Cosmology with SuMIRe PFS: Requirements on PFS spec

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IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Sep 09 @IPMU

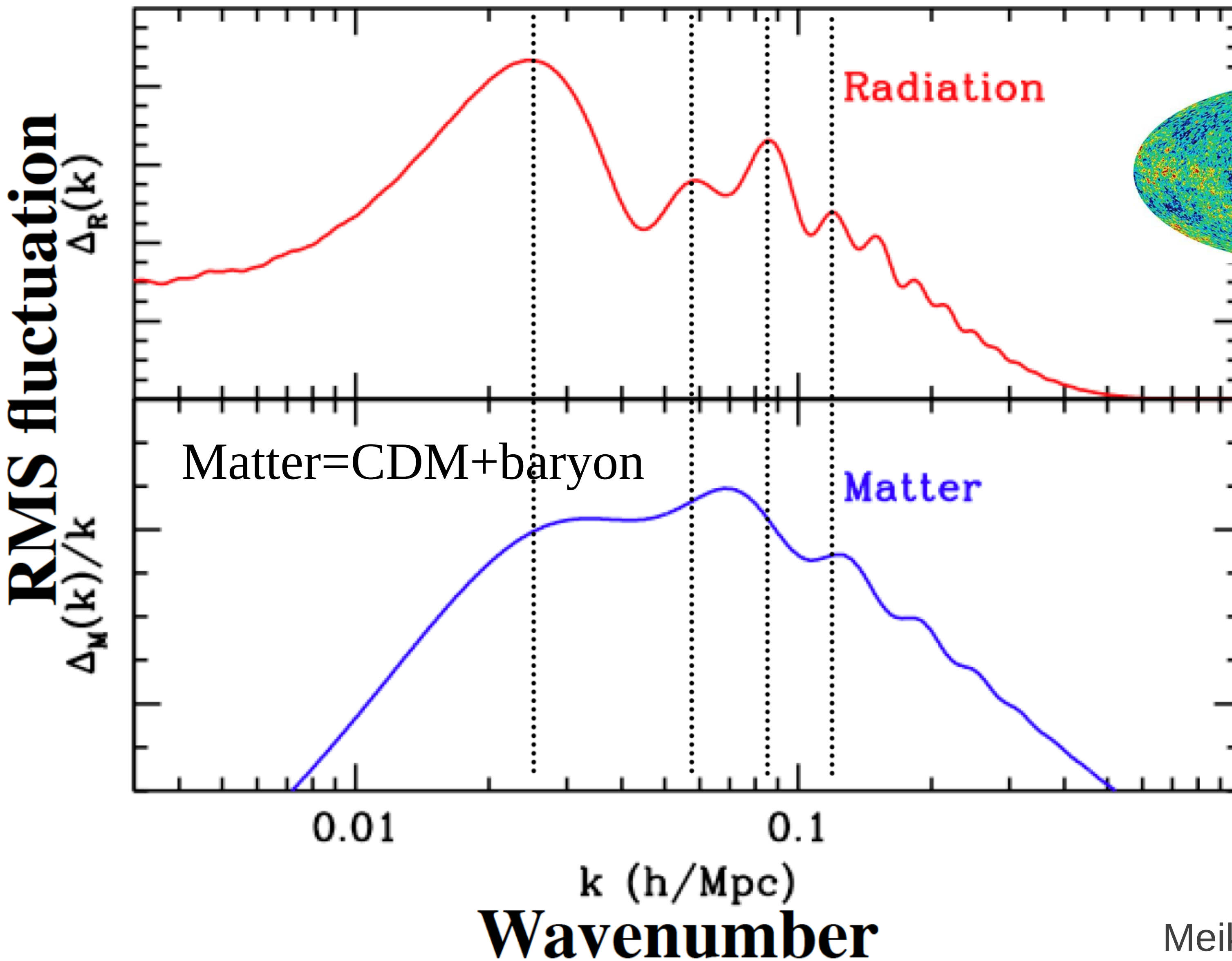
Astro2010

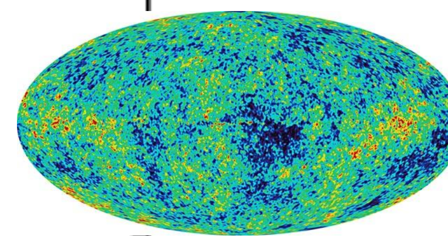
- Space-based survey
  1. WFIRST: Dark Energy and Exoplanet Statistics
     - 1.5m; 144MPx HgCdTe detectors, 200mas, grism; L2
     - Gravitational lensing, distant supernovae, BAO
  2. Explorer Program Augmentation
- Ground-based survey
  1. LSST: Dark Energy, Dark Matter and the time-variable universe
     - 8.4m; 3.5 sq. degree FoV; Observe half sky every four days with 6 filters
     - Gravitational lensing, distant supernovae, imaging BAO
  2. Mid-scale innovation program ← *PFS?*

➢ *HSC survey can play a pioneering role for these ultimate wide-field imaging surveys (we can scoop DE science!); URGENT TASK!*

➢ *The demand on the wide-field multi-object spectrograph capability is even more increasing; PFS can play a unique role in 2020's*

Baryonic Acoustic Oscillation (BAO)

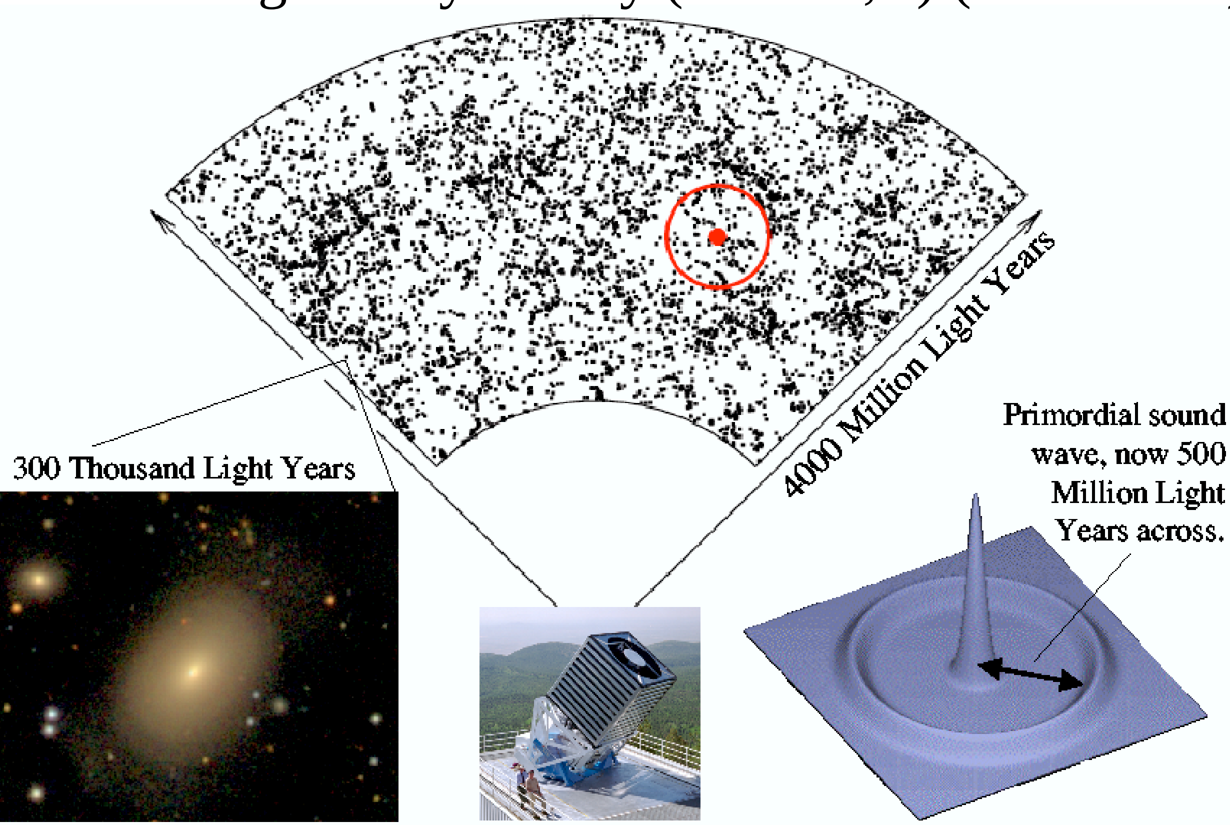


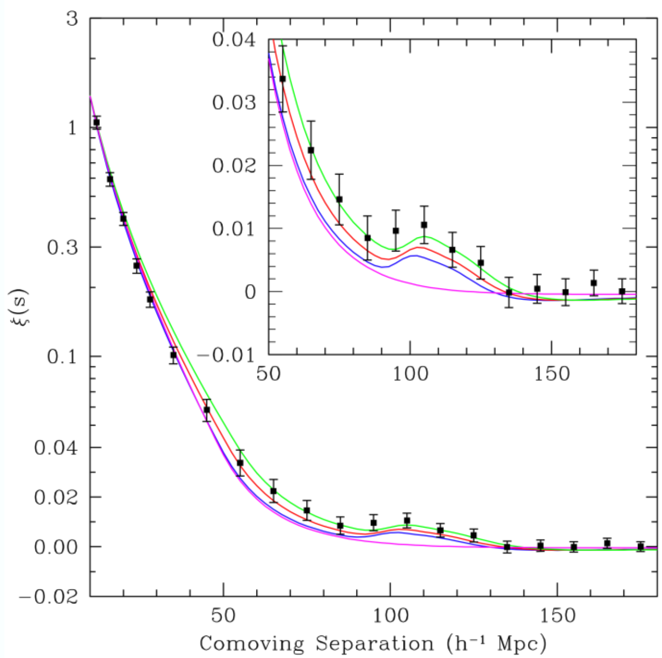


Meiksin et al. 98

BAO (contd.): standard ruler

Sloan Digital Sky Survey (SDSS-I,II) (2000-2008)





Eisenstein et al. (05)

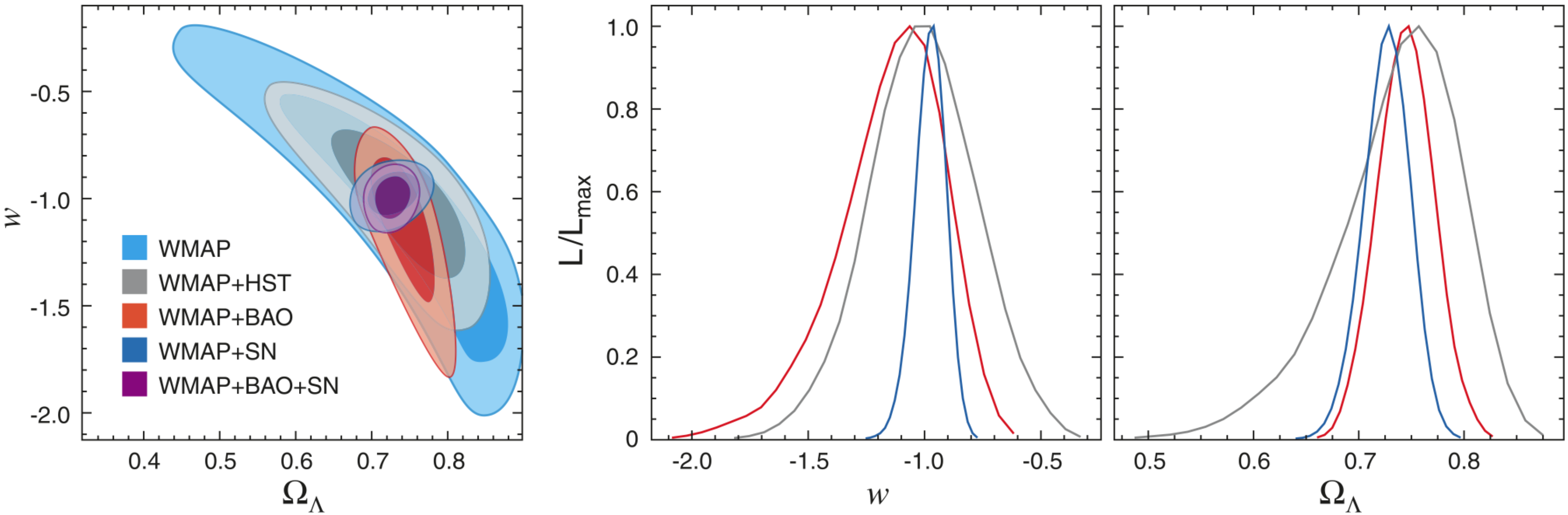
$$r_{\mathrm{BAO}} = D_A(z)\Delta\theta_{\mathrm{obs}} \qquad r_{\mathrm{BAO}} = \frac{\Delta z_{\mathrm{obs}}}{H(z_{\mathrm{survey}})}$$

Dark Energy Task Force Report (DETF)

a. The **BAO** technique has only recently been established. It is less affected by astrophysical uncertainties than other techniques.

BAO (contd.): the current status-of-art

A flat universe assumed



From WMAP 5-year paper (Komatsu et al.)

- WMAP5+SDSS BAO: $-0.68<1+w<0.21$ (95%C.L.)

Gravity Test

- Einstein gravity is right over all the length scales, from solar-system scales to the Horizon scale

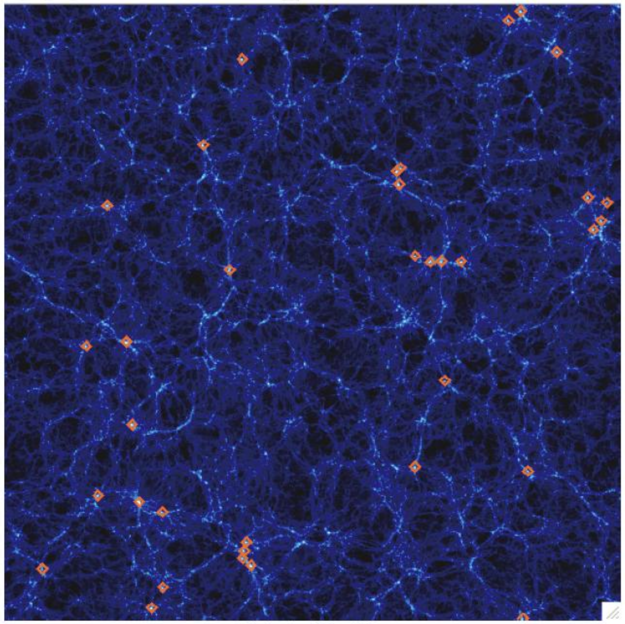
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

(Curvature of space-time = Matter)

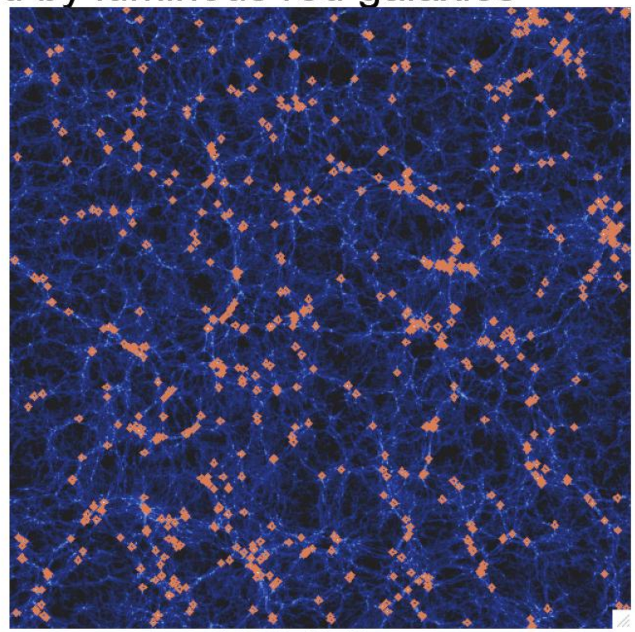
- The observed cosmic acceleration may be a signature of the modification in gravity law on cosmological scales
- Einstein gravity should be tested by data
- Imaging and redshift surveys are very powerful to test gravity

SDSS-III's Baryon Oscillation Spectroscopic Survey (BOSS)

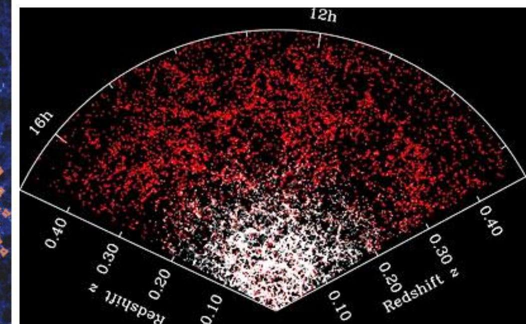
The cosmic web at z~0.5, as traced by luminous red galaxies



SDSS



BOSS



From D. Schlelegel's talk

A slice 500h^{-1} Mpc across and 10 h^{-1} Mpc thick

- Upgrade the SDSS (2.5m) spectrograph: increase to 1000 fibers with 2'' aperture; red-sensitive CCDs & better gratings
- Obtain 1.6M LRG spectra over $0.2<z<0.7$ ($0.2<z<0.6$ for better sampling) (2009-2014)

Things to be considered for designing SuMIRe BAO survey

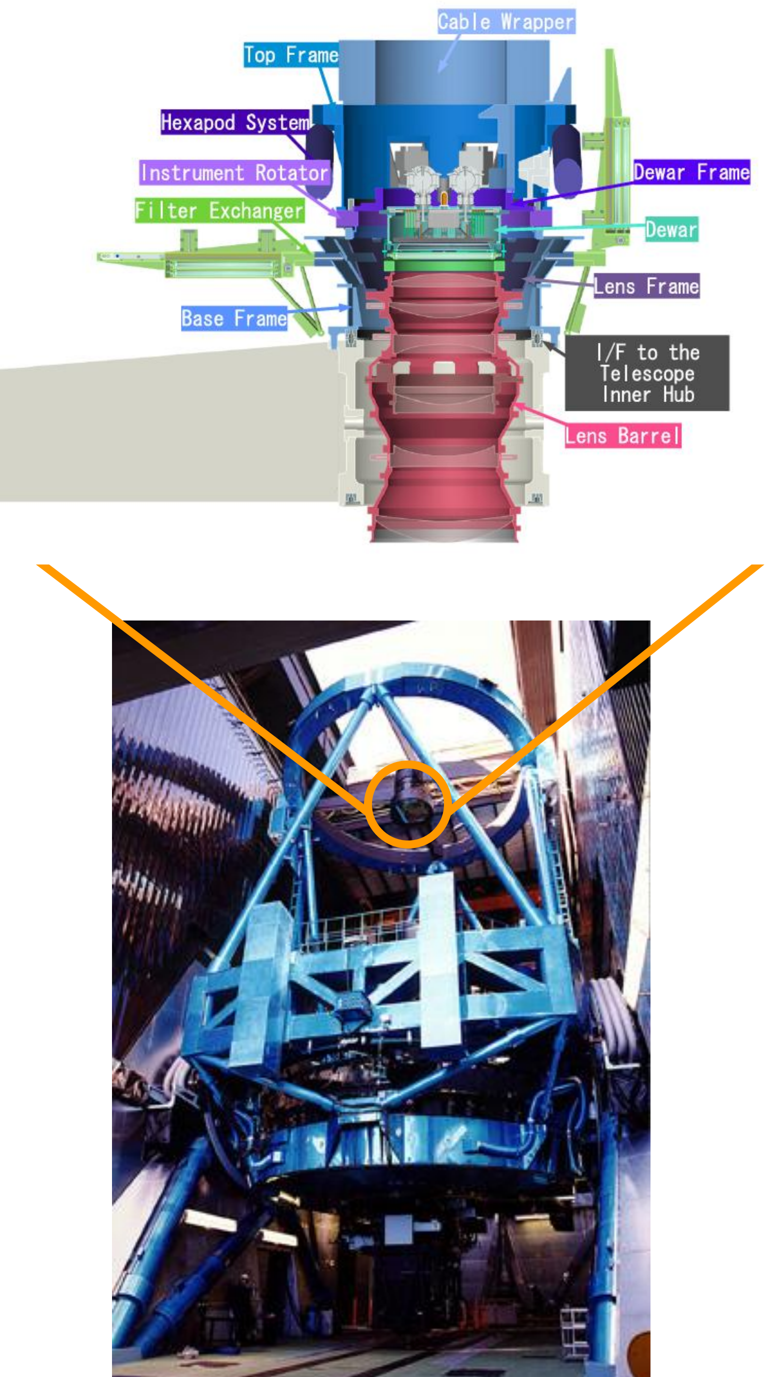
- Fully utilize unique capabilities of 8.2m Subaru Telescope (should be deeper, if optical, than 4m-class BAO surveys)
- Maximize a synergy with Hyper SuprimeCam imaging survey
  - SDSS-like survey extending out to higher redshifts (up to z~1.7): various science cases
  - Less systematic errors by studying the same region of sky with the same telescope
  - Utilizing the red-sensitive CCD chips (high QE up to 1100nm)
  - Cross-calibrations of the imaging- and redshift-survey methods (photo-z's, galaxy bias, selection function, etc.)
- Should be complementary to the existing and ongoing BAO surveys (or redshift surveys)
  - If combined with the BAO surveys, tighter constraints on the expansion history over a wider range of redshifts can be obtained

Planned BAO experiments

	BOSS	BigBOSS	SuMIRe PFS
Telescope	2.5m	4m @KPNO	8.2 Subaru Tel.
Pre-imaging survey	Done	Done + DES	Hyper SuprimeCam
Redshift	$0.2<z<1.7$	$0.2<z<2+z\sim3$	$0.6<z<1.6$
Sky coverage	10000 deg^2	14000-24000deg^2	~2000 deg^2
Field-of-view	7 deg^2	7 deg^2	1.8 deg^2
Number of fibers	1000	4000	2200-3000
Wavelength range	360-1000nm	340-1130nm	600-1100nm
Spectral resolution	1600-2600	2300-6000	~3000
Target galaxies	LRGs	LRGs+[OII] emitters	LRGs + [OII] emitters

- Note: HETDEX (Texas+) is a blind redshift survey targeting Ly-alpha emitters over $1.9<z<3.5$ and covering ~400 deg^2 area
- Subaru FMOS survey (~50 deg^2): H-alpha survey over $0.5<z<1.7$

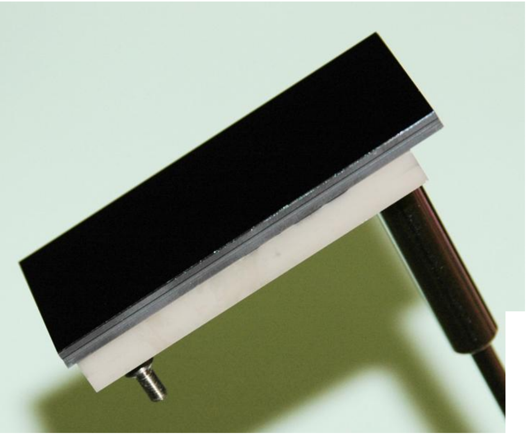
Hyper SuprimeCam Survey

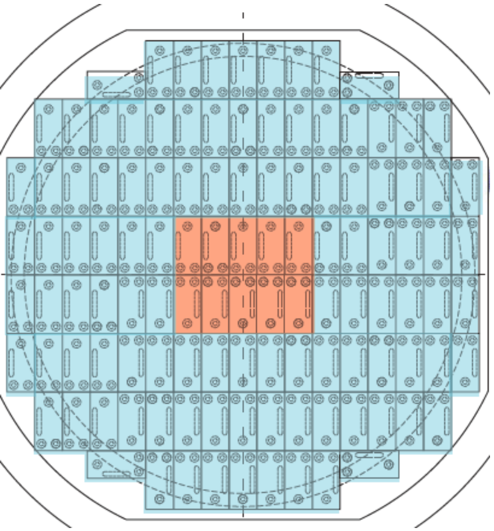


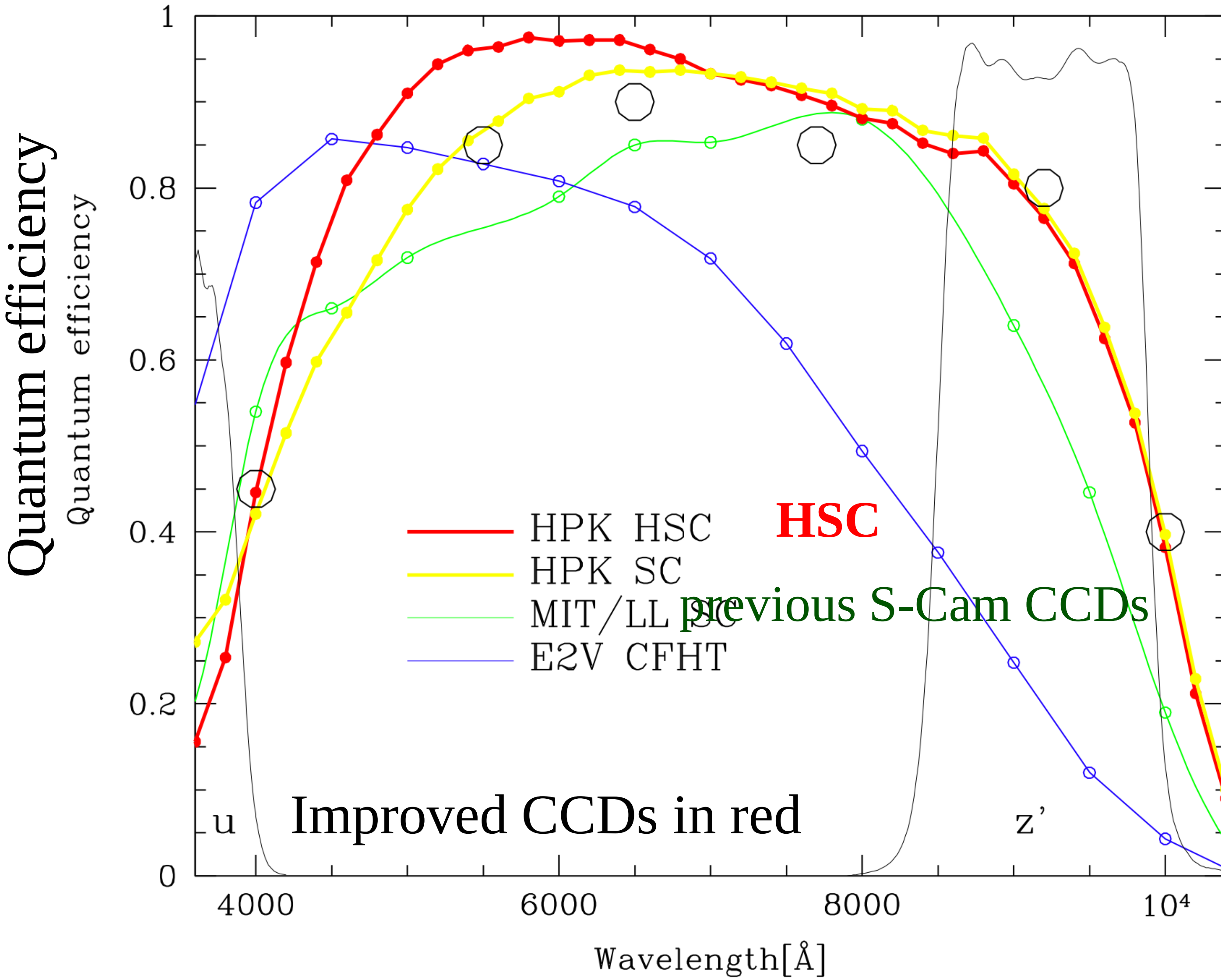
- Upgrade the prime focus camera
- **Funded, started since 2006**
- International collaboration: **Japan (NAOJ, IPMU, Tokyo, Tohoku, Nagoya), Princeton, Taiwan**
- Field-of-View: ~10 × Suprime-Cam
- Keep the excellent image quality
- Instrumentation well underway (being led by S. Miyazaki, NAOJ)
- HSC survey starting from 2012 - 2017
- Deep multi-band imaging (grizy; i~26, y~24) with ~1500 deg^2
- Primary science cases: (1) weak lensing, (2) galaxy clusters out to z~1.4 (WL + SZ+ optical), (3) QSOs at z~7

Full Depleted CCDs

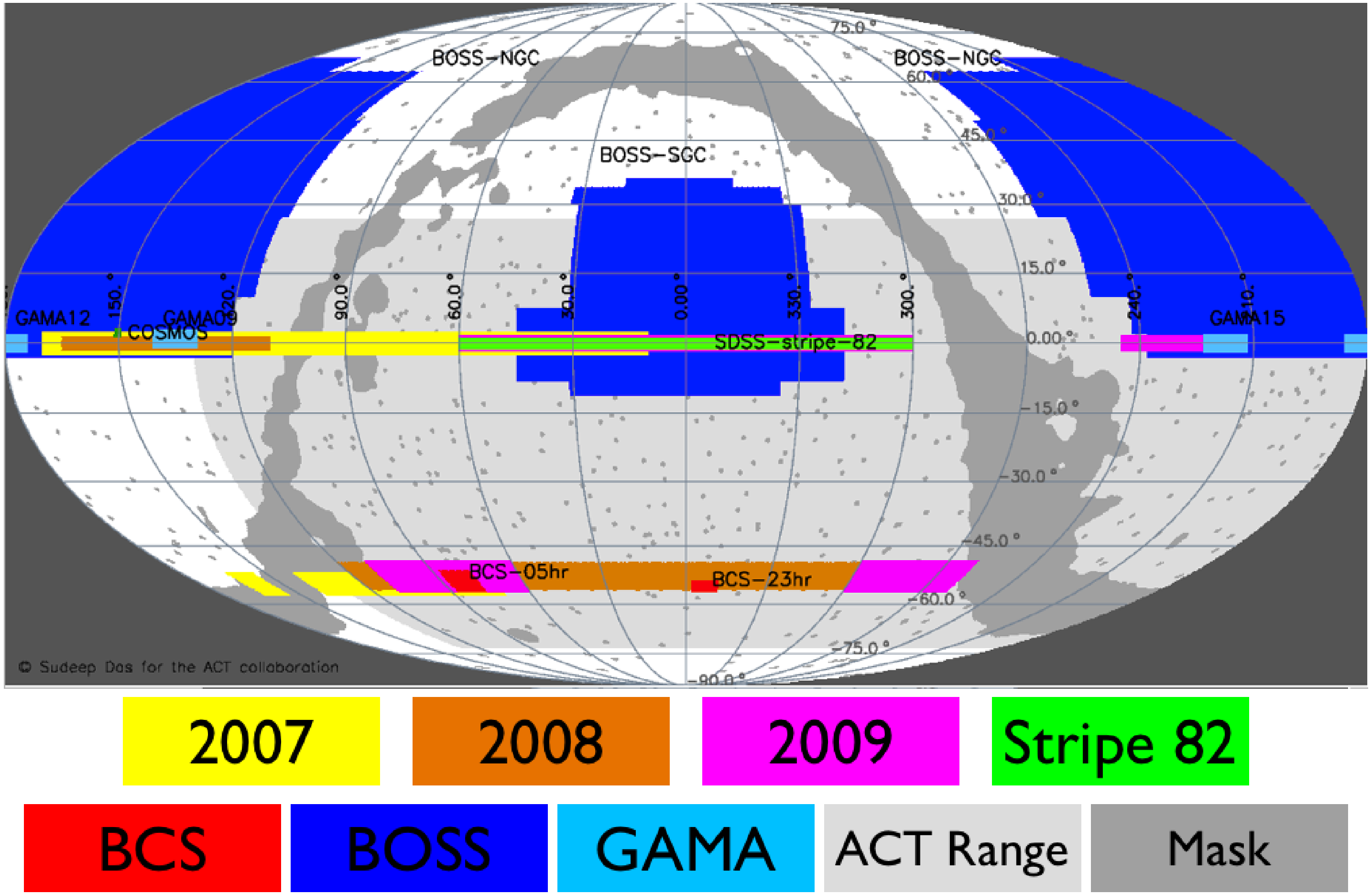
Developed by Hamamatsu Photonics-NAOJ collaboration







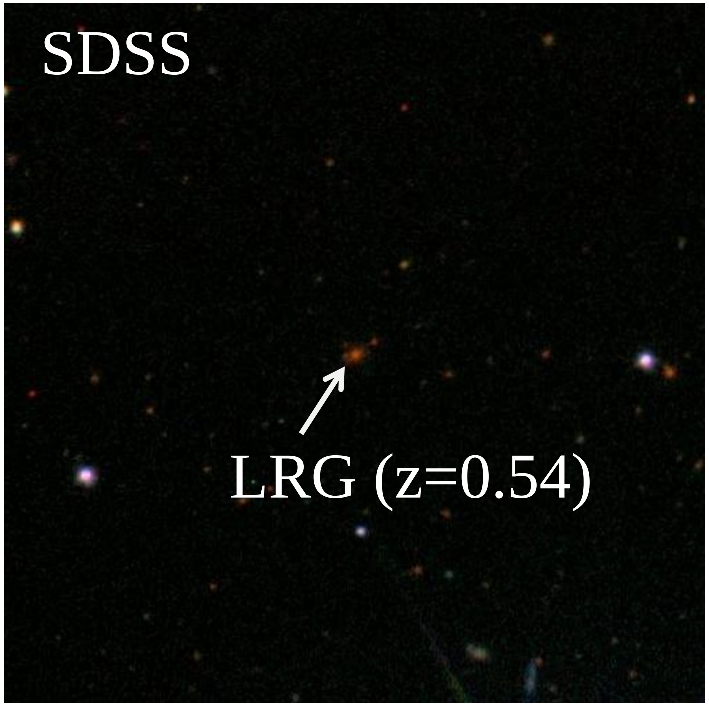
HSC-wide survey regions (TBD)

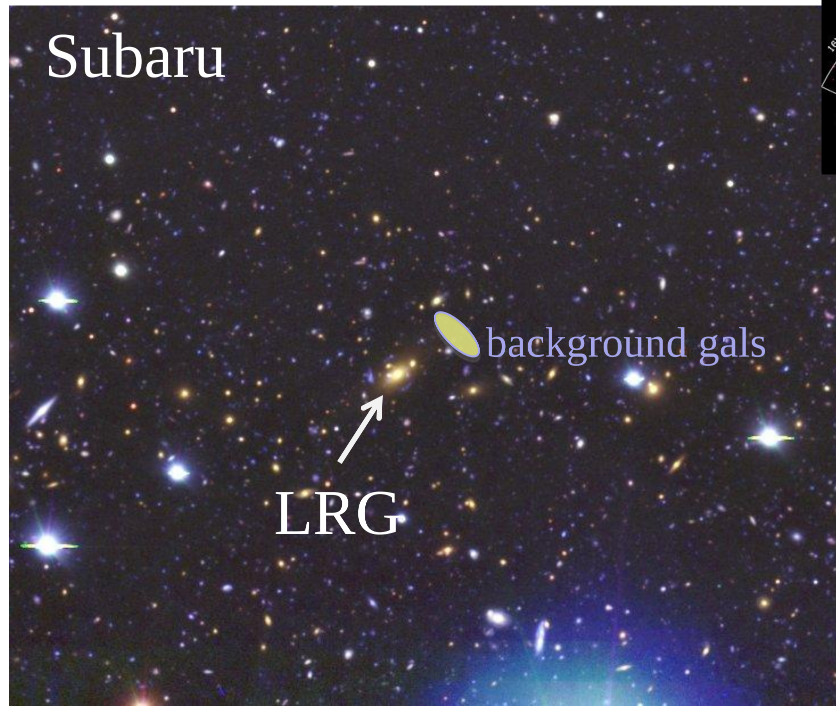


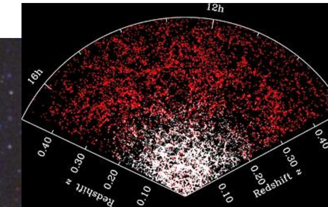
From ACTPol White Paper

- Strongest candidates of HSC-wide survey fields are around equators so that the HSC survey fields are accessible from the Sunyaev-Zel'dovich experiment ACT (Princeton+) and ALMA
- Also probably overlap with BOSS fields (the redshifts freely available)

Various synergies of HSC with other data sets
an example of BOSS







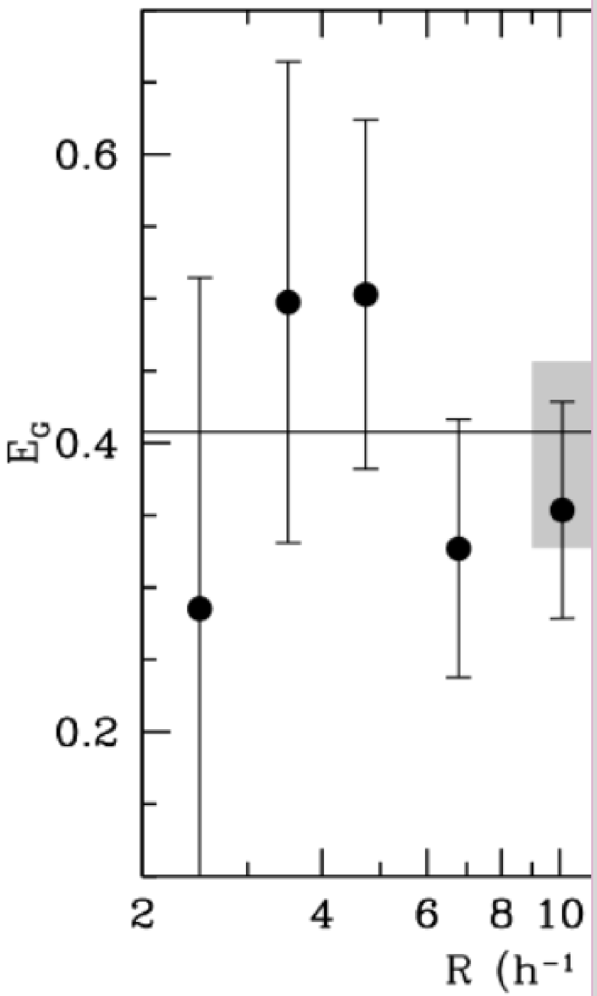
Credit: Masayuki Tanaka (IPMU)

- HSC data will add surrounding galaxies around each LRGs of BOSS (already started from 2010 – 2015?); *Note DES does not have BOSS spectra*
- Spectroscopic redshift confirmation of HSC-found clusters (up to z~0.7)
- LRGs or HSC-clusters-background galaxy lensing
- LRG properties in different environments (galaxy and DM overdensities)

Reyes et al., Nature, 10

$$E_G \equiv \frac{1}{\beta} \frac{\langle \text{lensing} \rangle (R)}{\langle \text{galaxy - galaxy} \rangle (R)} \rightarrow \frac{d \ln D}{d \ln a}$$

- Reyes et al. used the SDSS data to constrain the growth rate on large



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Nature **464**, 172-173 (11 March 2010) | doi:10.1038/464172a; Published online 10 March 2010

Cosmology: Gravity tested on cosmic scales

J. Anthony Tyson[1]

Einstein's theory of general relativity has been tested — and confirmed — on scales far beyond those of our Solar System. But the results don't exclude all alternative theories of gravity.

Top

Our understanding of the physics that underlies the dynamical evolution of the Universe and the development of cosmic structure is driven by astronomical observations. Historically, measurements on galaxy and larger cosmological scales conflicted with predictions based on a cosmological model that combined Albert Einstein's theory of gravity (general relativity) and the standard model of particle physics.

1. J. Anthony Tyson is in the Department of Physics, University of California, Davis, One Shields Avenue, Davis, California 95616, USA.
Email: tyson@physics.ucdavis.edu

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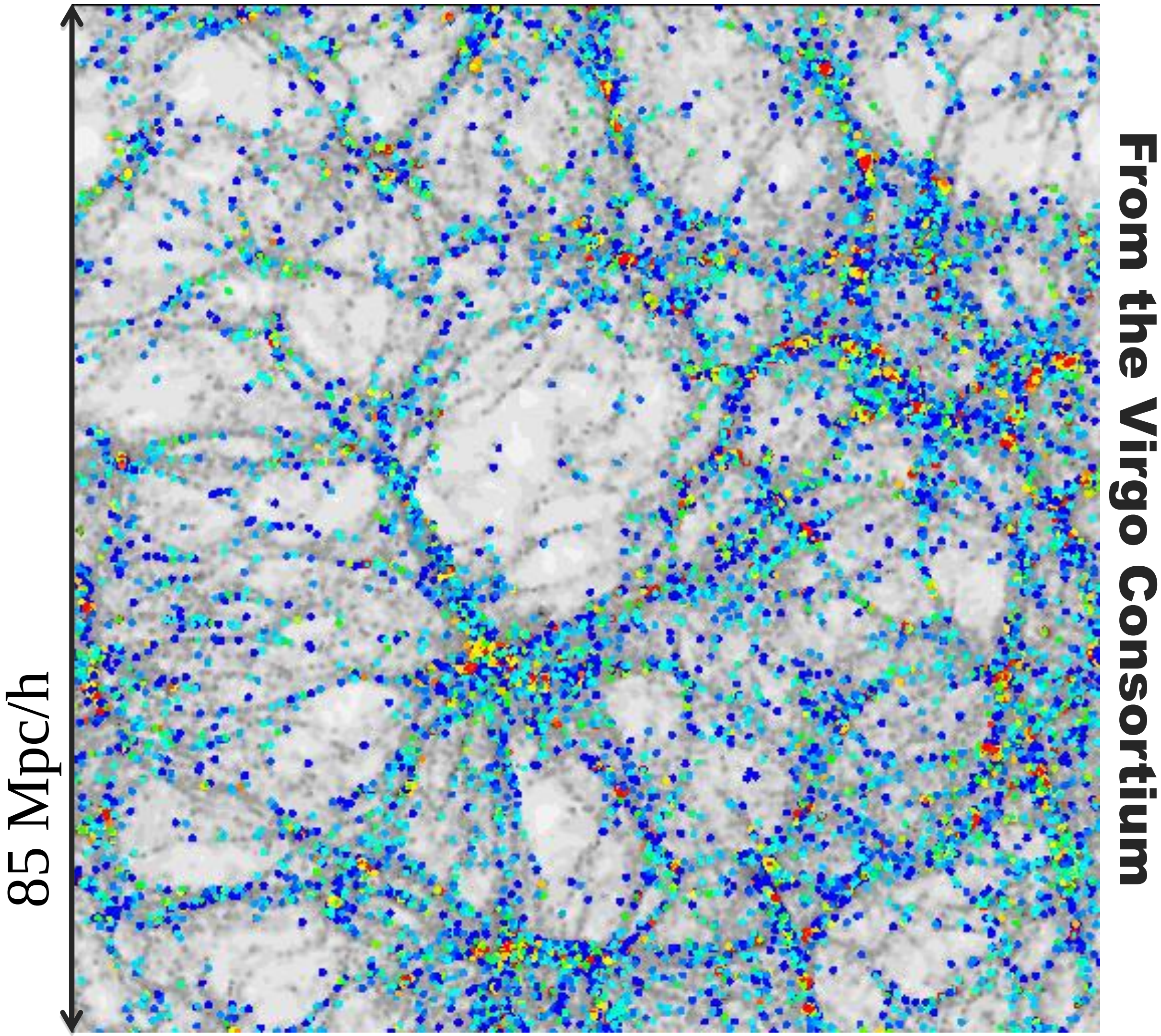
Redshfit range of SuMIRe PFS survey



- Large-scale structure is driven by dark matter distribution
- Galaxies are "*biased*" tracers of DM distribution

$$\delta_g = b\delta_m$$

- SuMIRe needs to probe the Universe at higher redshifts than done by BOSS (0.2<z<0.7)

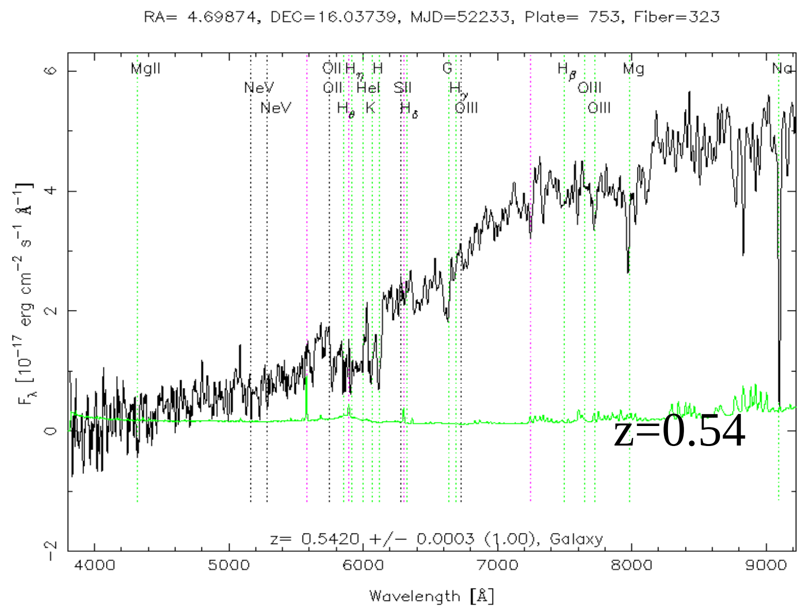
Redshift range (contd.)

- Targeted spectral features
  - Early-type galaxies: 4000A break + absorption lines
  - Emission-line galaxies: [OII] 3727A
- For optical wavelength coverage (up to 1000A), the targeted redshift ranges would be 0.6<z<1.7

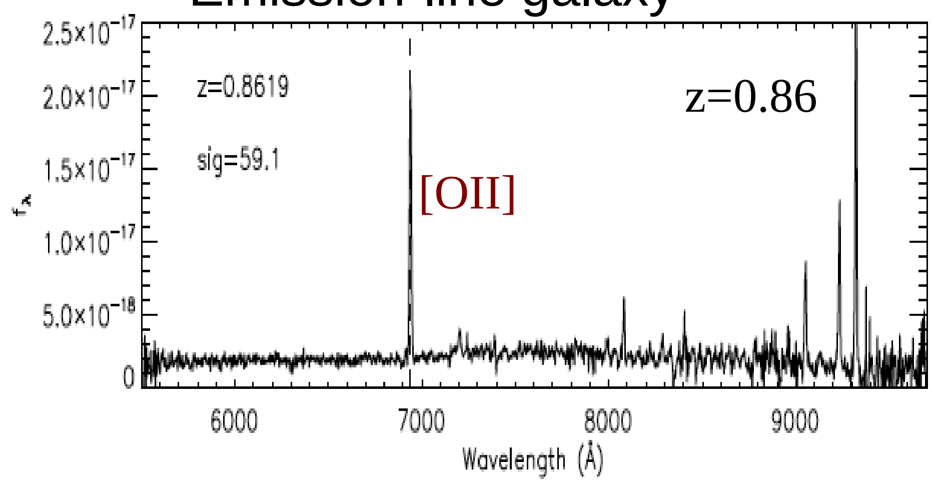
wavelength coverage: 600<λ<1000nm

- Only the red-side spectrograph needed (λ/pix~1A for 4000 pixels)
- Such a high-redshift survey in optical band can fully utilize the Subaru capability

Early-type galaxy



Emission-line galaxy



Number of fibers for SuMIRe PFS

- The cosmological precision of galaxy redshift survey is determined by the measurement accuracies of galaxy clustering
- The measurement errors of P_g(k): sampling variance due to a finite volume coverage and shot noise due to a finite number of galaxies

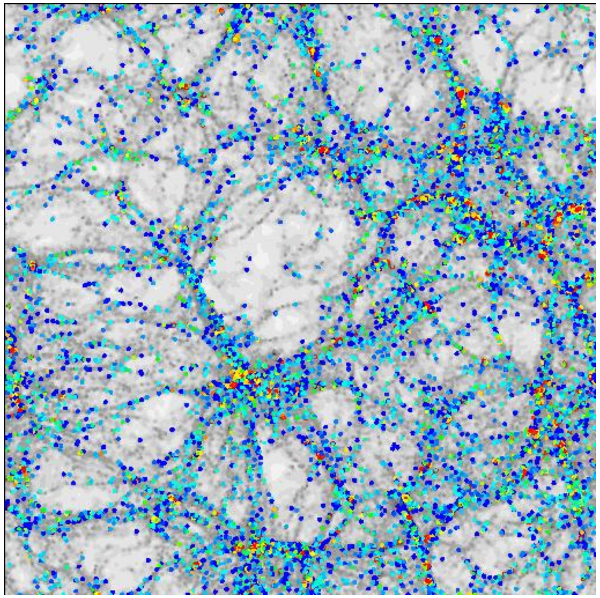
$$\left[\frac{\sigma(P_g)}{P_g(k)}\right]^2 = \frac{2}{N_k}\left[1+\frac{1}{\bar{n}_g P_g(k)}\right]^2$$

$$N_k \equiv \frac{4\pi k^2 \Delta k}{(2\pi/L)^3} = \frac{k^2\Delta k}{2\pi^2} V_{\rm survey}$$

$V_{\rm survey}$: survey volume

$P_g(k) \approx b^2 P_m(k)$ in the linear regime

$\bar{n}_g$: mean number density of galaxie



- To have the better accuracies, we need a wider survey area, a denser density of target galaxies, or target galaxies with higher biases
- A reasonable strategy for a choice of target galaxies: $n_g P_g$~ a few

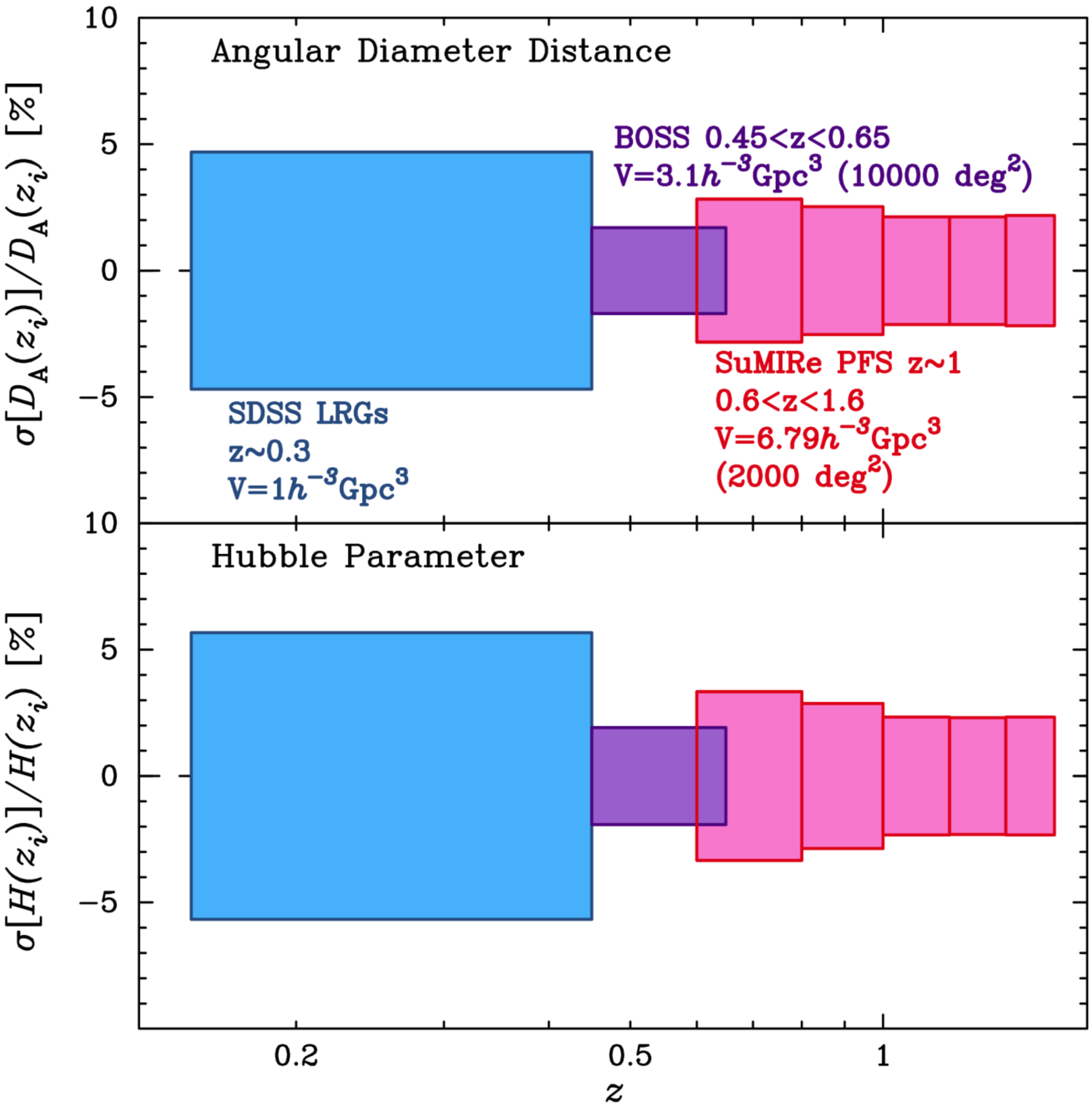
Number of fibers (contd.)

Redshift	Volume (h^{-3} Gpc^3)	# of galaxies (per field)	Number density (h^3 Mpc^{-3})	bias	nP @k=0.1hMpc^{-1}
0.6<z<0.8	0.8	212	3×10^{-4}	1.5	1.4
0.8<z<1.0	1.1	292	3×10^{-4}	1.5	1.2
1.0<z<1.2	1.4	495	4×10^{-4}	1.5	1.3
1.2<z<1.4	1.6	565	4×10^{-4}	1.5	1.2
1.4<z<1.6	1.7	600	4×10^{-4}	1.5	1.0

Total # of target galaxies per 1.8 sq. degrees=2164

- Target galaxies
  - For z<1.4, early-type galaxies favored (LRGs; b_LRG~2, ng~3×10^{-4} h^3Mpc^{-3})
  - For z>1.4, emission-line galaxies (OII) (b~1.2-1.5 in Coil et al. for the DEEP2 survey)
- zCOSMOS bright survey (I<22.5) implies
  - 1203 galaxies available (0.8<z<1, S/N>5) ← 292 required for SuMIRe
  - 1121 gals implied (1<z<1.4, red + emission-line gals with S/N>3) ← 1060 required for SuMIRe
  - Note: the VLT VIMOS does not use red-sensitive CCDs (see John's talk)
- For z>1.4, few study has been done: A narrow-band [OII] imaging survey (Hayashi et al. 10) implies ng~2×10^{-3} for z_AB<24, in a cluster region
- About 2200 fibers (100% success rate assumed) needed
- If one 15-30min exposure per field, it requires ~70 clear Subaru nights for 2000 deg^2

Forecasted the SuMIRe BAO experiment



A few % accuracies of H(z) and D_A(z) achieved for each redshift slice

Complementary to BOSS

SuMIRe: HSC+PFS

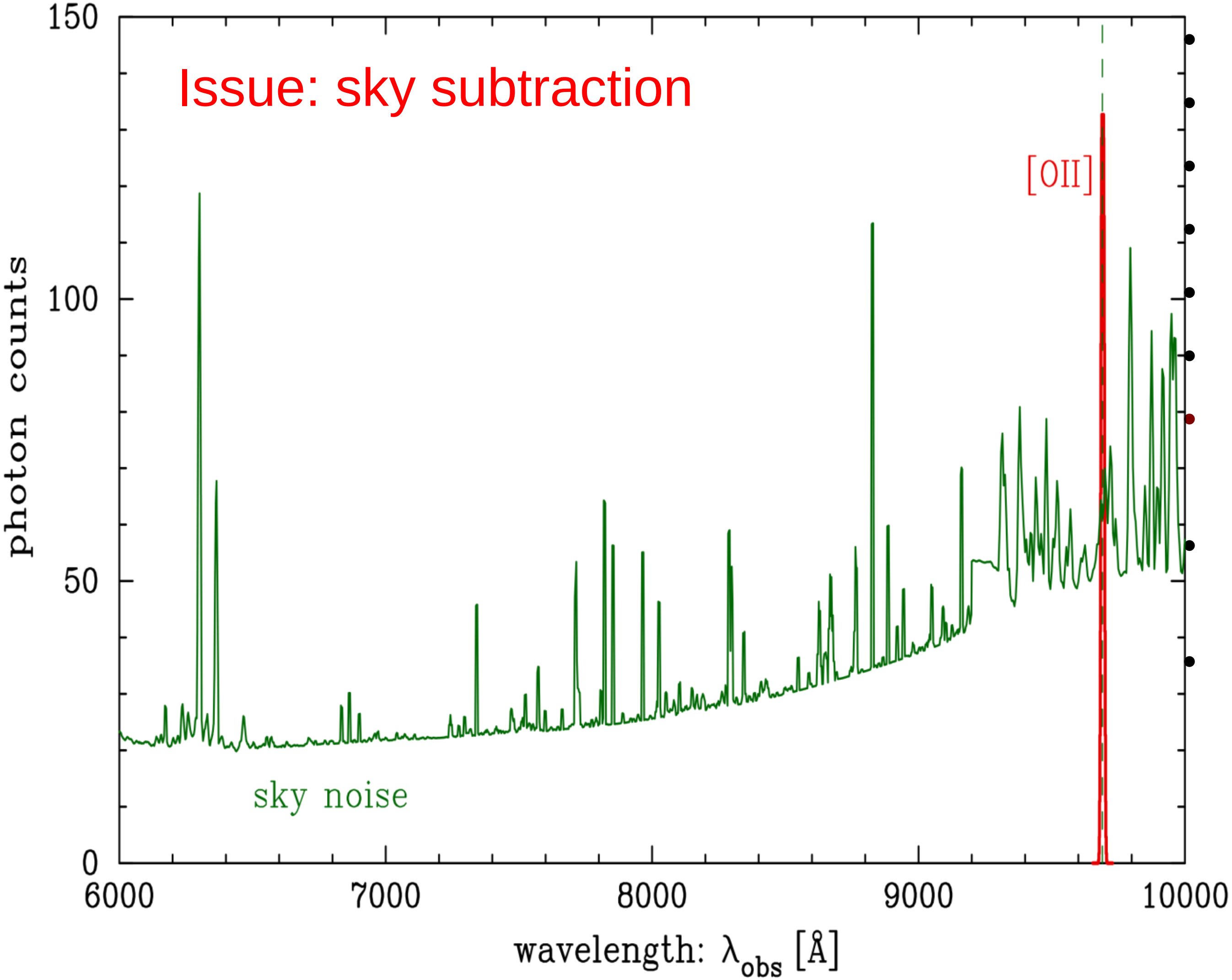
	BOSS	PFS (+BOSS)	SuMIRe (HSC+PFS+BOSS)
Redshift	$0.2<z<0.65$	$0.6<z<1.6$	$0<z<1.6$
Sky coverage	10000 deg^2	2000 deg^2	2000 deg^2
σ(w_constant)	0.083	0.046	0.028
DETF FoM	13	33	217
Growth: σ(γ)	-	-	0.032
σ(Σm_nu) [eV]	-	-	~0.06eV
σ(f_NL)	-	-	~5

$$G(a) \propto \exp\left(\int^a d\ln a' \left[\Omega_{\rm m}^{\gamma}(a') - 1\right]\right)$$ (GR: $\gamma \approx 0.55$)

- Planck priors assumed
- SuMIRe PFS: BAO alone (geometrical test alone)
- SuMIRe HSC+PFS: weak lensing + cluster counts + BAO + galaxy clustering (assuming that degeneracies with galaxy bias are broken): but the estimate above is somewhat conservative
  - Allows to constrain gravity theory on cosmological scales, neutrino masses and primordial non-Gaussianity

Requirements on the PFS spec

Simulating a galaxy spectrum….

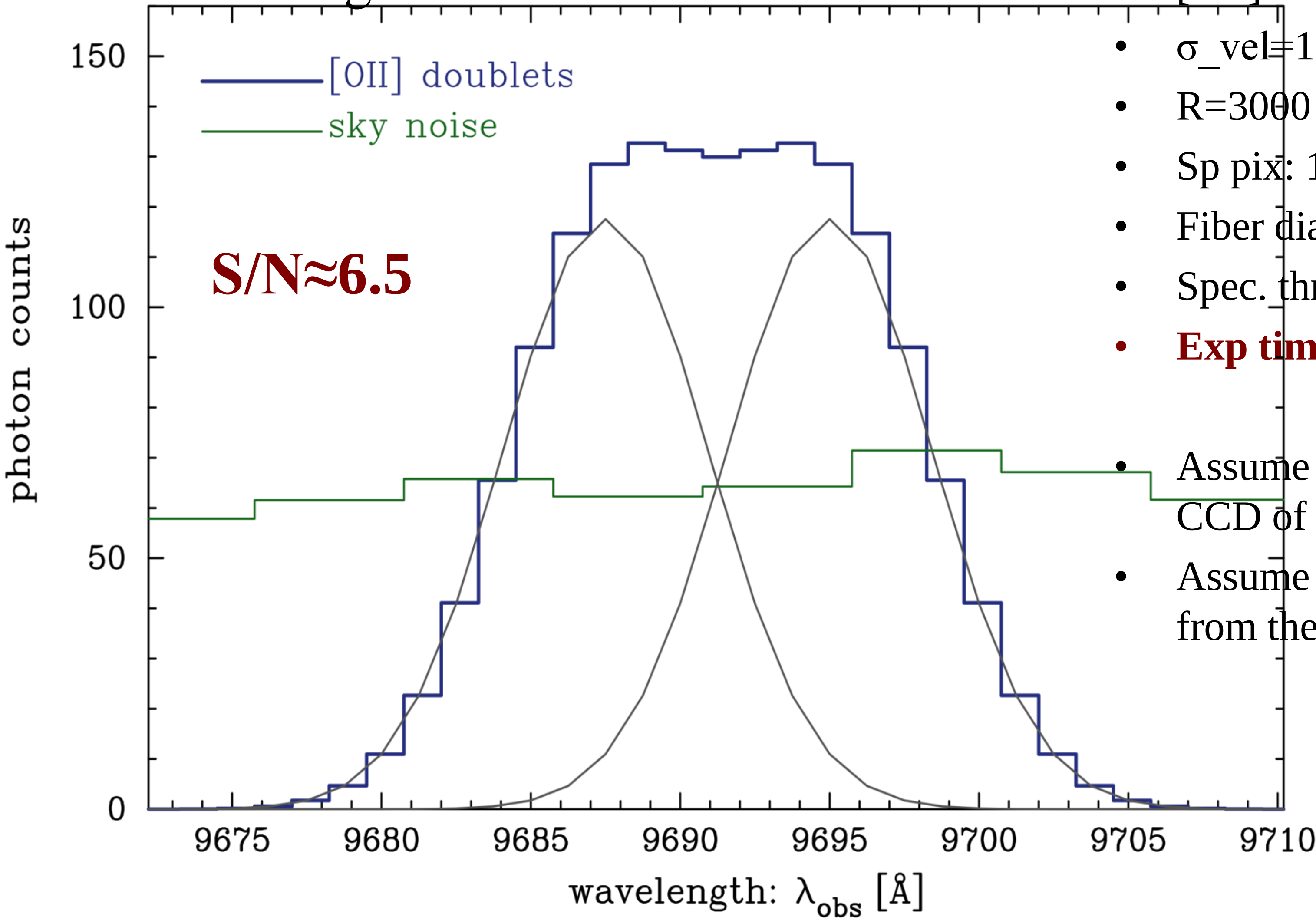


- Redshift: z=1.6
- [OII] flux: 5e-17 erg/s/cm^2
- σ_vel=100 km/s
- R=3000
- Sp pix: 1.25A/pix
- Fiber diameter: 1.2”
- Spec. throughput: 0.2
- **Exp time: 15min**

- Assume the red-sensitive CCD of Suprime-Cam
- Assume sky model taken from the Gemini website

Simulating [OII] line

Zooming in…



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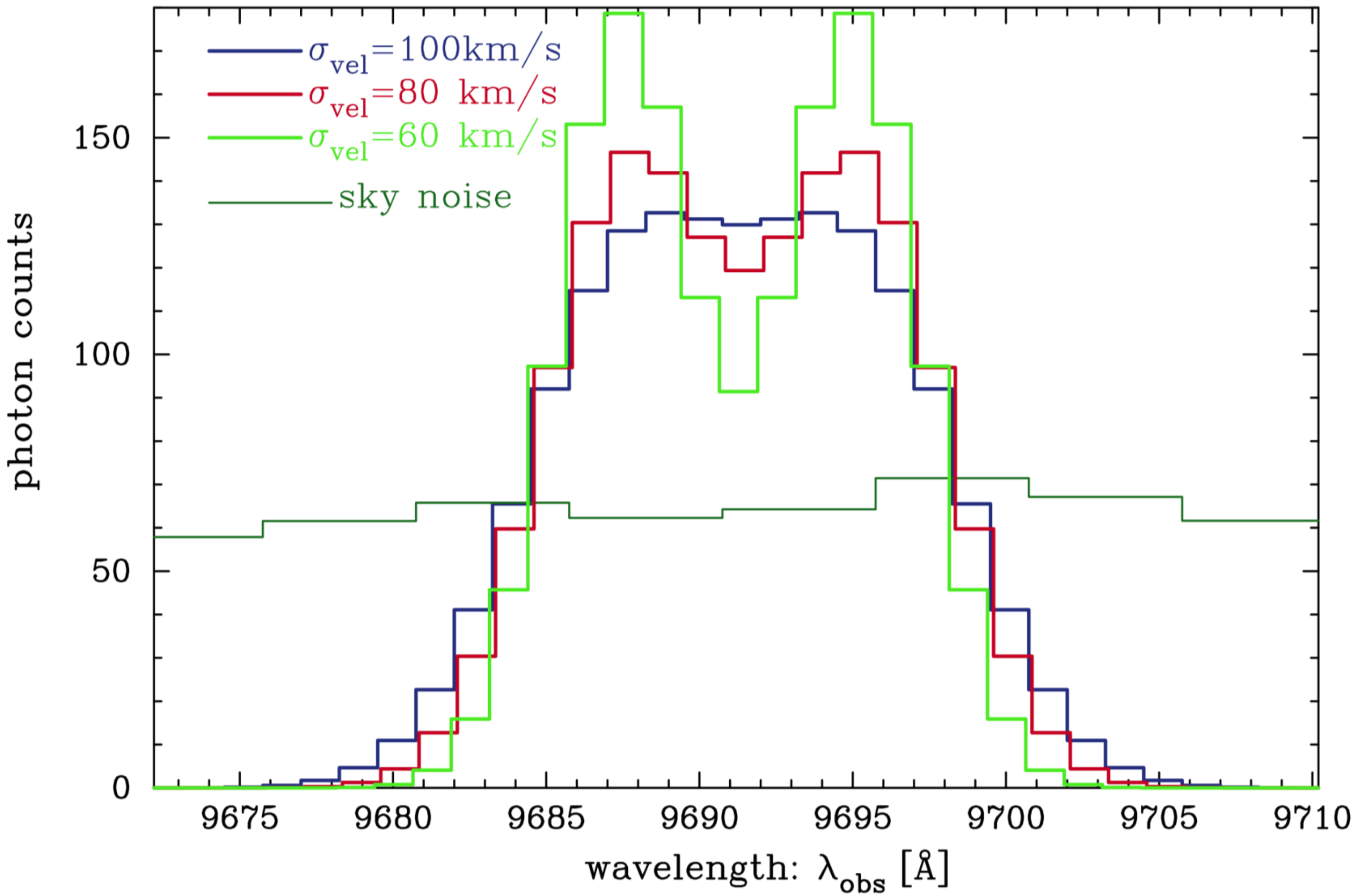
- Fiber diameter: 1.2’’
- Spec. throughput: 0.2
- **Exp time: 15min**

- Assume the red-sensitive CCD of Suprime-Cam
- Assume sky model taken from the Gemini website

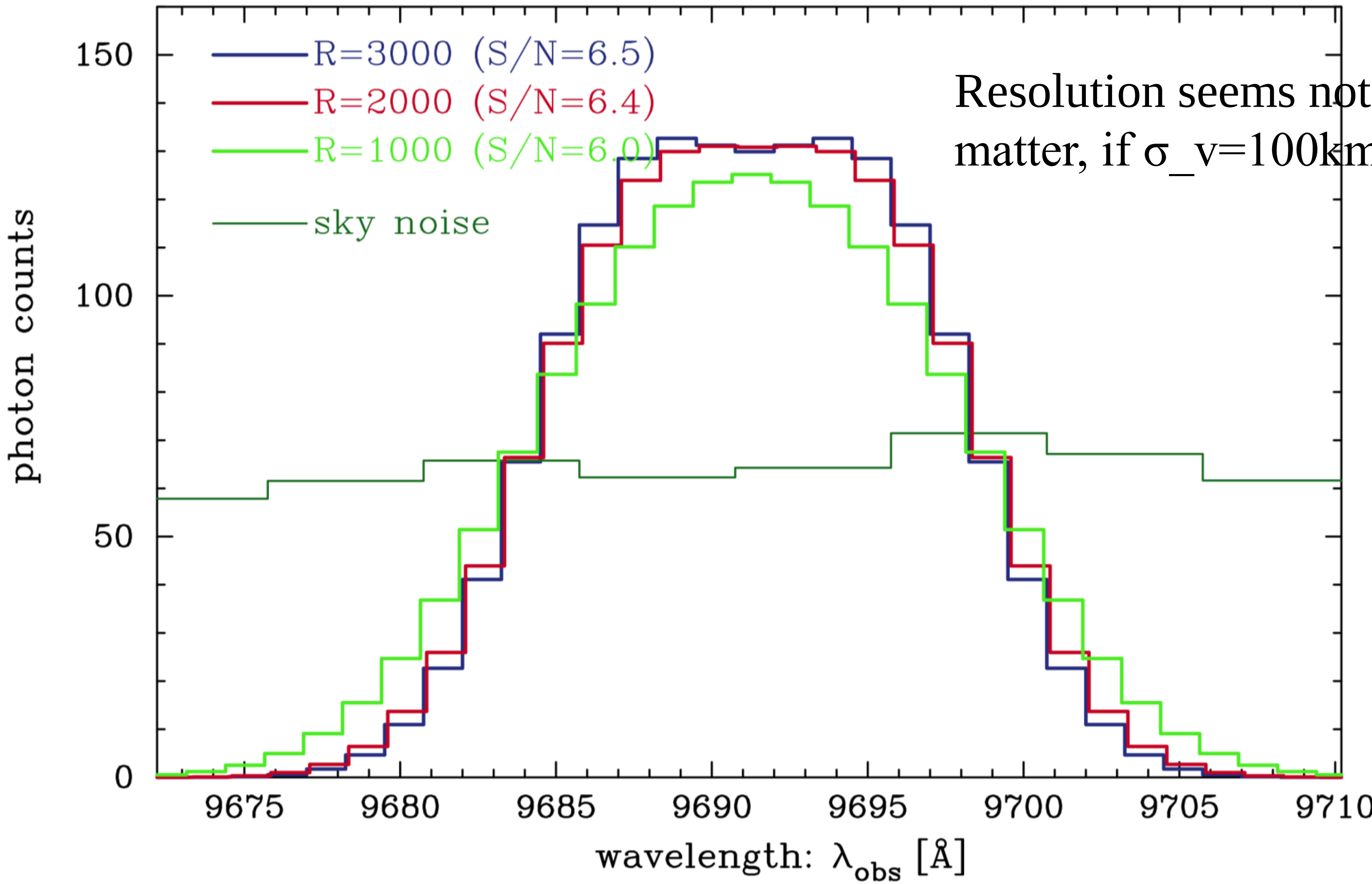
Simulating [OII] line (contd.)

- Line profile/strength also depends on properties of emission-line galaxies (its kinematics, size, …)



Simulating [OII] line (contd.)

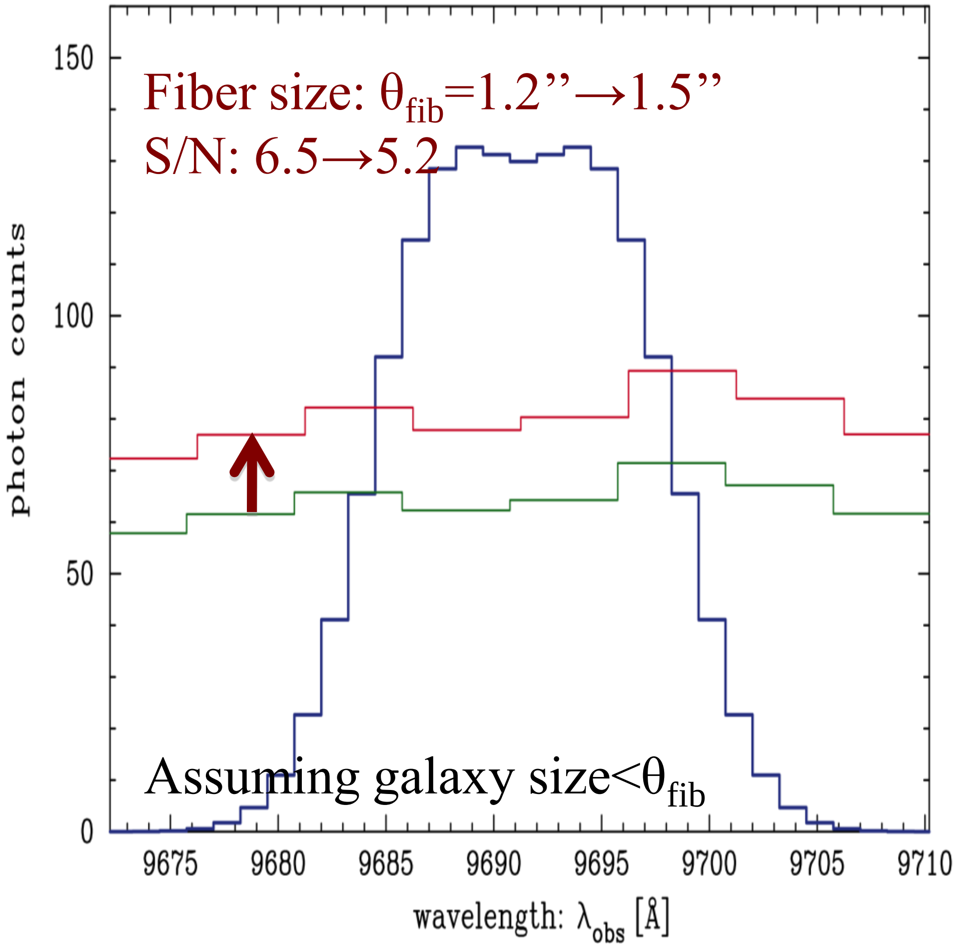
- Line strength depends on the PFS spec



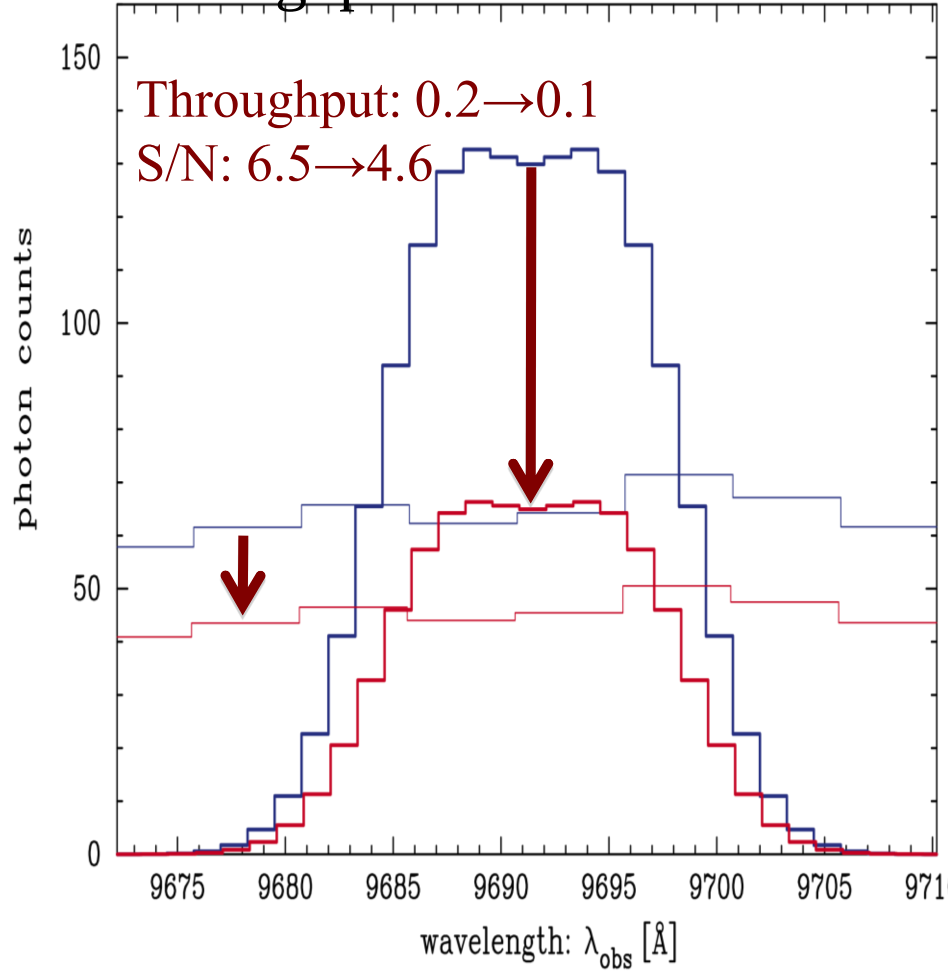
Resolution seems not so matter, if σ_v=100km/s

Simulating [OII] line (contd.)

Fiber size



Throughput



Target selection of [OII]-line galaxies

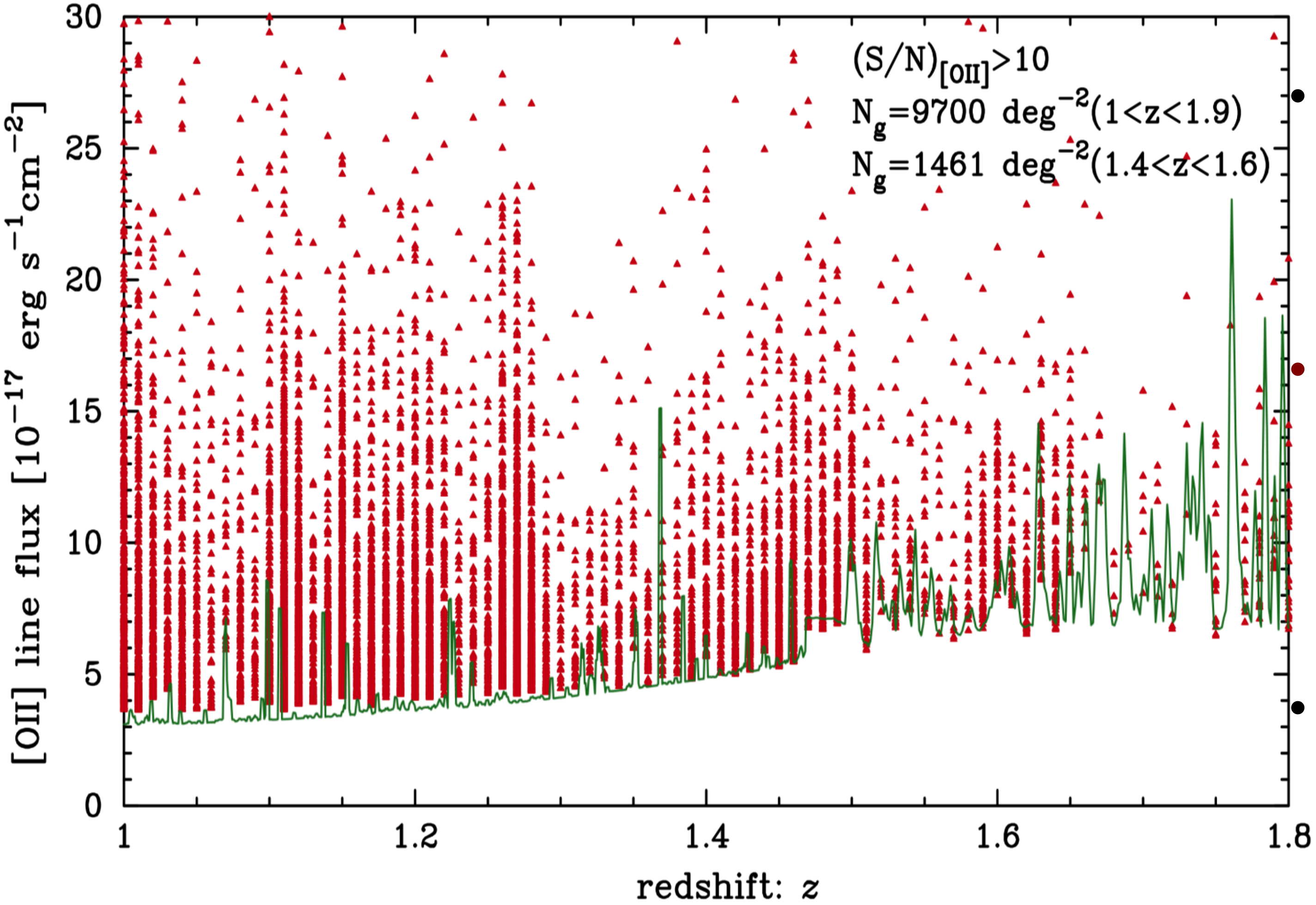
- Issues to be carefully studied are
  - A sufficient number of [OII]-line galaxies can be observed with a reasonable exposure (say, <30min) ?
    - At $z<1$, no problem as shown in COSMOS
  - How to identify target galaxies to observe with PFS?
    - BOSS LRG selection is about *95%* success rate
    - HSC multi-color is sufficient to efficiently identify the galaxies?
    - Or other datasets such as VIKING NIR data are needed?
- We are studying these issues using the mock catalog constructed based on the COSMOS, UDF, GOODS, VVDS data (kindly made available to us by S. Jouvel and J.-P. Kneib)
  - Simulated with HSC filter set (grizy)

Designing Future Dark Energy Space Missions: I. Building Realistic Galaxy Spectro-Photometric Catalogs and their first applications

S. Jouvel[1], J-P. Kneib[1], O. Ilbert[3,1], G. Bernstein[2], S. Arnouts[1,4], T. Dahlen[5], A. Ealet[9,1], B. Milliard[1], H. Aussel[7], P. Capak[6], A. Koekemoer[5], V. Le Brun[1], H. McCracken[8], M. Salvato[6], and N. Scoville[6]

Target selection

Q: are a sufficient number of galaxies available?
A: seems available

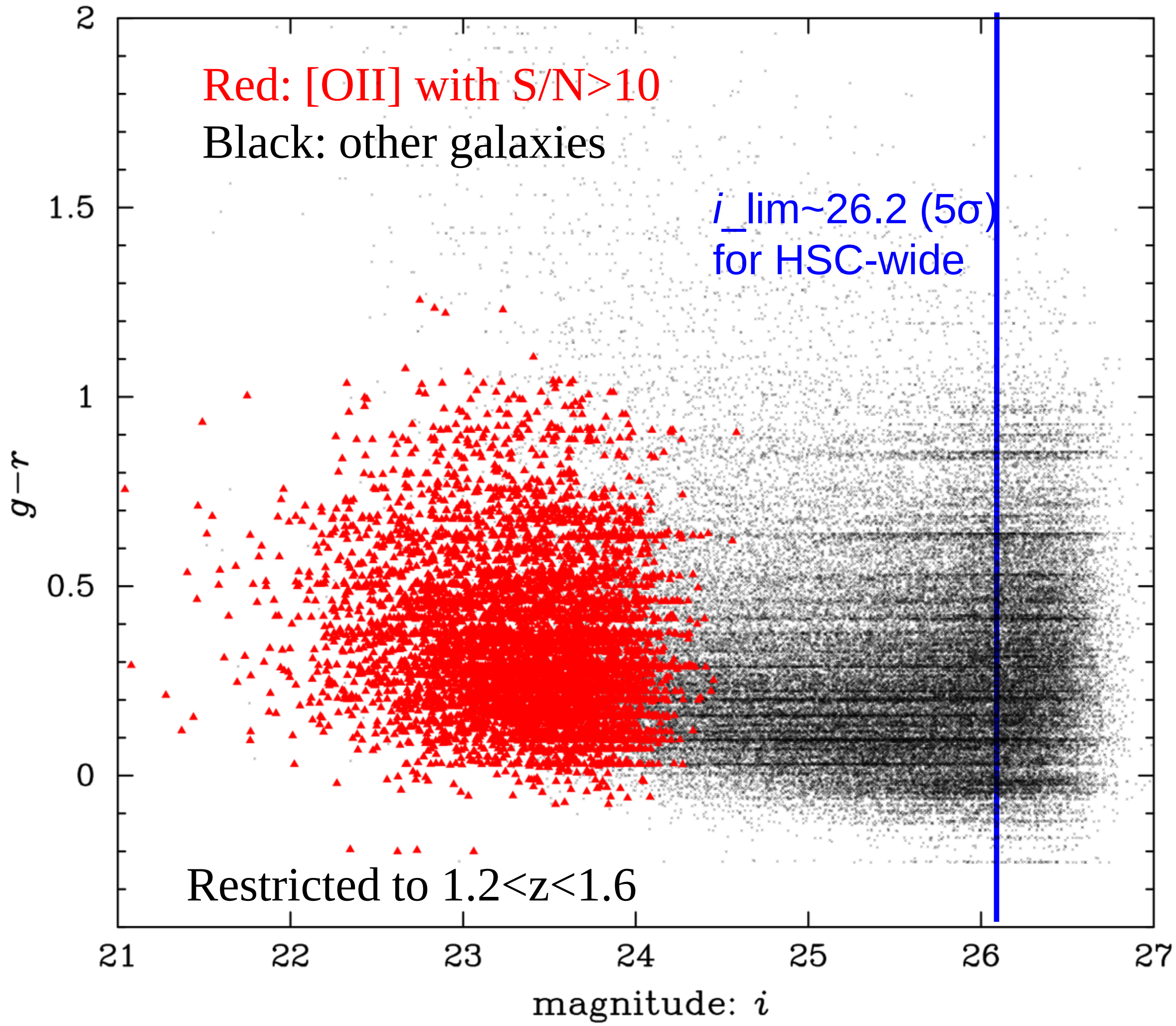


- **15min exp.**
- Over 1.4<z<1.6, 2581 gals are available per PFS FoV
- Looks sufficient compared to the BAO requirement (600 gals)
- **About 100 nights seem needed to cover 2000 deg^2** (note it depends on the success rate)
- The next issue: a uniform selection of galaxies in redshift space

Target selection (contd.)

Q: How can we pick up target galaxies? HSC is good enough?

A: Not sure yet, still need a more detailed study



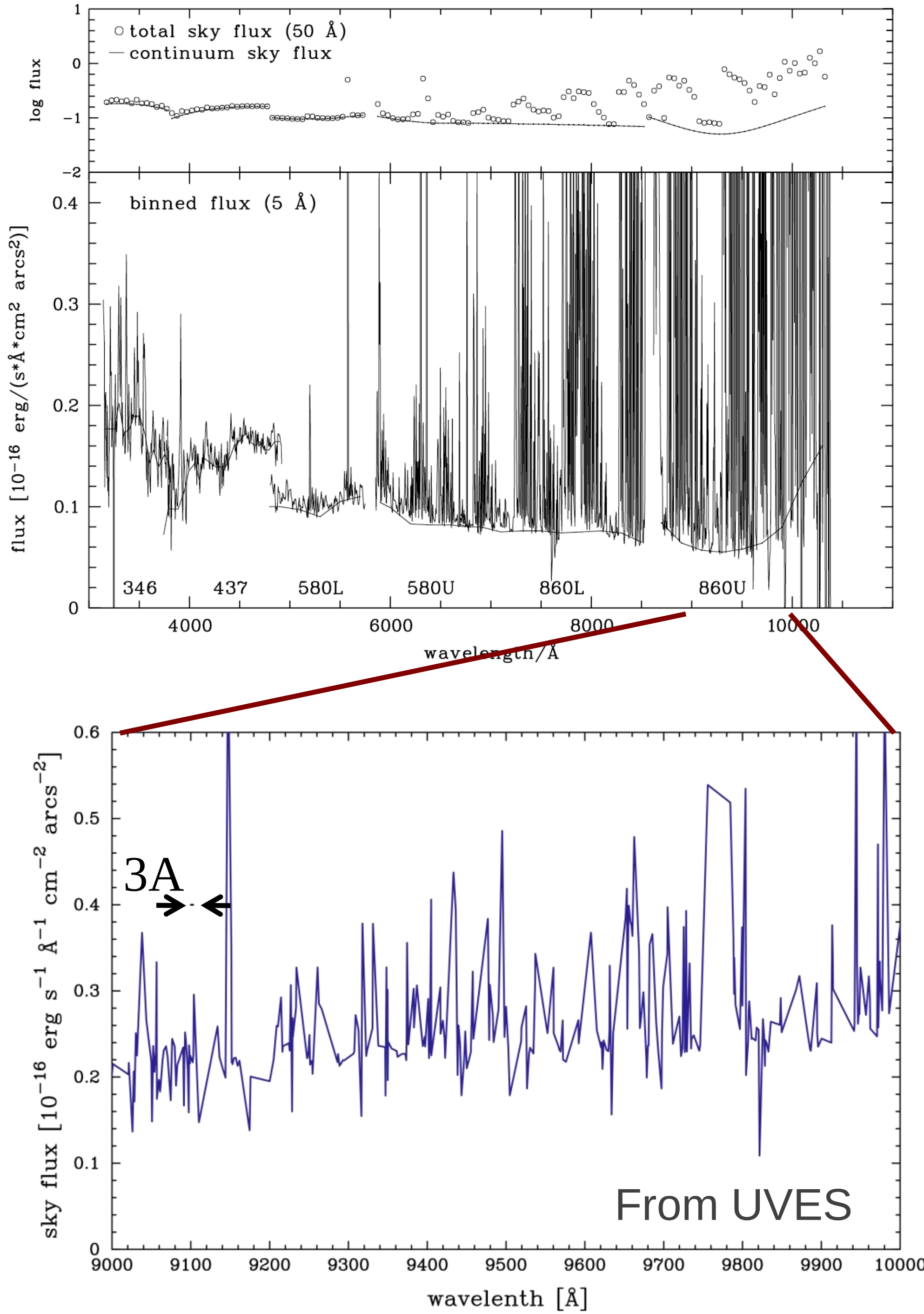
- The plot shows one example in magnitude-color diagram
- [OII] galaxies tend to be in bluer than galaxies w/o strong [OII] emission
- But also a significant overlap between these two populations (about 35% contamination)
- Need to study these with actual data (COSMOS, DEEP2)

Summary and Discussion

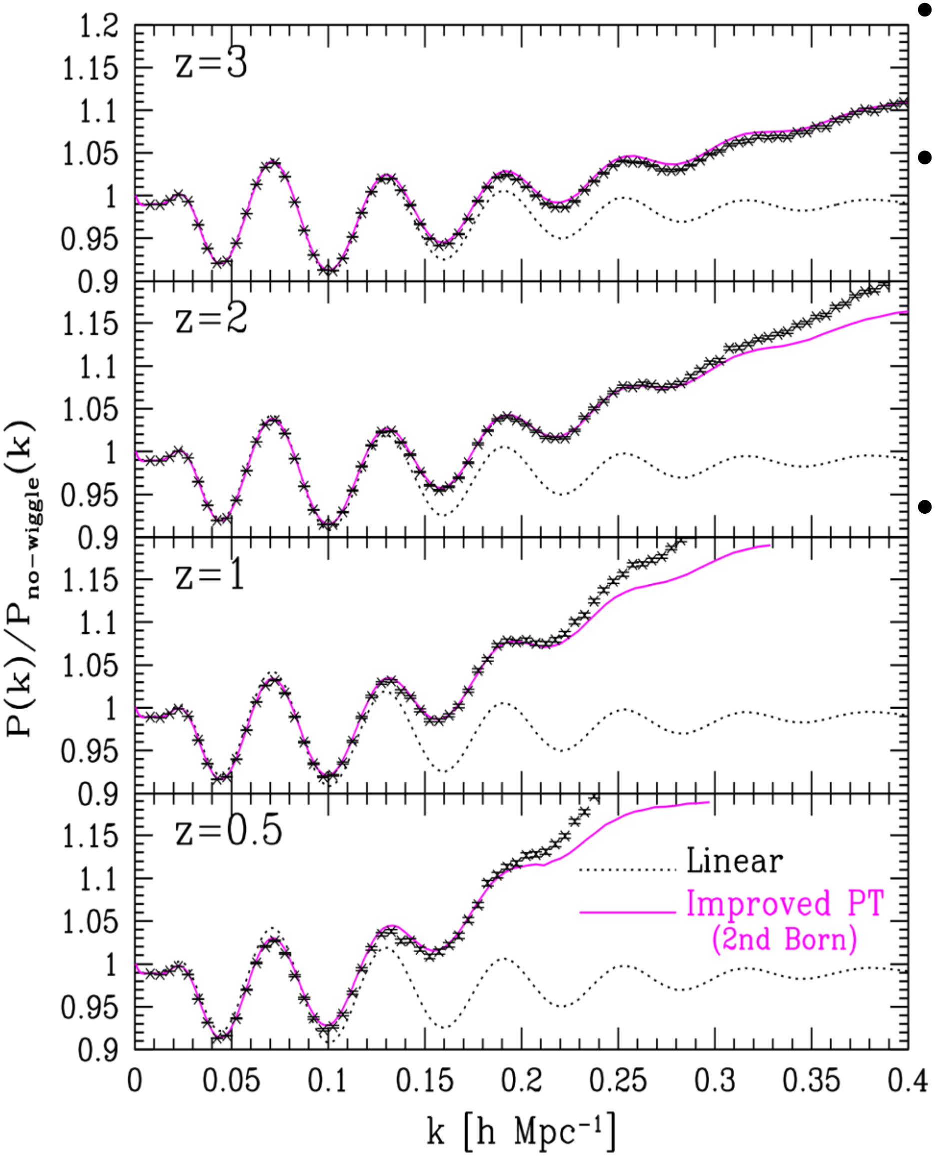
- SuMIRe HSC/PFS fully utilize unique capabilities of Subaru Telescope; probe the universe over wide range $0<z<1.6$
  - Also unique for other science cases (galaxy evolution and GA)
- Various dark energy experiments available: HSC WL, galaxy clusters, BAO, galaxy clustering, and SNe
- Combining various methods allows a robust test of dark energy properties as well as gravity theory on cosmological scales, with various systematic errors being calibrated
- BAO requirements: 600-1000A, >2200 fibers, R~3000
- About 100 nights are needed for PFS BAO survey (to cover 2000 deg^2)
- A more careful study needed: galaxy selection algorithms (HSC photo-z), the required throughput, the exposure time per field, the survey strategy

Spectral resolution

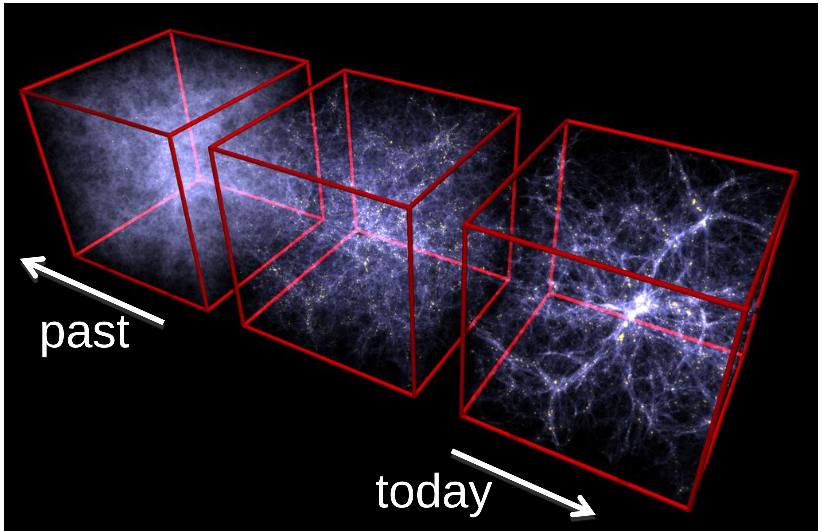
- At wavelengths longer than 7000A, sky emissions are high
- A resolution of R~3000 (Δλ=3A @ λ=9000A) would be needed to discriminate [OII] lines from sky emission lines
- A signal-to-noise ratio for detecting an emission line improves with R as S/N~R^1/2
  - zCOSMOS (R~600): R~3000 gives a factor 2 gain in S/N compared to zCOSMOS
- How sky subtraction can be done? Nod-and-Shuffle needed? If so, this raises the instrumentation cost?



Advantage of high-redshift survey



- Nonlinearities are smaller at higher redshifts
- Various efforts have been made in refining the theoretical models: N-body, analytic model, and so on (Crocce & Scoccimarro 06, 07,; Matsubara 08; Taruya et al. 09, 10; Saito et al. 09)
- A factor 2 gain in k_max is equivalent to a factor 8 gain in survey area



Filter design (HSC)