Cosmology with SuMIRe HSC/PFS

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Goal of my talk

- Estimate the power of PFS (its minimum design version; red-arm) for doing a cosmological survey (especially focused on BAO), compared to competing surveys of 4m-class telescope
- Estimate the feasibility of PFS BAO survey properly taking into account the PFS instrumentation parameters and the sky background in red wavelengths (working with Jim)
  - What is the minimum nights needed for the BAO survey?
  - What is the uniqueness of SuMIRe HSC/PFS surveys, compared to other surveys?

Astro2010

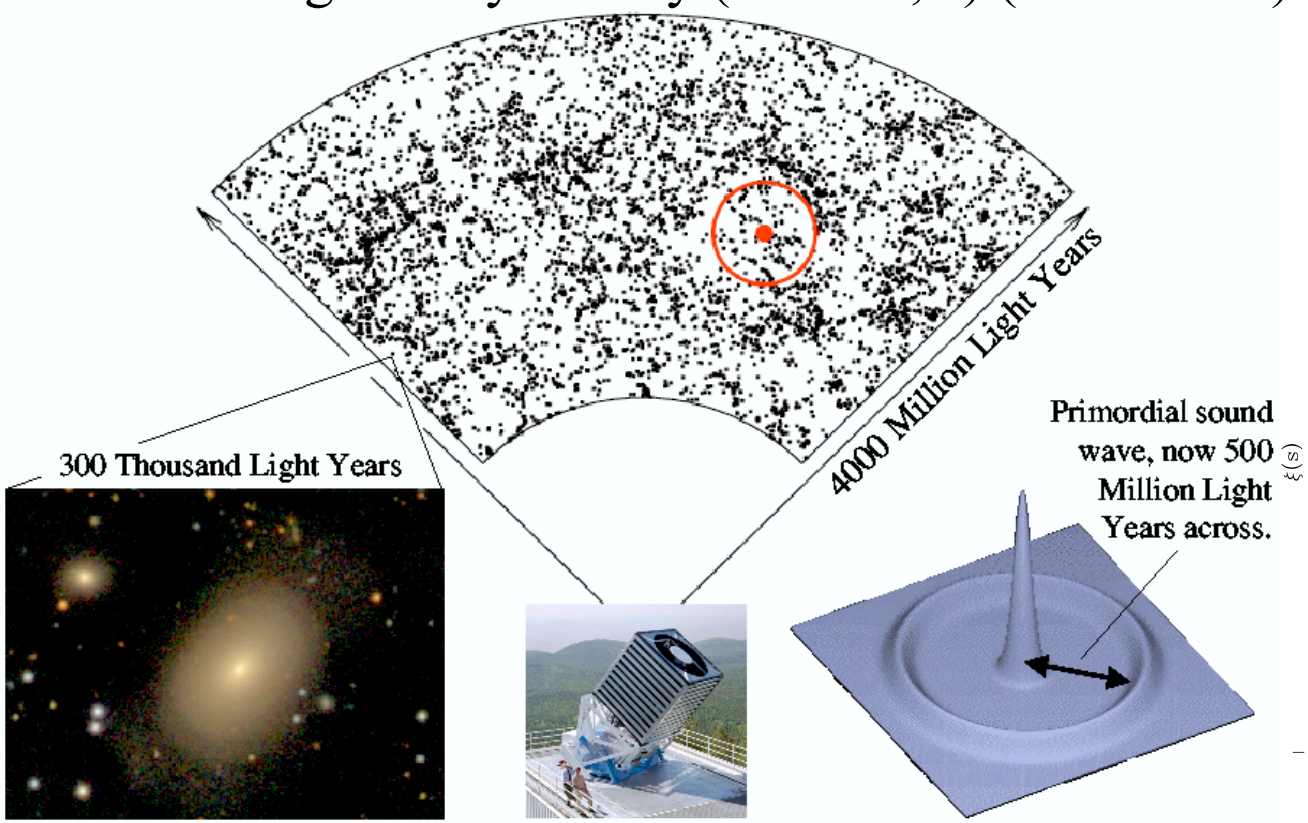
- Space-based survey
  1. WFIRST: Dark Energy and Exoplanet Statistics
     - 1.5m; 144MPx HgCdTe detectors, 200mas, grism; L2
     - Gravitational lensing, distant supernovae, BAO
  2. Explorer Program Augmentation
- Ground-based survey
  1. LSST: Dark Energy, Dark Matter and the time-variable universe
     - 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?*

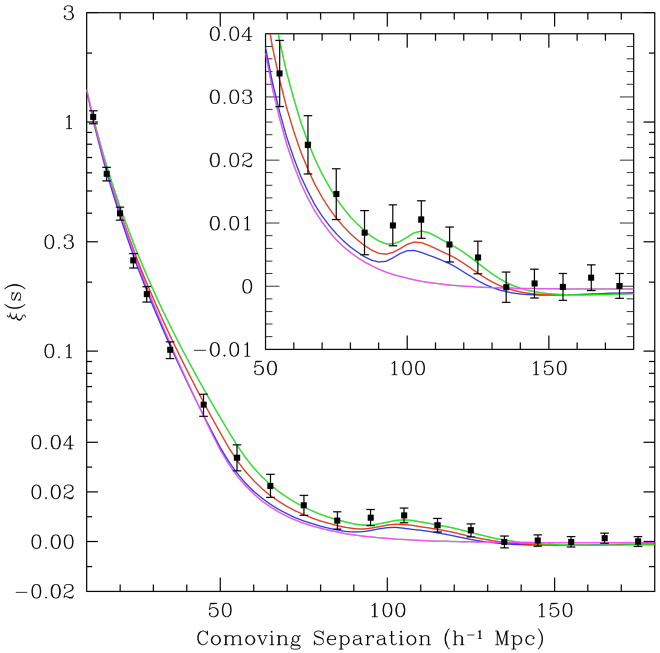
➢ *HSC survey can play a pioneering role for these ultimate wide-field imaging surveys (we can scoop DE science!); URGENT TASK!*

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

BAO: standard ruler

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





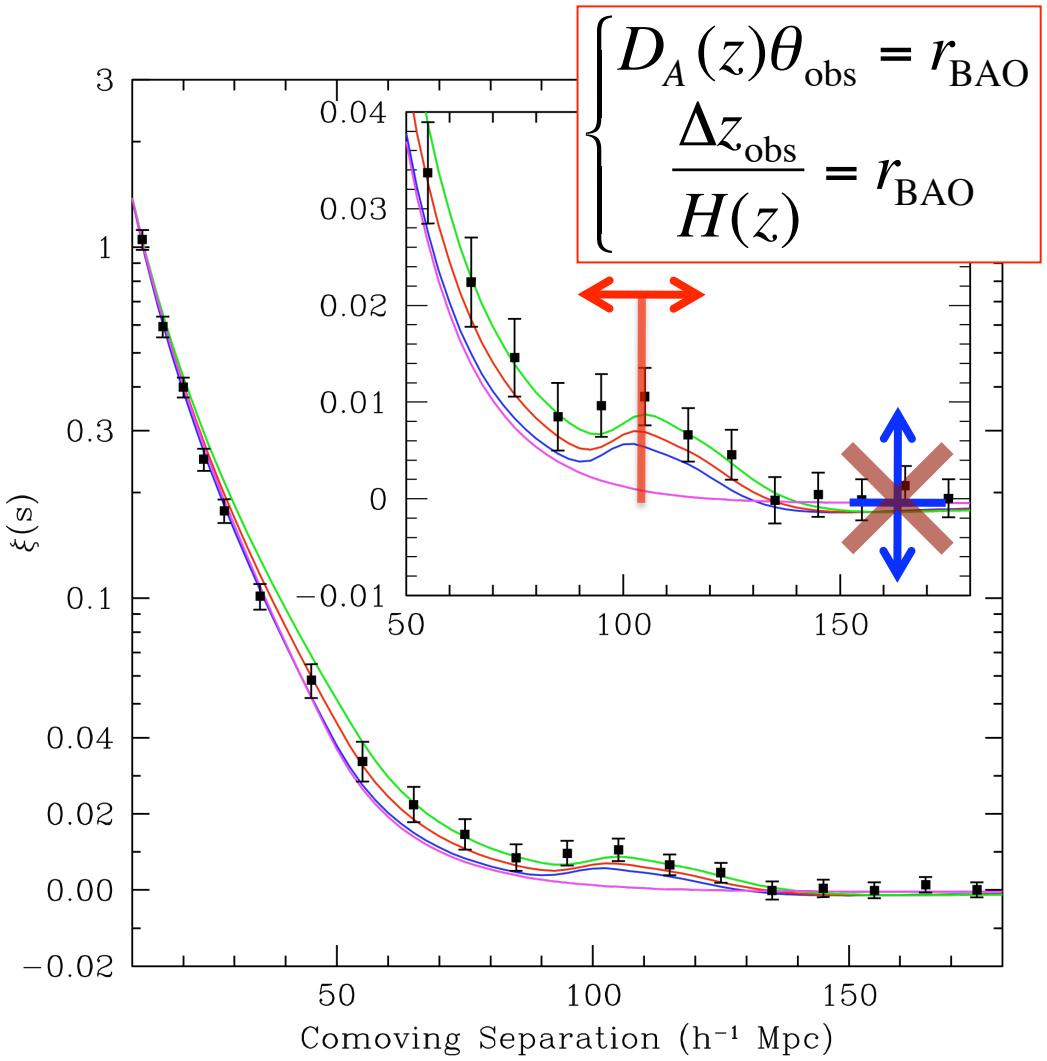
Eisenstein et al. (05)

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

Dark Energy Task Force Report (DETF)

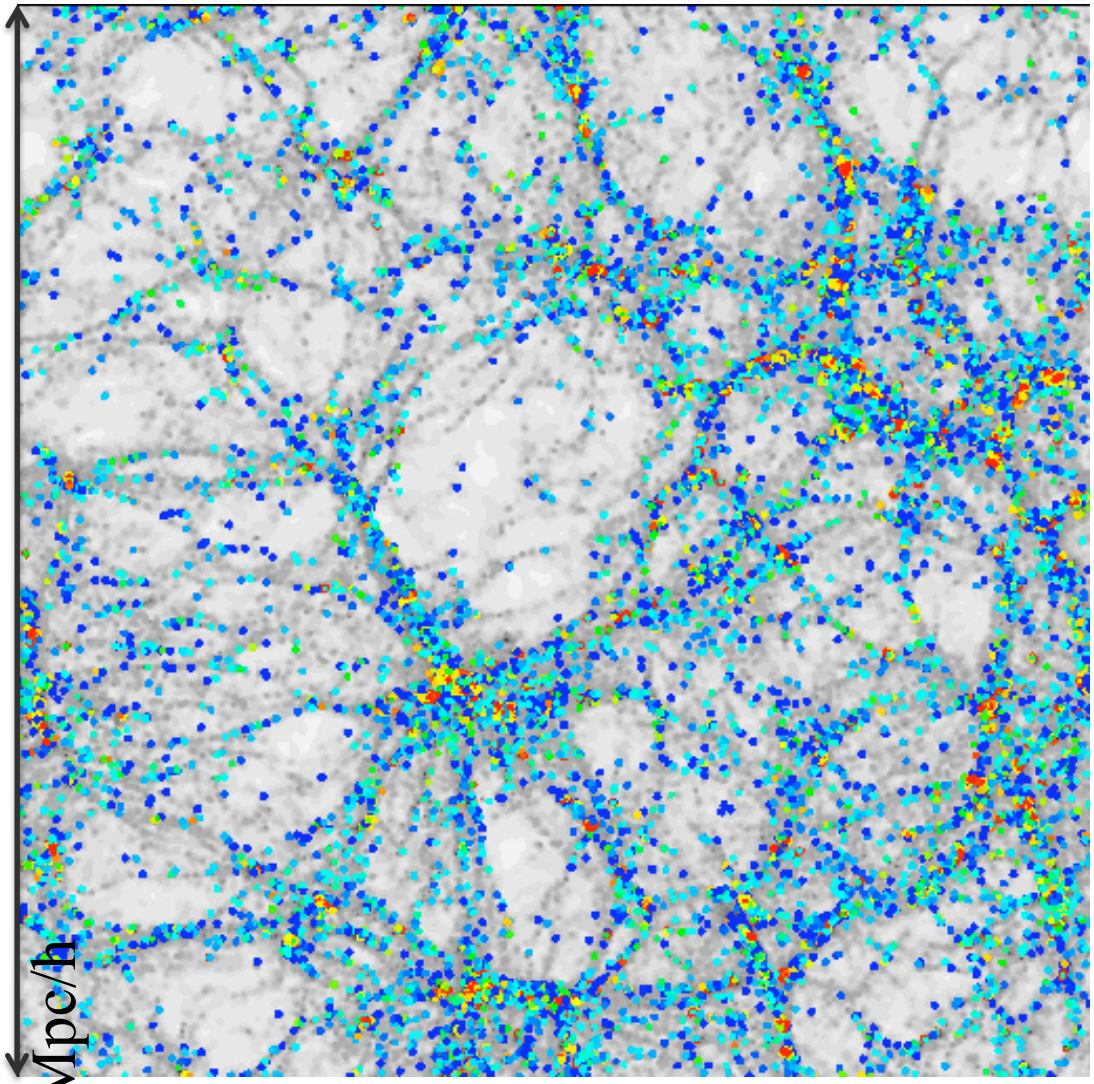
a. The **BAO** technique has only recently been established. It is less affected by astrophysical uncertainties than other techniques.

BAO geometrical test



- 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 measurement
- The amplitude uncertainty is marginalized over to obtain the distance constraints

Galaxy bias uncertainty



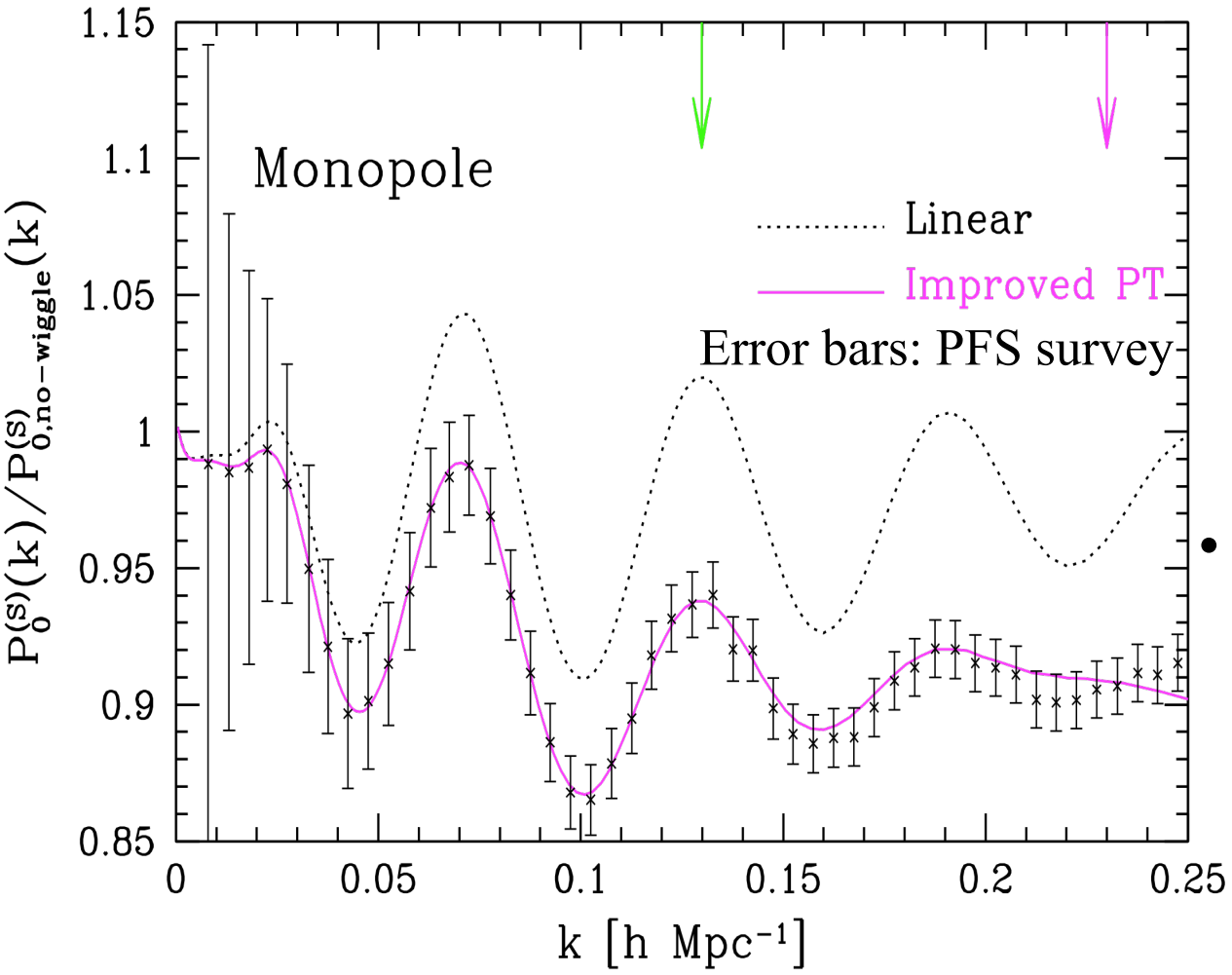
- Structure formation is driven by the "*invisible*" dark matter distribution
- Galaxies are "*biased*" tracers of DM distribution

$$\delta_g \neq \delta_m$$

- There is no sufficiently accurate theoretical model of galaxy formation
- Unavoidable uncertainty if a redshift survey alone is available (BigBOSS)

Dark matter clustering

see Taruya-san's talk for details



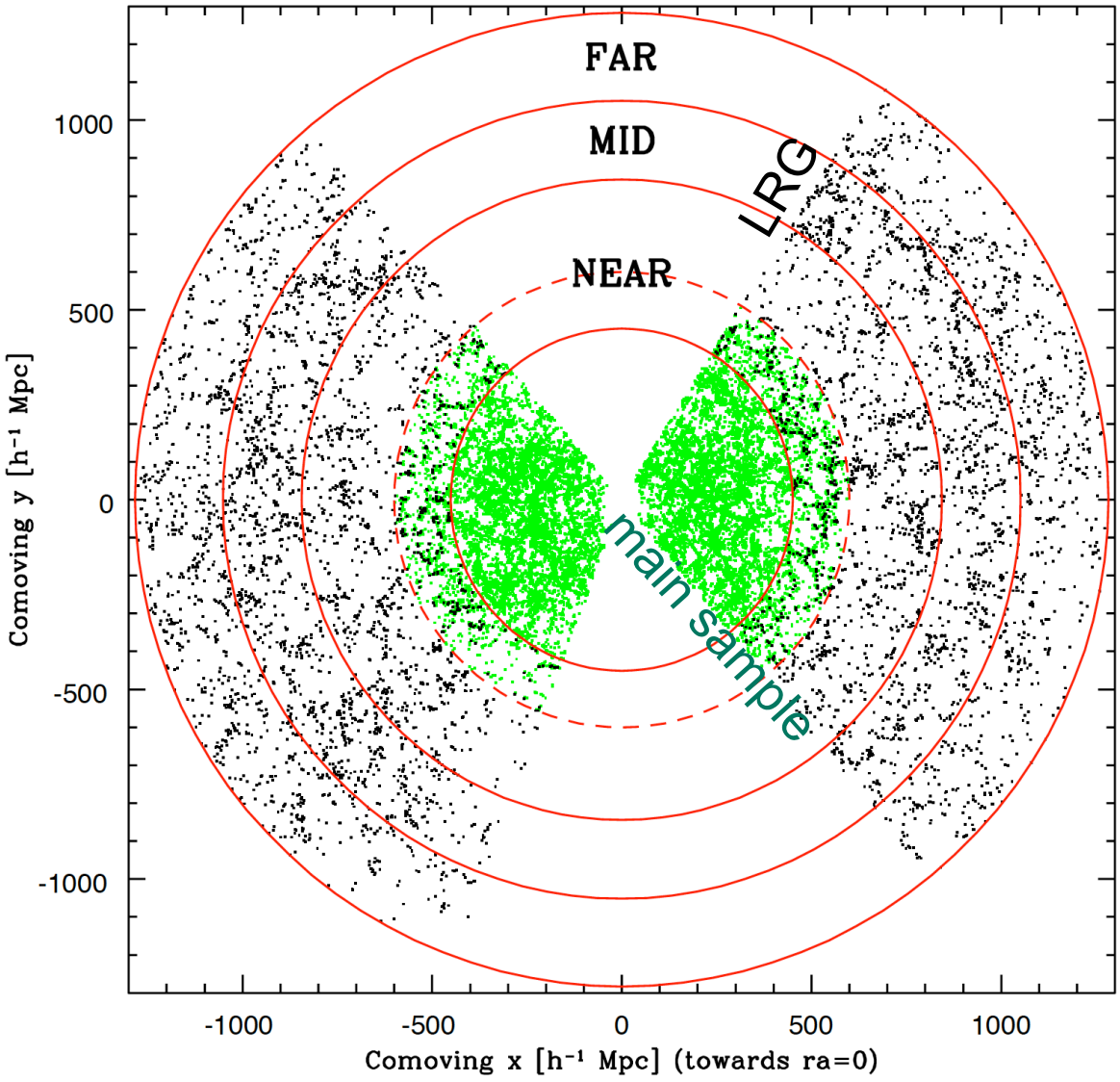
- Now sufficiently accurate models (simulations + analytic models) are available, for dark matter clustering including nonlinear effects
- For dark matter distribution, *if* measured, we can use the shape and amplitude information to do cosmology (WL, beyond BAO)

Planned BAO experiments

	BOSS	BigBOSS	SuMIRe PFS
Telescope	2.5m	4m @KPNO	8.2 Subaru Tel.
Pre-imaging survey	SDSS	***PTF (1.2m) ???***	HSC+
Redshift	0.2<z<1.7	0.2<z<2+z~3	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
Fiber density (per deg^2)	143	714	***1333***
Number of fibers	1000	**5000**	2400
Wavelength range	360-1000nm	340-1130nm	600-1100nm (380-1300nm)
Spectral resolution	1600-2600	2300-6000	~3000 (2000-4000)
Target galaxies	LRGs	LRGs+[OII] emitters	LRGs + [OII] emitters

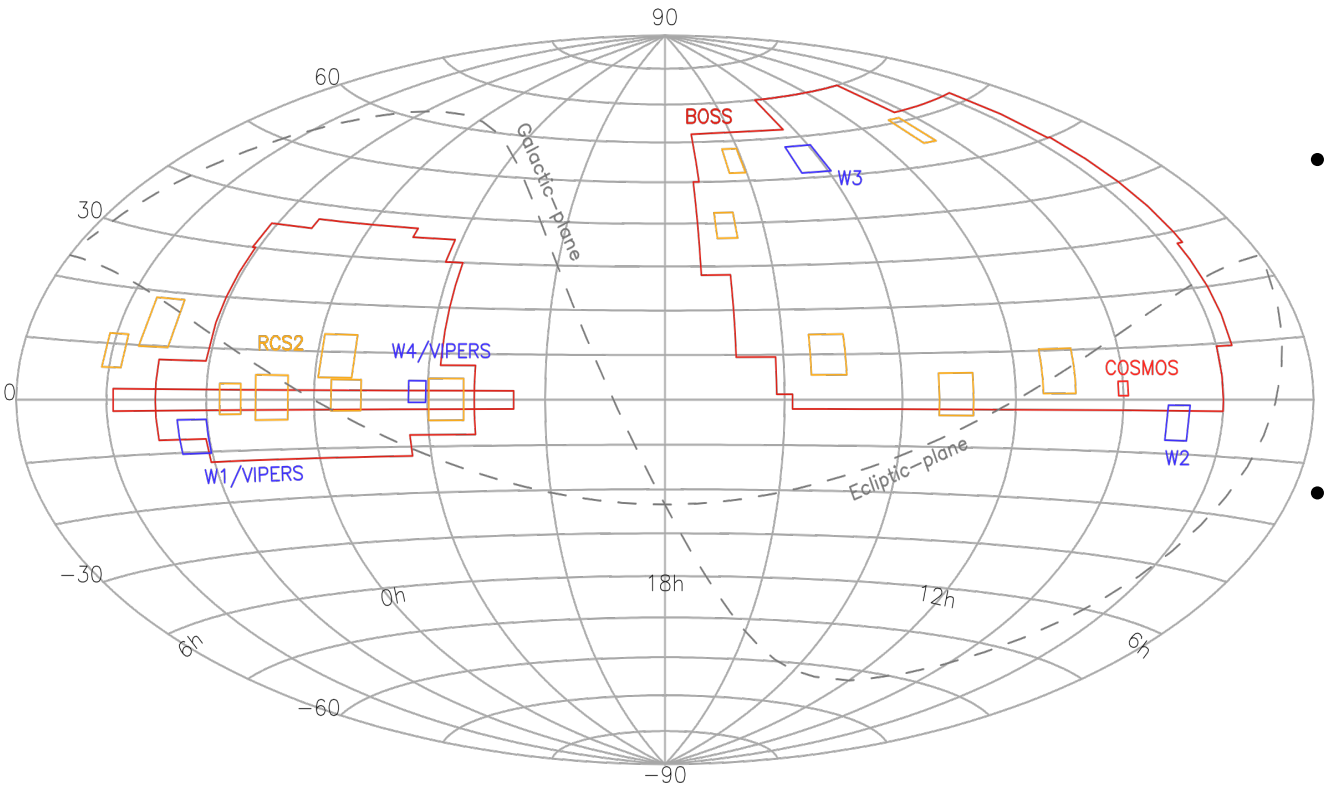
- Note: HETDEX (Texas+) is a blind redshift survey targeting Ly-alpha emitters over 1.9<z<3.5 and covering ~400 deg^2 area
- Subaru FMOS survey (~50 deg^2): H-alpha survey over 0.5<z<1.7

“Pre-”imaging survey



- The imaging data is needed to find target galaxies
- Example: BOSS=a spectroscopic follow-up survey of Luminous Red Galaxies (LRGs) constructed from the SDSS imaging survey

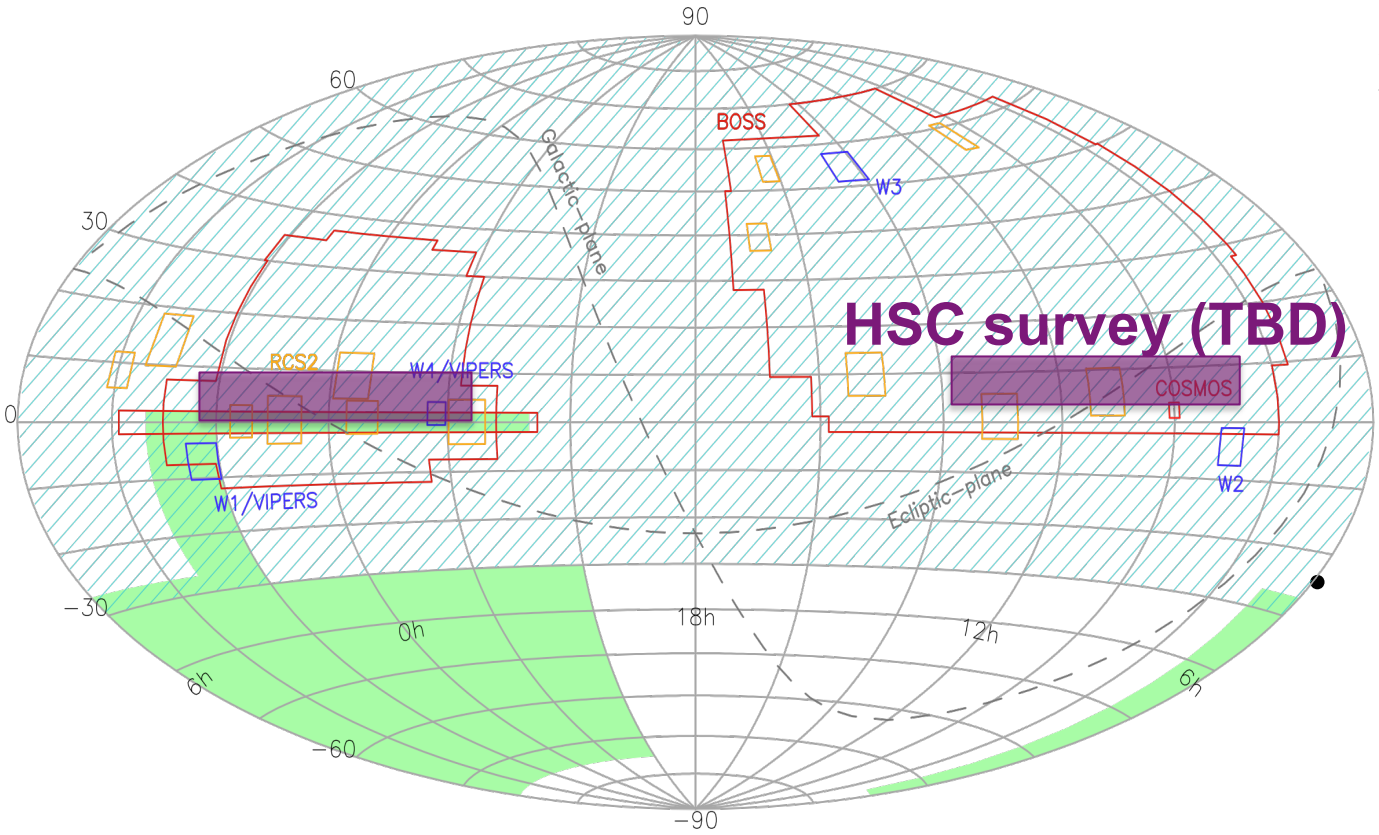
The current status of imaging surveys



Courtesy by A. Nishizawa

- Cosmology needs a connected, wide-area survey
- SDSS (i~21) is the largest, but the spectroscopic survey is already on-going (BOSS)
- The largest surveys, without spec. follow-up, are the data from CFHT (4m; i~24); ~a few 10's sq. degrees of each field
  - VVDS, VIPERS (VLT VIRMOS)

In 5 years (~2015)...

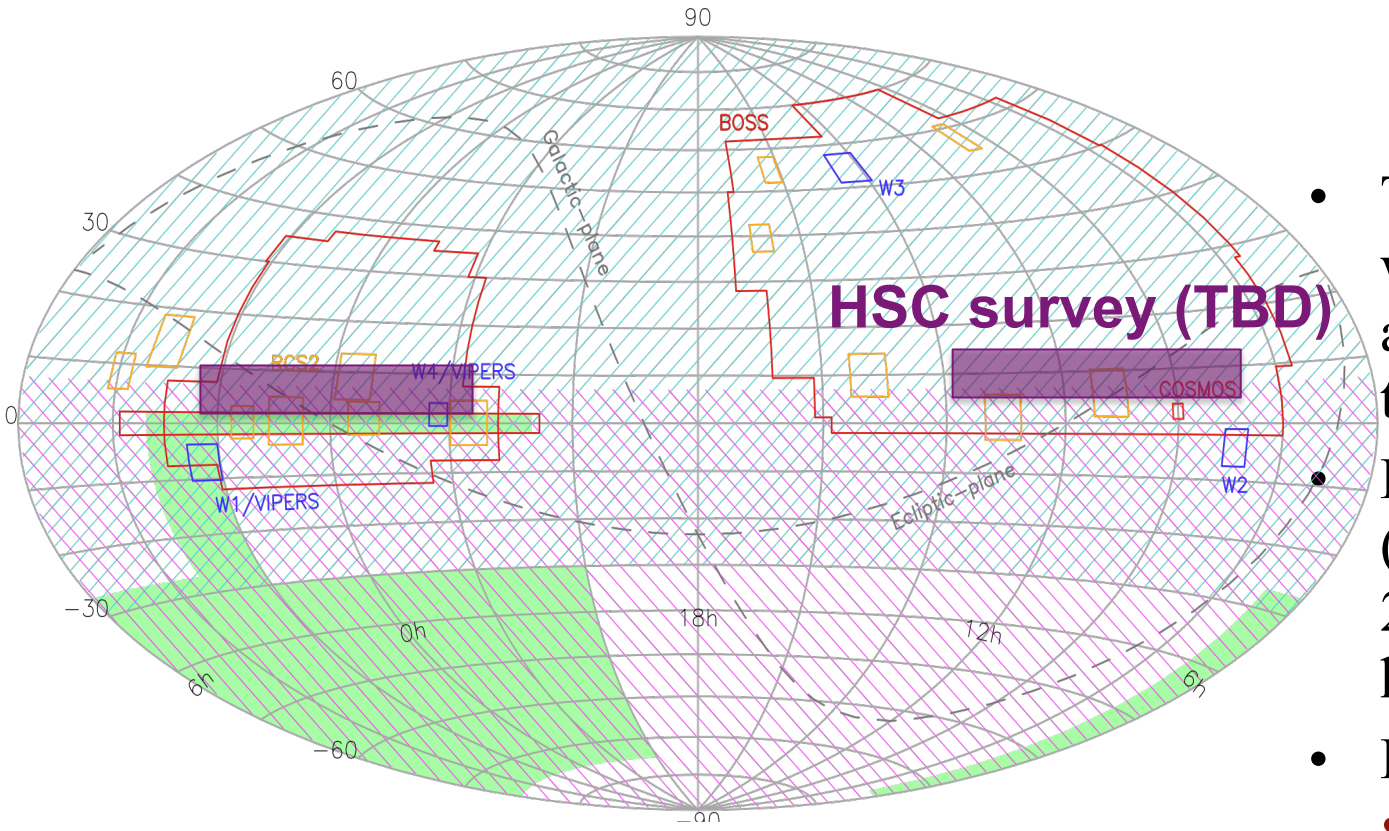


Dark Energy Survey (CTIO 4m, Chile; i~25)

Pan-Starrs (PS1) (1.8m, Hawaii; i~23)

- Various surveys planned, aimed at exploring DE
  - Pan-Starrs (1.8m, 3π survey over 3 years; i~23-24)
  - DES (4m; 5000 sq. degrees; i~25), almost no overlap with SDSS
- Hyper SuprimeCam Survey (2012-)
  - ~1500 sq. degrees
  - grizy (i~26)
  - Overlap with SDSS, ACT, UKIDSS, …
  - Need 10 nights to cover 500 deg^2 with igz (i~25)

Imaging survey (2020-)

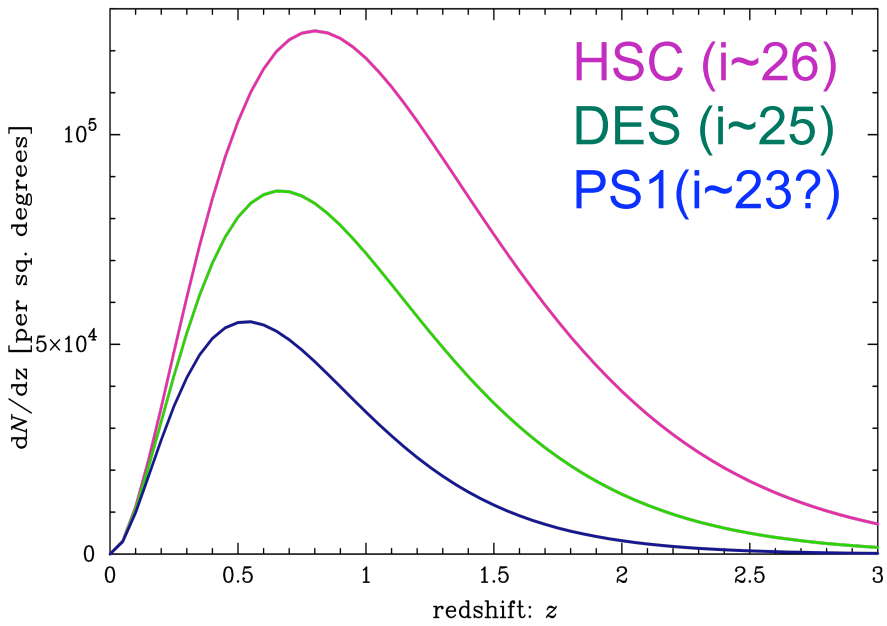


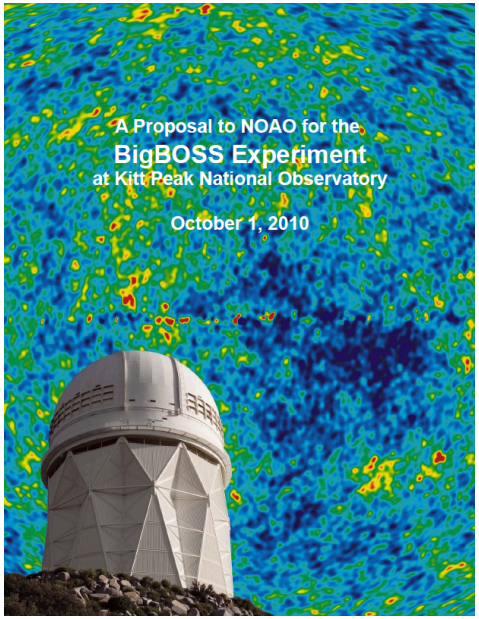
Dark Energy Survey (CTIO 4m, Chile; i~25)
Pan-Starrs (PS1) (1.8m, Hawaii; i~23)
LSST (8.4m [6m in effective], Chile; i~27 over 10 years)

- The ultimate imaging survey, LSST (ugrizy), will come online
  - 6m (effective), i~27, 10 years (2018-?)
- The imaging survey will be done for almost all sky (down to i~24th)
- Further, Euclid (including NIR; 2018-), WFIRST may happen
- However, ***no spectroscopic survey***, except for PFS, is planned to follow-up these imaging gals

Imaging survey (summary)

- BAO survey needs an pre-imaging survey with adequate depth that can cover its target redshift range
- PFS BAO survey
  - HSC can give an ideal data set for targeting galaxies for PFS survey
  - Minimize systematic errors by observing the same patch of the sky with the same telescope (HSC/PFS)
  - Improve cosmological constraints (see later)
- BigBOSS survey (may start from 2018-)
  - The Palomar Transient Factory (PTF; 1.2m) survey: 12,000 deg^2, R~23.5
  - PS1 (gi): i~23
  - Plan to use PS1(gi)+PTF(R) for target selection
  - *Very difficult to find target galaxies at z>1*
  - BigBOSS ≈ 0.6<z<1 BAO with 10000 deg^2





BigBOSS proposal to NOAO (Oct 1st, 2010)

Requirements on the target galaxy density

- The DM distribution (=cosmology) needs to be inferred from the observed galaxy distribution
- 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

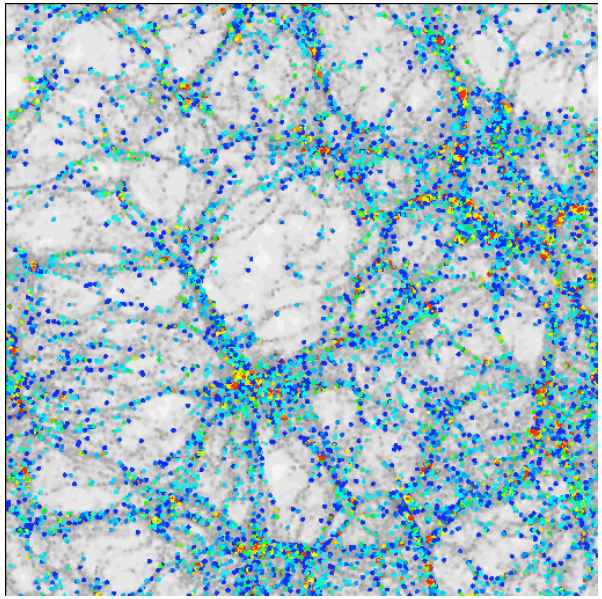
$$\left[\frac{\sigma(P_g)}{P_g(k)}\right]^2 = \frac{2}{N_k}\left[1+\frac{1}{\bar{n}_g P_g(k)}\right]^2$$

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

$V_{\rm survey}$: survey volume

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

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



- To have the better accuracies, we need a *wider* survey area, an adequate density of target galaxies, and/or target galaxies with higher biases
- A reasonable strategy for a choice of target galaxies: $n_g P_g \sim$ a few

Number of target galaxies (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: LRGs + emission-line galaxies over 0.6<z<1.6~1.7
  - 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)
- *PFS allows a uniform sampling of target galaxies over the whole range of redshifts, with a single exposure! (see below)*

Comparison with BigBOSS

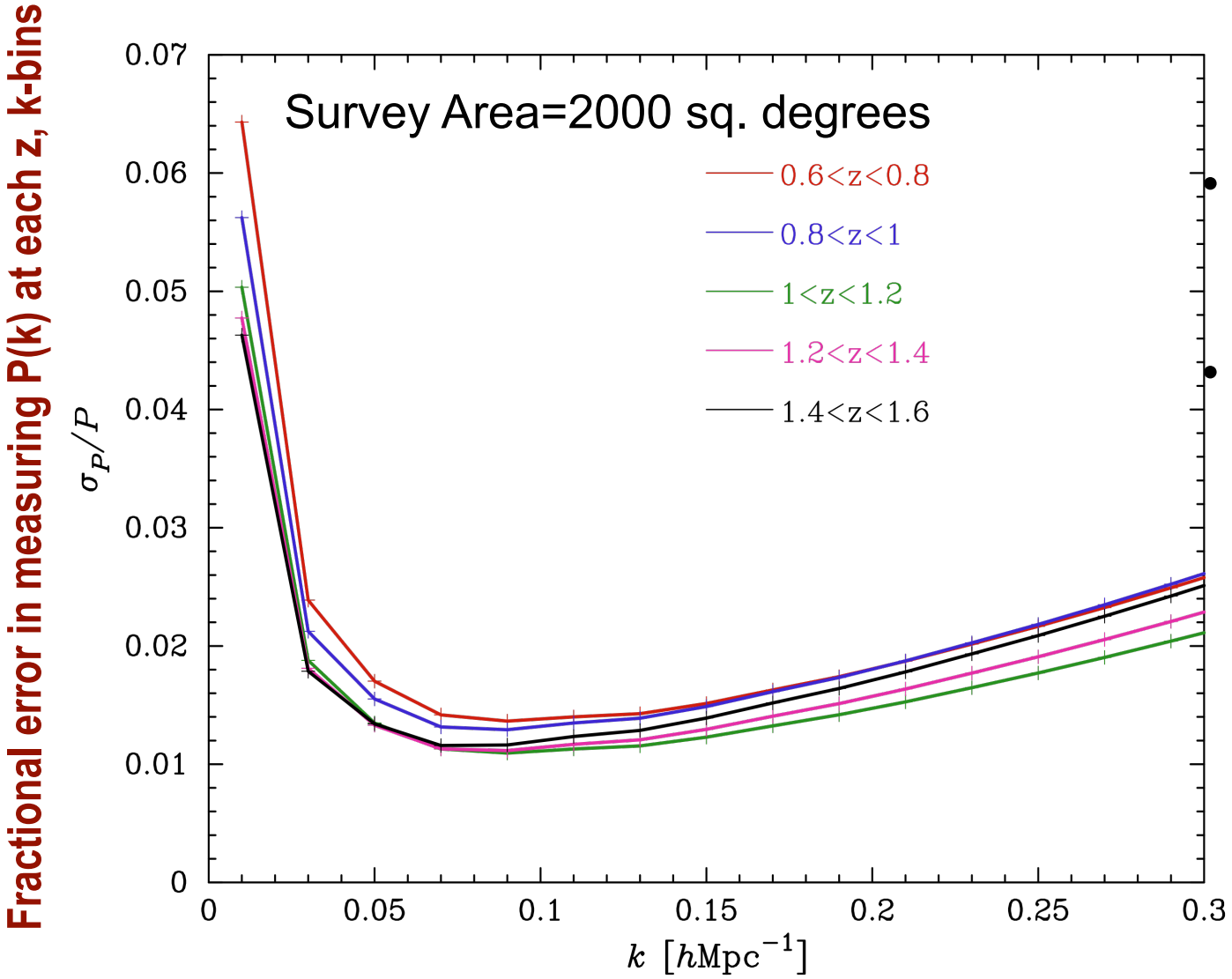
Table 2.3: Expected galaxy density distributions and resulting signal power to shot-noise power ratio at $k = 0.2\ h\ \mathrm{Mpc}^{-1}$.

From BigBOSS proposal

z	dn/dz_{LRG} (sq. deg.)$^{-1}$	dn/dz_{ELG} (sq. deg.)$^{-1}$	dn/dV_{LRG} ($10^{-4}h^3\mathrm{Mpc}^{-3}$)	dn/dV_{ELG} ($10^{-4}h^3\mathrm{Mpc}^{-3}$)	$nP_{0.2}$
0.15	47	247	2.78	14.63	2.56
0.25	117	148	2.78	3.50	1.44
0.35	209	69	2.78	0.93	1.18
0.45	314	120	2.78	1.07	1.20
0.55	426	429	2.78	2.80	1.38
0.65	443	888	2.28	4.58	1.36
0.75	533	1359	2.28	5.82	1.49
0.85	541	1712	2.00	6.32	1.43
0.95	435	1654	1.42	5.41	1.11
1.05	289	1284	0.86	3.80	0.73
1.15	104	941	0.29	2.57	0.37
1.25	0	680	0.00	1.74	0.18
1.35	0	582	0.00	1.41	0.14
1.45	0	630	0.00	1.45	0.15
1.55	0	592	0.00	1.31	0.13
1.65	0	424	0.00	0.91	0.09

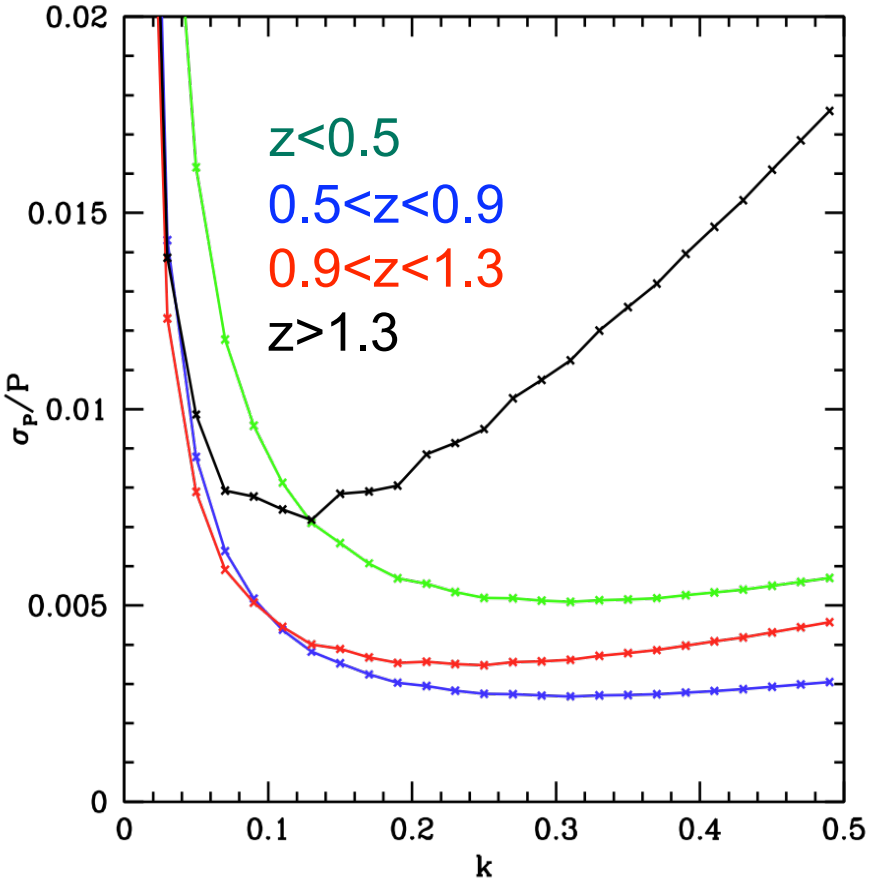
A fewer density of galaxies than required for BAO

Expected accuracies of P(k) with PFS



- All redshift slices are equally important
- PFS allows a % level precision in P(k) measurement at each redshift, up to k~0.3 (where the theoretical models are accurate enough)

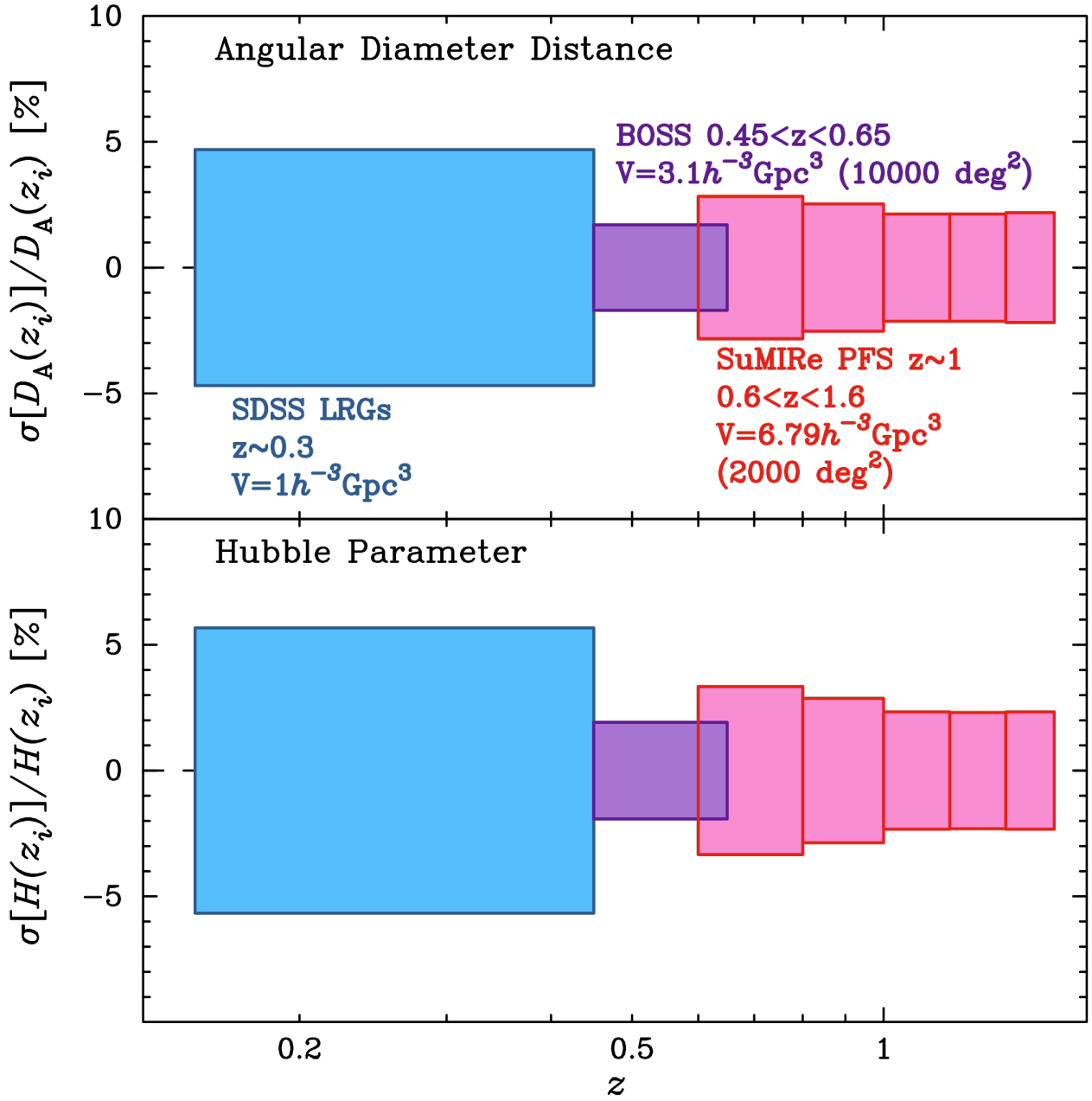
Again, in BigBOSS case



- Not powerful enough to survey galaxies at z>1.2
- Also true BigBOSS (4m) is not powerful to get a high-S/N spectrum of galaxy at such high redshifts (see below)

Figure 2.2: Expected fractional uncertainties in the power spectrum for bins of $\Delta k = 0.02h^{-1}$ Mpc (indicated by points). The curves represent different redshift bins $z < 0.5$ - green, $0.5 < z < 0.9$ - blue, $0.9 < z < 1.3$ - red, $z > 1.3$ - black. The gravitational growth function is best constrained on scales $k > 0.05h^{-1}$ Mpc (smaller than 200 Mpc).

Forecasted the SuMIRe BAO experiment



"Geometrical" test alone

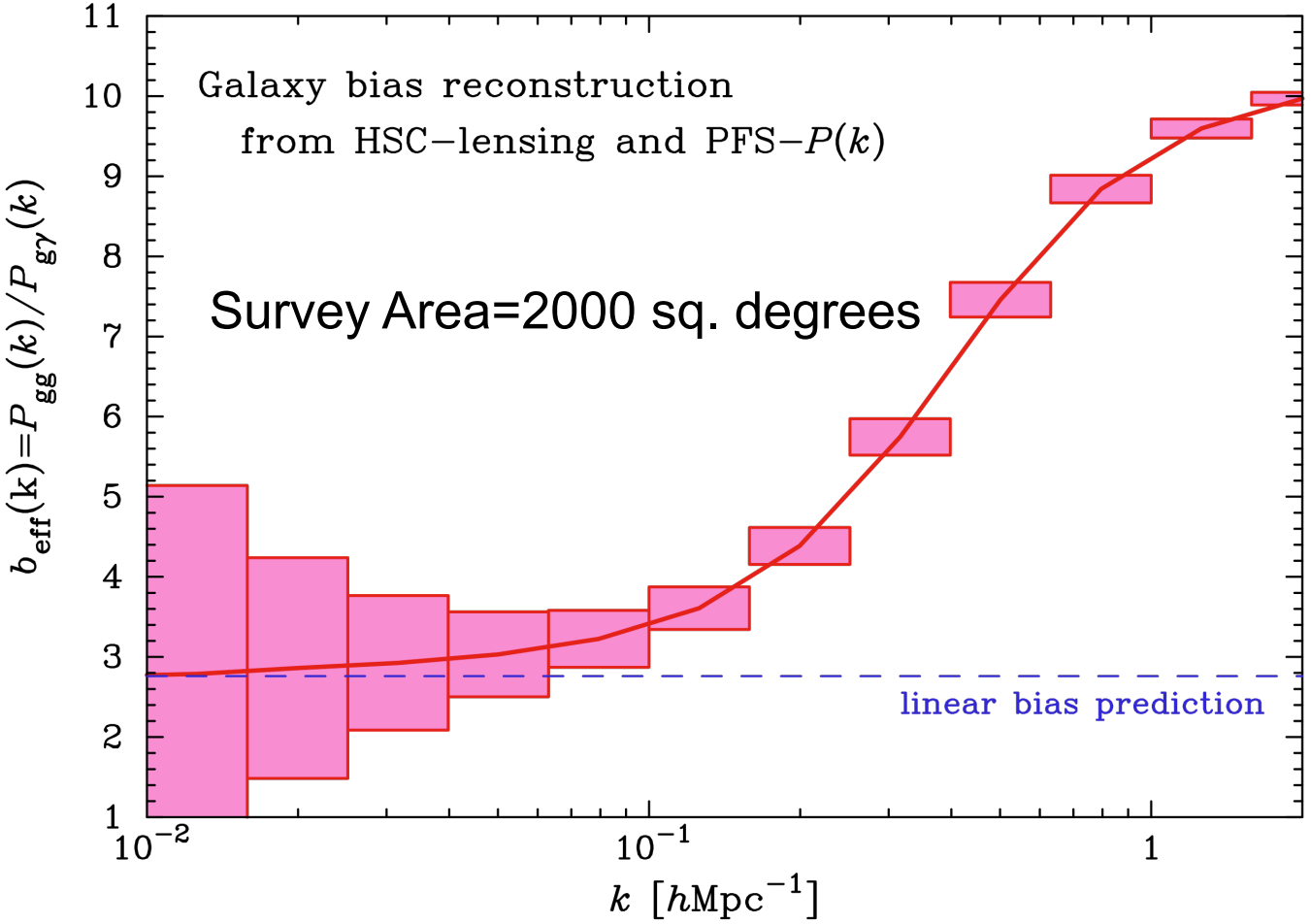
A few % accuracies of H(z) and D_A(z) achieved for each redshift slice

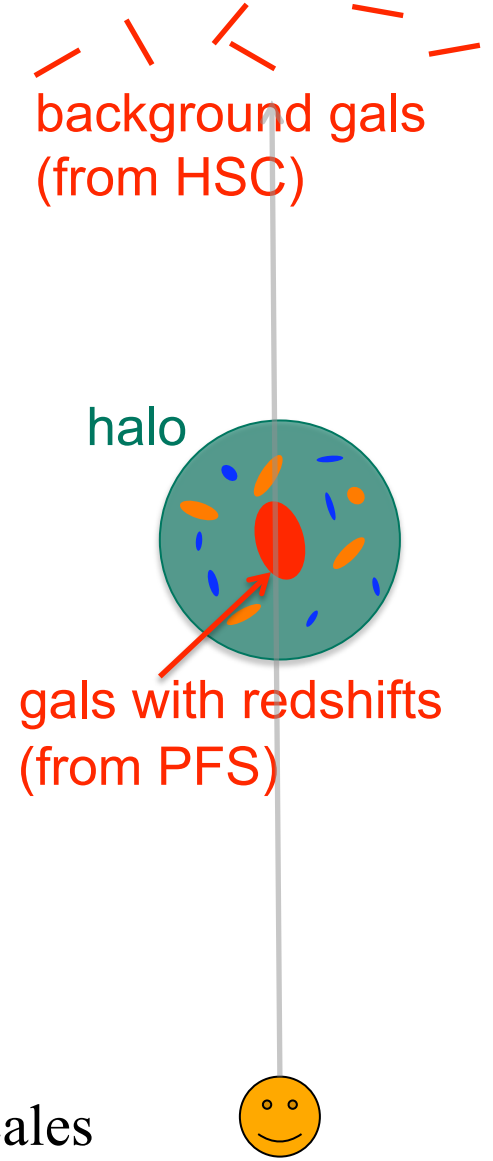
Complementary to BOSS

Another synergy btw HSC and PFS: a direct reconstruction of galaxy bias

$$P_{gg}(k) \propto \langle \text{galaxy} - \text{galaxy} \rangle \propto b^2 P_m(k) \quad \text{(linear regime)}$$

$$P_{\gamma g}(k) \propto \langle \text{shear} - \text{galaxy} \rangle \propto b P_m(k)$$



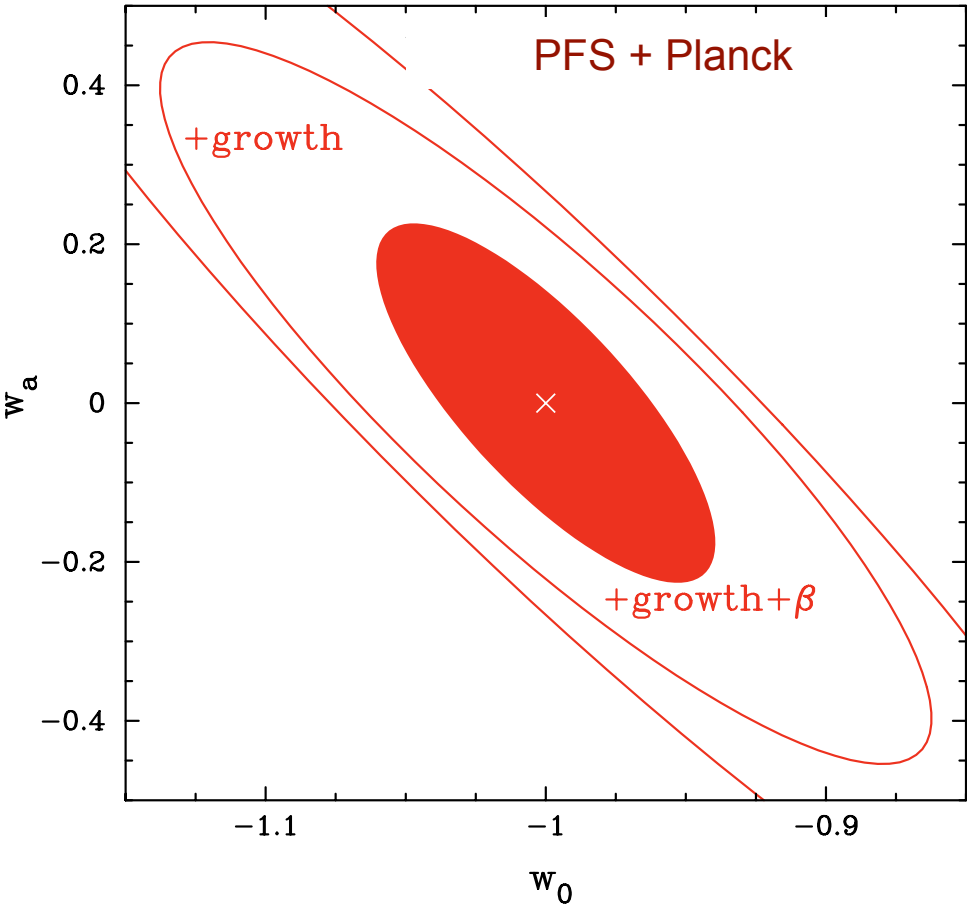


- Note that linear bias breaks down even at large BAO scales

"price" of bias measurement

$$P_{gg}(k) \Leftarrow b^2(\vec{k}) \otimes P_m(\vec{k})$$

- Again, the direct reconstruction of galaxy bias is unique for SuMIRe HSC/PFS
- Now can use the power spectrum amplitude information
- The growth of matter clustering is very sensitive to cosmology, and can be used to *test gravity on cosmological scales*



Gravity Test

- Einstein gravity is correct 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
- To do this, we need both the geometrical test (BAO, SN) and the structure formation probes (P(k), WL, clusters)
- SuMIRe HSC/PFS can test both DE and gravity (very unique!)

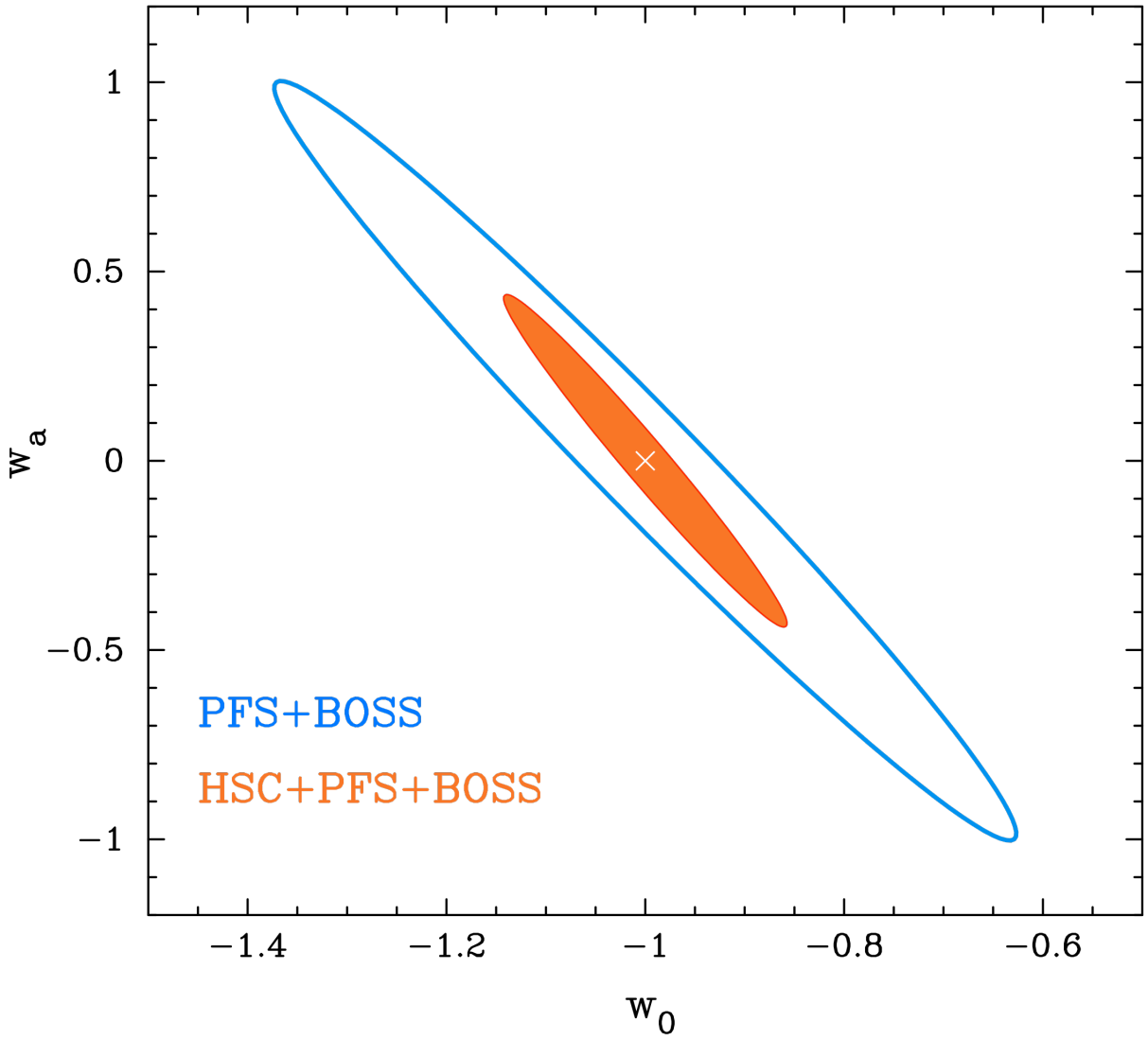
SuMIRe: HSC+PFS

	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	0.018
DETF FoM	13	33	192
Growh: σ(γ)	-	-	~0.03
σ(Σm_nu) [eV]	-	-	~0.06eV
σ(f_NL)	-	-	~10

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

- Planck priors assumed
- SuMIRe PFS: BAO alone (geometrical test alone)
- SuMIRe HSC+PFS: WL + cluster counts + BAO + galaxy clustering
- Te forecasts above is somewhat conservative (taking into account various systematic errors)
  - Allows to constrain gravity theory on cosmological scales, neutrino masses and primordial non-Gaussianity

Synergy of Imaging and Redshift Surveys



- Combining HSC and PFS improves the dark energy FoM by a factor of 6, compared to that from either of HSC or PFS alone
- Note 2000 deg^2 (even more improved if a larger survey area is available)
- σ(w_const)=0.02: equivalent to Stage-IV DE experiment

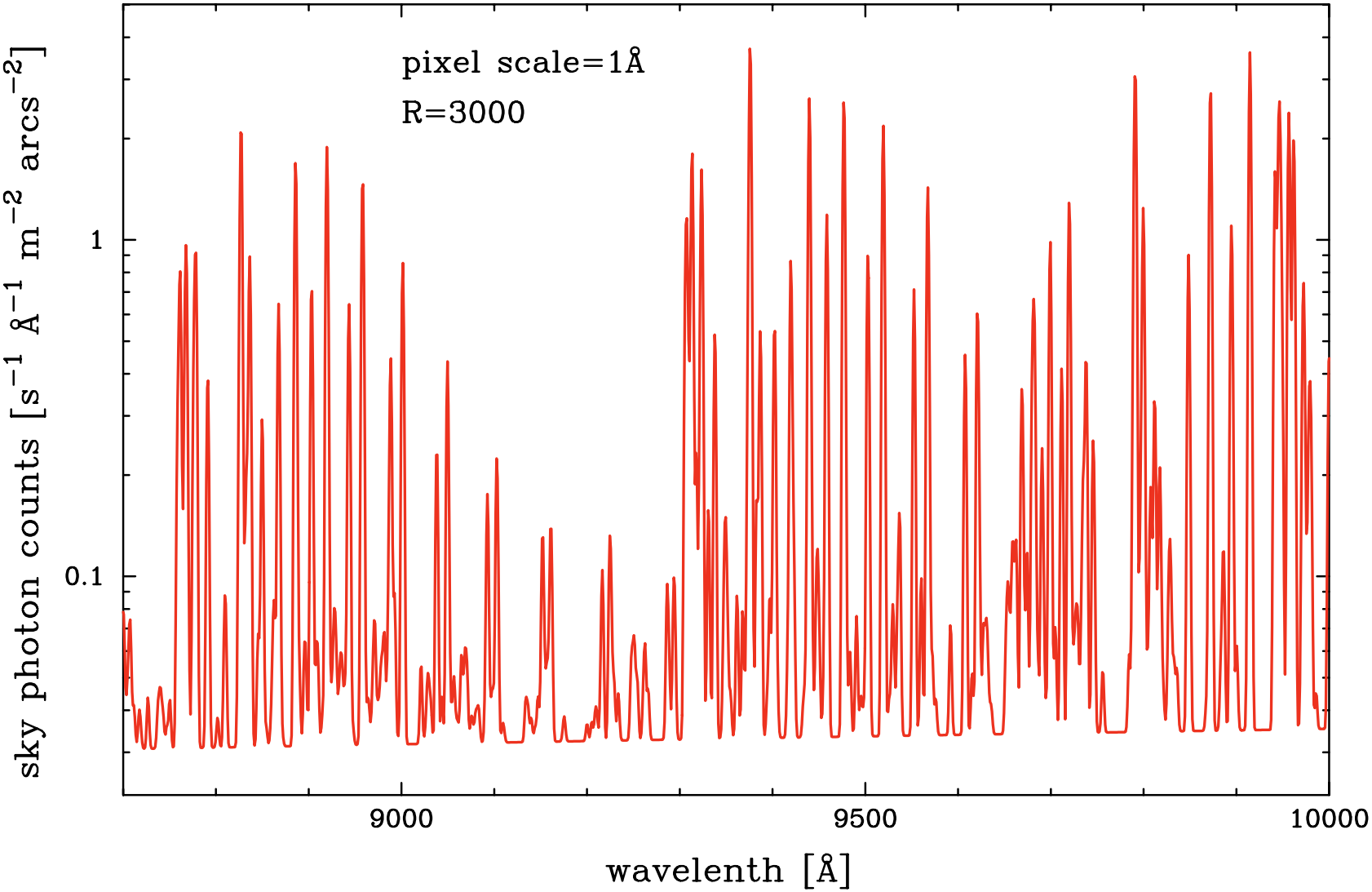
Feasibility of PFS survey

Q: What is the number of minimum nights to carry out the PFS BAO survey?

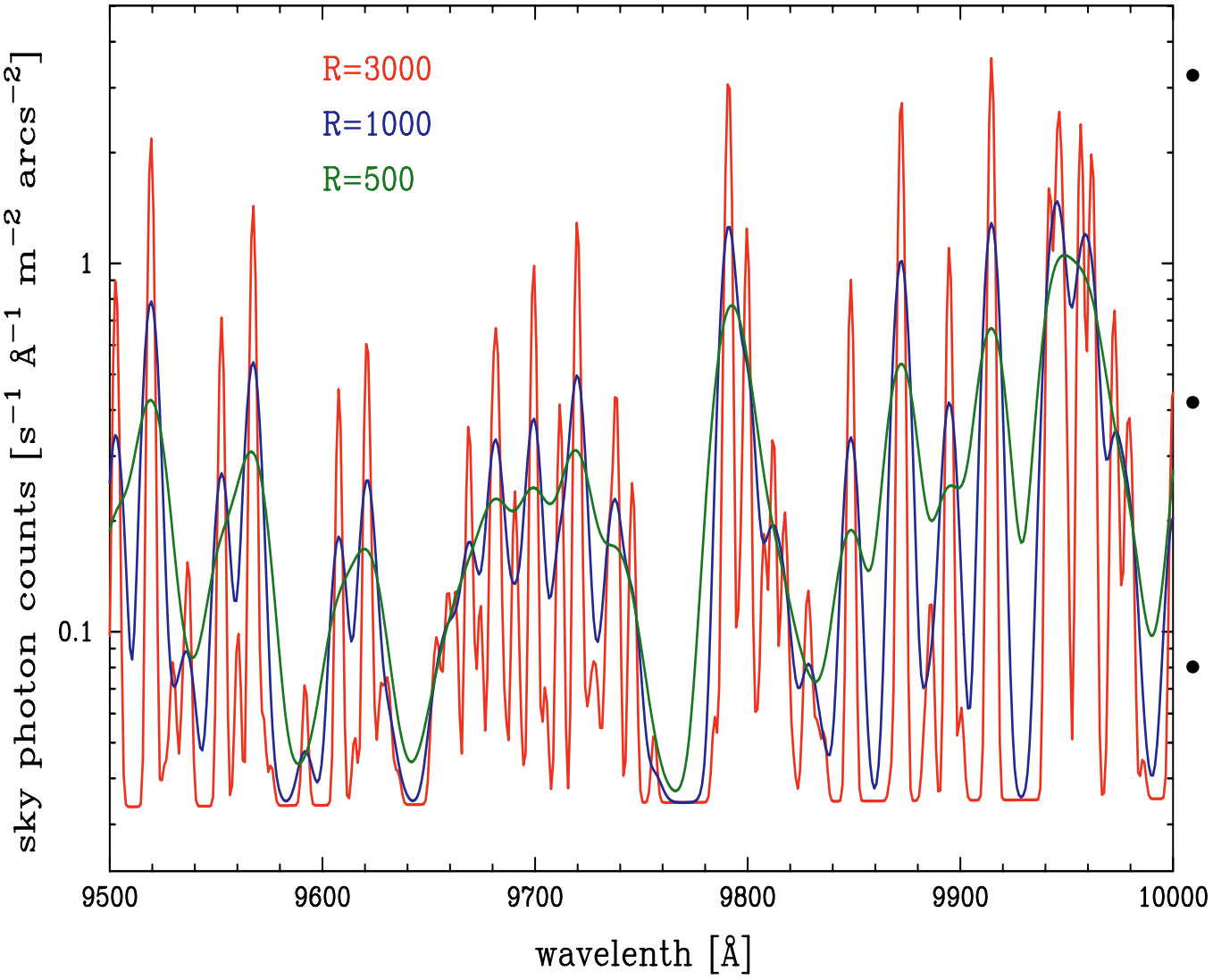
- The minimum PFS BAO survey is done over $0.6<z<1.7$, corresponding to the red wavelength range, $6000<\lambda<10000$A
- Sky is bright in the red wavelengths
- Need to estimate the sky background correctly, taking into account the PFS spectrograph parameters (resolving power, pixel scale, fiber size and so on)

Sky spectrum

Working with Jim, Michael and Iwata-san (Jim has always been correct in his calculations; I made a factor mistake in the unit conversion)



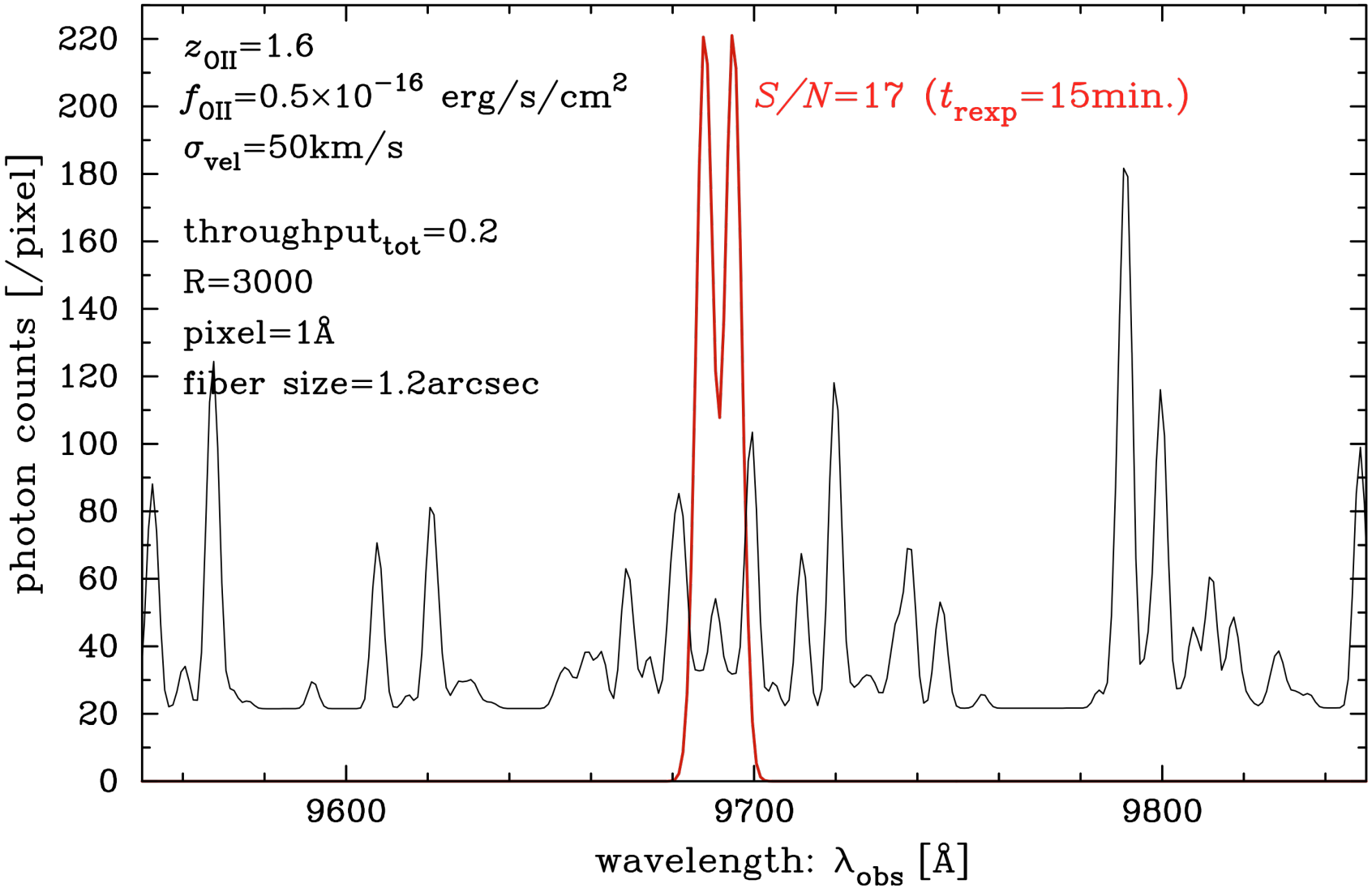
Sky spectrum (contd.)



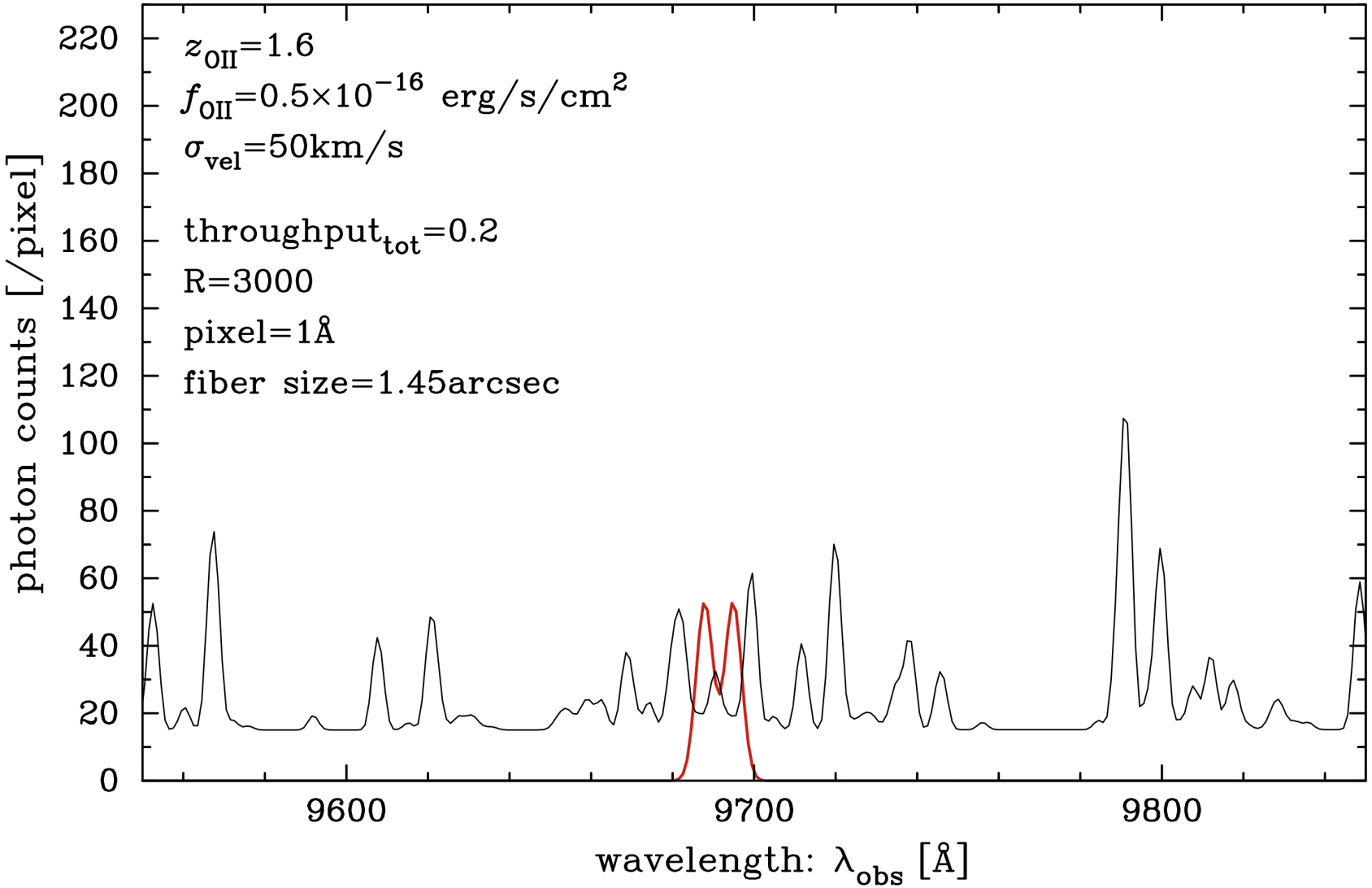
- Higher resolving power has a more window of wavelengths where sky is very low
- Relevant for high-z galaxy hunting with PFS, and also for TMT
- The accurate model of sky spectrum is very useful for NIR astronomy

Simulating [OII] line for PFS

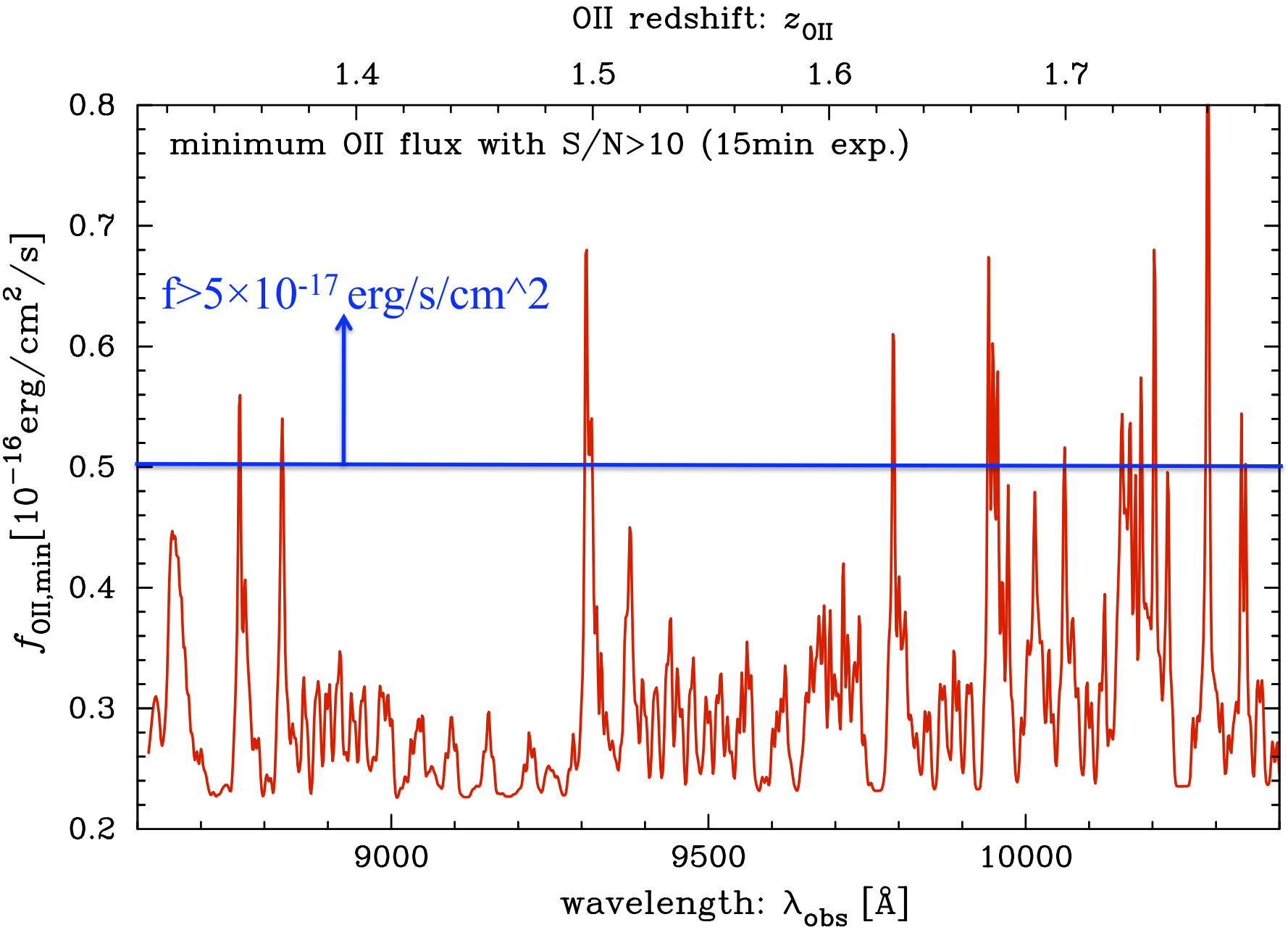
Assuming 15min exposure



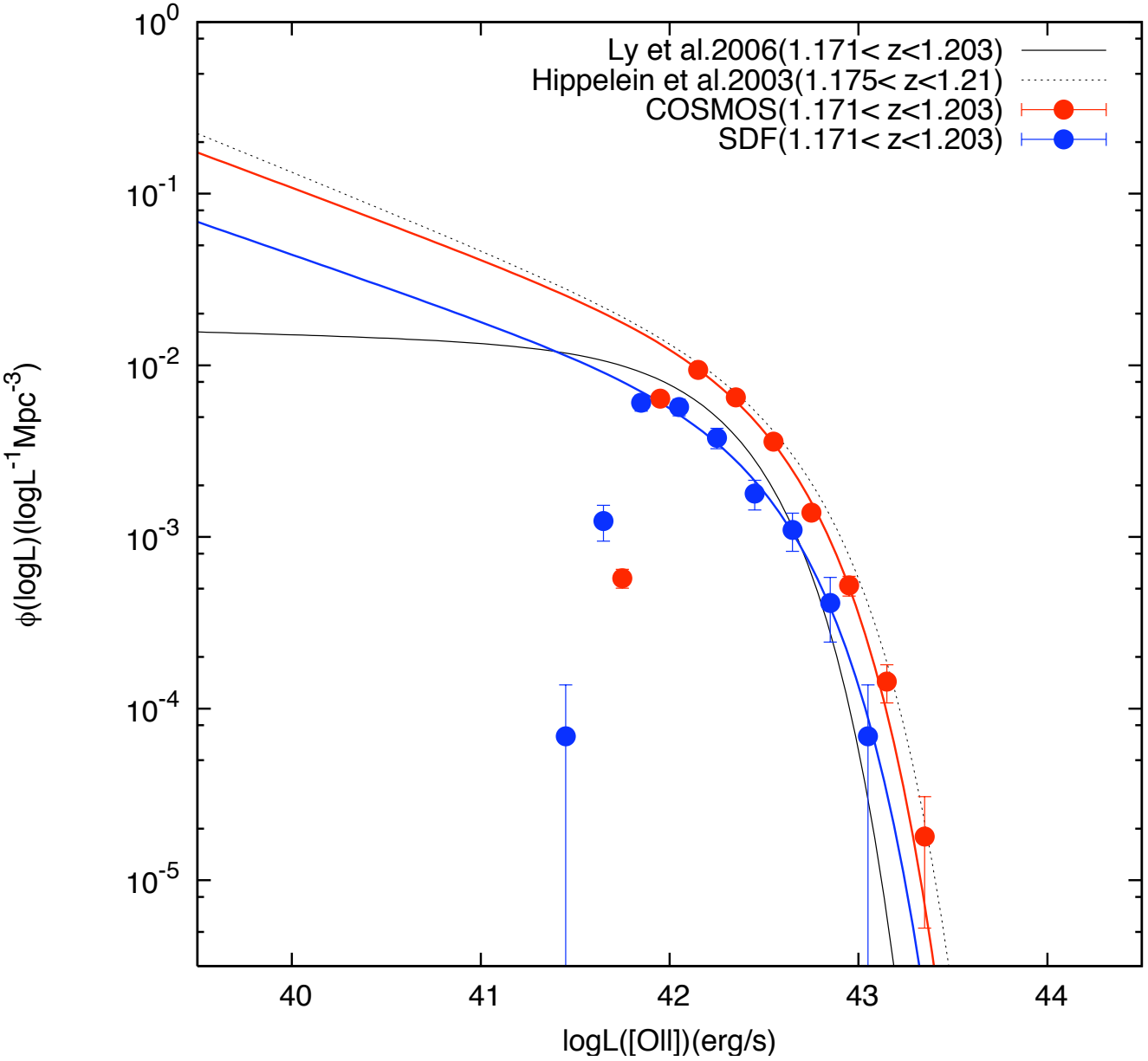
In a case with 4m telescope...



Flux thresholds for high-z [OII] emitters

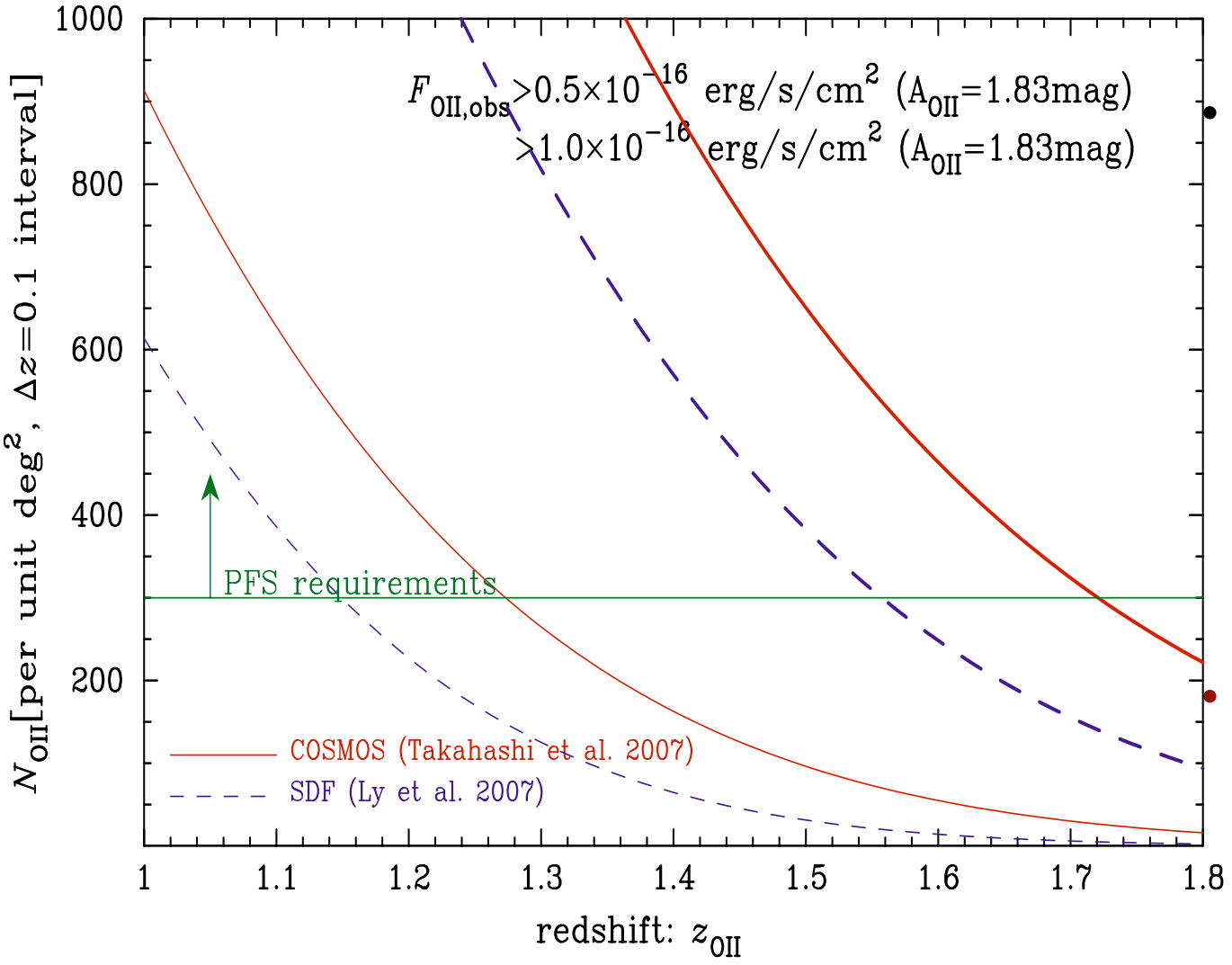


Enough number of OII emitters at z>1.2?



- Use the luminosity function of [OII] emitters, derived from the narrow-band imaging surveys

Enough number of OII emitters at z>1.2?



If targeting [OII] emitters with f_obs>5×10^{-17} erg/s/cm^2, a sufficient number density of the targets, required for BAO, seems available up to z~1.6

15min exposure time is enough per field

The required number of nights

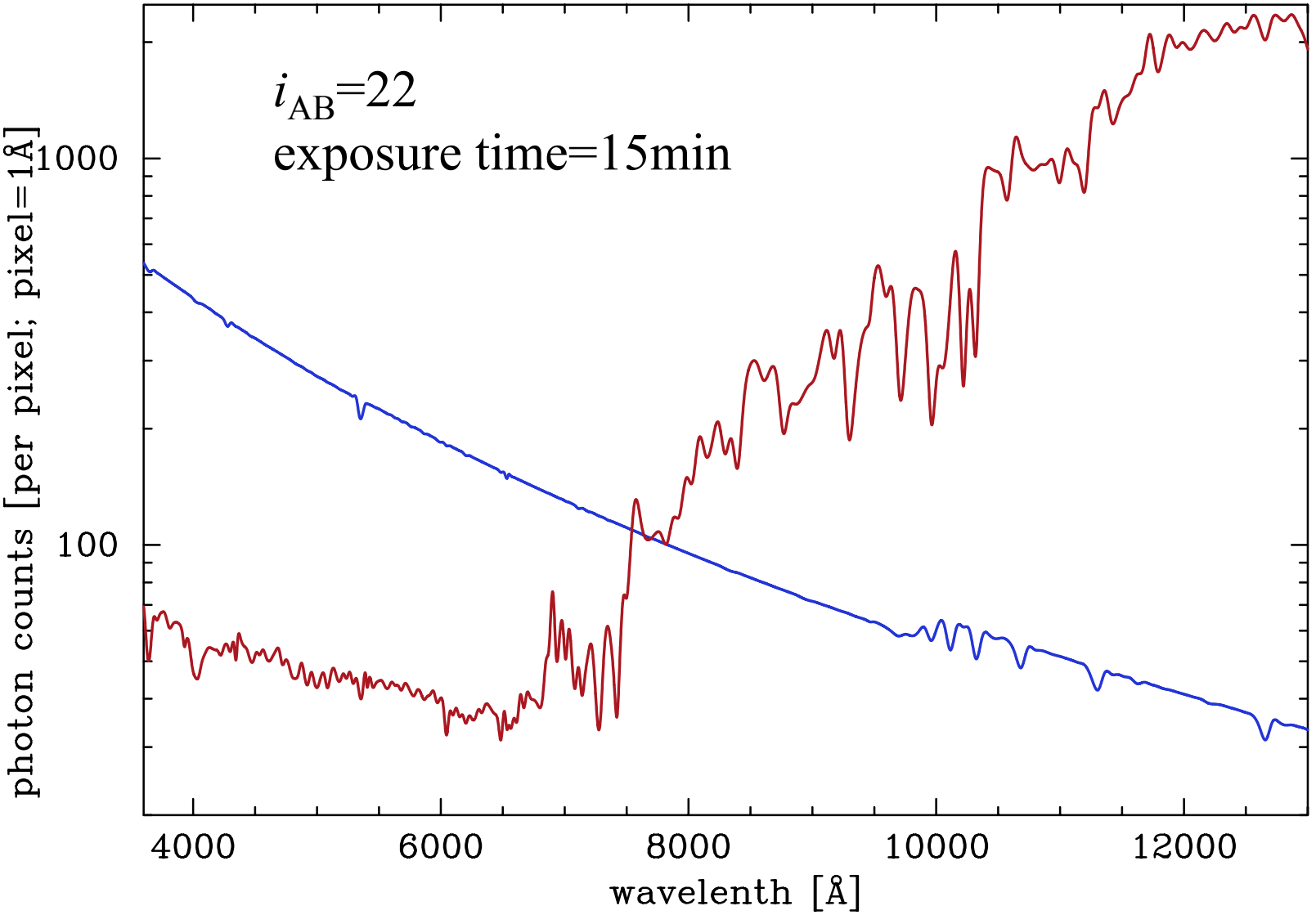
Q: What is the number of minimum nights to carry out the PFS BAO survey?

- *A: To cover 2000 deg^2 with PFS, we need*

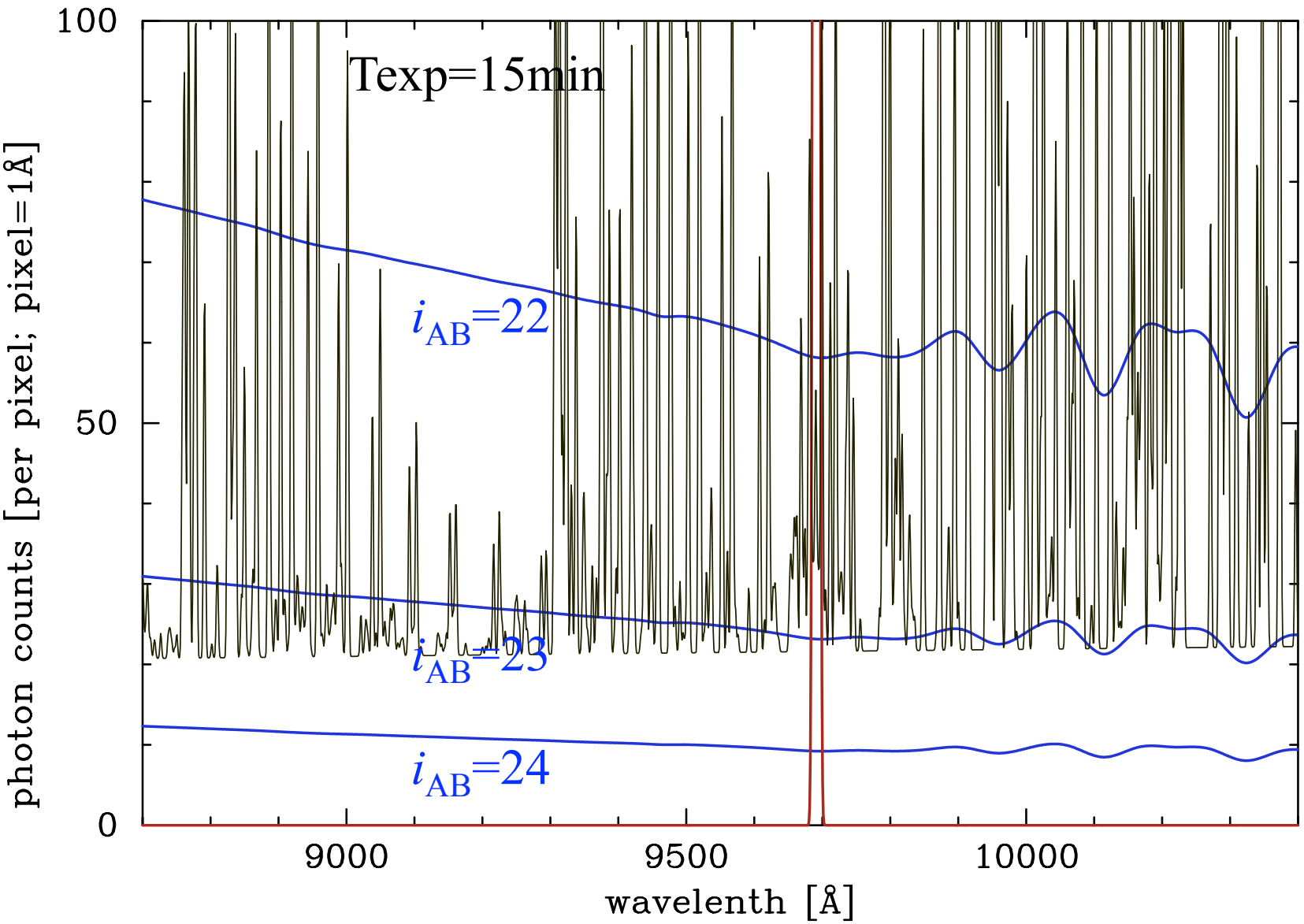
$$\# = \frac{2000\,\mathrm{deg}^2}{\pi\left(\frac{1.5\,\mathrm{deg}}{2}\right)^2 \times \frac{8[\mathrm{hours/night}] \times 60[\mathrm{min/hour}]}{15\,\mathrm{min/pointing} + 40\,\mathrm{sec}/60\,\mathrm{sec(overhead)}}} \approx 37\mathrm{nights}$$

- Assumed a single visit to each field (about 100% success rate of target selection)
- *PFS is so powerful instrument to allow a very quick BAO experiment up to z~1.6*
- *A further PFS BAO extension because more imaging survey data are available in PFS timeline: DES, Pan-Starrs, HSC shallow survey (giz, each 5min, i~25: 10nights=500 sq. degrees)*

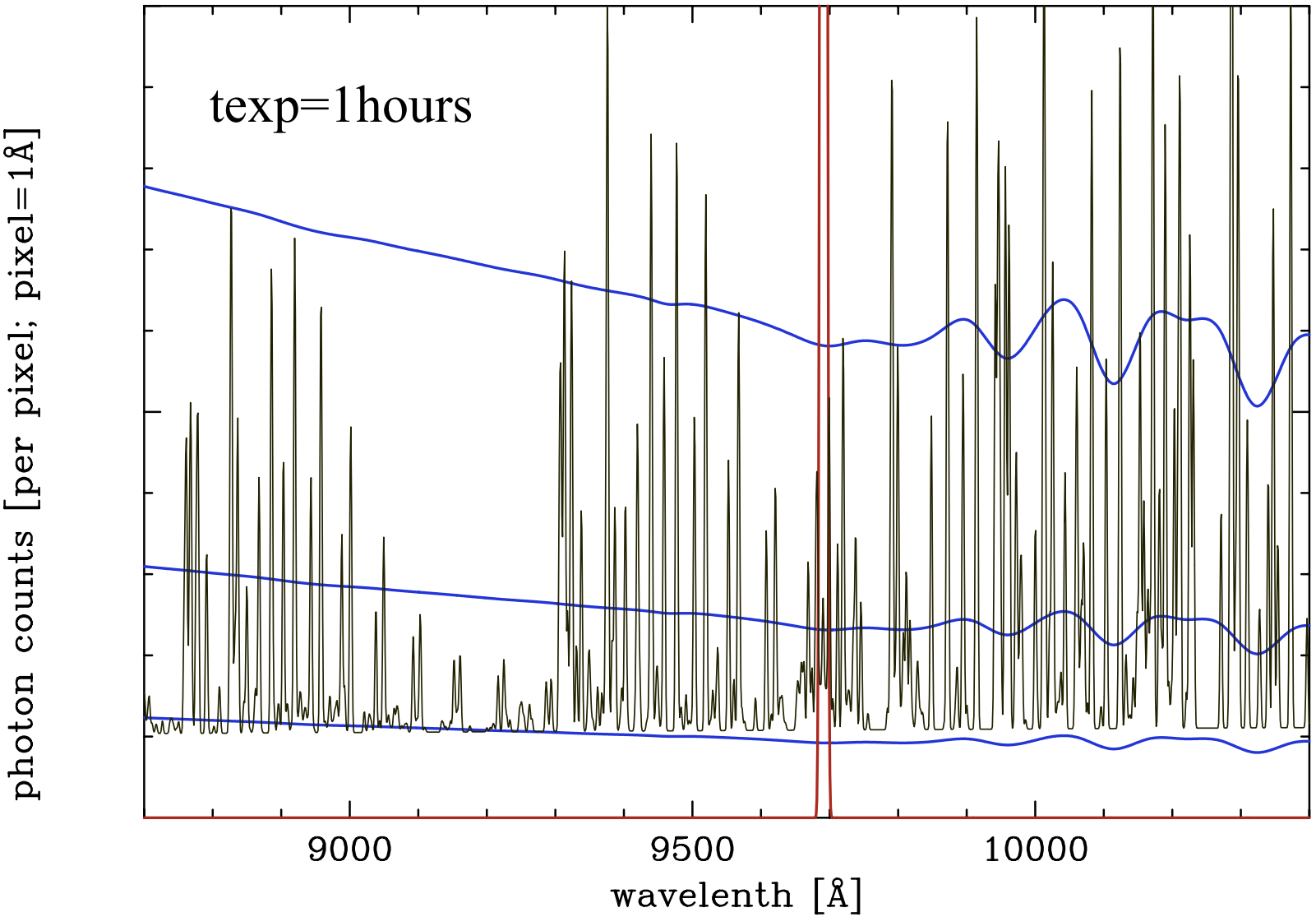
Continuum detection possible with PFS BAO survey?



SED continuum with PFS

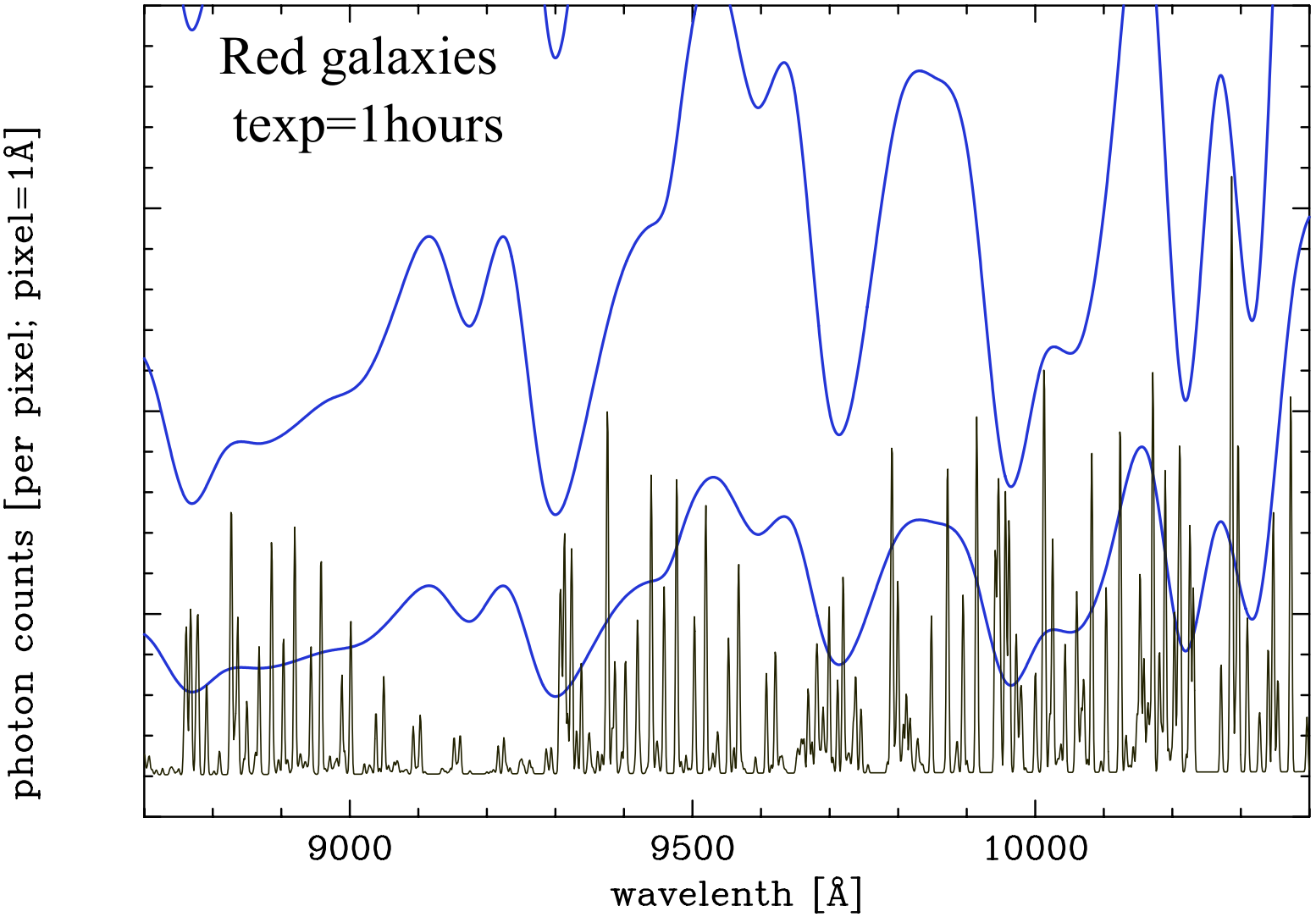


SED continuum with PFS (contd.)



Note: my estimate on sky continuum is larger than real

SED continuum with PFS (contd.)



We can use our sky model to estimate an exposure time needed for the continuum detection

Summary

- SuMIRe HSC/PFS are very unique even in TMT/LSST era
- Combining HSC-lensing and PFS galaxy clustering allows a very robust test of cosmology against various systematic errors: e.g., a direct reconstruction of scale-dependent galaxy bias
  - *A similar-level constraining power to Stage-IV survey ($1B experiments)*
  - Enables us to constrain both DE and gravity with the same data sets (in addition, neutrino masses, inflation and primordial non-Gaussianity)
- PFS is so powerful instrument to carry out BAO survey
  - ***~37 nights needed to cover 2000 deg^2***
  - ***If 2 visits per field are needed, we still need just ~75 nights***
- Tasks to be studied:
  - Estimate the usefulness of even higher redshift BAO survey with NIR (up to z~2.5) and blue (z~3) arms
  - A more optimal survey design needs to be realized: e.g. a part of BAO survey includes a deeper spectroscopic survey to construct a mag.-limited redshift sample for LSST and Euclid