Subaru Measurements of Images and Redshifts (SuMIRe): HSC and PFS

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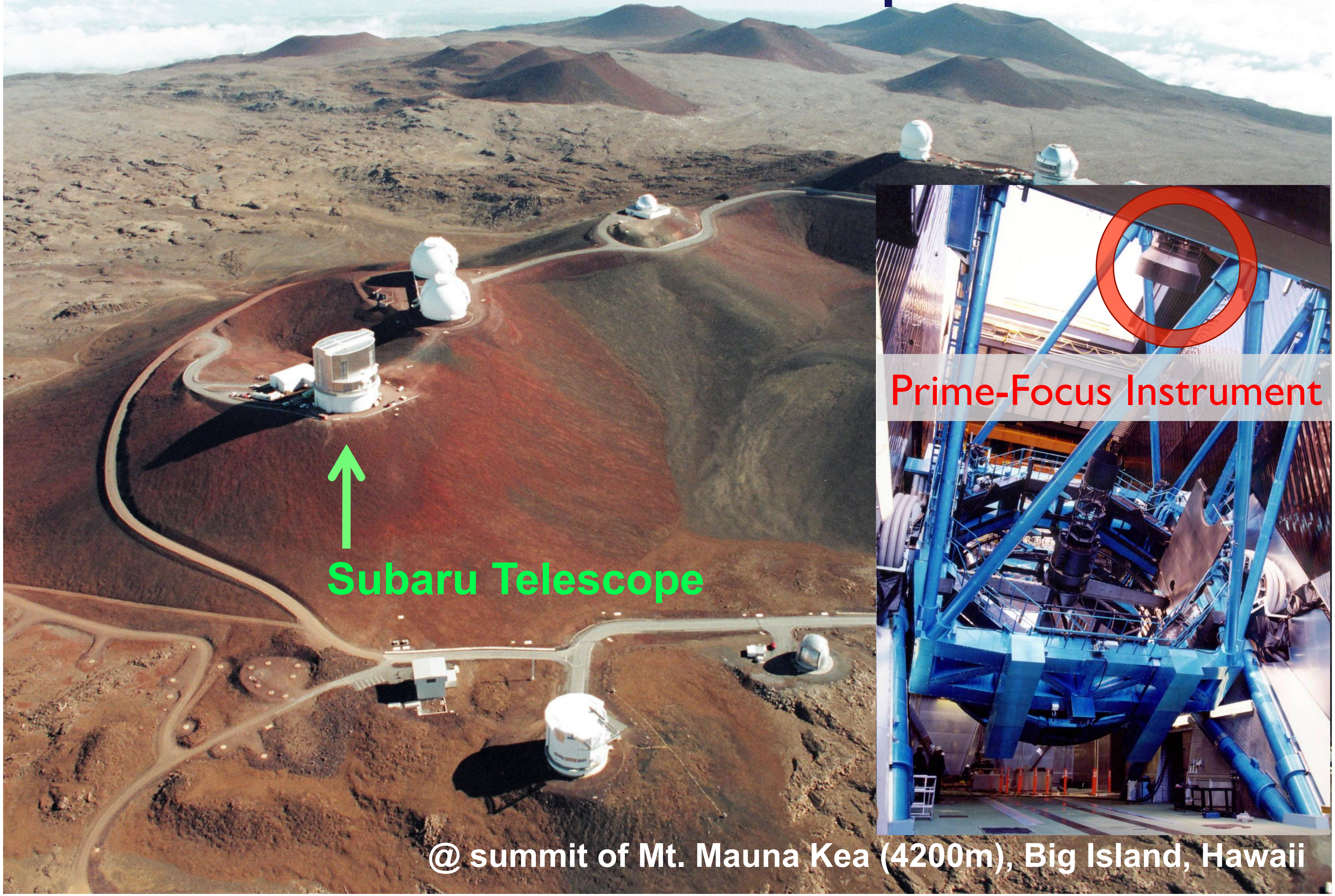
wpi

@The Return of de Sitter II, Munich, Oct 2013

Subaru Telescope



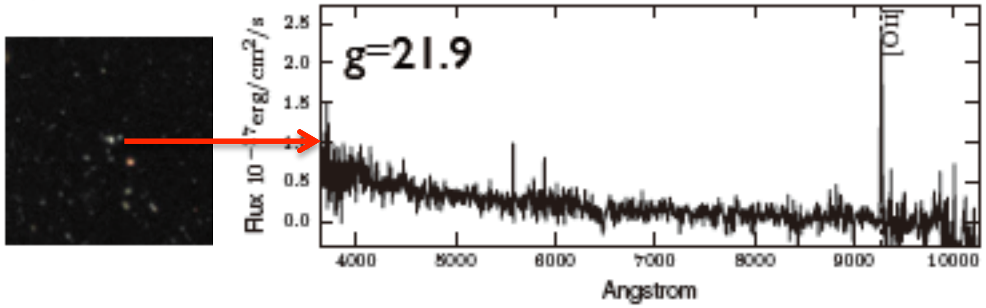
Galaxy survey; imaging vs. spectroscopy

Imaging

- Find objects
  - Stars, galaxies, galaxy clusters
- Measure the image shape of each object → *weak gravitational lensing*
- For cosmology purpose
  - *Pros*: many galaxies, a reconstruction of dark matter distribution
  - *Cons*: 2D information, limited redshift info. (photo-z at best)

Spectroscopy

- Measure the photon-energy spectrum of *target* object
- Distance to the object can be known → *3D clustering analysis*
- For cosmology
  - *Pros*: more fluctuation modes in 3D than in 2D
  - *Cons*: need the pre-imaging data for targeting; observationally more expensive (or less galaxies)



Impact of *unbiased* wide-area imaging/spectroscopic survey

- Examples; SDSS, COSMOS
- Legacy data set

The table shows scientific impacts of each optical telescope and survey, based on the stats of 2008-year papers published in journals

SDSS(2.5m) has brought more impacts than HST or 8m Tels

Trimble & Ceja (2010)

Table 6: Optical papers and citations by telescope/observatory.

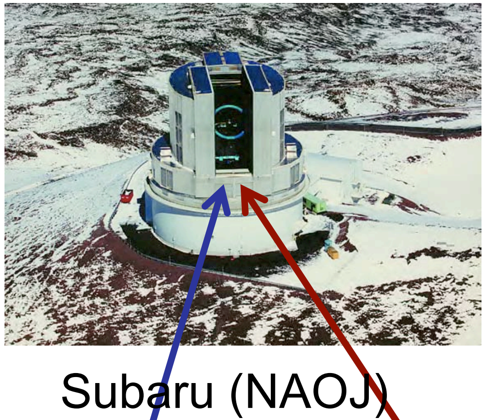
Telescope	Papers[1]	Citat.[1]	C/P[1]	Papers[2]
HST	206.6	765	3.70	391.5
VLT	139.1	452	3.25	290.6
Keck	59.6	333	5.59	121.5
CFHT	38.0	152	4.00	69.6
Gemini	34.3	108	3.15	63.7
Subaru	33.0	138	4.18	70.0
AAT	23.0	83	3.61	42.4
WHT	19.5	55	2.82	34.7
IRTF	16.9	46	2.72	31.2
UKIRT	15.8	54	3.42	34.3
Okayama 1.88m	9.9	30	3.03	17.0
U.Hi. 2.2m	5.1	17	3.33	10.4
HET	5.0	35	7.00	8.9
LBT	4.8	18	3.75	8.2
MDM 2.4m	4.6	17	3.70	7.0
APO 3.5m	4.5	16	3.56	9.5
Lyot (PduM)	3.0	5	1.67	8.9

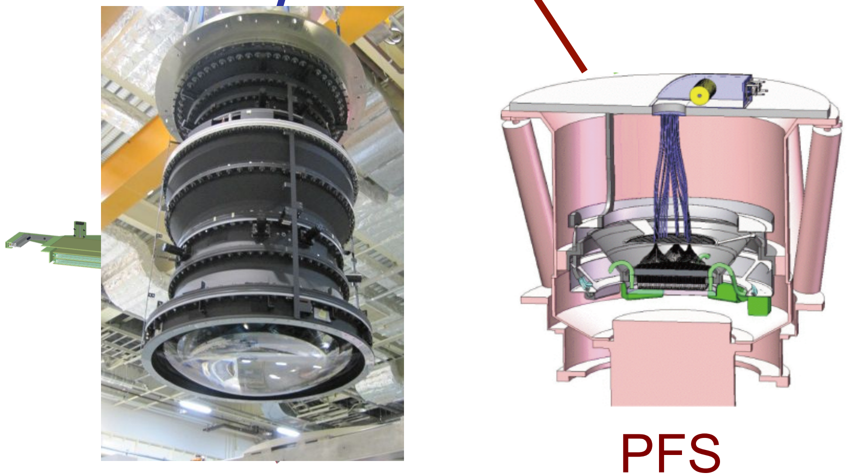
abridged …

Telescope	Papers[1]	Citat.[1]	C/P[1]	Papers[2]
SDSS	133.0	863	6.49	336.1
2MASS	136.2	479	3.52	275.8
48" Schmidts	45.8	95	2.07	100.7
MACHO, ASAS, etc.	29.1	123	4.23	47.1
TOTAL OPTICAL	1233.8	4764	3.86	2530.4

SuMIRe = Subaru Measurement of Images and Redshifts

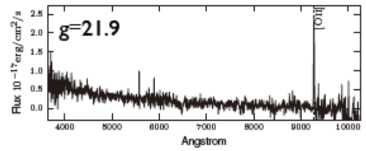
- IPMU director Hitoshi Murayama funded (~ $32M) by the Cabinet in Mar 2009, as one of the stimulus package programs
- Build *wide-field* camera (Hyper SuprimeCam) and *wide-field* multi-object spectrograph (Prime Focus Spectrograph) for the Subaru Telescope (8.2m)
- Explore the fate of our Universe: dark matter, dark energy
- Keep the Subaru Telescope a world-leading telescope in the TMT era
- Precise images of 1B galaxies
- Measure distances of 1M galaxies

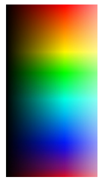




PFS

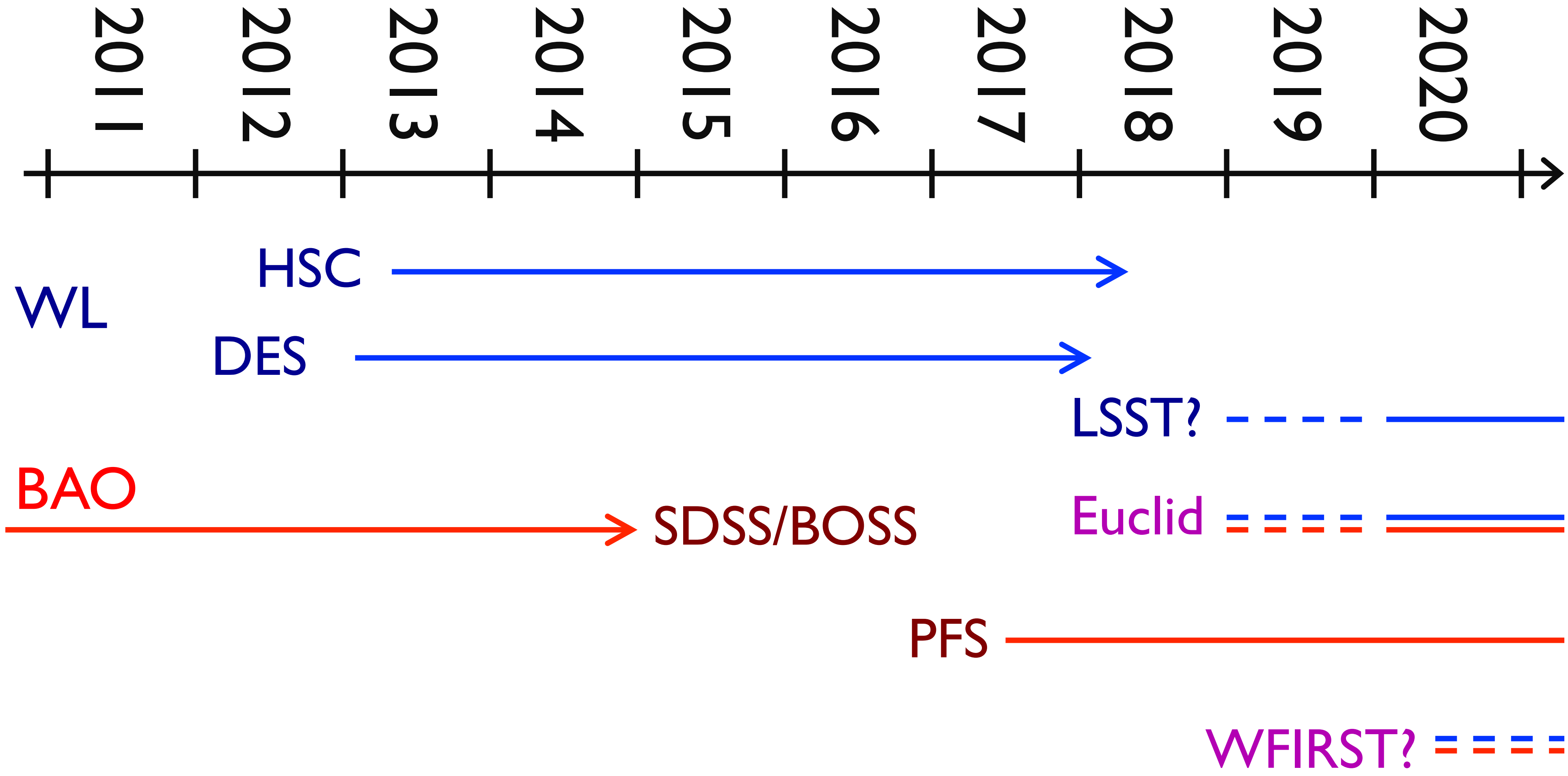
HSC






Survey astronomy/ Cosmology
SDSS III
BOSS (2009-)
KIDS (2012-)
Euclid (2021)
HETDEX (2014-)
HETDEX
Hobby-Eberly Telescope Dark Energy Experiment
DESI (2017?-)
A Proposal to NOAO for the
BigBOSS Experiment
at Kitt Peak National Observatory
October 1, 2010
DARK ENERGY SURVEY
DES (2012-)
LSST
Large Synoptic Survey Telescope
eBOSS
WFIRST (2020?-)
LSST (2020?-)
WFIRST
Wide-Field Infrared Survey Telescope

Time line (DE experiments)

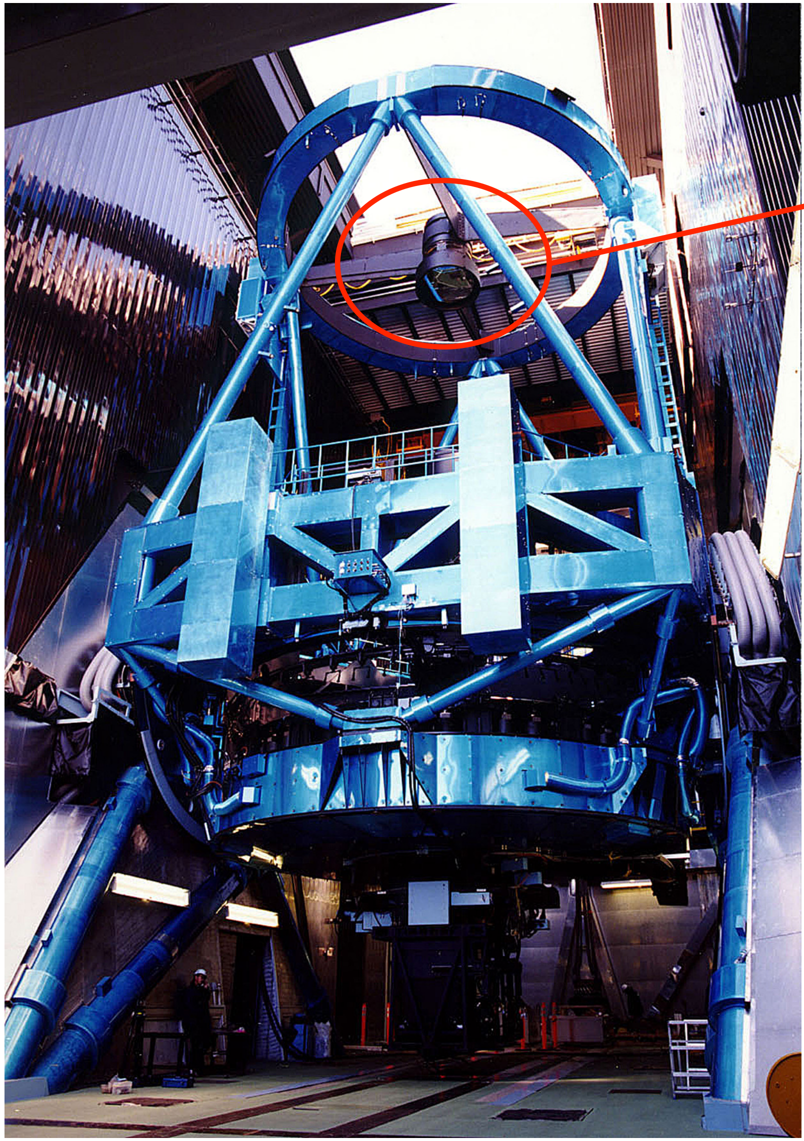


We are in a good position!

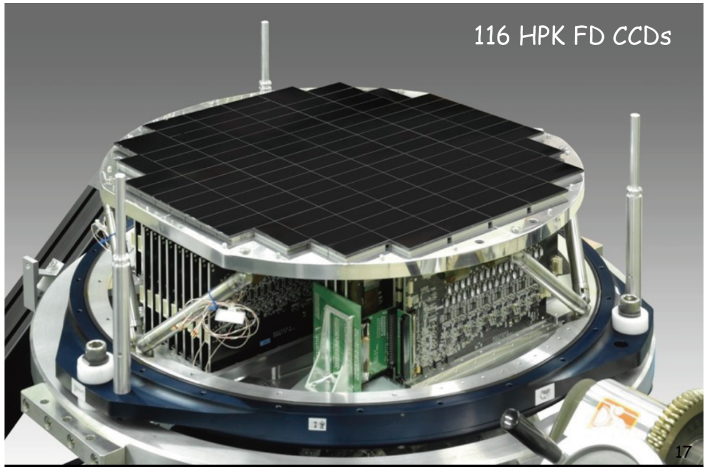
Hyper Suprime-Cam (HSC)

- Upgrade the prime focus camera
- Funded, started since 2006: total cost ~$50M
- International collaboration: Japan (NAOJ, IPMU, Tokyo, Tohoku, Nagoya, +), Princeton, Taiwan
- FoV (1.5° in diameter): ~10×Suprime-Cam
- Keep the excellent image quality
- Instrumentation well underway (being led by S. Miyazaki, NAOJ)
- *300 nights over 5 years approved!*
- HSC survey starting from 2012 – 2017 (PI: S. Miyazaki)
- Multi-band imaging (grizy; i~26, y~24) for 1400 square degrees

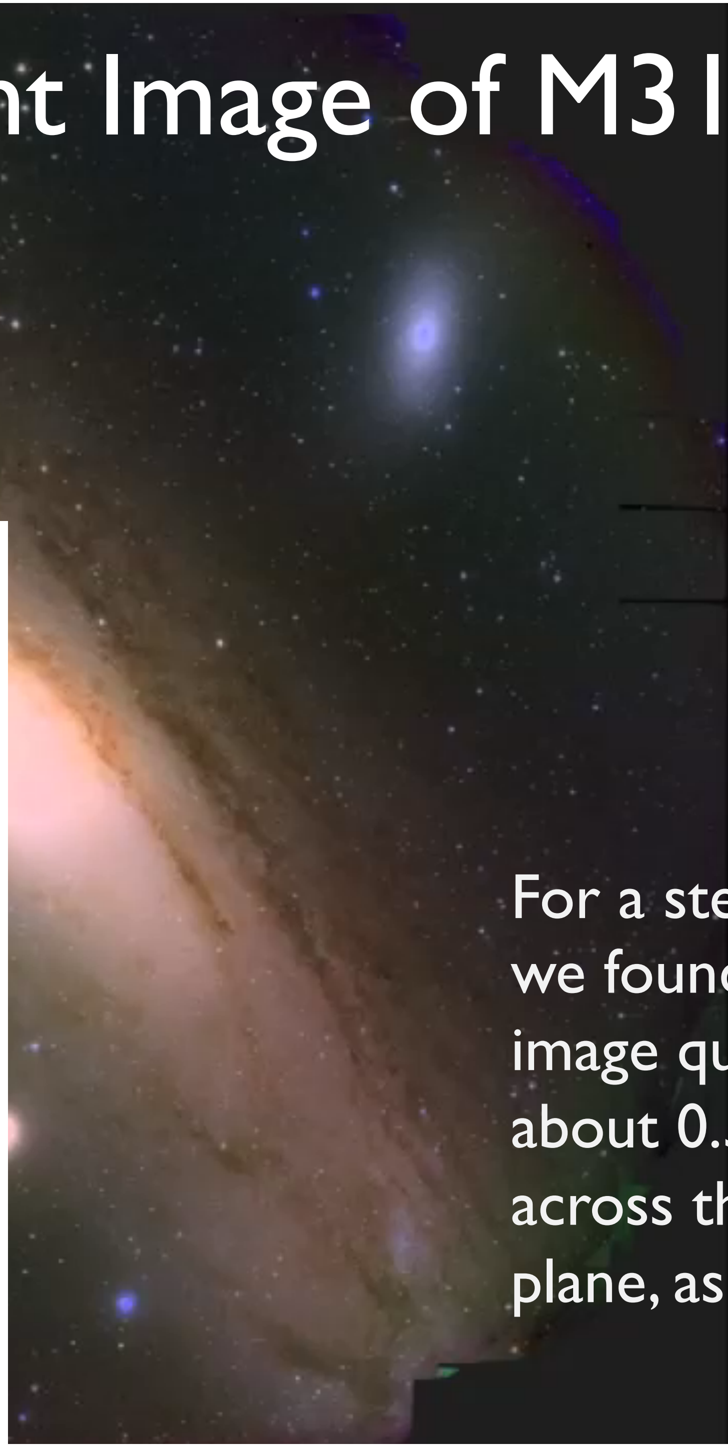
Hyper Suprime-Cam Project

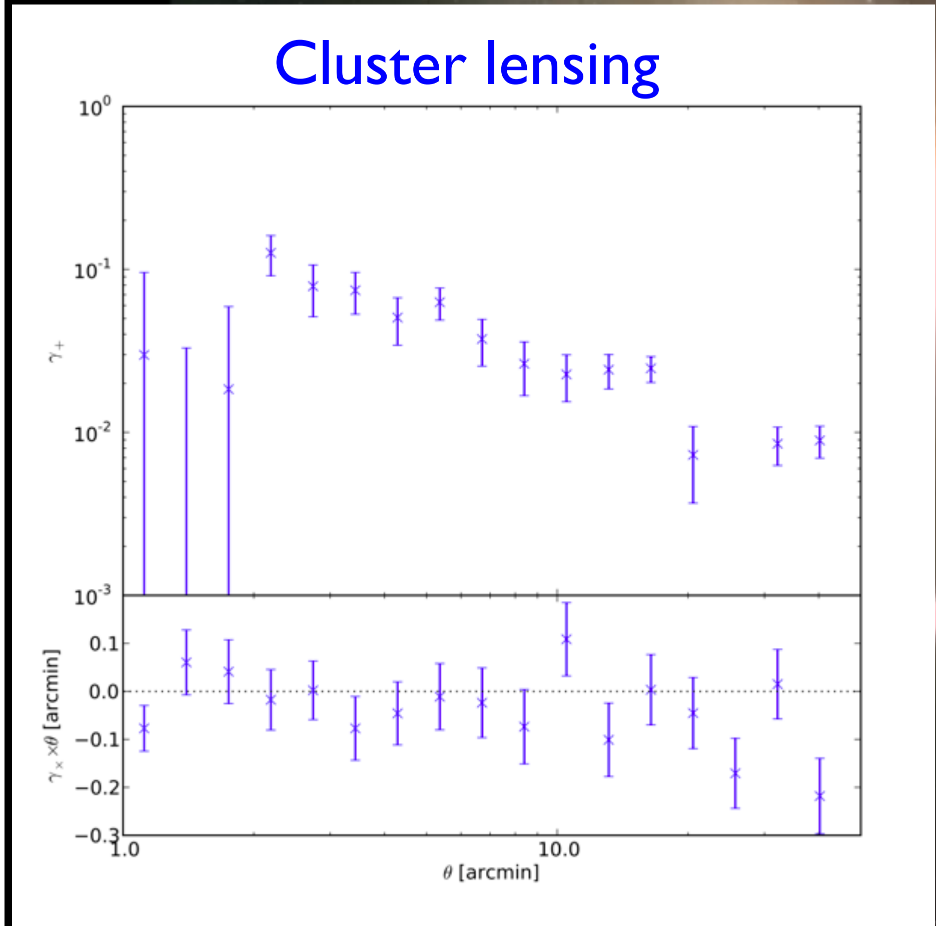


- All instruments at Mauna Kea
- The *largest* camera in the world
- 3m high
- 3 tons weighed
- 116 CCD chips (870 millions pixels)



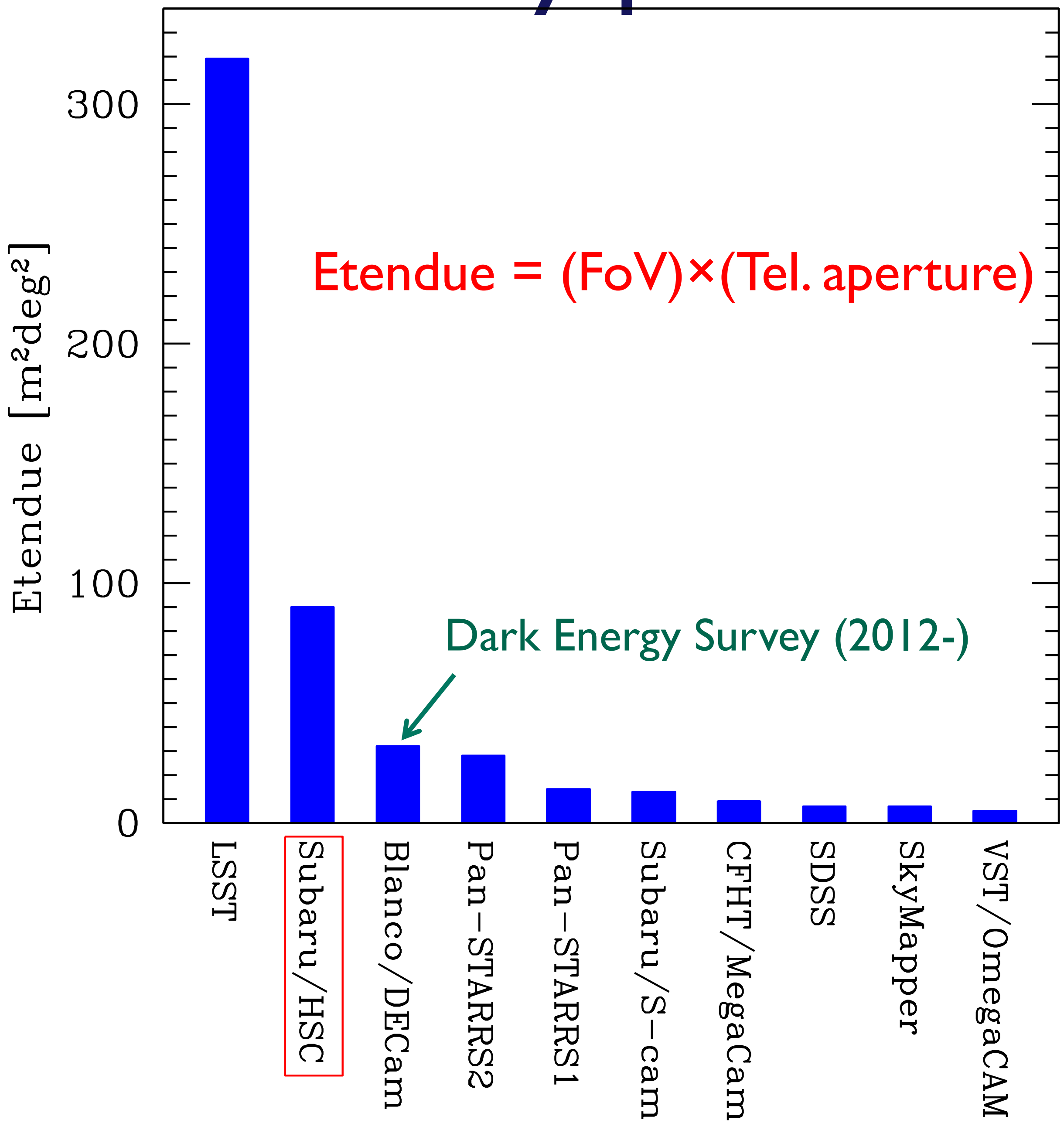
HSC First Light Image of M31





For a stellar field, we found that the image quality is about 0.5” FWHM across the focal plane, as designed!

Survey power of HSC

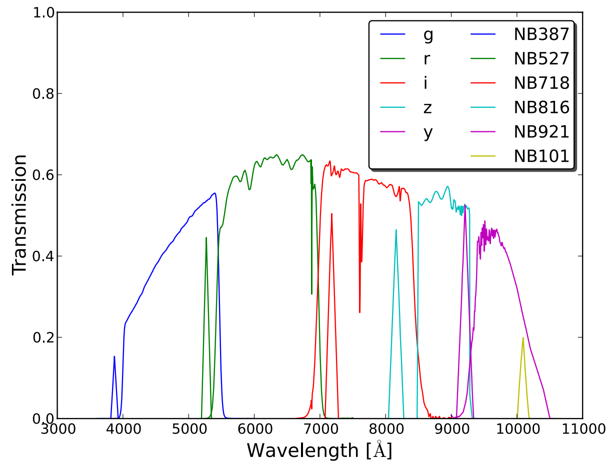


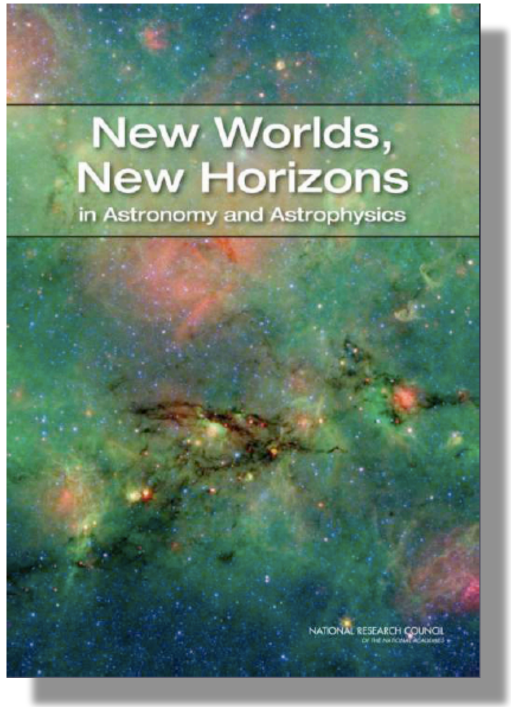
- Photon collecting power of 8.2m Subaru Tel.
- FoV
- In addition, excellent image quality

→ *These make HSC the most powerful survey camera/telescope before LSST*

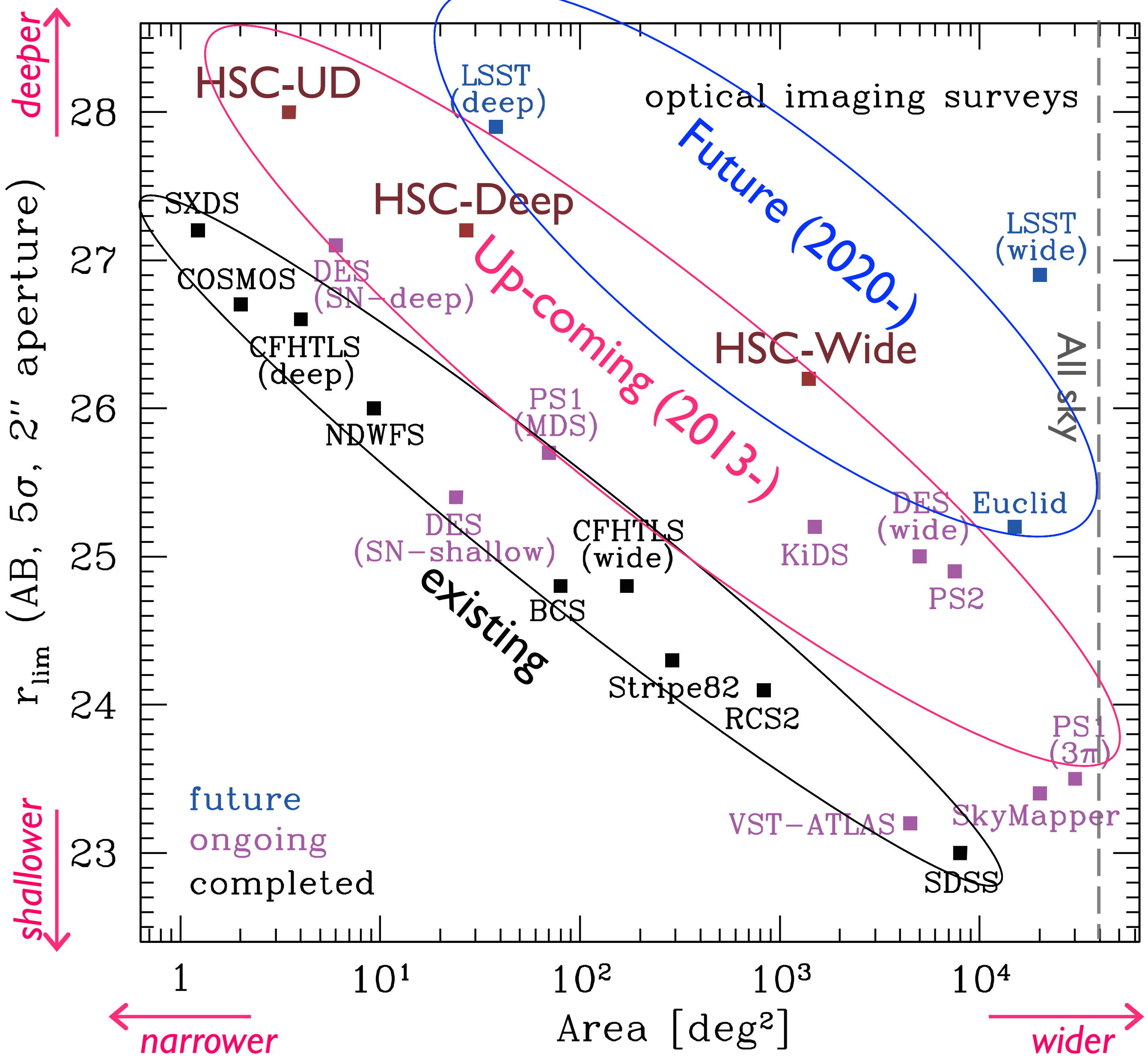
Planned HSC Survey

- Wide Layer: 1400 sq. degs., *grizy* ($i_{AB}=26$, 5σ)
  - Weak gravitational lensing
  - Galaxy clustering, properties of z~1 L_* galaxy
  - *Dark Energy*, *Dark Matter*, neutrino mass, the early universe physics (primordial non-Gaussianity, spectral index)
- Deep Layer: 28 sq. degs, *grizy*+NBs (*i*=27)
  - For calibration of galaxy shapes for HSC-Wide WL
  - Lyman-alpha emitters, Lyman break galaxies, QSO
  - Galaxy evolution up to z~7
  - *The physics of cosmic reionization*
- Ultra-deep Layer: 2FoV, *grizy*+NBs (i~28)
  - Type-Ia SNe up to z~1.4
  - LAEs, LBGs
  - Galaxy evolution
  - *Dark Energy, the cosmic reionization*





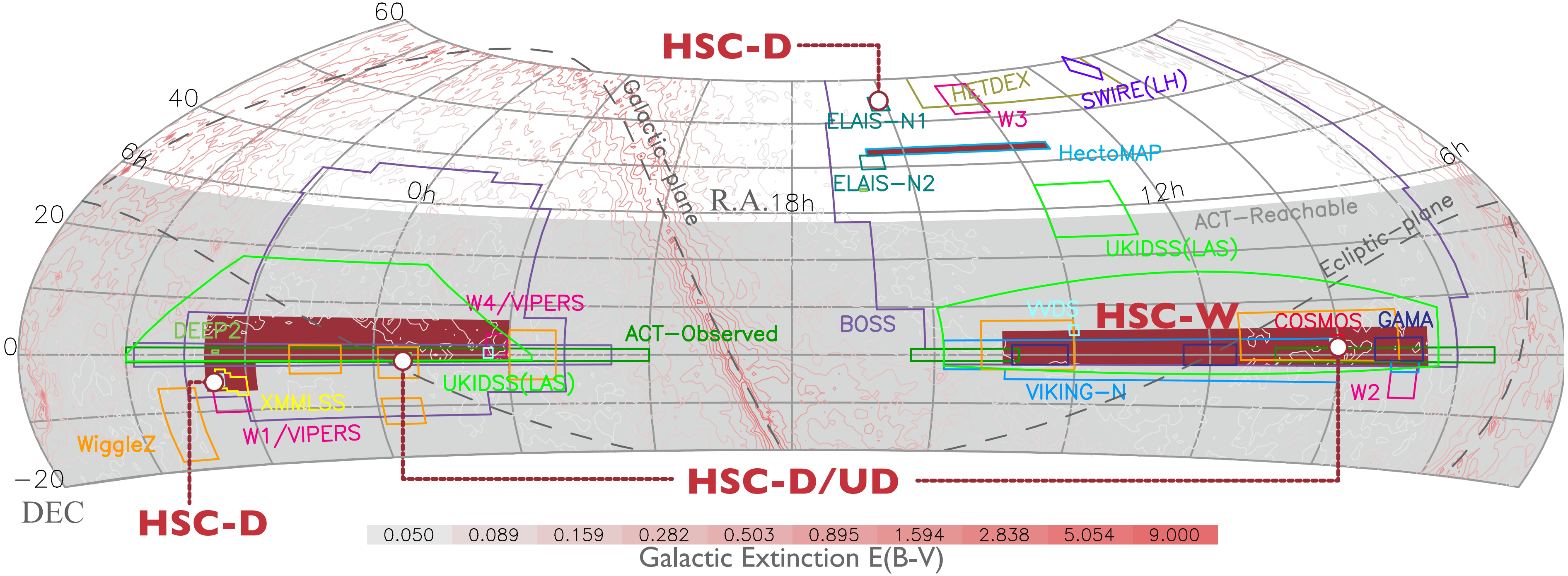
Planned HSC Survey



Black: existing
Magenta: upcoming
Blue: future

HSC Layers will explore new regions in survey parameter space

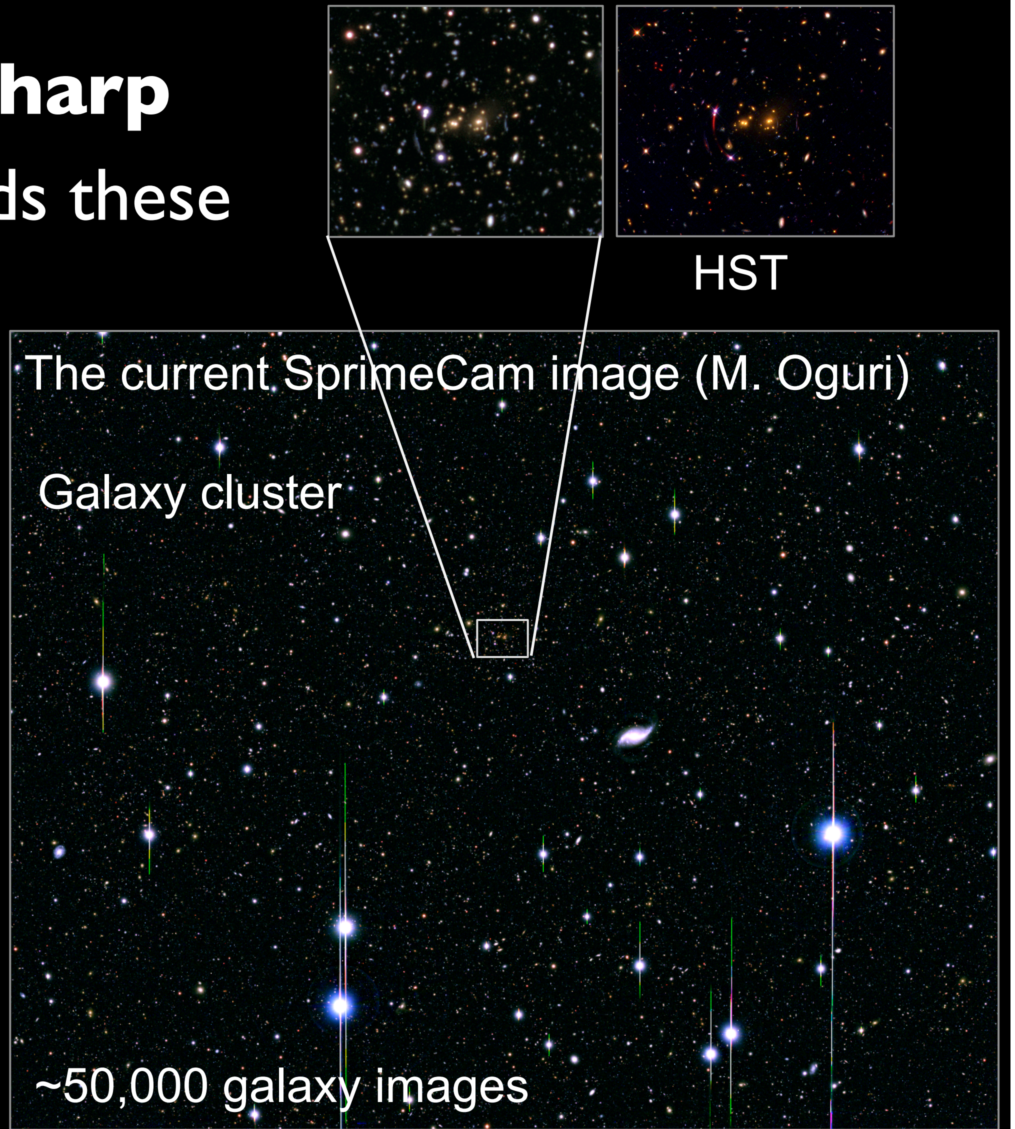
HSC Survey Fields



- The HSC fields are selected based on …
  - Synergy with other data sets: SDSS/BOSS, The Atacama Cosmology Telescope CMB survey (from Chile), X-ray (XMM-LSS), spectroscopic data sets
  - Spread in RA
  - Low dust extinction

Subaru Telescope: wide FoV & excellent image quality

- **Fast, Wide, Deep & Sharp**
- a cosmological survey needs these



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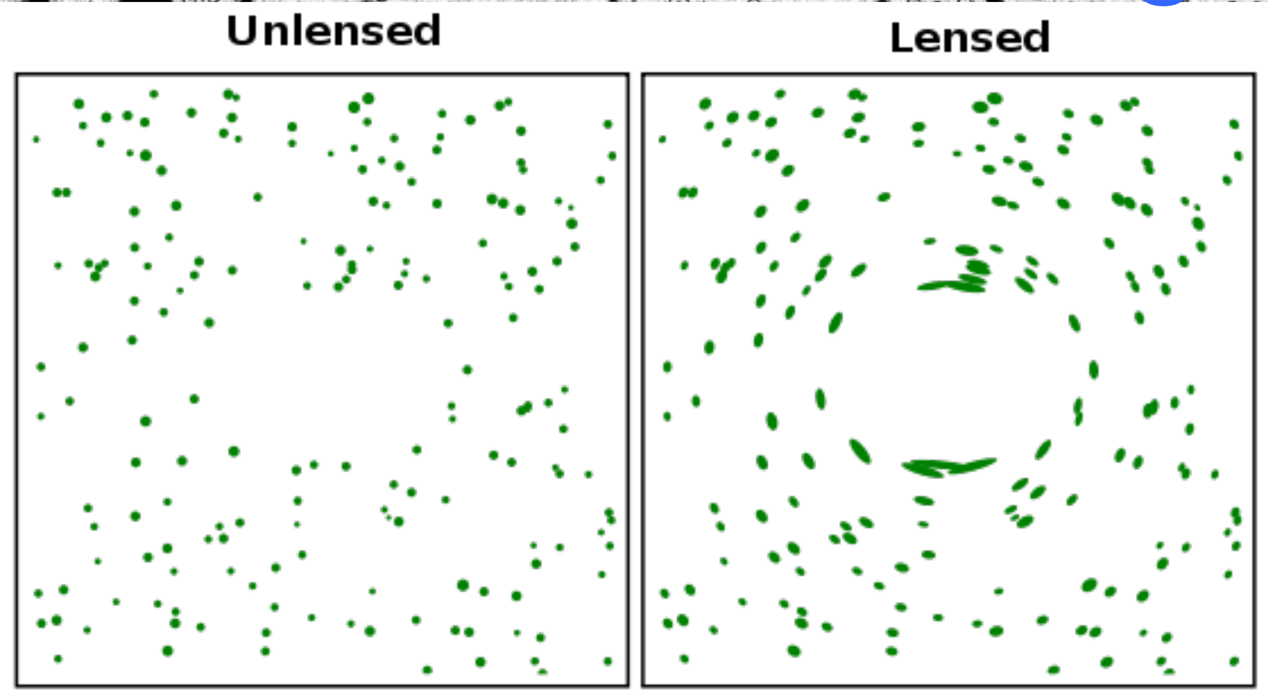
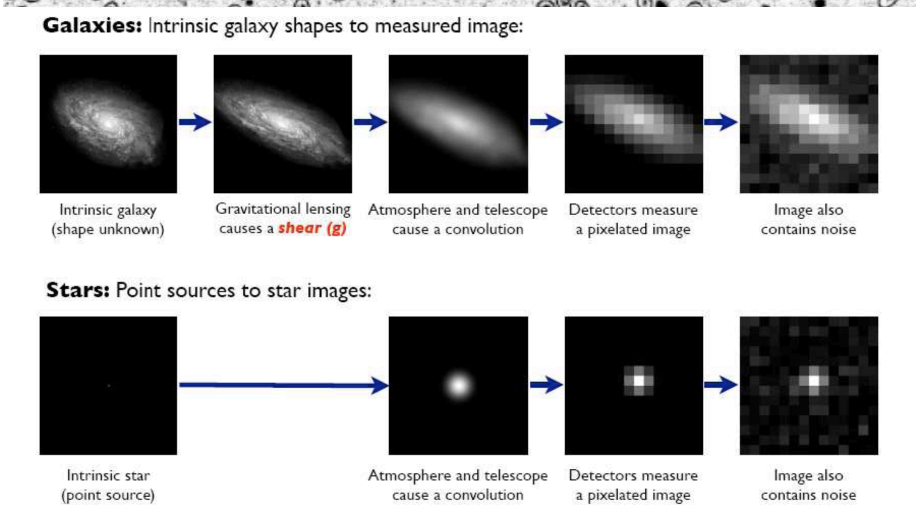
Hyper Suprime-Cam FoV

- **Fas**
- a cos

Statistical weak lensing





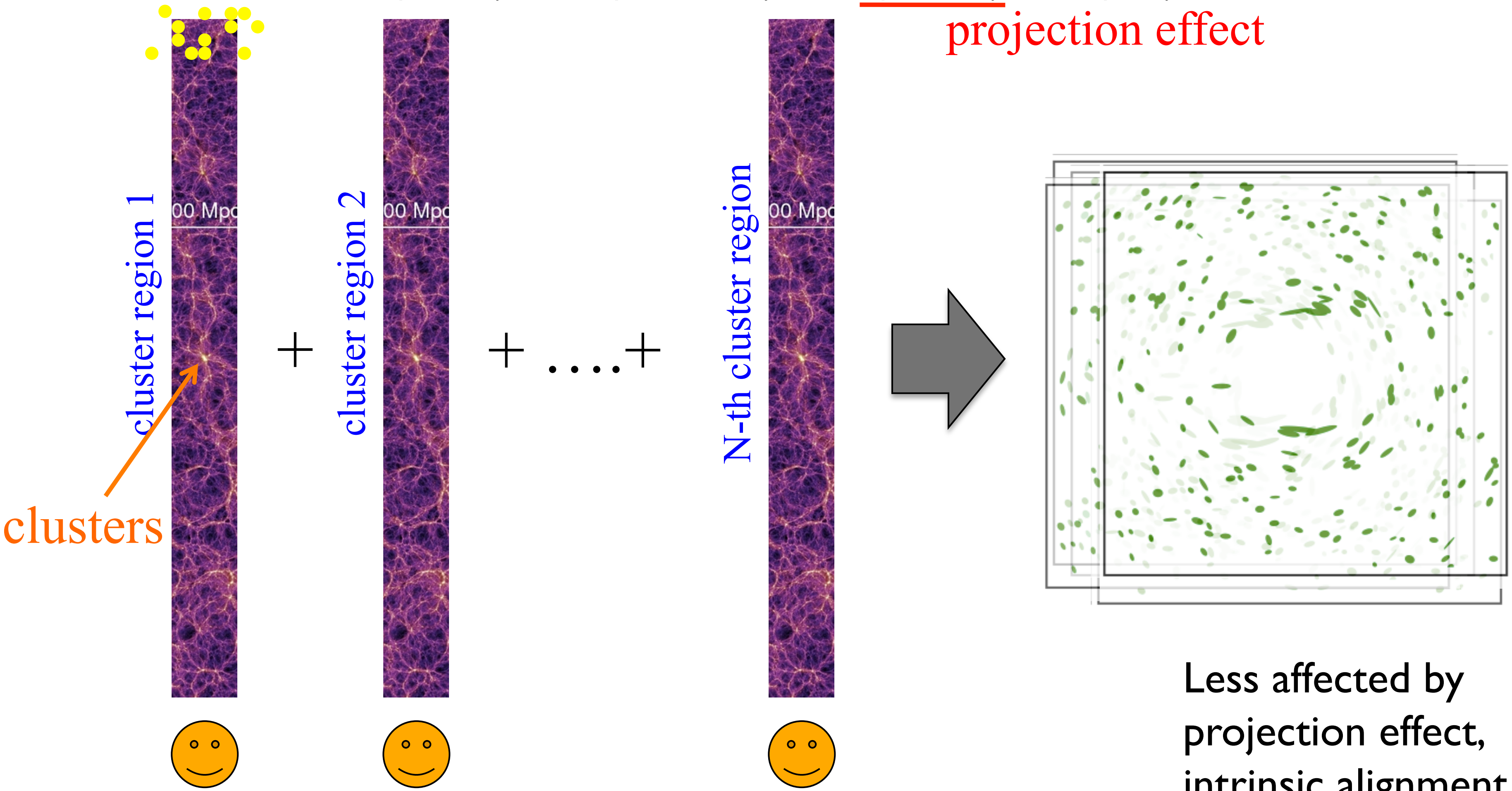
- Need statistics to reduce the intrinsic shape contamination
- Excellent image quality and deep image needed for an accurate WL measurement
- Issues; accurate shape measurements, PSF correction, pixelization effect

Stacked lensing: halo-shear correlation

$$\gamma_+^{\rm obs}(\theta_i) = \gamma_+^{\rm cluster}(\theta_i) + \underline{\gamma_+^{\rm LSS}(\theta_i)} + \varepsilon_+(\theta_i)$$

Oguri & MT 11

projection effect



$$\langle \gamma_+ \rangle(\theta) = \frac{1}{N_{cl}} \sum_{a=1}^{N_{cl}} \sum_{|\vec{\theta}'| \subset \theta} \gamma_{+(a\text{-th cluster})}(\vec{\theta}') \approx \left\langle \gamma_+^{\rm cluster} \right\rangle(\theta)$$

Less affected by projection effect, intrinsic alignment, sys. errors ....

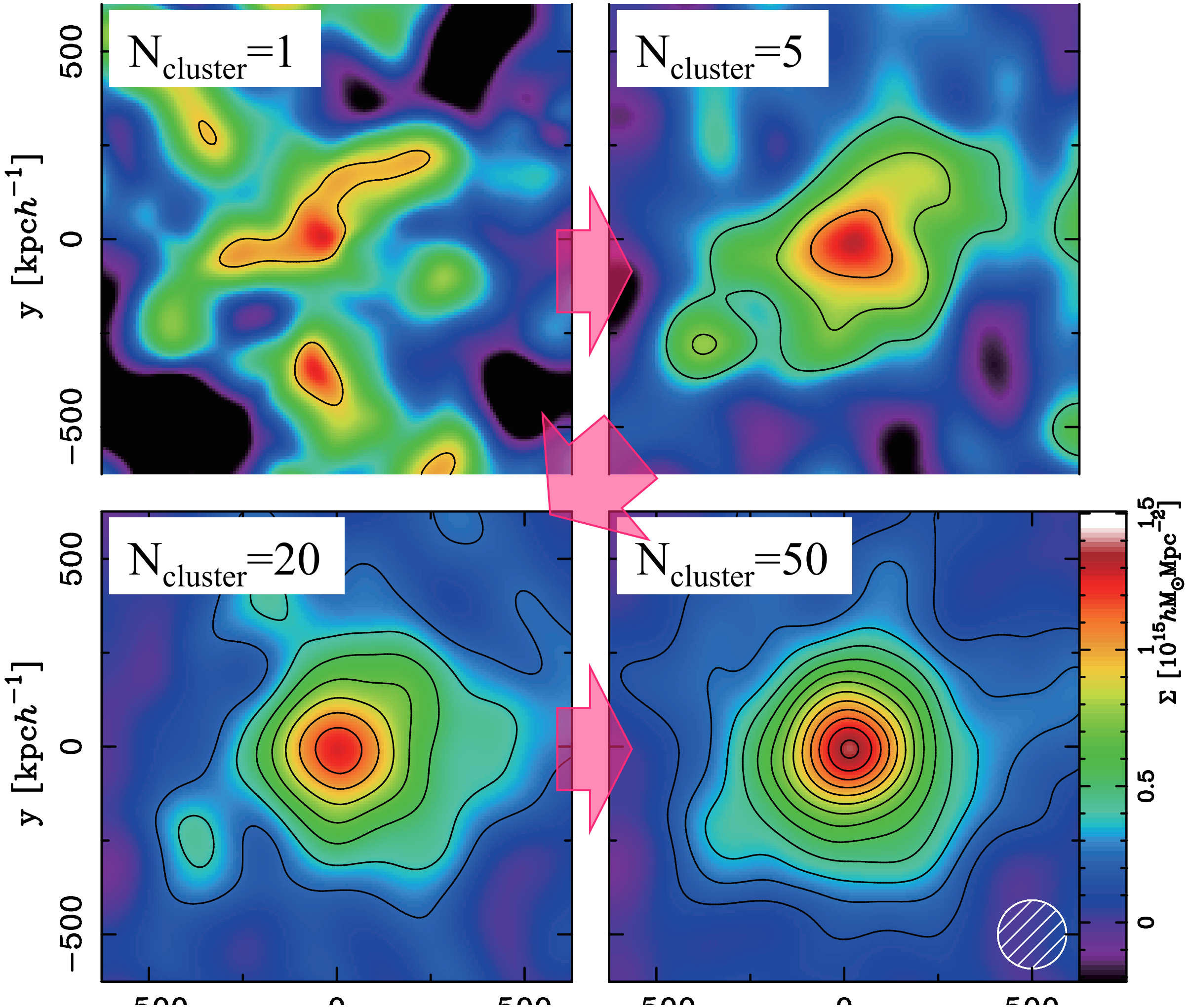
Note: halo center

A preparation study of HSC survey

DM distribution of galaxy clusters

N. Okabe

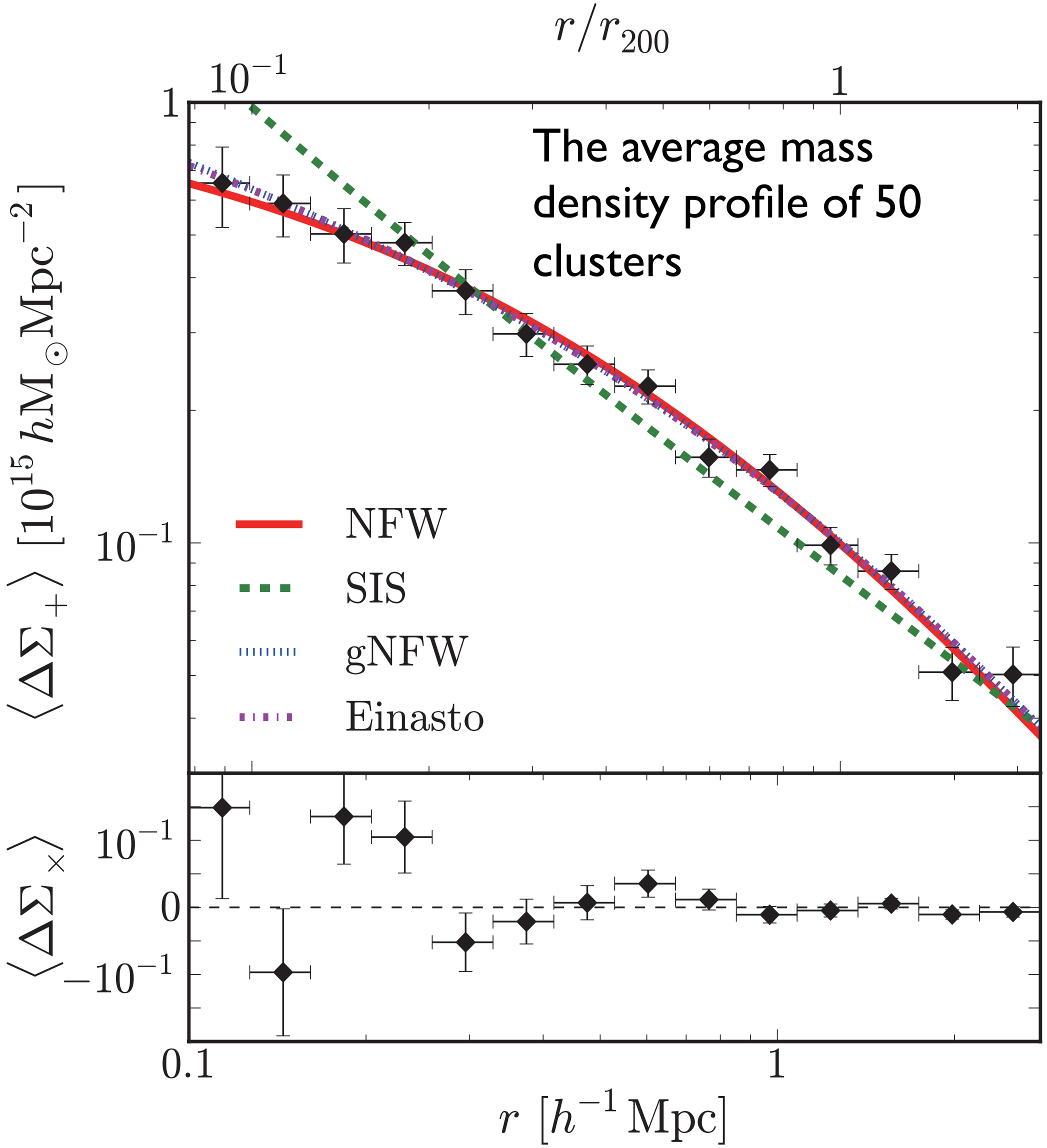
- Collected Subaru data of 50 clusters, *all* the most X-ray luminous clusters accessible from Subaru (about 15 Subaru nights; 5 yrs)
- The averaged DM distribution from the combined WL data

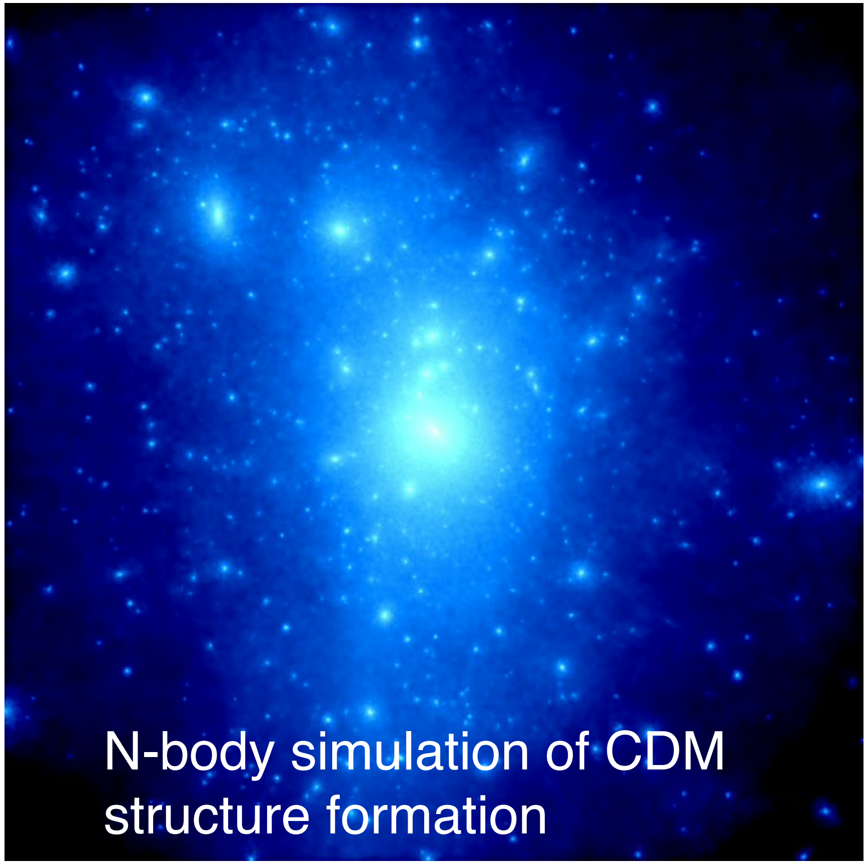


Signal-to-Noise ratio *(S/N)*~5 for one cluster ⇒ *S/N*~30 when 50 clusters combined

Okabe et al. 13, ApJ Letters
Okabe, MT+ 10

DM distribution of galaxy clusters (cont'd)

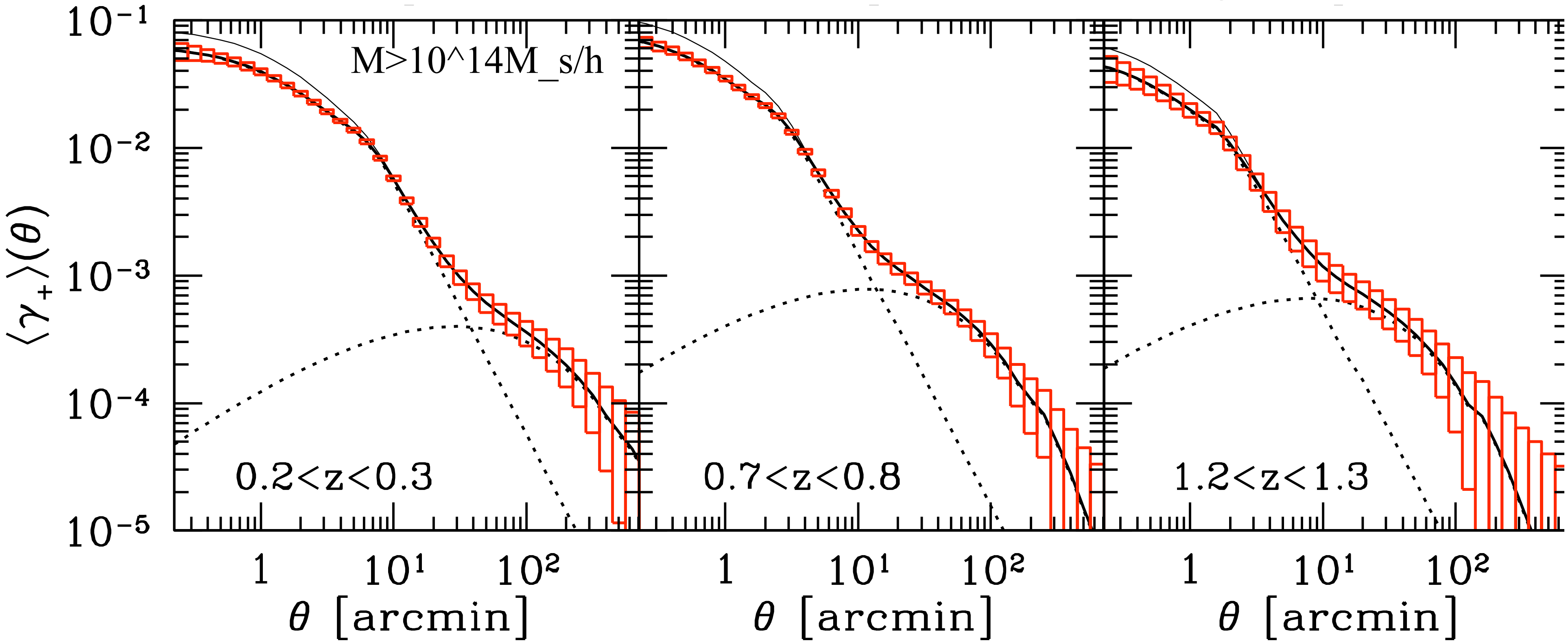




- Subaru WL result shows a perfect agreement with the CDM model prediction

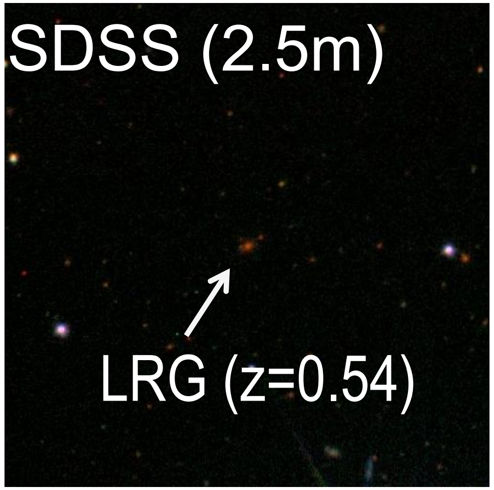
Forecast for stacked lensing with HSC

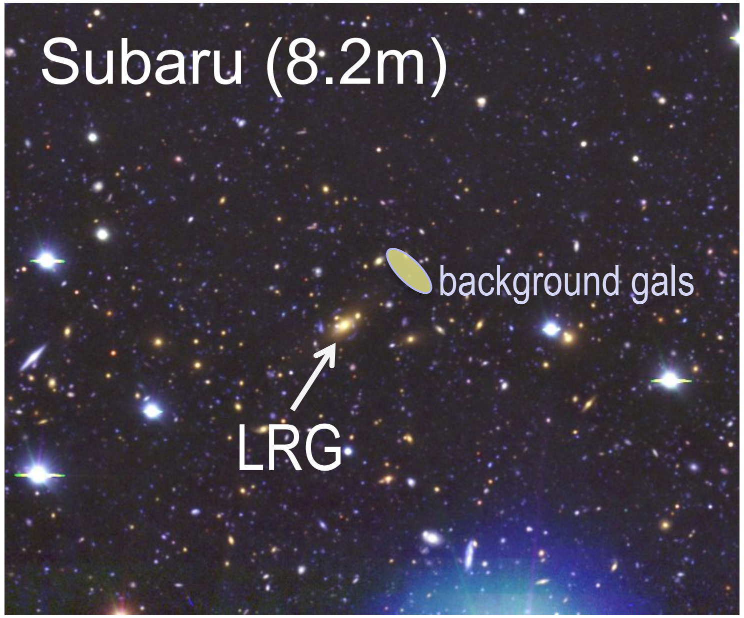
Oguri & MT 10



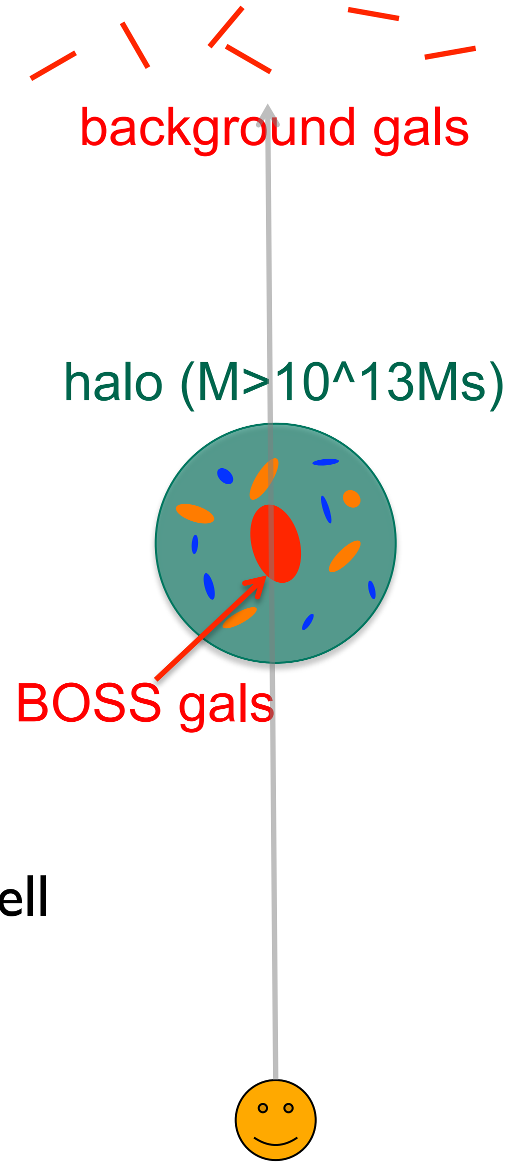
- HSC can achieve a high S/N detection of stacked WL signals out to z~1.3
- Small-angle signals are from one halo (the mean halo mass and the average shape of mass profile)
- Large-angle signals are from the mass distribution in large-scale structure

Synergy btw HSC and BOSS



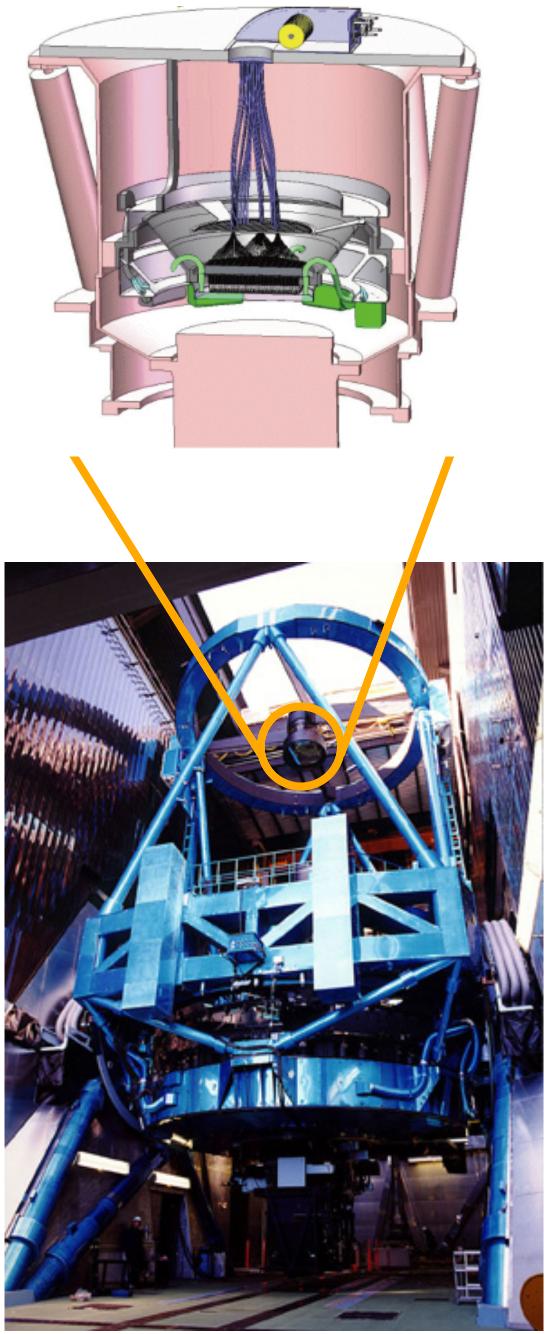


Credit: Masayuki Tanaka (IPMU)



- The deep HSC data will add background galaxies as well as member galaxies around each BOSS gal
- Cross-correlation of BOSS gals with HSC galaxies (shapes and positions)
- WL, galaxy clustering, CMB lensing, SZ, X-ray….

Prime Focus Spectrograph (PFS)



- Multi object fiber spectrograph for 8.2m Subaru
- International collaboration; Japan (IPMU+), Princeton, JHU, Caltech/JPL, LAM, Brazil, ASIAA
- Initiated by the stimulus funding (~$30M secure); $50M needed for the instrumentation
- The current baseline design
  - The same optics to HSC
  - 2400 fibers
  - 380-1300nm wavelength coverage
  - R~2000, 3000, 5000 (blue, red, NIR)
- The target first light; around 2017
- Capable of various science cases: cosmology, galaxy, galactic archeology

PFS collaboration

Caltech

Jet Propulsion Laboratory
California Institute of Technology

NAOJ

ACADEMIA SINICA

PRINCETON UNIVERSITY

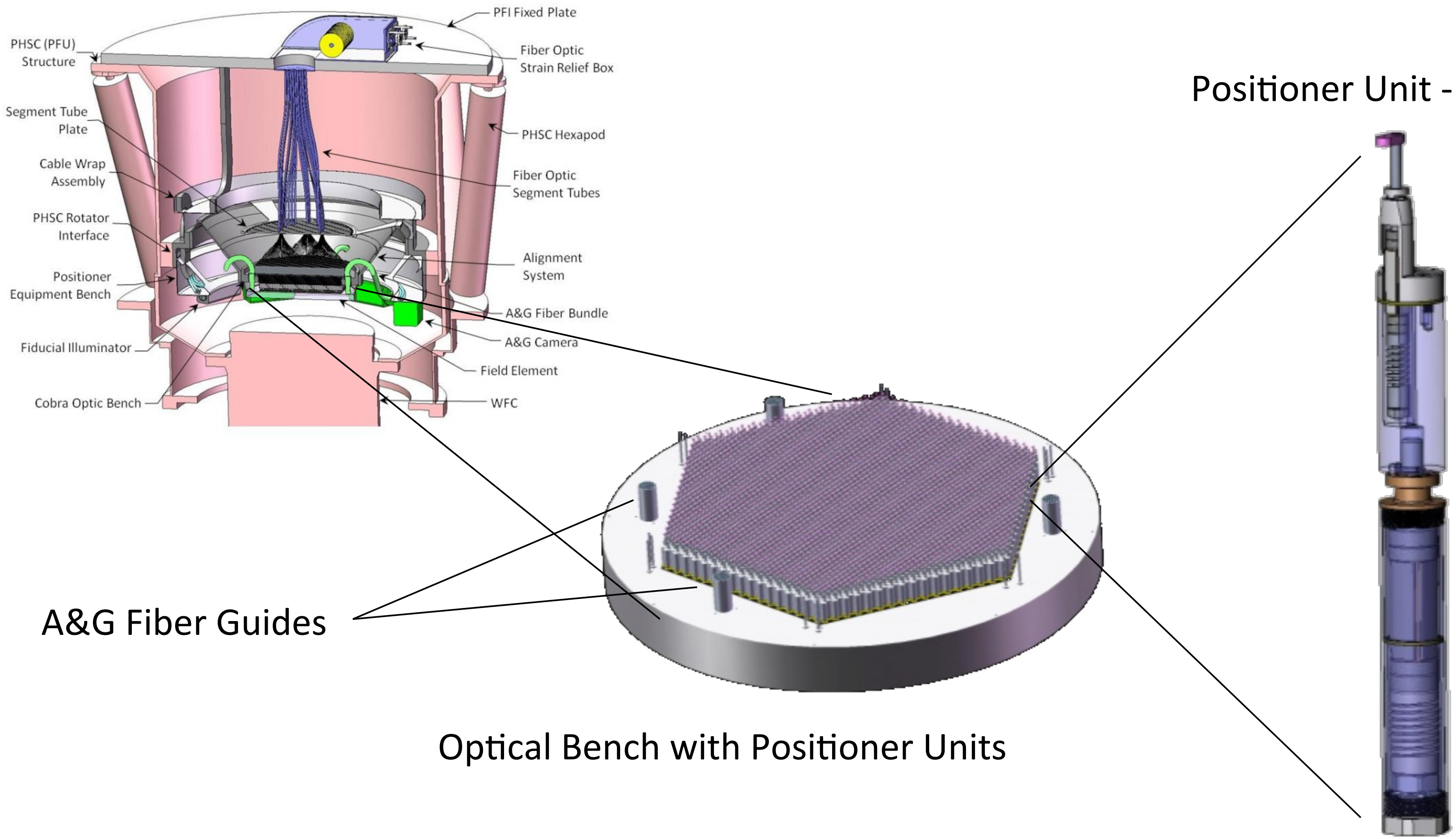
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

LNA LABORATÓRIO NACIONAL DE ASTROFÍSICA

LAM LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

JOHNS HOPKINS UNIVERSITY

PFS Positioner



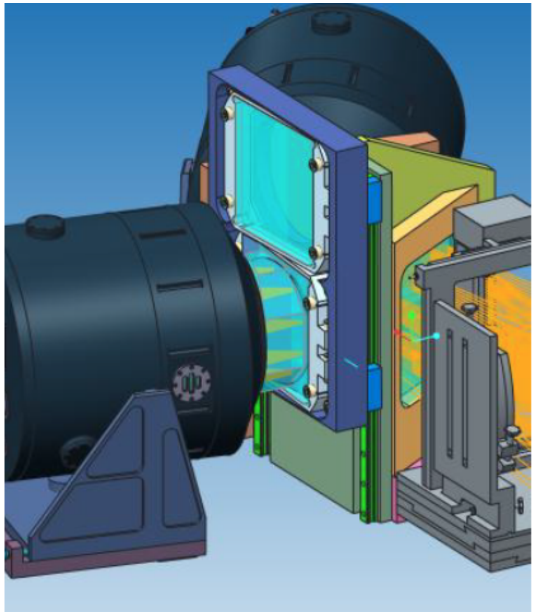
Cobra system is the most essential part of PFS, and will be built at JPL
Designed to achieve 5 μ m accuracy in < 8 iterations (40 sec)

PFS Specifications

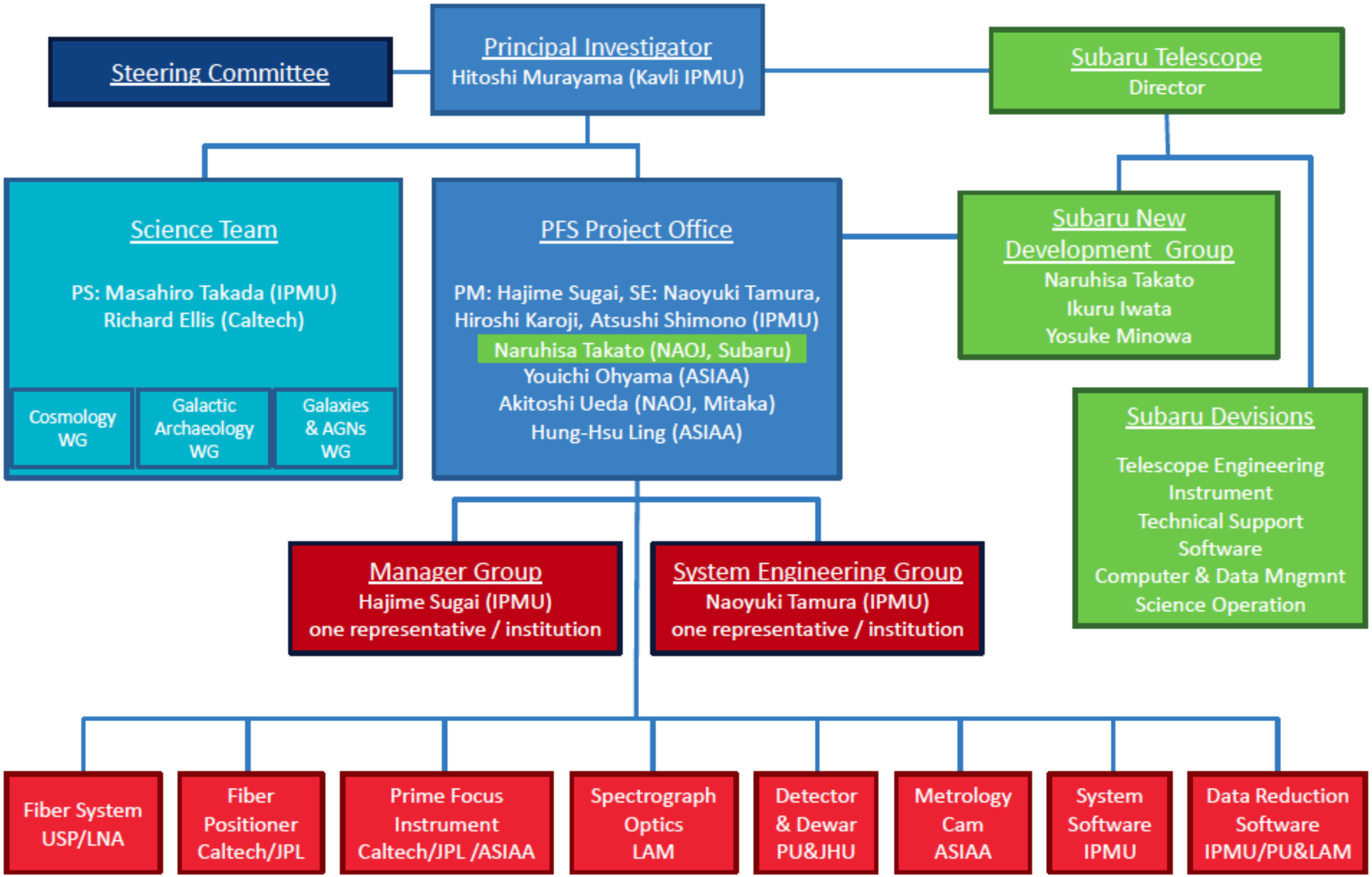
Approved by Preliminary Design Review (March, 2013)

Number of fibers	2400		
Field of view	1.3 deg (hexagonal-diameter of circumscribed circle)		
Fiber diameter	1.13” diameter at center	1.03” at the edge	
	Blue	Red	NIR
Wavelength range [nm]	380-650	630-970 (706-890)	940-1260
Central resolving power	~2350	~2900 (~5000)	~4200
Detector type	CCD	CCD	HgCdTe

- Share WFC with HSC
- 4 spectrographs for 600 fibers each
- λ =0.38-1.26 μ m with 3 arms
- Fiber density: 2200/sq. degs (⇔ ~140 for BOSS; ~570 for DESI)
- Now, a medium resolution mode (R~5000) for the red arm is *our baseline design*



PFS Organization Structure




PFS PDR, Feb 2013@Hilo
SUBARU TELESCOPE


4th PFS Collaboration Meeting, Mar 2013@Tokyo
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arXiv:1206.0737 Takada, Ellis, Chiba, Greene et al. (PASJ in press)

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EXTRAGALACTIC SCIENCE, COSMOLOGY AND GALACTIC ARCHAEOLOGY WITH THE SUBARU PRIME FOCUS SPECTROGRAPH (PFS)

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Draft version August 1, 2013

ABSTRACT

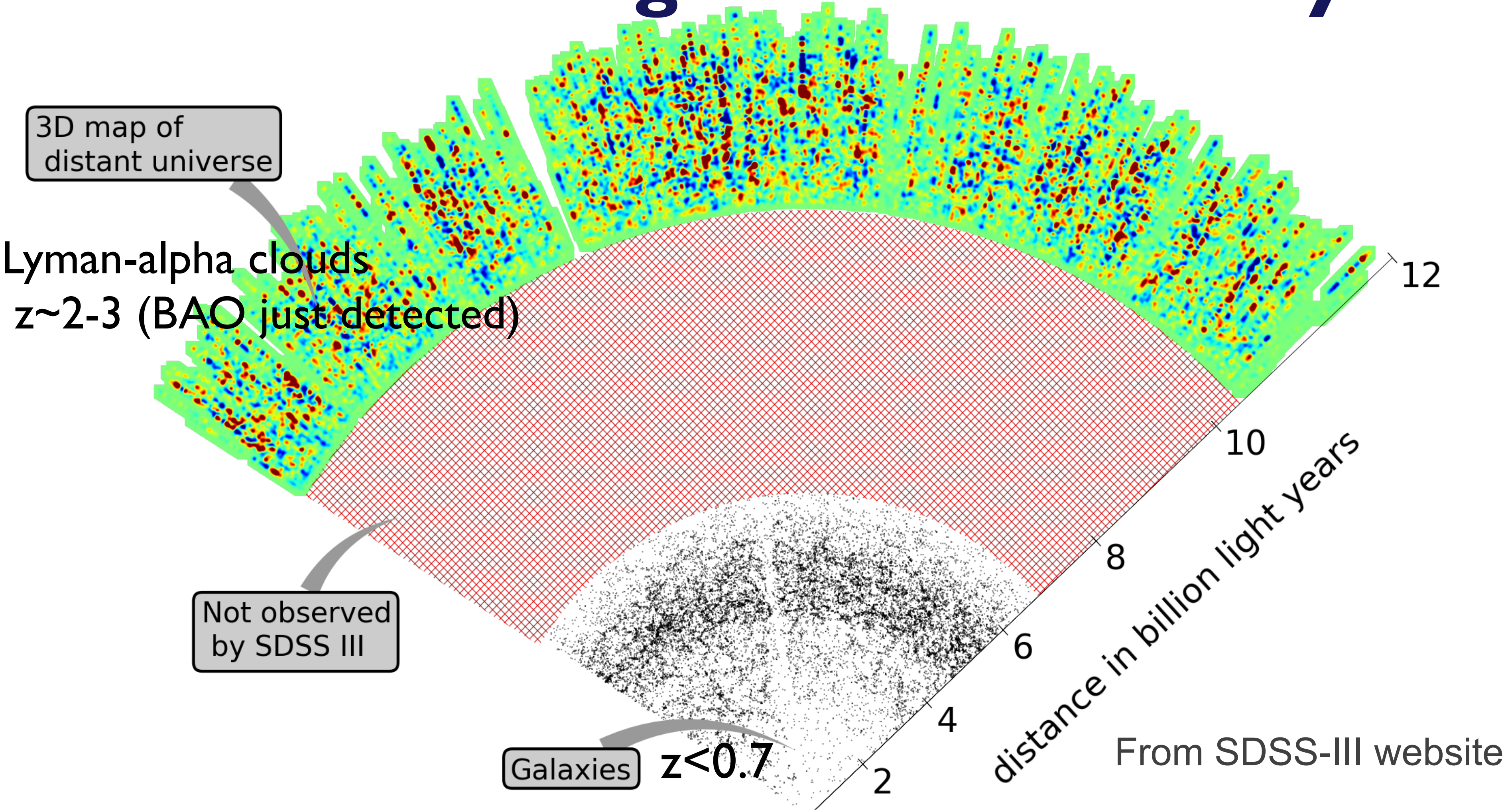
The Subaru Prime Focus Spectrograph (PFS) is a massively-multiplexed fiber-fed optical and near-infrared 3-arm spectrograph ($N_{\rm fiber}$=2400, 380$\leq \lambda \leq$ 1260nm, 1.3 degree diameter hexagonal field), offering unique opportunities in survey astronomy. Following a successful external design review the instrument is now under construction with first light anticipated in late 2017. Here we summarize the science case for this unique instrument in terms of provisional plans for a Subaru Strategic Program of $\simeq$300 nights. We describe plans to constrain the nature of dark energy via a survey of emission line galaxies spanning a comoving volume of $9.3h^{-3}$Gpc^3 in the redshift range $0.8 < z < 2.4$. In each of 6 independent redshift bins, the cosmological distances will be measured to 3% precision via the baryonic acoustic oscillation scale, and redshift-space distortion measures will be used to constrain structure growth to 6% precision. In the near-field cosmology program, radial velocities and chemical abundances of stars in the Milky Way and M31 will be used to infer the past assembly histories of spiral galaxies and the structure of their dark matter halos. Data will be secured for 10^6 stars in the Galactic thick-disk, halo and tidal streams as faint as $V \sim 22$, including stars with $V < 20$ to complement the goals of the Gaia mission. A medium-resolution mode with $R = 5,000$ to be implemented in the red arm will allow the measurement of multiple α-element abundances and more precise velocities for Galactic stars, elucidating the detailed chemo-dynamical structure and evolution of each of the main stellar components of the Milky Way Galaxy and of its dwarf spheroidal galaxies. The M31 campaign will target red giant branch stars with $21.5< V <22.5$, obtaining radial velocities and metallicities over an unprecedented area of 65 deg^2. For the extragalactic program, our simulations suggest the wide wavelength range of PFS will be particularly powerful in probing the galaxy population and its clustering over a wide redshift range. We propose to conduct a color-selected survey of $1 < z < 2$ galaxies and AGN over 16 deg^2 to $J \simeq 23.4$, yielding a fair sample of galaxies with stellar masses above $\sim 10^{10} M_\odot$ at $z \simeq 2$. A two-tiered survey of higher redshift Lyman break galaxies and Lyman alpha emitters will quantify the properties of early systems close to the reionization epoch. PFS will also provide unique spectroscopic opportunities beyond these currently-envisaged surveys, particularly in the era of Euclid, LSST and TMT.

Science Objectives: Three Pillars

All science cases are based on a spectroscopic follow-up of objects taken from the HSC imaging data (extending the SDSS to z~1-2)

- Cosmology
  - ~4M redshifts of emission-line galaxies
  - BAO at each of 6 redshift bins over $0.8<z<2.4$
  - Cosmology with the joint experiment of WL and galaxy clustering (HSC/PFS)
- Galaxy evolution studies
  - A unique sample of galaxies (~1M) up to z~2, with the aid of the NIR arm
  - Dense sampling of faint galaxies (also many pairs of foreground/background gals)
  - Studying cosmic reionization with a sample of LAEs, LBGs and QSOs
- Galactic Archaeology
  - ~1M star spectra for measuring their radial velocities
  - Use the 6D phase-space structure, in combination with GAIA in order to study the origin of Milky Way (also use the M31 survey)
  - Use a medium-resolution-mode survey of ~0.1M stars to study the chemo-dynamical evolution of stars in Milky Way

Redshift range for PFS survey



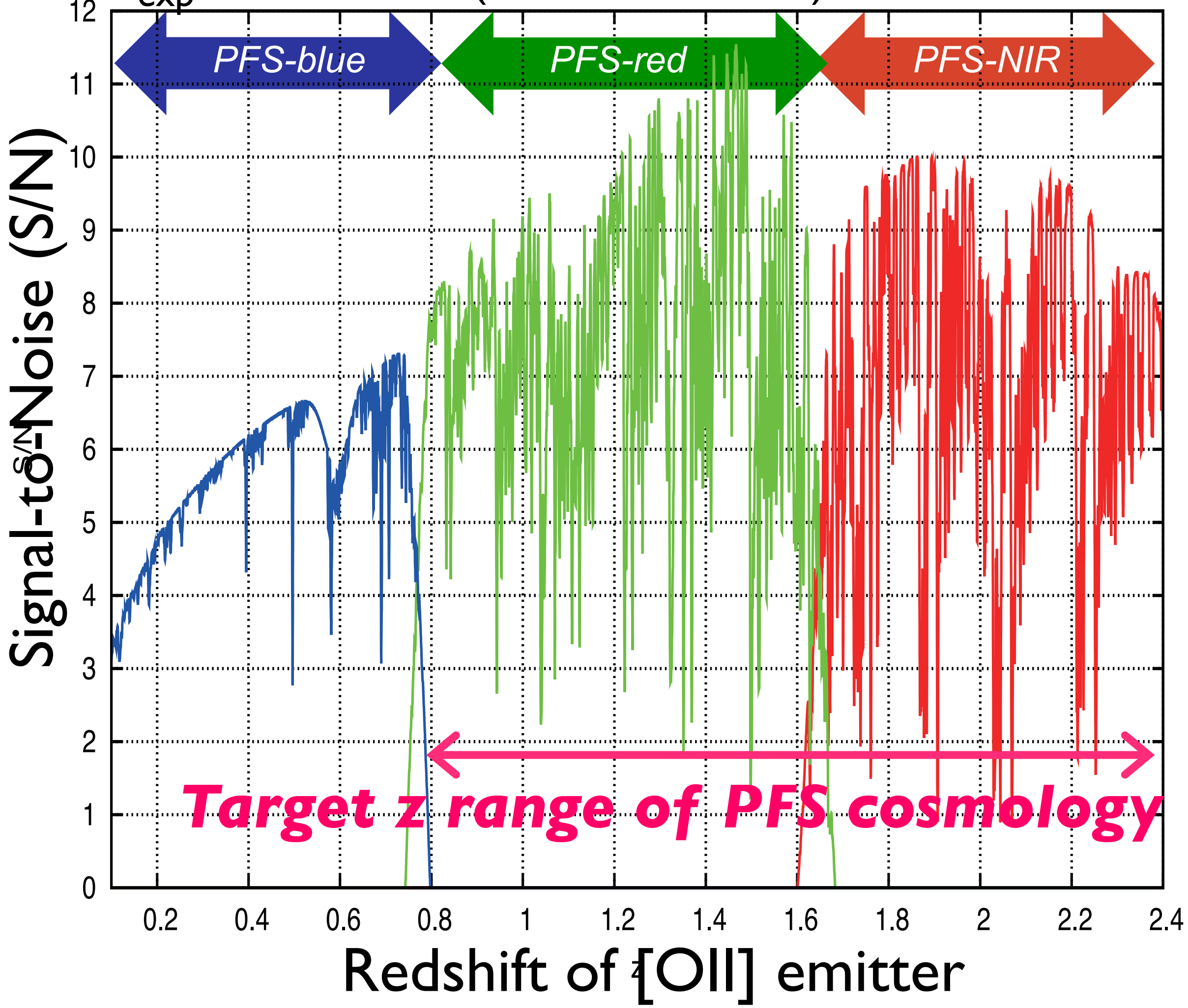
- 0.7<z<2 universe not yet observed
- SuMIRe = Imaging & spectroscopic surveys of the *same* region of the sky with the *same* telescope

Unique capability of PFS: high performance

A working example:

$f_{[OII]}$=5×10^{-17}erg/cm^2/s, σ_v=70 km/s, r_{eff}=0.3"

t_{exp}=2×450sec (15min in total)



- [OII] line (3727Å) feature used for cosmology survey
- Assuming baseline instrument parameters (fiber size, throughput, readout noise, etc.)
- *Conservative assumption*: 0.8" seeing, at FoV edge, 26 deg. zenith angle
- *Included sky continuum & OH lines*
- The PFS design allows

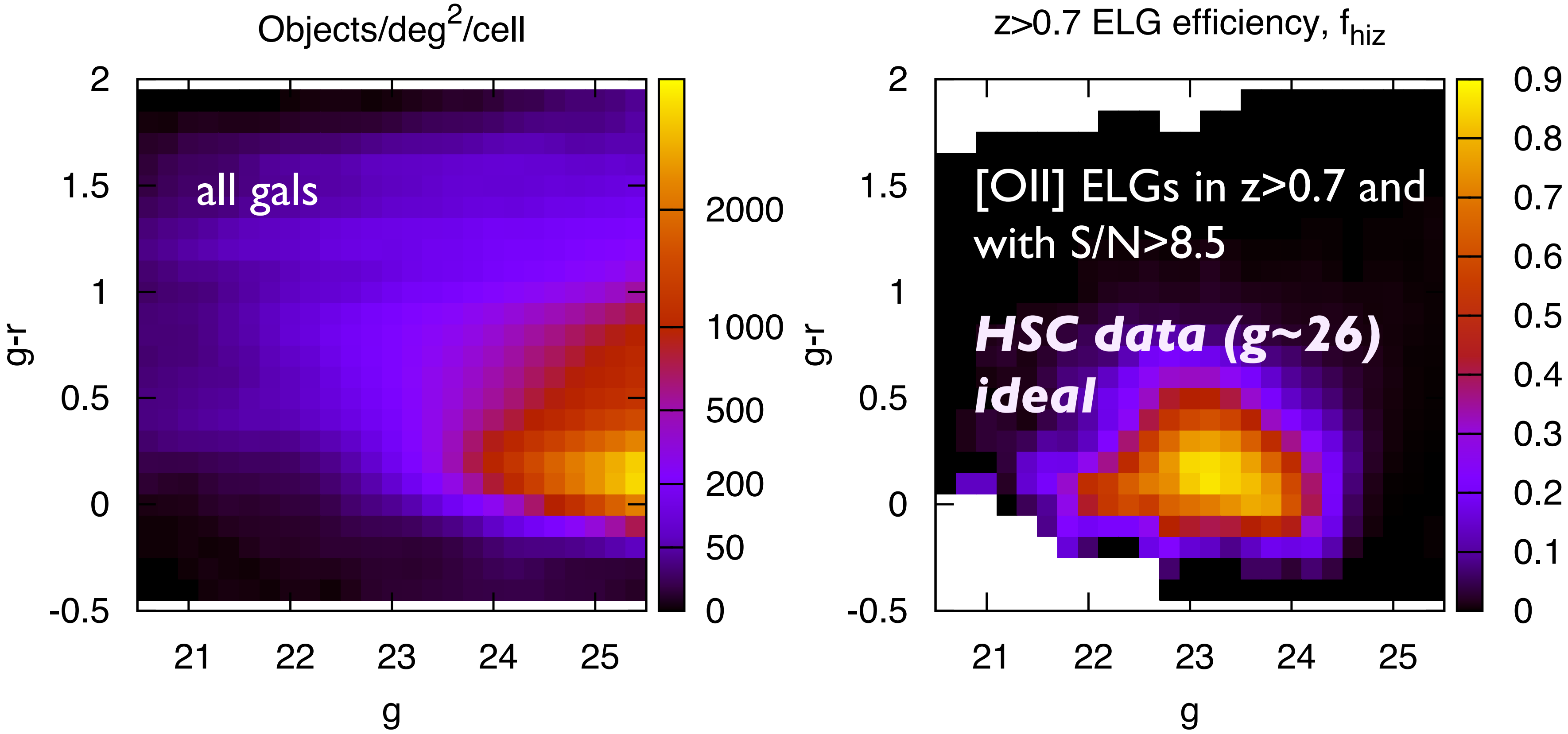
  a matched S/N in Red and NIR arms → a wide redshift coverage, **0.8<z<2.4**
- LSS more linear at higher z

Target selection of [OII] emitters

- Mock Catalog, based on the COSMOS 30 bands, zCOSMOS and DEEP2 (Jouvel et al. 2009, + further updates)
- The wide z-range allows an efficient target selection based on the color cut:

`22.8<g<24.2 & -0.1<g-r<0.3`

- 7847 targets per the PFS FoV (1.3 deg. diameter)~ 3×(# of PFS fibers)
- ~75% success rate for 2 visits of each field



PFS Cosmology Survey

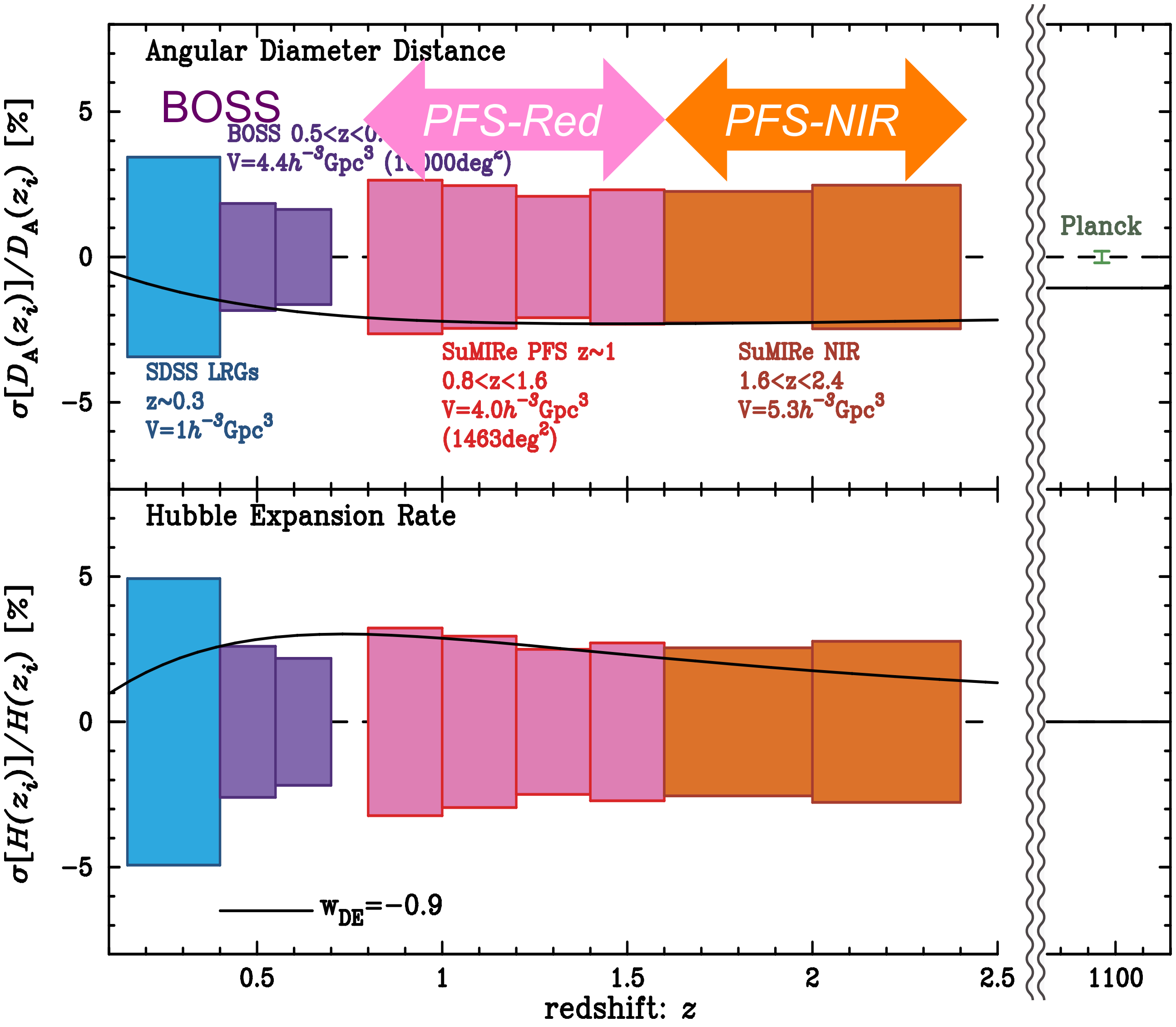
- Assume 100 clear nights to meet the scientific goals → the area of PFS survey

$$\frac{100[\text{nights}]\times 8[\text{hours}]\times 60[\text{min}]}{2[\text{visits}]\times(15[\text{min}]+3[\text{min}])}\times 1.098[\text{sq. deg. FoV}]=1464\ \text{sq. deg.}$$

Redshift	V_{survey} (h^{-3} Gpc^3)	# of galaxies (per FoV)	n_g (10^{-4} h^3 Mpc^{-3})	bias	$n_gP(k)$ @k=0.1hMpc^{-1}
0.8<z<1.0	0.79	358	6.0	1.26	2.23
1.0<z<1.2	0.96	420	5.8	1.34	2.10
1.2<z<1.4	1.09	640	7.8	1.42	2.64
1.4<z<1.6	1.19	491	5.5	1.5	1.78
1.6<z<2.0	2.58	598	3.1	1.62	0.95
2.0<z<2.4	2.71	539	2.7	1.78	0.76

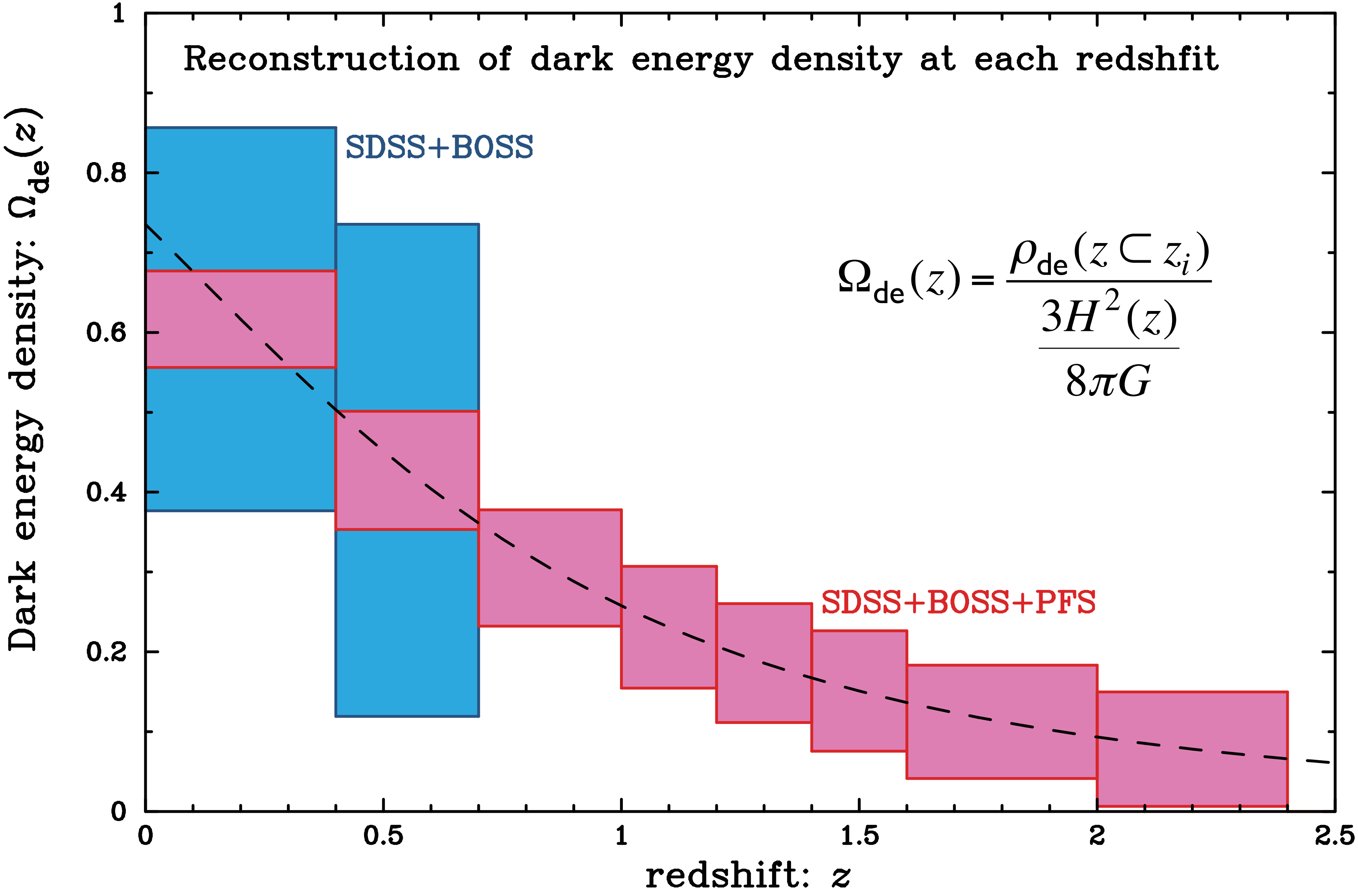
- The total volume: ~9 (Gpc/h)3 ~ 2 × BOSS survey
- Assumed galaxy bias (poorly known): b=0.9+0.4z
- PFS survey will have $n_gP(k)$~a few@k=0.1Mpc/h in each of 6 redshift bins

Expected BAO constraints

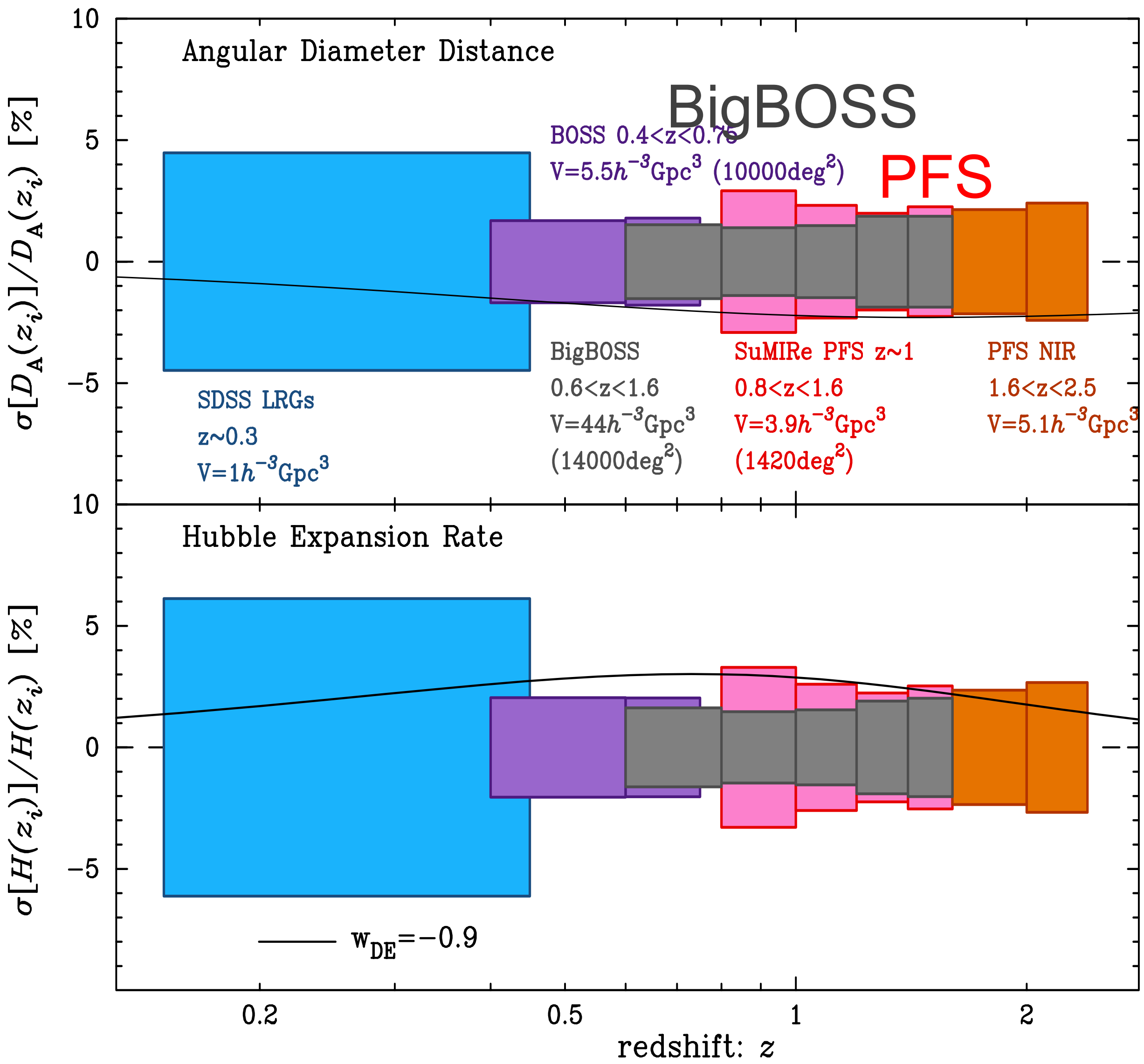


- The PFS cosmology survey enables a *3%* accuracy of measuring $D_A(z)$ and $H(z)$ in each of 6 redshift bins, over 0.8<z<2.4
- This accuracy is *comparable* with BOSS, but extending to higher redshift range
- Also very efficient given competitive situation
  - BOSS (2.5m): 5 yrs
  - PFS (8.2m): 100 nights

Model-independent DE reconstruction



PFS vs. BigBOSS



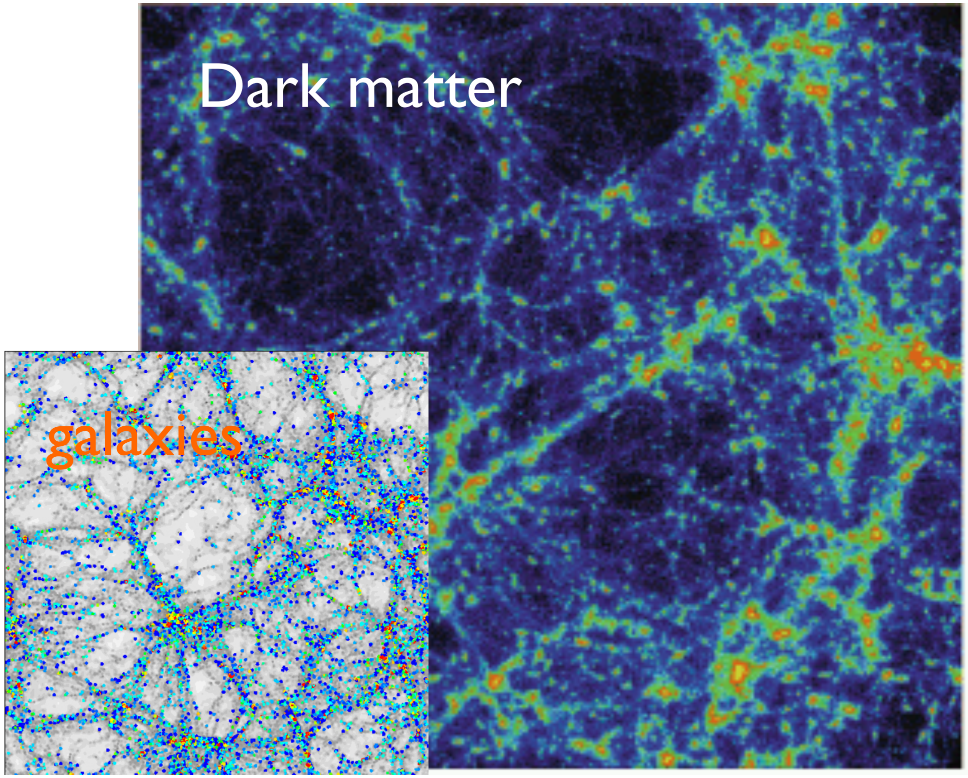
- 500 vs. 100 nights
- 14000 vs. 1420 sq. deg.
- BAO constraints; BigBOSS a factor 3 more powerful than PFS?

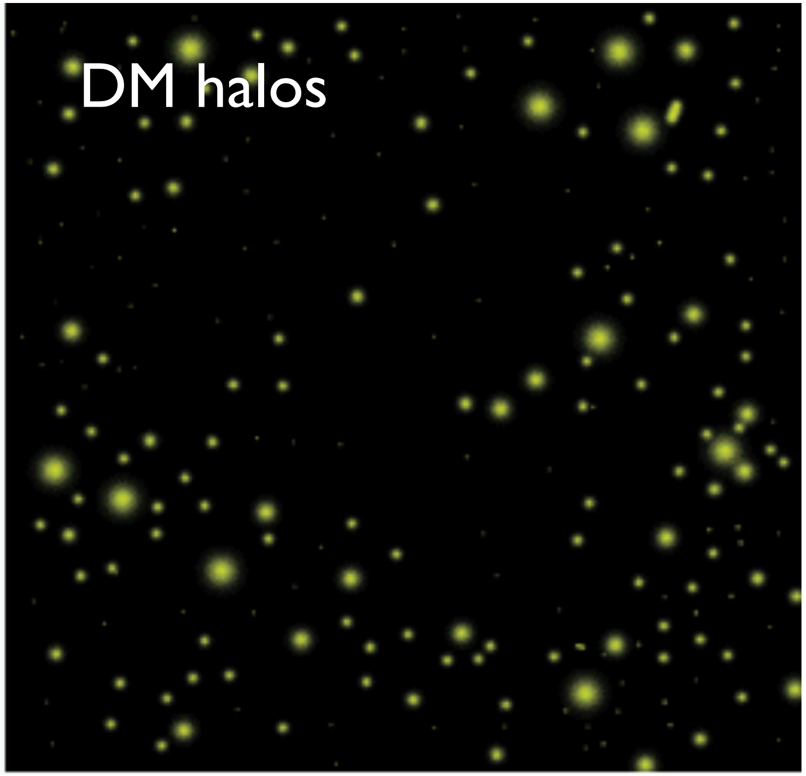
- *No! PFS has a comparable power with BigBOSS in z=1.2-1.6, also probes the new z-range*

Lensing and Clustering Complementarity

- Synergy btw imaging and spectroscopic surveys for the *same* region of the sky
- Weak lensing; can *directly* probe dark matter distribution around the *spectroscopic* galaxies
- Galaxy clustering; can probe 3D large-scale structure at a particular redshift, and also probe the peculiar velocity field via RSD
- Combining the two can calibrate *systematic errors* inherent in each probe, allowing us to derive improved cosmological constraints
- The synergy not yet been fully explored (The simple Fisher calculation doesn't give a strong synergy though)
- (Cosmic shear; a harder problem unfortunately)

Galaxy – DM Connection





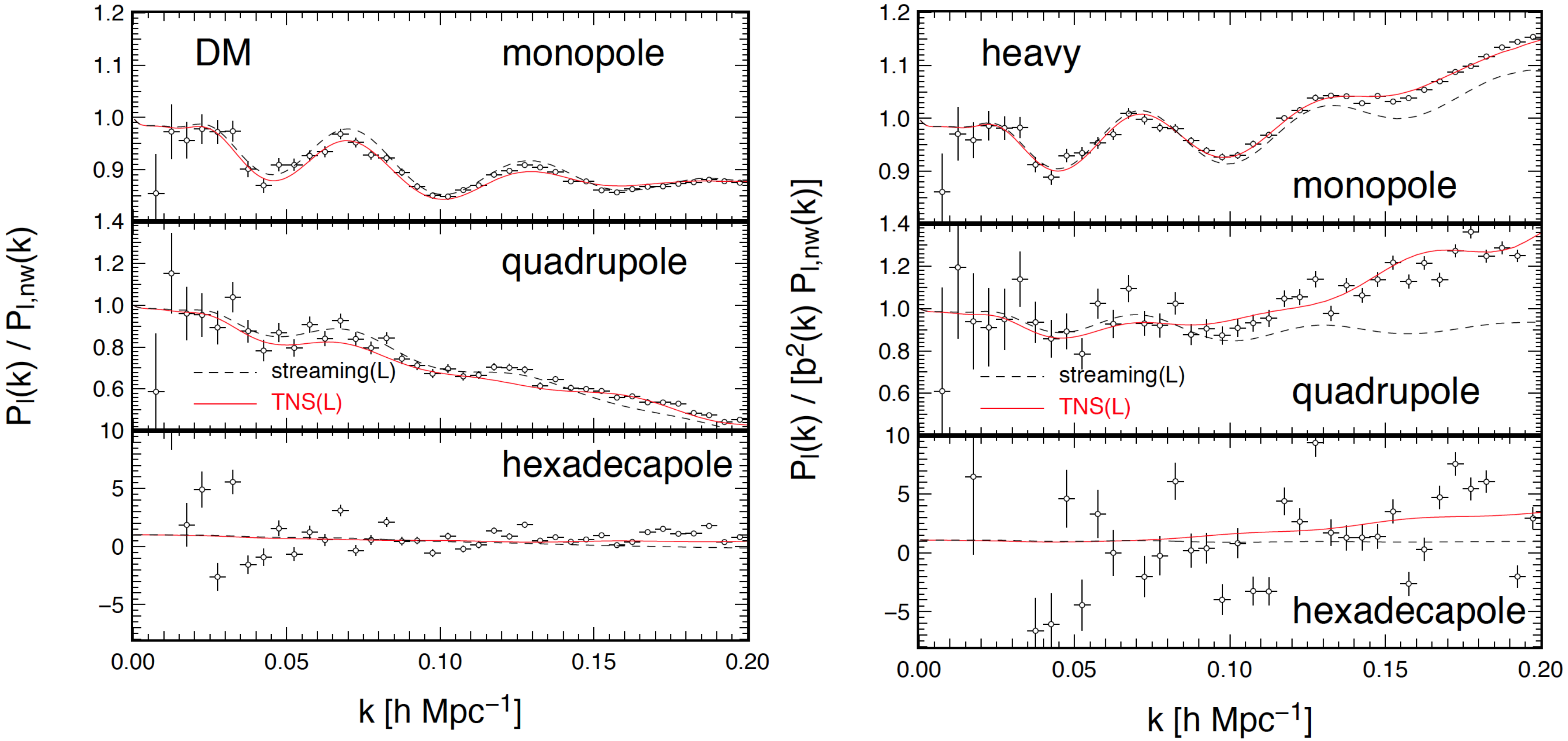
- Still impossible to accurately model galaxy formation from first principles
- Galaxies reside in dark matter halos
- Clustering of dark matter halos are relatively easy to model based on simulations and/or analytical models

DM halo clustering

- Various efforts and promising progresses in developments of DM halo clustering based on simulations & analytical methods
- k_{max}=0.1 ⇒ 0.2 h/Mpc is equivalent to a factor 8 larger survey volume

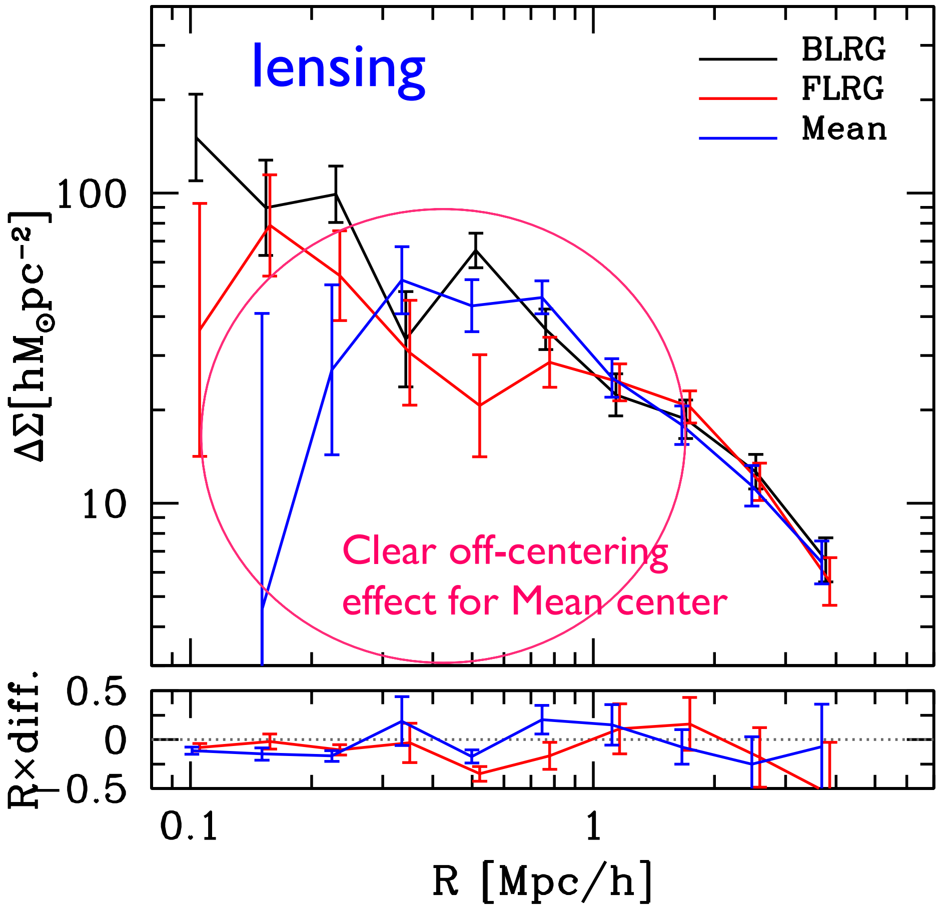
Nishimichi & Taruya 11

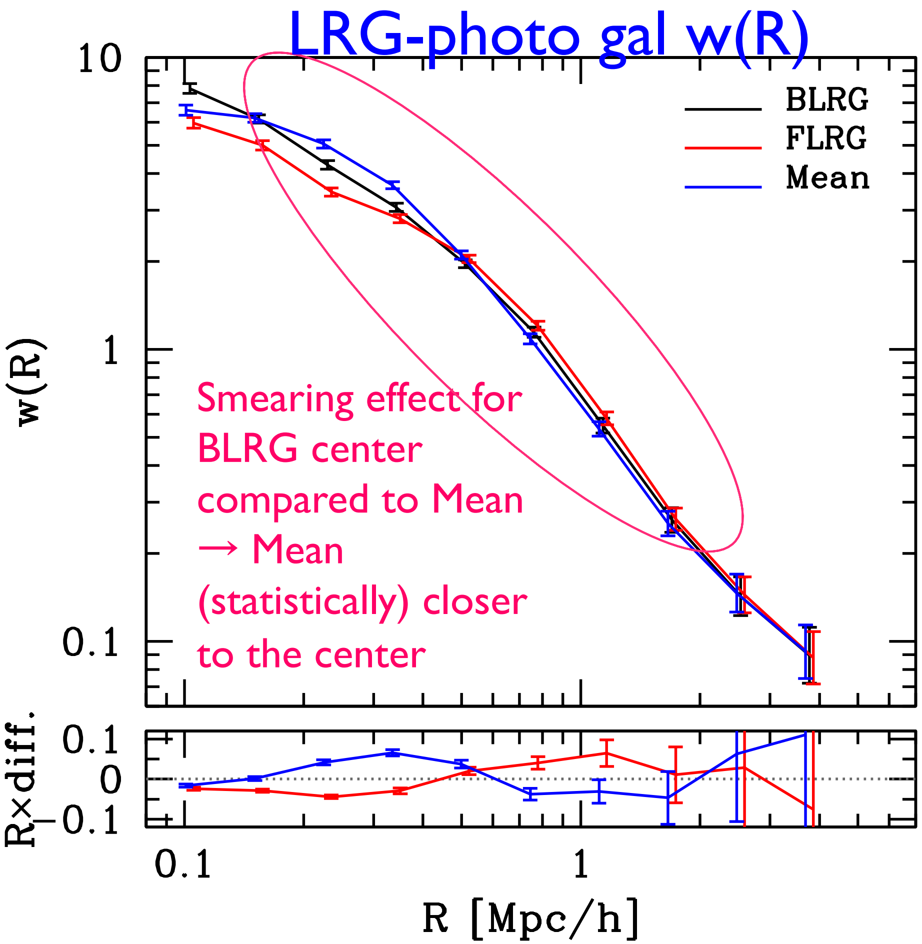
Baldauf+10; Okumura+12; Matsubara & Sato12; Nishizawa+13



Constraining off-centered LRGs for multiple-LRG systems

- Cross-correlations of LRG-inferred centers (BLRG, FLRG or Mean) with shapes (lensing) of imaging background galaxies or positions of imaging gals (different catalogs of the imaging gals)



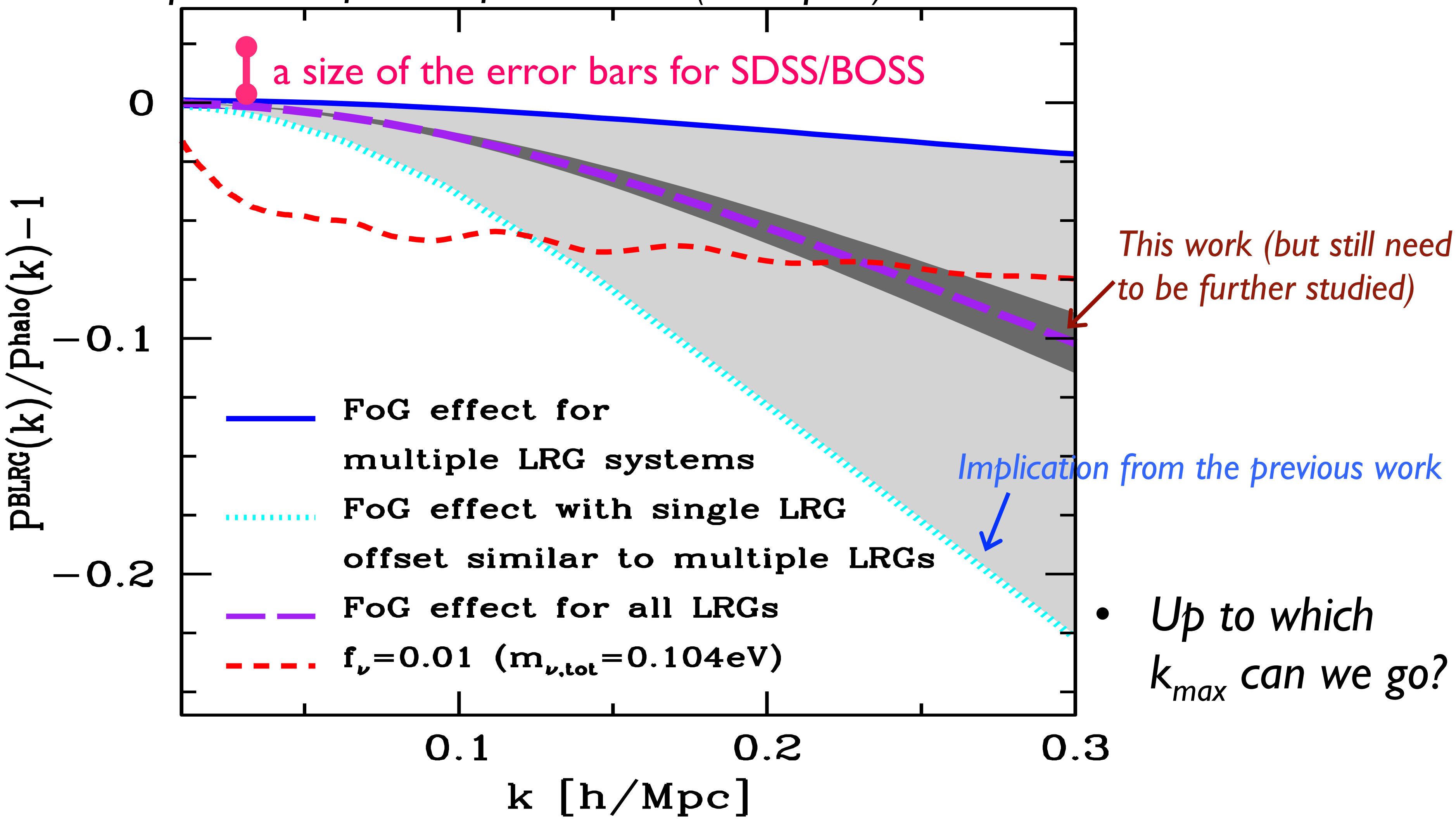


Current level of potential FoG contamination

Hikage, MT, Spergel 12
Hikage, Mandelbaum, MT, Spergel 12

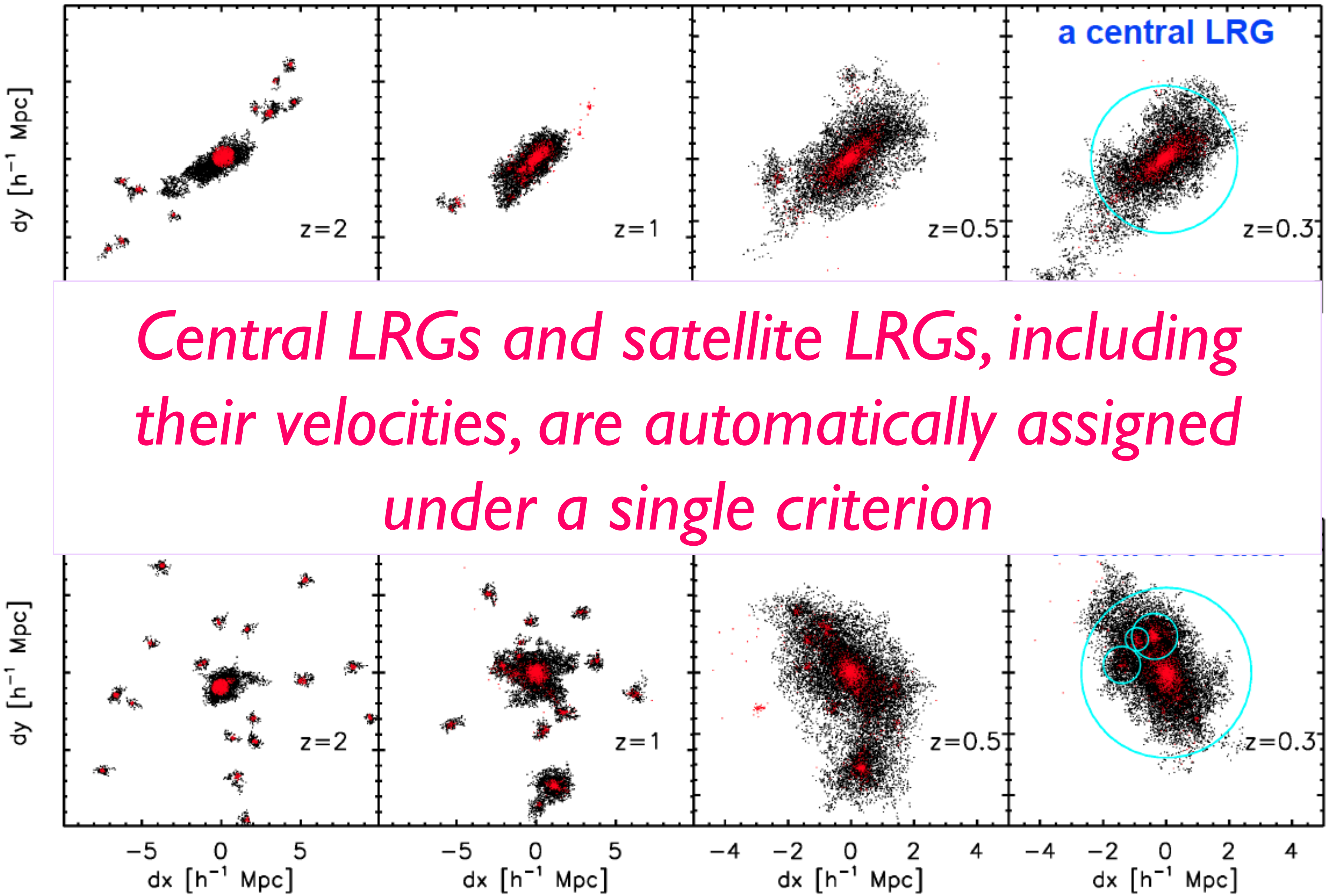
New!

Power spectrum of LRG-inferred halos (monopole)



- *Up to which k_{max} can we go?*

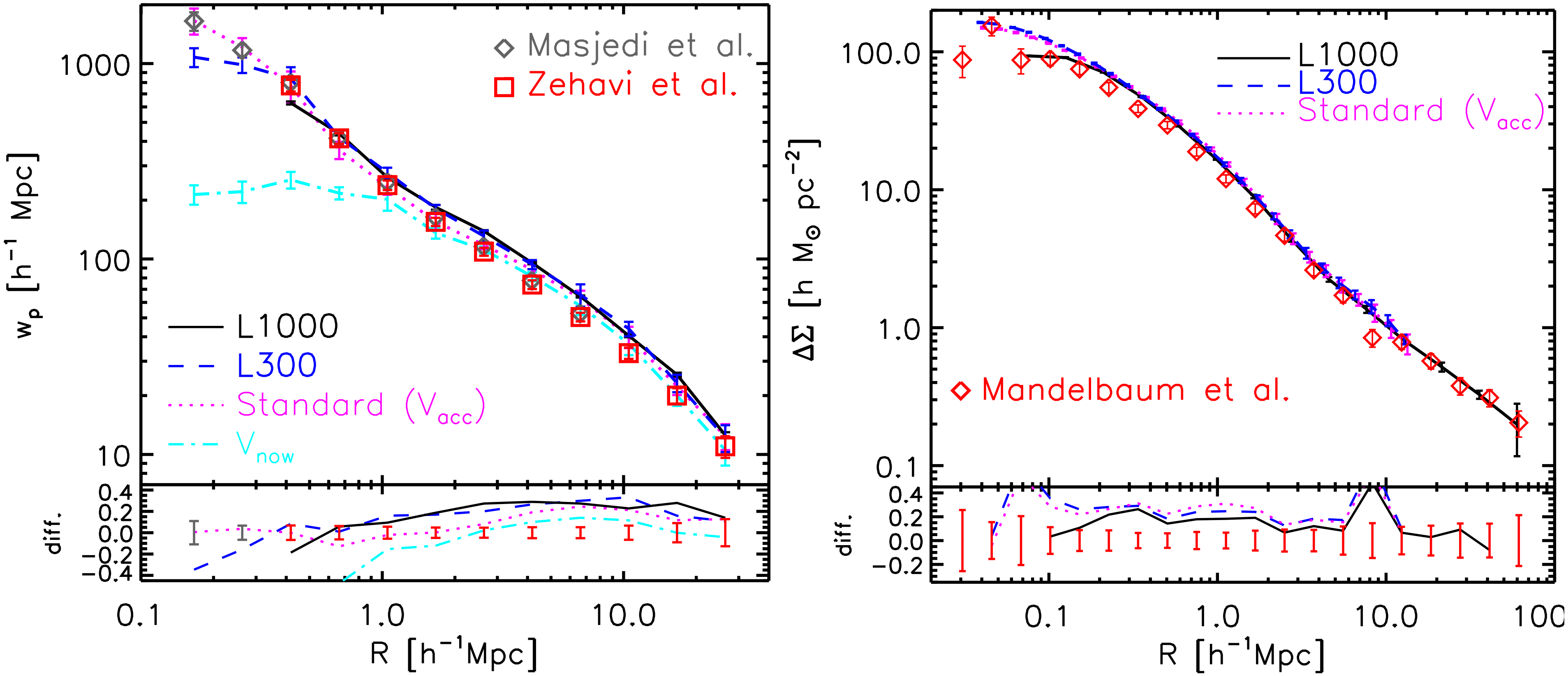
assembly of LRG host subhalos: examples



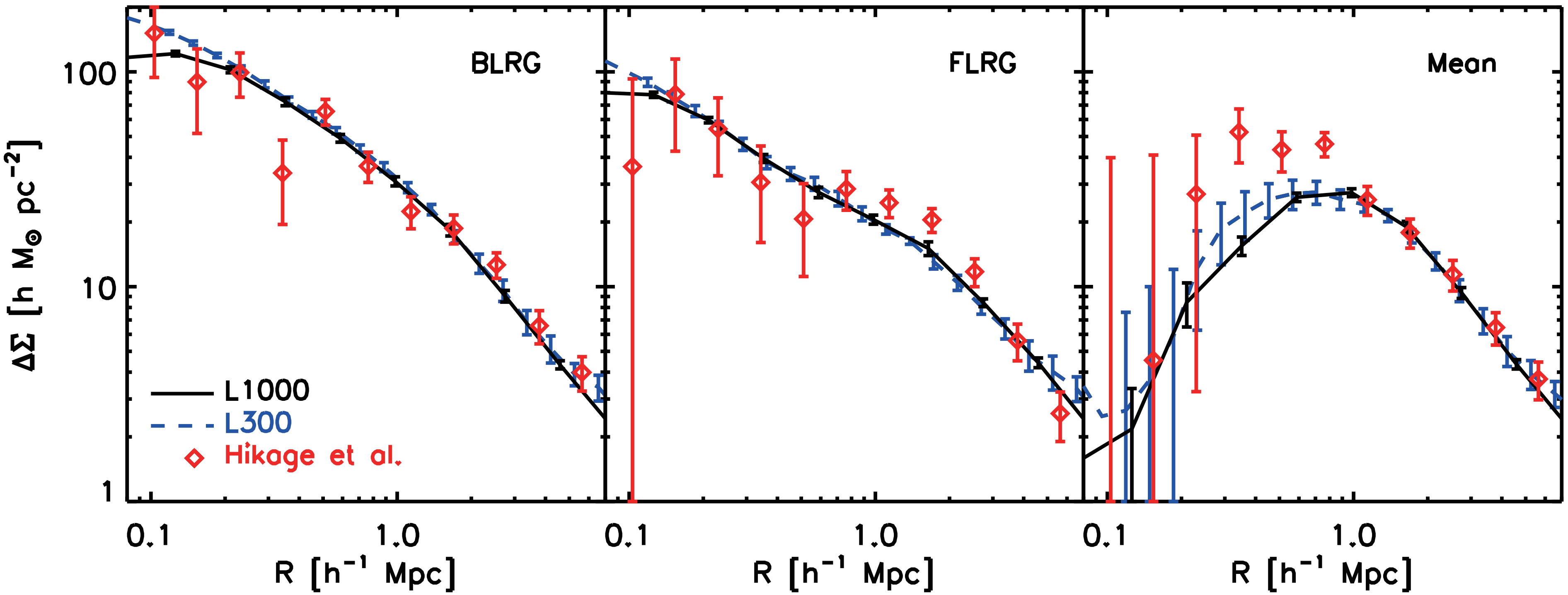
Central LRGs and satellite LRGs, including their velocities, are automatically assigned under a single criterion

Comparison with the clustering and lensing measurements

- Our mock catalog fairly well reproduce the measurements!



For multiple-LRG systems



- Again our mock catalog fairly well reproduces the lensing measurements for multiple-LRG systems
- Similarly, nice agreements for the redshift-space power spectra (i.e. smaller FoG contamination for single-LRG systems or BLRGs)

Summary

- SuMIRe (Subaru Measurements of Images and Redshifts) – projects with new Subaru prime-focus instluments
  - Hyper Suprime-Cam (HSC): start from 2014 for 5 years
  - Prime Focus Spectrograph (PFS): the first light planned to be in 2018
  - Imaging and spectroscopic surveys for the same region of the sky at the same telescope
- Science objectives
  - Three pillars: Cosmology, Galaxy evolution studies & Galactic Archaeology
  - Cosmology with combined probes: weak lensing, galaxy clustering, redshift-space distortion, clusters, and CMB lensing

2014 Aspen Summer WS July 20 – Aug 10
"Combining Probes in Cosmological Surveys"
S. Bridle, S. Dodelson, MT

ASPEN CENTER FOR PHYSICS

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July 20 - August 10
Combining Probes in Cosmological Surveys
Organizers:
Sarah Bridle, University of Manchester
Scott Dodelson, Fermi National Laboratory
Masahiro Takada, Kavli Institute for the Physics and Mathematics of the Universe

The Lambda-dominated Cold Dark Matter paradigm successfully explains a broad range of cosmological observations including the recent Planck measurement of cosmic microwave background anisotropies. However, the success is only phenomenological in that the model requires introducing new unknown physics in the form of inflation, dark matter and dark energy or modified gravity. Understanding the nature of this new physics is arguably the most tantalizing problem in cosmology today. Cosmological observations, such as galaxy surveys and cosmic microwave background experiments, offer the most promising way of making progress on these problems. The workshop will focus on learning even more about the new physics by combining the many probes made possible by these observations.