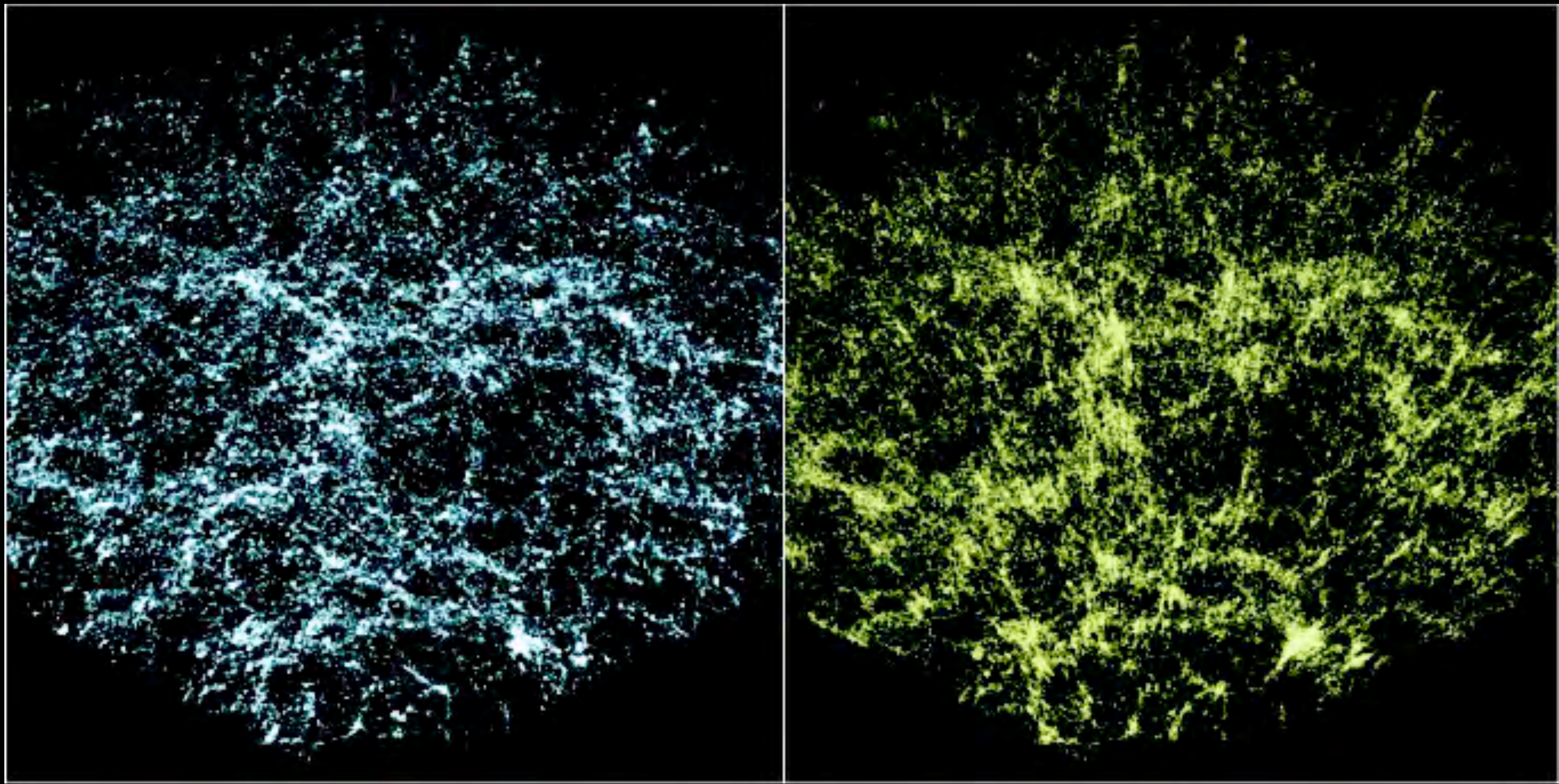
Testing the laws of gravity with redshift-space distortions (RSDs)

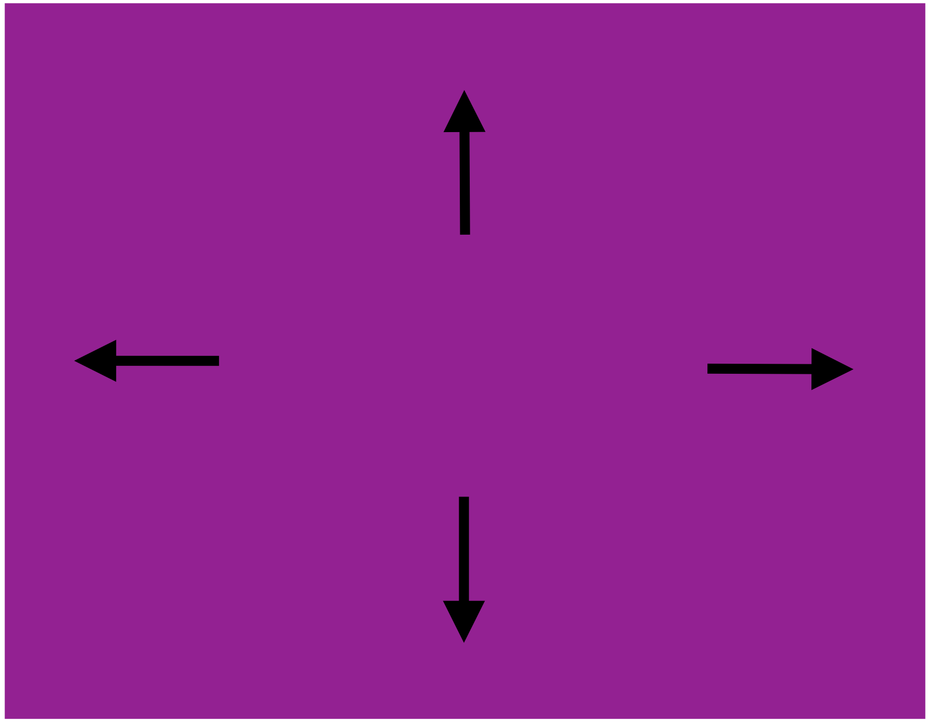


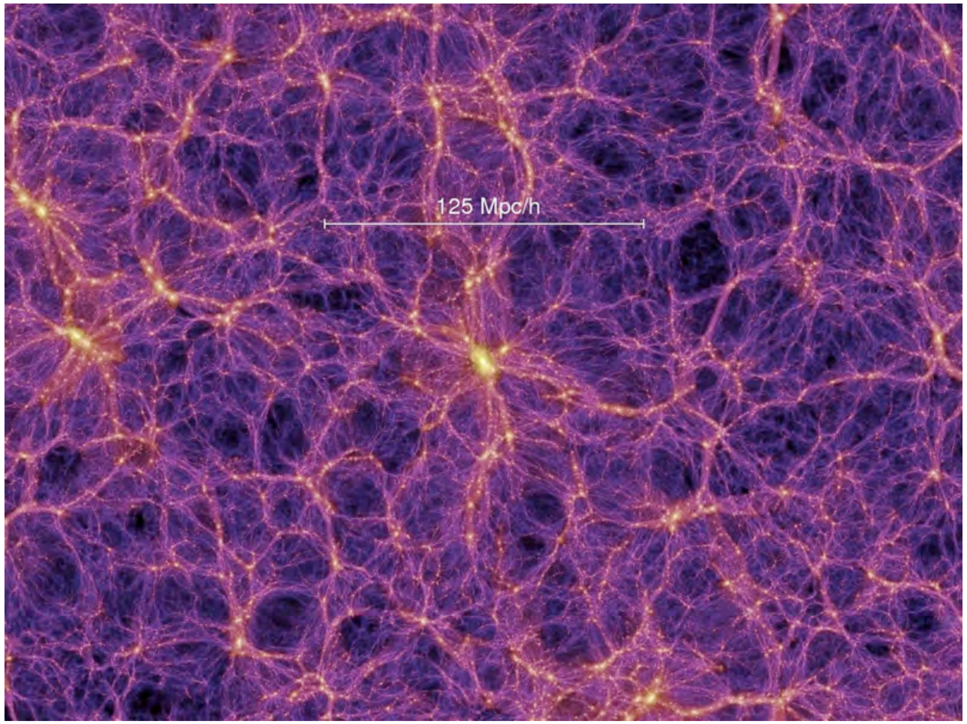
Chris Blake (Swinburne)

What observations can cosmologists make?

How fast is the Universe expanding with time?

How fast are structures growing within it?

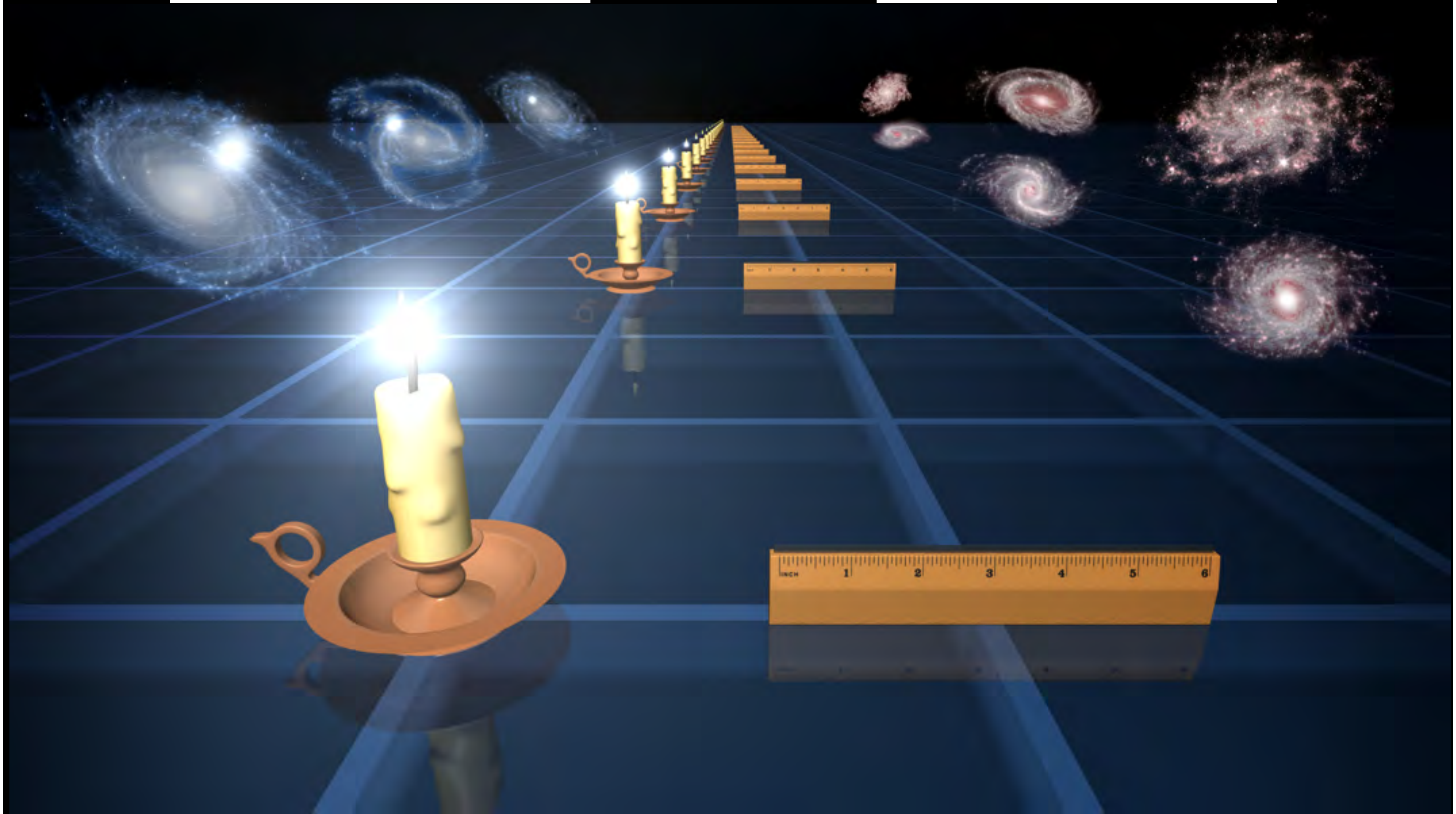




Expansion of the homogeneous Universe

Standard candles

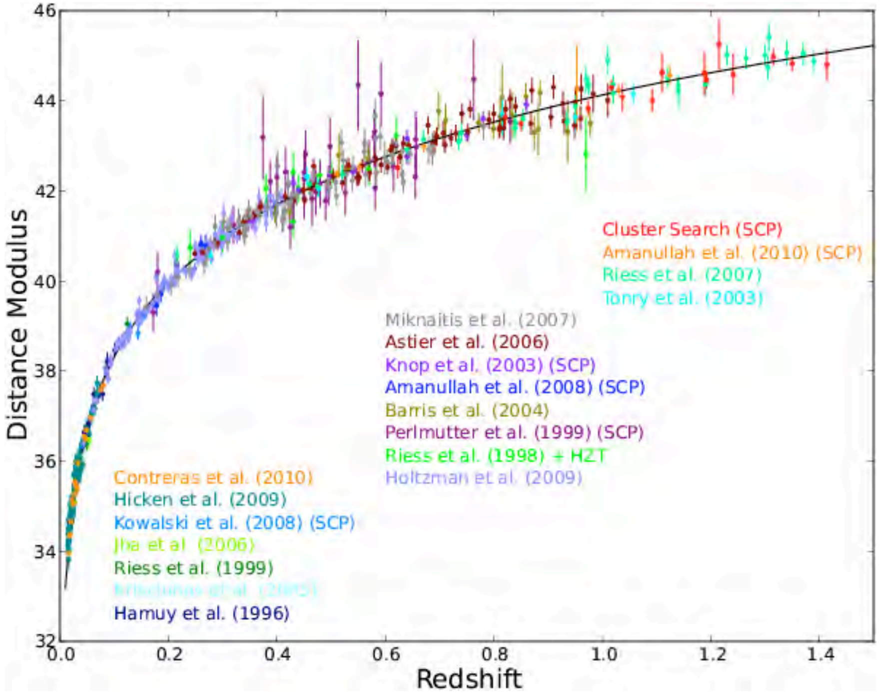
Standard rulers



Expansion of the homogeneous Universe

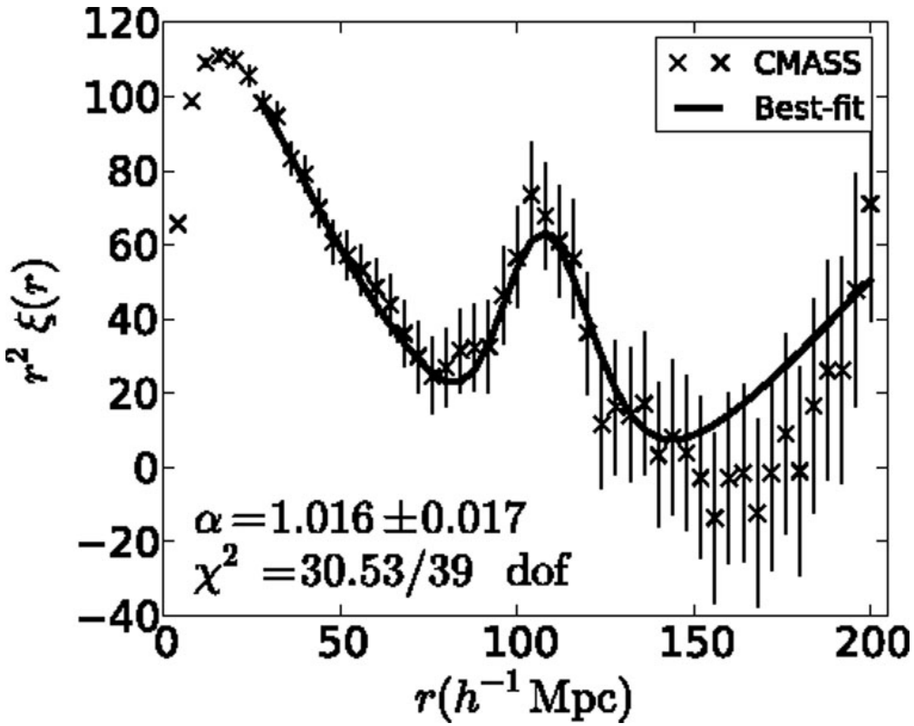
Standard candles

Credit : Amanullah et al. (2010)



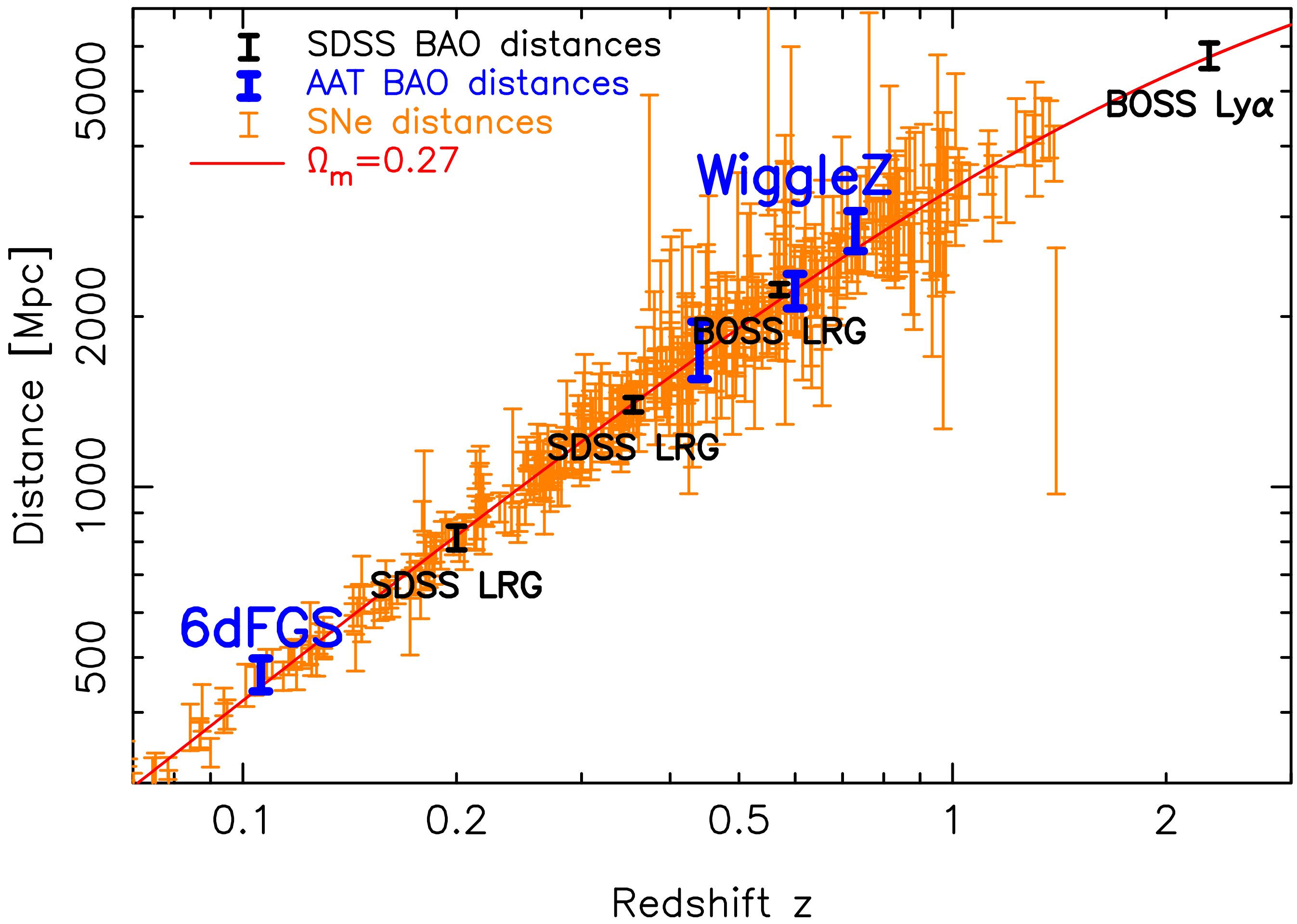
Standard rulers

Credit : Anderson et al. (2013)



- The cosmic expansion history over the last ~7 billion years has been measured with ~1% accuracy

Expansion of the homogeneous Universe



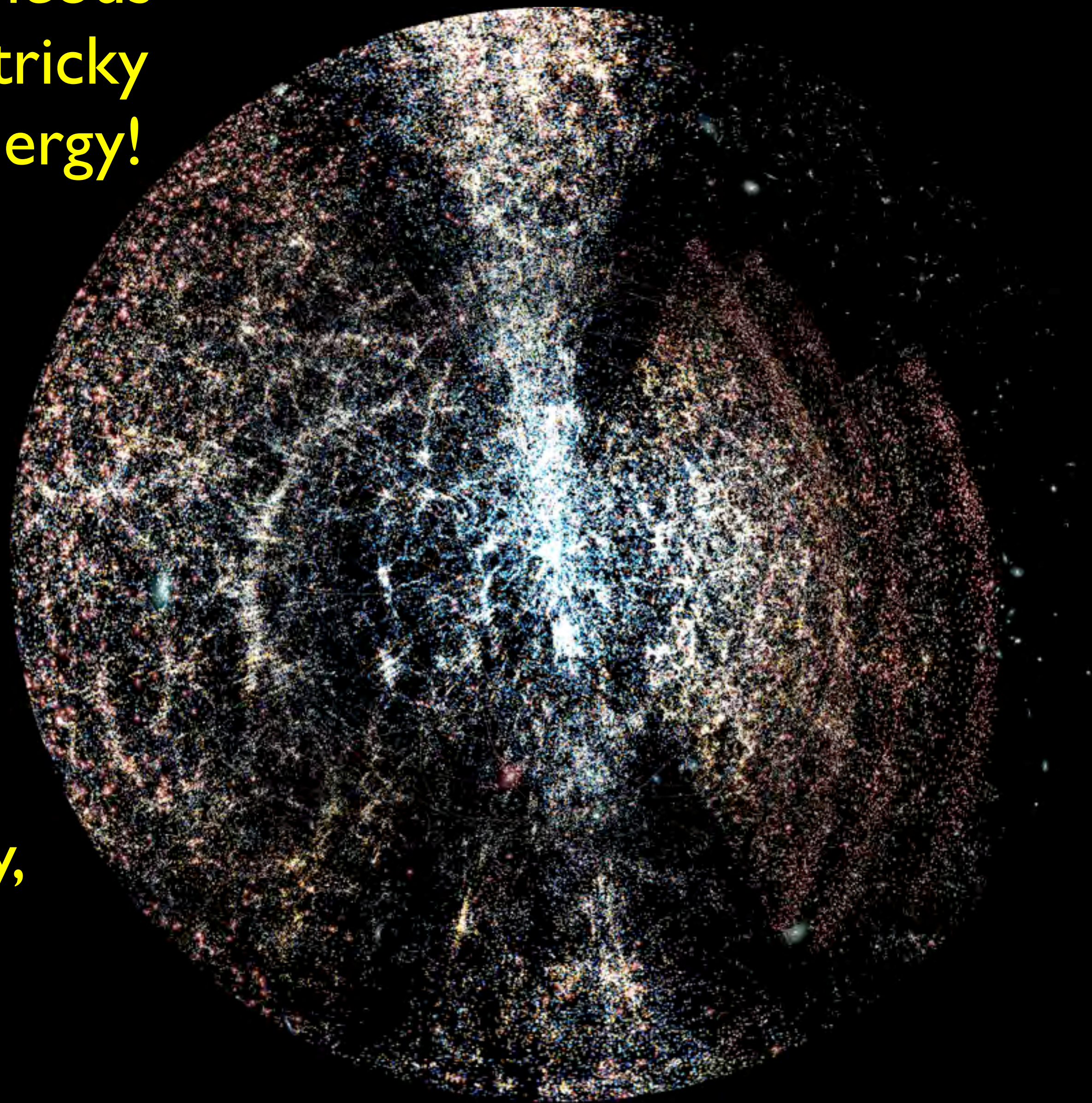
- The cosmic expansion history over the last ~7 billion years has been measured with ~1% accuracy

Growth of perturbations

In a perfectly homogeneous Universe, it would be tricky to understand dark energy!

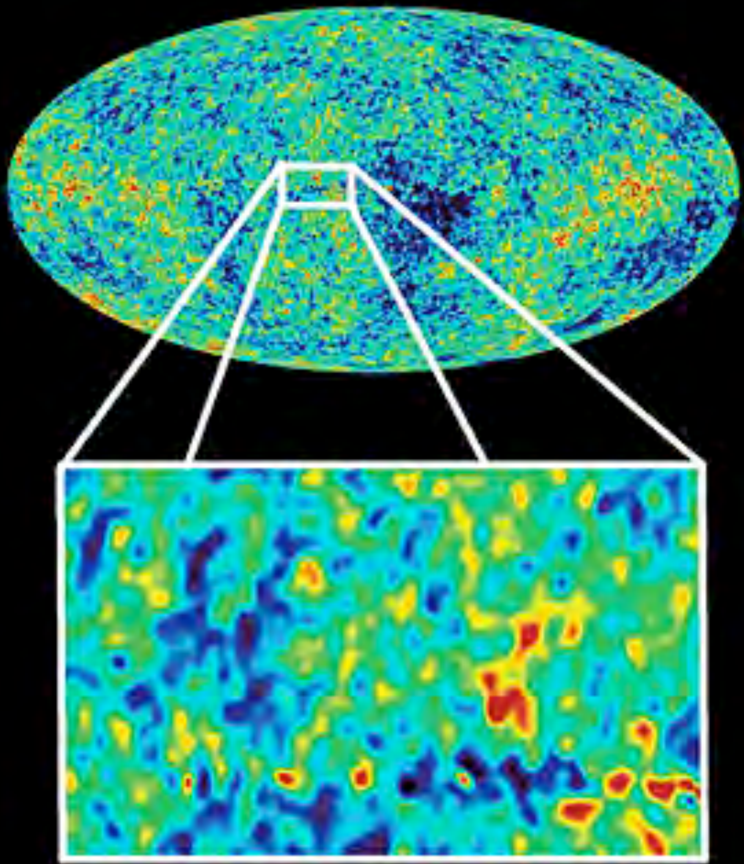
There are a rich variety of observable signatures in the clumpy Universe

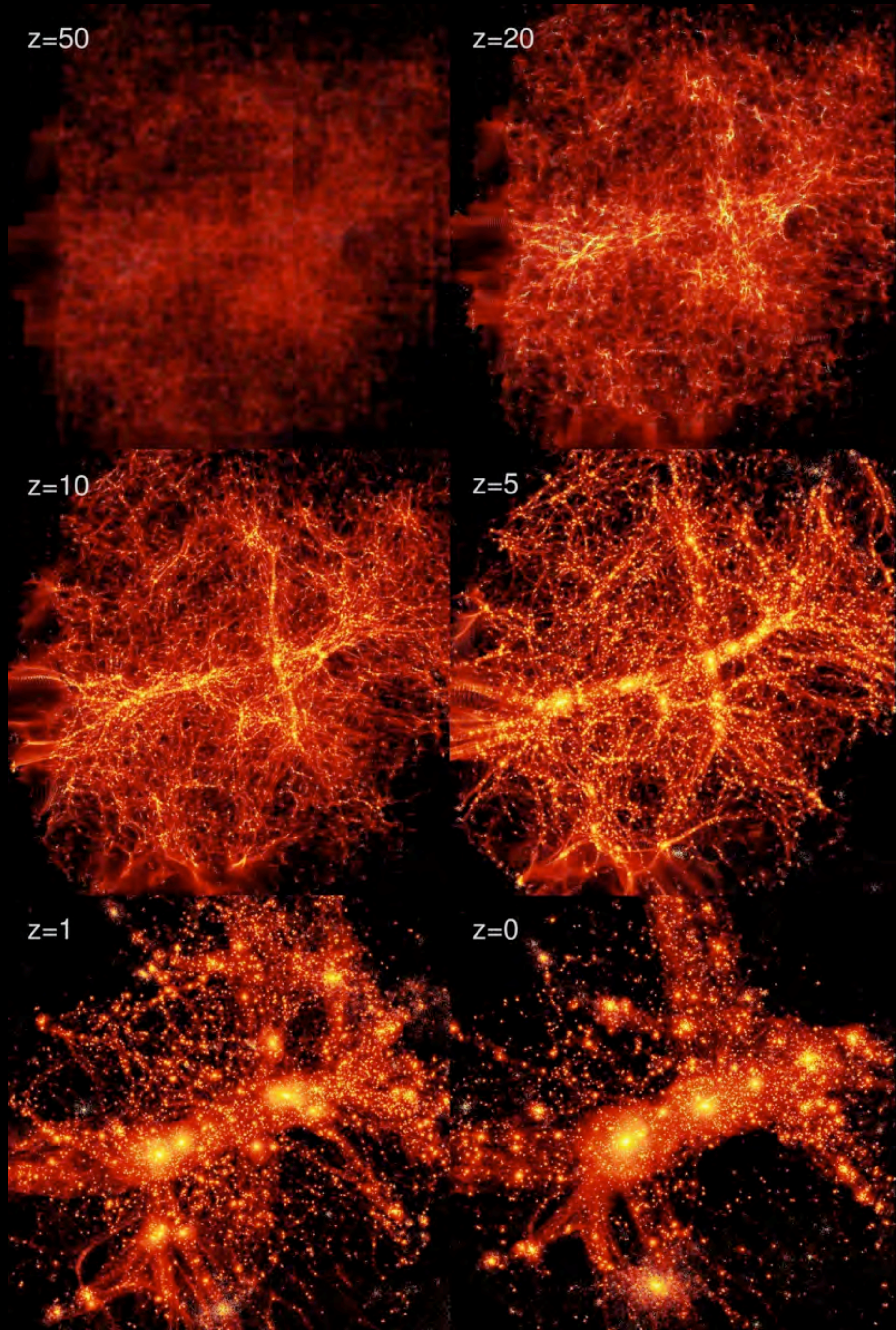
These have not been measured as accurately, and are crucial for distinguishing physics



Growth of perturbations

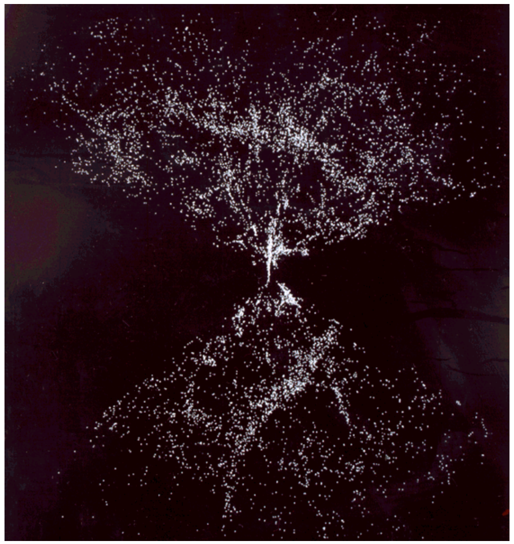
Measure these perturbations as a function of redshift (z) and scale (Fourier mode k)

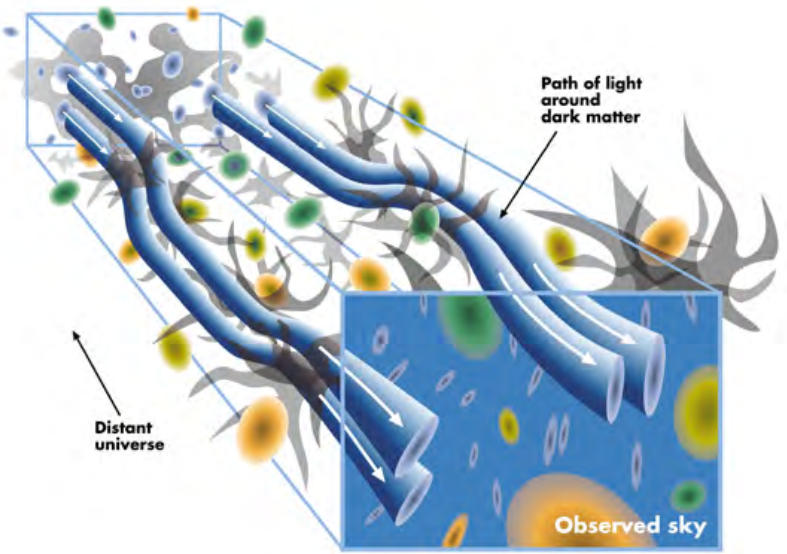


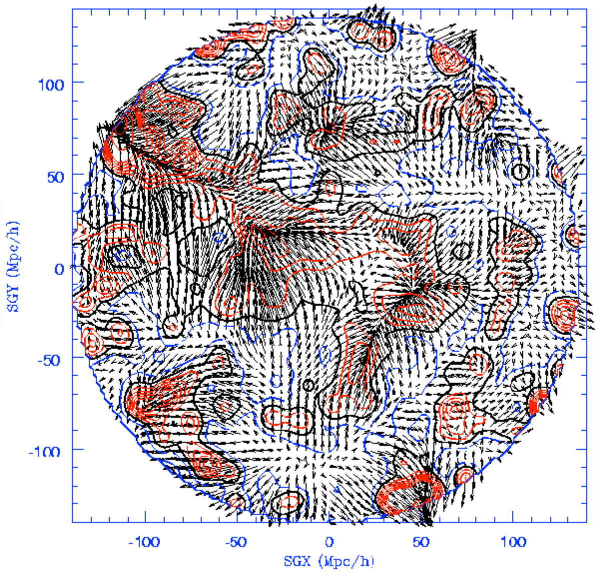


Growth of perturbations

- Clustering of galaxies [measured using a galaxy redshift survey]
- Velocities of objects [measured through the additional Doppler shift in the cosmological redshift]
- Gravitational lensing of light [measured through the correlated shapes of background galaxies as their light passes through structure]
- Abundance/properties of structures e.g. clusters/voids

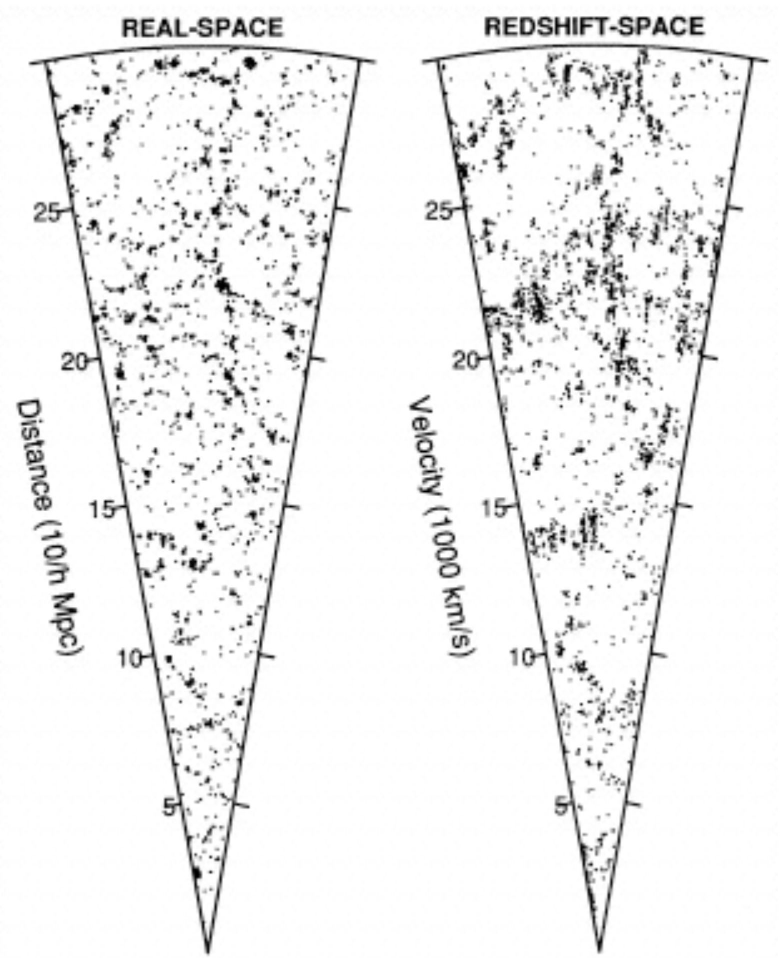






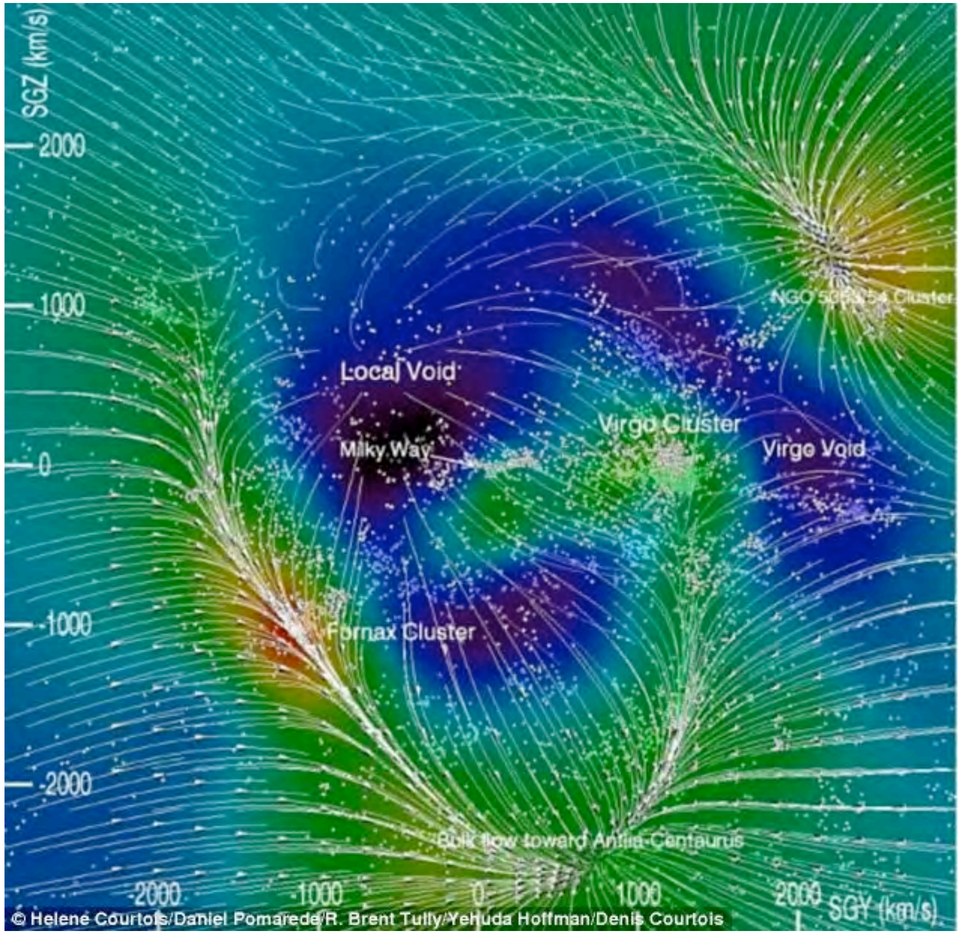
Overview

- What are redshift-space distortions (RSD)?
- How do we measure them?
- Linear theory
- Complicating issues!
- Current measurements
- Future directions



RSD basics

- Galaxies possess coherent "peculiar velocities" on top of the overall cosmological expansion



RSD basics

- Galaxies possess coherent "peculiar velocities" on top of the overall cosmological expansion

RSD basics

- These velocities are driven by the matter distribution, according to gravitational physics
- For example in linear perturbation theory:

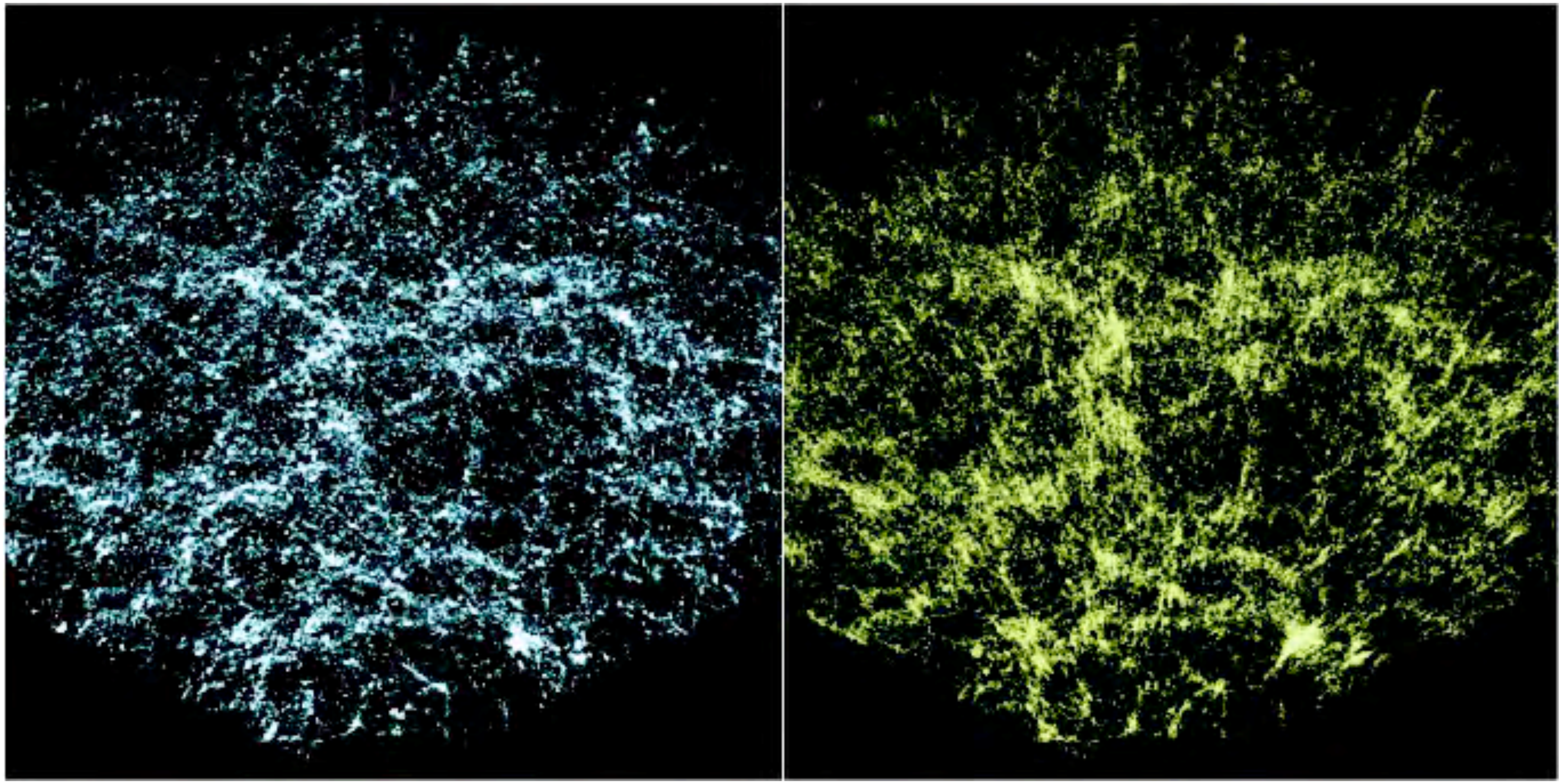
$$\theta = \vec{\nabla}.(\vec{v}/aH) = -f\,\delta_m$$

- in terms of the growth rate $f = d(\ln G)/d(\ln a)$
- where $\delta_m(a) = G(a)\,\delta_m(1)$
- The dependence of the growth rate on scale and time is a key discriminator between gravity models

RSD basics

- Can measure line-of-sight velocities because they add an extra Doppler shift to the galaxy redshift:

$$(1 + z_{\rm obs}) = (1 + z_{\rm cosmo})\,(1 + v_{\rm r}/c)$$



RSD basics

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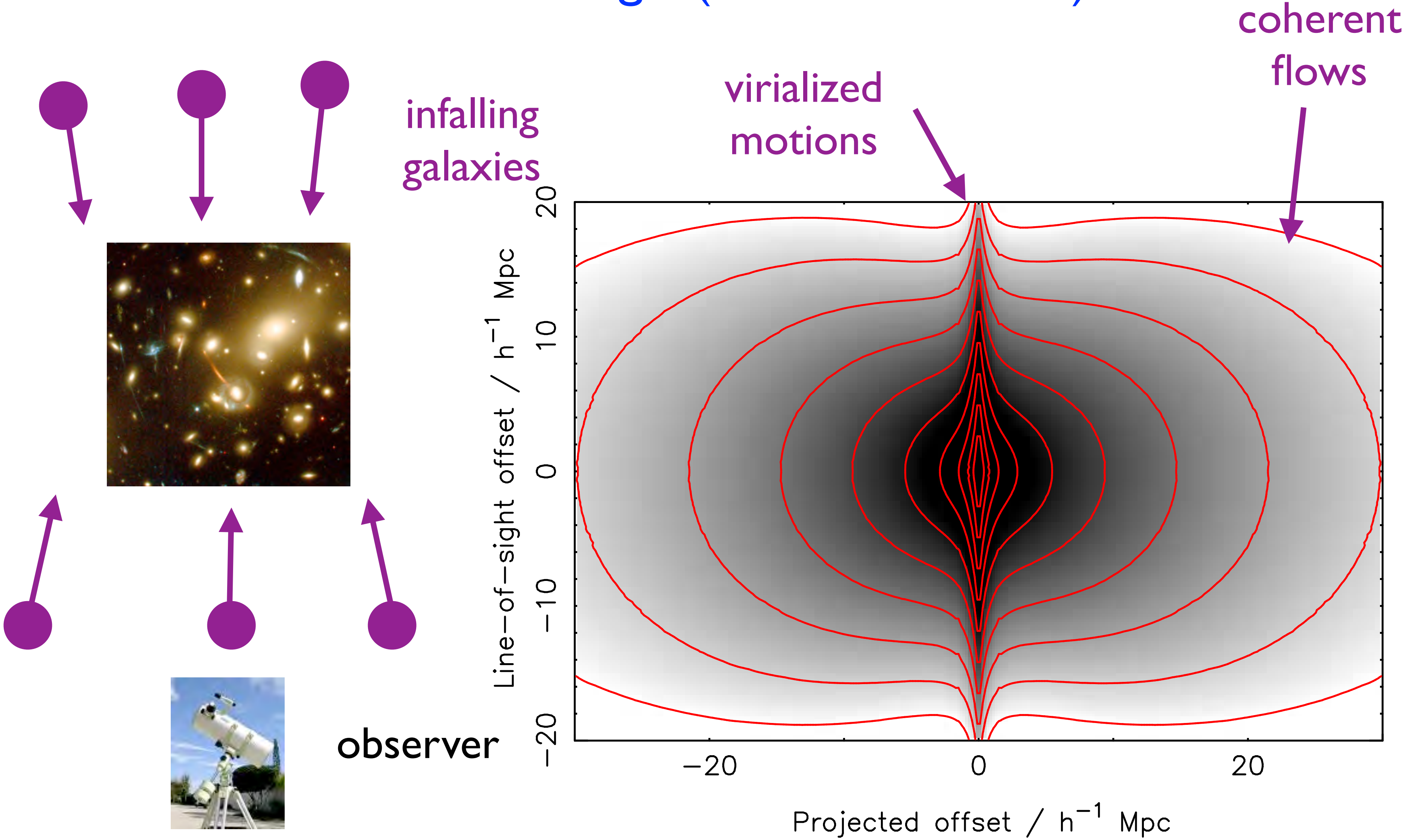
$$(1 + z_{\rm obs}) = (1 + z_{\rm cosmo})\,(1 + v_{\rm r}/c)$$

- Approach (1) : measure direct peculiar velocity v_r using standard-candle estimate of z_{cosmo}
- Approach (2) : measure redshift-space distortions in the clustering distribution of galaxies in "redshift space" (i.e. using positions based on z_{obs})
- The RSD approach has so far been the most accurate method of measuring cosmic growth

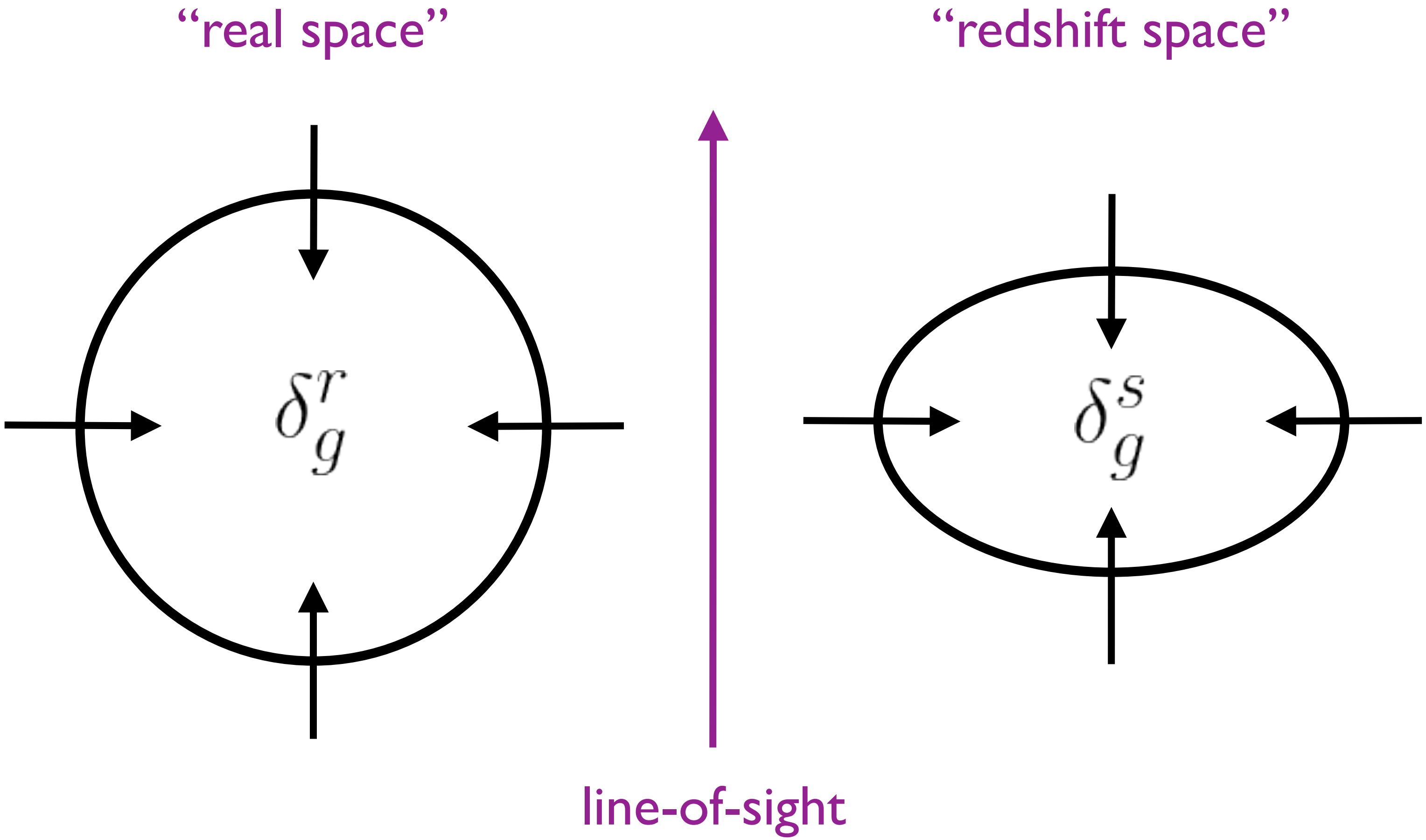
RSD basics

- What are we measuring? (cartoon version)



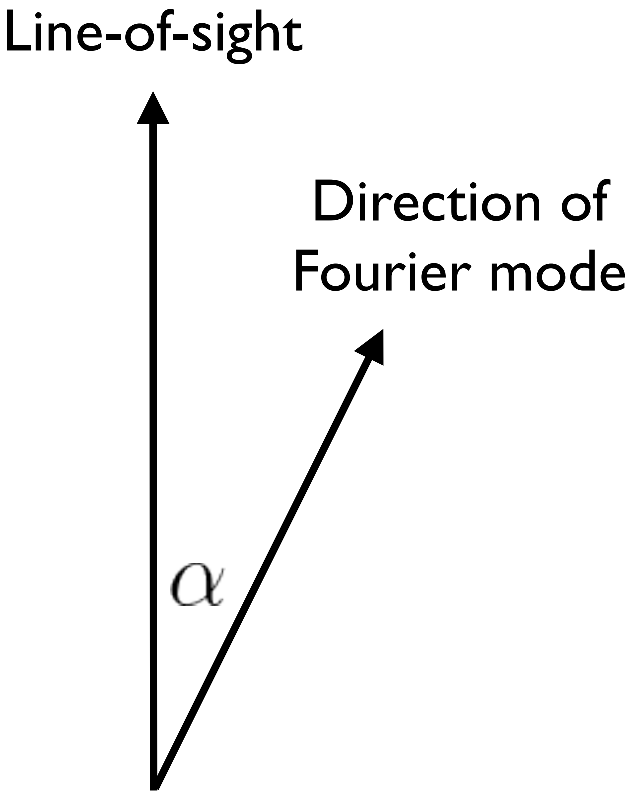
Linear RSD theory

- RSDs amplify galaxy overdensities and imprint a dependence on the angle to the line-of-sight



Linear RSD theory

- How is each Fourier galaxy overdensity mode modulated for a given velocity divergence field ?



$$\mu = \cos\alpha$$

Linear RSD theory

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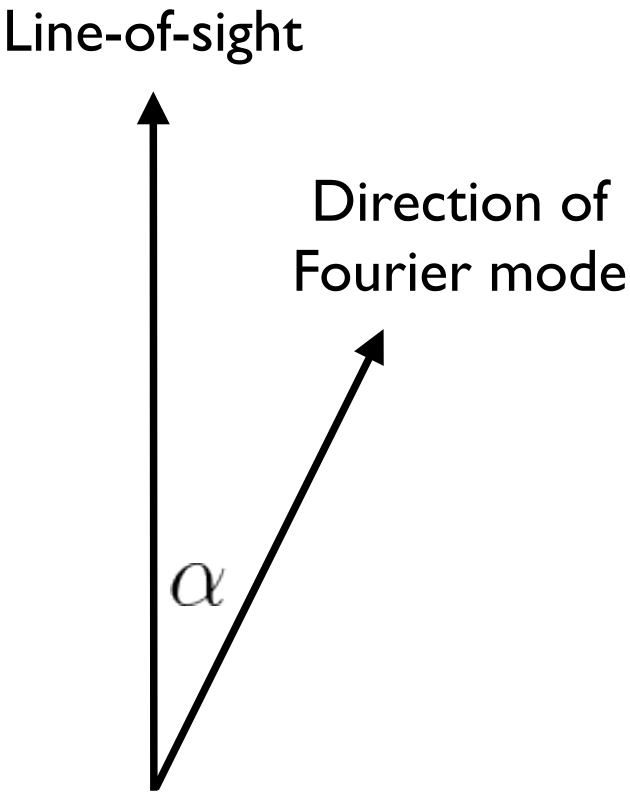

$$\mu = \cos\alpha$$

$$\tilde{\delta}_g^s(k, \mu) = \tilde{\delta}_g^r(k) - \mu^2\,\tilde{\theta}(k)$$

Small print:

- small overdensities
- velocity field irrotational
- continuity equation
- plane-parallel approximation

Linear RSD theory

$$P_g^s(k,\mu) = P_{gg}(k) - 2\mu^2\, P_{g\theta}(k) + \mu^4\, P_{\theta\theta}(k)$$

Linear RSD theory

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- Linear galaxy bias $\quad \delta_g = b\,\delta_m$

$$P_g^s(k,\mu) = P_m(k)\,(b + f\mu^2)^2$$

Linear RSD theory

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Linear RSD theory

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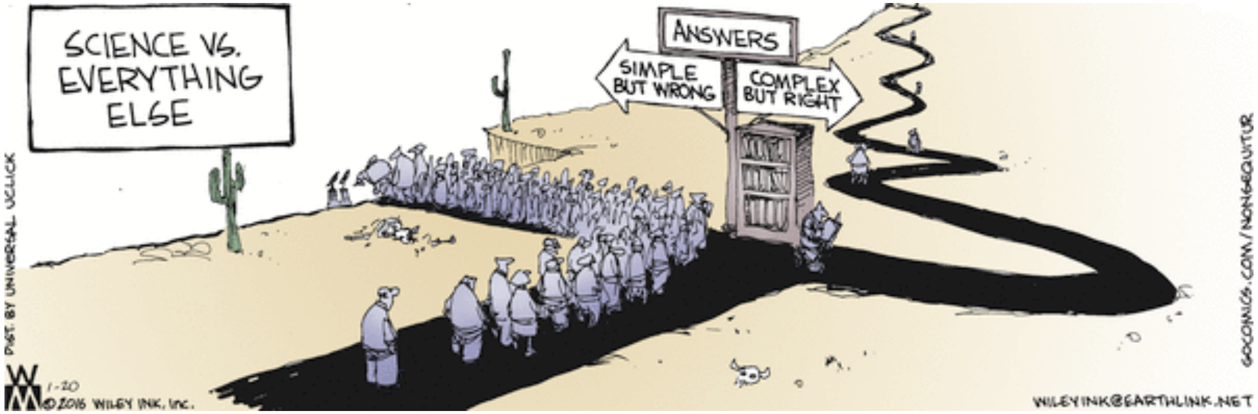
$$P_g^s(k,\mu) = P_m(k)\,(b + f\mu^2)^2$$

- Matter power spectrum $P_m(k) \propto \sigma_8^2$
- Conclusion (1) : Linear RSD measures $(f\,\sigma_8,\, b\,\sigma_8)$
- Conclusion (2) : Hexadecapole is sensitive to $P_{\theta\theta}(k)$ - a quantity which responds directly to mass (like lensing)

Issues!



- "Linear theory" never applies in practice!
- Perturbation theory breaks down
- Galaxy velocities have a random component
- Galaxy bias is not linear, local or deterministic
- The theoretical uncertainty in the model is greater than the observational errors!

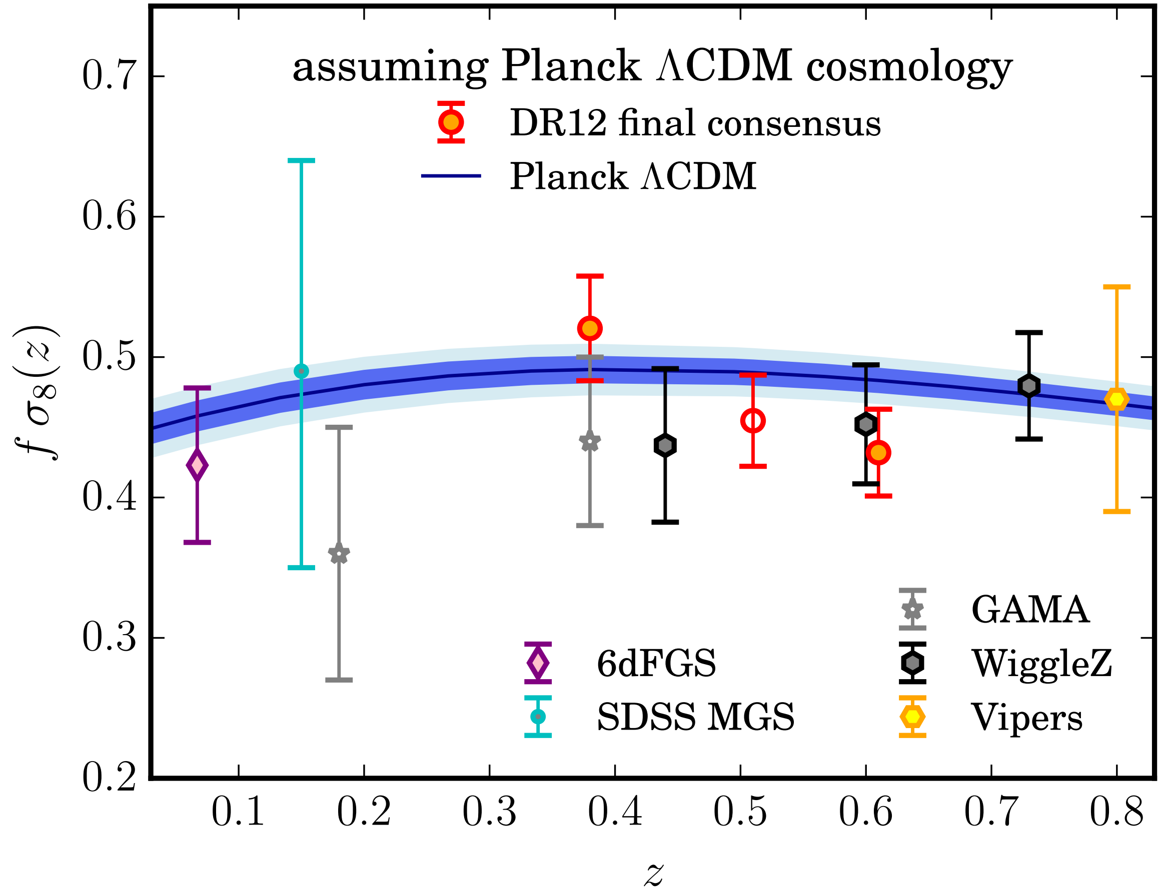
RSD measurements

- Perform a large galaxy redshift survey
- Assume a fiducial cosmology to measure the galaxy clustering as a function of scale and line-of-sight angle
- Compress this information (e.g. into multipoles)
- Fit for the growth rate, marginalizing over nuisance parameters (e.g. velocity dispersion, galaxy bias)
- Use mock catalogues built from N-body simulations to test the model and covariance
- Compare the measurements to cosmological models

RSD measurements

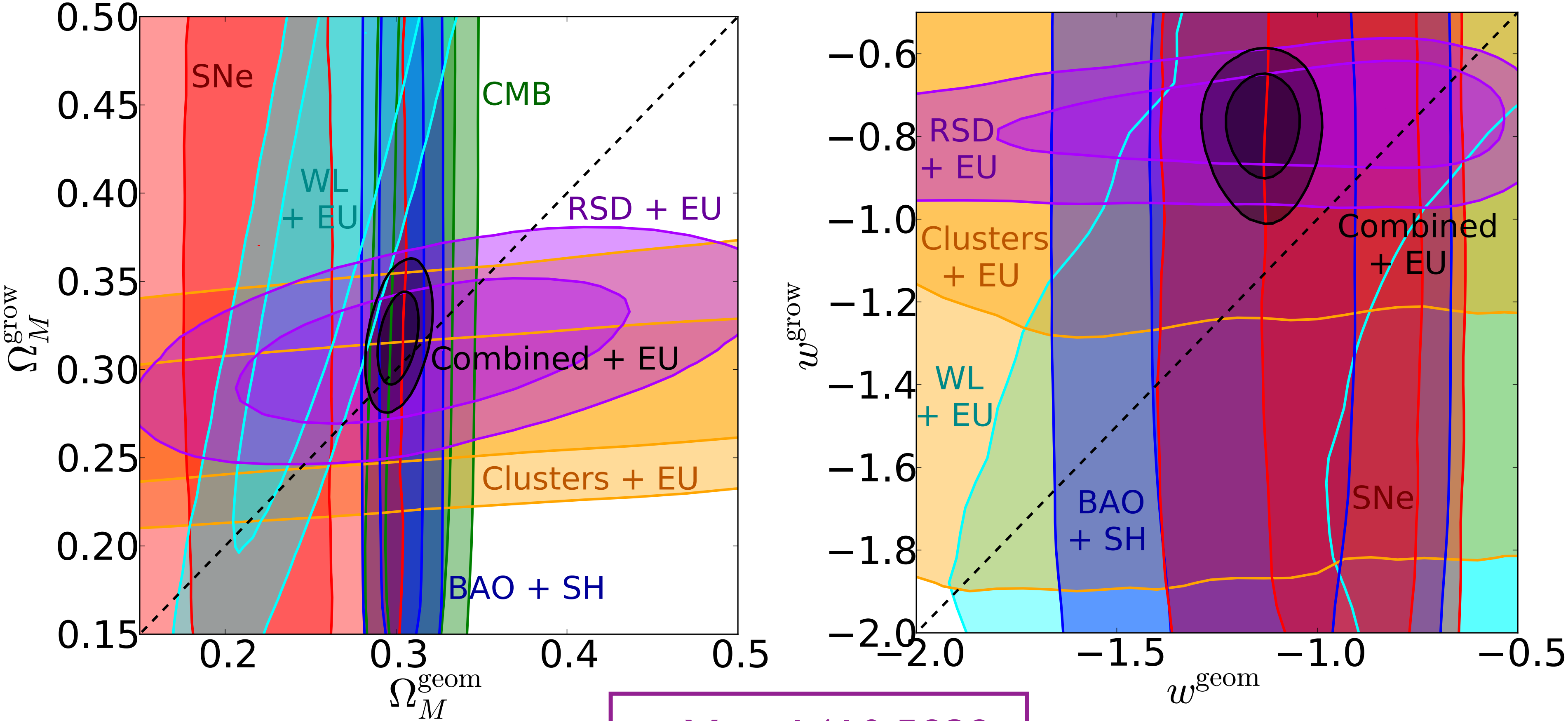
- Current status: ~10% growth measurements in the range z < 1, "reasonable agreement" with CMB

arXiv : 1607.03155



RSD measurements

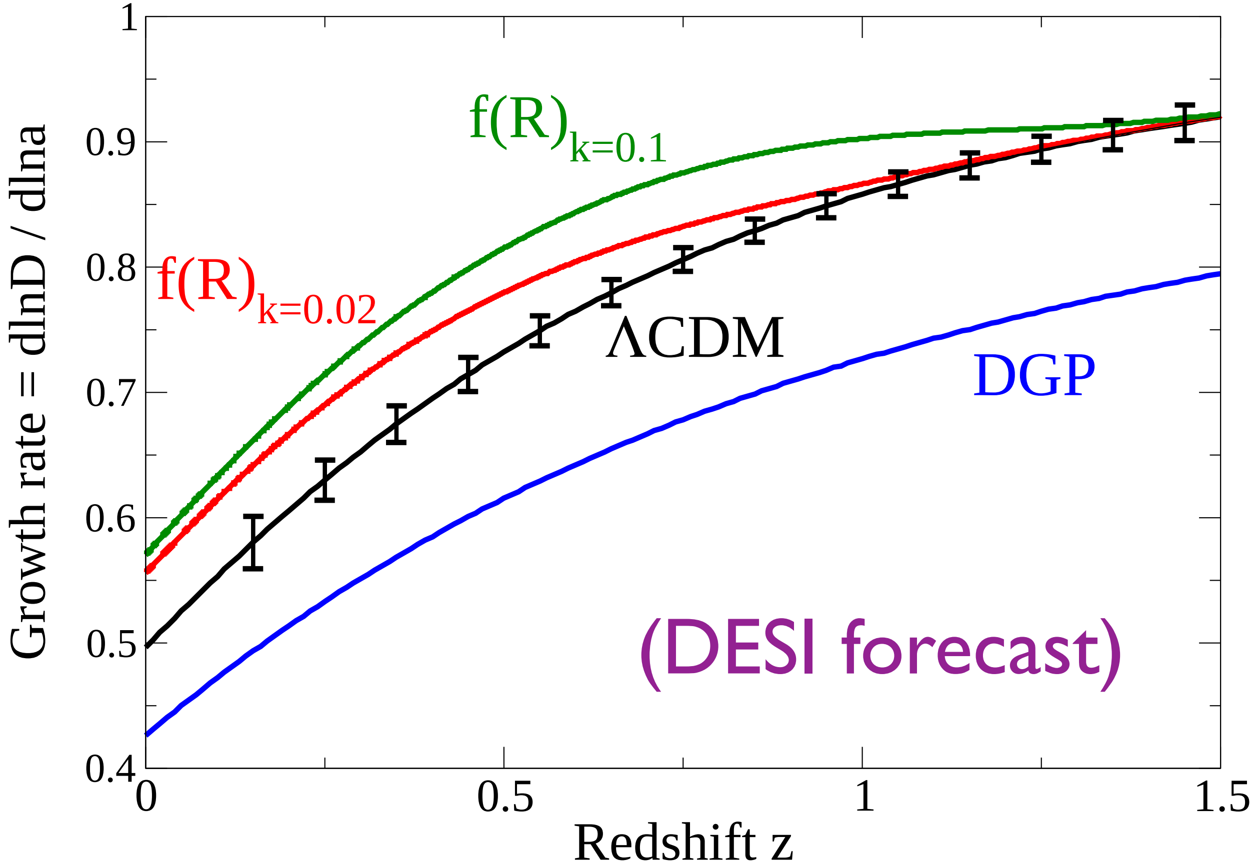
- Current status: some tensions between expansion and growth probes!



arXiv : 1410.5832

Future directions

- Future galaxy redshift surveys (e.g. DESI, Euclid, SKA) will allow per-cent level growth measurements



arXiv : 1309.5385

Future directions

- Modelling of small-scale intra-halo velocities could allow incredibly precise tests of gravitational physics

A 2.5% measurement of the growth rate from small-scale redshift space clustering of SDSS-III CMASS galaxies

Beth A. Reid[1,2,3]⋆, Hee-Jong Seo[3,4], Alexie Leauthaud[5], Jeremy L. Tinker[6], Martin White[1,7]

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[2] *Hubble Fellow*
[3] *Berkeley Center for Cosmological Physics, LBL and Department of Physics, University of California, Berkeley, CA, 94720, USA*
[4] *Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210, USA*
[5] *Kavli Institute for the Physics and Mathematics of the Universe, Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa, Japan 277-8583*
[6] *Center for Cosmology and Particle Physics, Department of Physics New York University, USA*
[7] *Departments of Physics and Astronomy, University of California, Berkeley, CA, 94720, USA*

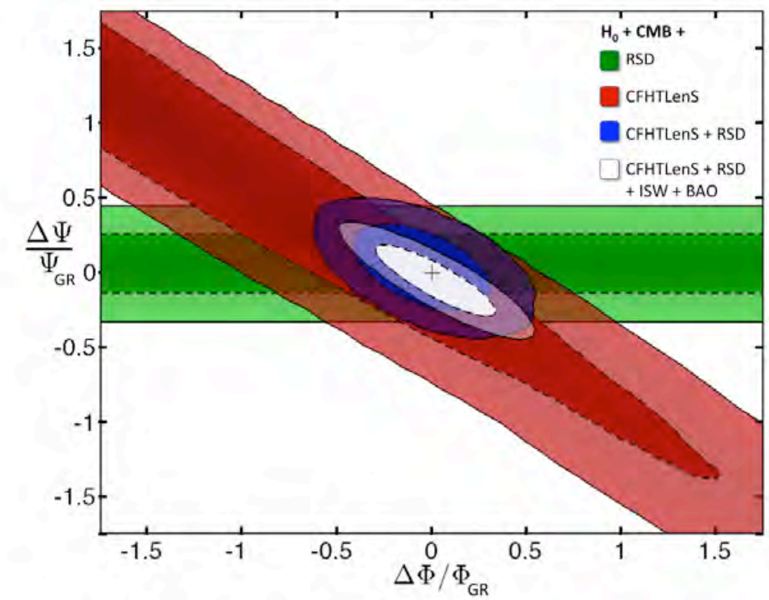
18 July 2014

ABSTRACT
We perform the first fit to the anisotropic clustering of SDSS-III CMASS DR10 galaxies on scales of $\sim 0.8-32\, h^{-1}$ Mpc. A standard halo occupation distribution model evaluated near the best fit Planck ΛCDM cosmology provides a good fit to the observed anisotropic clustering, and implies a normalization for the peculiar velocity field of $M \sim 2\times10^{13}\, h^{-1}\, M_\odot$ halos of $f\sigma_8(z = 0.57) = 0.450 \pm 0.011$. Since this constraint includes both quasi-linear and non-linear scales, it should severely constrain modified gravity models that enhance pairwise infall velocities on these scales. Though model dependent, our measurement represents a factor of 2.5 improvement in precision over the analysis of DR11 on large scales, $f\sigma_8(z = 0.57) = 0.447 \pm 0.028$, and is the tightest single constraint on the growth rate of cosmic structure to date. Our measurement is consistent with the Planck ΛCDM prediction of 0.480 ± 0.010 at the $\sim 1.9\sigma$ level. Assuming a halo mass function evaluated at the best fit Planck cosmology,

arXiv : 1404.3742

Future directions

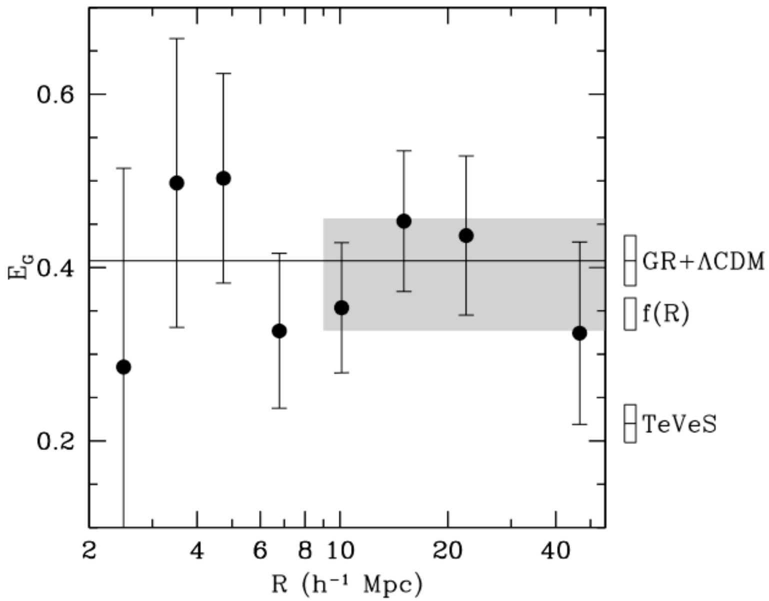
- Cross-correlations with weak lensing allow tests of the gravitational metric potentials (and systematics)



arXiv:1212.3339

CFHTLenS: Testing the Laws of Gravity with Tomographic Weak Lensing and Redshift Space Distortions

Fergus Simpson[1*], Catherine Heymans[1], David Parkinson[2], Chris Blake[3], Martin Kilbinger[4,5,6], Jonathan Benjamin[7], Thomas Erben[8], Hendrik Hildebrandt[7,8], Henk Hoekstra[9,10], Thomas D. Kitching[1], Yannick Mellier[11], Lance Miller[12]

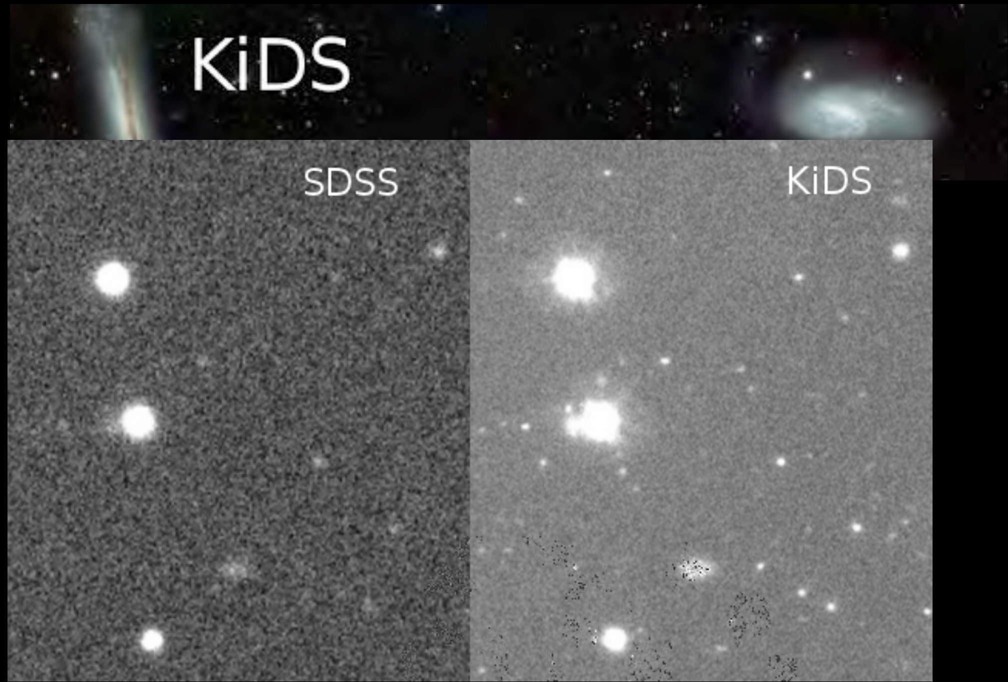


arXiv:1003.2185

Confirmation of general relativity on large scales from weak lensing and galaxy velocities[1]

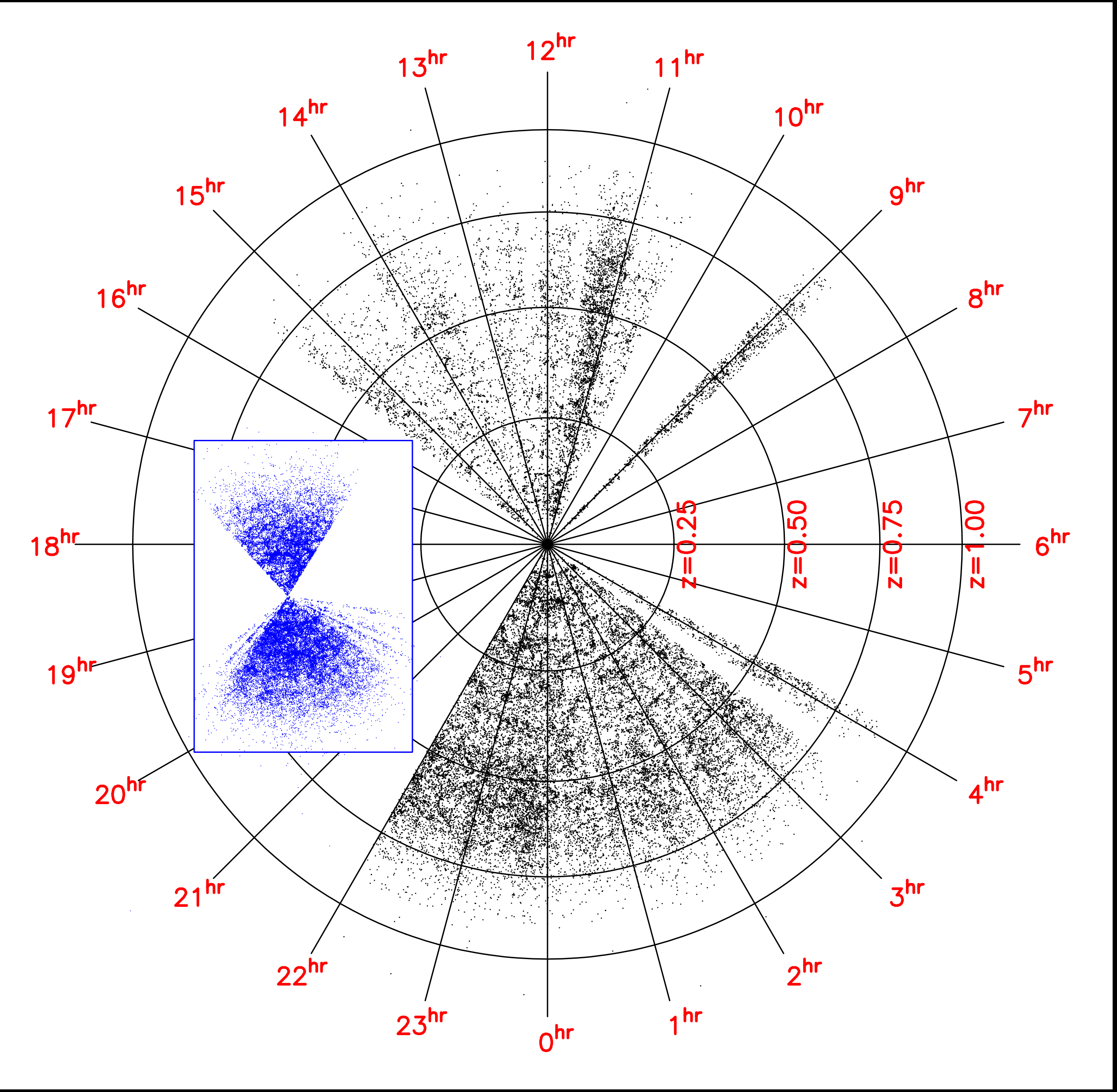
Reinabelle Reyes[1], Rachel Mandelbaum[1], Uros Seljak[2-4], Tobias Baldauf[2], James E. Gunn[1], Lucas Lombriser[2], Robert E. Smith[2]

2-degree Field Lensing Survey (2dFLenS)



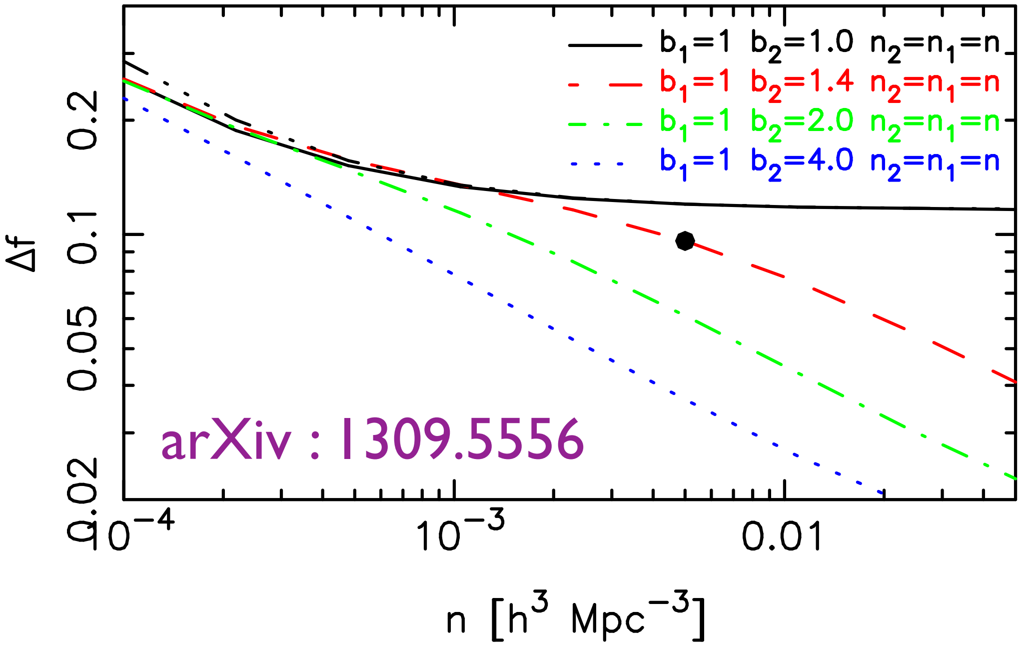
- 50 AAT nights used for spectroscopic follow-up of southern lensing surveys such as KiDS and DES
- Galaxy lens sample (~50,000) to test gravity by cross-correlating weak lensing and galaxy velocities
- Photo-z calibration samples (direct / cross-correlation)

2-degree Field Lensing Survey (2dFLenS)



Future directions

- Surveying multiple galaxy populations across the same volume enables growth measurements below the usual "sample variance" floor



$$\tilde{\delta}_1(\vec{k}) = (b_1 + f\mu^2)\,\tilde{\delta}_m(\vec{k})$$

$$\tilde{\delta}_2(\vec{k}) = (b_2 + f\mu^2)\,\tilde{\delta}_m(\vec{k})$$

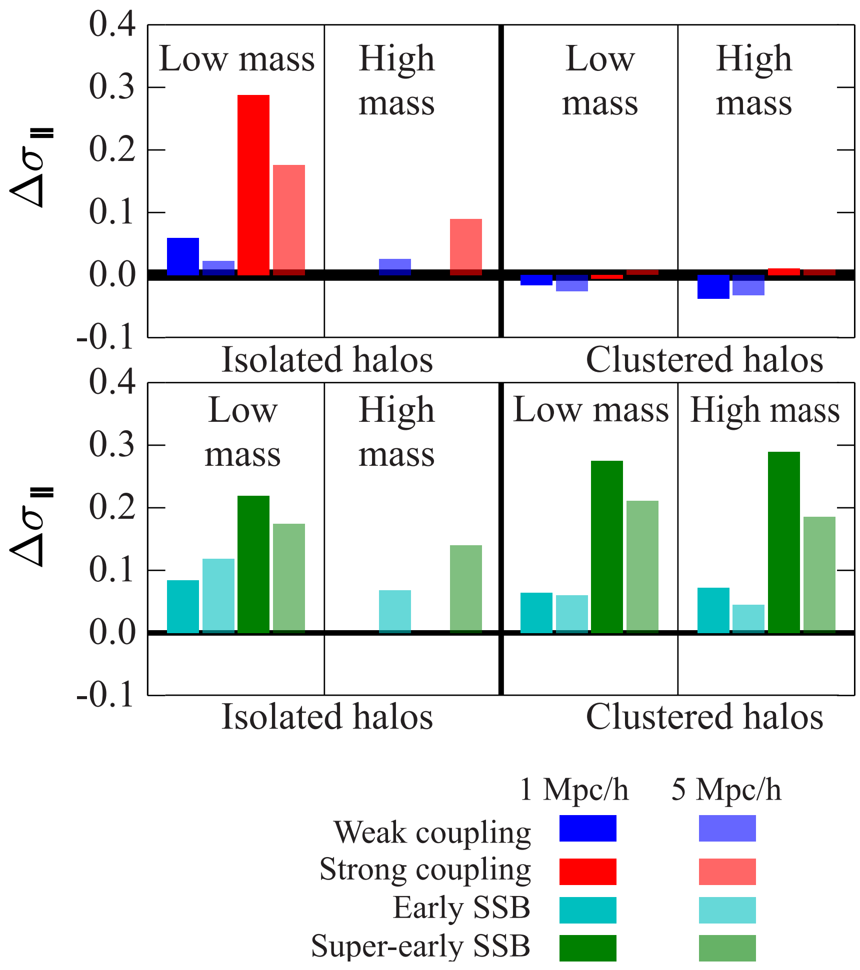
$$\frac{\tilde{\delta}_2(\vec{k})}{\tilde{\delta}_1(\vec{k})} = \frac{b_2 + f\mu^2}{b_1 + f\mu^2}$$

(also see Caitlin's talk!)

Future directions

- Environmental velocity statistics (e.g. around clusters, voids) can distinguish between screening mechanisms in modified gravity scenarios

(also see Ixandra's talk!)



arXiv : 1603.03072

Summary

- Need to simultaneously measure expansion and growth to distinguish dark energy physics
- Redshift-space distortions in galaxy surveys offer the most precise existing growth test
- Data is now more precise than our ability to model it!
- N-body simulations will be critical for calibrating models and exploring modified gravity effects
- The next decade will see orders of magnitude increases in data : will we be able to utilize it?