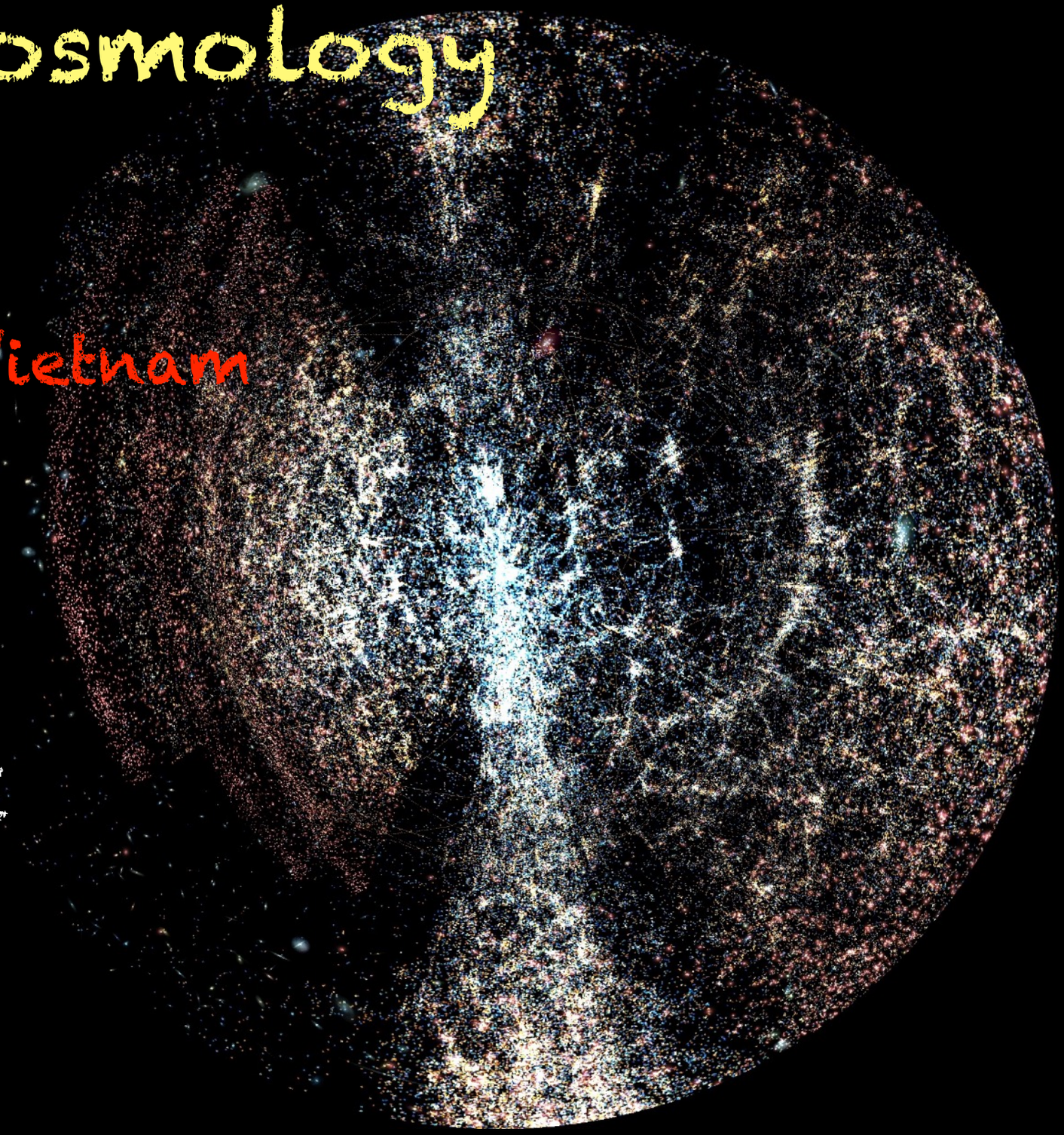
The challenges of using Baryon Acoustic Oscillations distances for cosmology

21st Rencontres du Vietnam

August 14, 2025

Stefano ANSELMI

INFN PADOVA



Collaborators

C. Carbone
P-S Corasaniti
M. O'Dwyer
G. Parimbelli
Y. Rasera
A. Renzi
A. Sanchez
R. Sheth
G. Starkman
F. Villaescusa-Navarro
M. Viel
I. Zehavi

Outline

from Baryon Acoustic Oscillations?

- Late time Cosmology Independent accurate distance measurements

relevant Challenges...

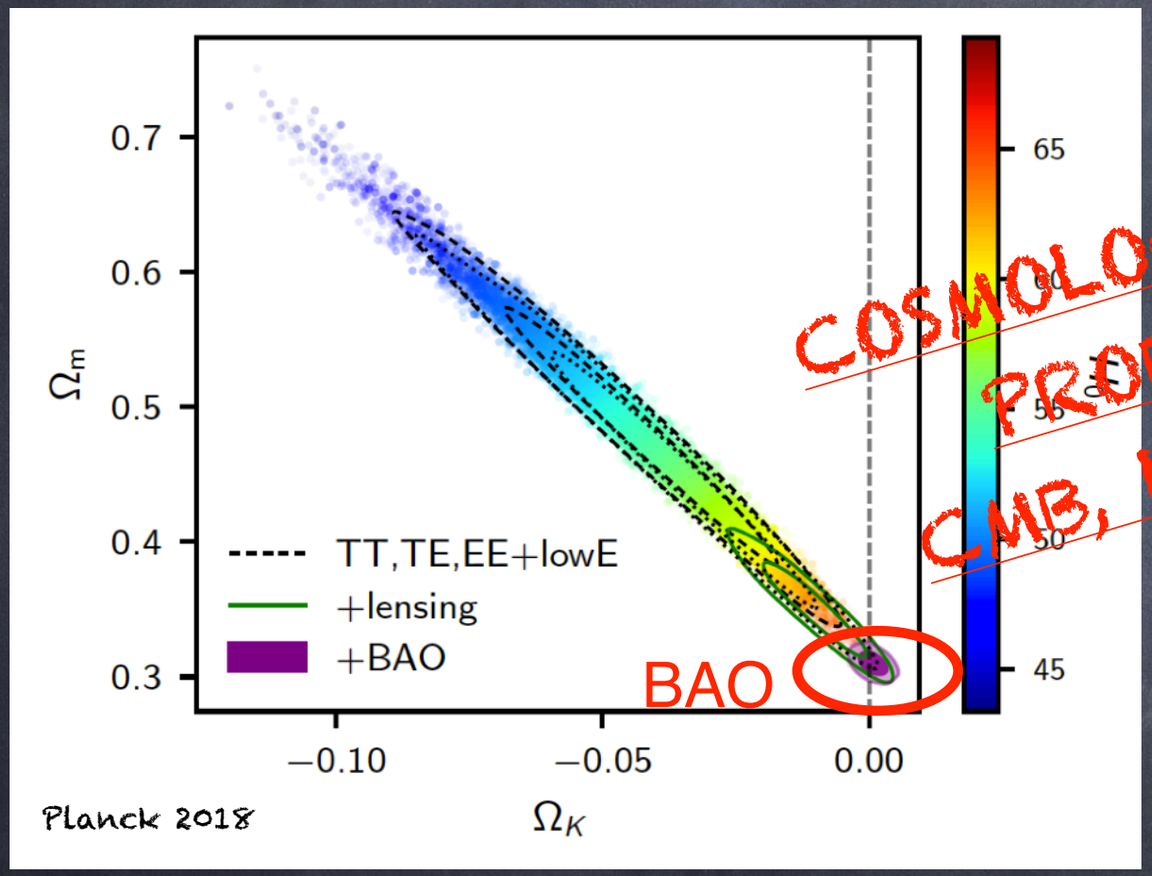
... their implications

New Proposals

Late Universe Acceleration

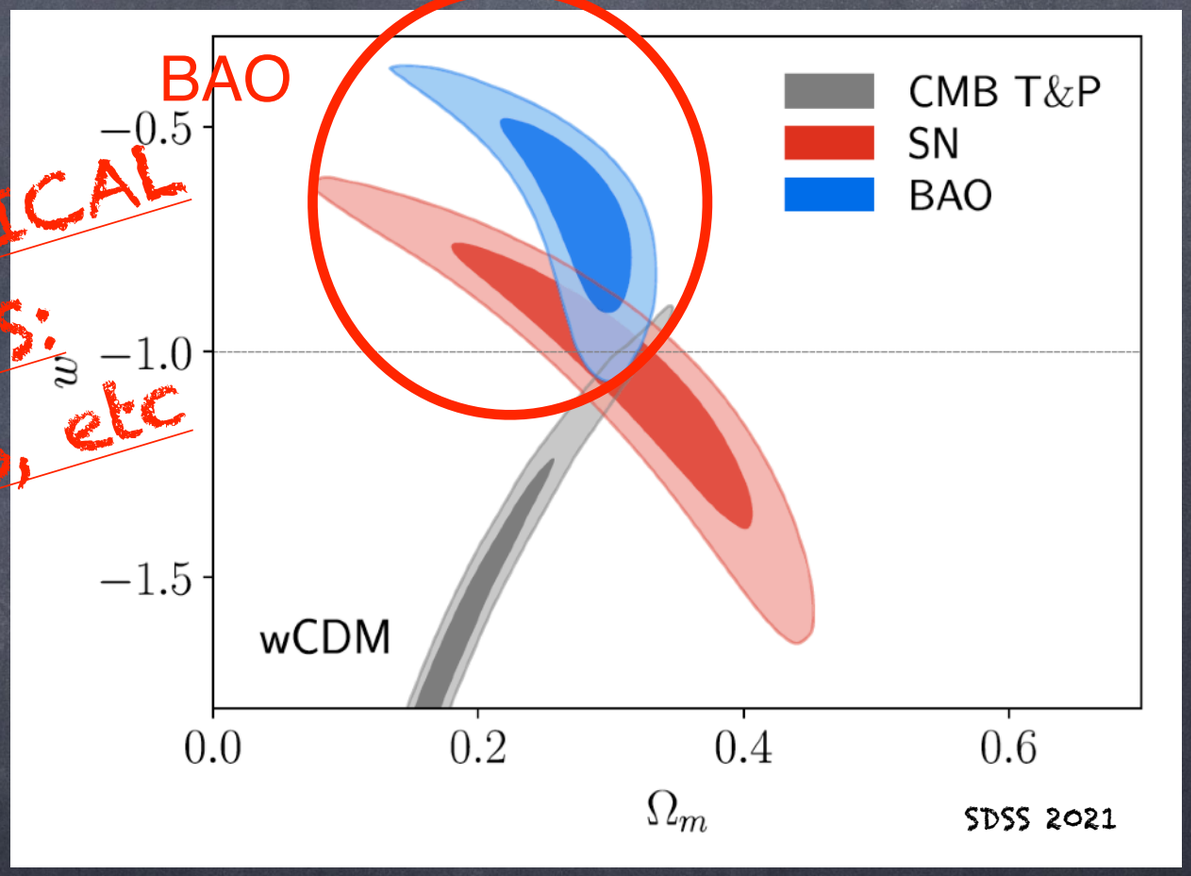
Probe Combination

energy densities



Different Probes

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



COSMOLOGICAL PROBES: CMB, LSS, etc

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

Which scale?

- Which scale in the clustering Correlation Function?

- Comoving baryon acoustic scale
  Baryon acoustic peak - Matter CF

r_d

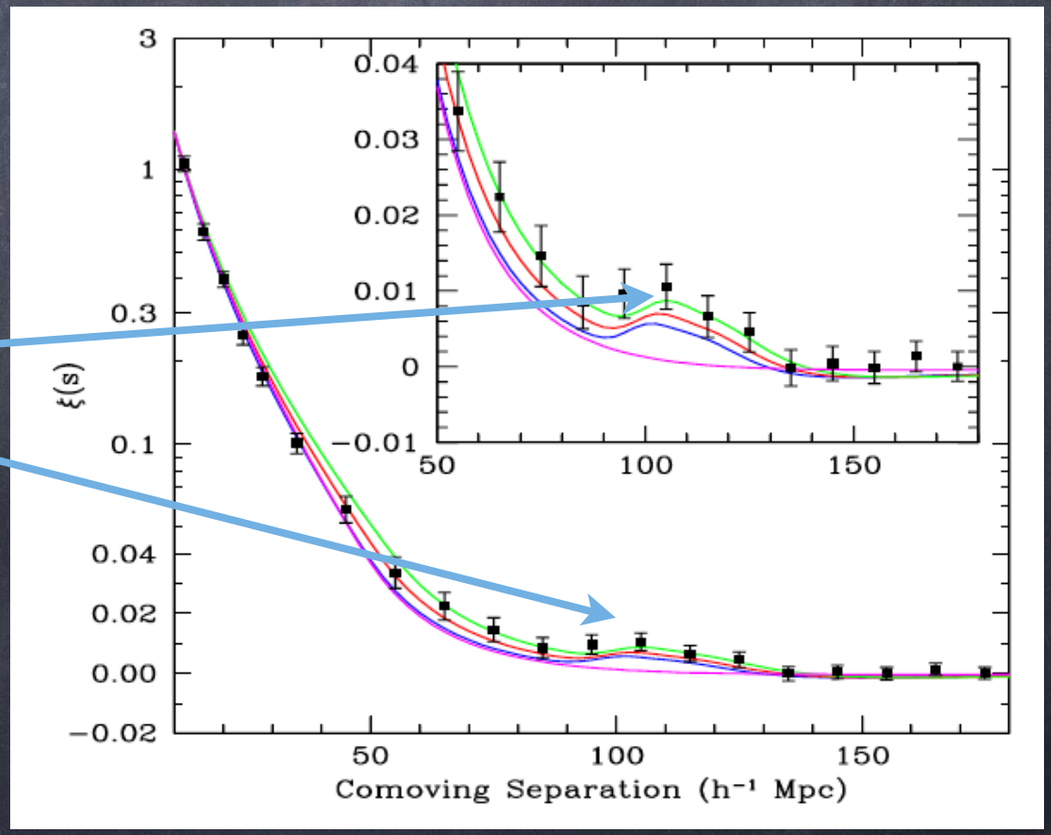
s_p

- rd is Geometrical (indep. primordial fluctuation)

Baryon acoustic peak POSITION!!

STANDARD RULER

Eisenstein et al (2005)



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~~ !!

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!

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

2pcf non-linearities

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

Smith et al (2008)

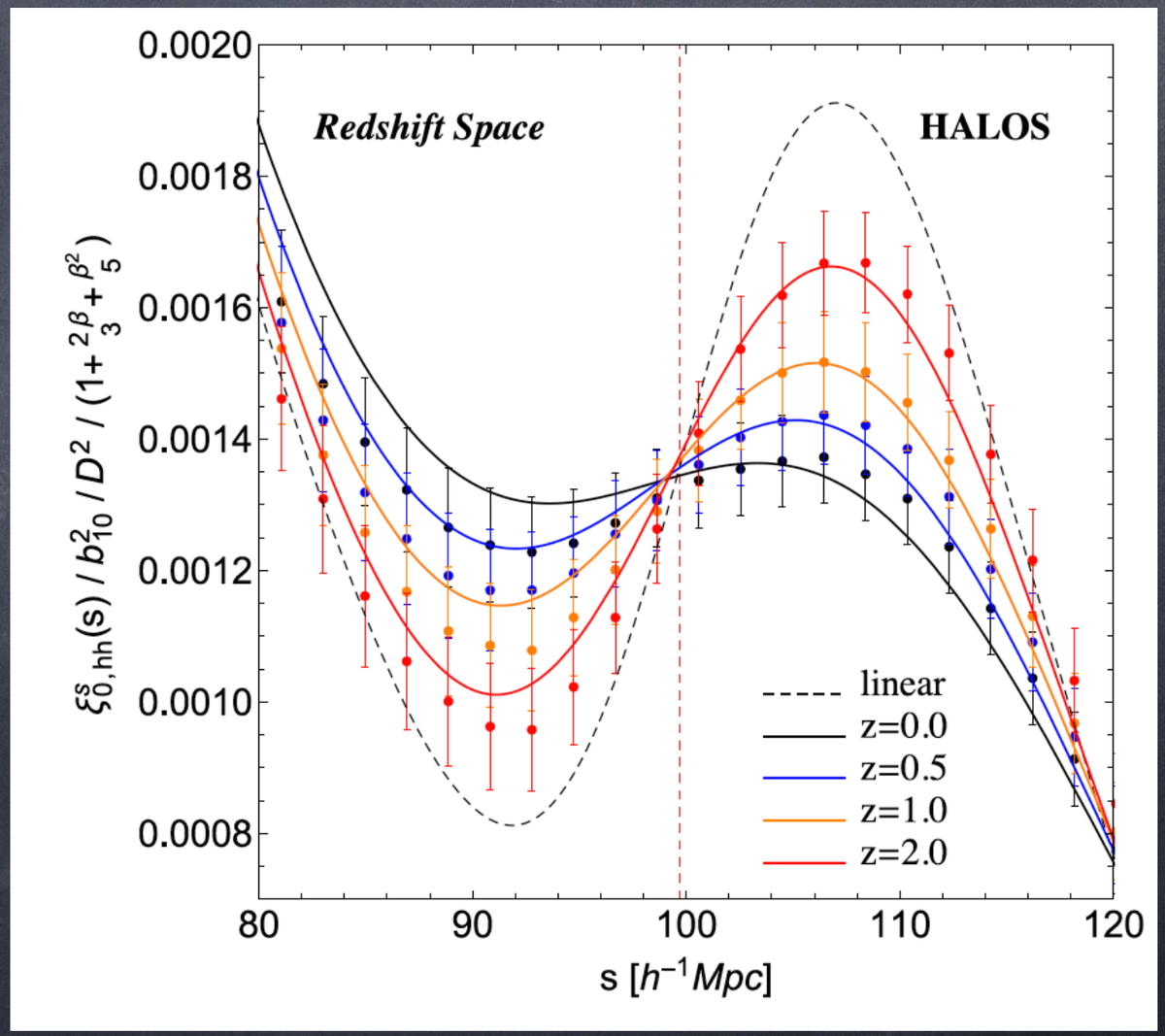
Crocce, Scoccimarro (2008)

Desjacques (2008)

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

2pcf in BAO range of scales

Relevant effects!



standard BAO (pre-DESI)

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

- Template fitting:

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

~ min. model

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

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

questions

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

1) parameter fixing:
proper error on cosmic distances?

2) which cosmological models?

3) which 2pcf model?

Cosm. model -> Unique galaxy 2pcf ?

PROPER INFERENCE ??

Build Understanding with the 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

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

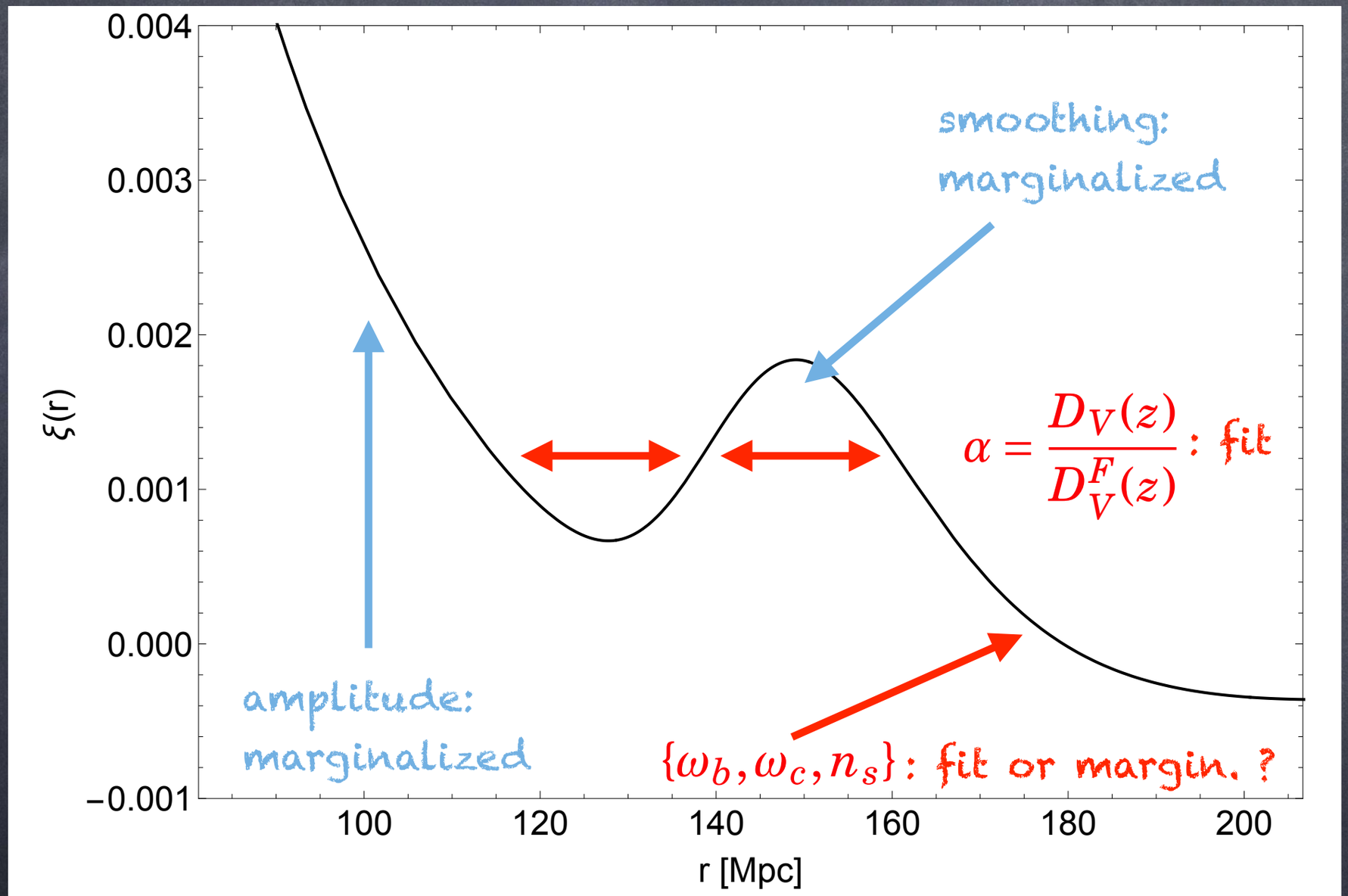
scale independent but time dependent for:

- 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

~ % error

BAO distances - cosmological models

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 ?

parameter fixing - error on distances

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 3):

which galaxy-2pcf theoretical model ??

which 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

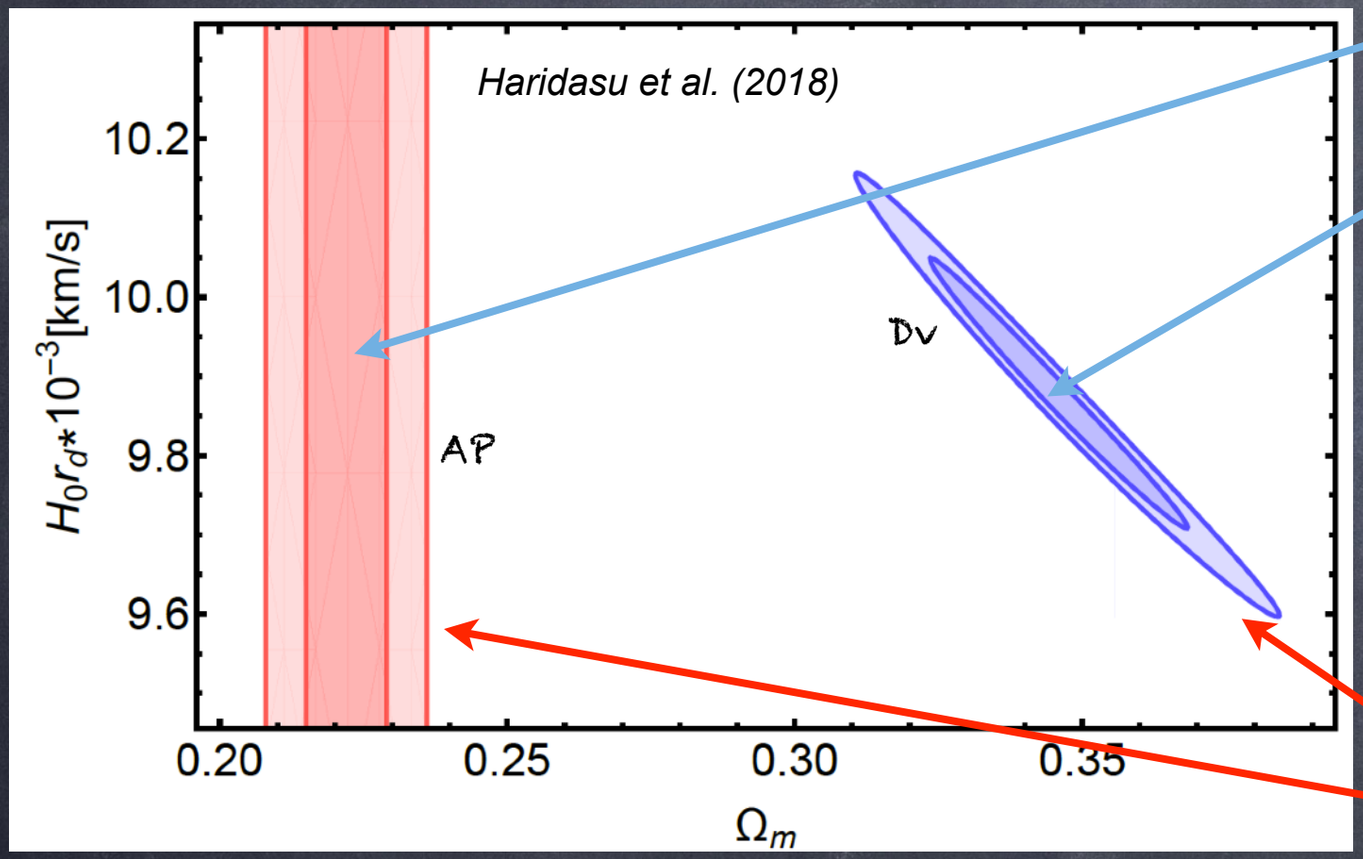
Only rule
unbiased results w.r.t. survey mocks

... 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

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

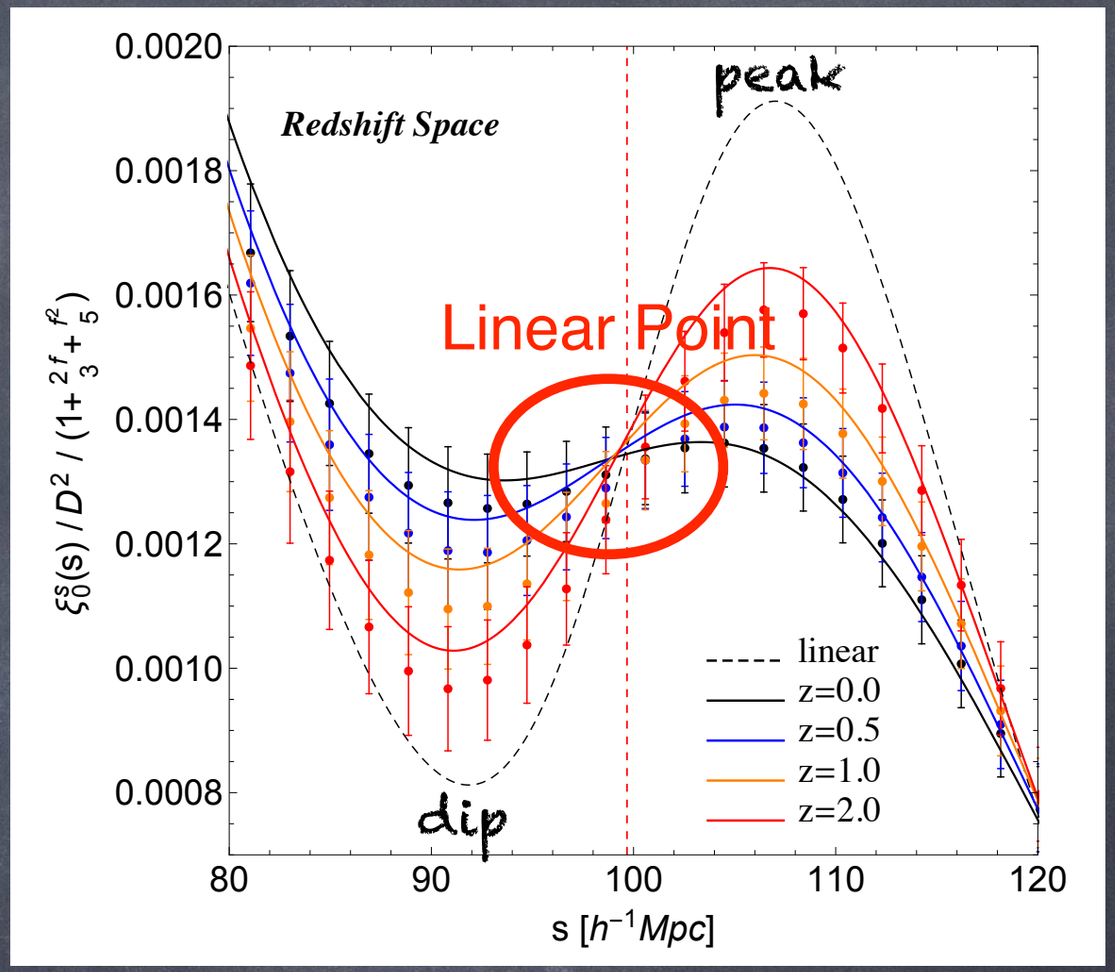
- ΛCDM
- Quintessence
- no flatness assumption

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

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

New Standard Ruler: the Linear Point

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



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

- **LINEAR POINT**
  - LP = peak-dip middle point
  - Linear at 0.5% -> red. indep.
  - Geometrical

- **NO 2pcf MODEL NEEDED**

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

model-independent parametric fit

CLASS/CAMB code

~~QUESTIONS~~
~~1) error estimation~~
~~2) cosmologies~~
~~3) 2pcf model~~

distance from SDSS galaxies

- BOSS collaboration; two galaxy samples: LOWZ and CMASS

Linear Point distance

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

CONSISTENT

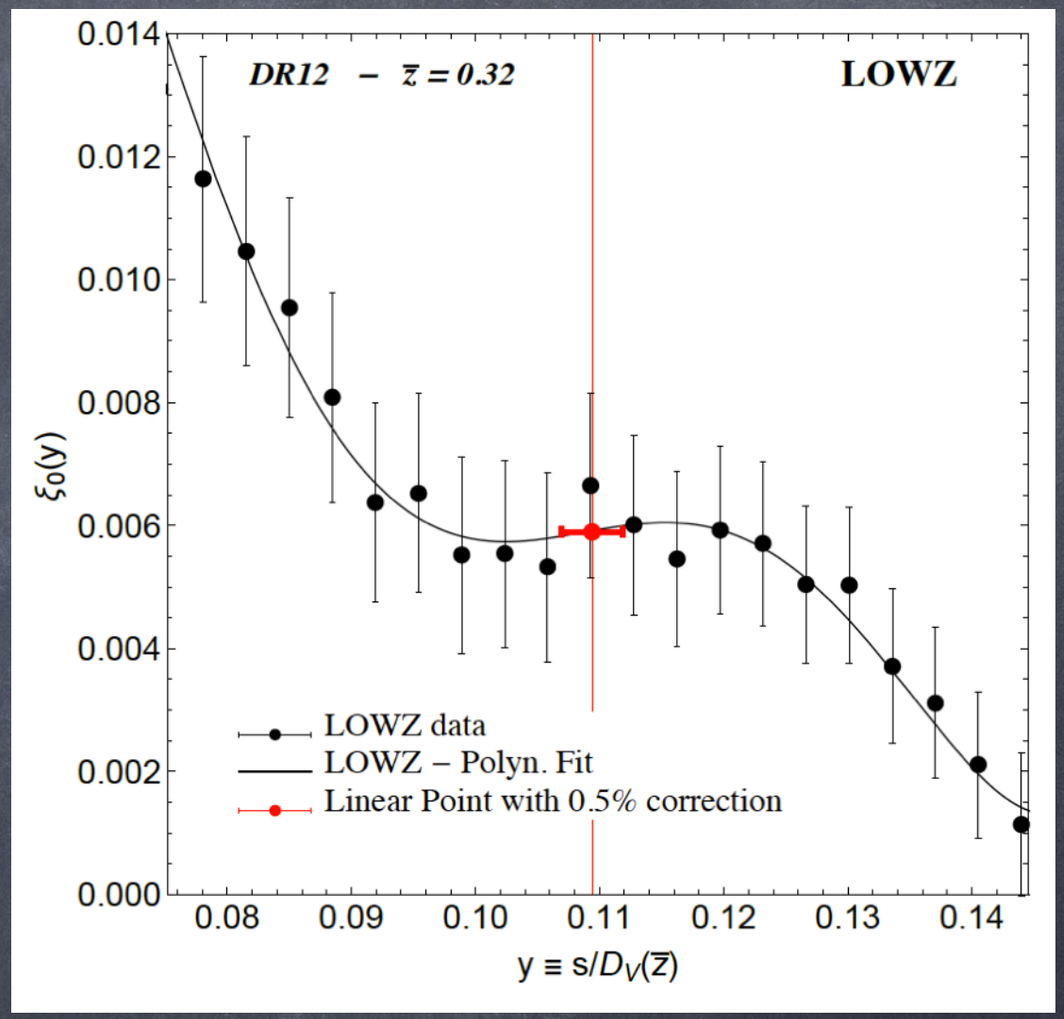
Standard BAO

Cuesta et al. (2016)

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

Standard BAO - post-reconstruction

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



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

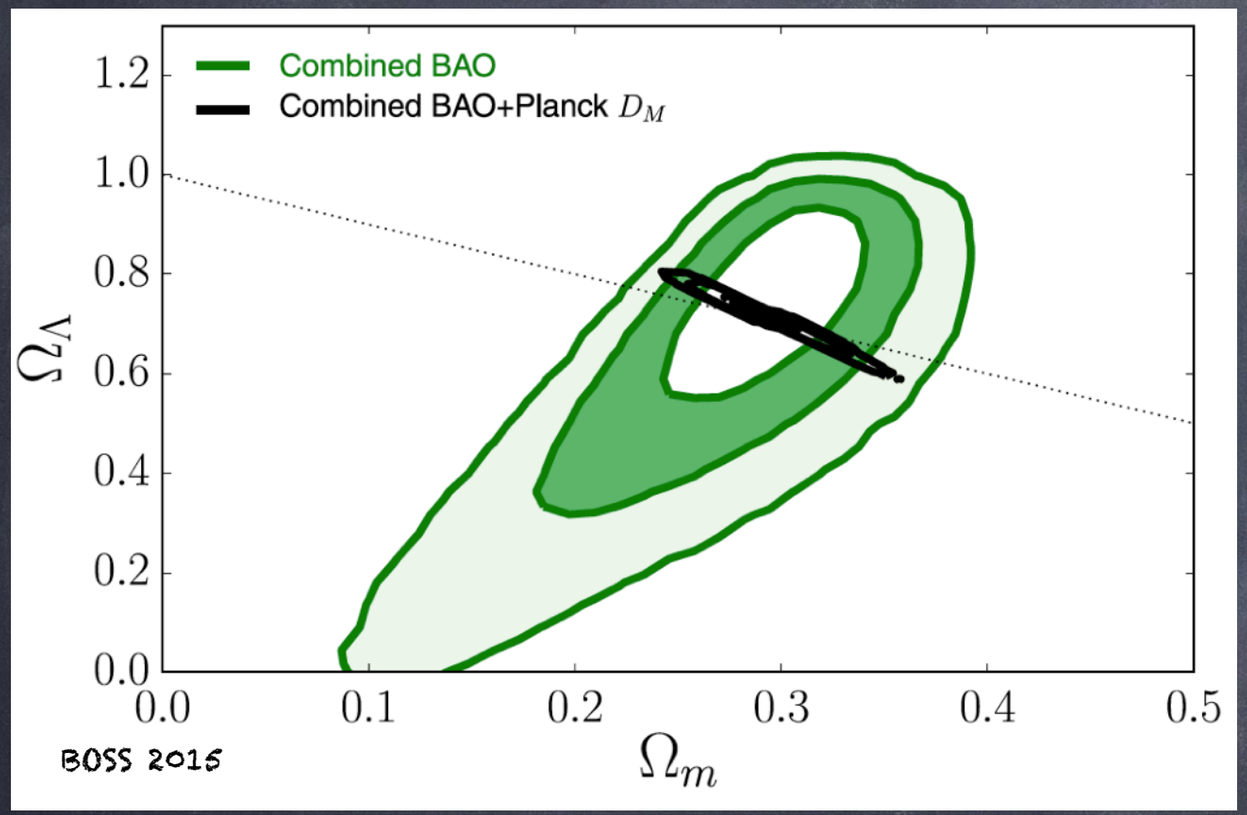
S.A, Corasaniti, Starkman, Sheth, Zehavi - PRD (2018)

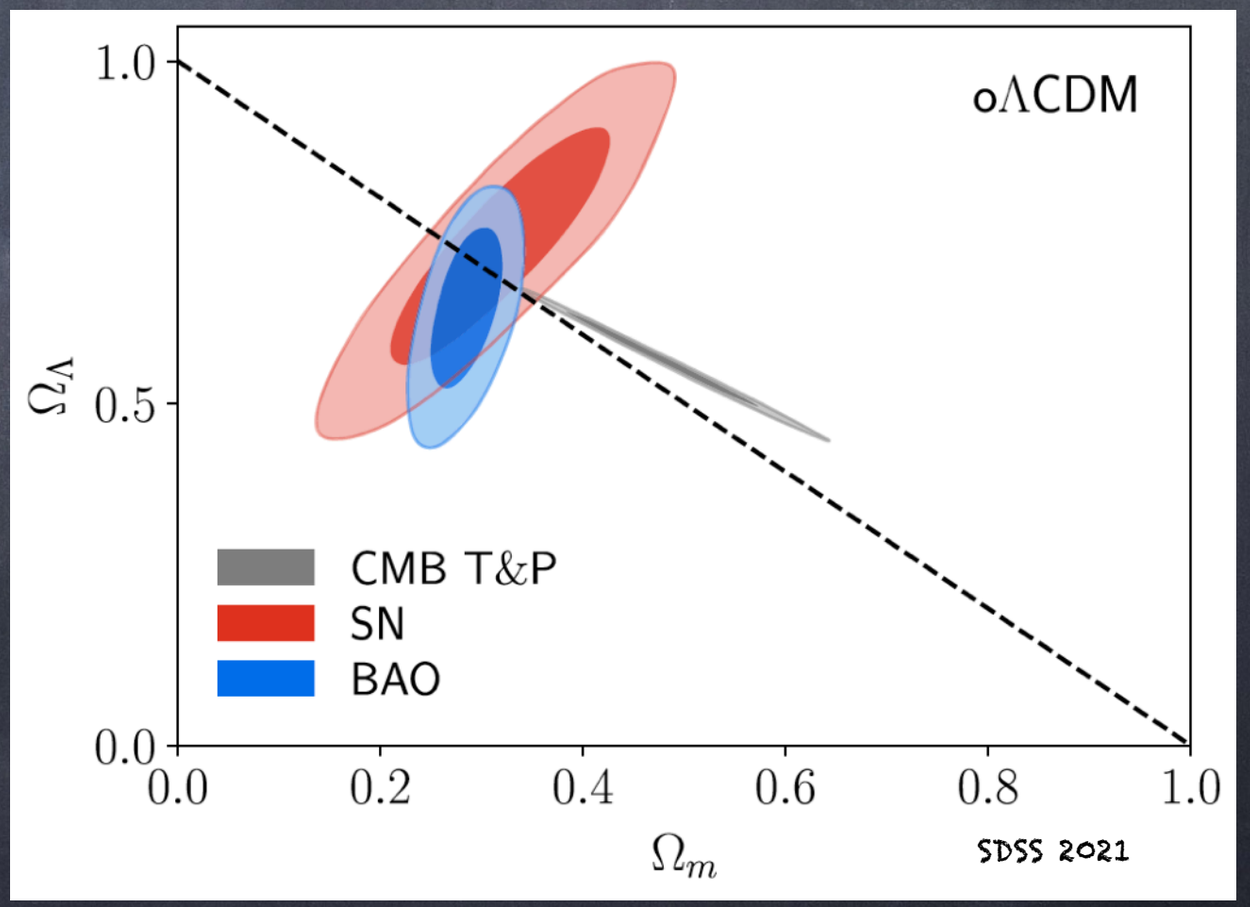
ERRORS!

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.

- Error: → up to 40%-50% smaller

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

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!
- NO first principle simulations for galaxies!

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

DESI BAO - cosm. distances

- 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

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

- BAO distance results: assume BAO-reconstruction

ERROR PROPAGATION ?

DESI: fiducial

- "true" -> Planck 2018 cosmology

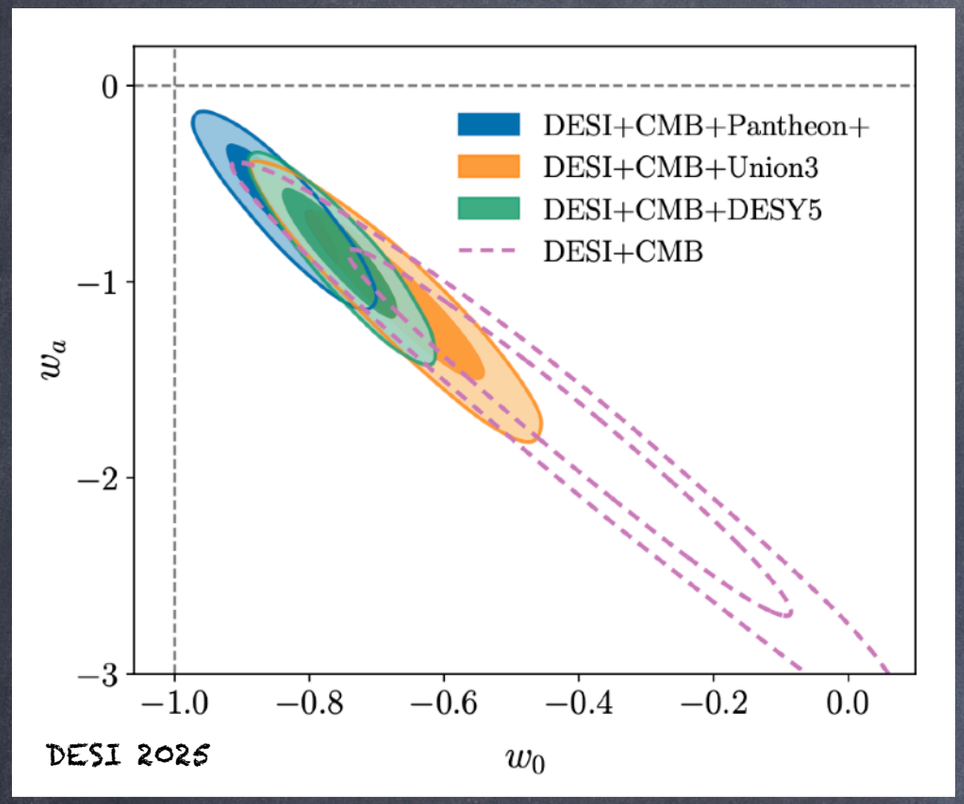
- Parameters fixed to different values:
  parameters for: A.P., P_{gg} "template", "BAO reconstruction" (b, f)

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

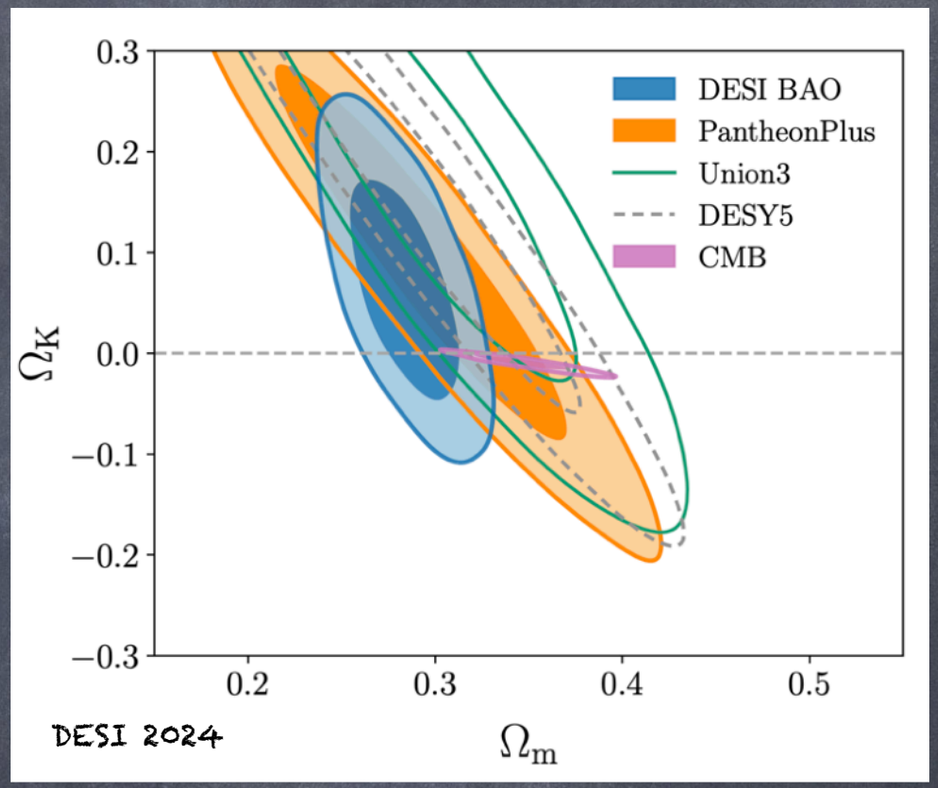
wide parameter range ?

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 ?

phantom crossing ?

- DESI:

  "The current data indicate a clear preference for models that feature a phantom crossing;..."

- 2pcf prediction (with template) for data fit -> flat-ΛCDM

- 2pcf prediction of phantom models?

  - Unique prediction for all "phantom models"?

  - Linear theory?

  - Non-linearities?

    Non-linear gravity, Redshift Distortions, Galaxies

  - In which parameter range?

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 is 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!!

further slides with some details

Example - first Euclid bin

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

  Parameter ERRORS: $\{230, 150, 45, 50, 90, 72\}\%$

- Change to: $\theta_\mu = \{r_d(\omega_b, \omega_c), \omega_c, n_s, A, \sigma_0, D_V(z)\}$

  Parameter ERRORS: $\{70, 150, 45, 50, 90, 72\}\%$

- Exploiting $r_d(\omega_b, \omega_c)$: $\theta_\mu = \{r_d(\omega_b, \omega_c)/D_V(z), \omega_c, n_s, A, \sigma_0, D_V(z)\}$

  Parameter ERRORS: $\{1.8, 150, 45, 50, 90, 72\}\%$

$\rho_{r_d, D_V} = 0.99992$

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

Linear Point with Massive Neutrinos

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

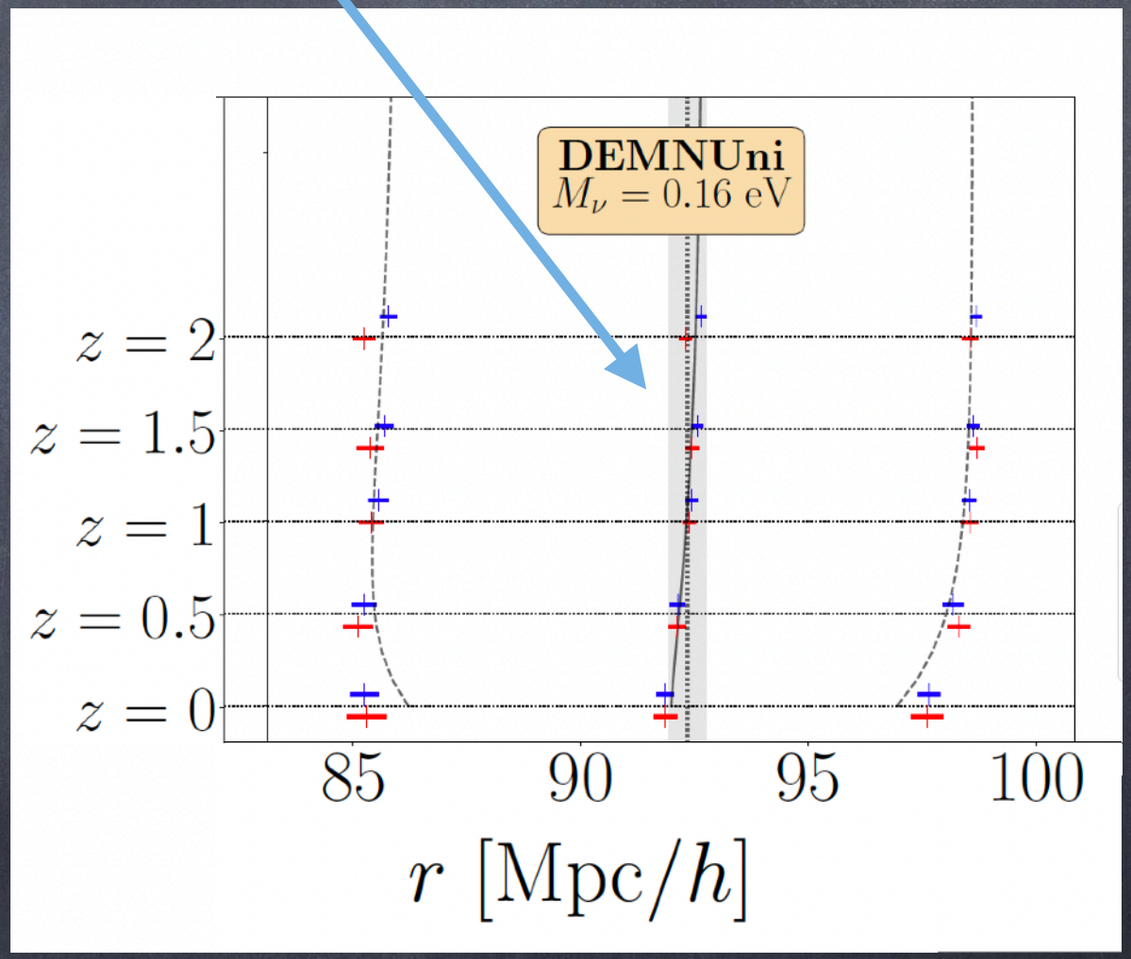
- BAO distances sensitive to Neutrino mass

  Thepsuriya, Lewis (2015)

- Scale dep. in linear theory

- LP properties retained for massive neutrinos

- LP constrains neutrino mass



Linear Point Validation

- Theoretical input: smooth differentiable function.
- Not unique estimator.
- Polynomial estimator.
  Reduce parameters: NO physical meaning.
  Range of scales: NO physical meaning.
- It should fit the data well (~ it is unbiased).
- N-body convergence + 0.5% uncertainty in the bias.

and priors ?

O'Dwyer, S.A, et al. - PRD (2020)

2pcf MODEL

- Fisher Matrix Limit -> no informat. priors -> Can be unphysical
- MCMC, physical priors: Tricky NOT to use other observ. priors

LINEAR POINT

- Polyn. parameters -> no physical meaning.
  NOT a problem
- Conditional cosmological analysis
  Ex: if LP detected -> n_s>0.5

DESI BAO (2)

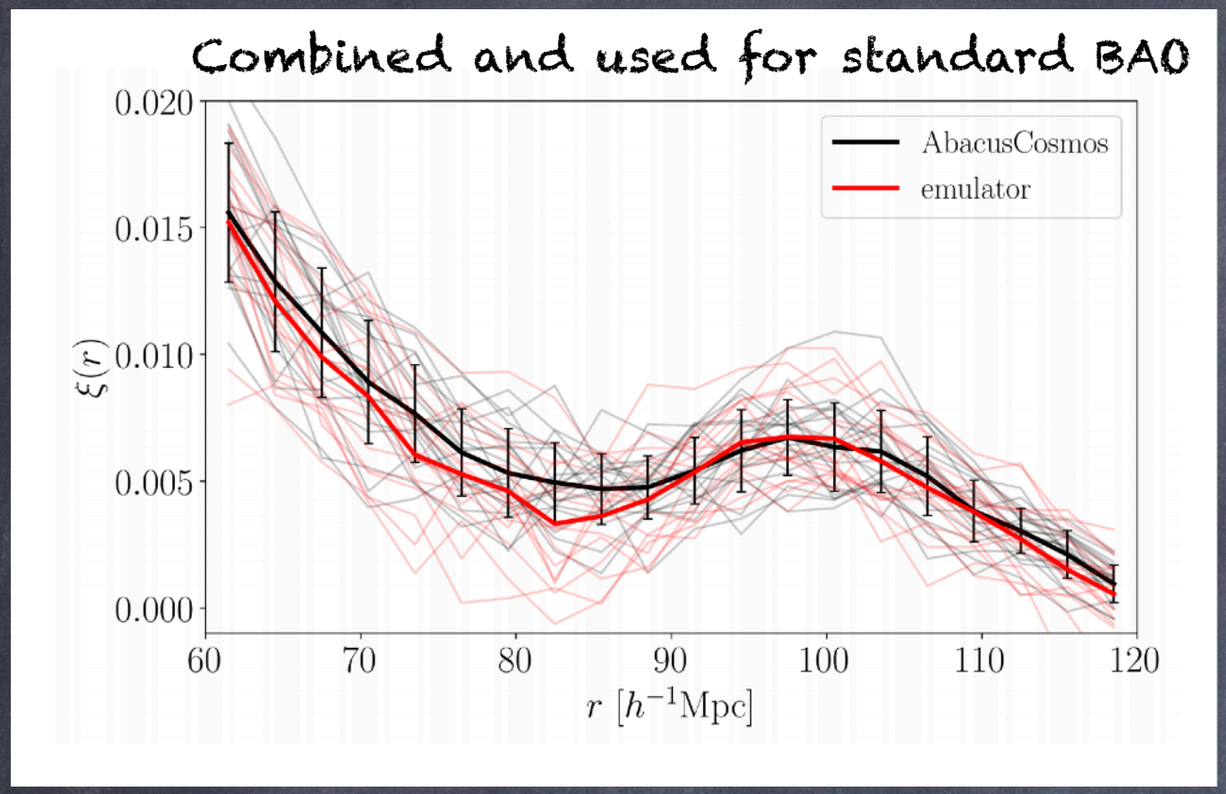
- P_{gg} ~ min. model for $\{\mathcal{B}(k,\,\mu),\,\mathcal{C}(k,\,\mu)]\}$

- $\mathcal{D}(k,\,\mu)$ -> "additional broadband" (unknown residual non-linearities and obs. syst.)

Cubic spline basis in Fourier space, based on the fid. r_d

Are we accurate enough ?

Simulations inconsistencies



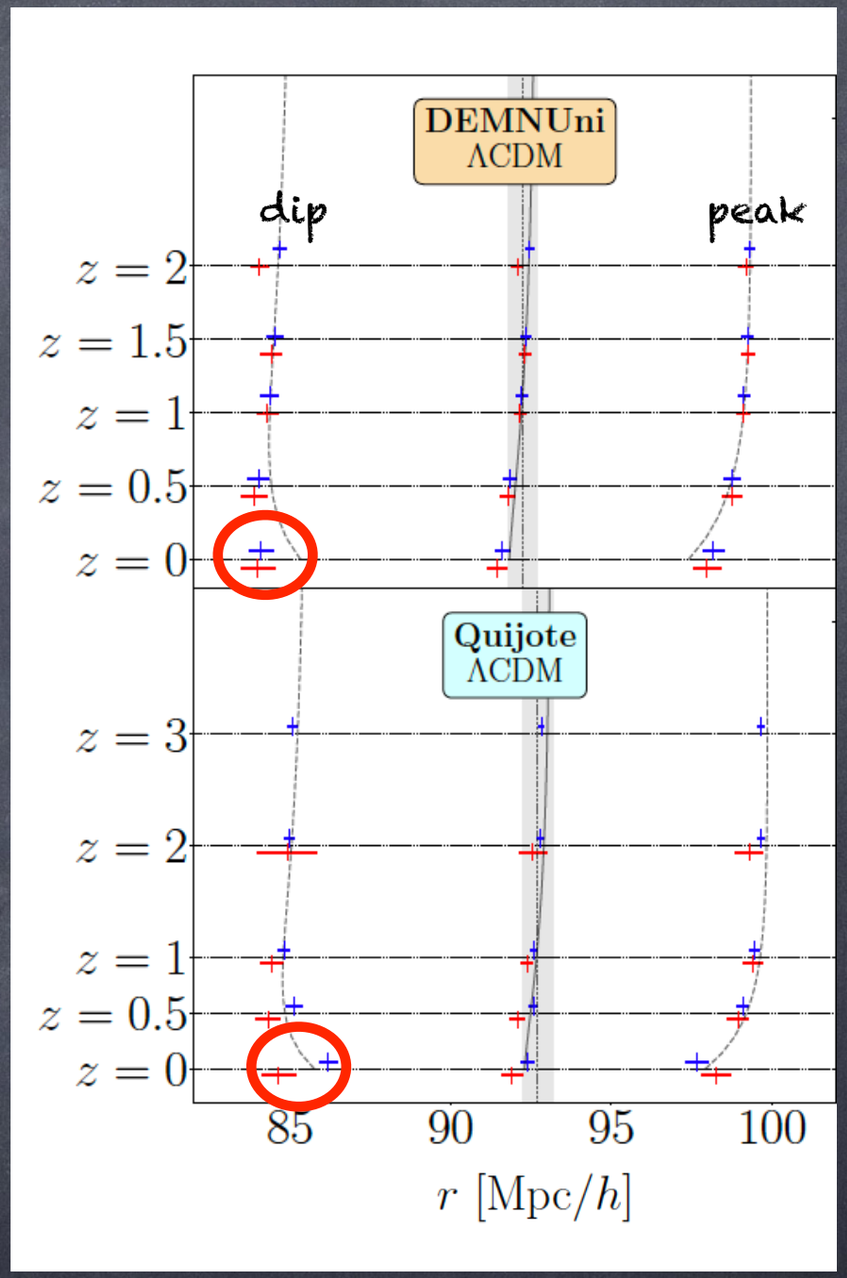
Yutong, Eisenstein (2019)

Nikakhtar, Sheth, Zehavi (2021a)

- Linear Point secular shift: 1% or 1.5% ?

  Nikakhtar, Sheth, Zehavi (2021b)

  Nikakhtar, Sheth, Lévy, Mohayaee (2022)



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

Can we claim we control systematics at better than 0.5%?