Physics of the accelerating Universe

The PAU (BAO) Survey

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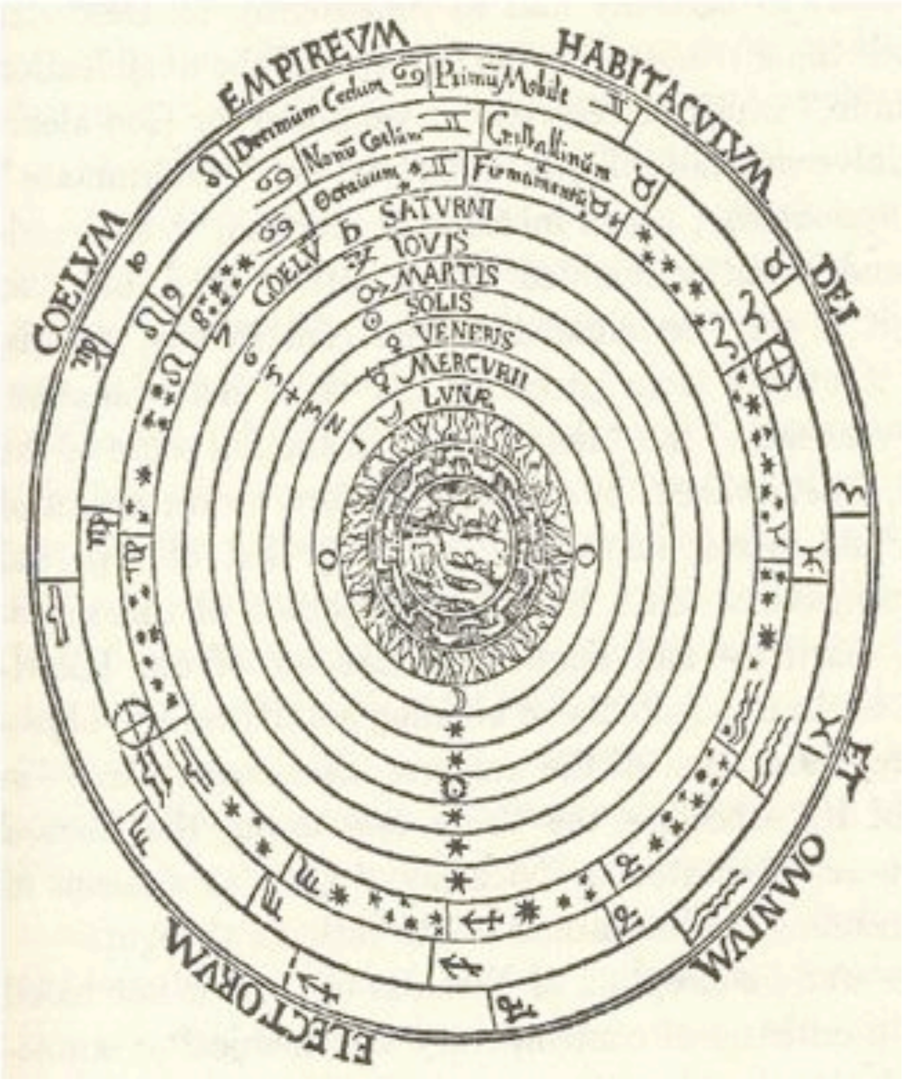
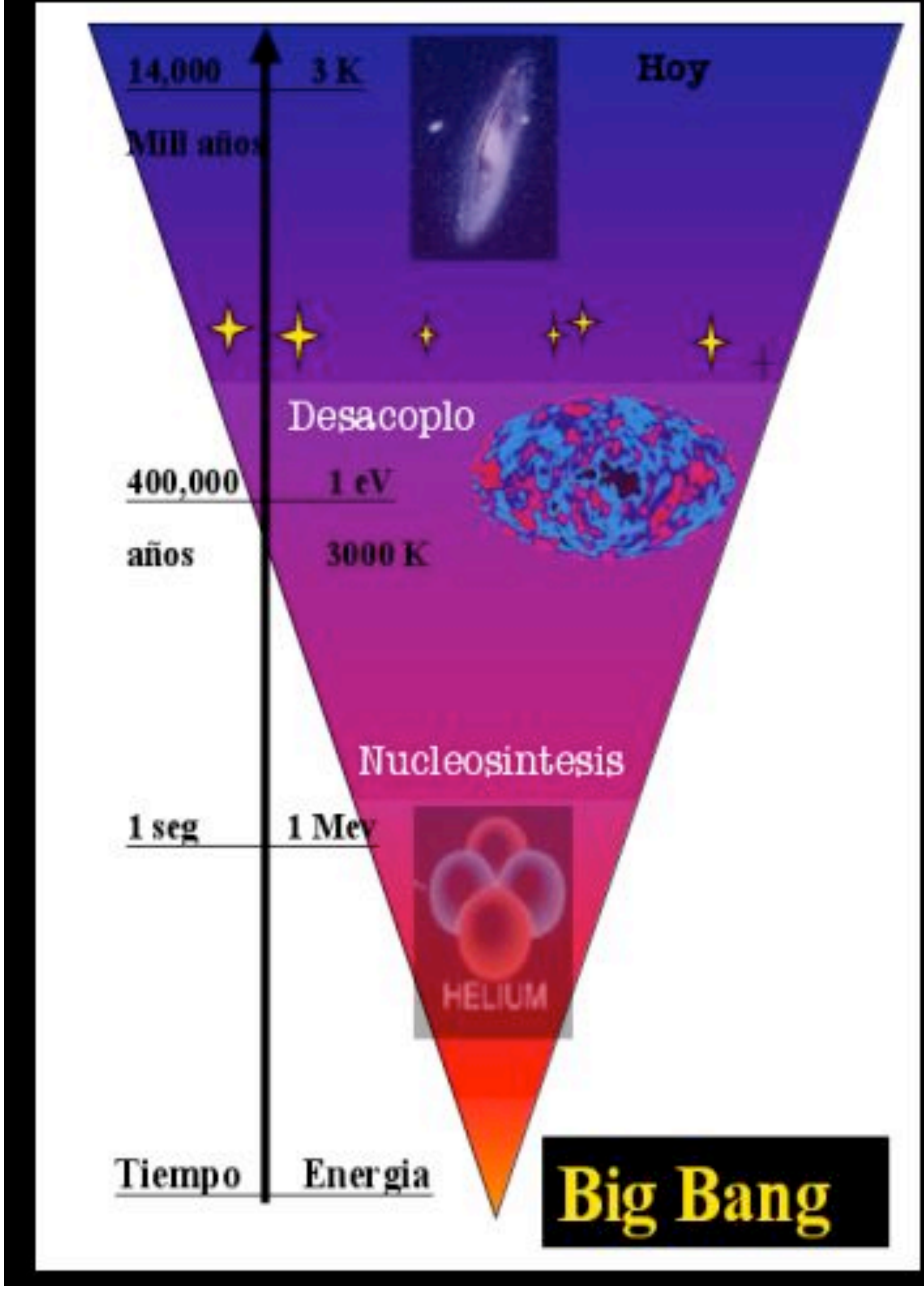
Saclay 24th June (San Juan)



Onion models have been used for centuries to indicate hierarchical spheres of influence. Alexandre Koyré's wonderful *From the Closed World to the Infinite Universe* (Koyré 1957) uses the beautiful 11-layered onion diagram of Peter Apian's 1539 *Cosmographia*, a pre-Copernican model of the universe, on its cover.

HOW DID WE GET HERE?



Two driving questions in Cosmology:

Background:

Evolution of scale factor a(t)

Expansion history

+ Symmetries
+ Einstein's Eq. (Gravity?)
+ matter-energy content ?

-> Friedman Eq.:

$$H^2(z) = H^2_0 \, [\, \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_K (1+z)^2 + \Omega_{DE} (1+z)^{3(1+w)} \,]$$

$$c\,dt = a\,d\chi \rightarrow \quad \chi = c \int dz/H(z)$$

Dark Matter and Dark Energy!

Fluctuations:

Structure Formation:

Growth history

+ origin of structure (Initial Conditions)
+ gravitational instability (Gravity?)
+ matter-energy content ?

$$d'' + H\,d' - 3/2\, W_m H^2 d = 0$$

+ galaxy/star formation (SFR): bias

Age-Temperature relation:

Wien law for BlackBody:

$E = h\,\nu_{max} \sim 2.8\, K_B\, T$

$(K_B \sim 10^{-4}\ eV/K)$

Today $E \sim 10^{-3}$ eV $\Leftrightarrow T_0 \sim 3$ K

$1/\nu_{max} \sim \lambda_{max} \sim 1.9$ mm

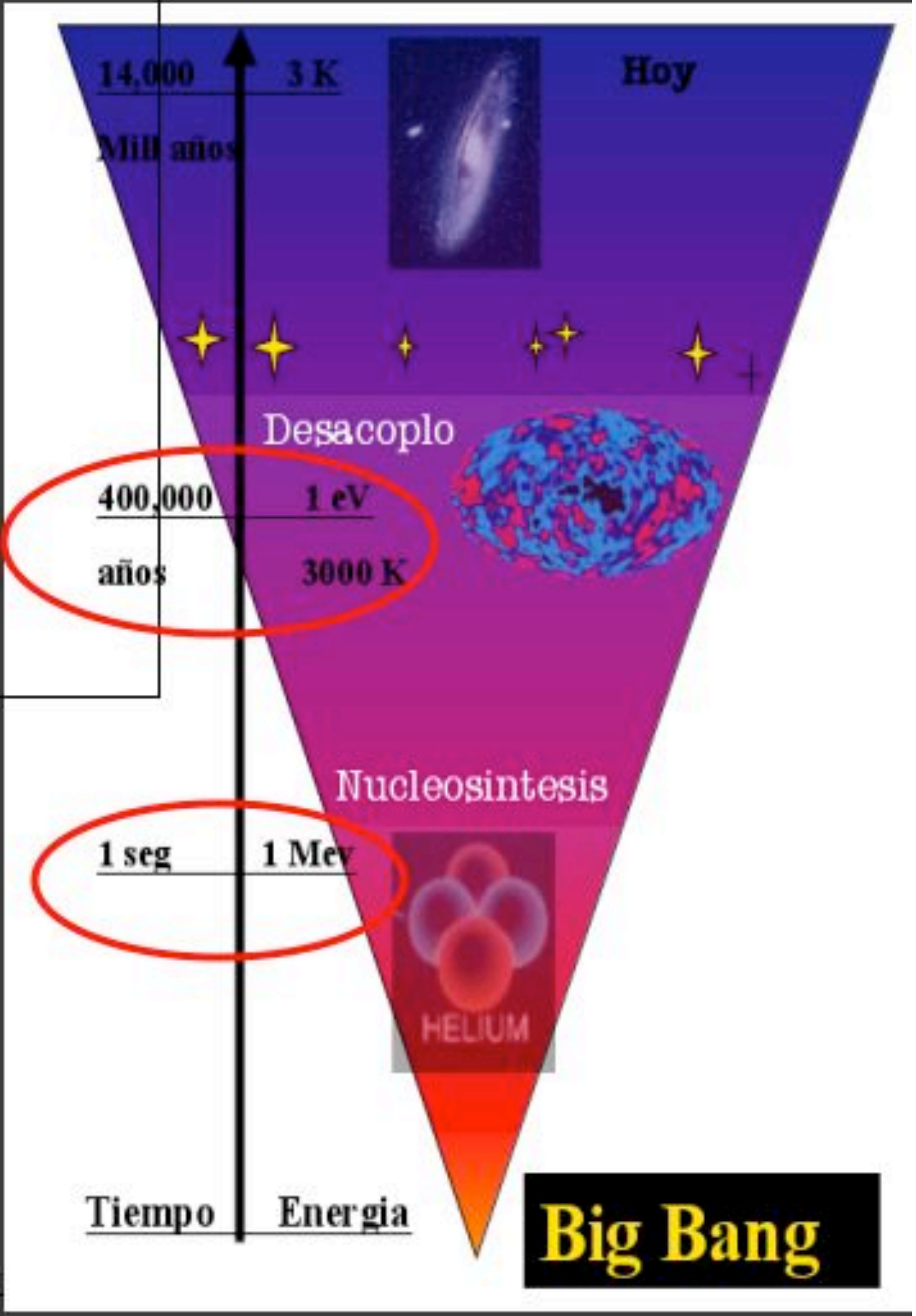
$$T = T_0/a = T_0\,(1+z)$$

-> given T we can calculate z

-> from z also the age t_0 : $dt = da/aH$

$$t_0(z) = H_0^{-1} \int_z^{\infty} \frac{dz}{(1+z)\ E(z)}$$

Tic



Standard Rulers (horizon) or Candles (SnIa)

Radial measurement (Obs: dz, ruler: dx): $H(z) = c\,dz / dx$

Angular measurement (Obs: θ , ruler: dx): $d_A(z) = a\,\chi = dx/\theta$

Luminosity measurement (Obs: m , ruler: M): $d_L(z) = \chi/a = 10^{(m-M)/5}$

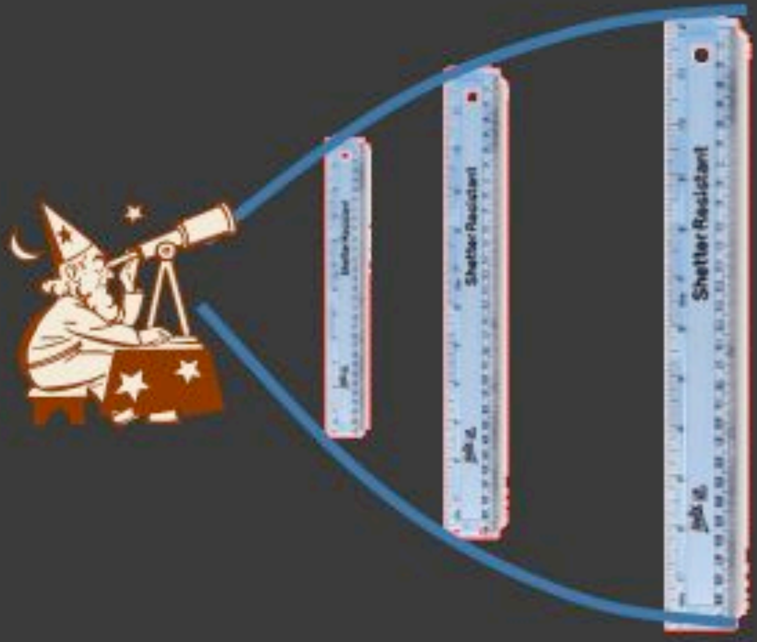
observations

FRW metric: $c\,dt = a\,d\chi$

need to find a=a(t)

$a = 1/(1+z)$; $H = a'/a$;

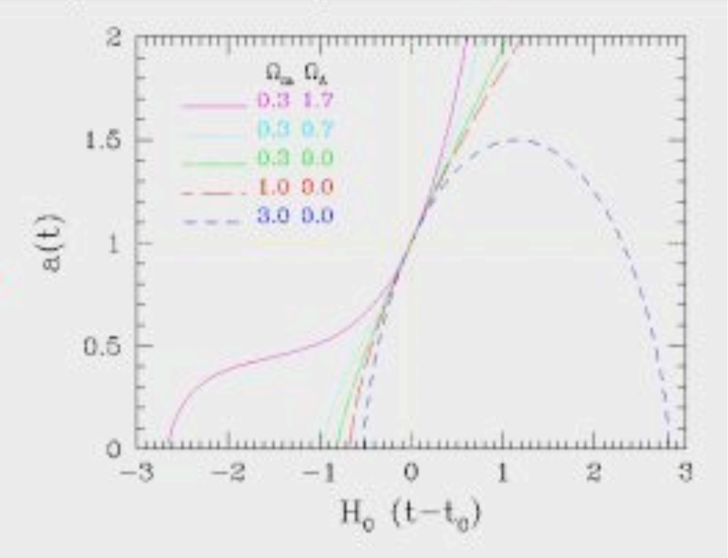
radial comoving distance $\chi(z) = c \int dz/H(z)$



interpretation

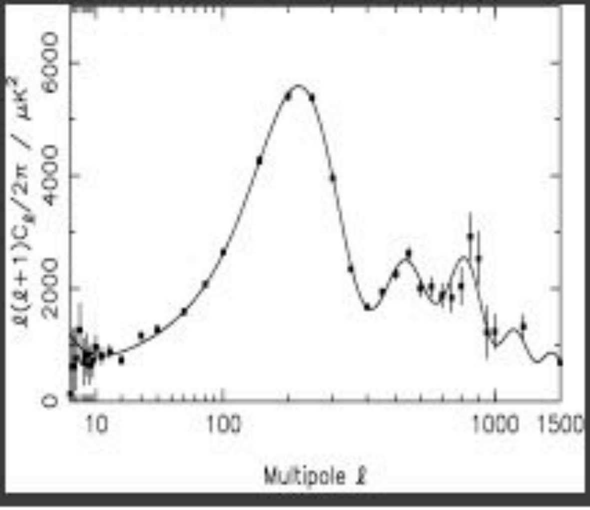
theory

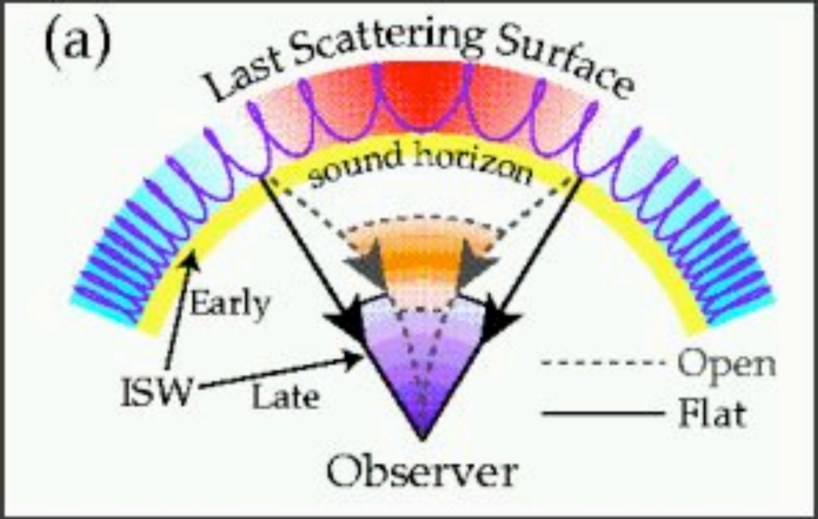
expansion history

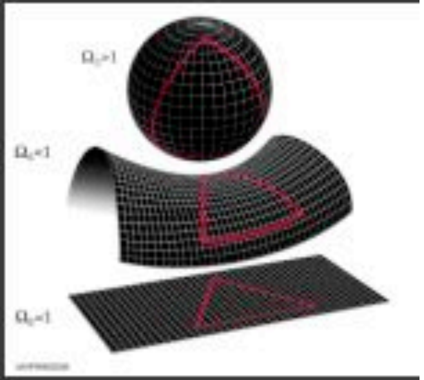


The Energy of the Universe

Acoustic Oscillations







$\Omega_T \approx 1$

"Wavelength" of baryonic acoustic oscillations is determined by the comoving sound horizon at recombination

$$k_{\rm bao} = 2\pi/s$$

At early times can ignore dark energy, so comoving sound horizon is given by

$$s = \frac{1}{H_0\Omega_m^{1/2}}\int_0^{a_*} da\,\frac{c_s}{(a+a_{\rm eq})^{1/2}}$$

Sound speed (dependent on baryon/photon ratio) is only weakly dependent on epoch, and can be approximated by

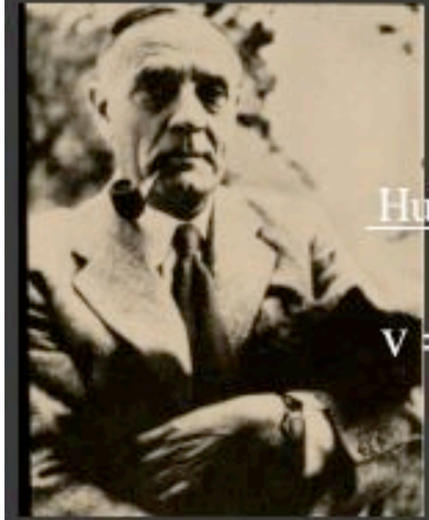
$$c_s \simeq \frac{0.9}{\sqrt{3}}c$$

$$\rho = \rho_c = 3H^2/8\pi G$$

Measurements:

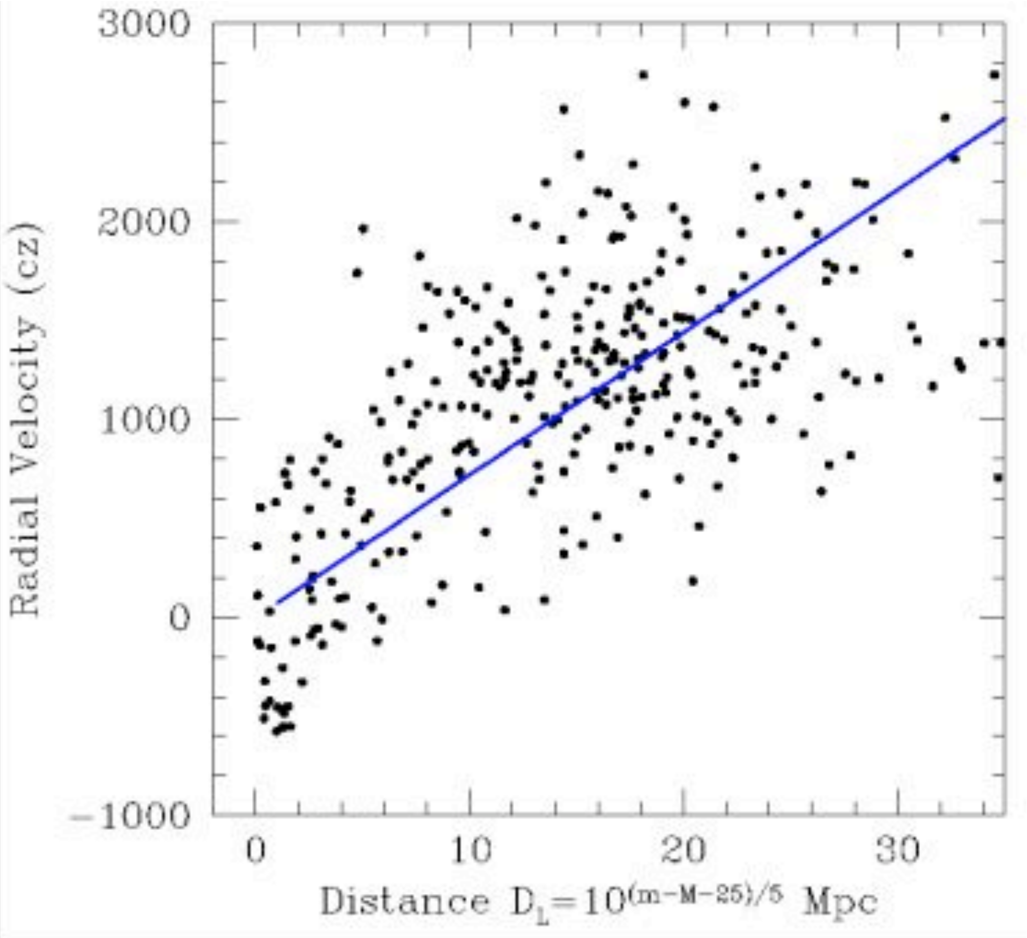
energy density vs expan rate

Problems to measure H_0



Hubble's law: (1929)

$v = cz \approx H\, d$



- initial value $H_0 = 500$ Km/h/Mpc
- $H_0 = 50$ (Sandage/Tammann) ?
- $H_0 = 100$ (deVaucoulers)?
-$H_0 = 72 \pm 8$ km/s/Mpc (HST)
--> h=0.72 ±0.08 -> t0 ~ 1 /H_0 ~14 Gyr!

Universe more empty that better human made vacum

$$\rho_c \equiv \frac{3\,H_0^2}{8\pi G} \simeq 1.88\times 10^{-29}\ h^2\ gr/cm^3$$
$$\simeq 1.06\times 10^{4}\ h^2\ eV/cm^3$$
$$\simeq 2.78\times 10^{11}\ h^2\ M_\odot/Mpc^3$$

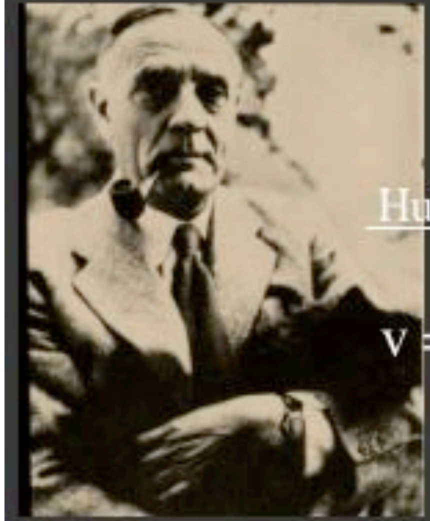
-Absolute distance callibrations are very difficult

-Scatter in distance indicators

-Peculiar velocities

-Malmquist bias

Problems to measure H_0



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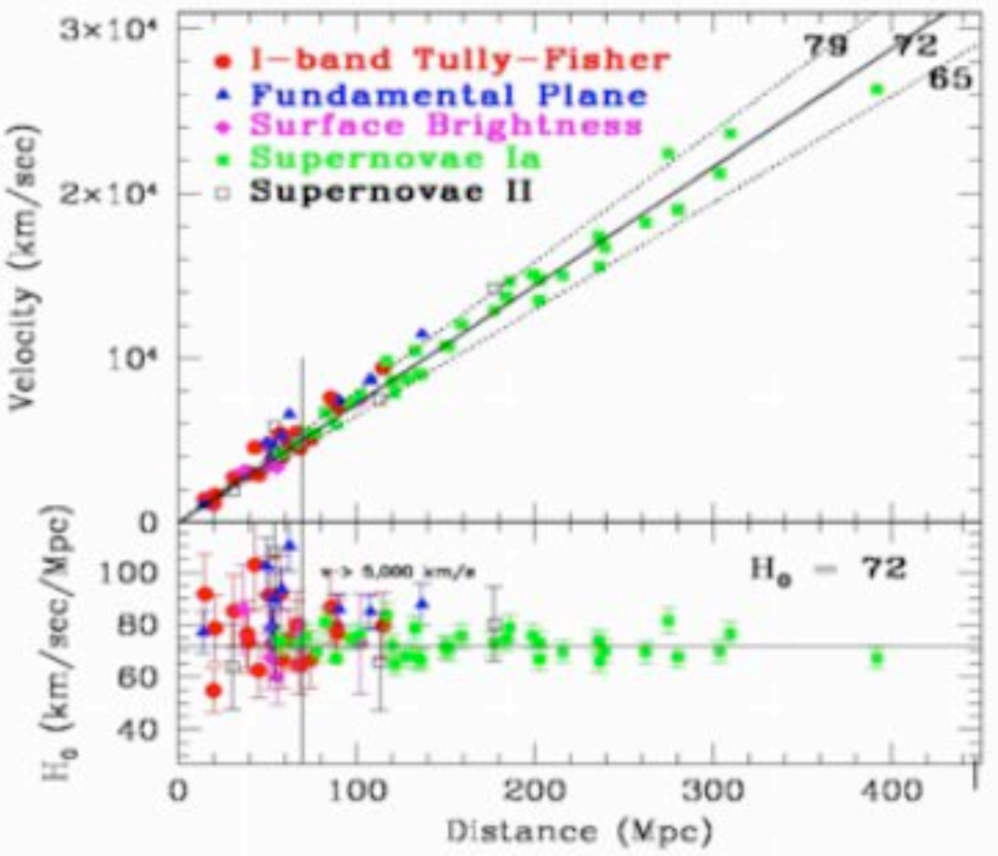

Universe more empty that better human made vacum

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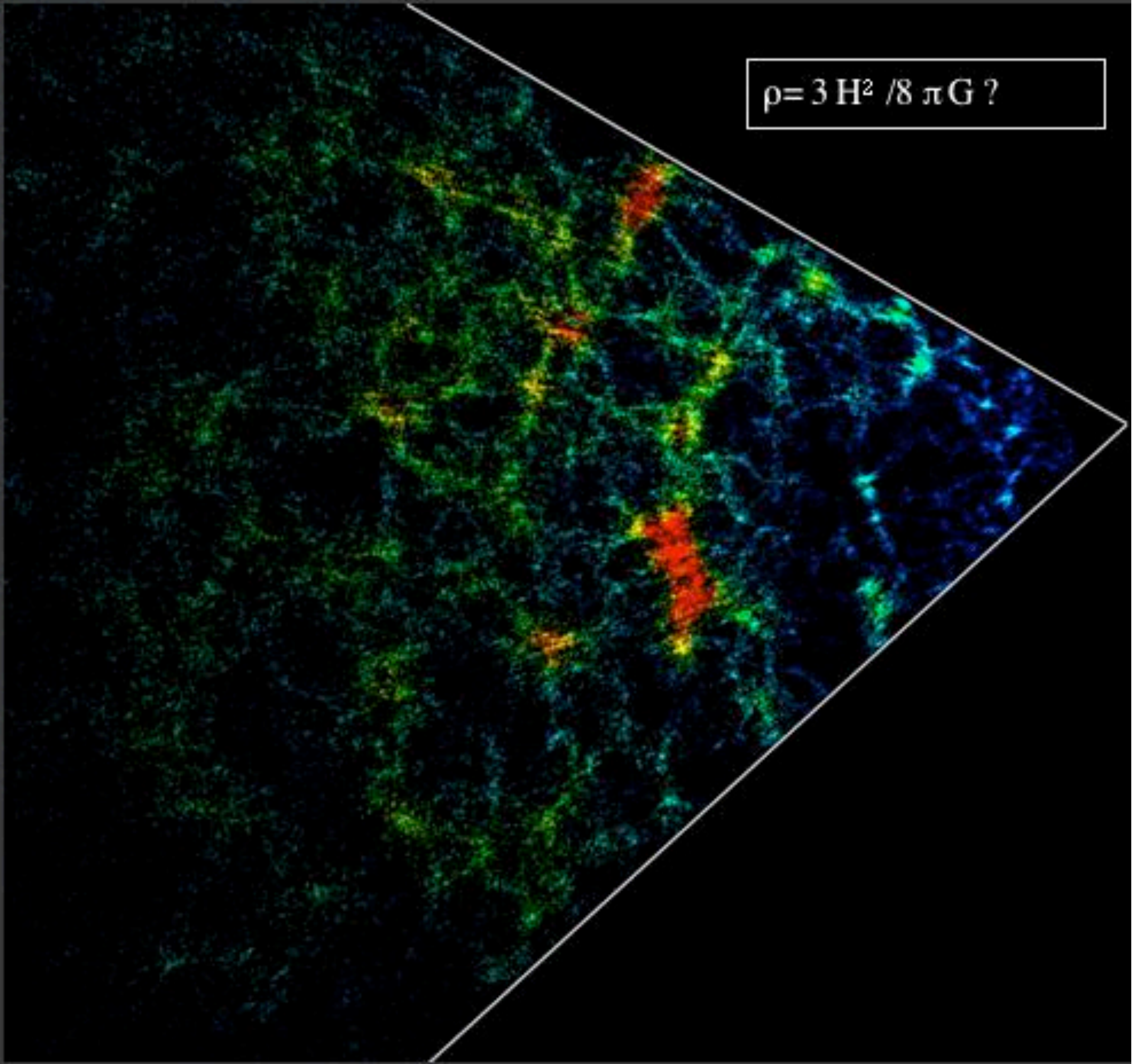
Absolute distance callibrations are very difficult

Scatter in distance indicators and in peculiar velocities

Malmquist bias

Measure Matter density


$\rho = 3H^2/8\pi G$?

Large Scale Galaxy Distribution with 250,000 Galaxies in 2DGRS (1,000,000 in SDSS, 40,000,000 in PAU)

Scale: 10^{+25} m **1000 Million lyr (300 Mpc)**

ρ_L= (1.82 +/- 0.17) 10^8 h L_{solar} Mpc^{-3}

$2.78 \times 10^{11}\ h^2\ M_\odot/Mpc^3$

For a typical galaxy: (M/L)* ~ 15 $(M/L)_{solar}$

-> $\Omega_* \approx 0.01$

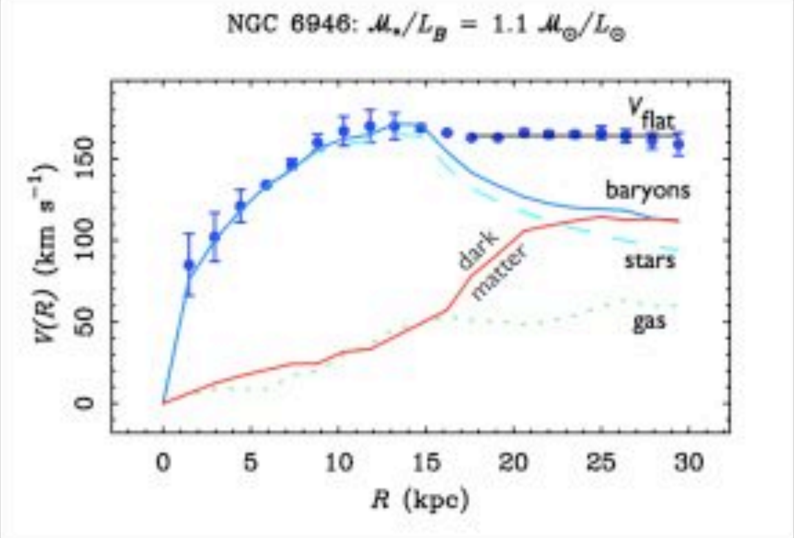
Rotational curves in spiral galaxies

+ virial theorem in Elliptical galaxies

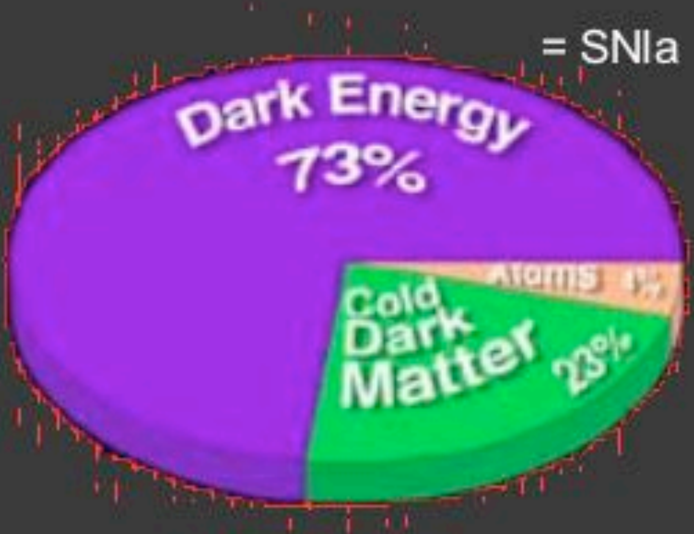
(+ baryon fraction in clusters):

M/L ~ 10-30 (M/L)*

-> $\Omega_m \approx 0.1 - 0.3$ **not so far from unity**



$-v^2/r = GM/r^2$

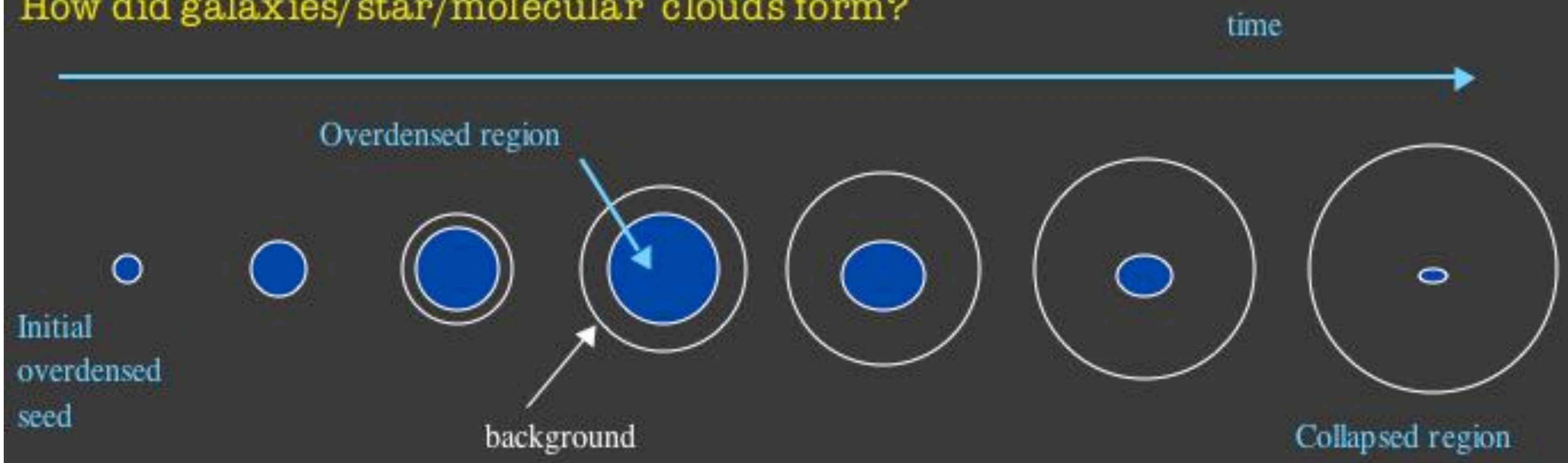


= SNIa

E.Gaztañaga, SACLAY '08

Where does Structure in the Universe come From?

How did galaxies/star/molecular clouds form?



time

Overdensed region

Initial overdensed seed

background

Collapsed region

Perturbation theory:

$$\rho = \rho_b\,(1 + \delta) \quad \Rightarrow \quad \Delta\rho = (\rho - \rho_b) = \rho_b\,\delta$$

$$\rho_b = M / V \quad \Rightarrow \quad \Delta M / M = \delta$$

With :

$$\delta'' + H\,\delta' - 3/2\,\Omega_m\,H^2\,\delta = 0$$

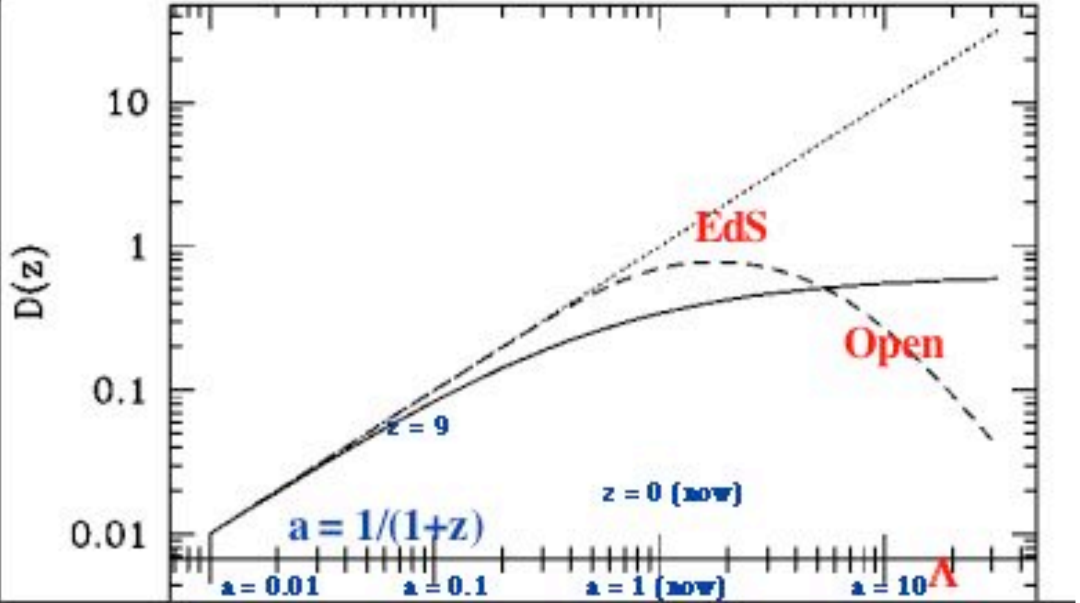
in EdS linear theory: $\delta = a\,\delta_0$

Jeans Instability (linear regime)

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

$$\begin{tikzcd} \delta_L(x,\tau) = D(\tau)\,\delta_0(x) \arrow[d, "\text{EdS}"] \\ \delta_L(x,\tau) = a(\tau)\,\delta_0(x) \end{tikzcd}$$

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



Another handle on DE:

-Friedman Eq. (Expansion history) can not separate gravity from DE

-Growth of sctructure could: models with equal expansion history yield difference D(z) (EG & Lobo 2001). astro-ph/0303526 & 0307034)

-Great, but how do you get D(z) from observations?

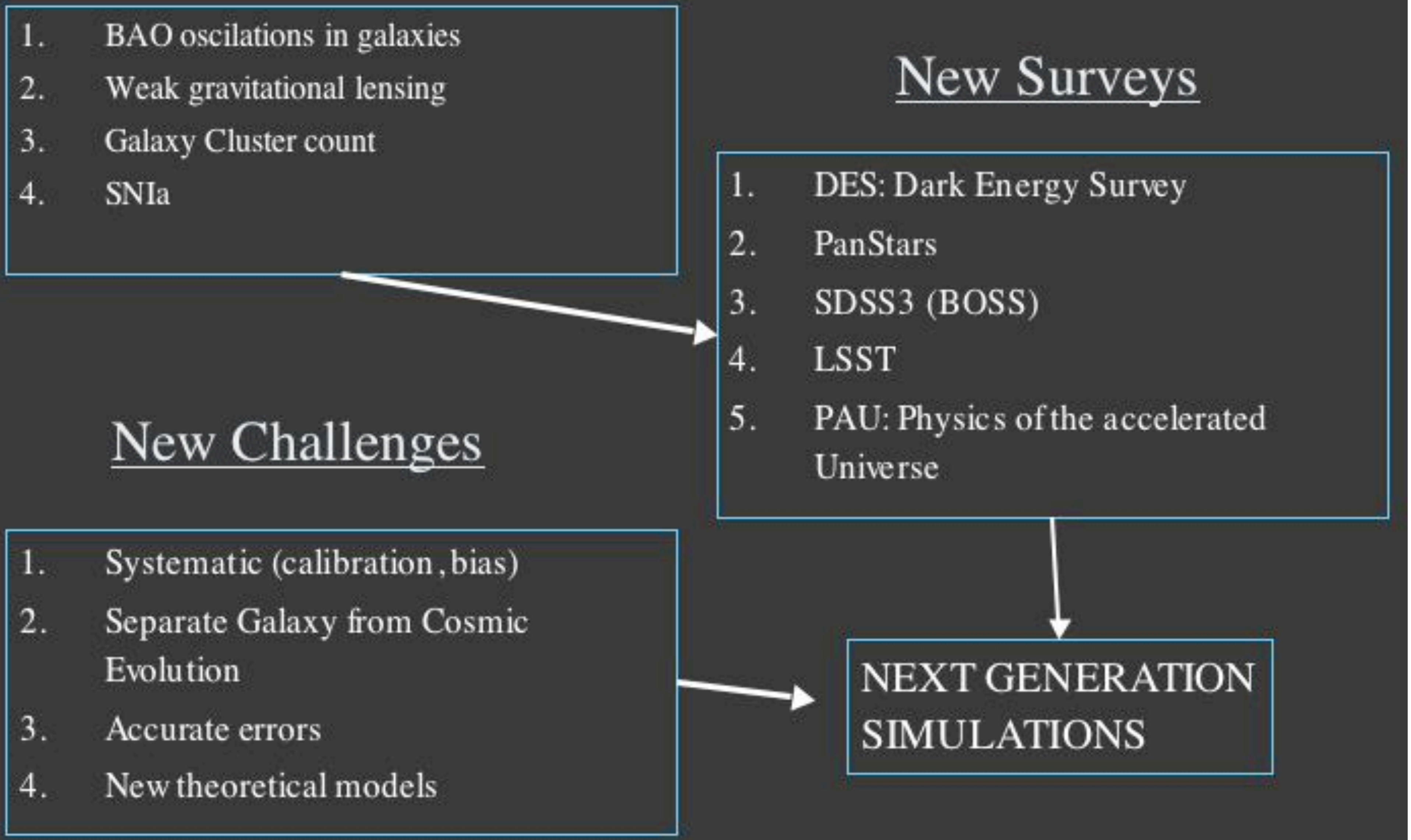
$$D = C_1\,a^{\alpha_1} + C_2\,a^{\alpha_2}\,,$$

$$\alpha_1 = \frac{2+\omega}{1+\omega} \simeq 1 + \frac{1}{\omega} + O\!\left(\frac{1}{\omega^2}\right),$$

$$\alpha_2 = \frac{-4-3\omega}{2+2\omega} \simeq -\frac{3}{2} - \frac{1}{2}\,\frac{1}{\omega} + O\!\left(\frac{1}{\omega^2}\right),$$

E.G &Lobo (2001)

New Tools for precision Test



1. BAO oscilations in galaxies
2. Weak gravitational lensing
3. Galaxy Cluster count
4. SNIa

New Surveys

1. DES: Dark Energy Survey
2. PanStars
3. SDSS3 (BOSS)
4. LSST
5. PAU: Physics of the accelerated Universe

New Challenges

1. Systematic (calibration, bias)
2. Separate Galaxy from Cosmic Evolution
3. Accurate errors
4. New theoretical models

NEXT GENERATION SIMULATIONS

Dark Energy Survey (DES)
Science Overview

- Study Dark Energy using 4 complementary* techniques:
  - I. Cluster Counts
  - II. Weak Lensing
  - III. Baryon Acoustic Oscillations
  - IV. Supernovae

- Two multiband surveys:
  - 5000 deg^2 *g, r, i, Z, Y* to *i~24*
  - 9 deg^2 repeat (SNe)

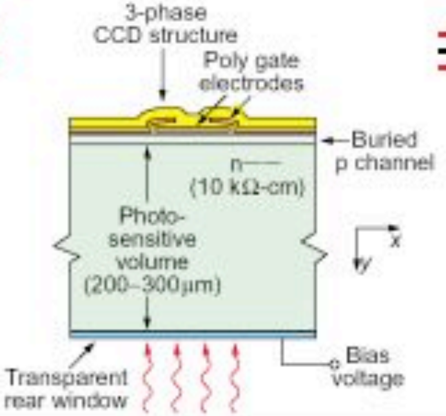
- Build new 3 deg^2 camera and Data management system
  - Survey 30% of 5 years
  - Response to NOAO AO

DES Forecast: FoM =4.6x

*in systematics & in cosmological parameter degeneracies
*geometric+structure growth: test Dark Energy vs. Gravity

DES CCDs

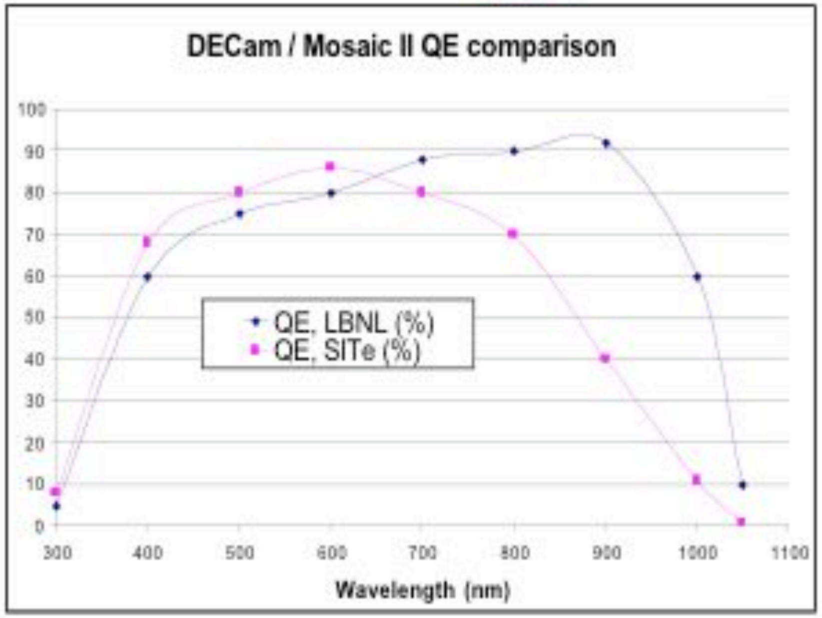
- Red Sensitive CCDs dev. by LBNL
  - QE> 50% at 1000 nm
  - 250 microns thick
  - readout 250 kpix/sec
  - 2 RO channels/device
  - readout time ~17sec



LBNL CCDs in use on WIYN telescope. From S. Holland et al, LBNL-49992 IEEE Trans. Elec. Dev. Vol.50, No 1, 225-338, Jan. 2003

Much more efficient in z than traditional thin devices

To get redshifts of ~1 DES will spend 46% of survey time in z –band

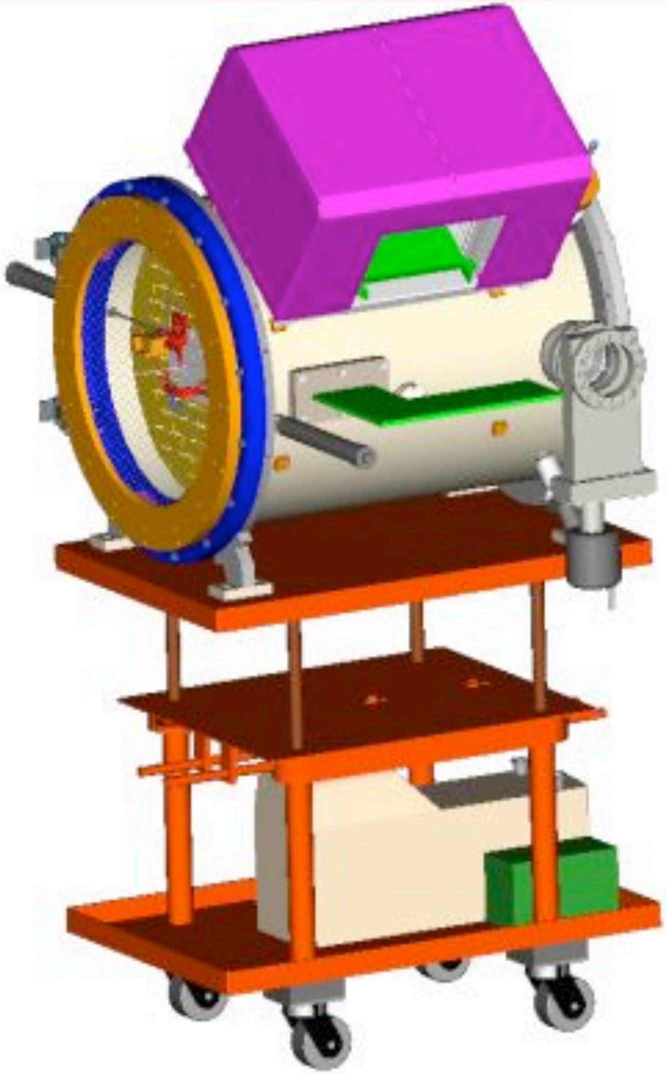


DES is the 1st production quantity application for LBNL CCDs

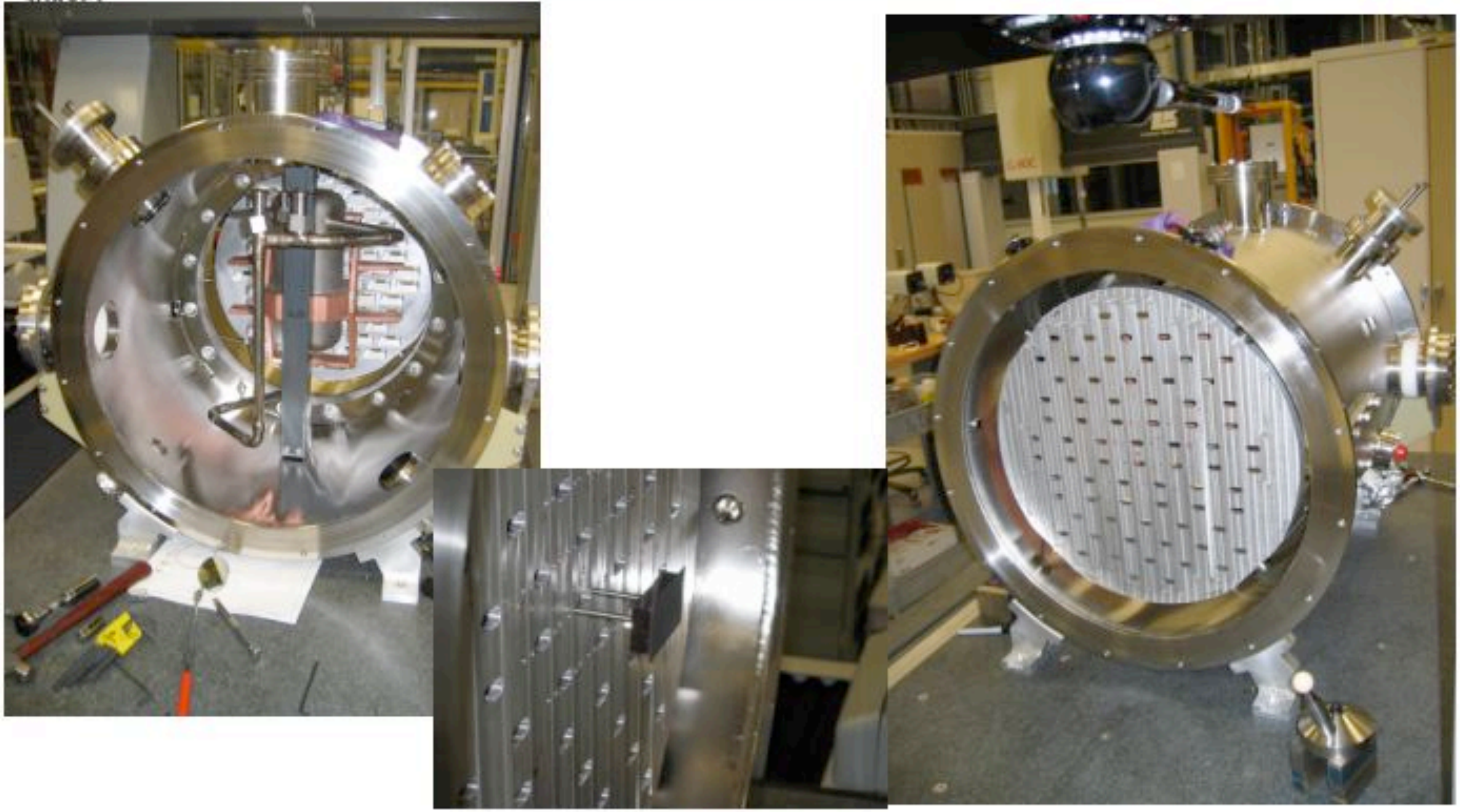
DES CCD design has already been used on telescopes in small numbers (3)

Multi-CCD Test Vessel

- Tests concepts for
  - window mount
  - focal plane support plate supports
  - cooling and vacuum controls
  - vacuum feed through board
  - can support a Monsoon crate
- Critical role: test readout of multiple CCDs in “real” configuration and with real cables



CCD Camera Vessel Prototype

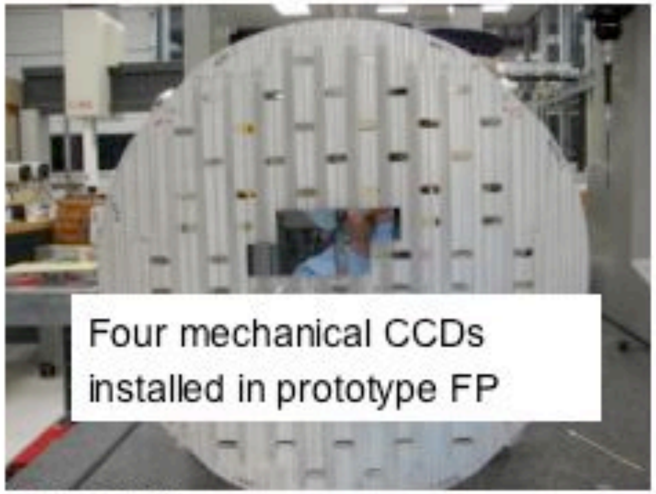


Front End Electronics

- We chose the Monsoon CCD readout system developed by NOAO for our CCD testing and characterization efforts.
  - Monsoon: designed to be compact and low power for large mosaic cameras
  - 3 types of boards: Master Control board, Clock board and Acquisition board
  - Testing individual CCDs we have achieved noise <10 e at 200 kpix/sec, this is within 20% of the goal of 250 kpix/sec – still some work to do
- For the PF cage we need higher density and are building on Monsoon:
  - Need a 12 channel instead of 8 channel Acquisition card (Fermilab)
  - Need more clock signals and buffers (Spain)
  - Master control board – convert optical link to S-link (Spain)
  - Compact, low noise power supplies, thermally controlled crates (UIUC)

Recent progress:
readout 2 CCDs from MCCDTV
Prototype 12 channel board
readout a CCD with < 10 e noise

Remaining open question is low noise readout of multiple CCDs with new electronics – should be able to answer in next few months with the multiCCD test vessel



Four mechanical CCDs installed in prototype FP

The PAU Project

- Large (~8,000 dg^2, $0.1<z<0.9$) photometric galaxy survey with purposely-built camera.

- Project has been proposed by 7 Spanish institution to a special program of the MEC (ministry of science). The team (40 persons) includes astrophysicists, cosmologist and particle physicists (experimenters and theorists).

- Funding (5 years) for the camera and other activities.

Physics of the accelerating Universe

CONSOLIDER PAU
FUNDING APPLICATION

AIHAMBRA PROJECT

DES PROJECT

Coordinator:
Enrique Fernandez

Insttutional PI

Enrique Alvarez (9)

Carlos Peña-Garay (9)

Mariano Moles (4)

Eusebio Sanchez (3)

Enrique Gaztañaga (13)

Ramon Miquel (5)

Manuel Delfino (2)

E.Alvarez[1], S.Antuch[1], F.Ballesteros[2], G.Baremboim[2], N.Benítez[3], C.Biggio[1], J.Campa[4], C.Carbone[5], L.Cardiel[6], A.Casas[1], F.Castander[5], J.Castilla[4], D. Cristobal-Hornillos[3], A.Crocce[5], M.Delfino[7], E.Fernández[6], E.Fernández-Martínez[1], C.Fernández-Sopuerta[5], A.Fernández-Soto[2], P.Fosalba[5], J. García-Bellido[1], E.Gaztañaga[5], B.Gavela[1], J.A.Grifols[6], C.Hernández-Monteagudo[5], R.Jiménez[5], J.A.Lobo[5], V.J.Martínez[2], E.Massó[6], O.Mena[5], R.Miquel[6], J.Miralda-Escudé[5], M.Moles[3], J.A.Ortega[5], A.Ortiz[2], A.Pacheco[7], S.Paredes[2], C.Peña-Garay[2], M.J.Pons[2], S.Rigolin[1], N.Rius[2], M.Salvatori[1], E.Sánchez[4], S.Sanchez[3], J.Varela[3], L.Verde[5], J.F. de Vicente[4].

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The PAU Project

- We still need to settle on
  - A telescope with a large fraction of the observing time (the goal is to complete the survey in 4 years). Several options being considered. There is funding for a PAU Purpose build Telescope in Spain (Javalambre,Teruel). Technical Design phase (Construction 2009-10)
  - Need collaborators (camera, survey itself, ...).

Physics of the accelerating Universe

The PAU Project

- Focus on measuring the Baryon Acoustic Oscillations peak, in both **angular** and **radial** directions.

- Simulations show that we can obtain a precision on z for LRG (luminous-red galaxies) of

$$\Delta z \sim 0.003\,(1+z)$$

- There will be a wealth of other physics that can be studied with the survey data.

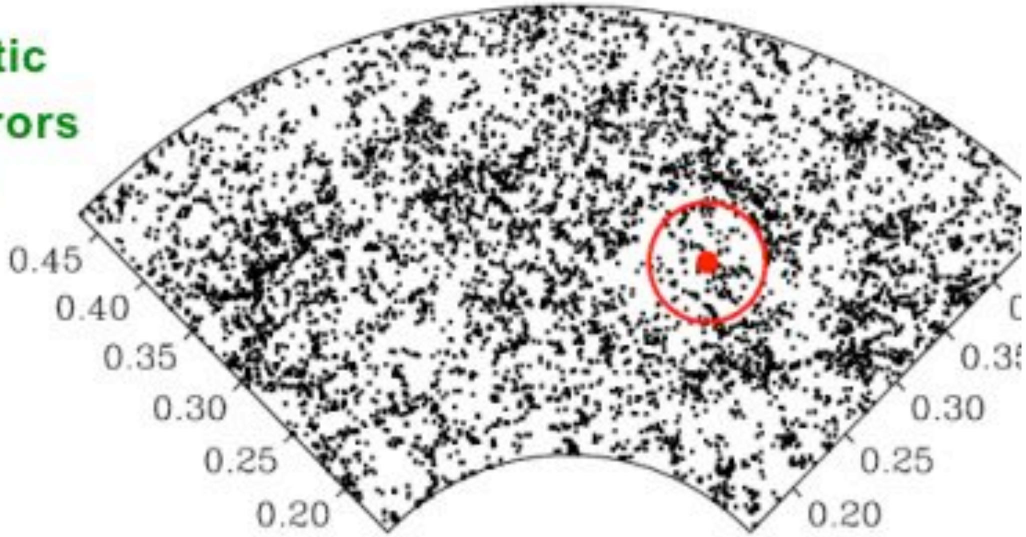
Physics of the accelerating Universe

BAO from Galaxy Redshift Surveys

- **Galaxy redshift surveys are used to measure the 3D clustering structure of matter: for BAO only need position and *z*, no flux, no shape.**
- **There can be several sources of systematic errors:**
  - **Light from galaxies is a "biased" estimator of matter content**
  - **Non-linear physics involved in galaxy formation**
  - **Redshift distortions**
- **However, all effects tend to predominantly change the amplitude of the correlations, but not the position of the measured acoustic peak**

- **BAO are quite insensitive to systematic errors. In any case, the systematic errors are very different from those of SNe.**

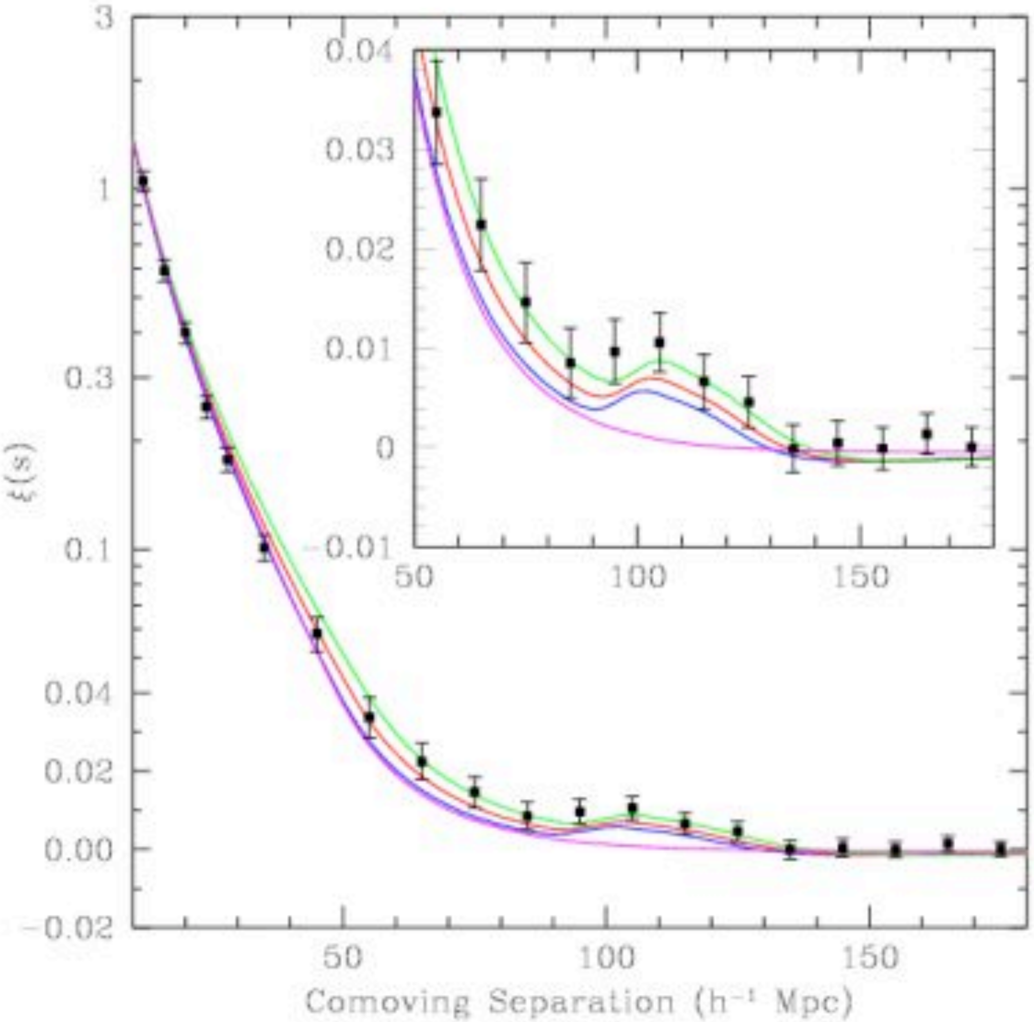
- **But the effect is small only visible at large scales which leads to huge surveys.**



Physics of the accelerating Universe

BAO measured in SDSS LRG data (Eisenstein et al. 2005)

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



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

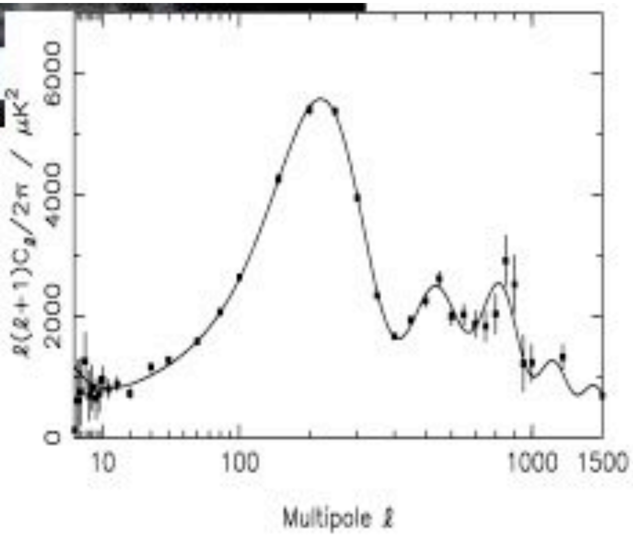
or

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

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

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

Physics of the accelerating U



Dark energy and BAO

BAO gives us a standard distance with

a co-moving value

r_{BAO}~ 100 Mpc/h (r_{BAO}= 146.8±1.8 Mpc, ΛCDM)

For a flat universe

radial

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

angular

$$d_A(z) = \frac{c}{1+z} \int_0^z \frac{dz'}{H(z')}$$

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

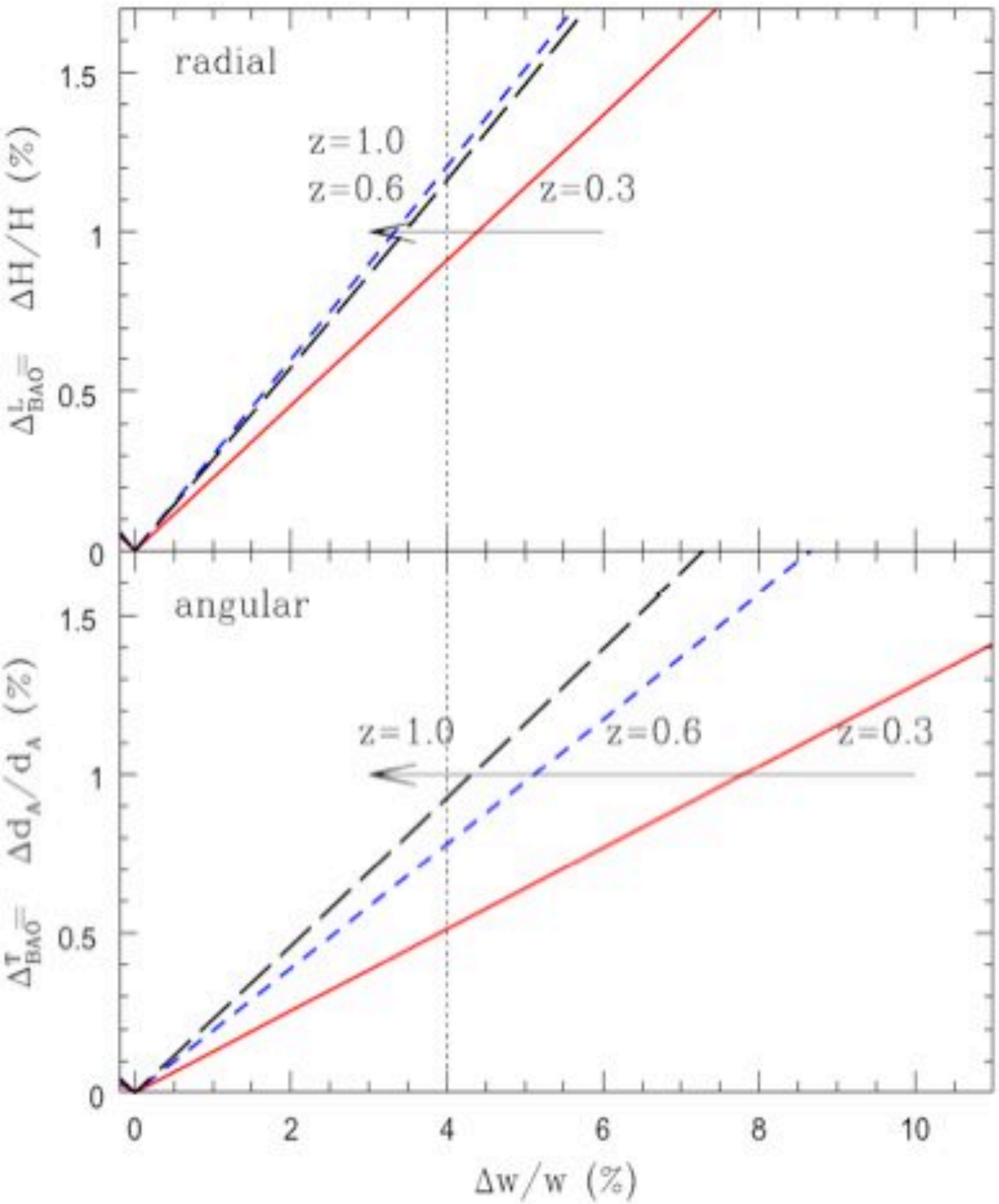
Physics of the accelerating Universe

Importance of measuring in the radial direction:

Assume flat universe, *w*=constant and Ω_m=.25

$$\frac{H^2(z)}{H_0^2} = \Omega_m(1+z)^3 + \\ + (1-\Omega_m)(1+z)^{3(1+w)}$$

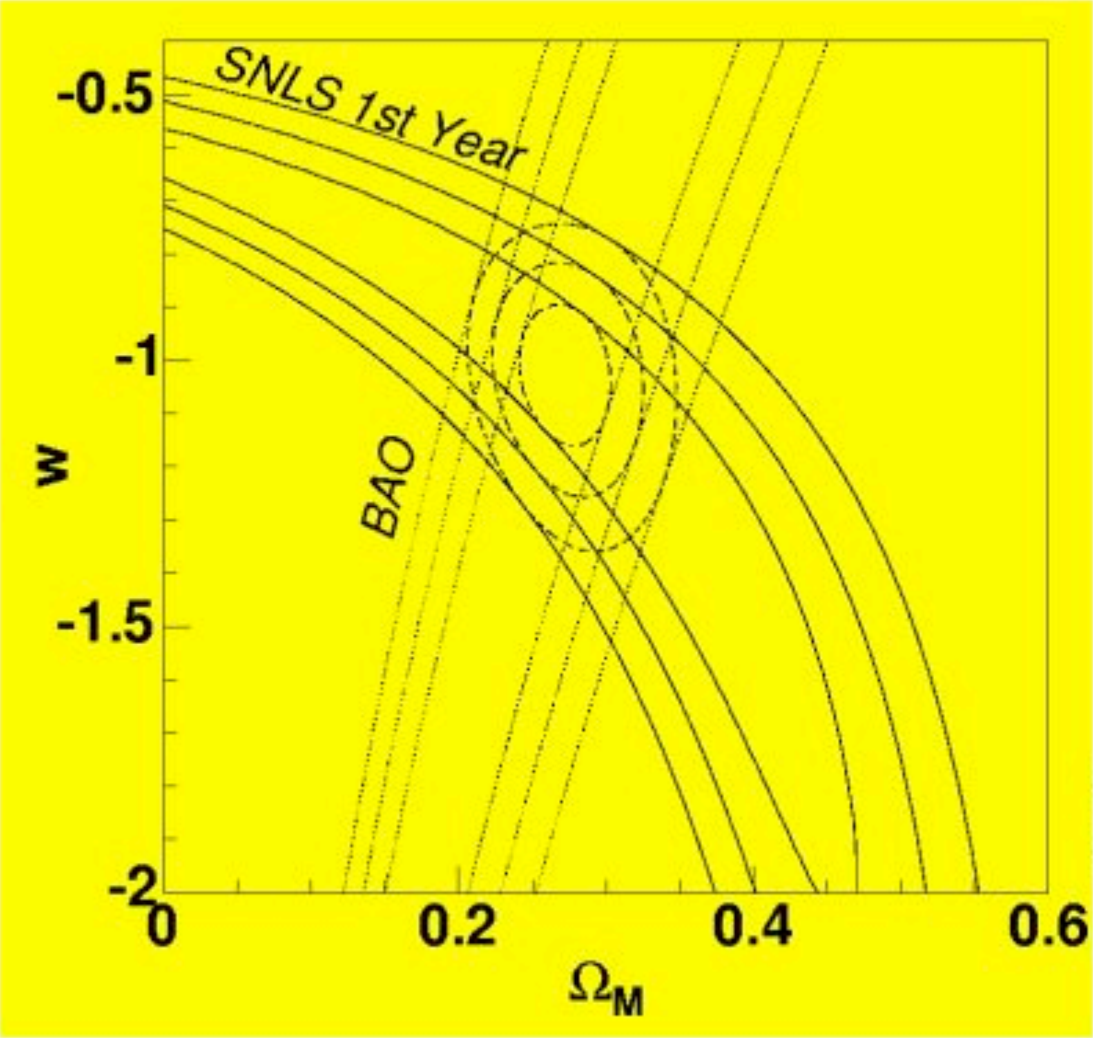
Error propagation:



Gaztañaga

Physics of the accelerating Universe

Cosmological Results from BAO



SNLS SNe: Astier et al. 2006

SDSS BAO: Eisenstein et al. 2005

Size and resolution requirements

- Statistical errors on galaxy-galaxy correlation functions are determined by “sample variance” and “shot noise”.
  - Sample variance: how many independent samples of the relevant scale (150 Mpc)^3 one has ⇒ volume
  - Shot noise (Poisson): how many galaxies included in each sample ⇒ density

Feldman, Kaiser, Peacock, ApJ 426,23 (1994)

$$\frac{\Delta P(k)}{P(k)} \propto \frac{1}{\sqrt{V}}\left(1+\frac{1}{nP(k)}\right)$$

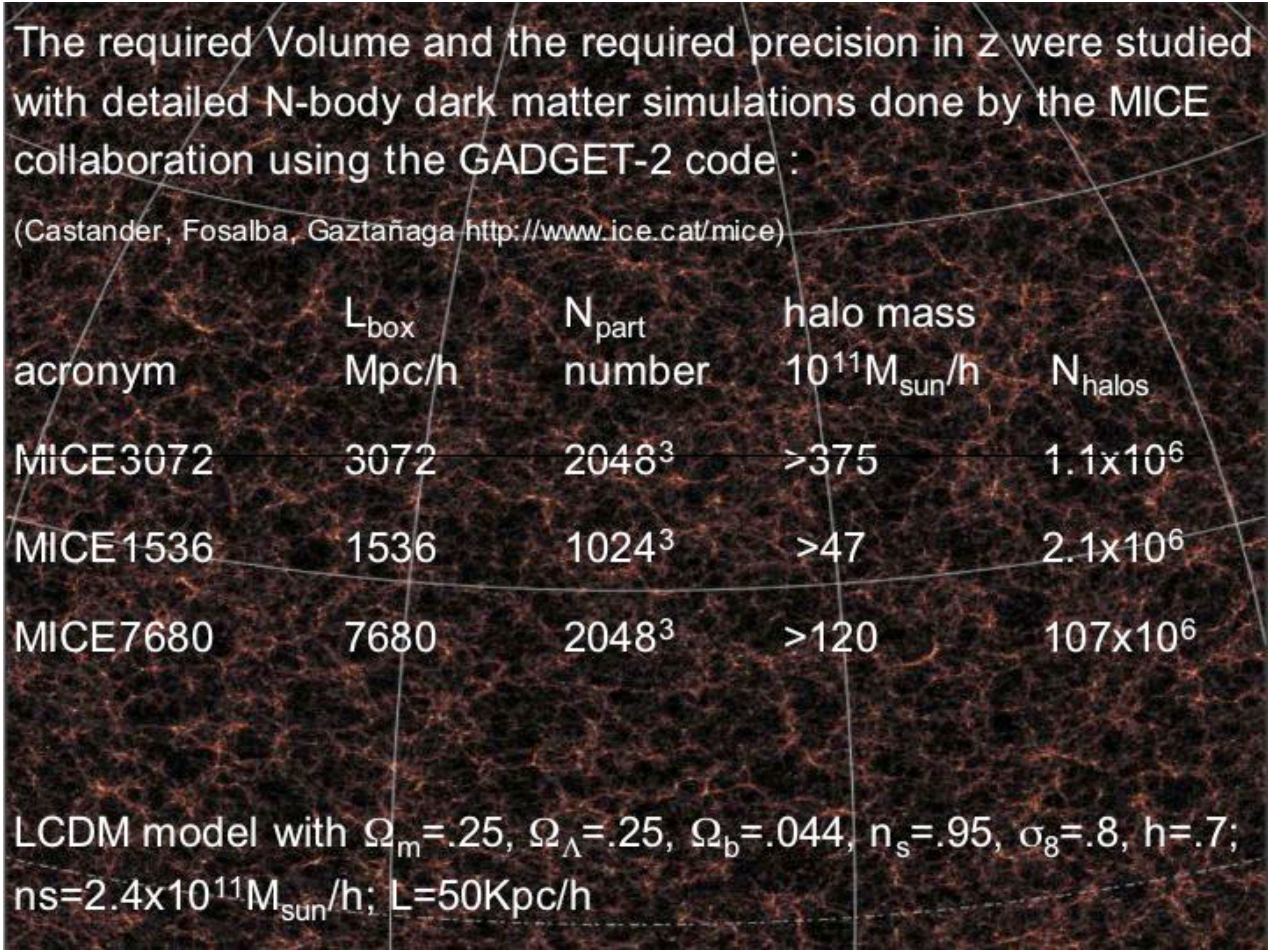
$P(k)$: power spectrum

n: galaxy density

Marenostrum Simulations

Marenostrum @ BSC

- 4800 processors (2400 dual nodes)
- 9.6 TB of RAM
- 42 Teraflops (5th in the World)
- Myrinet network
- 30 TB disk



The required Volume and the required precision in z were studied with detailed N-body dark matter simulations done by the MICE collaboration using the GADGET-2 code :

(Castander, Fosalba, Gaztañaga http://www.ice.cat/mice)

acronym	L_{box} Mpc/h	N_{part} number	halo mass $10^{11} M_{sun}/h$	N_{halos}
~~MICE3072~~	~~3072~~	~~2048^3~~	~~>375~~	~~1.1×10^6~~
MICE1536	1536	1024^3	>47	2.1×10^6
MICE7680	7680	2048^3	>120	107×10^6

LCDM model with Ω_m=.25, Ω_Λ=.25, Ω_b=.044, n_s=.95, σ_8=.8, h=.7; ns=$2.4 \times 10^{11} M_{sun}/h$; L=50Kpc/h

Size and resolution requirements

$$\frac{\Delta P(k)}{P(k)} \propto \frac{1}{\sqrt{V}}\left(1+\frac{1}{nP(k)}\right)$$

For the scales of interest for PAU (LRGs, $0.1<z<0.9$) $nP(k)>10$, so that the Poisson term is negligible.

Detailed calculations shown that, without shot-noise:

$$\Delta_{BAO} \simeq 0.33\left(\frac{r_{BAO}^3}{V}\right)^{1/2} \simeq 0.33\%\sqrt{13\,h^{-3}\,\mathrm{Gpc}^3/V}$$

With shot-noise: 0.35%, **for PAU: 0.36%** (only 10% degradation!) for error=10xPAU: 2.2%

We aim at **1% error in Δ_{BAO}** ⇒ $V=10h^{-3}\mathrm{Gpc}^3$ ⇒ Area =8,000 deg^2

We expect about 14M LRG, with L>L* above $I_{AB}=22.5$ in the sample.

Size and resolution requirements

To study the required precision in z the two-point correlation function of over 1M halos with $M>3.7\times10^{13}h^{-1}M_{sun}$ was studied.

The position of the halo was smeared with a Gaussian:

$$f(\delta r_z) \sim \exp\left[-\frac{1}{2}\left(\frac{\delta r_z}{\Delta z}\right)^2\right] \qquad \Delta z = \frac{\sigma_z(1+z)c}{H(z)}$$

→

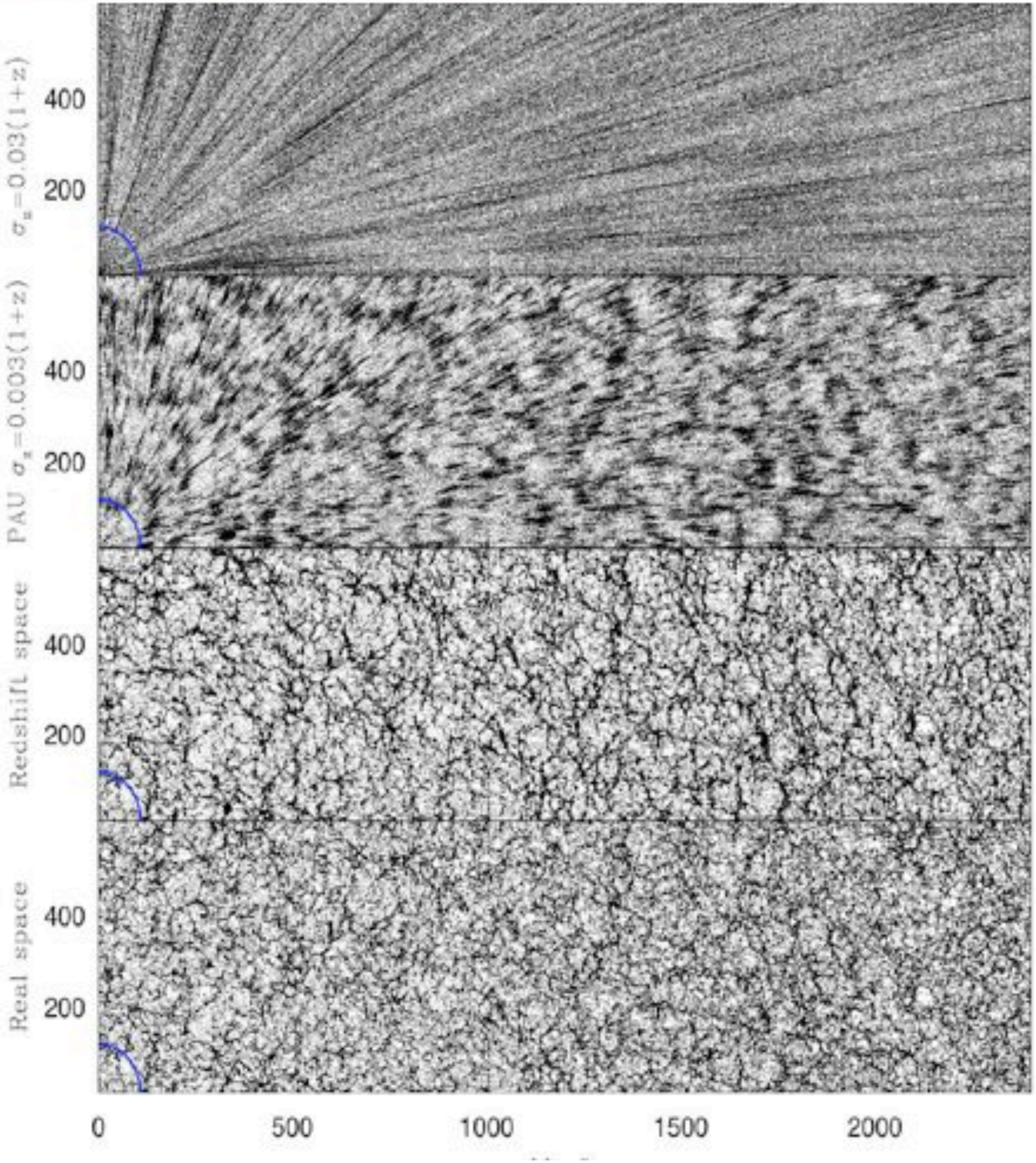
Physics of the accelerating Universe

z-space, $\Delta z = 0.03(1+z)$ + peculiar velocities

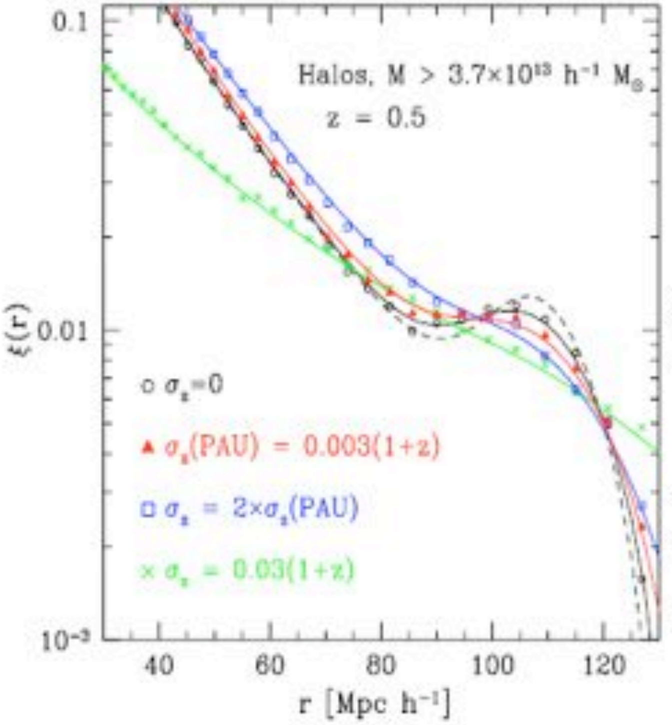
z-space, $\Delta z = 0.003(1+z)$ + peculiar velocities

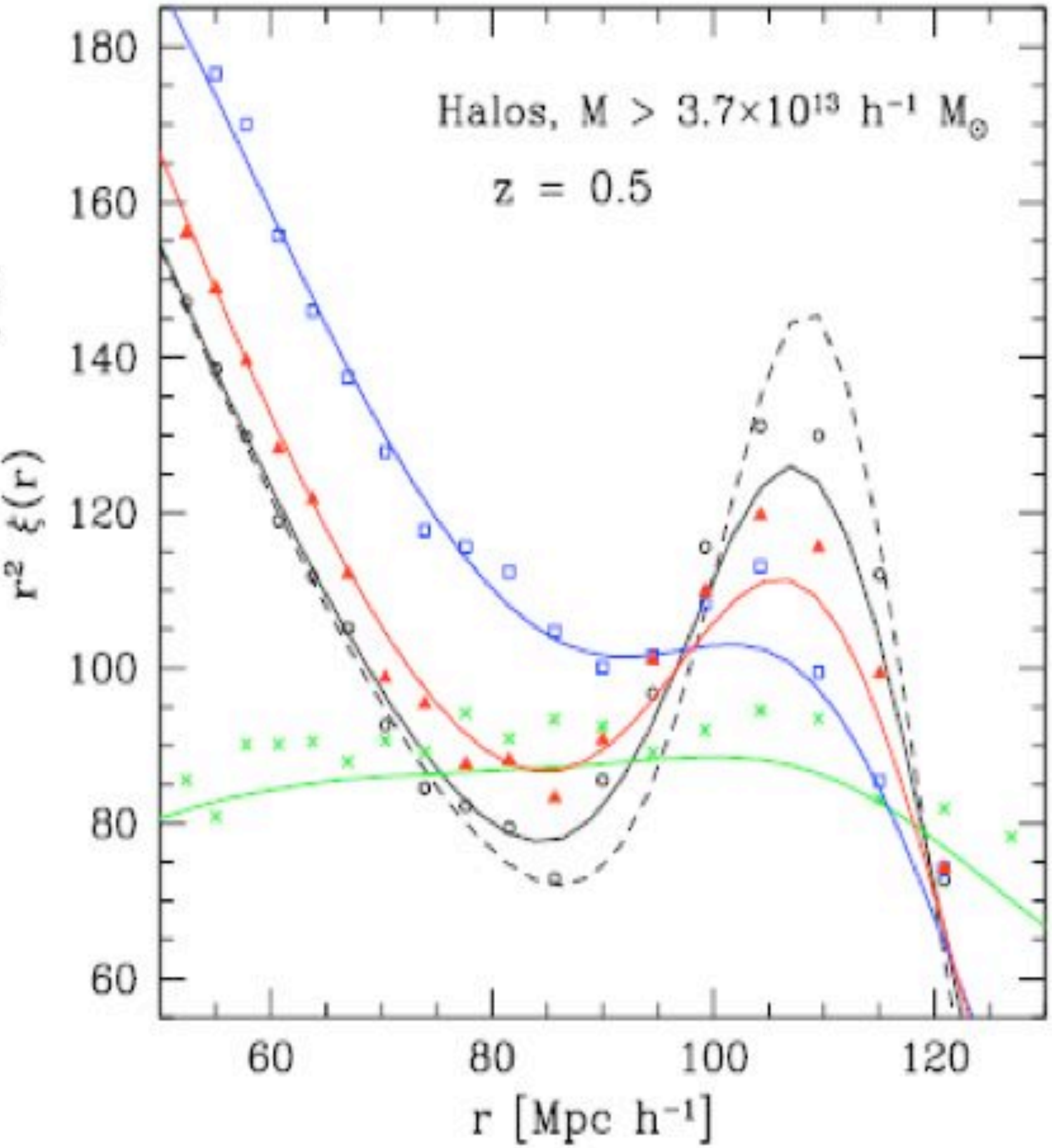
z-space, perfect z-resolution + peculiar velocities

Real space, perfect resolution



Gaztañaga





- - - linear corr. func. (b=3)

— non-linear (RPT; Crocce-Scocimarro, 2008)

▲ σ_z = 0.003 (1+z)

□ σ_z = 0.007 (1+z)

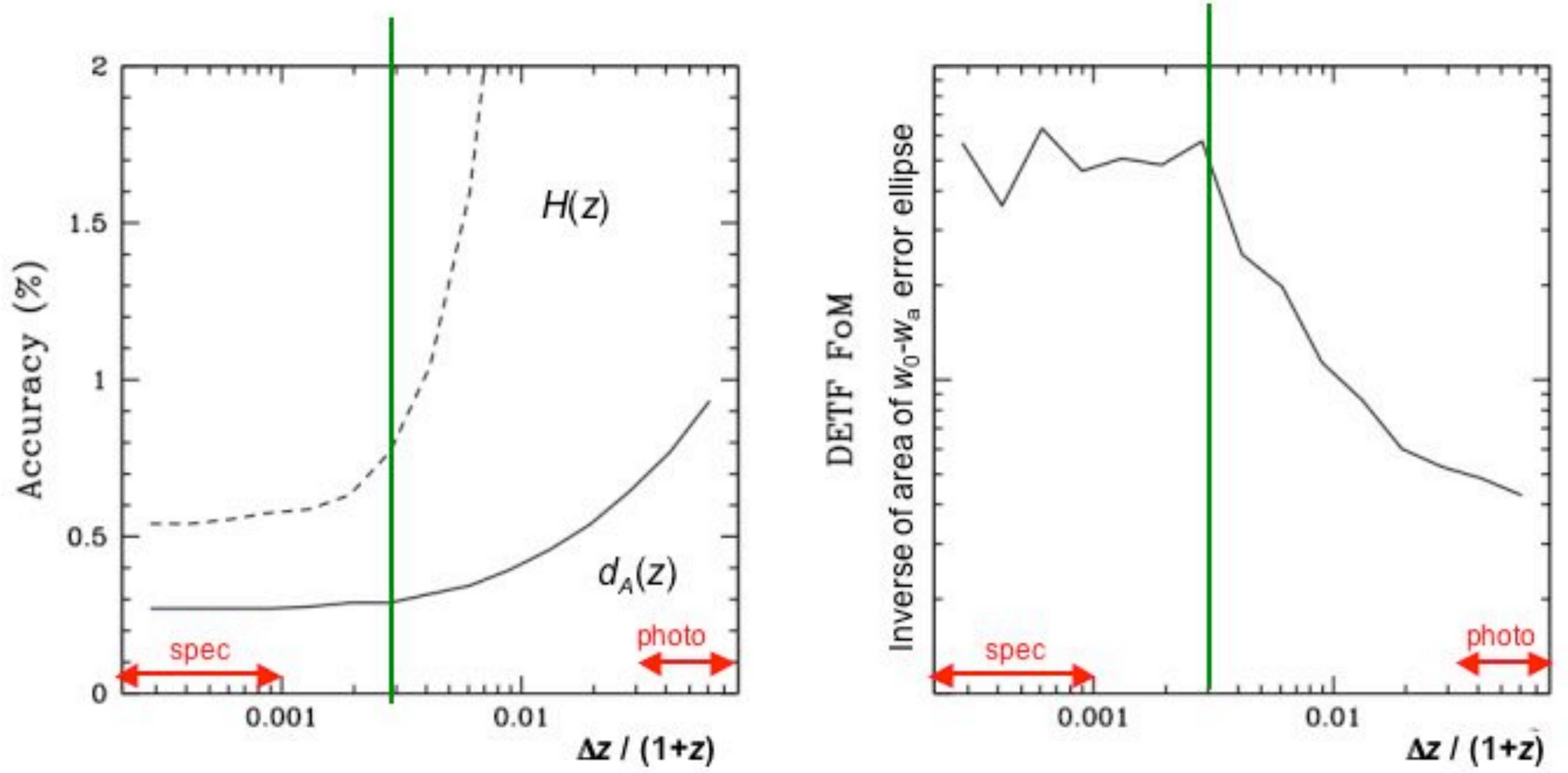
× σ_z = 0.03 (1+z)

Curves are analytical predictions derived from $P_\sigma(k_t,k_z)=P_{NL}\exp[-k_z^2\,\Delta_z^2]$

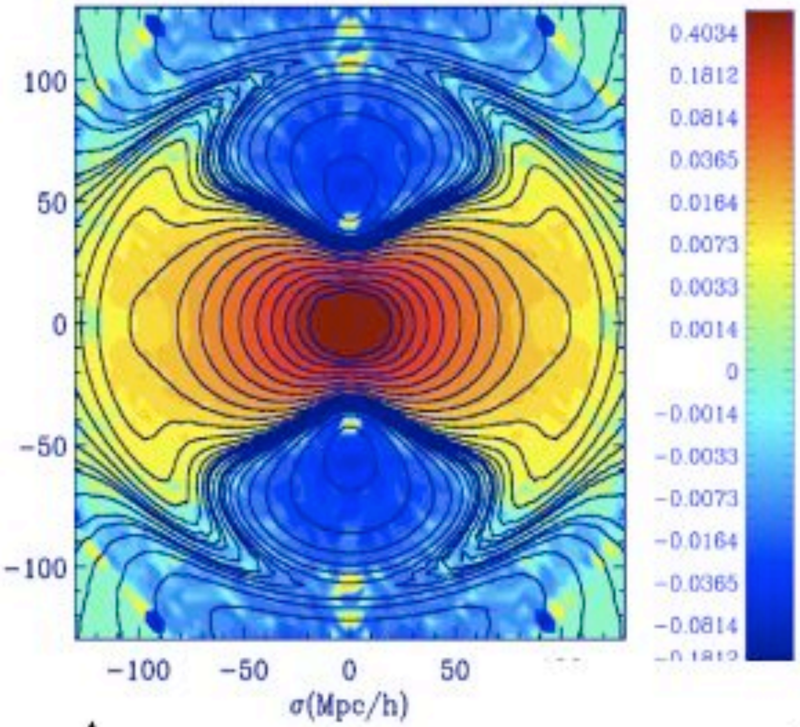
Crocce, Fosalba & Gaztañaga

Physics of the accelerating Universe

Requirements on Redshift Precision

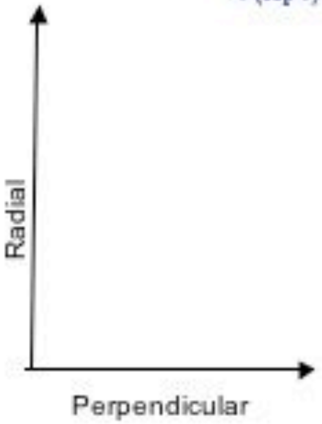


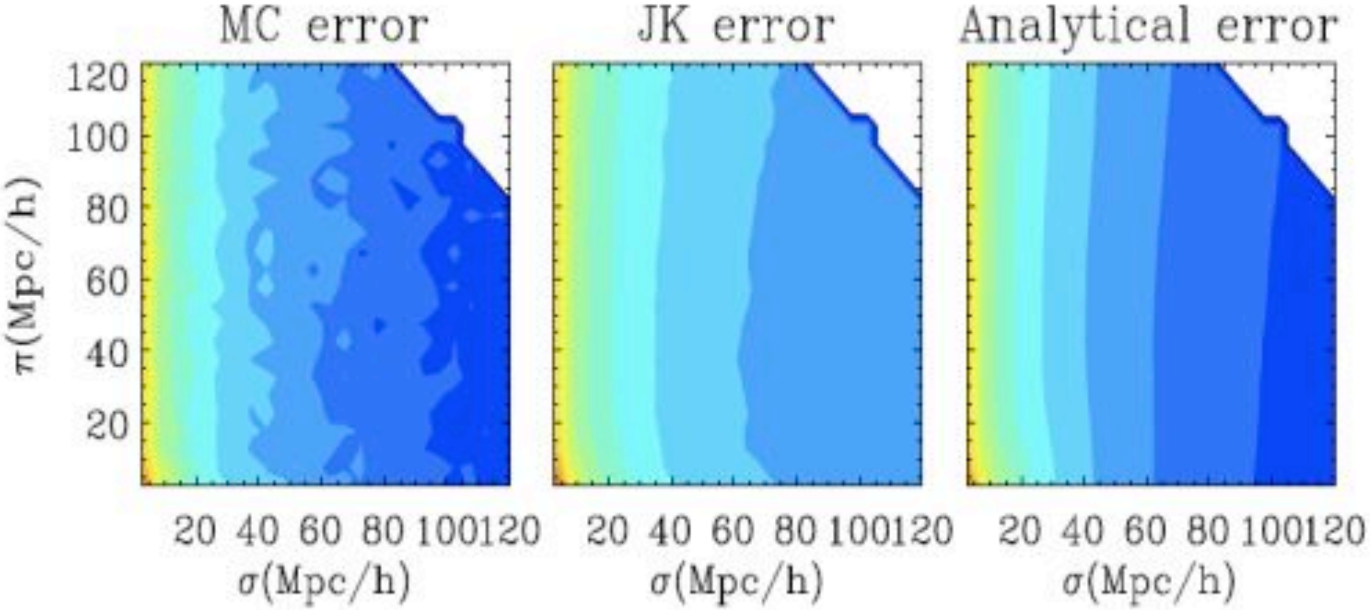
Padmanabhan



Separate Radial and Perpendicular BAO

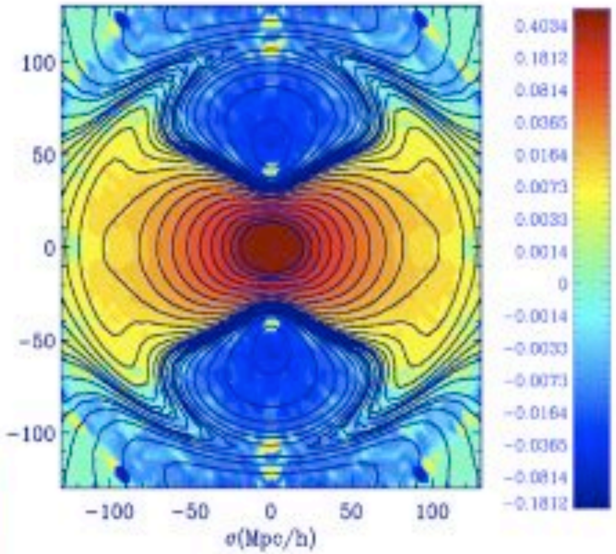
MICE L7689 simulation





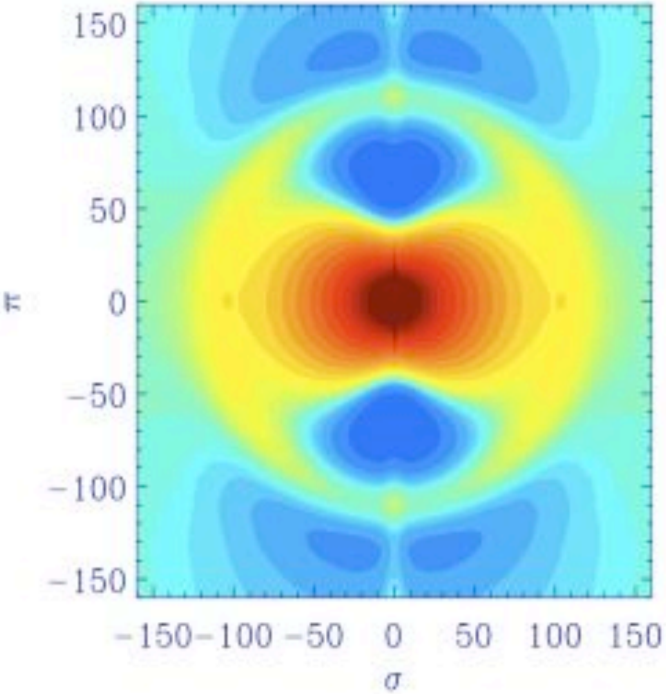
Cabré & Gaztañaga

Separate Radial and Perpendicular BAO

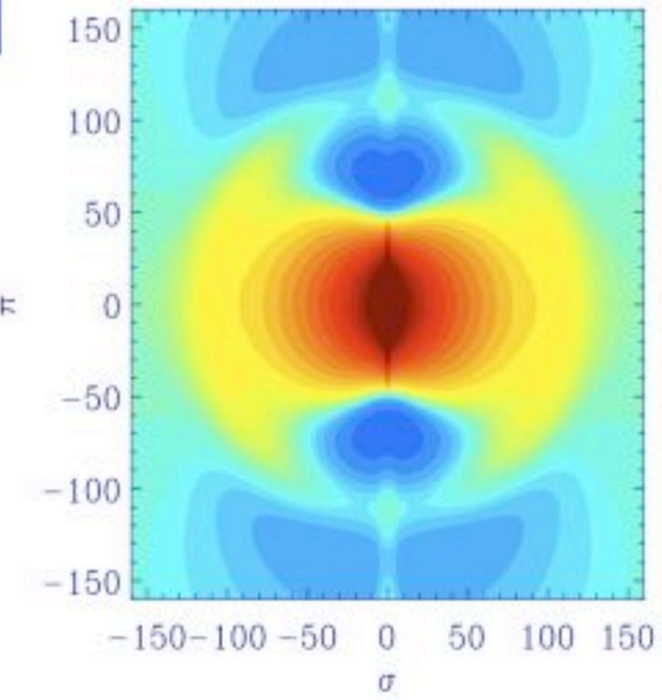


MICE L7689 simulation

Reddshift space, non-linear bias and lensing effects



PAU Photo-z

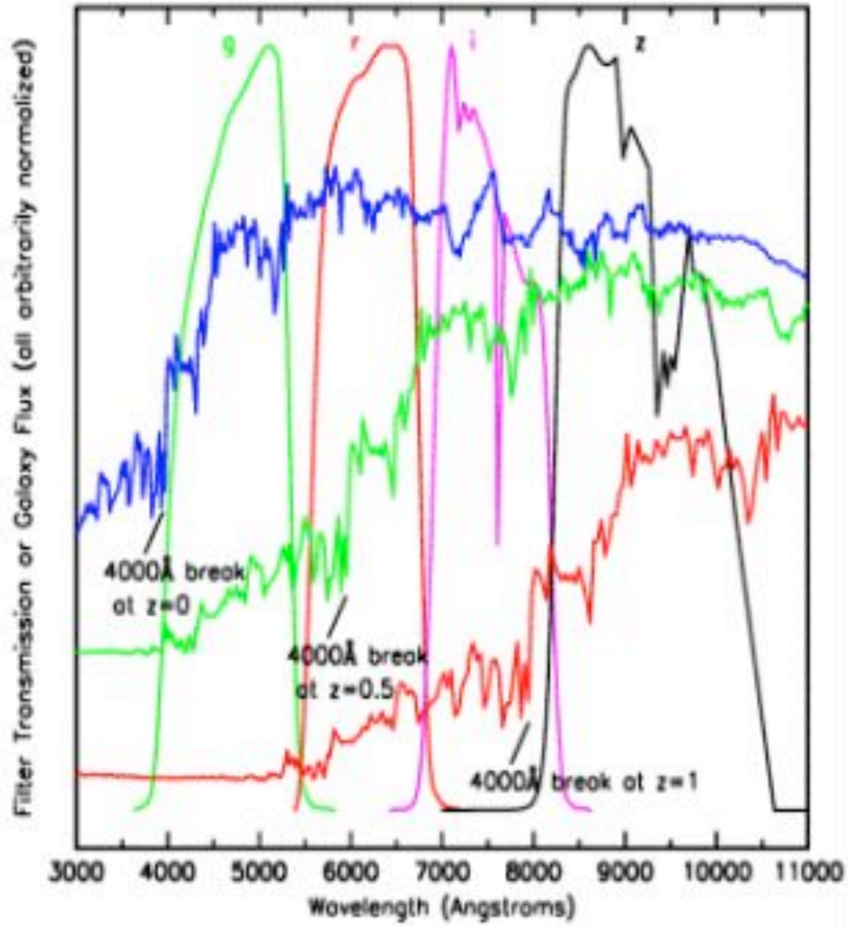


Cabré & Gaztañaga

Physics of the accelerating Universe

The PAU Survey

Photometric survey. Target “Luminous Red Galaxies” as in many other surveys. These are old elliptical galaxies, which are very bright and have a characteristic spectrum with a prominent break at 4000Å.

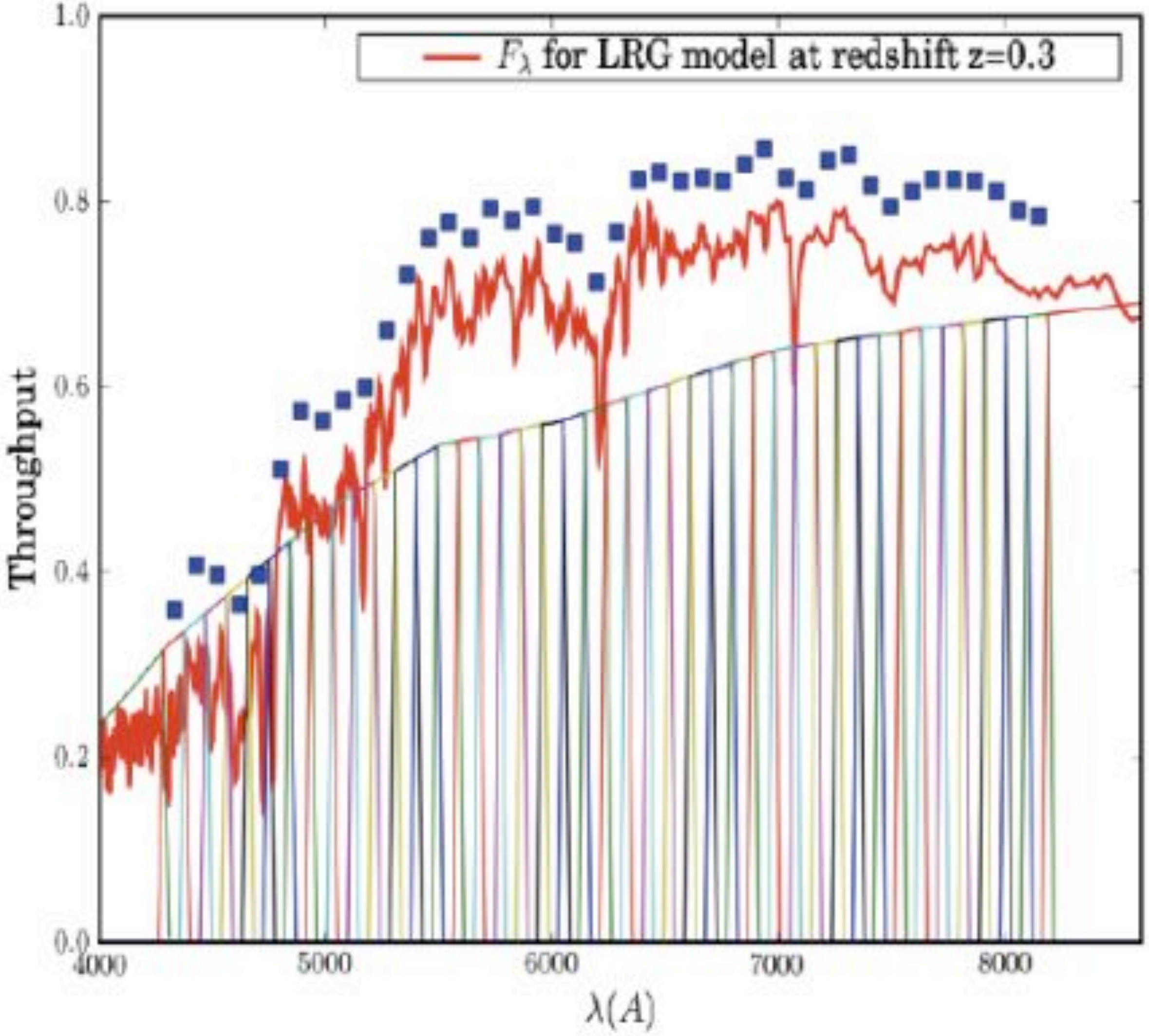


The position of the break (+) gives us z.

SDSS

Physics of the accelerating Universe

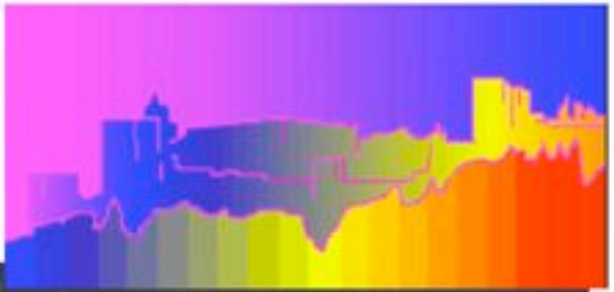
The PAU Survey: use a filter system consisting of ~40 filters (100Å wide), plus two wide filters (similar to SDSS *u* and *z*)

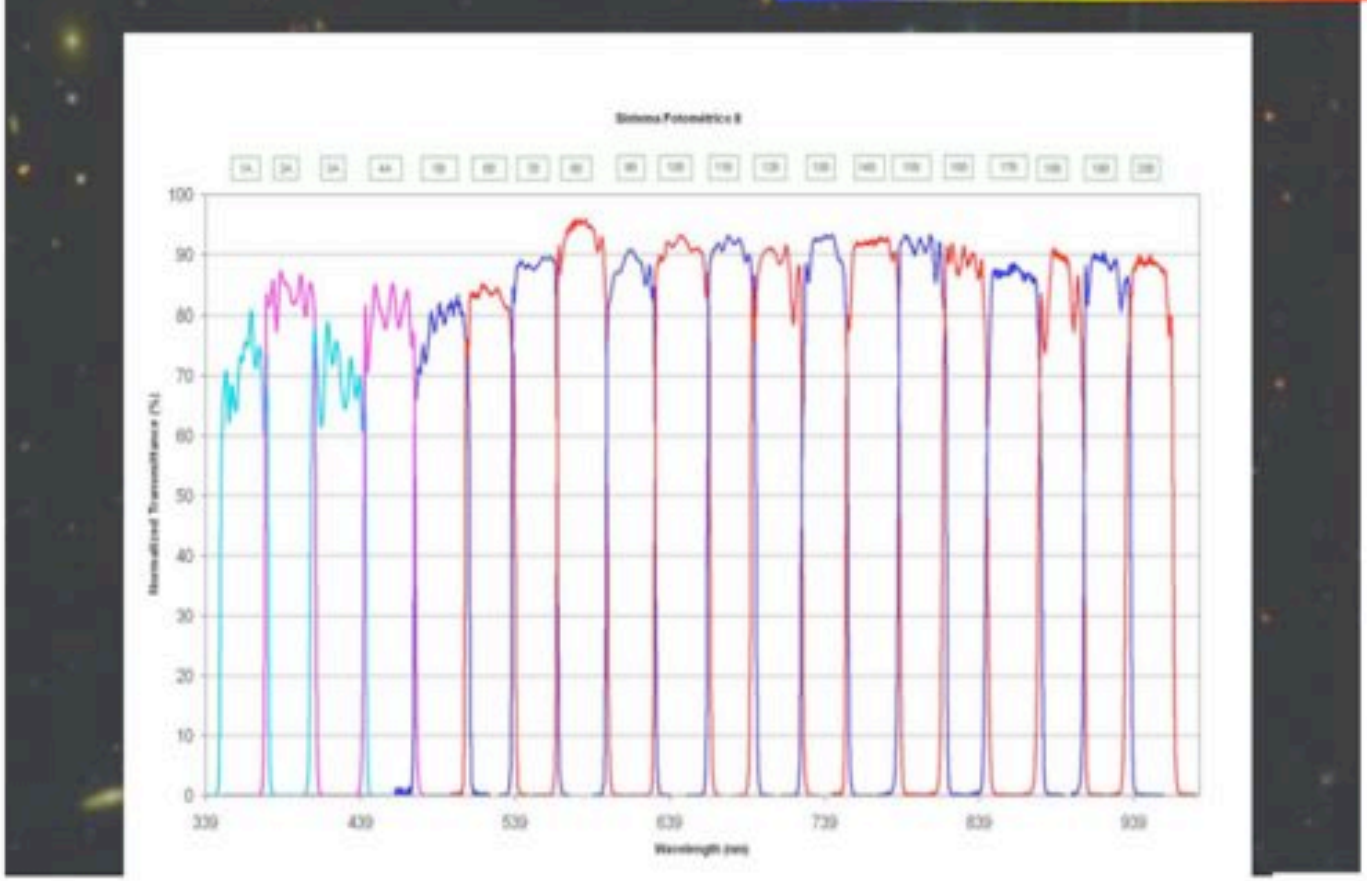


Benítez

ALHAMBRA

survey at Calar Alto





20 filters

Moles et al.

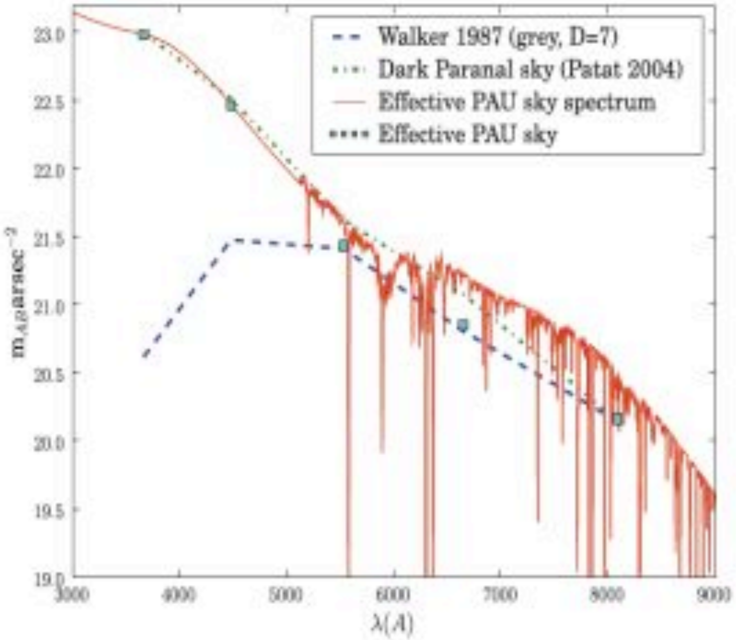
Expected z resolution

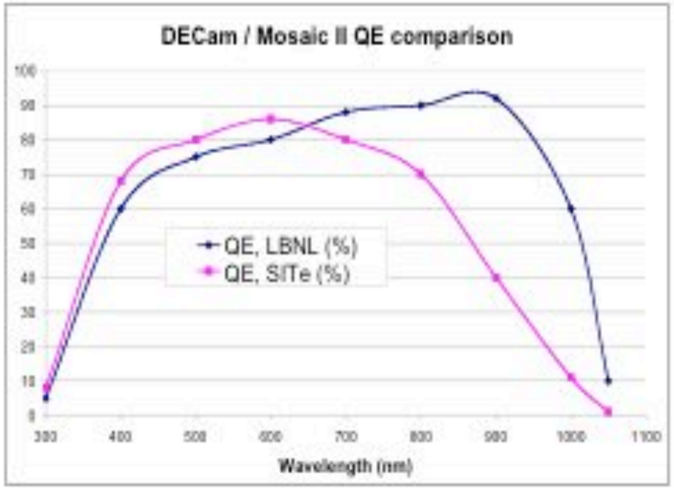
From back-of-the-envelope calculation (assume step-function in flux, falling between two filters):

$$\sigma_z \approx \frac{2\Delta\lambda}{4000}\frac{\sigma_f}{F} = 0.05\frac{\sigma_f}{F}$$ for $\Delta\lambda$=100Å filters

$\sigma_z = 0.003\ (1+z)$ at $z=0.9$ ⇒ $\sigma_f / F = 0.12$ ⇒need S/N~12, which is achievable for LRG at this redshift.

Physics of the accelerating Universe





Expected z resolution

Much more elaborated simulation:

- Exposure time calculator with observing conditions
- taken from several sites
- CCDs as in DES (LBL CCDs)
- Filters as in Alhambra
- 2m telescope; 6 deg^2 FoV camera
- optimization of exposure times
- Galaxies brighter than I_{AB}=23
- Model for LRG Bruzual&Charlot (11Gyr, Z=0.2)
- Photo-z's from BPZ (Benítez)

Physics of the accelerating Universe

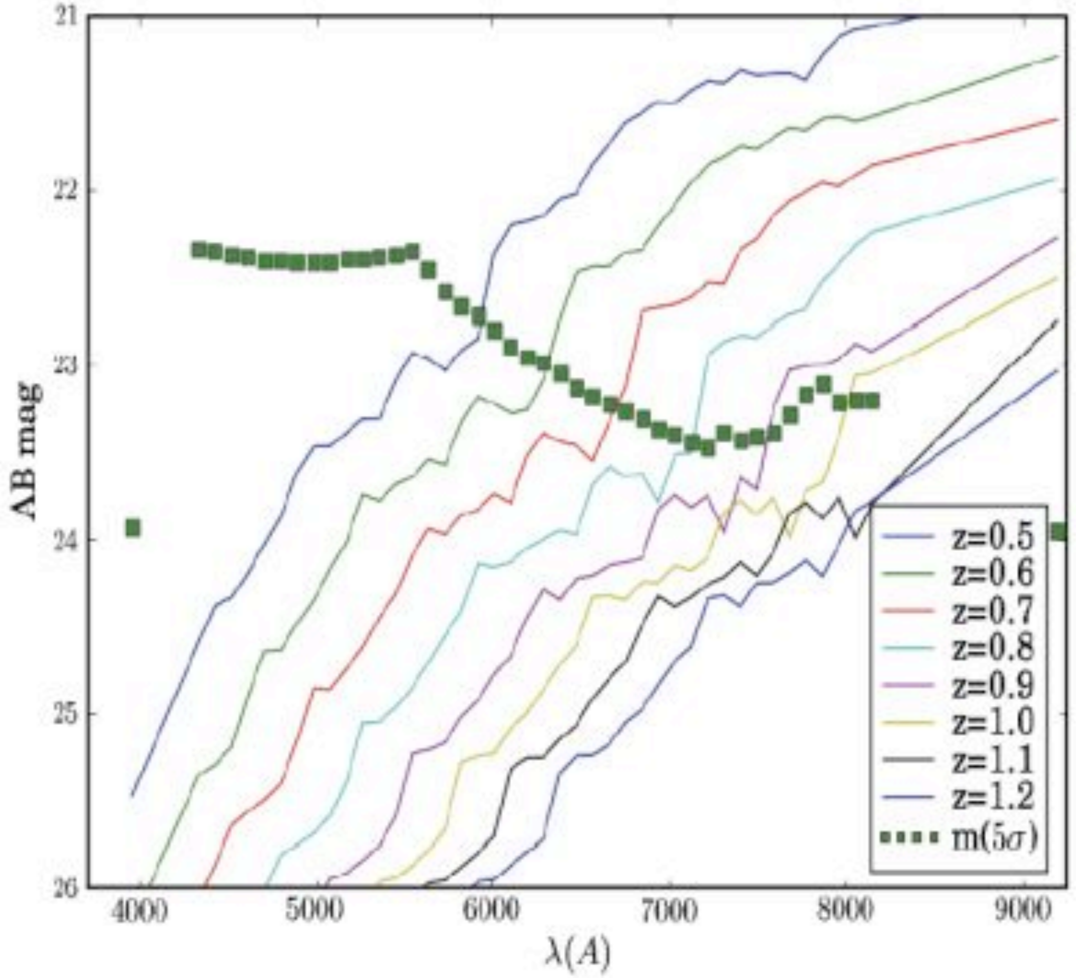
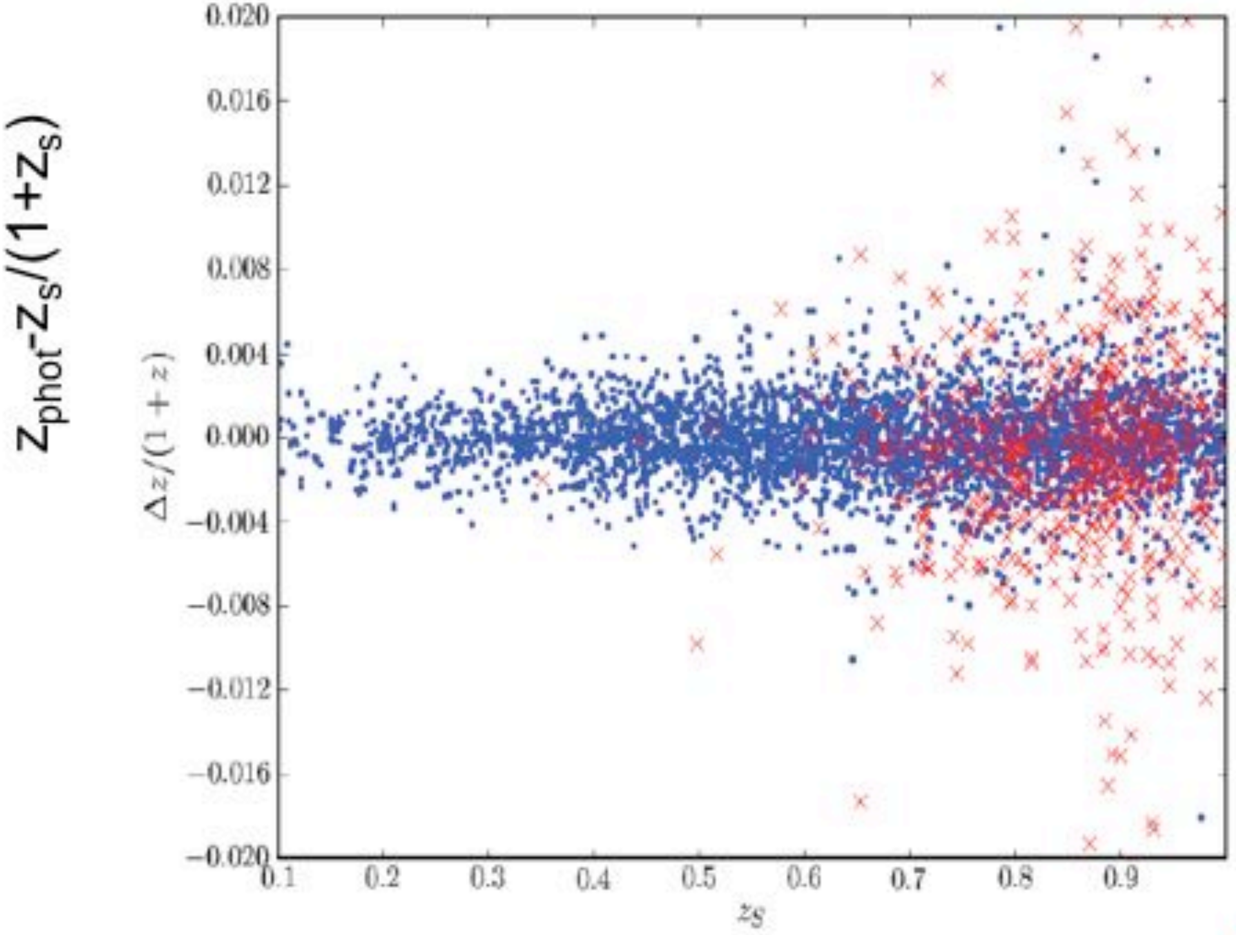


FIG. 8.— The expected 5-σ limiting magnitudes for point sources (squares) and the observed spectra of a $L_\star$ red galaxy at different redshifts (without taking into account spectral evolution, but taking into account aperture corrections). Note that we are able to catch the rest frame 4000 Å break with enough filters on both sides up to z=0.9.

Physics of the accelerating Universe



Use *odds* parameter from BPZ photo-z method to eliminate badly determined z's.

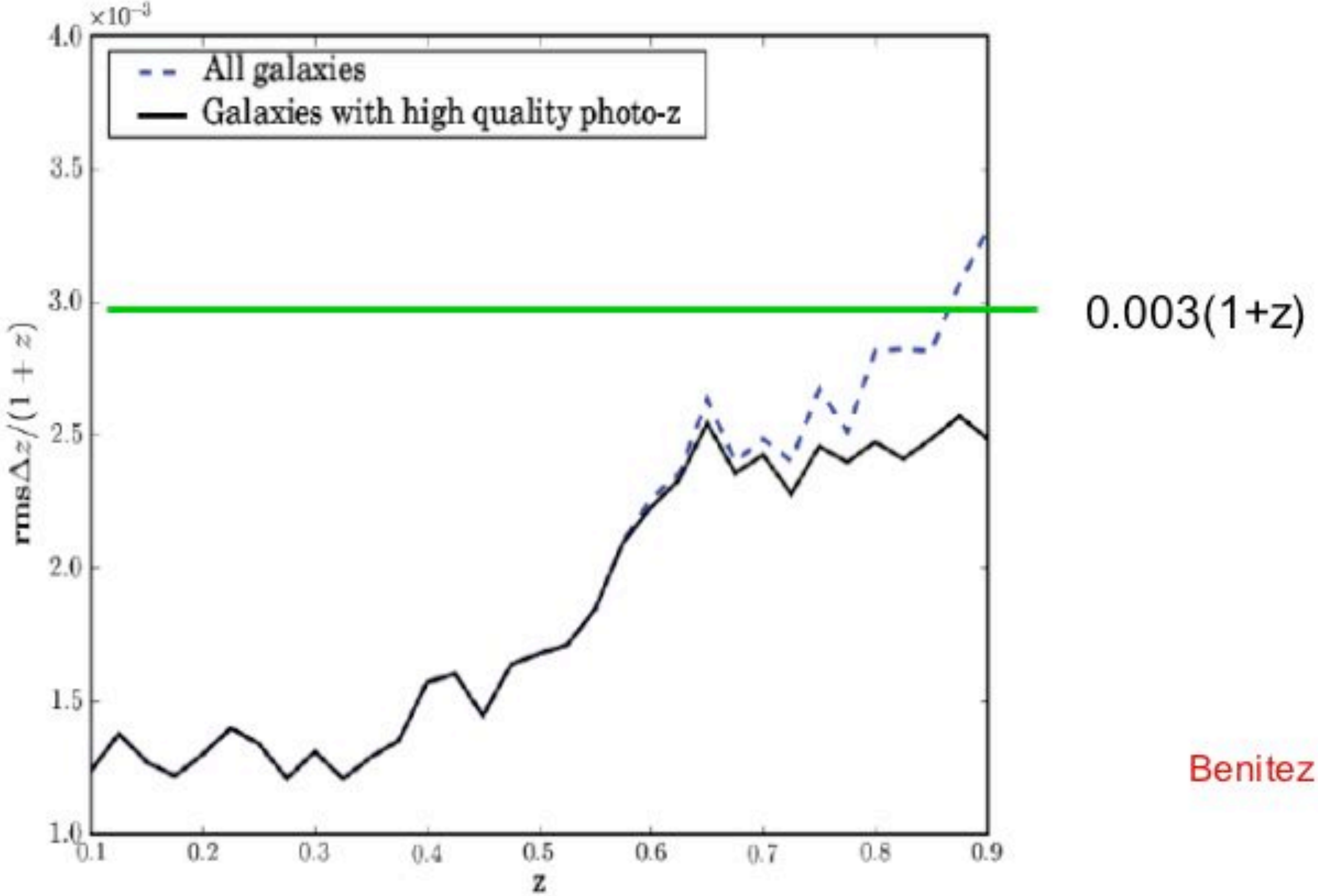
In red the LRGs for which the odds is less than 0.5.

Benitez

The r.m.s. of the remaining LRGs is well within the 0.003(1+z) limit

Physics of the accelerating Universe

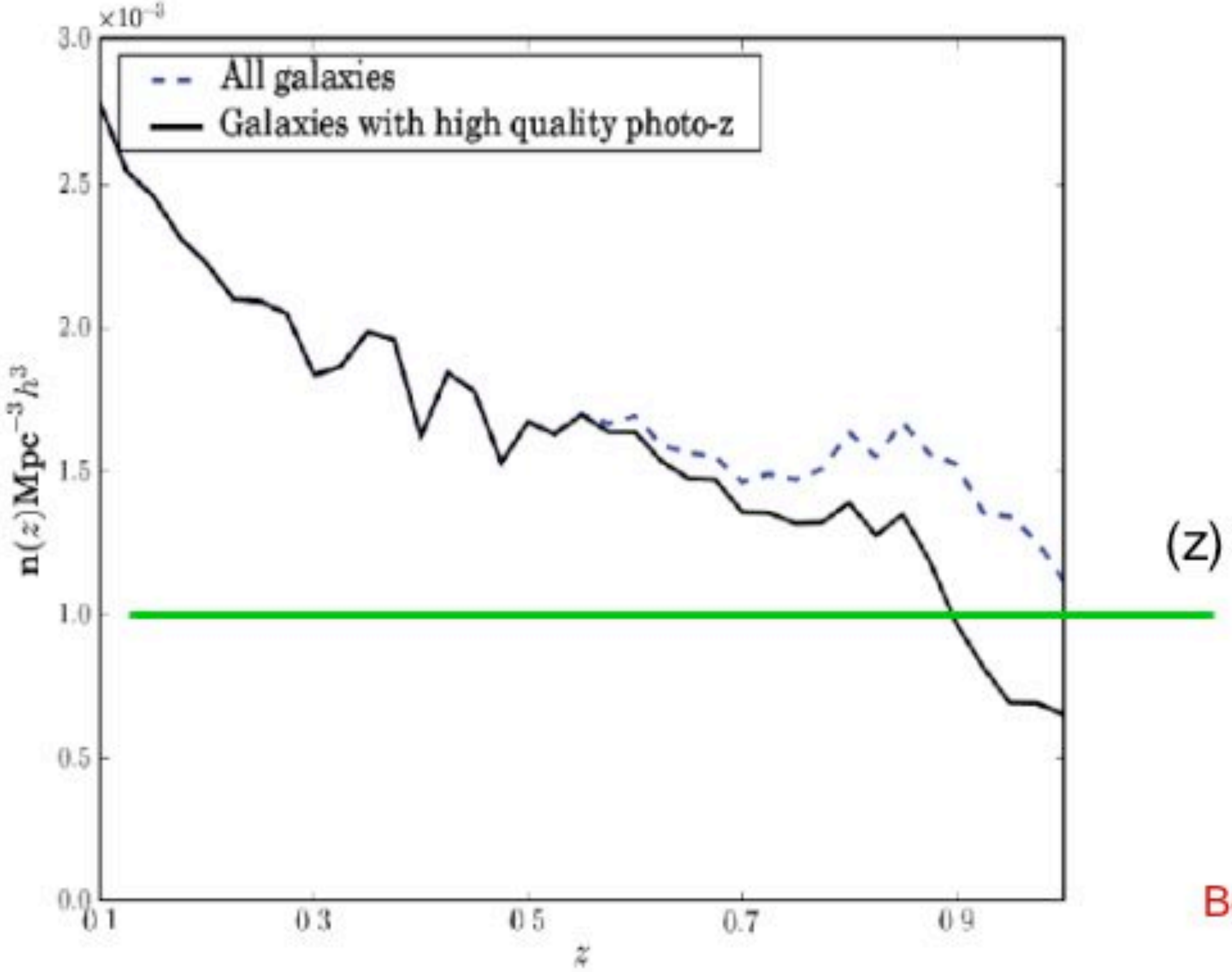
Δz r.m.s as a function of the true z



Benitez

Physics of the accelerating Universe

Spatial density of LRG with $I_{AB}<23$



$(z) > 10^{-3}\ (h/\mathrm{Mpc})^3$

Benitez

Physics of the accelerating Universe

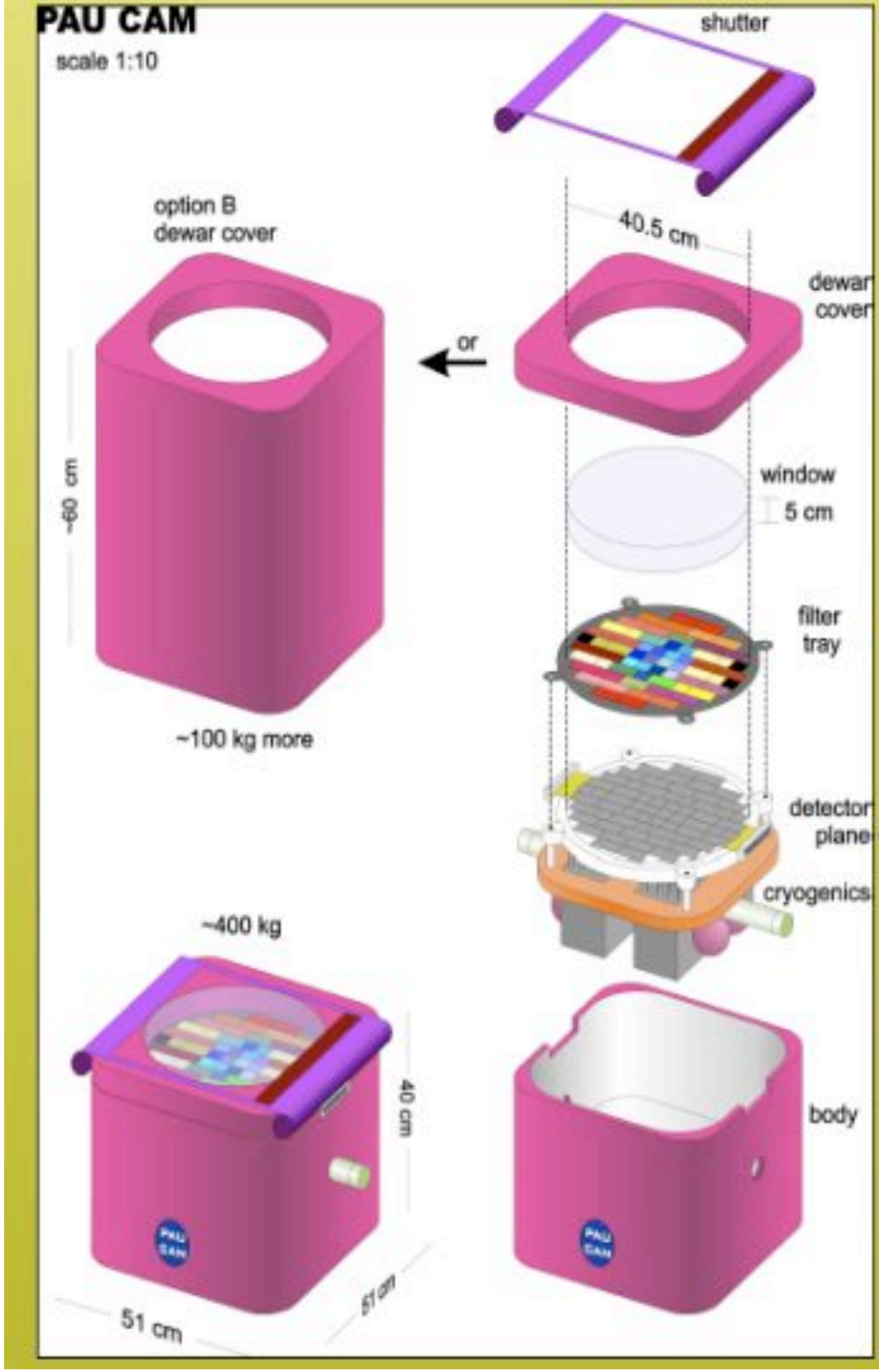
Telescope-camera system: 2m-class telescope with a ~ 6 deg^2 FoV camera ⇒ ~ 500 Mpixels with 0.40”/pixel ⇒ ~60 CCDs *2Kx4K*.

This is demanding but feasible.

Conceptual design studies for a telescope with the required parameters exist (from industry), as well as cost estimates.

Alternative is to place camera in an existing (larger diameter) telescope of smaller aperture. Possibility of using dichroic mirrors also being explored.

PAU CAM

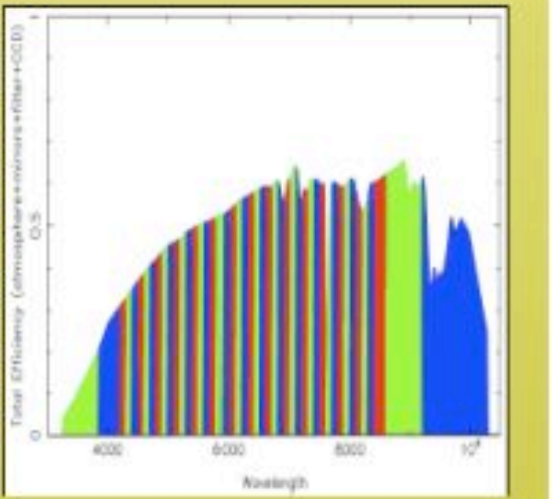


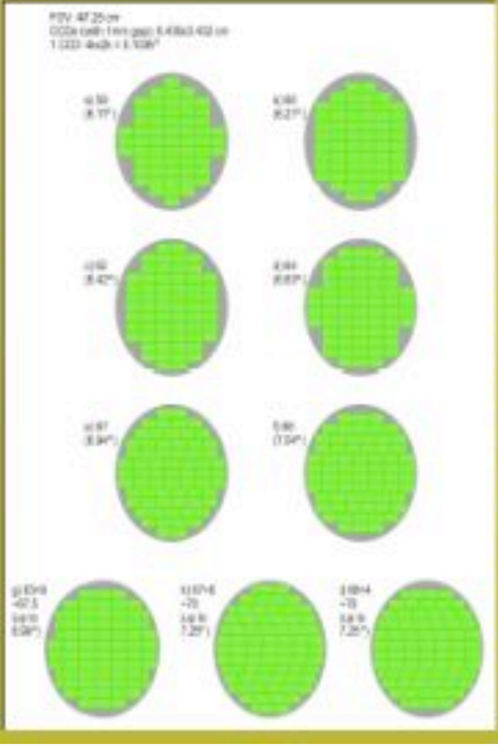
With these considerations and the time for the survey (4-5 years) we choose to do photometry in narrow-band filters.

FILTERS

40-45 narrow-band filters with a constant widht of ~100 Å and a transmission curves close to Heaviside functions, that are contiguous and non overlapping covering the spectral region between 4200 and 8500 Å and two broad-band filters in the red and blue wings.

Given the physical dimension of the camera focal plane, we opt to assign a filter for each detector.





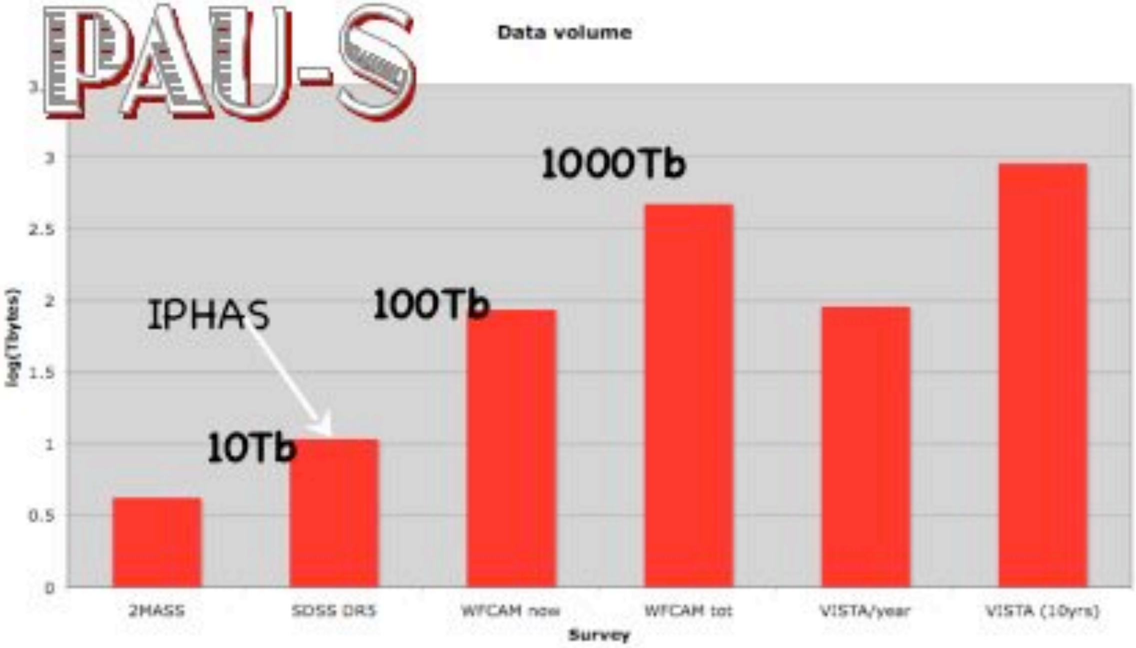
FOCAL PLANE

The camera will incorporate a large number of CCDs to cover $6\ deg^2$ field of view. For our plate scale of 0"4 /pixel, taht implies a 500 Megapixels camera or about 60 2Kx4K CCDs.

The figure shows possible schematic layouts of the CCD configuration in the focal plane.

The read-out time for the camera would be a considerable fraction of the total exposure (larger than 15%). When considering a survey of 4-5 years, this is not negligible amount of time. Thus, for this and others considerations we choose the Time-Delay and Integrate mode, also known as drift-scanning.

PAU-S



Based on 3 examples:

BOSS, DES, VISTA

But asuming cheaper labor and seed contribution from PAU

27 FTE (in 5 years)
= 4 Comp x 4yrs+2 Astro x4 Year
+ 3 mix x1 Year for prototype

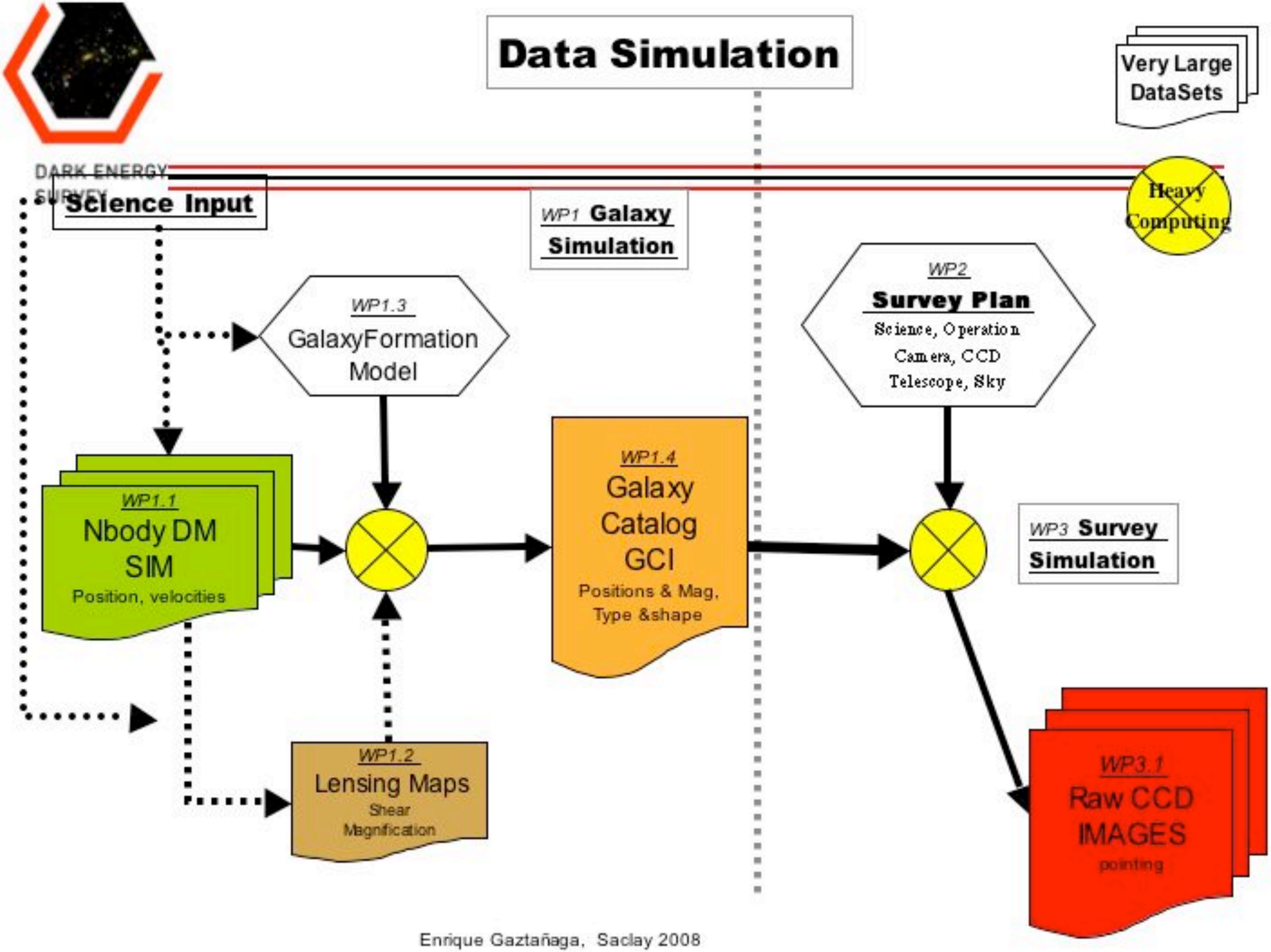
0.5-0.0 seed contribution (50Ke/FTE) from PAU teams:

- 12-24 FTE (x50 Ke) for 4yr Development +
- 150 Ke (Plan and prototype DM for 2008) +
- 200 Ke (Hardware ~ 200Tb)

Total ~ PAUS Development Cost: 0.95-1.55 Meuros

Data Simulation

DARK ENERGY SURVEY



Very Large DataSets

Heavy Computing

Science Input

WP1 **Galaxy Simulation**

WP1.3
GalaxyFormation Model

WP1.1
Nbody DM SIM
Position, velocities

WP1.2
Lensing Maps
Shear
Magnification

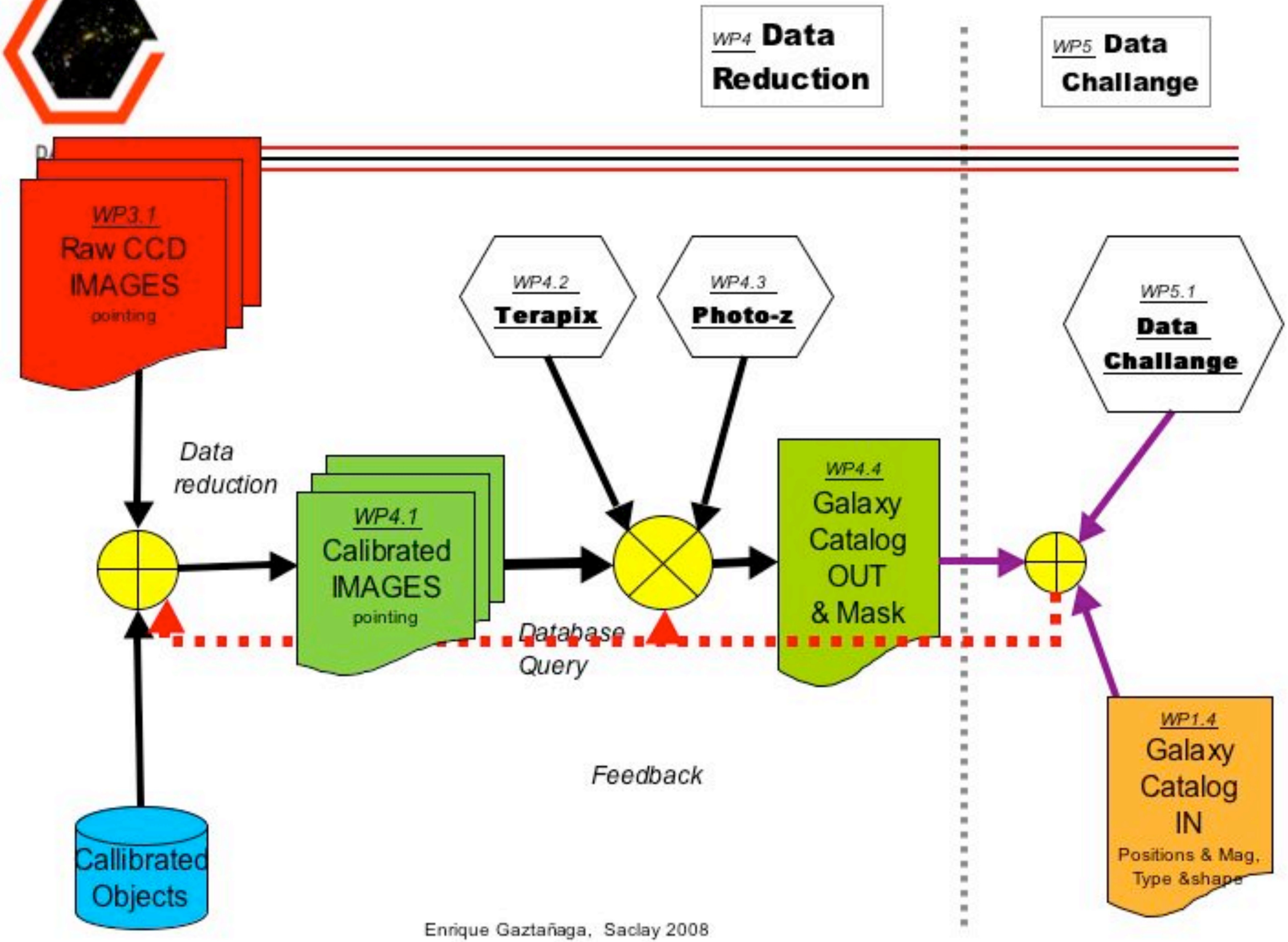
WP1.4
Galaxy Catalog GCI
Positions & Mag,
Type &shape

WP2
Survey Plan
Science, Operation
Camera, CCD
Telescope, Sky

WP3 **Survey Simulation**

WP3.1
Raw CCD IMAGES
pointing

Enrique Gaztañaga, Saclay 2008



WP4 **Data Reduction**

WP5 **Data Challange**

WP3.1
Raw CCD IMAGES
pointing

Data reduction

WP4.1
Calibrated IMAGES
pointing

WP4.2
Terapix

WP4.3
Photo-z

WP4.4
Galaxy Catalog OUT & Mask

WP5.1
Data Challange

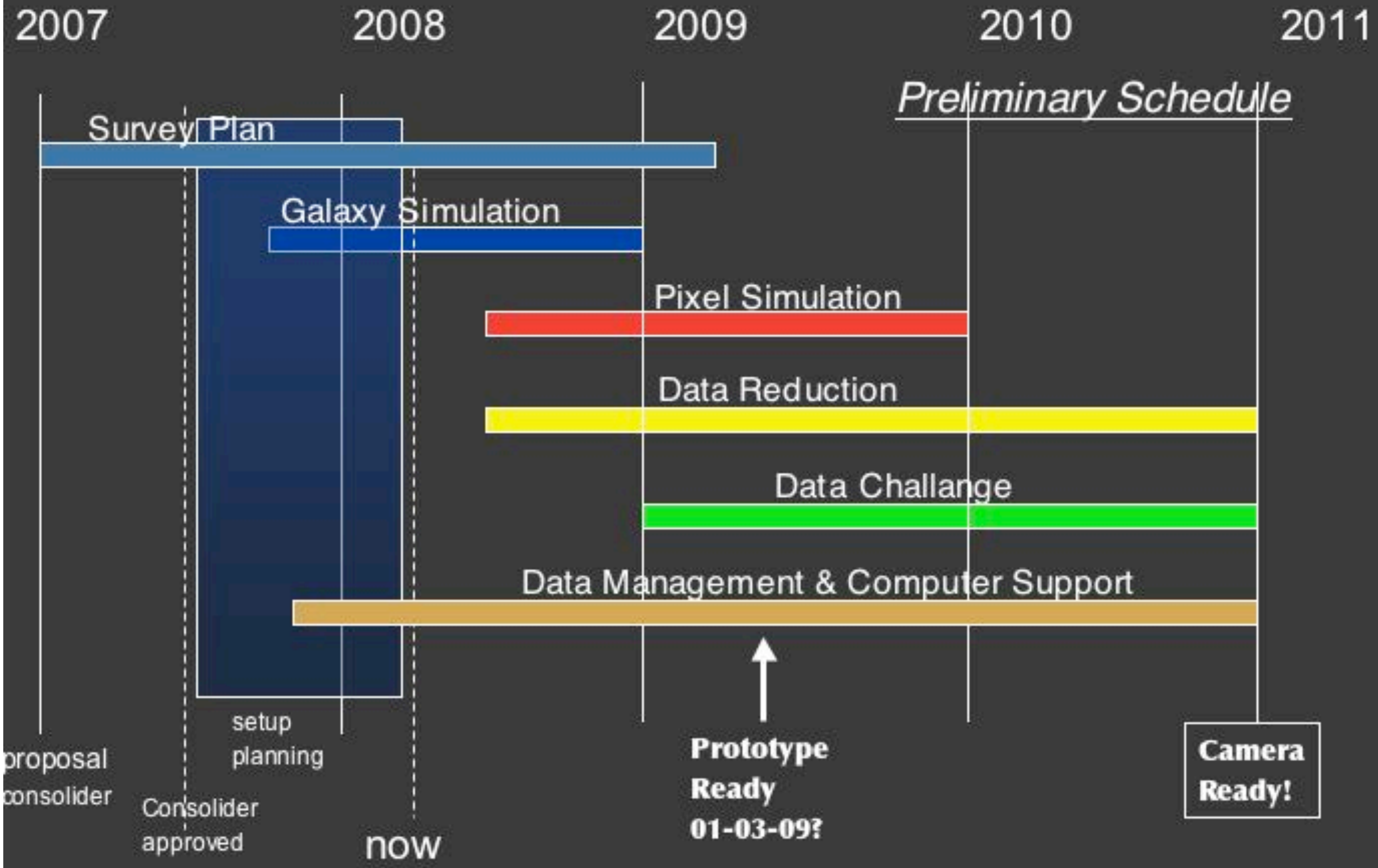
Database Query

Feedback

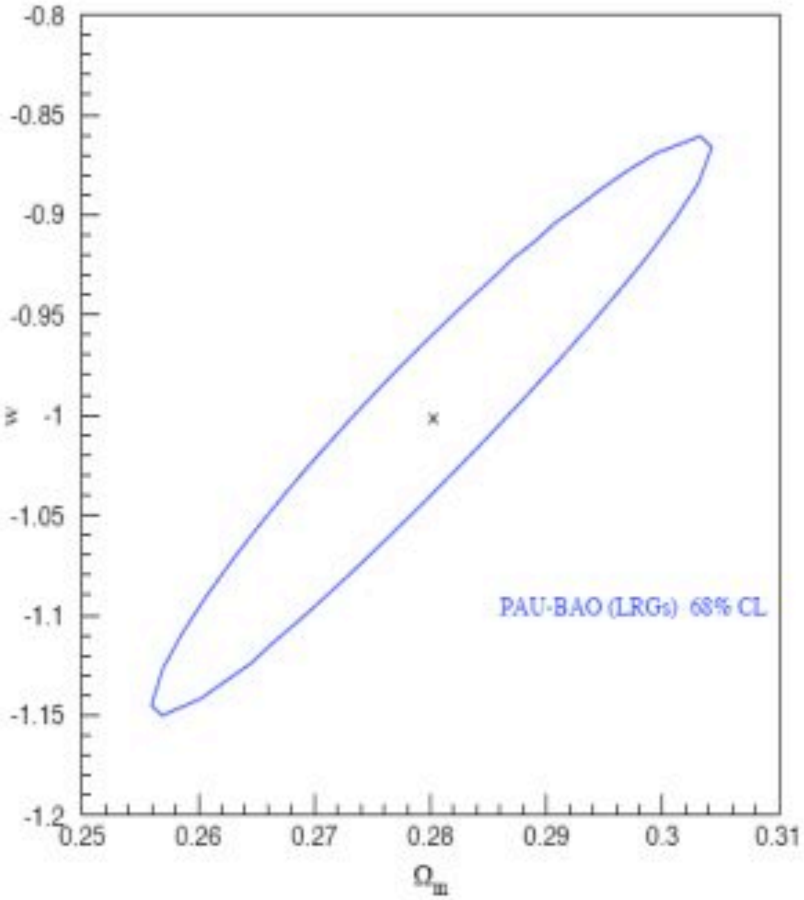
Callibrated Objects

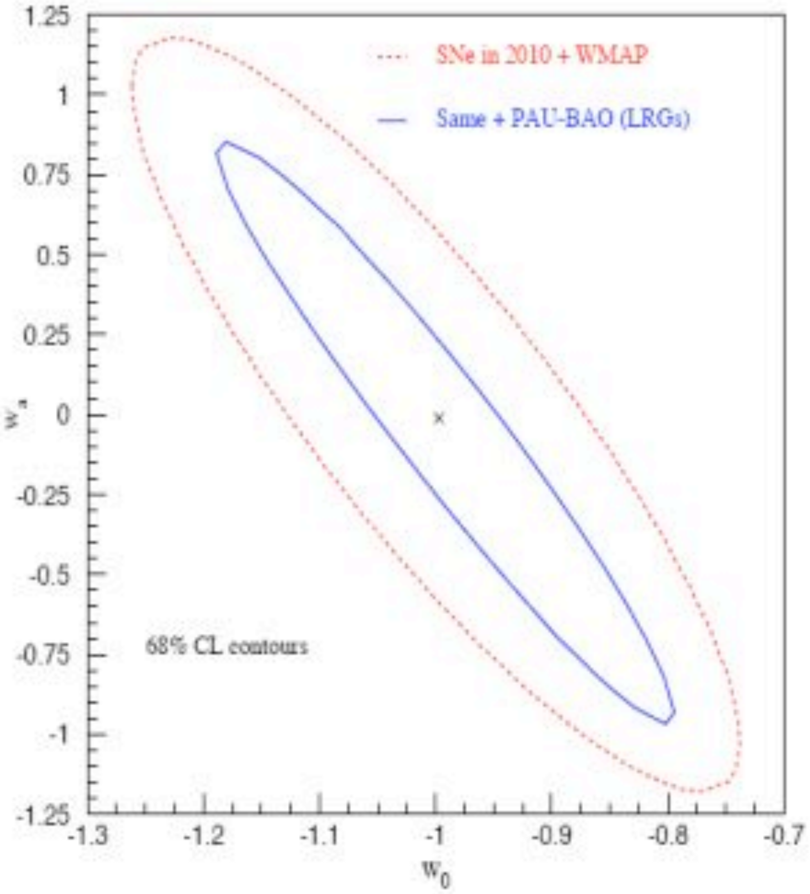
WP1.4
Galaxy Catalog IN
Positions & Mag, Type &shape

Preliminary Schedule



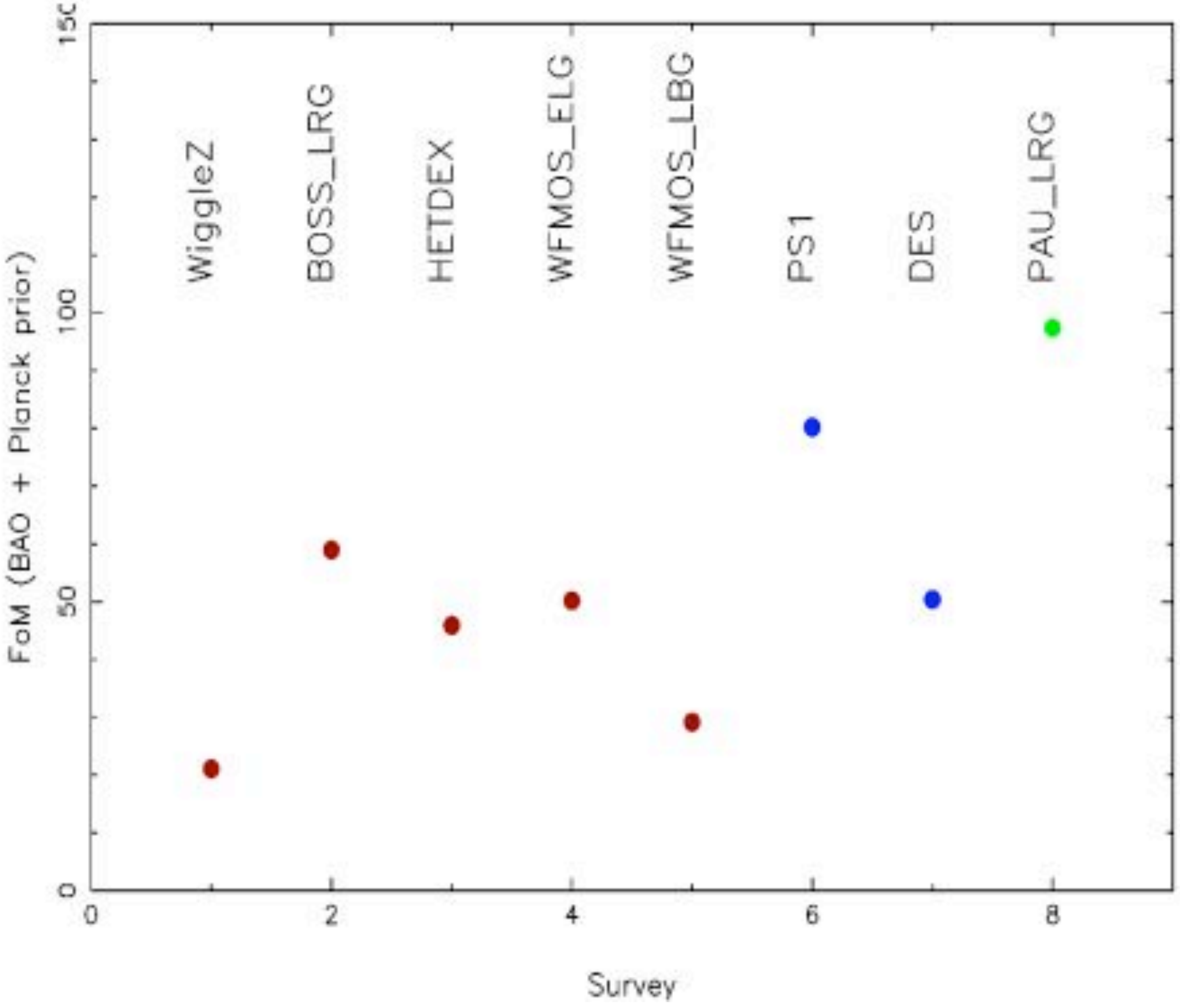
Dark Energy Parameters





Miquel

survey	z range	Number galaxies	Tracer	Area deg^2	Volume $(Gpc/h)^3$	Radial information	Time scale	reference
WiggleZ	$0.3 < z < 1.2$	2.8×10^5	ELG	1000	2.04	yes	2007-2009	Glazebrook et al. (2007)
BOSS-LRG	$0.2 < z < 0.8$	1.5×10^6	LRG	10000	8.06	yes	2009-2014	see text
HETDEX	$1.8 < z < 3.7$	1.0×10^6	LAE	200	1.91	yes	?	Hill et al. (2004)
WFMOS-ELG	$0.5 < z < 1.3$	2.0×10^6	ELG	2000	4.47	yes	?	see text
WFMOS-LBG	$2.3 < z < 3.3$	6.0×10^5	LBG	300	1.53	yes	?	see text
PS1	$0.3 < z < 1.5$	5.0×10^8	ALL	20000	65.3	no	?	
DES	$0.3 < z < 1.5$	1.5×10^8	ALL	5000	16.3	no	2011-2015	
PAU-LRG	$0.1 < z < 1.0$	1.5×10^7	LRG	8000	11.2	yes	2011-2015	this paper



Castander

Conclusions

- For the measurement of BAO a resolution in *z* of the of

  $\sigma(z) = 0.003\,(1+z)$ is close to optimal.

- This precision can be obtained photometrically with a multi-filter system of about ~40 filters, 100Å wide.

- A survey of 8,000 deg^2, from $0.1<z<0.9$ will give ~ 14 M LRG. From this sample the BAO scale can be measured both in the angular and radial (*z*) directions to 1%. This results in a substantial improvement of standard cosmological parameters, making it a competitive survey with respect to those being planned at present.

- New Window => 10^{12} low resolution spectra! (currently 10^{7} high resolution)