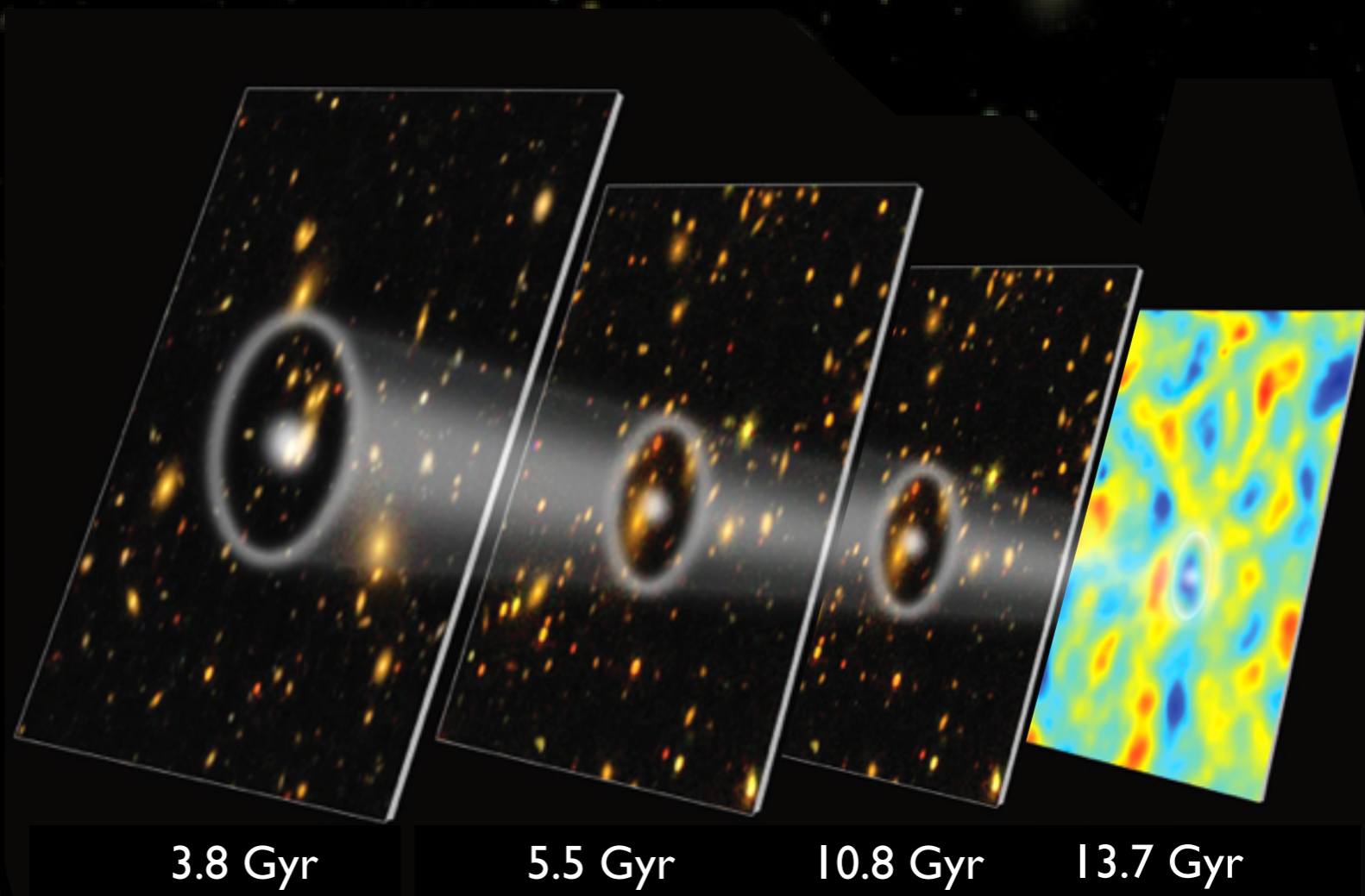


Update on SDSS3/BOSS



J.-Ch. Hamilton
APC, Paris

Menu

- Appetizers

- ★ The Dark Energy mystery
- ★ Distance measurements
- ★ BAO

- BOSS : Baryon Oscillations Spectroscopic Survey

- ★ The instrument
- ★ The survey strategy and status

- Results on BAO with BOSS

- ★ Galaxy survey key analysis issues and results
- ★ Lyman- α forest survey key analysis issues and results

- Conclusions and prospects

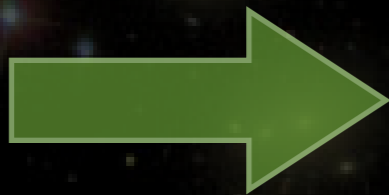
Dark Energy Problem...

- Λ CDM well established now (from an observational perspective)

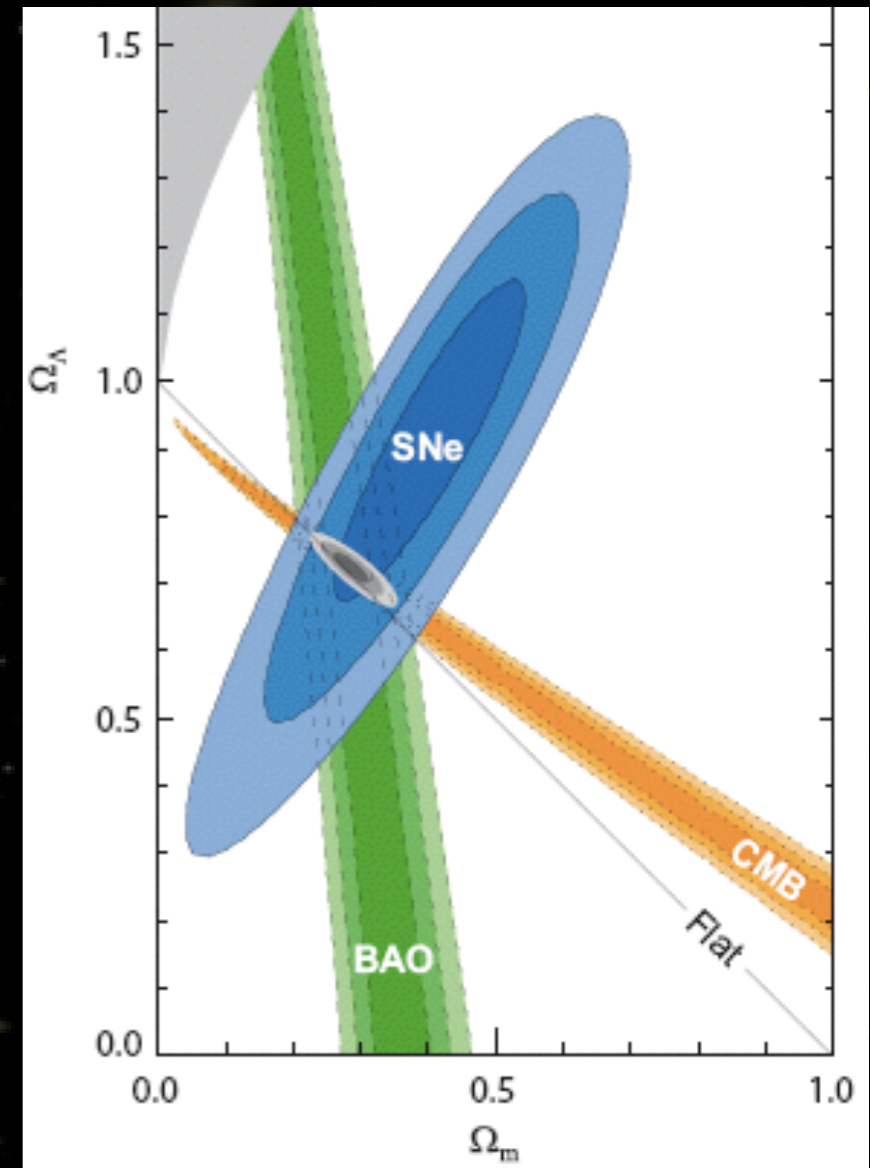
- ★ SNe
- ★ CMB
- ★ BAO
- ★ Lensing

- Nature of Λ ?

- Most upsetting question in cosmology...
 - value of Ω_Λ : seems more or less established...
 - equation of state for Λ :
 - -1 : \sim Cosmological constant [gravity]
 - other : Dark Energy [matter content]
 - ...

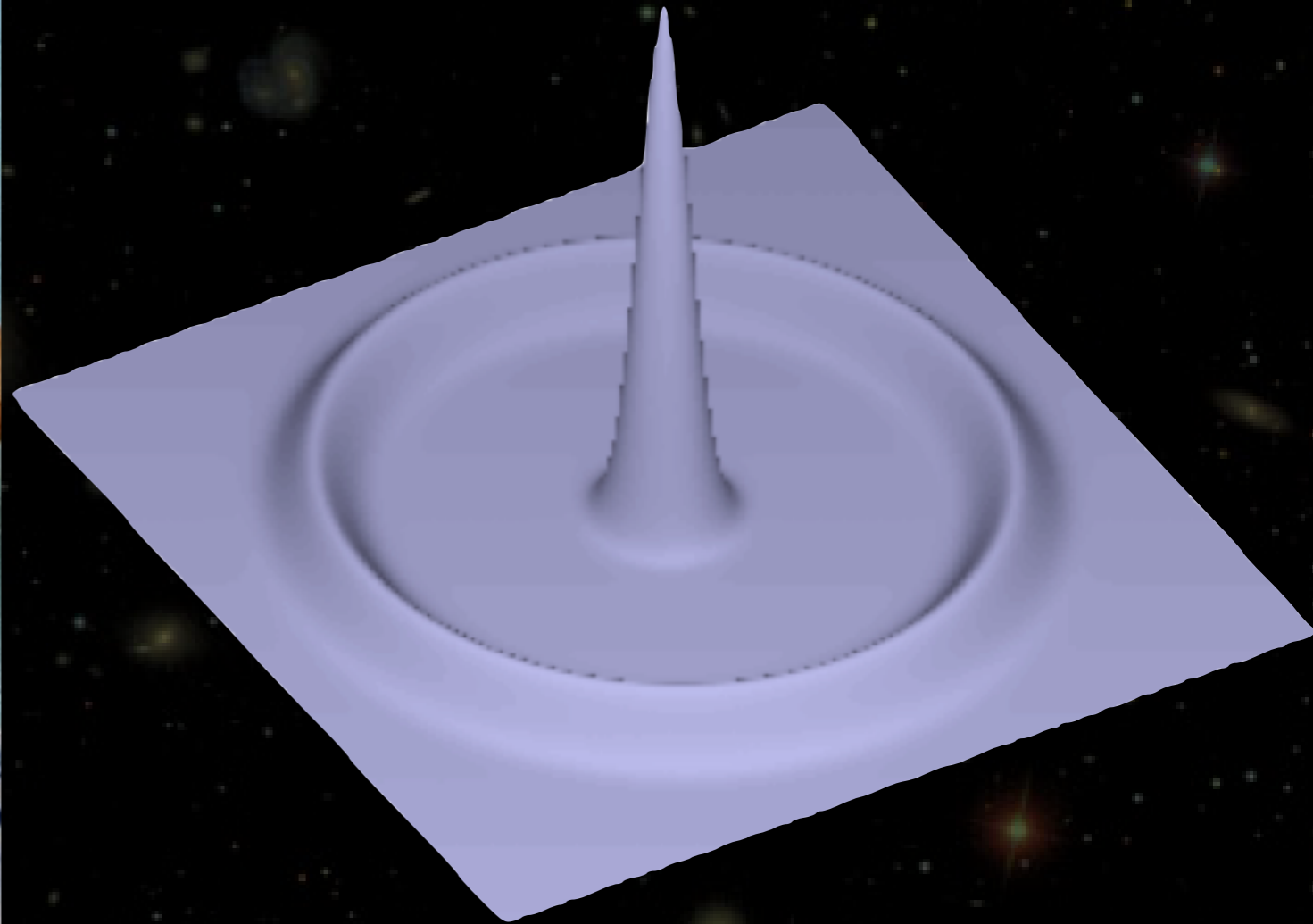


- Measurements of $H(z)$
- Measurements of Gravity
- More models and calculations...



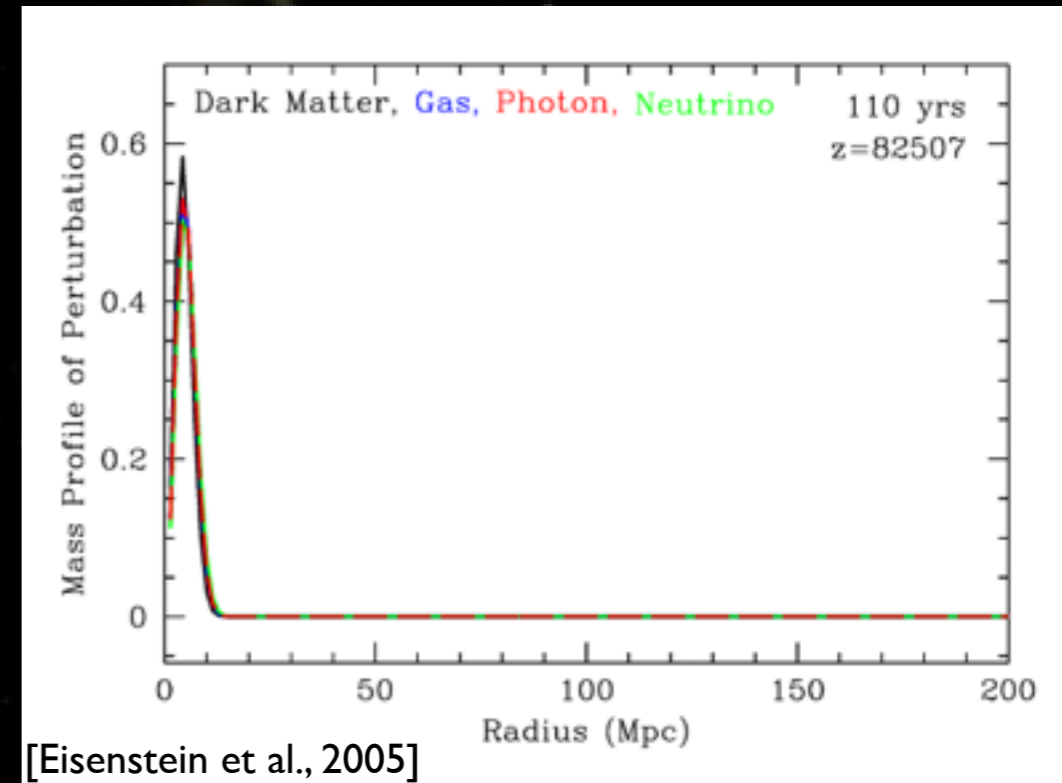
[Kowalski et al. 2008]

What are the BAO ?



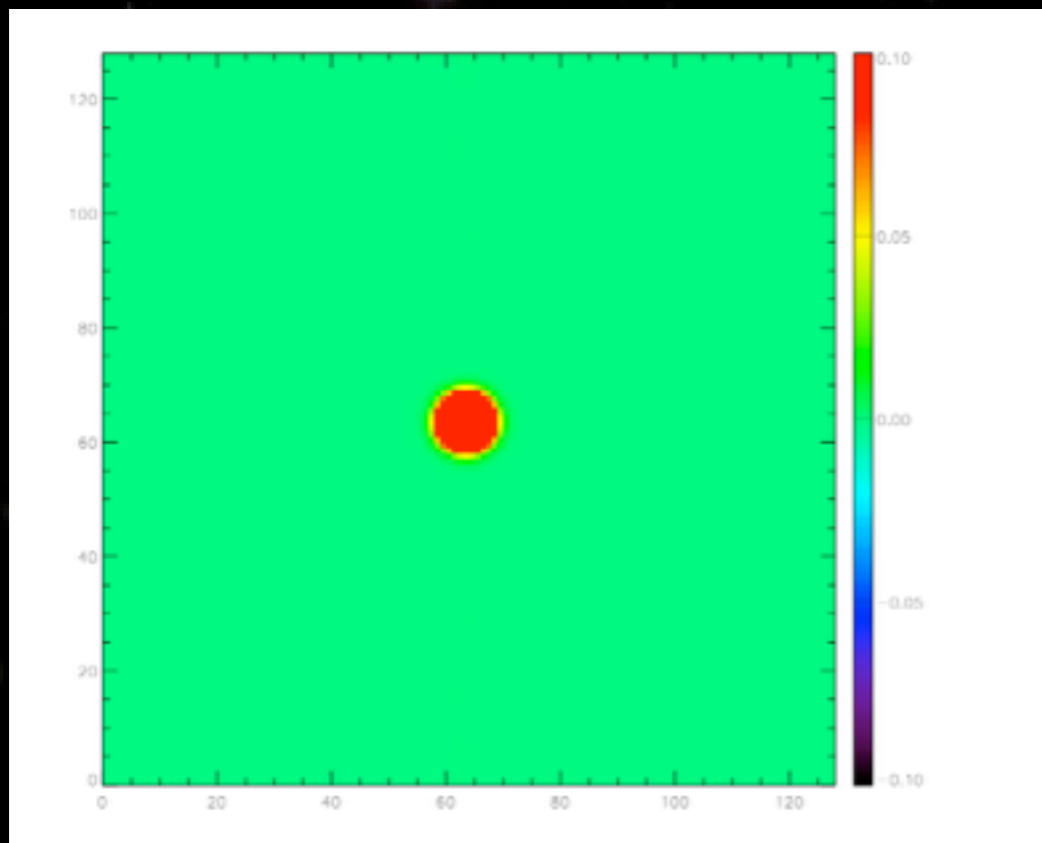
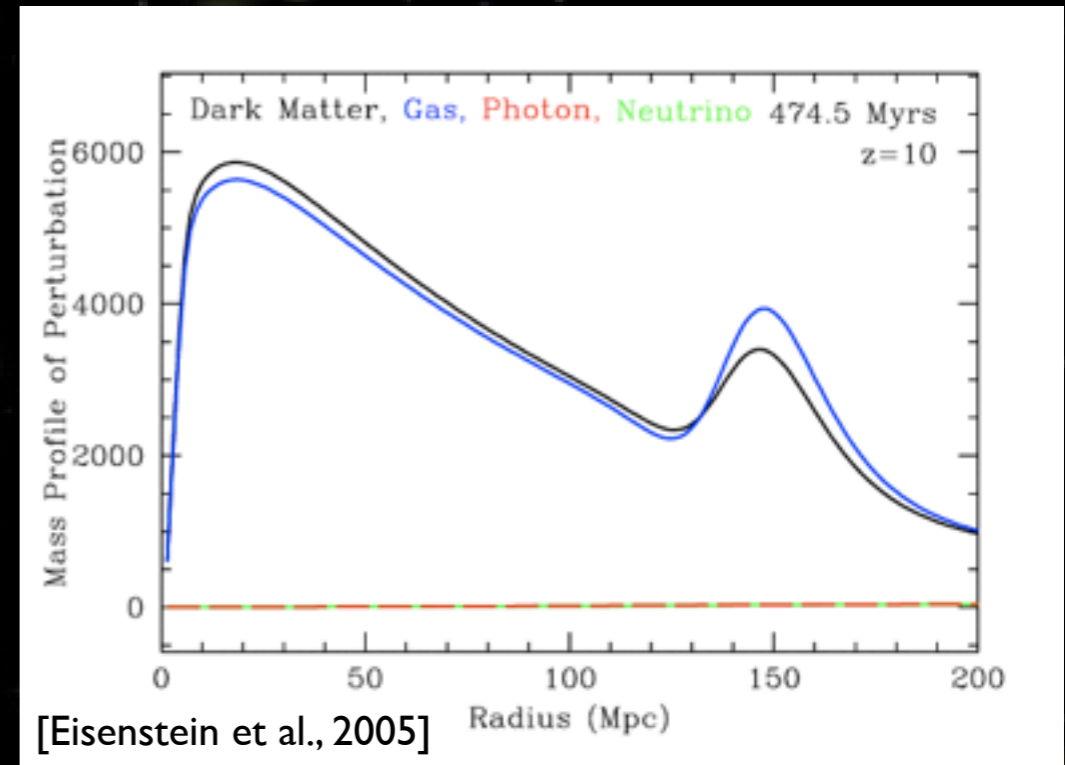
Baryon Acoustic Oscillations

- Early times: Ionized Universe
 - ★ Photons and baryons are coupled
 - ★ Pressure waves propagation
- Matter-radiations decoupling: Neutral Universe
 - ★ Photons escape (CMB)
 - ★ Baryons: excess at sound horizon (150 Mpc)
 - ★ Dark matter stayed at the center
 - ★ An excess remains at 150 Mpc

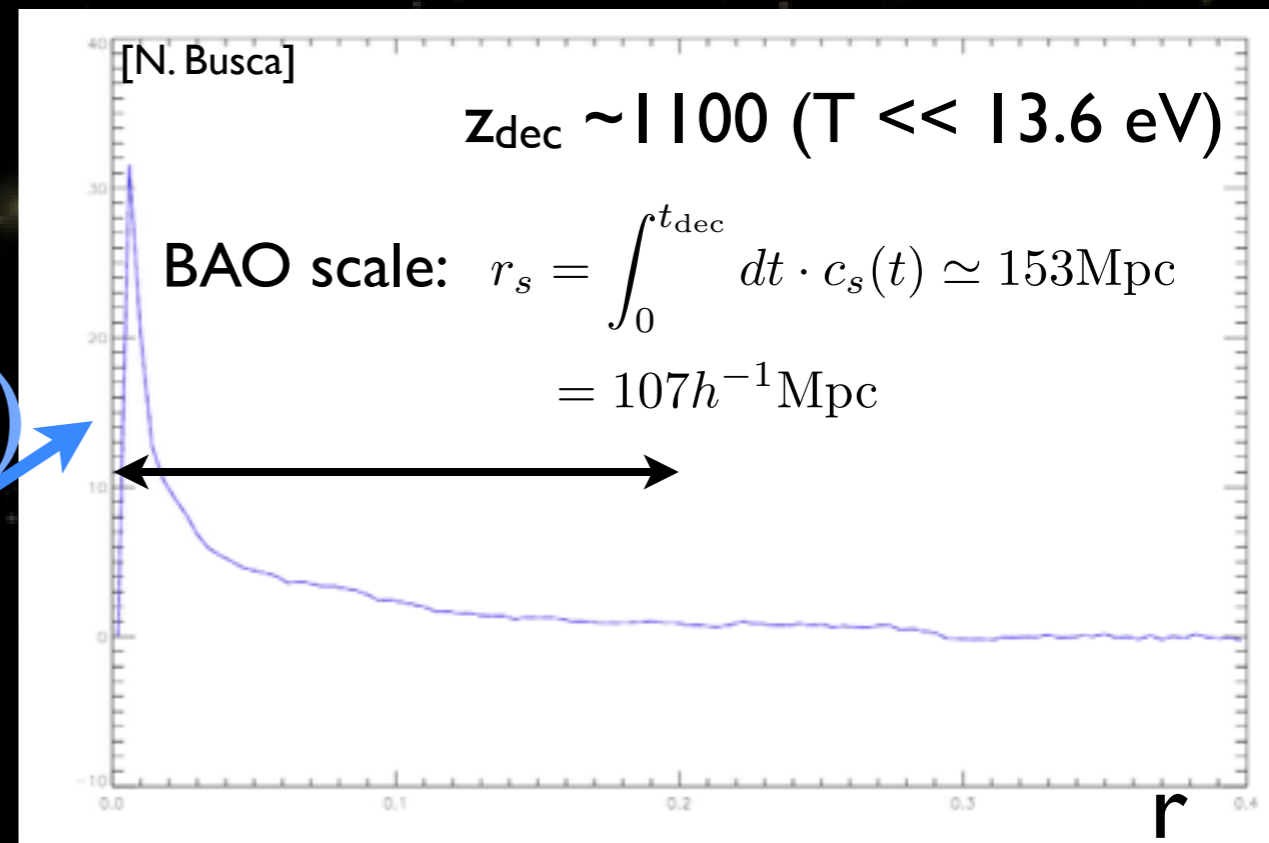


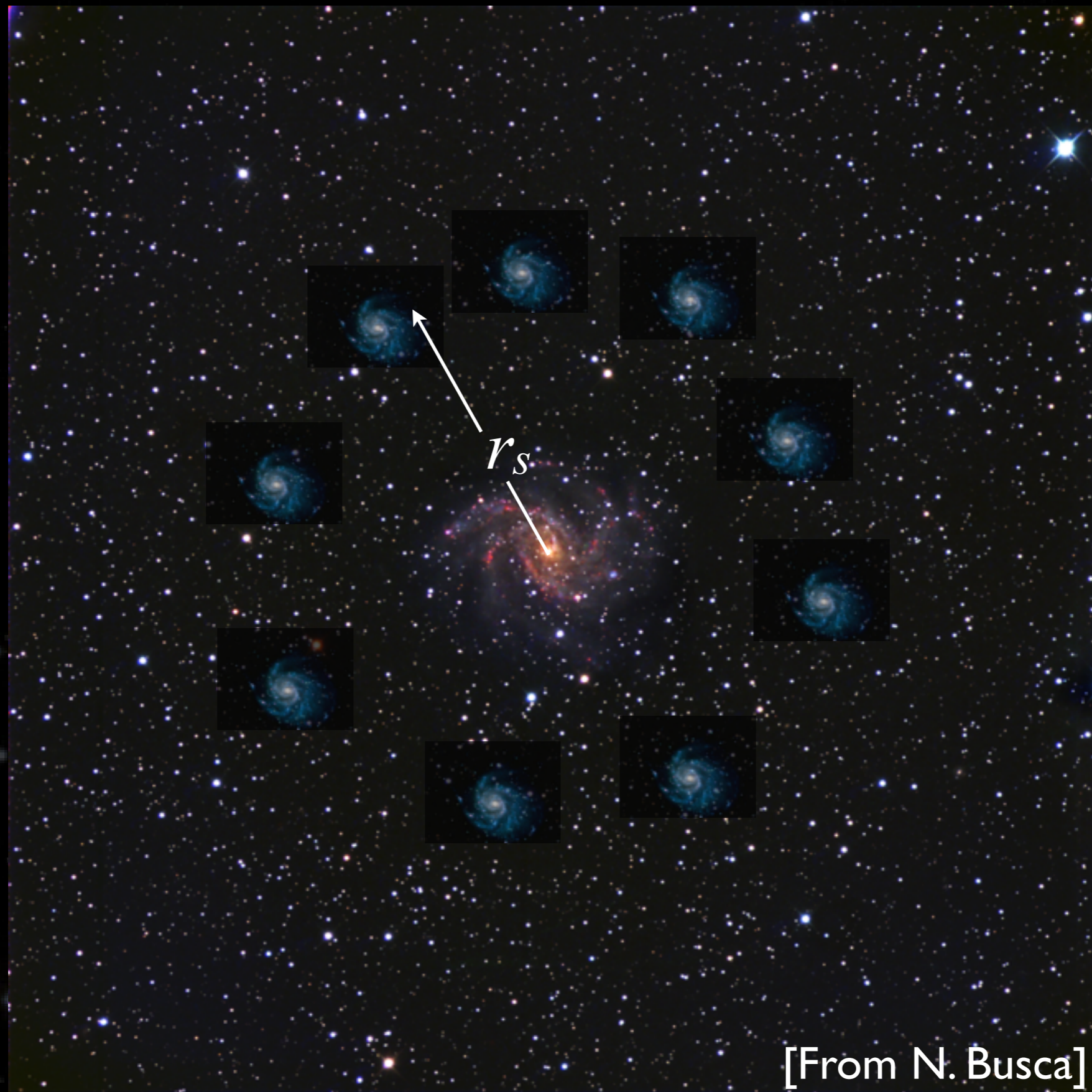
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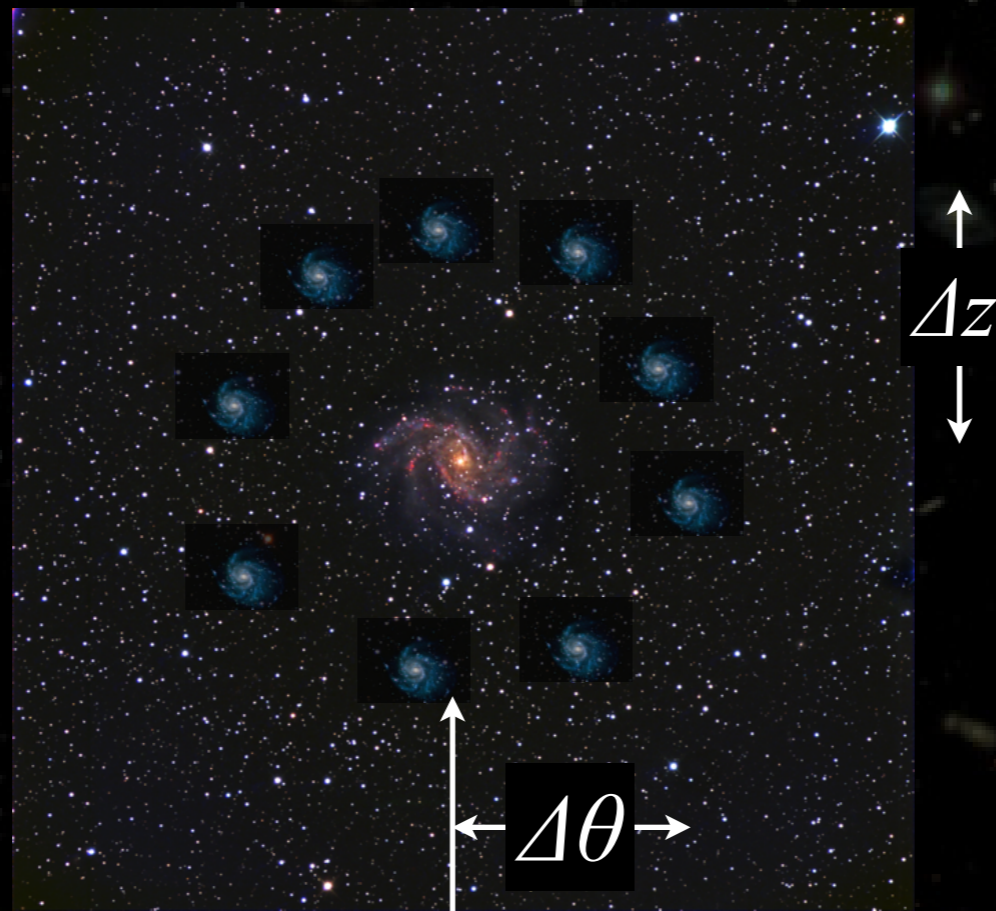


$\xi(r)$





[From N. Busca]



$$H(z) = \frac{c\Delta z}{r_s}$$

$$D_A(z) = \frac{r_s}{\Delta\theta}$$

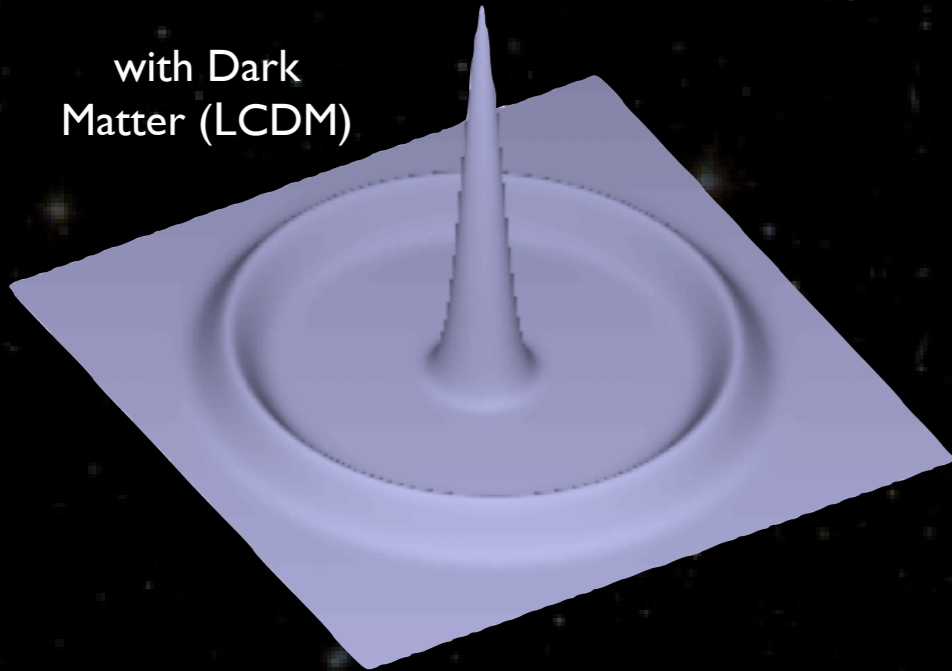
[From N. Busca]

BAO: standard ruler

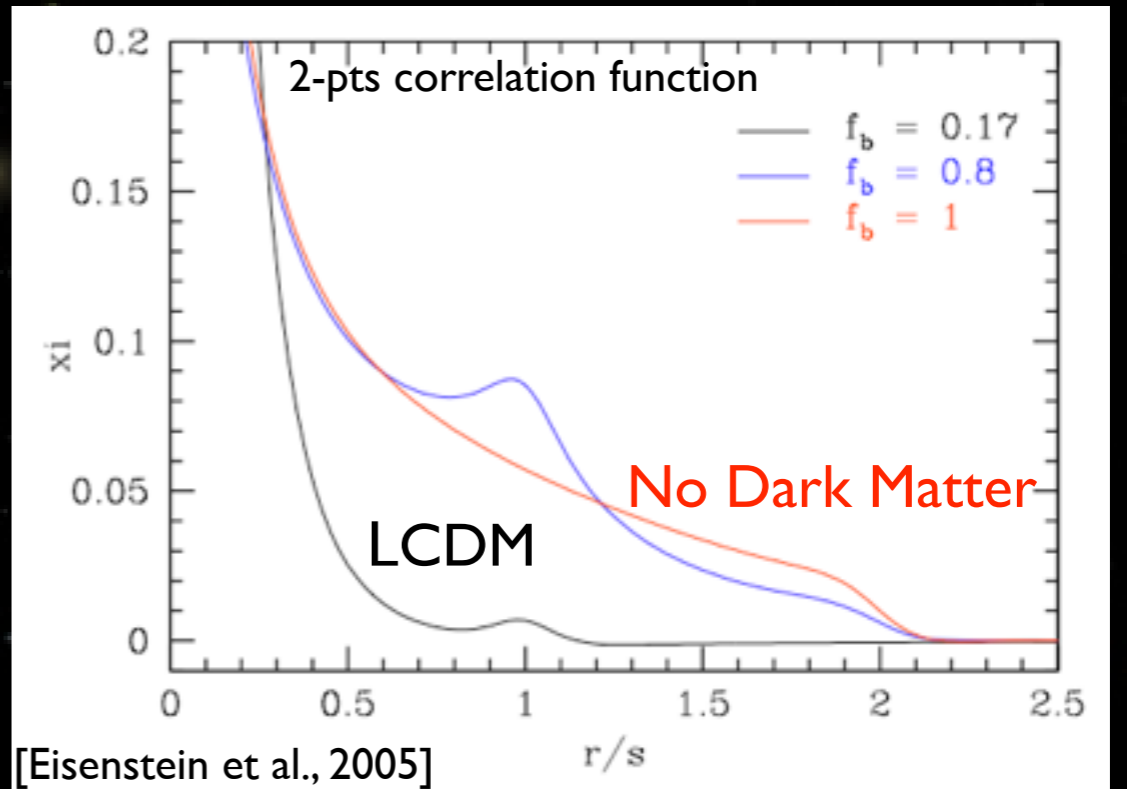
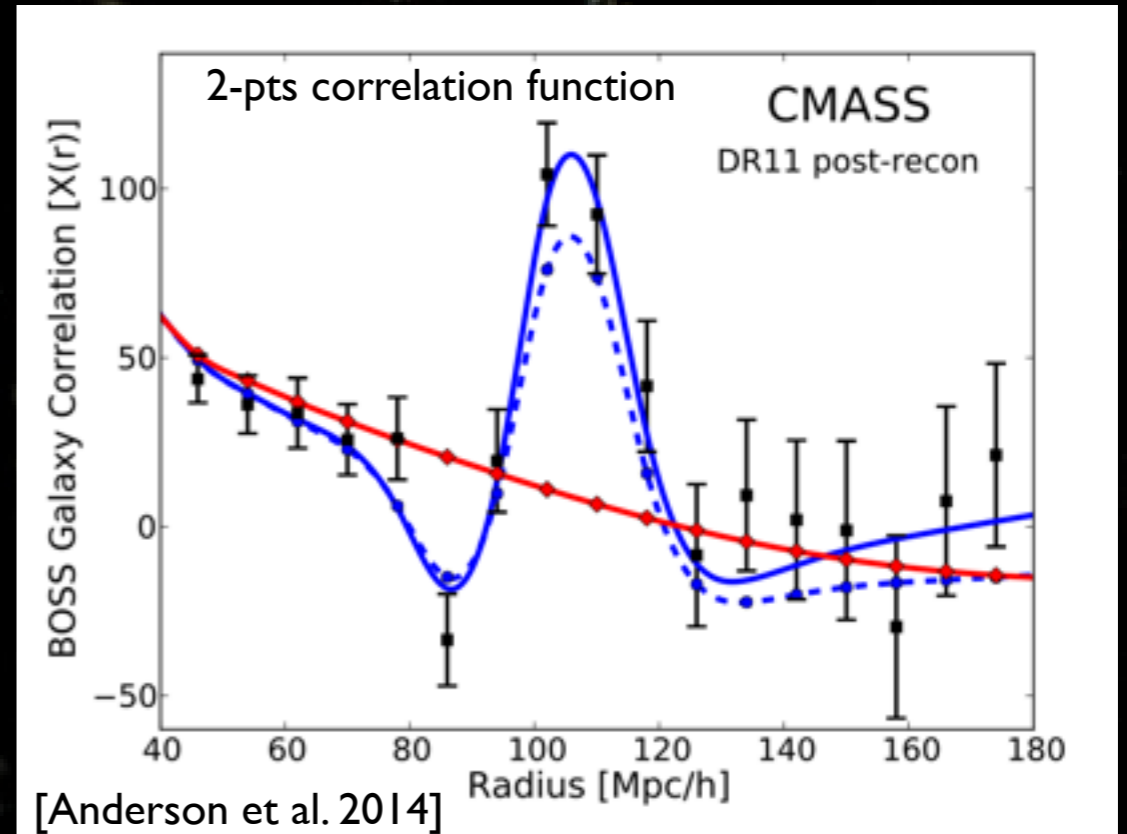
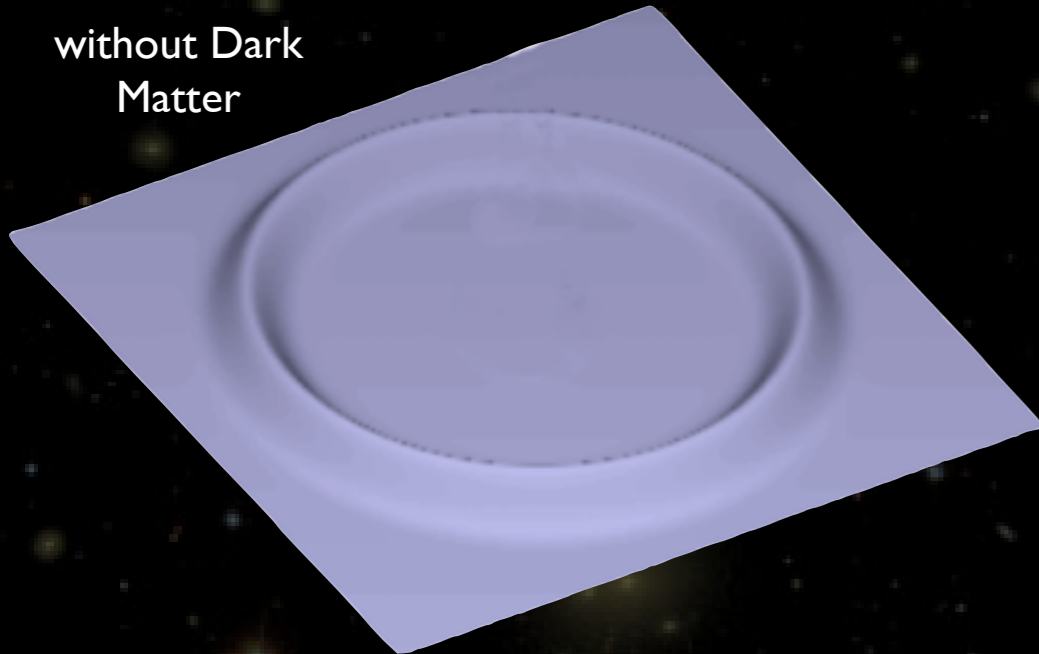


BAO and Dark Matter

with Dark Matter (LCDM)

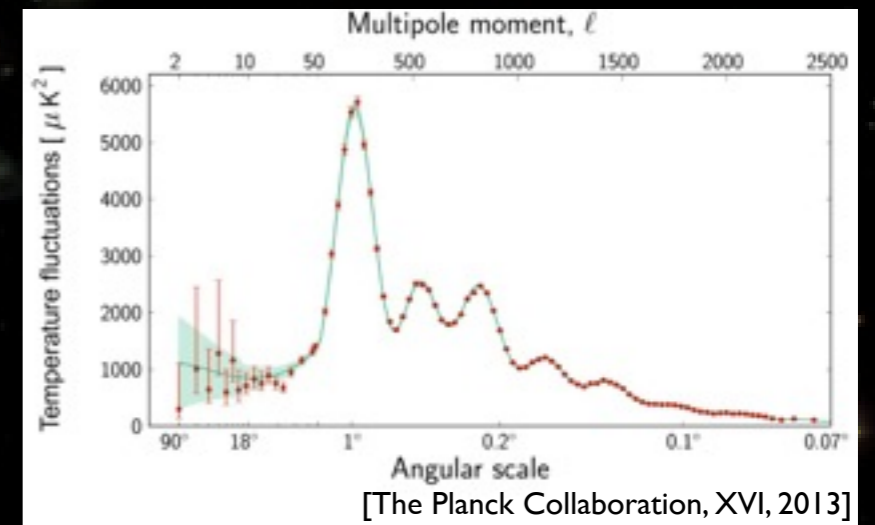
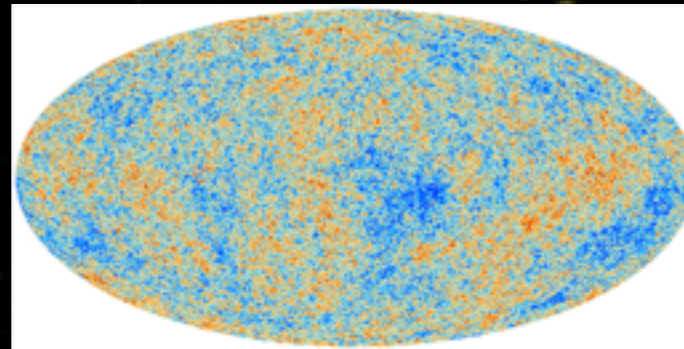


without Dark Matter

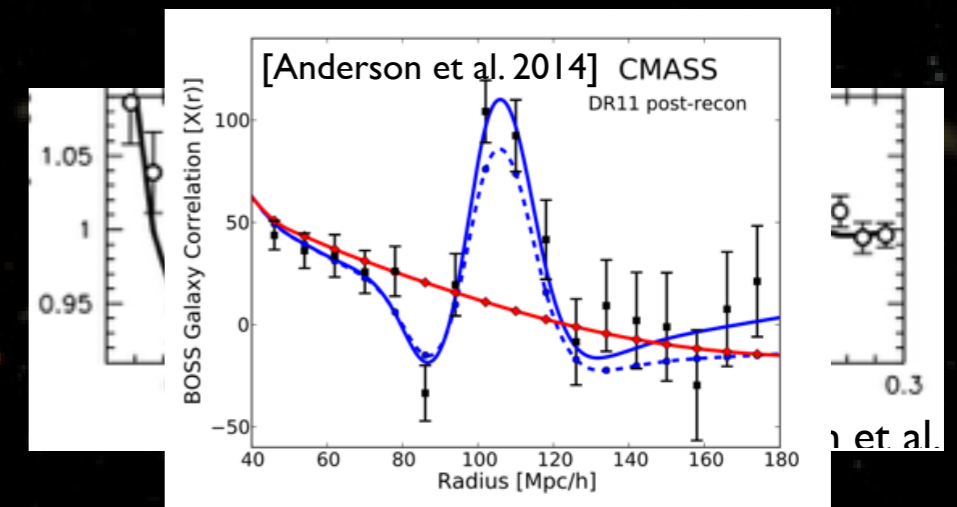
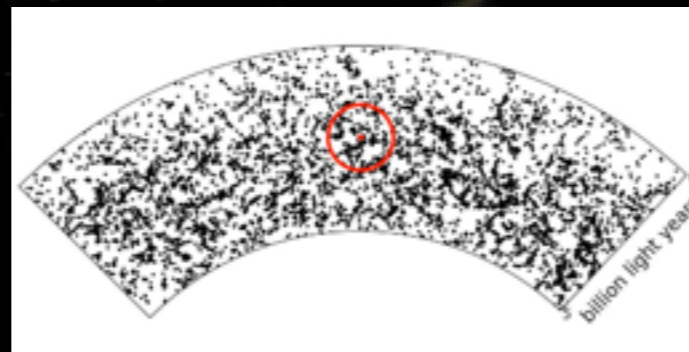


BAO observations

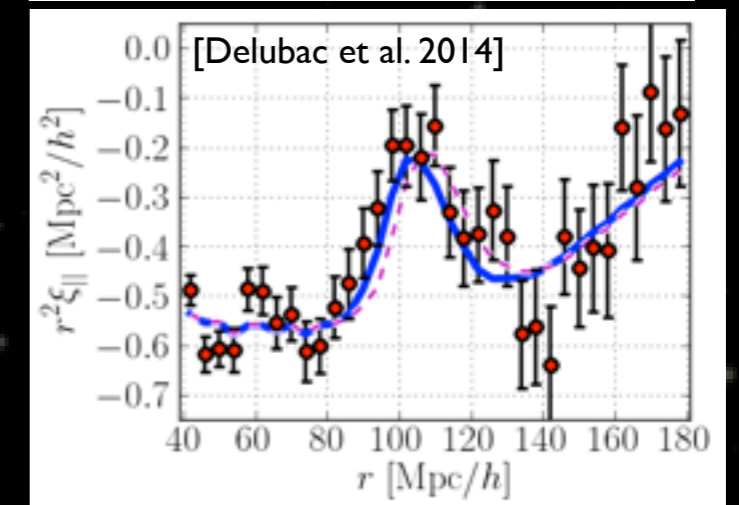
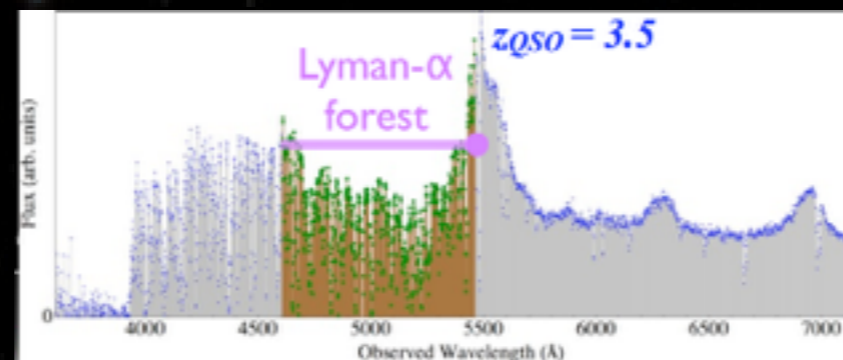
- CMB



- Galaxies



- Lyman- α Forest



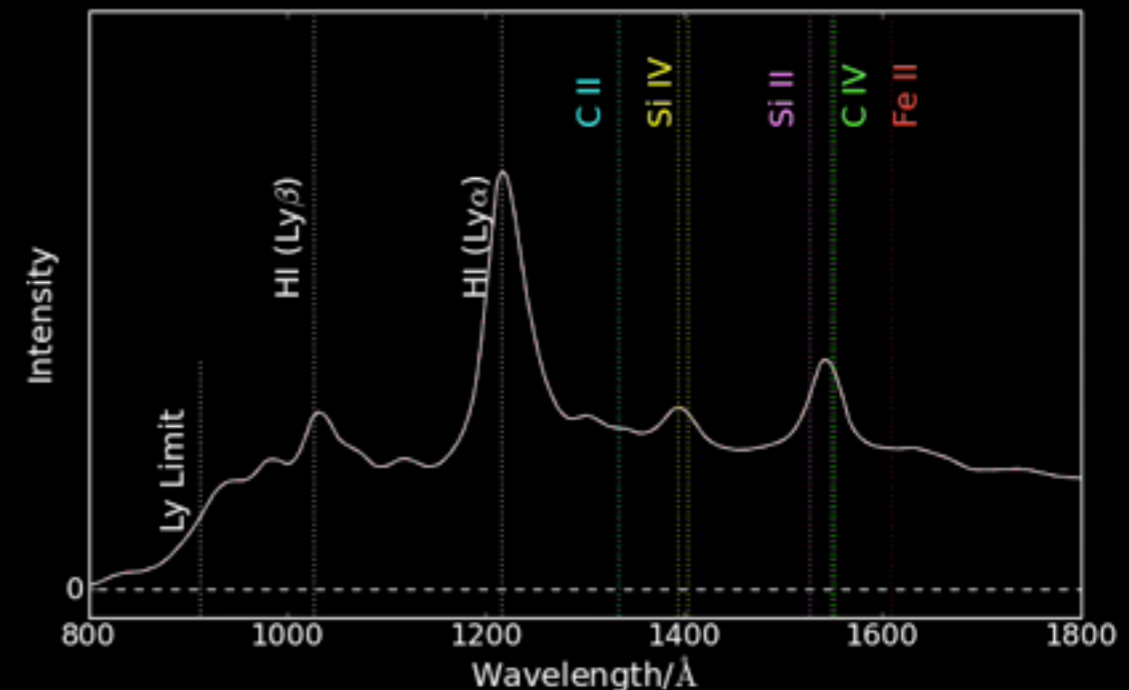
BAO in the Lyman- α forest

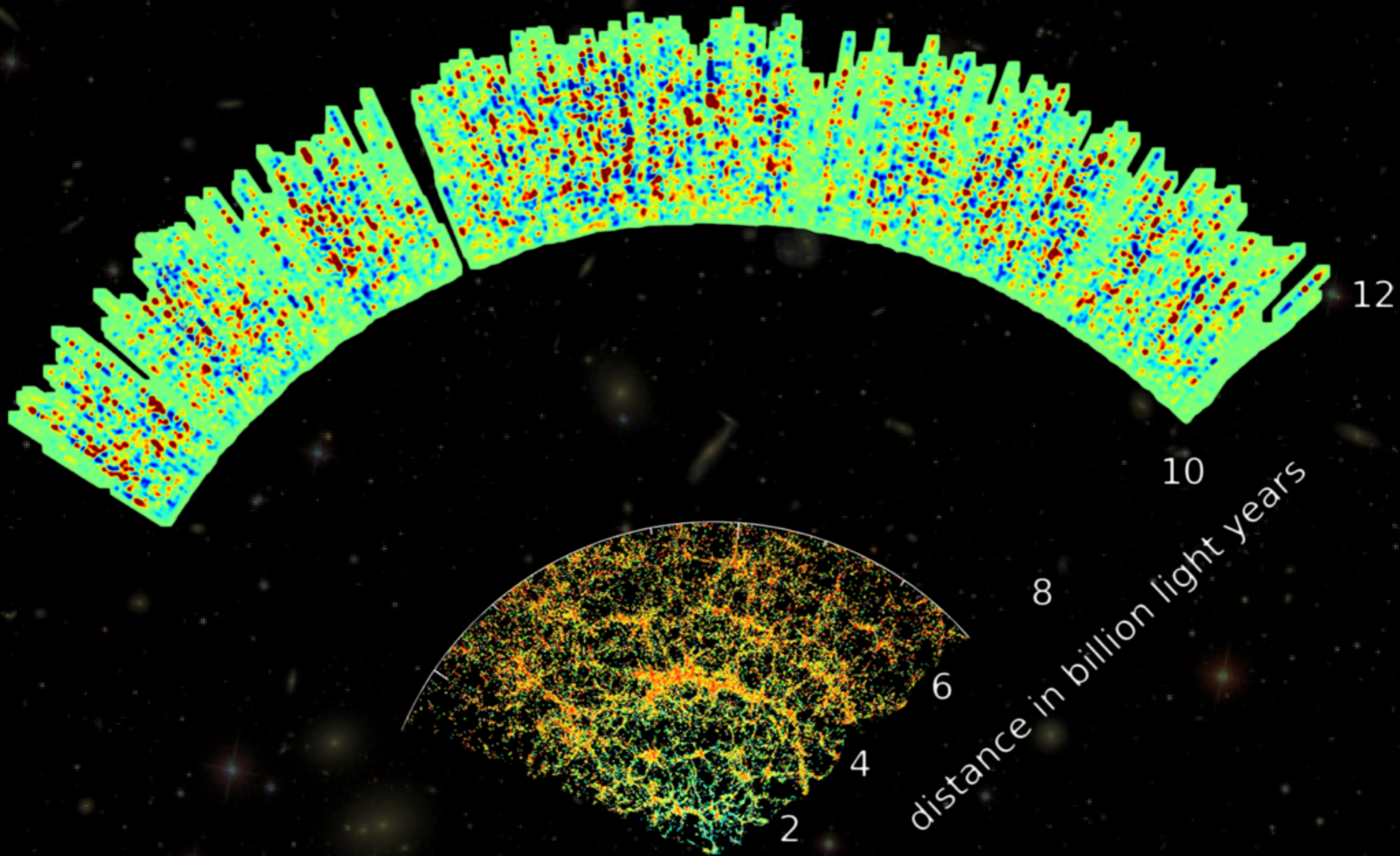
- Quasars:

- ★ massive black-hole accreting matter
- ★ ~First collapsed objects in the Universe
- ★ Very bright: visible up to $z > 6$
- ★ Spectra are well known and contain a continuum

- Lyman- α Forest

- ★ Absorption lines from neutral Hydrogen along the line of sight:
 - Quasar light gradually redshifted
 - Absorption by Lyman- α transition at fixed λ in the hydrogen cloud referential frame
 - Series of absorption lines in the quasar continuum:
 - Lyman- α forest
 - absorption \sim H density (related to that of D.M.)
- ➔ Measures the density of Dark Matter along the line of sight !!





3D or isotropized BAOs ?

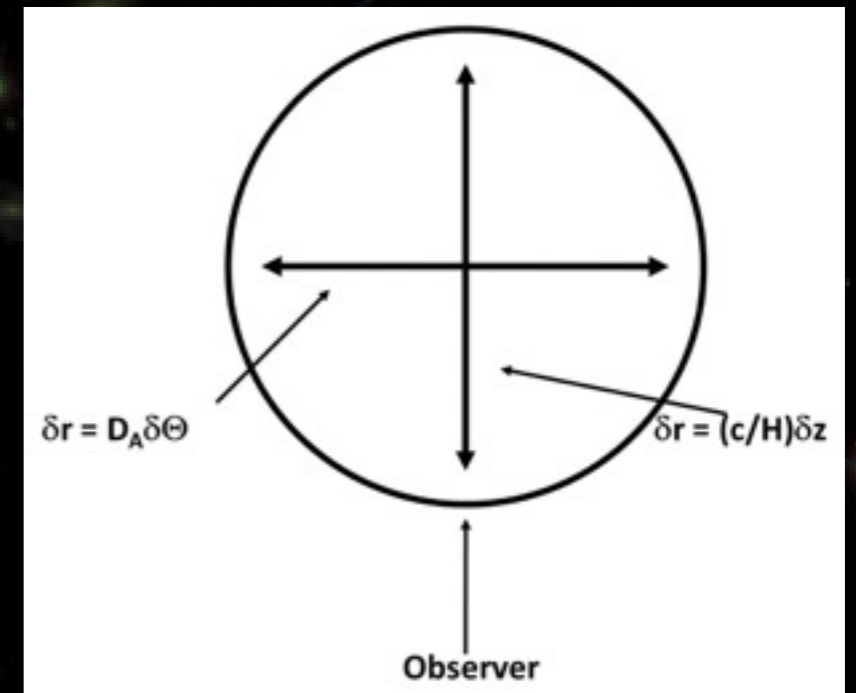
- Recap:

- ★ Transverse direction:

- Angular distance : $D_a(z) \propto \int \frac{dz}{H(z)}$

- ★ Radial direction:

- redshift depth : $\Delta z \propto \frac{1}{H(z)}$



- 3D measurements:

- ★ r_{\perp} (2D) and r_{\parallel} (1D)

- ★ Complementary cosmological information

- ★ Symetric if cosmo is correct

- ★ Alcock-Paczynski test (1979)

- Isotropized measurements

- ★ $\xi(r) = \xi(\sqrt{r_{\parallel}^2 + r_{\perp}^2})$

- ★ sensitive to $D_v(z)$

$$D_v(z) = \left[D_a^2(z) cz / H(z) \right]^{1/3}$$

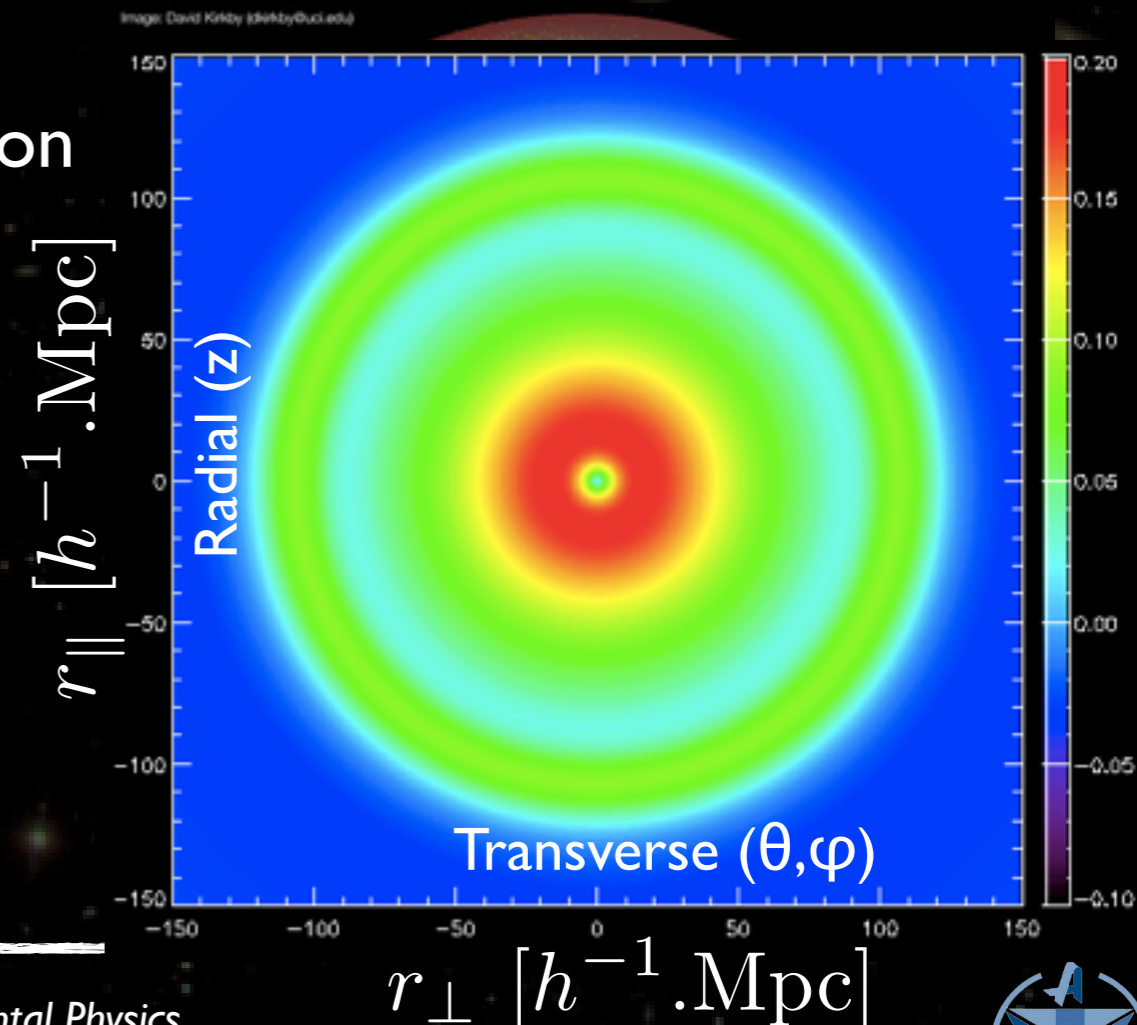
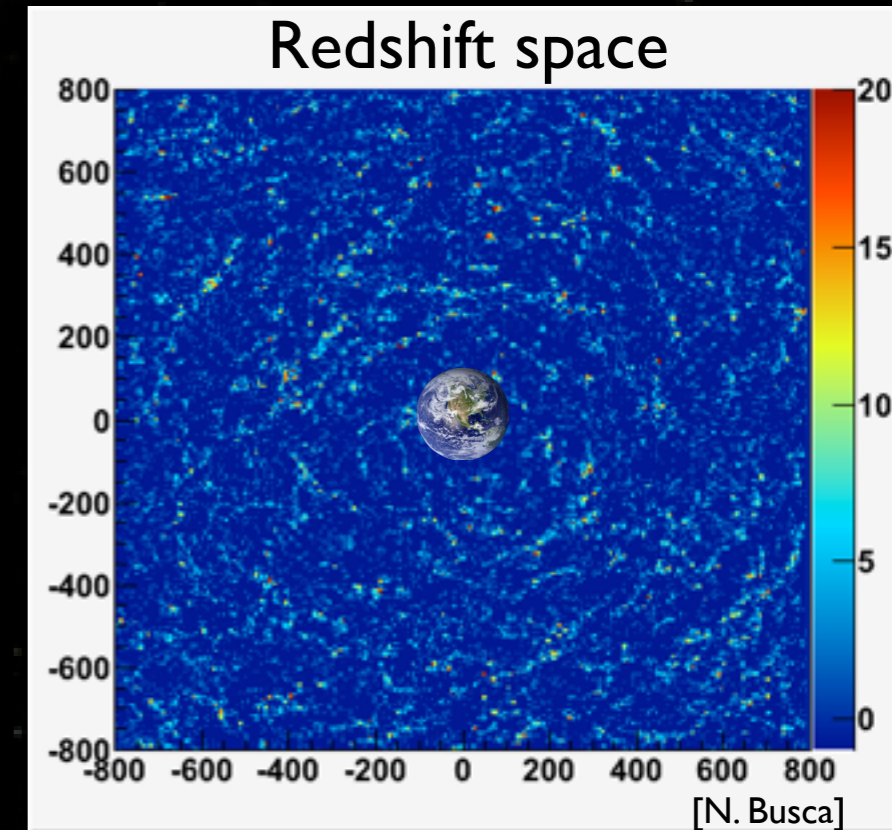


Image: David Kinby (kinby@uci.edu)

BAO in the «real world»

- Redshift space distortions
 - ★ One does not measure the positions of galaxies
 - ★ One measures (θ, φ, z)
 - ★ z is distorted: $z_{\text{meas}} = z_{\text{true}} + z_{\text{pec}}$
 - Kaiser effects (large scales):
 - Galaxies fall into DM potential wells
 - increases the clustering S/N ratio
 - Fingers of God (virialized clusters, small scales):
 - Random velocities of galaxies



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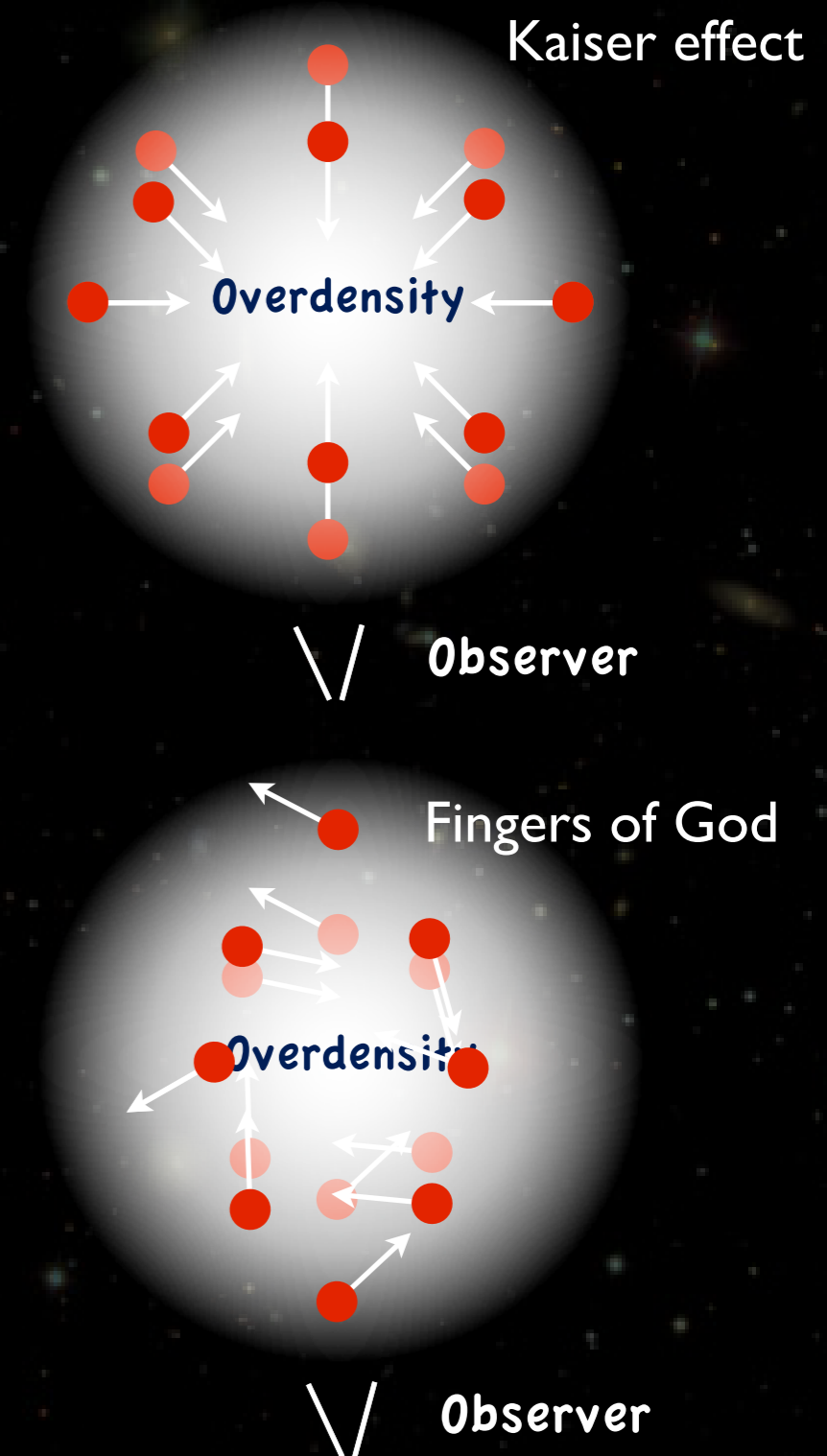
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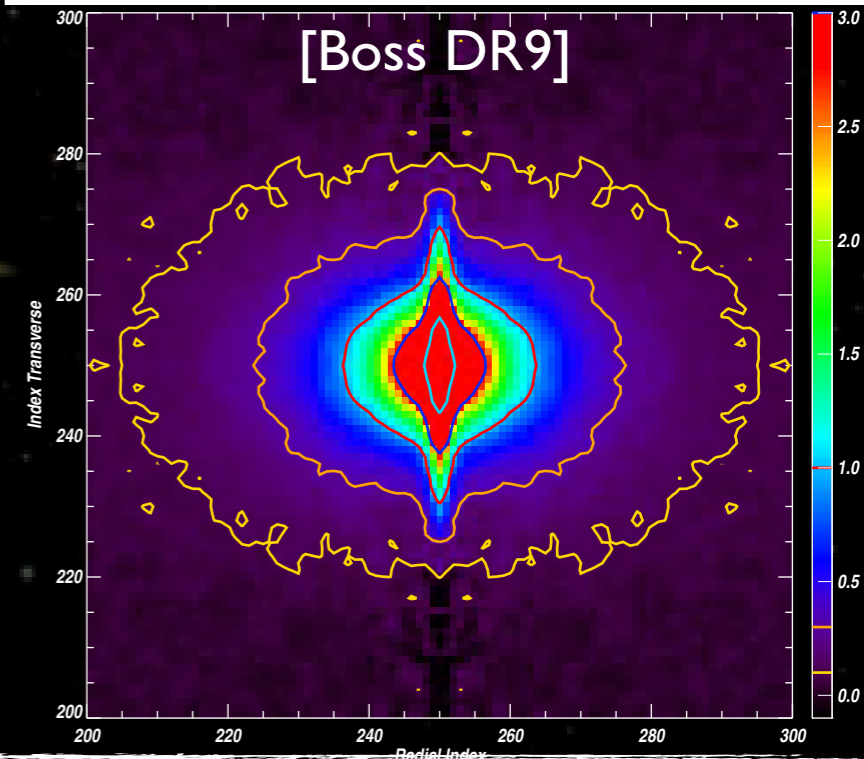
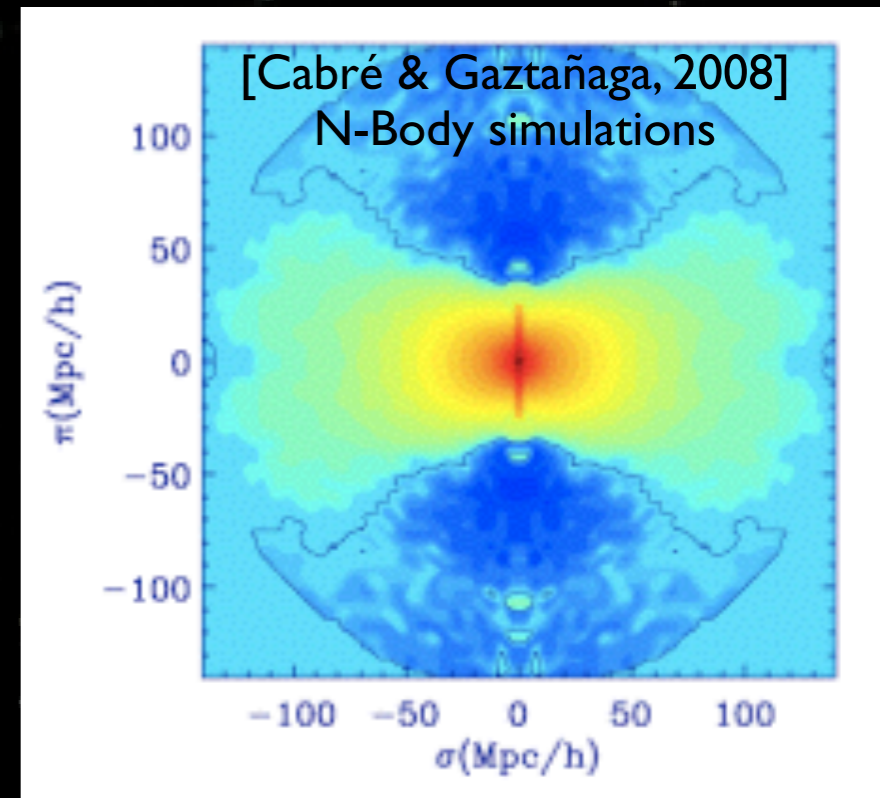
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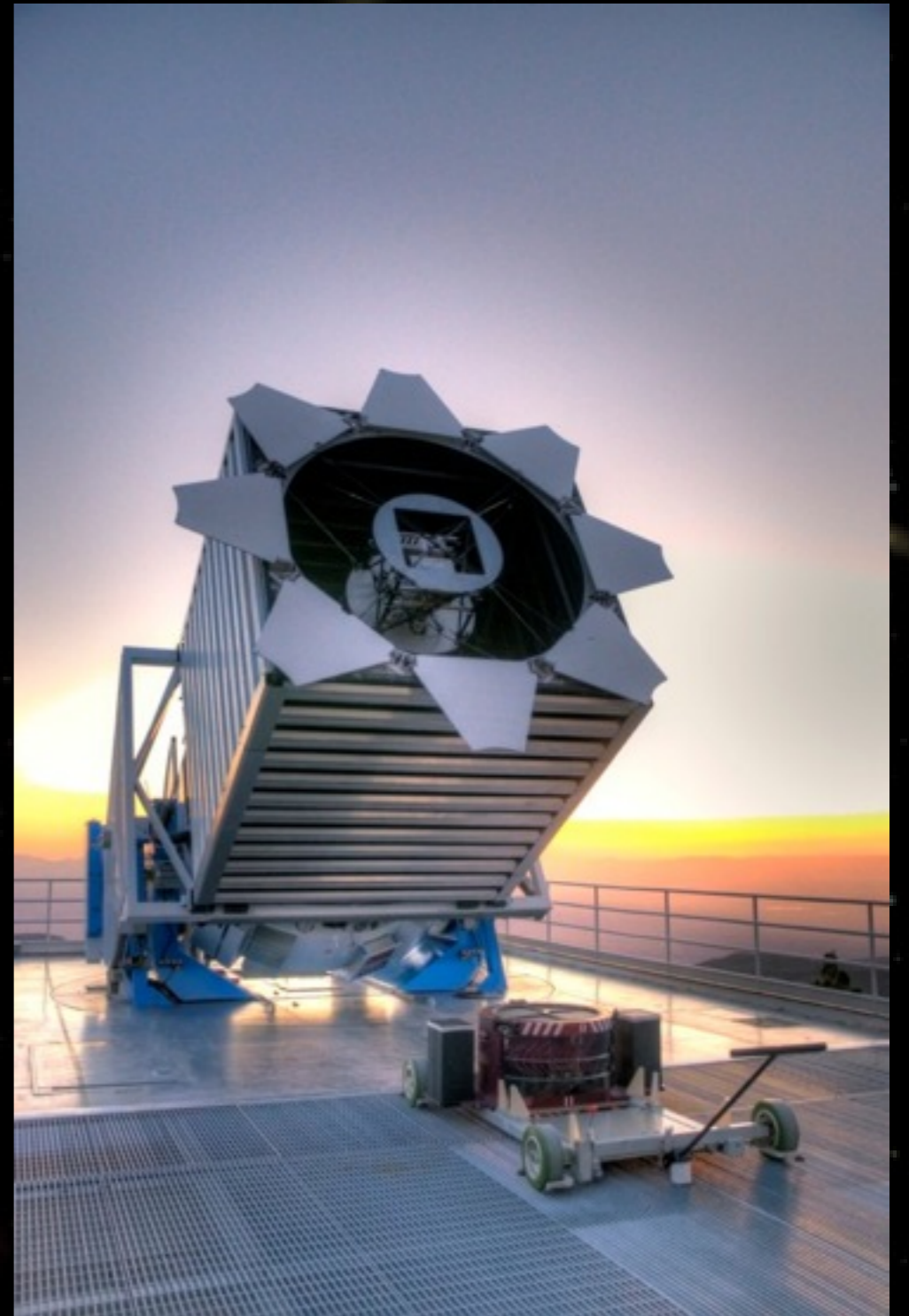
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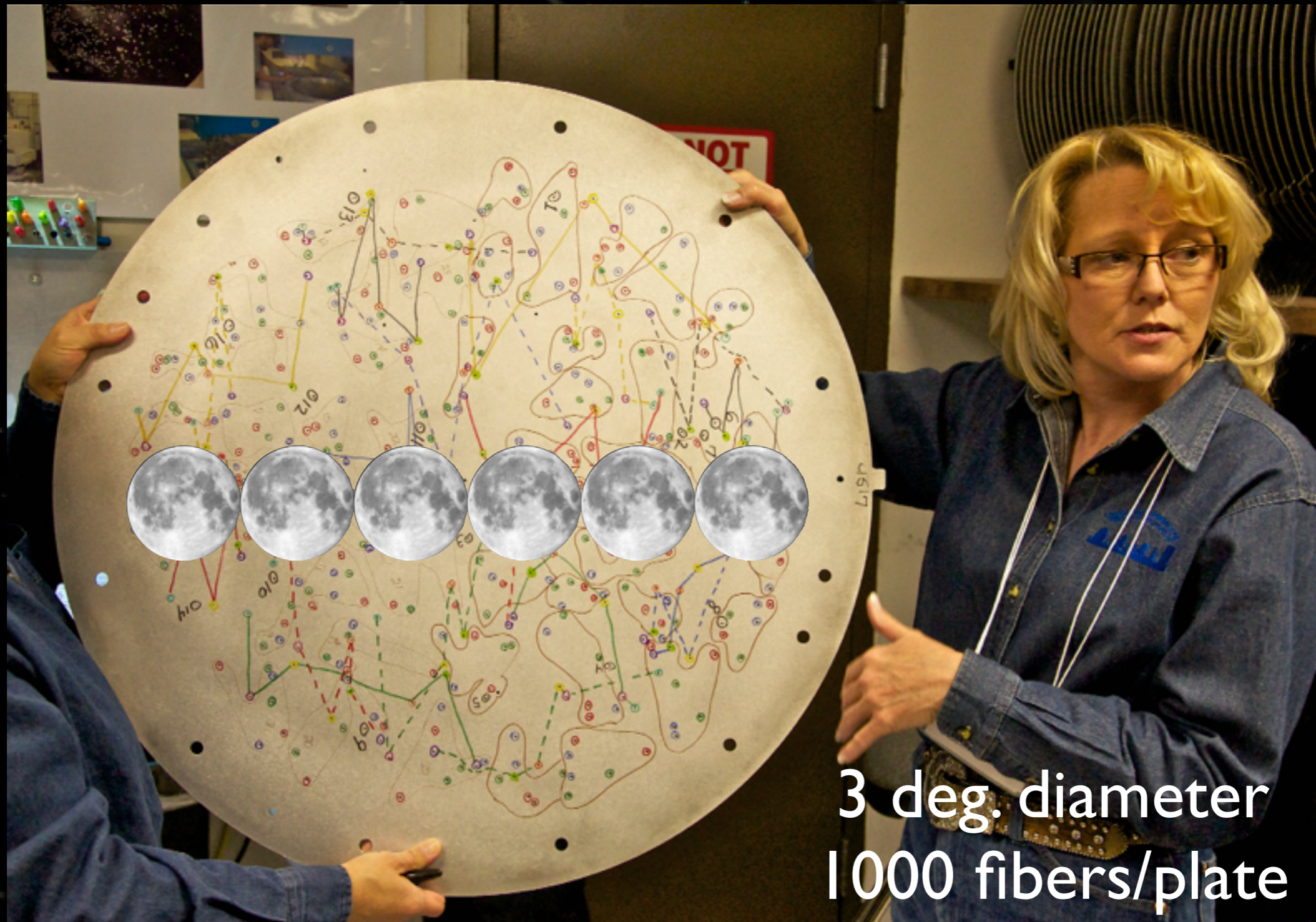
- Conclusions and prospects

SDSS-III / BOSS

- main SDSS-III project
 - ★ APO telescope (New Mexico, USA)
 - ★ 2.5 m diameter
- Spectroscopic survey
 - ★ SDSS-II photometry (targets)
 - ★ 2 two-arms spectrographs: 1000 fibers
 - $3600 \text{ \AA} < \lambda < 10000 \text{ \AA}$
 - $\lambda/\Delta\lambda \sim 3000$
 - ★ 10000 square degrees :
 - 1.5 Millions Luminous Red Galaxies at $\langle z \rangle \sim 0.6$
 - 150 000 Quasars with Ly- α forests at $\langle z \rangle \sim 2.3$
- Objectives:
 - ★ BAO peak position:
 - 1% at $z=0.6$
 - 1.5% at $z=2.3$
 - ★ Best constraints on the Dark Energy equation of state before next generation



a few plates per night



3 deg. diameter
1000 fibers/plate

a few plates per night

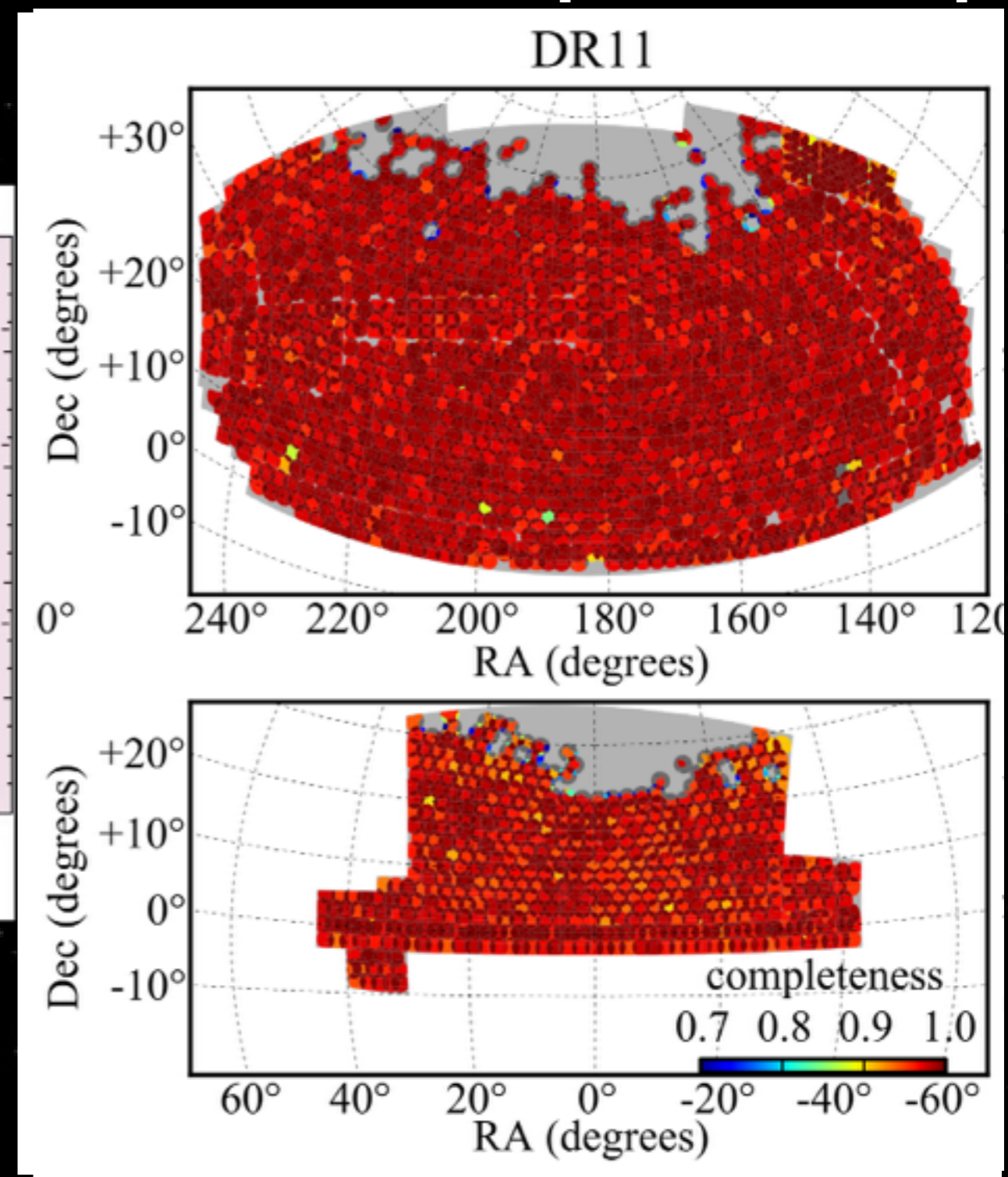
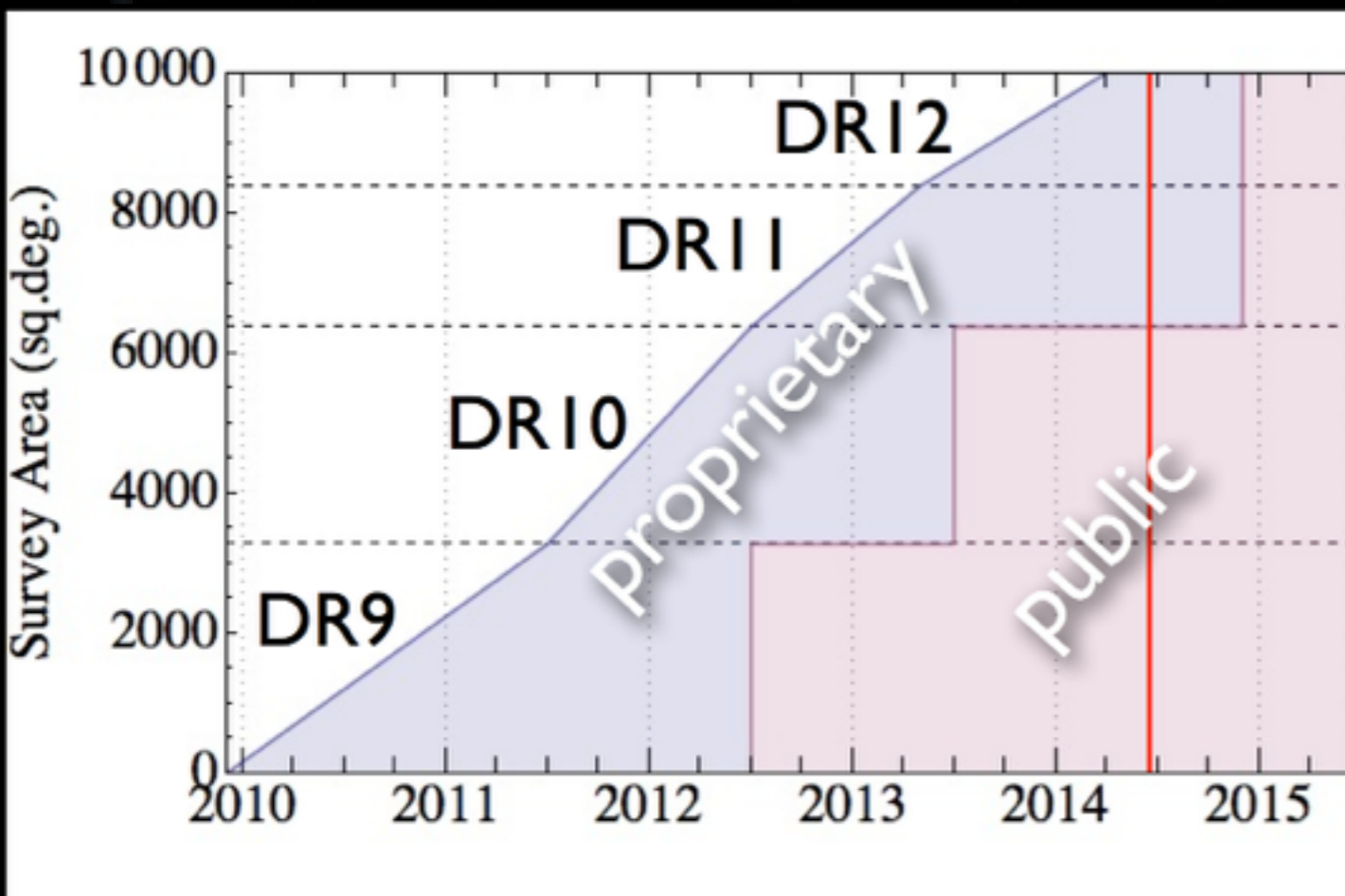


Bio-Mechanical Fiber Positioner

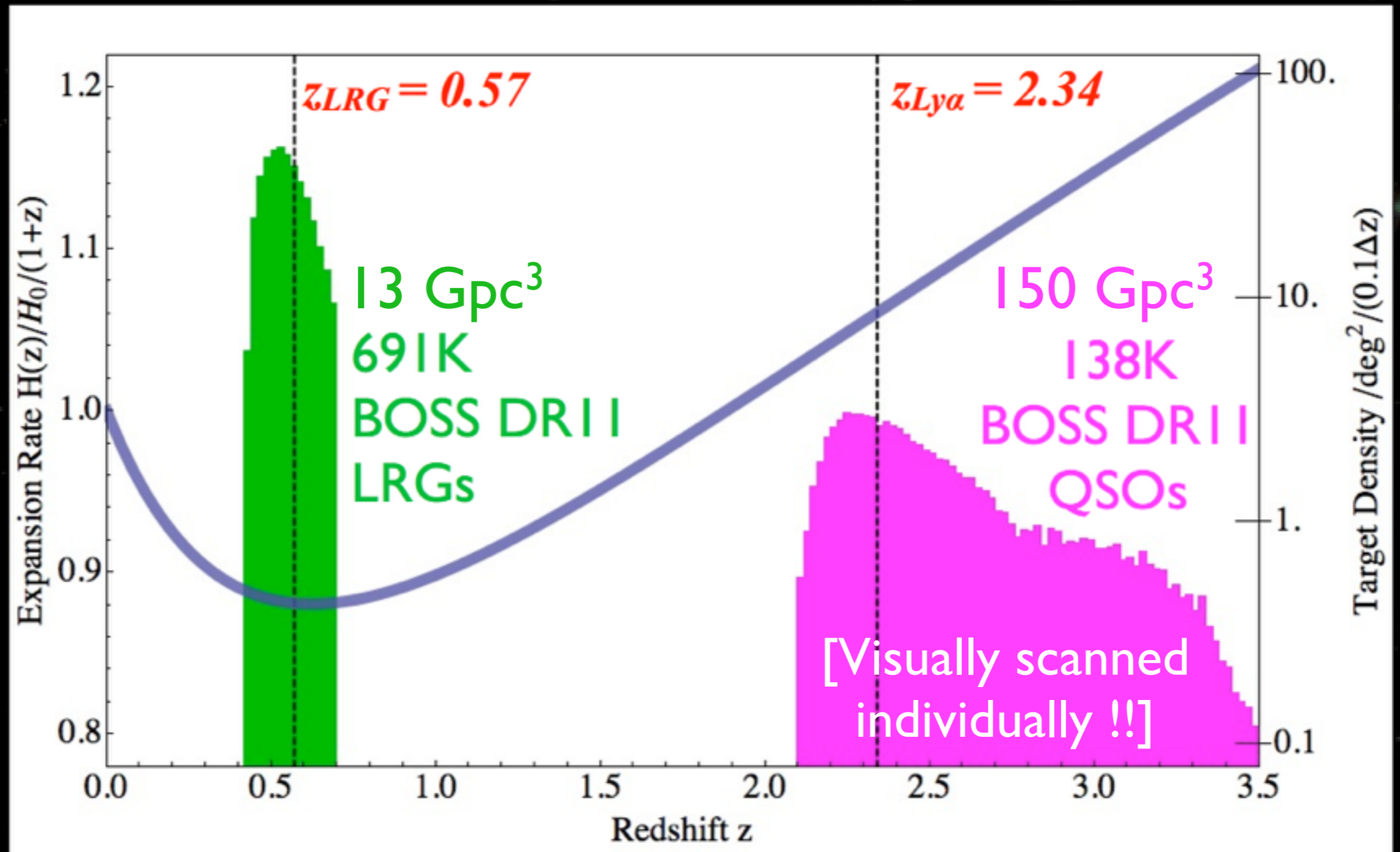


BOSS progress

[Anderson et al, 2014]



BOSS Redshift distribution



[From D. Kirkby]

A journey through BOSS dataset

Menu

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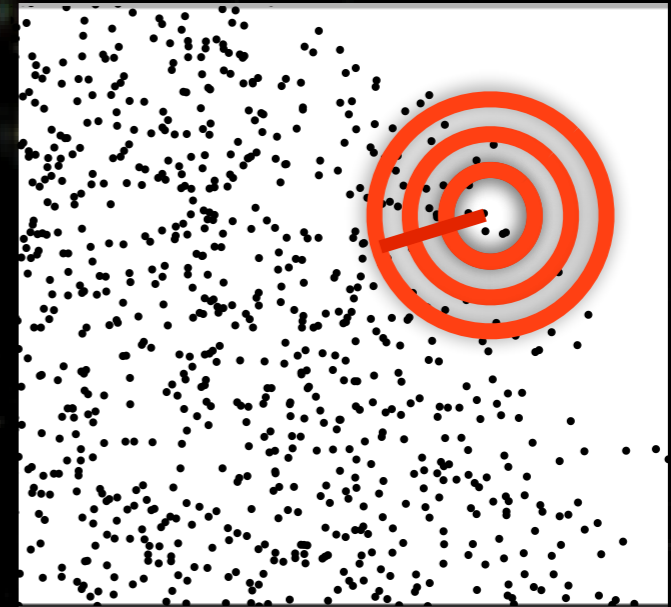
Completeness

- Definition:

$$Completeness = \frac{Spectra}{Targets}$$

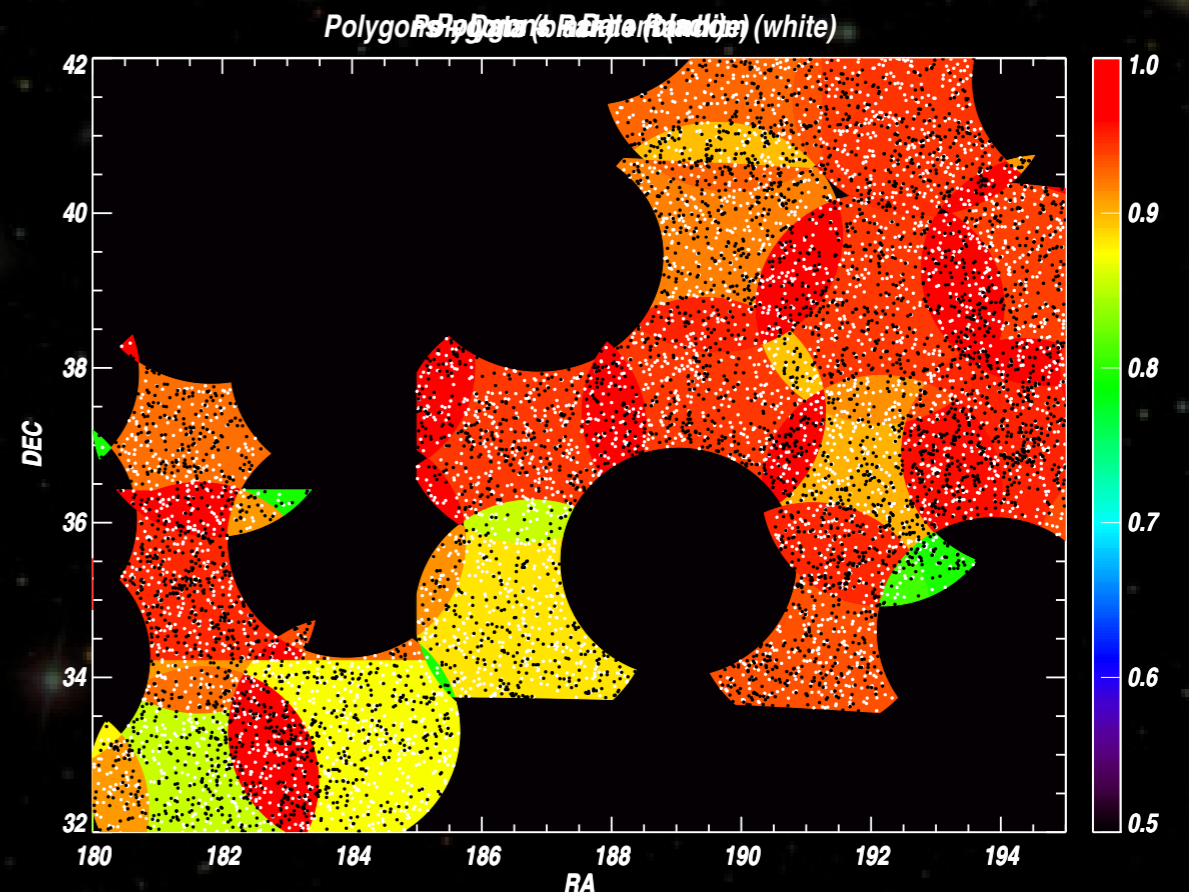
- rarely = 1 :

- ★ Survey in progress
- ★ Non-uniform success rate
 - essentially due to weather



- Importance:

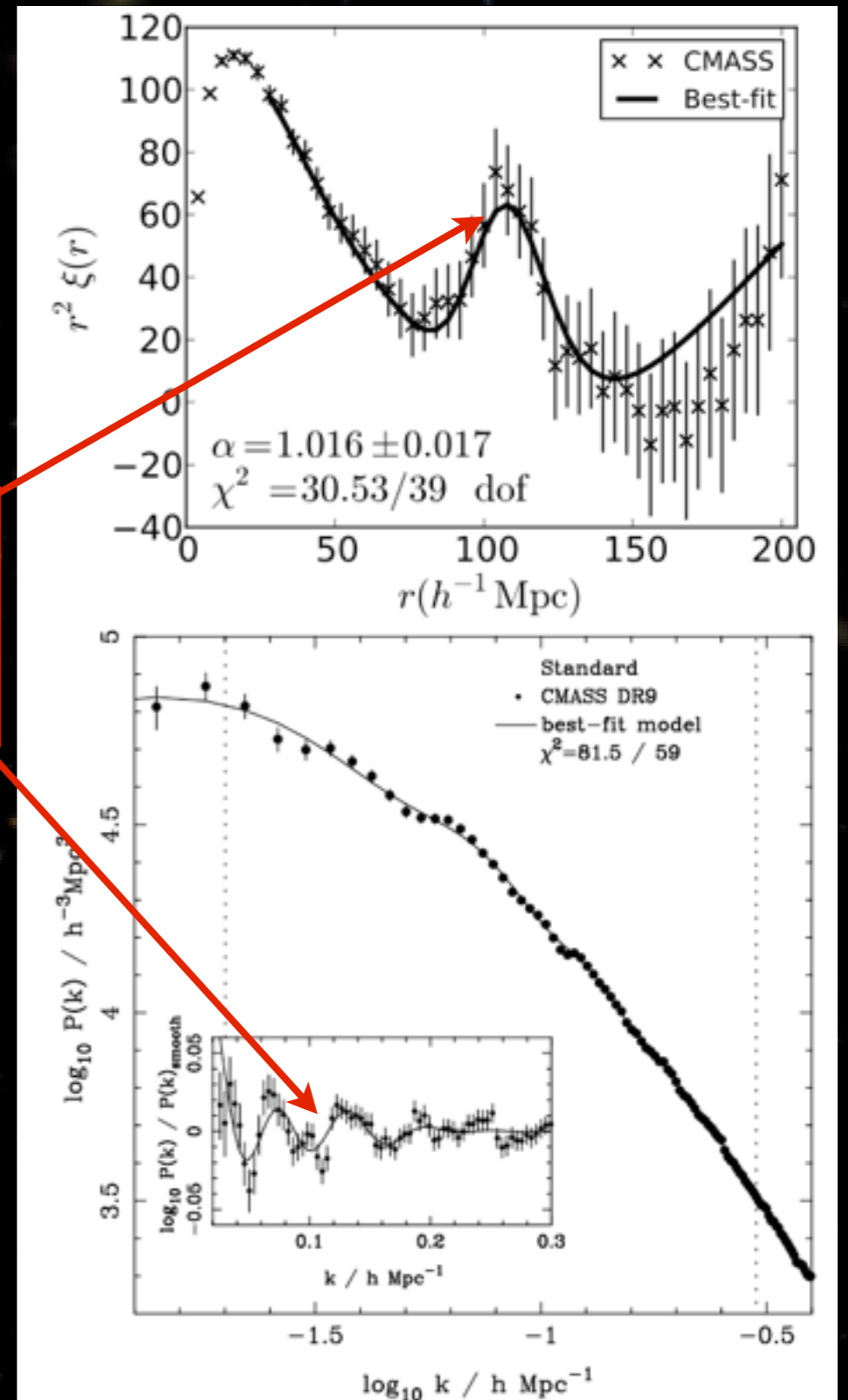
- ★ Correct $\xi(r)$ from the effects of non-uniform sampling
 - use of a «random» sample in the $\xi(r)$ estimator
 - $\hat{\xi}_{PH} = \frac{DD}{RR}$ [simple version: we actually use L.-S.]
- ★ weight as a function of galaxy density [Feldman, Kaiser, Peacock, 1993]



Isotropized $\xi(r)$ and $P(k)$: DR9 Galaxies

- both are equivalent in principle
 - ★ but very different practical implementation
 - ★ Uncertainties are different
- $\xi(r)$: Landy-Szalay estimator
- $P(k)$: FFT-based
- Error bars:
 - ★ N-body Simulations: LasDamas [McBride et al. 2011]
- NB: Choice of a fiducial cosmology (in order to have «r» instead of «z»)

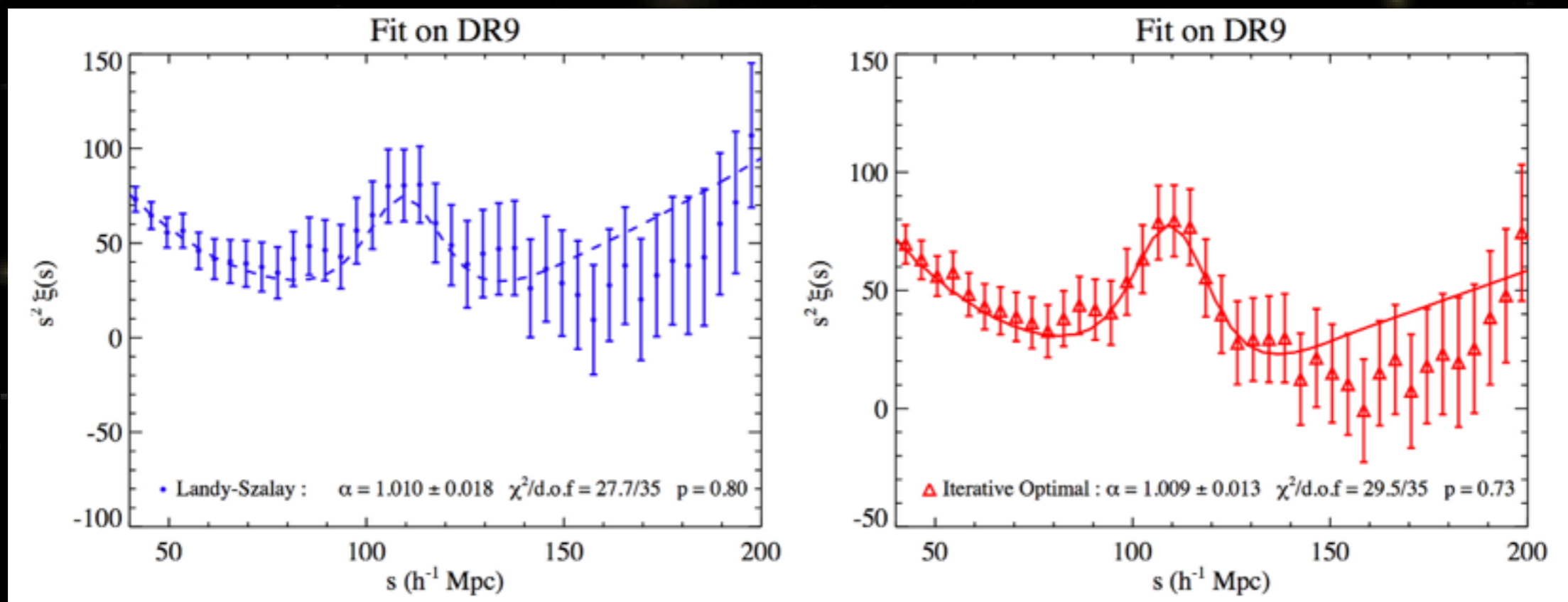
BAO
at 5σ



[Anderson et al, 2012]

Optimized $\xi(r)$ estimator @ APC

- Landy-Szalay Estimator only optimal for $\xi \rightarrow 0$
- S/N is now really high
 - ★ one can find a better estimator
 - ★ Optimal Estimator trained on mock simulations
 - ★ 20-25% improvement on error bars



[Vargas-Magaña, Bautista, Hamilton, Busca et al., 2013]

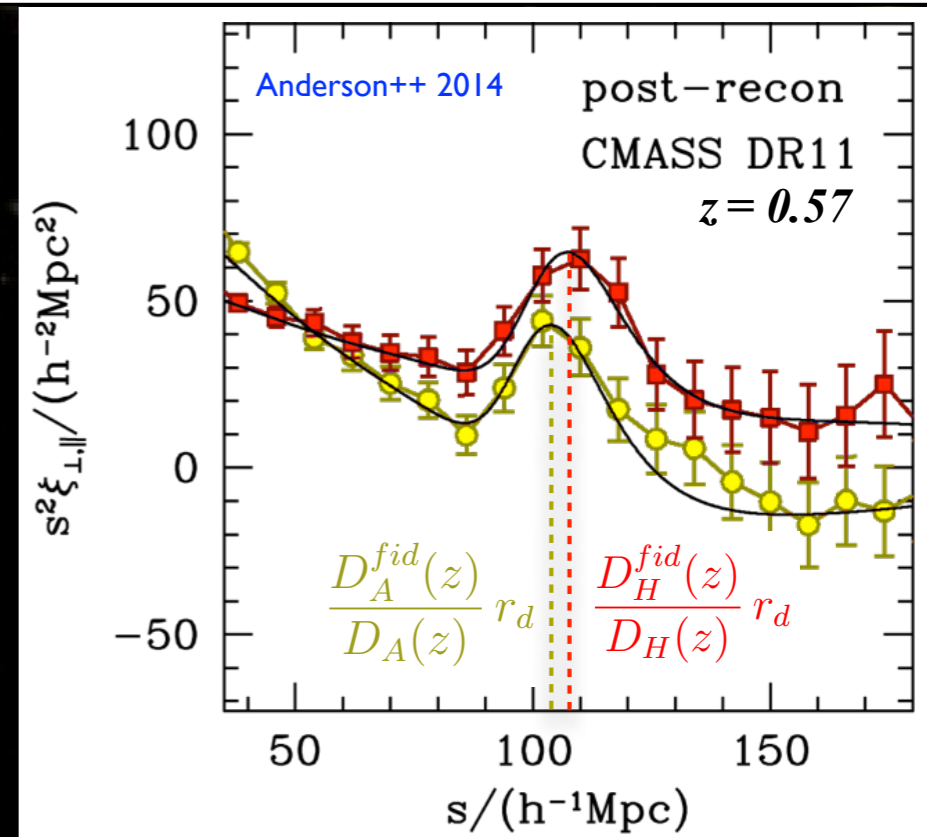
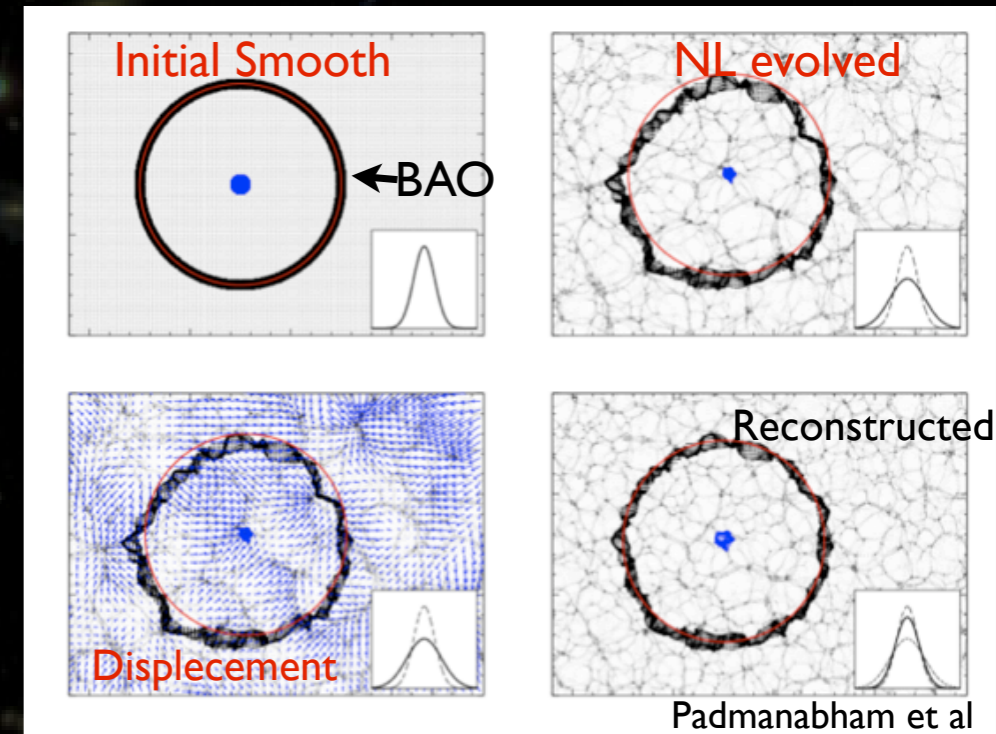
3D $\xi(r)$: DR11 Galaxies

- Uses « reconstruction »
 - ★ Incorporate galaxy positions to estimate velocity fields
 - ★ Correct for Non Linearities
 - ★ Enhances the BAO Peak S/N

- Measurement in 3D

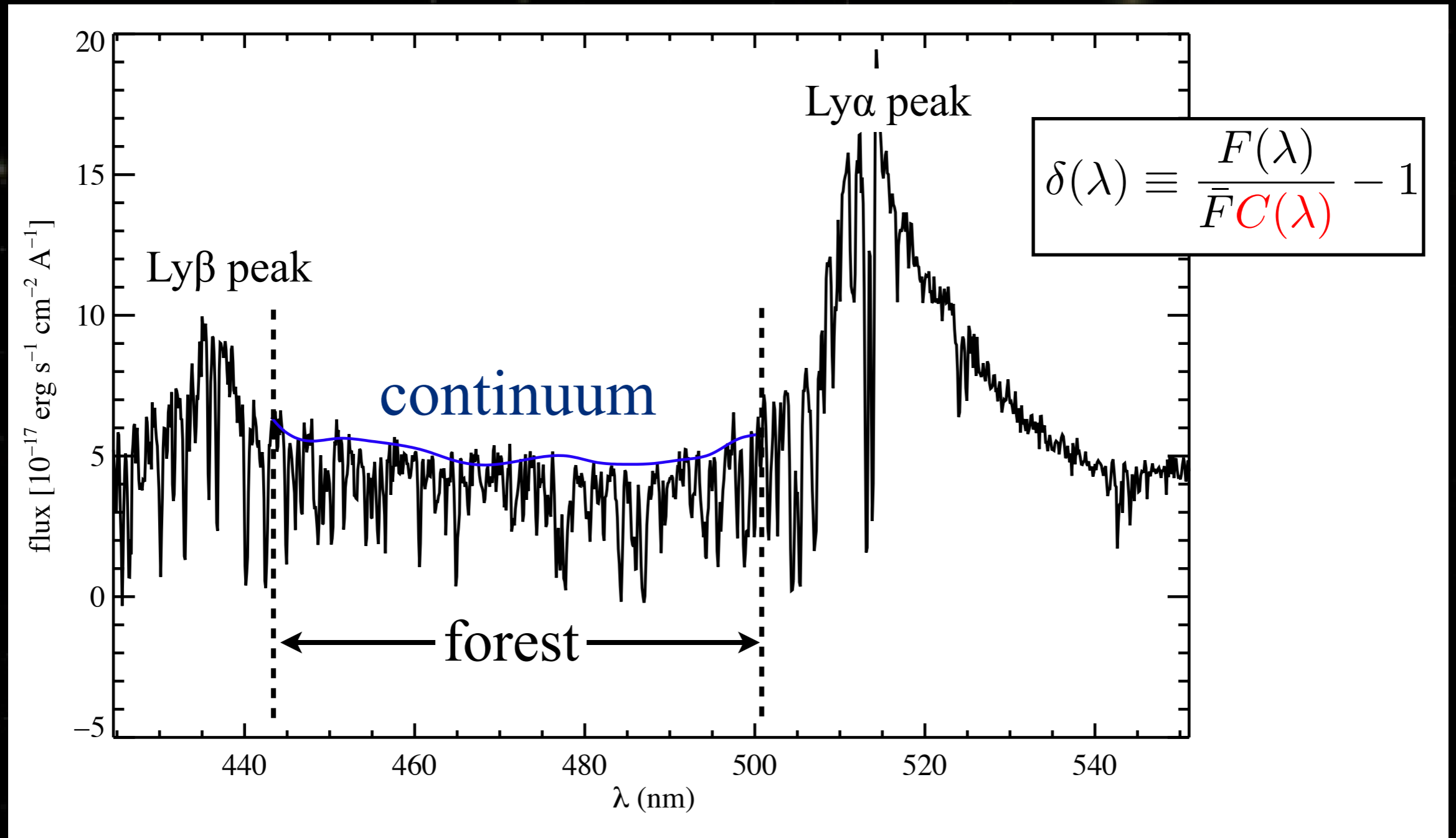
- ★ Radial gives $H(z)$
- ★ Transverse gives $D_A(z)$

- 7.8 σ detection of the BAO peak



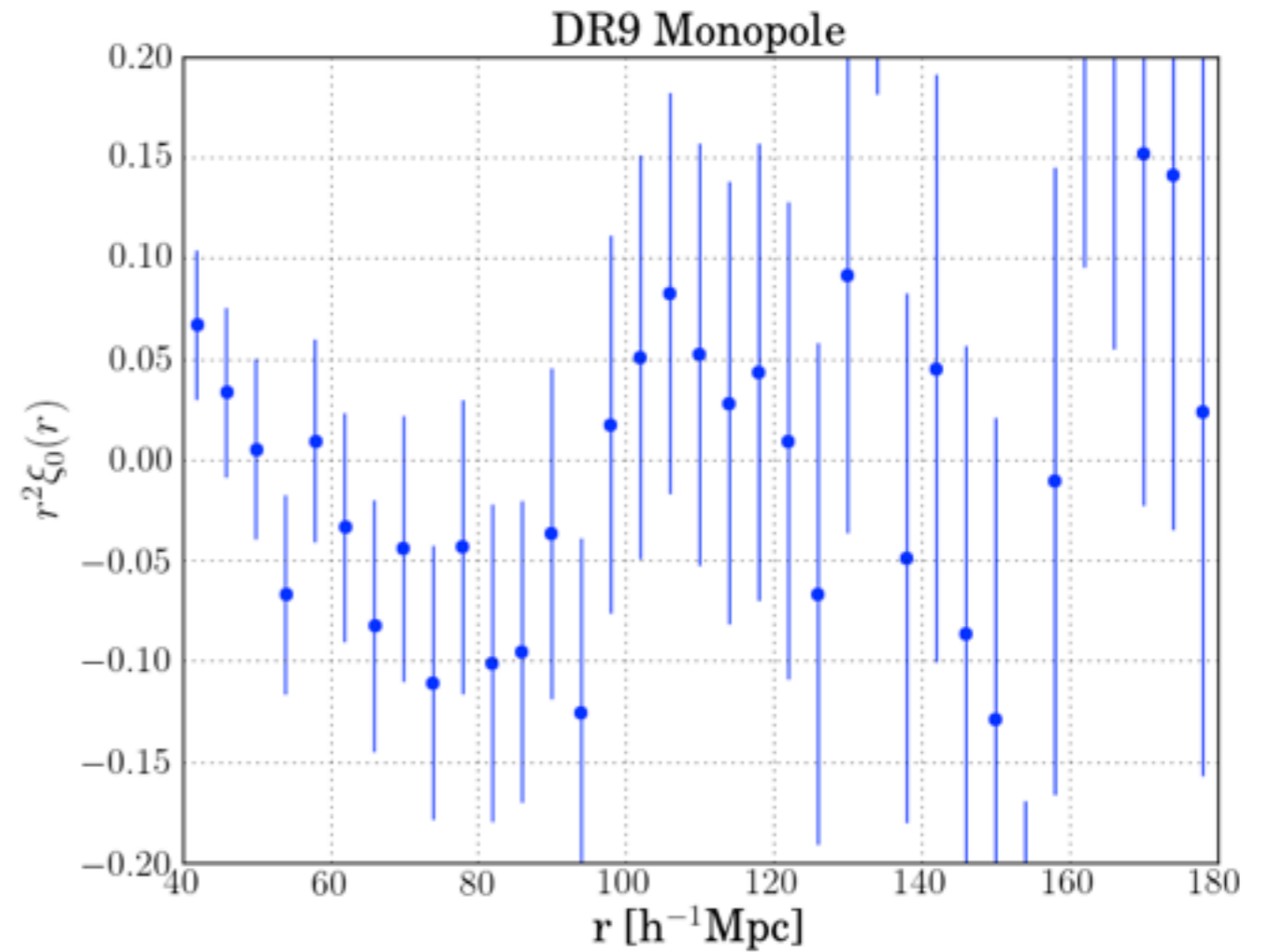
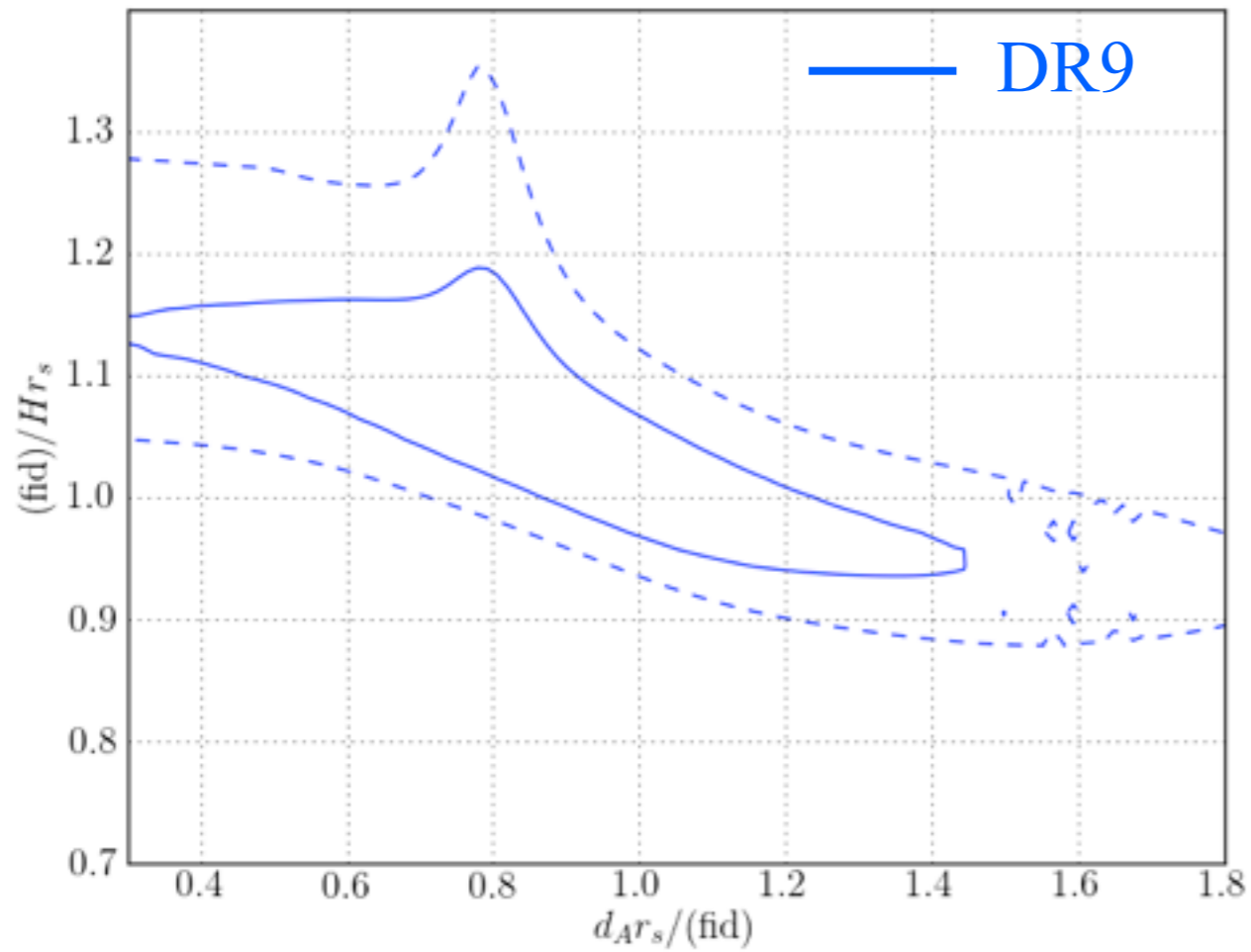
[Anderson et al., 1312.4877v2]

3D $\xi(r)$: DR1 I Lyman- α Forest



[From N. Busca]

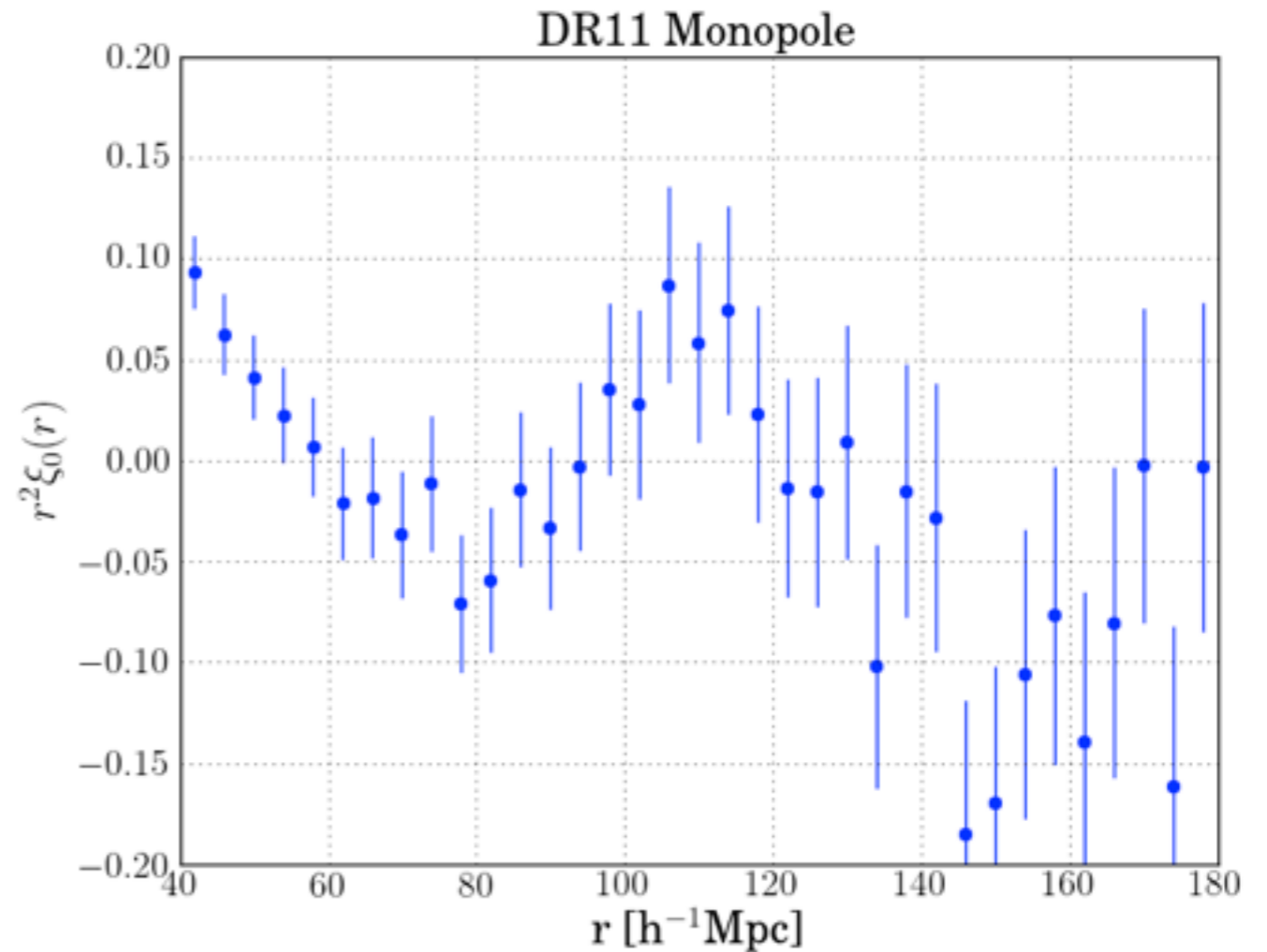
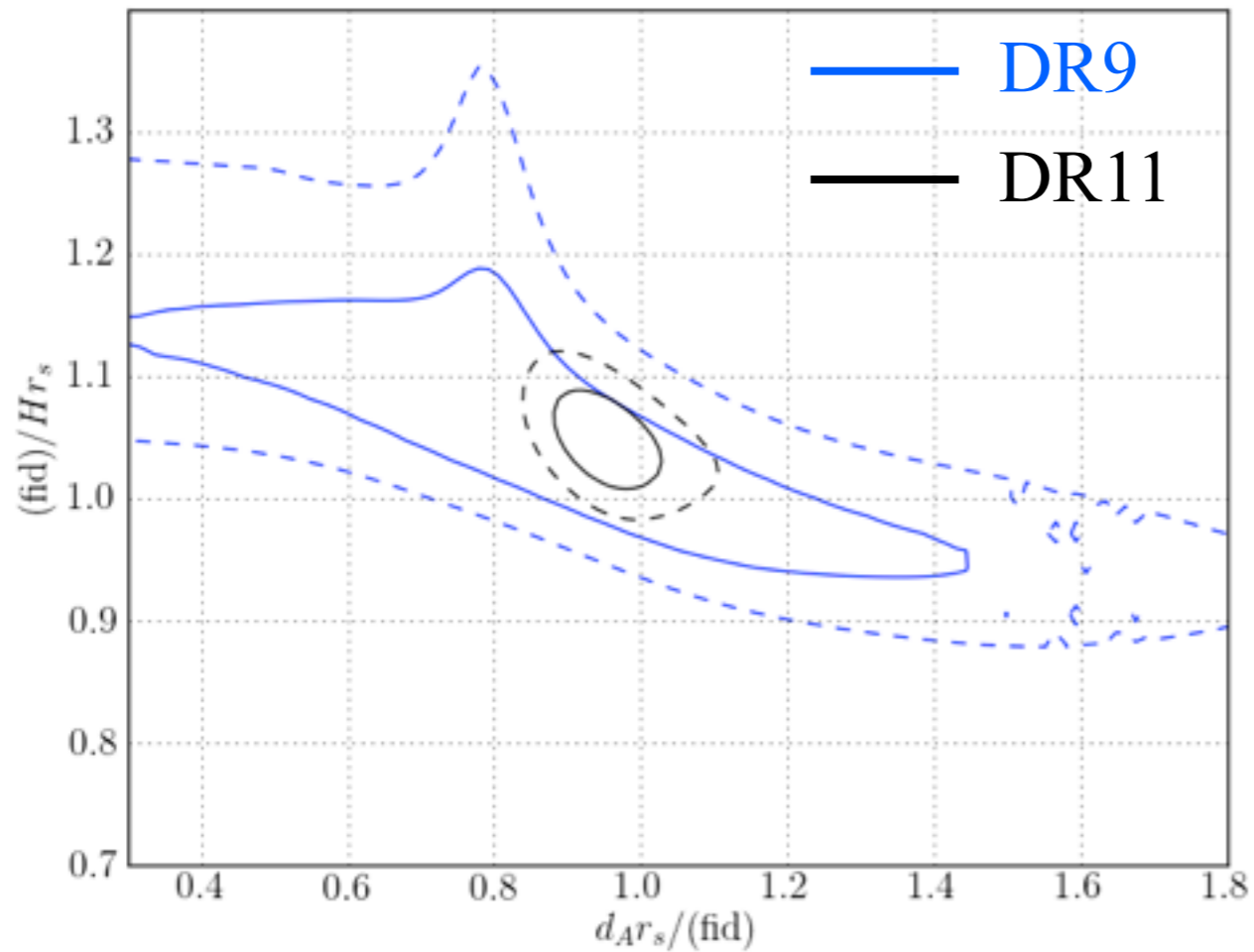
Lyman- α Forest: from DR9 to DR11



[From N. Busca]

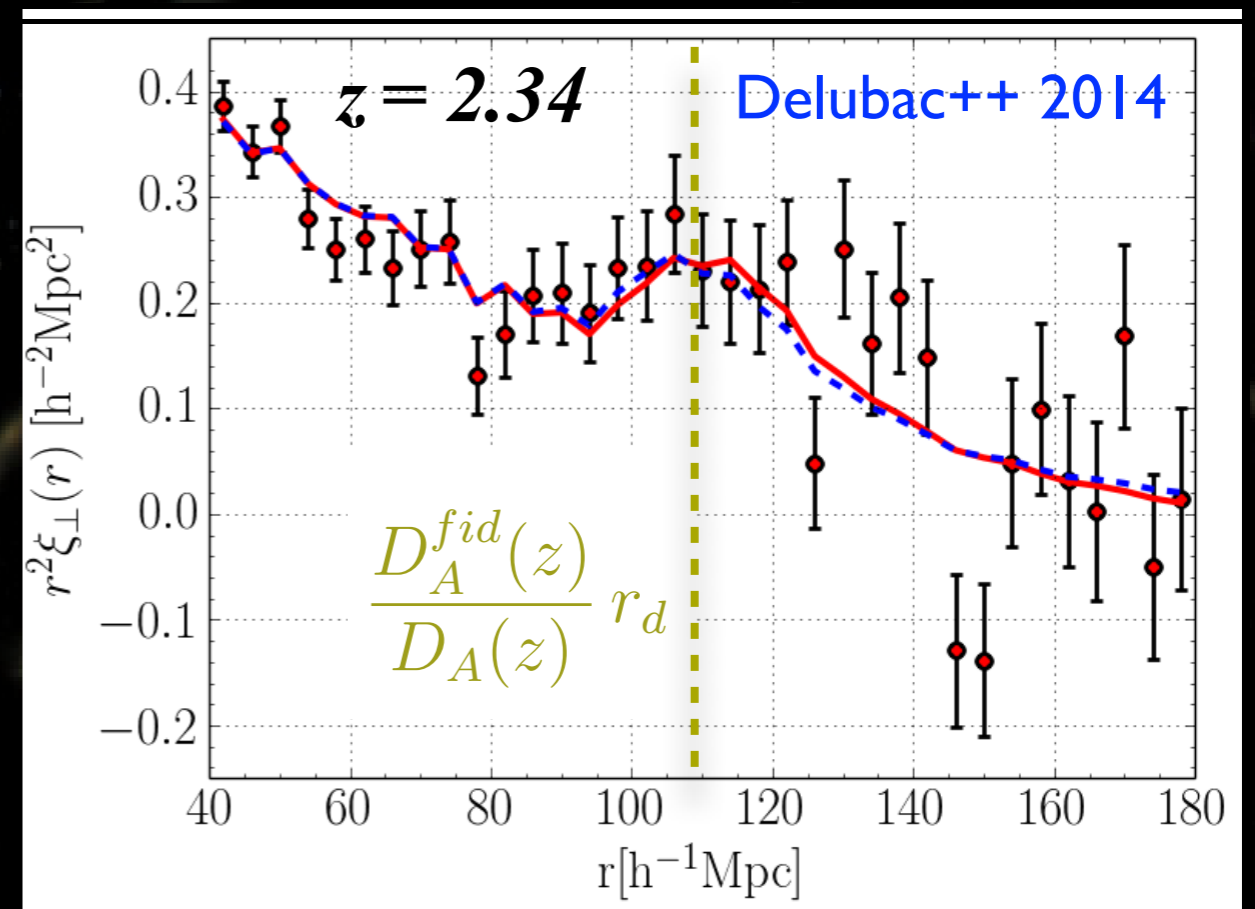
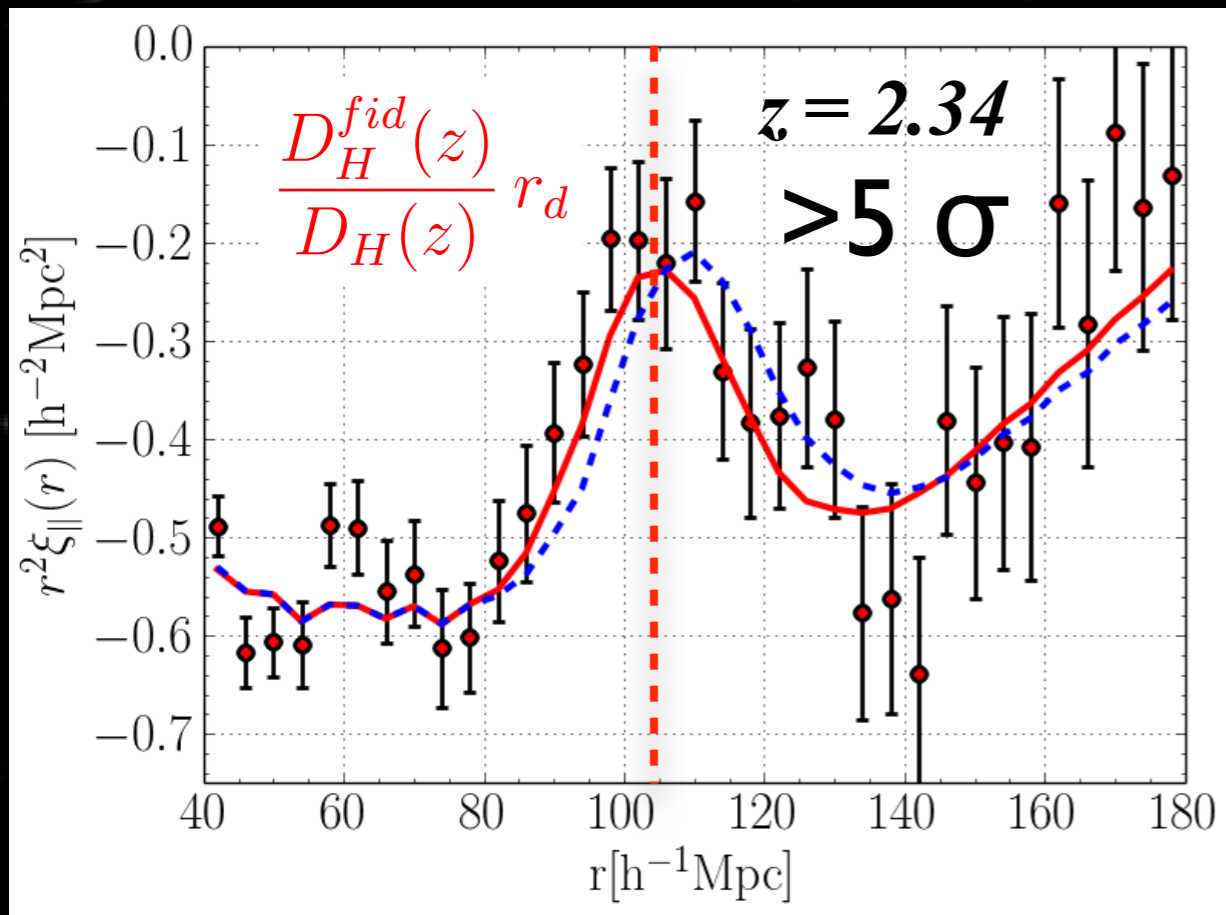
Lyman- α Forest: from DR9 to DR11

3% precision on H
5% precision on D_A



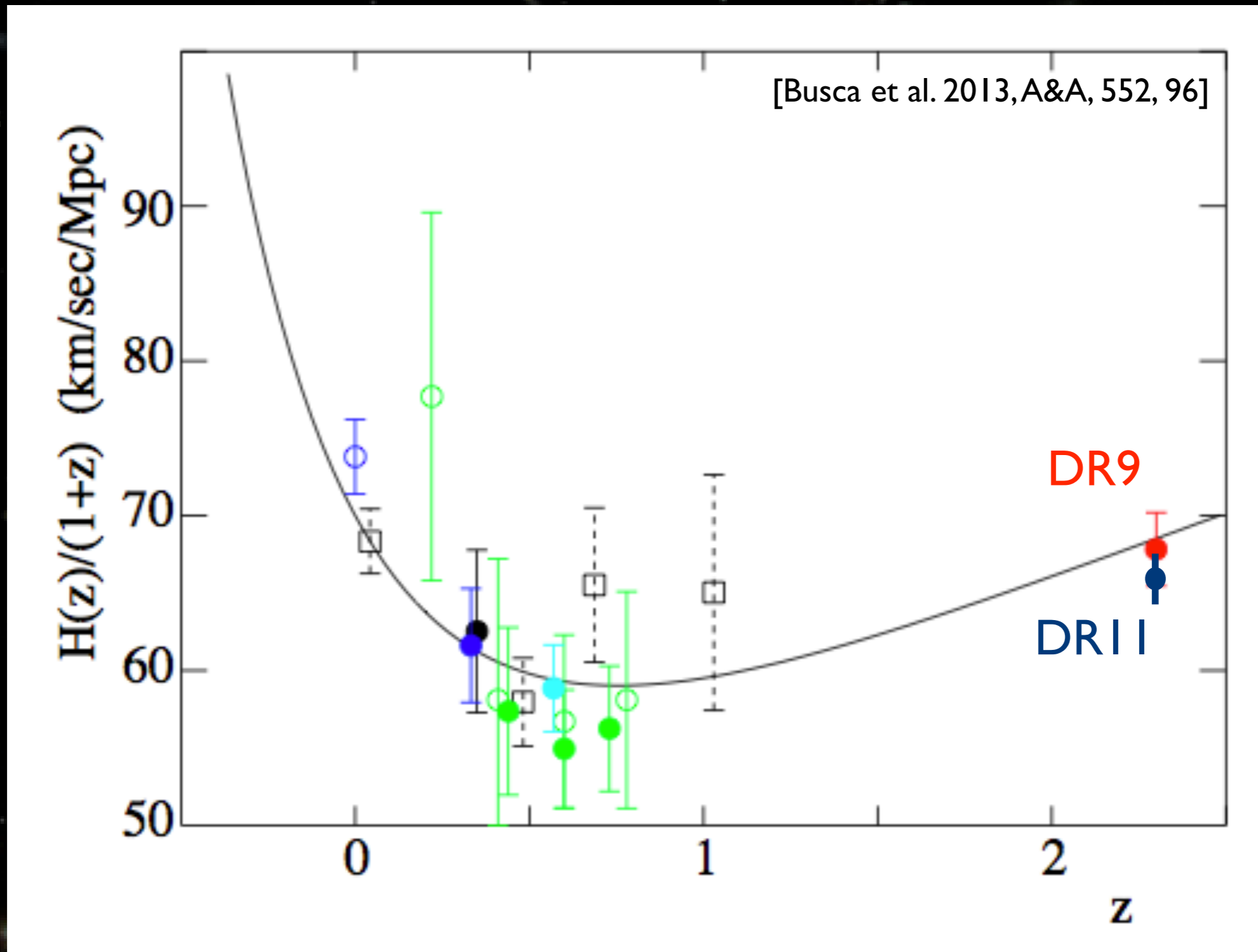
[From N. Busca]

3D Analysis with DR11 Lyman- α



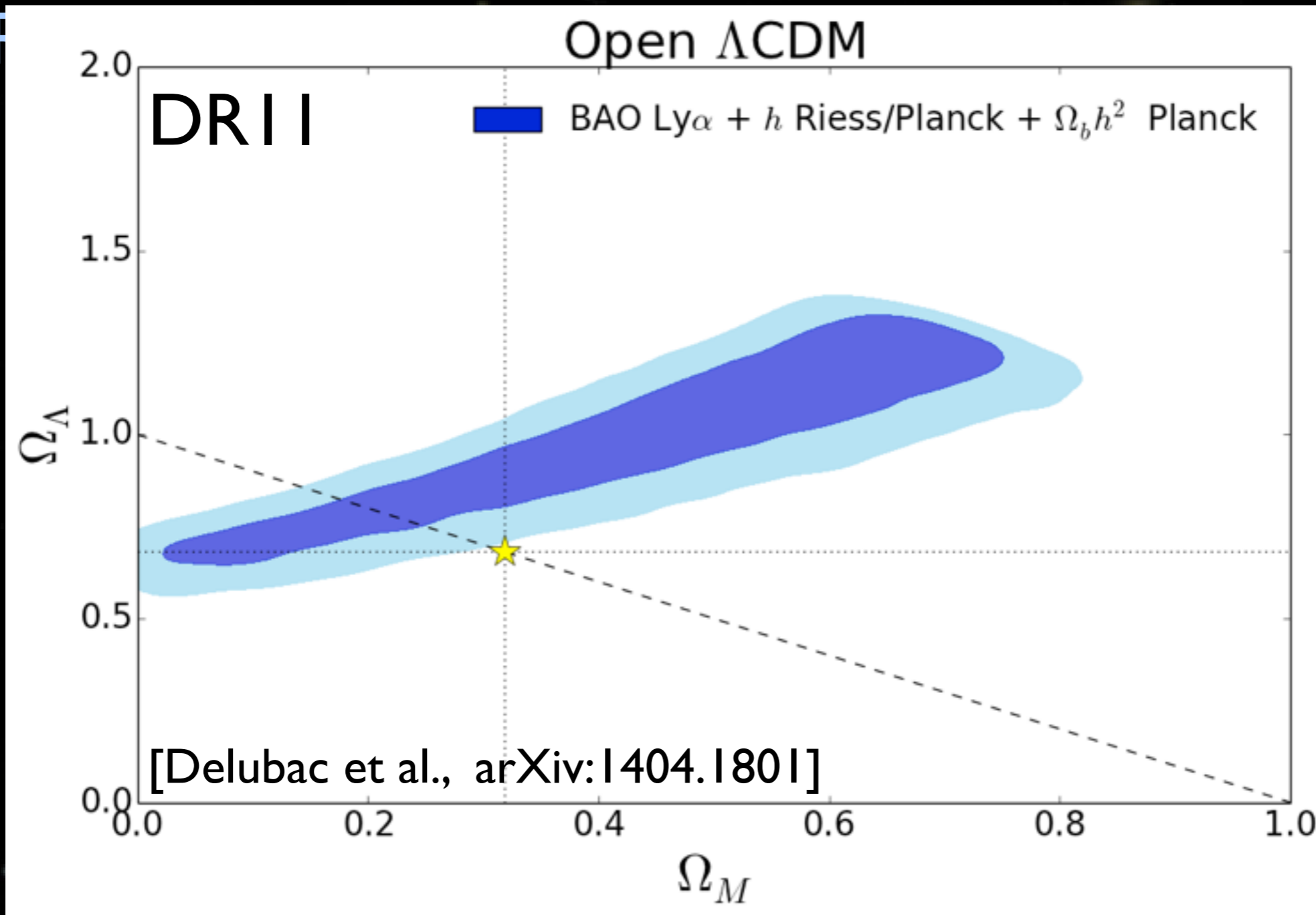
[Delubac et al., arXiv:1404.1801]

Expansion rate history



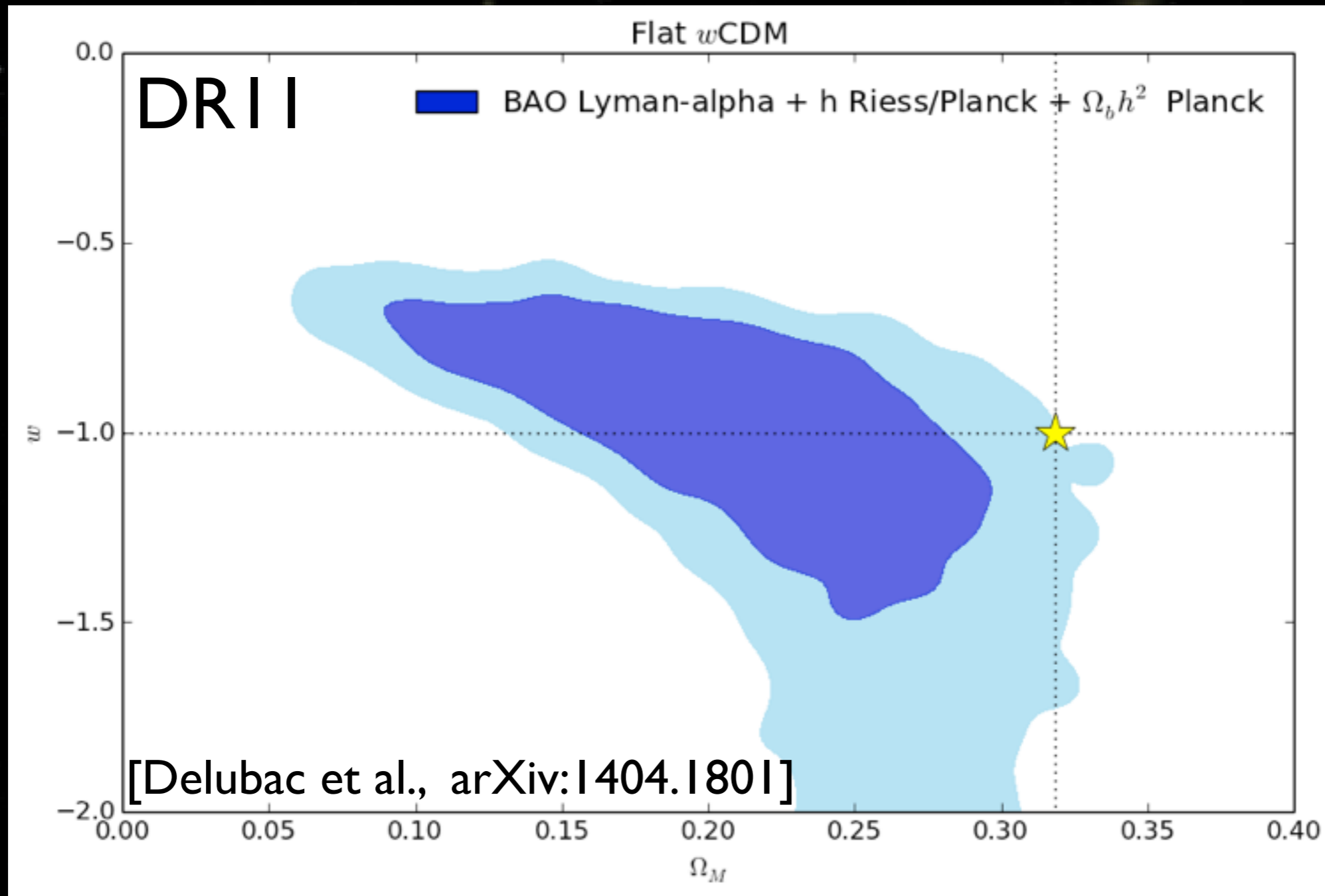
Cosmological constraints

• DR II



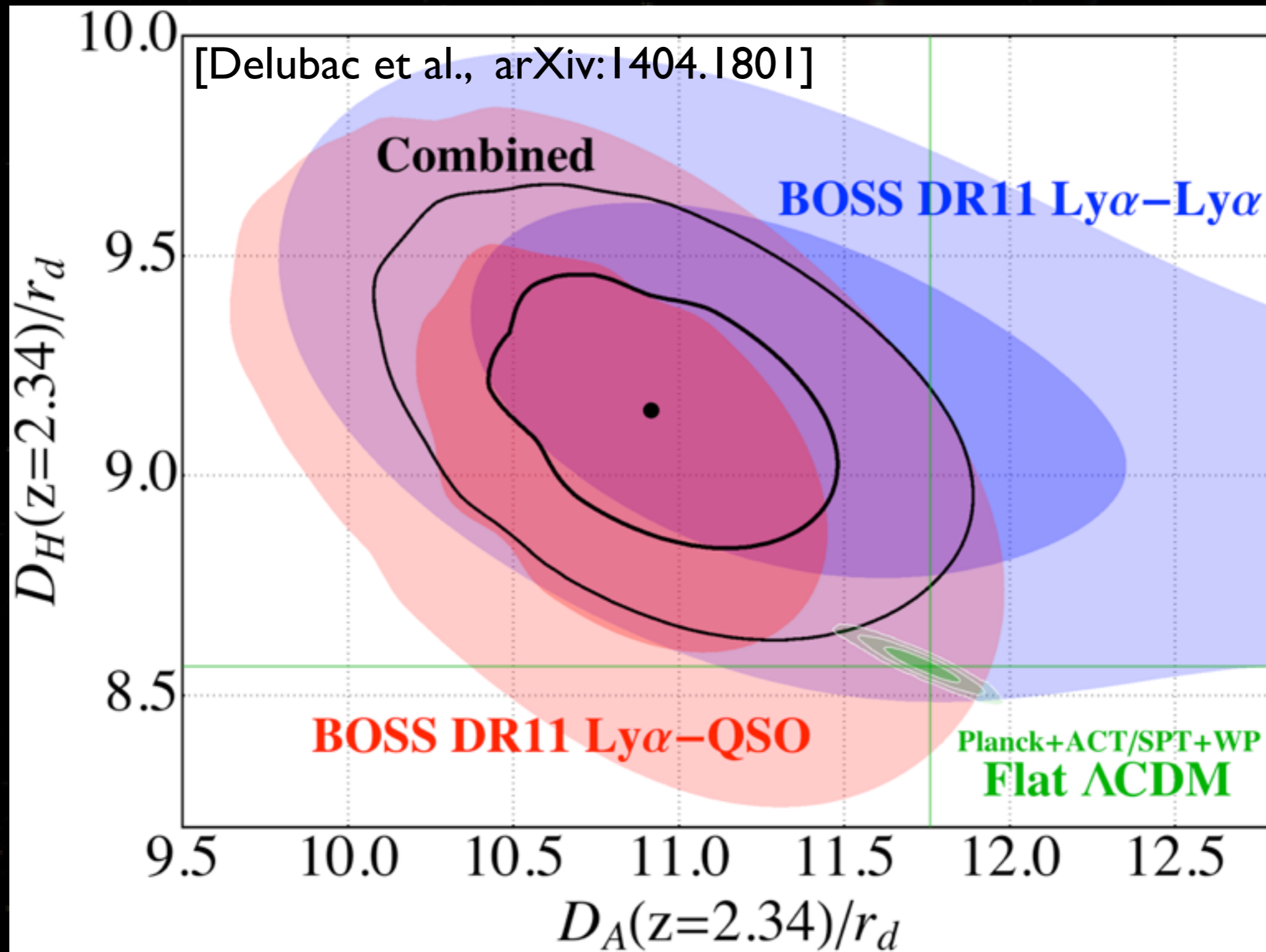
Small tension with Λ CDM

Cosmological constraints

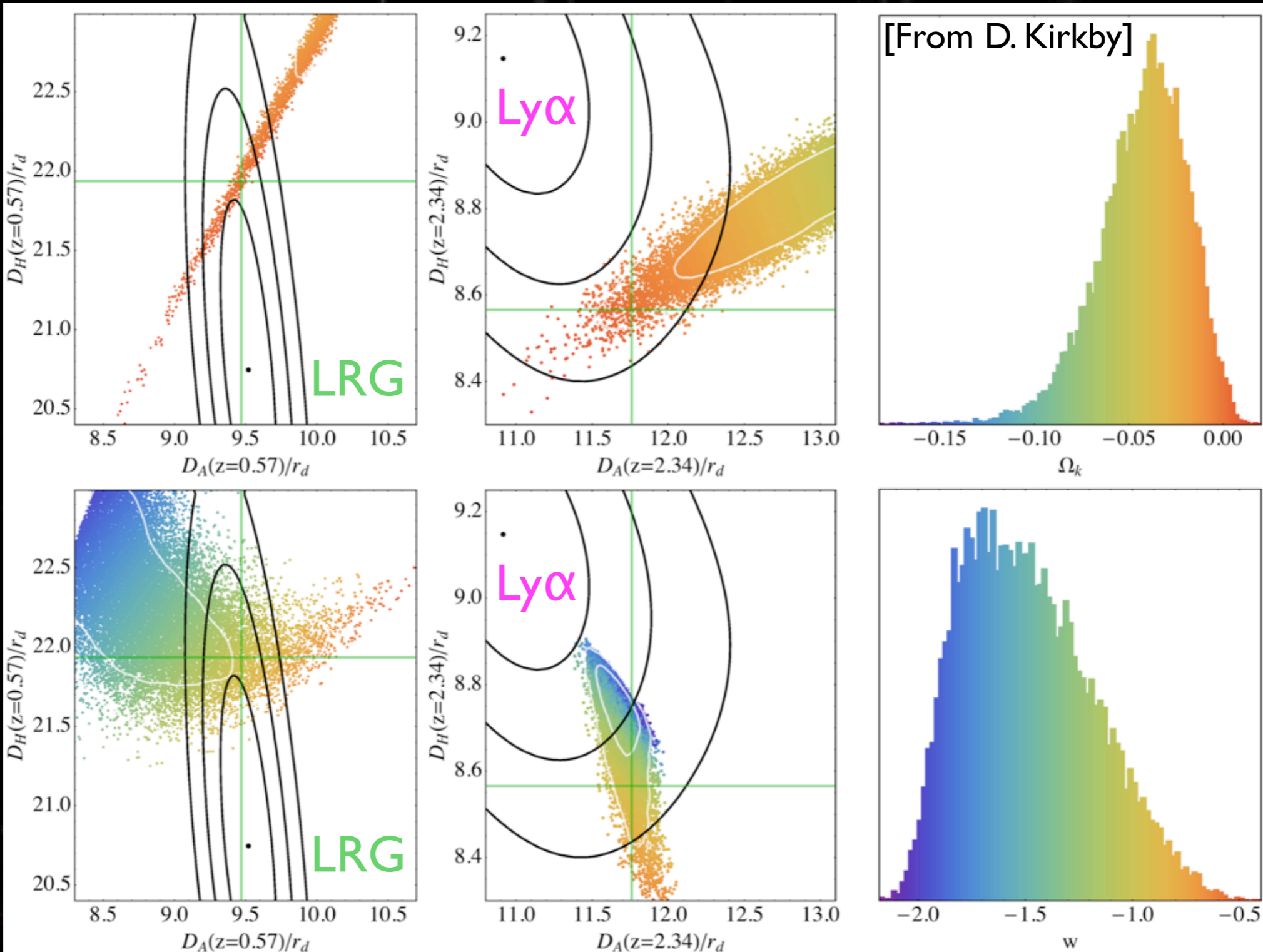


Small tension with Λ CDM

Tension with Planck



Tension with Planck



Conclusions

- BAO are a powerful tool for cosmology:
 - ★ Major prediction of standard cosmological scenario
 - ★ Direct evidence for Dark Matter
 - ★ Measures both $H(z)$ and $D_A(z)$ using 3D correlation function
- BOSS is dedicated to this observable
 - ★ BAO Detected with large significance with BOSS
 - With Galaxy-Galaxy, Ly α -Ly α , (QSO-Ly α)
 - ★ eBOSS starting now for three more years
- Lyman- α data in DR11 shows a 2.5σ tension with Planck
 - ★ No convincing explanation as of now
 - ★ An article with joint BAO (Galaxy & Lyman- α) and CMB constraints and discussions is in preparation

Thank you !