The 2MASS Tully Fisher Survey

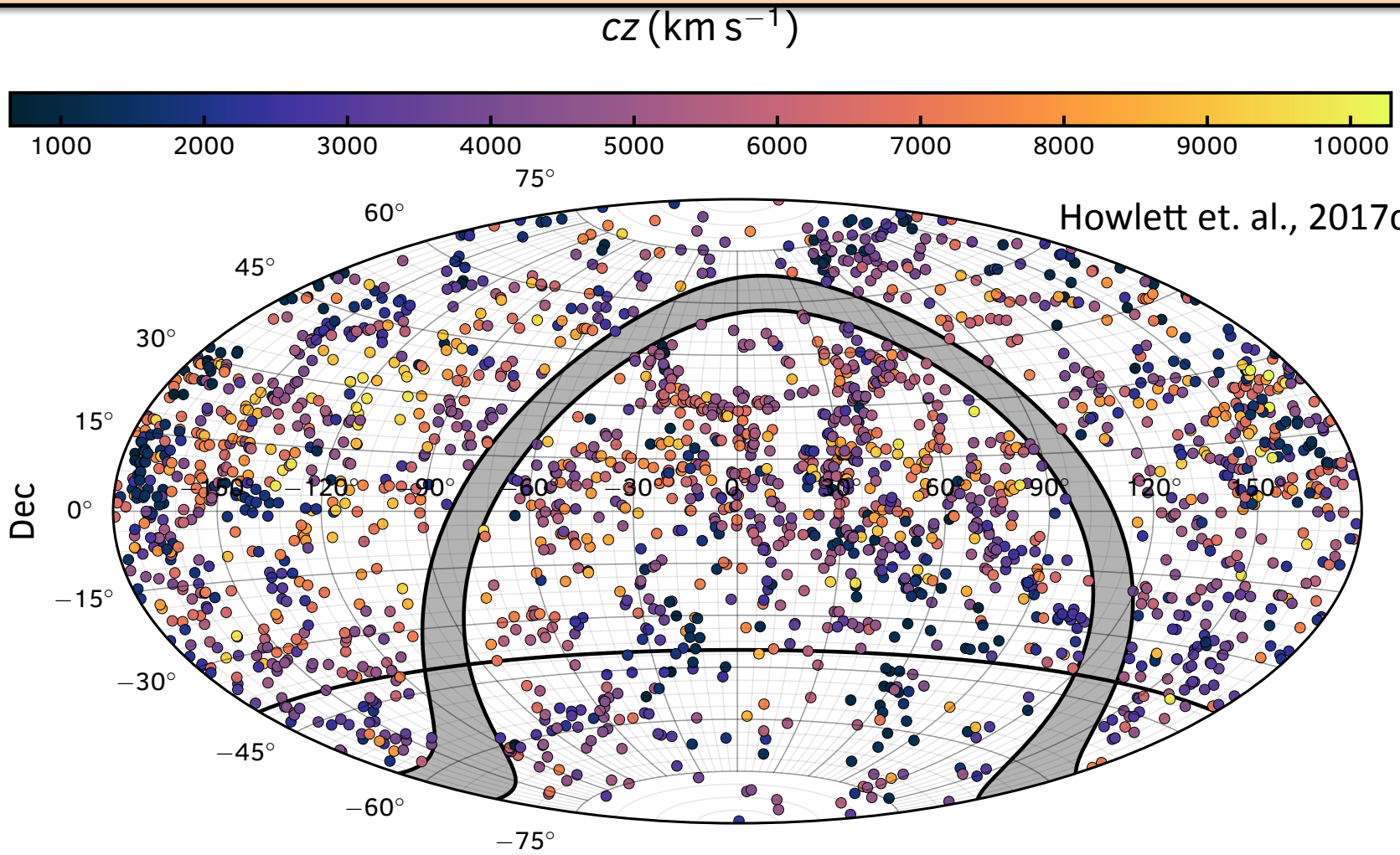
Cullan Howlett

CAASTRO PDRA @ International Centre for Radio Astronomy Research, UWA, Perth.

On behalf of Fei Qin, Lister Staveley-Smith, Tao Hong and the 2MTF team.

The 2MTF survey

The completed 2MTF survey consists of 2,062 galaxies with Tully-Fisher based peculiar velocities



The 2MTF survey

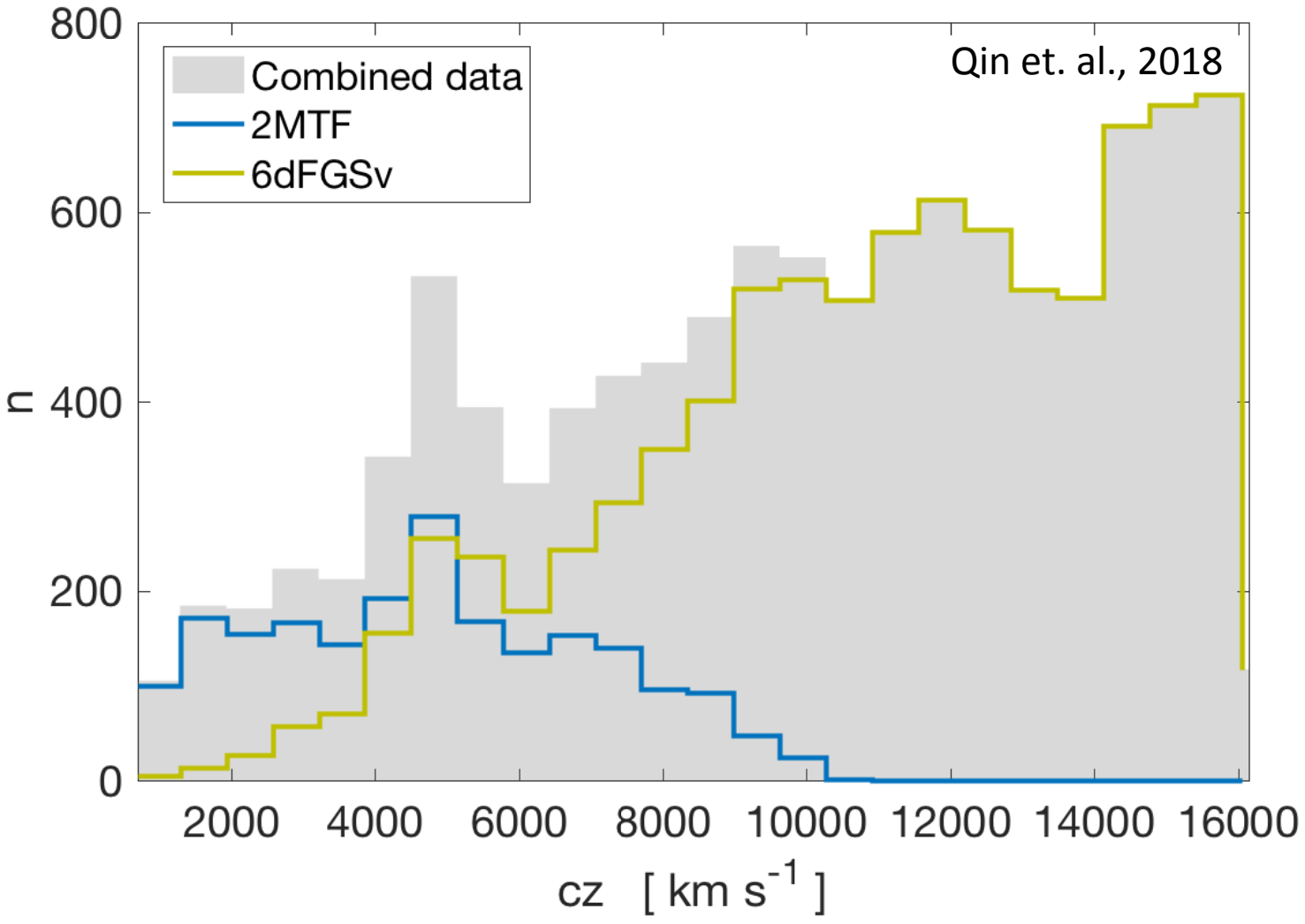
Targets were selected from the 2MASS redshift survey with K<11.25 and cz<10,000 km/s and axis ratio b/a<0.5 -> 6,600 targets

HI width measurements were obtained from a combination of archival data, the ALFALFA 100% dataset , and new Parkes and GBT observations.

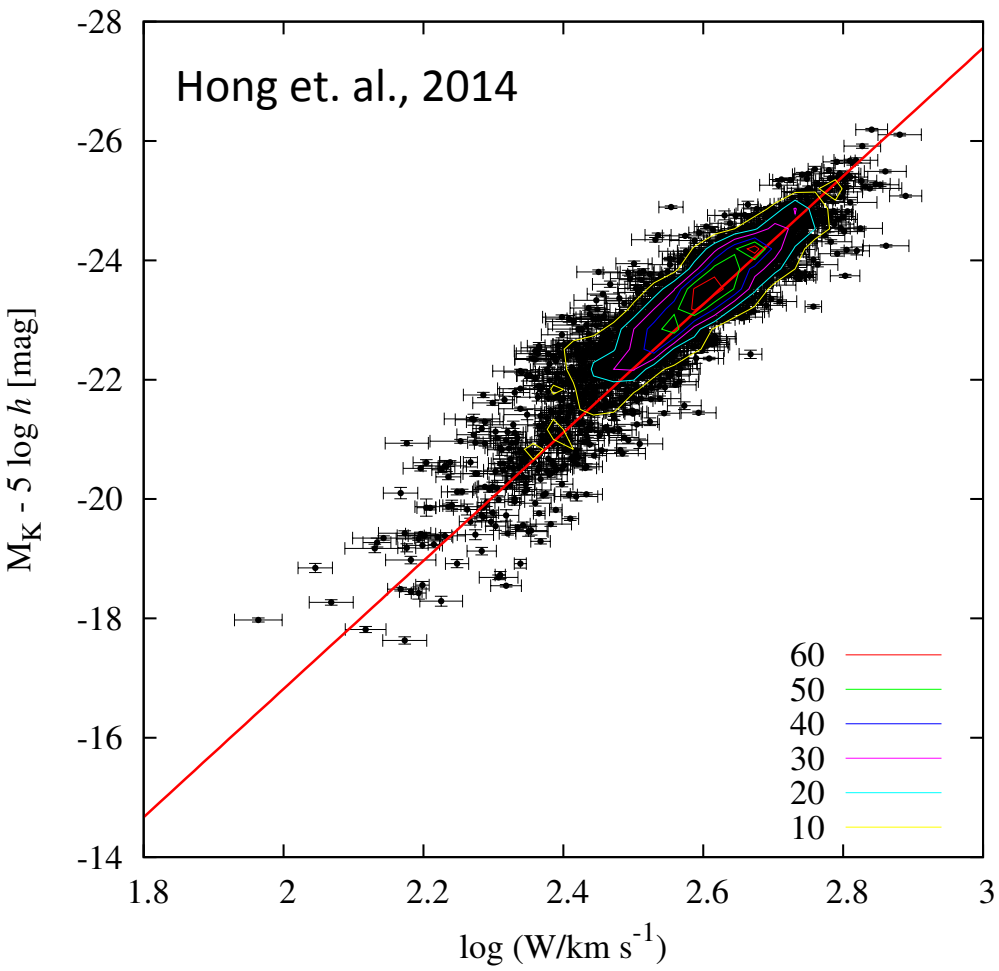
Only high-quality observations with S/N>5 and relative error <10% were used -> 2,062 objects in total each with HI widths and J, H, K imaging.

For objects with multiple HI observations we preferentially take more recent measurements, i.e., ALFALFA/Parkes/GBT.

The 2MTF survey



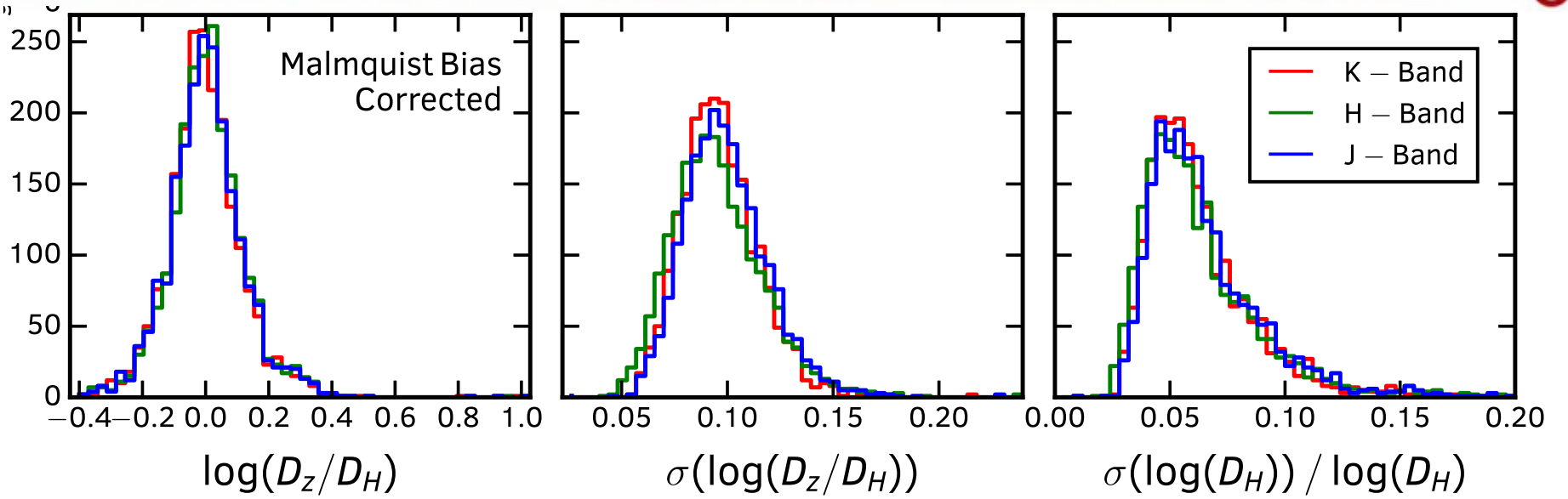
The 2MTF survey



Template TF relations were fit using an additional 888 cluster galaxies (Masters et. al., 2008)

Corrections for homogenous Malmquist bias were included by estimating the completeness using the target and observed K-band luminosity functions and reweighting the measured 'log-distance ratio' (Springob et. al., 2015)

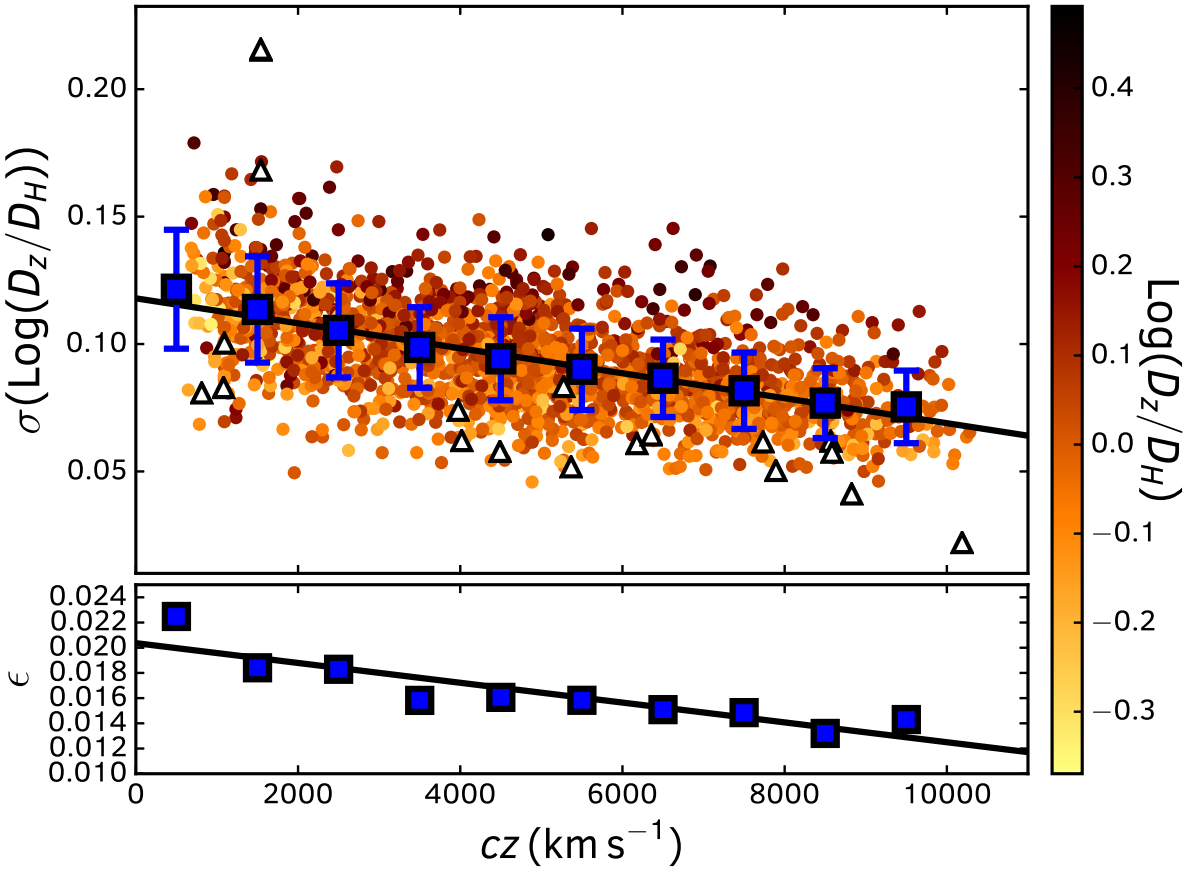
The 2MTF survey



Howlett et. al., 2017c

The 2MTF survey

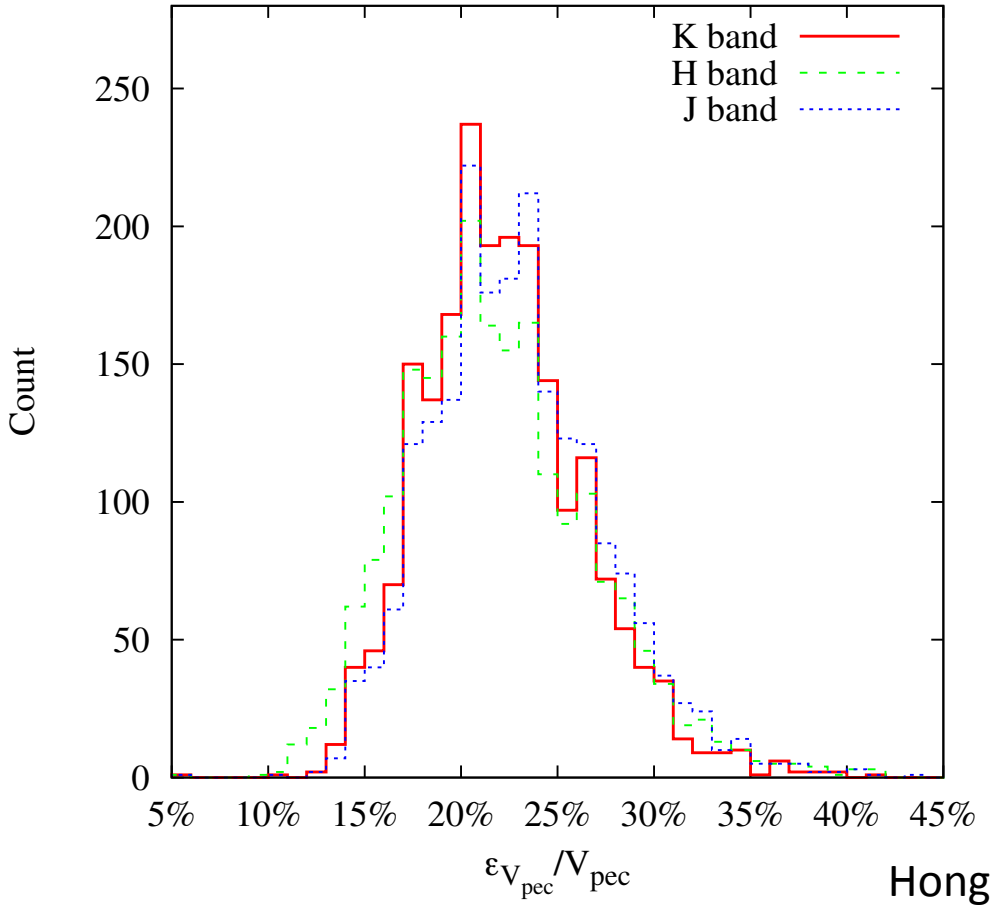
Howlett et. al., 2017c



We mainly work with Log-distance ratios as these have Gaussian errors, but can be easily translated into velocities.

The 2MTF survey

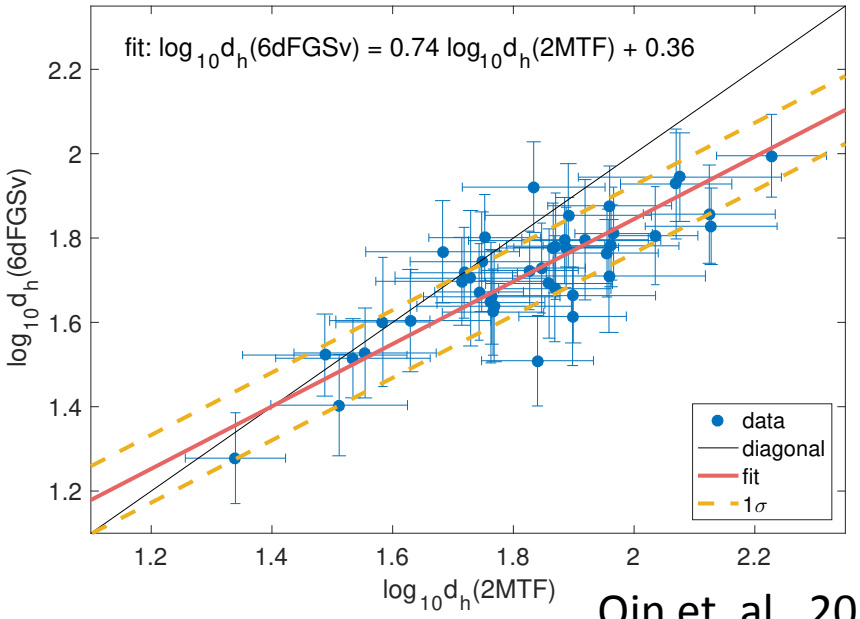
Typical velocity errors are only ~22%!



We have performed a number of comparisons with 6dFGSv and CosmicFlows 3

Hong et. al., in preparation

Comparisons – 6dFGSv

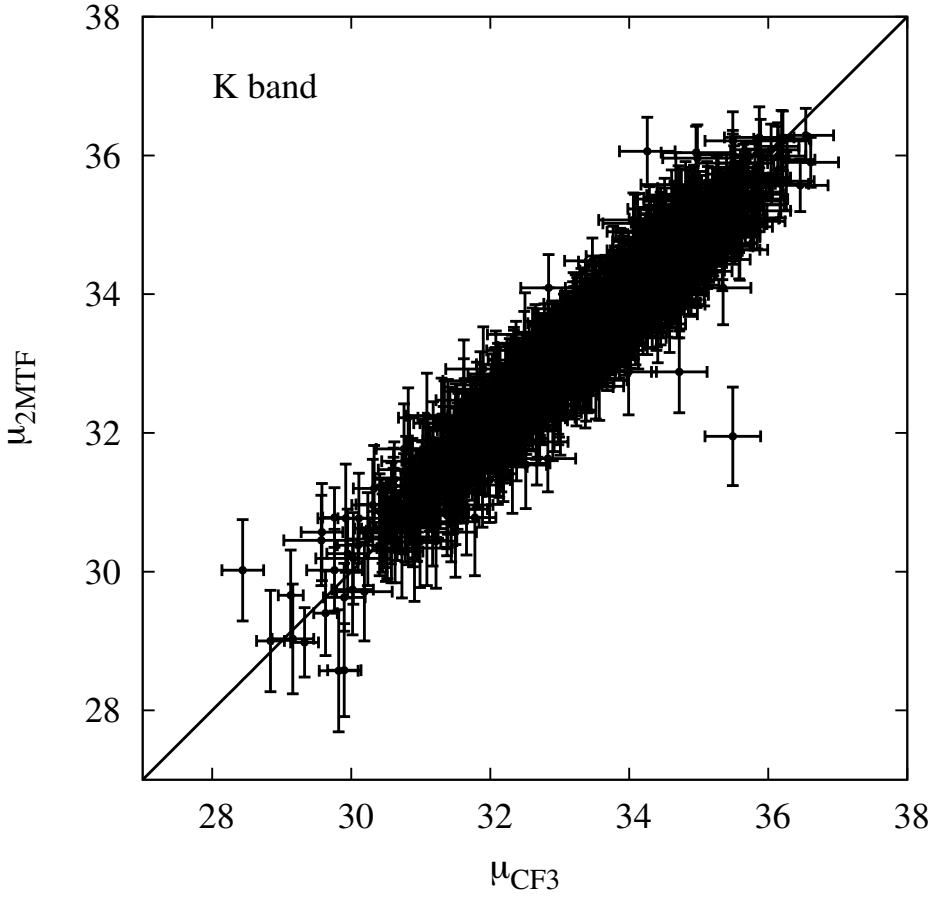


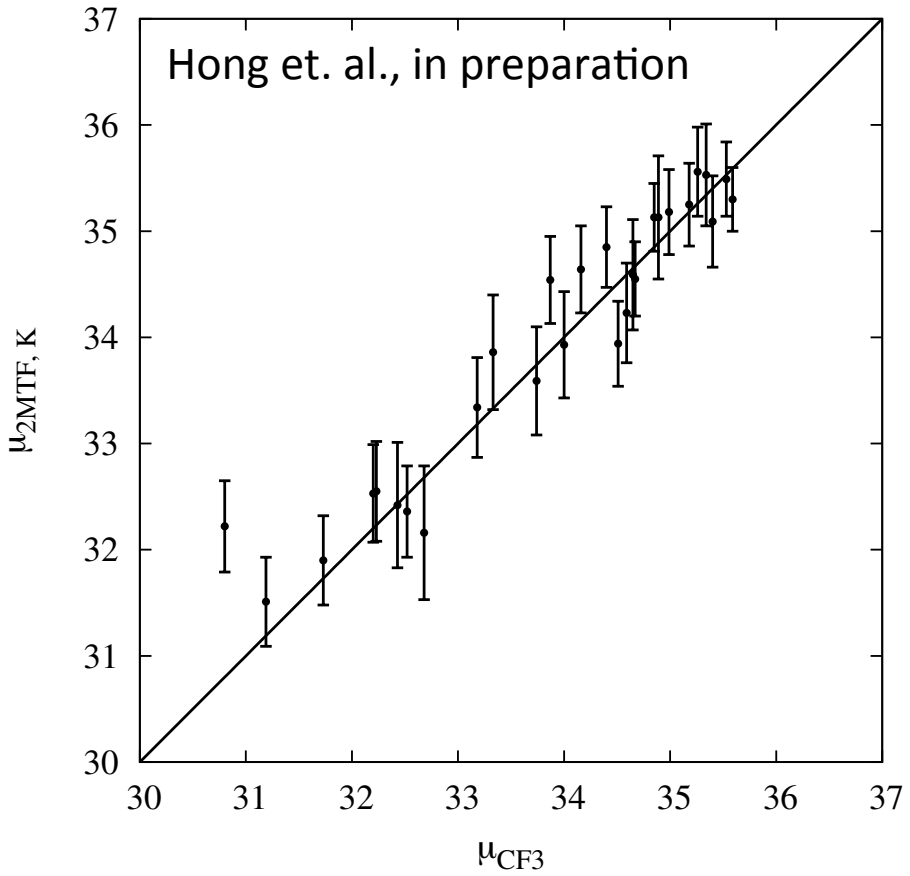
Qin et. al., 2018

Comparison of objects in 2MTF and 6dFGSv gives a few (biased) objects. Too 'spiraly' for 6dFGSv?

A better comparison using groups containing objects from both surveys shows excellent consistency

Comparisons – CF3





…as do the 1,117 common galaxies and 28 SN1a from CF3 data.

Science with 2MTF

With the final 2MTF data we have:

- Data release and chi^2 minimization Bulk Flow (Hong et. al., in preparation)
- Velocity power spectrum measurements (Howlett et. al., 2017c)
- Combination with 6dFGSv and new bulk flow estimator (Qin et. al., 2018)
- Combination with Cosmic Flows 3: bulk flow and shear moments (Qin et. al., submitted)
- Momentum and Density power spectrum measurements. Not in this talk but ask me later! (Howlett et. al., in preparation, Qin et. al., in preparation)

Velocity power spectrum

We used the correlations between 2MTF velocities to constrain the growth rate of structure at z=0:

On linear scales at z=0

$$\nabla \cdot \boldsymbol{v}(\boldsymbol{x}, a) = -aH(a)f(a)\delta(\boldsymbol{x}, a)$$

$$P_{vv}(k) = \left(\frac{H_0 f(k)}{k}\right)^2 P_{\theta\theta}(k).$$

Strong predictions from GR

Velocity power spectrum

We can estimate this using linear theory. Galaxy velocities should be drawn from a multivariate Gaussian with variance related to the velocity power spectrum.

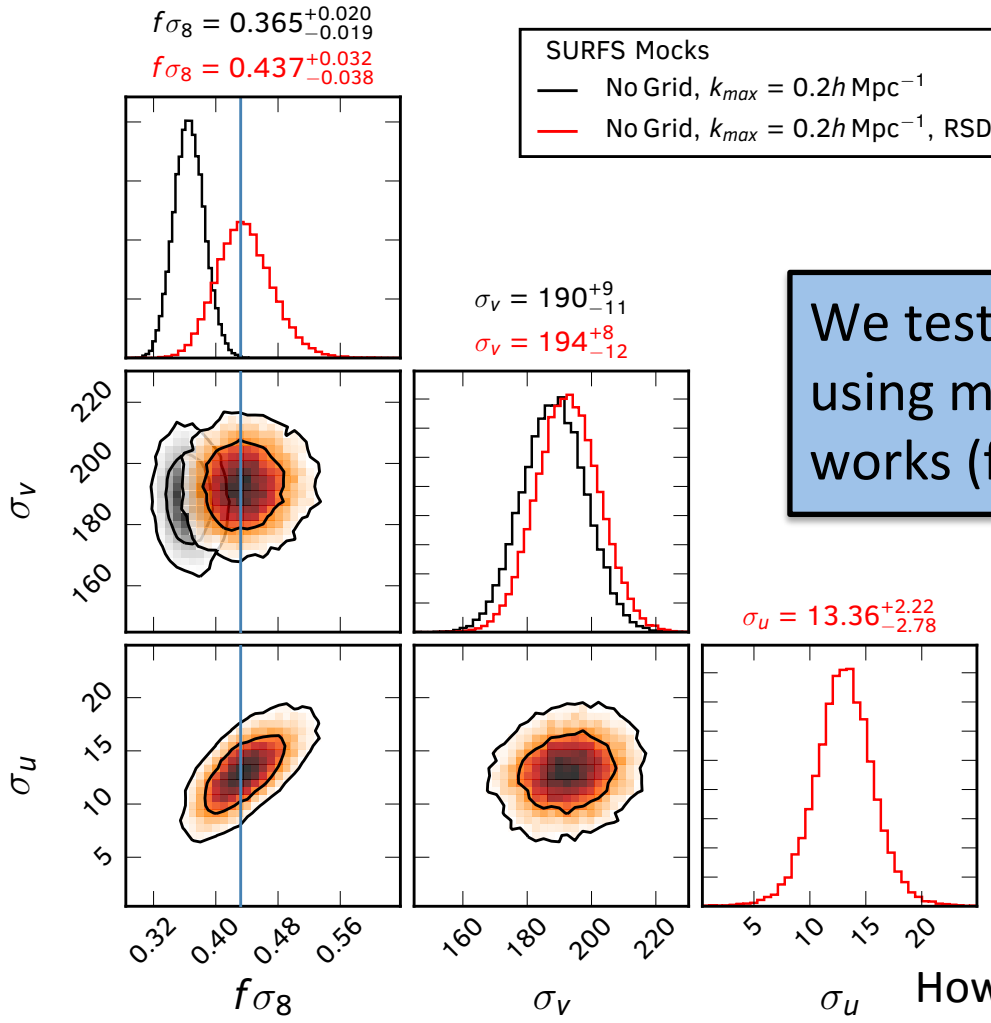
$$\mathcal{L}(\boldsymbol{\theta}) = \frac{1}{2\pi|\mathbf{C}(\boldsymbol{\theta})|}\exp\left(-\frac{1}{2}\boldsymbol{s}^T\mathbf{C}(\boldsymbol{\theta})^{-1}\boldsymbol{s}\right)$$

$$C_{ij}(\boldsymbol{x}_i, \boldsymbol{x}_j) = \frac{H_0^2}{2\pi^2}\int dk f^2(k) P_{\theta\theta}(k, a) W(\boldsymbol{x}_i, \boldsymbol{x}_j, k),$$

Measured velocities

Window Function

2MASS Tully-Fisher survey



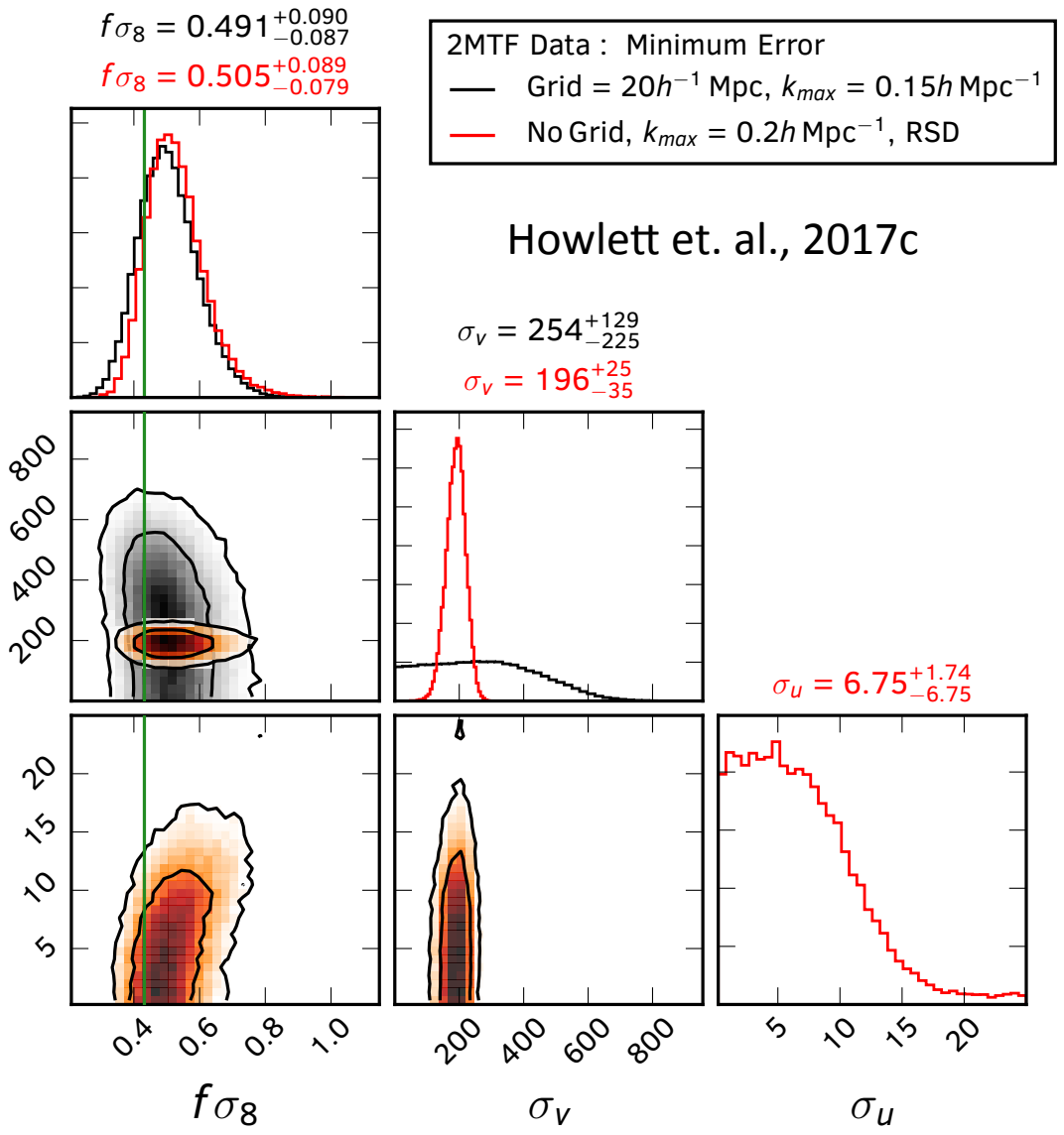
We tested several methods to fit this using mock surveys and confirmed it works (for certain choices).

Howlett et. al., 2017c

Velocity Power Spectrum

Fits to data:

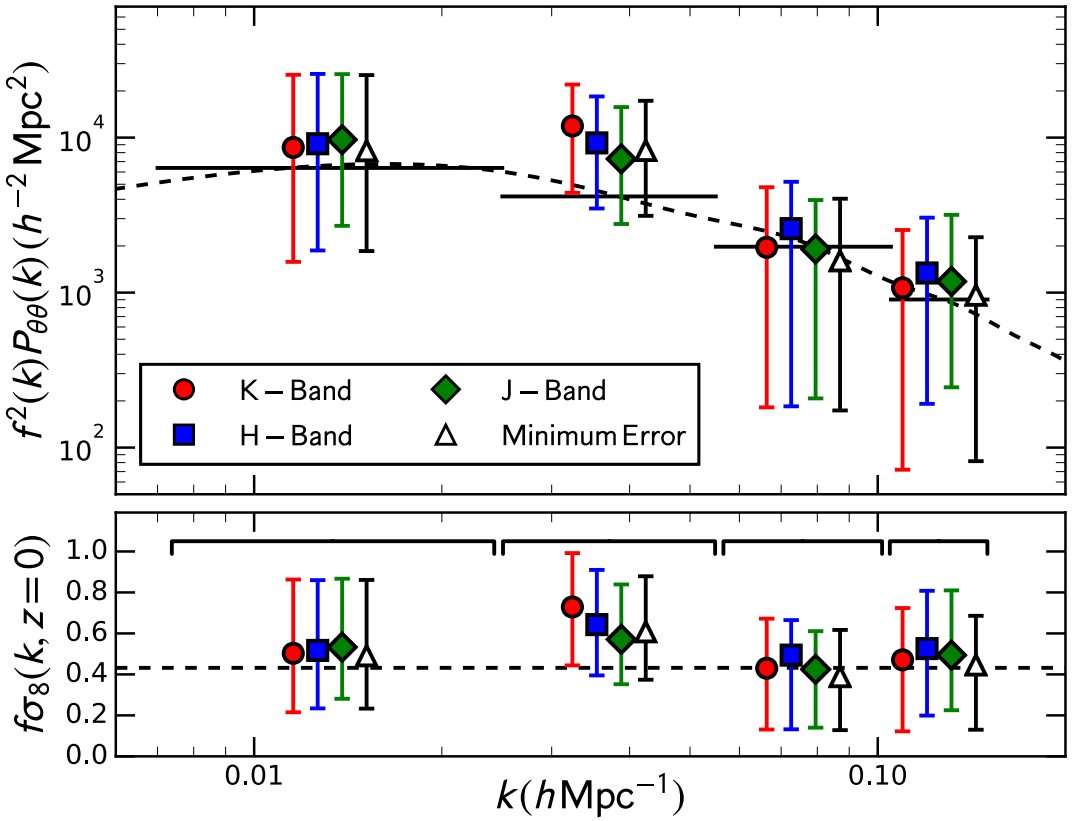
These constraints using 2000 PVs are nearly as good as the 6dFGS RSD constraints with 70,000 objects! And we haven't even included the correlation with density yet (exciting work in progress, ask me later!)



Velocity Power Spectrum

Can also fit in ‘k’-bins:

Howlett et. al., 2017c



Overall, all 2MTF results are consistent with GR.

New bulk flow estimator

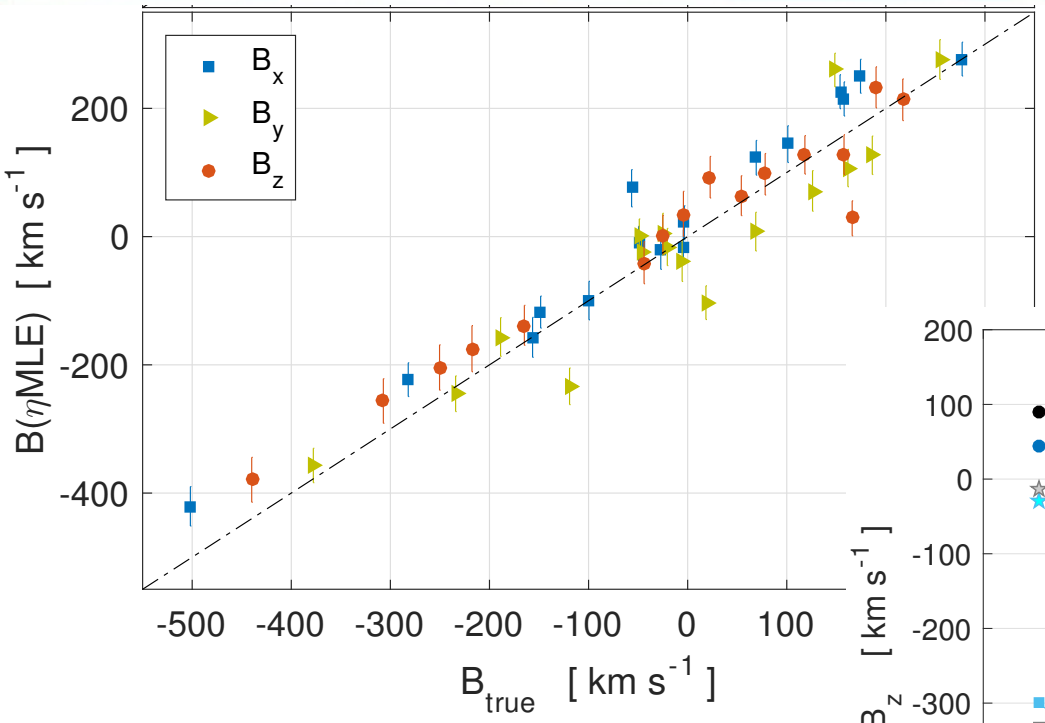
We combined the 2MTF and 6dFGSv data with a Maximum Likelihood method for estimating the bulk flow directly from the log-distance ratios

$$P(\boldsymbol{\eta}|\vec{B}) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi\left(\epsilon_i^2 + \epsilon_{\star,i}^2\right)}} \exp\left(-\frac{1}{2}\frac{(\tilde{\eta}_i(\vec{B}) - \eta_i)^2}{\epsilon_i^2 + \epsilon_{\star,i}^2}\right),$$

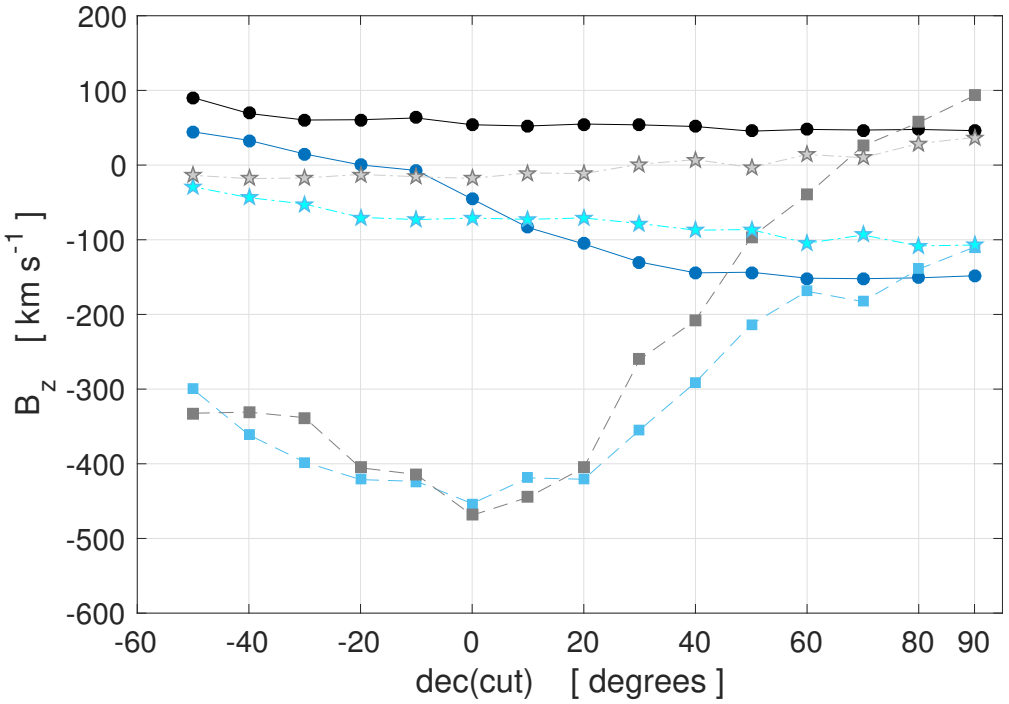
The model log-distance ratio is calculated from a model bulk flow and measured redshifts. We then fit for the model Bulk Flow using MCMC.

Unlike the normal Maximum Likelihood method, this preserves the Gaussianity of the measurement errors and is still fast.

New bulk flow estimator



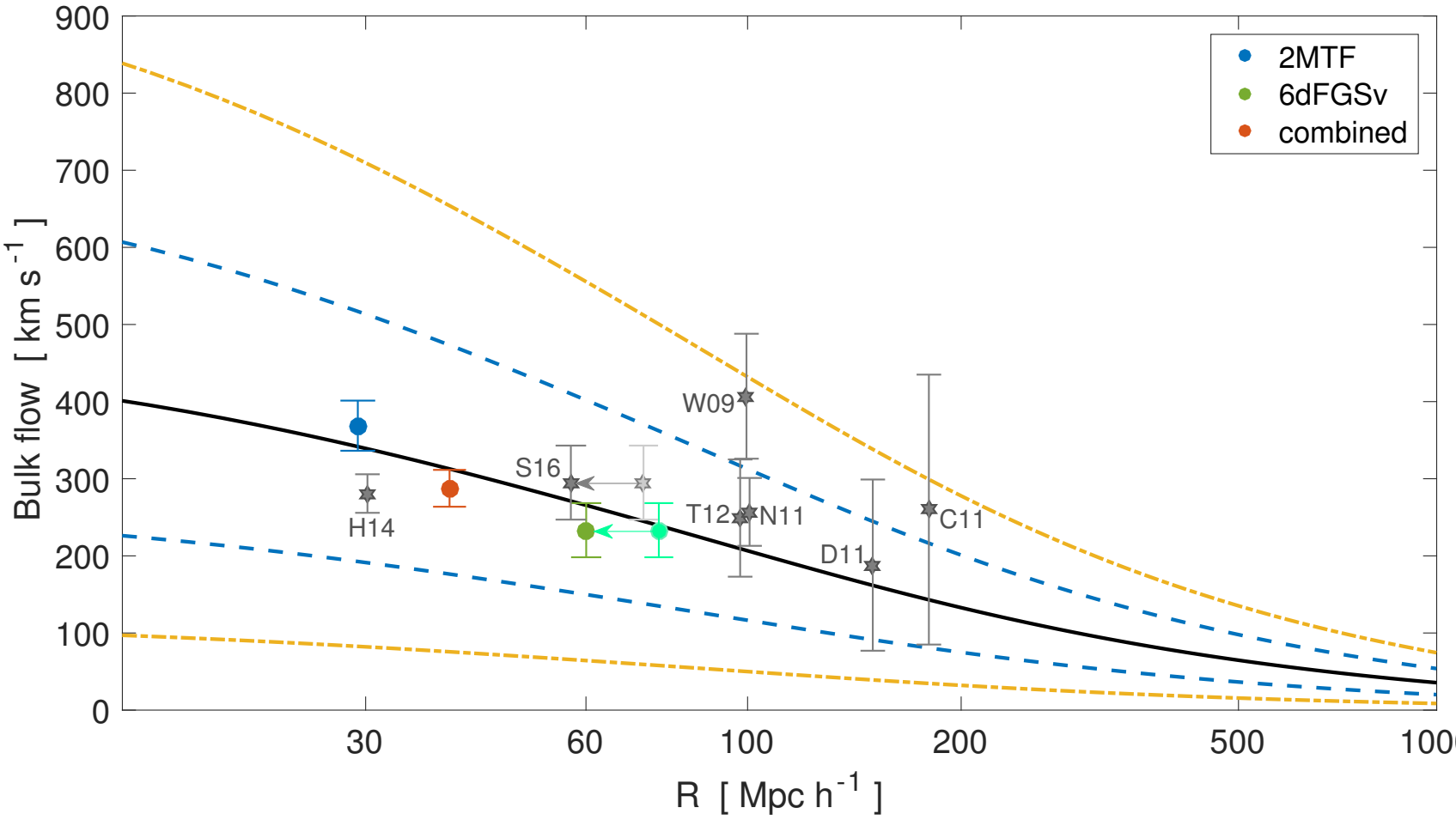
We again used mocks to verify our method was unbiased (for 2MTF)



However, we found a bias in 6dFGSv which was exacerbated by the hemispherical coverage. Motivation for all sky data!

New bulk flow estimator

We were able to correct for this by modifying the magnitude limit for the Malmquist bias correction. However, not the underlying cause?



Cull

The

s

3

Including Shear moments

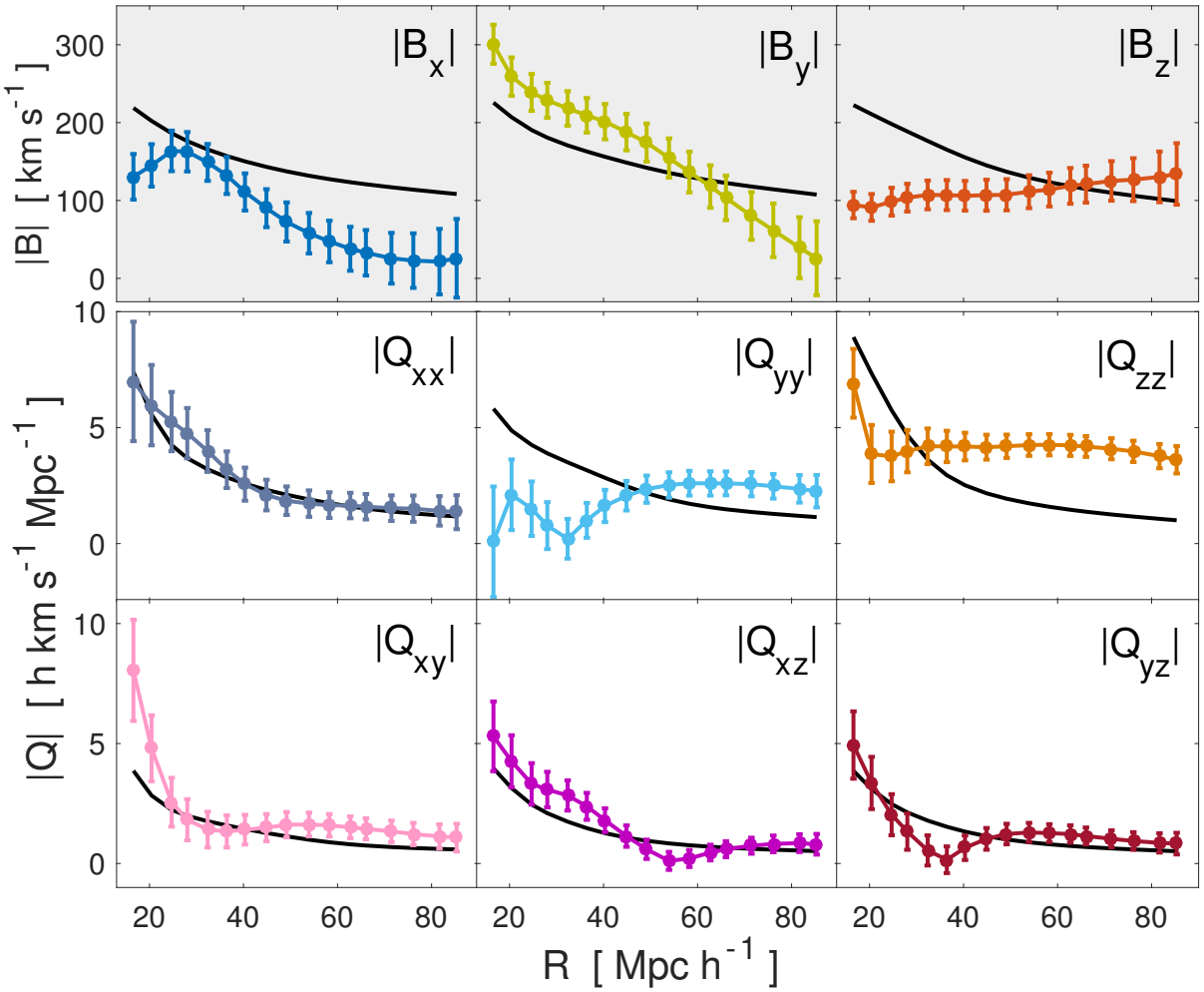
We extended our method to model the shear (quadrupole) components, and included CosmicFlows 3 data. Same as previous MCMC-based estimator, but now model includes bulk flow and shear:

$$d_h = -\frac{cH_0 + (\mathbf{B}\cdot\hat{\mathbf{r}}H_0 + cQ_{ij}\hat{\mathbf{r}}_i\hat{\mathbf{r}}_j)}{2H_0Q_{ij}\hat{\mathbf{r}}_i\hat{\mathbf{r}}_j} + \frac{\sqrt{(\mathbf{B}\cdot\hat{\mathbf{r}}H_0 + cH_0 + cQ_{ij}\hat{\mathbf{r}}_i\hat{\mathbf{r}}_j)^2 + 4cH_0Q_{ij}\hat{\mathbf{r}}_i\hat{\mathbf{r}}_j(cz - \mathbf{B}\cdot\hat{\mathbf{r}})}}{2H_0Q_{ij}\hat{\mathbf{r}}_i\hat{\mathbf{r}}_j}$$

We again verified this works using mock catalogues

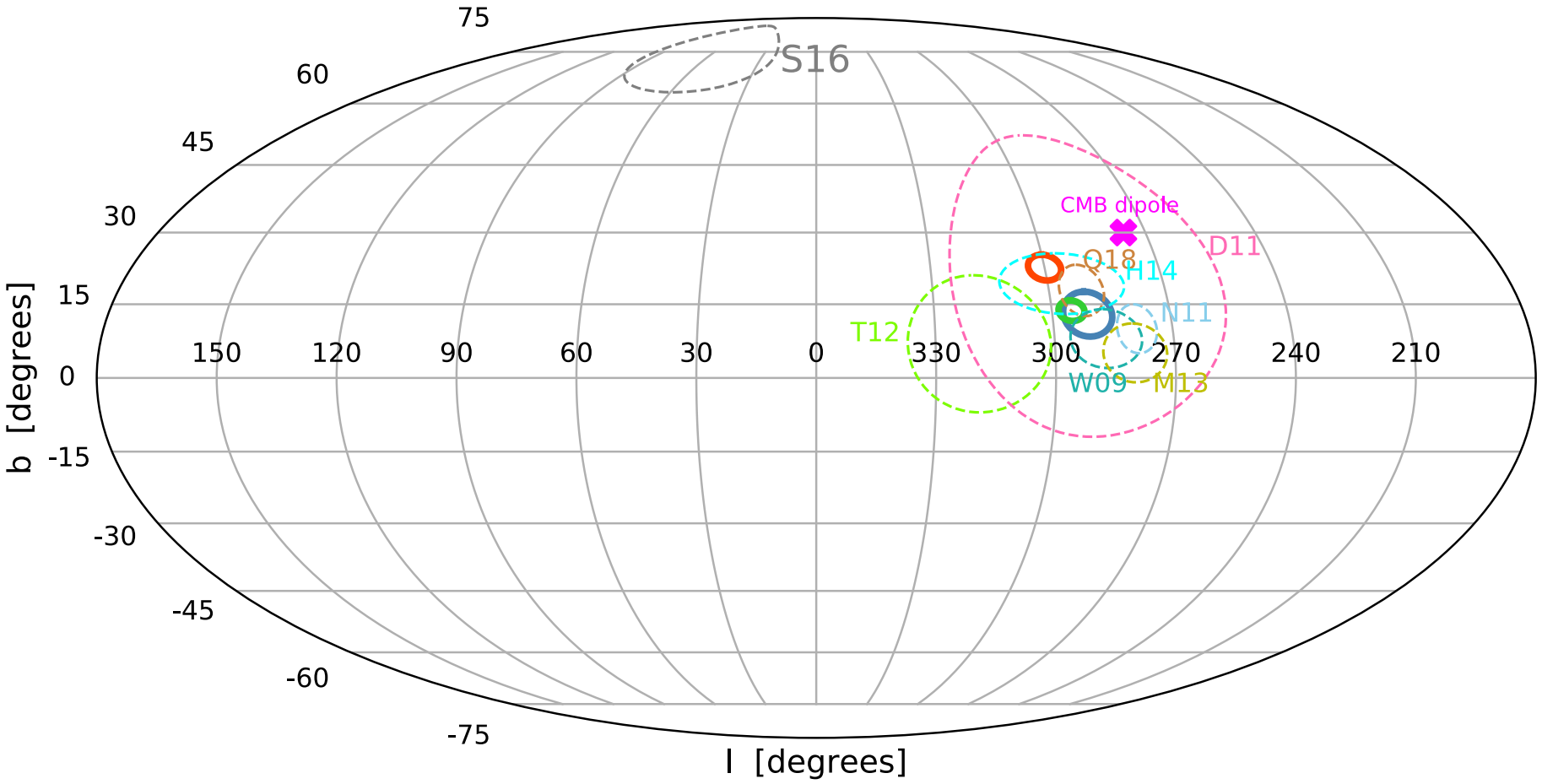
We also weighted the data (and LCDM predictions) to test different depths

Including Shear moments



We found all measurements of bulk flow and shear for the combined 2MTF and CF3 data at all depths to be within the cosmic variance for LCDM

Including Shear moments



Conclusions

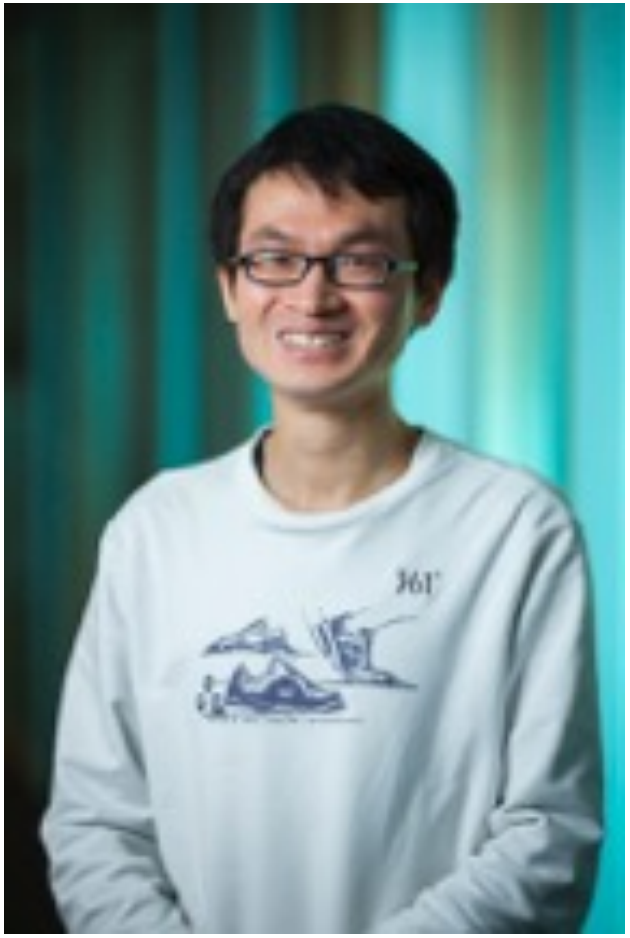
- The 2MASS Tully Fisher survey is now complete!
- The (very nearly) homogeneous sky coverage, well understood selection function and (relatively) small measurement errors make it one of the premier peculiar velocity surveys
- We have used it, alongside improved modelling techniques and other data, to make a number of better measurements at z=0:

See Hong et. al., 2014, Howlett et. al., 2017c, Qin et. al., 2018 for more info.

Look out for future Hong; Howlett or Qin papers on ArXiv: Final Data Release, Bulk Flow and Shear moments, Momentum Power Spectrum.

Conclusions

Finally, and most importantly, Fei Qin will be on the job market soon, so let him or me know of any opportunities!



Momentum P(k)

We are using the excellent data quality of 2MTF to test a new method for extracting cosmology from PV surveys. We can measure the 'momentum' (mass-weighted velocity) power spectrum from the velocities in the same way as a galaxy redshift survey

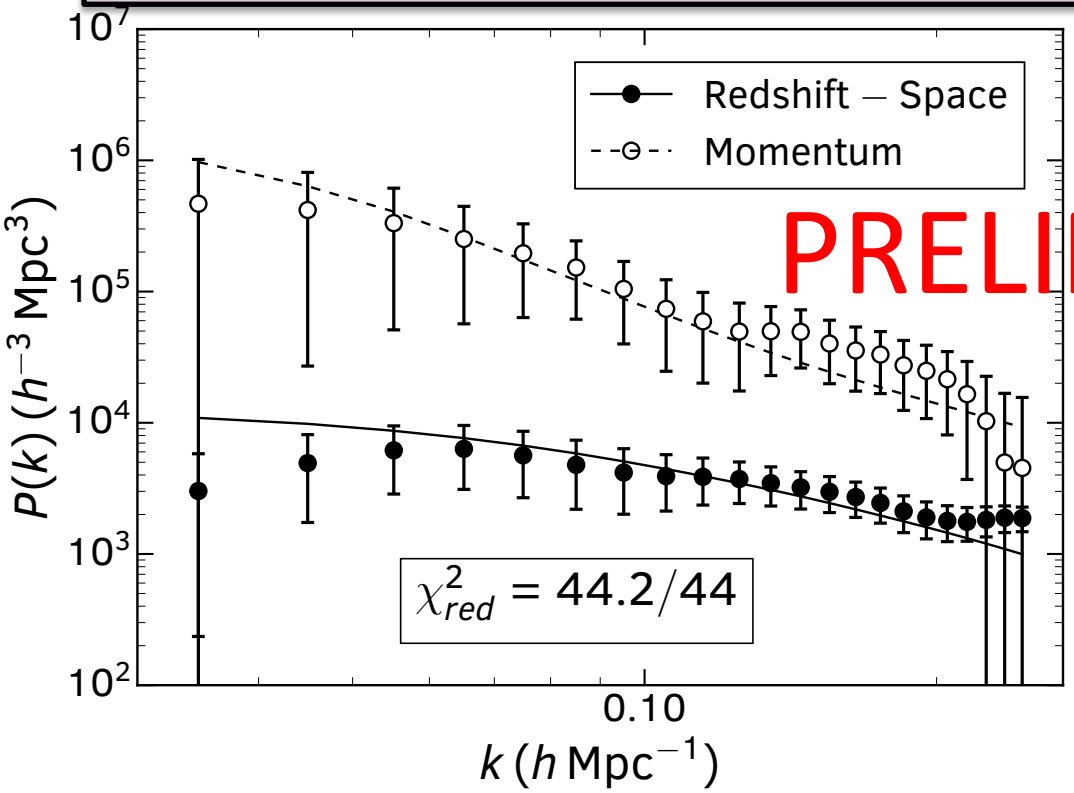
$$\widehat{P_\ell^p}(k) = |F_\ell^p(k)|^2 - N_\ell^p(k)$$

$$\langle |F_\ell^p(k)|^2 \rangle = \frac{(2\ell+1)}{A^2} \int \frac{d\Omega_k}{4\pi} \left[\sum_{\ell'} \int \frac{d^3k'}{(2\pi)^3} P_{\ell'}^p(k') G(\boldsymbol{k}-\boldsymbol{k}') S_{\ell,\ell'}(\boldsymbol{k},\boldsymbol{k}') + N_\ell^p(\boldsymbol{k}) \right]$$

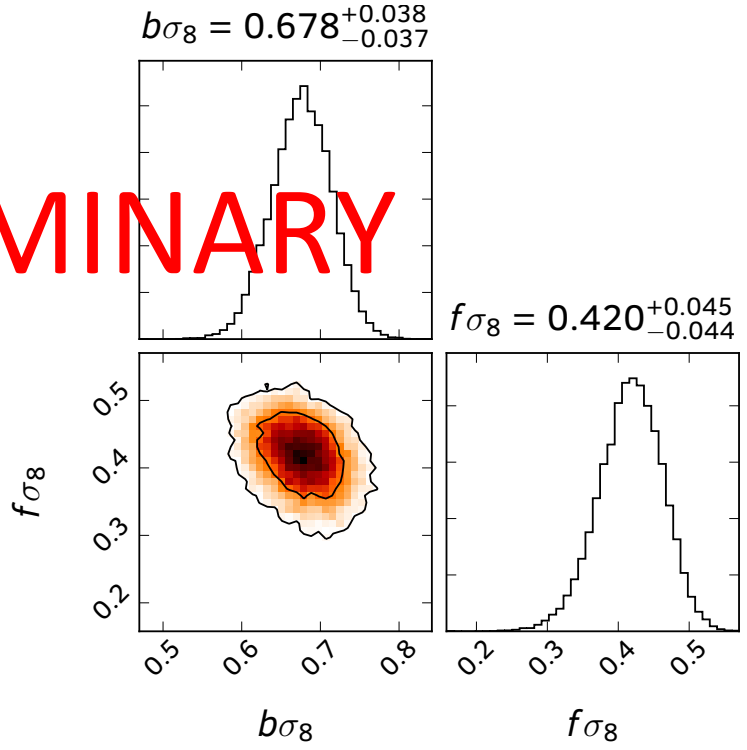
This allows us to use methods developed for RSD measurements (tried and tested over 20 years!) on PV surveys

Momentum P(k)

We can then easily combine density and velocity field measurements



PRELIMINARY



Preliminary 2MTF measurements surpass 6dFGS RSD constraints!