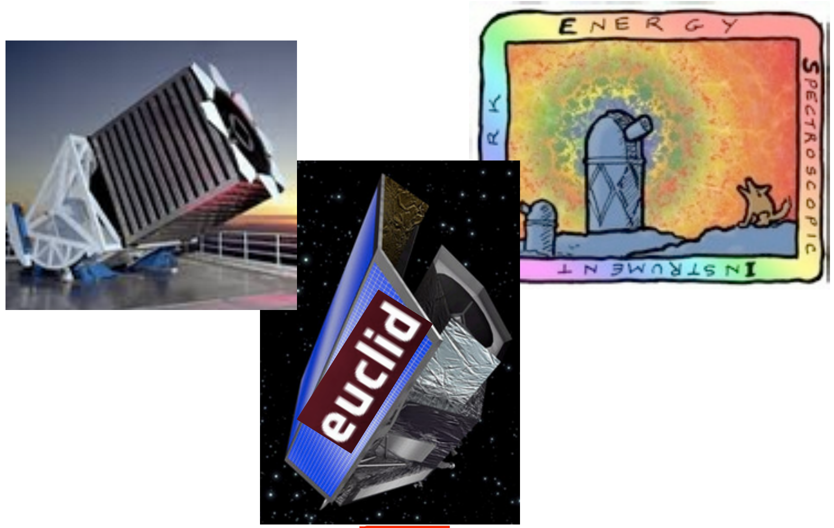
Galaxy gravitational redshifts and Lyman-alpha emission intensity: Results from SDSS/BOSS

Rupert Croft
Shadab Alam
Shirley Ho
Jordi Miralda-Escude
Zheng Zheng
+ SDSS/BOSS collaboration

THE MCWILLIAMS
Center for Cosmology

Carnegie Mellon University

observational cosmology

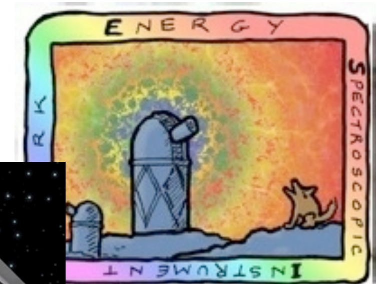


?

precision
cosmology:

BAO
lensing
redshift
distortions
…

observational cosmology



(1) Gravitational redshifts from large-scale structure

(2) Lya intensity mapping

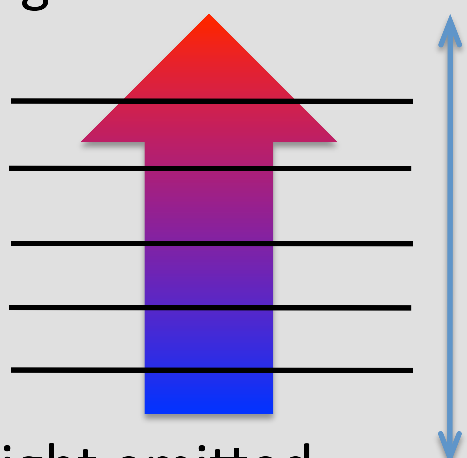
precision cosmology:

BAO
lensing
redshift distortions
…

Test of GR: lab measurement of gravitational redshifts.

1960 Pound-Rebka experiment

light received



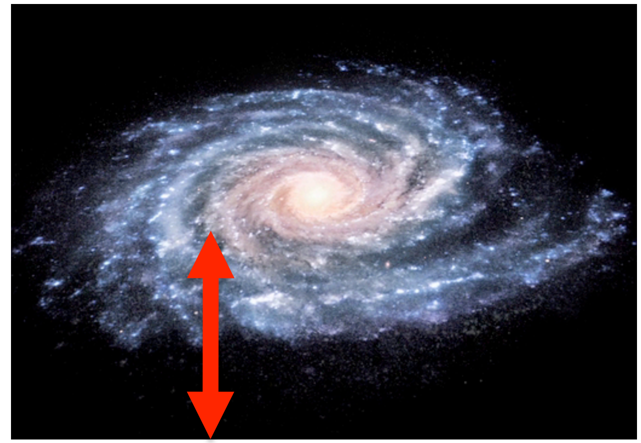
light emitted

gravitational
potential
difference

$$\Delta\phi$$

gravitational redshift

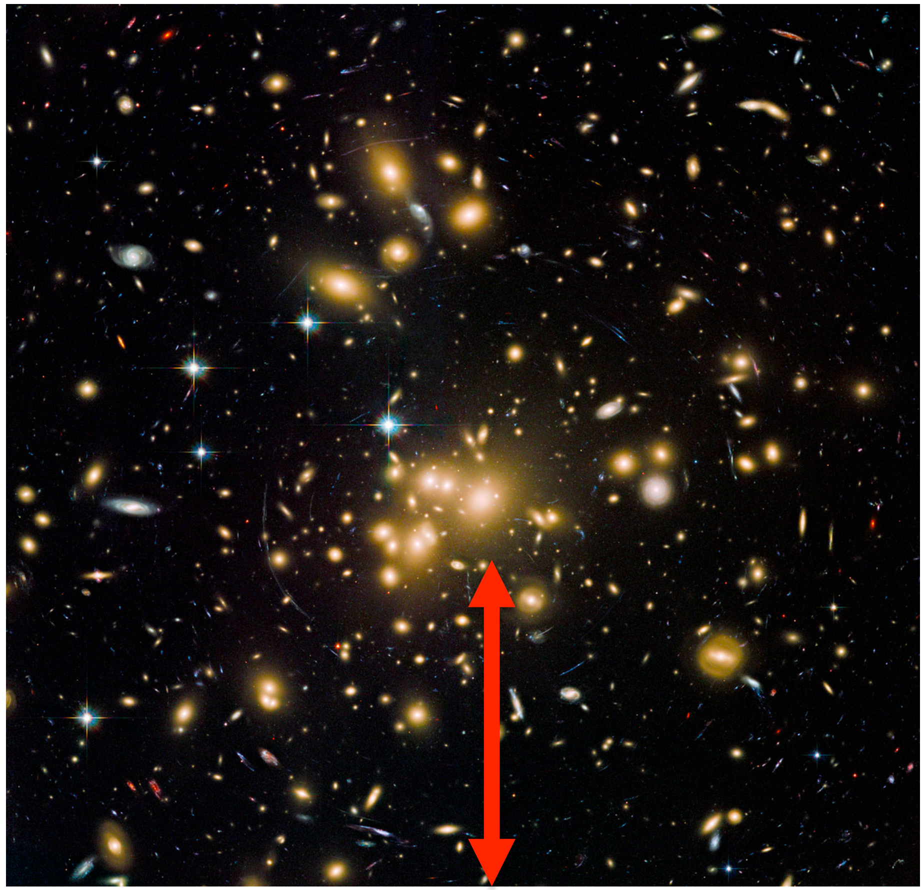
$$z_g = \frac{\Delta\lambda}{\lambda} \simeq \frac{\Delta\phi}{c^2}$$



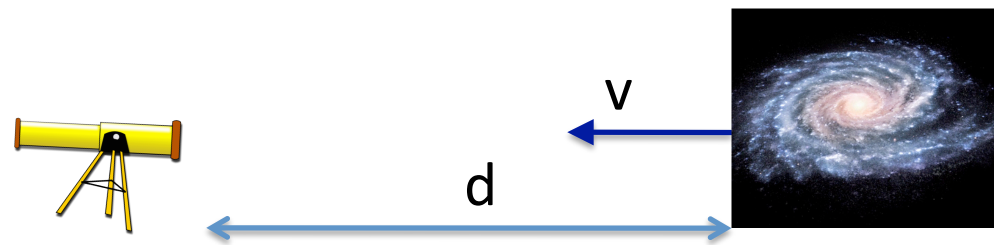
$cz_g = v \approx \frac{gh}{c} = 7.5{\times}10^{-7}$ m/s

$cz_g \sim$ 1 km/s

best place to look: galaxy cluster



prediction: cz=10-50 km/s (Nottale 1976)



redshift of a galaxy:

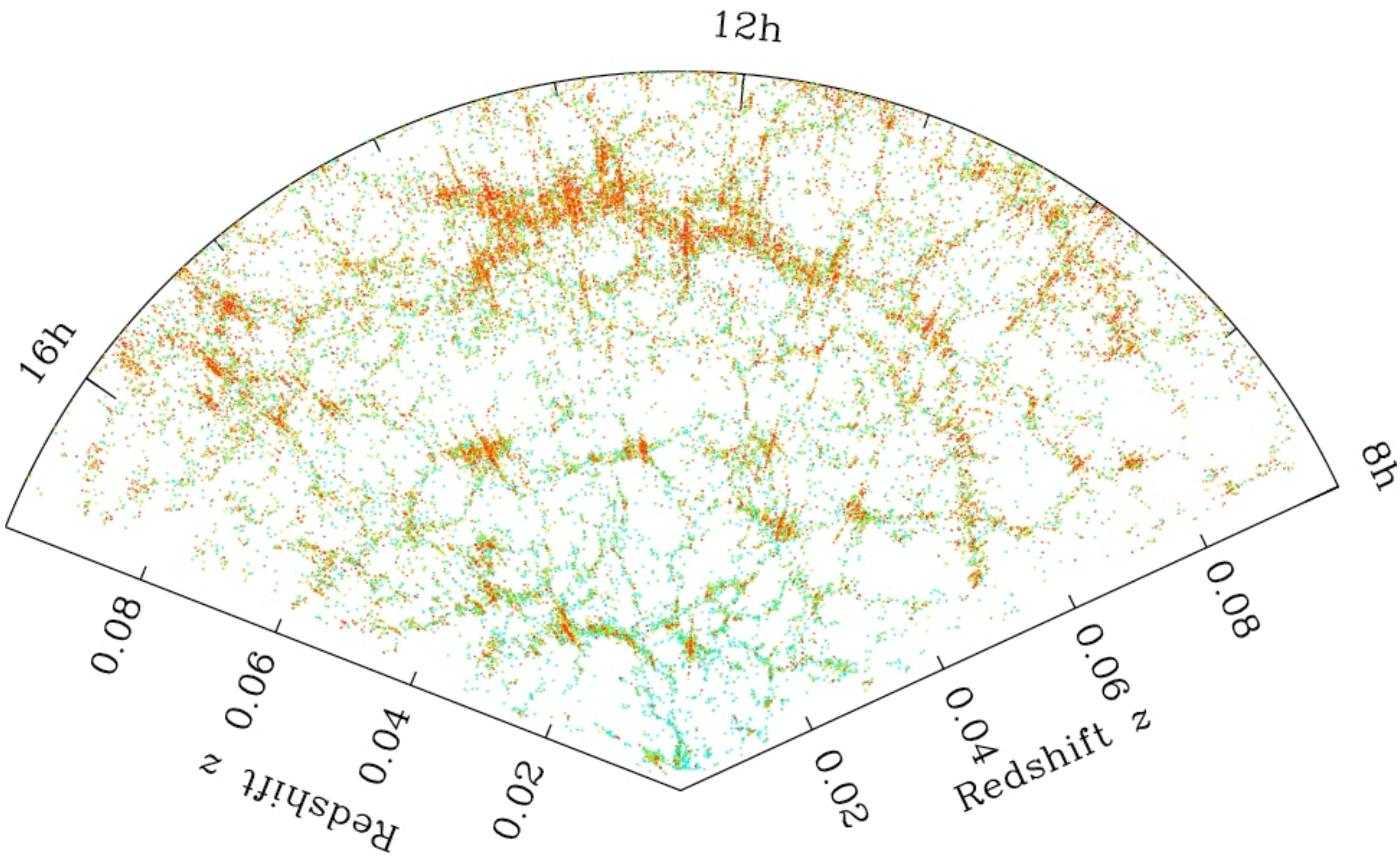
$$cz = Hd + v + \frac{\Delta\phi}{c}$$

Hubble expansion

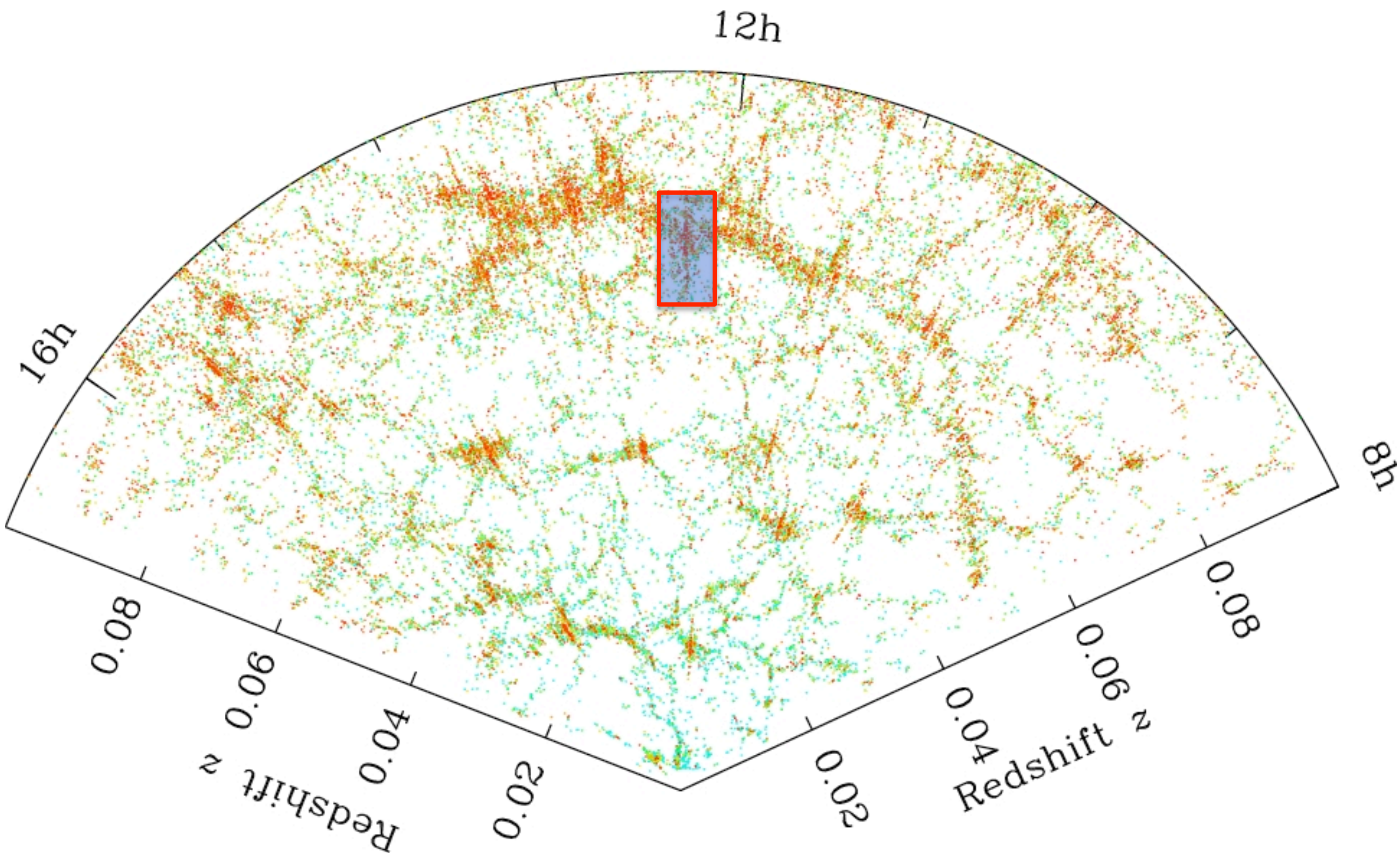
Peculiar velocity

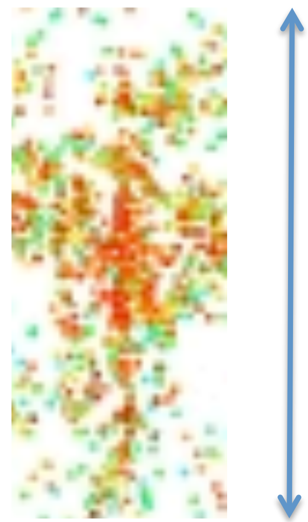
Gravitational redshift

Redshift map of SDSS galaxies



Redshift map of SDSS galaxies





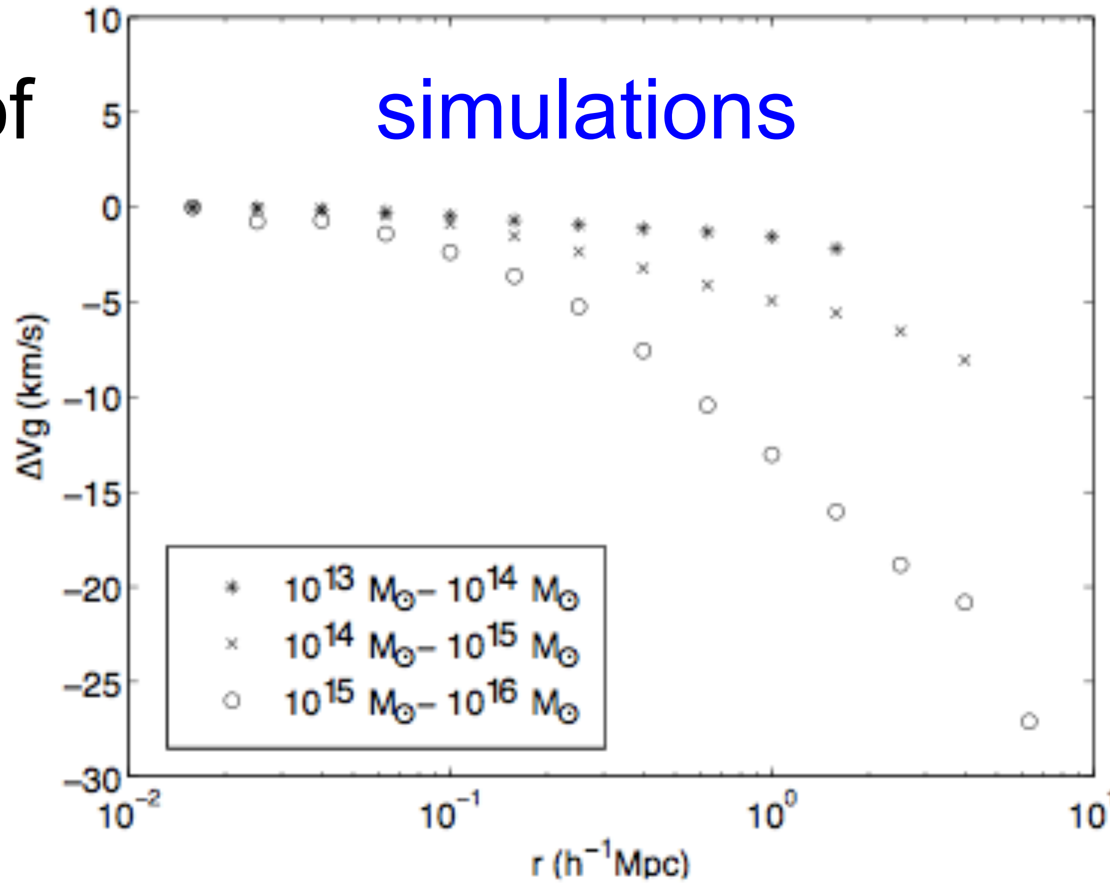
Peculiar motions
of galaxies in
clusters give velocity
dispersion
>1000 km/s

have ~100 galaxies
so Poisson error
on mean is ~100 km/s

z_g signal is ~10 km/s

Solution: average over many clusters

center of cluster



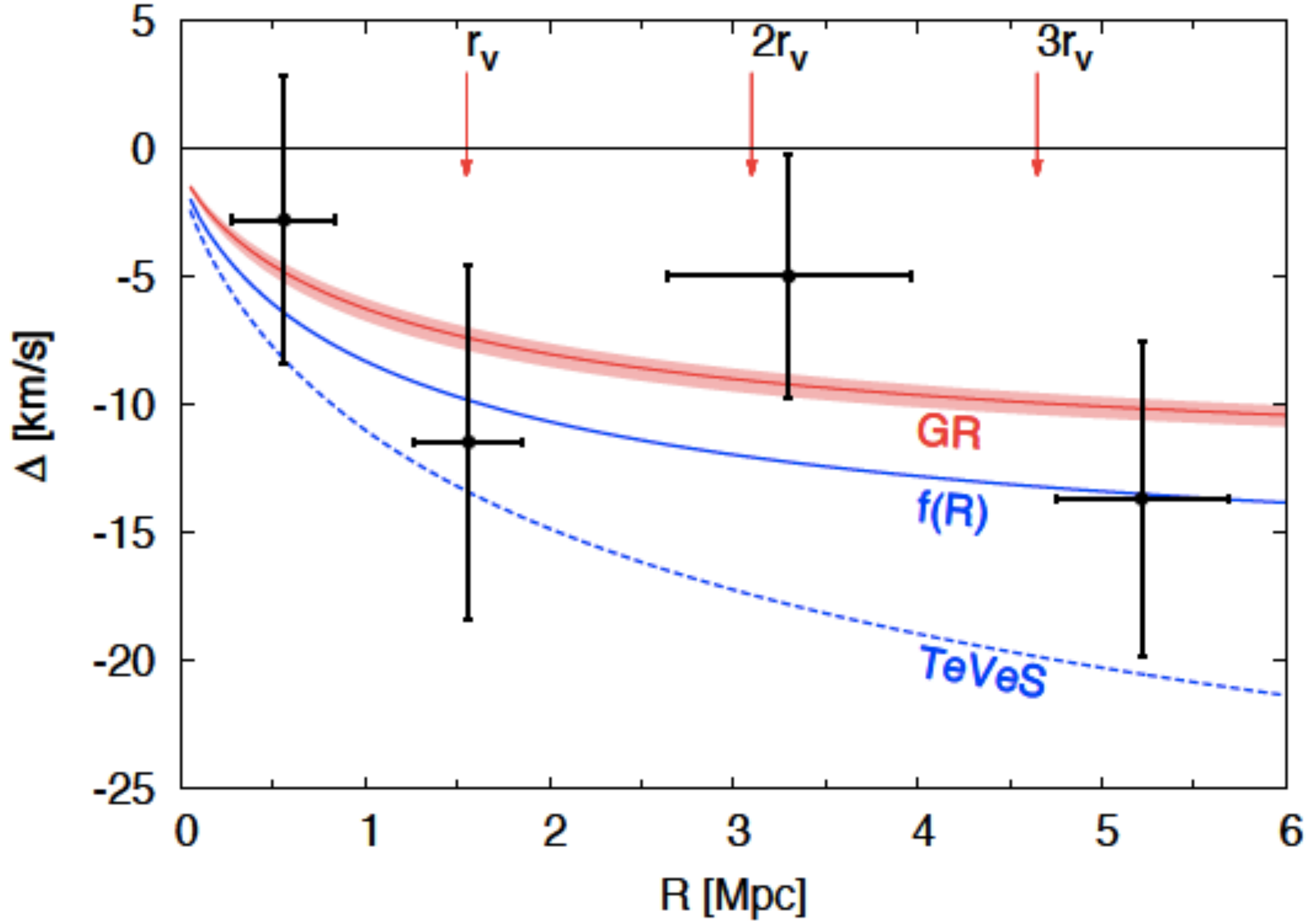
edge of cluster

relative blueshift

(Kim & RC 2004)

First application to observational data (SDSS) by Wojtak et al. (2011):
(Nature 477, 576)

relative redshift

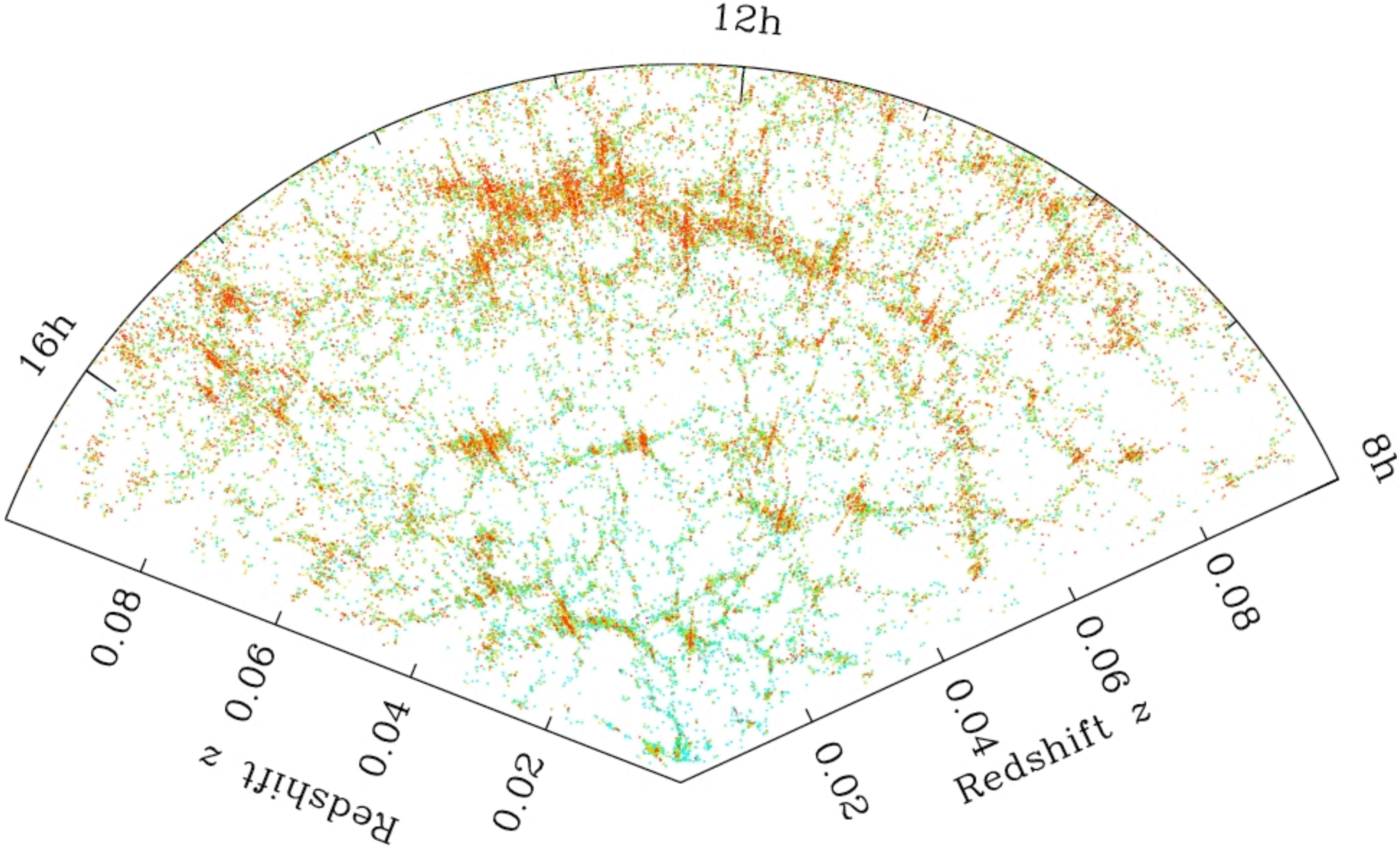


2.8 sigma

distance to central galaxy

(other measurements:
Dominguez 2012, Sadeh 2015, Jimeno 2015)

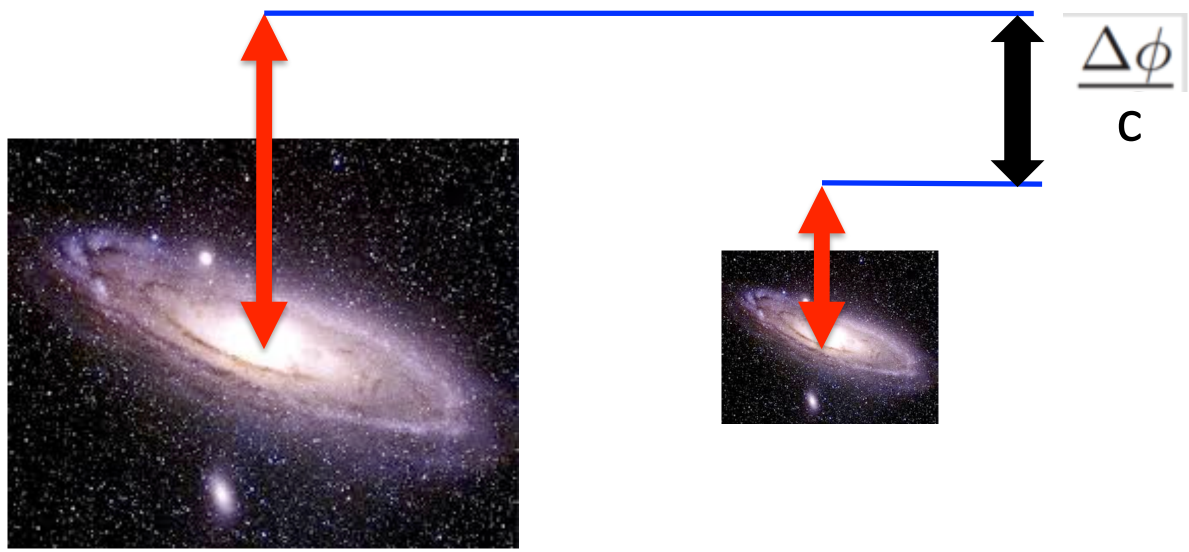
What about gravitational redshifts from large-scale structure?



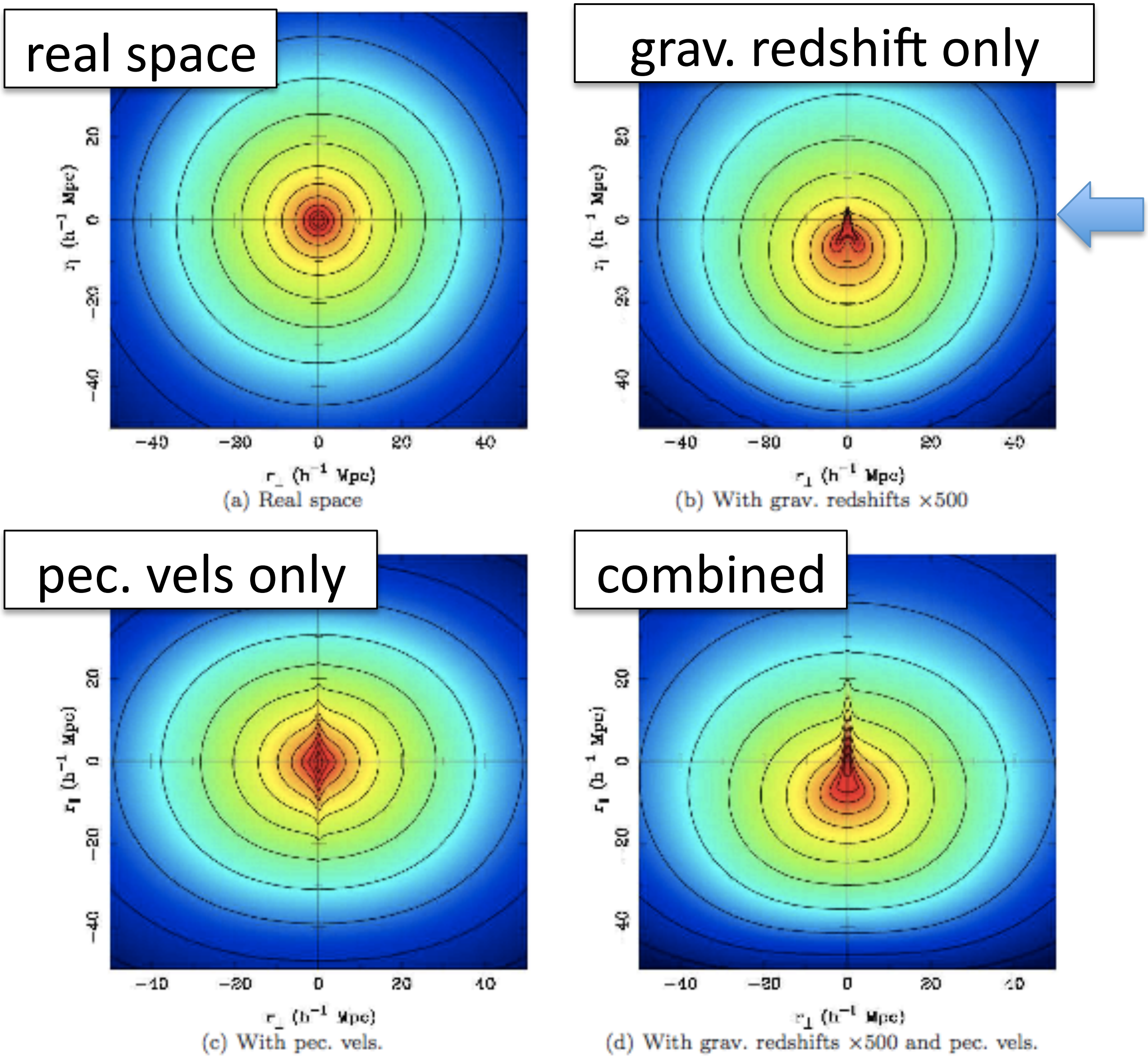
SDSS galaxies

Use all data: average over all pairs of galaxies:

most massive one in a pair will have higher z_g



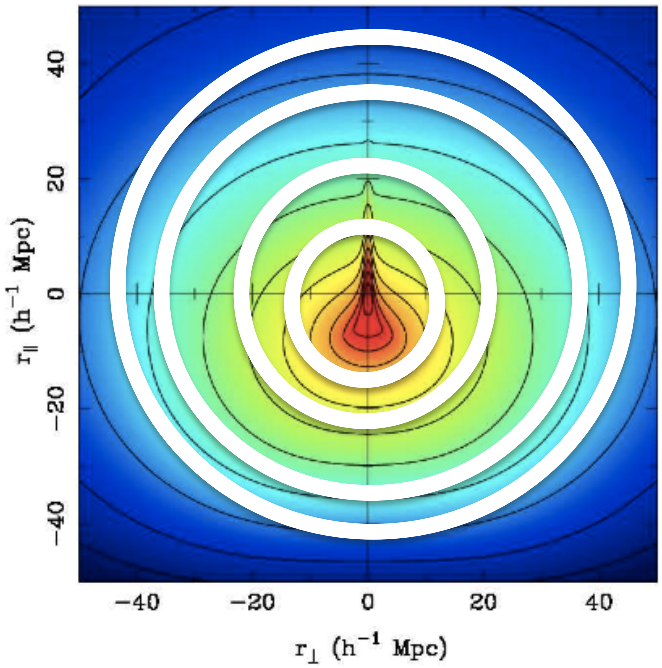
2d (parallel and perp to line of sight) cross-correlation function of top mass half and bottom mass half of galaxies.

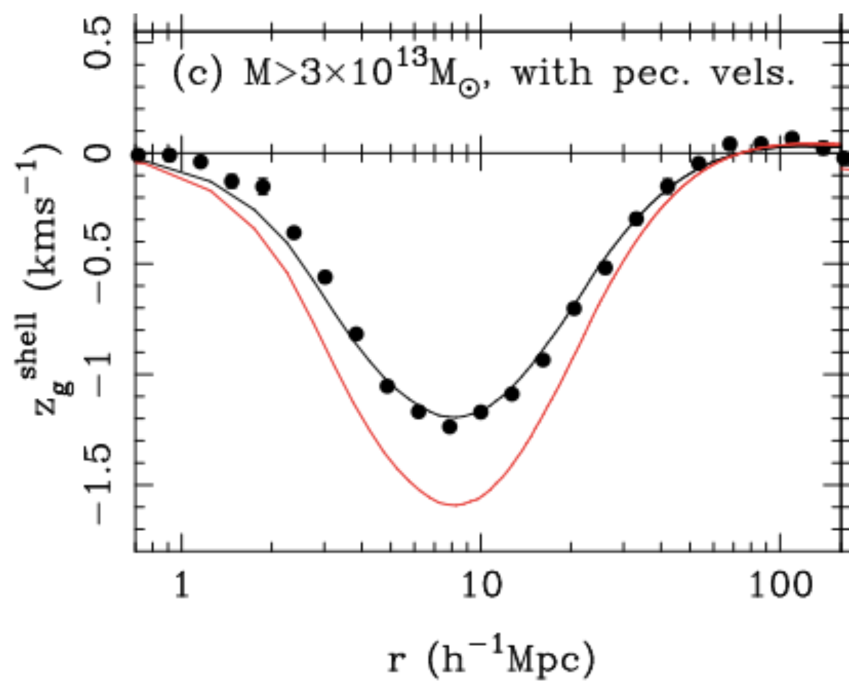


grav. redshift
x 500 !

prediction from
halo model
(RC, 2013)

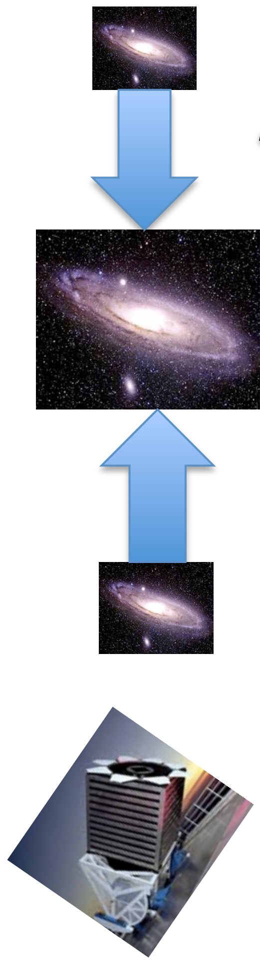
Estimator: compare mean redshift of pairs of galaxies in shells





Analytic theory vs simulation

Other relativistic effects:
Zhao & Peacock (2012), Kaiser(2013), Bonvin et al. (2014), McDonald (2009)
e.g., special relativistic beaming:

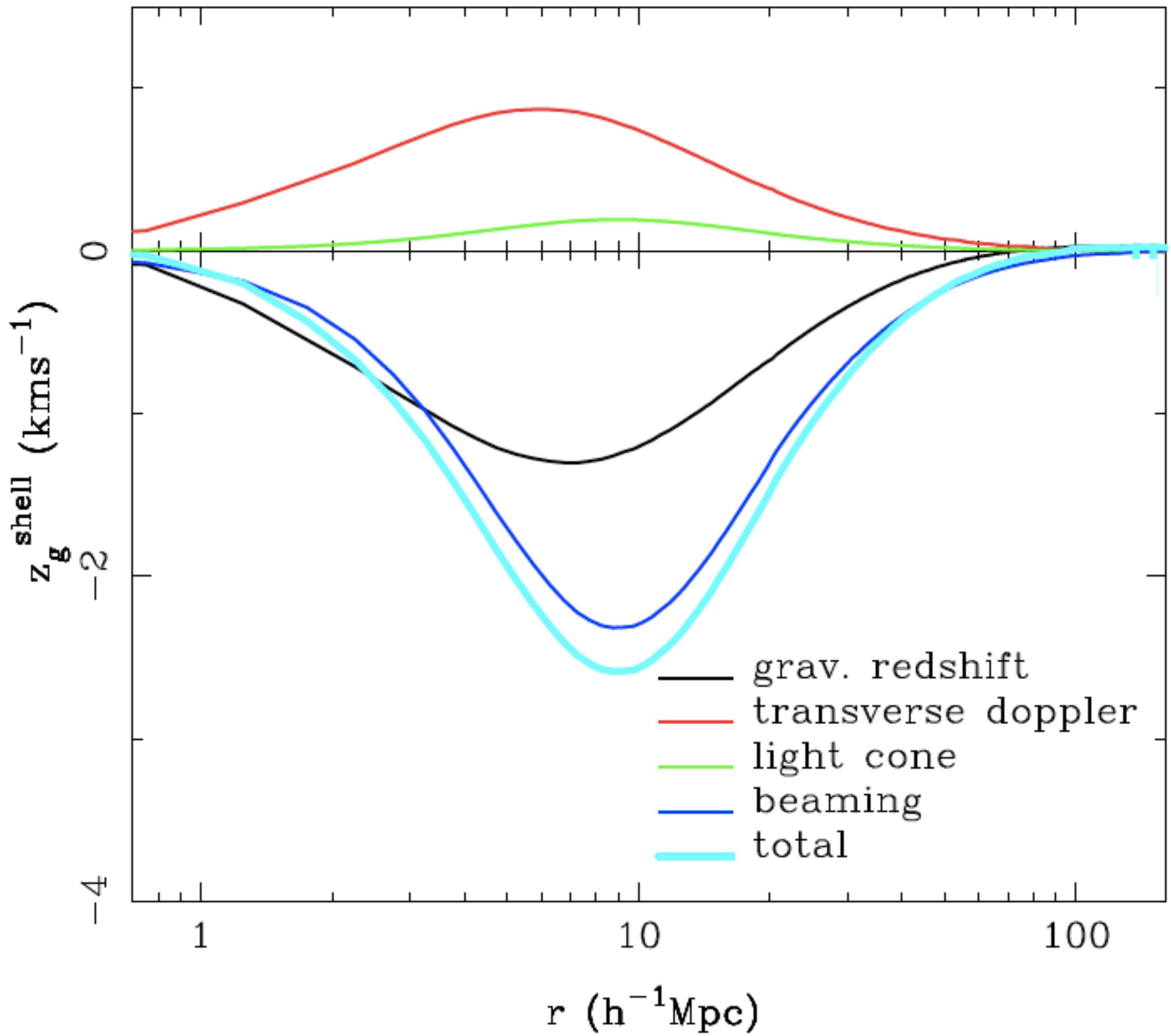


Galaxy behind big galaxy is falling towards observer: is brighter

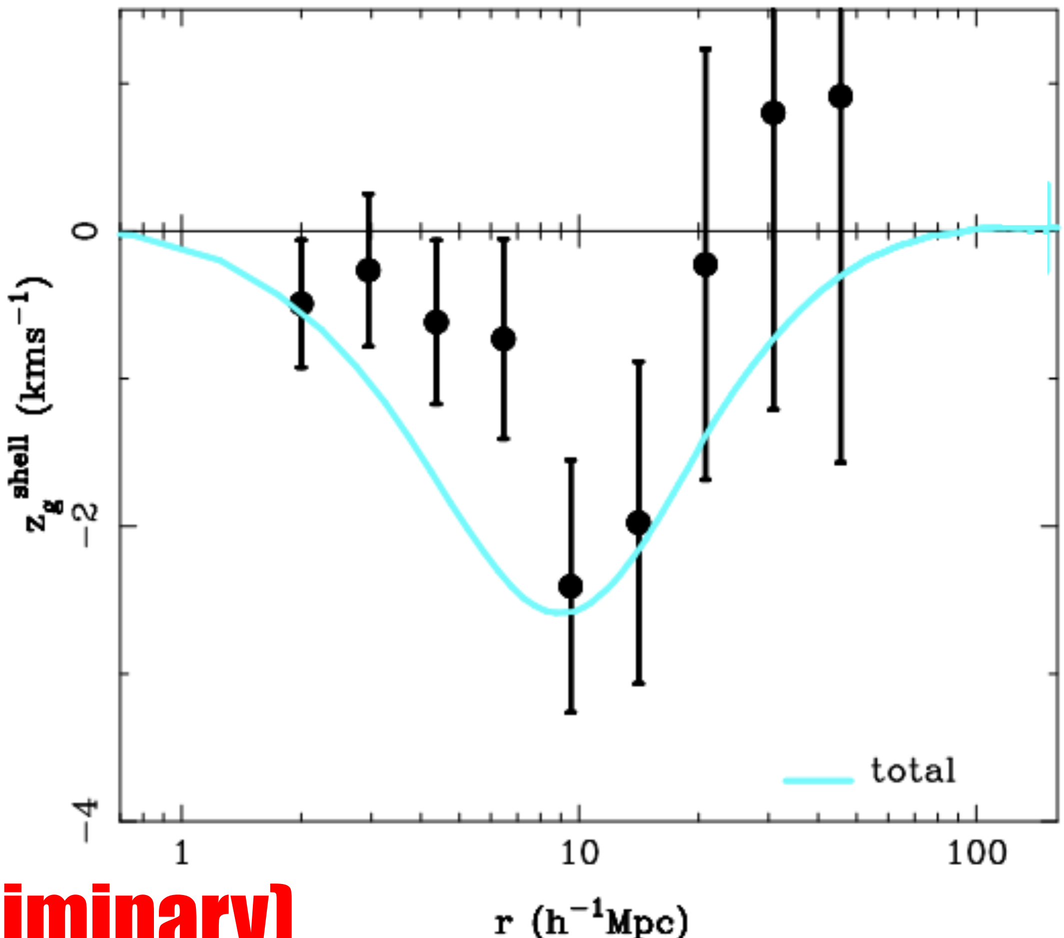
↓

see more of them in survey

Halo model of relativistic effects:



First measurement from SDSS data (CMASS+LOWZ):



(preliminary)

Shadab Alam et al., in prep.

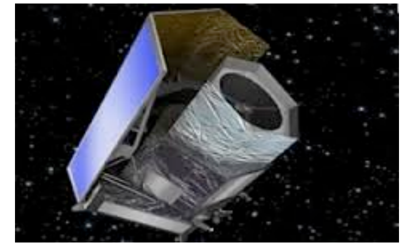
(using jackknife covariances: ~3.8 sigma)

Still more possible : optimal weighting+ more data available now

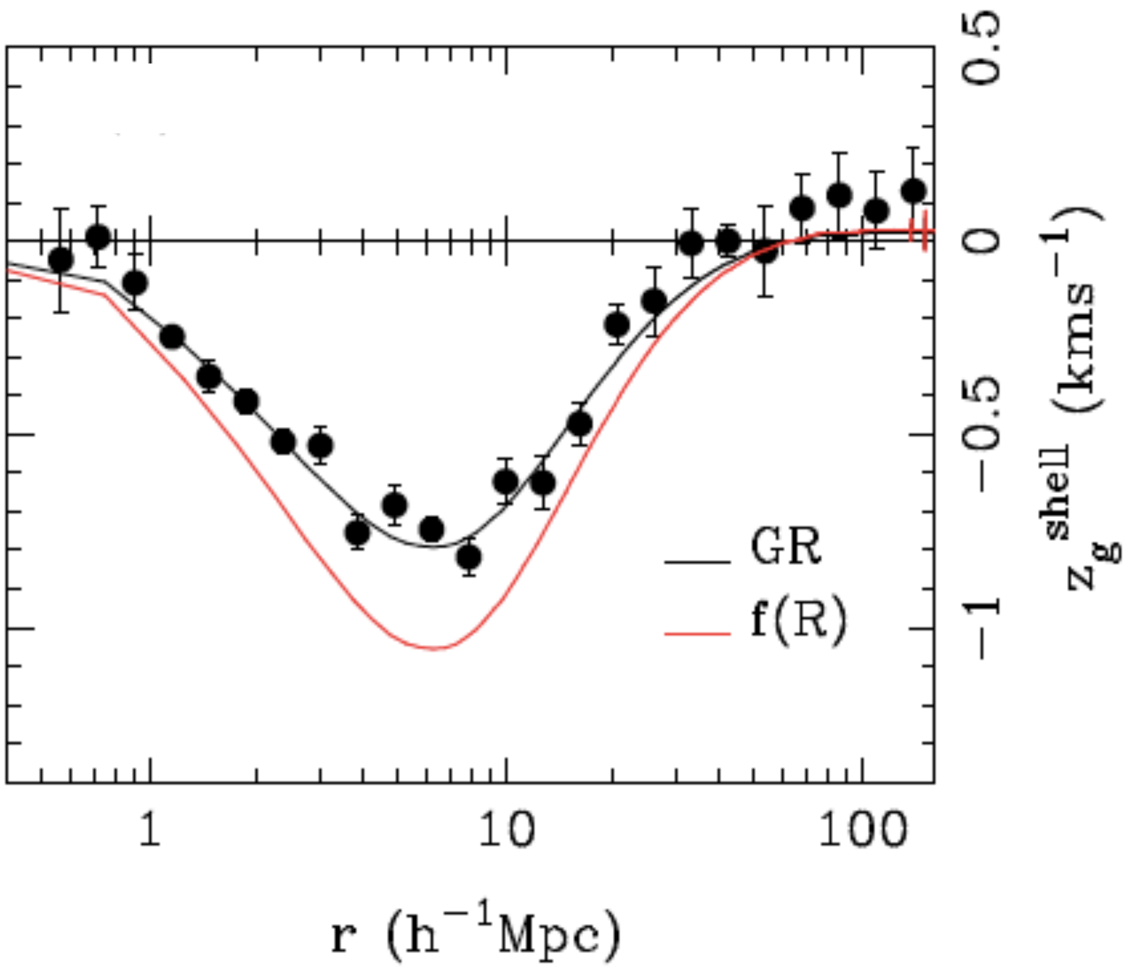
What will be possible with new surveys in ~10 years?

Simulation mock catalogs and analytic predictions for Euclid galaxy redshift survey:

(including mass-dependent weighting)



Relative redshift

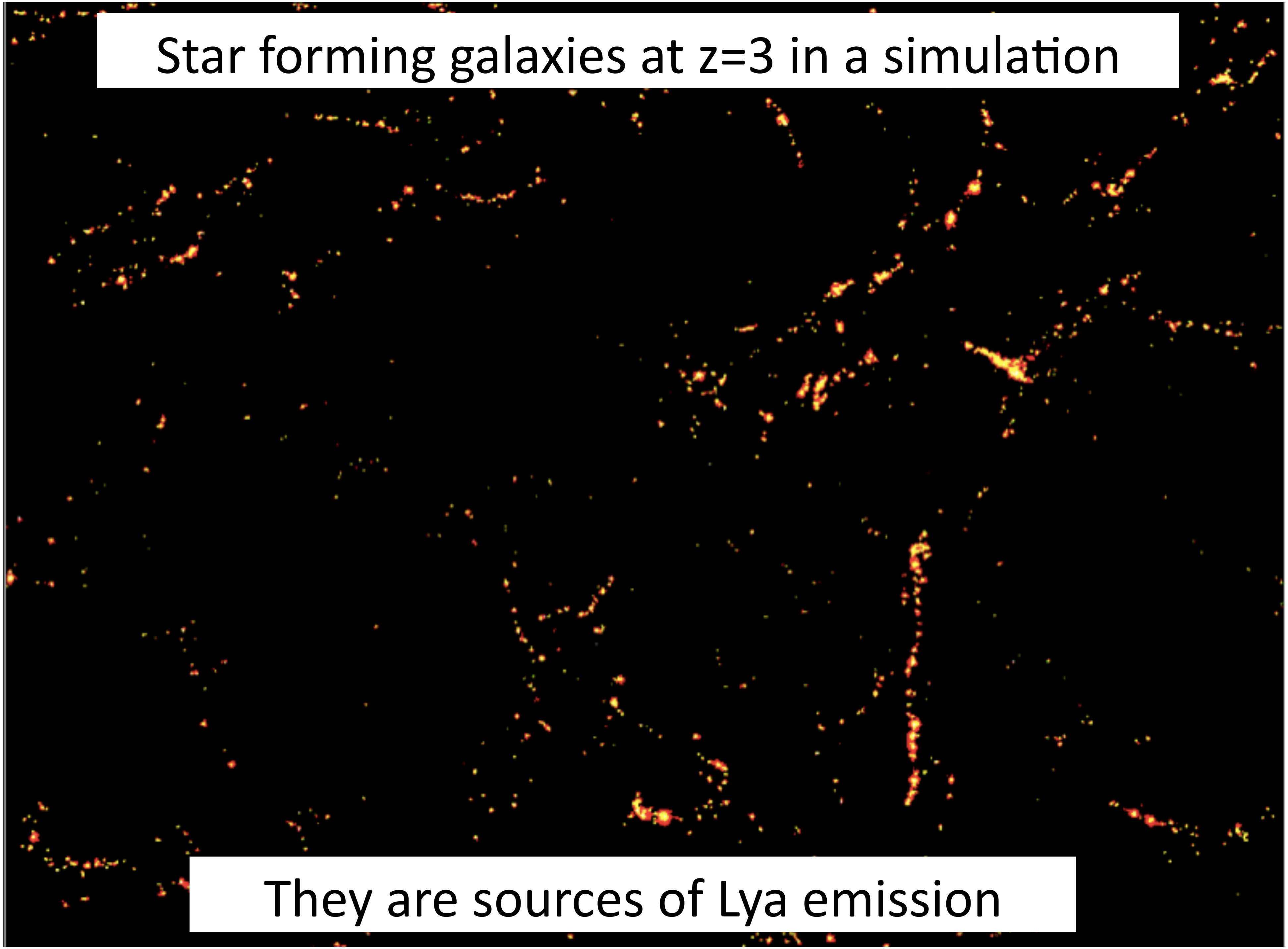


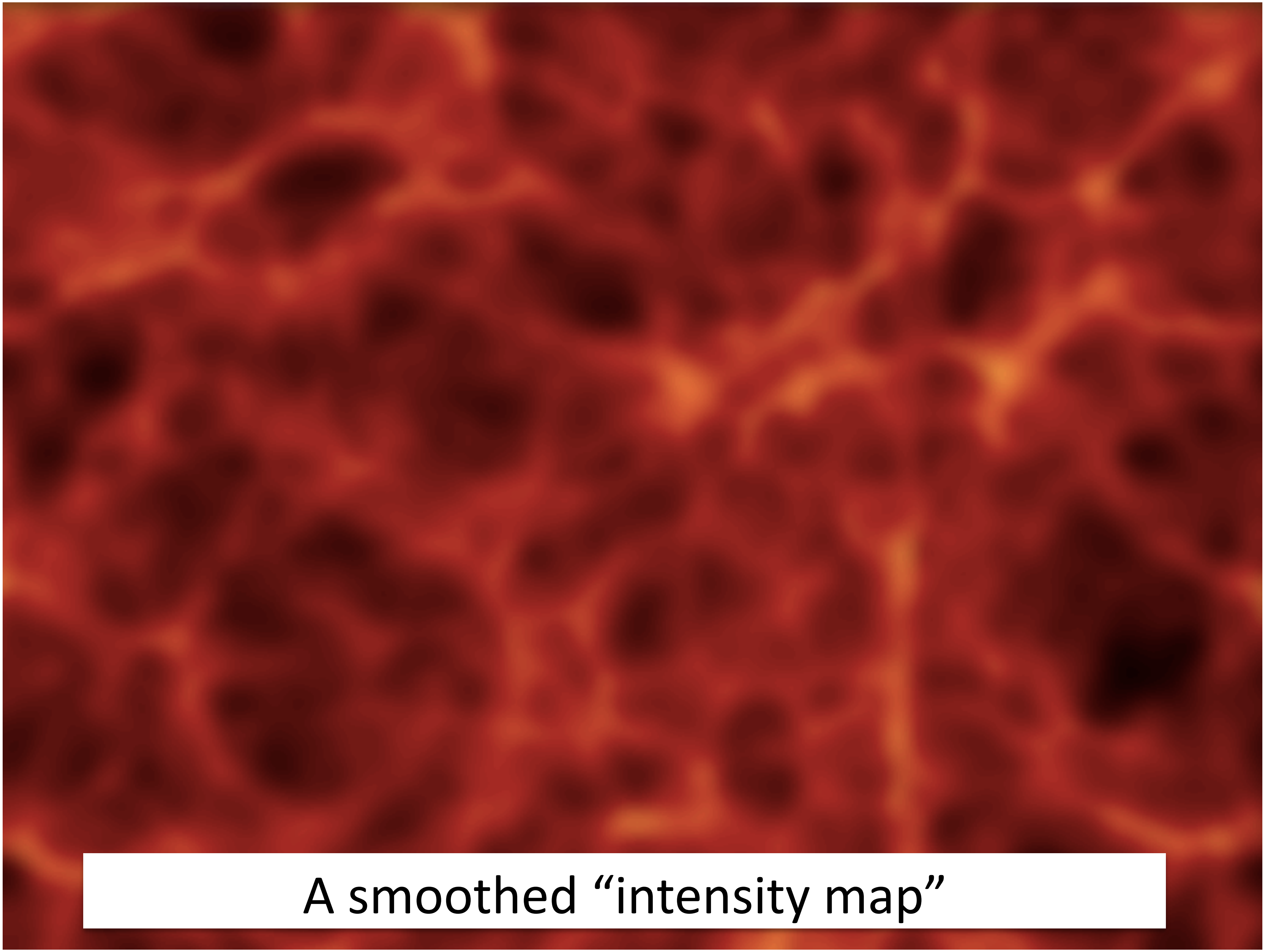
Distance to central galaxy

Will measure gravitational redshift amplitude to 2%.

Lya intensity mapping of the cosmic web

RC et al. 2015, arxiv:1504.0488

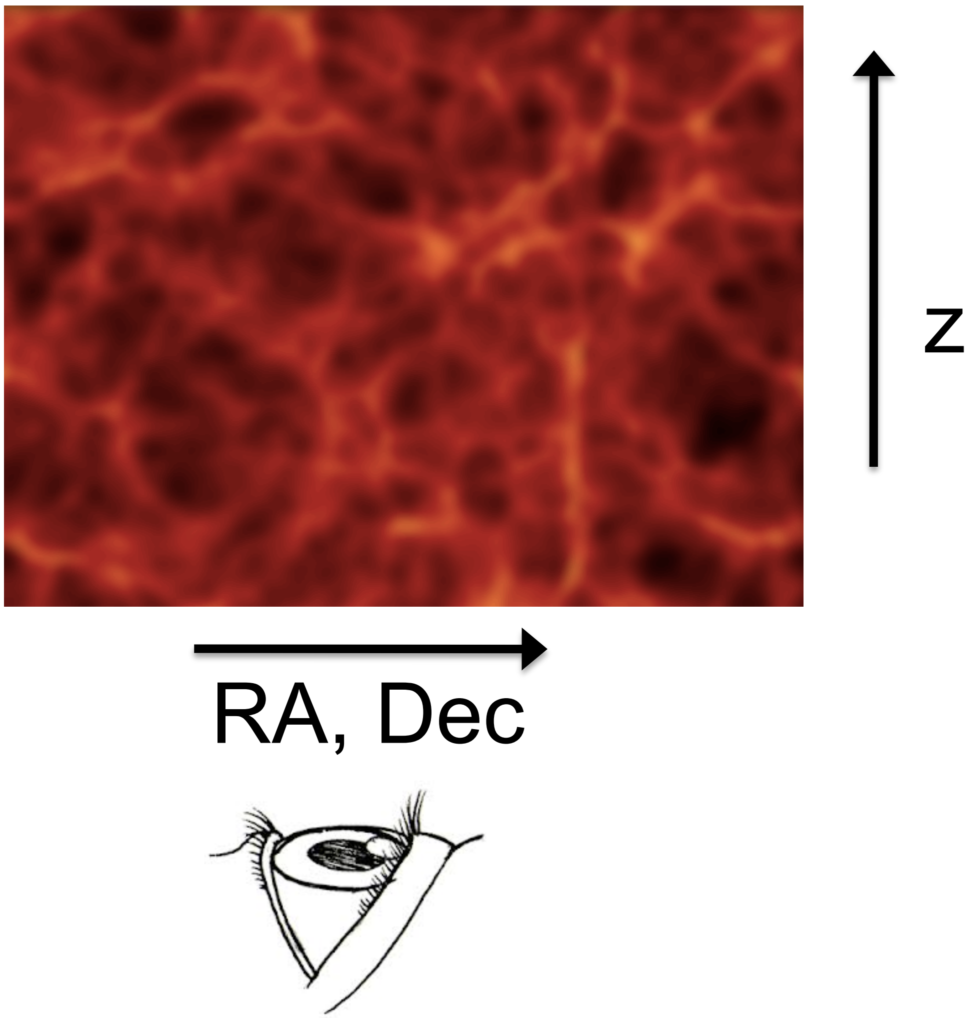

Star forming galaxies at z=3 in a simulation
They are sources of Lya emission



A smoothed “intensity map”

Observing the Lya map

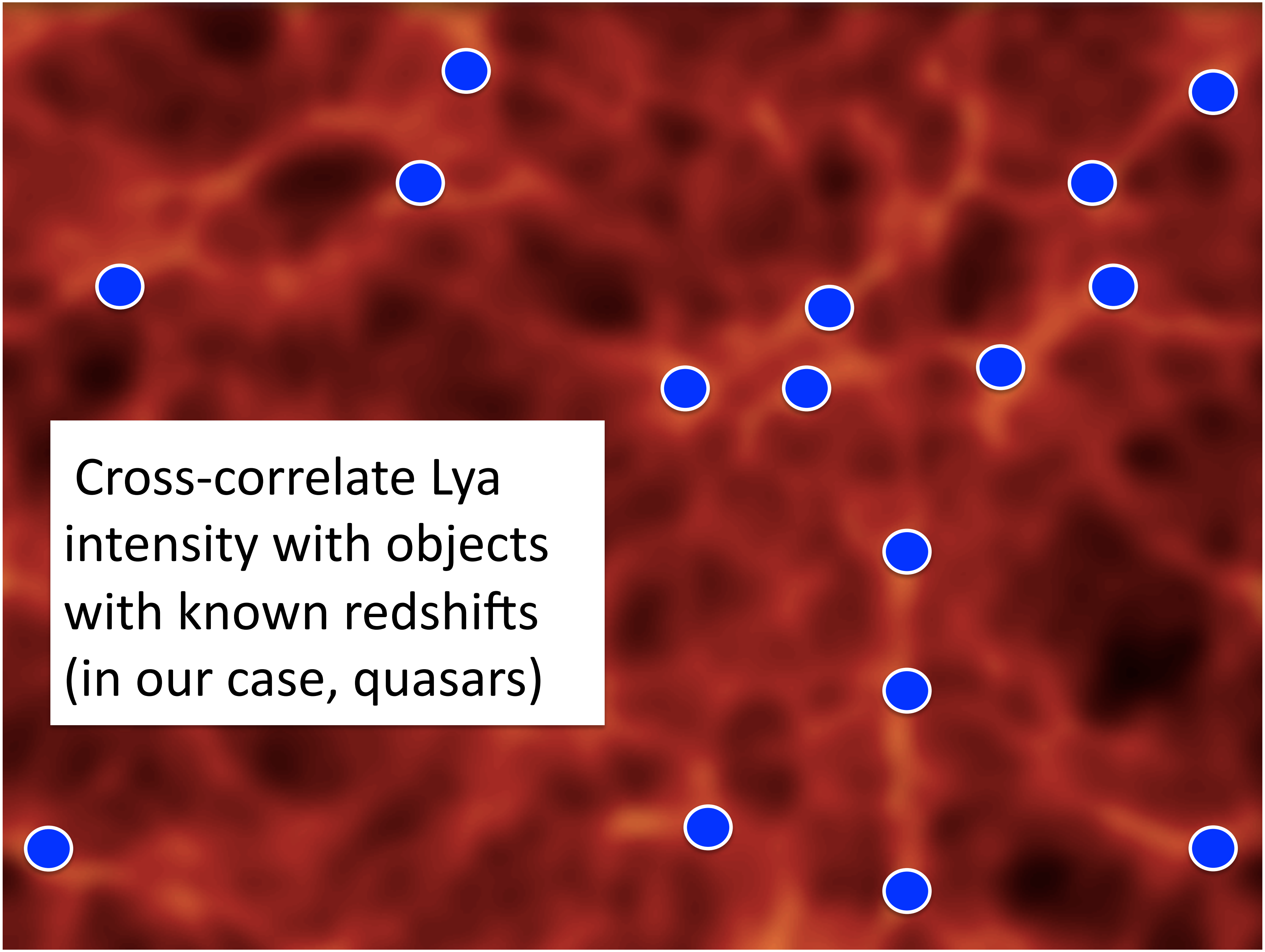
(spectra of every sky pixel observed)



We want to measure:

- Mean Lya intensity
- Lya clustering

How to deal with interloper emission?


Cross-correlate Lya intensity with objects with known redshifts (in our case, quasars)

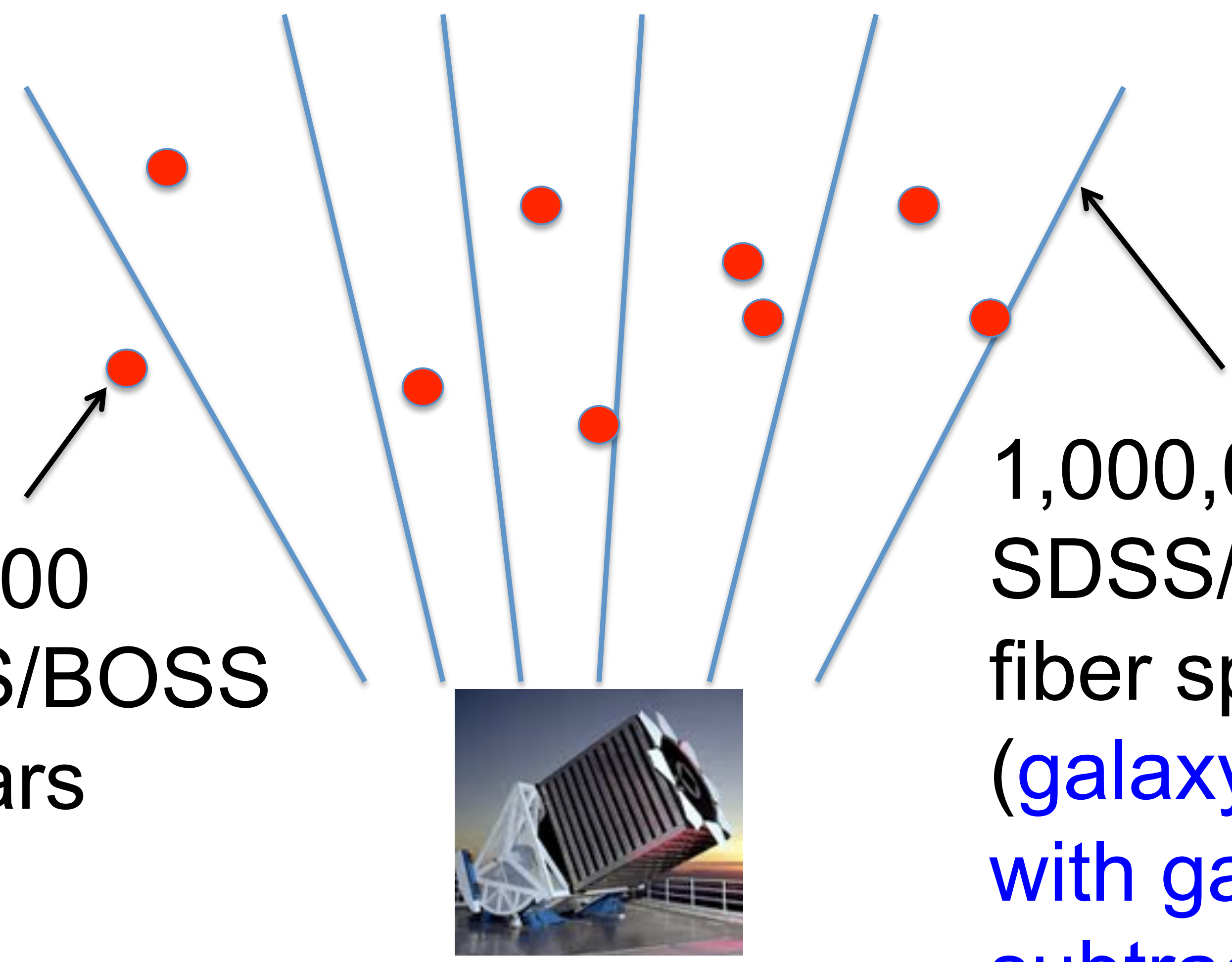
Why do intensity mapping?

It avoids biases from:

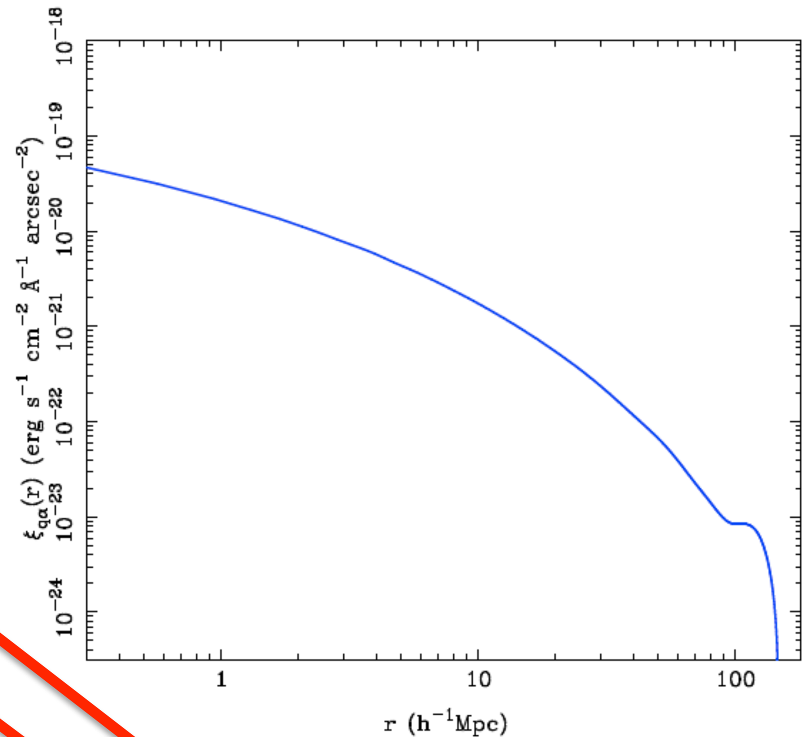
- source detection,
- luminosity measurement in an aperture
- determination of backgrounds
- extrapolation to faint objects

It is sensitive to all clustered emission.

our observational setup: cross-correlation of quasar positions with residual flux in pixels



the predicted quasar-Lya emission cross-correlation:



$$\xi_{q\alpha}(r) = b_q b_\alpha f_\beta \langle \mu_\alpha \rangle \xi_\rho(r)$$

quasar bias

lya emission bias

Kaiser redshift distortion factor

mean Lya surface brightness

CDM correlation function

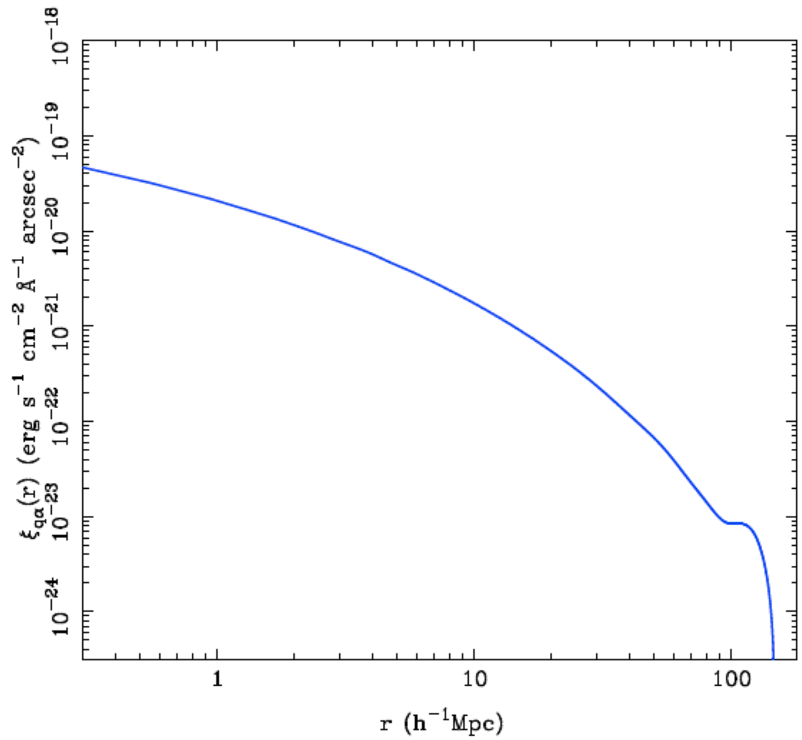
units are (SB): $\mathrm{ergs^{-1}\ cm^{-2}\ \AA^{-1}\ arcsec^{-2}}$

model has two parameters:

$$\xi_{q\alpha}(r) = b_q b_\alpha f_\beta \langle \mu_\alpha \rangle \xi_\rho(r)$$

$$b_q b_\alpha f_\beta \langle \mu_\alpha \rangle$$

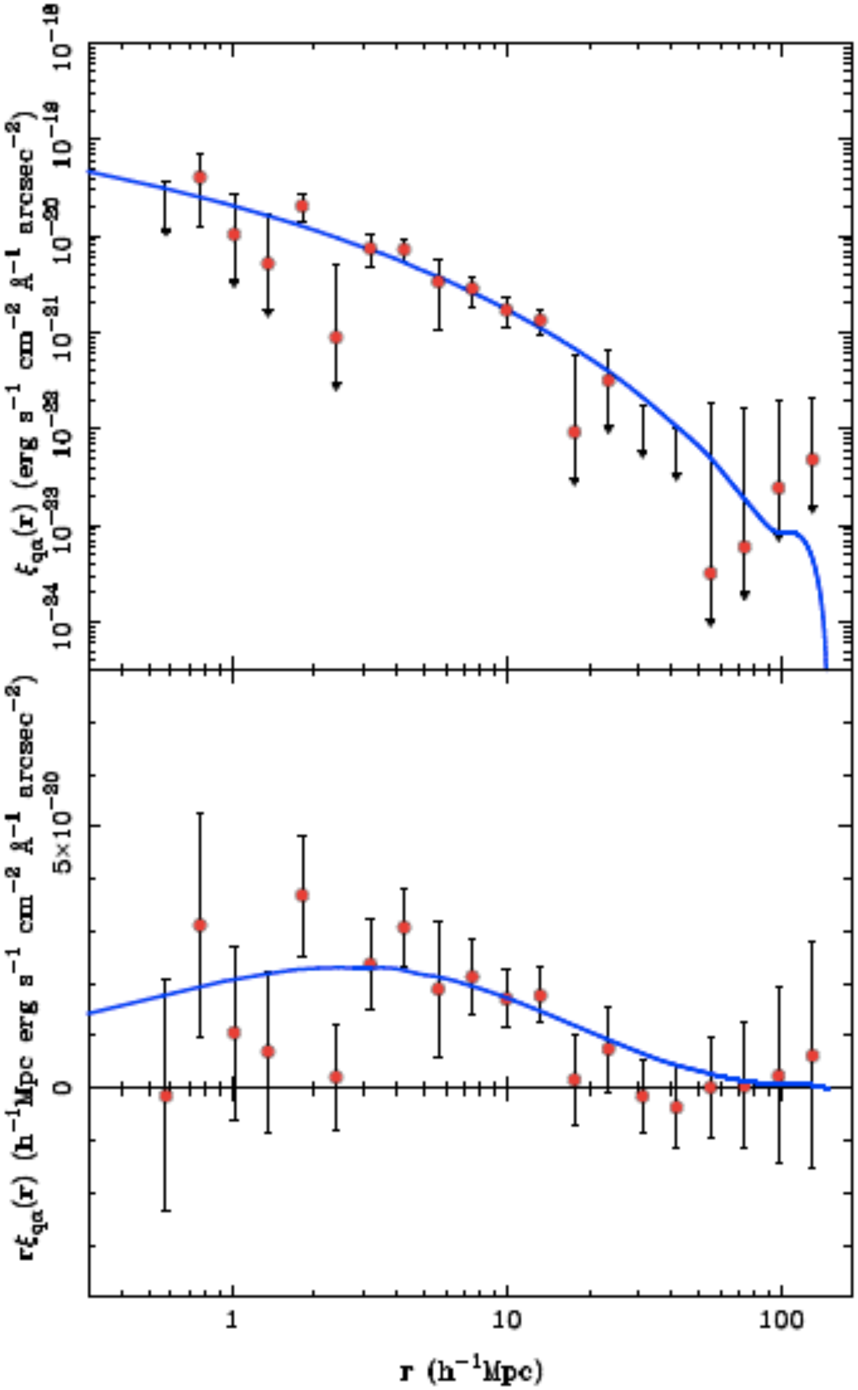
amplitude



shape of CDM correlation function parametrized by Ω_M (hold others fixed) result

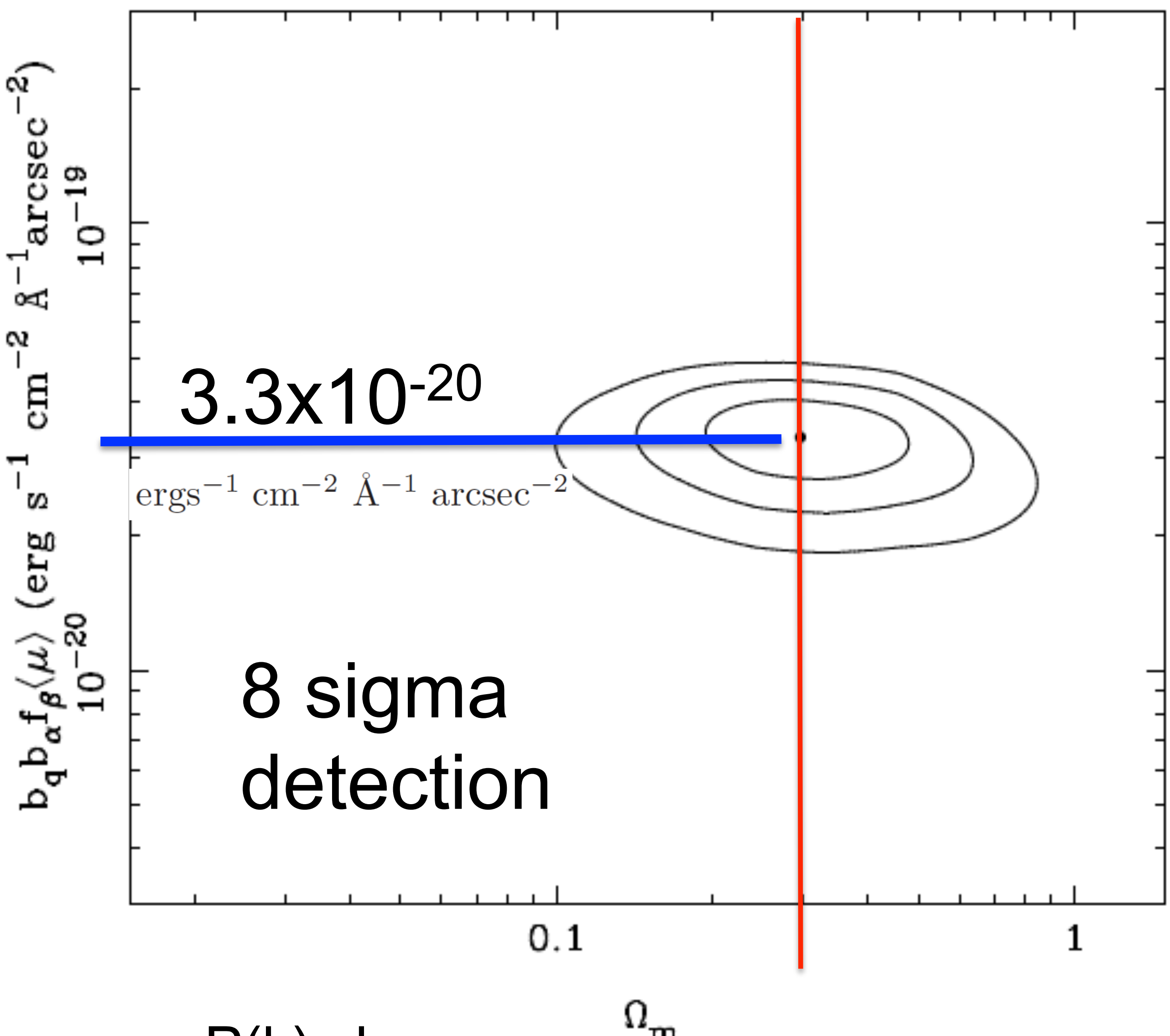
SDSS/BOSS

$$\xi_{q\alpha}(r)$$



CDM model fit

(using 100 jacknives to compute covariance matrix)



P(k) shape

Planck value=0.3

What is $\langle\mu_\alpha\rangle$?

We measure $\xi_{q\alpha}(r) = b_q b_\alpha f_\beta \langle\mu_\alpha\rangle \xi_\rho(r)$

Use other observations to constrain these

$$\langle\mu_\alpha\rangle = (3.9\pm0.9)\times10^{-21}(3/b_\alpha)\,\mathrm{erg\,s^{-1}\,cm^{-2}\,\AA^{-1}\,arcsec^{-2}}$$

(mean Lya surface brightness at <z>=2.55)

(note: scales with poorly known bias factor of Lya emission, b_α, should be ~3)

Interpretation

(1) Lya emission from star formation in galaxies.

Convert:

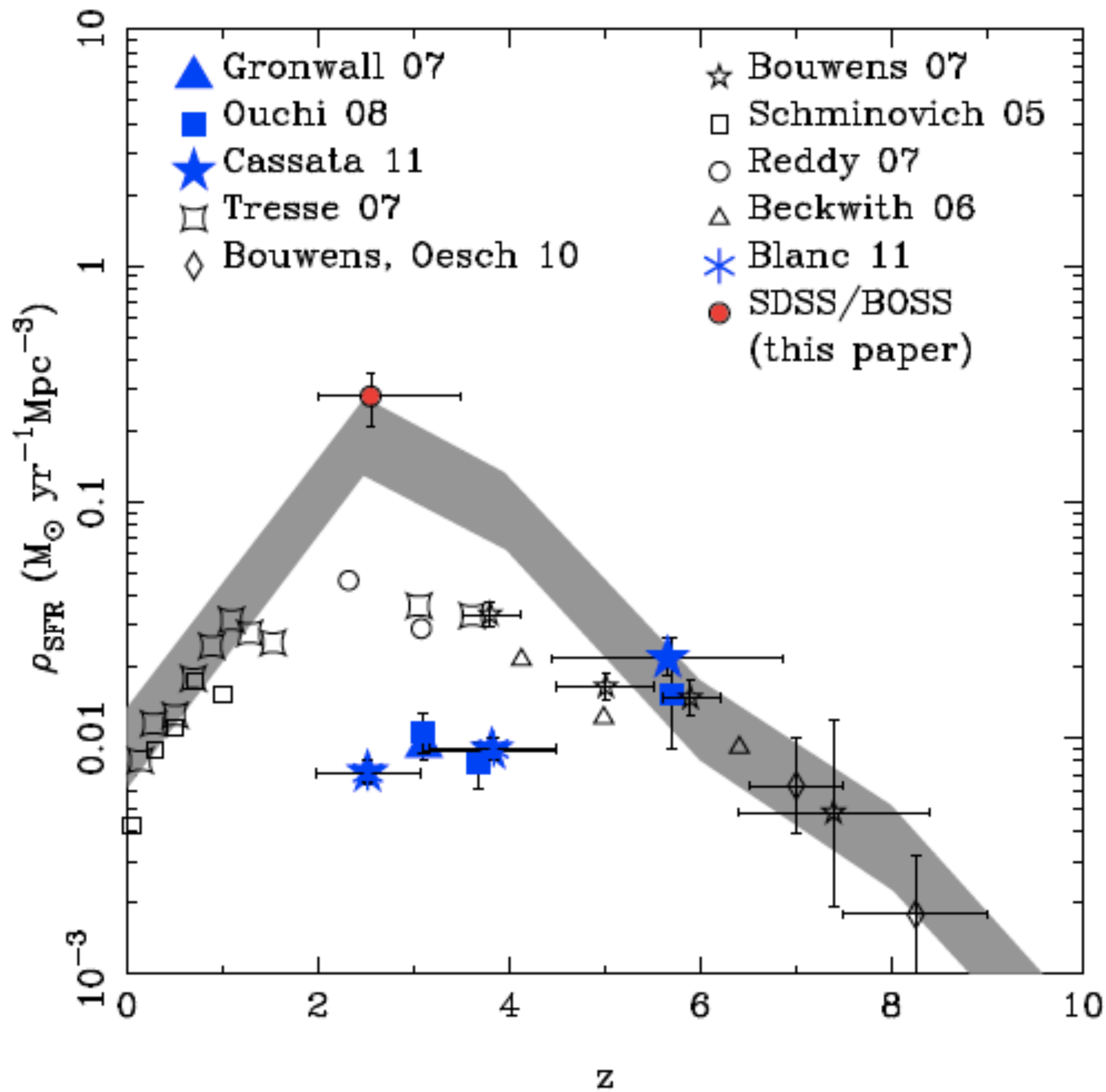
Lya SB -> luminosity density -> SFRD

$$\rho_{\rm SFR}(z = 2.55) = (0.28 \pm 0.07)(3/b_\alpha)\, M_\odot {\rm yr}^{-1}\, {\rm Mpc}^{-3}$$

Interpretation: other possible sources

(2) Scattering of quasar Lya
(3) Fluorescence of quasar radiation
(4) Fluorescence of UVBG
(5) Scattering of Lya from UVBG
(6) Cooling radiation
(7) Observed Low SB Lya halos

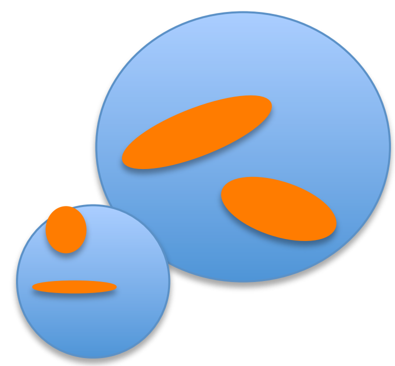
All expected to be negligible


Gronwall 07
Ouchi 08
Cassata 11
Tresse 07
Bouwens, Oesch 10
Bouwens 07
Schminovich 05
Reddy 07
Beckwith 06
Blanc 11
SDSS/BOSS
(this paper)
ρ_{SFR} ($M_\odot$ yr^{-1}Mpc^{-3})
z
10
1
0.1
0.01
10^{-3}
0
2
4
6
8
10

Consequences

- ✸This is 30x larger than previous results individually detected Lya emitters!
- ✸It is ~the same as the dust-corrected SFRD at this redshift.
- ✸Lya “escape fraction” is 100%

to explain this, we need all star forming galaxies to be surrounded by low surface brightness halos which have so far escaped detection.



Summary

2 results from SDSS/BOSS not in survey design

(1) First measurement of gravitational redshifts from LSS

➡ future: Euclid 50x more data

(2) First intensity mapping measurement in the optical

➡ future: we only used 1/200,000 of sky area!