SDSS III

Baryon Acoustic Oscillations and the Expansion History of the Universe

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Outline

- Motivation: The *distance - redshift* relation
- Physics of Baryon Acoustic Oscillations (BAO)
- Reconstruction of the linear density field
- Anisotropies in the galaxy distribution
- BAO measurements from BOSS (SDSS-III)
  Baryon Oscilation Spectroscopic Survey
  - The correlation function of galaxies: the LOWZ and CMASS samples
  - The correlation function of neutral Hydrogen: the Lyman-Alpha Forest
- Cosmological results from BAO measurements

The relation between distances and redshifts

Fundamental quantities

$a(t) = R(t)/R_0$ Scale factor

$\dot{a}(t)/a(t) = H(t)$ Hubble parameter

$D(z)=\int c\,dz/H(z)$ Comoving distance

$a = 1/(1+z)$

Fundamental quantities

$a(t) = R(t)/R_0$ Expansion history

$\dot{a}(t)/a(t) = H(t)$ Expansion rate

$D(z)=\int c\,dz/H(z)$ Distance-redshift relation

$a = 1/(1+z)$

Fundamental quantities

$a(t) = R(t)/R_0$ — Expansion history

$\dot{a}(t)/a(t) = H(t)$ — Expansion rate

$D(z) = \int c\,dz/H(z)$ — Distance-redshift relation

z is observable! $z = (\lambda - \lambda_0)/\lambda_0$

D is hard to measure at high z

$a = 1/(1+z)$

Why do we want to constrain the Distance-redshift relation?

$$D(z)=\int c\,dz/H(z)$$

$$H^2(z) = H_0^2 \left[\Omega_m(1+z)^3+\Omega_\Lambda \right]$$

Friedmann's equation

(ΛCDM model)

We can constrain the matter content of the Universe Ω_m ,

the dark energy content Ω_Λ ,

the spatial geometry of the Universe Ω_k ,

the equation of state of dark energy w_0 , and its time dependence w_a

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(OΛCDM model)

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Friedmann's equation

(owCDM model)

We can constrain the matter content of the Universe Ω_m ,

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$$H^2(z) = H_0^2 \left[\Omega_m(1+z)^3+\Omega_k(1+z)^2+ +\Omega_\Lambda(1+z)^{3(1+w_0+w_a)}e^{w_a z/(1+z)} \right]$$

Friedmann's equation

(ow_0w_aCDM model)

We can constrain the matter content of the Universe Ω_m ,
the dark energy content Ω_Λ ,
the spatial geometry of the Universe Ω_k ,
the equation of state of dark energy w_0 , and its time dependence w_a

What are Baryon Acoustic Oscillations?

The physics behind BAO

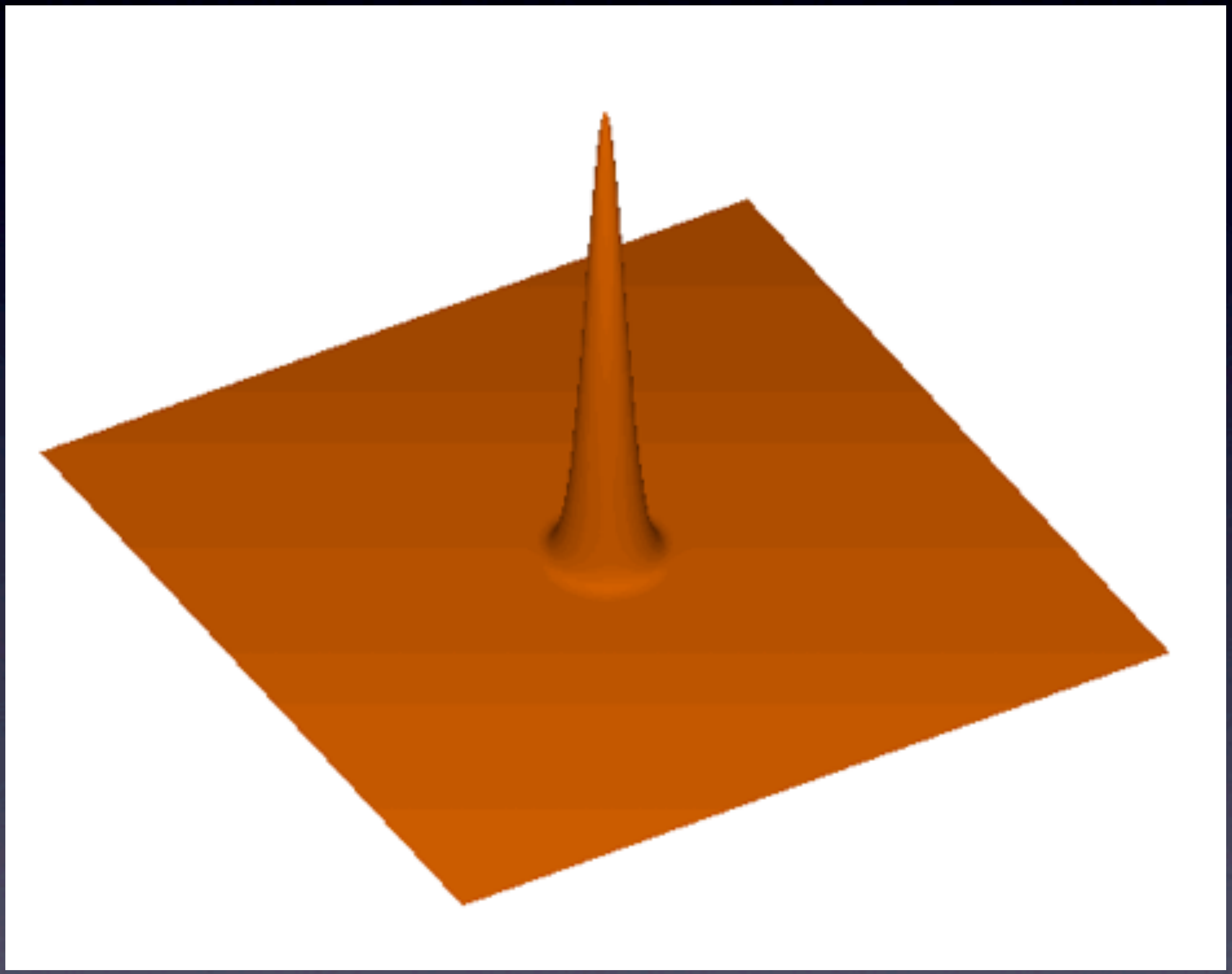
1 Inflation seeds the Universe with primordial perturbations

2 The photon-baryon fluid, reacts to the perturbation creating a spherical sound wave

3 The sound wave stops propagating shortly after electron/proton recombination leaving an overdensity at the same **fixed** scale, **everywhere**

Credit: Daniel Eisenstein (Harvard CfA)

The physics behind BAO



Credit: Daniel Eisenstein (Harvard CfA)

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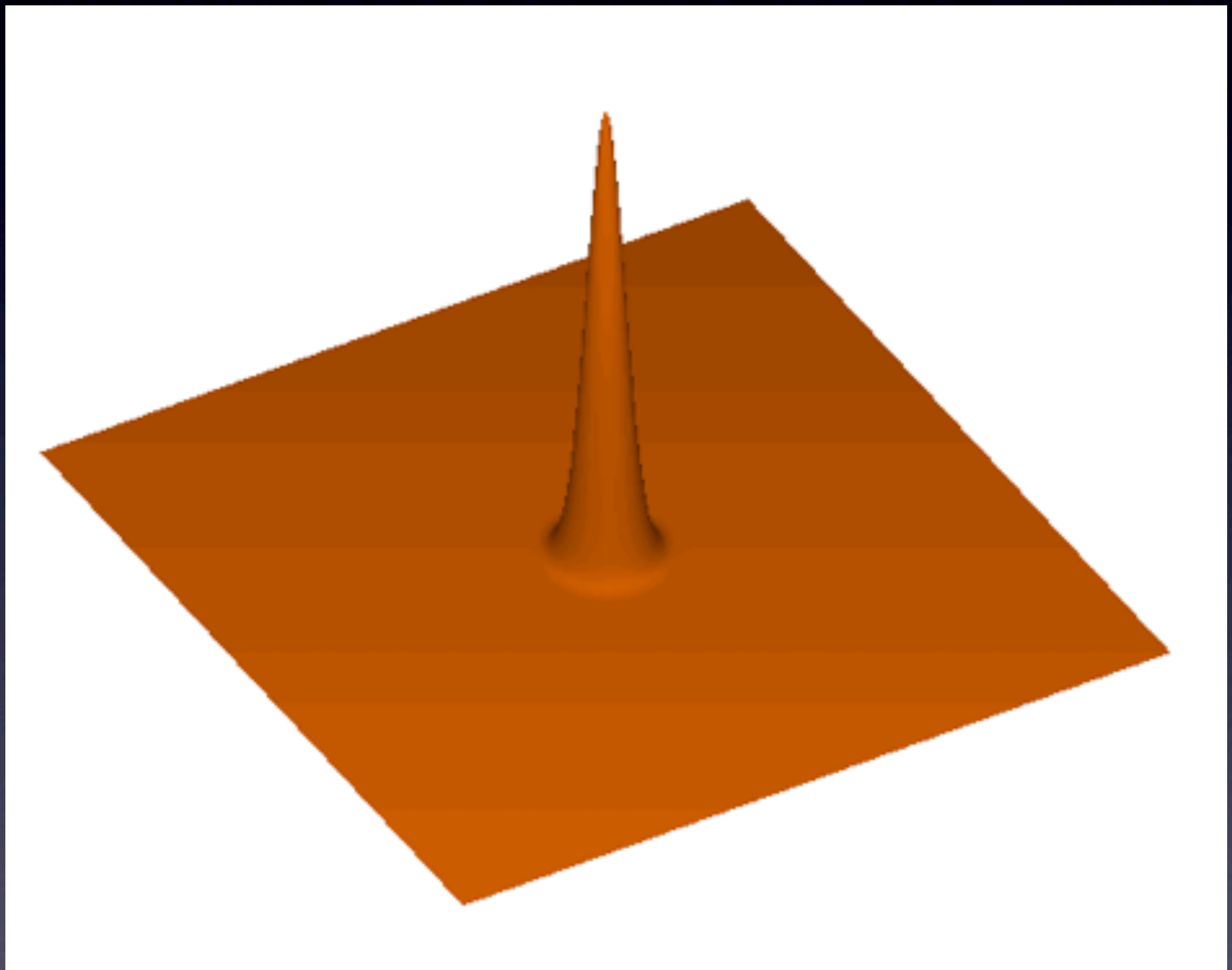


Credit: Daniel Eisenstein (Harvard CfA)

It can be used as a
standard ruler
to measure the Universe

1 Inflation seeds the Universe with primordial perturbations

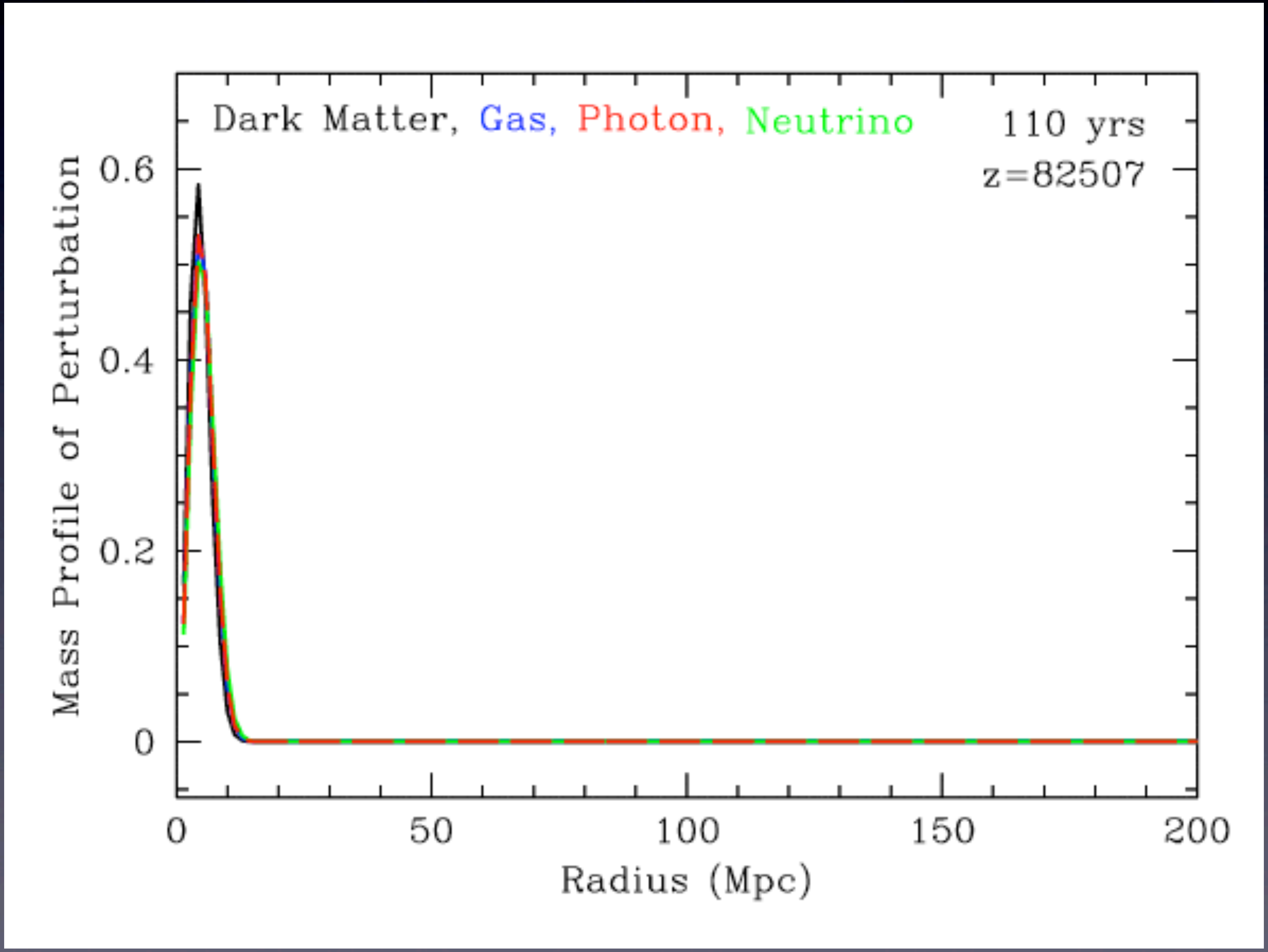
2 The photon-baryon fluid, reacts to the perturbation creating a spherical sound wave

3 The sound wave stops propagating shortly after electron/proton recombination leaving an overdensity at the same **fixed** scale, **everywhere**

Propagation of the baryon acoustic wave

Credit: Daniel Eisenstein (Harvard CfA)

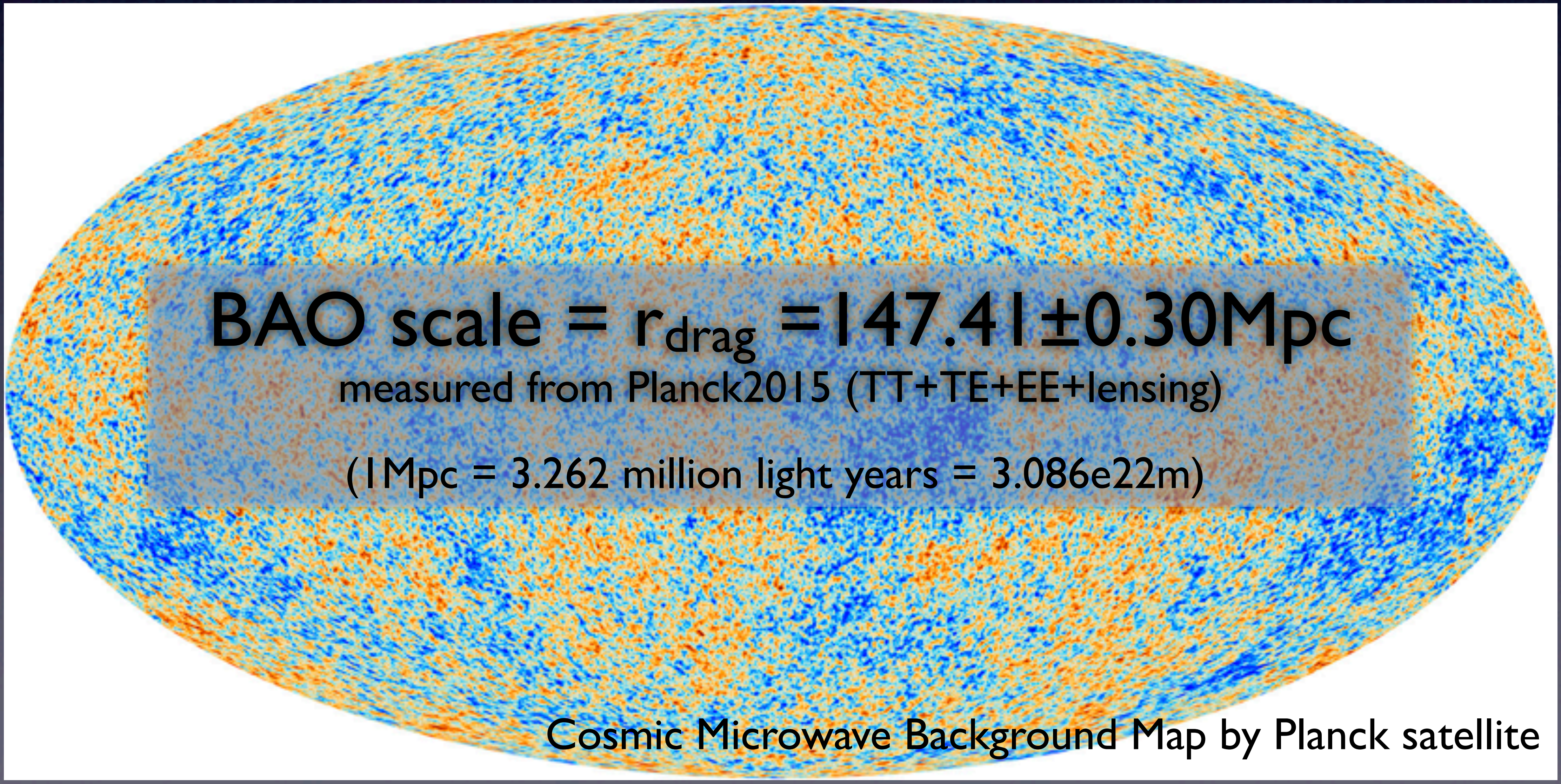
Propagation of the baryon acoustic wave



Credit: Daniel Eisenstein (Harvard CfA)

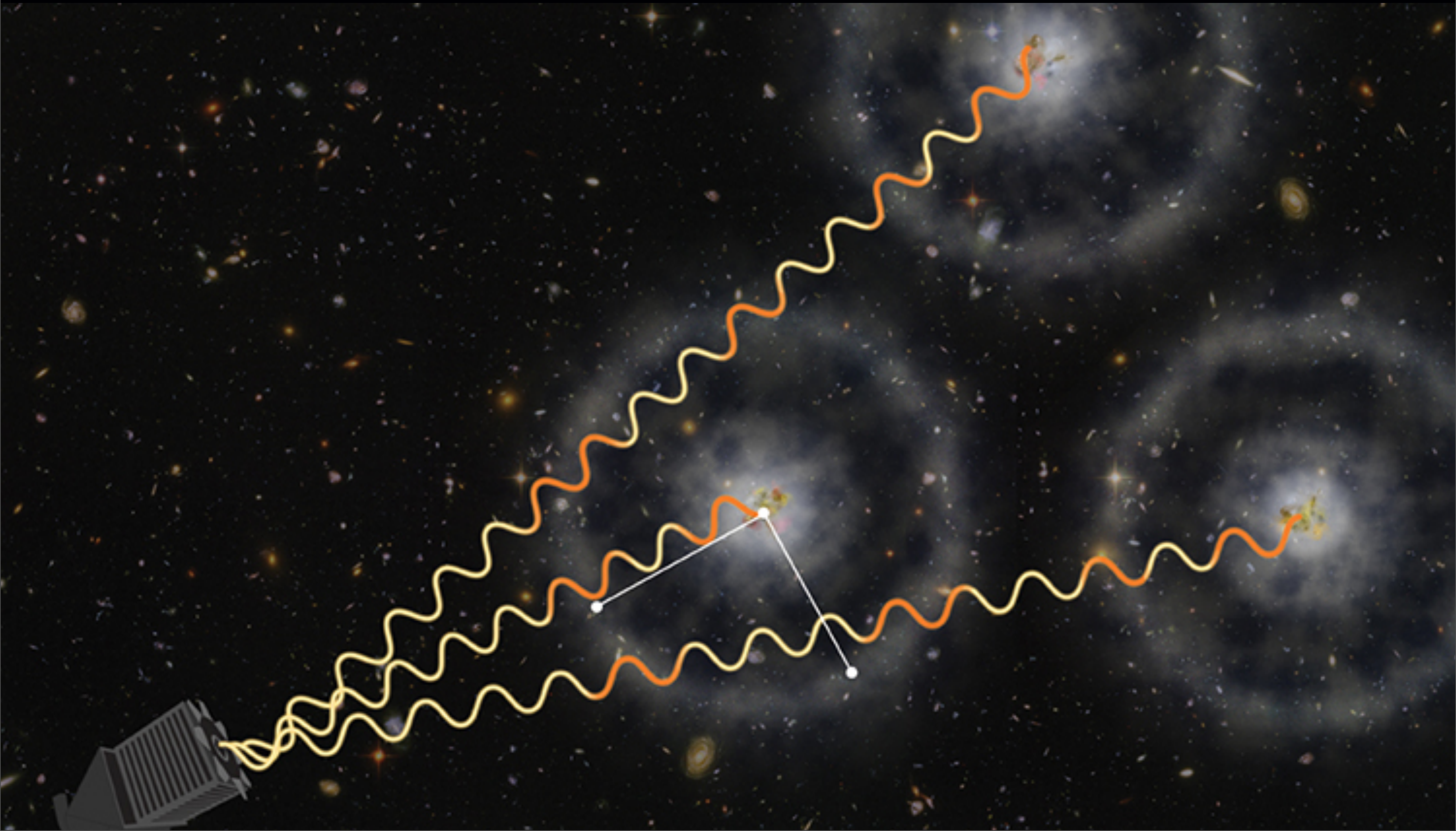
How long is the BAO standard ruler?

The Cosmic Microwave background (CMB) measures the matter and baryon densities ($\Omega_b h^2$, $\Omega_m h^2$) which determines the length of the standard ruler

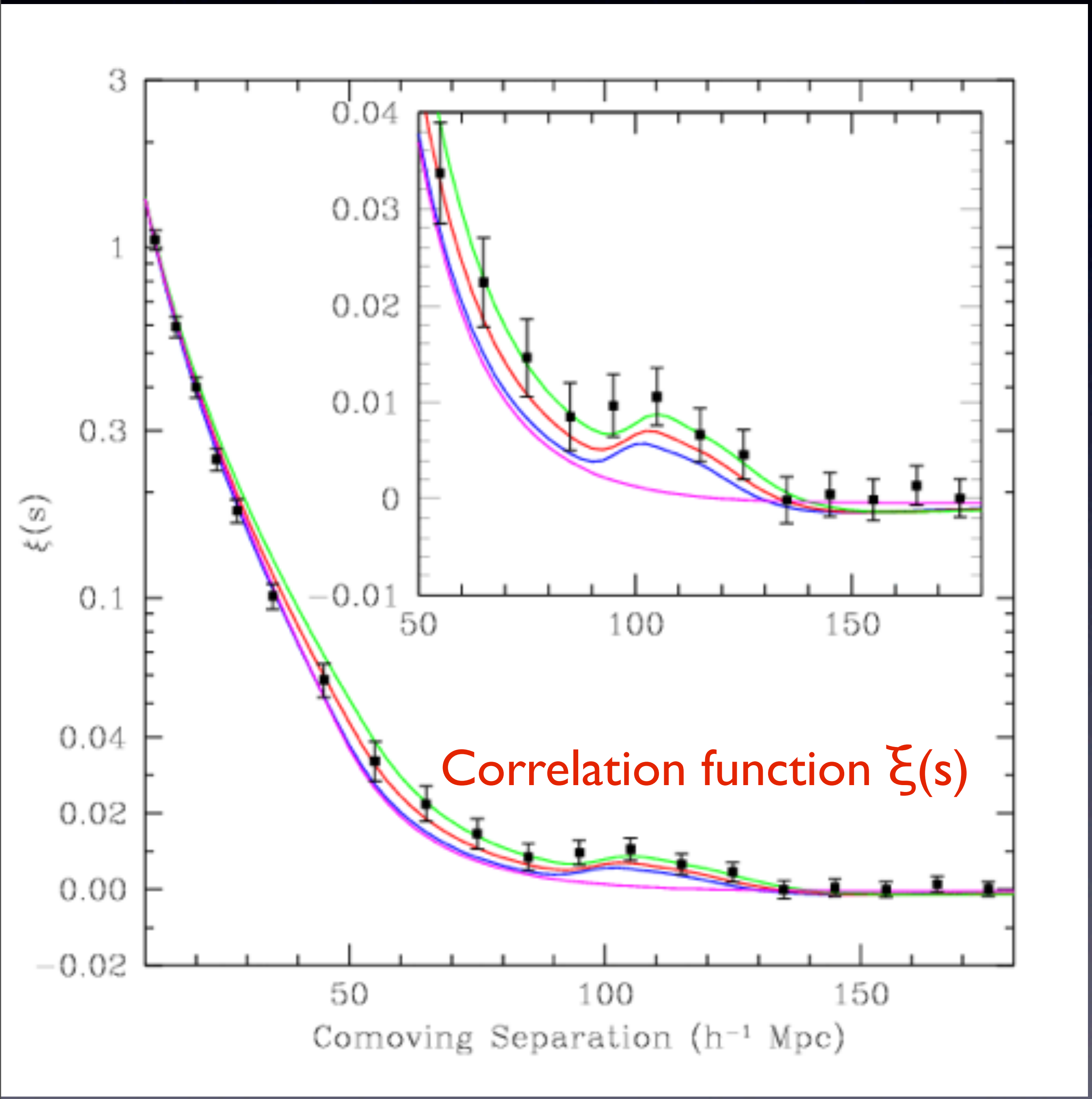


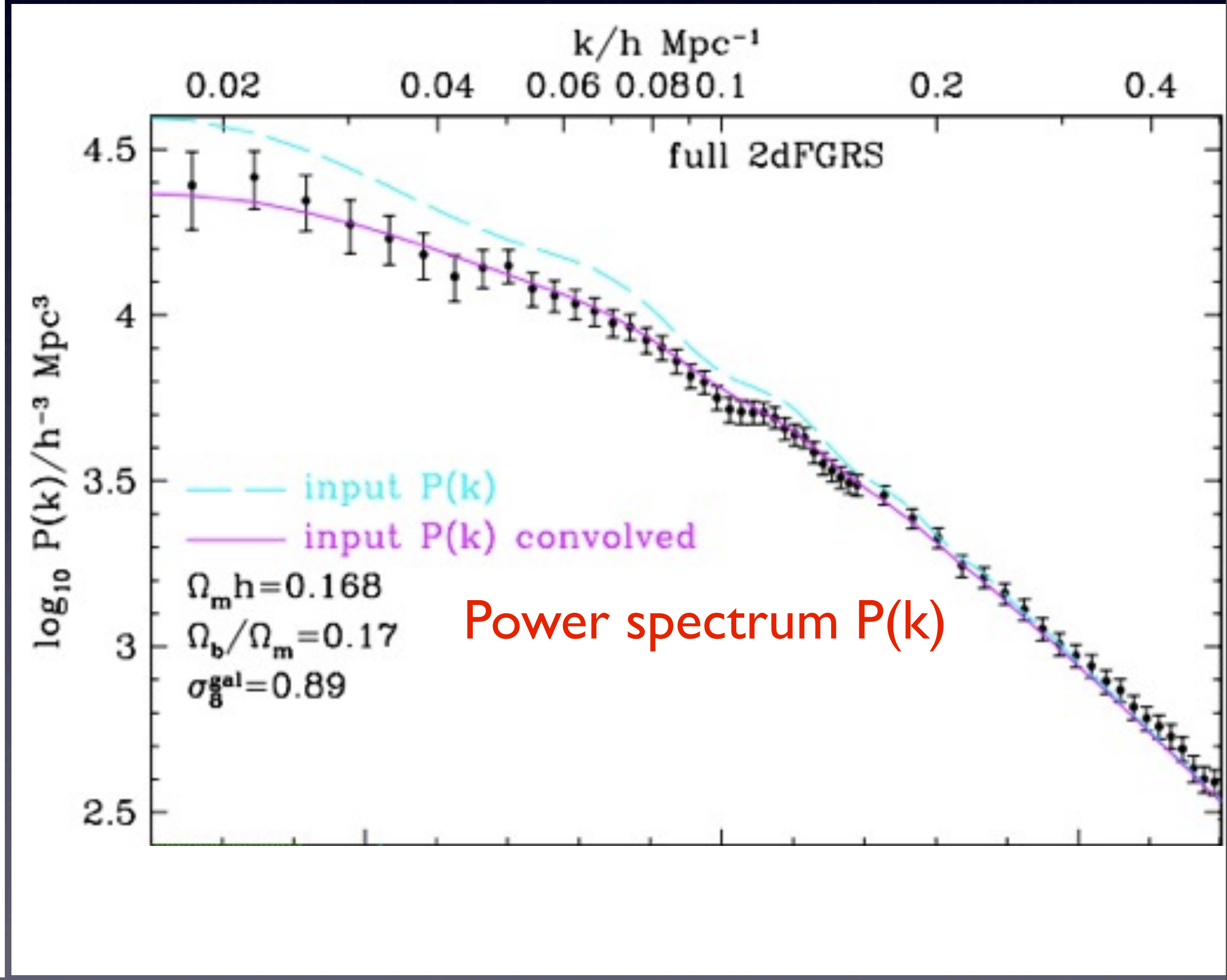
Cosmic Microwave Background Map by Planck satellite

How long is the BAO standard ruler?



The discovery: 10 years of the detection of BAO





Eisenstein et al 2005 (SDSS) Cole et al 2005 (2dF)

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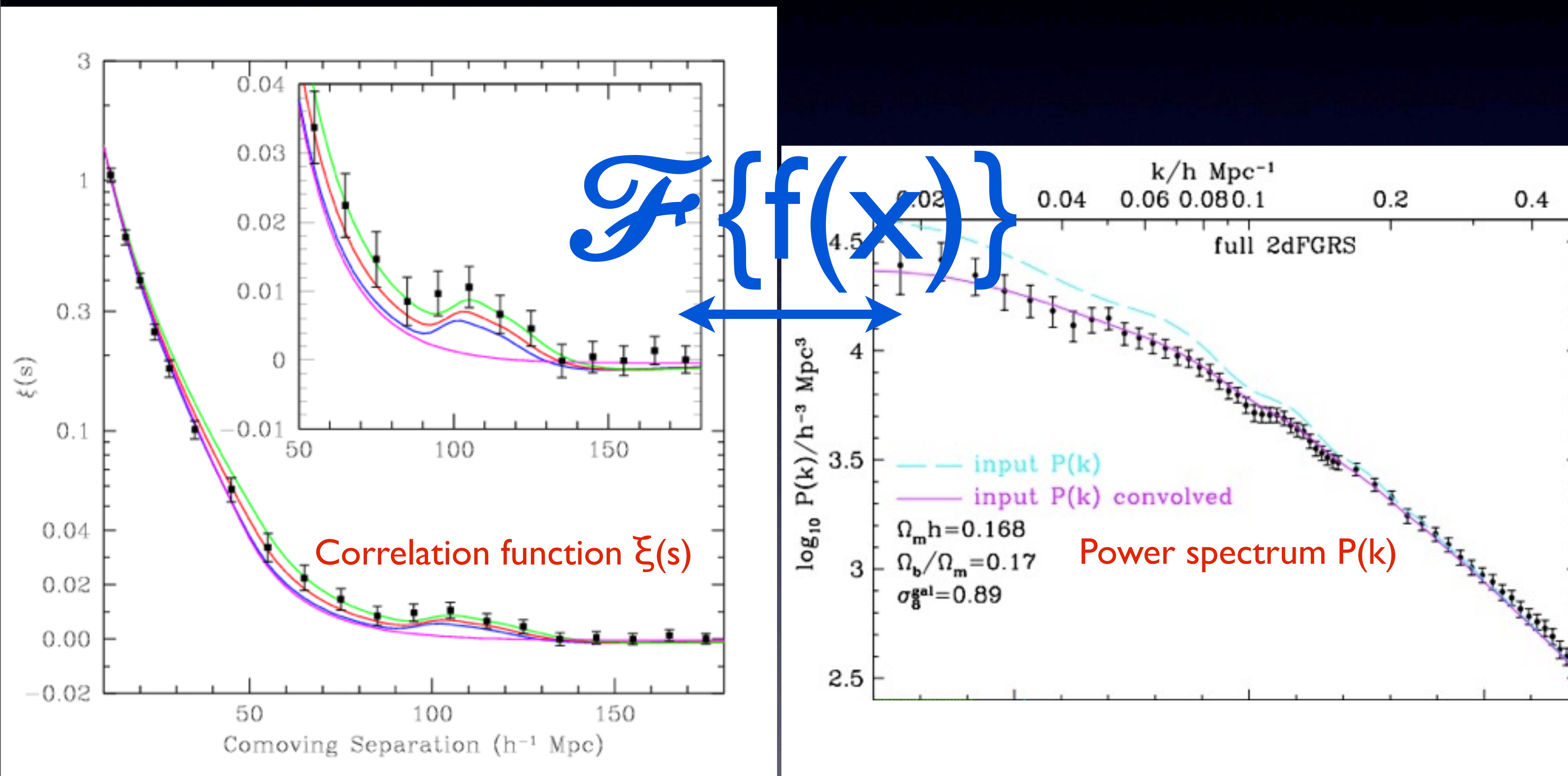

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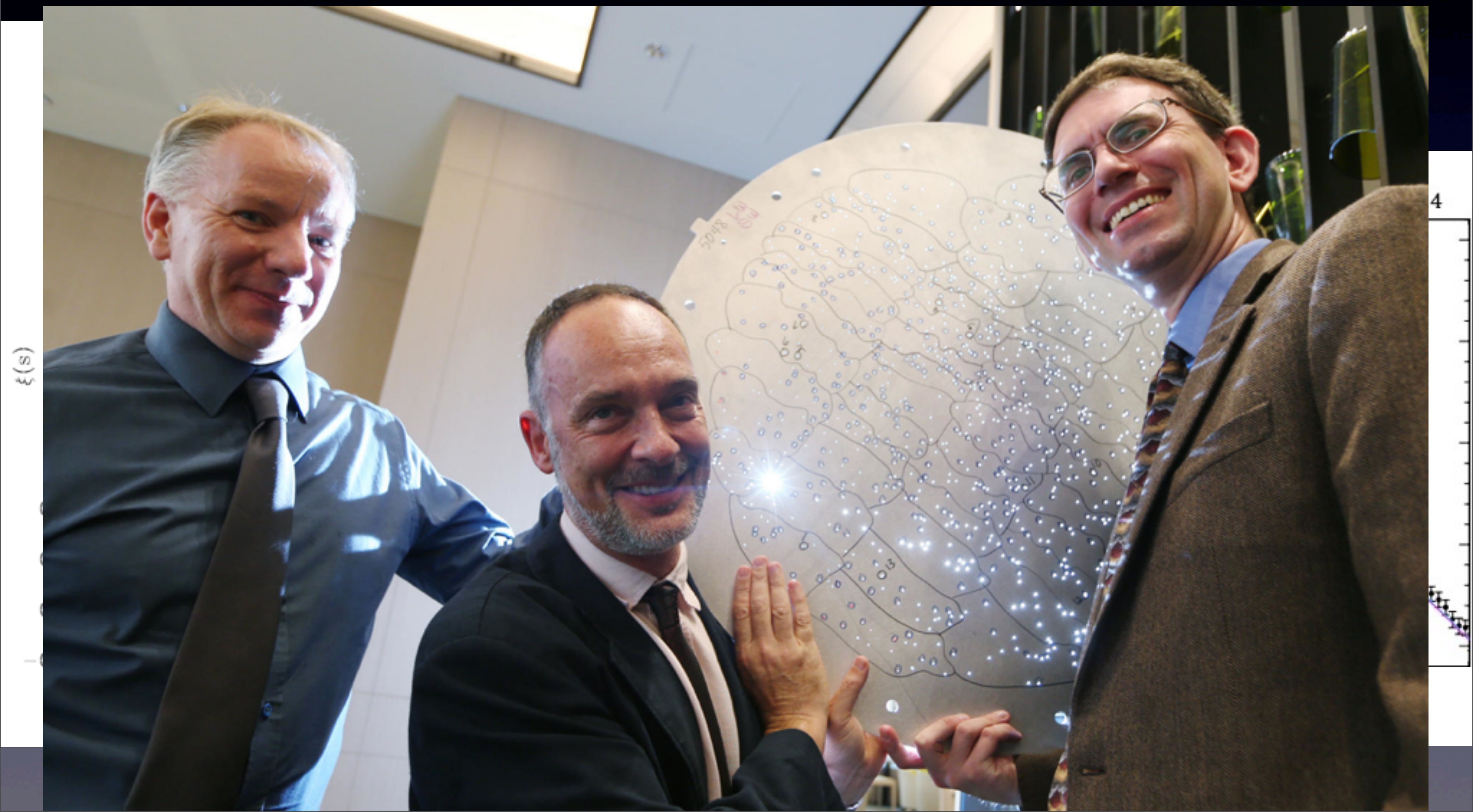


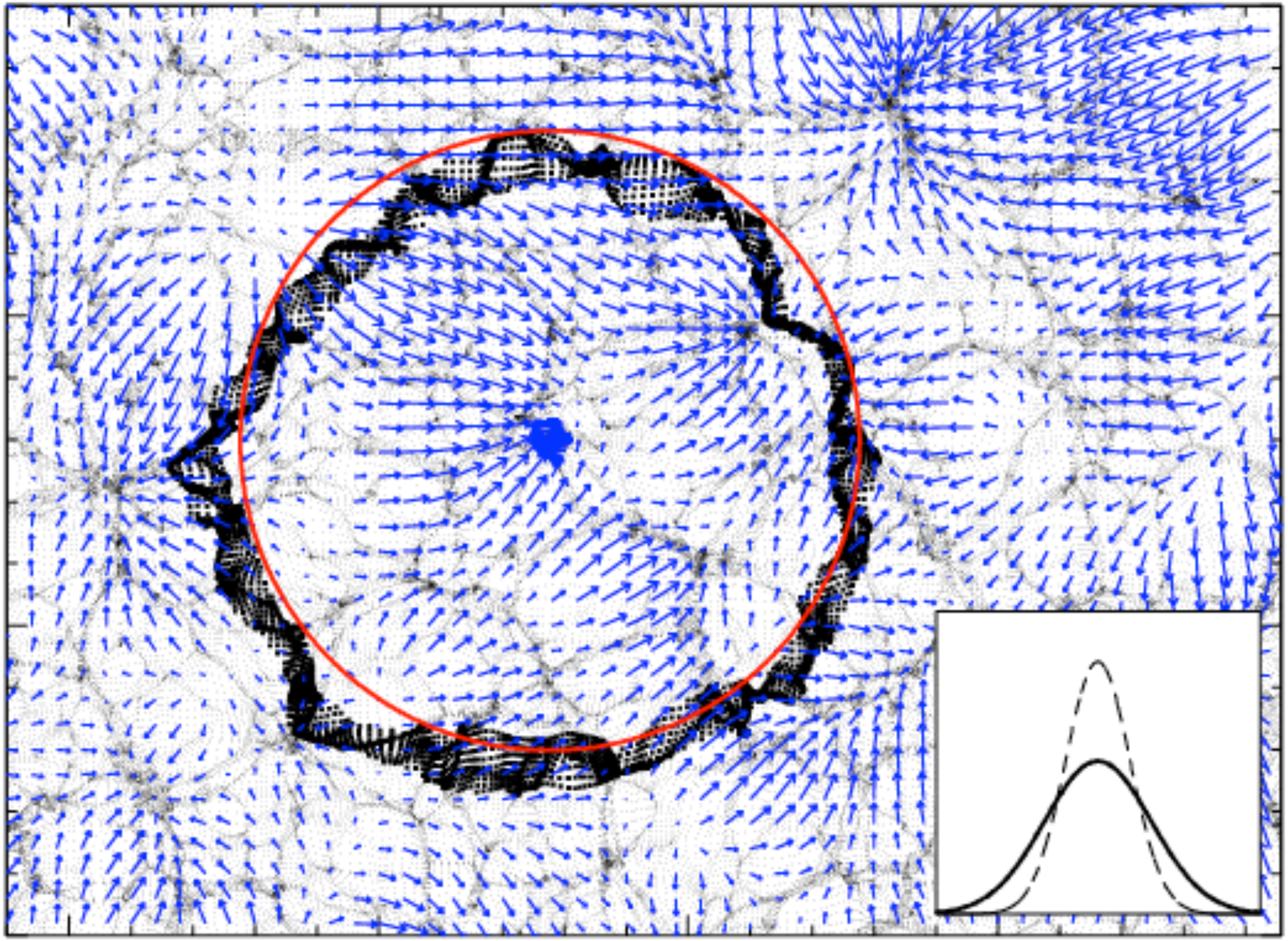
Reconstructing the linear density field

Evolution of the density field

Why reconstruction?

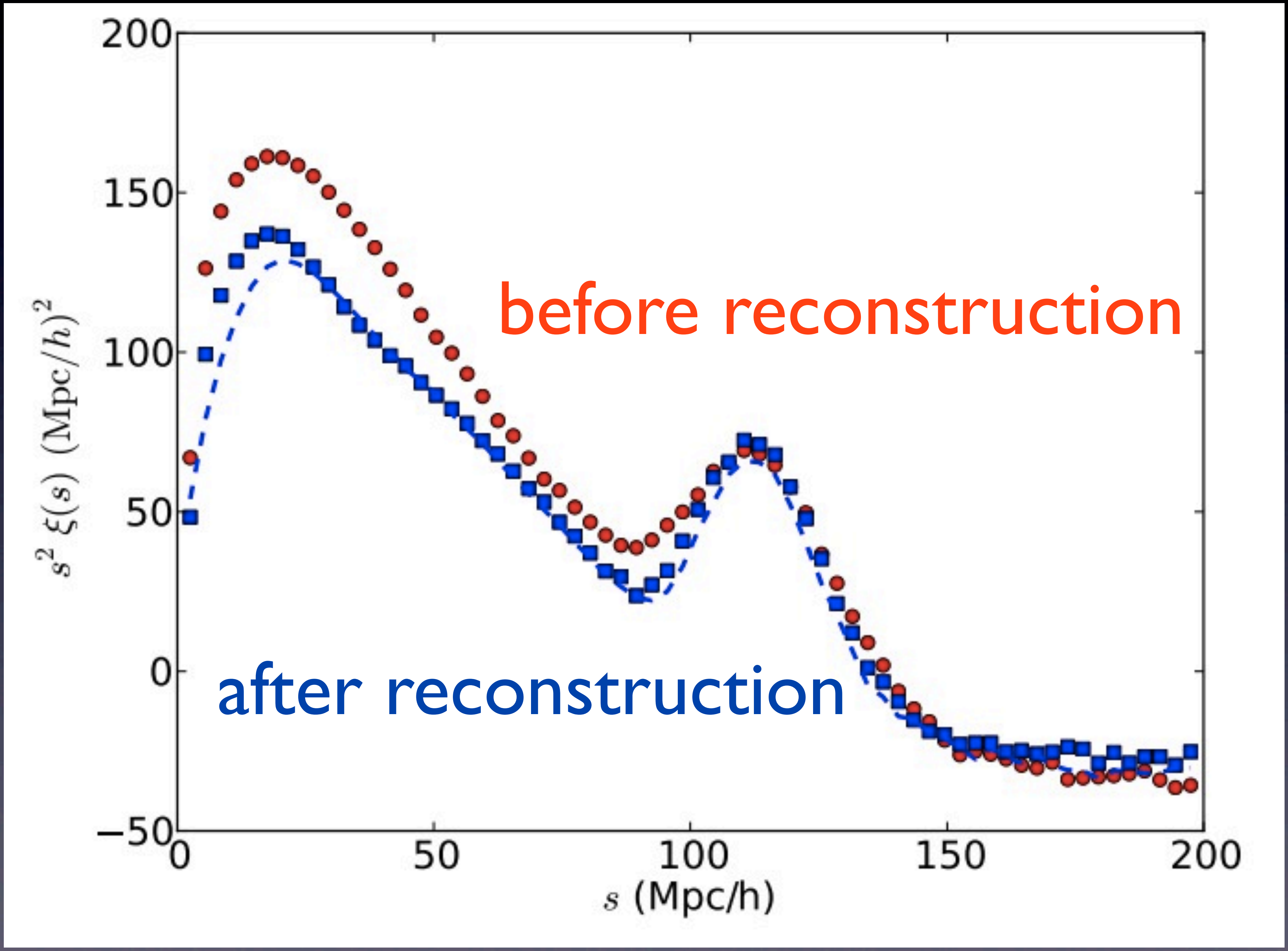
- Non-linear evolution makes the BAO peak **wider** and *less detectable*, which increases the error bar of the derived distance
- It would then be desirable to somehow "reconstruct" the *linear* density field
- The effects of non-linearities can (partially) be un-done using the galaxy positions, which estimate the gravitational potential field. No additional observations needed!

courtesy of Daniel Eisenstein



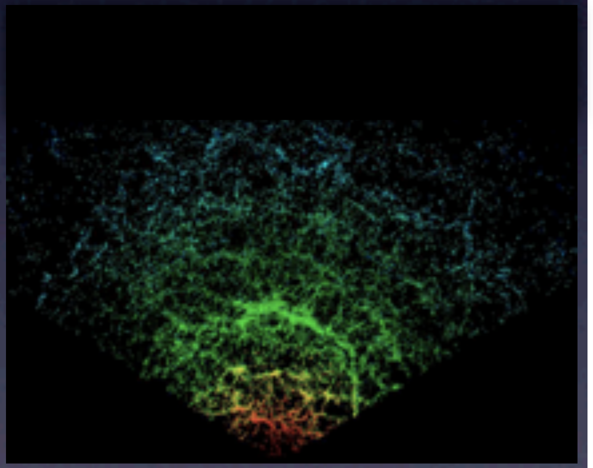
courtesy of Daniel Eisenstein

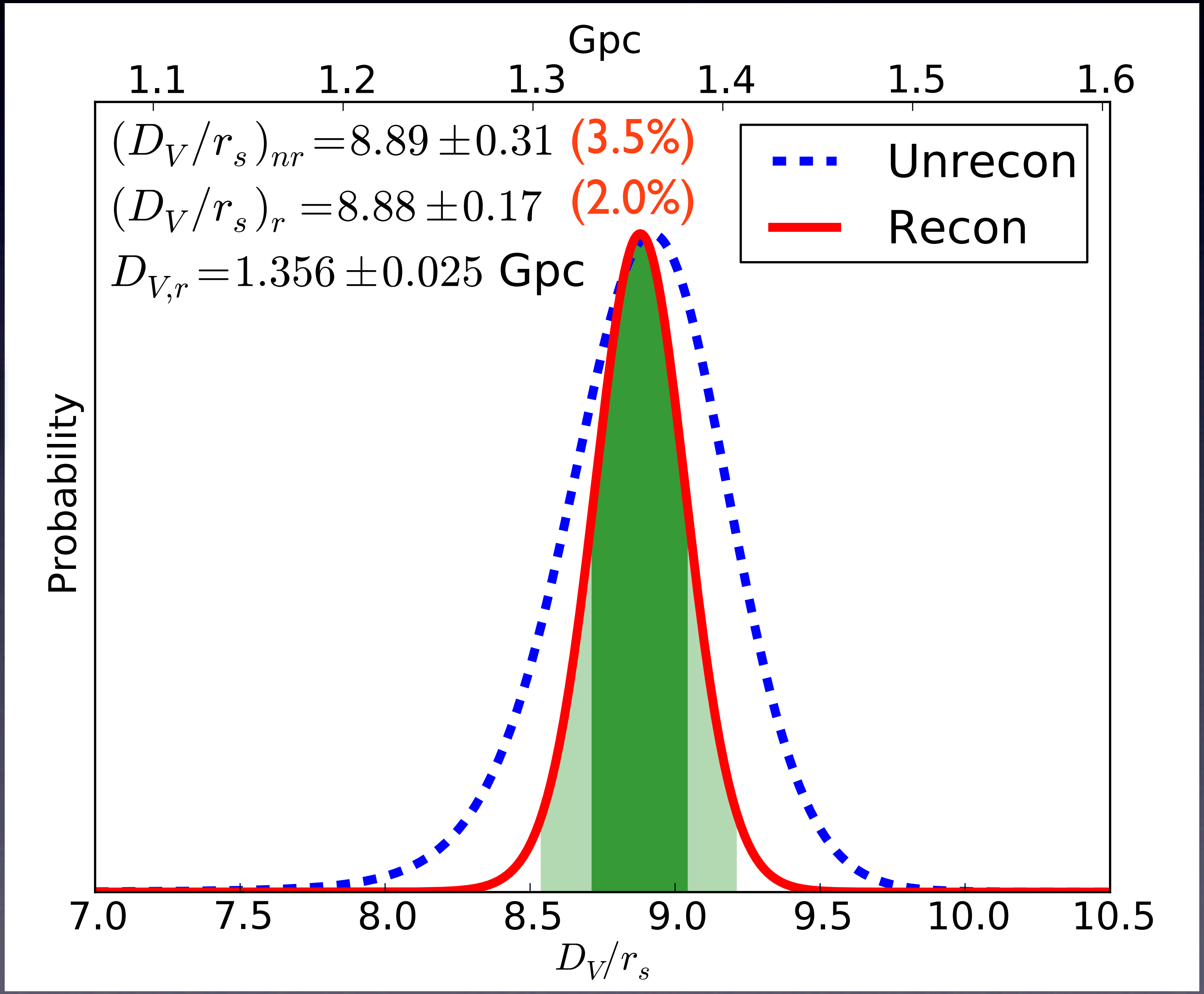
Effects of reconstruction



from Padmanabhan et al. (2012)

SDSS-DR7 Measurement of $D_V(z=0.35)$

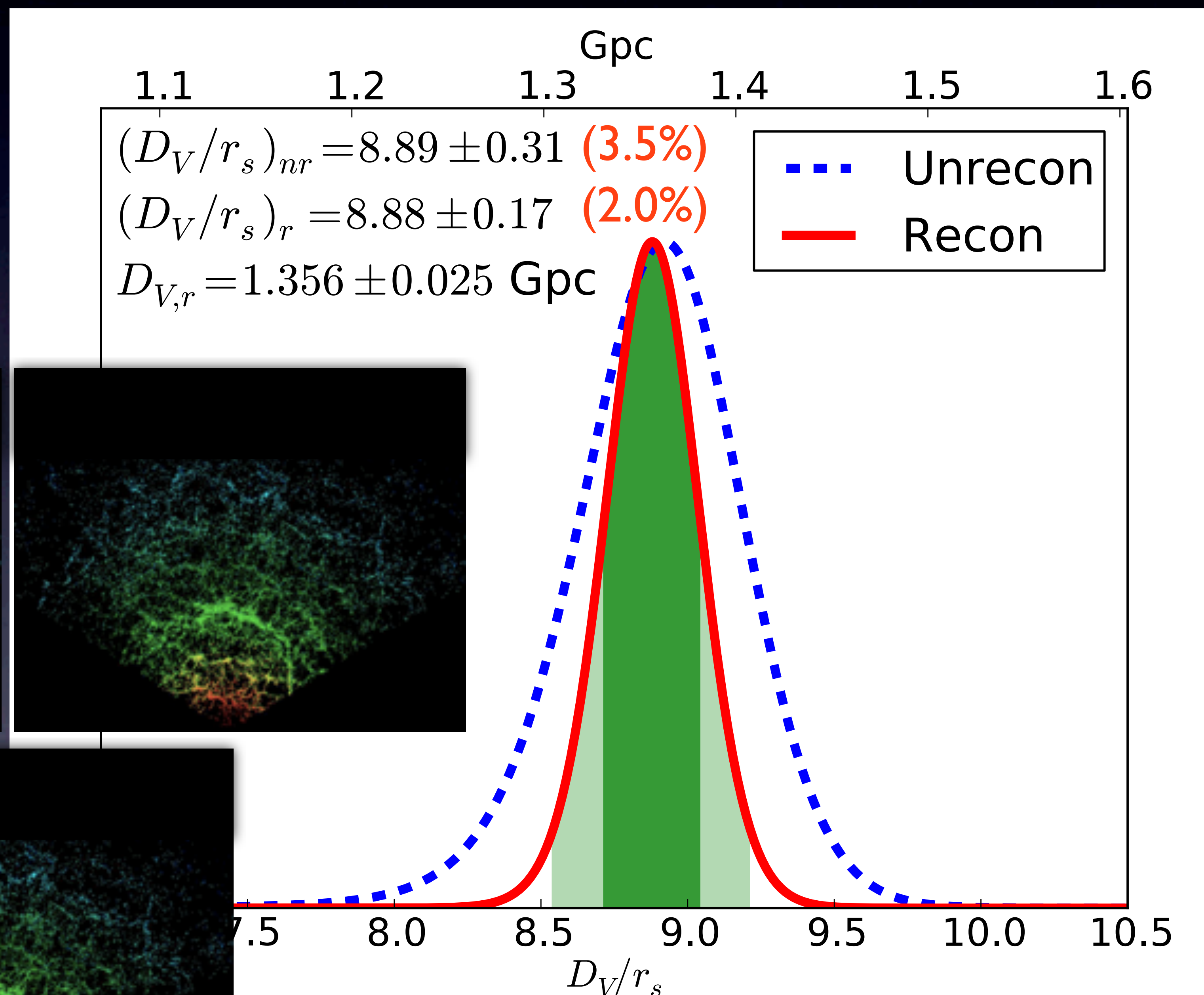


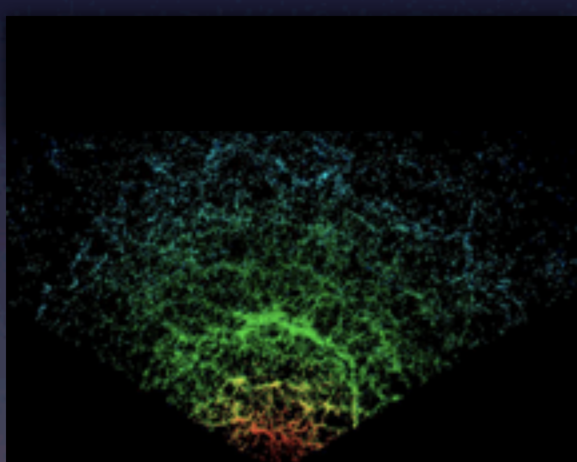


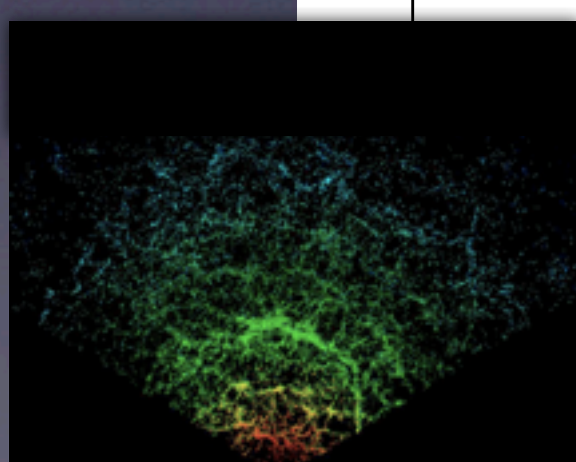
$\sigma \sim 1/\sqrt{V}$

from Padmanabhan et al. (2012)

SDSS-DR7 Measurement of $D_V(z=0.35)$



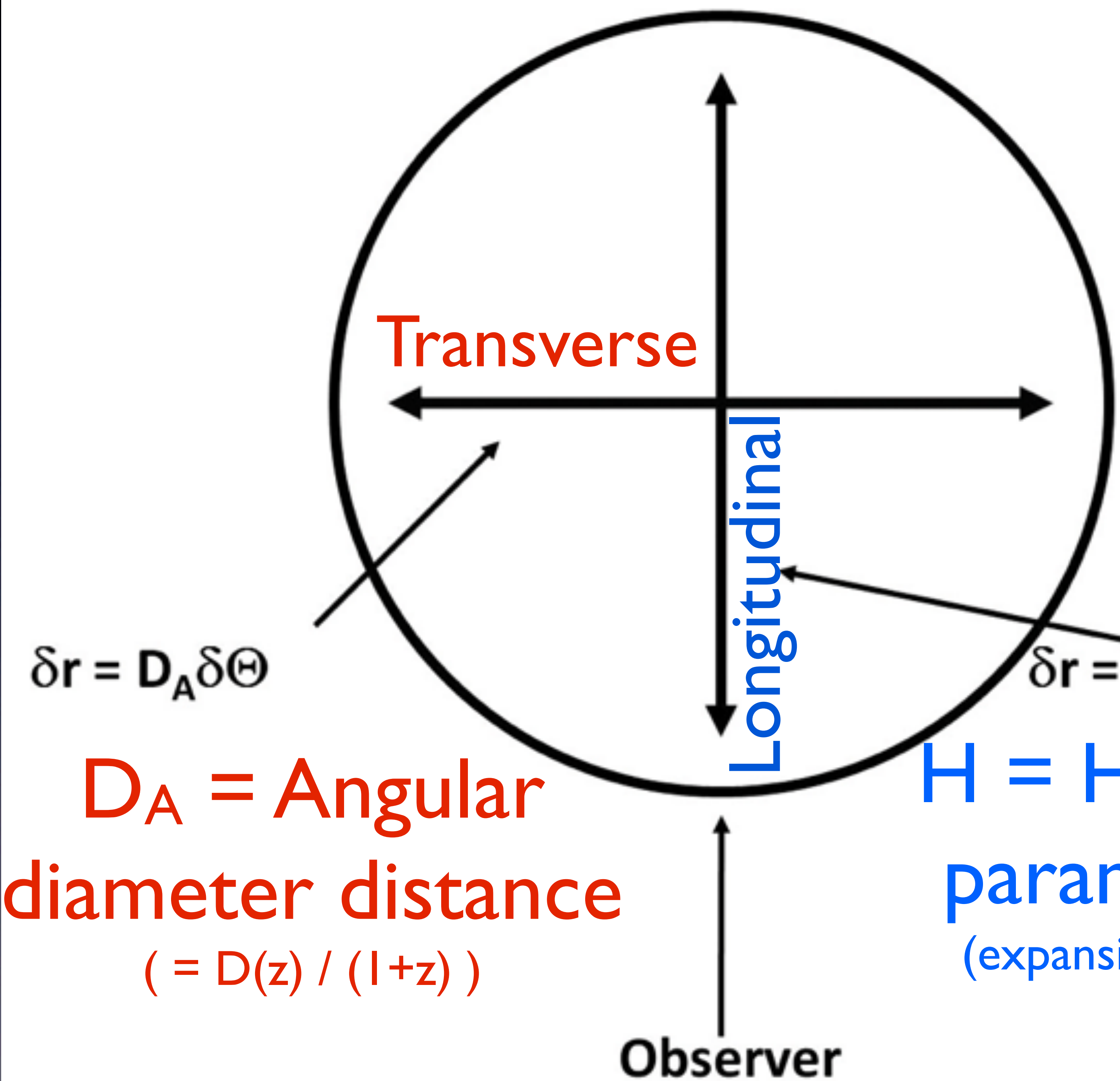




from Padmanabhan et al. (2012)

Anisotropic Clustering: The line-of-sight dependence

The line-of-sight dependence



D_A = Angular diameter distance
(= D(z) / (1+z))

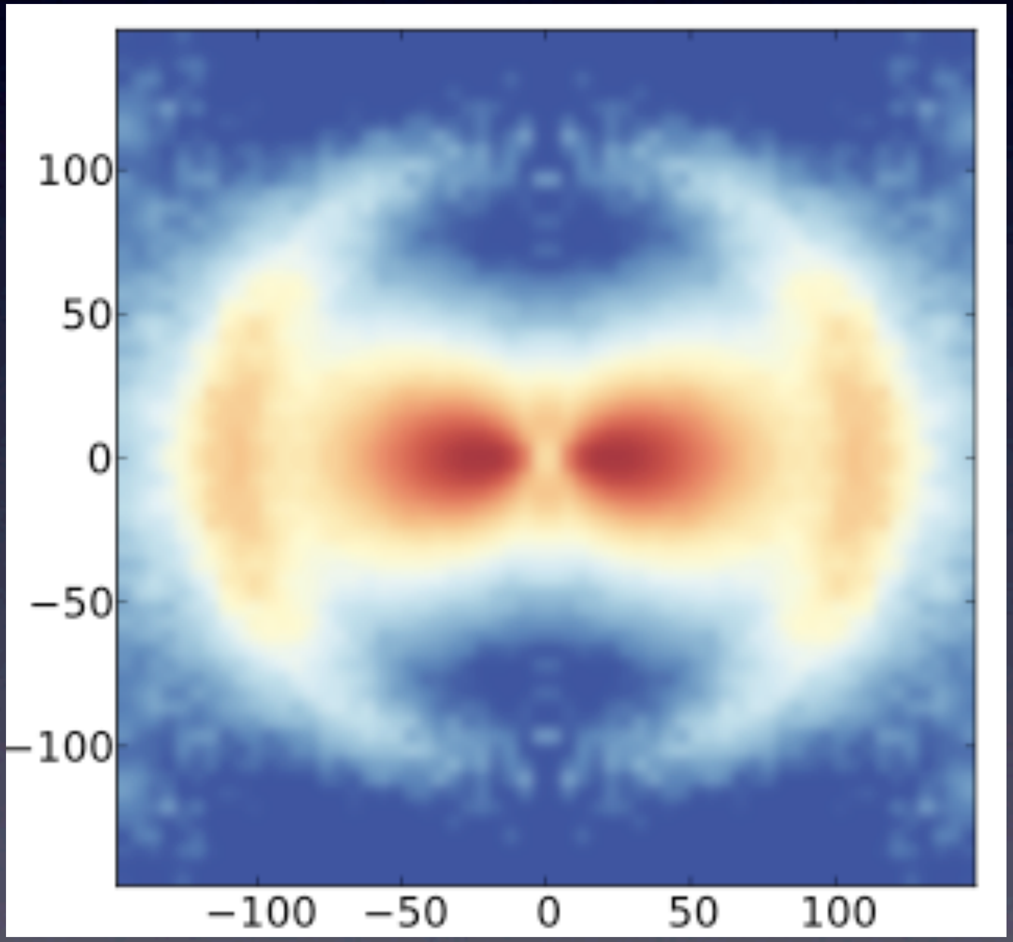
H = Hubble parameter
(expansion rate)

If we detect the BAO feature in these two directions, we can measure both $D_A(z)$ and $H(z)$

Alternatively, if we assume a *wrong* fiducial cosmology to convert (z,θ,Φ) into (x,y,z), we will measure an anisotropic clustering (even though the Universe *is* isotropic)

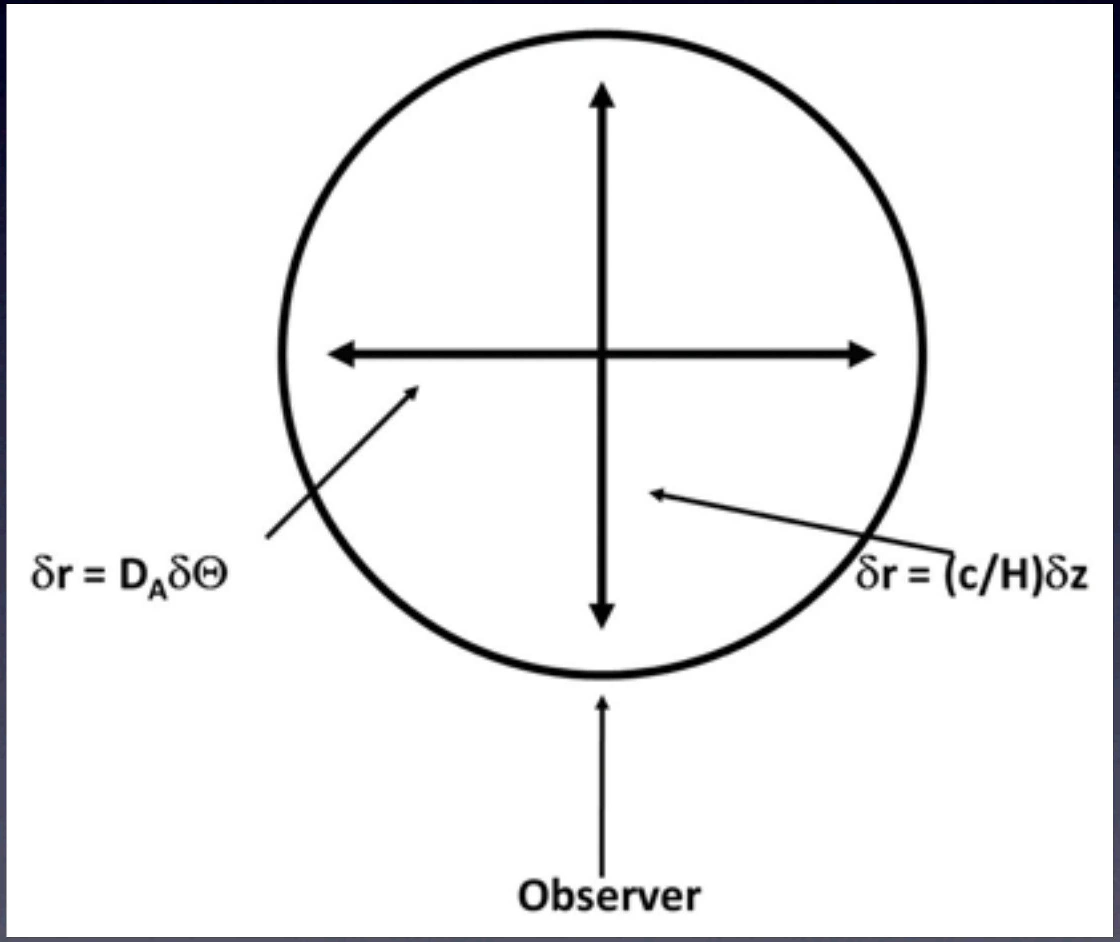
Two sources of anisotropies

Redshift-space distortions



Padmanabhan et al. 2012

Alcock - Paczynski effect



Two sources of anisotropies

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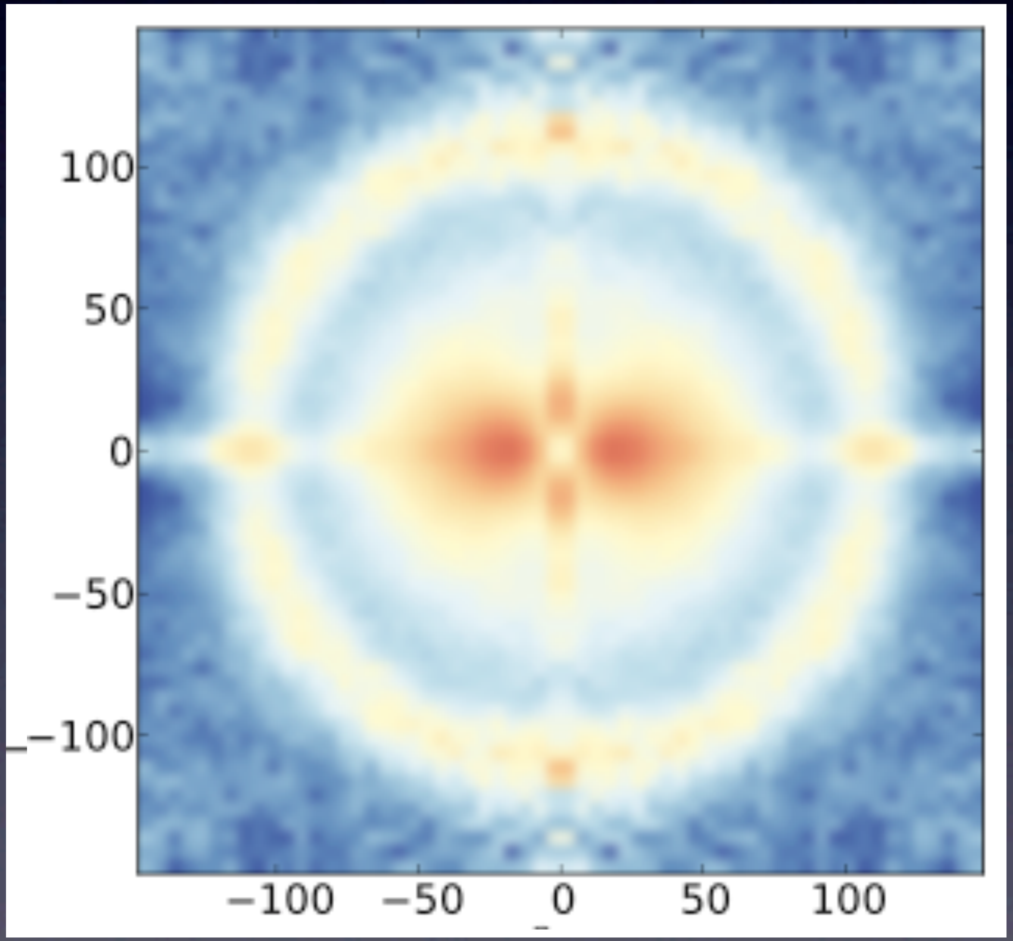

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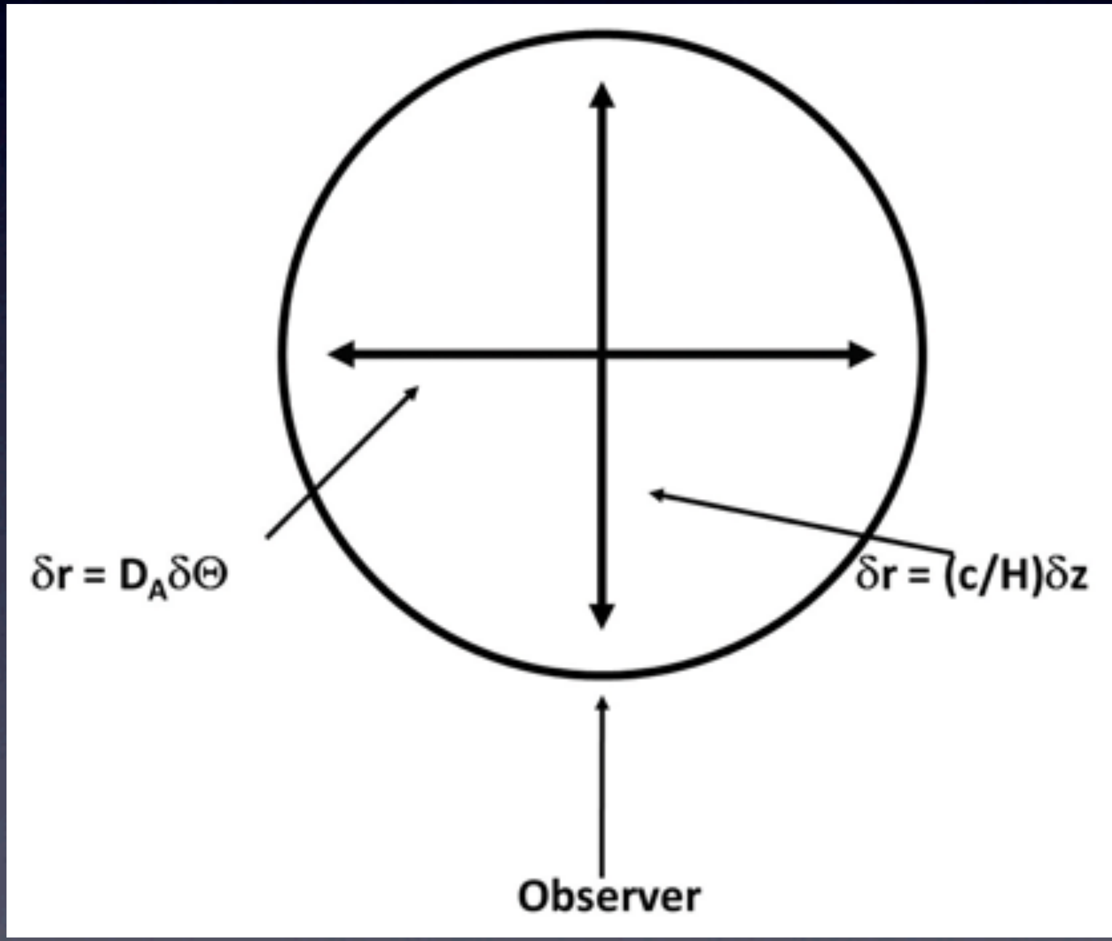
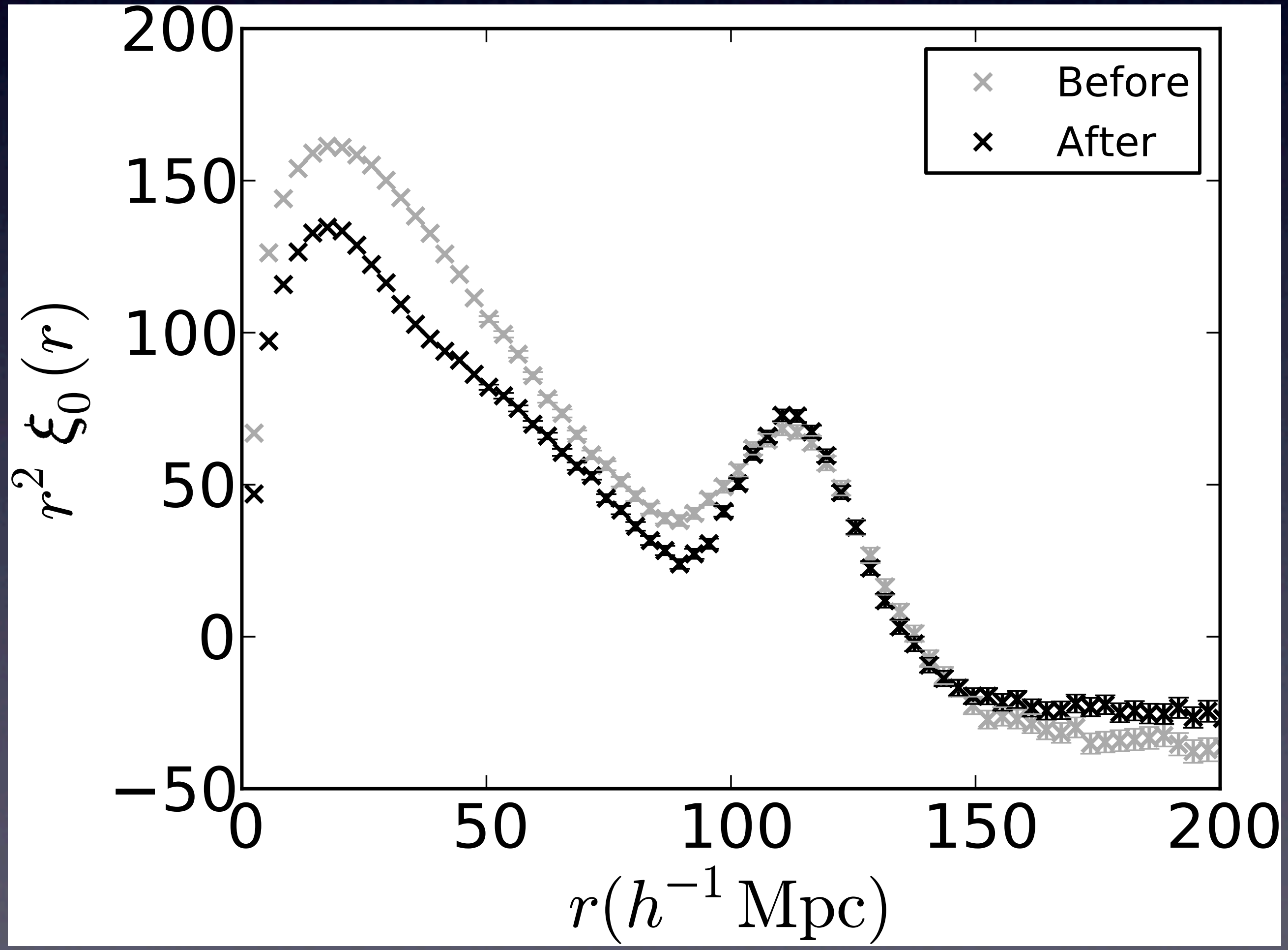
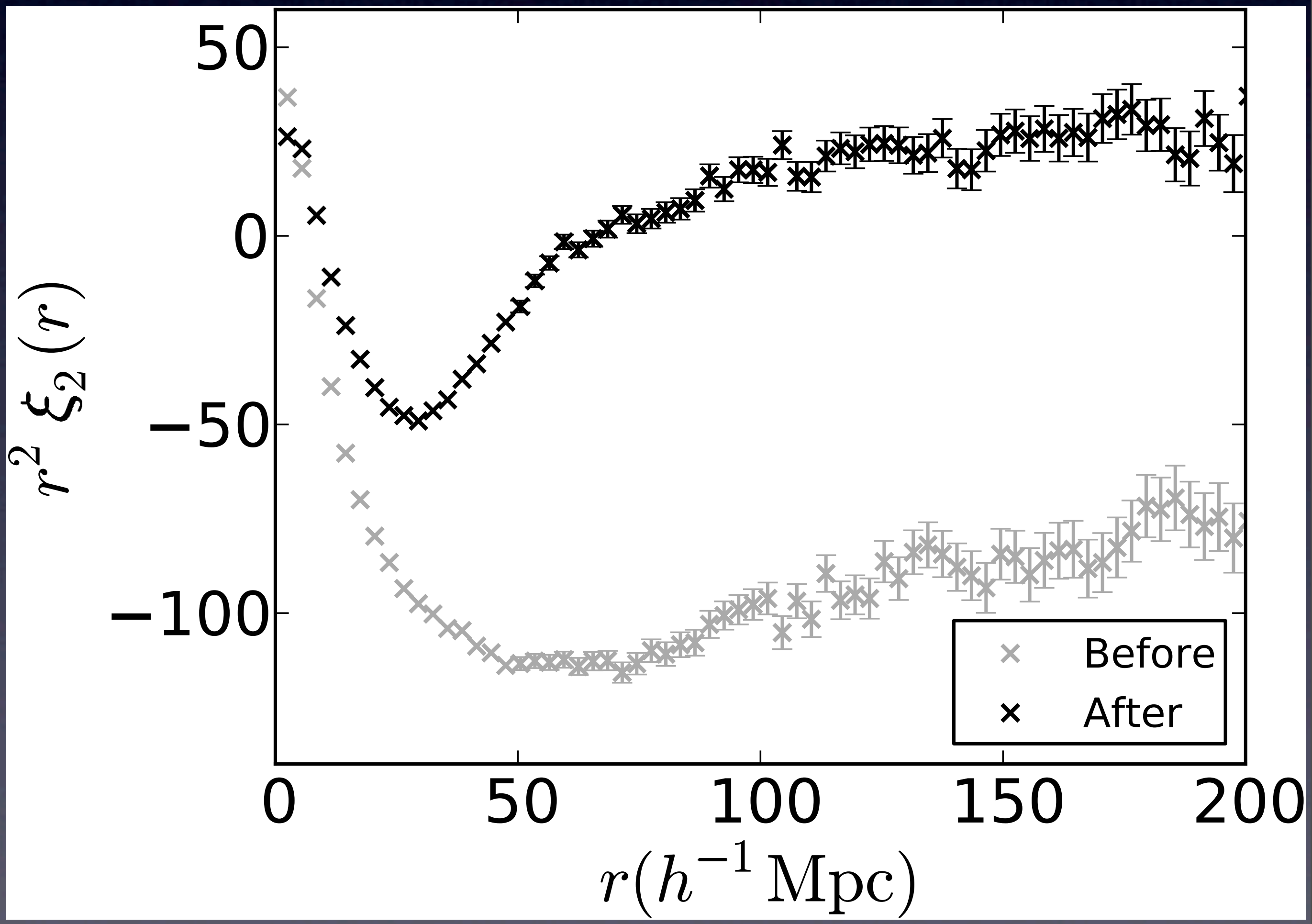


Padmanabhan et al. 2012

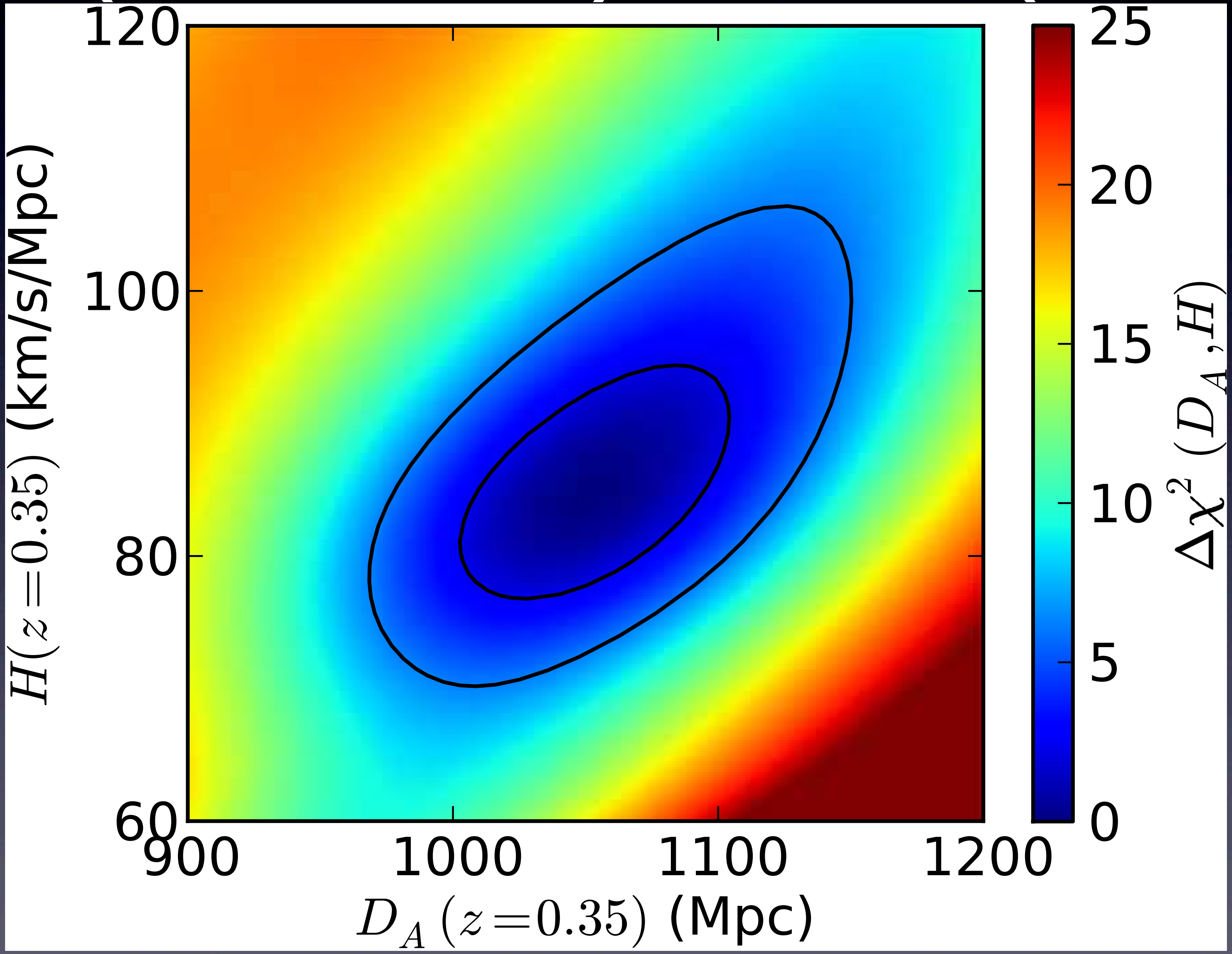
Effects of Reconstruction





from Xu et al. 2012

SDSS-DR7 Measurement of $D_A(z=0.35)$ & $H(z=0.35)$



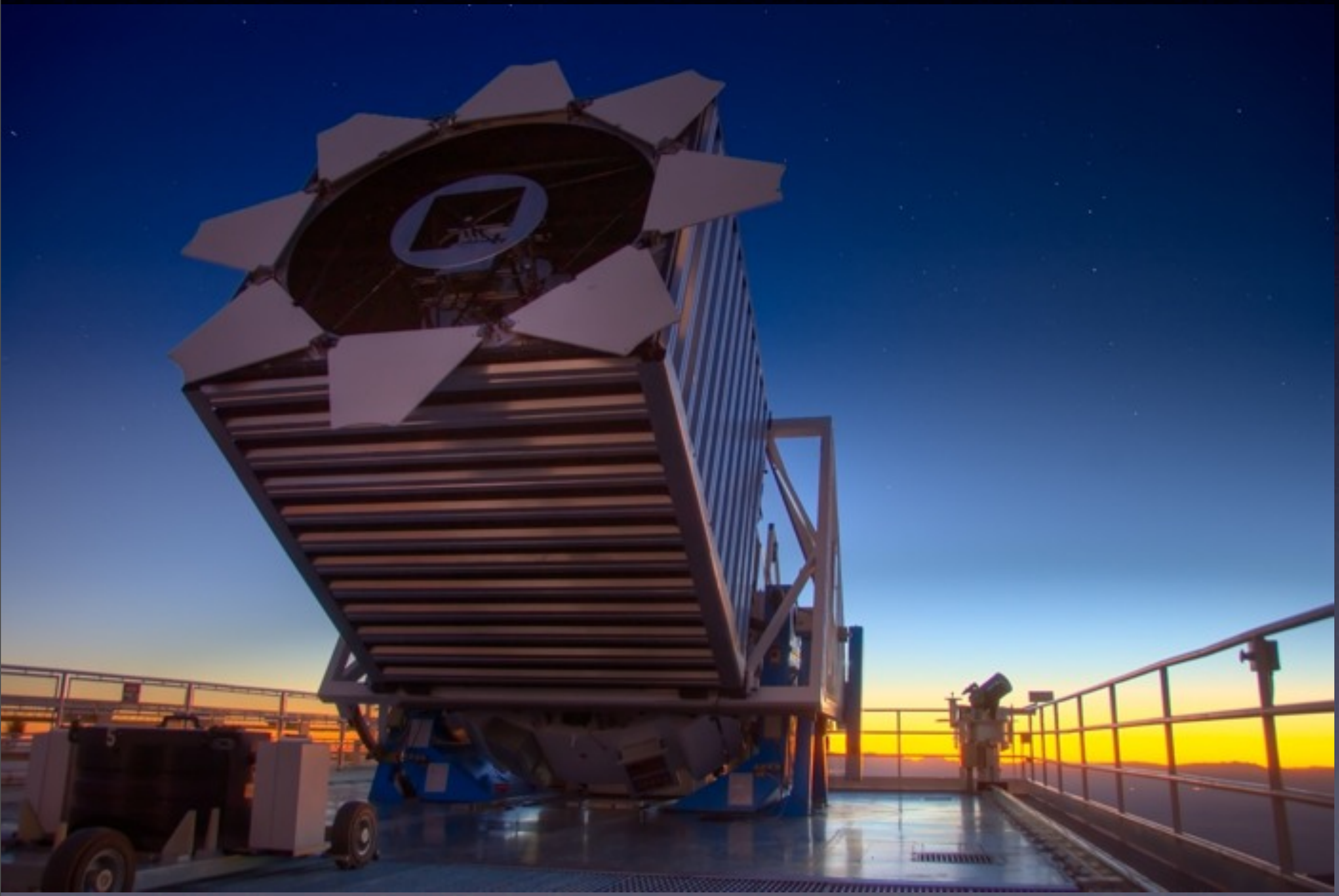
Xu et al. (2013)

$D_A(z=0.35)=1050\pm38$Mpc (3.6%)

$H(z=0.35)=84.4\pm7.1$km/s/Mpc (8.4%)

BOSS:
The Baryon Oscillation Spectroscopic Survey

BOSS at a glance

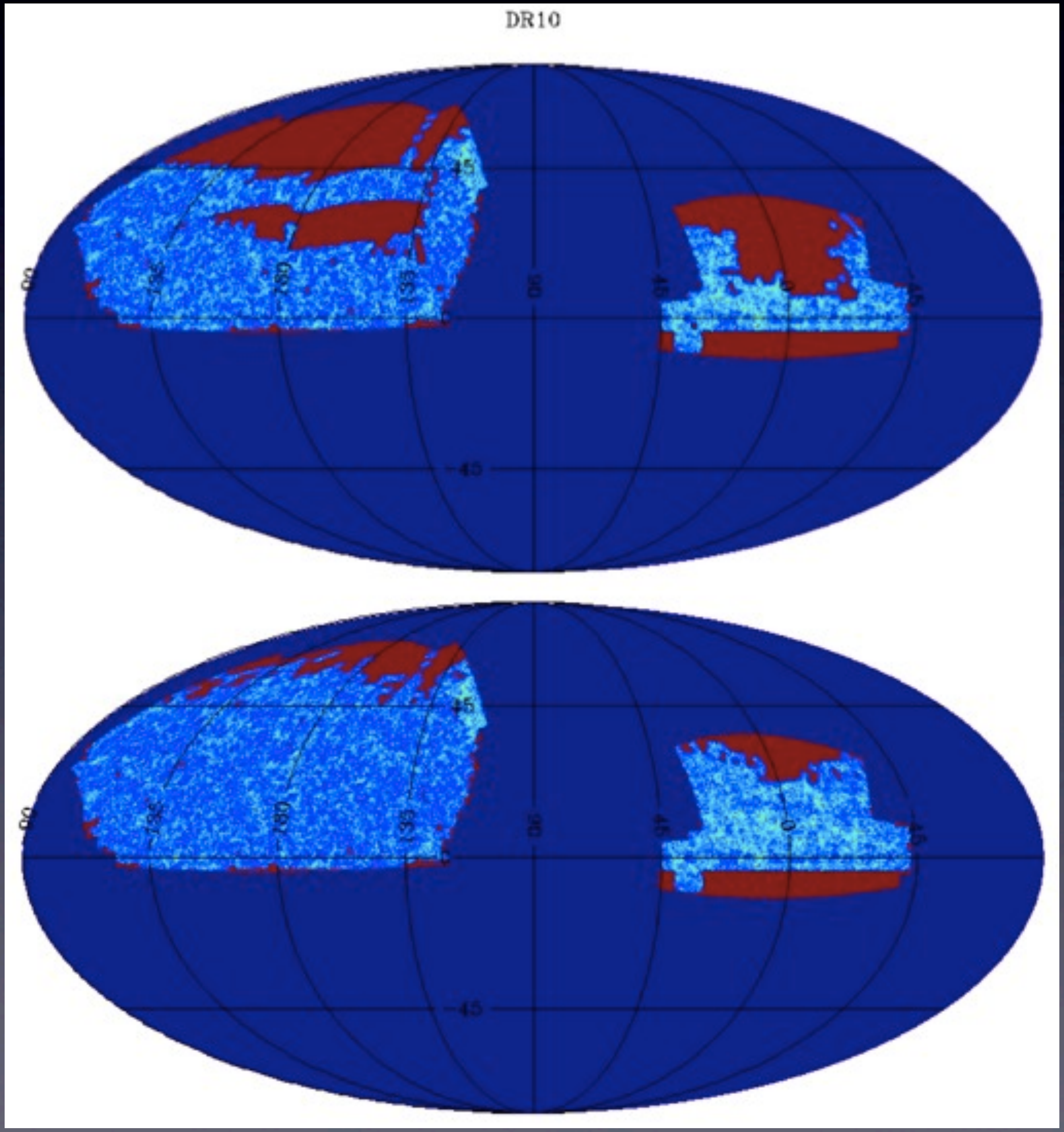


July 2008 - June 2014
51 participating institutions
> 1,000 scientists

SDSS Telescope
2.5m dedicated
Apache Point, NM
(operating since 1998)

https://www.sdss3.org/surveys/boss.php

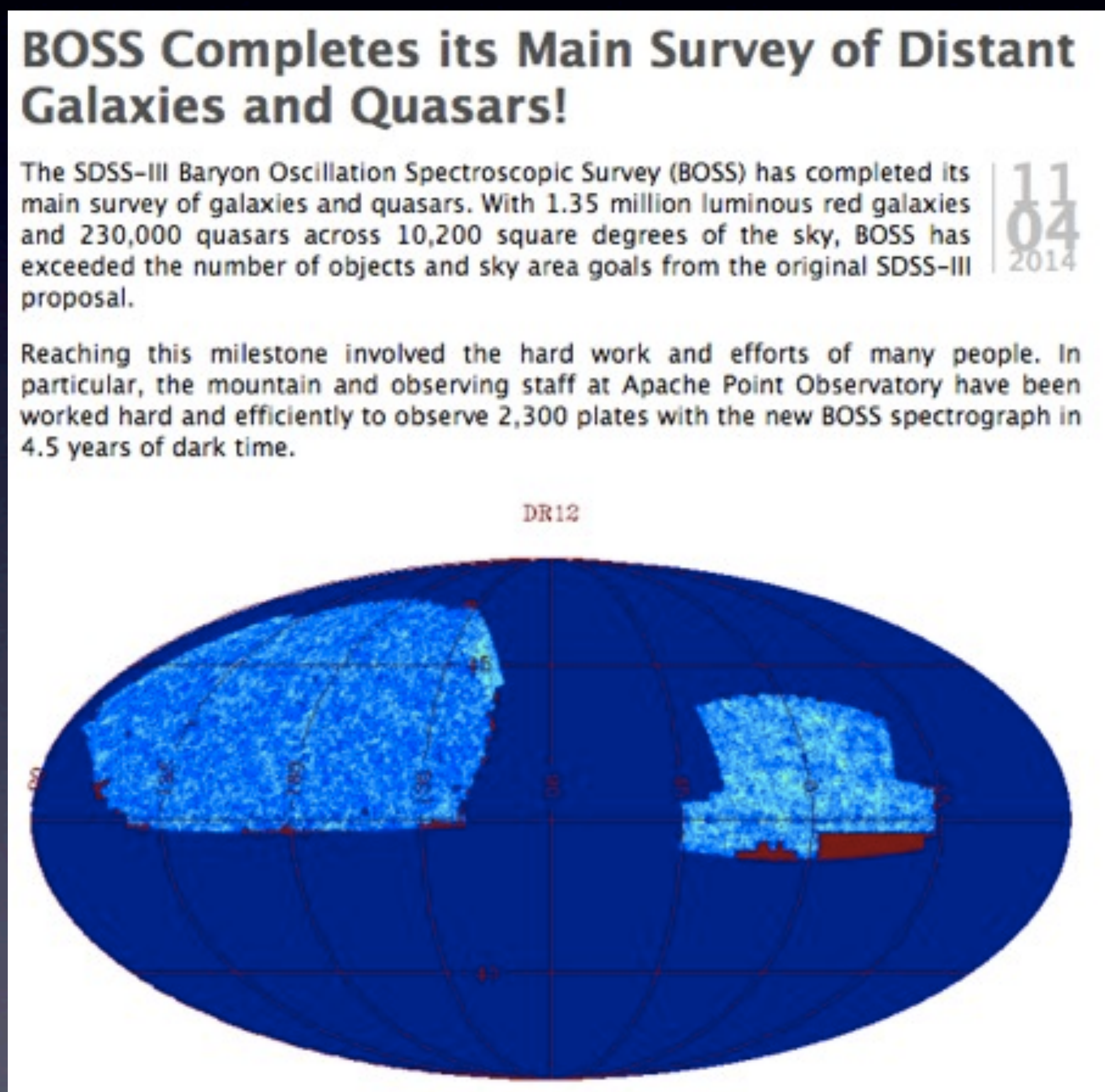
The Data Release 10 and 11 of BOSS



Data Release 10
6,373 sq.deg.
928,000 galaxies
182,000 quasars

Data Release 11
8,976 sq.deg.
1,157,000 galaxies
239,000 quasars

...and what is on DR12



BOSS Completes its Main Survey of Distant Galaxies and Quasars!

11 04 2014

The SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS) has completed its main survey of galaxies and quasars. With 1.35 million luminous red galaxies and 230,000 quasars across 10,200 square degrees of the sky, BOSS has exceeded the number of objects and sky area goals from the original SDSS-III proposal.

Reaching this milestone involved the hard work and efforts of many people. In particular, the mountain and observing staff at Apache Point Observatory have been worked hard and efficiently to observe 2,300 plates with the new BOSS spectrograph in 4.5 years of dark time.

Survey is DONE

1.35M galaxies

(1.20M in $0.15<z<0.70$)

290k quasars

(160k in $2.15<z<3.5$)

10,200 sq.deg.

Publicly available (Jan 5)

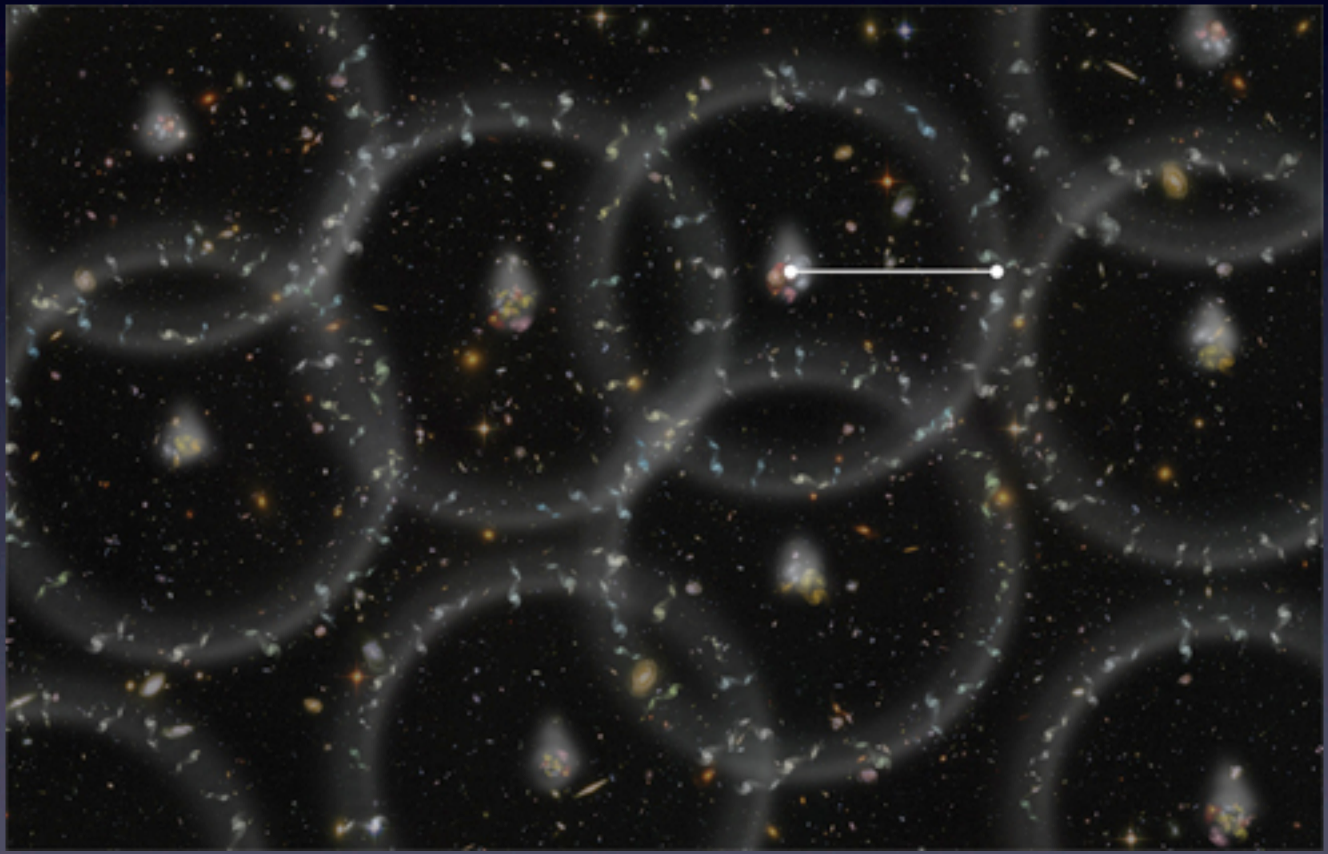
Analysis is in progress...

BAO papers very soon!

http://blog.sdss3.org

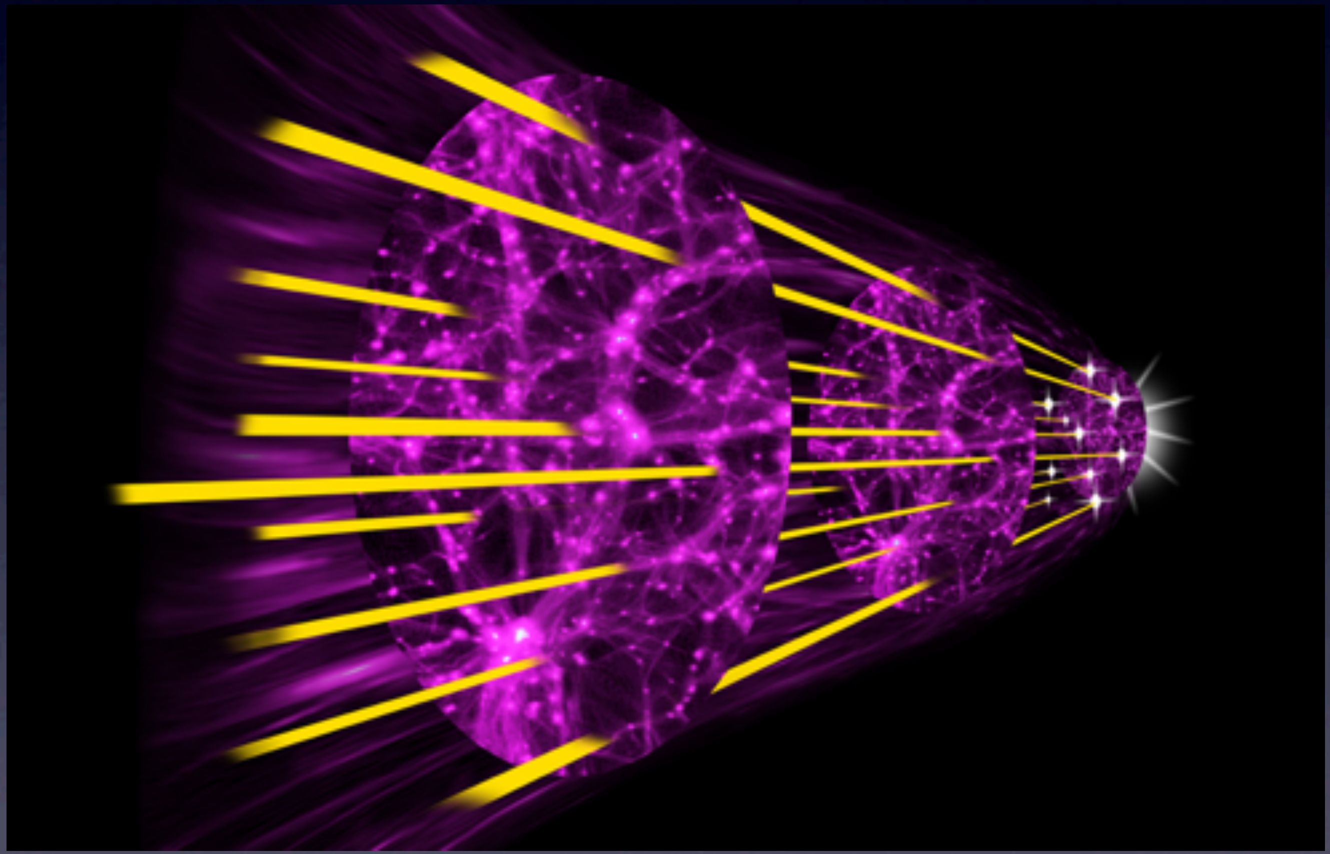
BOSS BAO measurements

Galaxy BAO

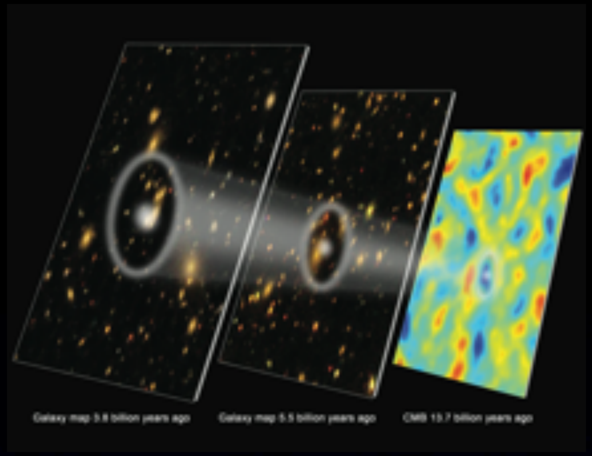


BAO from the clustering of galaxy pairs

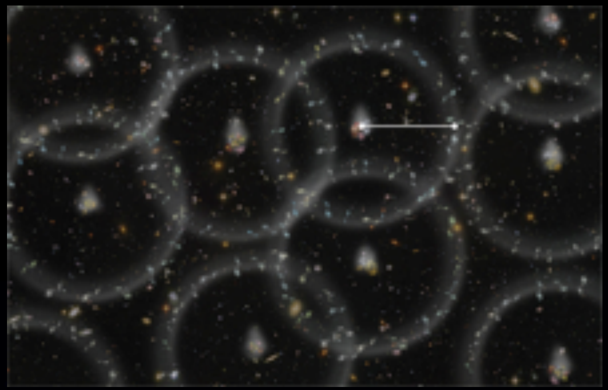
Lyman-alpha forest BAO

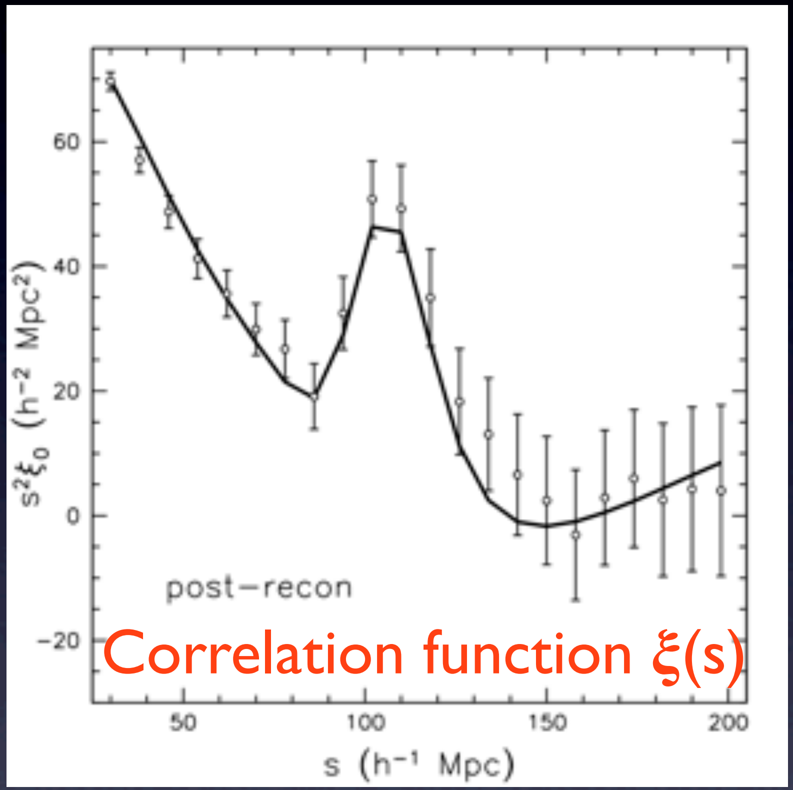


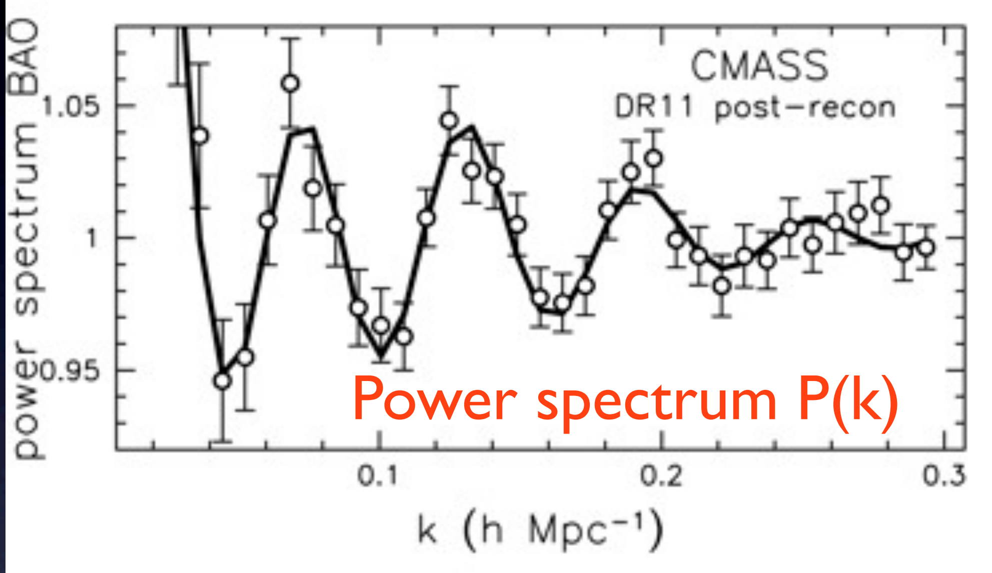
BAO from clustering of absorption features pairs



Galaxy BAO: CMASS





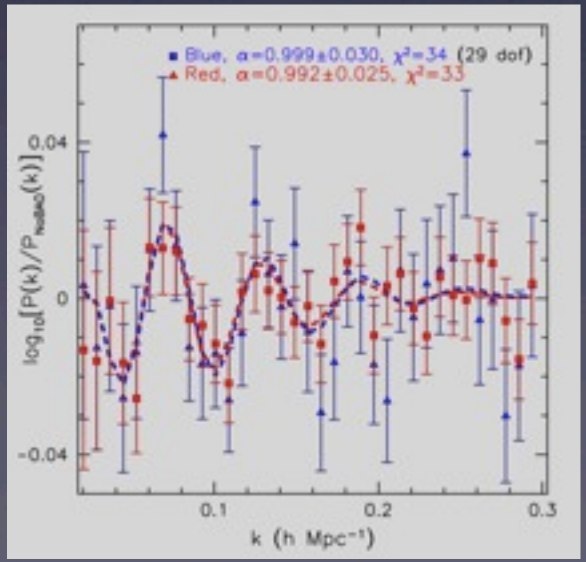


Anderson et al. 2014

690,000 galaxies between $0.43<z<0.70$ covering a total of 10Gpc^3

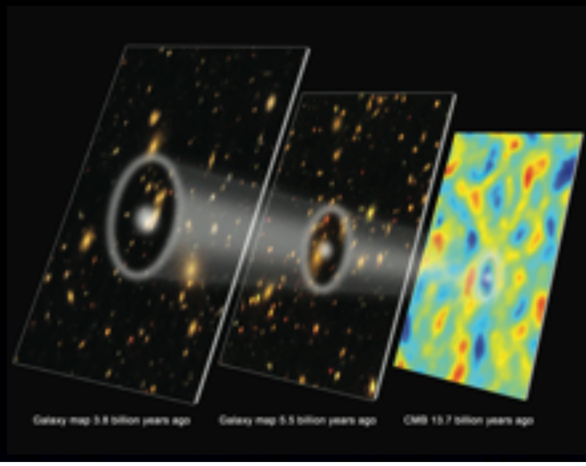
BAO detected at 8sigma in ξ(s) and P(k)

$D_V(z=0.57)=2056\pm20\text{Mpc}$ (1% error)

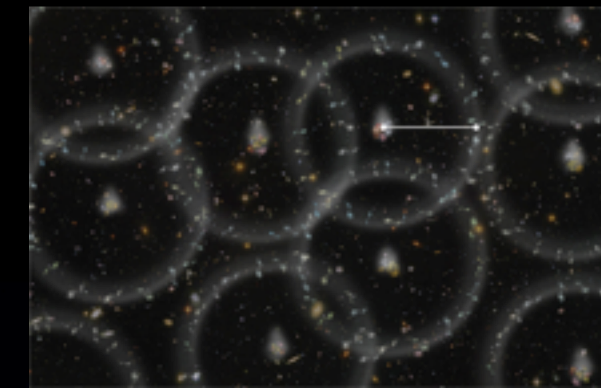


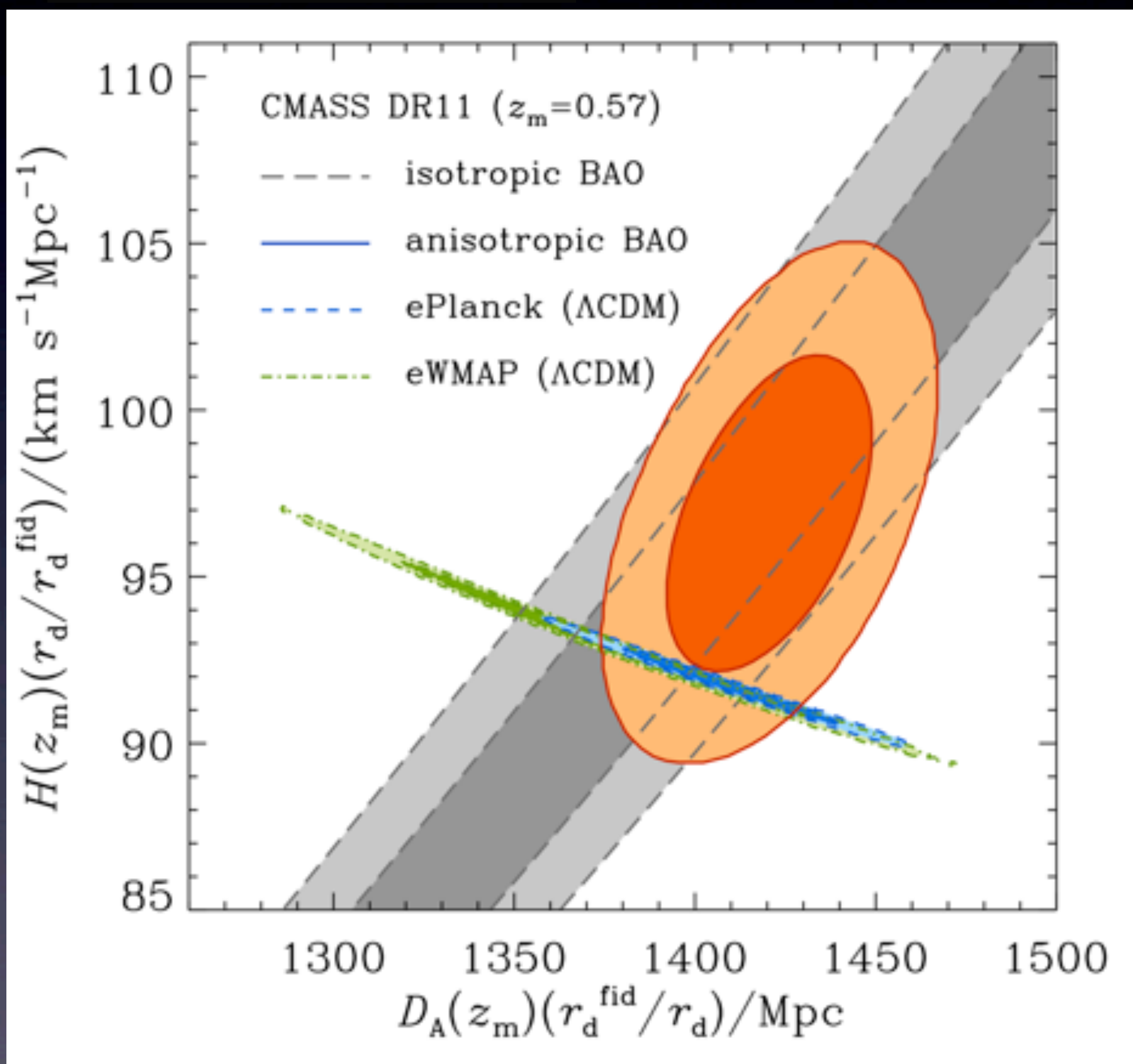
Results do not depend on galaxy color

Ross et al. 2014



Galaxy BAO: CMASS





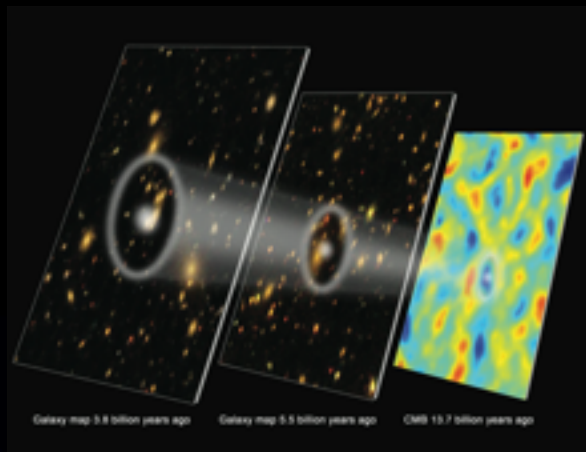
Anderson et al. 2014

Combining the monopole and the quadrupole of ξ(s) we can measure the angular dependence of clustering (with respect to the line of sight)

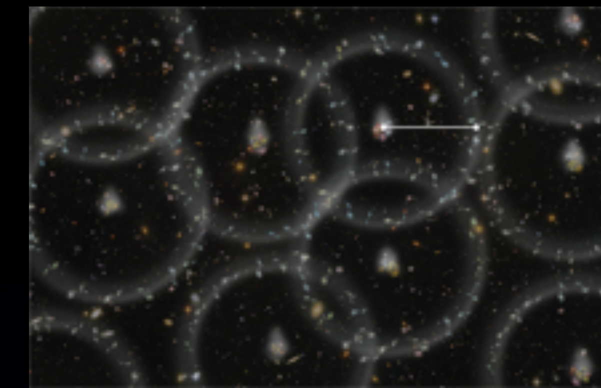
With this we can constrain the angular diameter distance $D_A(z)$ and the Hubble parameter $H(z)$

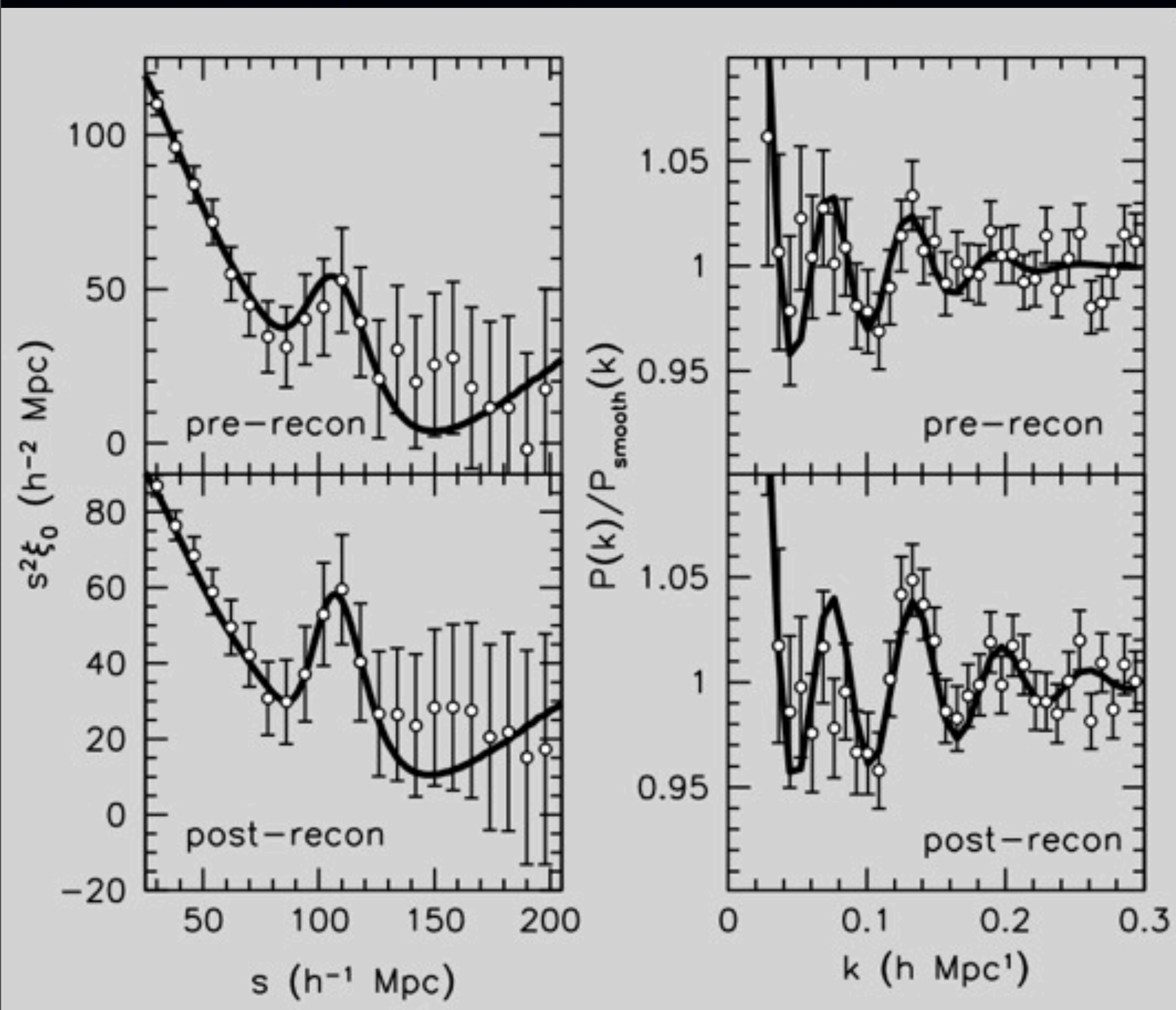
$D_A(z=0.57)=1421\pm20$Mpc

$H(z=0.57)=96.8\pm3.4$km/s/Mpc



Galaxy BAO: LOWZ





314,000 galaxies between $0.15<z<0.43$ covering 3Gpc^3

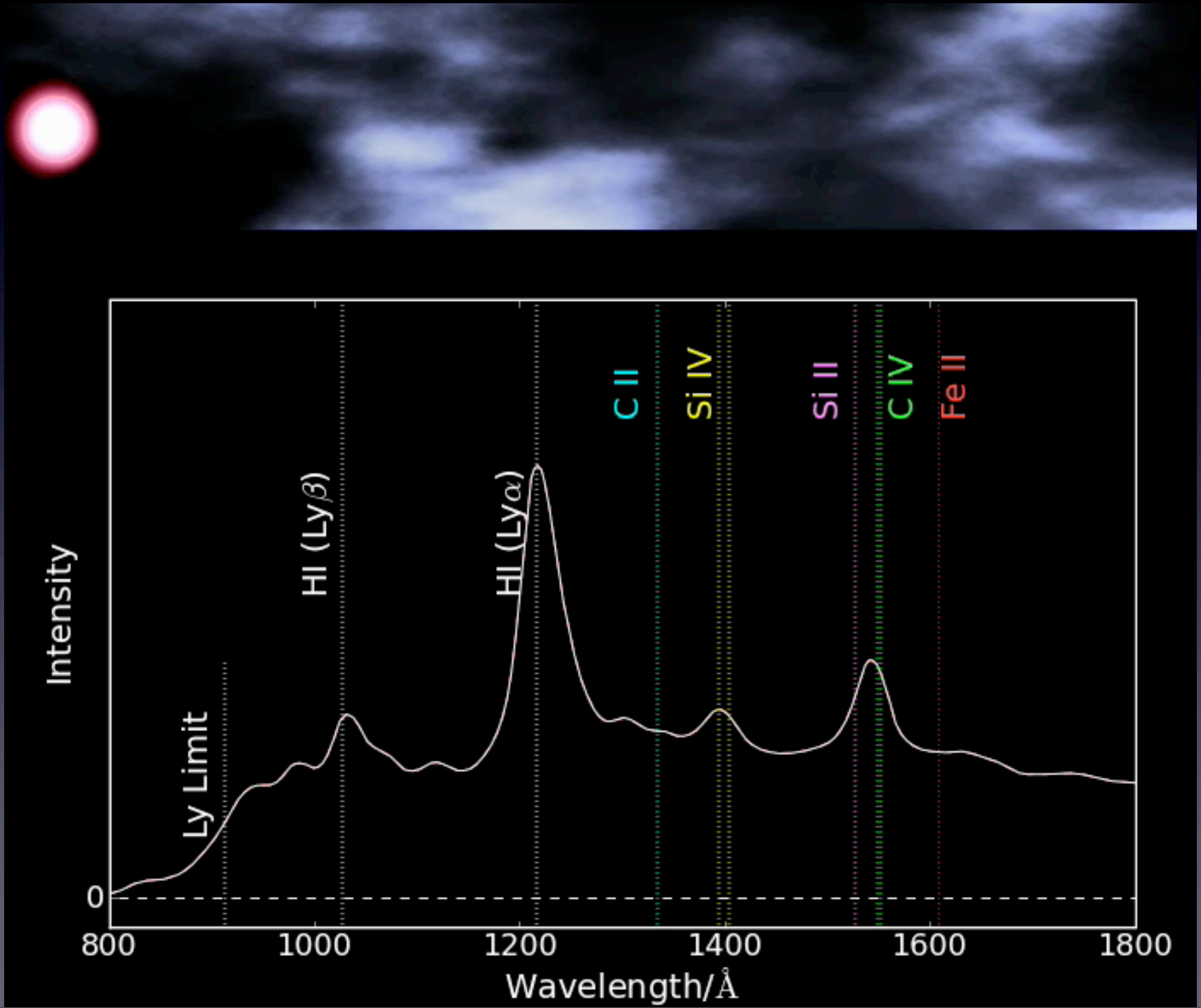
$D_V(z=0.32)=1264\pm25$Mpc

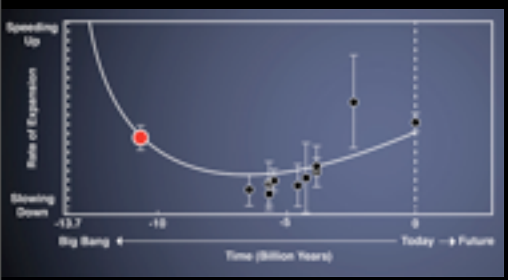
(a 2% measurement)

which is already as good as the SDSS-DR7 LRG result

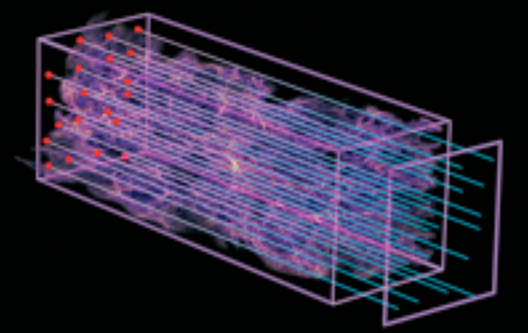
Tojeiro et al. 2014

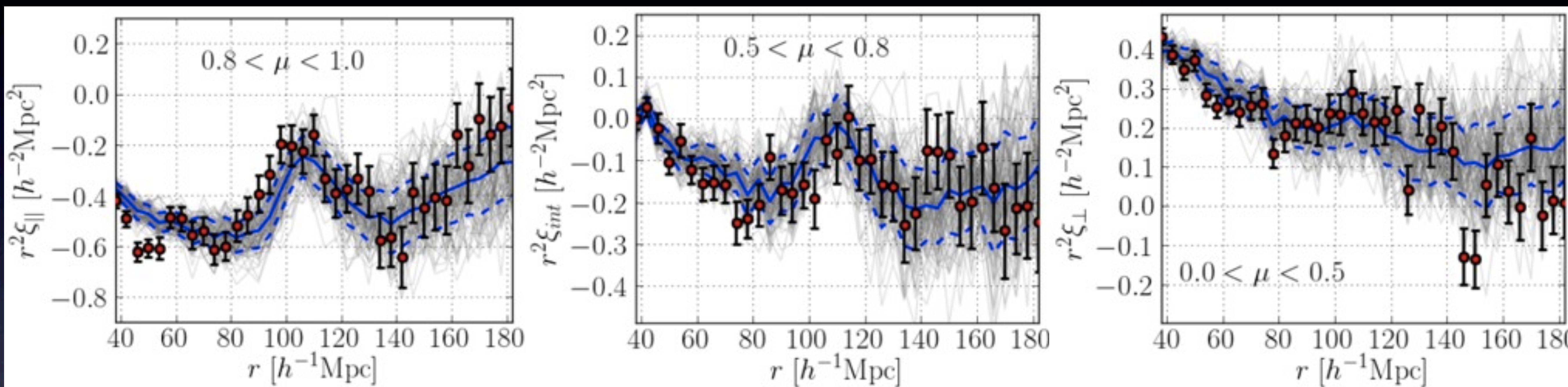
The Lyman-alpha forest





LyaF-LyaF auto-correlation





Delubac et al. 2014

137,500 quasars between 2.1<z<3.5

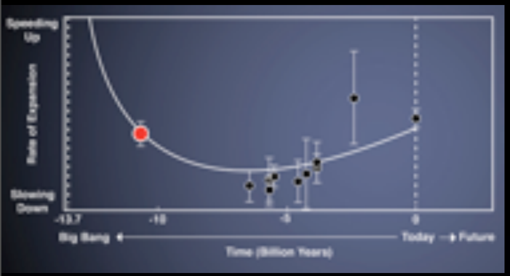
Volume sampled $50h^{-3}$Gpc^3

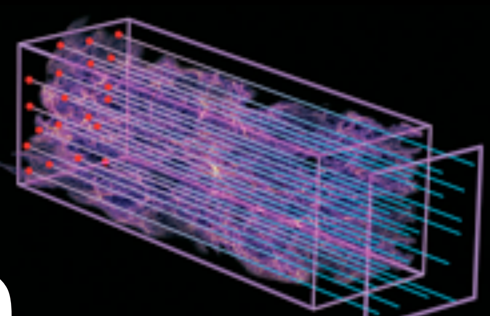
$D_A(z=2.34)=1662\pm96$Mpc

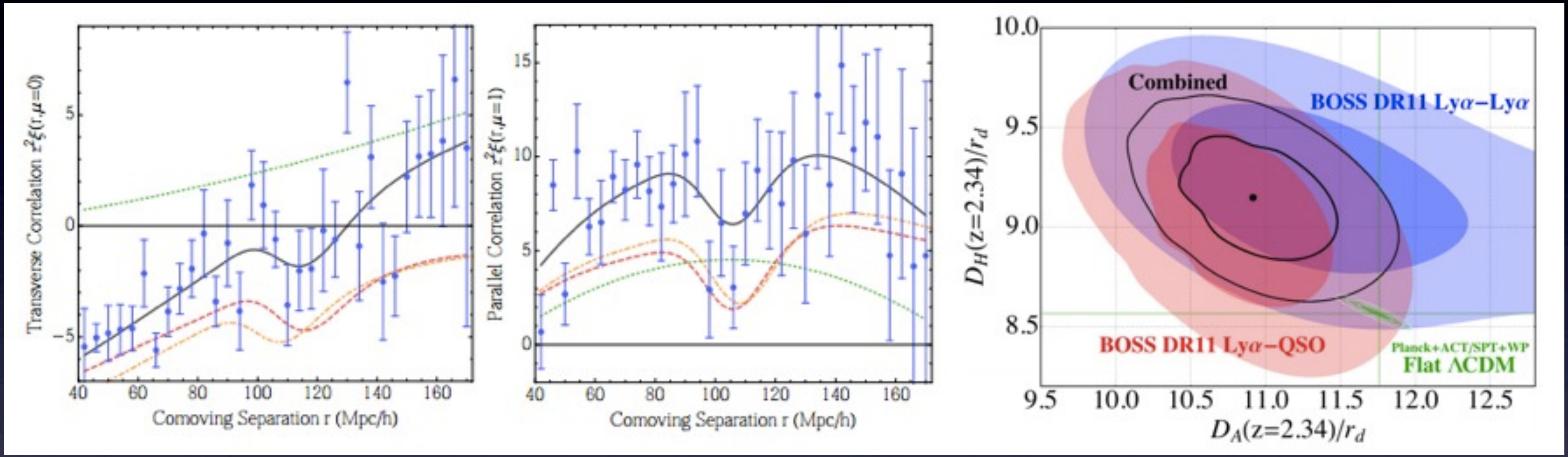
$H(z=2.34)=222\pm7$km/s/Mpc

Most of the signal comes from the line of sight

Quasar-LyaF cross-correlation







Font-Ribera et al. 2014

164,000 quasars between $2.0<z<3.5$
(of which 131,000 are in the LyA sample)

$D_A(z=2.34)=1590\pm60$Mpc

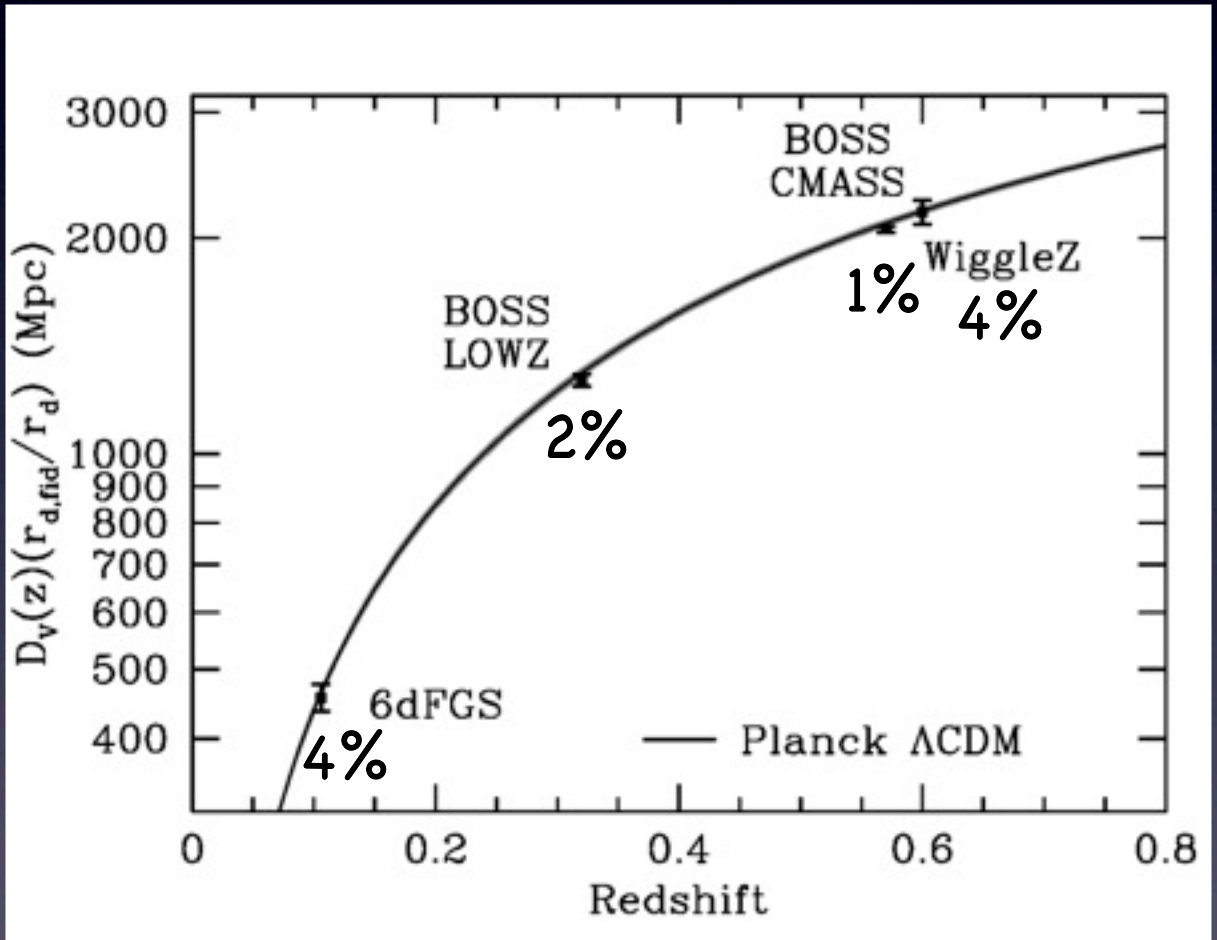
$H(z=2.34)=226\pm8$km/s/Mpc

(the error bar in D_A is 40% smaller than auto-corr)

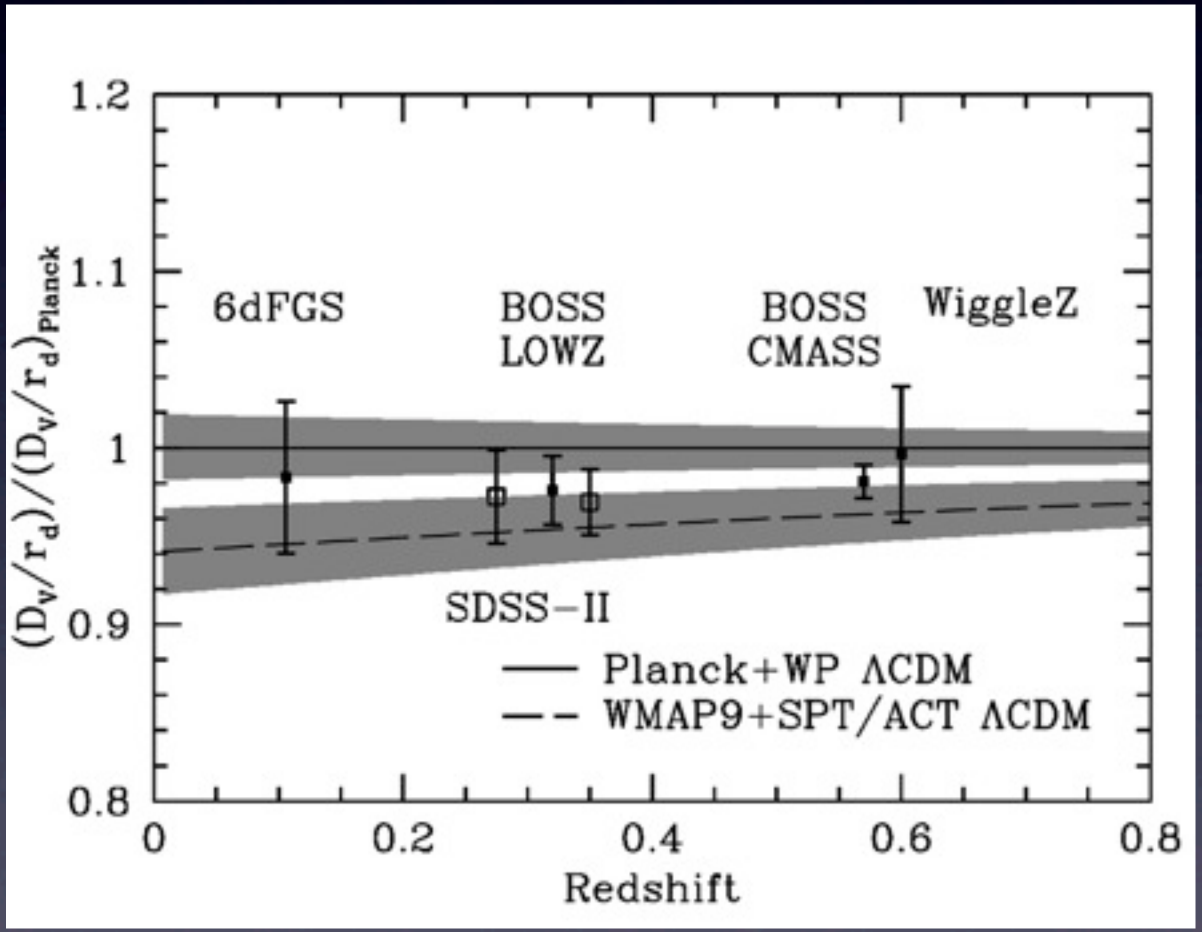
Cosmological Implications from BAO Distance Measurements

BAO Distance Measurements

Distance-redshift relation



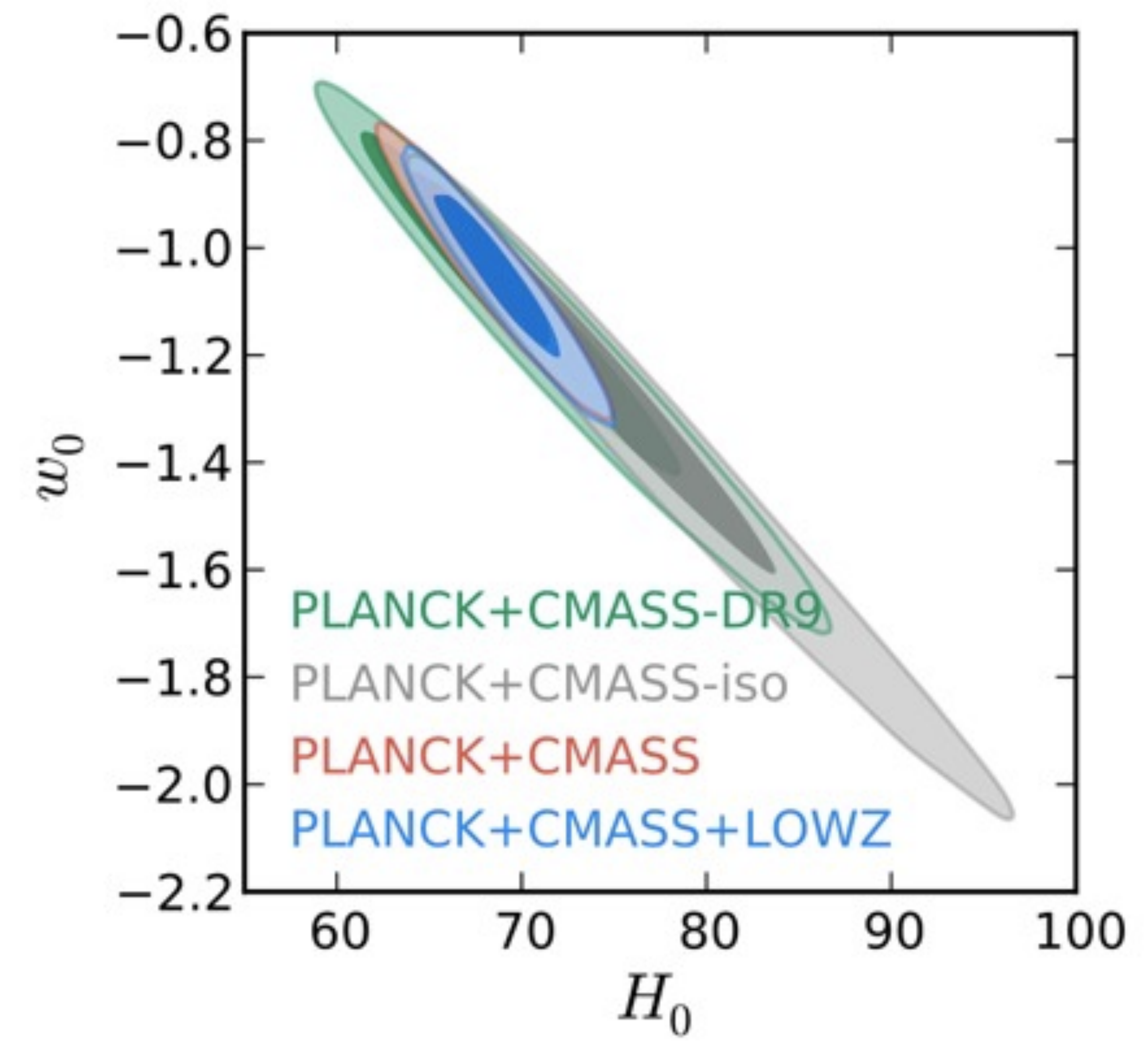
Normalized to Planck

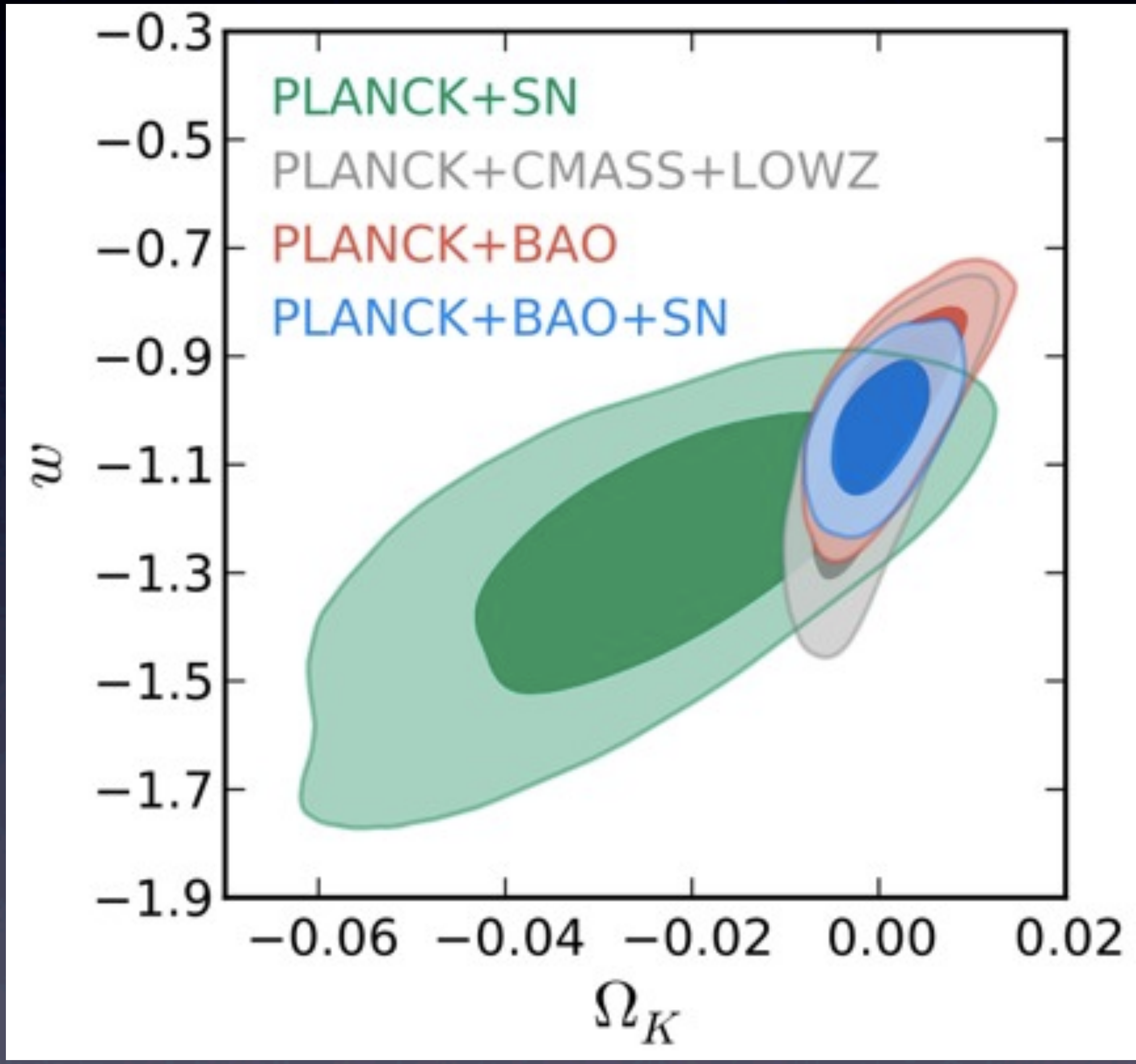


Anderson et al. 2014

Not any arbitrary expansion history can go through these data points!

Cosmological constraints on curvature and dark energy





The CMASS+LOWZ samples combined with Planck+SN are able to constrain curvature Ω_k to 3 parts in 1,000 and the equation of state of dark energy w by 7%

Conclusions

- BAO is a geometrical technique to probe the distance-redshift relation (i.e. the expansion history of the Universe) with high precision.
- The "standard ruler" for BAO is well measured by the CMB.
- Reconstruction techniques help reduce the error bar in BAO distances.
- The BAO feature has been measured in the clustering of galaxies, as well as in the distribution of neutral gas in the intergalactic medium.
- BOSS has measured distances to redshifts z=0.32 (2%), 0.57 (1%), and 2.34 (4%)
- The combination of BAO + CMB + SNe places strong constraints on the spatial curvature of the Universe and the equation of state of dark energy.

Thanks for your attention