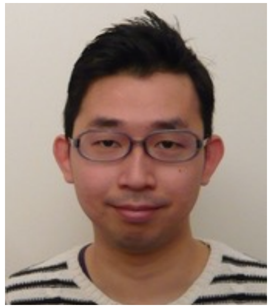
Precision cosmology with galaxy surveys: σ_8 tension?



Masahiro Takada (Kavli IPMU)

Based on collaboration with

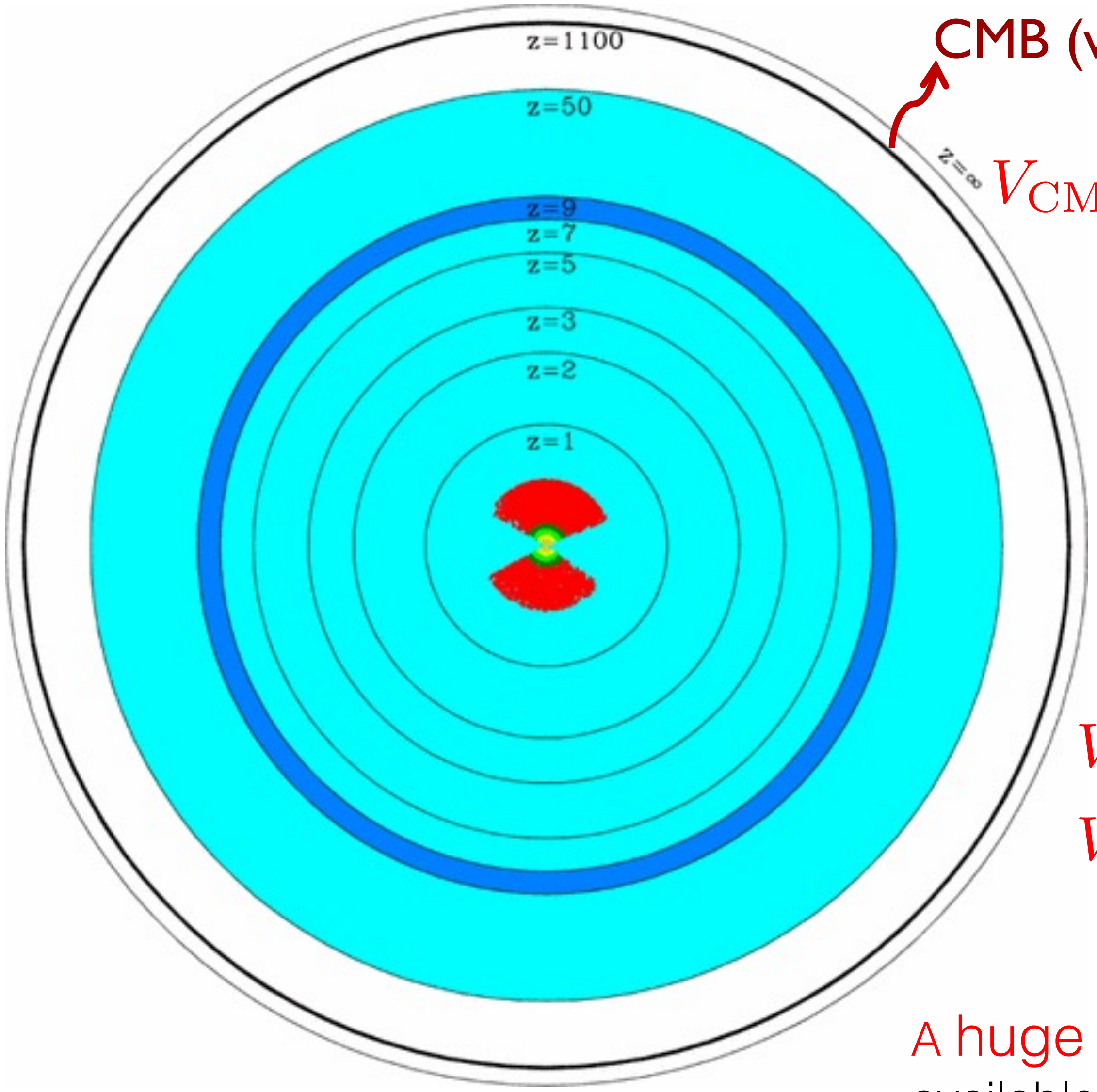
Takahiro Nishimichi (PI: YITP, Kyoto U.), Yosuke Kobayashi (Arizona U.),
H. Miyatake (Nagoya), Sunao Sugiyama (Kavli IPMU) et al.

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

wpi

CMB (~2D) vs. Galaxy Surveys (3D)



CMB (width ~ 5Mpc)

$$V_{\rm CMB} \sim 4\pi f_{\rm sky}(14~{\rm Gpc})^2 \times (0.005~{\rm Gpc})$$
$$\sim 7~({\rm Gpc}/h)^3$$

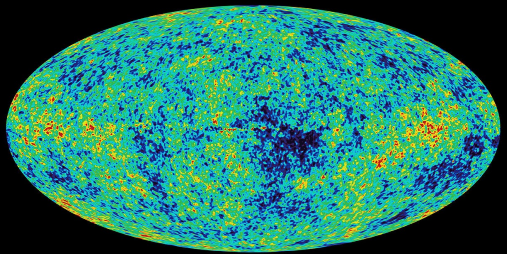
$$V_{\rm DESI} \sim 30(h^{-1}{\rm Gpc})^3$$
$$V_{\rm PFS} \sim 8.5(h^{-1}{\rm Gpc})^3$$

(Note the number density of PFS is higher than that of DESI by a factor of a few)

A huge 3D volume (= a huge discovery space) is still available for cosmology

Tegmark & Zaldarriaga 09

Need a stringent test of LCDM model



CMB at z~1000

ΛCDM extrapolation

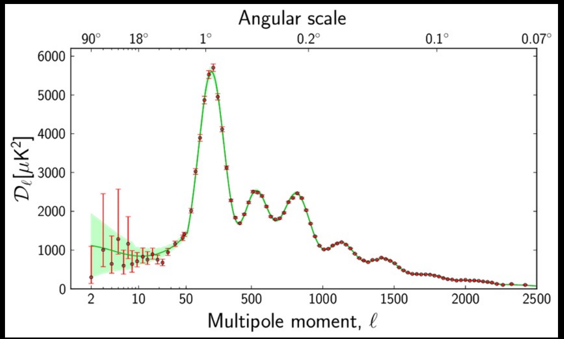
$\sigma_8^{\rm CMB}(z\sim 0)$
$S_8^{\rm CMB}(z\sim 0)$

$S_8 \equiv \sigma_8(\Omega_{\rm m}/0.3)^{0.5}$

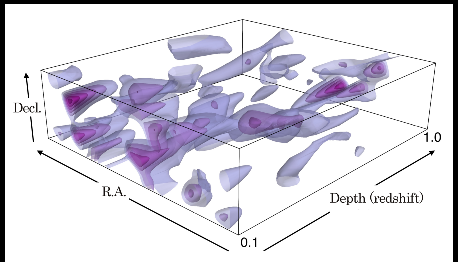
time

gravity (dark matter)

cosmic expansion (dark energy)



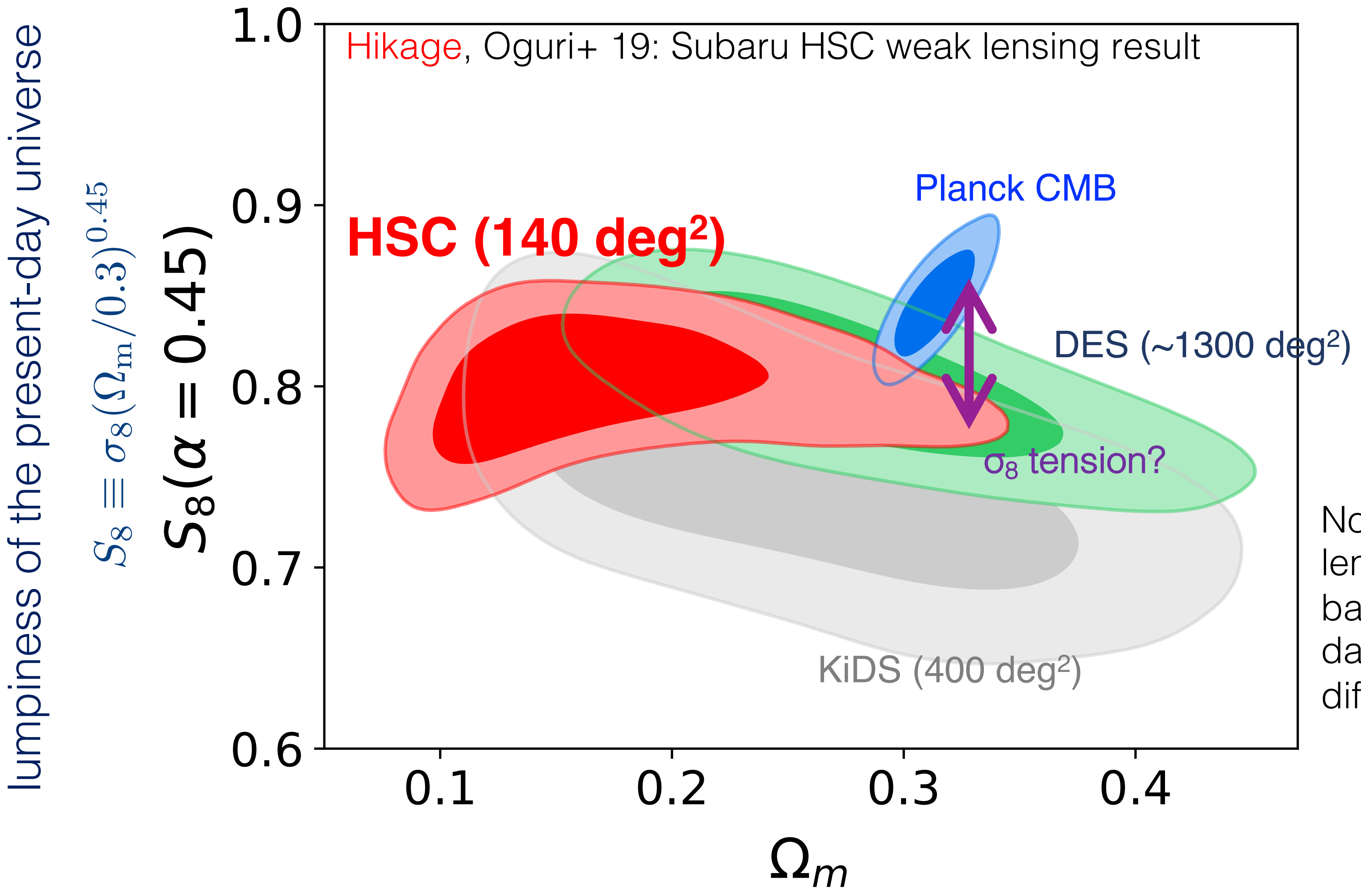
ΛCDM=~6 parameters



Galaxy surveys directly measure "**lumpiness**" of the universe

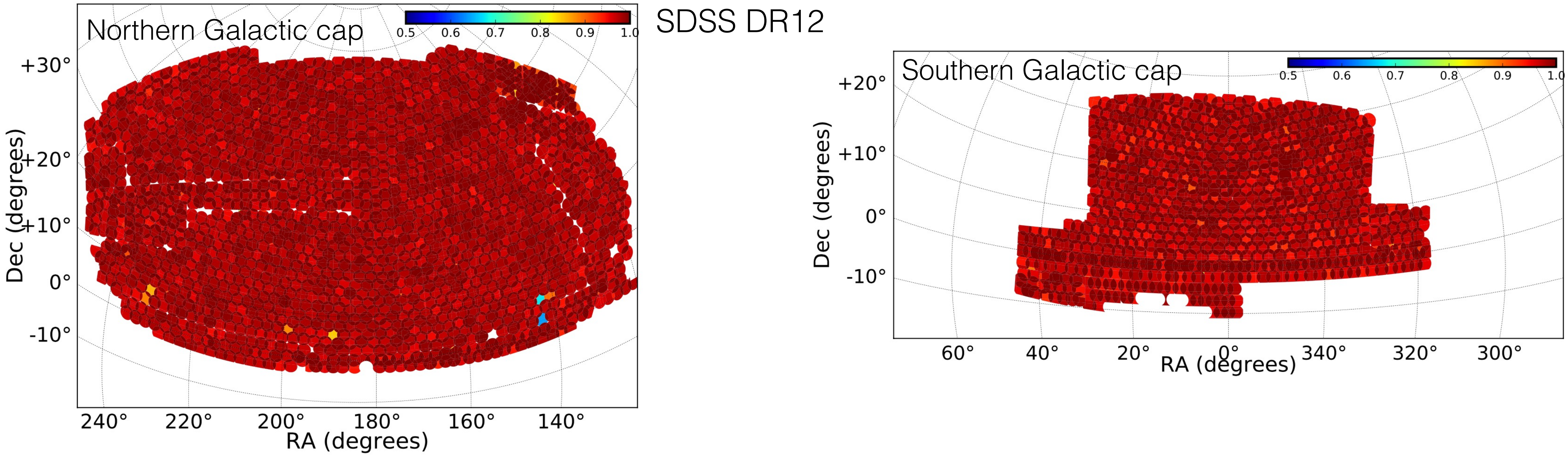
$\sigma_8^{\rm obs}(z\sim 0),\ \ S_8^{\rm obs}(z\sim 0)$

σ_8 tension? – a hint of new physics?



Note: the different weak lensing survey results are based on independent datasets (data from different regions of the sky)

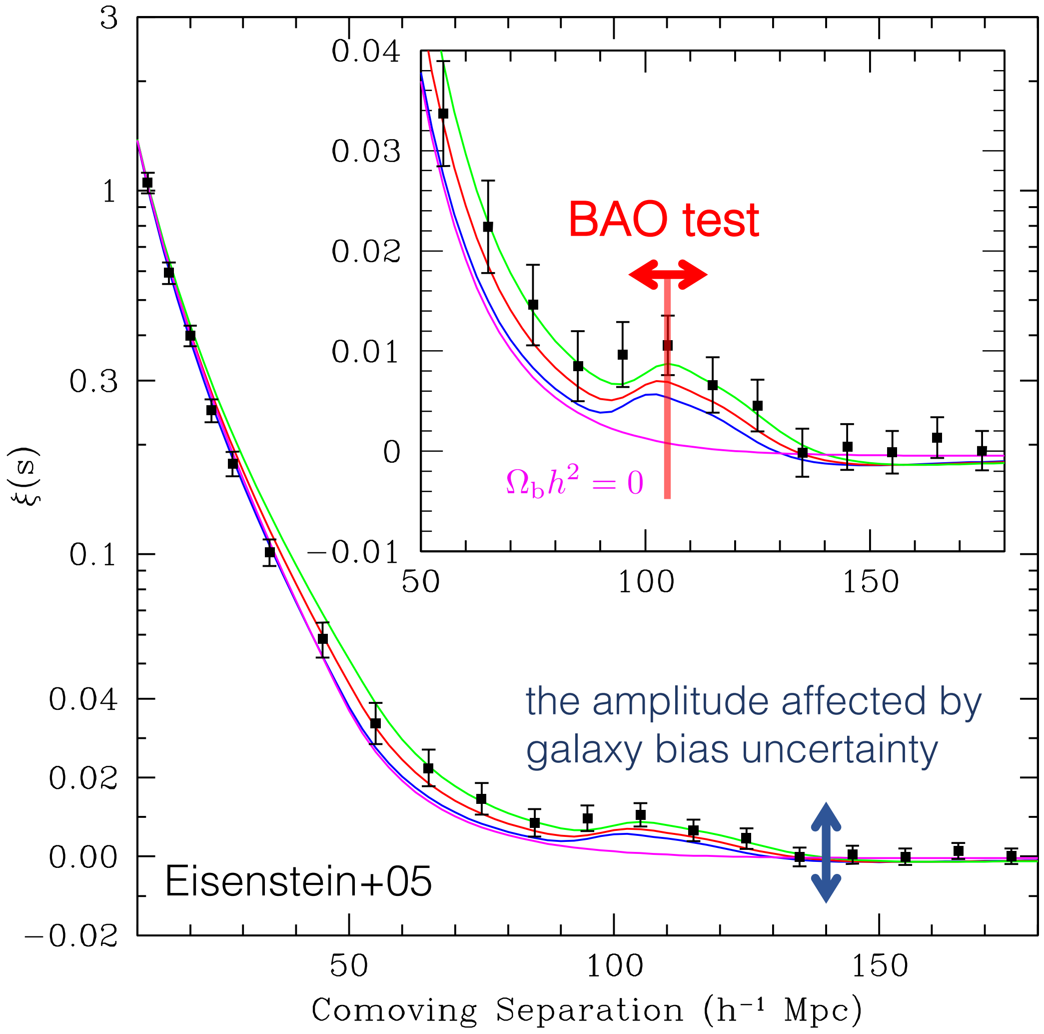
The SDSS spectroscopic survey: BOSS (completed)



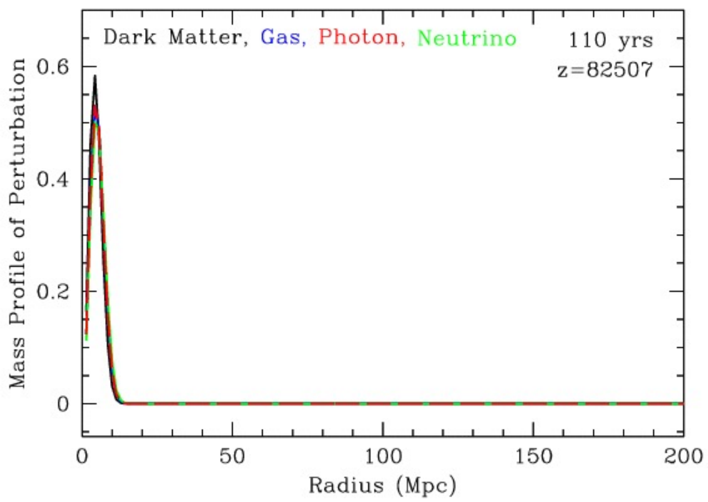
- This talk is based on the final BOSS data: ~1M early-type luminous galaxies ("LOWZ" and "CMASS" samples) over 0.2<z<0.75 and the solid angle of 10,000 sq. deg.
  - These galaxies are selected based on the specifically-tuned color and flux cuts
- Redshift-space power spectrum of galaxies – a very powerful method of testing cosmological models

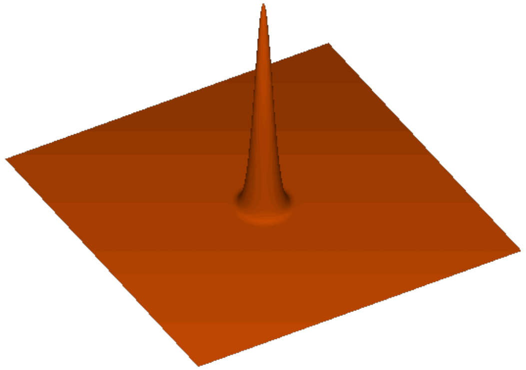
$$P^S_{\rm gg}(k,\mu) = |\delta^S_{\rm g}(\mathbf{k})^2|$$

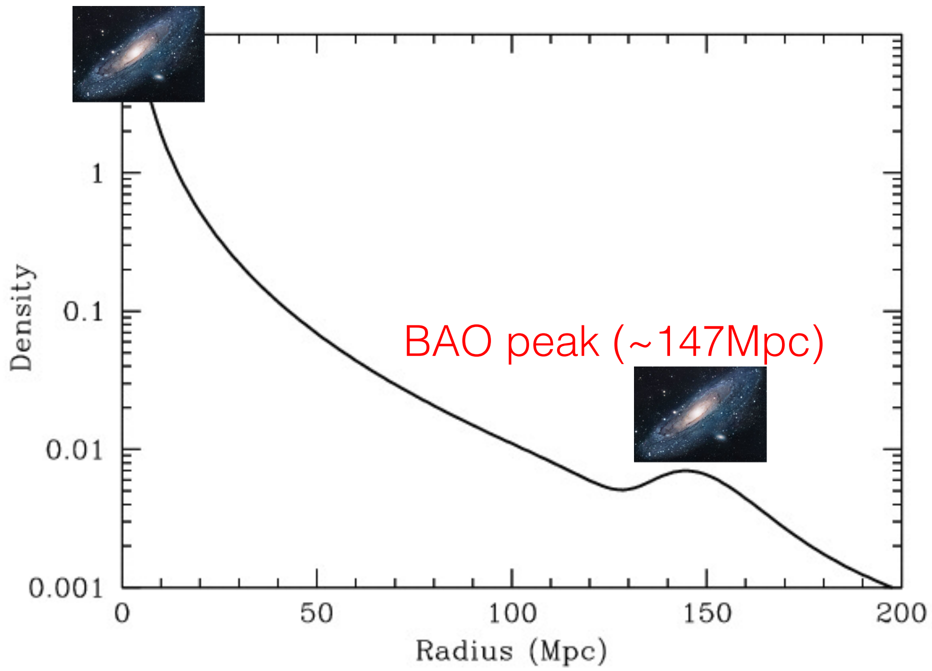
Power of spec-z galaxy survey: BAO geometrical test



animation: D. Eisenstein



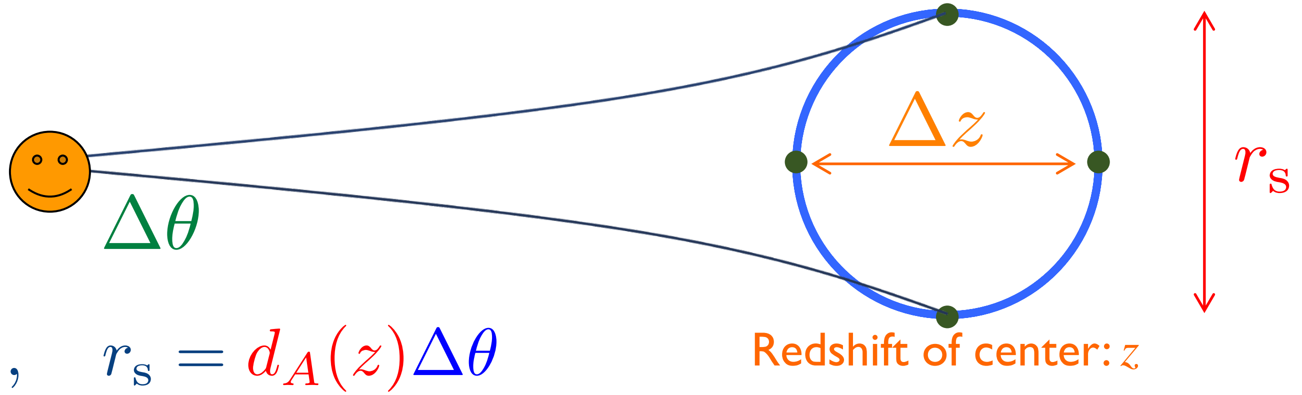




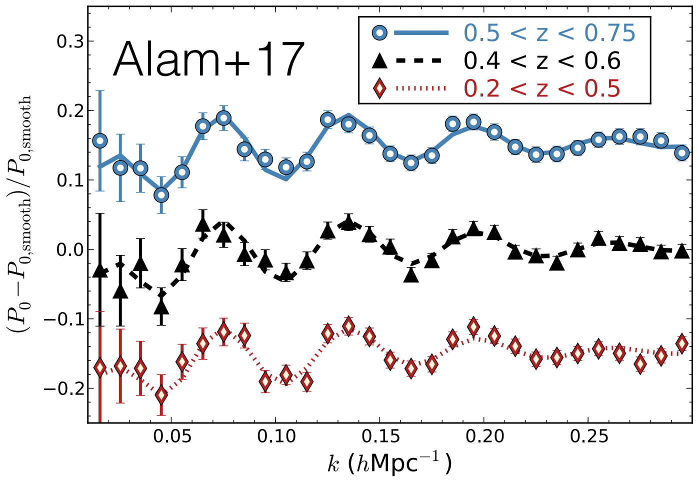
- Measure "scale" of separations in paired galaxies
- Free from galaxy bias uncertainty

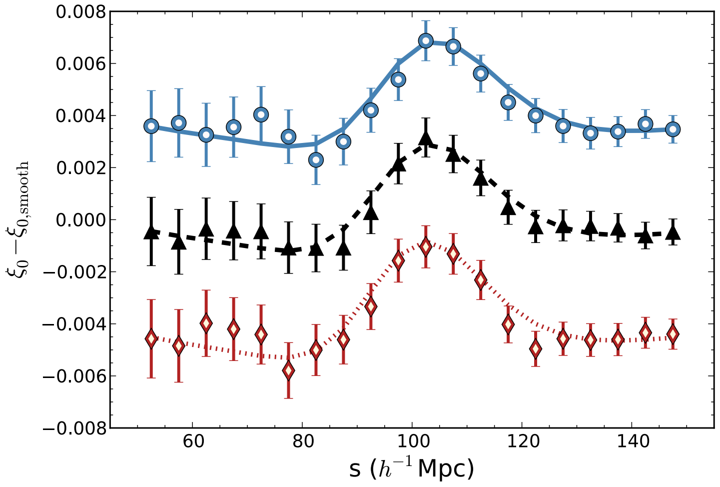
Power of spec-z galaxy survey: BAO geometrical test (cont'd)

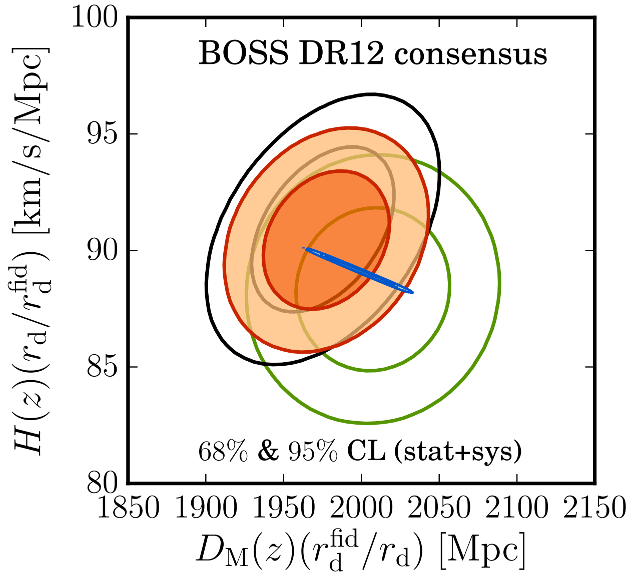
- Paired galaxies have preferred separation (rs) – standard ruler, i.e. baryon acoustic oscillation (BAO)
- The "observed" angular separation and redshift difference of BAO galaxy pairs give measurements of the angular diameter distance and the Hubble expansion rate (at the galaxy redshift)



$$r_s = \Delta\chi = \frac{\Delta z}{H(z)}, \quad r_s = d_A(z)\Delta\theta$$







Power of spec-z galaxy survey: redshift-space distortion (RSD)

- Galaxies have peculiar motions according to the gravitational field of large-scale structure

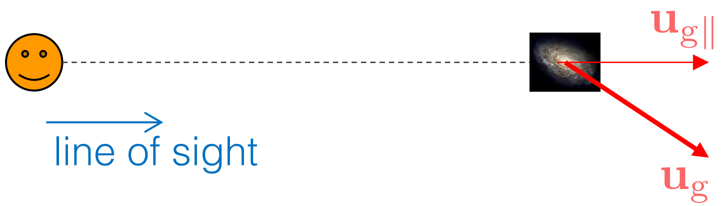
$$ds^2 = -(1+2\Psi(t,\mathbf{x}))dt^2 + a^2(1+2\Phi(t,\mathbf{x}))d\mathbf{x}^2$$

$$\frac{1}{a}\frac{d(au_{\rm g})}{dt} = \frac{1}{a}\nabla\Psi$$

Different types of galaxies would follow the same peculiar velocity field due to equivalence principle (the gravity field is by dark matter)

- The observed redshift of each galaxy is distorted by the peculiar velocity (RSD). This RSD effect causes anisotropic clustering pattern in the observed distribution of galaxies (Kaiser 87)

$$\Delta z = u_{\rm g\parallel} \to \Delta x_\parallel = \frac{1}{aH}u_{\rm g\parallel} \ (\text{“}\parallel\text{” is the line-of-sight component})$$



number conservation $\quad n_{\rm g}^S(\mathbf{s})d^3\mathbf{s} = n_{\rm g}(\mathbf{x})d^3\mathbf{x} \quad \to \quad 1+\delta_{\rm g}^S(\mathbf{s}) = \dfrac{1+\delta_{\rm g}(\mathbf{x})}{1+\frac{1}{aH}\frac{\partial u_{\rm g\parallel}}{\partial x_\parallel}}$

$$\simeq [1+\delta_{\rm g}(\mathbf{x})]\left[1-\frac{1}{aH}\frac{\partial u_{\rm m\parallel}}{\partial x_\parallel}\right]$$

peculiar velocity field is free from galaxy bias

If we assume linear theory, $\quad \delta_{\rm g}^S(\mathbf{k}) = \delta_{\rm g}(\mathbf{k}) + f\mu^2\delta_{\rm m}(\mathbf{k})$

Here we used $\quad \mathbf{k}\cdot\hat{\mathbf{n}}_{\rm los} = k\mu, \quad i\mathbf{k}\cdot\mathbf{u}_{\rm m} = a\dfrac{\partial\delta_{\rm m}}{\partial t} = a\dfrac{d\ln D+}{dt}\delta_{\rm m}, \quad f \equiv \dfrac{d\ln D_+}{d\ln a}$

Power of spec-z galaxy survey: RSD (cont'd)

- Linear theory prediction of redshift-space power spectrum

$$\delta_g^S(\mathbf{k}) = \delta_g(\mathbf{k}) + f\mu^2\delta_m(\mathbf{k})$$

$$\to P_{gg}^S(k,\mu) = \langle|\delta_g(\mathbf{k})|^2\rangle + 2f\mu^2\langle\delta_g(\mathbf{k})\delta_m(\mathbf{k})\rangle + f^2\mu^4\langle|\delta_m(\mathbf{k})|^2\rangle$$

$$= P_{gg}(k) + 2f\mu^2 P_{gm}(k) + f^2\mu^4 P_{mm}(k)$$

If we assume linear bias (b1) …

$$P_{gg}(k) \propto b_1^2\sigma_8^2$$

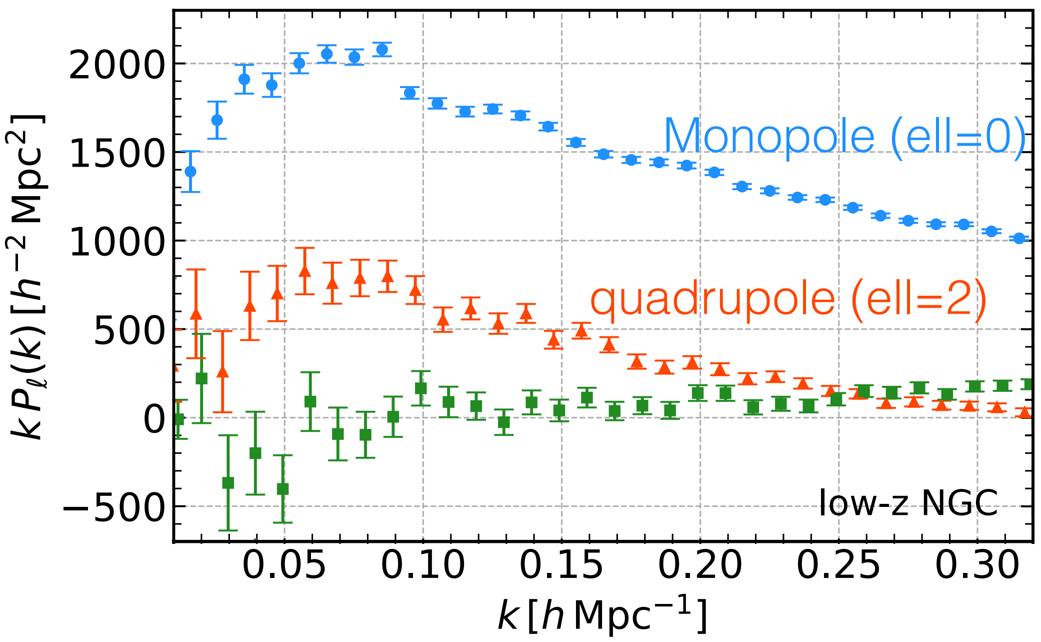
$$f\mu^2 P_{gm}(k) \propto b_1 f\sigma_8^2$$

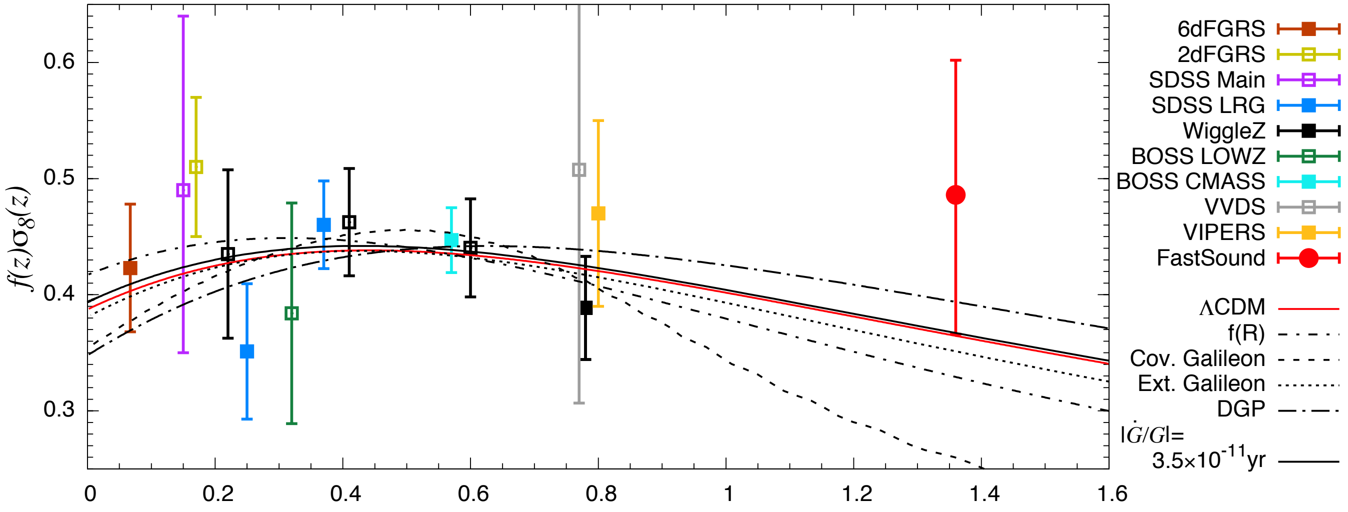
$$\to f\sigma_8$$

- So RSD can eliminate bias uncertainty (b1), and the analysis usually constrain f*sigma8
- However, only this combination is measured (sigma8 alone CANNOT be measured, with this method)

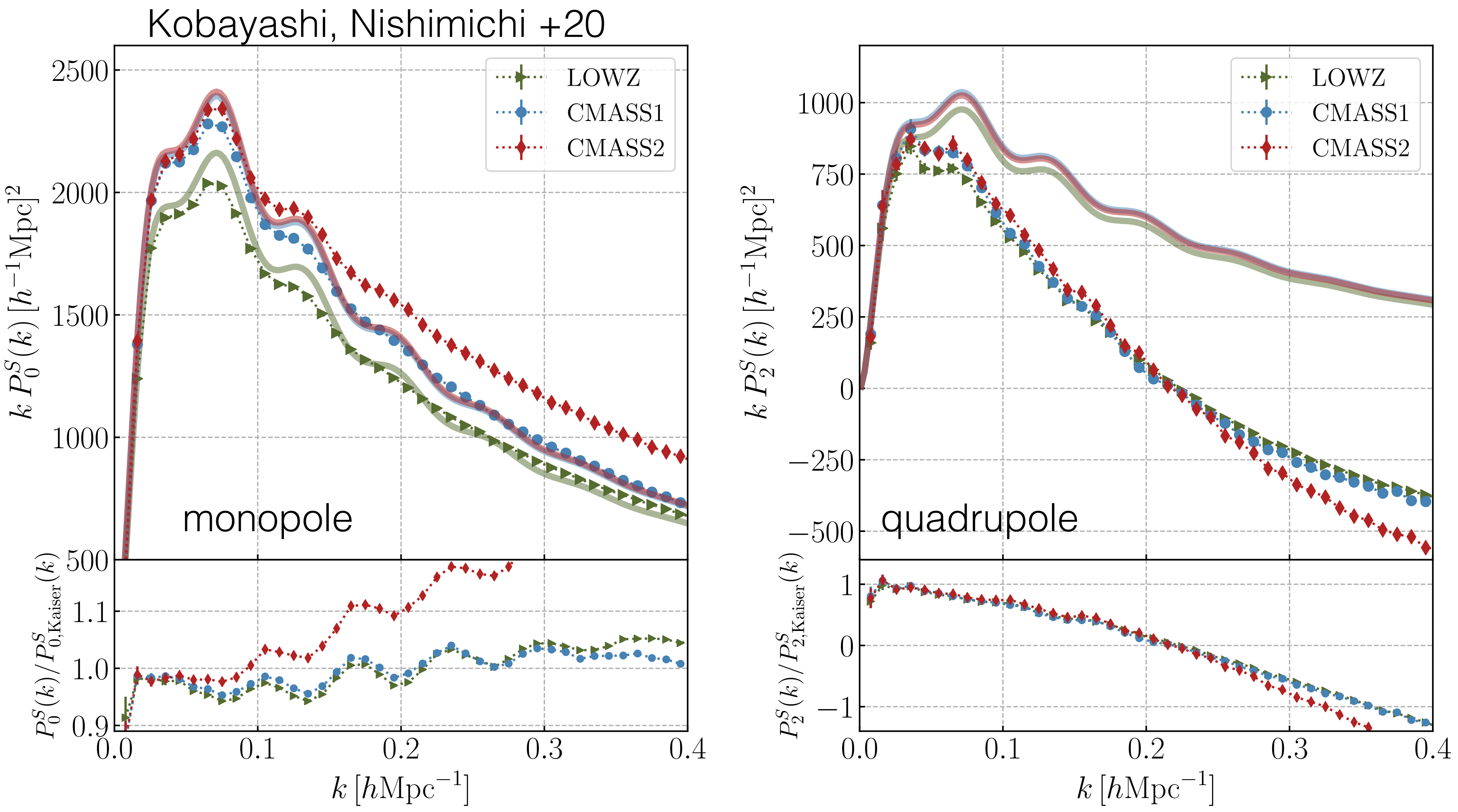
$$P_\ell(k) \propto \int d\mu\ P(k,\mu)\mathcal{L}_\ell(\mu)$$

BOSS DR12 (Beutler & McDonald 21)





Challenges with redshift-space galaxy P(k) cosmology: Nonlinearities



- Directly measure the redshift-space power spectra of halos (halos = places where galaxies would form)
- Run N-body simulations
  ⇒ Identify halos
  ⇒ Make redshift-space mapping
  ⇒ Measure power spectrum
- Linear Kaiser RSD quickly breaks down, at k>0.05h/Mpc (solid lines show linear theory prediction)

$$P_\ell(k) \propto \int \mathrm{d}\mu\ P(k,\mu)\mathcal{L}_\ell(\mu)$$

Method used in SDSS BOSS collaboration

- Perturbation theory of LSS (also see Leonardo's talk)

$$\delta_{\rm m} = \delta_{\rm m}^{(1)} + \delta_{\rm m}^{(2)} + \delta_{\rm m}^{(3)} \cdots$$

$$\theta = \hat{\mathbf{k}} \cdot \mathbf{u} = \theta^{(1)} + \theta^{(2)} + \theta^{(3)} + \cdots$$

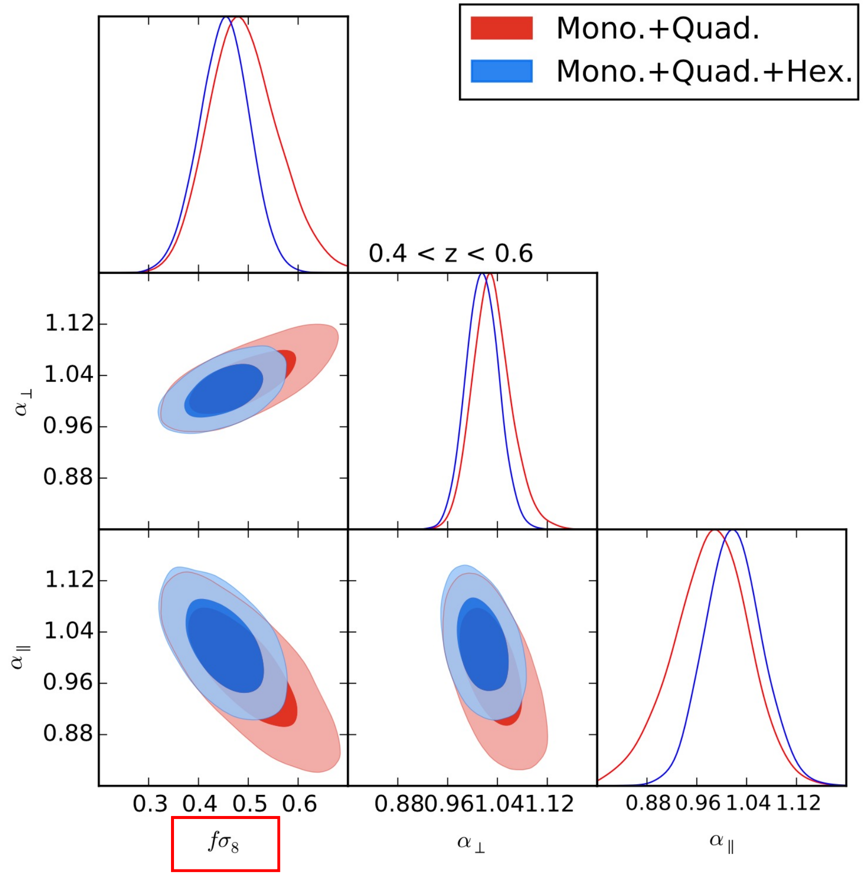
$$\delta_{\rm g} = b_1 \delta_{\rm m} + \frac{b_2}{2} \delta_{\rm m}^2 + \frac{b_s}{2} s_{\rm m}^2 + \cdots$$

$$P_{\rm gg}(k,\mu) = \exp[-(fk\mu\sigma_v)^2] \left[P_{{\rm g},\delta\delta}(k) + 2f\mu^2 P_{{\rm g},\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k) + b_1^3 A(k,\mu,f/b_1) + b_1^4 B(k,\mu,f/b_1)\right]$$

- Beutler et al (BOSS collaboration 2017) used the PT based model of Taruya, Nishimichi & Saito (2010: TNS)
- PT method should work for any type of galaxies
- However, Beutler et al. evaluated the nonlinear k-kernels (up to 2-loop terms) at the fiducial LCDM model, and varied only the following parameters in the likelihood analysis in a multi-dimensional parameter space, due to the computational limitation

$$\{b_1\sigma_8, b_2\sigma_8, \sigma_v, N, f\sigma_8, \alpha_\parallel, \alpha_\perp\}$$

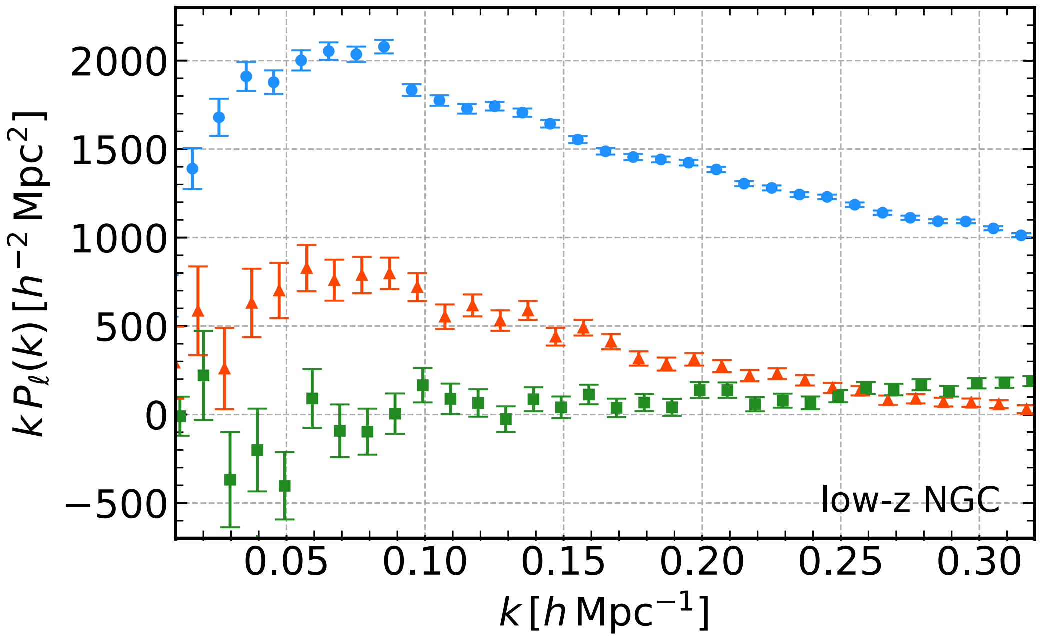
for each redshift slice, ~30 parameters in total



Potential of "full-shape" analysis

$$\delta_g = b_1 \delta_m + \frac{b_2}{2}\delta_m^2 + \cdots$$
$$= b_1 \left\{ \delta_m^{(1)} + \delta_m^{(2)} + \cdots \right\} + \cdots$$

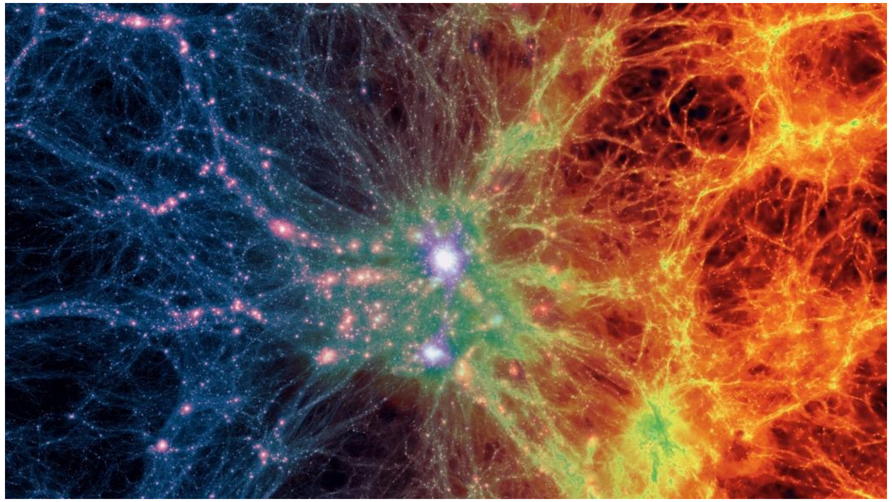
$\propto b_1\sigma_8$ $\quad \propto b_1\sigma_8^2$



- The forward nonlinear model under LCDM framework, which can work in the nonlinear regime, should give more constraining power due to the stronger cosmological dependences and allow us to measure sigma8 and f separately (f is also specified by cosmological parameters, e.g., $f \simeq \Omega_m(z)^{0.55}$)
- More cosmological information by going to the higher kmax (the information content in Fourier space is proportional to k_max^3); so far, kmax~0.15h/Mpc
- The full-shape cosmology analysis was finally done, very recently, by several independent groups: Princeton group (Ivanov, Simonovic, Zaldarriaga+20), Stanford group (Senatore, D'Amico+20), Japan group (Kobayashi, Nishimichi+21), and Berlekey group (Chen, Vlah & White 21)

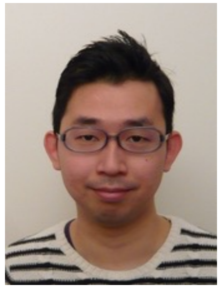
Challenges for upcoming galaxy survey cosmology

- Need to be prepared for ongoing and upcoming galaxy surveys (DESI, Subaru PFS, Euclid and Roman Space Telescope)
- Cannot yet model "galaxies" from first principles
- Need both "accurate" theoretical template and "robust" method
  - "accurate": accurately model the redshift-space clustering of galaxies, including nonlinear clustering, nonlinear RSD and nonlinear bias
  - "robust": need an "unbiased" estimate of the underlying cosmological parameters, by minimizing the systematic errors due to theory inaccuracy/limitation (e.g. galaxy bias)
- Possible options
  - Cosmological hydrodynamical simulations: still very expensive (and uncertainties in subgrid physics)
  - Perturbation theory (EFTofLSS): see Leonardo's talk
  - Emulation approach of halo model (this talk)



Blinded cosmology challenge

Nishimichi+ (incl. MT) 21



Takahiro Nishimichi
(YITP)

EFTofLSS is
not useful

me

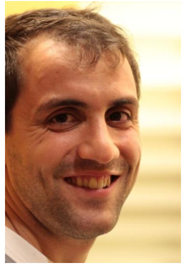
VS

EFTofLSS
should be
correct/work

M. Zaldarriaga (IAS, Princeton)

M. Simonovic
(CERN)

M. Ivanov
(NYU)

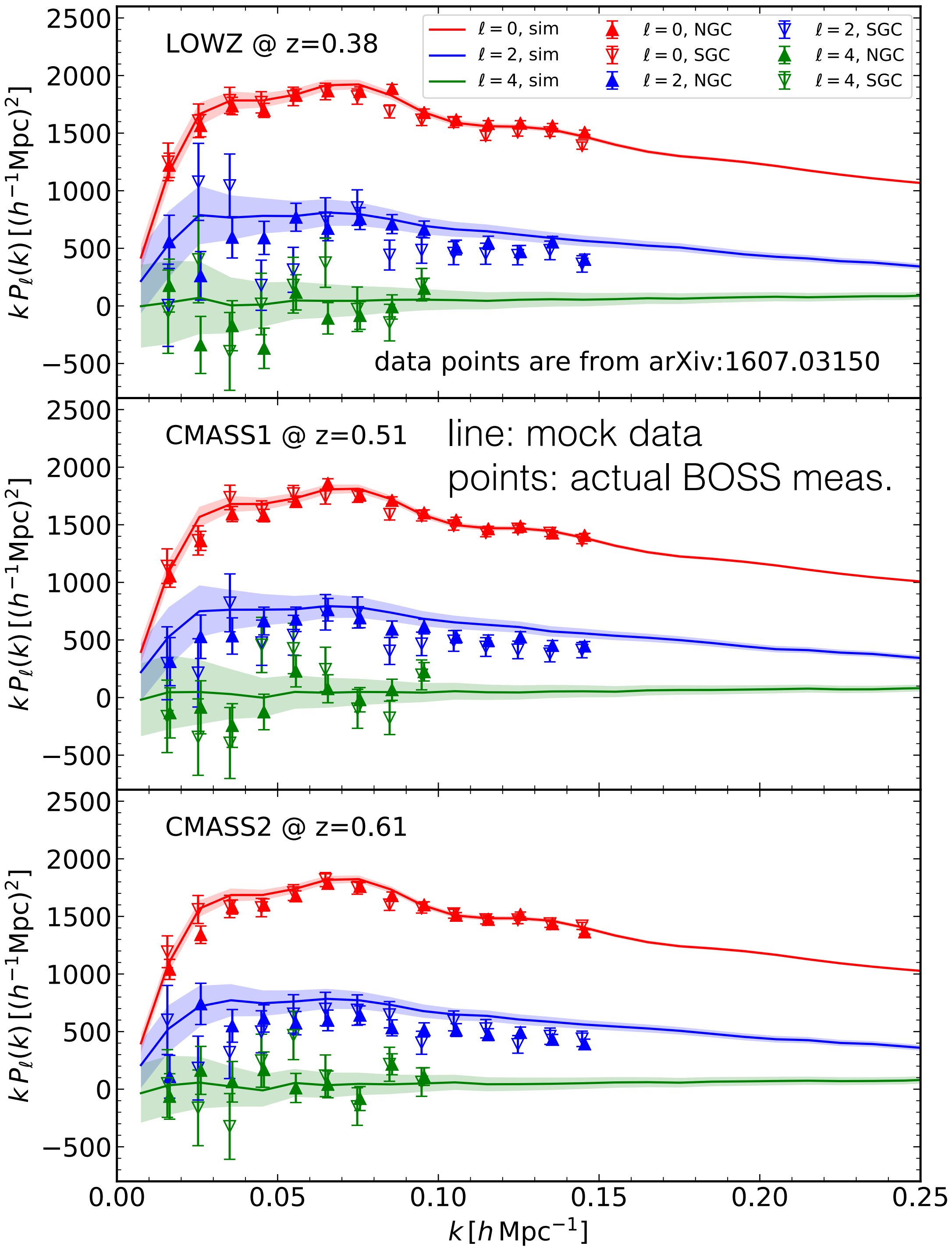


Leonardo Senatore
(KIPAC, Stanford)

+ others

Blinded cosmology challenge: Nishimichi+21

- Japan team's role: prepared BOSS-like mock power spectrum data, without telling which cosmological model was assumed
  - Used N-body simulations, and then populate BOSS-like galaxies
  - Volume ~600 (Gpc/h)^3 ≈100 V_BOSS: minimize statistical noise due to sample variance, to assess the accuracy of the method
  - Mock data include: nonlinear bias, nonlinear RSD, Alcock-Paczynski effect ($\Omega_{\rm m}^{(\rm fid)} = 0.3$ was assumed, which was informed to the analysis teams)
  - $f_{\rm b} \equiv \Omega_{\rm b}/\Omega_{\rm m} = 0.1571, n_s = 0.9649$ are fixed, and were informed to the analysis teams



Blinded cosmology challenge: Nishimichi+21

- East/West coast teams: the two teams analyzed the mock data to address whether the method recovers the cosmological parameters in the simulations
  - Both teams used EFTofLSS including up to 1-loop correction, but employed different parametrization and different prior ranges

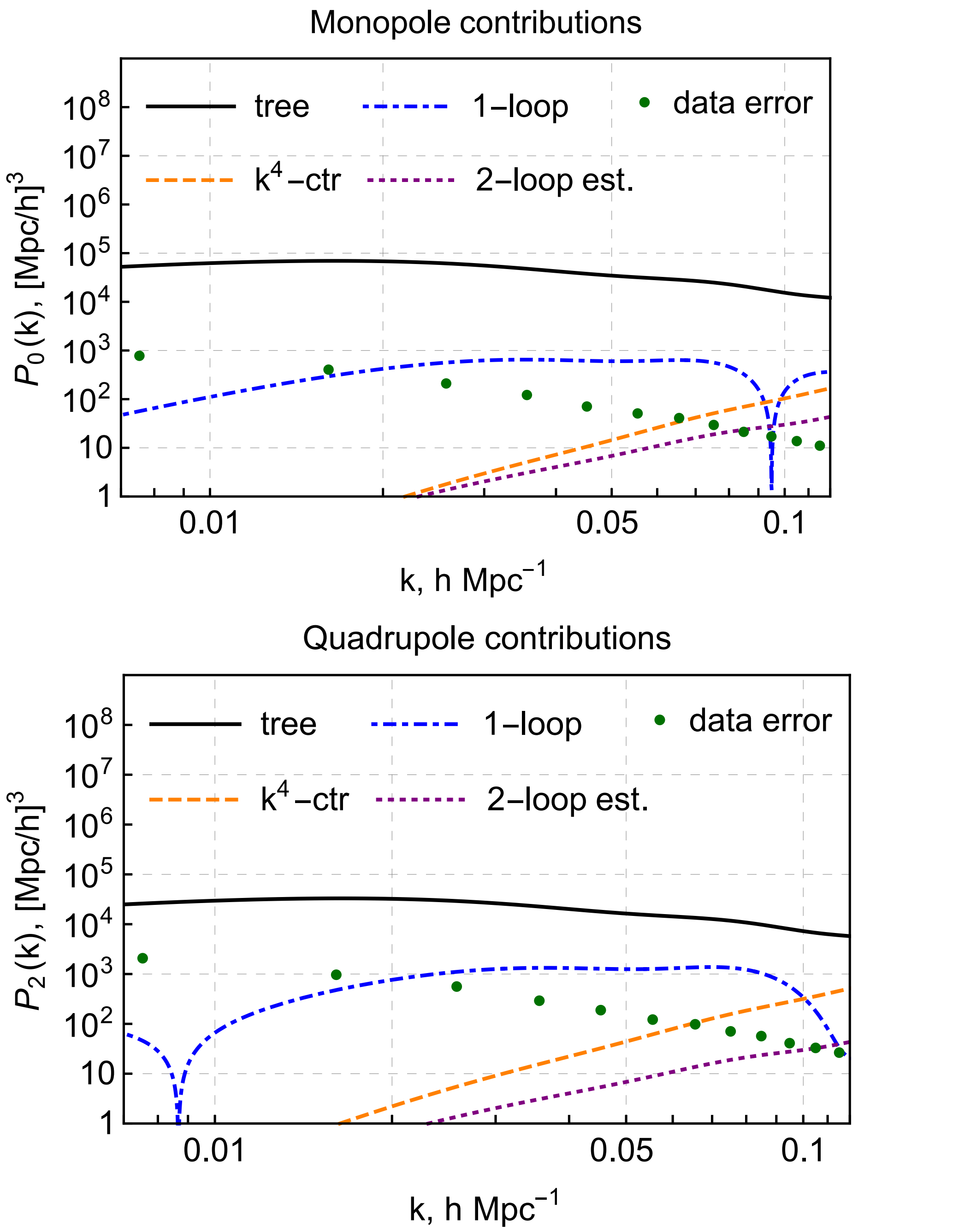
$$P_\ell(k) = P_\ell^{\rm tree}(k) + P_\ell^{\rm 1loop}(k) + \underbrace{P_\ell^{\rm ctr}(k) + P_\ell^{\nabla_z^4\delta}(k)}_{\text{counter terms}}$$

  - Model parameters: 3 cosmological parameters (As, H0, Omega_m) + many nuisance parameters

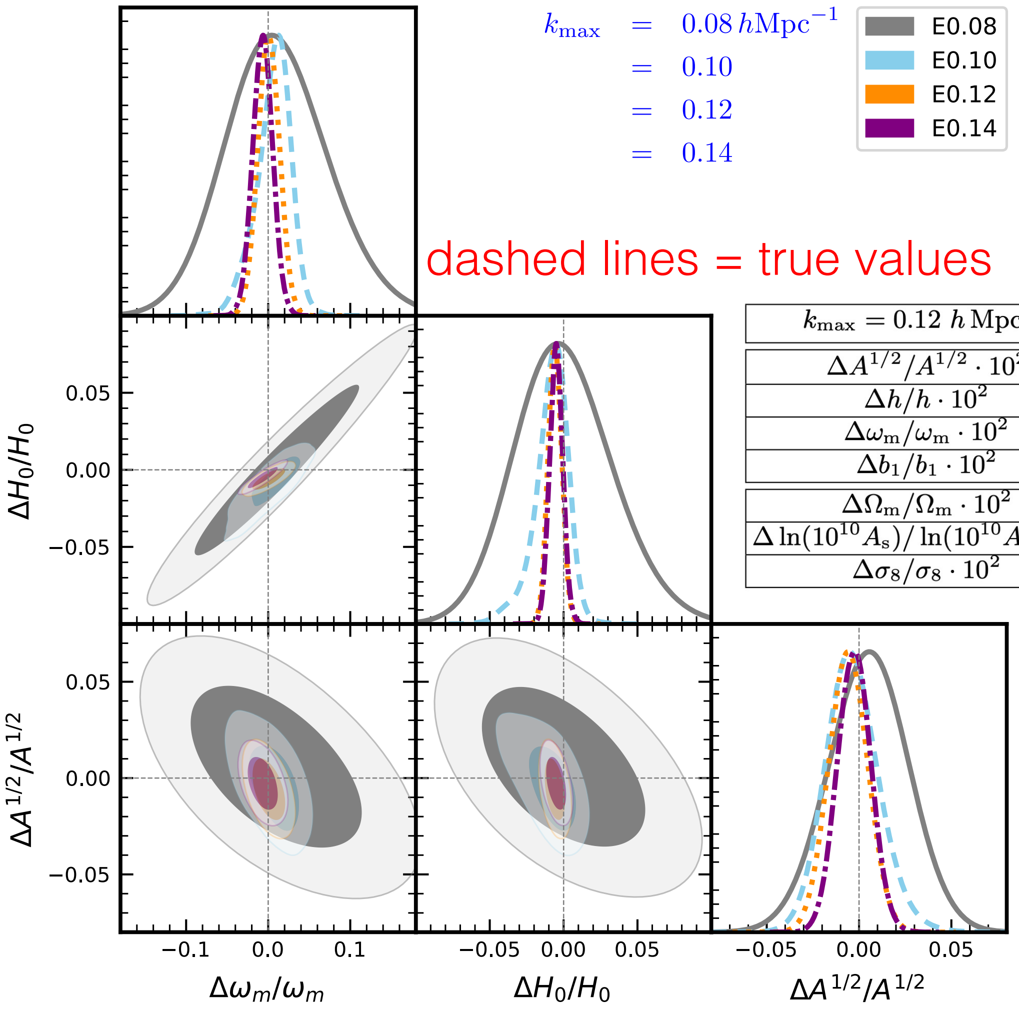
$$b_1, b_2, b_{\mathcal{G}_2}, P_{\rm shot} + c^{(0)}_{\nabla^2\delta}, c^{(2)}_{\nabla_z^2\delta}, c^{(0)+(2)}_{\nabla_z^4\delta}$$

- Agreed beforehand that the results are NOT changed after unblinding and publish whatever the results are, in the journal
- This level blinded analysis is for the first time

EFTofLSS has a better control of the next-order corrections



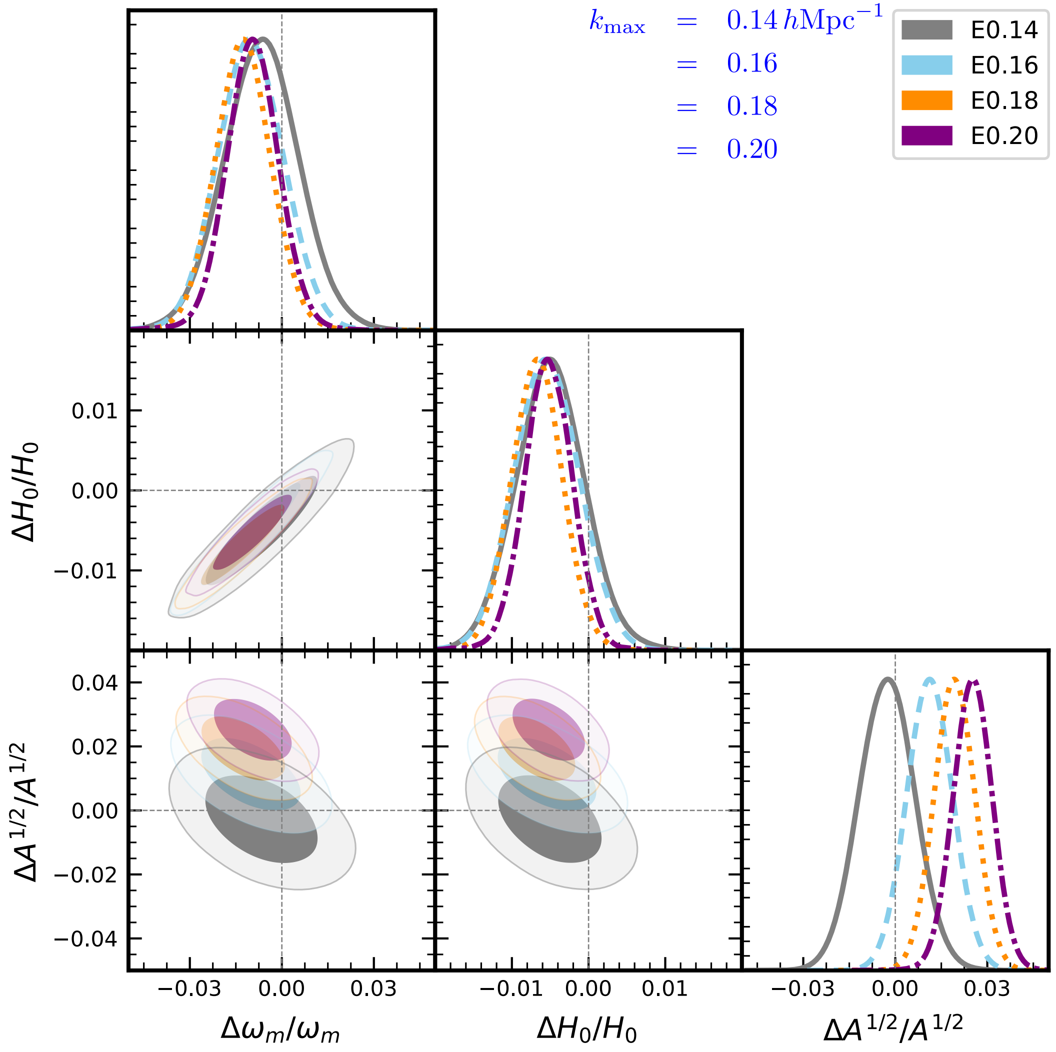
EFTofLSS works! (BAO is powerful)



dashed lines = true values

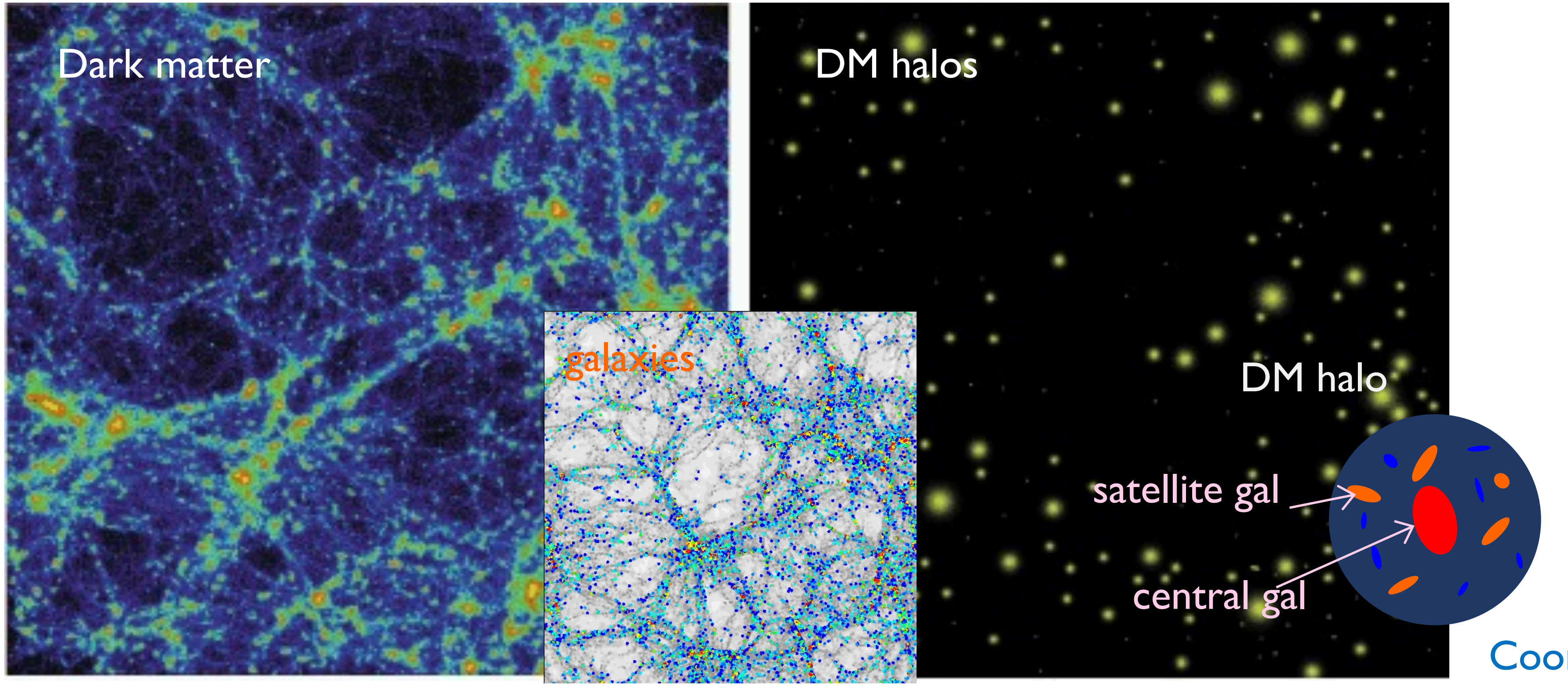
$k_{\rm max} = 0.12\ h\,{\rm Mpc}^{-1}$	best-fit	mean $\pm 1\sigma$
$\Delta A^{1/2}/A^{1/2} \cdot 10^2$	-0.15	-0.16 ± 1.0
$\Delta h/h \cdot 10^2$	-0.55	-0.59 ± 0.46
$\Delta \omega_{\rm m}/\omega_{\rm m} \cdot 10^2$	0.2	0.15 ± 1.4
$\Delta b_1/b_1 \cdot 10^2$	0.20	0.22 ± 1.2
$\Delta \Omega_{\rm m}/\Omega_{\rm m} \cdot 10^2$	1.3	1.2 ± 0.9
$\Delta \ln(10^{10} A_{\rm s})/\ln(10^{10} A_{\rm s}) \cdot 10^2$	-0.098	-0.11 ± 0.69
$\Delta \sigma_8/\sigma_8 \cdot 10^2$	-0.094	-0.022 ± 0.92

$V_{\rm mock} \simeq 600 V_{\rm BOSS}$



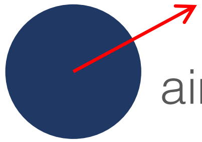
After this study, both East/West team published many papers for the cosmology analysis results of real BOSS data

Our approach: Simulation-based halo model approach (Kobayashi, Nishimichi, MT et al. 20/21)



Cooray & Sheth 2002

- Galaxies from in "dark matter halos" (this would be especially true for BOSS galaxies)
- Dark matter halos are relatively easy to simulate with N-body simulations (no need of hydrosims)
- Baryonic effects are "local" (< a few Mpc): mass and momentum are conserved on the larger scales



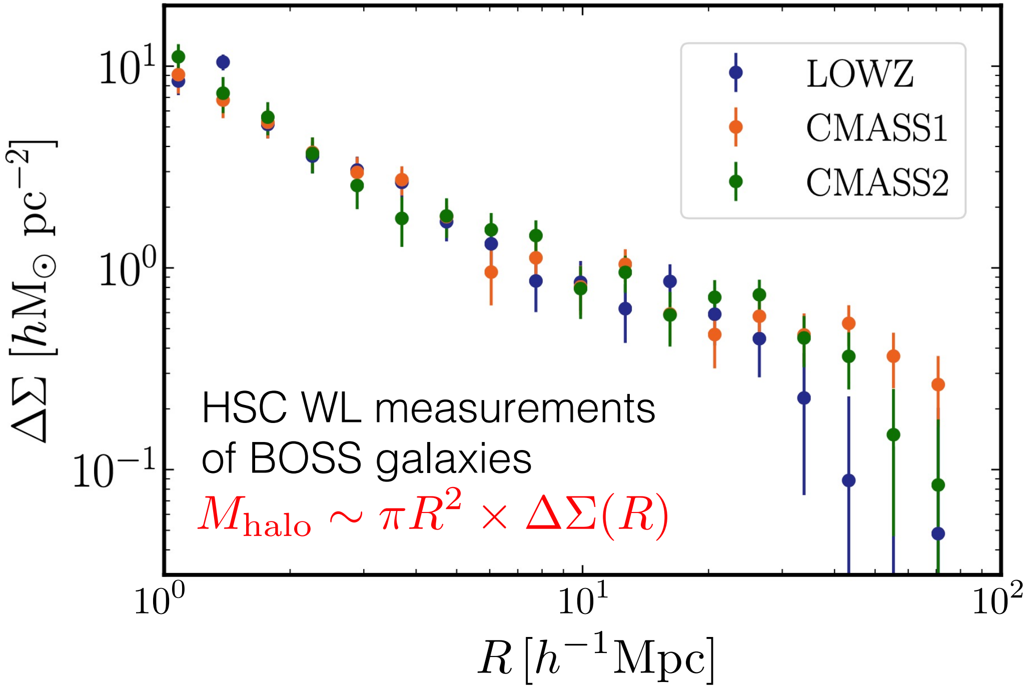
aim to accurately simulate position and bulk velocity of each halo

Galaxy-halo connection

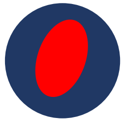
- From weak lensing measurements, we know BOSS galaxies reside in relatively massive halos with ~10^{13}Msun mass that are easy to simulate
- Typical velocity dispersions of BOSS galaxies inside halos are ~200km/s (Hikage & Yamamoto 13)
- A few % of BOSS galaxies are satellites residing in cluster-scale halos with ~10^{15}Msun (only up to ~10 BOSS galaxies in the same halo) (the rest are centrals)
  - Bulk motion of halos can be accurately simulated
  - International velocities (virial motions) of galaxies are very difficult to accurately model
  - RSD effect due to virial motions of galaxies – Fingers-of-God effect – is impossible to accurately model

$$\Delta x_{\parallel} \sim \frac{v_{\rm vir}}{aH} \sim 20h^{-1}{\rm Mpc}\left(\frac{v_{\rm vir}}{2000\,{\rm km/s}}\right)$$

A few % of satellite BOSS galaxies lead to systematic effects on k scales relevant for cosmology inference

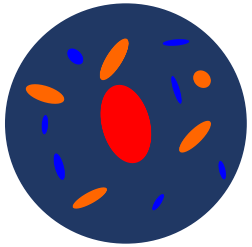


$M_{\rm h} \sim 10^{13} M_\odot$



$v_{\rm vir} \sim 200{\rm km/s}$

$M_{\rm h} \sim 10^{15} M_\odot$

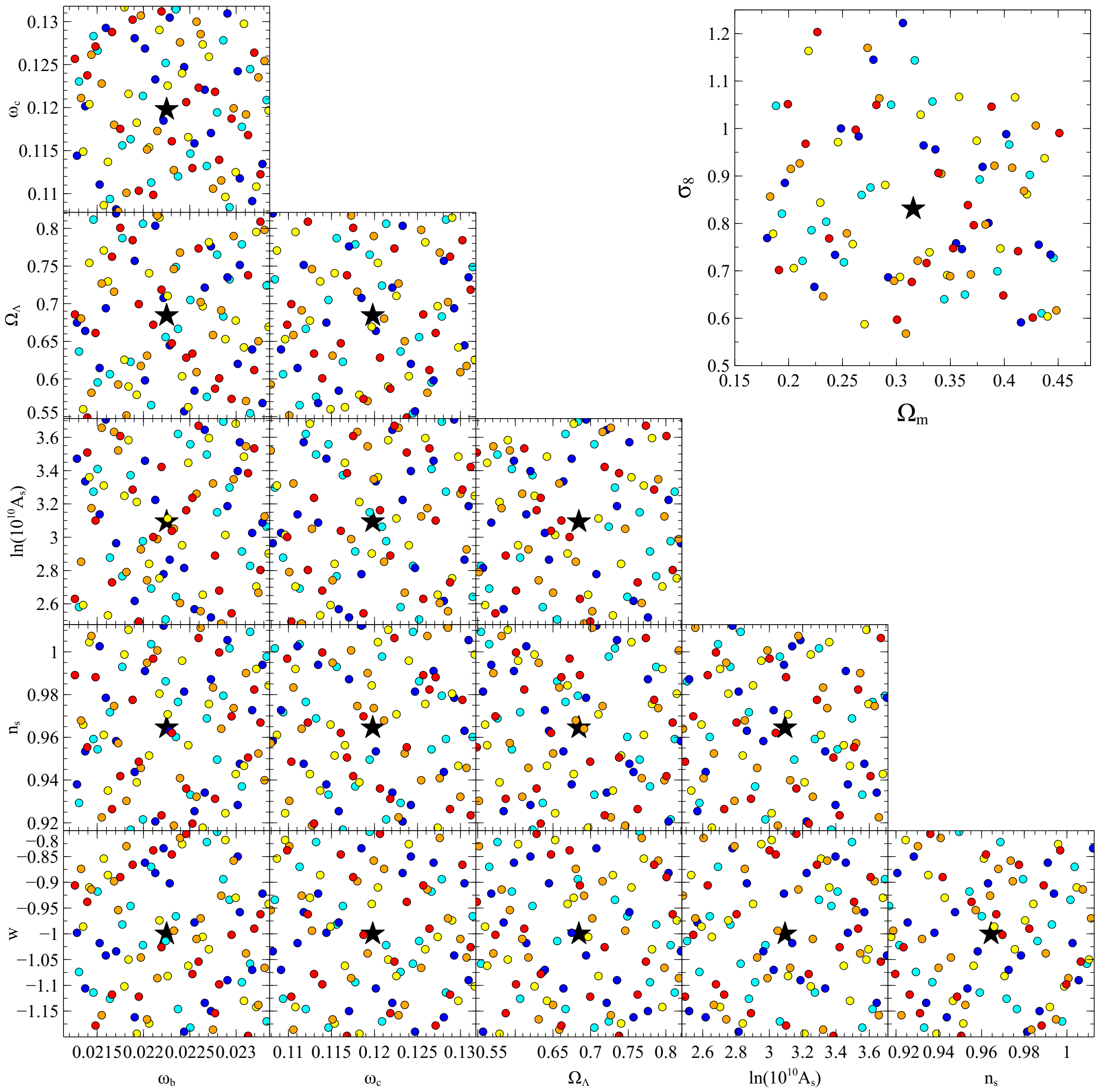


$v_{\rm vir} \sim 2000{\rm km/s}$

$v_{\rm vir} \propto M_{\rm halo}^{1/3}$

Dark Quest (Nishimichi+19)

- Campaign to run high-resolution N-body simulations for flat-geometry wCDM cosmologies
  - 6 parameters: $\mathbf{p} = \{\omega_{\rm b}, \omega_{\rm c}, \Omega_{\rm de}, \ln(10^{10}A_{\rm s}), n_{\rm s}, w_{\rm DE}\}$
  - 101 wCDM models: fiducial Planck cosmology + 100 models, sampled by Sliced Latin Hypercube Design
  - N-body simulations for each model: N_p=2048^3, for a volume of either 1 or 2 (Gpc/h) size (note: multiple realizations for Planck cosmology)
  - Identify halos in each output, by `Rockstar`, and define "central halos" based on the spherical-overdensity definition
  - Halos with M>10^{12}Ms/h, 0<z<1.5
  - A few 100TB data in total
- Dark Emulator for real-space halo quantities is publicly available (Nishimichi+21): https://github.com/DarkQuestCosmology/dark_emulator_public (>5,000 downloads!)



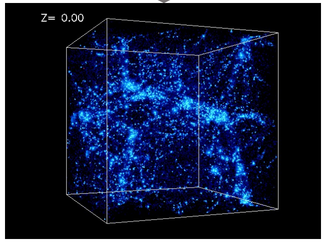
$$\omega_{\rm b} : \pm 5\%, \quad \omega_{\rm c} : \pm 10\%$$
$$\Omega_{\rm de} : \pm 20\%, \quad \ln(10^{10}A_{\rm s}) : \pm 20\%$$
$$n_{\rm s} : \pm 5\%, \quad -1.2 < w_{\rm de} < -0.8$$

Dark Emulator for redshift-space halo P(k)

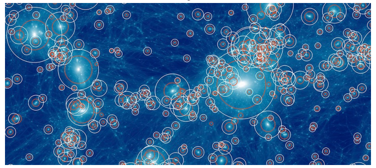
Kobayashi et al. 20

- Yosuke's PhD project at U. Tokyo
- Built dataset of redshift-space power spectrum of halos
    - Identify halos in each simulation realization, at each redshift output
    - Make redshift-space mapping
    - Measure redshift-space power spectra from the halo catalog in each realization
- Constructed the training datasets: 80 cosmological models, 21 redshifts, 10 halo bins ⇒ 168,000 instances

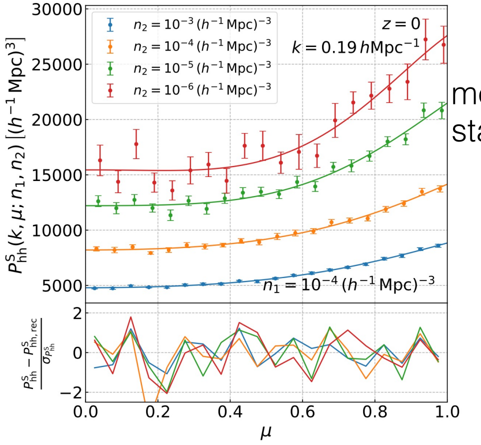
~1000 CPU cores (NAOJ)



N-body sim. (~2 days)



Identified halos (Rockstar)

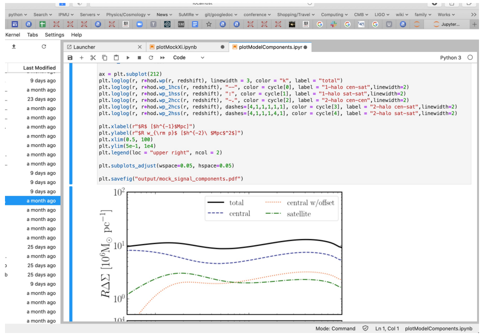


measure summary stats.

A few days

Yosuke Kobayashi
(Kavli IPMU⇒ Arizona)

=

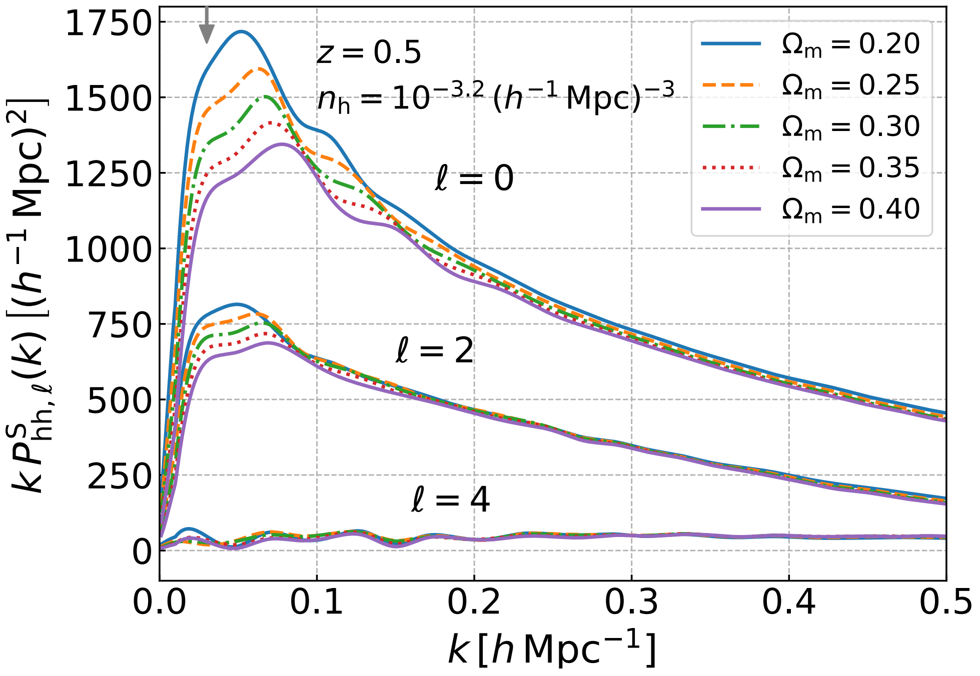


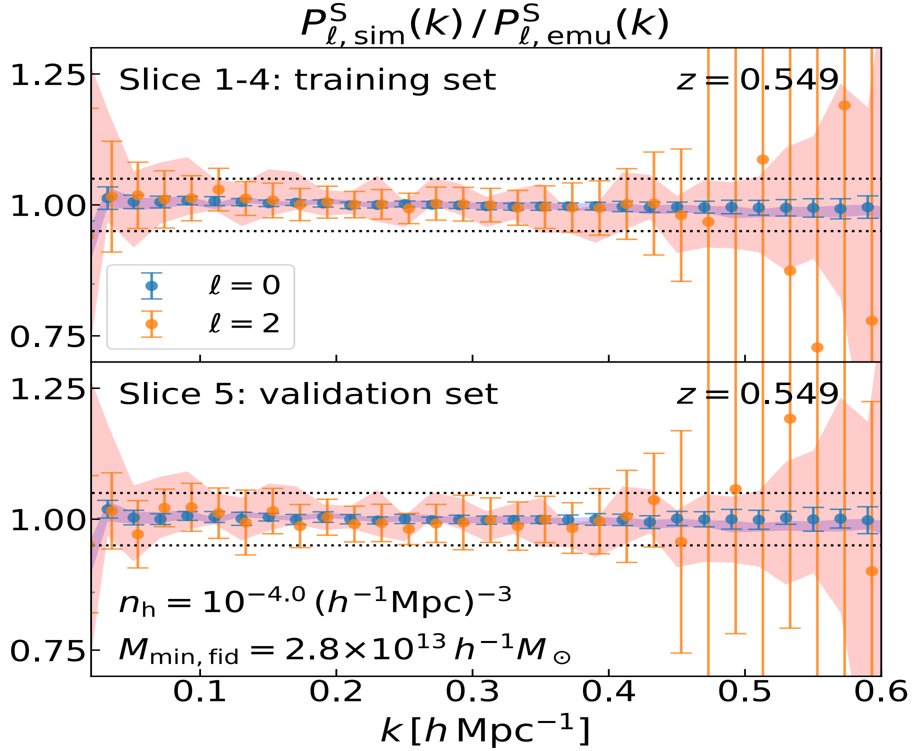
~0.1sec on laptop

~10^6-fold reduction in computation time

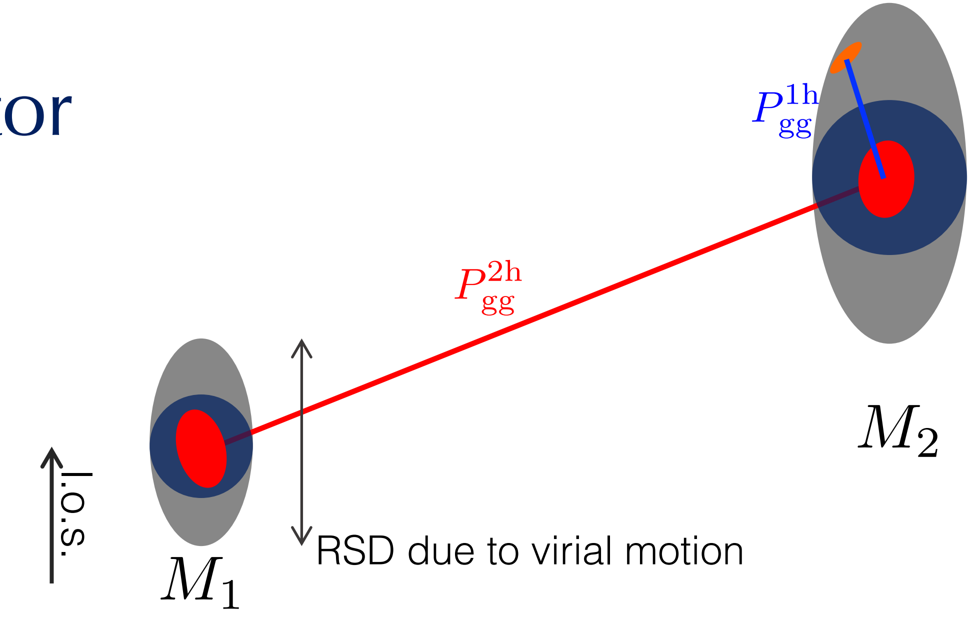
Dark Emulator (Kobayashi+20)

- Use a ML neural network to perform a multi-dimensional regression of the redshift-space halo power spectrum: we built "emulator" of $P_{\rm hh}(k,\mu; M_1, M_2, z, \mathbf{p}_{\rm cosmo})$
- Output P_hh in a 0.1sec for an input set of parameters, enabling parameter inference in a multi-dimensional parameter space
  - 620 (k,mu)-bins (31 k-bins × 20 mu-bins)
- Used validation datasets for 20 cosmological models
- Accuracies: monopole<1% and quadrupole: <5%, achieved, up to k=0.6 h/Mpc
- Switch to the linear theory prediction at very small k, where the sample variance of simulations is significant
- Dark Emulator for redshift-space halo power spectrum includes various nonlinear effects: BAO features, nonlinear clustering, nonlinear RSD, nonlinear bias, halo exclusion effect (effect of finite halo size)





From halos to galaxies in Dark Emulator



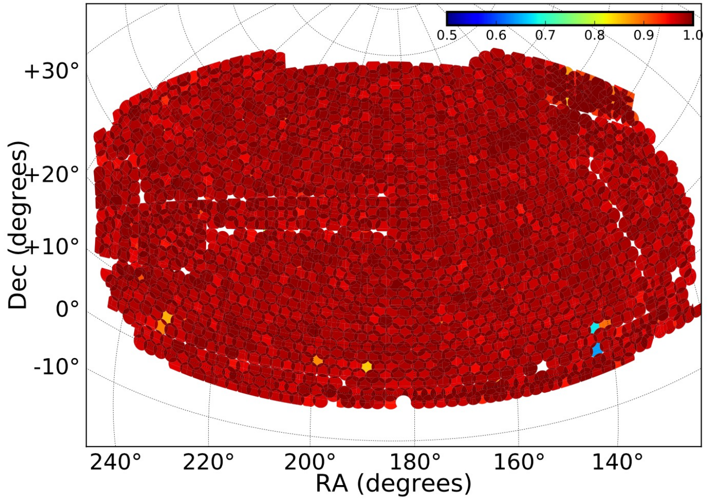
- Use the "halo model picture" (Seljak01; White01) to make model predictions of galaxy P(k) from the emulator: redshift-space galaxy power spectrum is given by the weighted sum of the halo spectrum

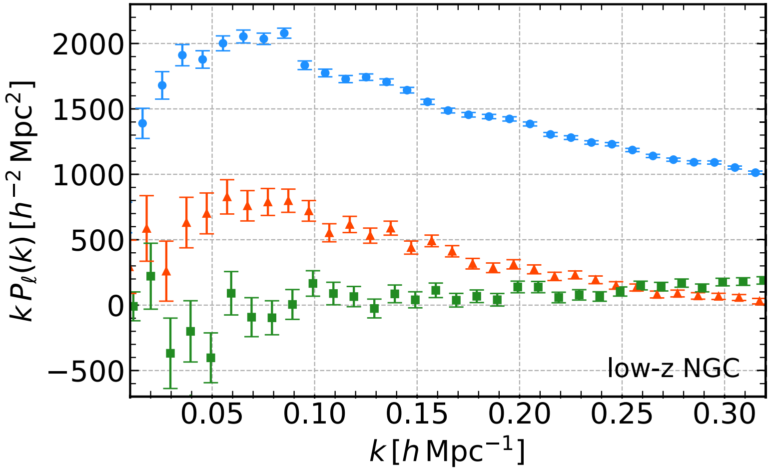
$$P_{gg}(k,\mu;\mathbf{p}_{\rm cosmo},\mathbf{p}_{\rm nuisance},z) = P_{gg}^{2h} + P_{gg}^{1h}$$
$$= \sum_{M_1,M_2} w(M_1)w(M_2)P_{hh}^{S}(k,\mu;\mathbf{p}_{\rm cosmo},z,M_1,M_2)F(k,\mu;M_1)F(k,\mu;M_2) + P_{gg}^{1h}(k,\mu)$$

red: carry cosmological dependence from Dark Emulator
blue: nuisance functions to model uncertainties in galaxy-halo connection

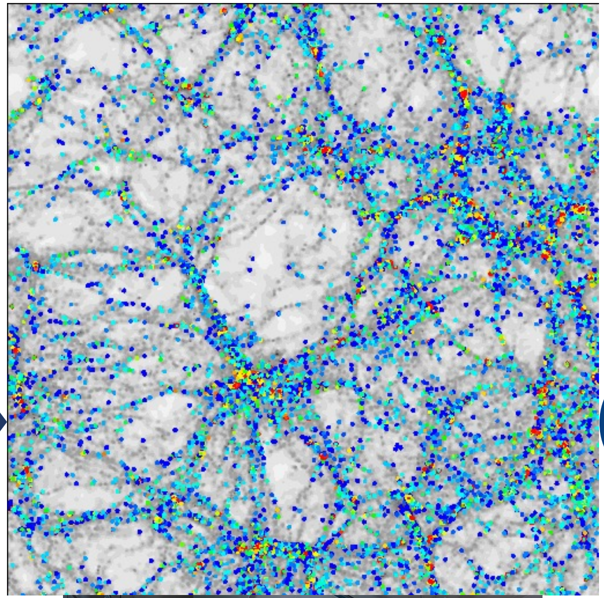
- Dark Emulator outputs P_gg in O(0.1) sec
- Philosophy: introduce a sufficient number of nuisance parameters to model uncertainties in galaxy-halo connection (galaxy bias), and then estimate cosmological parameters after the marginalization

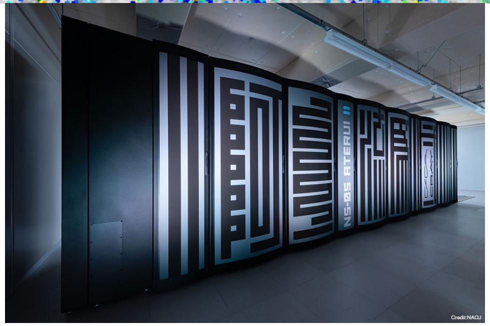
Full-shape cosmology analysis of BOSS with Dark Emulator





high-resolution N-body sims.





$$(\mathbf{p}_{\rm cosmo}, \mathbf{p}_{\rm nuisance})$$

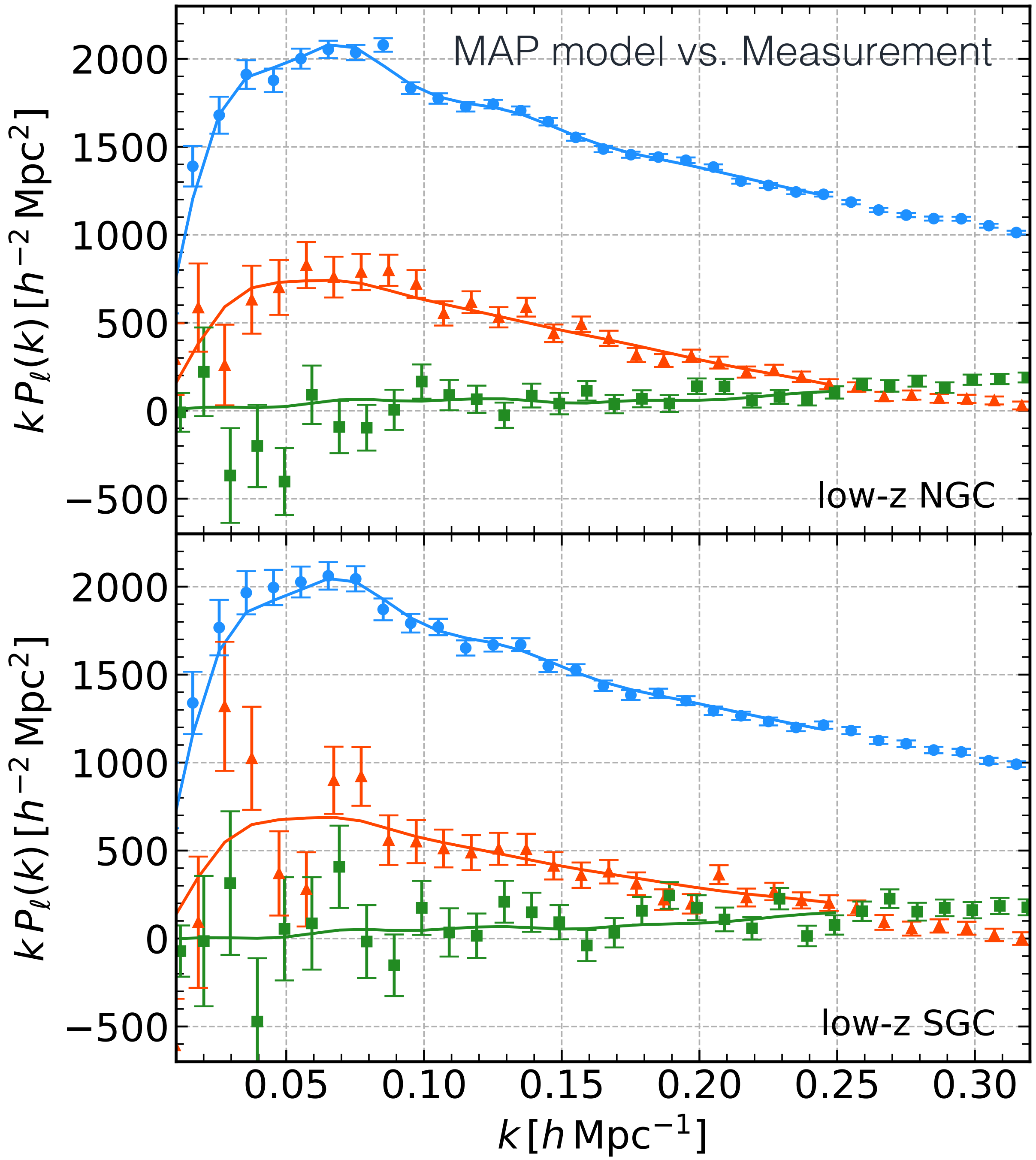
equivalent to parameter inference comparing the measurement with cosmological simulations

Kobayashi, Nishimichi, MT+21

Full-shape cosmology analysis of BOSS with Dark Emulator

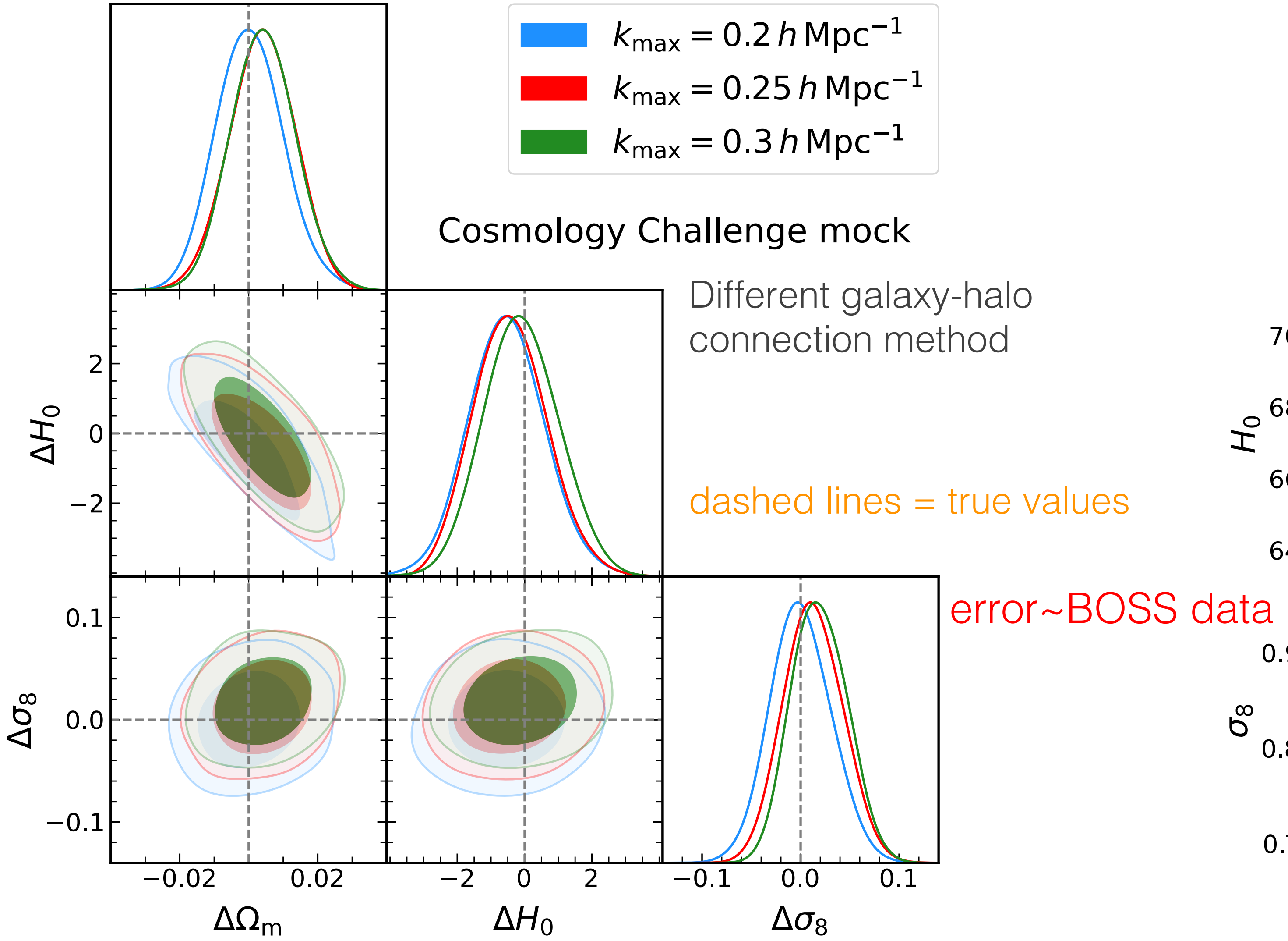
Kobayashi, Nishimichi, MT+21

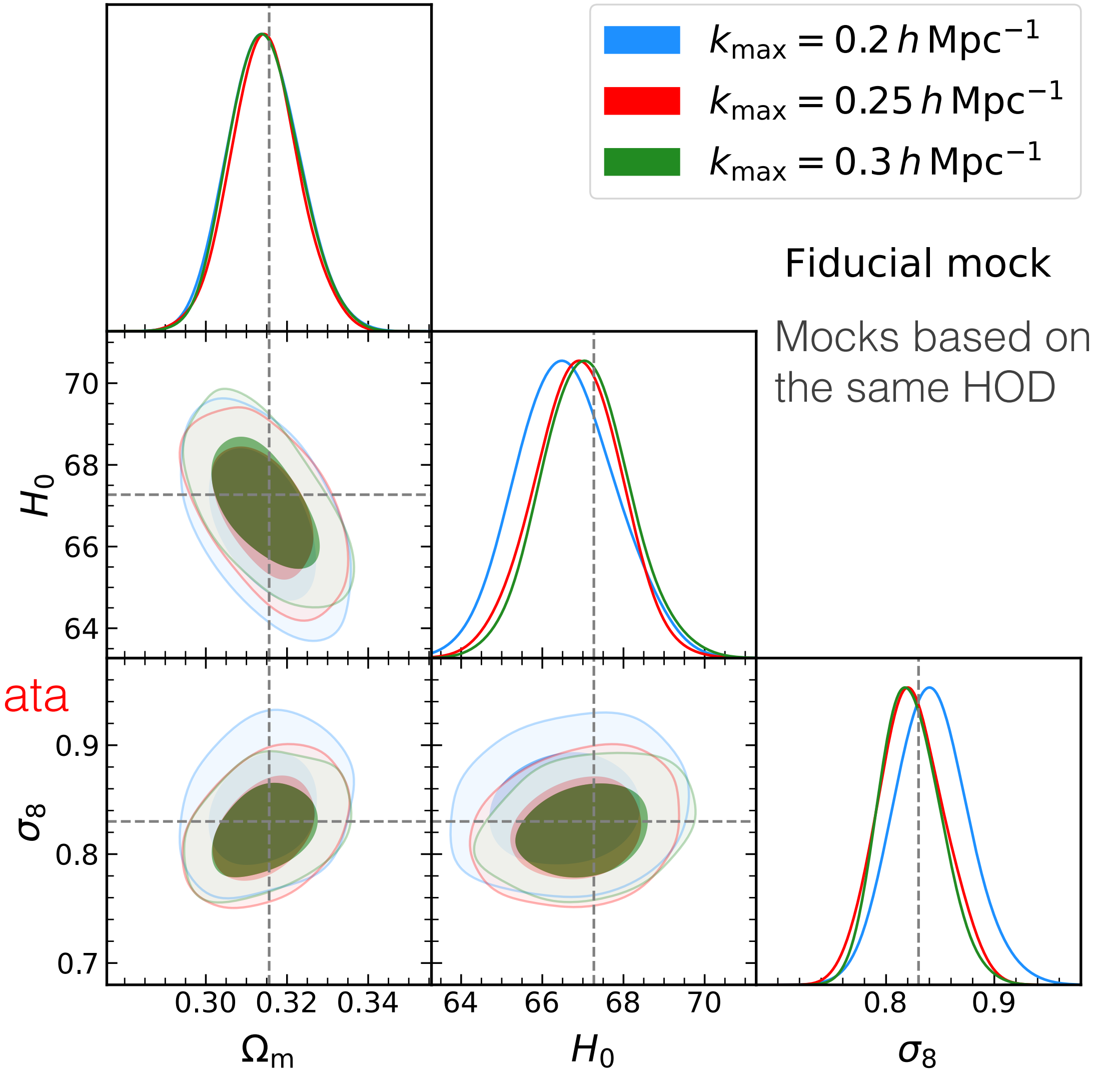
- BOSS DR12: 0.2<z<0.75
- 5 cosmo parameters with BBN prior on w_b and Planck prior on n_s
- 7 nuisance parameters for galaxy-halo connection, for each sample (we analyzed 4 samples)
- Wider prior on each of galaxy-halo connection parameters
- 5+7×4 = 33 parameters in total
- Dark Emulator can give a good fit to the data, up to ~0.3h/Mpc

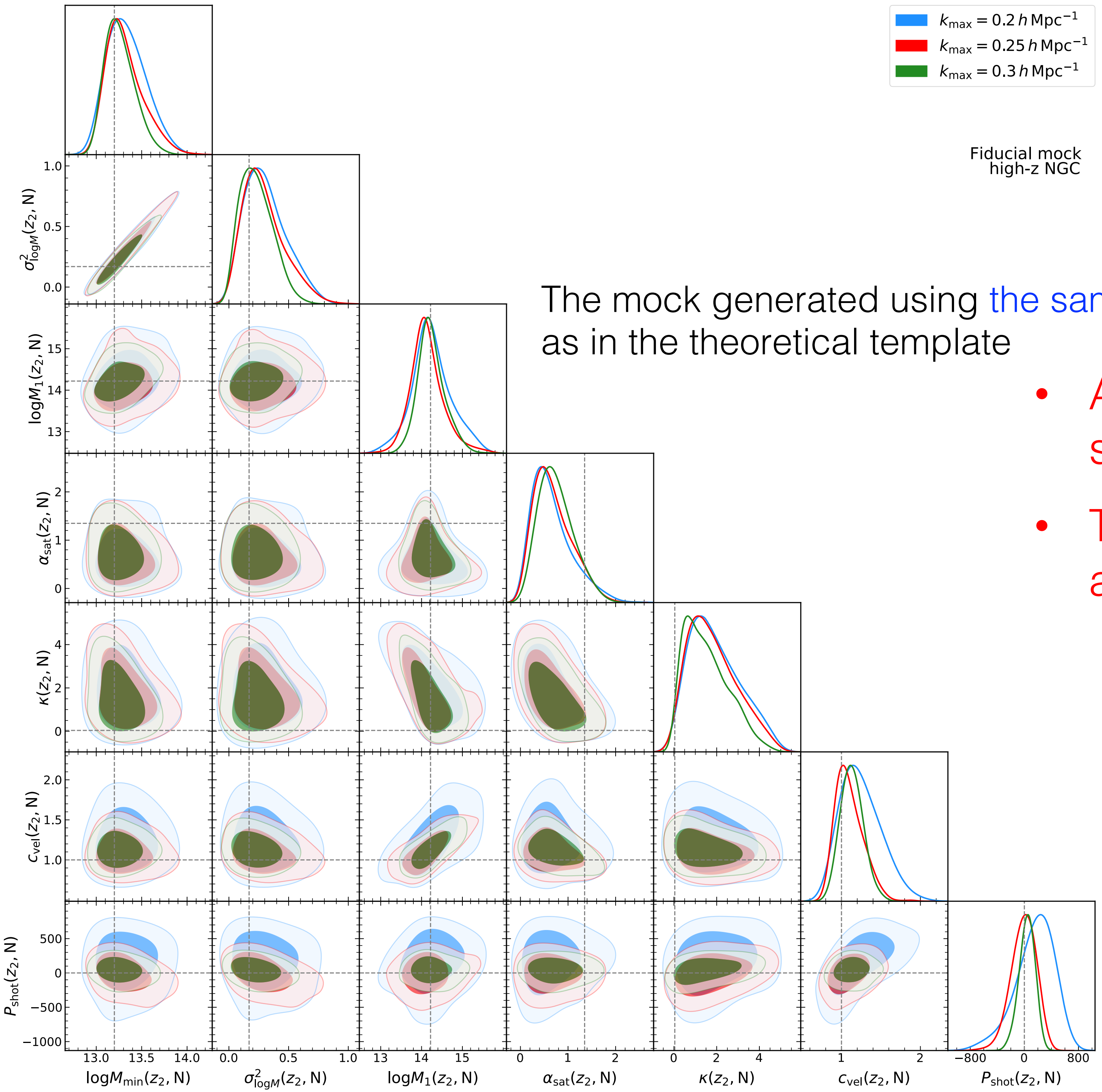


Validation of cosmology analysis pipeline

- Applied the analysis pipeline to the mock signal of power spectrum to check whether the method can recover the cosmological parameters; passed successfully!

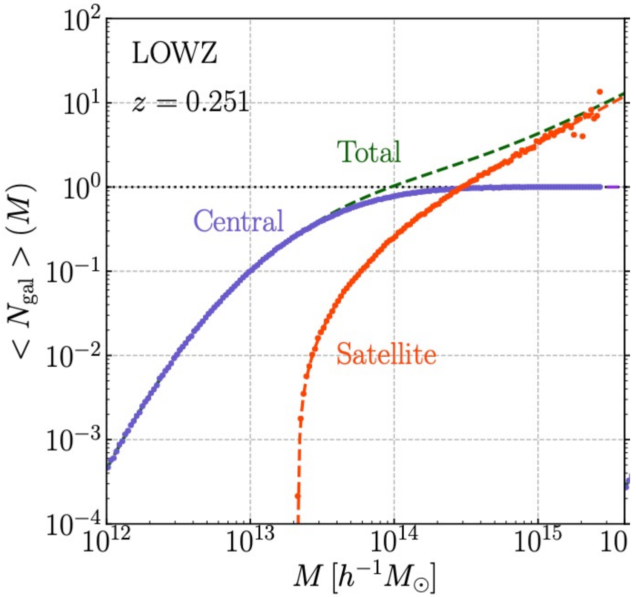




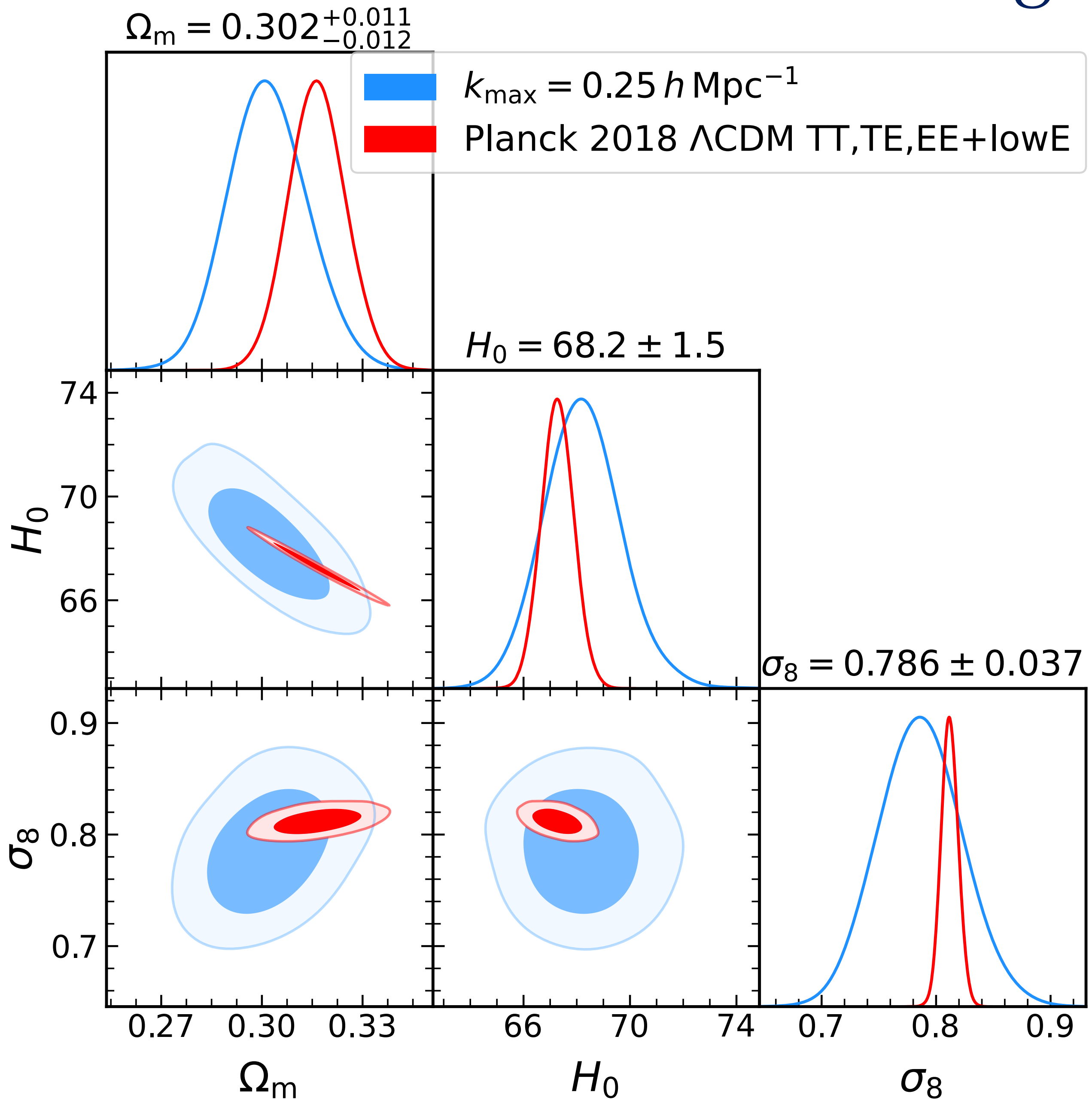


The mock generated using the same galaxy-halo connection (HOD) model as in the theoretical template

- Apparent errors of HOD parameters shrink with higher kmax
- The galaxy-halo connection paras are NOT necessarily recovered

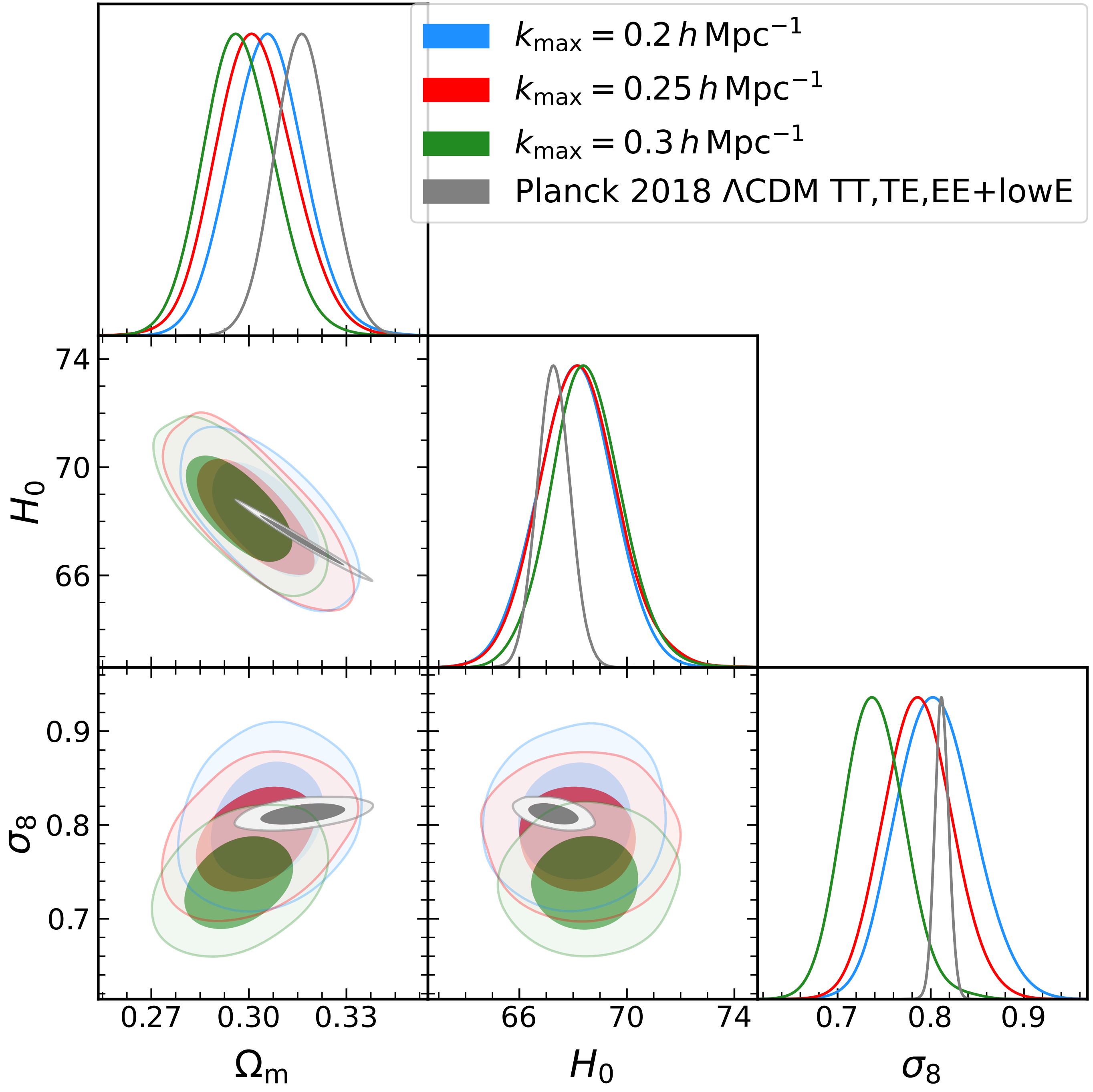


Results for real data after marginalization, for ΛCDM model



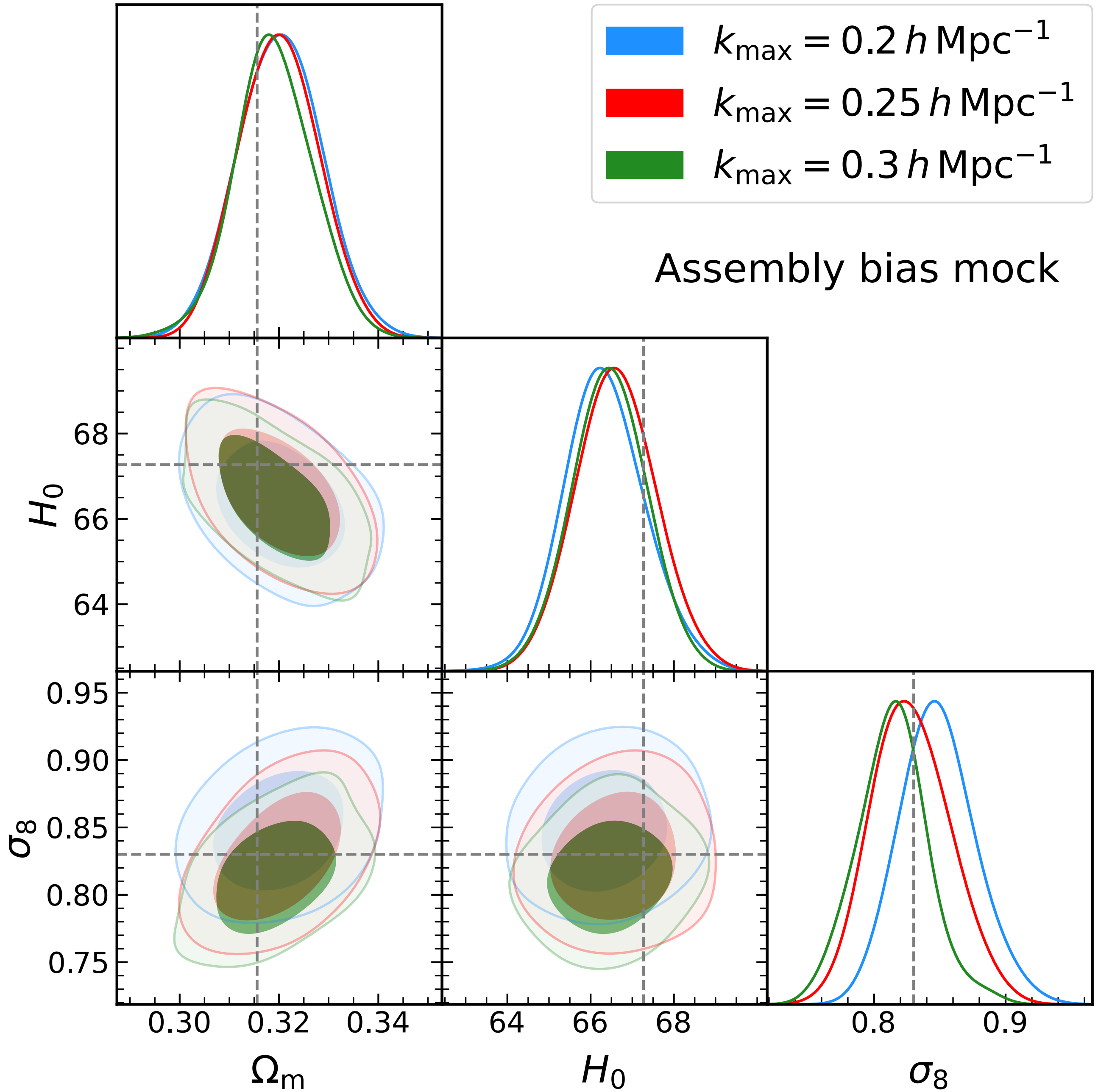
- Minimum use of CMB information: only for ns (BBN prior on wb)
- Broad priors of nuisance paras
- Include BAO, AP, RSD, broad-band shape
- Achieved ~5% precision of σ_8 determination (not for fsigma8)
- A slight tension for σ_8, compared to Planck

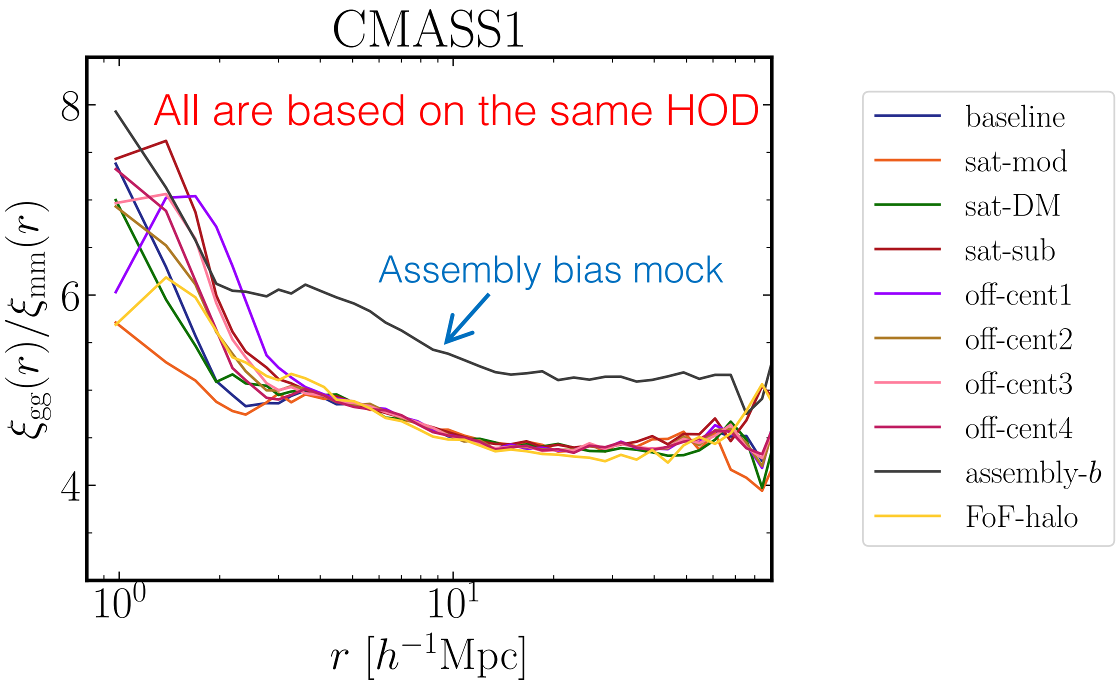
Parameter	MAP	Median	68% CI	Planck 68% CI
$\ln(10^{10}A_s)$	2.931	3.012	$3.014^{+0.0886}_{-0.0869}$	3.045 ± 0.016
Ω_m	0.2997	0.3016	$0.3008^{+0.0122}_{-0.0113}$	0.3166 ± 0.0084
H_0 [km s^{-1} Mpc^{-1}]	68.34	68.18	$68.16^{+1.40}_{-1.43}$	67.27 ± 0.60
σ_8	0.7540	0.7855	$0.7859^{+0.0361}_{-0.0368}$	0.8120 ± 0.0073
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.7536	0.7873	$0.7837^{+0.0477}_{-0.0420}$	0.834 ± 0.016
$f\sigma_8(z_{eff} = 0.38)$	0.4735	0.4708	$0.4665^{+0.0345}_{-0.0278}$	0.4771 ± 0.0066
$f\sigma_8(z_{eff} = 0.61)$	0.4335	0.4344	$0.4296^{+0.0337}_{-0.0261}$	0.4696 ± 0.0053



- Not much cosmological information at kmax>0.2h/Mpc (galaxy-halo parameters are tightened)
- Some systematic trend with kmax=0.3

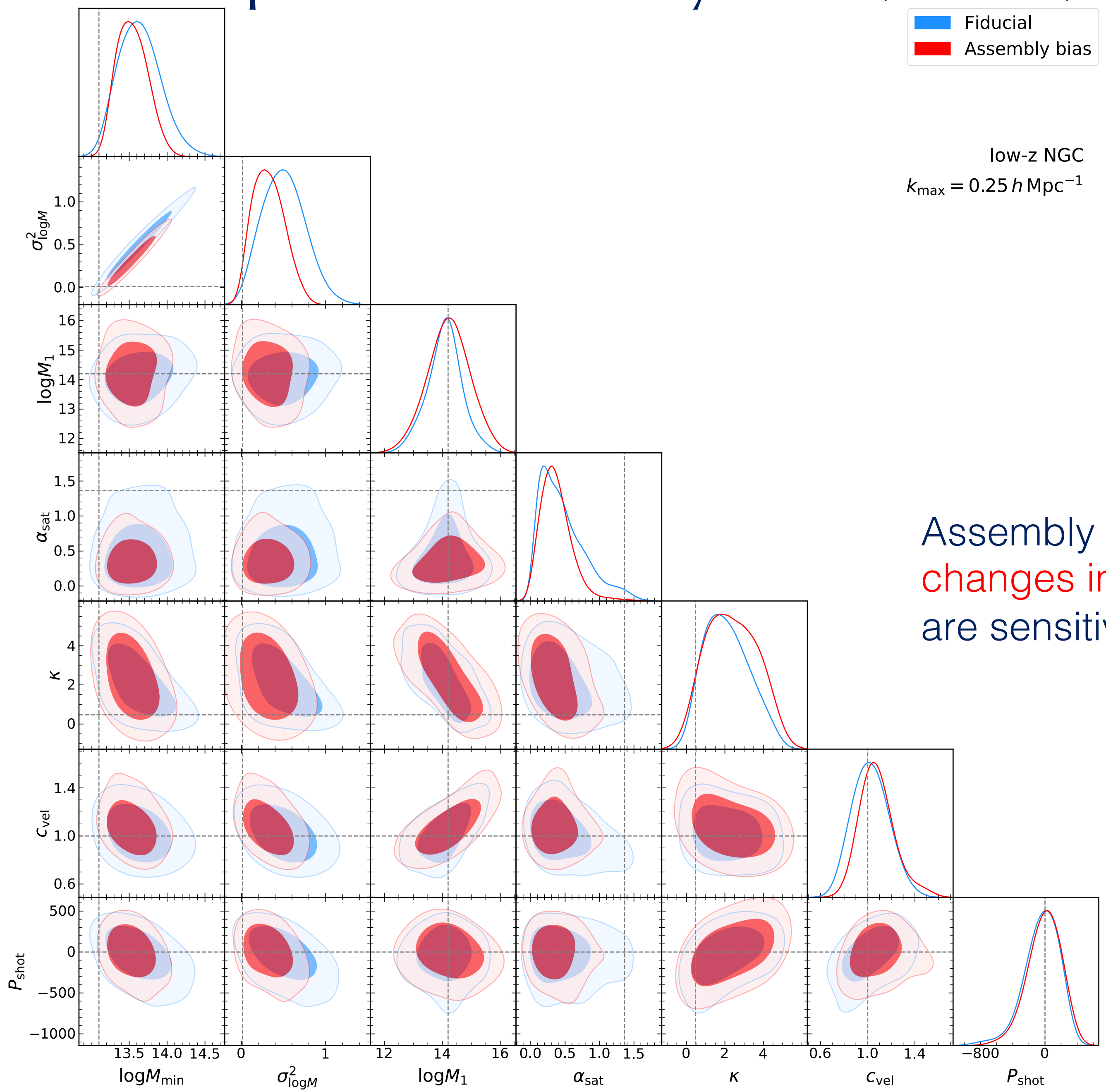
The impact of assembly bias

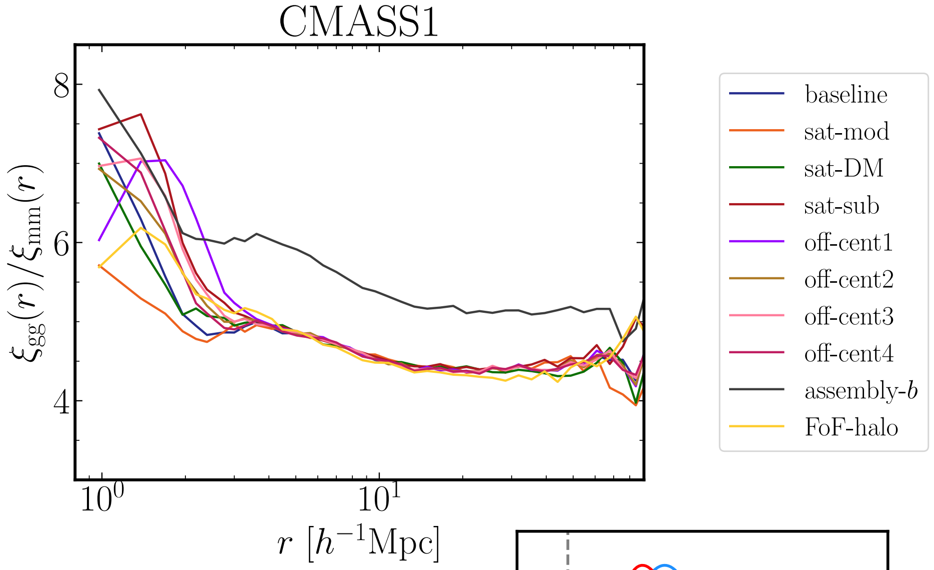




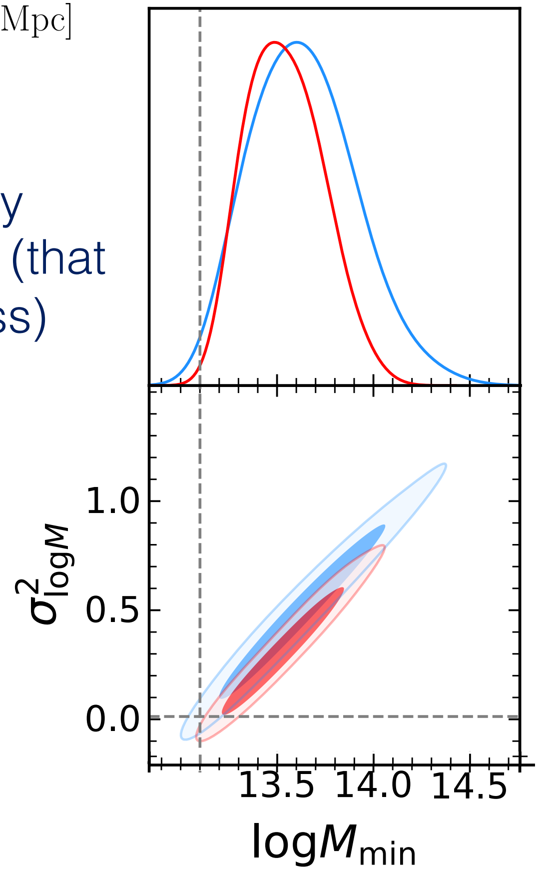
assembly bias, one of the most dangerous systematic effects for halo model picture (however, there is no evidence yet in actual data) – galaxies might preferentially form in certain types of halos depending on their assembly histories

The impact of assembly bias (cont'd)





Assembly bias effect is absorbed by changes in galaxy-halo parameters (that are sensitive to mean host halo mass)



Comparison with EFTofLSS results

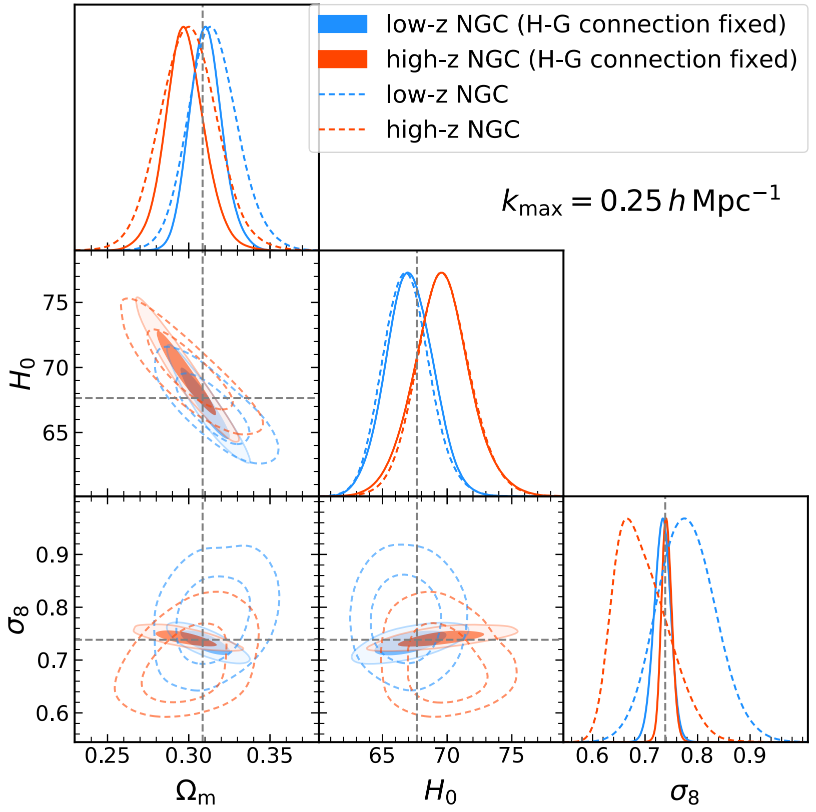
Kobayashi+ (Emulator) : $\sigma_8 = 0.786^{+0.036}_{-0.037}$ $\Omega_m = 0.301^{+0.012}_{-0.011}$ $H_0 = 68.2 \pm 1.4$

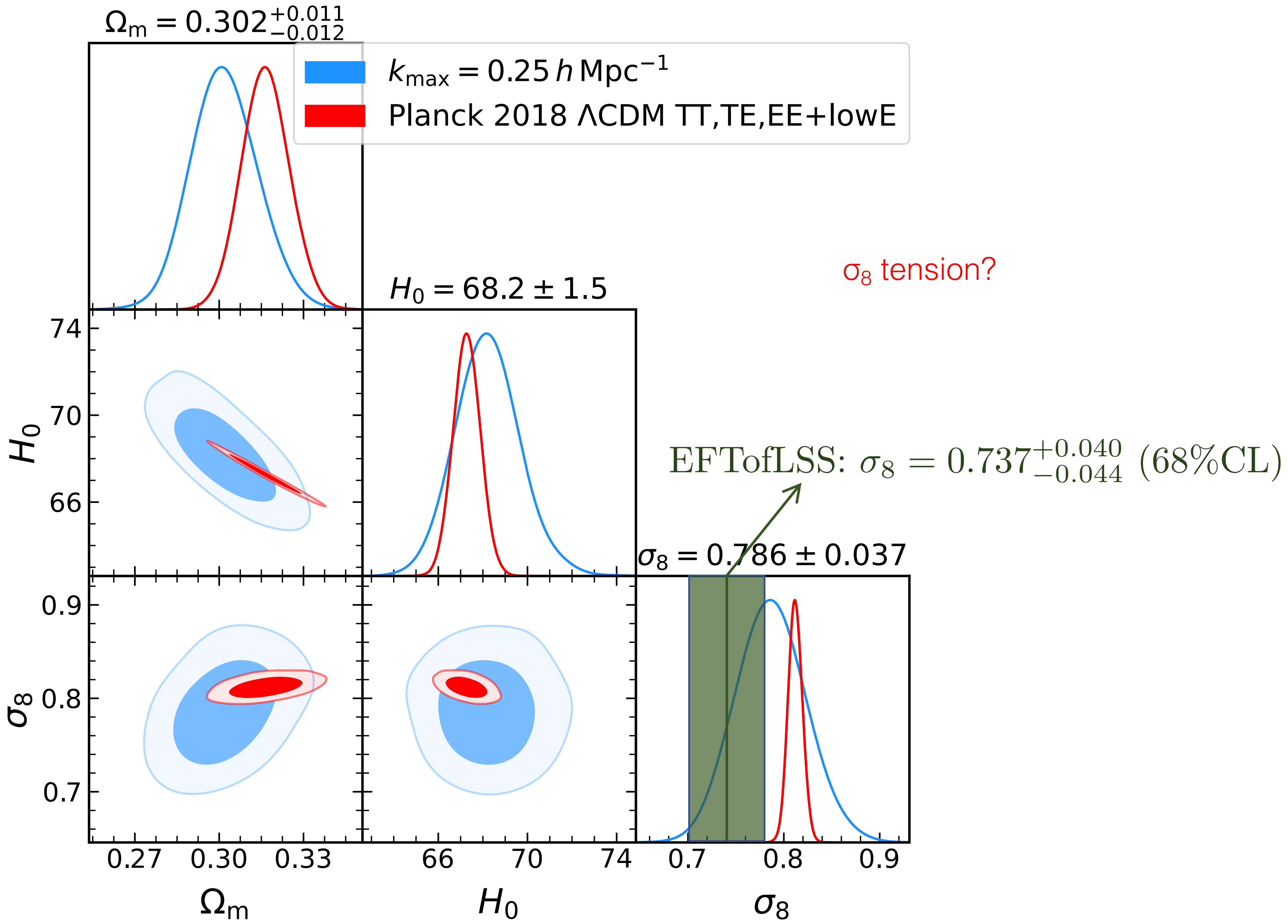
Princeton (Philcox+21): $\sigma_8 = 0.737^{+0.040}_{-0.044}$ $\Omega_m = 0.312^{+0.011}_{-0.012}$ $H_0 = 68.5^{+1.1}_{-1.3}$

Berkeley (Chen+21): $\sigma_8 = 0.738 \pm 0.048$ $\Omega_m = 0.305 \pm 0.01$ $H_0 = 68.5 \pm 1.1$

All these are based on the same (at least very similar) data and the similar priors

- Planck sigma8≈ 0.81 ± 0.007
- More stringent than the linear-theory like method (e.g., Beutler, 10% precision in fsigma8)
- Our method achieved the tightest constraint for sigma8, because our method should be based on more restrict model (halo model+Emulator) compared to EFTofLSS
- Our method is still conservative because we did not include any information on the mean host halo mass of BOSS galaxies, nor the mean number density
- In other words, there are a lot of rooms in the improvement: e.g. combine with HSC weak lensing (future plan)



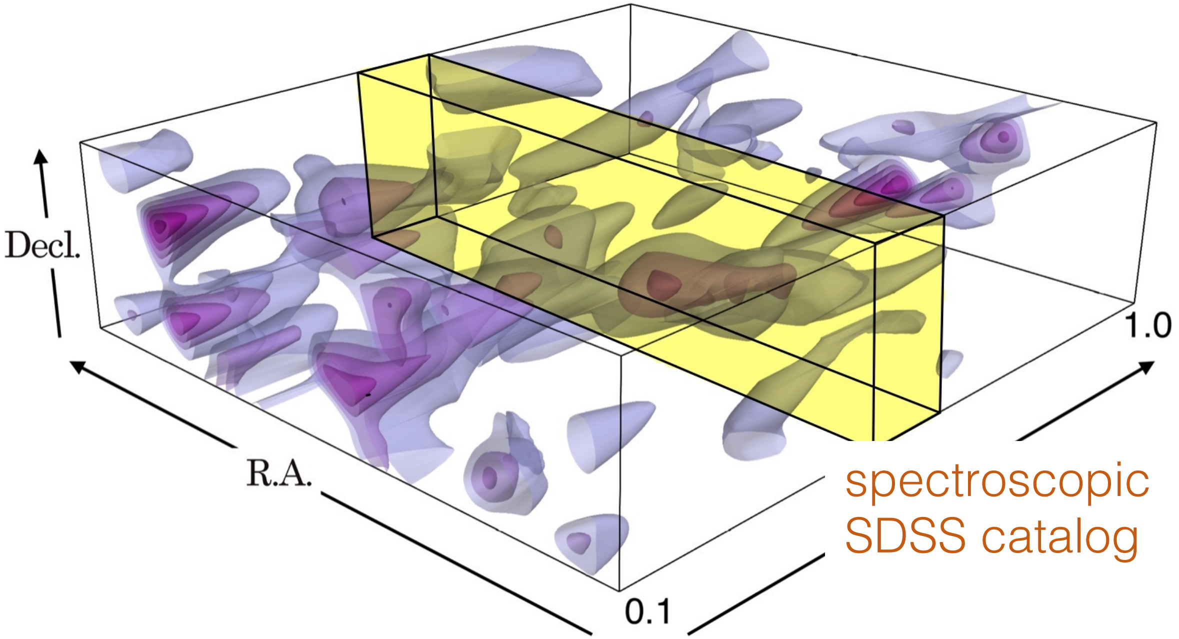


$\Omega_m = 0.302^{+0.011}_{-0.012}$
$k_{max} = 0.25\, h\, \text{Mpc}^{-1}$
Planck 2018 ΛCDM TT,TE,EE+lowE
σ8 tension?
$H_0 = 68.2 \pm 1.5$
EFTofLSS: $\sigma_8 = 0.737^{+0.040}_{-0.044}$ (68%CL)
$\sigma_8 = 0.786 \pm 0.037$
74
70
66
H_0
0.9
0.8
0.7
σ_8
0.27
0.30
0.33
Ω_m
66
70
74
H_0
0.7
0.8
0.9
σ_8

The new Subaru HSC weak lensing result

- New results: cosmological constraints, robust to photo-z errors (Miyatake+21)
- Used Dark Emulator for the theoretical template

$$\gamma(\boldsymbol{\theta}, z_s) \sim \int_0^{z_s} dz\, W(z, z_s)\bar{\rho}_m \delta_m(z, \chi\boldsymbol{\theta})$$



✓ Cross-correlation of HSC galaxy shapes and positions of spectroscopic SDSS galaxies

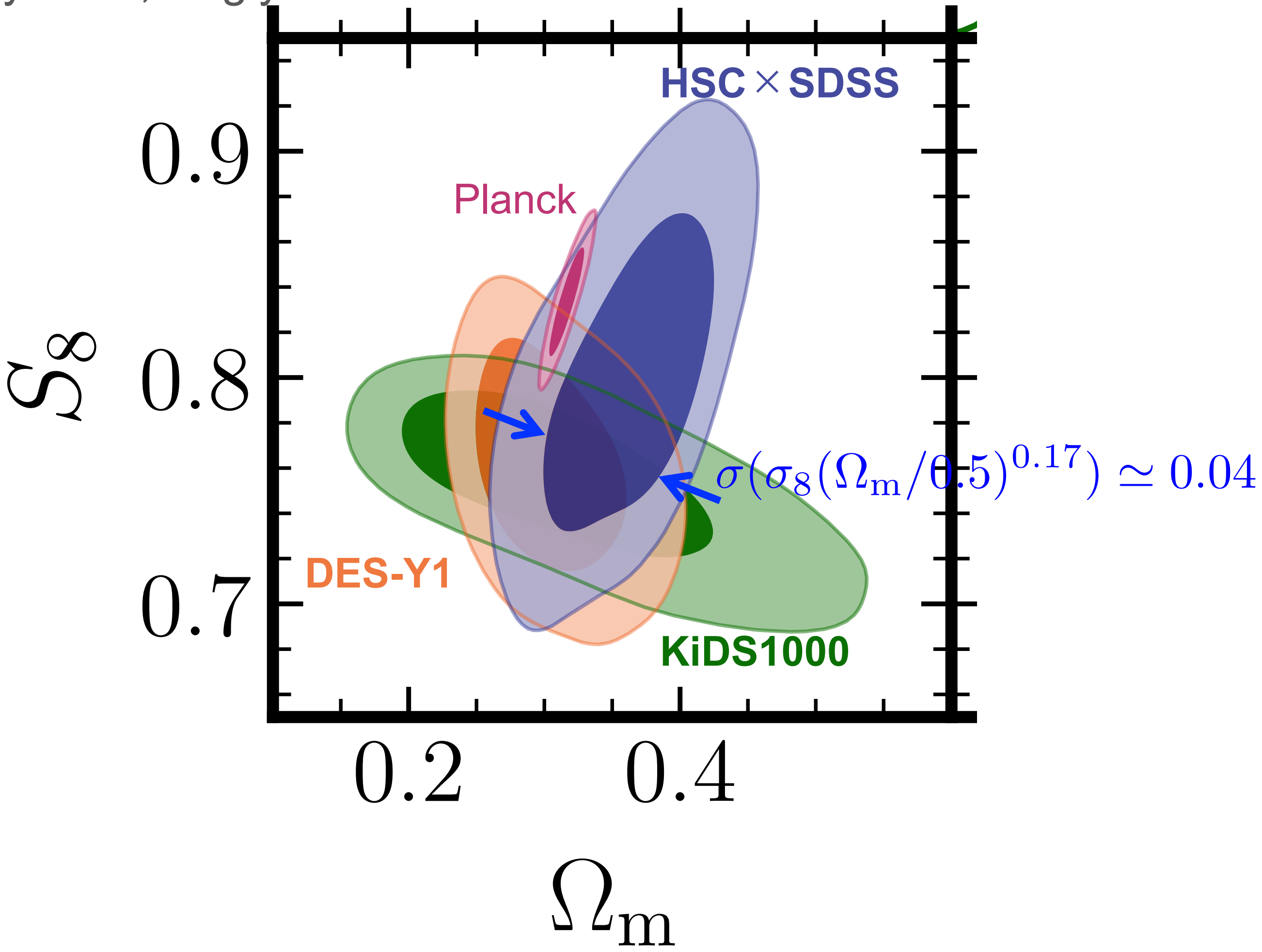
$$\langle \delta_g(z_l)\gamma(z_s)\rangle \to \xi_{gm}(r; z_l) \simeq b_g \xi_{mm}(r; z_l)$$

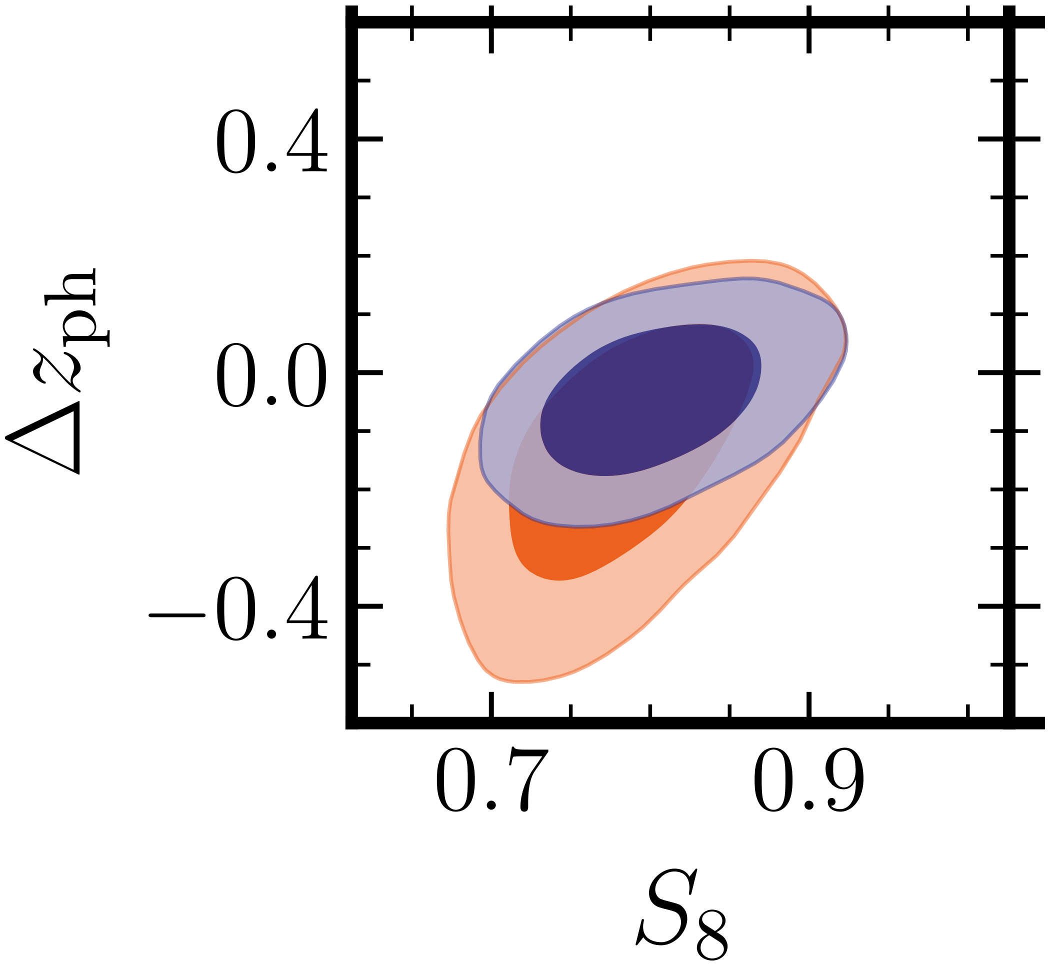
✓ Auto projected (not 3D) correlation of spectroscopic SDSS galaxies

$$\langle \delta_g(z_l)\delta_g(z_l)\rangle \to \xi_{gg}(r; z_l) \simeq b_g^2 \xi_{mm}(r; z_l)$$

✓ Combining these two allows to observationally disentangle galaxy bias uncertainty and matter correlation function

Miyatake, Sugiyama +21



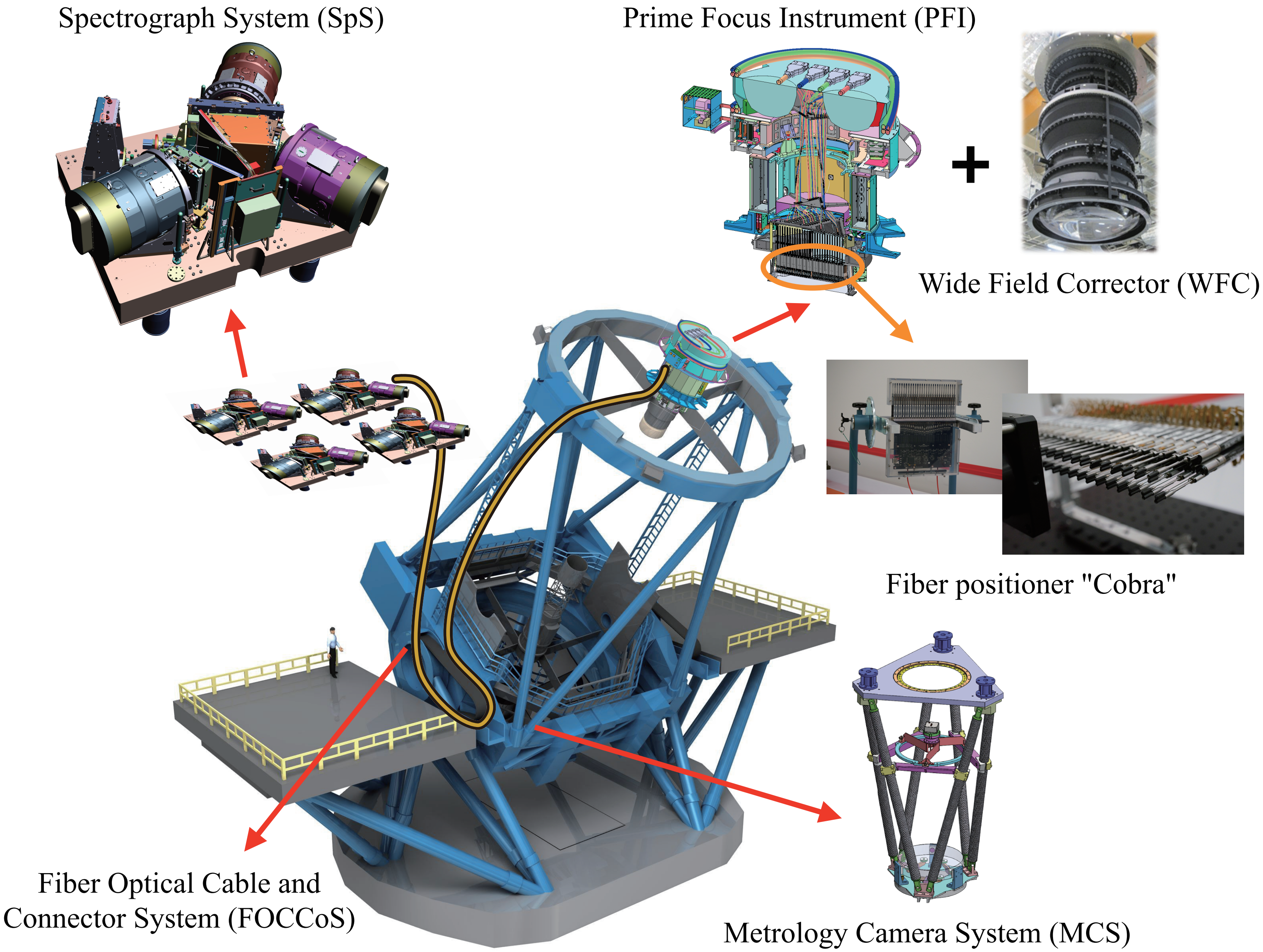


- ✓ HSC-Y1 at Ω_m~0.3 still indicates a tension with Planck?
- ✓ The upcoming HSC Year 3 data promises a significant improvement in cosmological parameters

- ✓ The constraint on S8 is not changed even if treating residual photo-z bias as a free parameter (other weak lensing surveys assume ~1% prior on photo-z, and uses COSMOS calibration)

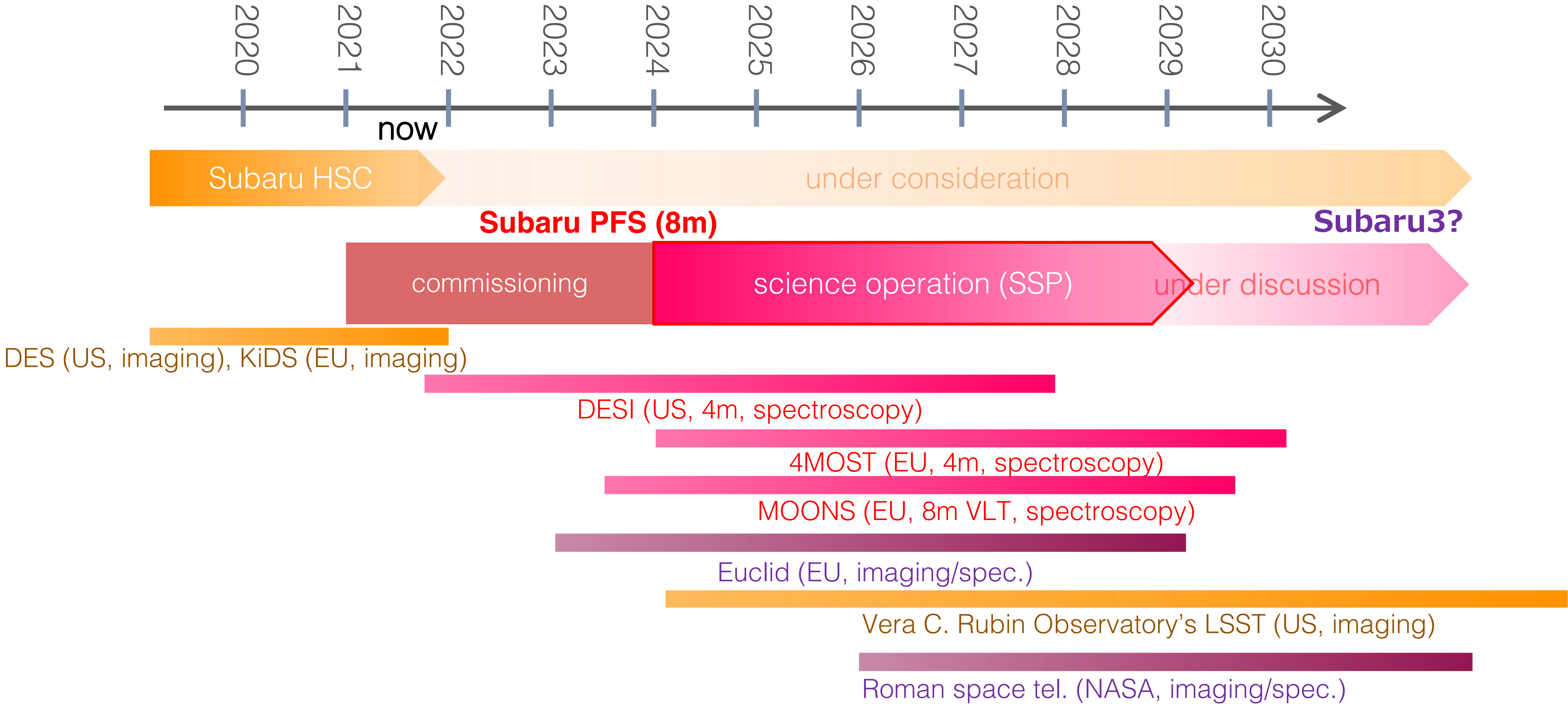
HSC team is now working on Year 3 dataset (a factor of 4 larger dataset) (Miyatake, Sugiyama, MT+)

Subaru Prime Focus Spectrograph



- ~$90M project, being led by Kavli IPMU (PI: Hitoshi Murayama, PM: Naoyuki Tamura, PS: MT)
- Institutes in 6 countries are involved (US, France, Taiwan, Brazil, Germany, China)
- Mentioned in several places of US Astro2020
- 2400 fibers, wide field-of-view, 8.2m collecting power
- Envision we will start our large-scale surveys, from early 2024
- PFS blog: https://pfs.ipmu.jp/blog/ja/

Landscapes in 2020s cosmology



summary

- Spec-z galaxy survey cosmology uses 3D Fourier information – a huge potential
- Independent groups are now making efforts to put galaxy survey cosmology at comparable level (robustness and precision) to that of CMB (see Leonardo's talk)
- Nonlinear clustering information, if reliably used, can boost the constraining power of cosmological parameters
- Stringent test of LCDM model – address whether a sigma8 tension is a hint of new physics
- We (being led by Takahiro and Yosuke) developed "Dark Emulator" for redshift-space halo power spectrum – eventually made public
- Subaru PFS (~$80M!) will be online in 2024 – exciting era to have Stage IV experiments together with DESI, Euclid, Roman
- Need more neat ideas/method/theory – discovery potential/opportunities for you!