Evading non-linearities: Baryon Acoustic Oscillations at the Linear Point

COSMO-15

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(collaboration with

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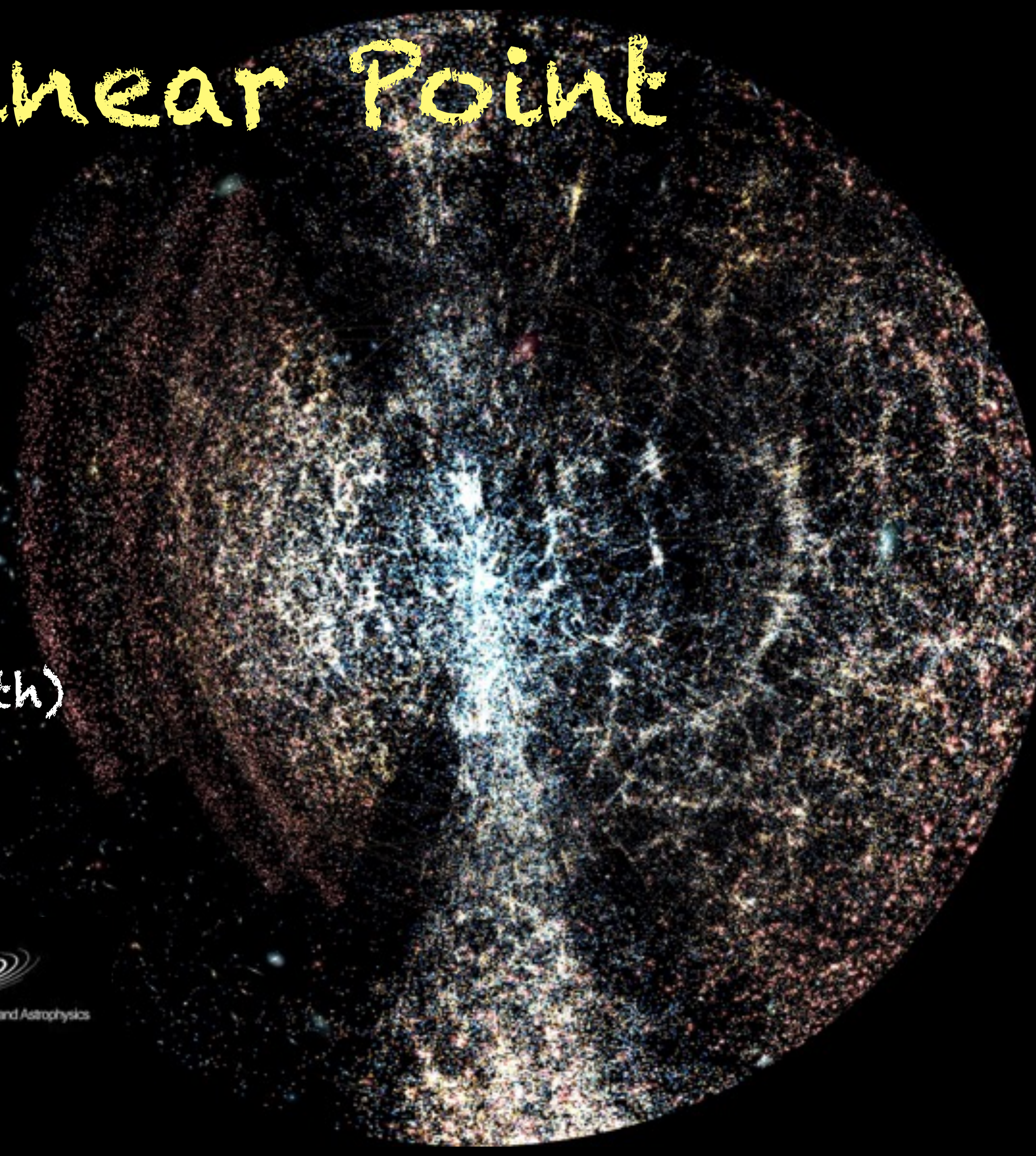
arXiv: 1508.01170



CASE WESTERN RESERVE UNIVERSITY EST. 1826

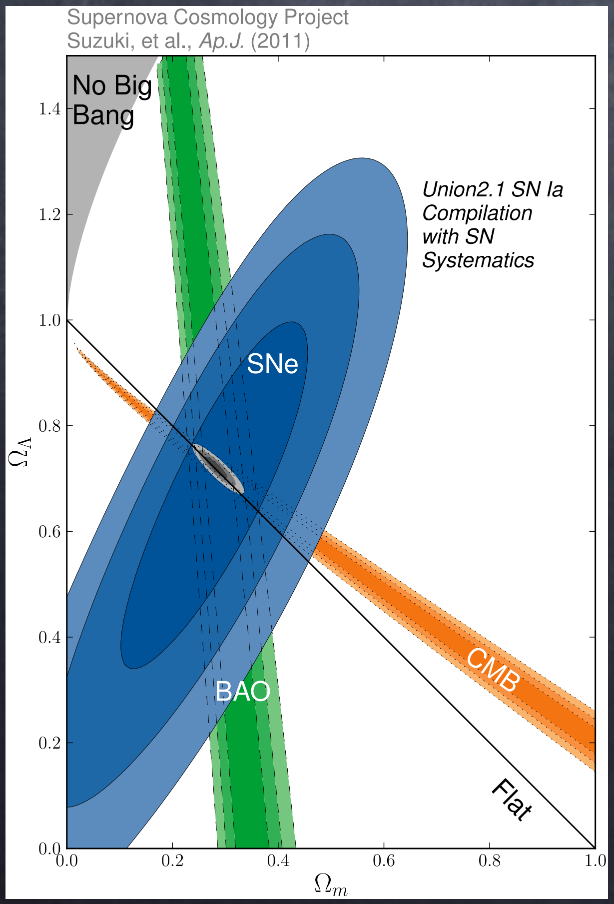
CERCA Center for Education and Research in Cosmology and Astrophysics

Outline

- LSS - understand the nature of cosmic accel.
- 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.
- Preliminary comparison with data!!

We are accelerating...

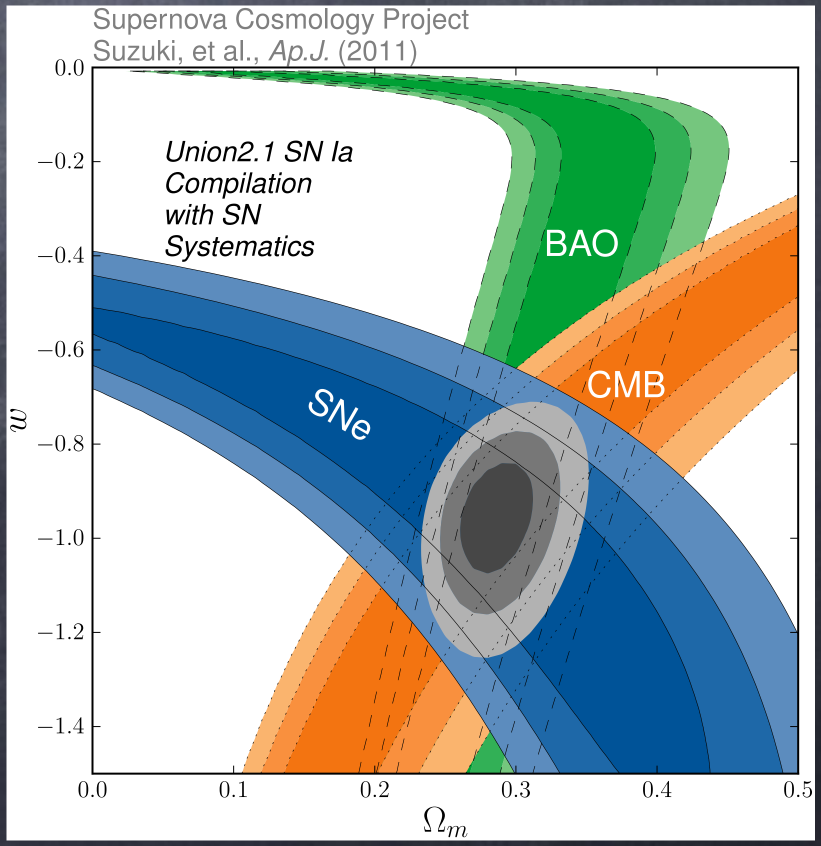
- Observational Evidences - Late Accelerated Expansion.
- SN-Type 1a - standard candles - late expansion on the Univ.
- CMB via Late Integrated Sachs-Wolfe effect (late time gravitational redshift of the photons).
- BAOs measured at different redshift (depend on cosmol. parameters)



Combining

SN-Type 1a + CMB + BAO

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 → PREFERRED SCALE (constant in redshift)

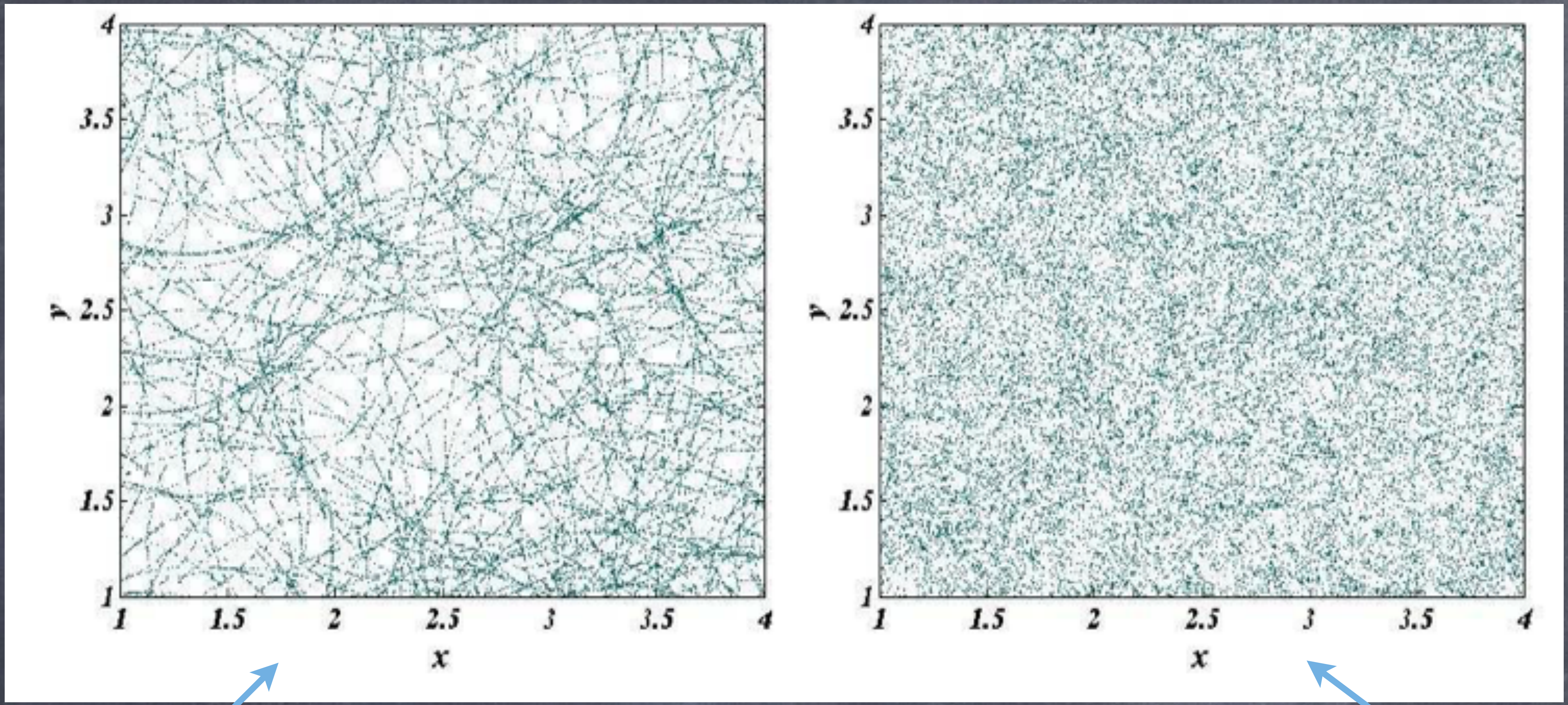
↓

Observed at different redshifts

↓

Constrain the angular diameter distance.

Cosmological parameters



intuitive picture

realistic picture

Angular Diam. Distance

actual size

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

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

cosm. parameters

Which scale?

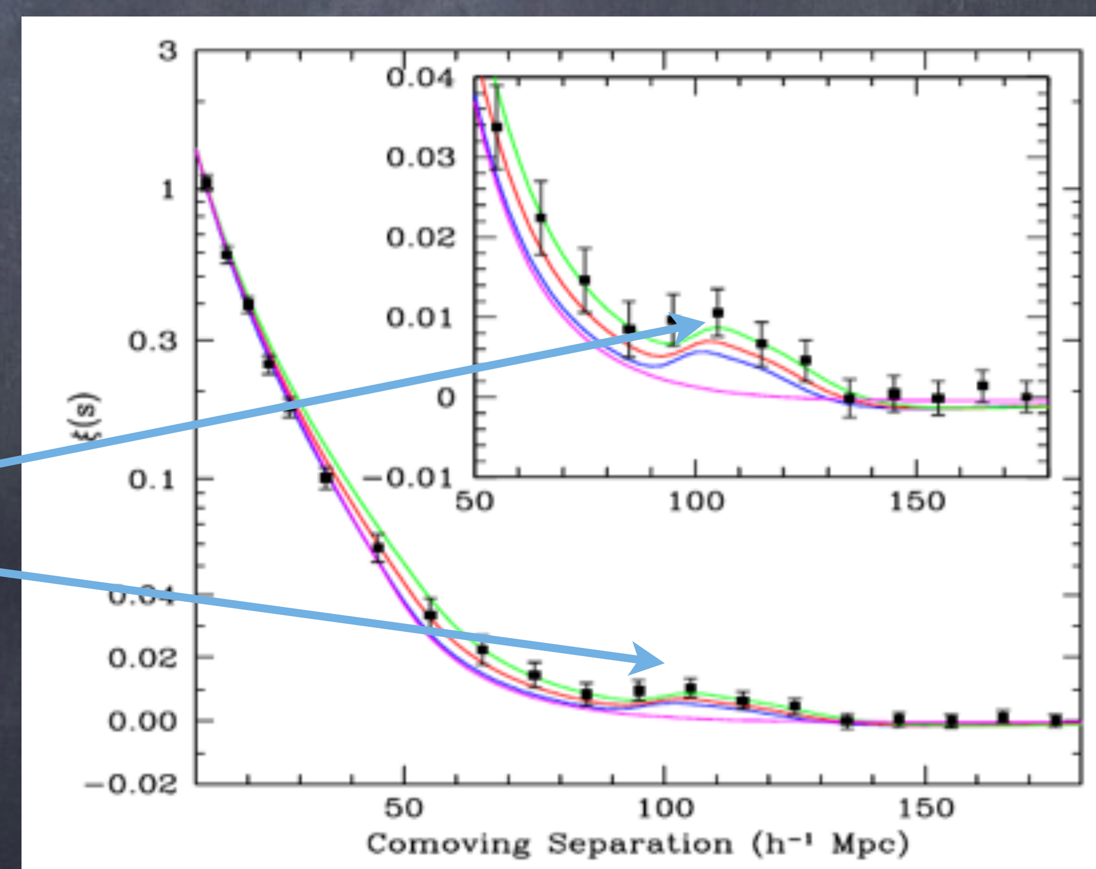
- Which scale in the clustering Correlation Function?

- Comoving baryon acoustic scale
  Baryon acoustic peak - Matter CF

r_d ↕ s_p

- r_d is Geometrical (indep. primordial fluctuation)

Eisenstein et al (2005)

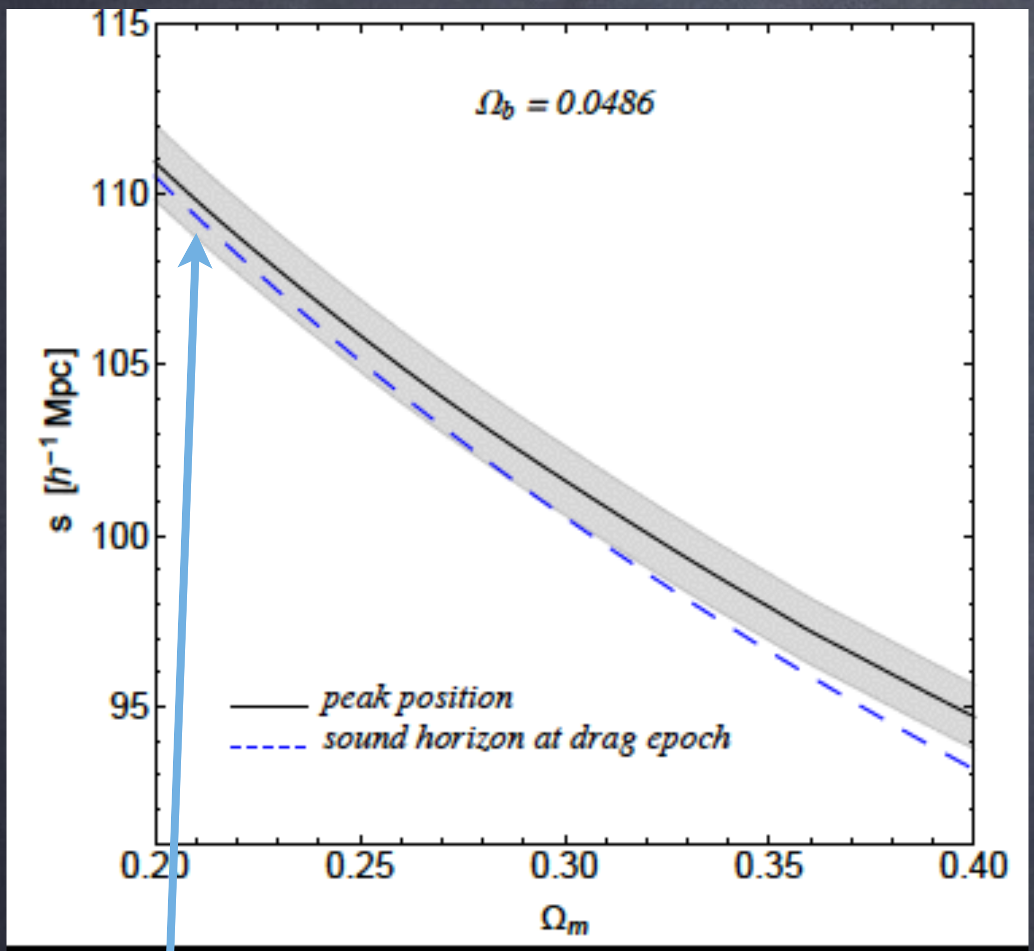


Baryon acoustic peak

Precision cosmology: breaks down!!

Linear

Sanchez et al. (2008)



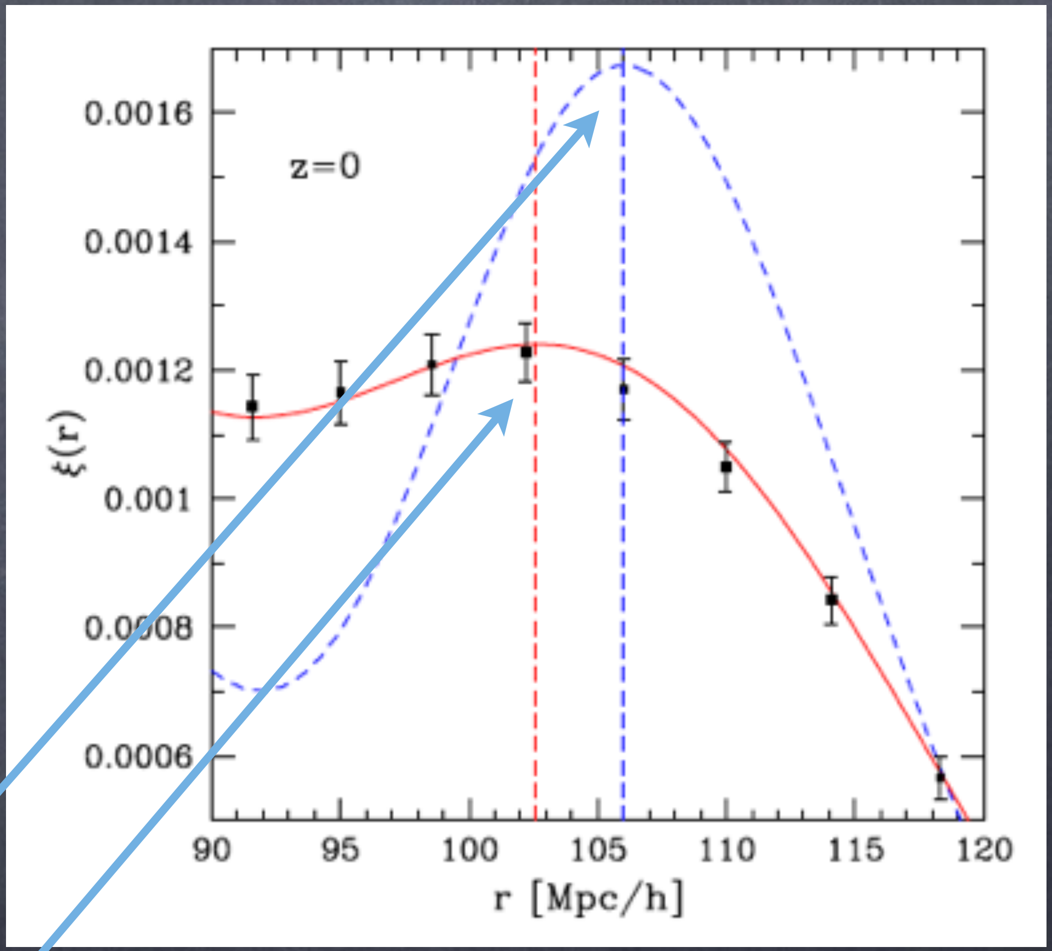
(CAMB code)

1 % region

Non-linear

Smith et al (2008)

Crocce, Scoccimarro (2008)



linear

non-linear

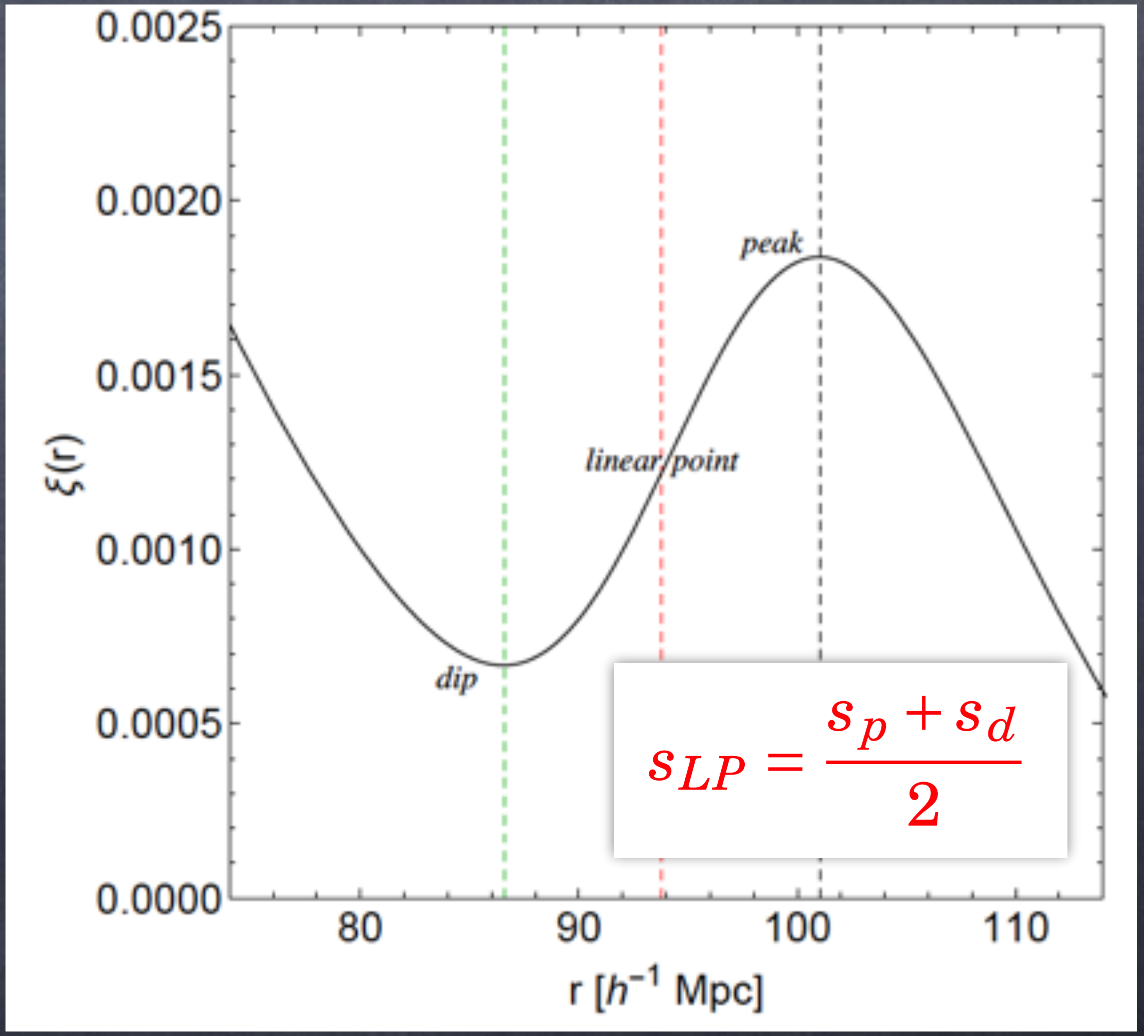
- non-linear gravity
- RSD
- Scale-dep bias

New BAO-CF ruler?

S.A, G. Starkman and R. Sheth - arXiv: 1508.01170

Ingredients needed

1) A geometrical point
2) Redshift independent (linear)
3) Easily identifiable

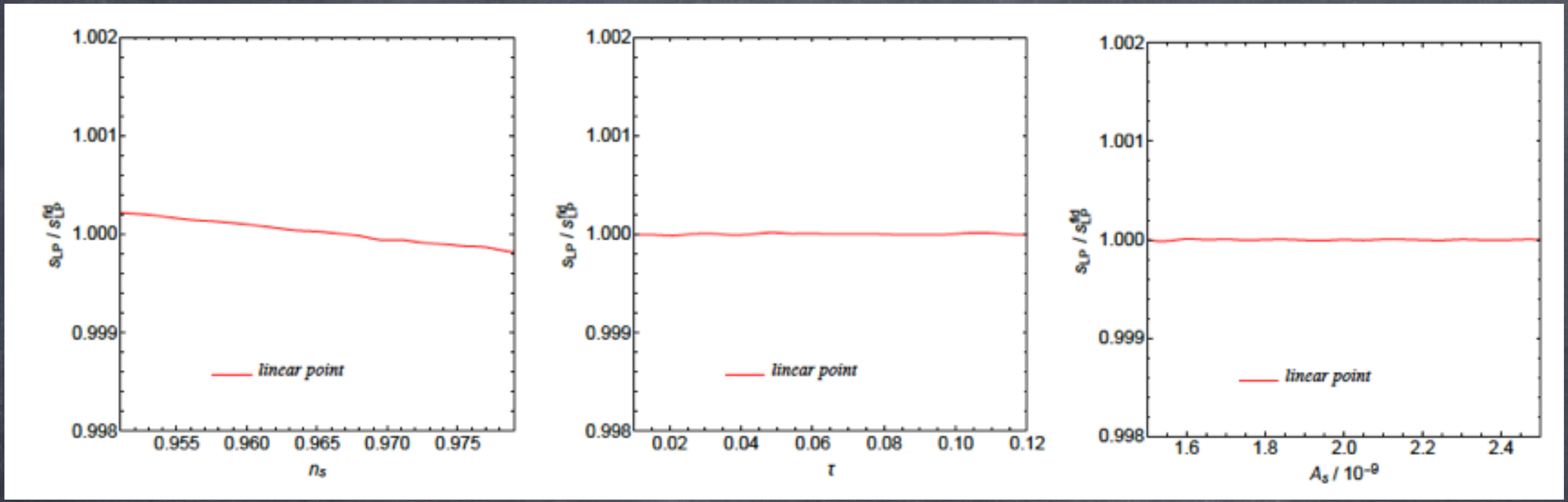


Corr. Func. BAO features

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

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

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

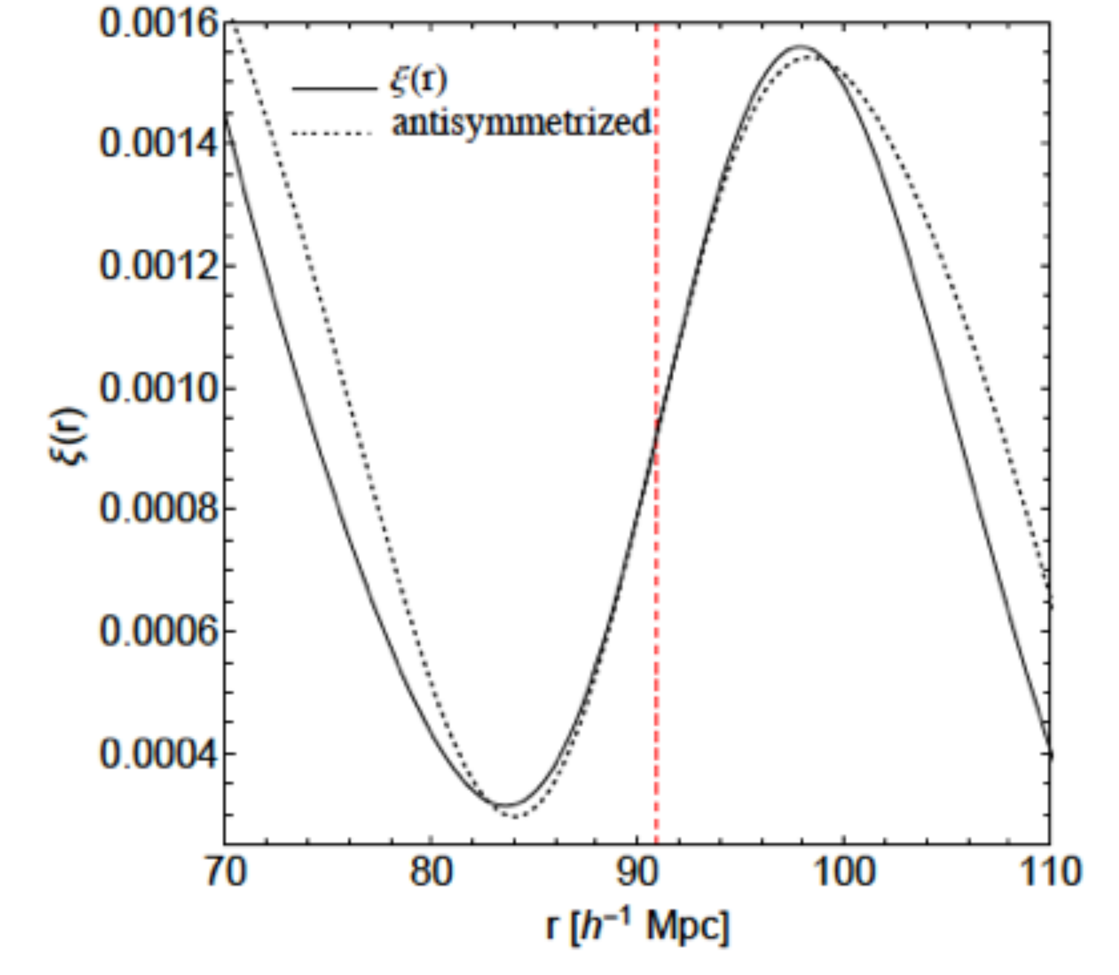
- Antisymmetry MEASURE

  $s_{LP} \sim s_A$ (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-linearities

Non-linear Gravity

Bharadwaj (1996)
Seo, Eisenstein (2007)
Peloso et al. (2015)

- BAO correlation function smoothed

- Dominant: displacements of galaxies from initial positions

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

$\sigma_v^2(z)$ → velocity disp. linear theory

Redshift Space Distortions

- Redshift space
  Bulk motions ⟶ redshift space distortions

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

BAO shift

S.A, G. Starkman and R. Sheth - arXiv: 1508.01170

3D convolutions

- Real space

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

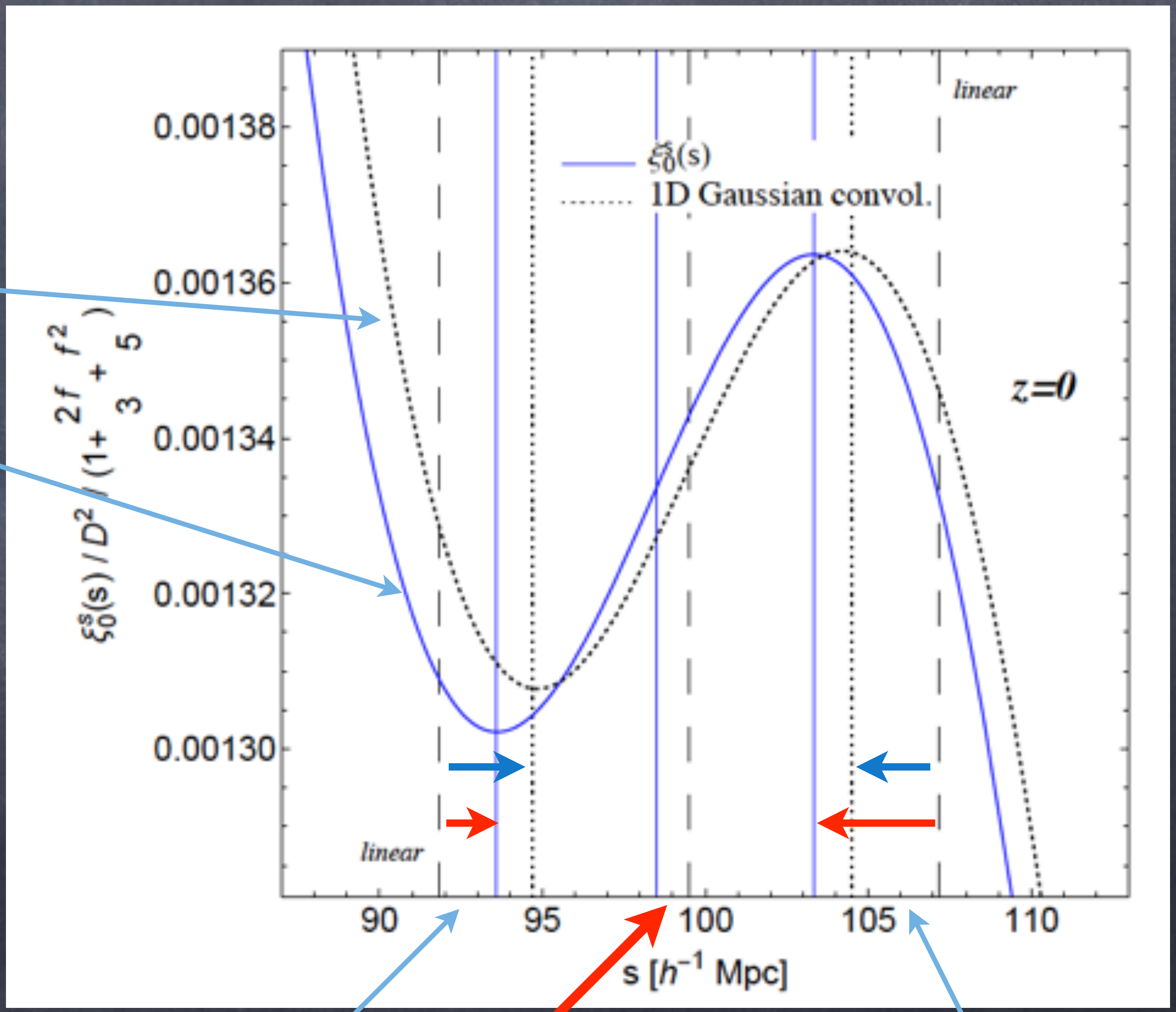
smoothing

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 %

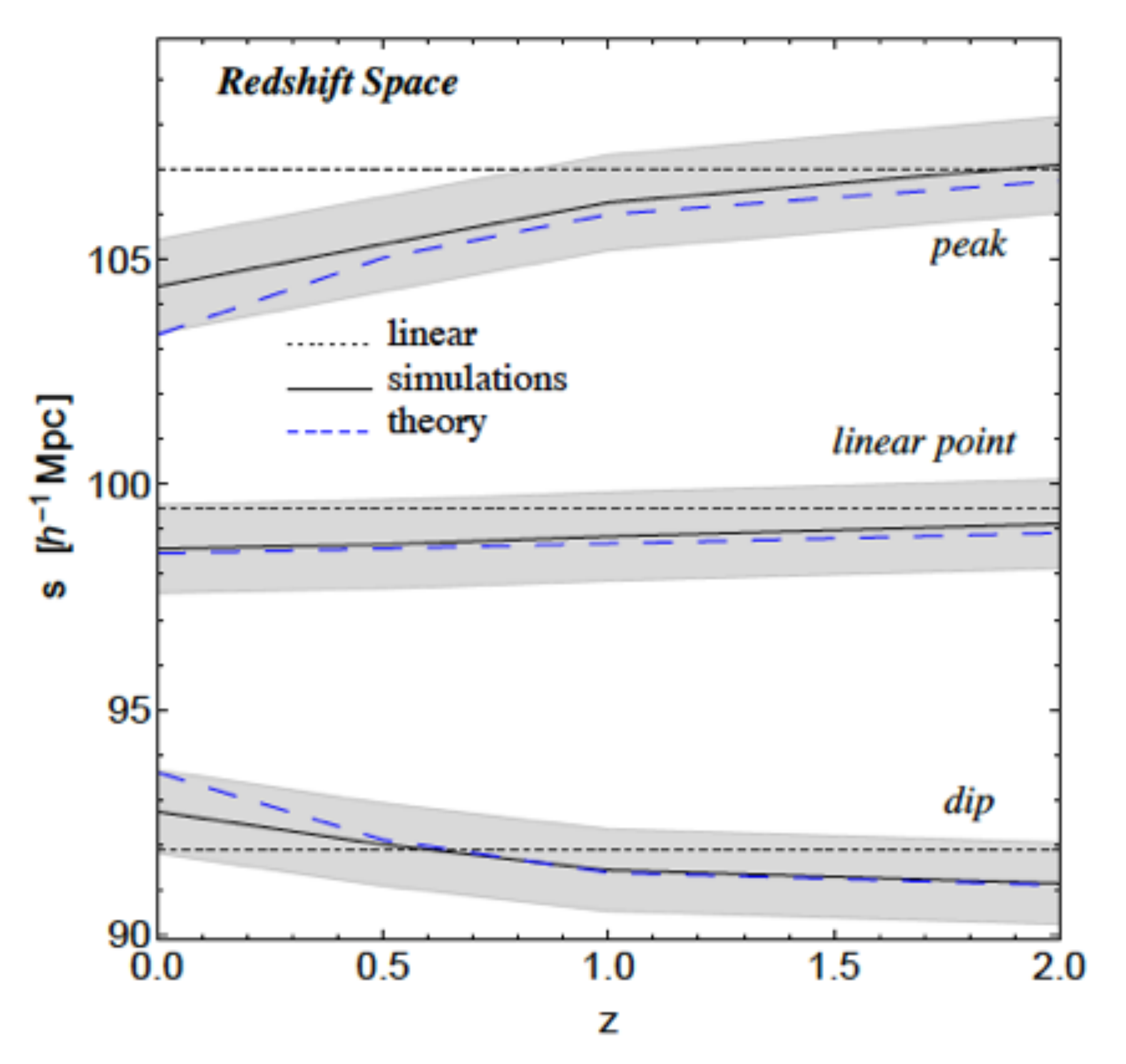
Distance measurements

S.A, G. Starkman and R. Sheth - arXiv: 1508.01170

- 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

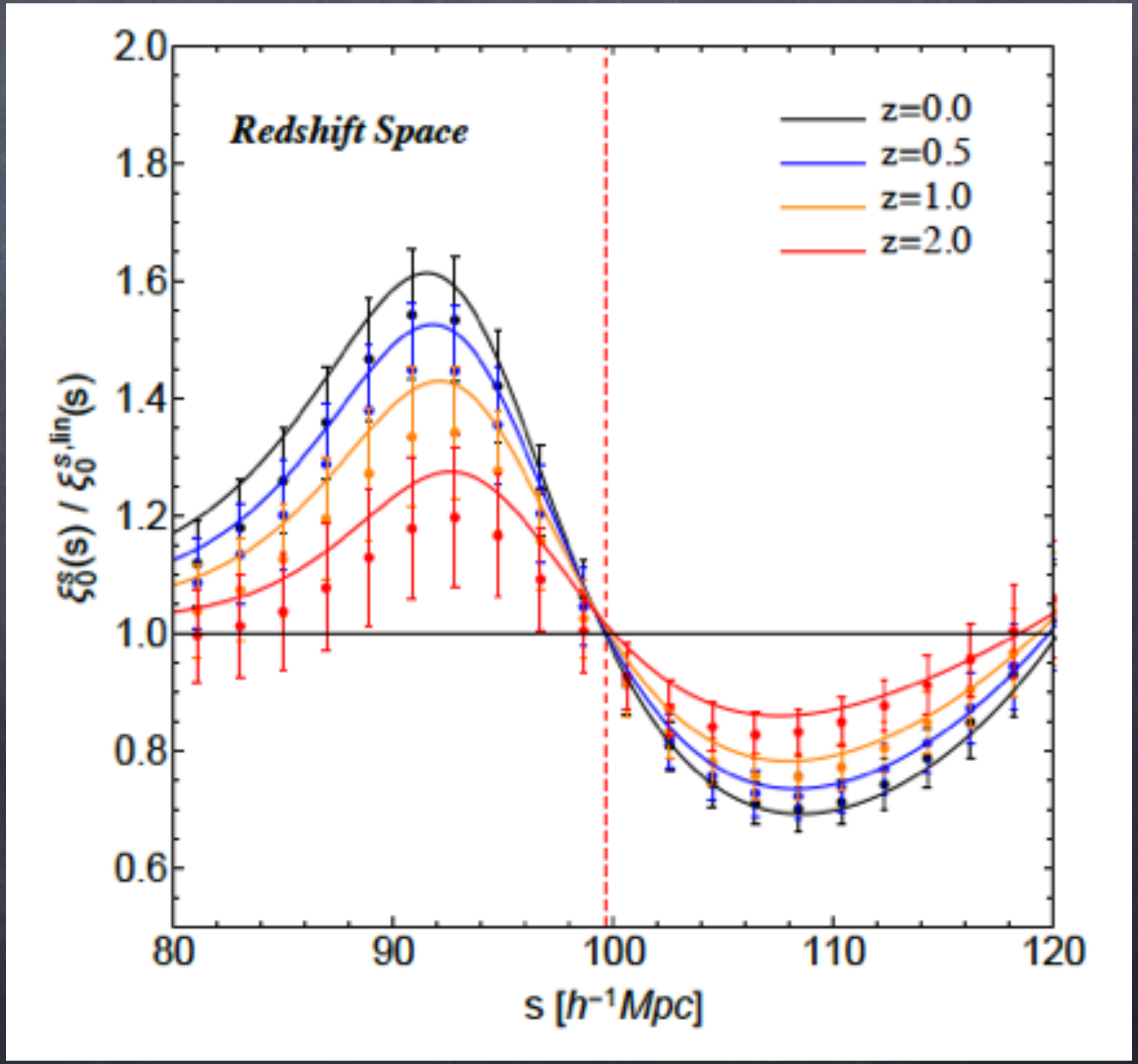
- Three GROWTH estimators

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

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

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



Biased tracers

S.A, G. Starkman and R. Sheth - arXiv: 1508.01170

- Preliminary investigation

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

- Dominant effect of velocities - Neglecting mode coupling

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

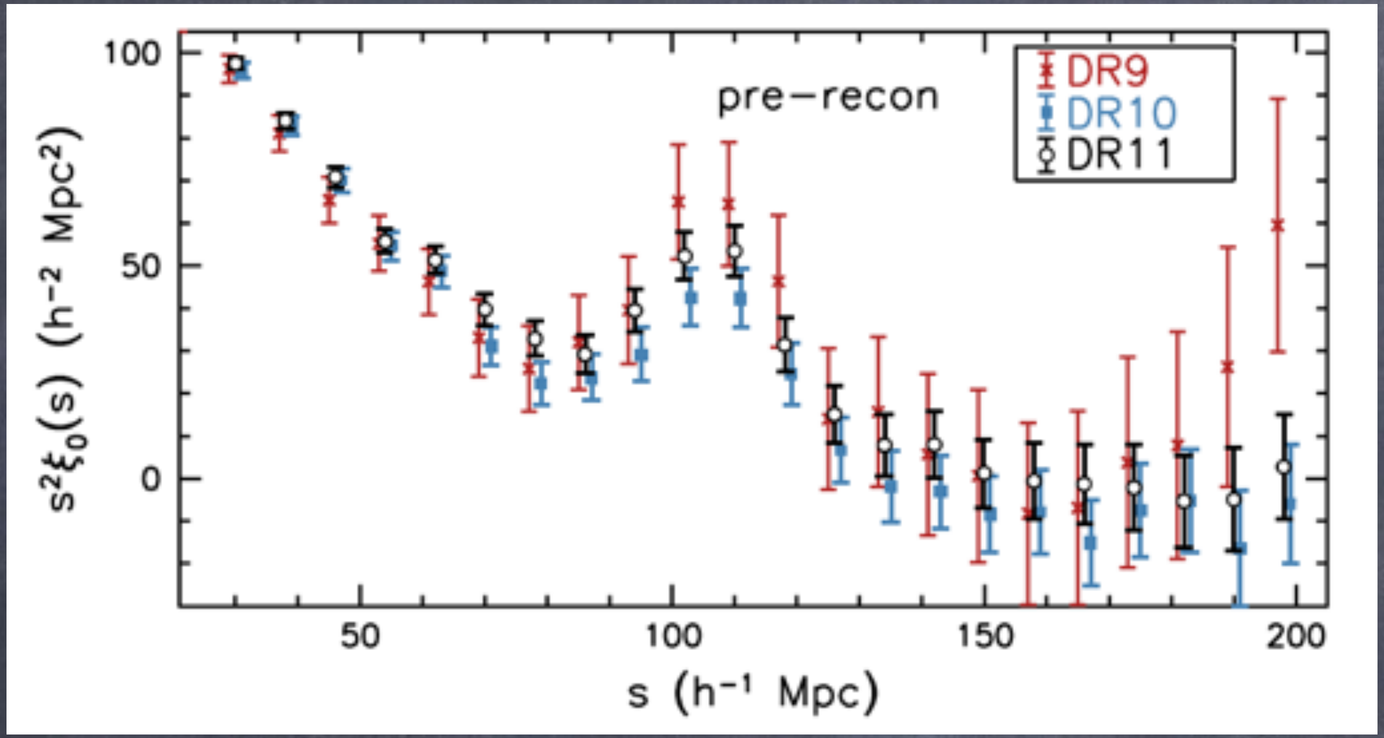
Preserve CF antisymmetry

Linear point position STABLE

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

Preliminary DATA comparison

- Correlation function BOSS data - DR11 (z=0.57)



BOSS, MNRAS (2014)

WORK IN PROGRESS!!

- High-order polynomial interpolation + 0.5 % correction

linear best fit model → $95.1h^{-1}\,\mathrm{Mpc}$

BOSS data → $95.1h^{-1}\,\mathrm{Mpc}$

- May remove the need to whole CF fit.

Sanchez at al. (2009)

Conclusions

- LSS studies are fundamental to constrain cosmology. LSS cosmological standard rulers are a powerful tool.
- The clustering Correlation Function peak is NOT redshift-independent.

Standard ruler

- Peak-dip mid point - Linear Point - is Geometrical and insensitive to nonlinearities to 0.5% (redshift indep.)

Growth

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

Data

- Preliminary data comparison encouraging - disentangle bias and growth - careful investigations to be done!!

THANK YOU!!