LSST:
photometric redshift and Baryon Acoustic Oscillations

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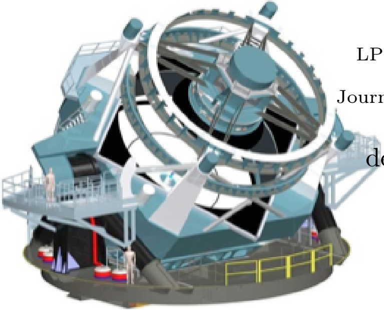
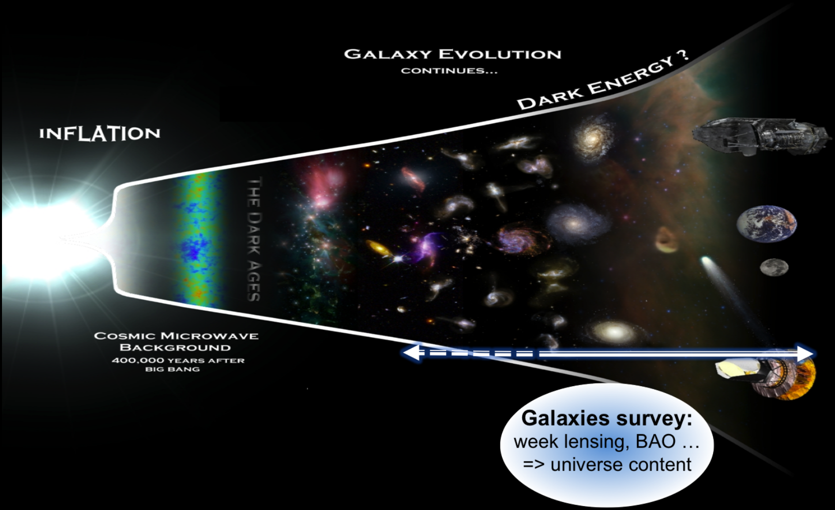


Contents

Introduction

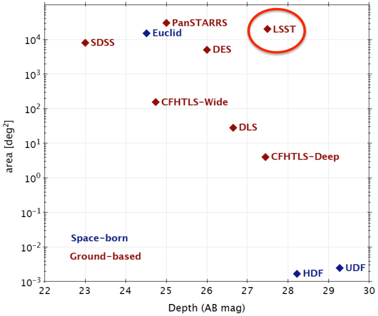


The Large Synoptic Survey Telescope: LSST

- **Site:** Cerro Pachón, Chili.
- **First light:** 2020.

- **Wide**
  - large aperture: 9.6 deg^2 ($\sim$50 full moon)
  - visible sky: 20 000 deg^2

- **Fast**
  - rapidly scan the sky:
    15s pose + 2s read + 15s pose +
    new pointing as reading
  - Revisit after 30-60 min;
  - Complete scan every 4 nights.

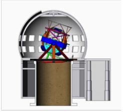


- **Deep**
  - Observe billions of galaxies
  - $m_r = 27.7$ (10 years)
    $m_x = -2.5\log(F_x)$
    $\Delta m = 3 \Leftrightarrow F/16$

LSST design

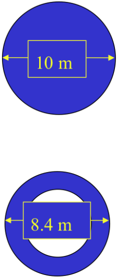
- Three mirror designs (Paul-Baker system)

Keck
(Hawaii)

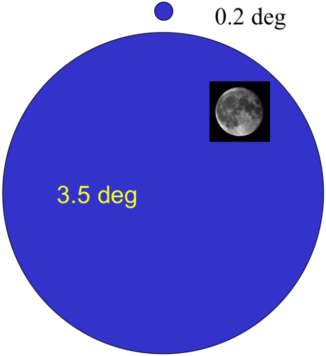


LSST

Primary mirror diameter



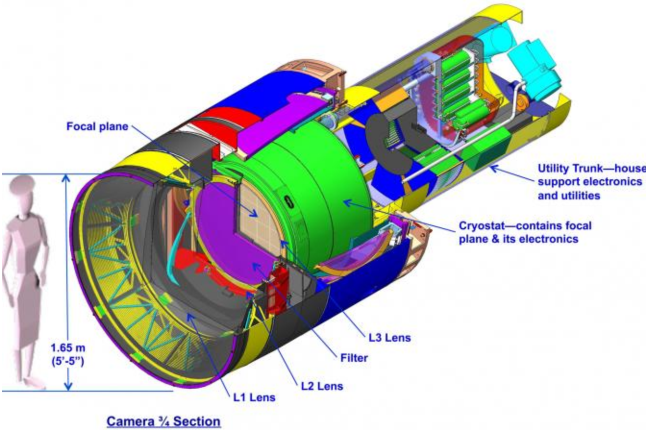
Field of view
Full moon = 0.5 deg



- Etendue = mirror surface × Field of view
(∼volume of universe ∼ depth × sky surface)

Camera

- **Focal plan:** 64 cm diameter, 189 CCDs, 3.2 billions pixels
- 3 lenses + 6 filters (ugrizy)
- Mass: 3000 kg



$\Rightarrow$ High precision on calibration is needed (test bench developed at LPSC).

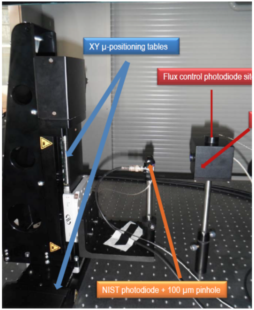
Camera Calibration Optical Bench (CCOB)

Goal:

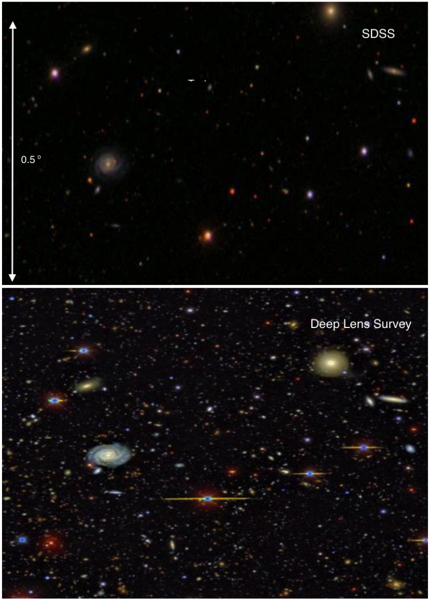
- scan in a few hours the entire Focal plane (189 CCD, 3.2 billions pixels),
- deliver camera first light (dead and bad px identification),
- measure the pixel to pixel relative response:
  - 0.5 % level precision on the entire focal plan,
  - 0.2 % level precision at a raft scale (3x3 CCD).

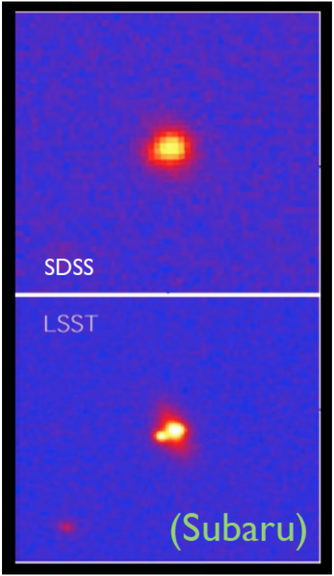
R&D:

- validation of LED as light source,
- beam caracterization at 10 μm (LSST pixel scale)
- beem profile must be controlled at 0.1% (vs voltage and temperature)
- test and select several LEDs in order to cover LSST wavelength range.



LSST image quality: depth and resolution



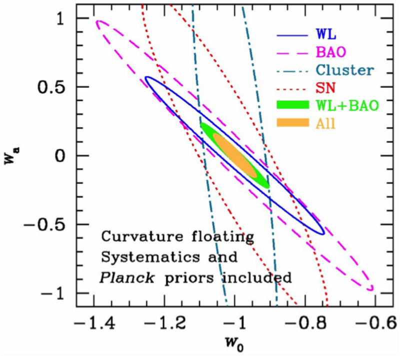


LSST science goals

4D universe mapping: (α, δ), z (redshift), time variation.

- Inventory of the Solar system:
  - hazardous asteroids,
  - Long Period Comets ...
- Mapping the Milky Way:
  - stellar populations (observation of billions of stars)
  - → star formation, evolution ...
- Transient objects:
  gamma ray burst, AGN ...

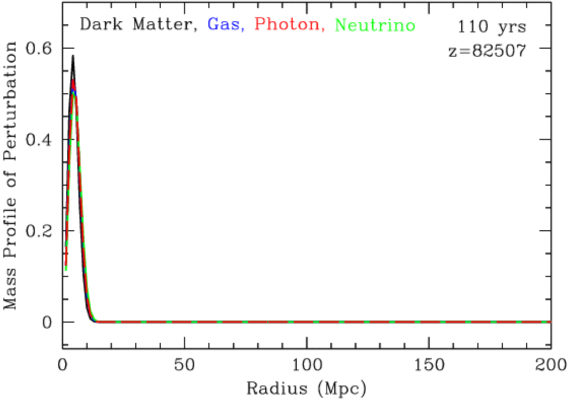
- Probe dark mater,
- **Probe dark energy** (p<0)
  $p = w\rho = [w_o + w_a(1-a)]\rho$
  Supernovae, weak lensing, **BAO**.



LSST science book

Structure formation in the universe relies on gravitational instability to aggregate the material.

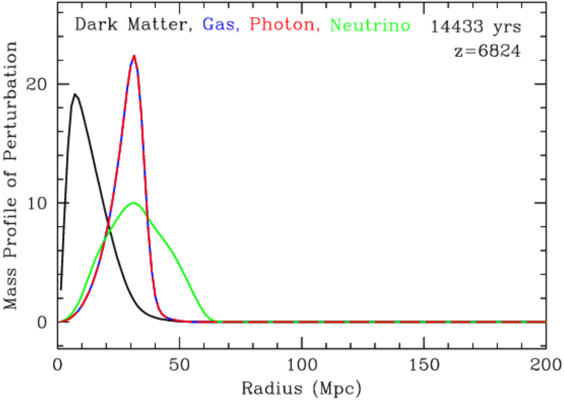
0) **Initial perturbations**: adiabatic → all of the species are perturbed the same fractional amount



What are BAO ?

Structure formation in the universe relies on gravitational instability to aggregate the material

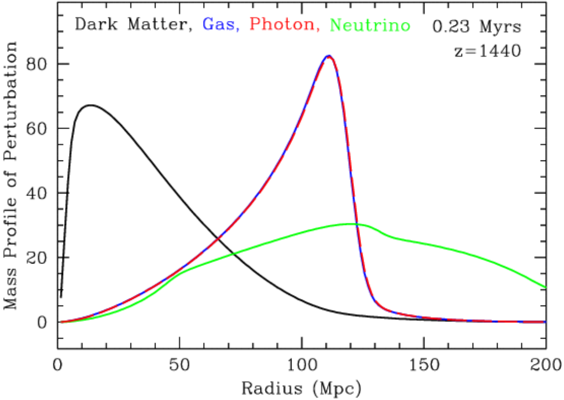
1) Spherical acoustic wave ; baryons coupled to photons; **neutrinos escape**, dark matter moves only in response to gravity and has no intrinsic motion



What iare BAO ?

Structure formation in the universe relies on gravitational instability to aggregate the material

2) Spherical shell of gas and photons continues to expand. The **neutrinos spread out**. The dark matter collects in the overall density perturbation.

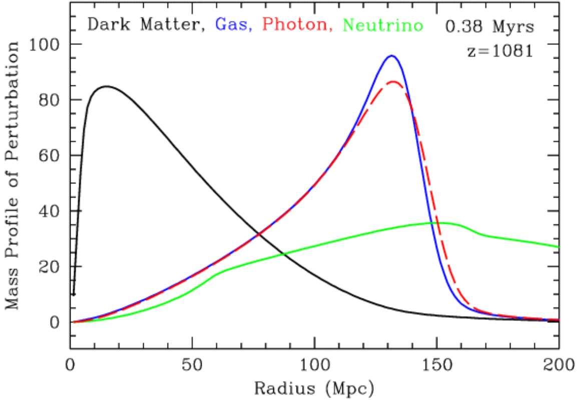


Daniel J. Eisenstein

What are BAO ?

Structure formation in the universe relies on gravitational instability to aggregate the material

3) Electrons and nuclei begin to combine into neutral atoms. The expanding universe is cooling. **Photons and gas coupling is reduced.**

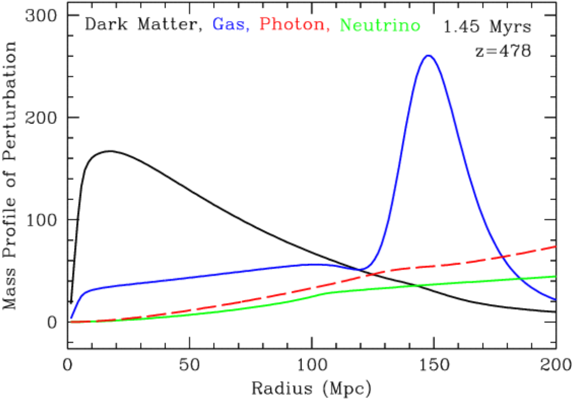


Daniel J. Eisenstein

What are BAO ?

Structure formation in the universe relies on gravitational instability to aggregate the material

4) **Decoupling** : sound speed vanished ; baryons carry the footprint of fuctuations in a shell about 150 Mpc. Photons escape (CMB)



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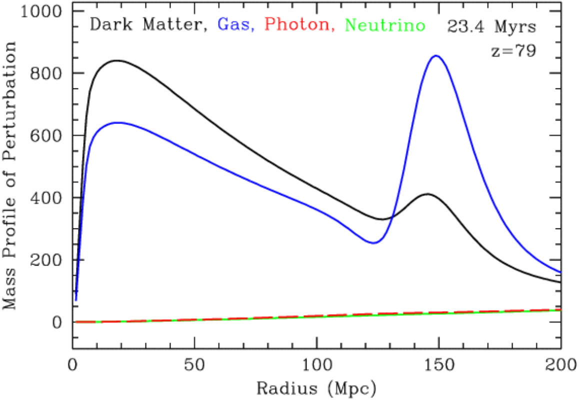
What are BAO ?

Structure formation in the universe relies on gravitational instability to aggregate the material

5) DM and baryons coupled by gravitation: the spherical shell of the gas perturbation has imprinted itself in the dark matter ⇒ **acoustic peak**.



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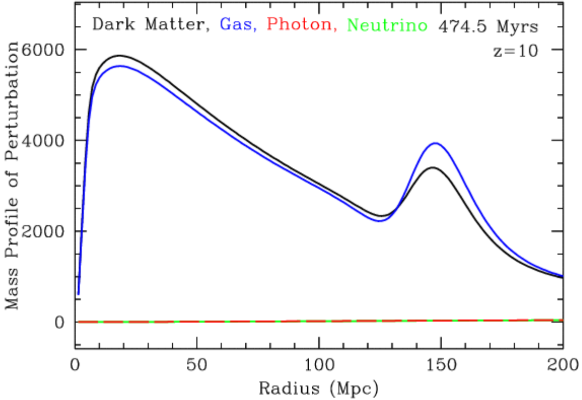
Structure formation in the universe relies on gravitational instability to aggregate the material

6) **The acoustic peak decreases** in contrast as the gas comes into lock-step with the dark matter.



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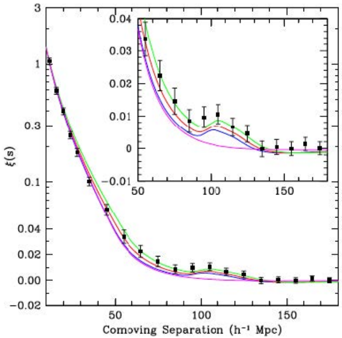
BAO as a cosmological probe

- Distance distribution measurement
  ⇒ **2 points correlation function** $\xi(r)$.
  → $\chi = 100h^{-1}Mpc$
- First measurement:
  2004 (2dFGRS and SDSS)
- A 3D measurement:
  - Position of acoustic peak
    ⇒ Size of the sound horizon $\mathbf{rs}(\Omega_m, \Omega_B)$
  - Transverse direction:
    ⇒ Sensitive to angular distance $\mathbf{d_A(z)}$
  - Radial direction:
    ⇒ Sensitive to Hubble parameter $\mathbf{H(z)}$:

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + (1-\Omega_m-\Omega_\Lambda)^2}$$

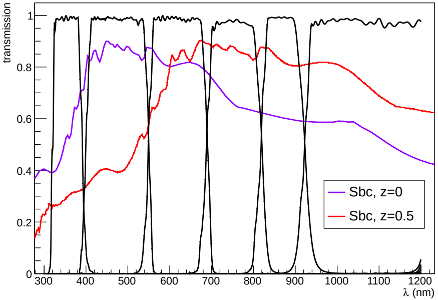


D. J. Eisenstein, astroph 2004

Photometric redshift reconstruction:

Method and filters design impact

Photometric redshifts with LSST



LSST specifications on $|\Delta z| = |\frac{z_p - z_s}{1+z_s}|$:

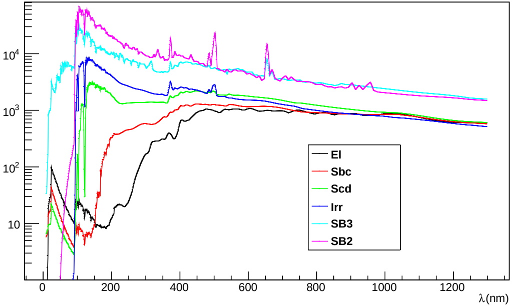
- 0.05 random error (RMS),
- bias $< 3.10^{-3}$,
- % outliers $< 10\%$ ($|\Delta z| \geq 0.15$).

LSST: 6 photometric bands ugrizy
⇒ **photometric redshift**

- machine learning method
- **template fitting method**
  - → we compute the integrated flux in each bands,
  - → we compare expected flux to some known emission spectrum at a range of redshift.

1) **Simulation Catalog**

- ΛCDM cosmology is assumed
- Absolute Magnitude, color excess E(B-V), z_{true},
- 51 galaxies spectral types interpolated between 6 main SEDs: El, Sbc, Scd, Irr, SB3, SB2.



M82 - elliptical galaxy

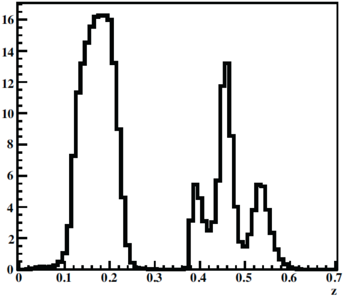
M31 Andromede - spiral galaxy

Likelihood reconstruction of z_p

2) **Photometric redshift reconstruction:** template fitting method

$$\chi^2(z,T,E(B-V)) = \sum_{i=1}^{Nbands} \left(\frac{F_i^{obs}(m_i) - NF_i^{exp}(z,T,E(B-V))}{\sigma(F_i^{obs}(m_i,\sigma(m_i)))} \right)^2$$

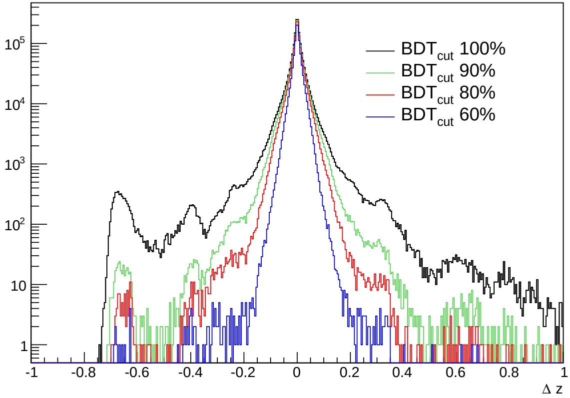
- Observation $\Rightarrow \mathbf{F_i^{obs}(m_i)}$
- 3D grid over z, spectral type T and color excess $E(B-V)$ $\Rightarrow \mathbf{F_i^{exp}(z,T,E(B-V))}$
- likelihood function computation
- marginalization over parameters $\Rightarrow$reconstructed redshift z_p.



Quality cut

Boosted Decision Tree (BDT)

- $|\Delta z| = |\frac{z_p - z_{true}}{1+z_{true}}| < 0.15 \Rightarrow$ "signal"
- Learning machine method: $\Rightarrow$ training set $\sim$ 450 000 galaxies
- 17 discriminant variables
    - PDF shape caracteristics: Npeak in the z marginalised pdf ...
    - color term (ex: r-i), z_p.

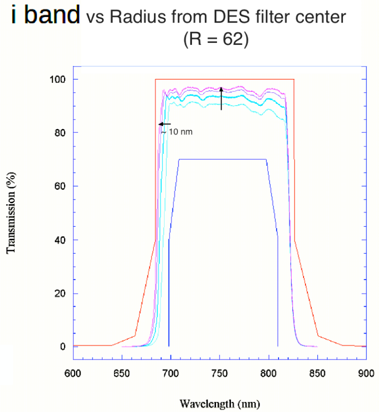


- $\mathbf{BDT_{cut}100\%}$:
  $bias = 1.8\ 10^{-3}$,
  $RMS = 0.06$
- $\mathbf{BDT_{cut}80\%}$:
  $bias = 1.2\ 10^{-4}$,
  $RMS = 0.03$

Impact of filters transmission shape

- The photo-z quality could be affected by different uncertainties on parameters which enter in the likelihood computation:
  - reddening or intergalactic medium law,
  - the SED library,
  - **filters**

- LSST filters are quite big (78 cm diameter)
  $\Rightarrow$ spatial inhomogeneities (coating)
- filters design is not fixed yet.



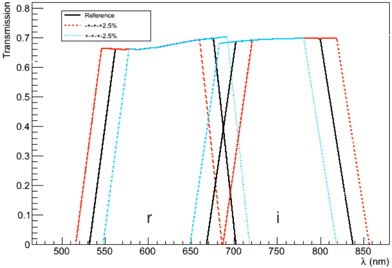
$\Rightarrow$ Impact of filters on photo-z quality ?
- impact of the incidence angle:
  $\rightarrow$ effective filter
- impact of slope design,
- impact of spatial variation (shift).

Impact of filter shifts

- Due to spatial variation, filters could be shifted up to ±2.5% (*LSST spec.*)

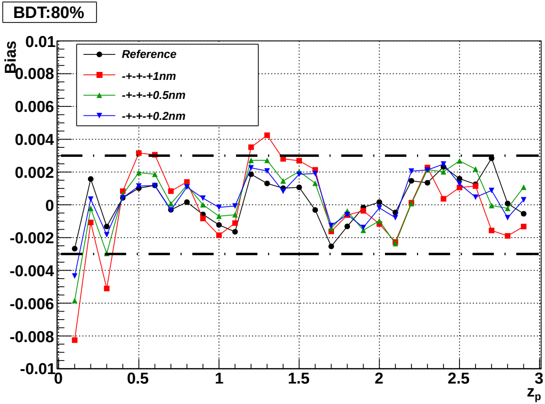
u	g	r	i	z	y
±9 nm	±12 nm	±16 nm	±19 nm	±22 nm	±25 nm

- Two scenarii tested:



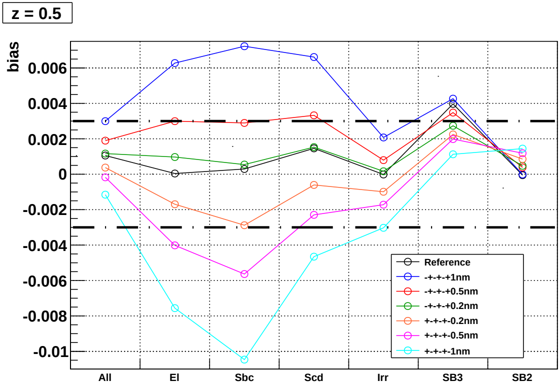
1) Extreme case: photo-z reconstruction with maximal shift,
2) Computation of effective filters for 10 years of observation,
   - small impact on photo-z quality,
   - in agreement with specification up to redshift 2.2.

3) Uncertainties on filters measurement:



- 1 nm uncertainties dramaticaly damaged photo-z,
- 0.5 nm uncertainties: non negligible impact,
- 0.2 nm uncertainties: similar to reference results.

Dependance on the galaxy spectral types



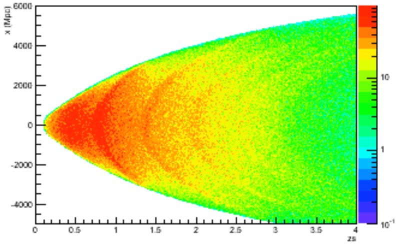
- Spiral galaxies are the most affected by uncertainties,
- Starburst are slightly affected
  - more numerous in the catalog,
  - photo-z quality is govern by starburst galaxies.

$\Rightarrow$ Filters mean wavelength must be known with a precision better than 0.2 nm.

Baryon Acoustic Oscillations (BAO)

BAO scale extraction

How can we constrain dark energy parameter w from BAO measurement?



1) **Spatial distribution** of galaxies is needed:
   - flat univers hypothesis,
   - ΛCDM cosmology,

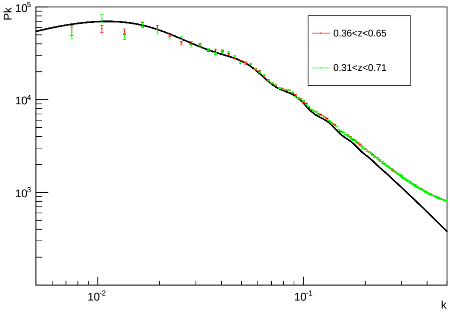
   $\Rightarrow$ projection of our simulated galaxies in a 3D Euclidean grille.

2) Matter power spectrum $\mathbf{P(k)} = TF(\xi(r))$ computation,
3) "wiggle only" method $\Rightarrow$ **BAO scale ka** measurement.
4) Constraints on dark energy parameter w:
   - ka: sound horizon in fourier space for one cosmology,
   - $ka = f(Dv)$,
   - $Dv = f(d_A^2(z, \mathbf{w}), H(z, \mathbf{w}))$,

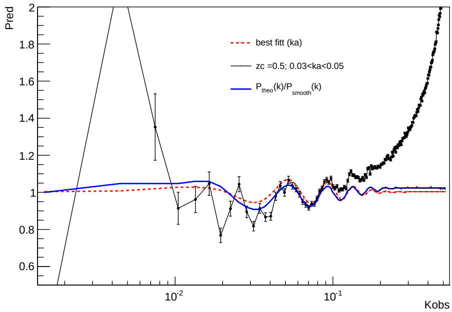
Galaxies distribution measurement $\Rightarrow$ constraintes on dark energy parameter.

BAO measurment (from known redshift)

- $P(k)$ is divided by a smooth spectra $P_{smooth}(k)$ (same cosmology without baryon).
- Fit by a decay sinusoidal function: $decSin(\mathbf{ka}, A)$
  χ^2 minimisation $\Rightarrow$ best fit $\Rightarrow$ ka.



$\Rightarrow$



Work in progress, nedd to be improve and extend to reconstructed redshift.

Conclusions and perspectives

LSST will observe billions of galaxies allowing the measurement of BAO scale at many z bins.

Calibration

- A test bech for the camera calibration is in developpement at LPSC (LED as light sources, stable vs voltage).

→ Beam shape caracterization.

Photo-z reconstruction

- Impact of filters "known" filter modification are negligible ,
- Filters has to be known with a precision better the 0.2nm.

→ Test the method using others SED library,

→ A real data catalog will be used to test the method.

BAO

- Power spectra reconstruction,

→ obtain dark energy constraints from the full chain of analysis.