The PAU survey:
a "high resolution" photo-z Terapixel machine

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Using galaxies to trace structure

Observables

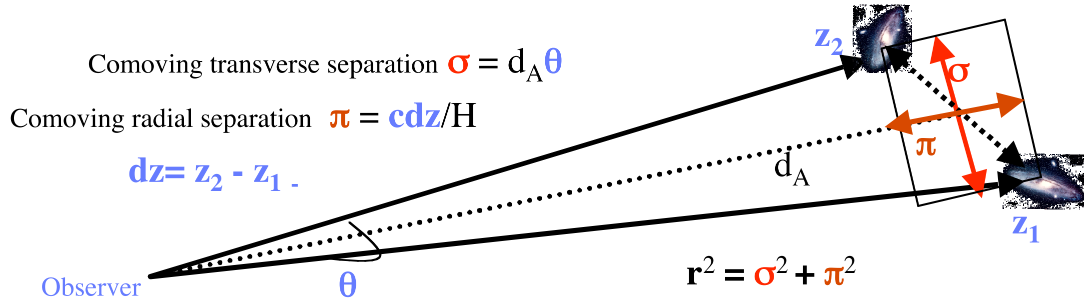
(null) Light-like radial ($d\Omega=0$) events

$cdt = adr \Rightarrow cdz = H\pi$

$\pi \equiv dr$

Light-like angular ($dr=0$) events

$cdt = a\, r\theta$



Comoving Radial distance

$$\pi = \frac{c}{H(z)} dz$$

(Angular) Comoving distance

$$S_k(\chi)^{-1} \equiv d_A(z) = \int_0^z \frac{c\,dz''}{H(z')} = (1+z) D_A(z)$$

$$H(z) = \frac{c\Delta z_{BAO}}{\pi_{BAO}} \qquad d_A(z) = \frac{\sigma_{BAO}}{\Delta\theta_{BAO}}$$

Observed

Known

Luminosity distance

$M = m + 2.5 \log(d_L / 10\mathrm{pc})$

$d_L = d_A (1+z) = D_A (1+z)^2$

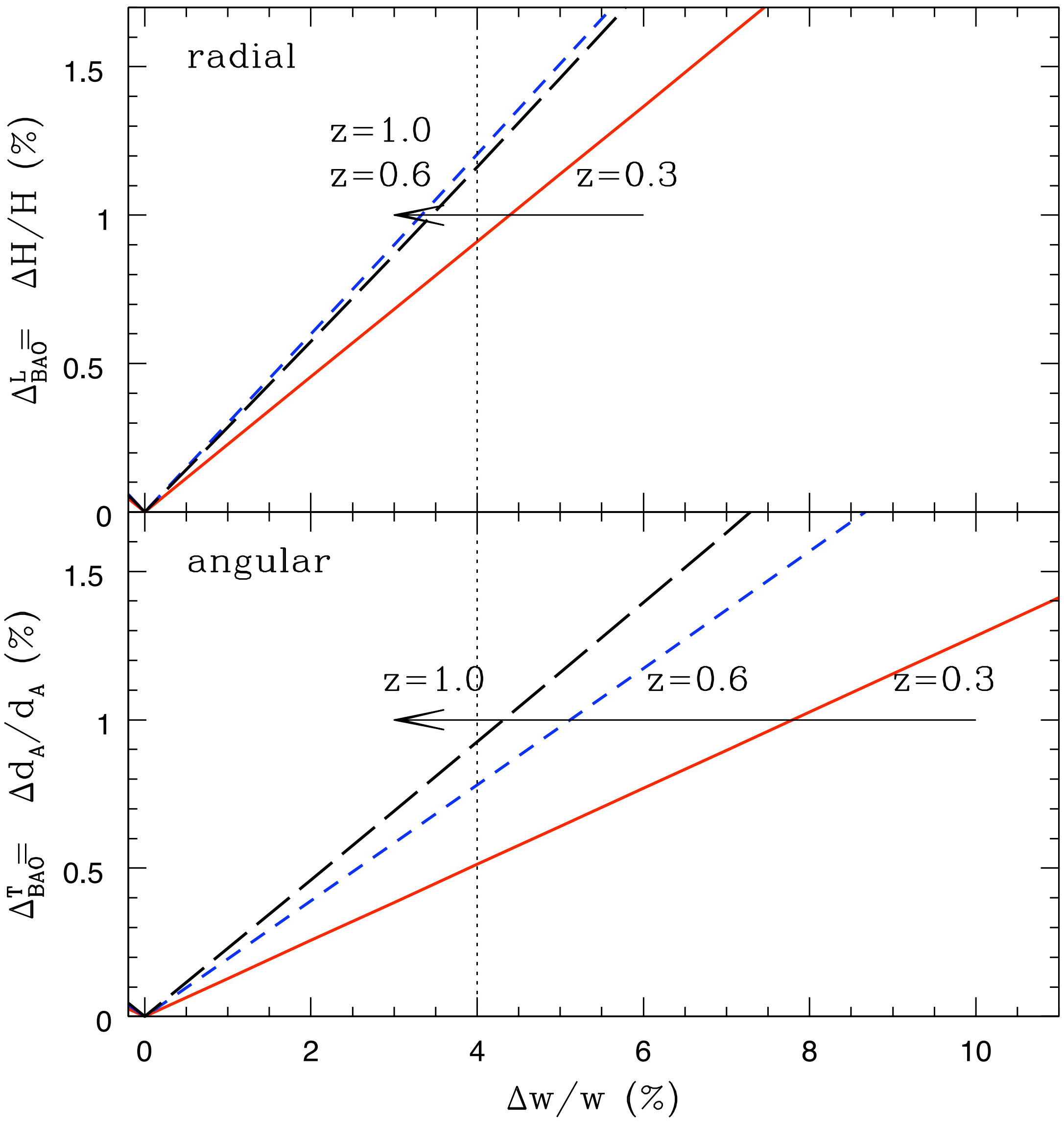
Comoving Horizon scale = conformal time

$$\eta \equiv \chi_H = \int_0^t \frac{cdt}{a} = \int_0^a \frac{cda}{a^2 H}$$

Age

$$t = \int_0^a \frac{cda}{aH}$$

BAO Sensitivity to Dark Energy



Tough measurement

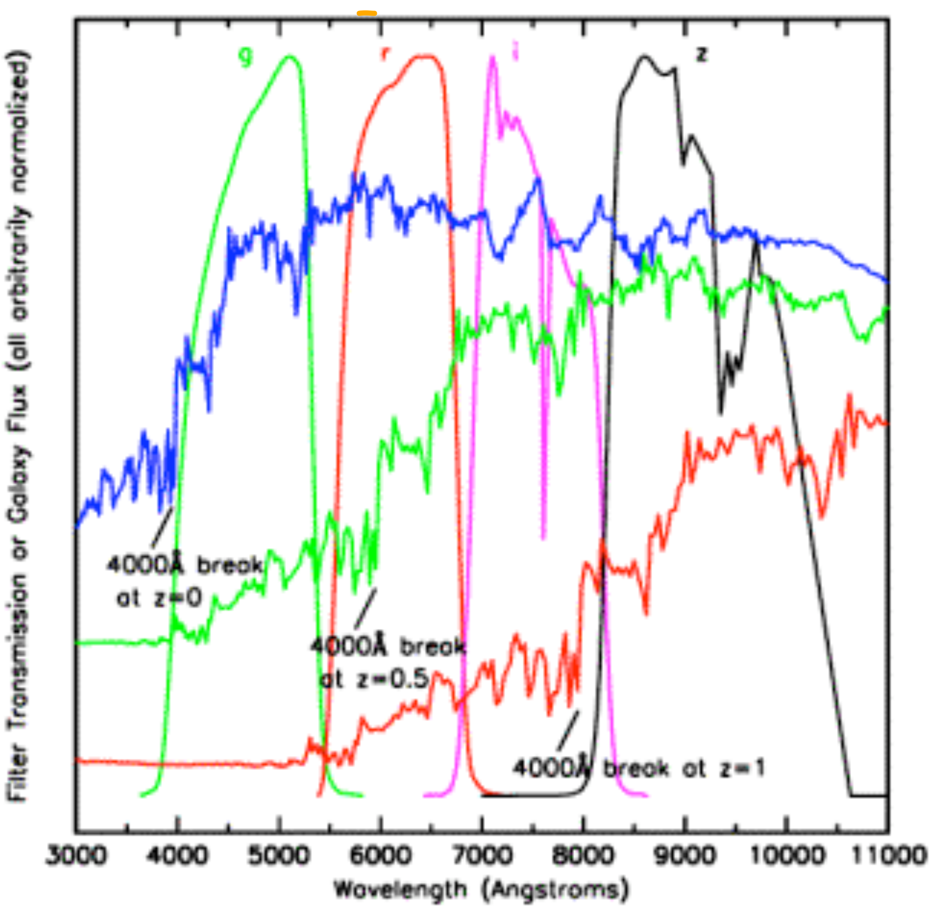
Worse if one wants to measure d*w*/d*a*

BAO about as sensitive to *w* as SNe

Radial direction is more sensitive to w, but has one dimension less than angular direction

Which Galaxies?

Most future surveys concentrate on "Luminous Red Galaxies": old elliptical galaxies, which are very bright and have a characteristic spectrum with a prominent break at 4000Å
Easy to measure redshift with spectrum or photometry (called photo-z)

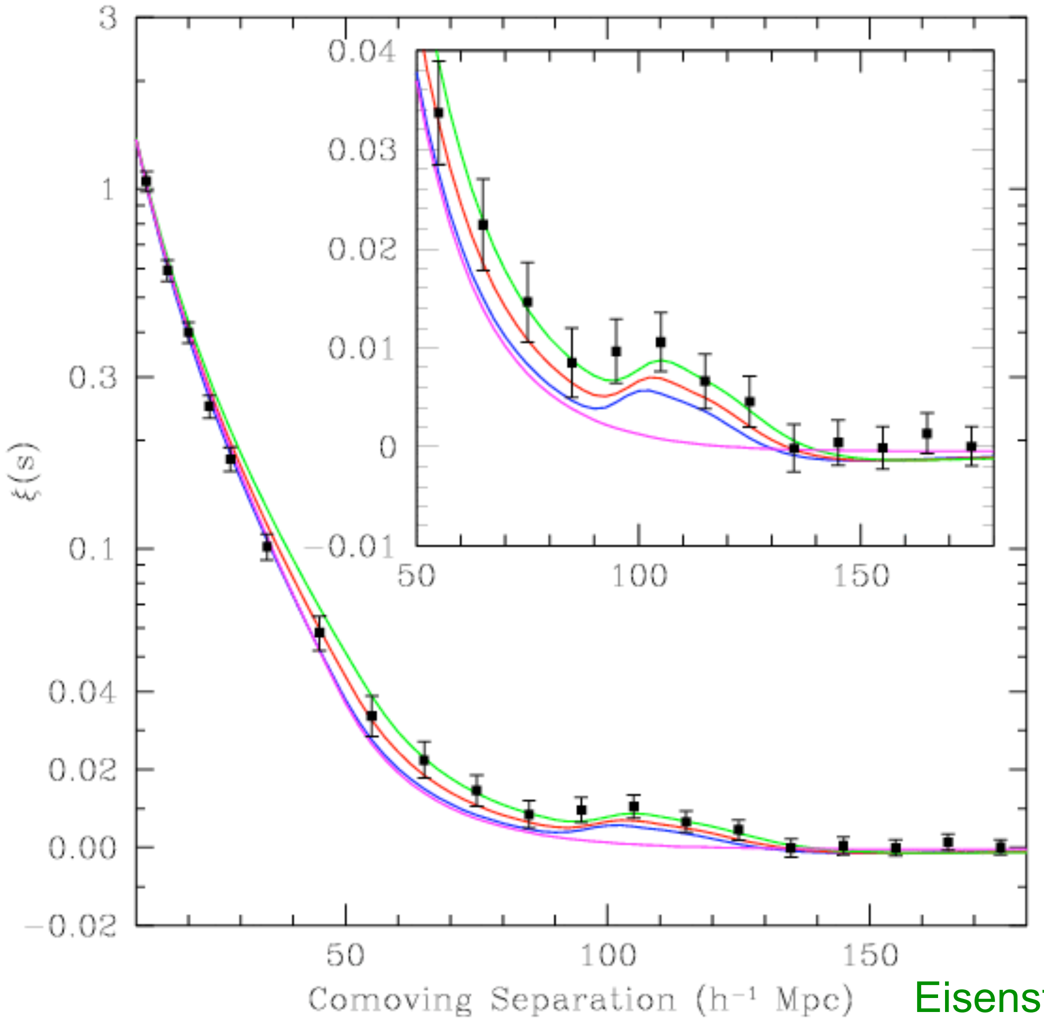


both very luminuos and invariable

SDSS

Galaxy-Galaxy Correlation Function

Based on 55000 "luminous red galaxies" from the SDSS spectroscopic galaxy survey



$$\xi(r) = \langle \delta(\vec{r}_1)\delta(\vec{r}_2) \rangle, \delta(\vec{r}) = \frac{\rho(\vec{r}) - \bar{\rho}}{\bar{\rho}}$$

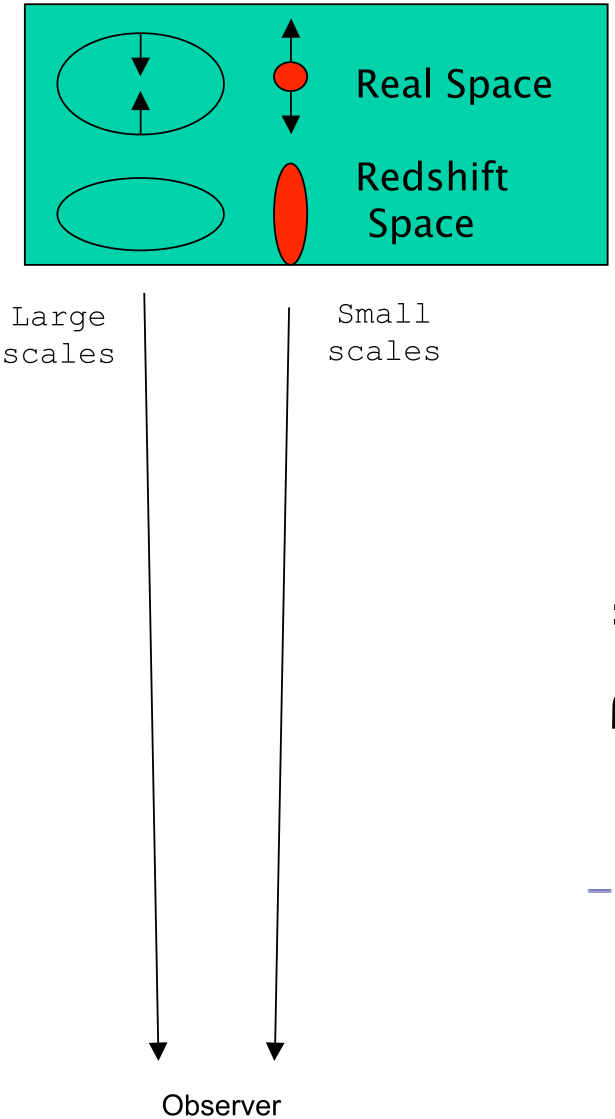
or

$$dP_{12} = \bar{\rho}^2[1 + \xi(r)]dV_1 dV_2, r = |\vec{r}_1 - \vec{r}_2|$$

3.5-σ detection of BAO at $\langle z \rangle = 0.35$ (confirmed by 2DF and SDSS photometric surveys at about 2.5 σ)

$h = H_0 / (100 \text{ km s}^{-1} \text{ Mpc}^{-1}) \sim 0.7$

Eisenstein et al. 2005

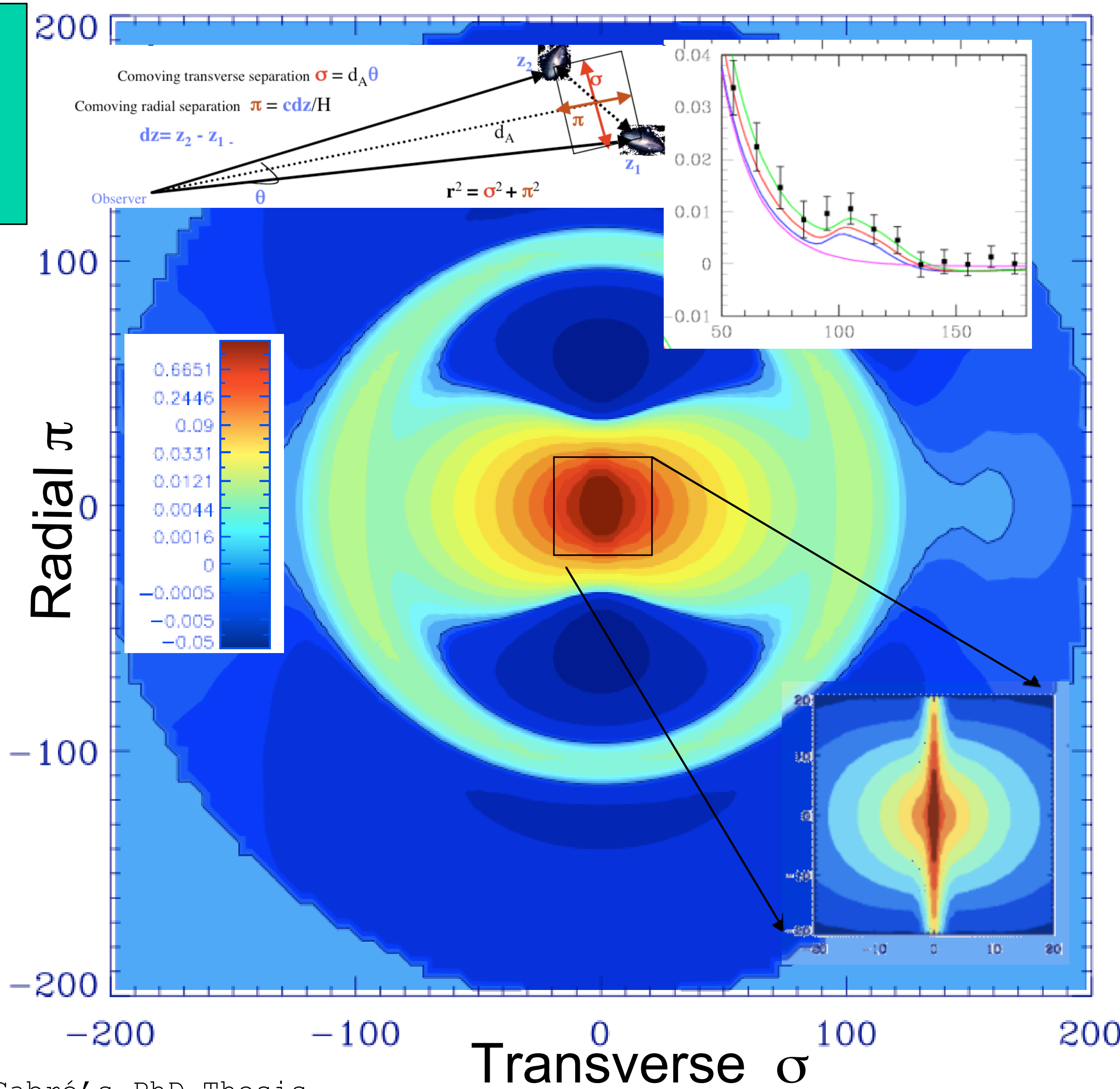


$\theta = -\beta\,\delta$

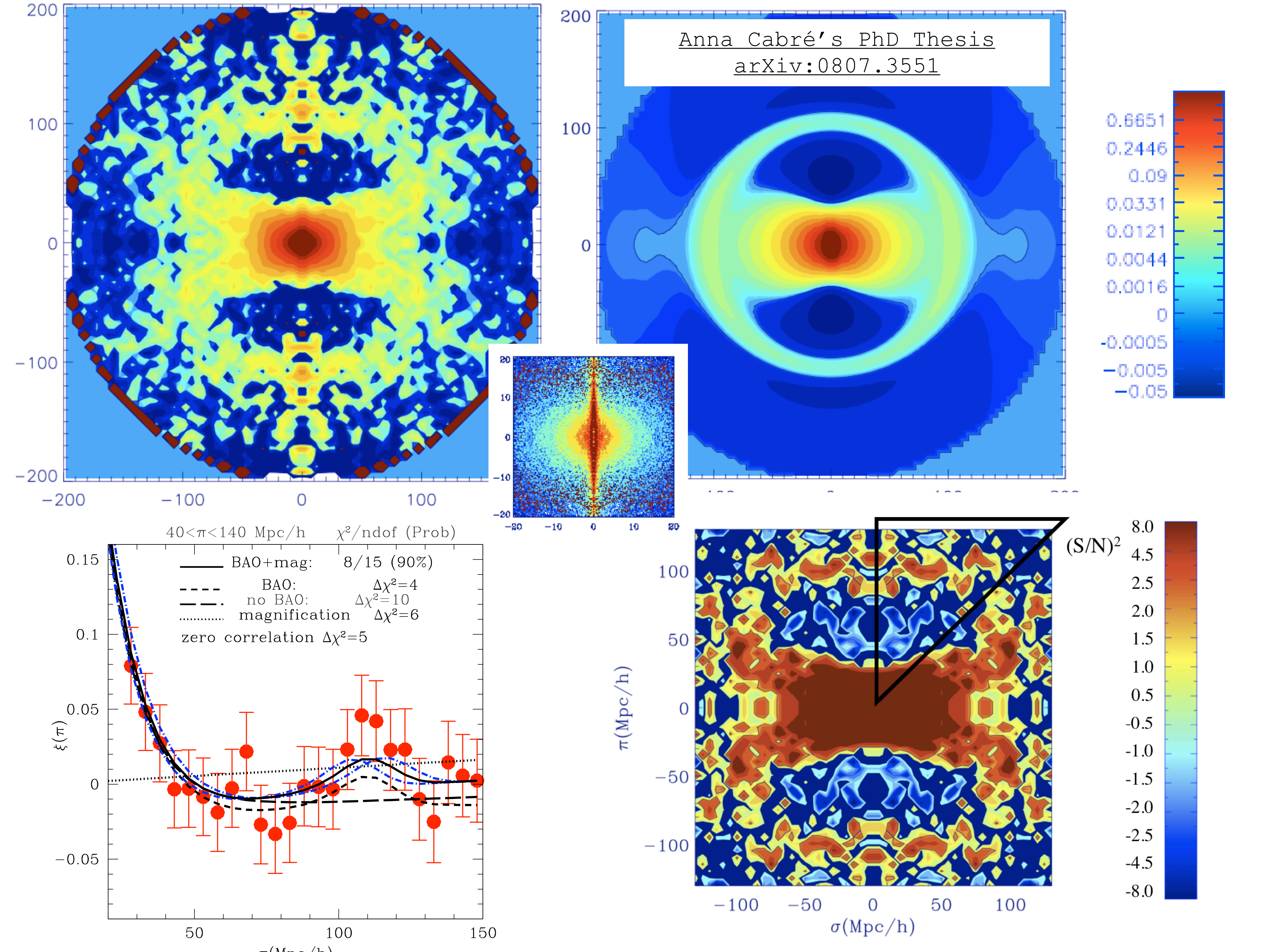
Growth

$V_p = \pi - \sigma$

mass



Anna Cabré's PhD Thesis
arXiv:0807.3551

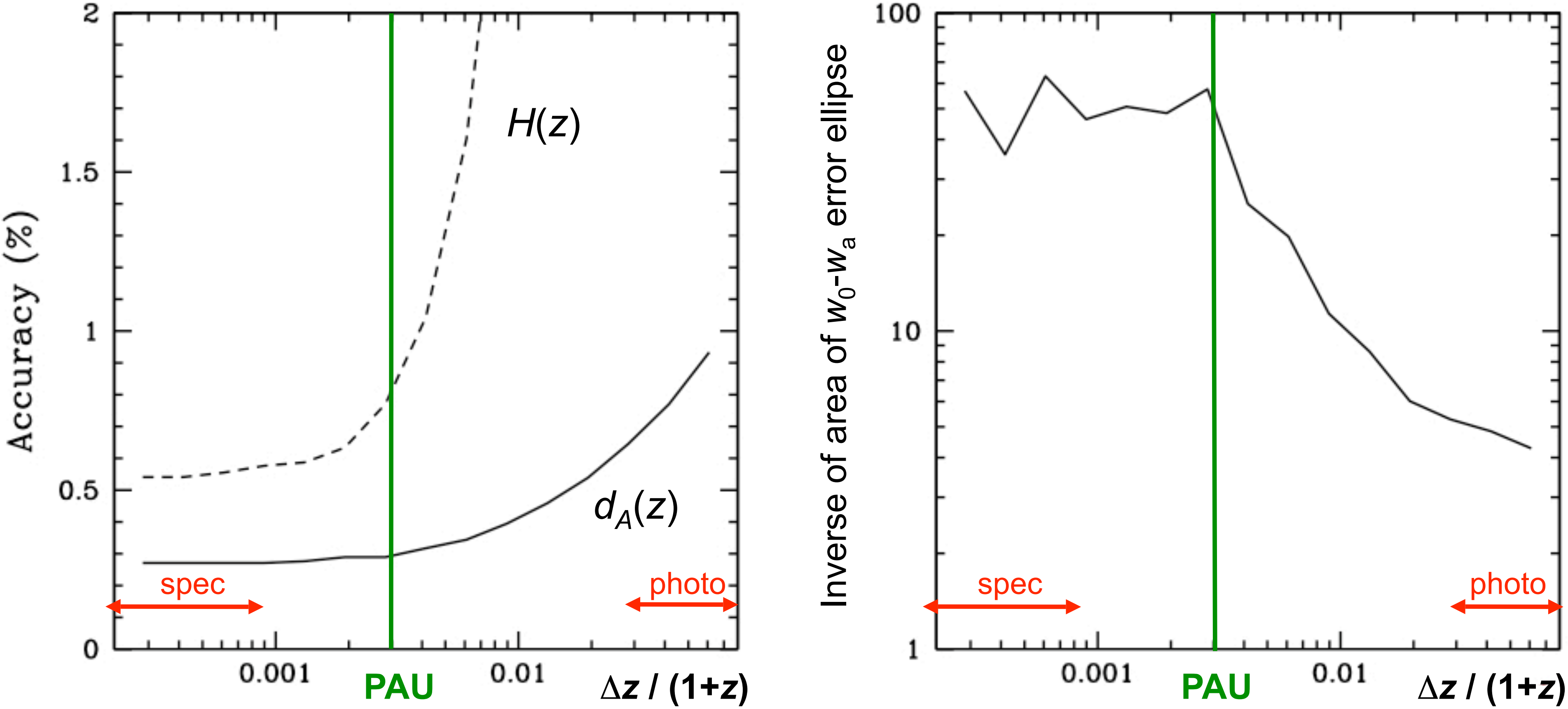


Anna Cabré's PhD Thesis
arXiv:0807.3551
0.6651
0.2446
0.09
0.0331
0.0121
0.0044
0.0016
0
-0.0005
−0.005
−0.05
40<π<140 Mpc/h
χ²/ndof (Prob)
BAO+mag: 8/15 (90%)
BAO: Δχ²=4
no BAO: Δχ²=10
magnification Δχ²=6
zero correlation Δχ²=5
ξ(π)
(S/N)²
8.0
4.5
2.5
2.0
1.5
1.0
0.5
-0.5
-1.0
-1.5
-2.0
-2.5
-4.5
-8.0
π(Mpc/h)
σ(Mpc/h)

Requirements on Redshift Precision

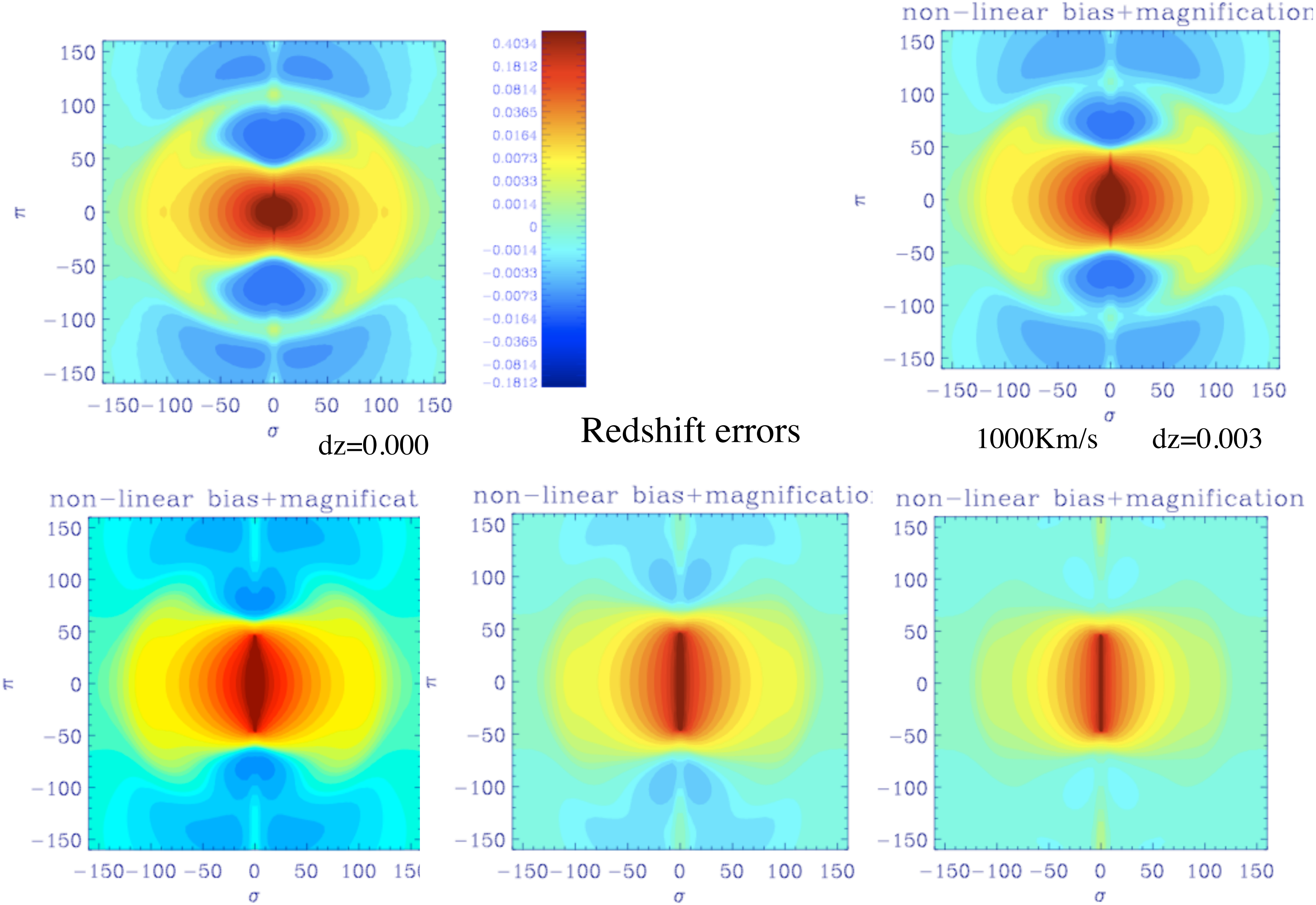
$$\frac{\sigma}{P} = \sqrt{\frac{2}{n_{\rm modes}}}\left(1 + \frac{1}{P\bar{n}}\right)$$

$$n_{\rm modes} = V 4\pi k^2 \delta k / (2\pi)^3$$



Padmanabhan

Redshift errors



dz=0.000

1000Km/s dz=0.003

2,000Km/s dz=0.006

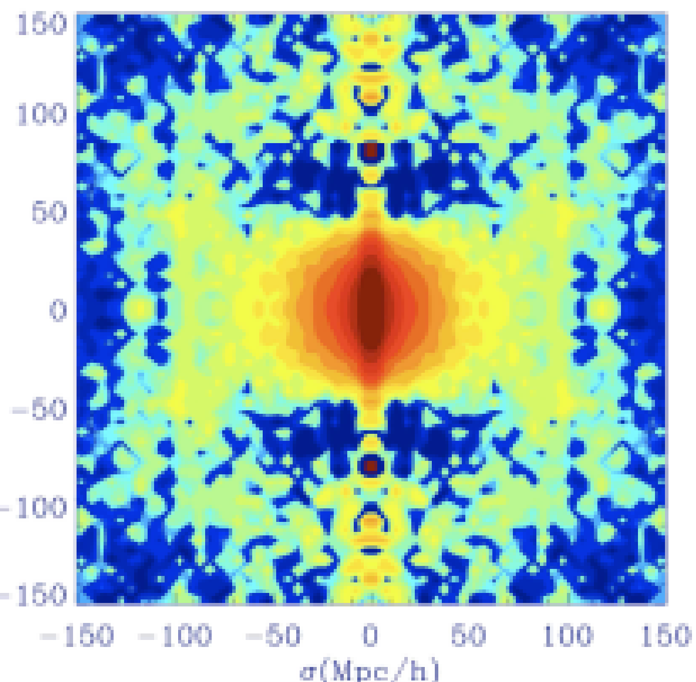
5,000Km/s dz=0.016

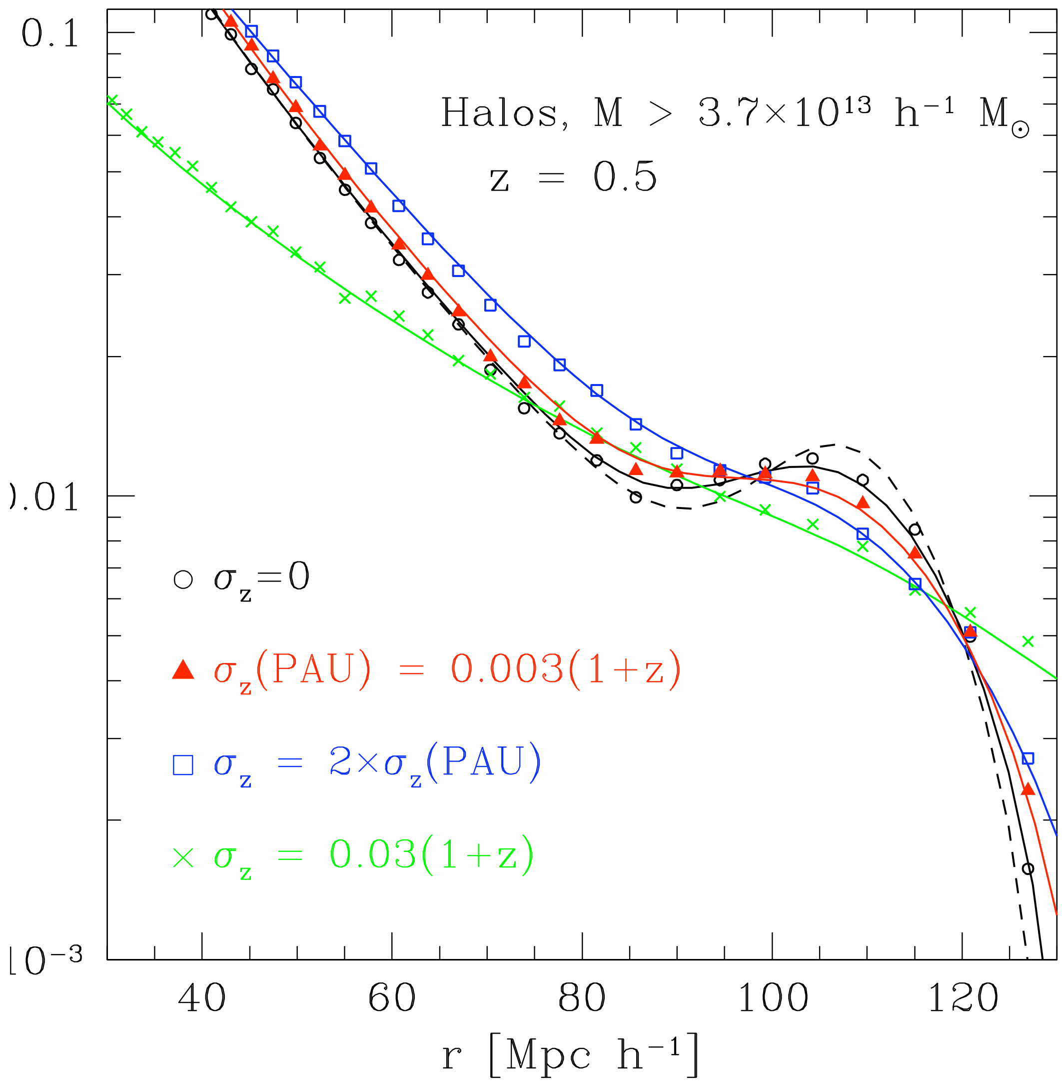
10,000Km/s dz=0.033

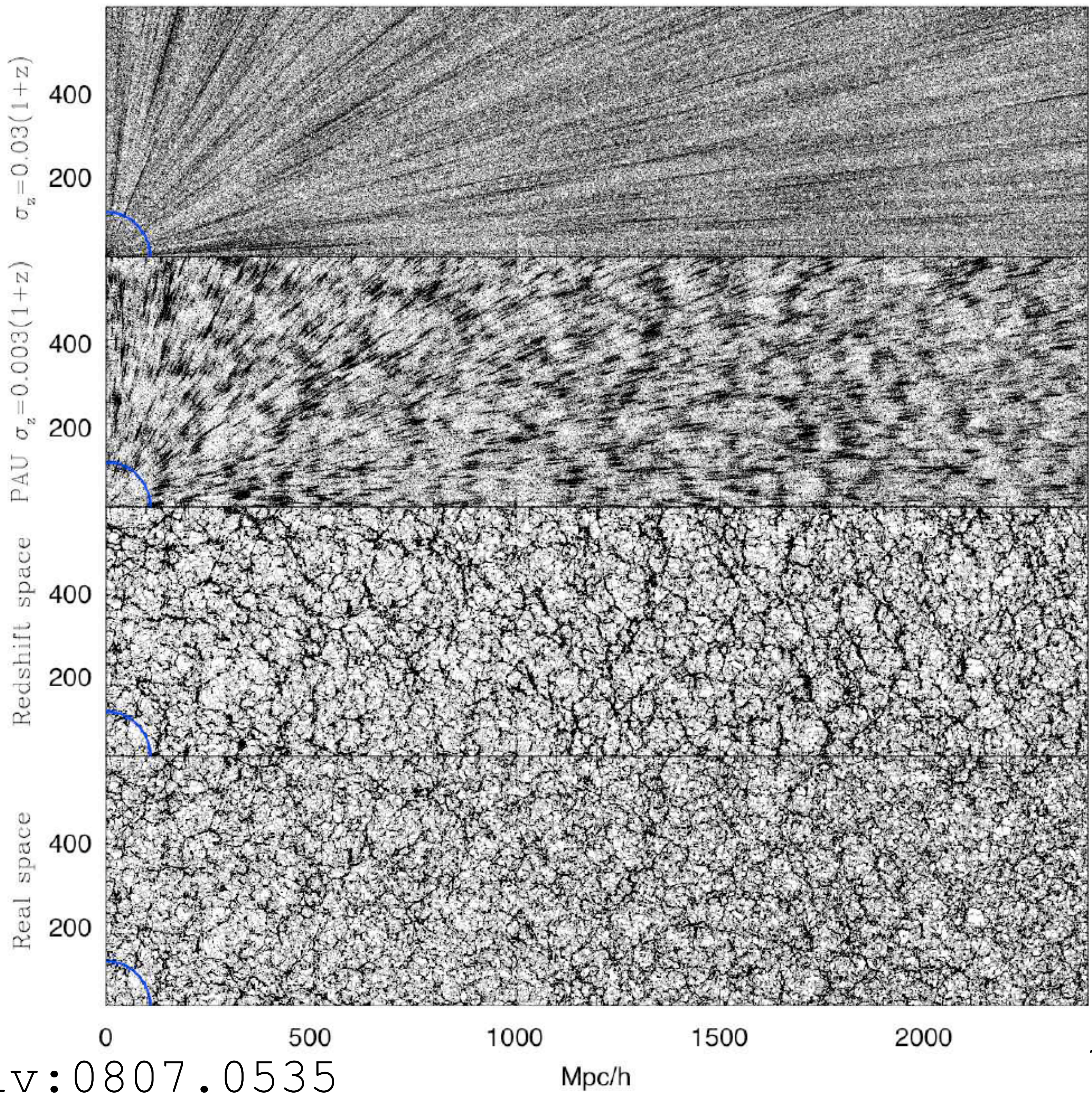
Requirements on Redshift Precision

3D reconstruction of BAO feature

Needs $\Delta z / (1+z) \sim 0.003$

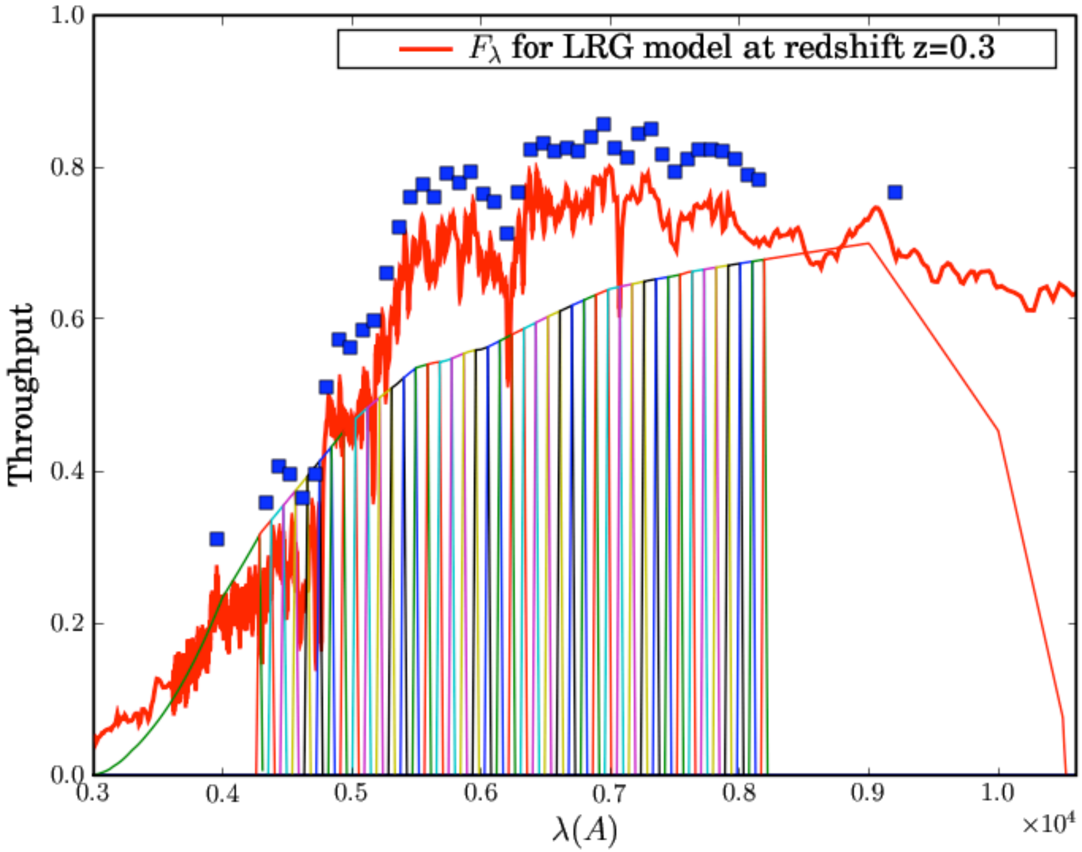




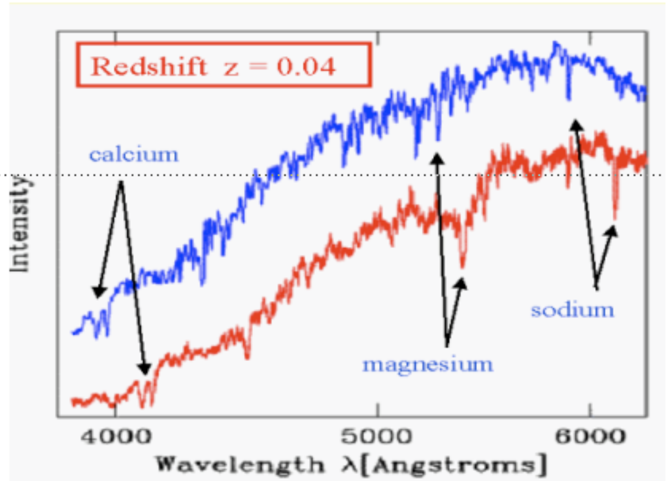


arXiv:0807.0535

Can Many Narrow Filters Do The Trick?

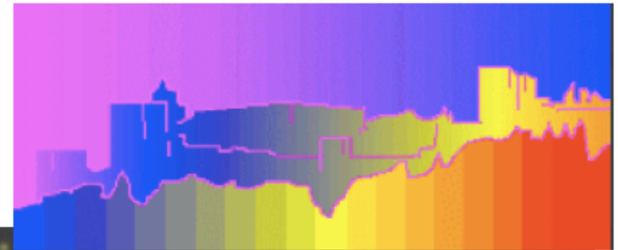


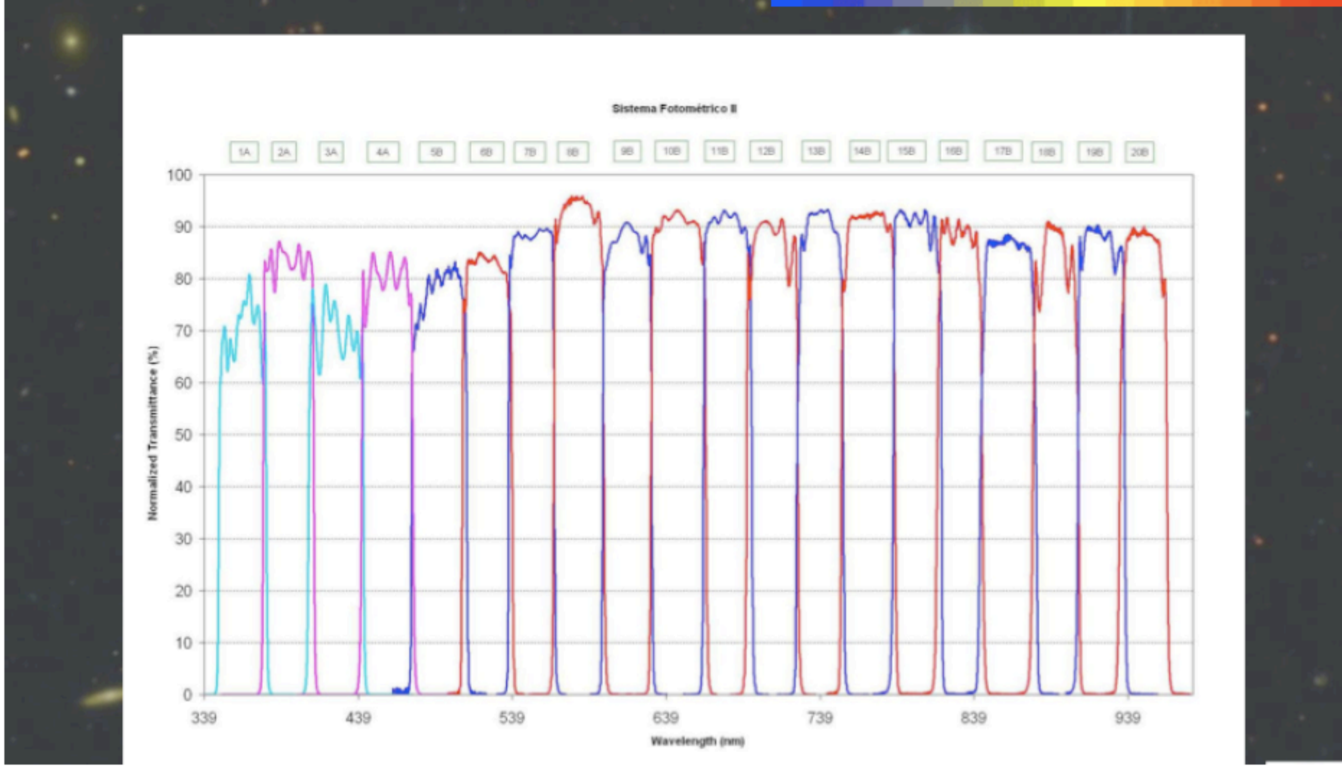
We explore the performance of a photometric system with 40 medium band non-overlaping filters (100A width)similar to that of ALHAMBRA but with more and narrower filters.



ALHAMBRA

Survey at Calar Alto





20 filters

4 sq. deg.

$m_{AB} < 25$

Is this enough?

Moles et al., 2008, AJ, 136, 1325

Benítez et al., 2009, ApJL, 692L

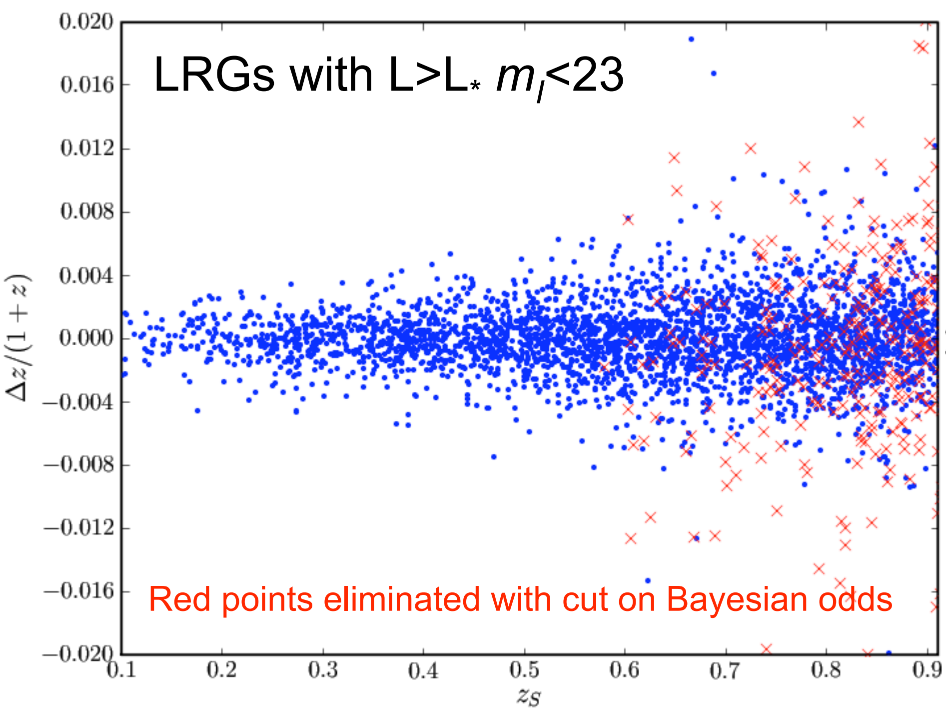
Cristóbal-Hornillos et al., 2009, arXiv0902.240

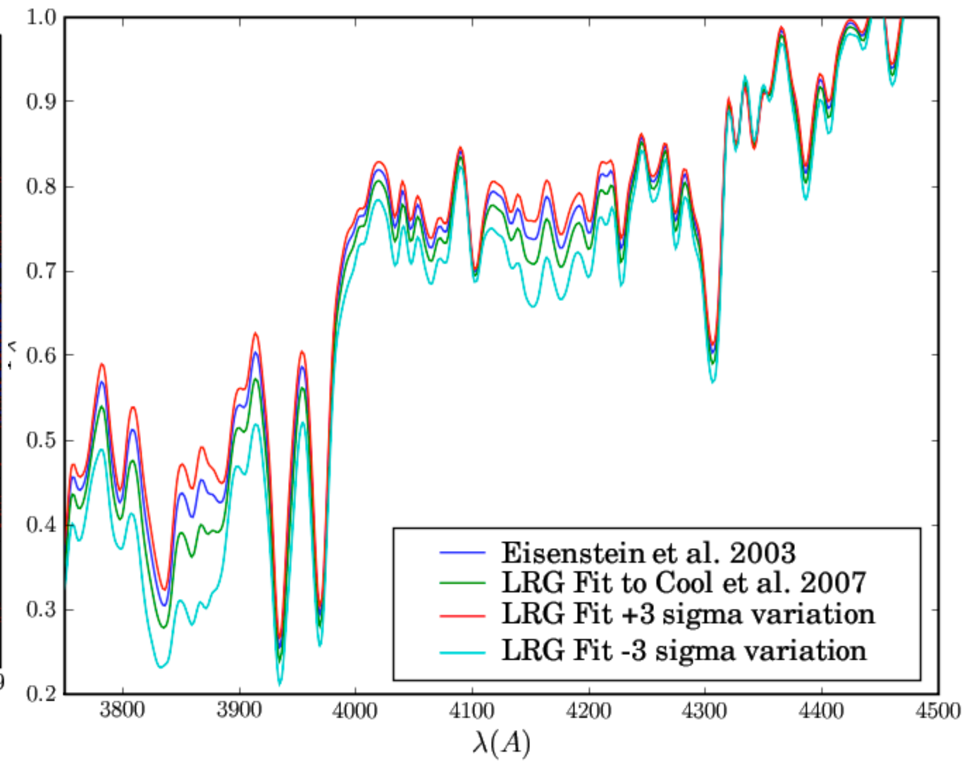
Redshift Determination: PAU forecast simulations

•v1: Choose a galaxy template representative of LRGs (Coleman Wu and Weedman 1980), recalibrated with photometry of real E/SO galx (Benitez etal 2004). Bruzual & Charlot library: ssp_11Gry_z02.
•v2: empirical average spectra + 1PCA (Eisenstein etal 2003) to describe intrinsic LRG variation.
•Create a library of spectra calibrated with Cool etal 2006 color-magnitude relation in broad band colors (z=0.1-0.4). Color variations equivalent to rms 1.8 times fl_E2003.
• Generate a realistic galaxy catalogue (magnitudes, spatial density)
• Add realistic photometric noise to simulate mock observations
• Add scatter to model intrinsic galaxy variation
•Recover redshifts with same templates
•FURTHER OPTIMIZATION: filter range and locations, exposure time distributions, model photometry
•SOME CAVEATS: unknown template variation outside 3750-7000A, LRG at z>0.5

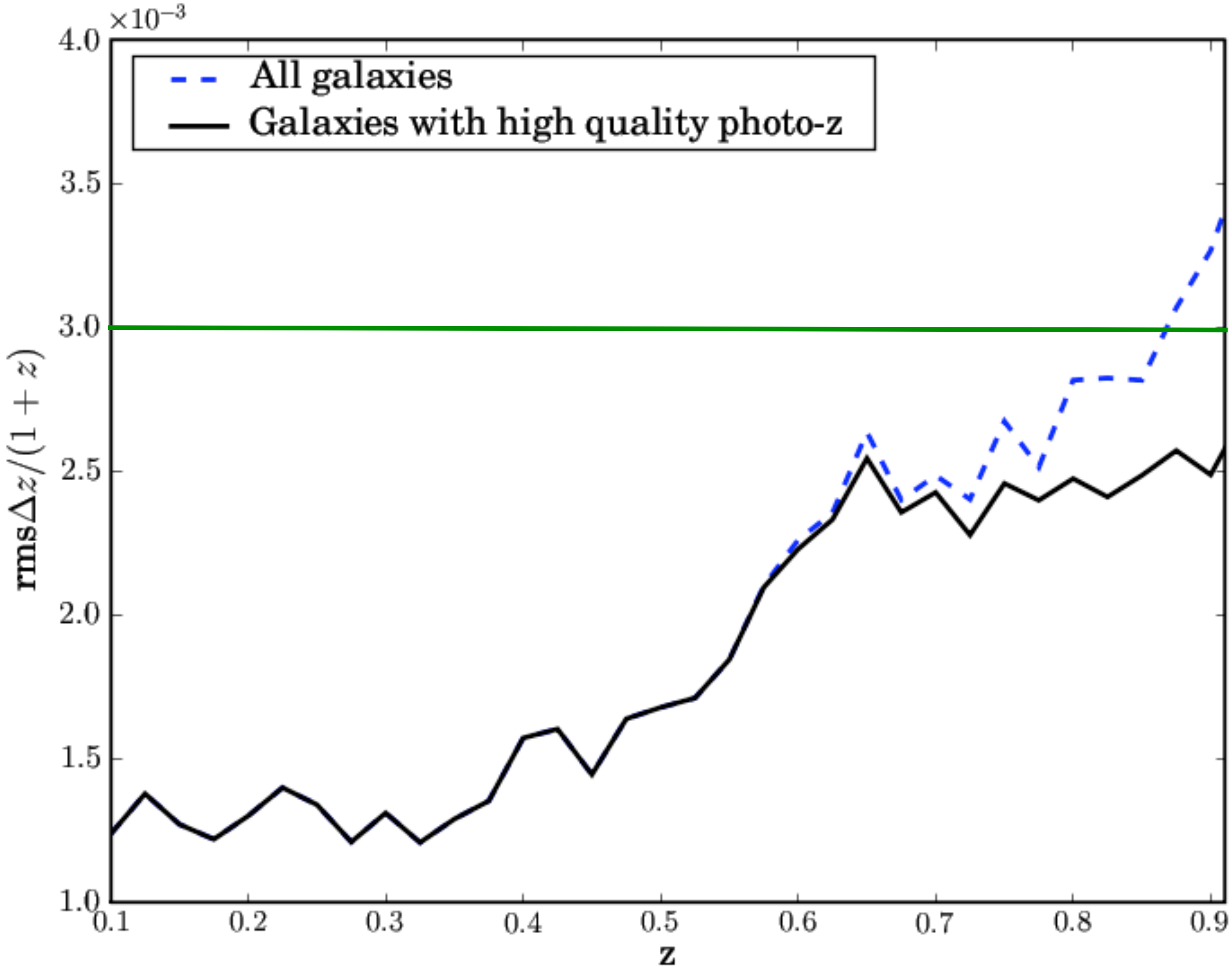
Intrinsic variation:
Selection effects

Benitez etal ApJ, V691,241-260 (2009)



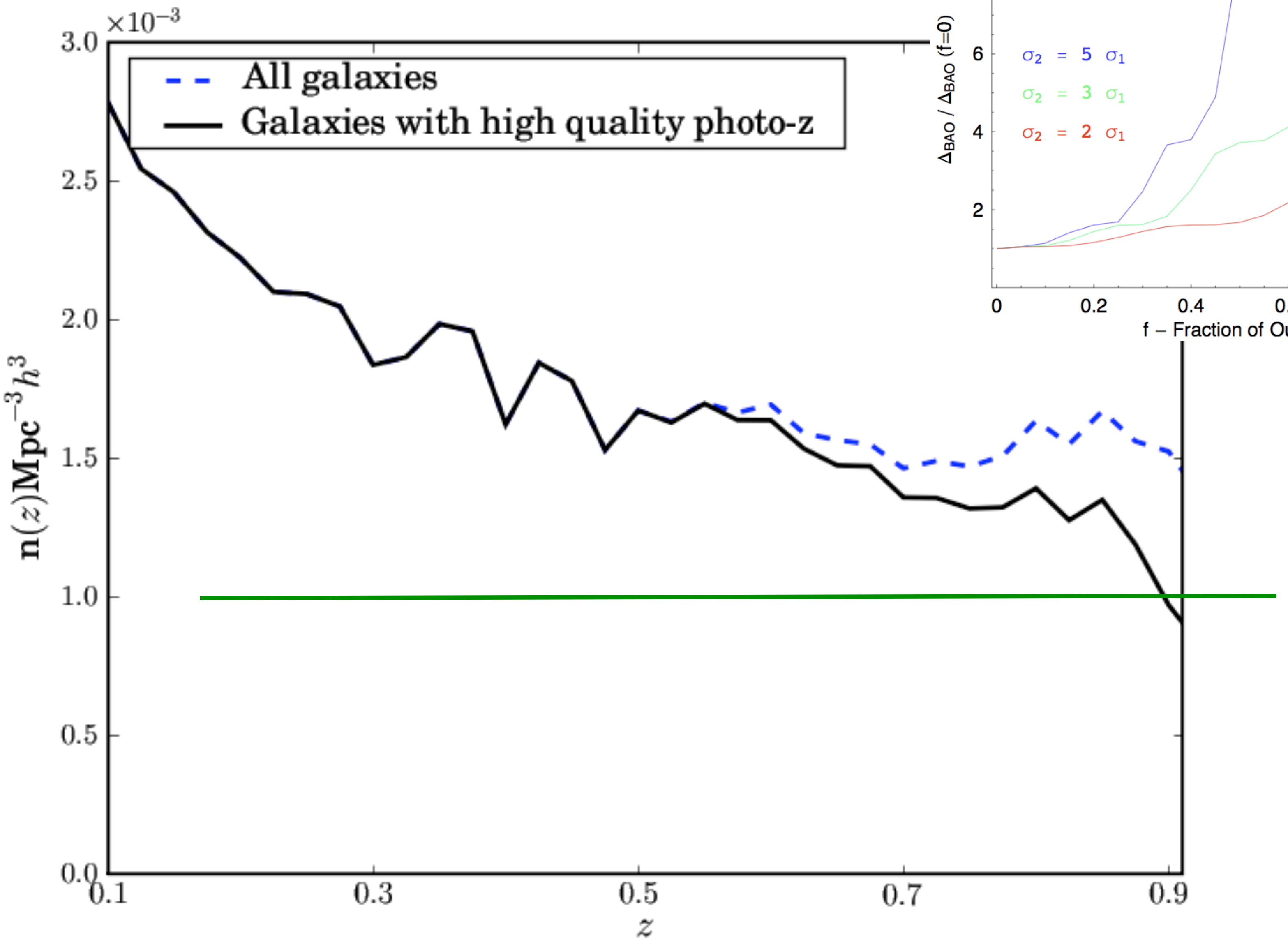


Redshift Resolution

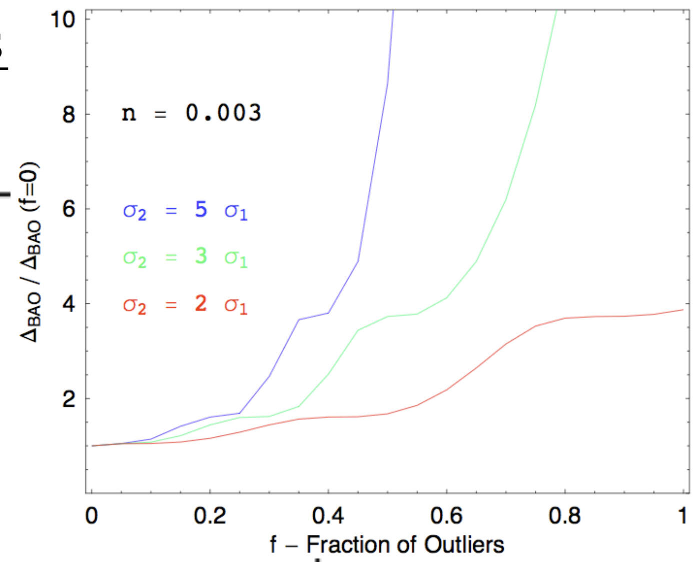


LRGs with L>L$_*$ m_I<23

Galaxy Density

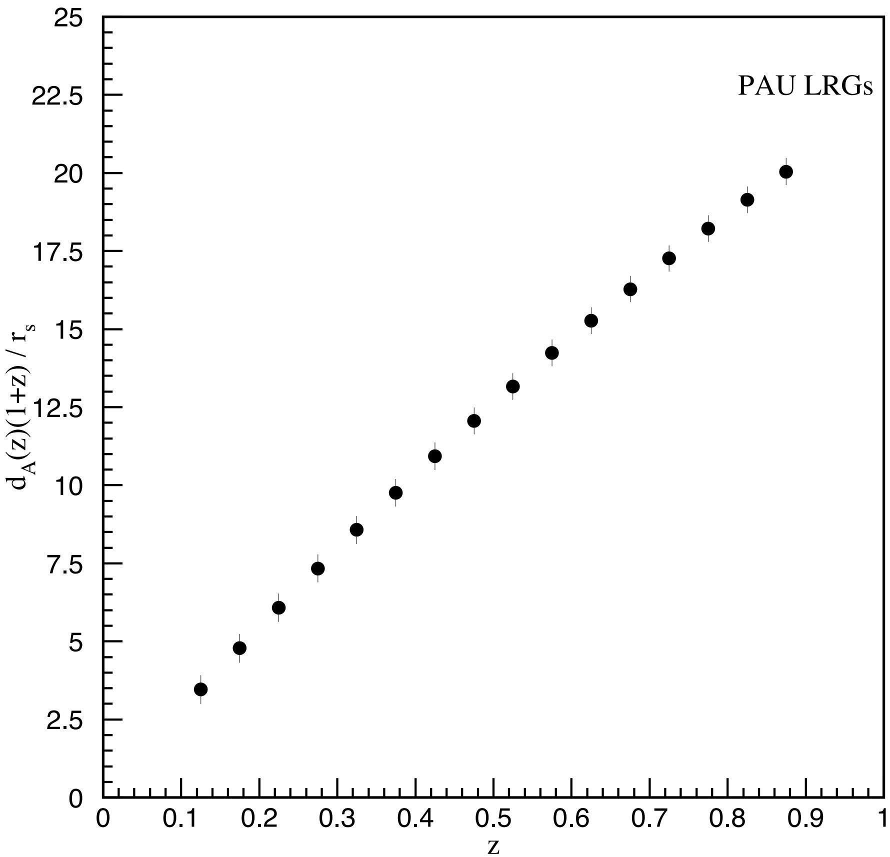


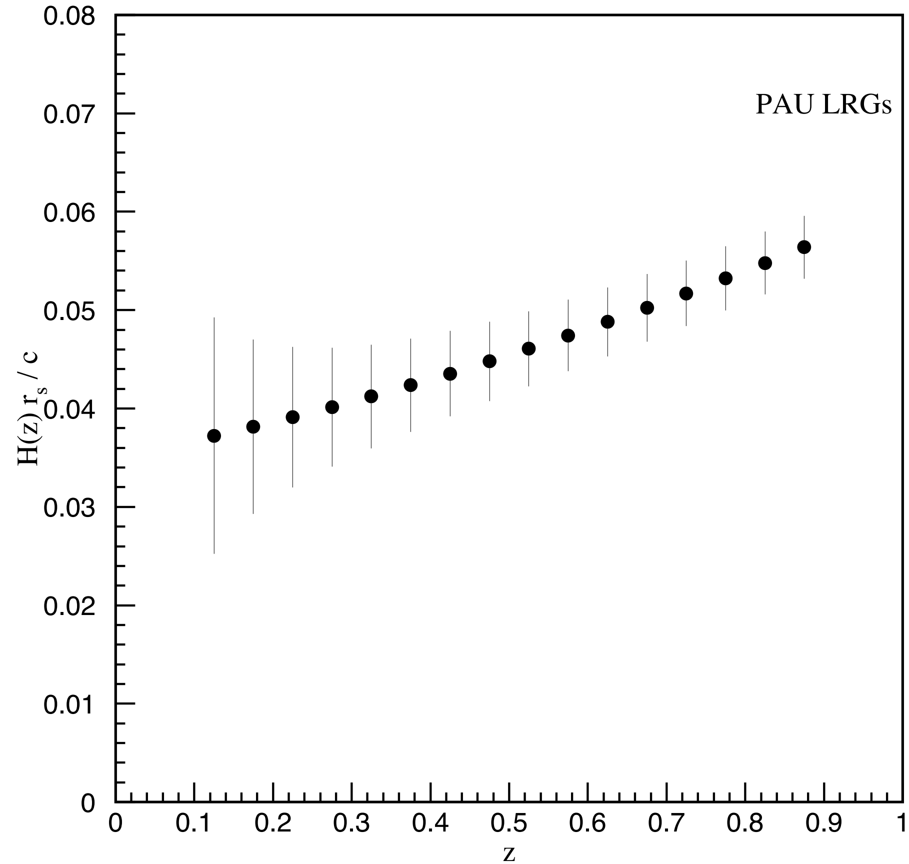
Outliers



LRGs with L>L$_*$ m_I<23

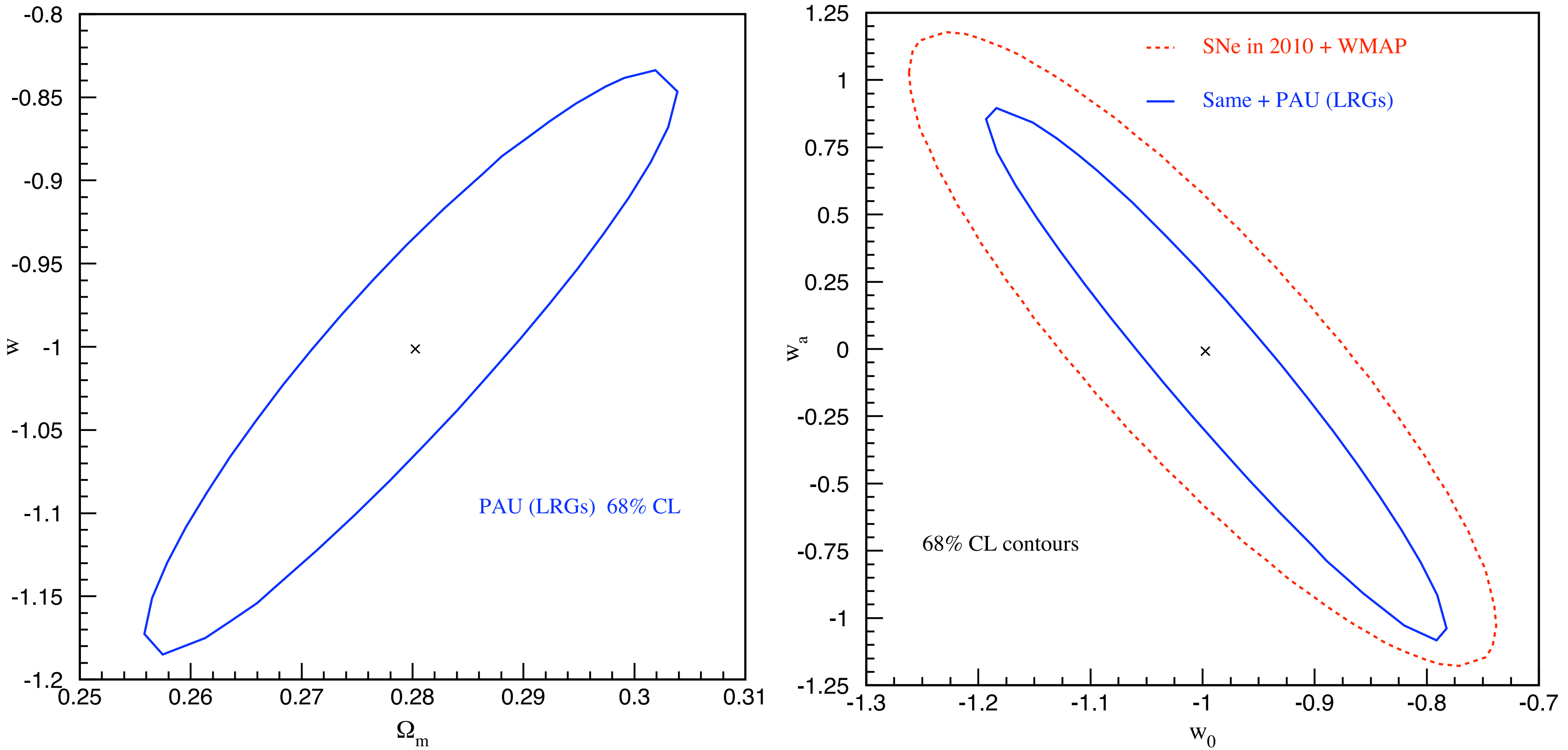
Precision on $d_A(z)$ and $H(z)$





16 bins with precision down to 2% for $d_A(z)$, 5% for $H(z)$

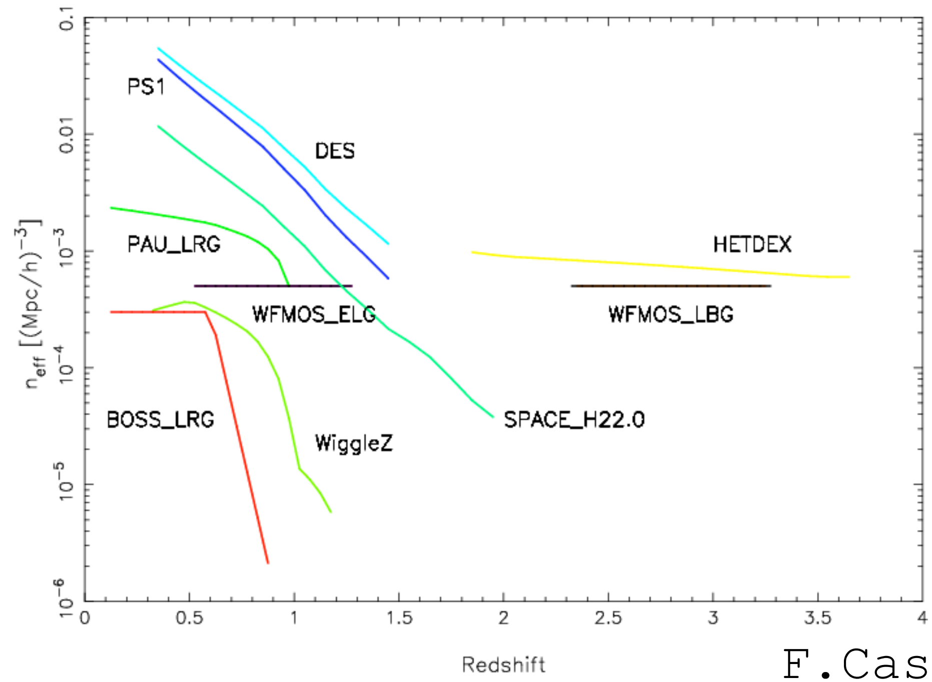
Dark Energy Parameters



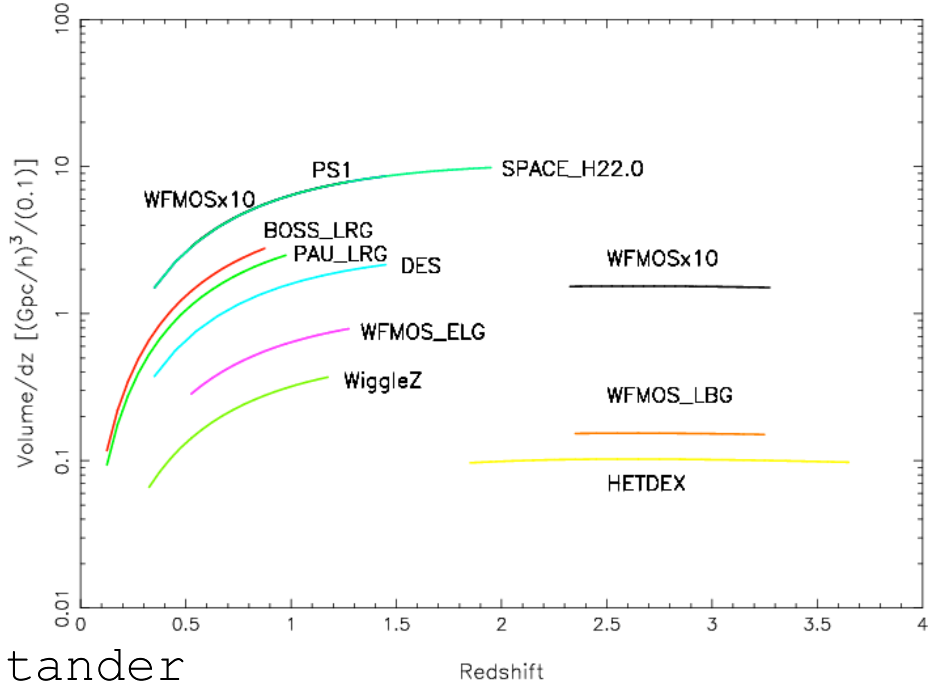
BAO surveys comparison

	Z range	N gals	Tracer	Area	Volume	technique	FoM
WiggleZ	$0.3<z<1.2$	2.8e+5	ELG	1000	2.04	spec	19
BOSS_LRG	$0.2<z<0.8$	1.5e+6	LRG	10000	8.06	spec	49
HETDEX	$1.8<z<3.3$	1.0e+6	LAE	200	1.91	spec	37
WFMOS_ELG	$0.5<z<1.3$	2.0e+6	ELG	2000	4.47	spec	43
WFMOS_LBG	$2.3<z<3.3$	6.0e+5	LBG	300	1.53	spec	24
PS1	$0.3<z<1.5$	5.0e+8	ALL	20000	65.3	photo	65
DES	$0.3<z<1.5$	1.5e+8	ALL	5000	16.3	photo	42
PAU_LRG	$0.1<z<1.0$	1.5e+7	LRG	8000	11.2	photo	82
WFMOSx10	$0.5<z<1.3$ $2.3<z<3.3$	2.0e+7 6.0e+6	ELG LBG	20000 3000	44.7 15.3	spec spec	186
SPACE $H<22.0$	$0.3<z<2.0$	1.5e+8	ALL	20000	112	spec	213

F.Castander

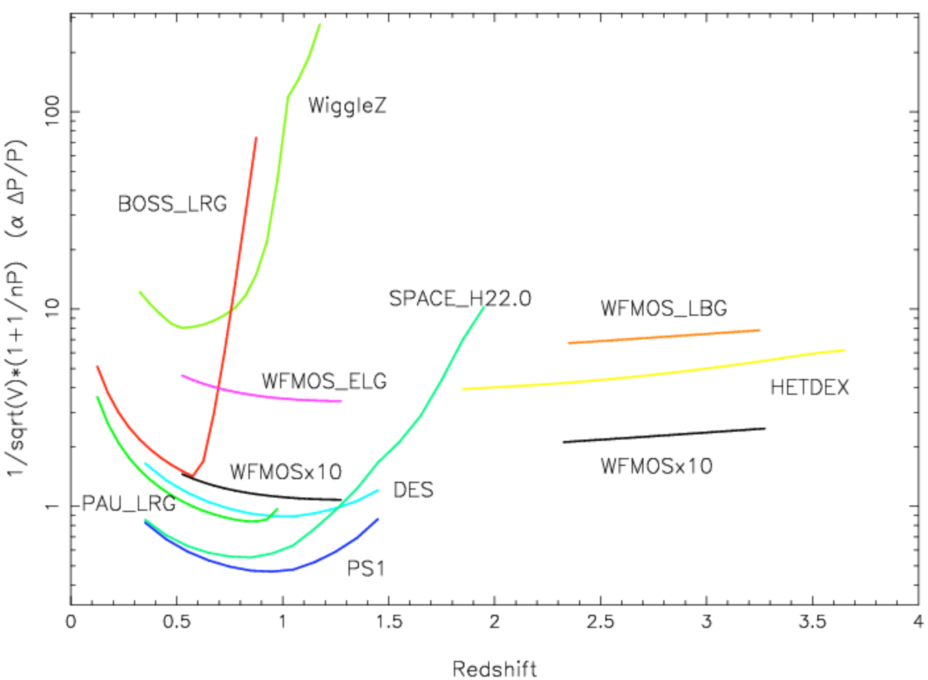


n_{eff} [(Mpc/h)$^{-3}$]
Redshift
PS1
DES
PAU_LRG
HETDEX
WFMOS_ELG
WFMOS_LBG
BOSS_LRG
SPACE_H22.0
WiggleZ

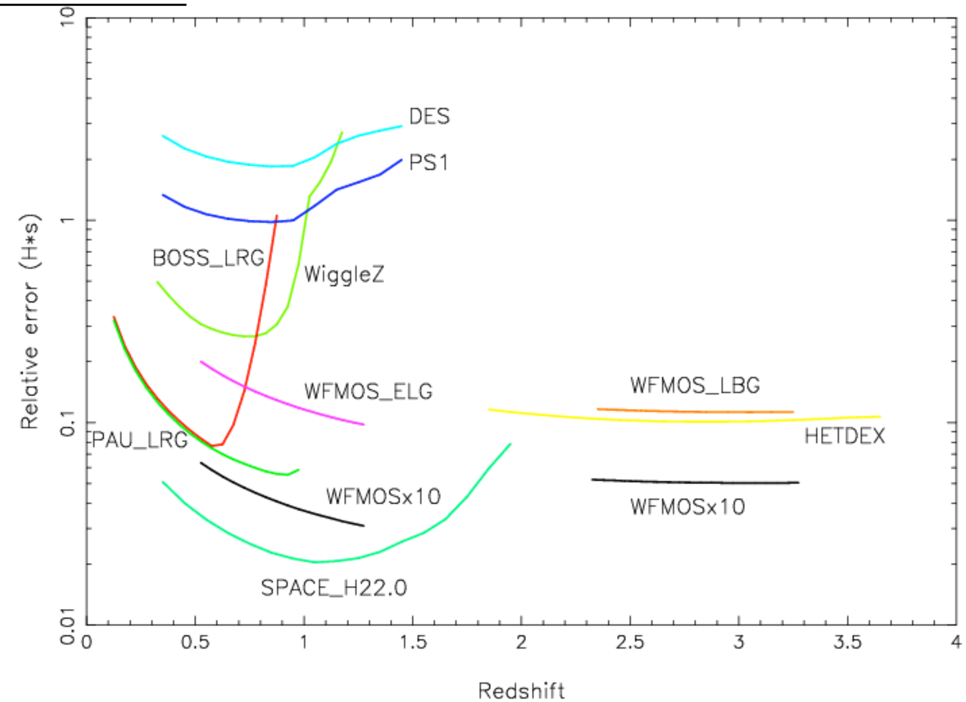


Volume/dz [(Gpc/h)^3/(0.1)]
Redshift
PS1
SPACE_H22.0
WFMOSx10
BOSS_LRG
PAU_LRG
DES
WFMOSx10
WFMOS_ELG
WiggleZ
WFMOS_LBG
HETDEX

F.Castander



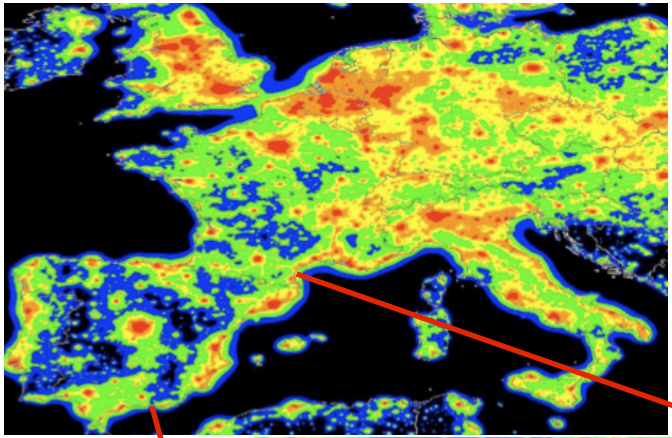
1/sqrt(V)*(1+1/nP) (α ΔP/P)
Redshift
WiggleZ
BOSS_LRG
SPACE_H22.0
WFMOS_LBG
WFMOS_ELG
HETDEX
WFMOSx10
DES
PAU_LRG
WFMOSx10
PS1

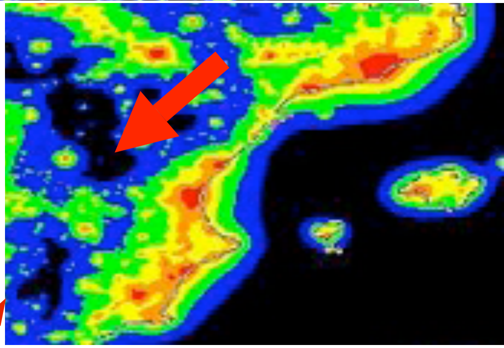


Relative error (H*s)
Redshift
DES
PS1
BOSS_LRG
WiggleZ
WFMOS_ELG
WFMOS_LBG
PAU_LRG
HETDEX
WFMOSx10
WFMOSx10
SPACE_H22.0

PAU = Physics of the Accelerating Universe

- ~45 particle physicists (theoreticians and experimentalists), astronomers, astrophysicists, cosmologists… Awarded a Spanish Consolider-Ingenio 2010 project (€5M over 5 years). PI: Enrique Fernández (IFAE). Main goals:
  - Design, build and commission a large (~6 deg^2) FoV CCD camera
  - Perform a photo-z BAO survey with it
  - Understand DE from theory point of view





- Telescope (funding independent from Consolider-Ingenio)
  - Newly built, dedicated 2.5 m class telescope
  - Wide field (3 deg diameter). Effective Etendue ~20
  - in Sierra Javalambre (1957m high, Teruel, Aragón)
  - Requirements set to fit PAU-BAO-LRG needs
  - funded by Fondo de Inversión de Teruel: 50% from the central government & 50% from the regional - Aragón - government.
  - Through the newly created Centro de Física del Cosmos de Aragón, (CEFCA). CEFCA includes a Data Center.Responsible: Mariano Moles

- The whole Survey run as a consortium (TBD), including other science

PAU-BAO Survey

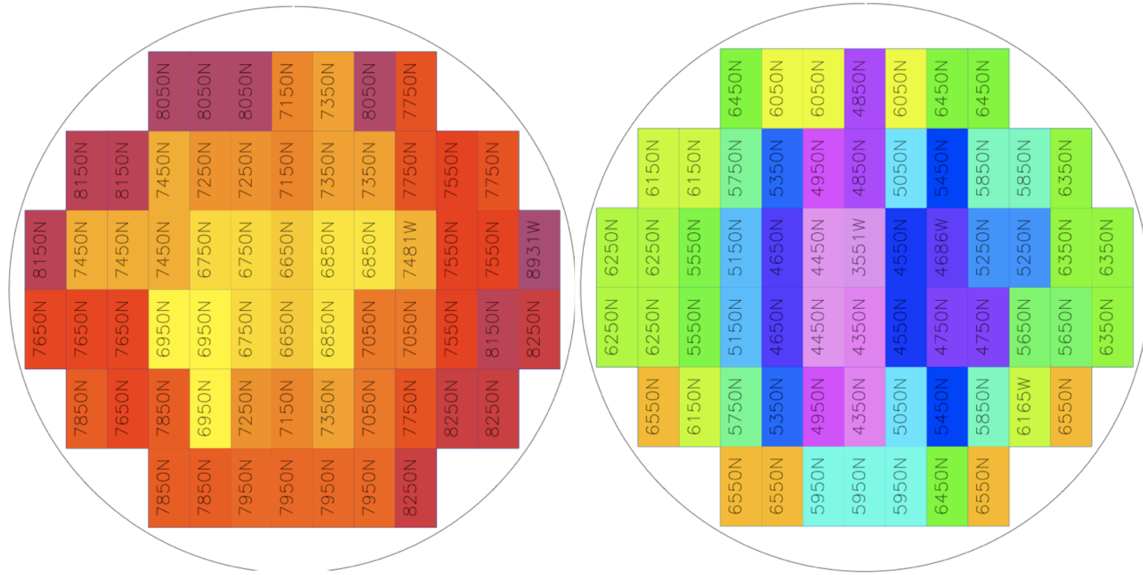
BAO LRG survey in a 2m (effective) class telescope (Ef.Etendue ~20) with a ~6 deg^2 FoV camera equipped with ~40 10nm-wide filters, ~500 Mpixels with 0.35”/pixel.

- 8,000 deg^2 in 4 years (but we have dedicated use of telescope for 5 years)
- $0.1 < z < 0.9$
- $m_I < 23$
- $n_{LRG} > 10^{-3}$ $(h/Mpc)^3$, nP ~10 at all scales
- V ~ 25 Gpc^3 ~ 9 $(Gpc/h)^3$
- N_{LRG} ~ 14 million (L > L*, $i_{AB} < 22.5$)
- N_{galaxy} ~ 200 million

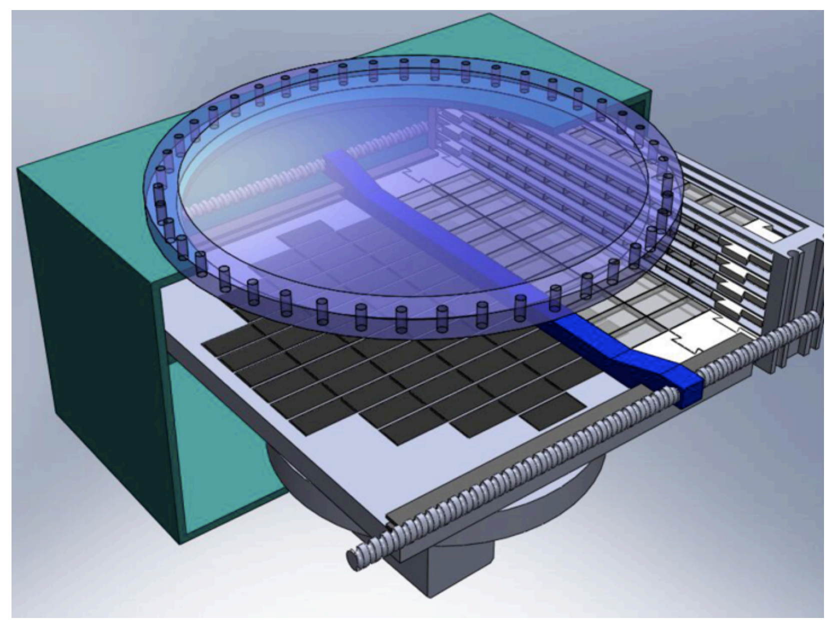
Selection effects

PAU Camera

Currently being defined!
Some initial ideas:



- Drift scan (TDI) technique minimizes dead time due to slew and read out.
- Filters atop sensors in two filter trays.
- Could use DES CCDs (commercial E2V another option).
- Use DES (Monsoon) electronics.



- Two trays: one blue tray observed once and one red tray observed twice (this gives an exposure of 16850sec)
- FOV Diametre 476 mm or 3 deg
- 5 wide (W=>SDSS) band filters (1 copy each) + 40 narrow (N) band filters (at least 2 copies each)
- Relative exposure time distribution between filters according to PAU paper.

MEASURING BARYON ACOUSTIC OSCILLATIONS ALONG THE LINE OF SIGHT WITH PHOTOMETRIC REDSHIFS: THE PAU SURVEY

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LHC-TR1 DM Center

(Dated: July 3, 2008)

The Astrophysical Journal, V691,241-260 (2009)

arXiv:0807.0535

DES PROJECT

www.darkenergysurvey.org

ALHAMBRA PROJECT

Moles et al., 2008, AJ, 136, 1325
Benítez et al., 2009, ApJL, 692L
Cristóbal-Hornillos et al., 2009, arXiv0902.240

Other Science: A terapixel redshift Survey

Selection effects

- Galaxy evolution
- Intergalactic dust
- Quasars and the Lyman alpha forest
- High-redshift galaxies
- Clusters (mass estimates)
- weak gravitational lensing (magnification, crosscorrel)
- Strong gravitational lensing
- Correlation of quasar absorption systems with galaxies
- Halo stars
- Local group stars
- Serendipitous discoveries
- …

Summary

- The accelerated expansion of the universe seems to change completely our understanding of the universe and its components. The quest to understand what causes the acceleration still open.
- Novel approach to photometric redshift determination allows measurement of the BAO feature along the line of sight in an efficient way.
- This leads to a statistically powerful, systematically robust determination of dark-energy parameters.
- Approach complements (for BAO and for other science) spectroscopic surveys. Terapixel redshifts.
- But project is challenging: new telescope with large FoV, new large camera, many filters, photo-z approach…
- Funding within reach.
- After a call for a conceptual design in 2008 (5 proposals) the telescope requirements have been set up. The bidding process is about to start.
- 24-30 months to have the telescope in the mountain.