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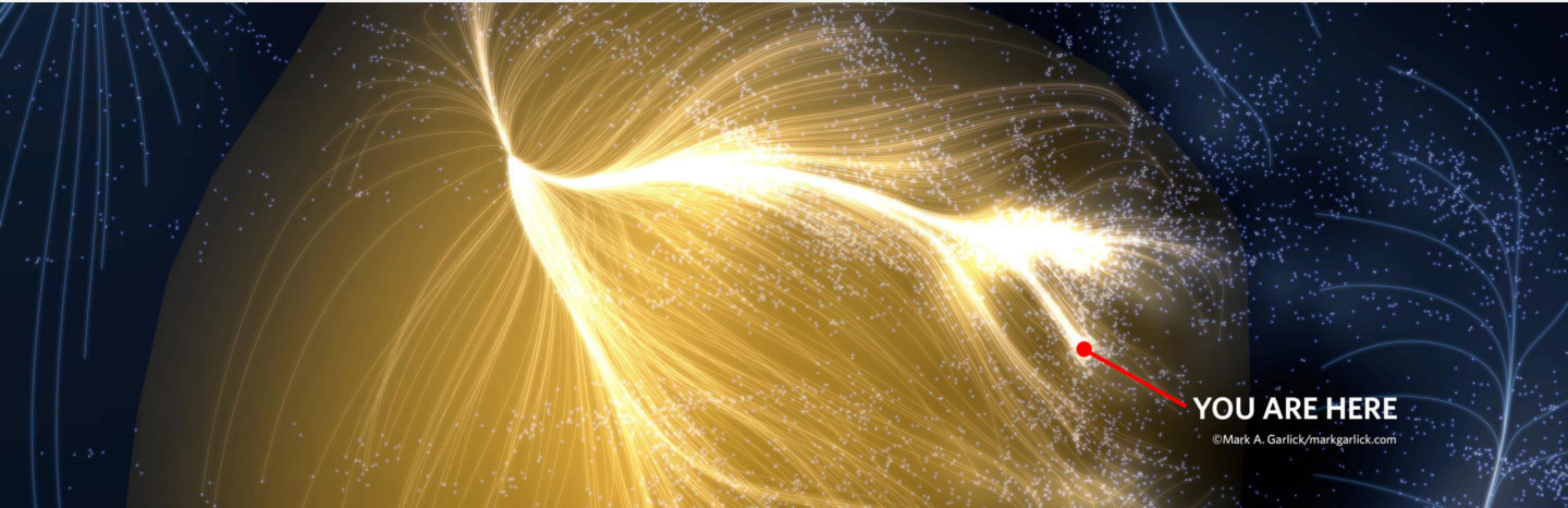
Cosmology with peculiar velocity surveys

Cullan Howlett



Contents

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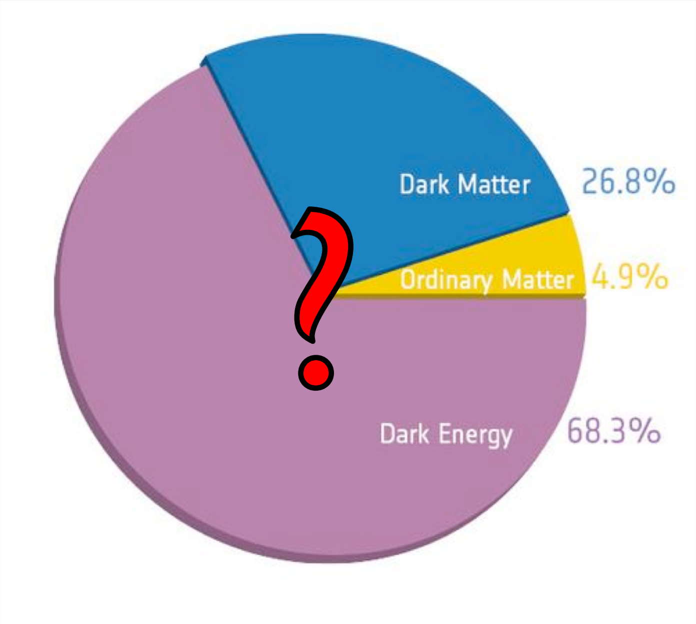
Direct measurements of galaxy peculiar velocities allow us to test gravity in the nearby Universe, and improve over standard clustering techniques.

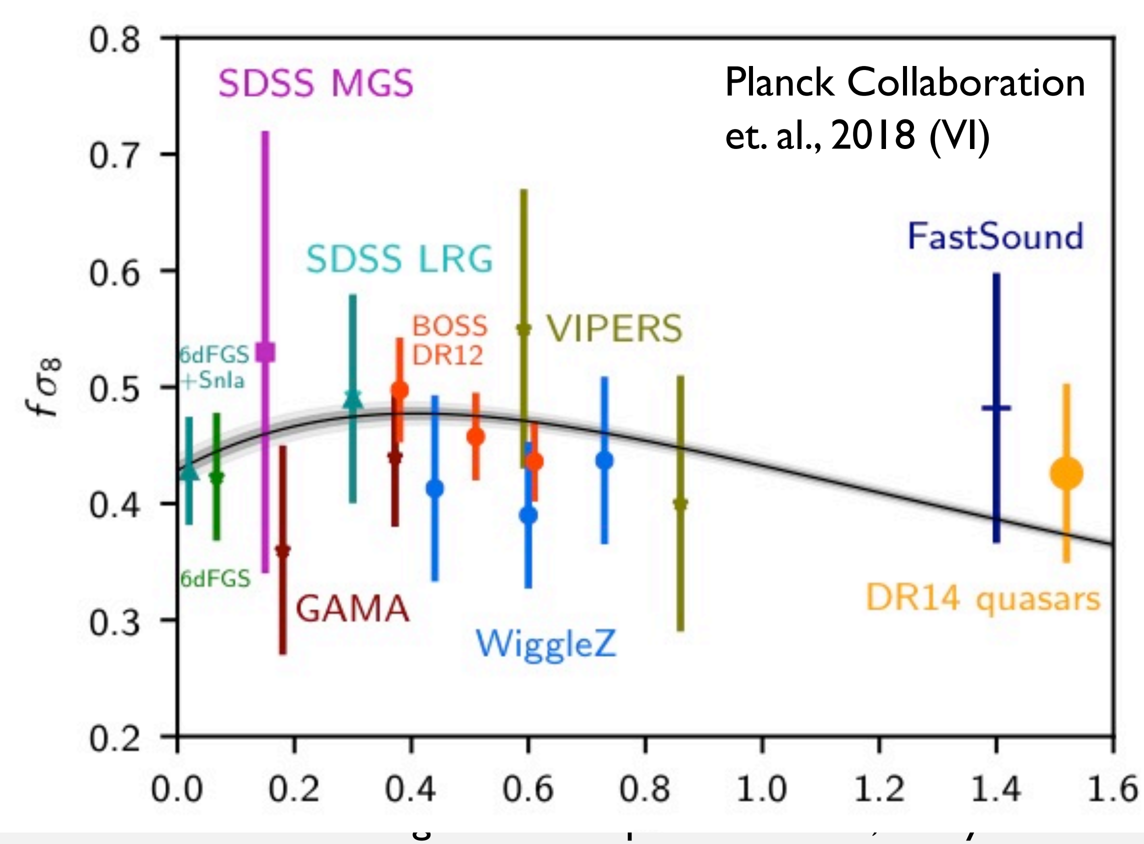
- How do we measure peculiar velocities?
- How can they be used for cosmology?
  - Results using current data
- Forecasts for future data.

Cosmic conundrum



Are the dark components of our Universe an exotic particle/field or a modification to gravity?

A common way to explore this is to measure the "growth rate of structure"



The growth rate of structure

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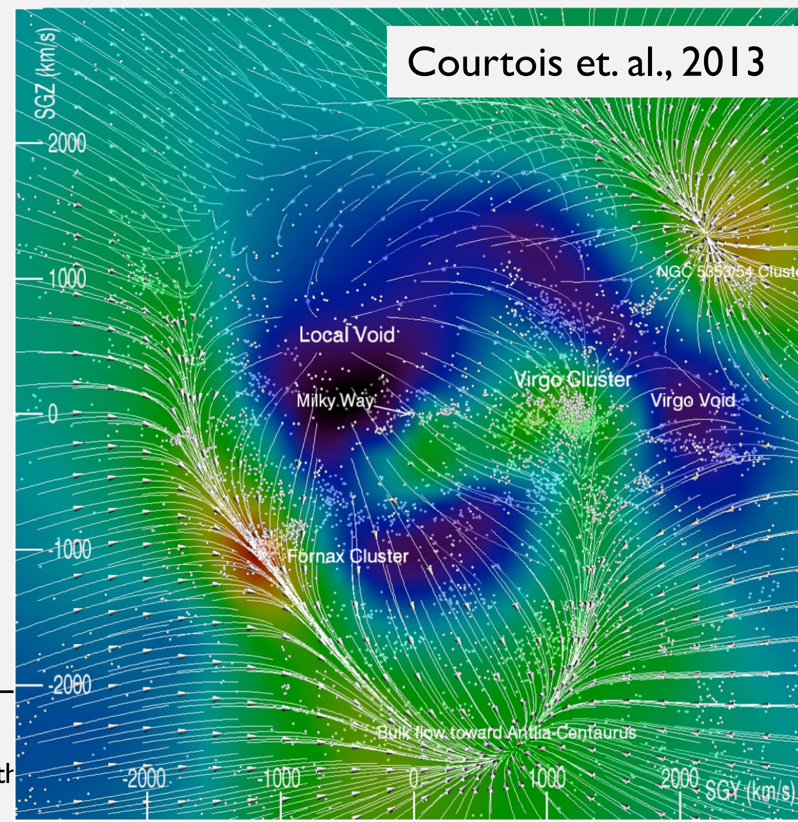
General Relativity (GR) gives strong predictions for the growth rate

- Evolves only with matter density
- Scale-independent (mostly...)

$$f(a) \approx \Omega_m^{0.55}(a)$$

Peculiar velocities are sourced by gravity and so offer a novel way to test this and confirm/falsify GR

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

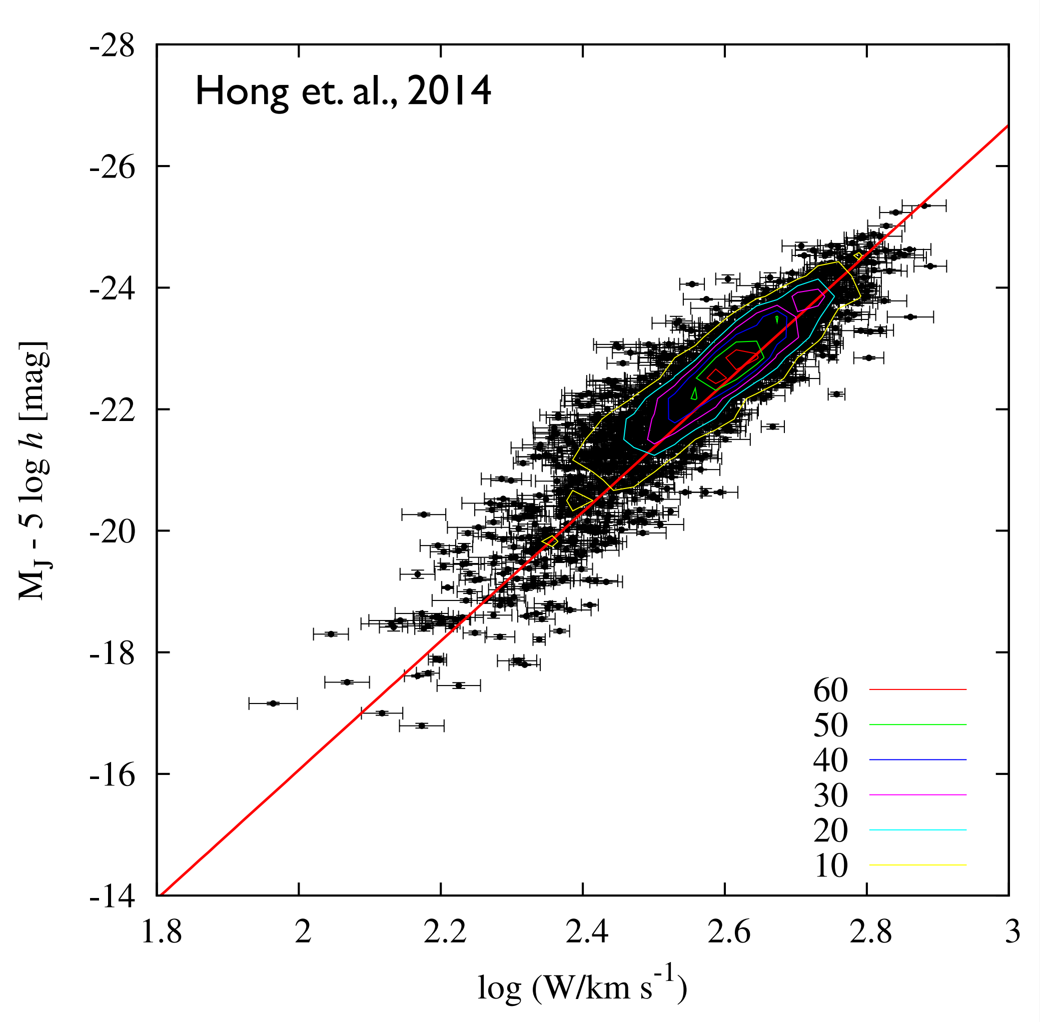


Courtois et. al., 2013

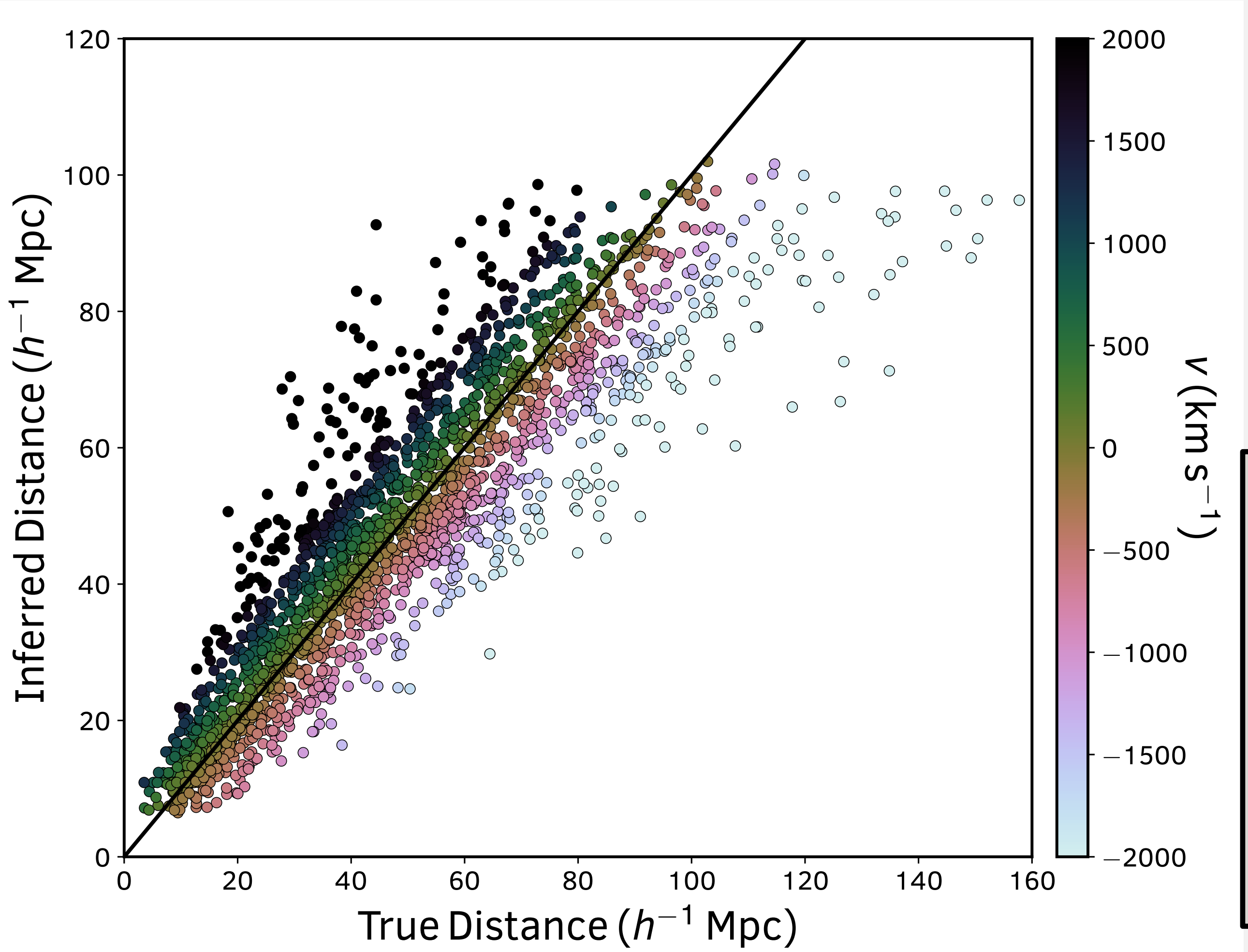
Peculiar Velocity Measurements

Peculiar velocities can be inferred from empirical distances and an observed redshift.

They are a direct measure of matter field, independent of galaxy bias and can be combined with redshift surveys to overcome cosmic variance.



Empirical Distance Measurements



Currently limited by small numbers and intrinsic scatter.

Around ~20,000 total PV measurements, but with varying selection functions and reliability

Empirical Distance Measurements

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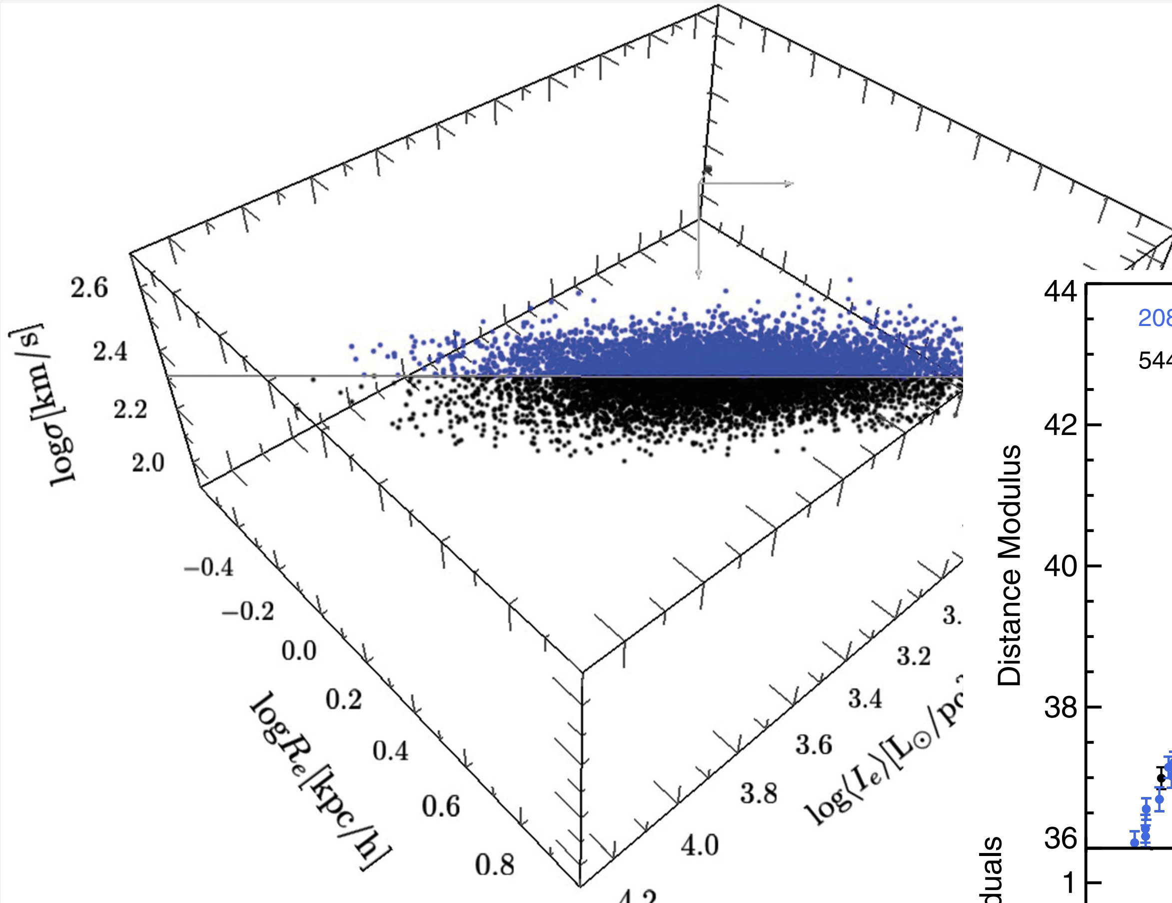
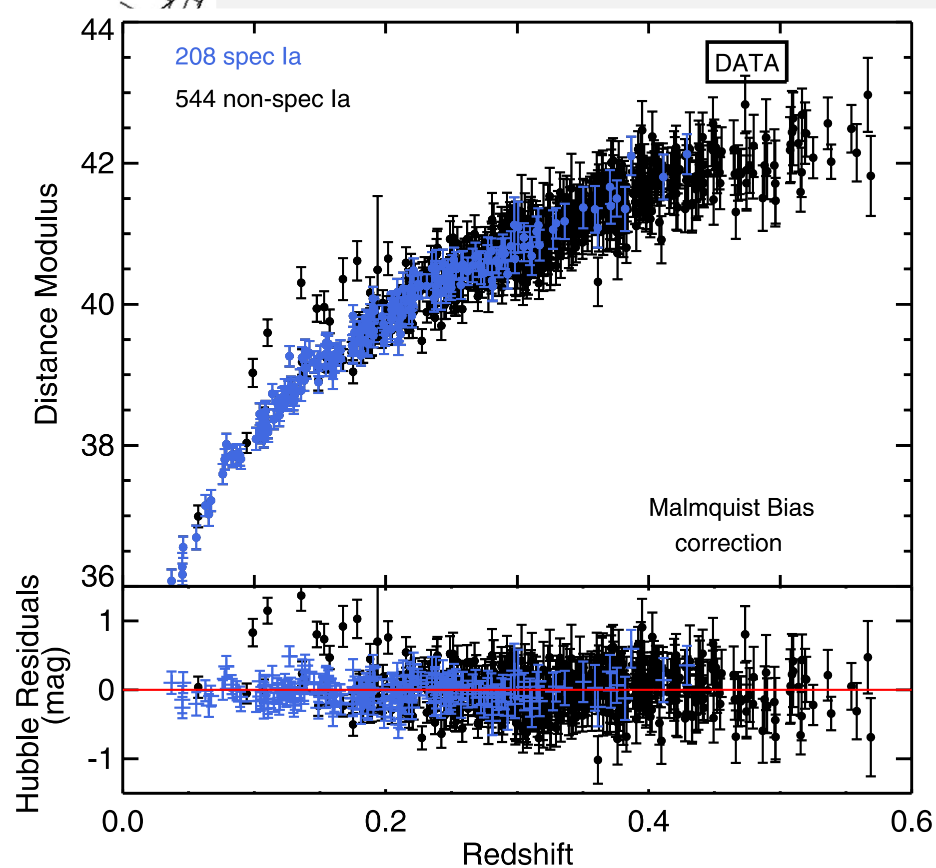


Campbell et. al., 2013



Magoulas et. al., 2012

Using PVs for cosmology

- Look at large scale moments of the velocity: Bulk Flow (Dipole), Shear (Quadrupole), etc.,
- Reconstruct the dark matter density field from the PVs and infer matter power spectrum.
- Use redshifts/density field to reconstruct the velocities and compare to PV measurements.
- Compute the clustering of the redshifts and PVs: Correlation function/power spectrum

On linear scales at z=0

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

Measured by PVs ($P_{vv}(k)$)

Calculate from density/theory ($P_{\theta\theta}(k)$)

Using PVs for cosmology

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- Look at large scale moments of the velocity: Bulk Flow (Dipole), Shear (Quadrupole), etc.,
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On linear scales at z=0

Please talk to me for more details on **other** methods

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

Measured by PVs

Calculate from density/theory

Velocity Correlations

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First method: look at the exact distribution of peculiar velocities as a function of separation and compare to theoretical covariance matrix

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

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

Measured velocities

Cosmology

Survey geometry

Doesn't give you a "measurement" of the clustering, but allows you to maximise the likelihood of a given cosmology.

Velocity Correlations

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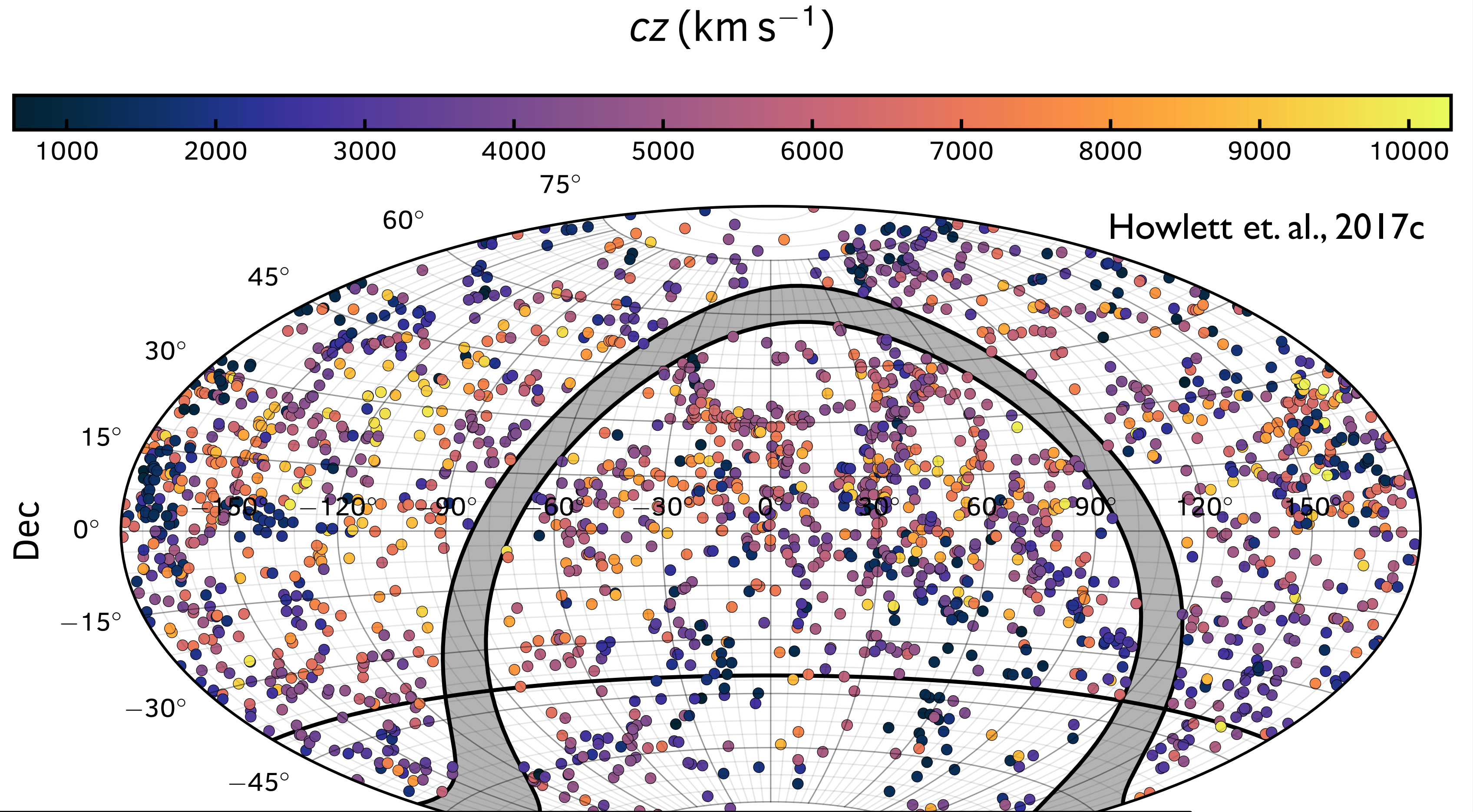
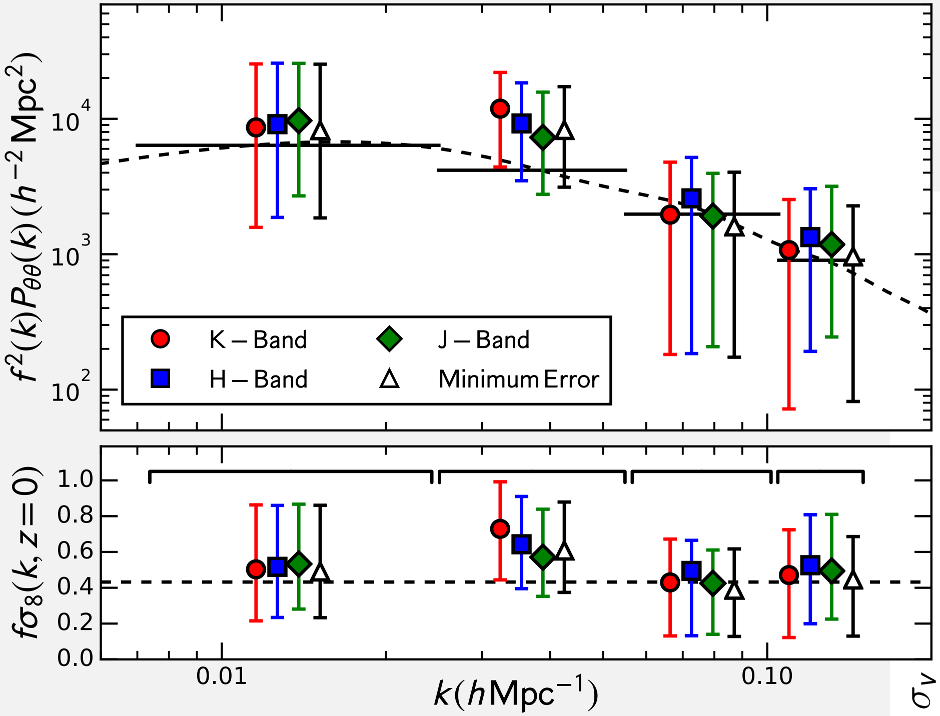
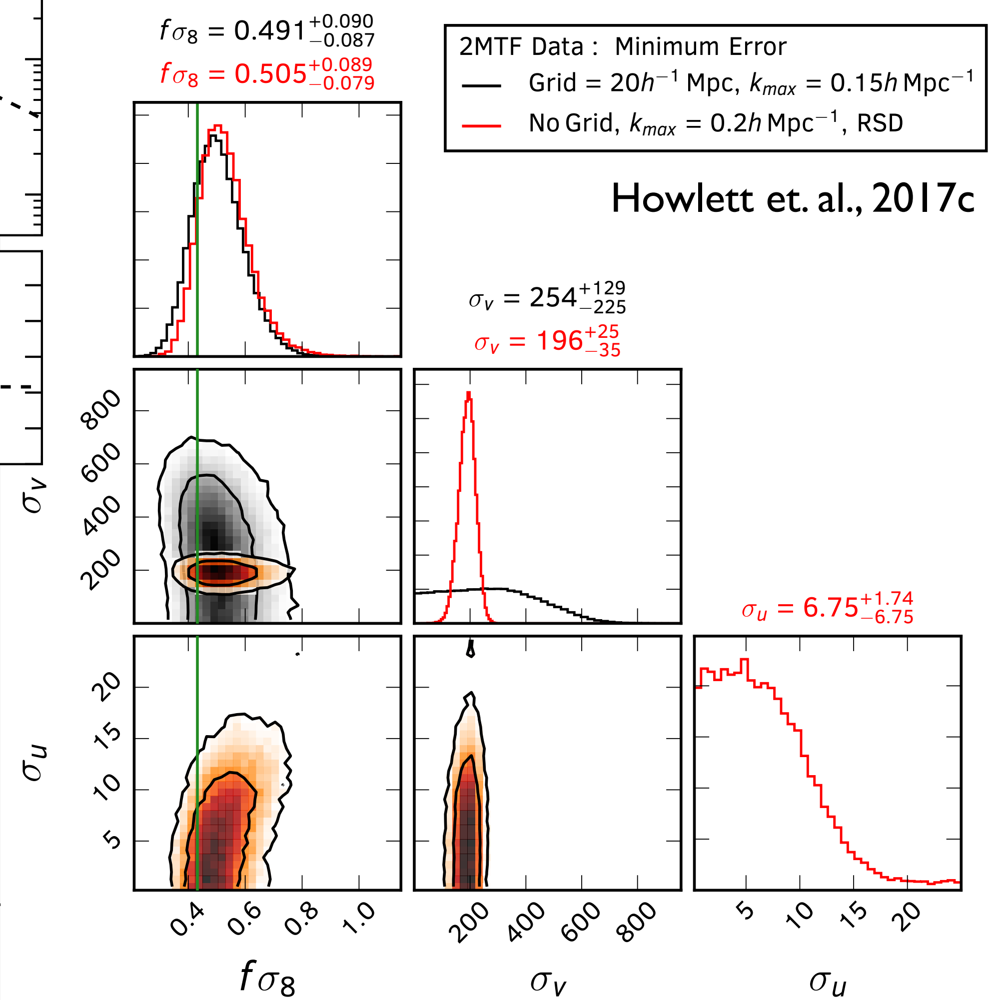


Applied to the 2,062 PVs in 2-Mass Tully-Fisher survey

Velocity Correlations





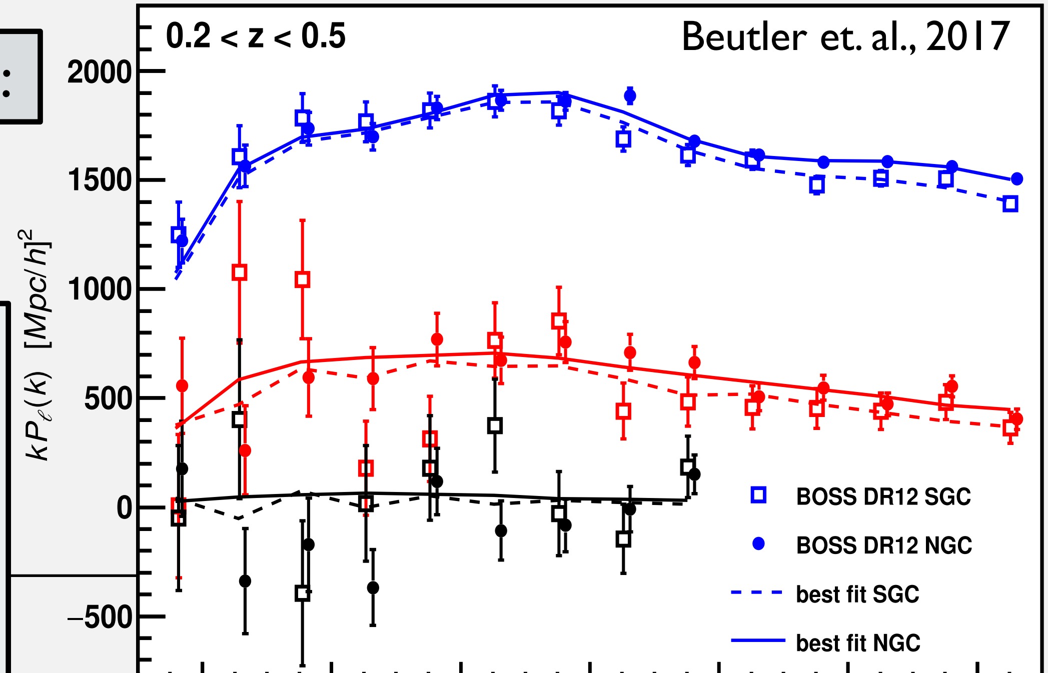
We find no scale-dependence on the growth rate. Our constraints are only ~1.5x worse than the 6dFGS RSD constraints (which use 70,000 objects).

Momentum Power Spectrum

Second method: Compute the anisotropic power spectrum in the same way as for large scale structure surveys at higher redshift:

- Grid the data on a regular grid
- Multiply by each line-of-sight vector
- Fourier transform
- Count the power in each cell and spherically average.

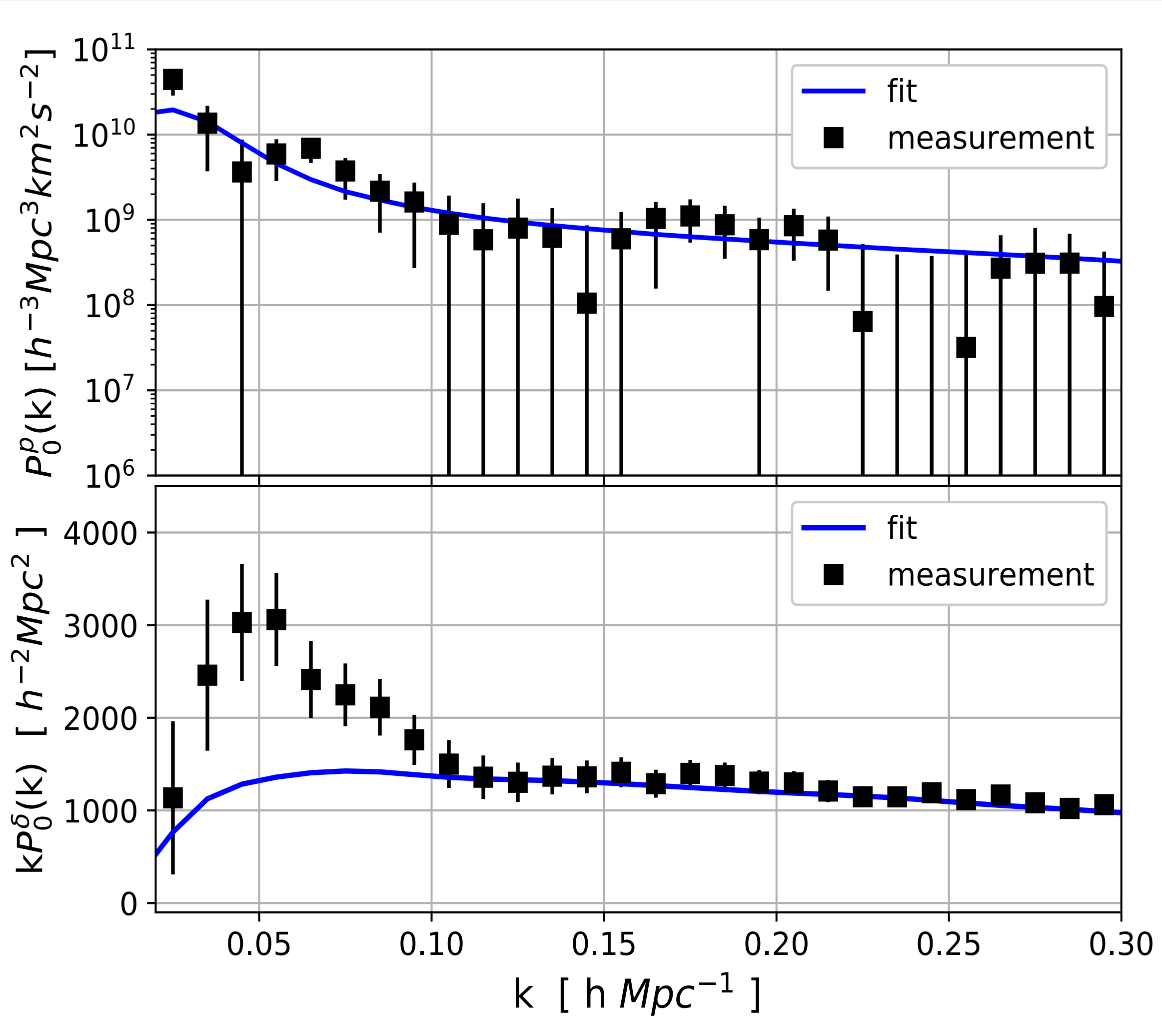
If you do this on the density field:



However, if you do this to the velocity field, you get the **momentum** power spectrum because you only have velocities where there are galaxies…

Momentum Power Spectrum

Qin et. al., 2019b: 2MTF + 6dFGSv

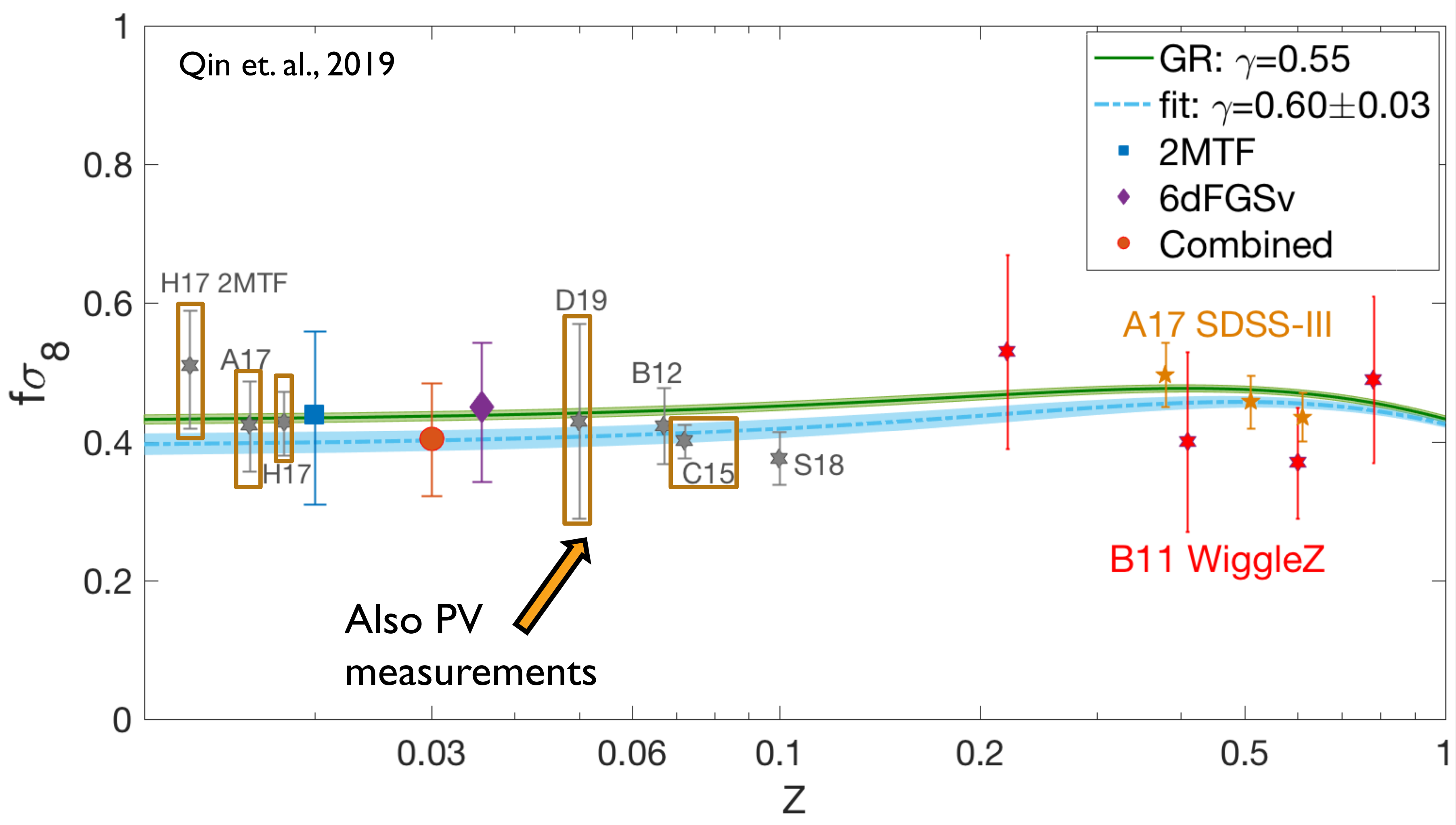


$$\rho(r) = (1 + \delta_g(r))v(r)$$

Nonetheless this is still great for cosmology because it is proportional to the growth rate on large scales.

It can also be fit alongside the density power spectrum to overcome cosmic variance.

Momentum Power Spectrum



Future Surveys

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Future surveys will increase the total number of PVs by an order of magnitude whilst also increasing redshifts and data robustness:

Survey	Redshifts ($z < 0.1$)	Possible PVs
Current	?????	20,000 combined
Taipan Galaxy Survey	400,000	50,000 FP
WALLABY	400,000	30,000 TF
DESI	1,000,000	Up to 100,000 FP?
LSST+Followup	?????	Up to 200,000 SNe?

These samples will improve our tests of cosmology at low redshift enormously

Future Surveys

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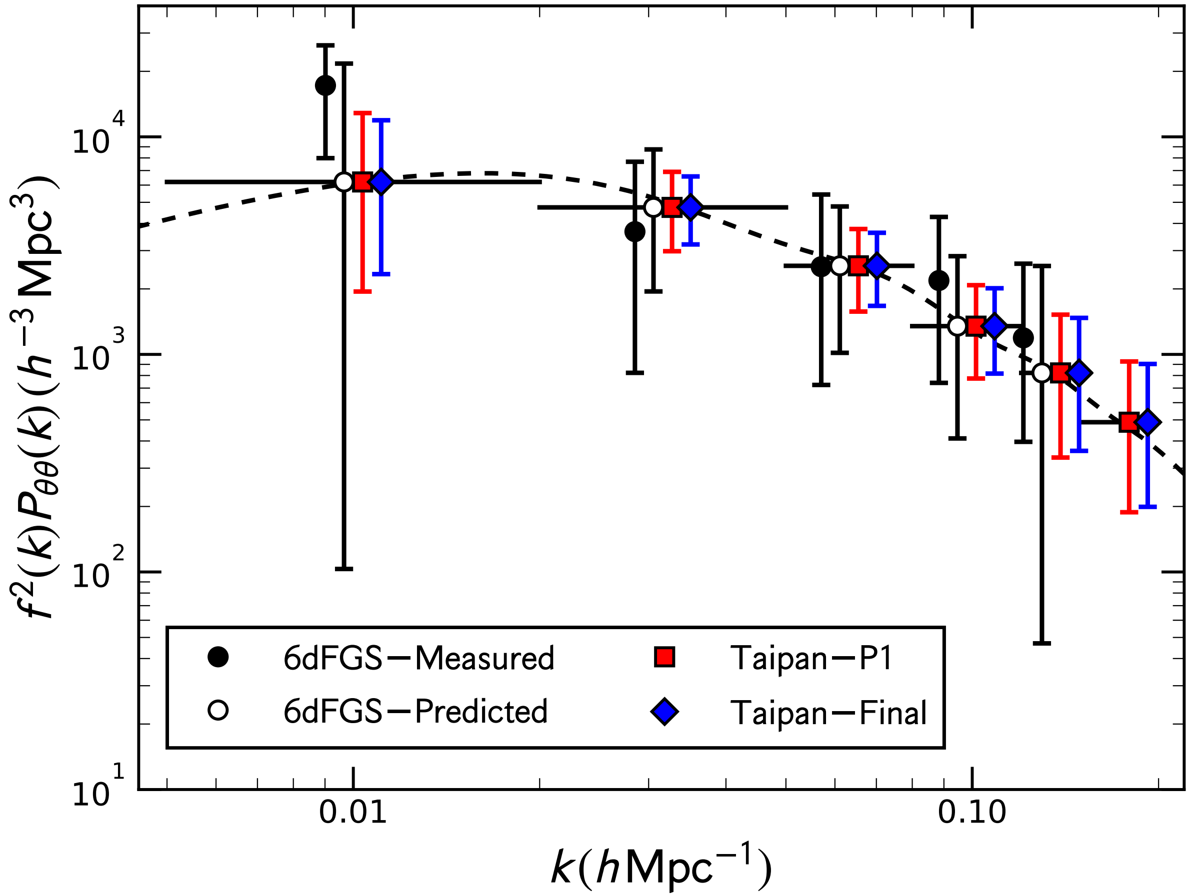

These surveys will allow for much more precise tests of scale-dependence

Da Cunha et. al., 2017

LSST SNe forecasts

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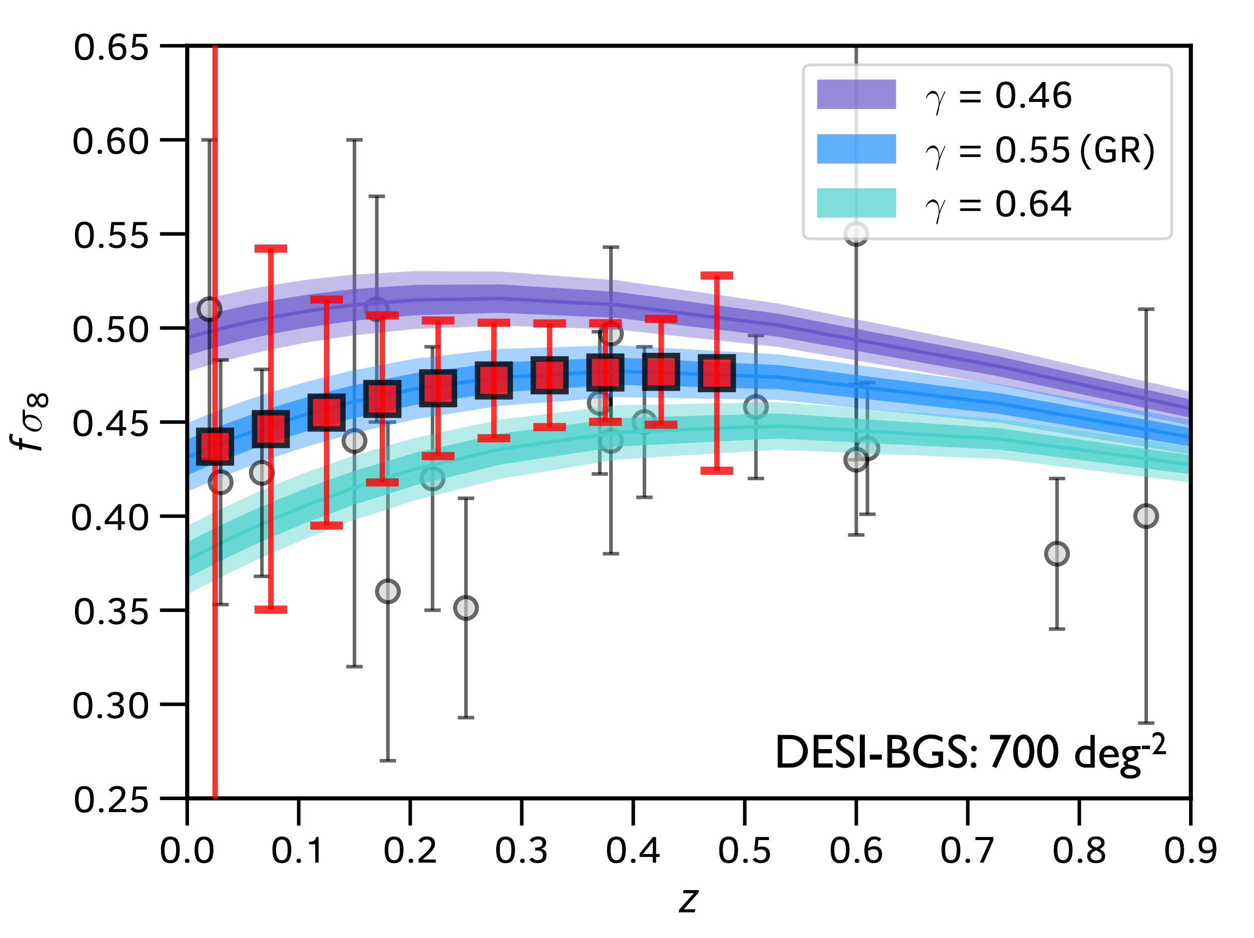
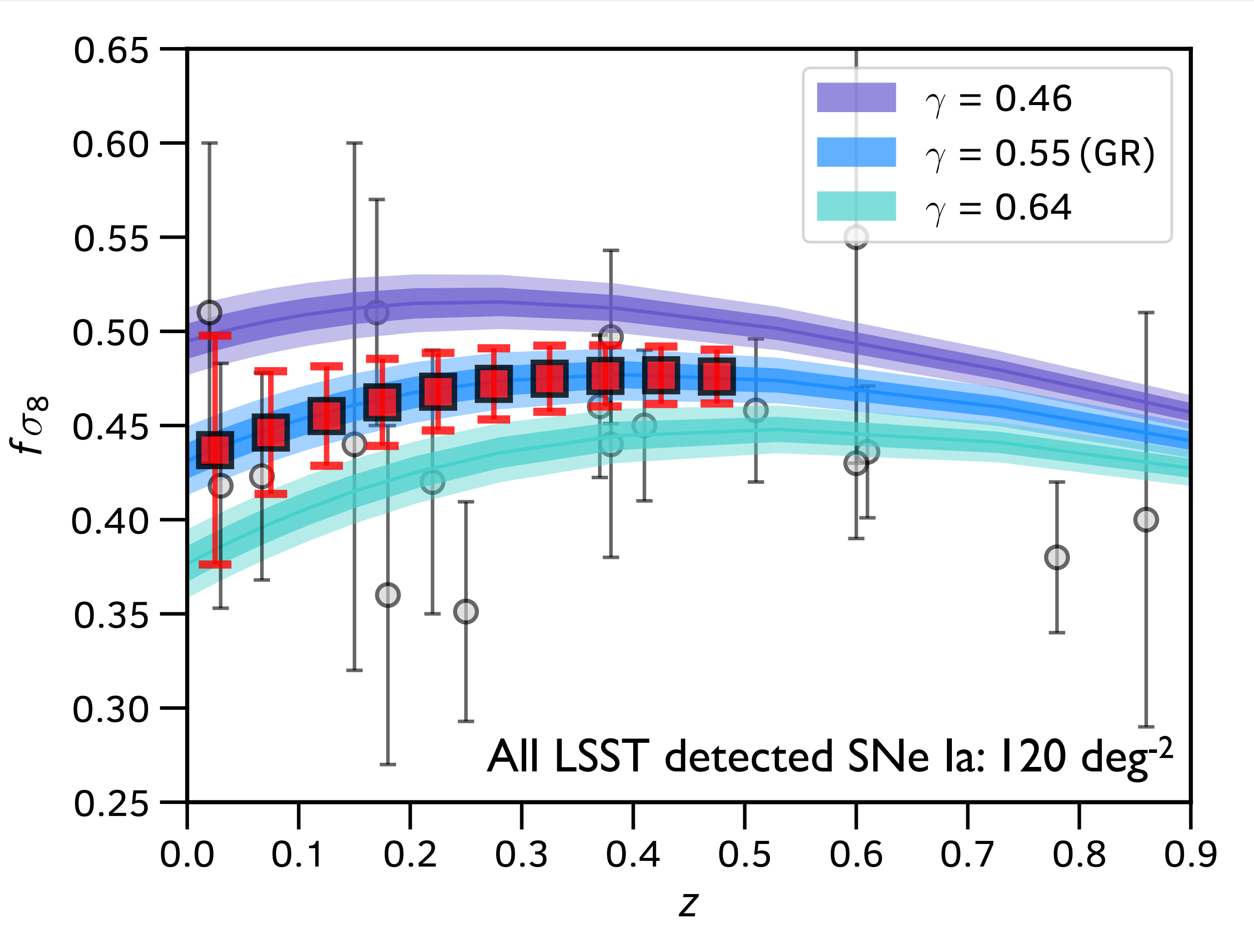


Although rare, SNe IA are much better distance indicators. Typical distance errors could be 8% compared to 20%

Howlett et. al., 2017b

LSST SNe forecasts



Howlett et. al., 2017b

Although rare, SNe IA are much better distance indicators. Typical distance errors could be 8% compared to 20%

However, lots of work needs to be done to actually obtain these future samples and control for systematics.

Conclusions

Direct measurements of galaxy peculiar velocities allow us to test gravity in the nearby Universe, and improve over standard clustering techniques.

- Peculiar velocities can be obtained from distance indicators.
- In the local universe they enable precise measurements of the growth rate of structure and can be combined with/improve upon redshift measurements.
- They give good constraints from current surveys.
- They'll be even better with future surveys and can add enormous value when combined with e.g., DESI.

If you have any questions about these slides or peculiar velocities in general, please get in touch!