Lyman-alpha forest lensing and gravitational redshifts in galaxies

Rupert Croft

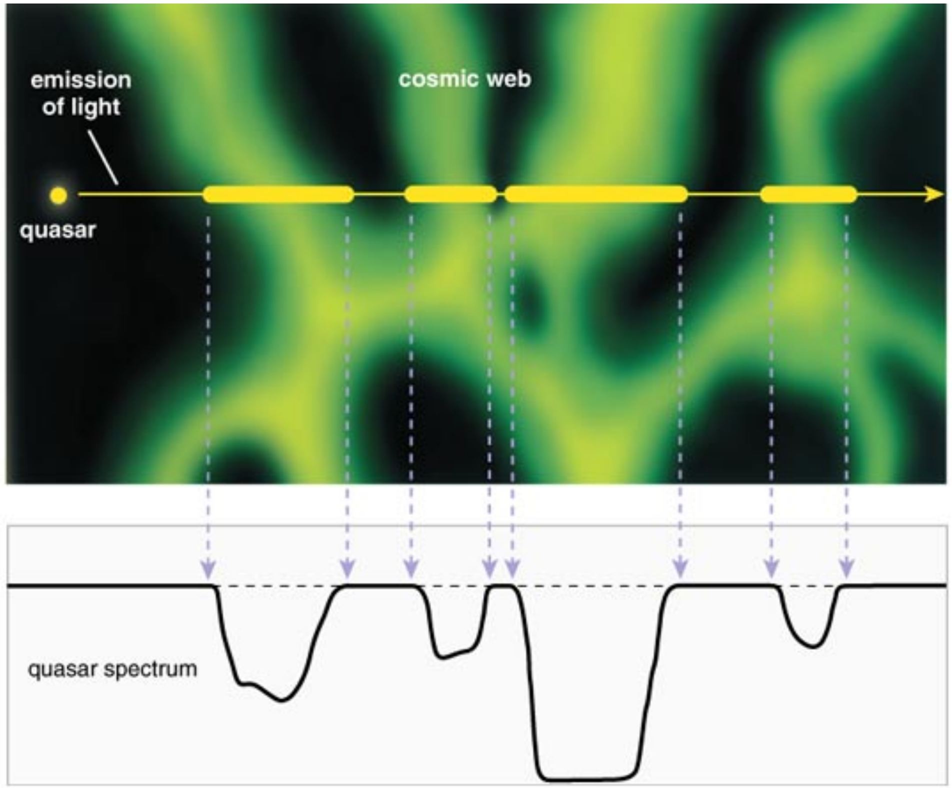
THE MCWILLIAMS
Center for Cosmology

Carnegie Mellon University

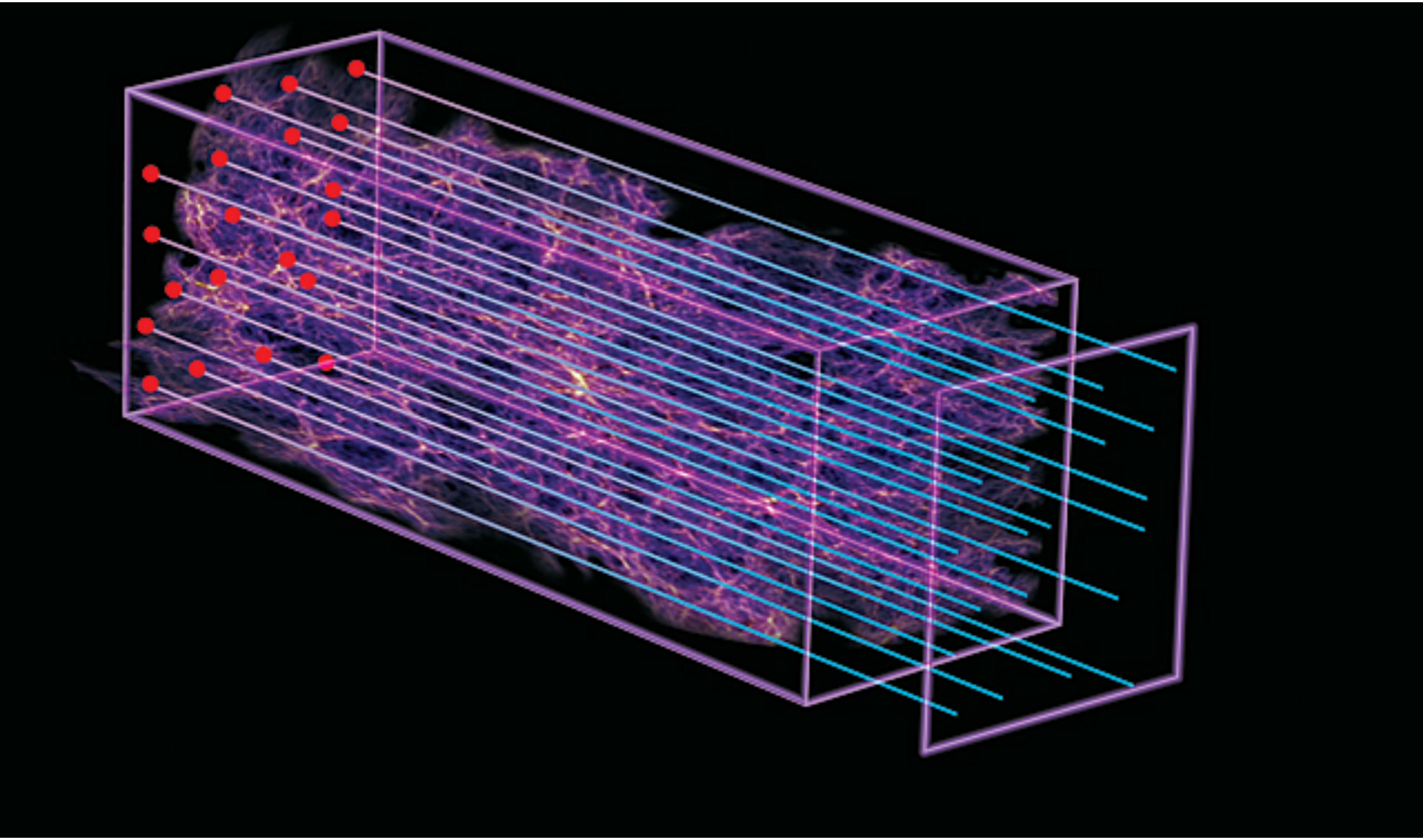
Hongyu Zhu (CMU)
Alexie Leauthaud (UC Santa Cruz)
Shadab Alam (ROE)
Shirley Ho (CMU/LBNL)
Elena Giusarma (LBNL)

Ben Metcalf (Bologna)
Alessandro Romeo (Bologna)

+SDSS MaNGA collaboration

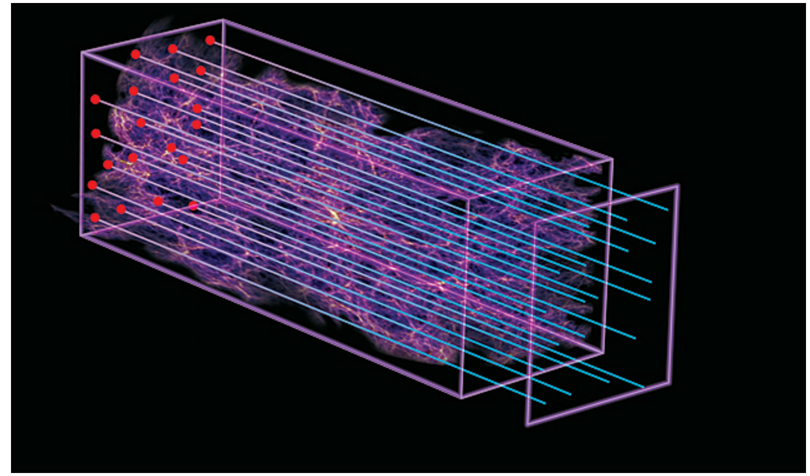


Lya forest absorption is a continuous field



with many sightlines can sample this field in 3D

exploiting the 3D forest



- Interpolate between sightlines to make space-filling map

(e.g., Pichon et al. 2002, Caucci et al. 2005, Lee et al. 2014, Cisewski et al. 2014, Lee et al. 2015, Stark et al. 2015, Ozbek et al. 2016)

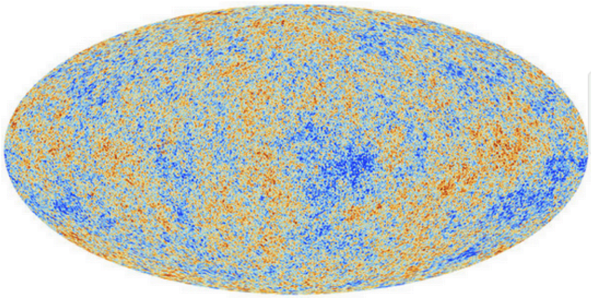
- Measure 3D clustering: BAO

(e.g., White 2003, McDonald & Eisenstein 2007, Busca et al. 2013, Slosar et al. 2013)

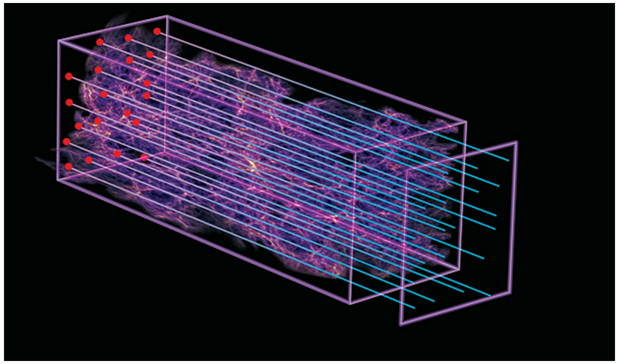
(with Alessandro Romeo and Ben Metcalf)

Lya forest lensing

source

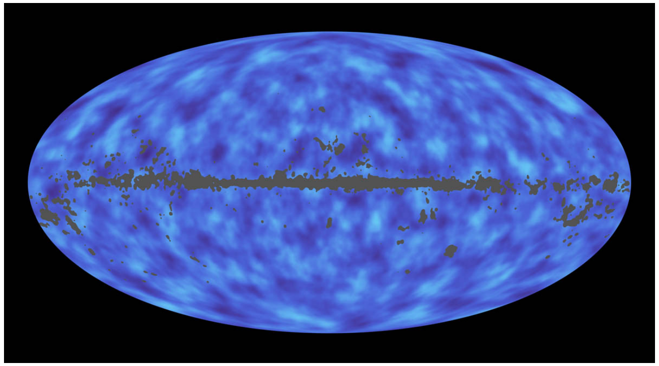


CMB T at z=1300



Lya forest at z=2-3

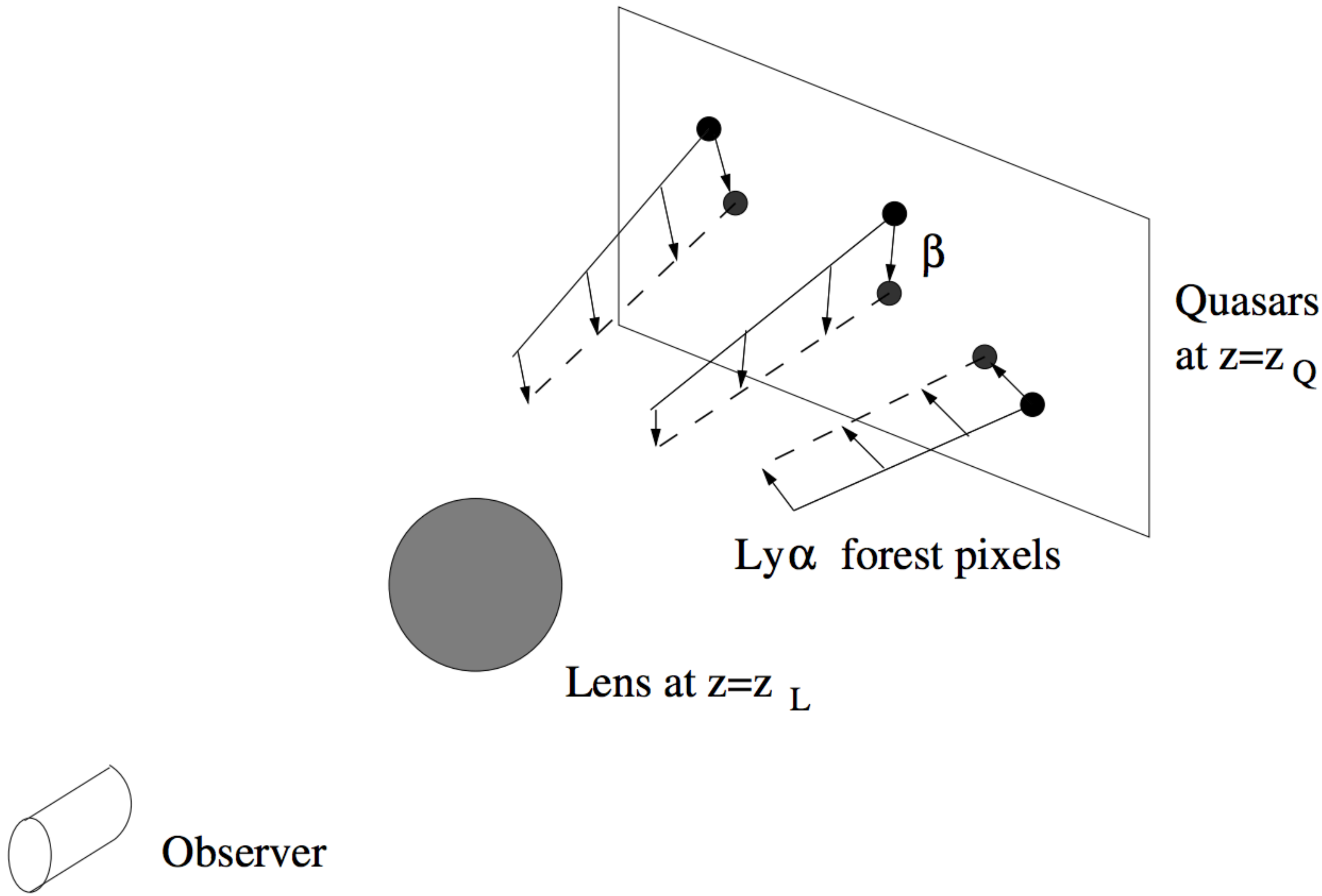
lens

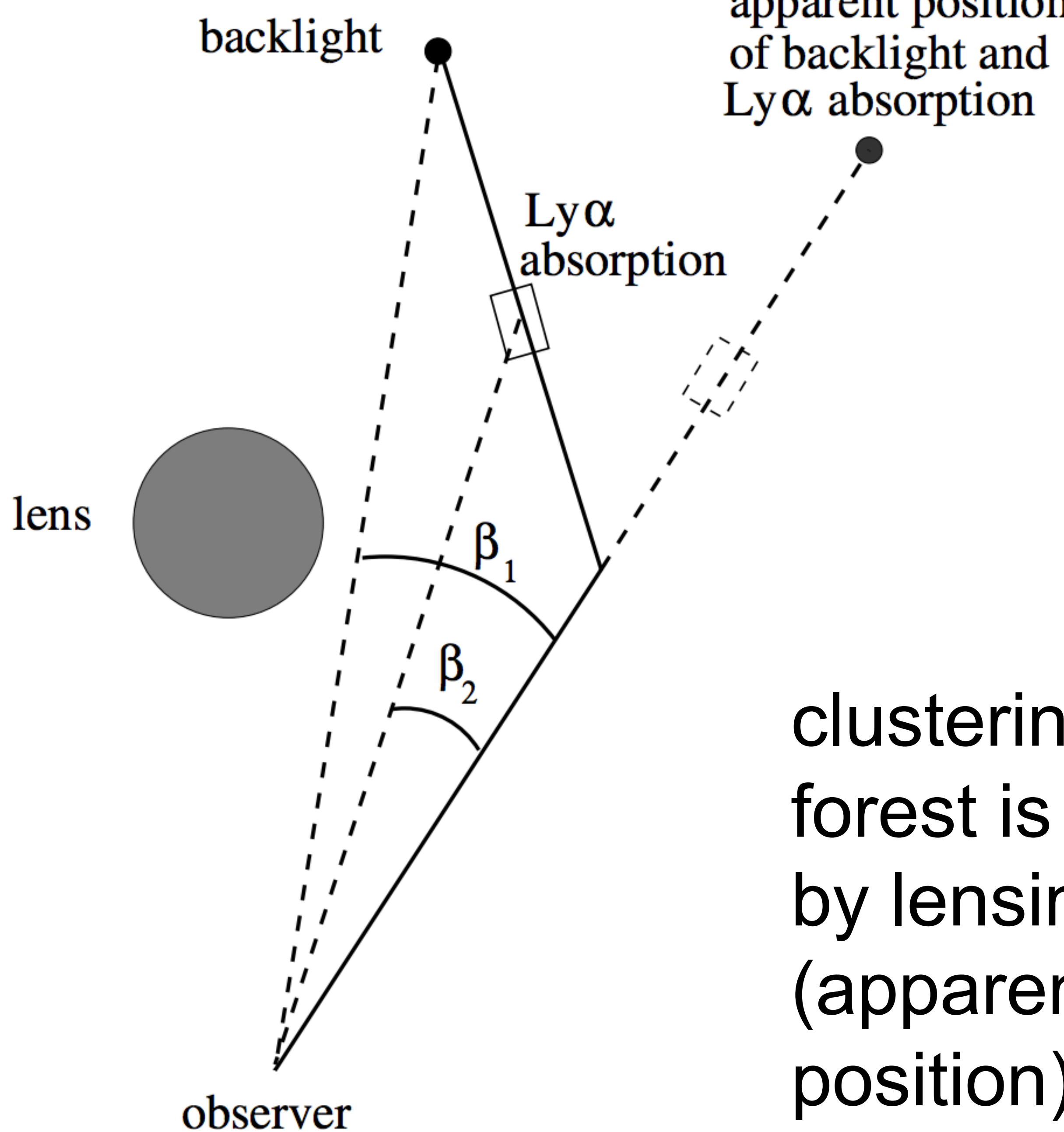


map foreground mass at z~2.5

map foreground mass at z~1

lens deflects forest pixels along with quasars





clustering of the forest is affected by lensing (apparent vs actual position)

Similar to lensing of 21cm temperature fluctuations:

$$\tilde{T}(\theta, \nu) = T(\theta - \alpha(\theta), \nu) \simeq T(\theta, \nu) - \alpha(\theta) \cdot \nabla_\theta T(\theta, \nu) + \ldots$$

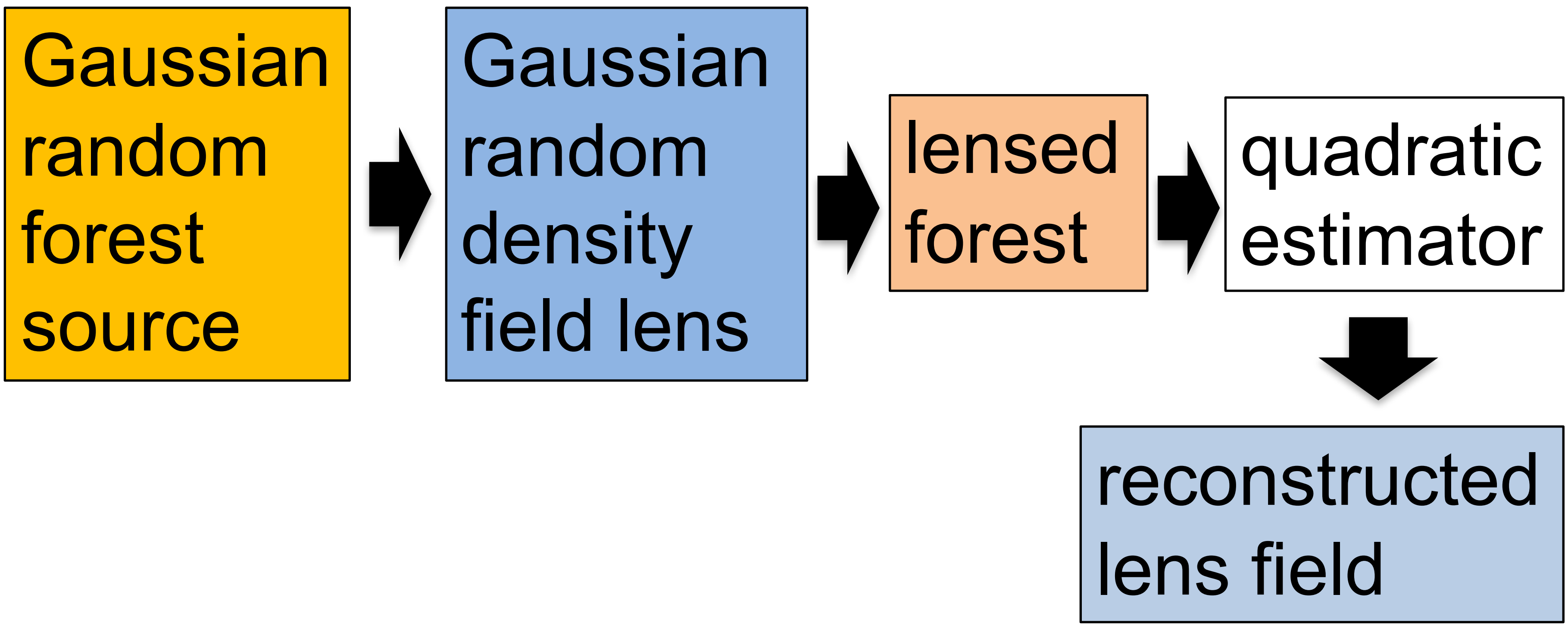
(e.g., Zahn and Zaldarriaga 2006, Pen 2004, Metcalf and White 2009)

Same advantage - many source planes lensed almost the same way.

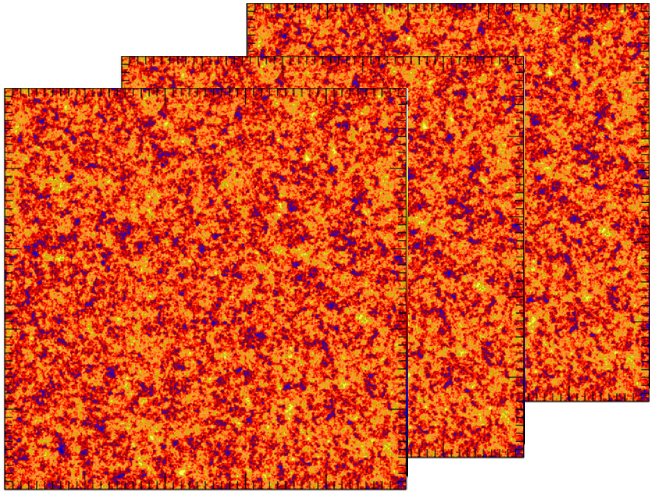
Deflection gradients small compared to Lya flux gradients.

Use quadratic estimator developed for 21cm (Zahn and Zaldarriaga 2006), based on 3D generalization of Hu and Okamato 2002)

initial simplest simulation test

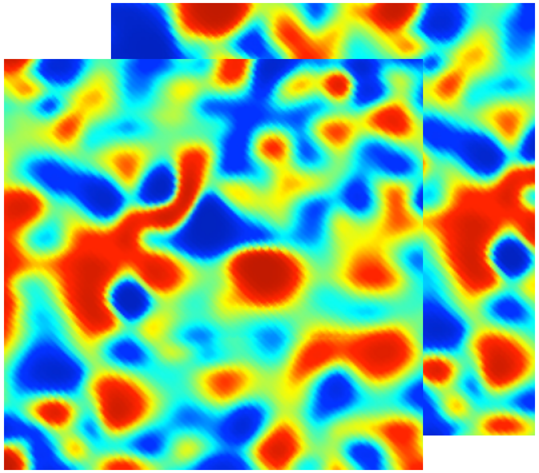


source density



quasars with
~arcmin separation

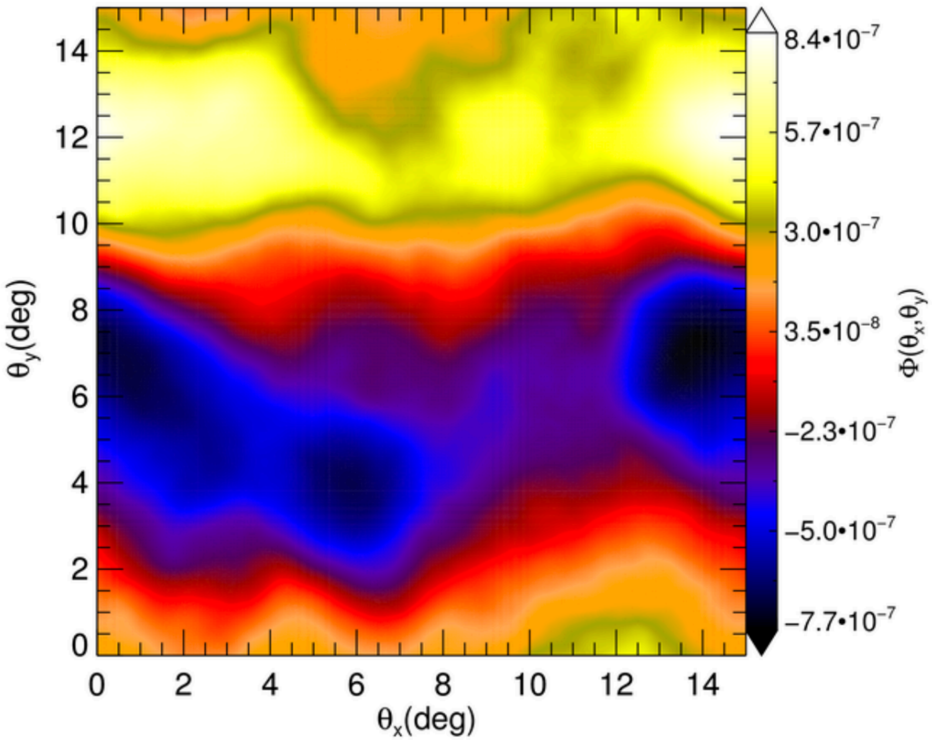
➡ lens maps



quasars with
~ BOSS separation

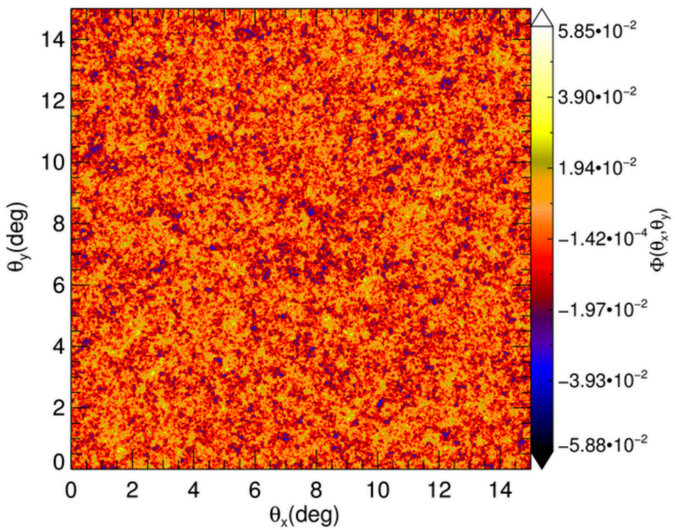
➡ lens P(k)

test

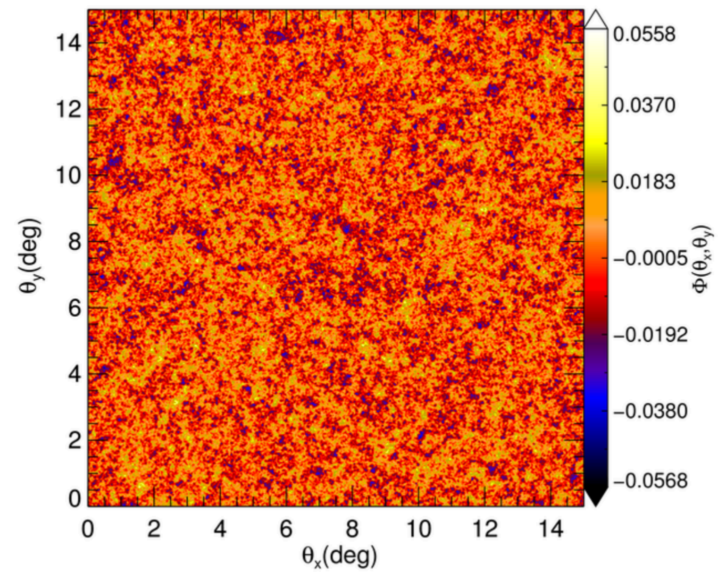


input potential at z~1

angular sampling in test: 2 arcmin between sightlines (similar to Subaru PFS survey)

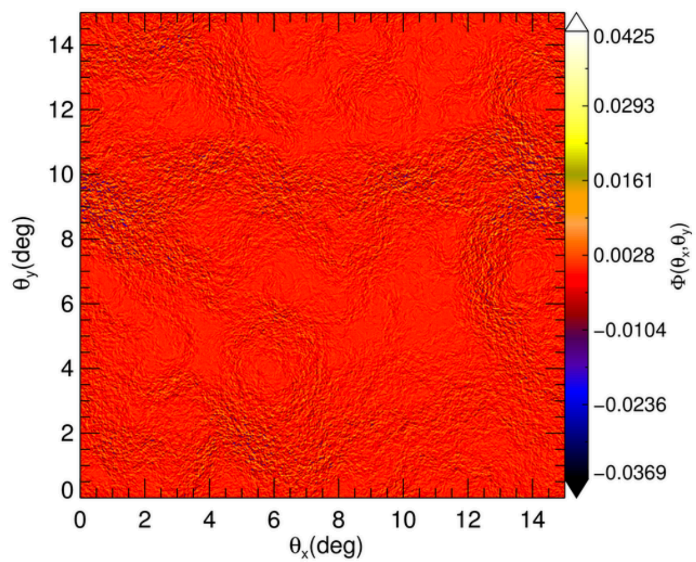


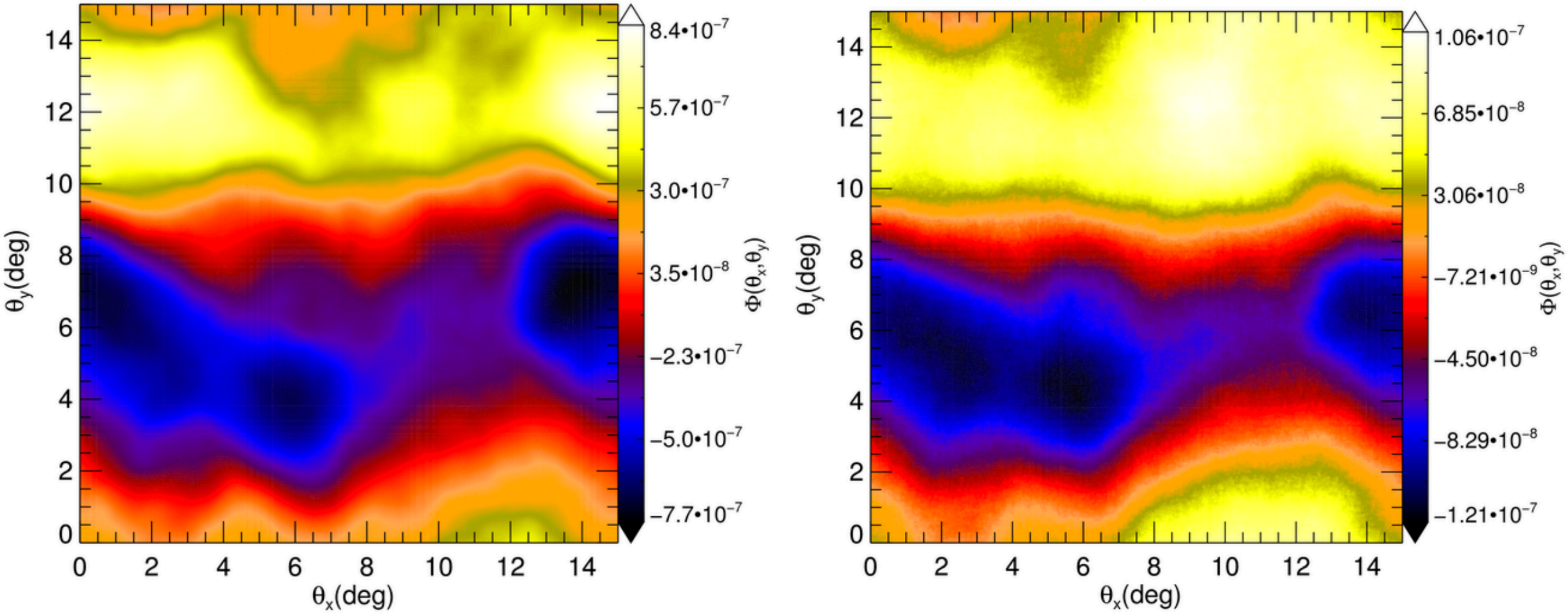
unlensed forest



lensed forest

difference

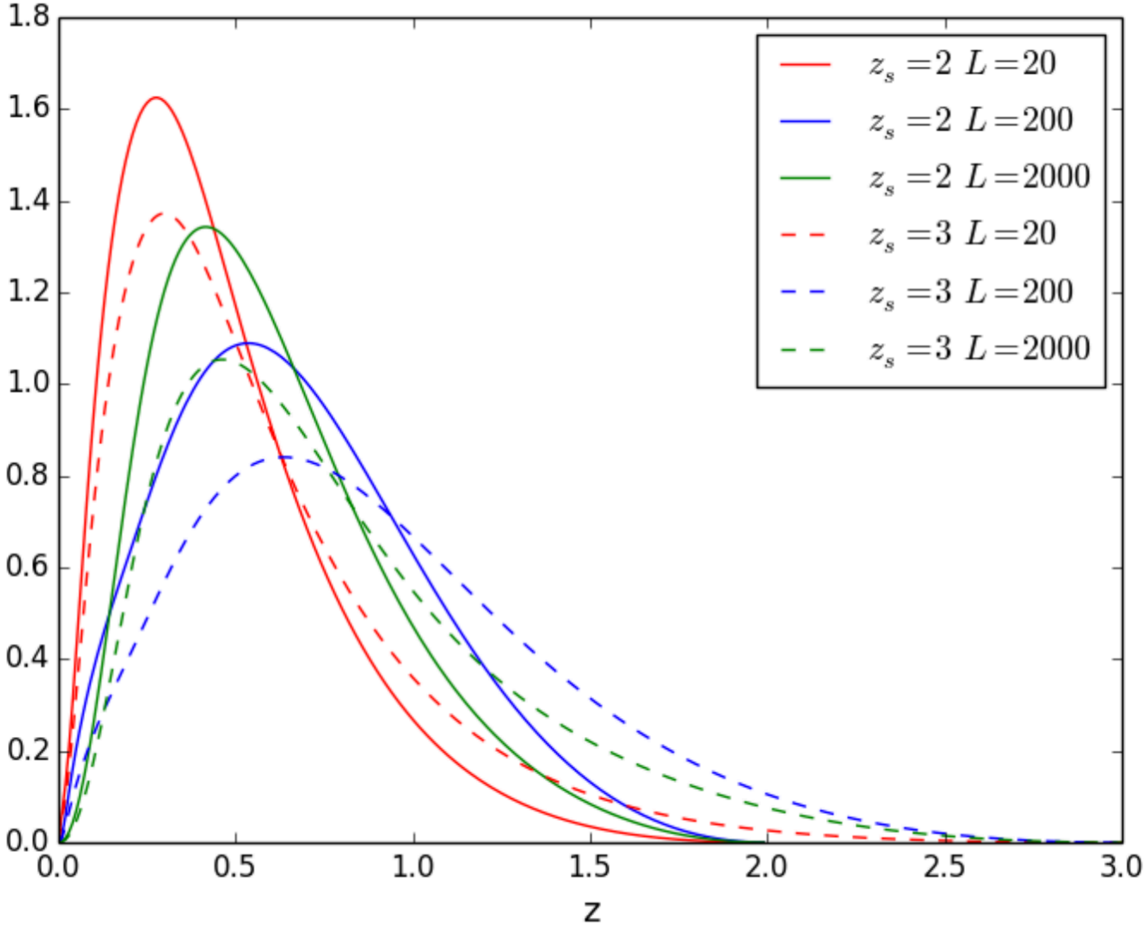




input potential

recovered potential

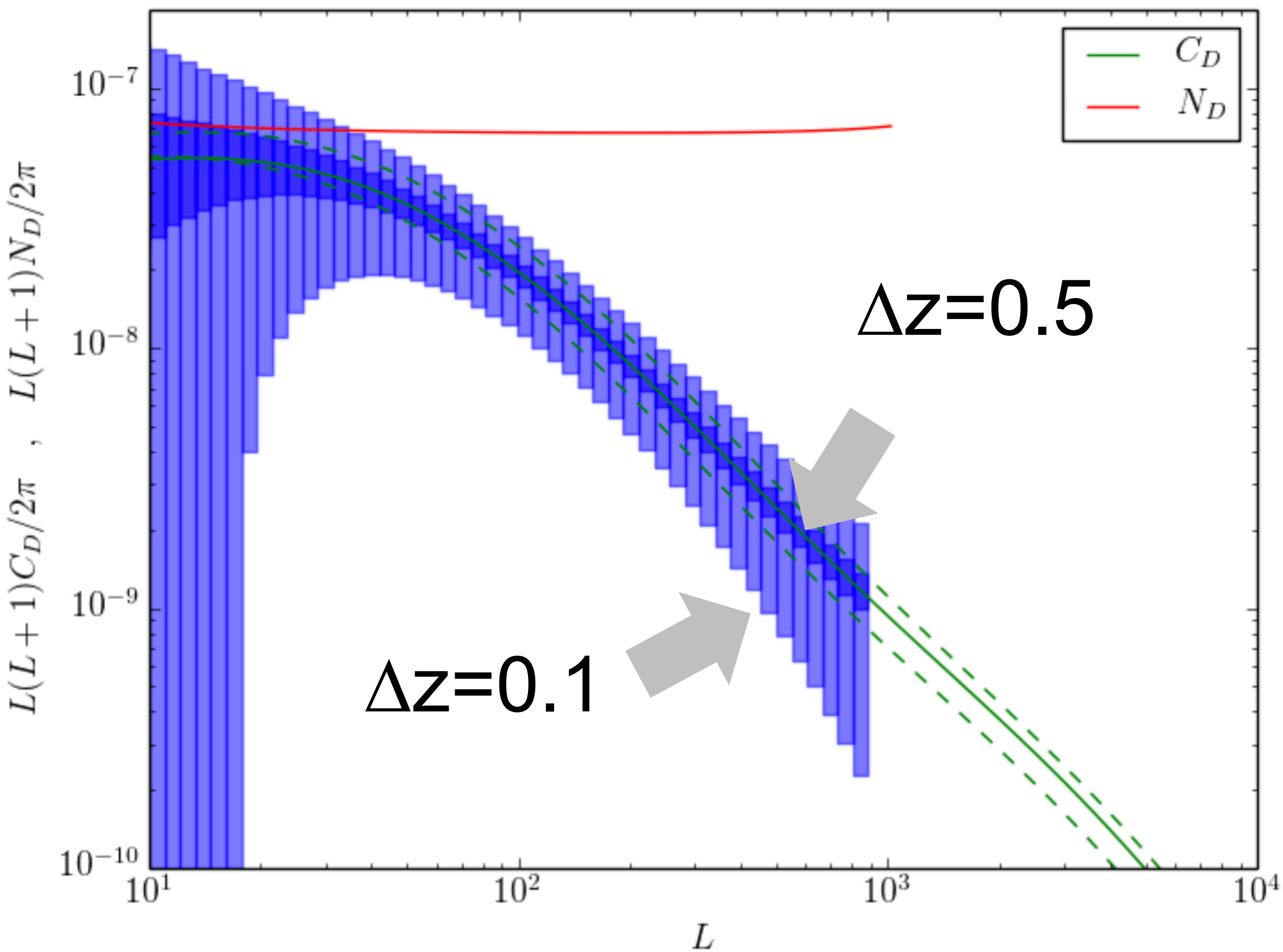
lensing kernel peaks at z=0.4-0.8 for forest (CMB kernel at z~1.8 and LSST at z~0.3)



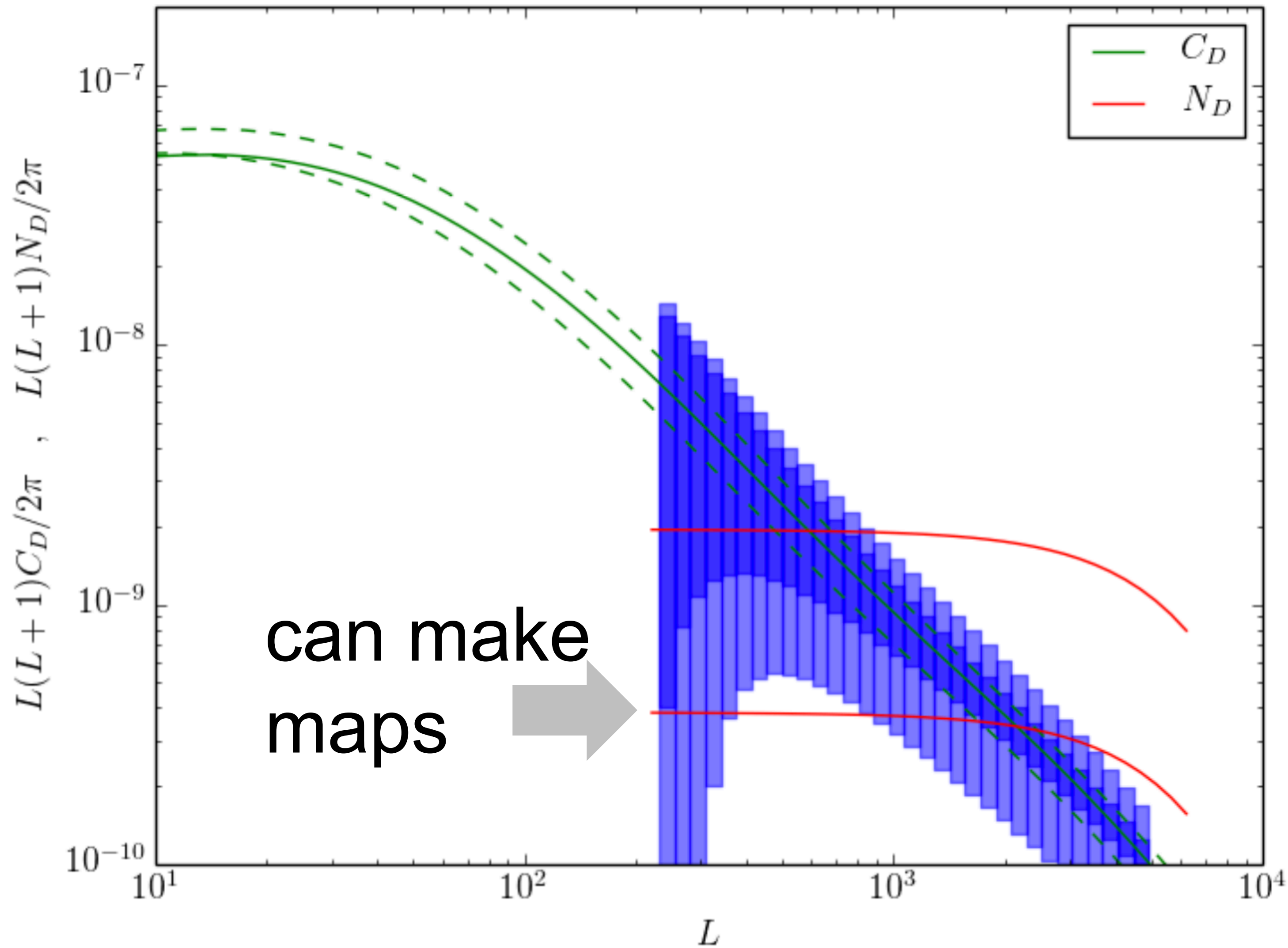
many upcoming surveys:

Dataset	When	Area	$N_{spectra}$	mean separation	mean S/N in flux
BOSS DR12	2016	10,000 sq. deg.	160,000	15 arcmin	2.72
eBOSS	2014-2018	7,500 sq. deg.	270,000	10 arcmin	2.99
CLAMATO	2014-2018	0.8 sq. deg.	1,000	1.7 arcmin	3.49
WEAVE	2018-2025	6,000 sq. deg.	400,000	7.5 arcmin	3.26
DESI	2018-2023	14,000 sq. deg.	770,000	8.1 arcmin	3.26
Subaru PFS	2019-2022	15 sq. deg.	7,400	2.7 arcmin	2.70
MSE	2025-	1,000 sq. deg.	1,000,000	1.9 arcmin	3

using galaxy spectra for forest



eBOSS forecast

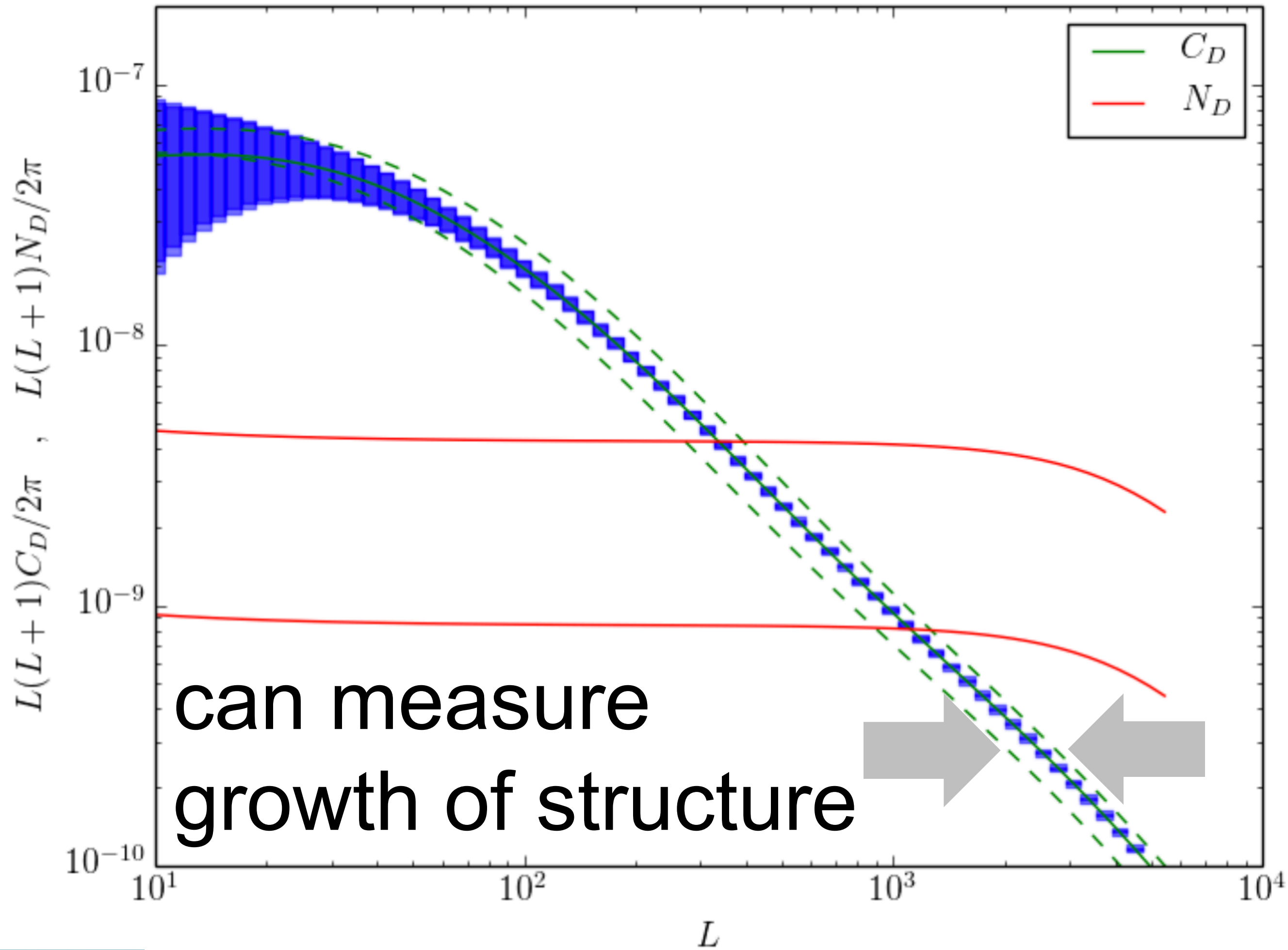


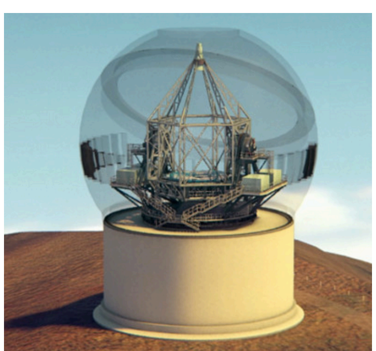
CLAMATO forecast

P(k) cumulative S/N forecasts

	BOSS DR12	eBOSS	CLAMATO	WEAVE	DESI	Subaru PFS	MSE
$\Delta z = 0.1$	1.3	3.7	2.7	7.3	7.0	4.2	53
$\Delta z = 0.5$	6.0	15.9	7.7	28.0	28.8	12.5	162

~3% error on σ_8





MSE forecast
(1000 sq. deg., 10^6 spectra)

work in progress…

next : realistic non Gaussian forest source field
non Gaussian lens field
non-grid based estimator
test estimator on realistic simulations

try for detection with eBOSS data
(cross-correlate with CMB lensing to
verify)

part II

Test of GR: lab measurement of gravitational redshifts.

1960 Pound-Rebka experiment

light received

light emitted

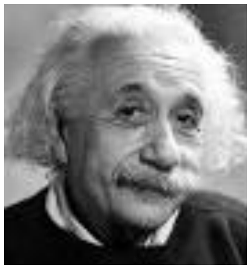
gravitational potential difference

$$\Delta\phi$$

gravitational redshift

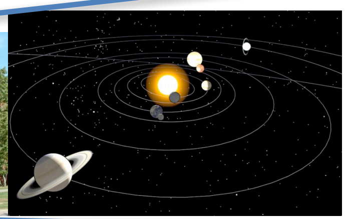
$$z_g = \frac{\Delta\lambda}{\lambda} \simeq \frac{\Delta\phi}{c^2}$$

Why extend the range of GR tests?

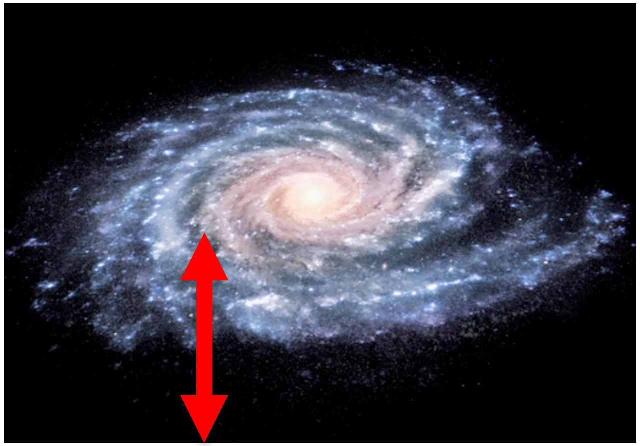


General relativity works on Earth and solar system scales…

… but the Universe as a whole is accelerating



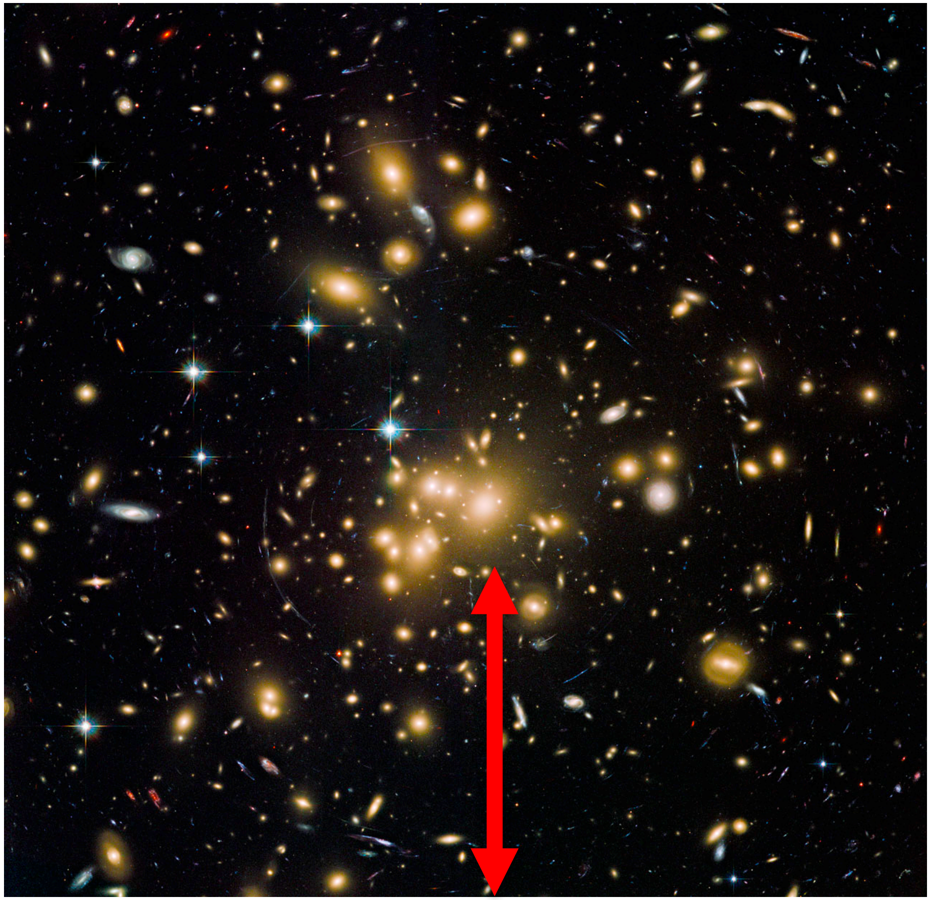
?



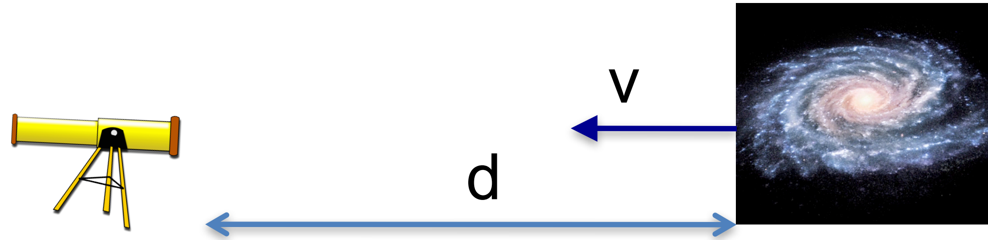
$cz_g = v \approx \dfrac{gh}{c} = 7.5\times10^{-7}$ m/s

$cz_g \sim$ 1 km/s

best place to look: galaxy cluster



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



redshift of a galaxy:

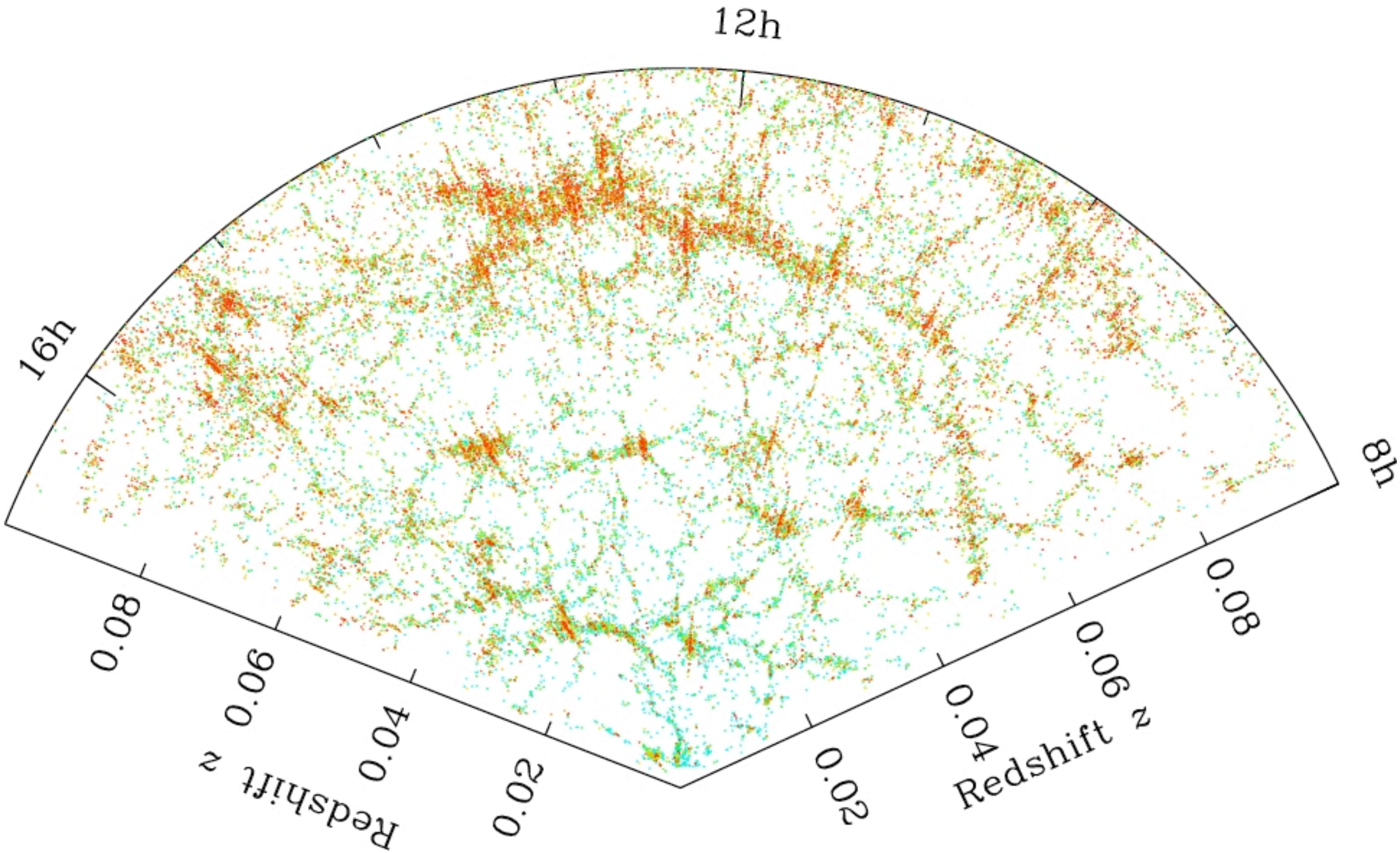
$$cz = Hd + v + \frac{\Delta\phi}{c}$$

Hubble expansion

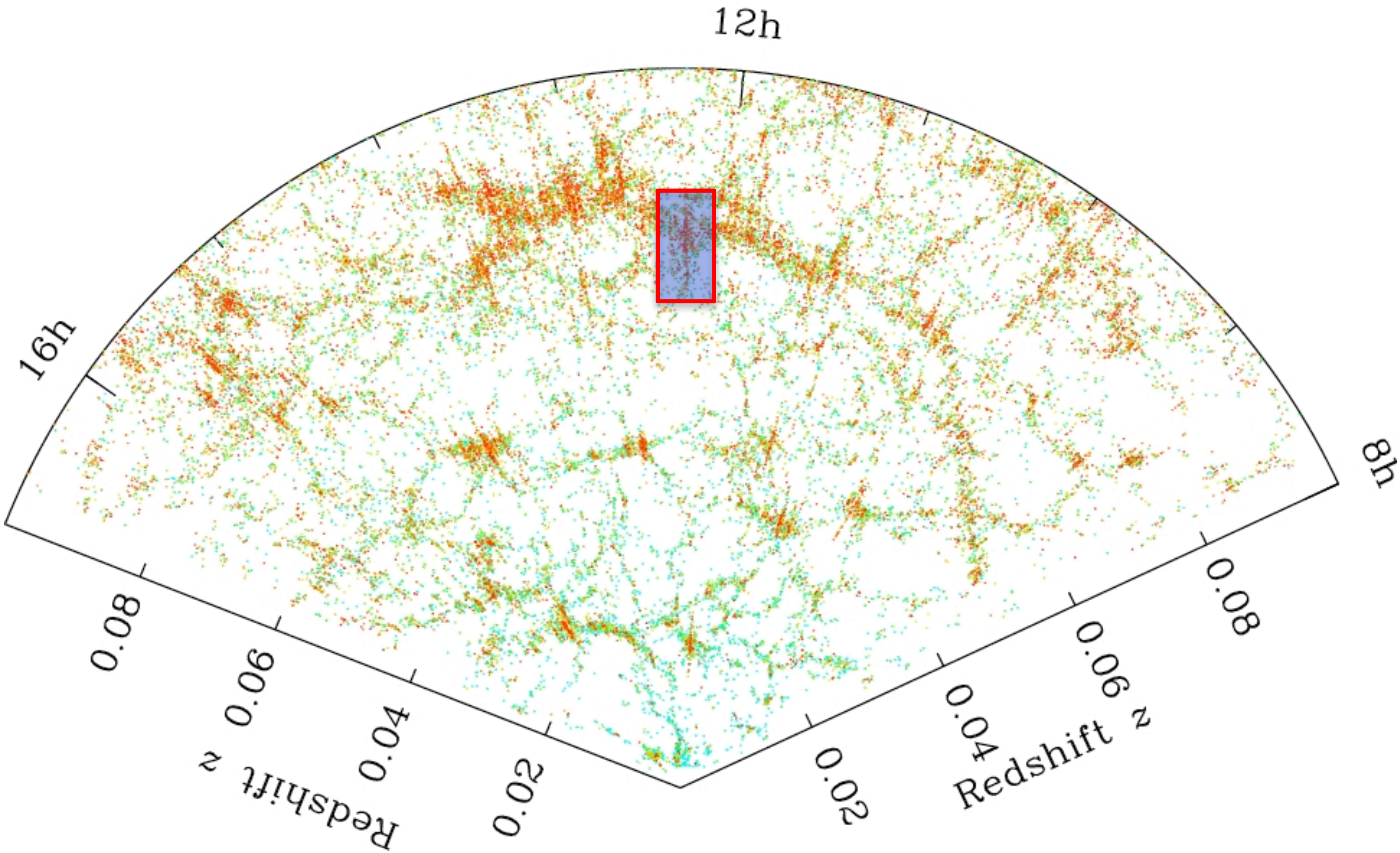
Peculiar velocity

Gravitational redshift

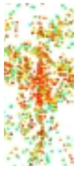
SDSS



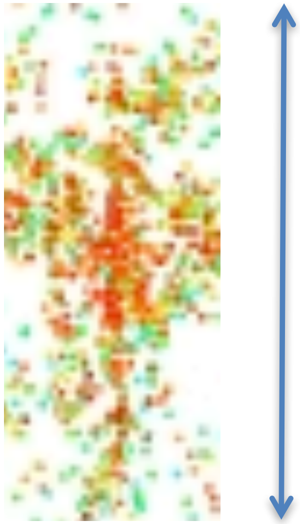
12h
16h
8h
0.08
0.06
0.04
0.02
Redshift z
0.02
0.04
0.06
0.08
Redshift z



12h
16h
8h
0.08
0.06
0.04
0.02
Redshift z
0.02
0.04
0.06
0.08
Redshift z



z_g measurement for single cluster is too noisy:



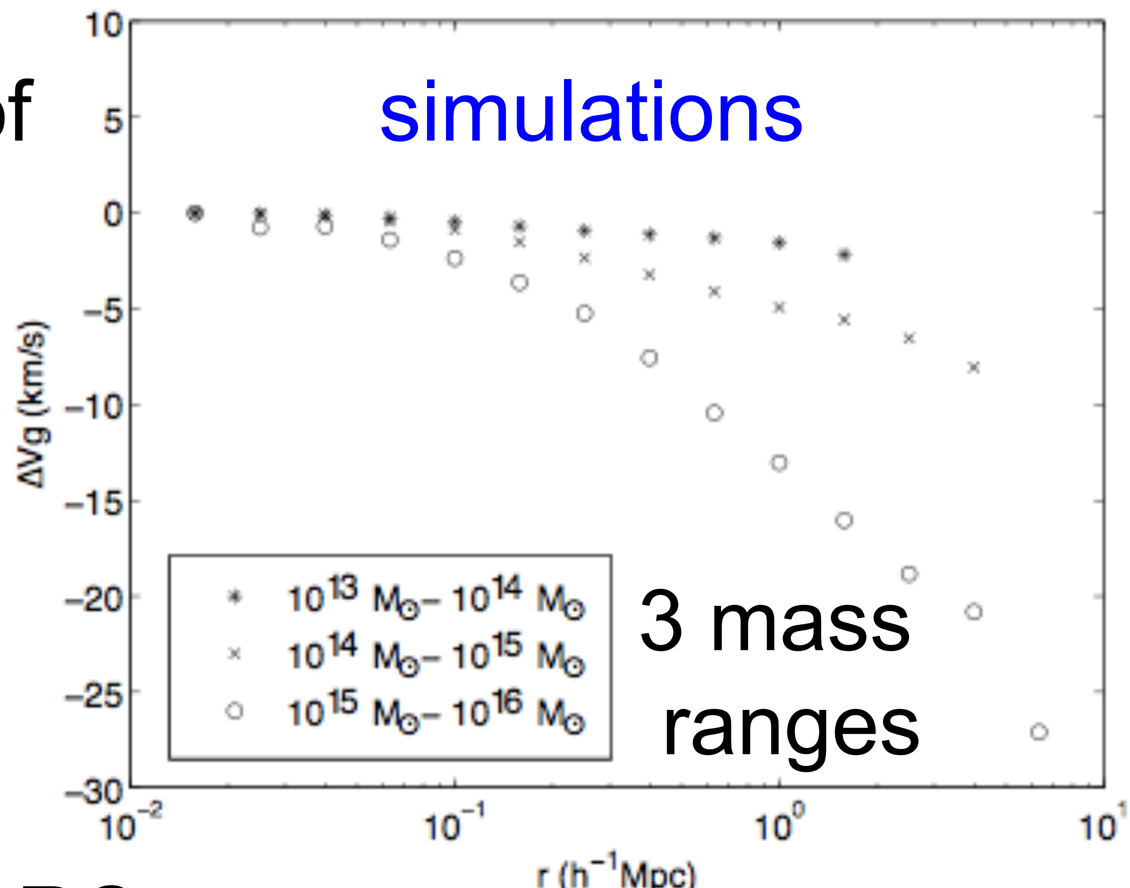
Cluster velocity
dispersion
>1000 km/s

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



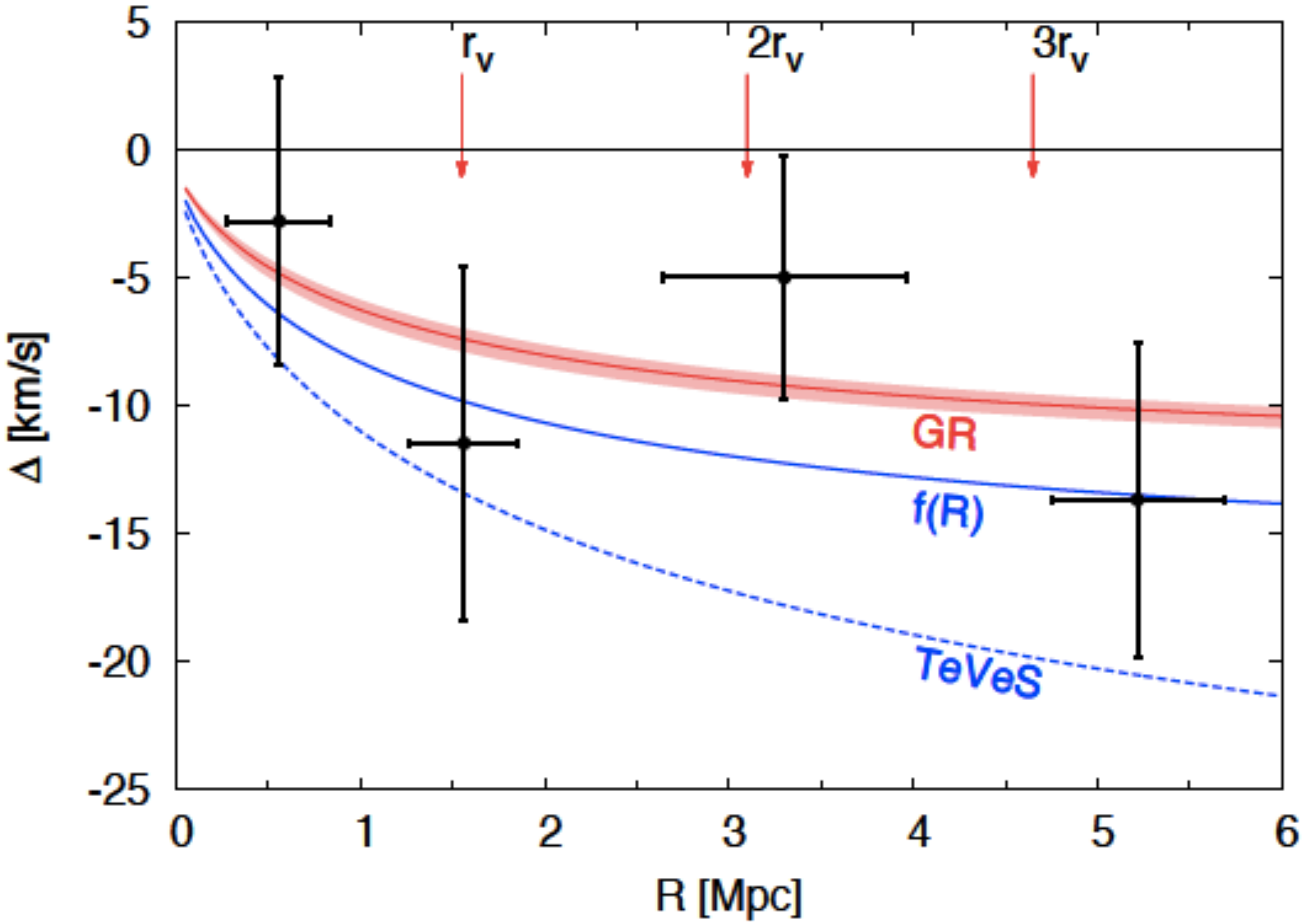
edge of cluster

relative blueshift (-ve redshift)

(Kim & RC 2004)

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

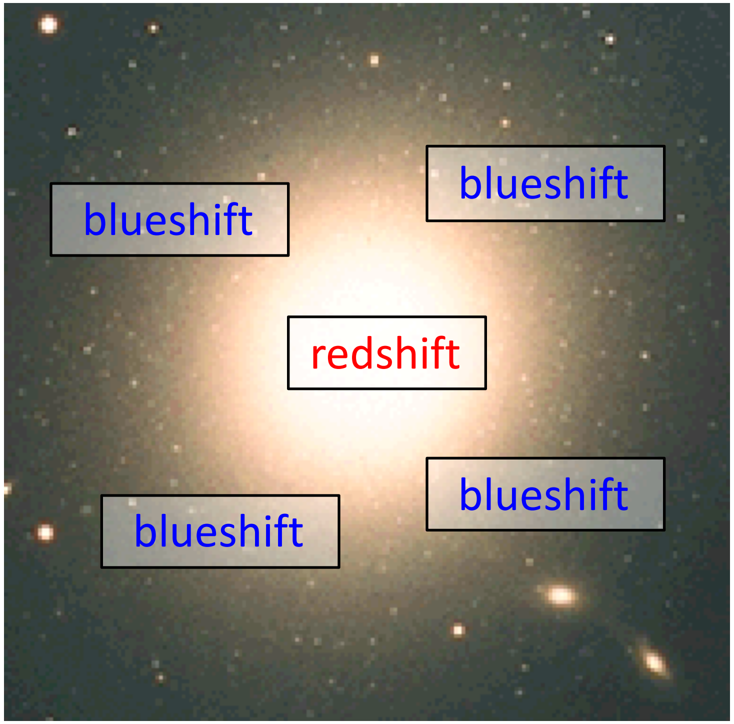
relative
redshift



2.8 sigma

distance to central galaxy

What about
z_g profile of stars in galaxies?



was tried long ago...

Mon. Not. R. Astron. Soc. **262**, L51–L54 (1993)

Non-equilibrium motions in galaxies and gravitational redshift

Massimo Stiavelli[1] and Giancarlo Setti[2,3]
[1] *Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy*
[2] *Istituto di Radioastronomia, via Irnerio 40, I-40128, Bologna, Italy*
[3] *European Southern Observatory, Karl-Schwarzschild Str. 2, D-8046, Garching bei München, Germany*

Accepted 1993 April 13. Received 1992 October 19

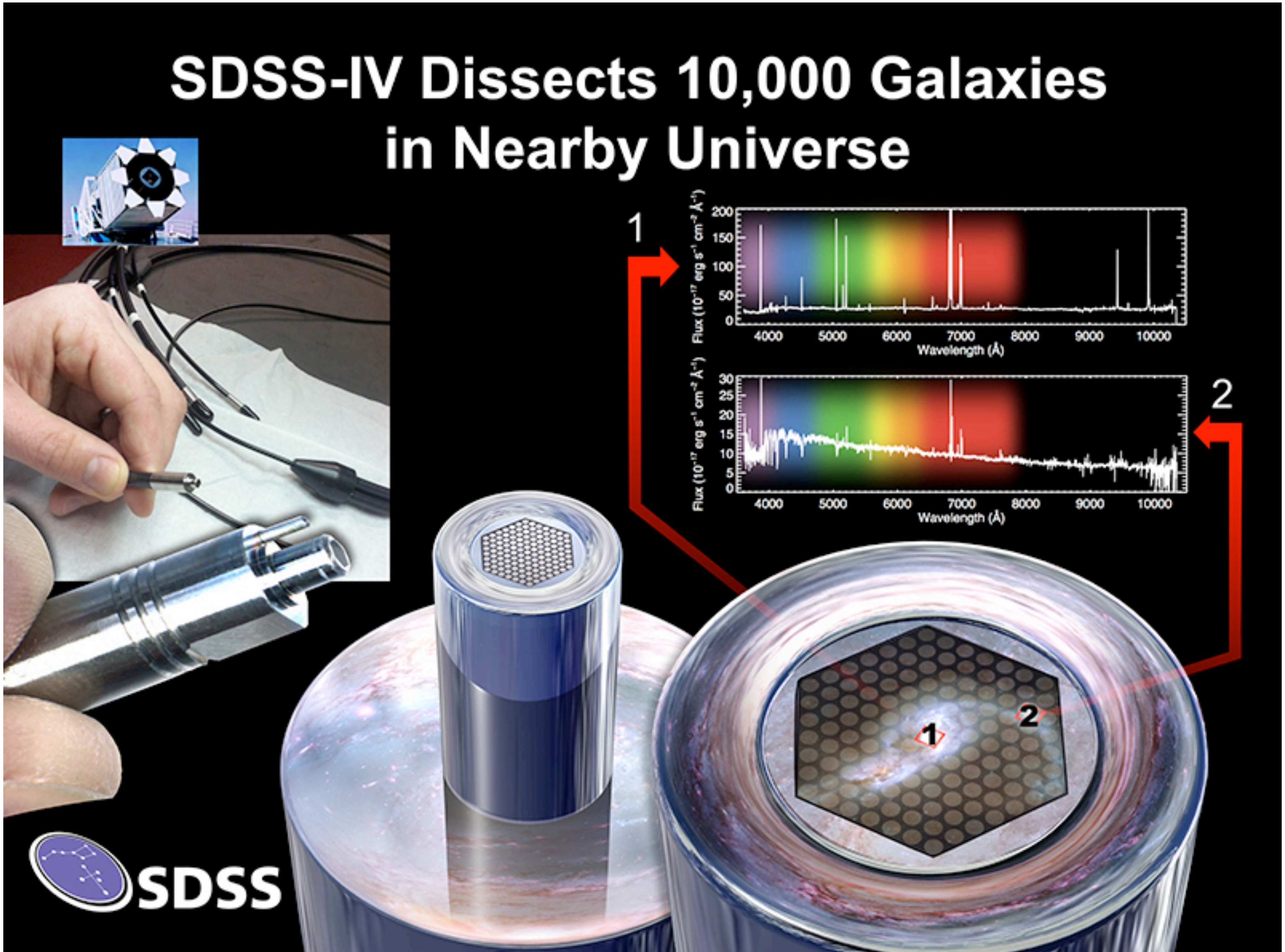
From
1993

Showed results for single galaxies – no detection

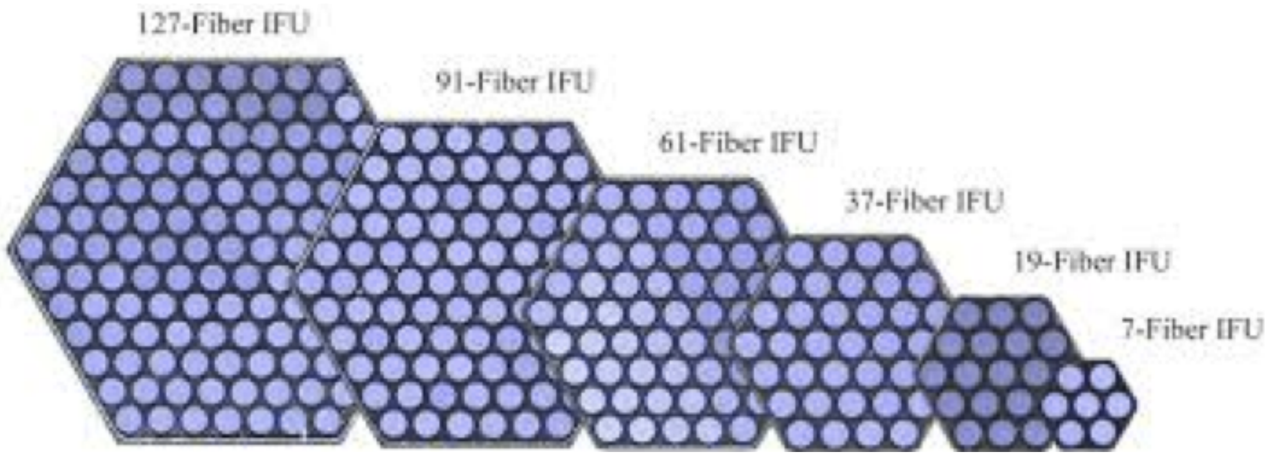
Also Coggins (U Nottingham
thesis, 2002) - no detection

We need large sample → statistical measurement

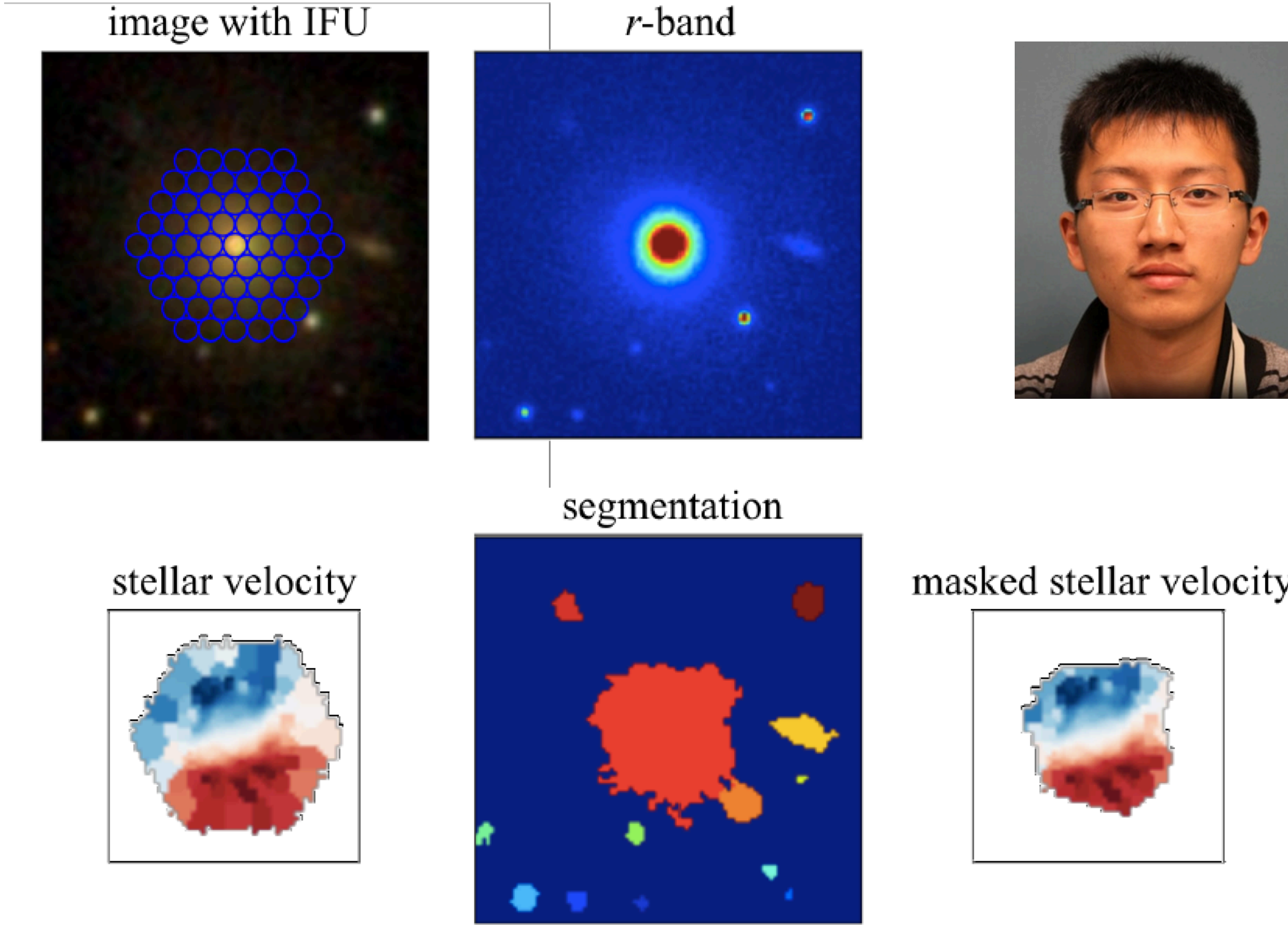
MaNGA


SDSS-IV Dissects 10,000 Galaxies
in Nearby Universe
1
2
Wavelength (Å)
Wavelength (Å)
SDSS

MaNGA has observed 299 BCGs so far with $M_{halo} > 10^{12.5}$ M_{sun} with IFUs, ~ 1kpc resolution

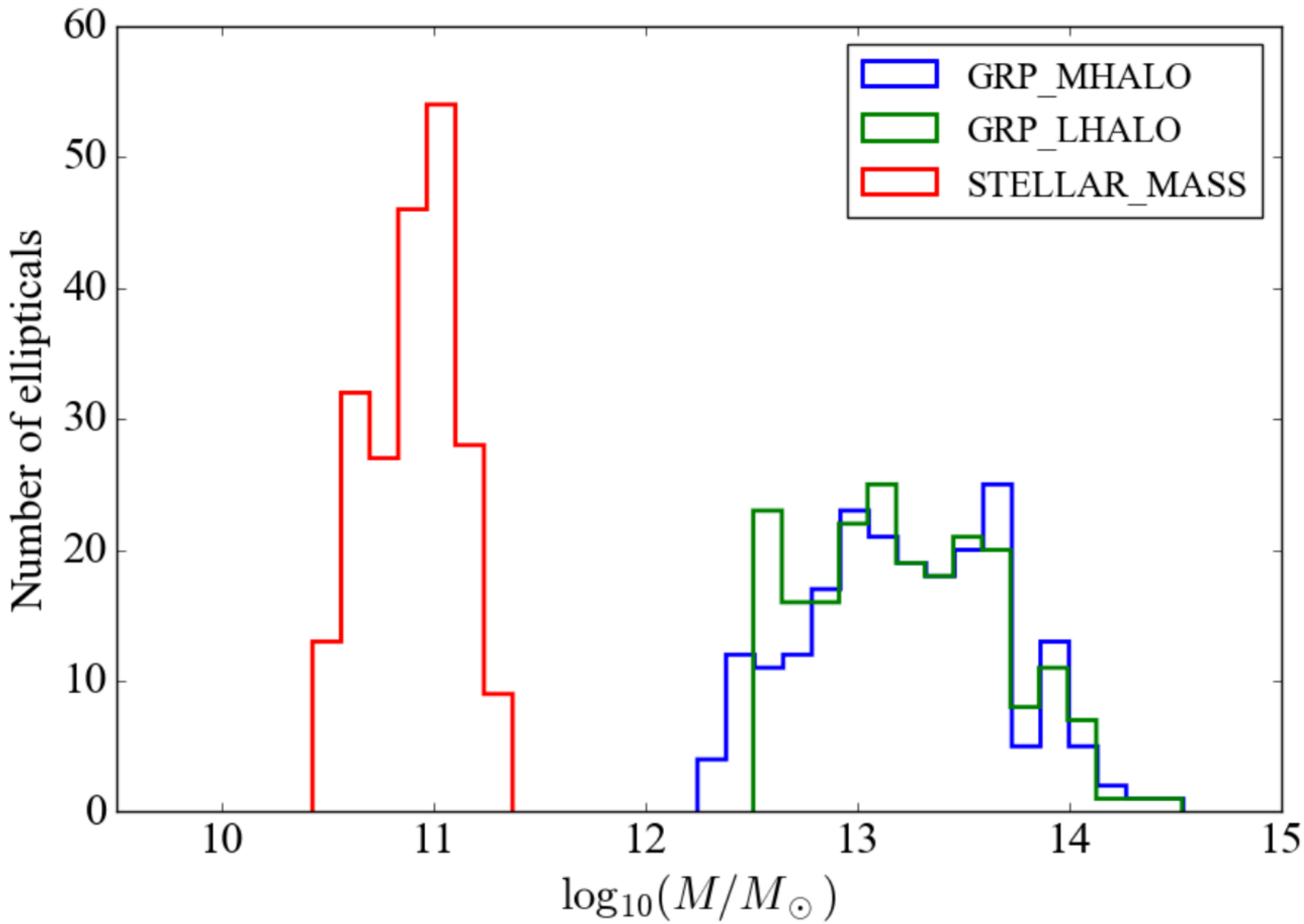


With stacking can try to make statistical measurement of relativistic effects on sub-galaxy scales (velocity error per fiber is ~20 km/s)



+ eliminate mergers, rescale and stack sample of 208 galaxies

stellar masses ~10^{11} M_{Sun} , halo masses ~10^{13} M_{Sun}



theoretical prediction

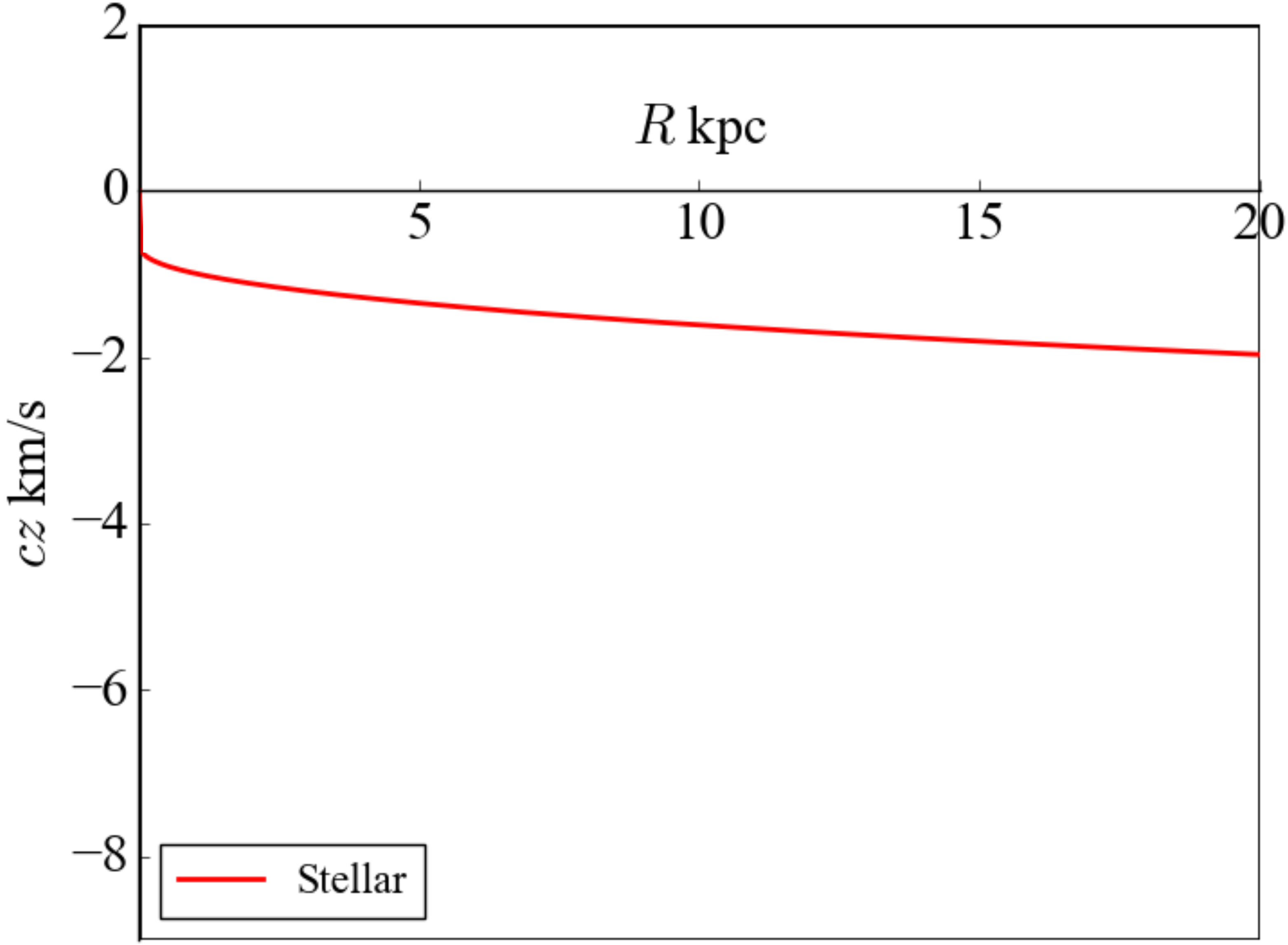
$$\rho(r) = \frac{(3-\gamma)M}{4\pi} \frac{a}{r^\gamma (r+a)^{4-\gamma}}$$

(1) use Dehnen profile for radially averaged density (gamma=1.24 for De Vaucouleurs)

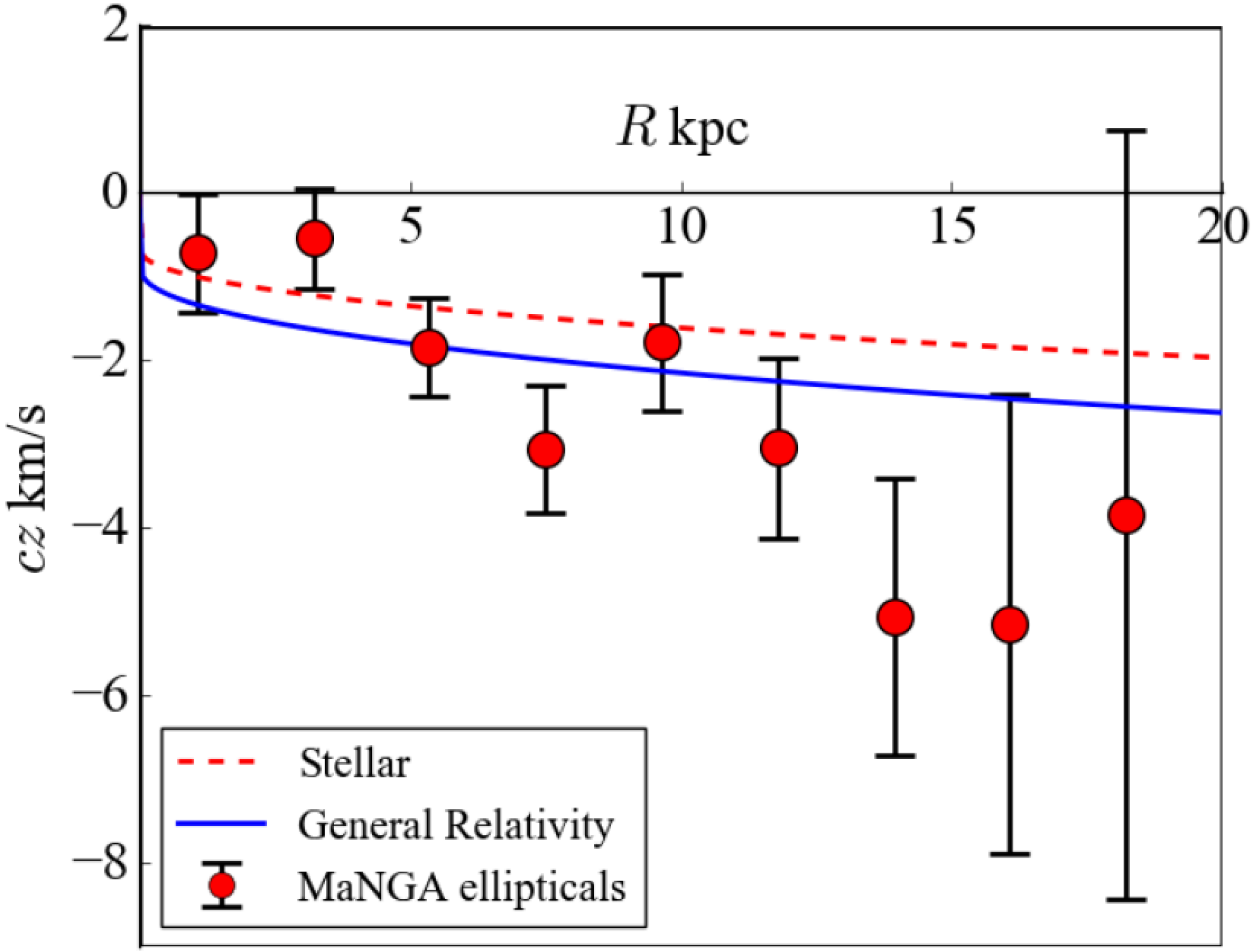
(2) project using galaxy luminosity profile

(3) assume GR

$\Rightarrow$ gravitational redshift profile

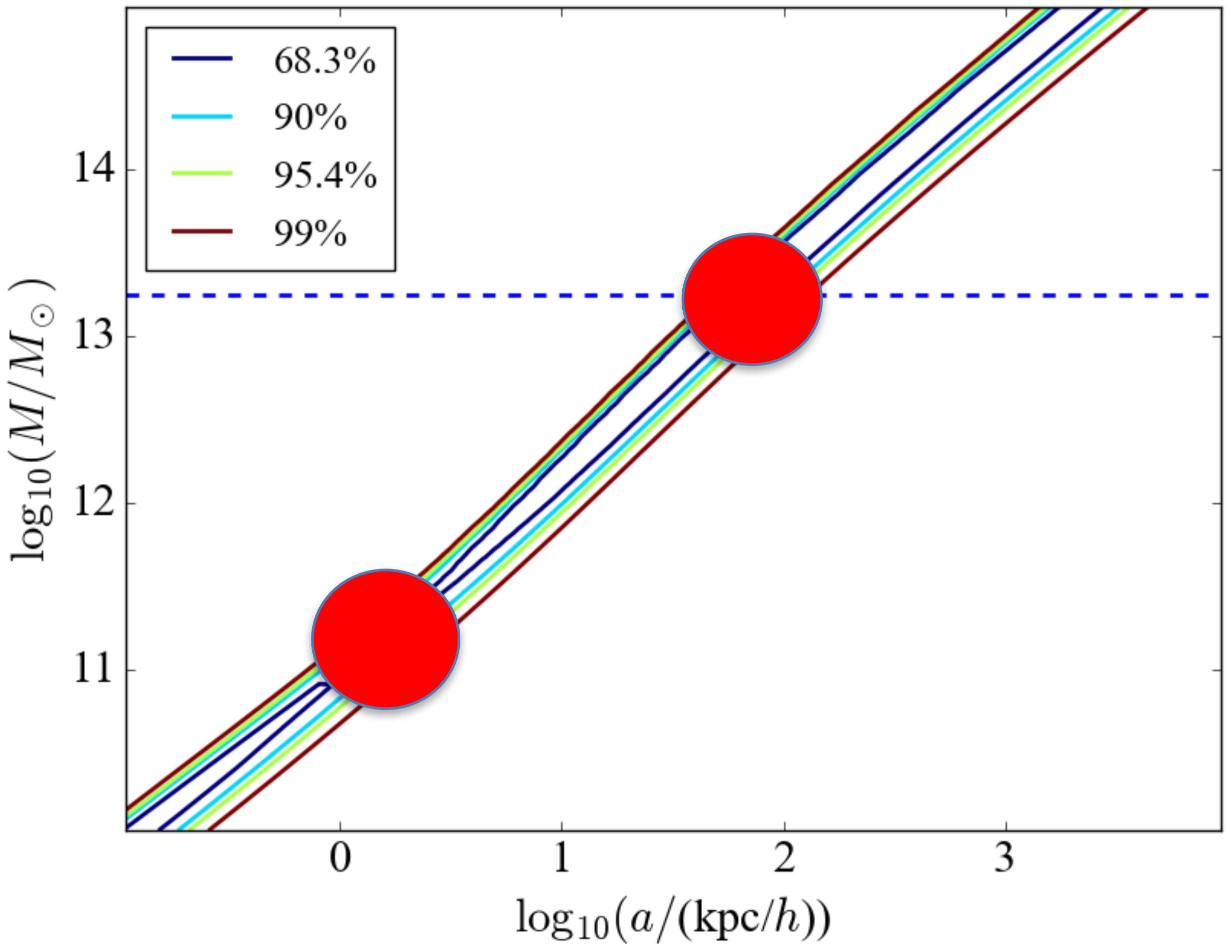


prediction using stellar mass



MaNGA result: from 208 galaxies

degeneracy in fit:
consistent with GR+ stellar mass or halo mass



(scale radius)

Other relativistic effects, Tranverse Doppler, beaming enter at the 0.1-0.2 km/s level (10% level).

Why relativistic effects could be useful to constrain mass of elliptical galaxies

-Unlike lensing, not projected measurement

-Unlike stellar dynamics, no need to make assumptions like equilibrium

Conclusions

- The Lya forest is a 3D continuous field which traces the mass distribution
- Lya forest lensing has some advantages of CMB lensing, but in 3D
- With IFU redshift data can measure gravitational redshifts due to galaxy potential wells – consistent with GR