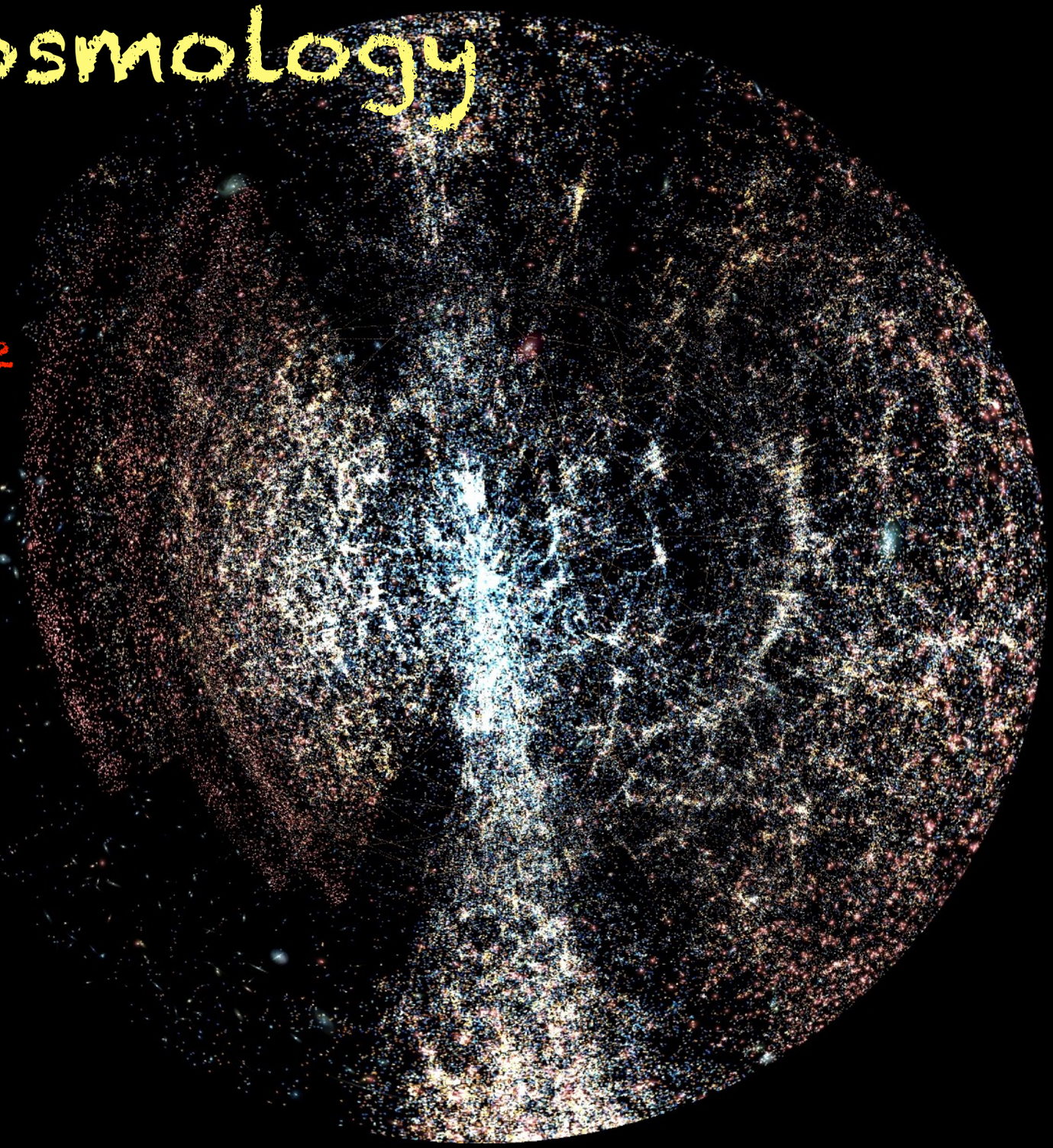
The challenges of using Baryon Acoustic Oscillations distances for cosmology



Standard cosmology at the threshold of change?

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June 3, 2024

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Outline

from Baryon Acoustic Oscillations?

- Late time Cosmology Independent accurate distance measurements

relevant Challenges...

... their implications

New Proposals

GOALS of BAO distances

- Constrain cosmological models
- Consistency tests (e.g. tensions)

HOW

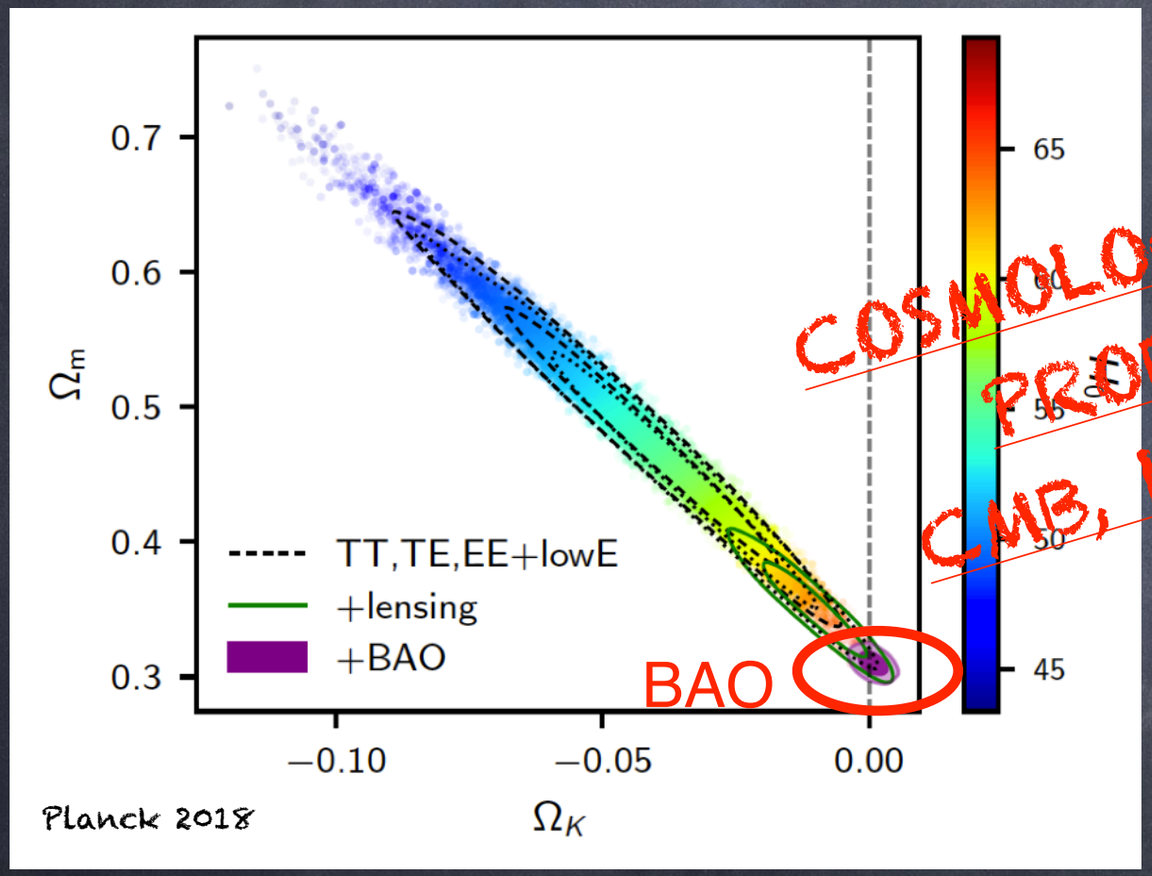
- BAO distances combined w/ other Cosmological observations.
  - Degeneracy among parameters are reduced.

- BAO distances alone (e.g. Dark Energy detection)

Late Universe Acceleration

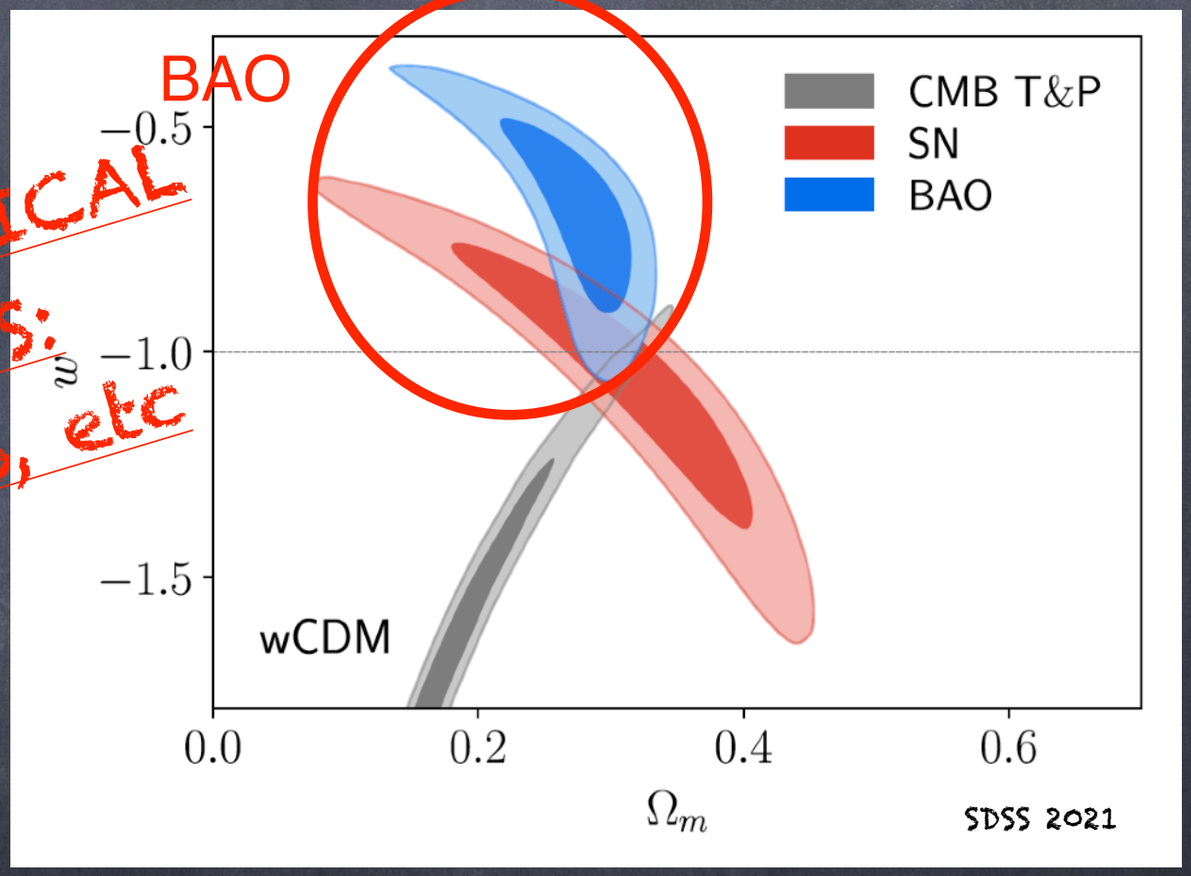
Probe Combination

energy densities



Different Probes

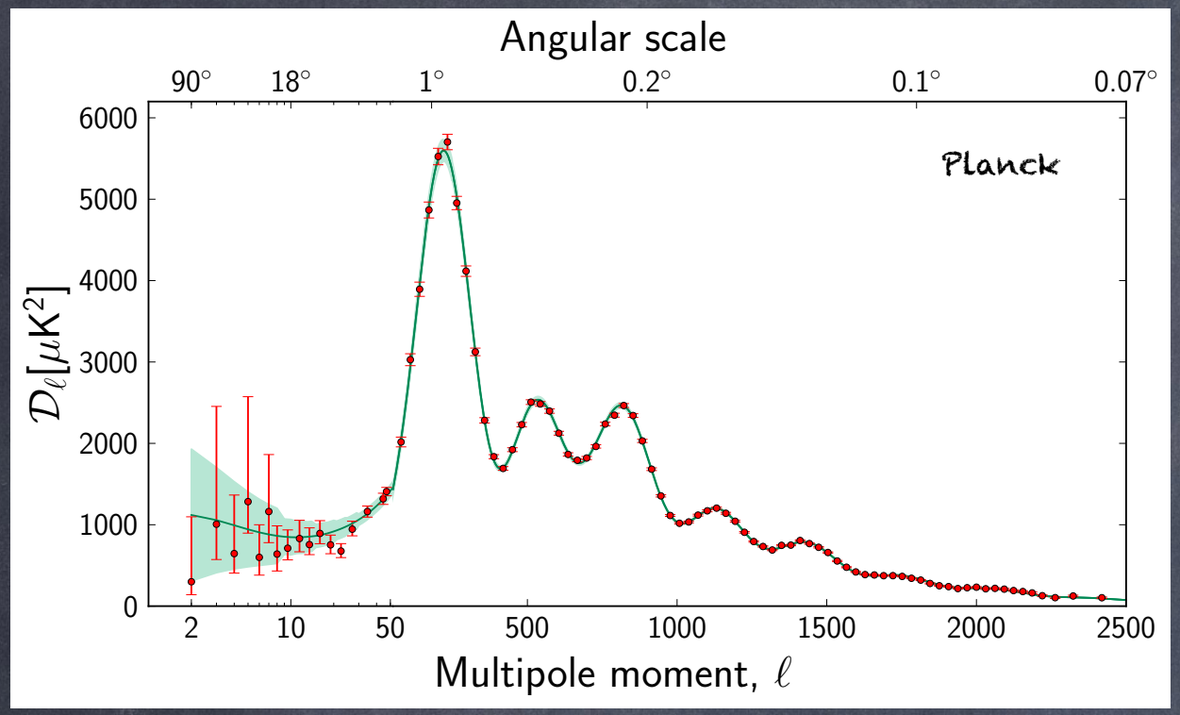
eq. state param. $P = \rho w$



COSMOLOGICAL PROBES: CMB, LSS, etc

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

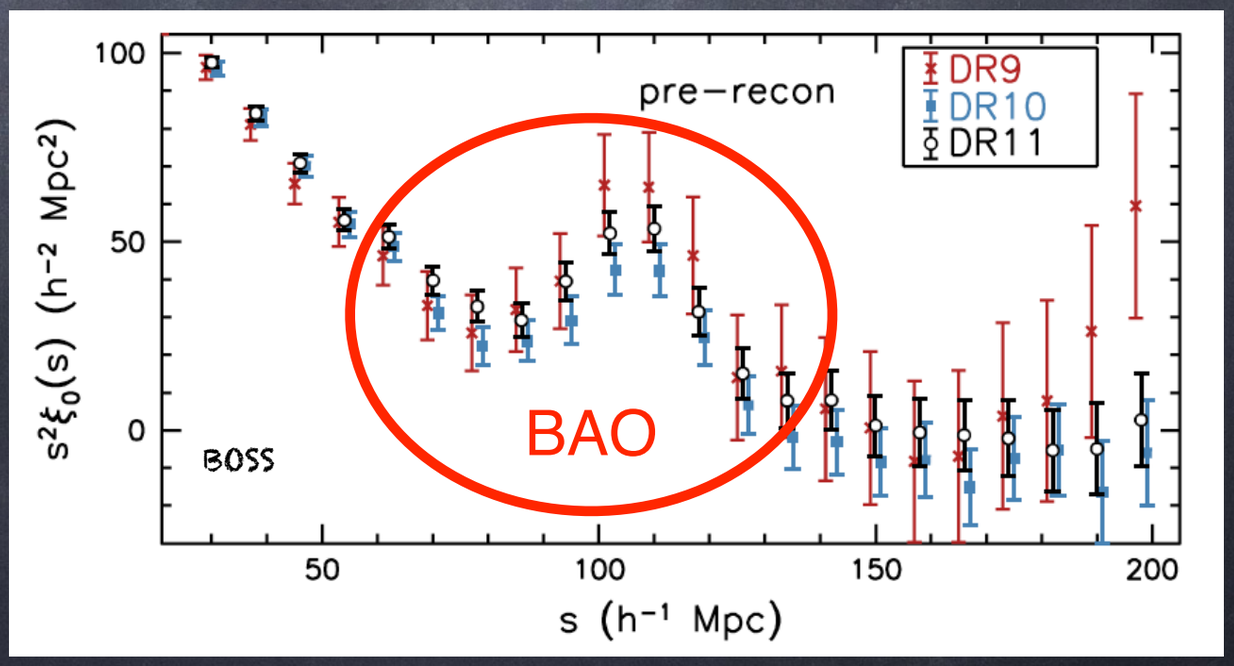
Early times...



Initial fluctuations

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

...late times



Baryon acoustic oscillations in the galaxy Correlation Function

Which scale?

- Which scale in the clustering Correlation Function?

- Comoving baryon acoustic scale
  Baryon acoustic peak - Matter CF

r_d

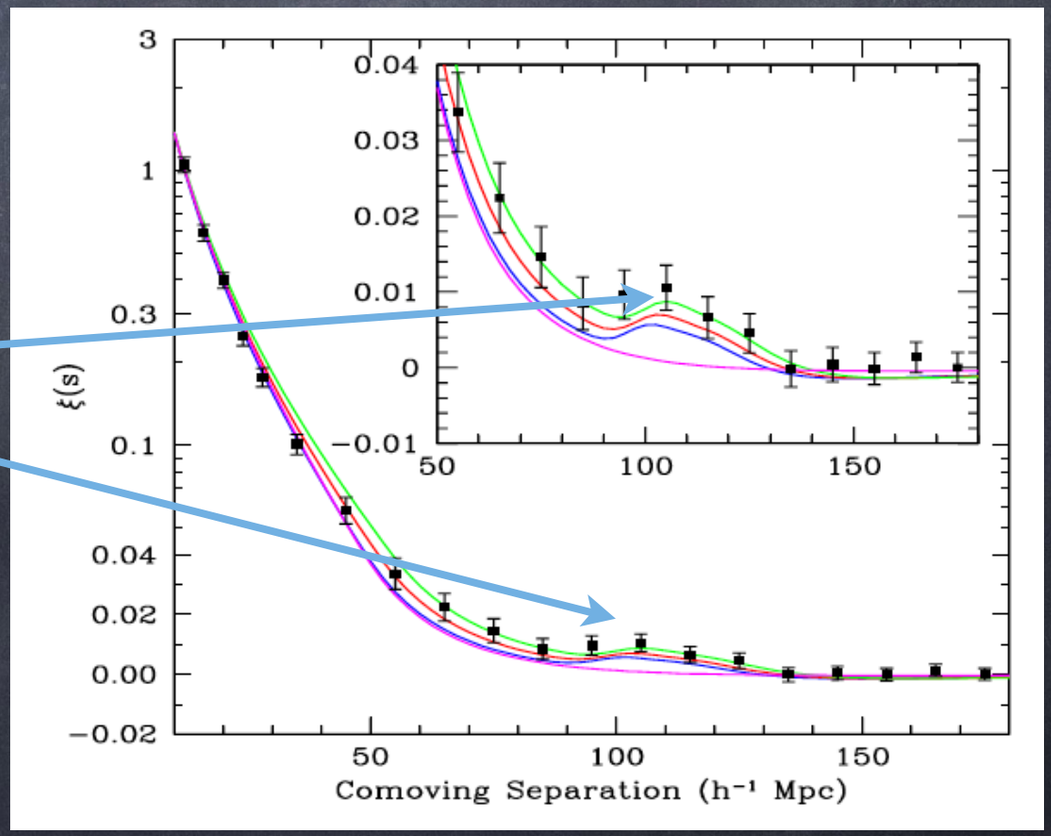
s_p

- rd is Geometrical (indep. primordial fluctuation)

Baryon acoustic peak POSITION!!

STANDARD RULER

Eisenstein et al (2005)



Cosmological standard ruler

Shanks et al. (1987)

Eisenstein et al (1998)

Bassett, Hlozek (2009)

- Object of known size constant in redshift.

Large Scale Structure

Statistical standard ruler

Clustering of galaxies ⟶ PREFERRED SCALE
(constant in redshift)

↓

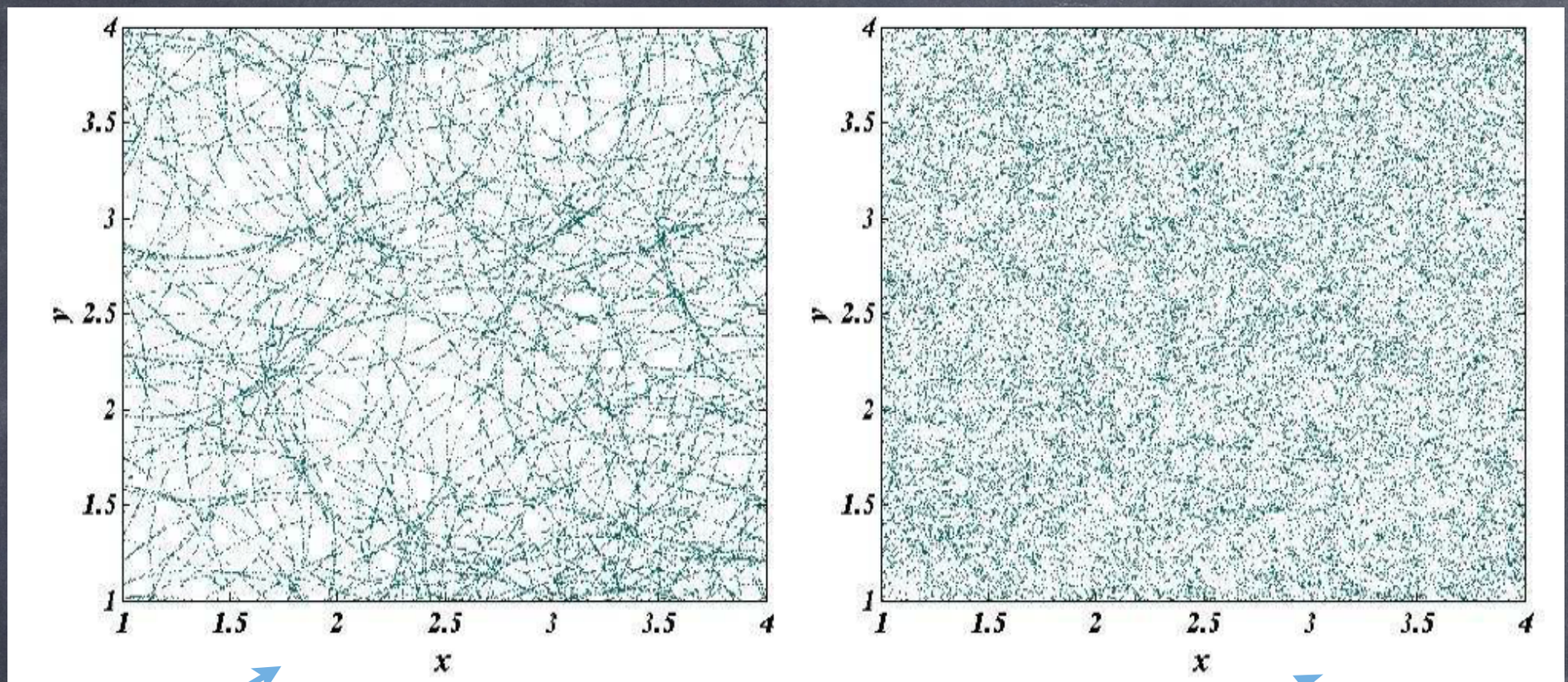
Observed at different redshifts

↓

Constrain the angular diameter distance.

Cosmological parameters

Bassett, Hlozek (2009)



intuitive picture

realistic picture

Angular Diam. Distance

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

actual size

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

cosm. parameters

Are BAO a background probe ?

BAO distances

Considered and used as late time background measurements

However, the galaxy 2pcf depends on

primordial fluctuations + background + late time non-lin +

+ non-standard cosmologies, ...

old idea ?

peak scale <-> sound-horizon

HOWEVER -> precision cosmology

~~peak <-> sound-horizon~~ !!

BAO distance

Xu et al. (2012)

- Comoving coordinates -> 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

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

Cosmological Distance: Dv

Distorted True small correction

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

Isotropic shift

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

MEASURED in a background-independent way

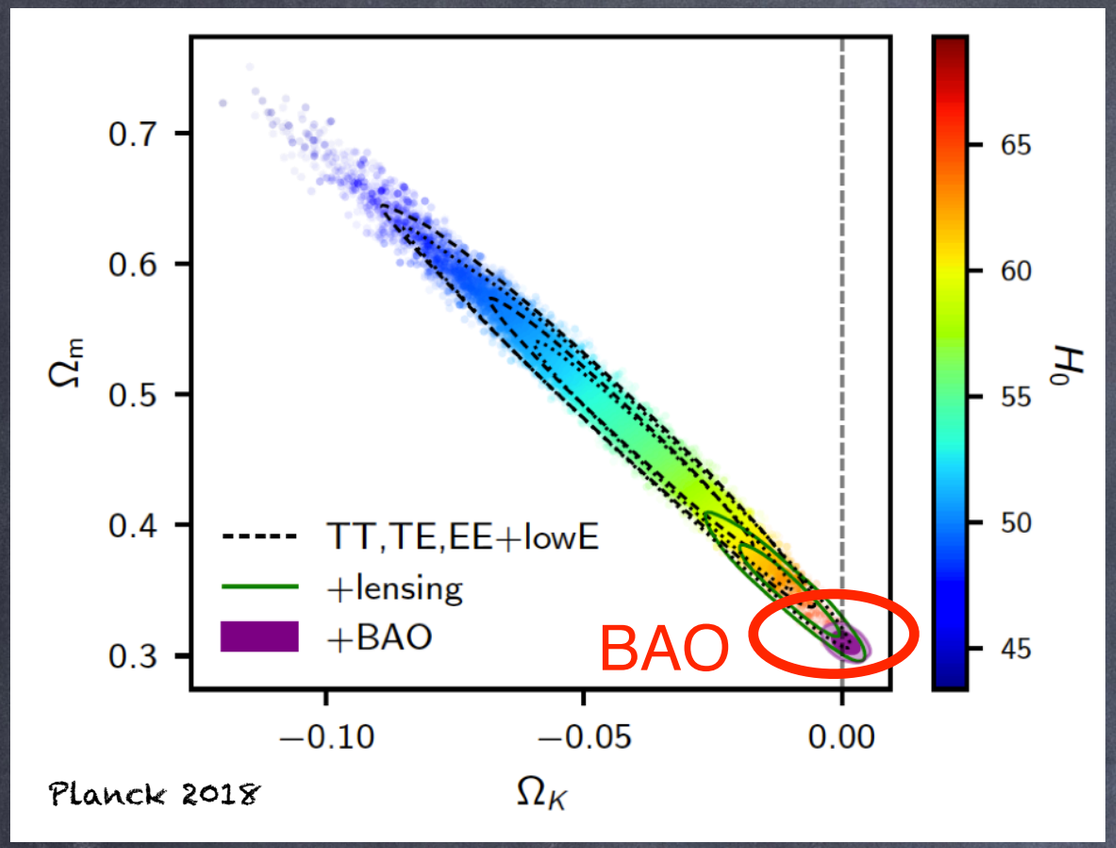
- But we need a 2pcf model

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

DATA THEORY

IT SHOULD NOT INTRODUCE UNWANTED DEPENDENCIES

BAO and cosmology



"BAO is now a mature field employing analysis techniques that have been tested extensively against simulations. There is no good reason to ignore these measurements."

Efstathiou (2021)

"However, for readers interested in spatial curvature, whether *Plik* or *CamSpec* is the more reliable likelihood is irrelevant because differences between Planck likelihoods are overwhelmed when Planck data are combined with BAO."

Efstathiou, Gratton (2020)

How cosmology indep?

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

PRACTICE

- BAO distances employed to constrain ANY cosm. model

IMPLICIT ASSUMPTION

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

QUESTION

- At what level is this true ?

We will try to answer to this question!

Cosmological Distance: Dv

Distorted True small correction

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

Isotropic shift

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

MEASURED in a background-independent way

- But we need a 2pcf model

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

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)

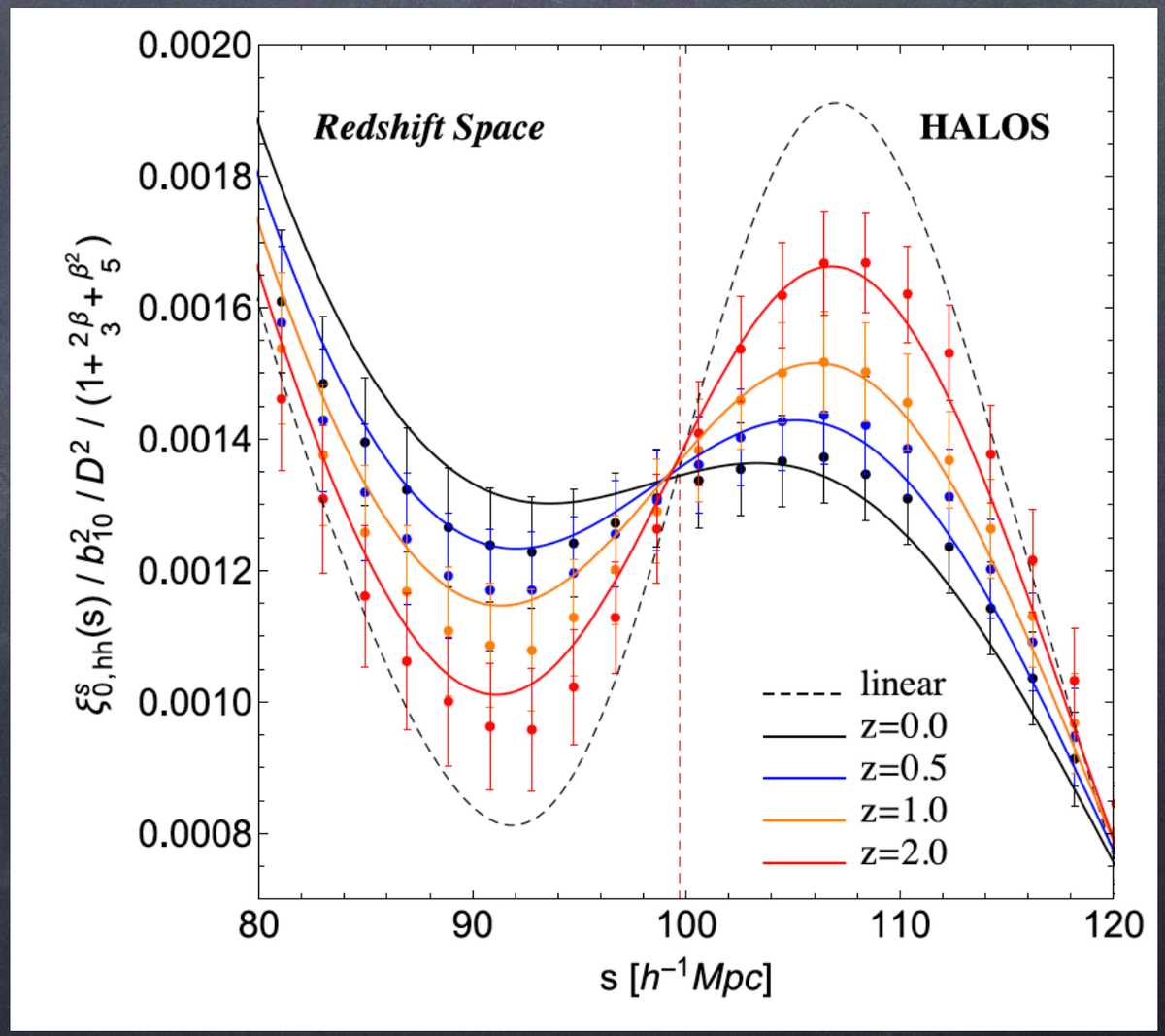
Crocce, Scoccimarro (2008)

Desjacques (2008)

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

2pcf in BAO range of scales

Relevant effects!



Minimal 2pcf model

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

- Minimal non-linear model for the 2pcf-monopole

$$\xi_0(s) \simeq \int \frac{dk}{k} \frac{k^3 P^{lin}(k; z=0)}{2\pi^2} A^2 e^{-k^2 \sigma_0^2} j_0(ks)$$

only dependence

$\{\omega_b, \omega_c, n_s\}$

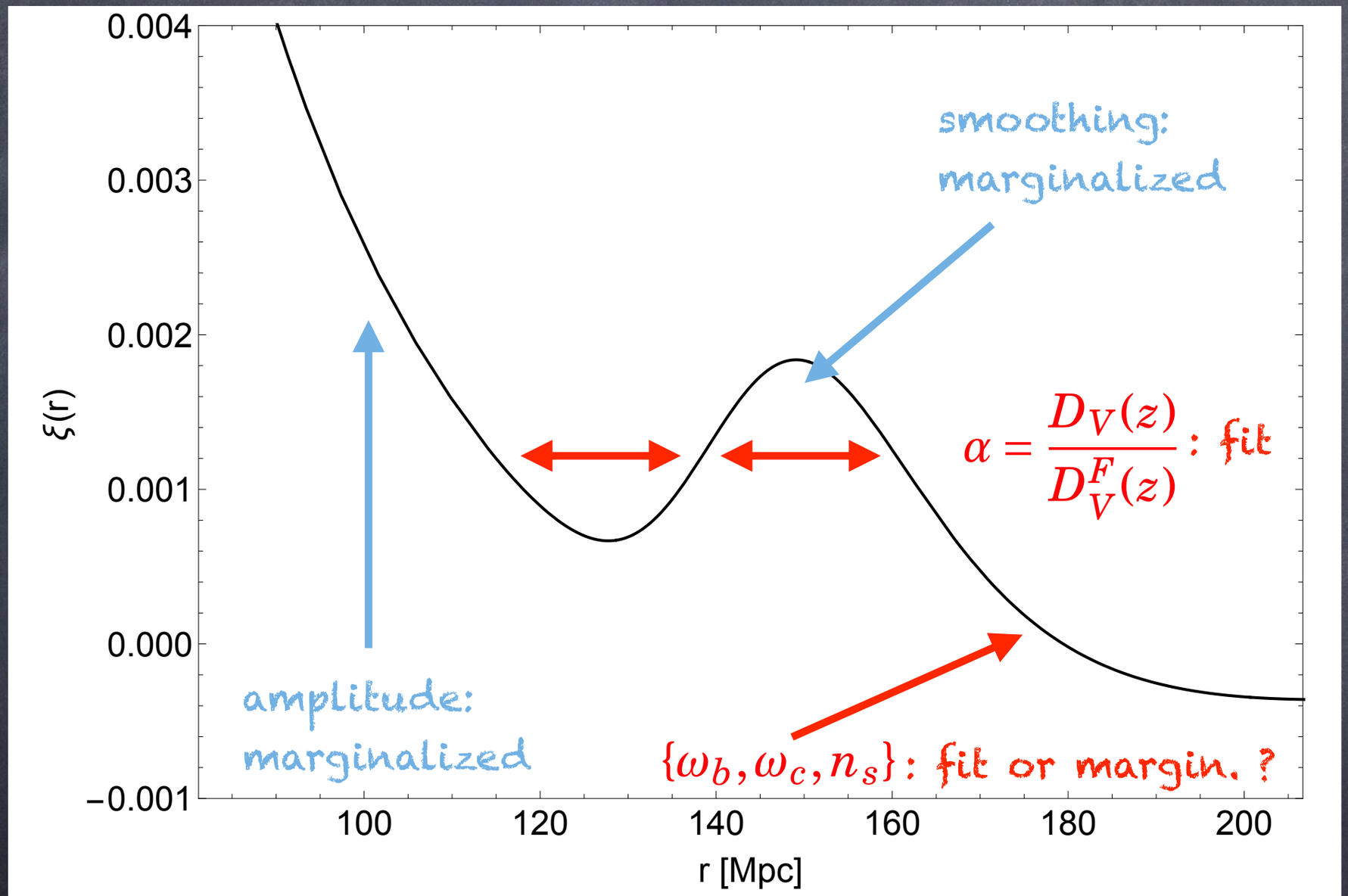
scale independent but time dependent for:

- ΛCDM
- quintessence
- flat and non-flat geom.

dependence

+ growth
+ Dark Energy model
+ curvature
+ tracer

visually



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

2pcf model-fitting

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

- 2pcf Alcock-Paczynski equation:

$$\xi_0^D(s^F) = \xi_0^{\rm model}\left(\alpha\, s^F\right) + O(\epsilon)$$

DATA THEORY

Parameters:

$$\theta_\mu = \{\omega_b, \omega_c, n_s, A, \sigma_0, D_V(z)\}$$

$D_V(z)$ PROPERLY ESTIMATED

- Dv problem -> large error ~ 100%
- $r_d(\omega_b, \omega_c)$ and $D_V(z)$
  - similar error
  - very high correlation coeff. ~0.9999

$$\frac{r_d(\omega_b, \omega_c)}{D_V(z)}$$

well constrained

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 (ΛCDM + 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:

$$\xi_0^D(s^F) = B^2 \xi_m^{\rm fixed}\Big(\alpha\, s^F\Big) + \xi^{\rm BB}(s^F) + O(\epsilon)$$

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

~ min. model

FIXED parameters

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

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?

standard BAO: problems

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

1) parameter fixing

2) which 2pcf model?

Cosm. model -> Unique galaxy 2pcf ?

PROPER INFERENCE ??

problem 1: parameter fixing

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

all dependencies fitted/marginalized

fixed parameters

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

Euclid forecasts

Errors underestimated by nearly a factor of 2!!

... but problem 2:

which galaxy-2pcf theoretical model ??

problem 2: 2pcf theoretical model

NON-LINEAR - state of the art: numerical approach

- Ab-initio N-body simulations for DM (nearly convergent).
  DM Halo identifiers (FoF, S.O., etc...).

- Too slow to run MCMC for data analysis.

- Galaxies? NO ab-initio simulations.
  - We lack a complete predictive theory for galaxy formation
  - Halo Occupation Distribution prescription.
    (how many galaxies fit in a halo)
  - How do galaxies precisely populate the matter field ???

Galaxy 2pcf theoretical model

2pcf MODEL

- Analytical 2pcf of galaxies NOT KNOWN:
  - non-linear gravity
  - Redshift-Space-Distortions (RSD)
  - galaxy bias
  - number of parameters
  - unknown range of scales
- Reference to "VALIDATE": N-body simulations + galaxies in halos

What that means?

2pcf-model Validation

- Fluid equations? Which starting equations?
  SPT? EFTofLSS? ...

- Perturbative order?

- Can we predict the range of scale ?

- Parameters: quantities to be measured from data.
  Meaning of fixing them?
  Misestimation of other parameter best-fits and errors.

- Select parameters? Need to be careful!
  Some parameters have a physical meaning

2pcf-model Validation

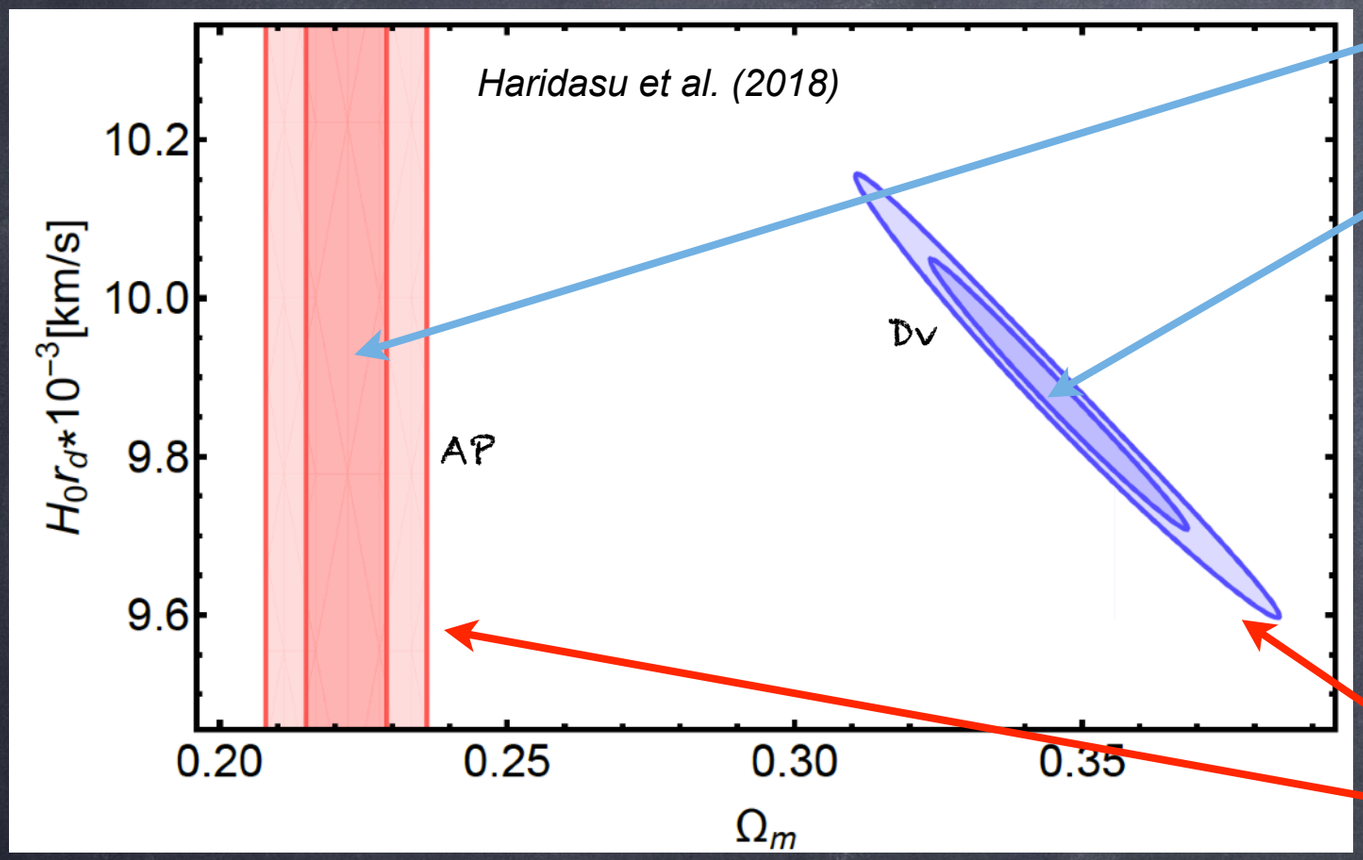
Only rule
unbiased results w.r.t. survey mocks

... and the error estimation?

error estimation

- kwCDM analyzed as flat-LCDM

  AP, DV: combinations of H(z) and $D_A(z)$



Euclid forecasts

Wrong model

↓

Best fit is biased

Wrong error

↓

False detection

STRONG-TENSION ⟷ MILD-TENSION

problem 2: complementary approach

Shanks et al. (1987)

Eisenstein et al (1998)

Bassett, Hlozek (2009)

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
- Quintessence
- no flatness assumption

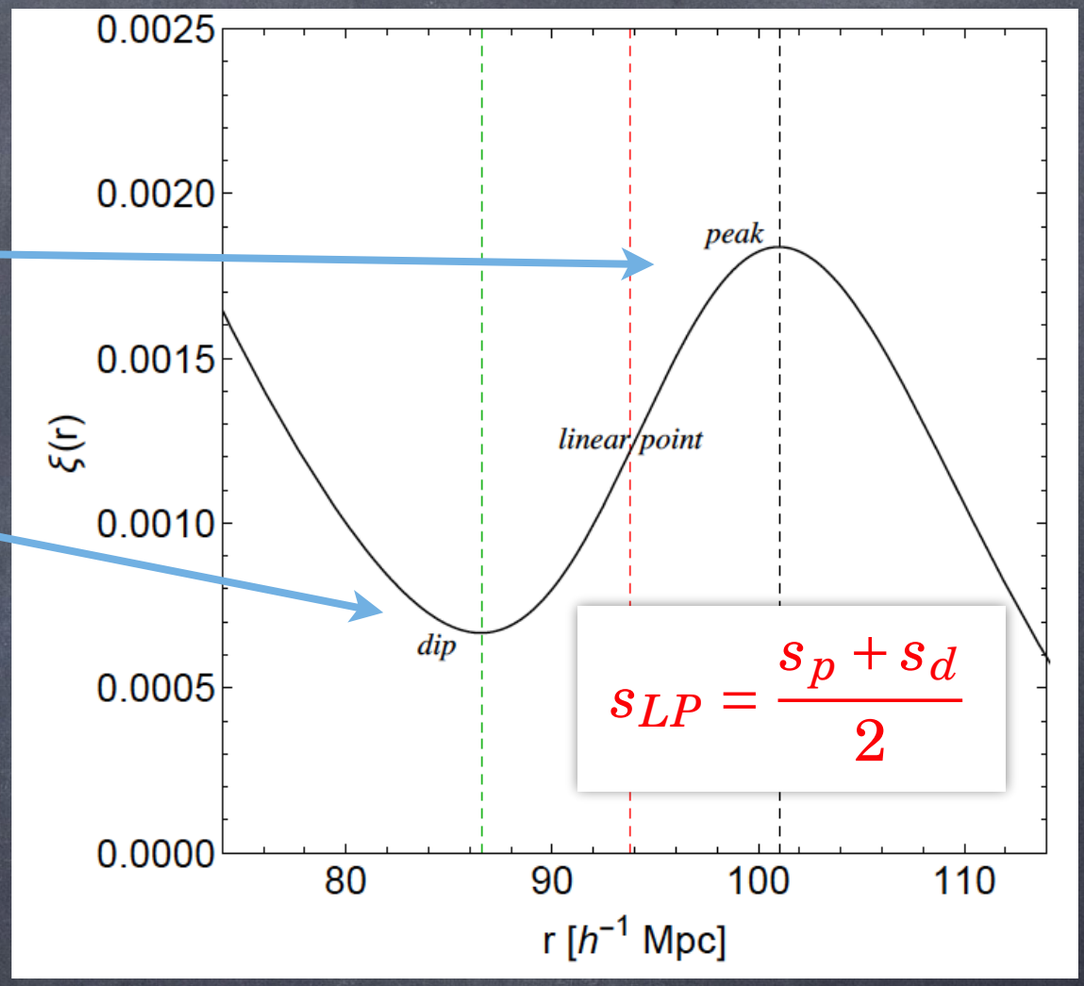
- A PREFERRED SCALE in the 2pcf -> Time/Model indep.

→ Can measure Dv in model-indep. way!!

New Standard Ruler: the Linear Point

Linear Point definition

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



Linear Point features

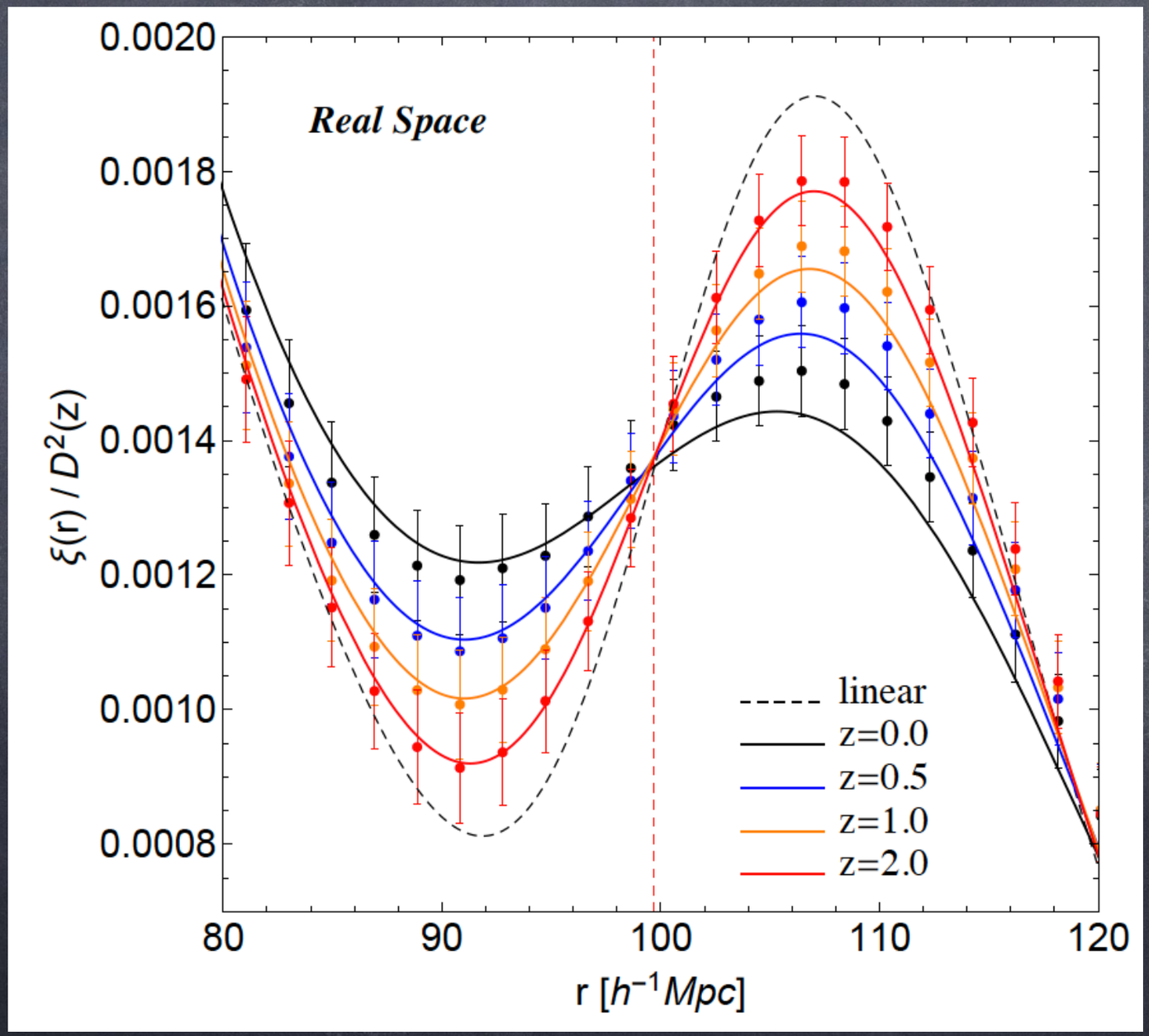
1) A geometrical point
2) Redshift independent at 0.5%, i.e linear
   Weakly sensitive to: Non-linear gravity, RSD, scale dep. bias
3) Background-Independent distances

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

Parimbelli, S.A, et al - JCAP (2021)

... from a "wrong" plot...

Since the CF amplitude is not used for BAO...



NO 2pcf model template

$$y \equiv \frac{s}{D_V(z)}$$

DATA

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

LINEAR THEORY

BAO distance

Model-independent

parametric fit

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

CAMB/CLASS code

NO FIXED PARAMETERS!!

- NO fiducial cosmology dependence

distance from SDSS galaxies

- BOSS collaboration; two galaxy samples: LOWZ and CMASS

Linear Point distance

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

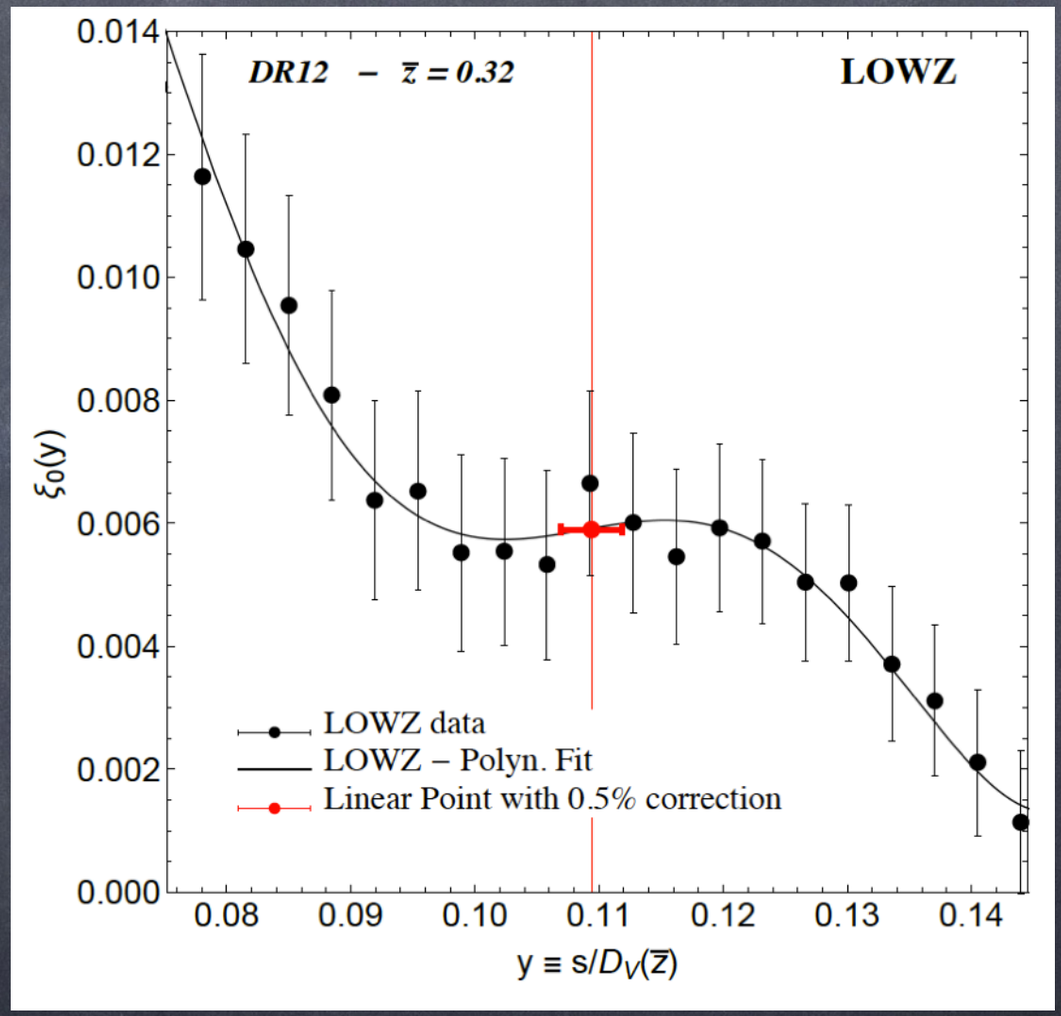
CONSISTENT

smaller errors

Standard BAO

Cuesta et al. (2016)

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



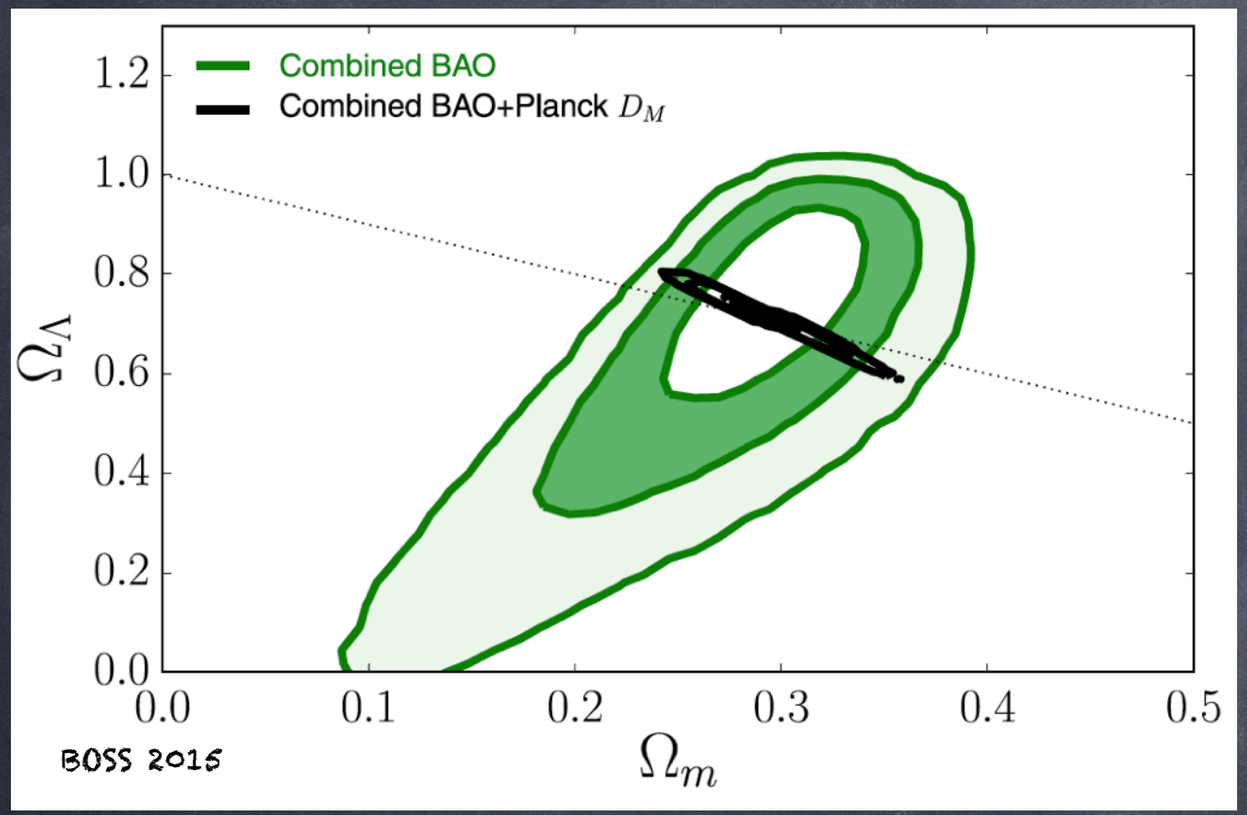
S.A, Corasaniti, Starkman, Sheth, Zehavi - PRL (2018)

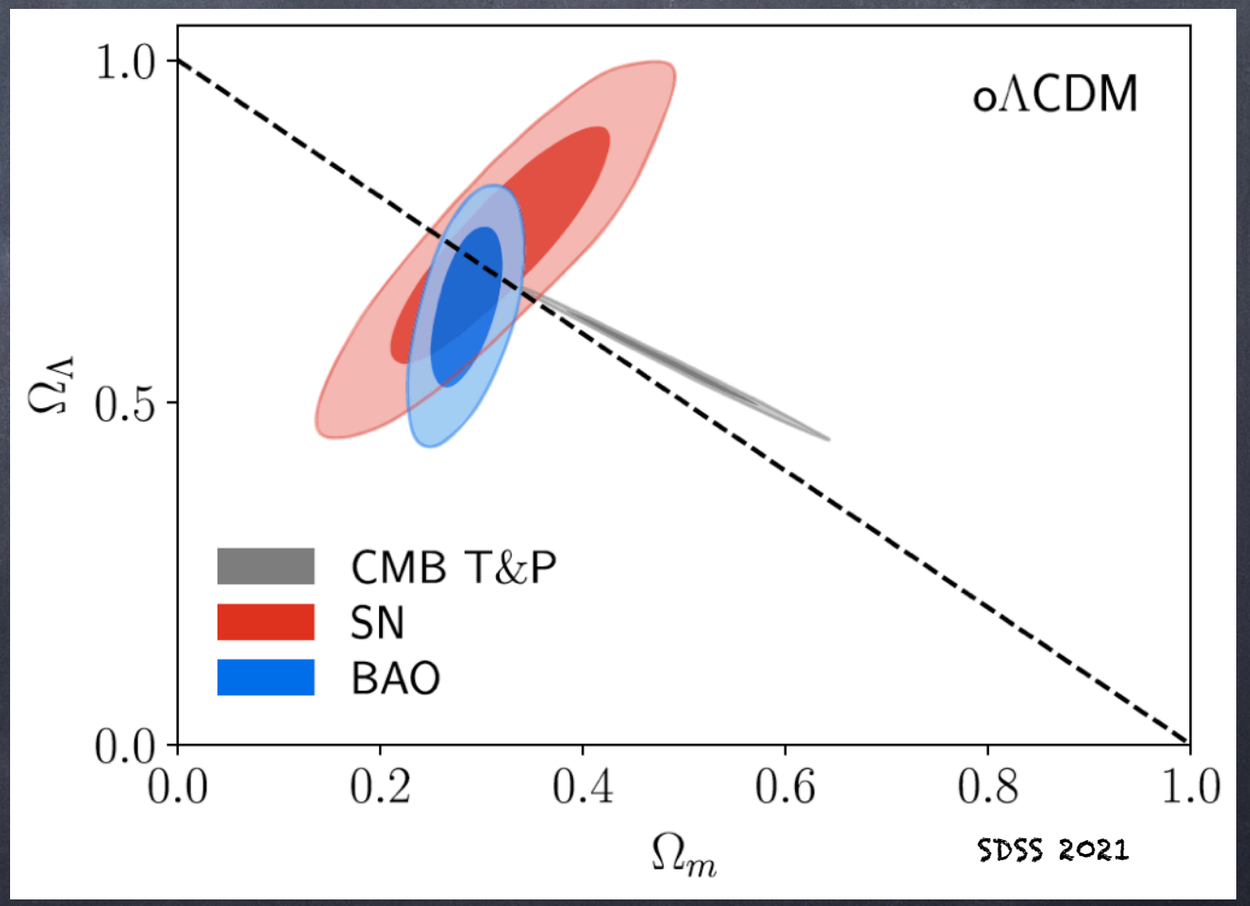
S.A, Corasaniti, Starkman, Sheth, Zehavi - PRD (2018)

Dark Energy detection with BAO

S.A., Starkman, Renzi - PRD (2023)

- BAO distances: crucial for "Dark Energy detection"





BAO distances: expectation

- Flexible enough to be used for many purposes.
  (e.g. Dark Energy detection, inverse distance ladder,
  tensions, BAO consistency tests, etc...)
- Possible to use only one BAO distance!

How wide the parameter range should be?

The widest possible...

S.A., Starkman, Renzi - PRD (2023)

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

- Accuracy can be improved

caveats

standard BAO

- Standard BAO fitting: parameters fixed to flat-LCDM close to Planck best-fit
- BAO reconstruction: parameters fixed [...]

general

(e.g. validation, covariance)

- flat-LCDM: "model" assumed for survey mocks and N-body
- Close to flat-LCDM Planck best-fit: sims cosmological params
- We need to model non-linear physics for wide-param range!

S.A., Starkman, Renzi - PRD (2023)

DESI: BAO-only (1)

- Template fitting:

$$P_{gg}(k,\,\mu) = \mathcal{B}(k,\,\mu)\,P_{nw}(k) + \mathcal{C}(k,\,\mu)\,P_{w}(k) + \mathcal{D}(k,\,\mu)$$

assumption

any BAO scaling information accounted by

$$P_w(k) \sim P_w^{\rm fixed}(r_d\,k/r_d^{\rm fixed})$$

FIXED parameters

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

DESI: BAO-only (2)

- P_{gg} ~ min. model for $\{\mathcal{B}(k,\mu), \mathcal{C}(k,\mu)]\}$

- $\mathcal{D}(k,\mu)$ -> broadband (unknown residual non-linearities and obs. syst.) based on the fiducial r_d

- BAO distance results: assume BAO-reconstruction

ERROR PROPAGATION ?

DESI: fiducial

- "true" -> Planck 2018 cosmology

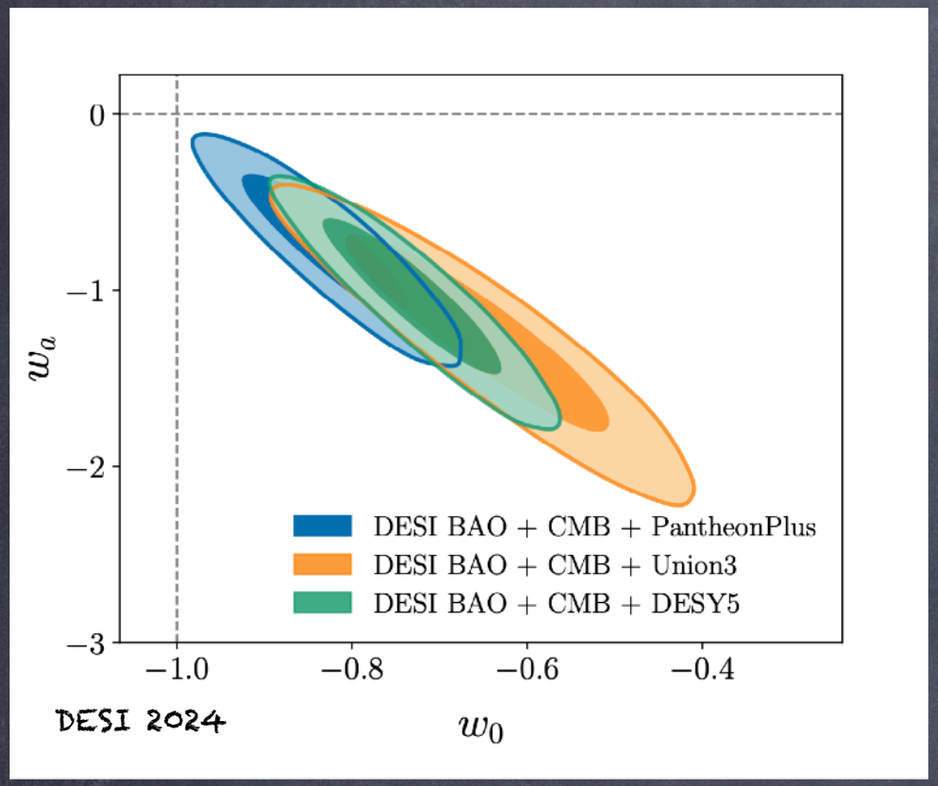
- Parameters fixed to different values:
  parameters for: A.P., P_{gg} "template", "BAO reconstruction" (b, f)

- 4 different cosmologies tested:
  Variations: $\omega_b \sim 1\%$ $\omega_c \sim 8\%$ $n_s \sim 2\%$ $\sigma_8 \sim 7\%$

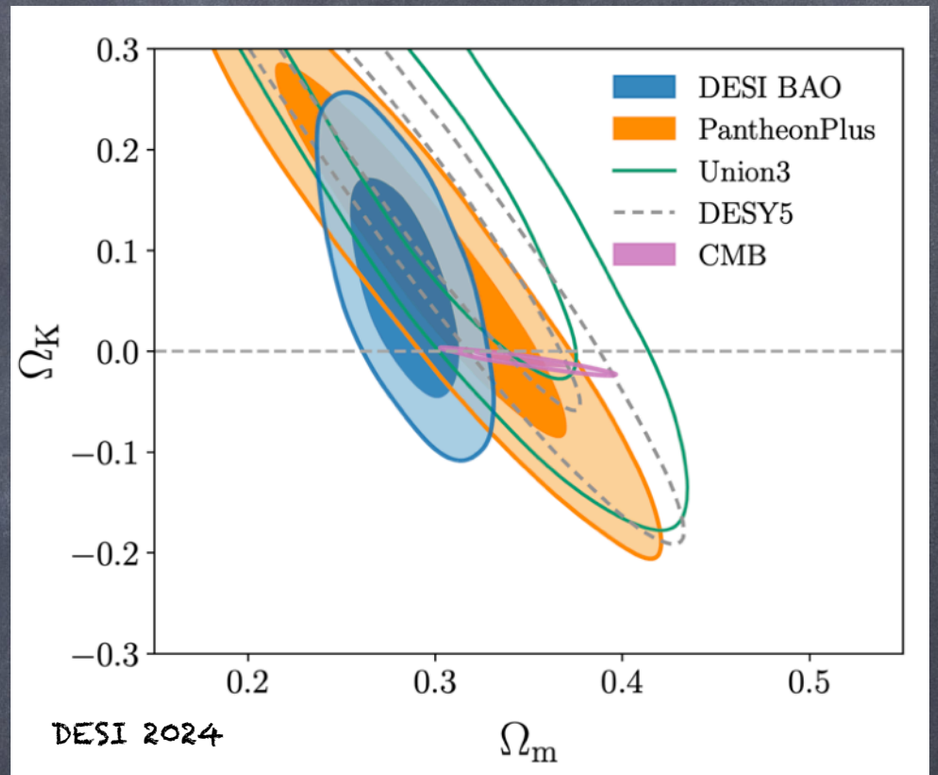
wide parameter range ?

DESI: cosmology

- Dark Energy evolution



- "Dark Energy detection"



- BAO distan. -> MODEL USED: Matter Perturbations + background

Modif. Gravity? non-quintessence models? DE-DM coupling? ...?

- Wide parameter range ?

Challenges to ΛCDM from BAO ?

Dynamical Dark Energy...

... or flat-ΛCDM consistency test ?

Vanilla flat-ΛCDM...

... and ΛCDM ?

S.A, Carney, Giblin, Kumar, Mertens, O'Dwyer, Starkman , Tian - JCAP (2023)

What do we learn about cosmology?

AIM

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

2pcf MODEL

- Galaxy clustering models: add extra assumptions
- Data vs Theory -> Testing cosmological model(s) + galaxy clustering model assumptions -> Learning about cosmology?

LINEAR POINT

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

Challenges to use BAO distances

- Cosm. applicability of standard BAO distances: UNCLEAR!
  flat-ΛCDM consistency check ?

- 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 (ongoing); Wide parameter range? Quadrupole 2pcf;
Observational systematics; Combine with other observations; ...

THANK YOU!!