SuMIRe Subaru Prime Focus Spectrograph (PFS)

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2nd PFS collaboration meeting, Jan 2012

3rd PFS collaboration meeting, Aug 2012

PFS Science Document in arXiv

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

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Draft version June 21, 2012

ABSTRACT

The Subaru Prime Focus Spectrograph (PFS) is a massively-multiplexed fiber-fed optical and near-infrared spectrograph ($N_{\rm fiber}$=2400, 380$\leq \lambda \leq$ 1300nm), offering unique opportunities in survey astronomy. Following a successful external design review the instrument is now under construction with first light predicted 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. As 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 both spiral galaxies as well as the structure of their dark matter halos. Complementing the goals of the Gaia mission ($V < 17$), radial velocities and metallicities will be secured for 10^6 Galactic stars to 17$< V <$ 20. Data for fainter stars to $V \simeq$21 will be secured in areas containing Galactic tidal streams. The M31 campaign will target red giant branch stars with 21$< V <$22.5 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 and 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.

Subject headings: PFS — cosmology — galactic archaeology — galaxy evolution

1. INTRODUCTION

There is currently a major expansion in survey imaging capability via the use of CCD and near-infrared detector mosaics on a wide range of ground-based telescopes. Such imaging surveys provide accurate photometric and other data to enable the study of gravitational lensing signals which trace the distribution of dark matter and to conduct census studies of Galactic structures and distant star-forming galaxies. For over a decade it has been recognized that a similar revolution

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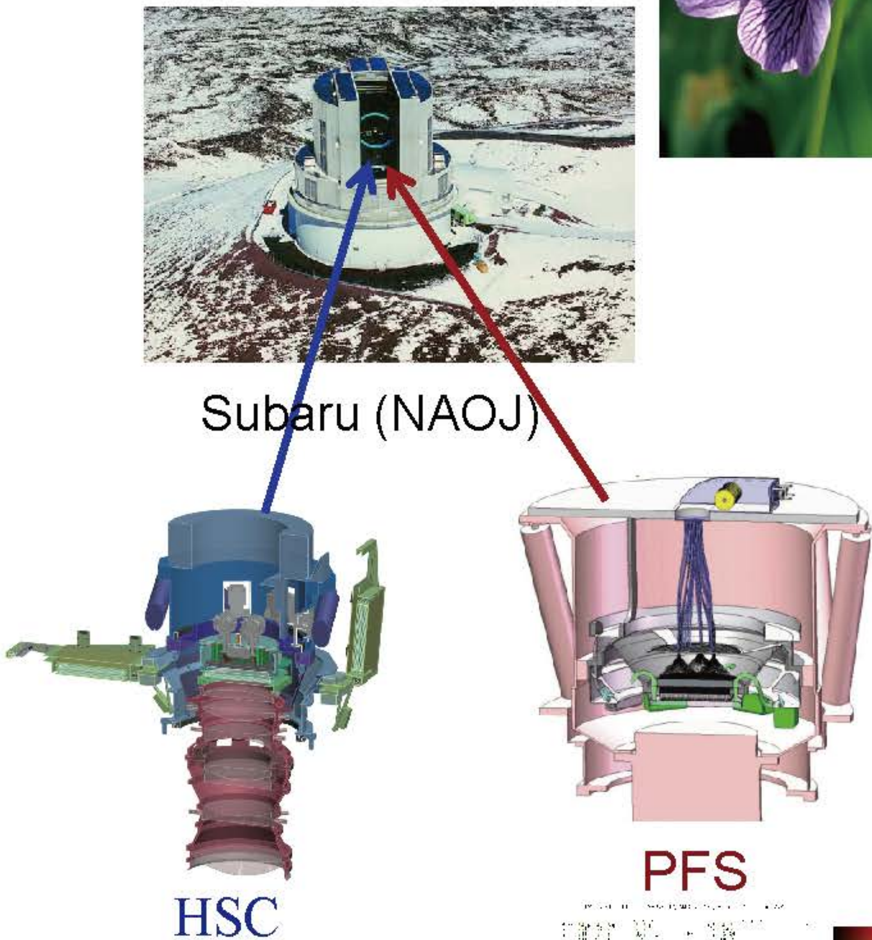
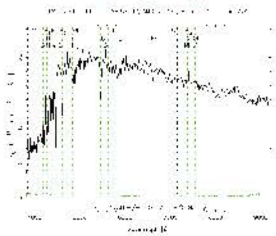
SuMIRe = Subaru Measurement of Images and Redshifts

- IPMU Director Murayama got ~40M$ in March, 2009
- Build wide-field camera and multi-object spectrograph
- Goals: the fate of the Universe
- Precision images of a few 10^9 galaxies (2013-17)
- Measure distances (redshifts) of a few10^6 galaxies (2018-22?)
- Precursor survey of ~1B$-class ultimate surveys, Euclid, LSST and WFIRST





PFS collaboration

Caltech

Jet Propulsion Laboratory
California Institute of Technology

NAOJ

ACADEMIA SINICA

PRINCETON UNIVERSITY

lead institution

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

LNA LABORATÓRIO NACIONAL DE ASTROFÍSICA

LAM

JOHNS HOPKINS UNIVERSITY

Brief History

- May ’09: Cancellation of WFMOS
- July ’09: Stimulus package from Japanese government
- July ’09: Hitoshi Murayama’s proposal of SuMIRe, focused on BAO cosmology
- Feb ’10: $40M approved ($18M for HSC & $22M for PFS)
- May ’10: start building collaboration
- Oct ’10: declared collaboration of Brazil, Caltech, JPL, LAM, Princeton (ASIAA and JHU added later)
- Jan ’11: endorsement by Subaru community
- April ’11: project office launched (Sugai-san joined IPMU)
- Dec ’11: MOU between IPMU and NAOJ
- March ’12: CoDR successfully passed

SAC recommendation on PFS

At the 2010 Subaru Users' Meeting
Jan 19, 2011

Subaru can maintain its position as one of the top telescope facilities in the world by having both a wide-field imager and a wide-field spectrograph.

The PFS instrument concept was initially developed primarily for a BAO survey, but after consideration of the instrument specifications, it was realized that PFS could have much broader scientific impact, in areas such as galactic archaeology and galaxy/AGN evolution.

Thus, with the conditions listed below, SAC recommends further development of the PFS project as a next-generation Subaru instrument.

Collateral Conditions

- PFS must satisfy instrument specifications agreed by the Japanese community.
- A firm management structure should be built in Japan to develop PFS, including the assignment of a Japanese project manager.
- SAC representative(s) should participate in important decision-making stages about international collaboration.
- There must be a framework for young Japanese students/researchers to get involved in the PFS instrumentation.

Please note the following premises for further discussion on the PFS project:

IPMU of the University of Tokyo, along with a major contribution to the realization of HSC, has started the Prime Focus Spectrograph (PFS) project in order to explore properties of Dark Energy by measuring the distance to galaxies, thus the geometry of the deep universe, and applying the analysis of the acoustic oscillation of baryon in the early universe. PFS will be another Subaru prime focus instrument with the same 1.5 degree diameter field view as HSC. It provides multiple object spectroscopic function by using more than 2,000 optical fibers. PFS is expected to be a unique instrument not only in studying the new field of dark energy astronomy but also to be a versatile instrument in promoting other research areas of astronomy such as the evolution of galaxies and active galactic nuclei, and galactic archaeology. IPMU intends to develop and build PFS as another unique instrument on the Subaru Telescope in collaboration with international institutions.

The PFS project is to equip the Subaru Telescope with a new spectroscopic instrument taking advantage of and enhancing the telescope's strength in the wide field observations. This matches Subaru Telescope's long-range strategy. Both the Japanese community of optical and infrared astronomy and the Subaru Advisory Committee has expressed a strong interest and are enthusiastic to bring a support to the project under the condition that the Subaru community is involved in the project decision making process and that the project allows participation of junior researchers in Japan. Subaru Advisory Committee considers the project a good opportunity for the astronomical community of Japan, as the instrument's expected capability has much scientific potential and it also enables young researchers to be involved with the development of a state-of-the-art large instrument.

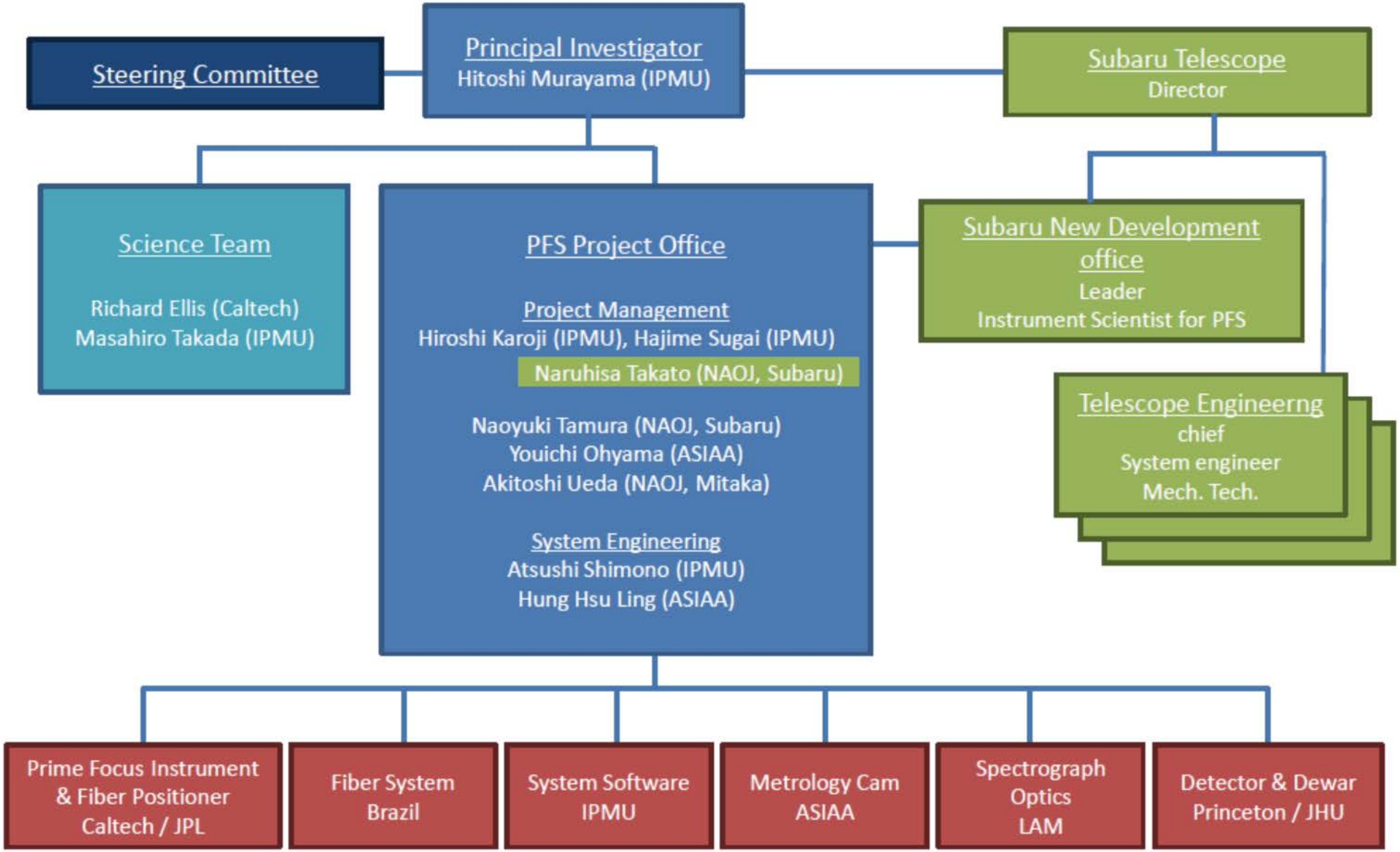
NAOJ and IPMU, therefore, agree to the followings.

1) NAOJ supports the PFS project that IPMU is intending to develop and build through international collaboration. In particular, NAOJ provides personnel to help design the instrument.

2) After its completion, NAOJ anticipates the PFS project in collaboration with the Japanese astronomical community to carry out a Subaru Strategic Science Program, which currently has a cap of 60 nights a year of the observing time up to about five years. NAOJ's Subaru Advisory Committee would review the Strategic Science Program with criteria including, the science justification, the number of nights, the memberships, their roles and how to share scientific benefits.

3) NAOJ will conduct a review on the project to make a decision on its further commitment to the project in conjunction with the Preliminary Design Review by the PFS project.

PFS Organization Structure



Science Team
Ellis, Takada

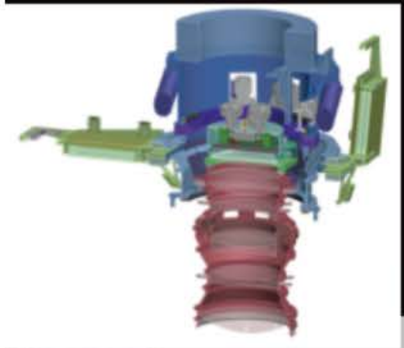
Cosmology
Takada, Kneib, Hirata

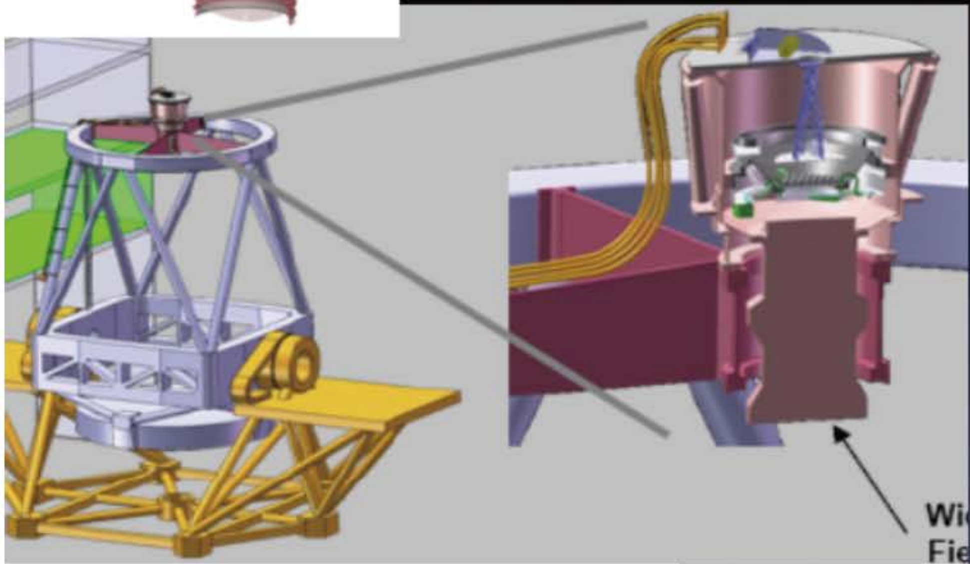
Galaxy
Bundy, Silverman, Ouchi, Greene

Archeology
Chiba, Cohen

AGN/QSO
Nagao, Strauss

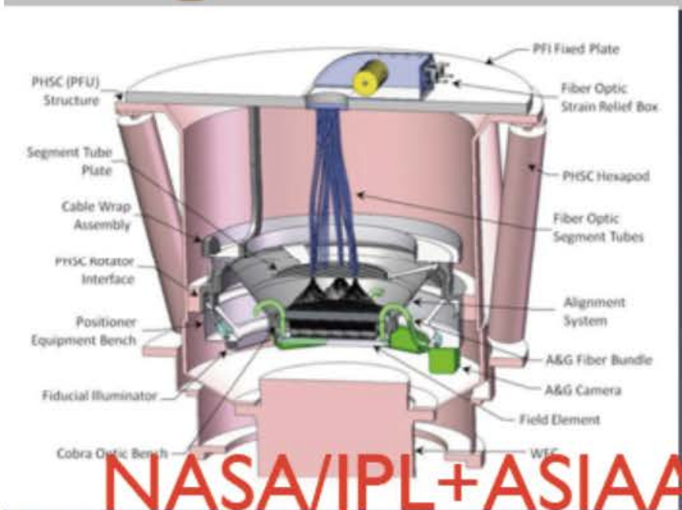
instrument team



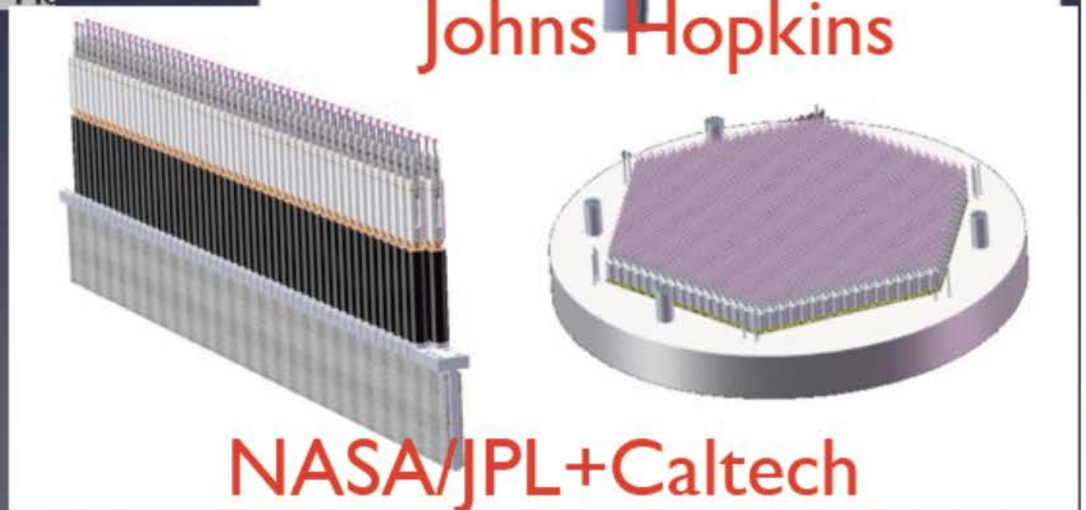


ASIAA

Princeton, Marseille, Johns Hopkins

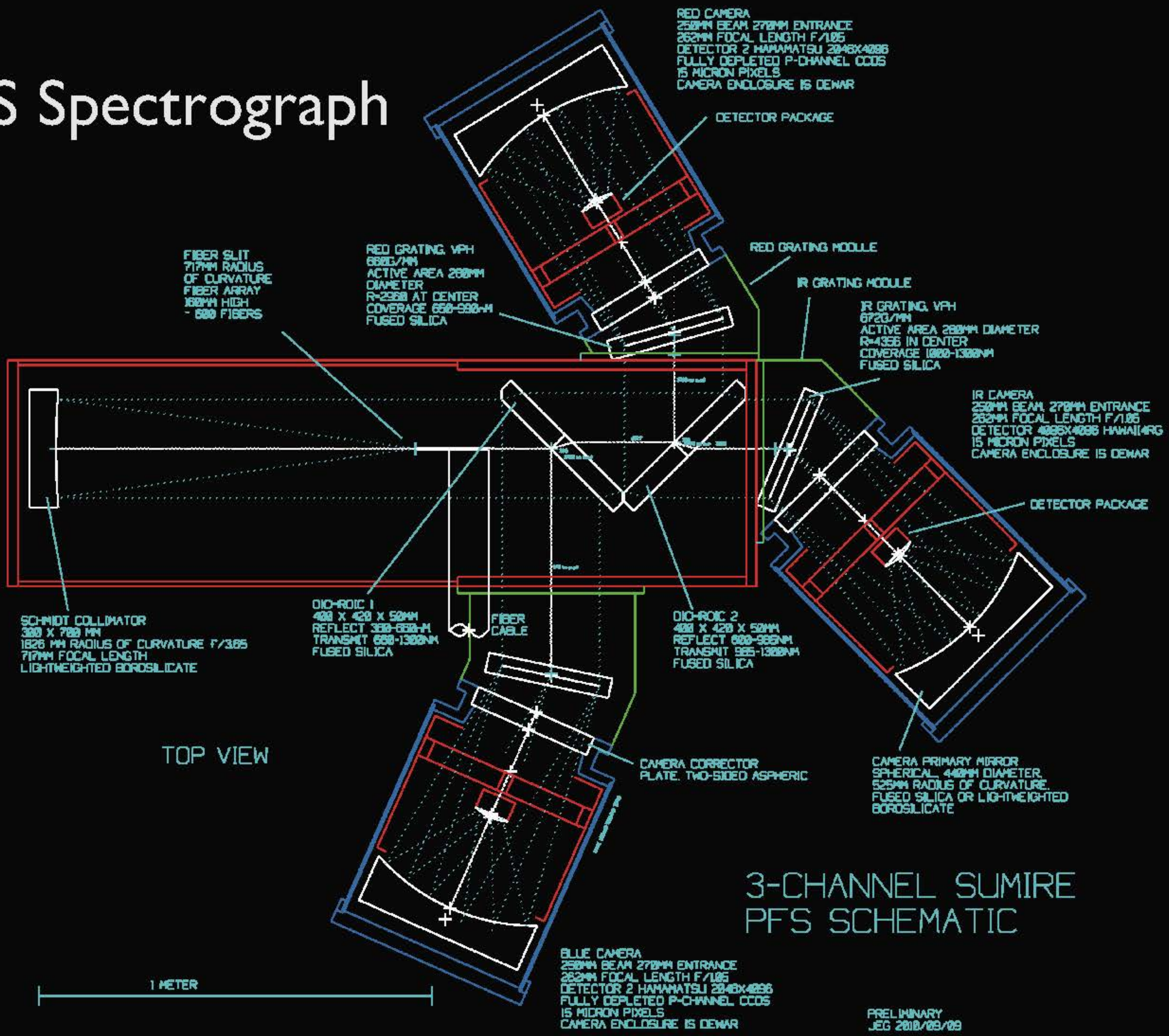


NASA/JPL+ASIAA



NASA/JPL+Caltech

PFS Spectrograph



Basic parameters

- The current baseline design parameters

Number of fibers	2400 (600 for each spectrograph)		
Field of view	1.3 deg (hexagonal diameter) 1.1 sq. degs		
Fiber diameter	1.13" diameter at the field center, 1.03" at the edge		
	Blue arm	Red arm	IR arm
Wavelength cov.[nm]	380 – 670	650 – 1000	970 – 1300
Spectral resol.	~2000	~3000	~4000
Pixel scale [A/pix]	0.71	0.85	0.81
Read-out [e rms/pxi]	3	3	4
Detector	CCD	CCD	HgCdTe
Thermal bckg [e/pix/s]	None	None	0.013

Multi-purpose

- Originally proposed for dark energy science with WL and BAO combining HSC and PFS
- Soon realized that PFS, massively-multiplexed fiber-fed optical and NIR spectrograph, at 8.2m Subaru is so powerful and unique instrument
- Various science cases with PFS
- Endorsed by Subaru community
- Main science cases
  - Cosmology: DE, test of gravity, neutrino masses, combined science with HSC WL
  - Galactic archaeology: near-field cosmology, DM, first stars
  - Galaxy formation: galaxy evolution, population, properties

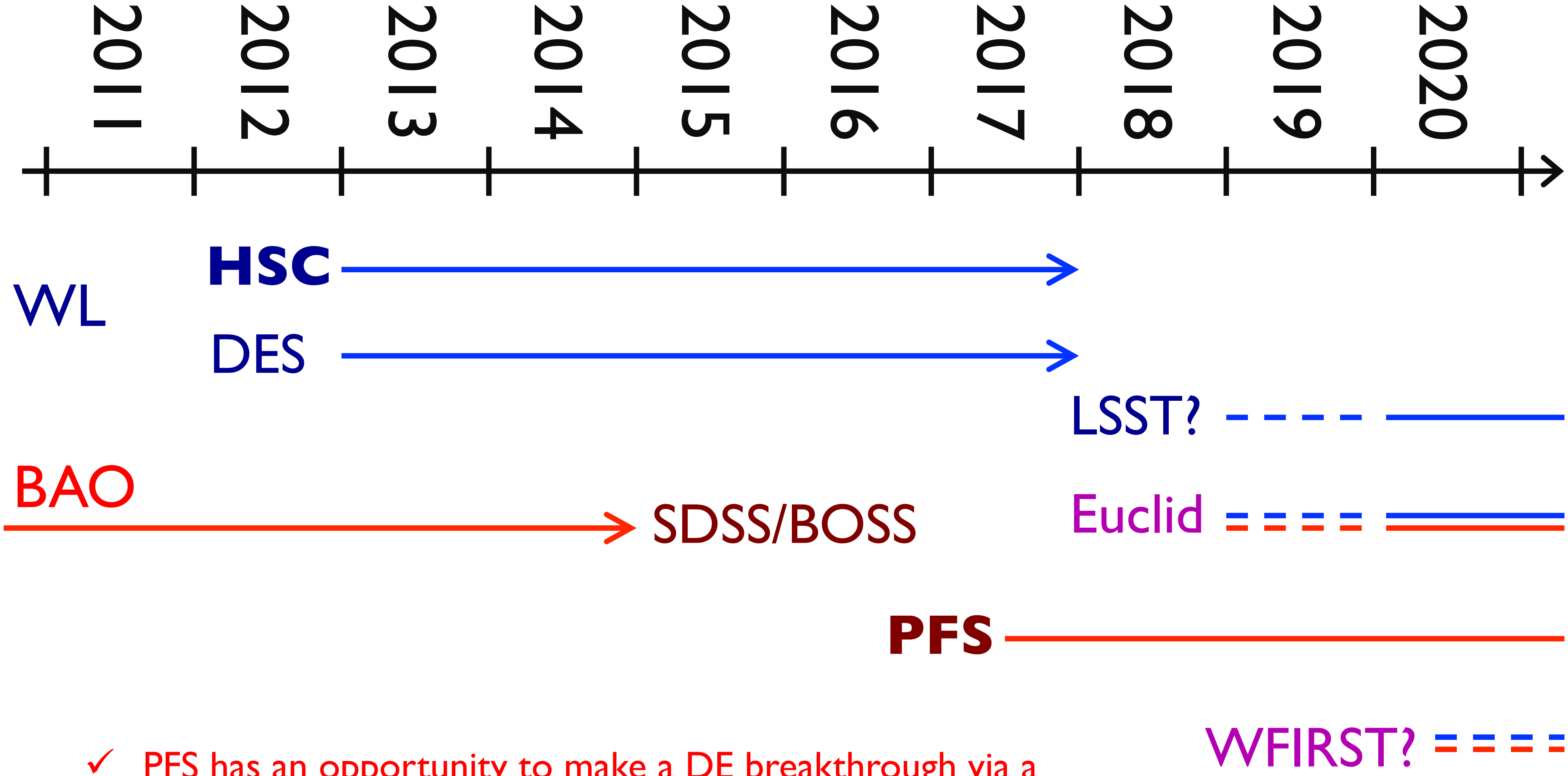
HSCとPFSのシナジー

- HSC-Wide: 宇宙論
  - 銀河とダークマター分布の関係（バイアスの直接観測）
  - Dark energy, 修正重力理論の検証
  - 宇宙論パラメータの制限の向上
- HSC-Deep/Ultradeep: 銀河形成
  - 銀河の性質の物理の制限（田中さんの講演）
- その他のHSCサーベイ
  - 銀河考古学（千葉さんの講演）

Boundary conditions

- PFS survey after HSC survey? (2017-?)
- Subaru Strategic Program (SSP) < 300 nights up to about 5 years duration (current limit)
- PFS is a "Subaru facility instrument" once delivered
- Japanese community is a part of the collaboration "*at will*"
- Reviewed by NAOJ around PRD
- PFS SSP survey proposal needs approval by SAC <1 year before the survey

Time line (DE experiments)



- ✓ PFS has an opportunity to make a DE breakthrough via a 3-5 year survey prior to the launch of Euclid

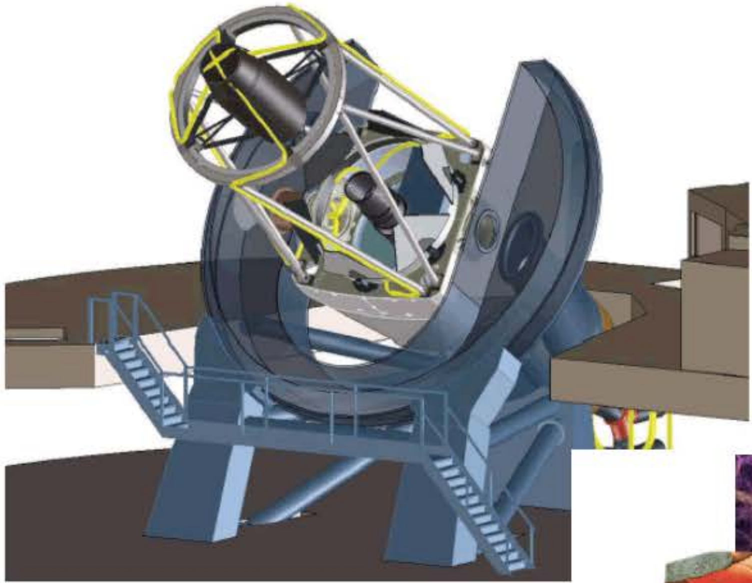
DE/BAO competition

4MOST

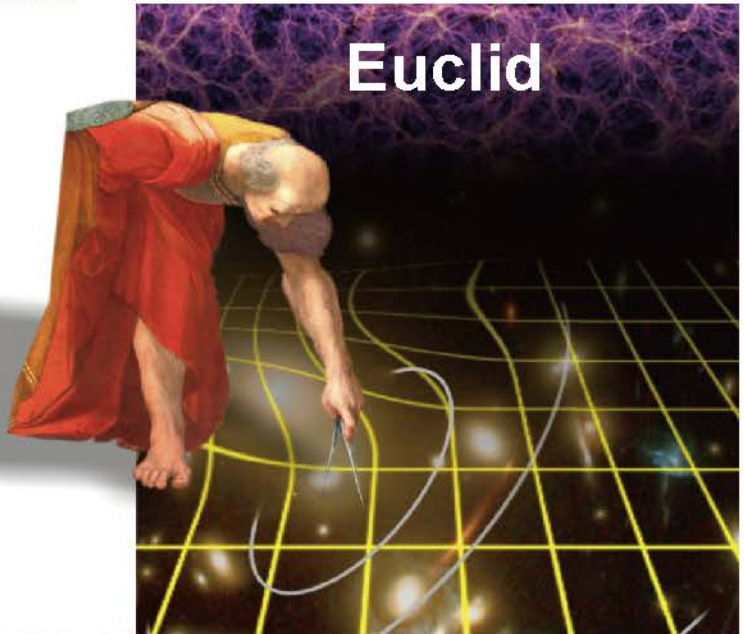
4-meter Multi Object Spectroscopic Telescope

Proposal for a Conceptual Design Study for ESO

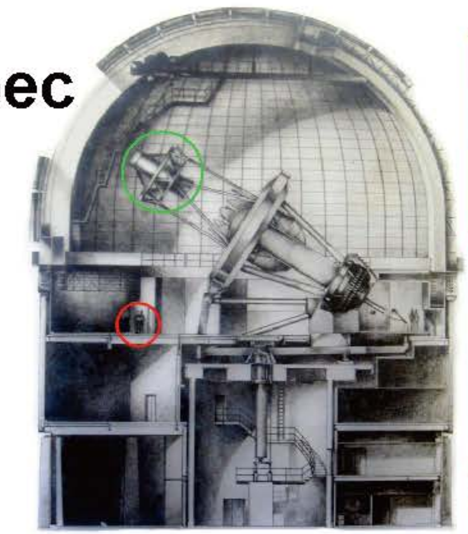
BigBOSS

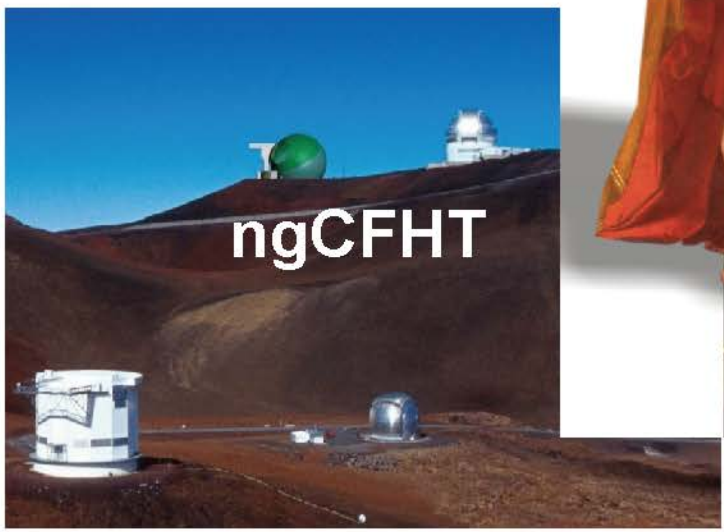


The need for a spectroscopic survey to exploit imaging surveys is increasingly realized



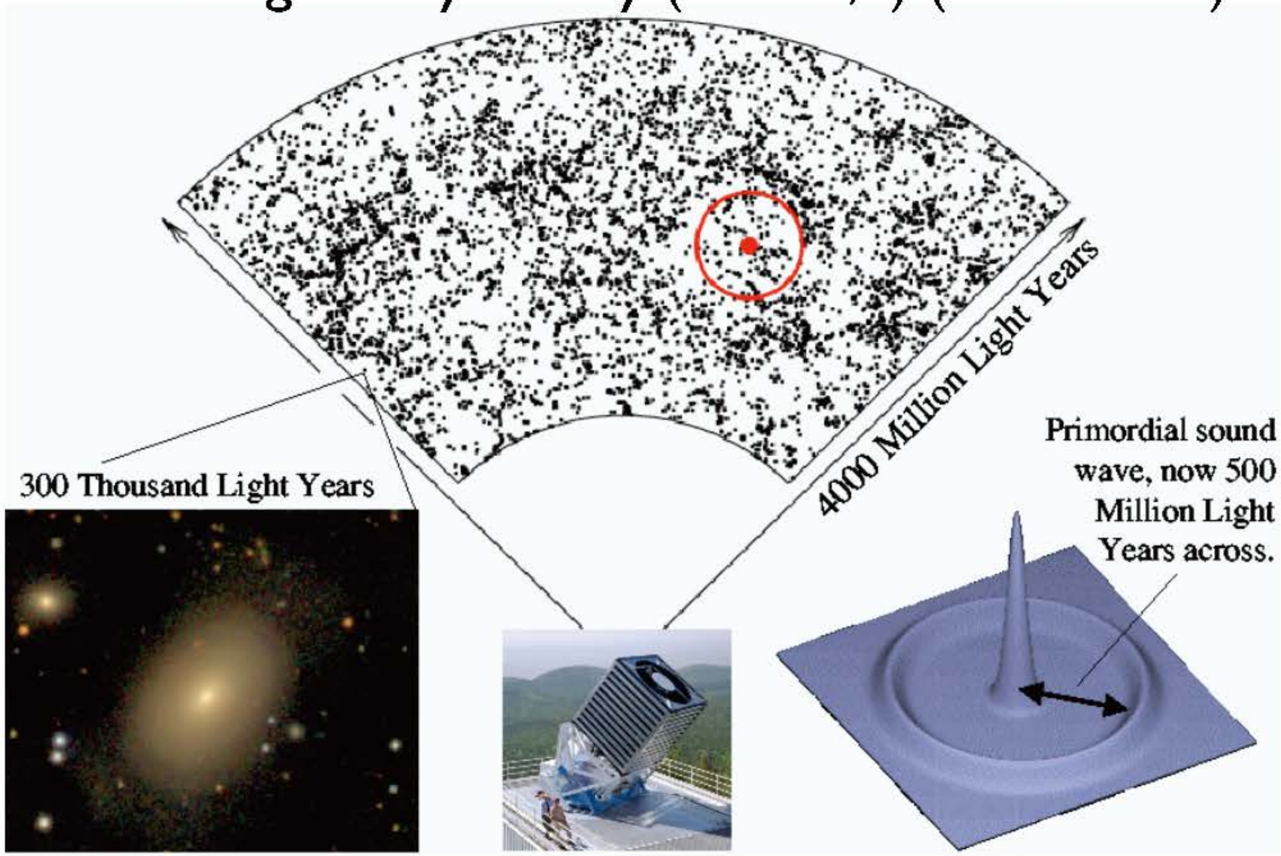
DESpec

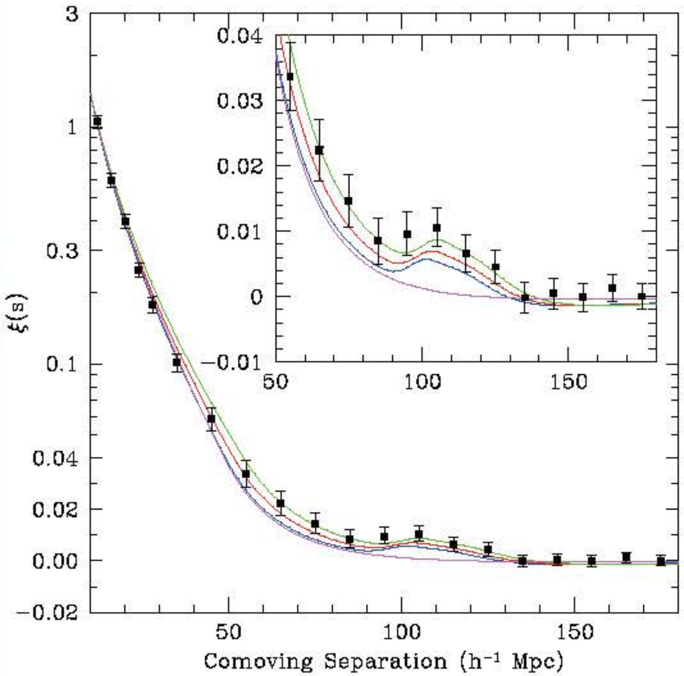




BAO: standard ruler

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





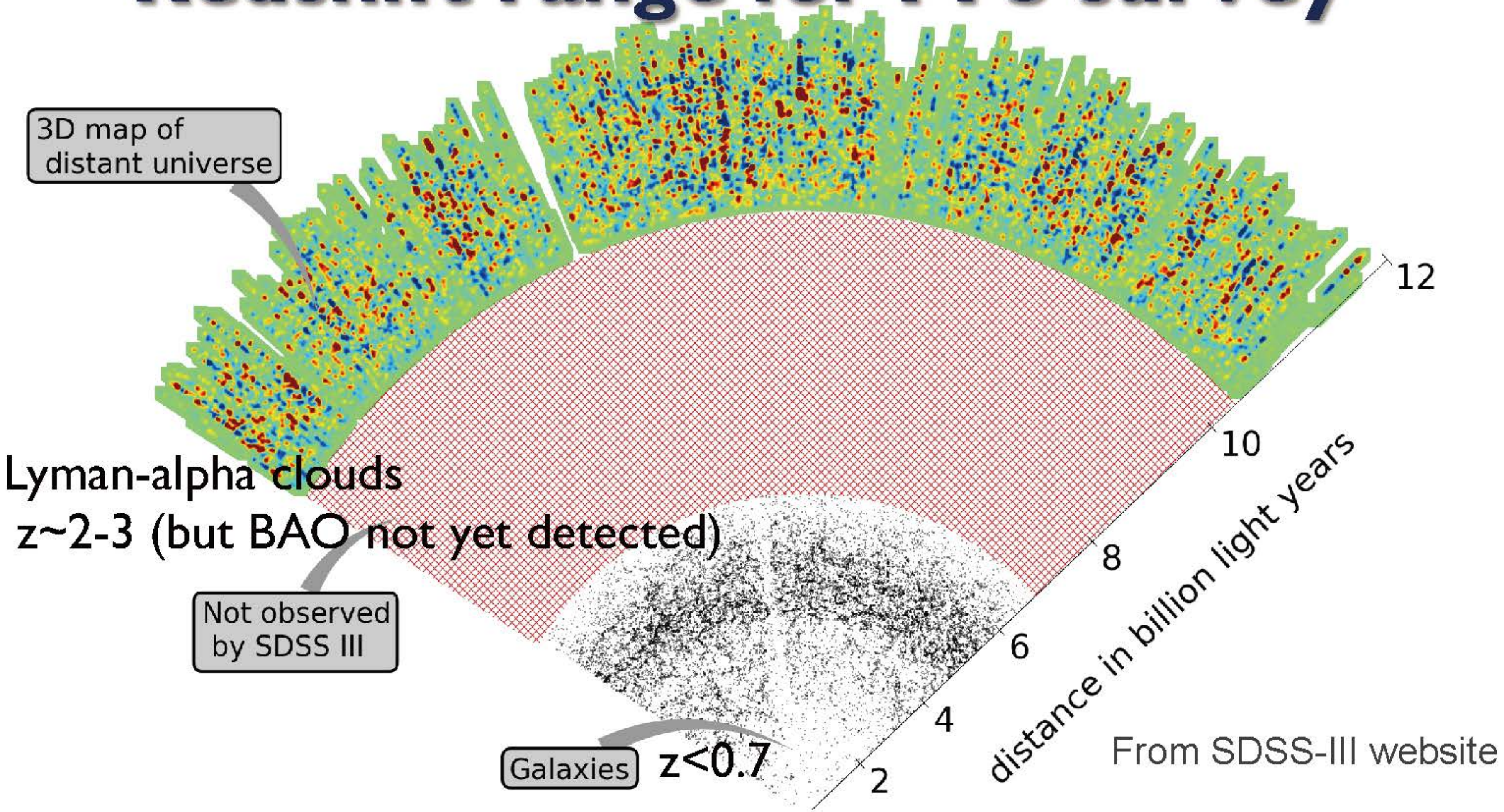
Eisenstein et al. (05)

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

Dark Energy Task Force Report (DETF)

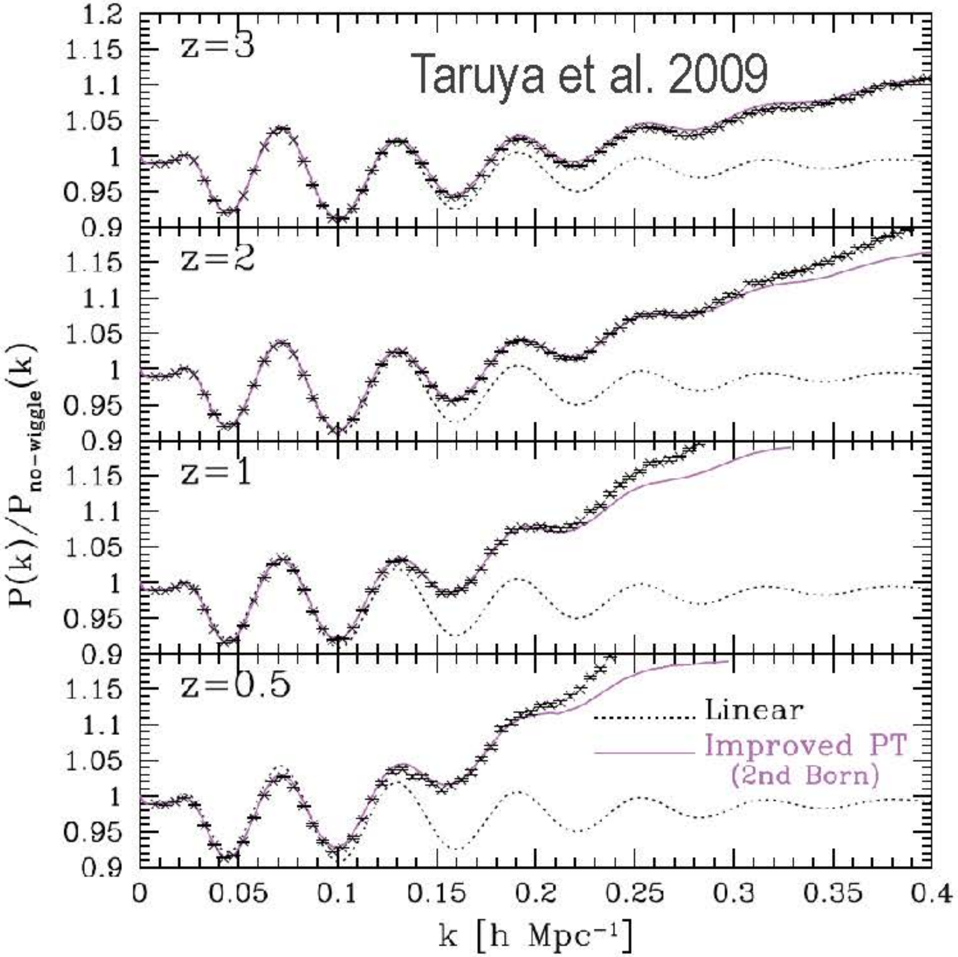
a. The **BAO** technique has only recently been established. It is less affected by astrophysical uncertainties than other techniques.

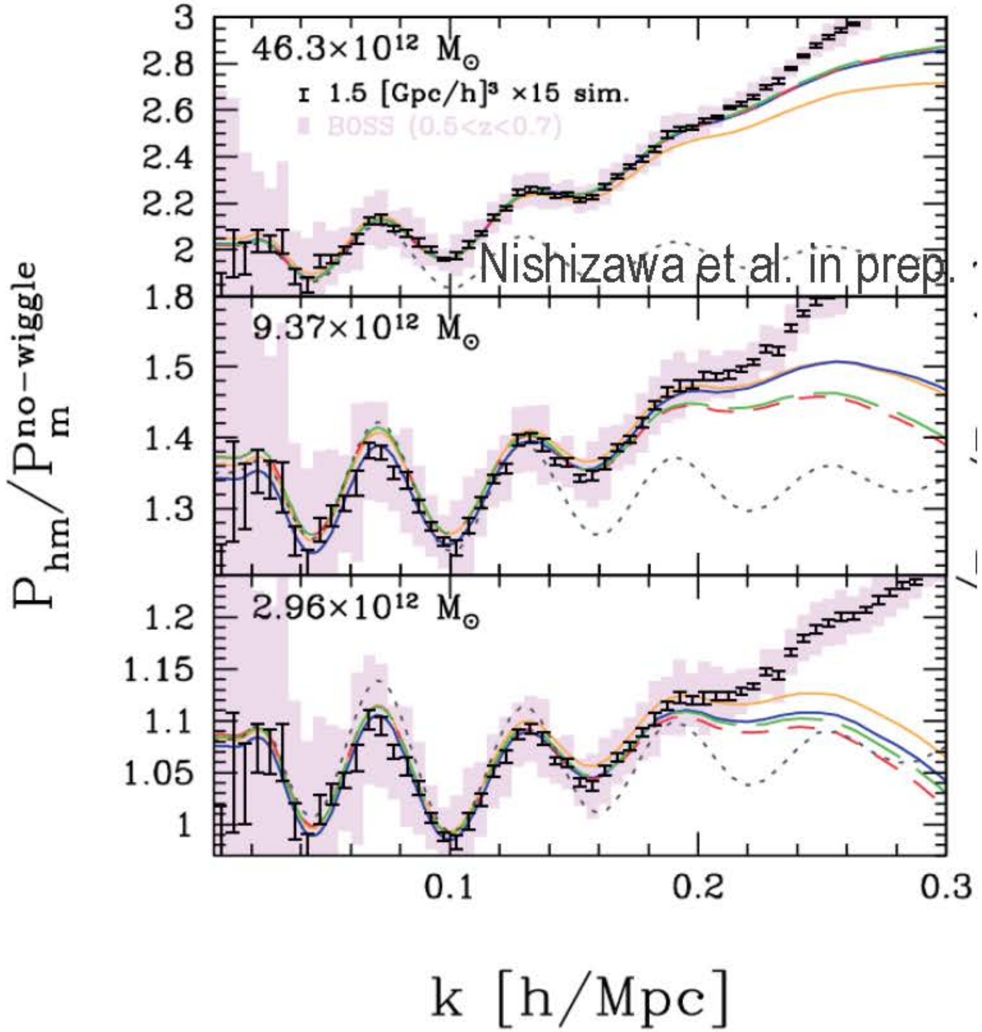
Redshift range for PFS survey



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

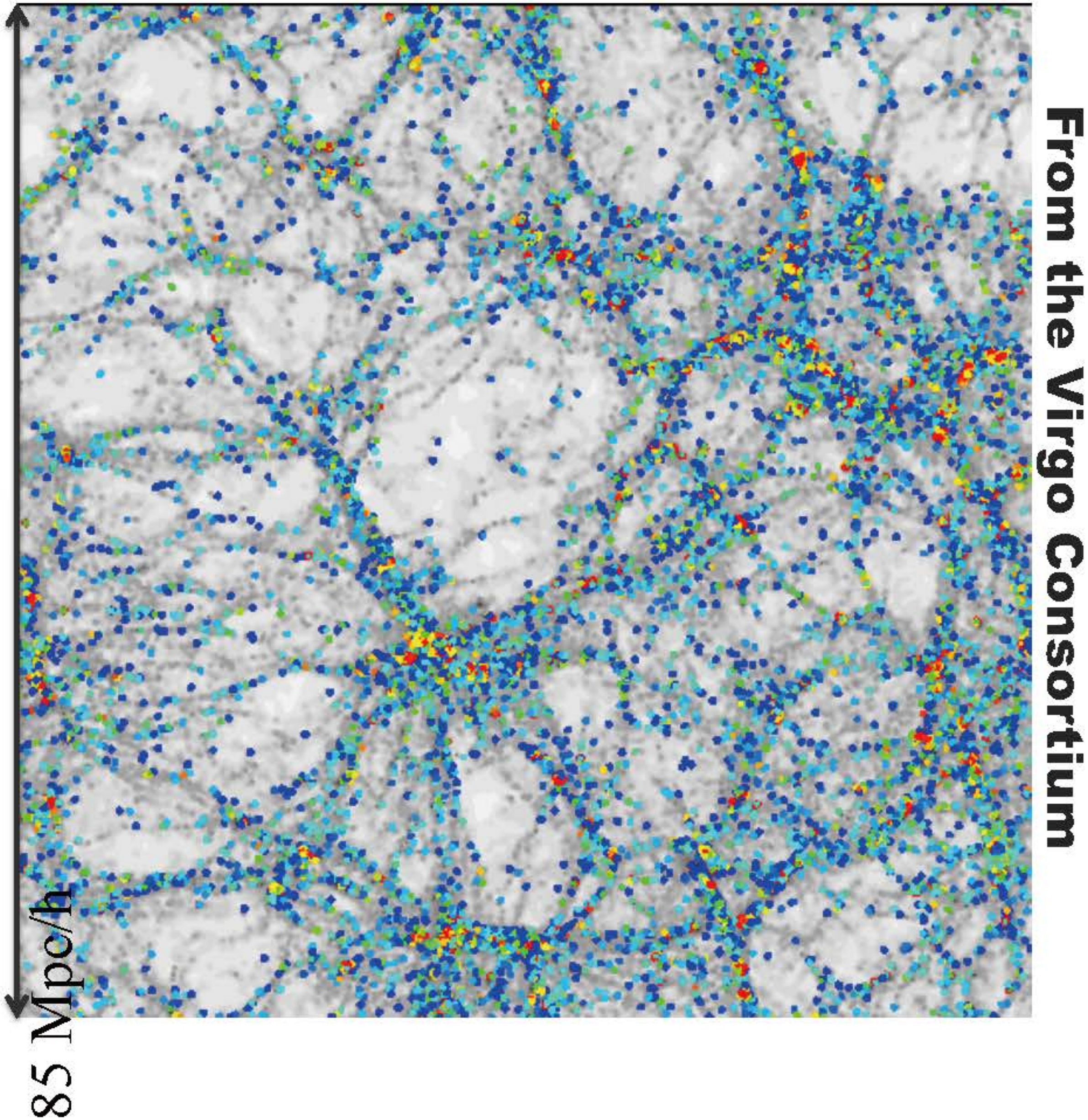
Theory is ready for DM and halo clustering





- *A factor 2* gain in the maximum wavenumber used in the analysis, e.g. k_max=0.1 → 0.2 Mpc/h, is equivalent to *a factor 8* gain in the survey area (in the sampling variance limited regime)
- More robust RSD: growth rate constraints

Galaxy bias uncertainty



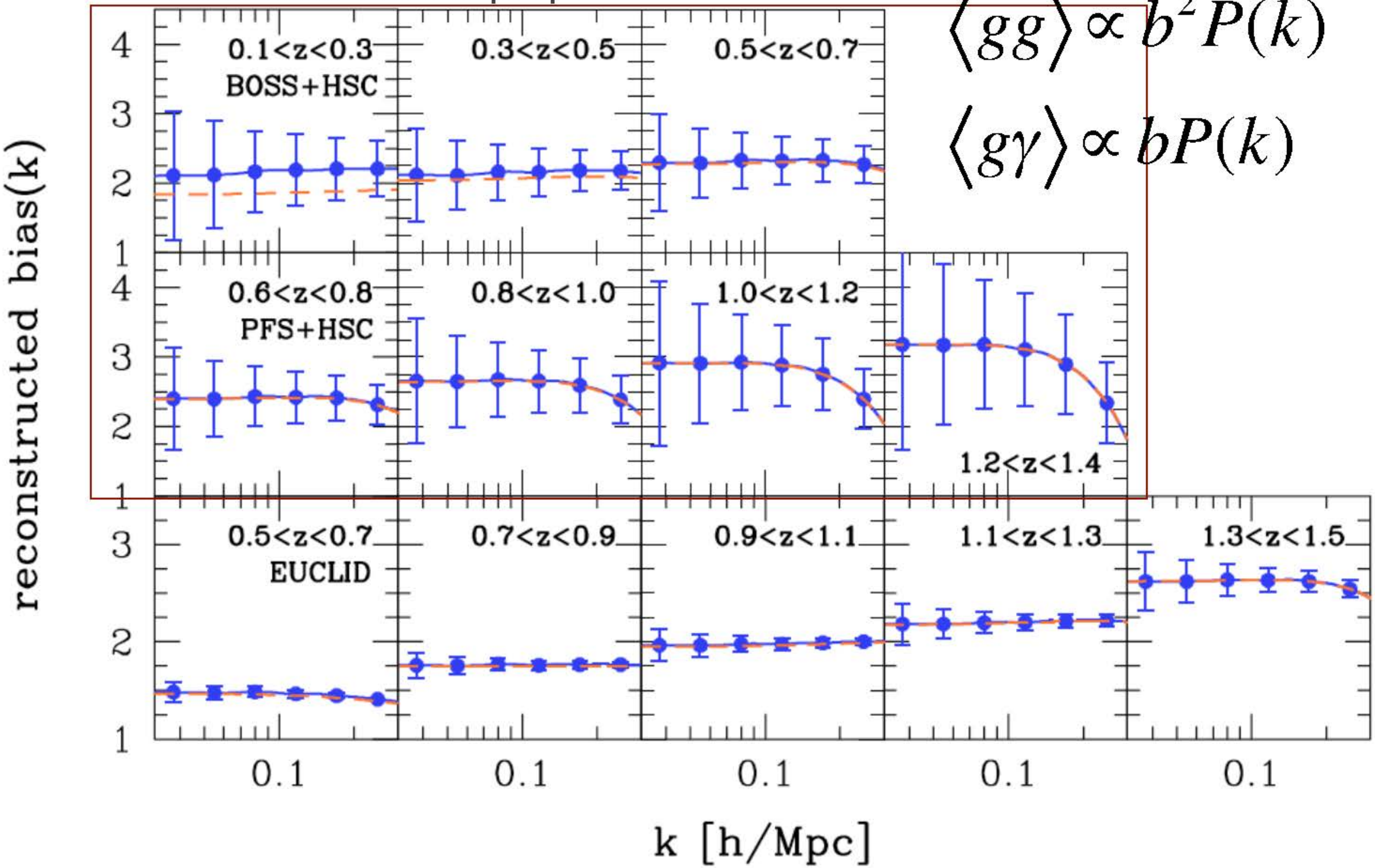
- Galaxies are "*biased*" tracers of DM distribution

$$\delta_g \neq \delta_m$$

- There is no sufficiently accurate theoretical model of galaxy formation
- Lensing can directly measure the galaxy bias → a synergy between the imaging and spectroscopic surveys for the same region of sky

銀河バイアス関数の直接測定

Nishizawa et al. in prep.



$$\langle gg \rangle \propto b^2 P(k)$$

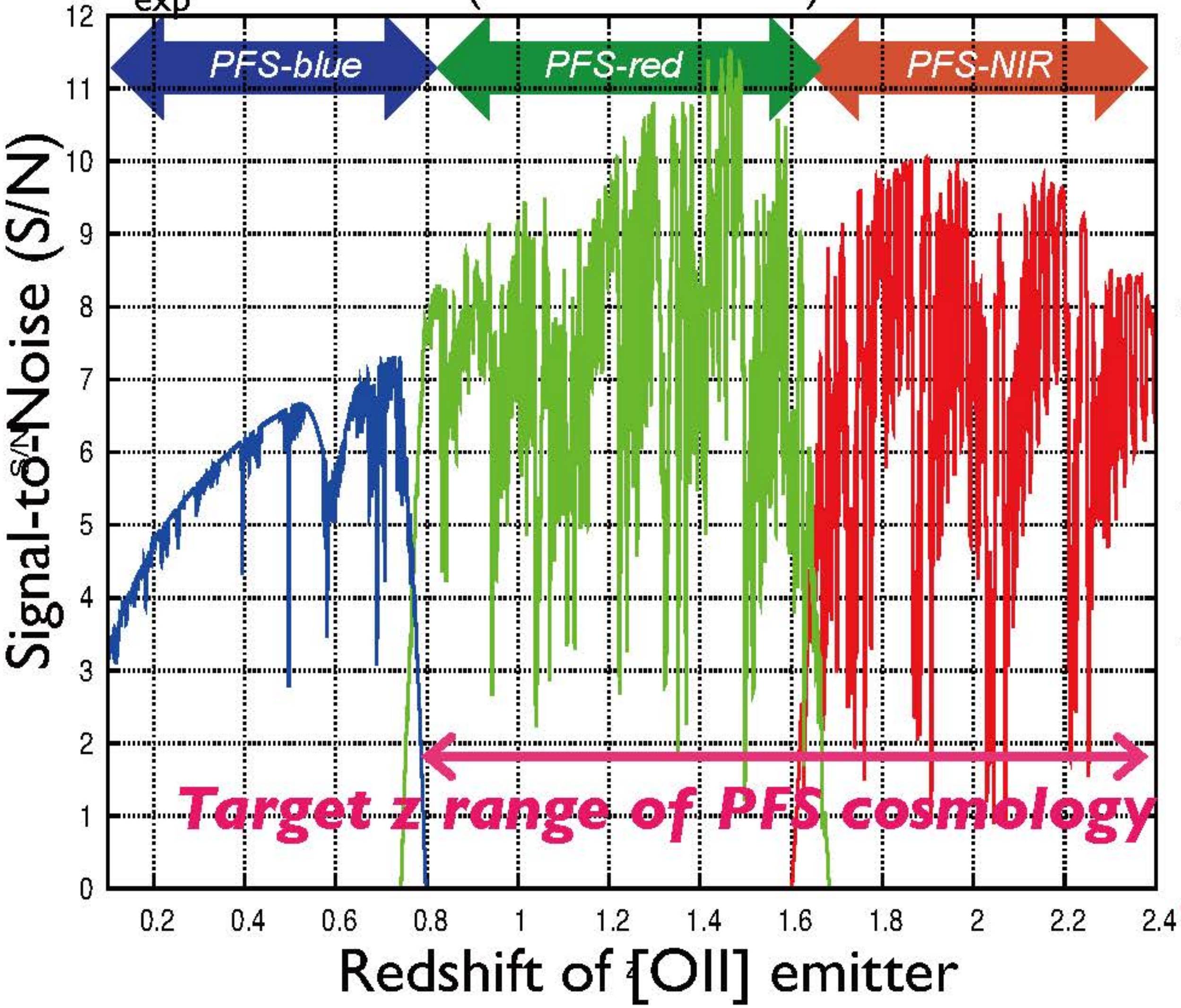
$$\langle g\gamma \rangle \propto bP(k)$$

Unique capability of PFS: high performance

A working example:

$f_{[OII]}=5\times10^{-17}$erg/cm^2/s, σ_v=70 km/s, r_{eff}=0.3”

t_{exp}=2×450sec (15min in total)



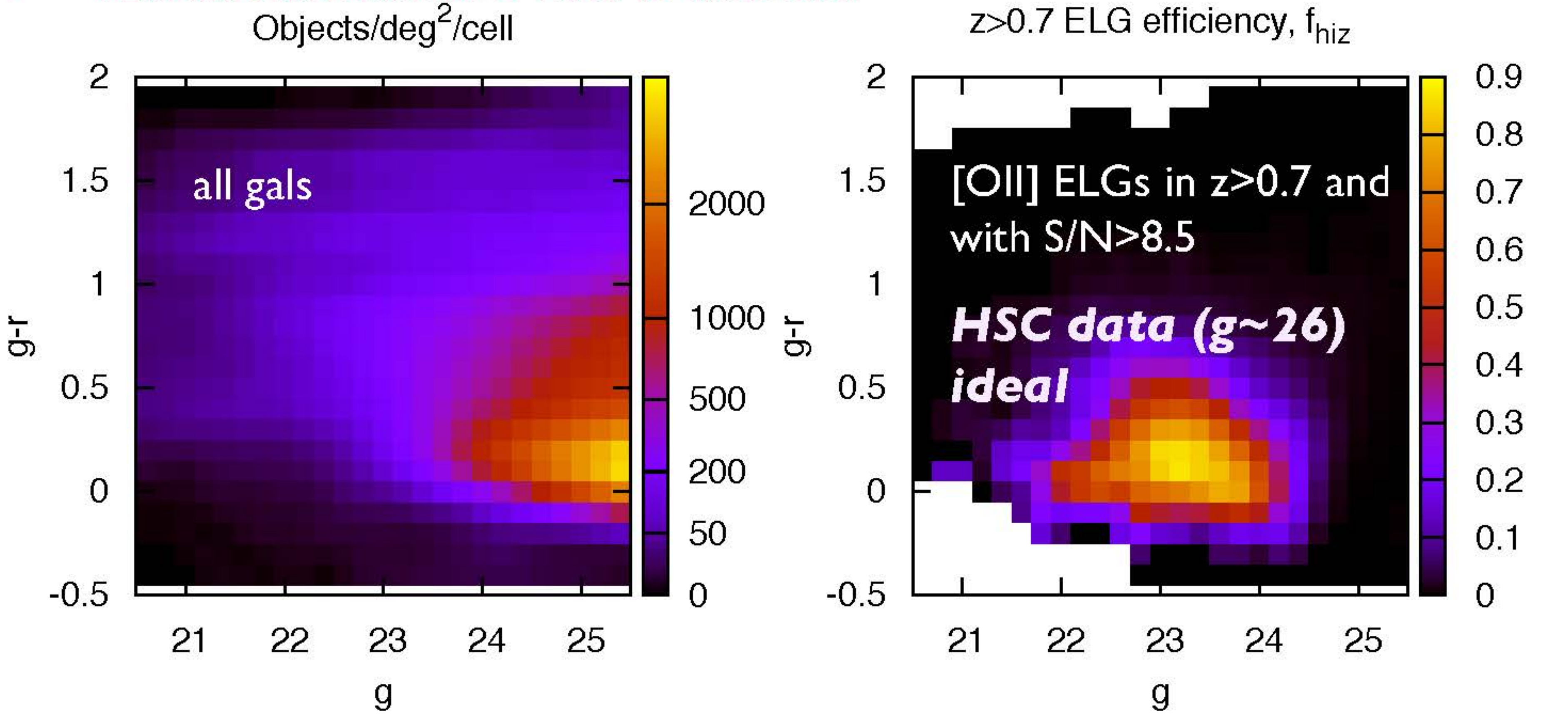
- [OII] line (3727Å) feature used for cosmology survey
- Assuming baseline instrument parameters (fiber size, throughput, readout noise, etc.)
- *Conservative assumption*: 0.8” seeing, at FoV edge, 26 deg. zenith angle
- *Included sky continuum & OH lines*
- The PFS design allows
  a matched S/N in Red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

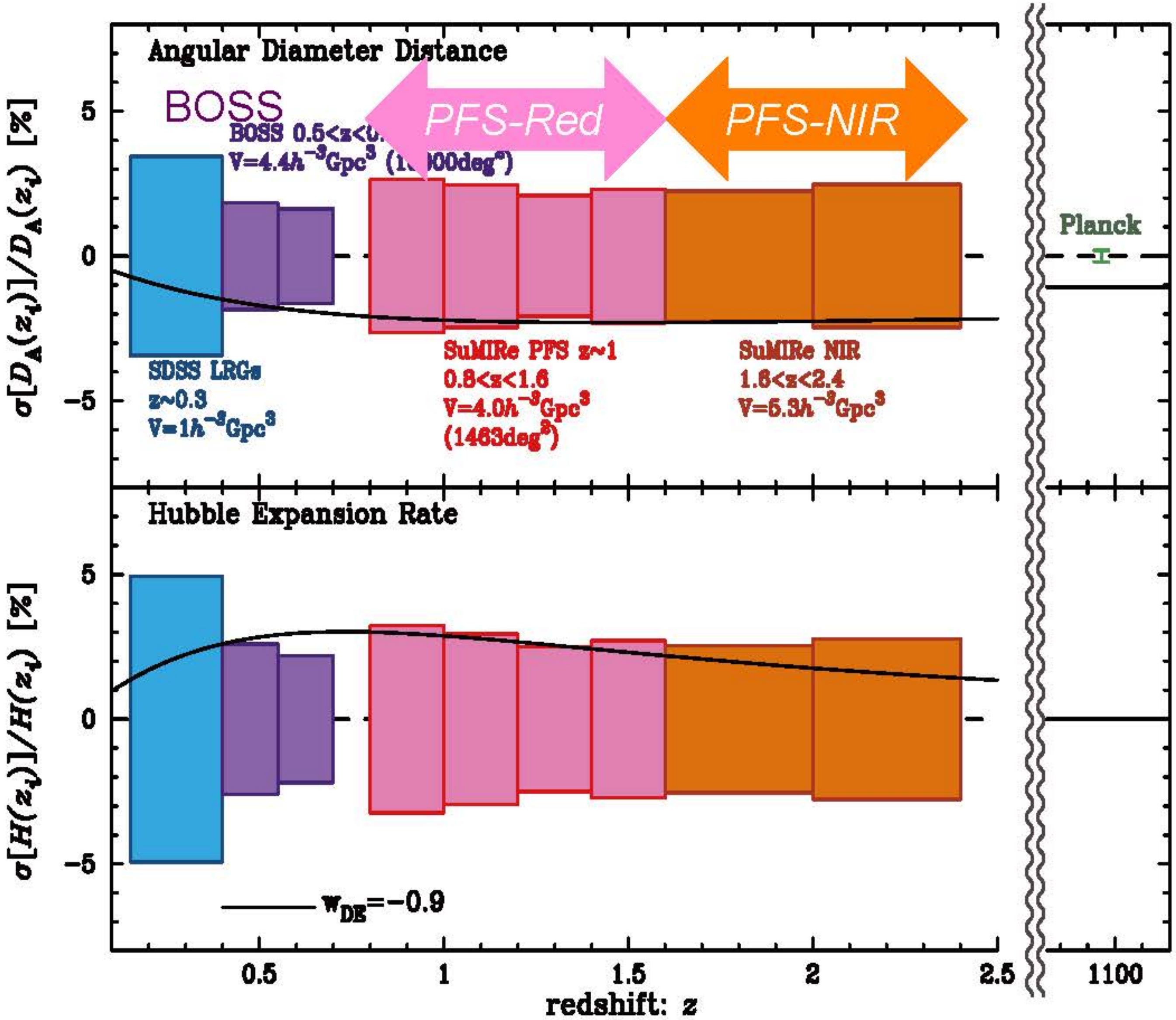
- Assume 100 clear nights to meet the scientific goals → the area of PFS survey

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

Redshift	V_{survey} (h^{-3} Gpc^3)	# of galaxies (per FoV)	n_g ($10^{-4}\,h^3$ Mpc^{-3})	bias	$n_g P(k)$ @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 $n_g P(k)$~a few@k=0.1Mpc/h in each of 6 redshift bins

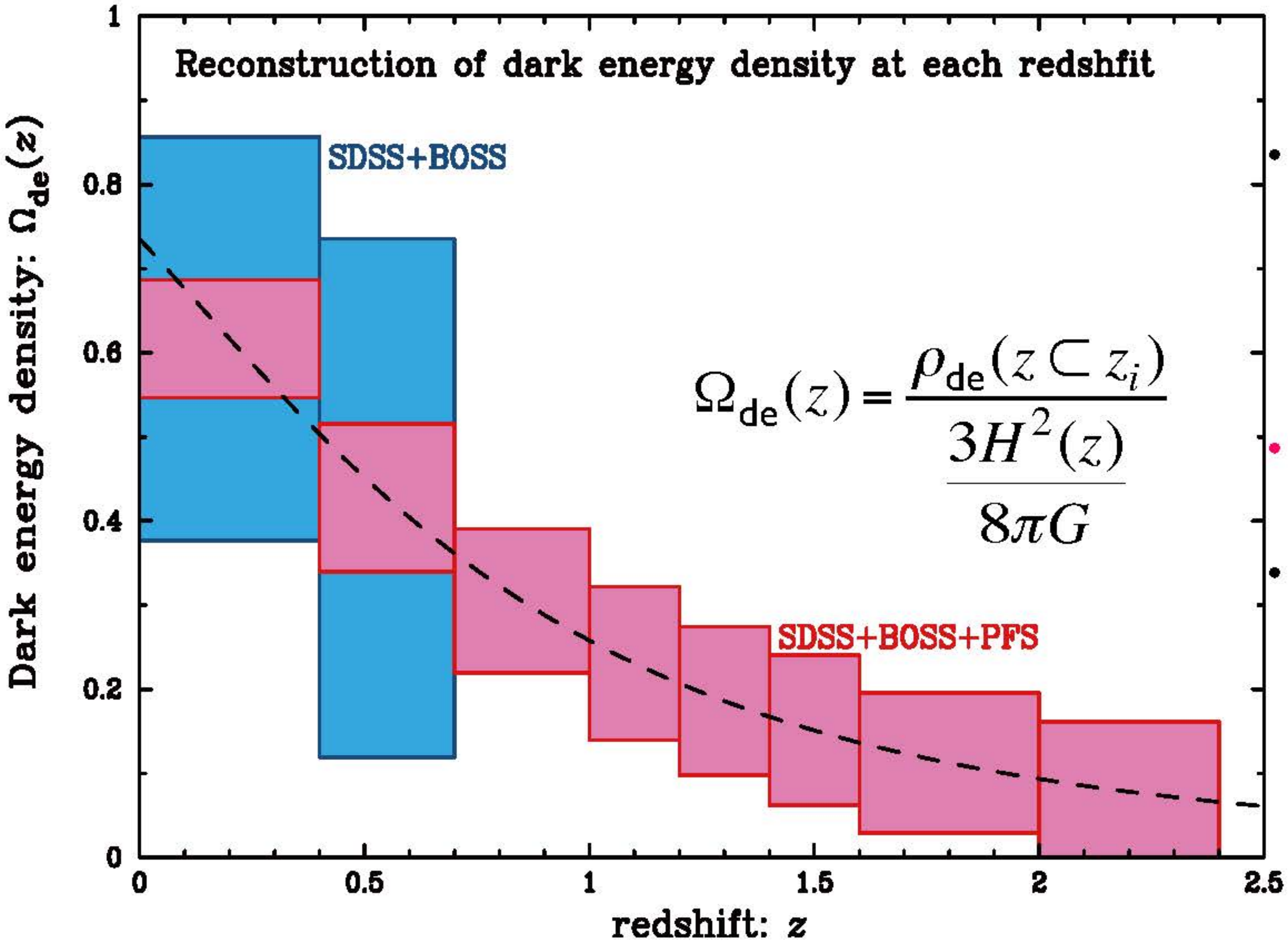
Expected BAO constraints



- 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

DE reconstruction

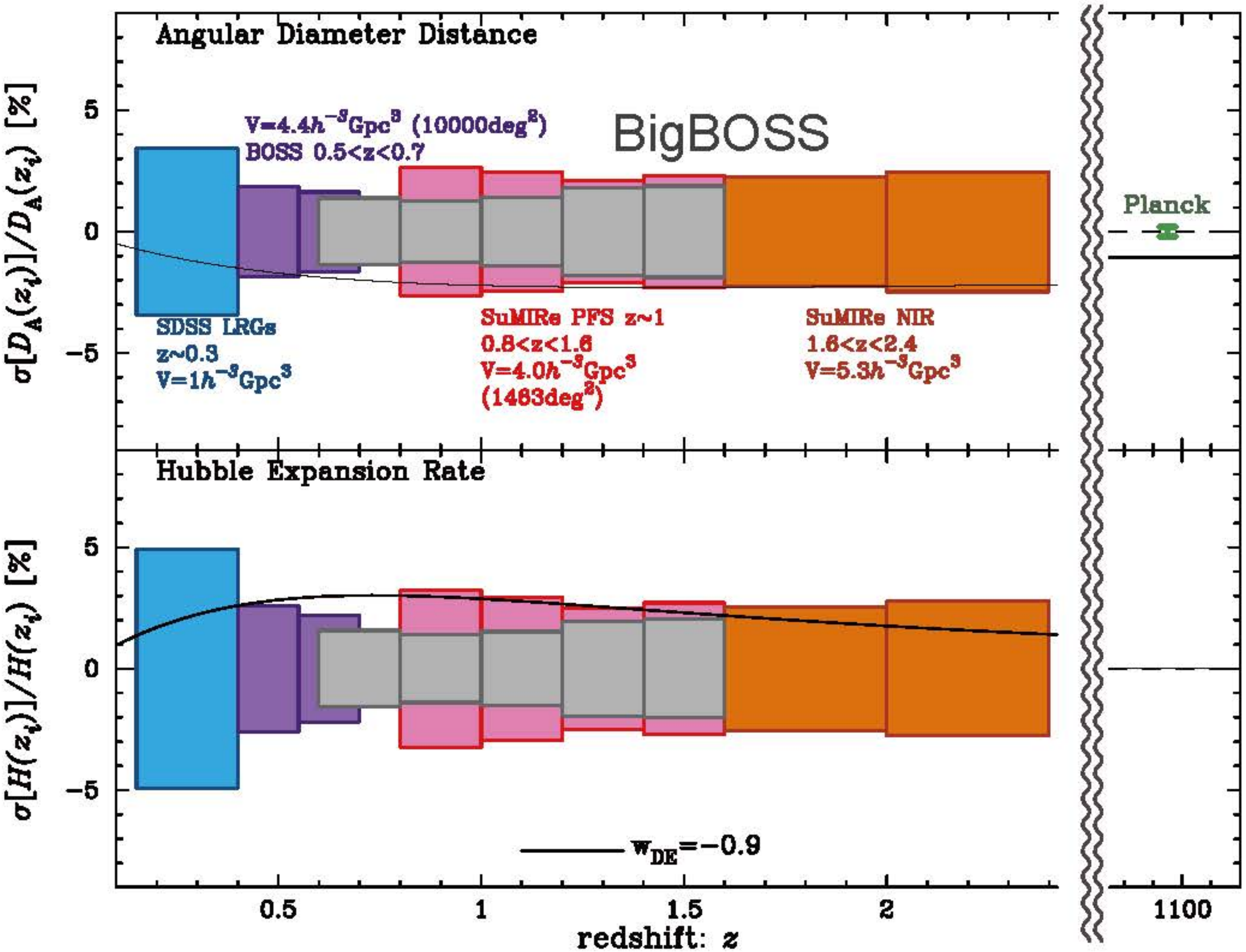
- The wide-z coverage of PFS+BOSS enables a reconstruction of DE densities as a function of redshift → can constrain a broader range of DE models



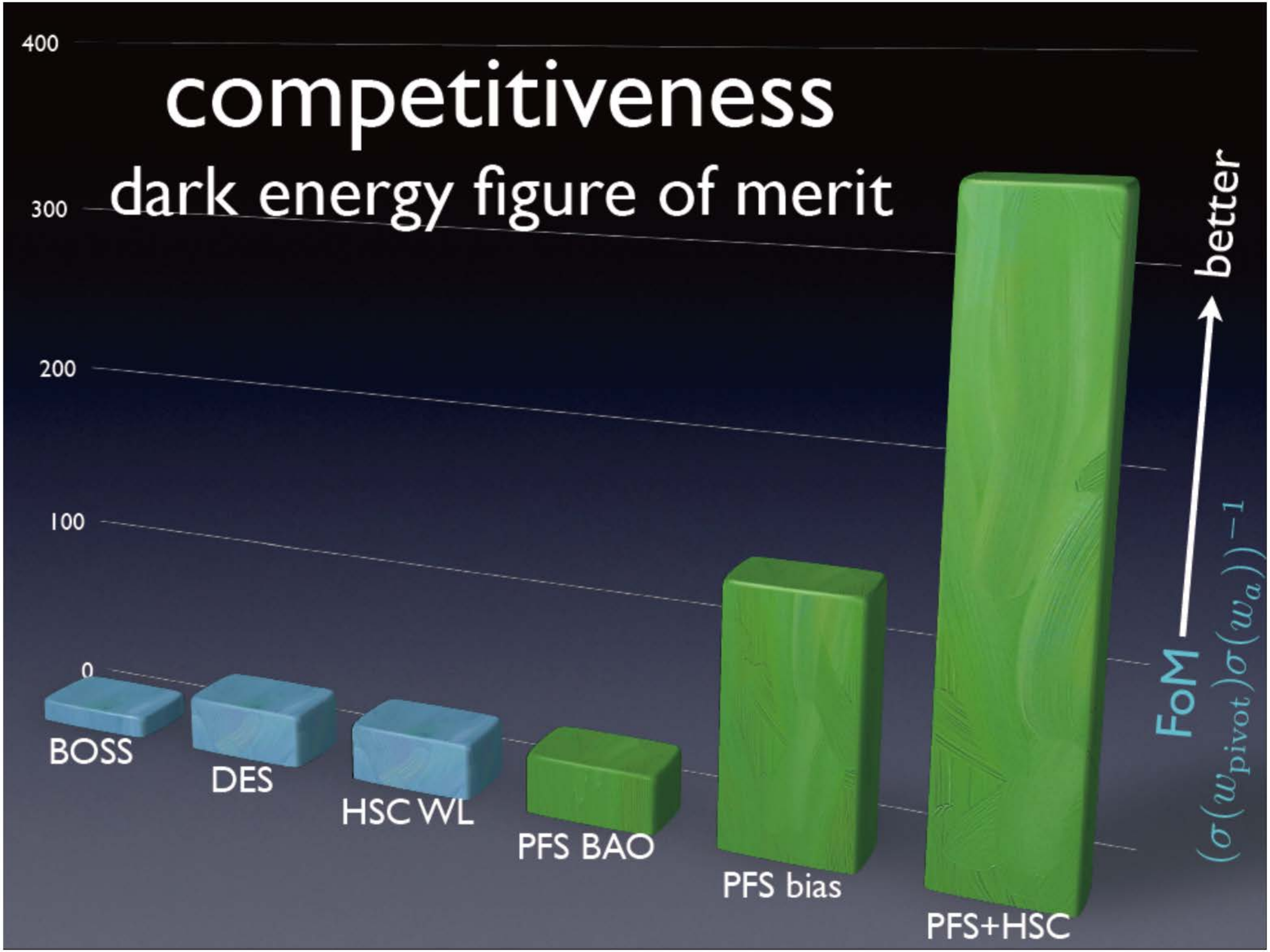
- PFS can significantly improve the accuracy of the reconstruction due to the increased z-bins
- 7% accuracy of $\Omega_{de}(z)$ in each of z-bins
- PFS+SDSS+Planck allows a detection of dark energy up to z~2, for a Λ-type model

But is PFS competitive with BigBOSS?

BigBOSS (4m) vs. PFS (8.2m)



- Survey parameters taken from BigBOSS proposal
- 500 vs. 100 nights
- 14,000 vs. 1,420 deg^2
- Naively, a factor $(10)^{1/2}$ difference
- *BigBOSS better than PFS at z<1.2 (but note target selection a big issue for BigBOSS)*
- *PFS comparable with BigBOSS for 1.2<z<1.6 but PFS can uniquely target1.6<z<2.4*
- *Synergy with HSC WL*
- *PFS more likely to complete before Euclid*



400
competitiveness
dark energy figure of merit
300
200
100
0
better
FoM
$(\sigma(w_{\rm pivot})\sigma(w_a))^{-1}$
BOSS
DES
HSC WL
PFS BAO
PFS bias
PFS+HSC

Galactic Archaeology Science

- Science objectives

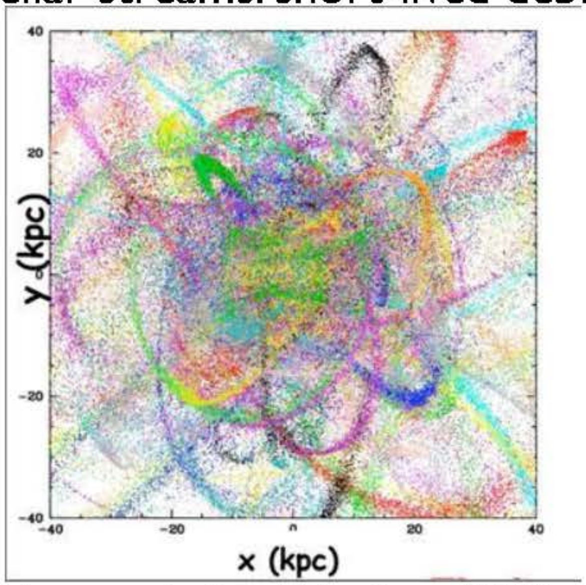
  PFS should measure radial velocities and metallicities for a large sample of old stars in the halos of the Milky Way and Andromeda:

  - To determine the merging history of the Milky Way and constrain the role and nature of dark matter in hierarchical clustering
  - To constrain the physical processes governing the assembly of the Galactic components through detailed studies of their baryonic properties
  - To compare the overall formation history of the Milky Way with Andromeda, noting the difference between the merging and baryonic processes on small scales between these bright galaxies.

- Goal
  - PFS should be designed to accomplish the above GA science objectives in about 100 nights of observing time.

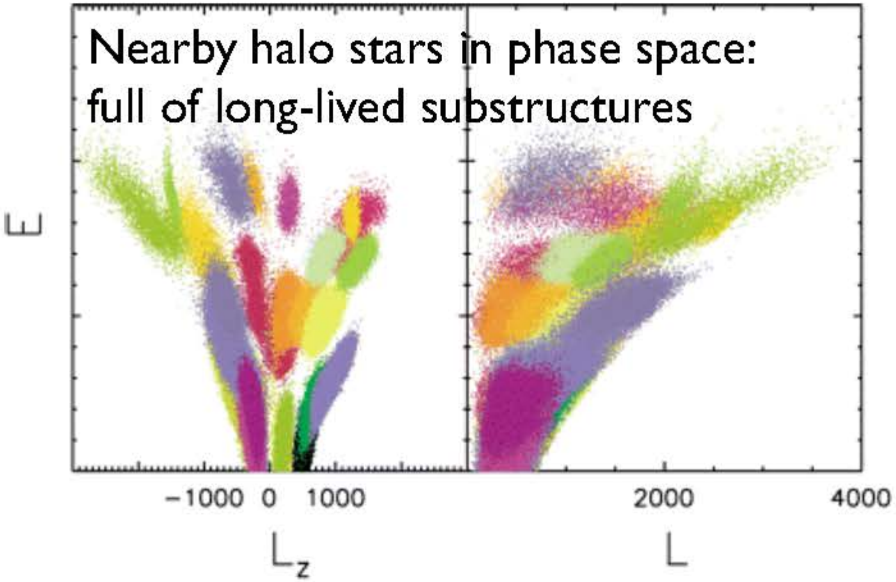
The merger history of Milky Way

Stellar streams: short-lived debris



(Freeman & Bland-Hawthorn 2002)

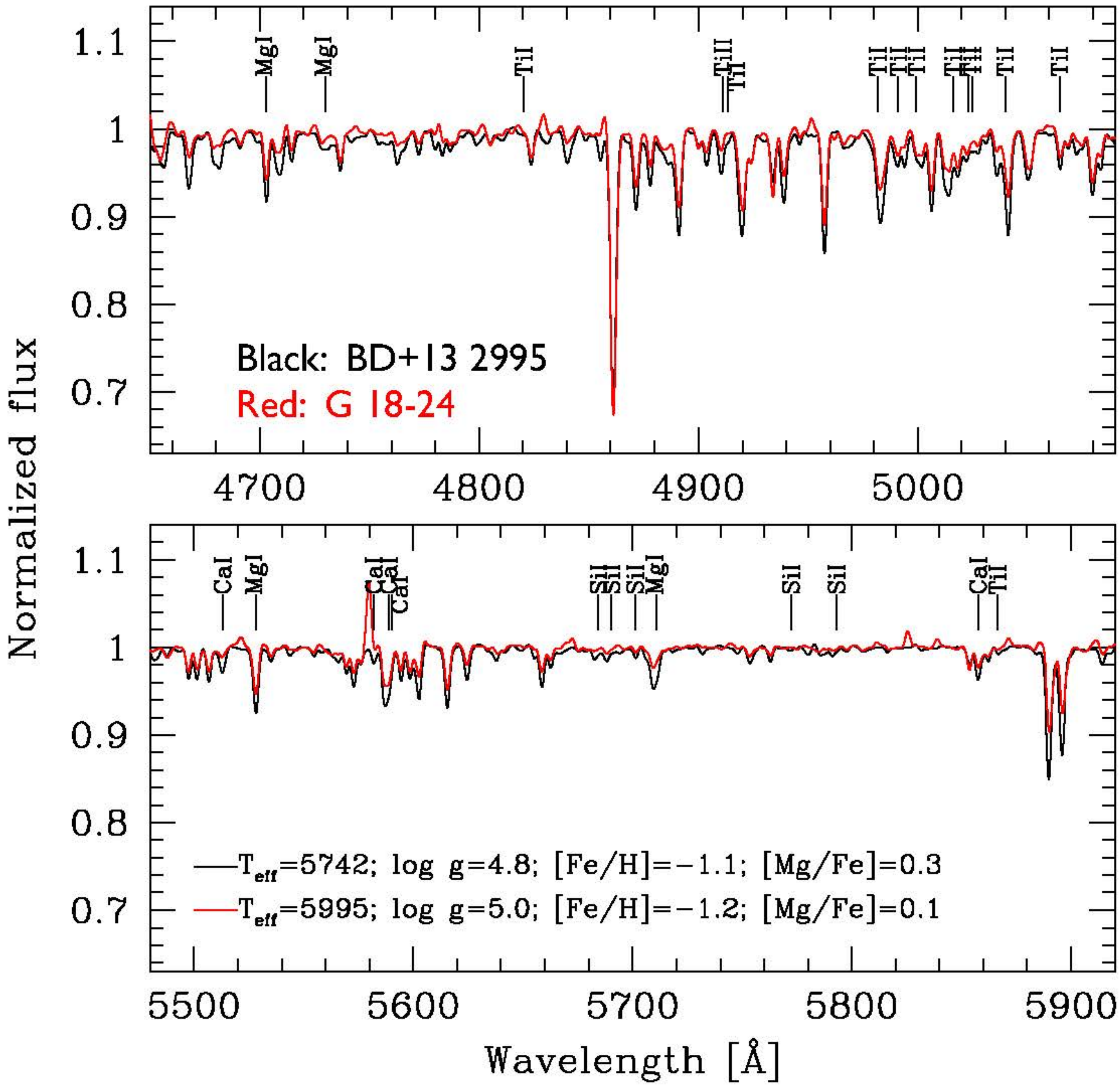
1. Space and velocity distributions of ancient stars
   ✓Merging history of dark matter halos
2. Chemical abundances of ancient stars
   ✓Star formation and chemical evolution



(Helmi & de Zeeuw 2000)

PFS provides radial velocities & [Fe/H] abundances
With Gaia ➔ full phase space data
will identify building blocks, thus providing merging and chemical history of the halo

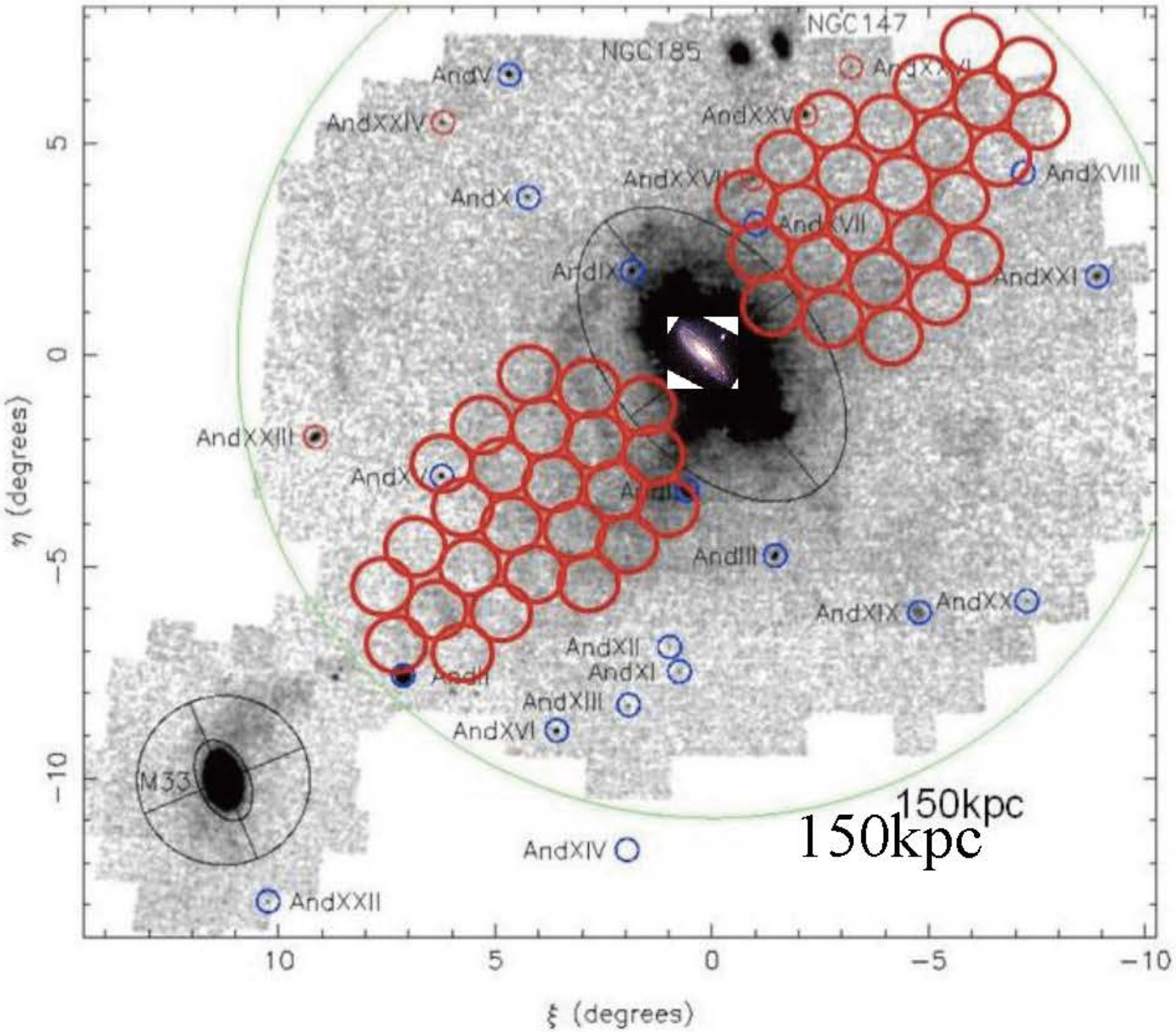
Expected spectra of metal-poor dwarf stars in the Milky Way



Degrade the real Subaru/HDS spectra to PFS resolution (R=2000, a few hours exp.)

The merger history of Andromeda

RGB map of i<23.5 with CFHT (Richardson+2011)



Halo substructures:
- Past merging events
- Disturbed by subhalos

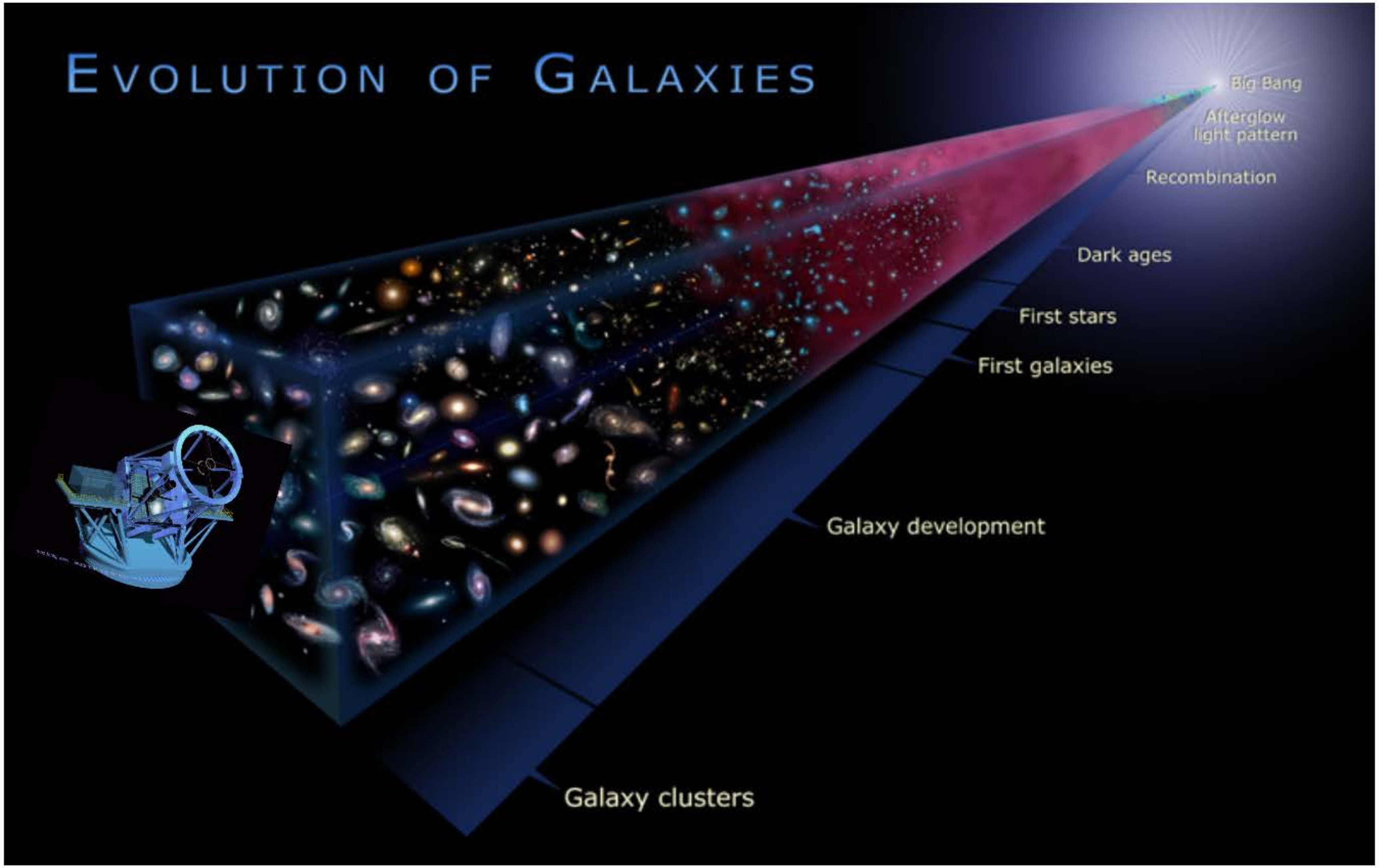
But
- Yet largely contaminated by the MW dwarf stars
- Genuine halo structures are yet unclear
- Metallicity distributions are yet unknown

Subaru/PFS combines the aperture and throughput to enable an important survey.

Galactic Archaeology Survey

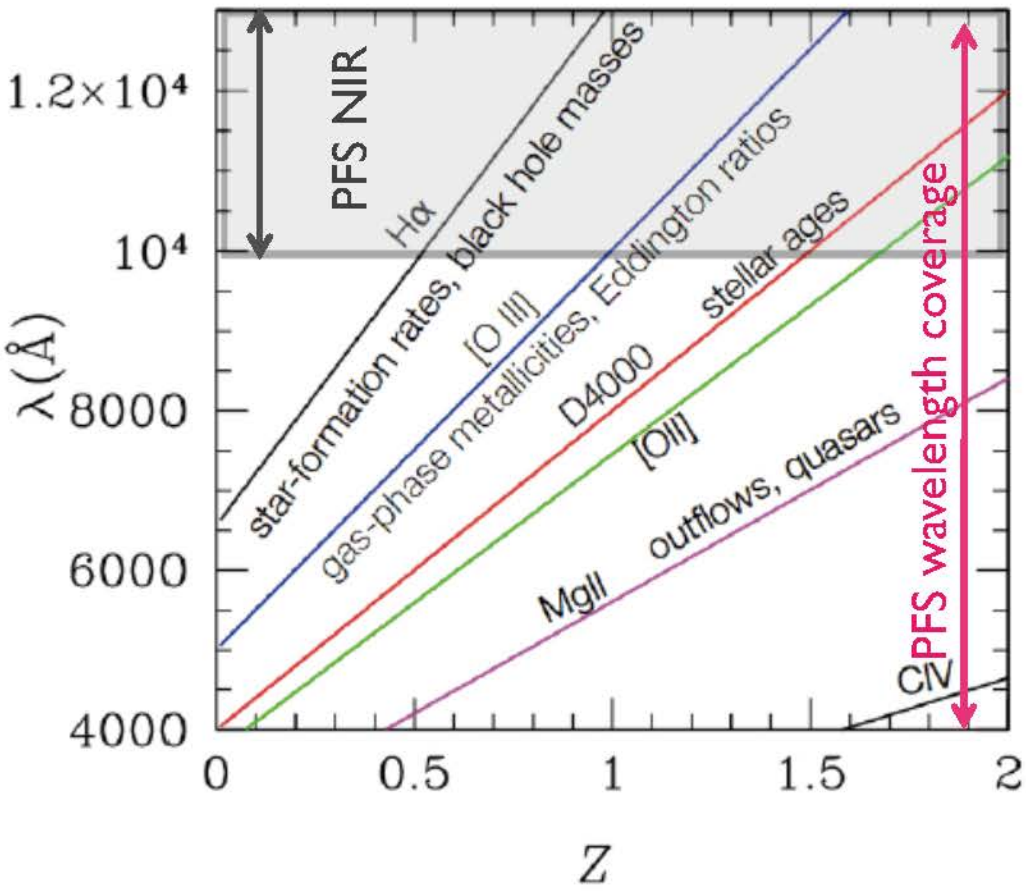
1. The Milky Way survey
   - Sample:
     (1) Gaia sample: ~ 10^6 stars with V<20 (Halo ~55%, Thick disk ~40%, Thin disk ~5%)
     (2) Faint sample: `Field of Stream' (Sgr stream, Orphan stream, Segue 1), outer disk, high latitude and halo/disk interface fields with V<21.5
   - Exposure time: 2 hr per field for S/N~30, V=21.5
   - Total area: ~ 390 deg^2 (~300 pointings)
   - Survey time: 75 nights
2. The M31 halo survey
   - Sample: RGBs with 21.5<V<22.5
   - Exposure time: 5 hr per field for S/N~20, V=22.5
   - HSC NB515 imaging removes foreground Galactic dwarfs
   - Total area: ~ 65 deg^2 (~50 pointings)
   - Survey time: 30 nights

PFS Galaxy Evolution
(SWG Co-chair: Jenny Greene)

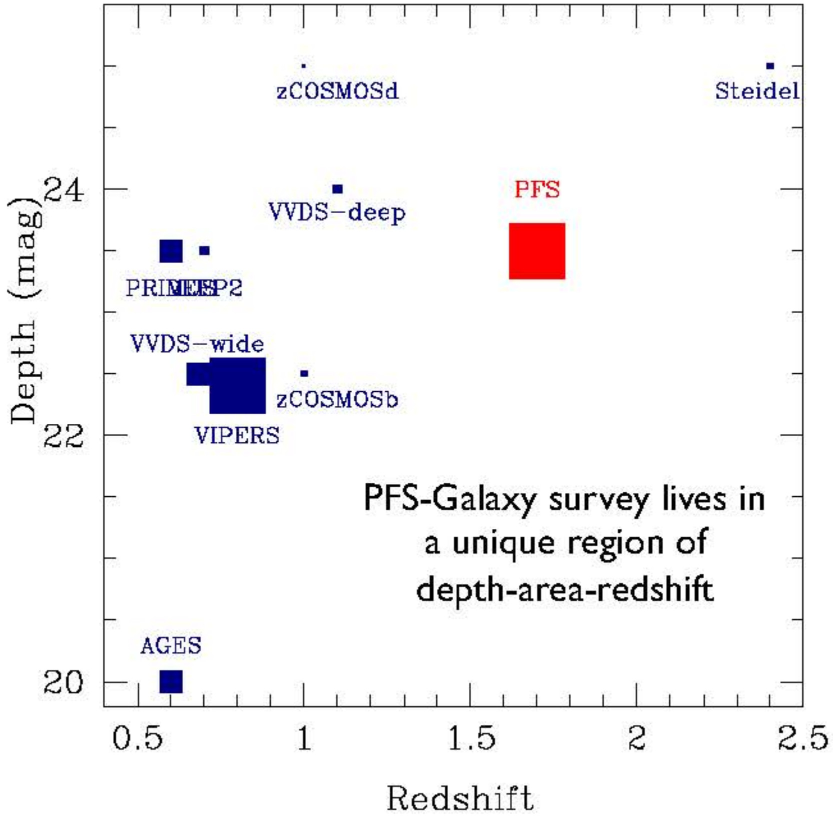


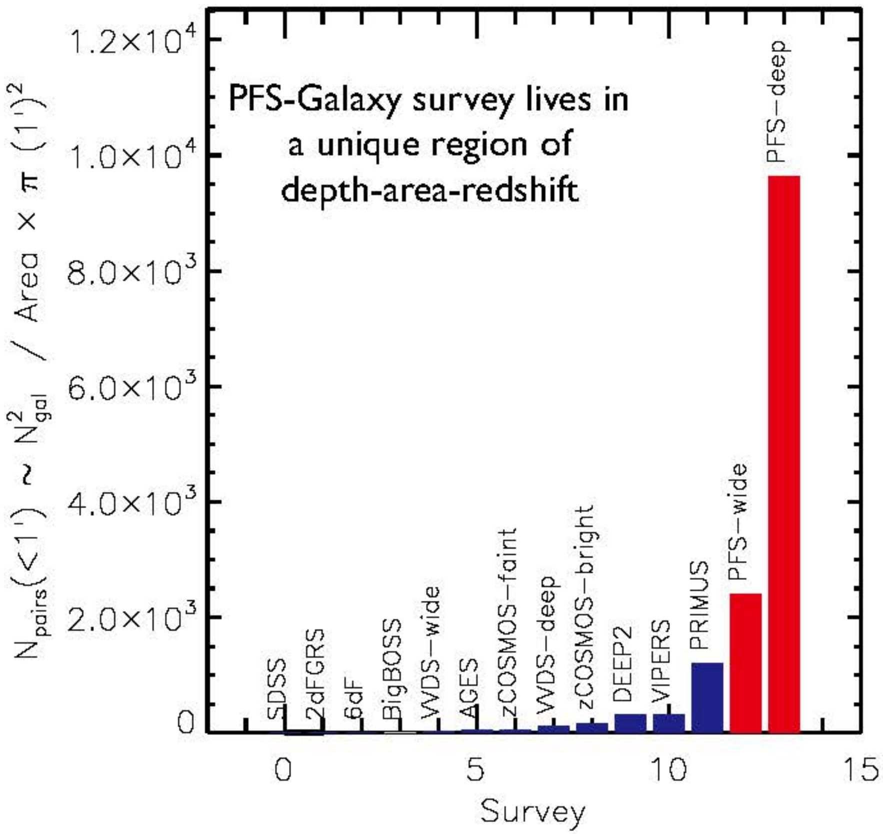
Key Science Goals

- **Growth of stellar mass:** luminosity, mass, SFR at 1<z<7
- **Clustering properties:** measure galaxy bias as a function of galaxy properties, redshift and environment
- **Gas Inflow and Outflow:** cross-correlations between absorption lines in the spectra and foreground galaxies
- **The Growth of Supermassive Black Holes:** quasar luminosity function at 3<z<7 to 3mag deeper than SDSS
- **Epoch of Reionization:** LAEs at 5<z<7; study the topology of the IGM at the end of the reionization era



Summary: PFS is unique

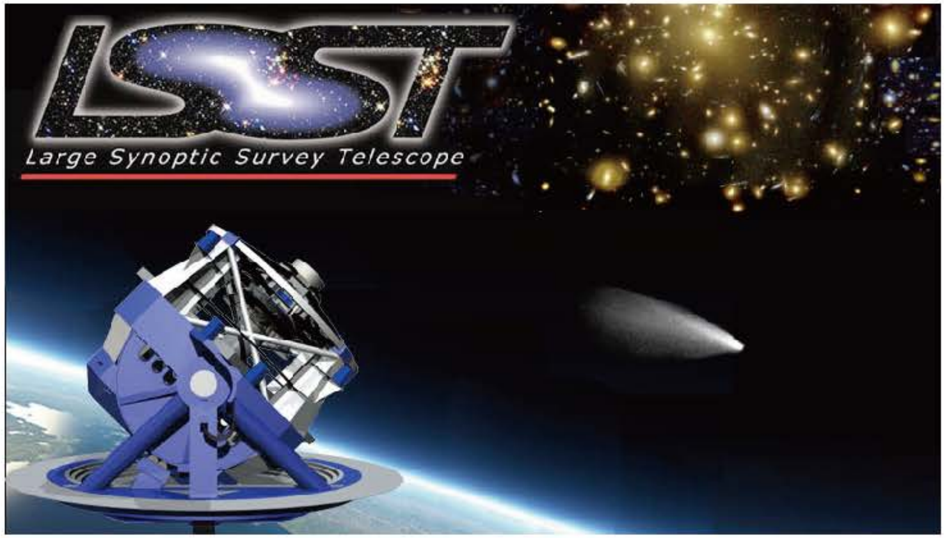




There is **no** existing or planned instrument with the wavelength range <u>and</u> multiplexing ability of PFS on **any** aperture telescope.

PFS allows a wide + deep galaxy evolution survey at a crucial, largely unexplored, epoch of cosmic history. Its high sampling will enable numerous clustering and cross-correlation probes of mass assembly

Longer Term Synergies with PFS



Summary

- HSC+PFS matches a long-term strategy of Subaru Telescope
  - Imaging + spectroscopic surveys allow a broad range of science cases (from Milky Way to cosmology)
  - Make Subaru a world-leading facility even in TMT era
  - Synergy with the future, Euclid, LSST, TMT, ELT
- PFS has unique capabilities: 2400 fibers, 380 – 1300nm
  - Allow strong science cases that cannot be done with 4m-class telescopes
  - Key sciences: cosmology, galactic archaeology, galaxy evolution
- Time scale
  - PDR (Jan, 2013) – CDR (??) – First light (2017?)
  - PFS SSP Survey: from 2017 or 2018 for 5 years