BOSS results on Dark Energy

- Introduction : cosmology, DE,
  baryonic acoustic oscillations (BAO)
- redshift space distortions (RSD)
- BAO with galaxy clustering
- BAO QSO Lyman α forest
- perspectives (eBOSS, Desi)

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Dark Energy and BAO

Rappels cosmologie

- principe cosmologique: (1 pc = 3.28 années lumière = 3.1 10^{16} m)

  à grande échelle (> qq 10 Mpc) homogène et isotrope

- paramètre d'échelle : a(t) ∝ distances intergalactiques

  en général normalisé tel que a(0) = 1

- expansion, cte de Hubble: $H_0 = \dot{a}(0) \approx 70\,(km/s)/Mpc$

  H_0=100 h, unité en Mpc/h

- coordonnées comobiles : $\chi = R/a(t)$ (suit l'expansion)

- redshift: photon émis à t_1 avec $\lambda=\lambda_e$ détecté à $t_0=0$, $\lambda=\lambda_d$

  $\lambda_d > \lambda_e$

$$1 + z = \frac{\lambda_d}{\lambda_e} = \frac{1}{a}$$

Densités et courbure de l'univers

- Densité critique : $\rho_c = \frac{3H_0^2}{8\pi G}$

  matière: $\Omega_m = \rho_m / \rho_c$

  radiation: $\Omega_r = \rho_r / \rho_c$

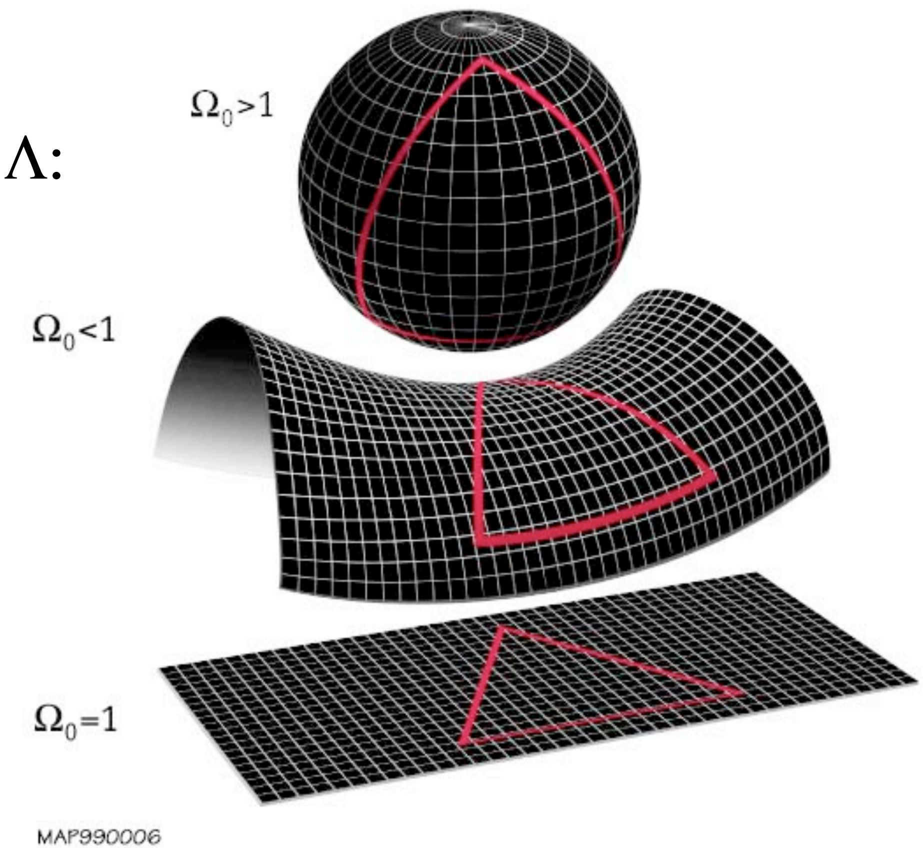
  vide ou constante cosmo Λ:

  $\Omega_\Lambda = \rho_\Lambda / \rho_c$

- total $\Omega_T = \rho_T / \rho_c$

- Relativité Générale :

  courbure de l'espace dépend de Ω_T



Equation de Friedmann

- conservation locale de l'énergie : $\frac{\partial \rho}{\partial t} = -3(\rho + P)\frac{\dot{a}}{a}$
- équation d'état p = w ρ ⇒ $\rho \propto a^{-3(1+w)}$

  - mat non relat.: w≈0 ⇒ $\rho \propto a^{-3}$
  - rayonnement : p=ρ/3 ⇒ $\rho \propto a^{-4}$ (dilatation λ: $a^{-3} \rightarrow a^{-4}$)
  - vide : ρ = cste ⇒ w = -1

- Equation Friedmann

$$\left(\frac{\dot{a}}{a}\right)^2 = H_o^2\left[\Omega_m \hat{a}^{-3} + \Omega_r \hat{a}^{-4} + \Omega_\Lambda \hat{a}^{-3(1+w)} + (1-\Omega_T)\hat{a}^{-2}\right]$$

expansion est sensible à w (i.e w_Λ)

Histoire de l'univers

- inflation
- premières minutes: nucléosynthèse
- plasma baryons + électrons

  pression due aux photons

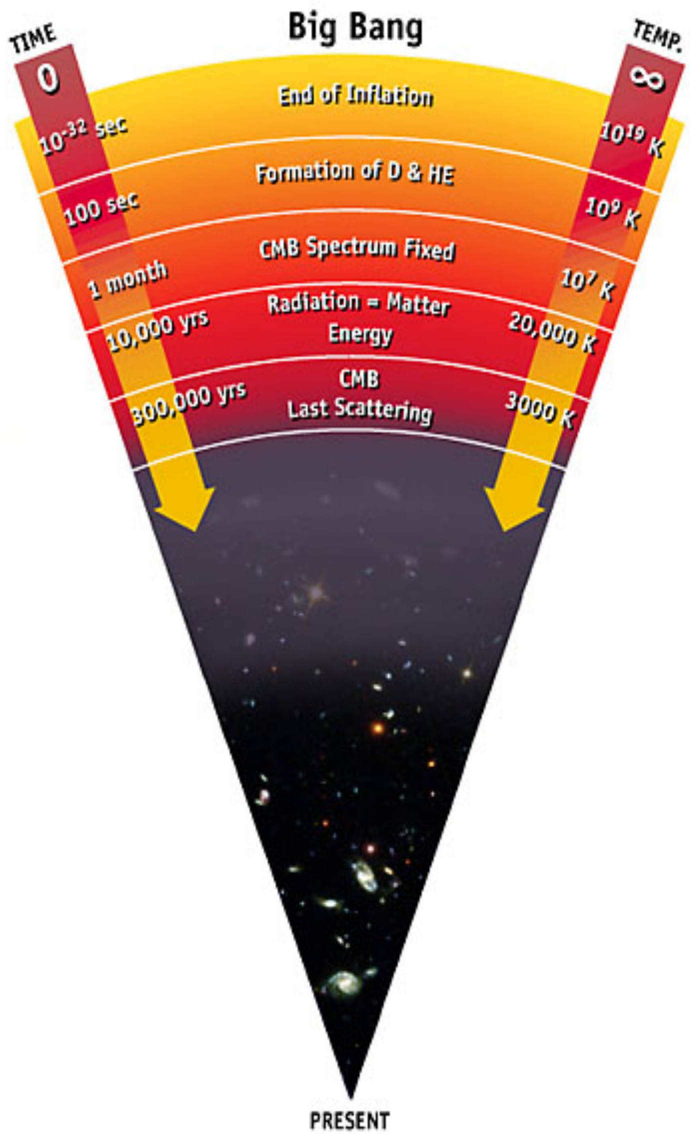
  surdensité se propage à v≈c/√3
- t~300 000 ans, T=3000 K, z=1100

  noyaux + e^- → atomes non chargés

  ⇒ se découplent des γ

  ⇒ l'univers devient transparent

  ⇒ fond diffus cosmologique (CMB)
- Onde a parcouru 150 Mpc comobile, distance caractéristique dans CMB



Les supernovae

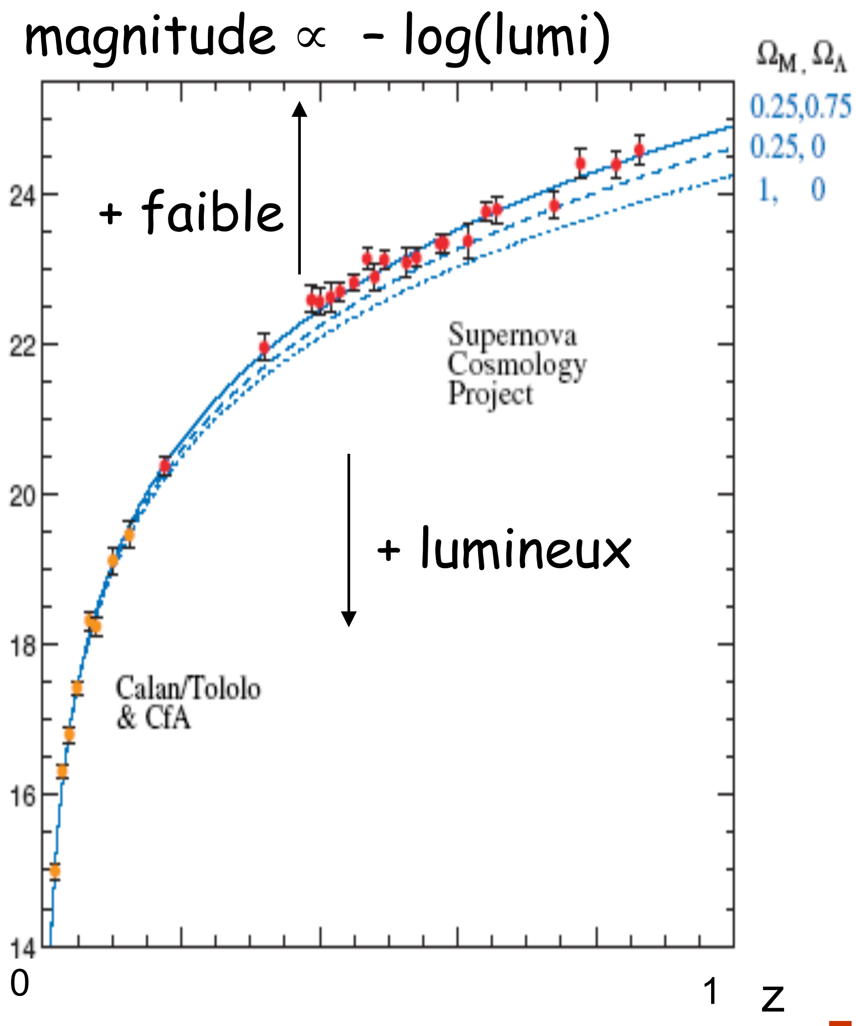
mesurer distance vs z

- SN1a: naines blanches (C-Ni) qui accrêtent la masse d'un compagnon quand $M=1.4M_{\odot}$: SN
- Masse fixée ⇒ lumi fixée

  "chandelle standard"
- lumi apparente (z)
- SN1a moins lumineuses ⇒ plus loin

  ⇒ plus temps entre z=0.6 et z=0

  accélération de l'expansion



"Modèle de concordance" ΛCDM

Cold Dark Matter + Λ, Ω_T=1
fluctuations primordiales Gaussiennes,

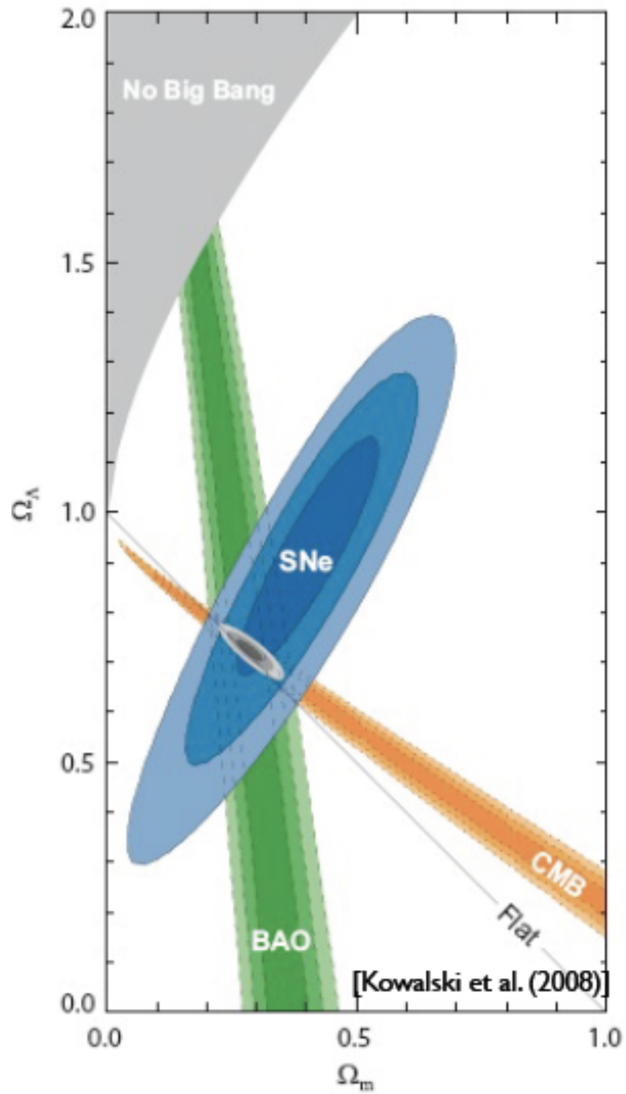
- 6 paramètres :

H_0~70 , Ω_m~0.3, Ω_b~0.04, réionisation, amplitude des fluctuations, et indice spectral n_s

- Décrit tous les résultats

  CMB, amas, SN, BAO, croissance des structures

Cosmologie de précision



Origines possibles de l'énergie noire

- constante cosmologique Λ -> ρ=cte=10^{-48} GeV^4

  énergie du vide

  on attendrait $(m_{pl})^4=10^{76}$ GeV^4

  ou au moins $(m_{EW})^4=10^8$ GeV^4 : fine tunning
- modèles de "quintessence" du à un champ scalaire
- modification de relat. gen. à grande échelle

mesures - géométriques (expansion) -> w (equ d'état)

- dynamiques (croissance structure) -> test GR

BAO

- at z >> 1000 : baryon-e$^-$ plasma coupled to photons
- Over-density (overpressure)

  $\Rightarrow$ acoustic waves
- z ~ 1100 recombination : baryon-photon decoupling $\Rightarrow$ pressure=0

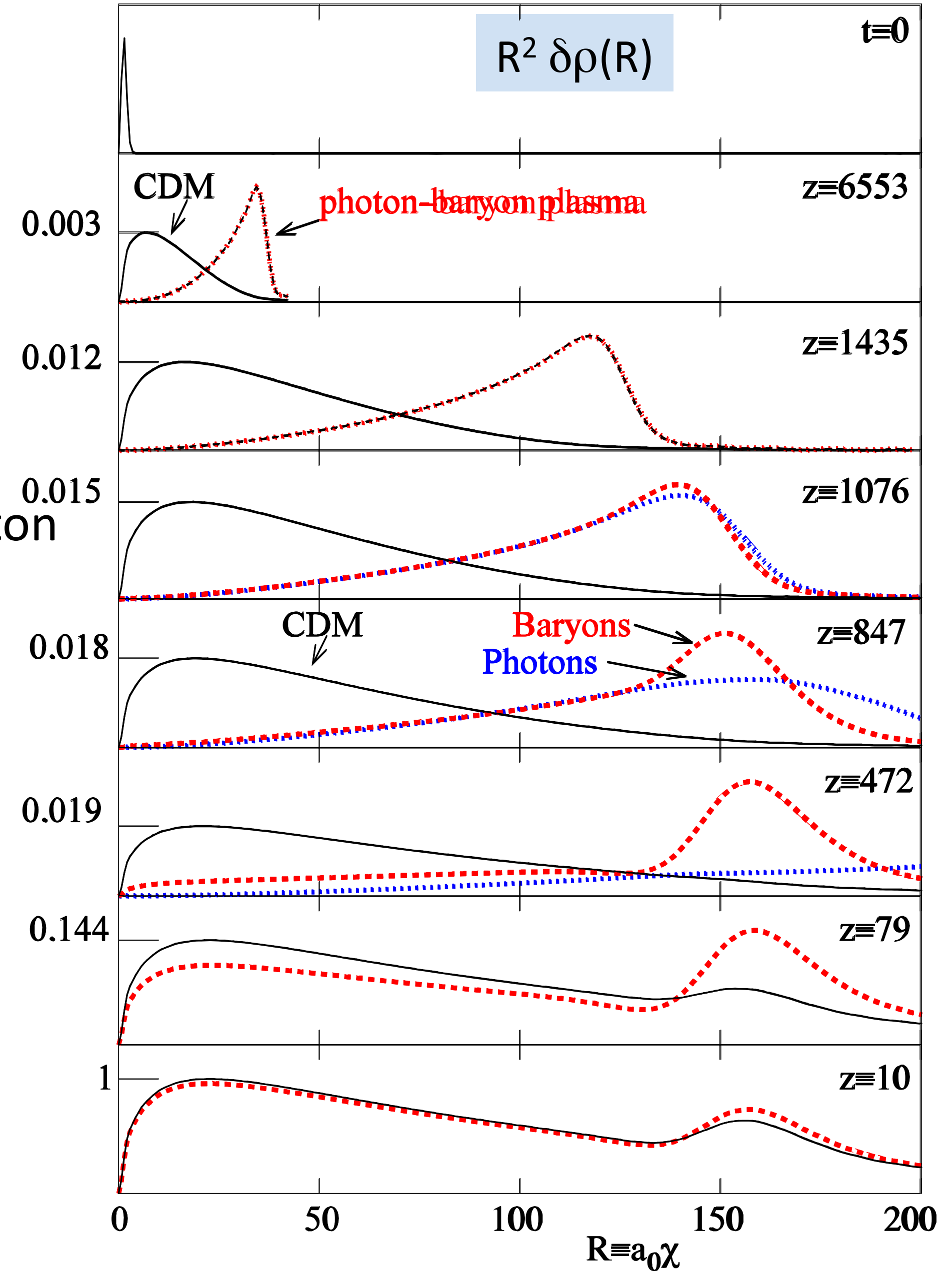
  $\Rightarrow$ frozen wave has travelled

  r_d = 150 Mpc (commoving)
- Peak at 150 Mpc in autocorrelation function at all z

$$\xi(\vec{r}) = \langle \rho(\vec{x})\rho(\vec{x}+\vec{r}) \rangle$$

a 150 Mpc standard ruler

- Geometrical measurement, linear physics: low systematic



A 3D survey

A 3D survey : RA, declination and z

$\Rightarrow$ correlation transverse and along line-of-sight

- transverse : $\Delta\theta = r_d / D_\perp$ with s=150 Mpc standard ruler

$$D_\perp(z) = (1+z) D_A(z) = \int_0^z \frac{c\,dz'}{H(z')}$$

a measurement of $D_A(z)$ same info as SNIa ($D_L = (1+z)^2 D_A$)

- radial : $\Delta z = r_d / D_z$ $\quad D_Z = \frac{c}{H(z)}$

  a measurement of H(z)

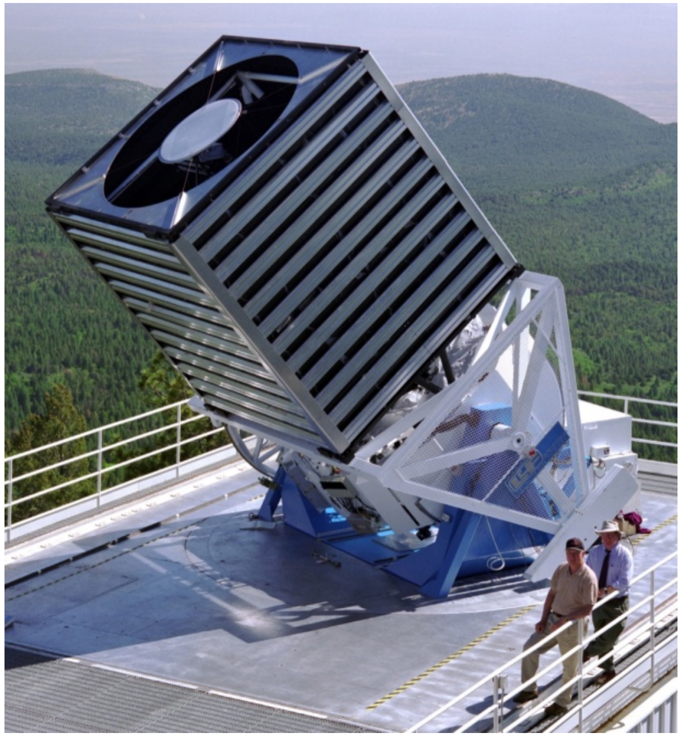
- Need accurate z : i.e. spectro

  photo-z : loss of stat by factor 5 relative to cosmic variance limit

The BOSS survey

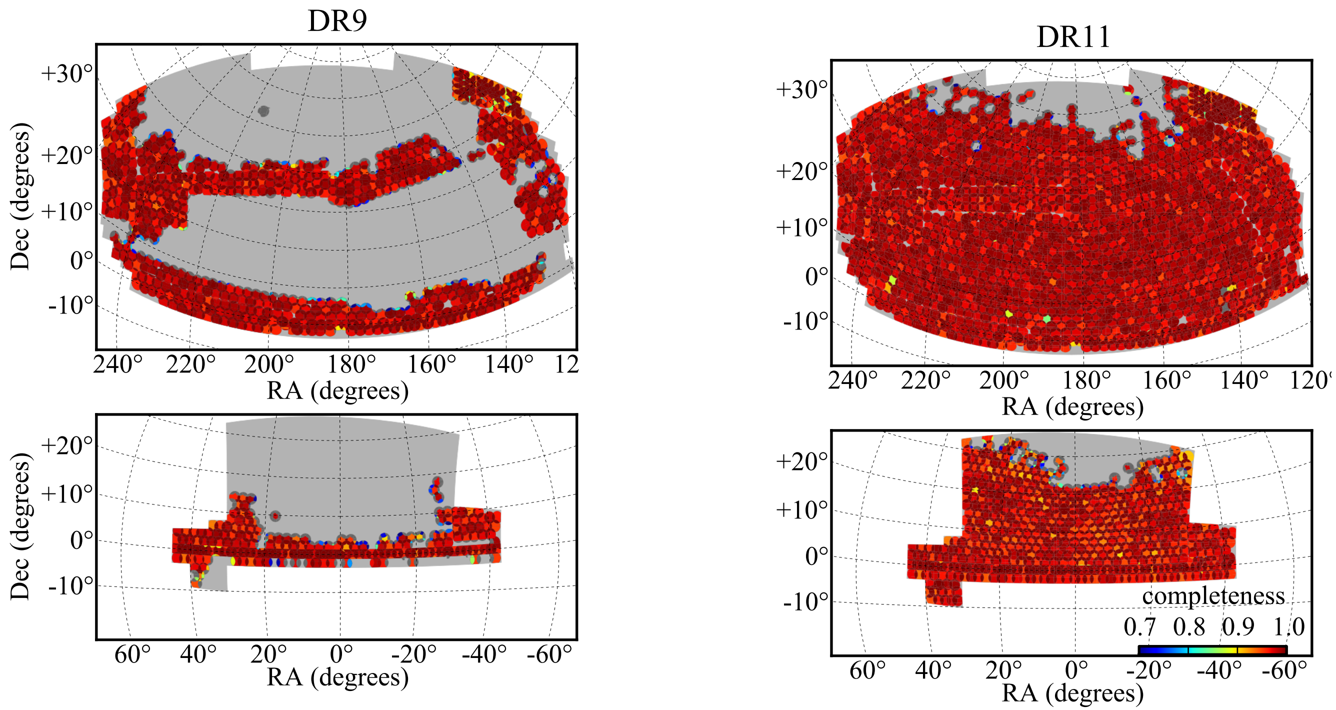
SDSS III / BOSS

- SDSS III : BOSS, Marvels (exo-planets), Segue and Apogee (Galaxy)
- US, Brazil, France, Germany, Korea, Spain, UK
- BAO using LRG and lyα forest of quasars (QSO)
- Telescope 2.5m, 7 deg^2 in APO, New Mexico
- Spectrometric survey
  10,000 deg^2 : LRG and quasars
- data taking 2009-2014
- France : QSO target selection, quasar catalogue, analysis : Lyman a BAO and m_ν

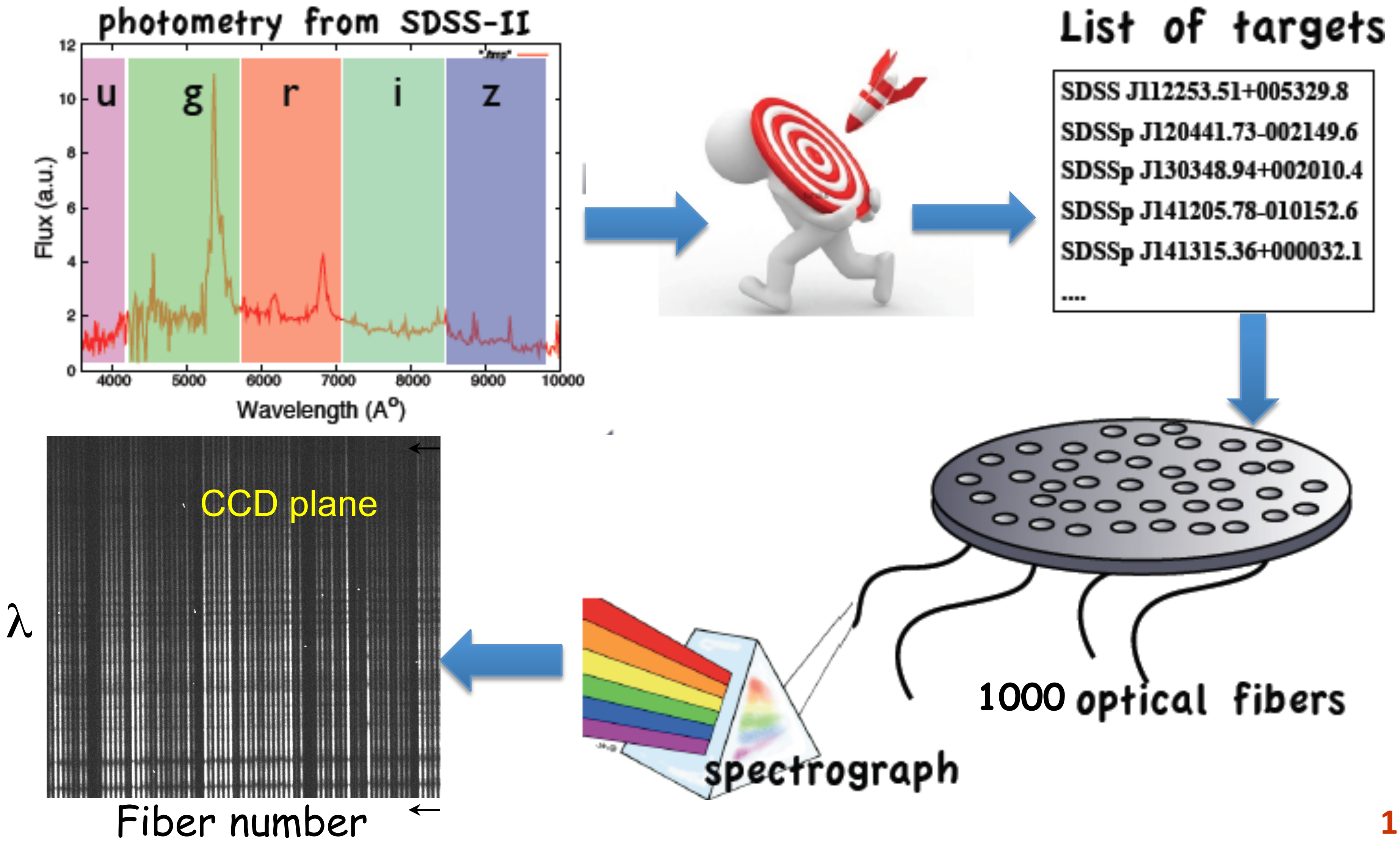


Data Release 11

- DR9 2635 deg^2 207k galaxies (0.4 < z < 0.7),
  49k QSO (2.1 < z < 3.5)
- DR11 8976 deg^2 691k galaxies, 138k QSO



BOSS data taking



Redshift Space Distortions

RSD

- radial positions are obtained from z

  but peculiar velocities δv bias position

  $$z_{obs} = z_{cosmo} + \delta v/c$$

- on large scales Kaiser effect

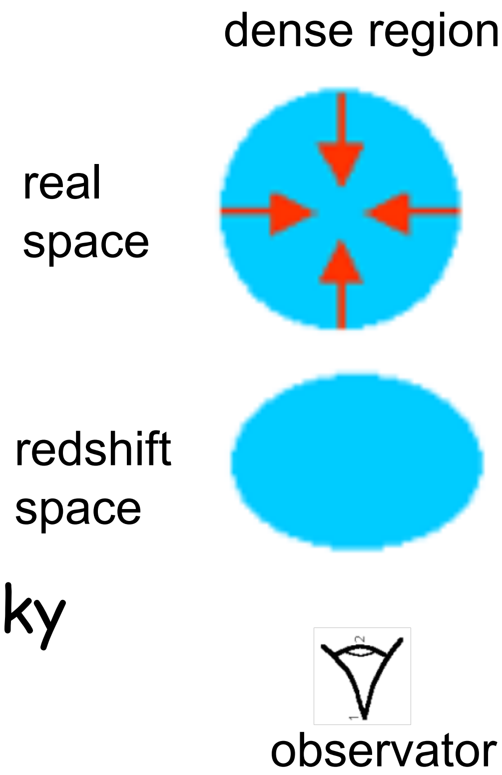
  matter moves towards dense regions

  enlarge anisotropies along the line of sky

- on small scales the velocities are random

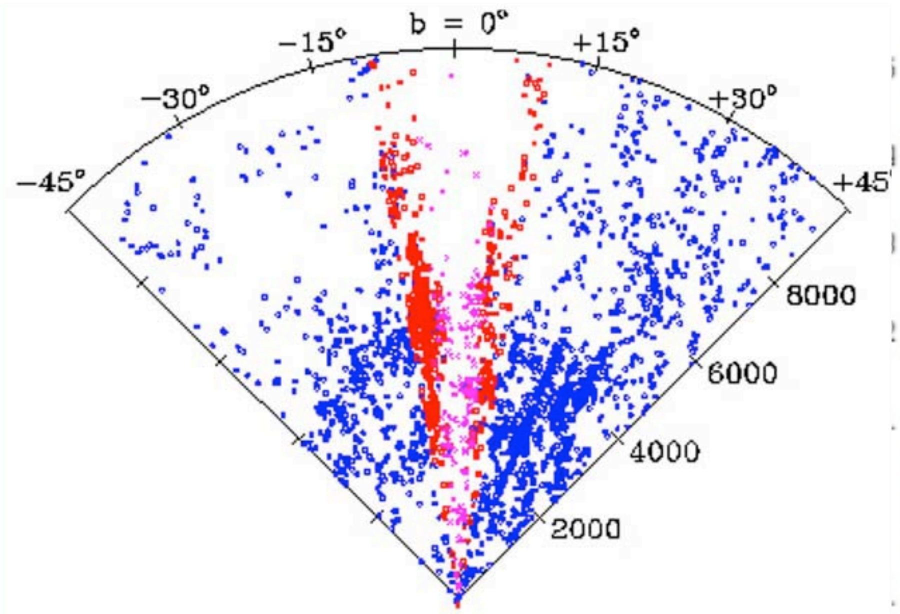
  this elongate the over-density along l.o.s

  "finger of god"



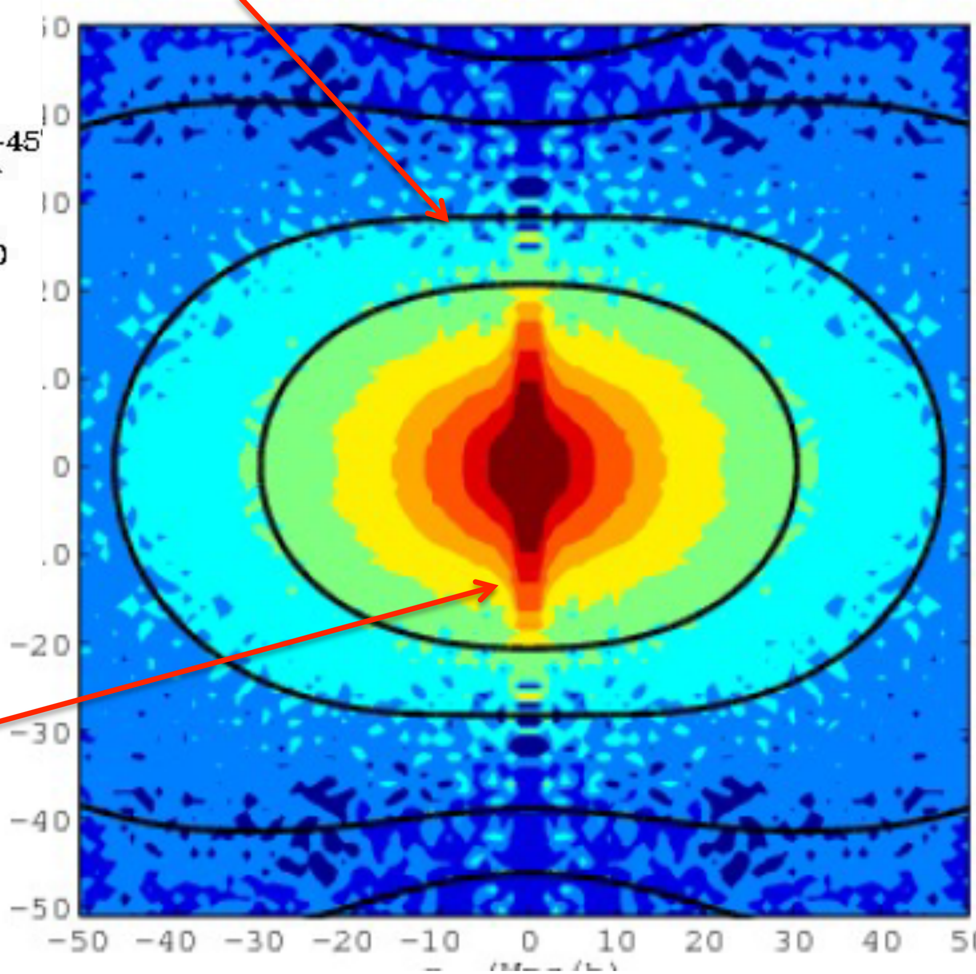
RSD

finger of god in a survey



correlation function

Kaiser effect



finger of god

What is measured ?

In linear theory :

- growth factor D(z): $\delta(x,z) = D(z)\,\delta(x,z=0)$
- growth rate $f = d \ln D / d \ln a = \Omega_m^{0.55}$ (G.R.)
- $P_{obs}(k) = b^2(1 + 2\mu^2\beta + \mu^4\beta^2)\, P_m(k)$ b=bias $\beta = f/b$

  power spectrum $P(k) = FT[\, \xi(r)\,]$ like c_l for CMB

- normalization σ_8 = rms fluctuation in 8 Mpc/h spheres

what is measured is $b\,\sigma_8$

=> globally RSD measure $f\,\sigma_8$

- BAO and SN are purely geometrical probes

  RSD probe the growth of structure -> test GR

Alcock Paszinki effect

- RSD result in an anisotropy of $\xi(r)$ or $P(k)$
- AP : using a wrong cosmology for θ, z -> Mpc
  also result in an anisotropy
- for a monotonous $P(k)$ the 2 effects are highly degenerate
  non linearities somewhat break the degeneracy
- BAO peak break the degeneracy :
  RSD does not affect the peak position
  while AP does !

analysis

- new estimator for P(k) Yamamoto et al. 2006
  does not assume parallel l.o.s.
- model for power spectrum
- systematics studies with N body simulation and P.T.
  for $0.01 < k < 0.15$ h/Mpc no significant syst
  for $k_{max} = 0.20$: 3.1% bias on $f\sigma_8$ (no bias on d_V and F_{AP})
- ref result for $k_{max} = 0.20$
  give also for $k_{max} = 0.15$

results

- BOSS measures (k_{max} = 0.20) :

$$V^{\text{data}} = \begin{pmatrix} D_V(z_{\text{eff}})/r_s(z_d) \\ F_{\text{AP}}(z_{\text{eff}}) \\ f(z_{\text{eff}})\sigma_8(z_{\text{eff}}) \end{pmatrix} = \begin{pmatrix} 13.88 \\ 0.683 \\ 0.422 \end{pmatrix} \quad \begin{matrix} \pm 1.3\% \\ \pm 4.6\% \\ \pm 11\% \end{matrix}$$

where $d_V(z) = \left[\frac{cz}{H(z)}[(1+z)d_A(z)]^2\right]^{1/3}$

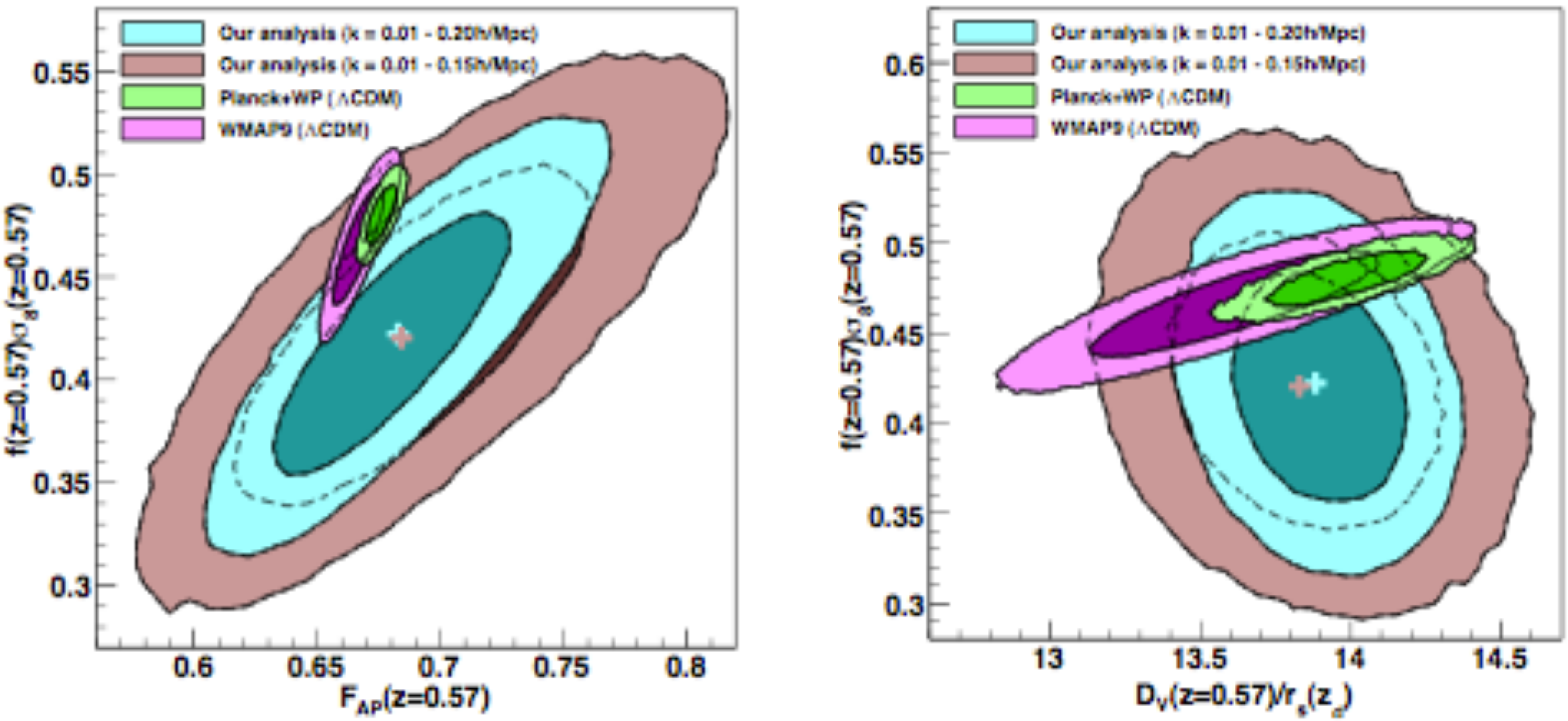
$$F_{\text{AP}}(z_{\text{eff}}) = (1 + z_{\text{eff}})D_A(z_{\text{eff}})H(z_{\text{eff}})/c$$

and covariance matrix

$$10^3 C = \begin{pmatrix} 36.400 & -2.0636 & -1.8398 \\ & 1.0773 & 1.1755 \\ & & 1.8478 + 0.196 \end{pmatrix}$$

comparison with CMB

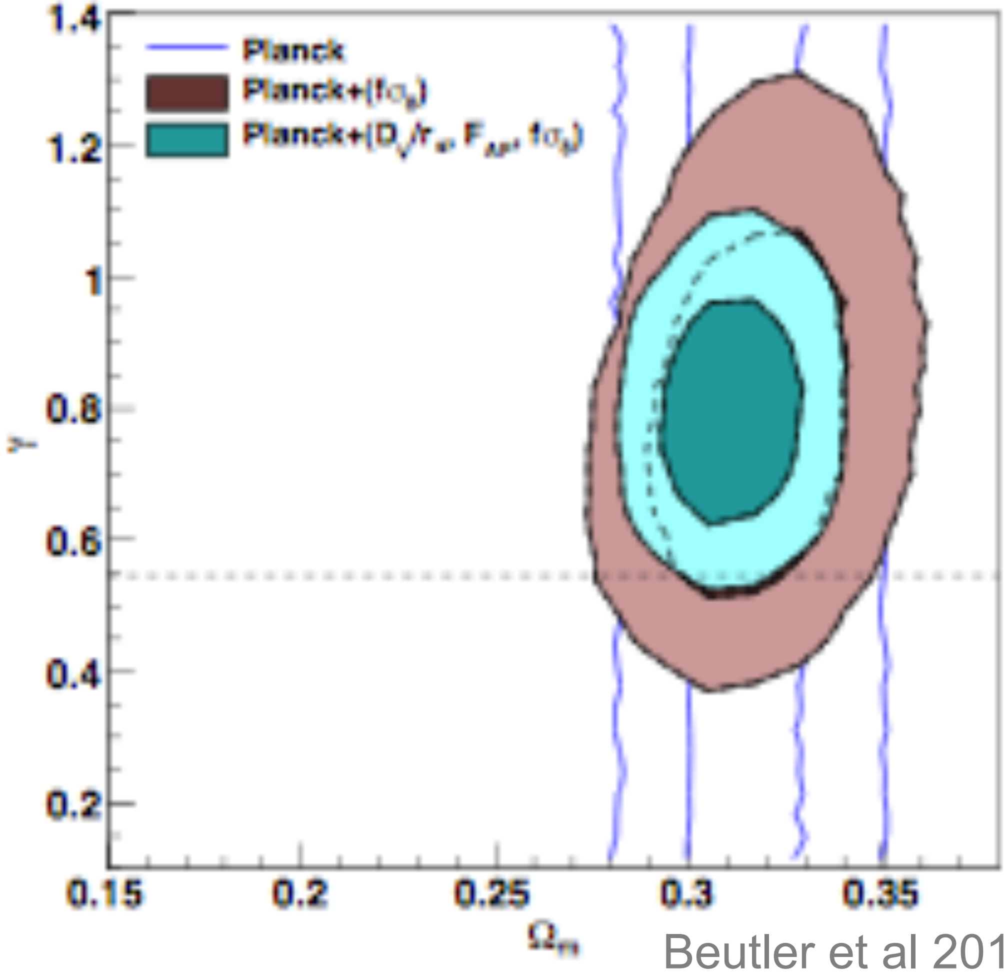
- CMB for ΛCDM (6 parameters)



Beutler et al 2013

testing GR

- BOSS measures $f\sigma_8$ and $f = \Omega_m^\gamma$
- combining with Planck
  -> accurate Ω_m and σ_8
  -> γ
- marginalizing
  $\gamma = 0.772^{+0.12}_{-0.10}$
- GR predicts $\gamma = 0.55$



Beutler et al 2013

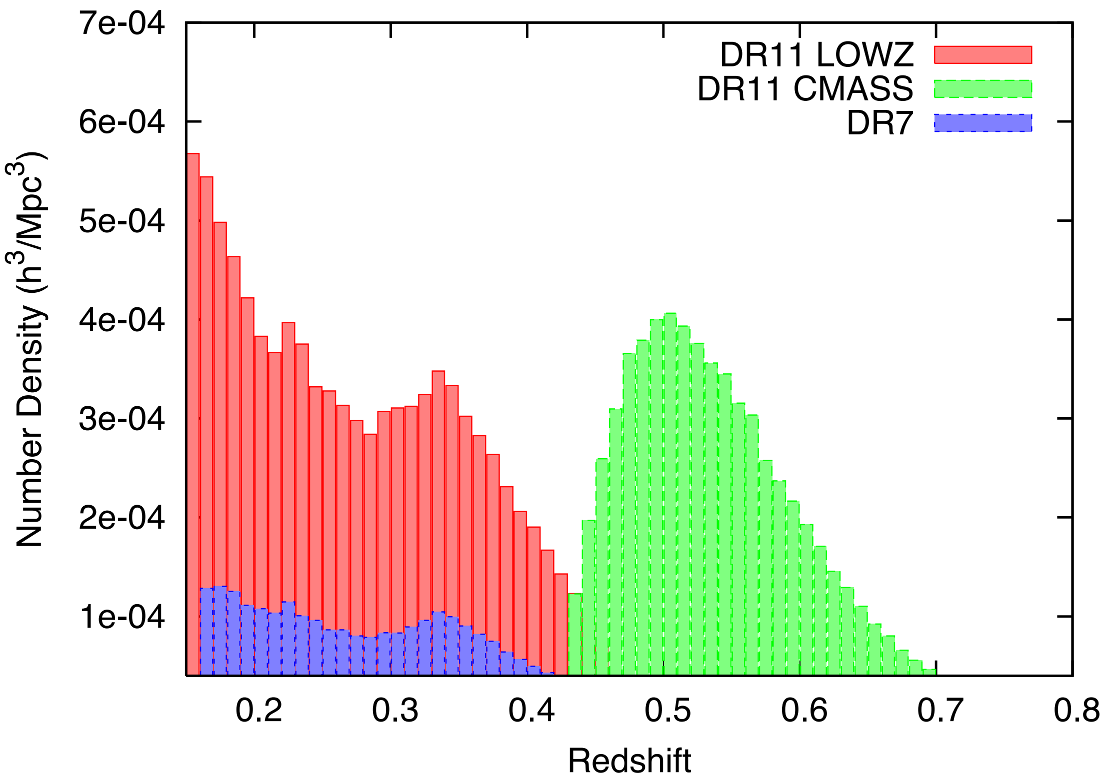
Galaxy clustering

Galaxy samples

- Large Red Galaxy (LRG) targets defined with color cuts

- CMASS
  $0.43 < z < 0.7$
  690,826

- LOWZ
  $0.16 < z < 0.43$
  313,780

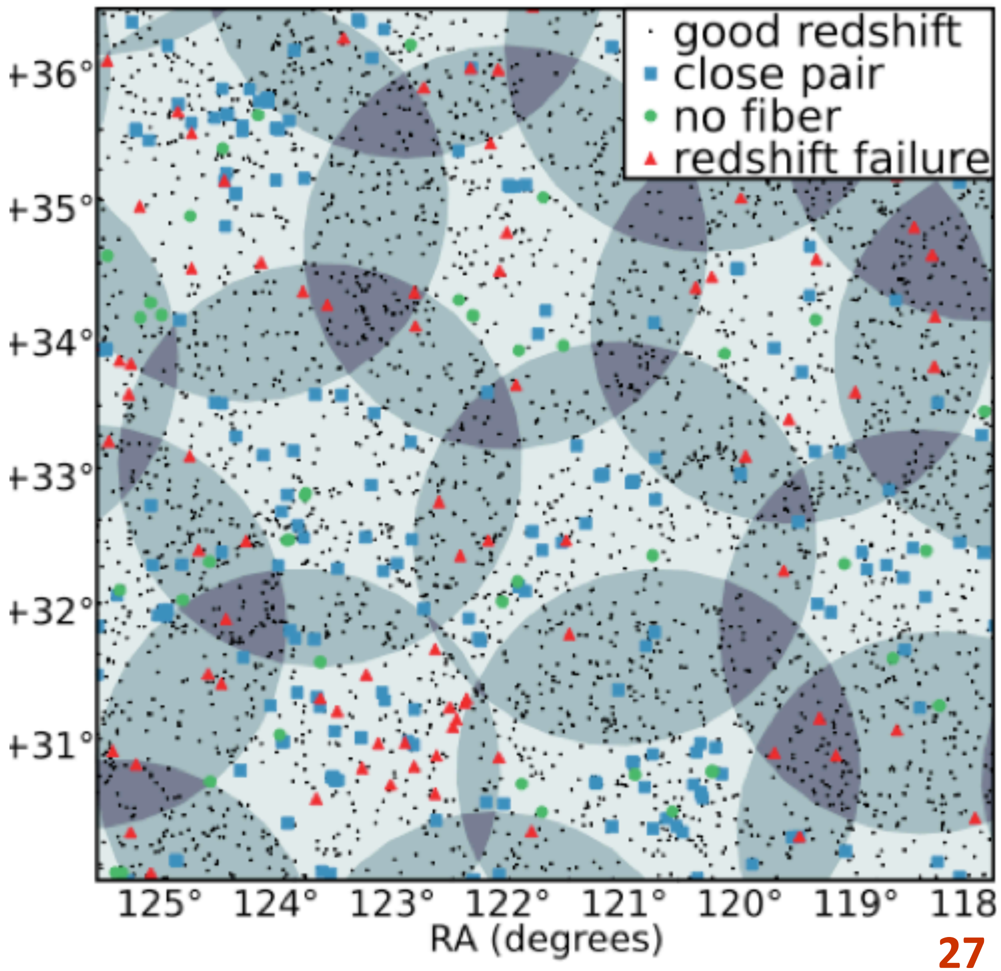


- measure correlation: $\xi(r) = \langle \delta(x)\delta(x+r) \rangle$ $\delta = (\rho / \langle\rho\rangle) - 1$
  $1 + \xi(r)$ = # pairs (r) / # random pairs

Survey geometry

- geometry defined by tiles and intersections: sectors
- masks :
  - bad photometry
  - centerpost
  - bright stars, QSO
- use Mangle package

- not all targets observed:
  - collisions (<62")
  - no fiber
  - redshift failure



Estimate $\xi(r)$

- completeness in each sector : $C = N_{fiber} / N_{target}$
  special treatment for previously known LRG
  for collisions, redshift failures

- generate random catalogues without clustering but
  with geometry and C : in each sector N ~ area * C

- ξ estimator : # pairs for Data-Data, Random-Random
  simple estimator: $1 + \xi(r) = DD(r) / RR(r)$
  Landy Szalay estimator with minimal variance :

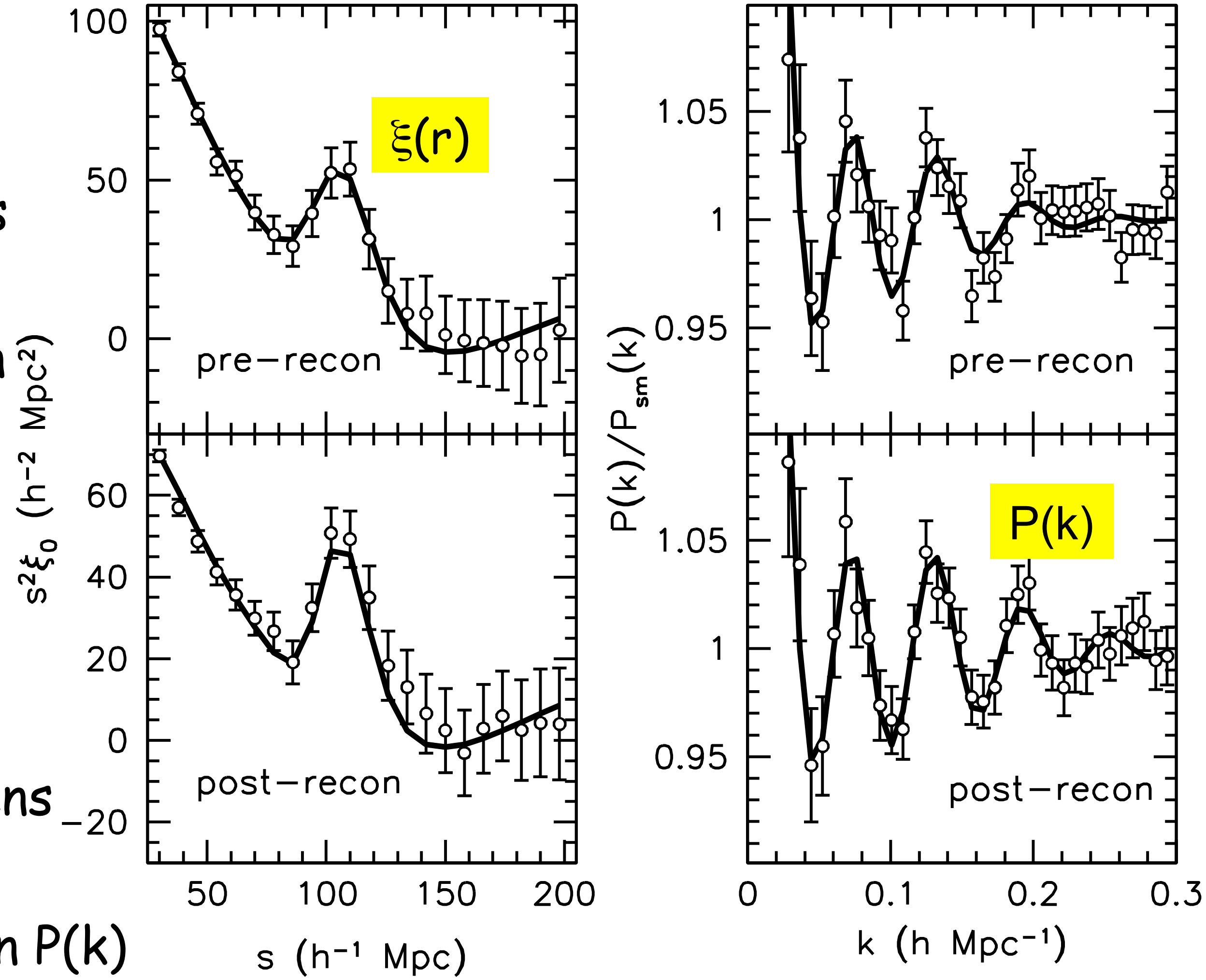
$$\xi(r) = \frac{DD(r) - 2DR(r) + RR(r)}{RR(r)}$$

Reconstruction

- nonlinear collapse -> displacement which erases the BAO features
- displacement field can be reconstructed from density field and corrected

Eisenstein et al 2007

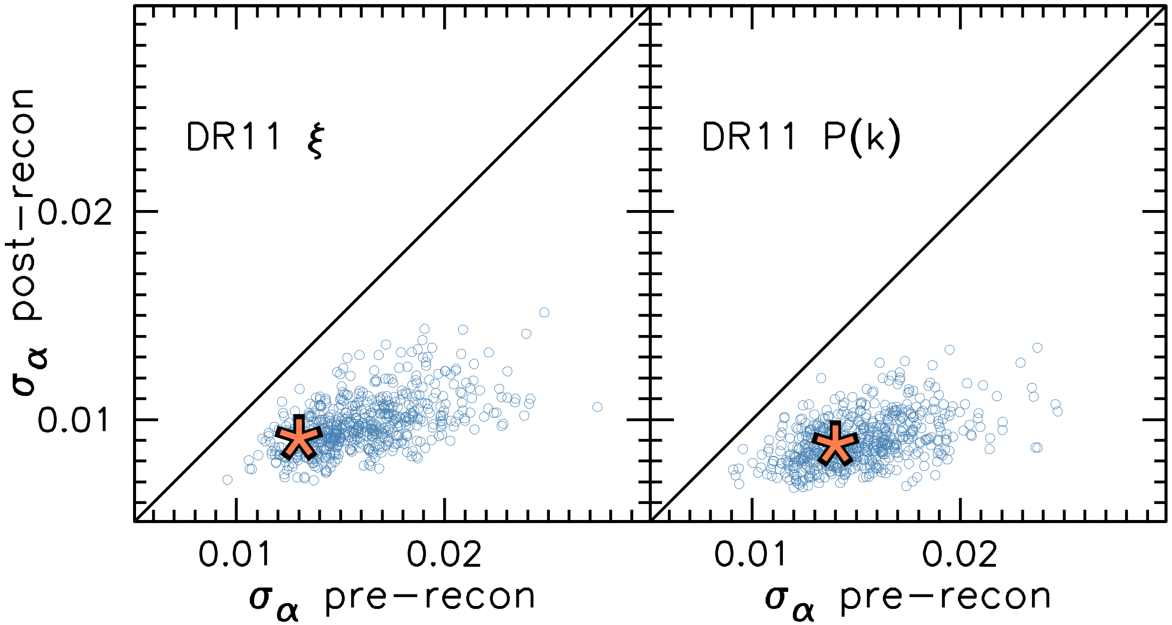
- reconstruction sharpens peak in ξ(r) and recovers small scales oscillations in P(k)



Anderson et al 2013

gain with reconstruction

- tested on mock galaxy samples
- statistical gain by a factor ~ 1.5



- without reconstruction 0.26 to 0.46% bias
- after : no bias at 0.04% accuracy

Isotropic analysis

- $$d_V(z) = \left[\frac{cz}{H(z)} [(1+z) d_A(z)]^2 \right]^{1/3}$$

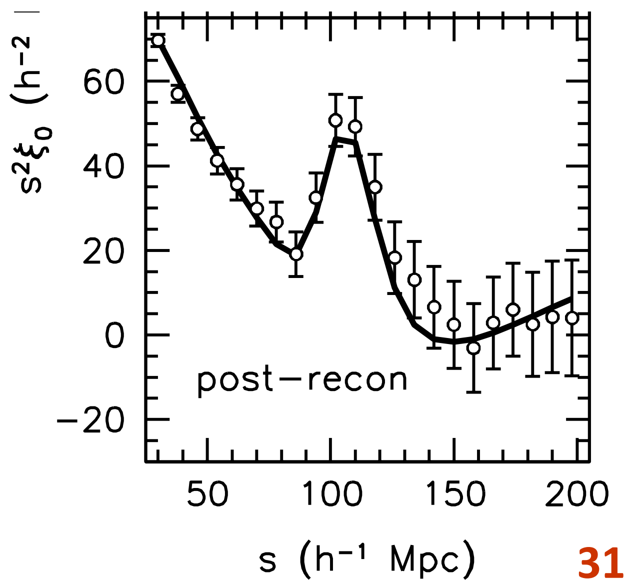
- fiducial cosmology: θ, z -> Mpc

  we measure d_V / r_d -> $\alpha = (d_V/r_d) / (d_V/r_d)^{fid}$

- model ξ^{mod} with non linear contribution

  fit ξ data with

  $$\xi^{fit}(r) = b^2 \xi^{mod}(\alpha r) + \frac{a_1}{r^2} + \frac{a_2}{r} + a_3$$



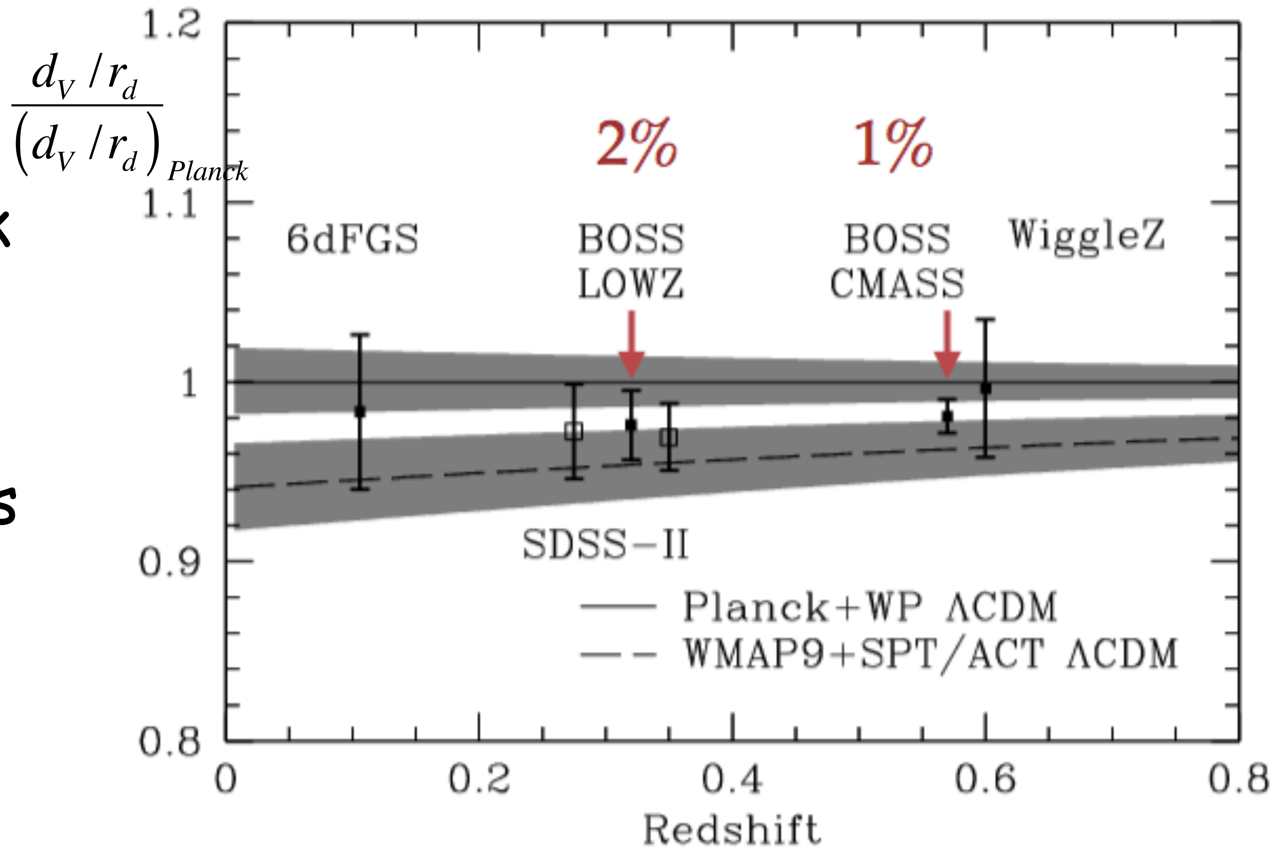
- nuisance parameters ->

  value of α rely only on peak position

- bias : b ~ 2

Isotropic results

- d_V/r_d divided by Planck prediction in ΛCDM (min 6 parameters)
- in between Planck and WMAP
- P(k) analysis gives same results



Anderson et al 2013

Anisotropic analysis

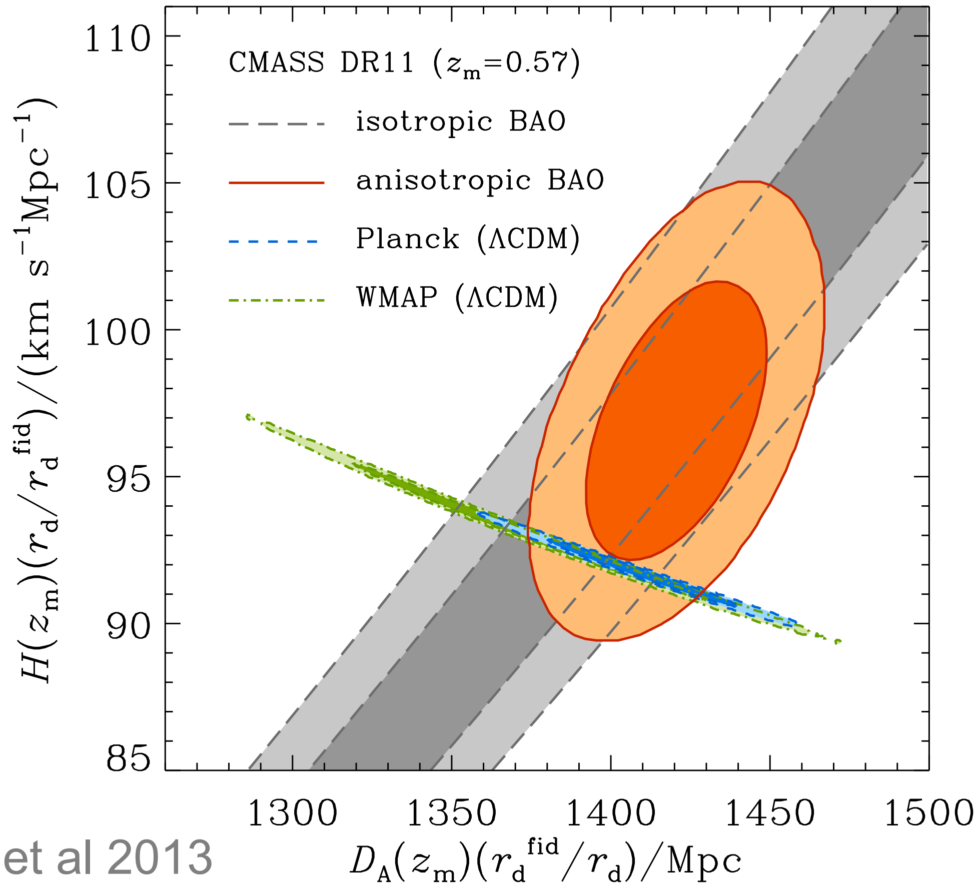
- ξ(r,μ) where μ =cos θ

  and θ angle / line of sight (l.o.s)
- similar fit with now

  2 physical parameters

$$\alpha_\perp = \frac{D_A(z) r_d^{fid}}{D_A^{fid}(z) r_d}$$

$$\alpha_\parallel = \frac{H^{fid}(z) r_d^{fid}}{H(z) r_d}$$

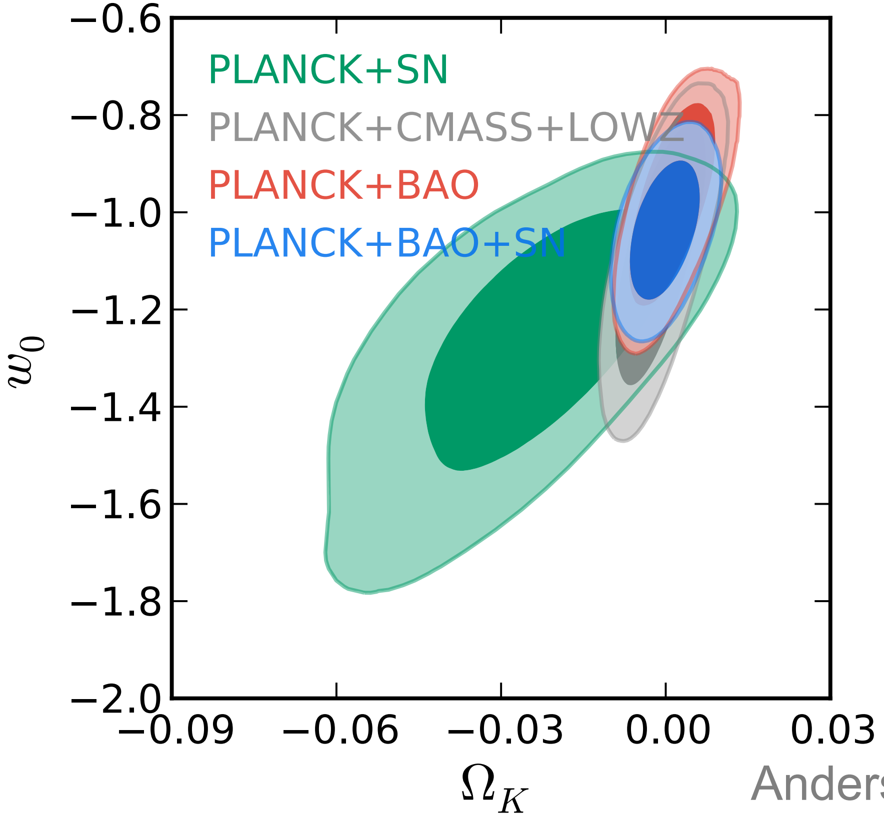


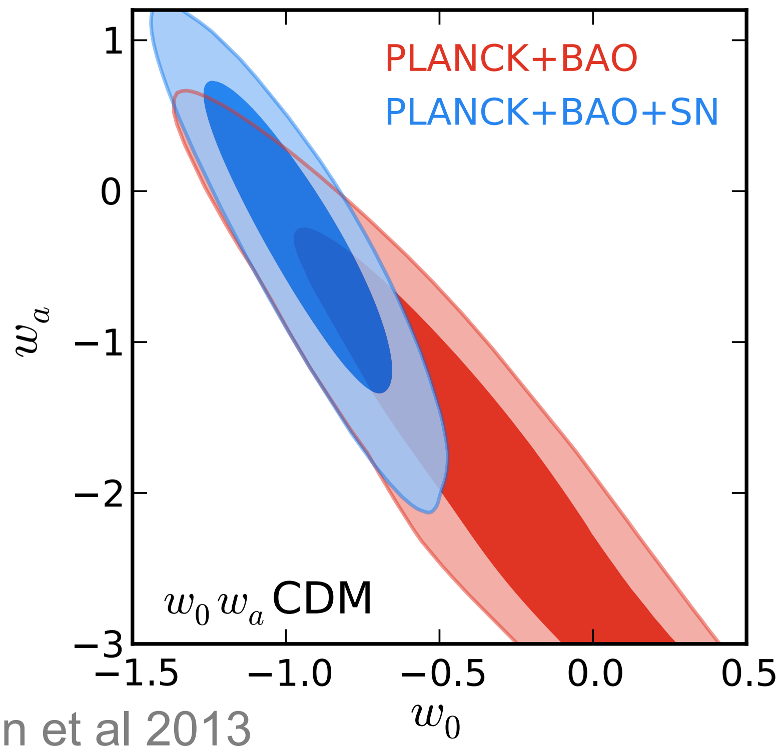
Anderson et al 2013

Cosmological constraints

- With minimal 6 parameters, BAO confirms CMB
- contributes when we add more parameters, e.g.

  curvature and w $\qquad w = w_0 + w_a(1-a) \quad a=1/(1+z)$



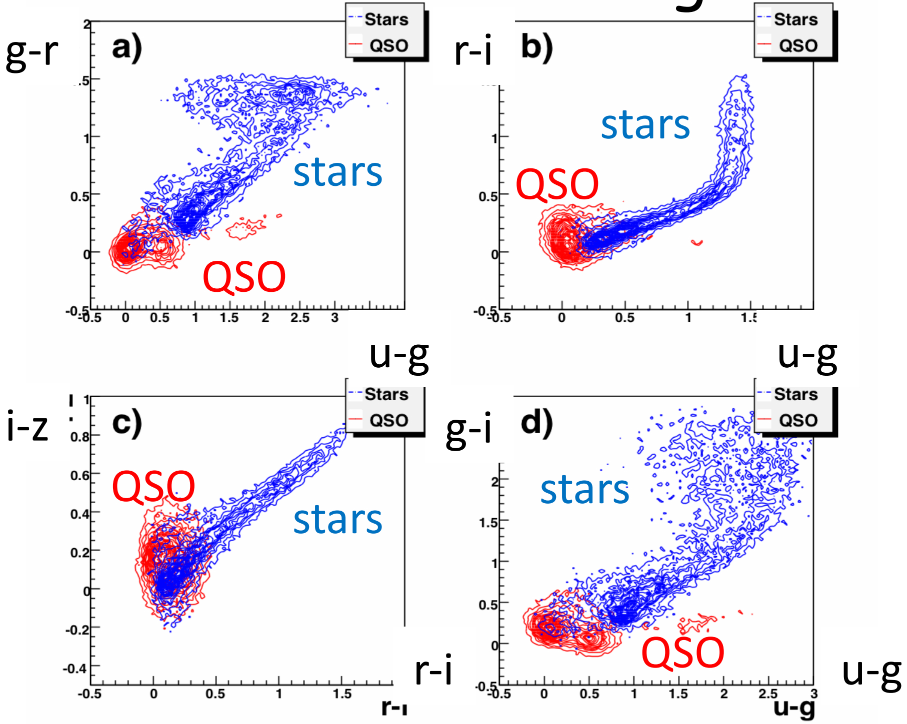


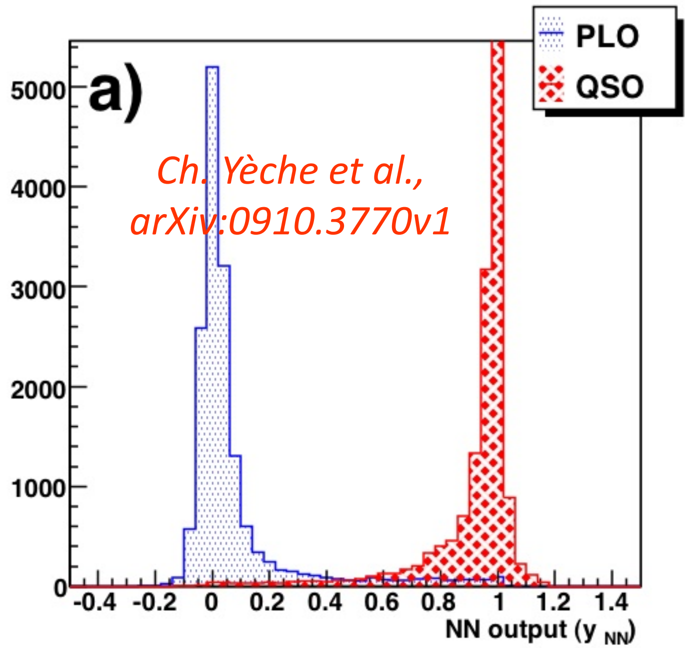
Anderson et al 2013

Lyman α forest clustering

QSO target selection

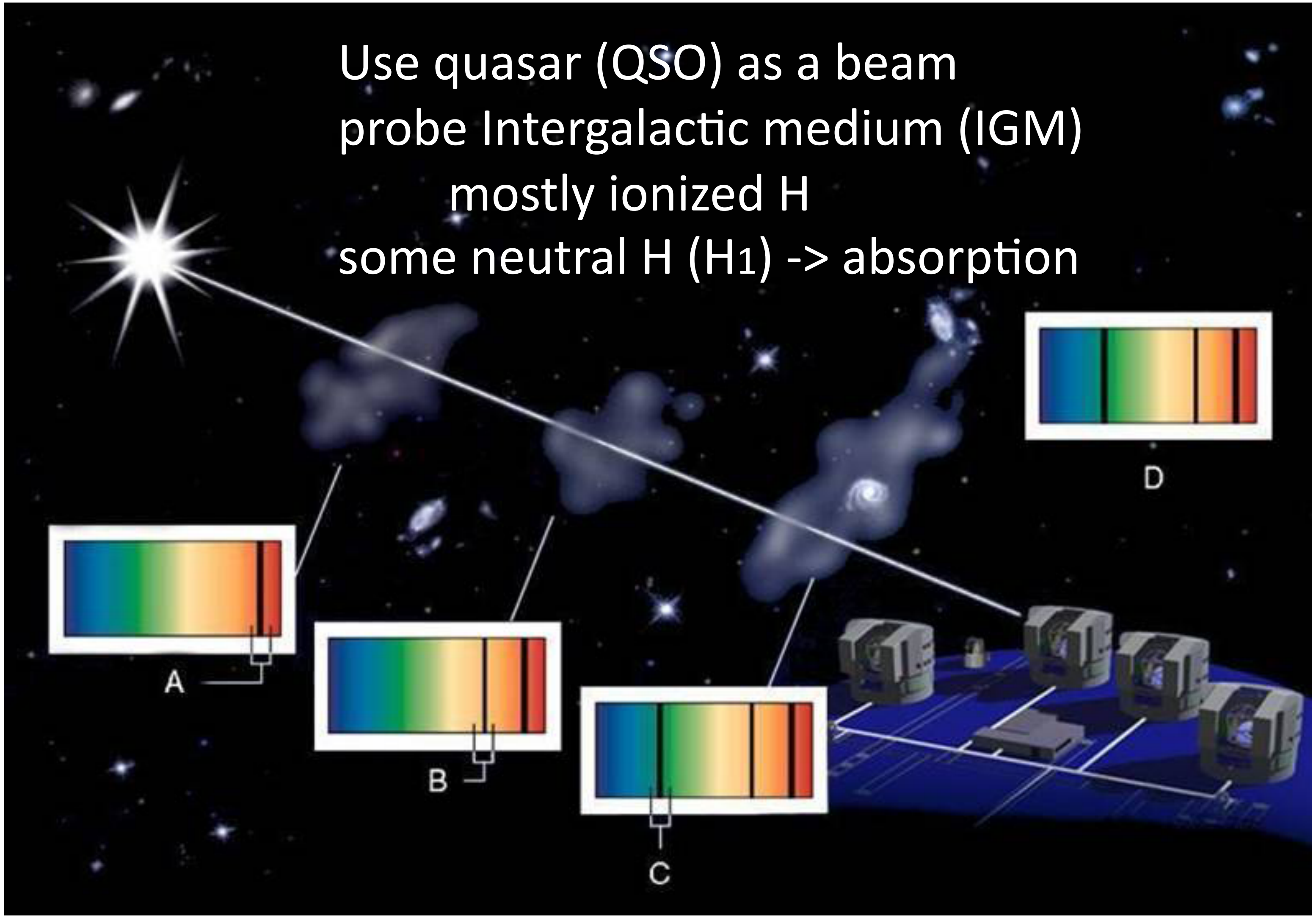
- Magnitude measured in 5 bands : u g r i z
- Selection based on colors: u-g, g-r, …
- 500 times more stars than QSO
- Likelihood (Berkeley) or NN (Saclay)
- 40 candidates/deg² → 17 QSO/deg²





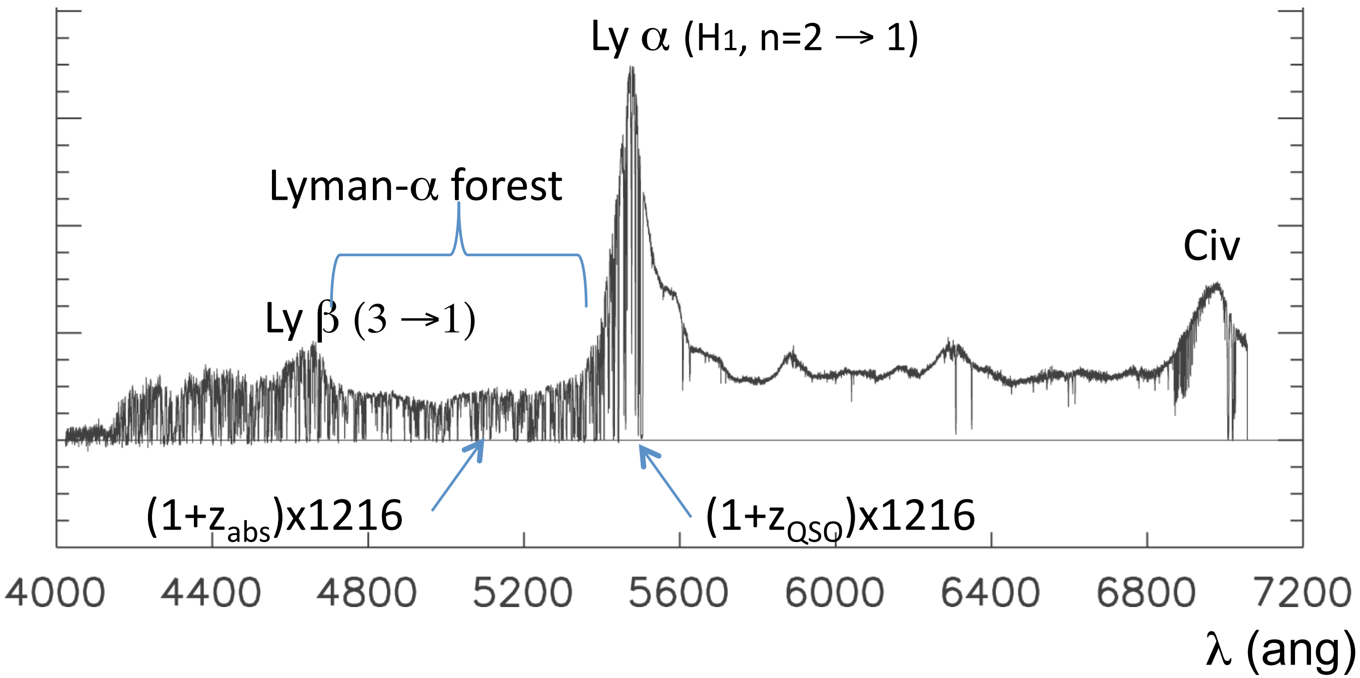
4 colors (u-g,g-r,r-i,i-z)

Quasars as an IGM probe



Lyman-α forest

- QSO "continuum" = unabsorbed spectrum
- transmitted flux fraction F = flux/continuum : $0 < F < 1$
- $F = \exp(-\tau)$, $\tau \propto n_{H1}$ $P_F(k) = b^2 P_{DM}(k)$ $b \sim 0.2$



at $z \approx 2.5$, Lyα forest: $\Delta z \approx 0.3$ ≈ 350 Mpc/h

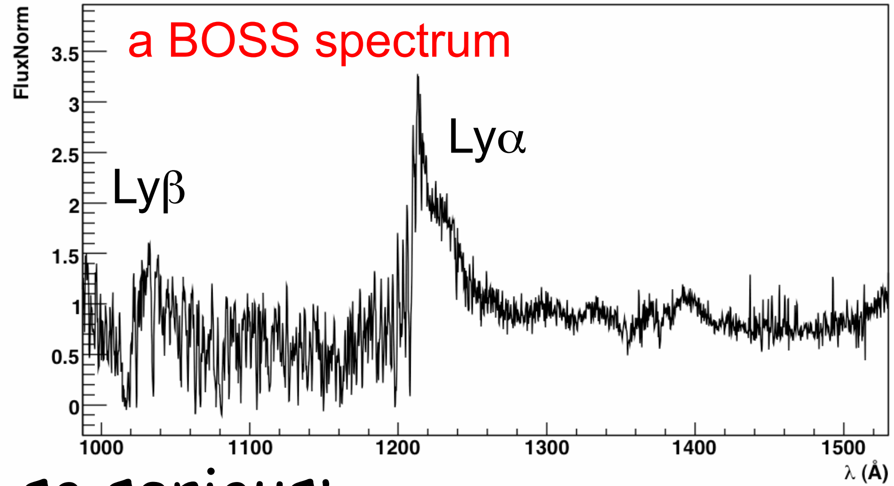
continuum

- not easy to find continuum with SDSS resolution and S/N
- several methods

C1: mean shape (from stacking) x (a λ +b)

C2: idem + likelihood using pdf of F (Busca et al. 2012)

C3: mean flux regulated PCA continuum (KG.Lee et al. 2011)



- However simulations show not so serious:
  using simplest continuum method
  ~10% increase of $\delta_{stat}(r_{BAO})$
  sub percent bias (JMLG et al. 2011)

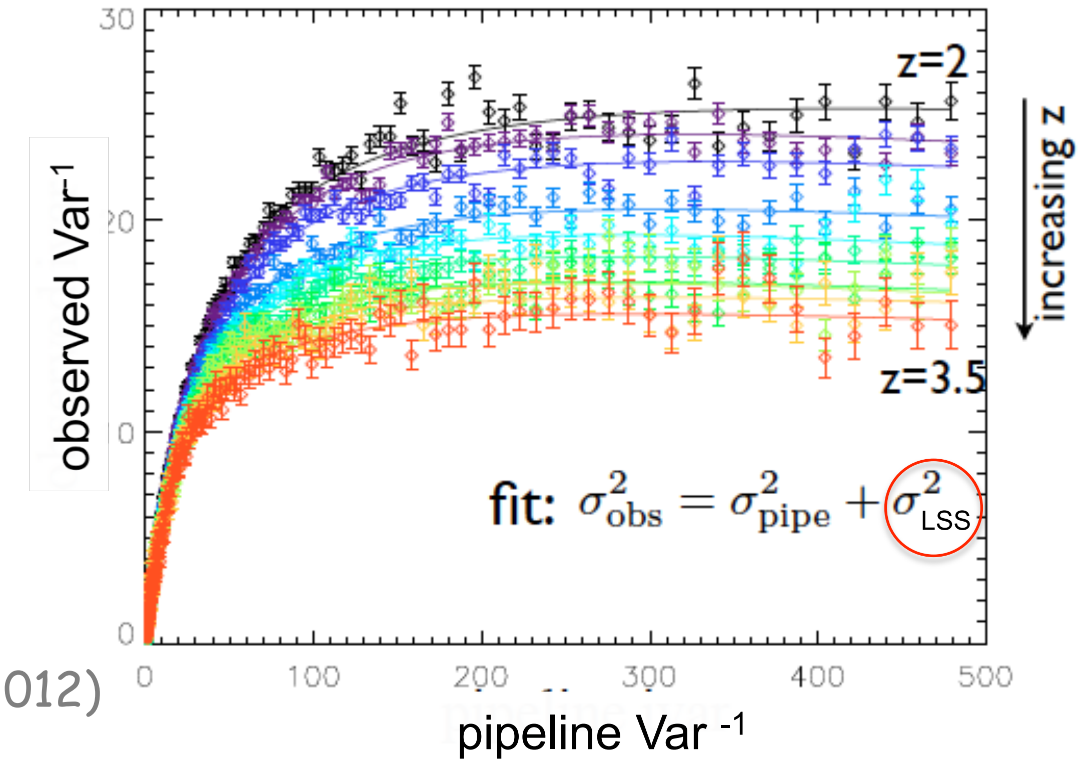
Weighting and ξ-estimators

- weight δ according to $\sigma^2_\delta = \sigma^2_{pipeline} + \sigma^2_{LSS}$

$\sigma^2_{LSS}(z)$ determined from data

- $w = 1/\sigma^2_\delta$

- $\hat{\xi}(r,\mu) = \dfrac{\sum_{ij} w_i w_j \delta_i \delta_j}{\sum_{ij} w_i w_j}$

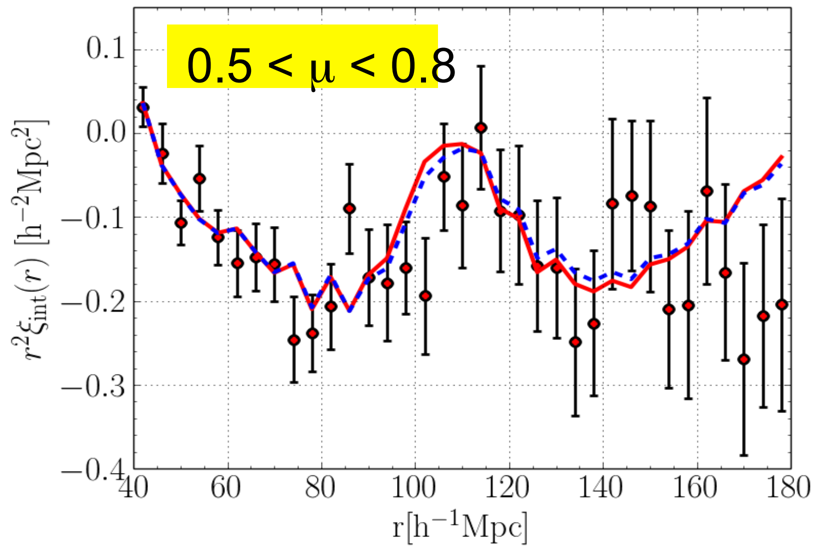


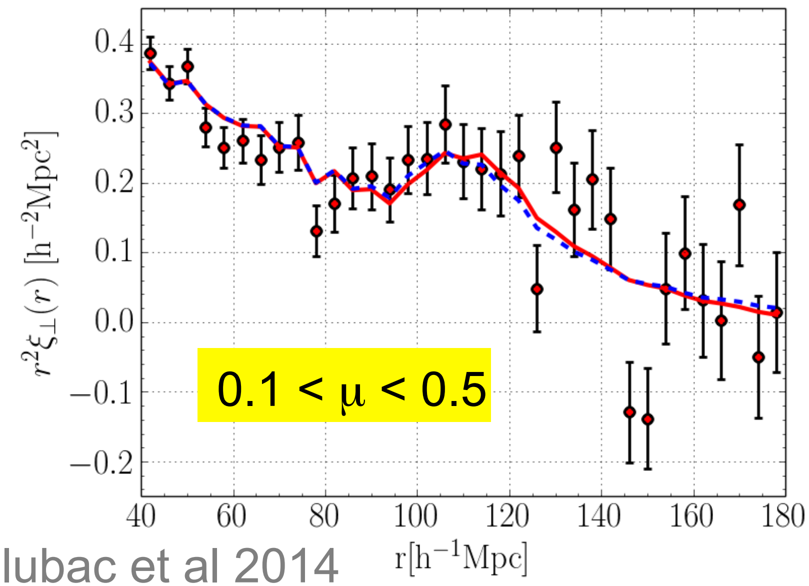
Busca et al 2012

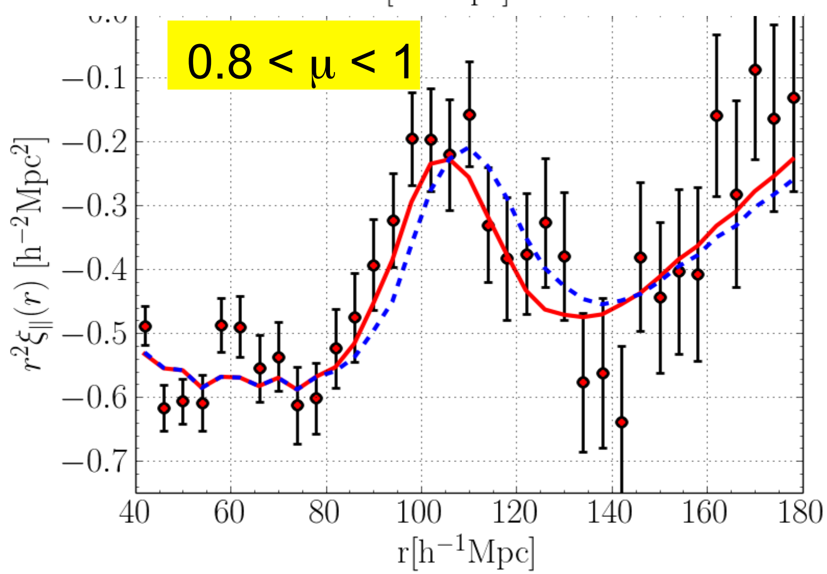
- more sophisticated ξ-estimators (Slosar et al. 2012) but same performances

results for $\xi(r)$

- large RSD for Lyman α
  $\beta \sim 1$ vs 0.2 for LRG
  -> more accuracy along l.o.s
- 5 σ detection







Delubac et al 2014

result of fit

- reference result C2

$$\alpha_\parallel = 1.054^{+0.032}_{-0.031}$$

$$\alpha_\perp = 0.973^{+0.056}_{-0.051}$$

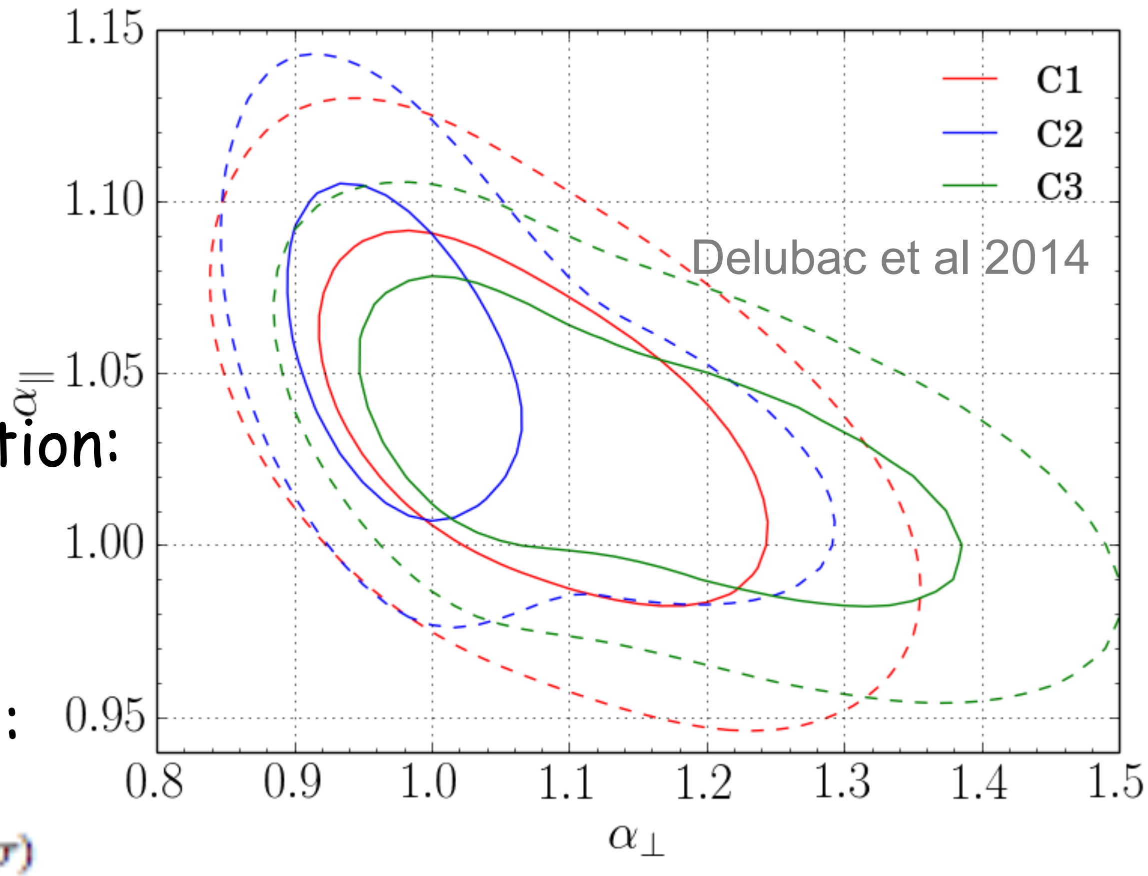
- most precise combination:

$$\alpha_\parallel^{0.7}\alpha_\perp^{0.3} = 1.025 \pm 0.021$$

- in terms of distances :

$$\frac{D_H(2.34)}{r_d} = 9.18 \pm 0.28(1\sigma) \ \pm 0.6(2\sigma)$$

$$\frac{D_A(2.34)}{r_d} = 11.28 \pm 0.65(1\sigma) \ ^{+2.8}_{-1.2}(2\sigma)$$



non Gaussian error on D_A

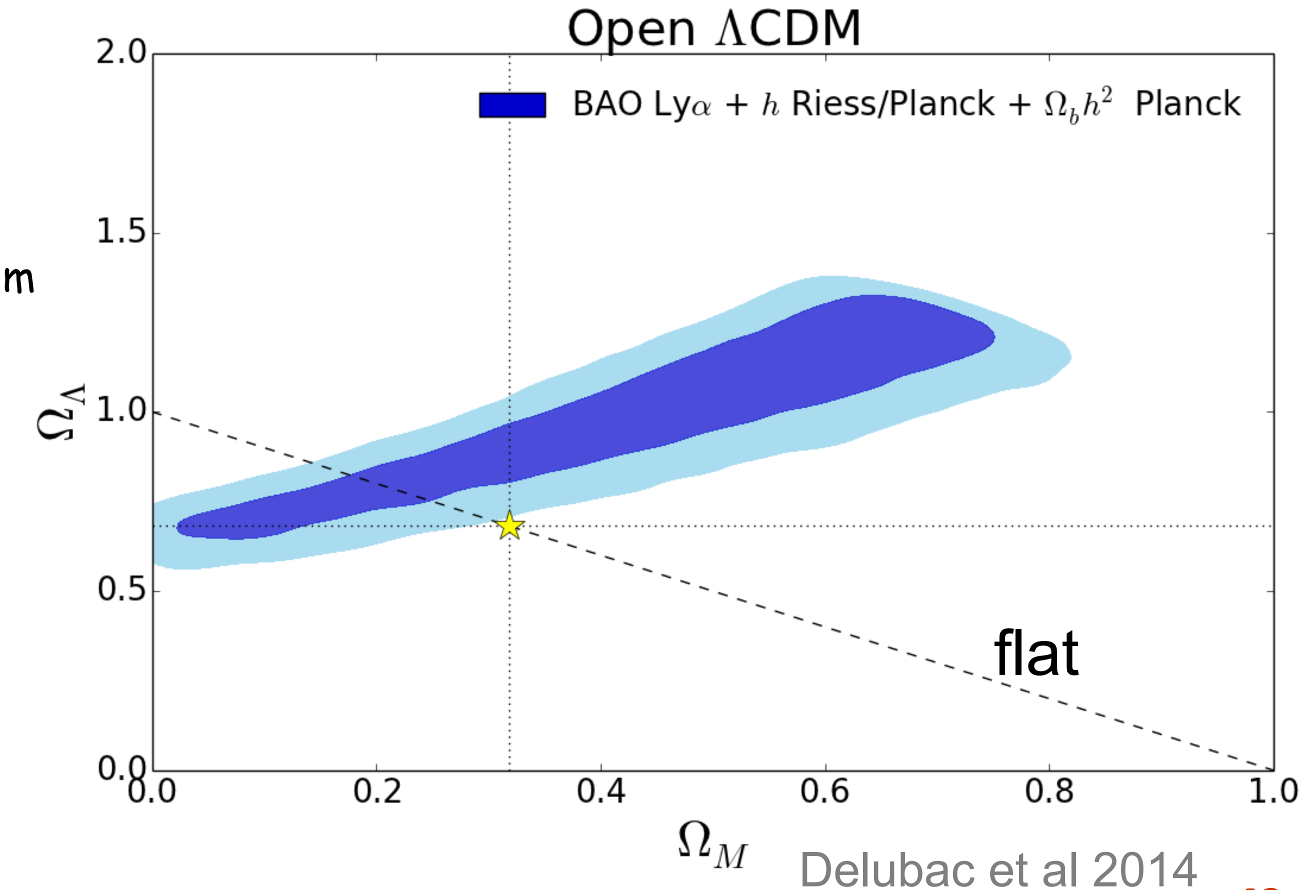
- α's depend on fiducial cosmology, D's do not

cosmological constraints

- Planck prior on $\Omega_b h^2$ and loose prior h = 0.706 +- 0.032
  -> $(\Omega_m, \Omega_\Lambda)$
- tension with

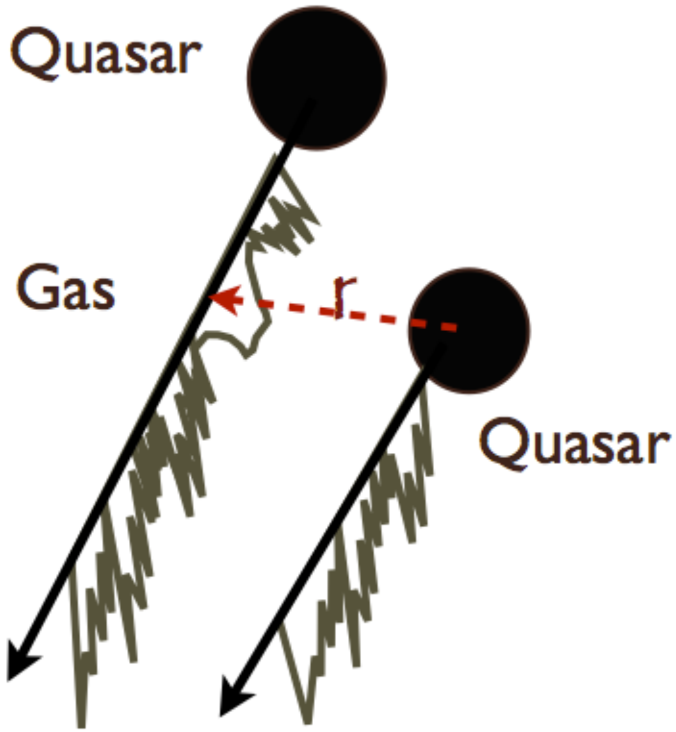
Planck cosmo

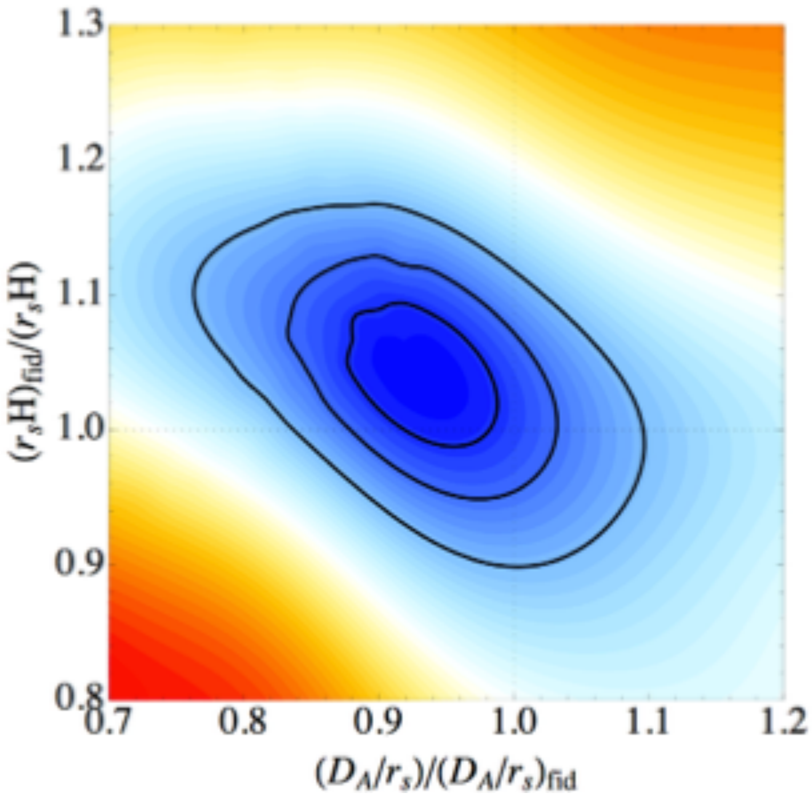
- need to lower Ω_m



Delubac et al 2014

QSO - Lyman α cross-correlation





- H(z) also tends to be high

Font et al 2013

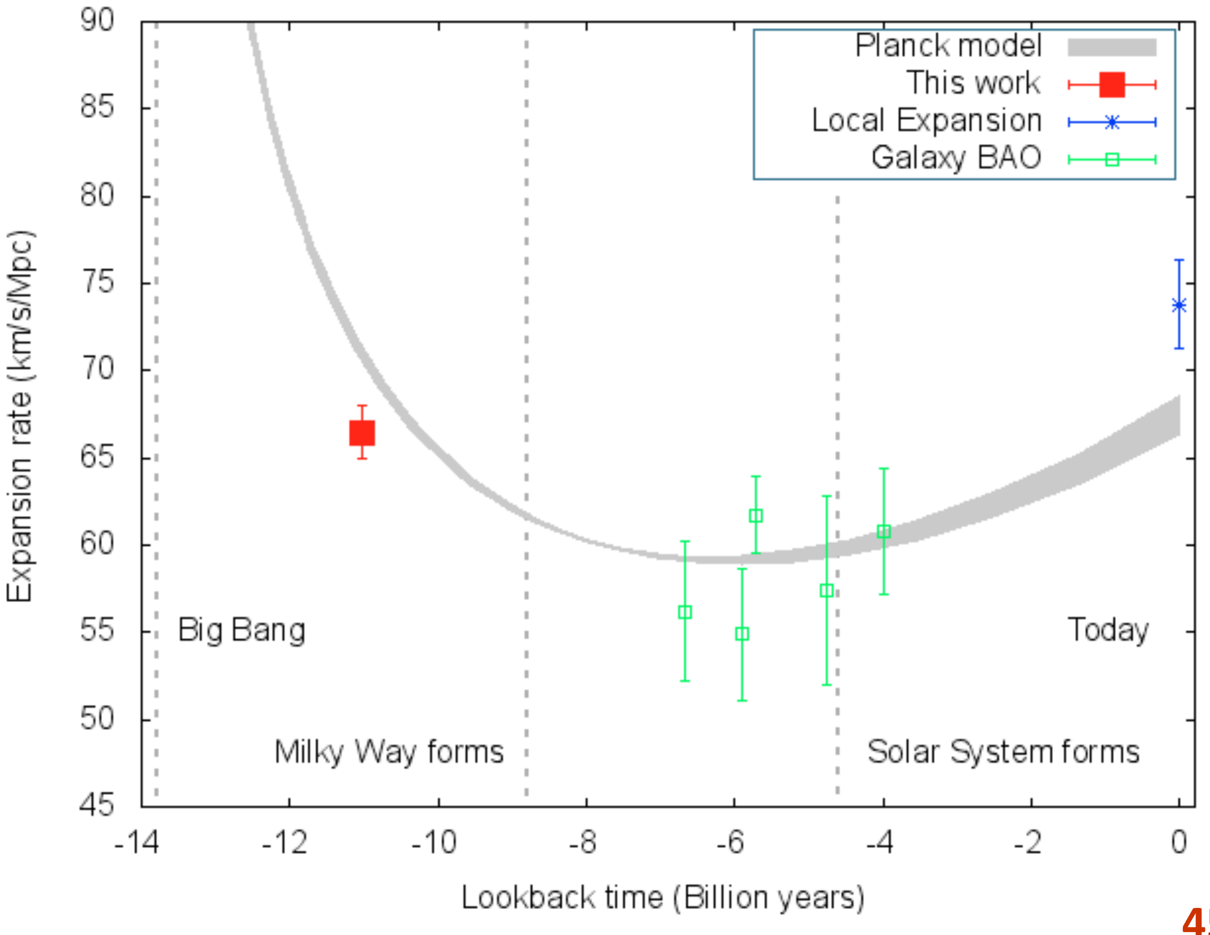
H(z) measurement

- Lyman α + QSO-Lyman α : H(z) r_d measured at 2.3%
- r_d known at 0.4% from CMB

(in standard models but N_{eff} ...)

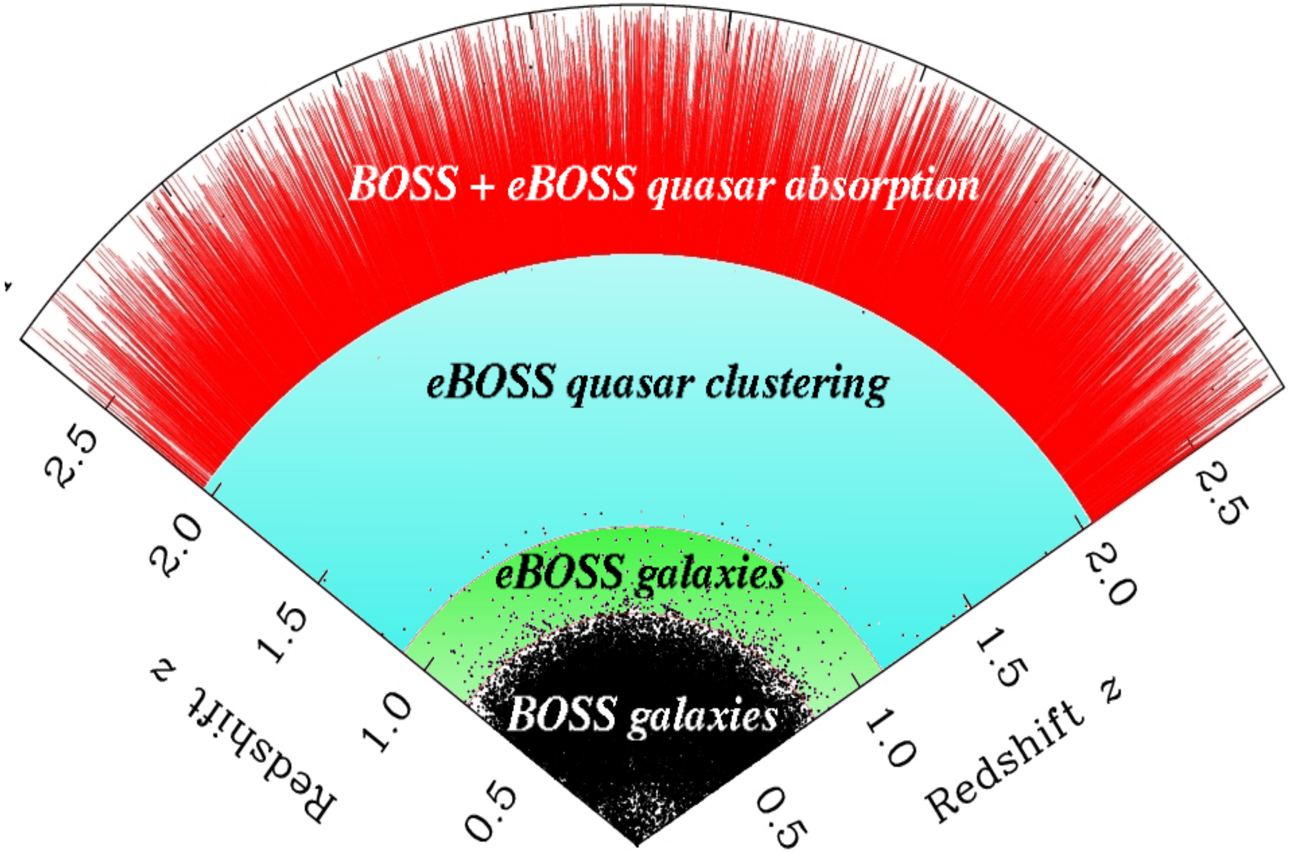
-> most accurate H(z) ever

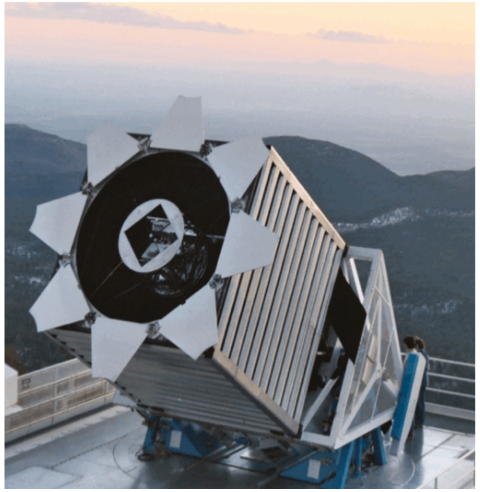
- Press release last Monday
- 2.5 σ from Planck



Perspectives

eBOSS 2014-2020





0.6<z<1.2

- ➢ LRG at z~0.7
- ➢Emission line galaxies (stars forming)

0.9<z<2.2 QSOs

- ➢ Tracers of cosmic structures
- ➢ Unexplored Universe

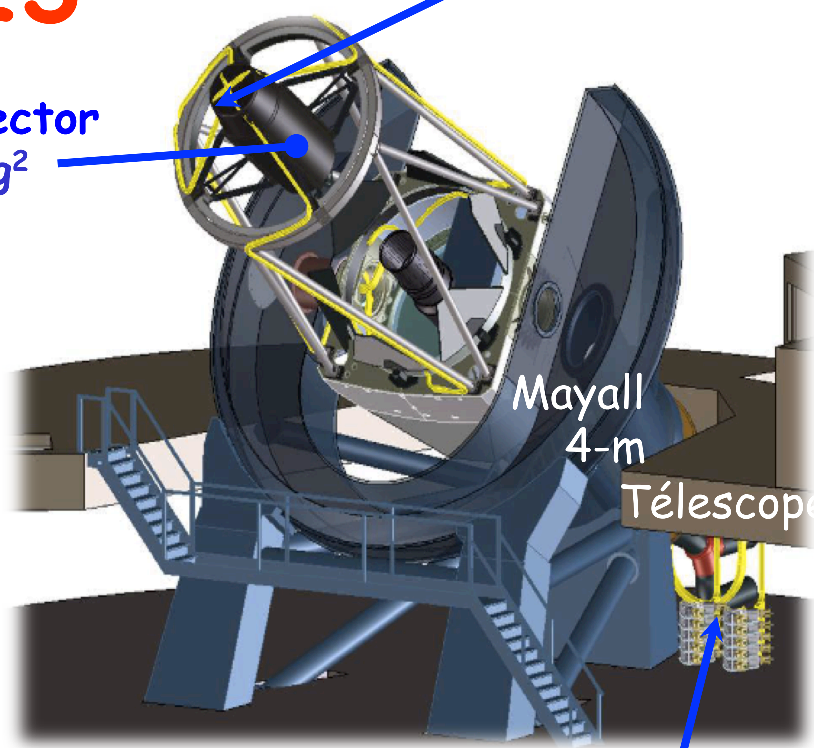
Ly-α QSOs, 2.2<z<5

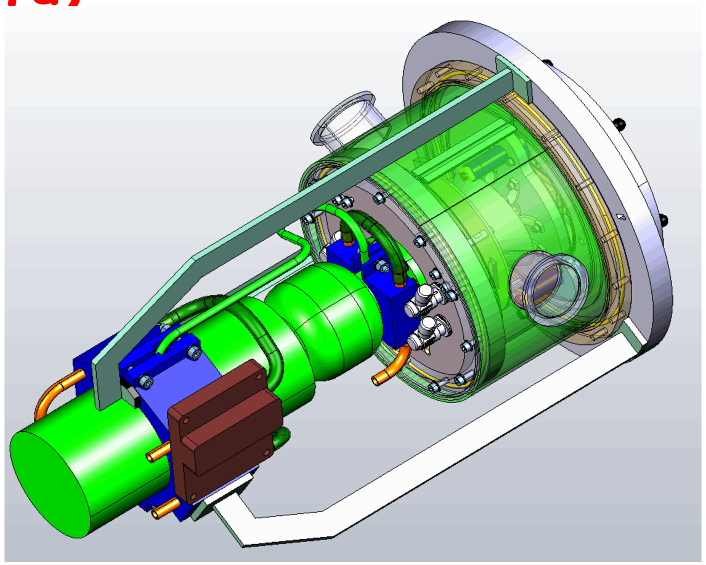
- ➢ Improvement of selection
- ➢ ~17 deg^{-2} ⟹ ~30 deg^{-2}

DESI 2018-2023

Instrument

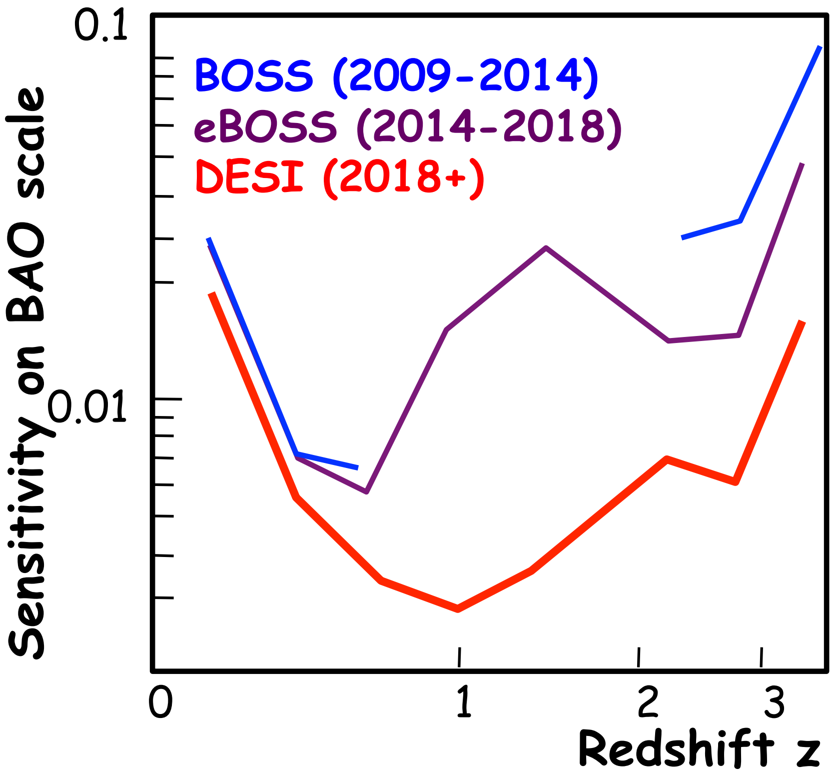
- 4m.telescope at Kitt Peak
- Wide FoV (~ 7 deg^2)
- Robotic positioner with 5000 fibers
- 10 spectrographs x 3 bands (blue, visible, red-NIR)
  →360-1020 nm
- **30 cryostats (built by Irfu)**

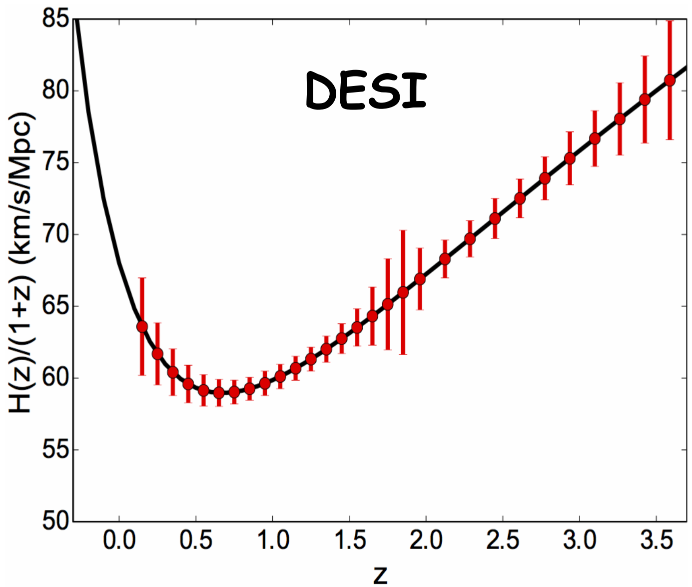




Scientific Project

- International Collaboration steered par Berkeley (DOE)
- 14000 deg^2 survey for $0.3<z<4.5$
- 20M galaxies and quasars





Science with eBOSS and DESI

Improvements with eBOSS

- Continuous measurement of BAO for 0.3<z<4.0.
- Exploration of unknown area: Dark matter → Dark energy

Improvements with DESI

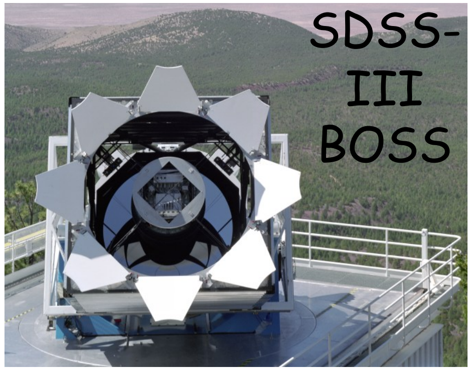
- **BAO:** 1 order of magnitude
- **Neutrino masses:** accuracy ~20-25 meV on Σm_ν

- **Important role of French groups for the two projects**

BAO Roadmap

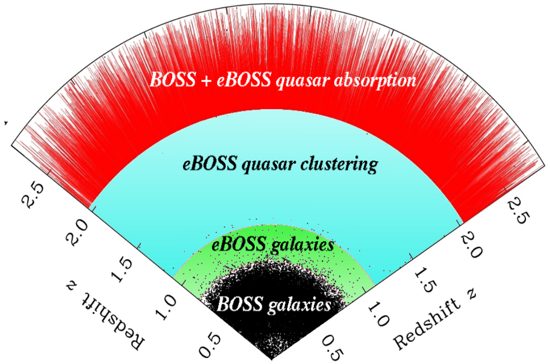
BOSS →2014

- BAO, a well established method
- BAO avec les Ly-α des QSOs
  → Decelerating Universe.
- Important role of FPG
  → 2013 price of "La Recherche" magazine



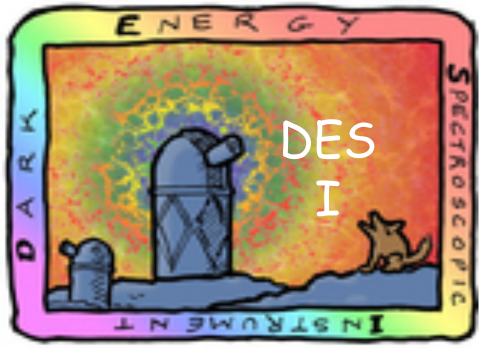
eBOSS 2014-2020

- Exploring unknown Universe:
  Dark matter → Dark energy
- DESI precursor (target selection)



DESI 2018-2023

- One order of magnitude compared to BOSS and eBOSS.
- Participation of Insu and Irfu to instrument construction.



Conclusions

- BOSS data taking finished, in advance ! very successful
  SEQUELS to prepare eBOSS
- LRG : 2% at z=0.32 and 1% at z=0.57
  agree with LCDM Planck
  useful with add. param.: e.g. good constraint on Ω_k
- Lyman α even better than expected
  2.5 σ tension with Planck
- RSD : 2 σ tension with GR + Planck
- neutrino mass (Lyman α 1D analysis at Saclay)
- great future : eBOSS and DESI