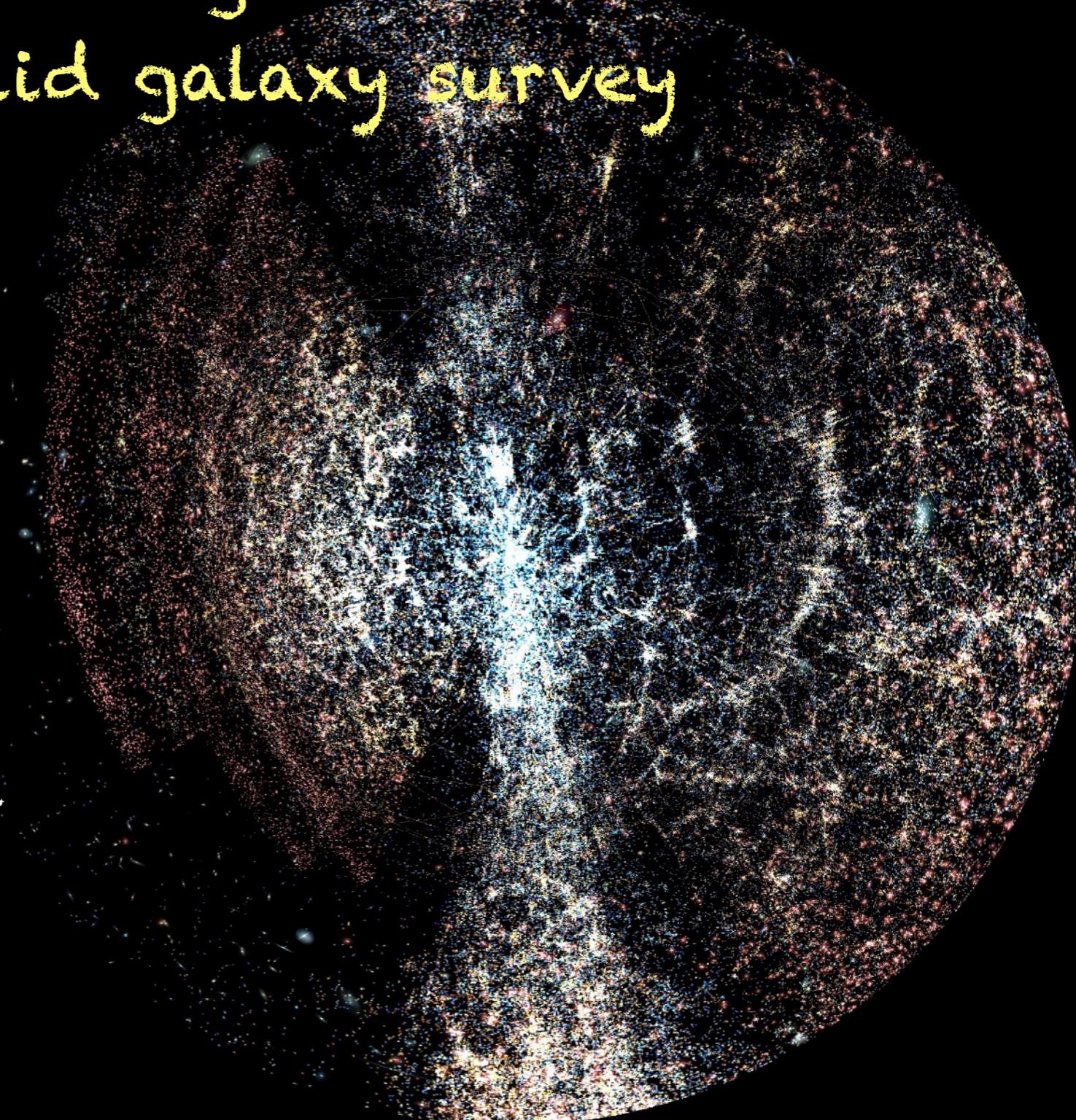


Baryon Acoustic Oscillations: difficulties, assumptions and a new promising cosmological standard ruler for the Euclid galaxy survey

ICHEP 2022

Bologna - July 9, 2022

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Funds

Funded by the MIUR PRIN Bando 2017, Grant No. 2017YJYZAH

Baryon Acoustic Oscillations (BAO)

from Baryon Acoustic Oscillations?

- Cosmology-Indep. Accurate distance measurements

GOALS

- Constrain cosmological models (at the DE time)
- Consistency tests (e.g. tensions)

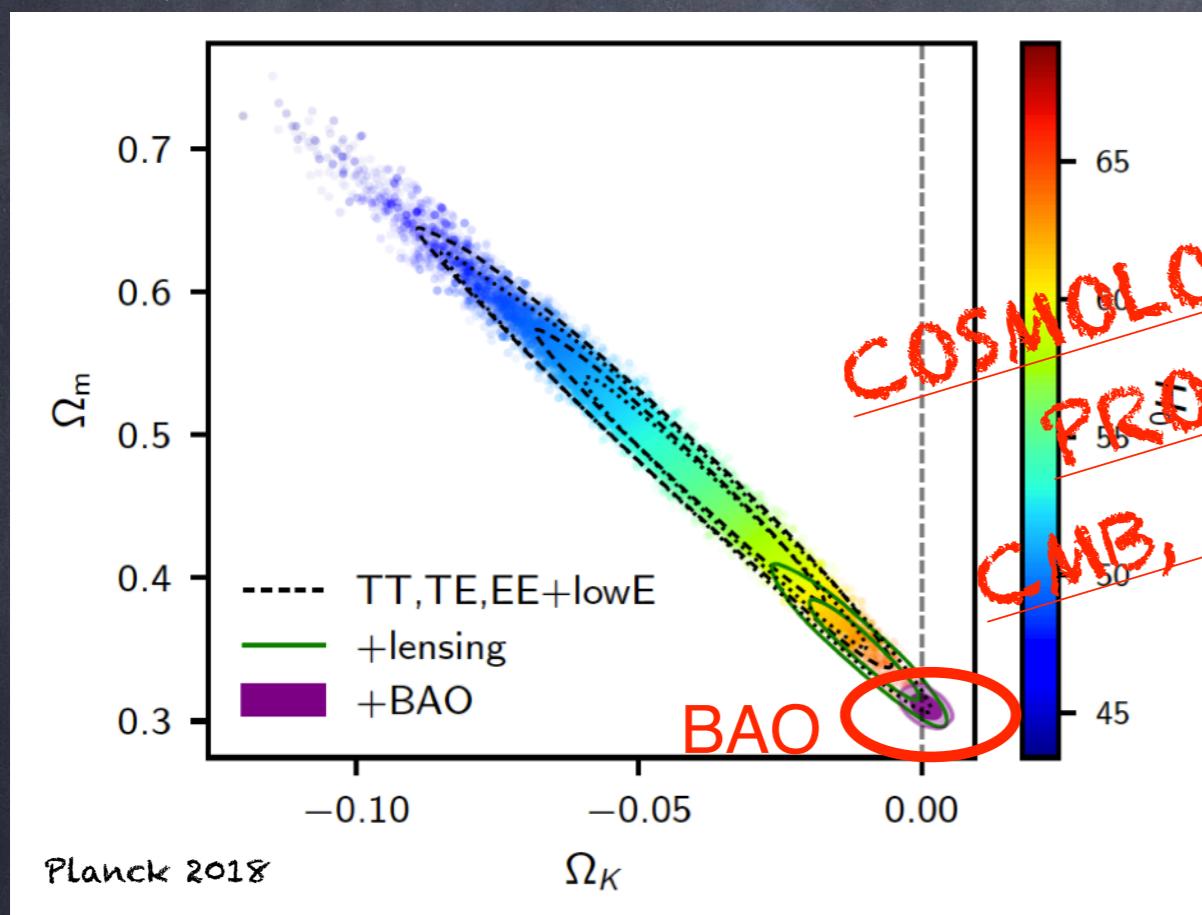
HOW

- BAO distances combined w/ other Cosmological observations.
 - Degeneracy among parameters are reduced.
- BAO distances alone (e.g. Dark Energy detection)

Late Universe Acceleration \leftrightarrow Dark Energy

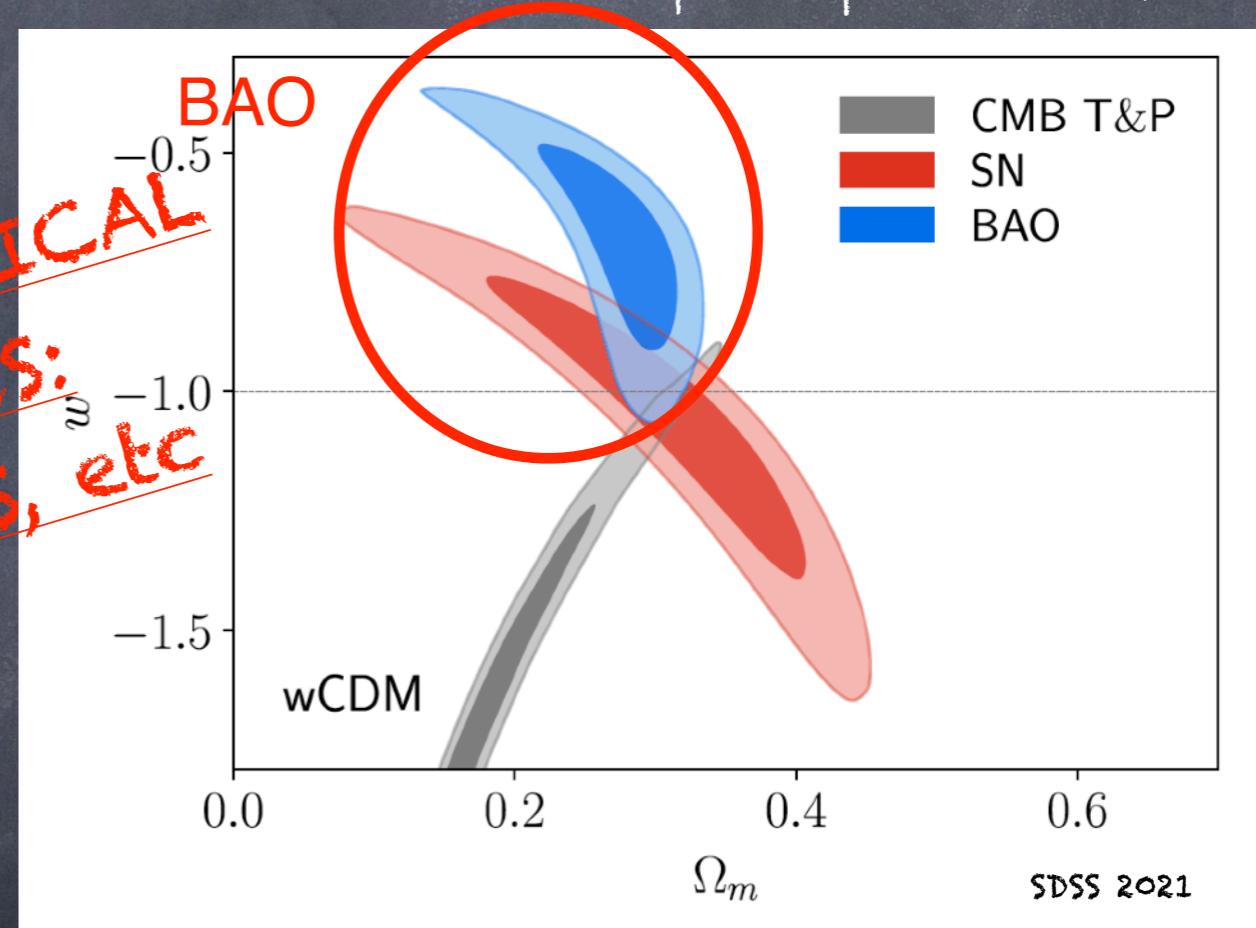
PROBE COMBINATION

energy densities



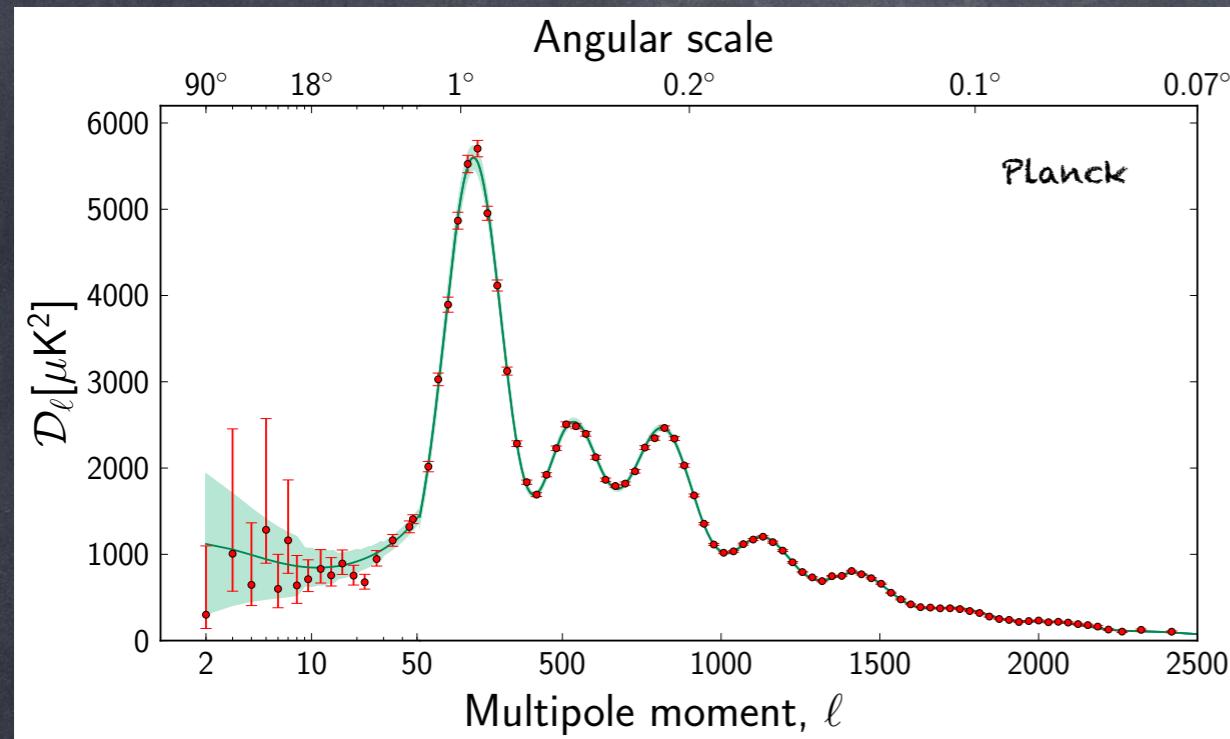
DIFFERENT PROBES

eq. state param. $P = \rho w$



BUT... let's take a step back...

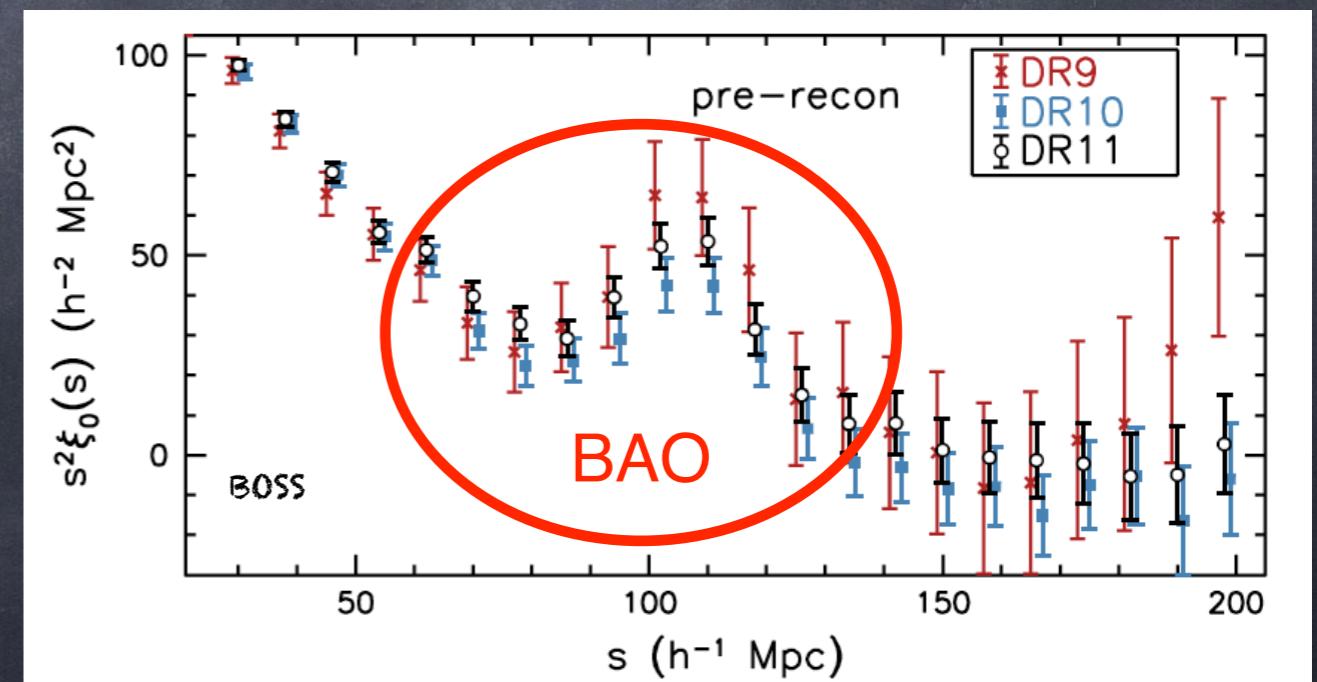
Early times...



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

Baryon acoustic oscillations in
the galaxy Correlation
Function

...Late times



Which scale?

- Which scale in the clustering Correlation Function?

- Comoving baryon acoustic scale
Baryon acoustic peak - Matter CF

- r_d is Geometrical (indep. primordial fluctuation)

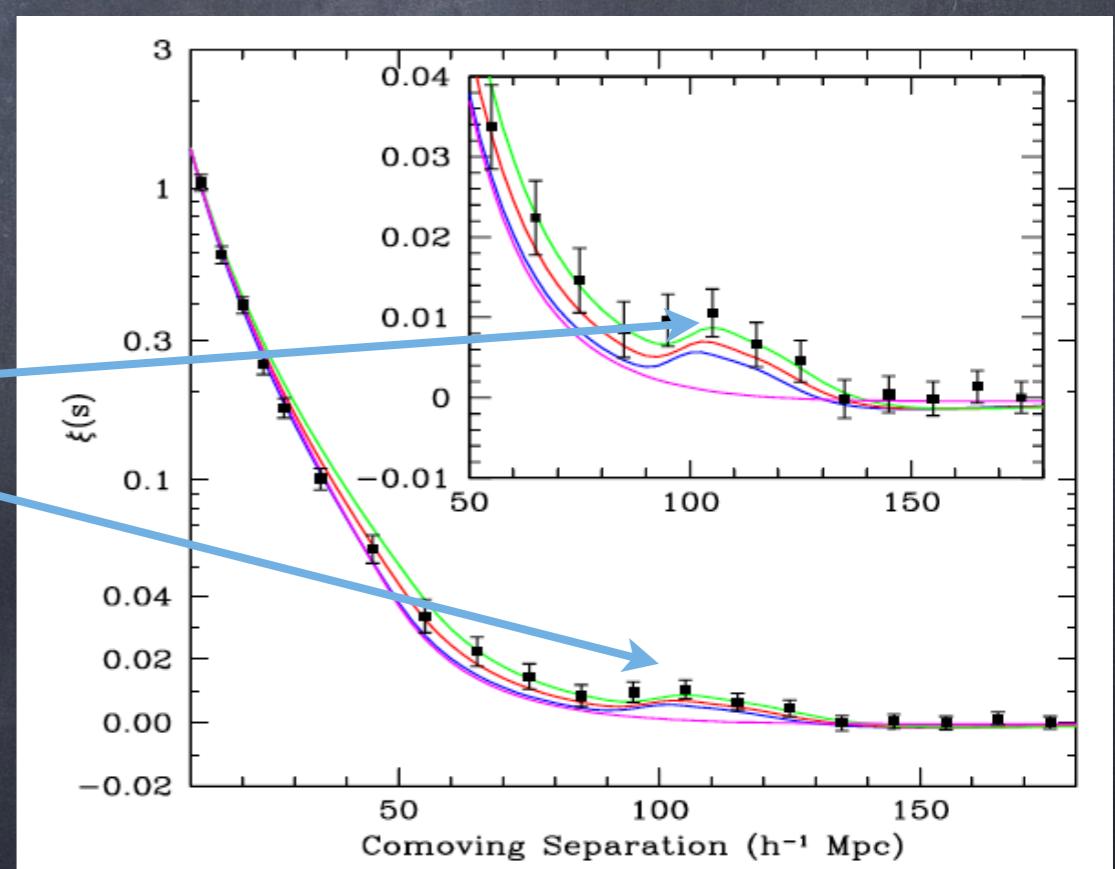


$$r_d$$

$$\uparrow$$

$$s_p$$

Eisenstein et al (2005)



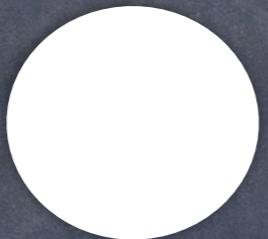
BAO distance \rightarrow Dark Energy

Xu et al. (2012)

- Comoving coordinates \rightarrow fiducial cosmology assumed.

Alcock-Paczynski distortion effect

Right Cosmology



Wrong Cosmology



- Clustering 2pcf monopole at redshift z

Distorted True

small
correction

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

Isotropic shift

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

BAO DISTANCE

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

How cosmology indep?

S.A, Corasaniti, Sanchez, Starkman, Sheth, Zehavi - PRD (2019)

PRACTICE

- ④ BAO distances employed to constrain ANY cosm. model

IMPLICIT ASSUMPTION

- ④ BAO: Cosmology-Indep. Accurate distance measurements
(Inference done without cosmolog. model assumptions)

QUESTION

- ④ At what level is this true ?
We will try to answer to this question!

Cosmological Distance: D_V

FROM Distorted True small
 $\xi_0^D(s^F) = \xi_0^T(\alpha s^F) + O(\epsilon)$ correction

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

MEASURED
in a background-independent way

- But we need a 2pcf model

$$\xi_0^D(s^F) = \xi_0^{\text{model}}(\alpha s^F) + O(\epsilon)$$

DATA

THEORY

IT SHOULD NOT INTRODUCE
UNWANTED DEPENDENCIES

2pcf non-linearities

- Non-Linear gravity
- Redshift Space Distortions (velocities)
- Bias (halos, galaxies)

Smith et al (2008)

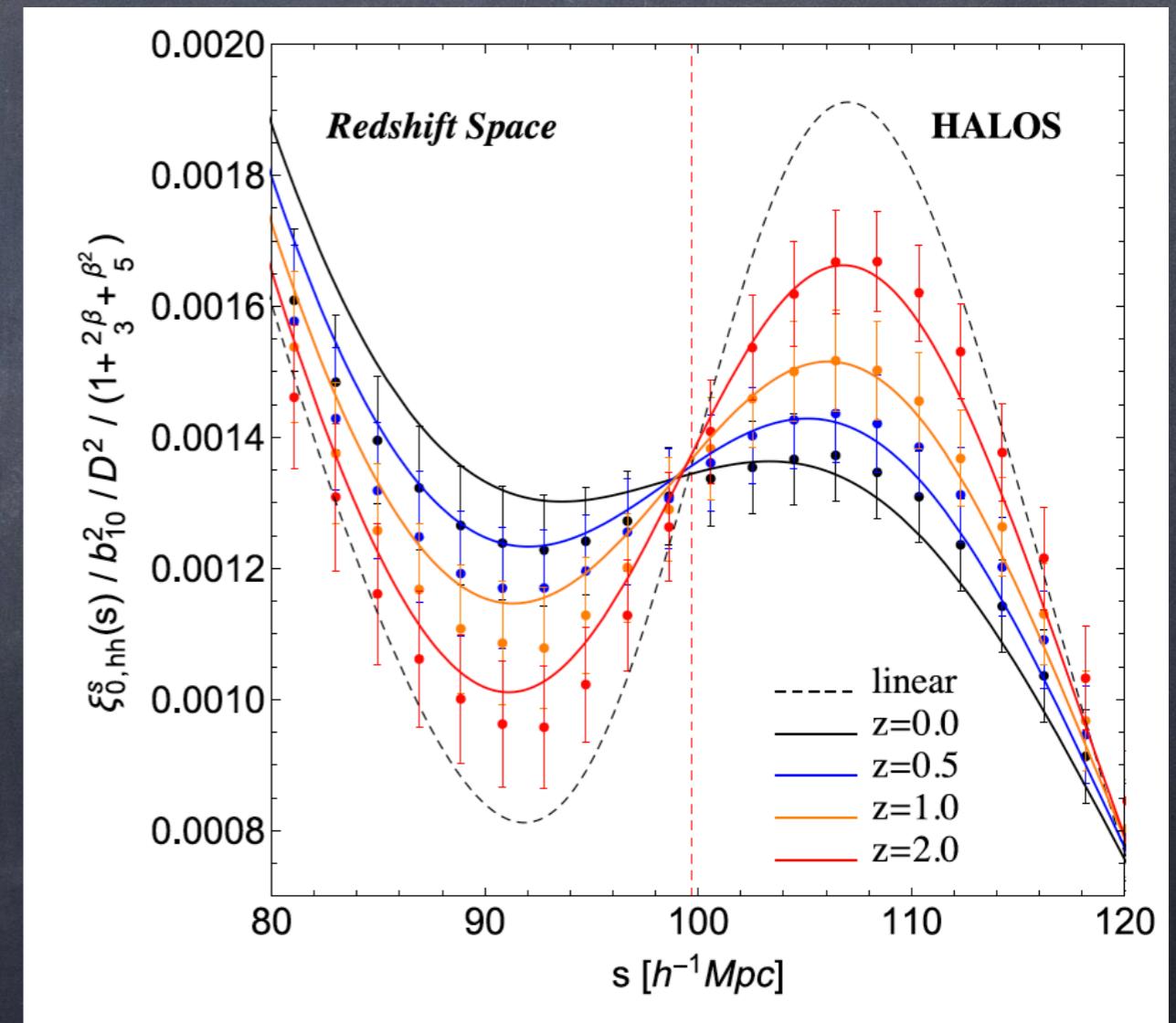
Crocce, Scoccimarro (2008)

Desjacques (2008)

S.A, Starkman, Sheth - MNRAS (2016)

2pcf in BAO range of scales

Relevant effects!



2pcf model-fitting

S.A, Corasaniti, Sanchez, Starkman, Sheth, Zehavi - PRD (2019)

- 2pcf Alcock-Paczynski equation:

$$\xi_0^D(s^F) = \xi_0^{\text{model}}(\alpha s^F) + O(\epsilon)$$

DATA THEORY

```
graph TD; D((xi_0^D(s^F))) --> DATA[DATA]; M((xi_0^model(alpha * s^F))) --> THEORY[THEORY]; M --> THEORY;
```

- Marginalize over parameters:

- DE dependent
- spatial curvature dep.
- initial fluctuation param.
- tracer dependent (e.g. galaxies)

BAO distances

S.A, Corasaniti, Sanchez, Starkman, Sheth, Zehavi - PRD (2019)

We obtained Cosmological Distances that are:

- 1) Geometrical (indep. primordial fluctuation parameters)
- 2) Dark-Energy model-independent (Λ CDM + Quintessence)
- 3) Spatial curvature-independent
- 4) Tracer-independent (galaxy, quasars, clusters etc...)

Purely-Geometric-BAO

Excluded ?

Modified gravity cosmologies ? DE-DM coupling ?

standard BAO (BAO-only)

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

- Template fitting:

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

FIXED parameters

$$\theta_{\mu}^{\text{fixed}} = \{\omega_b^F, \omega_c^F, n_s^F, \sigma_0^F\}$$

$$\xi^{\text{BB}}(s^F) = \frac{a_1}{(s^F)^2} + \frac{a_2}{s^F} + a_3$$

5 varied parameters

$$\theta_{\mu} = \{\alpha, B, a_1, a_2, a_3\}$$

marginalized

Cosmological information

- Because of cosm. param. fixing

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

prescription

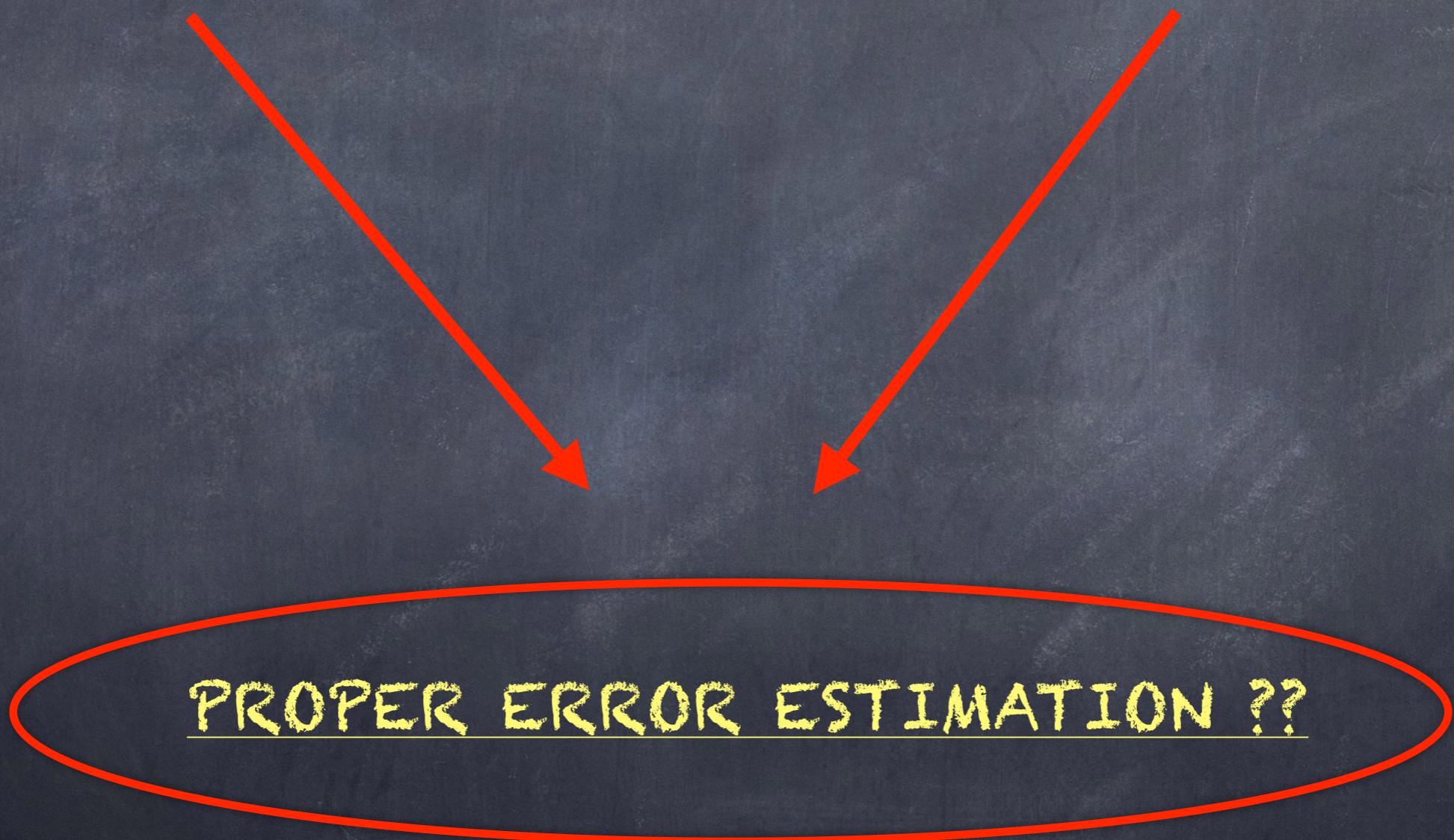
ARE ERRORS ON α PROPERLY ESTIMATED?

Problems

S.A, Corasaniti, Sanchez, Starkman, Sheth, Zehavi - PRD (2019)

1) parameter fixing

2) which 2pcf model?



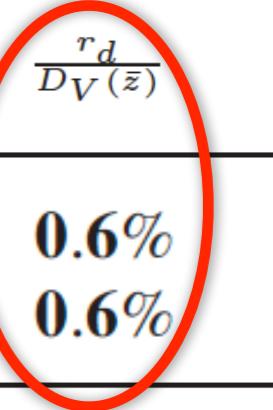
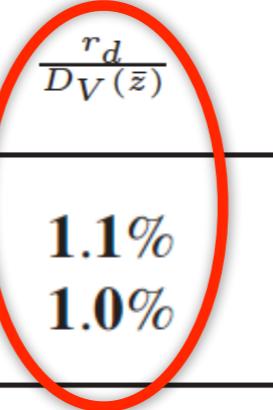
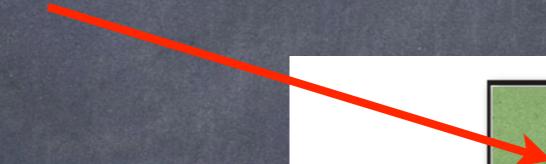
problem 1: parameter fixing

S.A, Corasaniti, Sanchez, Starkman, Sheth, Zehavi - PRD (2019)

All dependencies fitted

- Marginalizing over
DE + curvature + tracer
- No fixing parameters

Errors underestimated
by nearly a factor of 2!!



\bar{z}	CF-MF	standard-BAO
	$\frac{r_d}{D_V(\bar{z})}$	$\frac{r_d}{D_V(\bar{z})}$
1.1	1.1%	0.6%
1.3	1.0%	0.6%

Euclid forecasts

... but problem 2:

which galaxy-2pcf theoretical model?

problem 2: complementary approach

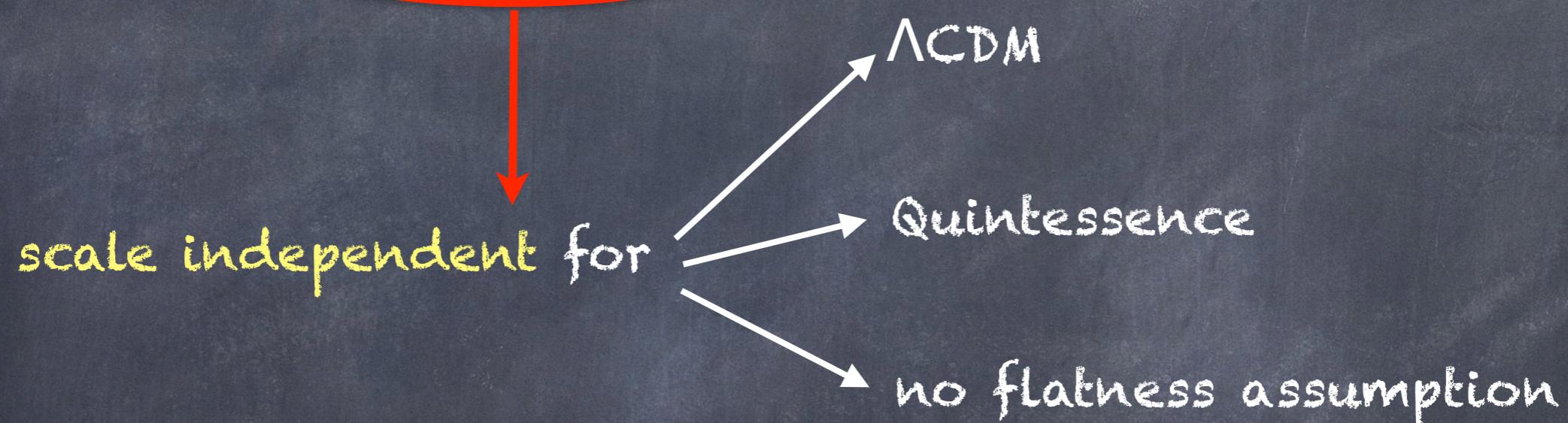
Linear approx.

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

Shanks et al. (1987)

Eisenstein et al (1998)

Bassett, Hlozek (2009)



- ② A PREFERRED SCALE in the 2pcf \rightarrow Time/Model indep.
→ Can measure D_V in model-indep. way!!

New Standard Ruler: the Linear Point

S.A. Starkman, Sheth - MNRAS (2016)

④ LINEAR POINT

- LP = peak-dip middle point
- Linear at 0.5% \rightarrow red. indep.
- Geometrical

④ NO 2pcf MODEL NEEDED

DATA

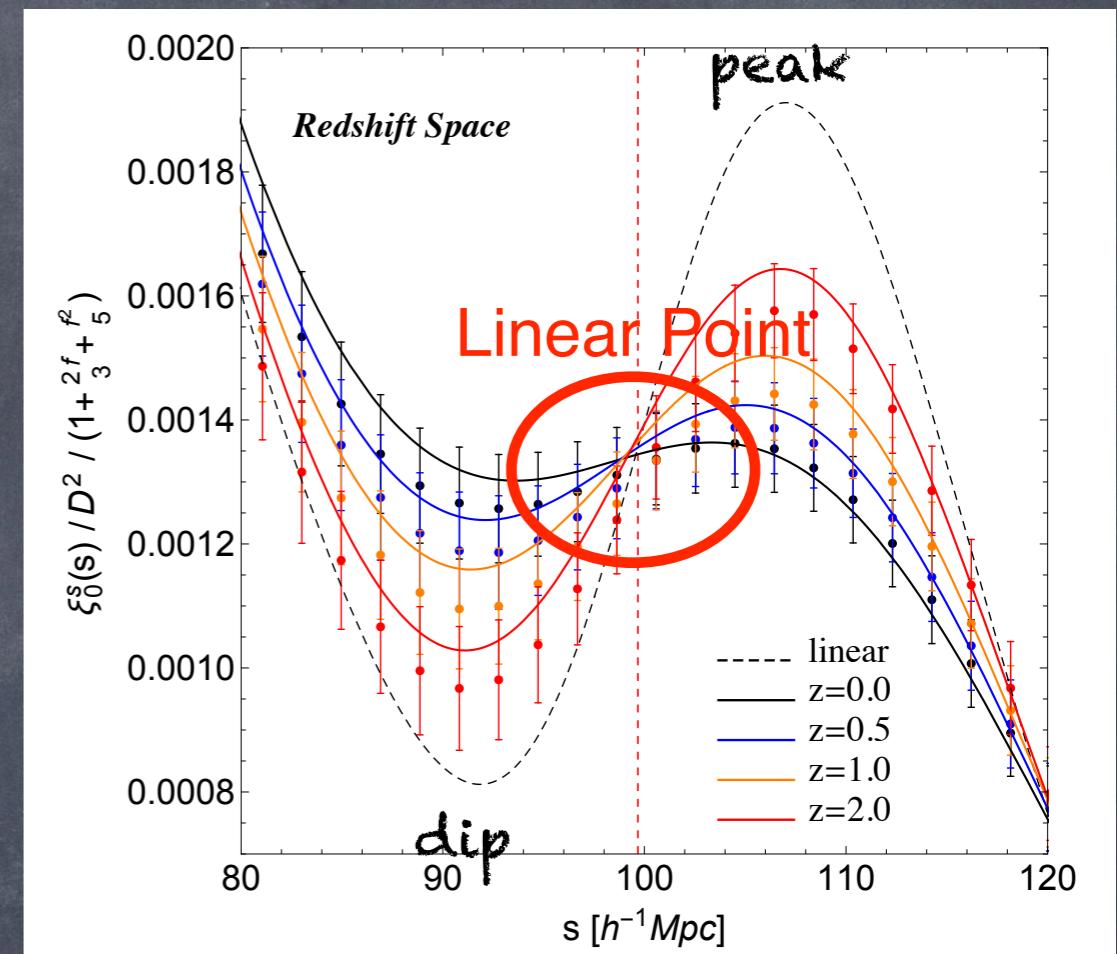
$$\xi_0^D \left(y_{LP}^{\text{gal}}(z) \right)$$

model-independent
parametric fit

LINEAR THEORY

$$= \xi_0^{\text{lin}} \left(\frac{SLP(\omega_b, \omega_c)}{D_V^T(z)} \right) + O(\epsilon)$$

CAMB code



④ DISTANCES MEASURED from SDSS galaxy data!!

What do we learn about Dark Energy ?

S.A., Starkman, Renzi - arXiv (2022)

AIM

- ④ Test cosmological model(s) with galaxy-clustering
- ④ Data vs Theory → Testing cosmological model(s) assumptions
- ④ Cosm. model → Unique galaxy 2pcf

2pcf MODEL

- ④ Galaxy clustering models: add extra assumptions
- ④ Data vs Theory → Testing cosmological model(s) + galaxy clustering model assumptions → Learning about Dark Energy?

LINEAR POINT

- ④ Attempt to reduce the non-cosmological assumptions
- ④ Data driven approach

Use BAO as a Dark Energy probe

- Cosm. applicability of standard BAO distances: UNCLEAR!
- Purely-Geometric-BAO: Cosmic Distance Measurements
Independent of (some) cosmological background models

Operatively



2pcf Model-Fitting – errors propagated
Standard BAO: error underest. by factor of 2.

Which model? Parameters? Range of scales?

Linear Point Standard Ruler

Model independent: 2pcf model not needed

... a lot to do...

Euclid Implementation (on-going); Quadrupole 2pcf? Different
galaxy populations? Combine with other observations; ...

THANK YOU!!