The local density & velocity fields from the 6dF Galaxy Survey

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Outline

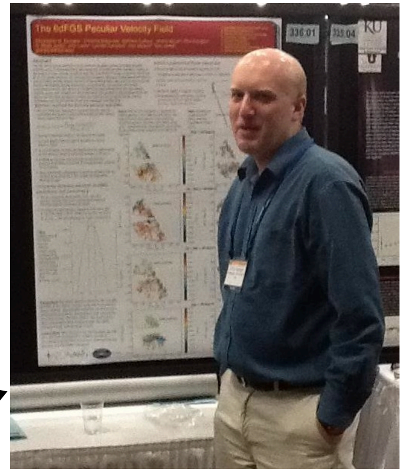
- The 6dF Galaxy Survey: a survey of galaxy redshifts (z) & peculiar velocities (v) in the local universe

- Results from the 6dGS z-survey:
  - H_0 from BAO measurements using the 6dFGS redshift survey

- Results from the 6dFGS v-survey:
  - Distances & velocities of early-type galaxies from Fundamental Plane
  - Local density and velocity fields
  - Cosmological parameters and implications

Florian Beutler

Also: Heath Jones, Lachlan Campbell, Jeremy Mould, Tom Jarrett, John Lucey, Rob Proctor, Pirin Erdogdu, Alex Merson et al.



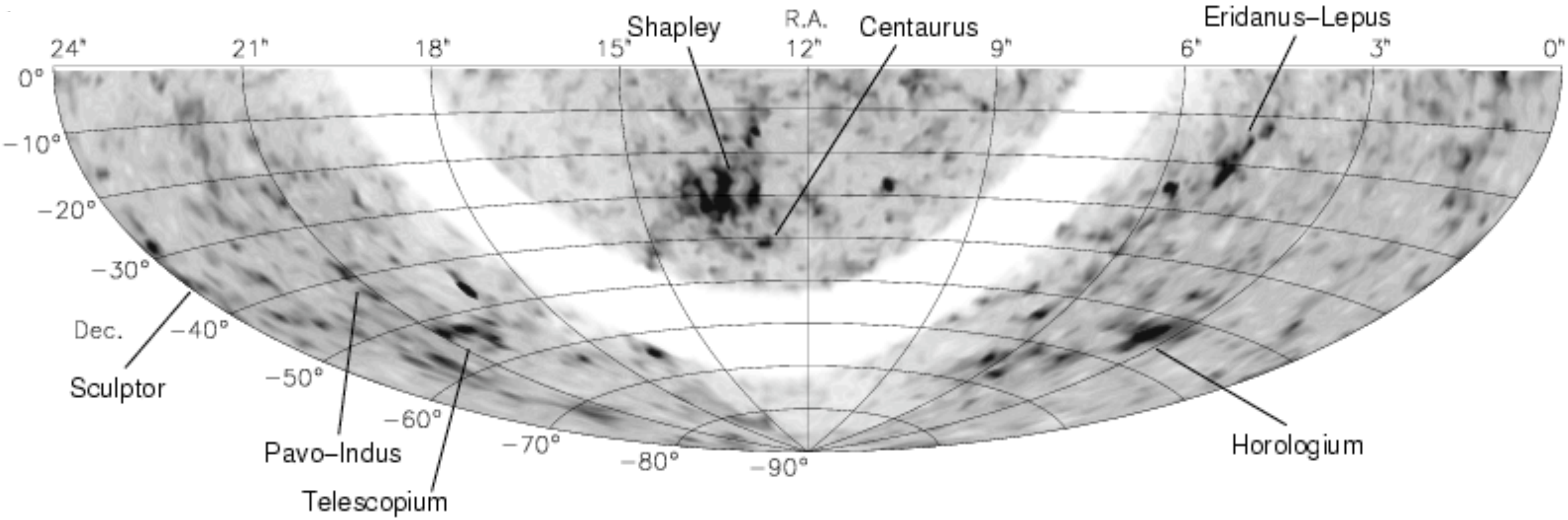
Chris Springob

Christina Magoulas

6dF Galaxy Survey

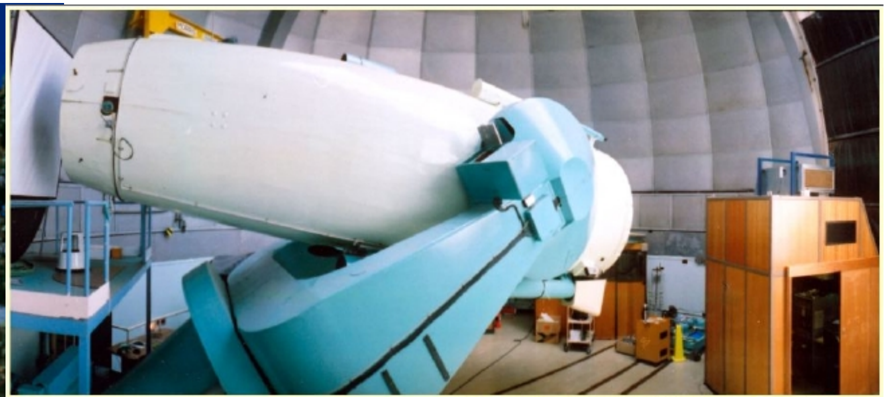
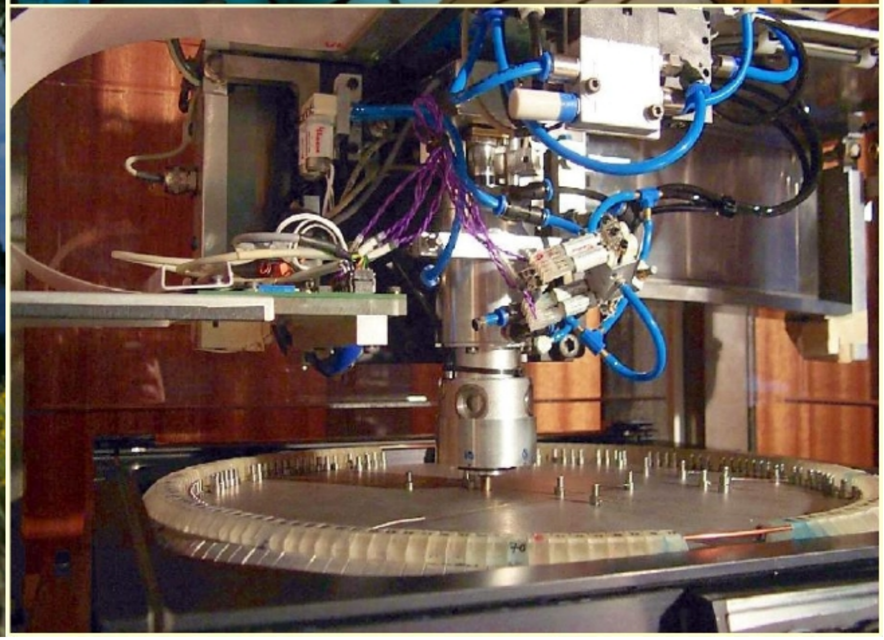
- 6dFGS was designed as a combined redshift and peculiar velocity survey to map the large-scale density/velocity fields in nearby universe
- Sample: NIR-selected galaxies from 2MASS survey with K<12.65 (similar limits in b, r, J, H)
- Area: 17000 deg^2 of southern hemisphere excl. ±10º about the Galactic plane (δ<0º, |b|>10º)

Magnitude limits	$K \leqslant 12.65$
	$H \leqslant 12.95$
	$J \leqslant 13.75$
	$r_{\mathrm{F}} \leqslant 15.60$
	$b_{\mathrm{J}} \leqslant 16.75$
Sky coverage (sr)	5.2
Fraction of sky	41%
Extragalactic sample, N	125 071
Median redshift, $z_{\frac{1}{2}}$	0.053
Volume V in $[0.5z_{\frac{1}{2}}, 1.5z_{\frac{1}{2}}]$ $(h^{-3}\,\mathrm{Mpc}^3)$	2.1×10^7
Sampling density at $z_{\frac{1}{2}}$, $\bar{\rho} = \frac{2N}{3V}$ $(h^3\,\mathrm{Mpc}^{-3})$	4×10^{-3}
Fibre aperture ($''$)	6.7
Fibre aperture at $z_{\frac{1}{2}}$ $(h^{-1}\,\mathrm{kpc})$	4.8



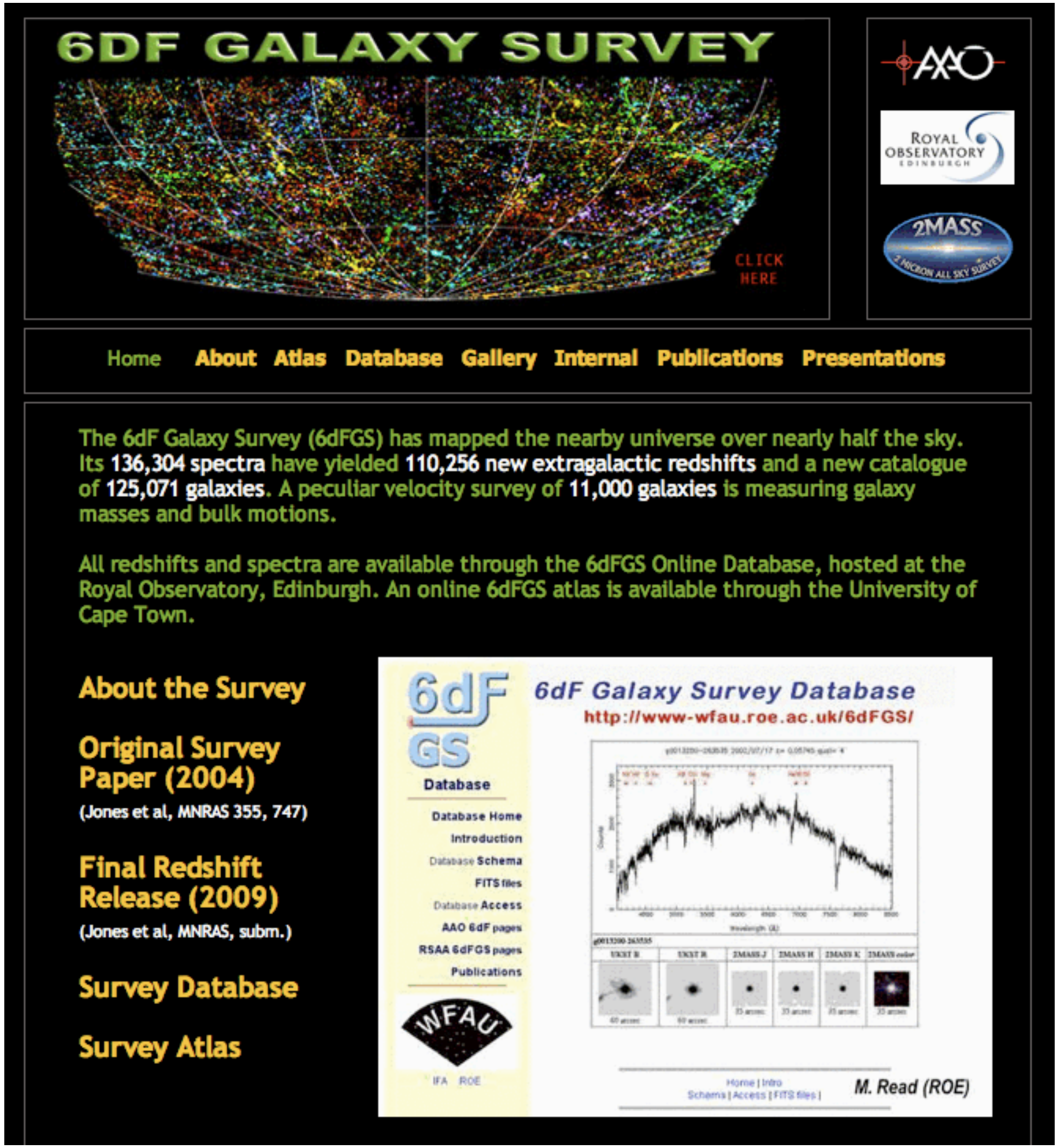
6dF Galaxy Survey

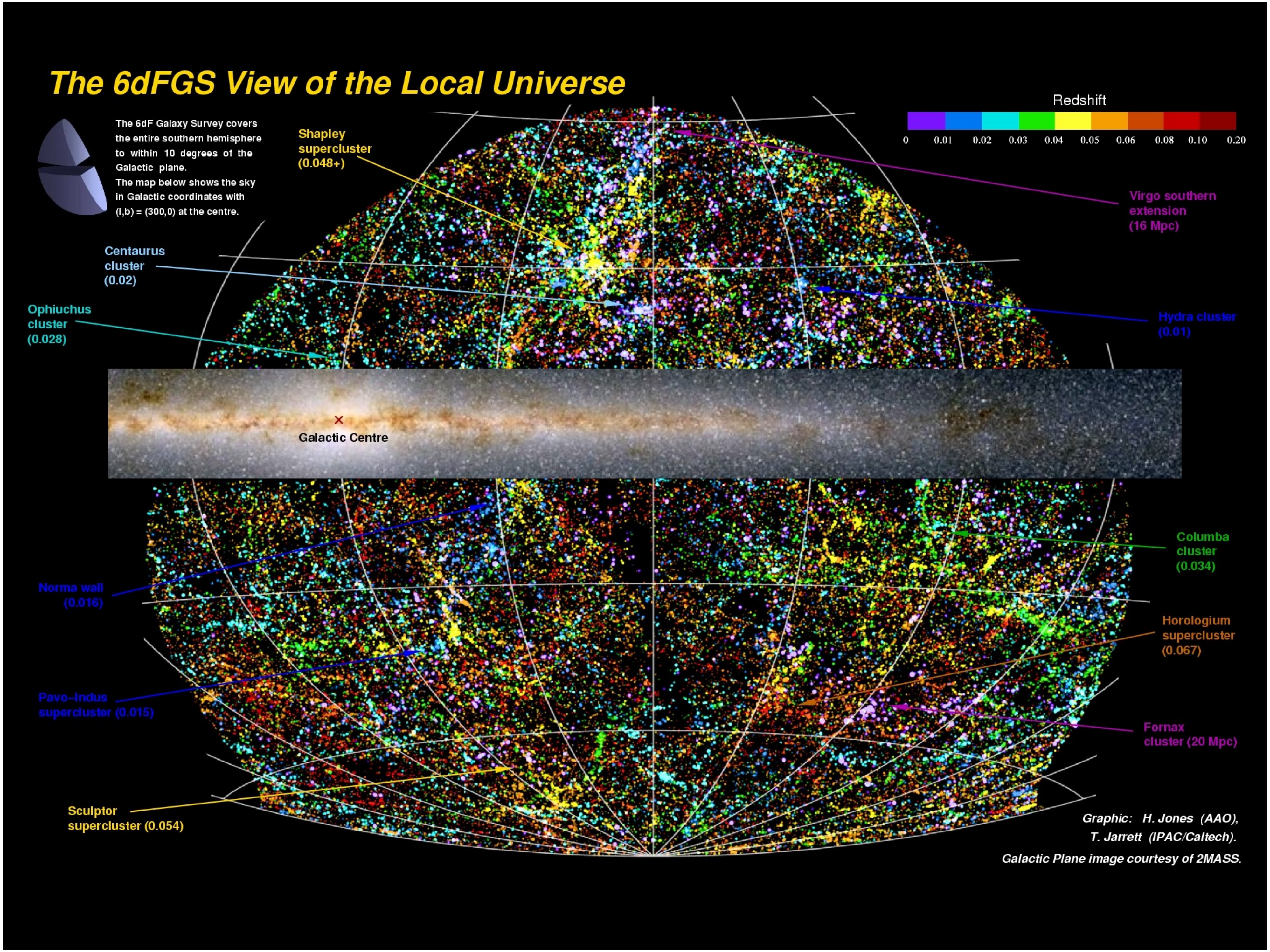
- Observations used the 6-degree Field (6dF) multi-object fibre spectrograph on the AAO's UK Schmidt Telescope over the period 2001-2006

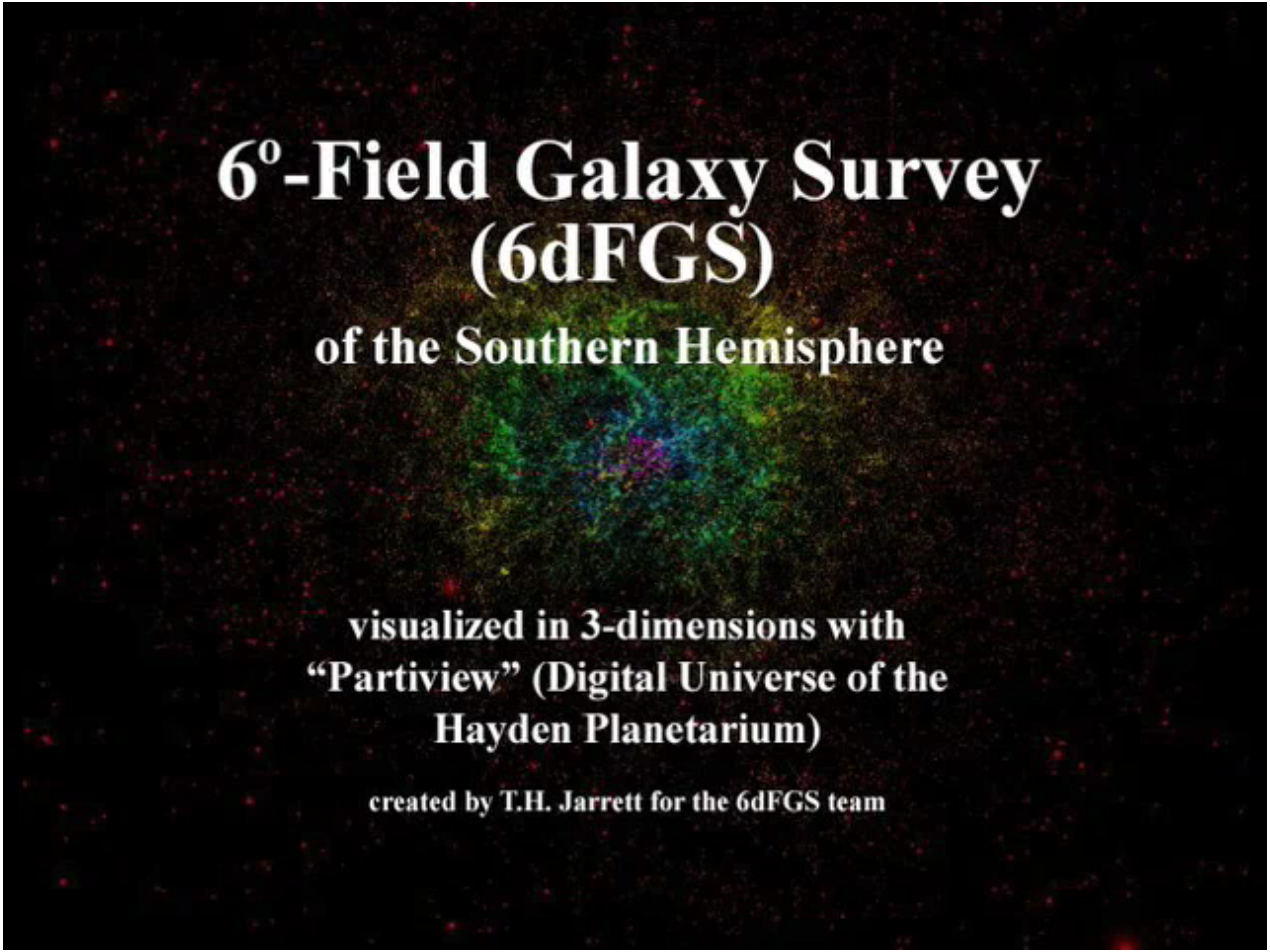




6dF Galaxy Survey

- z-survey: 125000 galaxy redshifts (137000 spectra) with <cz> ≈ 16500 km/s
- The 6dFGS database at www.aao.gov.au/6dFGS contains the photometric input catalogues, galaxy images and spectra, and the redshift catalogues
- v-survey: Fundamental Plane distances and peculiar velocities for 9000 early-type galaxies with cz < 16000 km/s



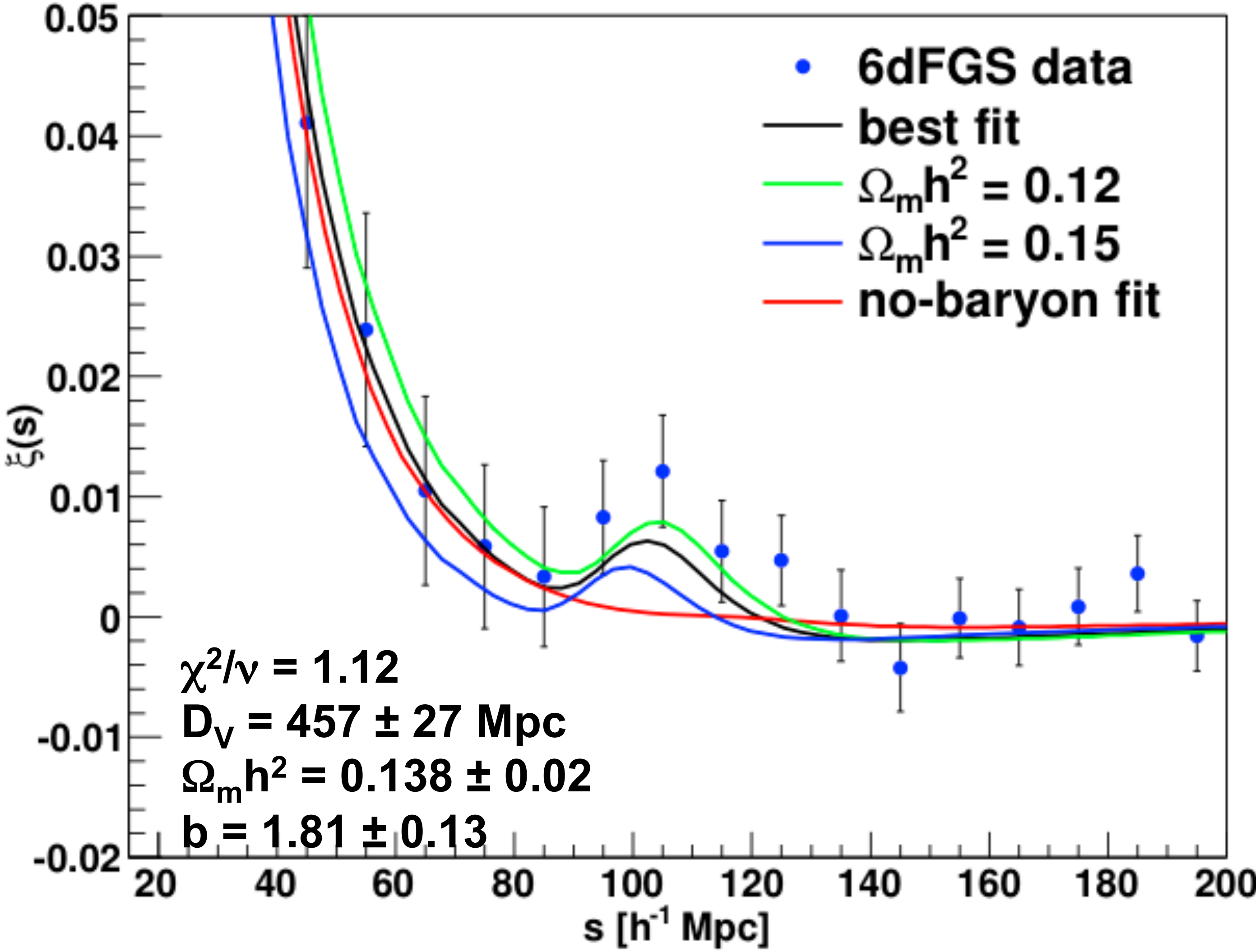

The 6dFGS View of the Local Universe
The 6dF Galaxy Survey covers the entire southern hemisphere to within 10 degrees of the Galactic plane.
The map below shows the sky in Galactic coordinates with (l,b) = (300,0) at the centre.
Redshift
0 0.01 0.02 0.03 0.04 0.05 0.06 0.08 0.10 0.20
Shapley supercluster (0.048+)
Virgo southern extension (16 Mpc)
Centaurus cluster (0.02)
Hydra cluster (0.01)
Ophiuchus cluster (0.028)
Galactic Centre
Columba cluster (0.034)
Norma wall (0.016)
Horologium supercluster (0.067)
Pavo-Indus supercluster (0.015)
Fornax cluster (20 Mpc)
Sculptor supercluster (0.054)
Graphic: H. Jones (AAO), T. Jarrett (IPAC/Caltech).
Galactic Plane image courtesy of 2MASS.


6°-Field Galaxy Survey
(6dFGS)
of the Southern Hemisphere
visualized in 3-dimensions with
"Partiview" (Digital Universe of the
Hayden Planetarium)
created by T.H. Jarrett for the 6dFGS team

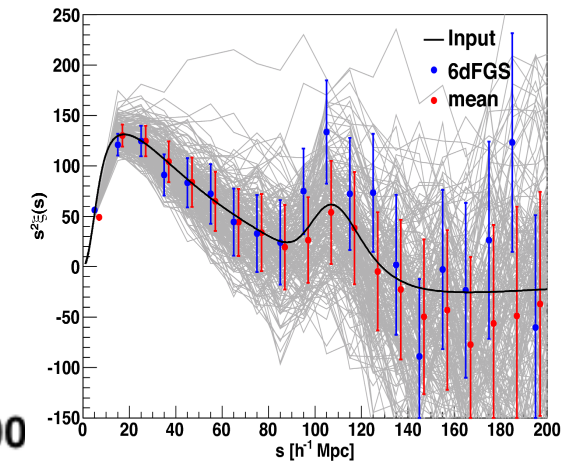
H_0 from BAO at low-z

- BAO give an absolute standard rod calibrated by CMB
  - well-understood linear physics; depends only on ρ_m and ρ_b
  - CMB provides calibration at z=1100 (breaks curvature-w degeneracy)
- BAO can in principle give ~1% distances over a wide range of redshifts, so are a powerful probe of cosmic geometry
  - BAO measure both H(z) radially and $D_A(z)$ tangentially
  - but this requires large samples: ~10^6 galaxies over ~1Gpc^3
- BAO are complementary to other probes of geometry
  - measure different cosmological properties
  - different physical basis and different systematics (non-linear clustering, redshift-space distortions, possible scale-dependent bias)
- At low z, measuring the BAO scale yields H_0 independent of the cosmological model - the method only requires calibration of the sound horizon scale by CMB observations

BAO in the 6dF Galaxy Survey



Florian Beutler



Beutler, Blake, Colless, et al., 2011, MNRAS, 416, 3017

Baryon acoustic oscillations and the local Hubble constant

6dFGS estimate of H_0

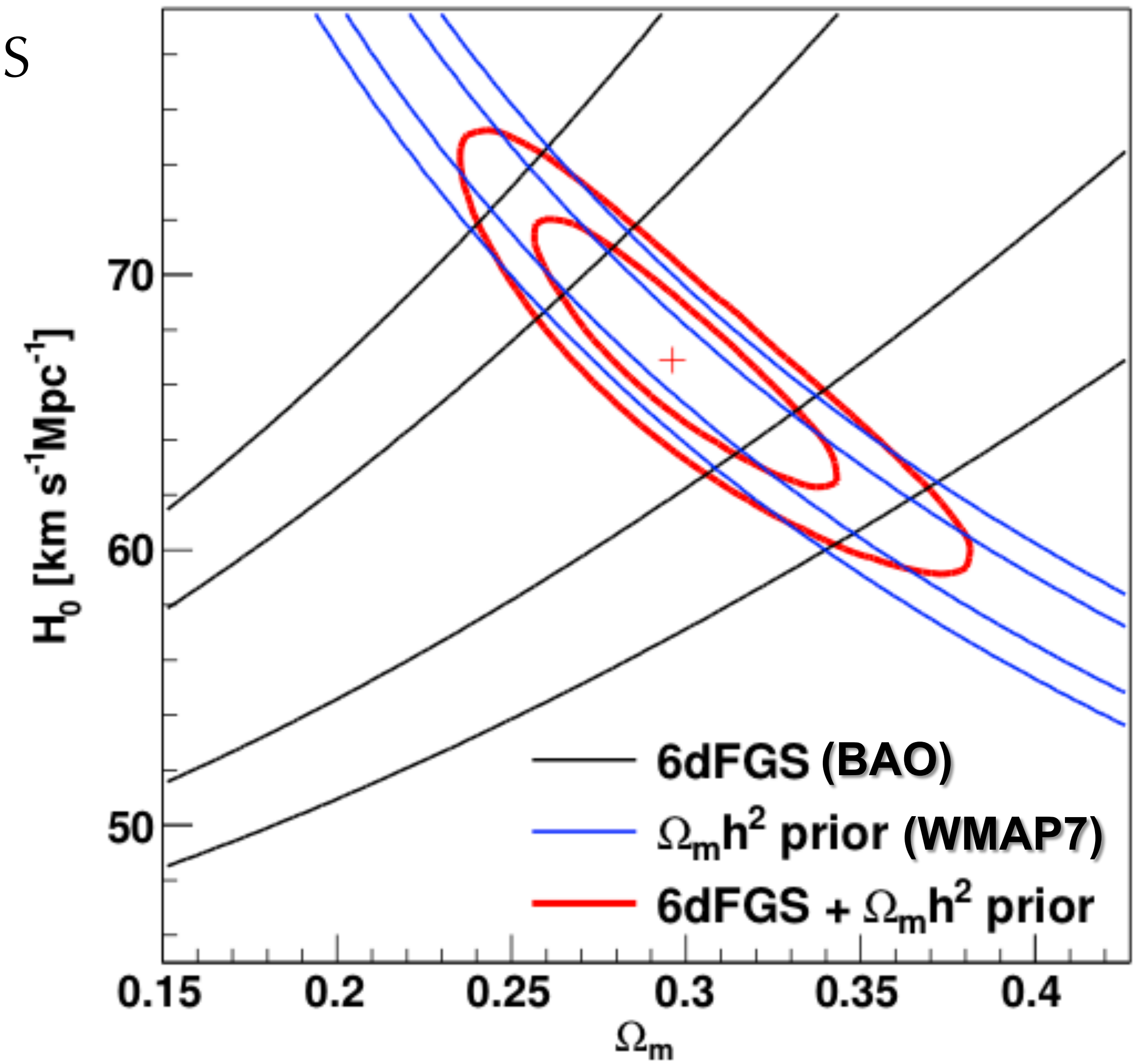
At low redshift, the 6dFGS z-survey measure of the BAO distance scale gives a model-independent estimate of H_0 with 5% precision:

$H_0 = 67 \pm 3.2$ km/s/Mpc

Compare to:

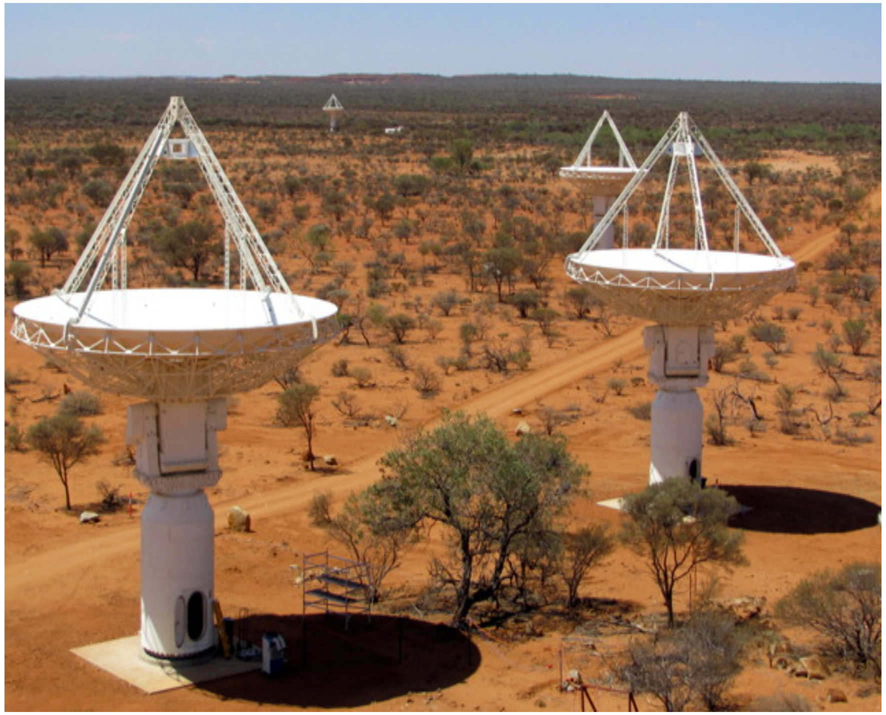
SH0ES
$H_0 = 74 \pm 2.4$ km/s/Mpc

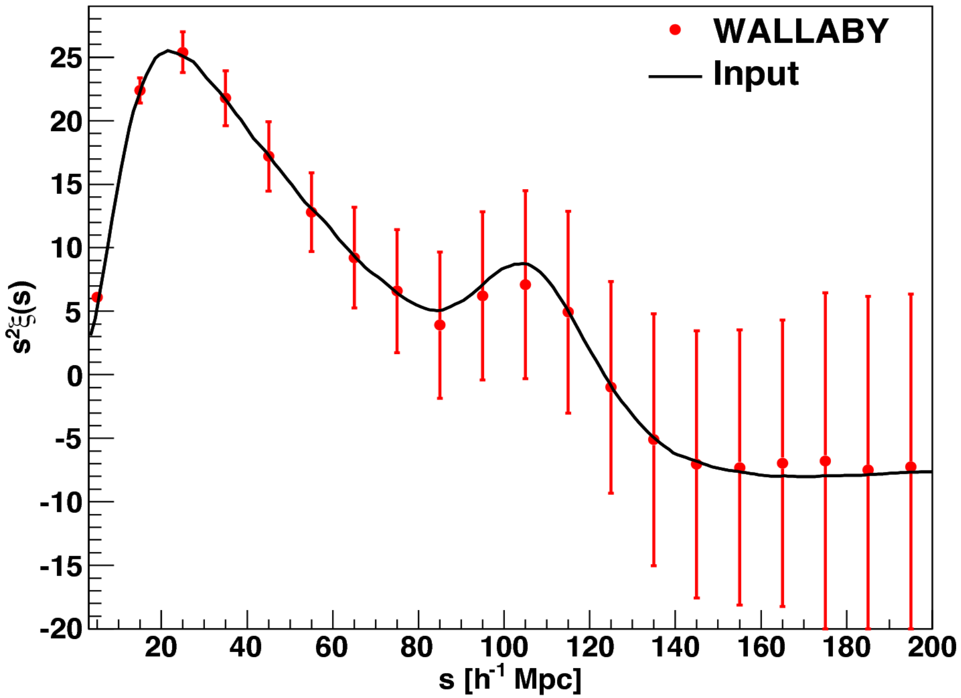
WMAP7 (model-dep.)
$H_0 = 70 \pm 2.5$ km/s/Mpc



Future surveys: WALLABY

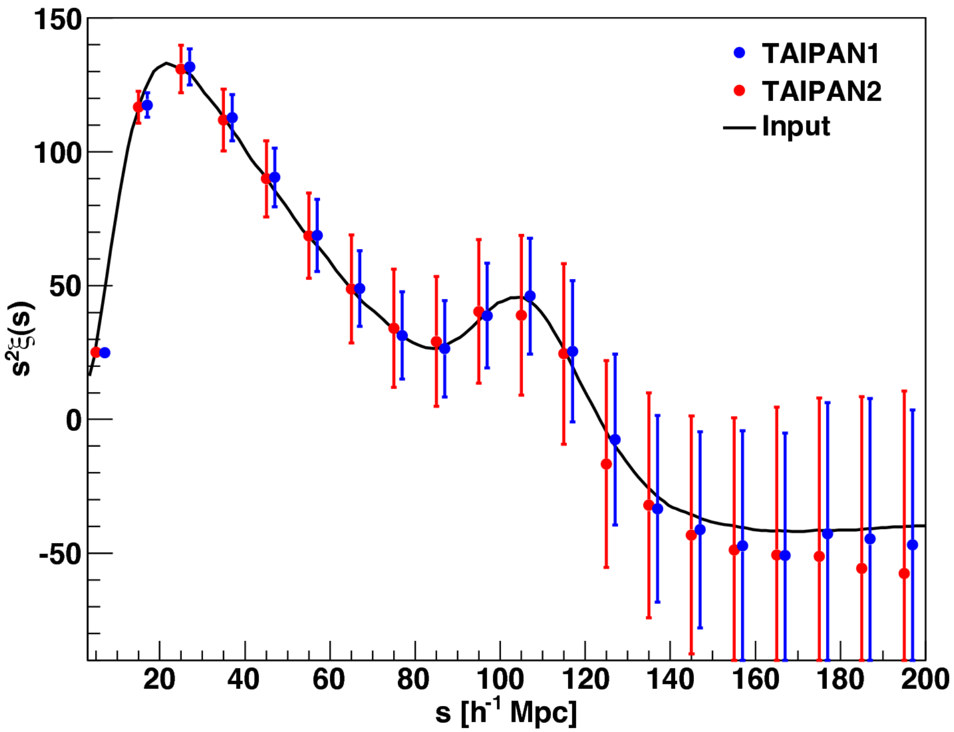
- WALLABY is an all-sky HI survey that will use ASKAP (the Australian SKA Pathfinder), currently under construction
- WALLABY will measure redshifts for ~600,000 HI galaxies with $b \approx 0.7$ and $\langle z \rangle \approx 0.04$ over a volume $V_{eff} \approx 0.12\ h^{-3}\ \mathrm{Gpc}^3$





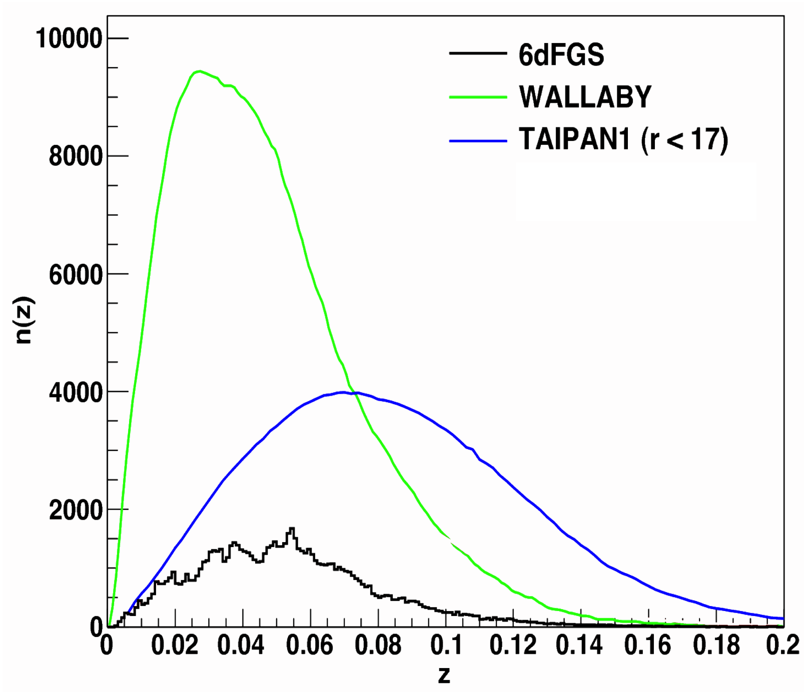
Future surveys: TAIPAN

- TAIPAN is an all-southern-sky optical z-survey using AAO's UK Schmidt Telescope (UKST), planned to start in 2015
- TAIPAN will obtain redshifts for ~400,000 galaxies with r<17 and <z> ≈ 0.07 over a volume $V_{eff} \approx 0.23\ h^{-3}\ Gpc^3$



H_0 from future low-z surveys

- How precisely can we measure H_0 with low-redshift BAO?
- The 5% precision of the 6dFGS BAO measurement might be improved by up to a factor ~2 using better BAO reconstruction
- Maximizing the survey volume at low redshift, as in the WALLABY and TAIPAN surveys, can win a further factor ~2 in precision
- Future low-z BAO measurements therefore plausibly provide a model-independent method of approaching 1% precision in H_0



6dFGS Fundamental Plane

- The Fundamental Plane (FP) subsample of the 6dFGS…
  - J, H, K photometric parameters (R_e, I_e) from 2MASS
  - redshifts and velocity dispersions (σ) from 6dFGS
  - all early-type galaxies in 6dFGS with $z<0.055$, $\sigma>100$ km/s
  - comprising a total of ~9,000 galaxies
- The Fundamental Plane is the empirically observed relation…

$$\log(R_e) = a \log(\sigma) + b \log(I_e) + c$$

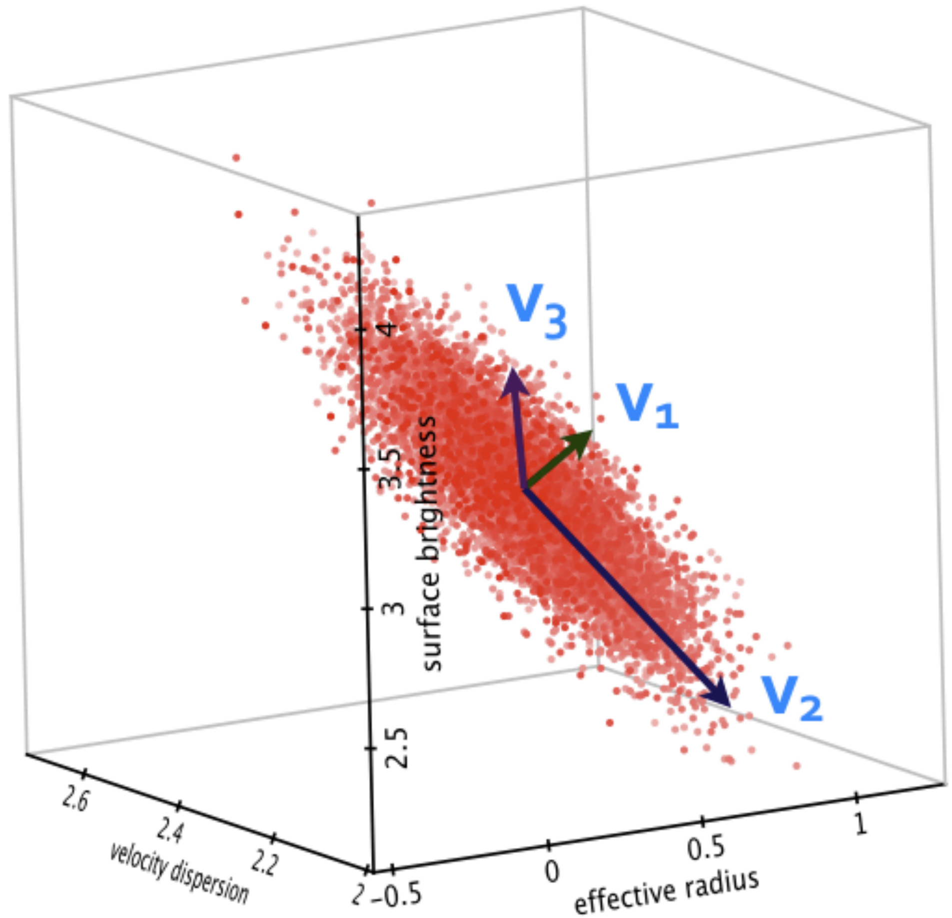
  where R_e is the half-light radius in kpc, σ is the velocity dispersion in km/s and I_e is the surface brightness in $L_\odot/pc^2$

- We usually write the Fundamental Plane as $r = a\,s + b\,i + c$ where $r = \log(R_e)$, $s = \log(\sigma)$ and $i = \log(I_e)$

Modeling the FP

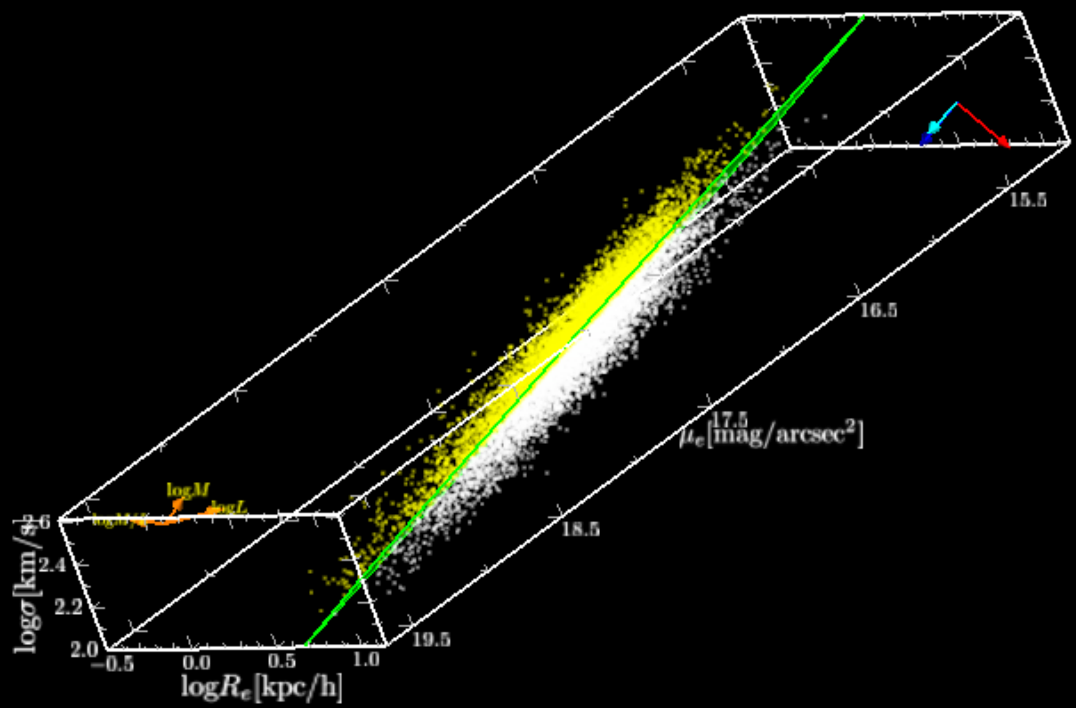
- We model the FP as a 3D Gaussian in (r,s,i) space; this is an excellent empirical match to the observed distribution
- The model is defined by the coefficients of the FP (a, b, c), and by the centroid (r, s, i) and dispersion (σ_1, σ_2, σ_3) of the 3D Gaussian
- The axes of the 3D Gaussian (v_1, v_2, v_3) are defined as:

  v_1 = through the plane (r↑, s↓, i↑)
  = short axis (normal to FP)
  v_2 = along the plane (r↓, no s, i↑)
  = long axis
  v_3 = across the plane (r↑, s↑, i↑)
  = intermediate axis



Fitting the FP

- We fit the 3D Gaussian model of the FP using a comprehensive and robust maximum likelihood method that accounts for:
  - errors in all the observed quantities for each galaxy & their correlations
  - sample selection effects & censoring (redshift range, lower limit on velocity dispersion, bright & faint magnitude limits, outlier rejection)



3D Visualization with S2PLOT by C.Fluke

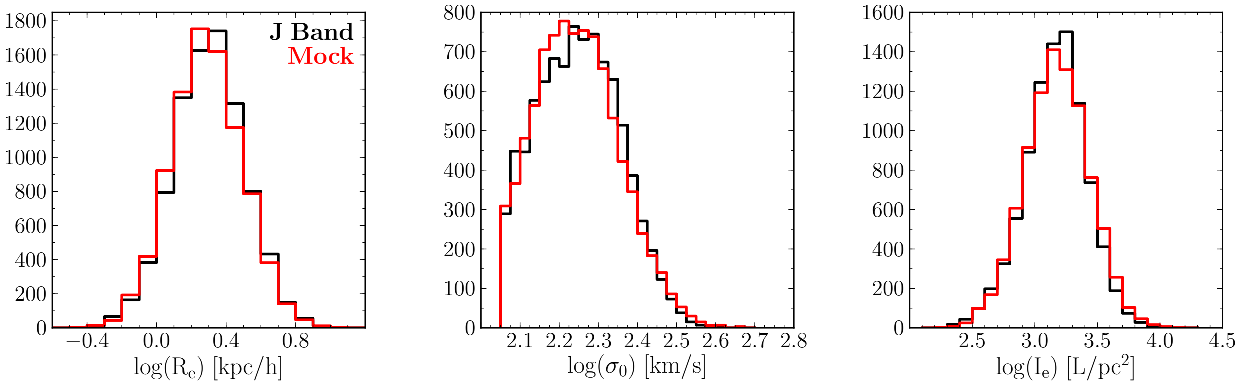
Fitted FP parameters and trends

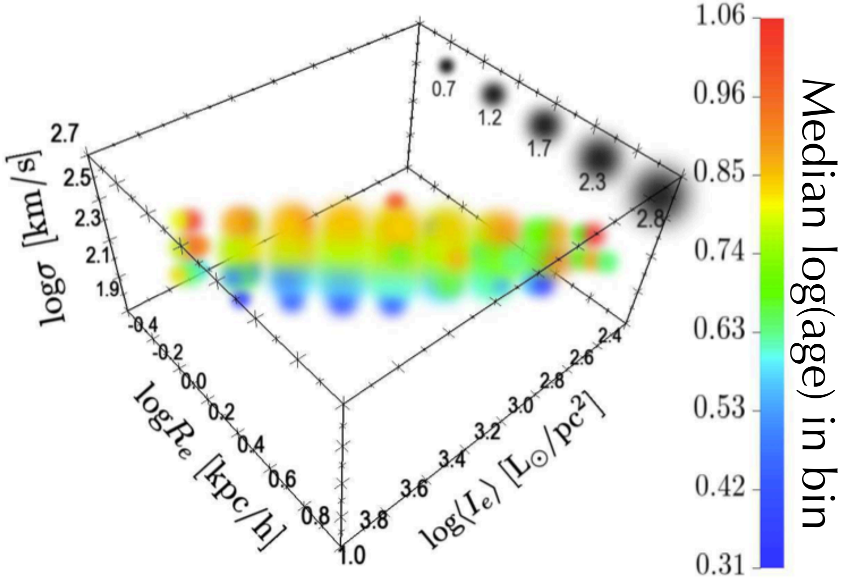
- In the J band, the best-fit FP is:

$$r = (1.52 \pm 0.03)\ s + (-0.89 \pm 0.01)\ i + (-0.33 \pm 0.05)$$

with intrinsic dispersions in the three axes of (0.05,0.32,0.17)

- The best-fit 3D Gaussian is a good representation of observed (r,s,i) distribution
- The 'intrinsic' scatter normal to the FP is due in part to the effect of stellar population age variations on M/L, but the very large uncertainties on individual age estimates mean it is not possible to correct the effect
- Small FP offsets between cluster & field galaxies and E/S0's & spiral bulges are observed and accounted for

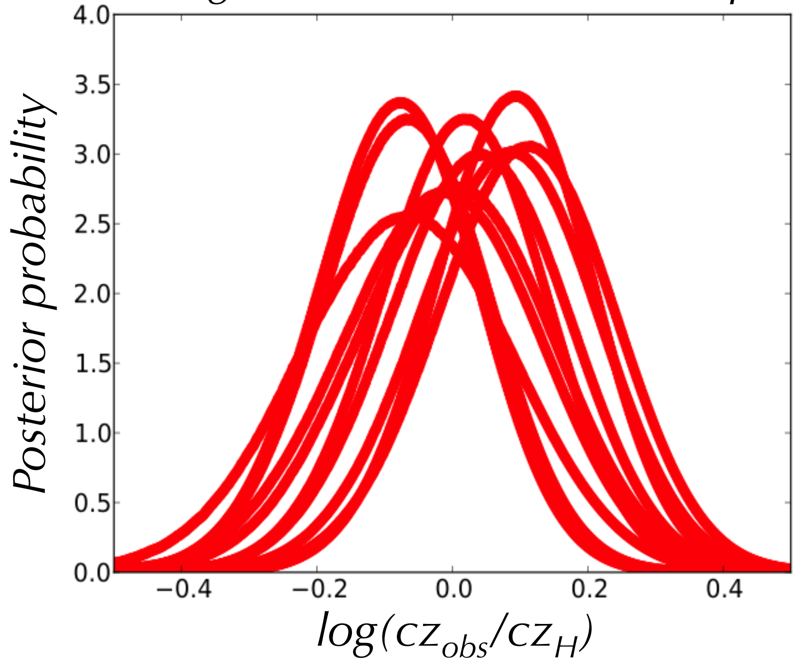




Bayesian peculiar velocities

- We determine Bayesian posterior probability distributions for the peculiar velocities given the observations & fitted FP model
  - Specify template FP relations using fitted 3D Gaussian model
  - For each galaxy, loop through all possible co-moving distances
  - Calculate likelihood of galaxy being at that distance, given its observed position in FP space and uncertainties
  - Multiply by chosen prior and normalize to obtain posterior probability distribution of the galaxy's distance/peculiar velocity
  - Apply appropriate weighting to account for galaxies too faint to be observed in the sample (homogeneous Malmquist bias)

Peculiar velocity distributions for the first 10 galaxies in the 6dFGS sample



N.B. the probability distribution of peculiar velocity for a given galaxy differs from that for a given point in real or redshift space

FP scatter and distance errors

- The scatter about the FP in $r \equiv \log(Re)$ translates into the uncertainty in individual distances and peculiar velocities
- The total scatter in r is given by the quadrature sum of the observational errors and the intrinsic scatter in r about the FP
- The inferred intrinsic scatter of the FP in distance is ~23%

$$\sigma_r^2 = \Delta r^2 - (a.\Delta s)^2 - \Delta X_{FP}^2$$

Photometric error
$\Delta X_{FP} = 3\%$

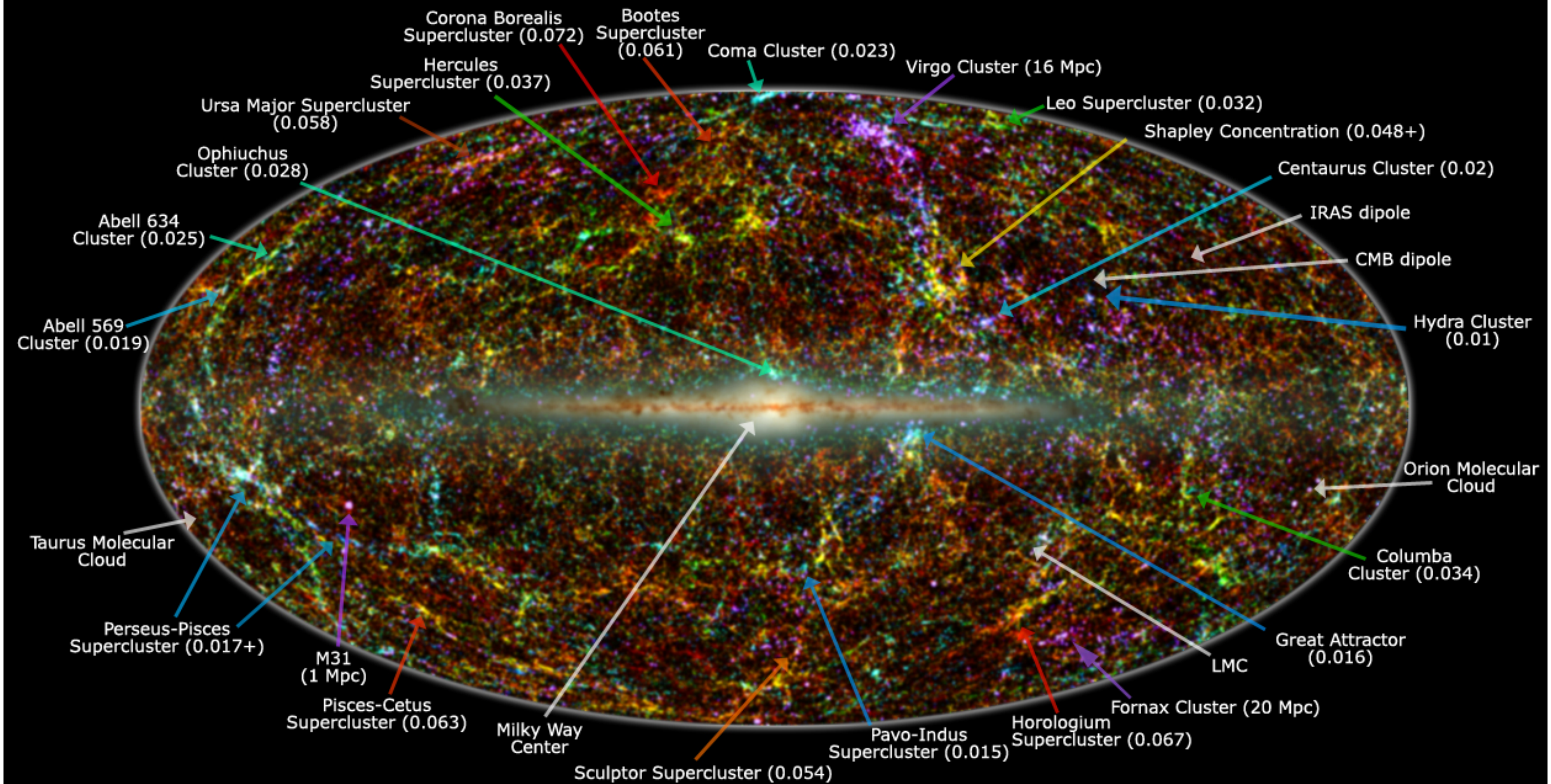
Intrinsic r error
$\sigma_r = 23\%$

Total scatter in r
$\Delta r = 29\%$

FP slope x obs error in s
$a.\Delta s = 1.5 \times 12\% = 18\%$

- Computing the distance errors from the posterior probability distributions, including homogeneous Malmquist bias, the rms distance error for galaxies in the 6dFGS sample is 27%

Local large scale structures



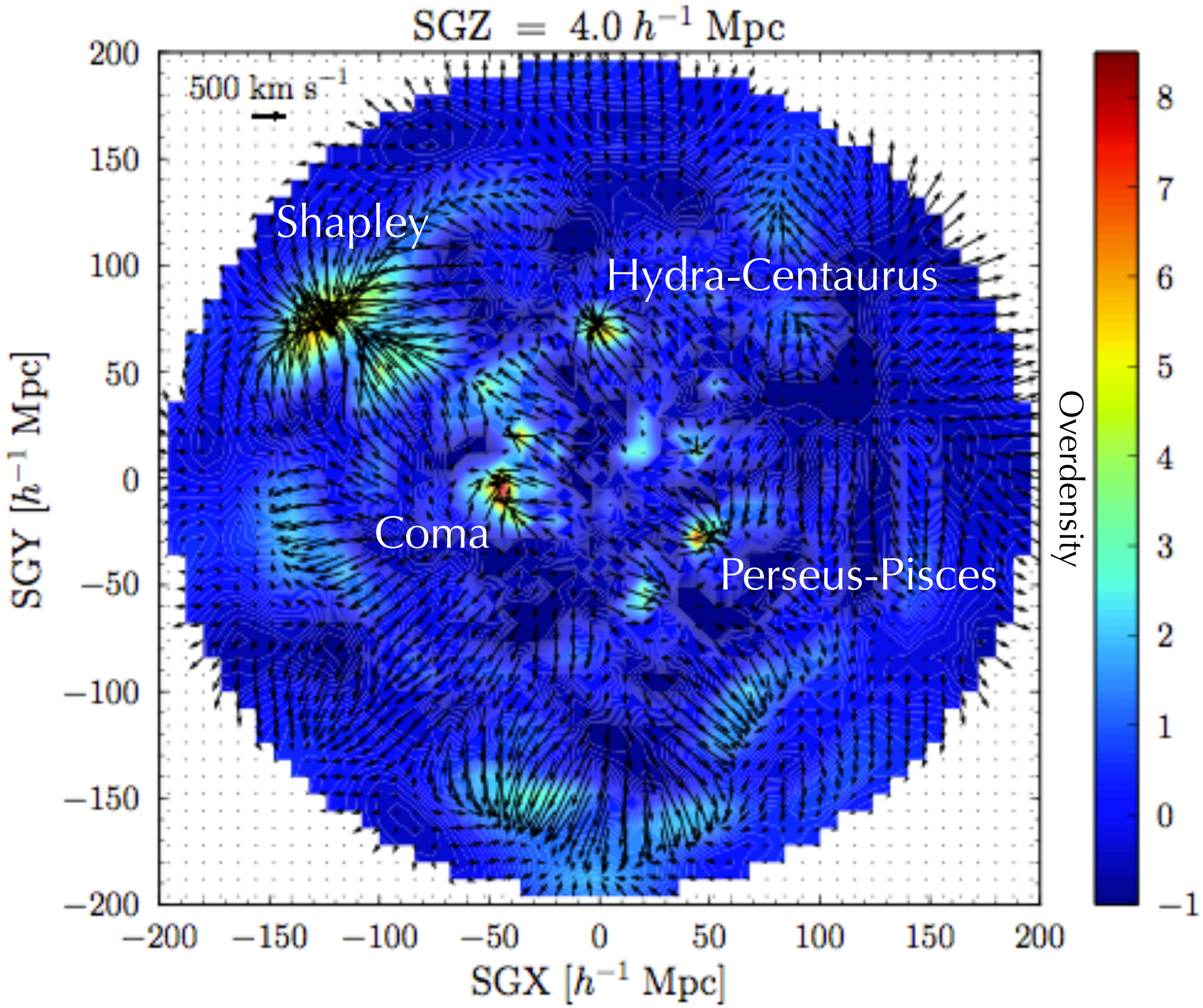
Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004);
familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift).
Graphic created by T. Jarrett (IPAC/Caltech)

Predicted peculiar velocity field

- Erdogdu et al. (2006, 2012) reconstruct the predicted linear peculiar velocity field from the 2MRS redshift-space galaxy distribution, assuming it is linearly biased:

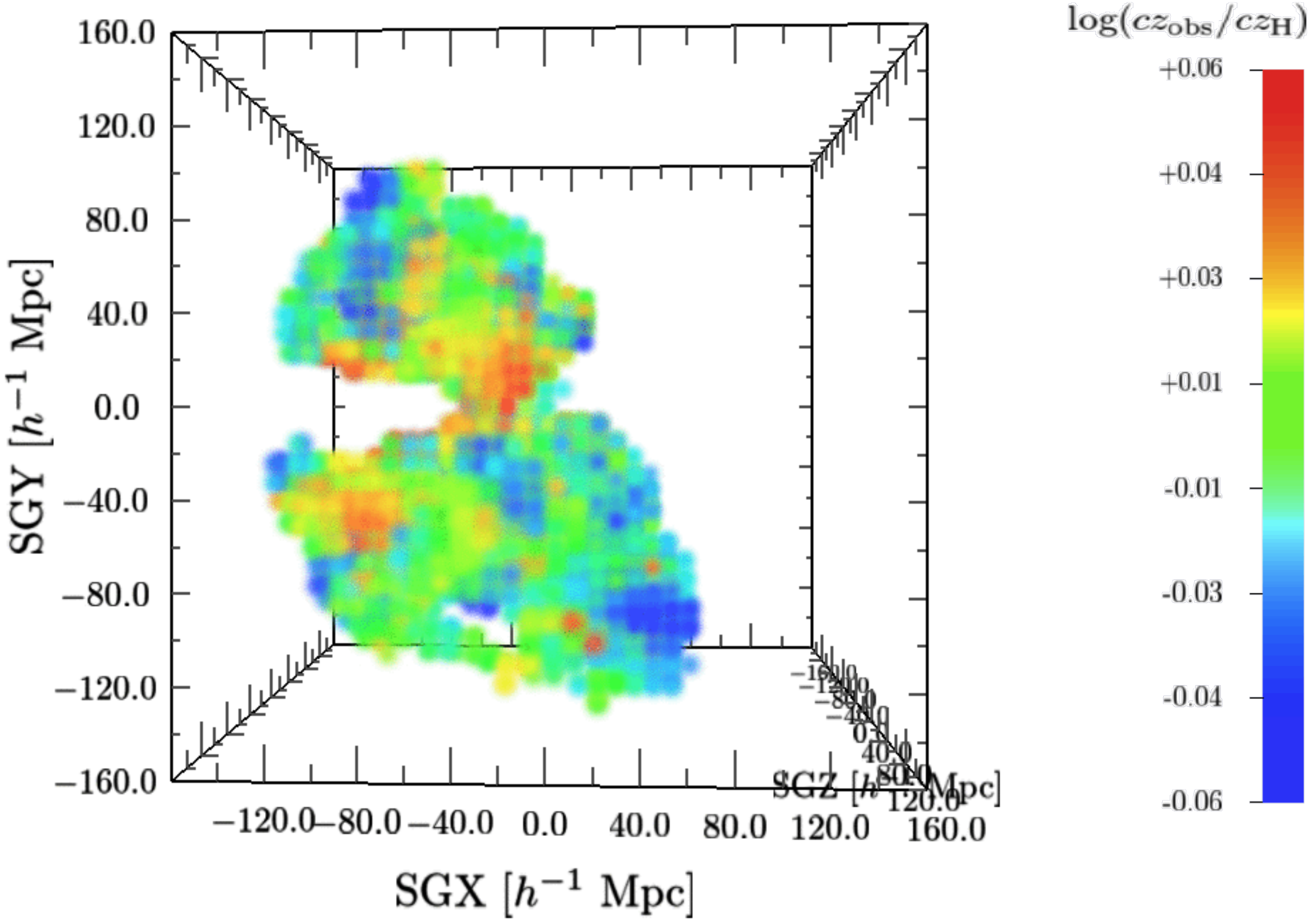
$$b=\delta_{gal}/\delta_{mass}$$

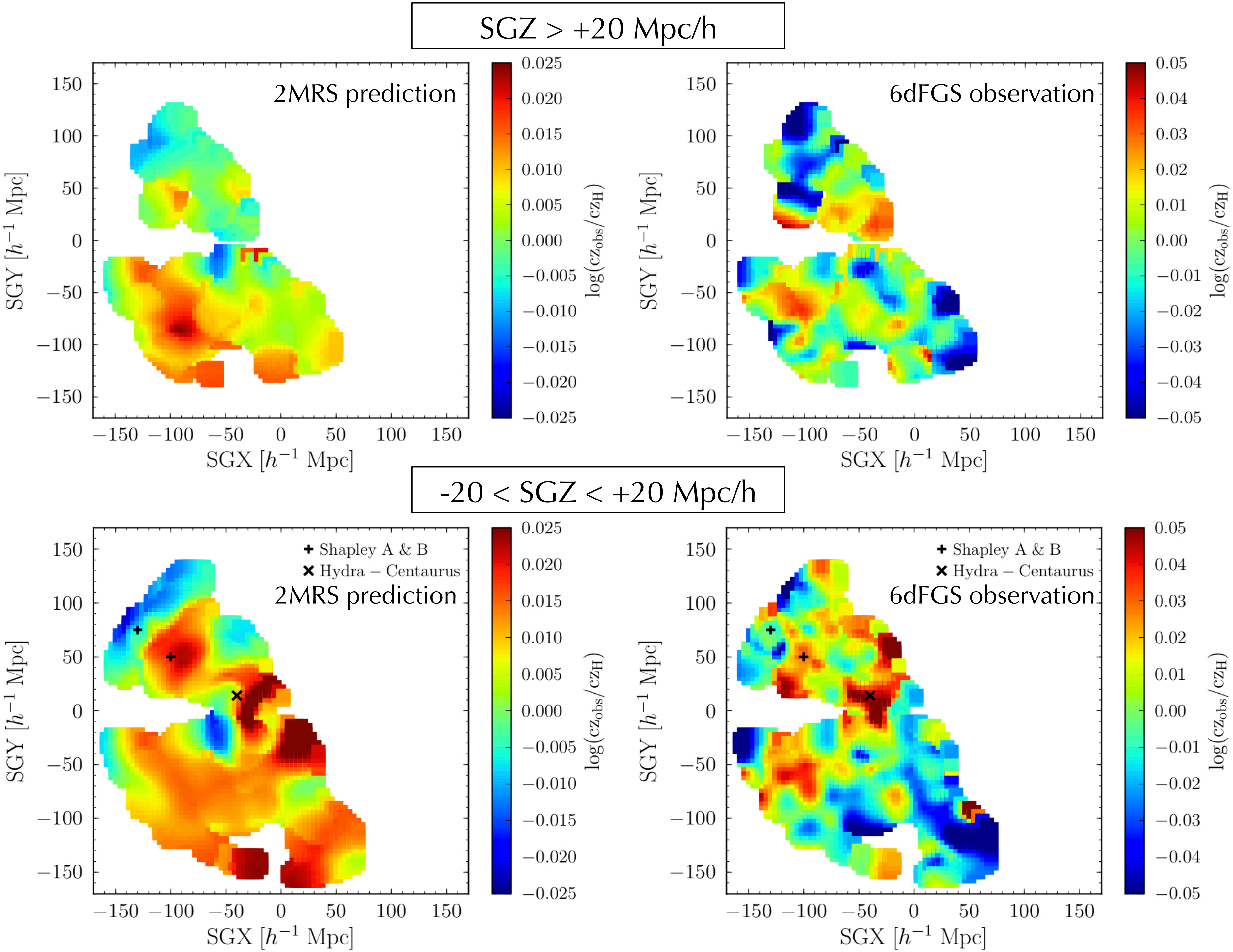
- To optimize S/N, the velocity field is Wiener filtered, smoothing and reducing the amplitude of small-scale velocities
- Velocity amplitudes set by the parameter $\beta = \Omega_m^{0.55}/b$
- Explore reconstructions including non-linear effects - e.g. Lavaux (2010) and Kitaura (2012)



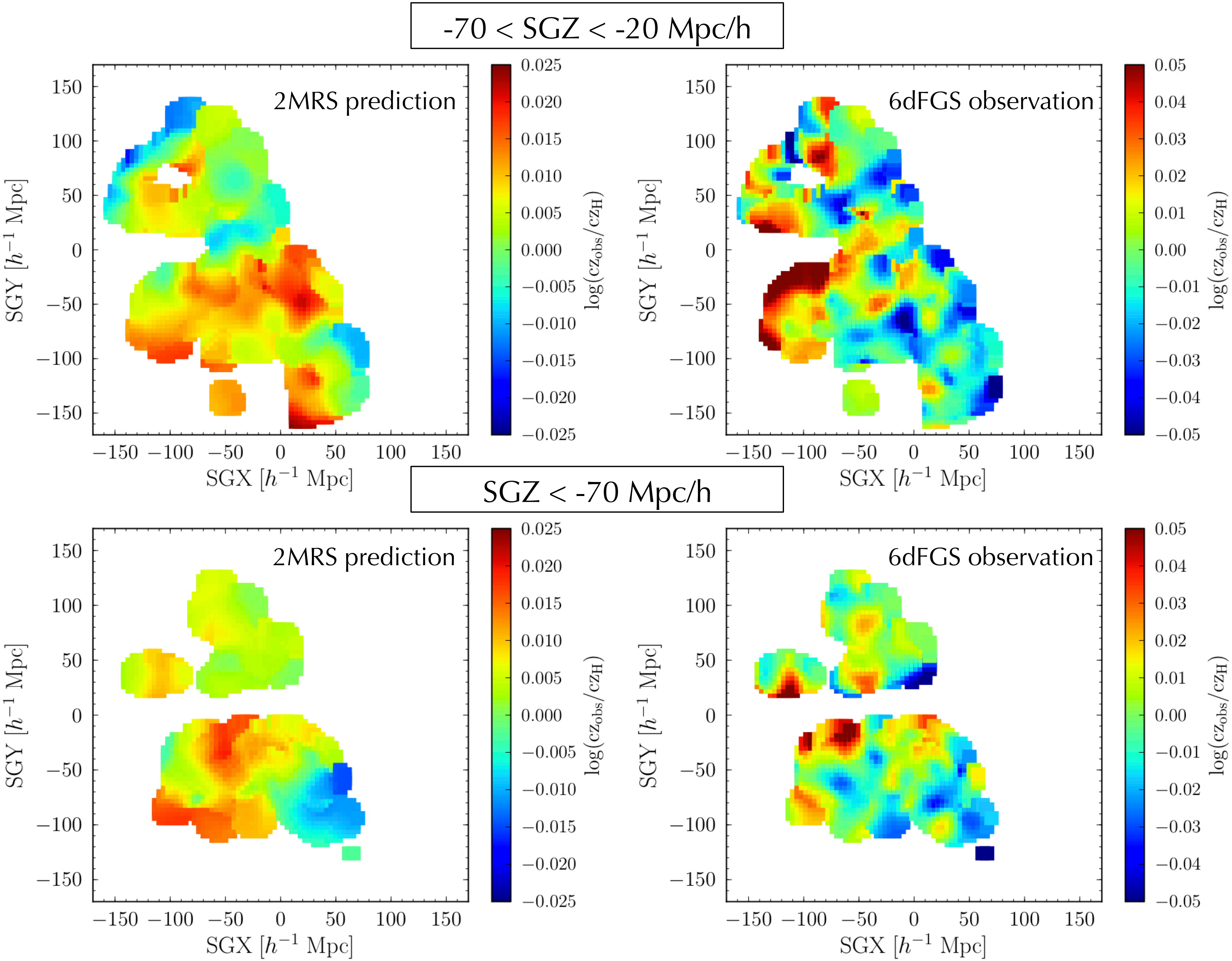
Reconstructed density (colours) & velocity (arrows) fields from the model of Erdogdu et al. (2006, 2012)

6dFGS observed velocity field





SGZ > +20 Mpc/h
2MRS prediction
6dFGS observation
-20 < SGZ < +20 Mpc/h
Shapley A & B
Hydra – Centaurus
SGX [h^{-1} Mpc]
SGY [h^{-1} Mpc]
$\log(cz_{obs}/cz_H)$


-70 < SGZ < -20 Mpc/h
SGZ < -70 Mpc/h
2MRS prediction
6dFGS observation
SGX [h^{-1} Mpc]
SGY [h^{-1} Mpc]
$\log(cz_{\rm obs}/cz_{\rm H})$

Fitting peculiar velocity models

- We can fit a peculiar velocity model to the galaxy observations in (r,s,i) space directly (i.e. without computing individual peculiar velocities) using a maximum likelihood approach:
  - Given the best-fit 3D Gaussian for the intrinsic galaxy distribution, and the individual galaxy parameters and uncertainties, we find the most likely parameters for a specified global peculiar velocity model
  - The simple peculiar velocity models we fit are:
    1. The velocity field reconstructed from 2MRS, scaled by $\beta \equiv \Omega^{0.55}/b$
    2. A pure bulk motion given by u_{bulk}
    3. The reconstructed velocity field from 2MRS scaled by β, plus a residual bulk motion u_{resid} *not* predicted from the density field

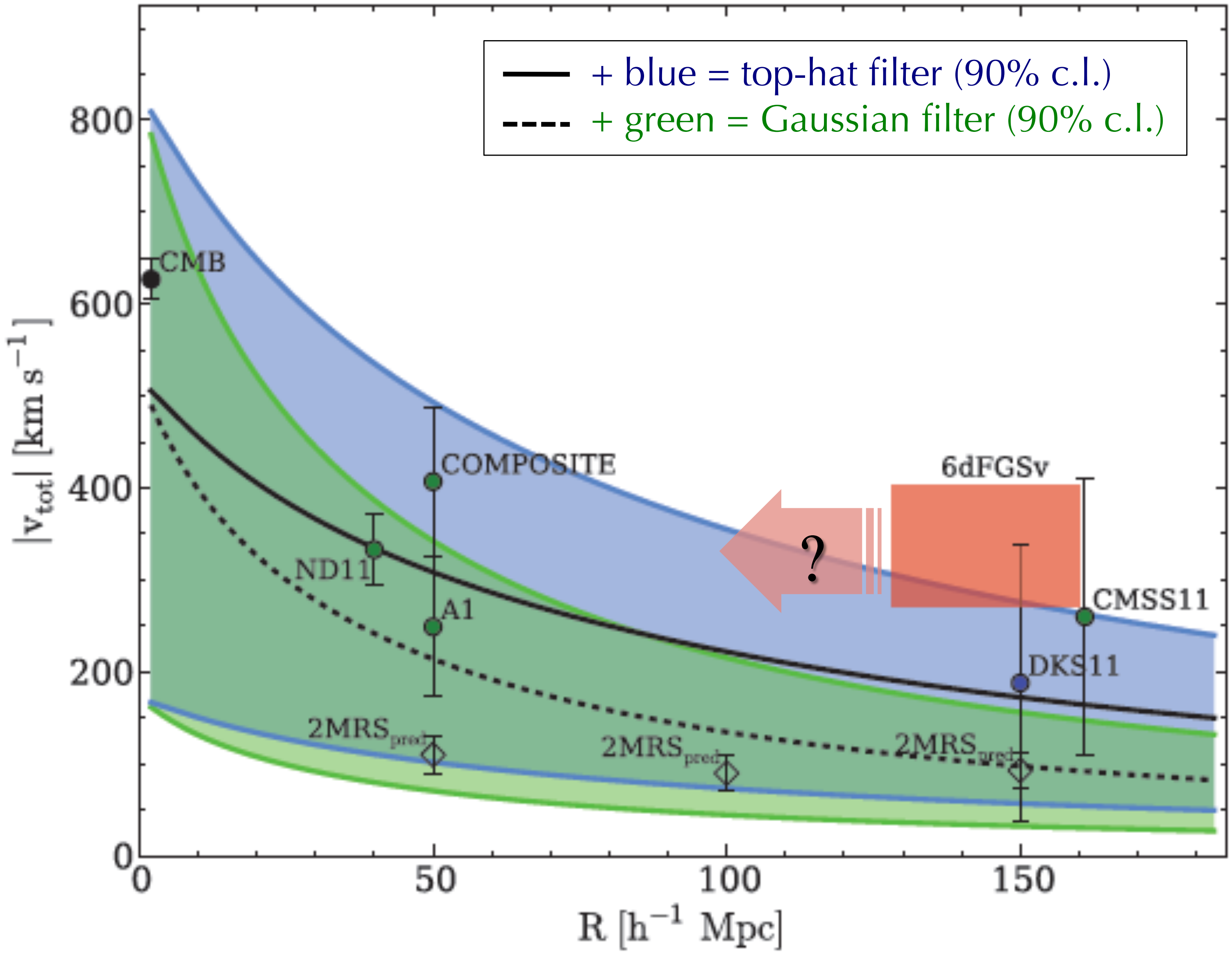
N.B. these simple models take no account of the way the galaxies sample the survey volume – cf. the 'minimum variance' estimation of velocity field moments used by Watkins, Feldman & Hudson (2009)

Fitting peculiar velocity models

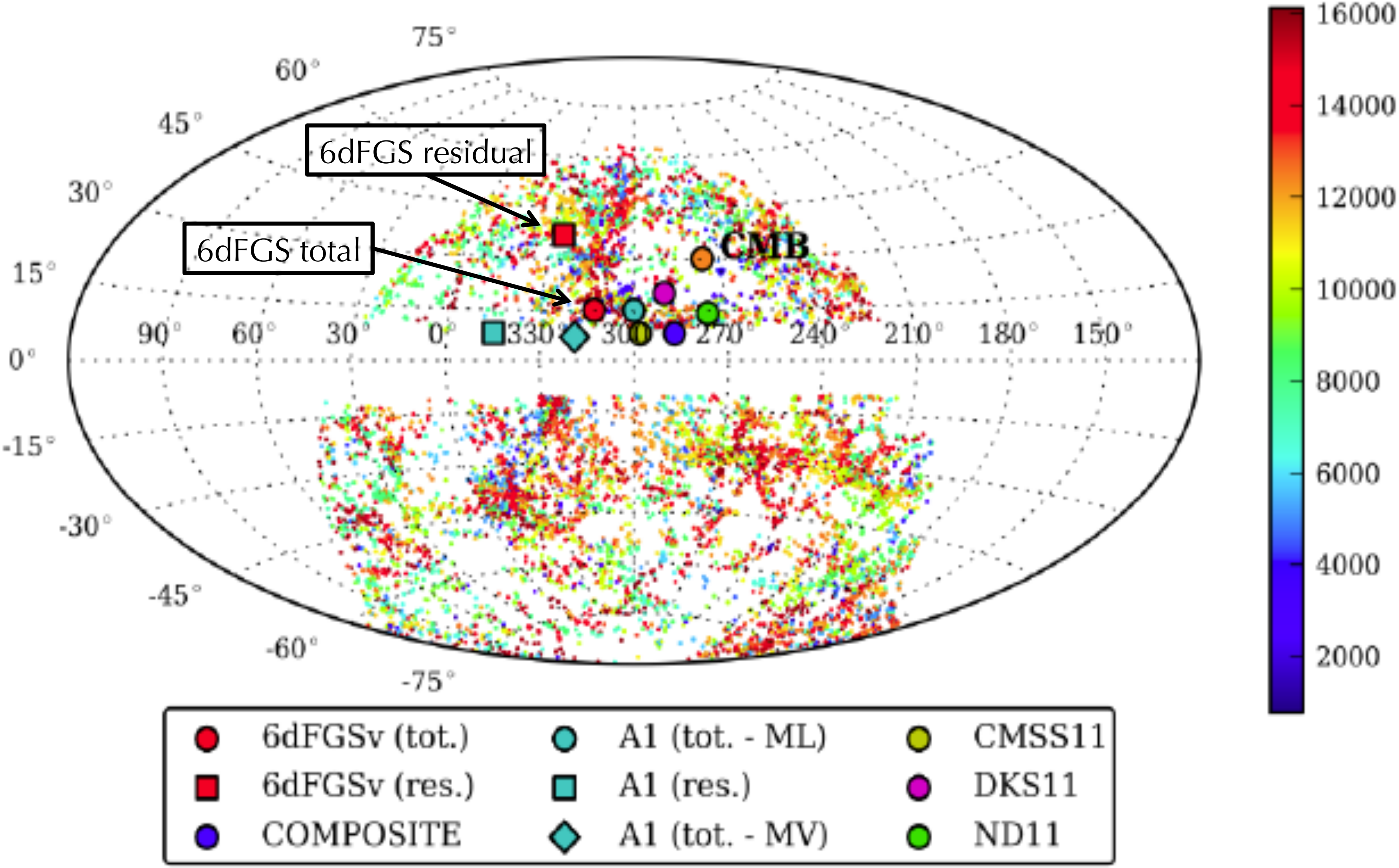
- The parameters obtained by maximum likelihood fitting models with β only (i.e. scaled reconstructed 2MRS velocity fields), a pure bulk flow u_{bulk}, and β plus a residual bulk flow u_{resid} are:

	β only	**u_{bulk} only**	**β and u_{resid}**
$\beta =$	0.29 ± 0.06	–	0.28 ± 0.05
$u_{SGX} =$	–	–324 ± 77 km/s	–205 ± 73 km/s
$u_{SGY} =$	–	+85 ± 46 km/s	+162 ± 48 km/s
$u_{SGZ} =$	–	–17 ± 46 km/s	+46 ± 49 km/s
$\lvert u \rvert =$	–	337 ± 66 km/s	273 ± 45 km/s
$l_{SG} =$	–	165 ± 10 deg	141 ± 16 deg
$b_{SG} =$	–	–3 ± 8 deg	11 ± 11 deg

Bulk motions on large scales



Direction of bulk flows



Future plans

- Existing data…
  - Fit the bulk flow in independent redshift shells – convergence?
  - Determine or constrain additional parameters:
    - Fit for additional parameters, using current maximum likelihood approach and minimum variance method of Watkins, Feldman & Hudson (2009)
    - Multipole analysis, following Feldman, Watkins & Hudson (2010)
    - Model comparison & bulk flows via hyper-parameters, Ma et al. (2012)
    - Peculiar velocity power spectrum, following Burkey & Taylor (2004)
    - Parameters to be determined or constrained include the bulk flow, shear, power spectrum shape Γ, correlation of luminous and dark matter r_g, etc.
- New data…
  - SDSS: add the extant SDSS FP data to extend the 6dFGS FP sample
  - TAIPAN: a new deeper FP survey using the UK Schmidt Telescope
  - HI surveys: complementary Tully-Fisher peculiar velocities from the 2MTF and WALLABY HI surveys

Summary

- We have measured FP parameters for ~9000 early-type galaxies
- We fit the galaxy distribution in FP space with a 3D Gaussian model
- We implement a Bayesian method for deriving the peculiar velocity probability distributions for each of the ~9000 galaxies
- We obtain estimates of the distances and peculiar velocities of these galaxies with rms errors of 27%
- We compare the measured peculiar velocities to the predicted velocity field from 2MRS and find reasonable agreement assuming $\beta = 0.29$
- We measure a bulk flow of 337 km/s, marginally larger than predicted by ΛCDM, much of which is residual motion not predicted from 2MRS
- More sophisticated analysis of existing data is required and planned
- Proposed new peculiar velocity surveys will provide additional data with greater precision for more objects over larger volumes