Baryon Acoustic Oscillations

Jim Rich

SPP-IRFU
CEA-Saclay
91191 Gif-sur-Yvette

james.rich@cea.fr

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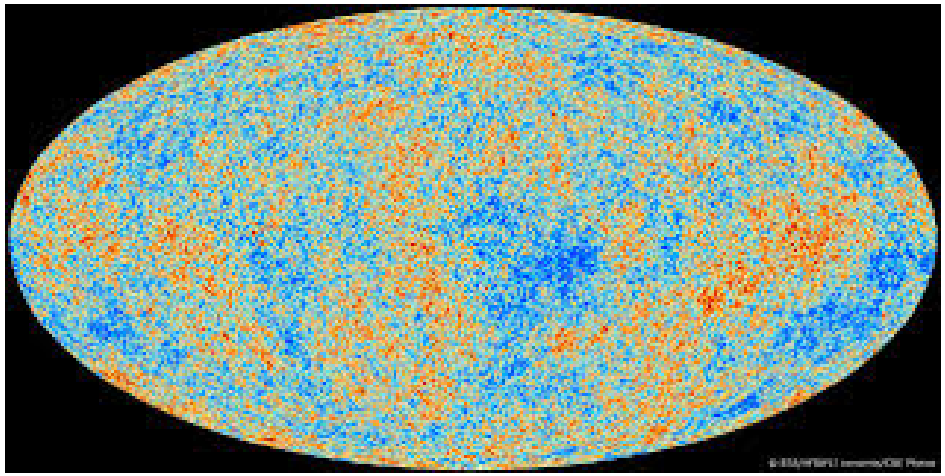
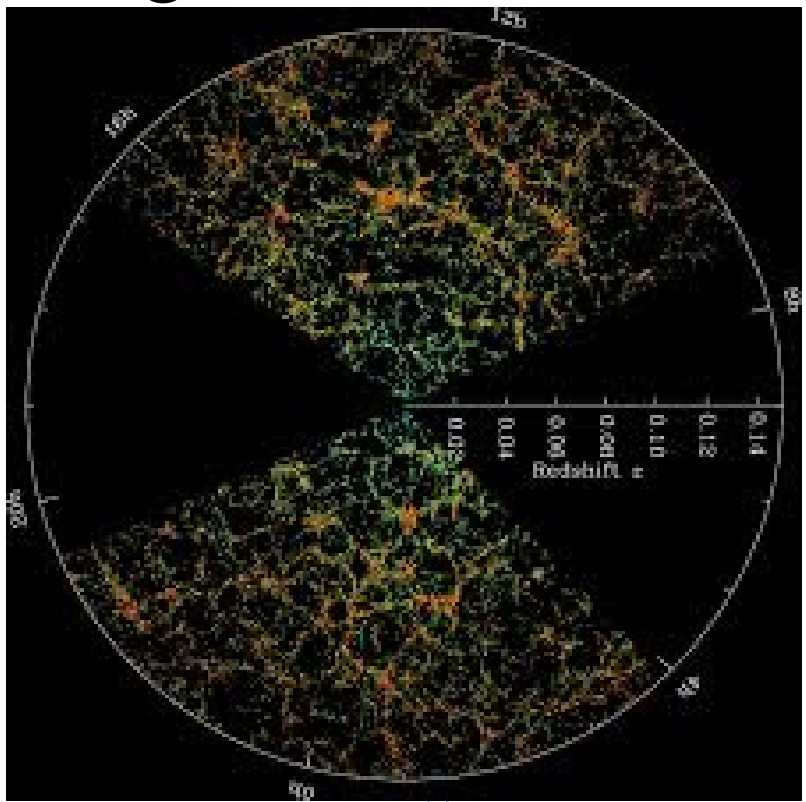
Baryon Acoustic Oscillations=BAO

Acoustic oscillations in pre-recombination universe imprinted on

CMB anisotropies & Large-Scale Structure

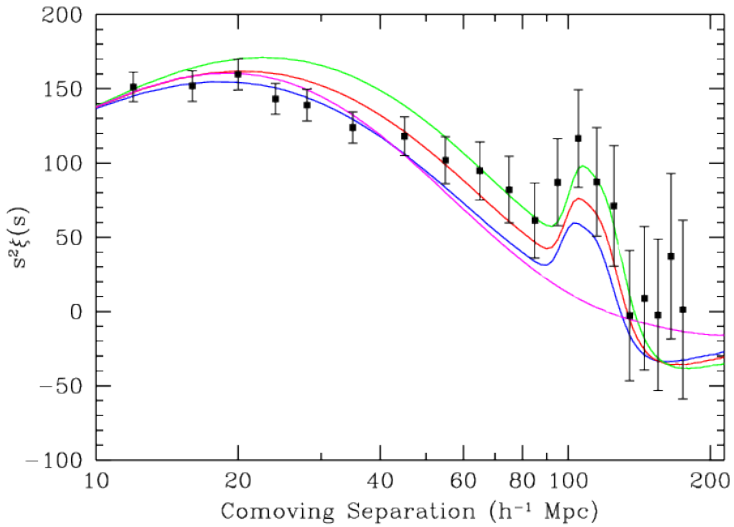




Outline

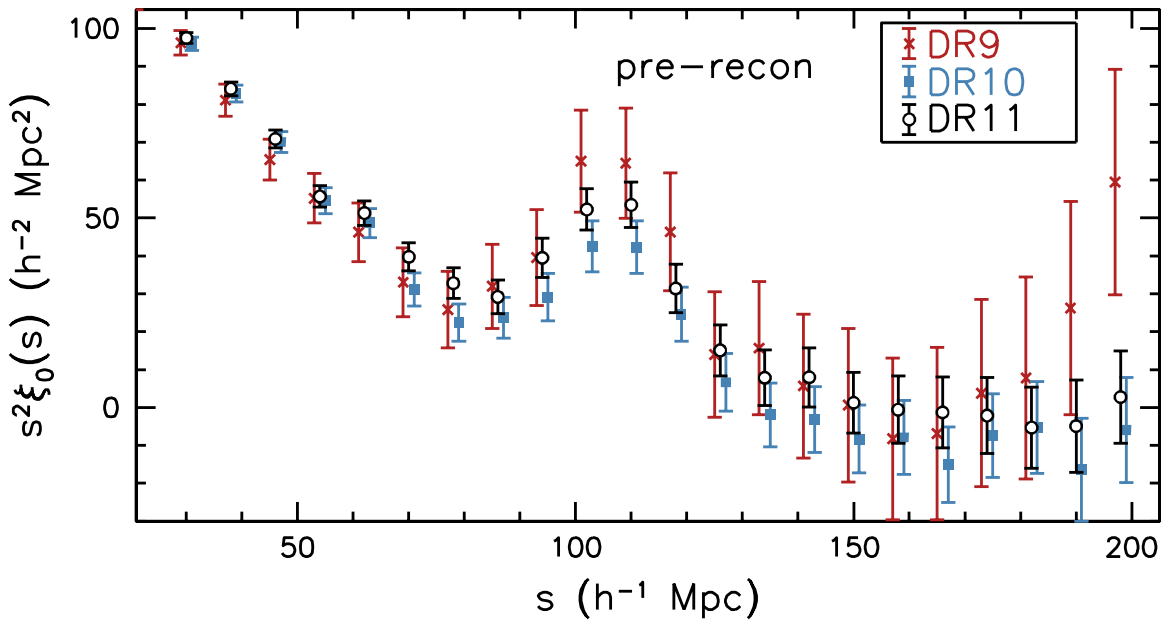
- Physics
- BOSS = Baryon Oscilltion Spectroscopy Survey (of SDSS-3)
- Present data
- Determination of cosmological parameters
- The future

BAO Peak in galaxy correlation function



SDSS (2006)

SDSS-BOSS (2014)



Galaxies like to be separated by 105Mpc/h (147.5Mpc).

Acoustic waves $\Leftrightarrow$ $\sim$perfect fluids

"perfect fluid": mean-free-path of particles much less than spatial extent of perturbation.

Early universe:

WIMPS: $\lambda_{mfp} \gg c/H(z)$ $\Rightarrow$no waves

photon-electron-proton plasma: $\lambda_{mfp} \ll c/H(z)$

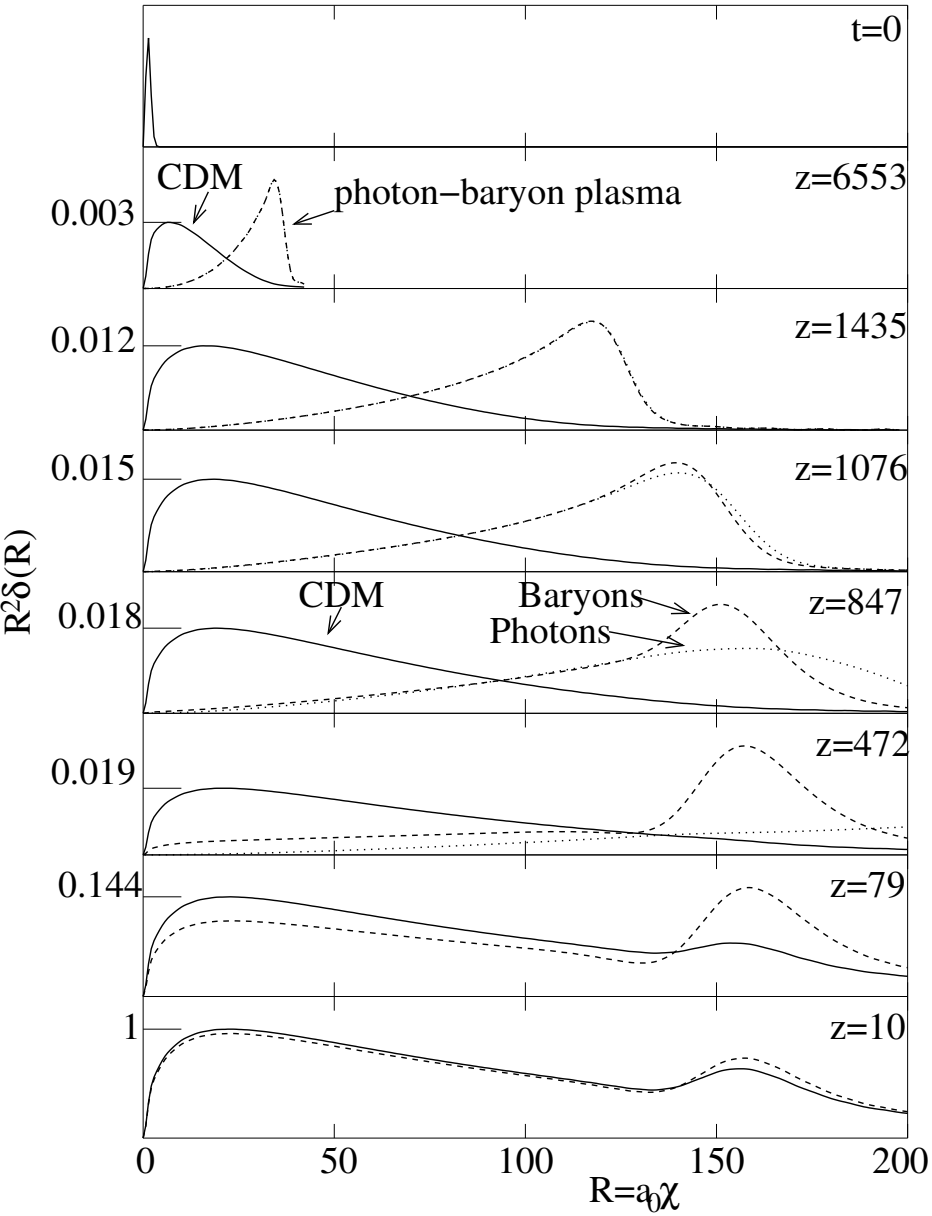
electron-photon (Compton) scattering + electron-proton (Coulomb) scattering.

$\Rightarrow$ plasma supports acoustic waves until recombination.

$$c_s^s = \left(\frac{dP}{d\rho}\right)_{\text{adiabatic}} \sim \frac{c^2}{3}$$

(since ρ is dominated by photons with $P = \rho/3$.)

A Universe with one perturbation



$t = 0$

$c_s \sim c/\sqrt{(3)}$
(γ,p,e plasma)

Wave stops at recombination
($r \sim 150\mathrm{kpc}$)

Today: Enhanced correlation
at $r = 147.5\mathrm{Mpc}$

Guesstimate of the sound horizon, r_d

$c_s \sim c/\sqrt{3}$ (relativistic plasma: $c_s^2 = p/\rho \sim 1/3$)

Age of universe at recombination $\sim$ 380000yr

$\Rightarrow r_d \sim 3.8 \times 10^5 \text{ly}/\sqrt{3}$ (at recombination, $z \sim 1060$)

$\sim$ 100kpc (at recombination, $z \sim 1060$))

$\sim$ 100Mpc (today)

Calculation of the sound horizon

Same as "particle horizon" except $c_s < c$
$c_s = (c/\sqrt{3}) f(\rho_{\rm B}/\rho_\gamma)$ (baryon inertia slows sound)

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)dz}{H(z)} = \sqrt{\frac{3}{8\pi G}} \int_{z_d}^{\infty} \frac{c_s(z)dz}{\sqrt{\rho_{\rm M} + \rho_\gamma + \rho_\nu}}$$

We normalized to the present photon density

$$r_d = \sqrt{\frac{3}{8\pi G \rho_\gamma(0)}} \int_{z_d}^{\infty} \frac{c_s(\rho_{\rm B}/\rho_\gamma)dz}{(1+z)^2\sqrt{\rho_{\rm M}/\rho_\gamma + 1 + \rho_\nu/\rho_\gamma}}$$

COBE gives us $\rho_\gamma(0)$ and the CMB spectrum shape (Planck) gives us the density ratios $\rho_{\rm M}/\rho_\gamma$, $\rho_{\rm B}/\rho_\gamma$, ρ_ν/ρ_γ.

r_d from COBE-Planck

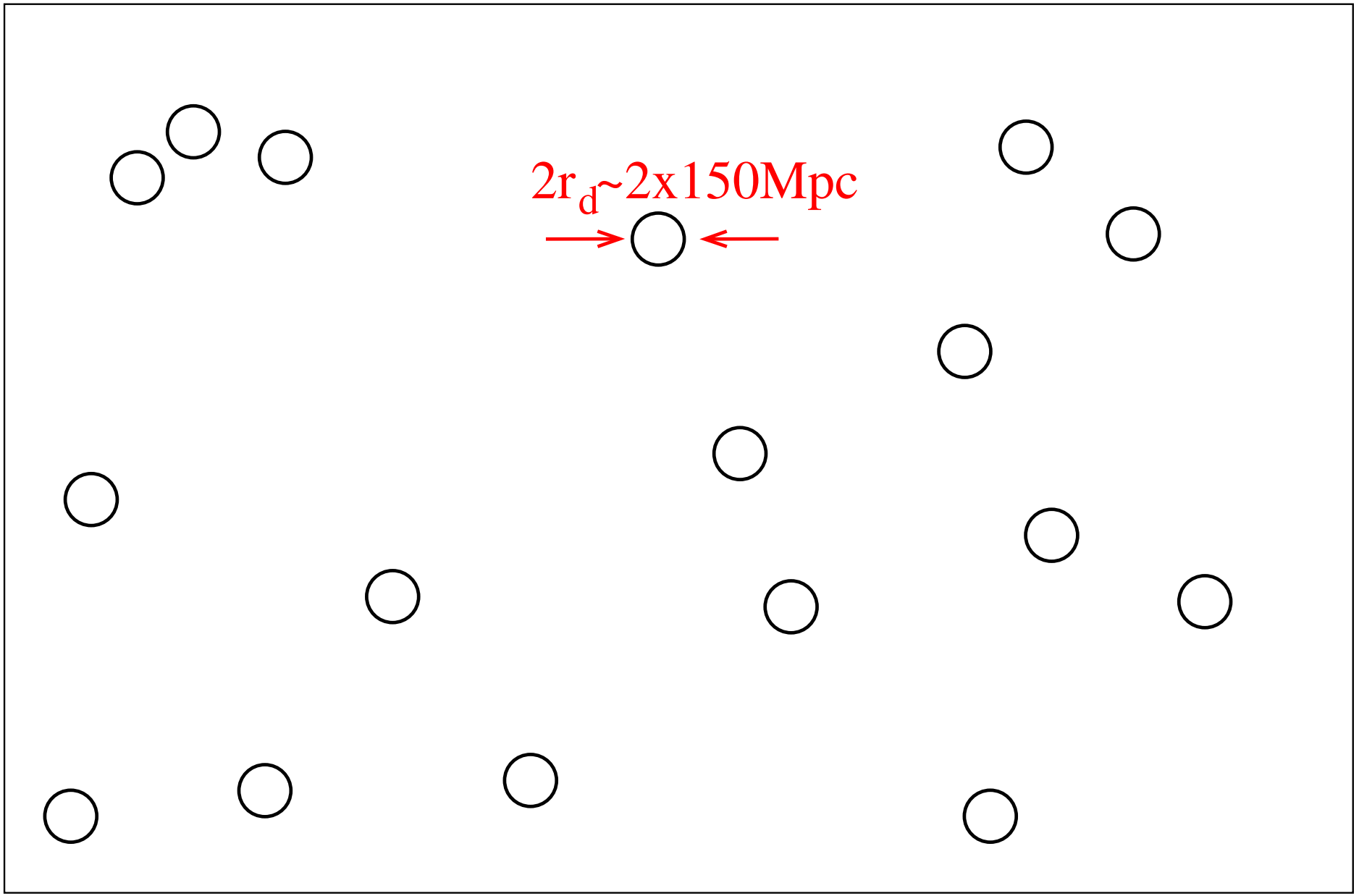
Imposing three neutrino families ($\rho_\nu = 0.23 N_\nu$) gives

$$r_d = (147.5 \pm 0.6)\mathrm{Mpc}$$

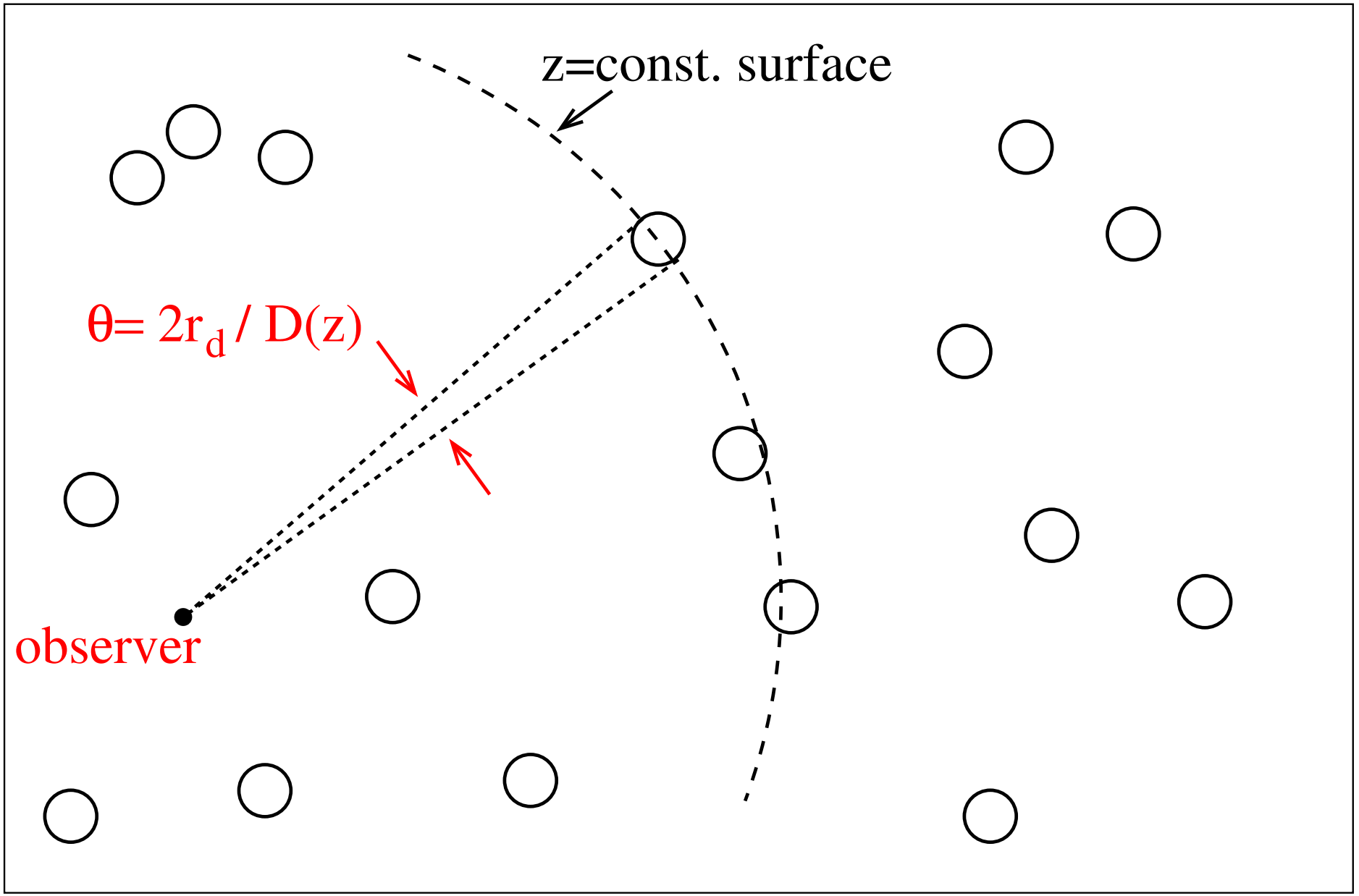
Fitting the CMB spectrum for N_ν gives $N_\nu = 3.36 \pm 0.7$ and

$$r_d = (143.4 \pm 3.1)\mathrm{Mpc}$$

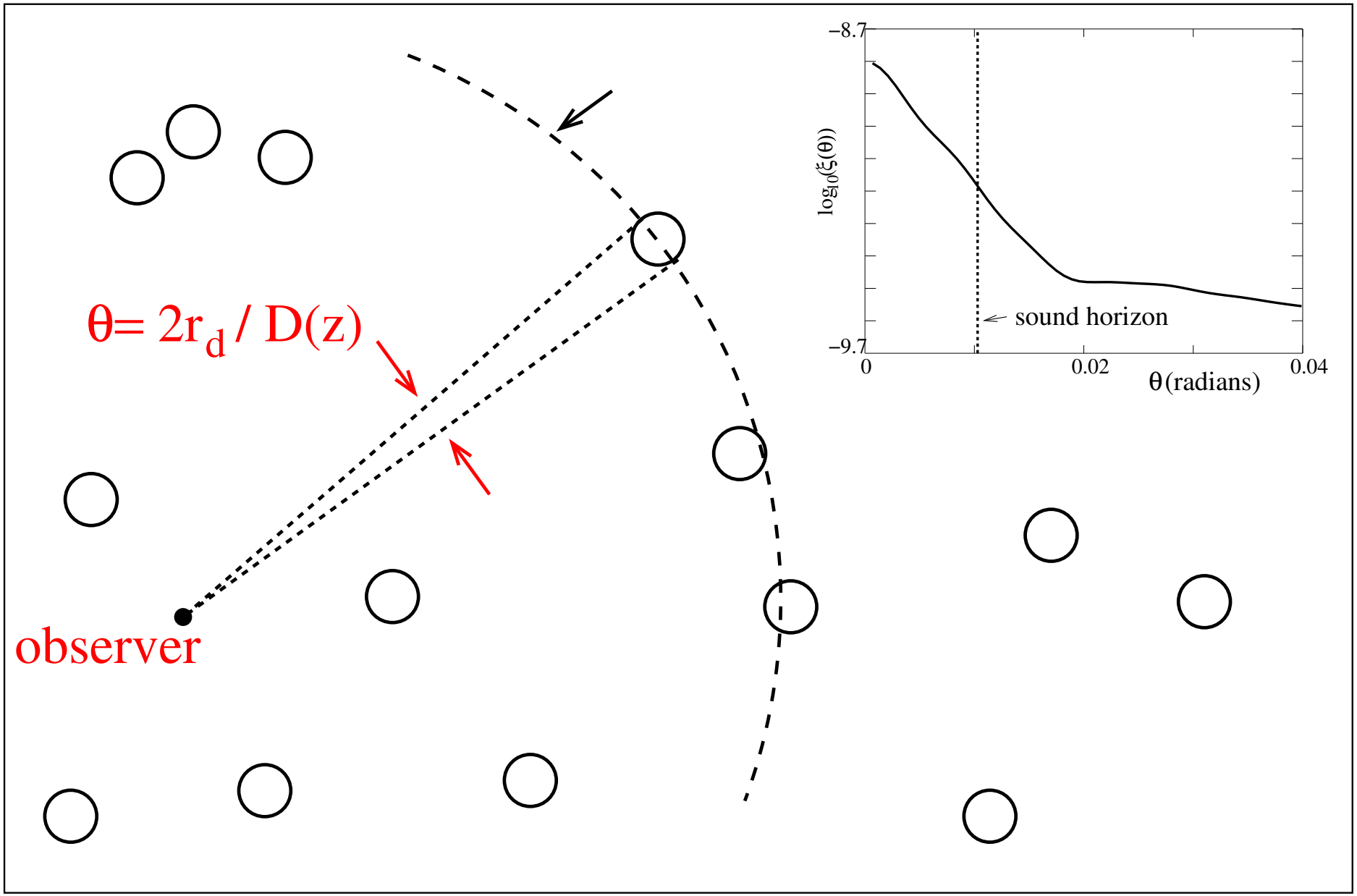
A universe with spherical structures:



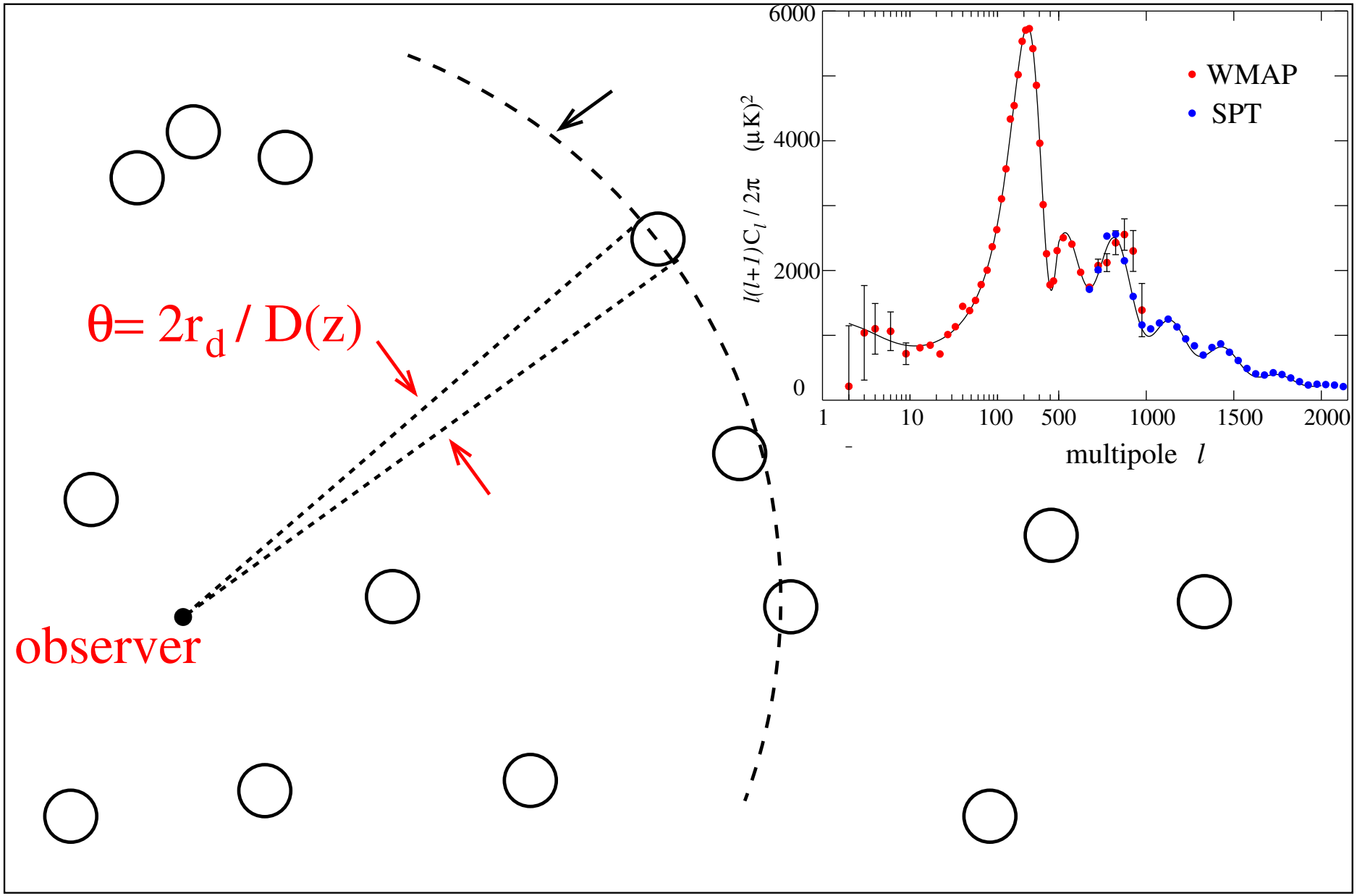
An Observer looking at redshift$= z$



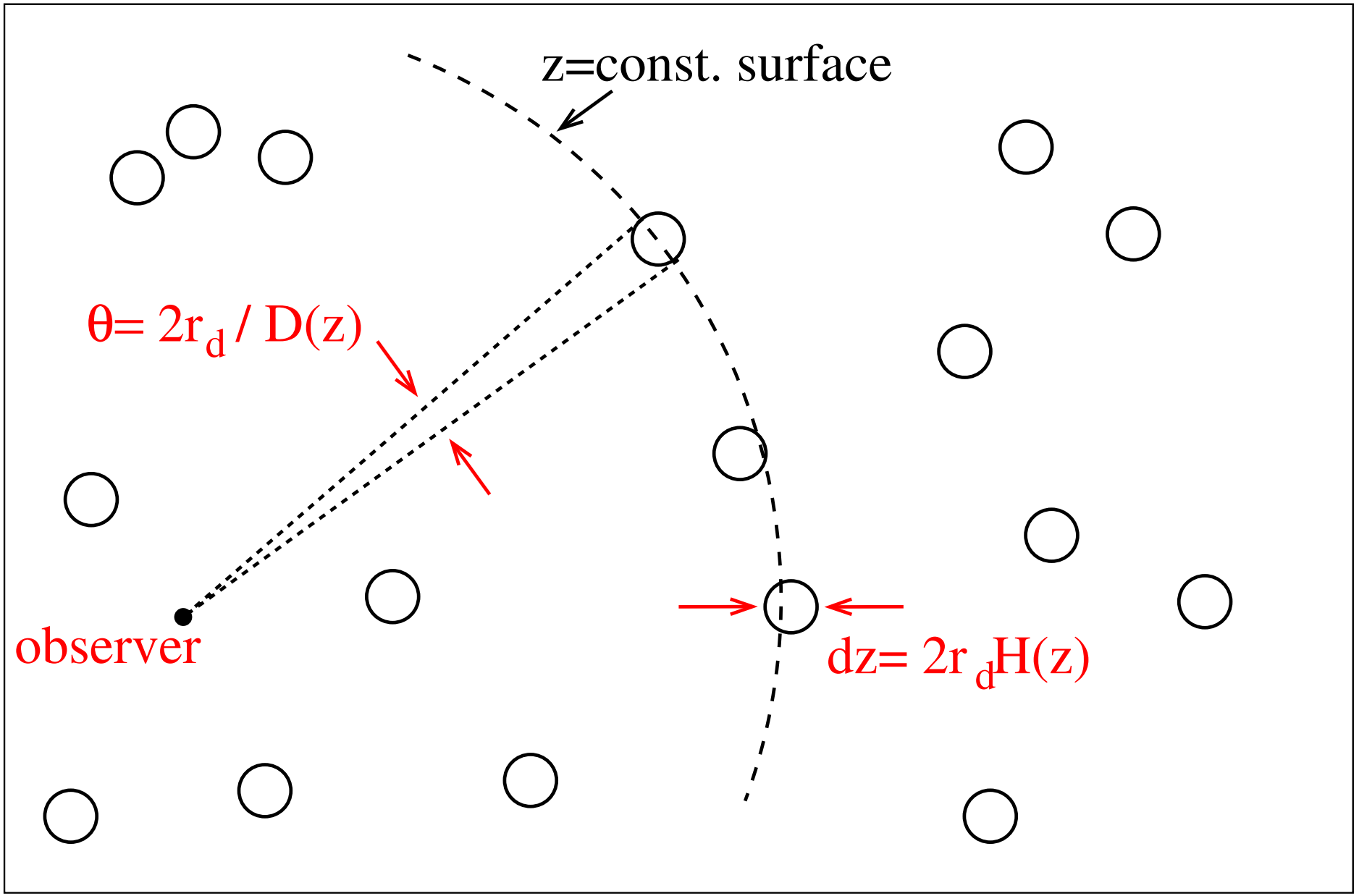
$z = 1090 \Rightarrow$CMB correlated $\theta < 2r_s/D$



Fourier Magic



Redshift surveys $\Rightarrow$ radial correlations



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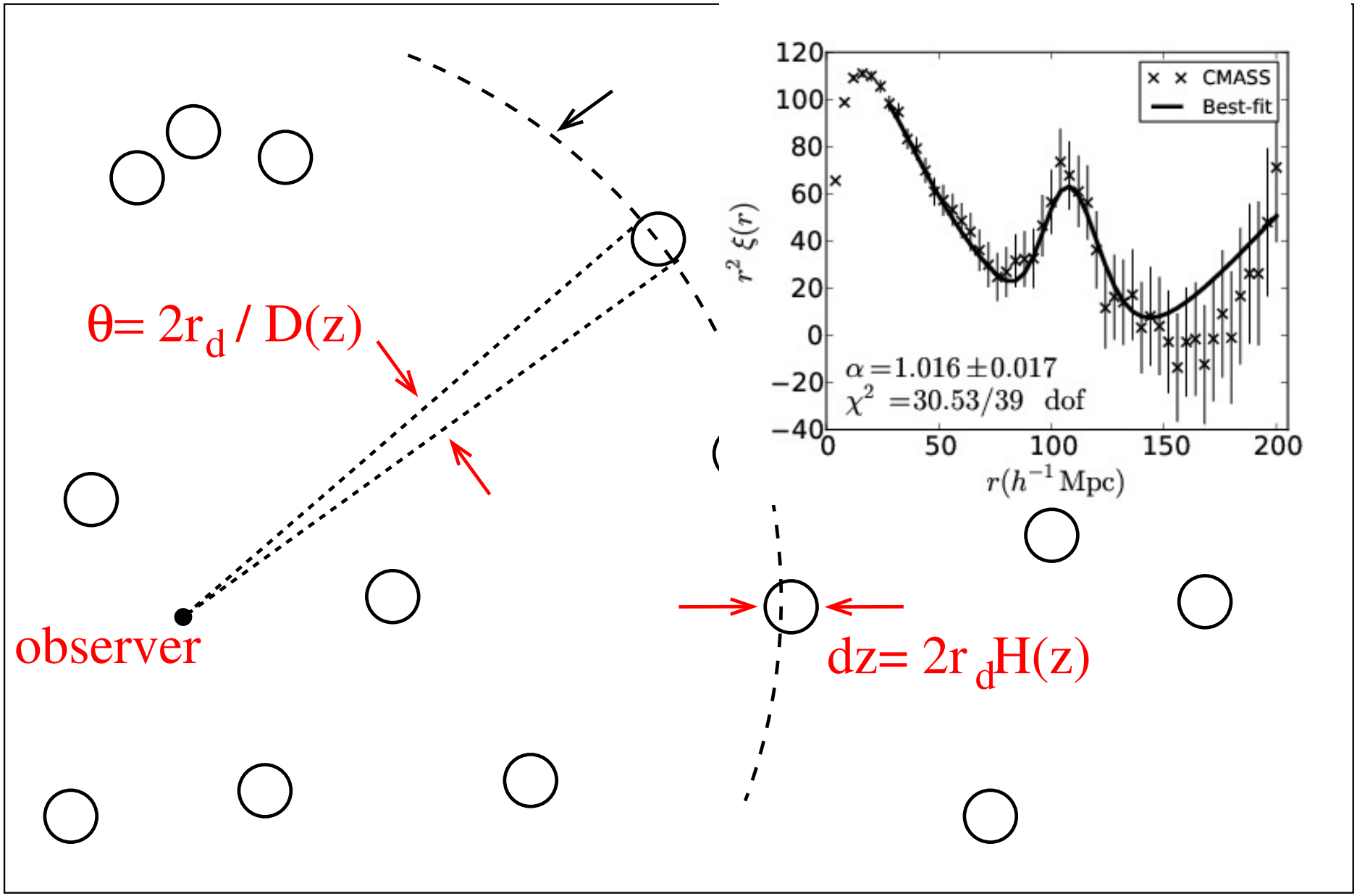


The best measurements of D/r_d

- z=0.57 (BOSS) Anderson et al (2013) D_V 1.0%
  Anderson et al (2013) D_A 3%, H^{-1} 8%
  Kazin et al (2013) D_A 3%, H^{-1} 7%
- z=0.35 (SDSS)Padmanabhan et al (2012) D_V 2%
  Xu et al (2013) D_A 4%, H^{-1} 9%
  Chuang et al (2013) D_A 6%, H^{-1} 7%
- z=0.27 (SDSS,2dF) Percival et al (2010) D_V 2.7%
- z=0.106 (6dF) Beutler et al (2011) D_V 6%
- z=2.3 (BOSS) Delubac et al (2014) D_V 2.5%
  D_A 8%, H^{-1} 4%
- z=1070 (Planck) Ade et al (2013) D_A 0.1%

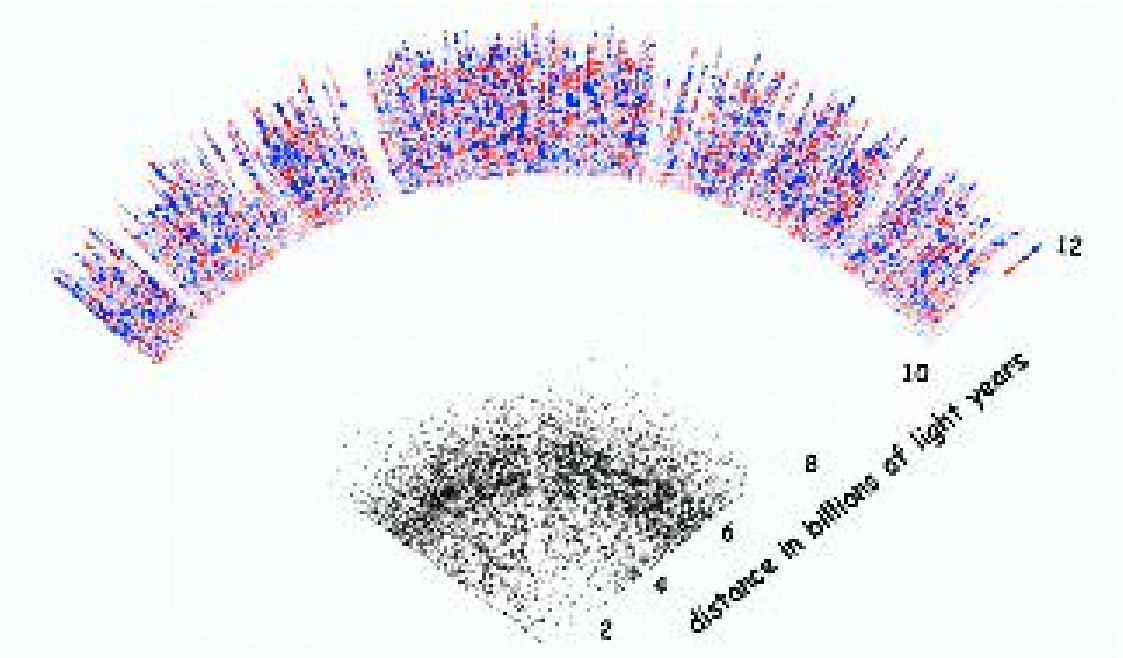
SDSS

Sloan 2.5m telescope
Apache Peak Observatory

1000 fibers connect
$7 deg^2$ focal plane
to spectrograph

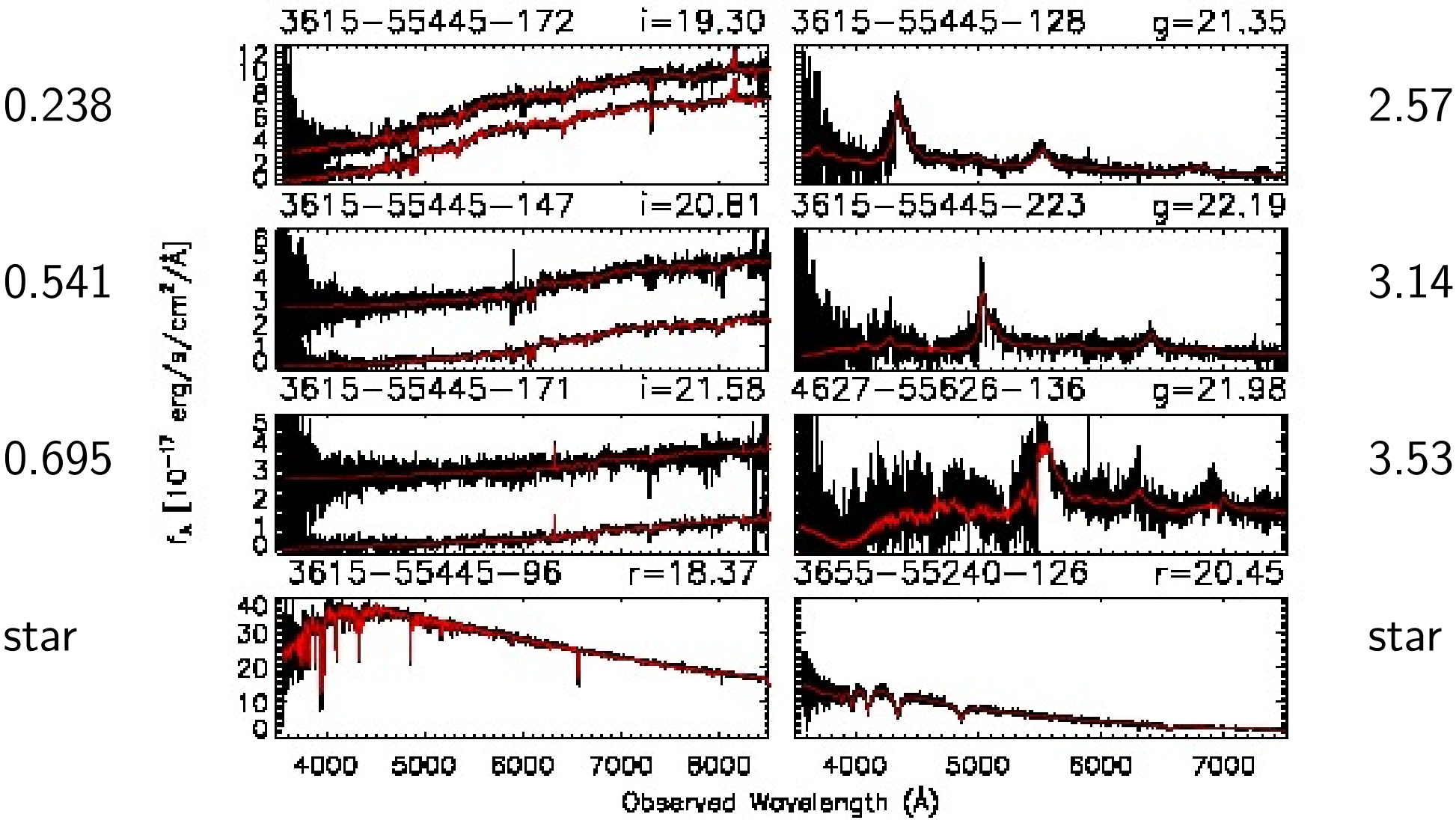
SDSS-BOSS: 2009-2014

Map of matter density using galaxies ($z \sim 0.6$) and atomic hydrogen ($z \sim 2.3$) (Lyα forest of quasars)



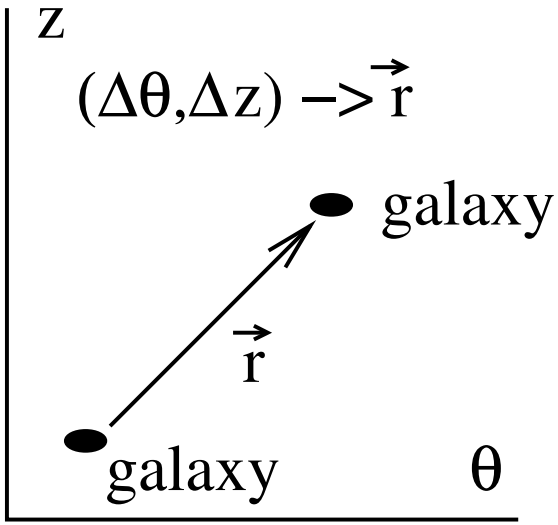
1.6×10^6 galaxies ($0.3 < z < 0.8$)
1.5×10^5 quasars ($z > 2$)
$\sim \pi$sr on sky

some BOSS spectra



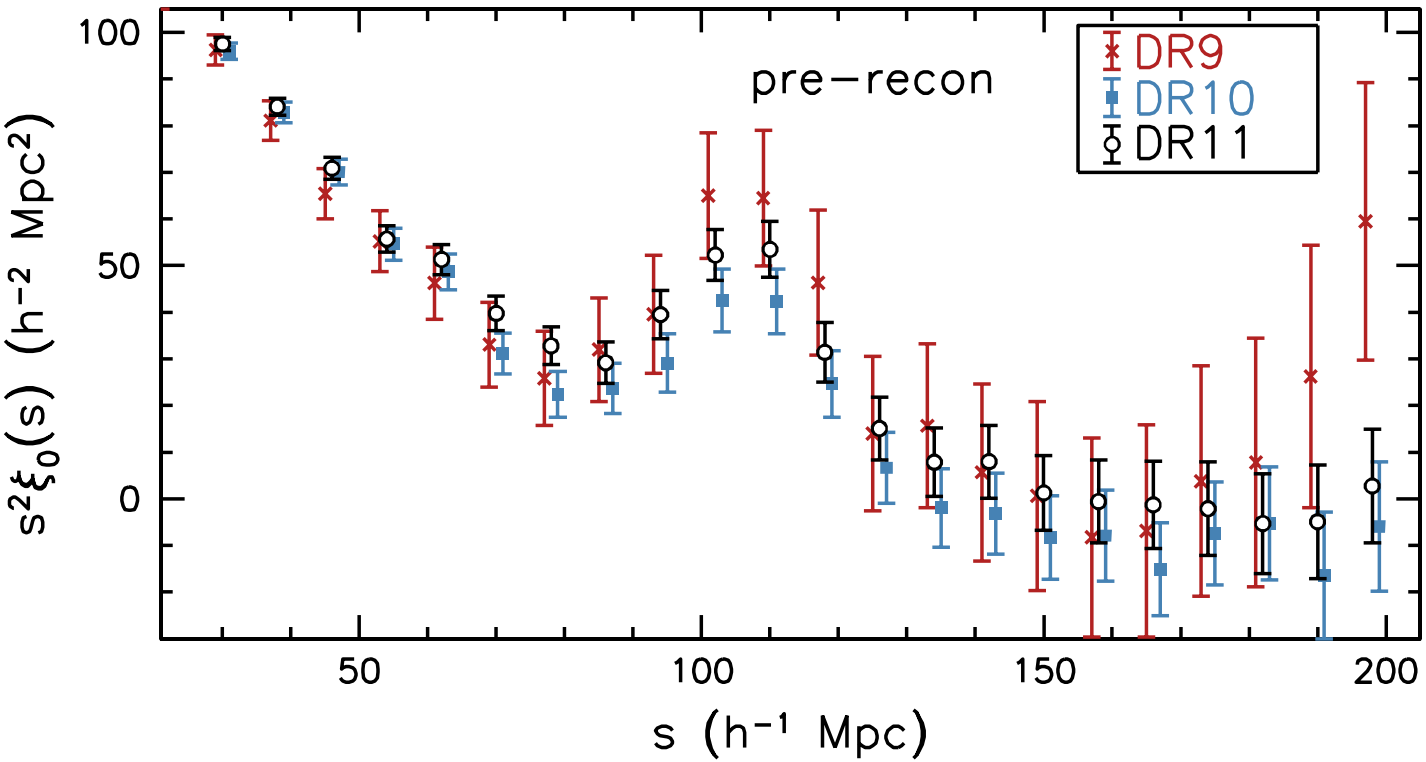
Galaxy Correlation function

1.Select galaxy candidates from SDSS photometry
2.Obtain spectrum $\Rightarrow$ galaxy/quasar/star and redshift
3.For galaxy pairs, calculate $\vec{r}$ from fiducial cosmology



4.Count pairs in $\vec{r}$ bins
5.compare with random $\Rightarrow \xi(\vec{r})$
6.Verify that BAO peak is at fiducial position. If not, change model.

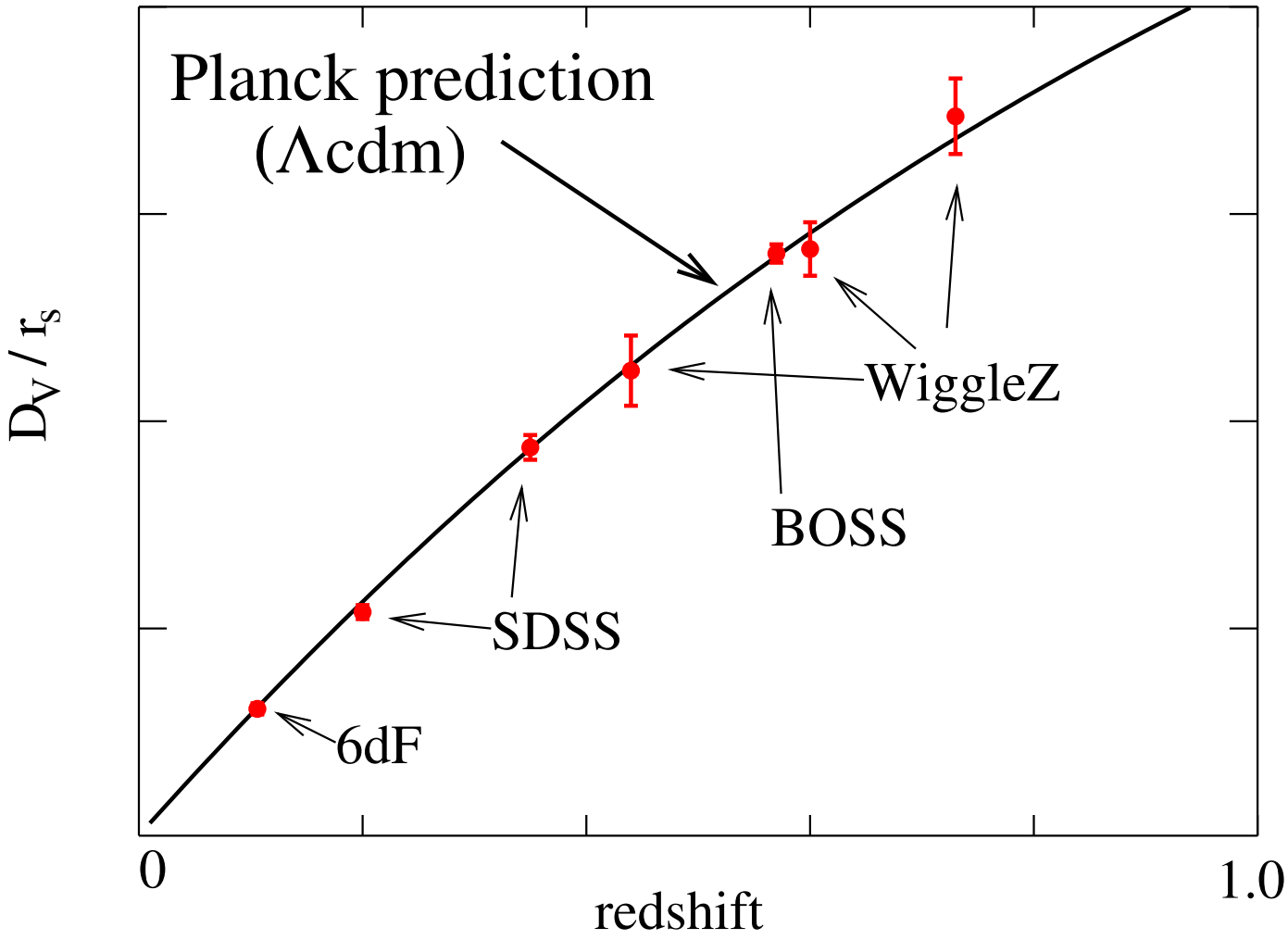
BOSS data at $z \sim 0.57$; arXiv:1312.4877



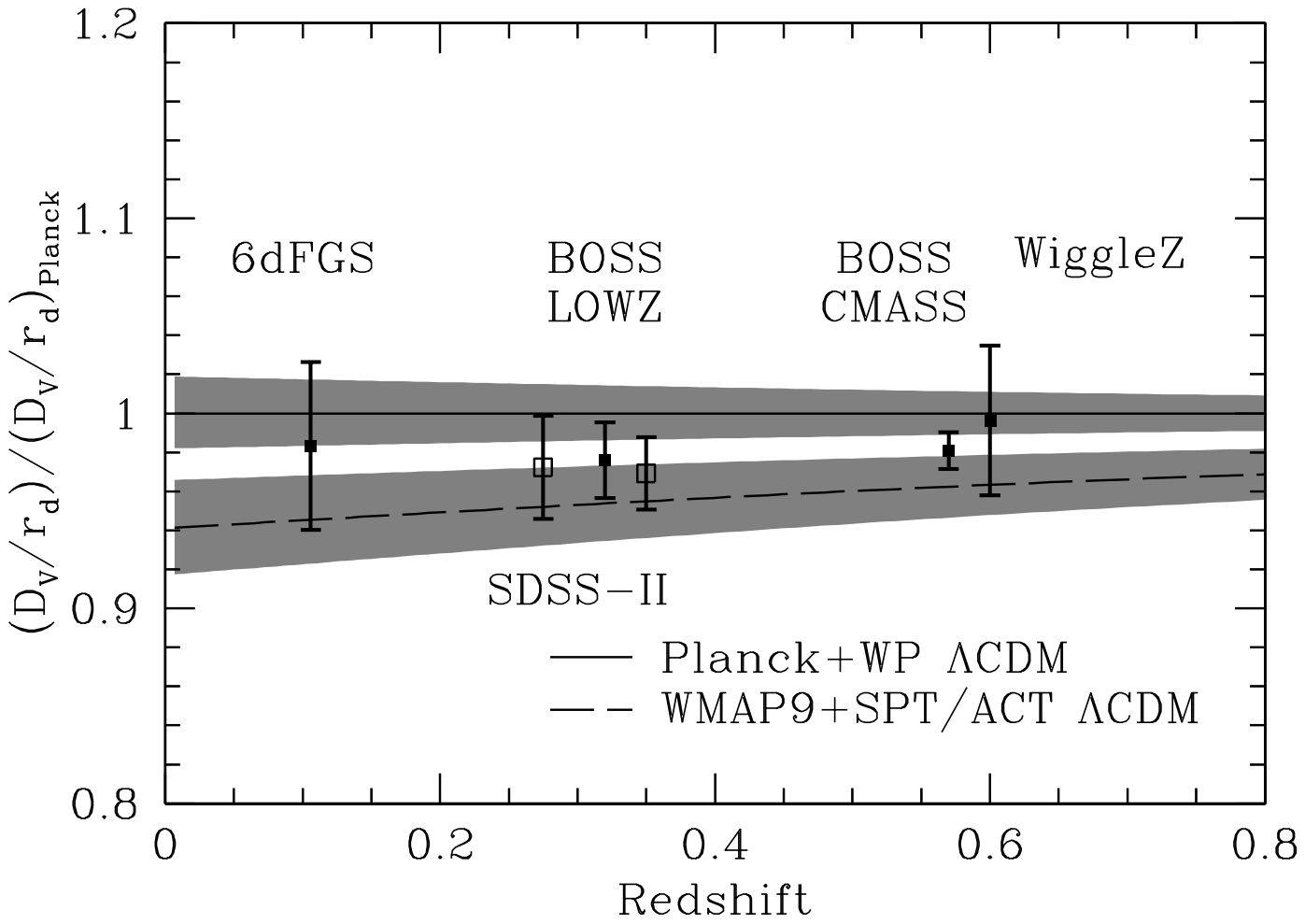
BAO peak is at position predicted by fiducial model, flat $\Lambda\mathrm{CDM}(\Omega_\mathrm{M}, h) \sim (0.27, 0.7)$.
$\Rightarrow (D_A(z = 0.57)/r_d, H(z = 0.57)r_d)$ are near values predicted by fiducial model.

$D_V(z)/r_s$

For angle-averaged analyses, combine $D_A(z)/r_d$ and $H(z)r_d$ to D_V/r_d, $D_V^3 \propto D_A^2/H$

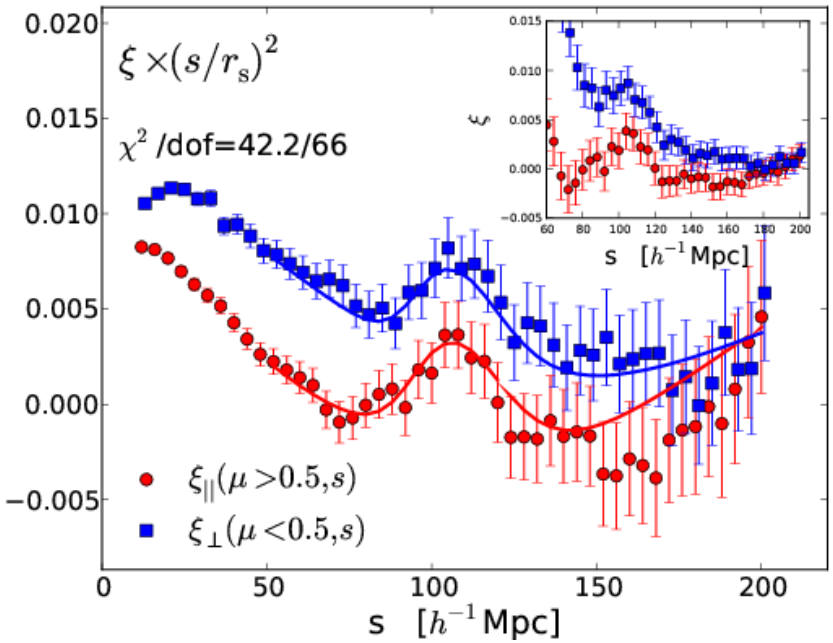


$D_V(z)/r_d$ vs. CMB-inspired flat ΛCDM models



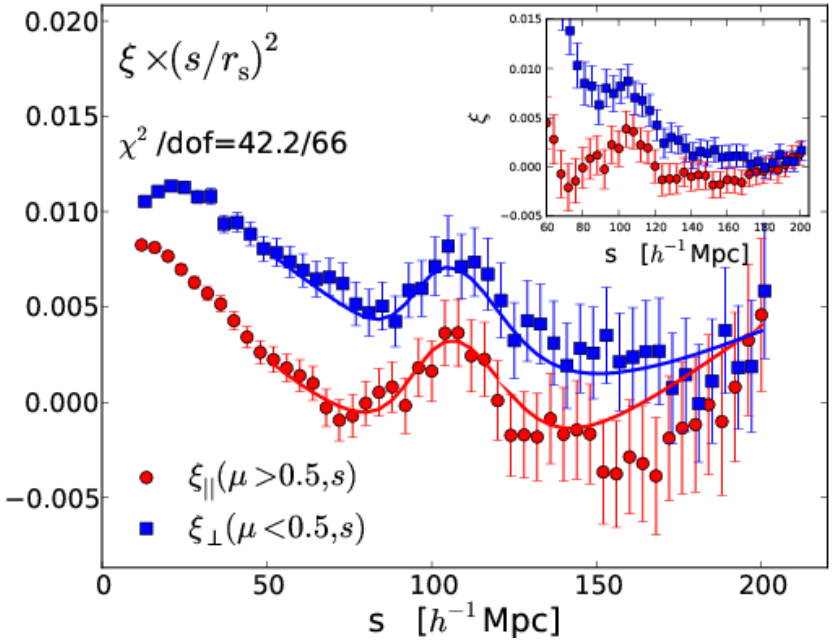
Sight "tension"

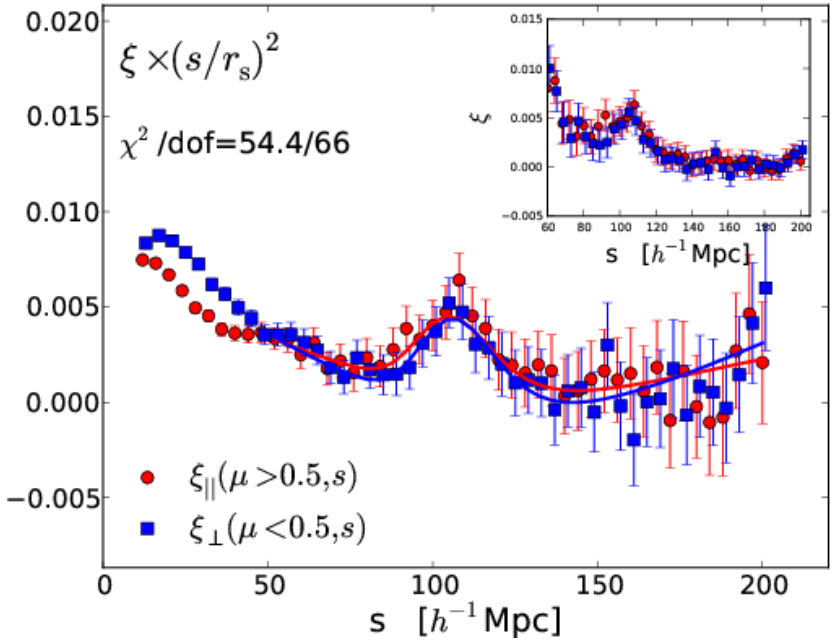
Transverse and Radial Correlations $\Rightarrow D_A(z)$, $H(z)$



"before reconstruction"

Transverse and Radial Correlations $\Rightarrow D_A(z)$, $H(z)$



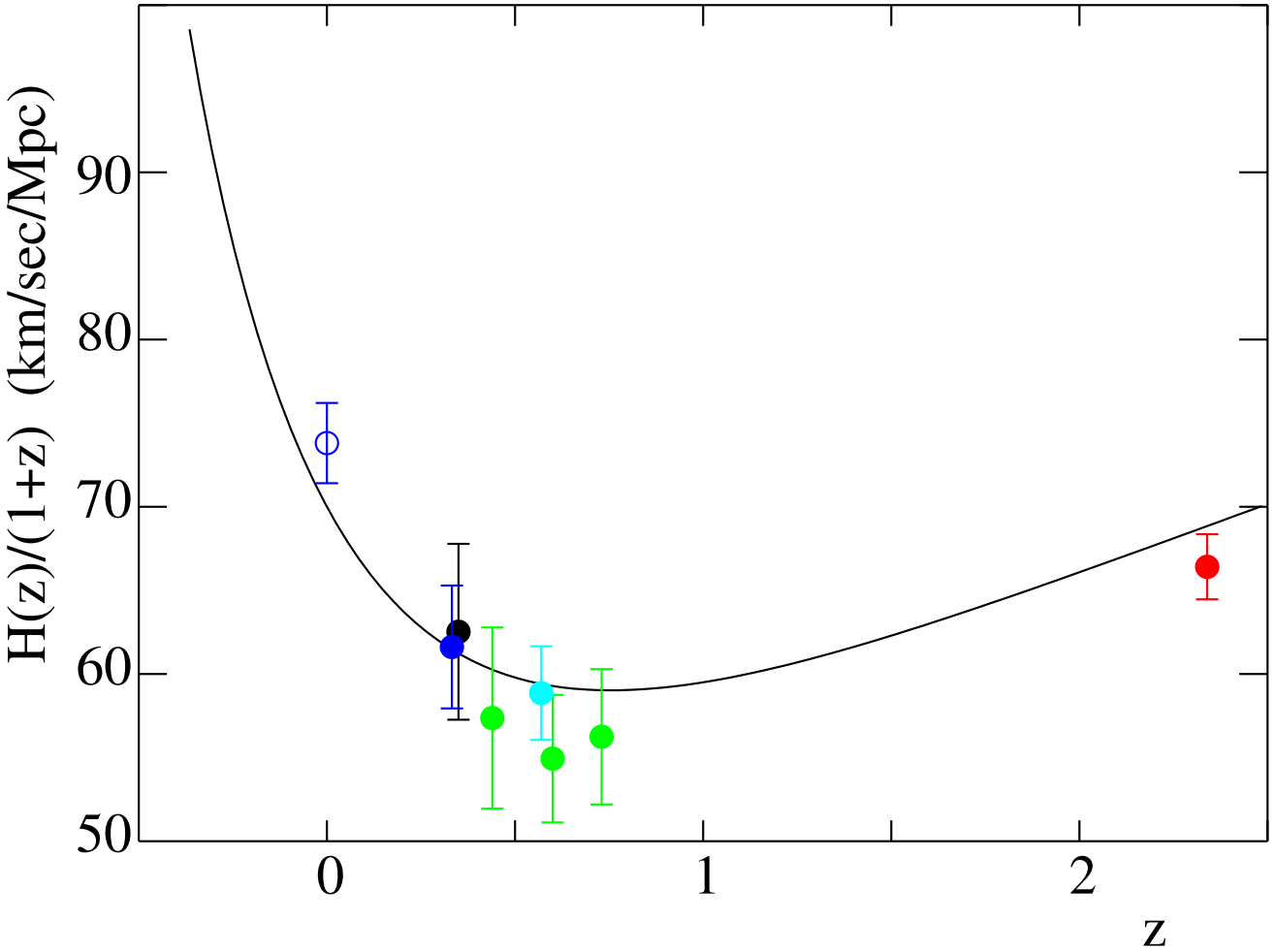


"before reconstruction"

"after reconstruction"

[Kazin et al (BOSS): arXiv:1303.4391]

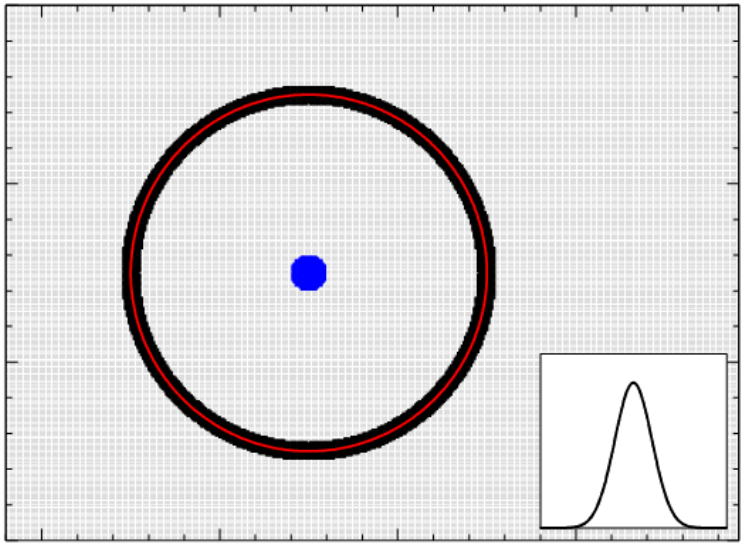
$H(z)/(1+z) = \dot{a}$: decelleration then acceleration!



But beware of systematics: H_0 not measured with BAO

Reconstruction (simulation)

Initial density field



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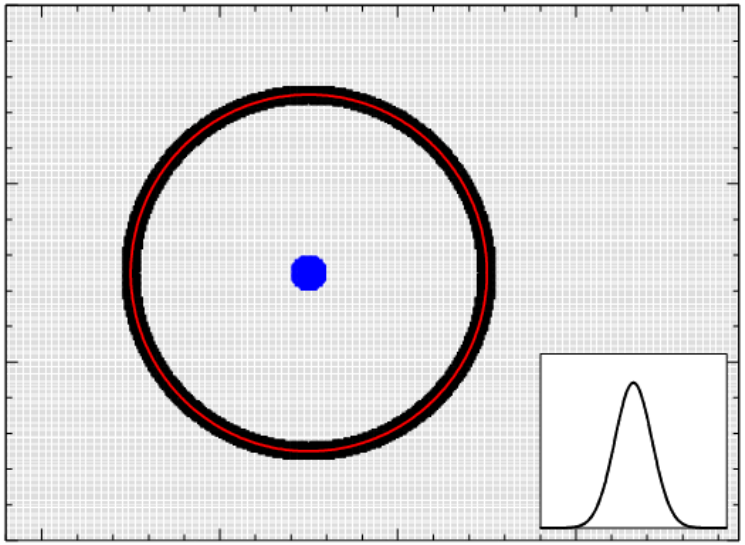
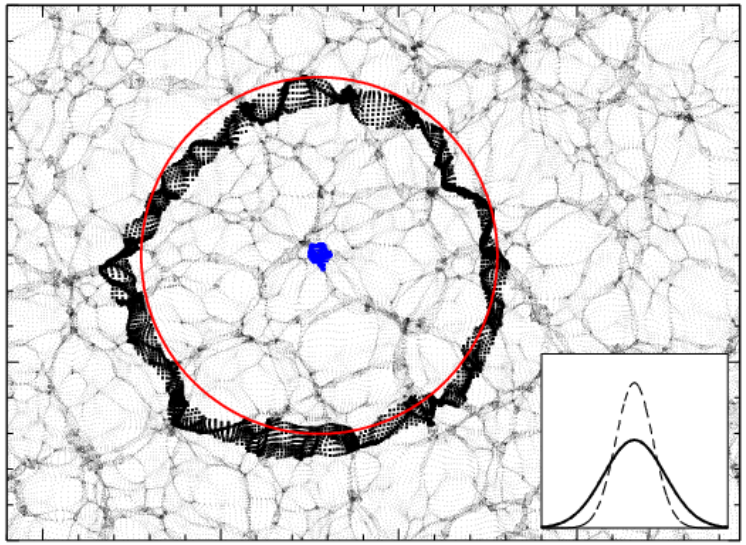


Evolved density field: ring distorted



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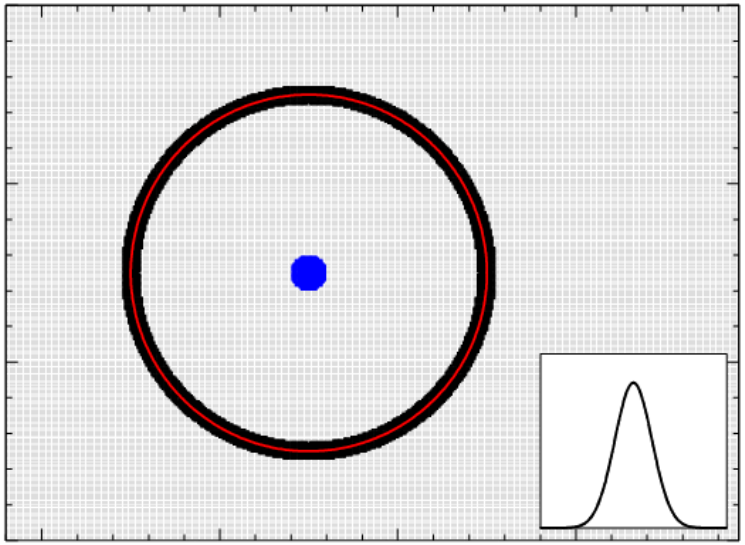

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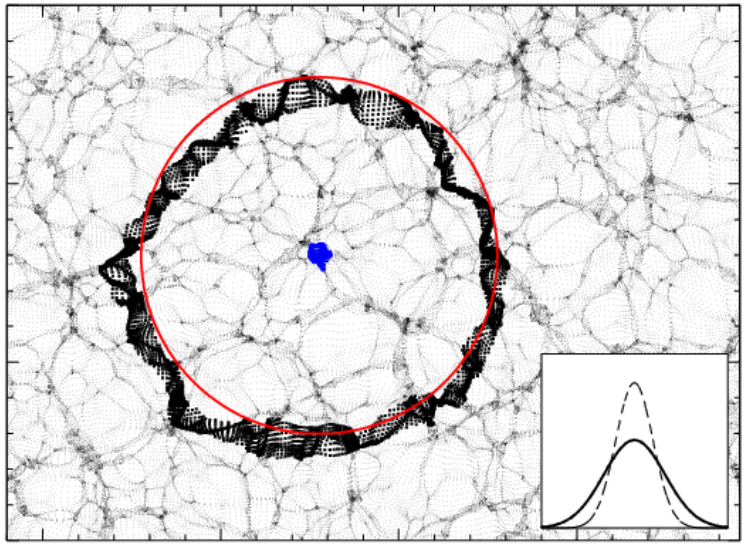
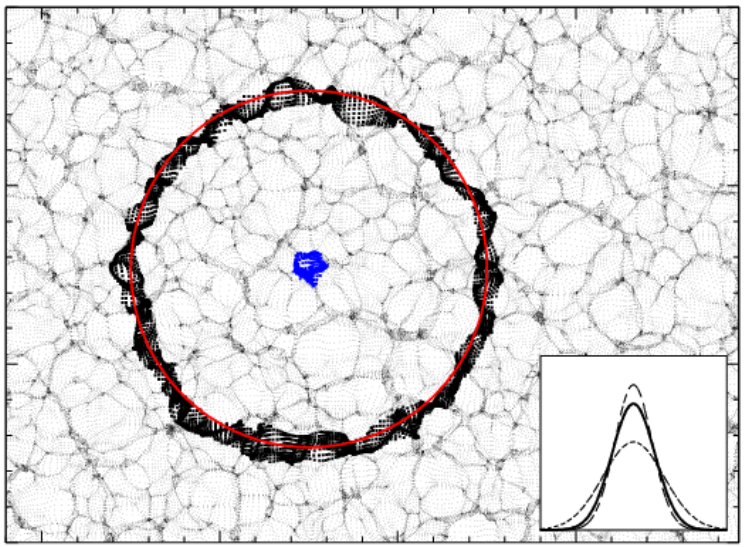
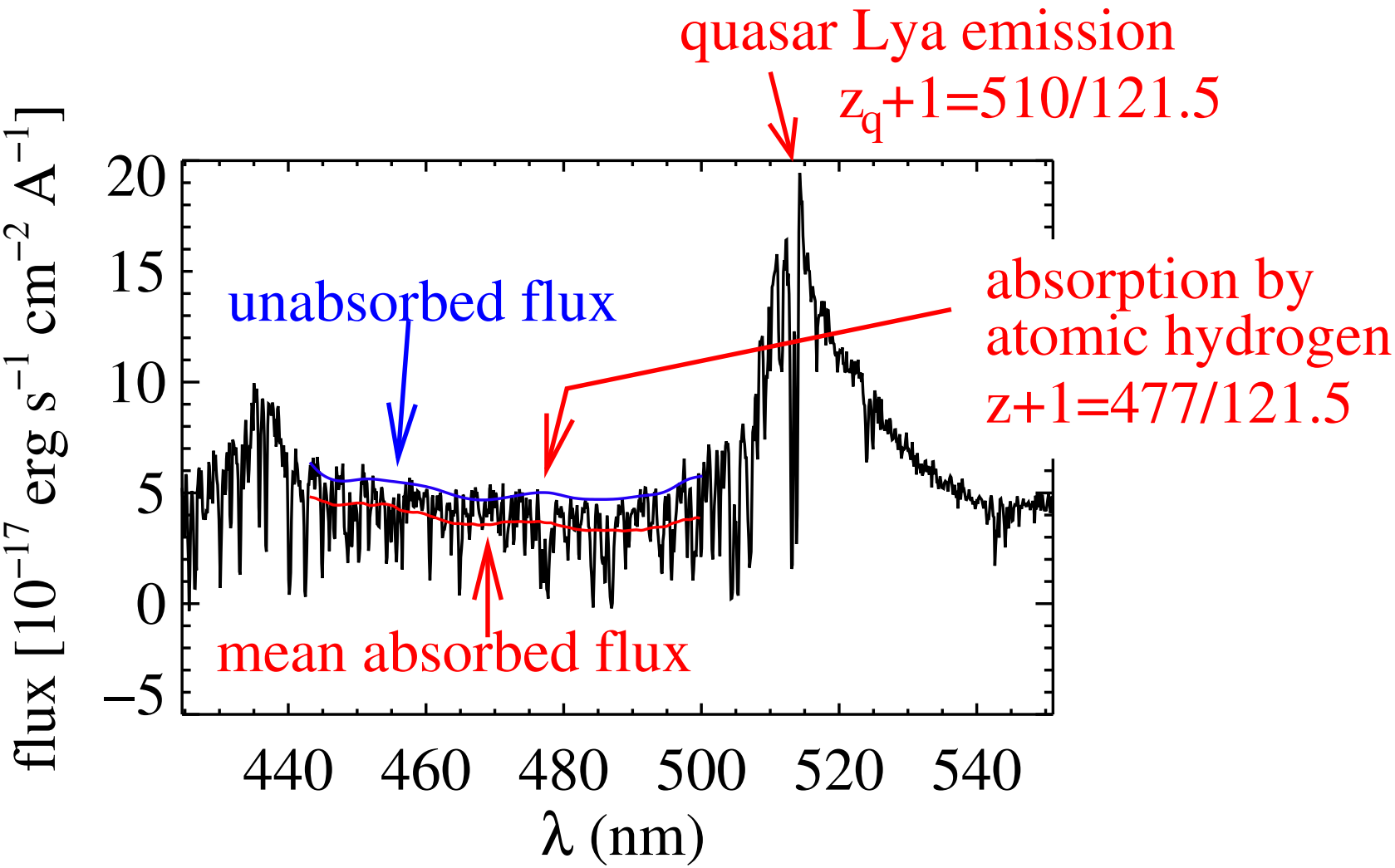




"Reconstructed" density field
Particules returned to calculated
"unperturbed position":
ring less distorted

Padmanabhan, et al: arXiv:1202.0090

Quasar Lyα forest: ($\lambda_{\mathrm{Ly}\alpha} = 121.5nm$)

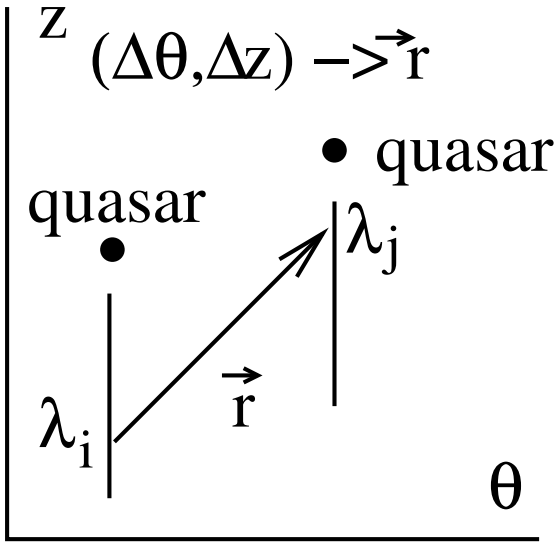


Me

"δ-field: $\delta(\lambda) \propto (flux - \langle flux \rangle)$ $\quad \delta \gtrless 0 \Rightarrow \rho \lessgtr \langle \rho \rangle$

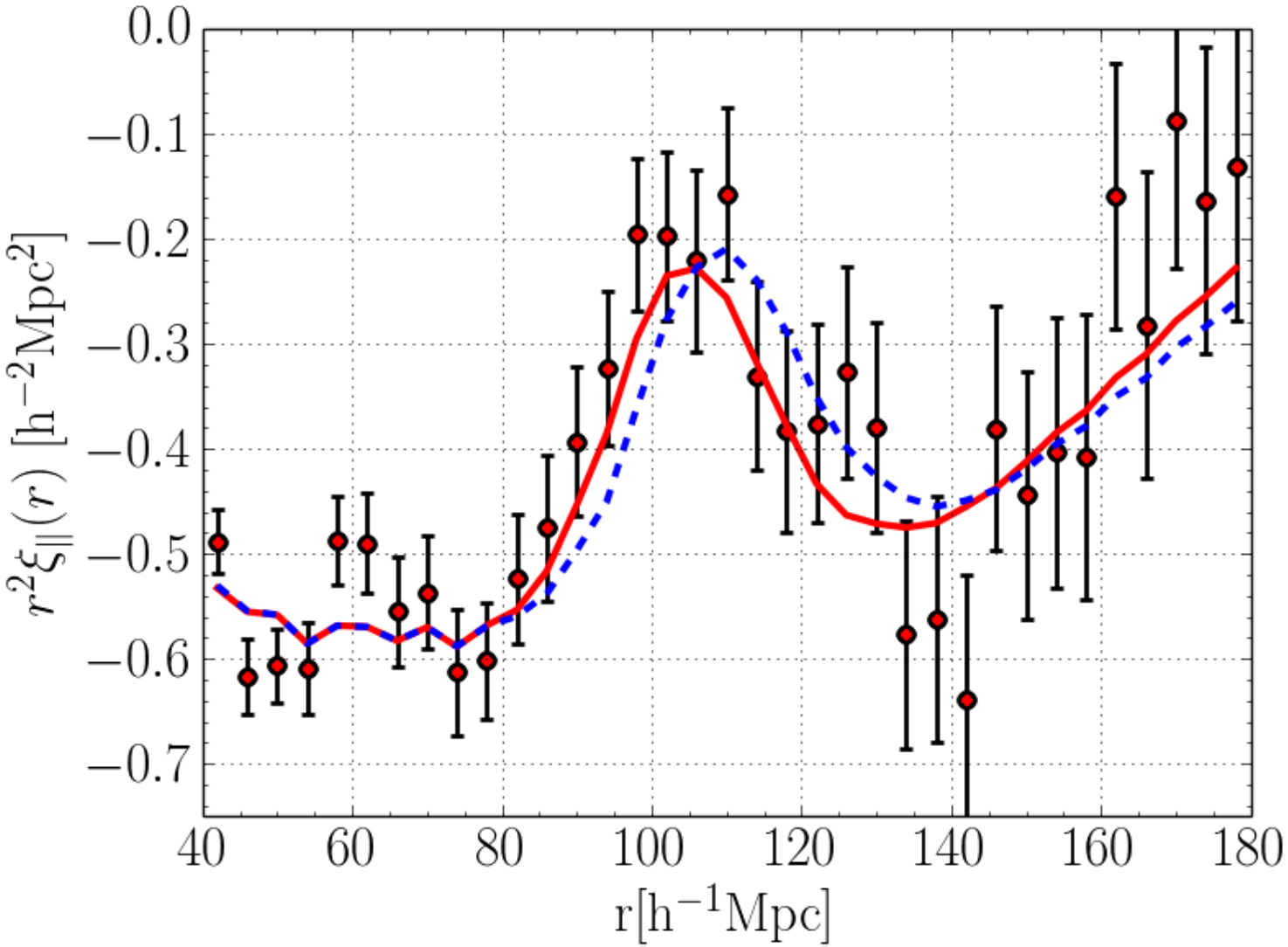
Lyα Forest Correlation function

1.Select quasar candidates from SDSS photometry
2.Obtain spectrum $\Rightarrow$ quasar/star and redshift
3.For quasar pairs, calculate $\vec{r}$ from fiducial cosmology



4. Calculate $\delta(\lambda)$ for each forest.
5. Calculate $\langle \delta_i \delta_j \rangle$ in bins of $\vec{r}$
   $\Rightarrow \xi(\vec{r})$
6.Verify that BAO peak is at fiducial position. If not, change model.

BOSS data at $z \sim 2.3$



BAO peak $\sim 1.5\sigma$ from Planck model.

ΛCDM Cosmological Parameters

H_0: present expansion rate
Major components: $\Omega_\Lambda, \Omega_{\rm M}$, $\quad \Omega_k = 1 - \Omega_{\rm M} - \Omega_\Lambda \sim 0$
Minor Components: $\Omega_{\rm B}$ $(= \Omega_{\rm M} - \Omega_{\rm CDM})$,$\Omega_\nu, \Omega_\gamma$
(Ω's are present densities in units of $\rho_{\rm c} = 3H_0^2/8\pi G$)

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($+$ A_s, n_s.....: primordial perturbation parameters)

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CMB temperature (COBE) determines $\Omega_\gamma H_0^2$:

$$\rho_\gamma(z=0) \sim (kT)^4/(\hbar c) = \Omega_\gamma H_0^2 (3/8\pi G)$$

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CMB anisotropy spectrum shape determines $\rho_{\rm M}/\rho_\gamma$, $\rho_{\rm B}/\rho_\gamma$

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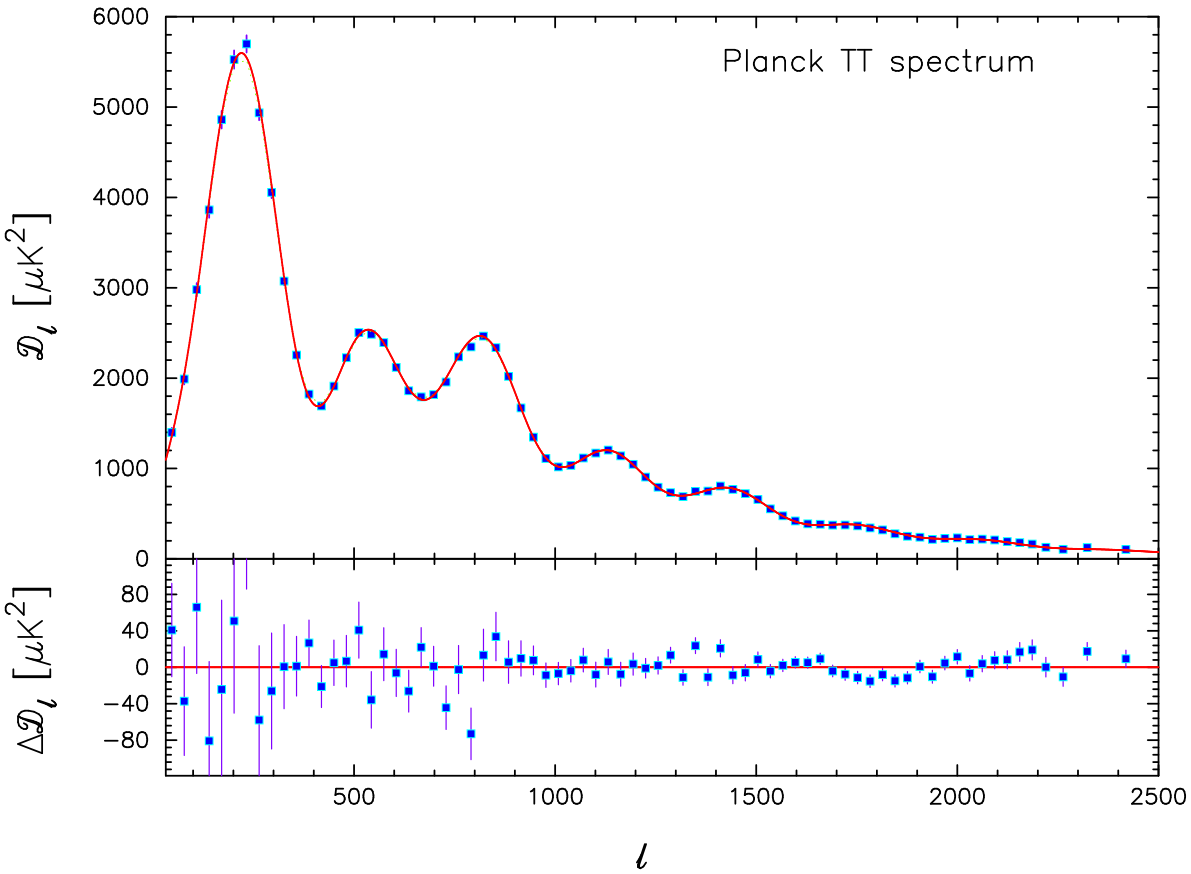
CMB anisotropy spectrum shape determines $\rho_{\rm M}/\rho_\gamma$, $\rho_{\rm B}/\rho_\gamma$
$\Rightarrow$ COBE + Planck determines $\Omega_{\rm M} H_0^2$, $\Omega_{\rm B} H_0^2$, $r_d(\Omega_{\rm M} H_0^2, \Omega_{\rm B} H_0^2)$

CMB anistropy spectrum



Spectrum shape (relative peak heights) gives $\rho_{\rm M}/\rho_\gamma$, $\rho_{\rm B}/\rho_\gamma$
$\Rightarrow \Omega_{\rm M}H_0^2, \Omega_{\rm B}H_0^2$

Peak positions ($1/\ell \sim 1/200$) gives $D_A(z = 1060)/r_d$, allowing the determination of one more combination of cosmological parameters.

Flat ΛCDM: CMB is enough

$\Omega_\Lambda = 1 - \Omega_{\rm M}$
$\Omega_\gamma H_0^2$ from CMB temperature
$\Omega_{\rm M} H_0^2$, $\Omega_{\rm B} H_0^2$ from CMB spectrum shape and $\Omega_\gamma H_0^2$
$\Rightarrow r_d(\Omega_{\rm M} H_0^2, \Omega_{\rm B} H_0^2)$

BAO at redshift $z = z_{rec}$ determines $D_A(z)/r_d$

$$\frac{r_d}{D_A} = \frac{r_d(\Omega_{\rm M} H_0^2, \Omega_{\rm B} H_0^2)}{D_A(H_0^2, \Omega_{\rm M} H_0^2)} \quad \text{only } H_0 \text{ is unknown!}$$

$$D_A(z) = \int_0^z \frac{dz}{\sqrt{H_0^2 + \Omega_{\rm M} H_0^2[(1+z)^3 - 1]}}$$

Flat ΛCDM: CMB is enough

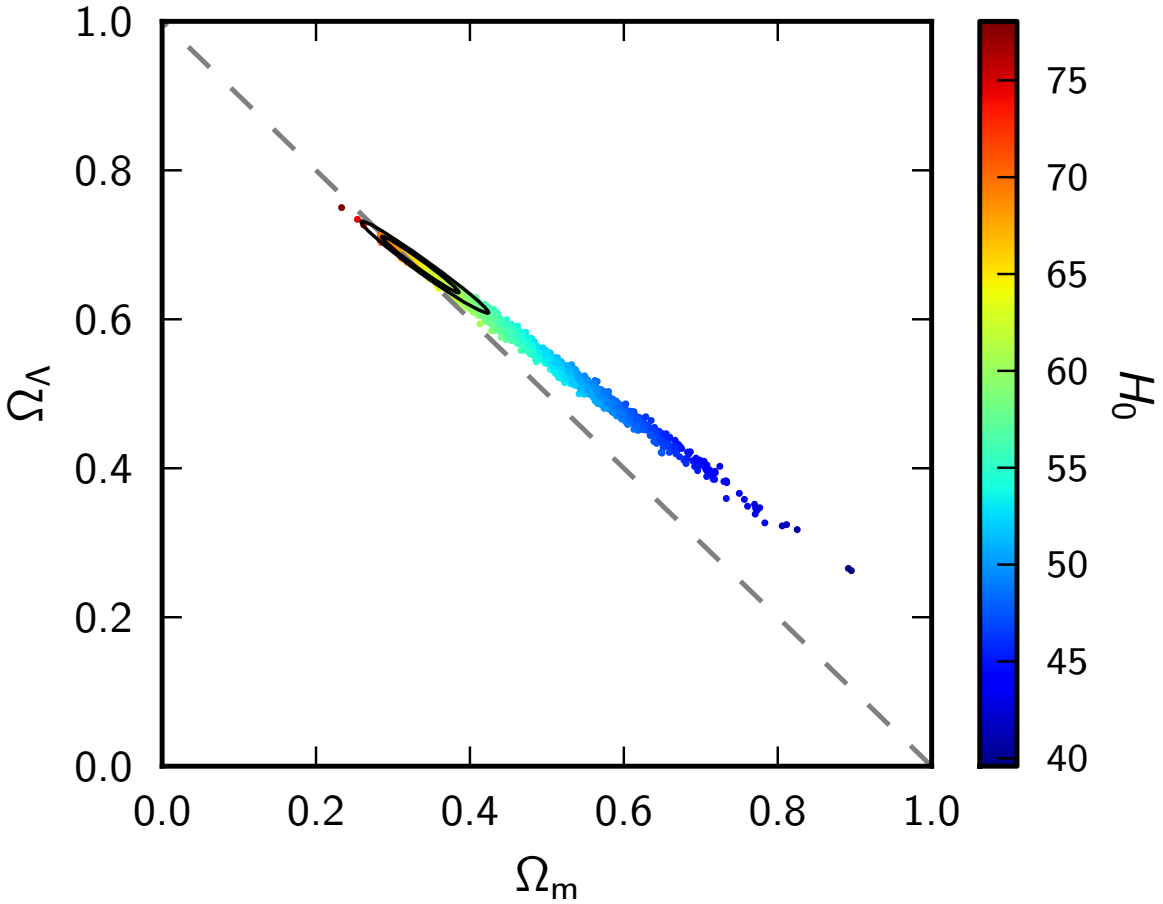
Planck + WMAP polarization (arXiv:1303:5076)

- $h = H_0/70\mathrm{km\,s^{-1}Mpc^{-1}} = 0.673 \pm 0.012$
- $\Omega_{\mathrm{CDM}} h^2 = 0.1199 \pm 0.0027$
- $\Omega_{\mathrm{B}} h^2 = 0.02205 \pm 0.00028$

$\Rightarrow (\Omega_{\mathrm{M}}, \Omega_\Lambda) = (0.315 \pm 0.017, 0.685 \pm 0.017)$
$\Omega_k = 1 - \Omega_{\mathrm{M}} - \Omega_\Lambda \equiv 0$ by assumption

Non-flat ΛCDM: CMB not enough

$D_A(H_0^2, \Omega_{\rm M} H_0^2) \rightarrow D_A(H_0^2, \Omega_{\rm M} H_0^2, \Omega_k)$ or $D_A(H_0, \Omega_{\rm M}, \Omega_\Lambda)$

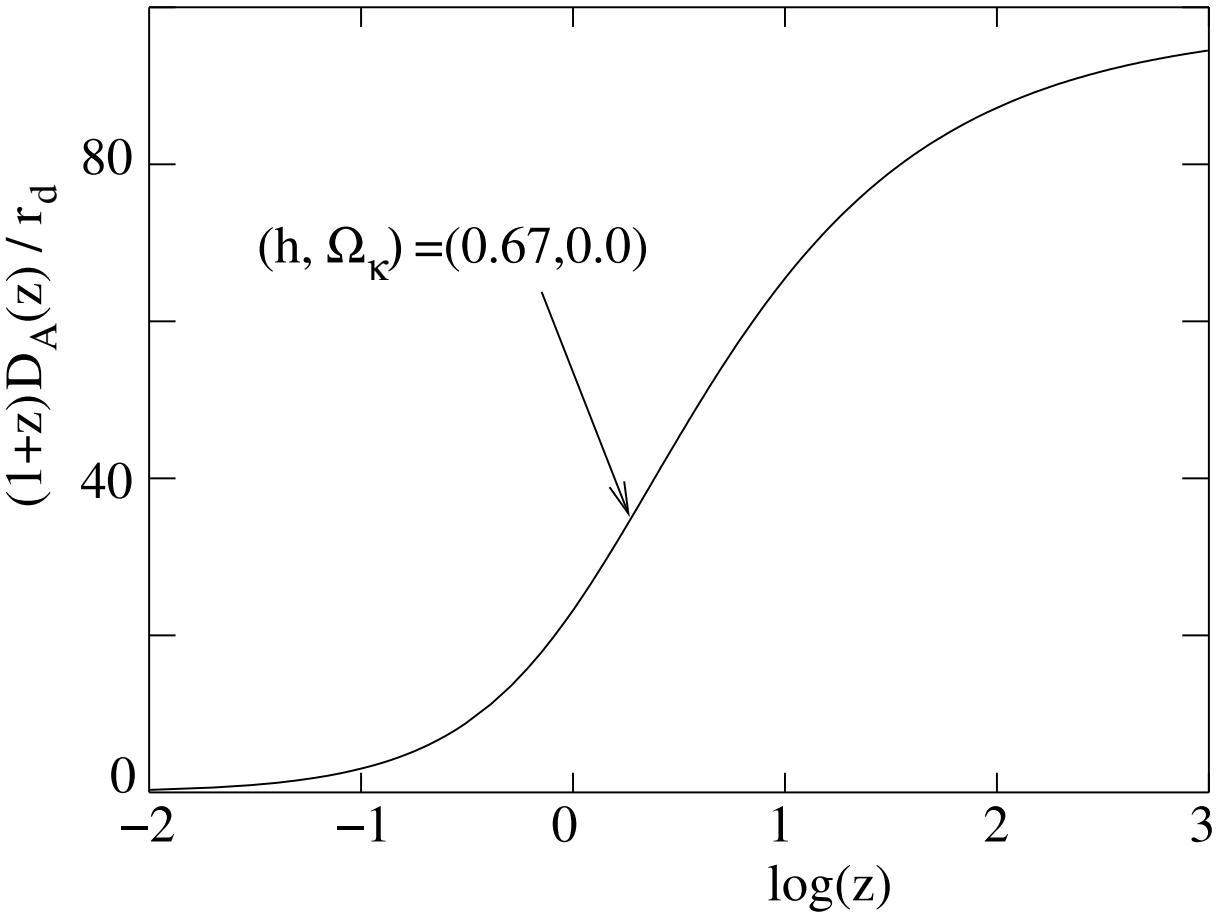


CMB Acceptable models need $(\Omega_{\rm M} h^2, \Omega_{\rm B} h^2) = (0.142, 0.022)$ (spectrum shape)

+

Combinations of $(\Omega_{\rm M}, \Omega_\Lambda)$ or (H_0, Ω_k) giving $r_d / D_A(1060) = 0.01041$

Three models that give the same $D_A(z = 1060)/r_d$



$(\Omega_{\rm M} h^2, \Omega_{\rm B} h^2)$
$= (0.142, 0.022)$
$r_d = 147.36$ Mpc

$(h, \Omega_k) = (0.67, 0.0)$

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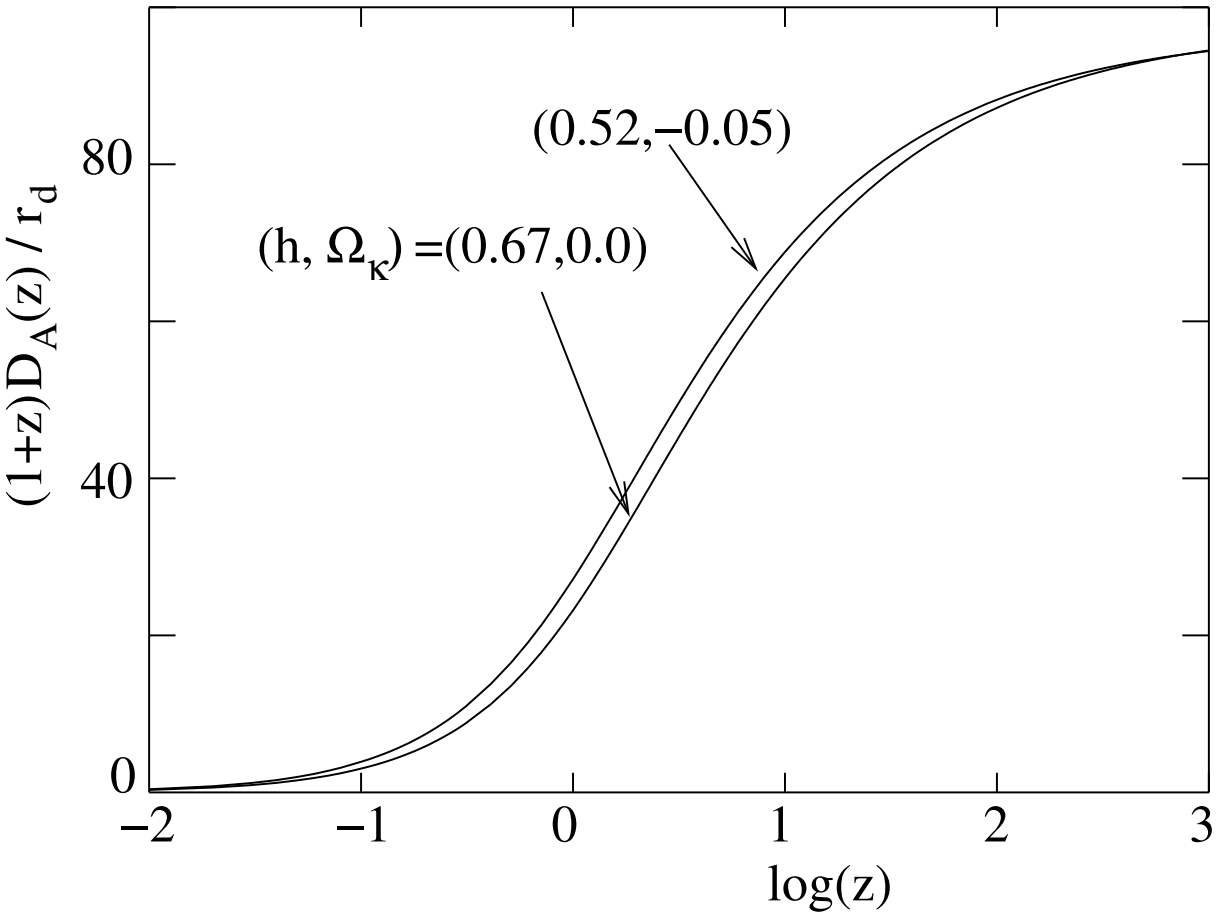
Three models that give the same $D_A(z = 1060)/r_d$



$(\Omega_{\rm M} h^2, \Omega_{\rm B} h^2)$
$= (0.142, 0.022)$
$r_d = 147.36$ Mpc

$(h, \Omega_k) = (0.67, 0.0)$
$(h, \Omega_k) = (0.52, -0.05)$

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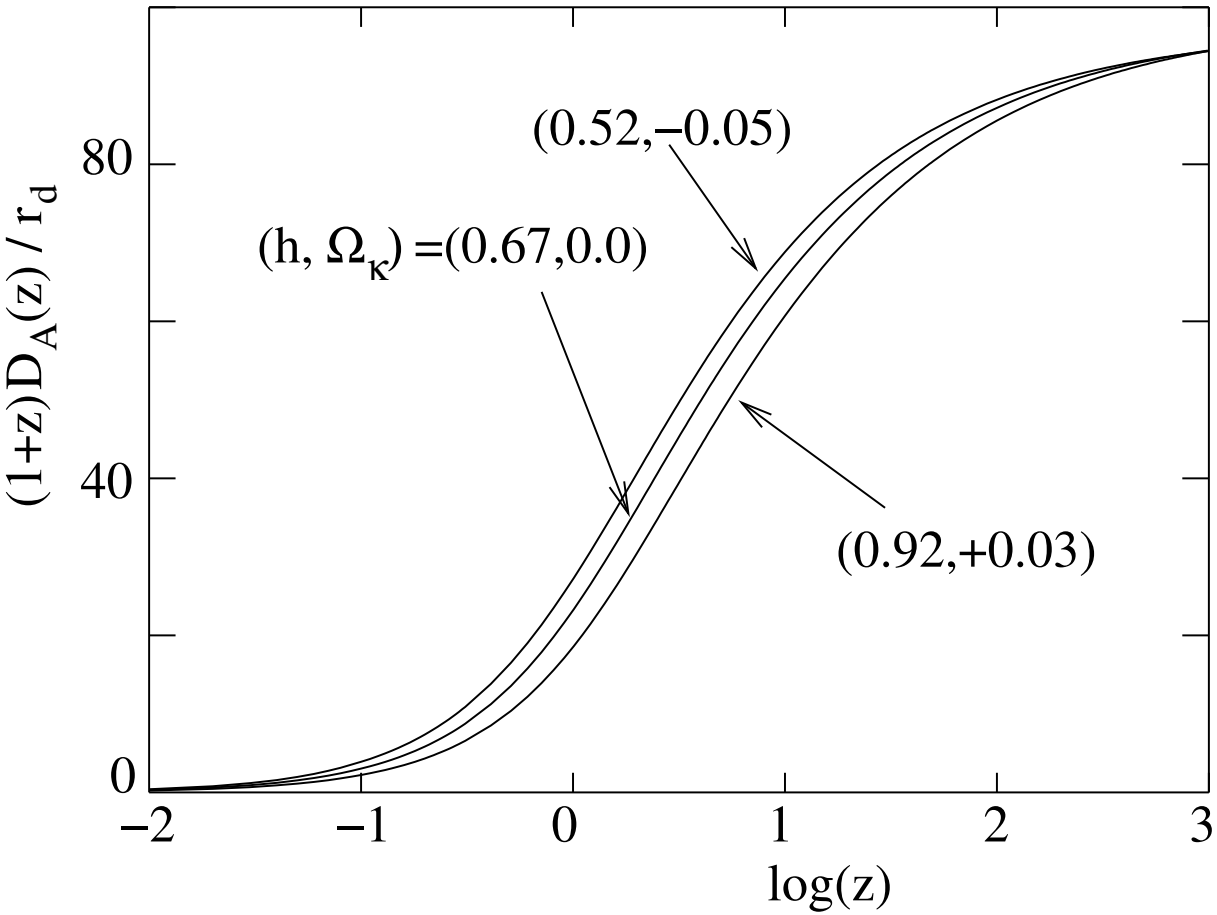
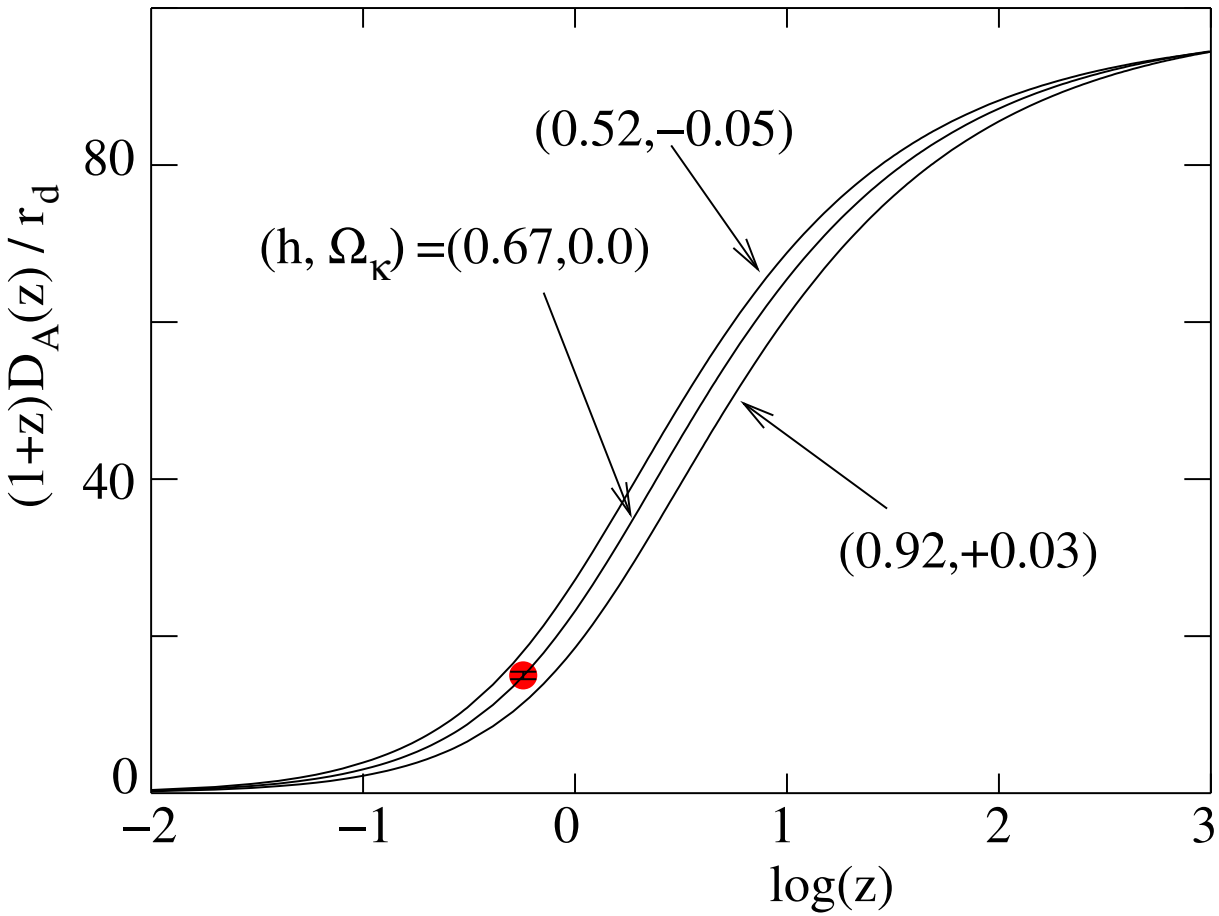
Three models that give the same $D_A(z = 1060)/r_d$



$(\Omega_{\rm M}h^2, \Omega_{\rm B}h^2)$
$= (0.142, 0.022)$
$r_d = 147.36$ Mpc

$(h, \Omega_k) = (0.67, 0.0)$
$(h, \Omega_k) = (0.52, -0.05)$
$(h, \Omega_k) = (0.92, 0.03)$

BAO at $z = 0.57$ picks flatness



$(\Omega_M h^2, \Omega_B h^2)$
$= (0.142, 0.0227)$
$r_d = 147.36$ Mpc

$(h, \Omega_k) = (0.67, 0.0)$
$(h, \Omega_k) = (0.52, -0.05)$
$(h, \Omega_k) = (0.92, 0.03)$

CMB + BAO: $\Omega_k = -0.0005 \pm 0.0066$

Extensions of flat ΛCDM that modify distance-redshift relation

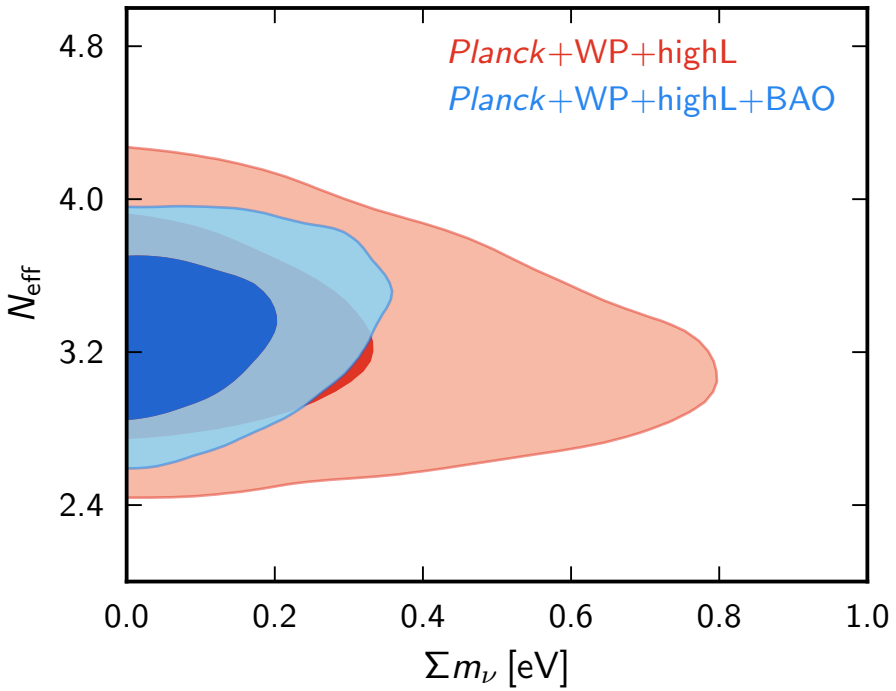
Examples of extensions:

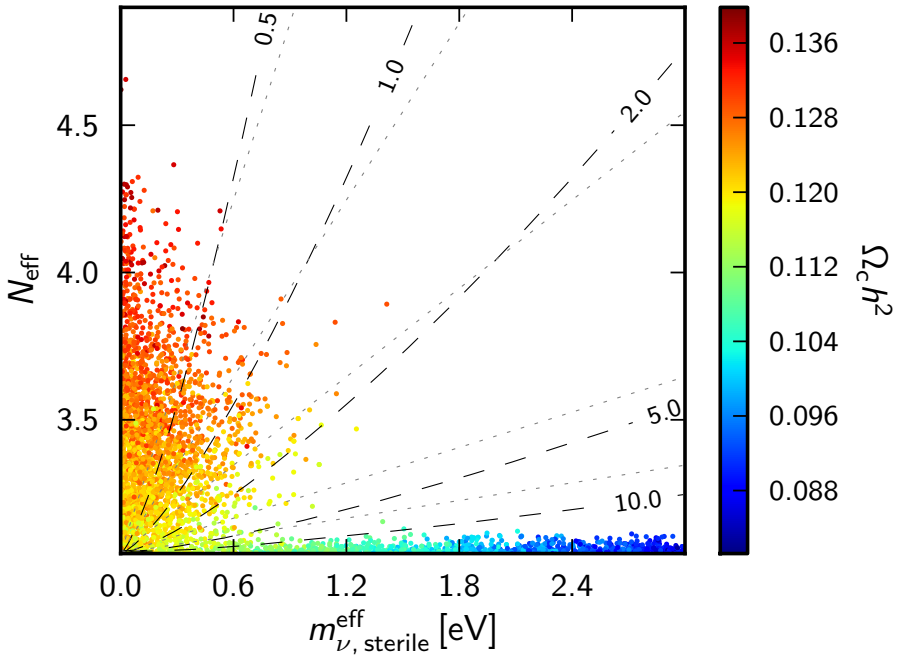
- curvature ($\Omega_\Lambda + \Omega_{\rm M} \neq 0$)
- neutrino mass (relativistic→non-relativistic after recombination.)
- $w \neq -1$ ($w =$ dark energy presure/density)
- w_a (evolving w)

Constraints requires CMB + something else

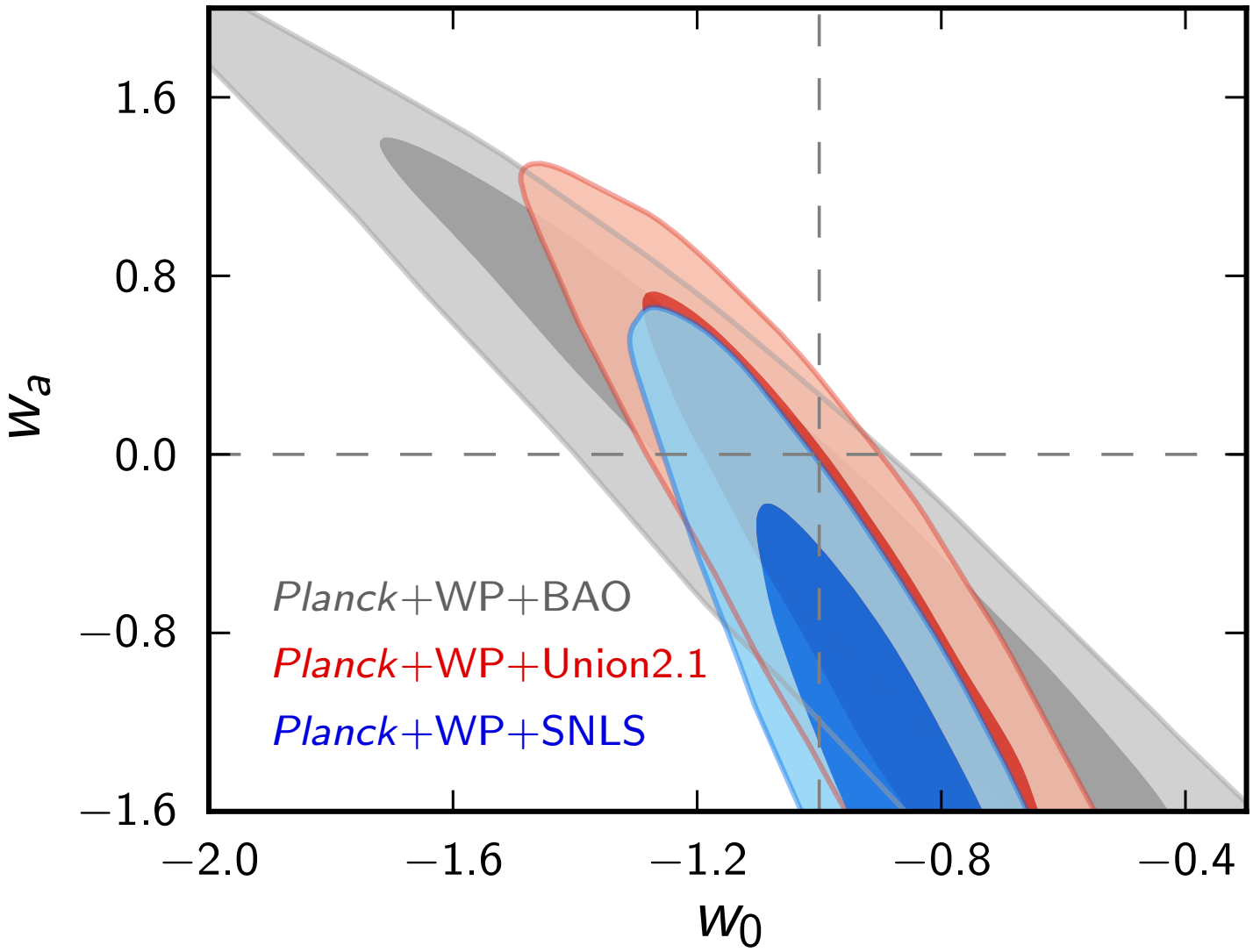
e.g. BAO, local H_0 meansurement, SNIa hubble diagram

Planck + BAO: Neutrino constraints

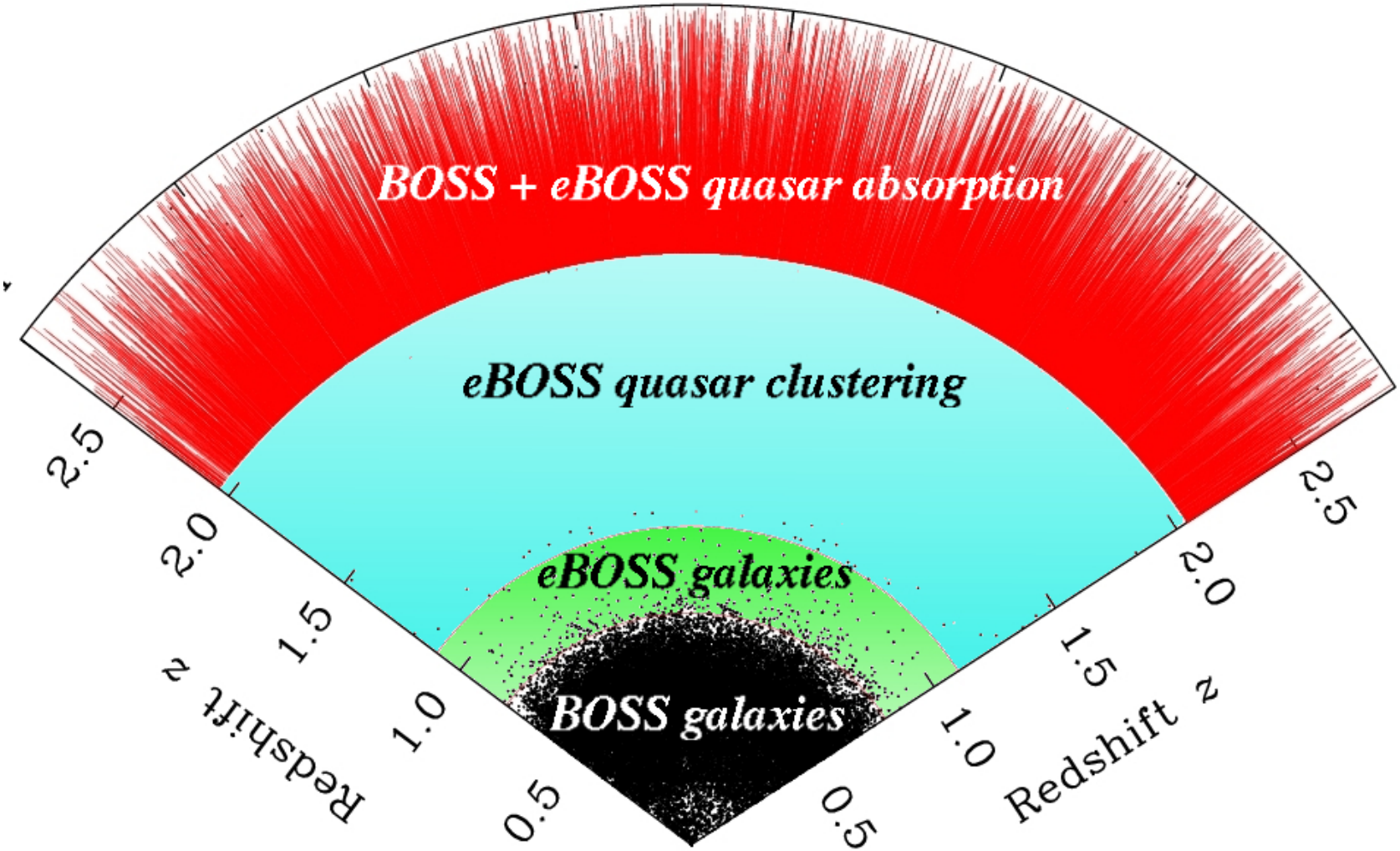




Planck + BAO: dark energy



The future is now: BOSS $\rightarrow$ eBOSS (2014-2018)



Future surveys:

- 2.5m Telescope $\rightarrow$ 4m class telescope
- 1000 fibers $\rightarrow$ 5000 fibers (automatic positioning)
- $\lambda/\Delta\lambda = 1560 - 2650 \rightarrow \lambda/\Delta\lambda = 3000 - 4800$
- SDSS photometry $\rightarrow$ SDSS+DES photometry
- 1.6million galaxies $\rightarrow$ 20million galaxies (LRG+OII-ELG)
- 150,000 forests $\rightarrow$ 600,000 forests (variability selection)
- northern hemisphere $\rightarrow$ northern + southern?

Followed by

- Euclid: emission-line galaxies
- SKA: 21cm emission

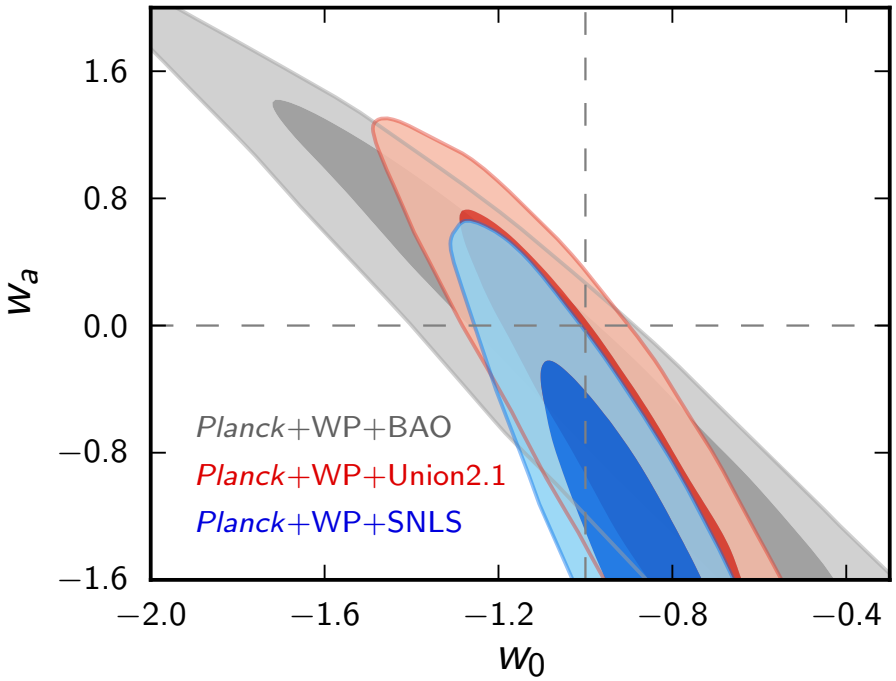
Future BAO systematics ($\Rightarrow$subpercent precision?)

- The BAO peak has FWHM $\sim$ 30Mpc.
- "Easy" to measure peak to $\sim$ 3Mpc (2%).

Future: 0.3% peak precision (comparable to Planck)
$\Rightarrow$ need better understanding of:

- Galaxy selection function ("random" catalog)
- Mean-flux to be subtracted in Lyα forest
  - quasar unabsorbed spectrum
  - photometric artifacts
- Broadband $\xi(r)$ and it's effect on "peak"
  - Non-linearities in Large-Scale Structure
  - Effect of fitting unabsorbed quasar spectrum
  - re-positioning of galaxies ("reconstruction")
  - redshift distortions

DETF Figure-of-Merit (arXiv:1106.1706)



- Galaxy BAO
  - Planck+StageIII-BAO: 31
  - Planck+4mBAO: 102
  - Planck+all StageIII+4mBAO: 178
- Galaxy and Lyα BAO
  - Planck+4mBAO:136
  - Planck+all StageIII+4mBAO: 217
- Galaxy broadband power spectrum + Lyα BAO
  - Planck+all StageIII+4mBAO ($k_{max} = 0.15$):324
  - Planck+all StageIII+4mBAO ($k_{max} = 0.30$):544
- Euclid:4020 (Redbook)

BAO: summary

- Cosmic Order written on a chaotic sky.
- A well-understood standard ruler.
  $\Rightarrow$reliable cosmological parameters
- Future 4m class projects well motivated for BAO + general use
- Improving on BAO precision is possible but challenging