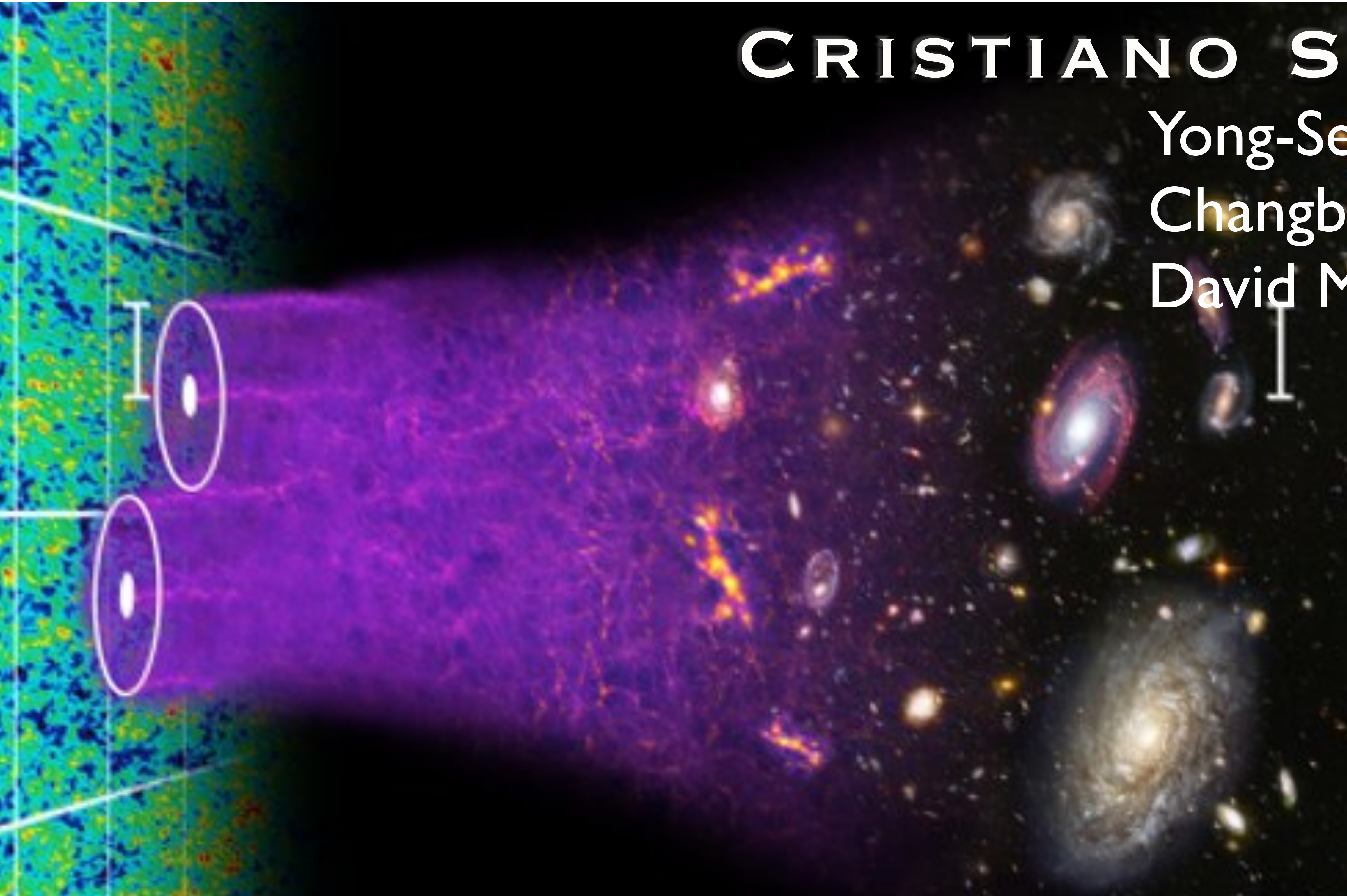
Cosmic Distances Probed Using The BAO Ring + Modified Gravity and Clustering

Cosmology Group at
Korea Astronomy and Space Science Institute



Cristiano Sabiu
Yong-Seon Song
Changbom Park
David Mota

Future Sky Surveys and Big Data, KASI - April - 2016

Outline

- Background
  - DESI
  - What do we want?
  - From observations to theory

- Model-independent estimates of cosmic observables
  - utilizing the Alcock-Paczynski effect
  - Clustering peaks (w/ YongSeon Song)

- Testing gravity
  - Higher Order Statistics
  - can we distinguish GR+LCDM from others?
    (w/ Chnagbom Park & David Mota)

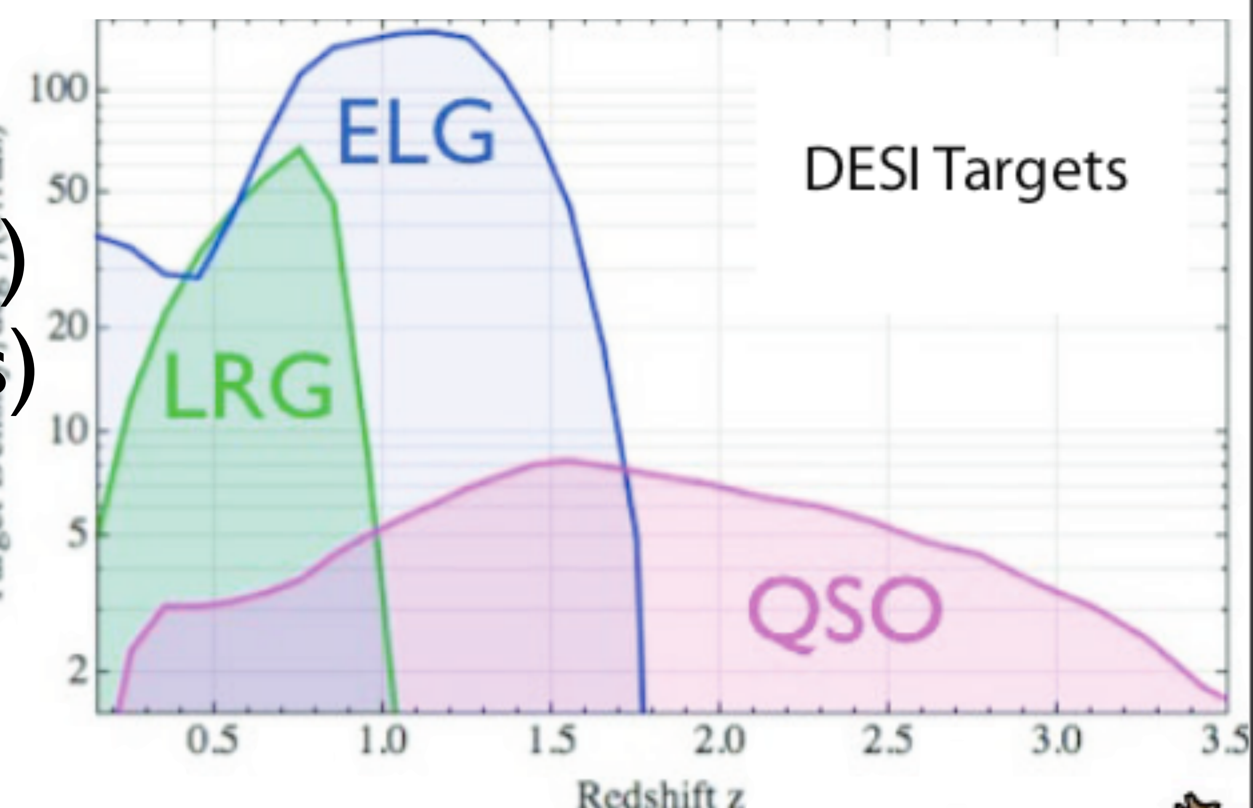
Next Generation Survey

The DESI (the Dark Energy Spectroscopic Instrument) project was formed in 2012 from the merger of the BigBoss and the DESpec wide field, multi-object spectrograph concepts.

The DESI collaboration is led by LBNL and has 21 US Universities, 5 DOE labs, 19 foreign institutions, totaling >200 collaborators.

Will produce the measurements of BAO by performing a spectroscopic survey over 14,000 sq. degrees out to redshifts of 3.5

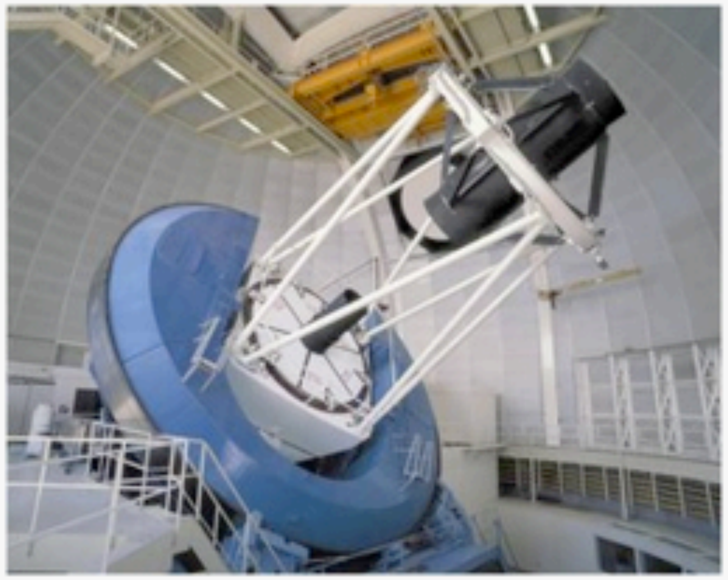
- 4M Luminous Red Galaxies (LRGs)
- 23M Emission Line Galaxies (ELGs)
- 1.4M quasars (QSO)
- 0.6M quasars at z>2.2 for Lyman-alpha-forest



DESI Survey

DESI will be conducted on the Mayall 4-meter telescope at Kitt Peak National Observatory starting in 2018. DESI is supported by the Department of Energy Office of Science to perform this Stage IV dark energy measurement using baryon acoustic oscillations and other techniques that rely on spectroscopic measurements.

Exterior of Kitt Peak Mayall 4-meter telescope (Image: NOAO/AURA/NSF)

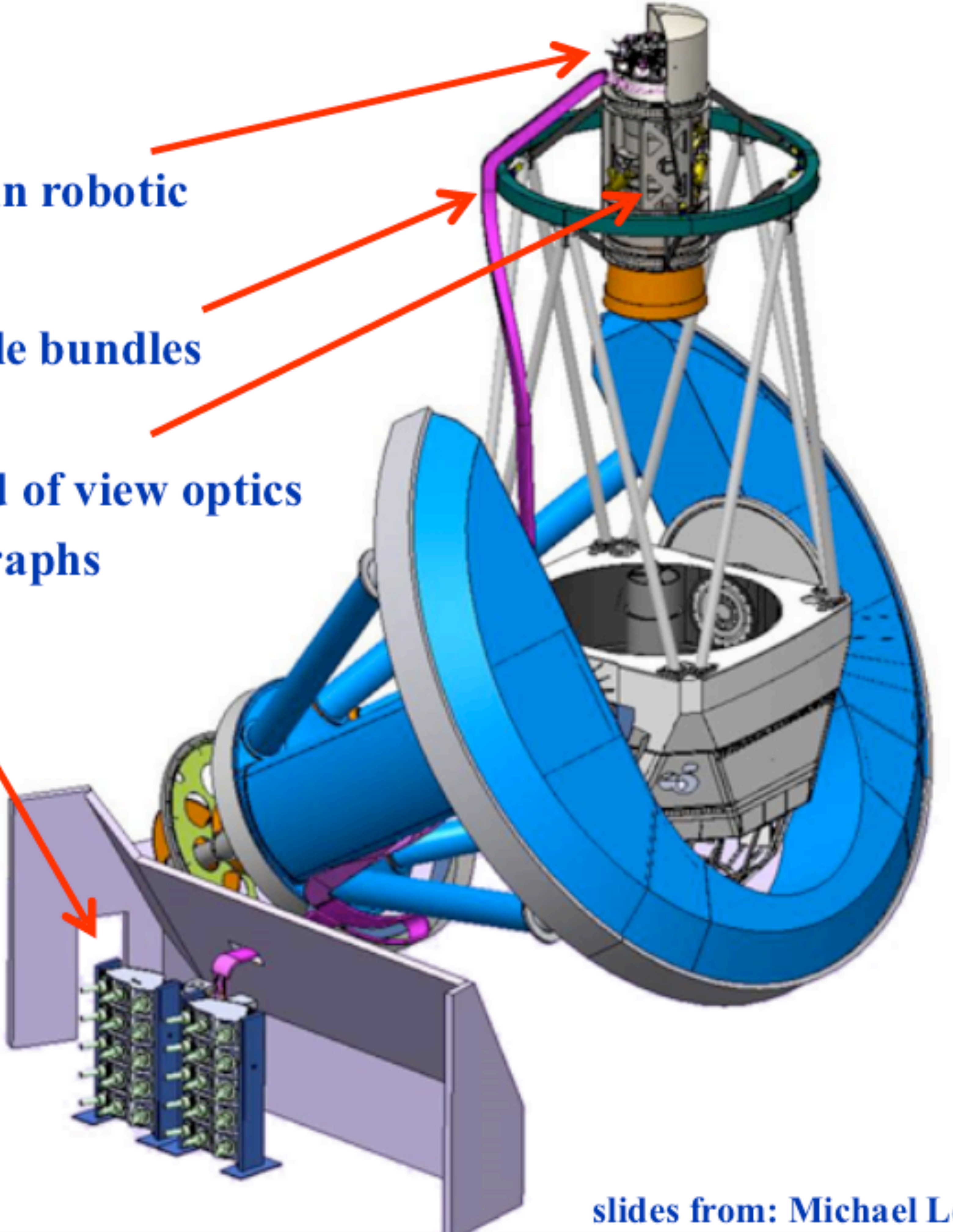


The Kitt Peak National Observatory's Mayall 4-meter telescope (Image: NOAO/AURA/NSF)

A model of the Mayall telescope with a DESI Prime Focus Assembly

DESI

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



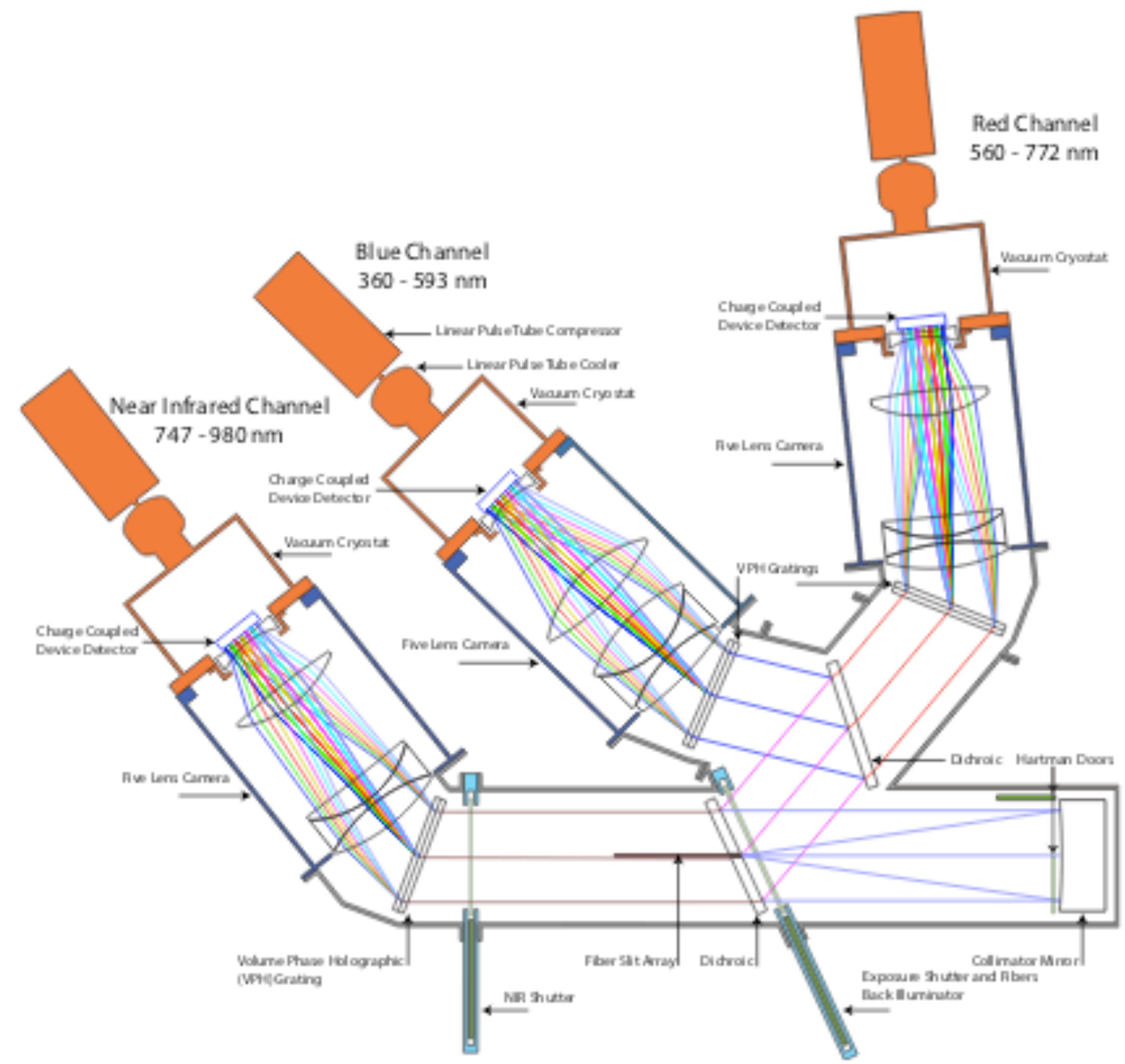
Mayall 4m Telescope Kitt Peak Tucson, AZ

Readout & Control

slides from: Michael Levi (LBNL)

DESI Survey

The spectrograph design was finalized last year. The three arms cover wavelength range from 360 nm to 980 nm with resolution
R =l/dl= 2000 - 5500
depending on wavelength, meeting or exceeding the DESI requirements.



The 1st spectrograph fabrication has started and will be complete this year

Each unit serves 500 fibers
One of ten units

DESI Survey

first light in about 3 years

1. An imaging (targeting) survey over 14,000 deg2

g-band to 24.0 mag

r-band to 23.6 mag

z-band to 23.0 mag

2. A spectroscopic survey over 14,000 deg2

10 million Bright Luminous Galaxies

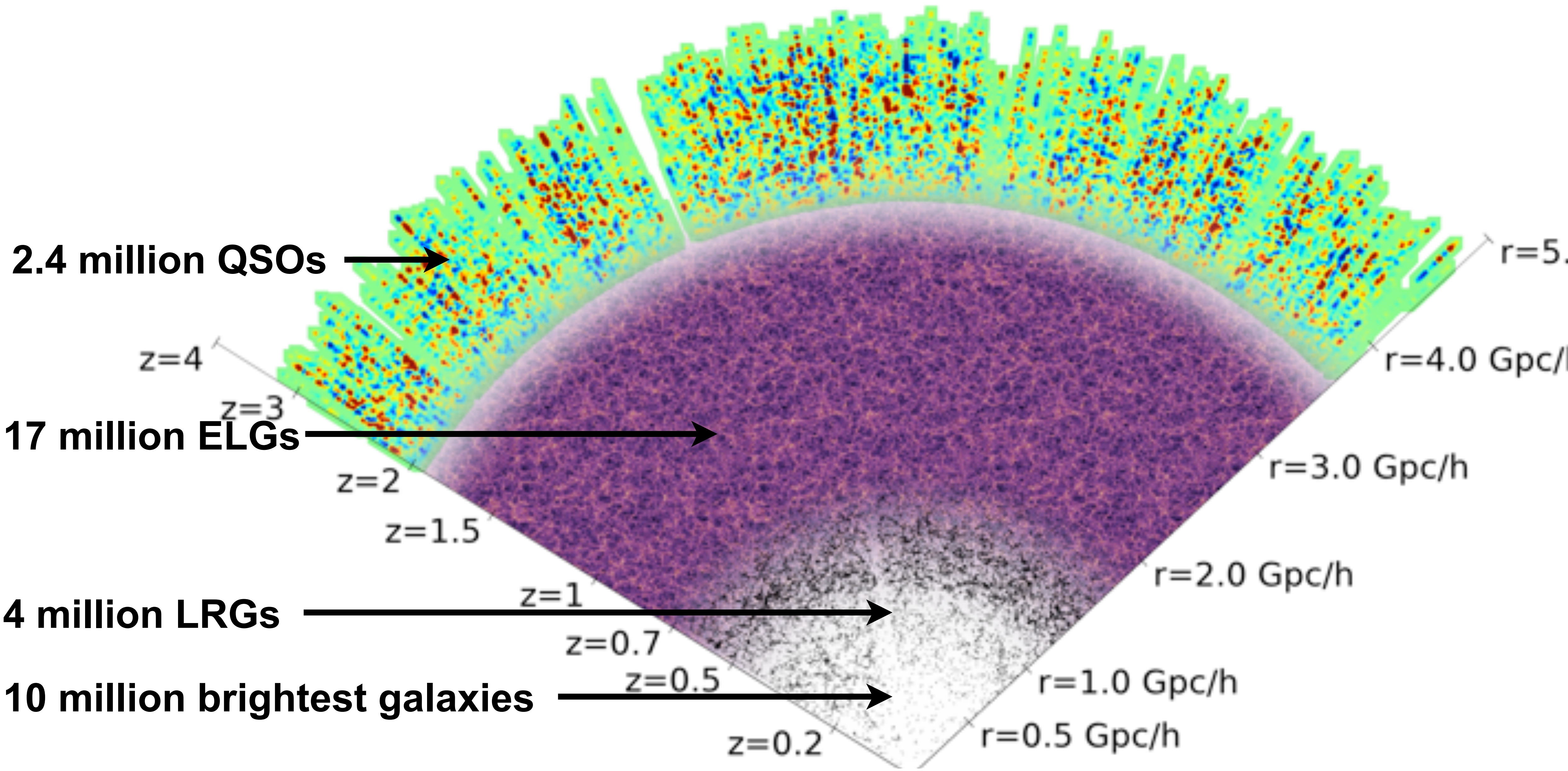
4 million Luminous Red Galaxies
23 million Emission Line Galaxies
1.4 million quasars
0.6 million quasars at z>2.1 for Lyman-alpha-forest

Last year, none of the imaging survey was secure
Today, mostly secured and in progress as public surveys

DESI Survey

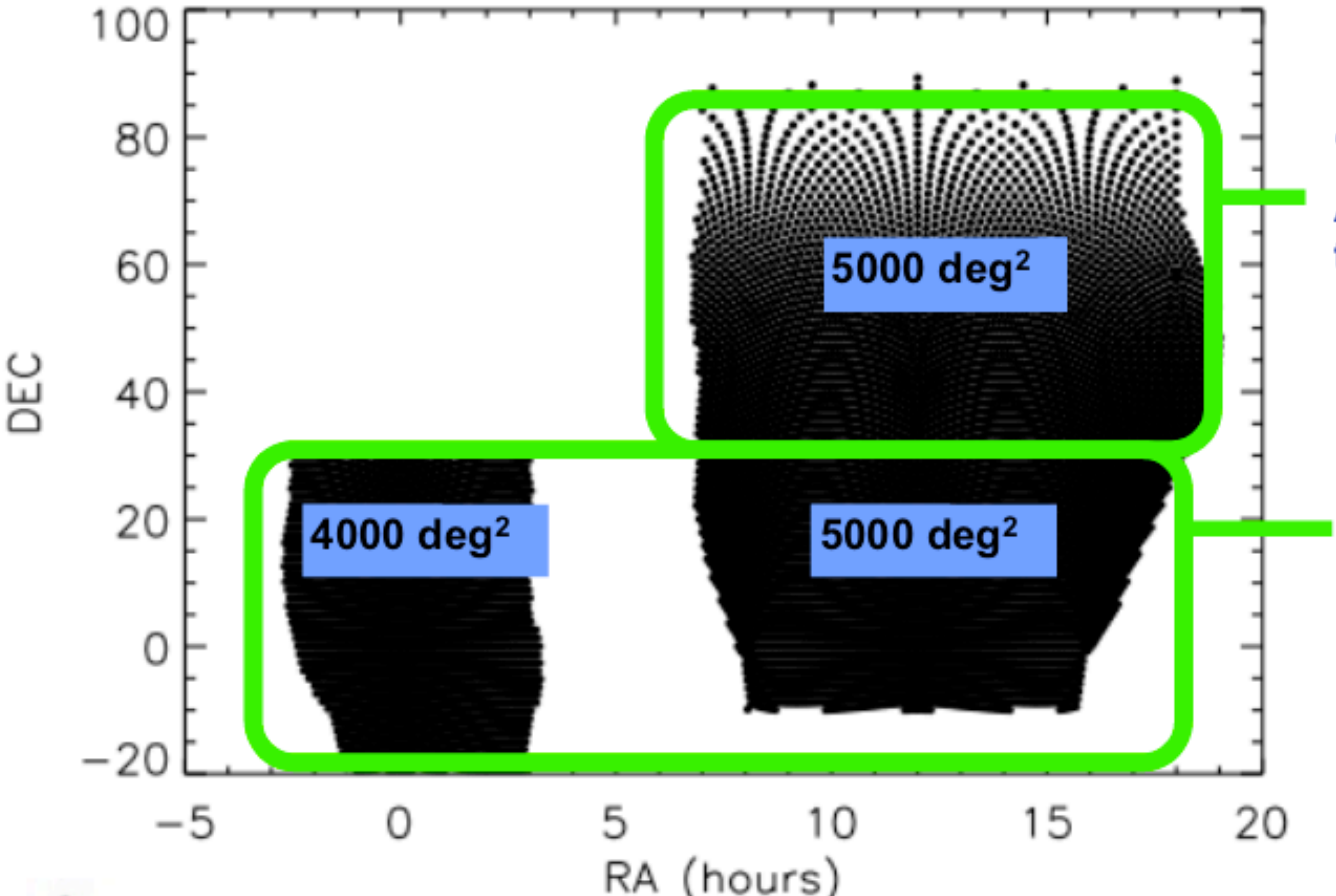
The largest spectroscopic survey for dark energy

SDSS ~$2h^{-3}Gpc^3$ ⇨ BOSS ~$6h^{-3}Gpc^3$ ⇨ DESI $50h^{-3}Gpc^3$



Survey Area

Main survey areas now selected.
Exact survey strategy still to be decided.



"North cap":

Accessible from Northern telescopes only

Observing gr bands with Bok
Plan to observe z with upgraded z band on Mayall.

"Equatorial":

Accessible from Northern or Southern telescopes

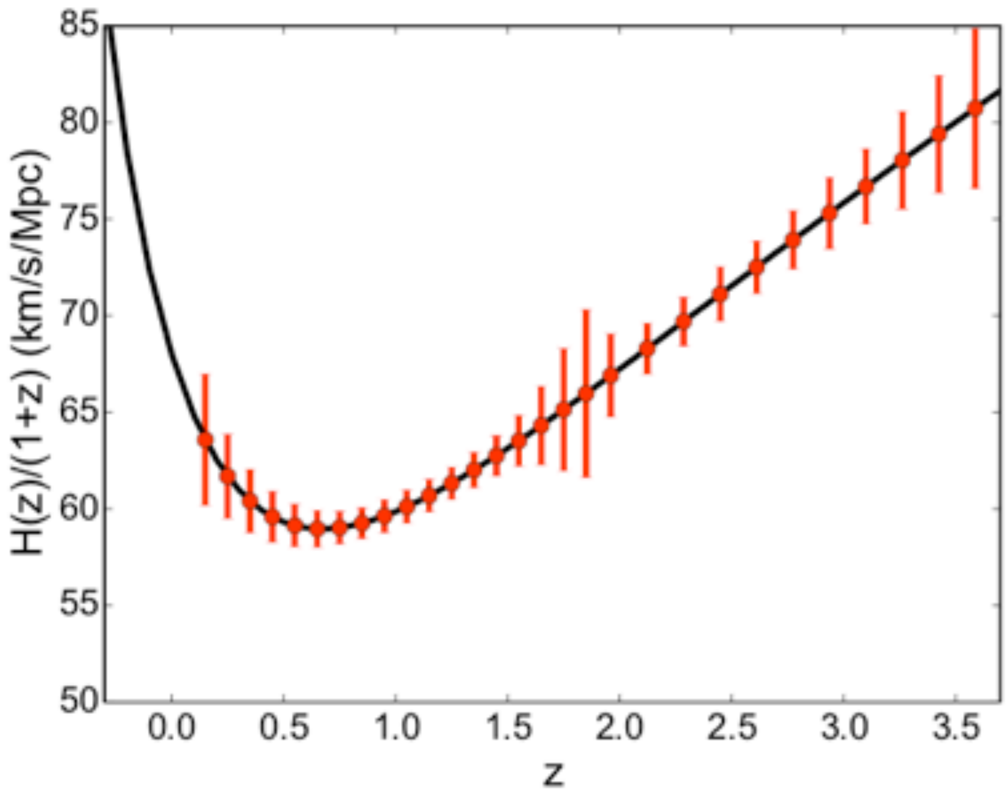
Observing grz with DECam.
Approved project for 6700 sq. degrees.

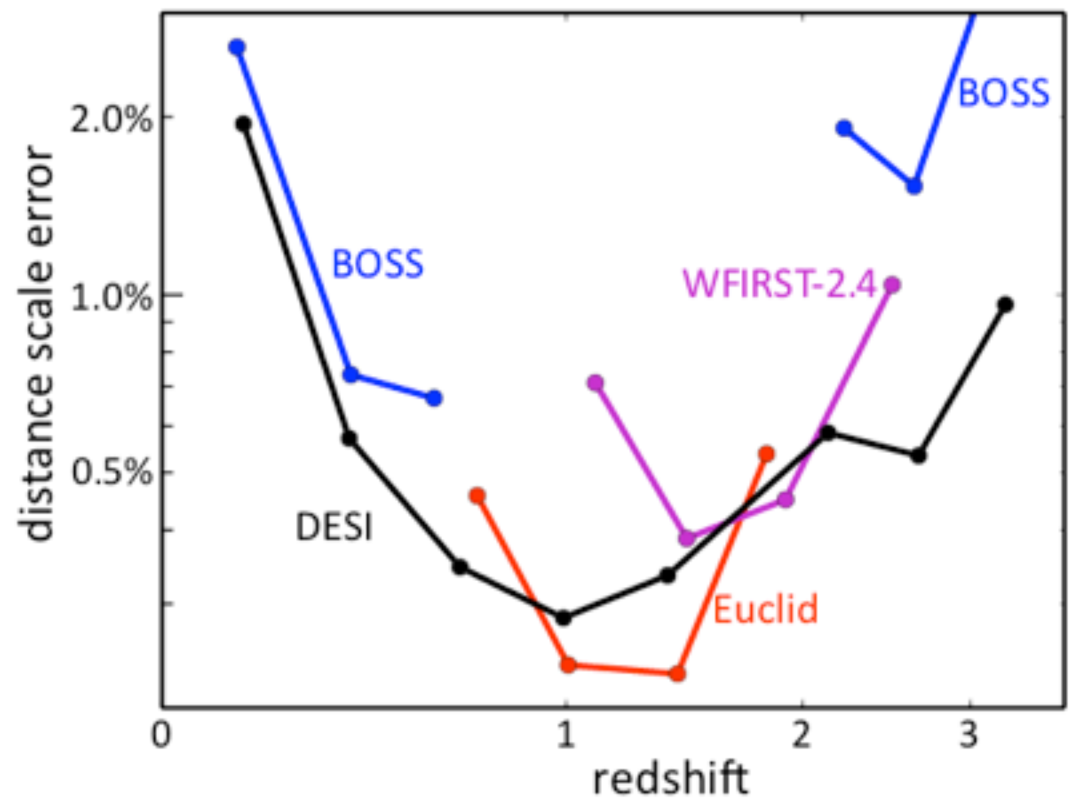
Survey Timeline

DESI Data Assemblies and Milestones

Imaging Surveys	2015--2018	Imaging DA Q3 2018
Prep for SV	2015--2018	December 2018
Science Verification	April--Oct 2019	SV DA March 2020
Season 1	Oct 2019--July 2020	DA1 Jan 2021
Papers on DA1		Nov 2021
Season 2	Aug 2020--Dec 2020	DA2 July 2021
Papers on DA2		April 2022
Season 6 (full data)	-- Dec 2024	DA6 July 2025
Final Cosmology Results		April 2026

DESI Expectation





DESI will produce a world leading survey of the the cosmic distance scale.

Will measure distance scale to better than 0.3% statistical errors.

Background

Key observables in spectroscopic galaxy surveys:

(1) Angular diameter distance $\mathbf{D_A}$
- Exploiting BAO as standard rulers which measure the angular diameter distance and expansion rate as a function of redshift.

(2) Radial distance $\mathbf{H^{-1}}$
- Exploiting redshift distortions as intrinsic anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

$$H(z) = H_0\sqrt{\Omega_m a^{-3} + (1-\Omega_m)a^{-3(1+w)}},$$

$$D_A(z) = \frac{1}{1+z}r(z) = \frac{1}{1+z}\int_0^z \frac{dz'}{H(z')},$$

(3) Growth Rate, f **(dδ/d ln a)**
- The coherent motion, or flow, of galaxies can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.

These are essential to test theoretical models explaining cosmic acceleration; **ΛCDM, Dynamical DE, Einstein's gravity**

From Observation to theory

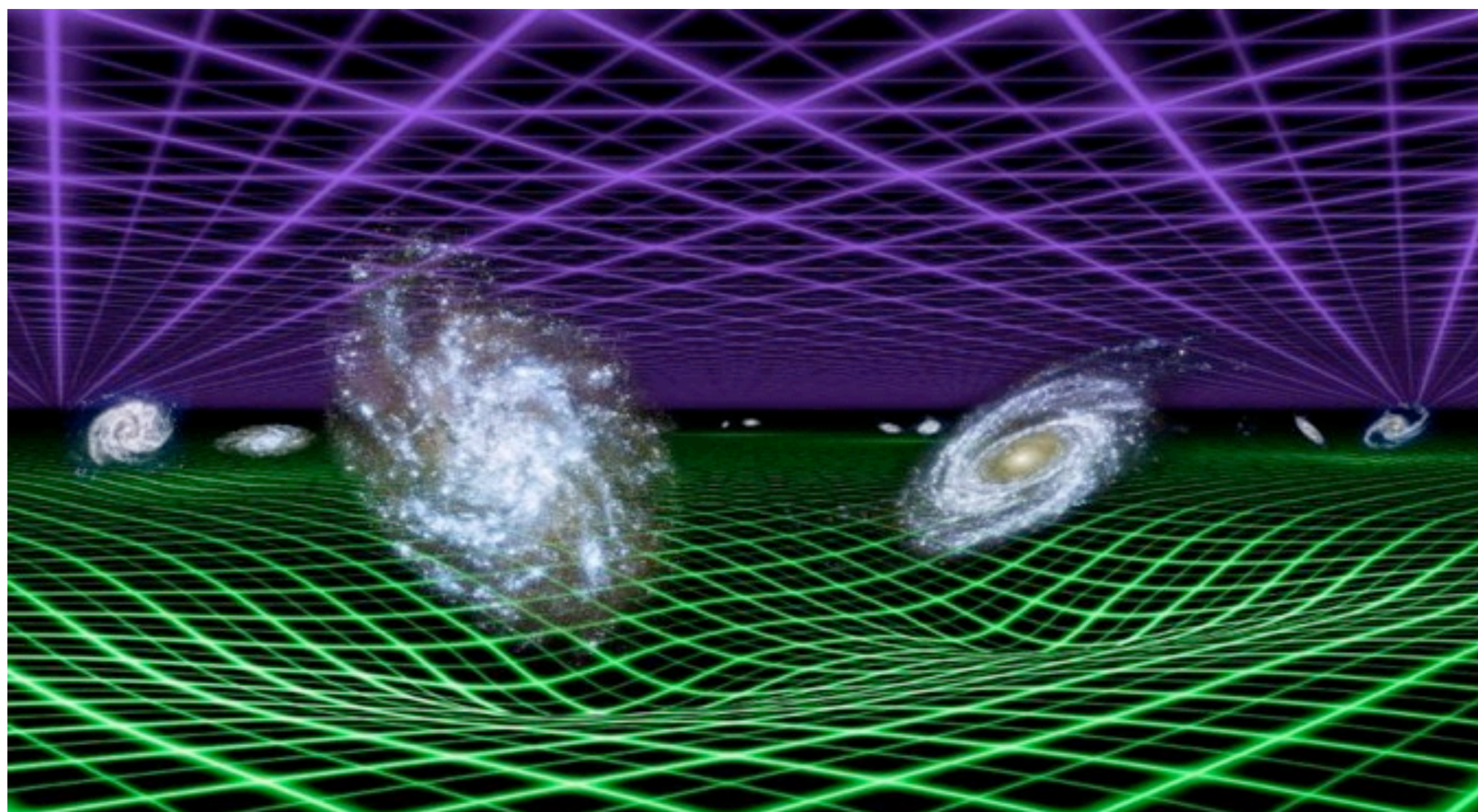
- We want to know the density perturbations in the universe (at various cosmic times). This will tell us about the cosmic expansion (a) and gravity, through the growth of structure.

We don't 'see' perturbations of the total density field.
We observe individual galaxies that trace that underlying matter distribution.

How are galaxies and DM related?

- Halo Model
- Bias
  - Scale Dependent?

- Velocity Field Bias?



From Observation to theory

- We want to know the density perturbations in the universe (at various cosmic times). This will tell us about the cosmic expansion (a) and gravity, through the growth of structure.

Also....
We don't 'see' the true radial position of galaxies
We see its redshift, which is composed of a hubble expansion and a peculiar velocity due to local gravitational dynamics.

Furthermore, even if the galaxy is not moving gravitationally, we still do not know its true position in comoving space, since we need to transform (theta, phi, redshift) -> (x,y,z) using a cosmological model with a specific choice of parameters. Eg LCDM Om=0.3, Ol=0.7, w=-1 etc etc

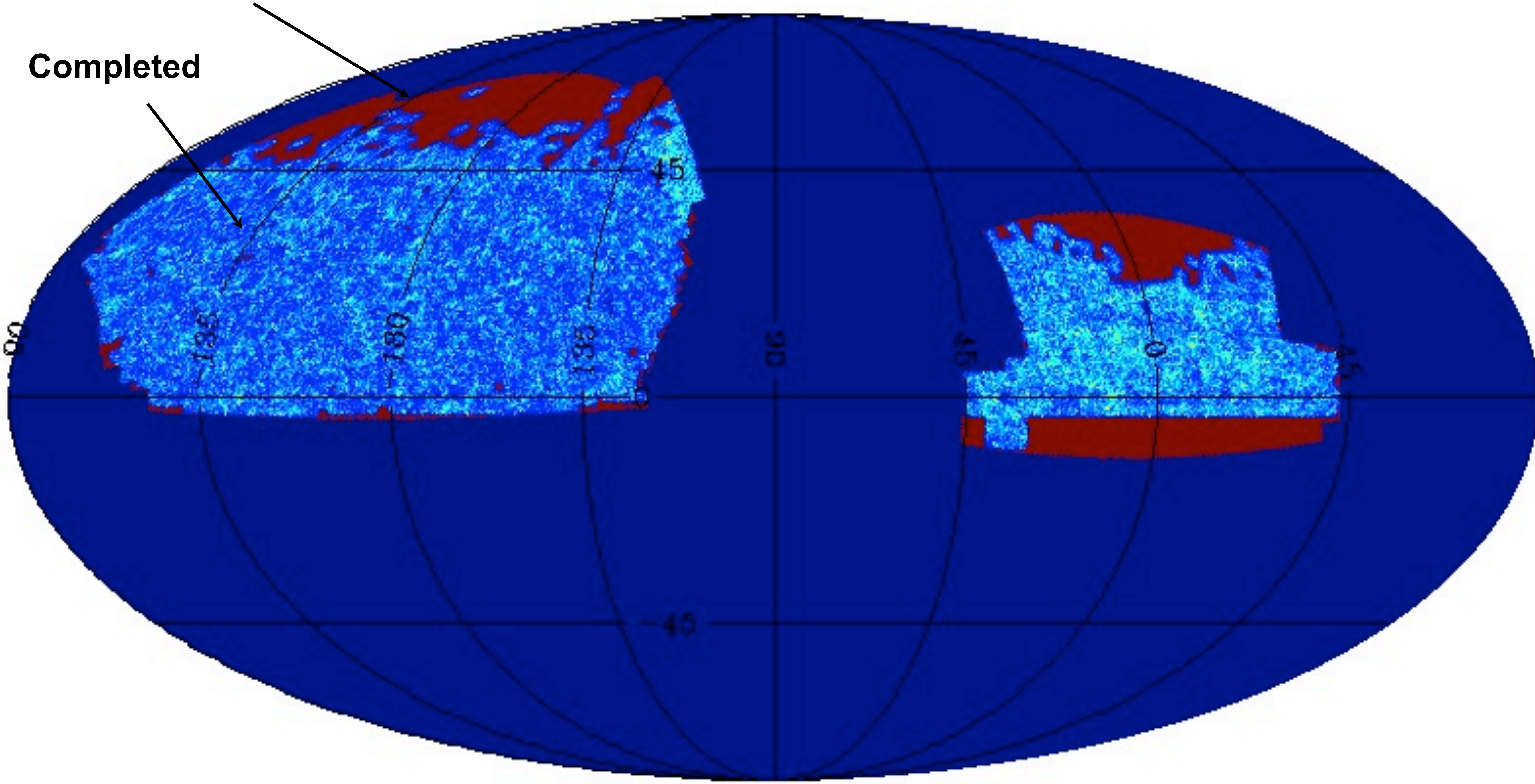
So, where do we go from here?

BOSS: Survey Progress

BOSS July 2013 (Data Release 11)

Final footprint

Completed



Correlation Functions

We want to evaluate:
where δ is the density contrast

$$\langle \delta(x)\delta(x+r) \rangle$$

We call this the Two Point Correlation Function (2PCF)

$$\xi_i(r) = \frac{n_i(r)}{\bar{n}.dV} - 1$$

The estimator for this statistic is:

$$\xi(r) = \frac{DD - 2DR + RR}{RR}$$

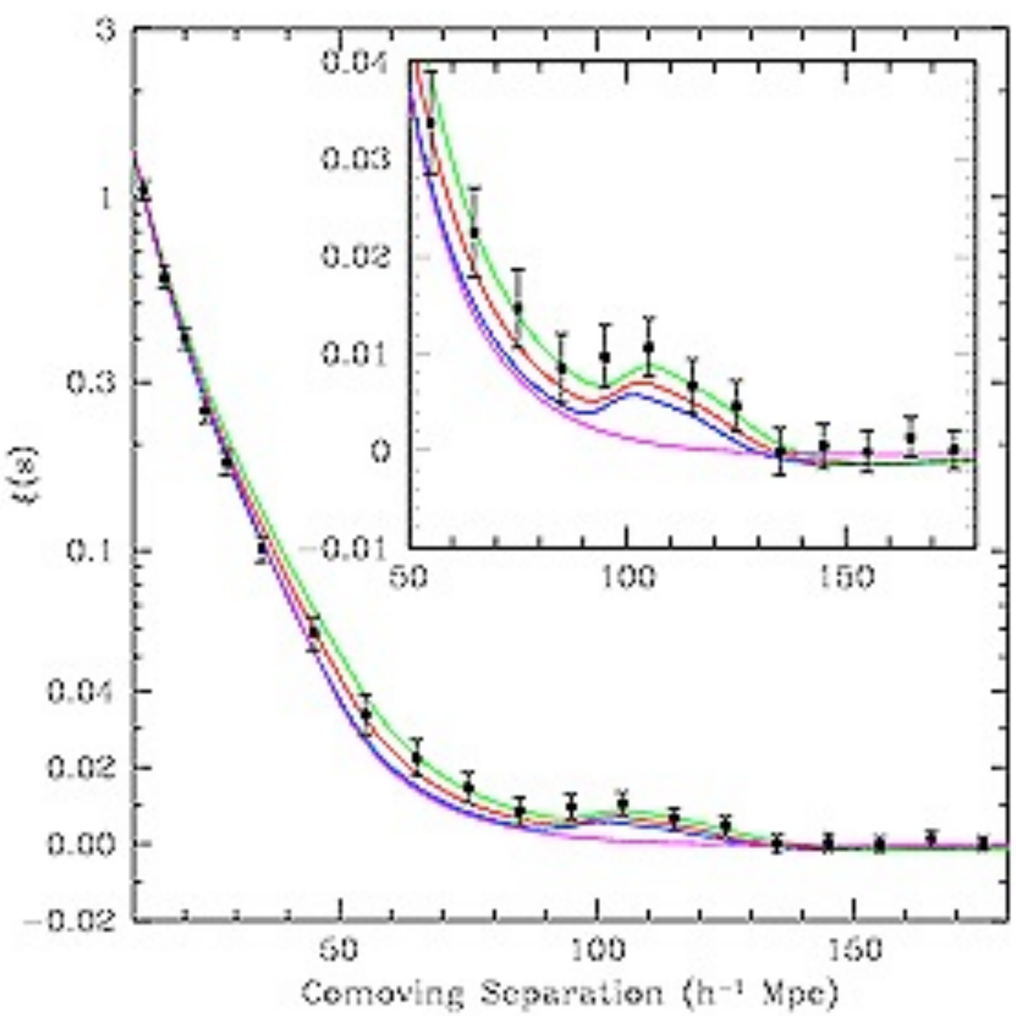
This lead to the probability:

$$dP = n^2[1+\xi(r)]dV_1 dV_2$$

Correlation Functions

We want to evaluate:
where δ **is the den**
contrast

$$\langle \delta(x)\delta(x+r)\rangle$$



(www.sdss3.org)

We call this the Tw
Correlation Funct

$$\frac{n_i(r)}{\bar{n}.dV} - 1$$

The estimator for
statistic is:

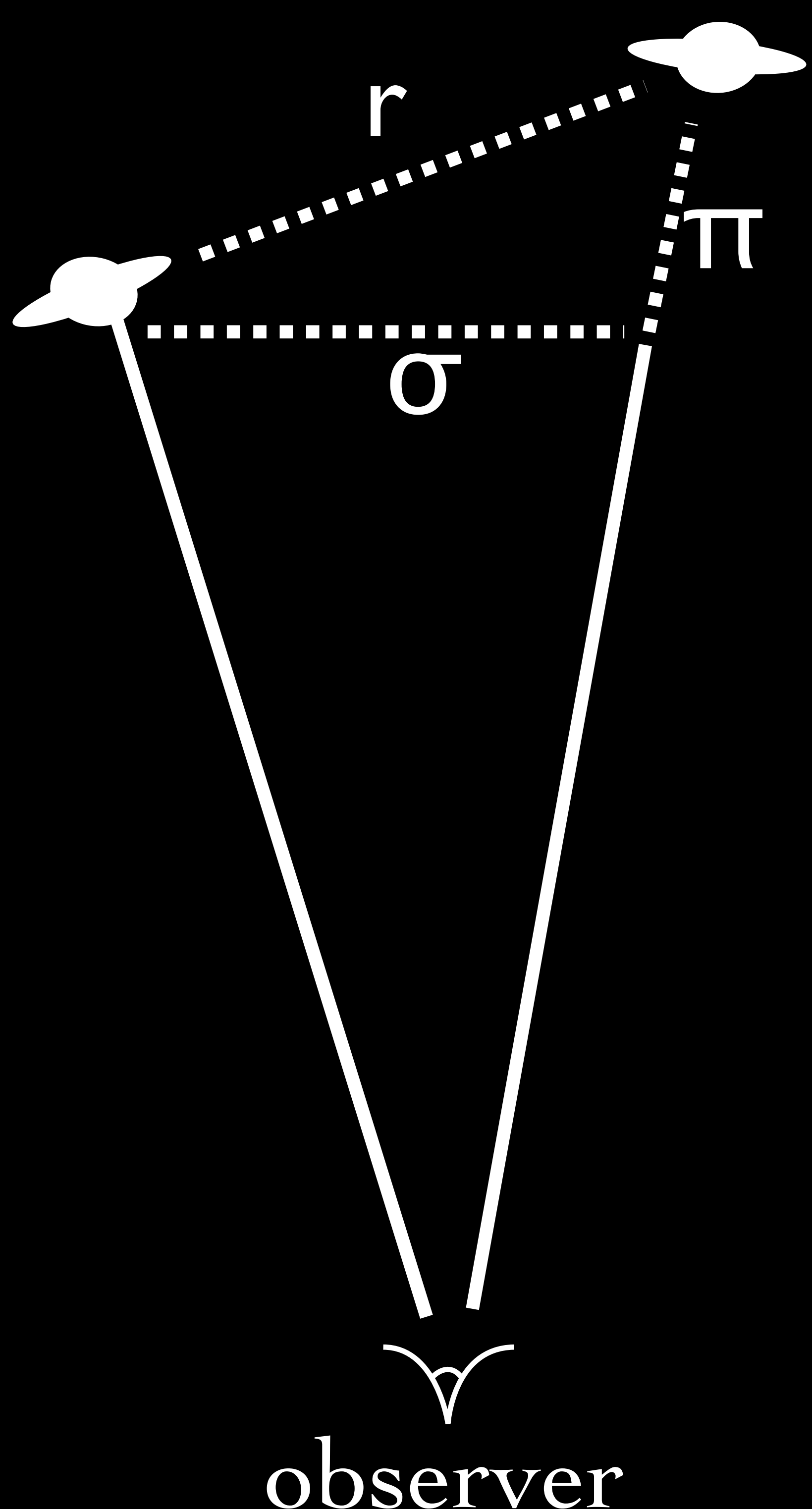
$$\frac{\ldots - 2DR + RR}{RR}$$

This lead to the probability:

$$dP = n^2[1+\xi(r)]dV_1 dV_2$$

Anisotropic 2PCF

From 1D to 2D



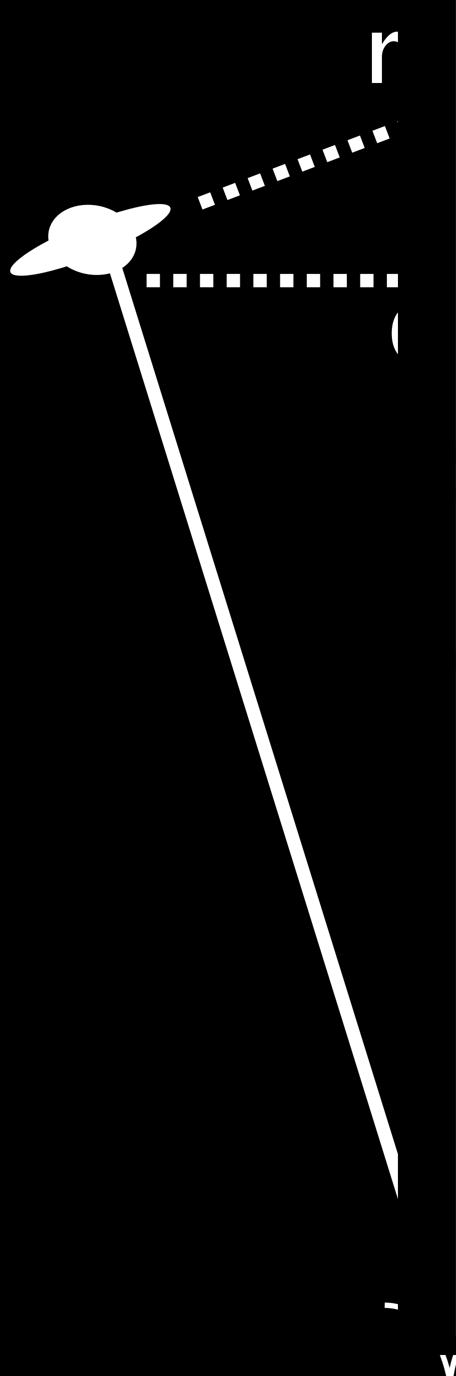
Bin galaxy pairs in two distances (π,σ) instead of the single distance between pairs, r.

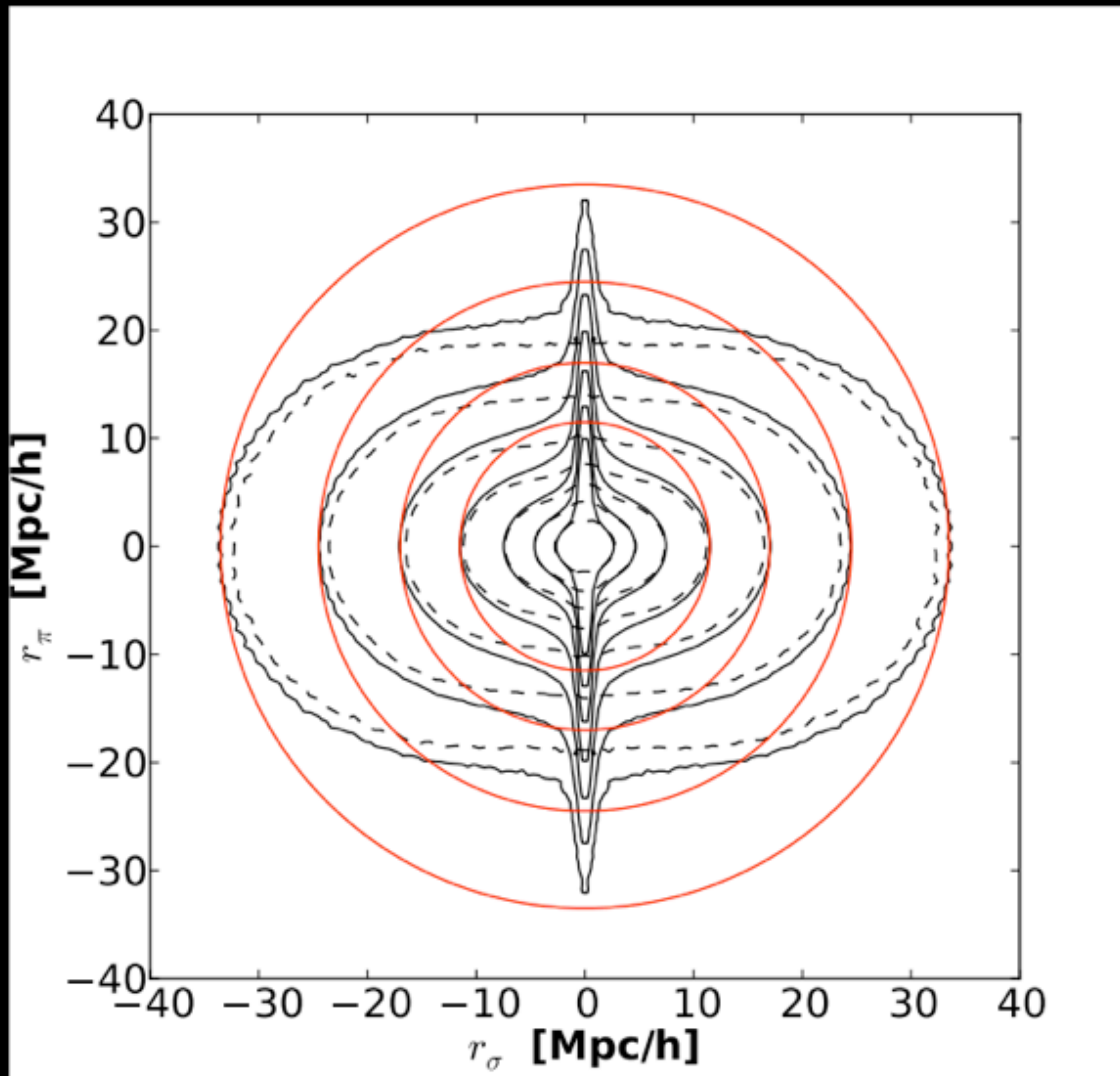
Apart from the binning this is the same as doing the 2PCF.

And if there are no preferred directions then the correlation function will give perfectly circular contours in (π,σ).

$$\xi(r) = \frac{DD - 2DR + RR}{RR}$$

Anisotropic 2PCF





nces (π,σ)
between

s the same

directions
will give
(π,σ).

RR

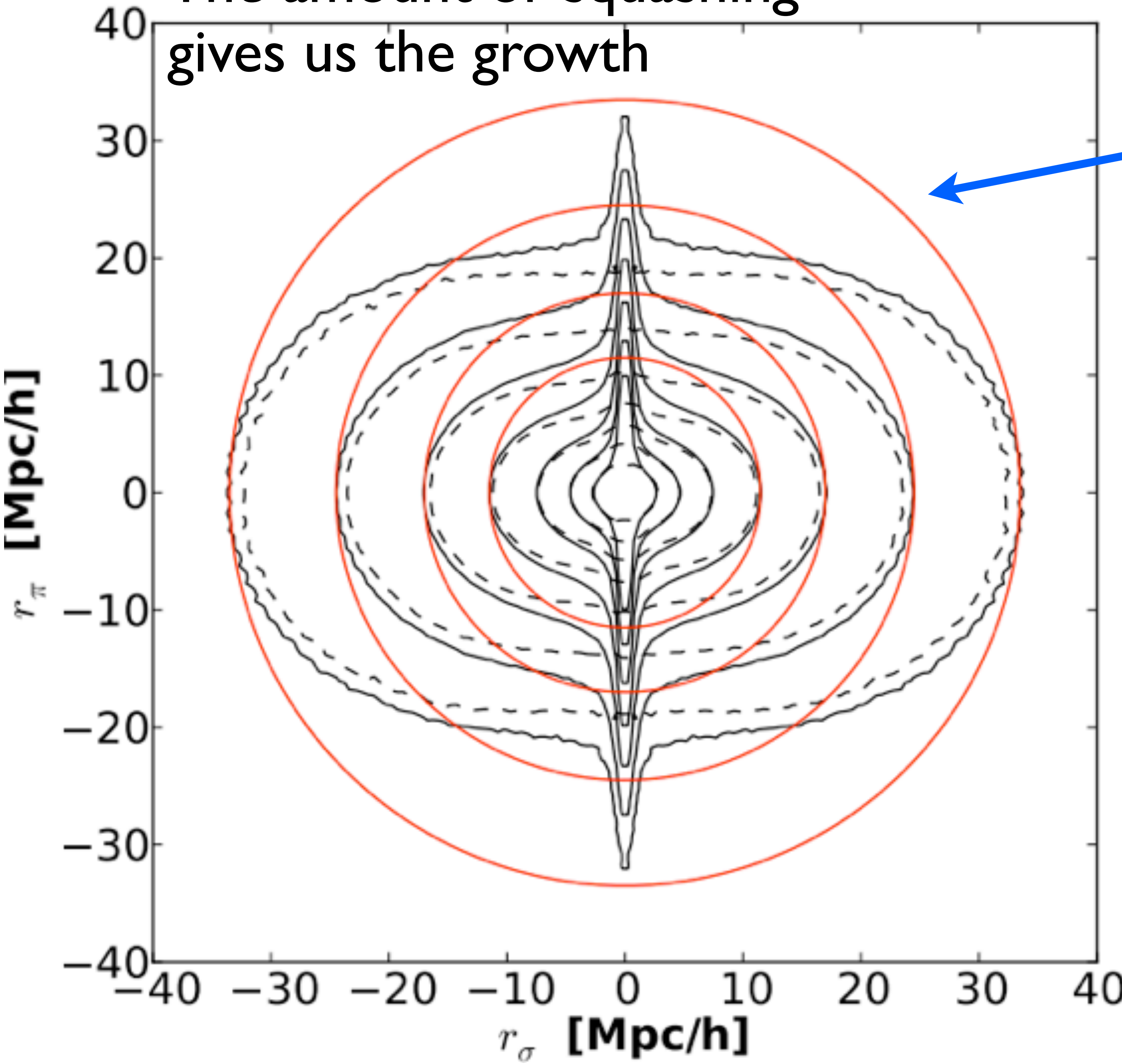
Anisotropic 2PCF

3 contributions to anisotropic clustering:

- Non-linear, Fingers of God (FoG)
- Linear, Large Scale Velocities (Kaiser)
- Incorrect cosmological parameters
  - Alcock-Paczynski effect (AP)

Anisotropic 2PCF

The amount of 'squashing'
gives us the growth



Red - No RSD
Dashed - Linear
Solid - Linear + FoG

Nonlinear regime
theoretically
difficult to model

M. White et al (2011)

TNS model

Taruya, Nishimichi, Saito (2010) arXiv: 1006.0699

In going to larger scales and with more precise measurements, theoretical advancements must also be utilized.

$$\tilde{P}(k,\mu) = \left\{P_{\delta\delta}(k) + 2\mu^2 P_{\delta\Theta}(k) + \mu^4 P_{\Theta\Theta}(k)\right\} \exp\left\{-(k\mu\sigma_{\rm p})^2\right\}$$ Streaming model

Kaiser and FoG cannot be so simply separated as the two functions are anisotropic in k-space. Since in general,

$$\langle ABe^C\rangle \neq \langle AB\rangle\langle e^C\rangle$$

TNS proposed an improved model of the redshift-space power spectrum, in which the coupling between the density and velocity fields associated with the Kaiser and the FoG effects is perturbatively incorporated into the power spectrum expression. The resultant expression includes nonlinear corrections consisting of higher-order polynomials.

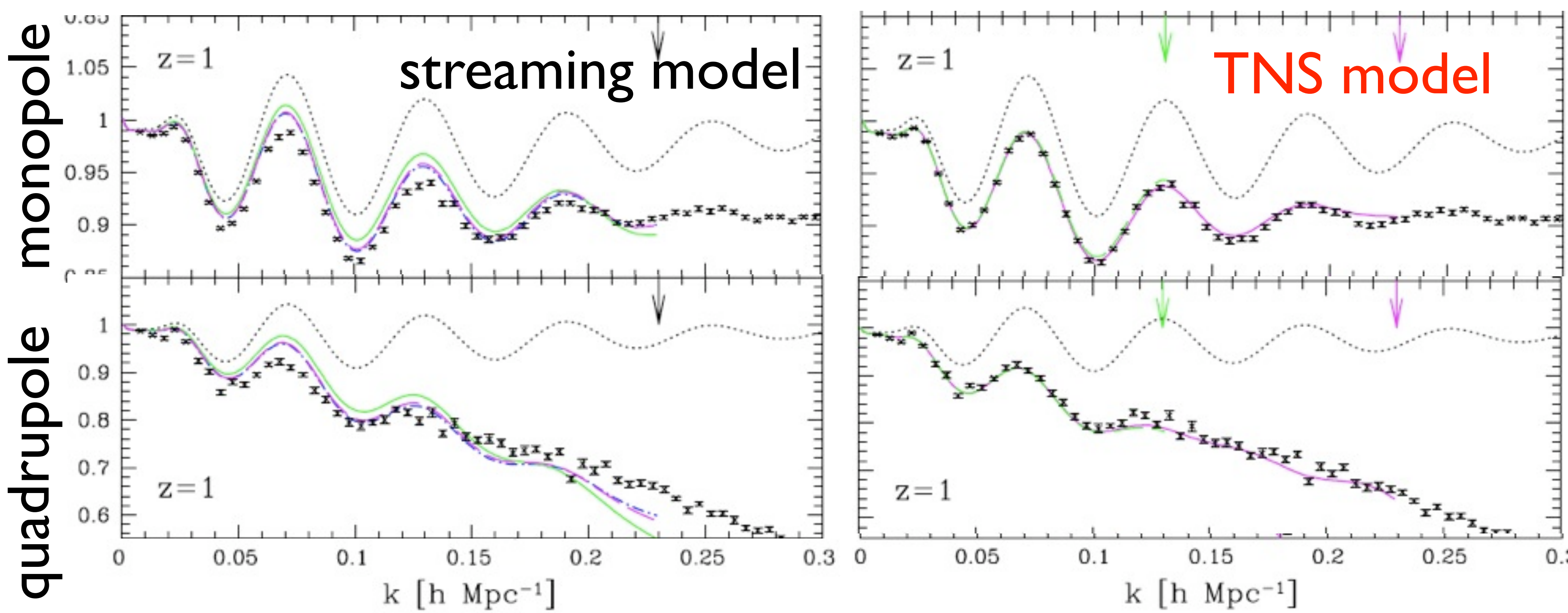
TNS model

$$\tilde{P}(k,\mu) = \{P_{\delta\delta}(k) + 2\mu^2 P_{\delta\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) + A(k,\mu) + B(k,\mu)\} G^{\rm FoG}.$$

$$\tilde{P}(k,\mu) = \sum_{n=0}^{4} Q_{2n}(k)\mu^{2n} G^{\rm FoG}(k\mu\sigma_p)$$

A(k, μ) andB(k, μ) terms are the nonlinear corrections, and are expanded as power series of μ, including the powers up to μ_6 for the A term and μ_8 for the B term.

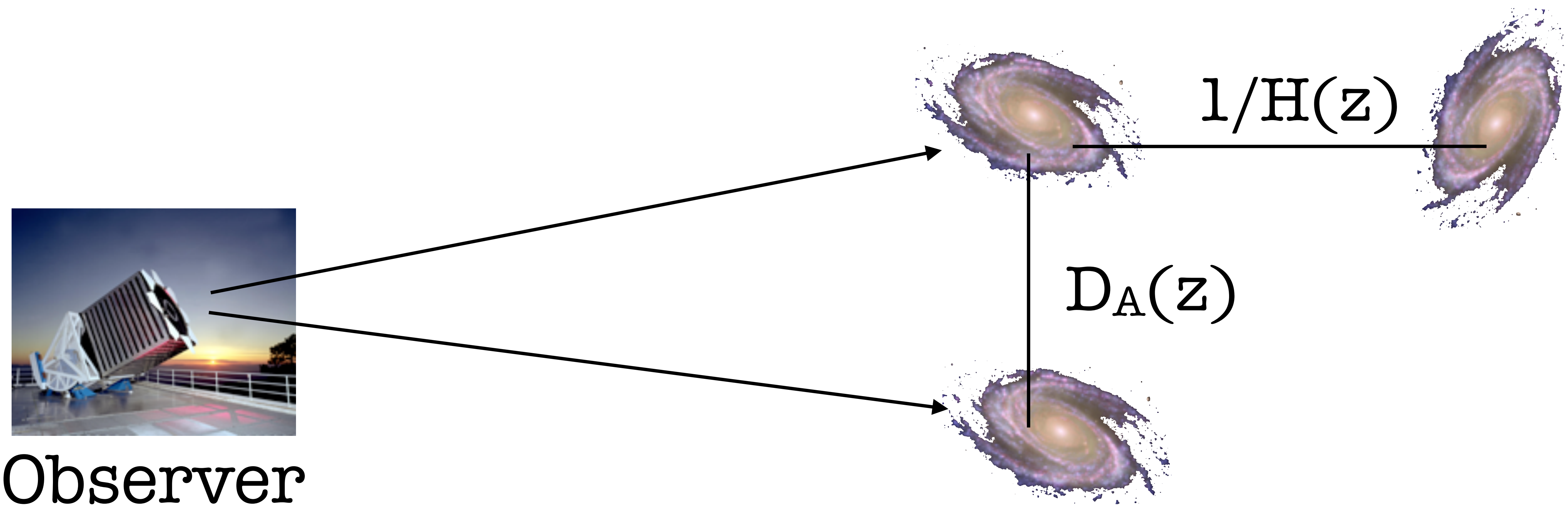
$$\begin{aligned} Q_0(k) &= P^{\rm lin}_{\delta\delta}(k) + \delta P_{\delta\delta}(k), \\ Q_2(k) &= 2P^{\rm lin}_{\delta\Theta}(k) + 2\delta P_{\delta\Theta}(k) + C_2(k), \\ Q_4(k) &= P^{\rm lin}_{\Theta\Theta}(k) + \delta P_{\Theta\Theta}(k) + C_4(k), \\ Q_6(k) &= C_6(k), \\ Q_8(k) &= C_8(k), \end{aligned}$$



Alcock-Paczynski Effect

We measure RA, Dec and Redshift for each galaxy. However we must choose a cosmological model to convert these positions into a cartesian comoving coordinate system.

Even without a standard ruler, we can measure the clustering along and perpendicular to the line of sight and thus constrain the combination of $D_A * H$



Alcock-Paczynski Effect

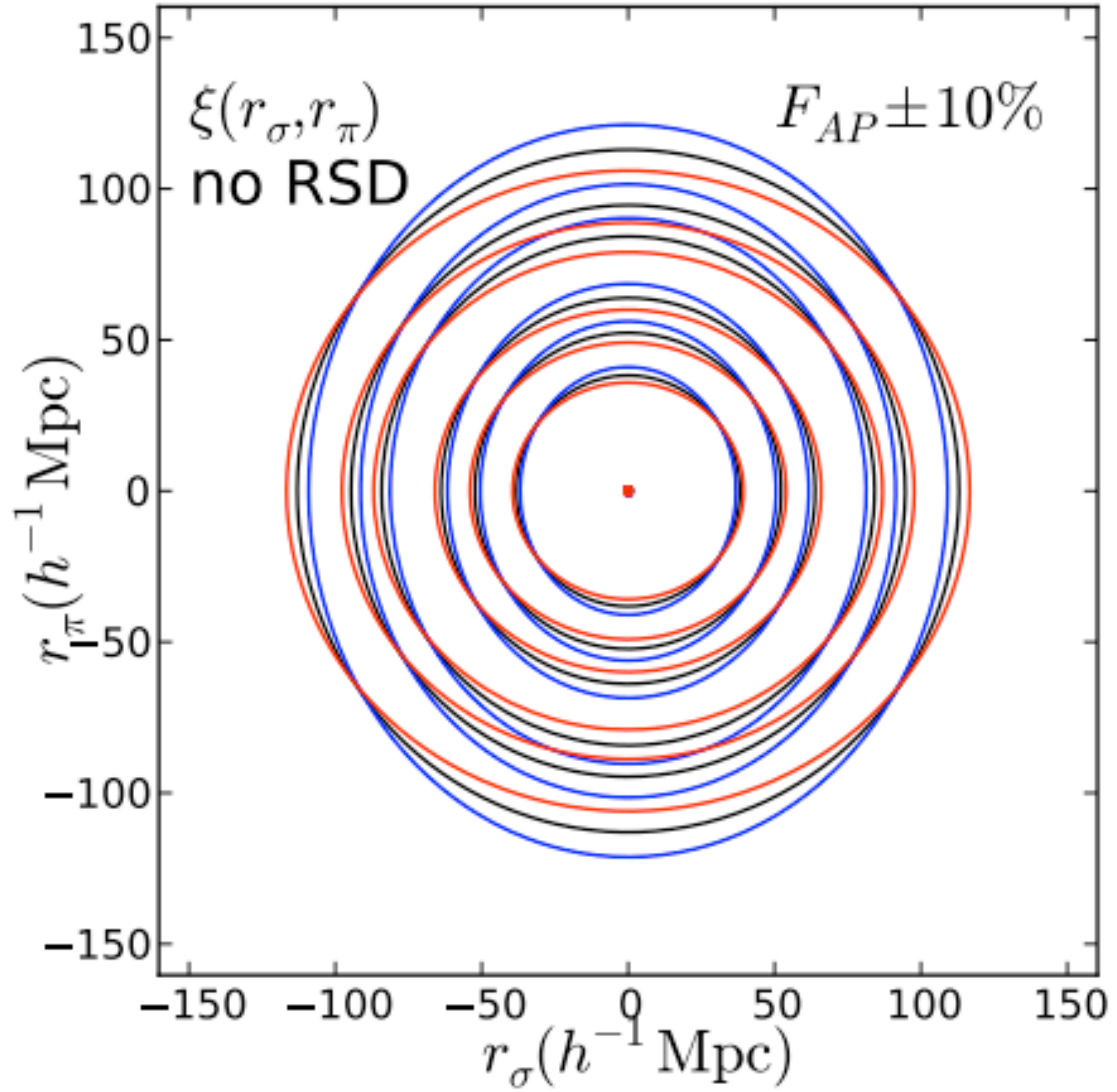
$\xi(r_p, \pi)$ appears anisotropic if you assume the wrong cosmology;

constrains the combination:
$F(z) \equiv (1+z)\, D_A(z)\, H(z)/c$

However geometric distortions can be modeled exactly:

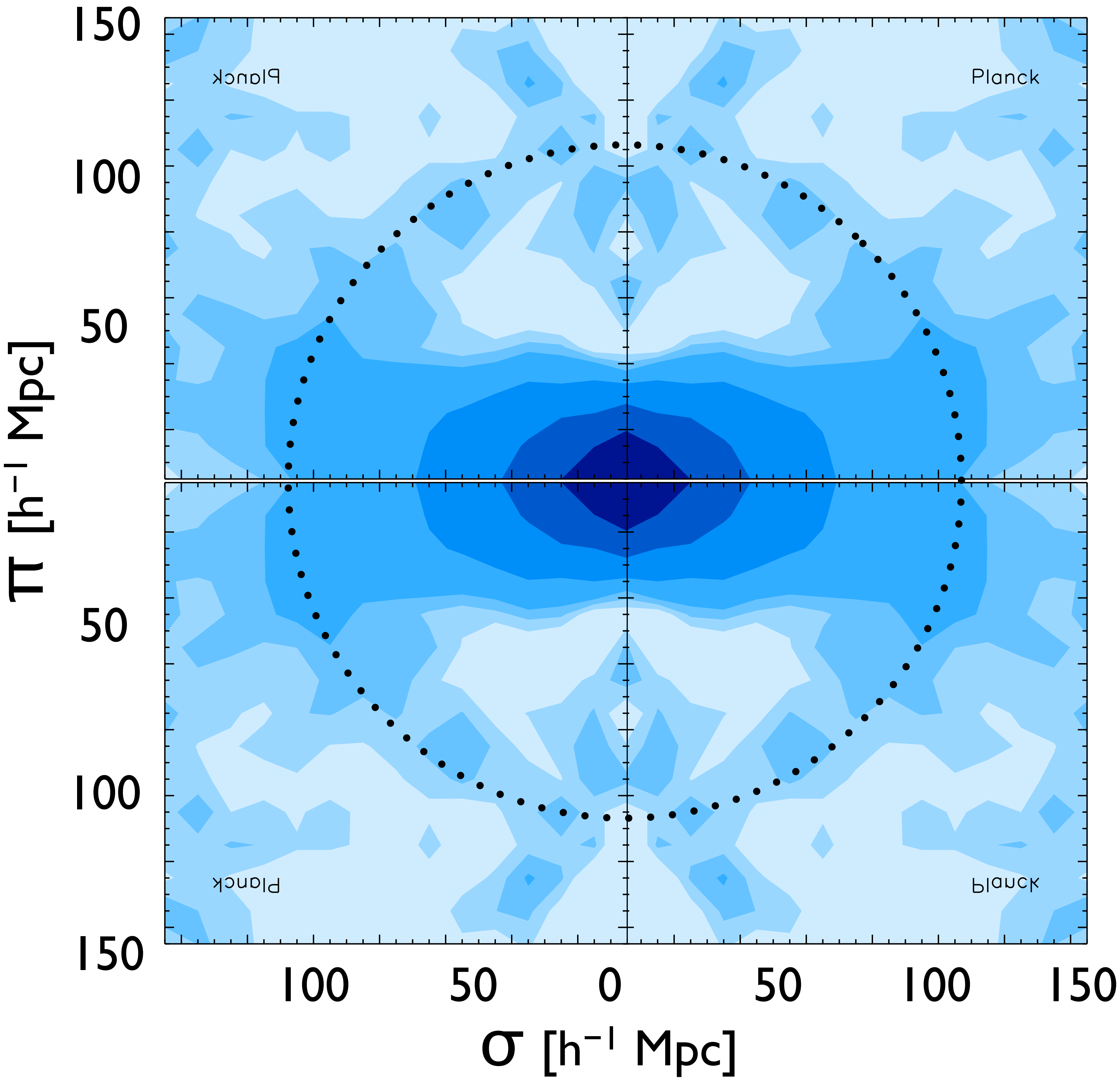
$$\xi^{\mathrm{fid}}(r_\sigma, r_\pi) = \xi^{\mathrm{true}}(\alpha_\perp r_\sigma, \alpha_\parallel r_\pi),$$

$$\alpha_\perp = \frac{D_A^{\mathrm{fid}}(z_{\mathrm{eff}})}{D_A^{\mathrm{true}}(z_{\mathrm{eff}})}, \qquad \alpha_\parallel = \frac{H^{\mathrm{true}}(z_{\mathrm{eff}})}{H^{\mathrm{fid}}(z_{\mathrm{eff}})},$$



2D Clustering on Large Scales

Linder, Oh, Okumura, Sabiu, Song (2013) arXiv:1311.5226



BOSS CMASS DR9

264,283 galaxies

target selection designed for "constant stellar mass" sample

0.43<z<0.7

limiting magnitude of r ~ 22.5

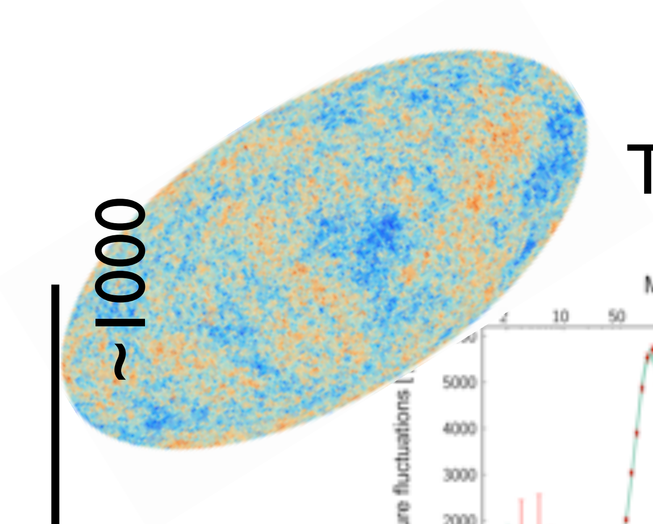
Veff ~ 2.2 Gpc3

Testing Cosmology

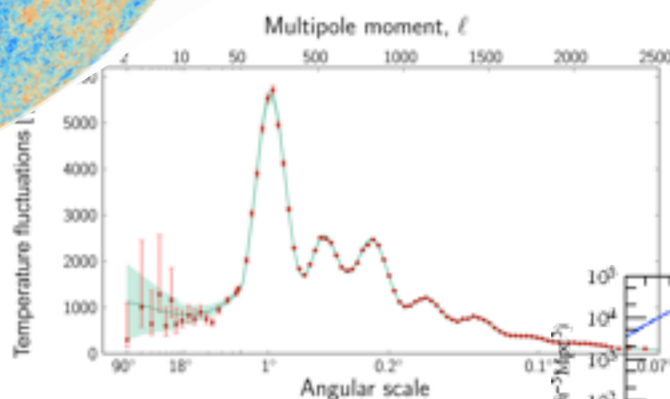
~1000

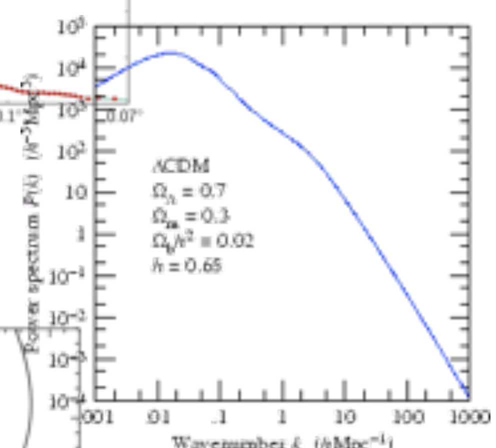
Redshift

0.57

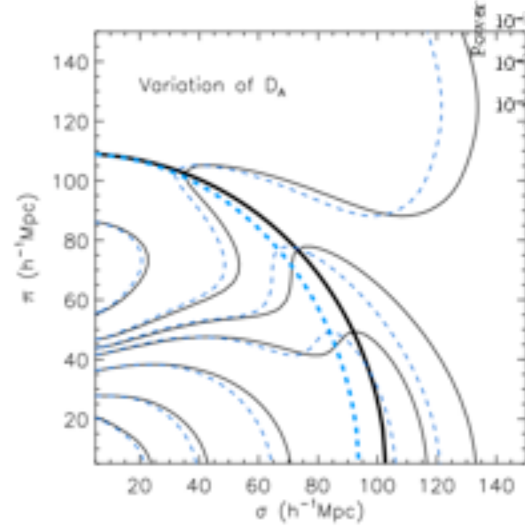


Taking Planck Power Spectrum as a temple





Calculate the non-linear PS at z=0.5
Resummed perturbation theory
RegPT (Taruya et al 2012)



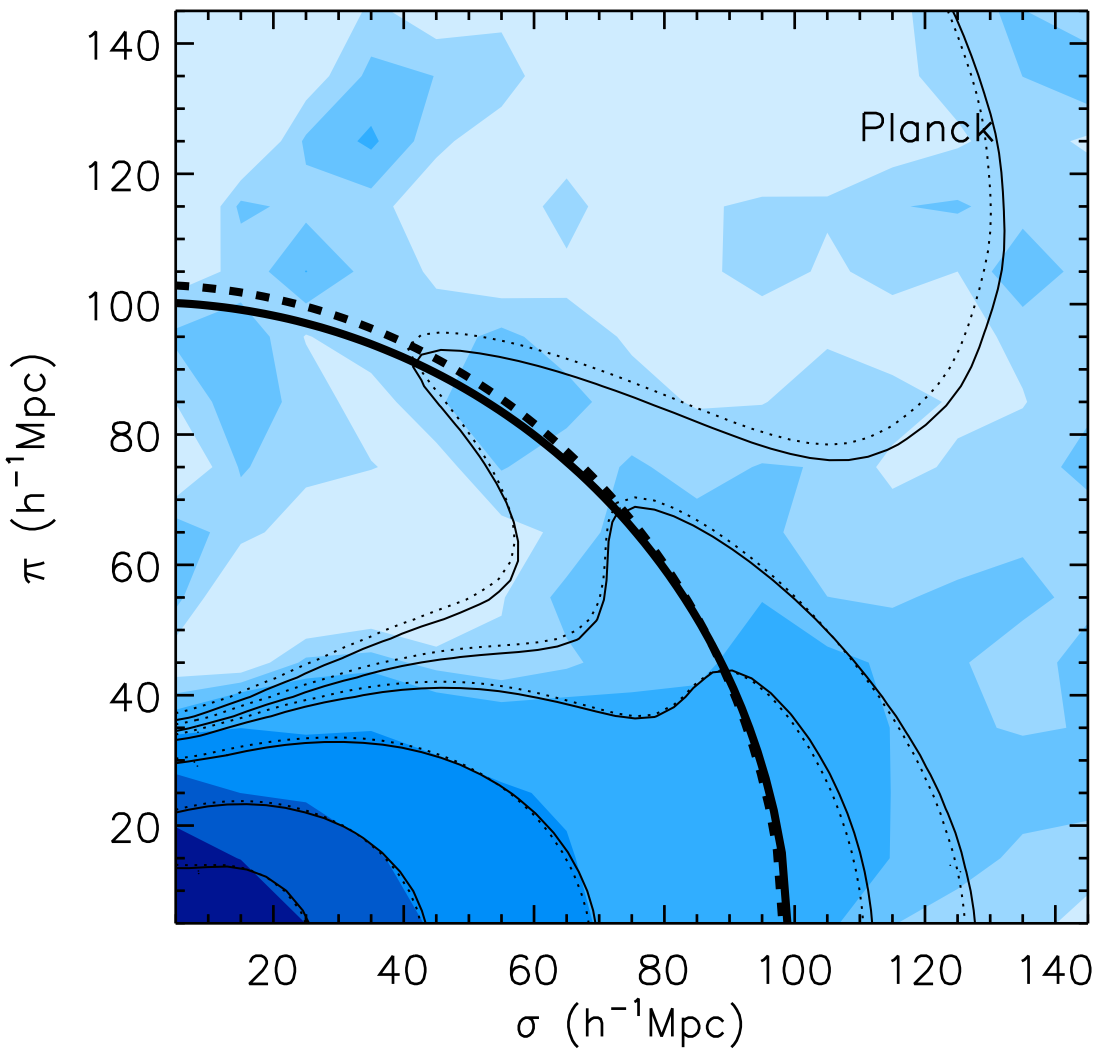
Generate the anisotropic correlation function using the TNS model (Taruya, Nishimichi, Saito, 2010)

This procedure has only 4 free parameters: Da, H, growth rate, bias

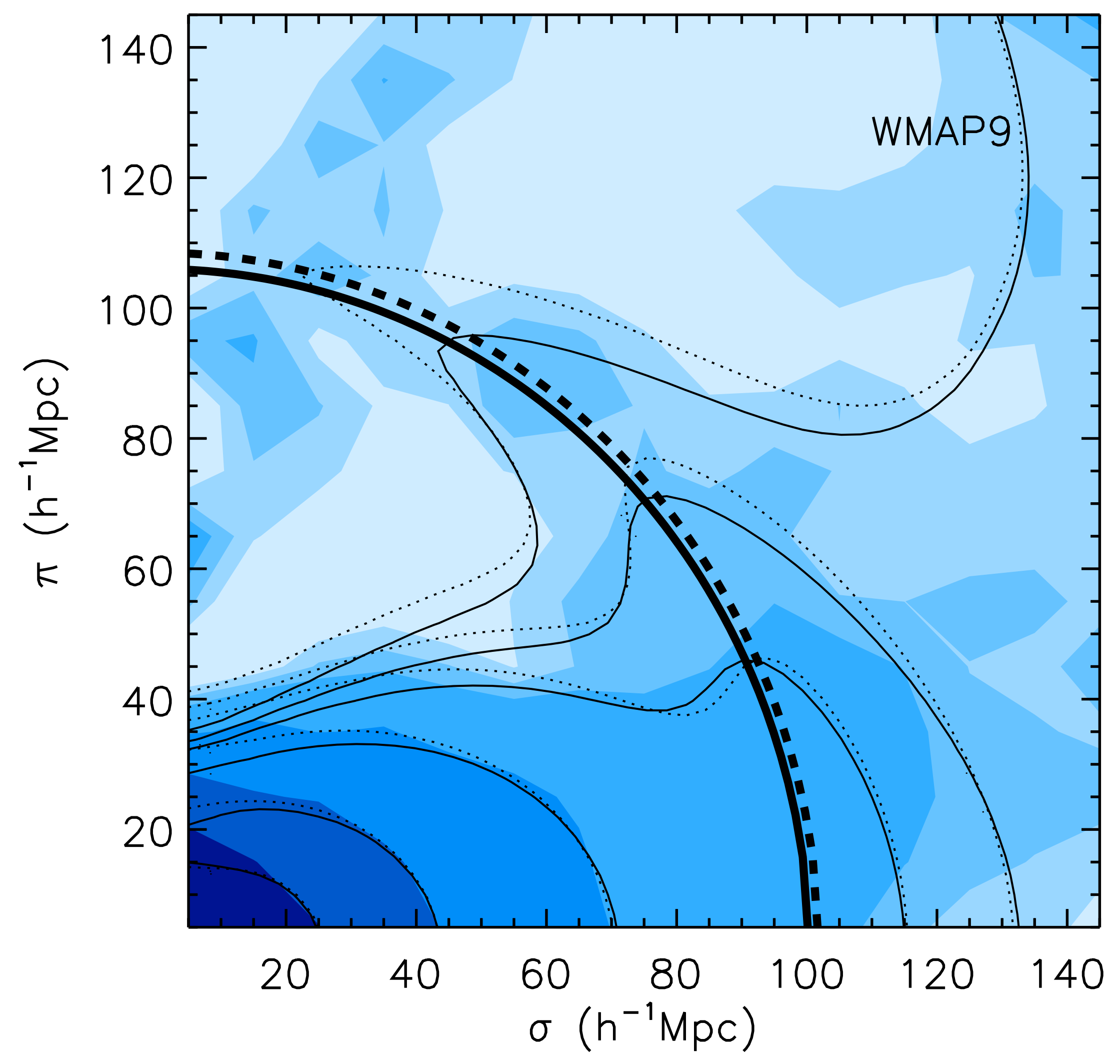
It does not assume any specific dark energy model or even the Friedmann-Robertson-Walker relation between the expansion rate H and distance DA, nor the general relativity relation between expansion and growth.

Testing Cosmology

Fitting the improved TNS model we obtain these fits to the data.

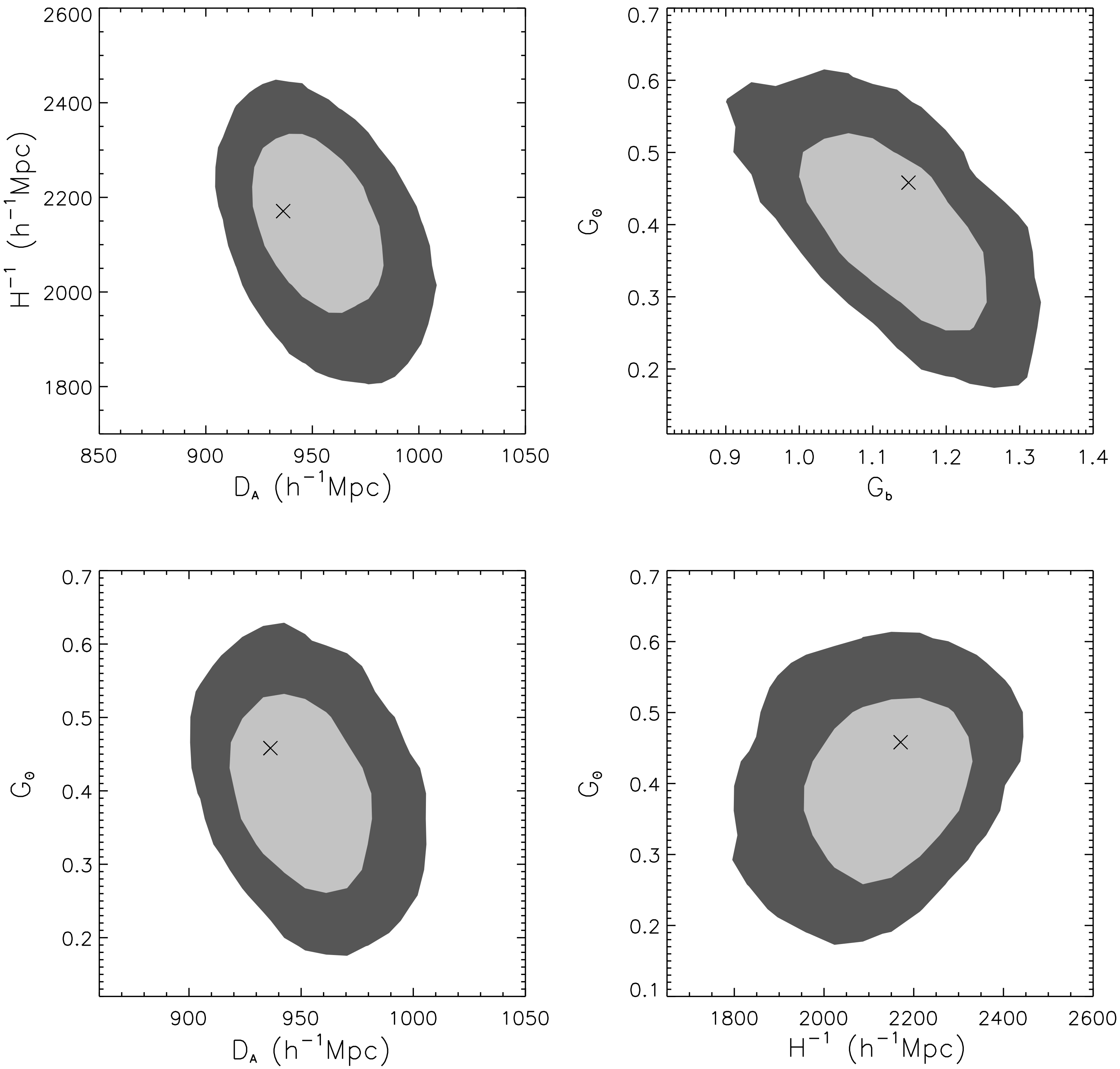


Parameters	Fiducial values With Planck prior	Measurements
$D_A\,(h^{-1}\,\mathrm{Mpc})$	932.6	$939.7^{+26.7}_{-32.6}$
$H^{-1}\,(h^{-1}\,\mathrm{Mpc})$	2177.5	$2120.5^{+82.3}_{-100.6}$
G_b	–	$1.11^{+0.07}_{-0.10}$
G_Θ	0.46	$0.47^{+0.10}_{-0.07}$
$\sigma_p\,(h^{-1}\,\mathrm{Mpc})$	–	$1.2^{+4.0}$



Parameters	Fiducial values With WMAP9 prior	Measurements
$D_A\,(h^{-1}\,\mathrm{Mpc})$	946.0	$916.2^{+27.2}_{-25.4}$
$H^{-1}\,(h^{-1}\,\mathrm{Mpc})$	2241.5	$2163.1^{+102.0}_{-85.8}$
G_b	–	$1.07^{+0.07}_{-0.09}$
G_Θ	0.44	$0.51^{+0.09}_{-0.08}$
$\sigma_p\,(h^{-1}\,\mathrm{Mpc})$	–	$1.0^{+4.6}$

Testing Cosmology



- Constrains from SDSS BOSS DR11

- Using PLANCK prior make model independent measurements of growth rate and geometrical quantities

- No deviation from “GR+LCDM” within observational limits

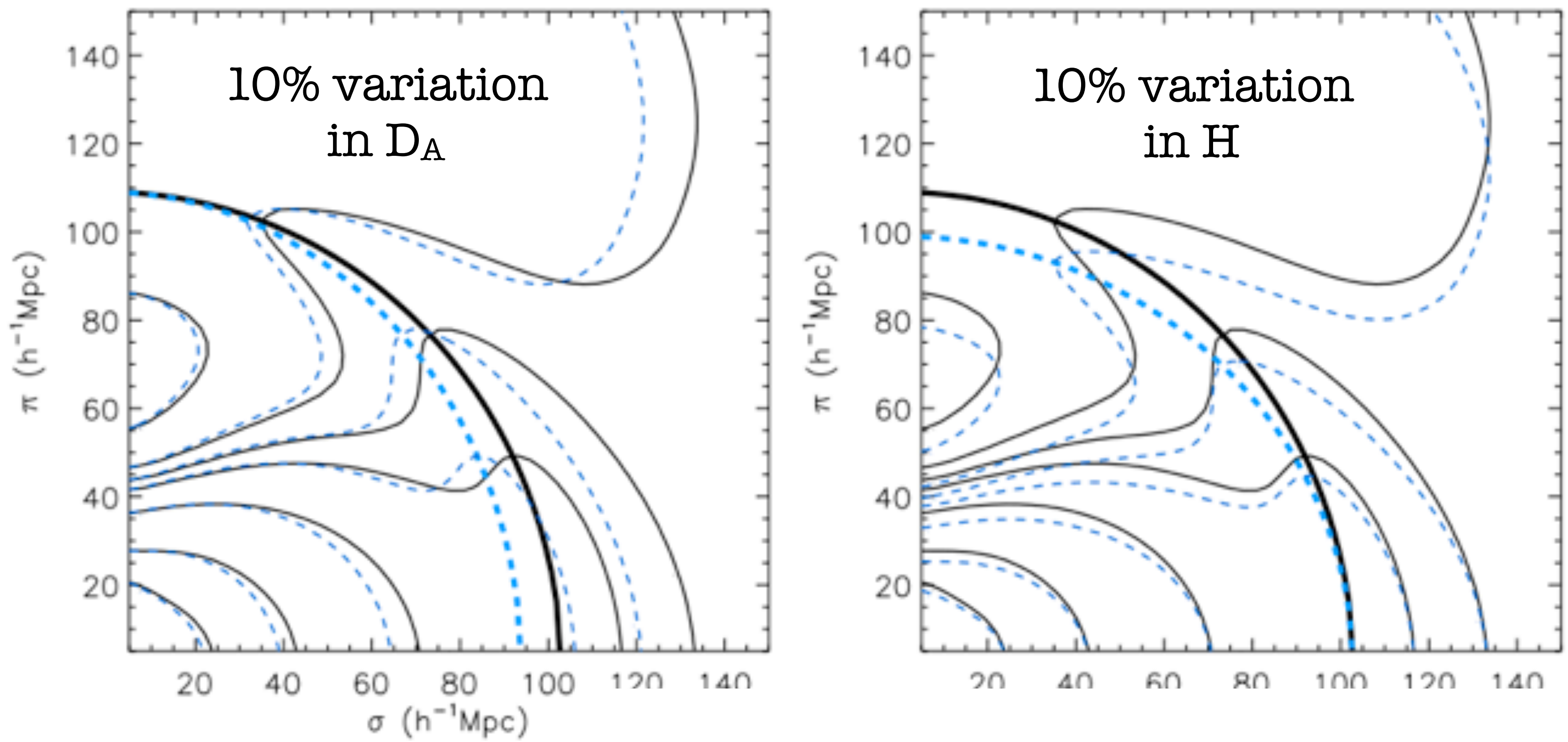
Song, Sabiu, etal (2014)
arXiv:1407.2257

Pure Alcock-Paczynski Measure

Theoretically the geometric distortions of the AP effect can be modeled exactly:

$$\xi^{\rm fid}(r_\sigma, r_\pi) = \xi^{\rm true}(\alpha_\perp r_\sigma, \alpha_\parallel r_\pi),$$

$$\alpha_\perp = \frac{D_A^{\rm fid}(z_{\rm eff})}{D_A^{\rm true}(z_{\rm eff})}, \qquad \alpha_\parallel = \frac{H^{\rm true}(z_{\rm eff})}{H^{\rm fid}(z_{\rm eff})},$$

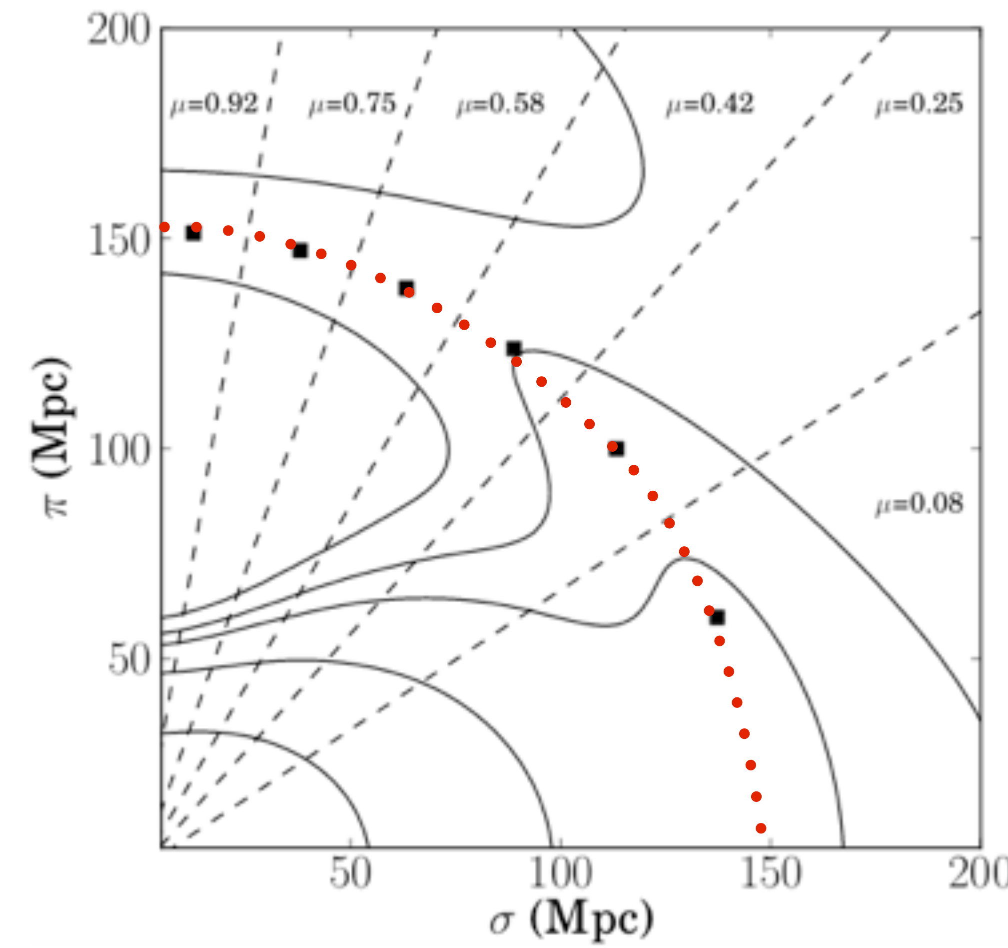


D_A, H vary peak positions off the BAO ring.

We want to avoid fitting the full shape of the anisotropic correlation function, as it depends on unknown systematic and physics, like scale dependent bias, etc.

A cleaner method would be to just measure the shape of the BAO ring.

We can do this by looking at many thin wedges in this 2D projection, i.e. many 'directionally constrained' 1-D correlation functions.



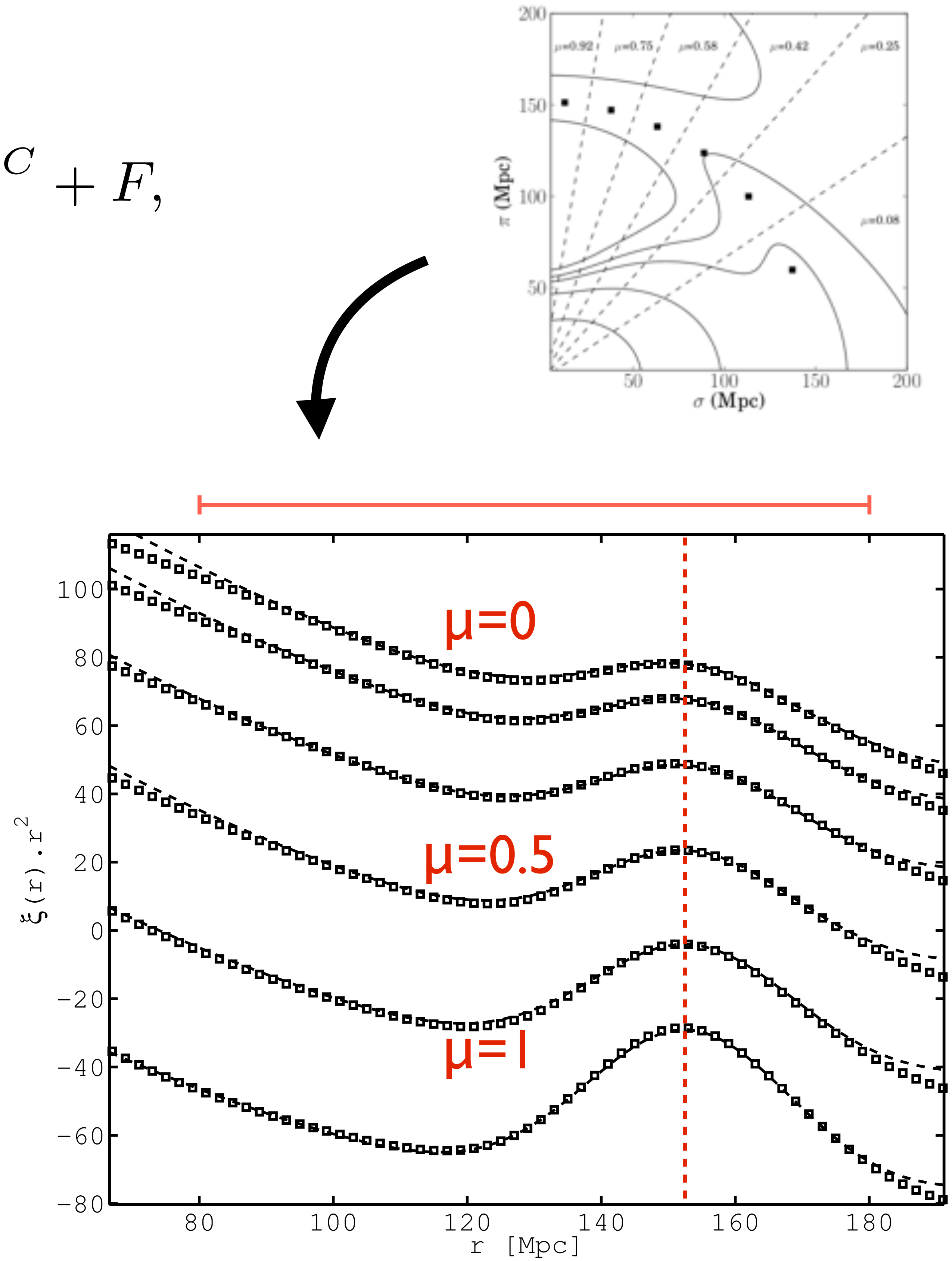
Anisotropic BAO Peaks

$$\xi_\mu(s) \times s^2 = A.s^2 + B.s + Ee^{-(s-D)^2/C} + F,$$

A simple function to approximate the shape of the correlation function

We use a quadratic plus a gaussian, fitted over the range 80<r<180 Mpc

We care only about locating the BAO peak position. The centre of the gaussian is controlled by D.

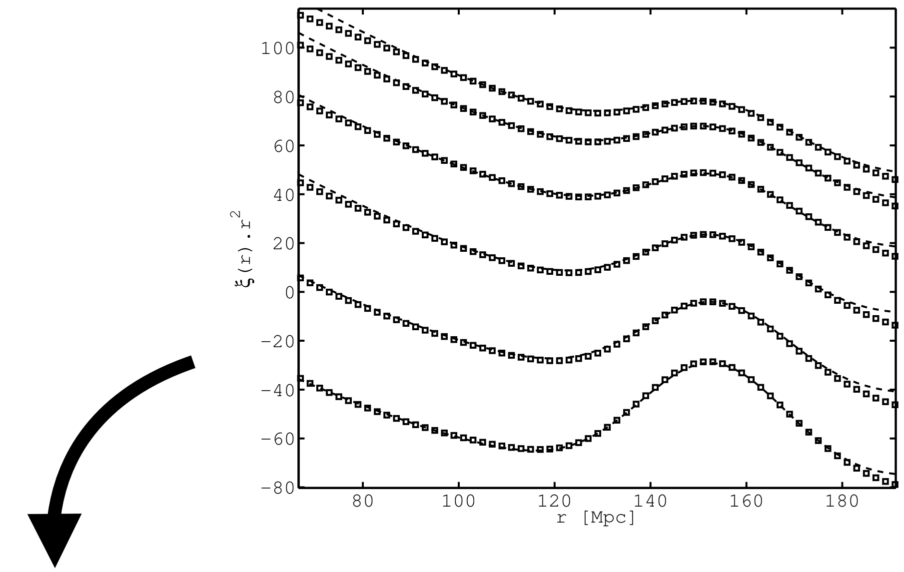


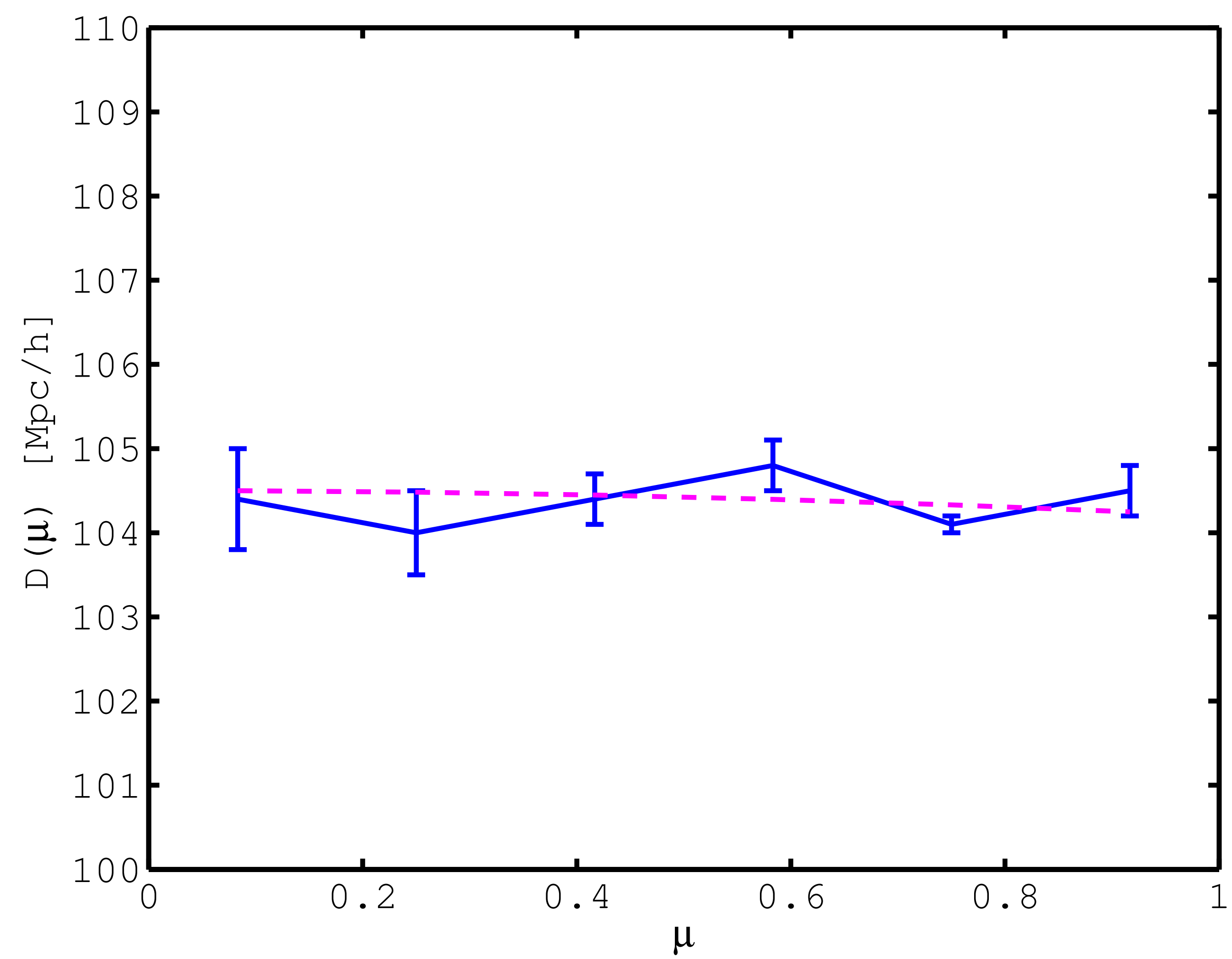
Anisotropic BAO Peaks

Simply we can fit an elliptic function to the obtained D(μ) and get a semi-major and minor distance defining an ellipse.

$$D(\theta) = \frac{D_{||} D_{\perp}}{\sqrt{\left(D_{||}\cos\theta\right)^2 + \left(D_{\perp}\sin\theta\right)^2}}$$

From this we constrain the two distances, $D_{//}$ along the line of sight and $D_{\perp}$ across the line of sight.

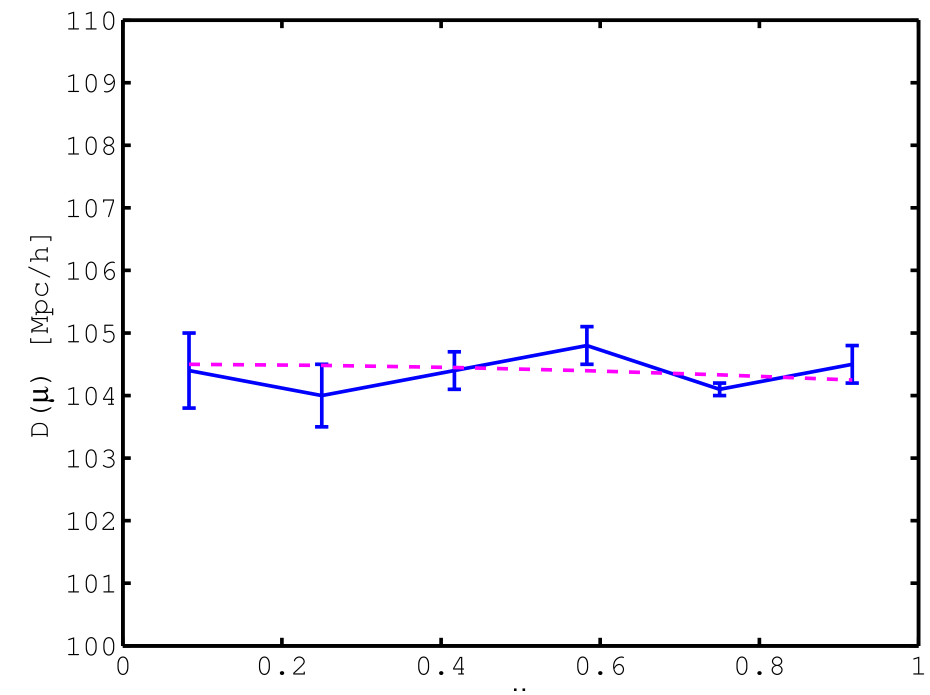




Anisotropic BAO Peaks

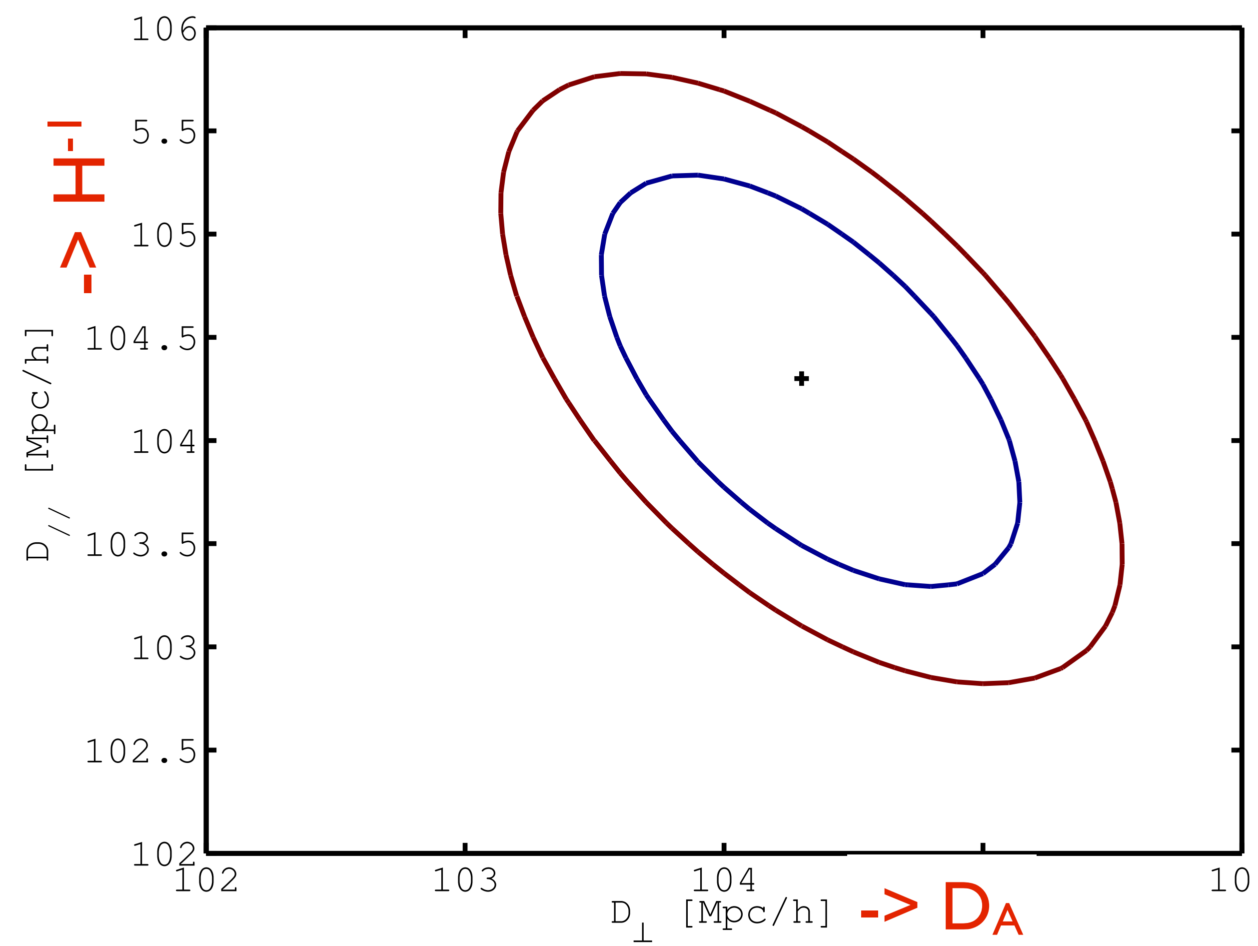
$$D(\mu) = \frac{D_{\perp}.D_{||}}{\sqrt{(D_{\perp}.\mu)^2 + D_{||}^2(1-\mu^2)}}$$

$$H_{obs}^{-1} = H_{fid}^{-1}\frac{D_{||,fid}}{D_{||,obs}},$$
$$D_{A,obs} = D_{A,fid}\frac{D_{\perp,fid}}{D_{\perp,obs}}.$$



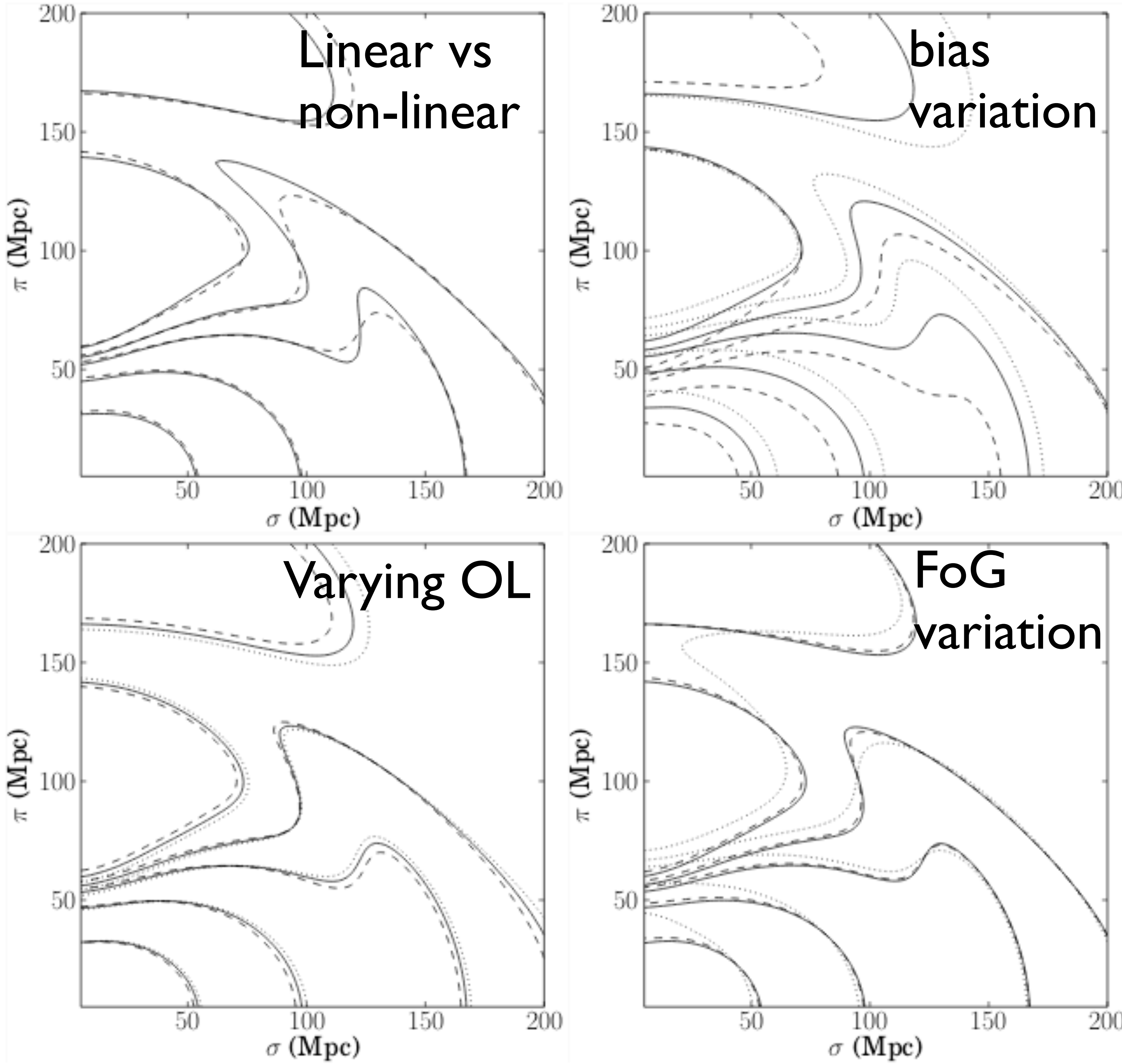
Next we create theoretical models that include different systematics and and observational effects.

In the fiducial case we obtain a simultaneous measurement of D_A and H^{-1}



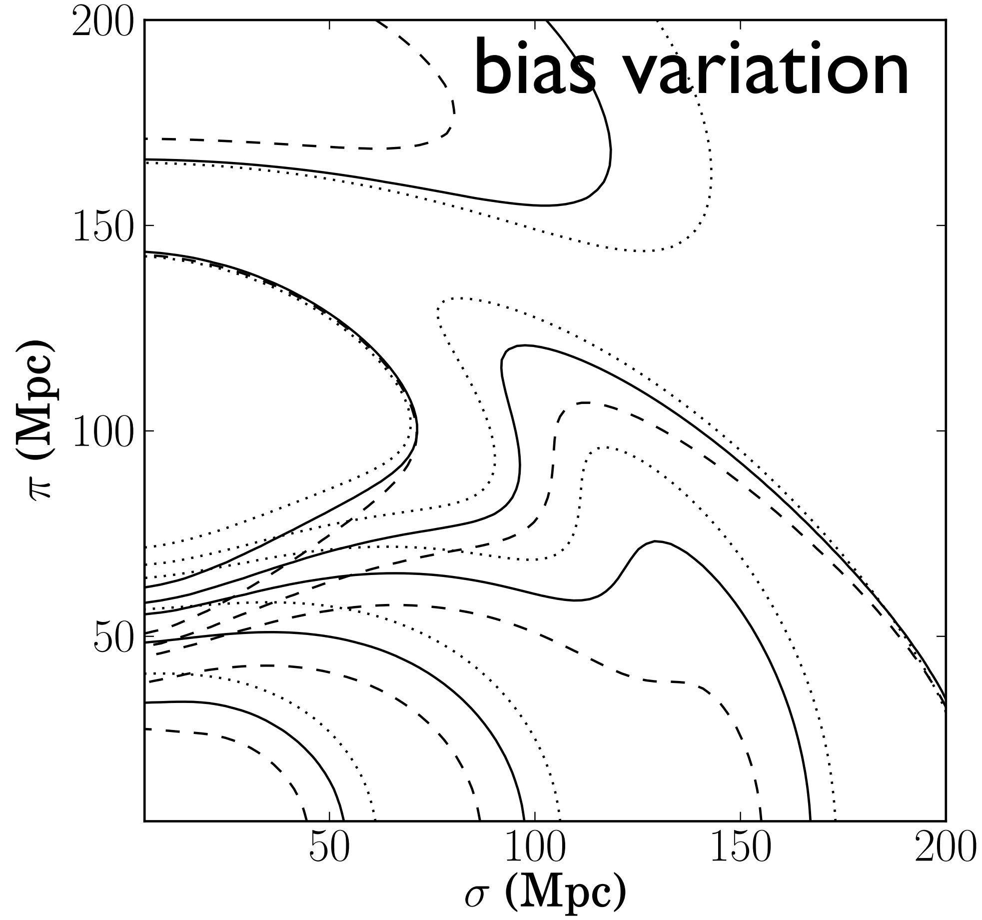
Anisotropic BAO Peaks

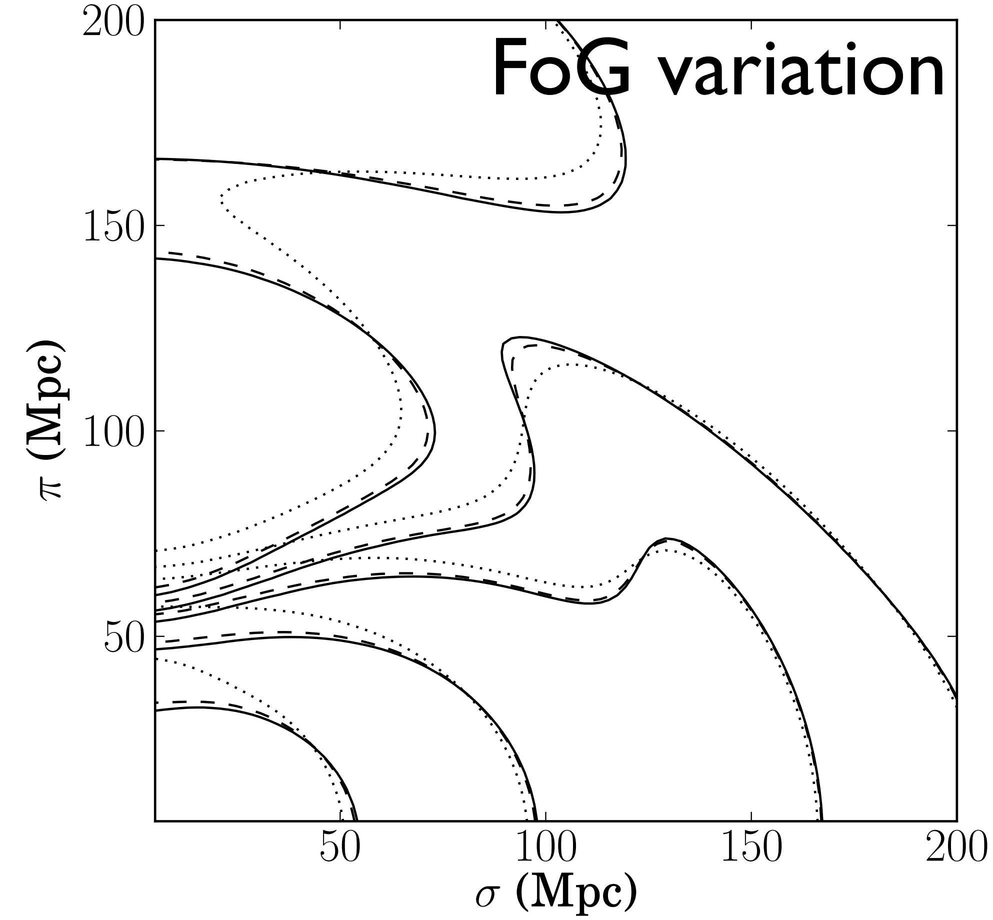
Check systematics



Anisotropic BAO Peaks

Will certain systematic uncertainties effect our methodology to reliably estimate the peak location?





bias	D_A(Mpc)	H^{-1}(Mpc)
1.5	1395.18 (0.00 %)	3241.28 (0.20%)
2.0 (fid)	1395.18 (0.00 %)	3234.76 (0.00 %)
2.5	1384.29 (-0.78%)	3234.76 (0.00%)

σ_v(Mpc)	D_A (Mpc)	H^{-1} (Mpc)
2	1392.47 (-0.19 %)	3253.96 (0.59%)
5 (fid)	1395.18 (0.00 %)	3234.76 (0.00 %)
8	1395.18 (0.00 %)	3234.76 (0.00 %)
11	1397.99 (0.20 %)	3166.40 (-2.11%)
15	1397.99 (0.20 %)	3077.53 (-4.86%)

Anisotropic BAO Peaks

Modeling the RSD effect

We show the derived distance measurements using models with various σv choices, of 0, 2, 4, 6, 8 Mpc/h. We find a significant trend with these values of σv with either D// and D⊥

But as we can see both D// and D⊥ can be modelled using a simple function:

$$D(\mu) = D^{fid}(\mu) + \alpha(\mu) + \beta(\mu)\sigma_v^2,$$

Although the dashed lines show 1% and 4% increase in H-1 which follows closely the σv induced anisotropy, so there will be some degeneracy.

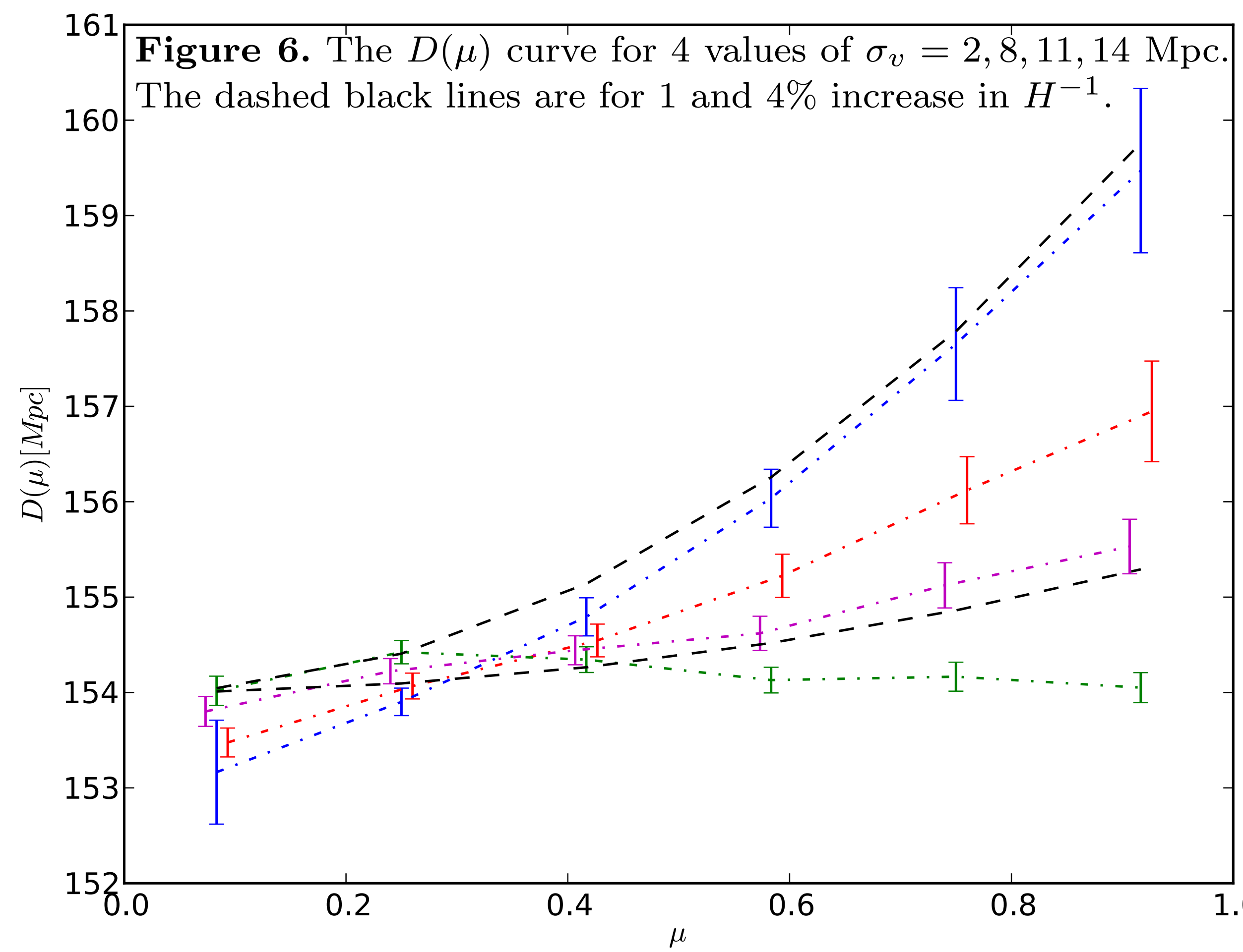


Figure 6. The $D(\mu)$ curve for 4 values of $\sigma_v = 2, 8, 11, 14$ Mpc. The dashed black lines are for 1 and 4% increase in H^{-1}.

	Ω_Λ	0.62		0.68		0.73	
		α_i	β_i	α_i	β_i	α_i	β_i
μ_i	0.08	-0.18	-0.004	-0.15	-0.004	-0.21	-0.004
	0.25	0.21	-0.003	0.07	-0.002	0.10	-0.002
	0.42	-0.17	0.002	-0.10	0.002	-0.09	0.002
	0.58	-0.51	0.009	-0.47	0.010	-0.42	0.009
	0.75	-0.77	0.018	-0.68	0.018	-0.65	0.018
	0.92	-1.07	0.027	-0.88	0.026	-0.89	0.027

minimal cosmo dependance

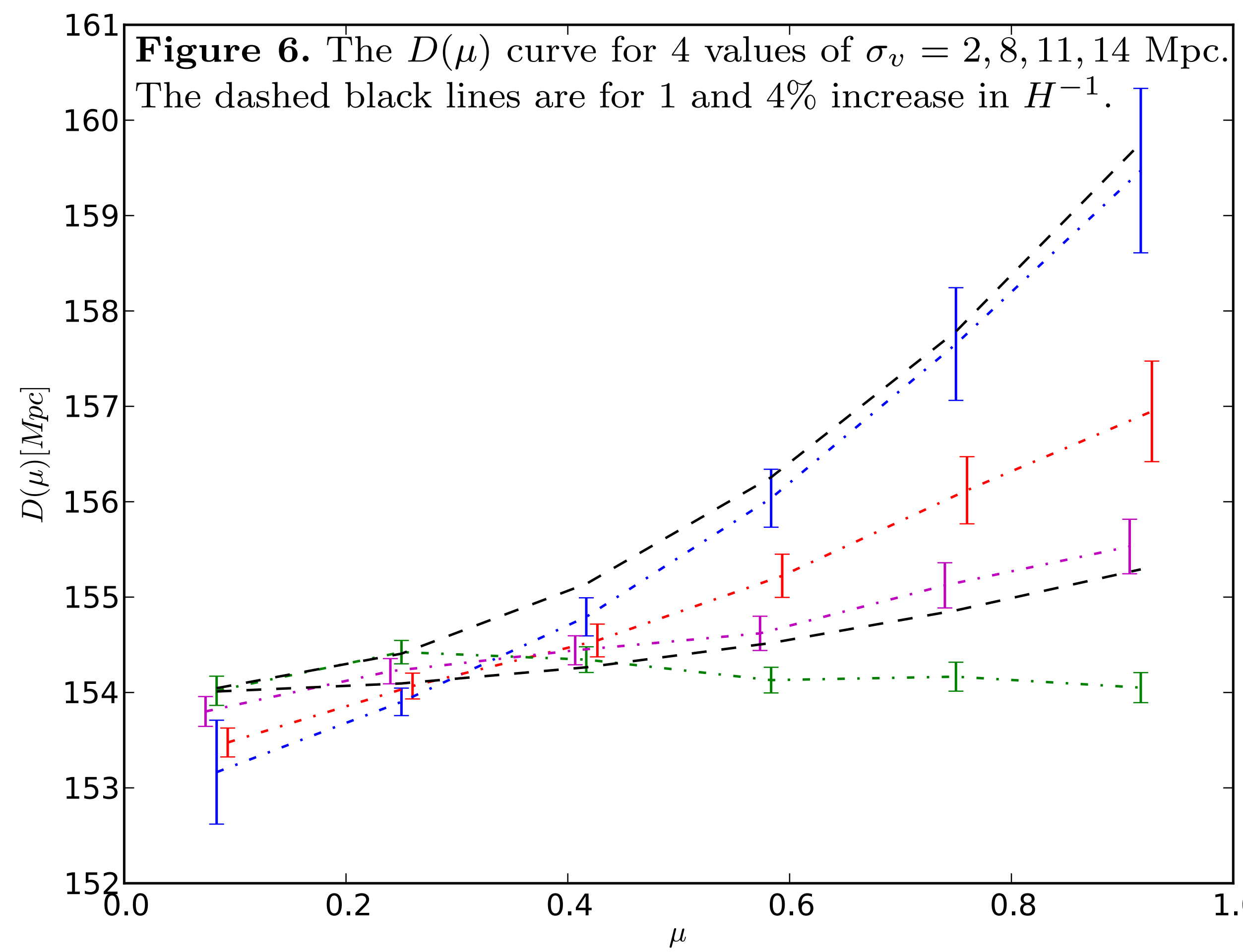
Anisotropic BAO Peaks

Modeling the RSD effect

Modeling the RSD effect allows us to make percent level predictions of Da, H for future surveys, like DESI

Firstly we fit the case without RSD. If we do not correct for the RSD effect we know from previous tests that our results on H^{-1} will be necessarily biased. We find $D_{||} = 155.15 \pm 0.51$ Mpc and $D_{\perp} = 154.04 \pm 0.30$ Mpc that results in the following constraints; $D_A = 1399.71^{+2.71}_{-2.74} (0.32^{-0.20}_{+0.19}\%)$ and $H^{-1} = 3196.79^{+10.57}_{-10.44} (-1.17 \pm 0.32\%)$, where the percentage denotes the deviation from fiducial model.

$D_{||} = 154.92^{+0.51}_{-2.29}$ Mpc and $D_{\perp} = 153.90^{+0.25}_{-0.25}$ Mpc with $\sigma_v = 6.8^{+2.0}_{-6.8}$ Mpc, which leads to $D_A = 1401.01^{+2.29}_{-2.26} (0.42^{-0.17}_{+0.16}\%)$ and $H^{-1} = 3201.66^{+47.94}_{-10.39} (-1.02^{+1.48}_{-0.32}\%)$.



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minimal cosmo dependance

Anisotropic BAO Peaks

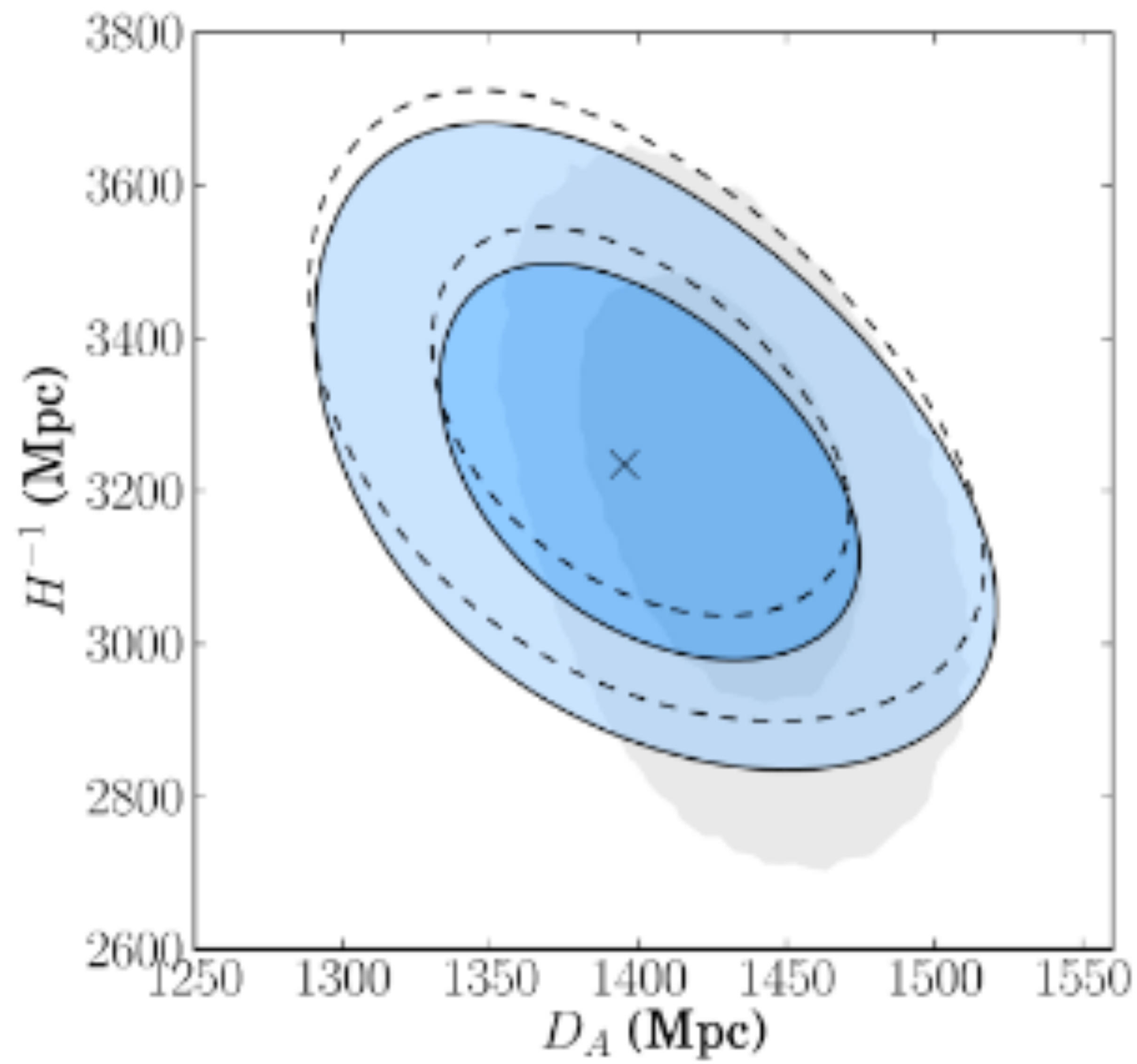
Sabiu & Song (2016) arxiv:1603.02389

Using 600 mock catalogues mimicking the BOSS survey

Modeling and marginalizing out the FoG systematic degrades the los BAO distance and hence H. However is provides a less biased result.

obtain constraints on DA & H at the level of 2% and 5% resp.

Next we will apply this methodology to SDSS BOSS data in Oh, Sabiu, Song (2016) in prep



Probing Scalar Field Theories CosKASI

Light scalar fields coupled to matter (baryons) are predicted by many theories beyond the standard model.

•

Coupled means we have a fifth−force in nature. If it exists, is there any room for cosmological signatures (of the fifth−force)?

•

A fifth−force is strongly constrained from local gravity experiments (inverse square law, solar--system tests, EP).

•

Naive conclusion: Either very short range or very weakly coupled, in other words: no cosmological effects of the fifth−force!

•

Not the case if the field has a screening mechanism. The fifth−force can remain 'hidden' to local experiments!

•

We consider two models that have this property: Chameleon & Symmetron

Probing Scalar Field Theories in redshift-space

We focus our analysis in two specific scalar tensor models: the symmetron model and a particular case of f(R) theories.

with Changbom Park & David Mota
arxiv:1603.05750

Npart=512^3
Side=256Mpc/h
at z=0.0
Dark matter and FoF halos

Both models include screening mechanisms, which reduce them to general relativity in high density regions and thus pass solar system tests.

N-body simulations from Llinares, Mota etal (2013) arXiv:1307.6748

Model	λ_0	z_{SSB}	β
Symm A	1	1	1
Symm B	1	2	1
Symm C	1	1	2
Symm D	1	3	1

Symmetron Model
Hinterbichler & Khoury (2010)

Model	n	$\lvert f_{R0}\rvert$	λ_0
fofr4	1	10^{-4}	23.7
fofr5	1	10^{-5}	7.5
fofr6	1	10^{-6}	2.4

f(R) Gravity Model
Hu & Sawicki (2007)

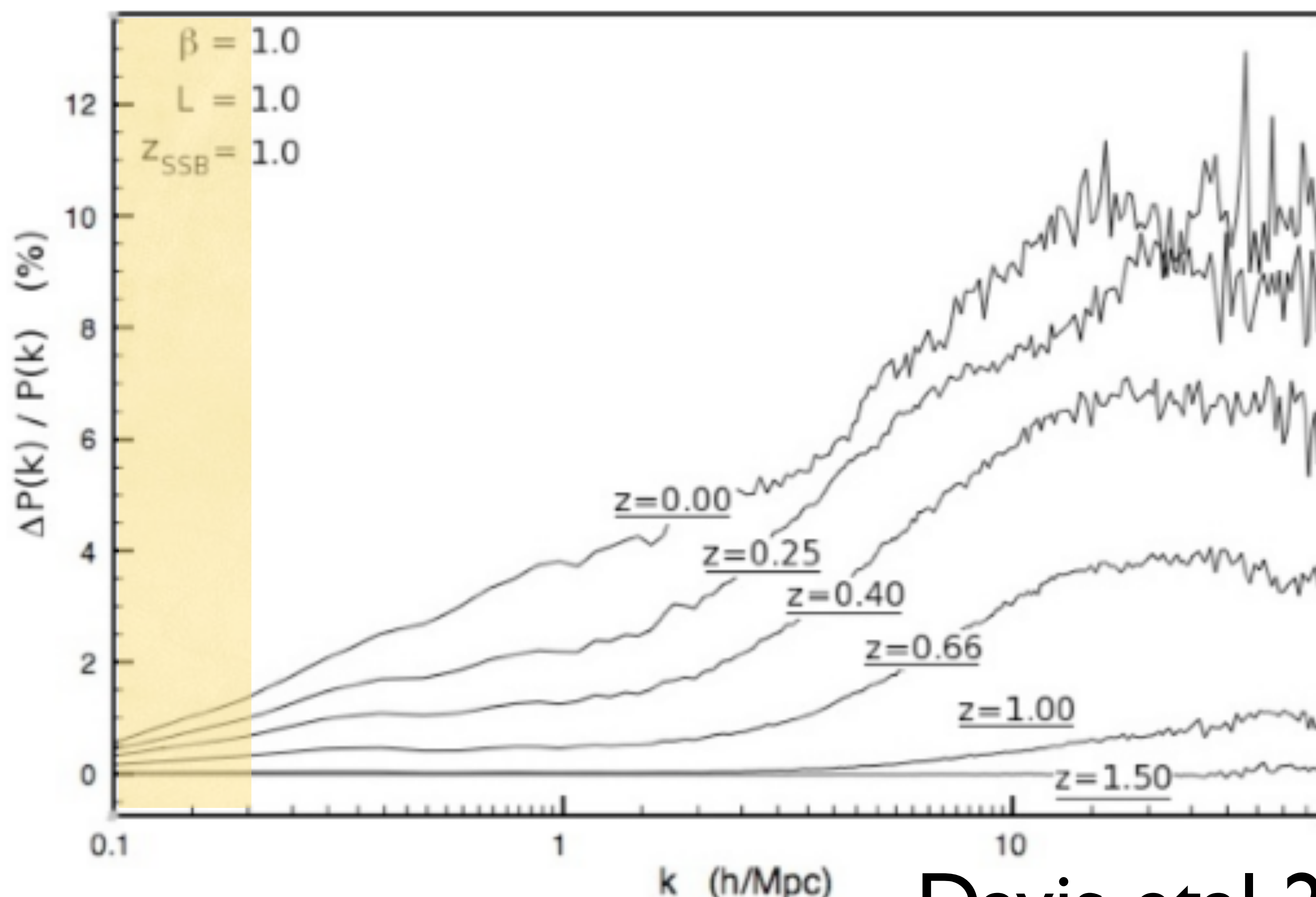
Probing Scalar Field Theories in redshift-space

Percent level difference at relevant scales and redshifts

Isotropic Power Spectrum not very sensitive to information in the velocity field

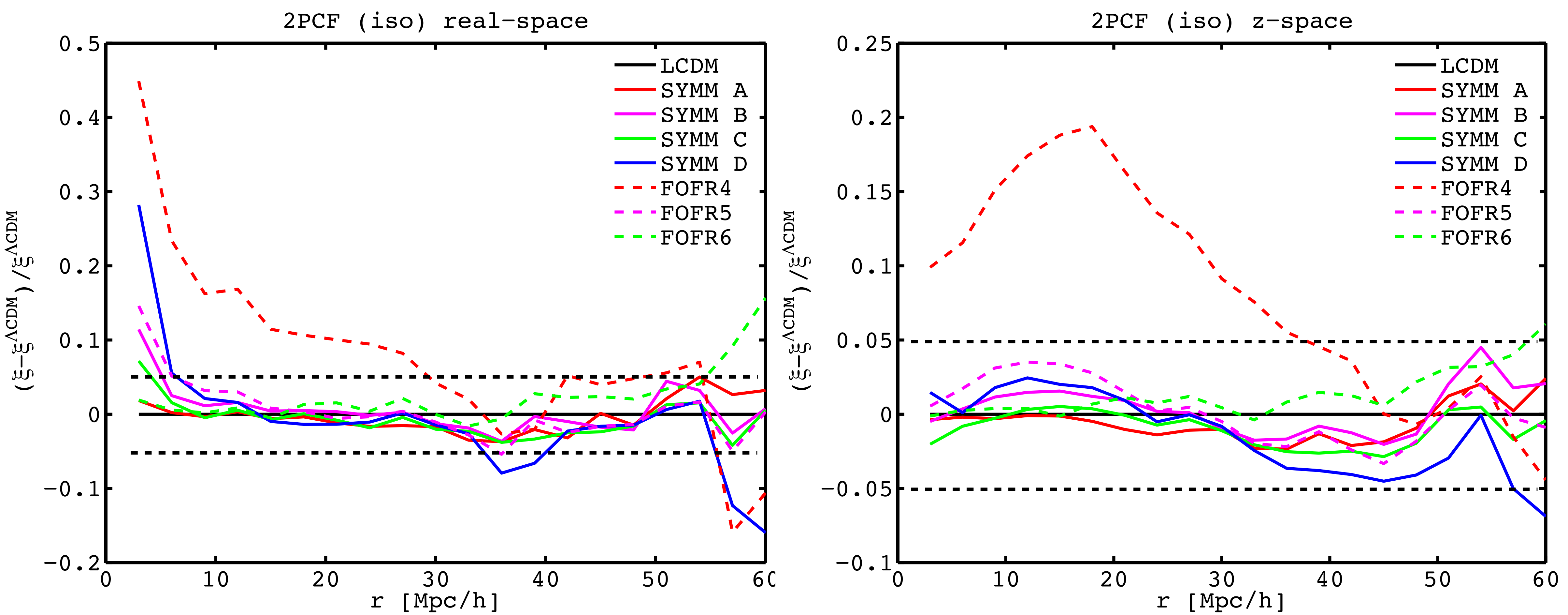
Look in redshift-space using anisotropic statistics?

Symmetron Power Spectrum



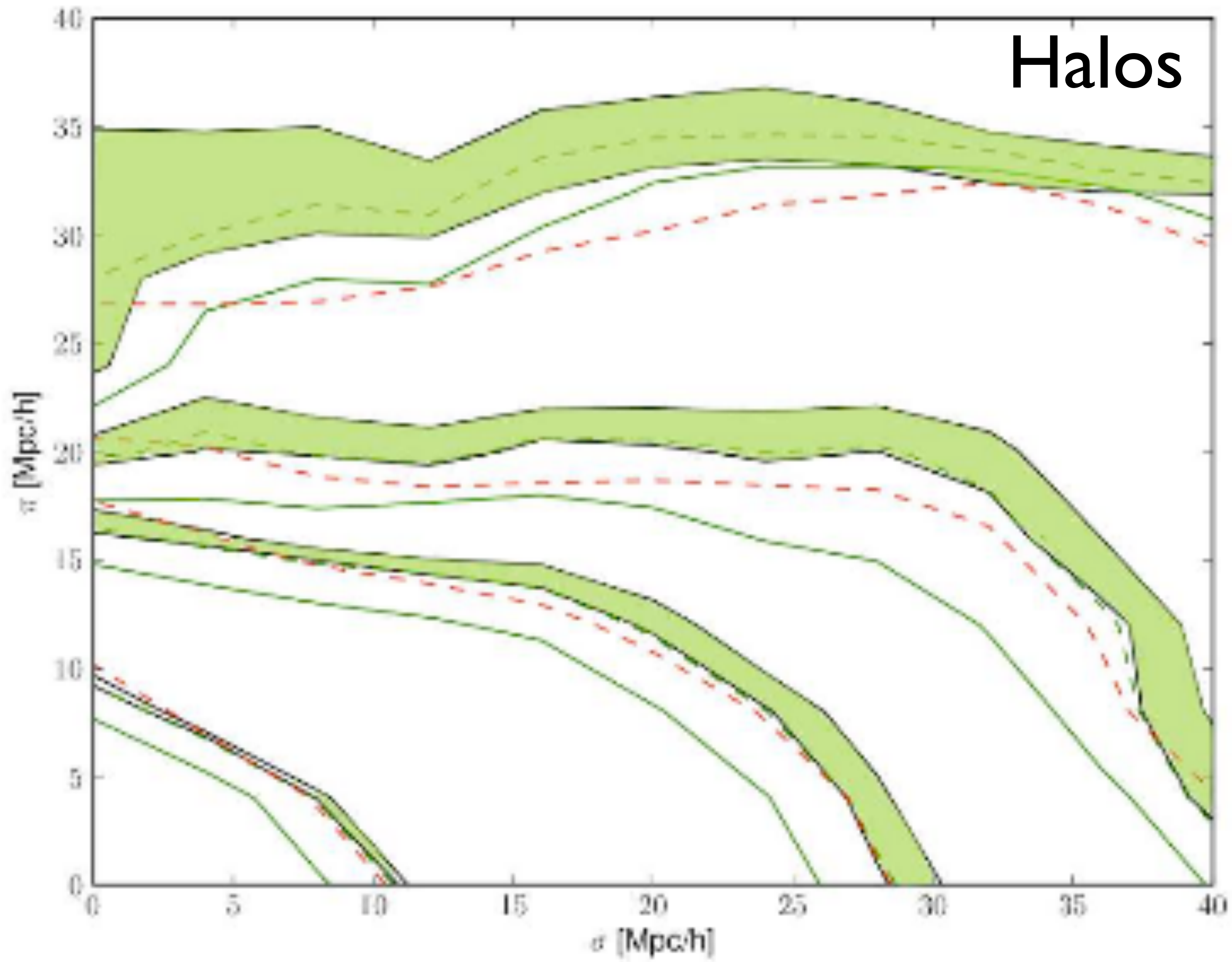
Davis etal 2011

Probing Scalar Field Theories in redshift-space



- Using iso-2PCF, more deviation from LCDM in redshift-space
- FOFR4 and SymmD models show largest difference > ~5%
- Maybe we can investigate velocity effect more specifically....

Probing Scalar Field Theories in redshift-space



- In anisotropic proj again FOFR4 shows large variation in DM
- Halo clustering exhibits wider dispersion amongst models
- So what? Can we construct a smoking gun test? maybe...

3-Point correlations (Fourier Dual of Bispectrum)

The complete statistical description of a field may require higher-order statistics,

$$\zeta(r_1, r_2, r_3) = \langle \delta_{gal}(r_1)\delta_{gal}(r_2)\delta_{gal}(r_3) \rangle$$

Probability of finding pairs/triplets of objects:

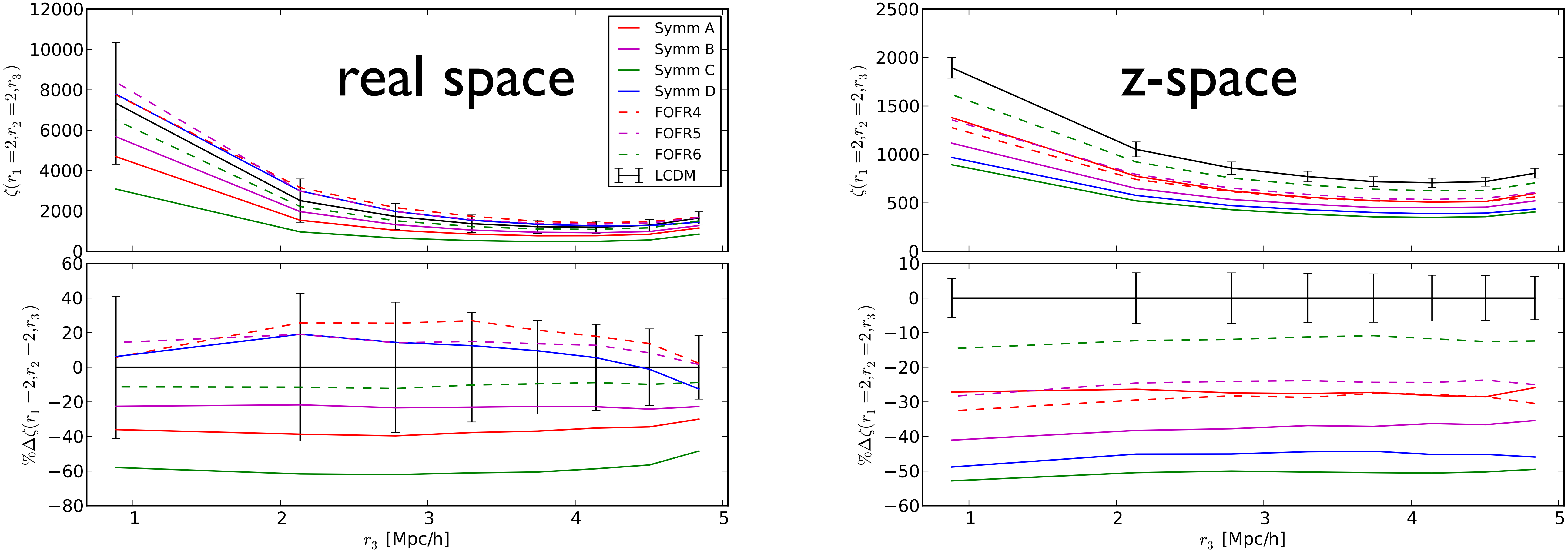
$$dP = n^3(1 + \xi(r_1) + \xi(r_2) + \xi(r_3) + \zeta(r_1, r_2, r_3))dV_1 dV_2 dV_3$$

random — correlated pairs — correlated triplets

It's difficult to compute and cpu intensive...
Im developing a code to do this using MPI, kd-trees, and some other tricks: https://bitbucket.org/csabiu/kstat

Probing Scalar Field Theories in redshift-space

The 3pcf in various modified gravity simulations



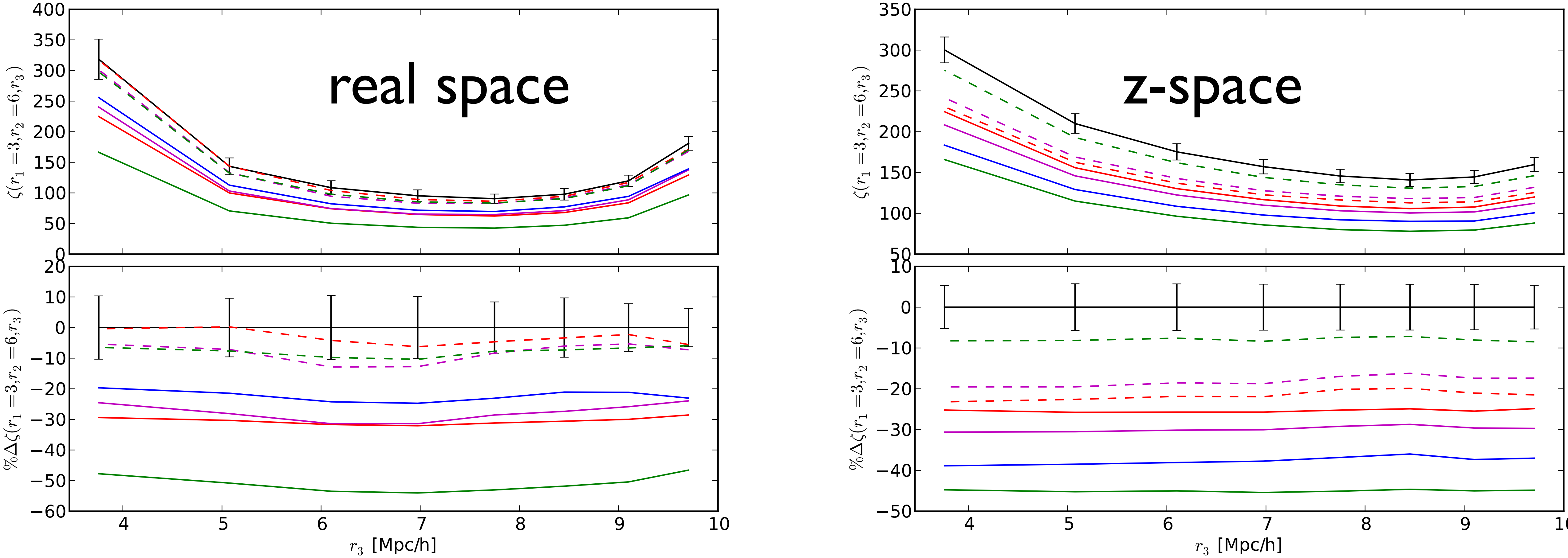
Small scale clustering with s=2, q=1

there is significant dispersion between models which suggest that the 3PCF is a more powerful probe of modified gravitational clustering.

The redshift space clustering tends to flatten the 3PCF, with FOFR4 displaying an extreme case of this.

Probing Scalar Field Theories in redshift-space

The 3pcf in various modified gravity simulations



larger configuration with s=3, q=2

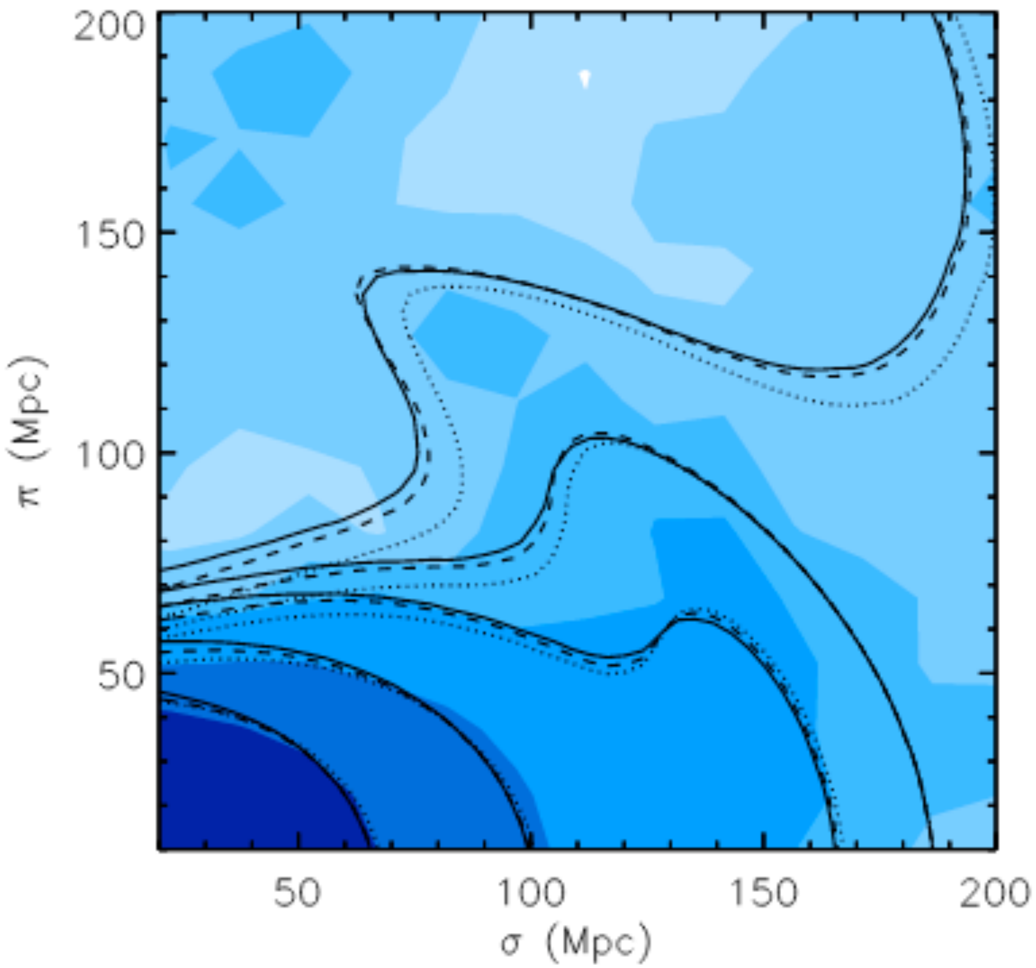
Should appear in A&A soon...
arxiv:1603.05750

Conclusions

We wanted clean measurements of Da and H(z) as they are fundamental quantities that describe the geometry and evolution of the background universe.
- we have shown that the clustering 'peaks' give us an unbiased constraint on these quantities

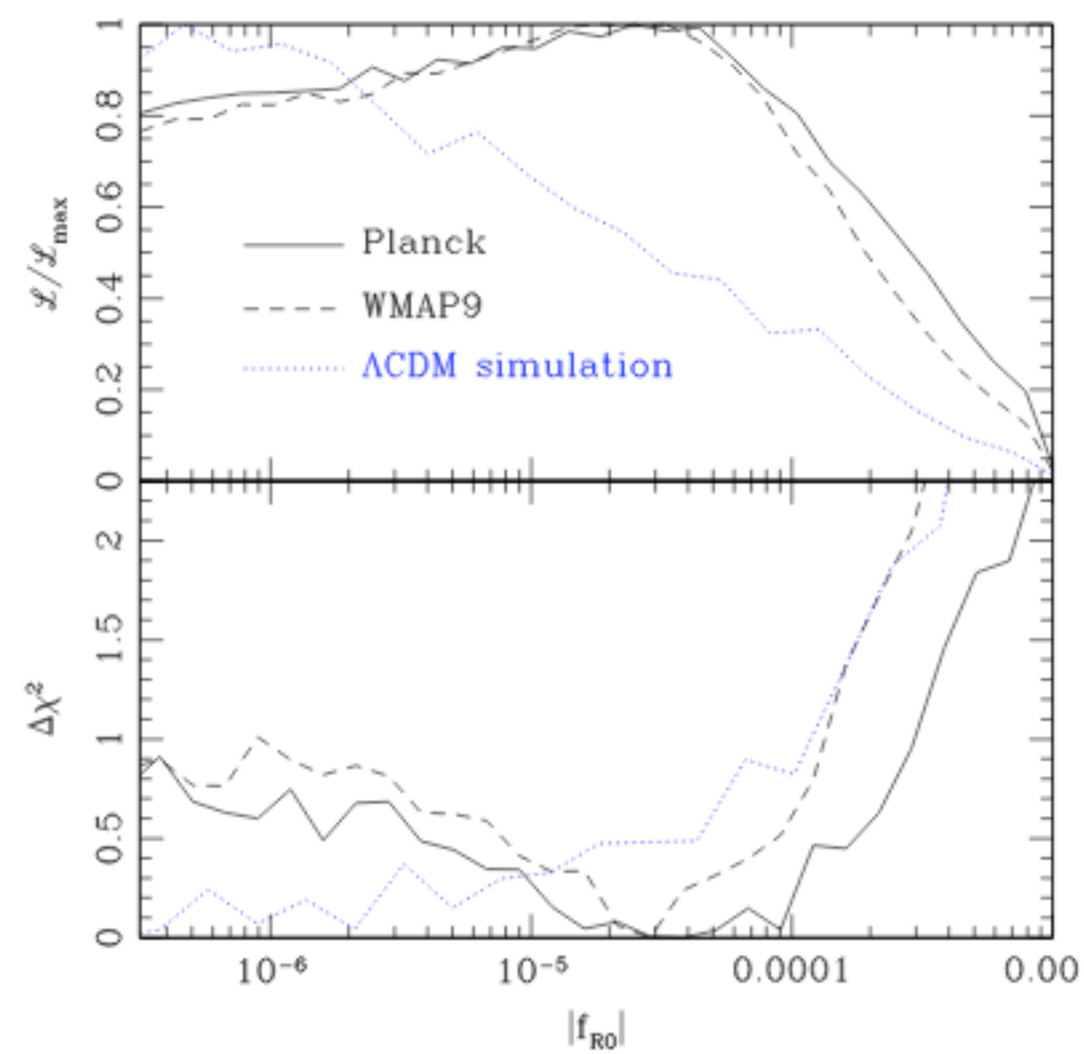
We hunted for mod. grav. induced variations in the velocity field and the local environment density...
- Measured the redshift-space clustering statistics
- Find deviations from LCDM above exp. error
- Although this is only a qualitative study so far, it is the 1st regarding redshift-space bispectra/3PCF in modified gravity.

Testing Cosmology



Constraints on f(R) modified gravity from SDSS BOSS

Filled contours - DR11 data
Solid line - LCDM best fit
Dashed - $|f_{R0}|=3.2\times10^{-5}$
Dotted - $|f_{R0}|=3.0\times10^{-4}$



No preference for f(R) over pure GR+LCDM

But future data may say more...

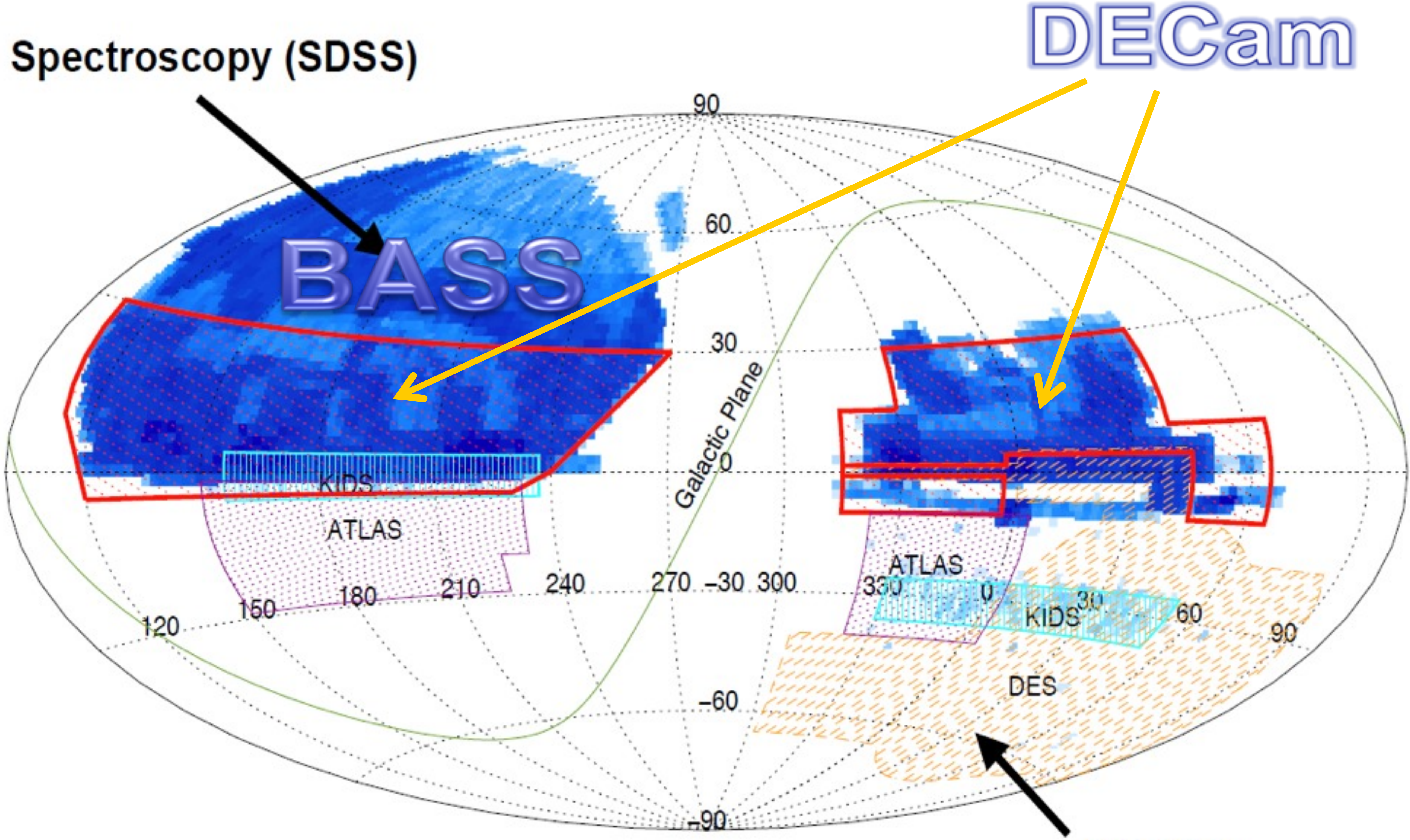
Song, etal (2015)
arXiv:1507.01592

Survey Sources

- **South:**
  - 6200 sq. deg. of SDSS footprint south of dec=+30 and excluding areas covered by DES, plus 500 sq. deg. from DES
  - Allocated 65 nights with Blanco/DECam in 2014B-2017A
  - g, r, z-bands
  - First public data release DR1 on March 18, 2015
- **North:**
  - Bok Telescope using 90Prime instrument
    - 5500 sq. deg.
    - Survey started
    - g, r-bands
  - Mayall 4m using Mosaic 3 instrument
    - Focal plane upgrade to Mosaic 1.1 instrument (from CTIO)
    - 5500 sq. deg. to start in 2016
    - z-band
- **Combined imaging: g=24.0, r=23.6, z=23.0**

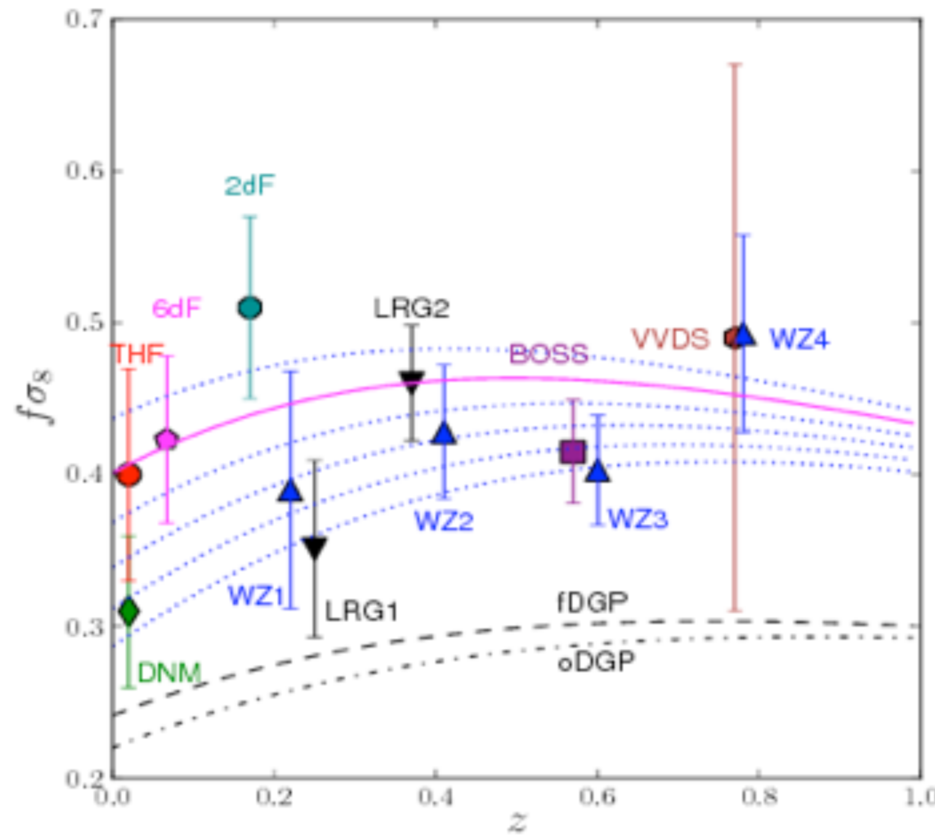
  (compare to SDSS g=22.2, r=22.2, z=20.5)

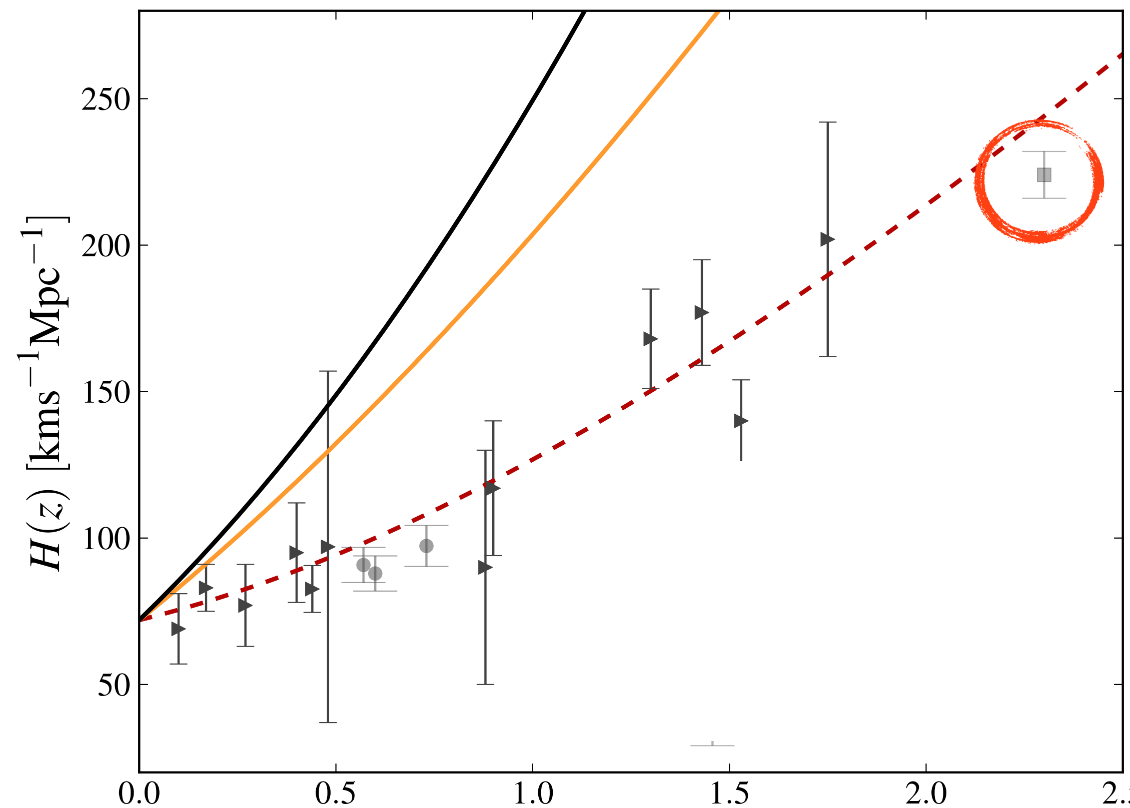
Survey Area

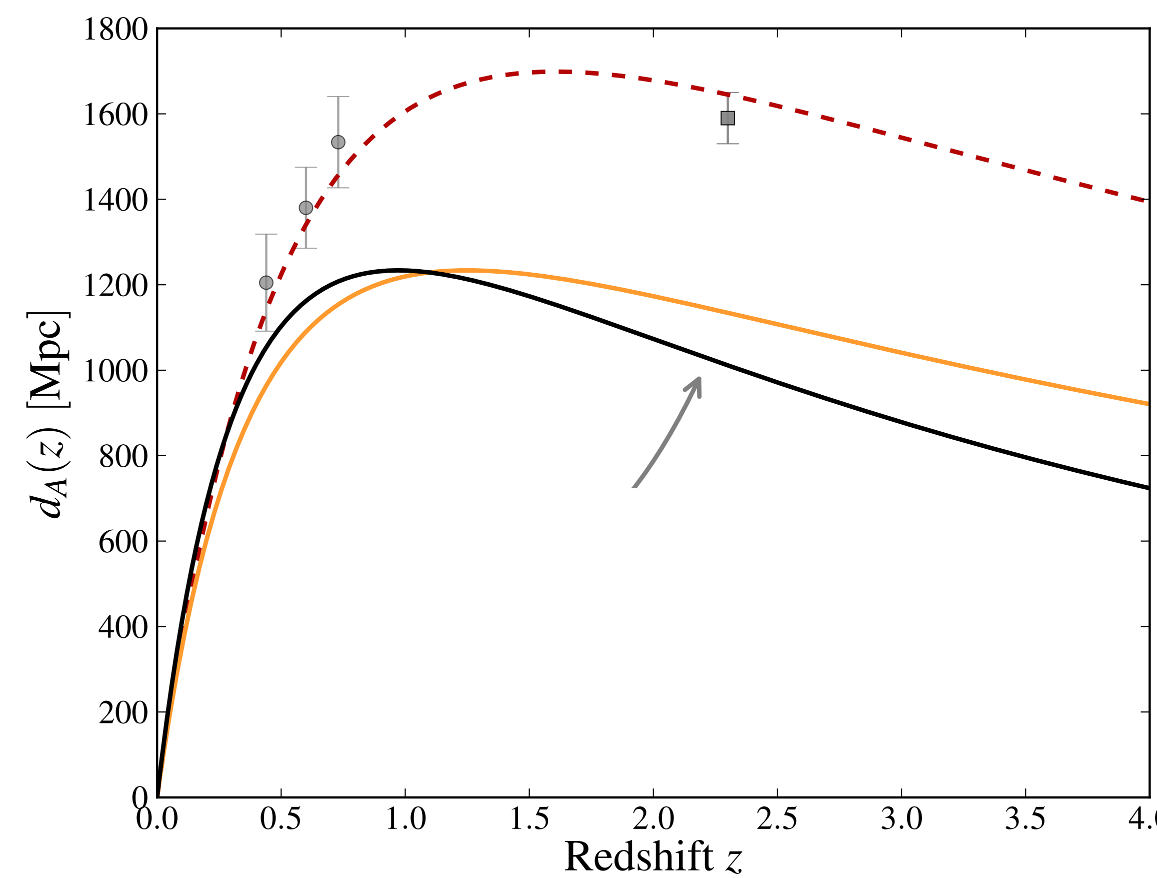


CREDIT: ZHOU Xu

Where are we?







What we want....

Model independent measurements of Growth Rates and fundamental metric quantities like a, a^dot, H(z), Da - at various redshifts or cosmic times

We are are pushing to higher redshift and reducing errorbars and trying to remove model dependences from our analysis, but it's not easy.