Overview of BOSS, LSST and DESI

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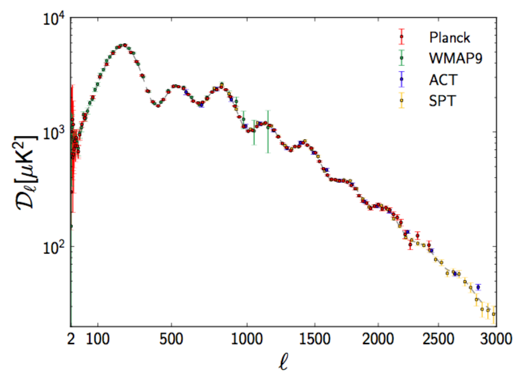
IPA 2014

Plan for the talk

- Scope very large, so talk will necessarily skim over important issues
- Potential in low-z surveys
- BOSS and BAO measurements
- DESI, LSST and the end of this decade
- Forecasts for relevant parameteres

CMB results



- Cosmic Microwave Background measurements form the cornerstone of modern cosmology
- See talk by Steven Gratton
- The main strength lies in the ease of theory predictions: linearized general relativity
- Minimal 6-parameter model can explain thousands of very high SNR data
- It is a measurement at $z = 1150$, mostly very degenerate to low-z universe
- Not the right tool to do dark energy or modified gravity

Brave New World: clustering in low-z universe

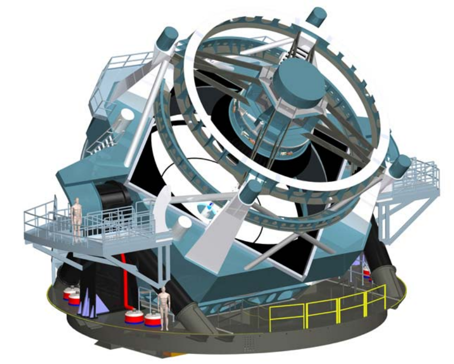
- Imagine how much physics we could do if we could model the low-redshift universe the same way we do CMB.
- Number of modes in CMB: $\sim 6 \times 10^6$ to $\ell = 2500$
- Number of modes in galaxy clustering $\sim 10^9$ (depending how you count)
- Can probe dark-energy, neutrino masses, small scales, etc.
- But can we model the low-z universe the same way we model power spectrum of CMB?

Low-z universe is hard!

- CMB is easy:
  - Initial fluctuations have a simple Gaussian structure and are small
  - Passively evolved to the decoupling using linearized GR
  - Can calculate them to arbitrary precision using well-understood perturbative schemes.
- Low-redshift universe seem hard:
  - After decoupling baryons fall into potential wells created by dark matter
  - Then gastrophysics takes over: gas cools, first stars alight, first supernovae explode, polluting their environments with metals...
  - We observe galaxies in redshift-space, their radial coordinate is the sum of real distance and peculiar velocity

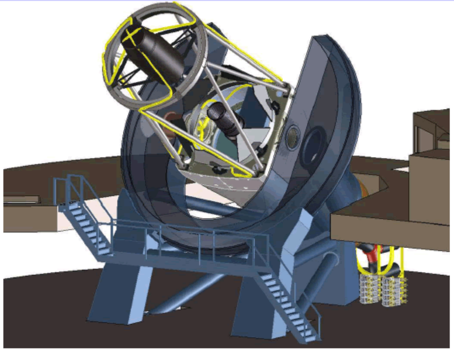
$$s = r + v_r$$

  - *All hell breaks loose!*



Photometric experiments:

- Take pictures of the sky
- 5 bands can give an estimate of a redshift
- Can measure billions of objects
- Biggest promise for cosmology is gravitational lensing
- CHFTLS, DES, Hyper Suprime-Cam, LSST, Euclid



Spectroscopic experiments:

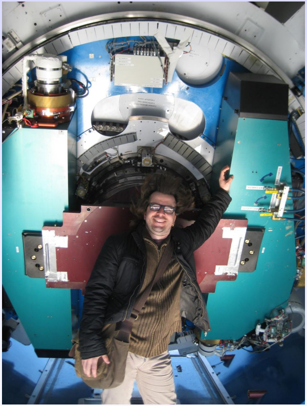
- Takes spectra of objects
- Spectra give redshifts and robust typing-real 3D experiment
- Need to use photometric data for targeting
- BAO, galaxy power spectrum, redshift-space distortions
- BOSS, eBOSS, DESI, Euclid

Baryon Oscillation Spectroscopic Survey (BOSS)

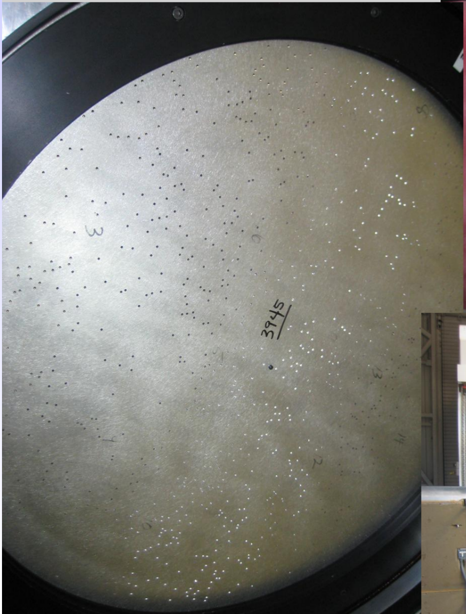
- BOSS is one of 4 experiments making up SDSS3.
- Uses 2.5m SDSS telescope
- Large etendue
- A 1000 fiber spectrograph
- Medium resolution: $R \sim 2000$
- Wavelength: 360nm (UV) 1000 nm (IR)

Baryon Oscillation Spectroscopic Survey (BOSS)

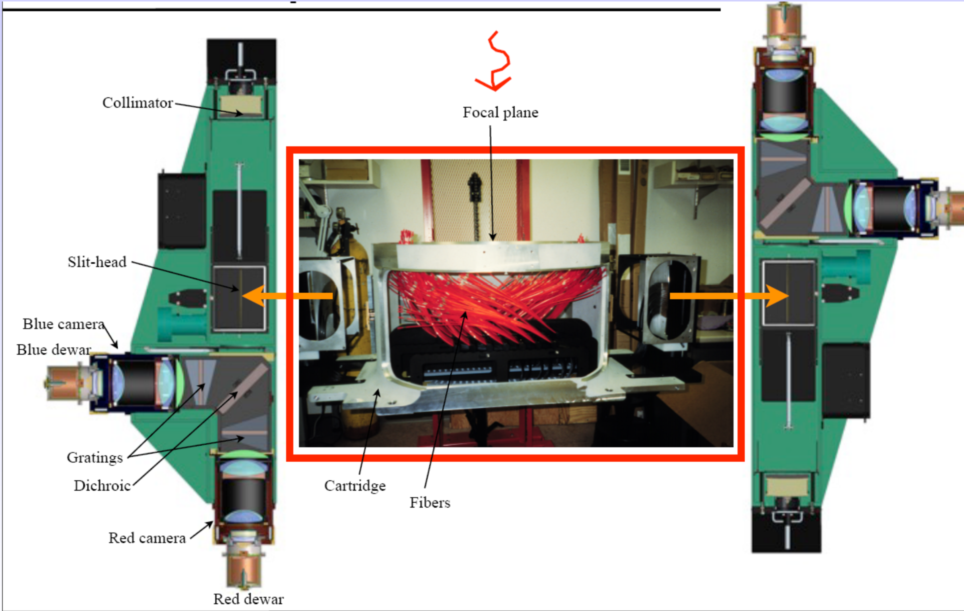
- Finished observations in June 2014 and got
  - 1.5 million LRG ($z < 0.7$)
  - 160,000 QSOs with usable forest
- Primary science goal is to measure dark energy through Baryonic Acoustic Oscillations.



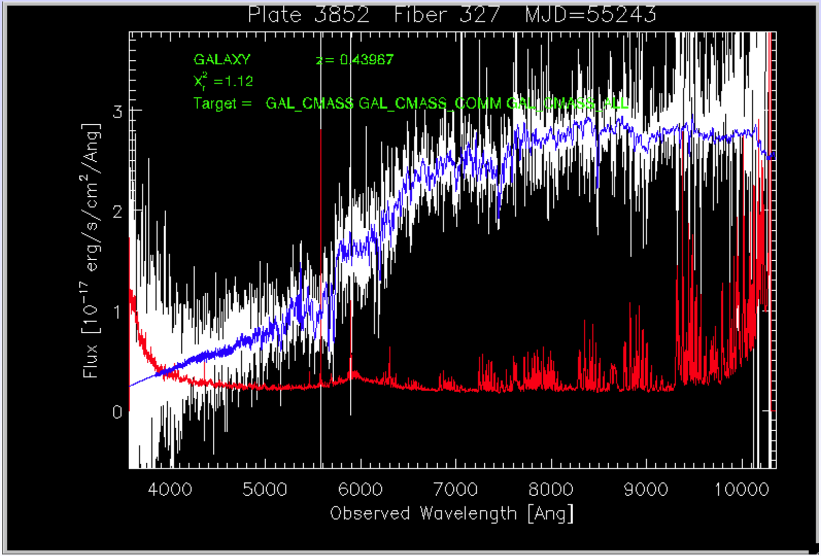
How BOSS works?



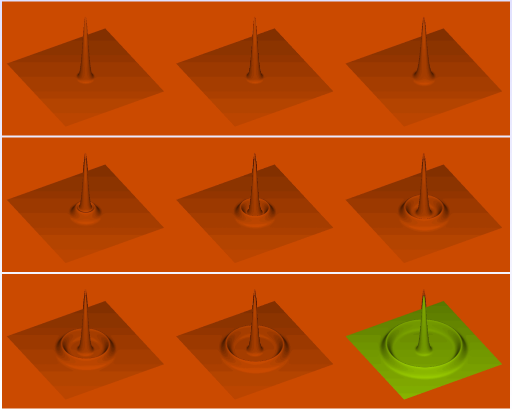
How BOSS works?



BOSS spectra

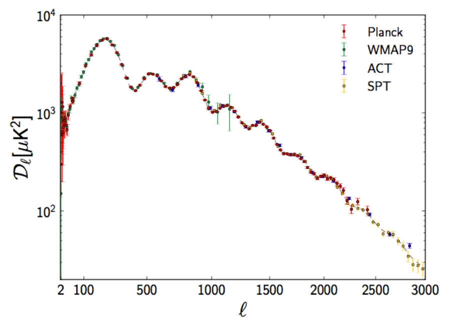


What is BAO?

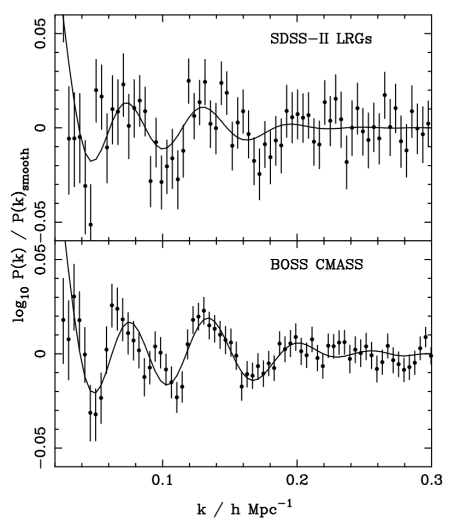


- Before recombination (i.e. formation of hydrogen atoms), primordial plasma supports acoustic waves
- Sound waves travel through Universe as long as it is in primordial plasma state
- We can see them in CMB power spectrum
- The characteristic scale is imprinted as a small bump into the correlation properties of dark matter
- It acts as a standard ruler, allowing very robust measurements of the expansion history of the universe.

What is BAO?

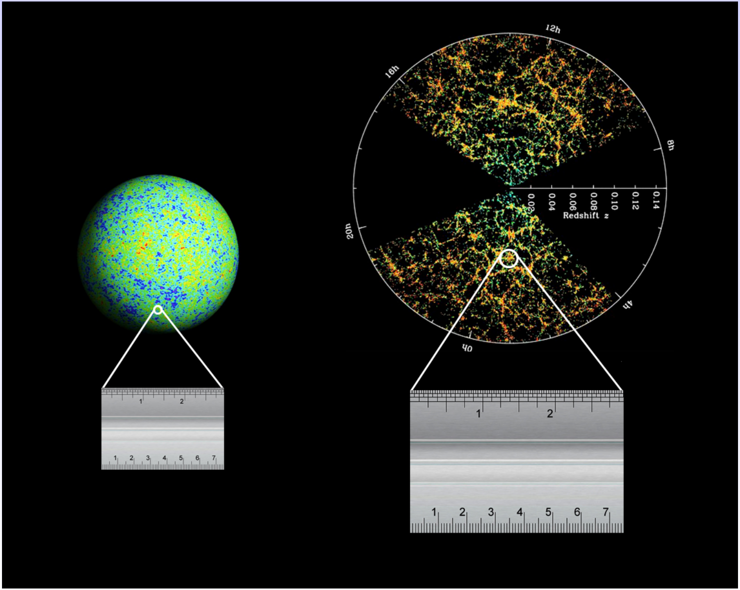


BAO in Cosmic Microwave Background

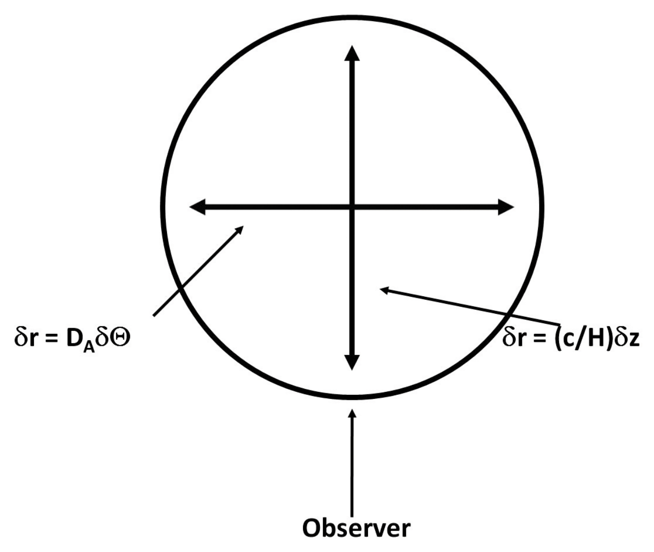


BAO in CMASS galaxies

BAO is a statical ruler

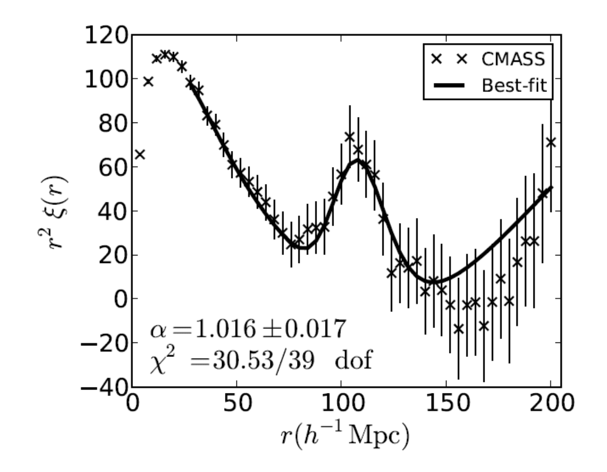


BAO is a statical ruler

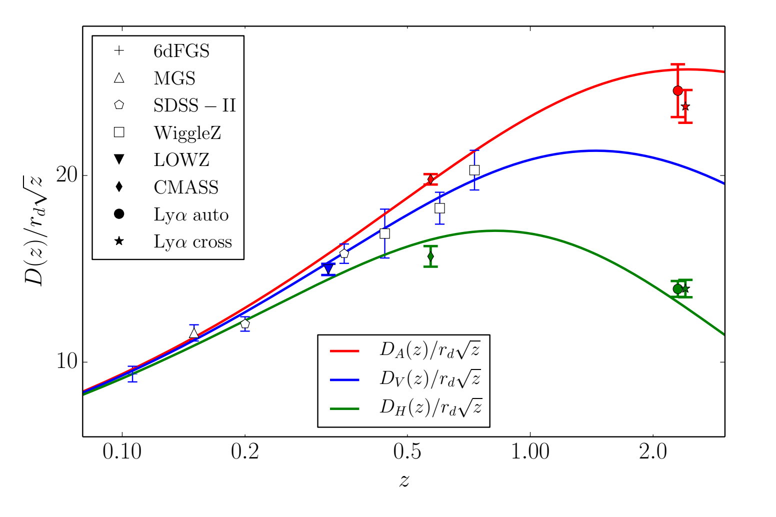


BAO measurements with galaxies

- Measuring BAO at low redshift ($z < 1.0$) became a standard lore of cosmology.
- You can have broadband contaminants that don't affect your measurement

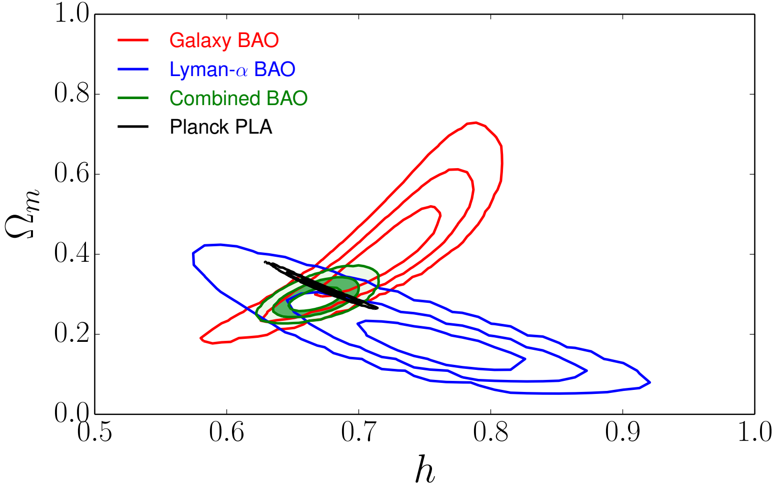


World BAO data

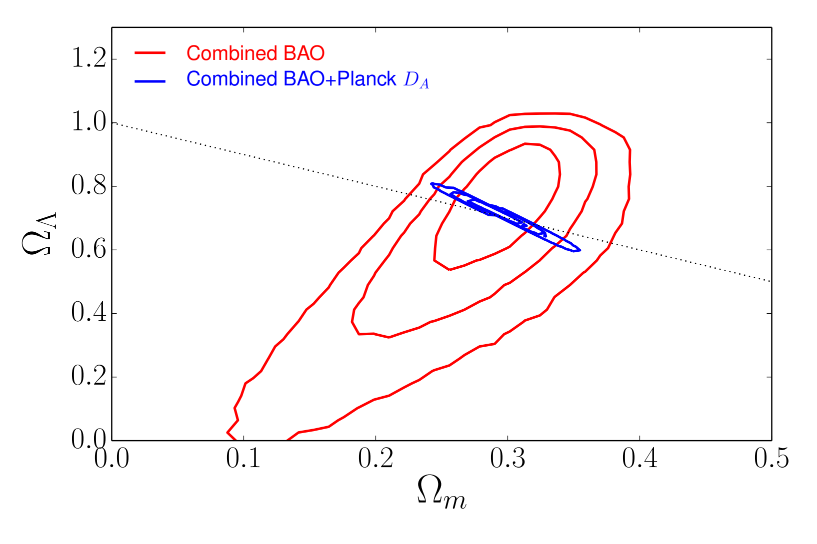


- Collection of world BAO data
- Lines are Planck best fit *predictions*

ΛCDM BOSS BAO

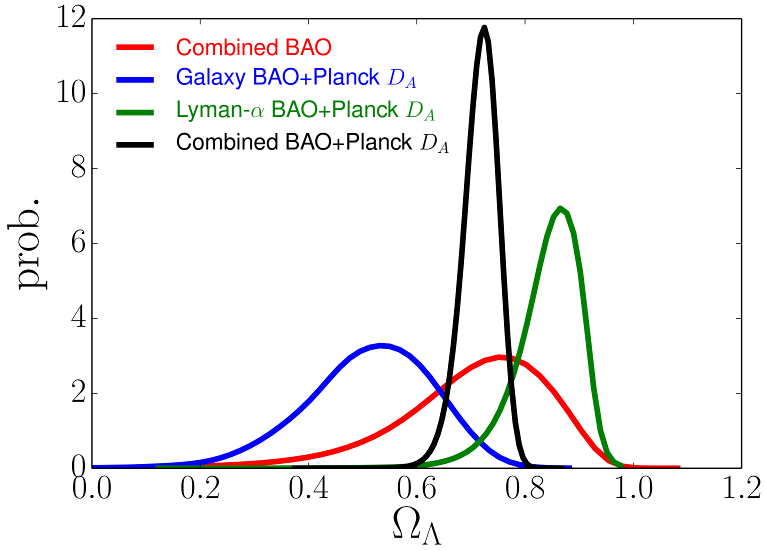


World BAO data

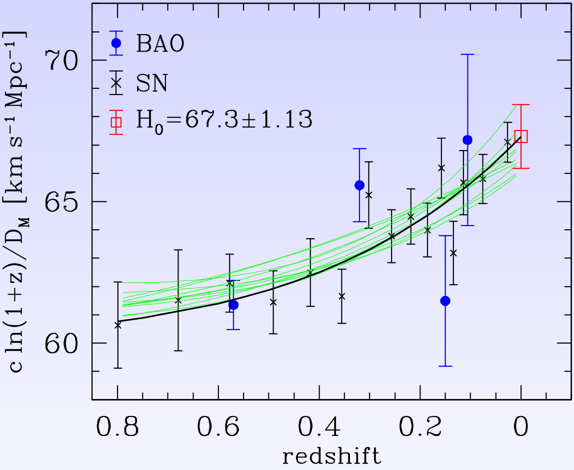


- BAO data alone detect the dark energy at $> 3\sigma$

World BAO data

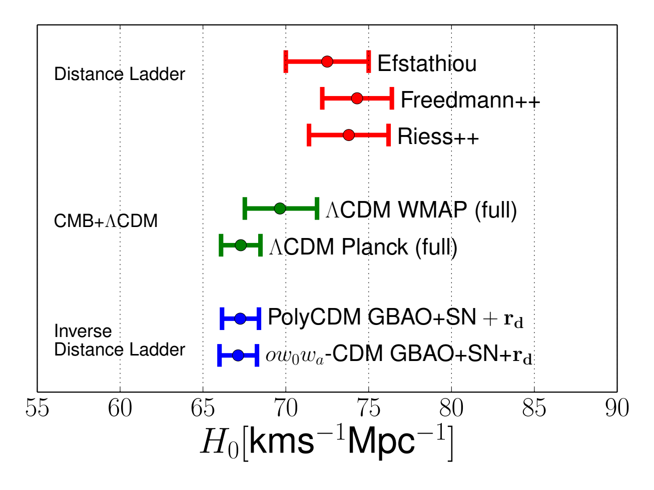


Inverse distance ladder



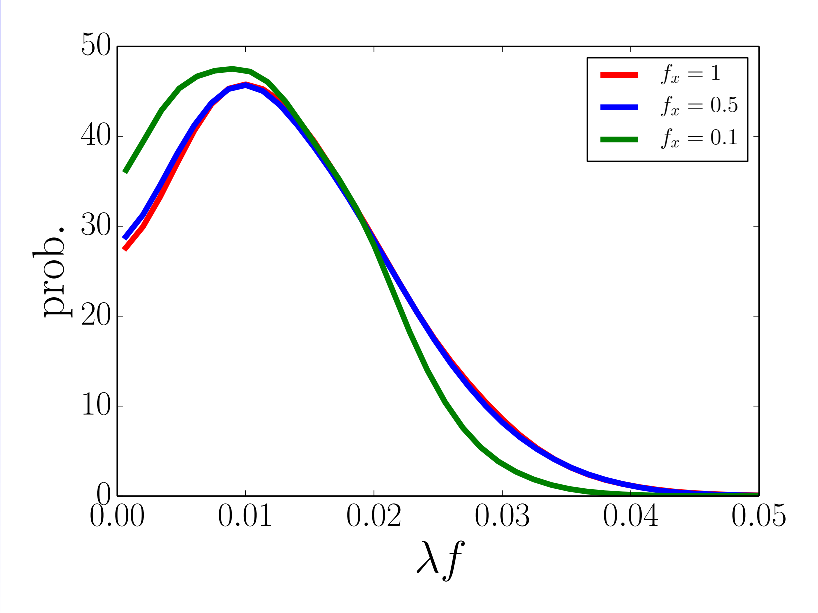
- Inverse distance ladder transfer H_0 measurement from redshift of observation to $z = 0$ using Supernovae Type Ia

Inverse distance ladder



- BOSS prefers low-h Universe: $H = 68.1 \pm 1.2$

Constraints on decaying dark-matter



Galaxy clustering: relying on symmetries

Two very robust assumption about the galaxy formation process:

- The only field that matters on large scales are the fluctuations in the matter fluctuations $\rho_m = \bar{\rho}_m(1 + \delta_m)$
- The galaxy formation process is local on some scale R:

$$\delta_g(\mathbf{x}) = F[\delta_m], \tag{1}$$

  where F is an arbitrary functional that, however vanishes for distances larger than R from $\mathbf{x}$.

Under these assumptions, in the $k \to 0$ limit, galaxies in redshift-space must trace dark-matter following

$$\delta_g(\mathbf{k}) = (b_\delta + b_\eta f \mu^2)\delta_m(\mathbf{k}) + \epsilon, \tag{2}$$

where bs are bias parameters and ϵ is a white noise stochastic variable.

Galaxy clustering: relying on symmetries

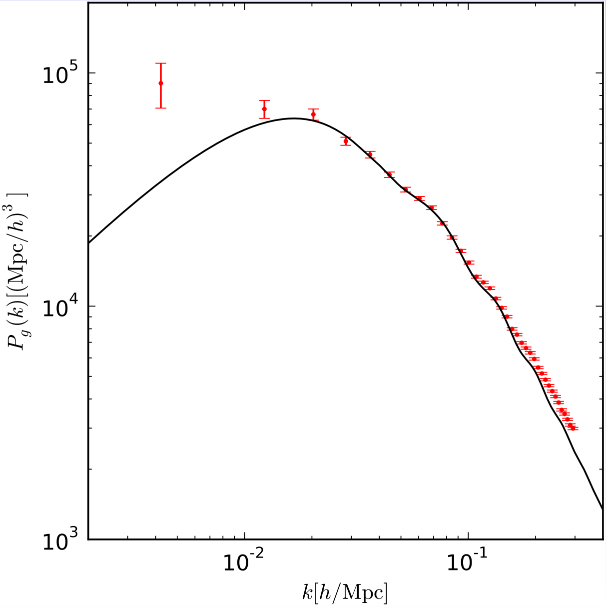
Under these assumptions, in the $k \to 0$ limit, galaxies in redshift-space must trace dark-matter following

$$\delta_g(\mathbf{k}) = (b_\delta + b_\eta f \mu^2)\delta_m(\mathbf{k}) + \epsilon, \tag{3}$$

This has all been derived with galaxies in mind (where one can show $b_\eta = 1$), but it is true for any local tracer and I am emphasizing the EFTish aspects.
Going to small scale gives:

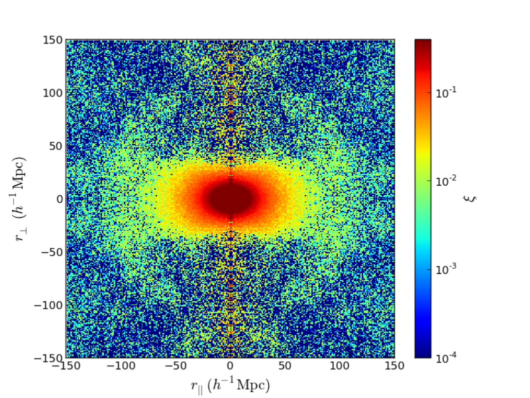
- More bias parameters: quadratic terms b_2, tidal terms b_{s^2}, etc.
- $k^2 R^2$ series correction to each bias parameter
- Similar terms for redshift-space distortions
- Fingers of God!
- Number of papers: McDonald & Roy, Seljak & McDonald, Schmidt et al, Scoccimarro et al., Ferraro et al., and all the paper-trail following...

Galaxy correlations in BOSS DR11



- Monopole power spectrum used in Anderson et al
- Note large scale junk
- Note the idiotic precision of the measurement
- Note small deviation from linear biasing kicking in as we go to smaller scales

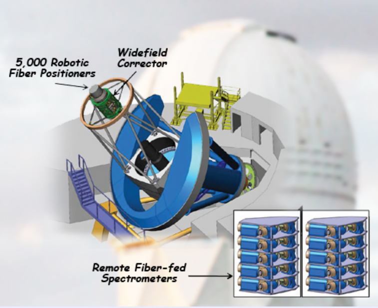
Galaxy correlations in BOSS DR11



- Redshift-space correlation function in BOSS DR11 (Samushia et al, arXiv:1312.4899)
- Note large RSD and small FoG (life not always so good)
- These measurements constraint growth parameters (modified gravity, dark energy, etc.)

Dark Energy Spectroscopic Instrument

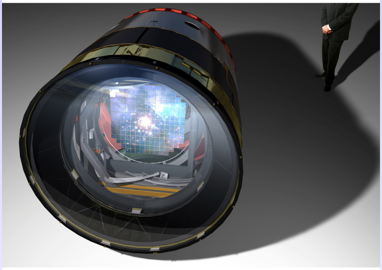
- BigBOSS+DESpec = DESI
- 4000 fiber robotically actuated spectrograph on 4m Mayal telescope
- Order of magnitude more powerful than BOSS with 20-30 millions measured spectra.
- Excellent complimentarity with photometric surveys such as LSST
- A DOE experiment run in the tradition of particle physics



Science:

- Will measure 3D power spectrum of galaxies with unprecedented precision
- Main project is measuring expansion history through BAO
- Statistically, the anisotropic power spectrum is the most promising

Large Synoptic Survey Telescope



- Wide, fast, deep
- 3.2 Gpix camera on effectively 6.7m telescope
- 9.6 square degrees FOV – massive etendue
- Passed CD0, CD1; DOE flagship DE experiment
- First light $\sim$2019

Science:

- Will measure positions of $\sim$ 10 billion galaxies
- Missing third dimension, so essentially a few thick slices in radial direction
- Designed to measure weak lensing
- Army of people working on understanding subtle instrumental effects

Fisher Forecasts

We did a paper with extensive Fisher forecast for DESI:

- `arXiv:1308.4164`
- The title is "DESI and other dark energy experiments in the era of neutrino mass measurements", but could as well have been "Reams and Reams of Tables"
- It is important to do forecast with a single code, to have directly comparable results
- See paper for gory details on method
- Our forecasts for some of the existing quantities are withing 10%-20% accurate
- We assumed we will be able to use all information available in power spectrum modes up to $k = 0.1h/\mathrm{Mpc}$ (cons.) or $k = 0.2h/\mathrm{Mpc}$ (opt.) – in practice will fit to higher k to constrain biases
- Important to marginalize over $\sum m_\nu$, since we *know* neutrinos have mass – it is not a fancy extension of the model, like $N_{\rm eff}$.

Results on neutrino mass

- Natural goal: $\sum m_\nu = 0.06$eV.
- To get 3σ, need error better than 0.02eV.
- Maybe universe is nice to use, in which case a 0.04eV sensitivity could give you a 3-σ detection at 0.12eV.

	ω_m	ω_b	θ_s	Σm_ν	$\log_{10}(A)$	n_s
value	0.141	0.0221	0.597	0.0600	-8.66	0.961
P	0.0037	0.00015	0.00035	0.35	0.0039	0.0038
$P + BgB + BIB$	0.00074	0.00015	0.00014	0.10	0.0038	0.0038
$P + BgA0.1 + BIB$	0.00070	0.00013	0.00014	0.068	0.0037	0.0031
$P + BgA0.2 + BIB$	0.00071	0.00012	0.00015	0.046	0.0037	0.0028
$P + DES$	0.0013	0.00013	0.00017	0.041	0.0036	0.0032
$P + BBgA0.1 + BBIB$	0.00044	0.00011	0.00014	0.024	0.0036	0.0024
$P + BBgA0.2 + BBIB$	0.00042	0.00010	0.00014	0.017	0.0035	0.0022
$P + LSST$	0.00080	0.00011	0.00015	0.020	0.0030	0.0029
$P + BBgA0.1 + BBIB + LSST$	0.00042	0.00010	0.00013	0.015	0.0028	0.0021
$P + BBgA0.2 + BBIB + LSST$	0.00041	0.00010	0.00013	0.014	0.0026	0.0020
$P + BB24gA0.2 + BB24IA + I1D + euA0.2 + LSST$	0.00032	$9.5e-05$	0.00013	0.011	0.0024	0.0014

- We should clearly see something by the end of the decade!
- See also Snowmass report on how to do this with CMB!

Neutrino masses

Two more important observations:

- Marginalizing over neutrino masses really kills our ability to measure dark energy! For example FoM for DESI drops from 340 to 120 (Planck + Gal ps + Lyα BAO)
- There is some evidence that neutrino mass signal does not come from supression of the power spectrum, but instead from measuring the amplitude of the power spectrum through RSD

Results on $N_{\rm eff}$

- Natural goal: $\Delta N_{\rm eff} = 0.04$
- This would confirm our understanding of the early universe

	ω_m	ω_b	θ_s	Σm_ν	$N_{\nu,l}$	$\log_{10}(A)$
value	0.141	0.0221	0.597	0.0600	3.05	−8.66
P	0.0050	0.00023	0.00042	0.35	0.18	0.0049
$P + BgB + BIB$	0.0033	0.00023	0.00026	0.12	0.18	0.0049
$P + BgA0.1 + BIB$	0.0031	0.00020	0.00025	0.086	0.18	0.0048
$P + BgA0.2 + BIB$	0.0025	0.00019	0.00022	0.061	0.15	0.0045
$P + DES$	0.0020	0.00019	0.00020	0.048	0.12	0.0038
$P + BBgA0.1 + BBIB$	0.0022	0.00016	0.00020	0.036	0.13	0.0046
$P + BBgA0.2 + BBIB$	0.0014	0.00014	0.00017	0.024	0.084	0.0042
$P + LSST$	0.00096	0.00014	0.00016	0.020	0.063	0.0031
$P + BBgA0.1 + BBIB + LSST$	0.00090	0.00012	0.00016	0.016	0.050	0.0029
$P + BBgA0.2 + BBIB + LSST$	0.00086	0.00012	0.00016	0.014	0.049	0.0027
$P + BB24gA0.2 + BB24IA + I1D + euA0.2 + LSST$	0.00078	0.00011	0.00015	0.011	0.041	0.0024

- In the ball-park, but not guaranteed detections
- Would be interesting to see, how to cook models that naturally give small, but detectable $\Delta N_{\rm eff}$

Running of spectral index

- Running of spectral index, would give the third number on inflation:

$$\alpha_s = d\frac{d\log n_s}{d\log k} \tag{4}$$

- Natural goal $O((n_s-1)^2) = 10^{-3}$
- I would really start to believe inflation
- Zaldarriaga is not amused

	Σm_ν	$\log_{10}(A)$	n_s	α_s
value	0.0600	−8.66	0.961	0.00
P	0.35	0.0043	0.0038	0.0054
$P + BgB + BIB$	0.10	0.0042	0.0038	0.0054
$P + BgA0.1 + BIB$	0.069	0.0042	0.0031	0.0053
$P + BgA0.2 + BIB$	0.046	0.0041	0.0028	0.0050
$P + DES$	0.041	0.0041	0.0032	0.0049
$P + BBgA0.1 + BBIB$	0.025	0.0040	0.0024	0.0051
$P + BBgA0.2 + BBIB$	0.017	0.0037	0.0022	0.0040
$P + LSST$	0.023	0.0039	0.0030	0.0038
$P + BBgA0.1 + BBIB + LSST$	0.018	0.0038	0.0022	0.0036
$P + BBgA0.2 + BBIB + LSST$	0.015	0.0033	0.0022	0.0033
$P + BB24gA0.2 + BB24IA + I1D + euA0.2 + LSST$	0.011	0.0025	0.0018	0.0016

- This is going down very very slowly.
- Really understading Lyman-α small scale power might help, but it is a daunting task!

For aficionados: $f_{\rm NL}$

- Via Dalal's effect:

Survey	$\Delta f_{\rm NL}$
BOSS	23
BOSS+eBOSS	11
DESI	3.8
BOSS+Euclid	6.7

- Not enough to be competitive with planck, BUT
- Bispectrum could save the day...

Conclusions

By now, I'm likely to be over-time, so you need to read this by yourselves:

- BOSS and other BAO experiments are doing amazing job at low-z
- Dark energy can be detected entirely within BAO data
- Clusterig of galaxies and other tracers useful despite astrophysics: On scales larger than locality scales one can make robust predictions despite astrophysics
- Guaranteed neutrino mass detection in next 10 years
- Very interesting limits on $N_{\rm eff}$, α_s
- $f_{\rm NL}$ great from 2-point, will see about 3-point