Masahiro Takada, JGRG 22(2012)111502

"SuMIRe project: Hyper Suprime-Cam (HSC) and Prime Focus Spectrograph (PFS)"

RESCEU SYMPOSIUM ON

GENERAL RELATIVITY AND GRAVITATION

JGRG 22

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Koshiba Hall, The University of Tokyo, Hongo, Tokyo, Japan

SuMIRe project:
Hyper Suprime-Cam (HSC) and Prime Focus Spectrograph (PFS)

Masahiro Takada
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KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

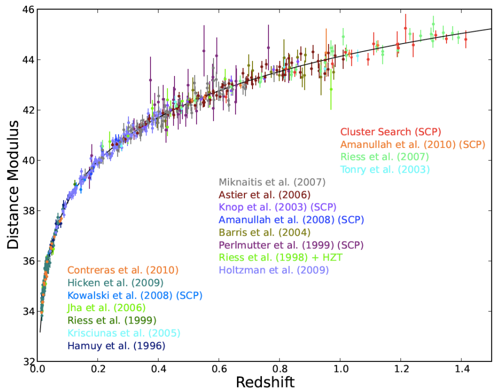
@ JGRG, U Tokyo, Nov 15, 2012

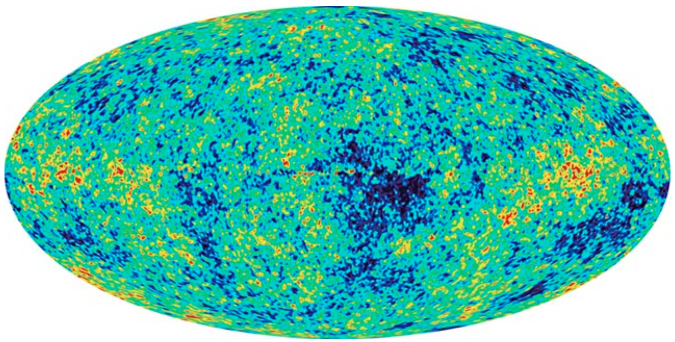
Futamase-sensei

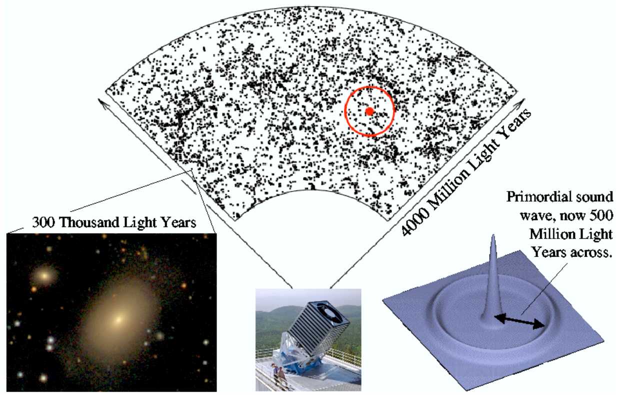
- Congratulations on your 60^{th} birthday!
- Congratulations to Sasaki-san and Kodama-san, too
- I was a graduated student of Futamase-sensei at Tohoku University
- My master thesis project as "Post-Newtonian Lagrangian perturbation approach to the large-scale structure formation" (1998)
- My PhD thesis project was "Weak lensing effect on CMB" (2001)

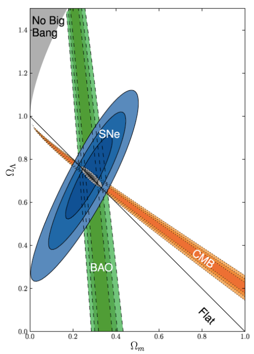
The golden age of cosmology

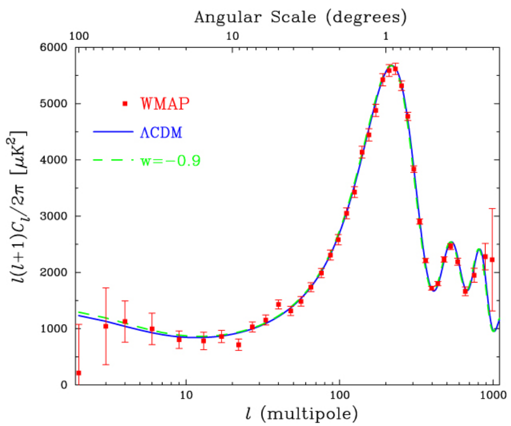
- Various data sets are now available
- The measurement accuracies are increasing improved
- Can test cosmological models/scenarios very precisely: the expansion history and the growth of structure formation

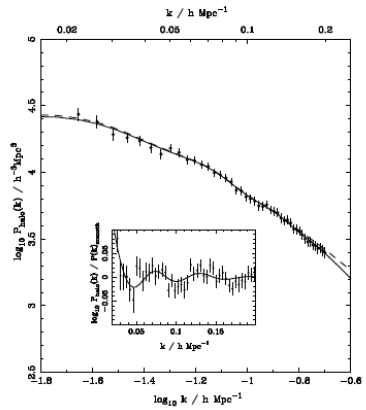






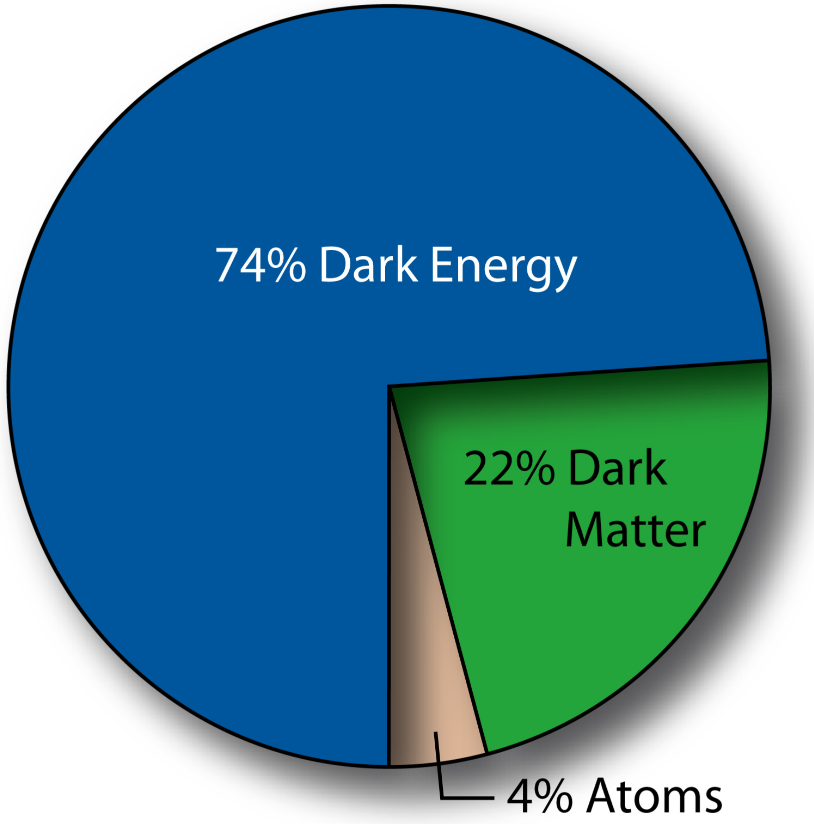






Big Questions in Cosmology

- What is the universe made of? – the nature of dark matter
- What is its fate? – the nature of dark energy
- How did the universe begin? – the nature of primordial fluctuations



From WMAP

Test of cosmic acceleration

- Geometrical test

$$H^2(z) = H_0^2\left[\Omega_{m0}(1+z)^3 - \frac{K}{H_0^2}(1+z)^2 + \underbrace{\frac{\rho_{\mathrm{de}}(z)}{\rho_{\mathrm{cr0}}}}_{\textit{Dark Energy}}\right]$$

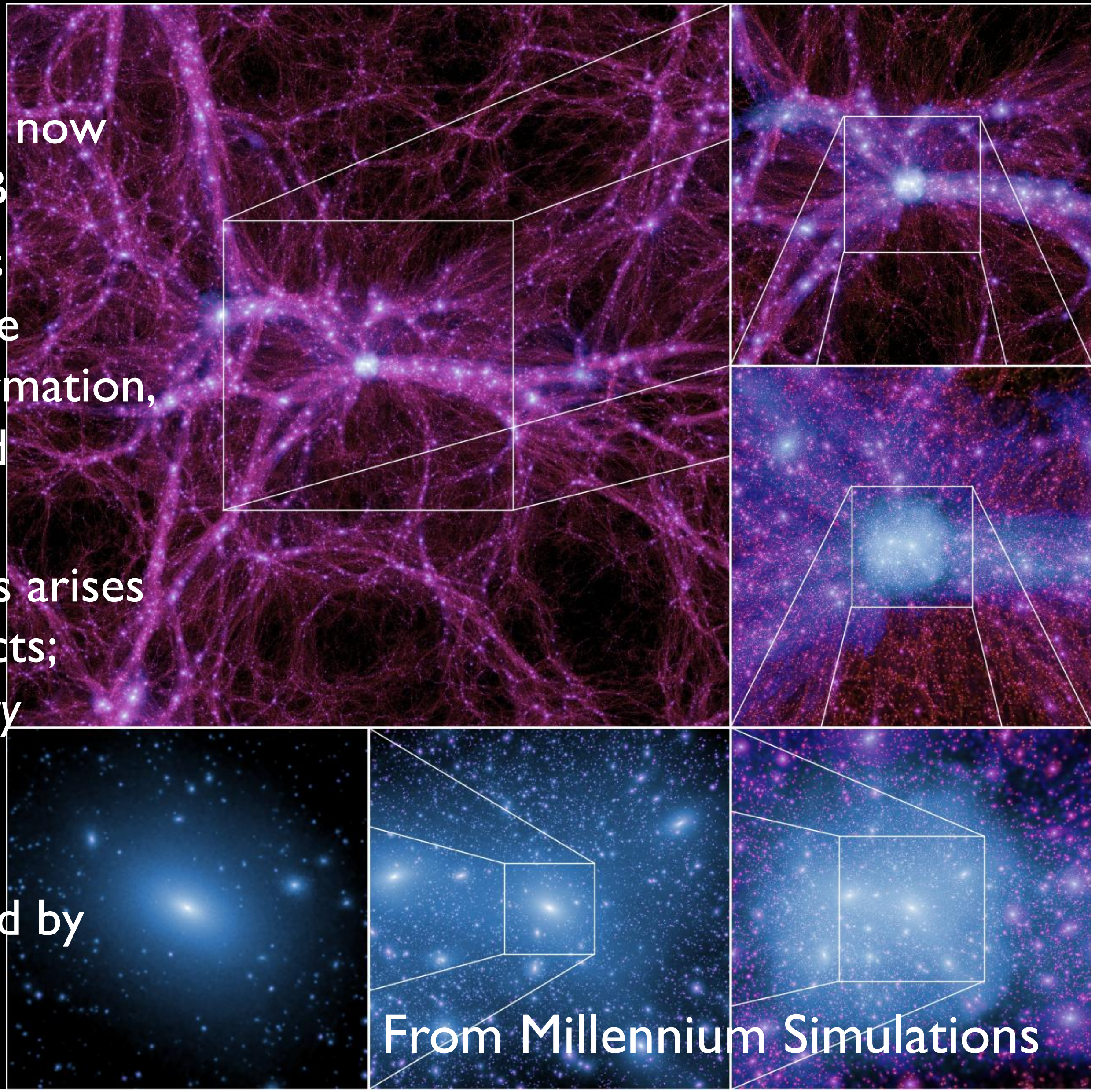
  – CMB, Type-Ia SNe, Baryonic Acoustic Oscillation (BAO)
- Growth of structure formation

$$\ddot{\delta}_m + \underbrace{2H\dot{\delta}_m}_{\textit{Cosmic Expansion}} - \underbrace{4\pi G\bar{\rho}_m\delta_m}_{\textit{Gravity}} = 0$$

  – Weak Lensing, Galaxy clustering, Counts of galaxy clusters
- *Goal*: Combine the geometrical and structure formation probes to distinguish DE and modification of gravity for the origin of cosmic acceleration

Large-scale structure formation

- The initial conditions are now well constrained by CMB
- The ΛCDM model gives specific predictions of the subsequent structure formation, based on the analytic and simulation methods
- The growth of structures arises from the competing effects; *cosmic expansion vs. gravity*
- Dark energy affects the structure formation
- The models can be tested by precise data



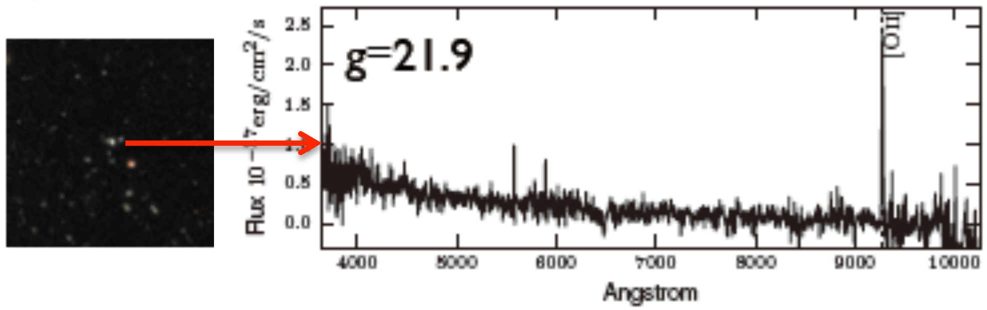
Galaxy survey; imaging vs. spectroscopy

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.

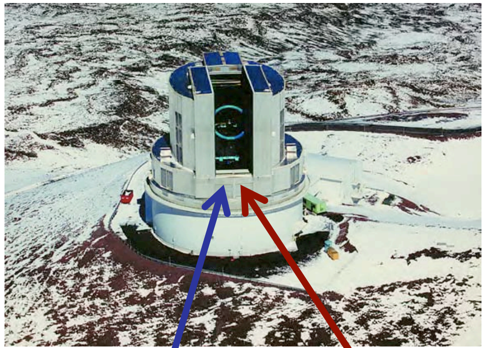
Telescope	Papers[1]	Citat.[1]	C/P[1]	Papers[2]
HST	206.6	765	3.70	391.5
VLT	139.1	452	3.25	290.6
Keck	59.6	333	5.59	121.5
CFHT	38.0	152	4.00	69.6
Gemini	34.3	108	3.15	63.7
Subaru	33.0	138	4.18	70.0
AAT	23.0	83	3.61	42.4
WHT	19.5	55	2.82	34.7
IRTF	16.9	46	2.72	31.2
UKIRT	15.8	54	3.42	34.3
Okayama 1.88m	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 …

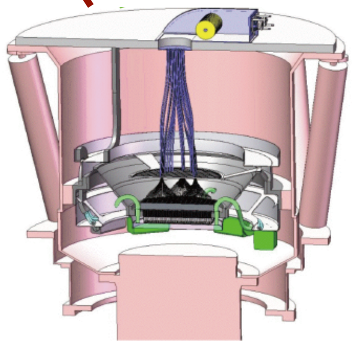
SDSS	133.0	863	6.49	336.1
2MASS	136.2	479	3.52	275.8
48" Schmidts	45.8	95	2.07	100.7
MACHO, ASAS, etc.	29.1	123	4.23	47.1
TOTAL OPTICAL	1233.8	4764	3.86	2530.4

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

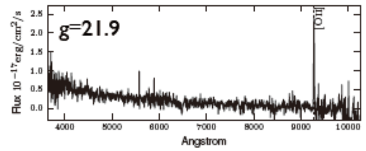


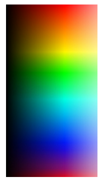
Subaru (NAOJ)



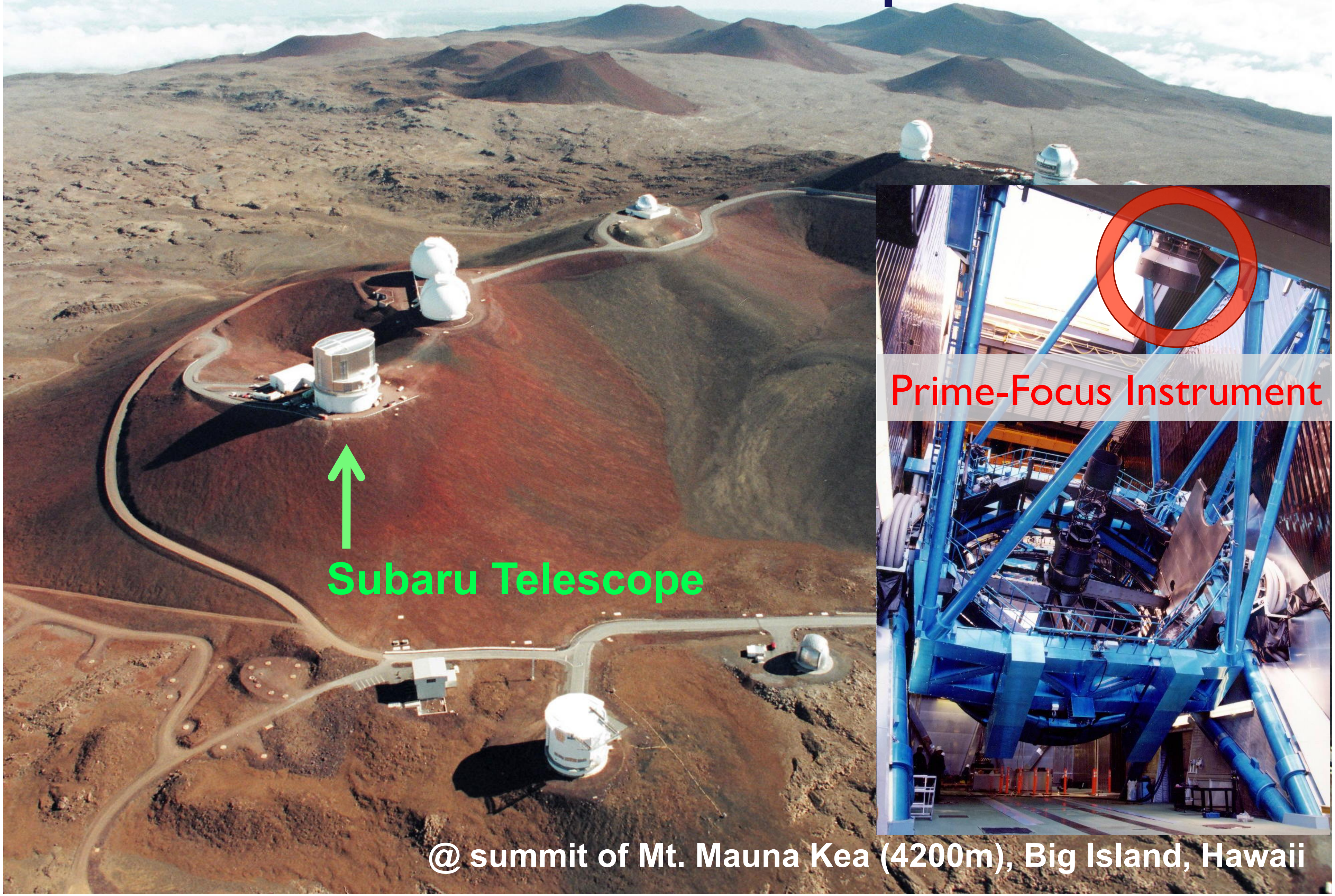
PFS

HSC

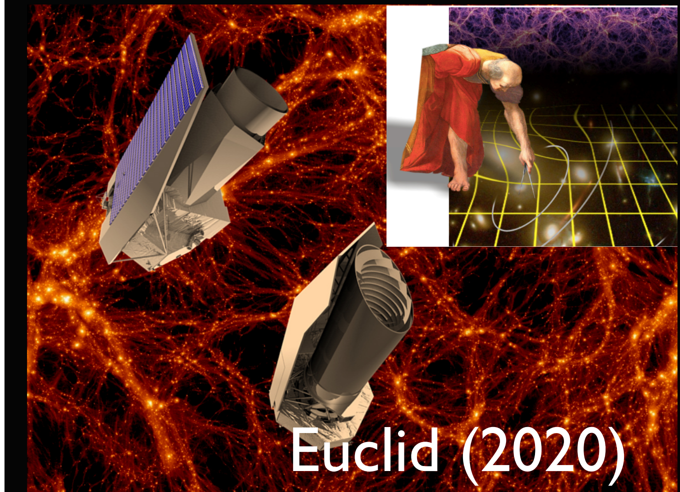


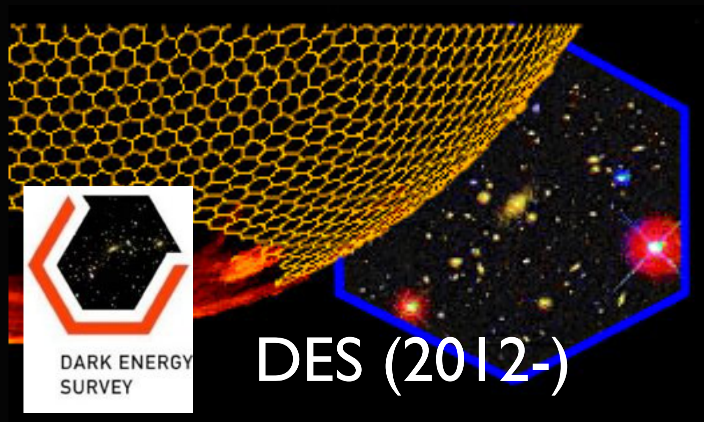


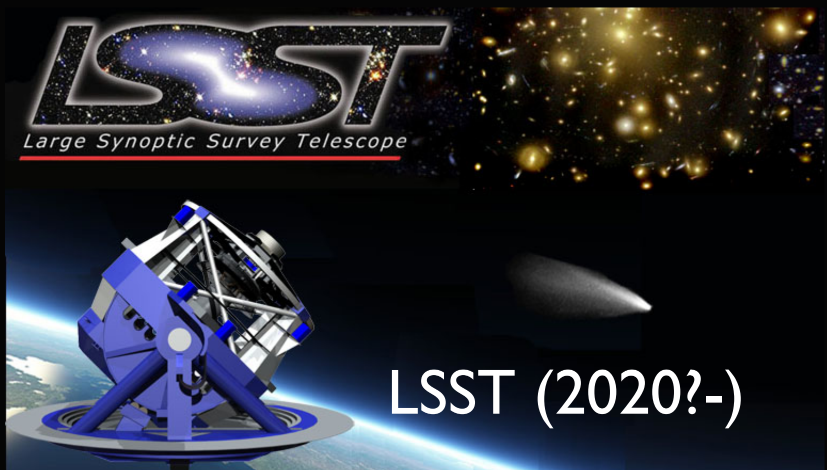
Subaru Telescope

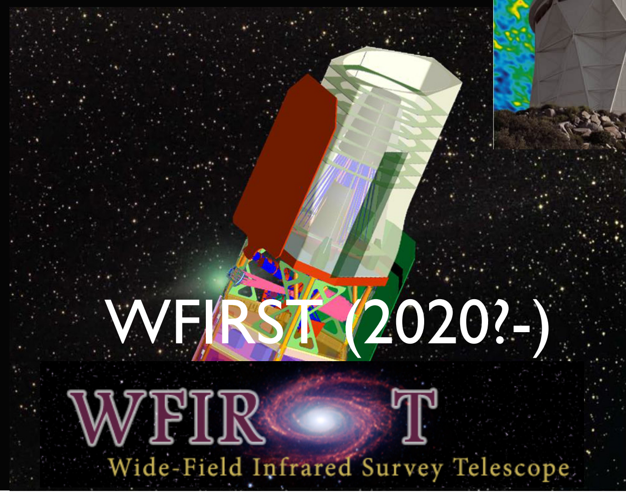


Dark Energy Competition

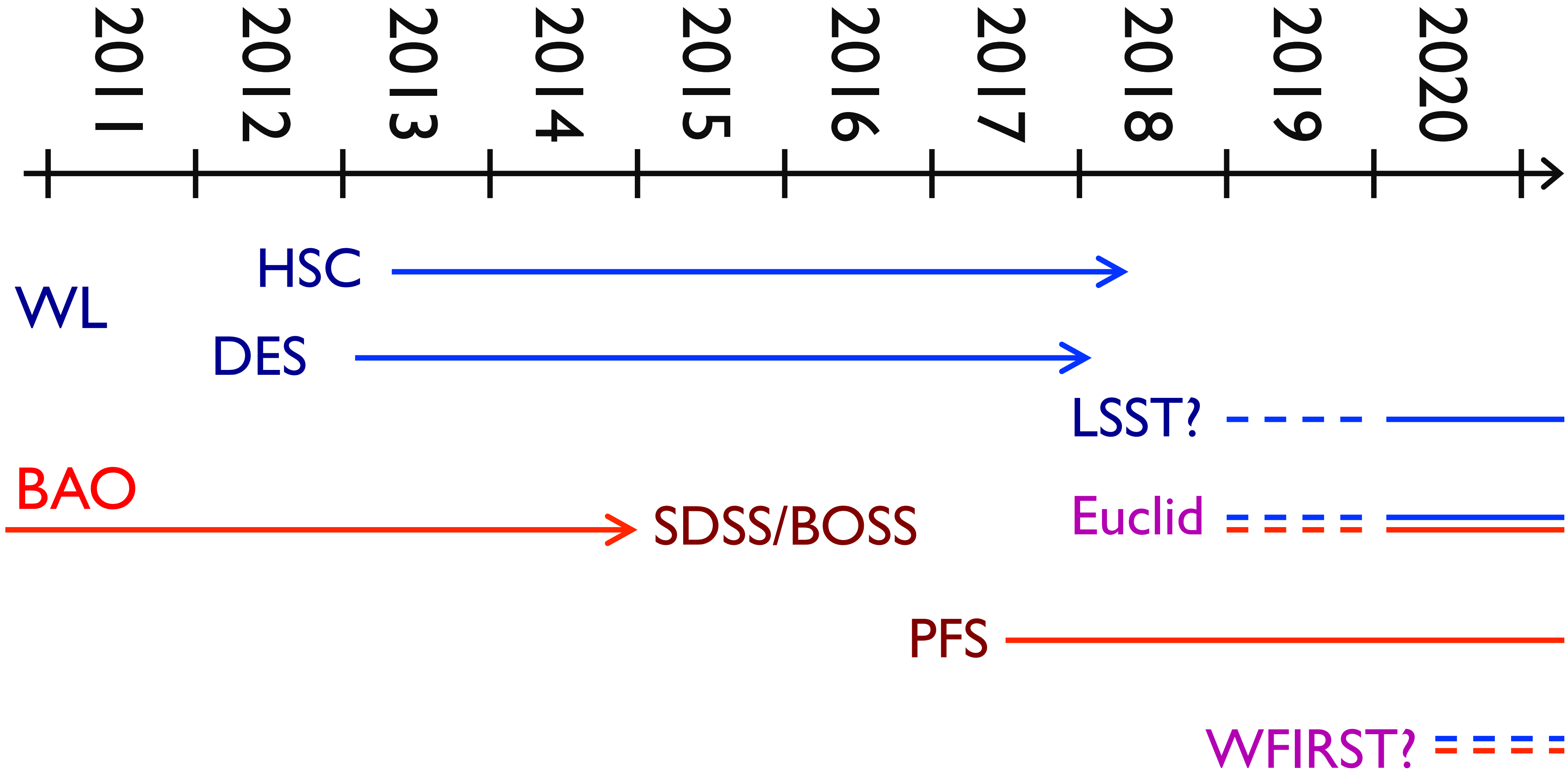








Time line (DE experiments)

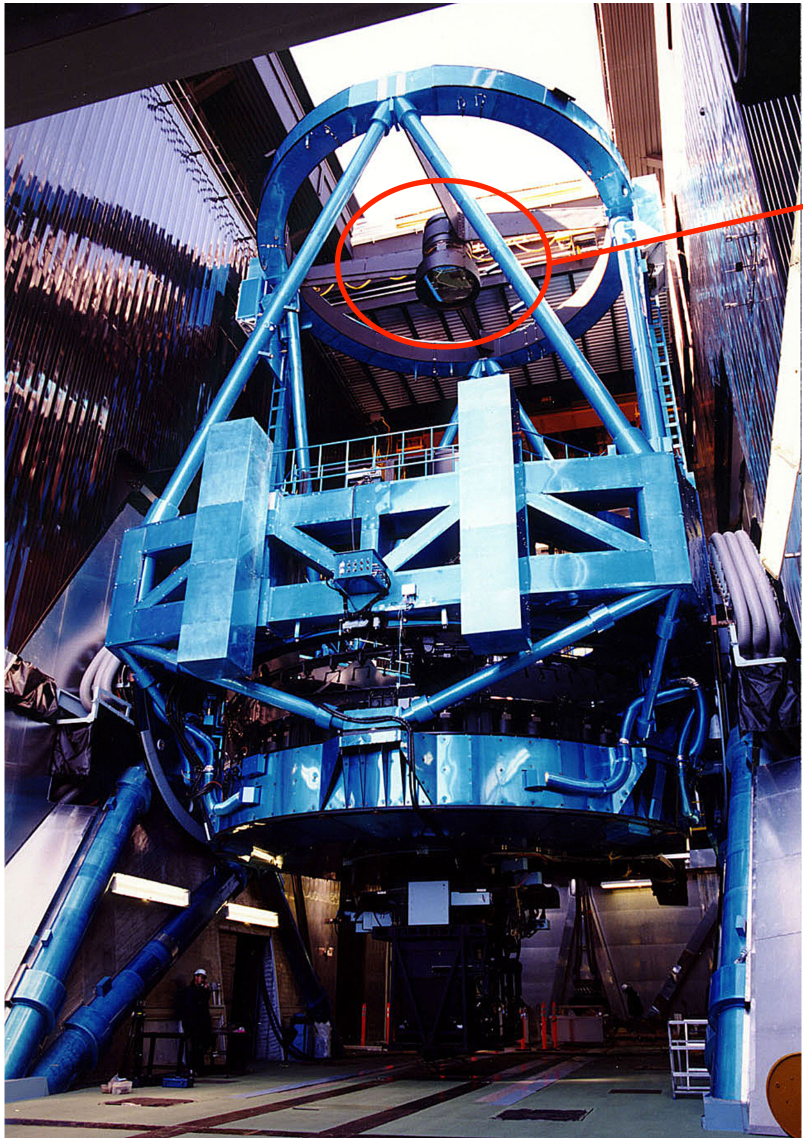


We are in a good position!

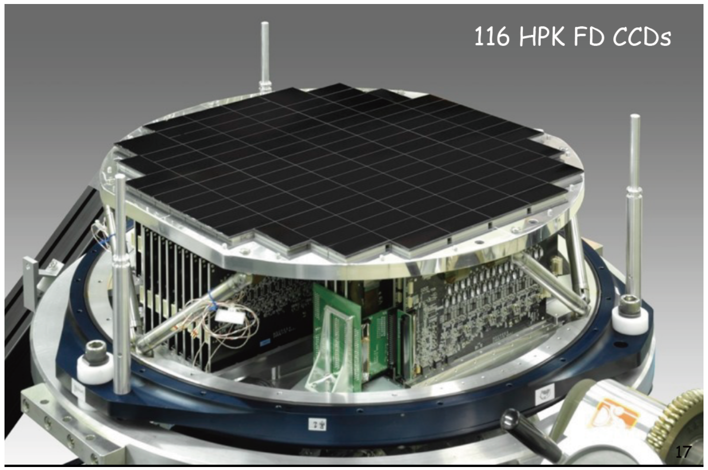
Hyper Suprime-Cam (HSC)

- 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)
- HSC survey starting from 2012 - 2017
- Deep multi-band imaging (grizy; i~26, y~24) with 1400 square degrees

Hyper Suprime-Cam Project



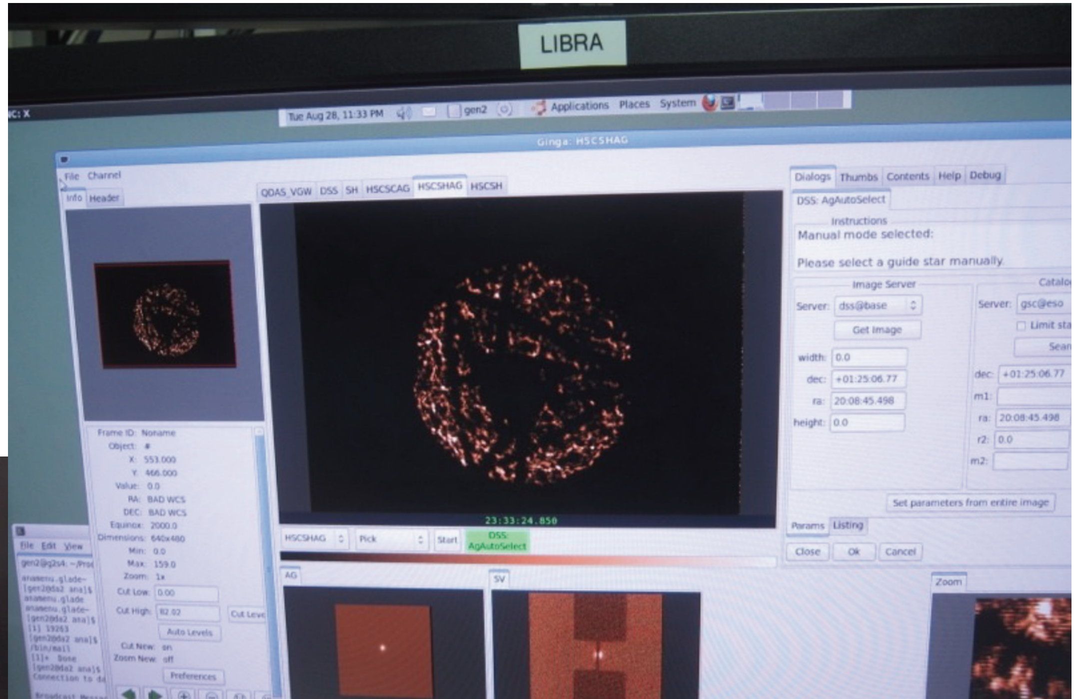
- All instruments at Mauna Kea
- The *largest* camera in the world
- 3m high
- 3 tons weighed
- 116 CCD chips (870 millions pixels)

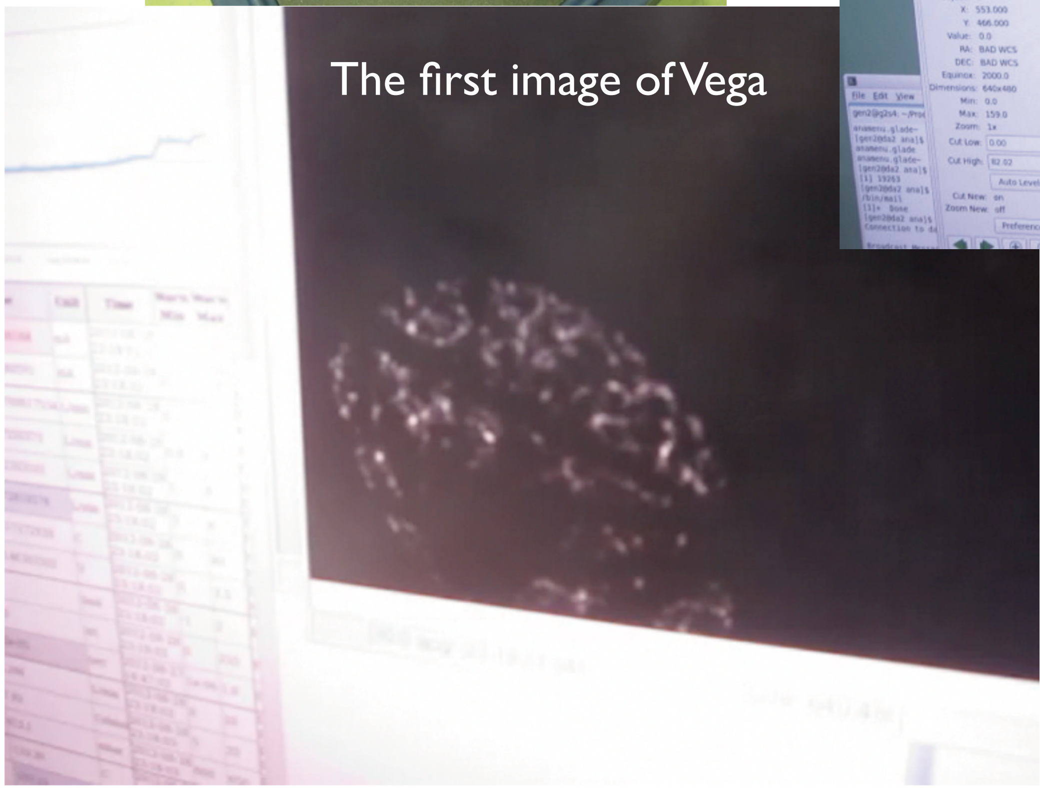


The Engineering first light!

From Satoshi Miyazaki (NAOJ, HSC PI)


Shack-Hartmann unit



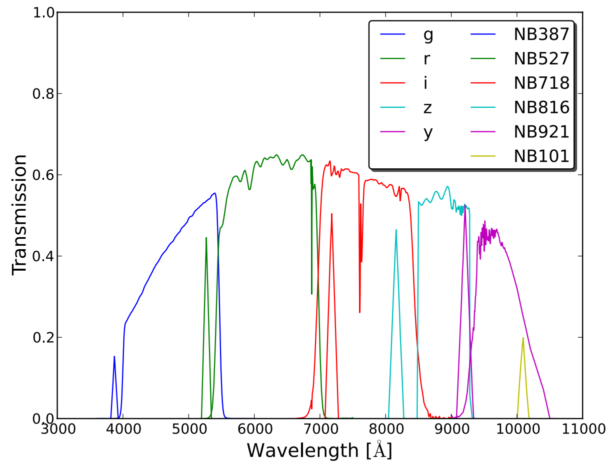

The first image of Vega

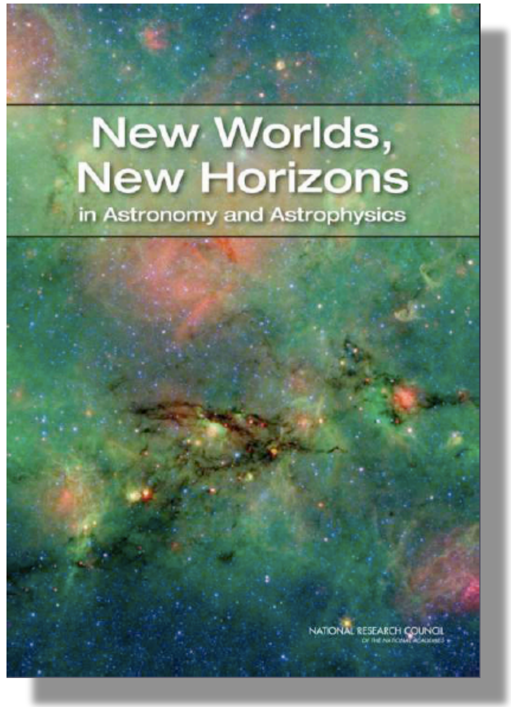
HSC Engineering First Light

- Press release (Sep 12)
- From homepages of IPMU and NAOJ
- Nature, the newspapers in Japan, YouTube
- YouTube: 3,998 hits (as of Nov 13)

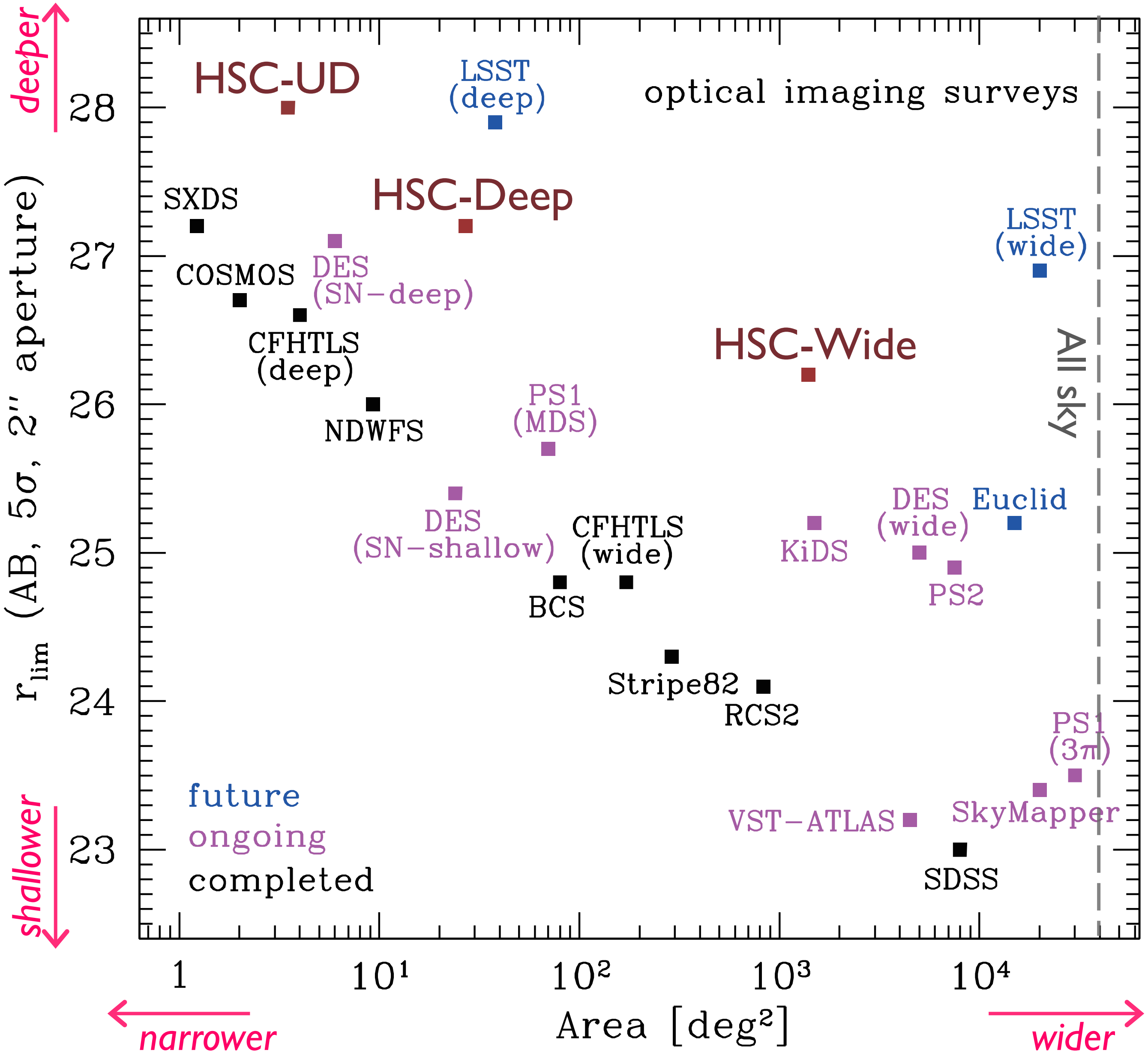
Planned HSC Survey

- 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



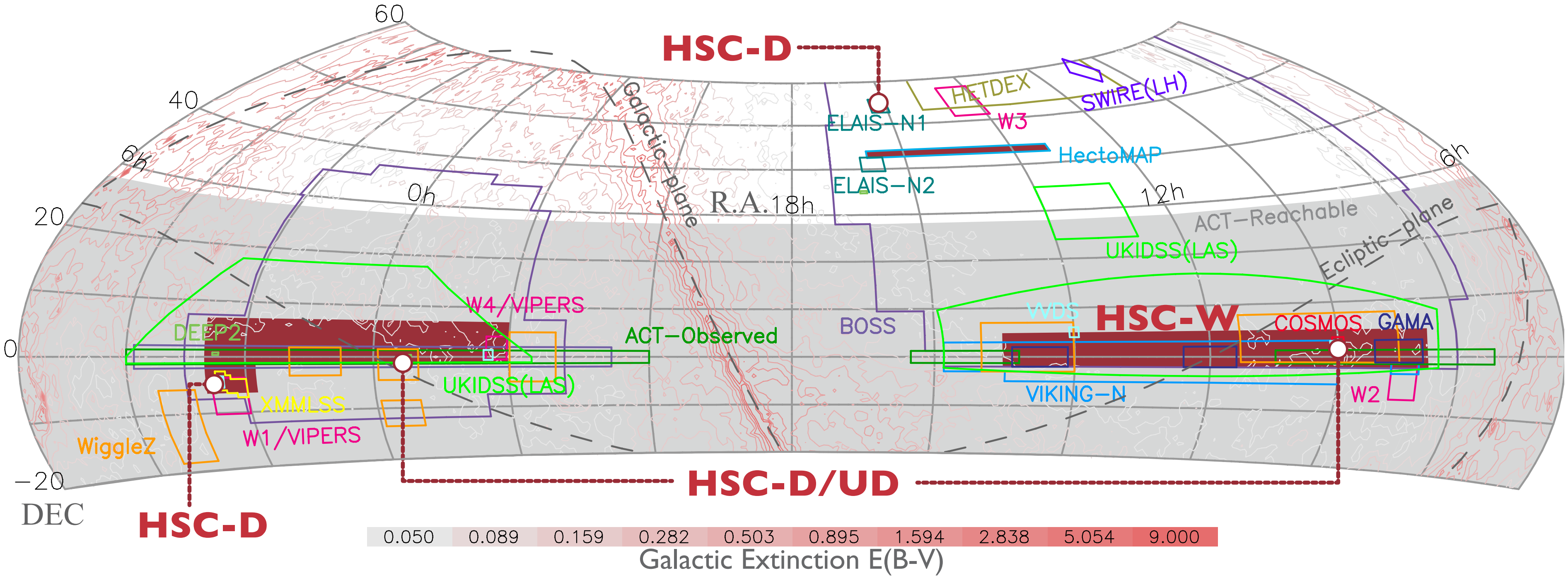
Black: existing

Magenta: upcoming

Blue: future

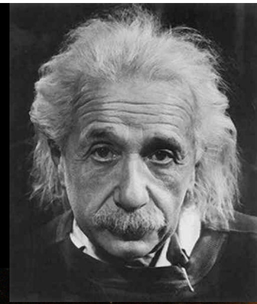
HSC Layers will explore new regions in survey parameter space

HSC Survey Fields



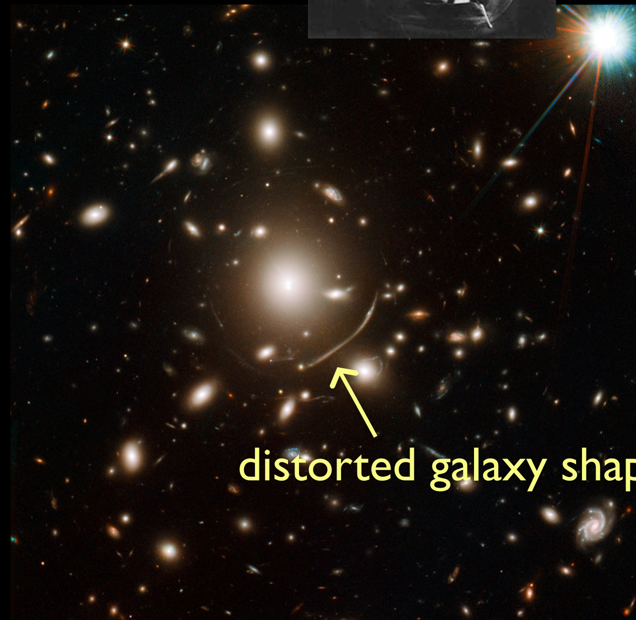
- The HSC fields are selected based on …
  - Synergy with other data sets: SDSS/BOSS, The Atacama Cosmology Telescope CMB survey (from Chile), X-ray (XMM-LSS), spectroscopic data sets
  - Spread in RA
  - Low dust extinction

Gravitational Lensing =Einstein's prediction



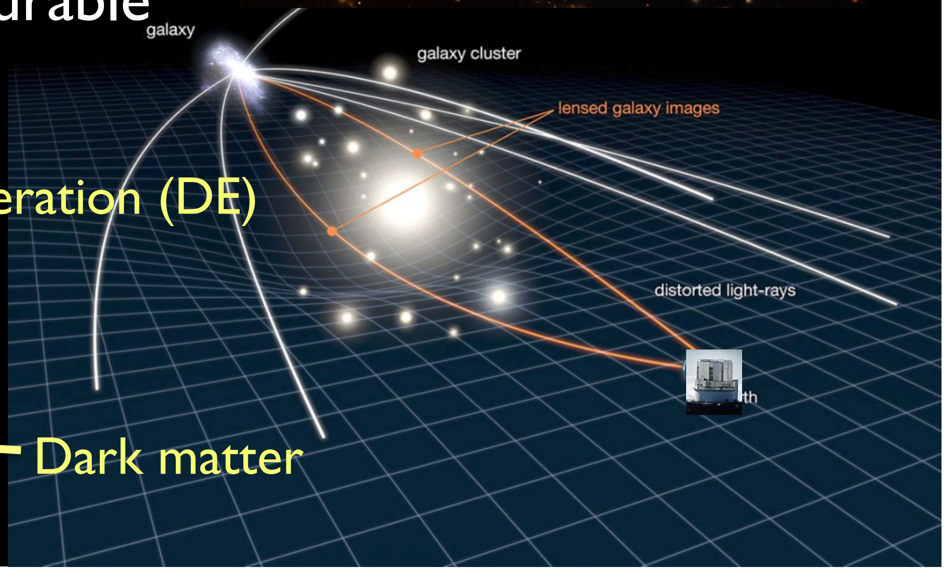
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$\Rightarrow$ light path: $\boldsymbol{x} = \boldsymbol{x}[z; g_{\mu\nu}]$



The *curved* space-time bends "light path"

The curvature of space-time is measurable via galaxy shapes



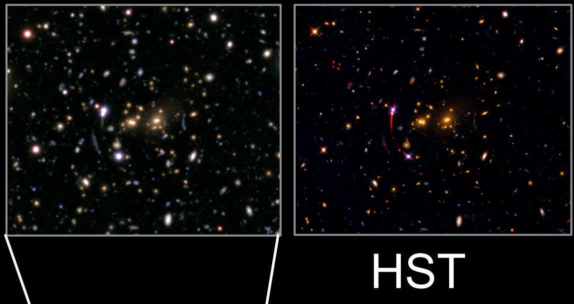
Cosmic acceleration (DE)

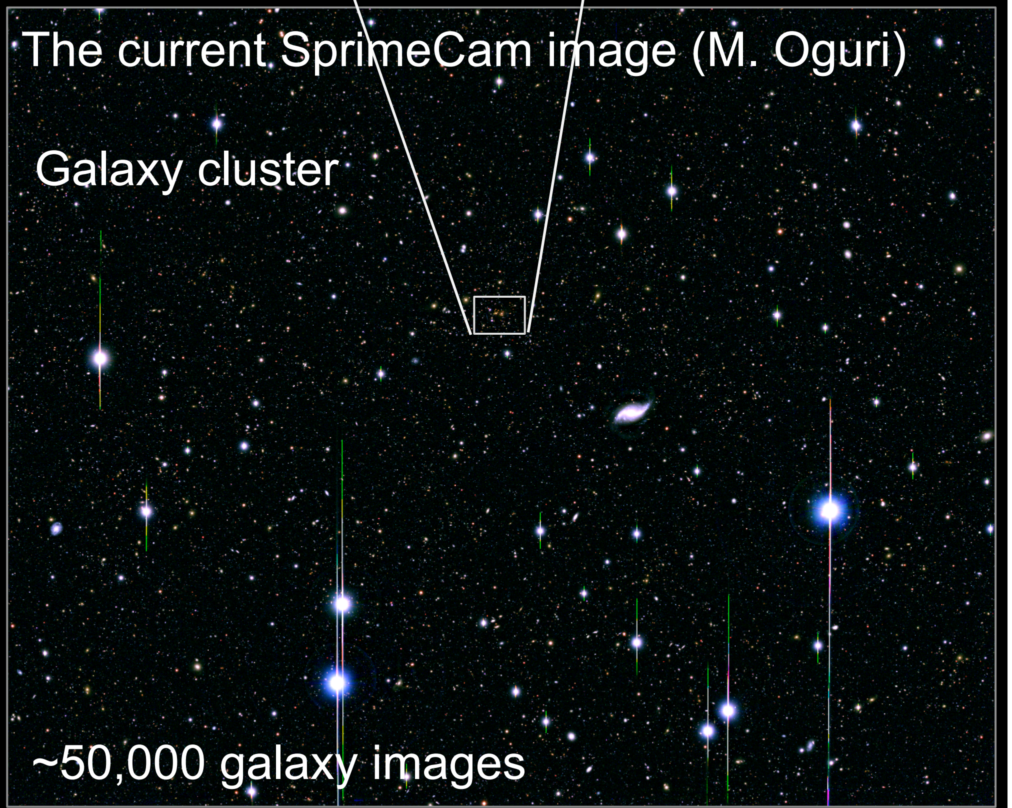
Lensing strength =
(geometry of the universe)
× (total matter of lens(es))

Dark matter

Subaru Telescope: wide FoV & excellent image quality

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





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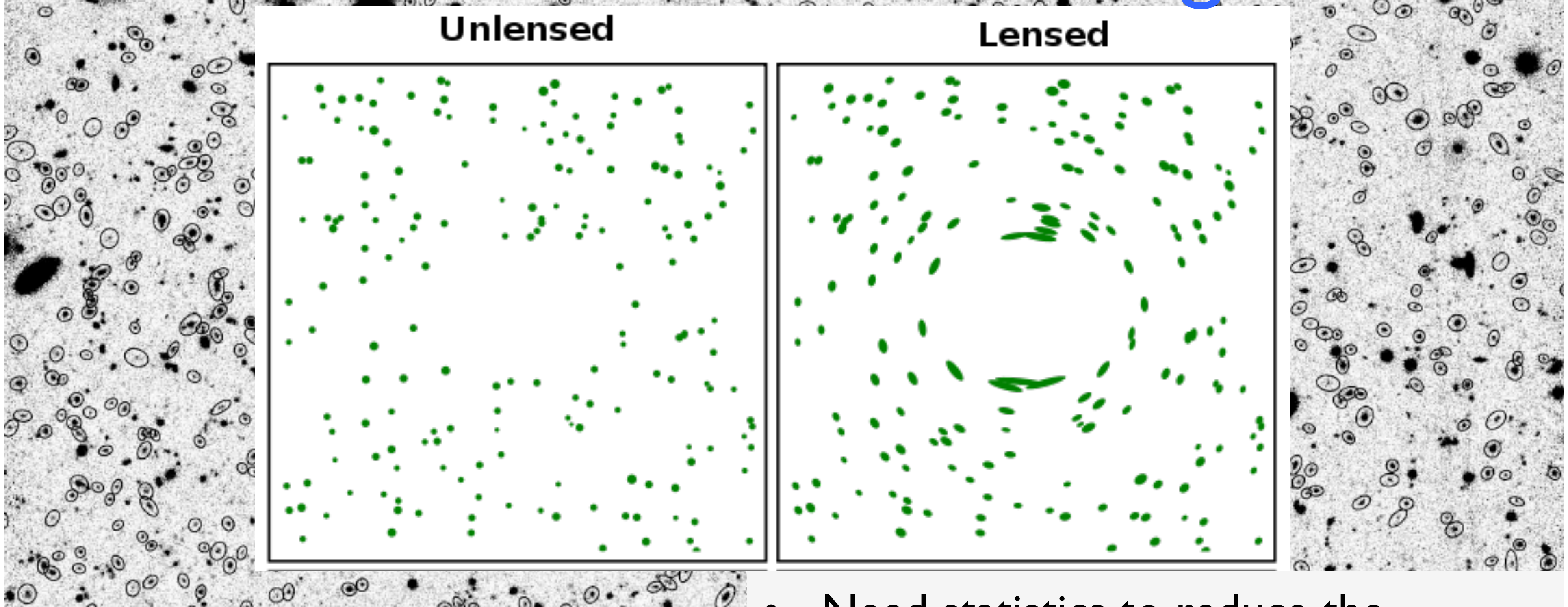
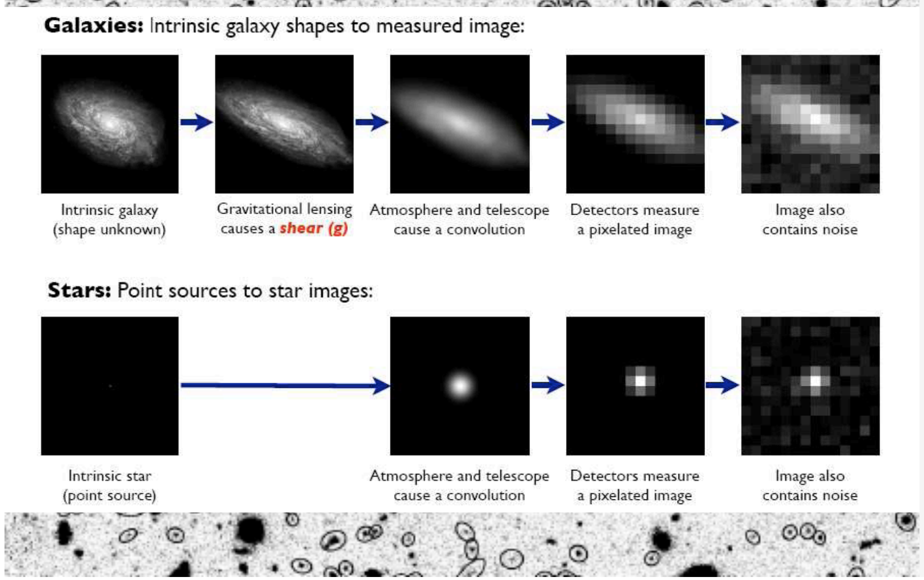
Hyper Suprime-Cam FoV

- **Fast**
- a cos

Statistical weak lensing





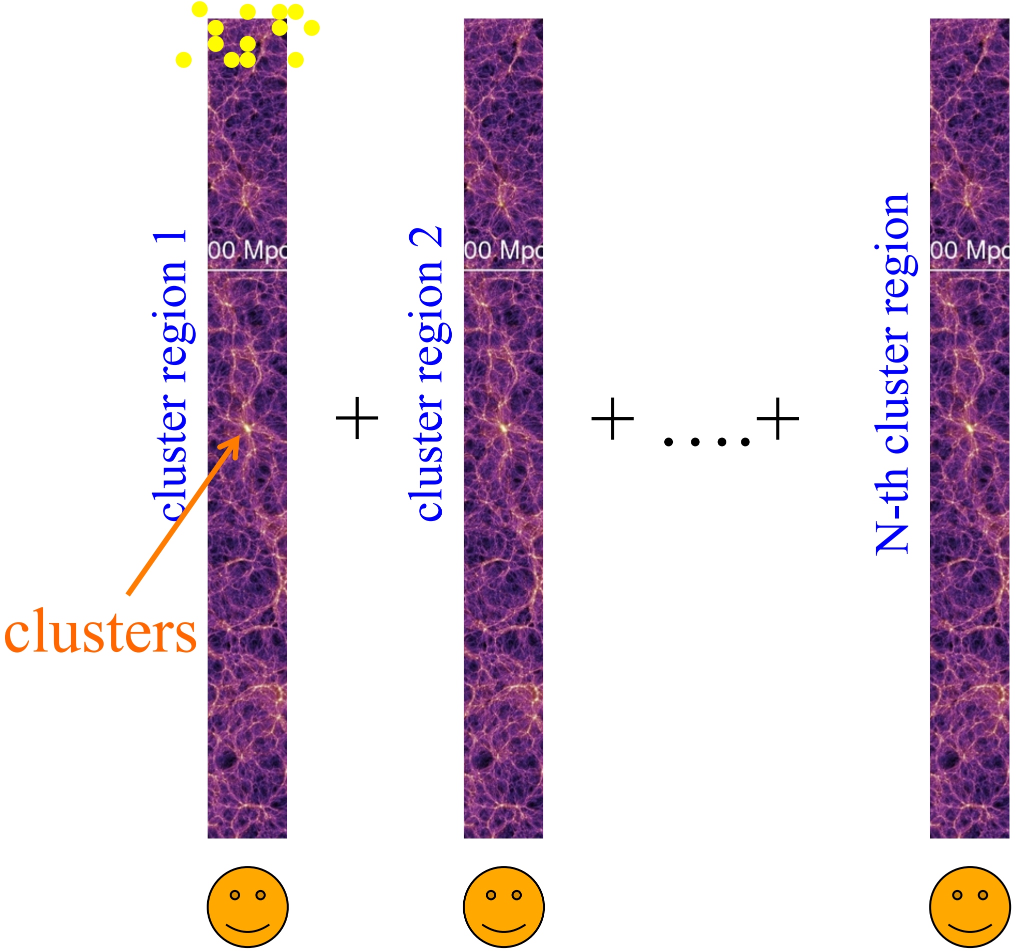
- Need statistics to reduce the intrinsic shape contamination
- Excellent image quality and deep image needed for an accurate WL measurement
- Issues; accurate shape measurements, PSF correction, pixelization effect

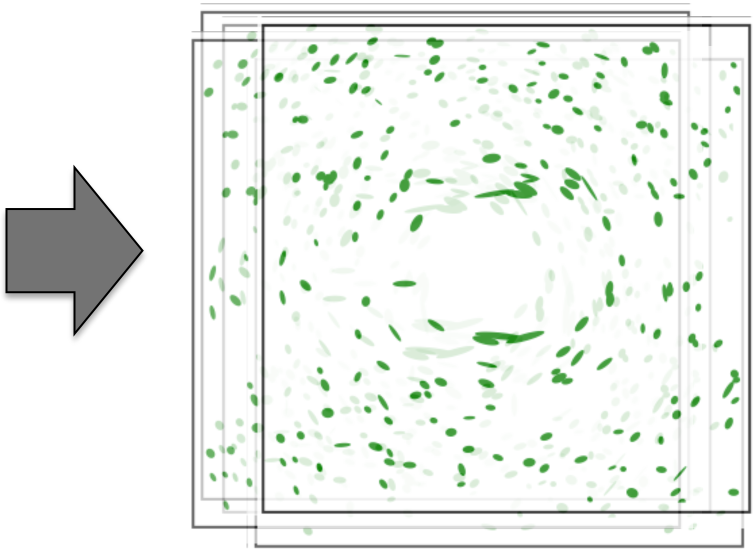
Stacked lensing: halo-shear correlation

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

Oguri & MT 11

projection effect





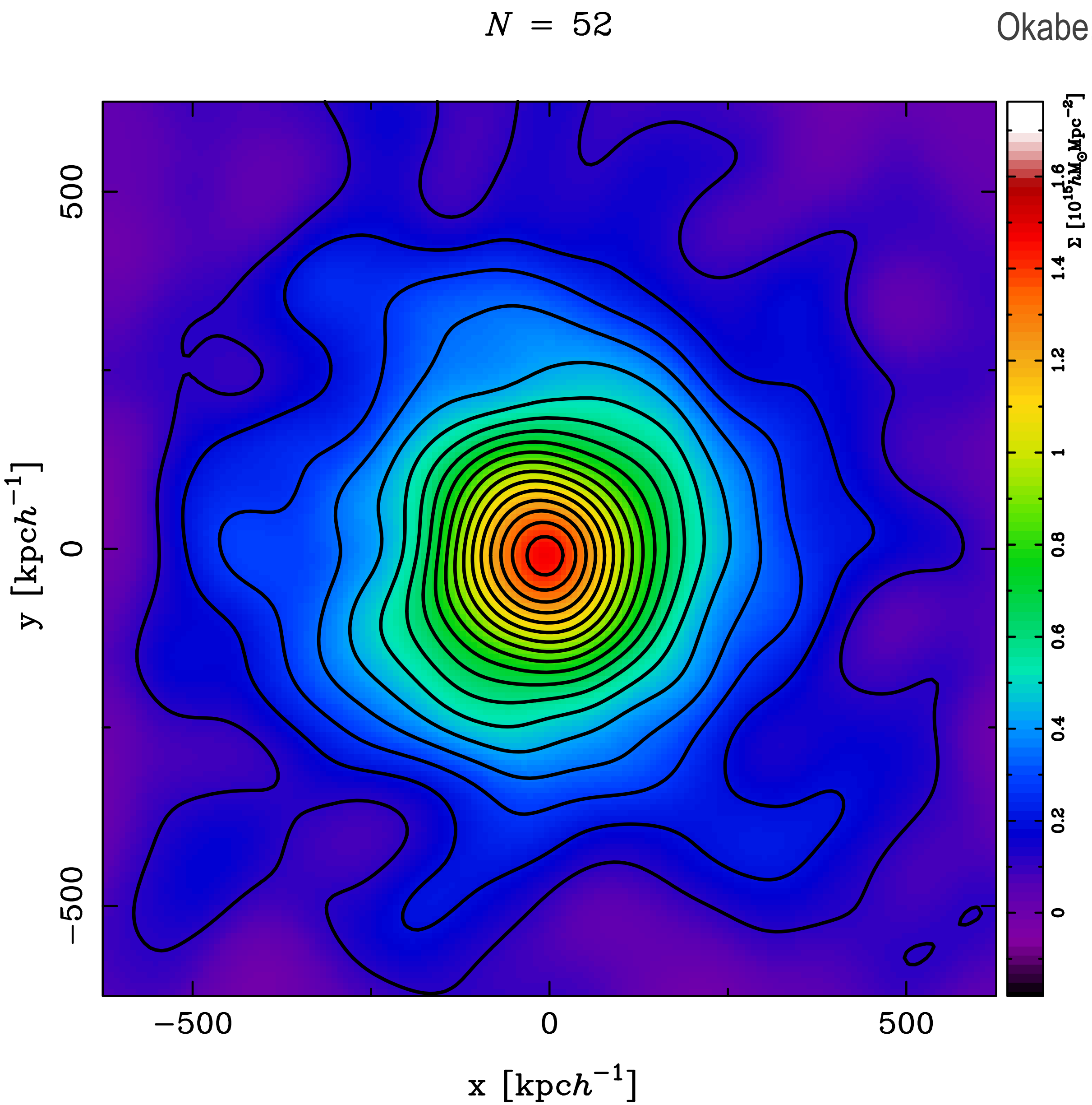
Less affected by projection effect, intrinsic alignment, sys. errors ….

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

Note: halo center

Average DM distribution of galaxy clusters

Okabe, MT, Umetsu, Graham, Futamase 10
Okabe, MT, Futamase et al. in prep.



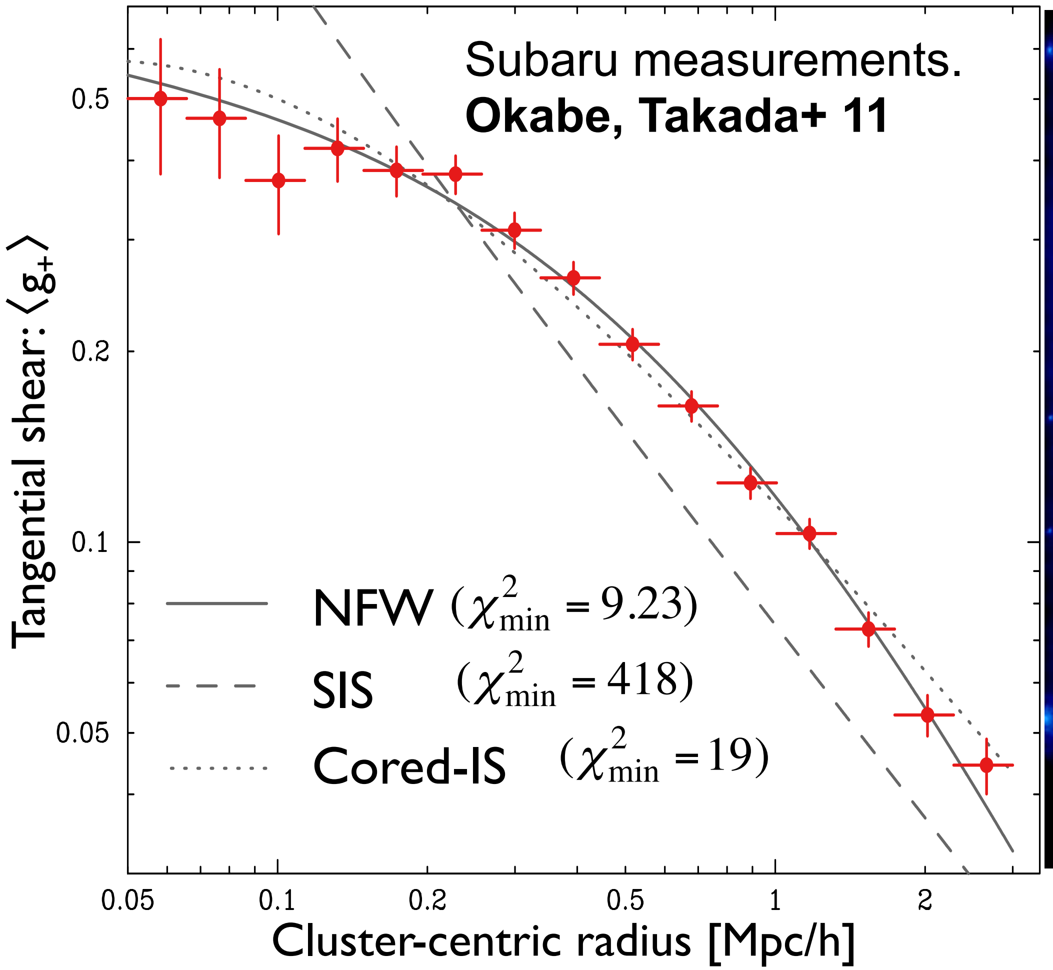
Stacked cluster lensing (all the ROSAT-selected clusters in z=0.15-0.3)

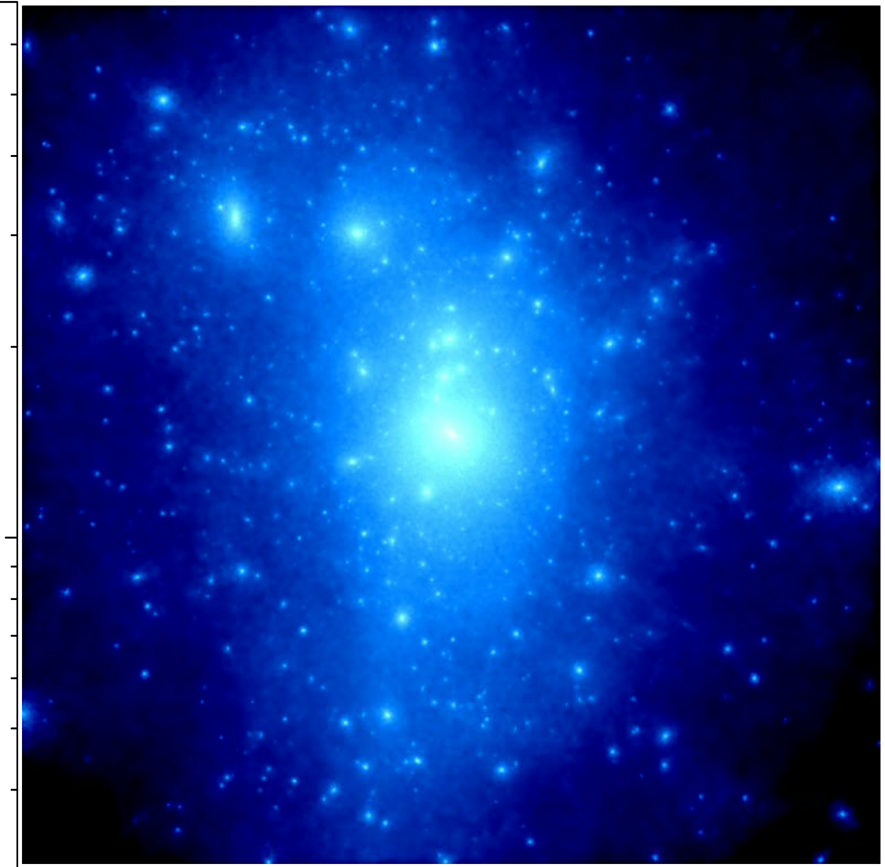
Have obtained Subaru data of all the 52 previously-known, X-ray luminous clusters in 0.15<z<0.3; S/N~50

Used ~*1M* galaxies in total for WL analysis

This projected started in 2005; it has taken 6 years so far (10 nights)

Stacked Lensing (contd.)



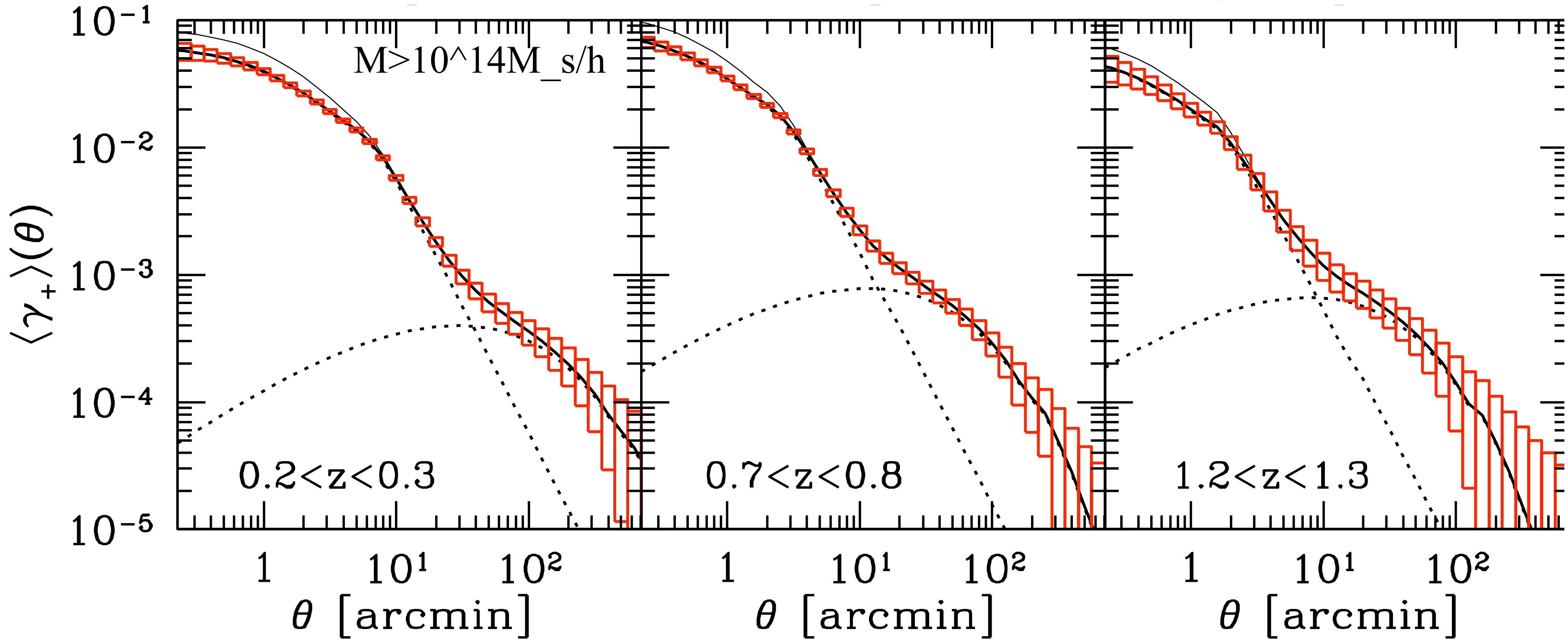


The precise meas. of mean mass: M_{vir}/10^14=$6.75^{+0.33}_{-0.32}$ (4%), c_{vir}=$4.10^{+0.21}_{-0.20}$(5%)

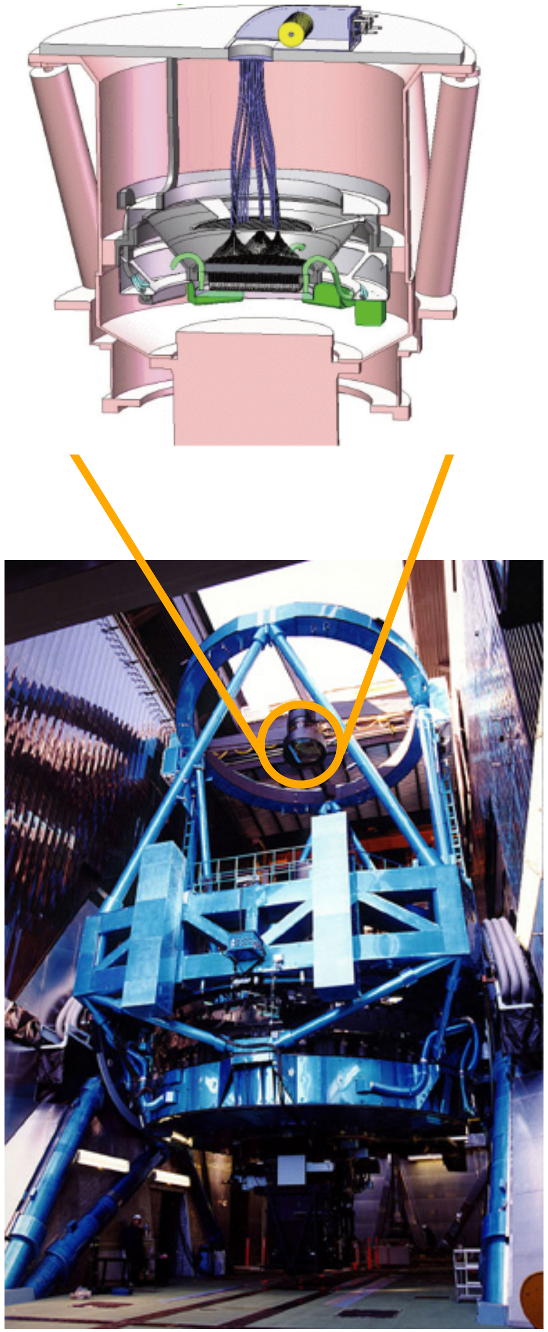
Excellent agreement with CDM simulation predictions

Forecast for stacked lensing with HSC

Oguri & MT 10



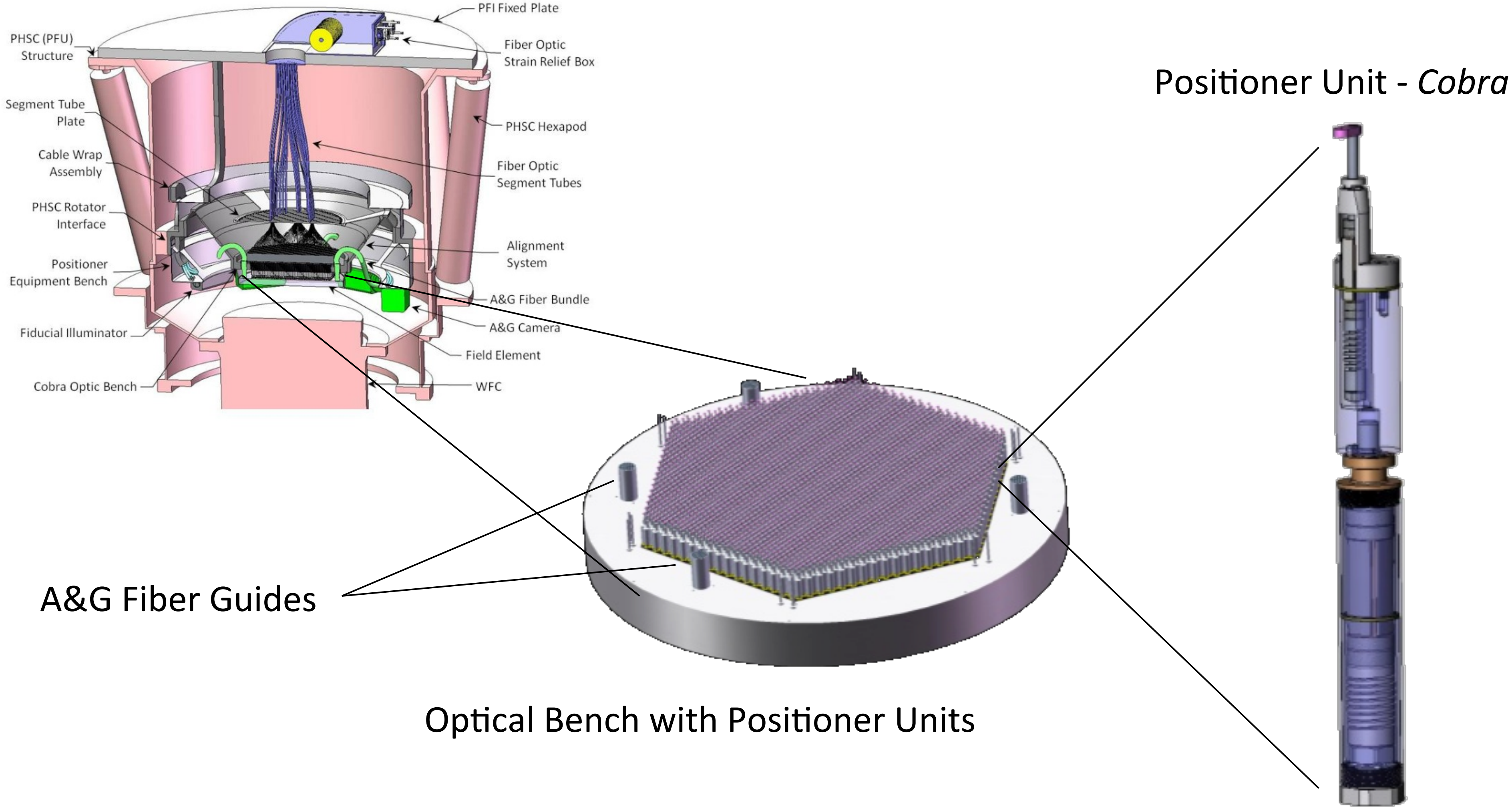
- HSC can achieve a high S/N detection of stacked WL signals out to z~1.3
- Small-angle signals are from one halo (the mean halo mass and the average shape of mass profile)
- Large-angle signals are from the mass distribution in large-scale structure



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 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)

- *Concept Design Review* (Mar 2012)
- Next milestone: Preliminary Design Review (Feb or Mar 2013)

PFS Science Document in arXiv

DRAFT VERSION JUNE 21, 2012
Preprint typeset using LaTeX style emulateapj v. 5/2/11

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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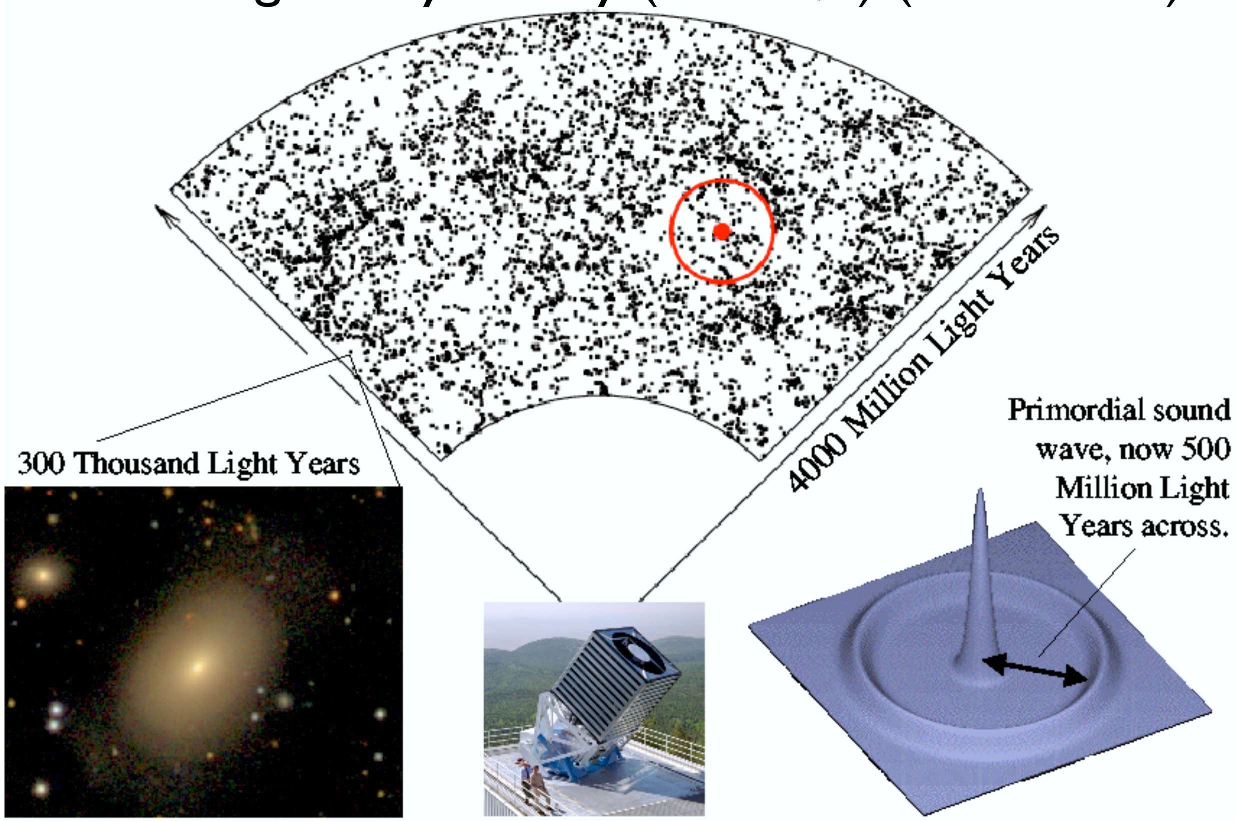
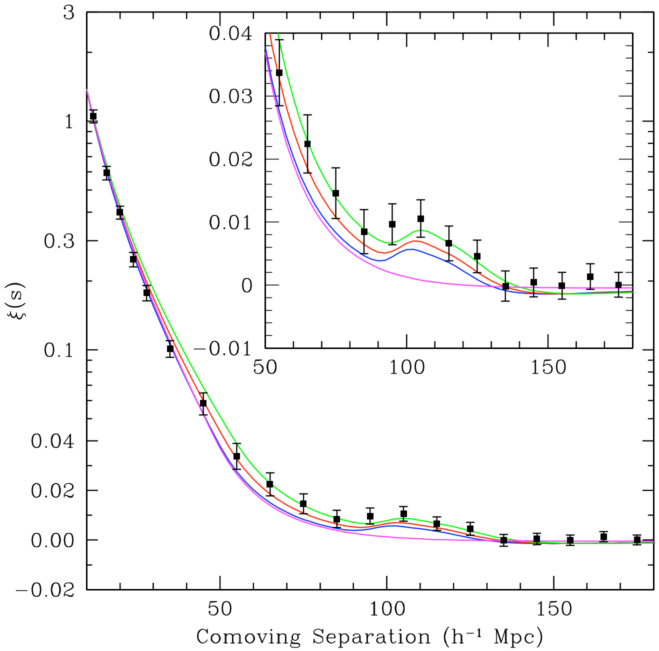
Baryon Acoustic Oscillation (BAO)

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





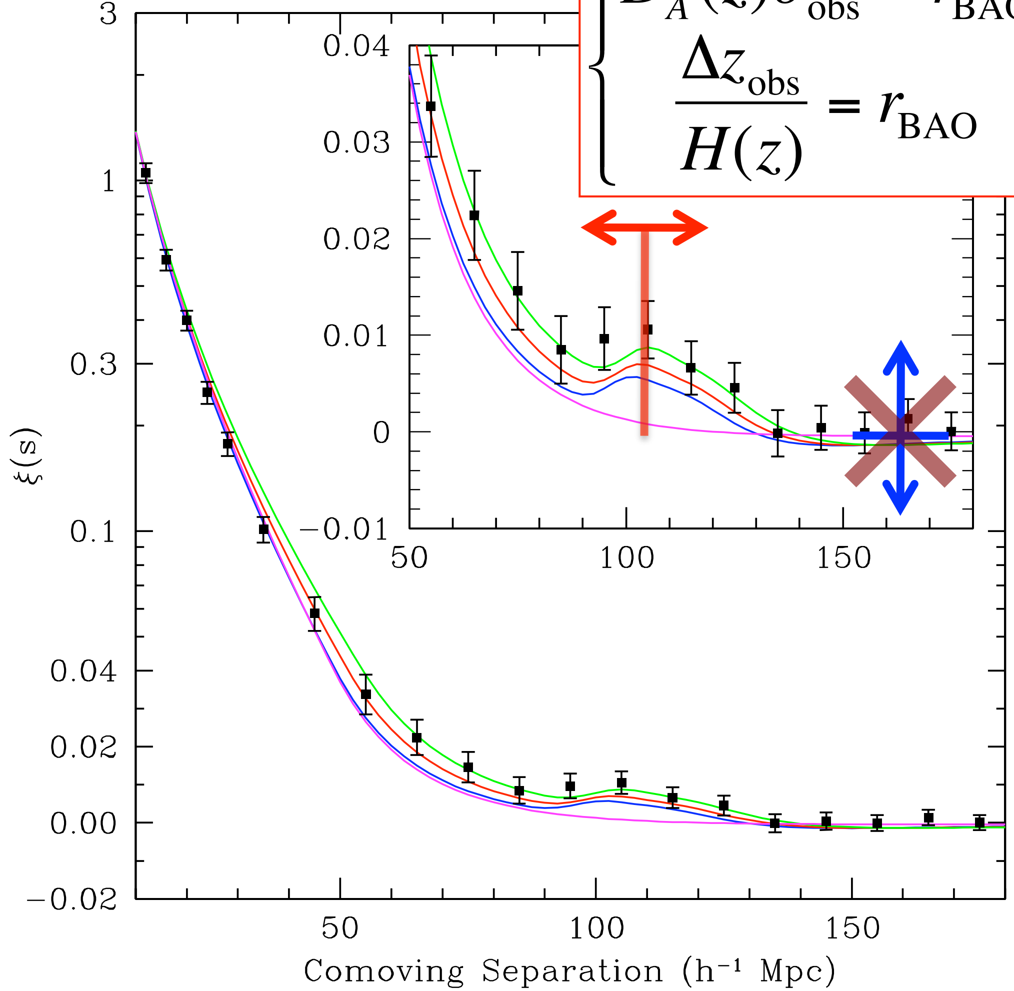
Eisenstein et al. (05)

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

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.

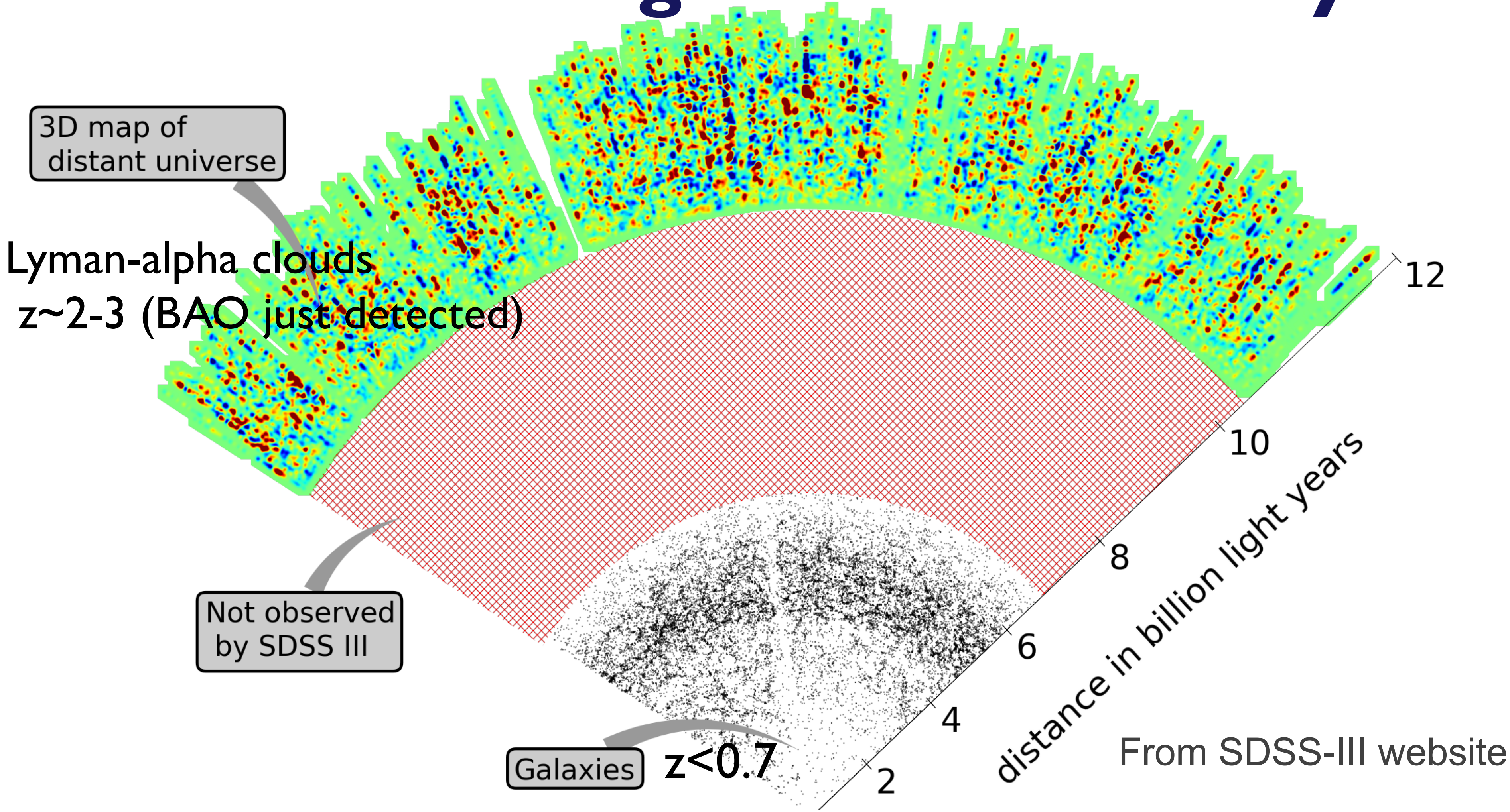
BAO geometrical test



$$\begin{cases} D_A(z)\theta_{\rm obs} = r_{\rm BAO} \\ \dfrac{\Delta z_{\rm obs}}{H(z)} = r_{\rm BAO} \end{cases}$$

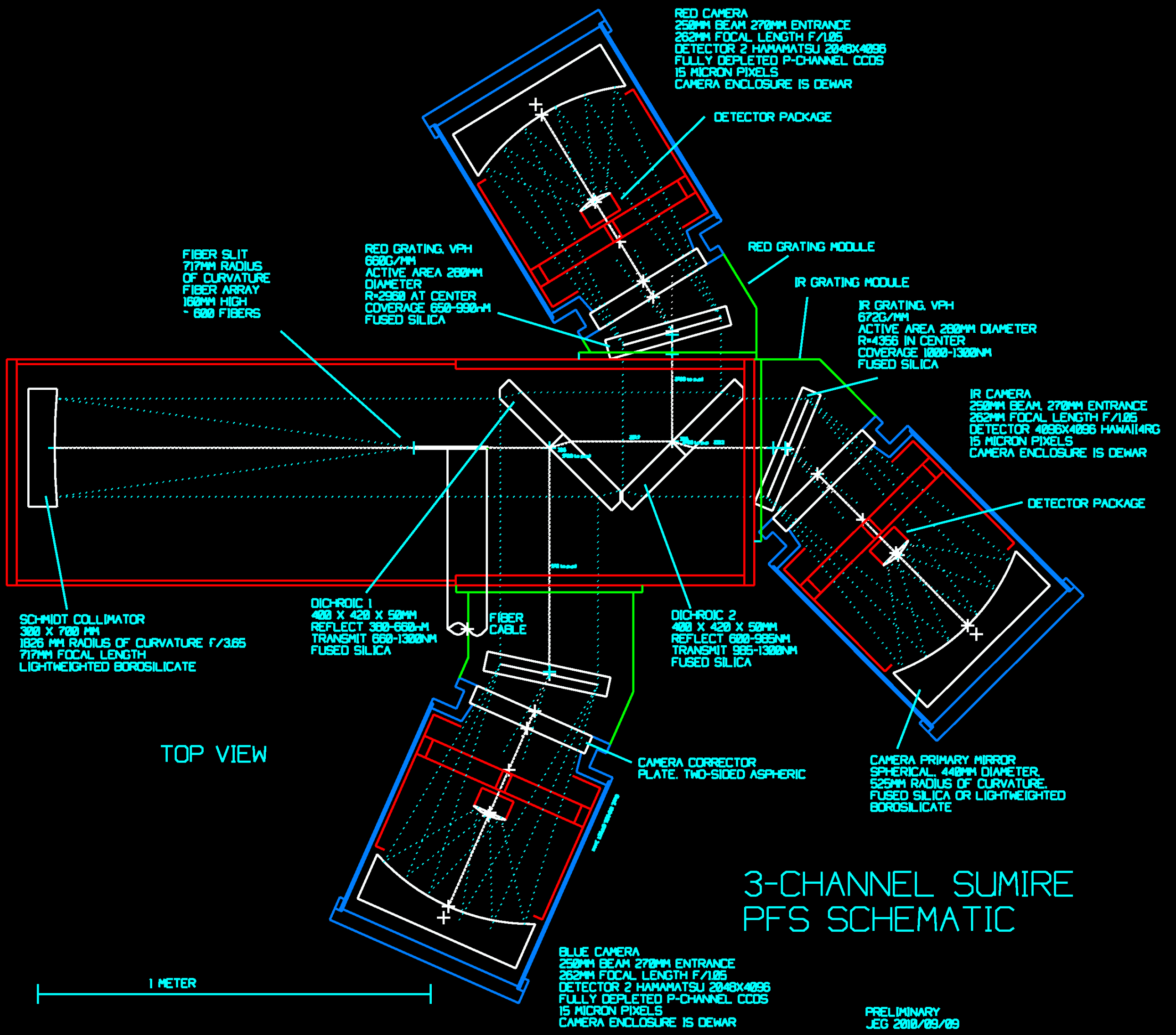
- Measure *the single length scale* (BAO) from the galaxy distribution
- *Not* use the clustering amplitude information to do cosmology due to galaxy bias uncertainties, even though much higher signal-to-noise ratios in the amplitude signals
- The amplitude uncertainty is marginalized over to obtain the distance constraints

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

PFS spectrograph design



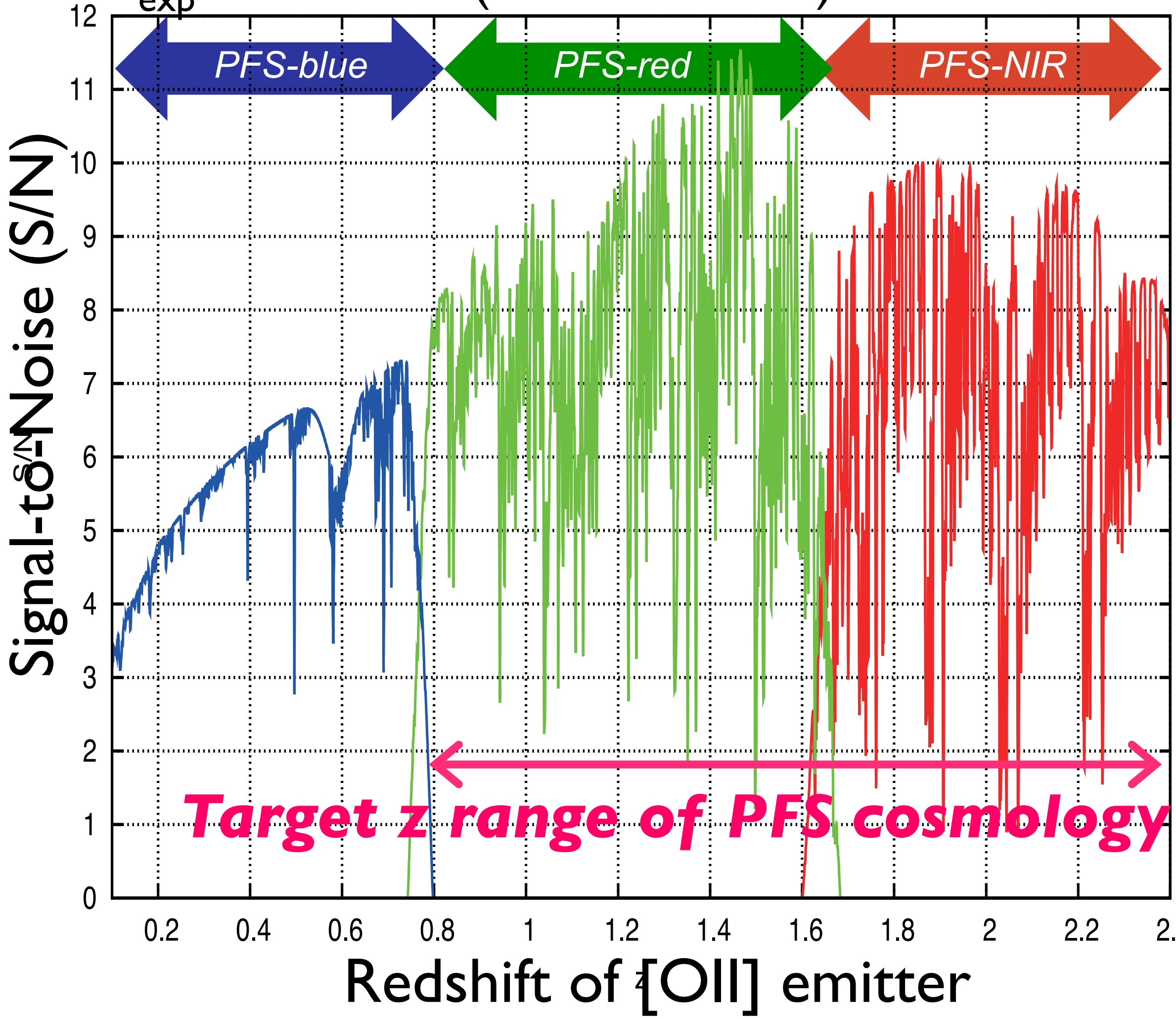
- Wide wavelength coverage: Blue (380-670), Red (650-1000) and NIR (970-1300) spectra at the same time

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

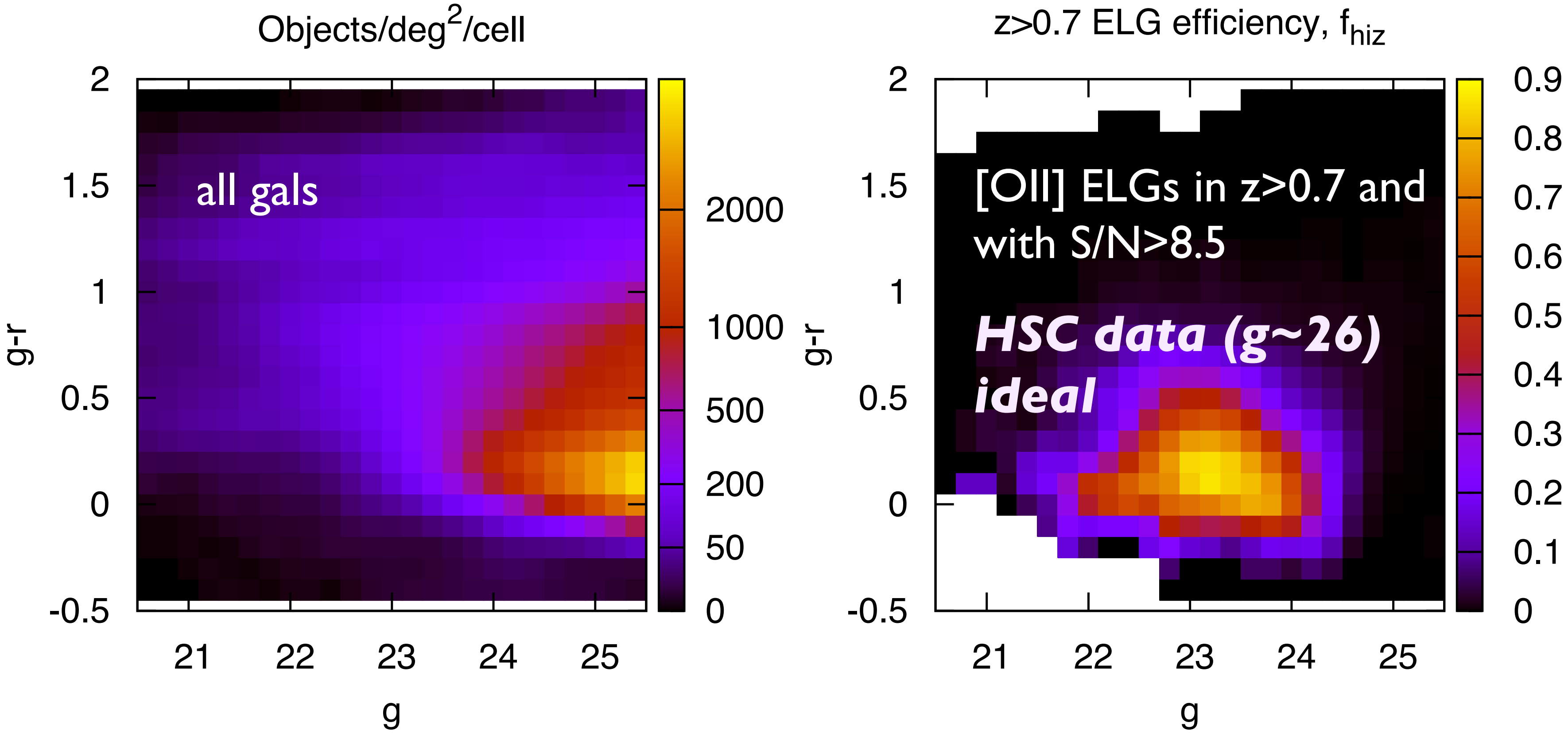
  a matched S/N in Red and NIR arms → a wide redshift coverage, **0.8<z<2.4**
- LSS more linear at higher z

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

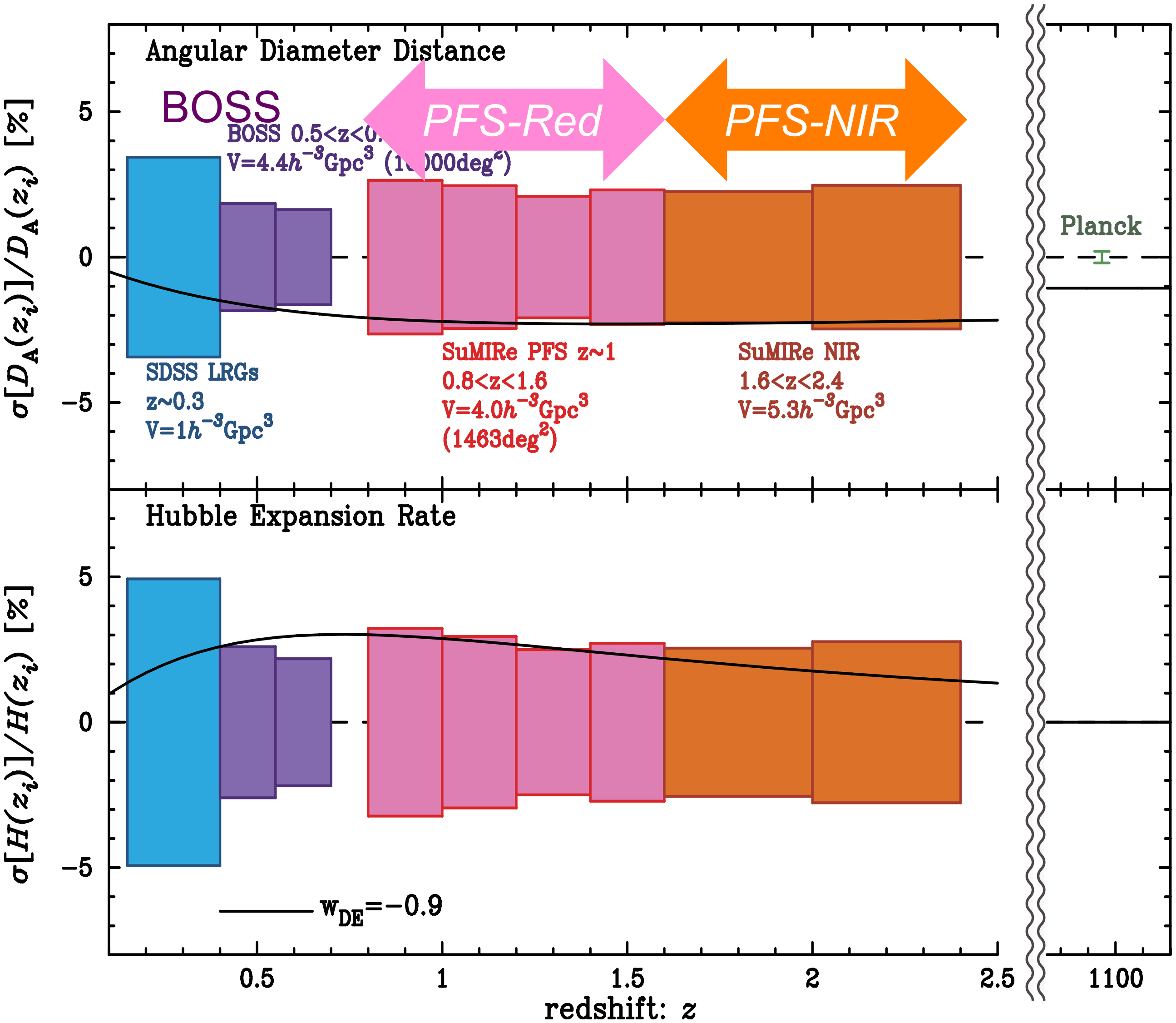
- Assume 100 clear nights to meet the scientific goals → the area of PFS survey

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

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

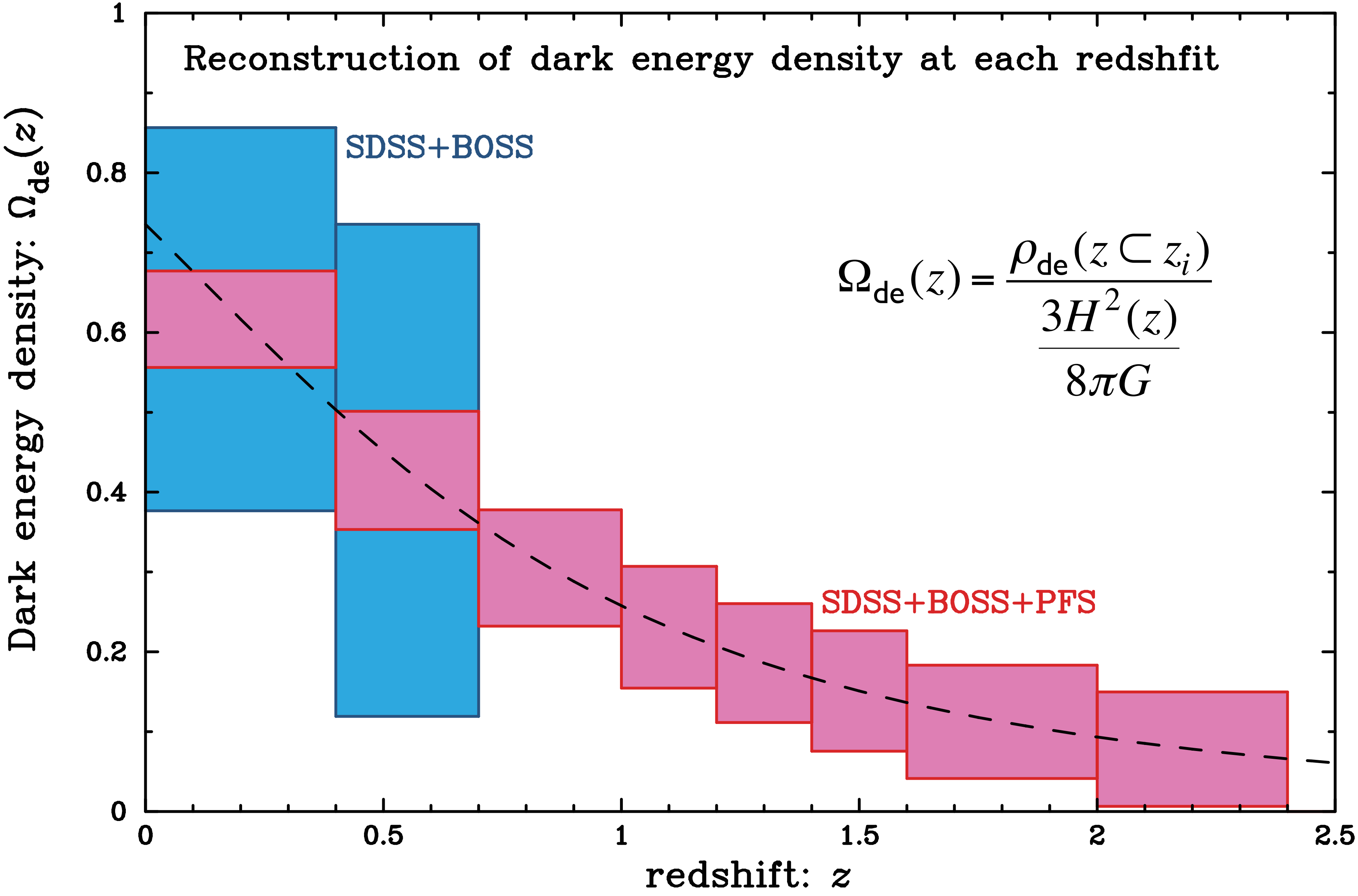
- The total volume: ~9 (Gpc/h)3 ~ 2 × BOSS survey
- Assumed galaxy bias (poorly known): b=0.9+0.4z
- PFS survey will have $n_gP(k)$~a few@k=0.1Mpc/h in each of 6 redshift bins

Expected BAO constraints

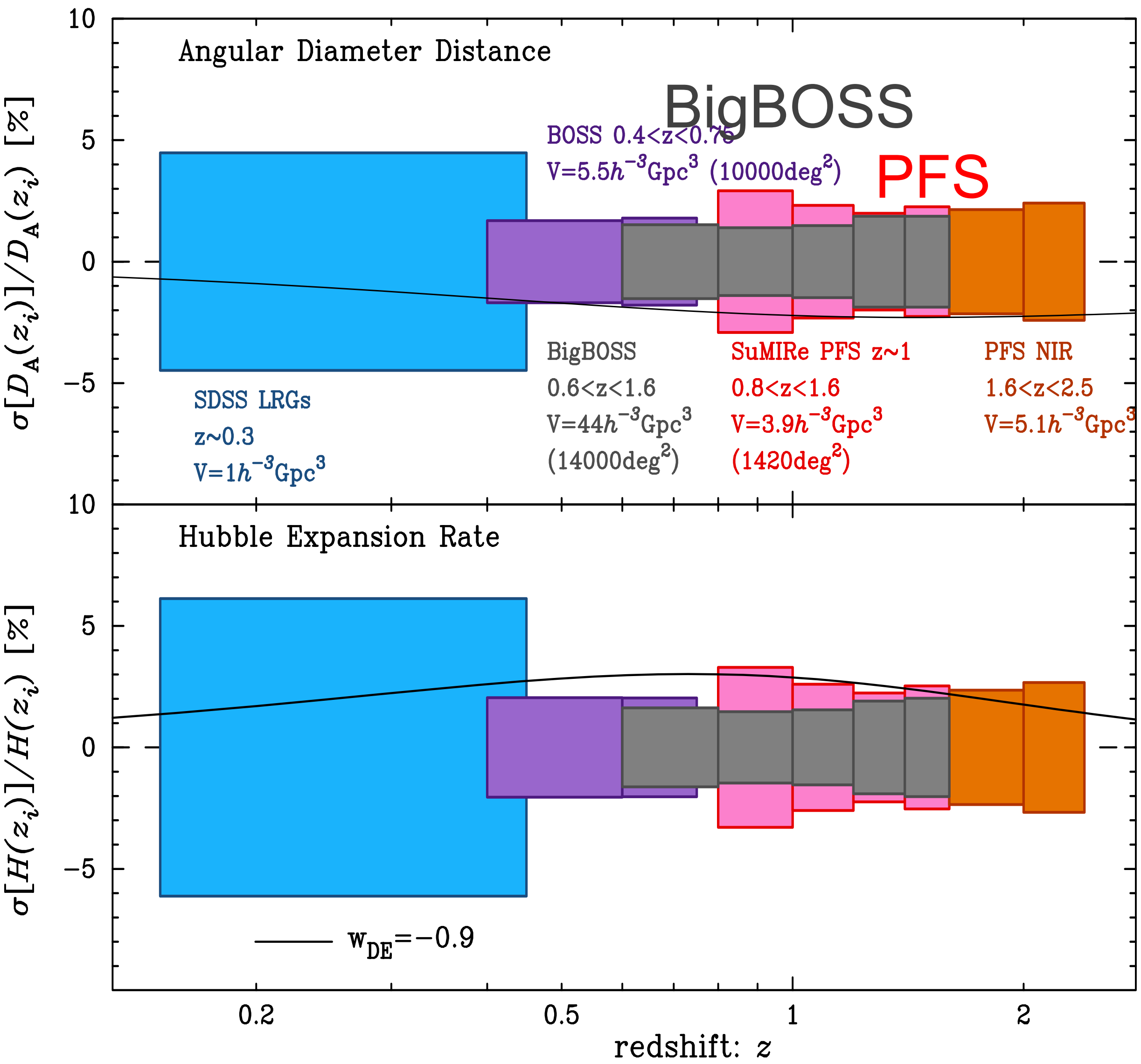


- The PFS cosmology survey enables a *3%* accuracy of measuring $D_A(z)$ and $H(z)$ in each of 6 redshift bins, over 0.8<z<2.4
- This accuracy is *comparable* with BOSS, but extending to higher redshift range
- Also very efficient given competitive situation
  - BOSS (2.5m): 5 yrs
  - PFS (8.2m): 100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

Model-independent DE reconstruction



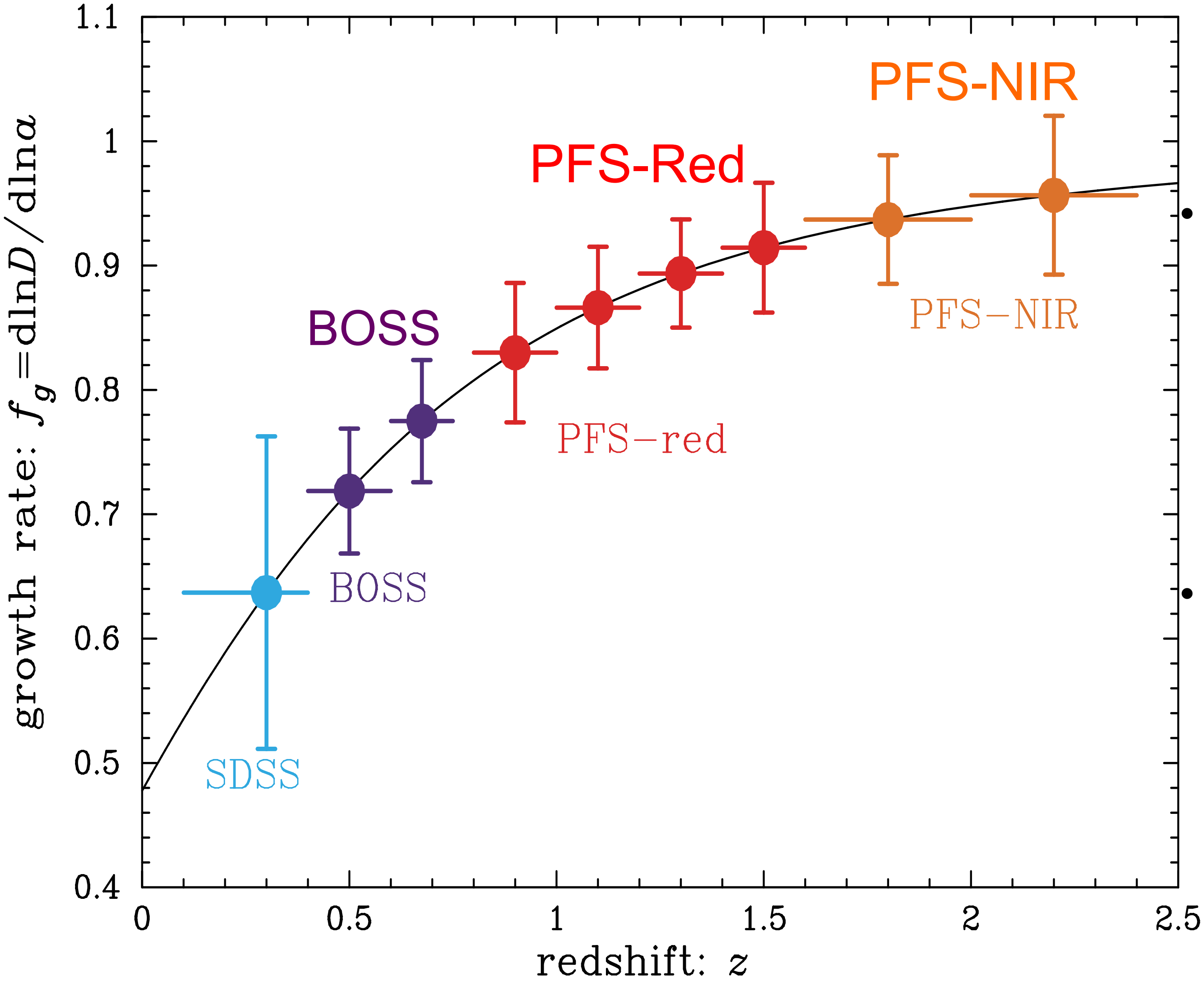
PFS vs. BigBOSS



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

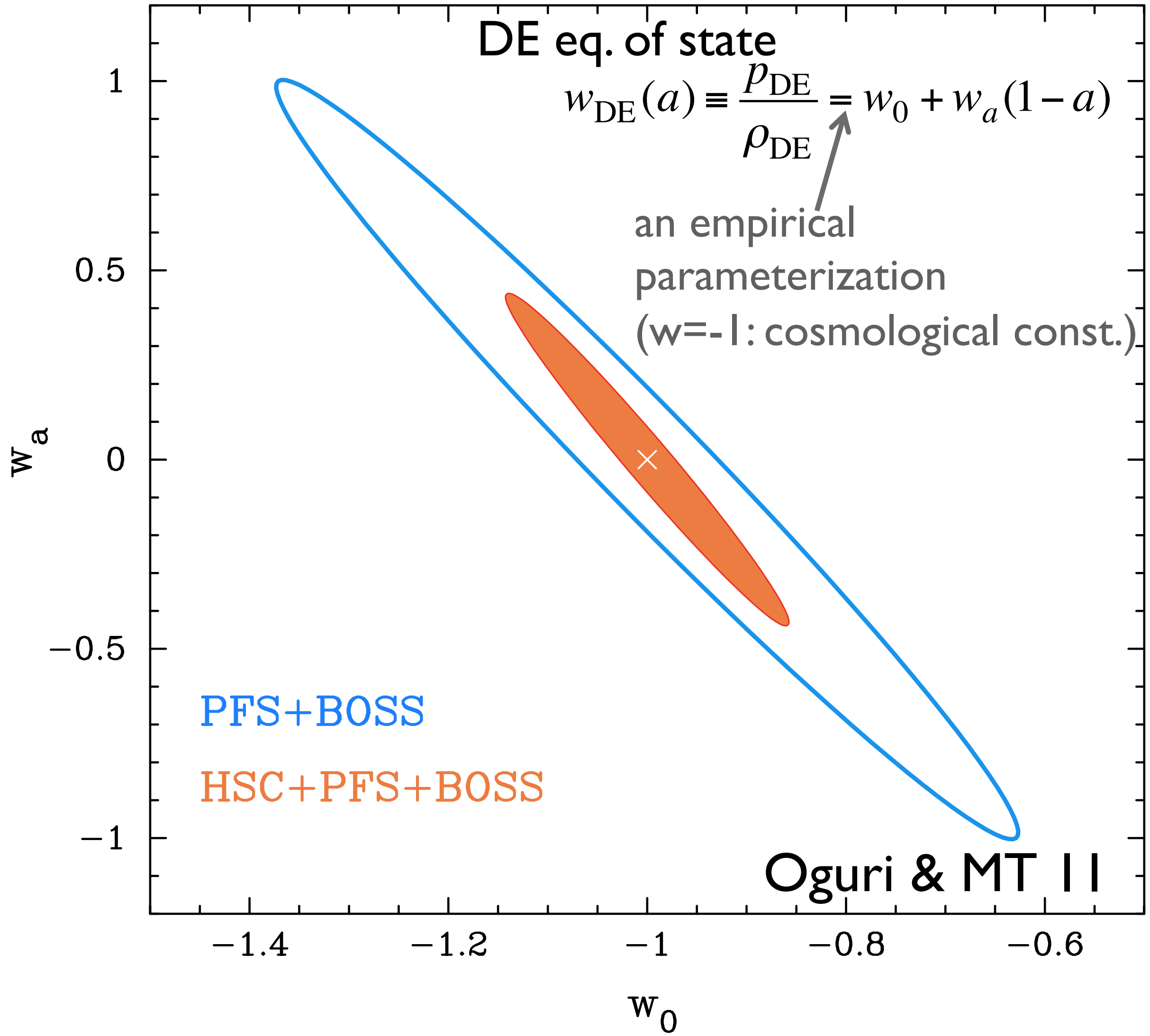
- *No! PFS has a comparable power with BigBOSS in z=1.2-1.6, also probes the new z-range*

Expected growth rate constraints



- The PFS survey design allows a 5% accuracy of constraining the growth rate in each redshift (each of 6 bins)
- Again complementary to BOSS

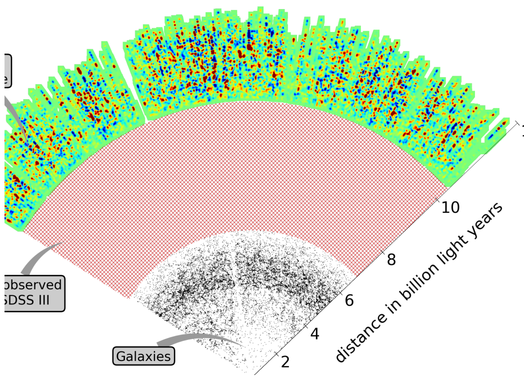
SuMIRe: HSC+PFS forecast

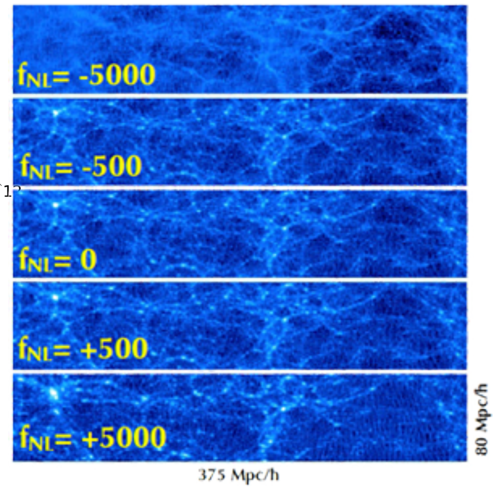


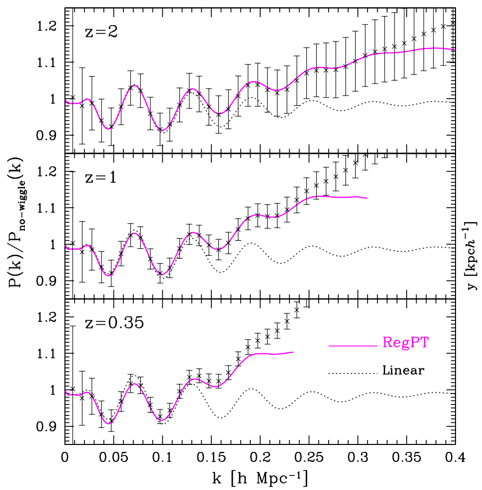
- Improves the dark energy FoM by a factor of 6 from either alone of the two
- σ(w_const)=0.02: equivalent to Stage-IV DE experiment
- There are more rooms to explore the synergy (not yet fully explored in the literature)
- Calibration issues of various systematics in each imaging and spectroscopic surveys

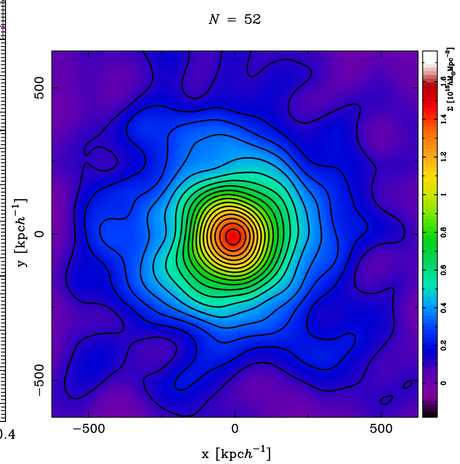
Cosmology frontier survey needs *help* from theory people!

- Need to resolve *many* issues in both theory and observation
- *New* ideas can be tested with upcoming data sets (SuMIRe in particular)
- Japan is *behind* observational cosmology (theory is stronger in Japan)
- *A big chance/opportunity* for Japanese community to *make a leap* to the *world frontier*
- *Discovery channels (hope serendipitous discoveries as in SK)*



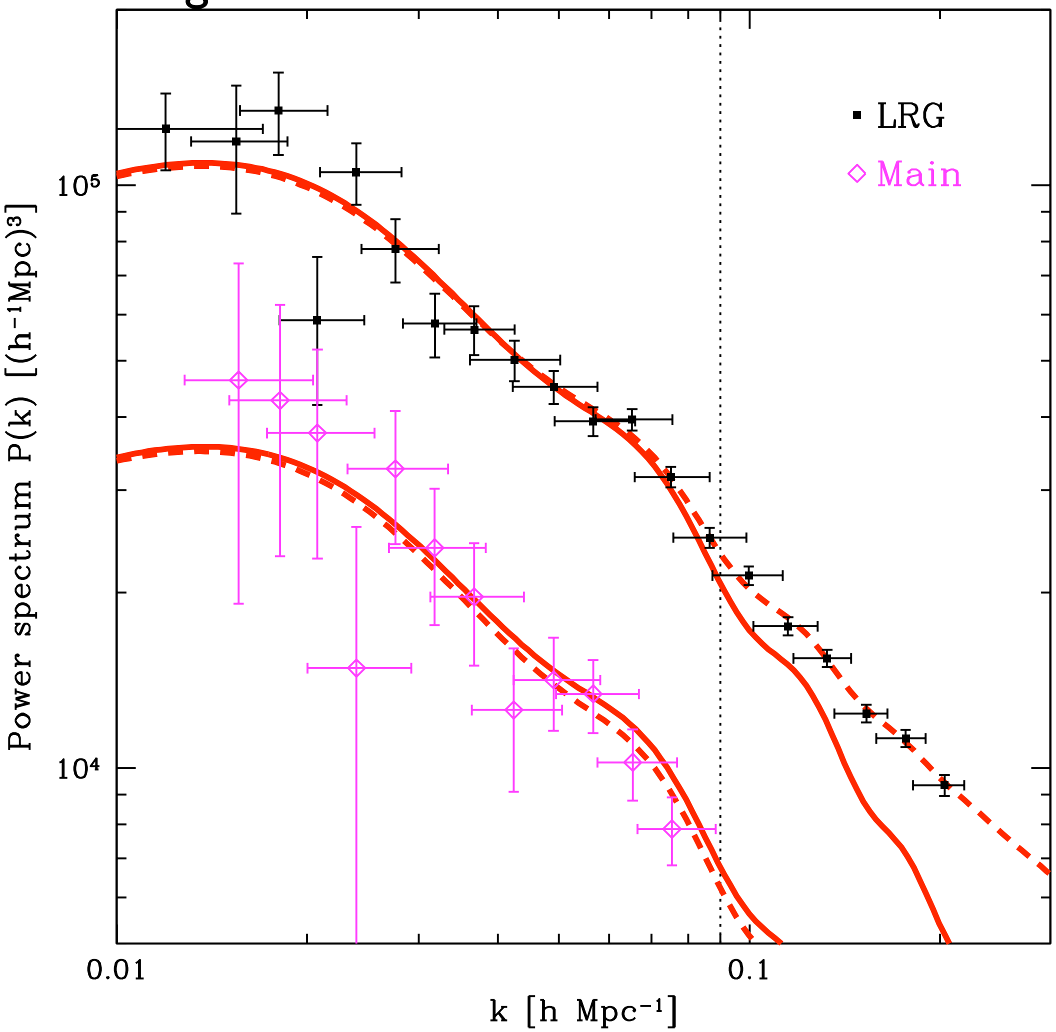






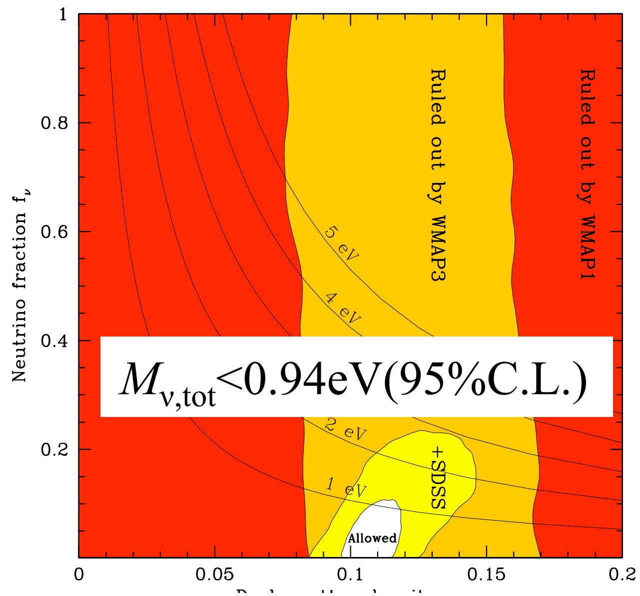
Current obs. cosmology driven by data

Tegmark et al. 06

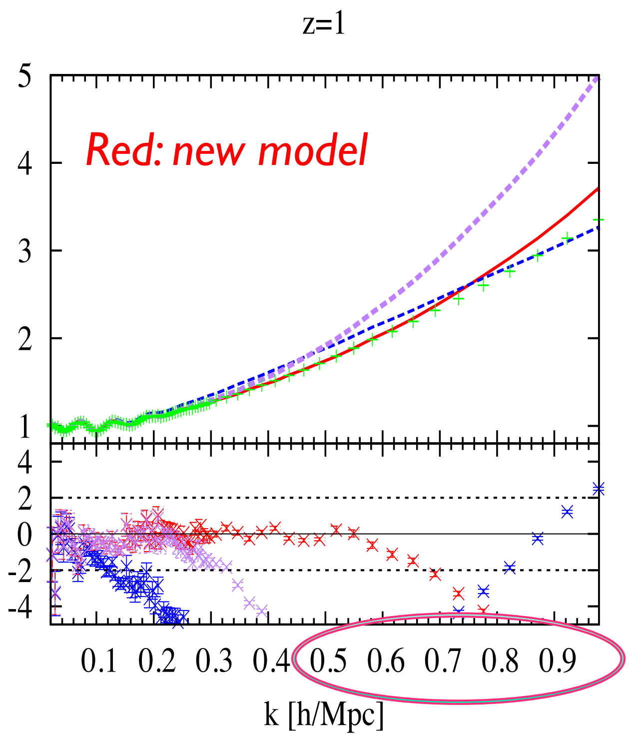


$$P_g(k) = b^2 P_m^L(k) \frac{1+Q_{\rm nl}k^2}{1+1.4k}$$

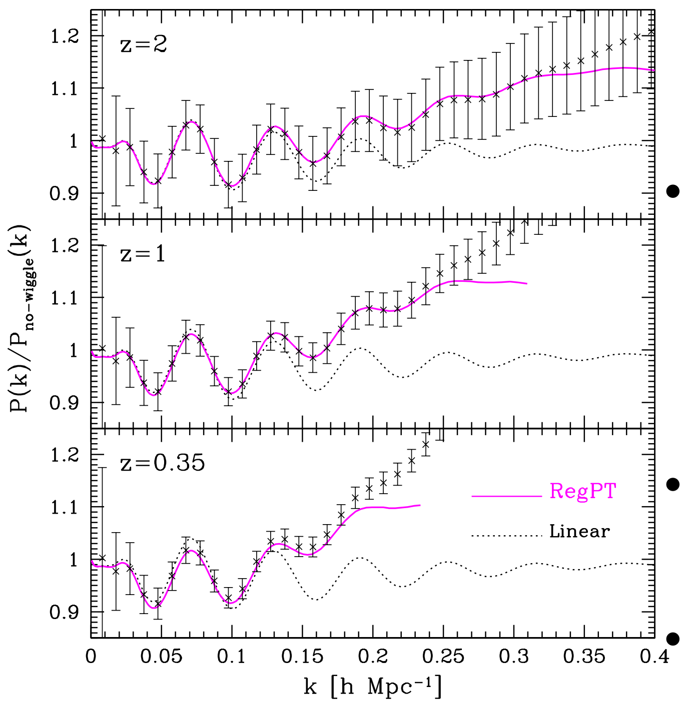
- The high-precision measurements/data available
- Empirical models often used
- Data is more advanced than the accuracy of model



New development in modeling nonlinear power spectrum



Sugiyama & Futamase 12



Taruya et al. 12
(also see Matsubara 08…)

- Various new methods to compute nonlinear power spectra have revisited
- Good examples; new ideas from theory people help! (for analysis/interpretation)
- The field led by many Japanese cosmologists
- Based on pioneer works; Kodama & Sasaki (84), Suto & Sasaki (91), Makino, Suto & Sasaki (92)

Summary

- SuMIRe = Subaru Measurement of Images and Redshifts
  - Unique capabilities of 8.2m Subaru Telescope (other projects all 4m-class telescopes besides LSST)
- Hyper Suprime-Cam Survey (HSC) = imaging of 1B gals
  - Start the wide-area survey from around Aug 2013 for 5 years
  - Use WL to recover the DM distribution up to z~1
- Prime Focus Spectrograph (PFS) = redshifts of 4M gals
  - Start the wide area survey from around 2018 for 5 years
  - Baryon Acoustic Oscillations to measure the cosmic expansion rate
- Imaging + spectroscopic survey is a very powerful combination
  - Cosmology: DE, DM, neutrino masses, curvature, inflation models (f_NL)
  - Not only for cosmology, also for galaxy evolution, the origin of Milky Way
- Great opportunities for young cosmologists to jump into, to "test" your models/ideas