

FUNDAMENTAL PHYSICS WITH LARGE/MEDIUM/SMALL SCALE STRUCTURES

LECTURE 3

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2022 Winter School
Tenerife (Spain)

*Euclid Flagship
Simulation*



PLAN

INTRO

FUNDAMENTAL PHYSICAL TESTS "BEFORE" GALAXIES ARE FORMED
IN THE POST-REIONIZATION UNIVERSE

IGM
INTENSITY MAPPING

GALAXY CLUSTERING: DYNAMICAL AND GEOMETRICAL PROBE

WEAK LENSING

GALAXY CLUSTERS

CONNECTIONS

FABIO FINELLI: CMB x LSS

KFIR BLUM: SMALLER SCALES
PROPERTIES OF GALAXIES

LUCA AMENDOLA: MODIFICATION OF
GRAVITY/DARK ENERGY

OLGA MENA: NEUTRINOS

TRACY SLATYER: DARK MATTER

GALAXY CLUSTERING

Baumann et al. 2012 EFT of the LSS

Philcox & Ivanov 2021 - Full Shape power spectrum analysis

Manzotti, Peloso, Pietroni, MV, Villaescusa-Navarro 14 - Coarse Grained perturbation theory

Galaxy Formation and Evolution - Mo, Van Den Bosch & White book

DESI Collaboration (2016), [arXiv:1611.00037](#)

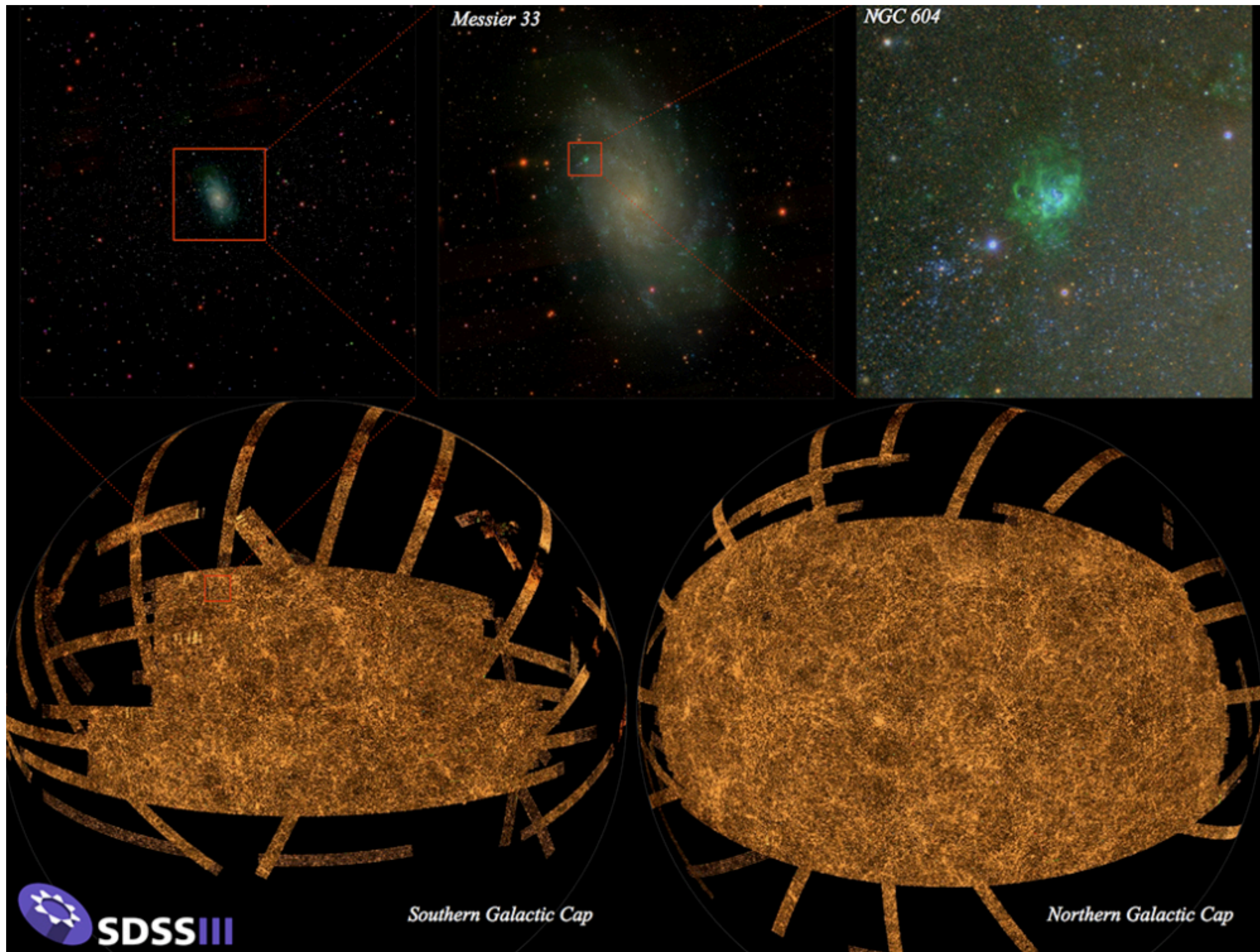
Alam et al. 2020 - full analysis of BOSS galaxy clustering

Semenaite+22, [arXiv: 2210.07304](#) - Beyond LCDM with galaxies

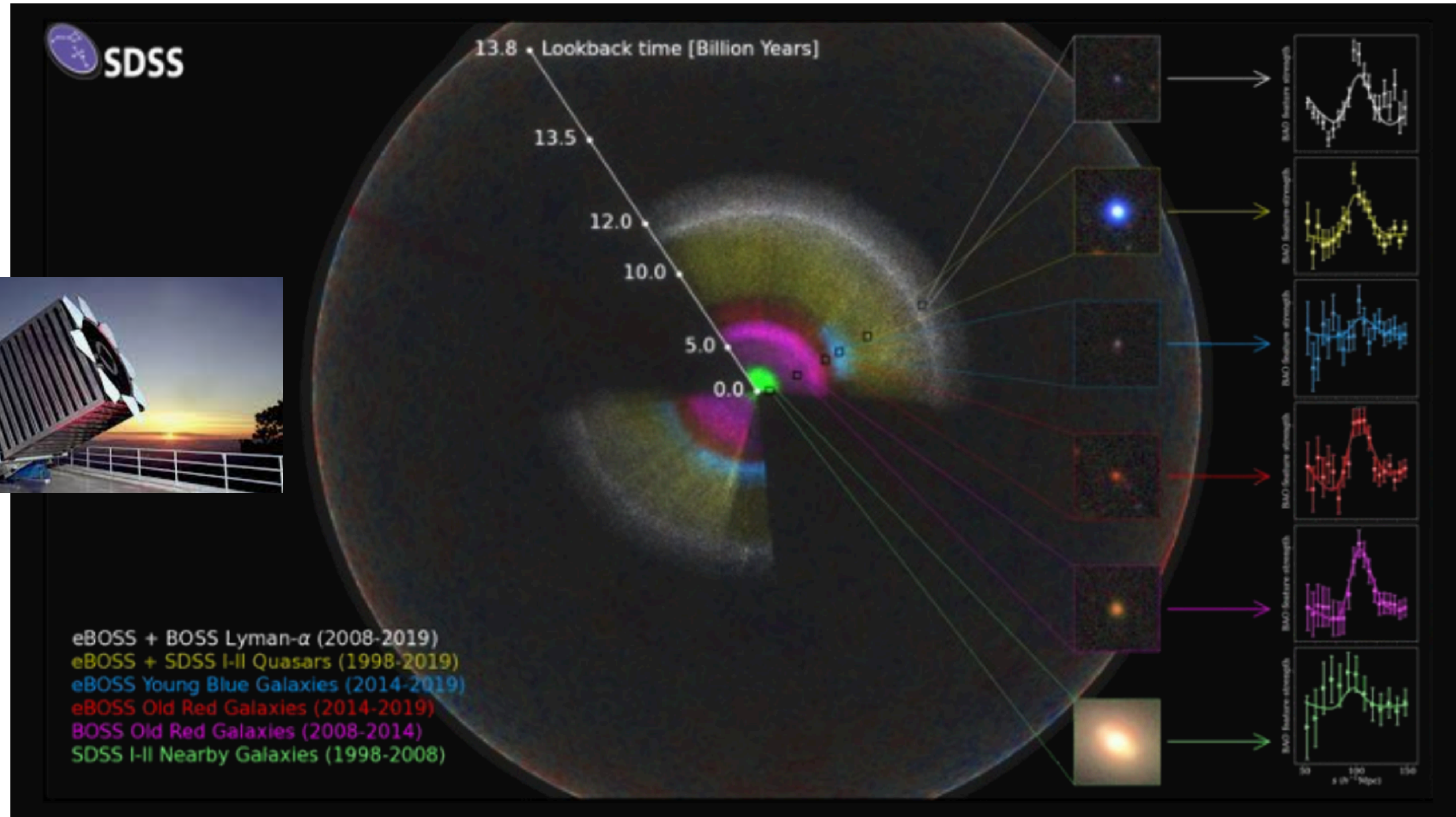
Chapman+21 - Growth with galaxy clustering

Tanseri+22 - Cross-correlation with CMB lensing

Obuljen+18 - BAO reconstruction with pixels

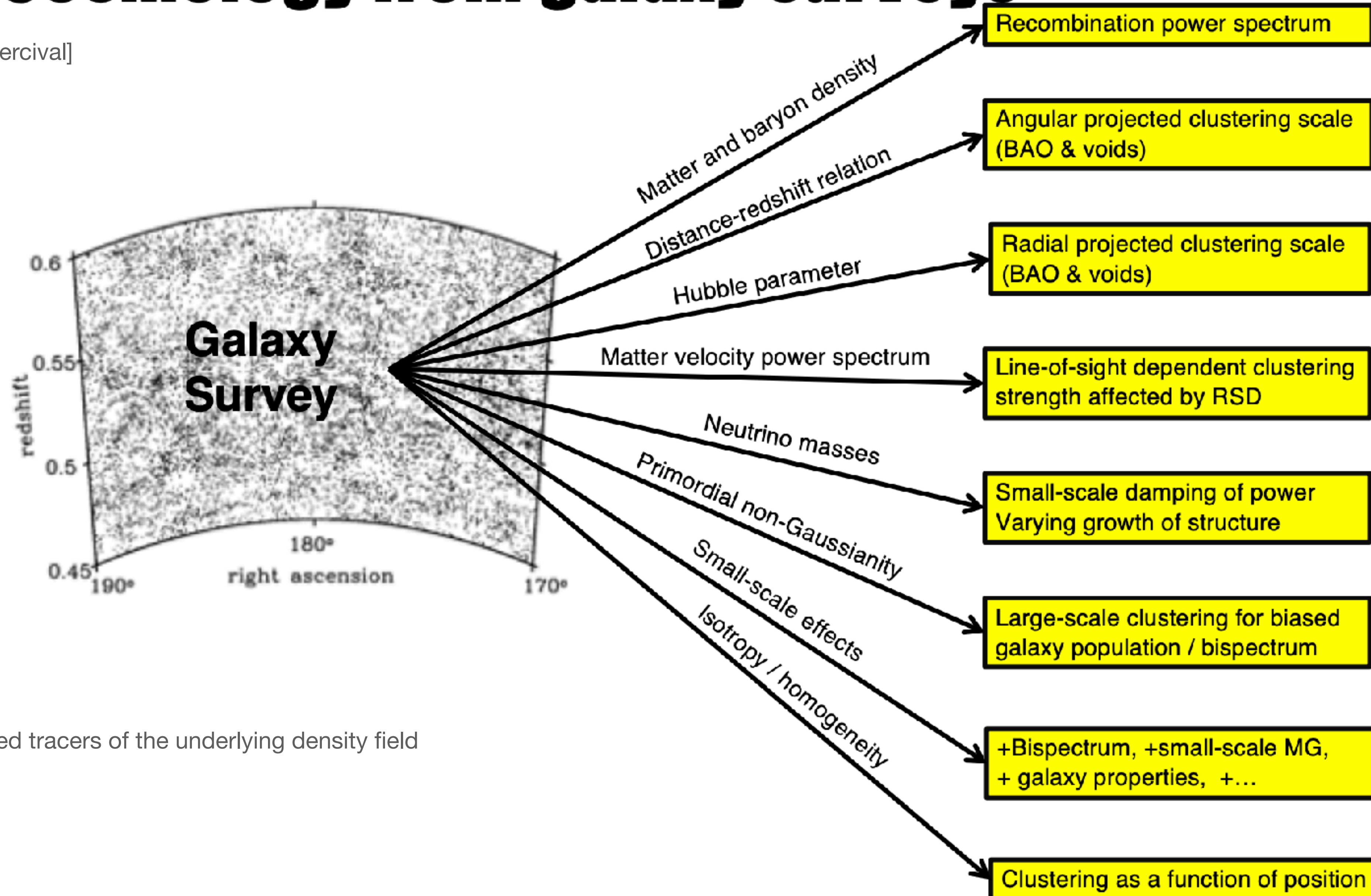


The Sloan Digital Sky Survey



Cosmology from galaxy surveys

[from Will Percival]



Galaxies biased tracers of the underlying density field

Galaxy Clustering: Basics - I

Statistical description of galaxy distribution should shed light on underlying density field

$$\xi(x) = \langle \delta_1 \delta_2 \rangle$$

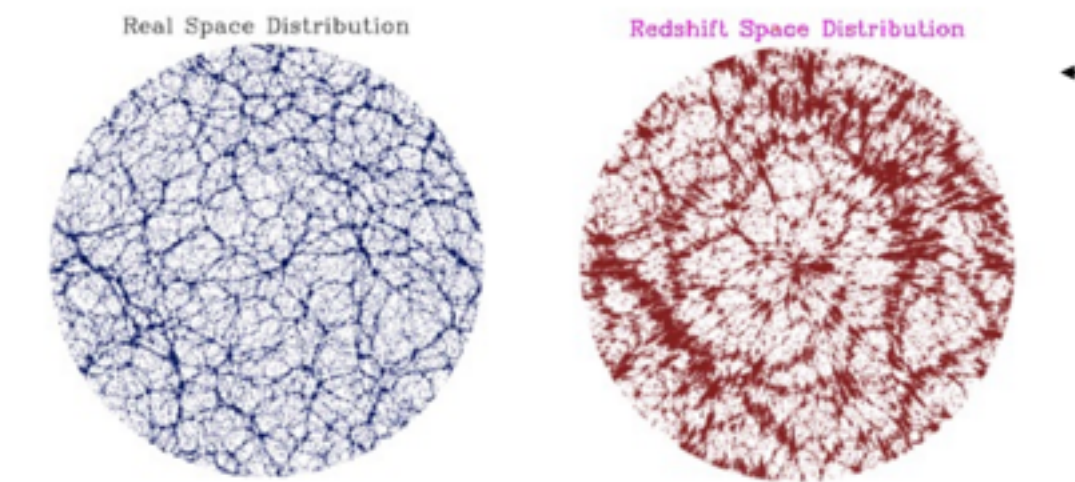
$$\xi(x) = \frac{1}{V_u} \sum_{\mathbf{k}} P(k) e^{i\mathbf{k} \cdot \mathbf{x}} = \frac{1}{(2\pi)^3} \int P(k) e^{i\mathbf{k} \cdot \mathbf{x}} d^3\mathbf{k},$$

$$P(k) = V_u \langle |\delta_{\mathbf{k}}|^2 \rangle$$

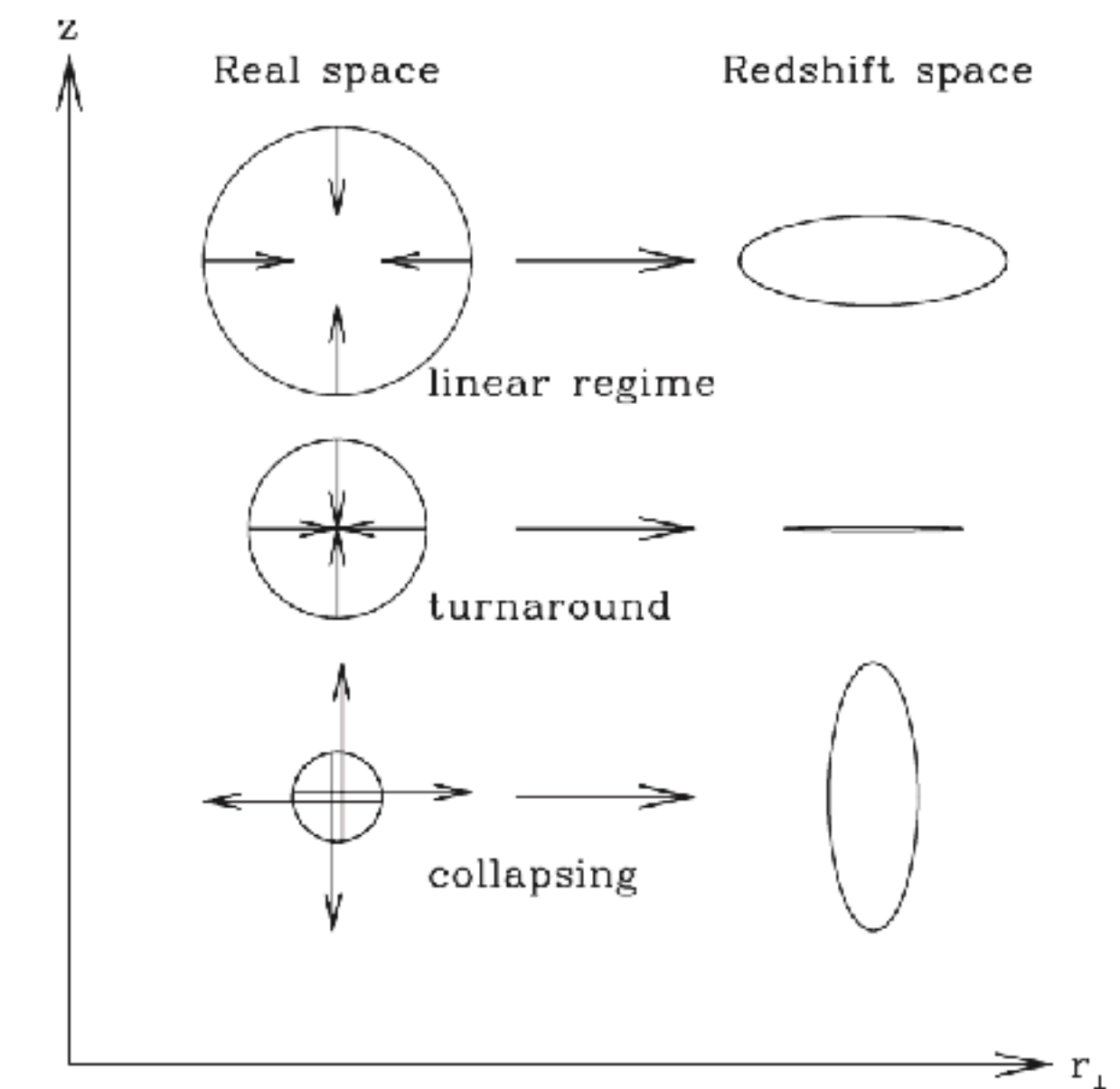
$$\left\langle p^{(1)}(\mathbf{x}_i) p^{(1)}(\mathbf{x}_i + \mathbf{x}) \right\rangle_{\mathbf{x}_i} = (\bar{n} \Delta V)^2 [1 + \xi(x)]$$

$$dN(r) = 4\pi r^2 \bar{n} [1 + \xi(r)] dr, \quad \text{Number of neighbours}$$

"Mean density profile"
around each particle



<https://feldman.ku.edu/>



Galaxy Clustering: Basics - II

Redshift space breaks the isotropy but can be used for constraining cosmological models

In linear theory....

$$\beta \equiv f(\Omega_m)/b$$

$$\delta^{(s)}(\mathbf{r}) = \left[1 + \beta \left(\frac{\partial^2}{\partial r^2} + \frac{2}{r} \frac{\partial}{\partial r} \right) \nabla_{\mathbf{r}}^{-2} \right] \delta(\mathbf{r})$$

$$\delta_{\mathbf{k}}^{(s)} = (1 + \beta \mu_{\mathbf{k}}^2) \delta_{\mathbf{k}}, \quad \text{where} \quad \mu_{\mathbf{k}} \equiv k_z/k.$$

Plane-parallel approximation

$$P^{(s)}(\mathbf{k}) = \sum_{\ell} \mathcal{P}_{\ell}(\mu_{\mathbf{k}}) P_{\ell}^{(s)}(k), \quad P_{\ell}^{(s)}(k) = \frac{2\ell+1}{2} \int_{-1}^1 P^{(s)}(\mathbf{k}) \mathcal{P}_{\ell}(\mu_{\mathbf{k}}) d\mu_{\mathbf{k}},$$

$$P_0^{(s)}(k) \equiv \left(1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2 \right) P(k)$$

$$P_2^{(s)}(k) = \left(\frac{4}{3}\beta + \frac{4}{7}\beta^2 \right) P(k), \quad P_4^{(s)}(k) = \frac{8}{35}\beta^2 P(k).$$

Linear large-scale model for power spectrum
(Kaiser 1987, MNRAS 227)

$$P^s(\mathbf{k}) = (b + f\mu^2)^2 P(k)$$

Redshift-space power spectrum

RSD term depends on $f\sigma_8$

Linear deterministic local bias

Angular correlation function, projected correlation function, evolution of correlation function etc.

Galaxy Clustering: Basics - III

But galaxies cannot be treated just like points

Selection effects: magnitude limited sample and/or volume limited sample

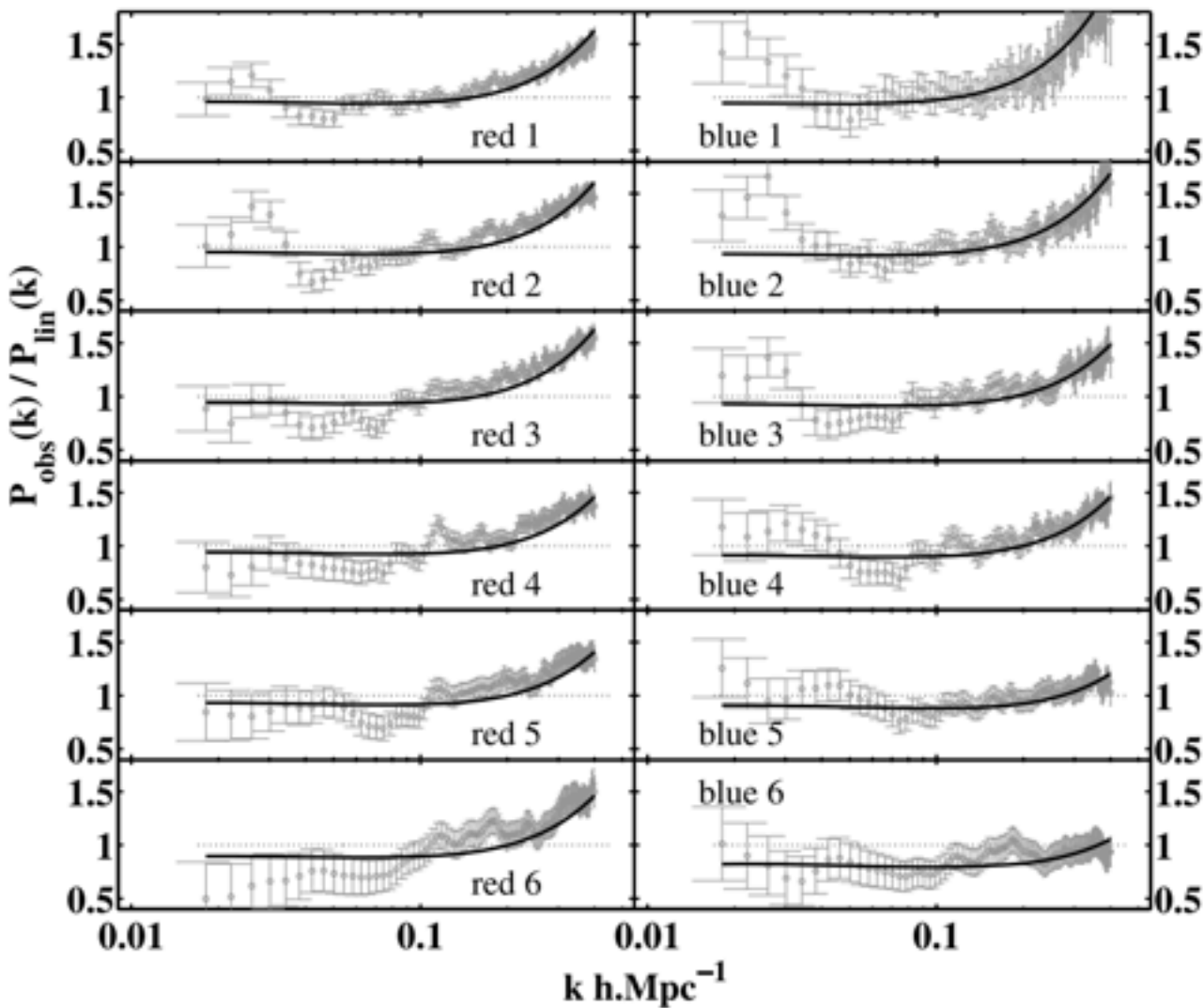
.... galaxy bias

$$b(k) = b_{\text{lin}} \sqrt{\frac{1 + Qk^2}{1 + Ak}}$$

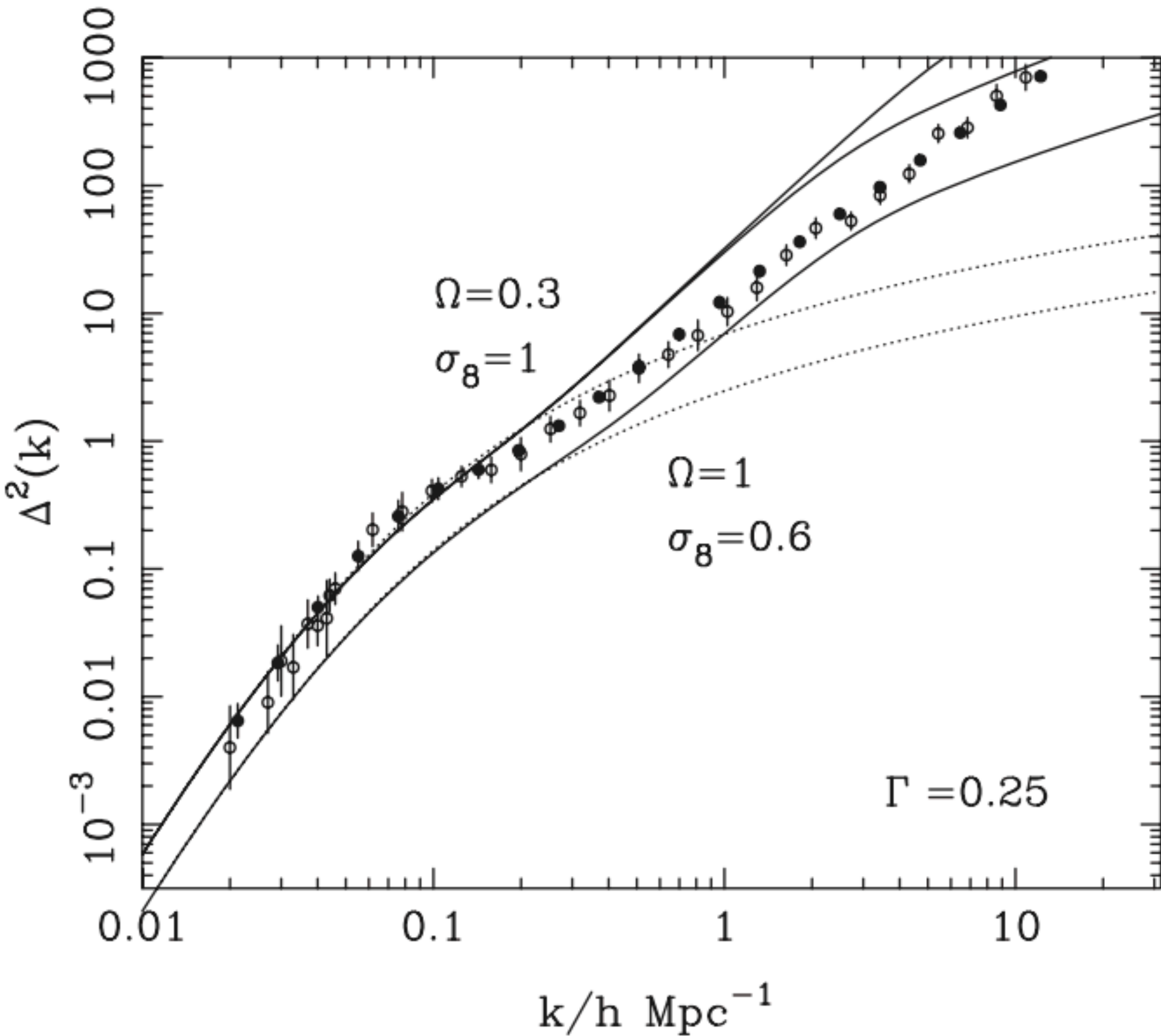
On top of that window function not really easy to deal with

Cresswell & Percival 2009

Bin	Absolute magnitude range	Mean $M_{0.1_r}$	Galaxy count
Red 1	$-22.30 \leq M_{0.1_r} < -21.35$	-21.79 ± 0.27	49 167
Red 2	$-21.35 \leq M_{0.1_r} < -20.89$	-21.12 ± 0.13	41 462
Red 3	$-20.89 \leq M_{0.1_r} < -20.47$	-20.70 ± 0.12	37 819
Red 4	$-20.47 \leq M_{0.1_r} < -20.00$	-20.27 ± 0.14	34 651
Red 5	$-20.00 \leq M_{0.1_r} < -19.34$	-19.75 ± 0.19	29 742
Red 6	$-19.34 \leq M_{0.1_r} < -17.00$	-19.01 ± 0.38	17 582
Blue 1	$-22.30 \leq M_{0.1_r} < -21.35$	-21.67 ± 0.24	17 480
Blue 2	$-21.35 \leq M_{0.1_r} < -20.89$	-21.22 ± 0.13	25 208
Blue 3	$-20.89 \leq M_{0.1_r} < -20.47$	-20.69 ± 0.12	28 928
Blue 4	$-20.47 \leq M_{0.1_r} < -20.00$	-20.27 ± 0.14	32 066
Blue 5	$-20.00 \leq M_{0.1_r} < -19.34$	-19.74 ± 0.19	36 889
Blue 6	$-19.34 \leq M_{0.1_r} < -17.00$	-18.91 ± 0.49	48 754



Peacock 1997 - Optical galaxies



Galaxy Clustering: Basics - IV

Galaxy (Halo) bias

$$N(1|0) dM_1 = \frac{M_0}{M_1} f(1|0) \left| \frac{dS_1}{dM_1} \right| dM_1,$$

Number of haloes

M0 could be halo

mass or mass of a Lagrangian region (not collapsed)

$$f(1|0) dS_1 \equiv \frac{1}{\sqrt{2\pi}} \frac{\delta_1 - \delta_0}{(S_1 - S_0)^{3/2}} \exp \left[-\frac{(\delta_1 - \delta_0)^2}{2(S_1 - S_0)} \right] dS_1.$$

.....

$$\delta_h^L(1|0) = \frac{N(1|0)}{n(M_1, z_1) V_L} - 1, \quad \text{where } V_L \equiv \frac{4\pi}{3} R_0^3.$$

$$\delta_h^L(1|0) = \frac{\nu_1^2 - 1}{\delta_1} \delta_0, \quad \text{where } \nu_1 = \frac{\delta_1}{\sqrt{S_1}}.$$

$$\delta_h(1|0) = \frac{N(1|0)}{n(M_1, z_1) V_L} \frac{V_L}{V_E} - 1, \quad V_L/V_E = 1 + \delta(t),$$

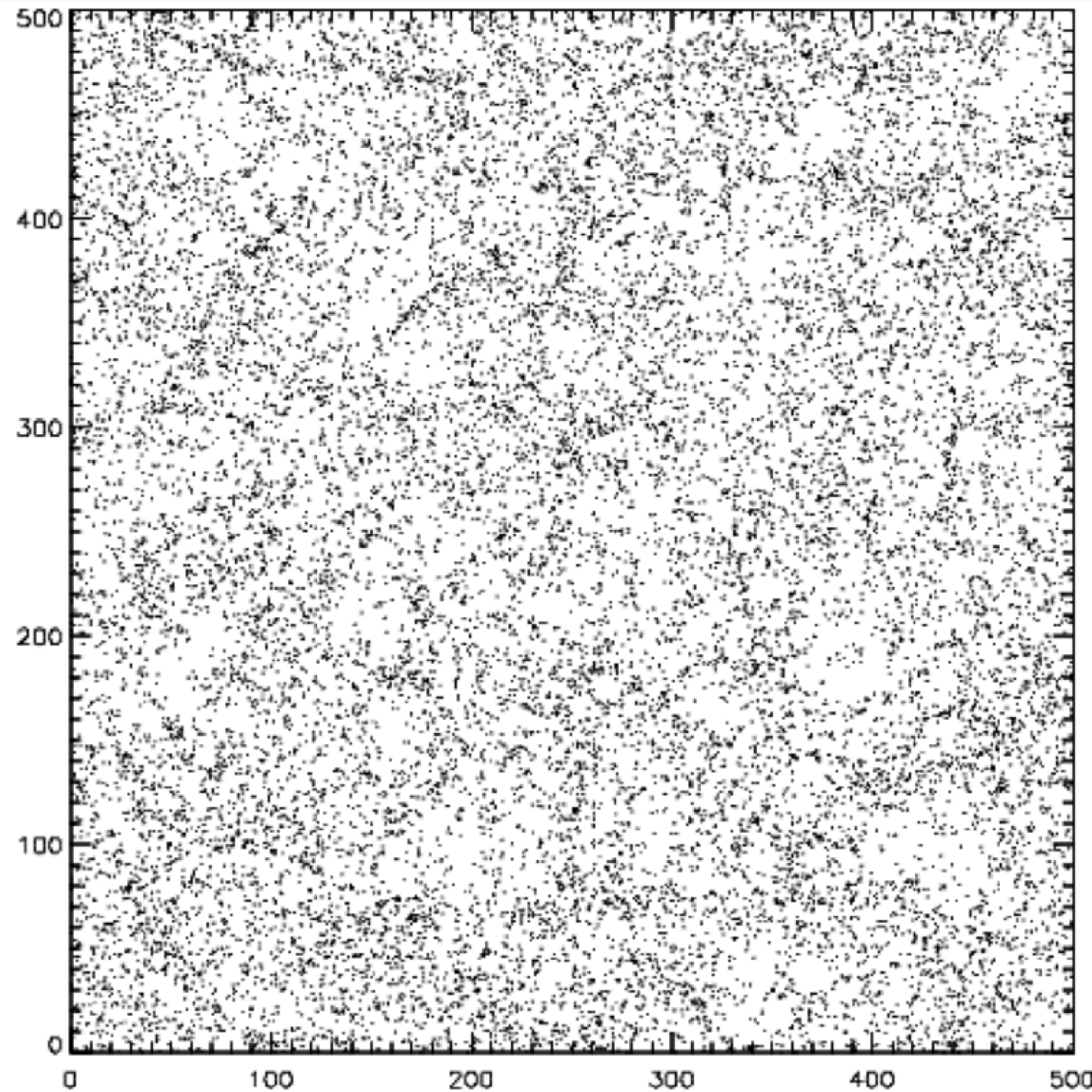
$$\delta_h(1|0) = \delta(t) + \frac{\nu_1^2 - 1}{\delta_1} \delta_0 + \frac{\nu_1^2 - 1}{\delta_1} \delta_0 \delta(t)$$

$$\delta_h(1|0) = b_h(M_1, \delta_1; t) \delta(t),$$

$$b_h(M_1, \delta_1; t) = 1 + \frac{1}{D(t)} \left(\frac{\nu_1^2 - 1}{\delta_1} \right)$$

Simple (linear) bias model

Galaxy Clustering: Assembly bias - I

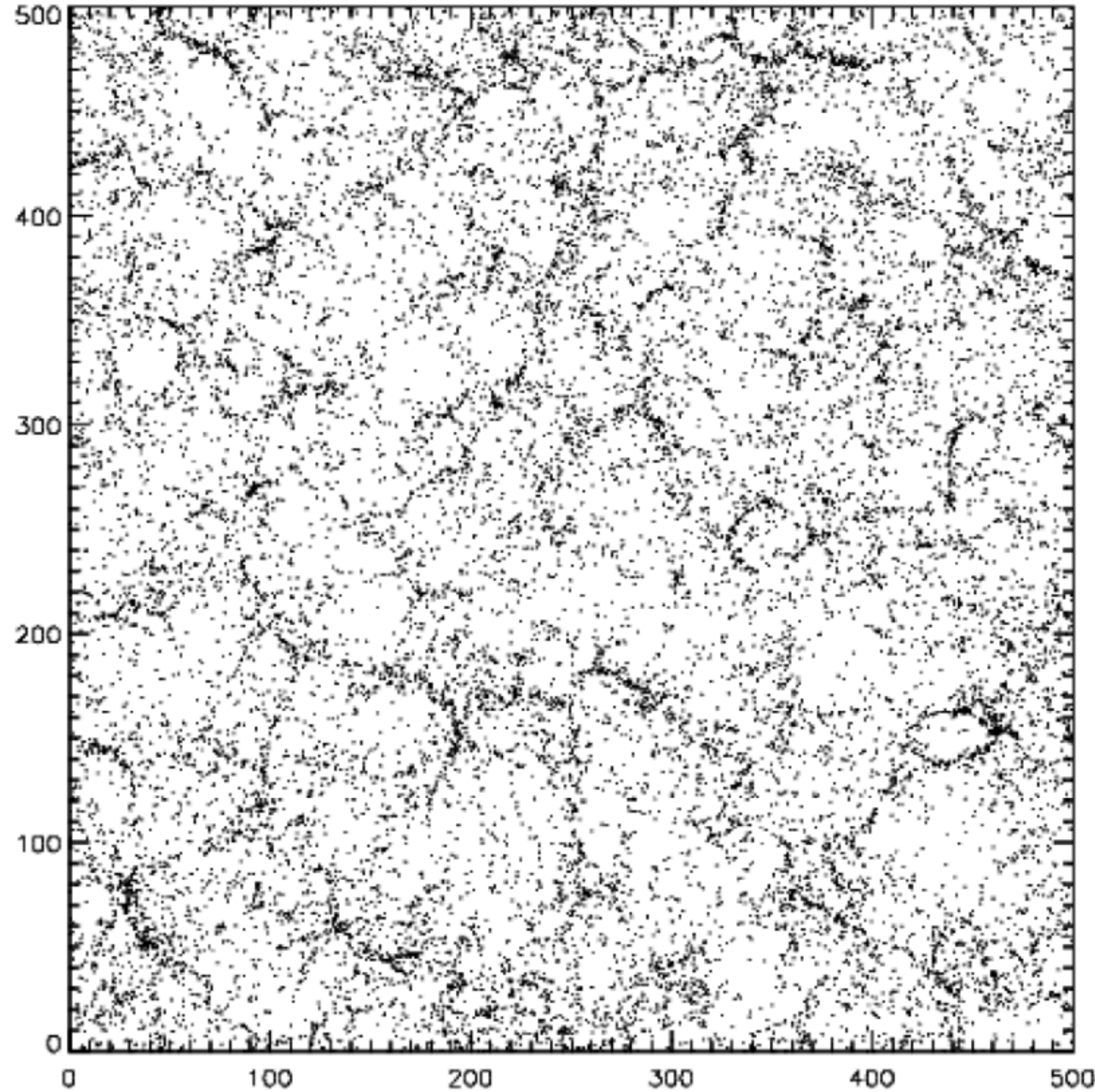


Gao, Springel & White 2005

The 20% of halos with the *latest* half-mass assembly redshifts in a 30 Mpc/h thick slice

$$M_{\text{halo}} \sim 10^{11} M_{\odot}$$

Galaxy Clustering: Assembly bias - II

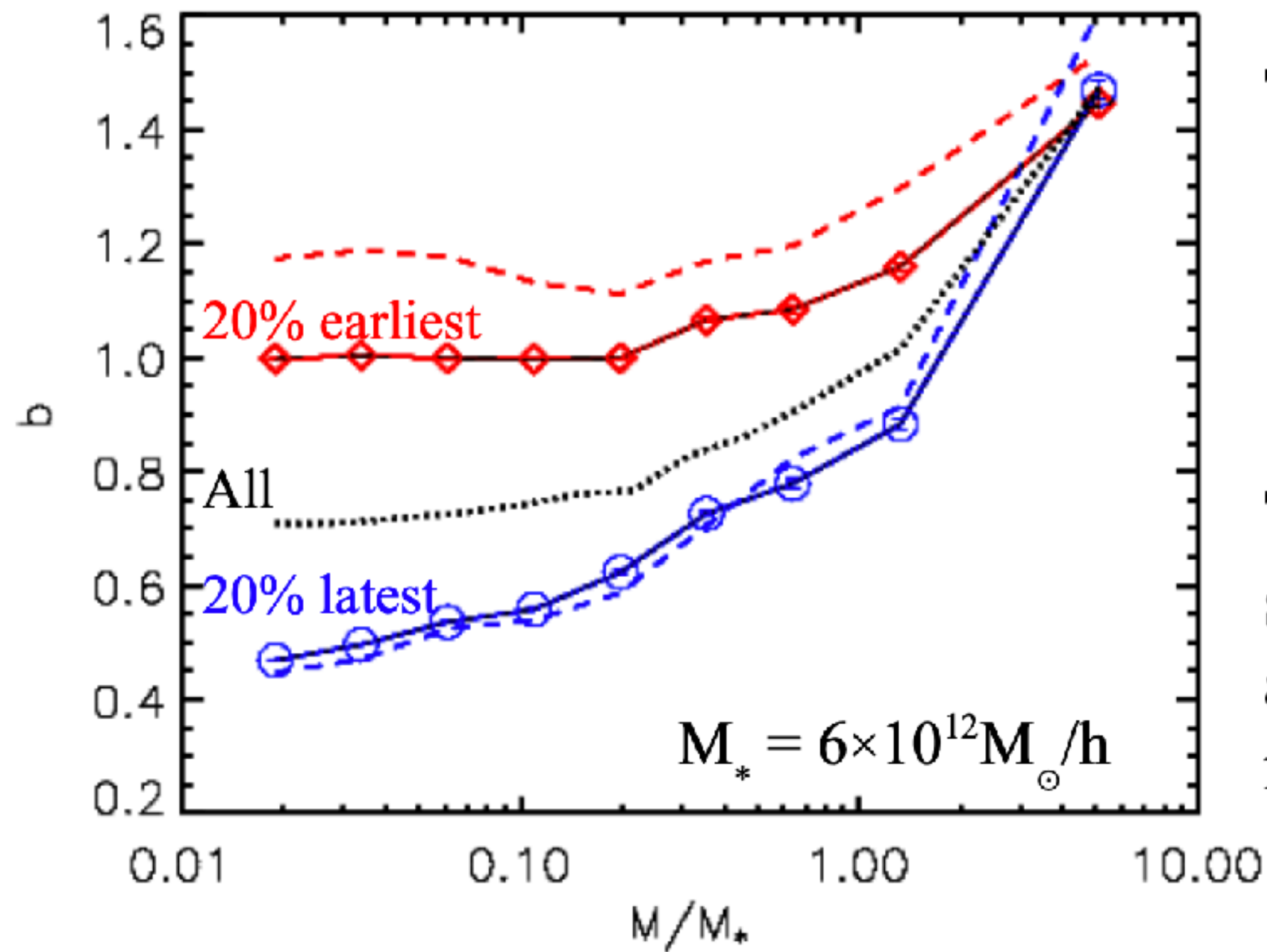


Gao, Springel & White 2005

The 20% of halos with the *earliest* half-mass assembly redshifts in a 30 Mpc/h thick slice

$$M_{\text{halo}} \sim 10^{11} M_{\odot}$$

Galaxy Clustering: Assembly bias - III



The dependence of bias on formation redshift is strongest at low mass

This behaviour is inconsistent with simple versions of excursion set theory, and of HOD and halo abundance matching models

Halo bias will not depend only on halo mass but also:

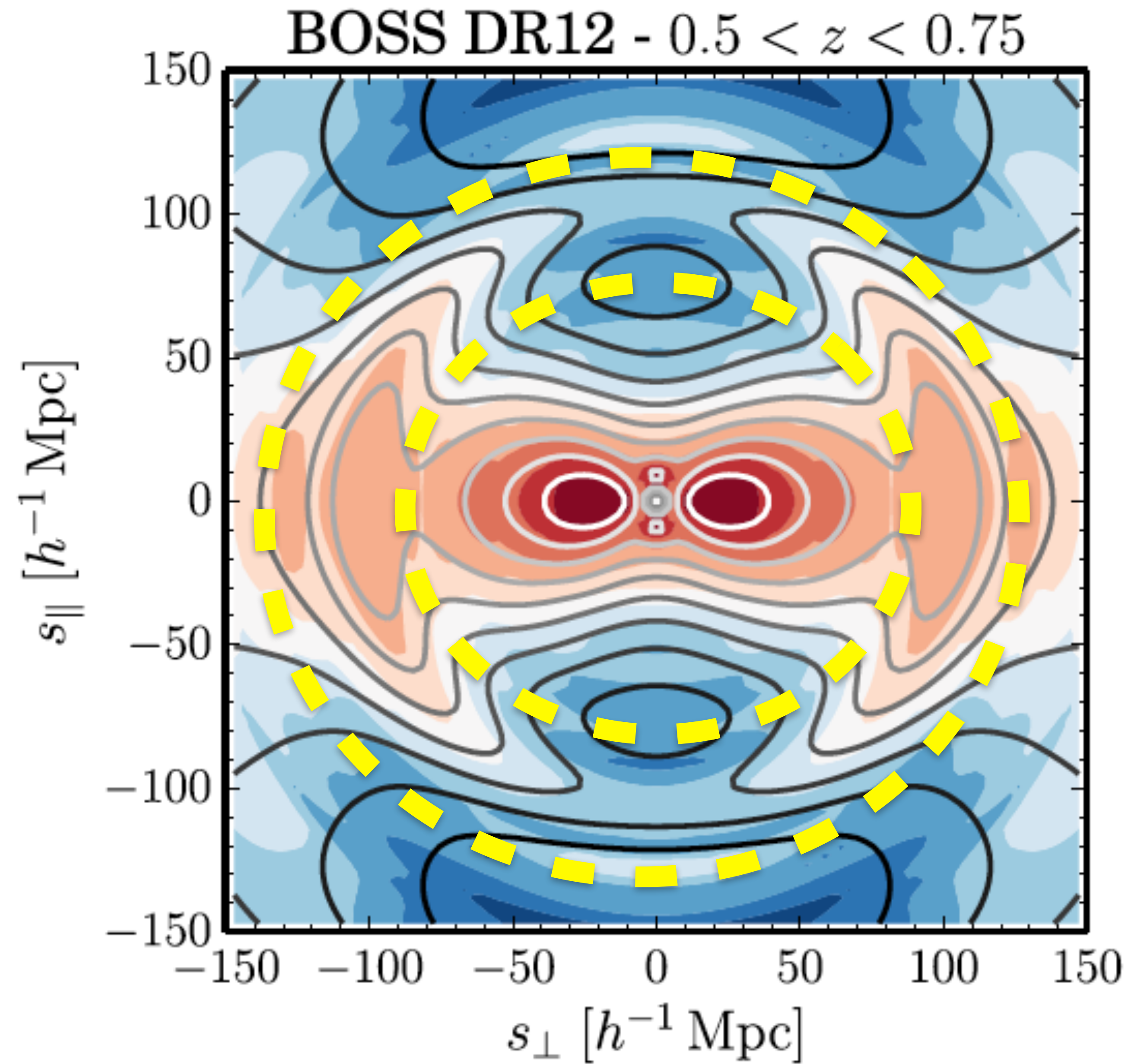
formation time
concentration
substructure content
spin
shape
saddle density
velocity anisotropy
.....



Problems for HOD
Halo Occupation Distribution
Approaches

including Intensity Mapping mocks-like
approaches

Baryonic Acoustic Oscillations



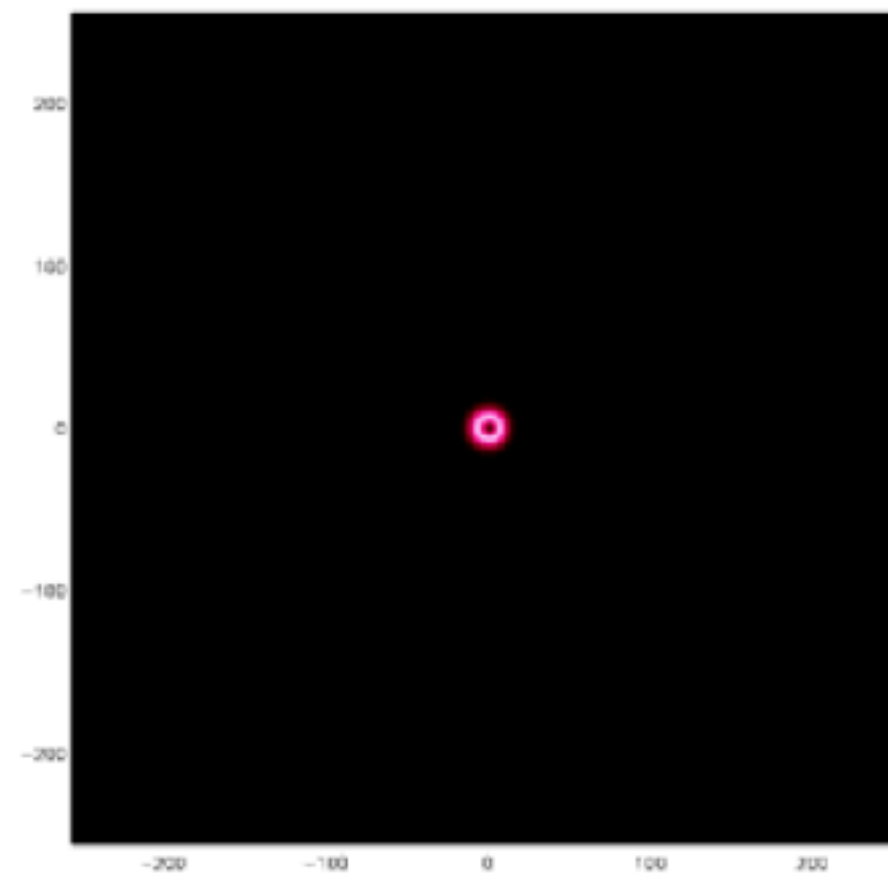
Combined effect of:

- 1) BAO
- 2) RSDs
- 3) for theory modelling (Alcock-Paczynski test)

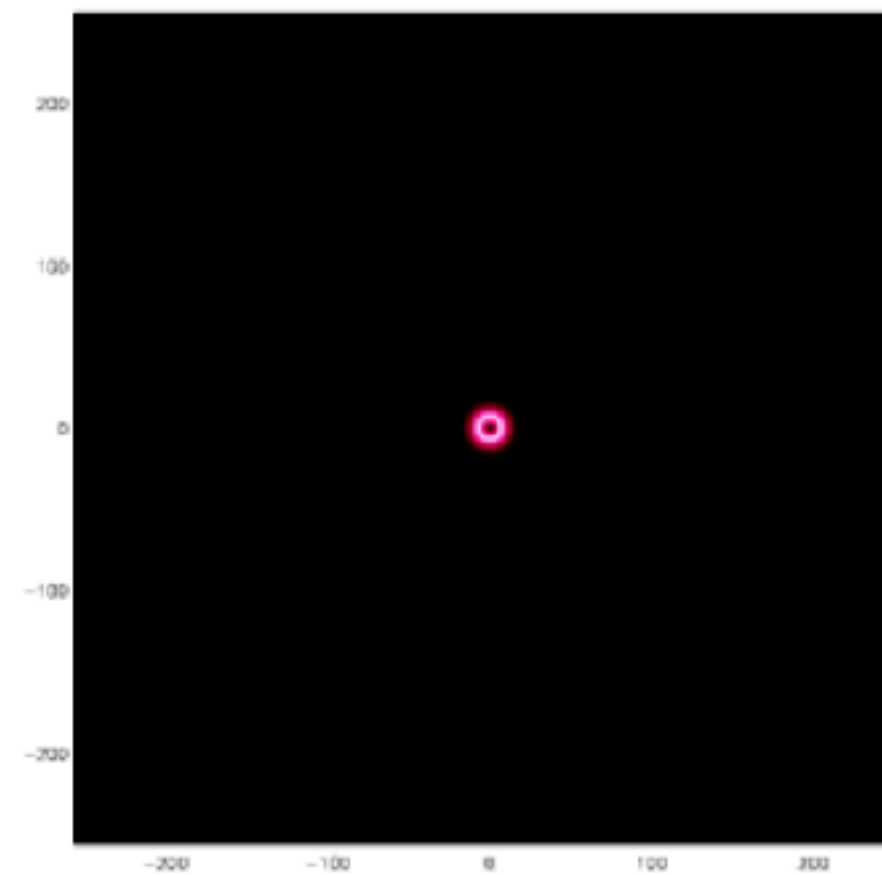
The acoustic wave

Start with a single perturbation. The plasma is totally uniform except for an excess of matter at the origin.

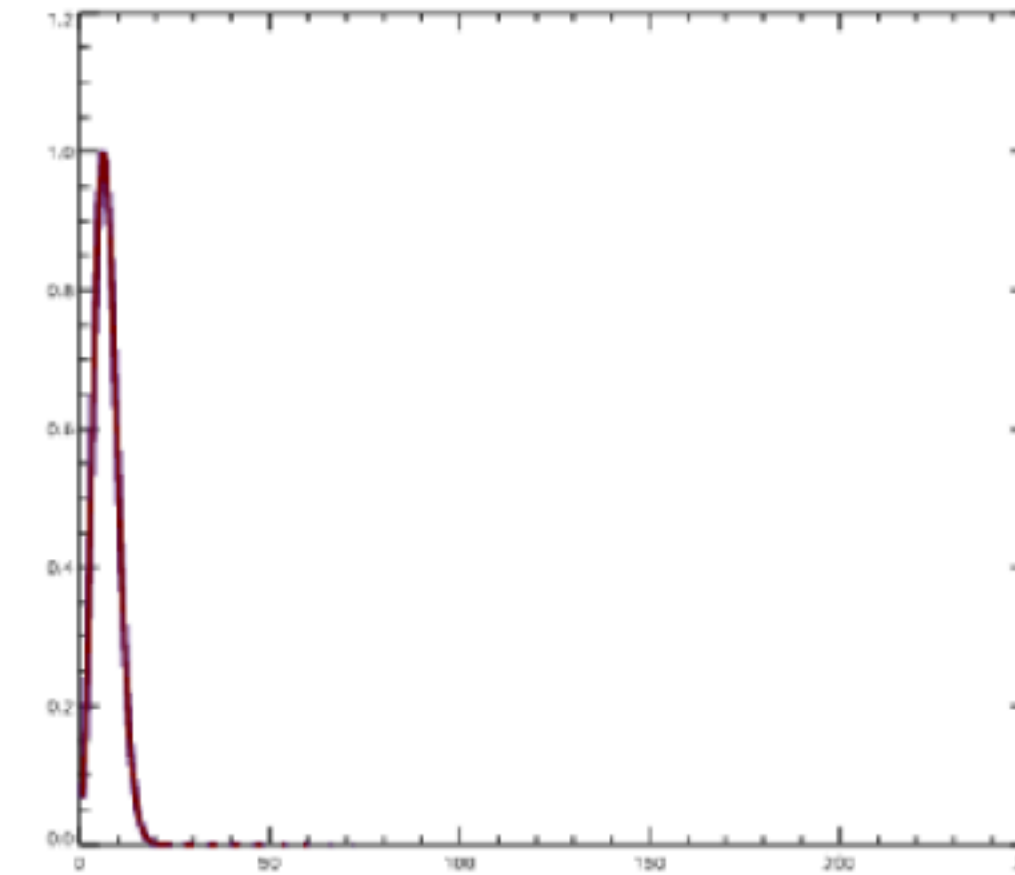
High pressure drives the gas+photon fluid outward at speeds approaching the speed of light.



Baryons



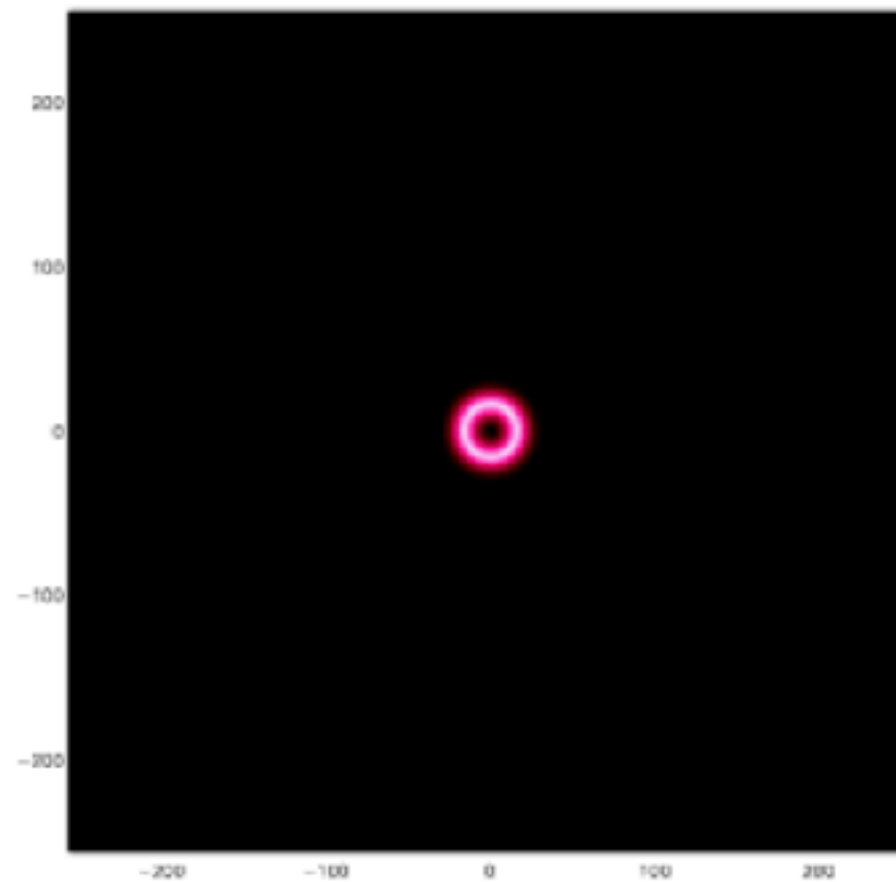
Photons



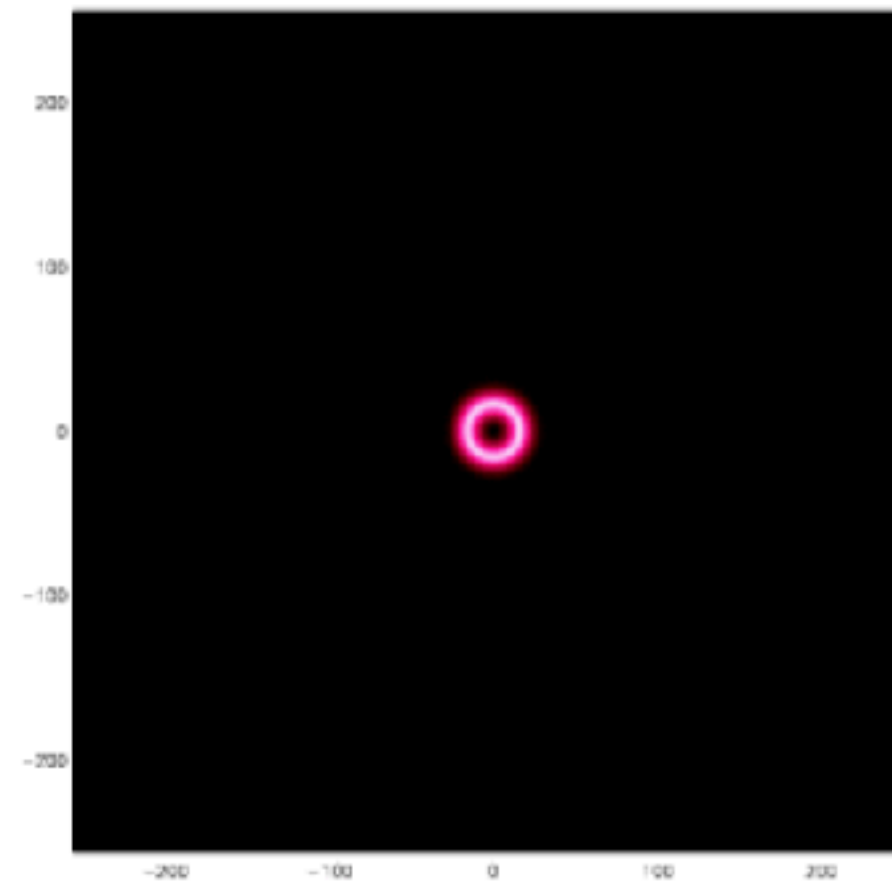
Mass profile

The acoustic wave

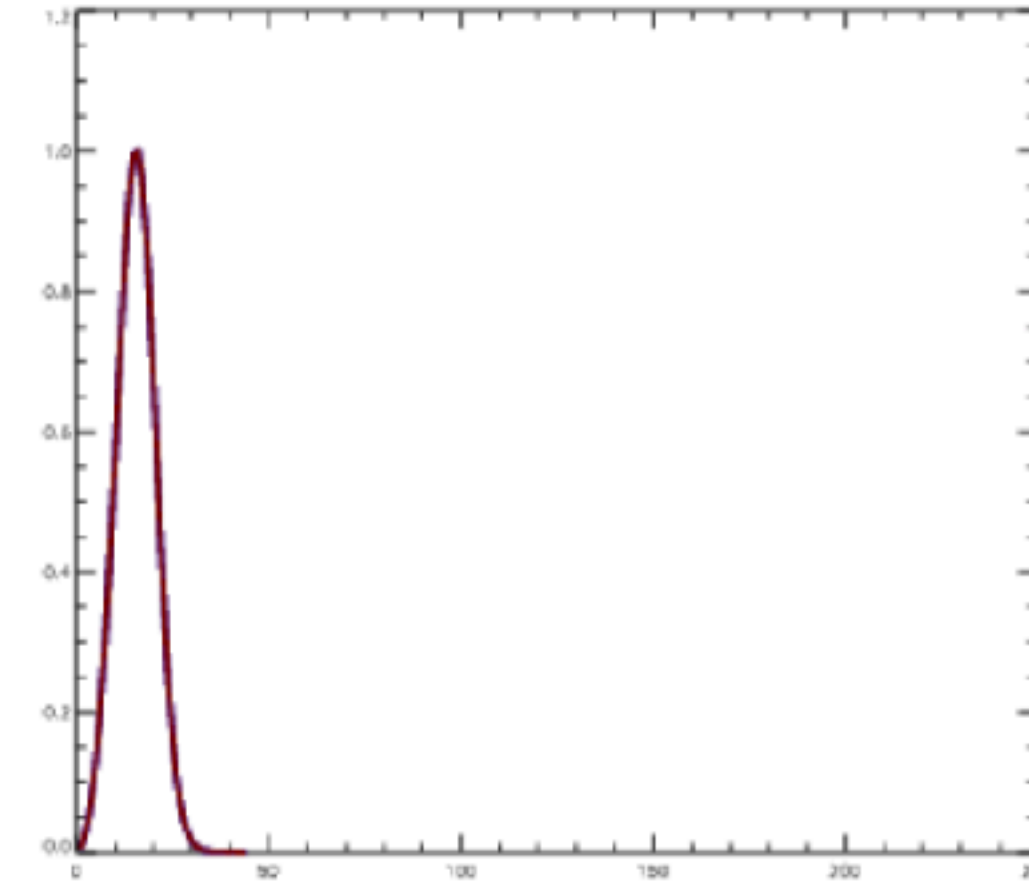
Initially both the photons and the baryons move outward together, the radius of the shell moving at over half the speed of light.



Baryons

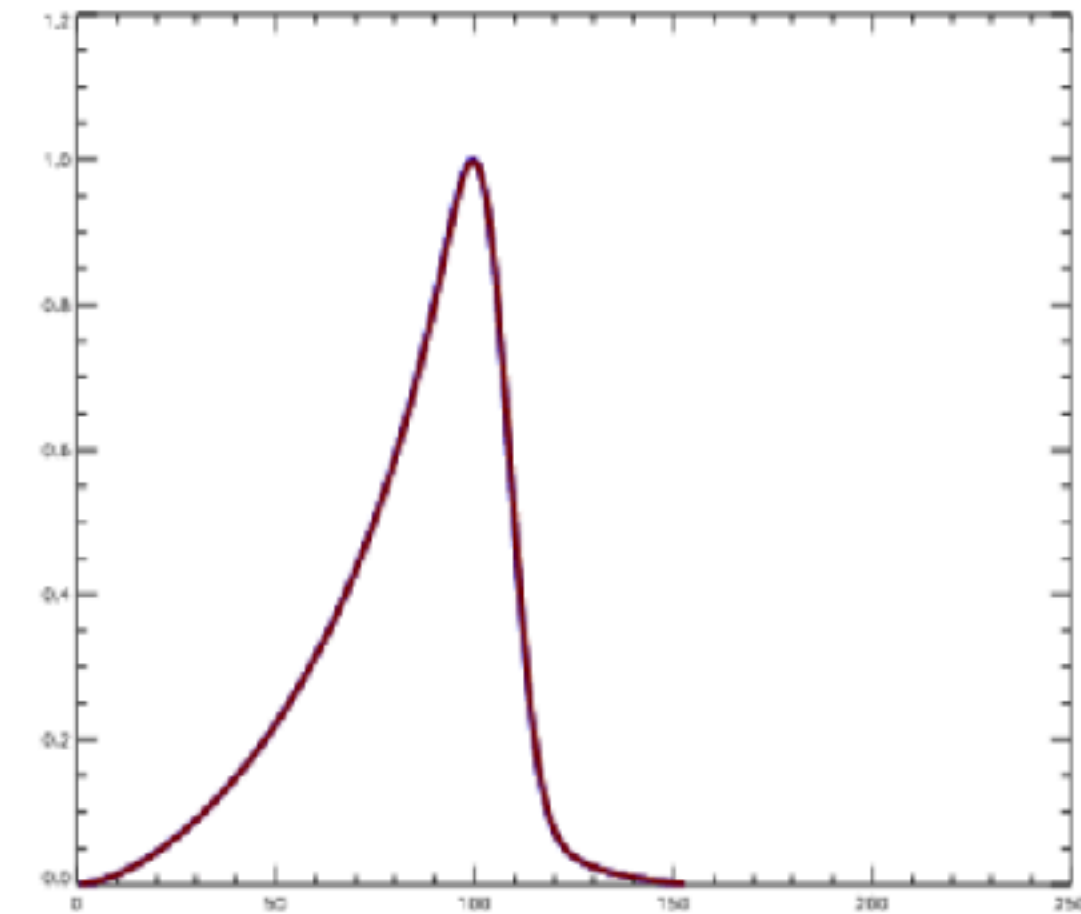
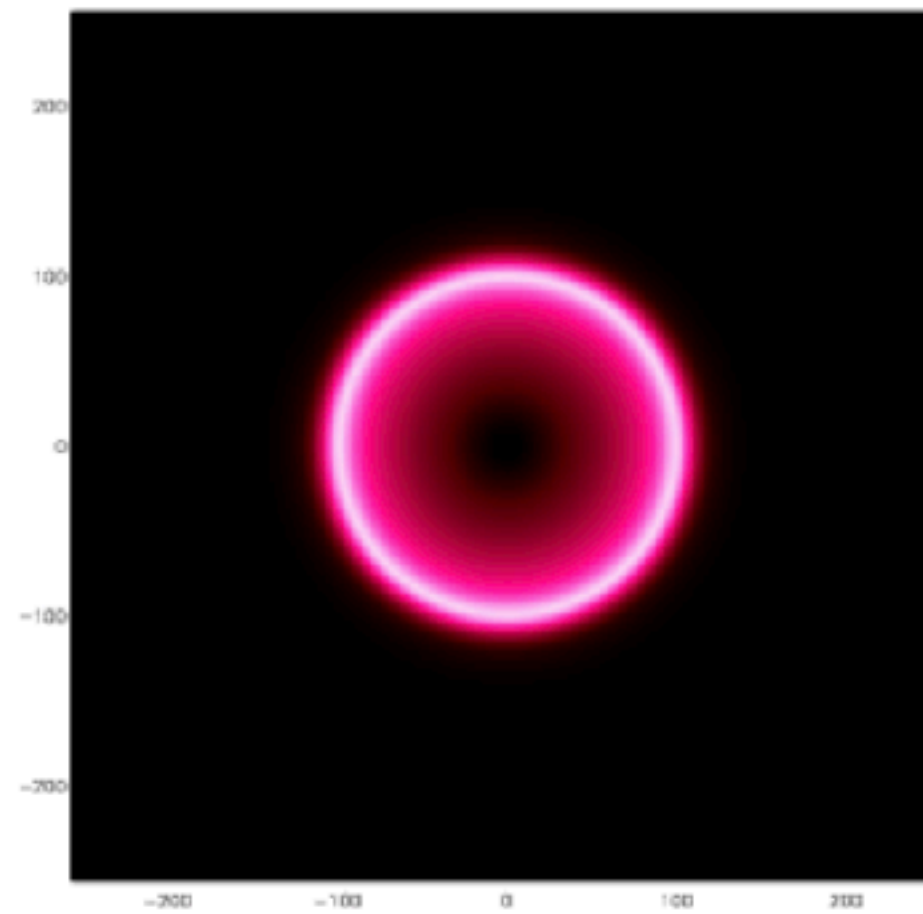
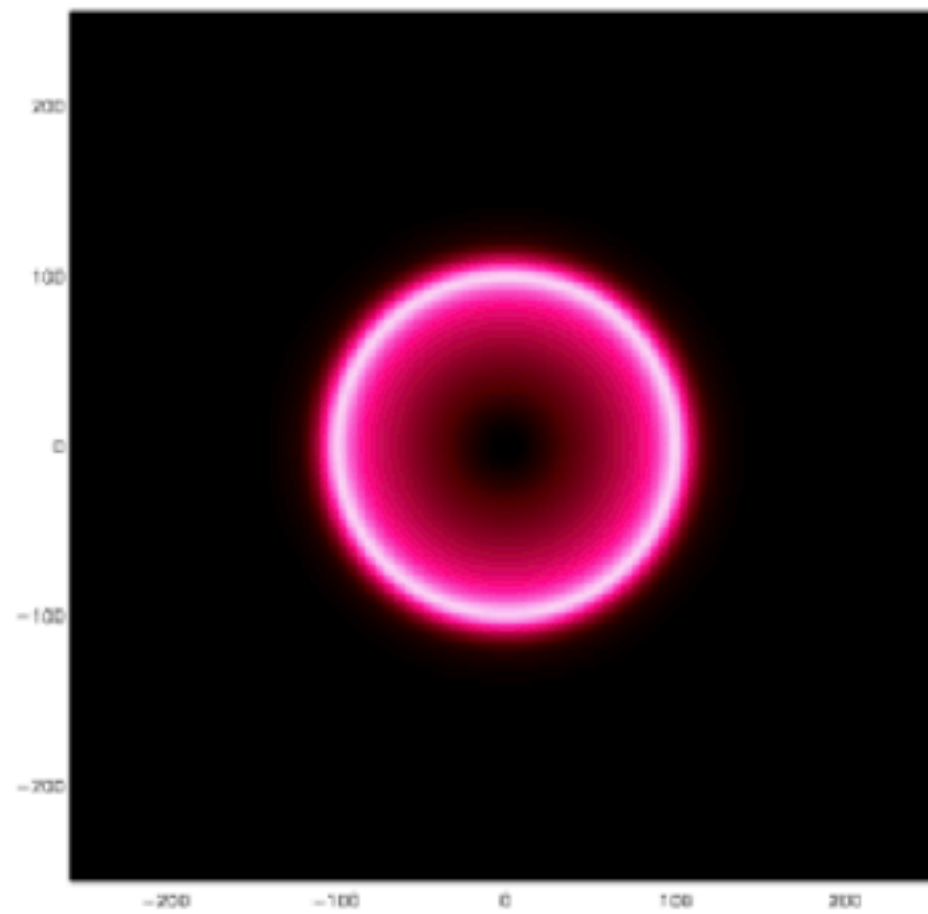


Photons



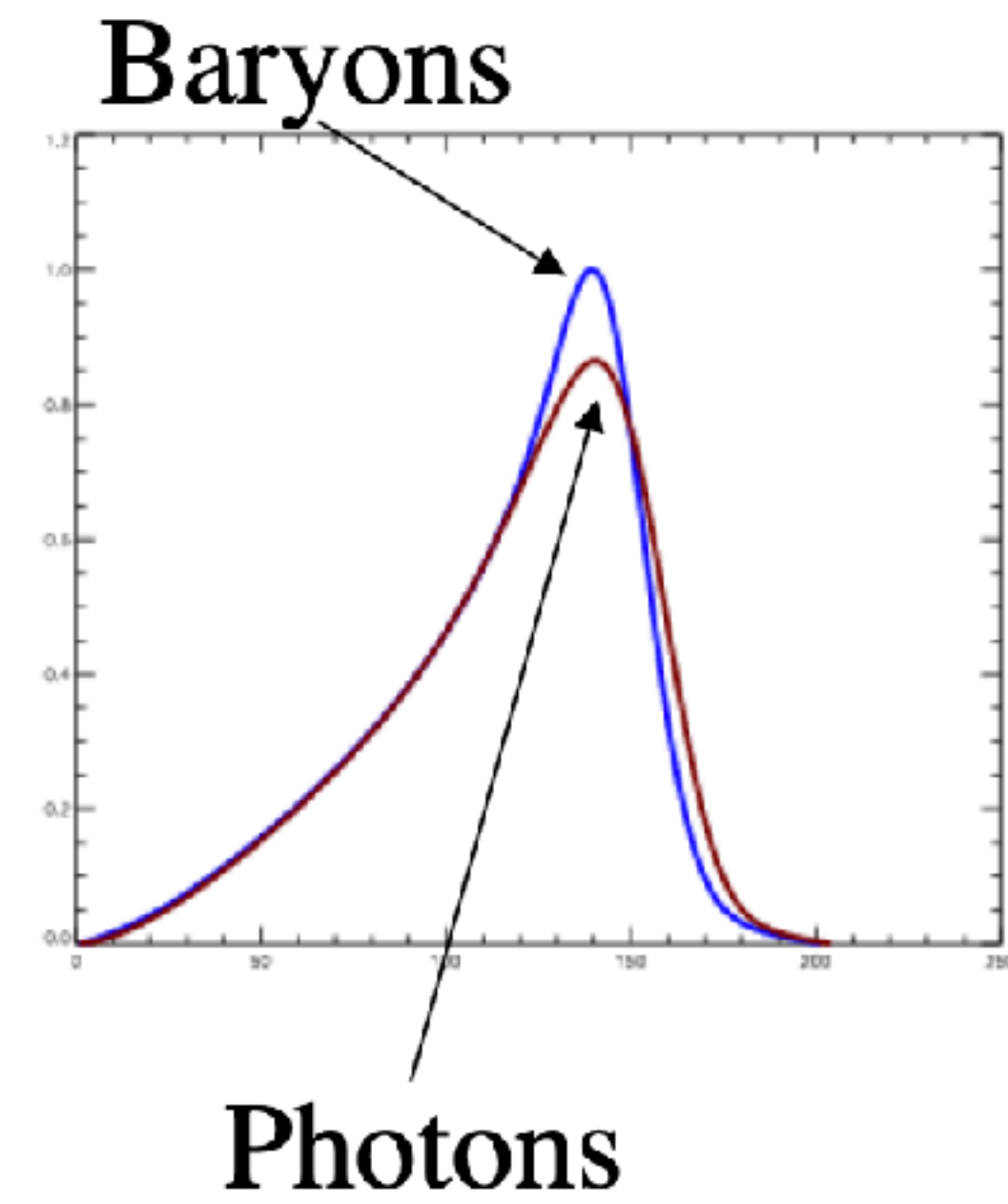
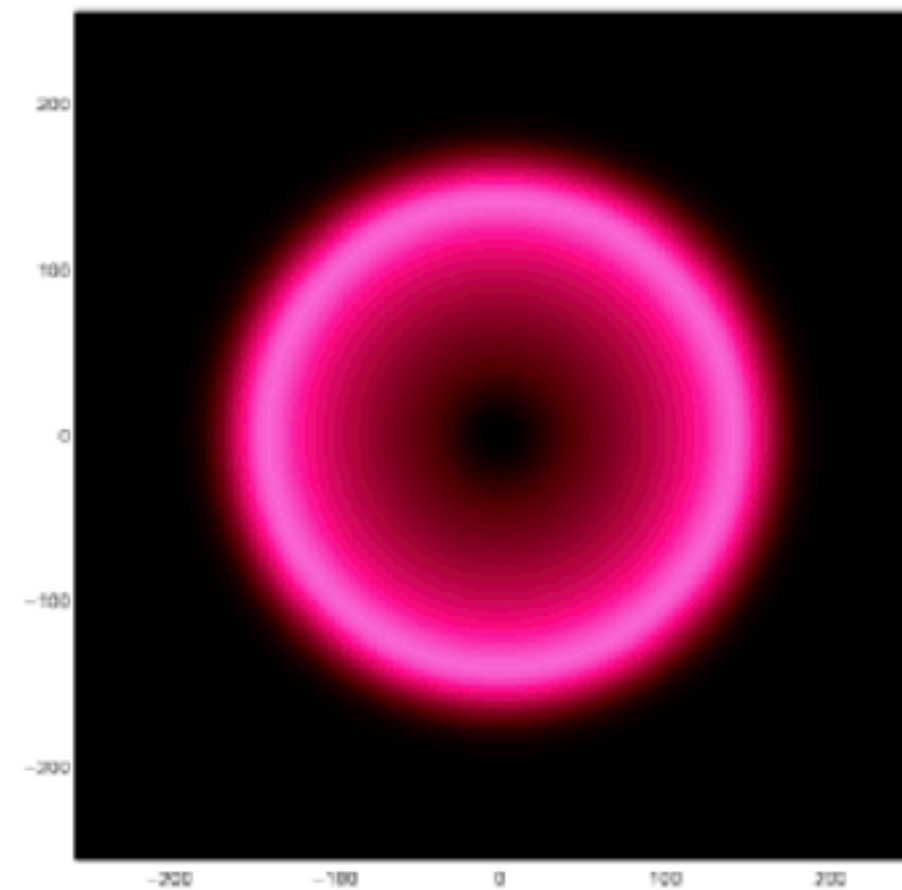
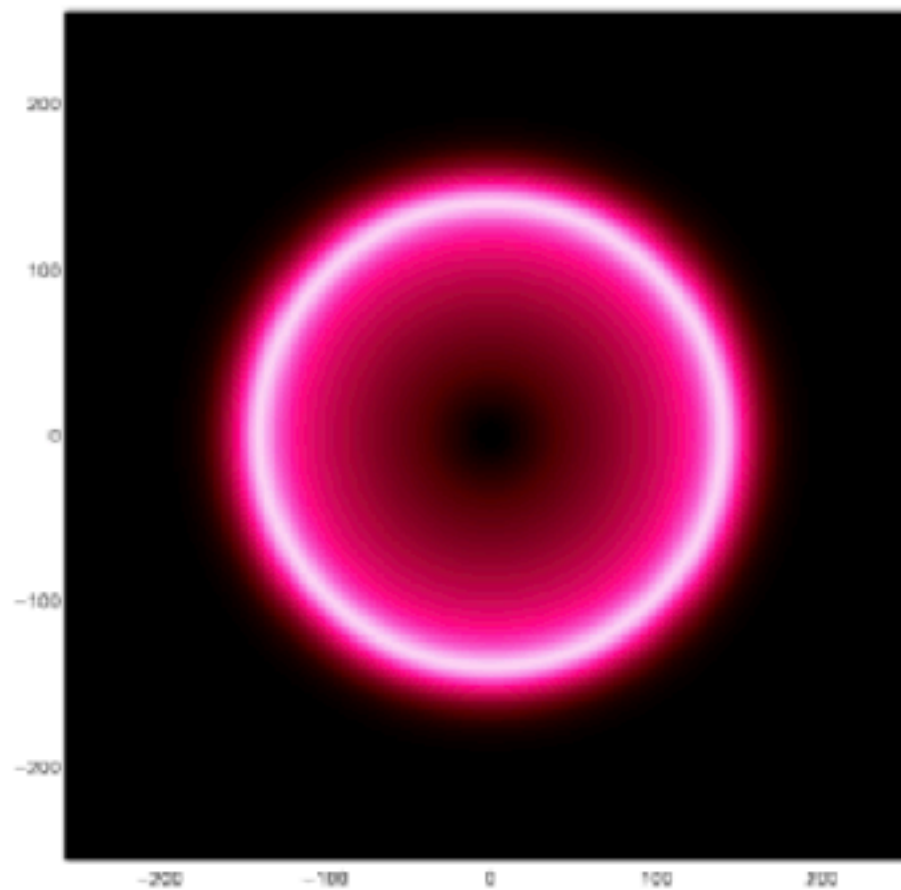
The acoustic wave

This expansion continues for 10^5 years



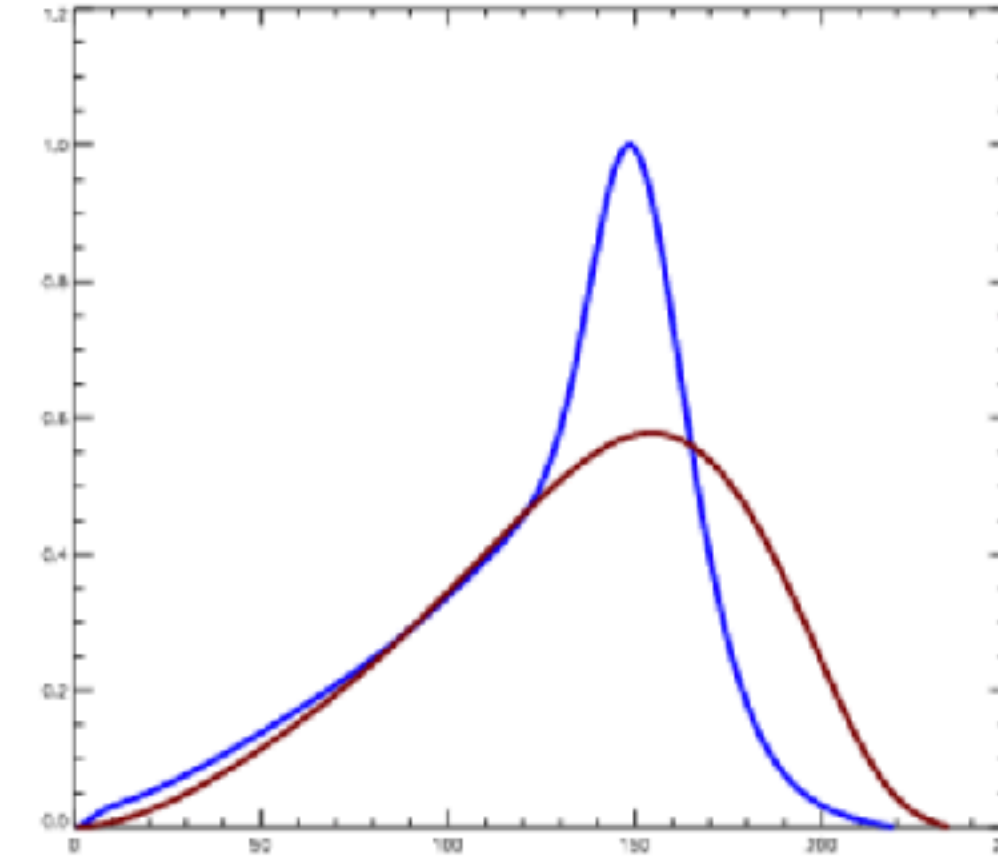
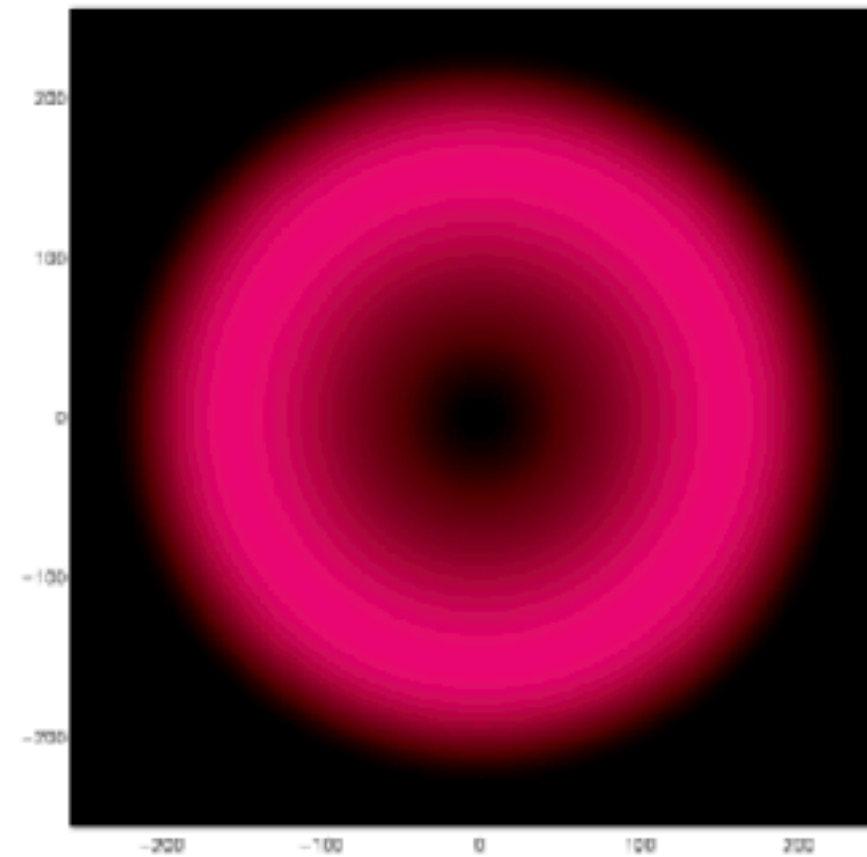
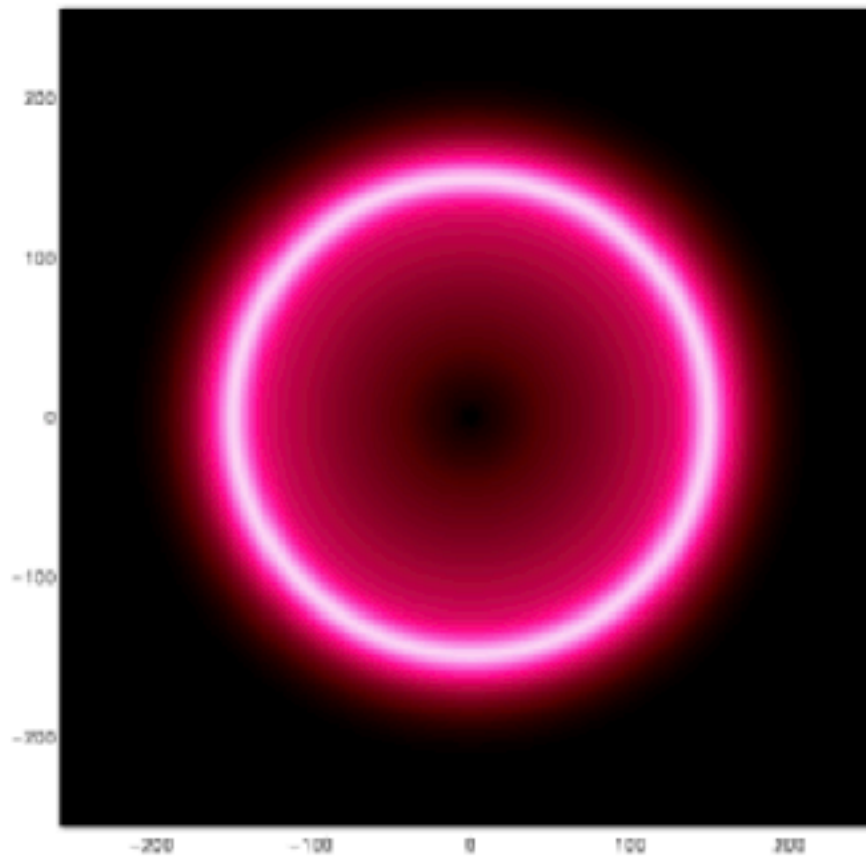
The acoustic wave

After 10^5 years the universe has cooled enough the protons capture the electrons to form neutral Hydrogen. This decouples the photons from the baryons. The former quickly stream away, leaving the baryon peak stalled.



The acoustic wave

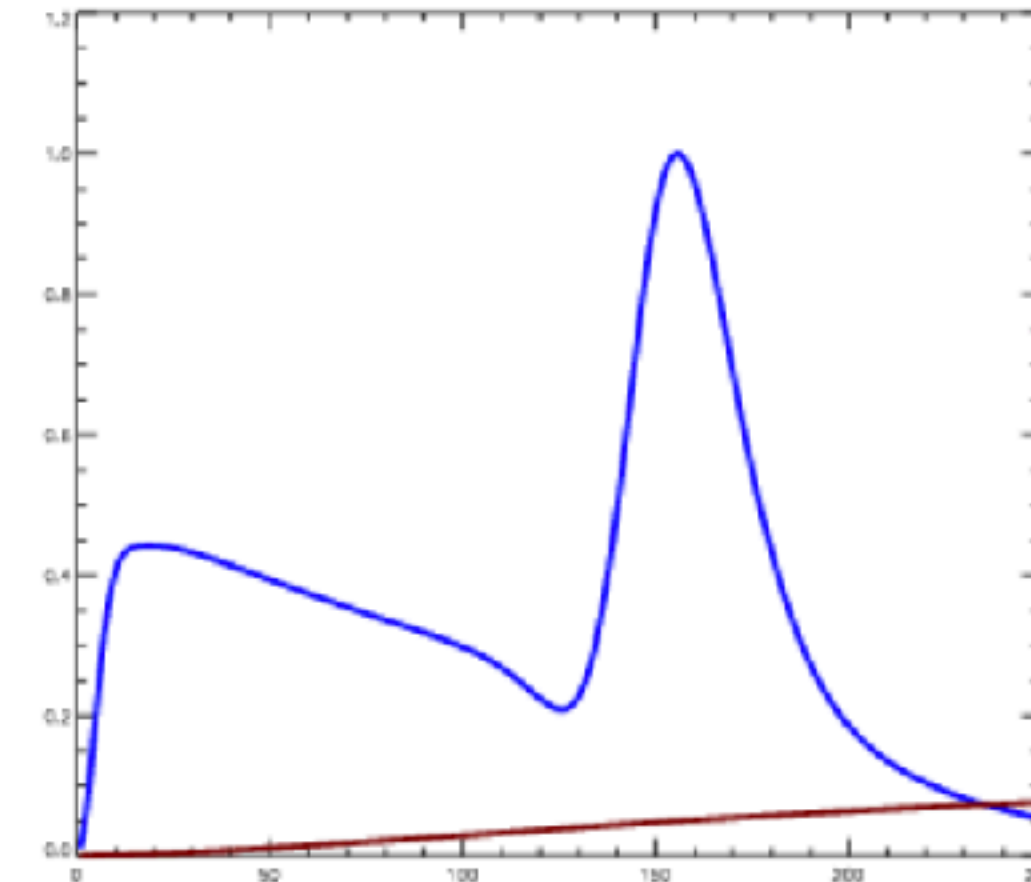
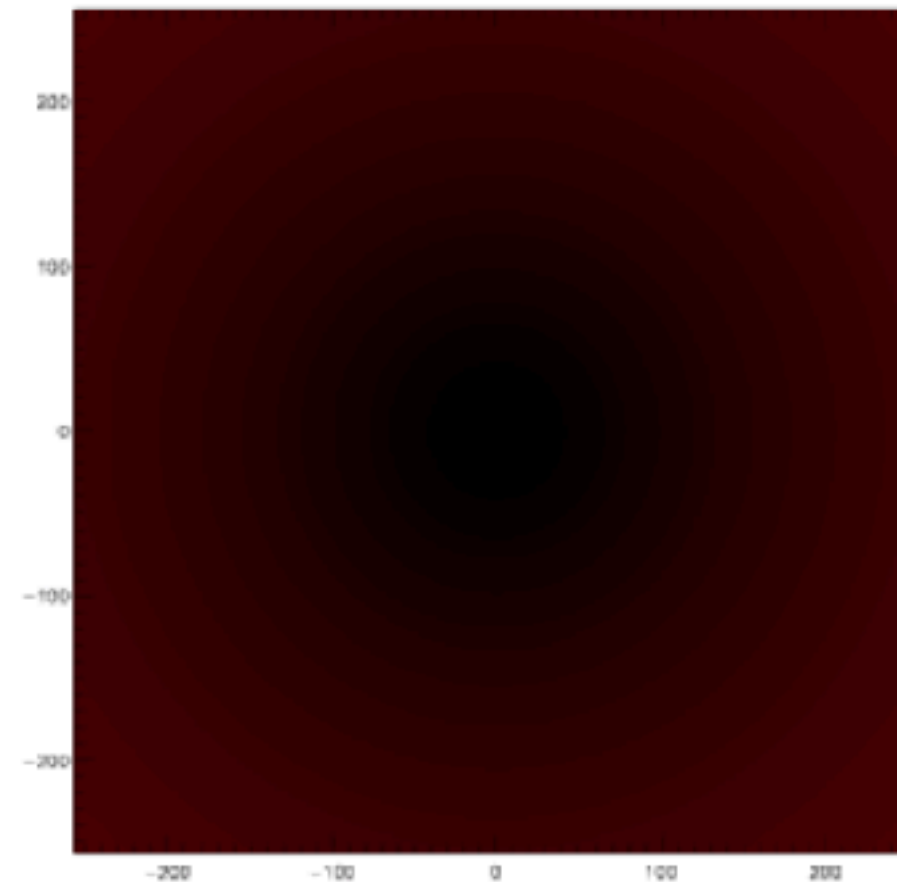
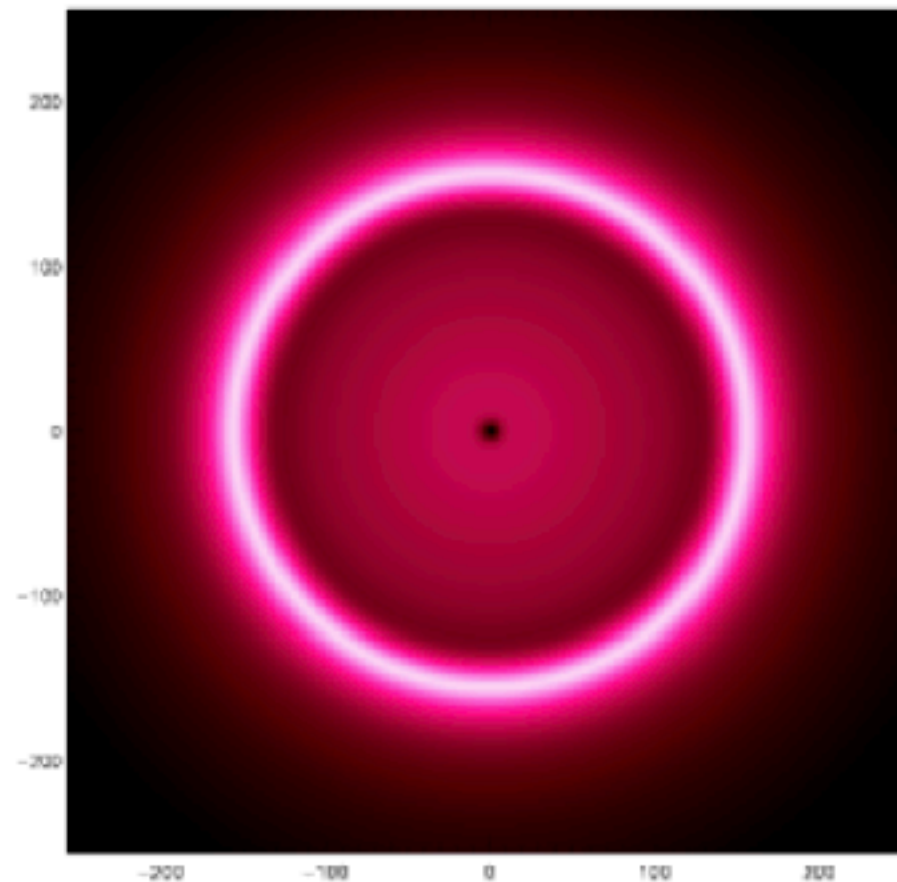
The photons continue to stream away while the baryons, having lost their motive pressure, remain in place.



The acoustic wave

The photons have become almost completely uniform, but the baryons remain overdense in a shell 100Mpc in radius.

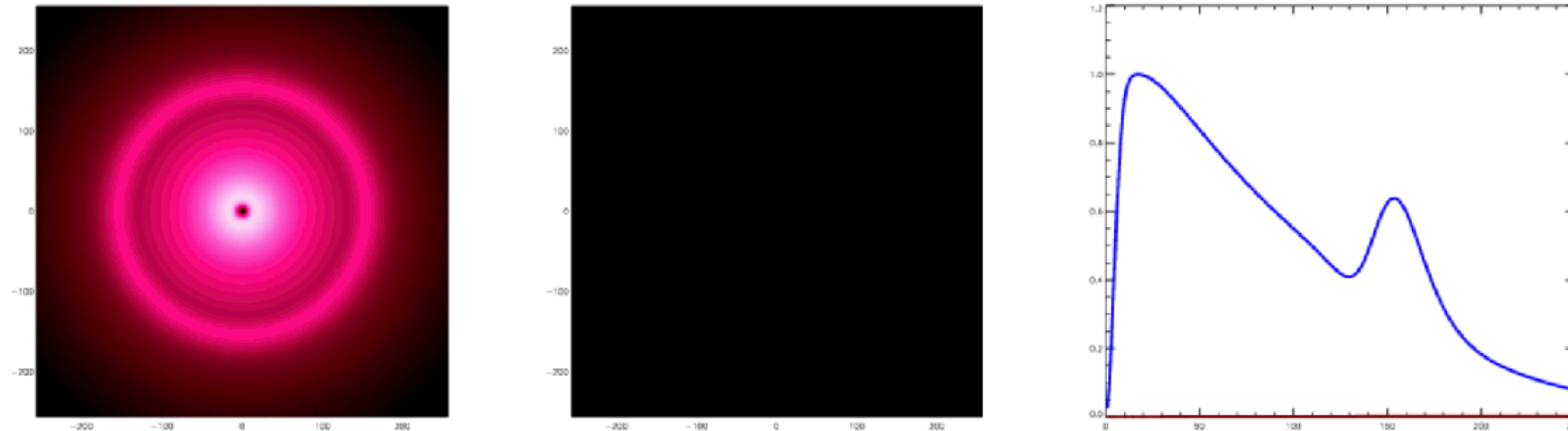
In addition, the large gravitational potential well which we started with starts to draw material back into it.



The acoustic wave

As the perturbation grows by $\sim 10^3$ the baryons and DM reach equilibrium densities in the ratio Ω_b/Ω_m .

The final configuration is our original peak at the center (which we put in by hand) and an “echo” in a shell roughly 100Mpc in radius.



Further (non-linear) processing of the density field acts to broaden and very slightly shift the peak -- but galaxy formation is a local phenomenon with a length scale ~ 10 Mpc, so the action at $r=0$ and $r\sim 100$ Mpc are essentially decoupled. We will return to this ...

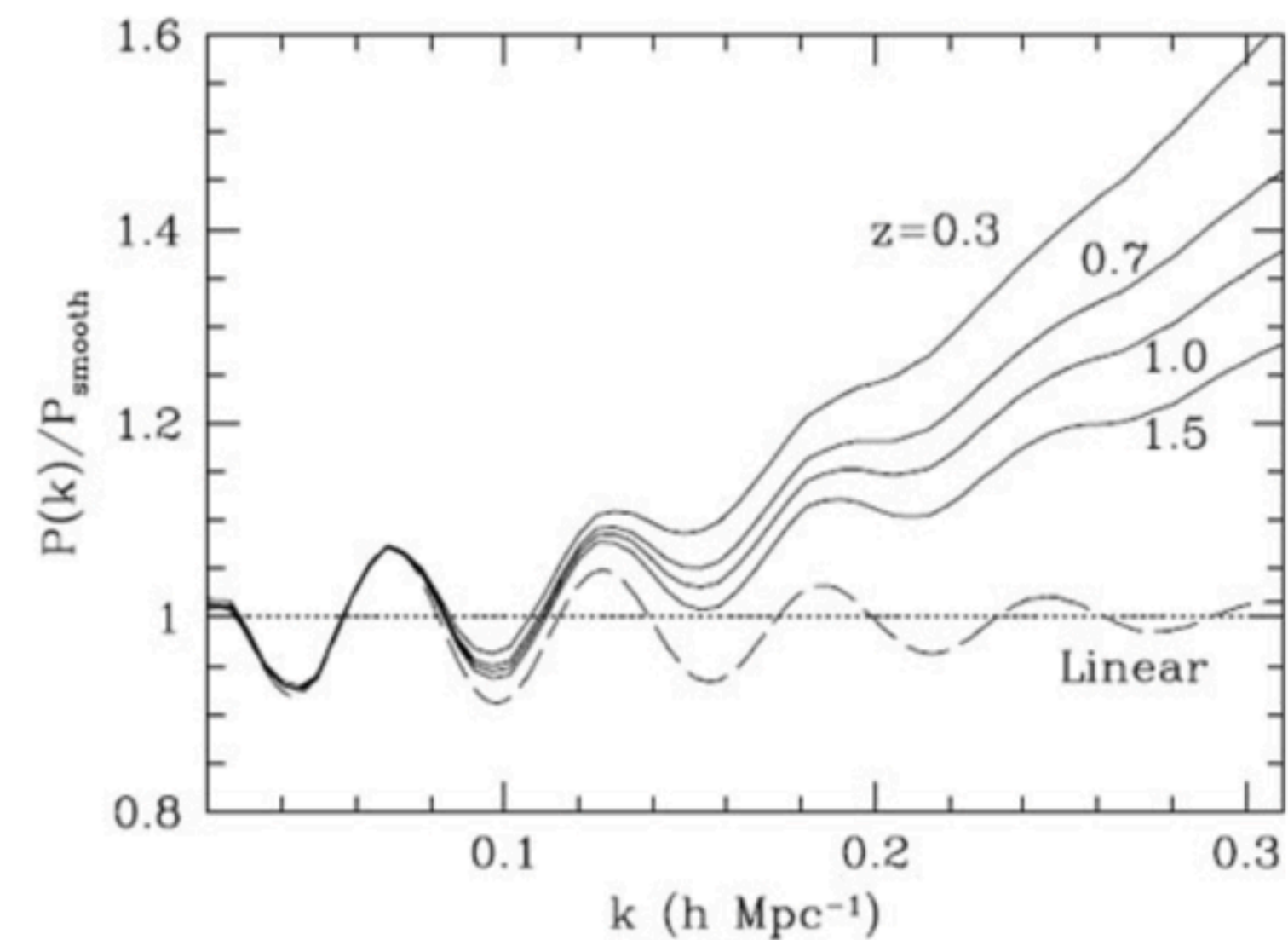
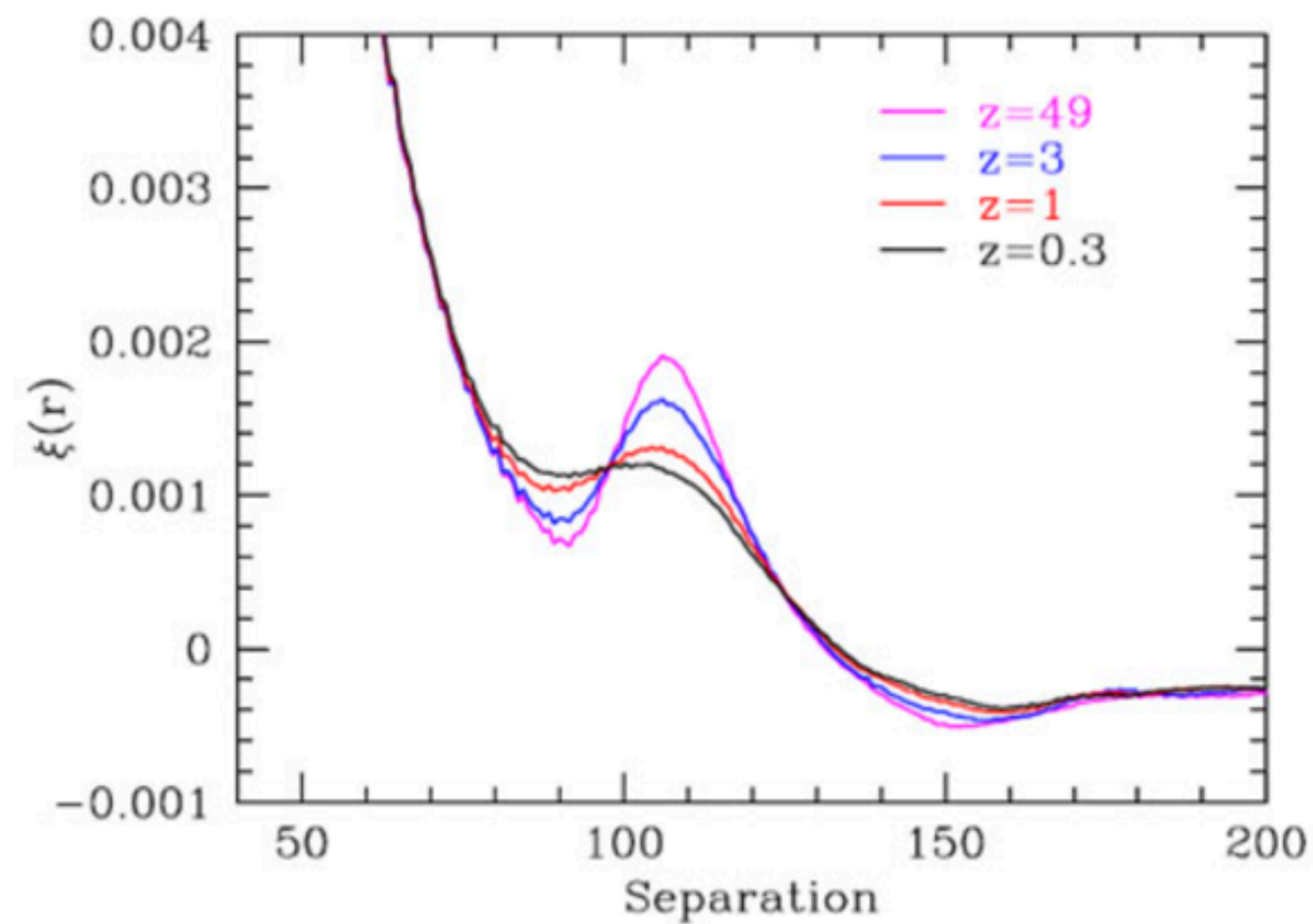
BAOs: maybe not just a geometrical probe

Padmanabhan+12: reconstruction algorithm

Bellini+2015 to constrain alternative theories of gravity

Peloso Pietroni Villaesca-Navarro Viel 2015: neutrino mass application

Seo and Eisenstein 2008



Height of the BAO peak change w.r.t. different normalization of power spectrum A

σ_v is a bulk flow term
calculated from linear power spectrum

$$\frac{\delta_A \xi(R)}{\xi(R)} = \frac{\delta A}{A} \left(1 - \frac{\sigma_v^2 \xi_2(R)}{R^2 \xi(R)} \right)$$

BAOs reconstruction

Baryon Acoustic Oscillations reconstruction with pixels

Andrej Obuljen,^{a,d} Francisco Villaescusa-Navarro,^{b,c,d} Emanuele Castorina,^{e,f} Matteo Viel^{c,d}

A position of a particle in Eulerian coordinates $\mathbf{x}$ after time t can be mapped to the initial Lagrangian position $\mathbf{q}$ using the displacement field $\Psi(\mathbf{q}, t)$:

$$\mathbf{x}(\mathbf{q}, t) = \mathbf{q} + \Psi(\mathbf{q}, t). \quad (4.1)$$

Lagrangian Perturbation Theory (LPT) gives a perturbative solution for this displacement field and the first order solution is the Zel'dovich Approximation (ZA) [49]. In ZA we can express the overdensity field in Eulerian coordinates in terms of the displacement field:

$$\delta(\mathbf{x}) = -\nabla_{\mathbf{x}} \cdot \Psi(\mathbf{x}). \quad (4.2)$$

In Fourier space the displacement field is thus given by:

$$\tilde{\Psi}(\mathbf{k}) = \frac{i\mathbf{k}}{k^2} \tilde{\delta}(\mathbf{k}). \quad (4.3)$$

1. The observed density field is convolved with a smoothing kernel $S(k)$ to reduce the small-scale non-linearities: $\tilde{\delta}(\mathbf{k}) \rightarrow \tilde{\delta}_{\text{nl}}^s(\mathbf{k})S(k)$, where $S(k)$ is usually a Gaussian filter $S(k) = \exp[-0.5k^2R_{\Psi}^2]$ with R_{Ψ} the displacement smoothing scale and $\tilde{\delta}_{\text{nl}}^s$ is the observed redshift-space density field.
2. We estimate the negative real-space displacement field from the smoothed density field:

$$\bar{\mathbf{s}}^r(\mathbf{k}) = -\frac{i\mathbf{k}}{k^2} \frac{\tilde{\delta}_{\text{nl}}^s(\mathbf{k})}{b} S(k),$$

where b is the linear galaxy bias.

3. We displace the galaxies by:

$$\mathbf{s}^s(\mathbf{x}) = \mathbf{s}^r(\mathbf{x}) + \frac{f - \beta}{1 + \beta} (\mathbf{s}^r(\mathbf{x}) \cdot \mathbf{z}) \mathbf{z}$$

to obtain the displaced density field $\delta_d(\mathbf{x})$, where f is the growth rate and β is the redshift-space distortion parameter: $\beta = f/b$ and $\mathbf{s}^s(\mathbf{x})$ is the negative redshift-space displacement field.

4. We shift a uniformly distributed grid of particles by the same $\mathbf{s}^s$ to obtain the shifted density field $\delta_s(\mathbf{x})$.
5. The reconstructed density field is then defined as $\delta_r(\mathbf{x}) \equiv \delta_d(\mathbf{x}) - \delta_s(\mathbf{x})$.

Galaxy Clustering - I: Theoretical Framework

Analysis of **anisotropic correlation function** focussed on the BAO signal

Two sources of anisotropies: Redshift Space Distortion (RSD)
Geometrical induced anisotropy (AP)

$$\xi(r, \mu) = \frac{DD(r, \mu) - 2DR(r, \mu) + RR(r, \mu)}{RR(r, \mu)}, \quad \xi_\ell(r) = \frac{2\ell + 1}{2} \int_{-1}^{+1} d\mu \xi(r, \mu) L_\ell(\mu)$$

Modelling of correlation function and power spectrum

$$P(k, \mu) = (1 + \beta\mu^2)^2 F(k, \mu, \Sigma_s) P_{\text{NL}}(k, \mu).$$

Finger of God effect

$$F(k, \mu, \Sigma_s) = \frac{1}{(1 + k^2 \mu^2 \Sigma_s^2)}$$

Gaussian damping of the BAO peak

$$P_{\text{dw}}(k, \mu) = [P_{\text{lin}}(k) - P_{\text{nw}}(k)] \times \exp \left[-\frac{k^2 \mu^2 \Sigma_{\parallel}^2 + k^2 (1 - \mu^2) \Sigma_{\perp}^2}{2} \right] + P_{\text{nw}}$$

$$P_{\text{l,t}}(k) = \frac{2l + 1}{2} \int_{-1}^1 P_t(k, \mu) L_l(\mu) d\mu$$

$$\xi_0(r) = B_0^2 \xi_{0,t}(r) + A_0(r),$$

$$\xi_2(r) = \xi_{2,t}(r) + A_2(r),$$

where

$$A_\ell(r) = \frac{a_{\ell,1}}{r^2} + \frac{a_{\ell,2}}{r} + a_{\ell,3}; \ell = 0, 2, \perp, \parallel$$

$$\xi_{\text{l,t}}(r) = i^l \int \frac{k^3 d \log(k)}{2\pi^2} P_{\text{l,t}} j_l(kr),$$

Galaxy Clustering - II: Theoretical Framework

$$\alpha = \alpha_{\perp}^{2/3} \alpha_{\parallel}^{1/3}, \quad \alpha_{\perp} = \frac{D_A(z) r_s^{\text{fid}}}{D_A^{\text{fid}} r_s},$$
$$1 + \epsilon = \left(\frac{\alpha_{\parallel}}{\alpha_{\perp}} \right)^{1/3}, \quad \alpha_{\parallel} = \frac{H^{\text{fid}}(z) r_s^{\text{fid}}}{H(z) r_s}$$

α , ϵ usually appear when referring to systematics/mocks
while distances and F_{AP} when quoting final
cosmologically relevant numbers

$$D_V(z) = \left(D_M^2(z) \frac{cz}{H(z)} \right)^{1/3}$$
$$F_{\text{AP}}(z) = D_M(z) H(z) / c.$$

Galaxy clustering challenges - ca 2020

Measurement of galaxy clustering hampered by **systematics** and **statistical errors**.

Estimating the window function and selection function is not trivial.

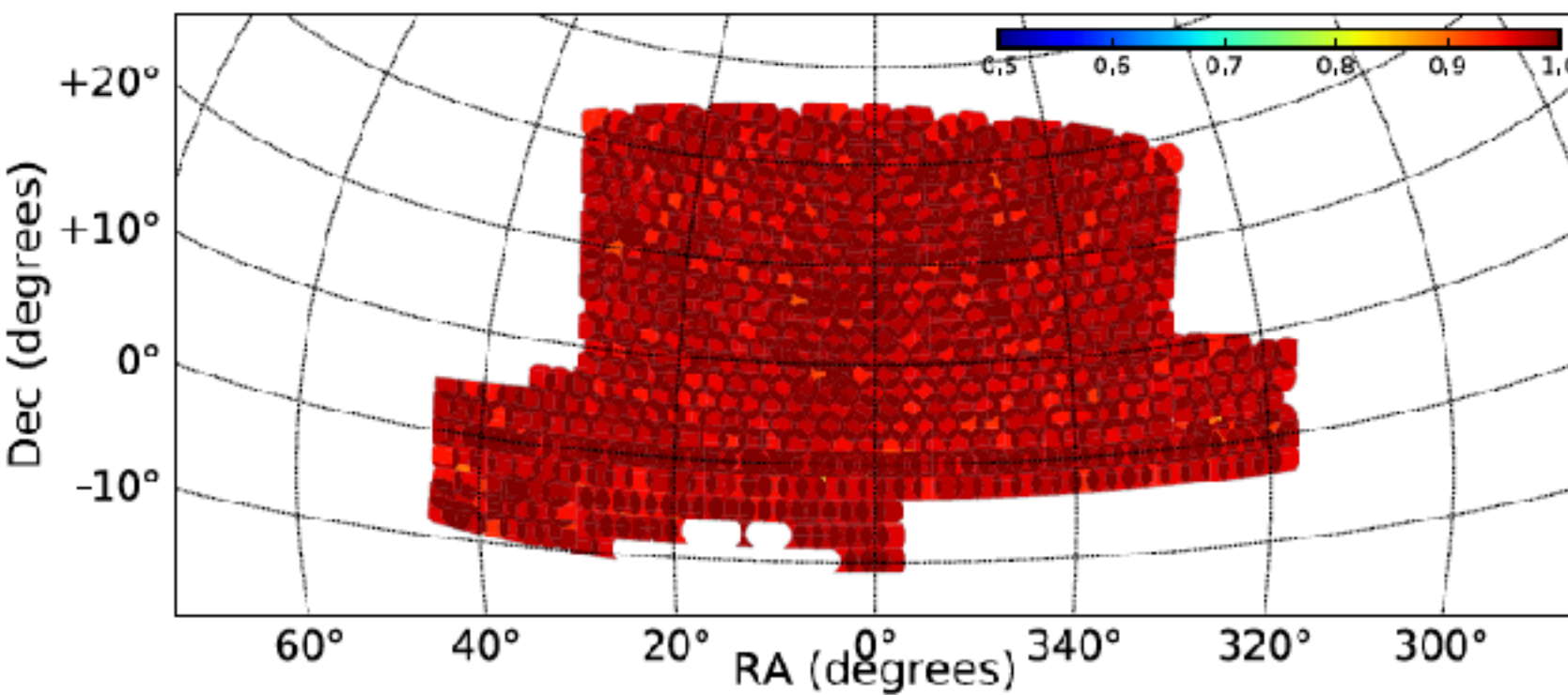
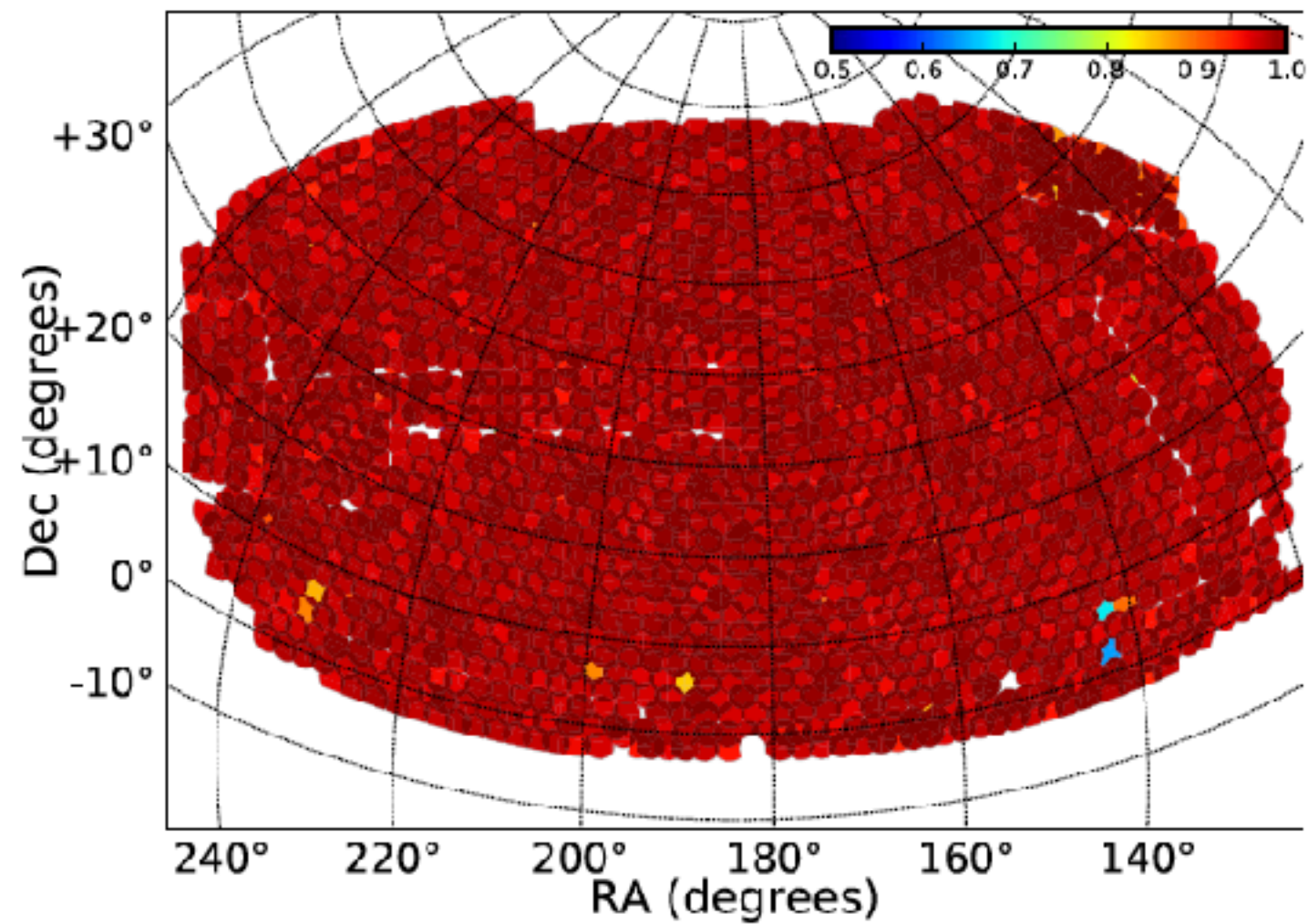
Focus on:

- 1) optimization of codes to handle large number of objects
- 2) getting reliable mocks
- 3) quantifying systematic effects
- 4) covariance matrix estimation
- 5) improving **reconstruction techniques**

State-of-the-art provided by BOSS survey (e.g. Alam+18, Vargas-Magana+18)

- 1) Systematics are estimated and appear as weights in the selection function
- 2) Mock generation using several different methods - based on Perturbation theory or N-body simulations
- 3) Estimation of the 2D correlation function using Landy-Szalay estimator
- 4) Analysis focused on BAO peak and in second instance on sub-BAO **shape** info
- 5) Different pipelines tested with estimation of systematic errors introduced in each step
- 6) Main conclusions: unlike naively expected latest BOSS results **are dominated by statistical errors**

Galaxy clustering: the data set



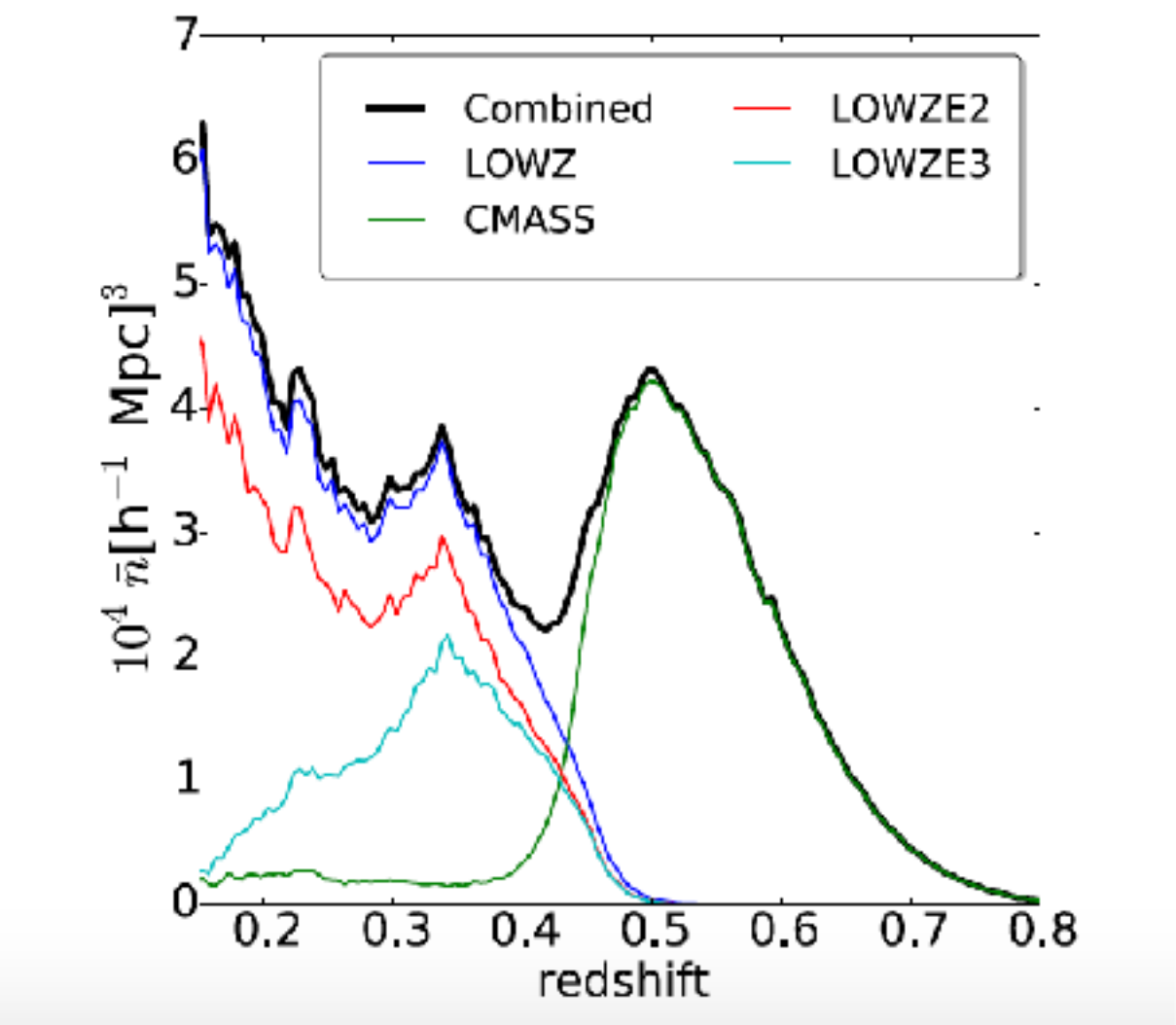
10,000 sq. deg. & 1.2 million galaxies in $V=20$ Gpc³

medium-resolution spectra
($R \approx 1500\text{--}2600$) in the wavelength range from 3600 to 10000 Å
through 2 arcsec fibres

LOWZ was designed to target luminous red galaxies up to $z \approx 0.4$, while CMASS was designed to target massive galaxies from $0.4 < z < 0.7$

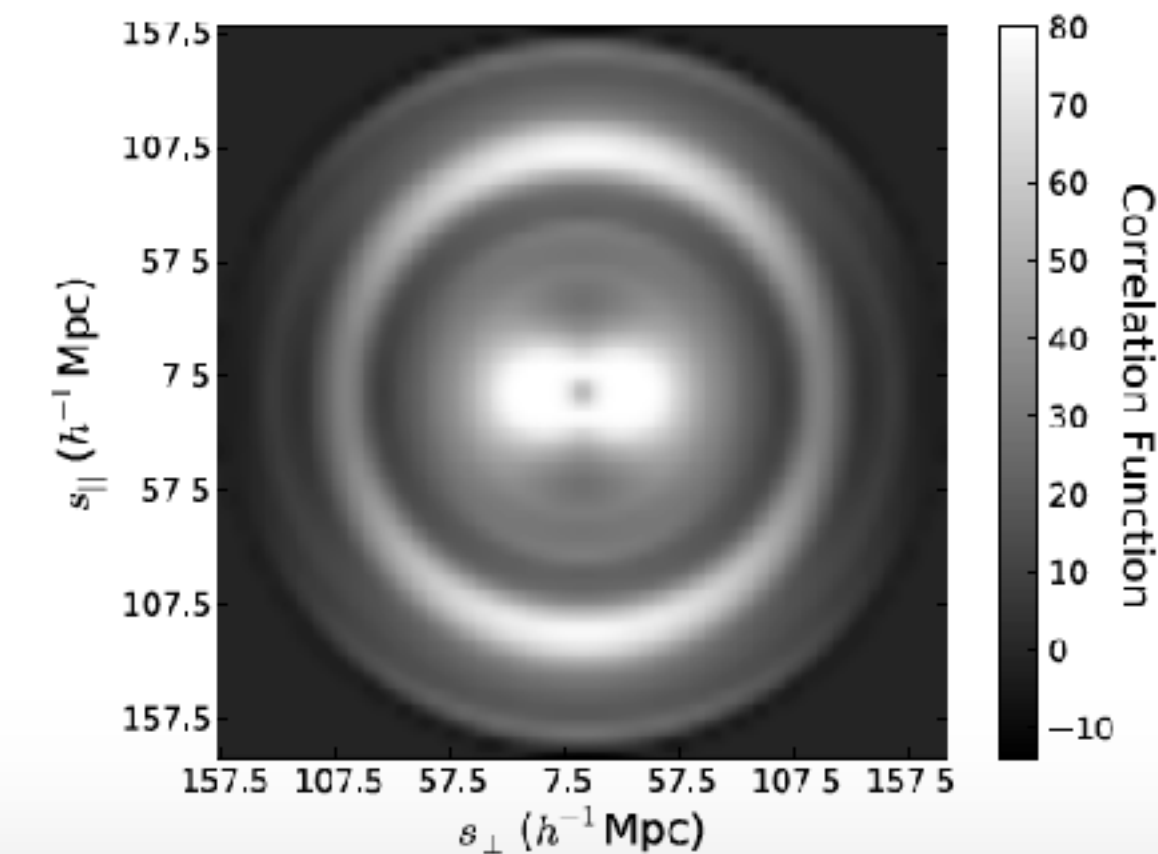
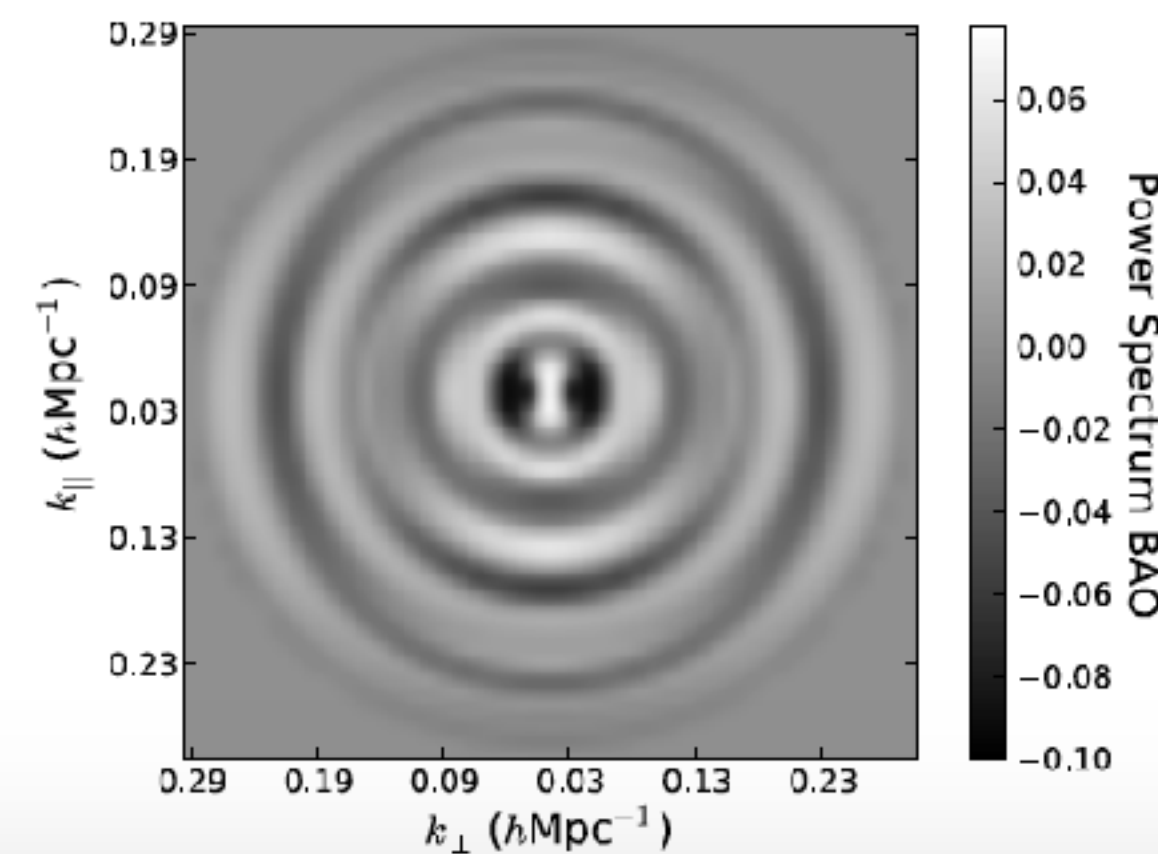
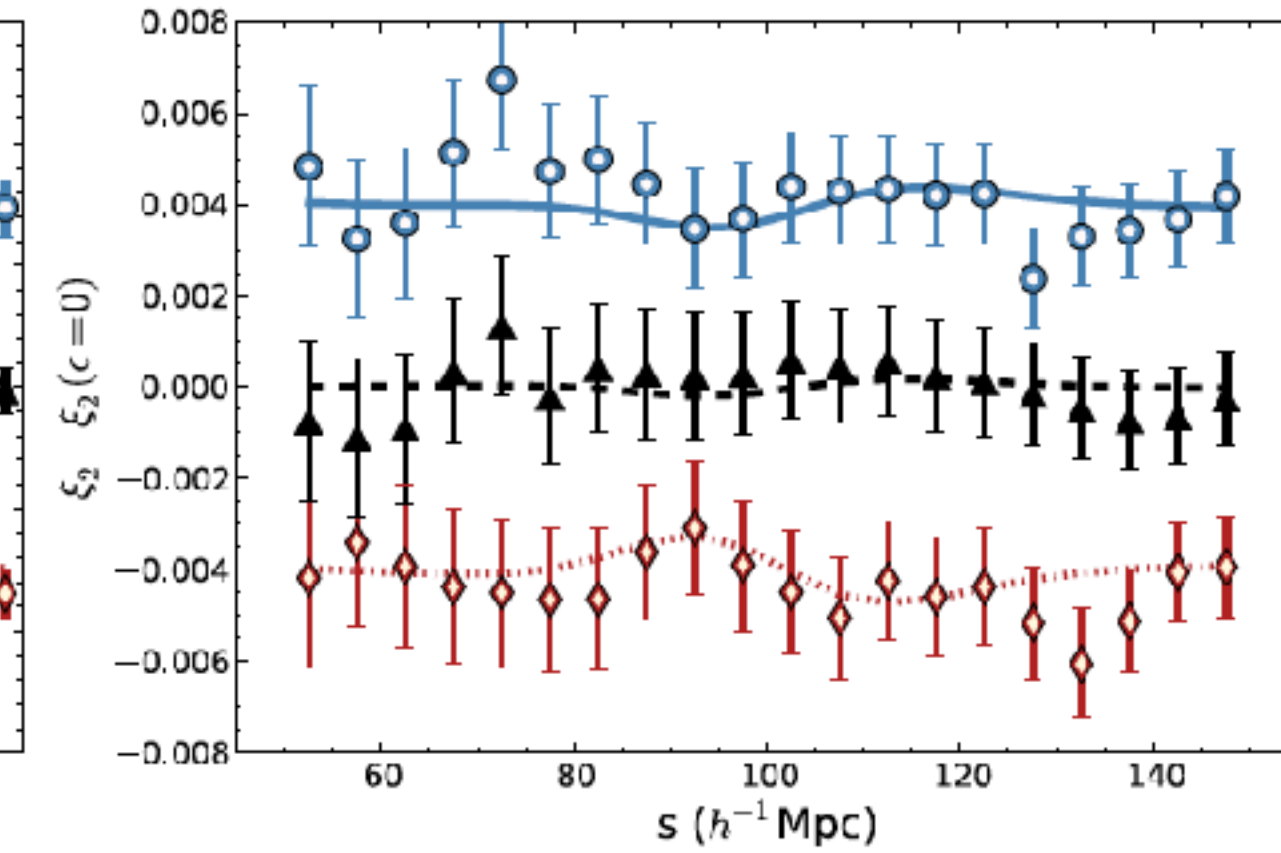
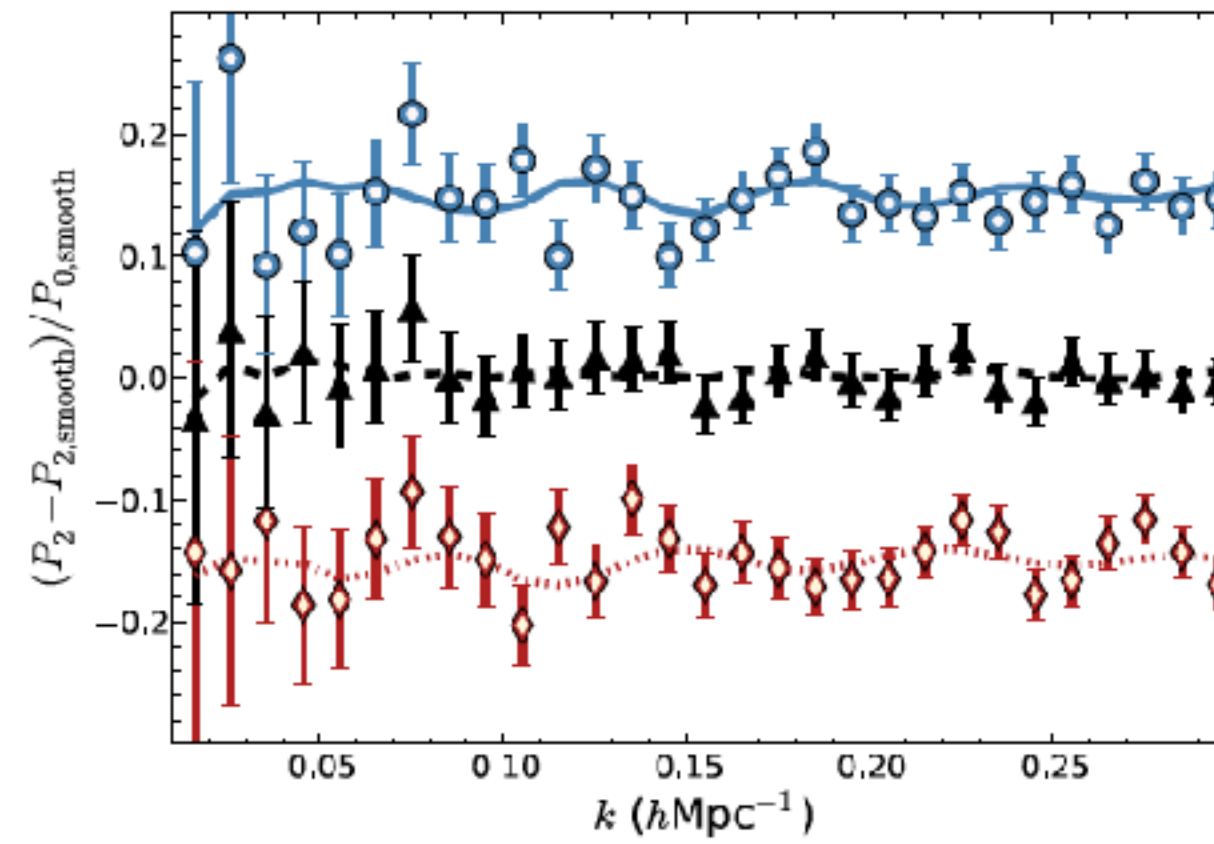
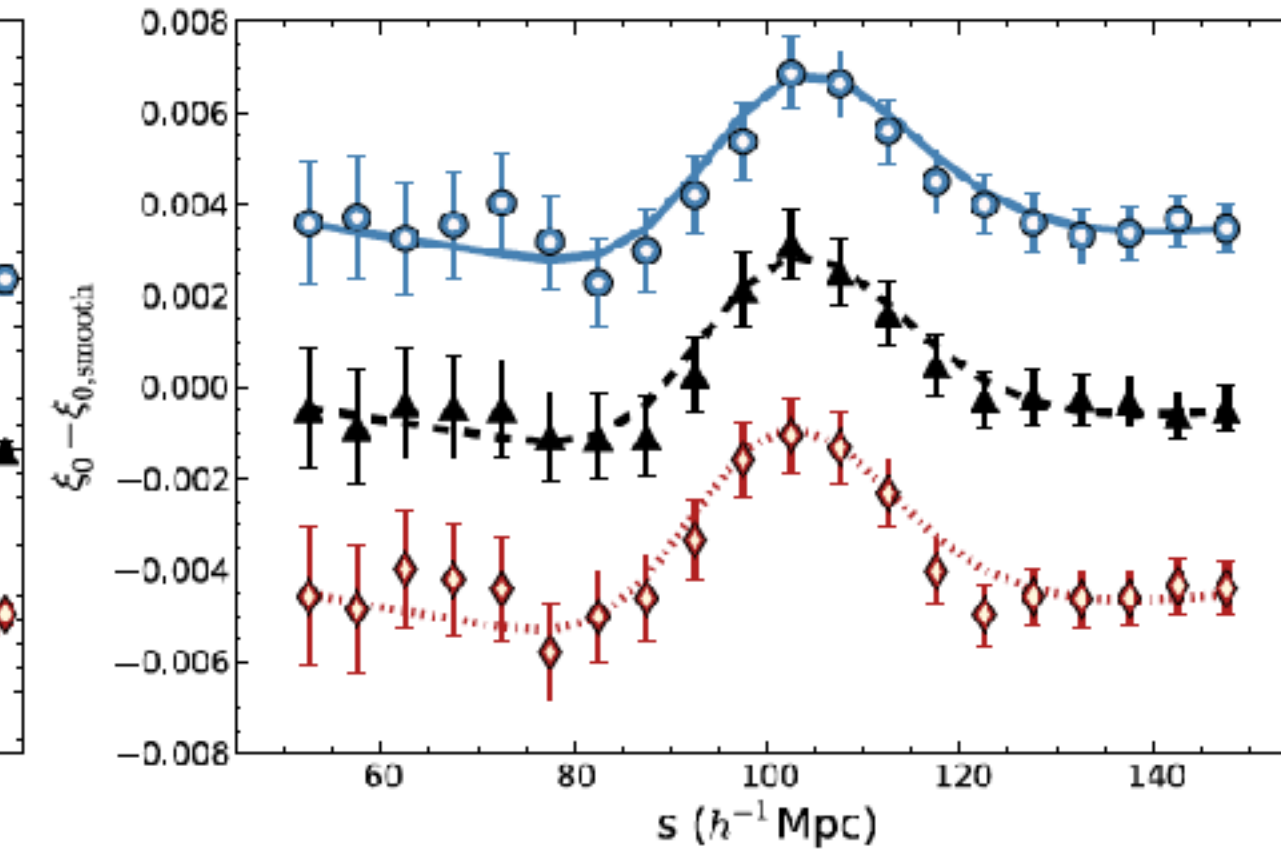
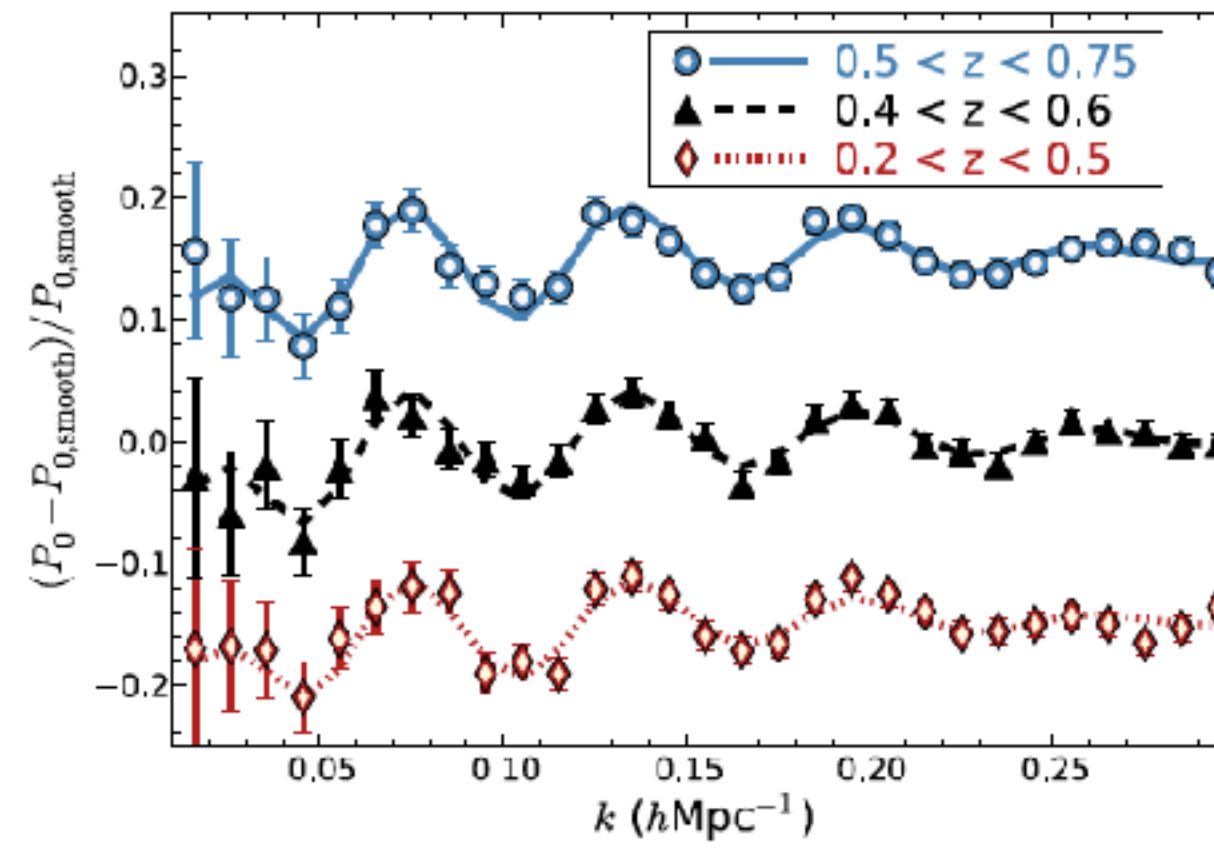
Seven data analyses performed with different methodologies (tested on mocks)

		N_{gals}	V_{eff} (Gpc ³)	V (Gpc ³)
$0.2 < z < 0.5$	NGC	429 182	2.7	4.7
	SGC	174 819	1.0	1.7
	Total	604 001	3.7	6.4
$0.4 < z < 0.6$	NGC	500 872	3.1	5.3
	SGC	185 498	1.1	2.0
	Total	686 370	4.2	7.3
$0.5 < z < 0.75$	NGC	435 741	3.0	9.0
	SGC	158 262	1.1	3.3
	Total	594 003	4.1	12.3

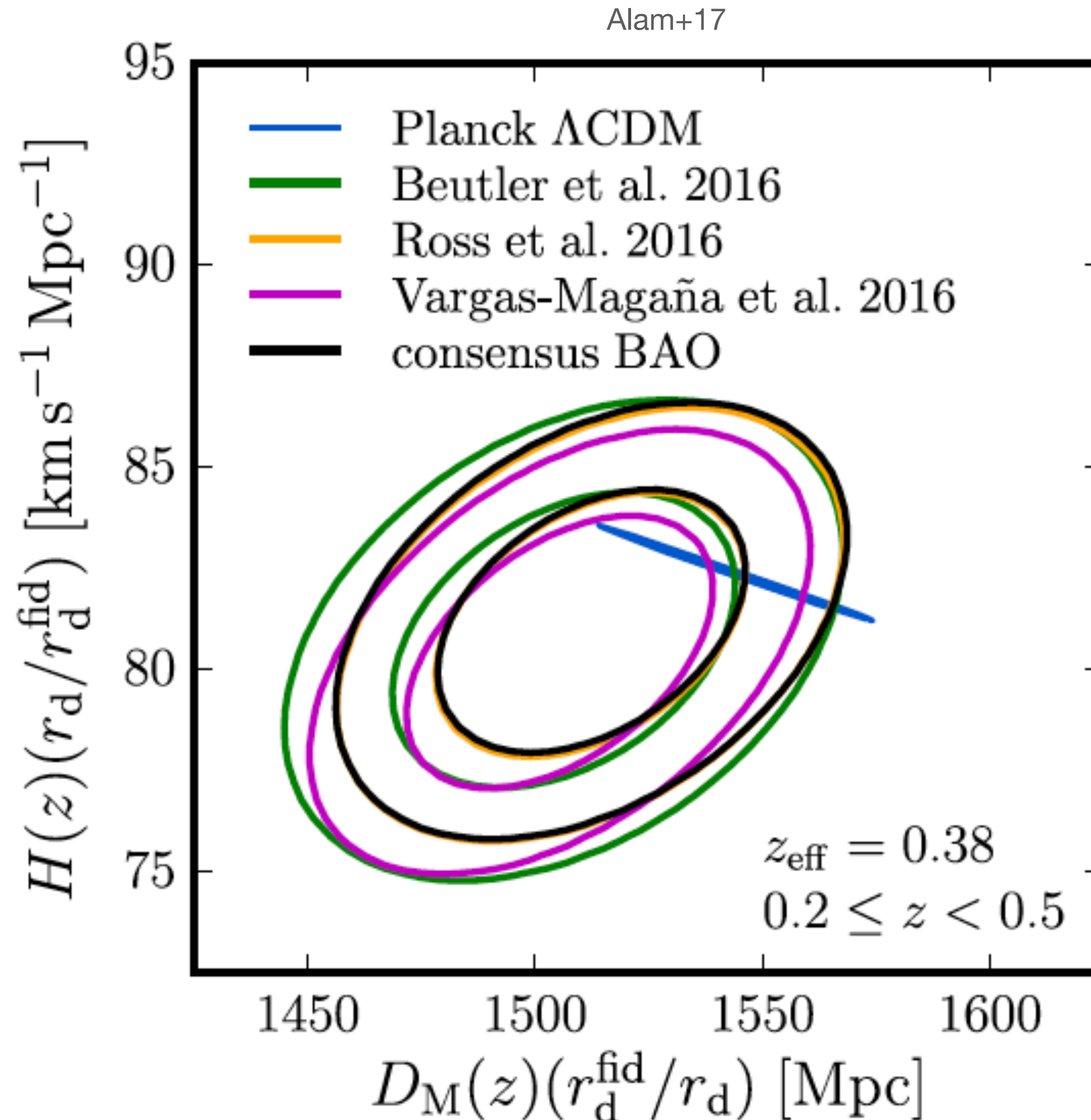


Galaxy clustering: the signal

Analysis
performed
in configuration
and Fourier
space
and gives
consistent
results



Galaxy clustering: constraints from BAOs



BAO measurement combined with CMB prior allows to measure $H(z)$ at 2.4% and $D_A(z)$ at 1.5% in each redshift bin when combined $D_A(z)$ measured at 1% and $H(z)$ at 1.6%

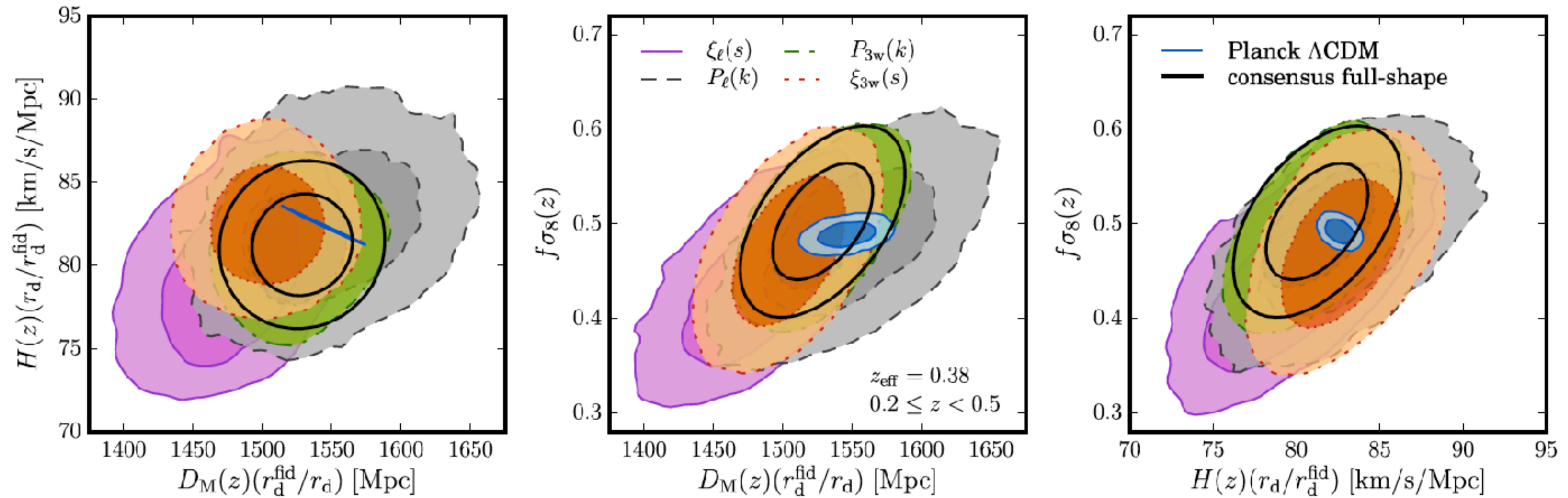
Perfect agreement with Planck

remarkable measurements not so much freedom to escape from LCDM

Consensus constraints are obtained by combined up to 7 different methods with strong covariance (mock estimated) but they improve the overall constraint significantly.

Galaxy clustering: constraints from full shape

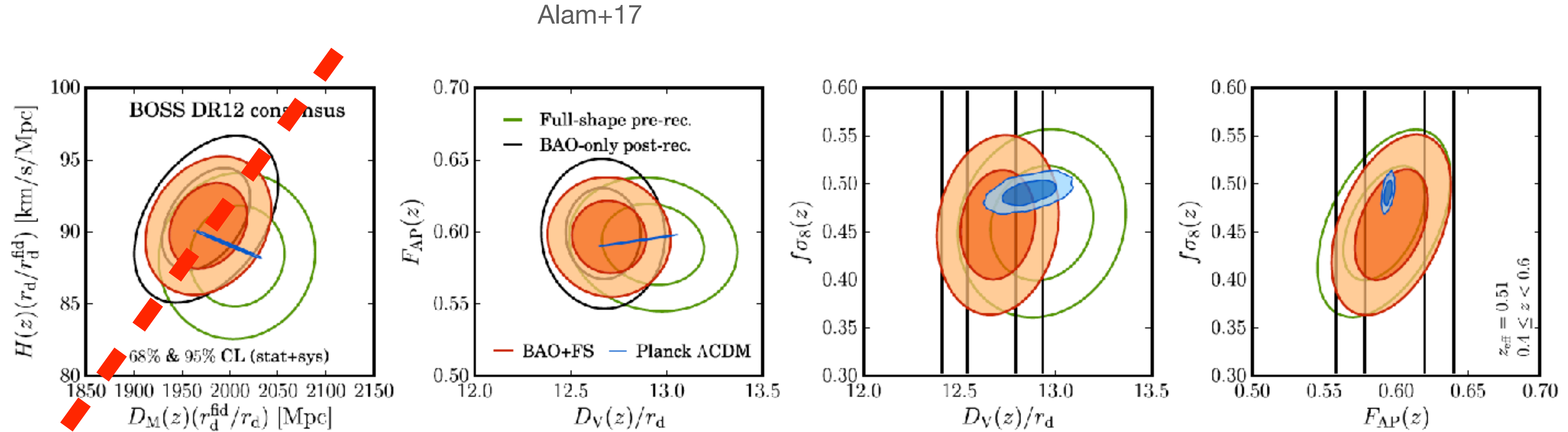
Alam+17



Full-shape measurement with a variety of methods, this allows to measure the $f\sigma_8$ combination with a 10% precision in each bin and overall a 6% measurement

Perfect agreement with Planck

BAO+full shape combined



$D_M(z)$ and $H(z)$ are more strongly correlated for the BAO-only analysis, so while the $D_V(z)$ constraints from postreconstruction BAO-only are appreciably tighter than those from pre-reconstruction FS, the marginalized constraints on $D_M(z)$ and $H(z)$ are not.

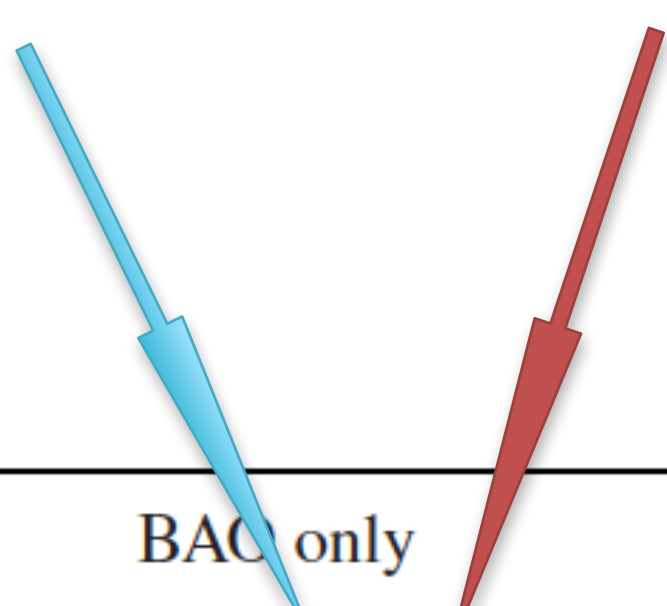
The constraints on $F_{\text{AP}}(z)$ from sub-BAO scales in the FS analyses help to **break the degeneracy** between D_M and H , leading to rounder confidence contours and smaller errors on F_{AP} .

Combined BAO+FS contours take advantage of both the **sharpening** of the BAO feature by reconstruction and the improved **degeneracy breaking from the sub-BAO Alcock–Paczynski effect**.

Constraints from post-reconstruction BAO measurements and pre-reconstruction full-shape

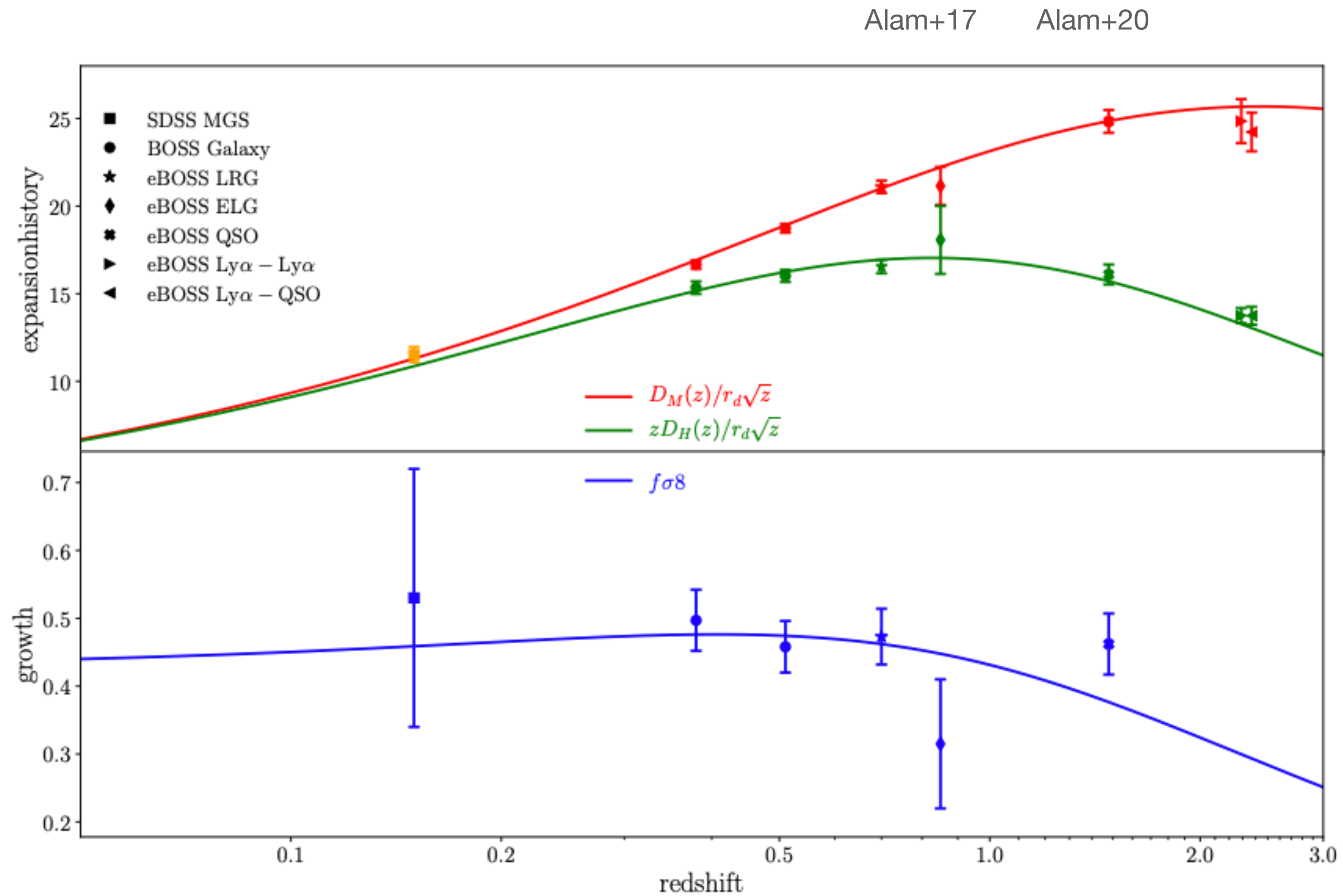
Alam+17

statistical error systematic error

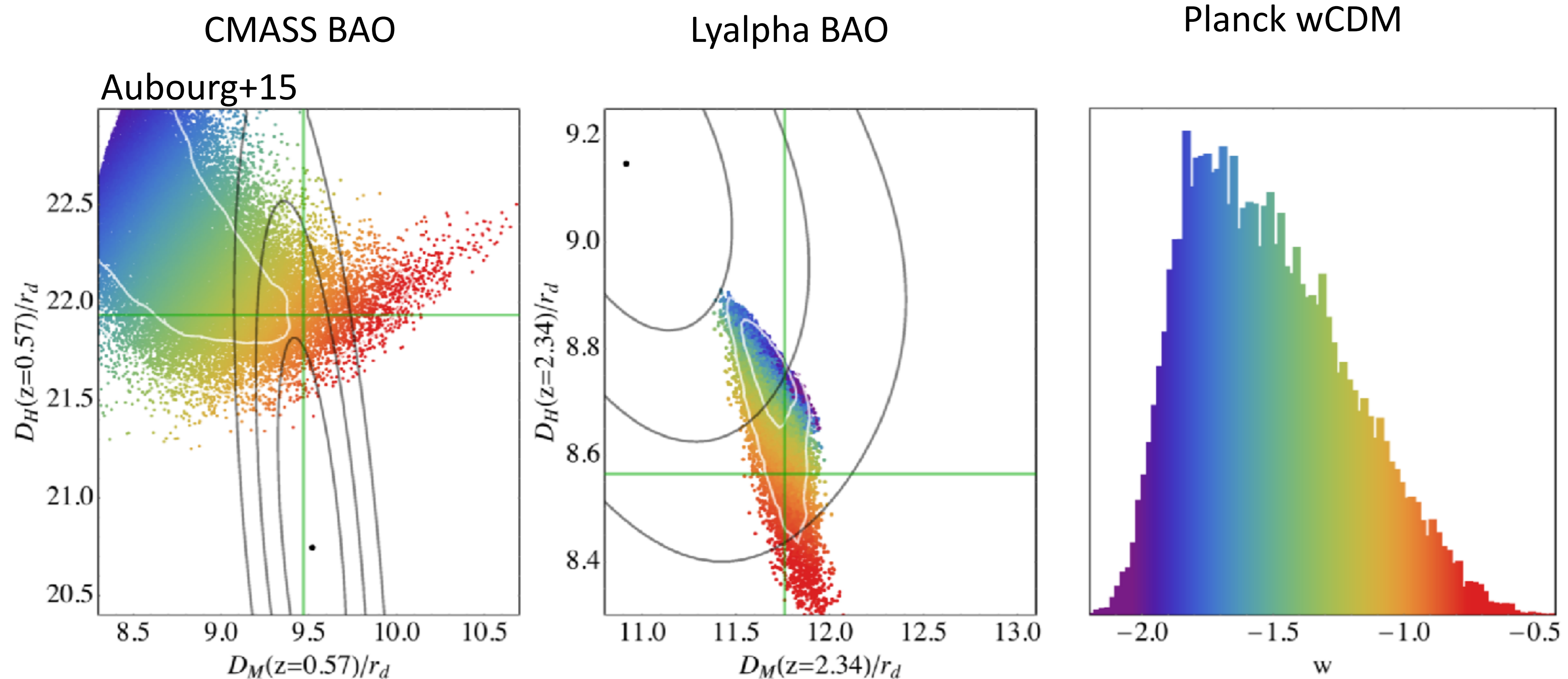


Measurement	Redshift	BAO only	Full shape	BAO + FS
$D_M(r_{d, \text{fid}}/r_d)$ (Mpc)	$z = 0.38$	$1512 \pm 22 \pm 11$	$1529 \pm 24 \pm 11$	$1518 \pm 20 \pm 11$
$D_M(r_{d, \text{fid}}/r_d)$ (Mpc)	$z = 0.51$	$1975 \pm 27 \pm 14$	$2007 \pm 29 \pm 15$	$1977 \pm 23 \pm 14$
$D_M(r_{d, \text{fid}}/r_d)$ (Mpc)	$z = 0.61$	$2307 \pm 33 \pm 17$	$2274 \pm 36 \pm 17$	$2283 \pm 28 \pm 16$
$H(r_d/r_{d, \text{fid}})$ (km s ⁻¹ Mpc ⁻¹)	$z = 0.38$	$81.2 \pm 2.2 \pm 1.0$	$81.2 \pm 2.0 \pm 1.0$	$81.5 \pm 1.7 \pm 0.9$
$H(r_d/r_{d, \text{fid}})$ (km s ⁻¹ Mpc ⁻¹)	$z = 0.51$	$90.9 \pm 2.1 \pm 1.1$	$88.3 \pm 2.1 \pm 1.0$	$90.5 \pm 1.7 \pm 1.0$
$H(r_d/r_{d, \text{fid}})$ (km s ⁻¹ Mpc ⁻¹)	$z = 0.61$	$99.0 \pm 2.2 \pm 1.2$	$95.6 \pm 2.4 \pm 1.1$	$97.3 \pm 1.8 \pm 1.1$
$f\sigma_8$	$z = 0.38$	—	$0.502 \pm 0.041 \pm 0.024$	$0.497 \pm 0.039 \pm 0.024$
$f\sigma_8$	$z = 0.51$	—	$0.459 \pm 0.037 \pm 0.015$	$0.458 \pm 0.035 \pm 0.015$
$f\sigma_8$	$z = 0.61$	—	$0.419 \pm 0.036 \pm 0.009$	$0.436 \pm 0.034 \pm 0.009$

BAO Hubble Diagram and Growth



BAO constraints at high and low redshift

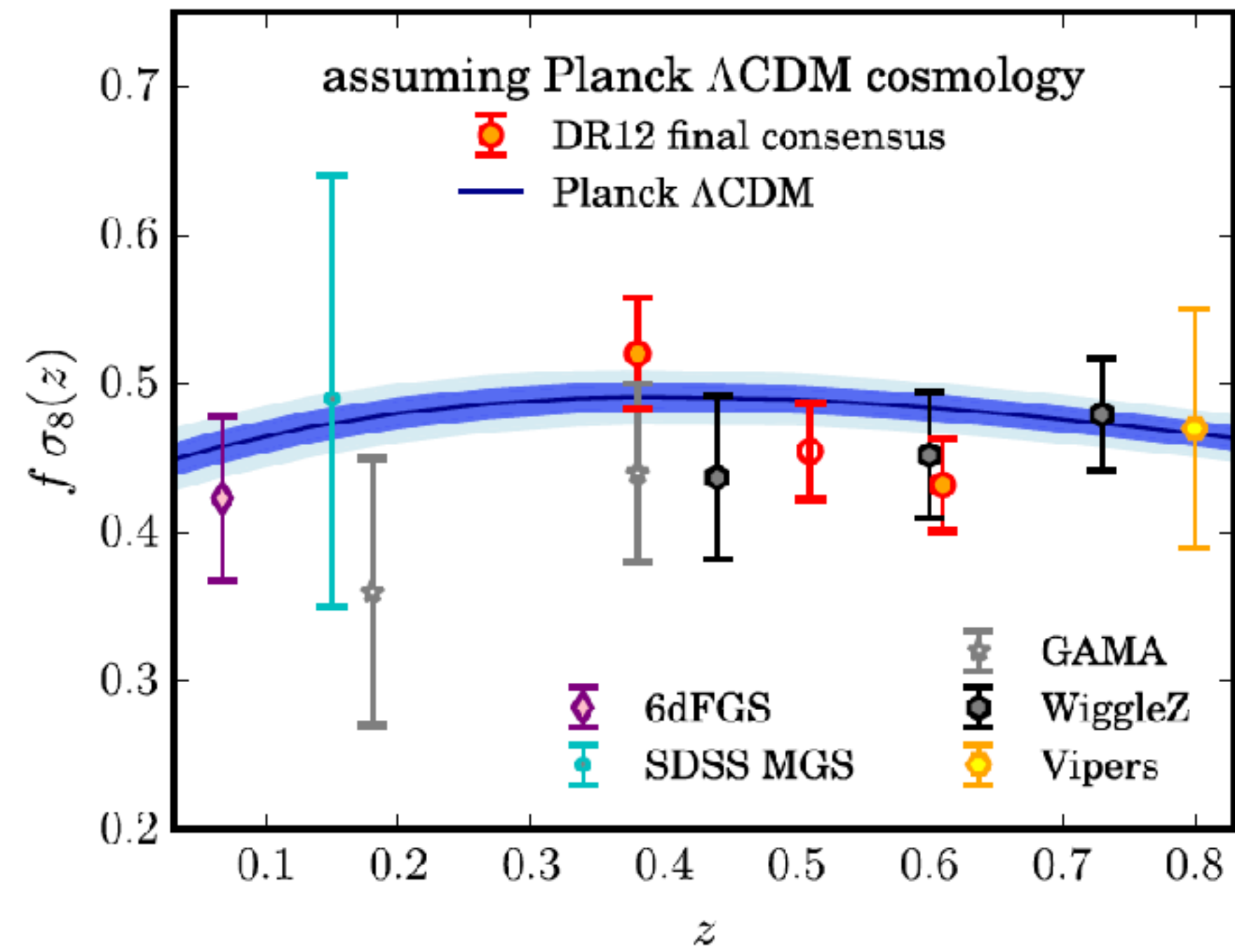
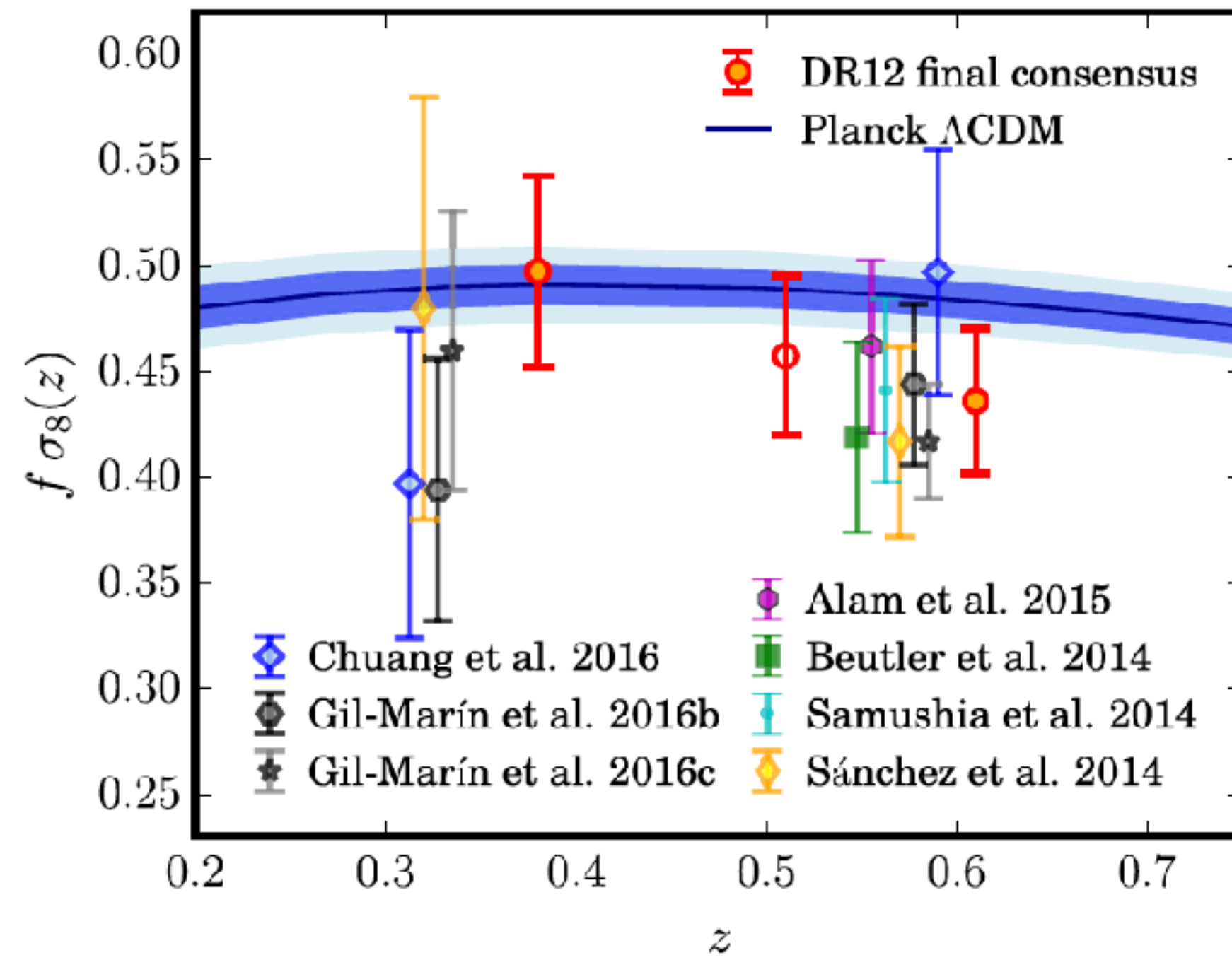


Tensions between Lya BAO and CMASS BAO

In general Early DE models can alleviate tensions of LCDM (low clustering amplitude and large H_0 are predicted at low z)

RSD measurements from BOSS

Alam+17

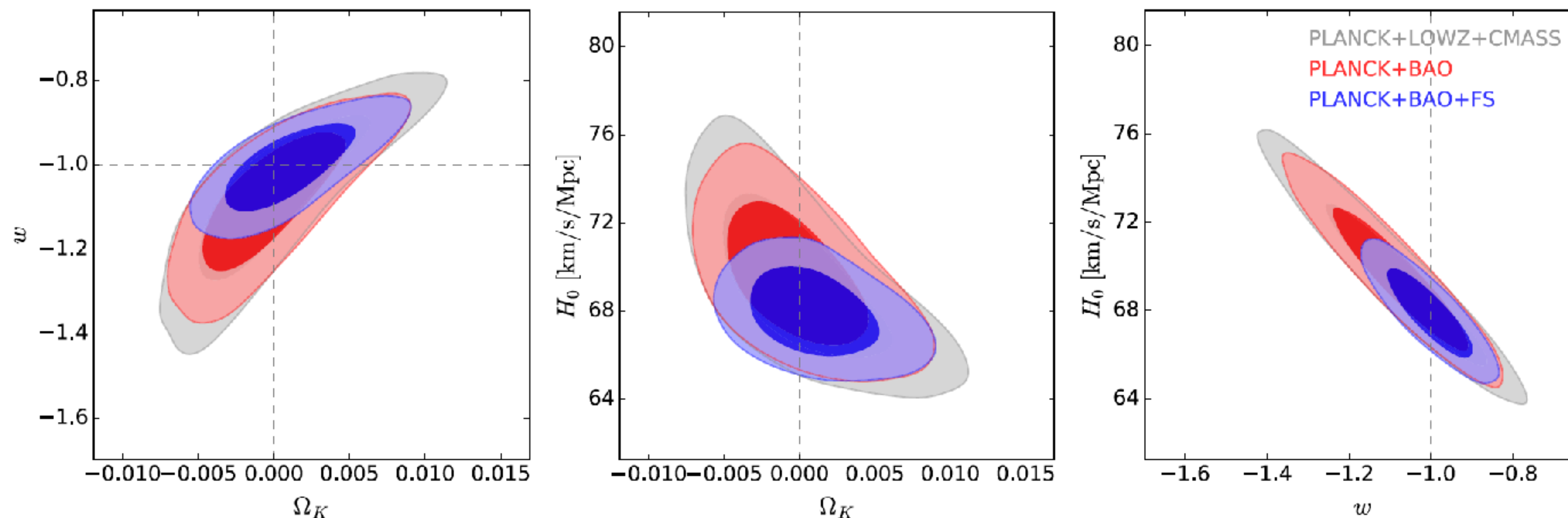


Planck + BOSS galaxy clustering - I

In the LCDM case $\Omega_m=0.311 \pm 0.006$ and $H_0=67.6 \pm 0.5$ km/s/Mpc

If Ω_k and w are varied $\Omega_k=0.0003 \pm 0.0026$ and $w=-1.01 \pm 0.06$

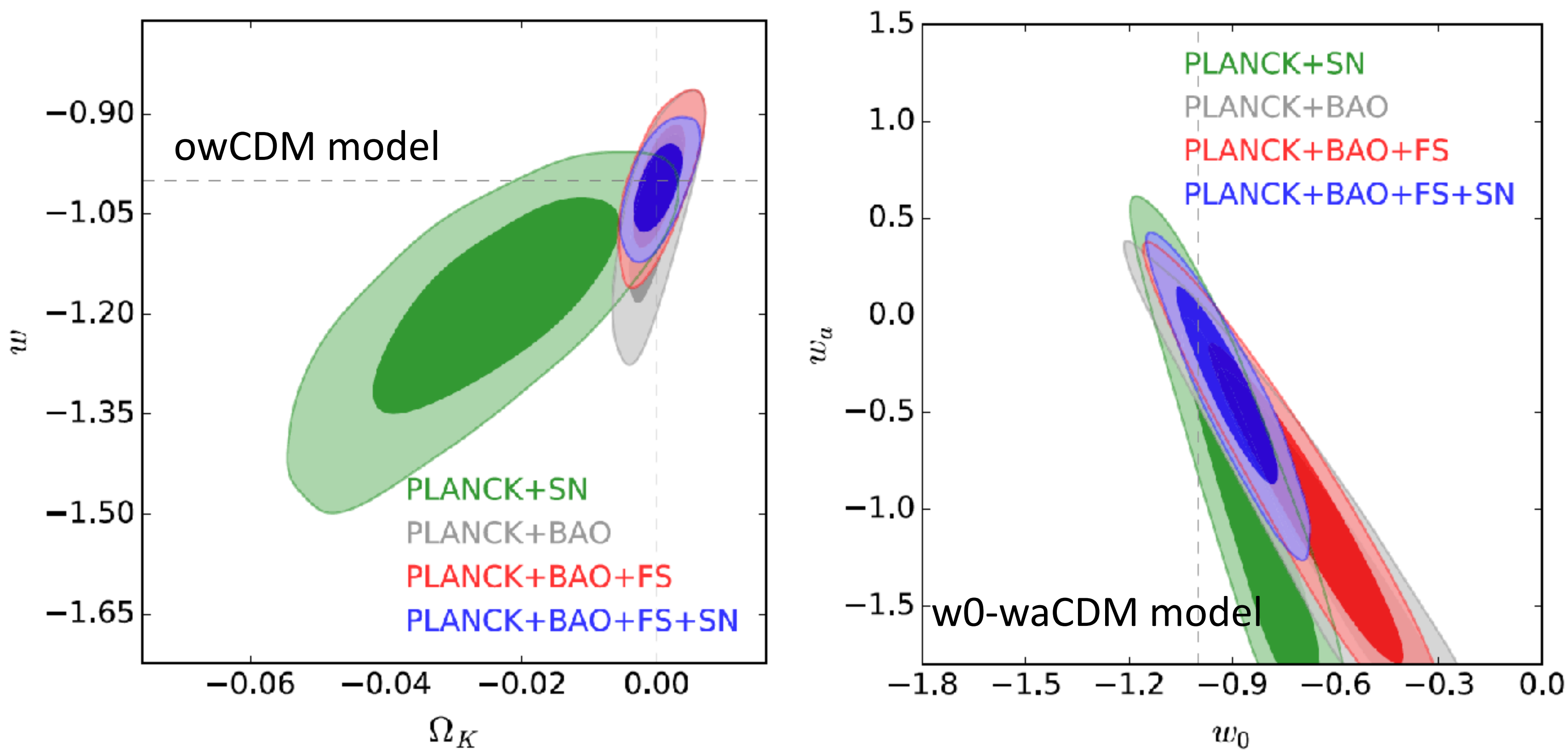
owCDM model



Main results:

- 1) impressive agreement with LCDM even after opening a 2 parameter space (w , Ω_k)
- 2) FOM for w CDM $\sim 20-30$
- 3) Adding z -bins helps

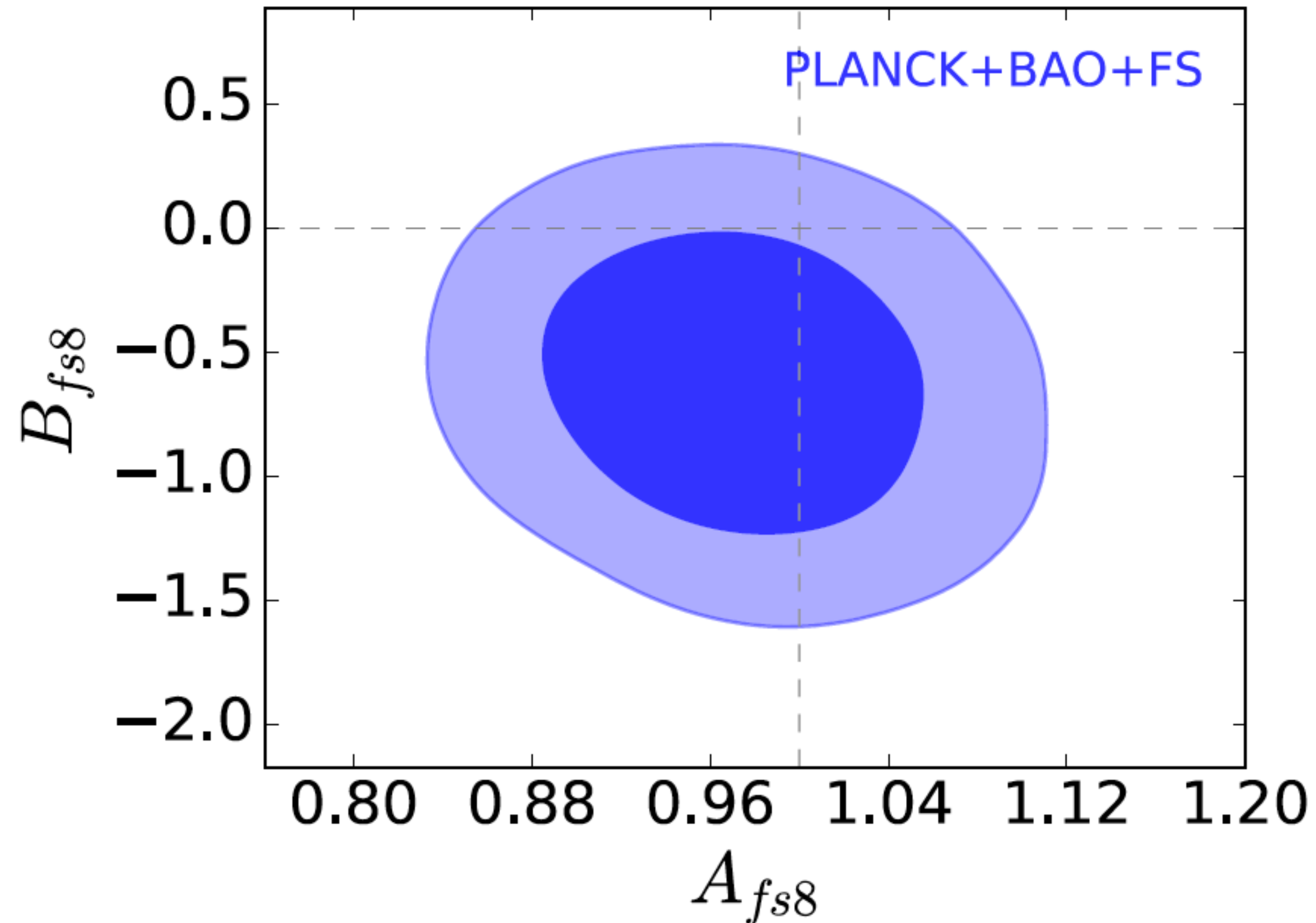
Planck + BOSS galaxy clustering - II



Cosmological model	Data sets	$\Omega_m h^2$	Ω_m	H_0 (km s ⁻¹ Mpc ⁻¹)	Ω_K	w_0	w_a
$w_0 w_a$ CDM	Planck + SN	0.1428 (14)	0.294 (16)	69.8 (18)	—	−0.85 (13)	−0.99 (63)
$w_0 w_a$ CDM	Planck + BAO	0.1427 (11)	0.336 (21)	65.2 (21)	—	−0.63 (20)	−1.16 (55)
$w_0 w_a$ CDM	Planck + BAO + FS	0.1427 (11)	0.334 (18)	65.5 (17)	—	−0.68 (18)	−0.98 (53)
$w_0 w_a$ CDM	Planck + BAO + FS + SN	0.1426 (11)	0.313 (9)	67.5 (10)	—	−0.91 (10)	−0.39 (34)
$ow_0 w_a$ CDM	Planck + BAO	0.1422 (14)	0.331 (21)	65.6 (21)	−0.0022 (30)	−0.66 (19)	−1.22 (53)
$ow_0 w_a$ CDM	Planck + BAO + FS	0.1422 (14)	0.333 (16)	65.4 (16)	−0.0020 (28)	−0.67 (18)	−1.12 (59)
$ow_0 w_a$ CDM	Planck + BAO + FS + SN	0.1420 (14)	0.314 (10)	67.3 (10)	−0.0023 (28)	−0.87 (11)	−0.63 (45)

Planck + BOSS galaxy clustering - III

$$f\sigma_8 \rightarrow f\sigma_8 [A_{f\sigma_8} + B_{f\sigma_8}(z - z_p)]$$



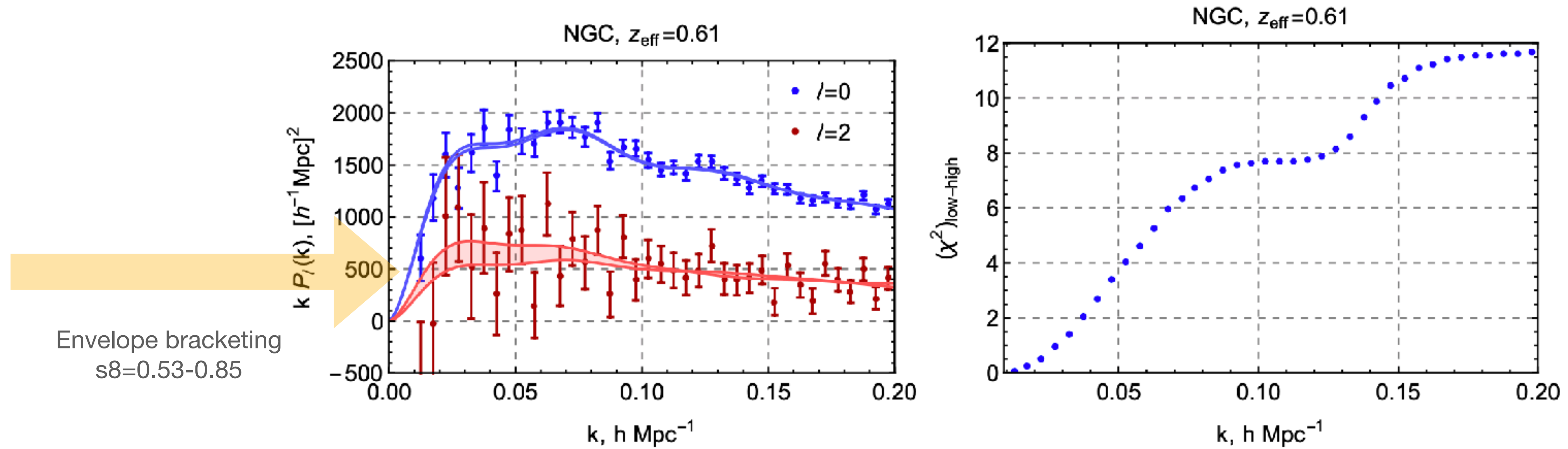
few percent
offset from GR
case - this is not
significant

B is different
from zero at
1.5sigma

6% error on A

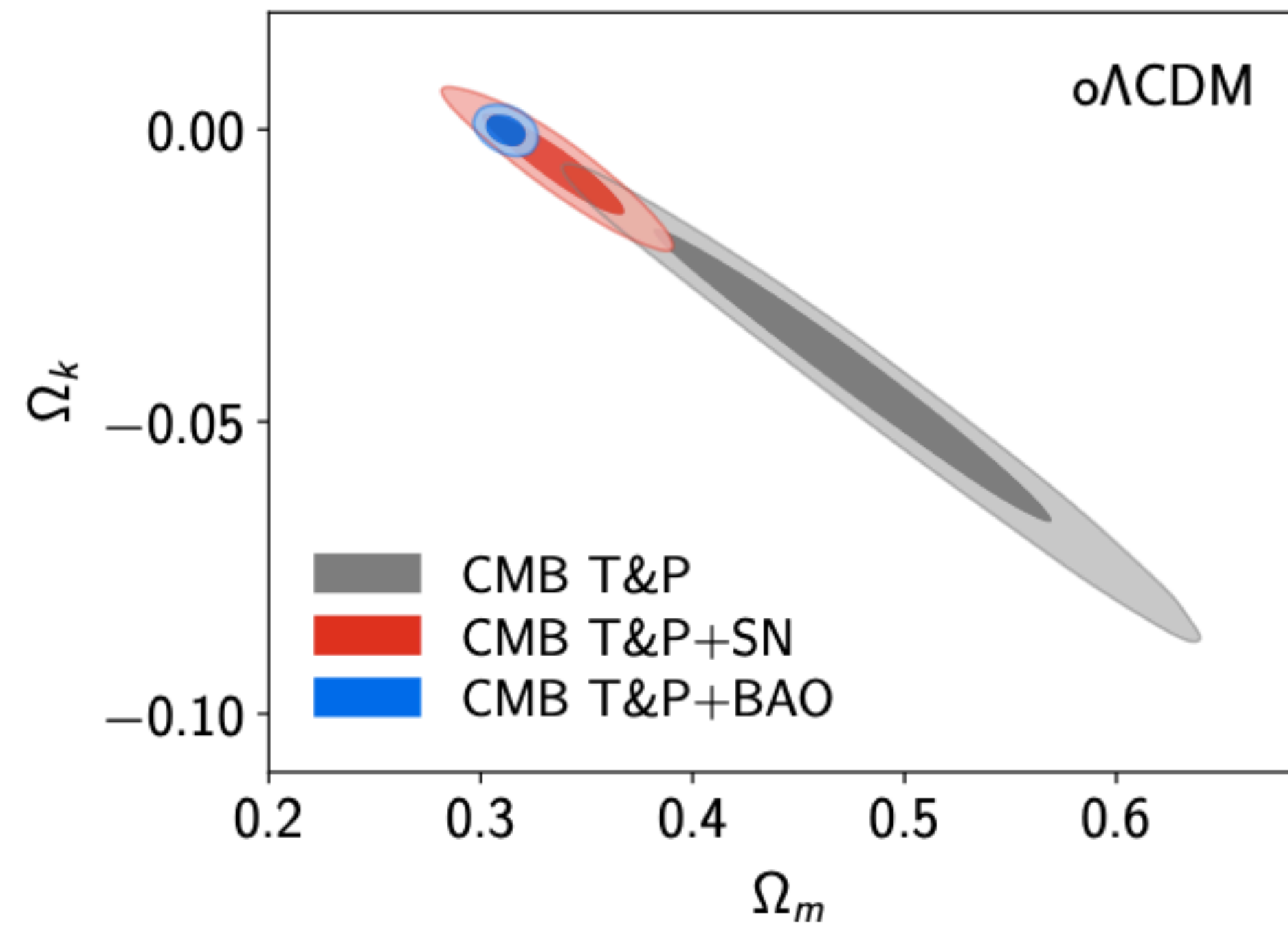
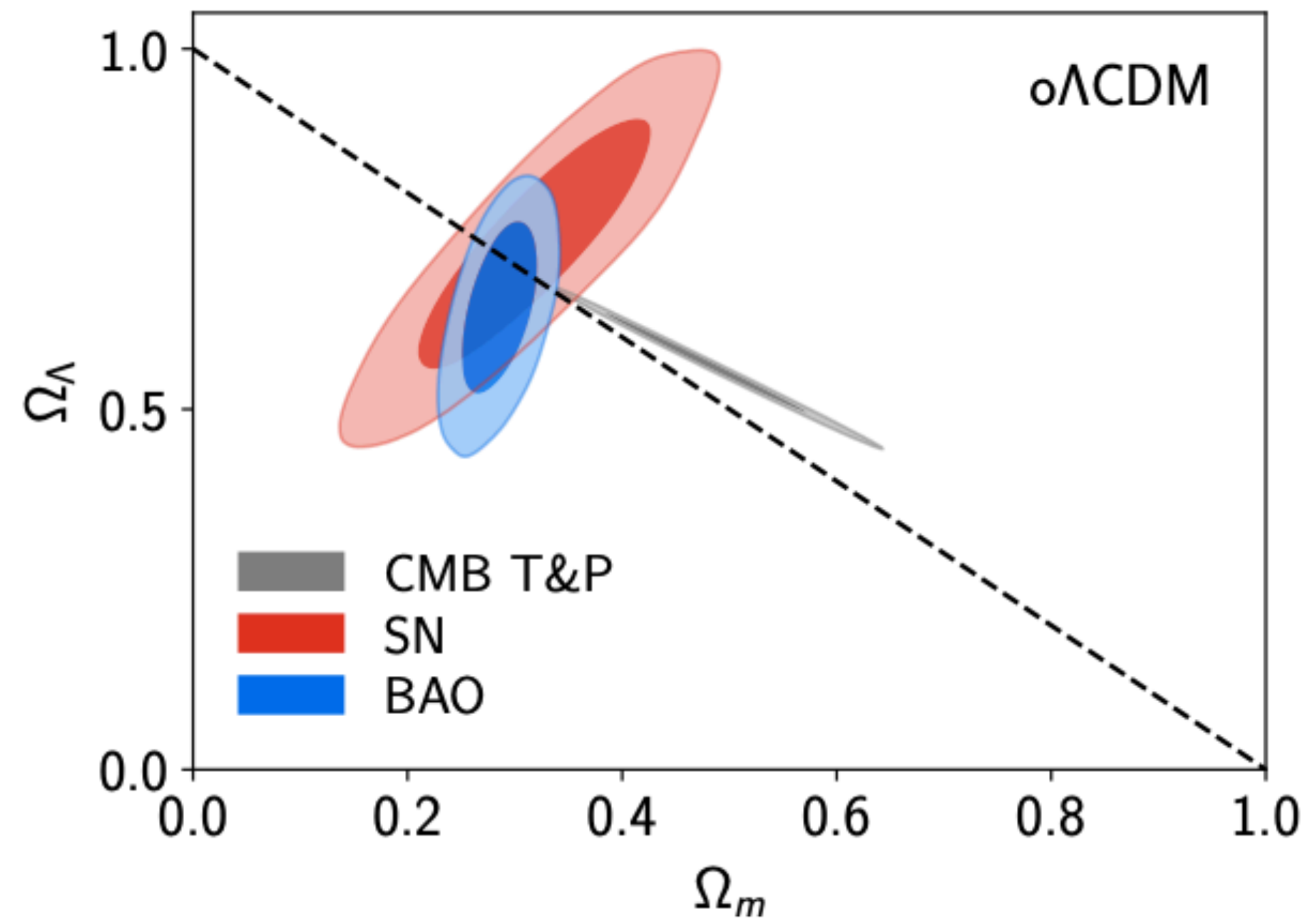
Again very stable
also when
curvature
and w are
considered

How sensitive are we to σ_8 ?



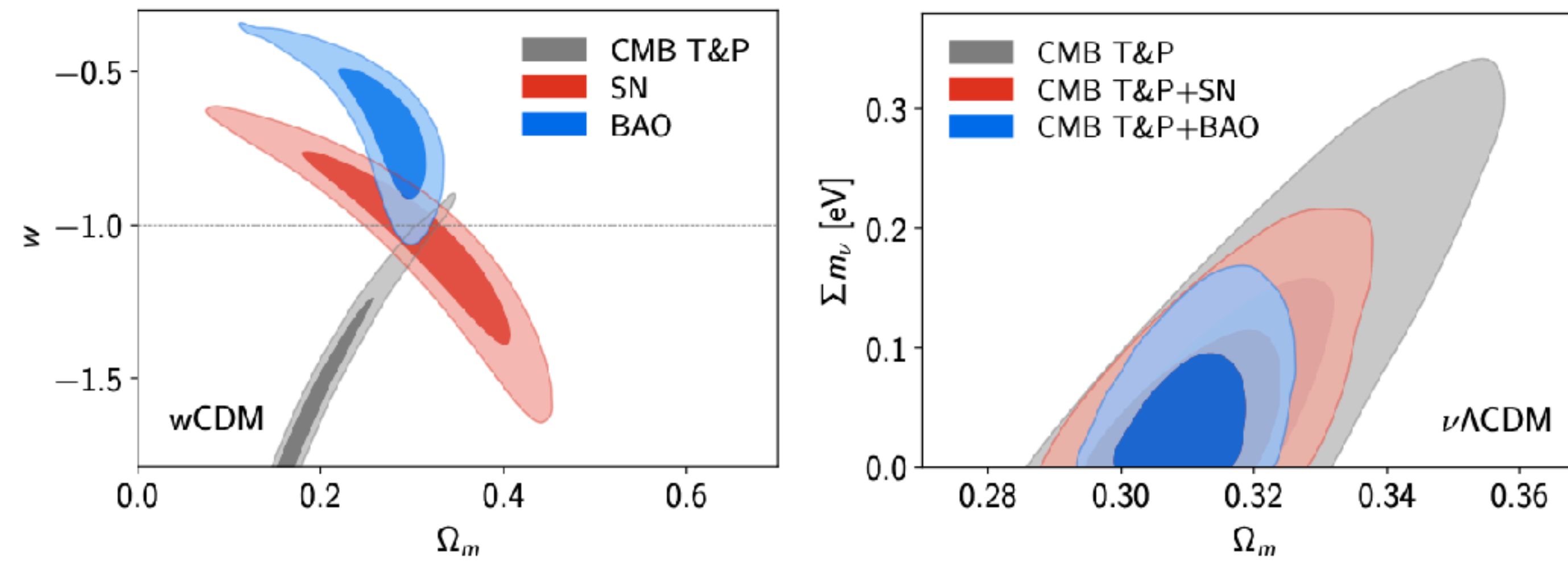
Curvature

Alam+21



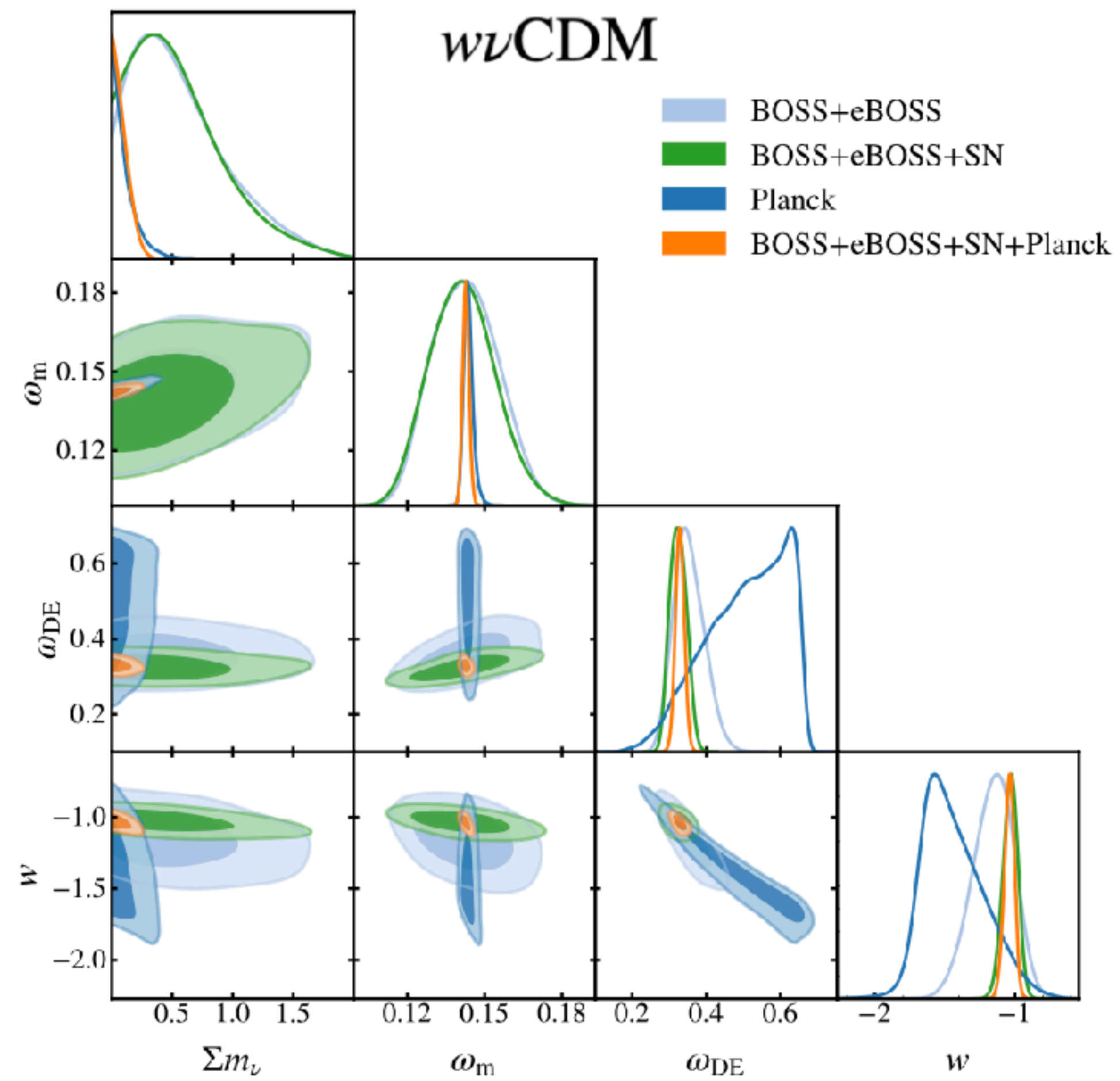
Dark Energy OR neutrinos

Alam+21



Dark Energy AND neutrinos

Semenaite+22



$M_{\nu} < 0.211$ eV (2sigma C.L.)

Galaxy Clustering + CMB lensing cross-corr: Neutrino constraints

$$P^{gg}(k) = b_{\text{auto}}(k)^2 P^{\text{mm}}(k) \approx \left(b_{\text{lin}} + b_{k^2\text{auto}} k^2\right)^2 P^{\text{mm}}(k)$$

$$P^{\text{mg}}(k) = b_{\text{cross}}(k) P^{\text{mm}}(k) \approx \left(b_{\text{lin}} + b_{k^2\text{cross}} k^2\right) P^{\text{mm}}(k),$$

b_{lin}	$b_{k^2\text{cross}}$ [$h^{-2}\text{Mpc}^2$]	$b_{k^2\text{auto}}$ [$h^{-2}\text{Mpc}^2$]	P_{shot} [$1/\bar{n}$]
[0.0, 5.0]	[−70.0, 30.0]	[−70.0, 30.0]	[0.03, 5.00]

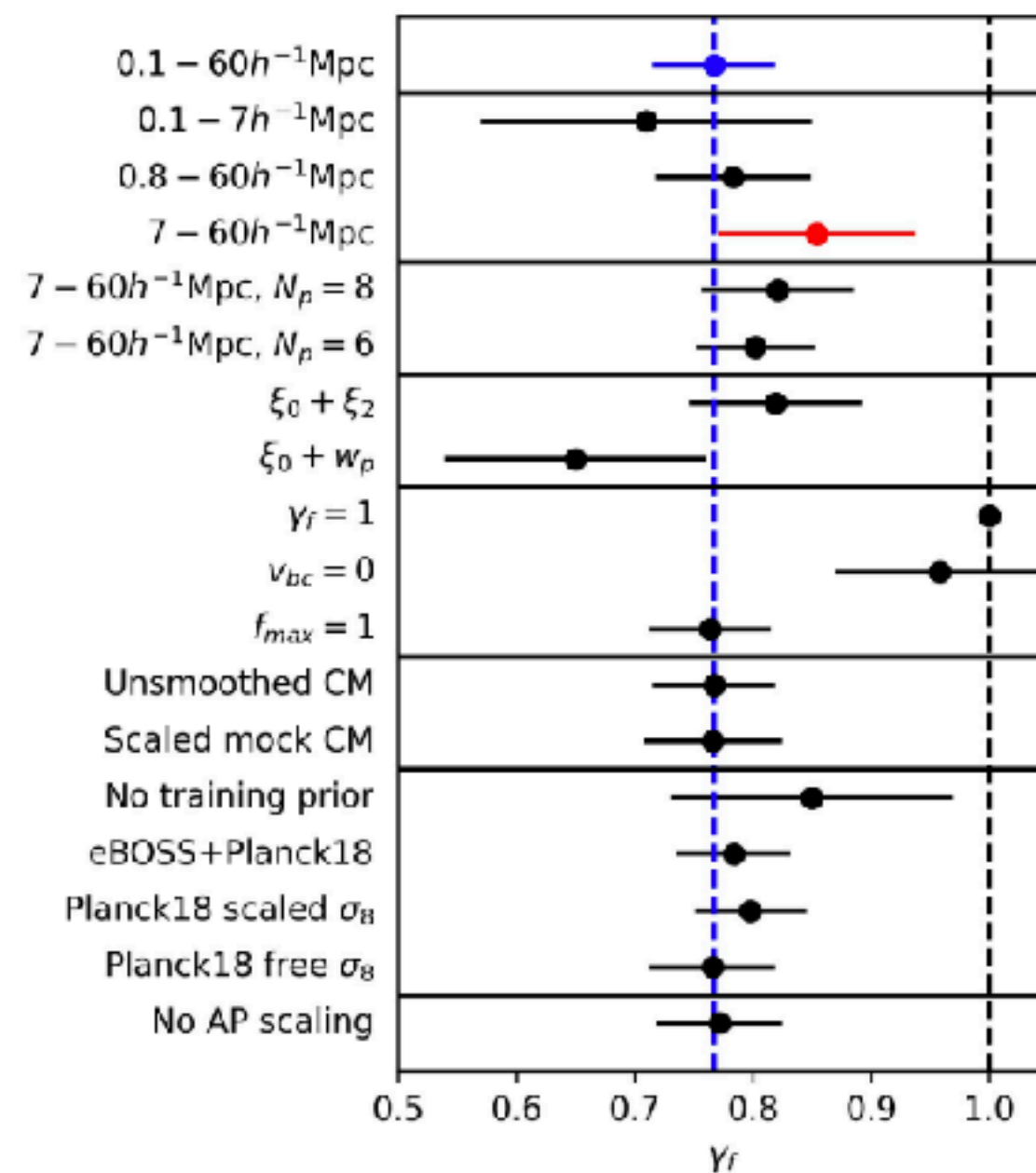
Datasets	b_{lin} [1]	$b_{k^2\text{cross}}$ [$h^{-2}\text{Mpc}^2$]	$b_{k^2\text{auto}}$ [$h^{-2}\text{Mpc}^2$]	P_{shot} [$1/\bar{n}$]	Σm_ν (95% C.L.) [eV]
$base \equiv Planck + BAO_{z_1} + P^{gg}(k)$	1.97 ± 0.05	–	-27.2 ± 10.0	1.39 ± 0.44	< 0.14
$base + C_\ell^{ng}$	1.97 ± 0.05	9.1 ± 3.1	-29.7 ± 10.1	1.51 ± 0.44	< 0.14
$base + C_\ell^{ng}$ (including C_{cross})	1.97 ± 0.05	8.8 ± 3.0	-28.7 ± 10.0	1.47 ± 0.43	< 0.14
$base + C_\ell^{ng}$ ($P_{\text{shot}} = 1$)	2.00 ± 0.05	5.1 ± 0.7	-16.1 ± 1.0	–	< 0.14
$base + C_\ell^{ng}$ ($k_{\text{max}} = 0.145\ h\text{Mpc}^{-1}$)	1.98 ± 0.05	7.0 ± 2.4	-22.2 ± 7.8	1.18 ± 0.36	< 0.14
$base + C_\ell^{ng}$ ($k_{\text{max}} = 0.160\ h\text{Mpc}^{-1}$)	2.01 ± 0.05	4.8 ± 1.8	-15.8 ± 5.8	0.86 ± 0.29	< 0.14
$base + C_\ell^{ng}$ ($k_{\text{max}} = 0.188\ h\text{Mpc}^{-1}$)	2.00 ± 0.05	5.3 ± 1.9	-17.0 ± 6.5	0.92 ± 0.31	< 0.14
$base + C_\ell^{ng}$ ($k_{\text{max}} = 0.205\ h\text{Mpc}^{-1}$)	2.01 ± 0.05	4.3 ± 1.6	-13.5 ± 4.7	0.75 ± 0.24	< 0.13
$base + ACT$	1.98 ± 0.06	–	-27.2 ± 10.0	1.39 ± 0.45	< 0.17

- The full-shape information content is comparable to the geometrical information content in the reconstructed BAO peaks
- Stable neutrino limits
- Lensing Convergence of CMB cross-correlated with galaxies: not very constraining (yet)

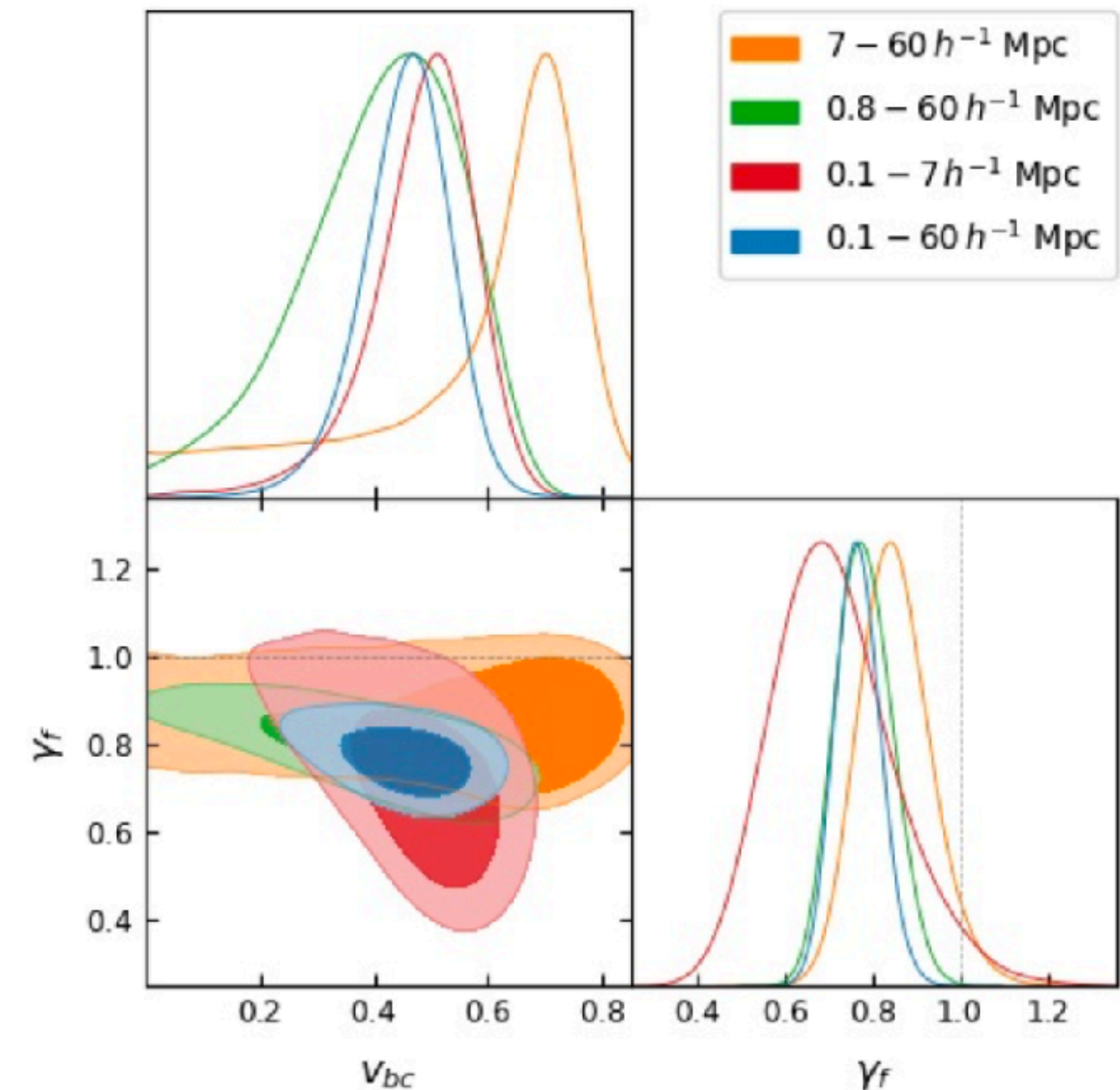
Matter Distribution at Small Scales

$$f\sigma_8 = \gamma_f f_{\Lambda\text{CDM}}\sigma_8$$

v_{bc} : parameter that controls in the HOD how the central galaxy is distributed within the DM halo - non-linear velocity



- Consistent with Λ CDM on largest scales (1.4σ) matches “standard” RSD model that agree with Λ CDM expectation
- Deviations on small scales (up to 4.5σ) - RSD equivalent of “lensing is low” is “non-linear velocity dispersion is low”
 - Insufficient mass in halos?
 - HOD model break down?
 - Simulations wrong?
 - Systematic errors?



BOSS: main conclusions

- 1) ~1% constraints on $H(z)$ and $DA(z)$ from BAO
- 2) amplitude of pec. vel. measured at ~10% level
- 3) No evidence for physics beyond Λ CDM
- 4) Agreement with Planck low values for H_0 , with limits remarkably stable also for ω CDM or ω_0 w Λ CDM models with 1sigma error bar of 1km/s/Mpc
- 5) Limits on neutrino mass are 0.16 eV, which become 0.25 when removing RSD and ~0.3 when opening the w parameter space
- 6) No support for $N_{\text{eff}} > 3$

*OVERALL the stage is set and future seems promising for the next experiments like eBOSS, DESI, WFIRST/ROMAN, Euclid, LSST etc.
it is expected that statistical errors will improve and a new level of systematics will be hit (sub-percent precision constraints)*

Latest analyses on galaxy clustering

The BOSS DR12 Full-Shape Cosmology:

Λ CDM Constraints from the Large-Scale Galaxy Power Spectrum and Bispectrum Monopole

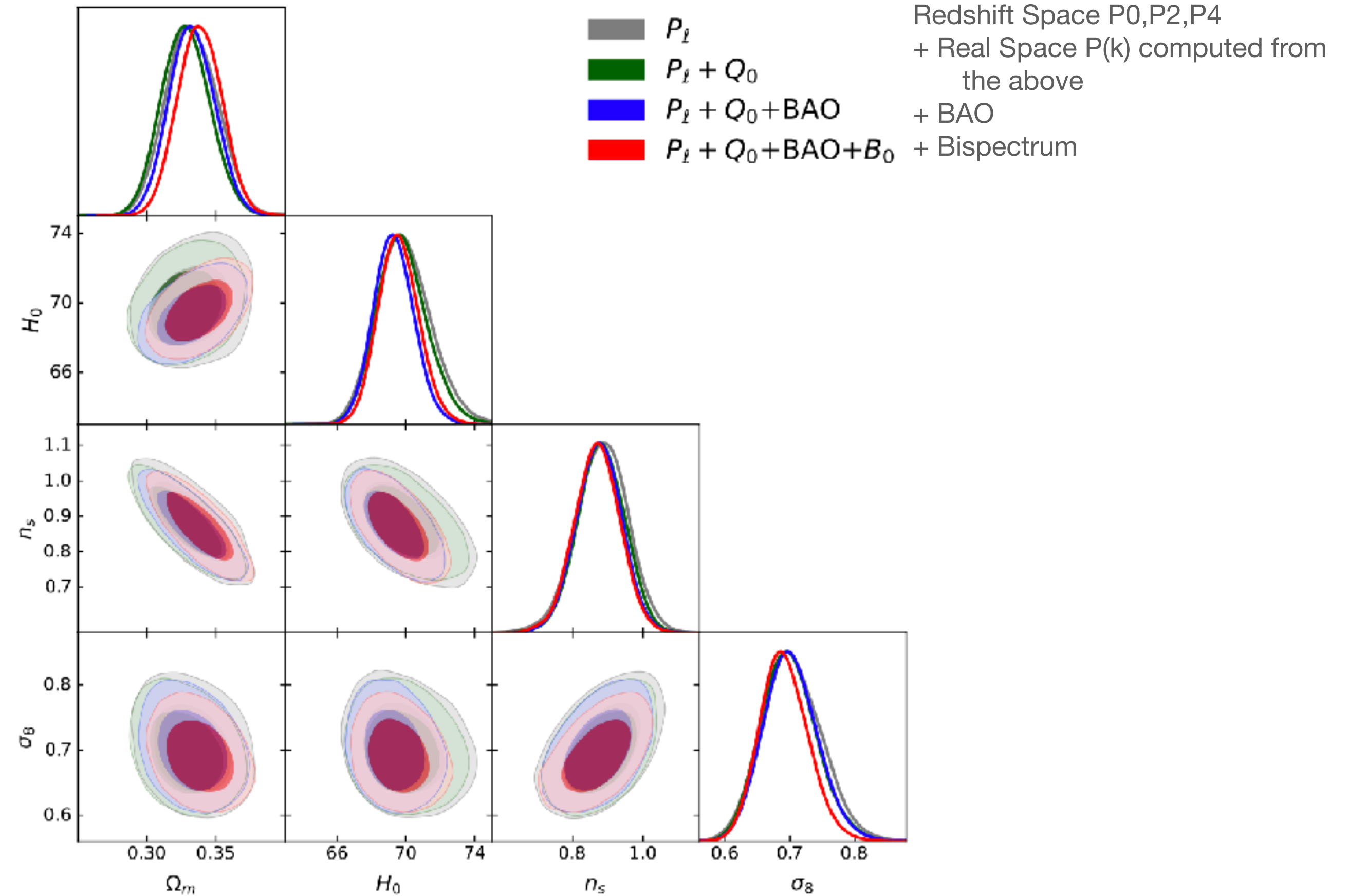
Oliver H. E. Philcox^{1,2,*} and Mikhail M. Ivanov^{2,†}

¹*Department of Astrophysical Sciences, Princeton University,
Princeton, NJ 08540, USA*

²*School of Natural Sciences, Institute for Advanced Study, 1 Einstein Drive,
Princeton, NJ 08540, USA*

We present a full Λ CDM analysis of the BOSS DR12 dataset, including information from the power spectrum multipoles, the real-space power spectrum, the reconstructed power spectrum and the bispectrum monopole. This is the first analysis to feature a complete treatment of the galaxy bispectrum, including a consistent theoretical model and without large-scale cuts. Unlike previous works, the statistics are measured using **window-free estimators**: this greatly reduces computational costs by removing the need to window-convolve the theory model. Our pipeline is tested using a suite of high-resolution mocks and shown to be robust and precise, with systematic errors far below the statistical thresholds. Inclusion of the bispectrum yields consistent parameter constraints and shrinks the σ_8 posterior by 13% to reach $< 5\%$ precision; less conservative analysis choices would reduce the error-bars further. Our constraints are broadly consistent with *Planck*: in particular, we find $H_0 = 69.6^{+1.1}_{-1.3} \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\sigma_8 = 0.692^{+0.035}_{-0.041}$ and $n_s = 0.870^{+0.067}_{-0.064}$, including a BBN prior on the baryon density. When n_s is set by *Planck*, we find $H_0 = 68.31^{+0.83}_{-0.86} \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\sigma_8 = 0.722^{+0.032}_{-0.036}$. Our S_8 posterior, 0.751 ± 0.039 , is consistent with weak lensing studies, but lower than *Planck*. Constraints on the higher-order bias parameters are significantly strengthened from the inclusion of the bispectrum, and we find no evidence for deviation from the dark matter halo bias relations. These results represent the most complete full-shape analysis of BOSS DR12 to-date, and the corresponding spectra will enable a variety of beyond- Λ CDM analyses, probing phenomena such as the neutrino mass and primordial non-Gaussianity.

Note: BBN prior is used



Theory model underneath is based on Effective Field Theory of the LSS

$$Q_0(k) \equiv P_0(k) - \frac{1}{2}P_2(k) + \frac{3}{8}P_4(k)$$

The S8 tension

$$S_8 \equiv \sigma_8 (\Omega_m/0.3)^{0.5}$$

$$S_8^{Planck} = 0.832 \pm 0.012$$

CMB

$$S_8^{DES} = 0.776 \pm 0.017$$

DES (Weak lensing and clustering)

$$S_8 = 0.734^{+0.035}_{-0.041}$$

Galaxy Clustering Full Shape

Agreement with WL and 2.5sigma tension with CMB!

Effective field theory of LSS

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + \frac{1}{m} \mathbf{p} \cdot \nabla f - m \nabla \Phi \cdot \frac{\partial f}{\partial \mathbf{p}} = 0 \quad \text{VLASOV EQ.}$$

- 1) Start from Vlasov
- 2) Filter Vlasov and define IR and UV regimes
- 3) Small scales "backreact" on Large Scales with an effective pressure

$$\begin{aligned} m \int_{\mathbf{p}} f(\mathbf{x}, \mathbf{p}, t) &\equiv \rho_m(\mathbf{x}, t), \\ m \int_{\mathbf{p}} \frac{p_i}{m} f(\mathbf{x}, \mathbf{p}, t) &\equiv \rho_m v_i(\mathbf{x}, t), \\ m \int_{\mathbf{p}} \frac{p_i p_j}{m^2} f(\mathbf{x}, \mathbf{p}, t) &\equiv \rho_m v_i v_j(\mathbf{x}, t) + \kappa_{ij}(\mathbf{x}, t). \end{aligned}$$

Moments of f
to define density
velocity and stress energy tensor

$$\partial_t \rho_m + \nabla_i (\rho_m v^i) = 0. \quad \text{Continuity}$$

$$\rho_m [\dot{v}^i + v^j \nabla_j v^i] + \rho_m \nabla_i \Phi = 0. \quad \text{Euler}$$

Ansatz for a generic fluid with viscosity

$$\kappa_{ij} = -p \delta_{ij} + \eta \left[\nabla_i v_j + \nabla_j v_i - \frac{2}{3} \delta_{ij} \nabla \cdot \mathbf{v} \right] + \zeta \delta_{ij} \nabla \cdot \mathbf{v}.$$

NOW: separate the scales between long modes (l) and short modes (s)

Effective energy densities gets velocity and gravitational correction and can be derived in full GR as well

$$\rho_\ell \left[\dot{v}_\ell^i + v_\ell^j \nabla_j v_\ell^i \right] + \rho_\ell \nabla_i \phi_\ell = -\nabla_j [\tau^j_i]_\Lambda,$$

[...] Lambda is
spatial average over 1/Lambda scale

$$\tau^i_j \equiv \rho_m v_i^s v_j^s - \frac{\phi_{,k}^s \phi_{,k}^s \delta_{ij} - 2 \phi_{,i}^s \phi_{,j}^s}{8\pi G}.$$

Effective stress tensor in Euler eq.
induced by small scale
fluctuations

Note validity range: $\frac{k}{k_{\text{NL}}} \ll 1$

$$(2\pi^2)^{-1} P_{\text{lin}}(k_{\text{NL}}) k_{\text{NL}}^3 \approx 1. \quad k_{\text{NL}}^{-1} \sim 5 \text{ Mpc}$$

Effective field theory of LSS - II

Now the problem is to calculate the effective stress tensor

Biased tracers (e.g. galaxies, DM haloes)

$$\delta_g = b_1 \delta + \frac{b_2}{2} \delta^2 + b_{\mathcal{G}_2} \mathcal{G}_2 + b_{\nabla^2 \delta} \nabla^2 \delta + b_{\Gamma_3} \Gamma_3 + \varepsilon + \dots$$

$$\frac{1}{a\rho} \partial_j \tau^{ij} = \int d\tau' K(\tau, \tau') \partial^i \delta(\mathbf{x}_{\text{fl}}[\mathbf{x}, \tau; \tau'], \tau') + \dots,$$

Time propagator Fluid element

$$\mathcal{G}_2(\Phi) \equiv (\partial_i \partial_j \Phi)^2 - (\Delta \Phi)^2, \quad \Gamma_3 \equiv \mathcal{G}_2(\Phi) - \mathcal{G}_2(\Phi_v)$$

Taylor expand the above

+ redshift space distortions...
+ baryons....
+ neutrinos....

$$\delta^{\text{ctr.}} = -c_0 \left(\frac{k}{k_{\text{NL}}} \right)^2 - (c_1 \mu^2 + c_2 \mu^4) \left(\frac{k}{k_{\text{NL}}} \right)^2$$

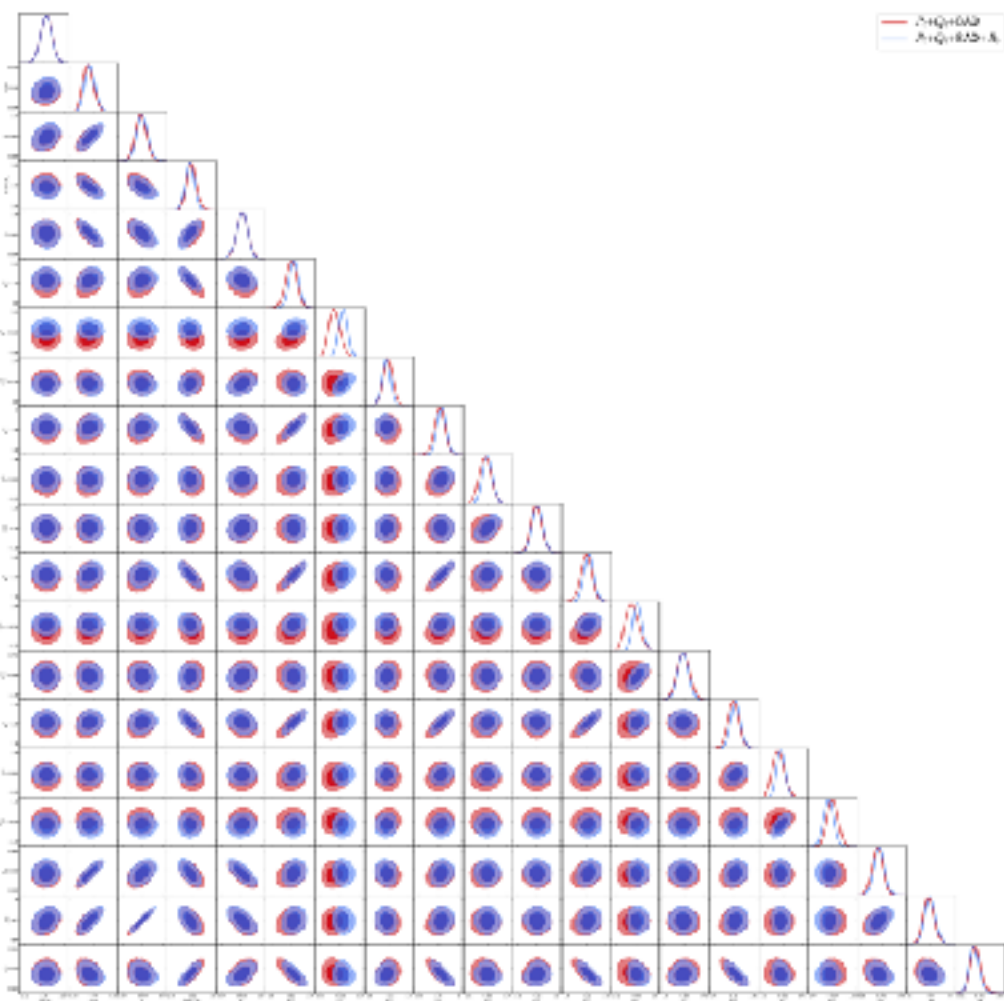
modelling of Fingers of God

$$-\frac{1}{a\rho} \partial_j \tau^{ij} = -c_s^2 \partial^i \delta + \frac{c_v^2}{\mathcal{H}} \partial^i \partial_k v^k - c_1 \partial^i \delta^2 - c_2 \partial^i (s^{kl} s_{kl}) - c_3 s^{ij} \partial_j \delta - \frac{1}{a\rho} \partial_j \tau_{\text{stoch.}}^{ij}$$

Insert the above in Euler equation --> and compute!
Convenient to set the stress energy to zero first
and then look for corrections to this

Things get non-trivial with many parameters... but...

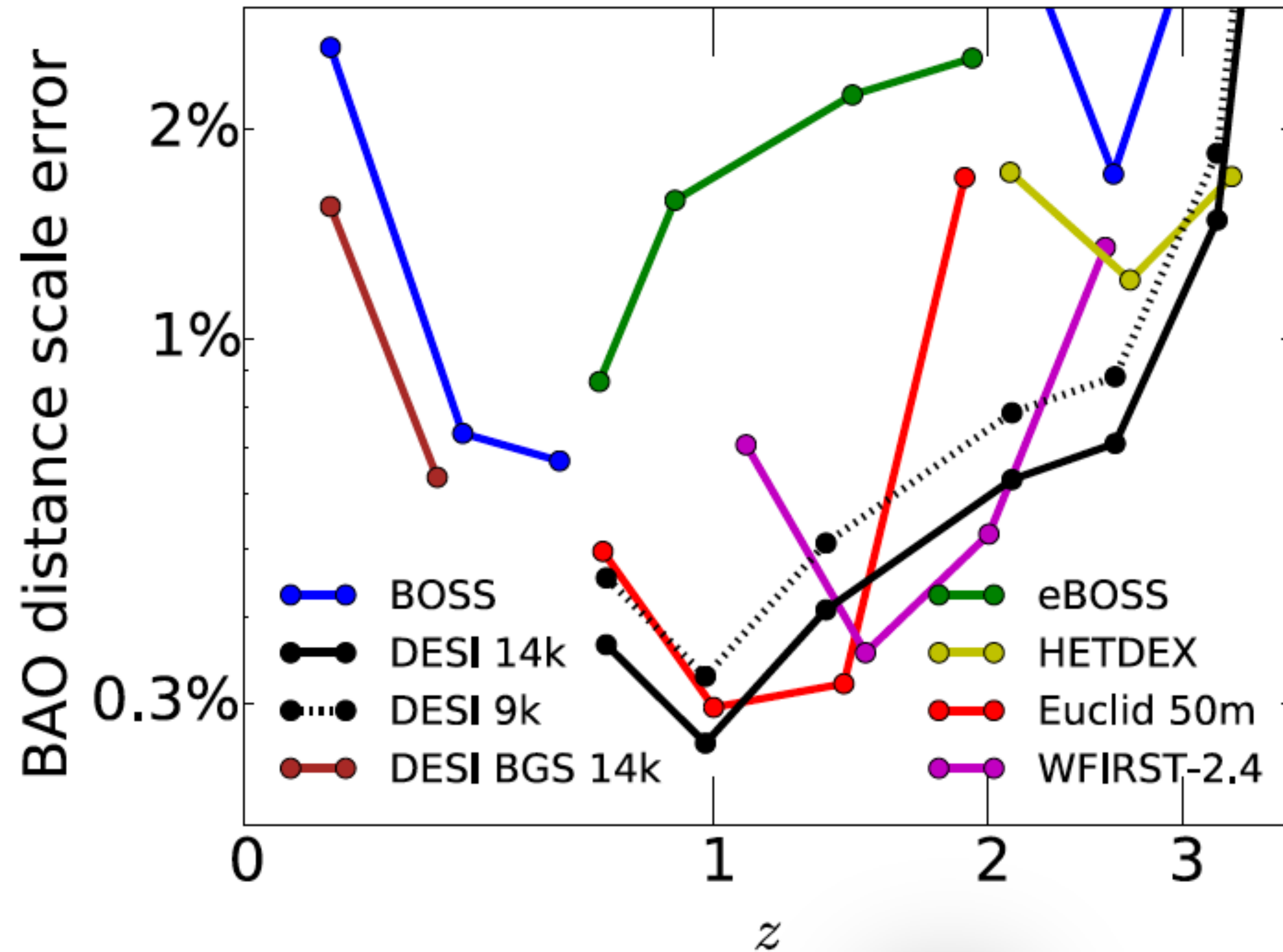
$$\delta = [\delta_{(1)} + \delta_{(2)} + \delta_{(3)} + \dots] + \delta_{(1)}^c + \dots$$



from BOSS DR12

Future seems bright

DESI paper (2016) - stage IV experiment - Y1 DR in Fall 2023 / early data release in Jan 23



"Conclusions"

Future galaxy redshift surveys (e.g. DESI from the ground or Euclid from the sky) will continue an on-going effort to map the large-scale galaxy distribution

Different features of the galaxy power spectrum provide different constraint on the cosmological model:

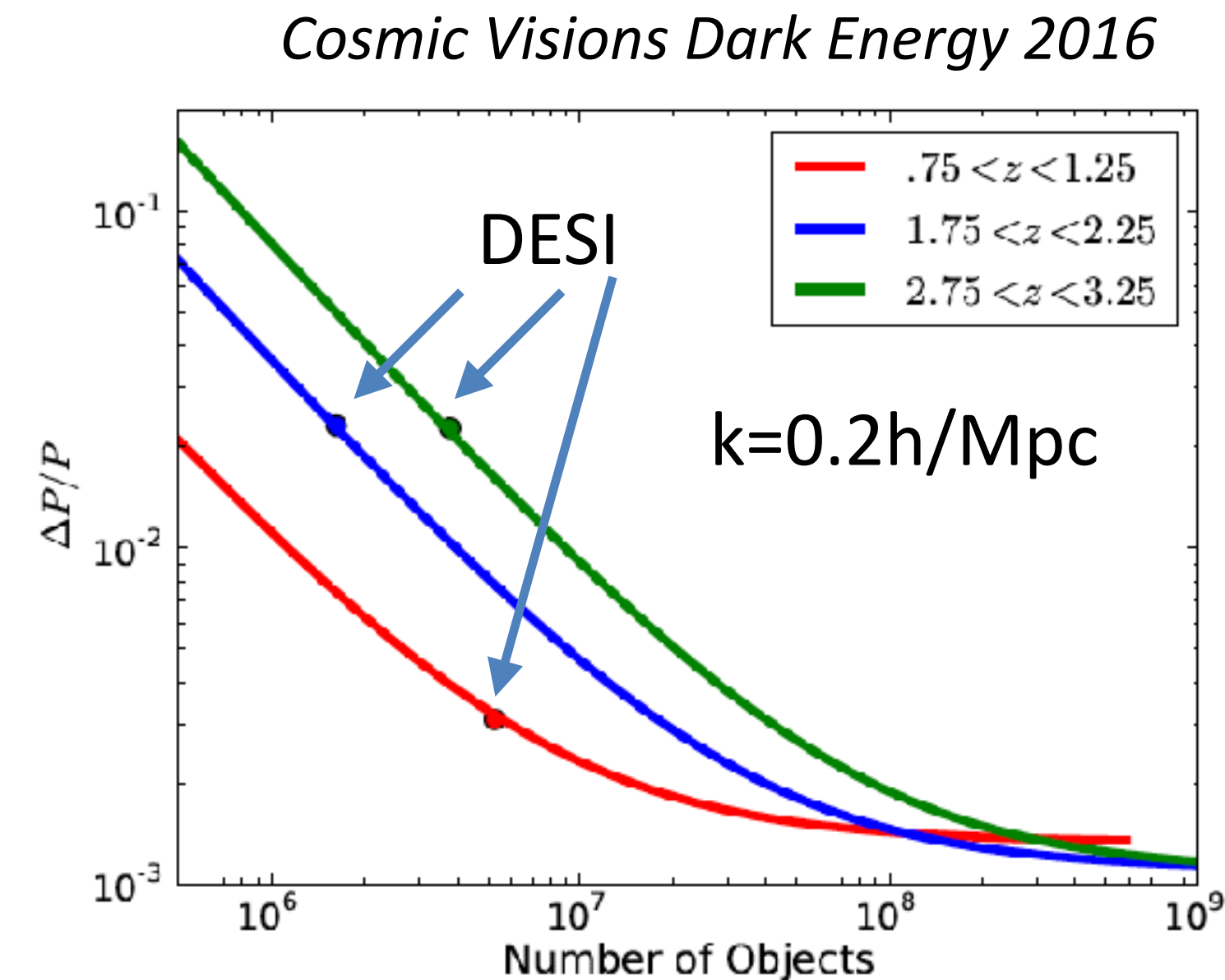
- BAO are a standard ruler, a geometrical probe of the expansion history
- The anisotropy of the galaxy power spectrum (Redshift-Space Distortions) measure instead the growth of structure
- The “shape” of the power spectrum provide an upper bound on neutrino masses

Current efforts are aimed at extracting all available information in 2-point and higher-order correlation functions and extend PT predictions beyond the Standard Cosmological Model ---> Bispectrum/Trispectrum.... etc

Challenges of GC studies for dark energy

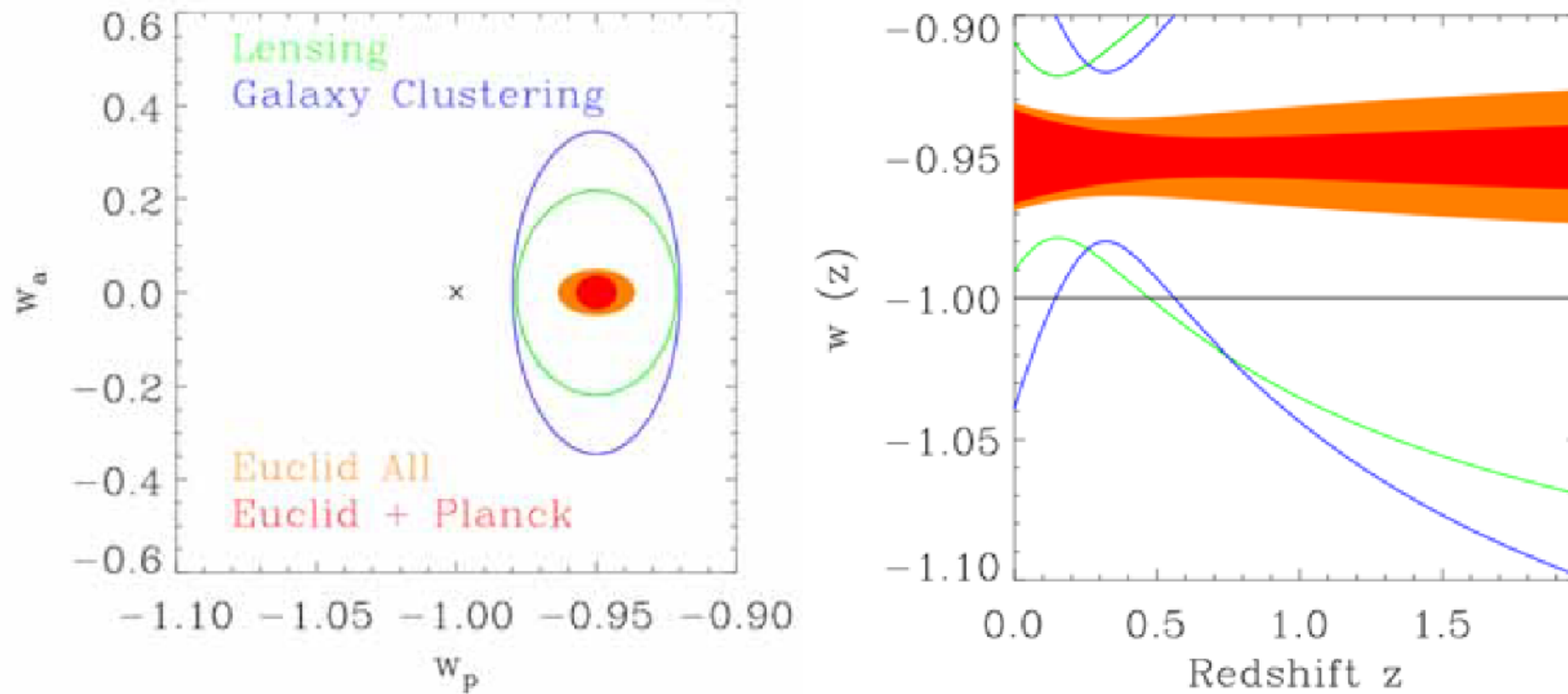
- bias modelling at mildly non-linear scales to exploit also other smaller volume surveys
- neutrino mass measurement and modelling of neutrino induced non-linearities in GCs (scale dependence of the bias)
- higher order statistics and the search for non-Gaussianities
- Cross correlations
- Multi purpose experiments with high degree of complementarity
- Machine learning and data science (pixel-by-pixel analysis)
- **High redshift regime/huge discovery potential**

*Ultimate error achievable
on the power spectrum
(maximum amount of
information in the sky)*



Euclid

Euclid definition study report 2011



GC+WL

GC+WL+GCs+ISW

	Dark Energy		
Parameter	w_p	w_a	FoM
Euclid Primary	0.015	0.150	430
Euclid All	0.013	0.048	1540
Euclid + Planck	0.007	0.035	4020
Current	0.100	1.500	~10
Improvement Factor	>10	>50	>300

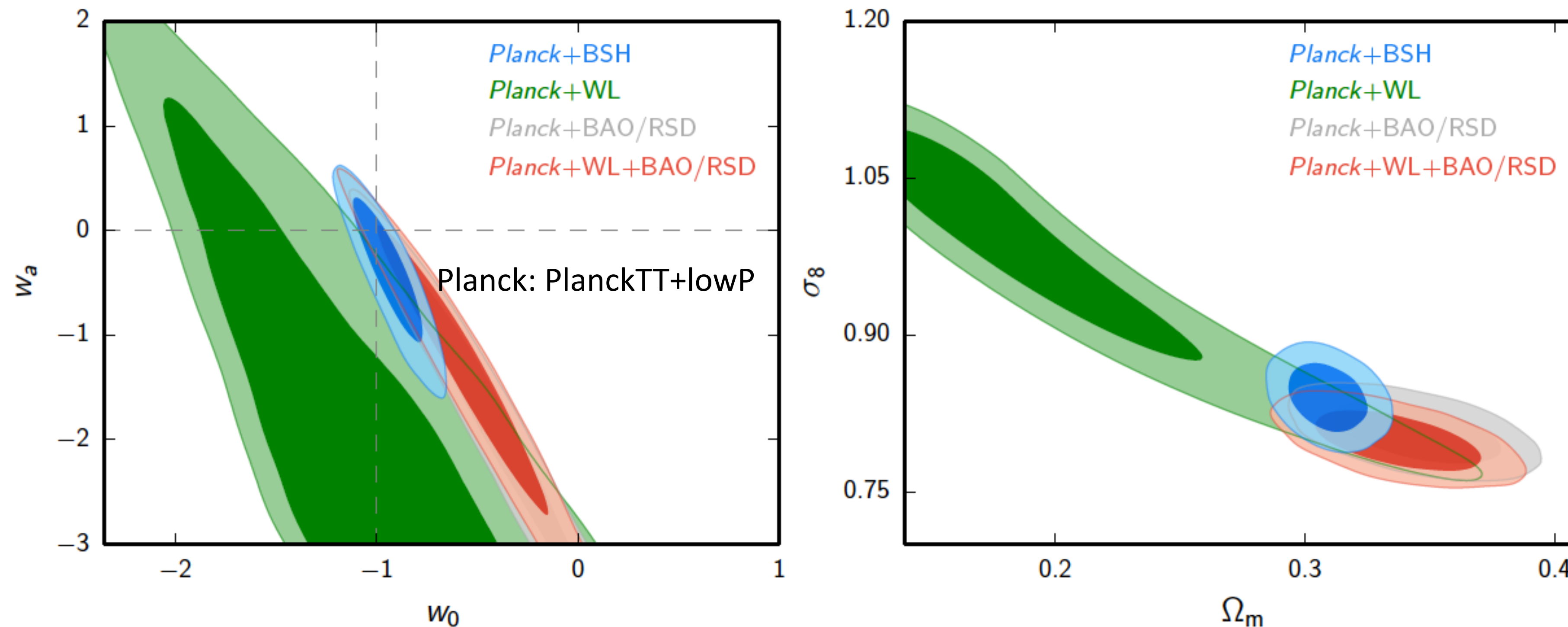
DESI constraints

Table 2.9: DETF Figures of Merit and uncertainties σ_{w_p} and σ_{Ω_k} . σ_{w_p} is the error on w at the pivot redshift, which also equal to the error on a constant w holding $w_a = 0$. σ_{Ω_k} is the error on the curvature of the Universe, Ω_k . All DESI lines contain the BGS, and BOSS in the range $0.45 < z < 0.6$ that does not substantially overlap with DESI. All cases include *Planck* CMB constraints. The pivot point, where $w(a)$ has minimal uncertainty is indicated by a_p . We note that a FoM of 110 is 10 times the Stage II level of [109], which we take to be the definition of Stage IV. DESI BAO galaxy exceeds this threshold even with a 9,000 square degree survey.

Surveys	FoM	a_p	σ_{w_p}	σ_{Ω_k}
BOSS BAO	37	0.65	0.055	0.0026
DESI 14k galaxy BAO	133	0.69	0.023	0.0013
DESI 14k galaxy and Ly- α forest BAO	169	0.71	0.022	0.0011
DESI 14k BAO + gal. broadband to $k < 0.1 \ h \text{ Mpc}^{-1}$	332	0.74	0.015	0.0009
DESI 14k BAO + gal. broadband to $k < 0.2 \ h \text{ Mpc}^{-1}$	704	0.73	0.011	0.0007
DESI 9k galaxy BAO	95	0.69	0.027	0.0015
DESI 9k galaxy and Ly- α forest BAO	121	0.71	0.026	0.0012
DESI 9k BAO + gal. broadband to $k < 0.1 \ h \text{ Mpc}^{-1}$	229	0.73	0.018	0.0011
DESI 9k BAO + gal. broadband to $k < 0.2 \ h \text{ Mpc}^{-1}$	502	0.73	0.013	0.0009

Dark Energy after Planck - I

Planck Paper XIV “Dark Energy and Modified Gravity” (2016)

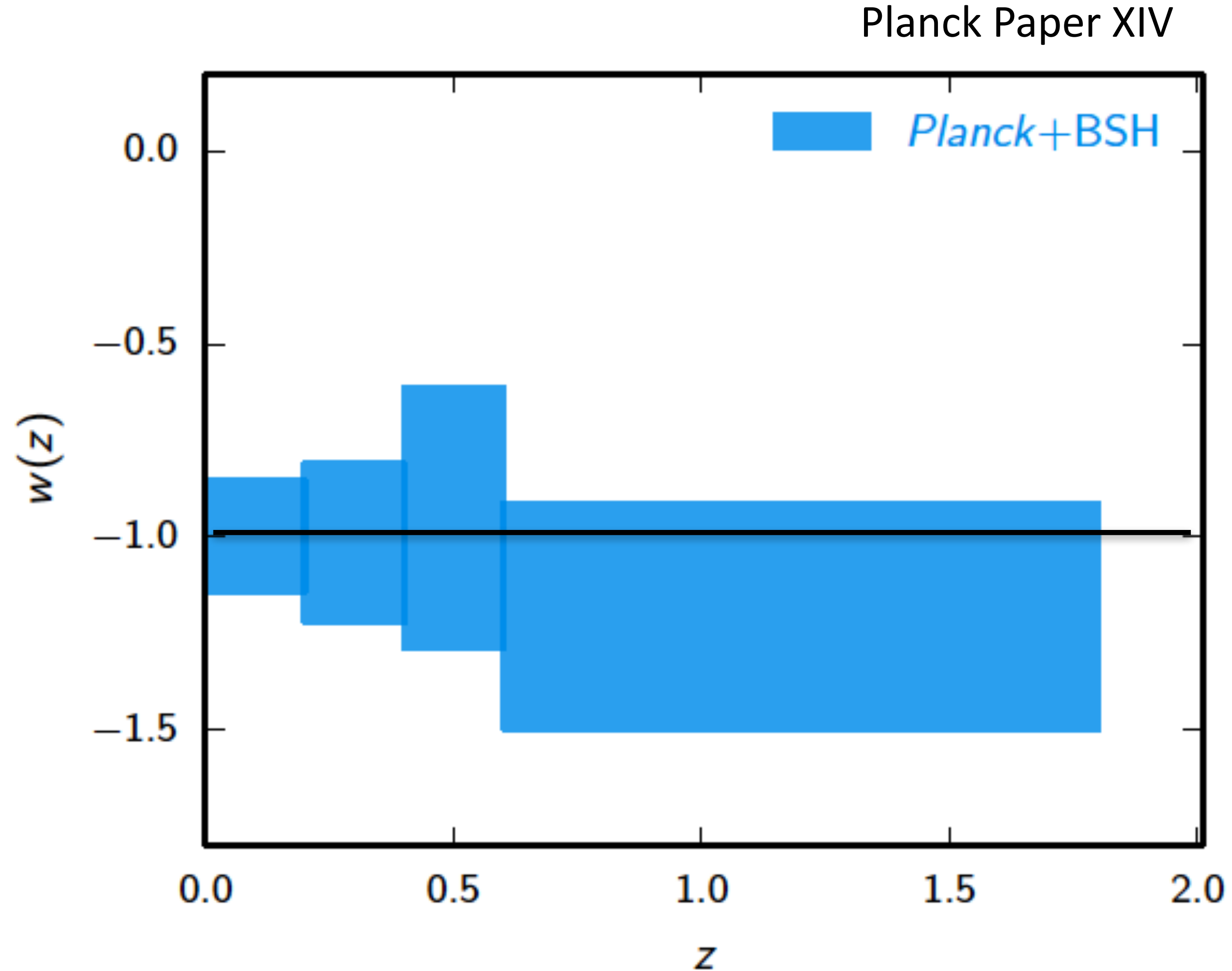


Planck+BSH combination has a $\Delta\chi^2=-0.8$ w.r.t. base Λ CDM

WL is CFHTLenS: prefers w_0-w_a at 2σ w.r.t. Λ CDM, wants higher σ_8 and (not shown) value of H_0

Implications for the small scale crisis of Λ CDM

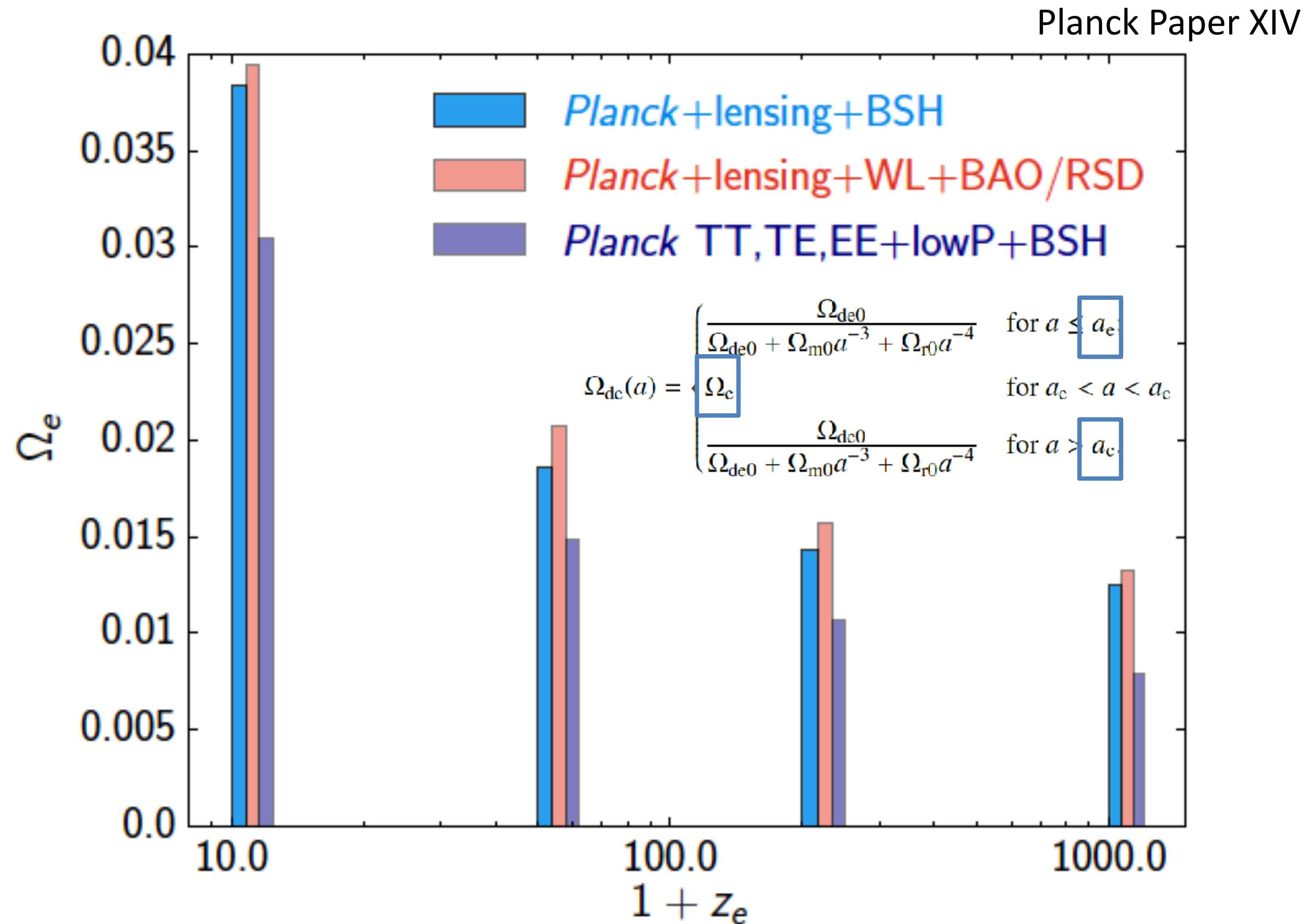
Dark Energy after Planck - II



Principal Component Analysis reconstruction in 4 bins, increasing number of bins does lead to same conclusions.

$$w(z) = p_{i-1} + \Delta w \left(\tanh \left[\frac{z - z_i}{s} \right] + 1 \right) \text{ for } z < z_i, i \in \{1, 4\}.$$

Dark Energy after Planck - III



Note further that Planck is providing a measurement of the sound horizon at the drag epoch with an error of 0.2% ...

Dark Energy after Planck - IV

Remarkable results from Planck experiment in constraining DE properties

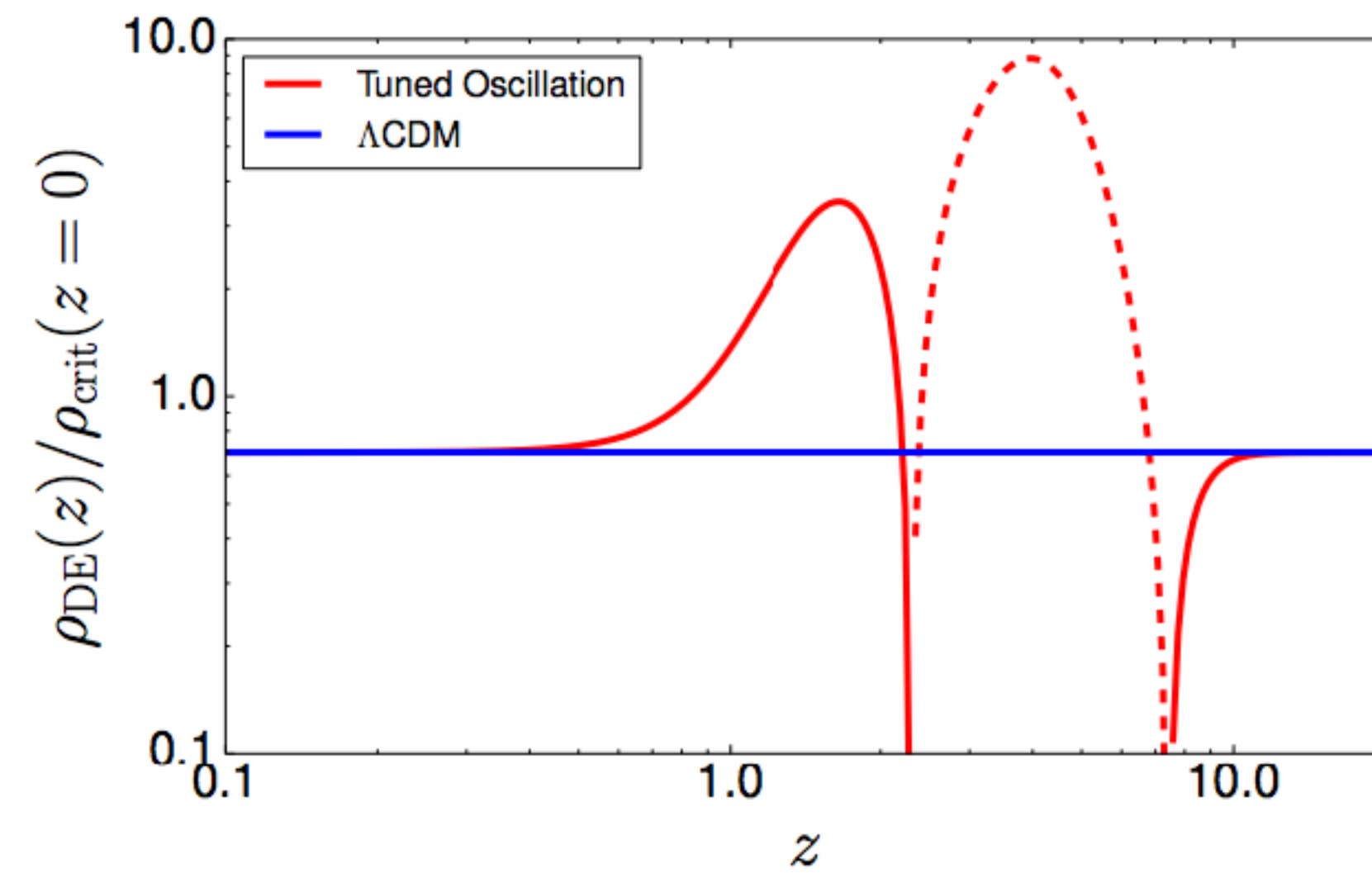
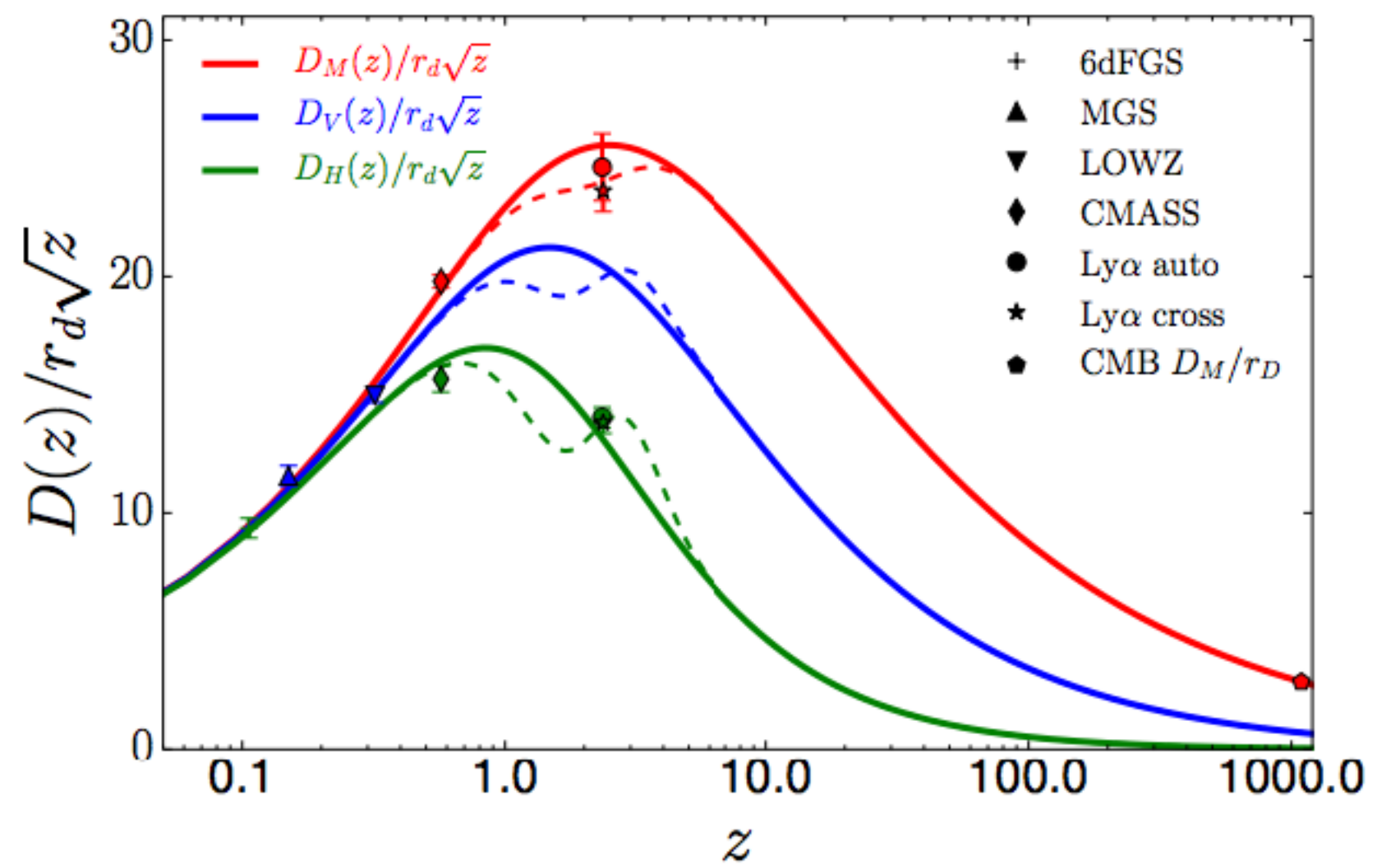
1) In (w_0-w_a) , Planck TT+lowP+BSH is compatible with LCDM, as well as BAO/RSD. When adding WL to Planck TT+lowP, both WL and CMB prefer the (w_0-w_a) model with respect to LCDM at $\sim 2\sigma$ (with preference for high values of H_0 , excluded when including BSH). CMB lensing does not change the numbers.

2) Tests on time varying $w(z)$ are compatible with LCDM for all data sets tested.

3) EDE model with constant fraction till recent. Constraints are incredibly tight: previous constraints improved by a factor 3-4, $\Omega_e < 0.0036$ for PlanckTT,TE,EE+lowP+BSH. Polarization improves limits by a factor 2.

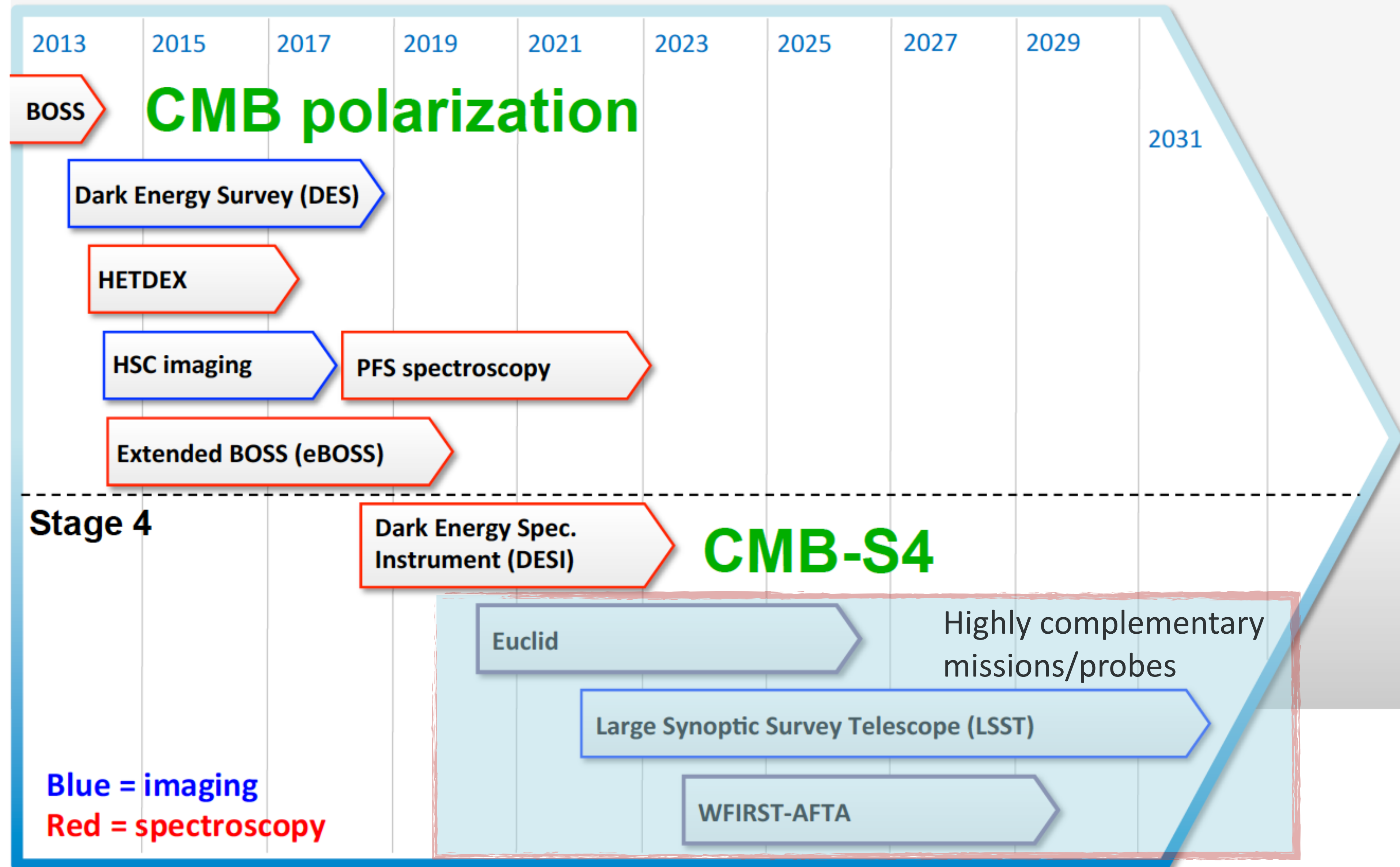
4) $\Omega_e(z)$ as a function of z_e , the redshift starting from which a fraction is present. $\Omega_e < 2\%$ (95% C.L.) even for z_e as late as 50 (important results in the era of **structure formation** with implications for EDGES and other science). CMB lensing is important.

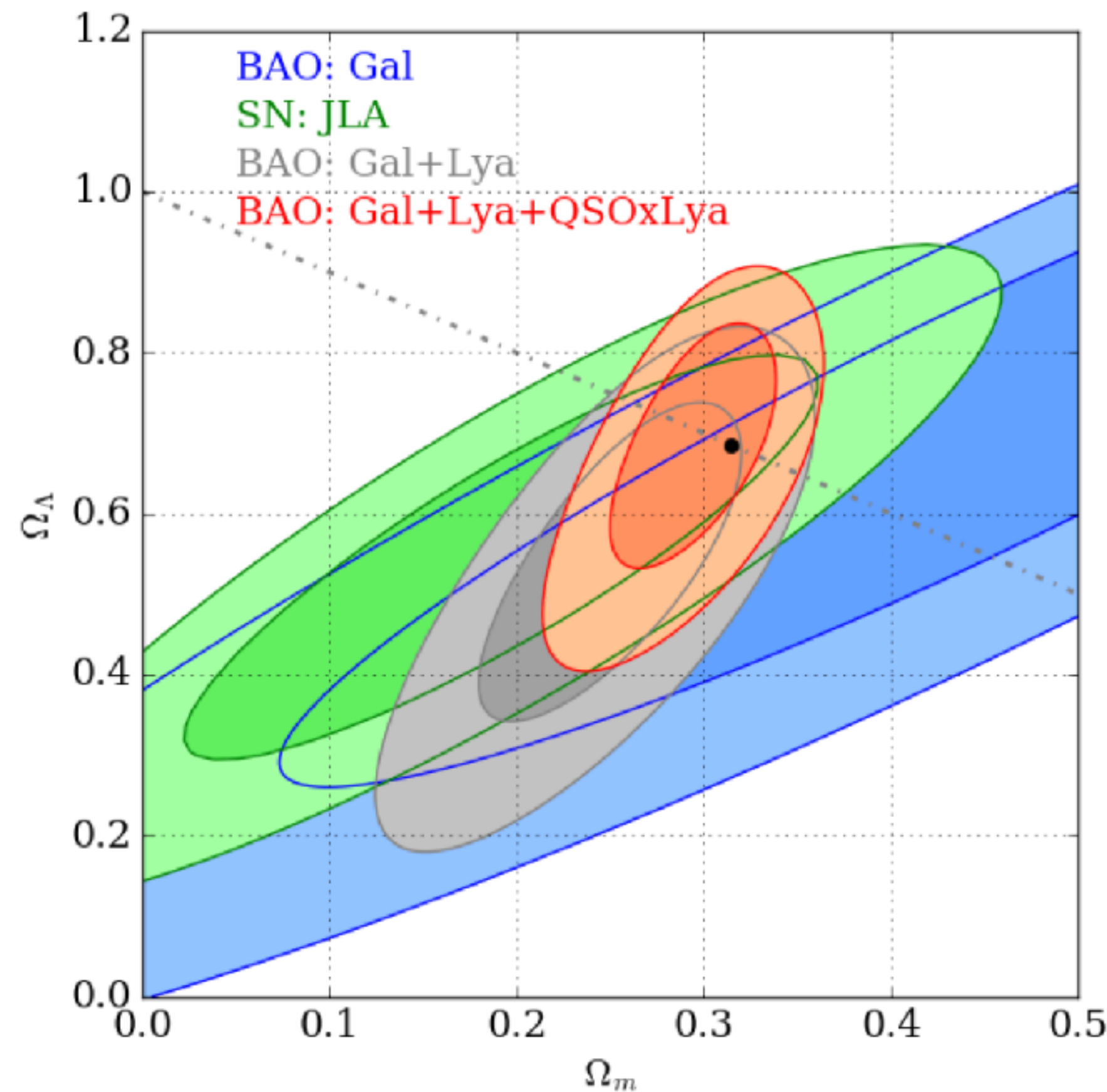
Lyman-alpha BAO: a tuned oscillation?



$\Delta\chi^2 = -6.6$ with 3 d.o.f. for this model

Dark Energy Experiments: 2013 - 2031





$$\Omega_M = 0.296 \pm 0.029$$

$$\Omega_\Lambda = 0.699 \pm 0.100$$

$$\Omega_k = -0.002 \pm 0.119$$

- Redshift covered $z=2.1-3.5$, $\langle z \rangle = 2.33$.
- 160,000 QSOs (DESI will have ~ 10 times more).
- Statistical improvement over DR9, DR11 (Delubac+14) hinted for a change in the sign of dark energy density to reconcile with Planck.
- Better physical modelling for high column density systems, UV fluctuations, broad band power (marginalized over).
- Complementarity with low redshift BAO, high redshift BAO provide a stronger support for $\Omega_\Lambda > 0$ (independent of CMB).

