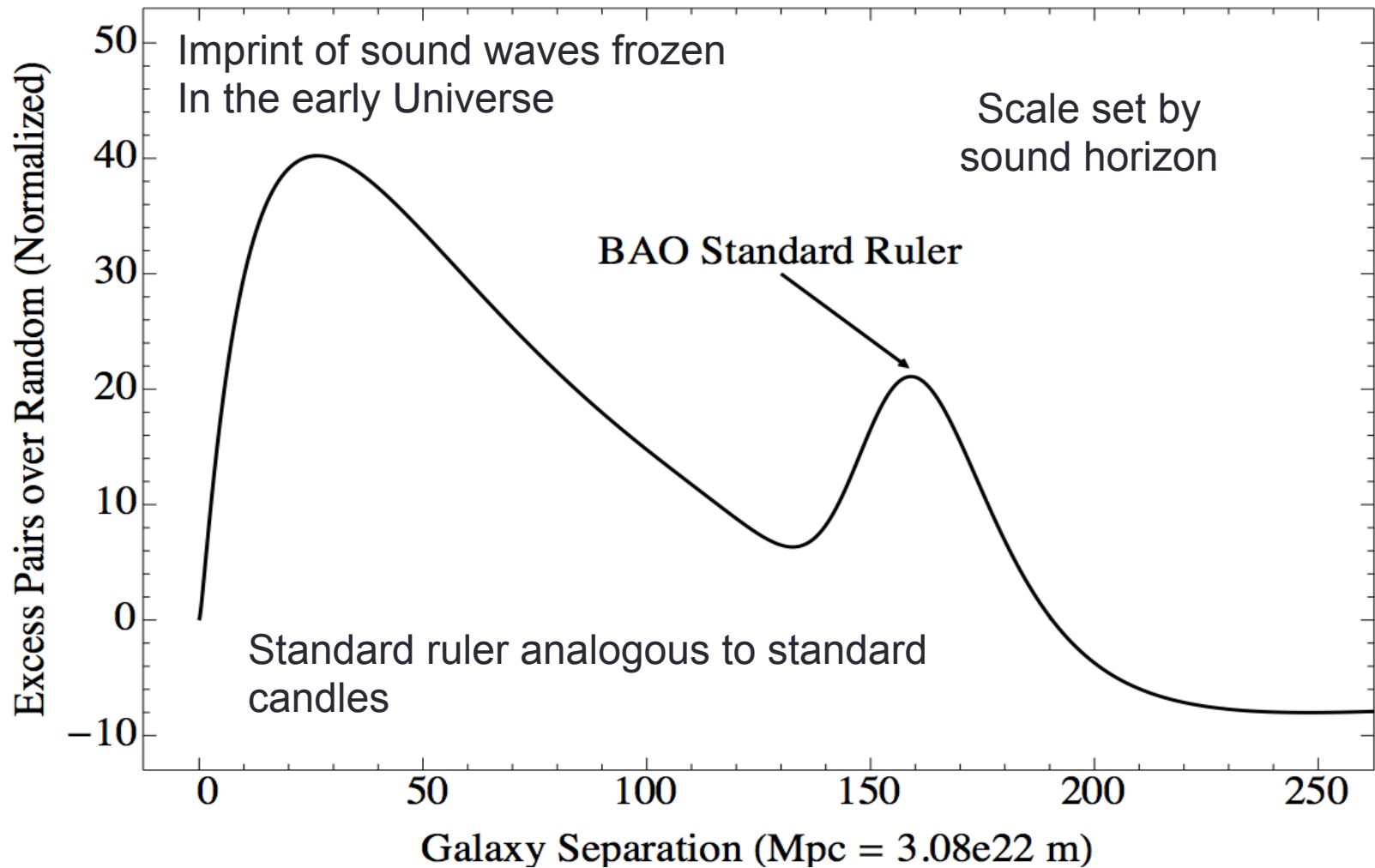


DARK ENERGY WITH GALAXY SURVEYS

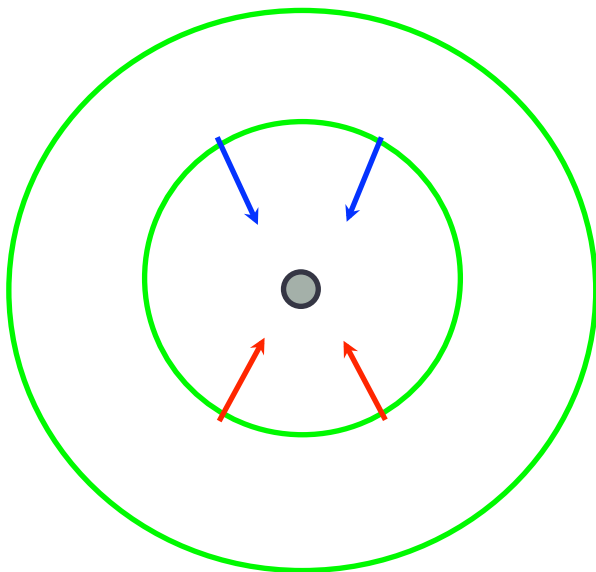
Nikhil Padmanabhan
Yale University

The Standard Ruler in the Galaxy Correlation Function

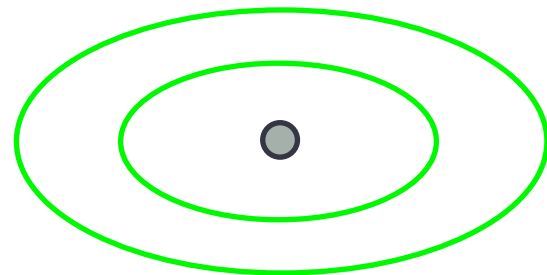


Beyond BAO : Measuring growth

- observed $z_{\text{spec}} = z_{\text{cosmo}} + v_p/aH$
- peculiar velocities (v_p) sourced by matter density fluctuations (δ_m)

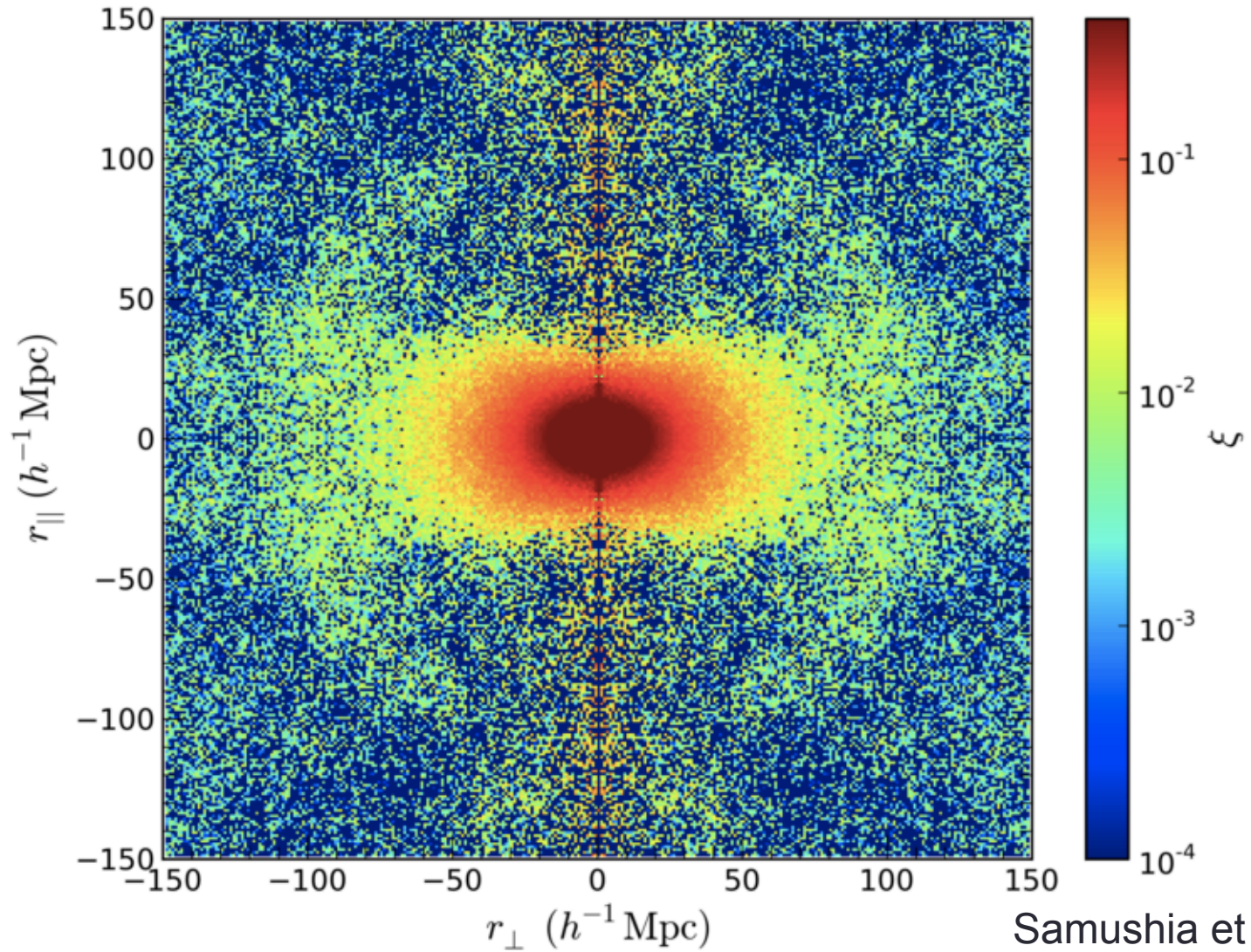


“real” space



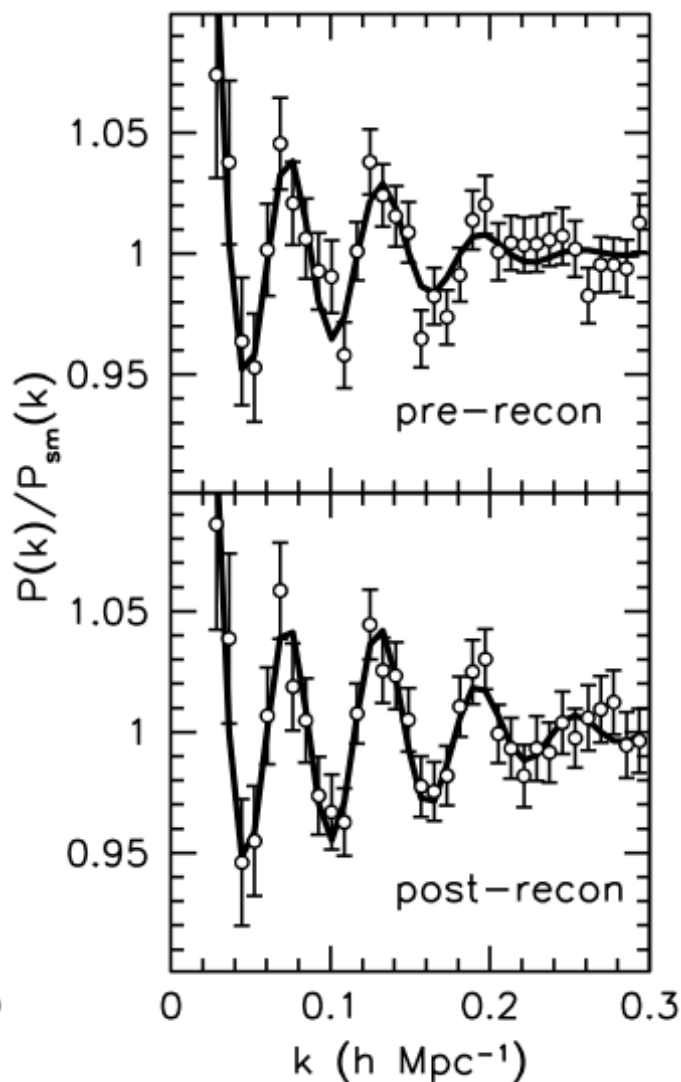
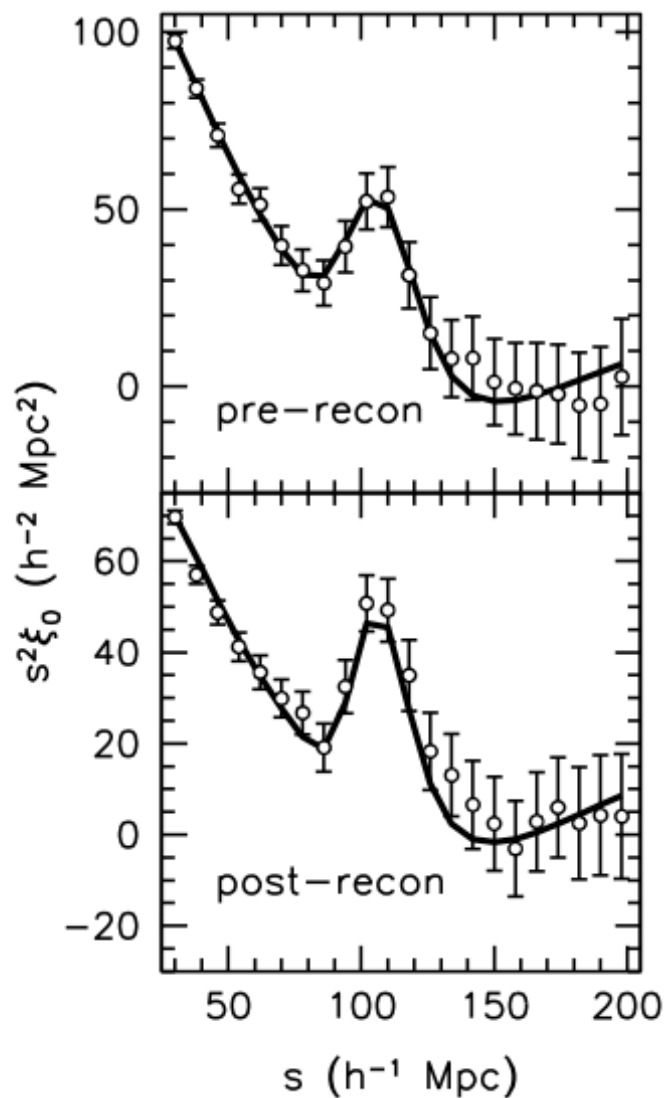
“redshift” space

The BOSS 2D galaxy correlation function



Samushia et al, 2014

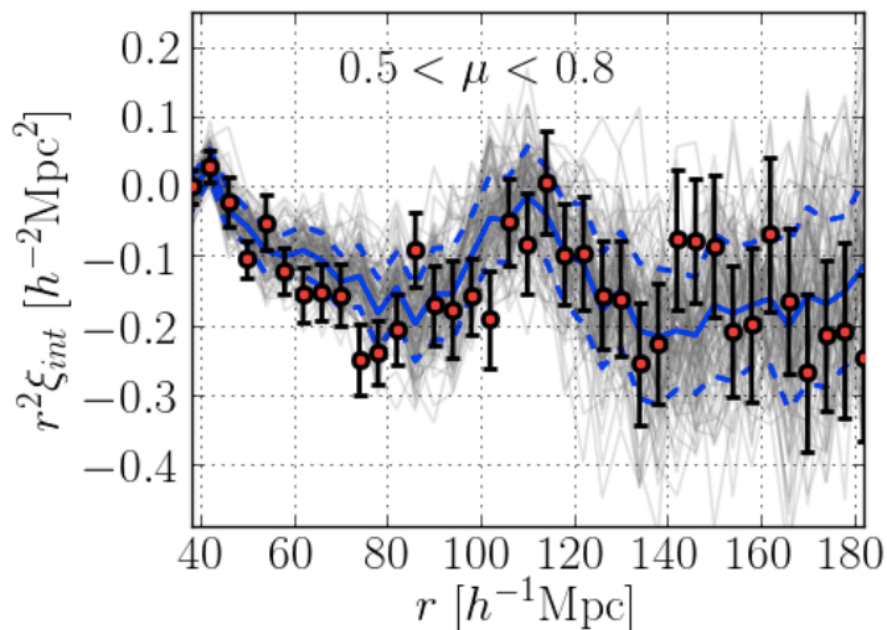
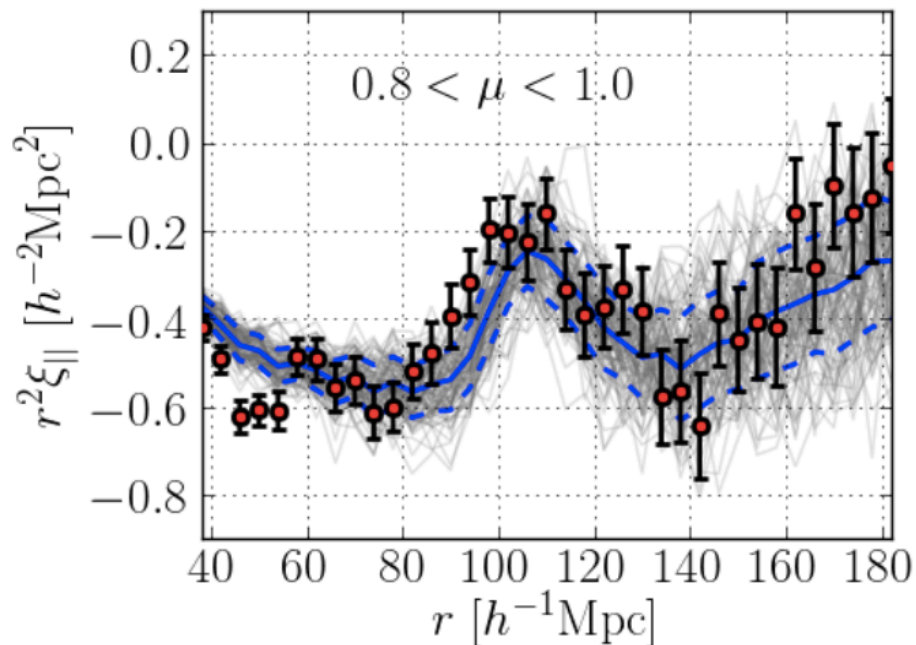
The BAO feature in BOSS galaxies



8 sigma
detection

~1%
distance at
 $z \sim 0.55$,
~2% at
 $z \sim 0.35$

The BAO feature in the Ly- α forest

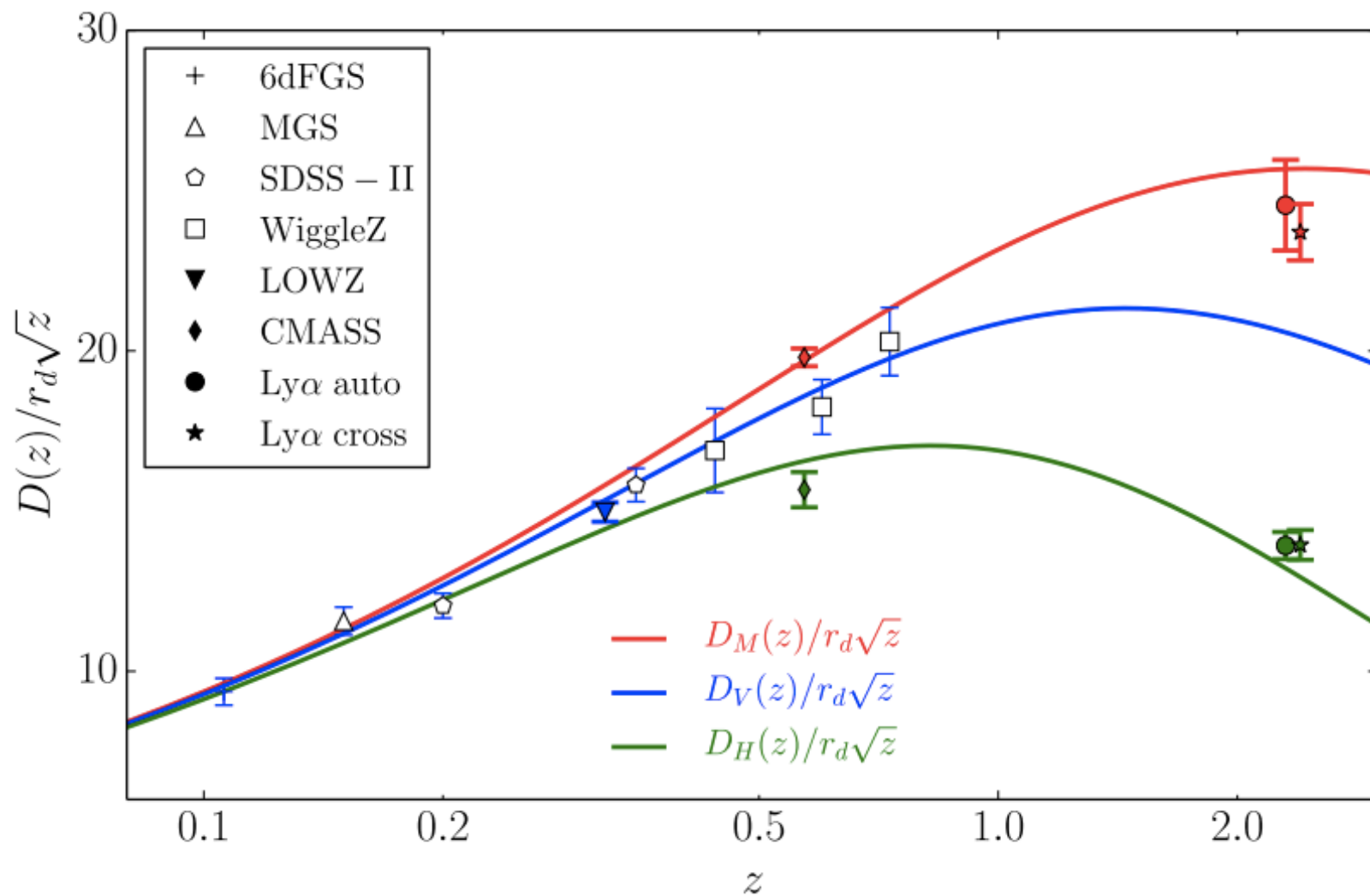


~2% distance measurements at $z \sim 2.5$

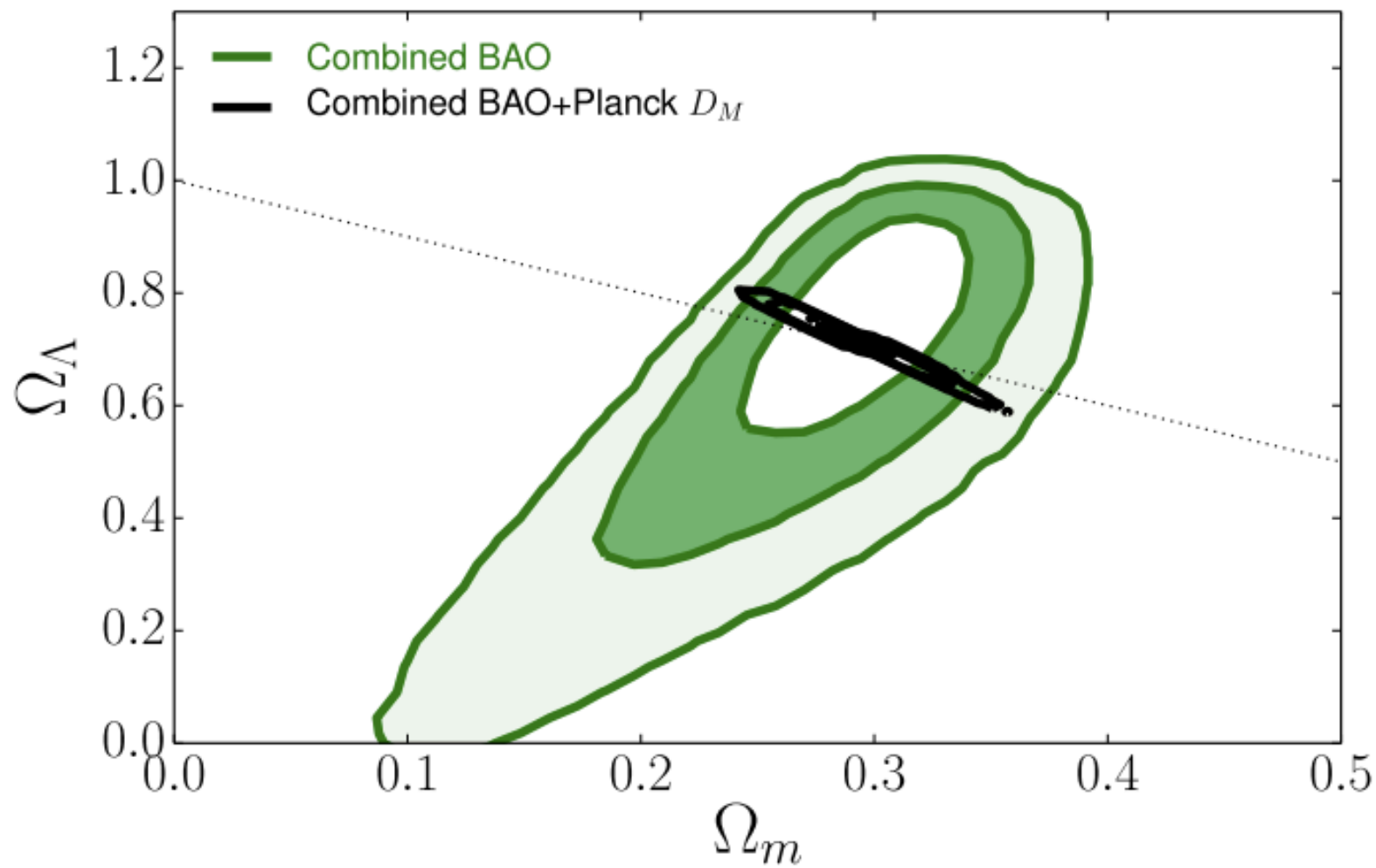
Delubac et al 2014

Note : synergies with WFIRST-AFTA HLS

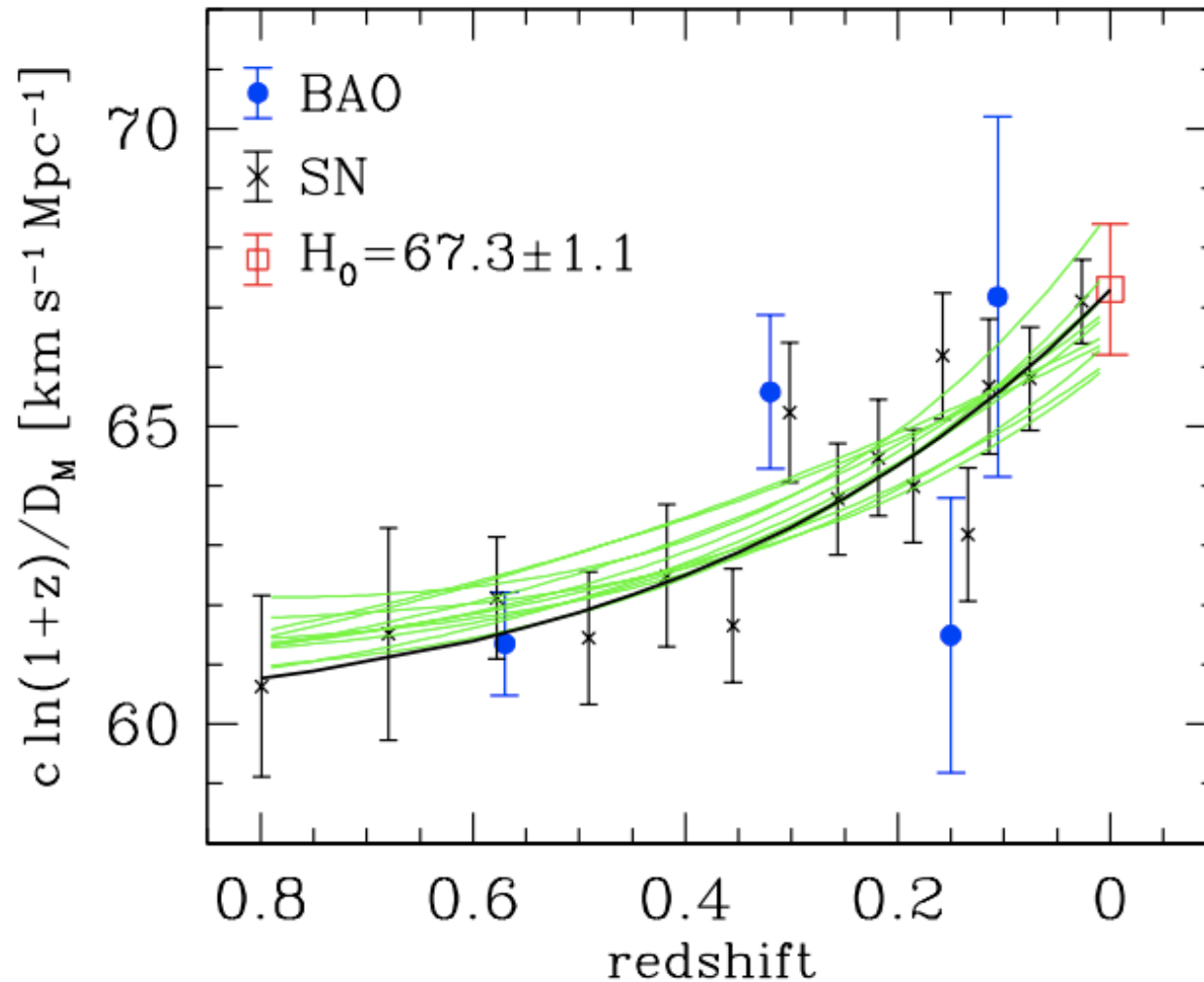
A BAO Hubble diagram



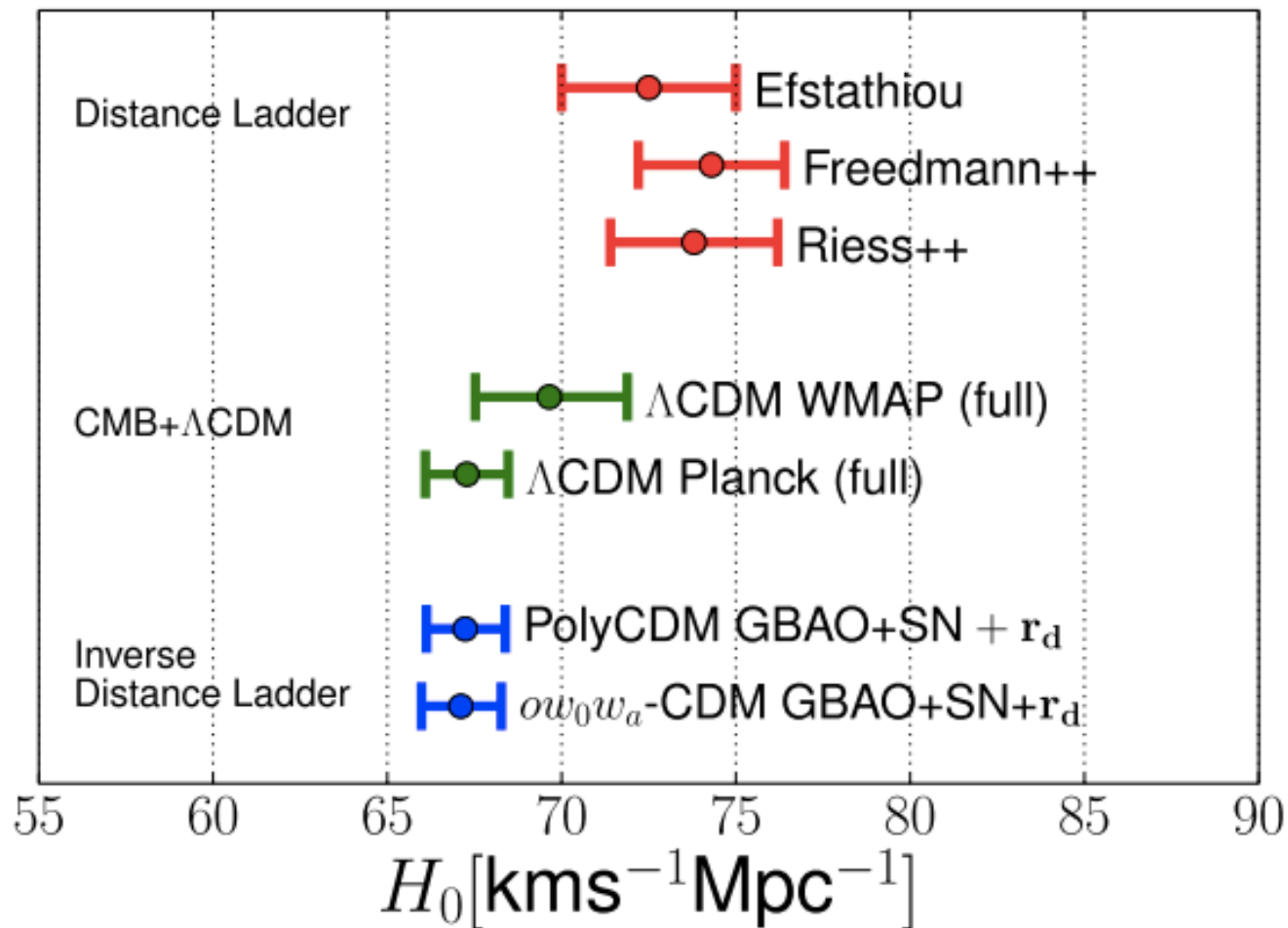
Measuring Dark Energy



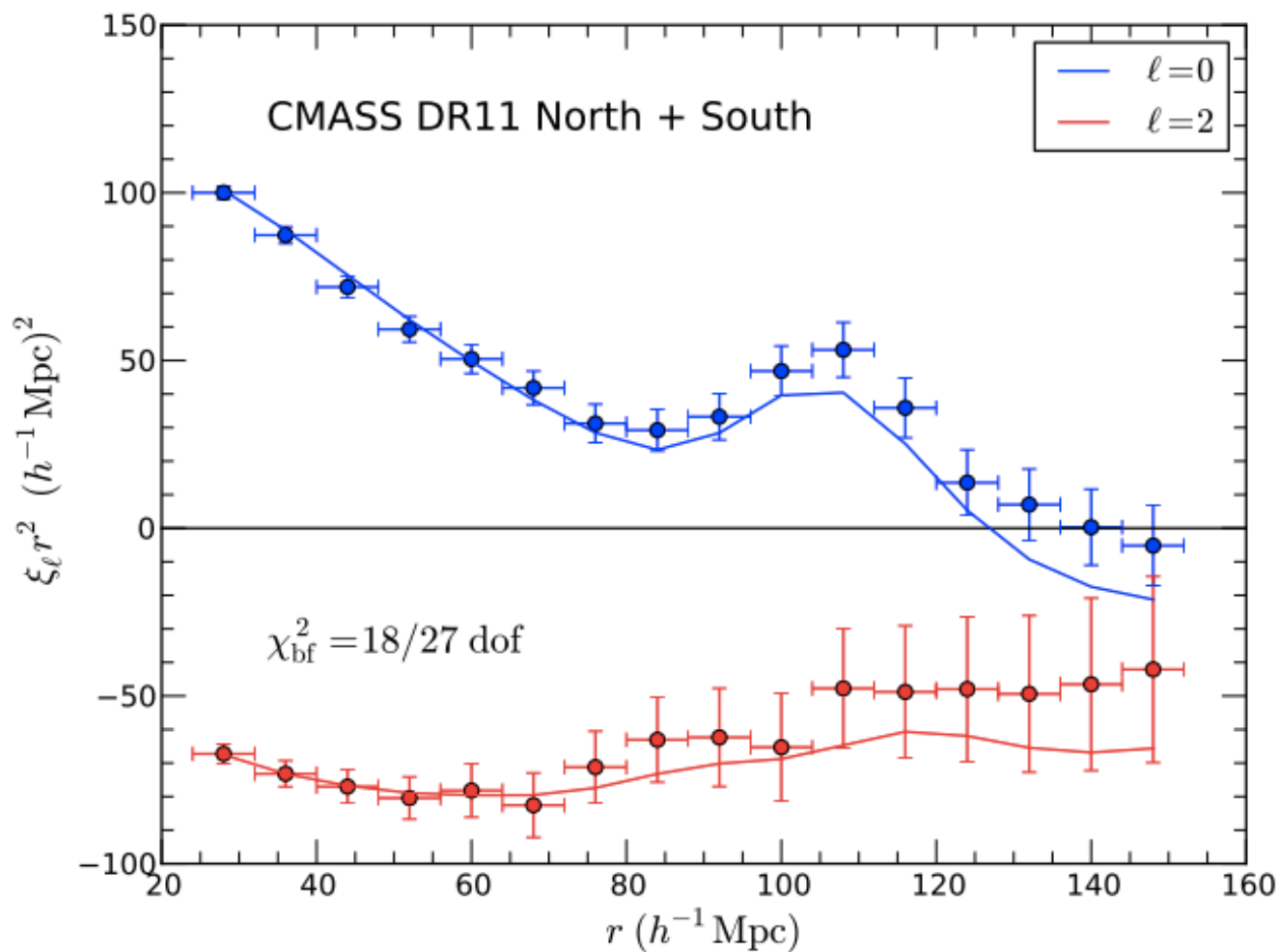
The Cosmic Fire Escape



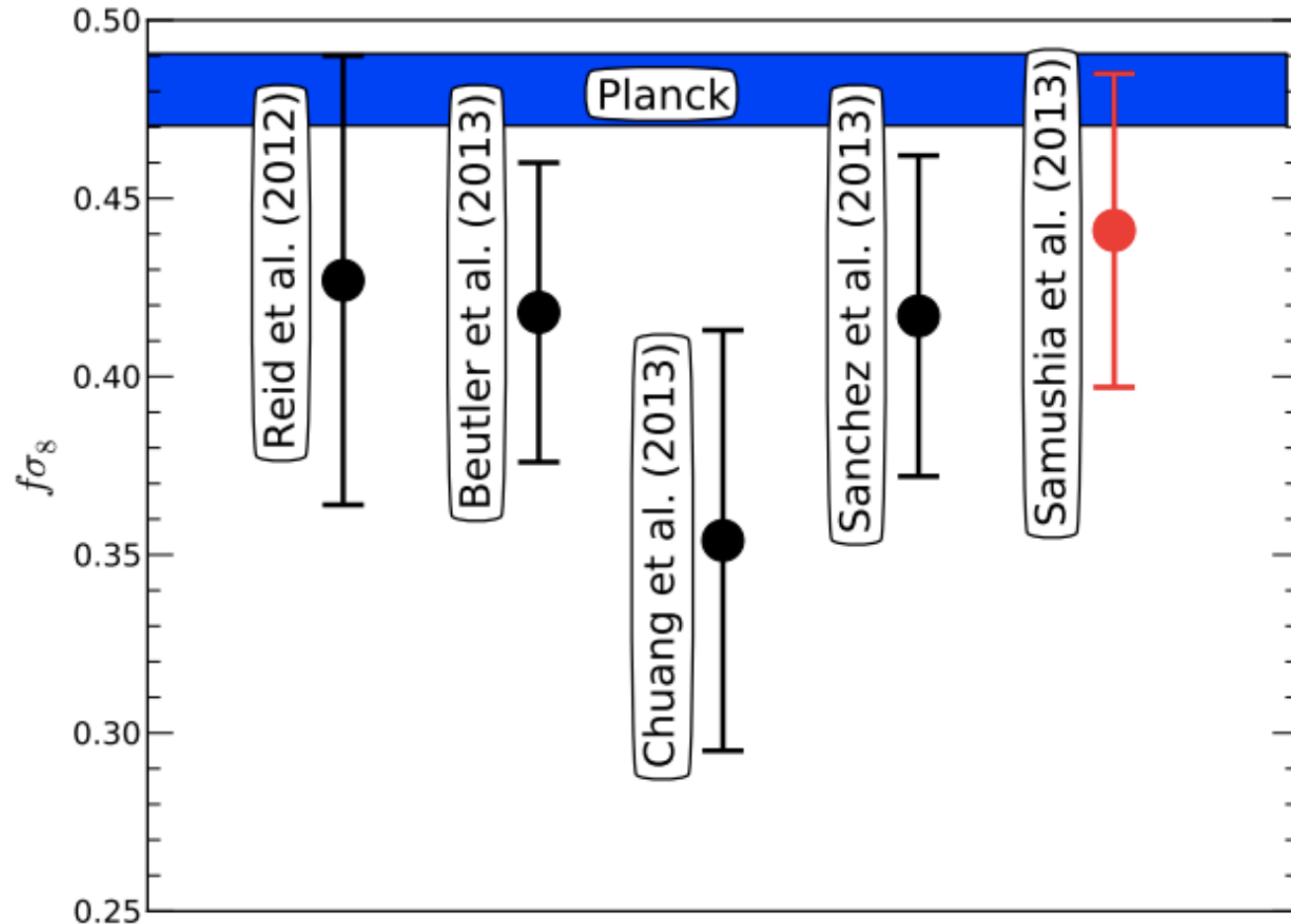
Tensions in the Hubble Constant?



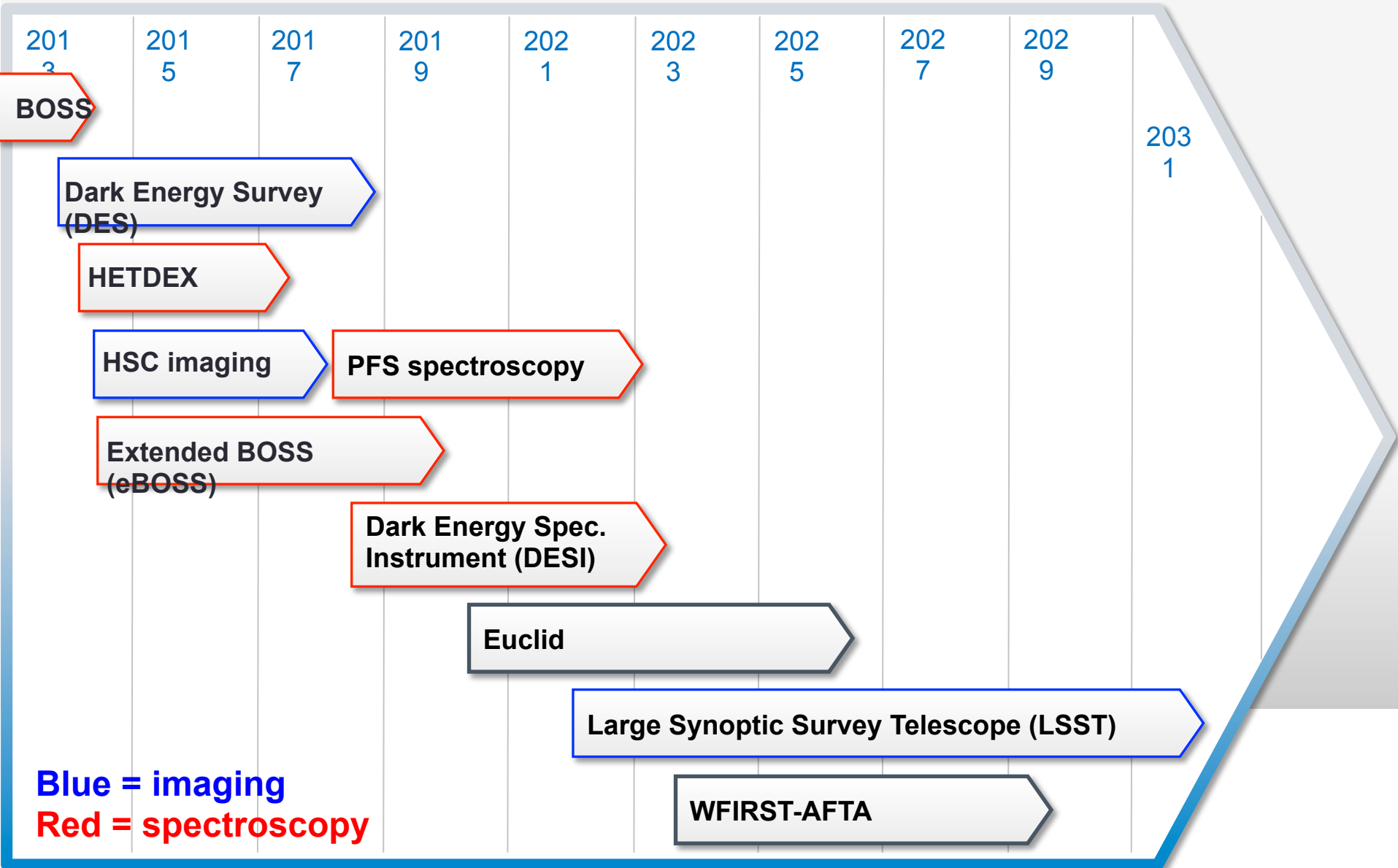
Fitting the full correlation function



Constraints on growth



Dark Energy Experiments: 2013 - 2031



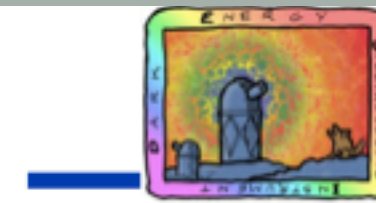
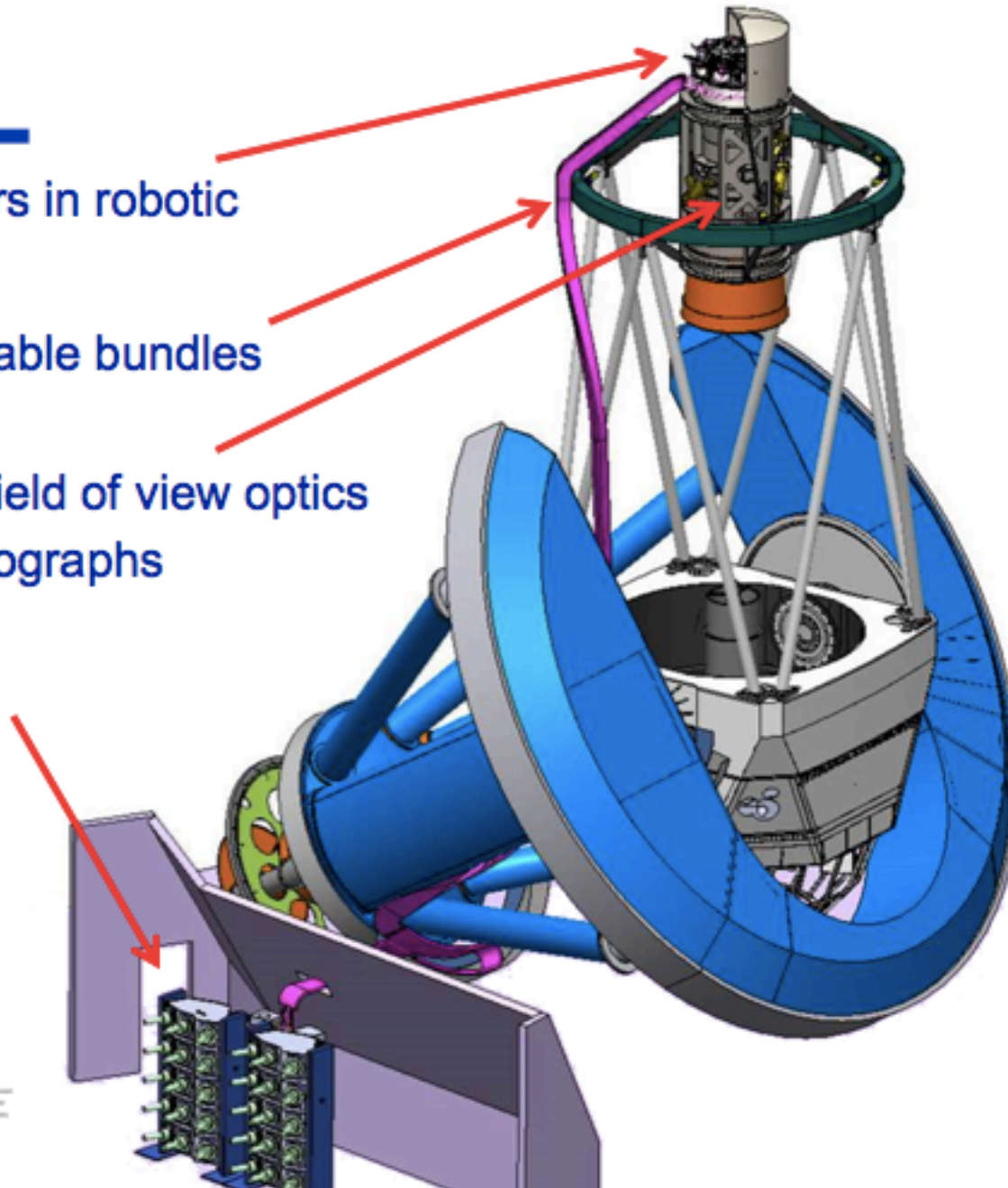
... and many others (JPAS, PAU, KIDS..)

Weinberg et al, Snowmass 2013

DESI

- 5000 fibers in robotic actuators
- 10 fiber cable bundles
- 3.2 deg. field of view optics
- 10 spectrographs

Readout
& Control

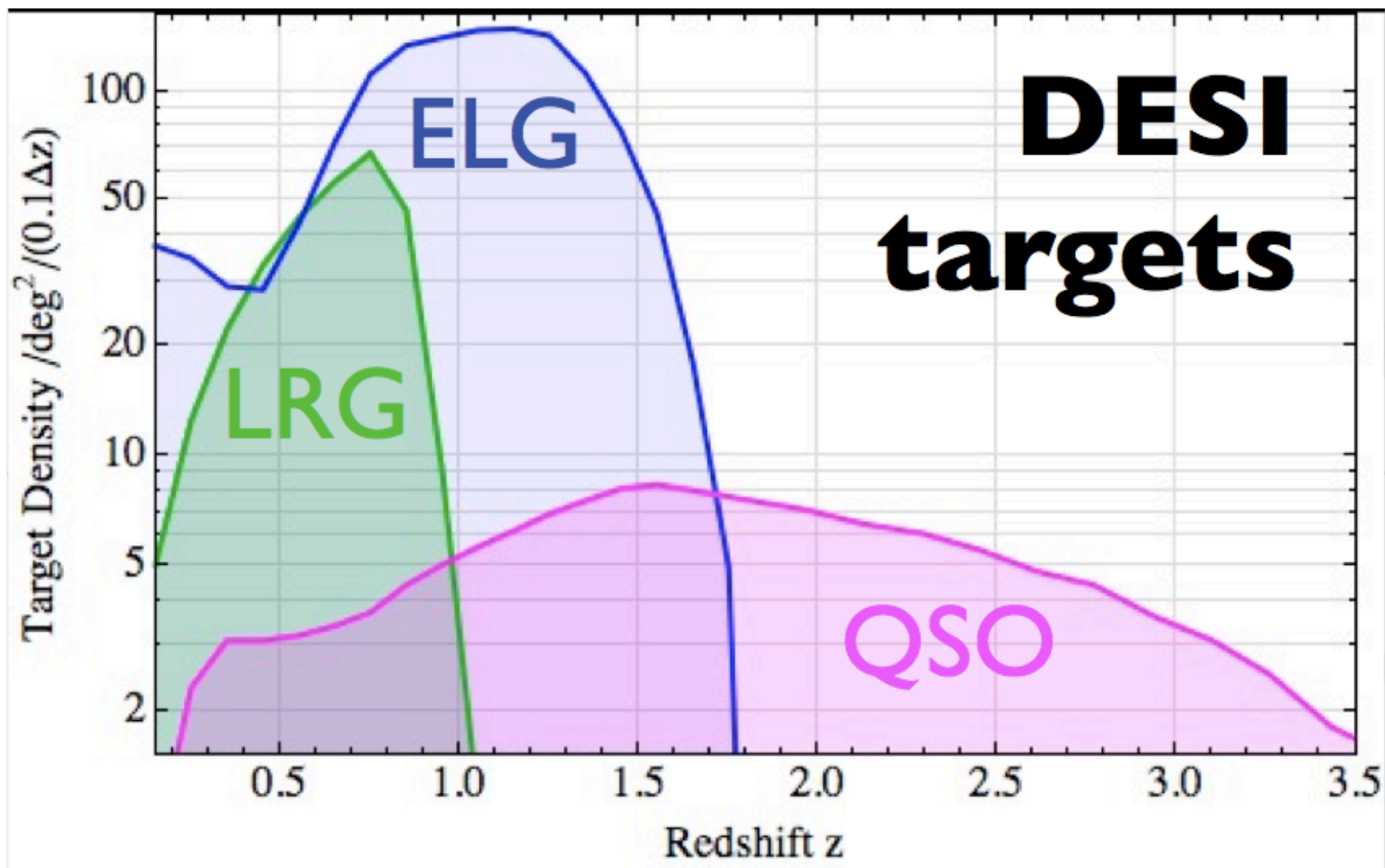


**Mayall 4m
Telescope
Kitt Peak
Tucson, AZ**

The DESI Survey

- 2018-2023
- 14000 sq. deg.
- Tracers
 - Bright galaxy survey ($r < 19.5$, $z < 0.2$)
 - Red galaxies ($z < 1$)
 - Emission line galaxies ($z < 1.7$)
 - Tracer QSOs ($1 < z < 3$)
 - Lyman-alpha forest
 - Designed to have multiple possible cross correlations
- Imaging
 - DECam data ($\text{dec} < 30$) : 9000 sq.deg --- these data will be made public over the next ~4 years
 - Bok, Mosaic data ($\text{dec} > 30$)
 - WISE data

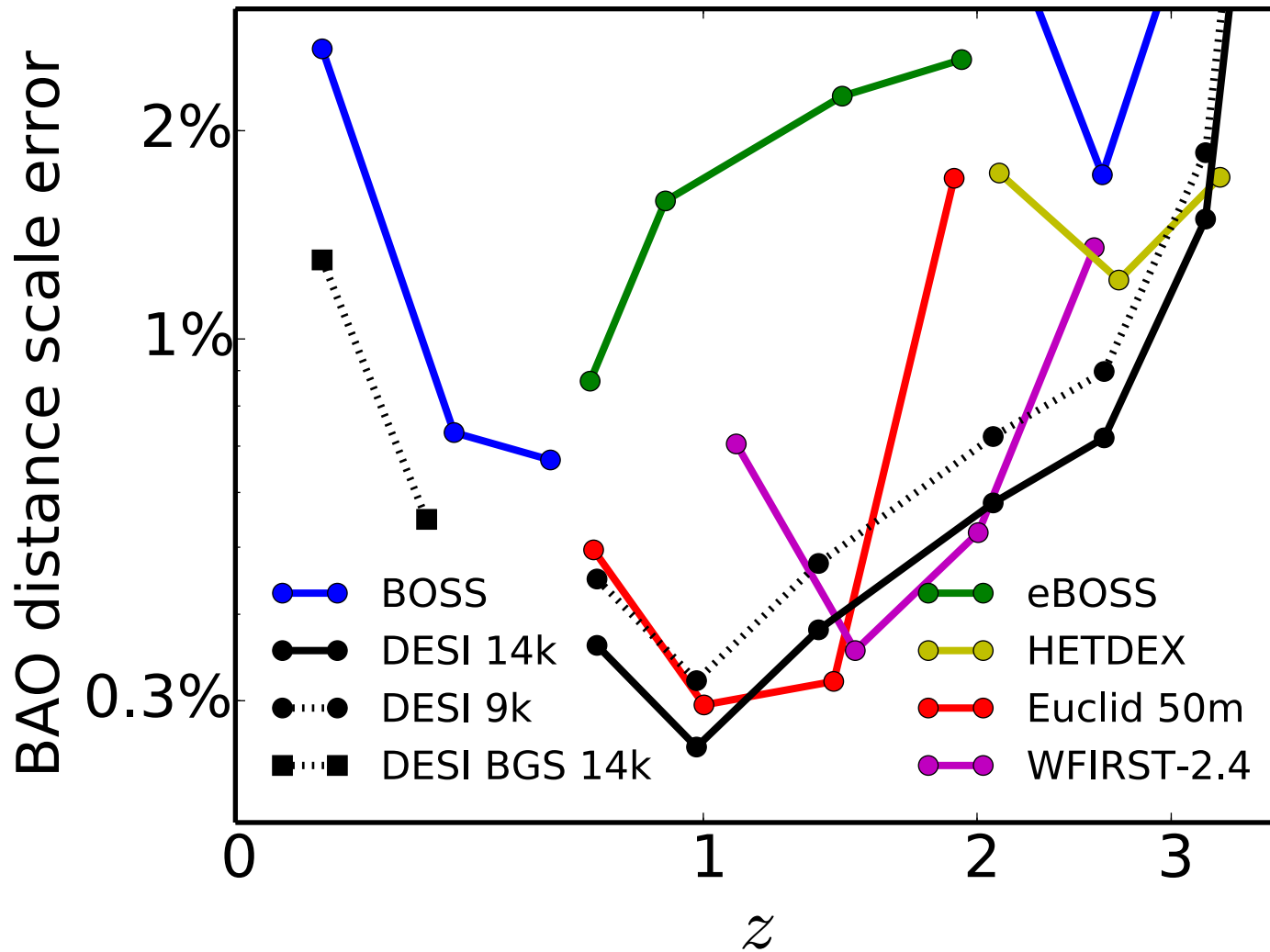
DESI Targets



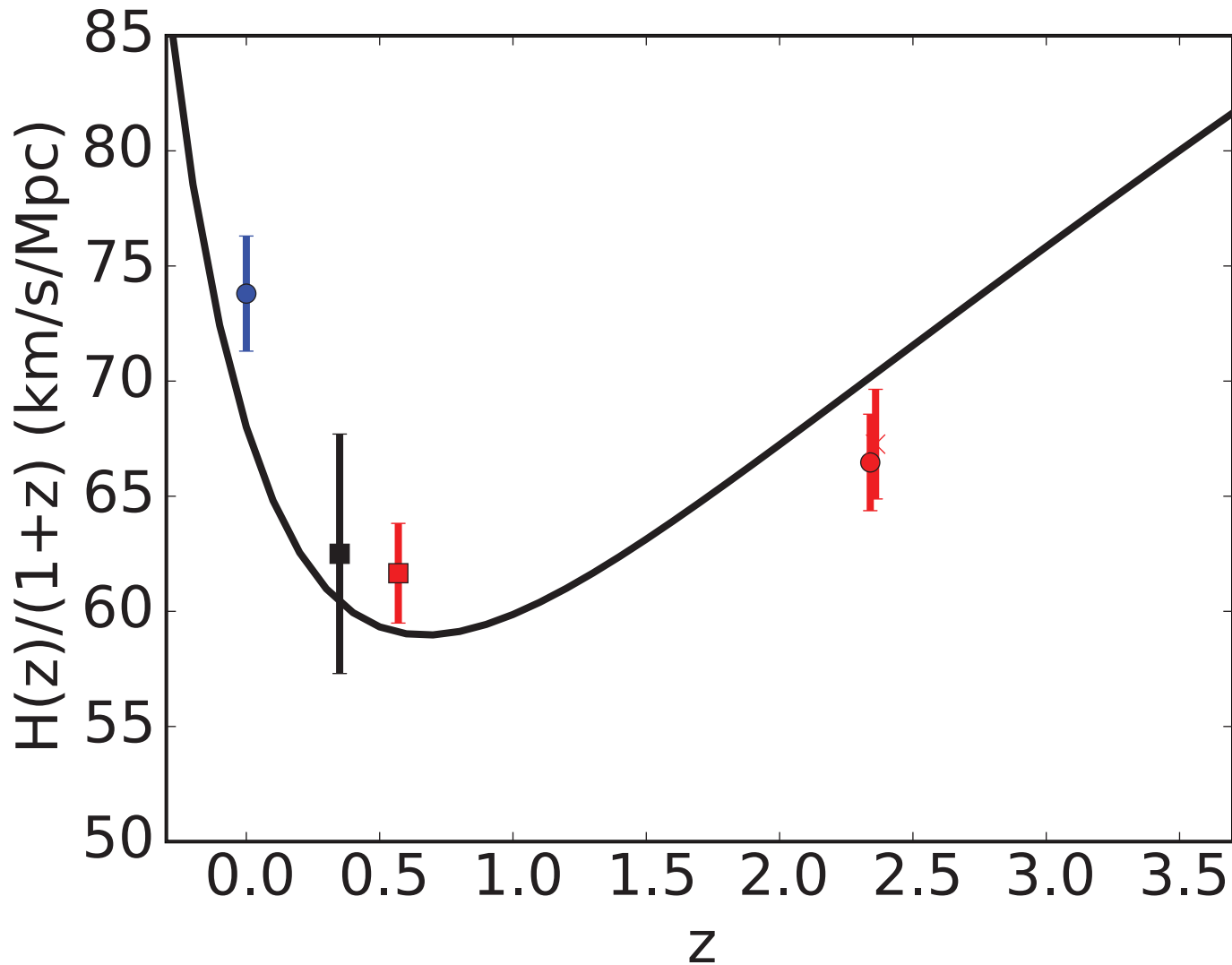
The DESI Survey

- 14000 sq. deg.
- Tracers
 - Bright galaxy survey ($r < 19.5$, $z < 0.2$)
 - Red galaxies ($z < 1$)
 - Emission line galaxies ($z < 1.7$)
 - Tracer QSOs ($1 < z < 3$)
 - Lyman-alpha forest
 - Designed to have multiple possible cross correlations
- Imaging
 - DECam data ($\text{dec} < 30$) : 9000 sq.deg --- these data will be made public over the next ~ 4 years (g,r,z : 25,24,23)
 - Bok, Mosaic data ($\text{dec} > 30$) (g,r,z)
 - WISE data (W1, W2)

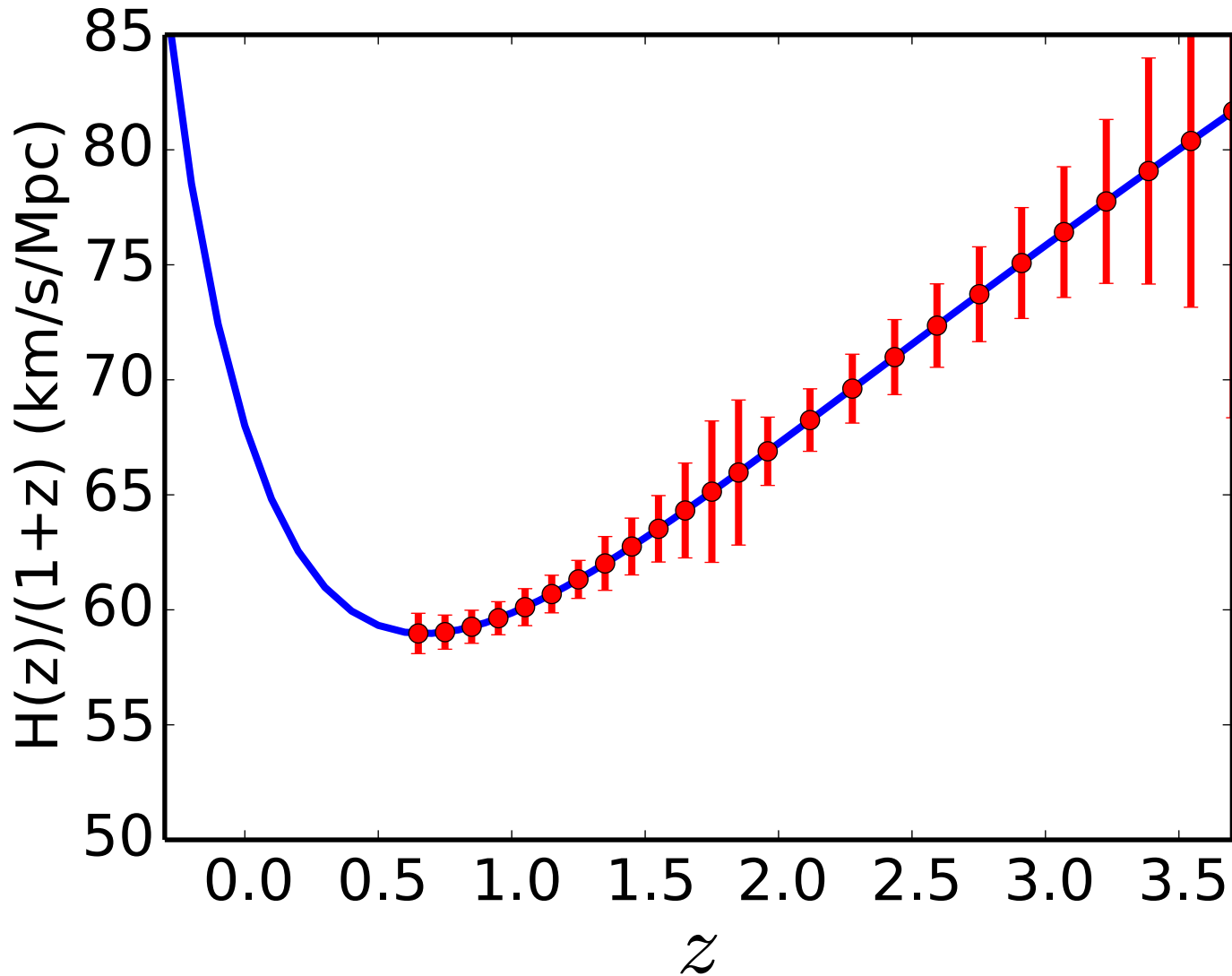
Forecast Distance Errors



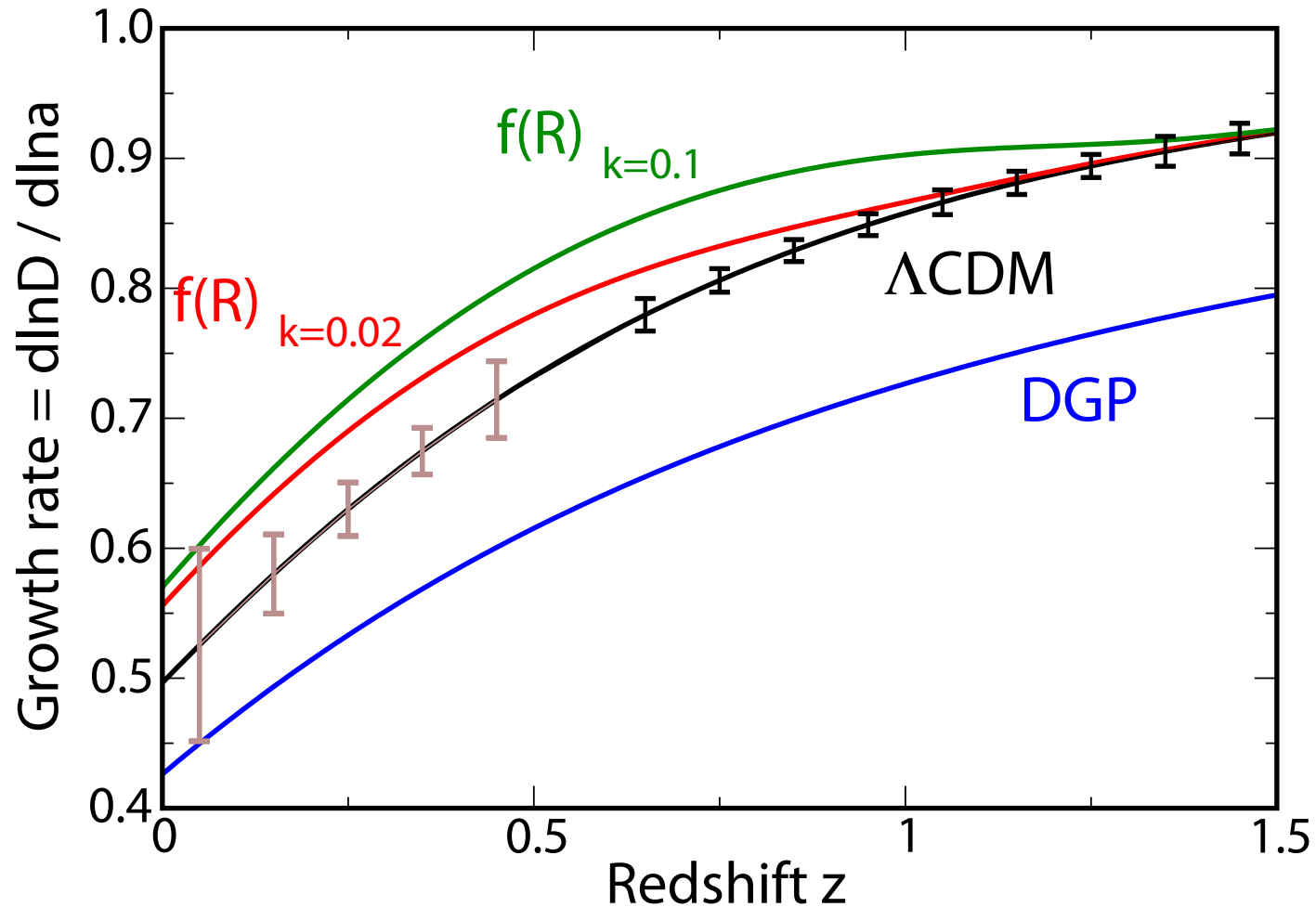
Current Hubble Diagram



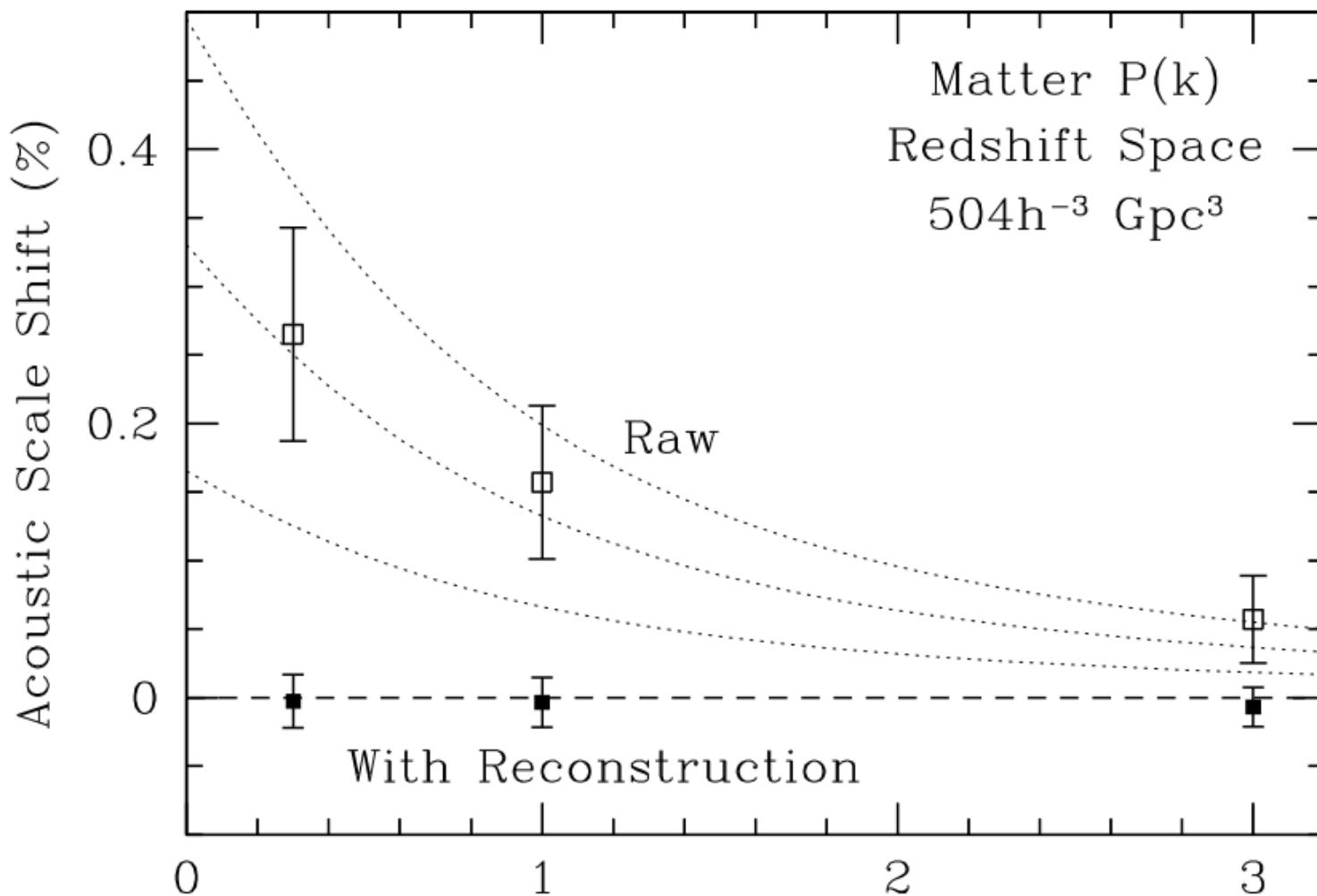
The DESI Hubble Diagram



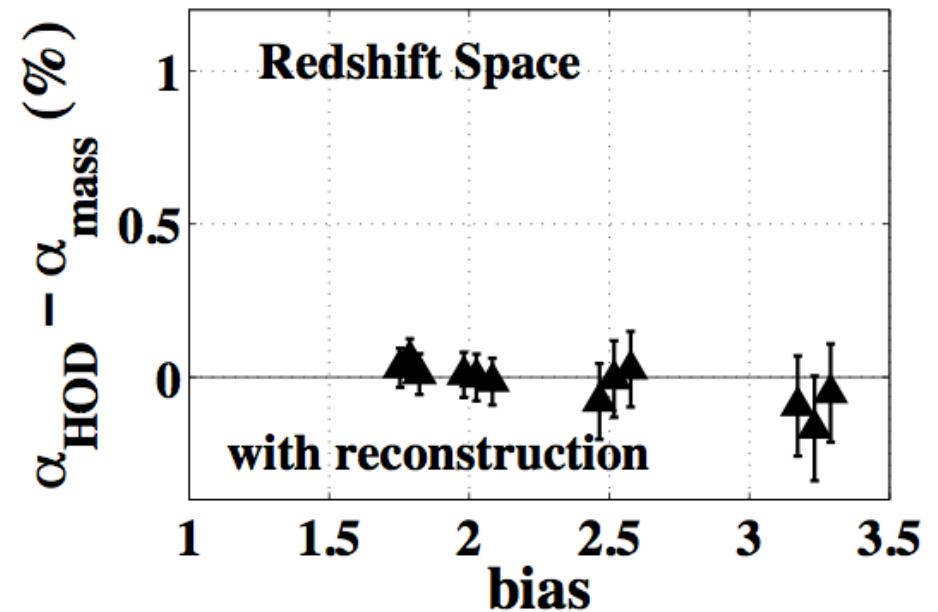
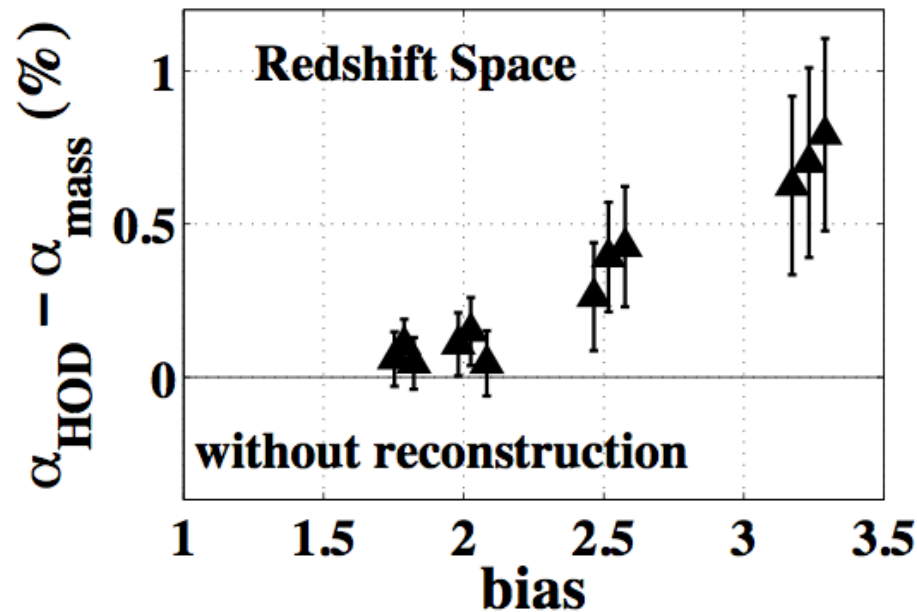
DESI measures the growth of structure



Robustness of the BAO ruler



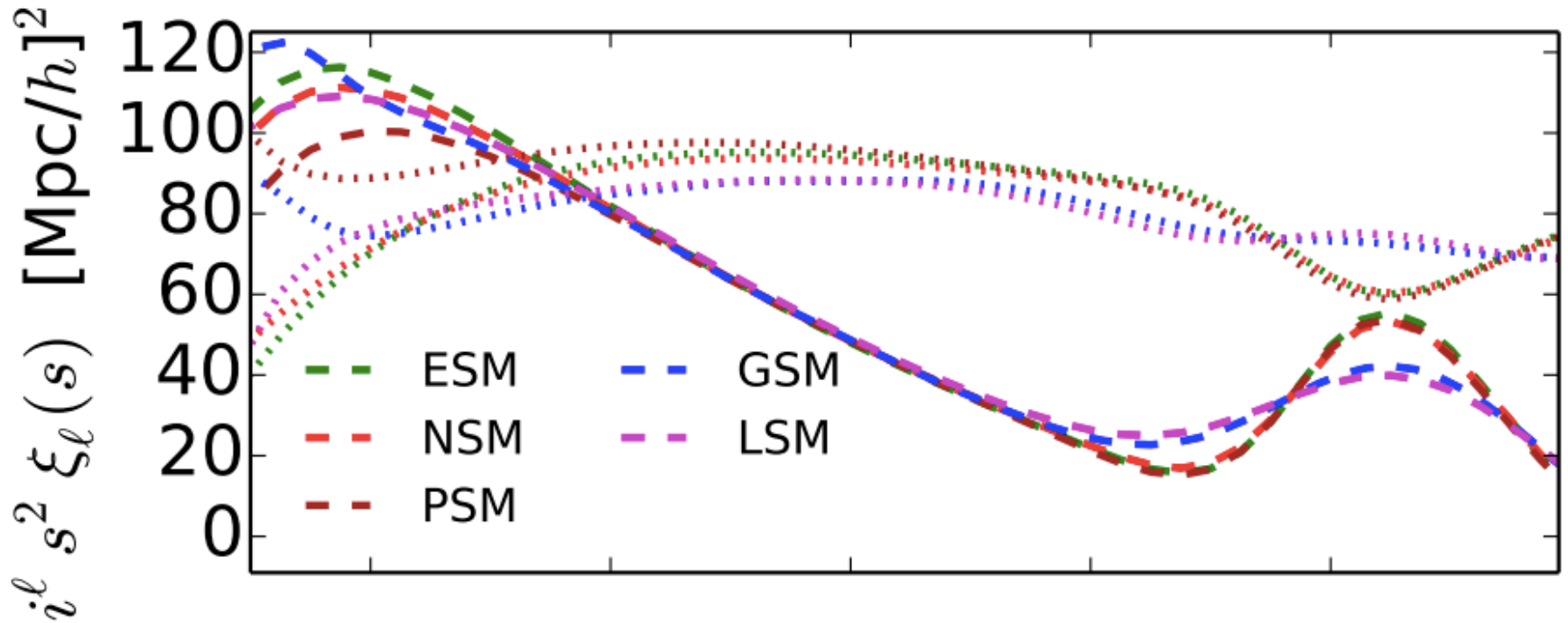
Robustness of the BAO ruler



Mehta et al, 2011

Robustness of the BAO ruler understood both through simulations and theory;
eg. Crocce & Scoccimarro 2007, NP & White 2009, Sherwin & Zaldarriagga 2012

Predicting the shape of the two-pt function



White et al, 2014

WFIRST-AFTA will enable cross-checks with different samples

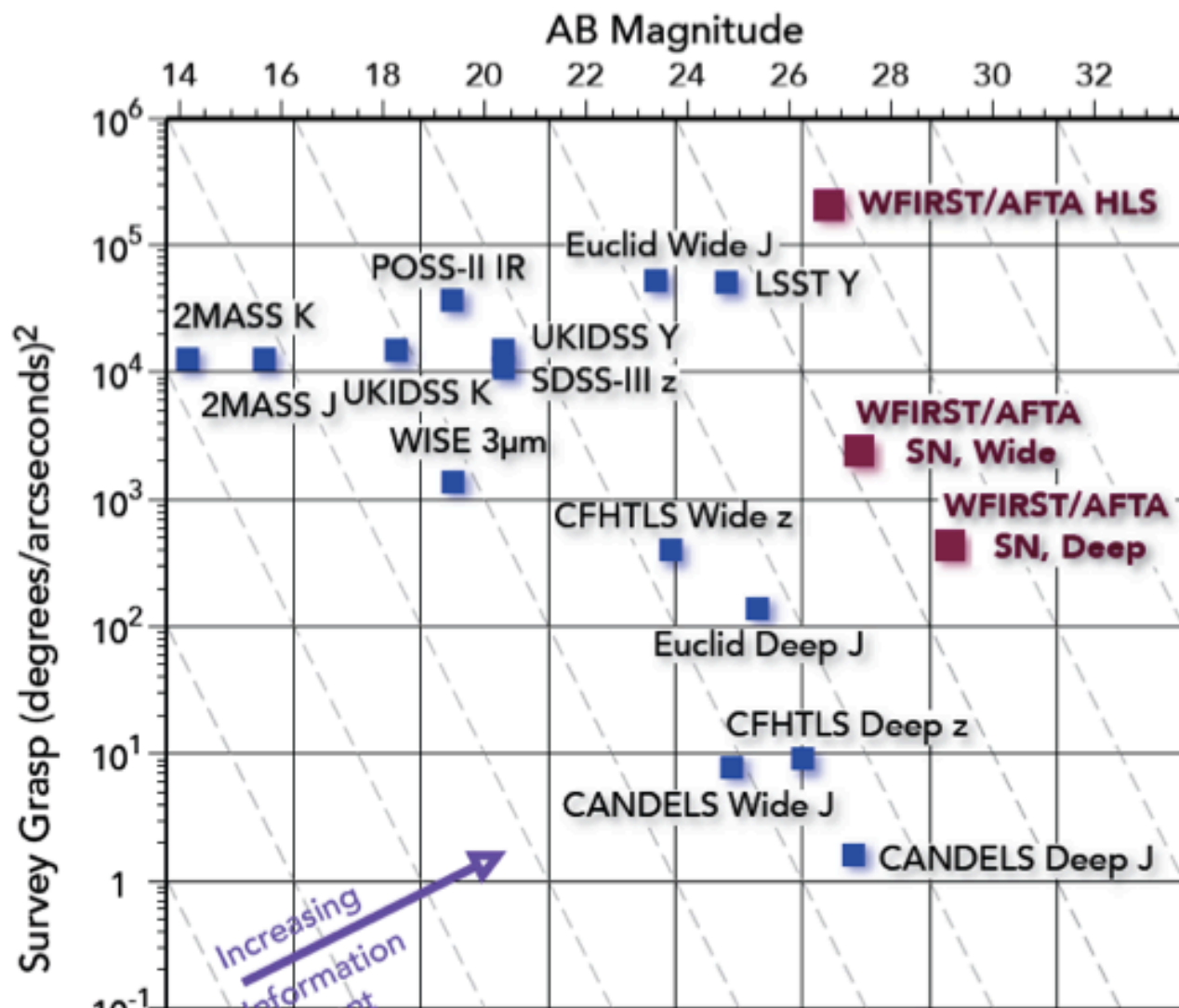
Designing next generation surveys

- Simplest picture : volume, number density, tracers

$$\begin{aligned} V_{\text{eff}}(k, \mu) &= \int \left[\frac{n(\mathbf{r})P(k, \mu)}{n(\mathbf{r})P(k, \mu) + 1} \right]^2 d\mathbf{r} \\ &= \left[\frac{nP(k, \mu)}{nP(k, \mu) + 1} \right]^2 V_{\text{sur}} \\ &= \left[\frac{nP(k)(1 + \beta\mu^2)^2}{nP(k)(1 + \beta\mu^2)^2 + 1} \right]^2 V_{\text{sur}}, \end{aligned}$$

DE surveys have chosen minimal number density, maximal area
What k scale? Current surveys make conservative choices
HLS makes a different trade

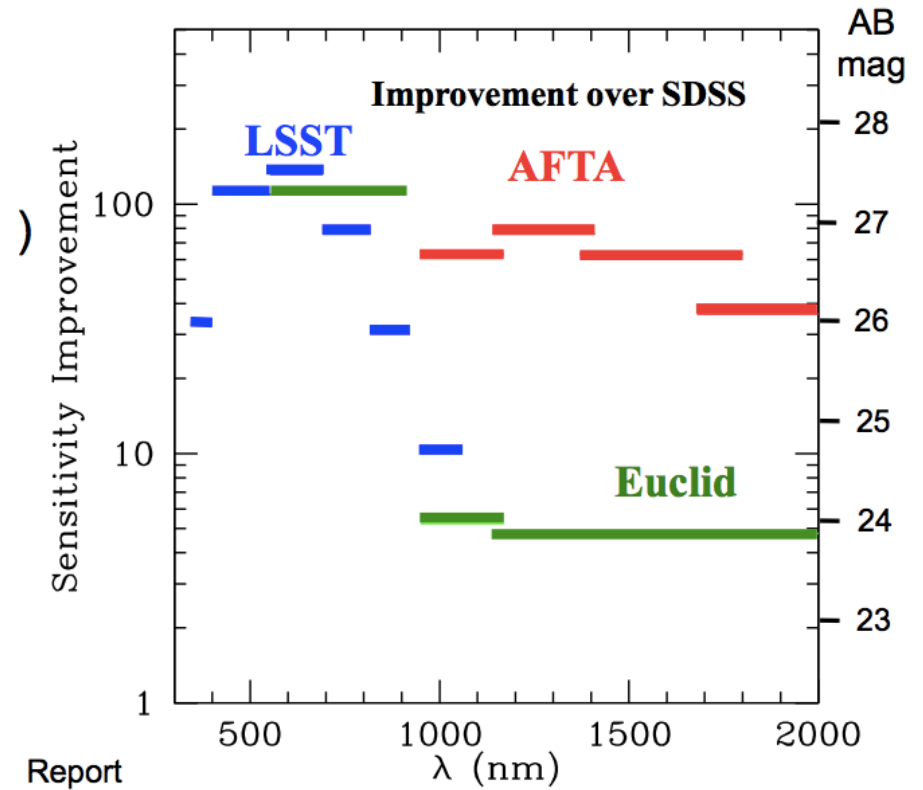
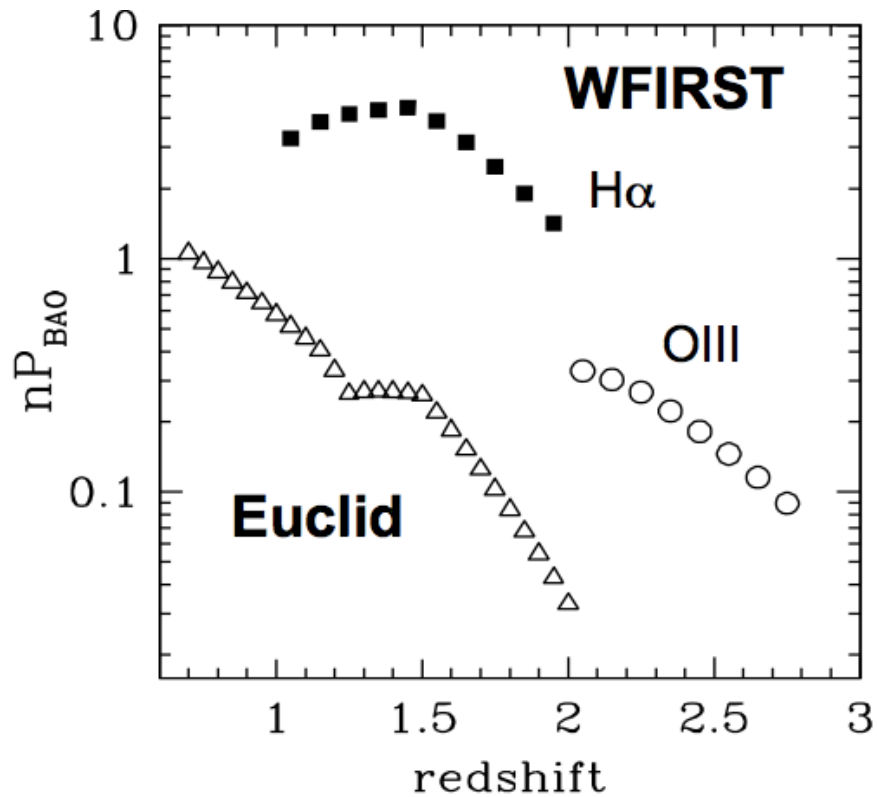
WFIRST-AFTA compared



Areas

Number densities

WFIRST-AFTA compared



Some concluding thoughts

- Measurements in the WFIRST-AFTA era
 - Distance measurements ($z < 3$)
 - Sparse galaxies at high redshift
 - Overlapping DESI Lyman-alpha forest measurements
 - Growth measurements
 - $z < 2$ from the ground
 - $2 < z < 3$: newer with AFTA
- Beyond two points
 - Higher order correlations
 - Reconstruction of (initial) density fields
- Modeling/ Analysis
 - Good shape for BAO, although interesting observational challenges left
 - Larger uncertainties for RSD; AFTA offers a number of cross-checks (not unique)