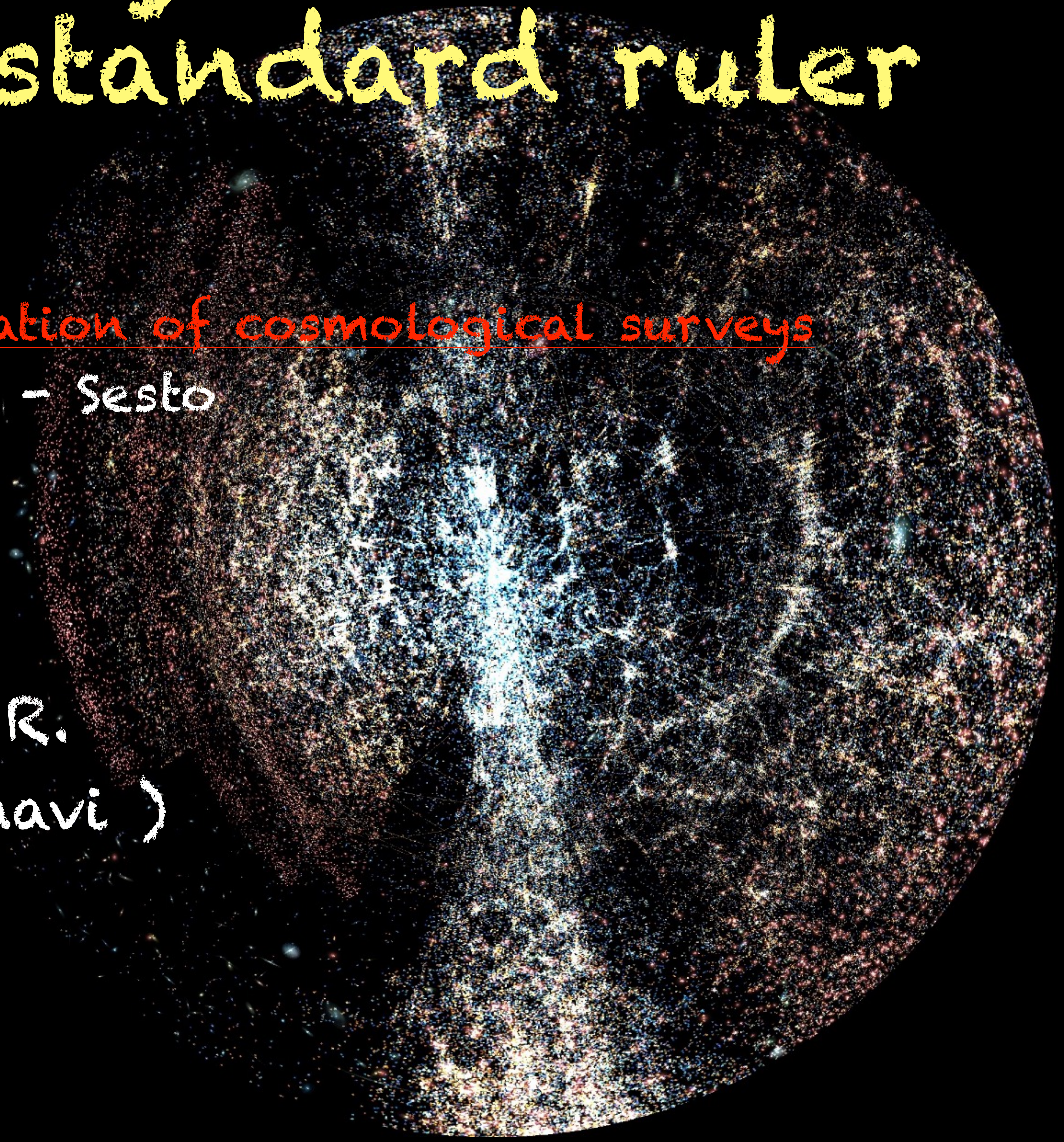
The Linear Point
A cleaner Baryon Acoustic Oscillation standard ruler



Paving the way for next generation of cosmological surveys

July 2, 2018 - Sesto

Stefano ANSELMI

(with , P-S Corasaniti, R. Sheth, G. Starkman, I. Zehavi)

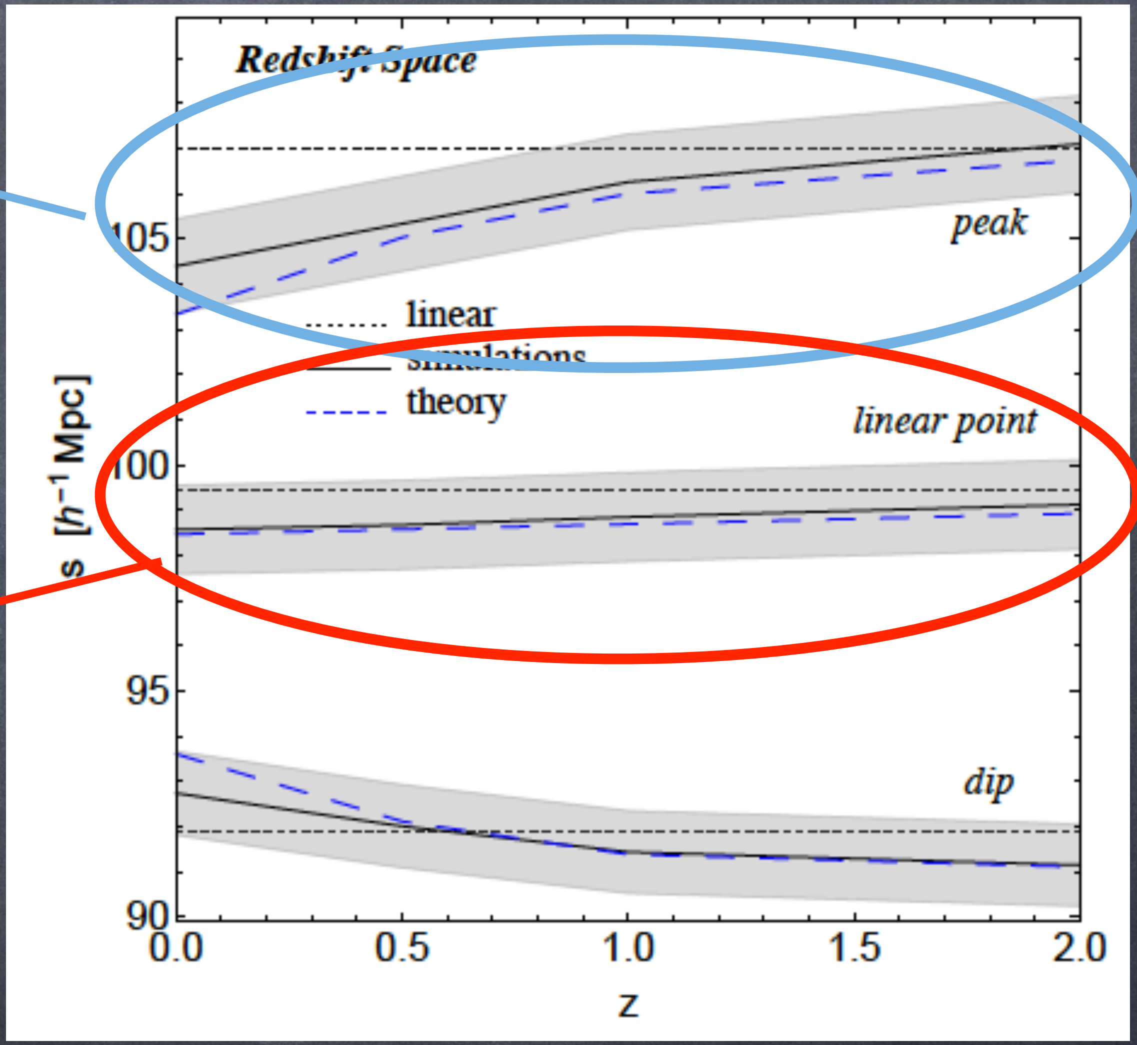
Outline

- The Baryon Acoustic Oscillations cosmological standard ruler.
- Correlation function BAO peak - redshift dependent.
- A NEW standard ruler: the LINEAR POINT
  Accurate distance measurements
- Growth measurements.
- LINEAR POINT standard ruler with GALAXY DATA!!
- Conclusions / future prospects.

The two Rulers

Traditional Ruler

- Correlation function
  Peak Position
- Redshift dependent!!



New Ruler

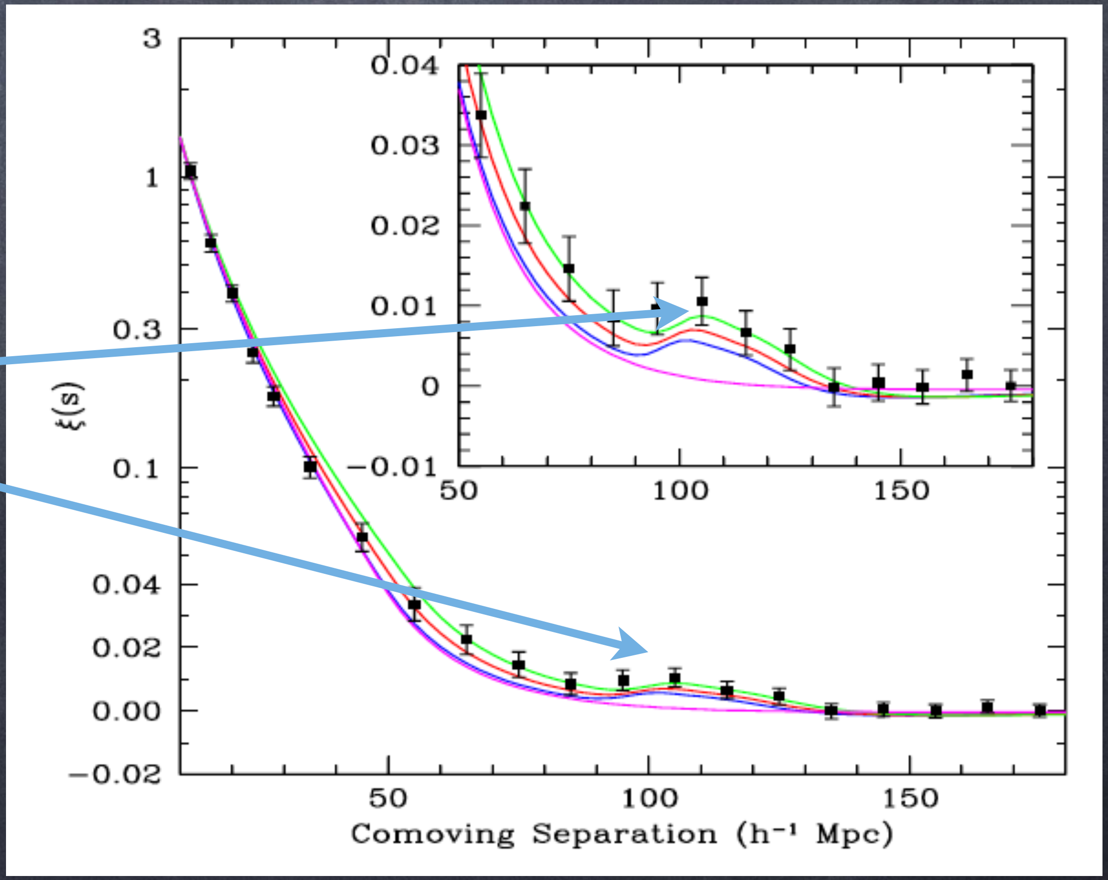
- Correlation function feature:
  the Linear Point position
- Redshift independent!!
- Model-independent estimator
  applied to SDSS data

Which scale?

- Which scale in the clustering Correlation Function?
- Comoving baryon acoustic scale
  Baryon acoustic peak - Matter CF
- rd is **Geometrical** (indep. primordial fluctuation)

$$\begin{tikzcd} r_d \arrow[d, leftrightarrow] \\ s_p \end{tikzcd}$$

Eisenstein et al (2005)

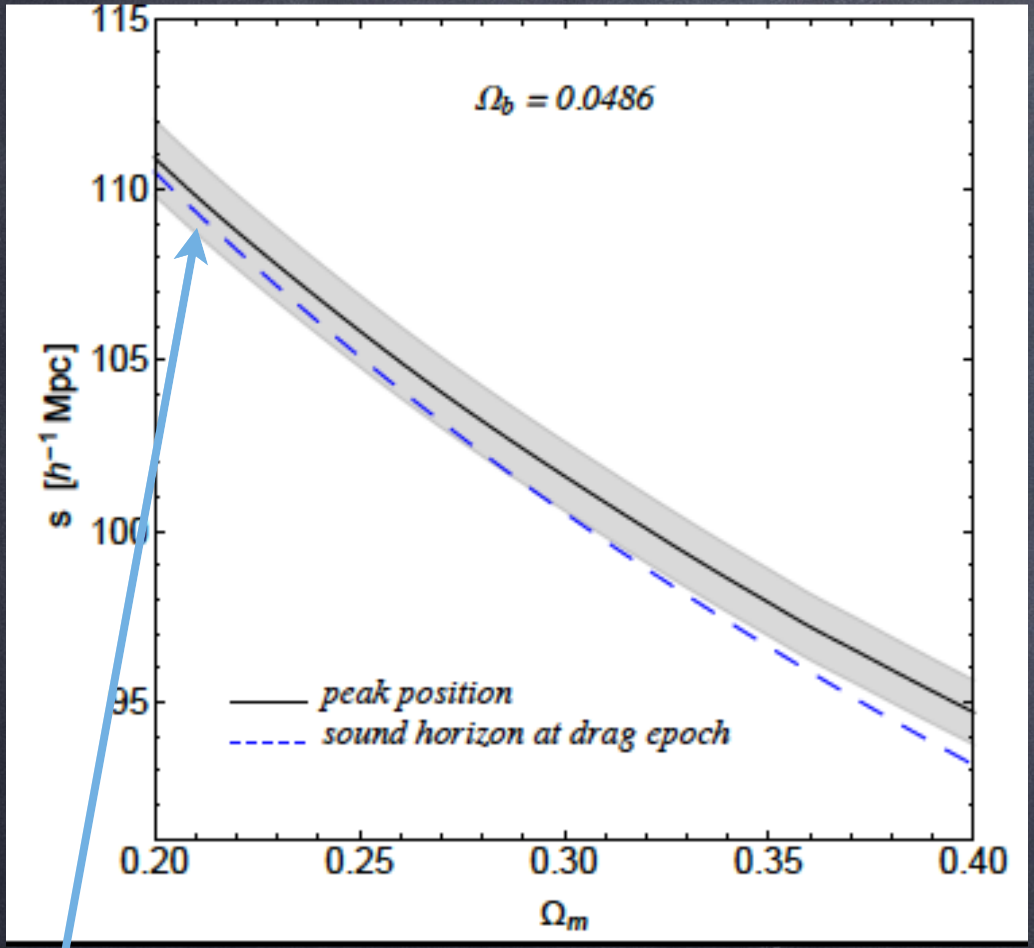


Baryon
acoustic peak
POSITION!!
STANDARD RULER

Precision cosmology: breaks down!!

Linear

Sanchez et al. (2008)



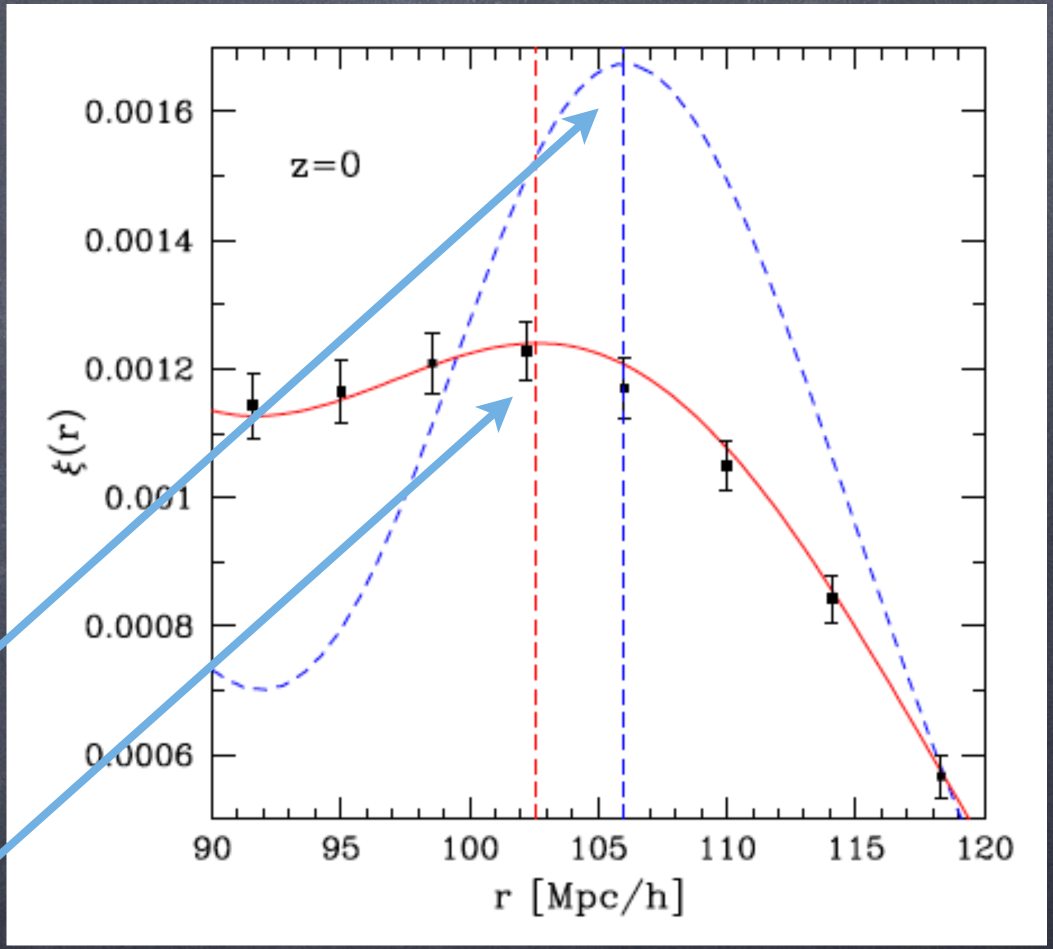
(CAMB code)

1 % region

Non-linear

Smith et al (2008)

Crocce, Scoccimarro (2008)



linear

non-linear

- non-linear gravity
- RSD
- Scale-dep bias

New BAO-2pcf ruler?

S.A, G. Starkman and R. Sheth (2016)

Ingredients needed

1) A geometrical point

2) Redshift independent (linear)

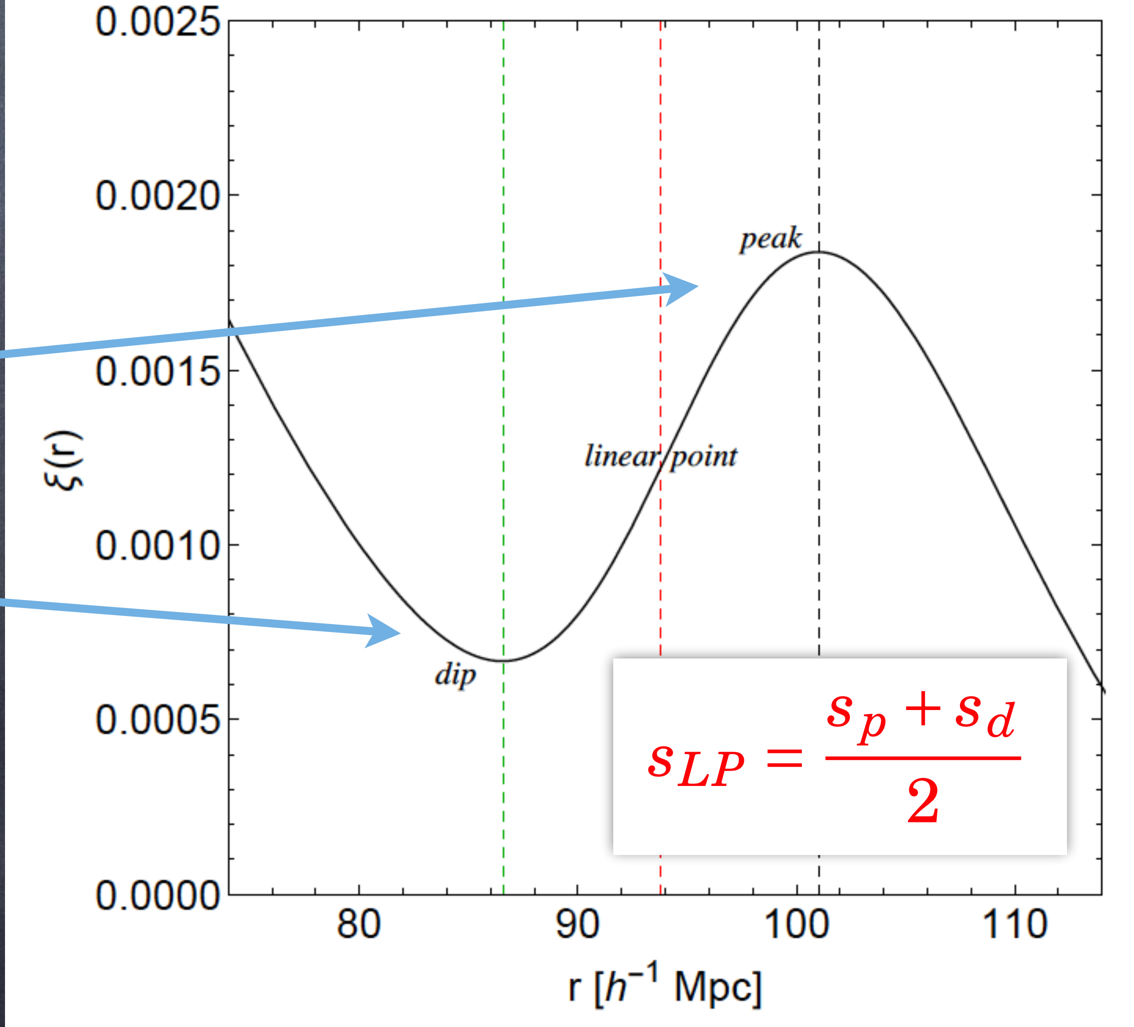
3) Easily to identify

Corr. Func. BAO features

- peak (s_p)
- dip (s_d)

- LINEAR POINT: s_{LP}
  (peak-dip middle point)

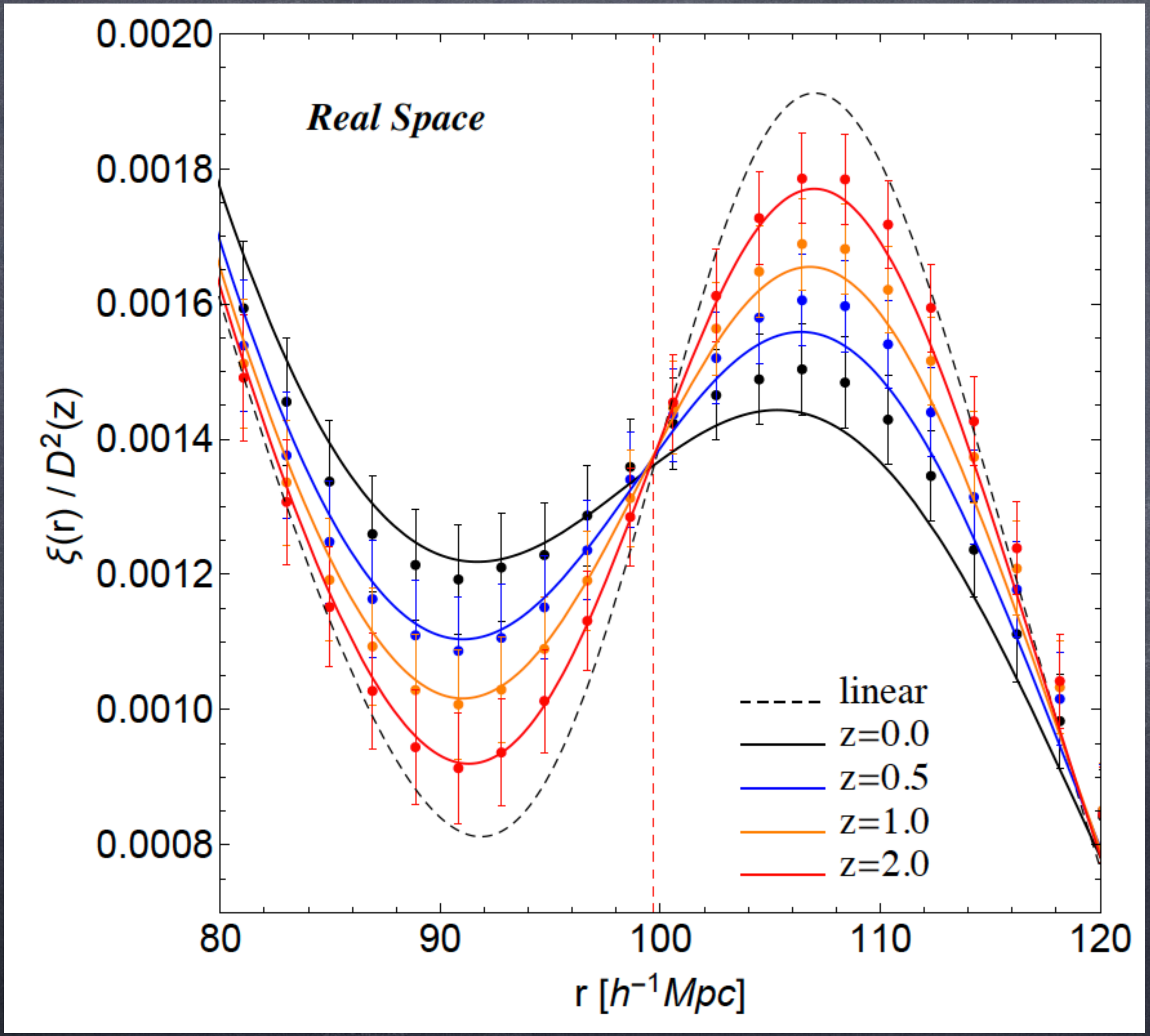
- antisymmetric 2pcf



$$s_{LP} = \frac{s_p + s_d}{2}$$

… from a "wrong" plot…

Since the Cf amplitude is not used for BAO…



Linear analysis

Linear point position is GEOMETRICAL

Independent on (n_s, τ, A_s) at the 0.02 %

CF Antisymmetry measure

Position

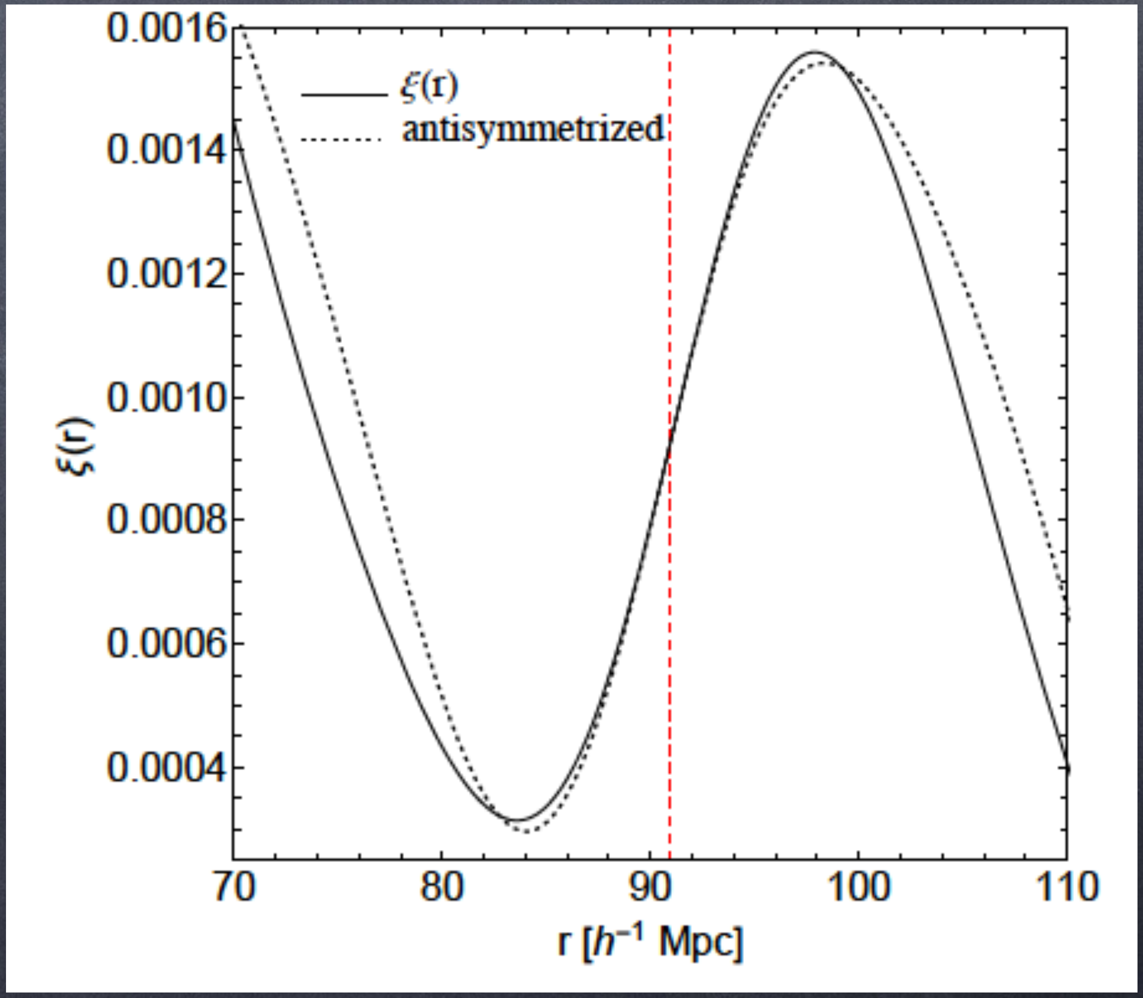
$$s_{LP} = \frac{s_p + s_d}{2}$$

Amplitude

$$\xi^{lin}(s_A) = \frac{\xi^{lin}(s_p) + \xi^{lin}(s_d)}{2}$$

$s_{LP} \sim s_A$ (0.2 %)

$\xi^{lin}(s_{LP}) \sim \xi^{lin}(s_A)$ (2-3 %)



Non-linearities

Non-linear Gravity

Bharadwaj (1996)

Seo, Eisenstein (2007)

Peloso et al. (2015)

- BAO correlation function smoothed

- Dominant: displacements of galaxies from initial positions

$$\xi^{nl}(r) \approx \int \frac{\mathrm{d}k}{k}\,\frac{k^3 P^{lin}(k)}{2\pi^2}\, e^{-k^2 \boxed{\sigma_v^2(z)}} j_0(kr)$$

velocity disp. linear theory

Redshift Space Distortions

- Redshift space

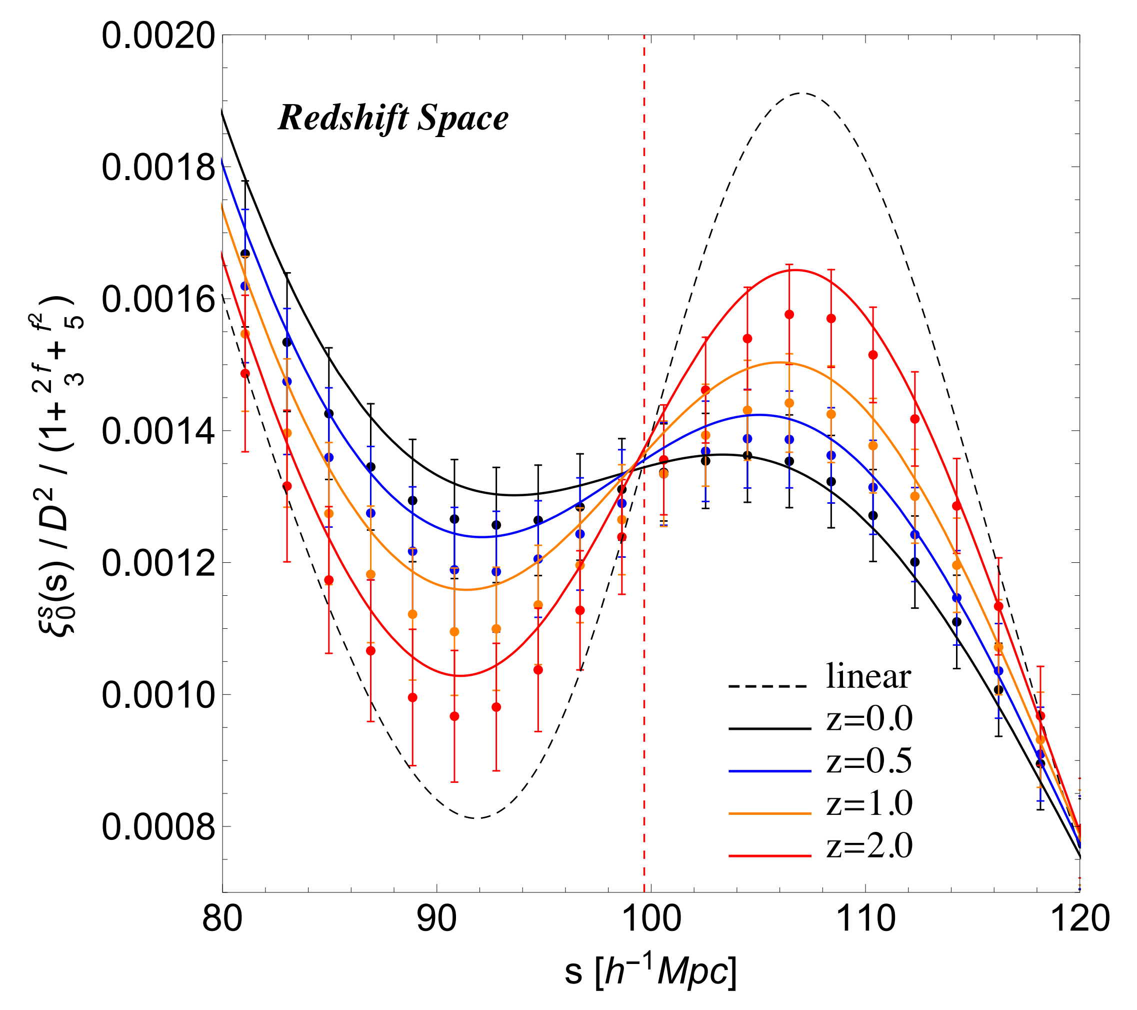
  Bulk motions ⟶ redshift space distortions

MONOPOLE: $$\xi_0^{s,nl}(s) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}\mu \int \frac{\mathrm{d}k}{k}\,\frac{k^3 P^{lin}(k)}{2\pi^2}(1+\mu^2 f)^2 e^{-k^2\sigma_v^2(1+\mu^2 f(2+f))} j_0(ks)$$

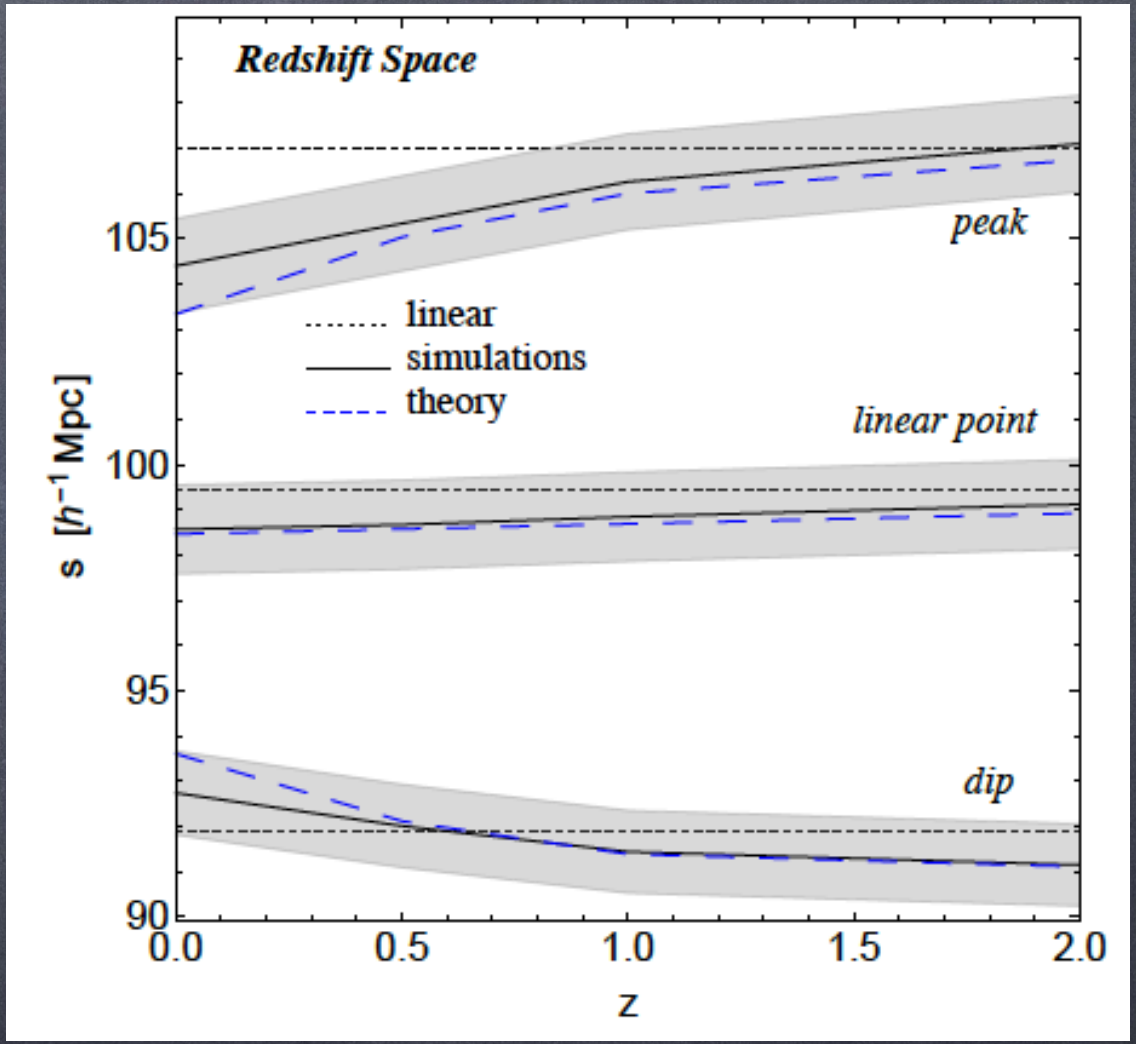
N-Body - COMPARISON

S.A, G. Starkman and R. Sheth, MNRAS (2016)

Amplitude



Position



- Peak and dip at < 1%
- Linear point at < 0.5 %

BAO shift

S.A, G. Starkman and R. Sheth, MNRAS (2016)

3D convolutions

- Real space

$$\xi^{nl}(|\mathbf{x}|;R) \simeq \int \mathrm{d}r' \frac{r'}{r} \frac{e^{-\frac{(r-r')^2}{2R^2}}}{(2\pi R^2)^{1/2}} \xi^{lin}(r')$$

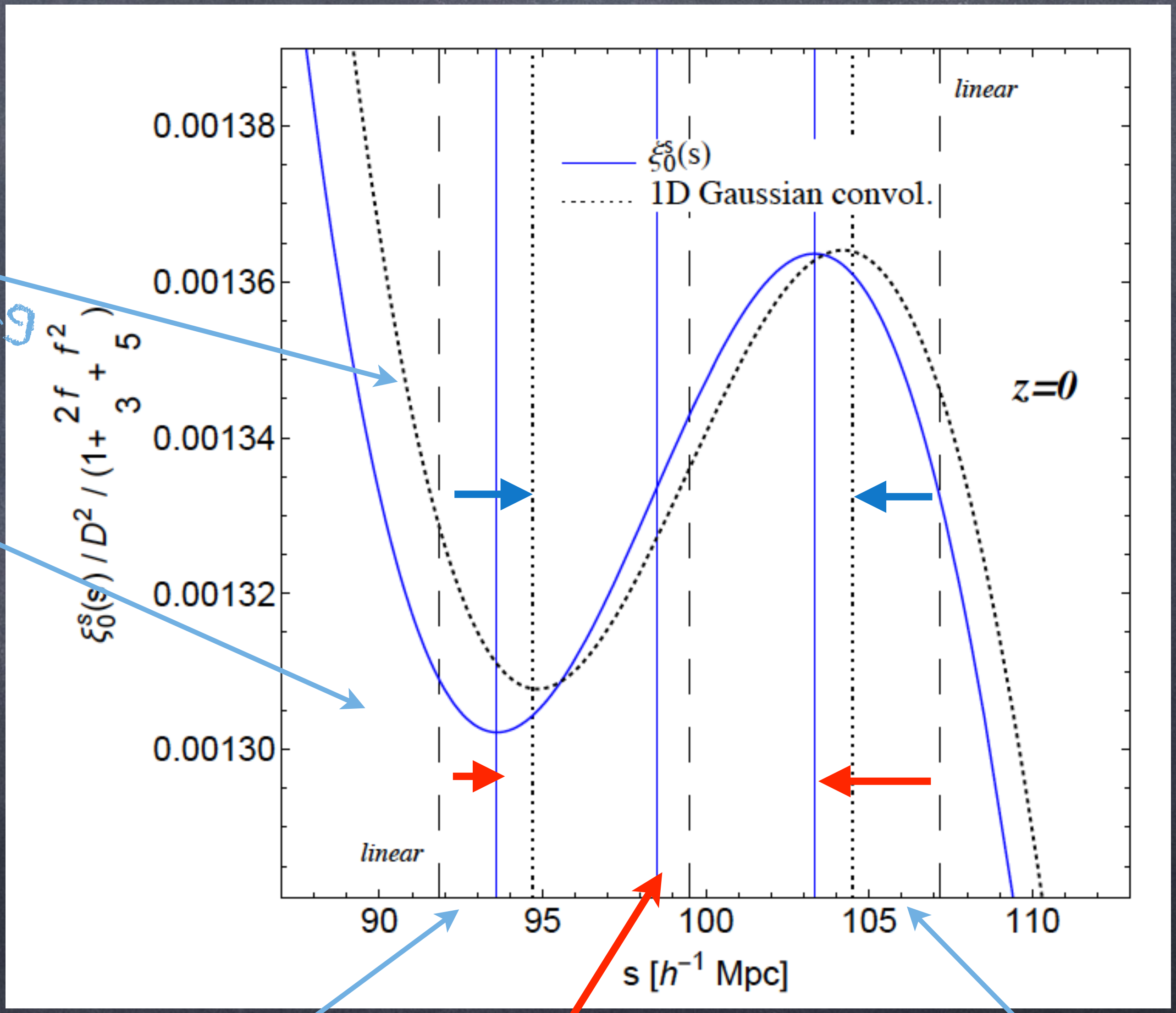
smoothing

whole CF shift

- Redshift space

$$\xi_0^{s,nl}(s) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}\mu (1+\mu^2 f)^2 \, \xi^{nl}(|\mathbf{x}|;S_G)$$

Redshift Space - MONOPOLE



1.5 %

1 %

3.5 %

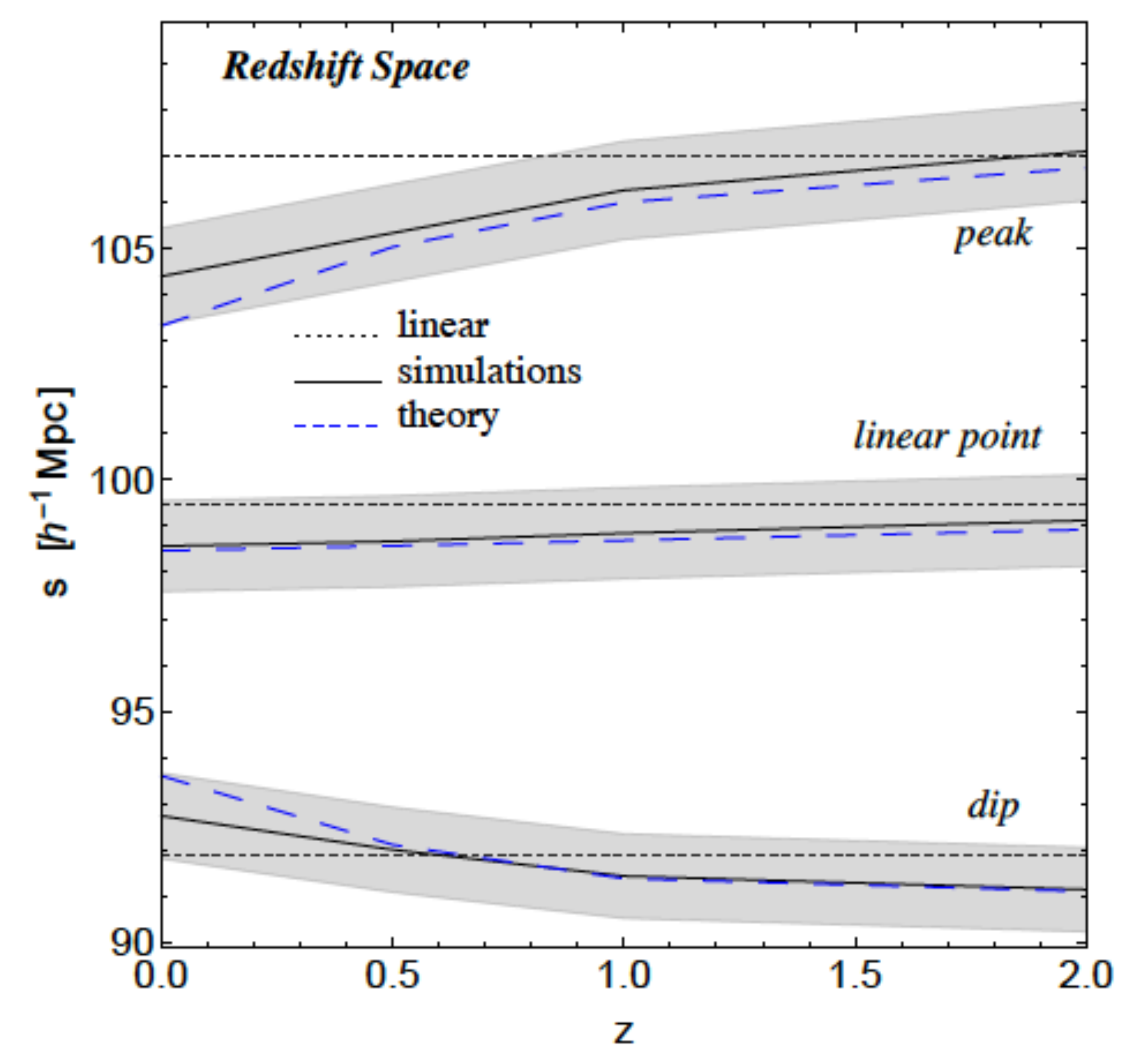
Distance measurements

S.A, G. Starkman and R. Sheth (2016)

- Simulation comparison

  Peak and dip at 1%

  Linear point at < 0.5 %



DISTANCE MEASUREMENTS AT 0.5 %

$$s_{LP} = \frac{s_p + s_d}{2} \times 1.005$$

Growth measurements

- Peak and dip: same smoothing

Linear Point amplitude

linear few percent.

EXPLOITING THE ANTISYMMETRY

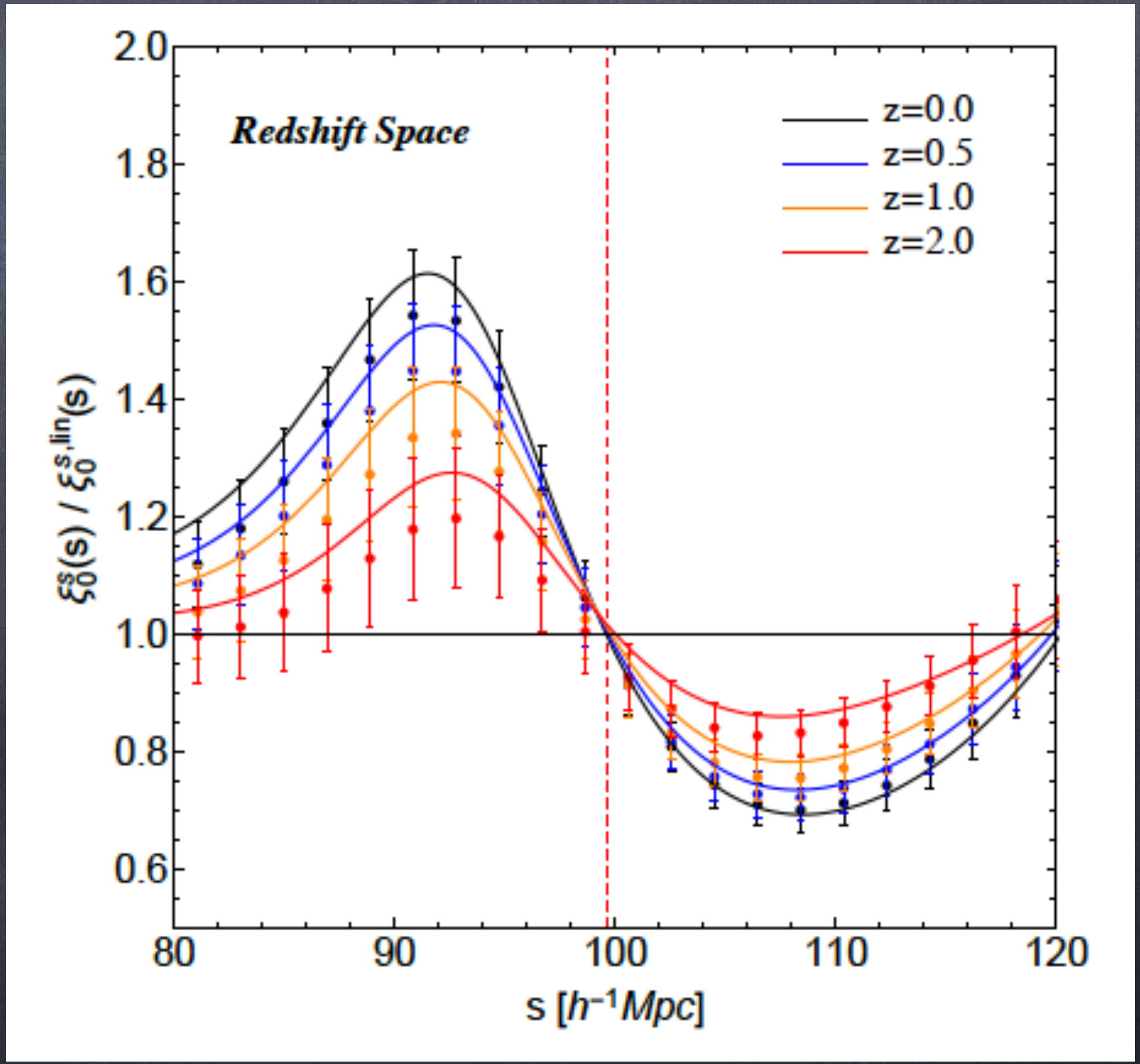
- Three GROWTH estimators

Linear: $$\frac{D^2(z)}{D^2(z')}\frac{1+\frac{2}{3}f(z)+\frac{1}{5}f^2(z)}{1+\frac{2}{3}f(z')+\frac{1}{5}f^2(z')}$$

1) $$\simeq \frac{\hat\xi_0^s(\hat s_{LP},z)}{\hat\xi_0^s(\hat s'_{LP},z')}$$

2) $$\simeq \frac{\hat\xi_0^s(\hat s_p,z)+\hat\xi_0^s(\hat s_d,z)}{\hat\xi_0^s(\hat s'_p,z')+\hat\xi_0^s(\hat s'_d,z')}$$

3) $$\simeq \frac{\sum_{\hat s_d\le x_i\le\hat s_p}\hat\xi_0^s(x_i,z)/N(z)}{\sum_{\hat s'_d\le x_i\le\hat s'_p}\hat\xi_0^s(x_i,z')/N(z')}$$



Biased tracers

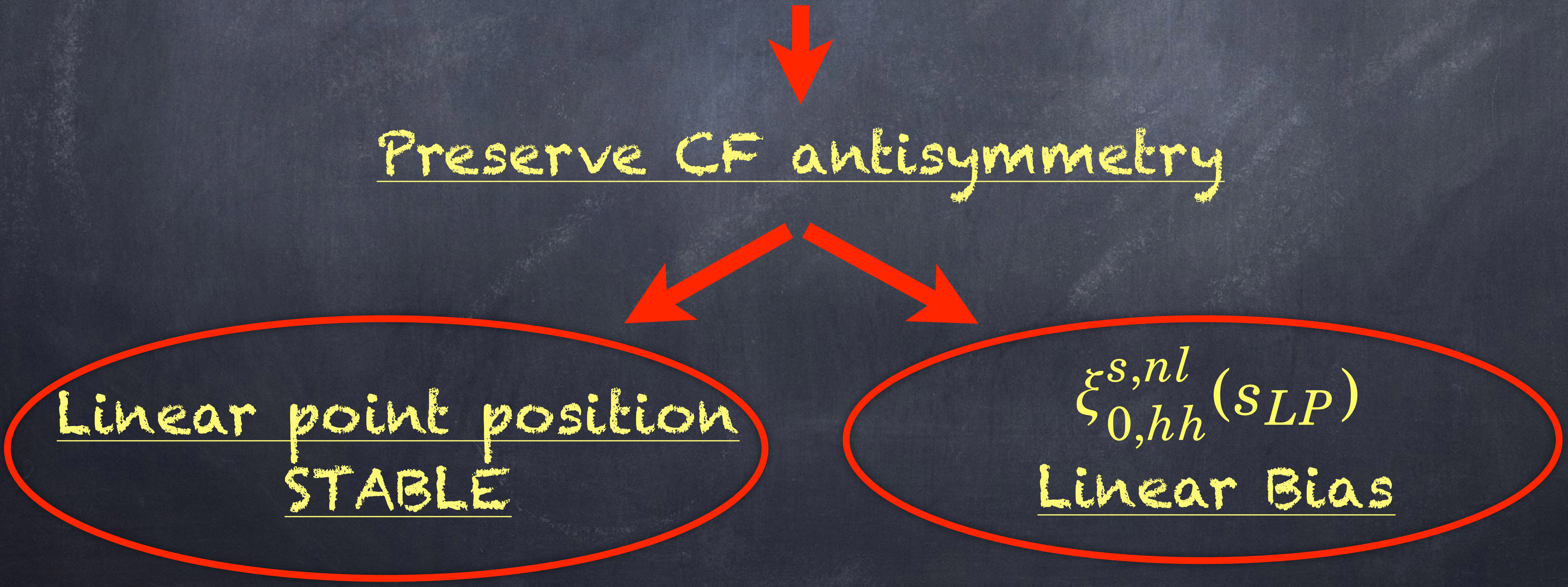
S.A, G. Starkman and R. Sheth, MNRAS (2016)

- Preliminary investigation

  Peaks theory approach to halo bias [Bardeen et al. (1986)]

- Dominant effect of velocities

$$\xi^{s,nl}_{0,hh}(s) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}\mu \int \frac{\mathrm{d}k}{k}\frac{k^3P^{lin}(k)}{2\pi^2}\left[b^E_{10}(z)+b^E_{01}(z)k^2+\mu^2 f\right]^2 e^{-k^2\sigma_v^2(1+\mu^2 f(2+f))}\, j_0(ks)$$



Preserve CF antisymmetry

Linear point position
STABLE

$\xi^{s,nl}_{0,hh}(s_{LP})$
Linear Bias

exploit the Linear Point with real data

in collaboration with

P-S Corasaniti, G. Starkman, R. Sheth and I. Zehavi

REFERENCES

1) galaxy data; PRL (2018) in press

2) mock catalogue validation; PRD (2018) in press

2pcf in clustering data

- Working in comoving coordinates.

Fiducial cosmology assumed

Alcock-Paczynski distortion effect

- 2pcf monopole in redshift space

Distorted True small correction

$$\xi_0^D(s^F) = \xi_0^T(\alpha s^F) + O(\epsilon)$$

Isotropic shift

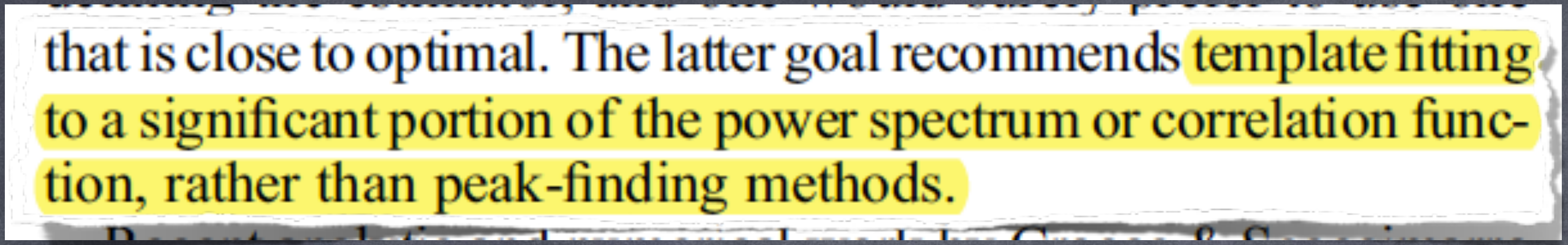
$$\alpha = D_V(z)/D_V^F(z)$$

isotropic volume distance

$$D_V(z) = \left[(1+z)^2 D_A^2(z)\frac{cz}{H(z)}\right]^{1/3}$$

Current BAO definition

Seo et al. (2008)
Xu et al. (2012)



that is close to optimal. The latter goal recommends template fitting to a significant portion of the power spectrum or correlation function, rather than peak-finding methods.

$$\xi_0^D(s^F) = B^2 \xi_m^{\text{fixed}}\left(\alpha\, s^F\right) + A(s^F) + O(\epsilon)$$

Fixed parameters (ΛCDM)

$\{\, \Omega_b^F, \Omega_c^F, n_s^F, h^F, \Sigma_{NL} \,\}$

5 varied parameters

$\{\alpha, B, A_1, A_2, A_3\}$

marginalized

Cosmological information

PRESCRIPTIONS

Template

N-body validated

$$\alpha = \frac{D_V(z)}{D_V^F(z)} \frac{r_d^F}{r_d^{CMB}}$$

A complementary approach: the Linear Point

linear approx.

$$\xi^{obs}(r,z) \overset{\downarrow}{=} b_{10}(z)^2\boxed{D(z)^2}\left(1+\frac{2\beta}{3}+\frac{\beta^2}{5}\right)\xi_m(r,0)$$

scale independent for

- ΛCDM
- smooth quintessence
- clustering quintessence
- phenomen. models of w(z)

$$P(z) = w(z)\rho(z)$$

Linear Point position -> scale -> D(z) indep.

Measuring the distance

S.A, Starkman, Corasaniti, Sheth, Zehavi
PRL (2018)

$$\xi_0^D\left(\frac{s^F}{D_V^F(z)}\right)=\xi_0^T\left(\frac{s^T}{D_V^T(z)}\right)+O(\epsilon)$$

$$y\equiv\frac{s_F}{D_V^F(z)}$$

Linear scale

CMB

z indep.

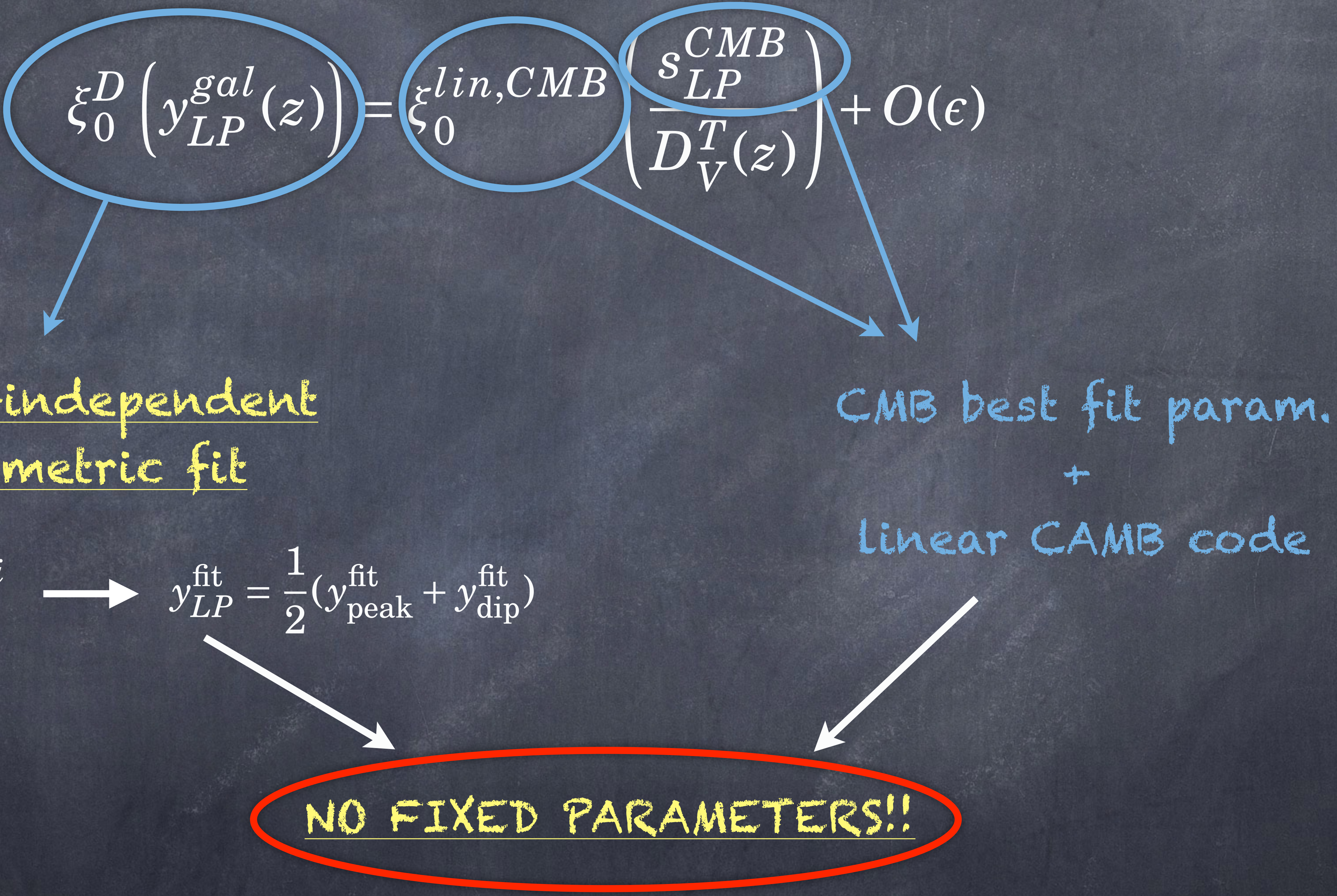
$$\xi_0^D\left(y_{LP}^{gal}(z)\right)=\xi_0^{lin,CMB}\left(\frac{s_{LP}^{CMB}}{D_V^T(z)}\right)+O(\epsilon)$$

galaxies

$$D_V^T(z)=\frac{s_{LP}^{CMB}}{y_{LP}^{gal}(z)}$$

DE information

NO 2pcf model template



$$\xi_0^D\left(y_{LP}^{gal}(z)\right)=\xi_0^{lin,CMB}\left(\frac{s_{LP}^{CMB}}{D_V^T(z)}\right)+O(\epsilon)$$

Model-independent parametric fit

CMB best fit param.
+
linear CAMB code

$$\xi_0^{\rm fit}(y)=\sum_{i=0}^{5}a_i\,y^i \longrightarrow y_{LP}^{\rm fit}=\frac{1}{2}(y_{\rm peak}^{\rm fit}+y_{\rm dip}^{\rm fit})$$

NO FIXED PARAMETERS!!

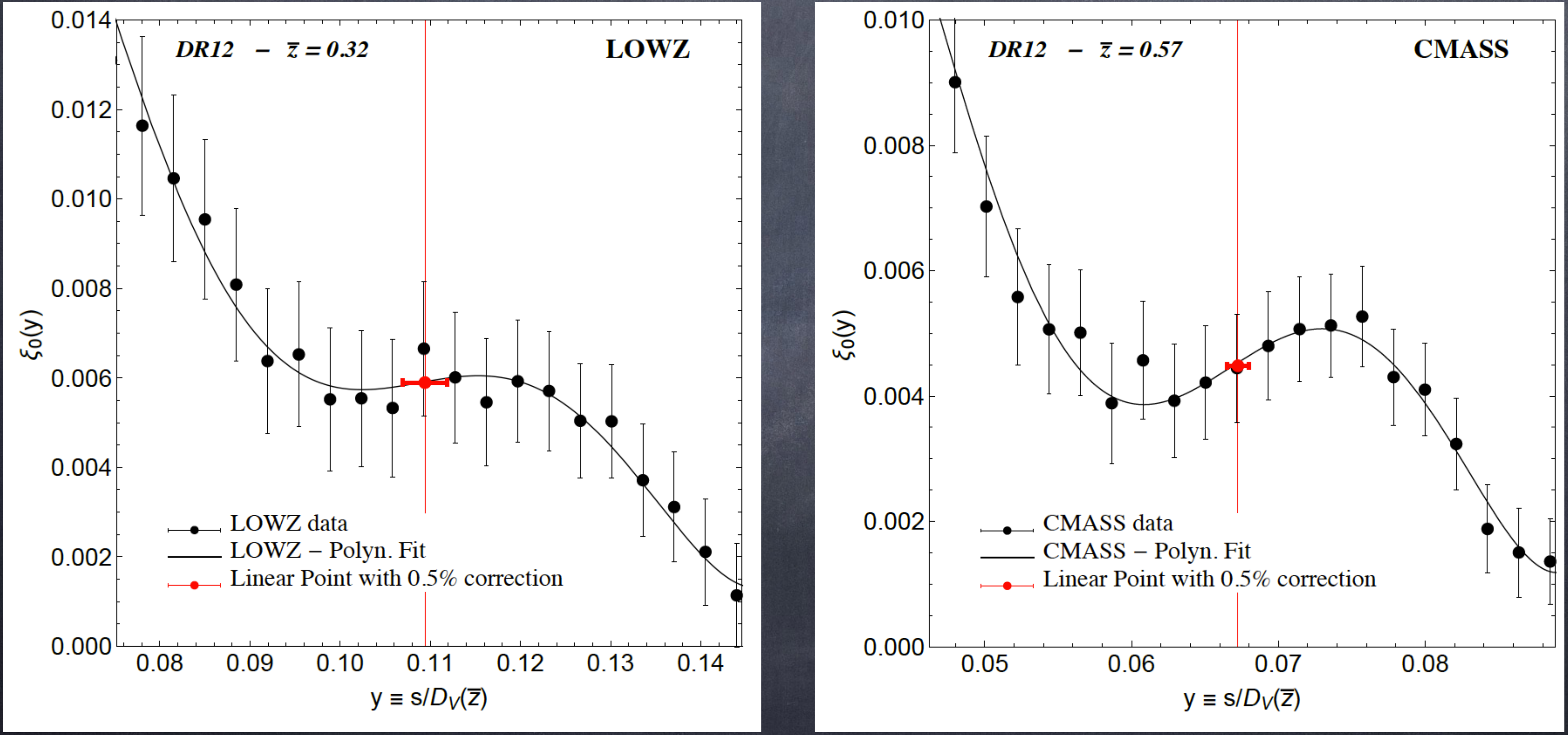
- Only fiducial cosmology dependence -> Alcock-Paczynski

SDSS galaxies

S.A, Starkman, Corasaniti, Sheth, Zehavi
PRL (2018)

- BOSS collaboration: two galaxy samples

  LOWZ and CMASS



SDSS galaxies

S.A, Starkman, Corasaniti, Sheth, Zehavi
PRL (2018)

PRE-reconstruction
DATA

Linear Point distances

$$D_V^{LP}(\bar{z}=0.32)=(1264 \pm 28)\mathrm{Mpc}$$
$$D_V^{LP}(\bar{z}=0.57)=(2056 \pm 22)\mathrm{Mpc}$$

CONSISTENT

smaller errors

PRE-reconstruction
DATA

BOSS distances

Cuesta et al. (2016)

$$D_V^{BOSS}(\bar{z}=0.32)=(1247 \pm 37)\mathrm{Mpc}$$
$$D_V^{BOSS}(\bar{z}=0.57)=(2043 \pm 27)\mathrm{Mpc}$$

BAO reconstruction

Eisenstein et al. (2007)
Padmanabhan and White (2009)

- IDEA: recover the "lost information"
  approximate non-linear treatment -> galaxies are "sent back" to their linear theory positions.

- Data treatment -> amplify the S/N and reduce non-linear effects.

- Algorithm inputs - no error propagation
  - growth rate
  - matter-galaxy bias

SDSS galaxies

S.A, Starkman, Corasaniti, Sheth, Zehavi

PRL (2018)

PRE-reconstruction

DATA

Linear Point distances

$$D_V^{LP}(\bar{z} = 0.32) = (1264 \pm 28)\mathrm{Mpc}$$

$$D_V^{LP}(\bar{z} = 0.57) = (2056 \pm 22)\mathrm{Mpc}$$

CONSISTENT

larger errors

POST-reconstruction

DATA

BOSS distances

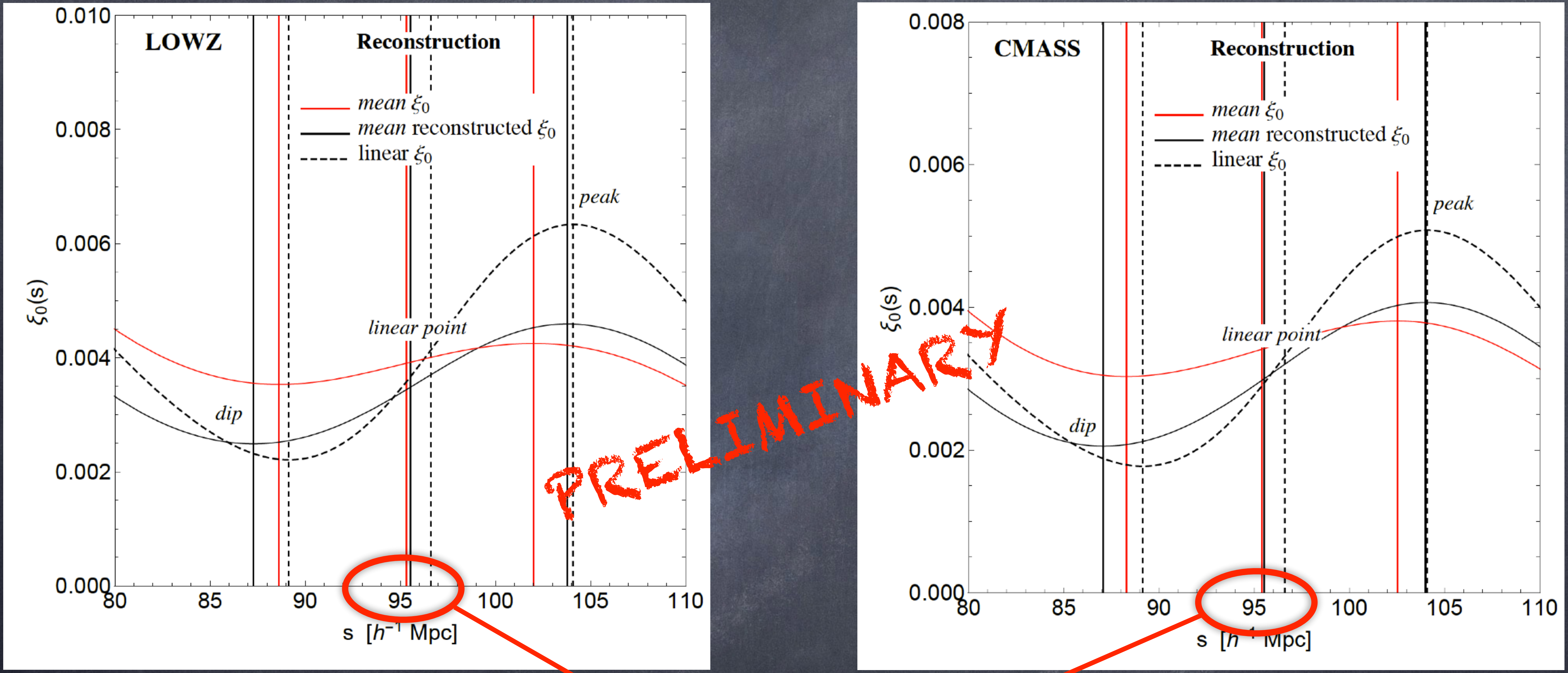
Cuesta et al. (2016)

$$D_V^{\mathrm{BOSS;post-recon}}(\bar{z} = 0.32) = (1265 \pm 21)\mathrm{Mpc}$$

$$D_V^{\mathrm{BOSS;post-recon}}(\bar{z} = 0.57) = (2031 \pm 20)\mathrm{Mpc}$$

Linear Point and reconstruction?

BOSS BAO-(DR12) mocks



by chance

reconstruction invariant

Invariant in real data?

PRE-reconstruction DATA

$$s_{LP}^{\mathrm{pre-recon}}(\bar{z} = 0.57) = (94.2 \pm 1.0)\mathrm{Mpc/h}$$

POST-reconstruction DATA

$$s_{LP}^{\mathrm{post-recon}}(\bar{z} = 0.57) = (96.1 \pm 0.8)\mathrm{Mpc/h}$$

large discrepancy

Known possible reasons… ????

- 0.5% uncertainty ? NO
- Extraction bias ? NO
- Statistical scatter ? 2%
- Reconstruction ? mocks ?

→ improved theoretical tools needed ?

Why the Linear Point ?

THEORETICAL FEATURES

- New theoretically defined "OBSERVABLE" (no estimator needed): peak/dip mid-point

ESTIMATOR FEATURES

- Simple / model-independent estimator (2pcf model poorly known).
- No fixed parameters / all the uncertainties are propagated.
- BAO reconstruction needs to be improved (error prop + modeling)

FOR COSMOLOGY

- Datasets combined -> syst. blow up -> multiple approaches needed. LINEAR POINT is cleaner: it can help!!

Complementarity w.r.t. standard BAO

STANDARD BAO WITH RECONSTRUCTION

- Fully relying on N-body sim. for:

  1) BAO estimators 2) BAO reconstruction

- Valid for parameters/models where sim. accurate (ΛCDM)

LINEAR POINT

- Simulations/mocks -> LP estimation error(s)
- N-body sim. -> linearity validation, extend beyond ΛCDM

BAO-only measurements ?

Sanchez, Baugh, Angulo (2008)

Sanchez, Crocce et al. (2009)

Sanchez et al. (2012)

- BAO full fitting -> model dependent

  NEED of 2pcf motivated theoretical model

$$\xi_0^D(s^F) = \xi_0^{Model}\left(\frac{D_V^{Model}(z)}{D_V^F(z)} s^F\right) + O(\epsilon)$$

Distorted

Fit

α

1) Derived parameter

   DE model dependent

α

2) Free parameter

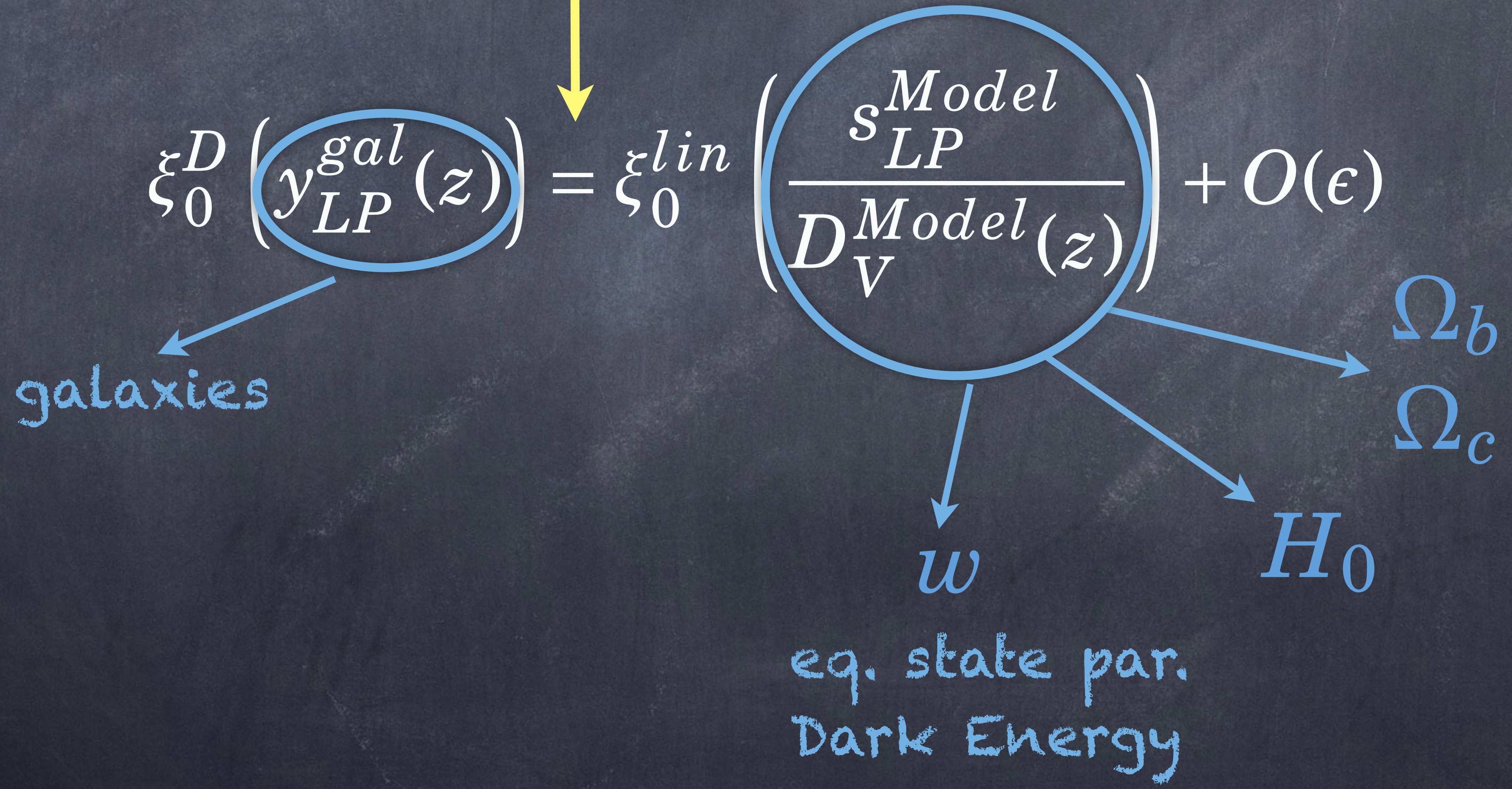
   large degeneracies -> non informative

How with the Linear Point ?

$$\xi_0^D\left(\frac{s^F}{D_V^F(z)}\right) = \xi_0^T\left(\frac{s^T}{D_V^T(z)}\right) + O(\epsilon)$$

$$y \equiv \frac{s_F}{D_V^F(z)}$$

known linear physics



$$\xi_0^D\left(y_{LP}^{gal}(z)\right) = \xi_0^{lin}\left(\frac{s_{LP}^{Model}}{D_V^{Model}(z)}\right) + O(\epsilon)$$

galaxies

Ω_b

Ω_c

H_0

w

eq. state par.
Dark Energy

Conclusions

Standard ruler

- Peak-dip mid point - Linear Point - is Geometrical and insensitive to nonlinearities to 0.5% (redshift indep.)
- "Model-independent" Standard Ruler. Distances from DATA.
- Complementary BAO ruler!

Growth

- The clustering 2pcf is linear at the LP →
  Peak-dip range: antisymmetry preserved →

Three growth estimators

... to do...

- Comparison with the CF full fitting (Eucl. forec., ongoing)
- Different galaxy populations? Clusters? Quasars? Neutrinos ?
- Angles and redshifts ?
- Modified gravity + ... + ... + ...

THANK YOU!!