Cosmic Visions Dark Energy: Science

Low Resolution Spectroscopy

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Cosmology Using Low Resolution Spectroscopy in the 2020s

February 16-17, 2016 • Chicago, IL

for k<0.2 we only need r>20 Mpc/h (or dz>0.0035)

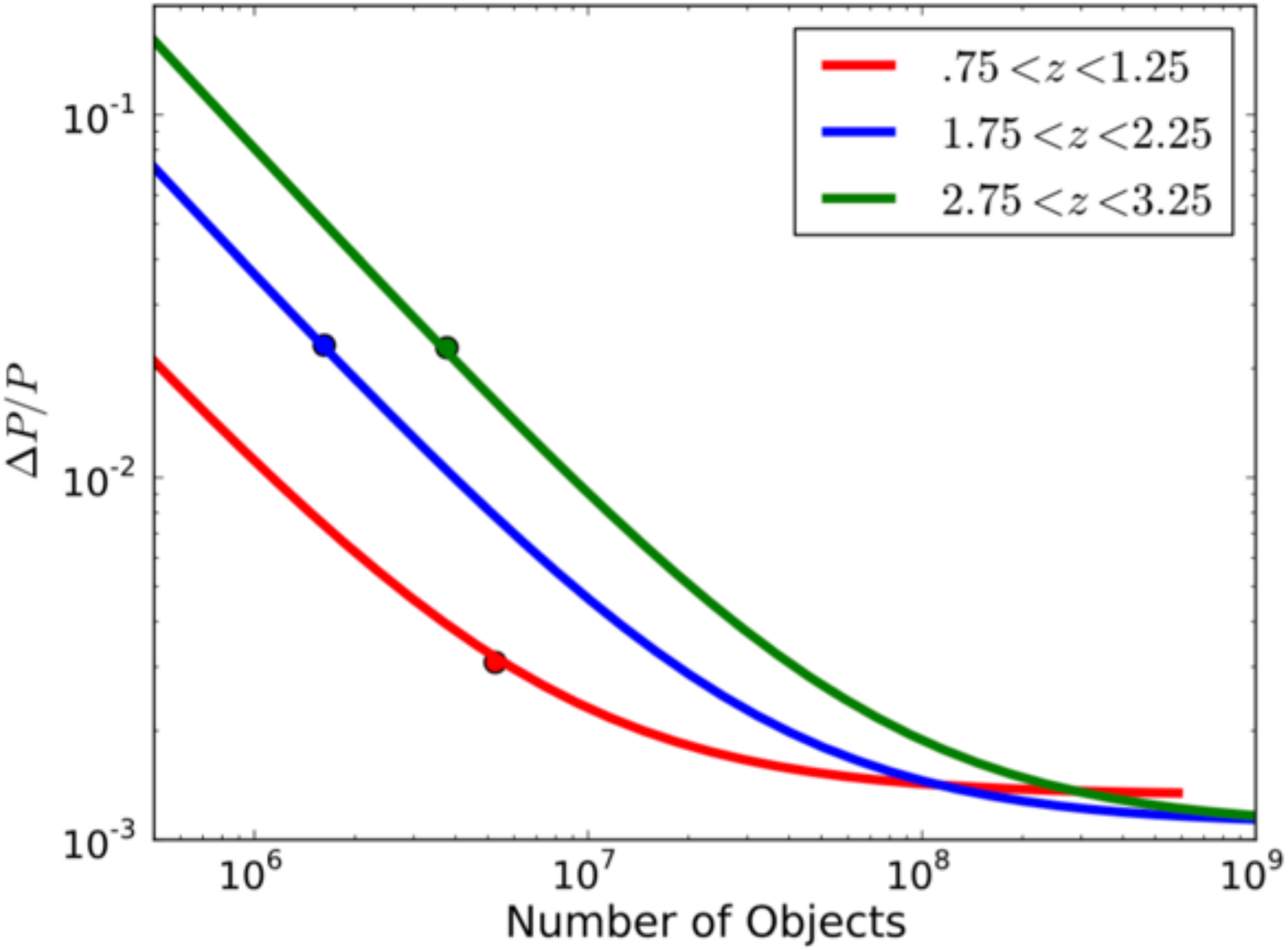
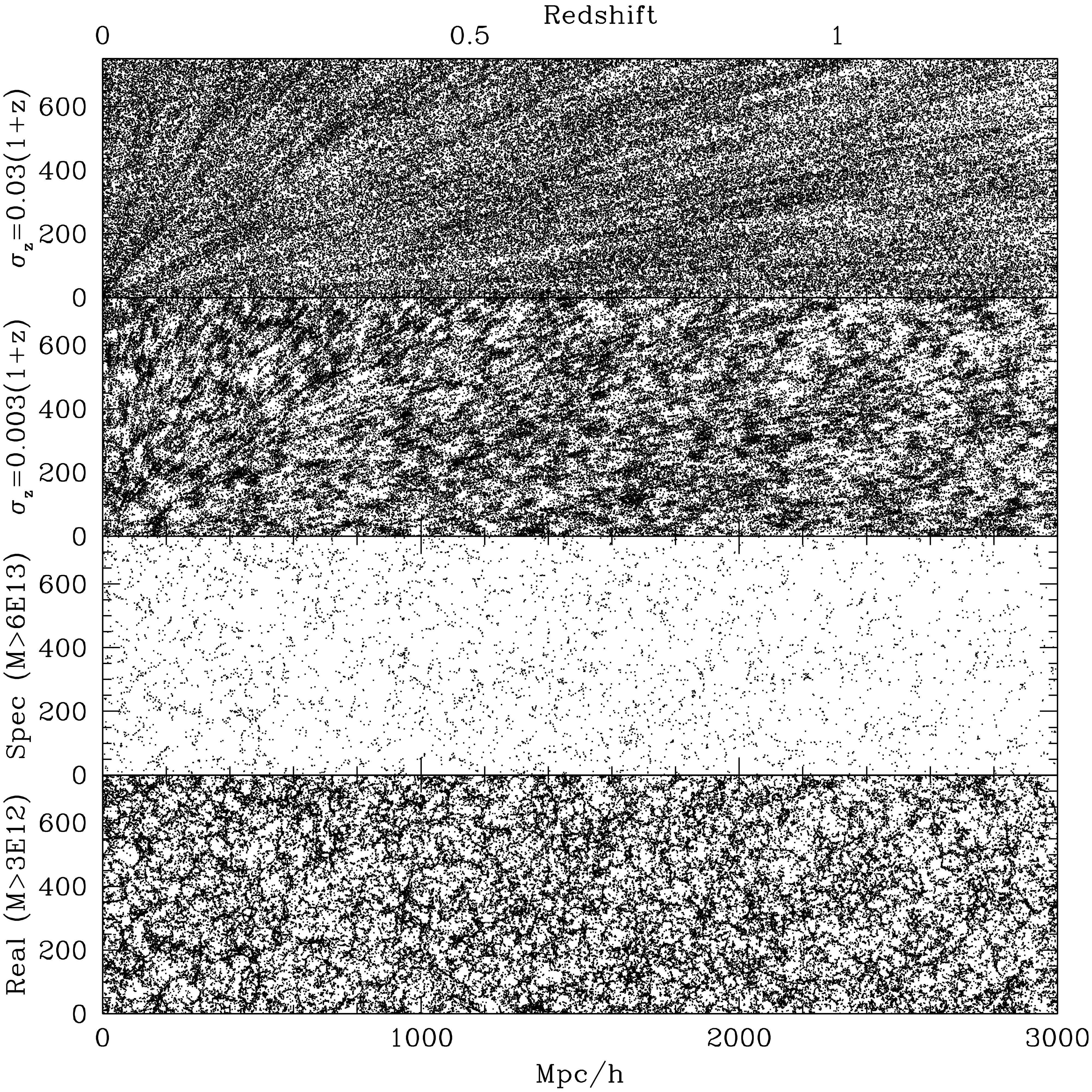
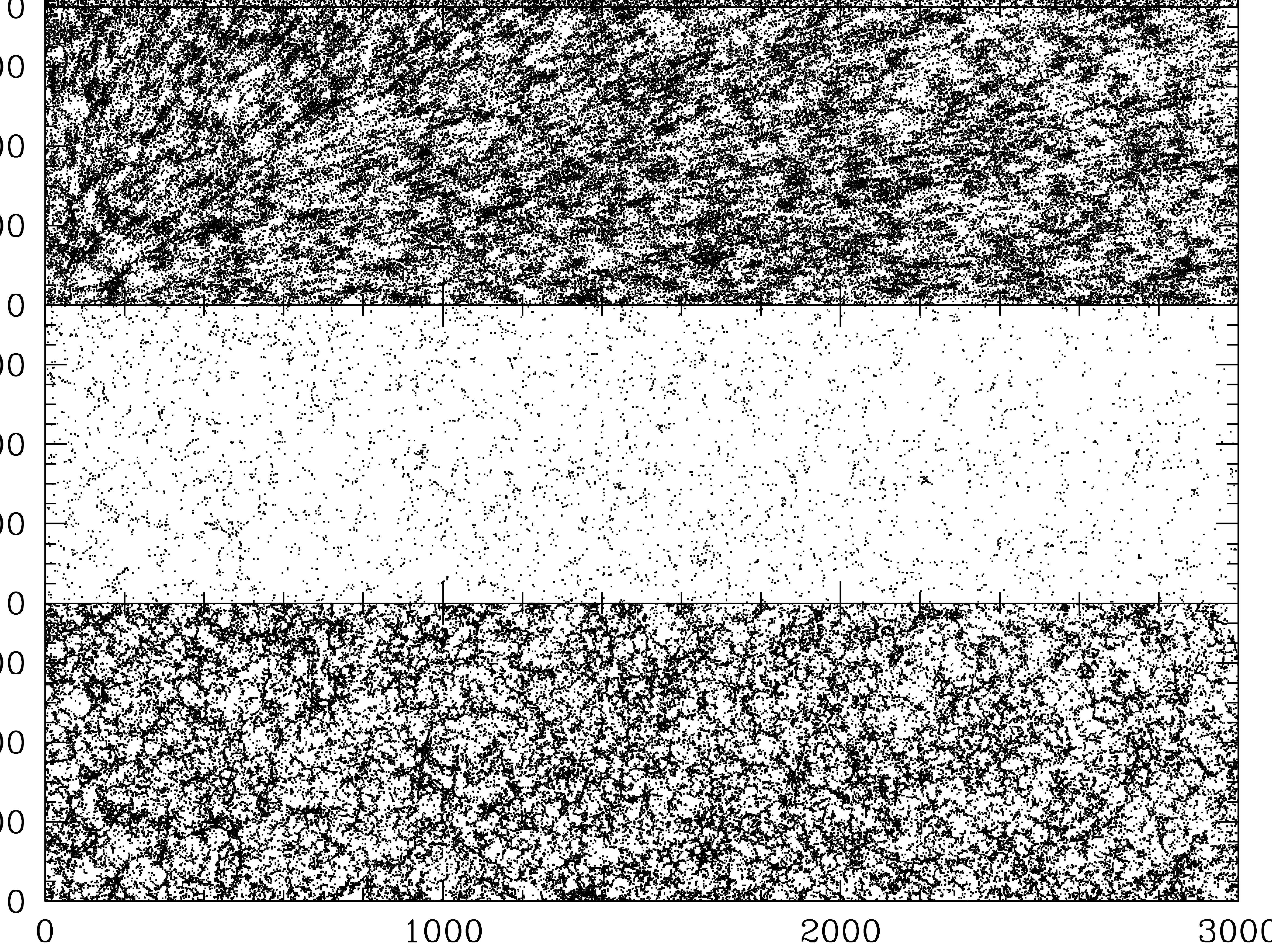


Figure 1. *Fractional error in the power spectrum on linear scales* ($k = 0.2hMpc^{-1}$) *that quantifies inhomogeneities for various redshifts as a function of the number of objects surveyed. The dots are projections for DESI: at* $z = 1$ *DESI will be within a factor of 3 of the ultimate error, but at higher redshift, there is at least of factor of ten more information to be mined by future surveys. LSST will measure many more objects but will have imperfect radial information so therefore less effective information per object.*

Galaxy
Halos
(50%)
in
10 Mpc/h
thick slice

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1000
2000
300

LowR Techno

see Juan Estrada's talk

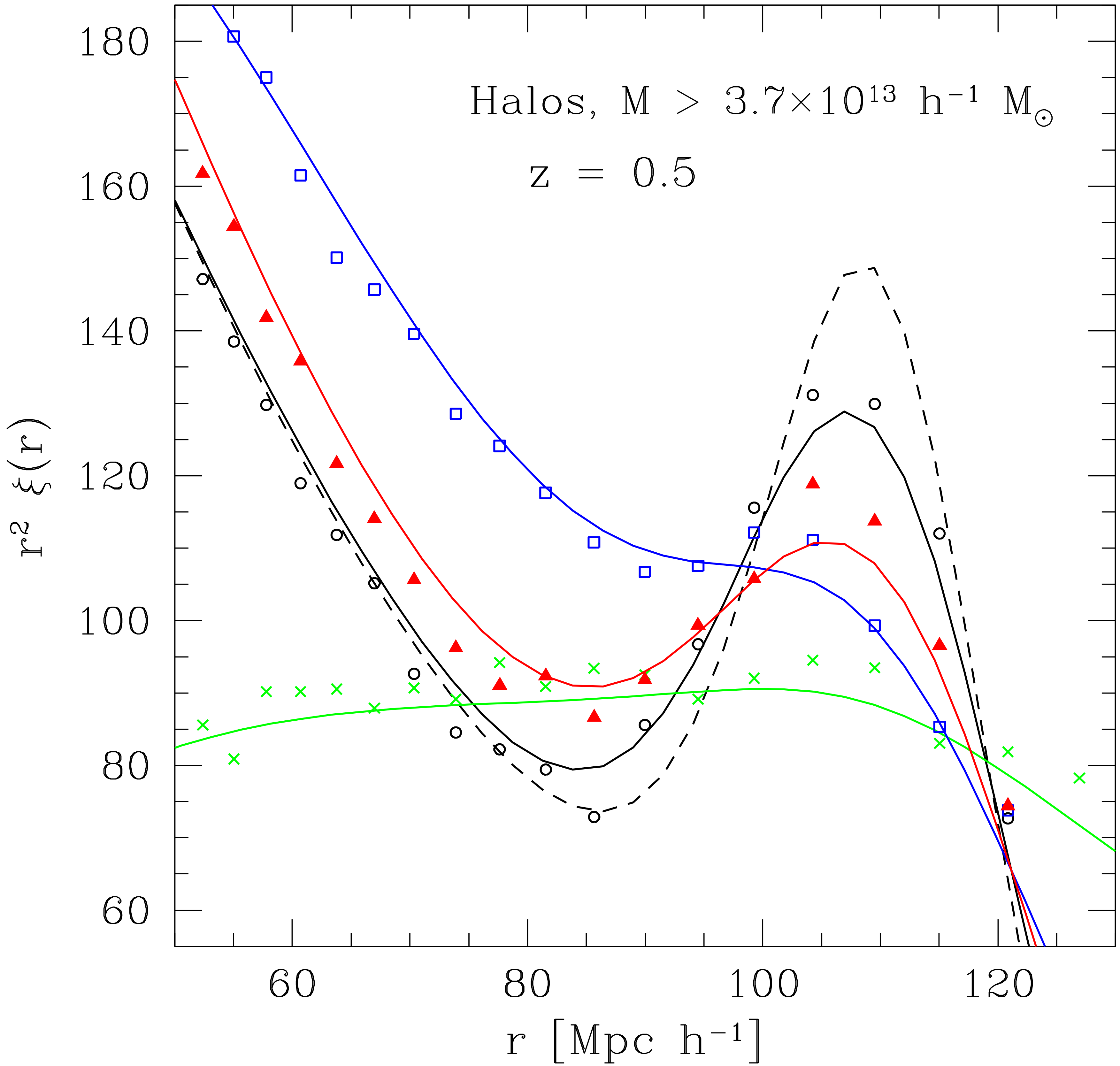
Narrow bands
Linear Variable Filters (Spherex)
Prisms
MKIDS

PAUS a pathfinder

dashed: linear theory
Lines: non-linear predictions
Points: simulation measurements
black: spectroscopic

- **red: dz= 0.0035(1+z)**
- **blue: dz= 0.007(1+z)**
- **green: dz= 0.03(1+z)**

BAO

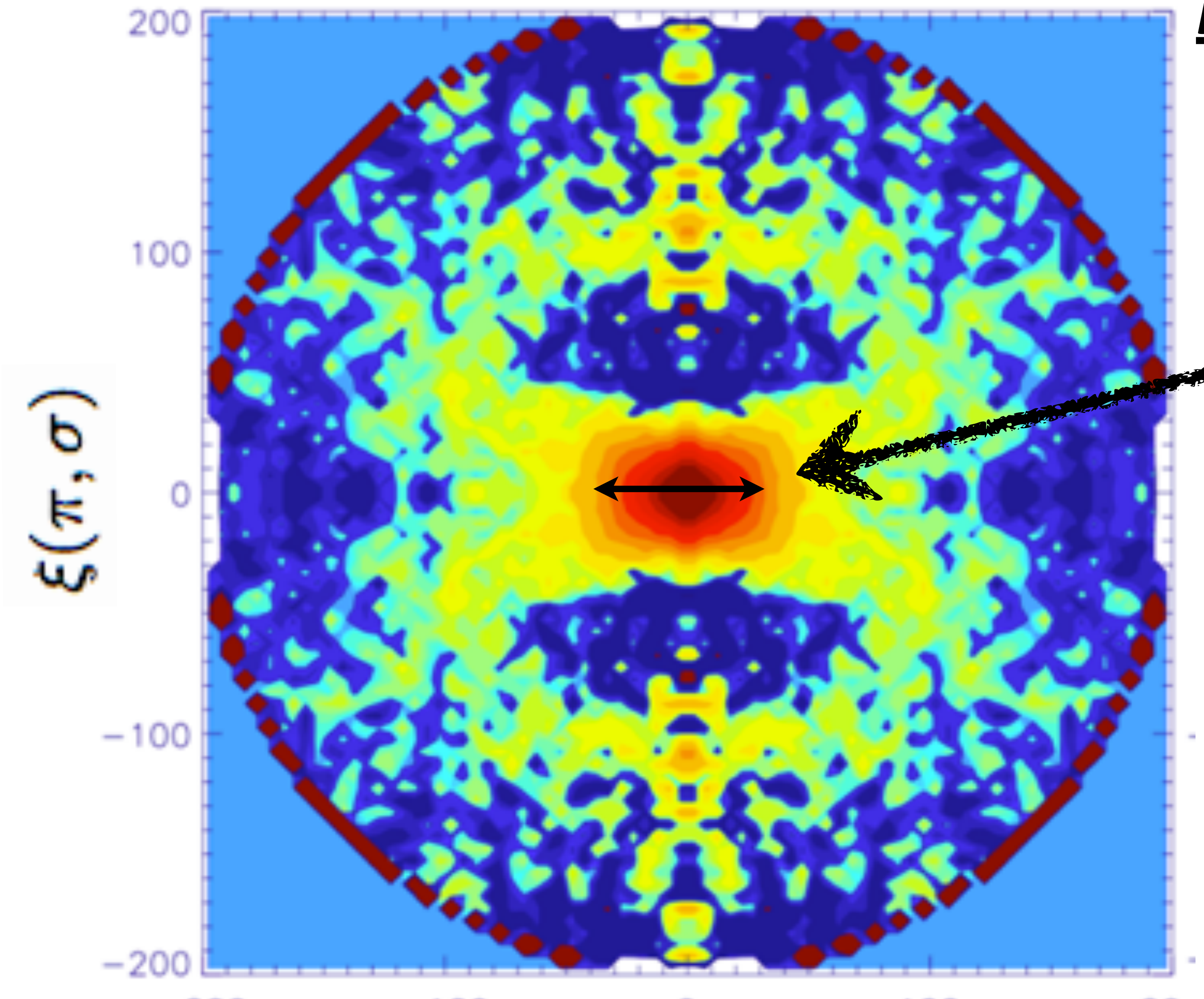


2009ApJ...691..241B

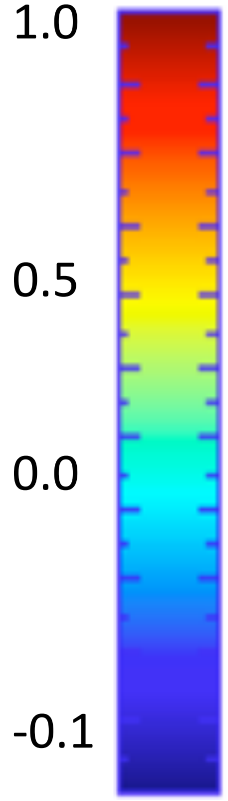
Redshift Space Distortions (RSD)

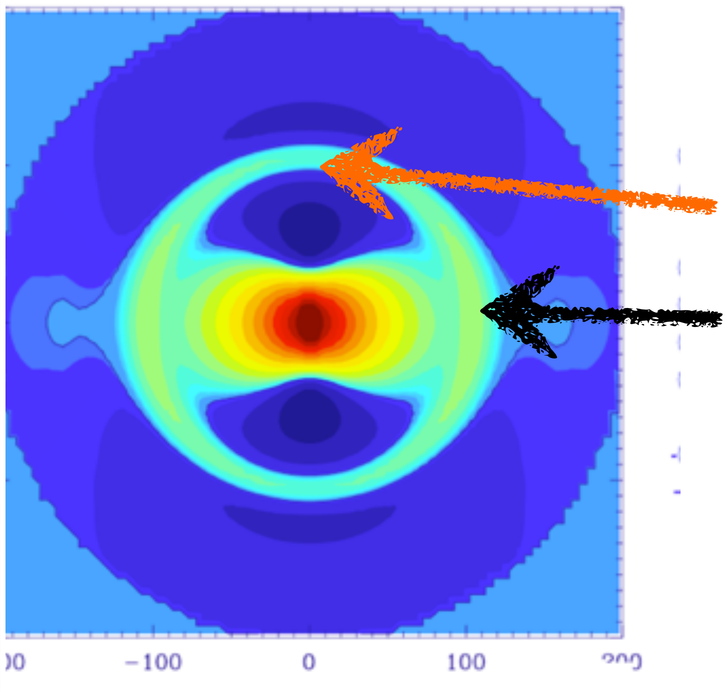
$$\delta_g(k,\mu) = (b + f\mu^2)\delta(k)$$

Measure both bias and growth!



Anna Cabré's PhD Thesis arXiv:0807.3551





BAO: $\xi(\pi,\sigma)$

radial H(z)

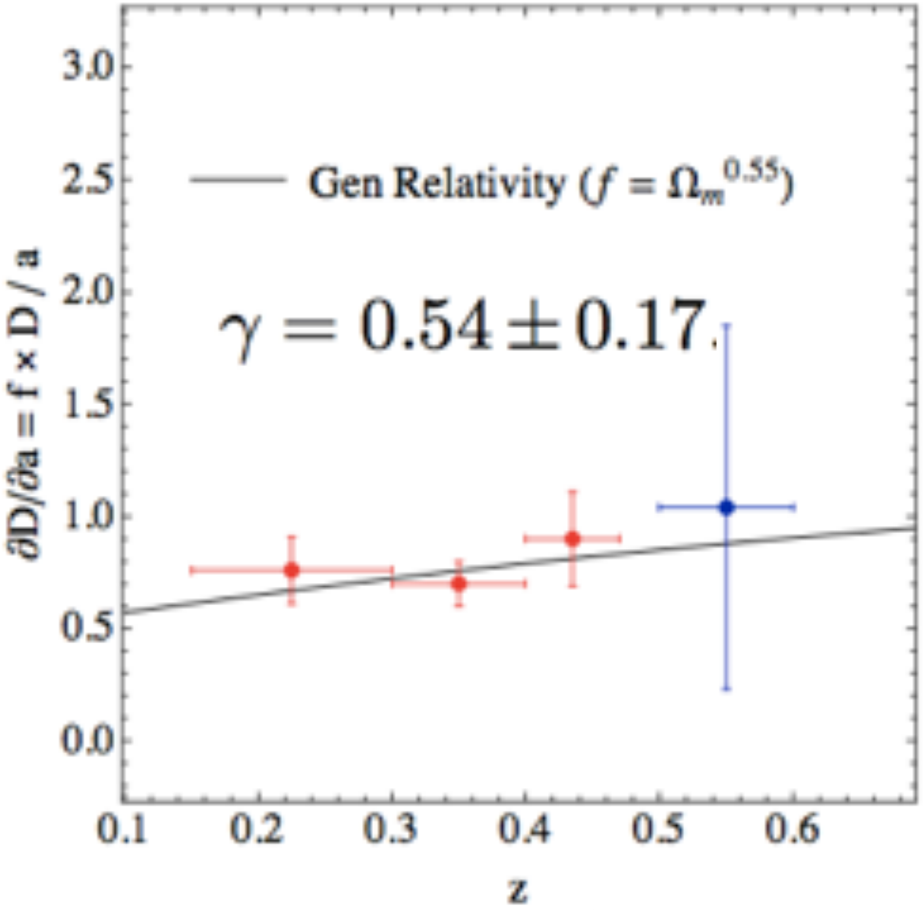
H(z=0.34) = 83.8 ±3.0± 1.6

EG, Cabre & Hui (2009)

Transverse $\int$ cdz/H(z)

θ(z=0.34) = 3.90 ± 0.38

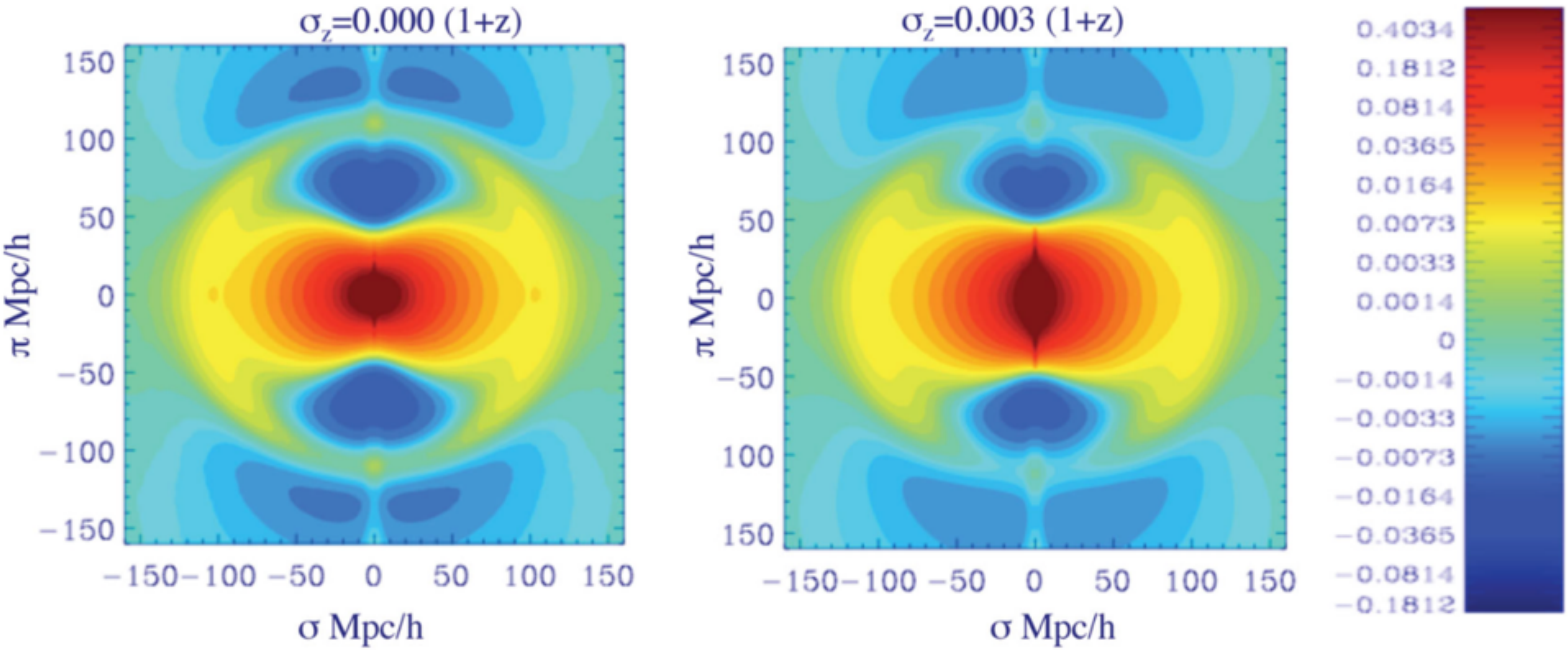
Carnero etal 2011



FoMγ= 6 Crocce etal 2011

(Forecast for DES: Ross etal 2011)

RSD + RadialBAO



2012MNRAS.422.2904G

kSZ

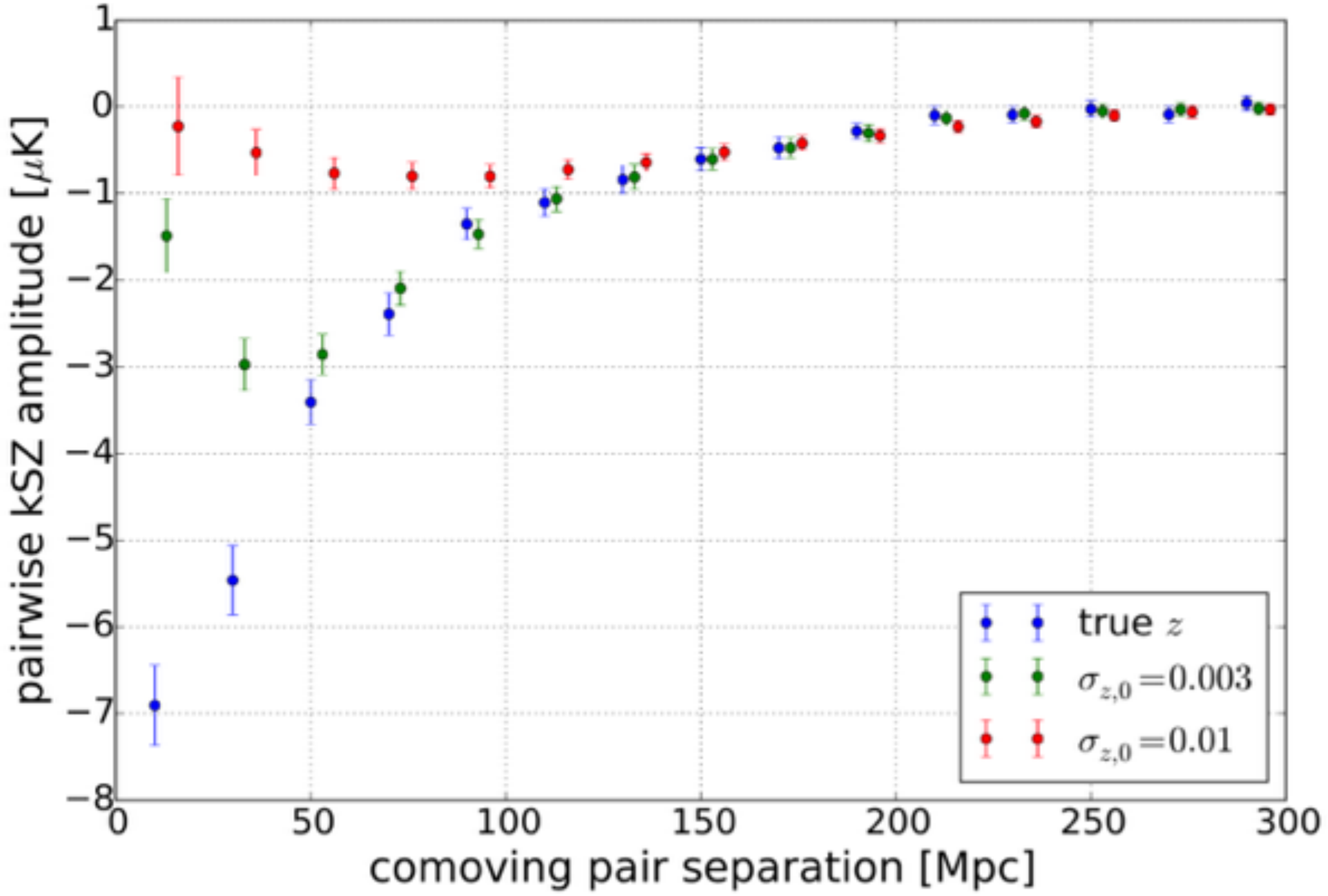


FIG. 5: Simulated pairwise kSZ measurement: We show in blue the measured signal using the true redshifts, and in green and red the results with added redshift uncertainties (averaged over multiple realisations of the redshift errors).

Tommaso Giannantonio

Lensing (CMB or Shear) x LSS:

does not requiere spectroscopic z
benefit from high density & multi tracers

Clustering-Based Redshift Estimates

larger densities (accuracy should be OK)

Galaxy Clusters

Cluster finding
mass calibration
velocity dispersion

Priors on WL shapes

kinematics WL

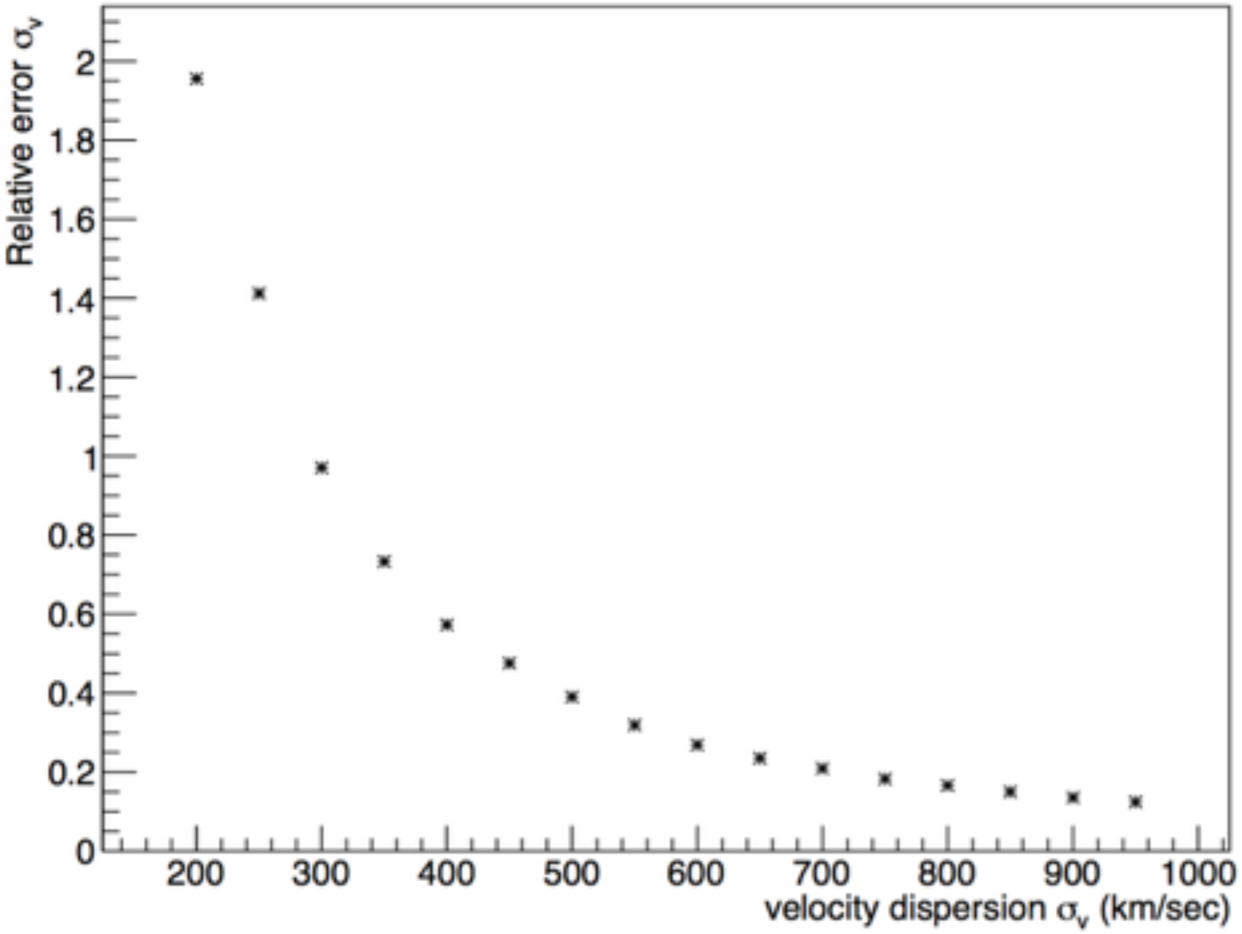
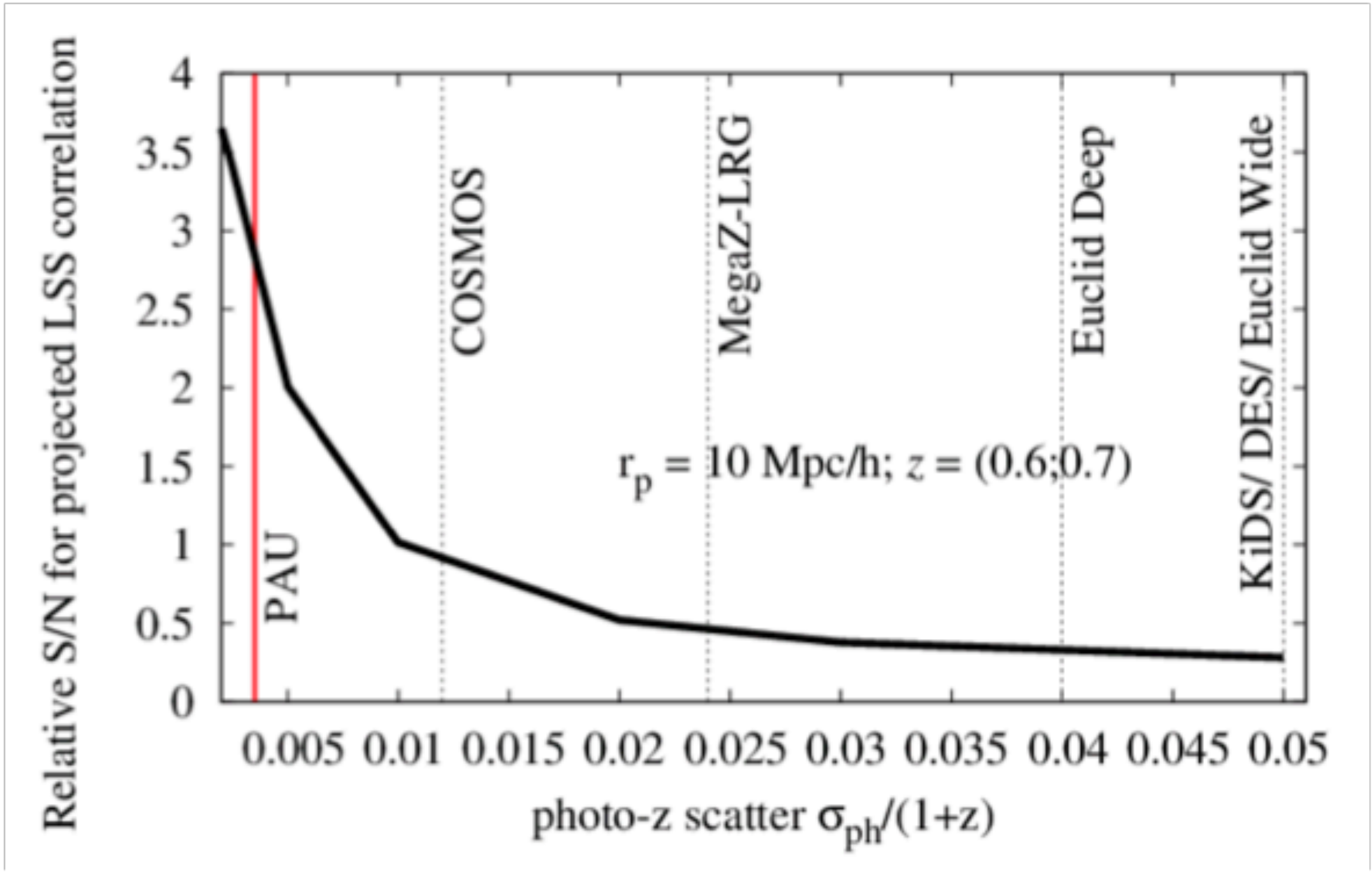


FIG. 4: Uncertainty in the measurement of the velocity dispersion for a galaxy cluster using a Low-Res instrument with $\sigma_z/(z+1) = 0.003$ capable of targeting 50% of the cluster members. The results show that for velocity dispersion lower than 600 km/sec there very little information obtained from this measurement.

Need for better z resolution (for 2D clustering)

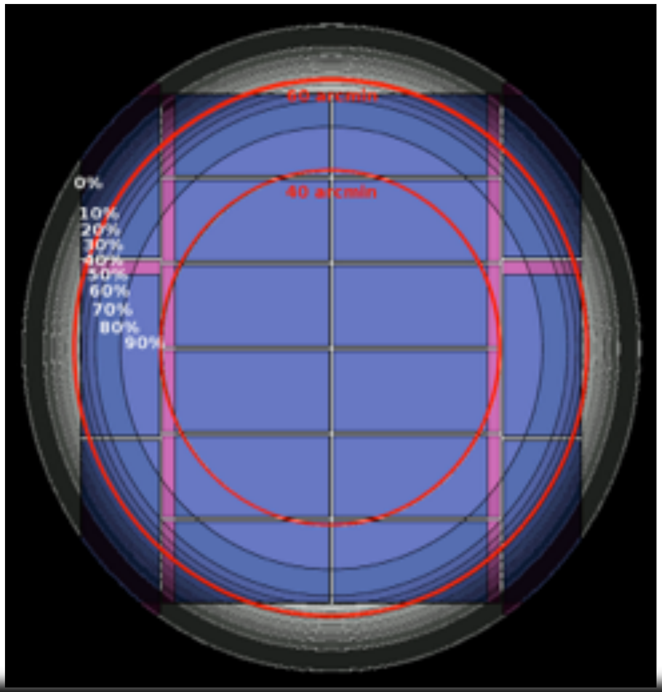


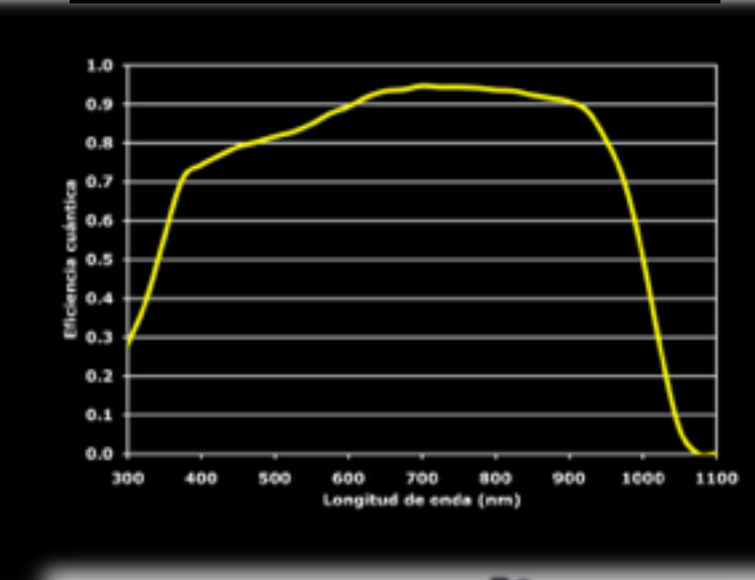
Relative S/N of projected large-scale structure clustering correlation (applicable to intrinsic alignment and galaxy clustering) as a function of the photometric redshift error. Since intrinsic alignments and galaxy clustering are local effects, redshift uncertainty quickly degrades the signal. PAUS will achieve a factor 3 gain in S/N over e.g. COSMOS and more than a factor of 6 compared to KiDS or DES surveys.

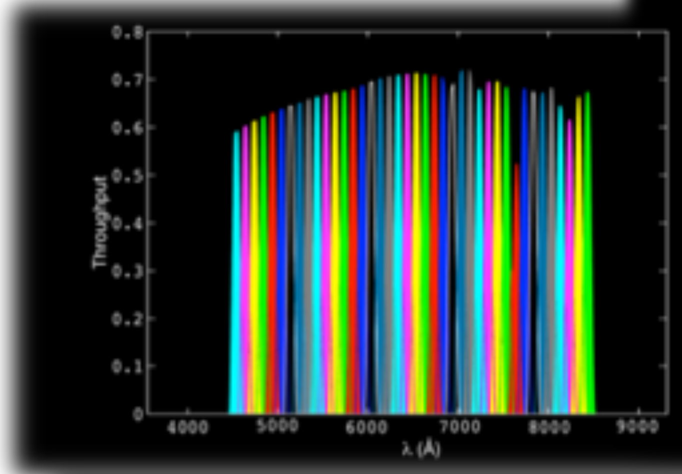
B.Joachimi

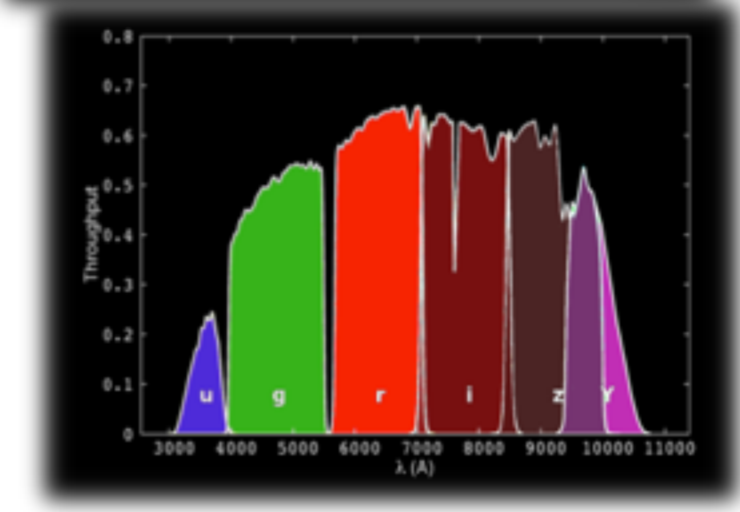
The PAUcam@WHT

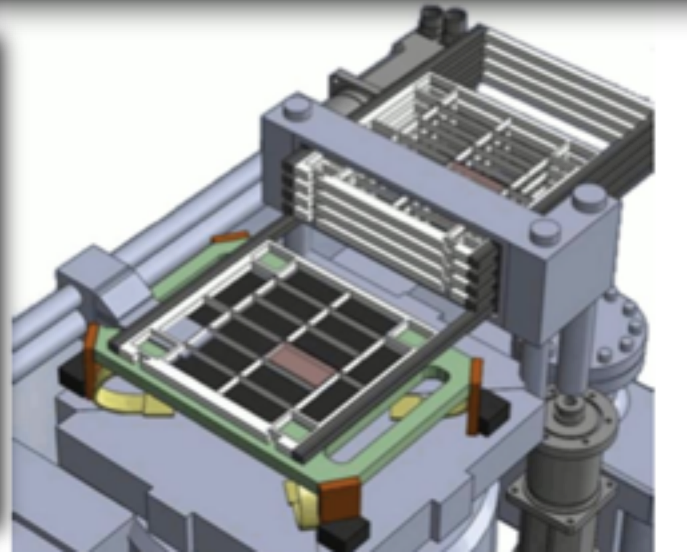
- New camera for WHT with 18 2k x 4k CCDs covering 1 deg ∅ FoV. Made in Spain
- 40 x130Å-wide filters covering 4500-8500 Å (100Å steps) in 5 movable filter trays, which also include standard ugrizY filters.
- As a survey camera, it can cover ~1 deg^2 per night in all filters to i~23 (with 8 ccd's)
- Can provide low-resolution spectra ($\Delta\lambda/\lambda$ ~ 2%, or R ~ 50) for >30000 galaxies, 5000 stars, 1000 quasars, 10 galaxy clusters, **per night**.
- Expected galaxy redshift resolution $\sigma(z) \sim 0.0035\times(1+z)$
- IA, groups, photo-z calibration, sample variance cancelation





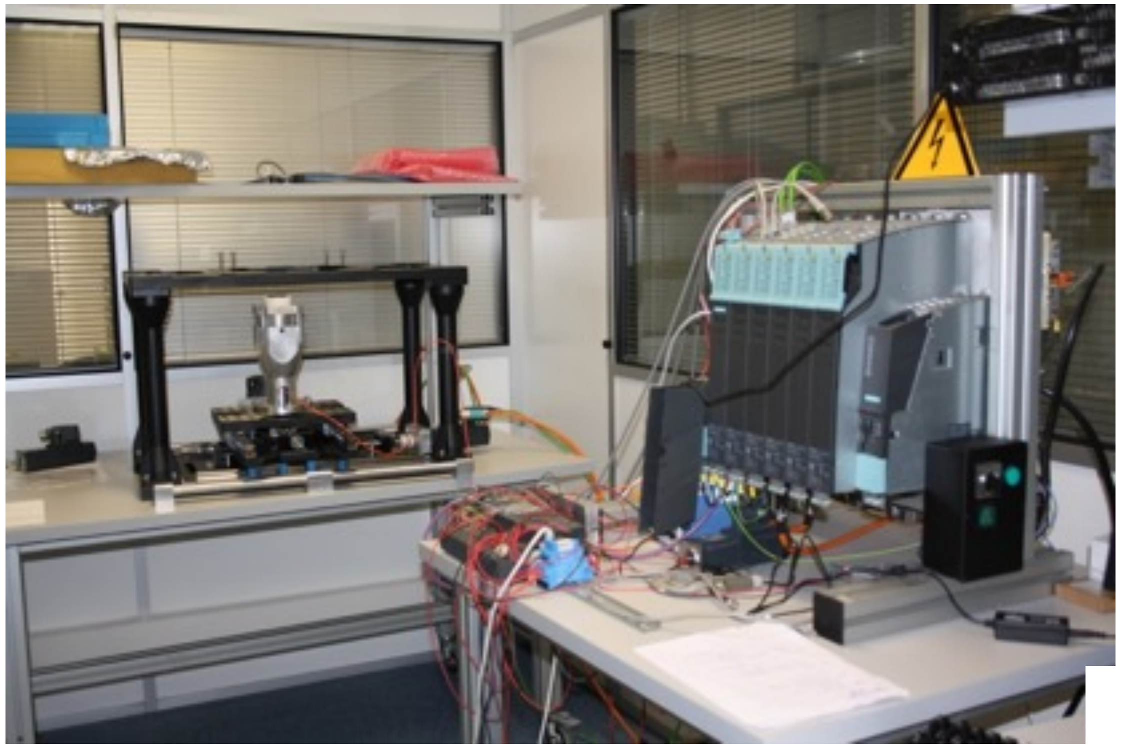






Lab Infrastructure for DES/PAU

(Barcelona)



3D metrology bench

New developments:

Carbon fiber cryostat with moving filters and temperature control

in house electronics and control software

community pipeline

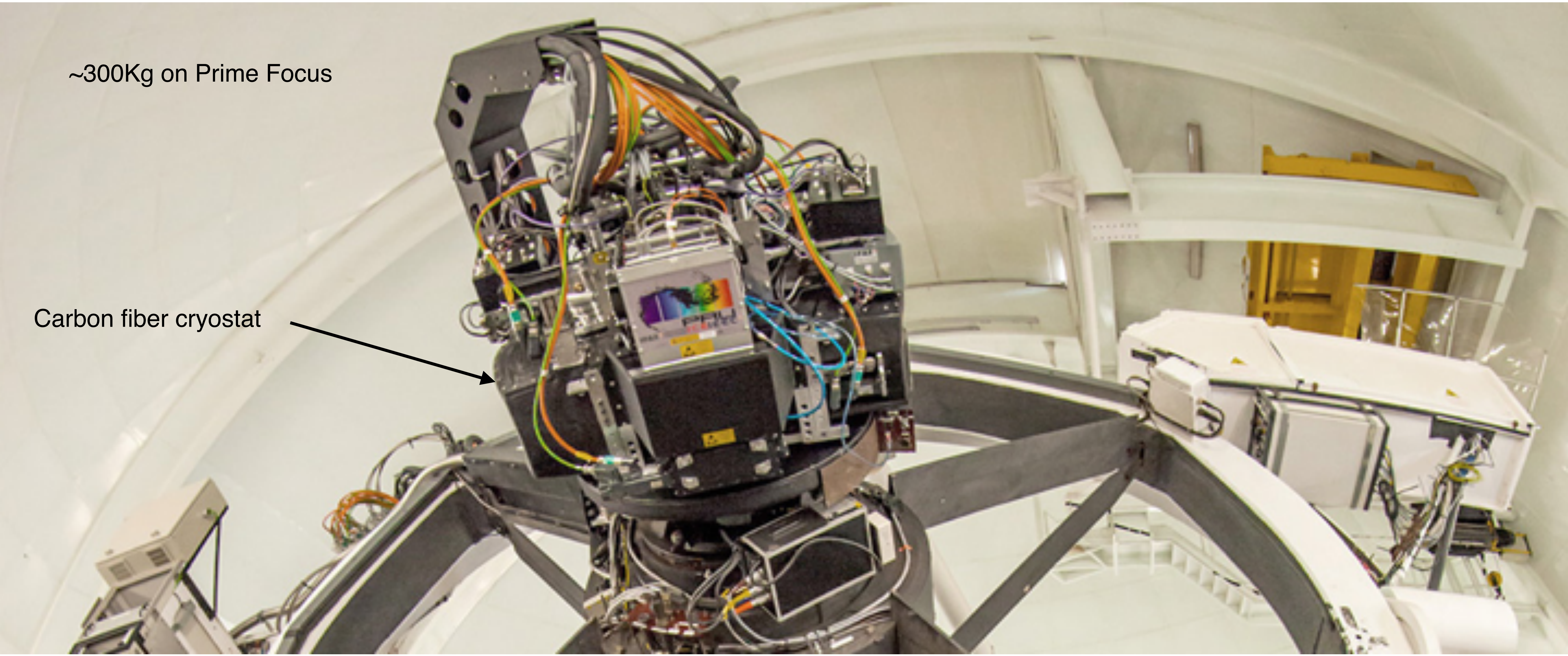
CCD test station

Clean room class 10K, 1K, 100

Fully computerized machining tool (lathe)

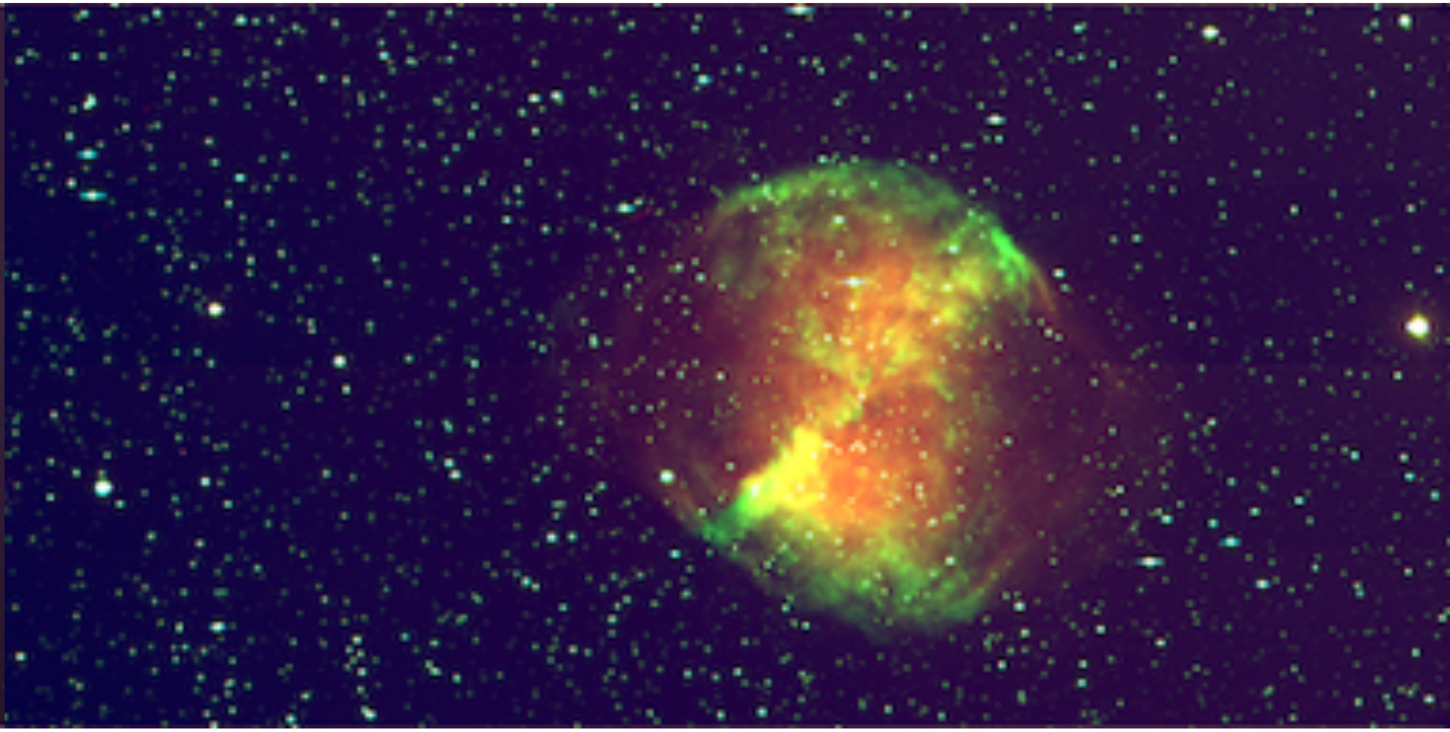
PAU

First Light from PAUcam



~300Kg on Prime Focus

Carbon fiber cryostat



PAU Survey (PAUS) Collaboration (Sep 2015)

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Ignacio Sevilla
Juan de Vicente

Durham University

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Konrad Kuijken

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Jorge Carretero
Manuel Delfino
Christian Neissner
Nadia Tonello
Pau Tallada

University College London

Benjamin Joachimi

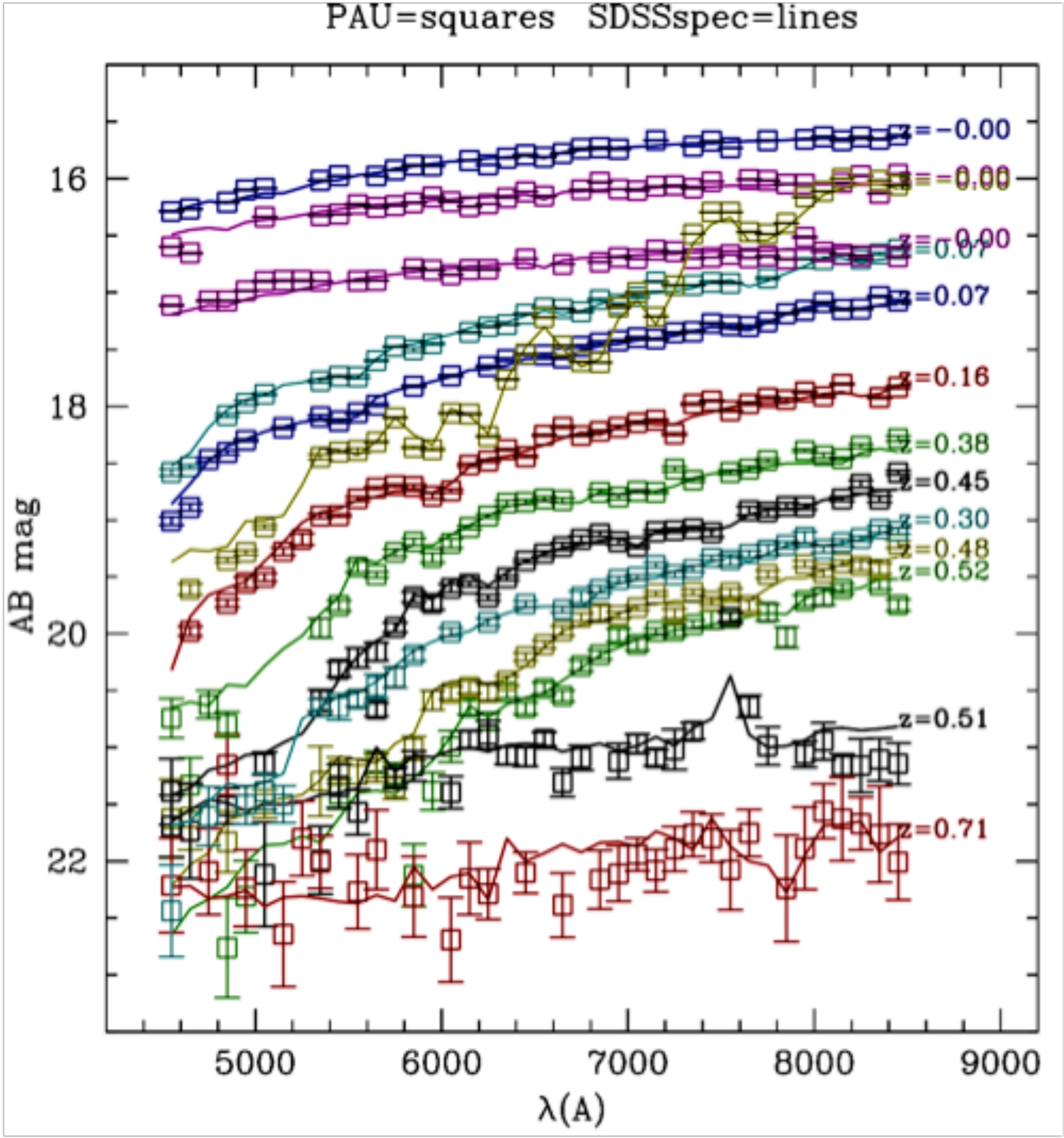
pausurvey.org

Some example results from April 2016 run

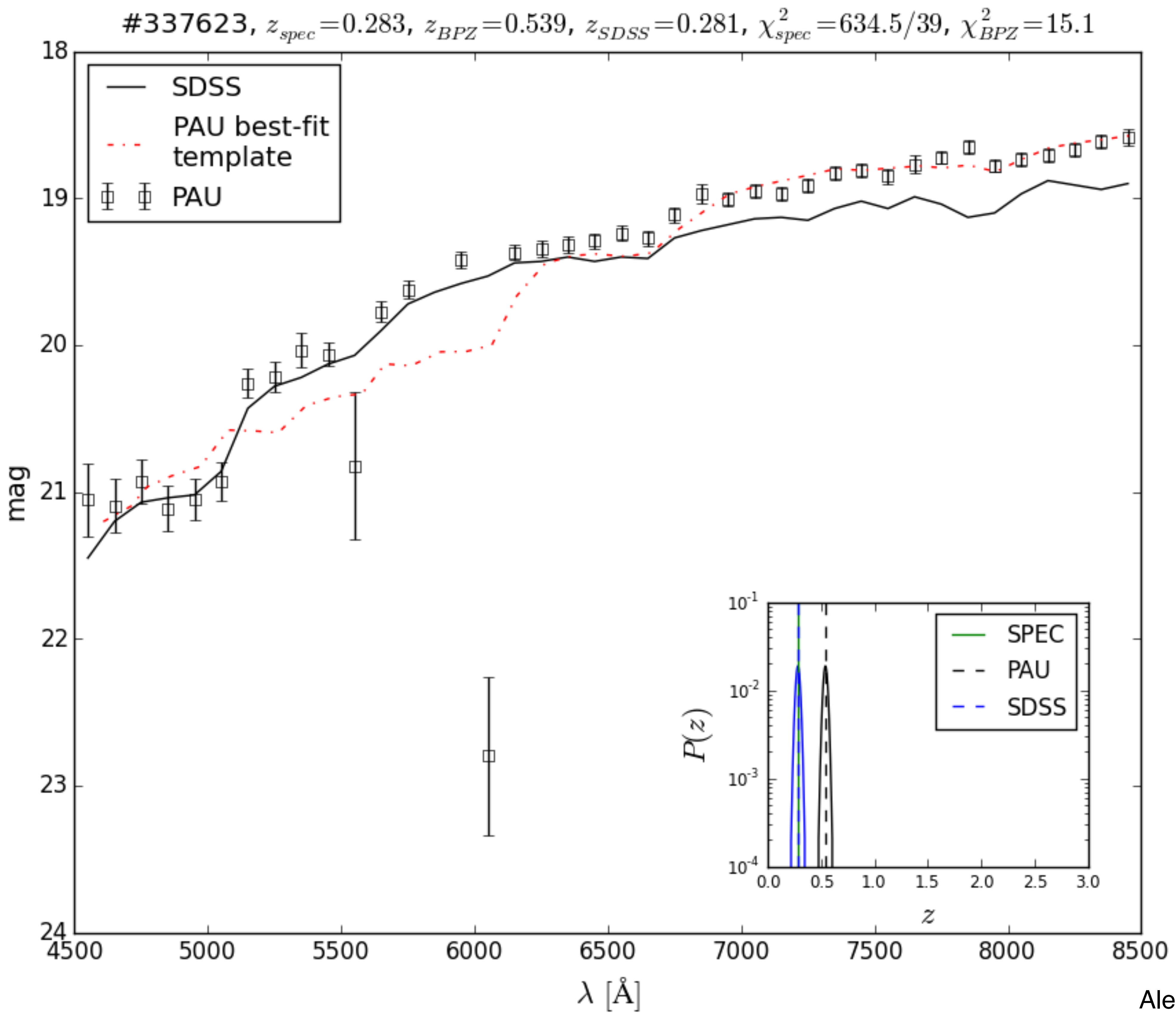
Each PAU spectra consist of up to 200 (40x5) independently calibrated flux measurements

Here we use 12 pixel diameter apertures (best for bright galaxies)

Noise is for large aperture photometry (limiting error could be much smaller for faint galaxies)



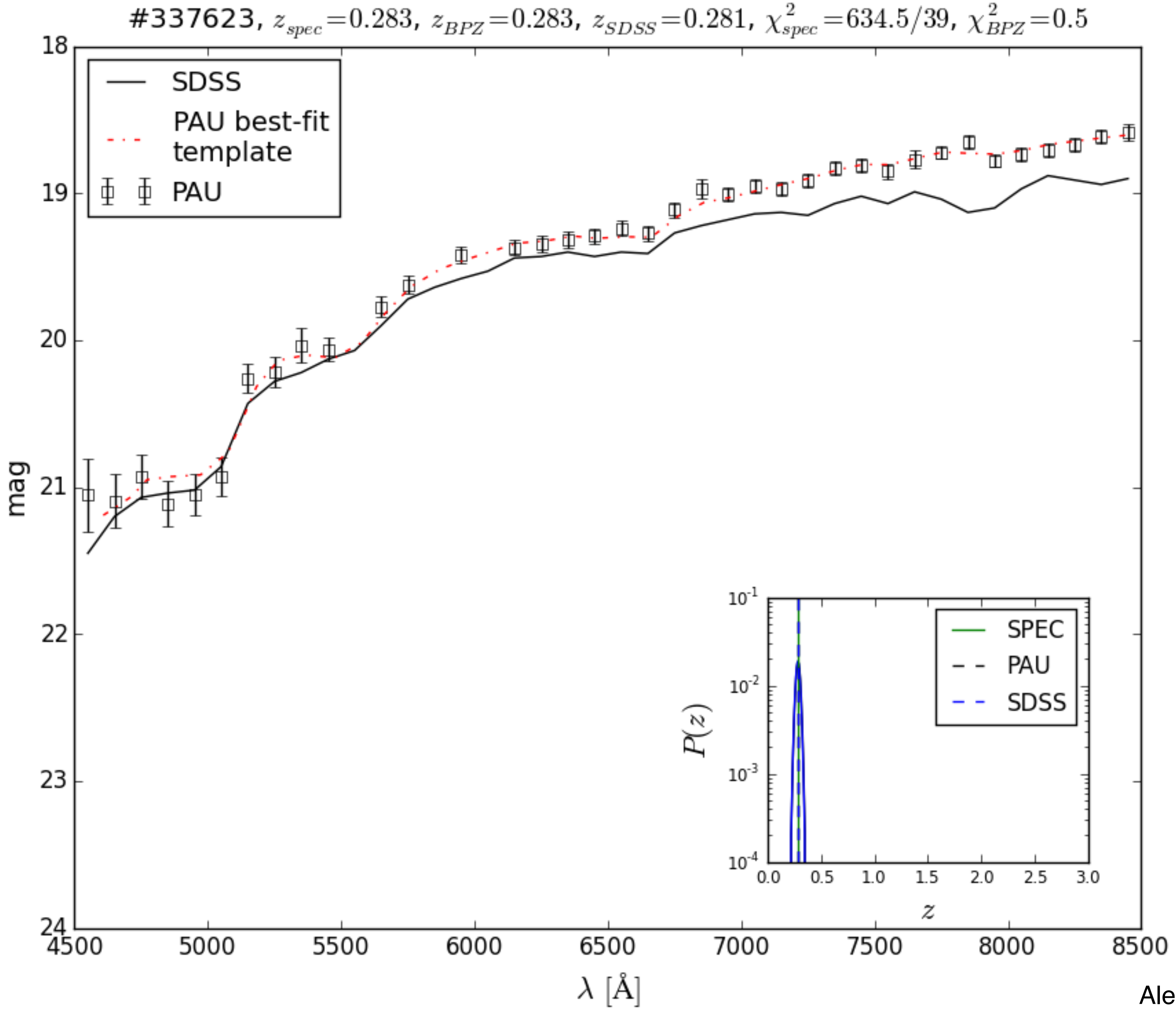
Outlier



Alex Alarcon

Alex Alarcon

Outlier



Alex Alarcon

PAUcam and PAUS Summary

- PAUcam is a ***new instrument*** that is working in WHT 4.2m Telescope in La Palma and is open to the community used. PAUCam was completely build/design in Spain by our group, with new technological ideas.
- PAUcam has ***narrow band filters*** (130A) SED over 4500-8500A in steps of 100A and also Broad Band UGRIY with a FoV of 1deg2 (0.5deg2 without distortions).
- We have observed 27nights (15A-16A) with PAUcam (26 more nights in 16B). We plan to do ~***100 deg2 complete to iAB-22.5-23.0*** (eg compare to SDSS r~17.77 or GAMMA r~19) with the PAU Survey International Collaboration (***PAUS***).
- Data (~3Tb) have been reduced with a new pipeline in a record time (a few hours to complete a run). We are debugging data reduction, ***calibration and optimizing photometrical*** errors.
- First results show ***very accurate redshifts*** errors, as expected. More work needed on outliers, scatter light.
- PAUS closes a ***gap between spectroscopic and photometric*** redshift technique and provides 4 new ways to calibrate photometric surveys (DES, Euclid, LSST, WFIRST):
  - **accurate and complete redshift samples to train and validate photo-z codes**
  - **dense galaxy samples to apply cross-correlation clustering N(z) calibration**
  - **understand spectroscopic target selection and incompleteness**
  - **calibrated templates for photo-z codes.**
- PAUS bridges a gap between sparse WIDE Surveys (SDSS) and small pencil-beam Surveys (COSMOS) to probe ***intermediate to small scales*** (1-20 Mpc/h) over different environments (100deg2), where the statistical S/N is largest. Higher resolution allows to measure intrinsic galaxy shape alignments and 3D galaxy clustering for different populations.
- PAUS ***SED are flux calibrated*** and have the potential to open a new window in statistical studies of galaxy evolution and star SED templates.
- Current FoV is only 0.35deg2. DES is x10 larger => ~10 deg2/night. Could cover ~15,000 deg2 in 5yrs. More work is needed here: Do we need all filters? different filter range? to i<24 eeds x6 (8m Telescope)

2D vs 3D clustering: Photo-z vs Spectro-z

1) Can measure photometric clustering with 3D (need to assume cosmology)

2) Can measure spectroscopic clustering with 2D angular cross-correlations (no assumptions, but many observables and large covariance)

3) Can use a mix approach 2Dx3D covariance. But should not ignore it!

1. de Putter R., Dore O., Takada M., astro-ph:1308.6070

Forecasts are made by combining 2D and 3D Fisher matrices

- *WL only*: $\mathbf{F} = \mathbf{F}^{\rm 2D}_{\{\gamma,p\}} + \mathbf{F}^{\rm CMB}$
- *GC only*: $\mathbf{F} = \mathbf{F}^{\rm 3D*}_{ss} + \mathbf{F}^{\rm 2D}_{\{s\}} + \mathbf{F}^{\rm CMB}$
- *GC* + *WL* (no overlap): $\mathbf{F} = \mathbf{F}^{\rm 3D*}_{ss} + \mathbf{F}^{\rm 2D}_{\{s\}} + \mathbf{F}^{\rm 2D}_{\{\gamma,p\}} + \mathbf{F}^{\rm CMB}$
- *GC* + *WL* (full overlap): $\mathbf{F} = \mathbf{F}^{\rm 3D*}_{ss} + \mathbf{F}^{\rm 2D}_{\{\gamma,p,s\}} + \mathbf{F}^{\rm CMB}$

$\mathbf{F}^{\rm 3D*}_{ss}$ has *transverse* modes (μ≈0) removed

2D Limber=no radial modes, no covariance

p=photo-z
s=spec-z

See, e.g., *Cai & Bernstein 2012*, *Gaztanaga et al 2012*

Overlaping F (photo:2D) and B (spec:3D) Surveys

- Non-zero covariance: <FF,BB>≠ 0
- New observables: <FB> (<FF>, <BB>)

different sky

$$\begin{bmatrix} (FF,FF) & 0 \\ (FF,BB)=0 & (BB,BB) \end{bmatrix}$$

same sky

$$\begin{bmatrix} (FF,FF) & & \\ (FF,FB) & (FB,FB) & \\ (FF,BB) & (FB,BB) & (BB,BB) \end{bmatrix}$$

» *<u>New framework to combine then</u>*

$$C_l = \frac{1}{2\pi^2} \int 4\pi k^2 dk\ P(k)\ \psi_l^2(k) \quad \Longrightarrow \quad C_{ij}(l) = \sum_x H_{ix} H_{jx}.$$

RSD:

$$\boxed{\psi_l(k) = \int dz\ \phi(z)\ D(z)\ b(z,k)\ j_l(kr(z))}$$

$$\begin{aligned}
\psi_l^{\mathrm{RSD}} &= \int dz\ f(z)\ \phi(z)\ D(z) \\
&\quad [L_0(l)\ j_l(kr) + L_1(l)\ j_{l-2}(kr) + L_2(l)\ j_{l-2}(kr)] \\
L_0(l) &\equiv \frac{(2l^2+2l-1)}{(2l+3)(2l-1)} \\
L_1(l) &\equiv -\frac{l(l-1)}{(2l-1)(2l+1)} \\
L_2(l) &\equiv -\frac{(l+1)(l+2)}{(2l+1)(2l+3)}
\end{aligned} \tag{6}$$

WL:

$$\boxed{\psi_l(k) = \int dz\ p_{\kappa_j}(z)\ D(z)\ j_l(kr(z))}$$

$$p_{\kappa_j}(z) \equiv \frac{3\Omega_{m0} H_0 r(z)}{2H(z)a(z)r_0} \int_z^\infty dz' \frac{r(z';z)}{r(z')} \phi(z')$$

Forecast WL+RSD (galaxy clustering)

Nuisance parameters: one bias per z-bin & pop , photo-z transitions (rij, can be measured), noise (σ/n)

Cosmological: Om - ODE - h - sig8 - Ob - **w0 - wa - γ** - ns - bias(z)

shear-shear (2D): $<\gamma\, \gamma>$

galaxy-shear (2D need narrow bins) $<g\, \gamma>$

galaxy-galaxy (3D or narrow bins): $<g\, g>$ including BAO, RSD and WL magnification

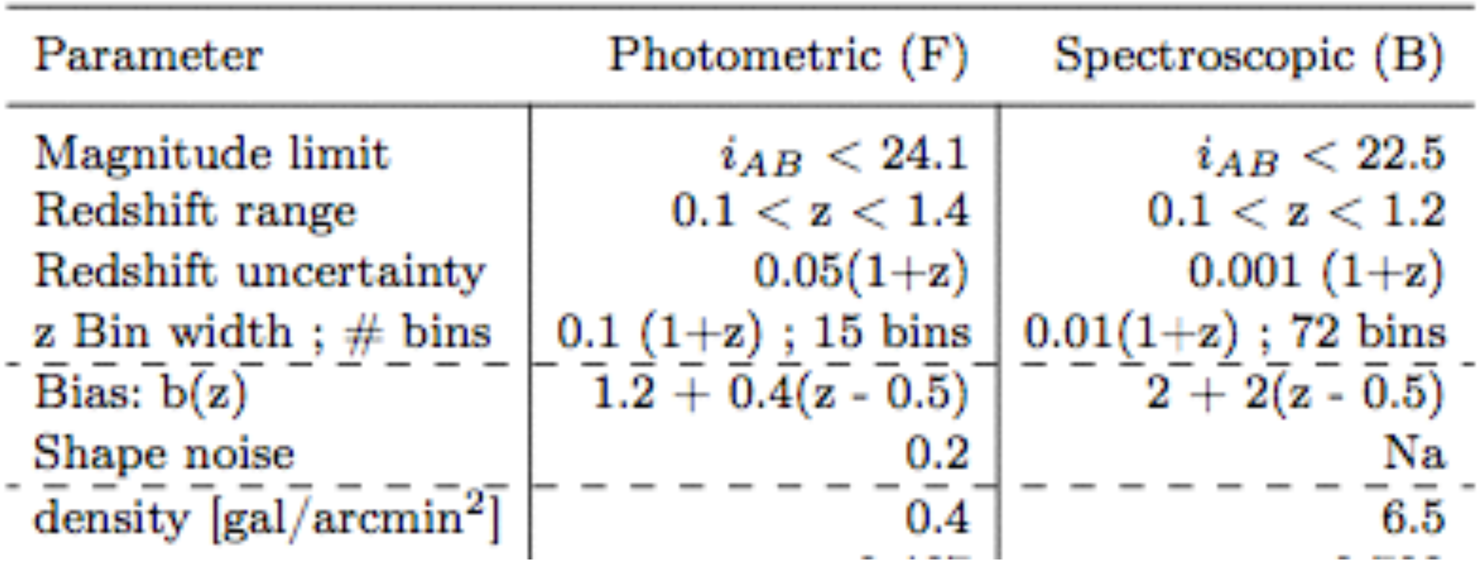
F= Faint (Photometric dz~0.05) sample: $<\gamma_F\, \gamma_F>$, $<g_F\, \gamma_F>$, $<g_F\, g_F>$

B= Bright (Spectroscopic dz~0.003) sample: $<g_B\, g_B>$, [$<\gamma_B\, \gamma_B>$, $<g_B\, \gamma_B>$]

F+B= No overlap => no cross $<FB>=0$ & no Covariance : $<FF\, BB>=0$

FxB= Overlaping => $<FB>\neq 0$ & $<FF\, BB> \neq 0$

lowRes

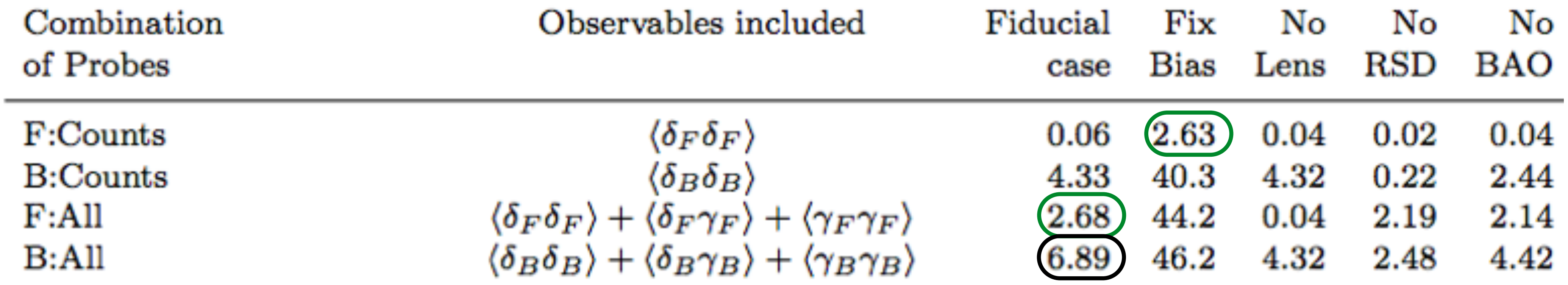


Parameter	Photometric (F)	Spectroscopic (B)
Magnitude limit	$i_{AB} < 24.1$	$i_{AB} < 22.5$
Redshift range	$0.1 < z < 1.4$	$0.1 < z < 1.2$
Redshift uncertainty	0.05(1+z)	0.001 (1+z)
z Bin width ; # bins	0.1 (1+z) ; 15 bins	0.01(1+z) ; 72 bins
Bias: b(z)	1.2 + 0.4(z - 0.5)	2 + 2(z - 0.5)
Shape noise	0.2	Na
density [gal/arcmin^2]	0.4	6.5

Important => same lmax=300 for BAO, WL and RSD (no Limber!)

F Photometric

B Spectroscopic

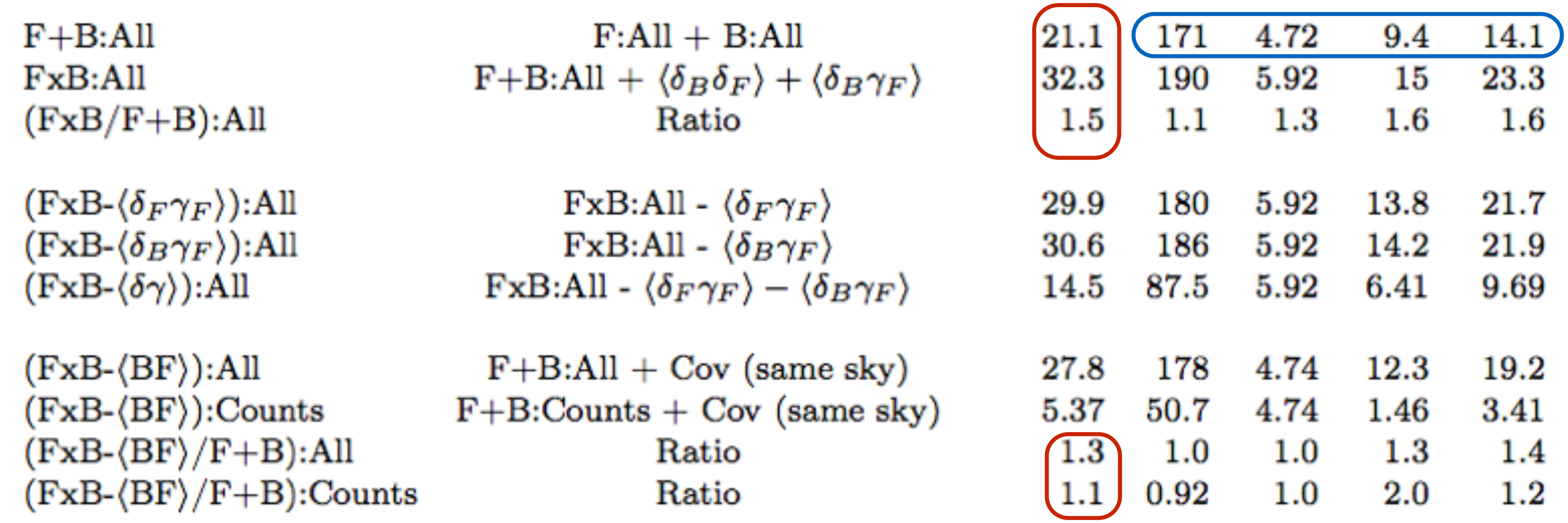


Combination of Probes	Observables included	Fiducial case	Fix Bias	No Lens	No RSD	No BAO
F:Counts	$\langle\delta_F\delta_F\rangle$	0.06	2.63	0.04	0.02	0.04
B:Counts	$\langle\delta_B\delta_B\rangle$	4.33	40.3	4.32	0.22	2.44
F:All	$\langle\delta_F\delta_F\rangle + \langle\delta_F\gamma_F\rangle + \langle\gamma_F\gamma_F\rangle$	2.68	44.2	0.04	2.19	2.14
B:All	$\langle\delta_B\delta_B\rangle + \langle\delta_B\gamma_B\rangle + \langle\gamma_B\gamma_B\rangle$	6.89	46.2	4.32	2.48	4.42

B ~ 3F but B ~ F for fixed bias or no RSD

(F:All) most of the FoM comes from WL, but when bias is known, Counts alone is as good

F+B combine



F+B:All	F:All + B:All	21.1	171	4.72	9.4	14.1
FxB:All	F+B:All + $\langle\delta_B\delta_F\rangle + \langle\delta_B\gamma_F\rangle$	32.3	190	5.92	15	23.3
(FxB/F+B):All	Ratio	1.5	1.1	1.3	1.6	1.6
(FxB-$\langle\delta_F\gamma_F\rangle$):All	FxB:All - $\langle\delta_F\gamma_F\rangle$	29.9	180	5.92	13.8	21.7
(FxB-$\langle\delta_B\gamma_F\rangle$):All	FxB:All - $\langle\delta_B\gamma_F\rangle$	30.6	186	5.92	14.2	21.9
(FxB-$\langle\delta\gamma\rangle$):All	FxB:All - $\langle\delta_F\gamma_F\rangle - \langle\delta_B\gamma_F\rangle$	14.5	87.5	5.92	6.41	9.69
(FxB-$\langle$BF$\rangle$):All	F+B:All + Cov (same sky)	27.8	178	4.74	12.3	19.2
(FxB-$\langle$BF$\rangle$):Counts	F+B:Counts + Cov (same sky)	5.37	50.7	4.74	1.46	3.41
(FxB-$\langle$BF$\rangle$/F+B):All	Ratio	1.3	1.0	1.0	1.3	1.4
(FxB-$\langle$BF$\rangle$/F+B):Counts	Ratio	1.1	0.92	1.0	2.0	1.2

F+B ~10F ~ 3B Spec>Photo, but combination is much better than either

FxB ~ 1.5(F+B) Samesky is better (60% Covariance and 40% CrossFB)

Importance of physical effects: bias (x5) > WL (x7) > RSD (x2) > BAO (x1.5)

1502.03972

Martin Eriksen

Same sky (+50% in FoM) vs separate sky contributions:

astro-ph:1109.4852

a) New observables (<FB>): +20% in FoM
b) Covariance: +30% in FoM (WL +20%, RSD +30%, bias +40%)

Notes:

- If correlation small, then both a) and b) will be small.
- If different sky, but same probes: expect F+B ~ 2FxB because the area in F+B is 2 times larger
- Even if <FB> correlations are very small FxB ~ F+B because F and B are complementary in the FoM. So there is a lot to learn by F and B combination. In this case same sky has advantage of join nuisance and systematics effects => covariance =reduce nuisance Example: HOD modeling.

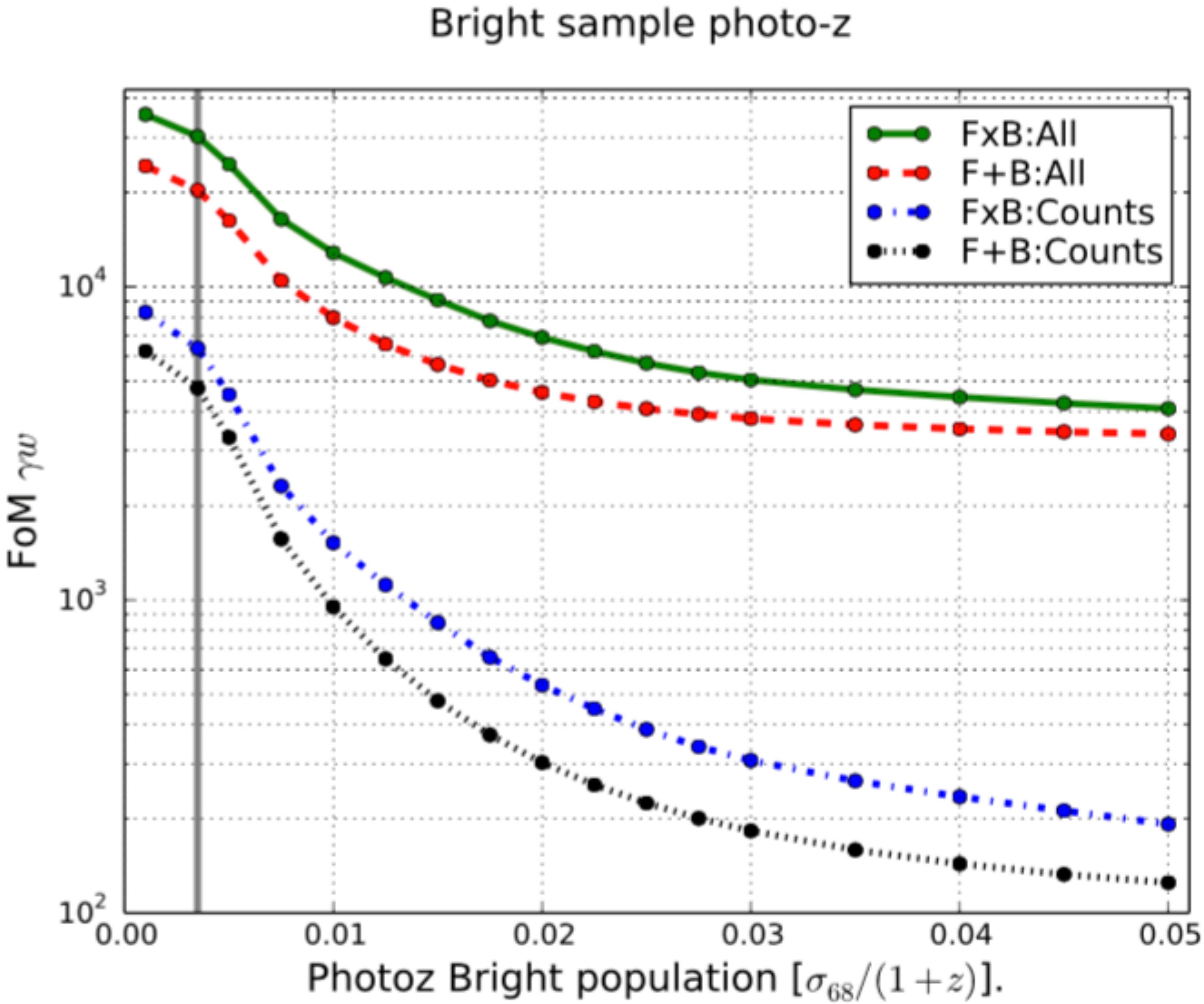
nuisancei ncrease errors

$$F = \begin{bmatrix} d_P^2 & r_{P1}\, d_P d_1 & r_{P2}\, d_P d_2 \\ r_{P1}\, d_P d_1 & d_1^2 & r_{12}\, d_1 d_2 \\ r_{P2}\, d_P d_2 & r_{12}\, d_1 d_2 & d_2^2 \end{bmatrix}$$

covariance in nuisance
reduce errors

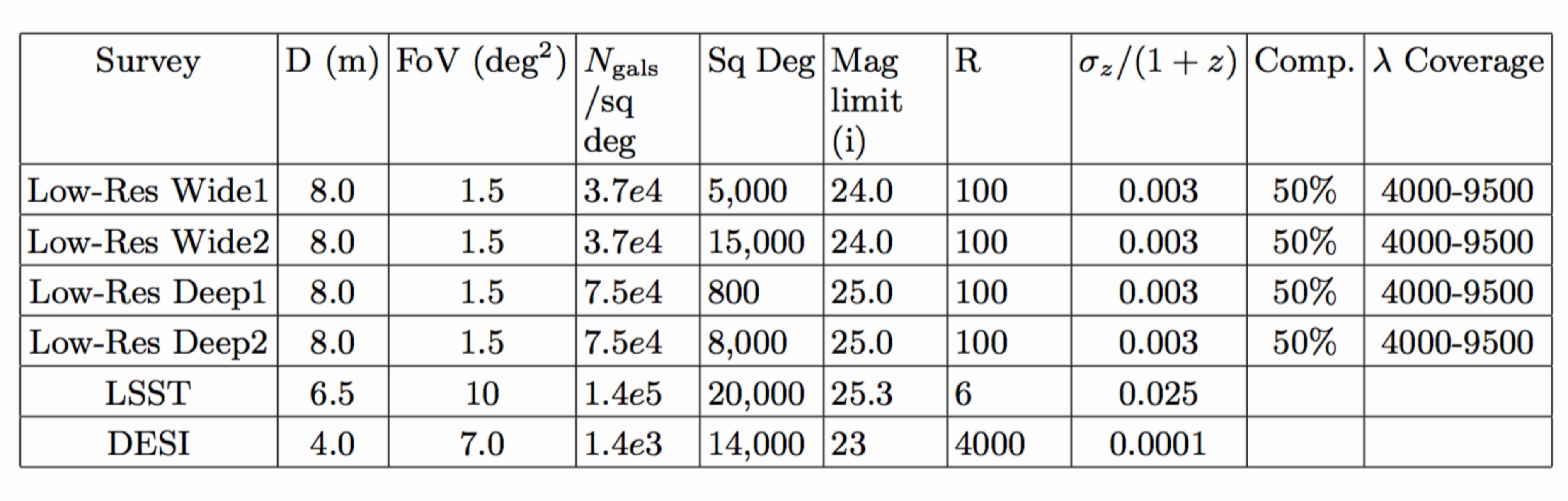
$$\sigma_P^2 = \frac{1}{d_P^2}\left[1 - \left(\frac{2\alpha^2}{1+r_{12}}\right)\right]^{-1}$$

$$\alpha \equiv r_{p1} = r_{p2}.$$



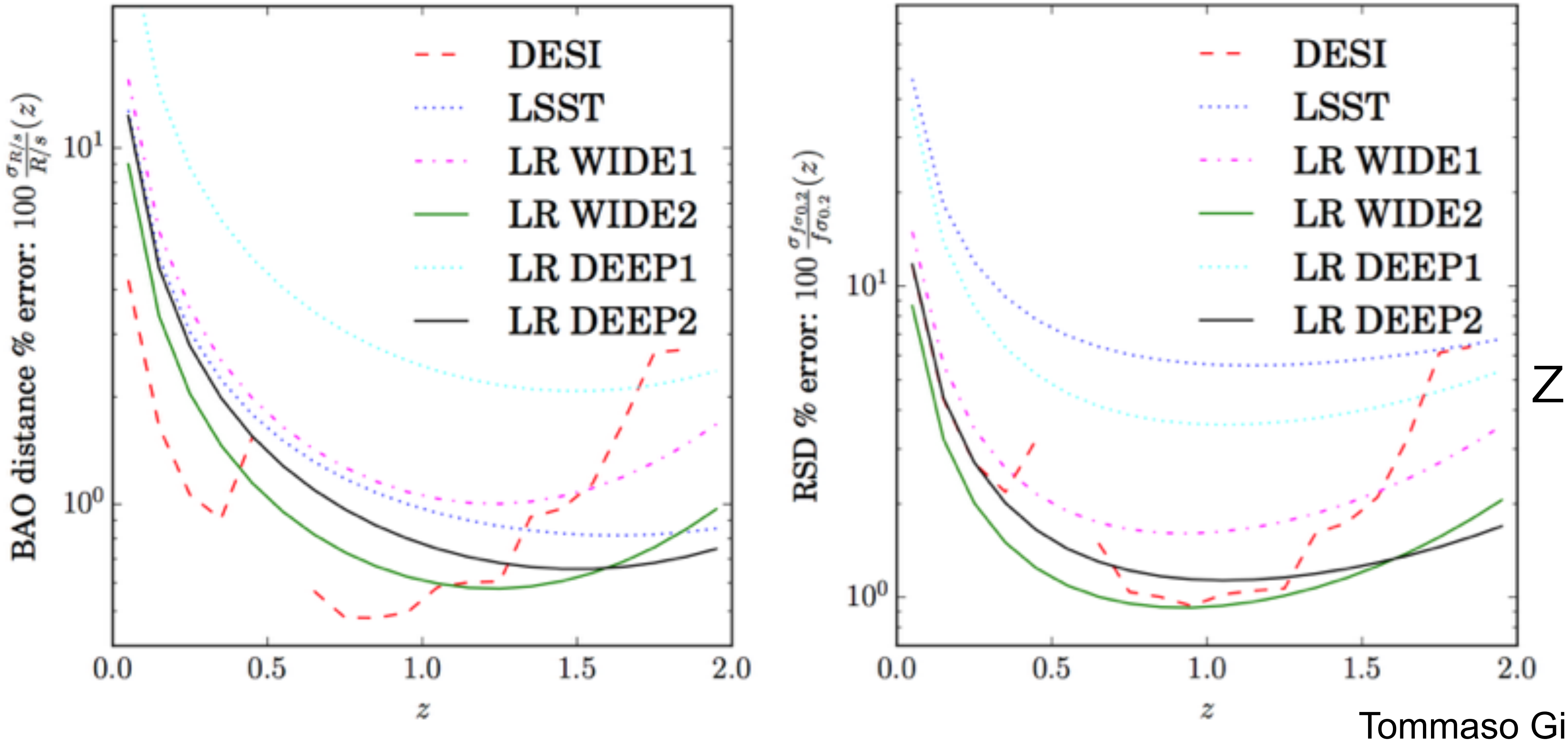
Eriksen & EG 2015

Martin Eriksen



Survey	D (m)	FoV (deg^2)	$N_{\rm gals}$ /sq deg	Sq Deg	Mag limit (i)	R	$\sigma_z/(1+z)$	Comp.	λ Coverage
Low-Res Wide1	8.0	1.5	3.7*e*4	5,000	24.0	100	0.003	50%	4000-9500
Low-Res Wide2	8.0	1.5	3.7*e*4	15,000	24.0	100	0.003	50%	4000-9500
Low-Res Deep1	8.0	1.5	7.5*e*4	800	25.0	100	0.003	50%	4000-9500
Low-Res Deep2	8.0	1.5	7.5*e*4	8,000	25.0	100	0.003	50%	4000-9500
LSST	6.5	10	1.4e5	20,000	25.3	6	0.025		
DESI	4.0	7.0	1.4e3	14,000	23	4000	0.0001		

FoM γw RSD+BAO	+WL
2070	19700
7080	80300
173	1570
3780	39000
5840	55900



z>1.5

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FIG. 1: Fractional errors on the BAO distance scale dilation factor R (left) and on the parameter combination best constrained by redshift-space distortions, $f\sigma$ (right), where we include scales at $k < 0.2h/\mathrm{Mpc}$. We can see that DESI will set the benchmark for the accuracy of both measurements; LR surveys will approach DESI accuracy, but they will not easily exceed it. The high number density that is achievable with photometric and LR surveys could provide relatively high accuracy in the high-redshift regime ($z > 1.2$), where DESI is far from the cosmic variance limit; however, in this range the success rate of photometric redshifts is expected to degrade rapidly, thus making our LR forecasts at $z > 1.2$ certainly optimistic.

Conclusions

- On linear scales there is no need for dz<0.003
- Higher densities reduce shot-noise and allow sample variance cancelation and multi-tracer approach
- Reduce selection effects
- Allow calibration of Broad Band Photo-z (LSST): z-clustering or cross-correlation, photo-z and SED

Need more work (your help: come to parallel Room 213. 10:30 Friday)

Incorporate CMB-S4
Biases (WL calib, dz calib, galaxy bias)
More science cases?
Programatics?