U.Chicago 21th April 2009

Baryon Acoustic Oscillations with Luminous Red Galaxies & the PAU Survey

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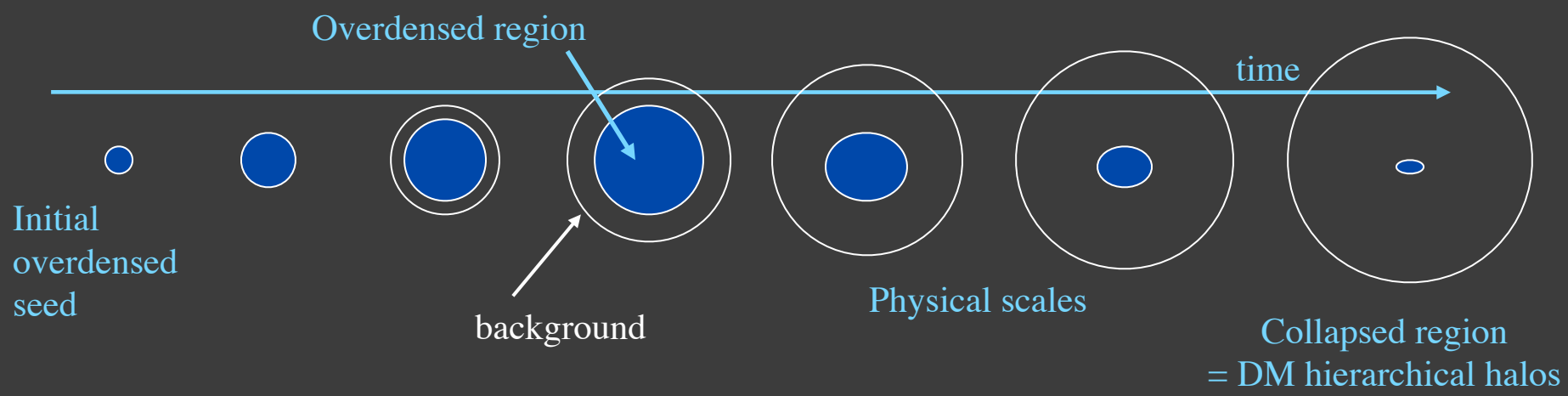
Two applications of anisotropic 2-point galaxy correlation:

- redshift space distortions: growth history
- Alcock-Paczynski (1979) test: expansion history

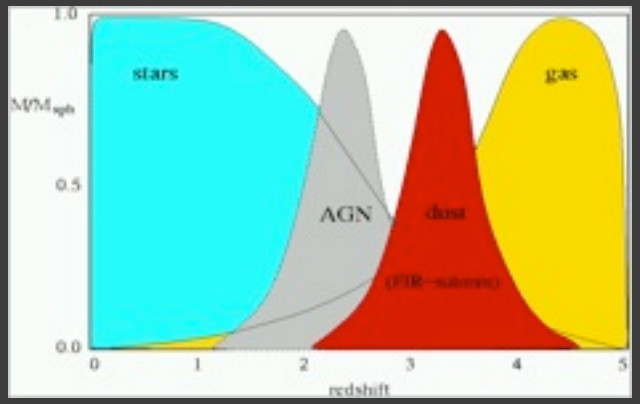
Where does Structure in the Universe come From? How did galaxies/star/molecular clouds form?

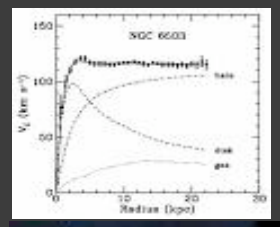
Stage-I: gravitational collapse from some initial seeds



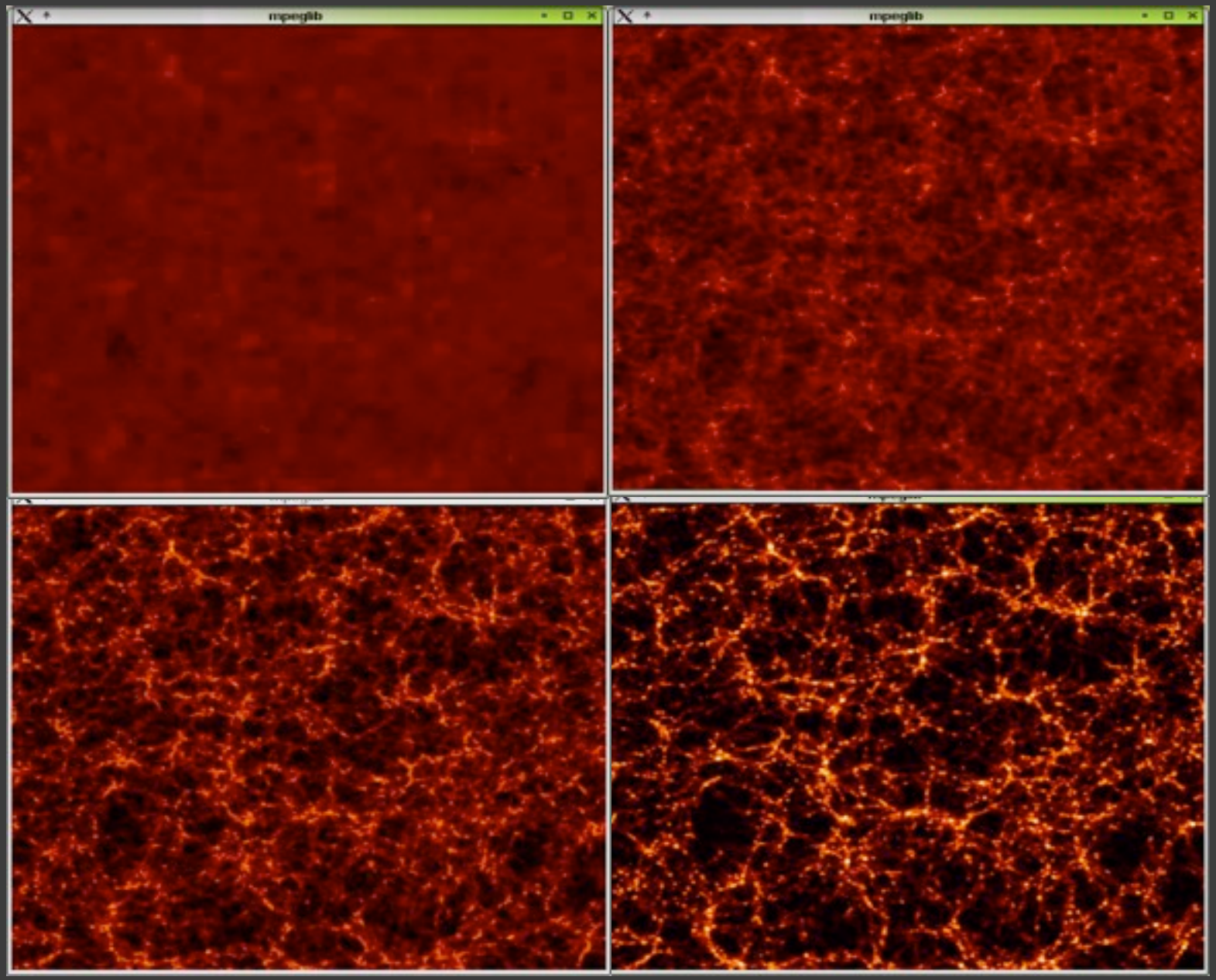
Stage-II: baryon radiative cooling into gas and stars

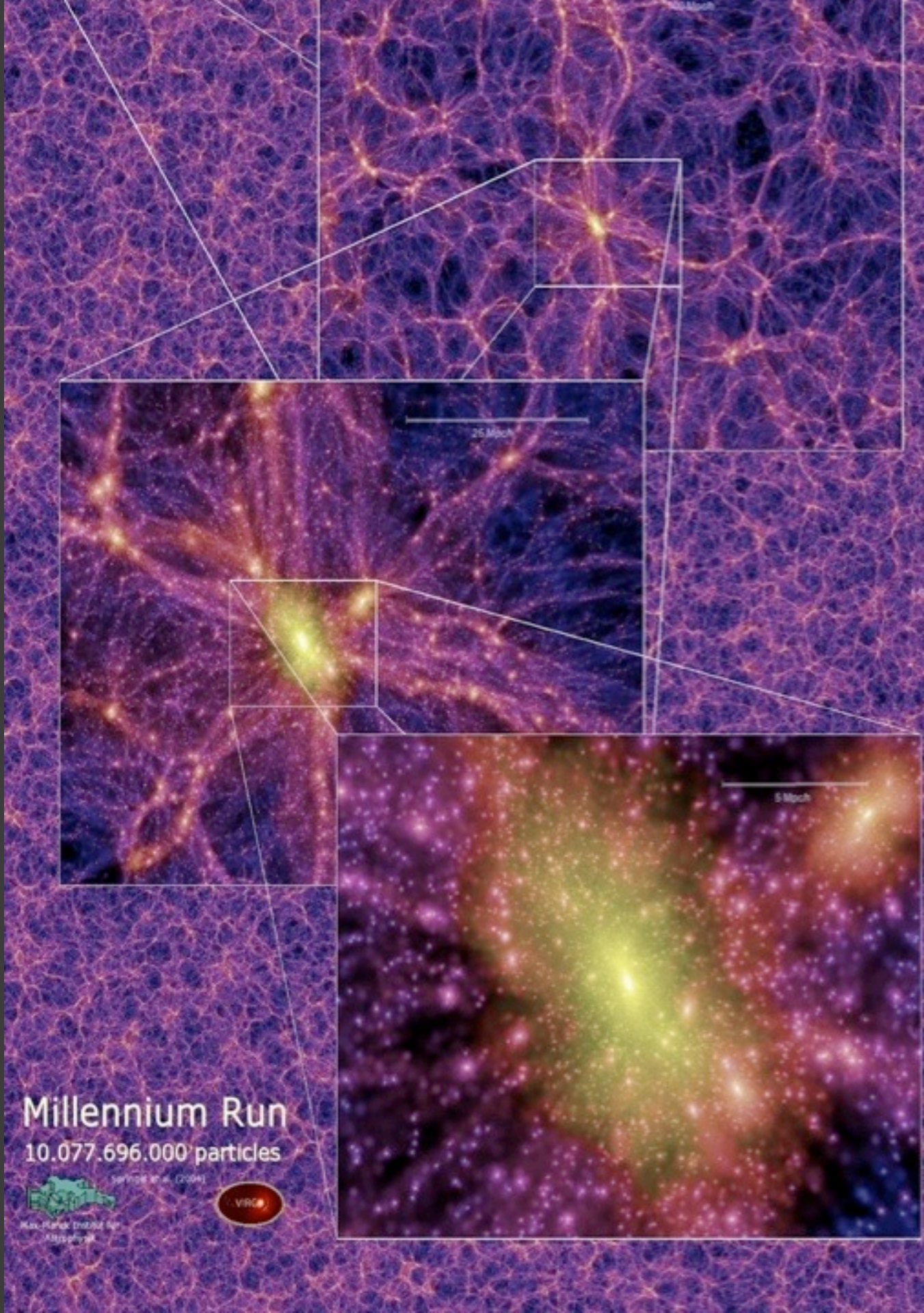
DM remains In halos





Disk formation: colapse is faster in direction parallel to spin axis

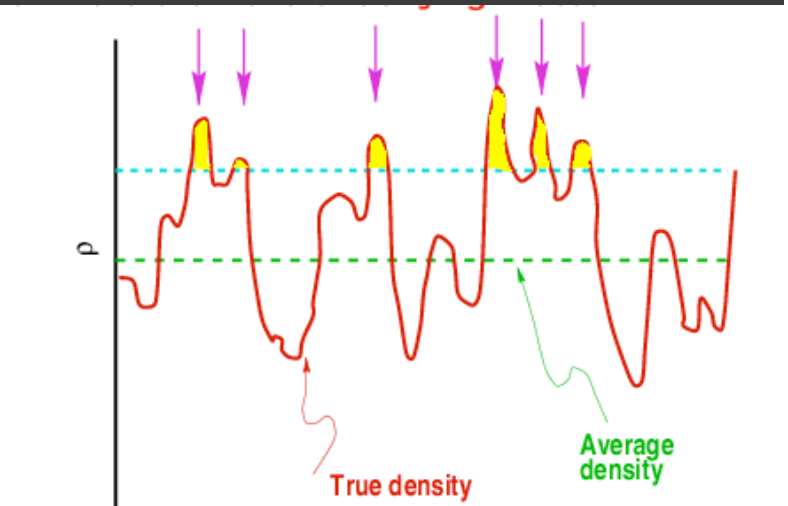

mpeglib
mpeglib

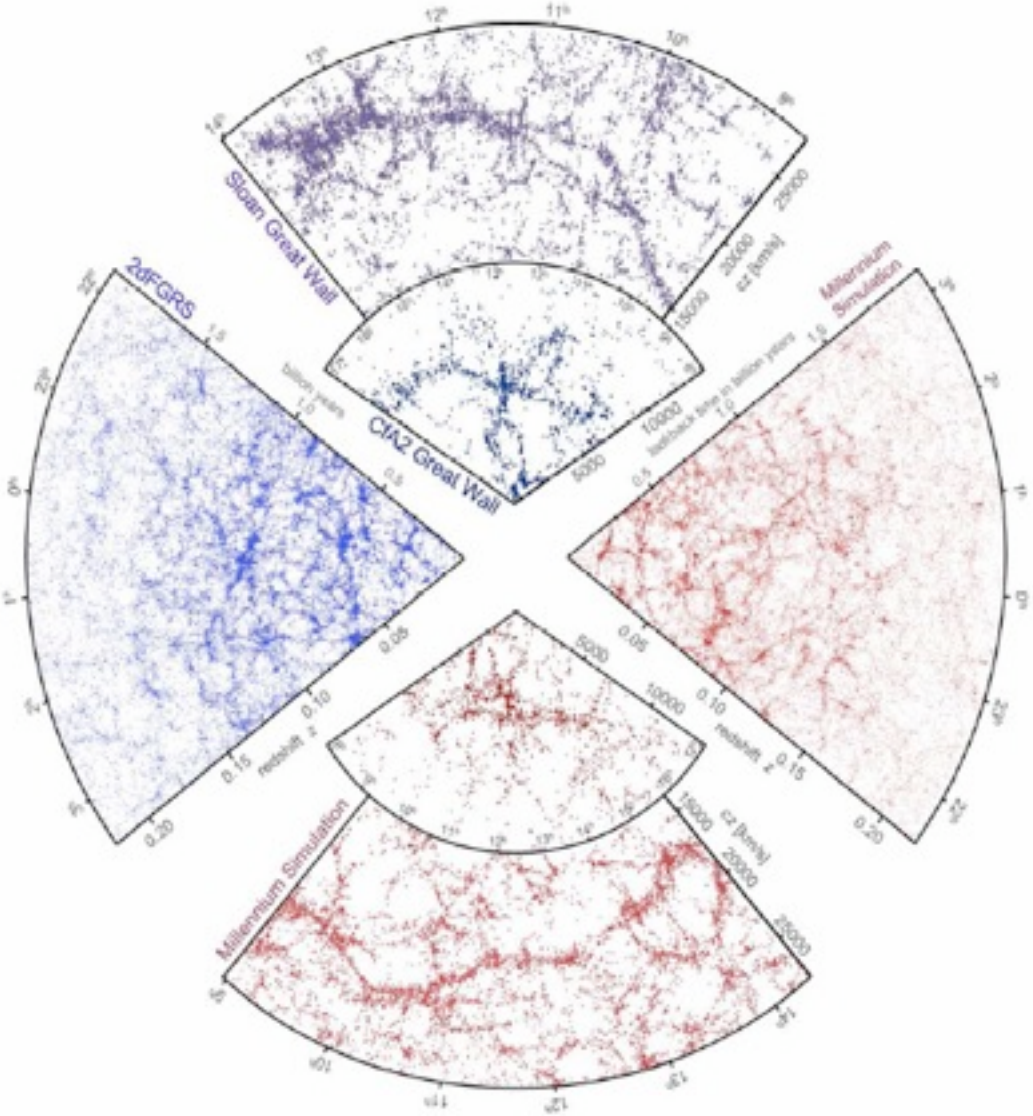

25 Mpc/h
5 Mpc/h
Millennium Run
10.077.696.000 particles
Springel et al. (2004)
Max-Planck Institut für Astrophysik
VIRGO

Does light traces mass?

Not on small (galaxy) scales but MAY BE on larger scales?

Bias: rare peaks in a Gaussian field (Kaiser 1984) Linear bias "b":





$\delta(peak) = b\,\delta(mass)$ *with* $b = \nu/\sigma$ $(\nu = \delta_c/\sigma)$

$\Rightarrow \xi_2(peak) = b^2\,\xi_2(m)$ $b = b(M)$

Can we really test this picture?

Can we separate the imprint of:

- the initial conditions: gaussianity, P(k)
- Gravity (+background evolution)
- Matter/Energy content
- Gastrophysics

If yes, we could learn about:

- The early universe & Fundamental Physics
- Background evolution
- Galaxy/Star Formation

Stress-Energy Conservation II. Fluctuations

$$\delta T^{\mu\nu}_{;\nu} = 0$$

$$\frac{\partial \delta}{\partial \tau} + \nabla \cdot [(1+\delta)\mathbf{v}] = 0$$

$$\frac{\partial \mathbf{v}}{\partial \tau} + \mathcal{H}\mathbf{v} + \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla \Phi$$

$$\text{Poisson } (\Omega_m = 1): \quad \nabla^2 \Phi = \frac{3}{2}\mathcal{H}^2 \delta$$

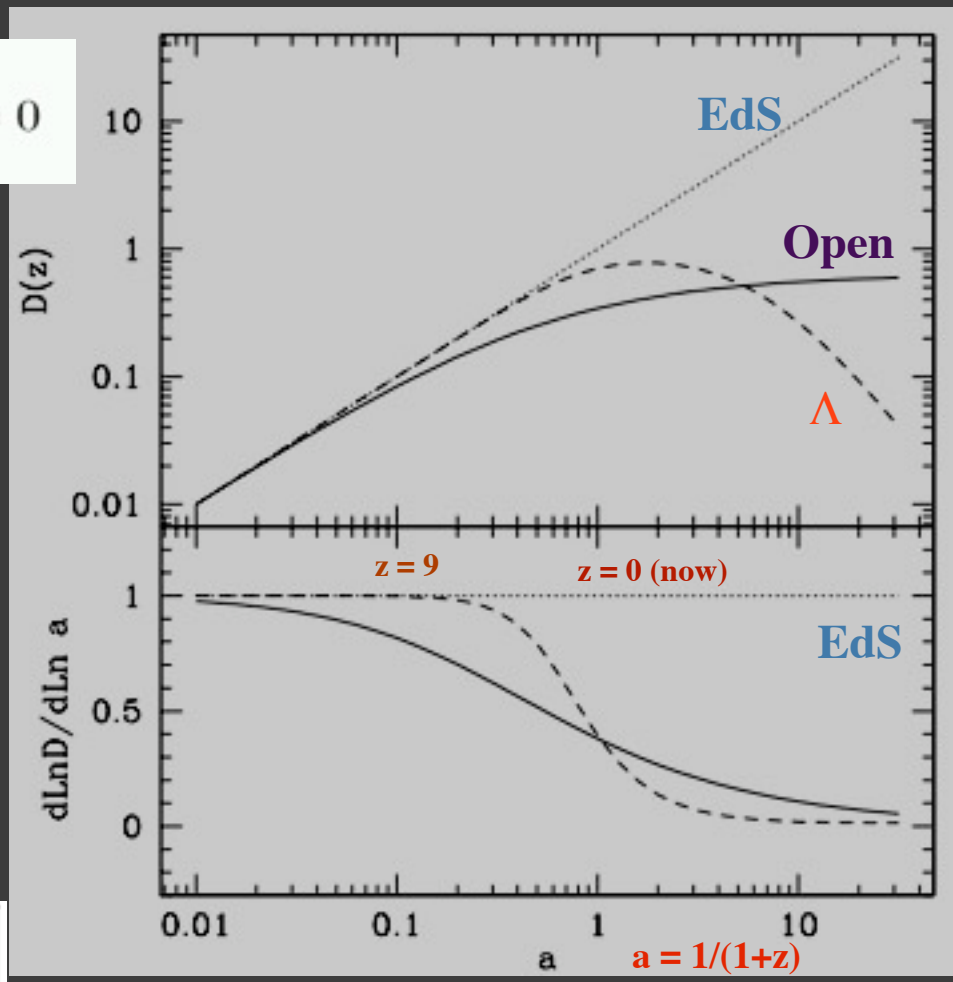
$$\nabla \cdot \mathbf{v} \equiv -\mathcal{H}\Theta, \qquad \mathcal{H} \equiv Ha$$

Jeans Instability (linear regime)

$$\frac{d^2\delta_k}{d\tau^2} + \mathcal{H}\frac{d\delta_k}{d\tau} - \left(\frac{3}{2}\mathcal{H}^2\Omega_m - k^2 v_s^2\right)\delta_k = 0$$

If $\frac{3}{2}\mathcal{H}^2\Omega_m > k^2 v_s^2$ fluctuations will grow

$\delta_L(x,\tau) = D(\tau)\ \delta_0(x)$



Another handle on DE:

-Where Friedman Eq. (Expansion history) may not separate modified gravity from DE:
Growth of sctructure could: models with equal expansion history yield difference D(z) (EG & Lobo 2001), **astro-ph/0303526 & 0307034)**

$$f \equiv \frac{a}{D}\frac{dD}{da} = \frac{d\log D}{d\log a}$$

$$\dot{\delta} = \frac{\dot{D}}{D}\delta = -\frac{\vec{\nabla}\vec{v}}{a} \equiv -H\theta$$

$$\theta = -f(\Omega)\,\delta$$

Velocity growth factor: tell us if gravity is really responsible for structure!
Could also tell us about cosmological parameters

Observations require an statistical approach:

Evolution of (rms) variance $\xi_2 = < \delta^2 >$ instead of δ

Or power spectrum $P(k) = < \delta^2(k) > \Rightarrow \xi_2 = \int dk\, P(k)\, k^2\, W(k)\, dk$

IC problem: Linear Theory $\delta = D\, \delta_0$

$$\xi_2 = < \delta^2 > = D^2 < \delta_0^2 >$$

Normalization $\sigma_8^{\,2} \equiv < \delta^2(R=8) >$

To find D(z) -> Compare $< \delta^2 >$ at two times or find evolution invariants

Problem: statistical bias: $\delta_{gal} = b\, \delta_{dm} \Rightarrow < \delta^2_{gal} > = b^2 < \delta^2_{dm} >$

So linear measurements constrain degenerate product: D(z)*b(z) ; $b*\sigma_8$

$$\theta = -\, f(\Omega)\, \delta = -\, f(\Omega)/b\, \delta_{gal}$$

β

Using galaxies to trace structure

Observables

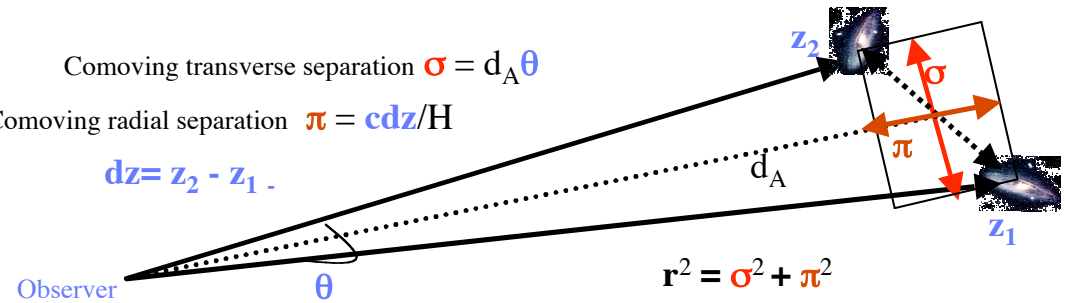
(null) Light-like radial ($d\Omega=0$) events

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

$$\pi \equiv dr$$

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

$$cdt = a\, r\theta$$



Comoving Radial distance

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

(Angular) Comoving distance

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

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

Observed

Known

Luminosity distance

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

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

Comoving Horizon scale = conformal time

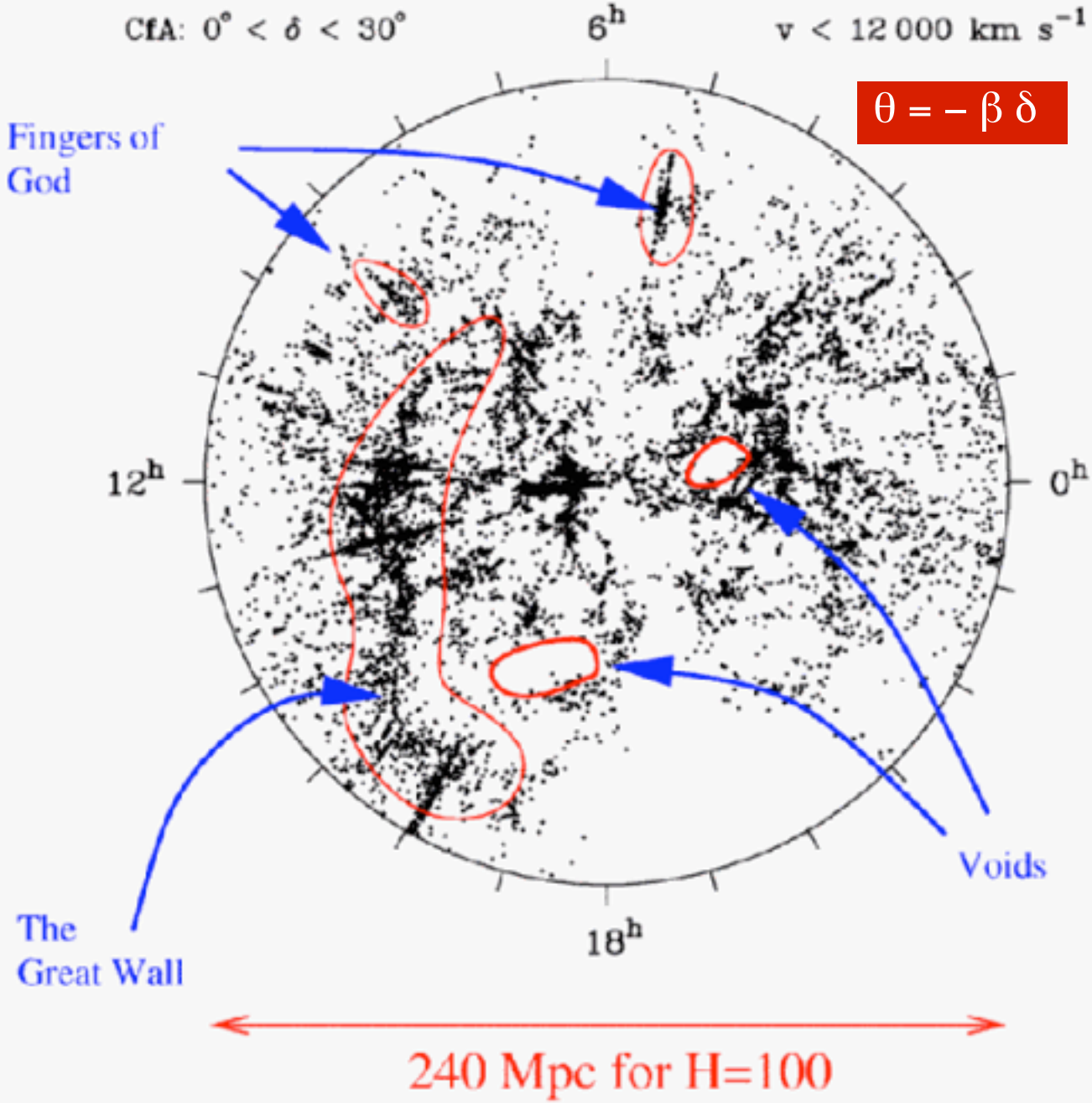
$$\eta \equiv \chi_H = \int_0^t \frac{cdt}{a} = \int_0^a \frac{cda}{a^2 H}$$

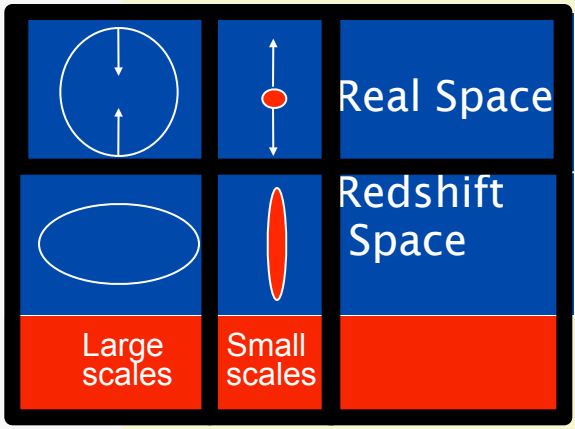
Age

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

Alcock-Paczynski (1979) test

redshift space distortions





surveys (mid-1980s)

Inverting v = cz = Hd gives an approximate distance.

Applied to galaxies on a strip on the sky, gives a 'slice of the universe'

Comparison of BAO Surveys

Spectroscopic

Photo-z 40-filter

Photo-z 5-filter

Project	Redshift	Area (deg^2)
WiggleZ	0.4-1.0	1000
HETDEX	2.0-4.0	350
WFMOS	0.5-1.3 2.3-3.3	2000 300
BOSS LRG + QSO	0.1-0.8 2.0-3.0	10000 8000
PAU-BAO	0-1	10000
Pan-STARRS*	0-1?	20000
DES*	0-1.5?	4000
LSST*	0-1.5?	20000

Padmanabhan

Spectroscopic accuracy trade-off with number density

Angular

Spectrum

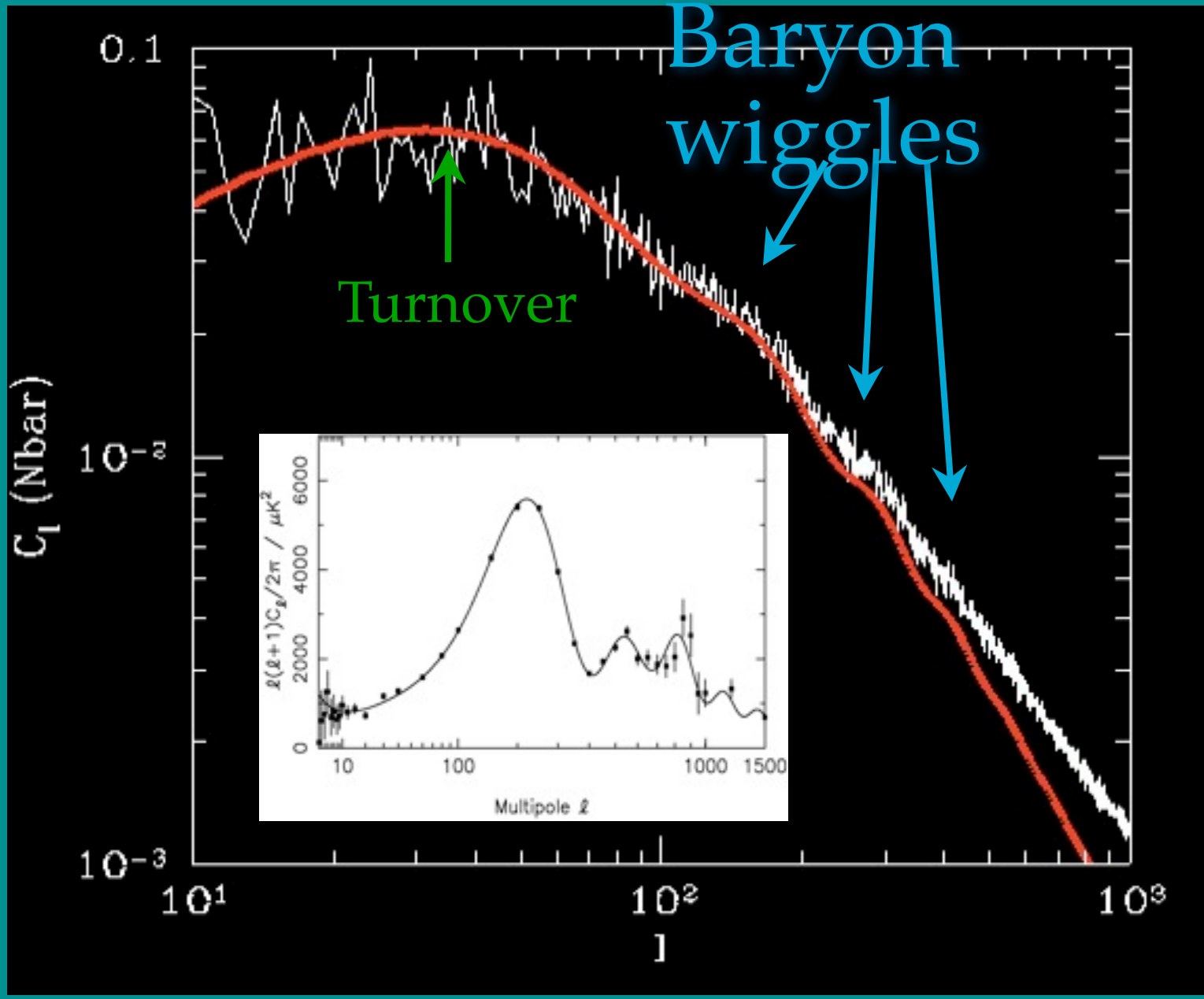
For single redshift slice:

z =0.9-1.0

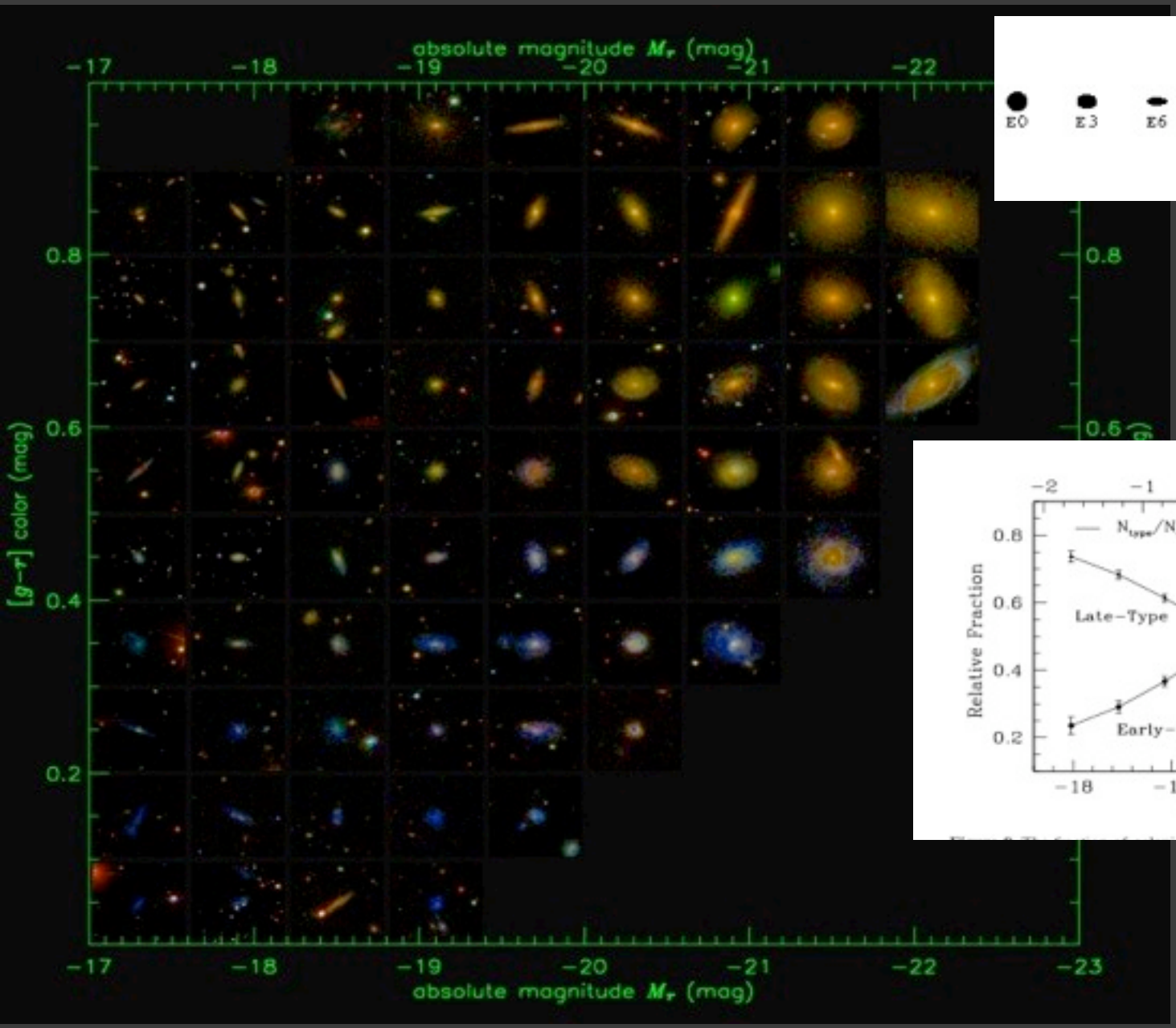
Of MICE

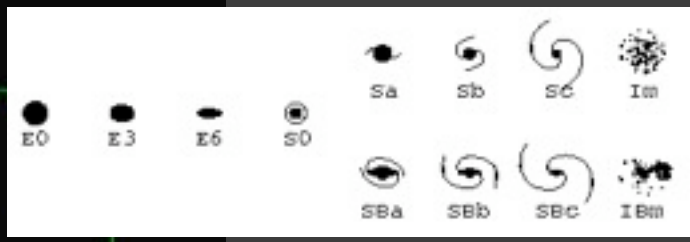
Simulation

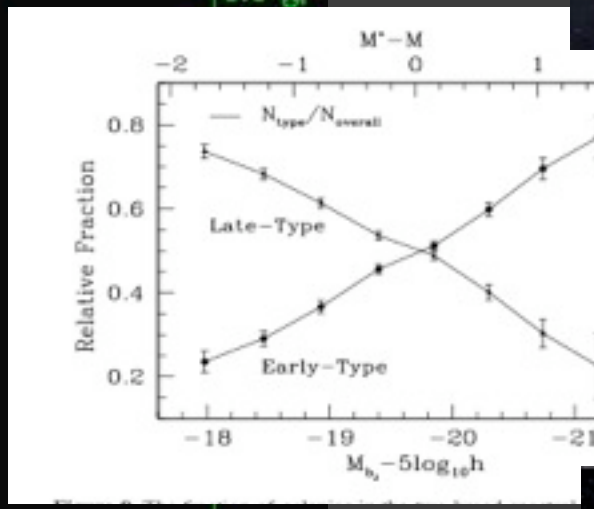
www.ice.cat/mice



SDSS LRG







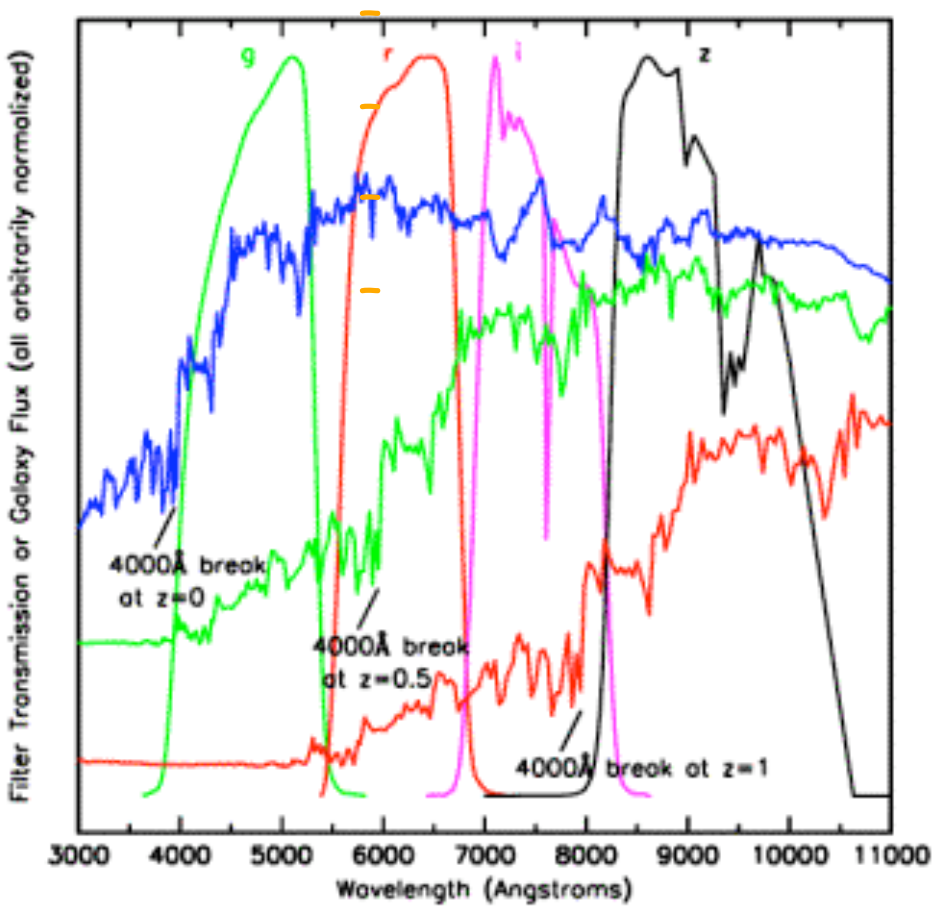
Hogg & Blanton

Which Galaxies?

SDSS

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*)



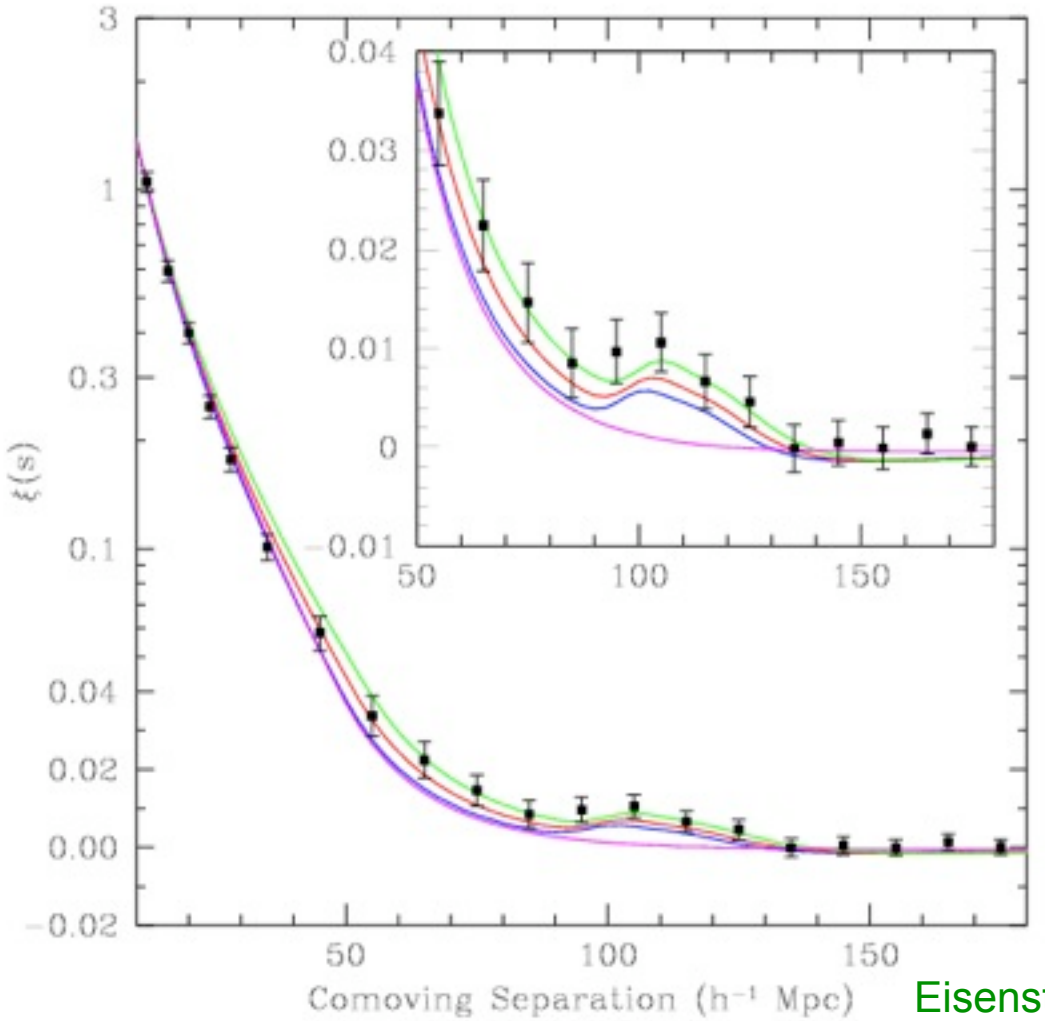
both very luminuos and invariable

large biased amplitude b^2=4

large density (ie clusters)

Galaxy-Galaxy Correlation Function

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



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

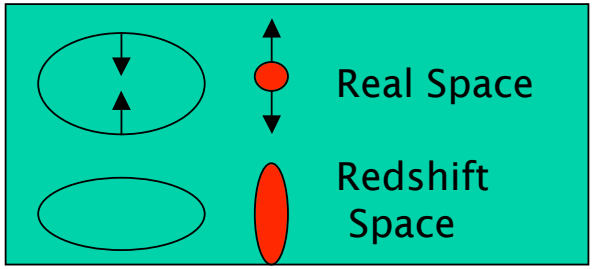
or

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

3.5-σ detection of BAO at <*z*> = 0.35 (confirmed by 2DF and SDSS photometric surveys at about 2.5 σ)

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

Eisenstein et al. 2005



Large scales

Small scales

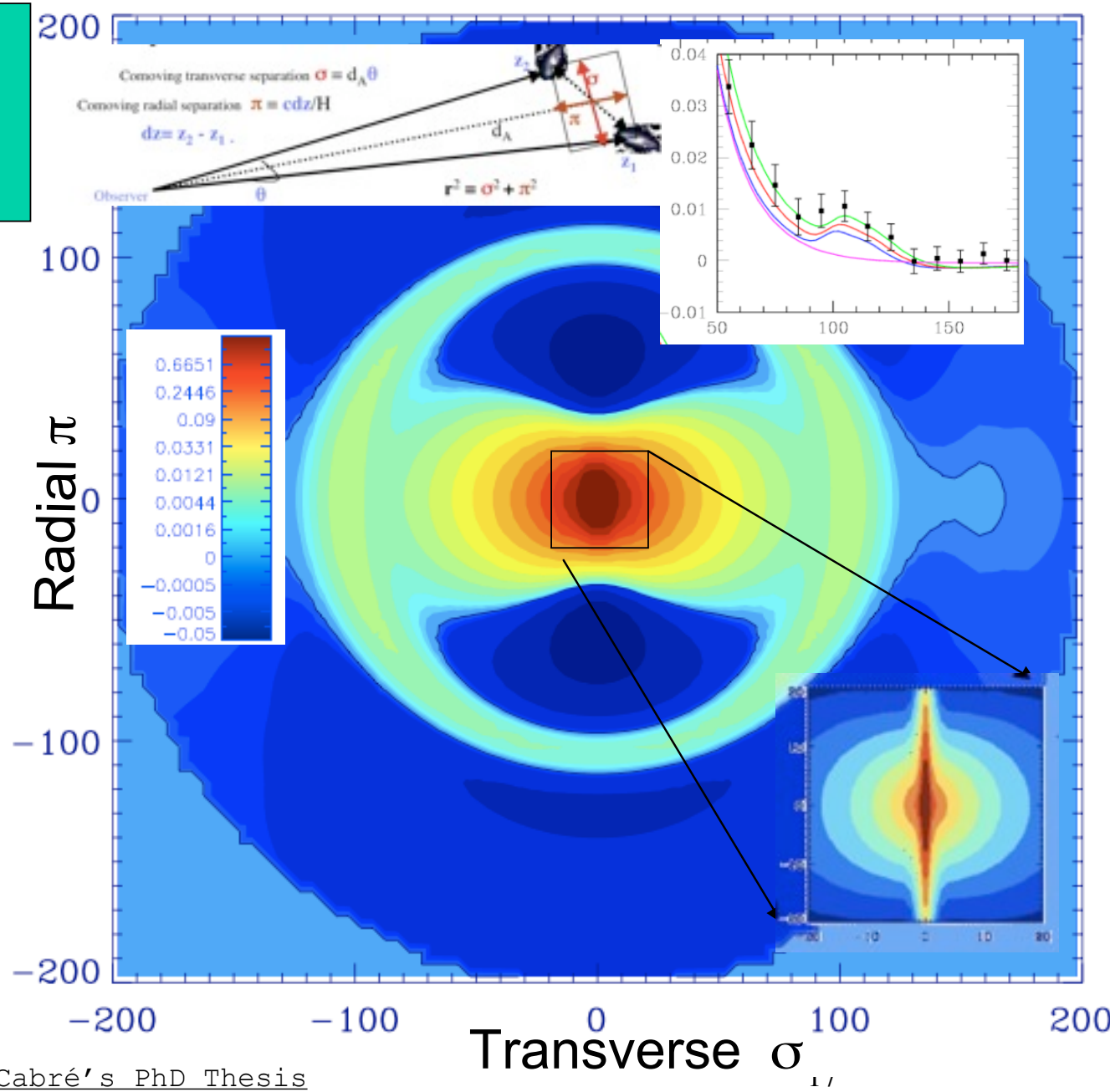
Observer

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

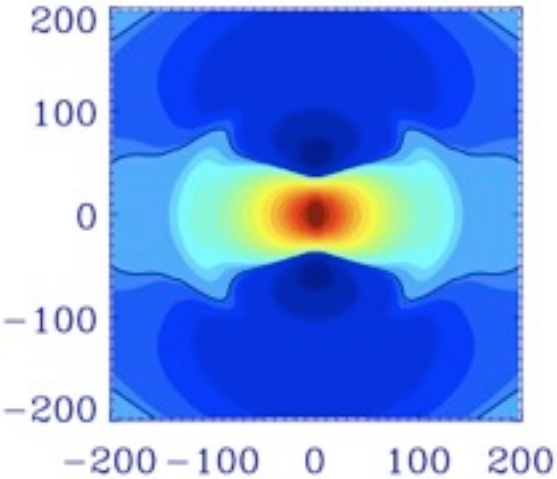
Growth

$v_p = \pi - \sigma$

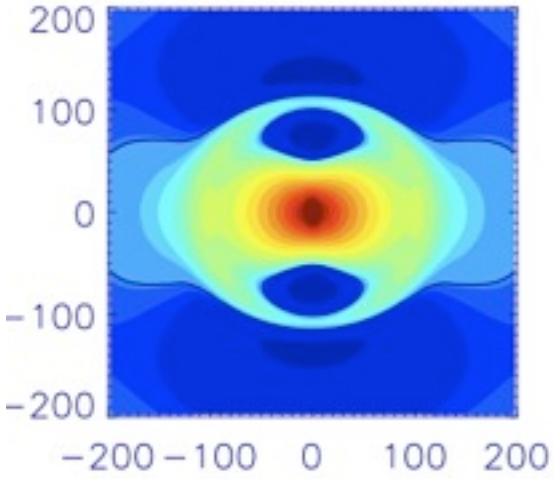
mass



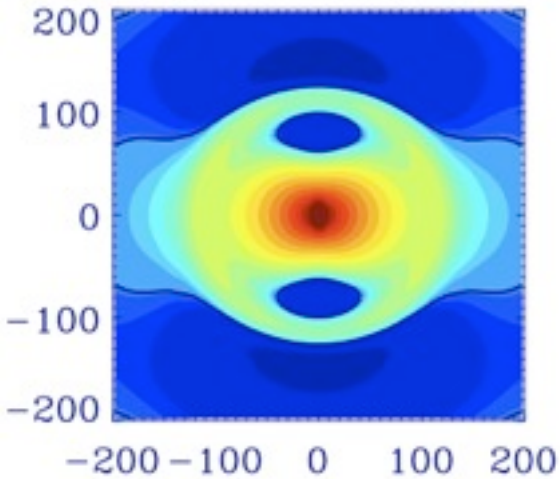
Anna Cabré's PhD Thesis
arXiv:0807.3551



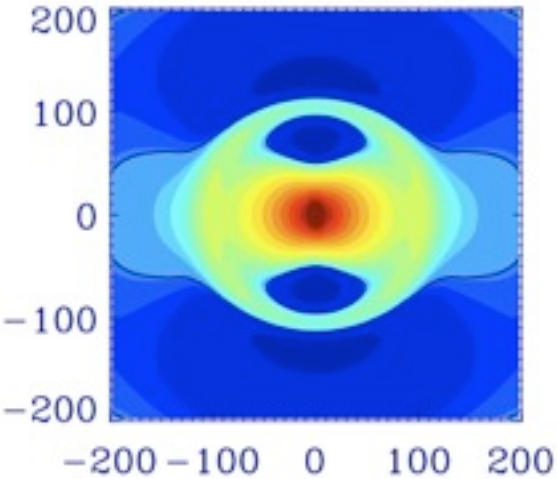
om=0.25 ob=0.02 ns=1



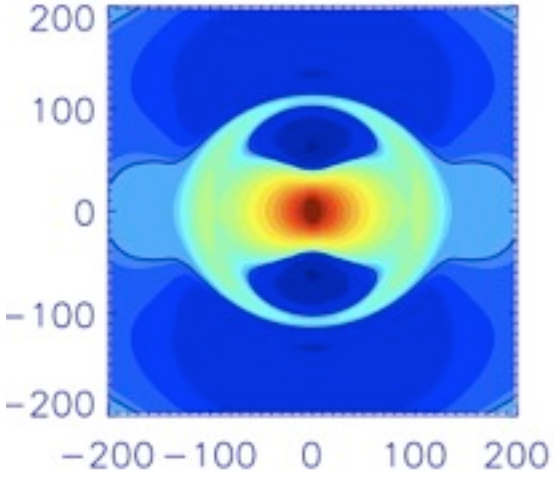
om=0.25 ob=0.05 ns=0.9



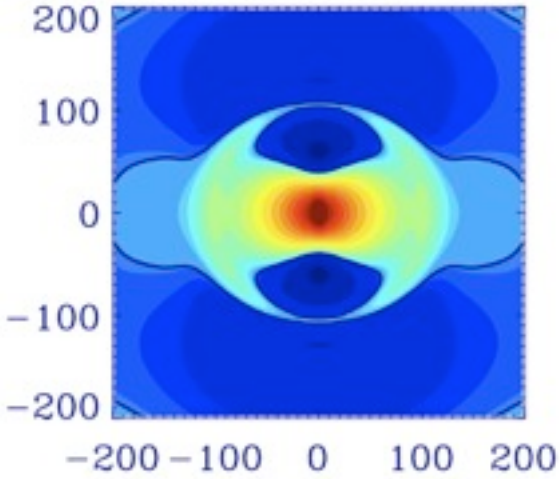
om=0.2 ob=0.05 ns=1



om=0.25 ob=0.06 ns=1



om=0.25 ob=0.05 ns=1.1



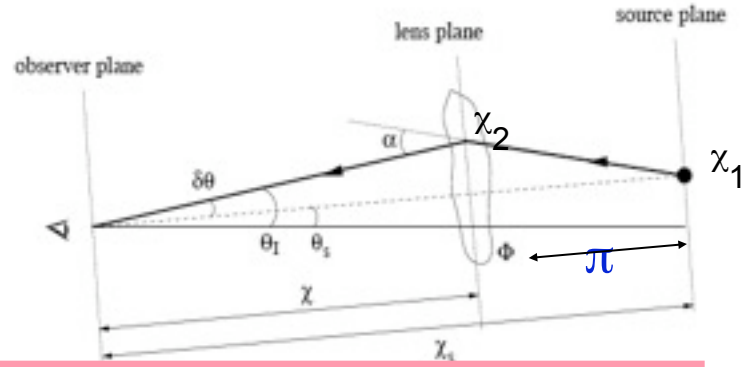
om=0.28 ob=0.05 ns=1

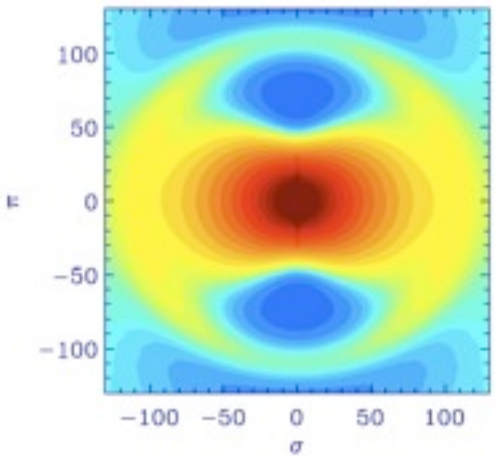
Magnification:

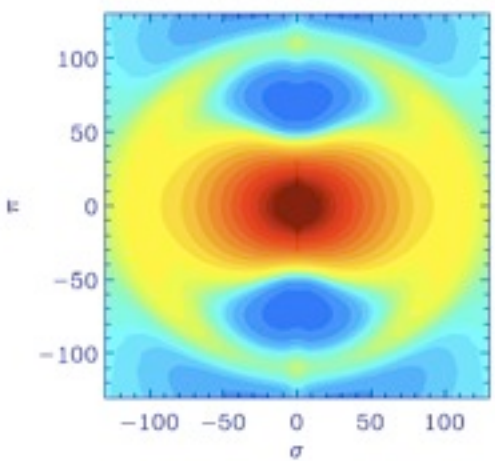
$$\delta_\mu = (5s-2)\kappa$$

$$\delta_{obs} = \delta_g + \delta_\mu + \delta_v$$

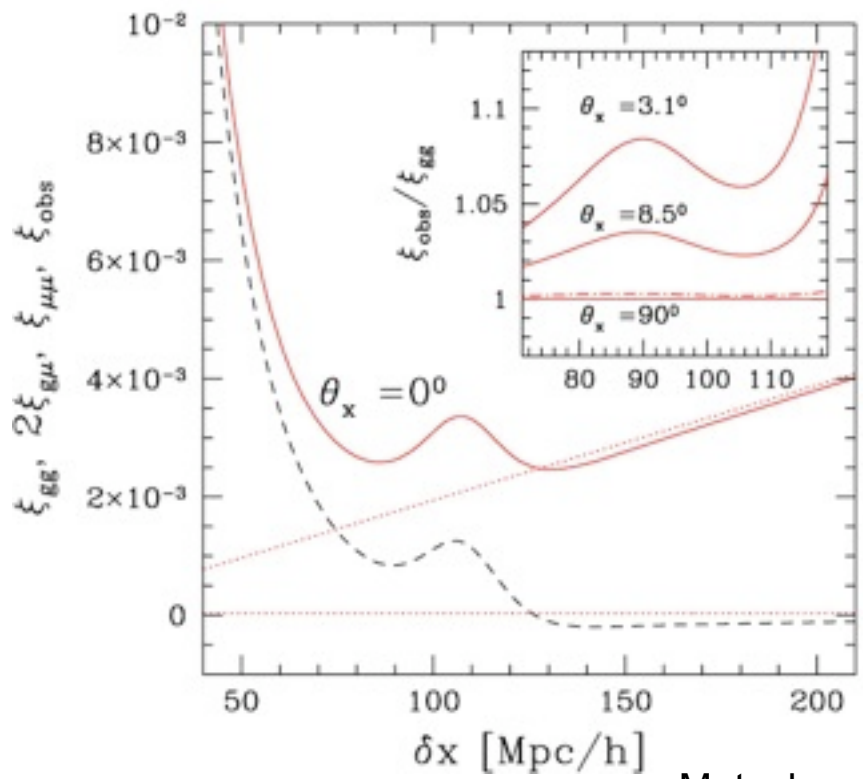
$$\xi_{obs} = \xi_{gg} + \xi_{gv} + \xi_{vg} + \xi_{vv} + \xi_{g\mu} + \xi_{\mu g} + \xi_{\mu\mu}$$







$$\xi_{g\mu}(\chi_1, \boldsymbol{\theta}_1; \chi_2, \boldsymbol{\theta}_2) = \frac{3}{2} H_0^2 \Omega_m (5s-2) \int_0^{\chi_2} d\chi \frac{(\chi_2 - \chi)\chi}{a(\chi)\chi_2} \xi_{gm}(\chi_1 - \chi, \sigma)$$



σ is small -> non-linear effects (bias +DM+z-distortions)

This is a linear in expansion in π

Matsubara 2000, astro-ph/0004392
Hui, EG, LoVerde, 2007, 0706.1071

SDSS LRG

2-point Correlation

$$\xi(\sigma,\pi) = \frac{DD - 2DR + RR}{RR} = < \delta(r_1)\, \delta(r_2) >$$

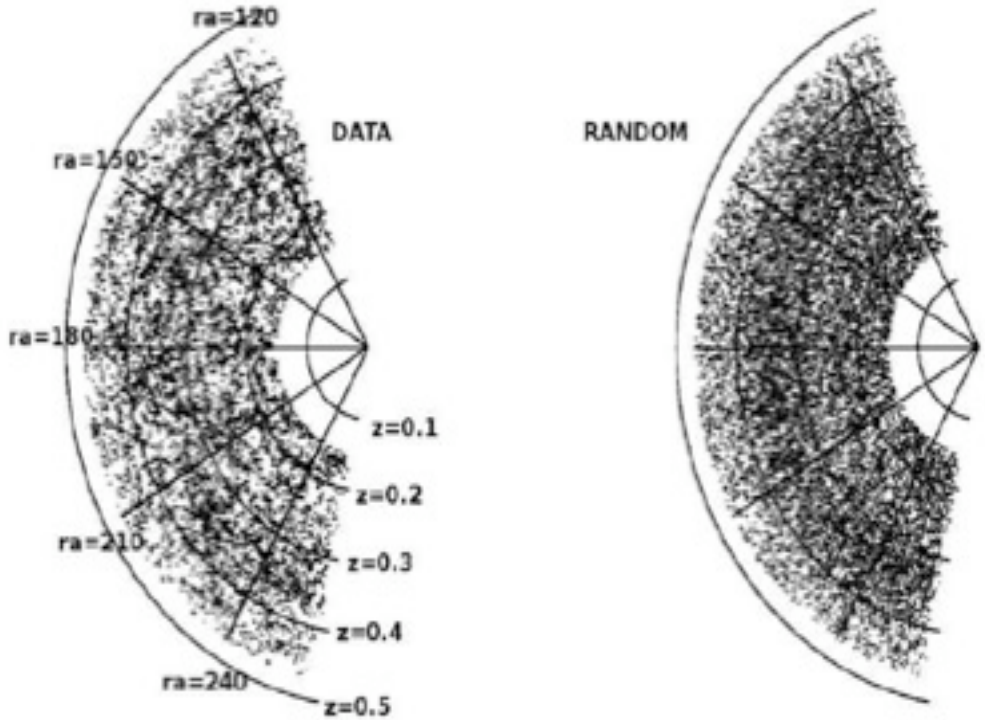


FIG. 15: Slice in dec = 32-40 deg showing ra vs redshift, in order to see the structure of the data (left panel). We also plot the random distribution for this slice (right panel)

SDSS LRG

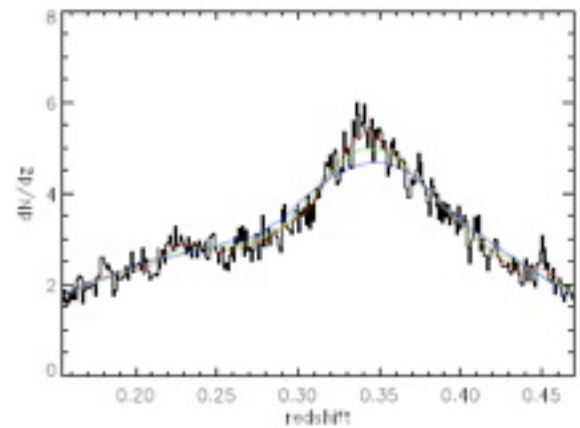


FIG. 32: Selection function for data (black histogram) and smoothed for the random catalogs with a bin in redshift of z=0.02 (red), z=0.05 (green) and z=0.08 (blue)

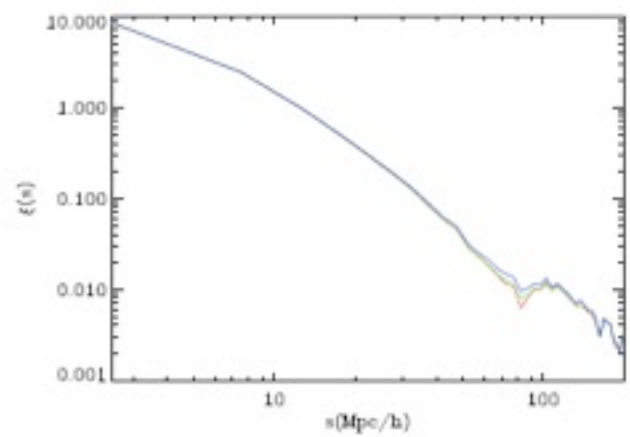
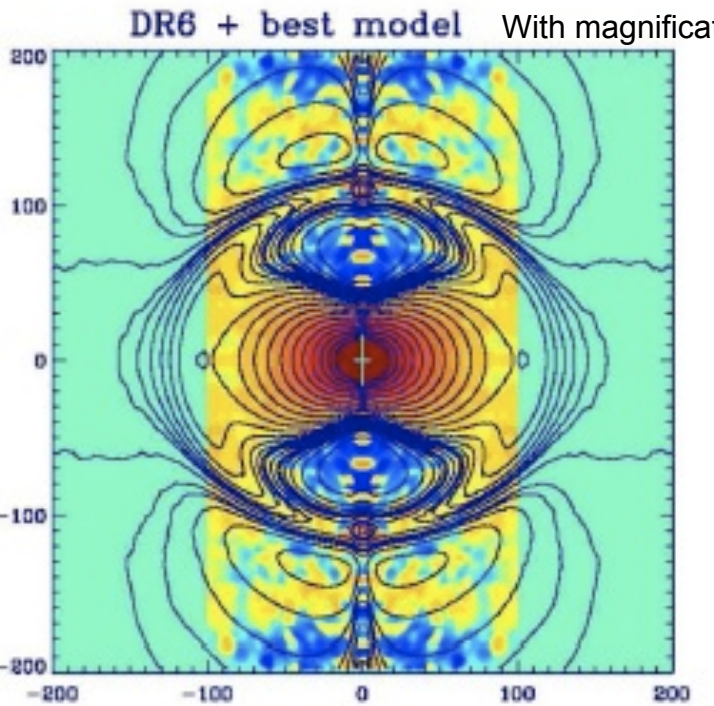
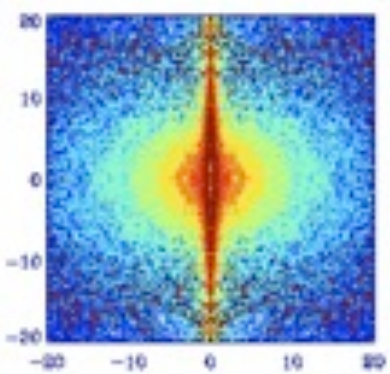


FIG. 33: Redshift-space correlation using different redshift smoothing in the random selection function of 0.02 (red), 0.05 (green) and 0.08 (blue)





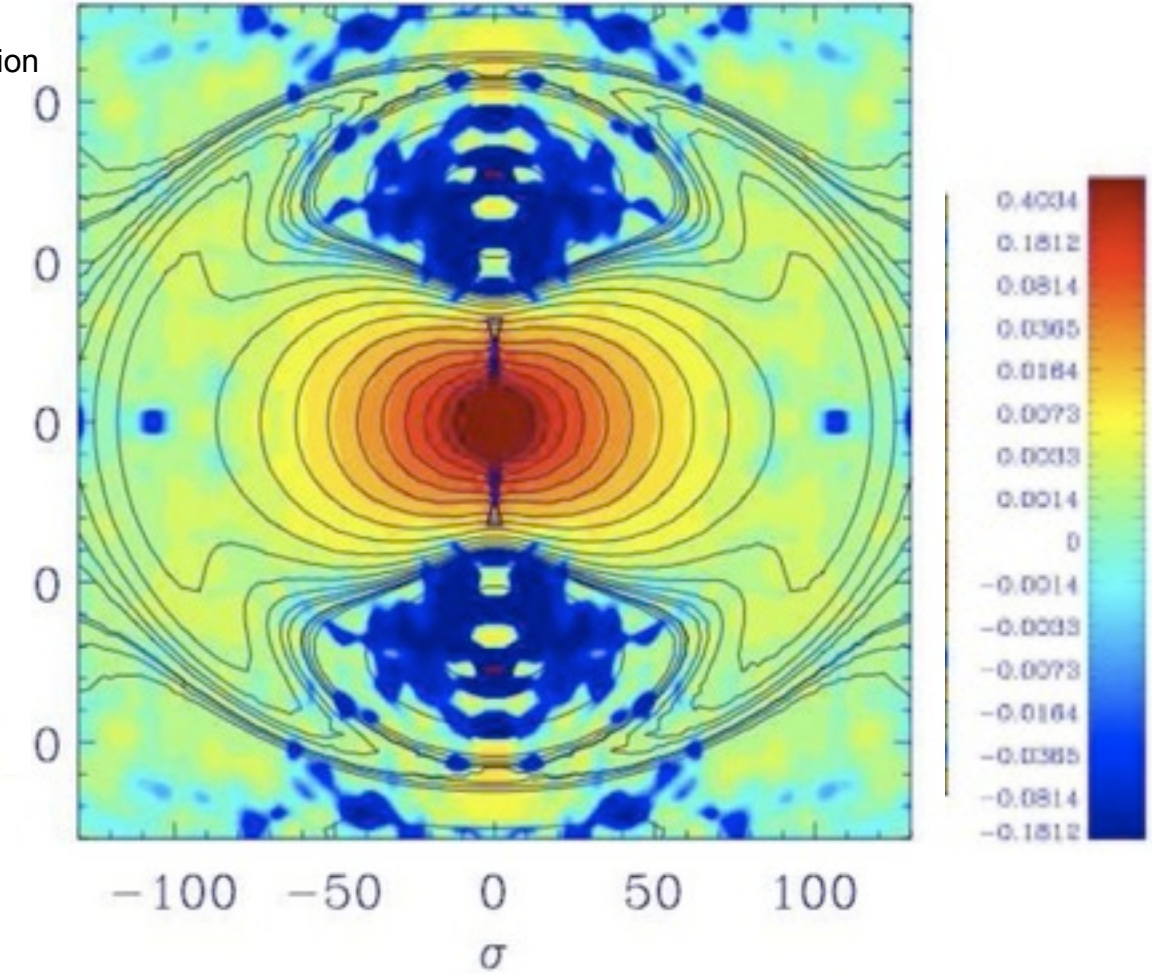


FIG. 22: Best Hamilton model fit (solid lines) to the 2-point anisotropic redshift correlation function $\xi(\sigma, \pi)$ for LRG galaxies (colors). Colors are as in Fig.13). The agreement with the model is excellent at all levels.

What are the errorbars? Need 100's of 1Gpc^3 volumes!

MICE

Marenostrum Institut de Ciències de l'Espai Simulations

Project to develop very large numerical simulations in cosmology using the **Marenostrum** supercomputer (Barcelona)

- 10.000 processors, 20 TB RAM , 100 Teraflops

- GADGET N-body simulations with 10^9-10^{10} dark-matter particles in volumes 1-500 Gpc^3
  - ***dynamical range of 5 orders of magnitude***

- Terabytes of simulated data stored at Port d'Informació Cientifica
  (LHC data storage center @ Barcelona)

➢Team: (core@ICE): P.Fosalba, F.Castander,E.Gaztañaga
Collaborators: V.Springel (MPA), C.Baugh (Durham), M.Manera (NYU), M.Crocce, A.Gonzalez, A.Cabré,

project web: www.ice.cat/mice

MICE

Marenostrum Institut de Ciències de l'Espai Simulations

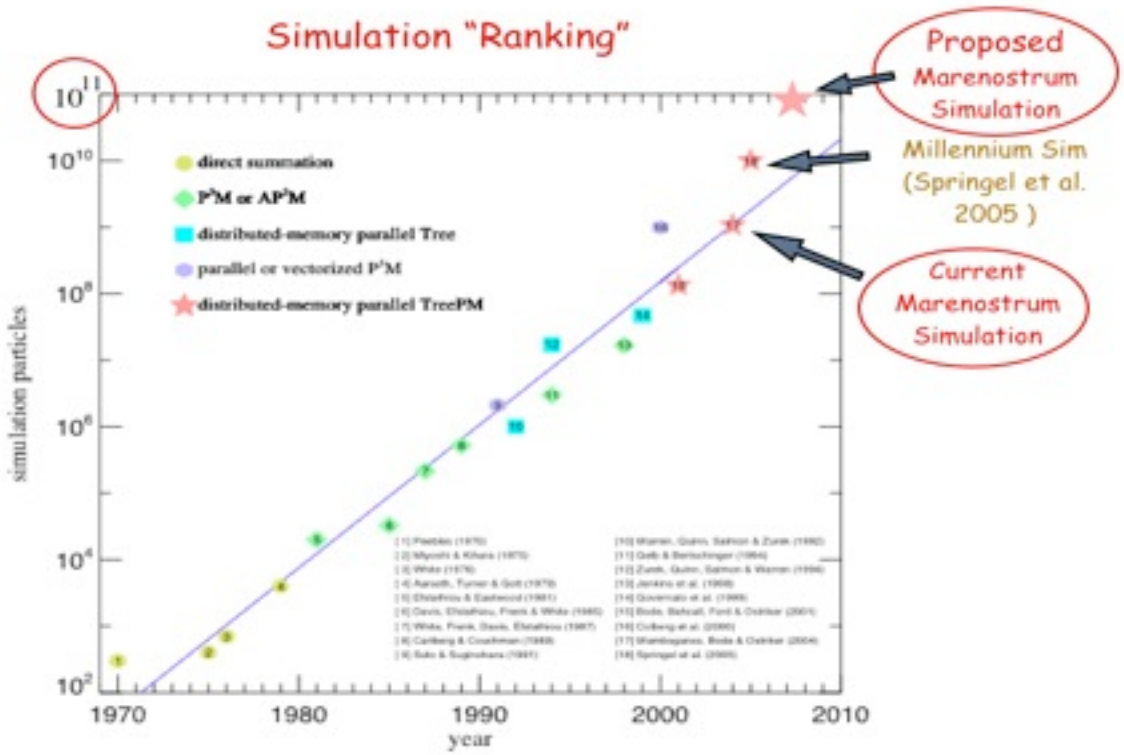
Where do we stand ?

N	Box	Mass
1024^3	1500 Mpc	$2.4\ 10^{11}\ M_{sun}$
1024^3	3000 Mpc	$1.9\ 10^{12}\ M_{sun}$
2048^3	3000 Mpc	$2.4\ 10^{11}\ M_{sun}$
2048^3	7700 Mpc	$3.7\ 10^{12}\ M_{sun}$
4096^3	***3000 Mpc***	***$3.0\ 10^{10}\ M_{sun}$***

runing….

Millennium Simulation:

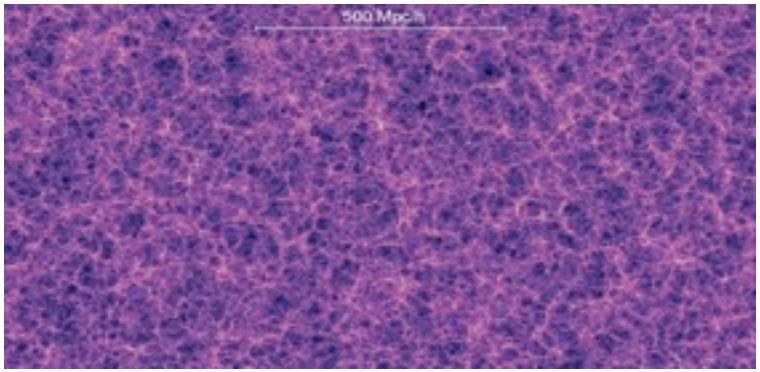
2160^3 500 Mpc $9\ 10^8\ M_{sun}$



Volume MICE ~ 200x Millennium

Resotucion MICE ~ 64x Hubble Vol

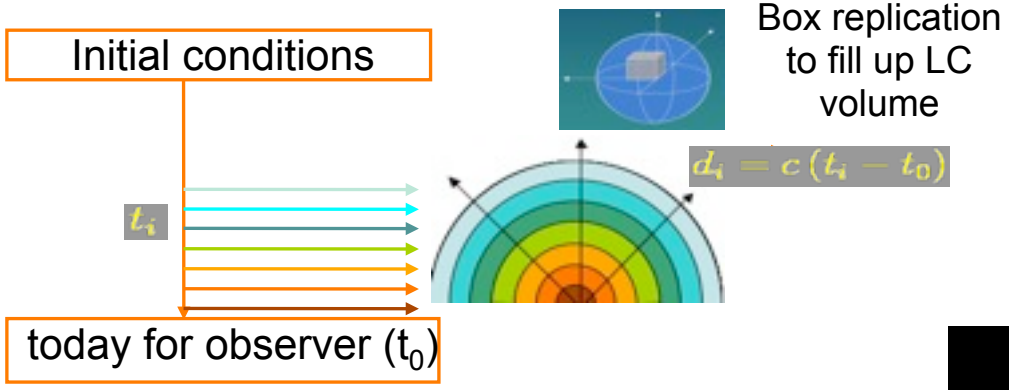
➡ *BAO scale to 1% accuracy*



Millennium (Springel et al 2006)

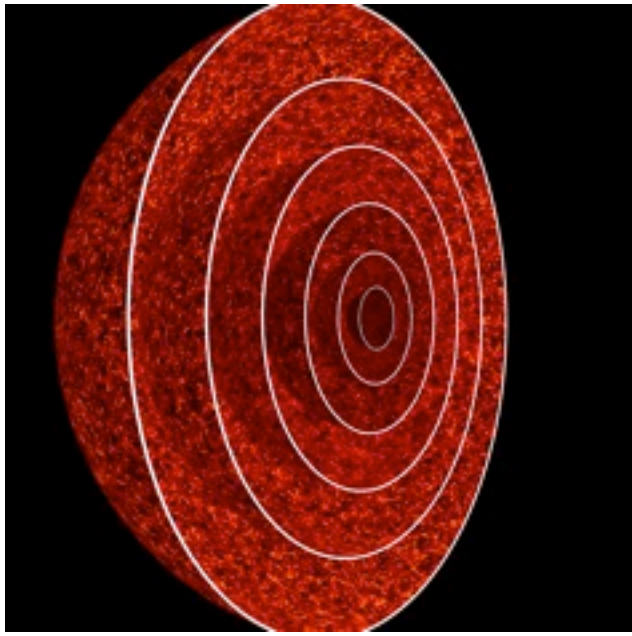
Modeling photo-z galaxy surveys

Construction of lightcone "on-the-fly" from n-body simulations



lightcone discretization in angular maps ("**onion shells**") mimics loss of information in photo-z galaxy surveys

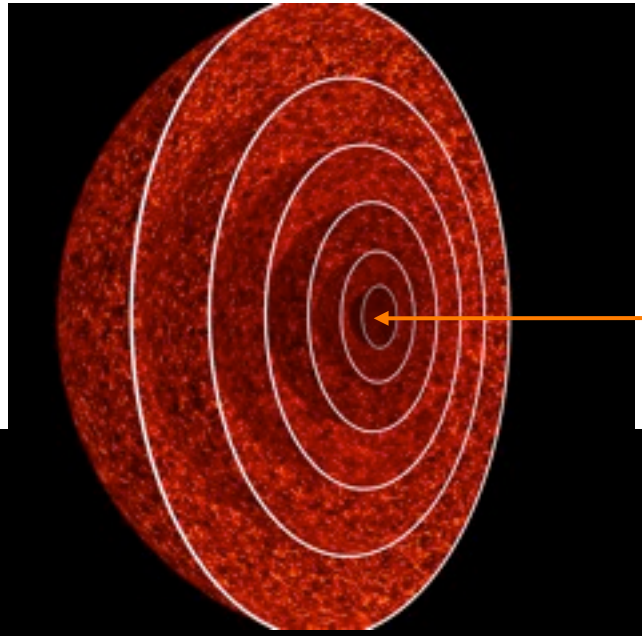
- data compression factor ~ 1000 (from TB to GB)



(P.Fosalba et al, arXiv:0711.1540)

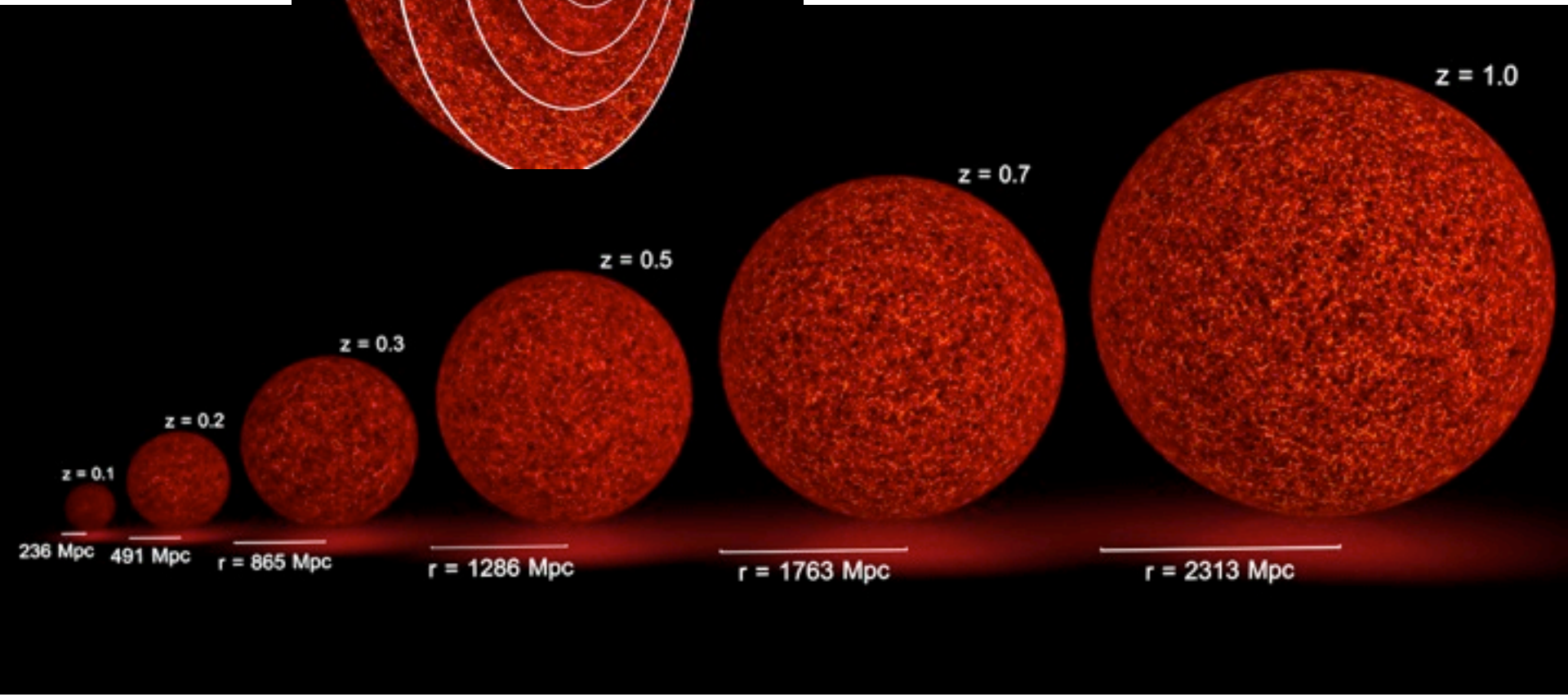
MICE

Marenostrum Institut de Ciències de l'Espai Simulations



"Onion shells"

observer



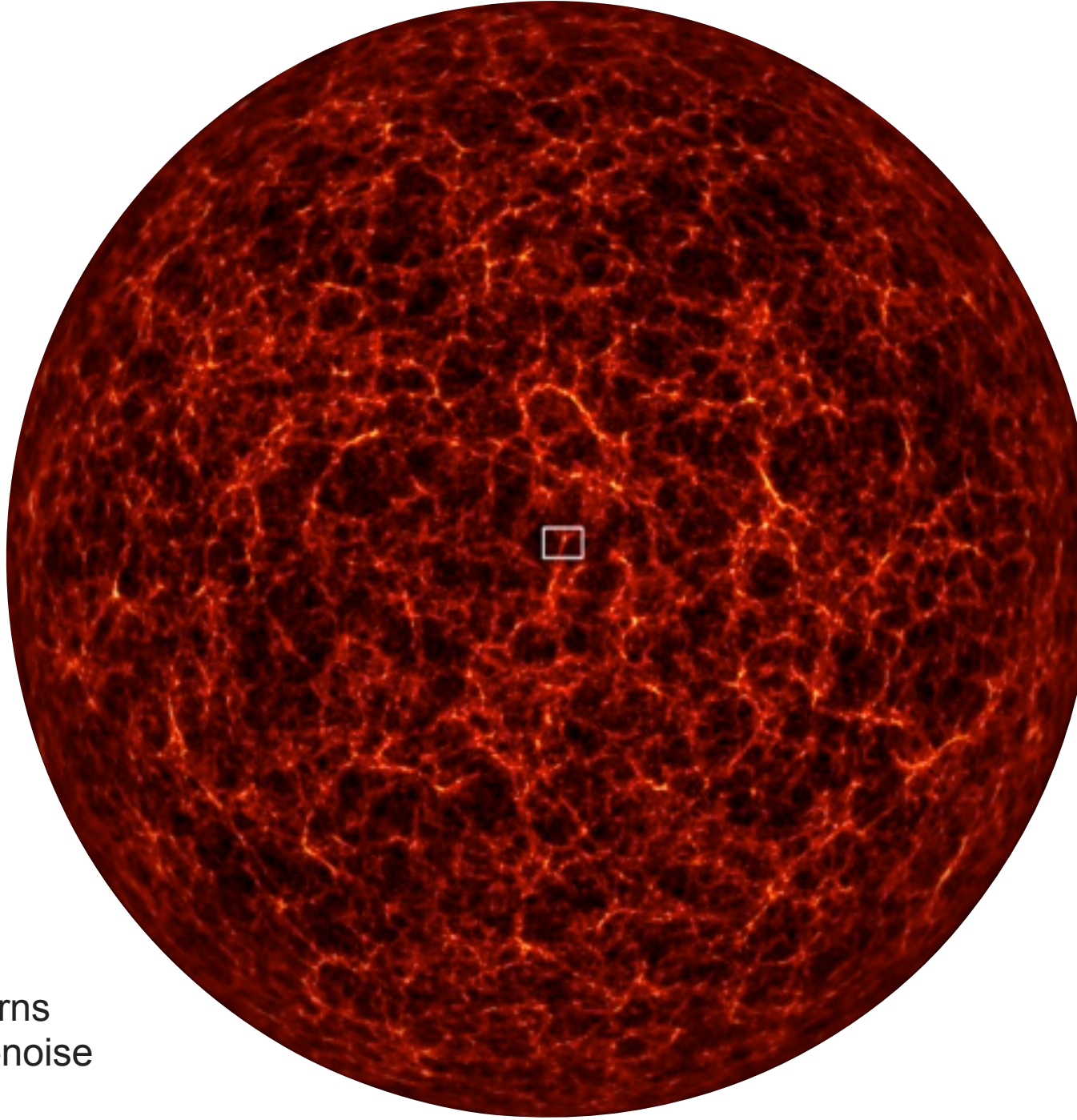
(P.Fosalba et al, arXiv:0711.1540)

DM snapshots

MICE

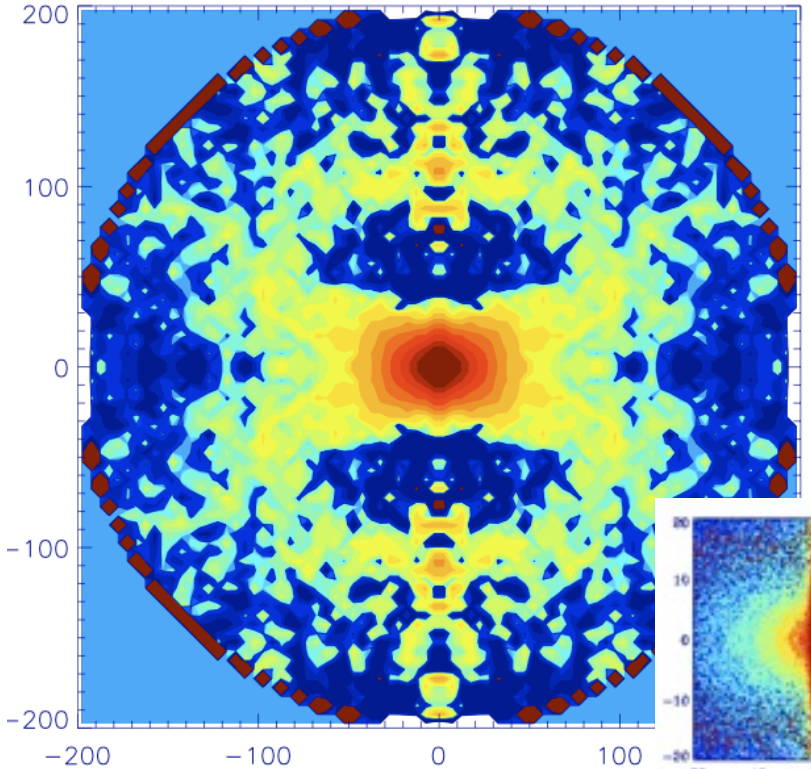
Marenostrum Institut de Ciències de l'Espai Simulations

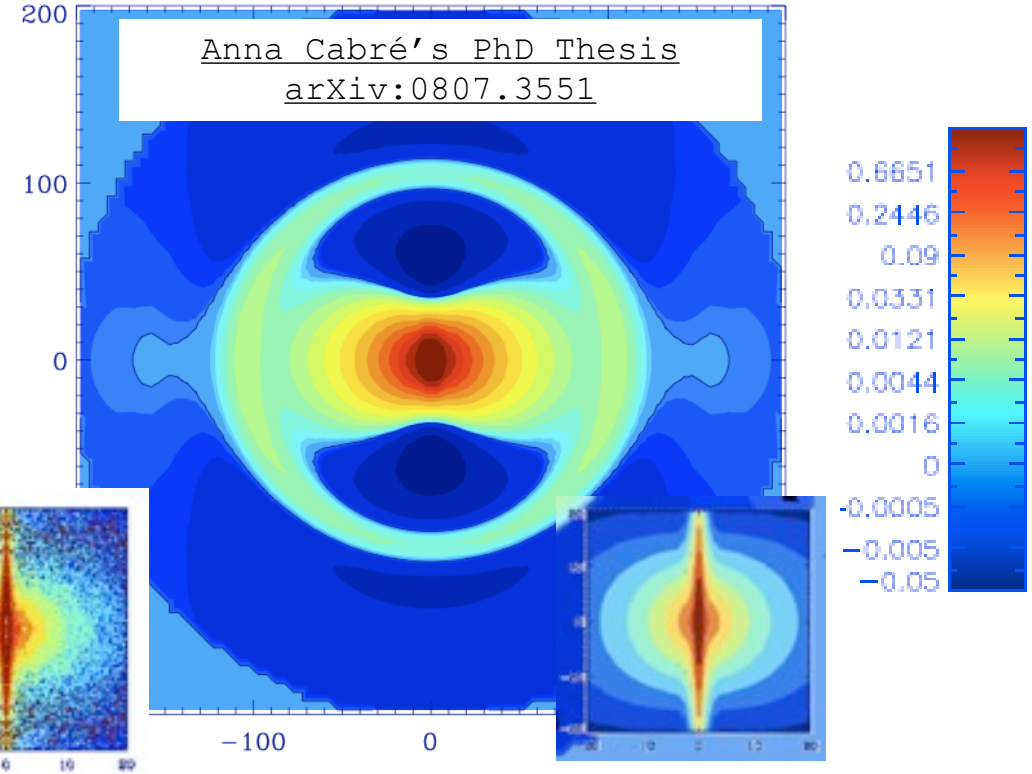
All-sky

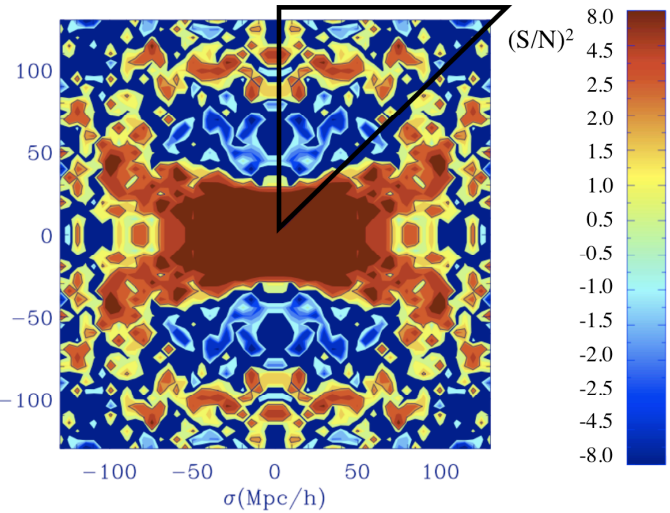


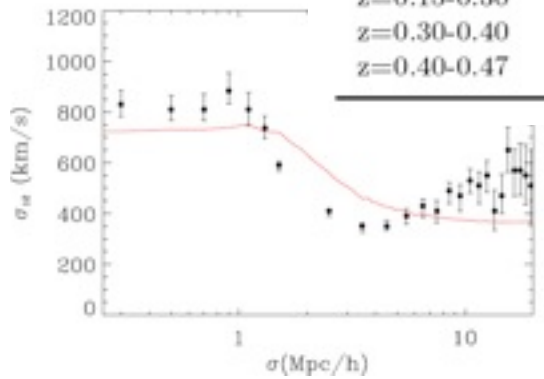
Use DM and halos as mock LRG galaxies. Turns out that errors are shot-noise dominated!

Anna Cabré's PhD Thesis
arXiv:0807.3551



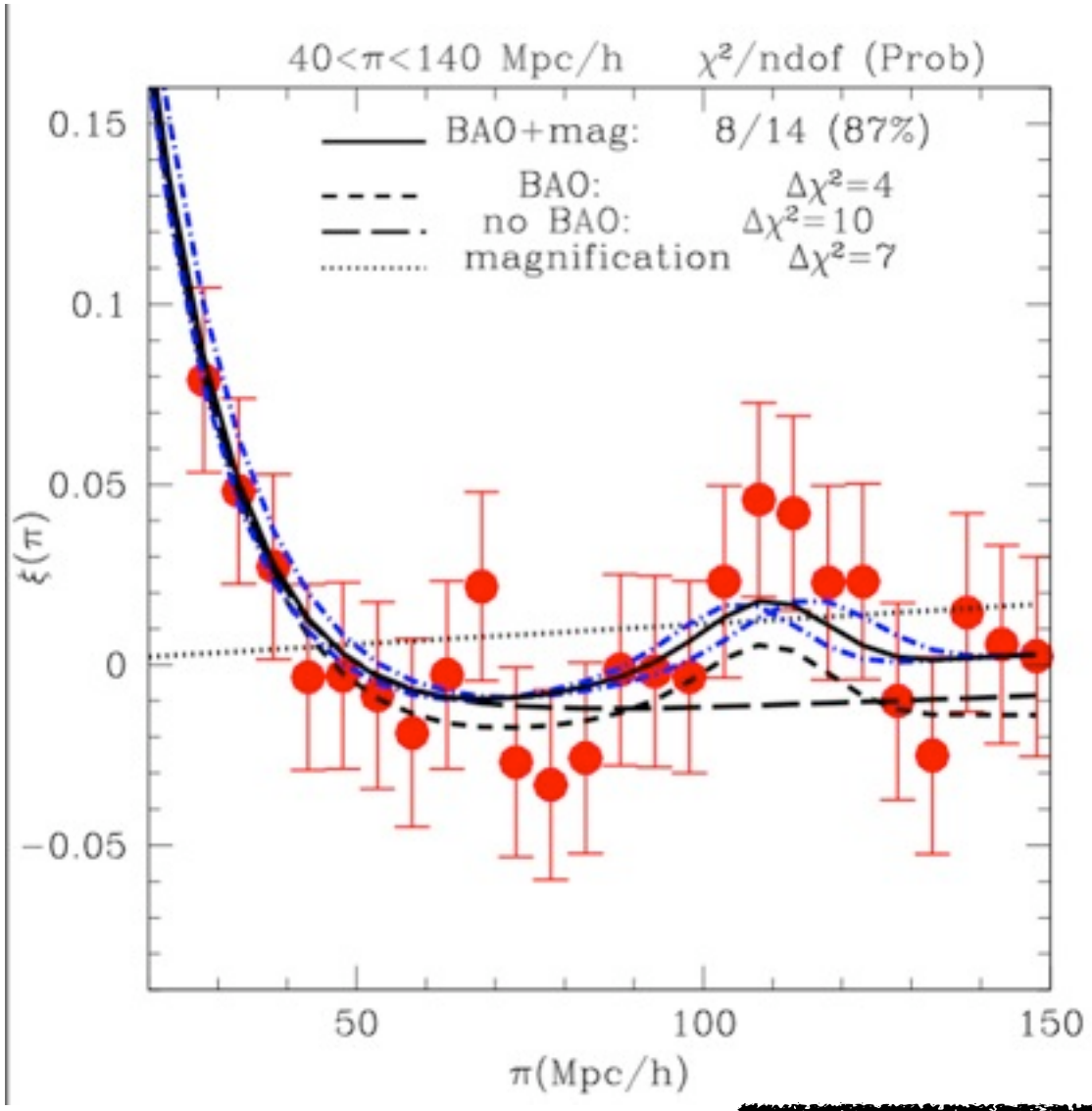


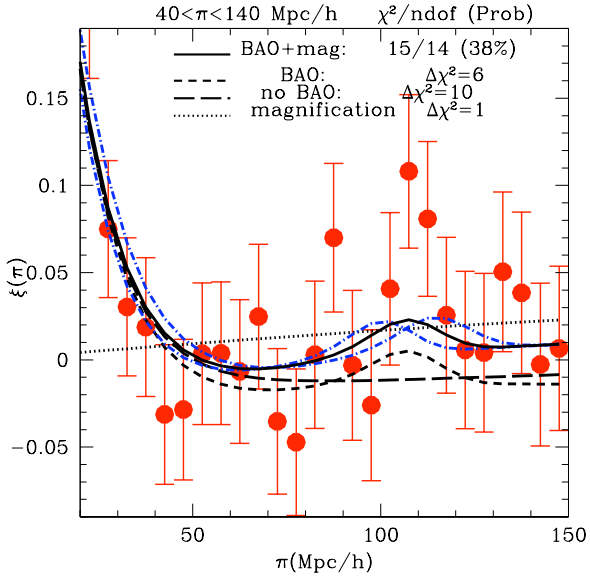




Sample	$Amp = b\sigma_8$	Ω_m	b	$f(\Omega_m)$
z=0.15-0.47	1.47-1.65	0.225-0.265	1.73-1.94	0.54-0.73
z=0.15-0.34	1.45-1.62	0.230-0.275	1.71-1.91	0.48-0.70
z=0.34-0.47	1.55-1.82	0.215-0.285	1.82-2.14	0.56-0.87
z=0.15-0.30	1.45-1.80	0.240-0.320	1.71-2.11	0.48-0.83
z=0.30-0.40	1.42-1.60	0.210-0.260	1.67-1.88	0.48-0.69
z=0.40-0.47	1.60-2.00	0.195-0.305	1.88-2.35	0.51-0.98

Radial BAO: shape method





Gaussian priors:

Ω_B = 0.044± 0.003 (WMAP5)

Ω_m = 0.245± 0.020 (paper-I)

β = 0.34± 0.03 (paper-I)

$b^*\sigma_8$ = 1.56 ± 0.09 (paper-I)

Flat Priors:

A = 2 ± 3 (lensing mag.)

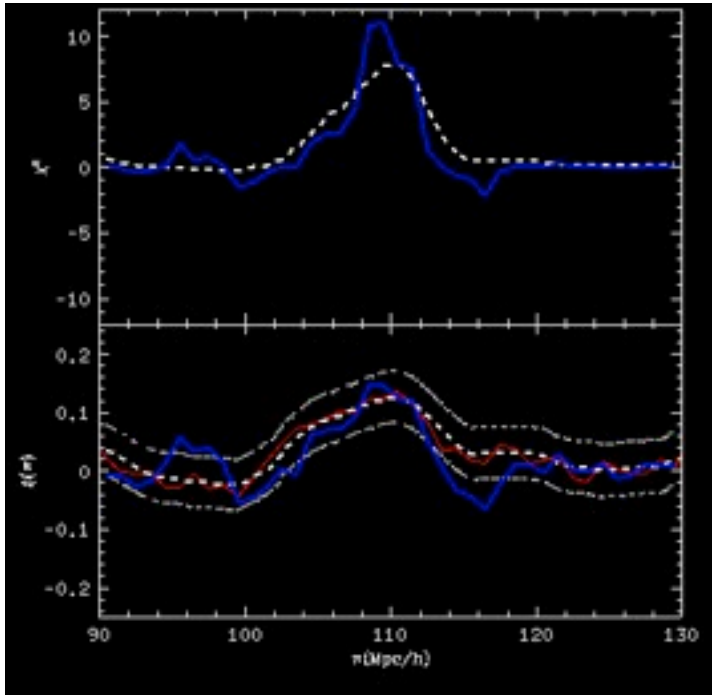
h=0.72, n=0.96, σ_8 =0.85

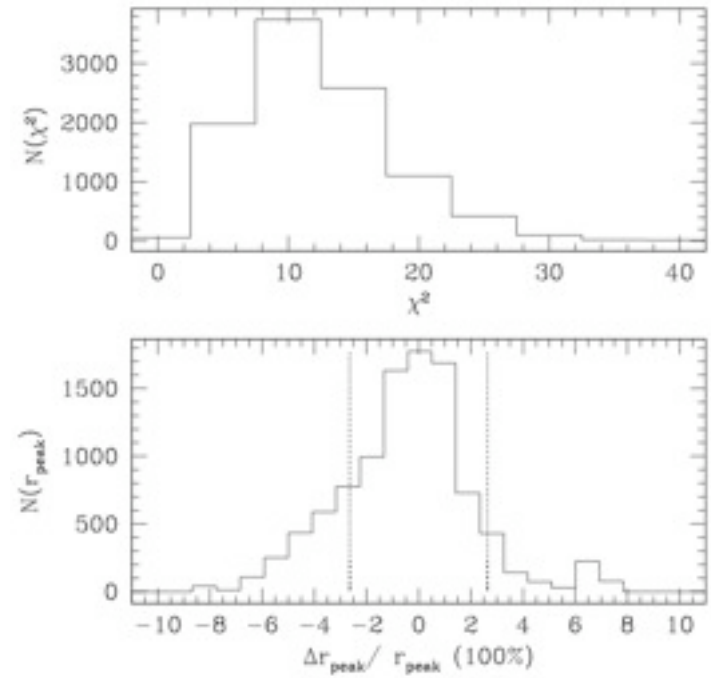
$$D_r = 0.998 \pm 0.037 \quad (1\sigma)$$

Does not need a standard ruler

$H(z=0.34) = 83.9 \pm 3.1\ (\pm\ 0.8)$ Km/s (h/0.72)

Radial BAO: peak method



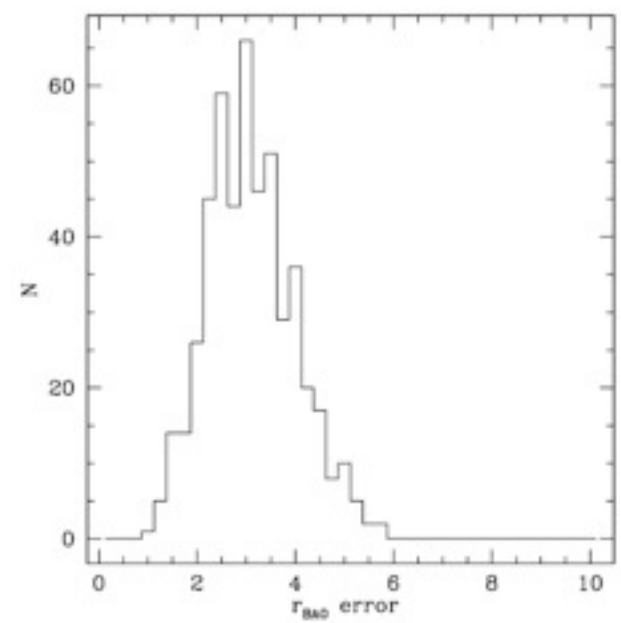


1) find peak from maximum in S/N (chi2 from S=0)
2) find error from distribution of 10,000 montecarlo simulations:
   2a) based model: 5Mpc/h top hat smoothed data
   2b) add 10,000 noise realizations and find peak as in 1)
3) systematic error: add noise to base model 2a) & repeat 2) 500 times
4) find H(z) from WMAP5 rBAO ruler

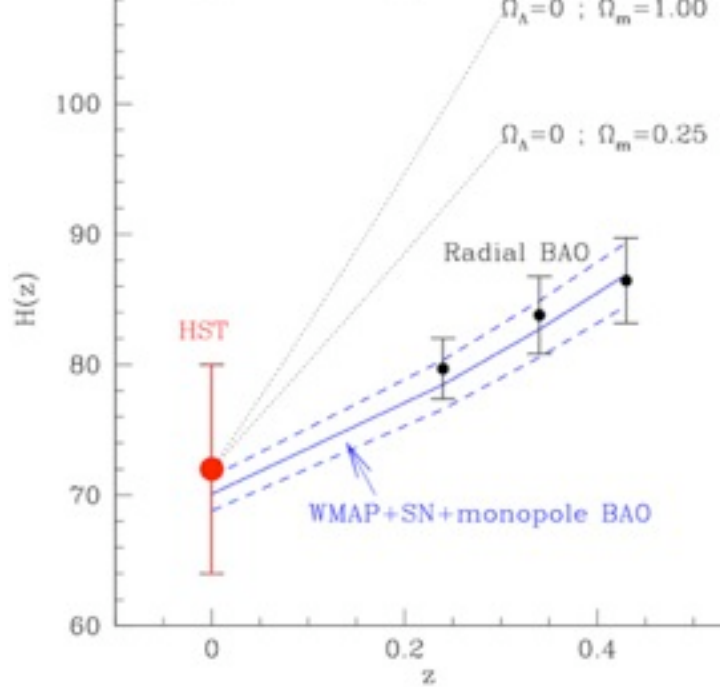
r_{BAO}= 154.3±2.0 Mpc, (WMAP5, Komatsu etal 2008)

$$H(z) = \frac{c\Delta z_{BAO}}{r_{BAO}}$$

H(*z=0.24*)= 79.7 ± 2.3 (± 1.3)
H(*z=0.34*)= 83.8 ± 3.0 (± 1.6)
H(*z=0.43*)= 86.5 ± 3.3 (± 1.7)



Summary Radial BAO



Radial correlation matches well model:

3.2 σ detection of BAO, 2 σ dection of lensing

Measurements of H(z) with 2 methods:

- Shape in 40-140 Mpc/h range (marginalized):
  - H(z=0.34)= 83.87 ± 3.10 (± 0.84) Km/s/Mpc (h/0.72)
- Peak location between 100-120 Mpc/h (+BAO-WMAP5):
  - H(z=0.24)= 79.69 ± 2.32 (± 1.29) km/s/Mpc
  - H(z=0.34)= 83.80 ± 2.96 (± 1.59) Km/s/Mpc (not independent)
  - H(z=0.43)= 86.45 ± 3.27 (± 1.69) Km/s/Mpc

Data Set	Ω_m	$\sigma(\Omega_m)$	Ω_k	$\sigma(\Omega_k)$	w	$\sigma(w)$
RBAO + WMAP5 + SNe [16]	0.249	$^{+0.013}_{-0.012}$	0.0062	$^{+0.0058}_{-0.0057}$	-0.930	$^{+0.053}_{-0.054}$

arXiv:0808.1921

How much can this be improved?

Comparison of BAO Surveys

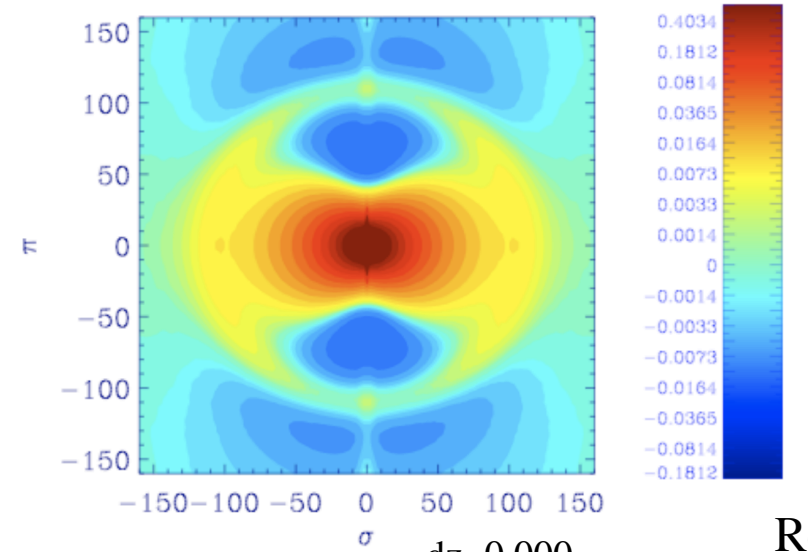
Spectroscopic

Photo-z 40-filter

Photo-z 5-filter

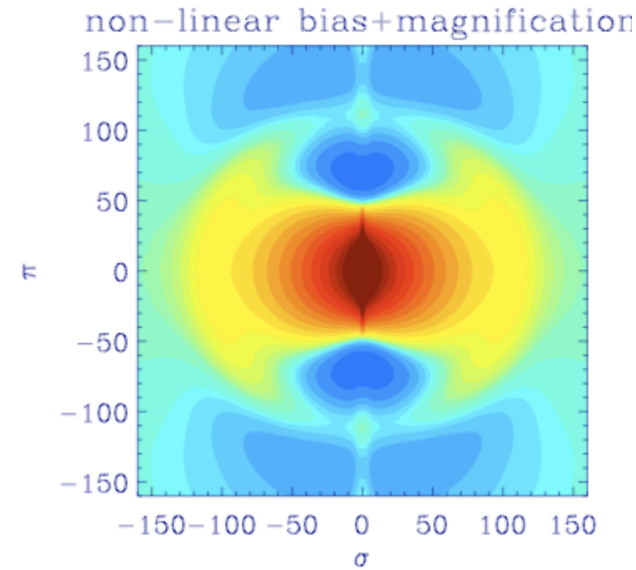
Project	Redshift	Area (deg^2)
WiggleZ	0.4-1.0	1000
HETDEX	2.0-4.0	350
WFMOS	0.5-1.3 2.3-3.3	2000 300
BOSS LRG + QSO	0.1-0.8 2.0-3.0	10000 8000
PAU-BAO	0-1	10000
Pan-STARRS*	0-1?	20000
DES*	0-1.5?	4000
LSST*	0-1.5?	20000

Padmanabhan

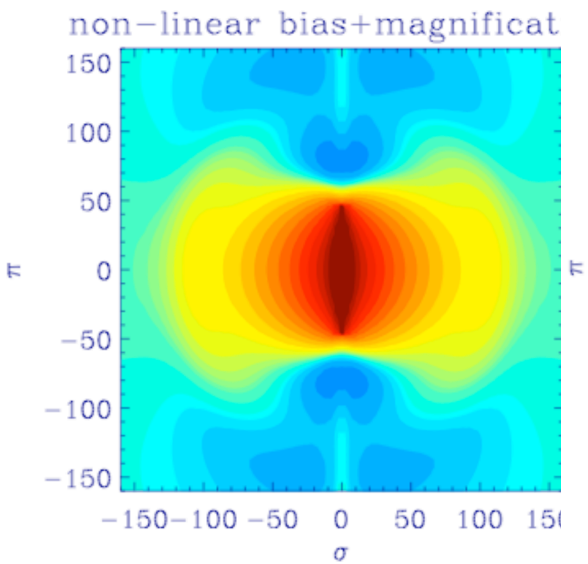


dz=0.000

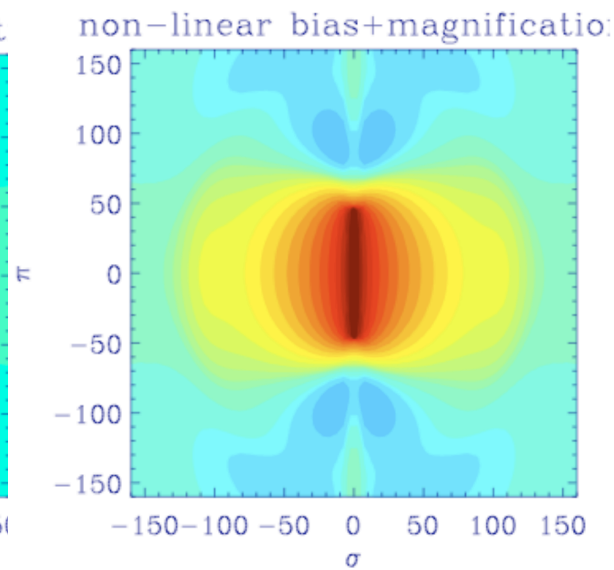
Redshift errors



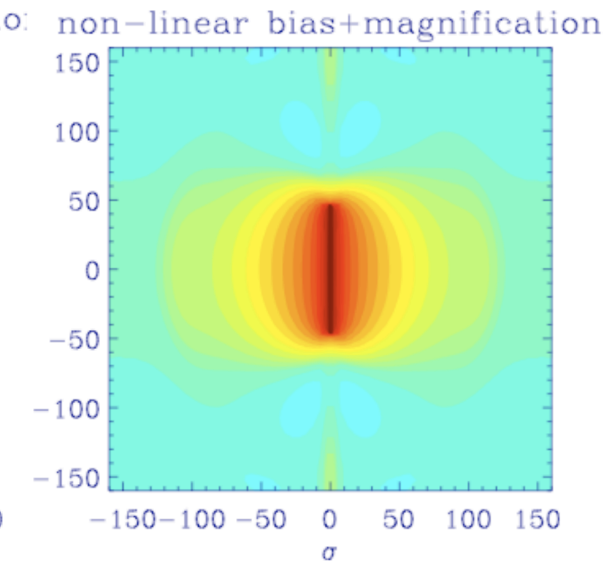
1000Km/s dz=0.003



2,000Km/s dz=0.006



5,000Km/s dz=0.016

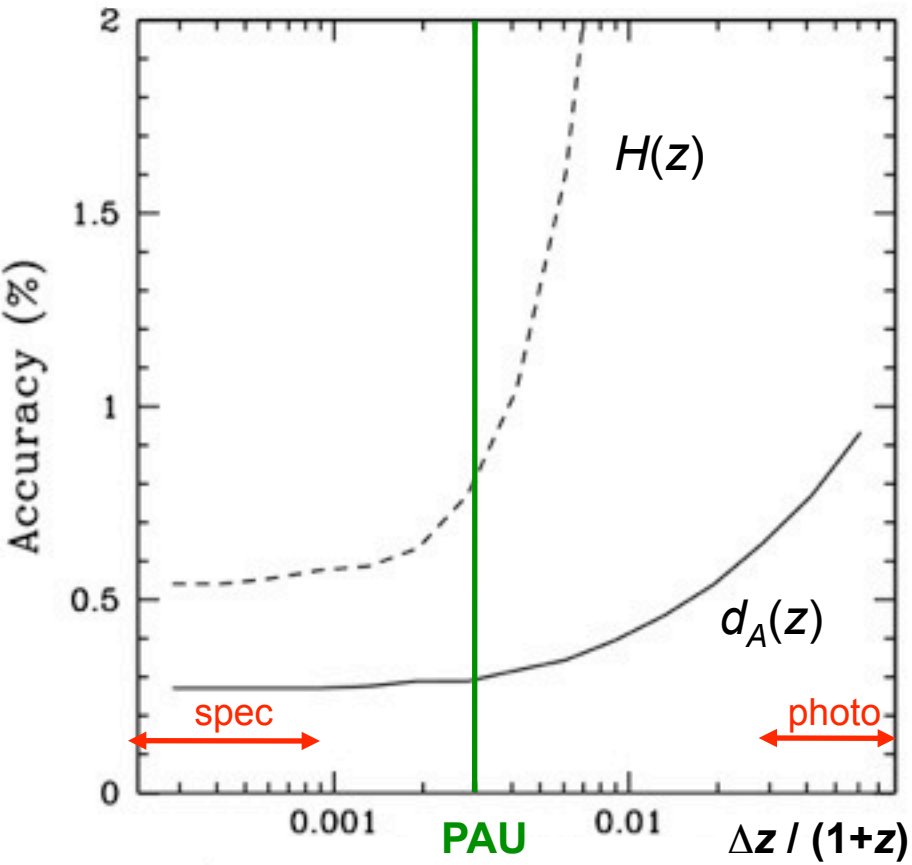


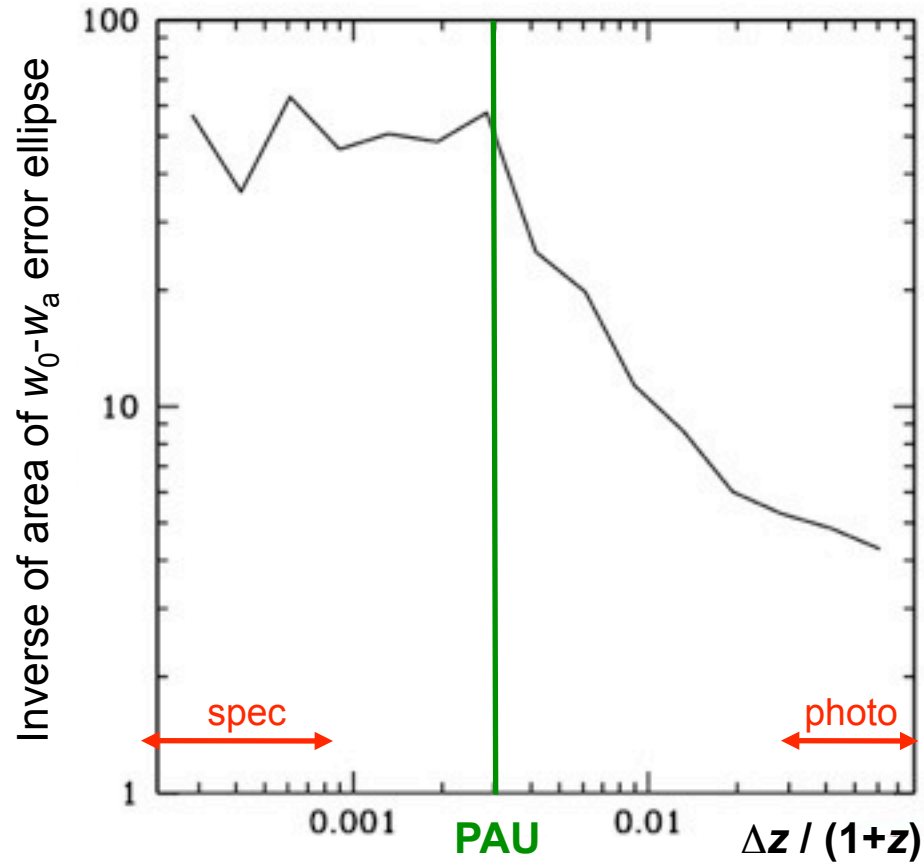
10,000Km/s dz=0.033

Requirements on Redshift Precision

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

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





Padmanabhan

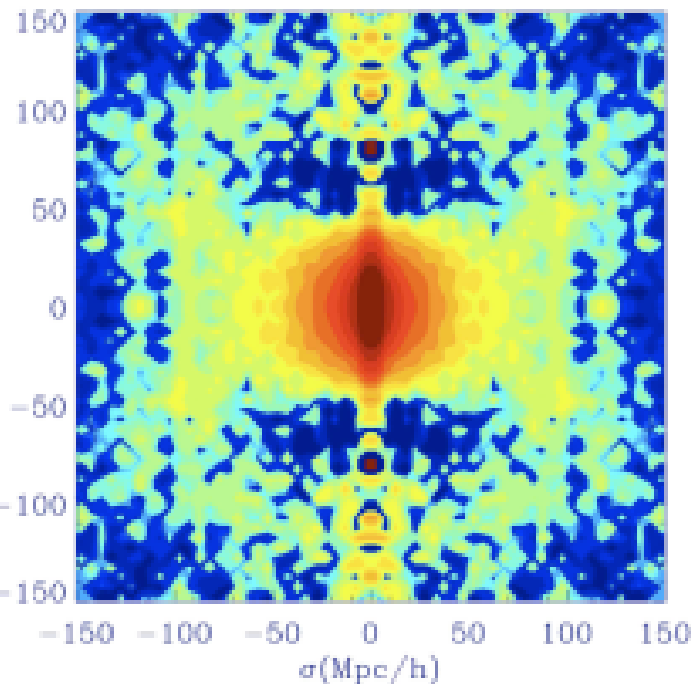
Spectroscopic accuracy is not needed: trade-off with number density

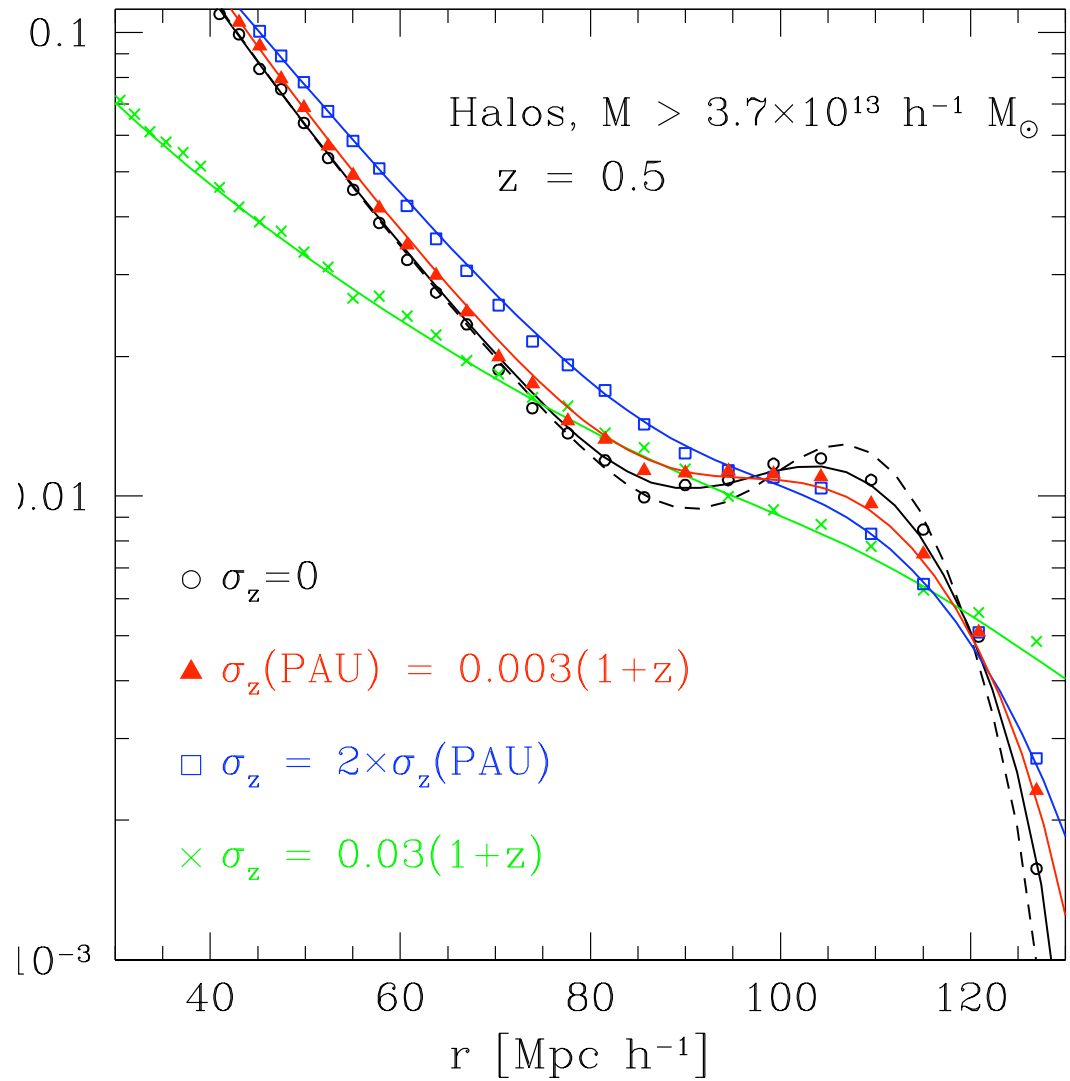
arXiv:0807.0535

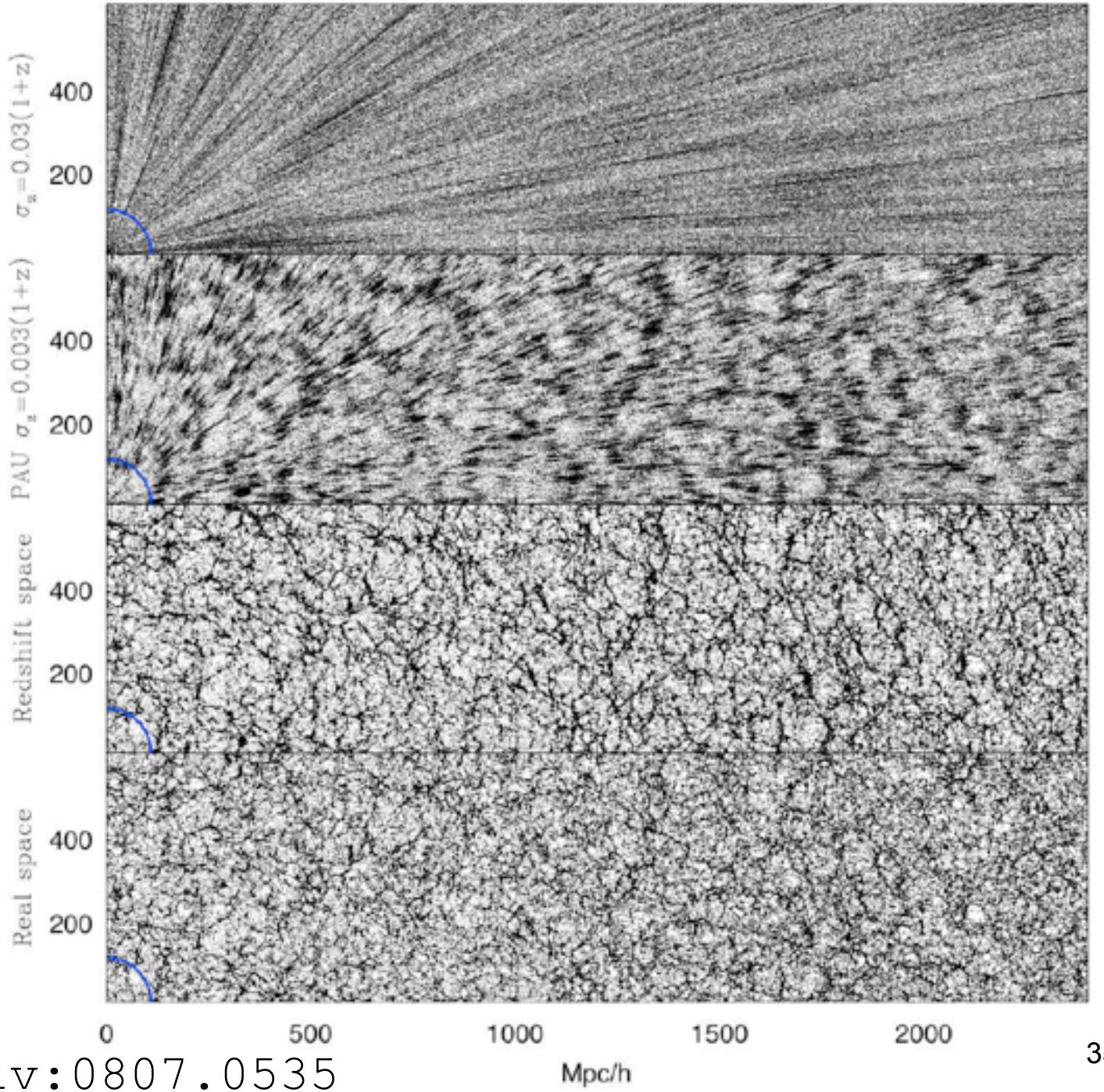
Requirements on Redshift Precision

3D reconstruction of BAO feature

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

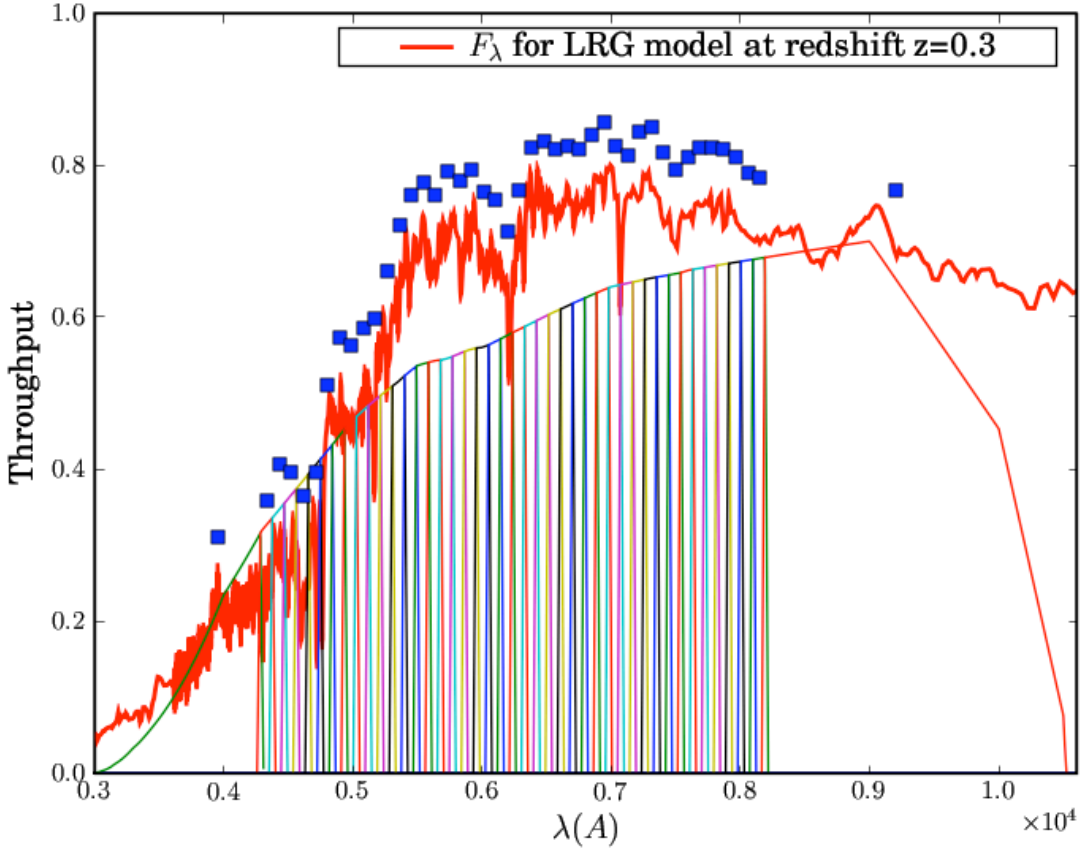




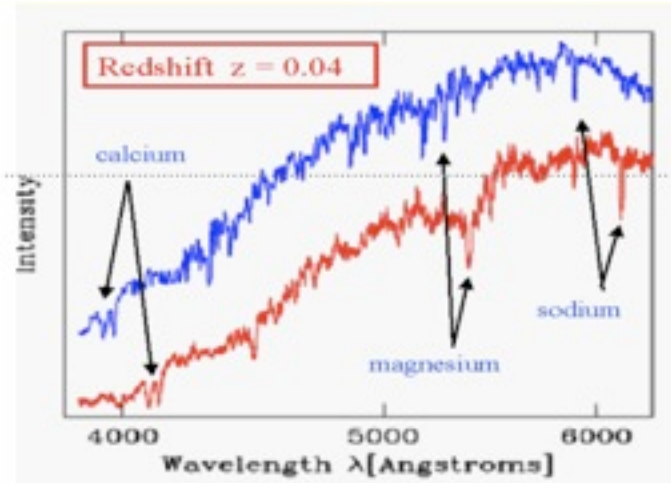


arXiv:0807.0535

Can Many Narrow Filters Do The Trick? PAU Survey

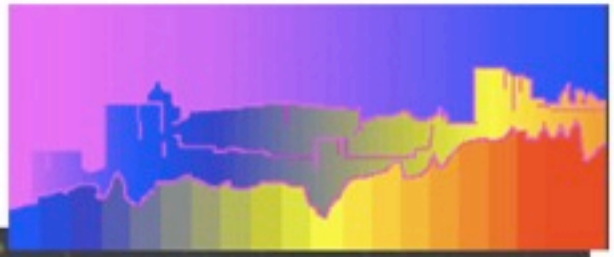


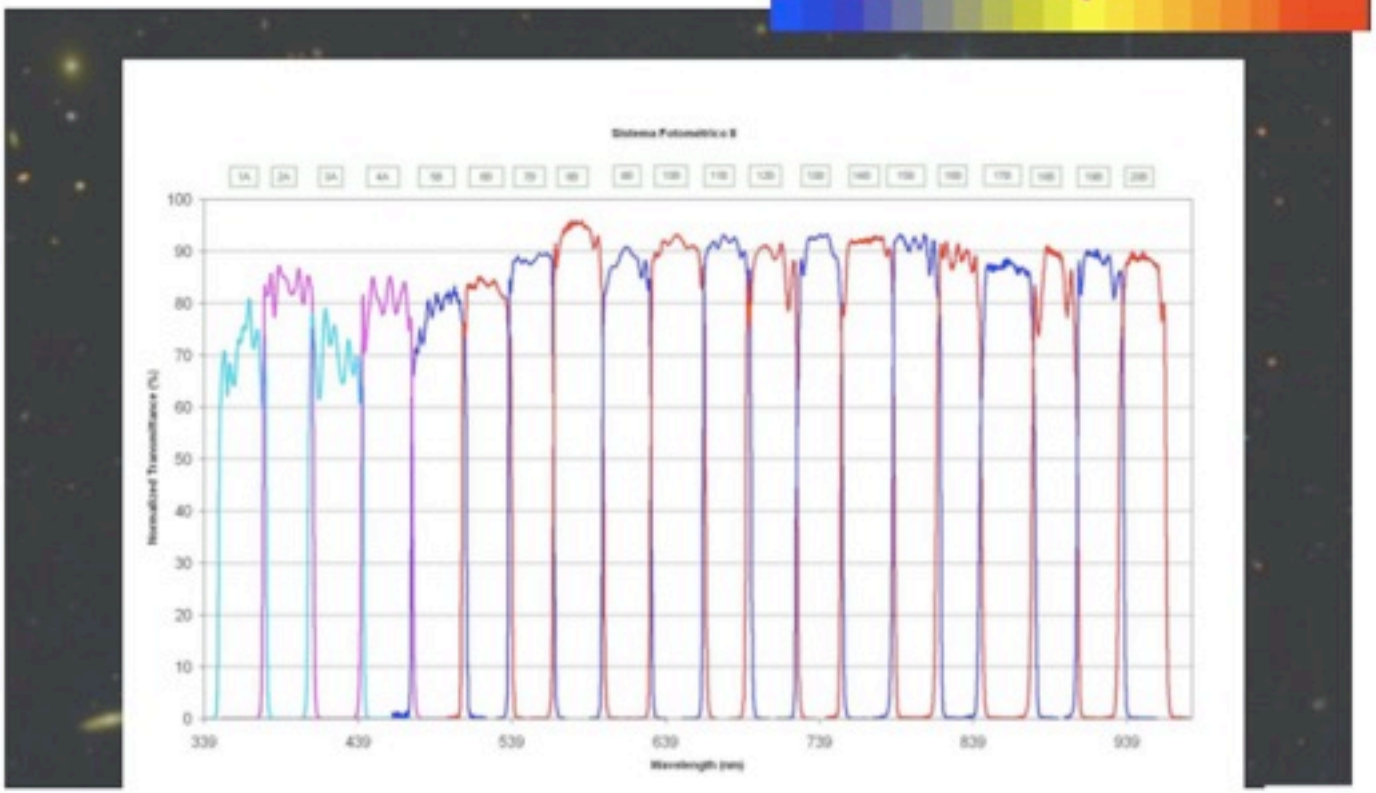
We explore the performance of a photometric system with 40 medium band non-overlaping filters (100A width)similar to that of ALHAMBRA but with more and narrower filters.



ALHAMBRA

Survey at Calar Alto





20 filters

4 sq. deg.

$m_{AB} < 25$

Is this enough?

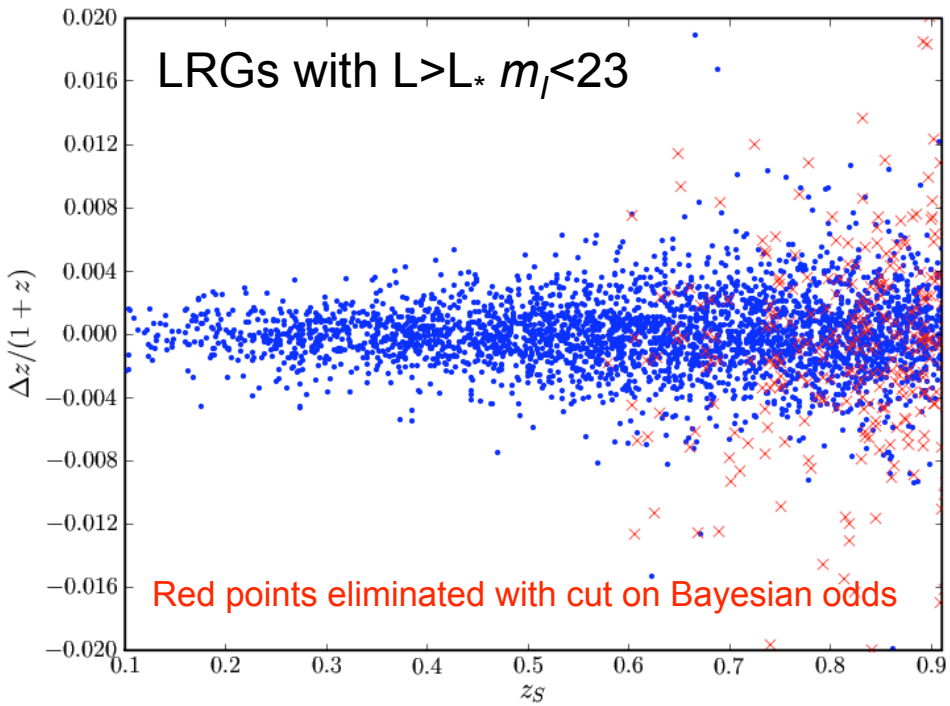
Moles et al., 2008, AJ, 136, 1325
Benítez et al., 2009, ApJL, 692L
Cristóbal-Hornillos et al., 2009, arXiv0902.240

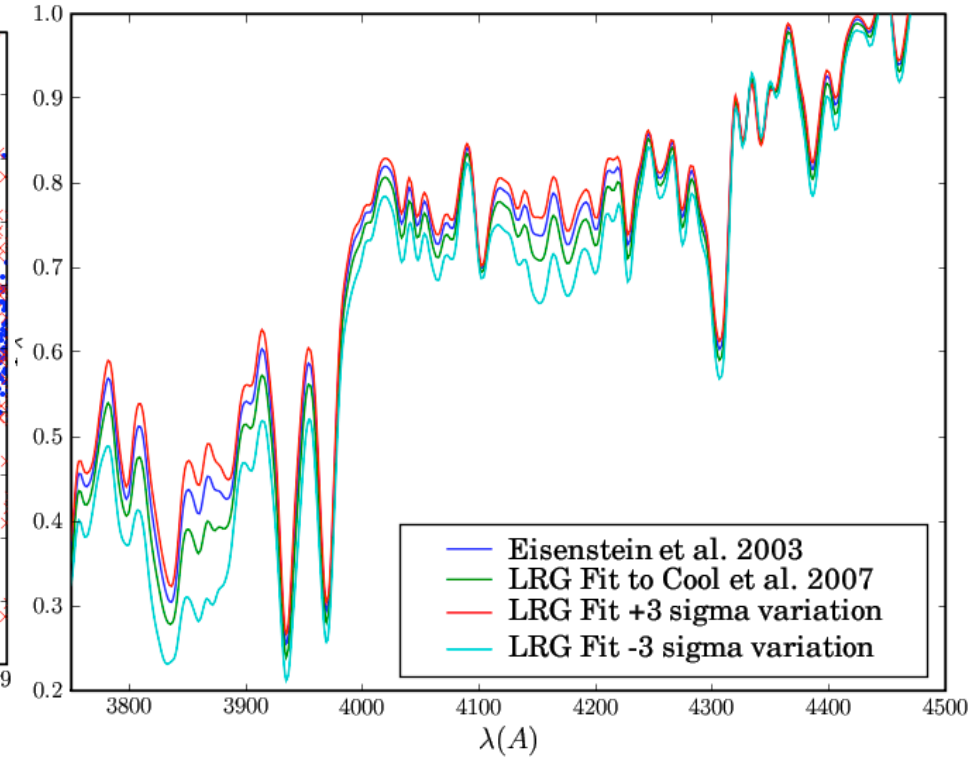
Redshift Determination: PAU forecast simulations

- 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

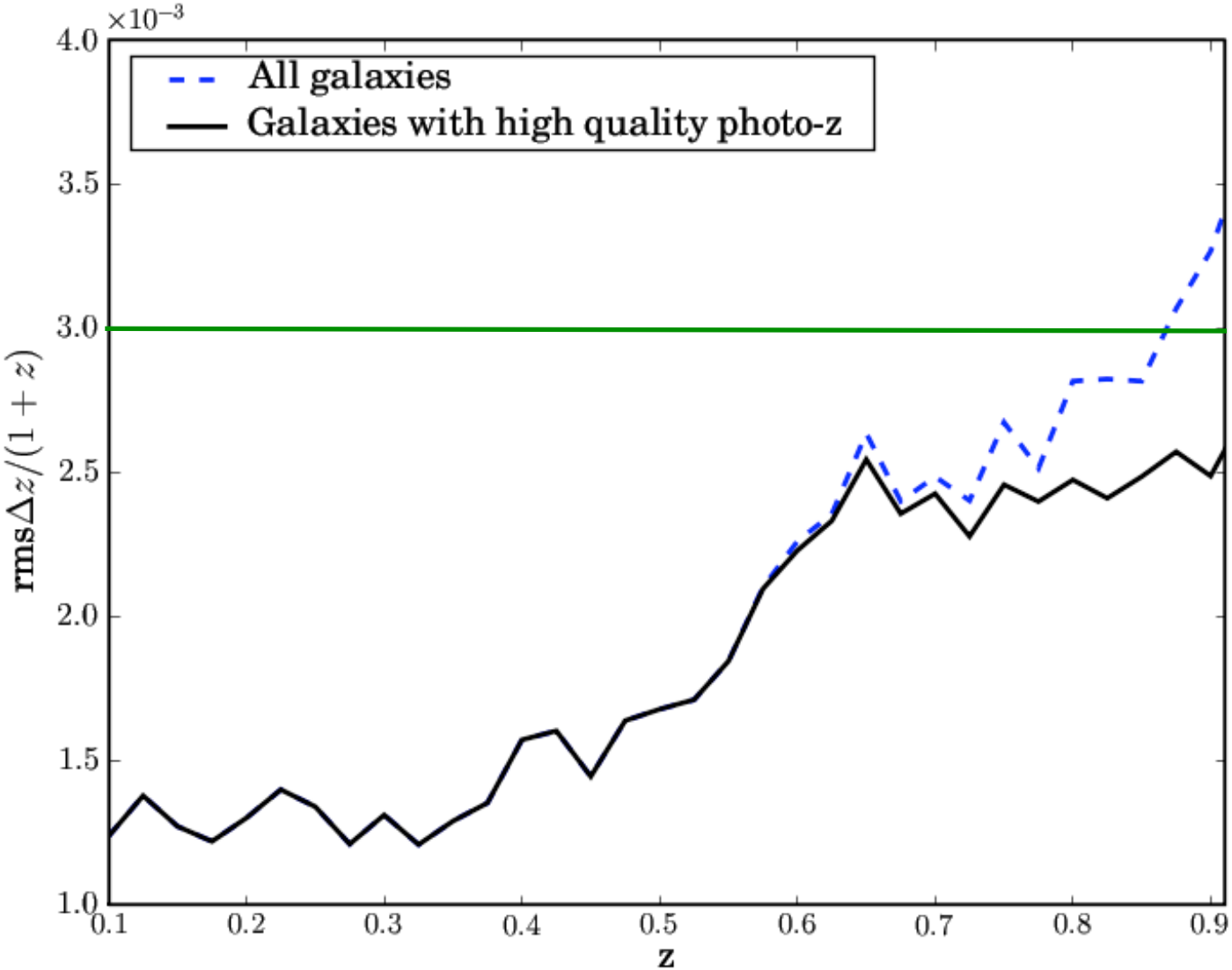
Intrinsic variation: Selection effects

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





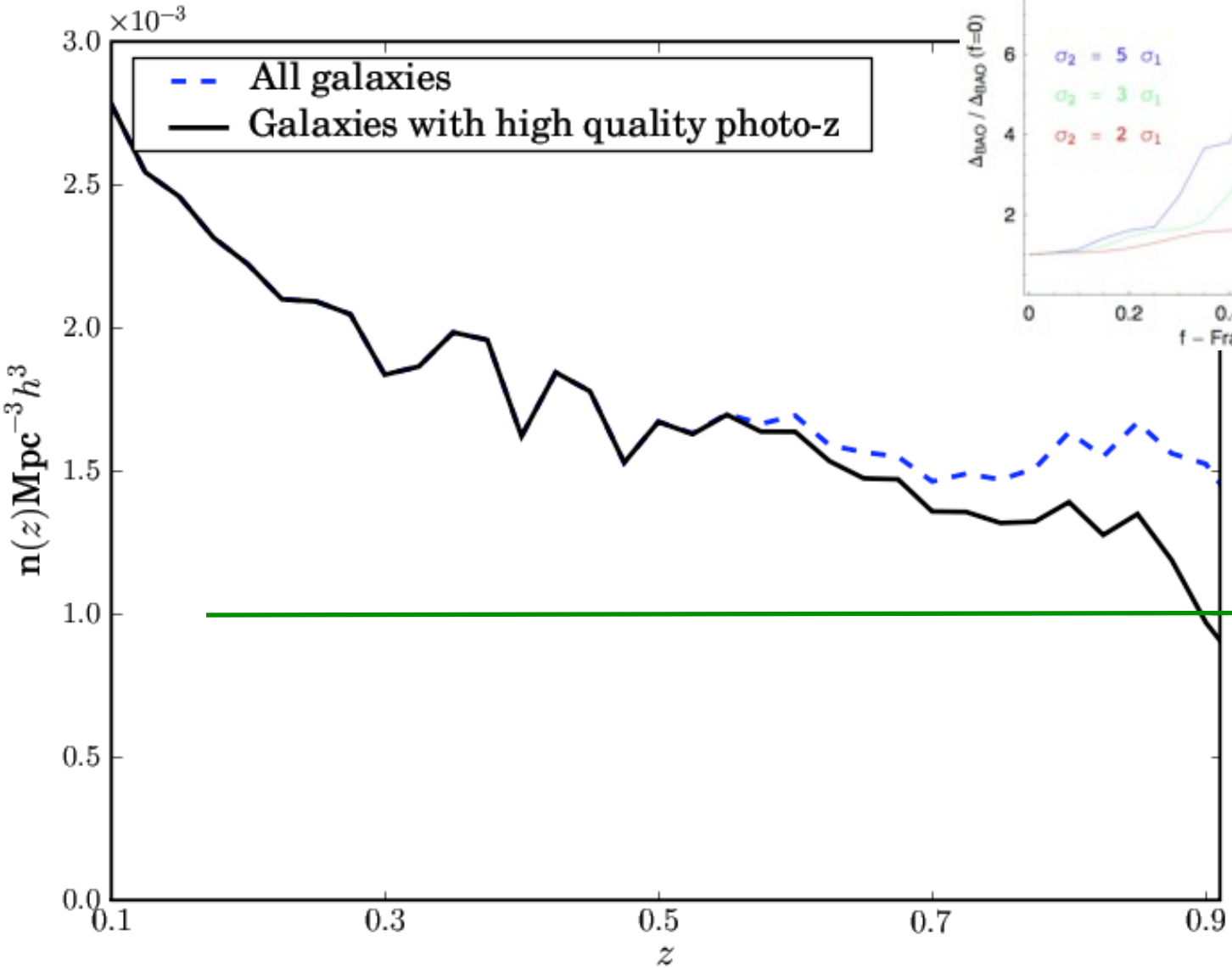
Redshift Resolution

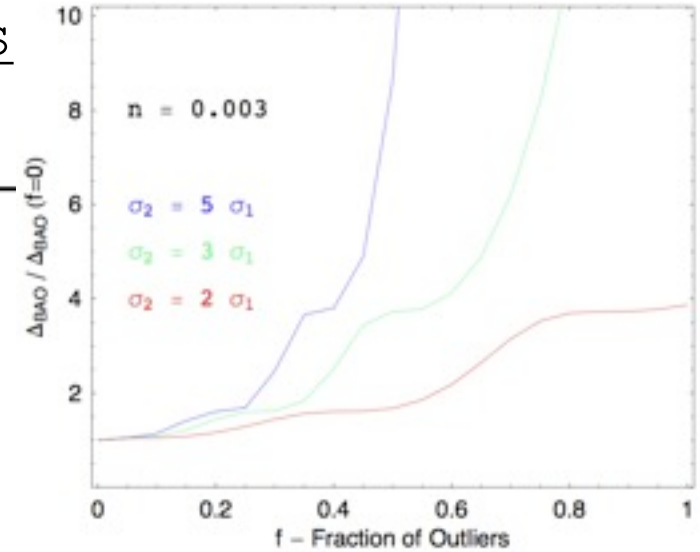


LRGs with L>L$_*$ m_I<23

Galaxy Density

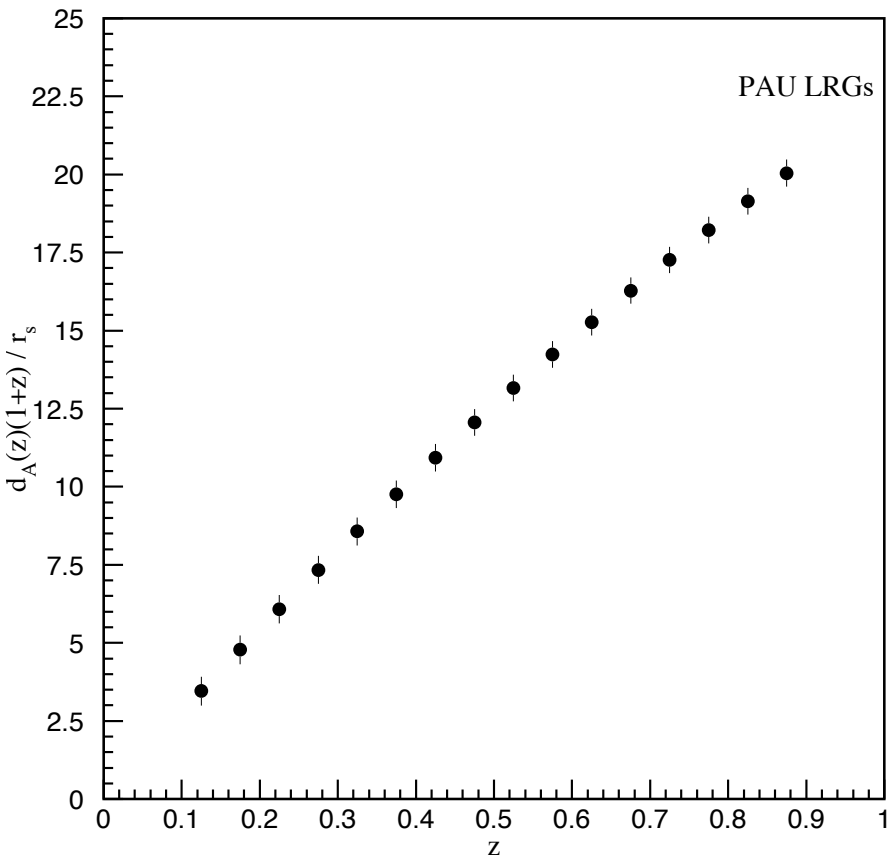
Outliers

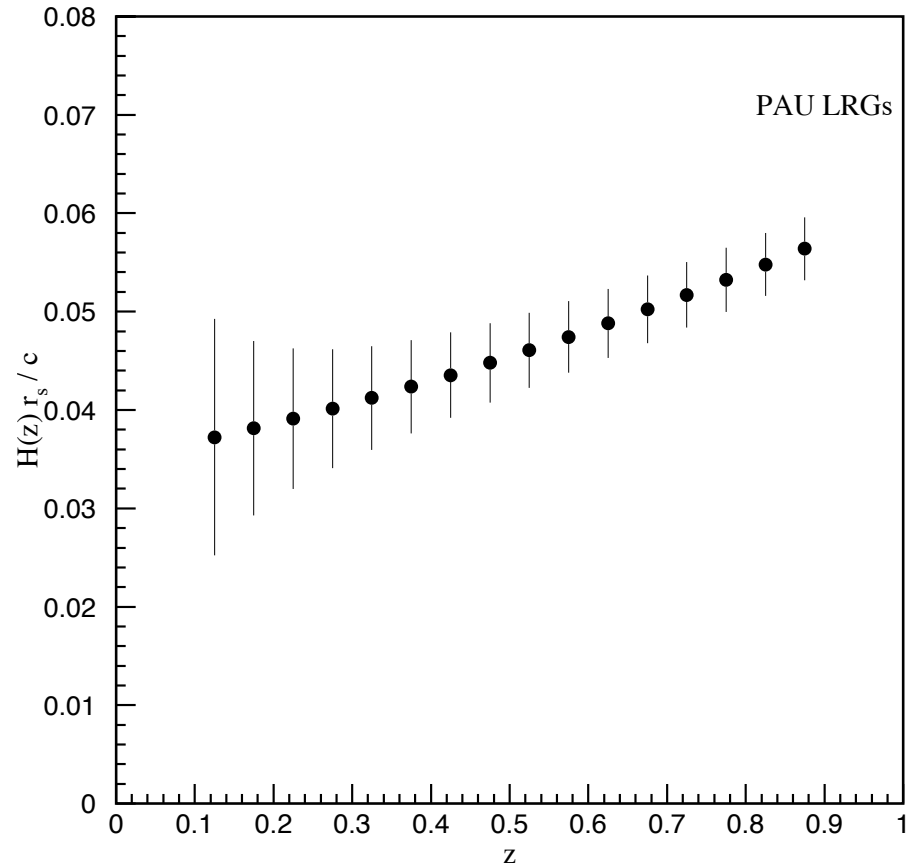




LRGs with L>L$_*$ m_I<23

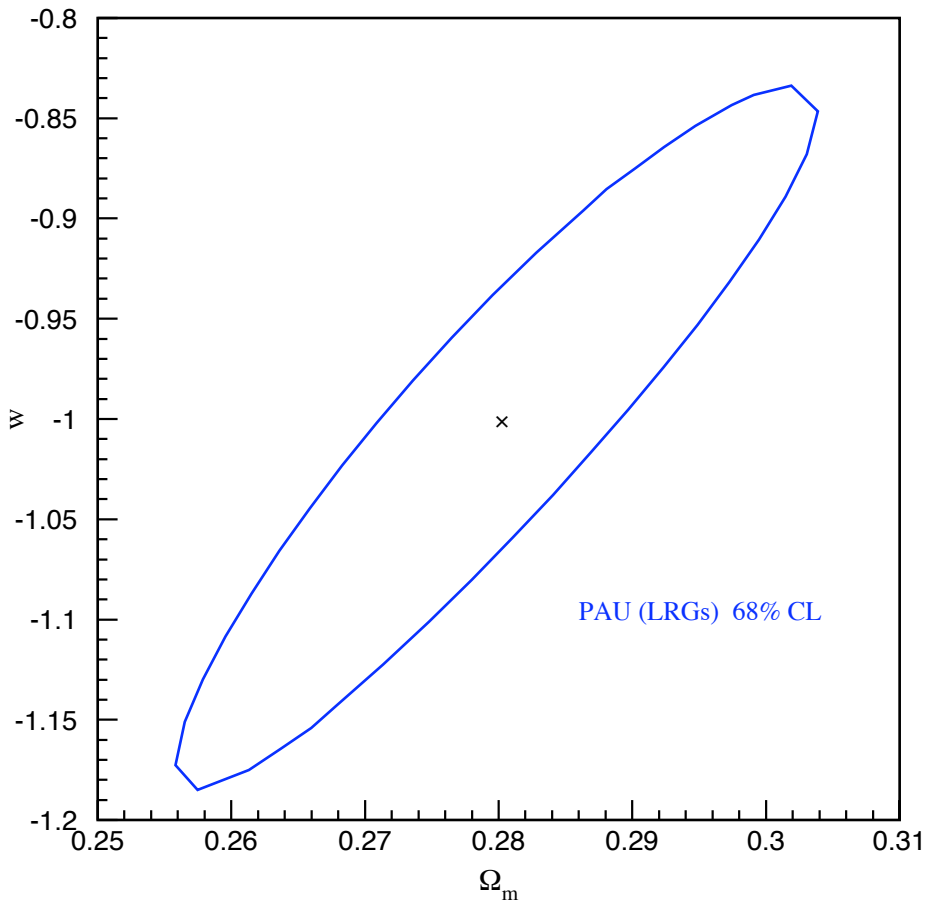
Precision on $d_A(z)$ and $H(z)$

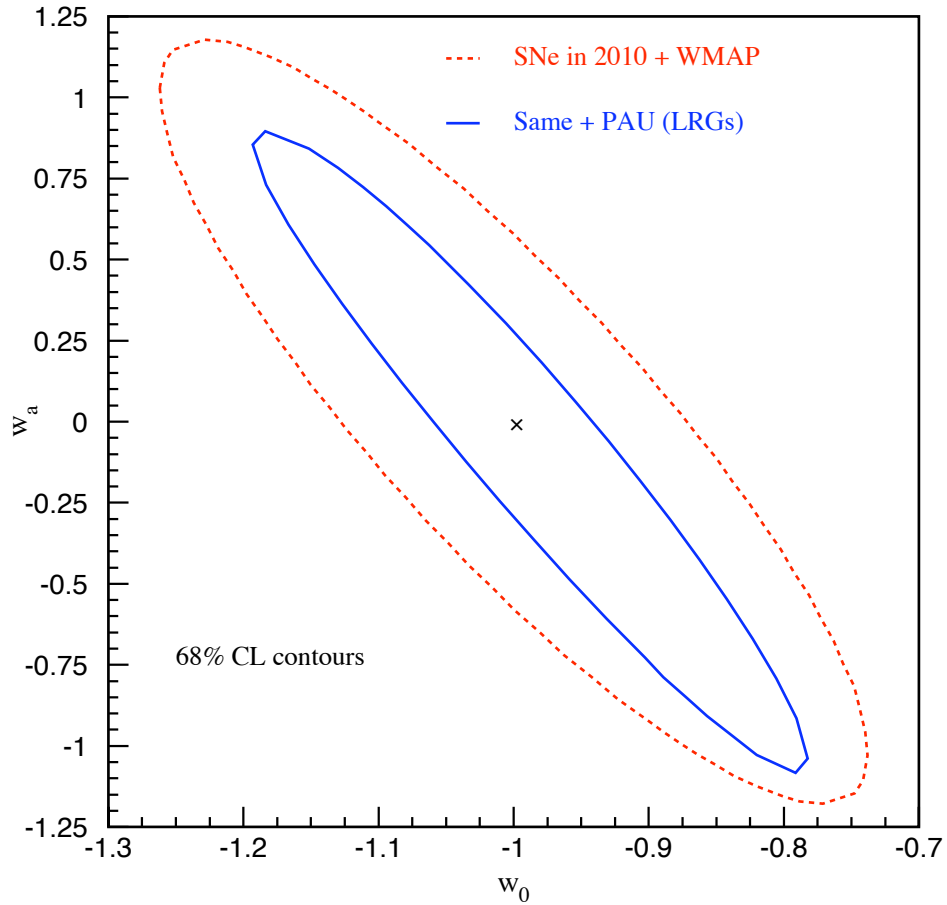




16 bins with precision down to 2% for $d_A(z)$, 5% for $H(z)$

Dark Energy Parameters





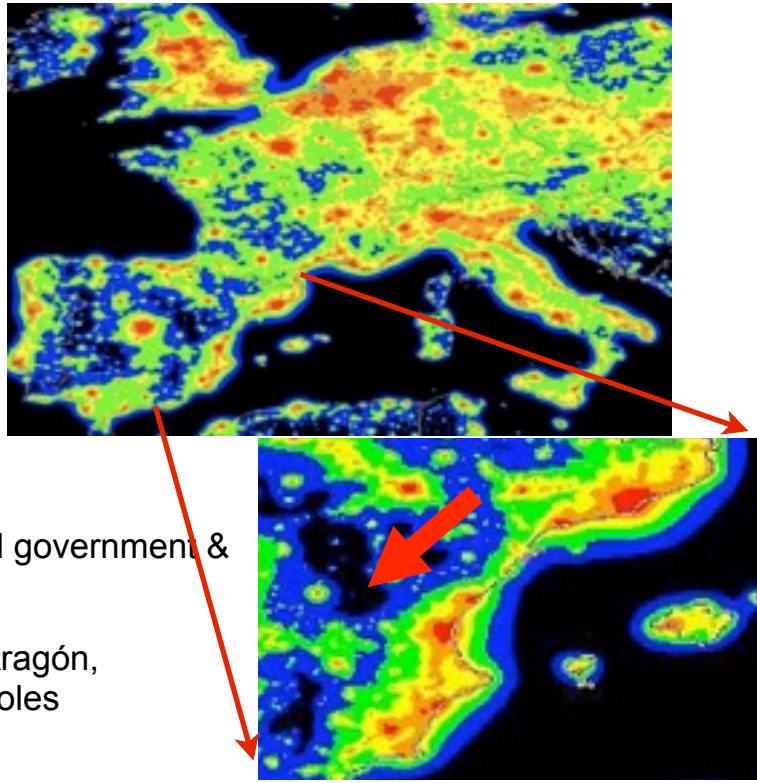
BAO surveys comparison

	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

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

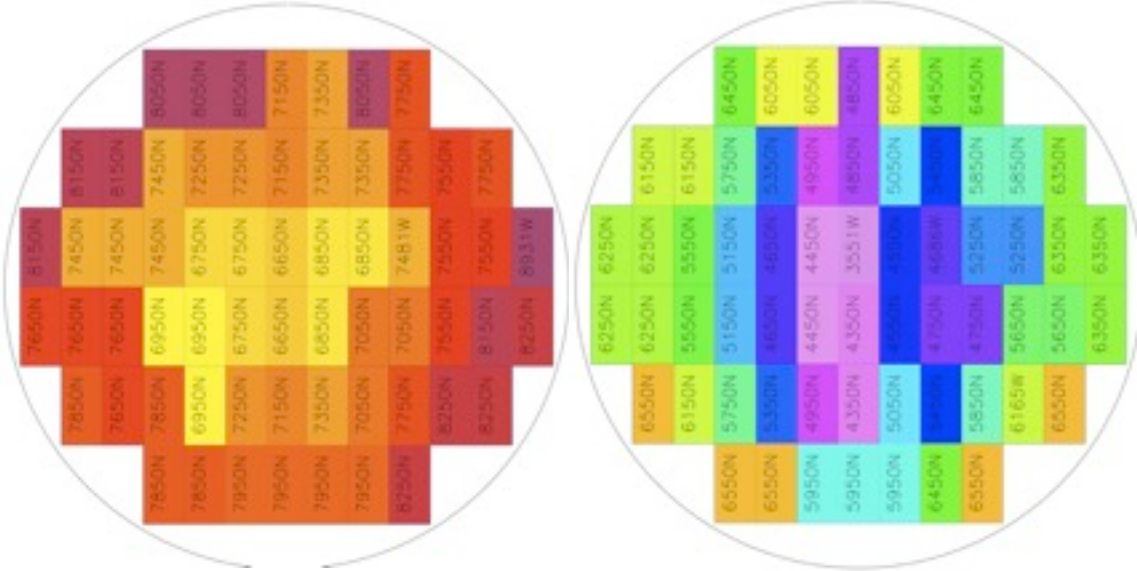
BAO LRG survey in a 2m (effective) class telescope (Ef.Etendue ~20) with a ~6 deg^2 FoV camera equipped with ~40 10nm-wide filters, ~500 Mpixels with 0.35”/pixel.

- 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

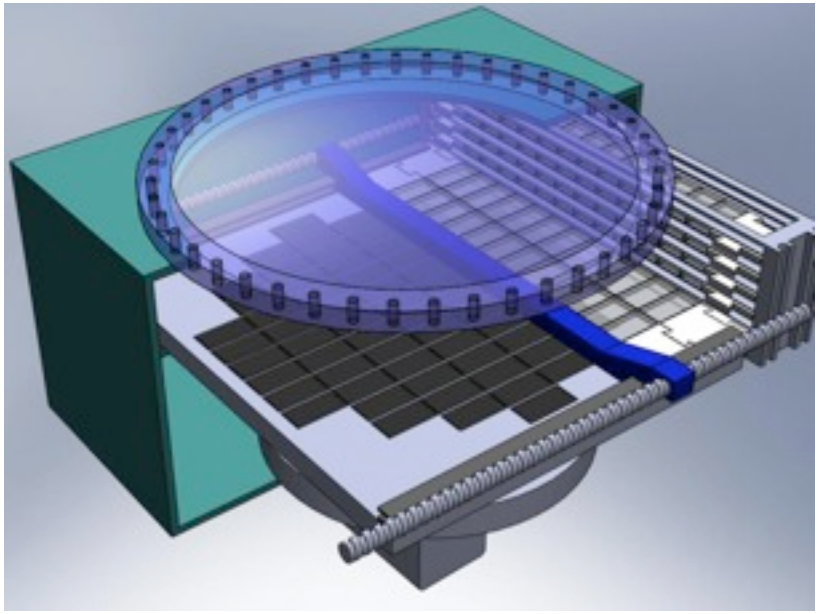
Selection effects

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

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

- 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
- …

Selection effects

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.