The Evolution of Galaxies: What Subaru/SuMIRe Can Tell Us

Jim Gunn, IPMU Colloquium 7 Dec 2011

Surveys

Astrophysics is the pursuit of understanding the universe and its contents.

There are basically two approaches to this pursuit:

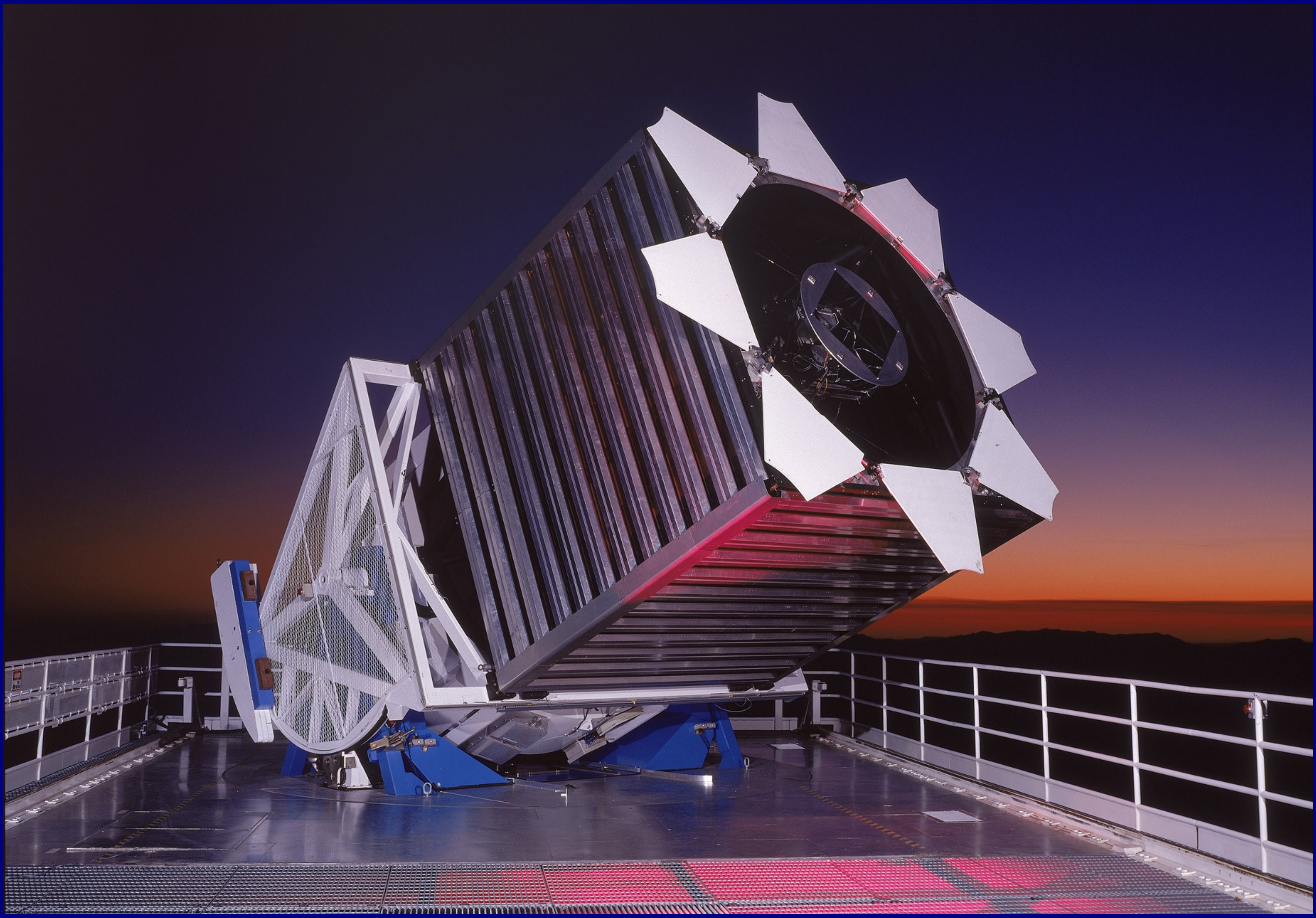
1. *Understand in detail how an individual object (star, galaxy, planet) works.*

2. *Realizing that there are too many objects and that their variety is too great to study them all In detail, attempt a statistical approach by studying very large numbers to study their properties and, especially, their interactions and population properties.*

General goal of astronomical surveys, starting, perhaps, with Ptolemy.

Both are necessary, clearly,
MUST have surveys before any general lessons can be learned from (1)--
must know the general characteristics of the population.
First large photometric/spectroscopic survey of galaxies was SDSS:

The SDSS 2.5-meter telescope



The Legacy of the Sloan Survey:
What did SDSS do?

Reminder: AB magnitude = $-2.5\log_{10}(f_\nu/3.63\text{e-}20\ \text{erg/s-cm}^2\text{-Hz})$

Photometry: DR8 – 470 million objects, 210 million galaxies and
260 million stars, to g,r magnitude ~ 22

Spectra: 920,000 galaxies, 580,000 stars, 130,000 quasars
Galaxies to r magnitude ~18
(BOSS will add another 2 million very luminous galaxies to i >19m,
Redshift ~0.6)

SDSS I-II: Complete census of luminous galaxies over about a quarter of the sky to redshift ~0.12, volume ~0.05 cubic Gpc, lookback time ~ 1.5 billion years. The universe is 13.5 billion years old, so this Is ~12 percent of the age of the universe. We see the universe in Sloan only in its old age. SDSS tells us about the universe TODAY

For the future, we need surveys with the kind of information (and more if possible) that SDSS provided to high redshift, to explore the evolution to the present state.

Cosmological equations

a the scale factor, $H = da/dt$

Friedman equation:

$(da/dt)^2 - 8\pi G\rho a^2/3 - \Lambda a^2/3 = -k$ If the DE is a cosmological constant

$\rho = \rho_m + \rho_r + \rho_? = \rho_{m0}(1+z)^{-3} + \rho_r (1+z)^{-4} + \rho_?(1+z)^{-3(1+w)}$

$\Lambda/8\pi G$

$\Omega_x = 8\pi G\rho_x/3H^2$

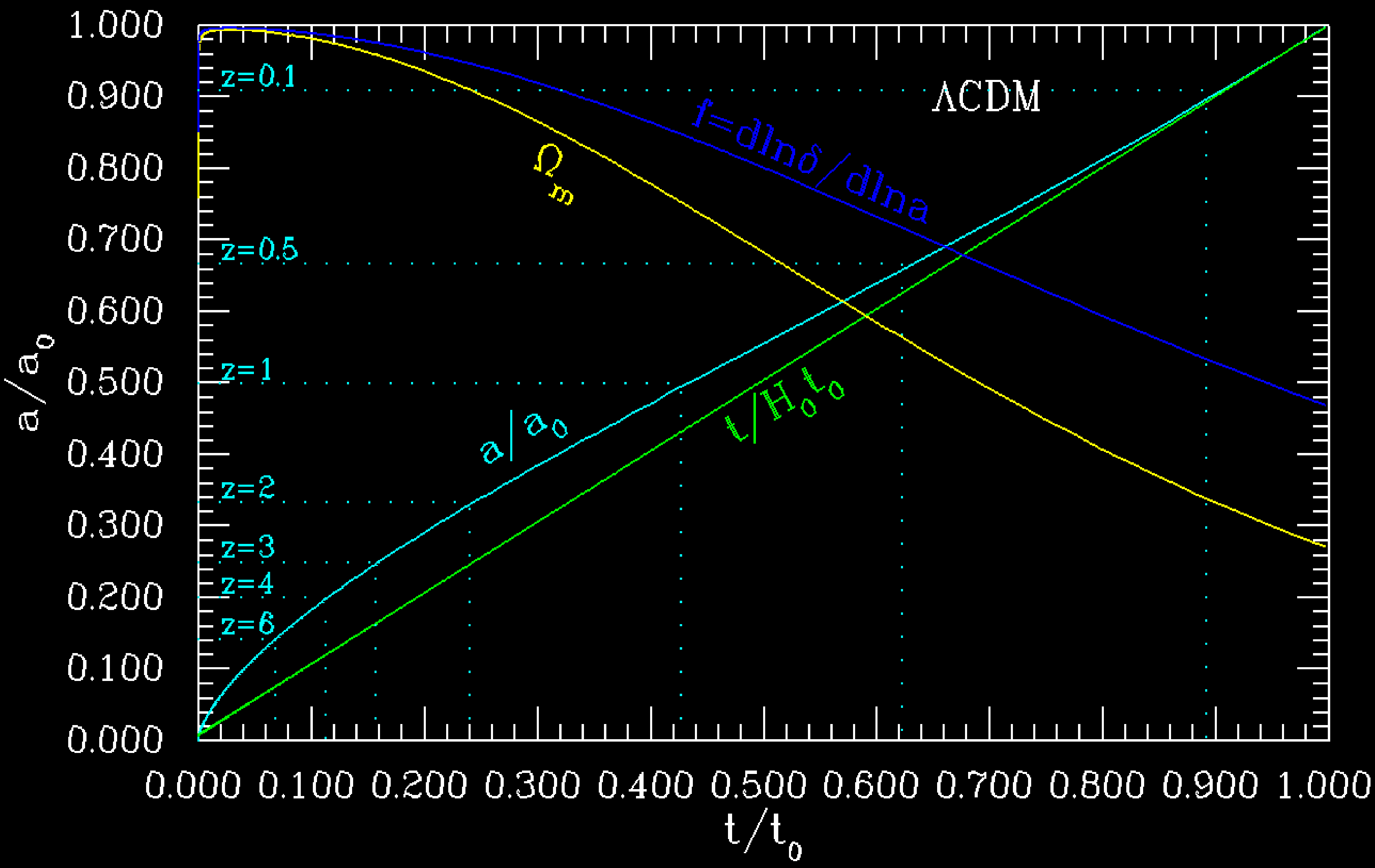
for ΛCDM with current (WMAP 7) parameters, $\Omega_{m0} \sim 0.27$.

Redshift 0.5, $a = 0.67a_0$, $t \sim 0.62t_0$, $\Omega_m \sim 0.55$

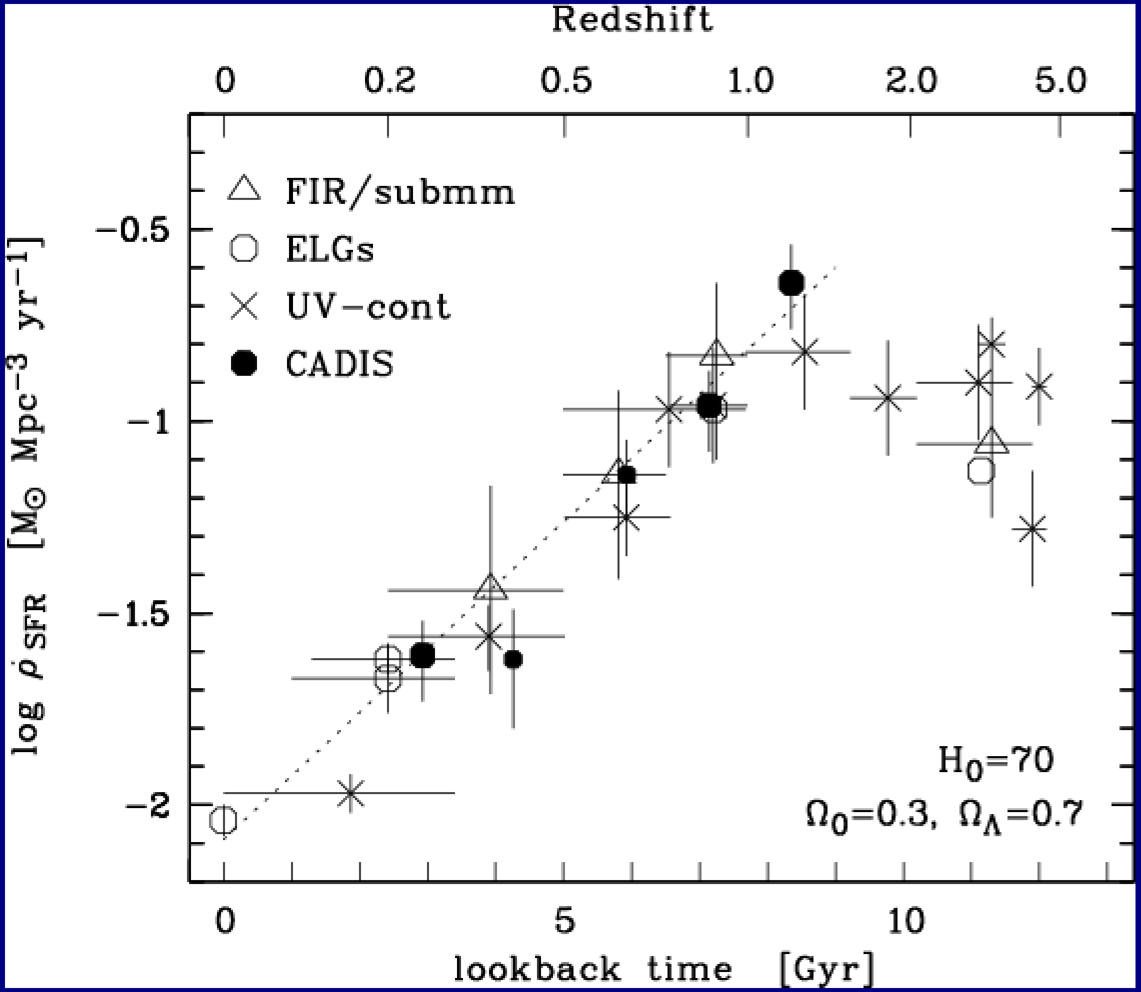
Redshift 1.0, $a = 0.5a_0$, $t \sim 0.43t_0$, $\Omega_m \sim 0.75$

Redshift 2.0, $a = 0.33a_0$, $t \sim 0.24t_0$, $\Omega_m \sim 0.75$

This plot shows the scale factor a as a function of cosmic time, the fraction of the critical density made up by matter Om, and the growth rate f of linear perturbations. SDSS explores only the far left.



The Universe in its Youth was Enormously More Active Than Now:



The rate of forming new stars has dropped by a factor of more than 30 since it peaked between redshift 1 and 2.

If we could do a survey to redshift 2, we could map most of the history of the formation and evolution of galaxies and the stars which make them up in detail over the last 10 billion years of cosmic history. The universe began 13.5 billion years ago, so this is 75% of its history.

Questions for Such a Survey:

1. *What is the history of the stellar populations of galaxies ?*

2. *The history of star formation and the initial mass function (IMF) of stars ?*

3. *What establishes the dynamics of the baryonic component—in simple terms, $\rho_{DM}(r,t)$ and $\rho_{baryon}(r,t)$, as reflected in sizes and radial profiles?*

4. *The history of heavy-element abundances ?*

5. *The growth and activity of supermassive black holes in galactic nuclei ?*

6. *The effect of environment and history thereof ?*

7. *What are the feedback mechanisms which regulate star formation, and how important are they?*

8. *What are the history and driving forces for outflows and infall, and what finally establishes the baryon/dark matter ratio?*

The Parameter Space

Answers to *all* these questions depend AT LEAST on

1. Dark Halo mass

2. Local density

And probably more, but if we could begin to understand THESE,

;-)))

Things we know:

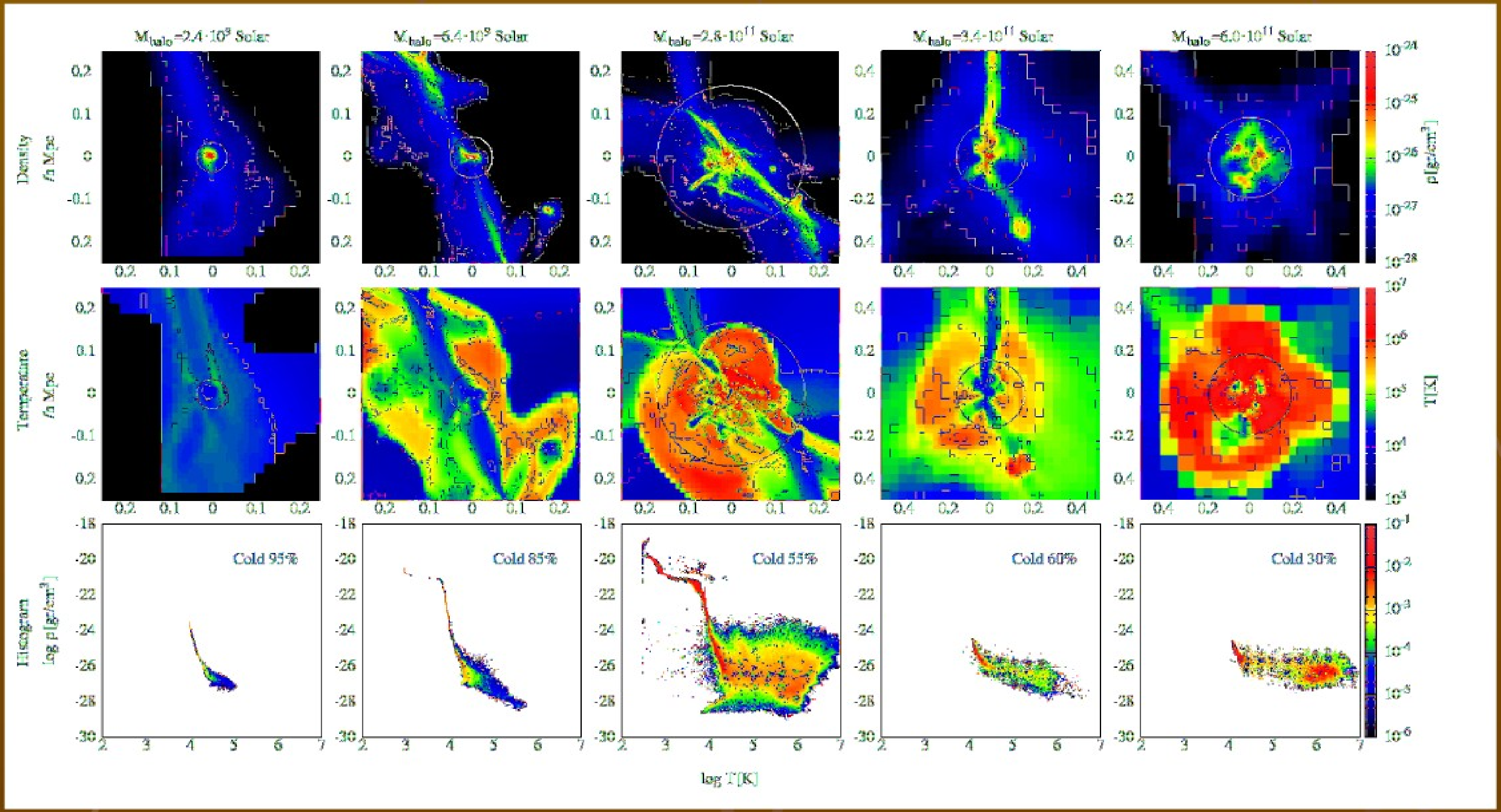
Galaxies are bluer and younger at high redshift (!!)
Galaxies are less metal-rich at high redshift
Galaxies are less clustered at high redshift
Galaxies (some galaxies) are smaller at high redshift

These (except perhaps for the last) we expect from simple considerations

We know all of these from relatively small samples, most with strong and not-well-understood selection effects.
We need much larger samples to study them well.

What do we expect?

Opinion appears to be converging on a picture in which galaxies are `fed' by filaments of cold gas until the dark halo grows to ~$10^{11.5}$ M_{sun}, after which the hot gas halo, which is also growing, cuts off the cold flows. This is shown in this ART simulation by Kravtsov:



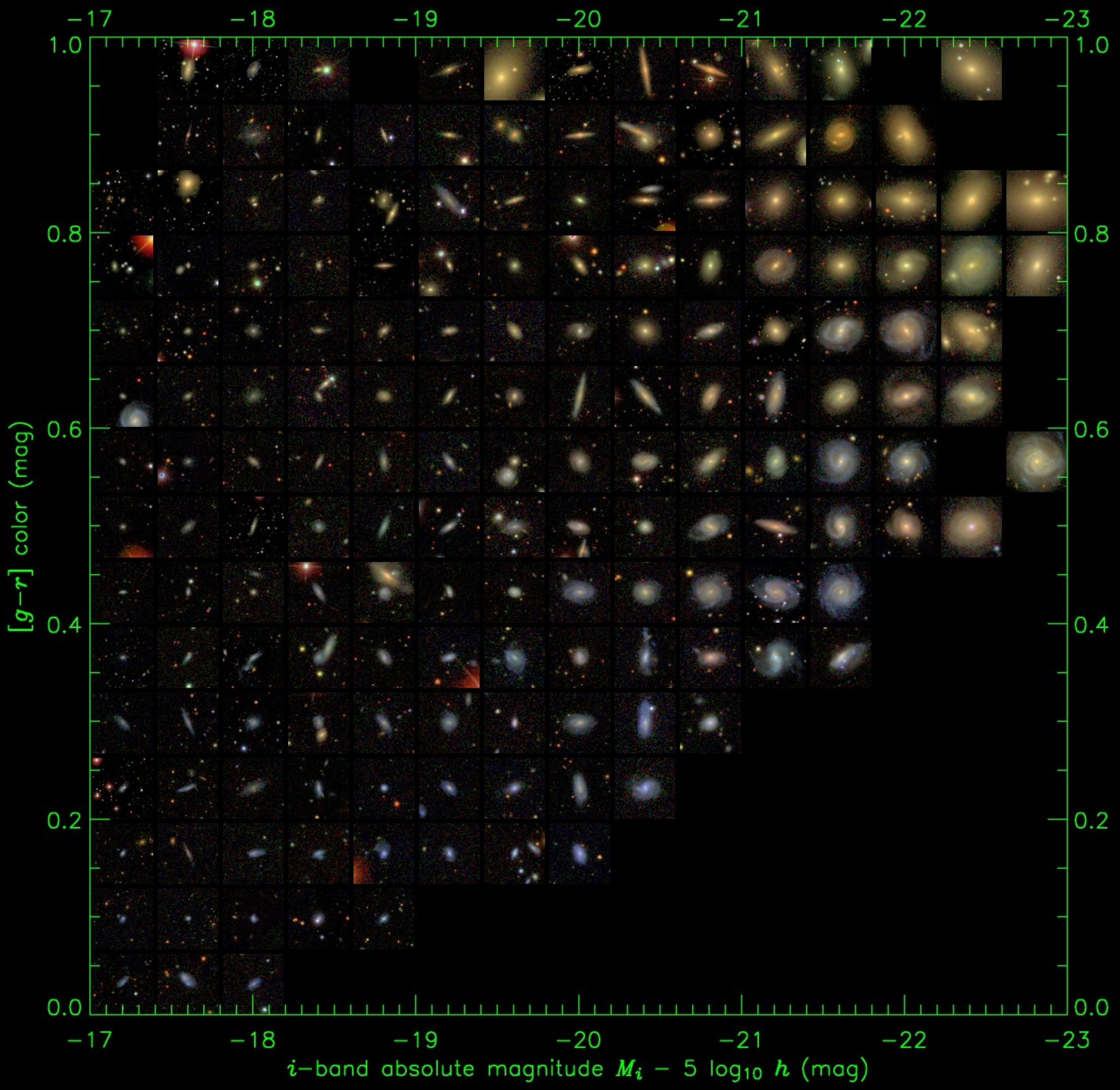
Galaxies Today

This mosaic from Hogg and Blanton illustrates the sequence of properties of normal galaxies with color and luminosity today.

They have used four photometric indices

luminosity
color
surface brightness
Sersic index n

Sersic:
$B(r) \sim \exp(-r^{1/n})$

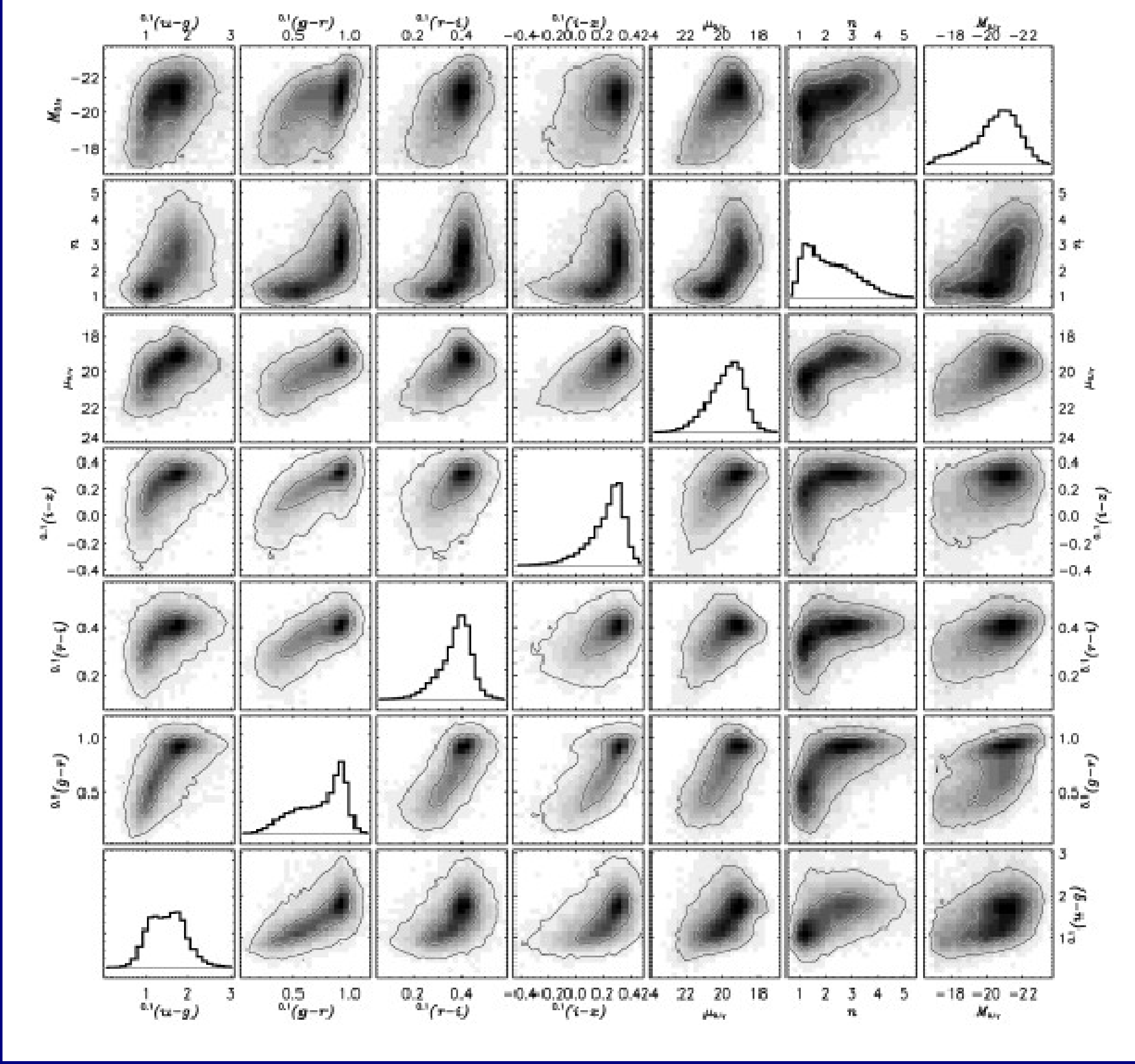


Galaxies Today

This is the distribution in the SDSS sample of these indices. today.

MOST of the luminosity (and stellar mass) in the universe today is in bright galaxies.

There are two sequences, narrow red and broad blue.

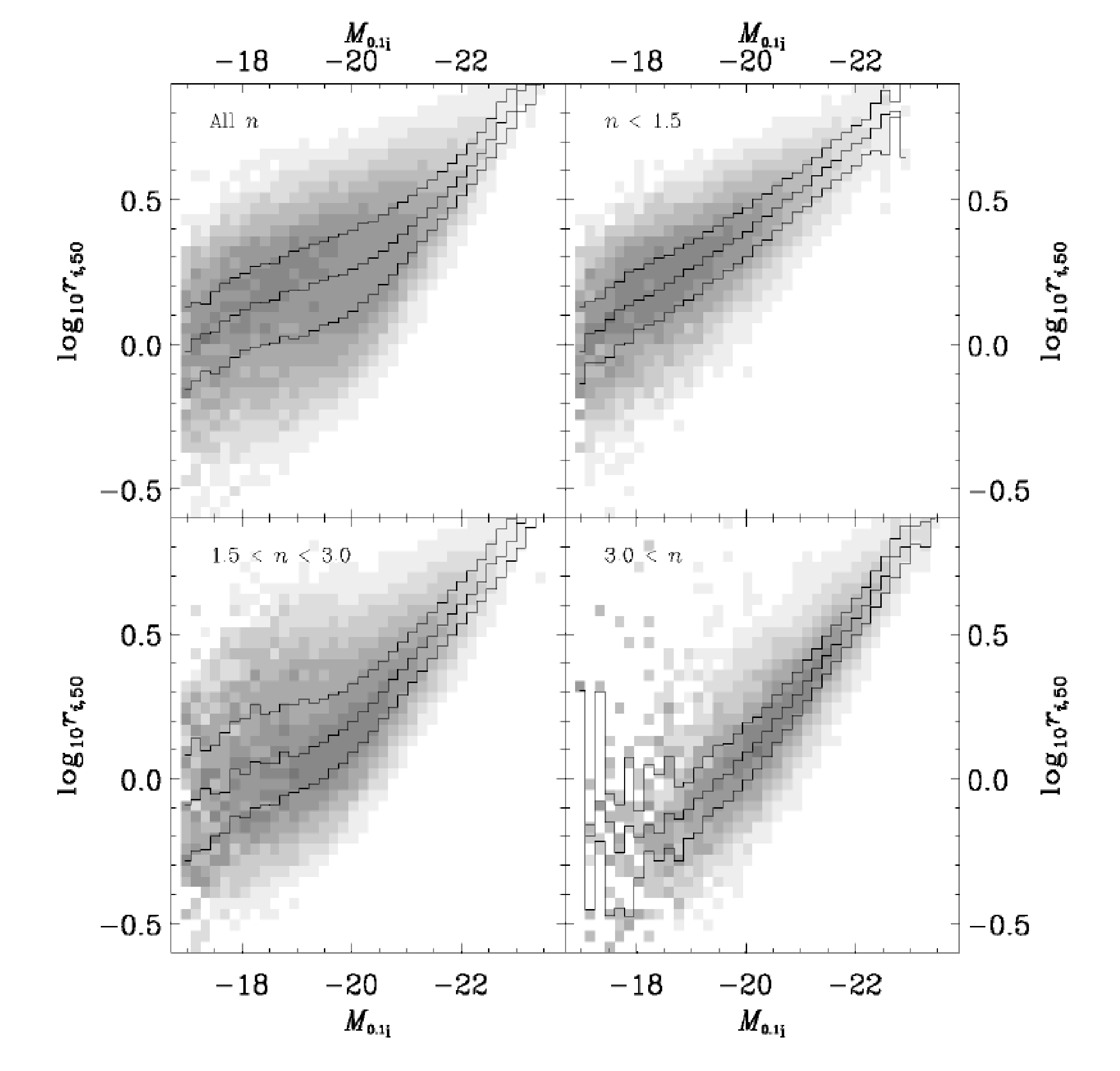


Half-light radii for galaxies with various Sersic profiles.

Typical bright (L*) galaxies have r_es between 2 and 4 h^{-1} kpc, larger for late-type systems than early-type. (3 kpc ~ 0.5 " for z > ~0.6

(r_e ~ 1.7/a for an exp. disk)

relations similar for all n.



Measuring Sizes and Shapes at High Redshift

r_e ~ 3 kpc for L* galaxies

Sloan: seeing ~1.5 arcseconds, HWHM at z=0.1 is 1.1/h kpc

Subaru Survey ~ 0.7arcseconds, HWHM at z=1 is 2.2/h kpc,
~constant for $0.5<z<2$.

Harder than with Sloan at a given S/N, but possible with high S/N

Also, some kinds of galaxies are smaller at high redshift, some by a lot.

An example:

A galaxy with an re of 2.2kpc/h in an image with 0.7" FWHM seeing
and S/N=30 for a star of the same brightness has:

flux density meassured with an S/N of 20
re meassured with an S/N of 10
Sersic n measured with an S/N of 3

What the profiles look like:

The profiles for various Sersic indices are very similar in the presence of seeing

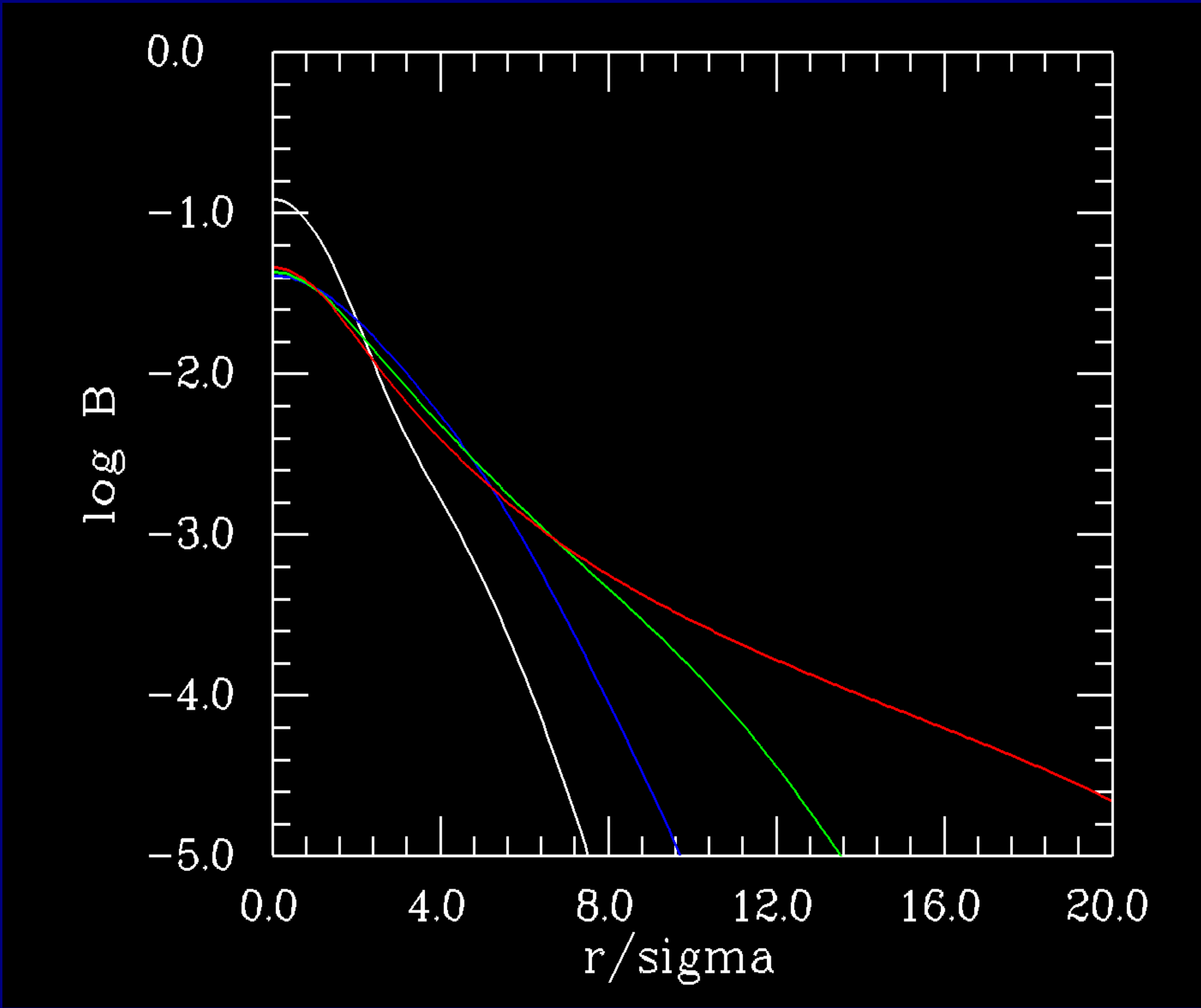
(here Re = 0.7” FWHM, r_e = 2 kpc, z~1)

white: star
blue: n=1
green: n=2.5
red: n=4

If one does optimal least sq profile fitting,

$\sigma(\ln n) \sim 7\sigma(m)$,

So must have high S/N images to measure n, S/N > 30



How Can we Do This??? What do we need?

Coming soon is the HSC imaging survey. It will provide one ingredient of the survey we need:

VERY high S/N/excellent seeing/image quality to measure structure and fluxes and colors reliably. Without these, we can do almost nothing.

If the flux accuracy is good, we can get reliable photometric redshifts to accuracies of a few percent for red galaxies to ~10 percent for blue ones.

These (with GREAT care) will allow determinations of

1. *Luminosity functions and luminosity evolution*

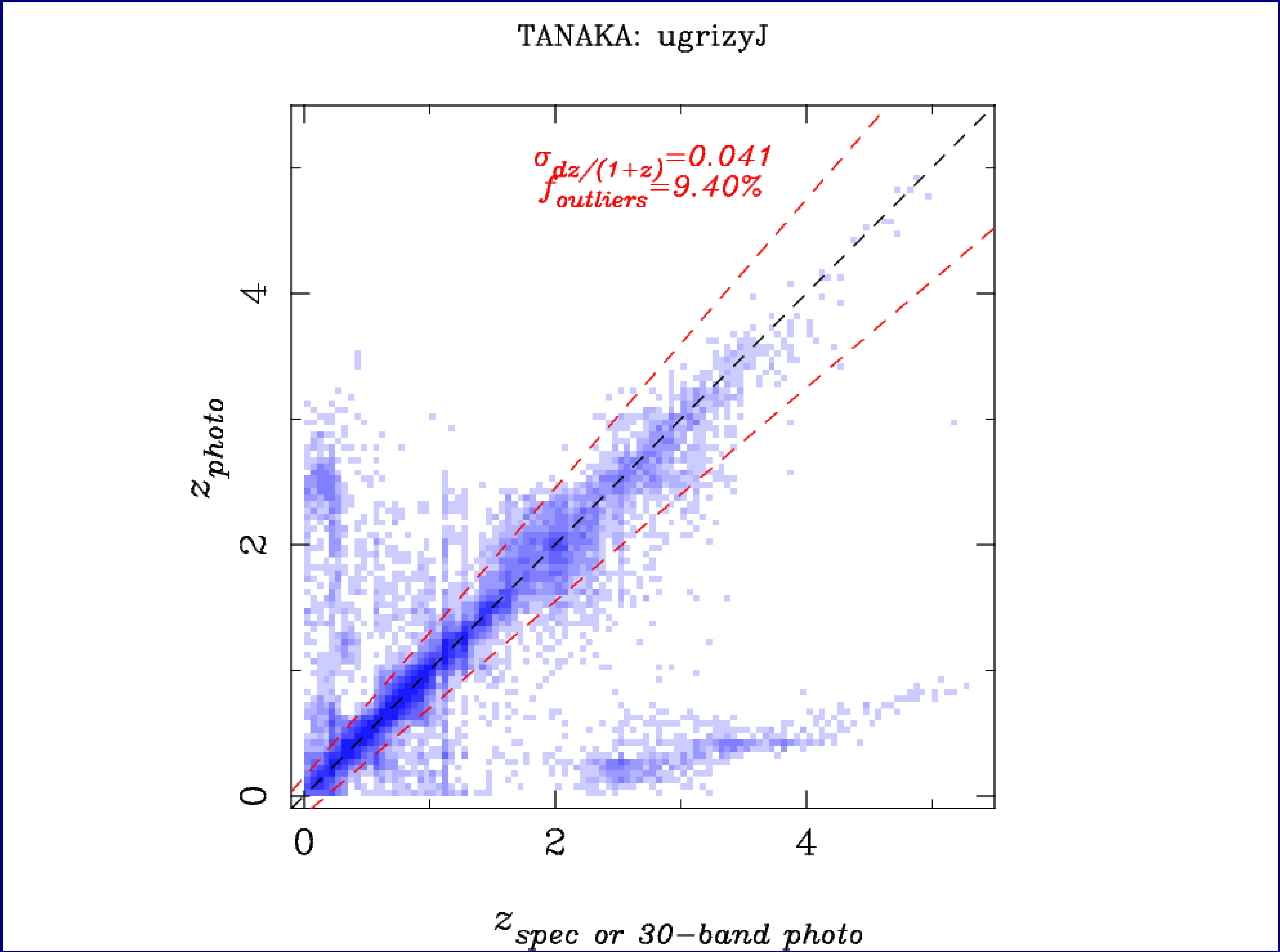
2. *Size evolution*

3. *The number and size evolution of massive clusters*

4. *Some information about the evolution of AGN and quasars*

5. *Clustering on very large scales*

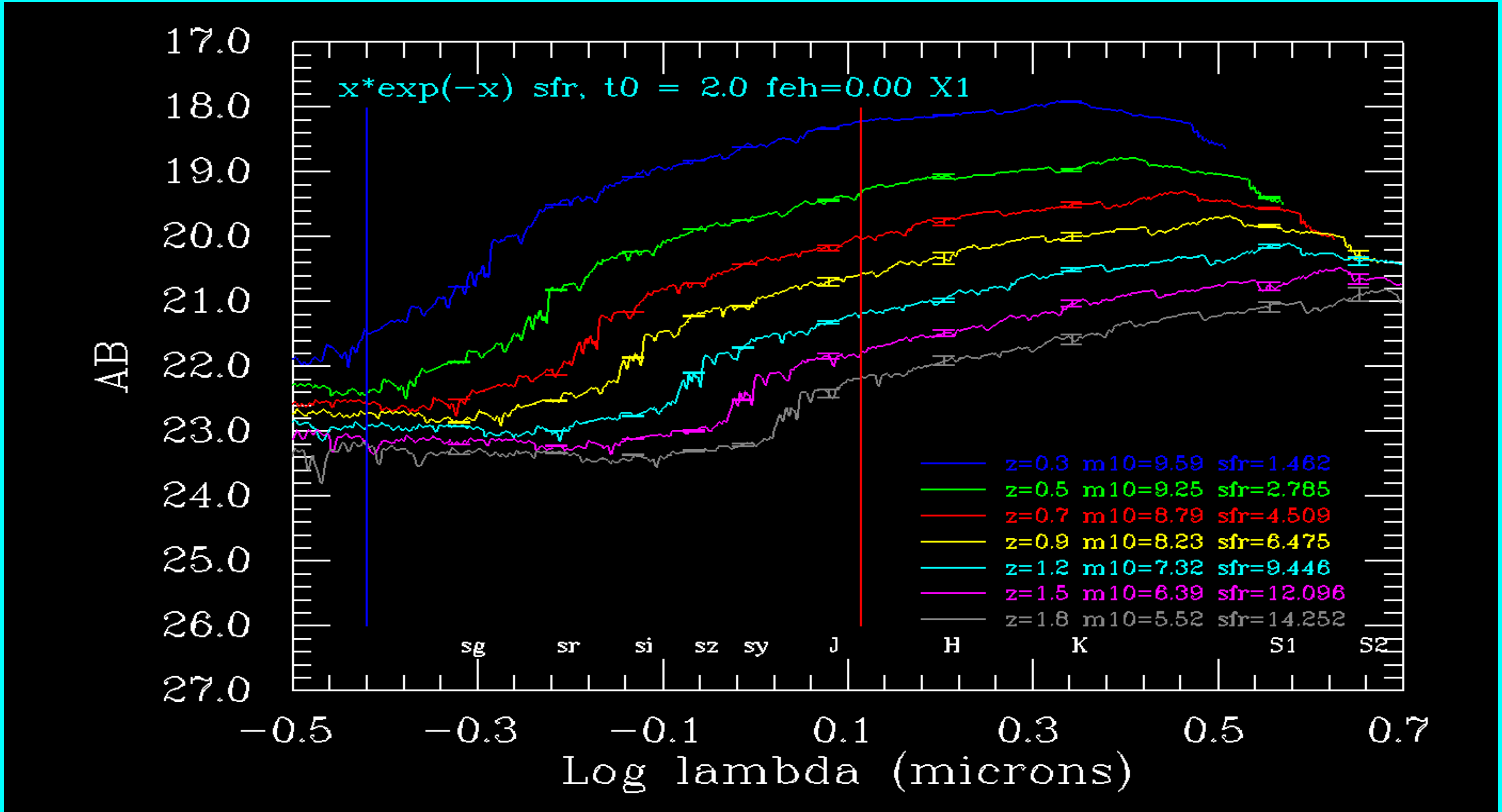
A photometric redshift algorithm applied to simulated data



x*exp(-x) sfr, t0 = 2.0 <feh>,sd=0.0 0.3

Mi.1 = -21.54 .1colors(ug,gr,ri,iz) = 1.46 0.89 0.34 0.29

z	Volc	knL*	1''	m*	m*dot	Mi.1	gr.1	g	r	i	z	y	j
0.10	(ref)		1.8	9.8e+10	6.1e-01	-21.73	0.89	17.78	17.02	16.69	16.43	16.24	16.01
0.50	0.009	29	6.1	9.3e+10	2.8e+00	-22.32	0.72	21.89	20.89	20.26	19.92	19.75	19.39
0.70	0.010	34	7.2	8.8e+10	4.5e+00	-22.54	0.66	22.47	21.91	21.06	20.71	20.45	20.10
0.90	0.018	58	7.9	8.2e+10	6.5e+00	-22.71	0.60	22.78	22.49	21.85	21.27	21.06	20.64
1.20	0.027	87	8.4	7.3e+10	9.4e+00	-22.88	0.54	22.97	22.95	22.73	22.15	21.70	21.25
1.50	0.032	104	8.6	6.4e+10	1.2e+01	-22.96	0.49	23.14	23.22	23.14	22.98	22.46	21.84
1.80	0.037	122	8.6	5.5e+10	1.4e+01	-23.00	0.45	23.34	23.36	23.43	23.31	23.21	22.27
HSCDeep 5 sigma limits:								27.80	27.30	27.10	26.20	25.70	
HSCWide 5 sigma limits:								26.70	26.10	26.10	25.20	24.70	



However, we need more to do the job right:

Optimistic accuracies of photometric redshifts place the errors in ln (1+z) at ~.04 or a little better. So we lose

1. Essentially all dynamical information in populations of galaxies. errors of .02 -> v ~ 6000km/s. There ARE no structures with velocity dispersions this large, nor do peculiar velocites ever get this large

2. All dynamical information IN galaxies—no velocity dispersions or rotation.

3. All but crudest chemical information – yet to be demonstrated that even this is reliably obtainable.

4. All but the crudest stellar population information

Experience with SDSS indicates that the synergy between imaging and spectroscopy is profound, and one really needs to do an SDSS-style survey with imaging AND spectroscopy these redshifts.

What do we need?

*Suppose we want a spectroscopic survey to z ~ 2 to do an investigation on the galaxy population in several redshift bins on samples which are comparable in size to the Sloan main survey, to investigate the *evolution* of chemical, dynamical, and clustering properties analogous to those done on the SDSS sample.*

The volume of the SDSS main sample to a luminosity limit of L is about 0.04 h-3Gpc3, and contains about 300,000 galaxies brighter than L* to the main limit.*

So we would like comparable comoving volumes in several redshift bins out to some highest practicable redshift, which we would like to be at least 2, to cover the main epoch of star formation....ie, the formation of baryonic structures.

Can We Do This With the Technology Available Today?

The short answer is *YES*. The long answer is somewhat more involved.

Wavelengths: At z=2, $\lambda_{obs} = 3\,\lambda_0$

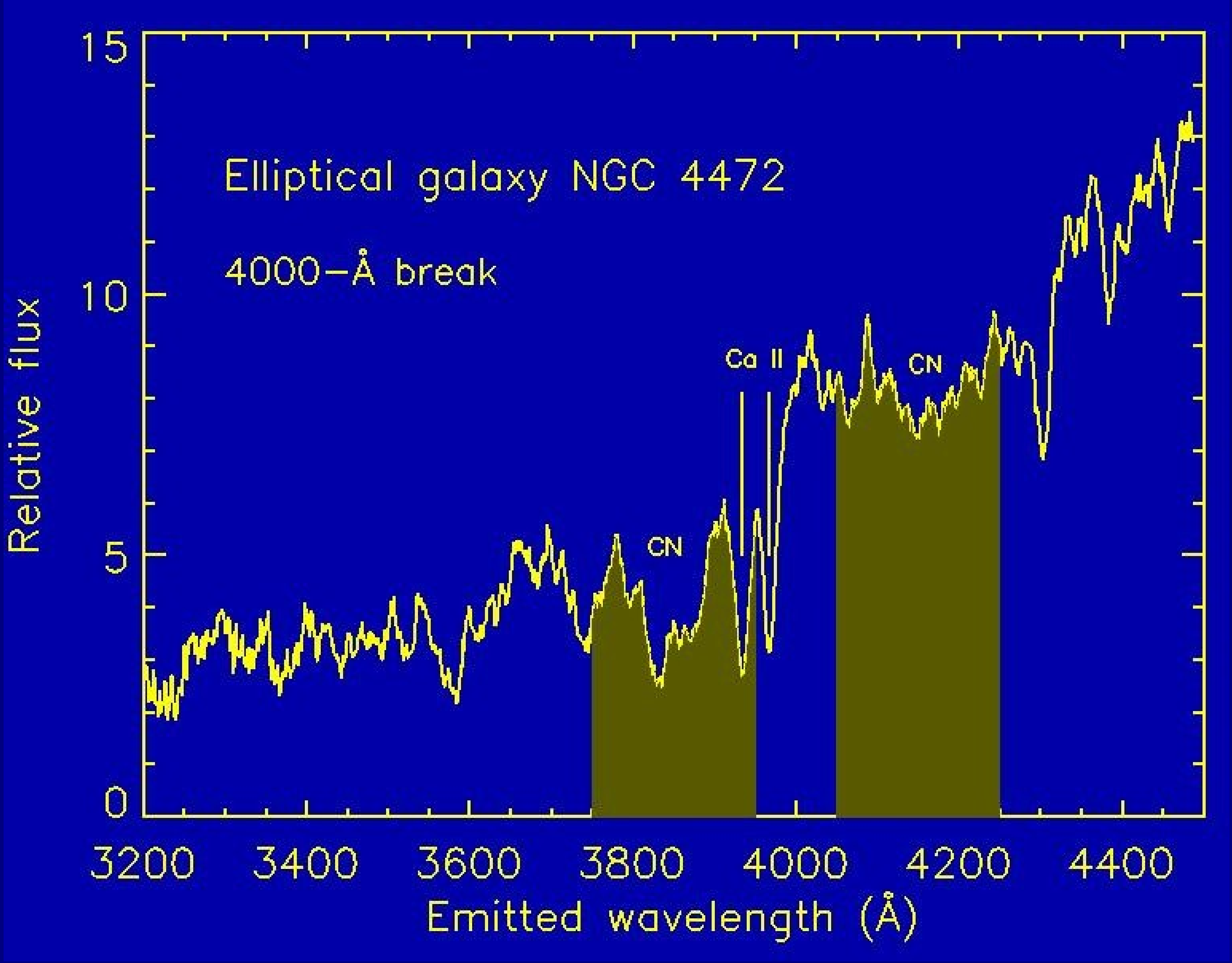
So	Hδ 4100	-> 12300
	CaII H+K 3950	-> 11500
	O[II] 3727	-> 11200

All necessary to get any handle on the stellar population older than a few tens of megayears, are in the near IR, longer than silicon detectors can go. Need to go to ~1.3 microns to do any good at all. Farther would be better, but is very hard.

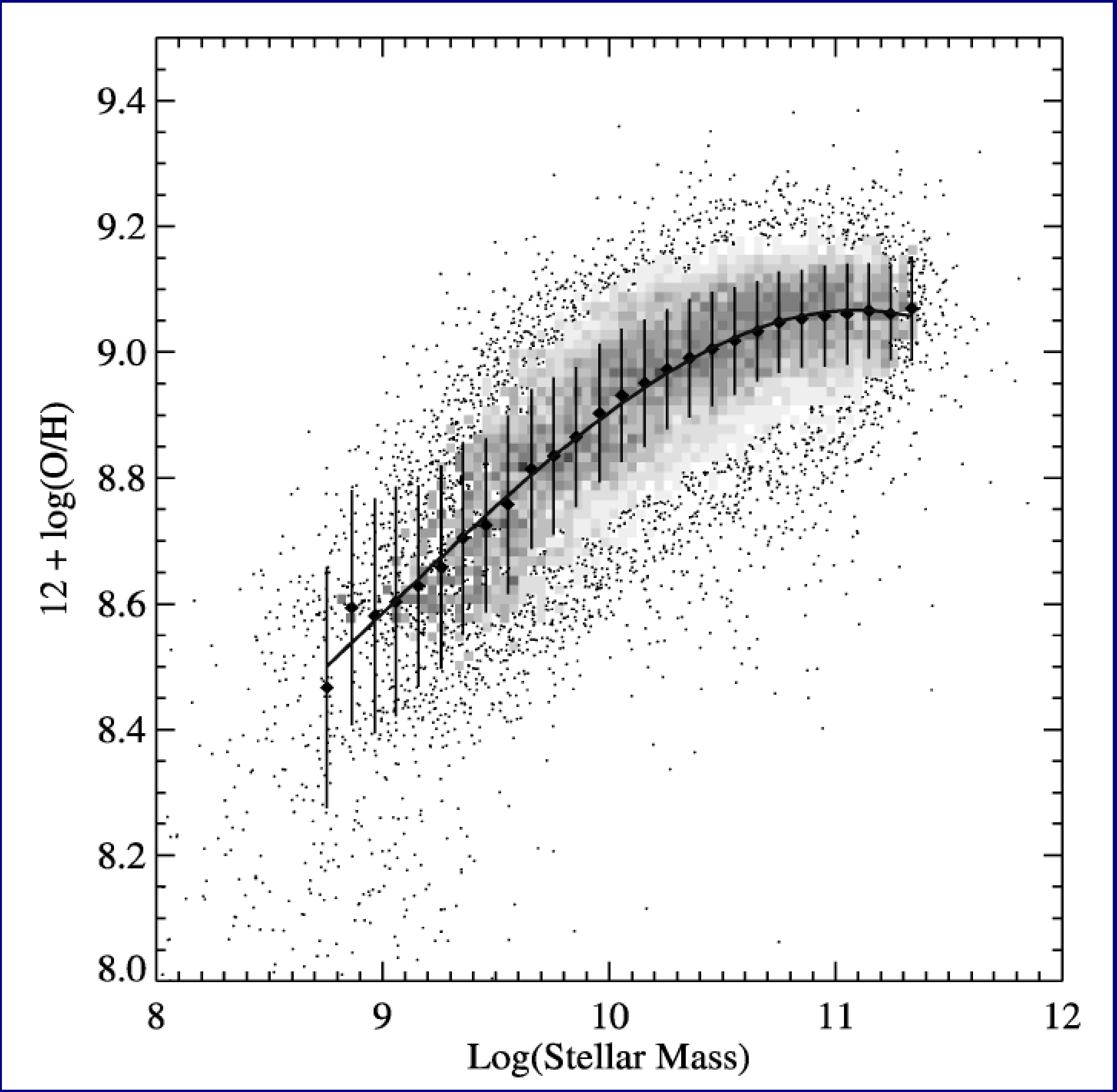
If we can do this, will have information in addition on dynamics, 3d clustering, and metallicity – almost everything we have from the SDSS.

The 4000A Break Region of the Spectrum of an Elliptical Galaxy

At redshift 1.95, a spectrograph which reaches to 1.3 microns records the spectrum to a rest wavelength of 4400A, which includes lines of many of the common elements, so provides good abundances.



This plot from Christy Tremonti's thesis shows the gas-phase oxygen abundance as a function of stellar mass for SDSS galaxies. It is clear that the metallicities of galaxies are lower at high redshift from data on small samples, but the quantitative trend and the environmental dependence are unknown.



What Would the Ingredients of Such a Survey be?

Fact: Our canonical luminous L Galaxies at z=2 are about 5m fainter at z=2 than at z=0.12, We must do *spectroscopy* at 23rd magnitude in the near IR.*

Imaging: You MUST know what you are looking at, and exactly where it is, to put a fiber on it.

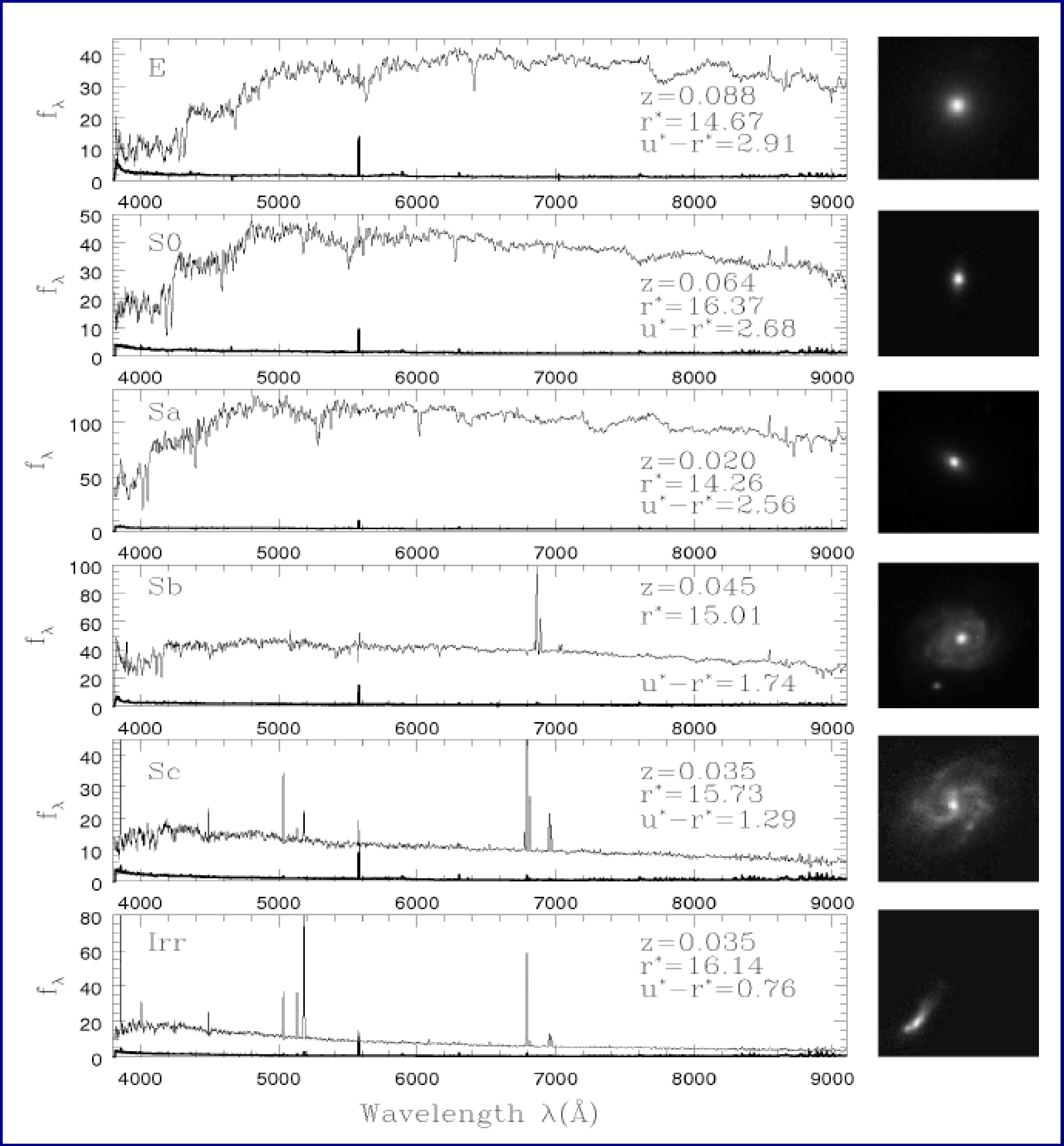
In SDSS, the imaging went about 4.5 magnitudes deeper than the spectroscopy. Need this to characterize the targets well.

The HSC deep survey will survey about 30 square degrees to about 27th magnitude with Subaru. This is about 4 magnitudes deeper than we need to go with spectroscopy. OK.

Enough area? Not quite SDSS, but OK. If we imagine 5 slices in redshift,

Boundaries	0.6-0.8	0.8-1.05	1.05-1.35	1.35-1.65	1.65-2.00	
Mean z	0.7	0.9	1.2	1.5	1.82	
Area/SDSS vol	110	80	60	50	50	sq. deg
HSC deep frac	27%	37%	50%	67%	67%	
# of L*galaxies	80000	110000	150000	200000	200000	

Spectra and morphologies of typical galaxies today. We do not know the history of these phenomena. There is evidence that spiral galaxies have not changed their properties very much since z=1, but early-type galaxies have changed drastically in the same period. Earlier, we have little data.



So Can we Do It? YES—the instrument is PFS, a Japanese-led international project:

1. Fiber positioner: 2400 little motor-driven robots to place fibers on objects. Caltech

2. PFI: (Prime Focus Inteface) Interfaces positioner with telescope and manages top end of fiber harnesses. Caltech/NAOJ/IPMU

3. Fibers: Run from prime focus to fixed spectrograph(s) in instrument room in Subaru dome. About 50 meters. Brazil (Sao Paulo group)

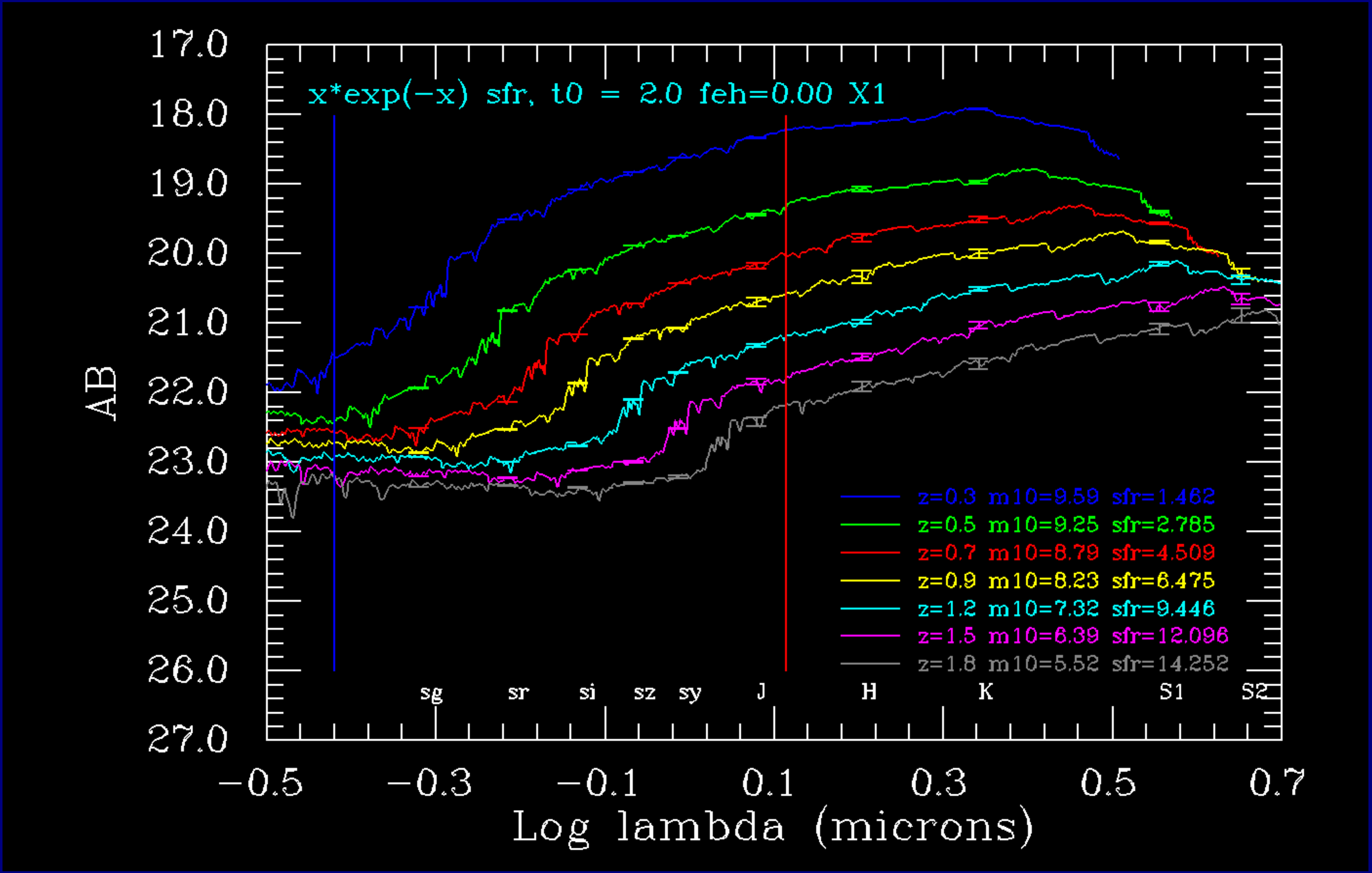
4. Spectrographs: Need 4 large spectrographs, 600 fibers each. Cover blue (3800A) to near IR (13000A) in 3 channels. 12 detectors/dewars. Princeton/JHU/France (Marseille)

5. Software: Control and Data Reduction Marseille, (?) Princeton (?)

6. Project management and Optics, IPMU (Tokyo)

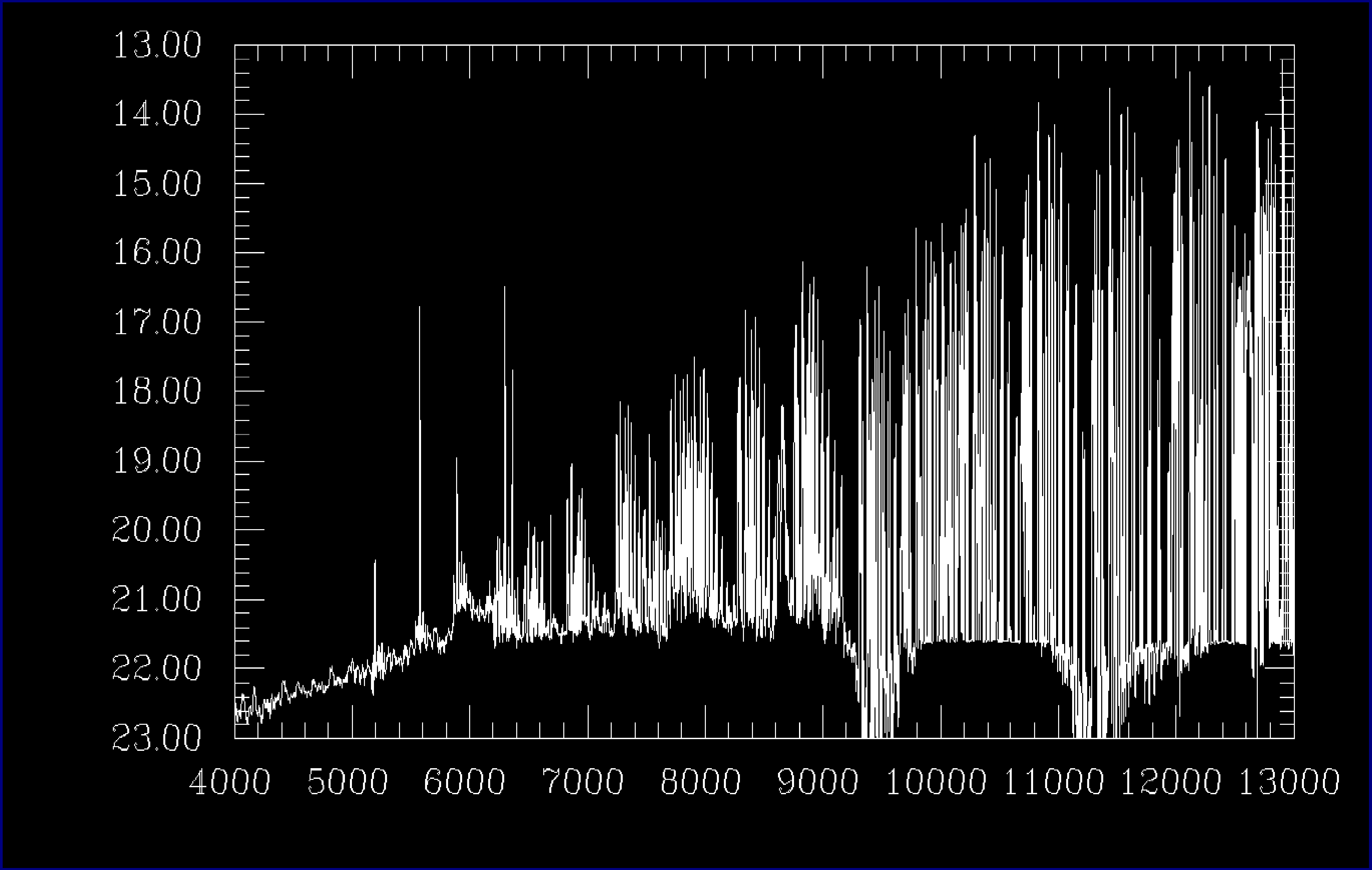
SuMIRe (Subaru Measurement of Images and Redshifts encompasses the HSC and PFS instruments and surveys.

Galaxy Spectra



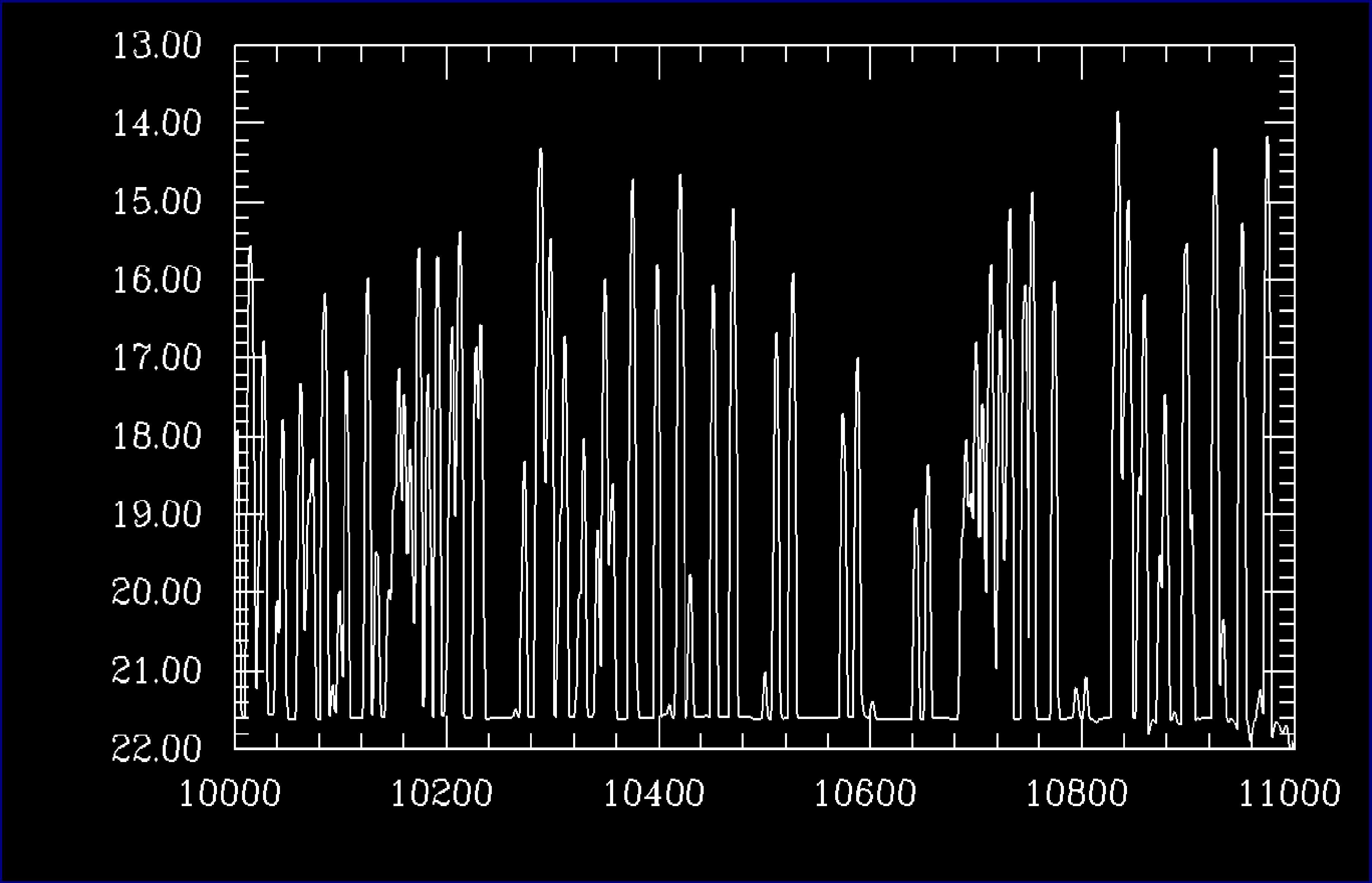
Spectra for a (model) typical L galaxy at redshifts between 0.5 and 2.2. SFR at z=2 is about 30 times present SFR, like typical rate. Need to go to 23rd magnitude (or a bit fainter in the visible)*

A Problem: The Sky



Working in the near IR is very difficult because of the OH airglow. Can you work *between* the OH lines?

A Problem: The Sky



Yes, with high enough resolution. At low resolution, there is no `between'.

****We can use about 60% of the spectrum at R~4500****

What about the Instrument?

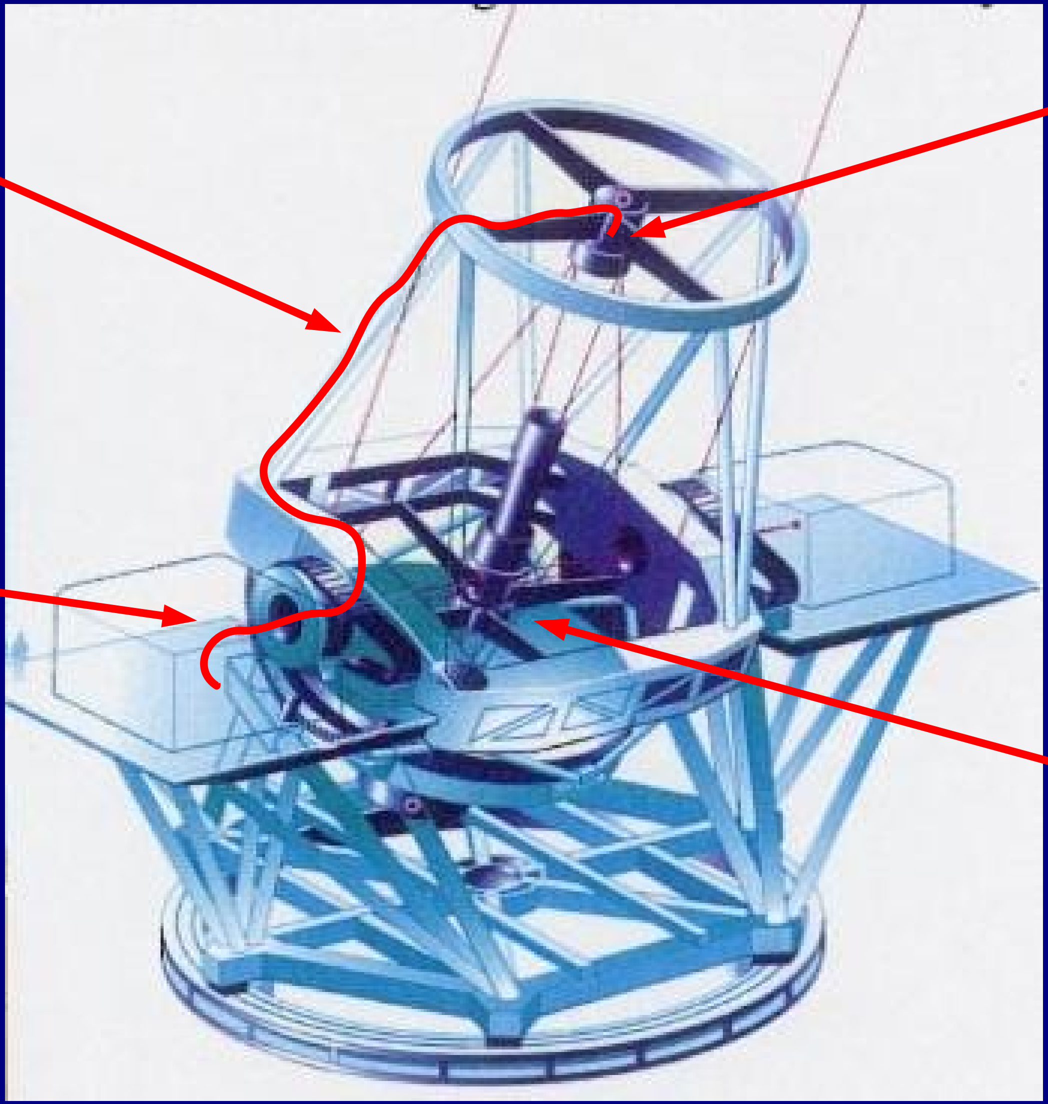
1. The telescope:
   The spectrograph must go on Subaru, unless we want to spend $200 million+ on a new one. The Japanese were the only builders of large (8-10M) telescopes with enough foresight to provide a wide-field survey capability. (Besides, it is a Japanese project)

2. The Spectrograph array and fiber system:
   This will all be new; we will talk about it a little now.

Subaru on the summit of Mauna Kea

The General Layout of SuMIRe-PFS

Fiber cable run. 2400 fibers, 600/ spectrograph, 20 30-fiber bundles. 50 meters total run

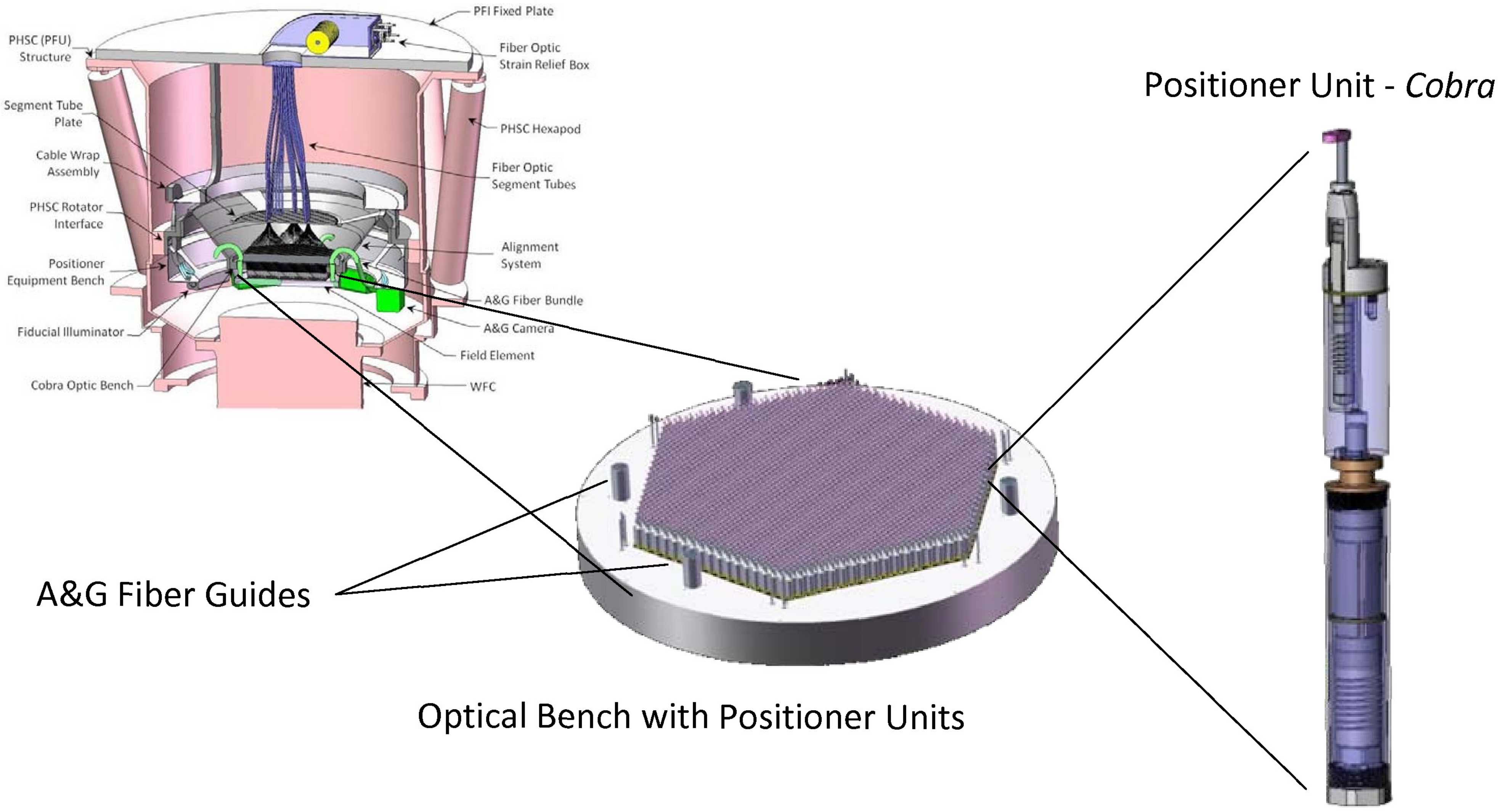


Prime Focus Cage. Fiber Positioner Lives Here

Nasmyth Instrument Room Spectrographs Live Here

8.2m Primary Mirror

PFS Positioner



Cobra system tested at JPL in partnership with New Scale Technologies
Designed to achieve 5 μm accuracy in < 8 iterations (40 sec)
Up to 4000 positioners 8mm apart in hexagonal pattern to enable field tiling

The Spectrographs

Desiderata:

1. High Throughput

2. As wide a wavelength range as is practical (3800-13000 is doable)

Important scientific note: All galaxies forming stars have Ly-alpha 1216A and [OII] 3727 in strong emission lines; often nothing else. We can follow [OII] to redshift 2.48; Ly-alpha enters our range at z=2.12. No `redshift desert'.

3. Sufficient resolution to
   a. Do the science
   b. Work on faint objects in the red, *between* the OH lines

4. Simple optics to keep the surface count and costs low.

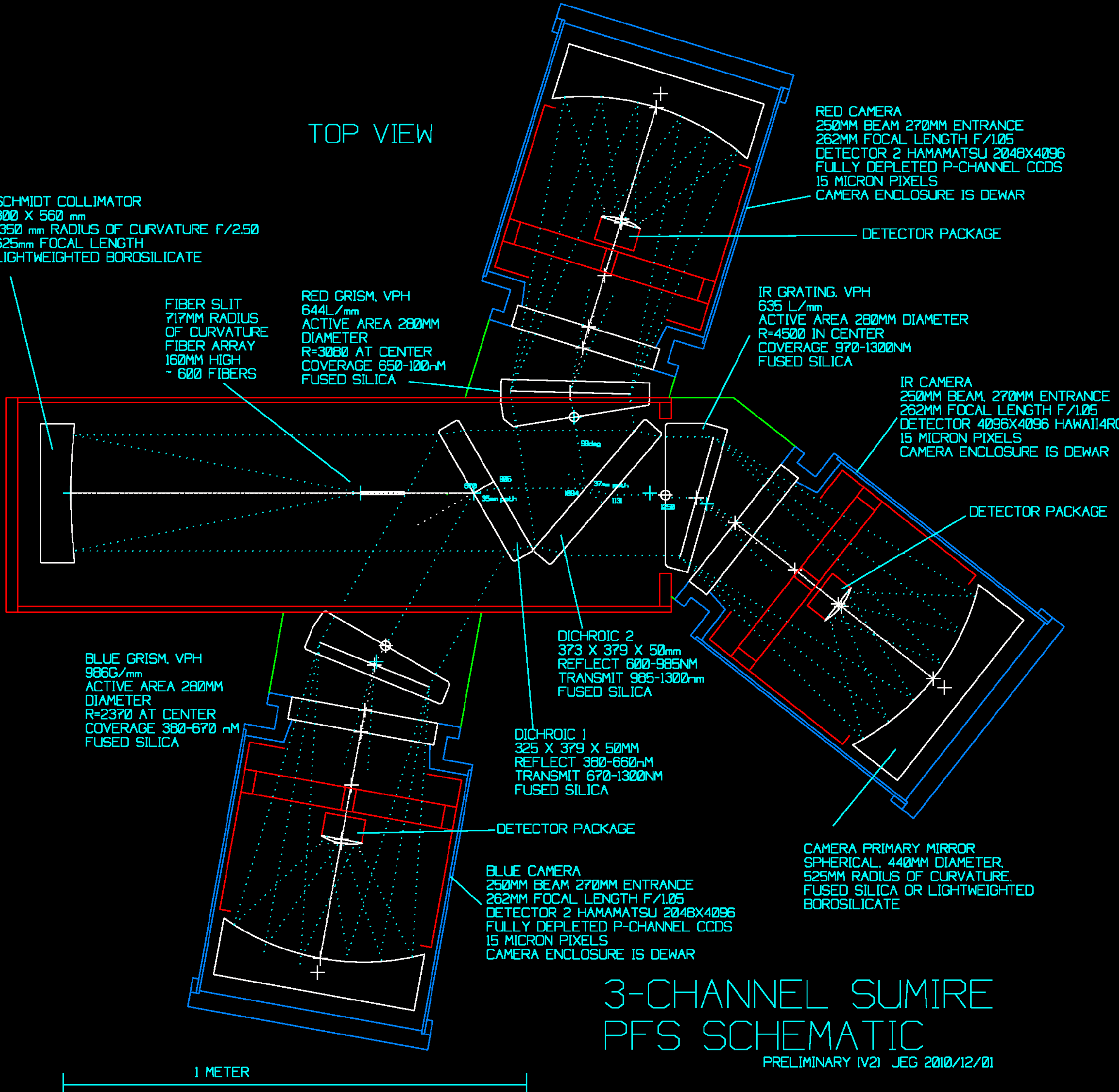
5. A state-of-the-art faint object instrument. Subaru is the ONLY large telescope on which it can be effectively used.

The Spectrographs

Three channels to get sufficient resolution. ~3A resolution over whole spectrum 3800-13000A

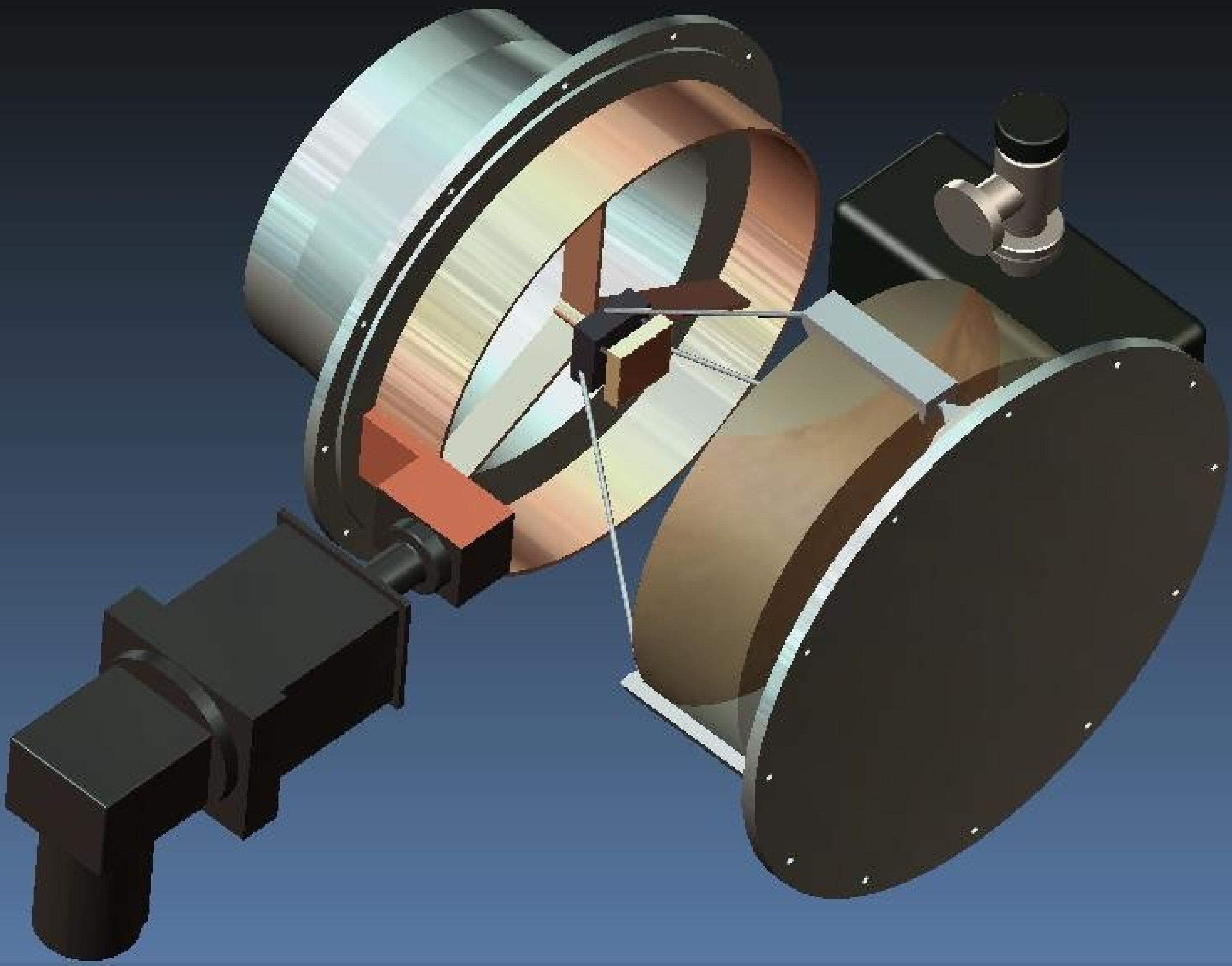
Optical channels	*3800 – 6500*
	6500 – 10000
IR channel	*10000 – 13000*

Looks roughly like this:

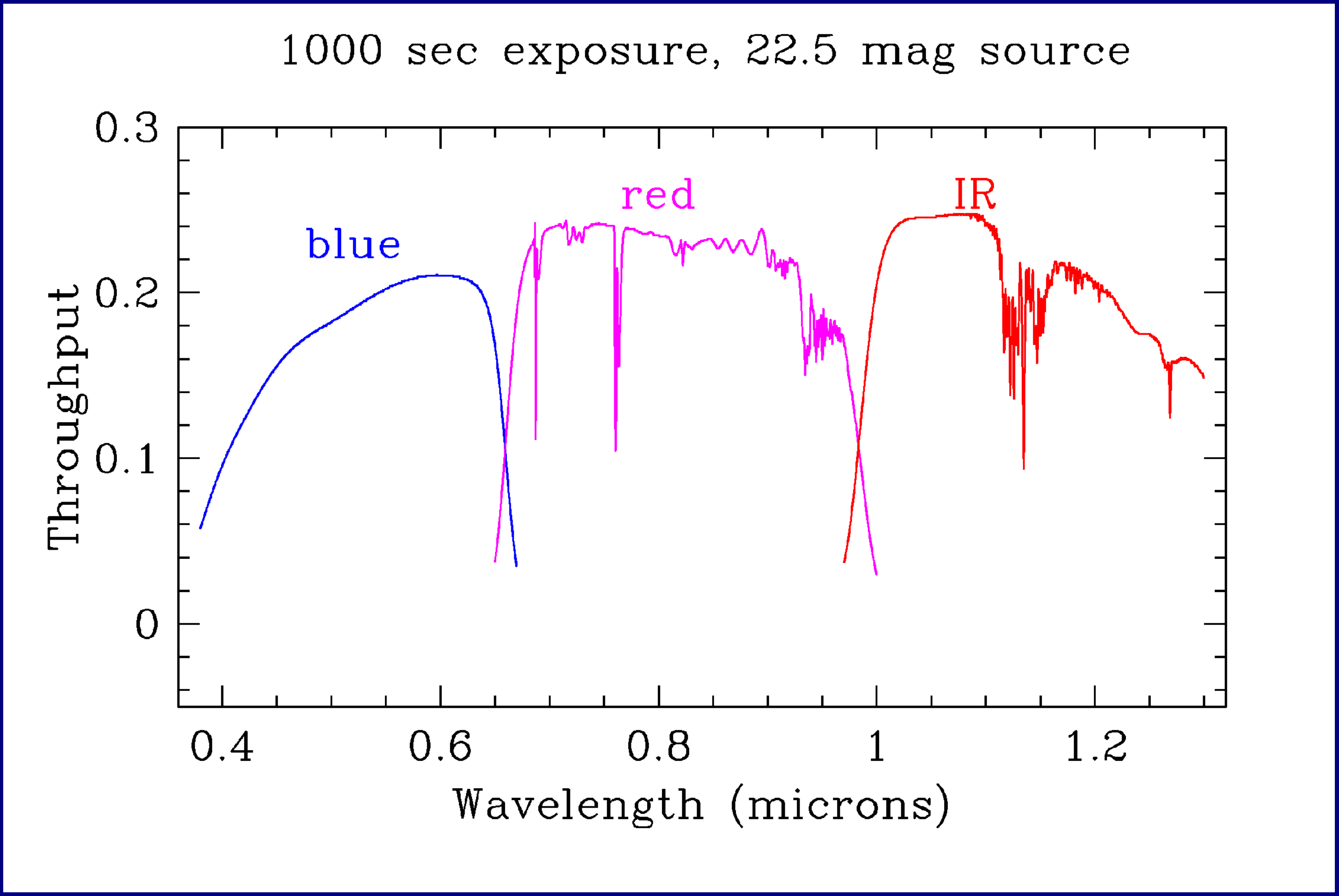


3-CHANNEL SUMIRE PFS SCHEMATIC

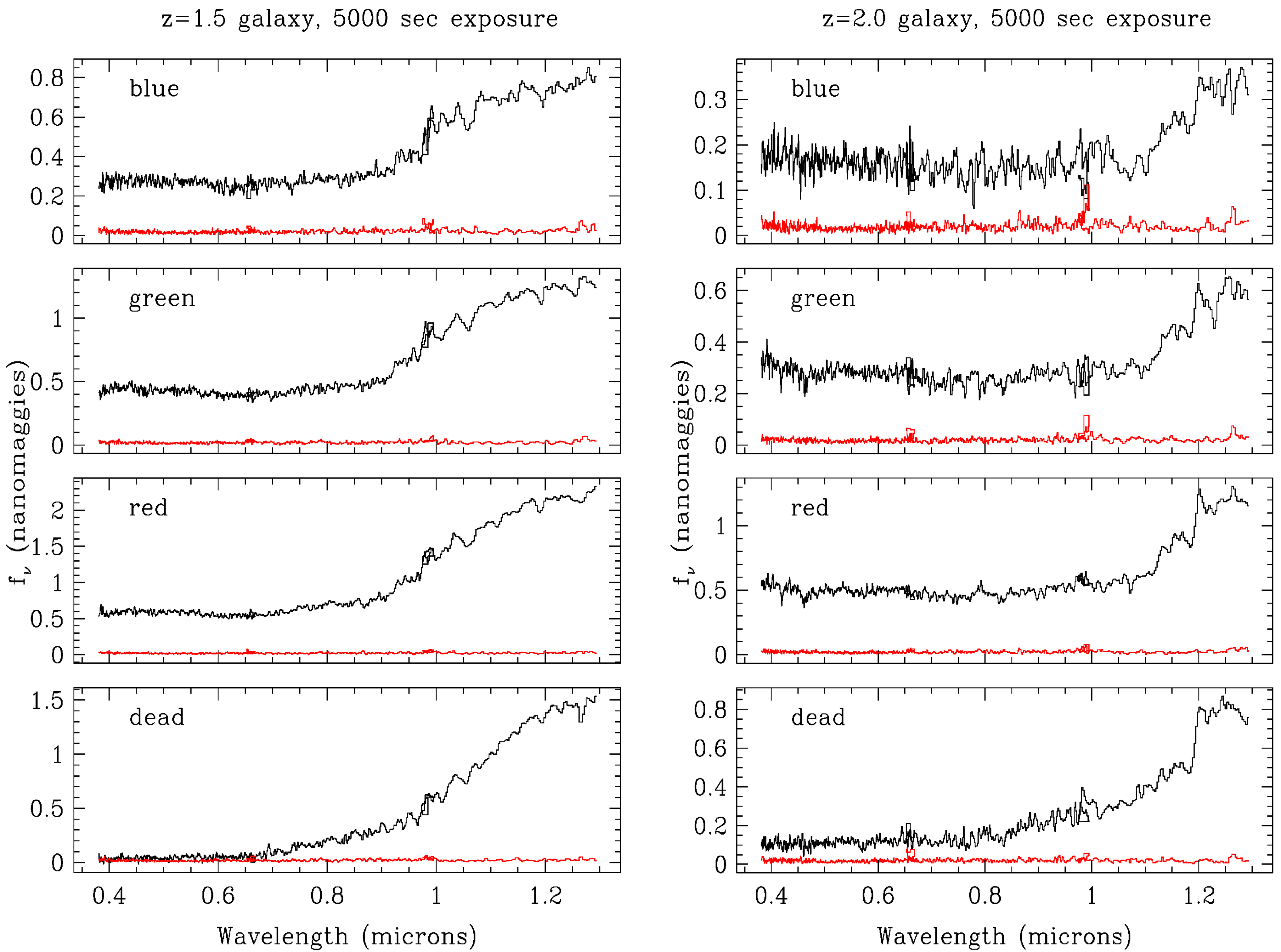
PRELIMINARY (V2) JEG 2010/12/01



The Spectrographs: Performance



Point-source throughput with all instrumental losses and seeing loss at input in 0.7" seeing (29%)


z=1.5 galaxy, 5000 sec exposure
z=2.0 galaxy, 5000 sec exposure
blue
green
red
dead
blue
green
red
dead
f_ν (nanomaggies)
f_ν (nanomaggies)
Wavelength (microns)
Wavelength (microns)

There is an enormous amount of work to be done, both on the HSC survey and on PFS and its survey. This work is centered at HERE at IPMU.

The performance I discussed is theoretical for BOTH instruments. It depends on excellence of engineering (we believe accomplished for HSC, but all of PFS is to come) and of reduction software.

The guiding principle for the SDSS was ALWAYS to work to the photon noise limit for both hardware and software. A good principle, I believe, but there are many unanswered questions at this point, including

1. Can we *reach* the photon noise limit for HSC in the deep and ultradeep surveys, or will sysematics limit us brighter?

2. Can we calibrate the HSC survey accurately enough to do lensing and photometric redshifts to the required accuracy? (~1%)

3. Can we subtract the sky accurately enough in PFS? (this is the analog of (1) for spectroscopy, but it has some of (2) as well. (we need sub-1% sky subtraction in the continuum)

Questions: Review

1. What is the history of the stellar populations of galaxies ? PFS

2. The history of star formation and the initial mass function (IMF) of stars ?
   HSC and PFS; the IMF if we are lucky.

3. What establishes the dynamics of the baryonic component—in simple terms, $\rho_{DM}(r,t)$ and $\rho_{baryon}(r,t)$, as reflected in sizes and radial profiles? Mostly HSC, with some help (real redshifts) from PFS

4. The history of heavy-element abundances ? PFS

5. The growth and activity of supermassive black holes in galactic nuclei ?
   PFS, sample selection from HSC

6. The effect of environment and history thereof ? HSC for surface densities, PFS for LOS information and dynamics

7. What are the feedback mechanisms which regulate star formation, and how important are they? PFS and some luck.

8. What are the history and driving forces for outflows and infall, and what finally establishes the baryon/dark matter ratio?

Intimately connected with (7). PFS

The prospects are very exciting, but there IS a lot of work to do.

SDSS has told us what the universe is like today in some detail, and SuMIRe can tell us how it came to be the way it is, if we do our work well.

The Beginning

BAO and 3727

Number density of 3727 emitters, L>1e42 erg/sec is 3e-4 at z=1, 8e-4 at z=1.5, probably ~2e-3 at z=2. Number density of L galaxies is 3e-3*

Detection:

z	λ3727	R	f42	fph42	ndet/s	SkyAB	nsky/s
0.7	6335	2700	9.1e-16	2.9e-4	40	21.5	0.7
1.0	7455	2600	3.6e-16	1.3e-4	18	21.0	1.2
1.4	8945	3300	1.6e-16	7.2e-5	10	20.3	1.8
1.8	10435	3800	8.7e-17	4.6e-5	6.4	19.7	2.7
2.2	11925	4500	5.3e-17	3.2e-5	4.5	19.2	3.6
2.5	13045	5200	3.9e-17	2.5e-5	2.5	18.7	3.3