, deeper peculiar velocity surveys
- Homogeneous selection
- Accurate modelling of systematics

WALLABY Peculiar Velocities

- Widefield ASKAP L-band Legacy All-sky Blind surveY
- 21cm HI survey
- All southern sky
- z < 0.05
- Westerbork Northern HI Sky Survey (WNSHS, with Apertif) will provide coverage >+30° in north
- Photometry from SkyMapper or WISE?
- ~30,000 WALLABY + WNSHS Tully-Fisher distances

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
- Max z ~ 0.15
- 125,000 redshifts, 9000 FP peculiar velocities
- Largest combined redshift *and* peculiar velocity survey by a factor of 2



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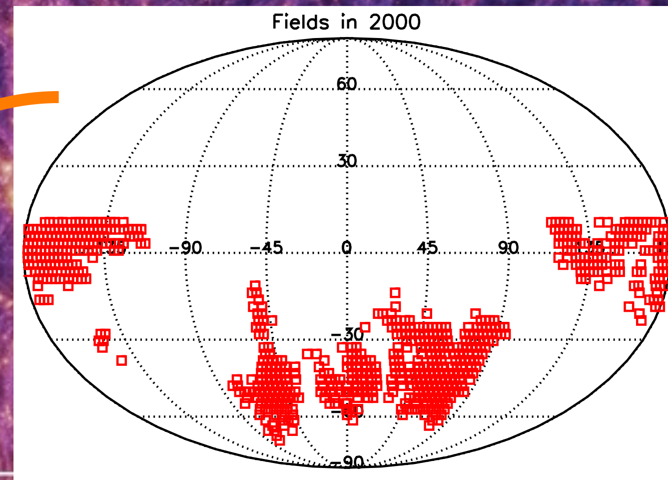
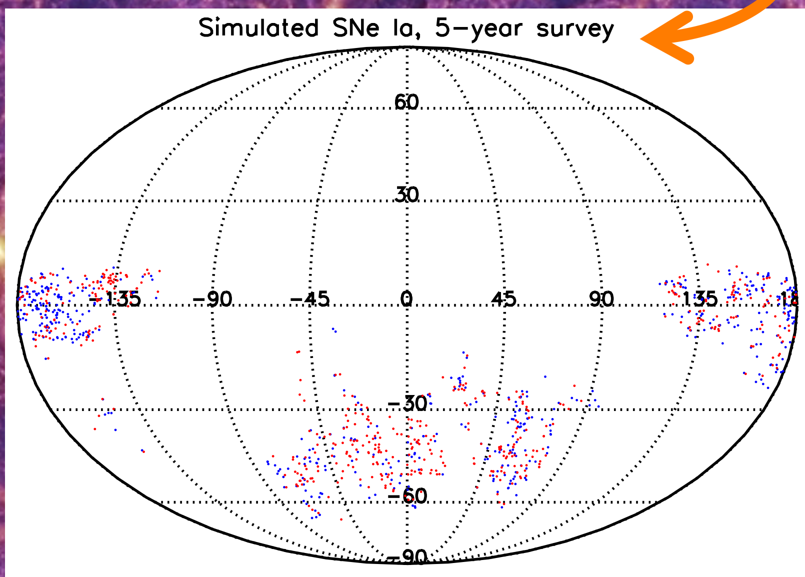
SkyMapper Supernova Survey

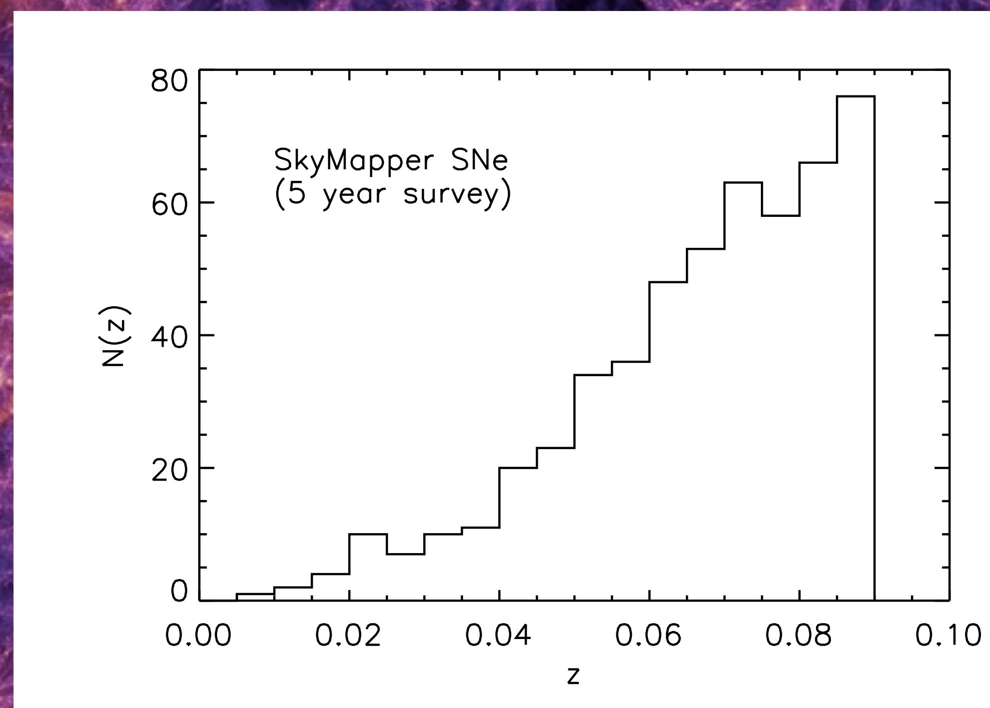
- Optical widefield automated survey telescope at Siding Spring Observatory, Australia
- Supernova Survey (Keller et al 2007):
  - 1250 deg^2 of sky
  - ~500 SNe per year
  - z<0.085
  - 6.5% distance errors

Image: ANU

Simulating the SkyMapper Supernova Survey





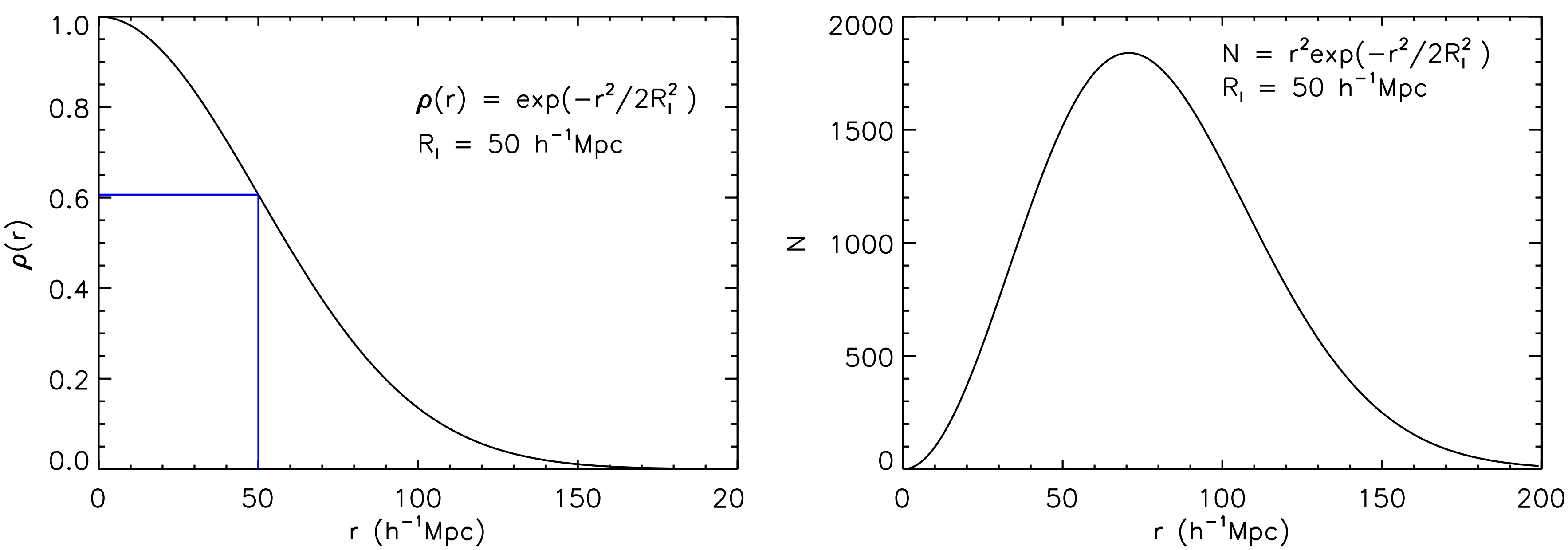


~500 Type Ia SNe over 5 years

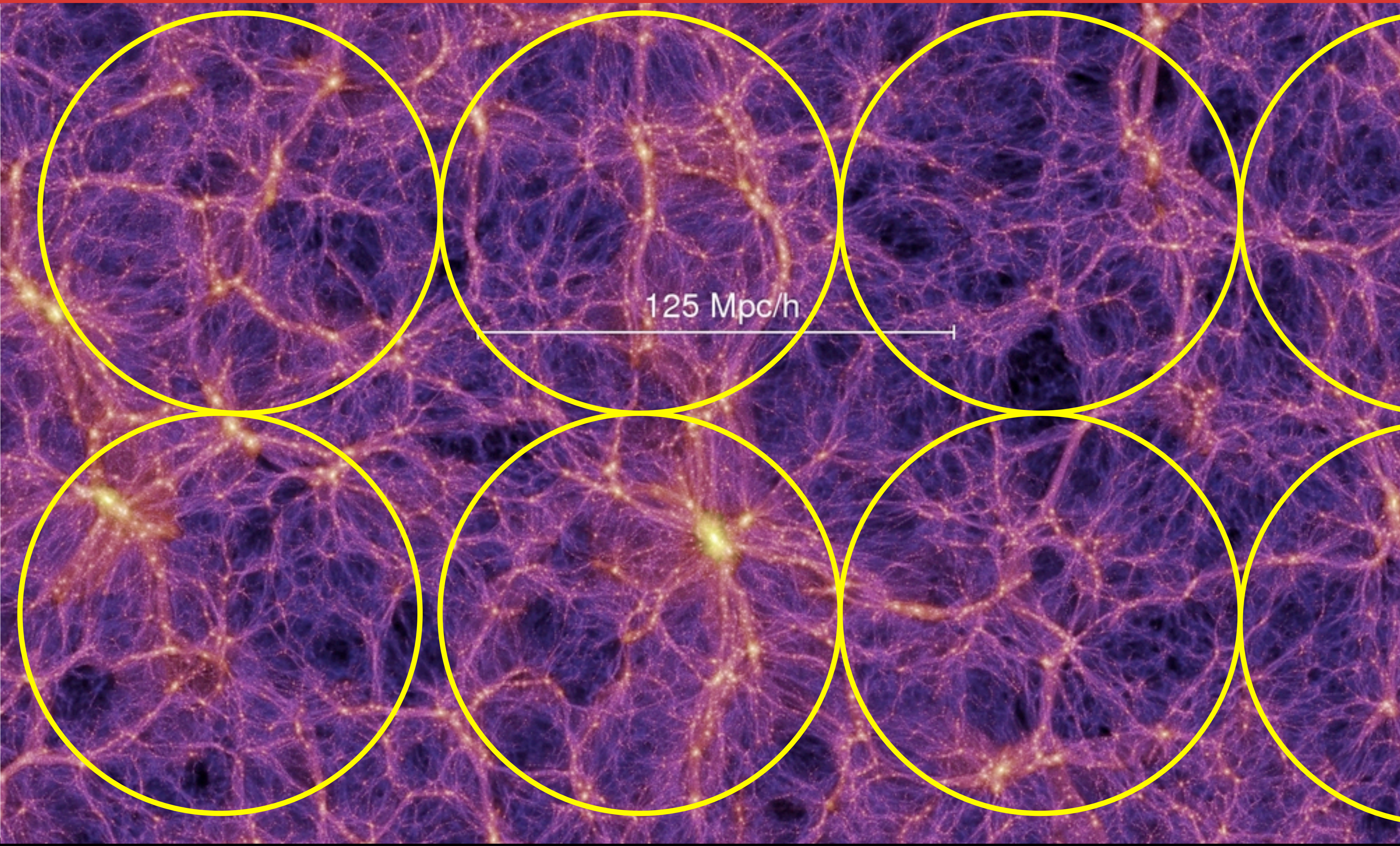
(Scrimgeour et al. 2013, in prep)

Bulk Flows: Minimum Variance Weights

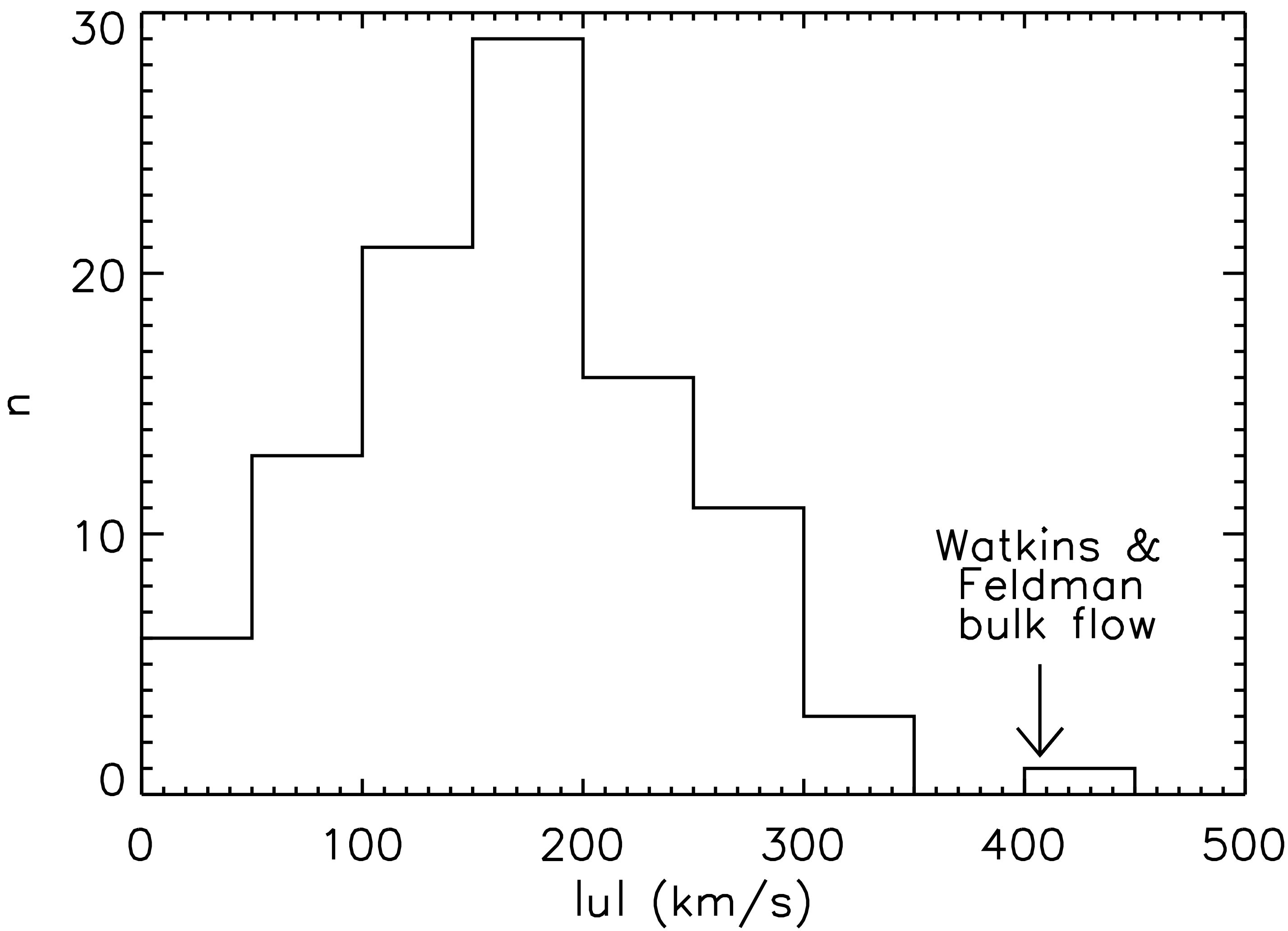
- Watkins et al. (2009), Feldman et al. (2010)
- Bulk flow: $\boldsymbol{u} = (u_1\hat{\boldsymbol{x}}_1, u_2\hat{\boldsymbol{x}}_2, u_3\hat{\boldsymbol{x}}_3)$
- Different surveys difficult to compare
  - Different volumes, geometry, sparseness
- Calculate weights to mimic 'ideal' survey geometry
  - Minimise variance between measured and 'ideal' bulk flow



Bulk flow distribution

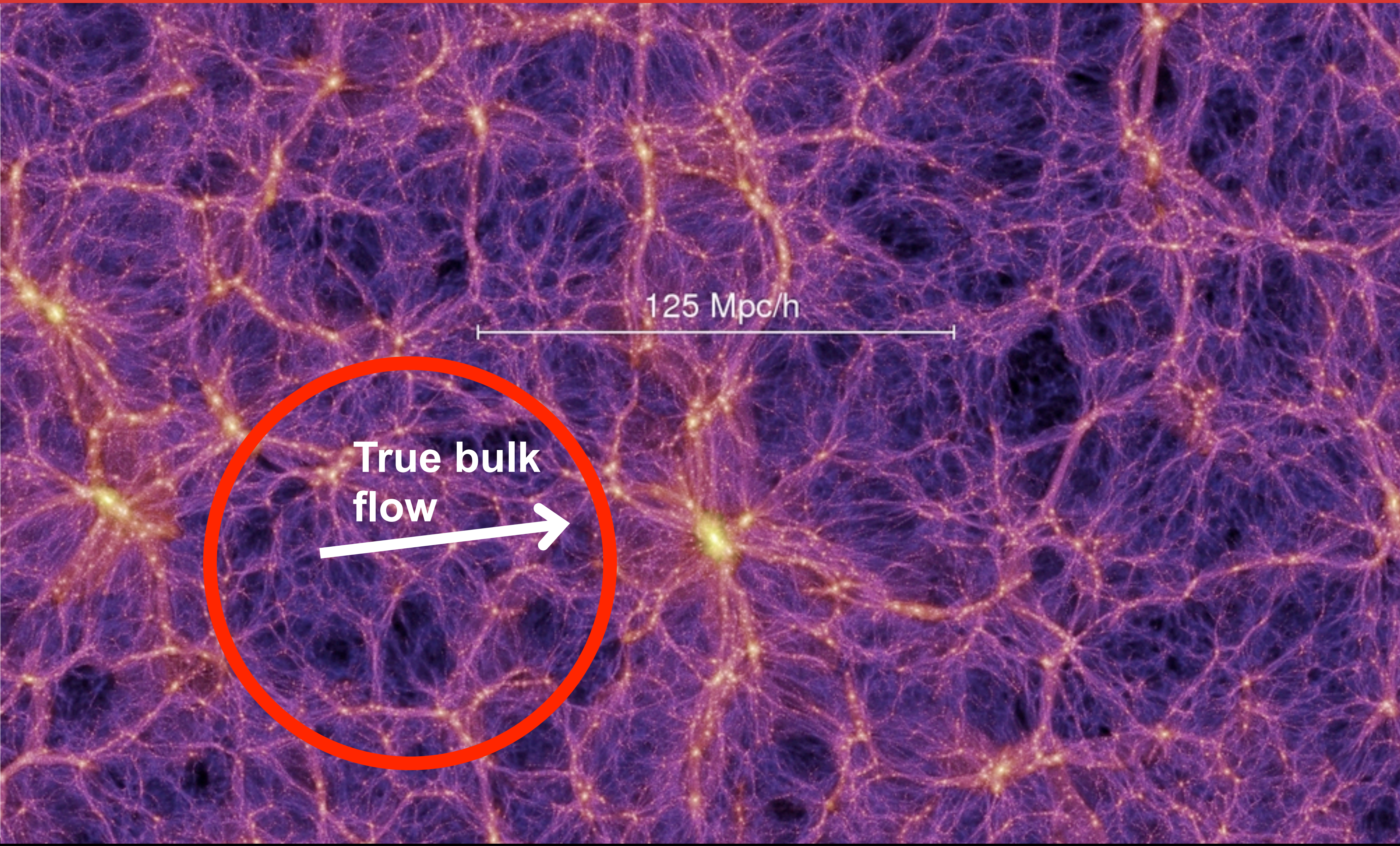


Bulk Flows: ΛCDM results for SkyMapper



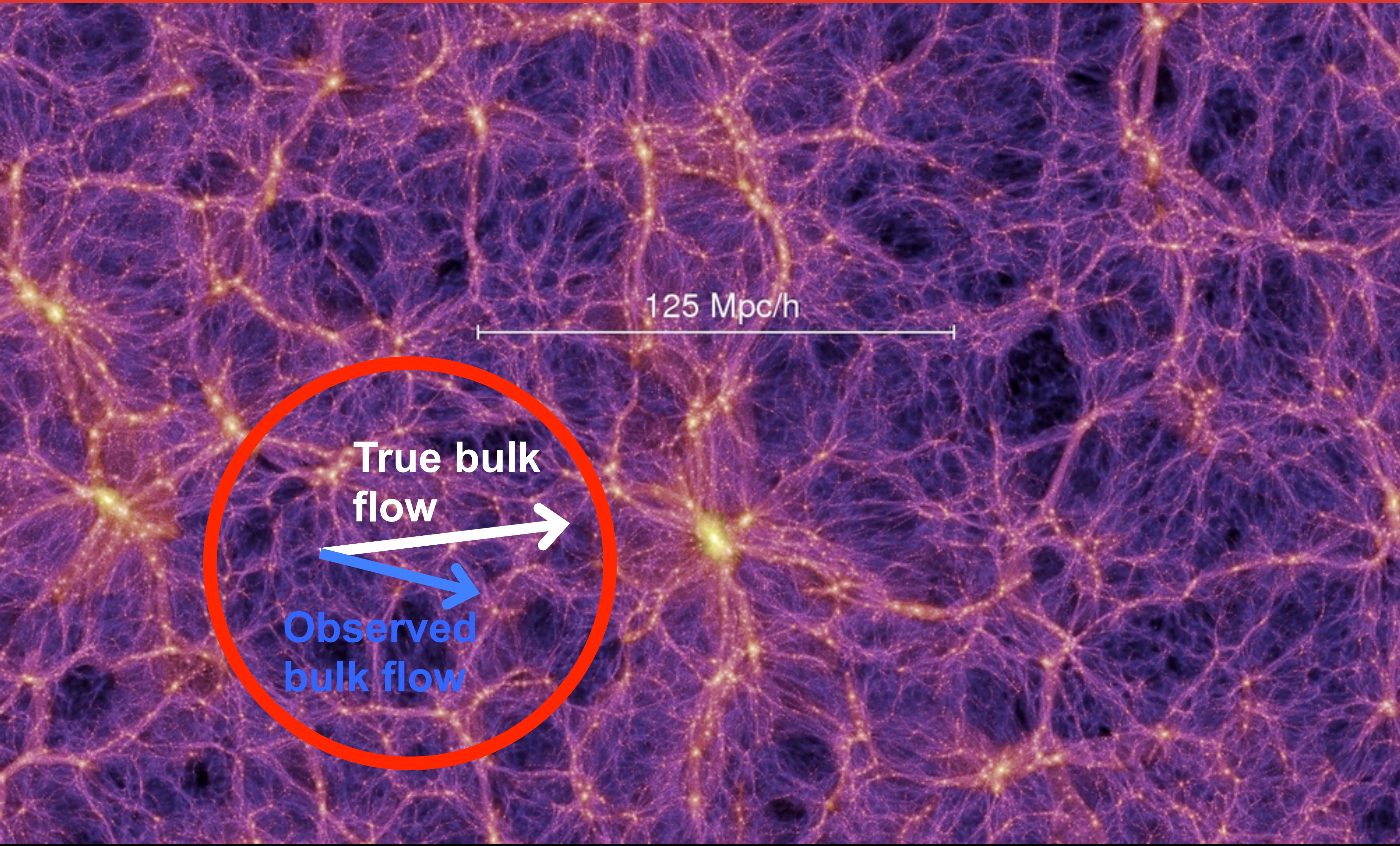
(Scrimgeour et al. 2013, in prep)

The ‘residual’ bulk flow

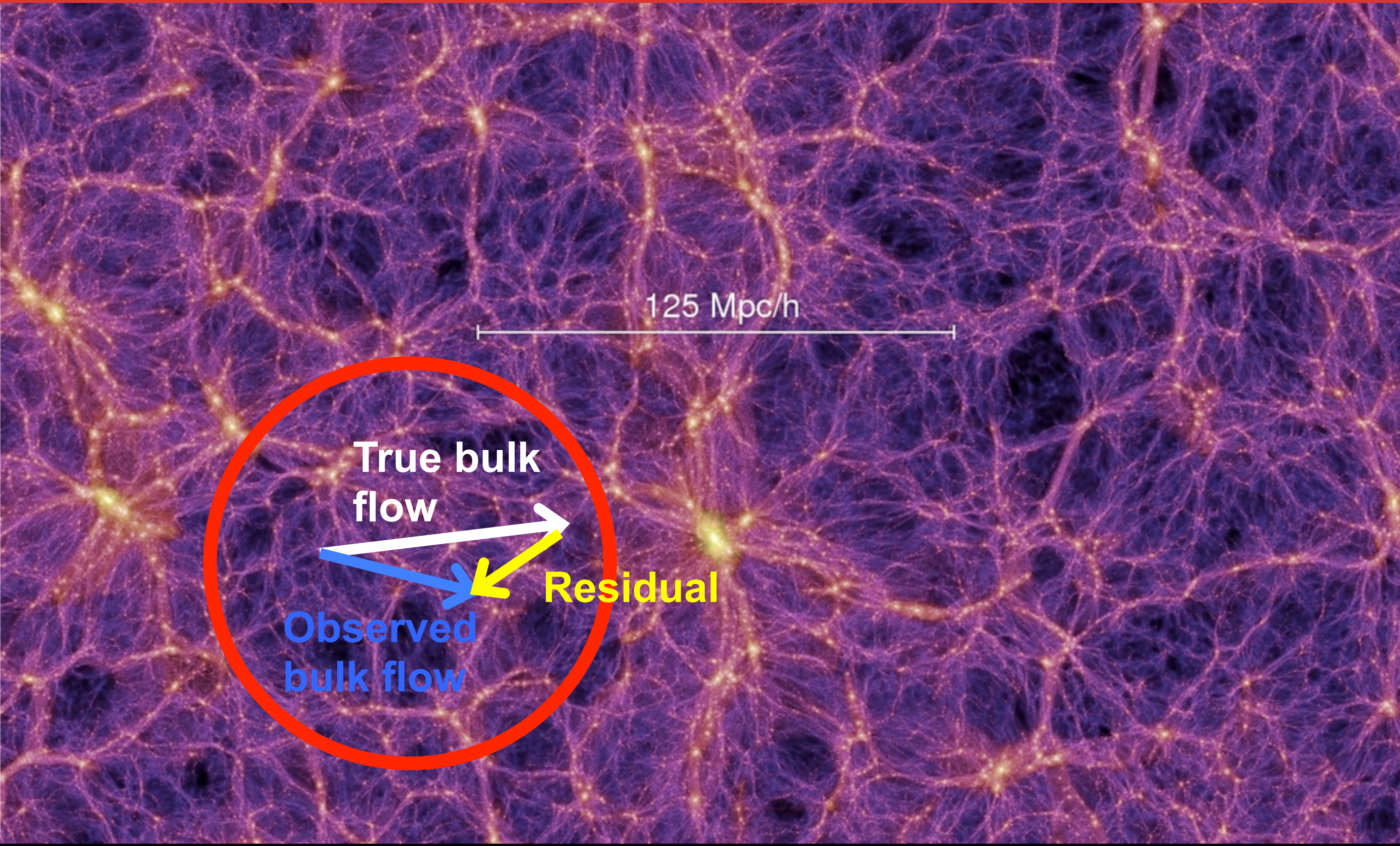


The ‘residual’ bulk flow

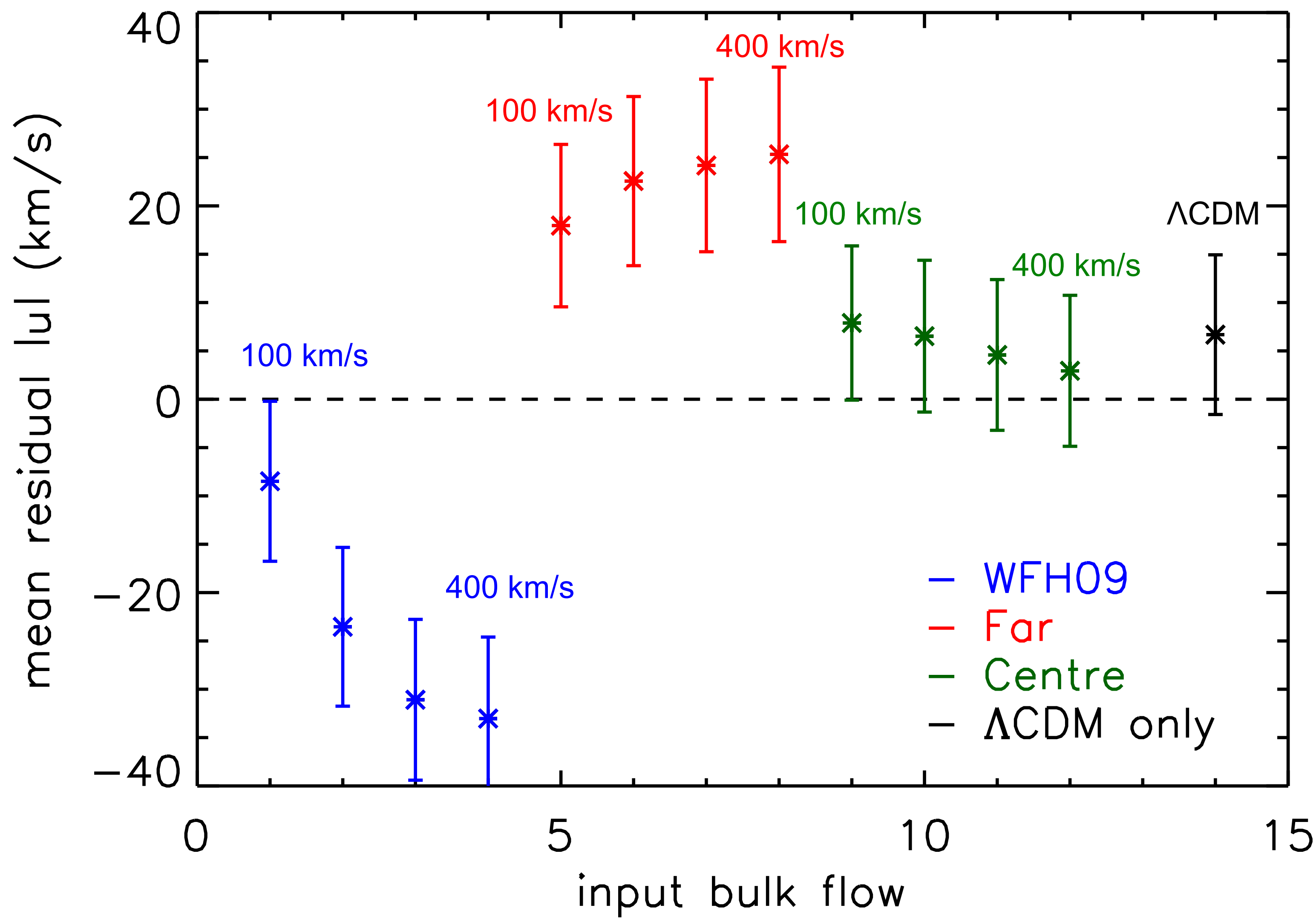
International Centre for Radio Astronomy Research



The ‘residual’ bulk flow

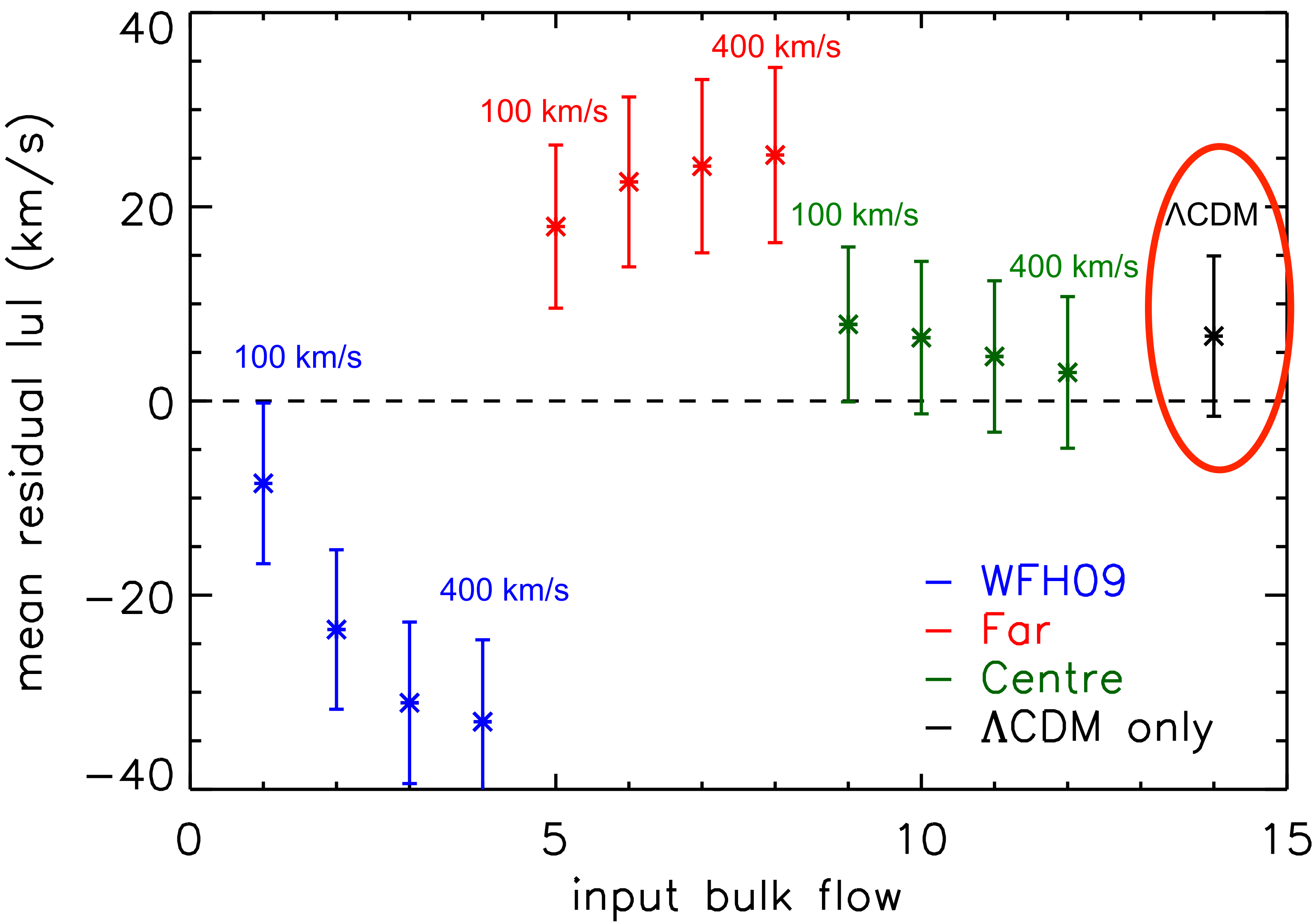


Bulk Flow Systematics from partial sky: tests with SkyMapper



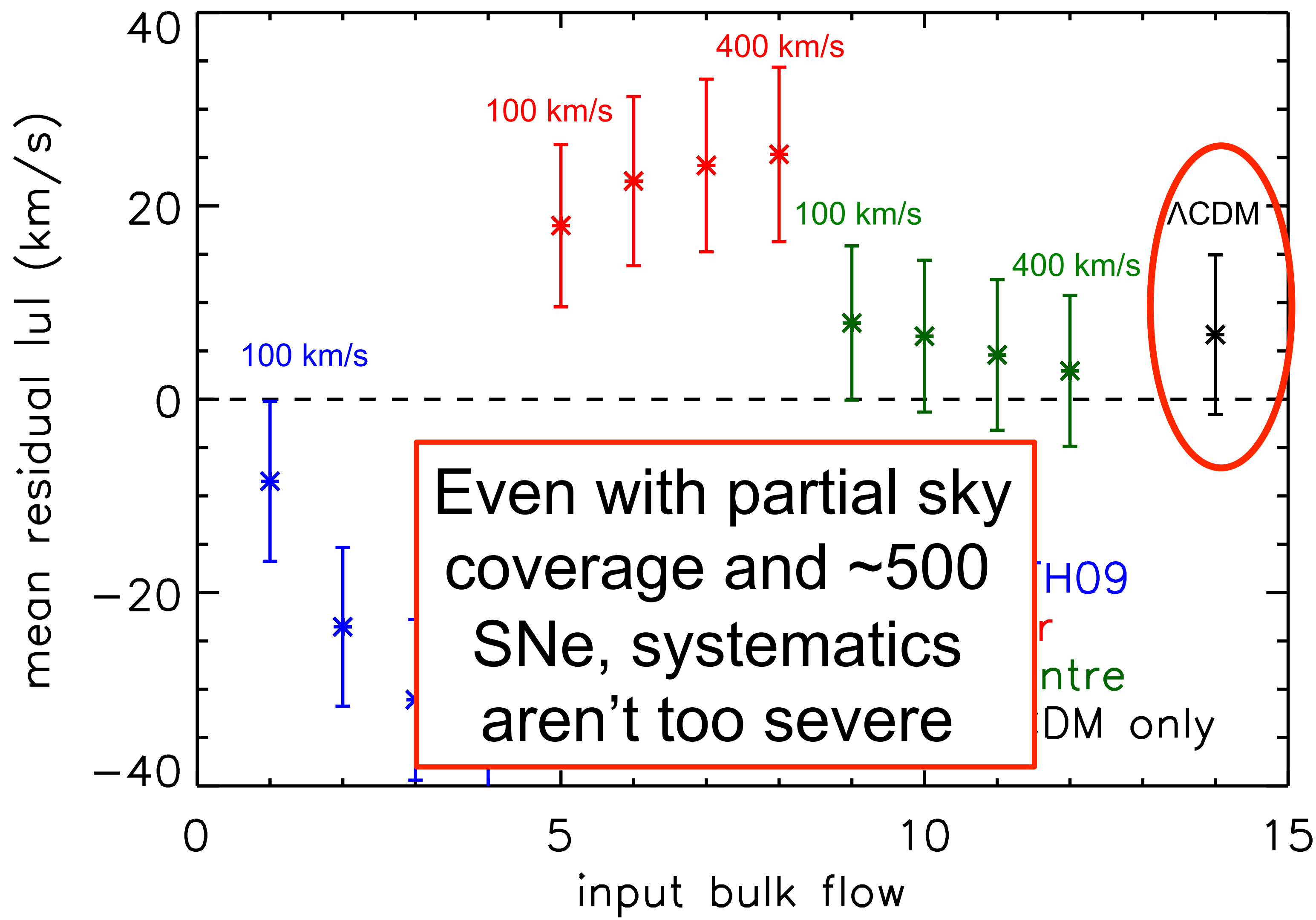
(Scrimgeour et al. 2013, in prep)

Bulk Flow Systematics from partial sky: tests with SkyMapper



(Scrimgeour et al. 2013, in prep)

Bulk Flow Systematics from partial sky: tests with SkyMapper



Even with partial sky coverage and ~500 SNe, systematics aren't too severe

(Scrimgeour et al. 2013, in prep)

6dFGS, WALLABY and TAIPAN velocities

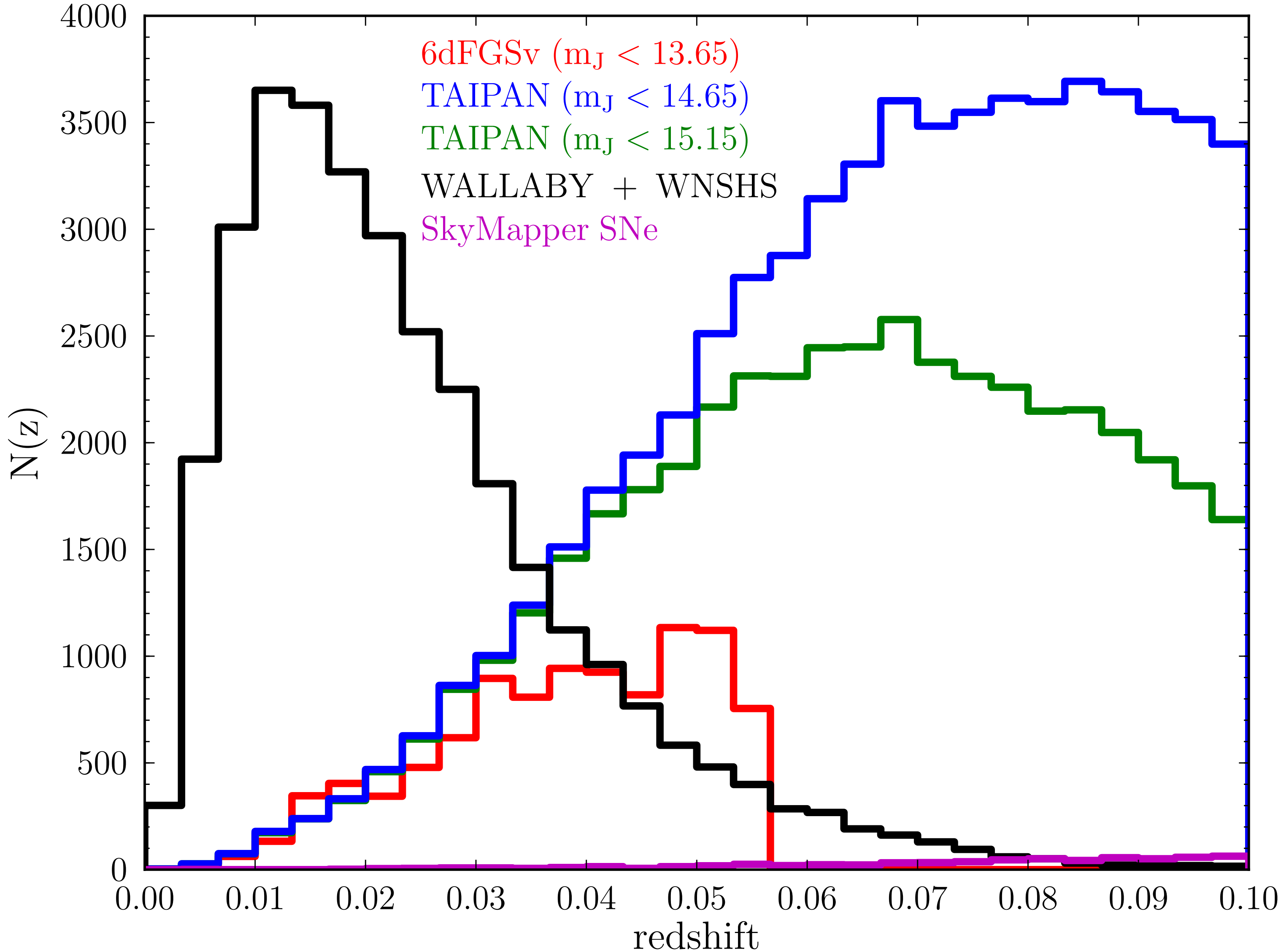
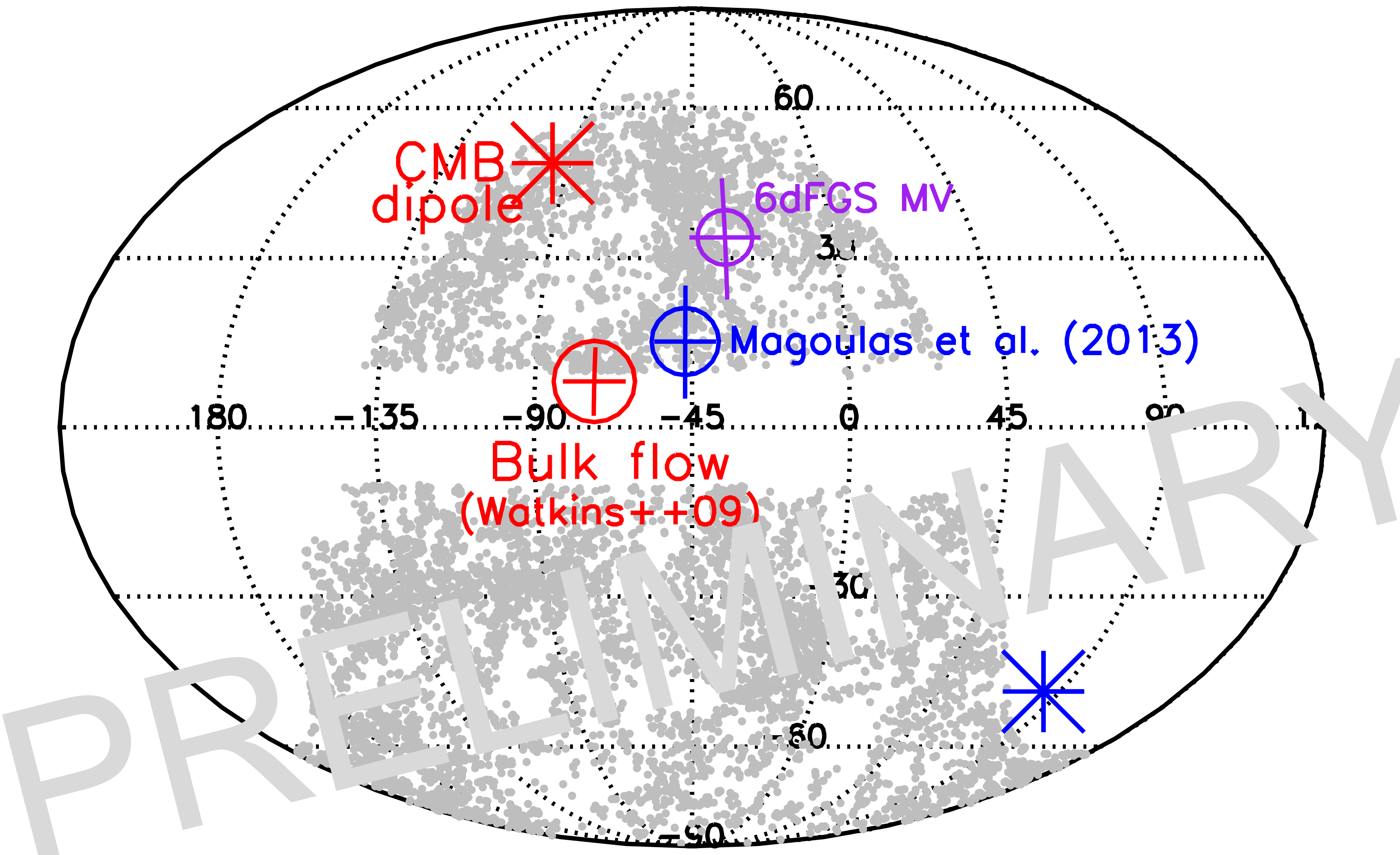


Image: Christina Magoulas, Morag Scrimgeour, Lister Staveley-Smith

6dFGS Bulk Flow Results (preliminary)

- $|u| = 275 \pm 57$ km/s



(Scrimgeour et al. 2013, in prep)

ICRAR International Centre for Radio Astronomy Research

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

Cosmology with Peculiar Velocity Surveys

- Exciting time for peculiar velocity cosmology!
  - 6dFGS available, SkyMapper & WALLABY coming up
- Upcoming surveys may solve bulk flow problem?
- 6dFGS bulk flow appears to be consistent with ΛCDM
- Need to further develop ways to analyse data and deal with systematics…