Title: Cosmology and cosmography from peculiar velocities in the nearby Universe

Speakers: Mike Hudson

Series: Cosmology & Gravitation

Date: November 26, 2019 - 11:00 AM

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Abstract:

Maps of the mass density field can be used to predict peculiar velocities point-by-point. The comparison of these predictions to peculiar velocity data can be used to determine the cosmological parameter combination f sigma_8. I will briefly discuss the history of this field, present some of our recent results as well as other applications to calibrating the Hubble constant via SNe and gravitational waves, and discuss ongoing work to improving these measurements, through better modelling and, more importantly, acquiring more peculiar velocity data.

COSMOLOGY AND COSMOGRAPHY FROM PECULIAR VELOCITIES IN THE NEARBY UNIVERSE

MIKE HUDSON

UNIVERSITY OF WATERLOO | WATERLOO CENTRE FOR ASTROPHYSICS

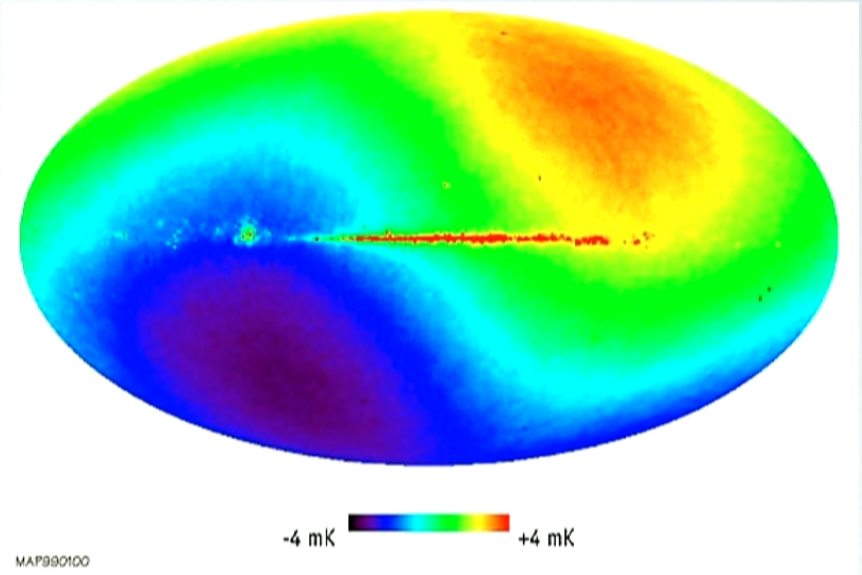
OUTLINE

- Introduction to peculiar velocities
- Cosmology from comparing the density field to the peculiar velocity field
- Future prospects

For example, if the solar motion with respect to the clusters represents the rotation of the galactic system, this motion could be subtracted from the results for the nebulae and the remainder would represent the motion of the galactic system with respect to the extra-galactic nebulae.

Hubble, 1929 (PNAS)

Our Local Group has a peculiar velocity of ~600 km/s with respect to the Cosmic Microwave Background



A Doppler effect due to motion wrt to the CMB.

NOT a dipole "intrinsic" to the last scattering surface.

- Planck 2013 results. XXVII. Doppler boosting of the CMB: *Eppur si muove*

MEASURING PECULIAR VELOCITIES

$$v = cz - H_0 r$$

1. Direct distance estimates
   - *cz* is easy
   - $H_0 r$ is difficult:
     - Supernovae (5-10%), Tully-Fisher (20%), Fundamental Plane (20%)
2. Statistically, via "redshift-space distortions"
3. Kinetic Sunyaev-Zeldovich effect

PECULIAR VELOCITIES AND GRAVITY

$$\rho_m(\mathbf{r}) \quad \rightarrow \quad \mathbf{a}(\mathbf{r}) = G \int d^3\mathbf{r}' \rho_m(\mathbf{r}') \frac{(\mathbf{r}' - \mathbf{r})}{|\mathbf{r}' - \mathbf{r}|^3}$$

PECULIAR VELOCITIES AND GRAVITY

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$$\delta_m(\mathbf{r}) = \frac{\rho_m(\mathbf{r}) - \overline{\rho_m}}{\overline{\rho_m}} \quad \rightarrow \quad \mathbf{v}(\mathbf{r}) = \frac{f H_0}{4\pi} \int d^3\mathbf{r}' \delta_m(\mathbf{r}') \frac{(\mathbf{r}' - \mathbf{r})}{|\mathbf{r}' - \mathbf{r}|^3}$$

Peebles, 1976

PECULIAR VELOCITIES AND GRAVITY

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Peebles, 1976

$$f \equiv \frac{d \ln D_+}{d \ln a} \simeq \Omega_{\rm m}^{\gamma} \qquad \Upsilon = 0.55 \text{ in flat } \Lambda\text{CDM}$$

COSMOLOGICAL PARAMETERS

USING THE GALAXY DENSITY FIELD

S. S. Boruah

G. Lavaux

J. Jasche

"TENSION" IN σ_8

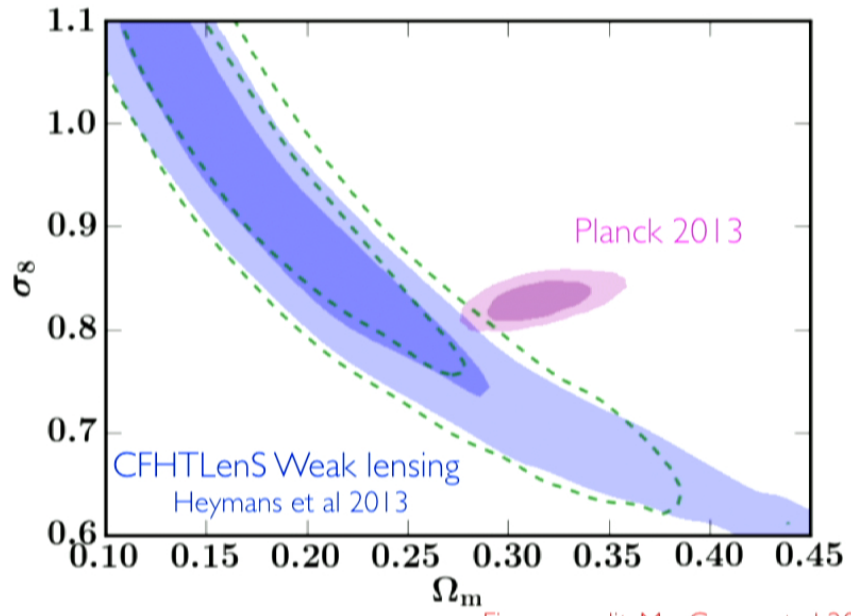
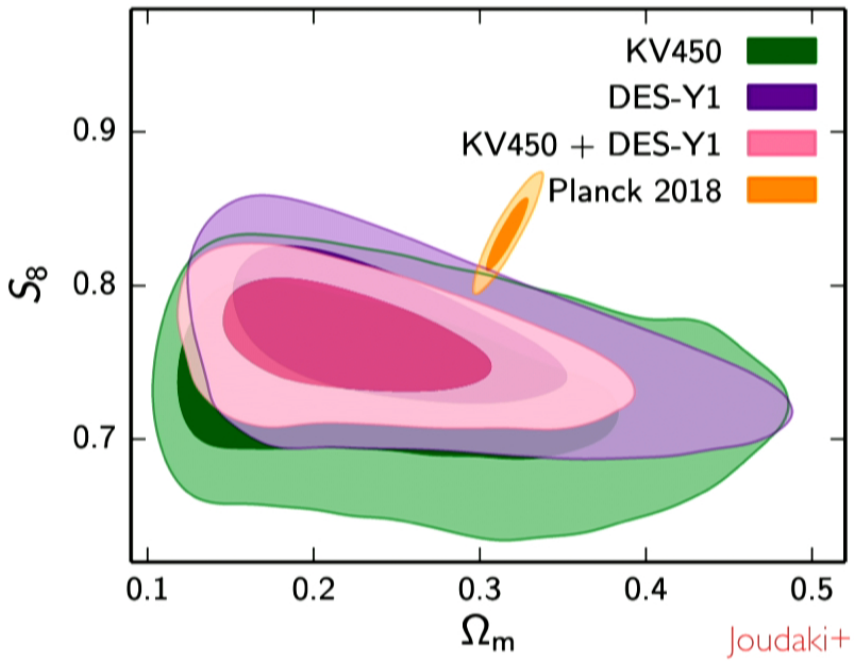


Figure credit: MacCrann et al 2014

Systematic errors in lensing or Planck?

or new physics?

"TENSION" IN σ_8



Joudaki+ 19

Systematic errors in lensing or Planck?

or new physics?

ASSUME GALAXY DENSITY TRACES MASS

$$\delta_g = b\,\delta_m$$

β

$$\mathbf{v}(\mathbf{r}) = \frac{f}{b}\frac{H_0}{4\pi}\int_0^{R_{\max}} d^3\mathbf{r}'\delta_g(\mathbf{r}')\frac{(\mathbf{r}'-\mathbf{r})}{|\mathbf{r}'-\mathbf{r}|^3} + \mathbf{V}_{\text{ext}}$$

β

$$\mathbf{v}(\mathbf{r}) = \frac{f}{b}\frac{H_0}{4\pi}\int_0^{R_{\max}} d^3\mathbf{r}'\delta_g(\mathbf{r}')\frac{(\mathbf{r}'-\mathbf{r})}{|\mathbf{r}'-\mathbf{r}|^3} + \mathbf{V}_{\rm ext}$$

$$\delta_g = b\delta \qquad f(\Omega_{\rm m}) = \Omega_{\rm m}^{\gamma}$$

$$\sigma_{8,g} = b\sigma_8$$

$$\beta = \frac{f}{b}$$

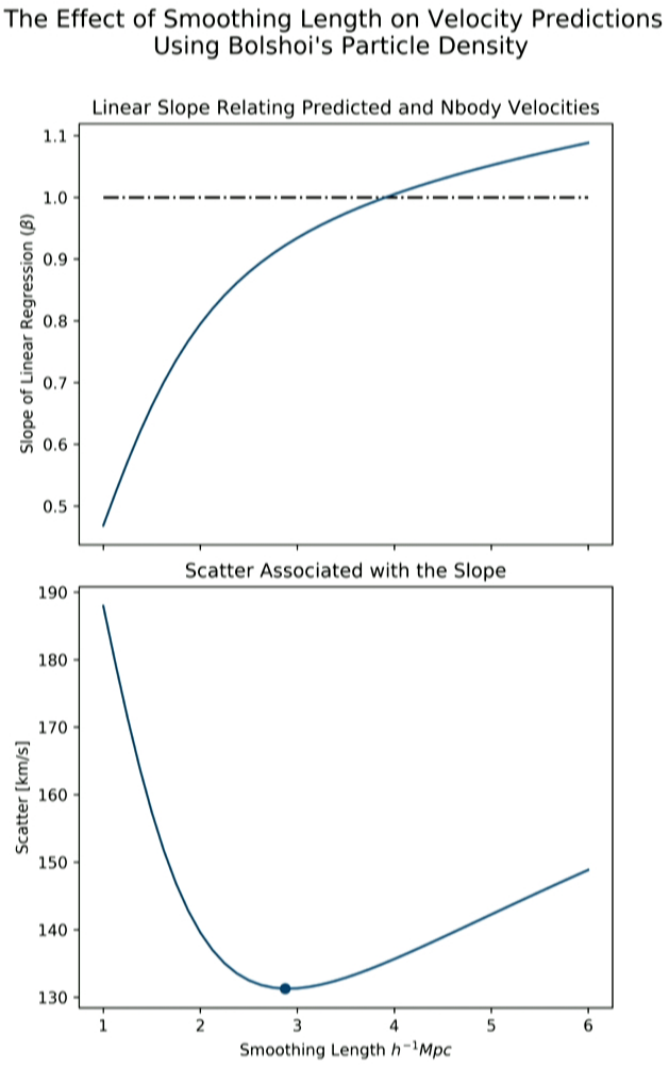
$$f\sigma_8 = \beta\sigma_{8,g}$$

Measurable

SMOOTHING FOR LINEAR THEORY

Tests on N-body simulations suggest that 4 Mpc/h Gaussian smoothing yields:

- unbiased peculiar velocities
- scatter ~140 km/s.



Hollinger, MH in prep

β

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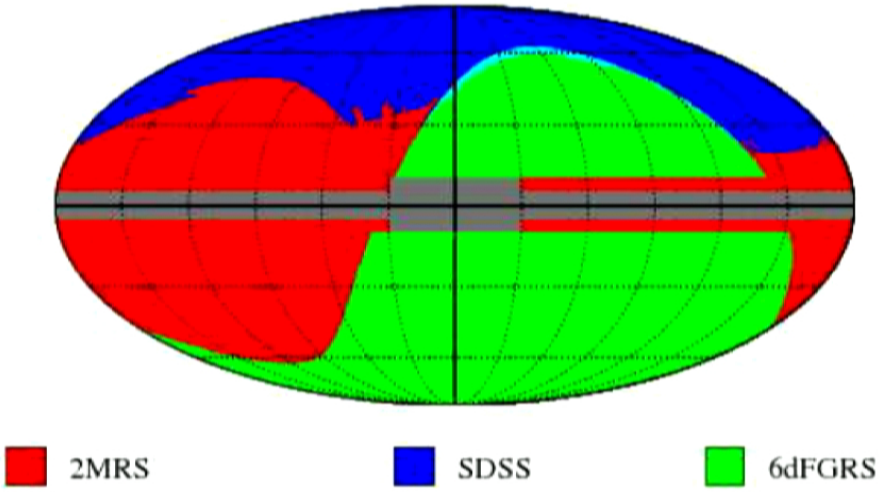
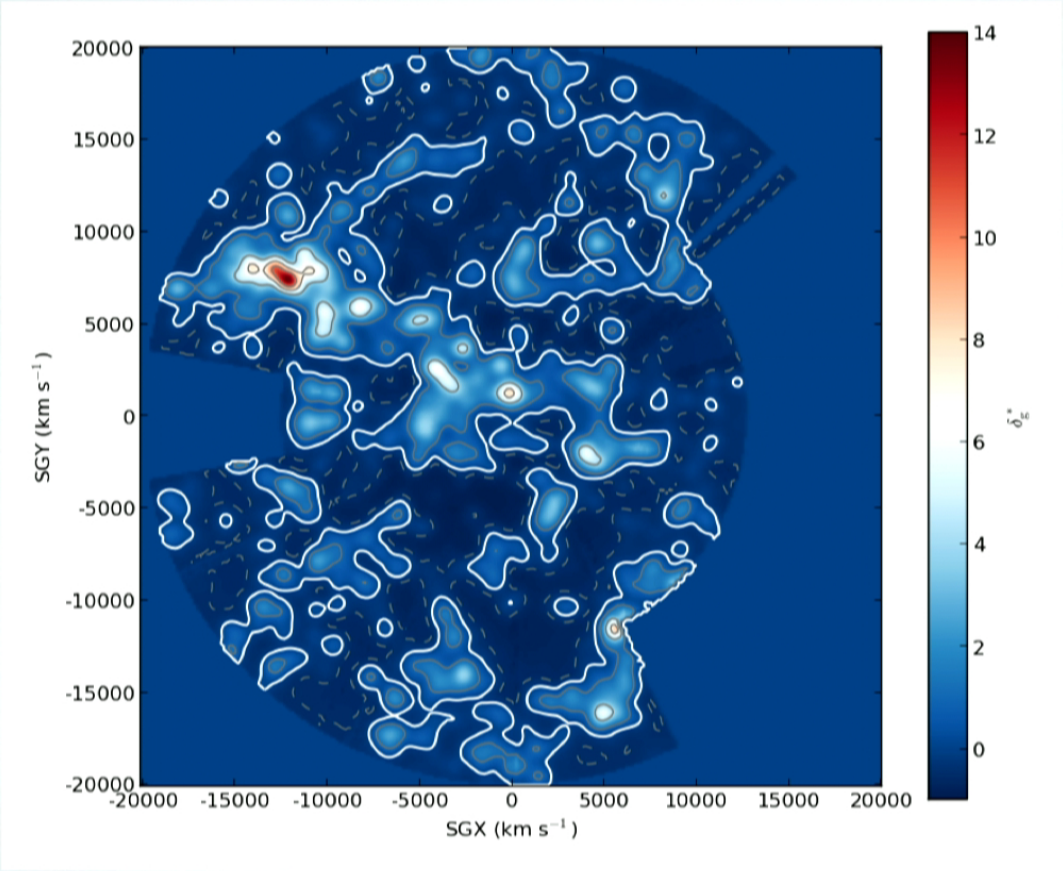
2M++

Lavaux & Hudson 2011, MNRAS, 416, 2840

- Combine 2MRS (K<11.5), 6dF (K<12.5) and SDSS (K<12.5)
- ~70k galaxies
- 200 Mpc/h in 6dF and SDSS areas

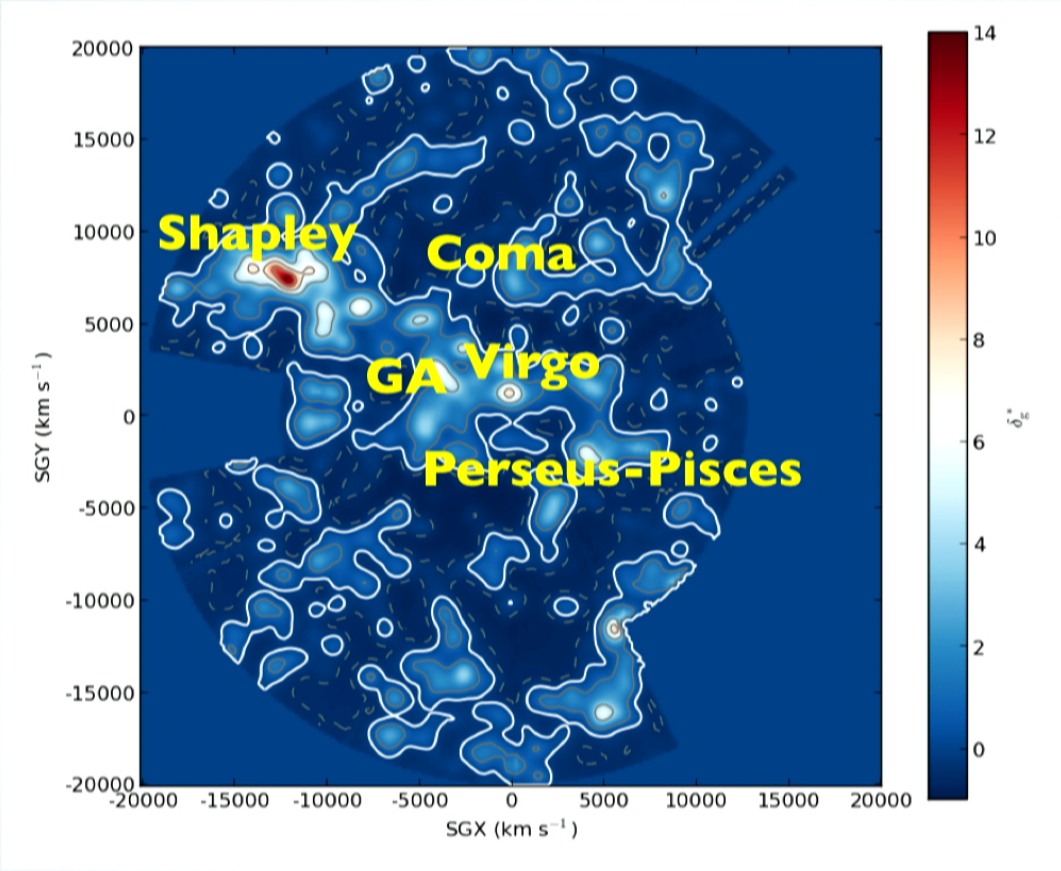


2M++ RECONSTRUCTION



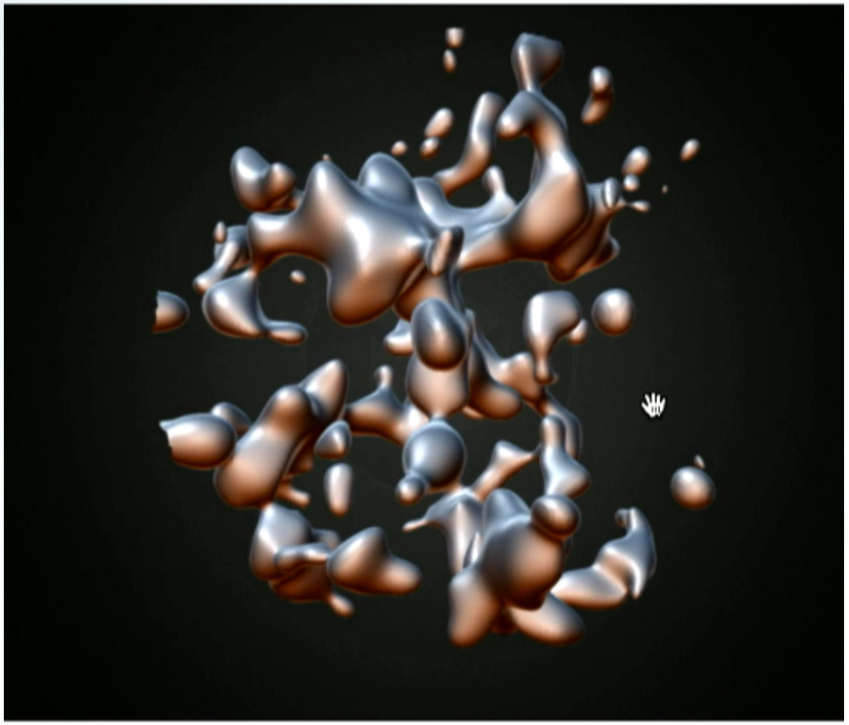
Carrick et al 15, MNRAS, 450, 317

2M++ RECONSTRUCTION



Carrick et al. 15, MNRAS, 450, 317

NOW IN 3D!



https://skfb.ly/Iy7R

PECULIAR VELOCITY DATA

- **SFI++** (3177 spirals with Tully Fisher)
- **"Second Amendment" SNe** (455)

2M++

β

$$\mathbf{v}(\mathbf{r}) = \frac{f}{b}\frac{H_0}{4\pi}\int_0^{R_{\max}} d^3\mathbf{r}'\delta_g(\mathbf{r}')\frac{(\mathbf{r}'-\mathbf{r})}{|\mathbf{r}'-\mathbf{r}|^3} + \mathbf{V}_{\text{ext}}$$

COSMOLOGICAL PARAMETERS

Combined with galaxy clustering measurements, peculiar velocities yield:

$$f\,\sigma_8 = 0.396 \pm 0.019\ (5\%!)$$

Peculiar velocities are consistent with other cosmological probes on small (~20 Mpc/h) scales.

PECULIAR VELOCITY DATA

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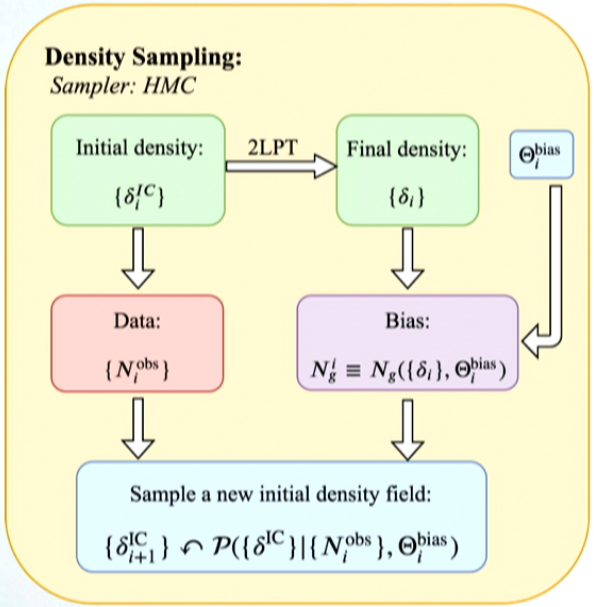
FORWARD MODELLING WITH BORG

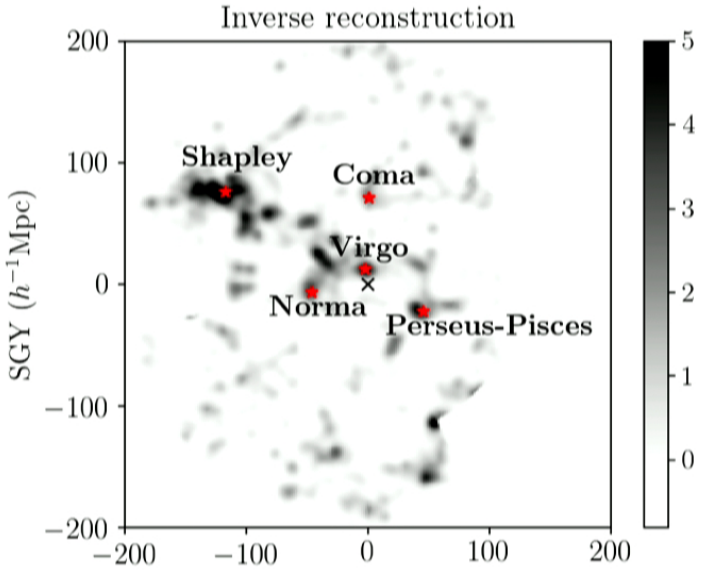
Bayesian Origin Reconstruction from Galaxies

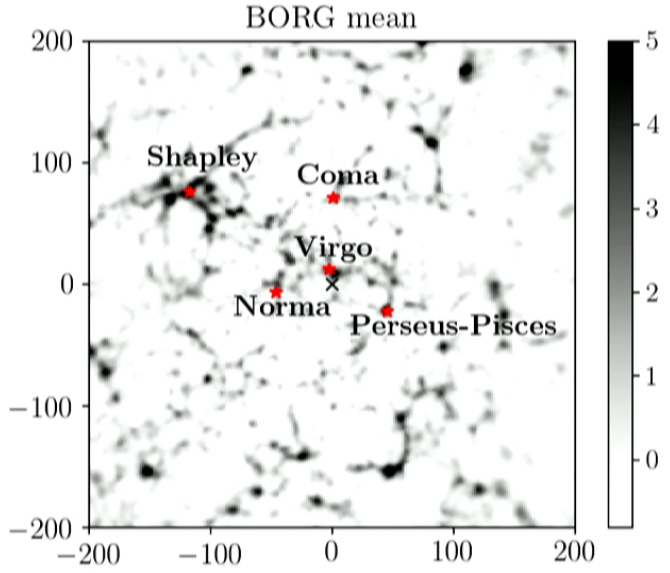


2nd order perturbation theory
non-linear bias model

Lavaux and Jasche 2016
Jasche and Lavaux 2019
Boruah et al 2019

INVERSE VS BORG



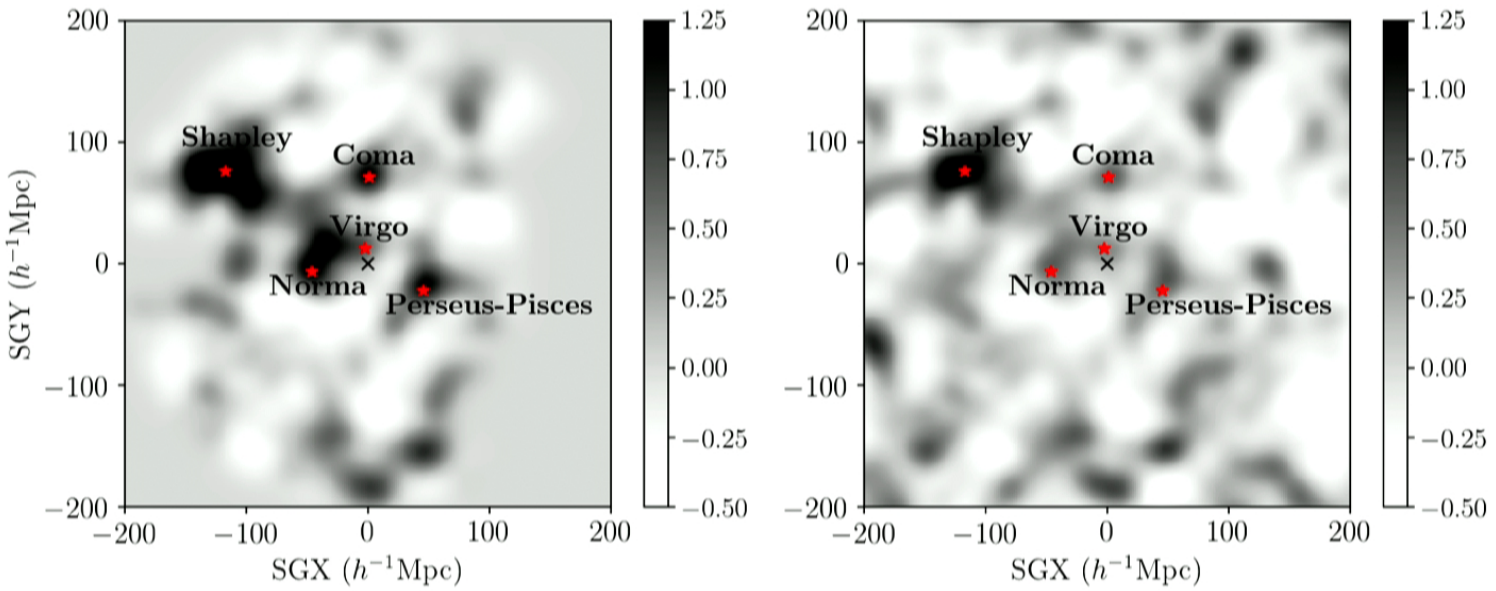


4 Mpc/h Gaussian

3 Mpc/h voxel

Boruah et al 19

INVERSE VS BORG



10 Mpc/h Gaussian for both

Boruah et al 19

Reconstruction scheme	Sample	$\tilde{h}$	$f\sigma_{8,\mathrm{lin}}$	$\lvert \boldsymbol{V}_{\mathrm{ext}} \rvert$(km/s)	l(deg)	b(deg)
Inverse	SFI++ groups	0.974 ± 0.008	0.376 ± 0.030	172^{+28}_{-29}	294^{+10}_{-12}	18^{+7}_{-6}
	SFI++ field galaxies	0.949 ± 0.005	0.385 ± 0.025	167^{+20}_{-21}	285^{+7}_{-9}	18^{+7}_{-6}
	A2 supernovae	—	0.393 ± 0.026	147^{+25}_{-25}	302^{+10}_{-10}	-1^{+8}_{-7}
	All combined	—	$\mathbf{0.396 \pm 0.019}$	$\mathbf{147^{+17}_{-13}}$	$\mathbf{292^{+6}_{-6}}$	$\mathbf{10^{+4}_{-4}}$
BORG	SFI++ groups	0.966 ± 0.007	0.449 ± 0.031	210^{+25}_{-25}	306^{+9}_{-9}	21^{+7}_{-6}
	SFI++ field galaxies	0.941 ± 0.005	0.419 ± 0.022	241^{+16}_{-15}	316^{+5}_{-5}	31^{+4}_{-3}
	A2 supernovae	—	0.339 ± 0.037	157^{+29}_{-29}	300^{+10}_{-10}	5^{+8}_{-6}
	All combined	—	$\mathbf{0.406 \pm 0.017}$	$\mathbf{211 \pm 12}$	$\mathbf{309^{+4}_{-4}}$	$\mathbf{28^{+4}_{-4}}$

Boruah et al 19

β

$$\mathbf{v}(\mathbf{r}) = \frac{f}{b}\frac{H_0}{4\pi}\int_0^{R_{\max}} d^3\mathbf{r}'\delta_g(\mathbf{r}')\frac{(\mathbf{r}'-\mathbf{r})}{|\mathbf{r}'-\mathbf{r}|^3} + \mathbf{V}_{\rm ext}$$

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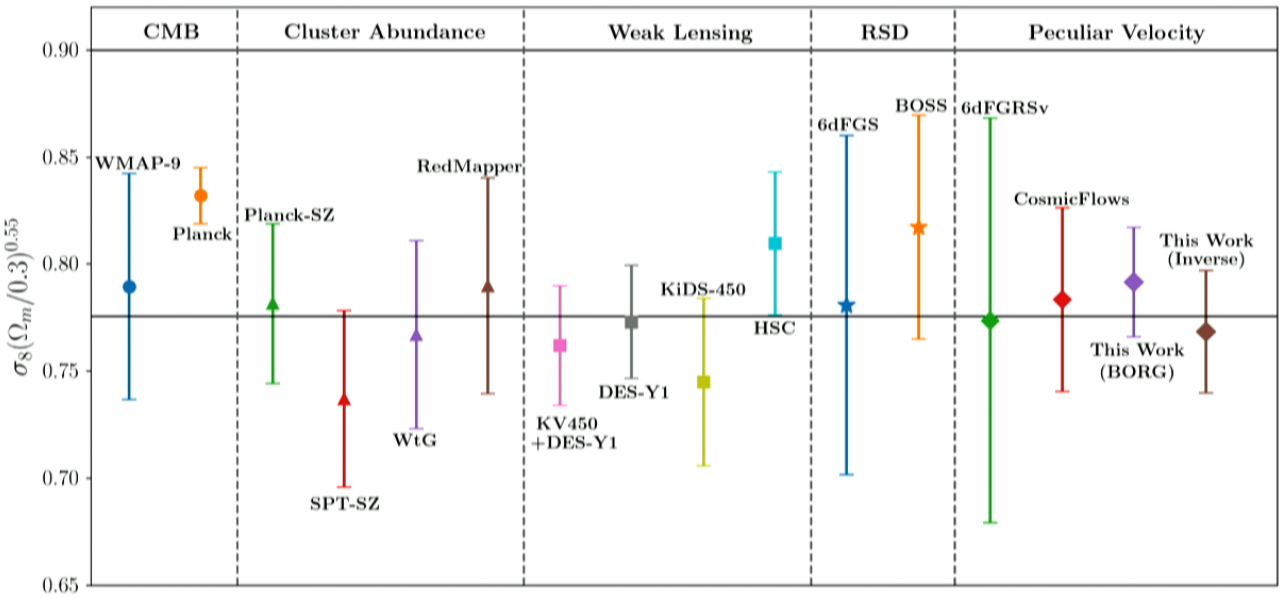
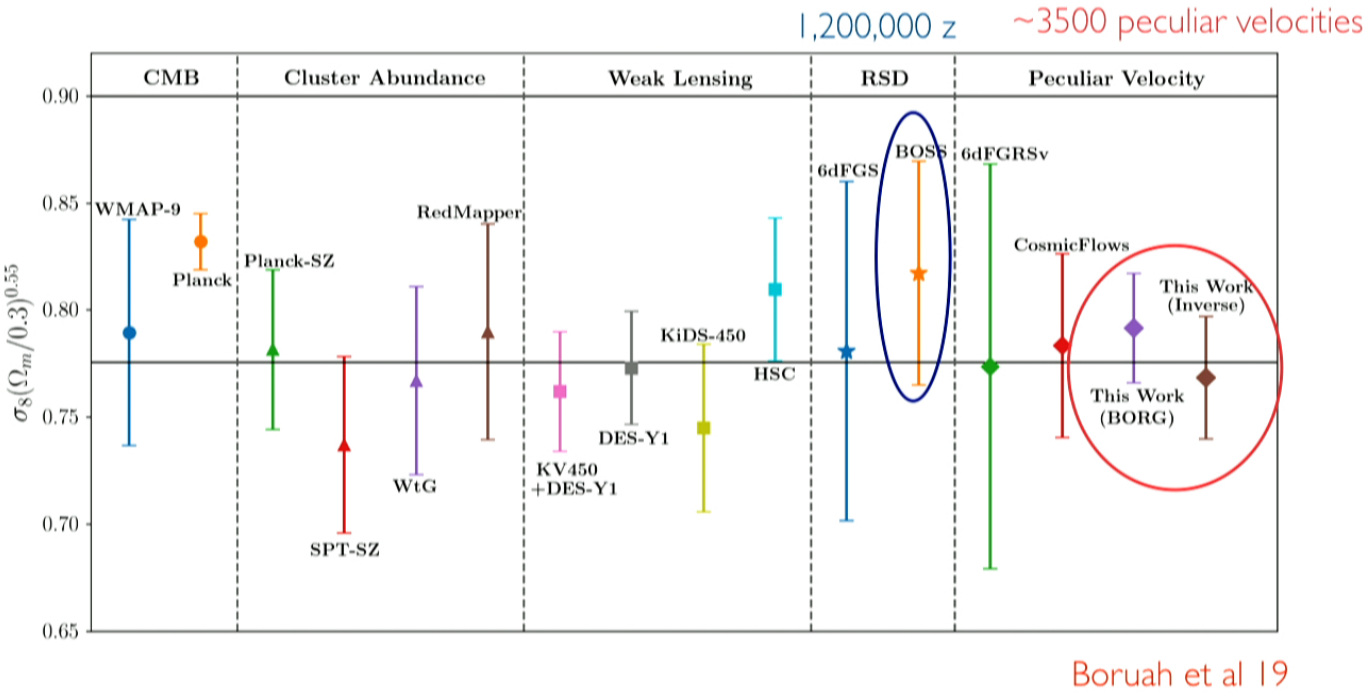


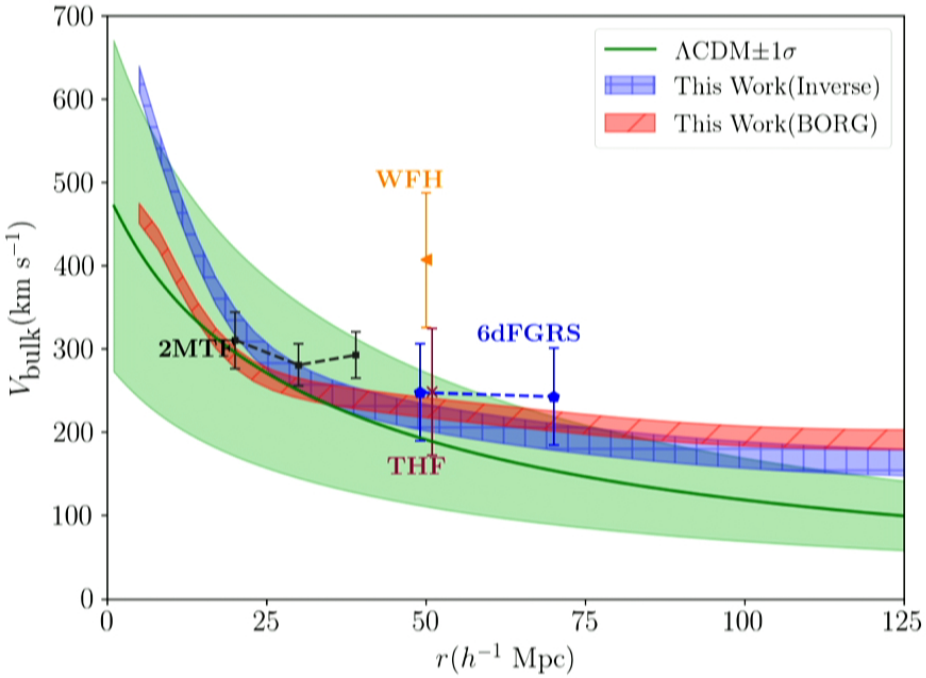
Boruah et al 19

$f\sigma_8$ (at z = 0) from different probes



$f\sigma_8$ (at z = 0) from different probes

THE BULK FLOW



Boruah et al 19

The residual bulk flow suggests that 2M++ map does not account for *all* of the Local Group's motion. There remains unaccounted for

$$V_{ext} = 150 \pm 20 \text{ km/s towards } l=300, b=10$$

Are the missing sources:

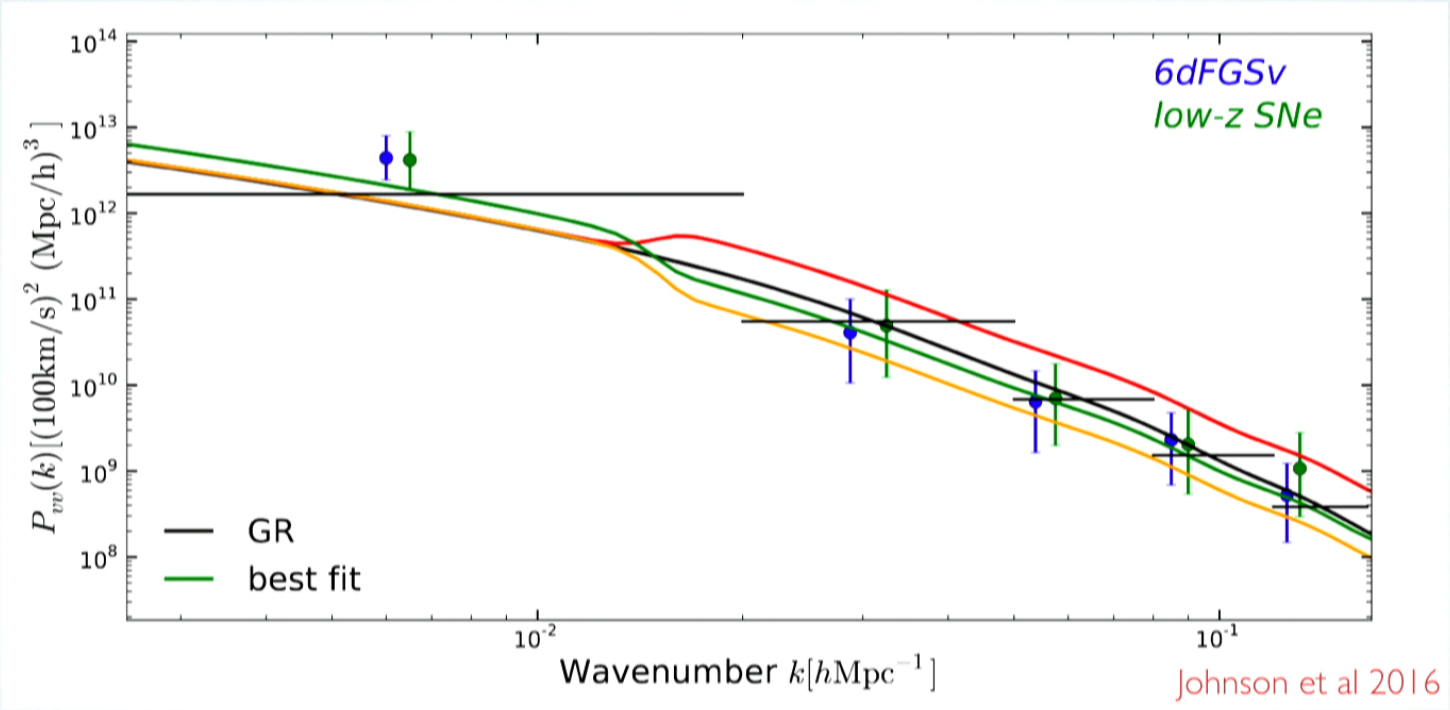
The residual bulk flow suggests that 2M++ map does not account for *all* of the Local Group's motion. There remains unaccounted for

$$V_{ext} = 150 \pm 20 \text{ km/s towards } l=300, b=10$$

Are the missing sources:

- Beyond 200 Mpc/h?
- In the Zone of Avoidance (e.g. Vela supercluster)?

VELOCITY POWER SPECTRUM



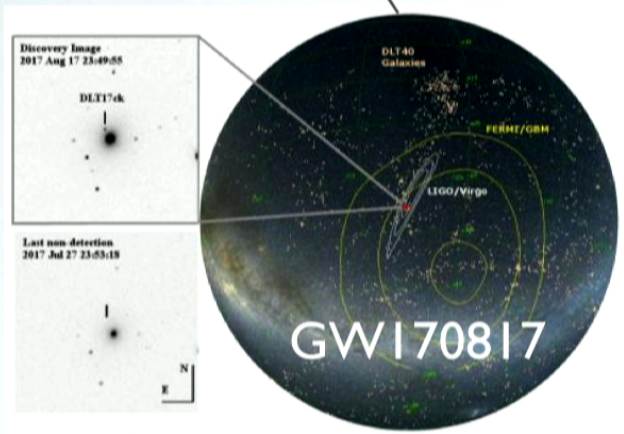
CLEANING THE HUBBLE DIAGRAM

- For many applications, peculiar velocities are a "nuisance" that pollutes the Hubble diagram at low redshift
- Correcting for peculiar velocities using the density field allows for a cleaner Hubble diagram
  - Corrections now used by SNe teams as well as newer distance indicators …

MEASURING H_0 WITH GRAVITATIONAL WAVE "SIRENS"

$H_0 = cz_{Hubble} / D$

$cz_{Hubble} = cz - v_{pec}$



Cosmic Flows

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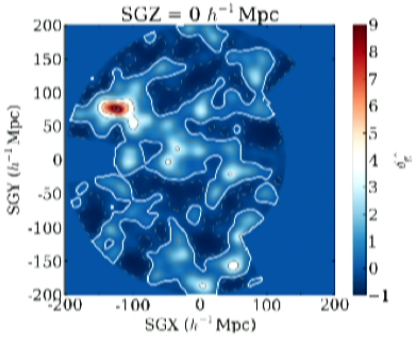
Density and Peculiar Velocity Fields in the Nearby Universe

We present a model for the density and predicted peculiar velocity fields within 200 Mpc/h. This model can be used to estimate the density within a depth of 200 Mpc/h. It can also be used to calculate predicted peculiar velocities within the same volume. These predictions can also be used to correct observed redshifts for the effects of peculiar motions restoring them to the Hubble flow. This has applications for SNe and measurements of the Hubble constant.



The density field in the Supergalactic Plane, smoothed with a 10 Mpc/h Gaussian

Please also have a look at our new project involving detailed modeling of large scale structure statistics.

Data

The density field is based on the 2M++ redshift compilation, which in turn is based on the 2MRS, 6dF and SDSS redshift surveys. Self-consistent distances to all galaxies are calculated consistent with their observed redshifts and linear perturbation theory.

Download

From the download page, you can obtain the density and peculiar velocity fields in ASCII or numpy format.

Distances to galaxies and clusters

Coming soon! Stay tuned for updates.

How to acknowledge

Please cite the following papers:

- "Cosmological parameters from the comparison of peculiar velocities with predictions from the 2M++ density field", Carrick J., Turnbull S., Lavaux G. & Hudson M. J., MNRAS, 2015. (ADS, MNRAS, arXiv)

A BiBTeX file with the above references can be downloaded here.

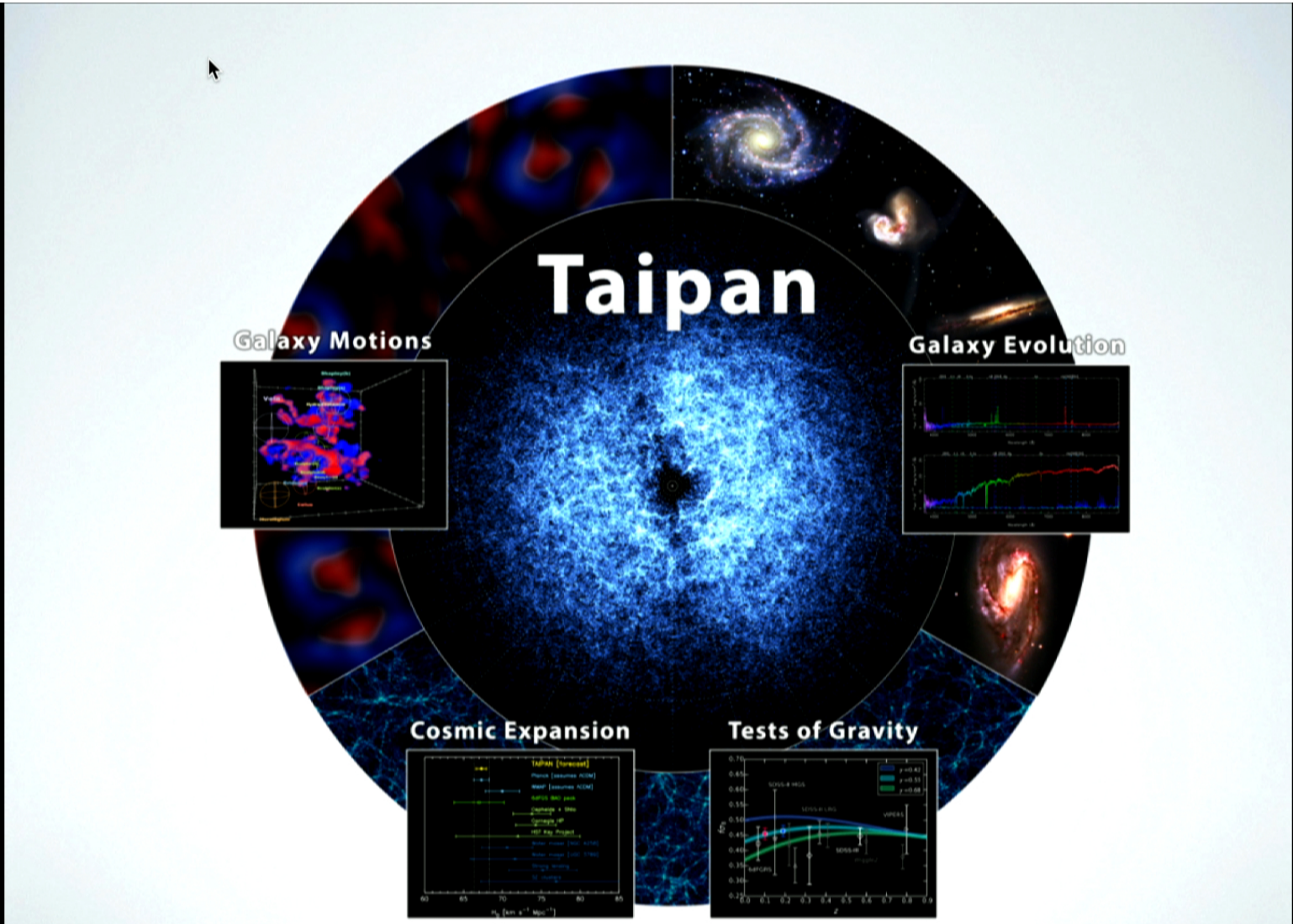
Register for updates

NEW! The lookup galaxy tool is fully functioning.

cosmicflows.iap.fr

FUTURE

Better DATA


Taipan
Galaxy Motions
Galaxy Evolution
Cosmic Expansion
Tests of Gravity

FUTURE

Better DATA

- Deeper ***all-sky*** redshift surveys (TAIPAN + DESI):
  ➡ better density field

- New large peculiar velocity datasets from
  - Fundamental Plane (TAIPAN: 50k)
  - Tully-Fisher (WALLABY)
  - SNe (LSST etc)

But need to control systematics to <1%

TAKE HOME MESSAGES

- Only ~3500 peculiar velocities give competitive constraints on $f\sigma_8$.
- Bulk flows on largest scales:
  - still a few hints of "tension" with ΛCDM
  - ~150 km/s of the LG's motion remains unexplained

Cosmic flows estimated from direct peculiar velocity estimates have great potential : need systematic better-than-SDSS surveys!