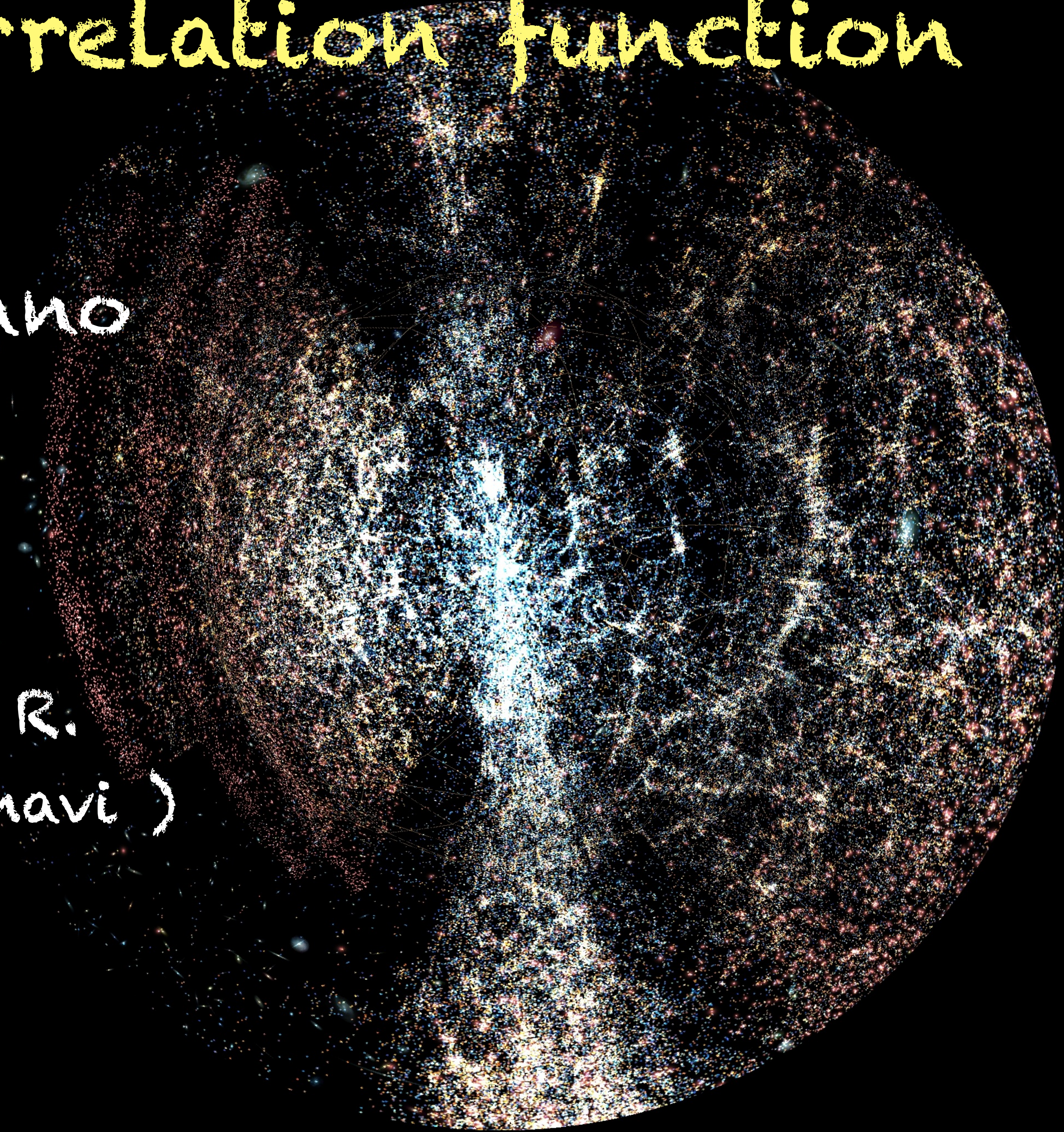
The Linear Point: a cleaner cosmological standard ruler in the galaxy correlation function



University of Milano

November 30, 2017

Stefano ANSELMI

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

l'Observatoire de Paris

IAP

Outline

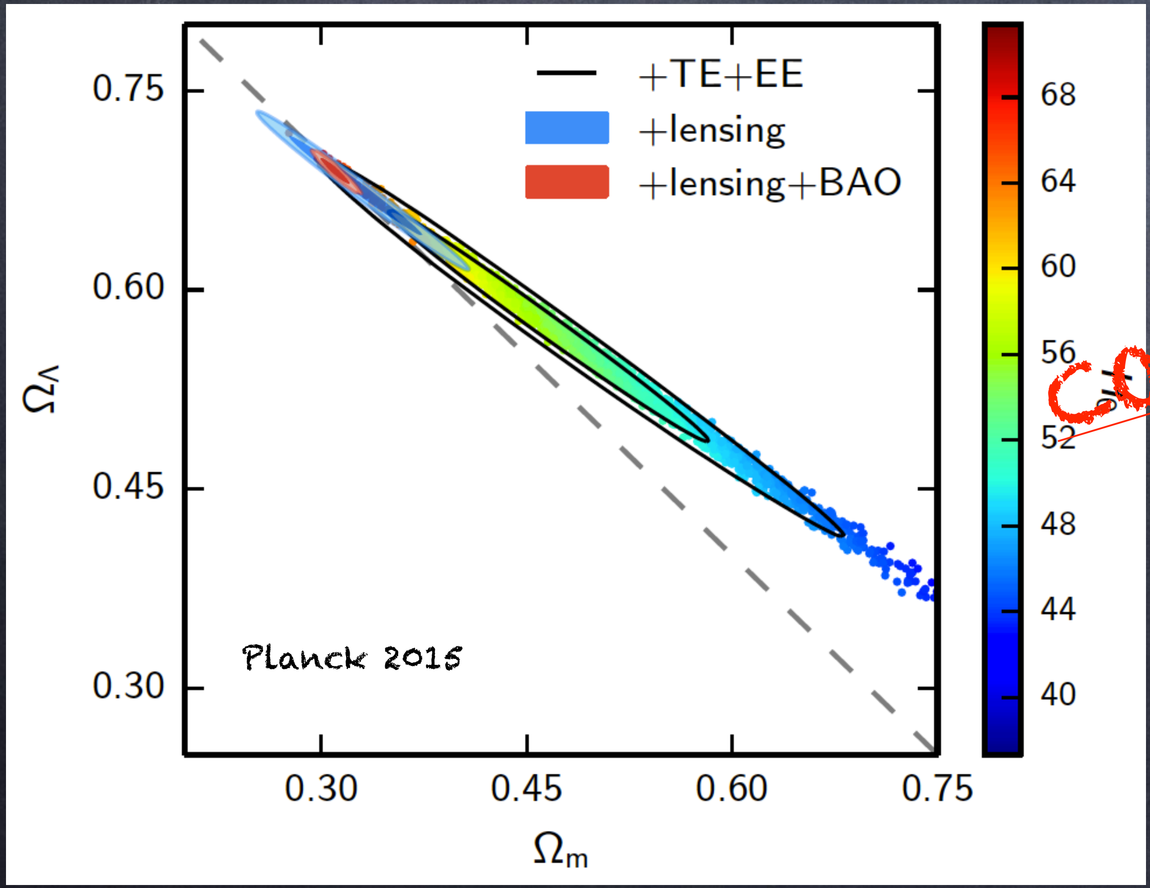
- The Baryon Acoustic Oscillations cosmological standard ruler.
- Correlation function BAO peak - redshift dependent.
- A NEW standard ruler: the LINEAR POINT
  Accurate distance measurements
- Growth measurements.
- LINEAR POINT standard ruler with GALAXY DATA!!
- Non-standard cosmologies ?

We are accelerating...

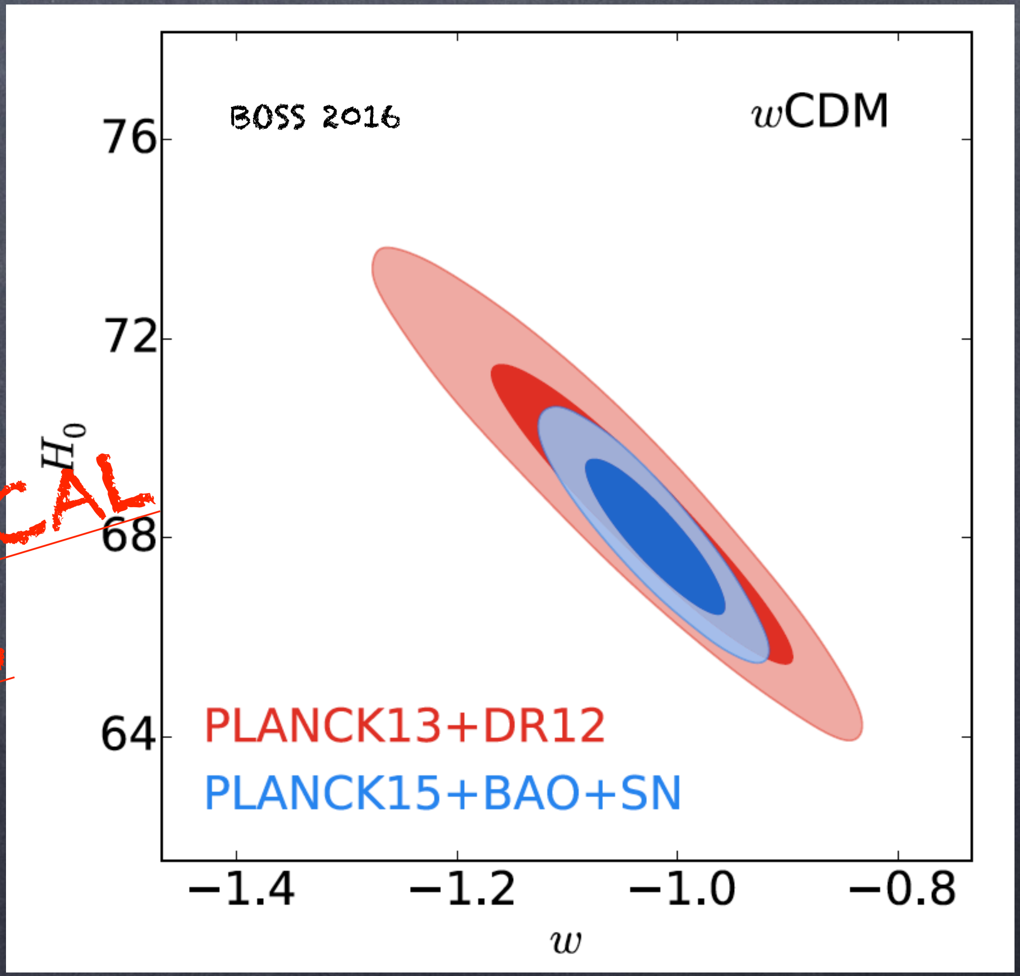
Observational evidences

- SN-Type 1a - standard candles
- CMB via Late Integrated Sachs-Wolfe effect (late time gravitational redshift of the photons).
- BAOs measured at different redshifts

energy densities



Combining
COSMOLOGICAL
PROBES



eq. state param.

$P = \rho w$

Cosmological standard ruler

- Object of known size constant in redshift.

Large Scale Structure

Statistical standard ruler

Shanks et al. (1987)

Eisenstein et al (1998)

Bassett, Hlozek (2009)

Clustering of galaxies $\longrightarrow$ PREFERRED SCALE (constant in redshift)

↓

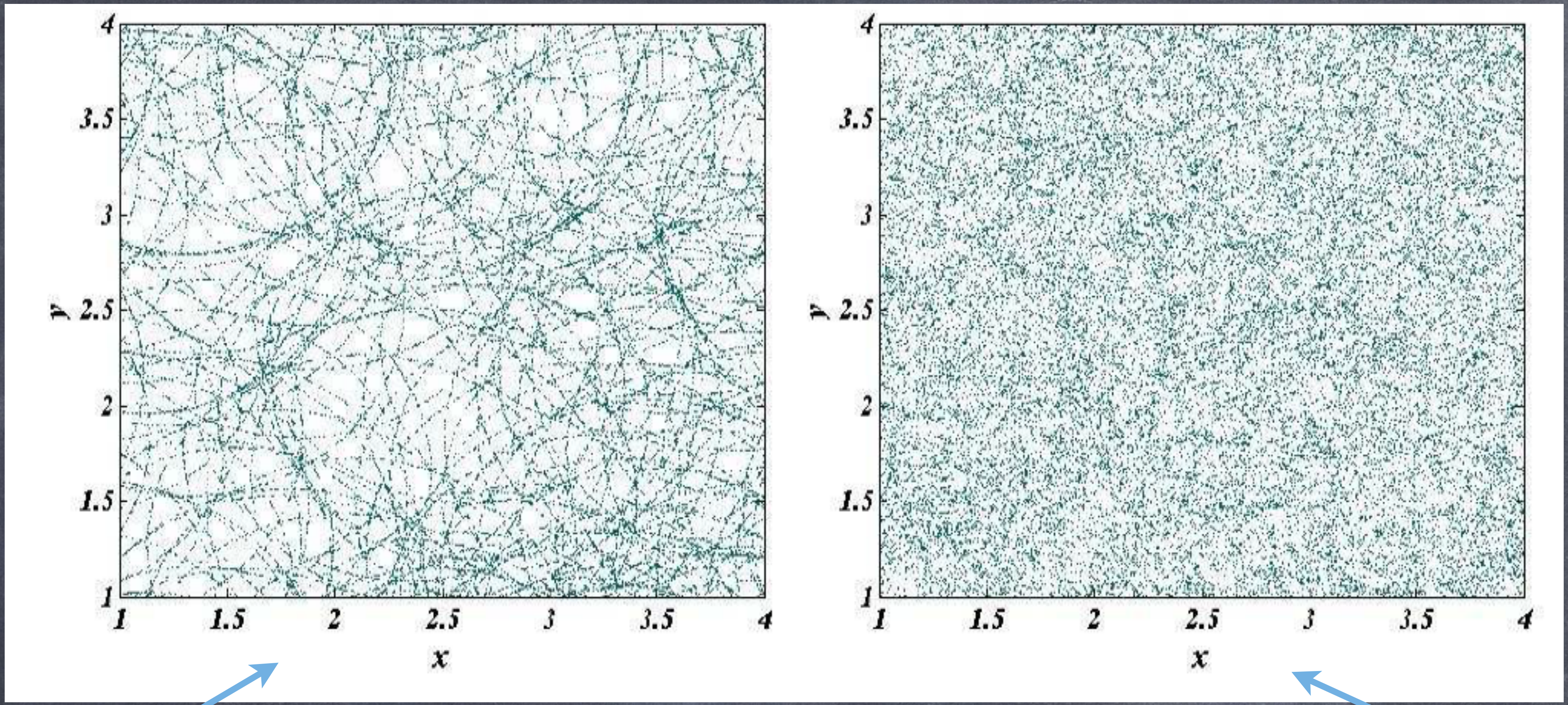
Observed at different redshifts

↓

Constrain the angular diameter distance.

Cosmological parameters

Bassett and Hlozek (2009)



intuitive picture

realistic picture

Angular Diam. Distance

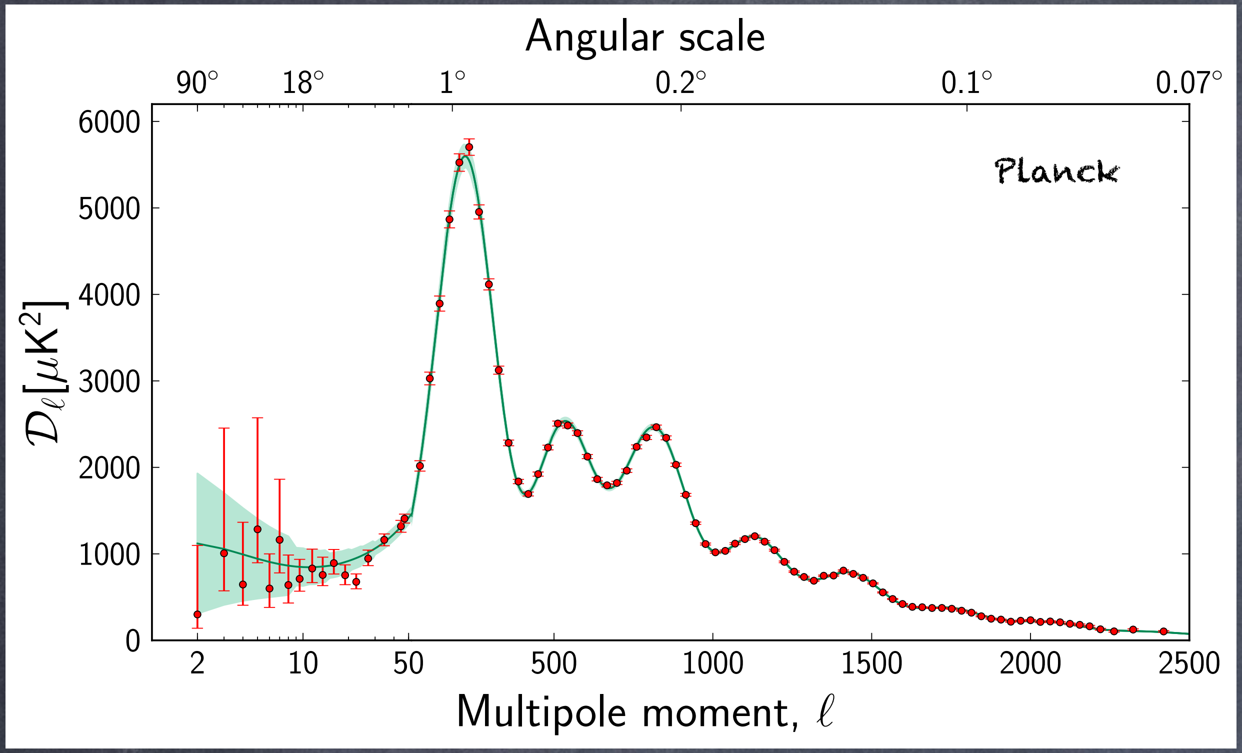
$$d_A = \frac{x}{\theta}$$

actual size

$$d_A = \frac{\chi}{1+z}$$

cosm. parameters

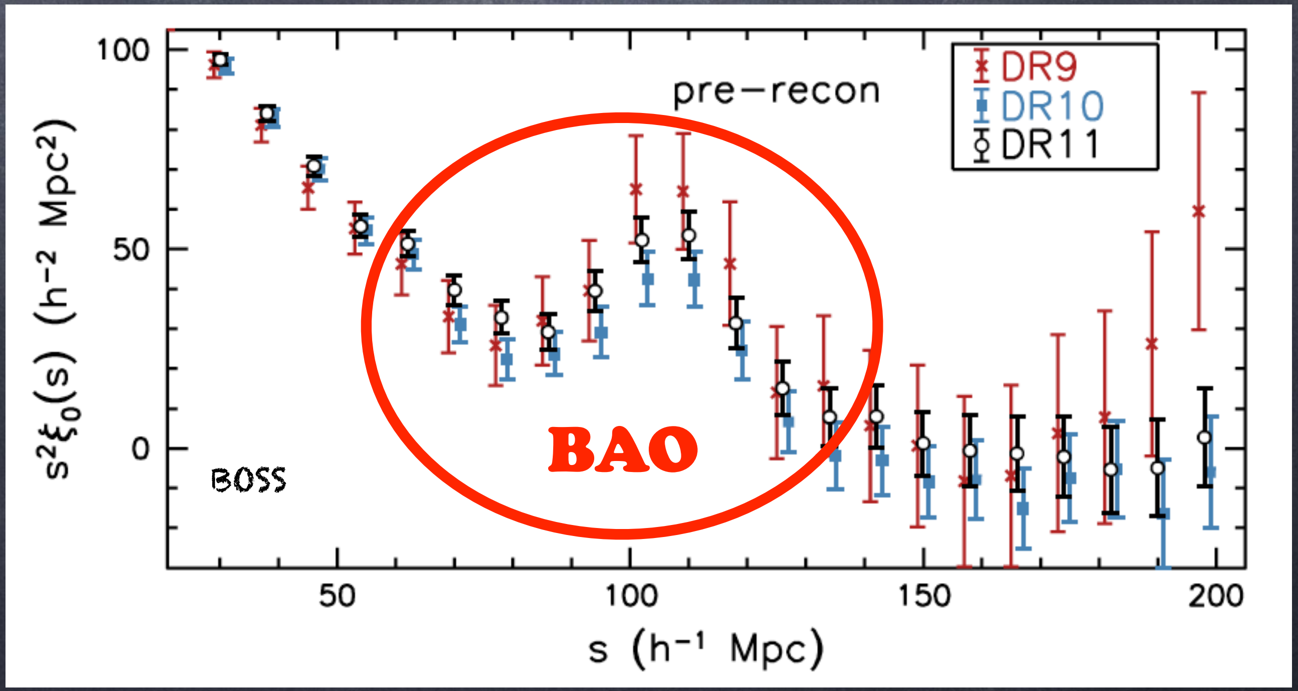
Early times...



Initial fluctuations

temperature fluctuations in the CMB ($\delta T/T \sim 10^{-5}$)

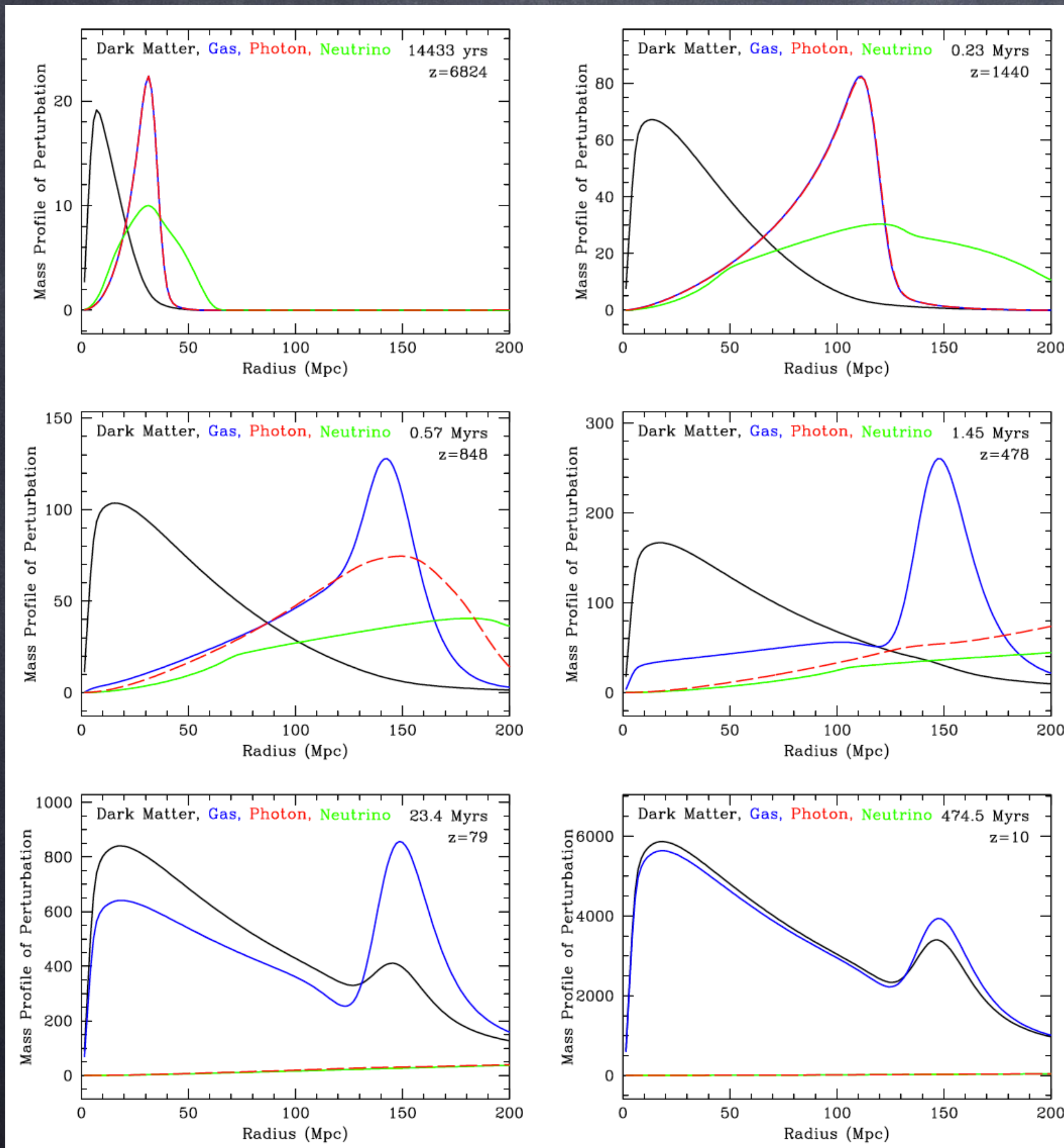
...late times



Baryon acoustic oscillations in the matter Correlation Function

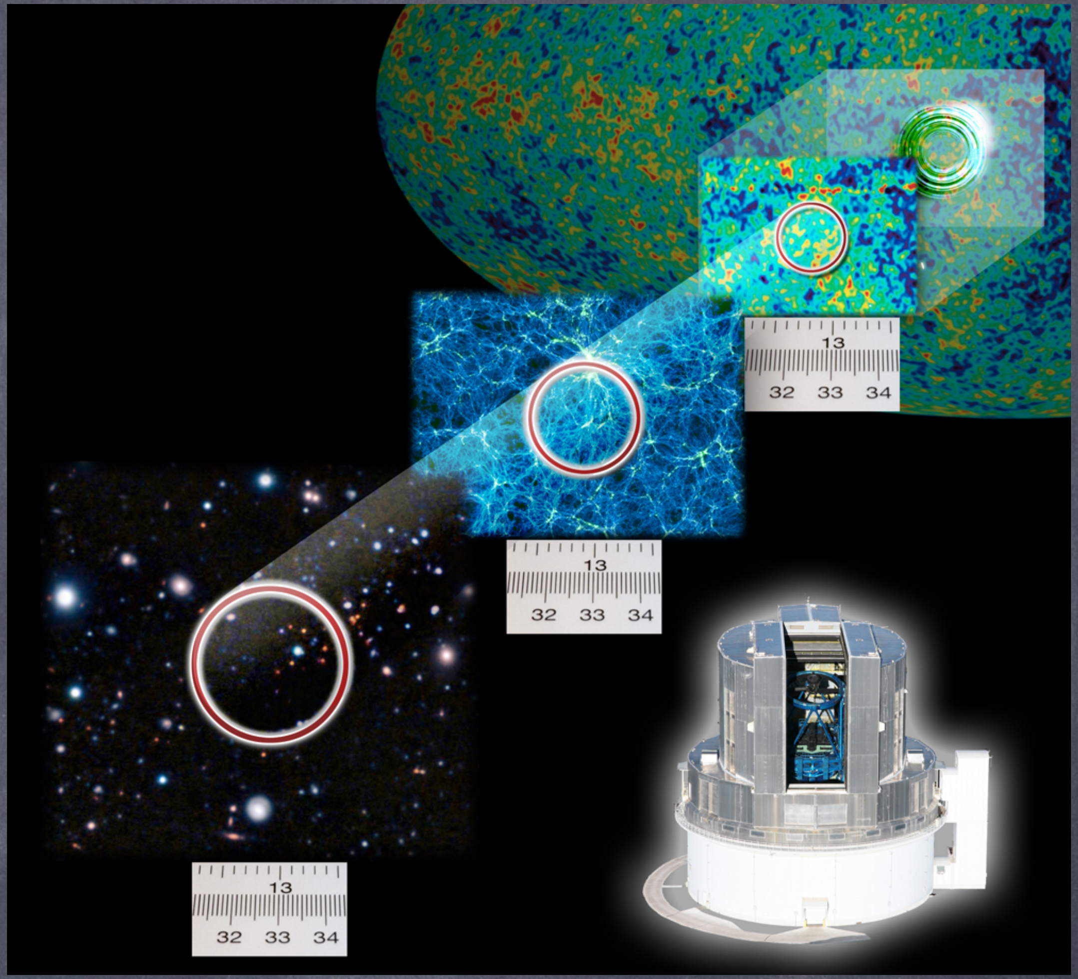
BAO evolution

initial overdensity

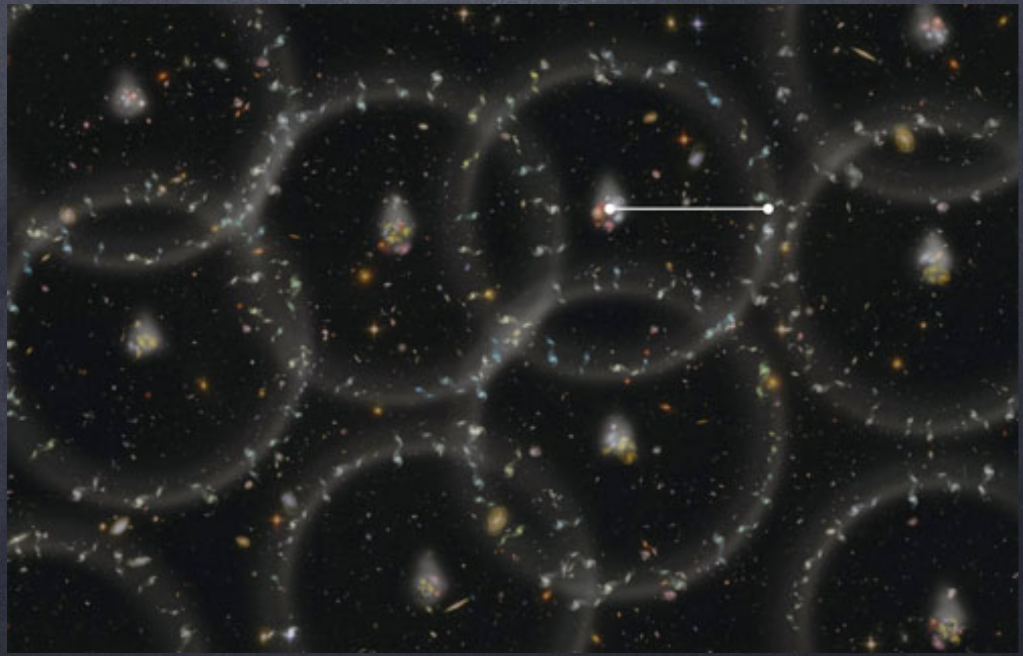


Eisenstein et al (2007)

the ruler



BAO in galaxies



Which scale?

- Which scale in the clustering Correlation Function?

- Comoving baryon acoustic scale
  Baryon acoustic peak - Matter CF

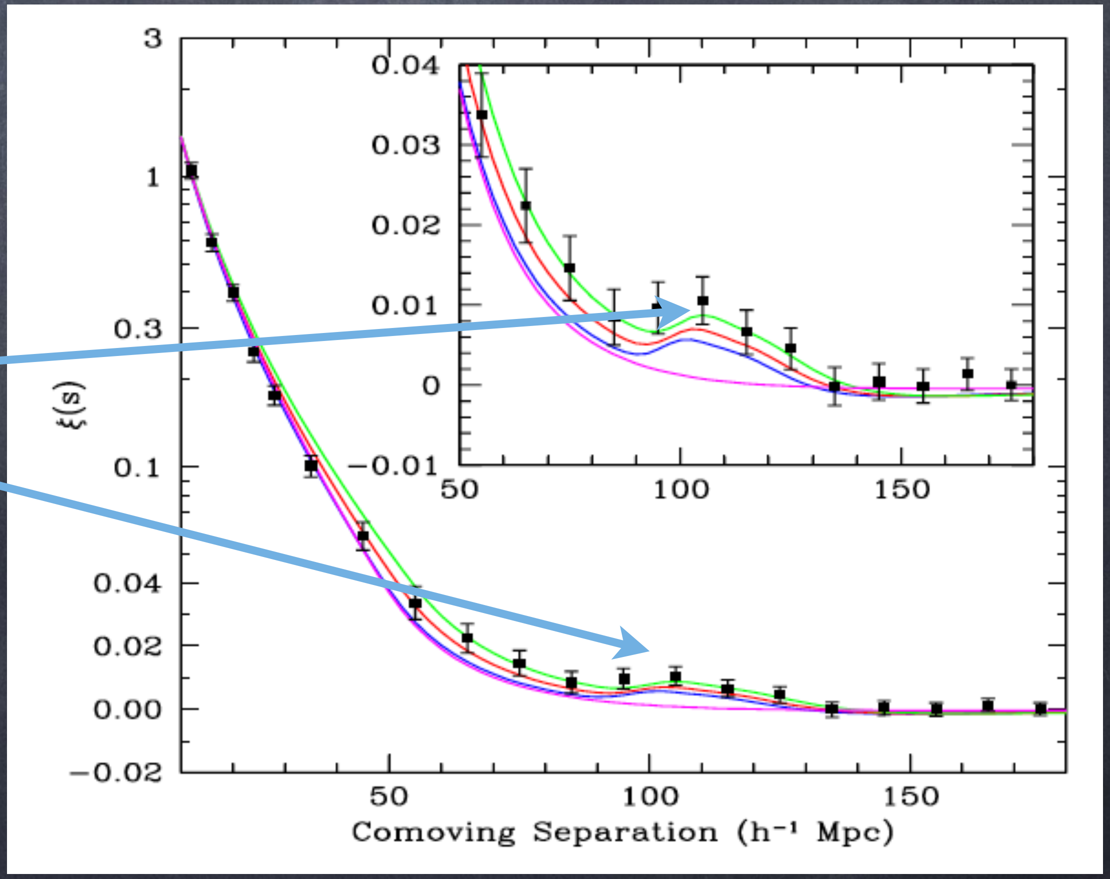
r_d

$\updownarrow$

s_p

- r_d is Geometrical (indep. primordial fluctuation)

Eisenstein et al (2005)



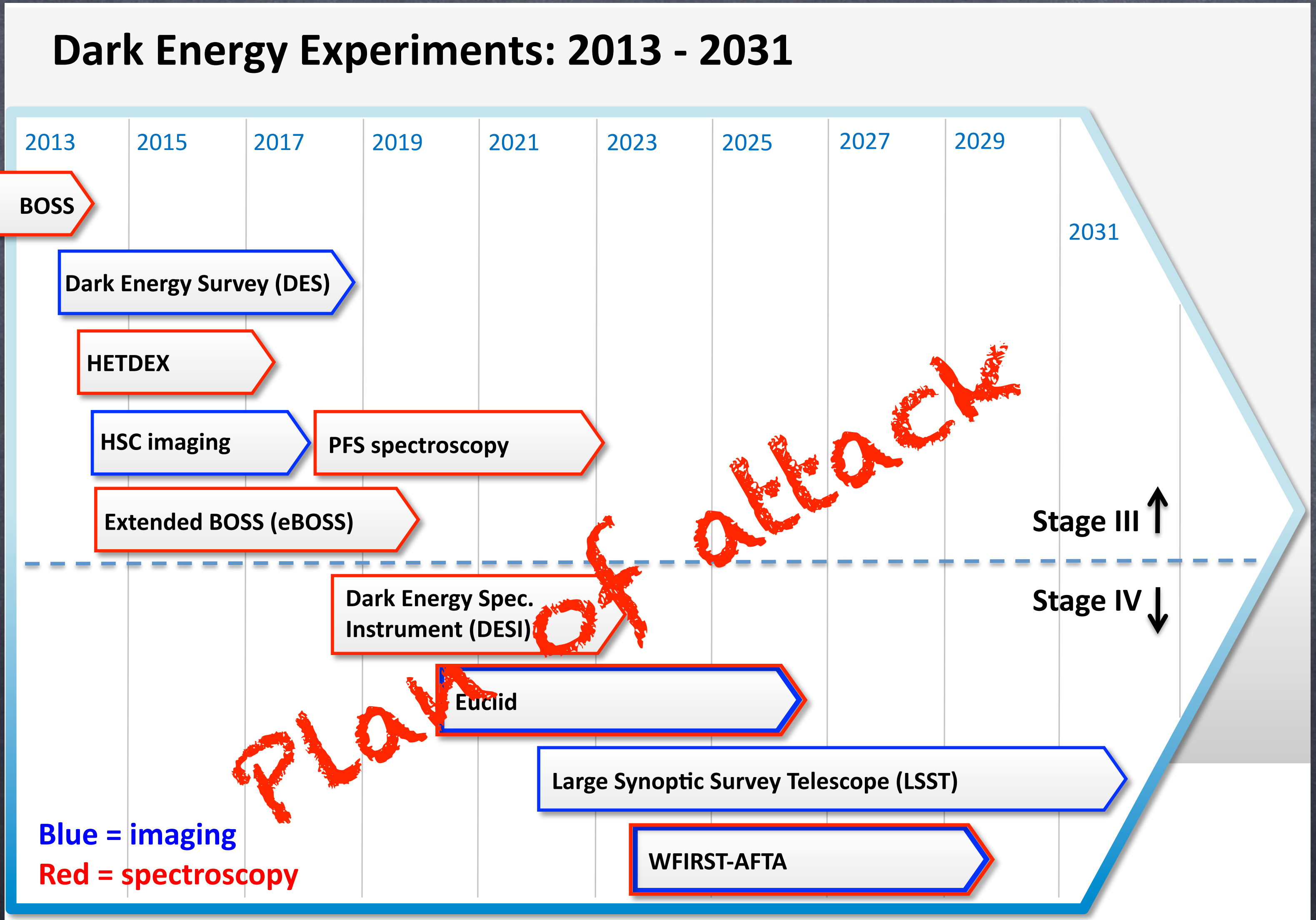
Baryon acoustic peak POSITION!!

STANDARD RULER

Precision cosmology with LSS

GOAL

MEASURE density Correlation Function at the % level

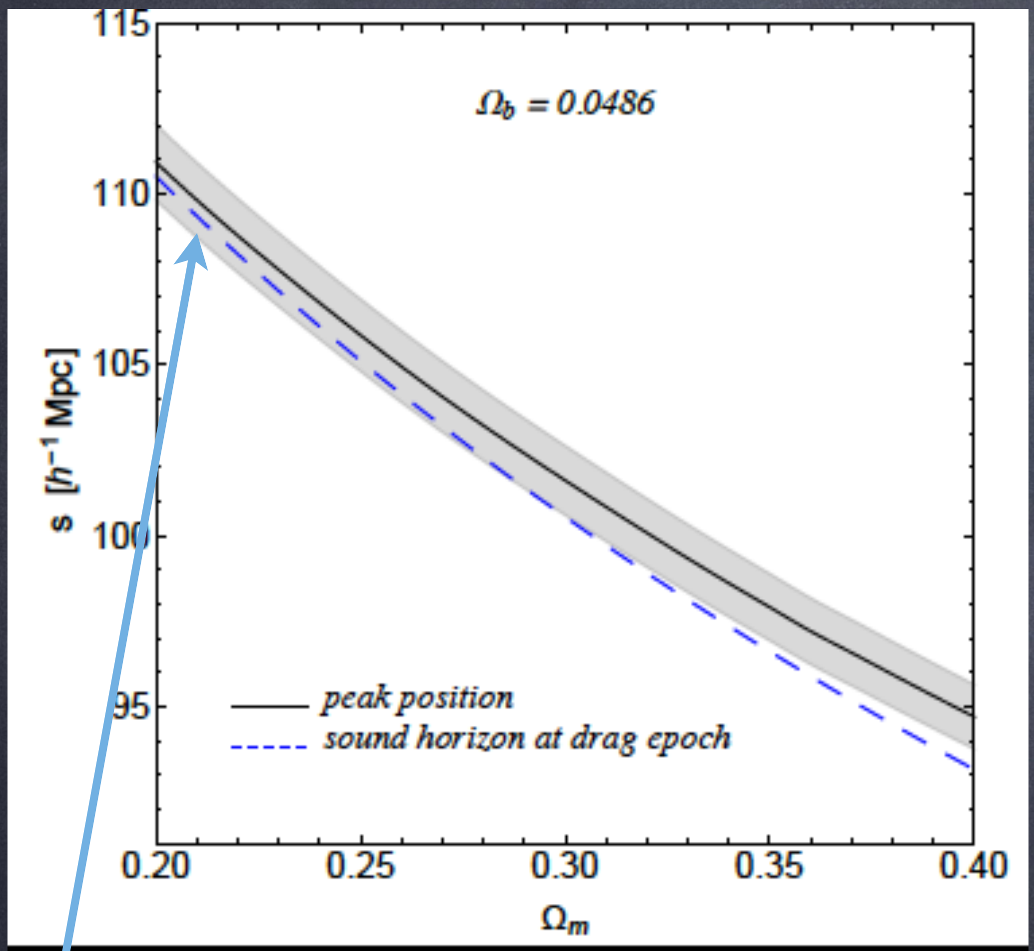


S.Dodelson y K. Honscheid, arXiv:1309.5386

Precision cosmology: breaks down!!

Linear

Sanchez et al. (2008)



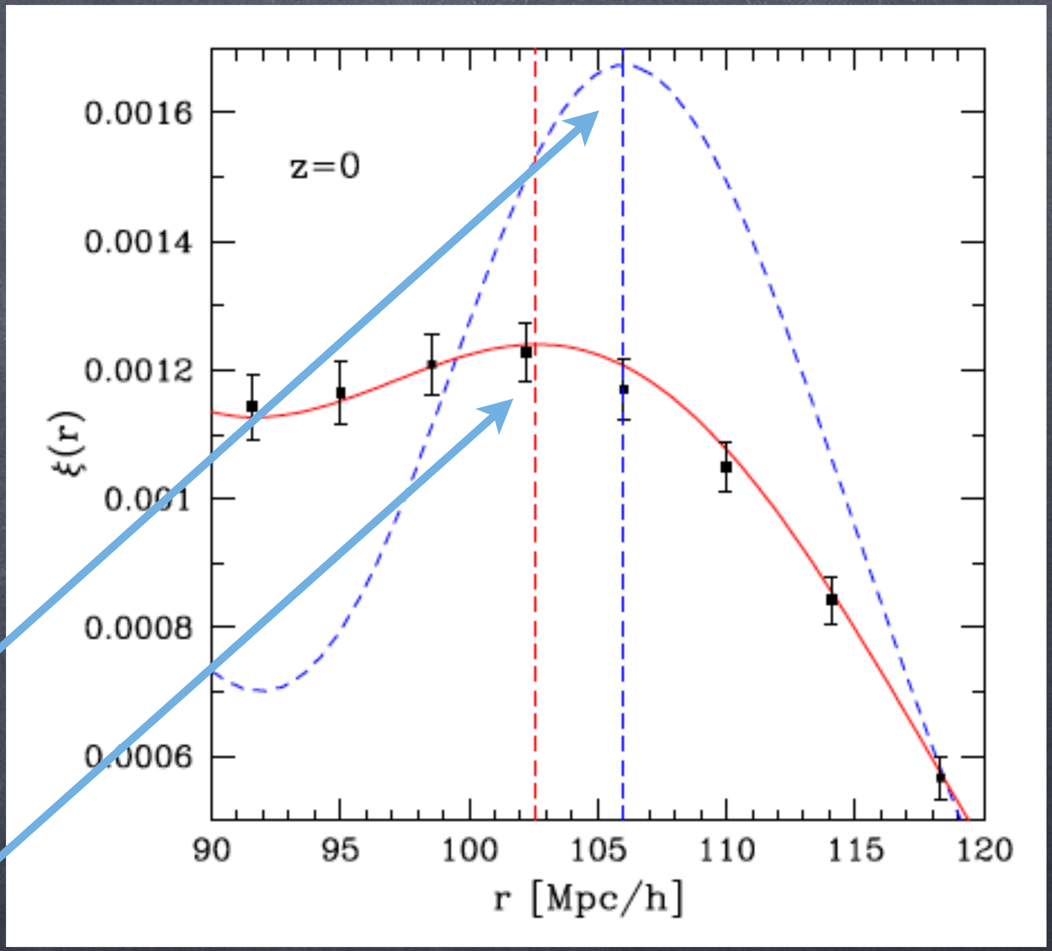
(CAMB code)

1 % region

Non-linear

Smith et al (2008)

Crocce, Scoccimarro (2008)



linear

non-linear

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

New BAO - Corr. Funct. ruler ?

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

Obvious connection with a "CMB" scale

NOT RELEVANT

Ingredients needed

1) A geometrical point

2) Redshift independent (linear)

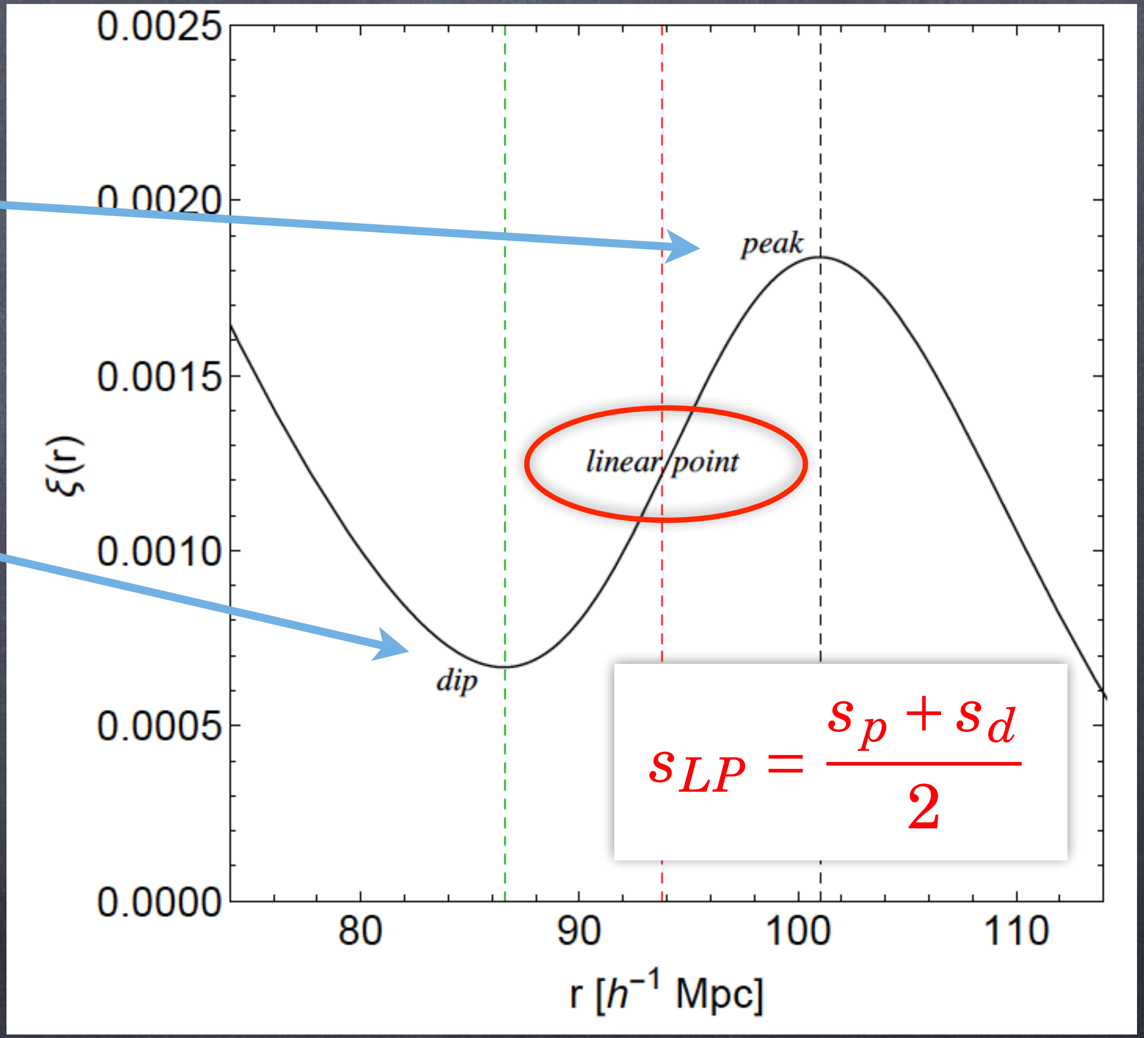
3) Easily identifiable

YES!! - the LINEAR POINT

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

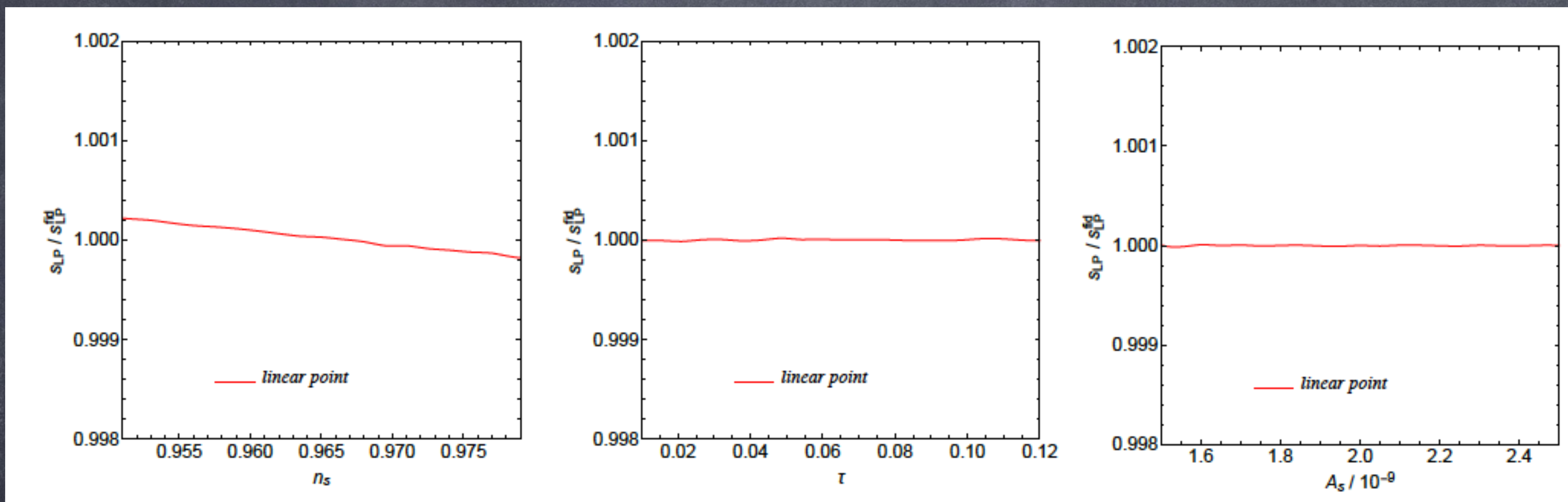
Corr. Func. BAO features

- peak (s_p)
- dip (s_d)
- LINEAR POINT: s_{LP}
  (peak-dip middle point)
- antisymmetric 2pcf



Linear analysis

Geometric



Independent at the 0.02 %

- Peak and Dip - NOT GEOMETRIC at nonlinear level.

Antisymmetry

- Position

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

- Amplitude

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

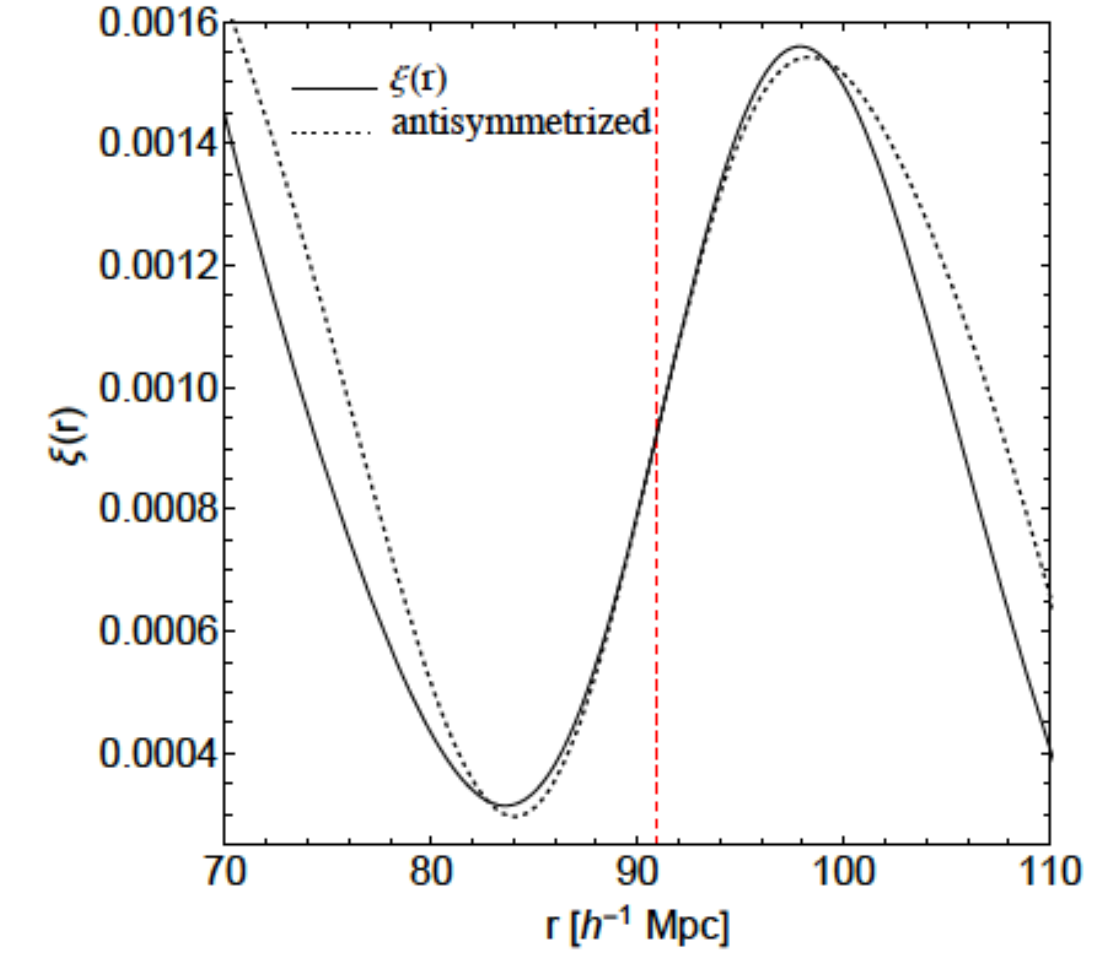
- Antisymmetry MEASURE

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

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

- Non-linearities IMPROVE the antisymmetry

  $\xi^{nl}(s_{LP}) \sim \xi^{nl}(s_A)$ (1 %)



Non-linear gravity

Bharadwaj (1996)

Crocce, Scoccimarro (2006)

Peloso et al. (2015)

Zel'dovič approximation

Assume particles move in a straight line with their linear perturbation theory velocity

- Dominant: displacements of galaxies from initial positions

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

velocity disp. linear theory

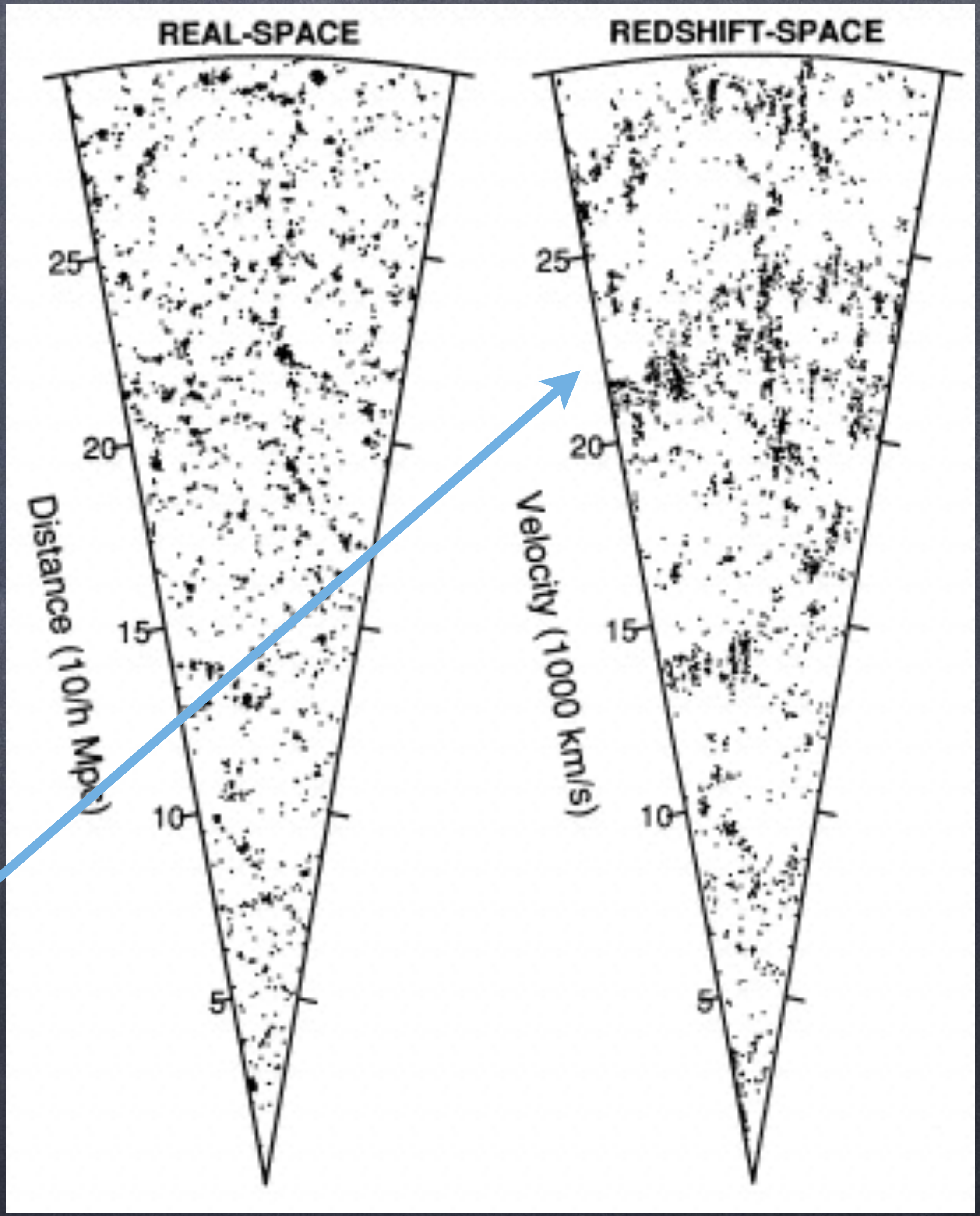
- BAO correlation function smoothed

- Good for CF - Not enough for PS.

Peculiar velocities

- Peculiar velocities: wrt Hubble flow.

- Distortion of the cosmological redshift.

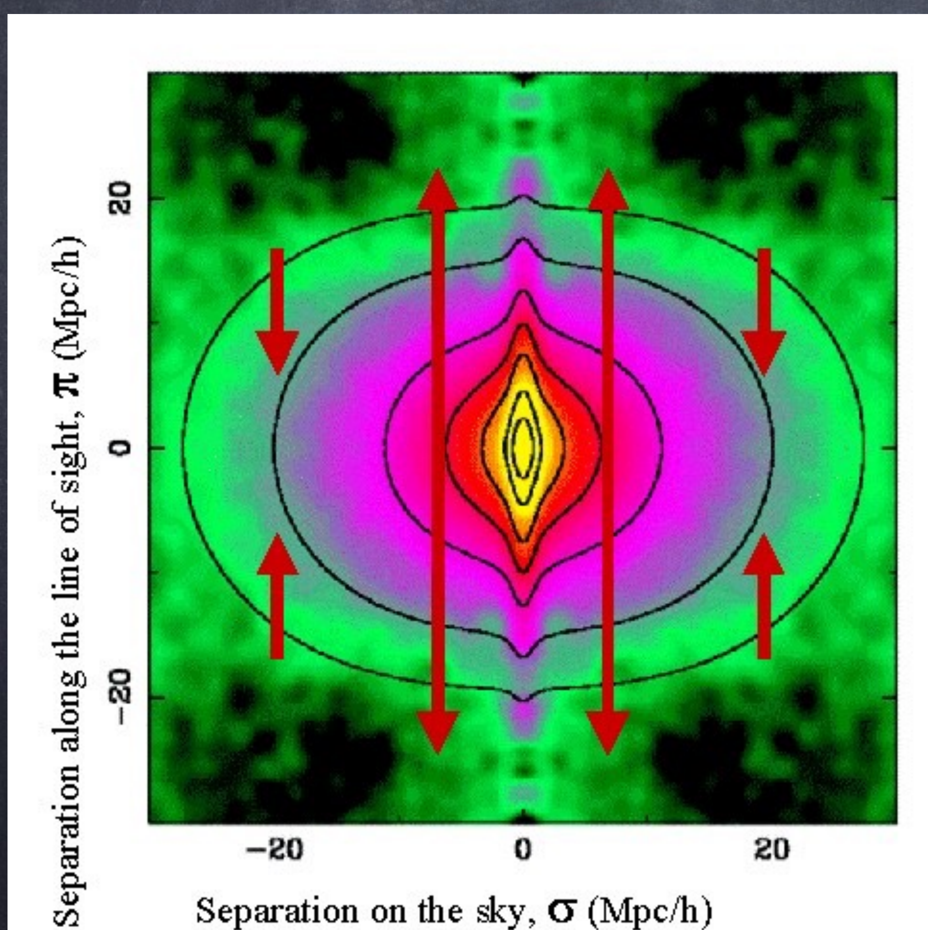


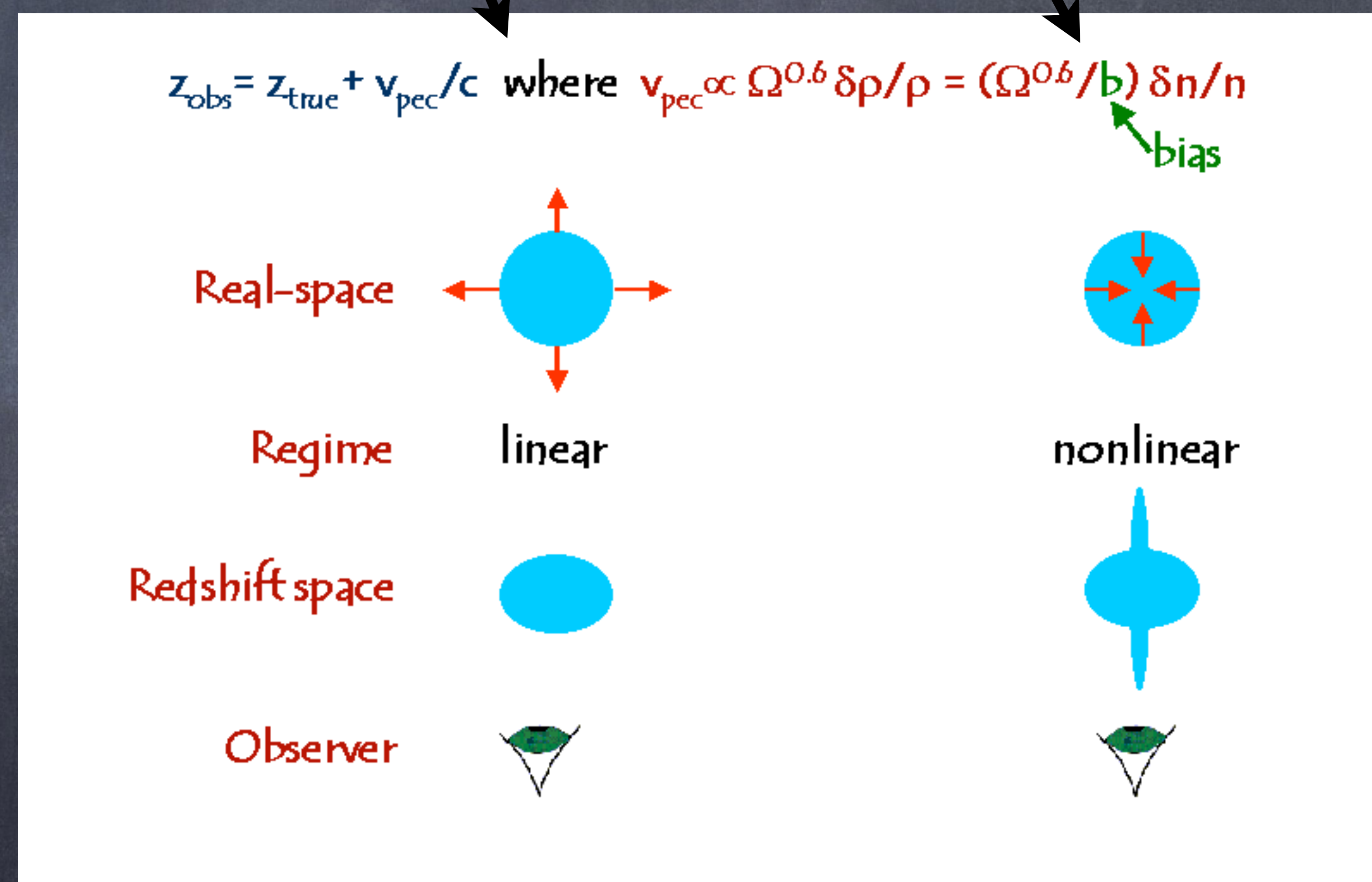
Finger of God effect

Redshift Space Distortions

Small Scale - "Finger of God"

Large Scale - Cluster size - "Kaiser effect".





Non-linearities - RSD

Eisenstein, Seo, White (2007)

Matsubara (2008)

Redshift Space Distortions

- Lagrangian Perturbation Theory

- Redshift space
  Bulk motions $\longrightarrow$ redshift space distortions

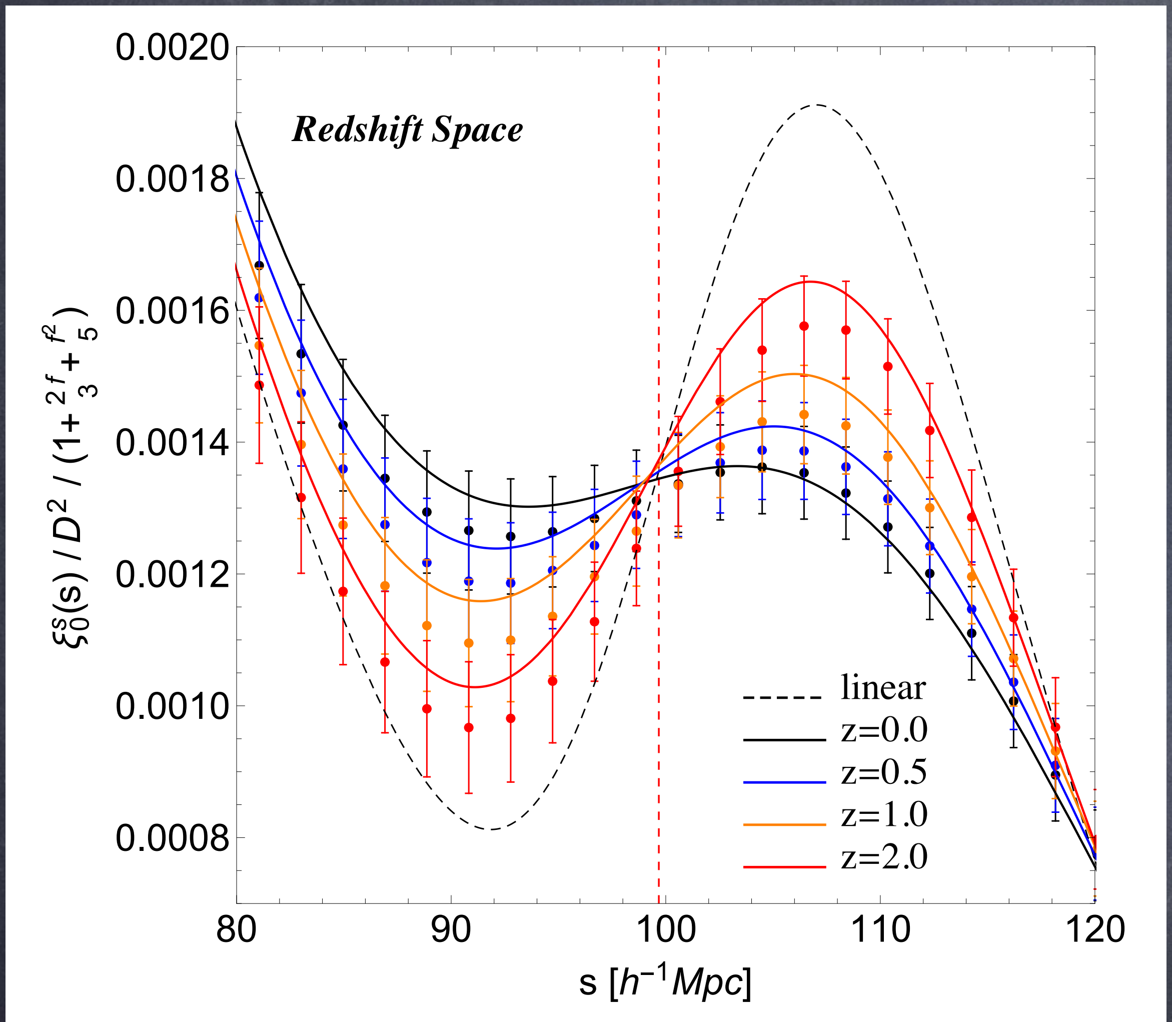
- Multipole expansion

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

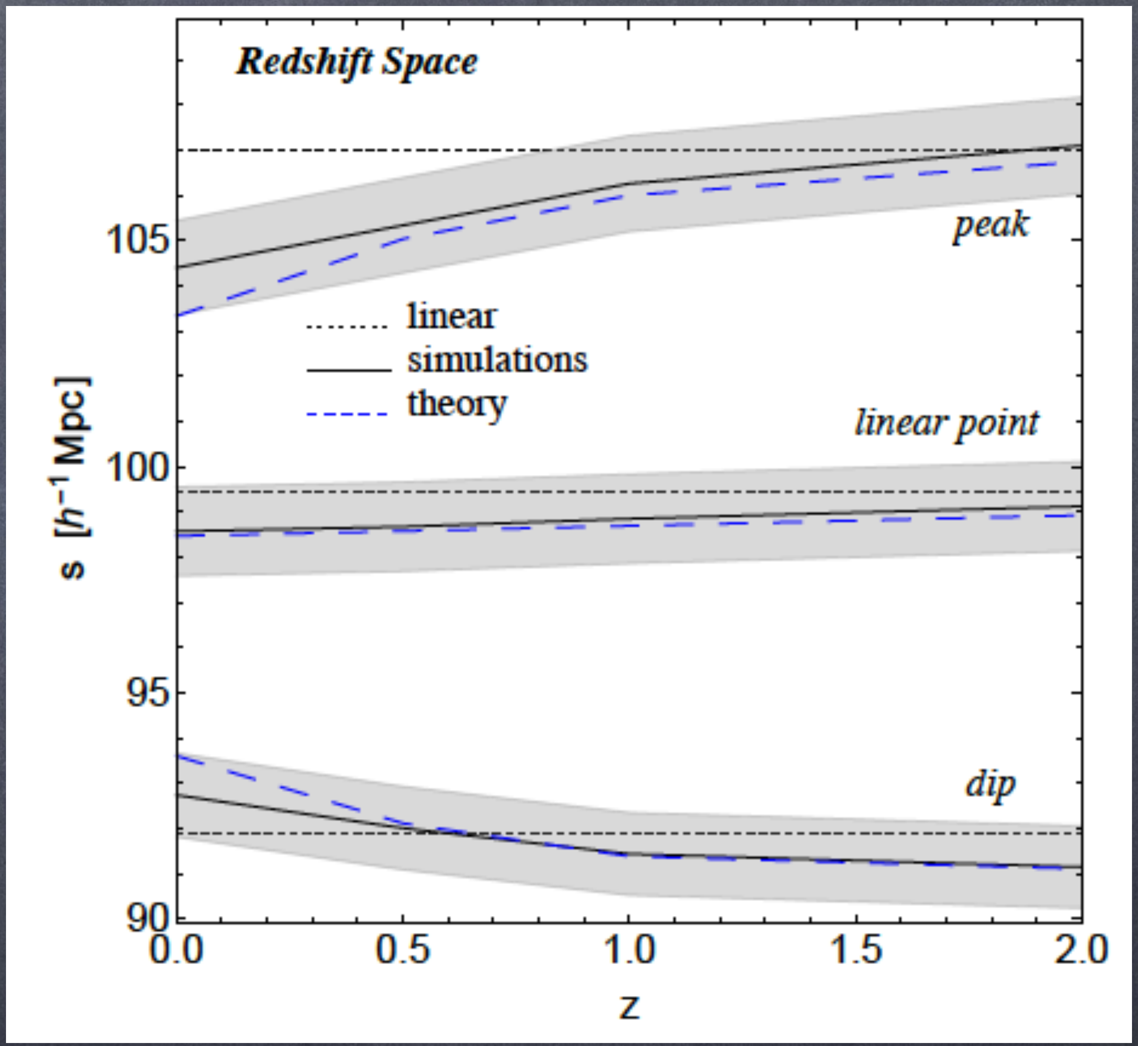
N-Body - COMPARISON

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

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

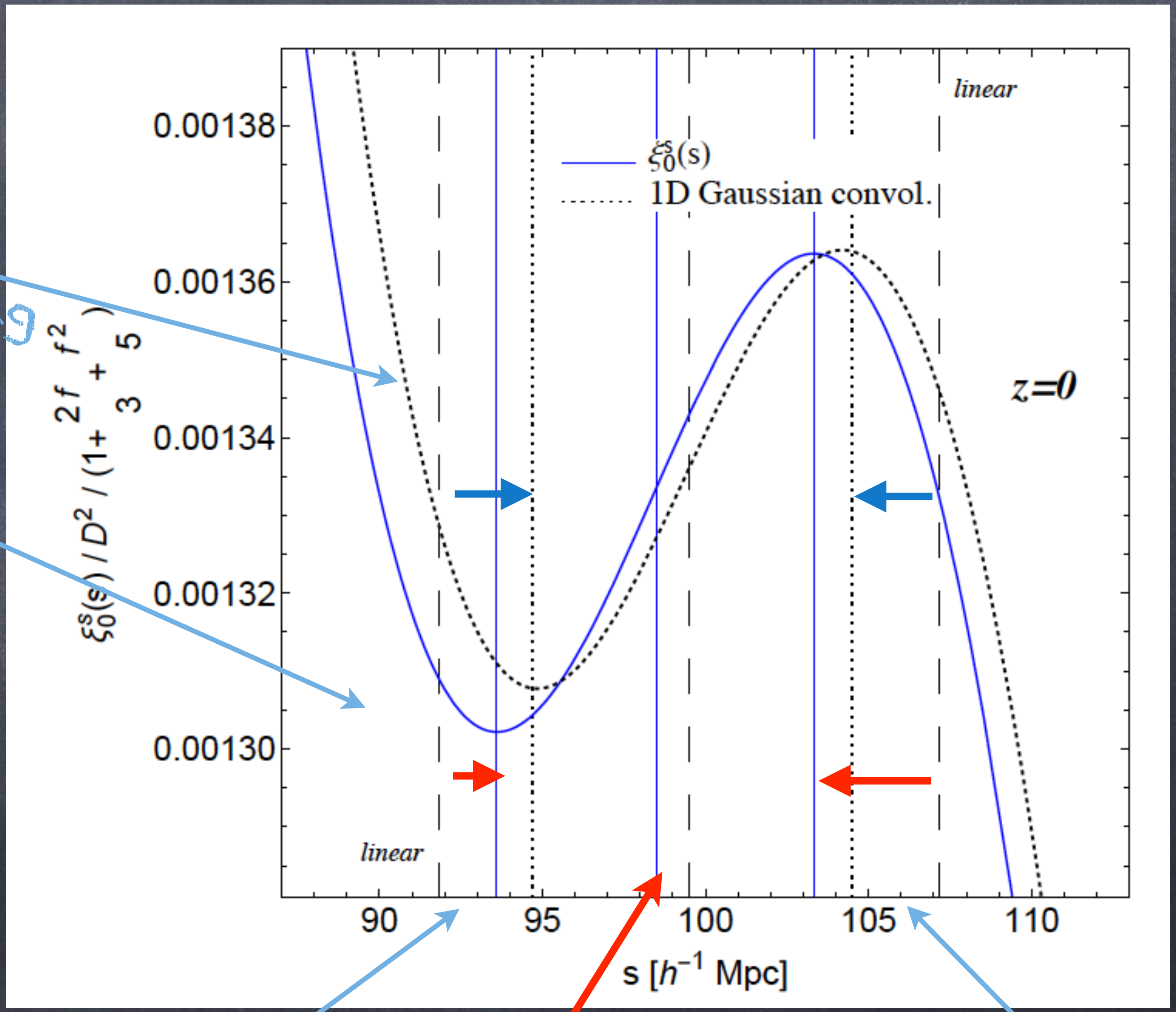
smoothing

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, MNRAS (2016)

DISTANCE MEASUREMENTS AT 0.5 %

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

Z=0 FIXING

$$s_{lin,w} = 0.7 s_d + 0.3 s_p$$

(same correction...)

EXACTLY LINEAR

$$s_{lin}(z) = c(z) s_d + d(z) s_p$$

Growth measurements

- Peak and dip: same smoothing

  Linear Point amplitude

  linear few percent.

EXPLOITING THE ANTISYMMETRY

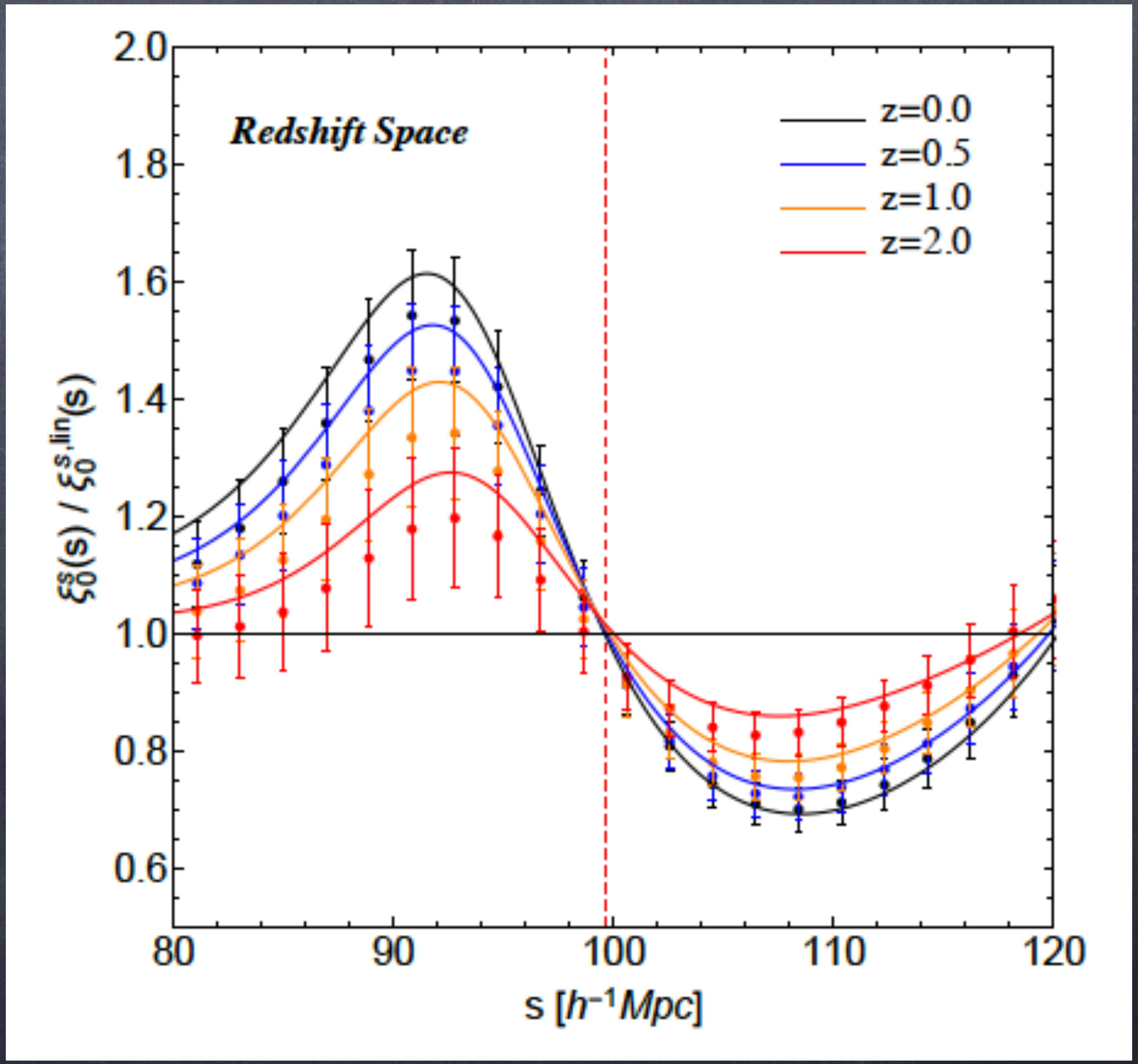
- Three GROWTH estimators

  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) $$\simeq \frac{\hat{\xi}^s_0(\hat{s}_{LP},z)}{\hat{\xi}^s_0(\hat{s}'_{LP},z')}$$

  2) $$\simeq \frac{\hat{\xi}^s_0(\hat{s}_p,z)+\hat{\xi}^s_0(\hat{s}_d,z)}{\hat{\xi}^s_0(\hat{s}'_p,z')+\hat{\xi}^s_0(\hat{s}'_d,z')}$$

  3) $$\simeq \frac{\sum_{\hat{s}_d\le x_i\le \hat{s}_p}\hat{\xi}^s_0(x_i,z)/N(z)}{\sum_{\hat{s}'_d\le x_i\le \hat{s}'_p}\hat{\xi}^s_0(x_i,z')/N(z')}$$



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

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

Preserve CF antisymmetry

Linear point position
STABLE

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

Consequences

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

Distance measurements

- Linear point stable.
- S_{LP} measured as for DM.

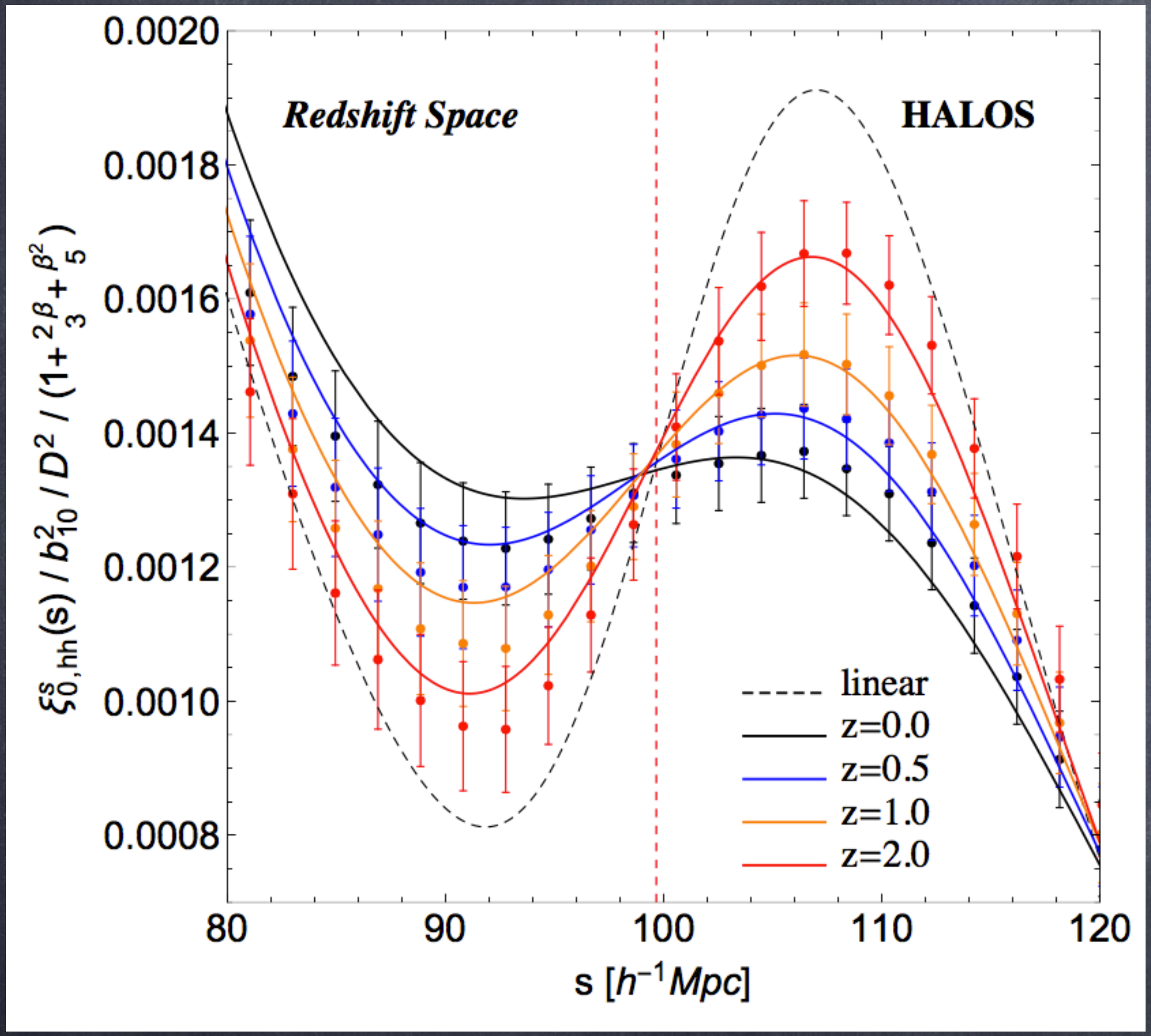
Growth measurements

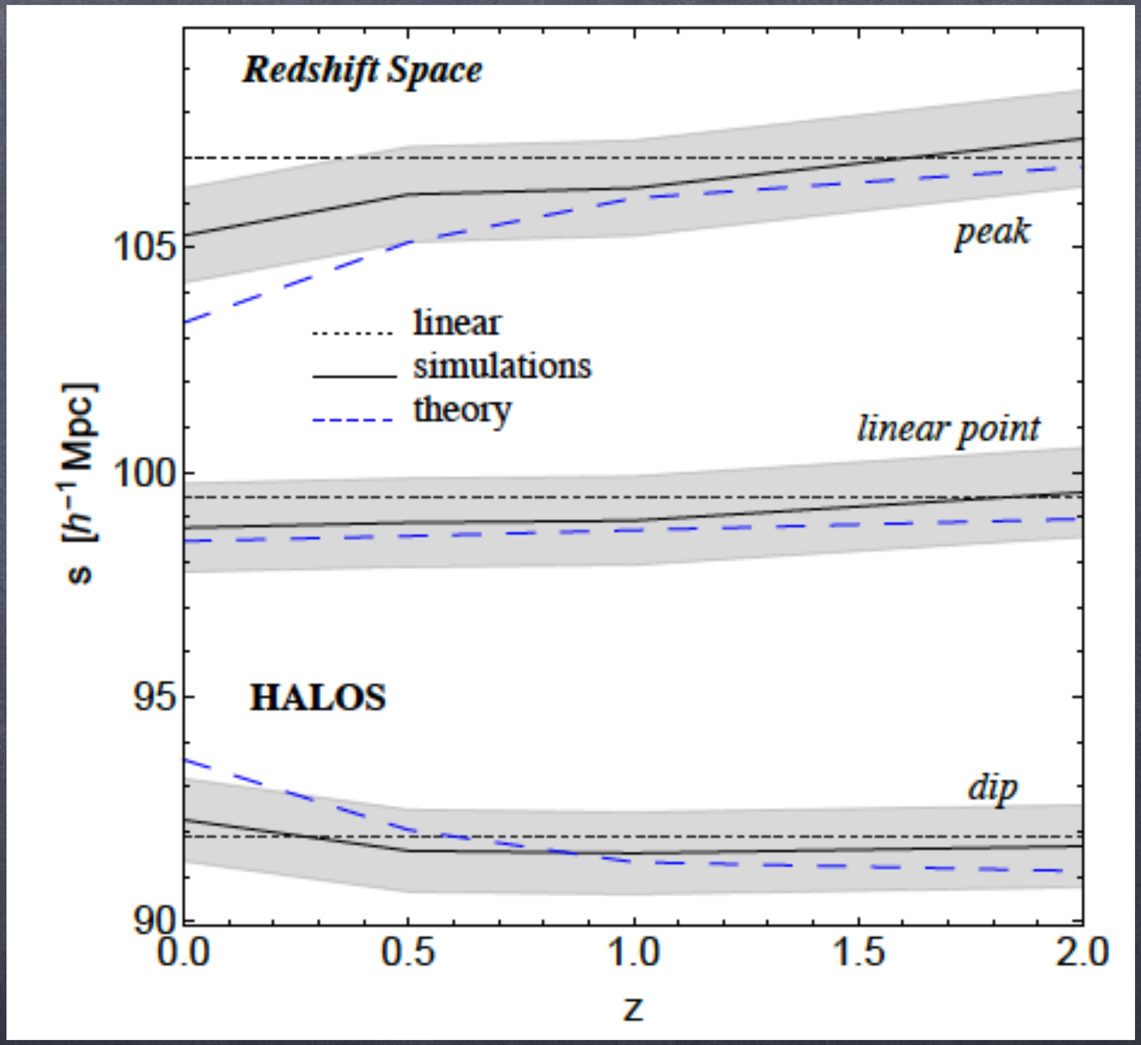
Linear: $$\frac{b_{10}^2(z)D^2(z)}{b_{10}^2(z')D^2(z')}\,\frac{1+\frac{2}{3}\beta(z)+\frac{1}{5}\beta^2(z)}{1+\frac{2}{3}\beta(z')+\frac{1}{5}\beta^2(z')}$$

- Same estimators as for DM
- Only sensitive to Linear Bias

N-Body halos

- Amplitude
- Position





- Low mass halos ($M > 1.37 * 10^{12}$ M_{sun}/h) - Linear Bias
- More massive halos ?

Growth test!!

- Redshifts: z=0, z=0.5

$$b_{10}(z=0) = 1 \qquad b_{10}(z=0.5) = 1.29$$

$$b_{01} \approx 0$$

- Linear

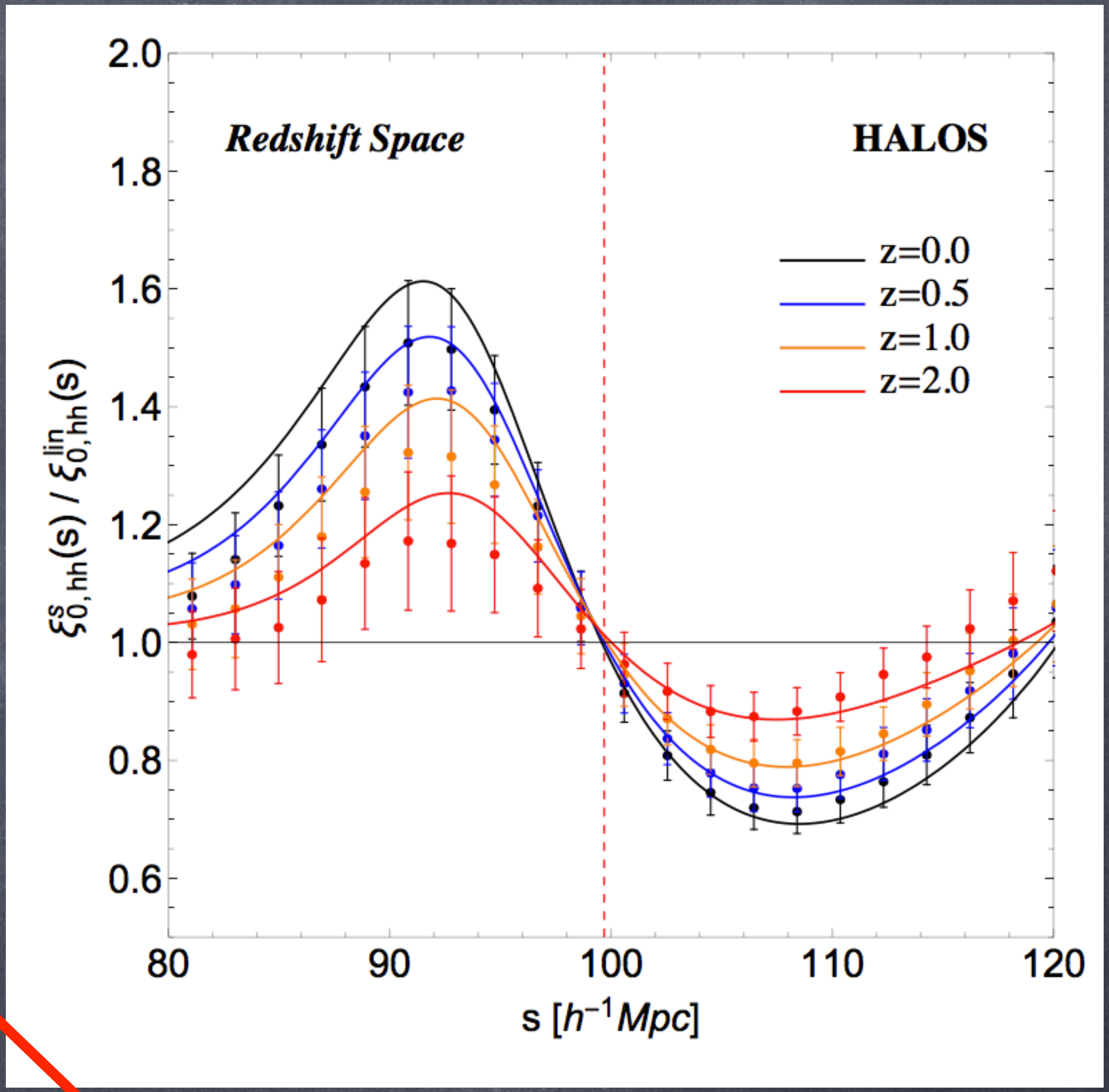
$$\frac{b_{10}^2(z) D^2(z)}{b_{10}^2(z') D^2(z')} \frac{1 + \frac{2}{3}\beta(z) + \frac{1}{5}\beta^2(z)}{1 + \frac{2}{3}\beta(z') + \frac{1}{5}\beta^2(z')} \approx 0.9347$$

- Non-linear theory

(all the estimators) ≈ 0.9359

- Simulations (poly. interp.)

(1), 2), 3)) $\approx (0.9303, 0.9338, 0.9321)$



1% AGREEMENT

How to use the Linear Point in practice ?

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

1) galaxy data; arXiv: 1703.01275

2) mock catalogue validation; arXiv: 1711.09063

2pcf in clustering data

- Working in comoving coordinates

measured (θ, z) $\xrightarrow{\text{FIDUCIAL cosmology assumed}}$ comoving FIDUCIAL distances

Alcock-Paczynski effect

Right Cosmology

z

θ

Wrong Cosmology

Alcock-Paczynski distortions

- Definitions

Isotropic volume distance

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

Anisotropic shift

$$1+\epsilon = \left[\frac{H^F(z) D_A^F(z)}{H(z) D_A(z)}\right]$$

Isotropic shift

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

- 2pcf monopole in redshift space

$$\underbrace{\xi_0^D(s^F)}_{\text{Distorted}} = \underbrace{\xi_0^T}_{\text{True}}(\alpha s^F) + O(\epsilon)$$

Current BAO definition

BAO

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.

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

$$P_m = (P^{lin}(k) - P^{smooth}(k))\, e^{-k^2 \Sigma_{NL}^2} + P^{smooth}(k)$$

$$A(s^F) = \frac{A_1}{(s^F)^2} + \frac{A_2}{s^F} + A_3$$

Based on fit to simulations

- Non-linear physics
- Wrong cosmology templ.

Parameters used

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

- 5 parameters varied

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

Cosmological information

marginalized

- Fixed parameters: $\{\Omega_b^F, \Omega_c^F, n_s^F, h^F, \Sigma_{NL}\}$

- Prescription: $\alpha = \dfrac{D_V(z)}{D_V^F(z)} \dfrac{r_d^F}{r_d^{CMB}}$

Linear Point - comoving ruler

linear approx.

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

scale independent for

- ΛCDM
- smooth quintessence
- clustering quintessence
- phenomen. models of w(z)
  $P(z) = w(z)\rho(z)$

Linear Point scale

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

Dark Energy INDEPENDENT
"CMB" comoving position

+

Dark Energy DEPENDENT
galaxy comoving position

$$d_A(z) \quad \text{and} \quad H(z)$$

$$\downarrow$$

$$w(z)$$

Measuring the distance

S.A, Starkman, Corasaniti, Sheth, Zehavi

arXiv: 1703.01275

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

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

Linear scale

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

CMB

z indep.

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

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

CMB best fit param.
+
linear CAMB code

NO FIXED PARAMETERS!!

- Only fiducial cosmology dependence -> Alcock-Paczynski

Validation - mock catalogues

S.A, Corasaniti, Starkman, Sheth, Zehavi
arXiv: 1711.09063

- Estimation bias

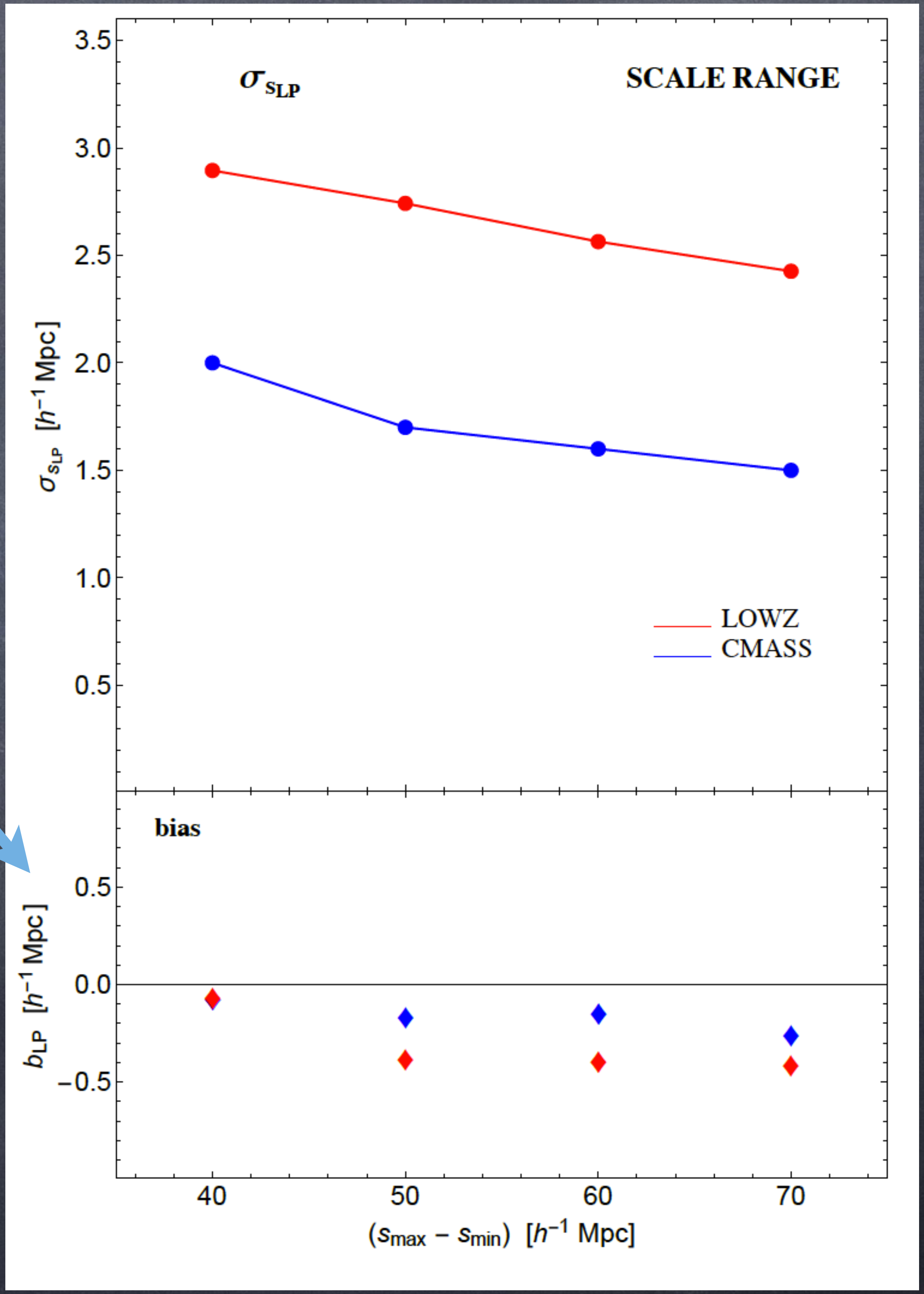
$$b_{LP} = \bar{s}_{LP} - s_{LP}^{\text{true}}$$

- Negligible estimation bias

$$b_{LP} \leq 0.2 \times \bar{\sigma}_{s_{LP}}$$

- Mock Acceptance Rate
  No LP information

estimation bias



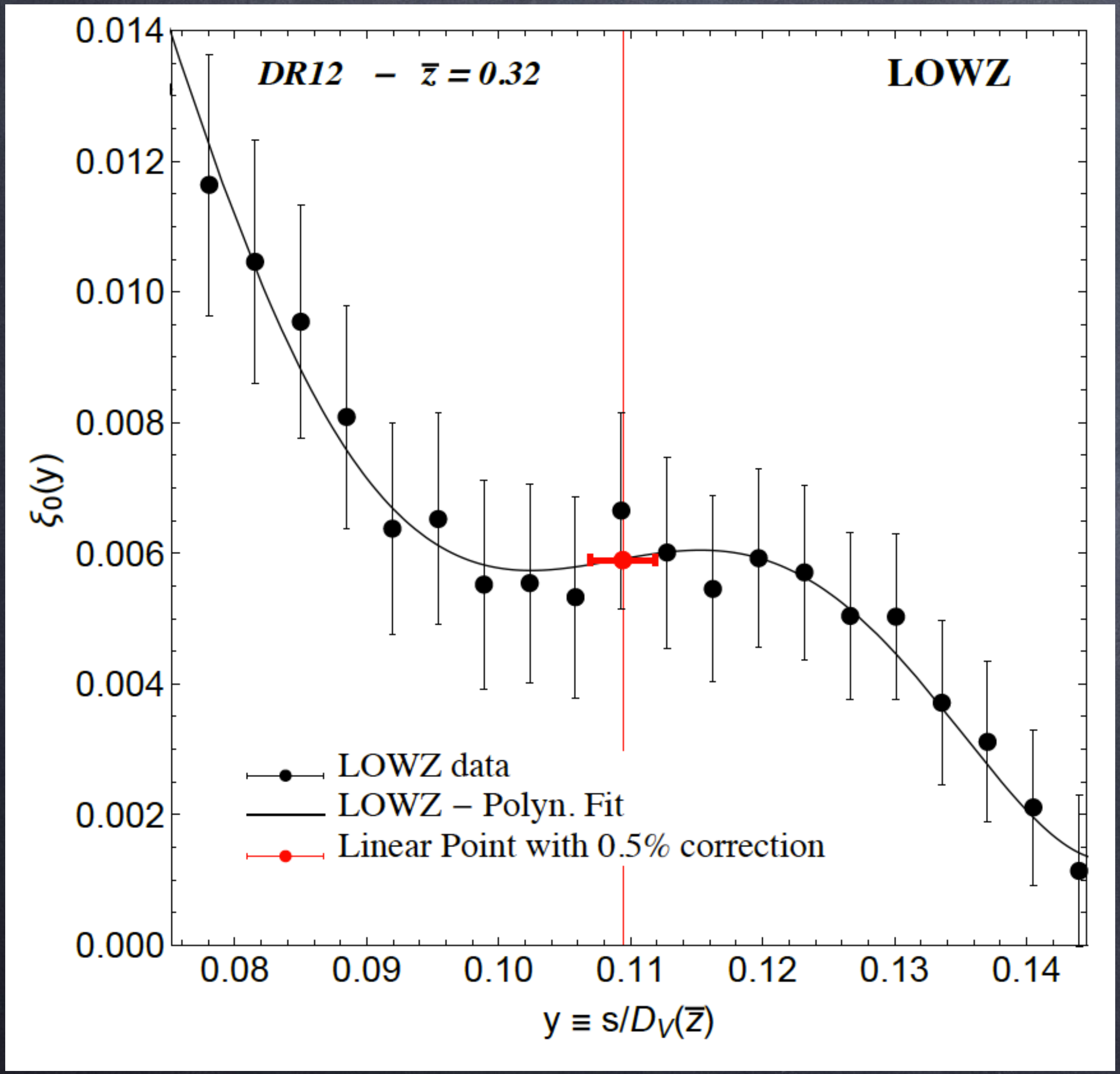
SDSS galaxies

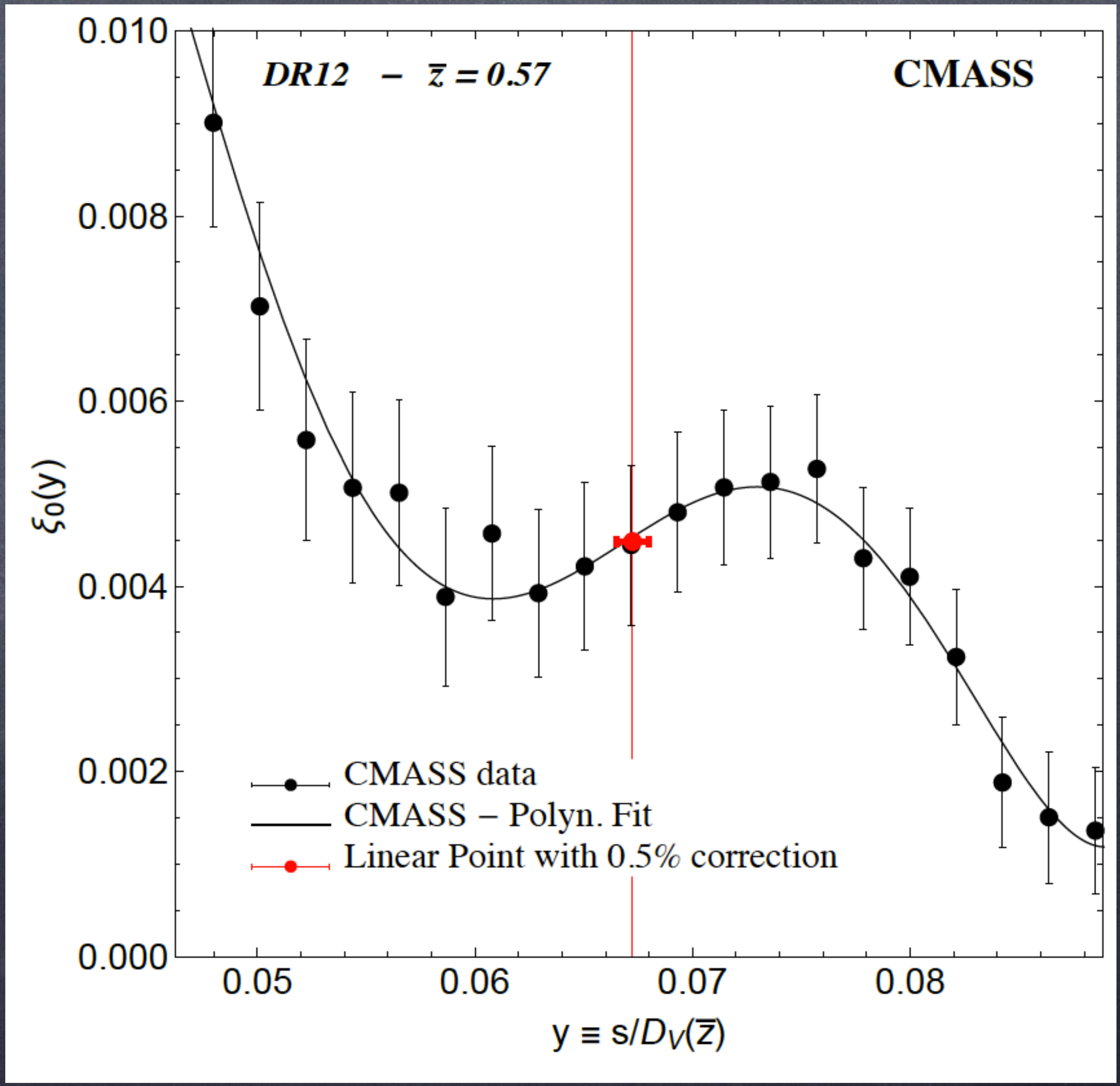
S.A, Starkman, Corasaniti, Sheth, Zehavi

arXiv: 1703.01275

- BOSS collaboration: two galaxy samples

  LOWZ and CMASS





SDSS galaxies

S.A, Starkman, Corasaniti, Sheth, Zehavi

arXiv: 1703.01275

PRE-reconstruction DATA

Linear Point distances

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

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

-24%

-18%

BOSS distances

Cuesta et al. (2016)

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

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

Why the Linear Point ?

THEORETICAL REASONS

- All the uncertainties correctly propagated.
- No uncontrolled prior assumed.
- Simple and model-independent (2pcf model poorly known).

RESULTS

- Linear Point -> less data but smaller error
- Fixed-template -> more data but larger error

- Fixed-template agrees at 1σ with the LP...

... but in the future ?

… worse… BAO reconstruction

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

- Increase the S/N and reduce non-linear effects.
- IDEA: numerical prescription to “send back” galaxies to their linear theory positions.
- Algorithm needs to assume values for (instead of fitting)

  - growth rate
  - matter-galaxy bias

QUESTIONS

- Legitimate to reduce the sample variance of observ. ?
- How do we control extra prior information in the data ?

PRE-RECONSTRUCTION DATA

S.A, Starkman, Corasaniti, Sheth, Zehavi
arXiv: 1703.01275

Linear Point distances

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

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

POST-RECONSTRUCTION DATA

Cuesta et al. (2016)

BOSS analysis

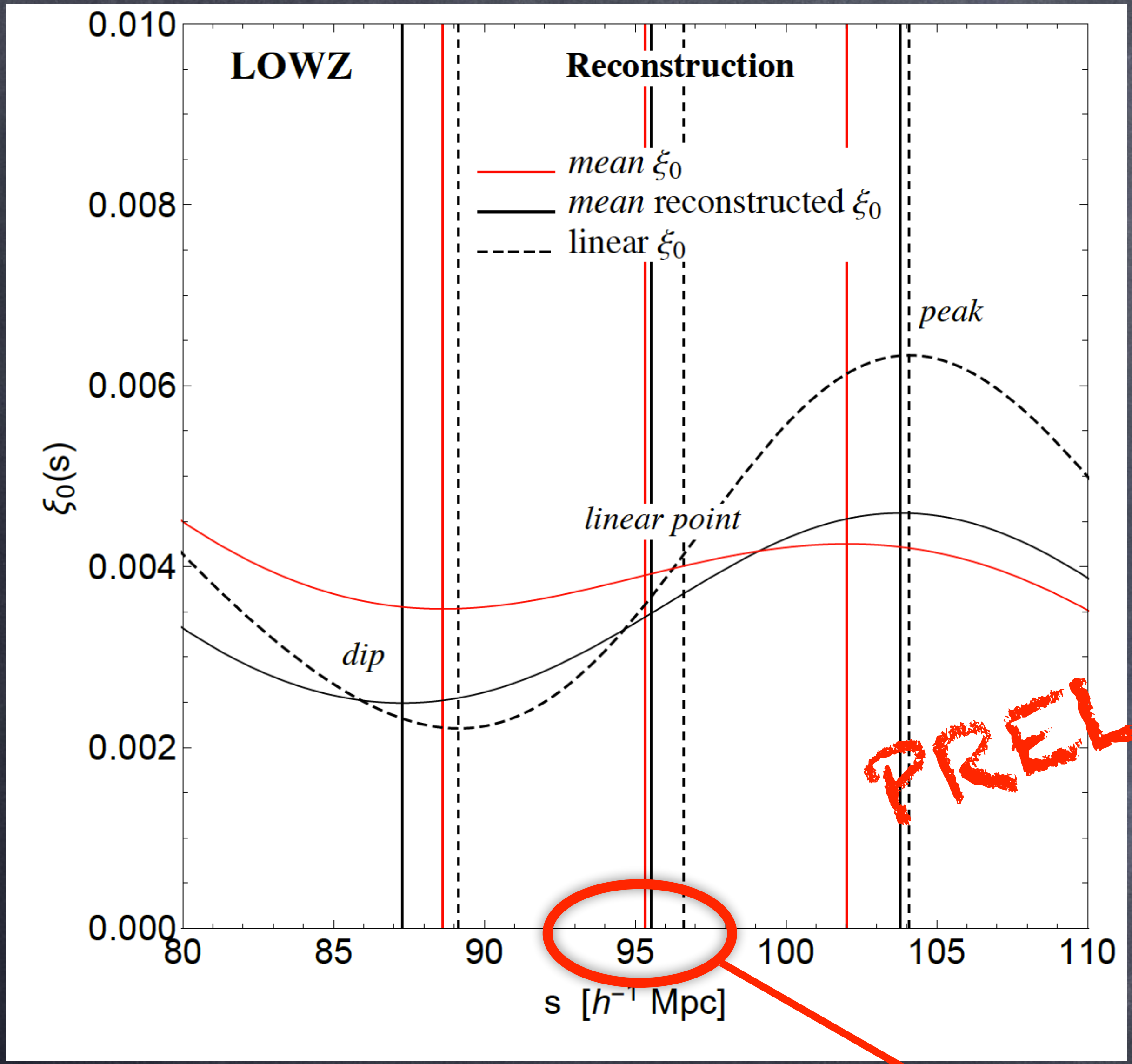
$$D_V^{\mathrm{BOSS;post-recon}}(\bar{z} = 0.32) = (1265 \pm 21)\mathrm{Mpc}$$

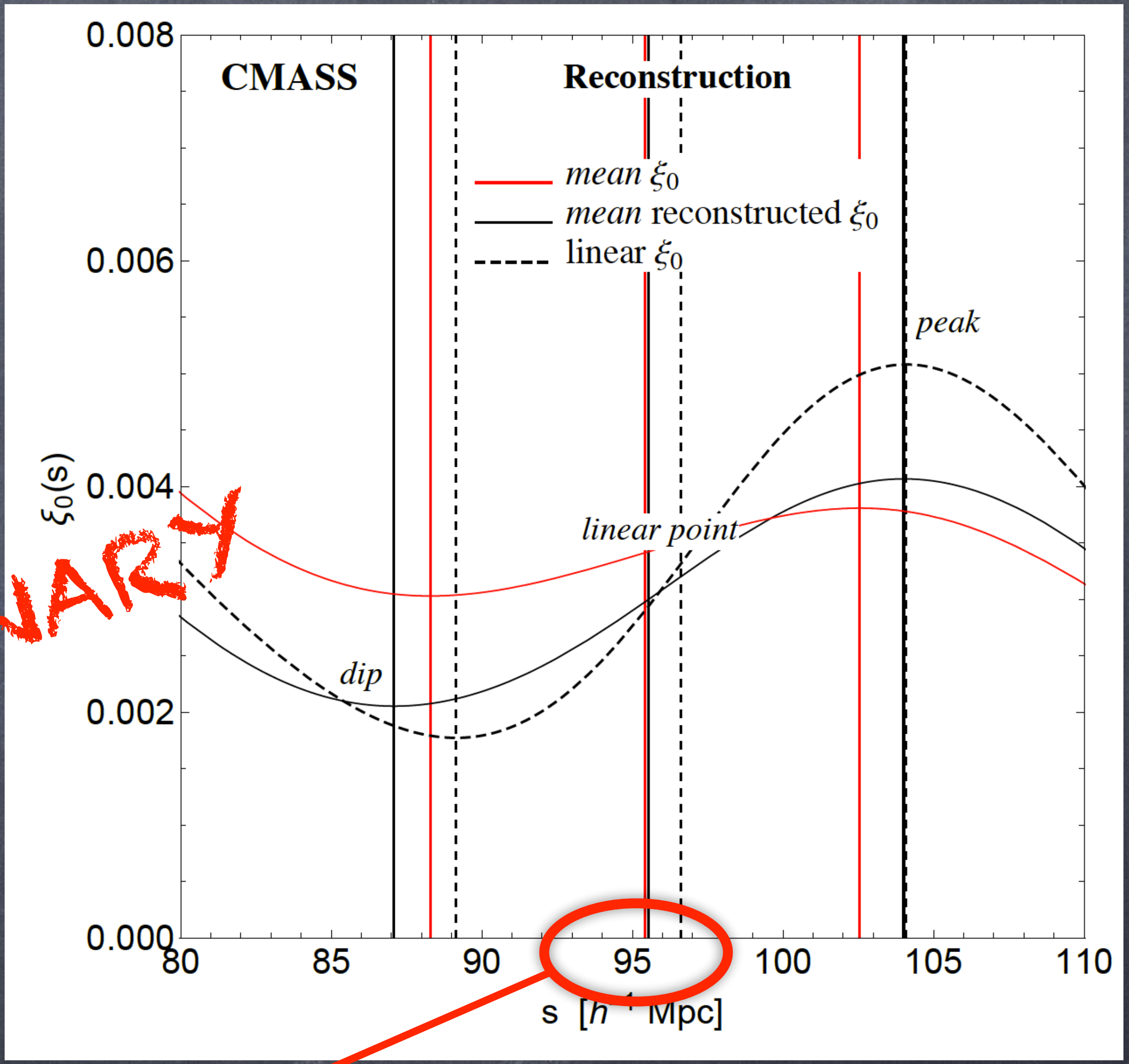
$$D_V^{\mathrm{BOSS;post-recon}}(\bar{z} = 0.57) = (2031 \pm 20)\mathrm{Mpc}$$

- Good agreement
- POST-reconstruction -> smaller errors...

... but is everything consistent ?

BOSS BAO-(DR12) mocks





PRELIMINARY

by chance

reconstruction invariant

Invariant in real data?

PRE-RECONSTRUCTION DATA

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

large discrepancy

POST-RECONSTRUCTION DATA

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

Known possible reasons... ????

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

improved theoretical tools needed ?

Measure CMB-BAO tension ?

- How cosmol. params from BAO only ?

Sanchez, Baugh, Angulo (2008)

Sanchez, Crocce et al. (2009)

Sanchez et al. (2012)

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

Distorted

Fit

α

Prediction of the model

Not a fitted parameter

PROBLEM!!

NEED of 2pcf motivated theoretical model

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

Work in angles - redshifts

angular diameter distance

$$D_A(z) = \frac{r(z)}{1+z}$$

comoving distance

$$r(z) = \int_0^z \frac{dz'}{H(z')}$$

$$r(z_1, z_2, \theta) = \sqrt{r(z_1)^2 + r(z_2)^2 - 2r(z_1)r(z_2)\cos(\theta)}$$

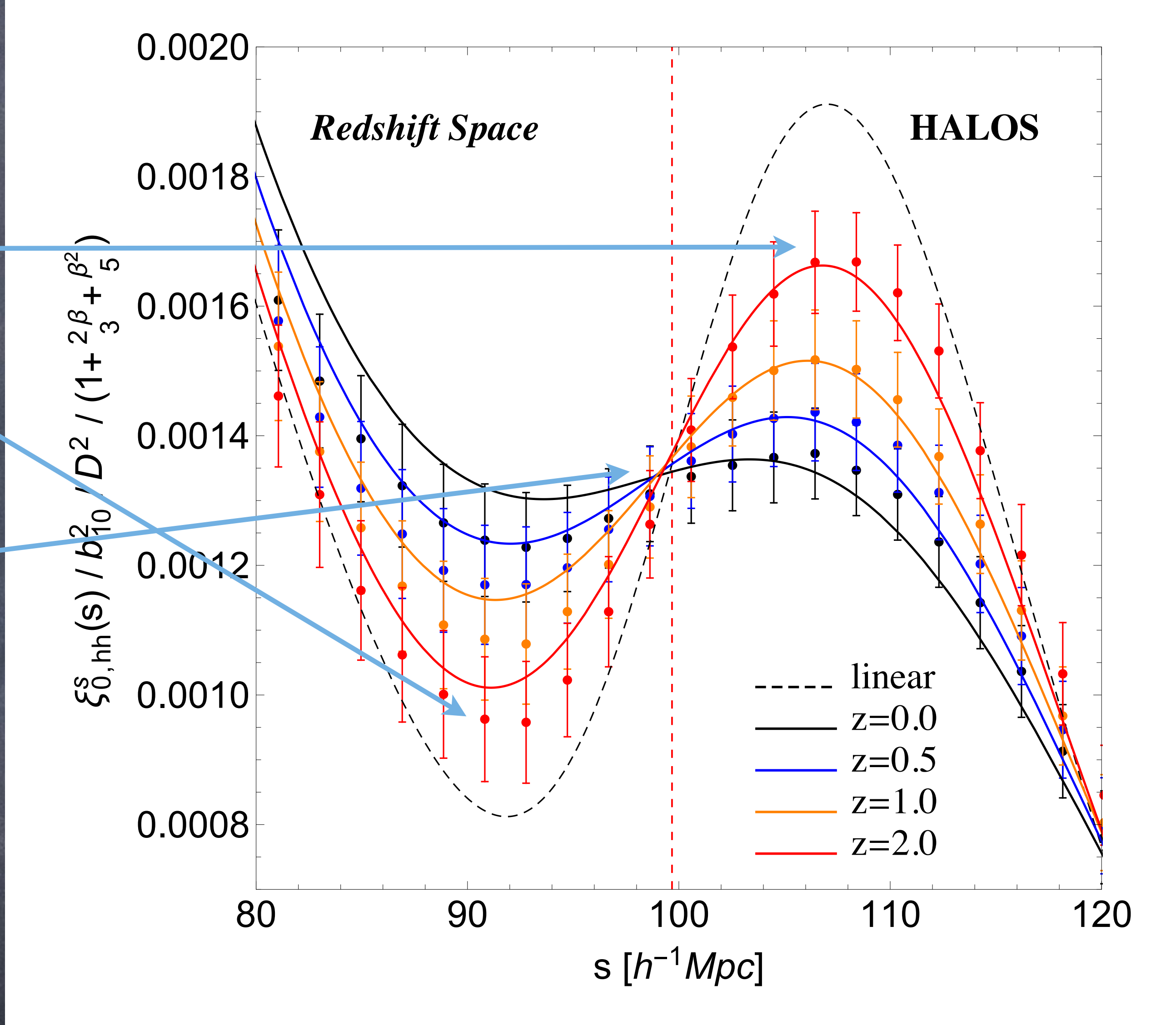
$$\xi(\theta, z_1, z_2) = \xi(r(z_1, z_2, \theta), z_1, z_2)$$

longitudinal (redshifts)

transverse (angles)

- LP properties stable?

Disentangle bias - growth



Peak - Dip

- growth - smoothing
- scale dep. bias

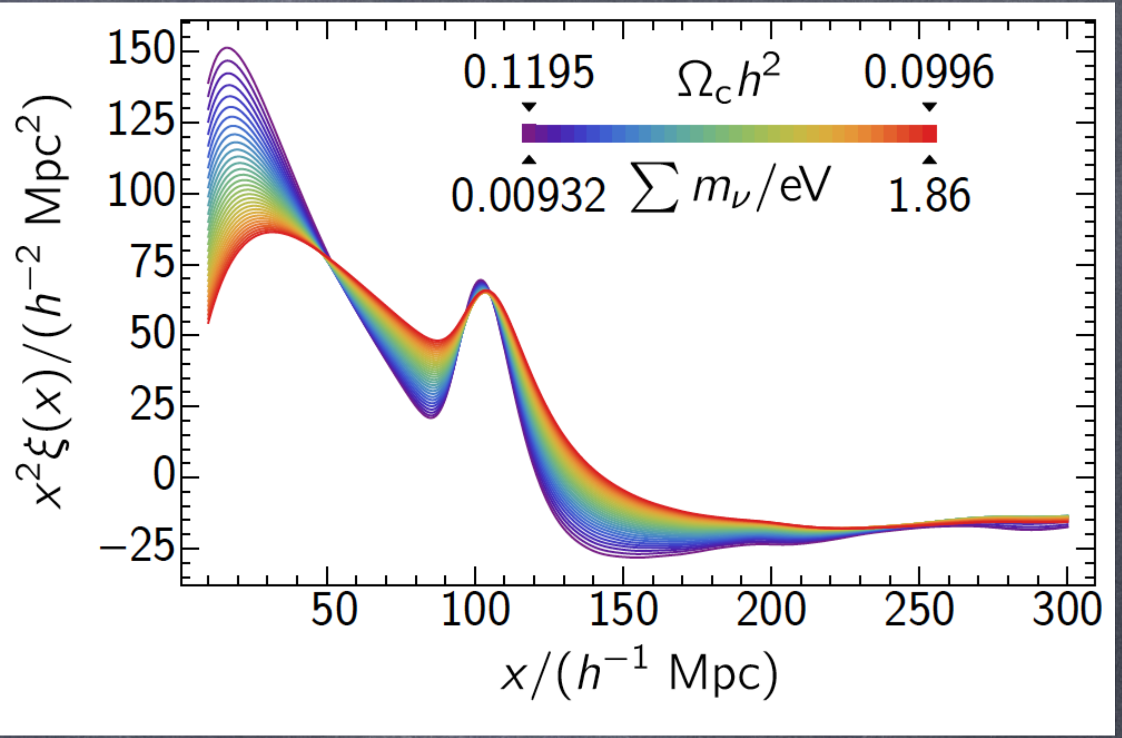
Linear Point

- NO smoothing
- NO scale dep. bias

f, D, b_{10}, b_{01} enter differently

Neutrinos

Thepsuriya, Lewis (2015)



- Peak-dip antisymmetry preserved ?
- Linear point ?
- BAO information -> constrain neutrinos ?
- Different bias.
- Corr. Function: Non Linear descriptions as LCDM for CDM

Peloso et al. (2015)

Non standard-cosmologies ??

DARK ENERGY / MODIFIED GRAVITY

FACT

models where a preferred scale appears

- Spoil the peak-dip antisymmetry at the linear level ?
  Scale dependent growth.
- Non-linearities: different wrt LCDM. What is their effect ?
- peak-dip anti-symmetry as a modified gravity smoking gun ?

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.
- Clean-up the BAO + Reconstruction under inspection!

Growth

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

... to do...

- Different galaxy populations? Clusters? Quasars? 21-cm?
- Angles and redshifts ?
- Neutrinos ?
- Modified gravity + ... + ... + ...

THANK YOU!!