SuMIRe PFS:

A Large Multifiber Faint-Object Spectrograph for SUBARU

Jim Gunn, Princeton University NAOJ 9 Dec 2010

Why a large, deep spectroscopic survey?

There are on the books a large number of deep imaging surveys, all so far using a few broad-band filters. The adherents argue that the distance and SED information which is crucial to doing ANY extragalactic science with these surveys can be obtained with photometric redshifts.

Optimistic accuracies of photoz's place the errors in ln(1+z) at .03 or a little better for red galaxies. Thus we lose

1. Essentially all dynamical information in populations of galaxies.
errors of even 0.02 are velocities of 6000 km/sec; There are no structures with velocity dispersions this large, nor do peculiar velocities get this large.

2. All dynamical information IN galaxies (no velocity dispersions, no rotation information)

Why a large, deep spectroscopic survey? (Cont)

3. All but the very crudest chemical information, and it is yet to be demonstrated that even that is obtainable in any reliable way.

4. All but the very crudest stellar population information.

5. For BAO, loss of the very powerful H(z) determination, and loss of enough LOS information to make an imaging-only survey an order of magnitude less sensitive than a spectroscopic one.

Experience with the SDSS indicates that the synergy between imaging and spectroscopy is profound, and one would like to do a series of SDSS-style surveys at higher redshift to follow the evolution of the galaxy population, as well as emission-line BAO surveys and very faint stellar surveys. Is this possible??

What do we need?

*Suppose we want a spectroscopic survey at high (how high? we will consider this later) redshift, to do an investigation on the galaxy population in several redshift bins on samples which are comparable 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 (z~0.12) is about 0.04 $h^{-3}Gpc^{3}$, 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.

What do we need?

Consider something like this:

Boundaries	0.6-0.8	0.8-1.05	1.05-1.35	1.35-1.65	1.65-1.95	2.0	2.5
Mean z	0.7	0.9	1.2	1.5	1.8	2.0	2.5
Area/.04Gpc^3	110	80	60	50	50	50	50
λ_{3727}	0.63	0.71	0.81	0.93	1.04	1.12	1.30
λ_{4000}	0.68	0.76	0.88	1.00	1.12	1.20	1.40
λ_r	1.07	1.19	1.38	1.57	1.76	1.95	1.64
AB(r,L*)	20.8	21.3	22.0	22.4	22.9	23.4	24.5

So a few tens of sq. deg is a reasonable size scale for such a survey. Probably at least 4 fields, of variable extent to different limits, somewhat larger than 100 sq degrees at bright limits aiming at galaxies with redshifts less than 1, smaller as one goes fainter and more distant. If we step the coverage to keep the volume roughly constant, there will be ~$3x10^5$ bright galaxies per `cell', 1.5 million in all.

These areas are comparable to those in the proposed HSC deep survey, and that survey would be used to provide targets.

Some preliminary technological considerations

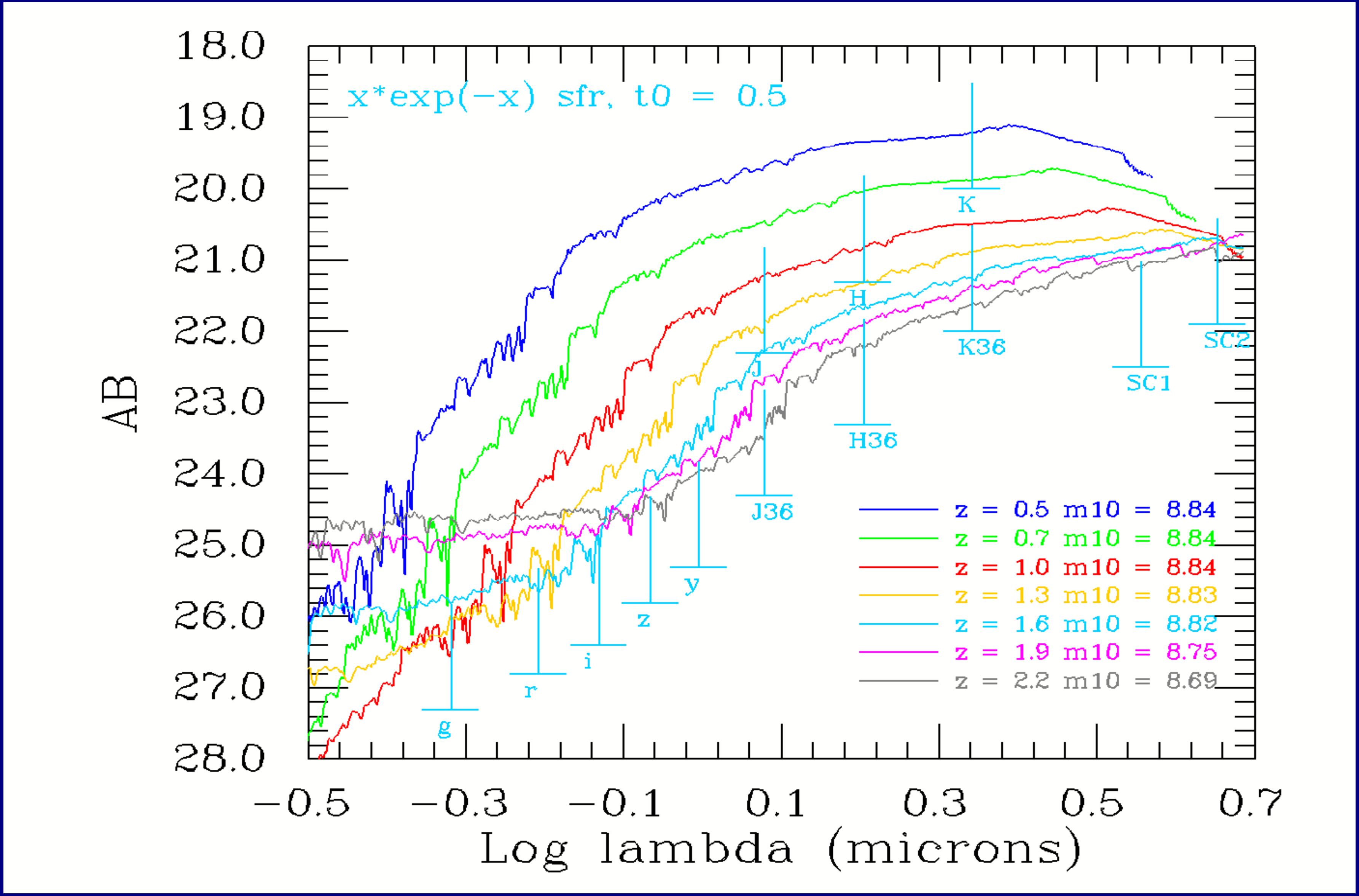
Wavelengths of interest: One needs a handle on the old stellar populations of galaxies. Even at redshift 1, this certainly involves the near IR. 6500A -> 1.3 microns. At redshift 2, 6500A -> 1.8 microns. At the very least, need to reach beyond the 4000A break, 1.2 microns at z=2.

So ideally, we would like to go to at least 1.8 microns. It becomes very difficult beyond that because the thermal background becomes very high. Furthermore, at 1.8 microns the spectrograph must be cooled, and will be much more expensive than a room-temperature instrument. We consider here an instrument which goes from 3800A to 1.3 microns, which can be constructed with ordinary optical materials and, if the detector cutoff can be tailored sufficiently well, can be entirely at room temperature except for the detector and the lenses immediately in front of it.

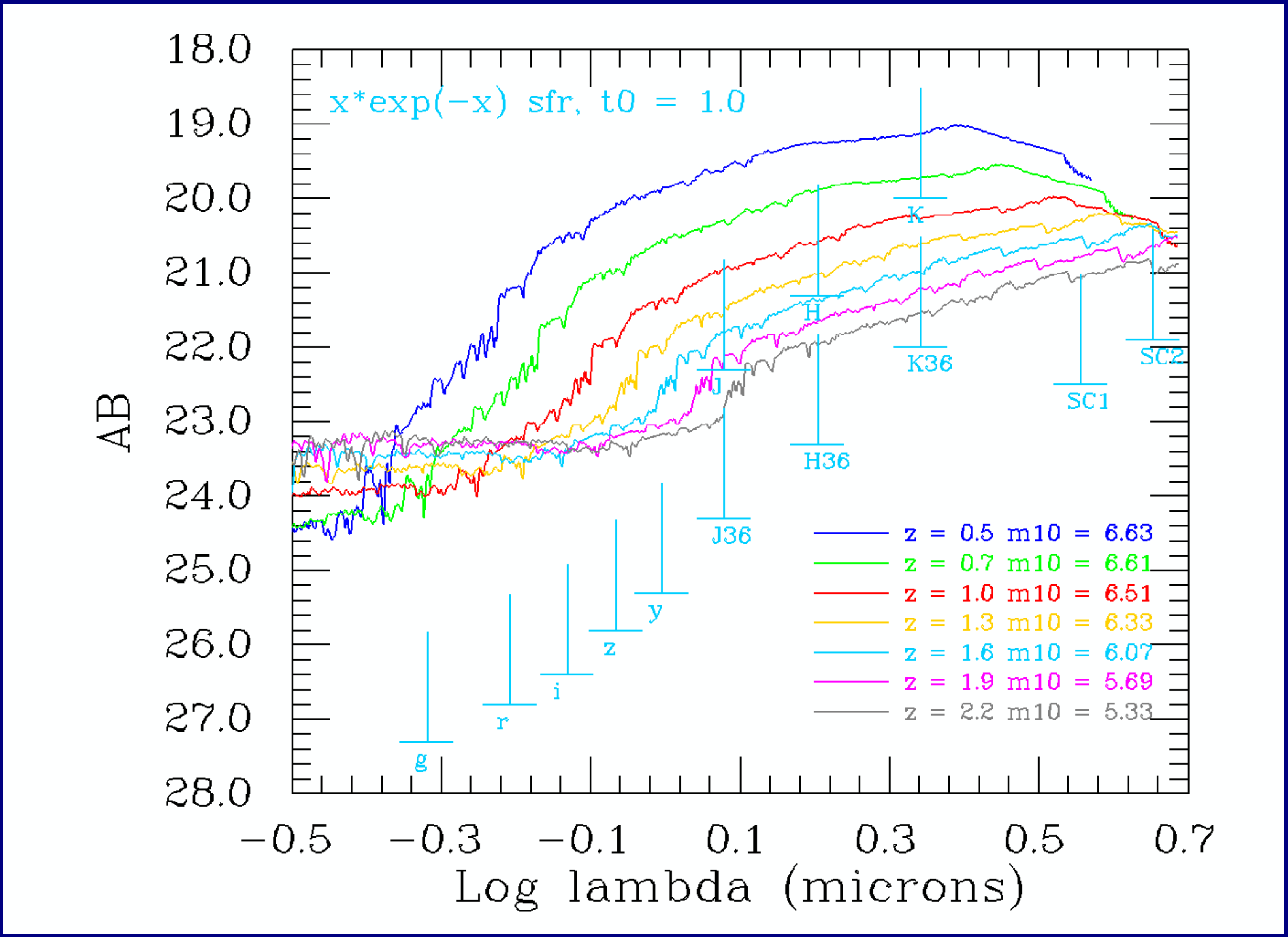
THERE IS NO REDSHIFT DESERT WITH THIS SPECTROGRAPH:
3727: 0.17 -> 2.48 Ly-a 2.13 -> 10.7!

How deep do we need to go?

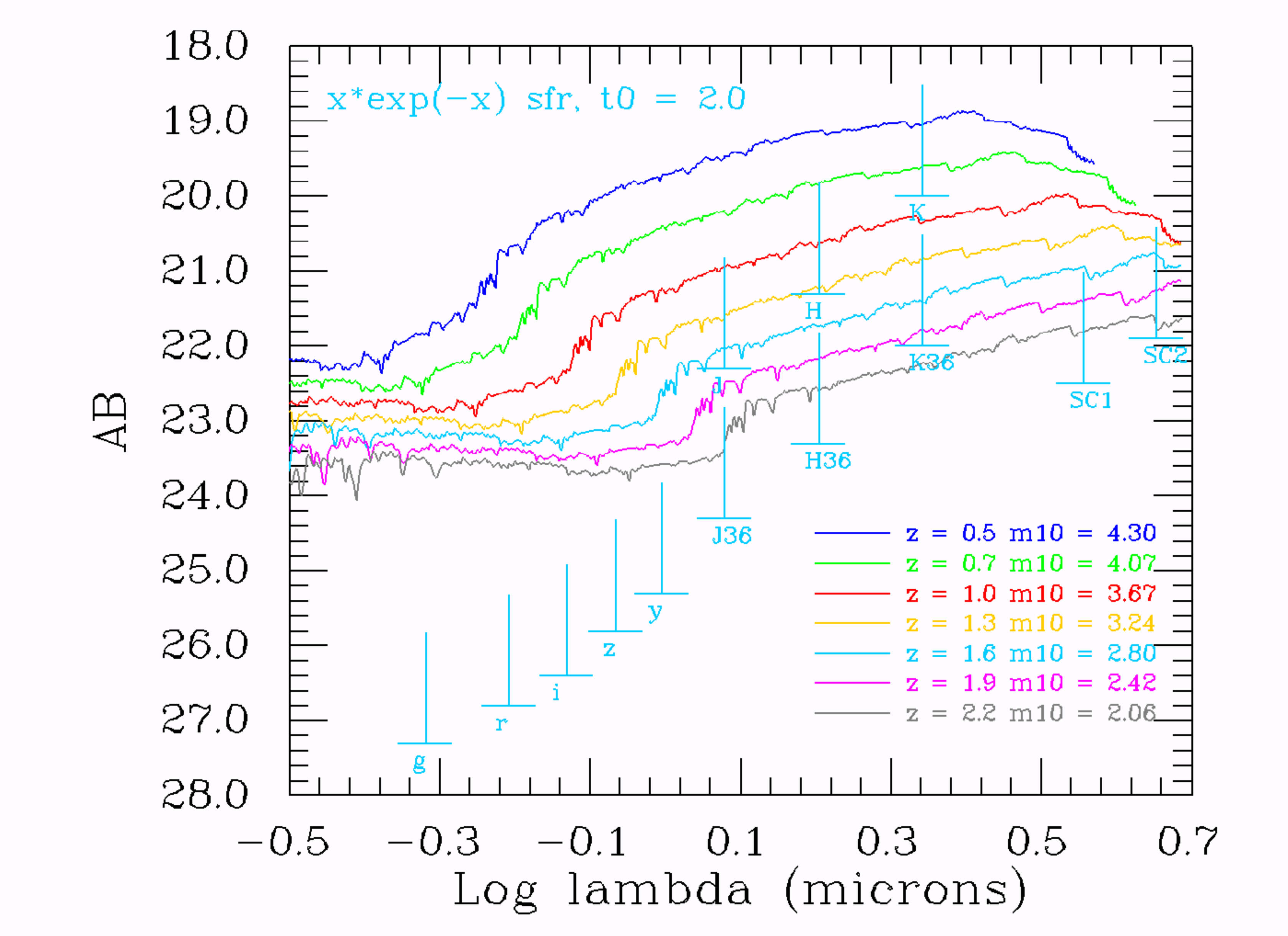
How deep do we need to go??



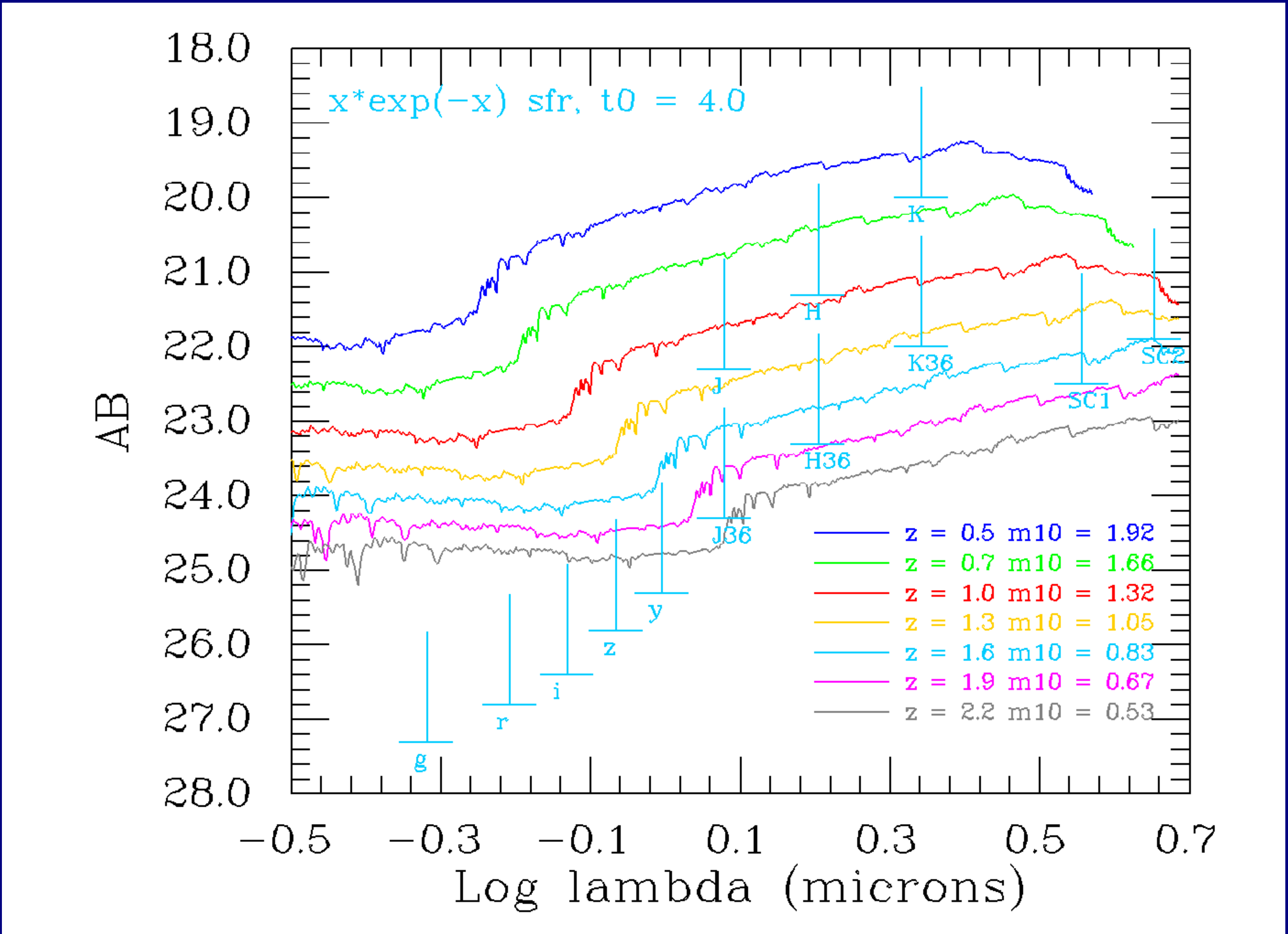
*SEDs for a galaxy which is L*i today at redshifts between 0.5 and 2.2, showing Subaru shallow survey limits, limits for half-hour exposures with VISTA, and 5 minute exposures with IRAC, for a galaxy with a very short characteristic SFR time, 0.5 Gyr.*



SEDs for a galaxy which is L*i today at redshifts between 0.5 and 2.2, showing Subaru shallow survey limits, limits for half-hour exposures, with VISTA, and 5 minute exposures with IRAC, for a galaxy with a short characteristic SFR time, 1.0 Gyr.



*SEDs for a galaxy which is L*i today at redshifts between 0.5 and 2.2, showing Subaru shallow survey limits, limits for half-hour exposures, with VISTA, and 5 minute exposures with IRAC, for a galaxy with a moderate characteristic SFR time, 2.0 Gyr.*



*SEDs for a galaxy which is L*i today at redshifts between 0.5 and 2.2, showing Subaru shallow survey limits, limits for half-hour exposures, with VISTA, and 5 minute exposures with IRAC, for a galaxy with a longish characteristic SFR time, 4.0 Gyr.*

Magnitude Limits:

We thus need to reach AB limits at 1.2 microns of about 23.5 and at 1 micron of 24.5 for blue galaxies which are the progenitors of L* galaxies today at z=2 (but this is a little optimistic because of merging)

Can we do this?

More Technology: The Sky

Working in the IR is incredibly difficult because of the OH airglow, but the sky is reasonably dark between the lines. At low resolution, however, the lines overlap and there IS no `between the lines'.

IR detectors are incredibly expensive—current prices on good 4K^2 HgCdTe devices, 15 micron pixels, 70+% QE, very low dark currents, ~15 electrons read noise per nondestructive read, is ~$700K.

Wavelength coverage vs resolution is thus a crucial tradeoff. Can we cover, say, the 1.0-1.3 micron band at a resolution which does not result in a ridiculously expensive instrument?

We can model the cumulative fraction of pixels which are fainter than some limit as a function of resolving power. Will see that resolving power is dictated by detector size, camera focal ratio, and fiber size.

Resolving power and the Sky

We need high resolving power to work between the OH lines.
If we build a 3-channel spectrograph , using 1.1 arcsecond fibers and 4K x 4K detectors, we could do something like this:

	wavelength	R	50%	60%	70%
	4500	1890	22.4	22.3	22.0
blue(0.38u->0.65i)					
	5500	2380	21.6	21.5	21.4
	7000	2350	21.36	21.5	21.3
red(0.65u->1.0u)					
	9000	3200	20.7	204	19.8
	10500	3800	20.4	19.5	18.6
ir(1.0u-> 1.3u)					
	12500	4800	20.1	18.9	17.4

What would a system with these parameters look like?

For Subaru,

F/2.24 with HSC corrector. Scale 89μ/arcsec

Need (?) to transform f/ratio with optics or tapered fibers to something significantly slower than f/2.4

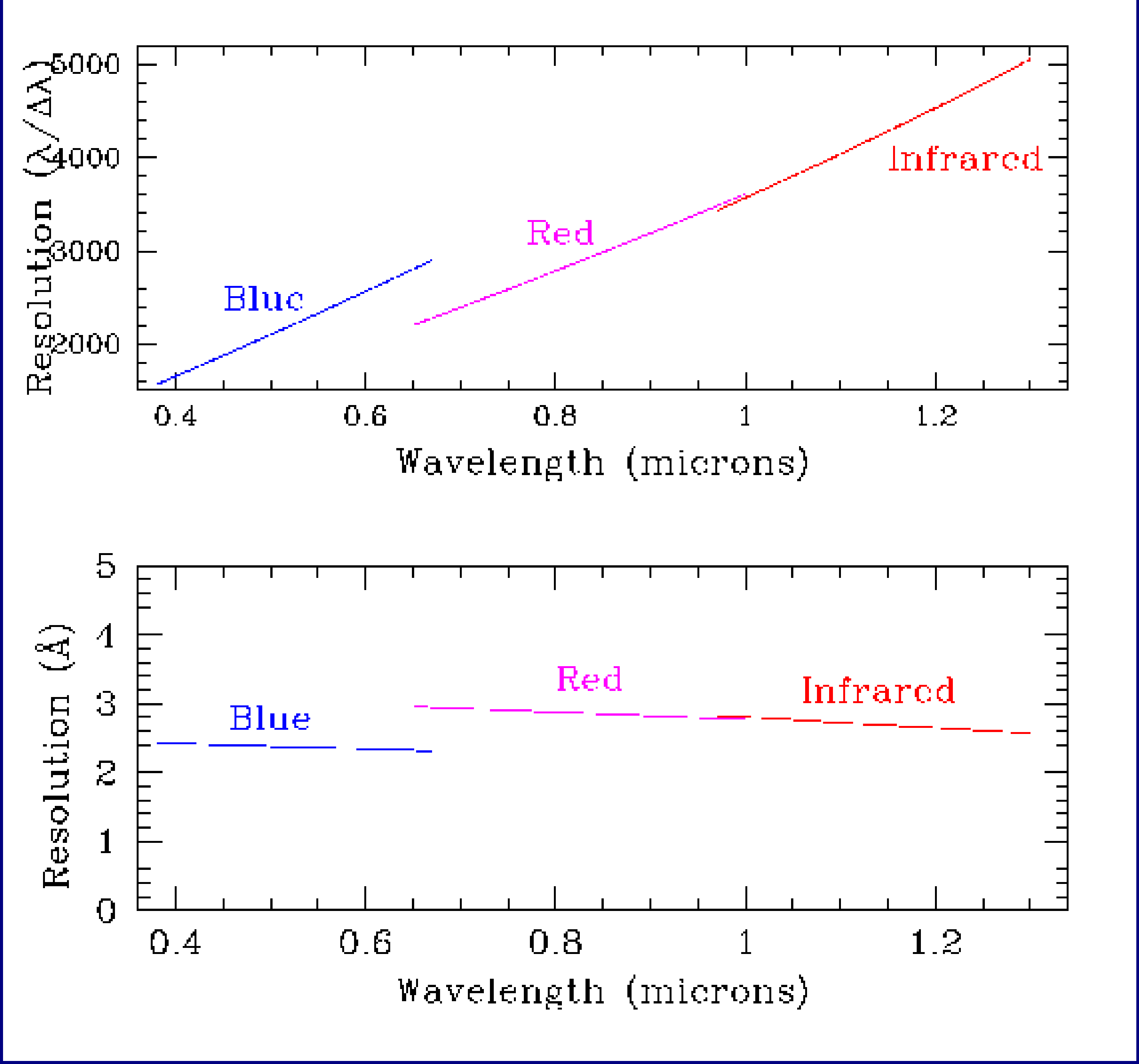
Best:
100u -> 128u : 2.24 -> 2.85 (2.50 w/FRD)
OK:
100u -> 200u : 2.24 -> 4.5 (3.6 w/FRD) (faster is better)

1.1 arcsec -> 9 kpc for z ~ 0.7 or greater.
SDSS has 3 arcsec fibers; z=0.12 -> 7 kpc,

f/1.05 camera, f/2.85 collimator; fiber projects to ~54u
fwhm ~ 47u, 3.13 pixels

1200 resolution elements on 4K pixel detector... sets resolution

Resolving Power vs Wavelength for 3-channel PFS



Sensitivity

Assume throughput of 25%. Normalize to AB=22.5, 1 hr (3x1000s) exposures

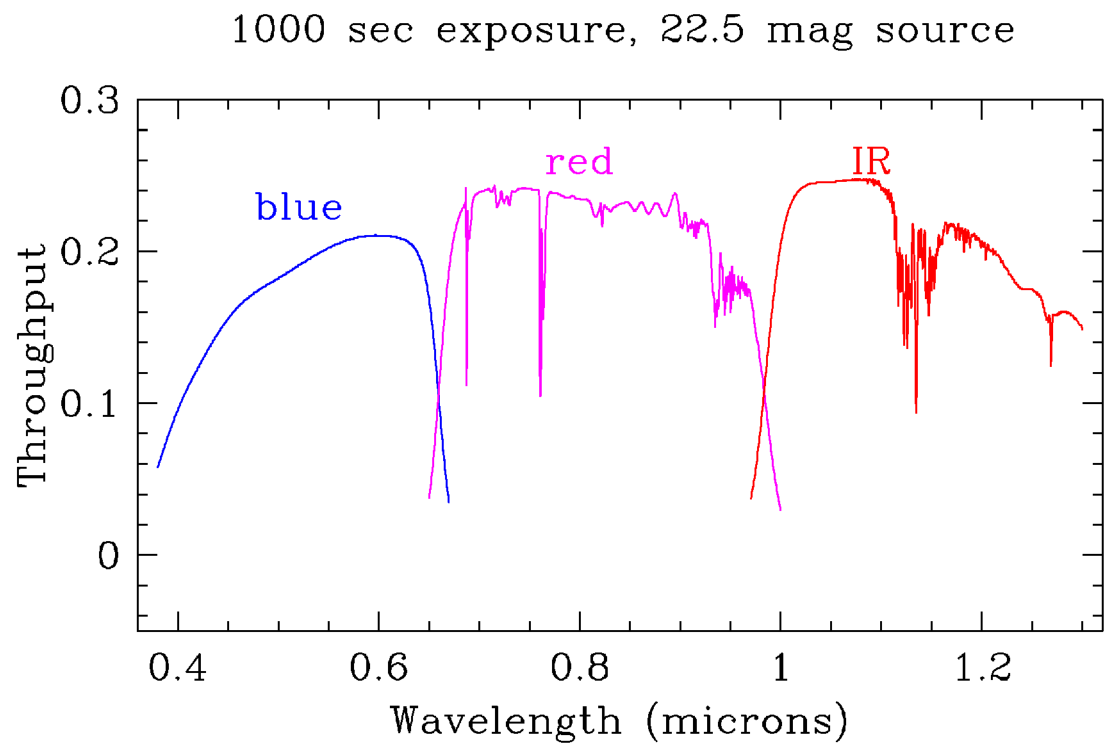
In BLUE, (R=2400) get 300 electrons per V pixel,
400 electrons from sky; S/N ~ 14 per pixel
For GALAXIES, degrade to R=1000, S/N ~ 20, 5 at AB=24

In RED, (R=3100) get 300 electrons per V pixel
800 electrons from sky, S/N ~ 8.5 per pixel
For GALAXIES, at R=500, S/N ~ 20 , 5 at AB=24

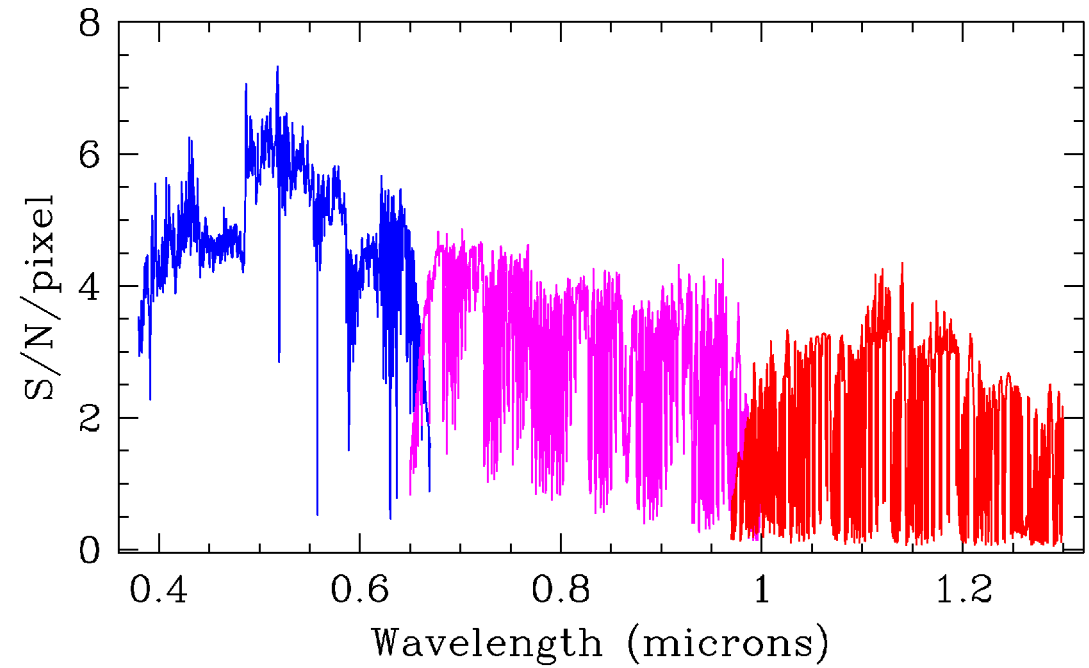
In IR, (R=4500) get 160 electrons per V pixel
300 electrons from sky, S/N ~ 5 per pixel
For Galaxies, at r=300, S/N ~ 20, 5 at AB=24

MUCH shorter times for BAO using 3727

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



Per-pixel S/N in 1000s at 22.5 (R=500 is ~30 pixels in IR)



How Long? How Many Fields?

1 hour per field, 2000 objects, 2000 objects/hr. 1.5 million spectra, 700 hours, 90 good nights, 20 fields, 37 visits/field. Field size does not matter; only number of fibers.

BAO survey?

Shorter; brighter objects, 1 visit per field, 30min exposures, 2000 sq degrees, 500 hours, 70 good nights, ~2 million spectra, ~4 Gpc^3

$SFR=(t/t_0)exp(-t/t_0)$

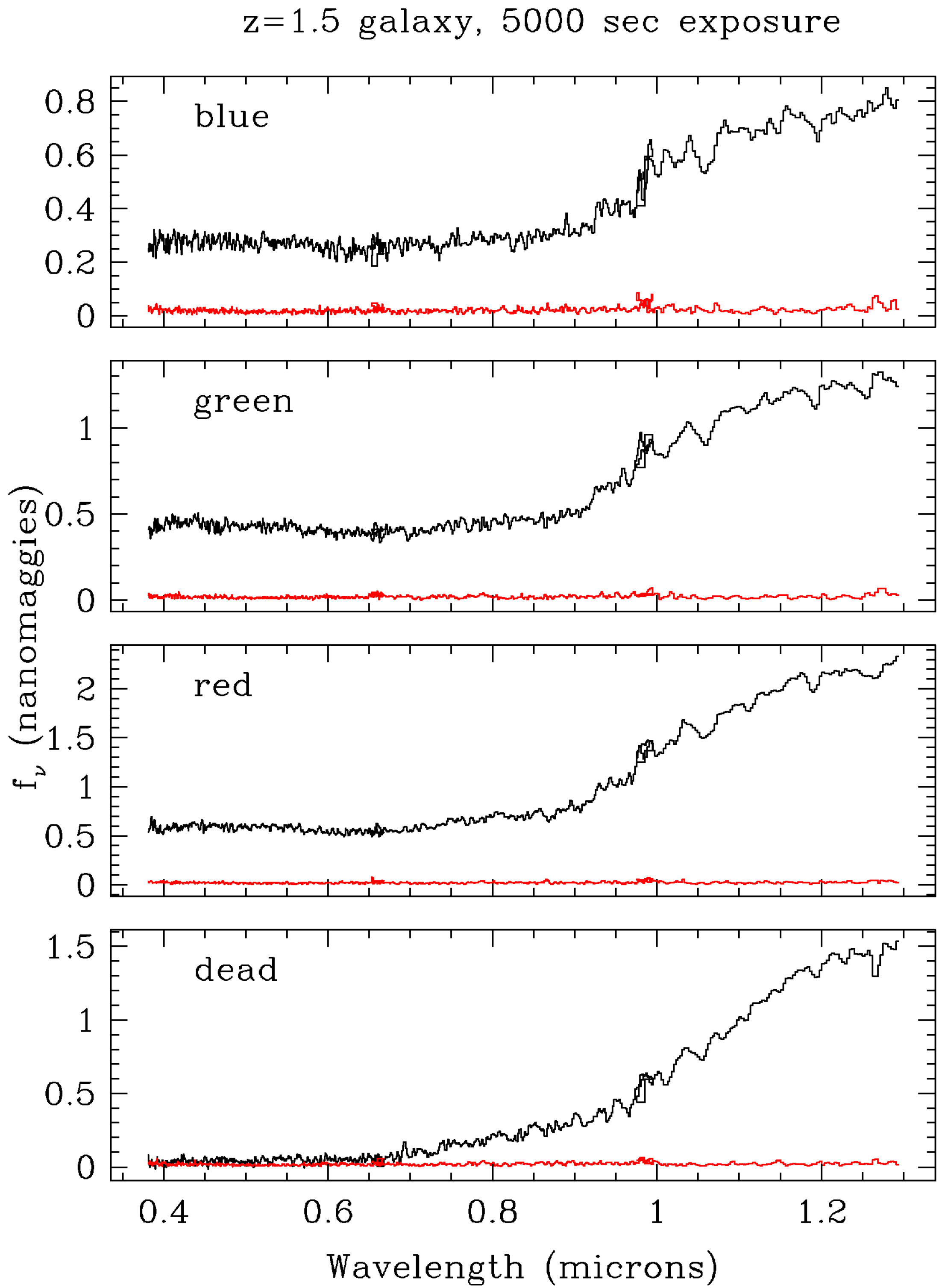
t_0= 4Gyr

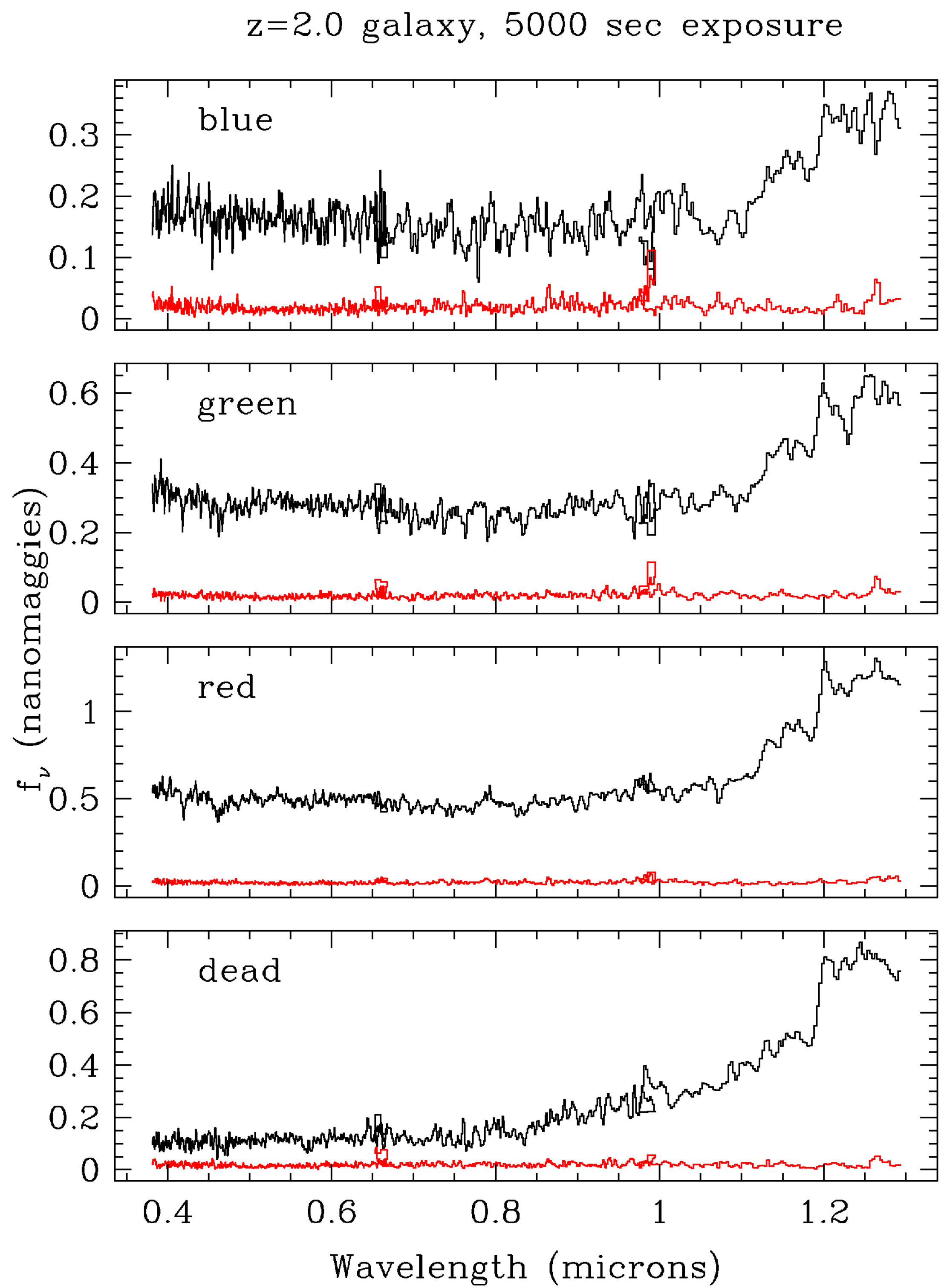
t_0= 2.8Gyr

t_0= 1.6Gyr

t_0= 0.5Gyr

R=400,300,200 B, R, IR

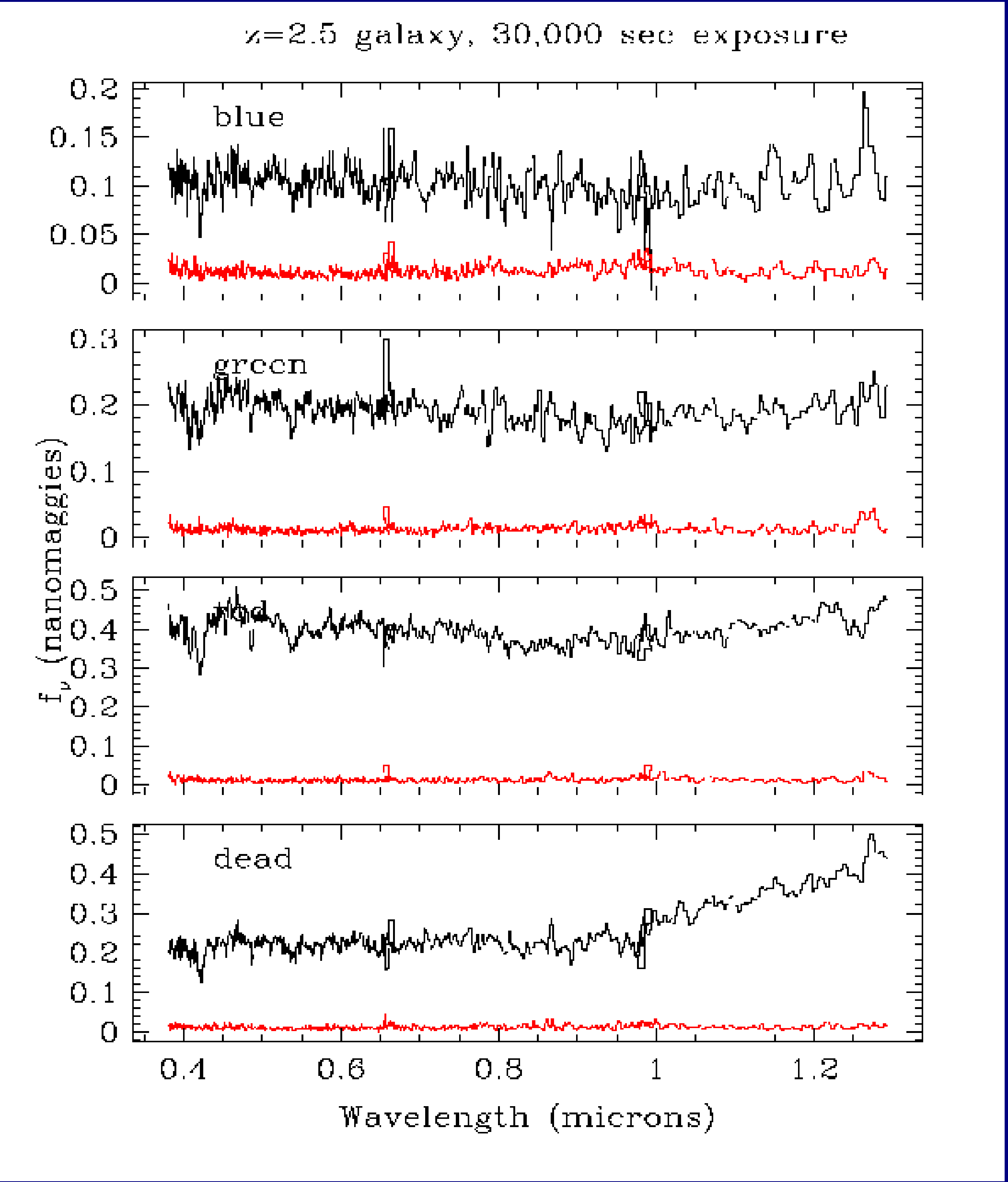




z=2.0 galaxy, 5000 sec exposure
blue
green
red
dead
f_ν (nanomaggies)
Wavelength (microns)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1
1.2

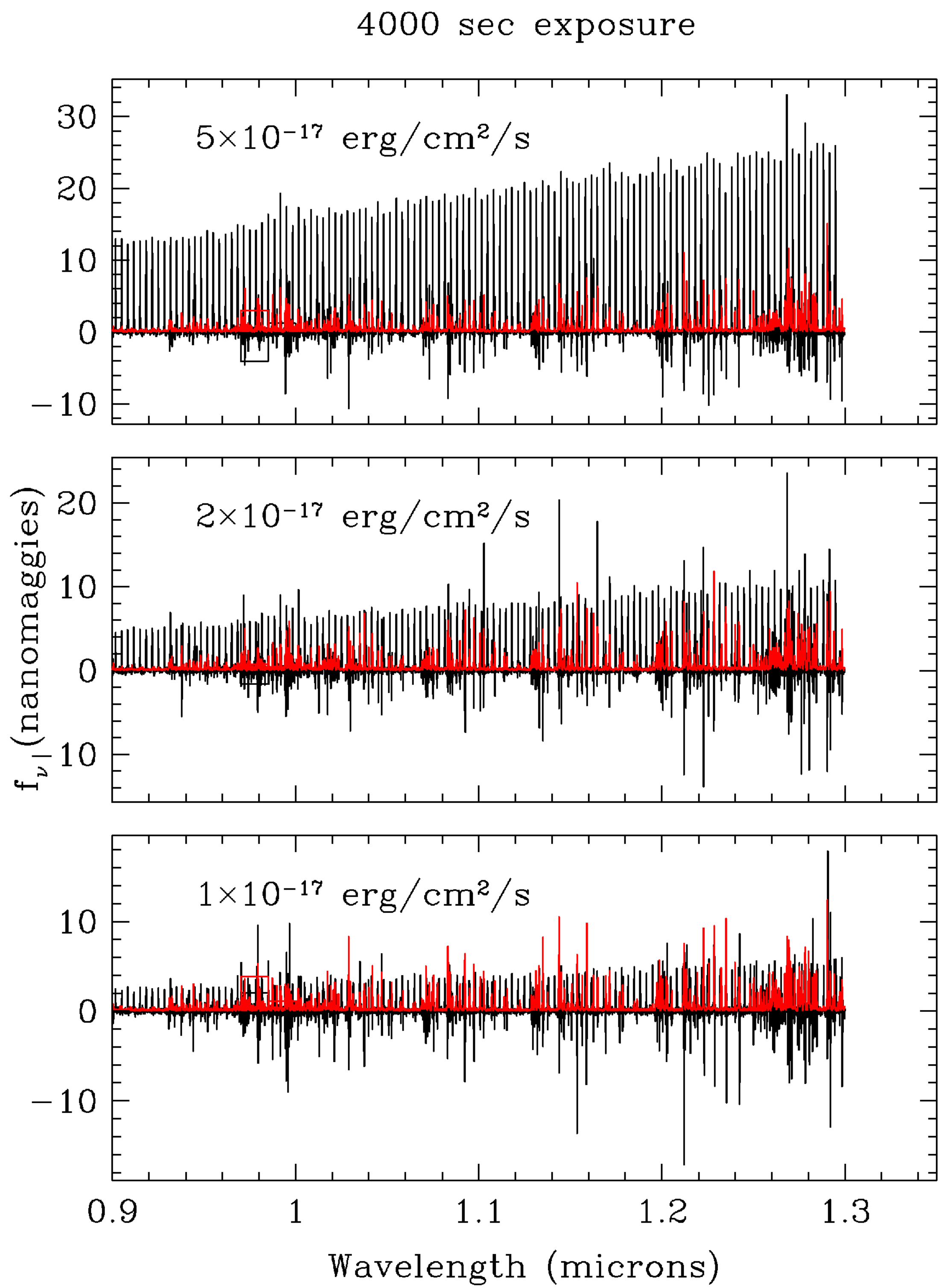
z=2.5; 4000A break beyond end of FSR; must rely on emission

3727 at 1.30u, Ly-a at 4250



These are simulated spectra with lines of constant cgs flux every 33 A through the spectrum

At z~2, the space density of 3737 sources with L~1e42 erg/sec is comparable with L galaxies; the flux is 4e-17*



The Spectrographs

Desiderata:

1. High Throughput

2. As wide a wavelength range as is practical

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. This is our chance to make the most powerful (and useful) spectrograph in the world. Let us use it.

Optics – Camera Speed is Everything

1. The facts of life:
   Subaru is an 8.2m telescope
   $d_{detector} = D_{tel} f_{cam} \gamma''/206265 = 40u\ f_{cam} \gamma''$

   So for a 100u fiber, 1.13", the spot size is 45u f_{cam}

2. Detector manufacturers do not like big pixels, so all pixels in modern detectors are 15u.

3. So f/1 gives a resolution of 3 pixels. Any faster is probably too fast, any slower wastes detector real estate AS THE SQUARE. Fewer fibers, fewer resolution elements

4. $R = \lambda c/d\lambda = (\lambda c/D\lambda)\ N_{pix}/N_{res}$; $N_{res}=d_{detector}/d_{pixel}$ so $R \sim 1/f_{cam}$

5. Fiber FRD, lack of telecentricity makes these worse; to get all the light, focal ratio of collimator must be smaller, need even faster camera by ratio of ideal to real collimator f/ratio

Optics – Simplicity is Almost Everything Else

1. Want few elements to minimize light loss, cost

2. Simplest fast camera is Schmidt. One aspheric, two refractive elements, simple spherical mirror.

3. Disadvantage: Detector is at prime focus of mirror, IN THE BEAM.
   => Beam must be large.
   How large? 4Kx4K 15u detector is 62mm square
   250mm beam has 8% obscuration, OK. Camera IS the dewar.

4. Why 250mm??

5. Kaiser can make superb 280mm VPH gratings in one shot, no bigger. Angles such that 250mm beam is OK. Cost ~$40K

Bad news: Simple Schmidt does not make good enough images.
Baker-Nunn lesson: First-order correction with aspherics on both surfaces of thick corrector is OK. Canon can make and test such surfaces.

The spectrograph.

1. Need R ~ 3000 or greater in the red (.7->1u) and 4000 or greater in the IR (1->1.3u) to work with the sky OH.

2. Science (?) says R~2000 in the blue (lessons from SDSS).

3. To go from ~4000 to 1.3u requires 3 channels to meet the resolution requirements with an f/1 camera and 1" fibers with 4K^2 15u pixel detectors.

4. Propose 3 channels:

3800 – 6700A	*R=2050 at center*
6500 – 10000A	*R=2950 at center*
9700 – 13000A	*R=4350 at center*

f/1.05 camera f/2.8 collimator, (best) or f/1.05 camera, f/3.7 collimator. (OK)

Requires f/ratio transformer; more later

The Spectrograph

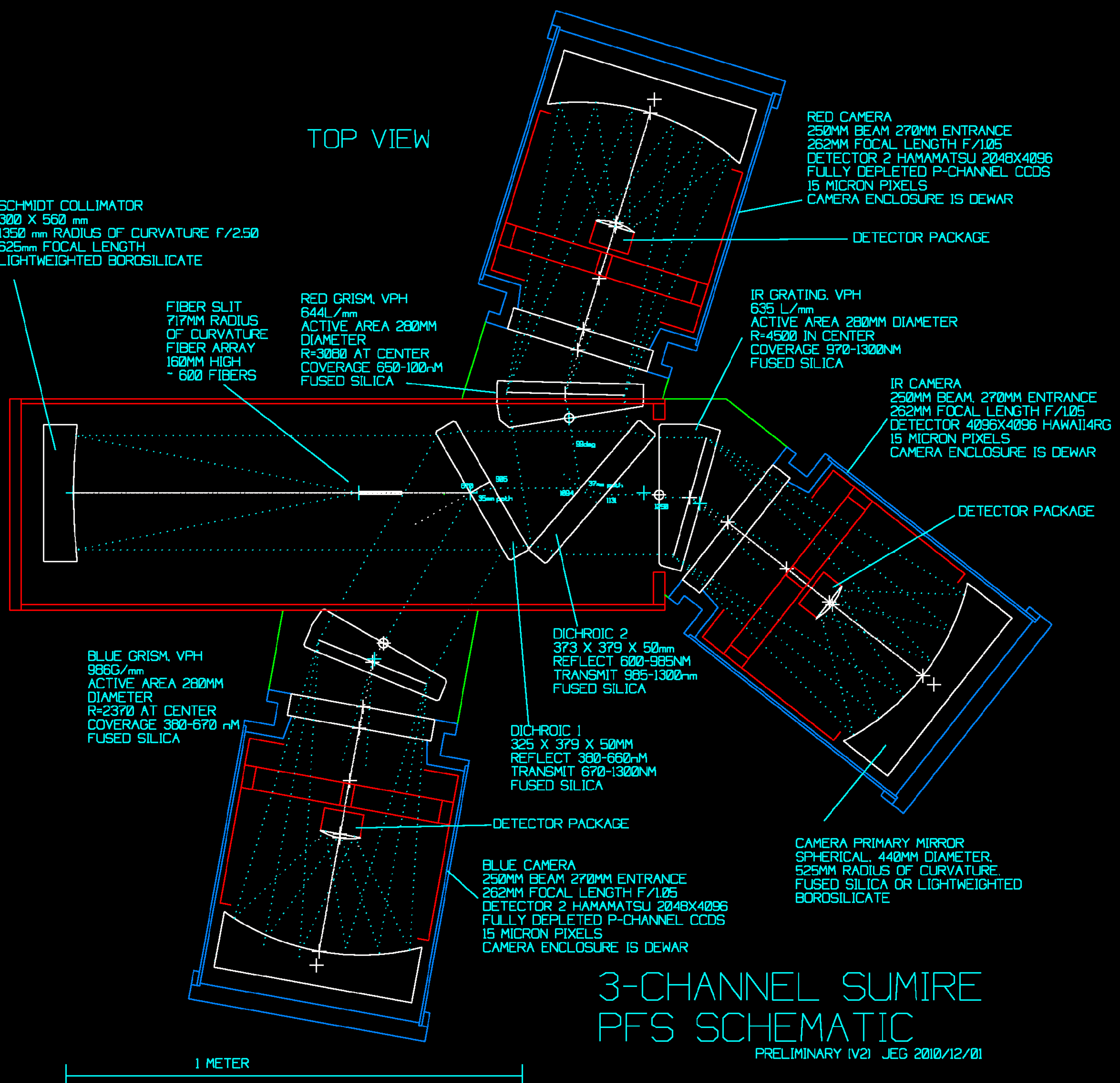
These 3 cameras, optically almost identical

Schmidt collimator, f/2.5 from fiber with ideal f/ratio 2.8. Microlens f/ratio transformer, 100u at telescope focus, 128u in long harness and in spectrograph. (Use SDSS connectors at PFU)

Two dichroic splitters:

first at 6600A, reflects 3800 – 6600, trasmits longer
second at 9850A, reflects 6600 – 9850, transmits longer

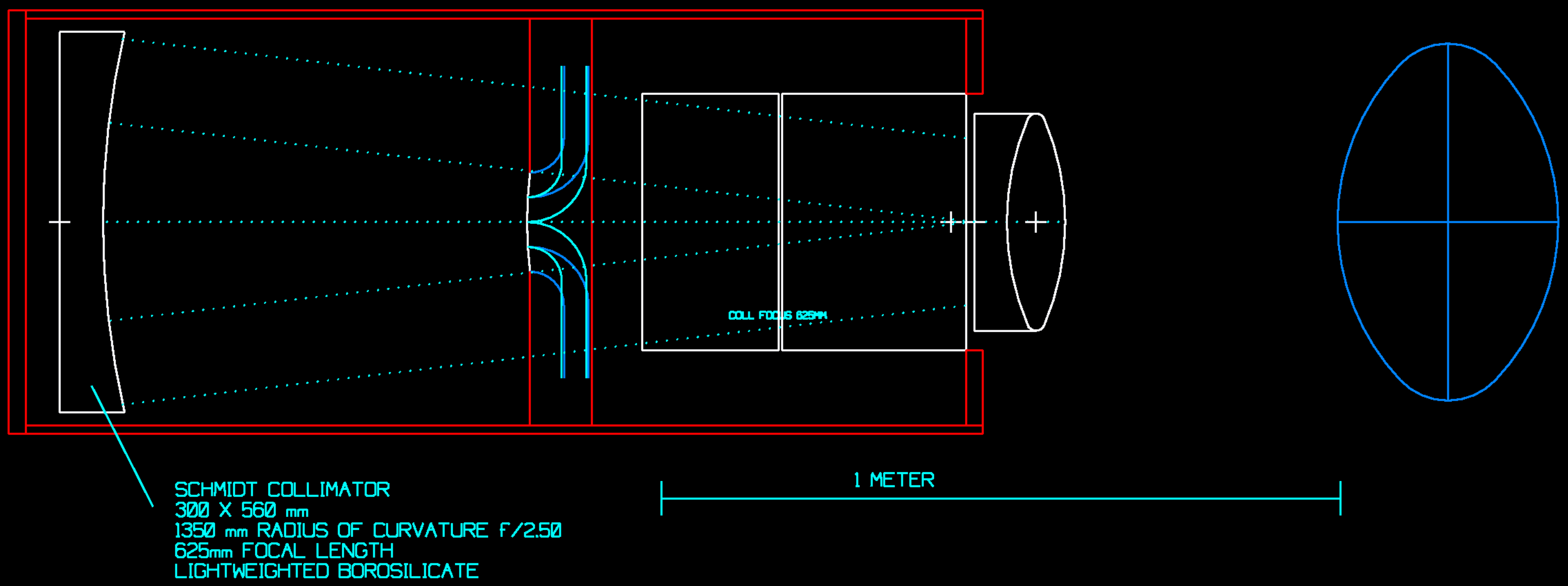
Looks roughly like this



3-CHANNEL SUMIRE PFS SCHEMATIC

PRELIMINARY (V2) JEG 2010/12/01

SIDE VIEW, MAIN BOX STRUCTURE ONLY



Blue Channel

Room to swing dewar to larger angles. Can replace grating with higher density one to reach R~5000 or perhaps even 8000 over blue range 3800-6500.

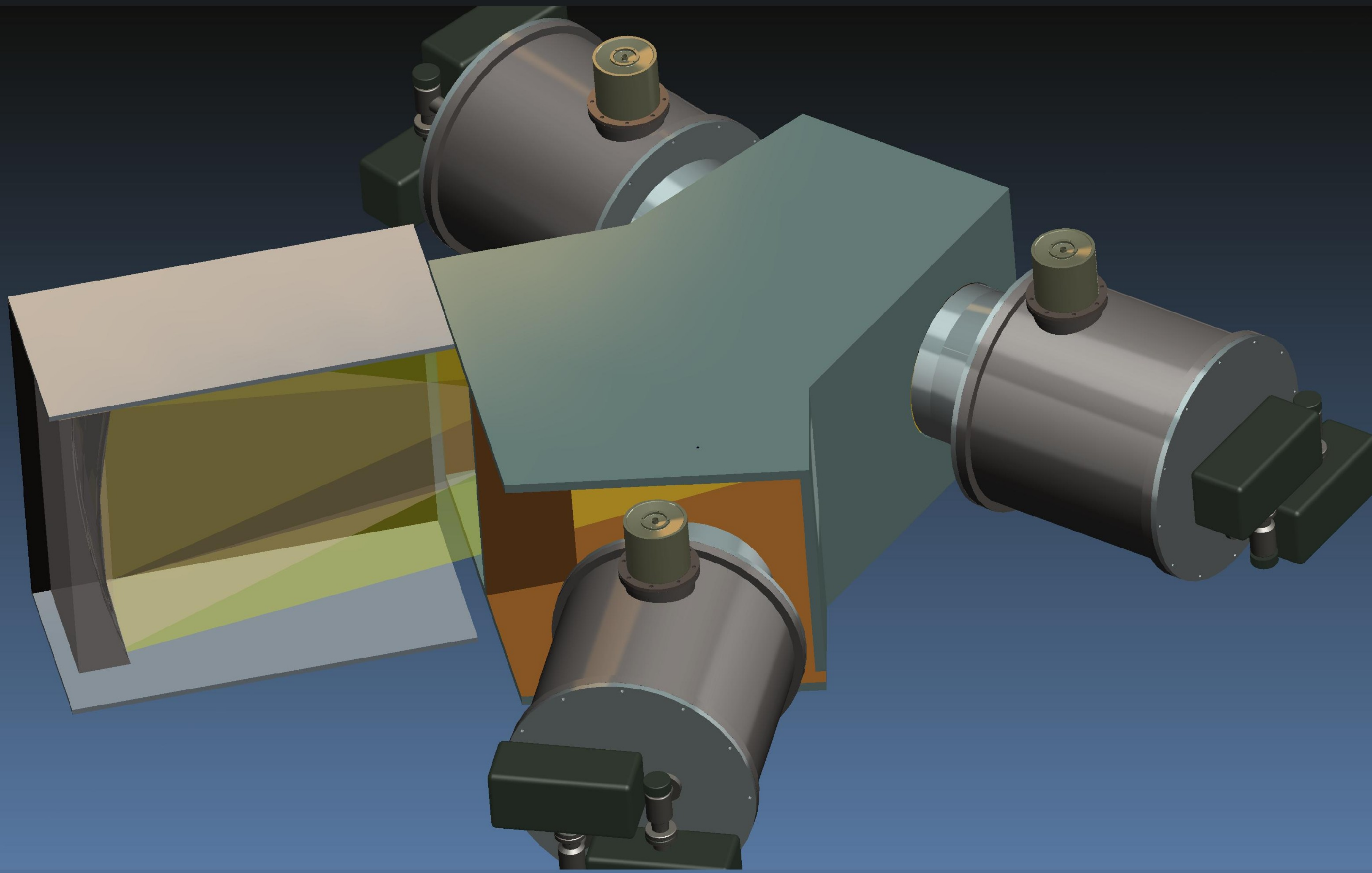
The Spectrograph

600 fibers per spectrograph with 3 pixel (45u) spacing

So 4 spectrographs.

Simple bolted or welded rectangular aluminum box with internal baffles/gussets.

Might look like this physically:

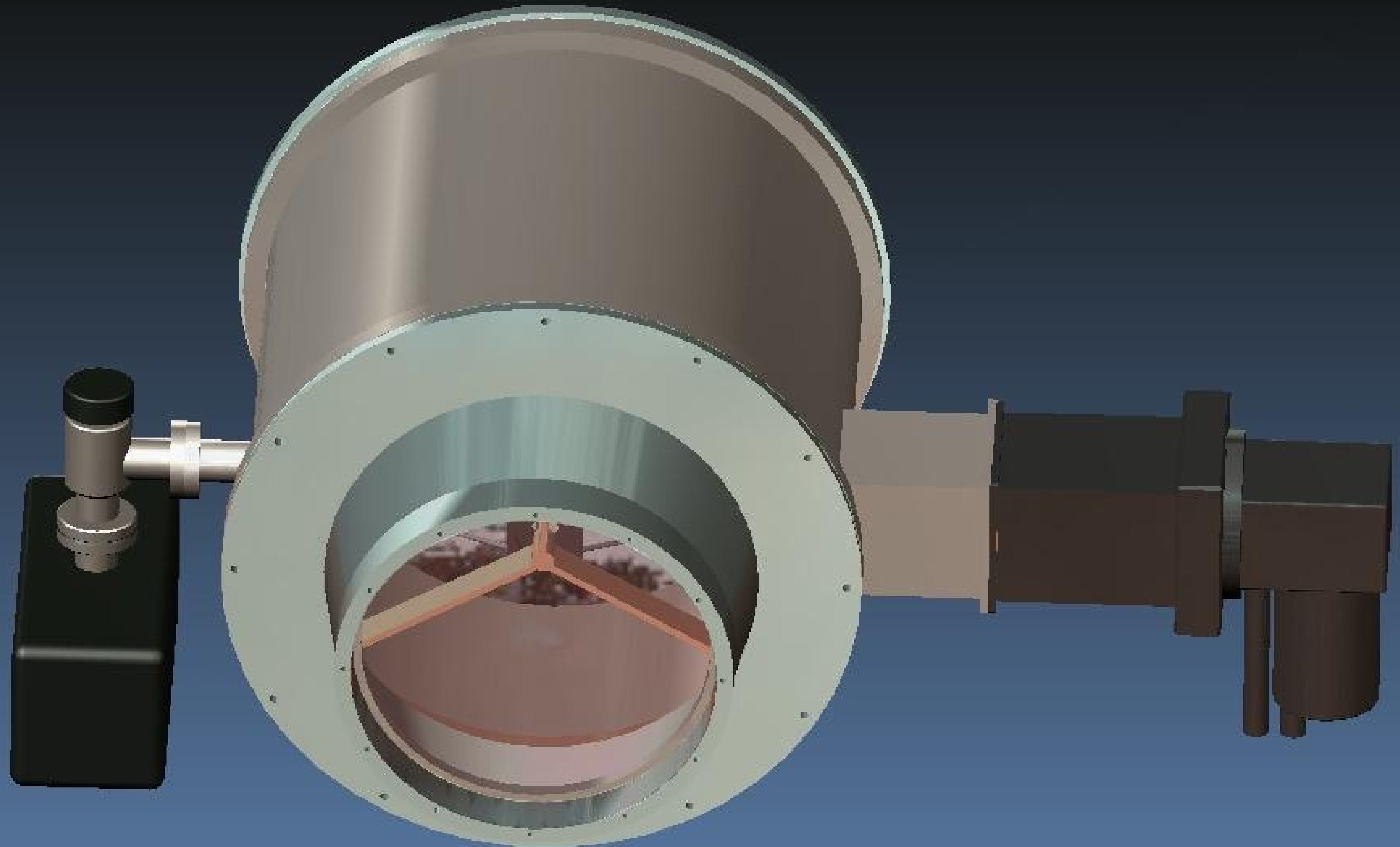


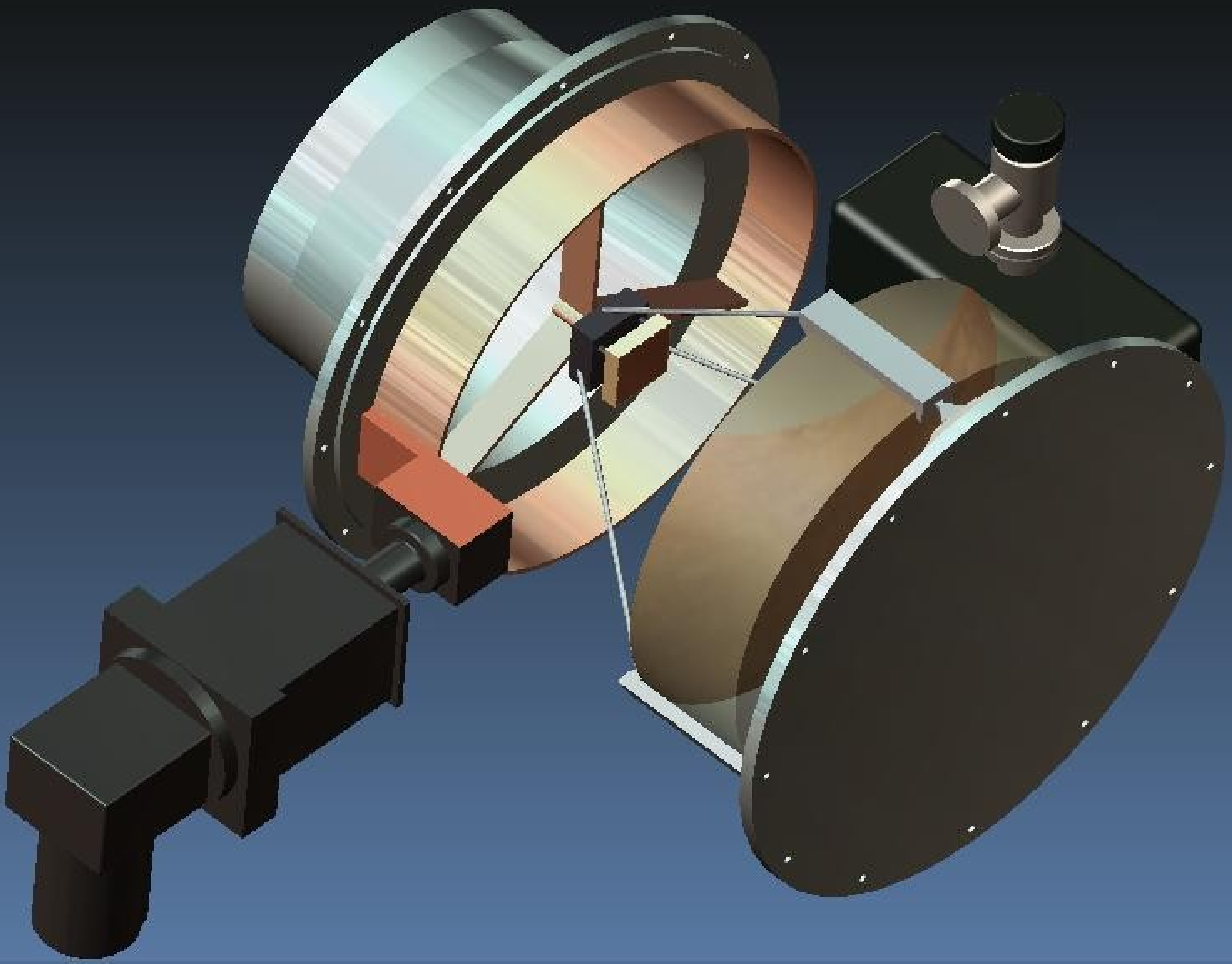
The Camera/Dewar

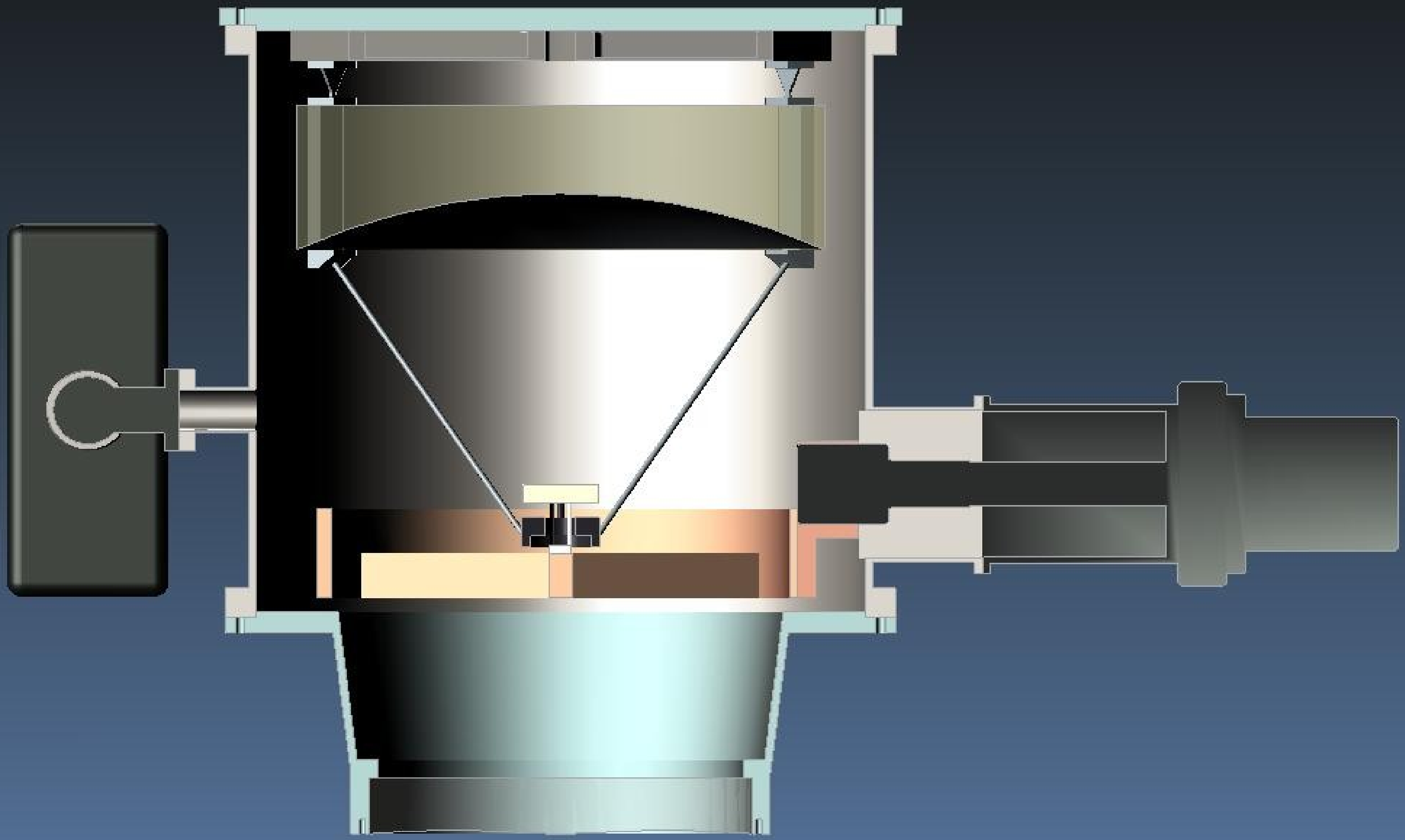
Performance: 25u images with crude hand optimization. Baker-Nunn gives 12u images over curved field, no reason to expect worse here.

Camera body is cryostat; Double-sided Schmidt corrector is vacuum window. Proven design.

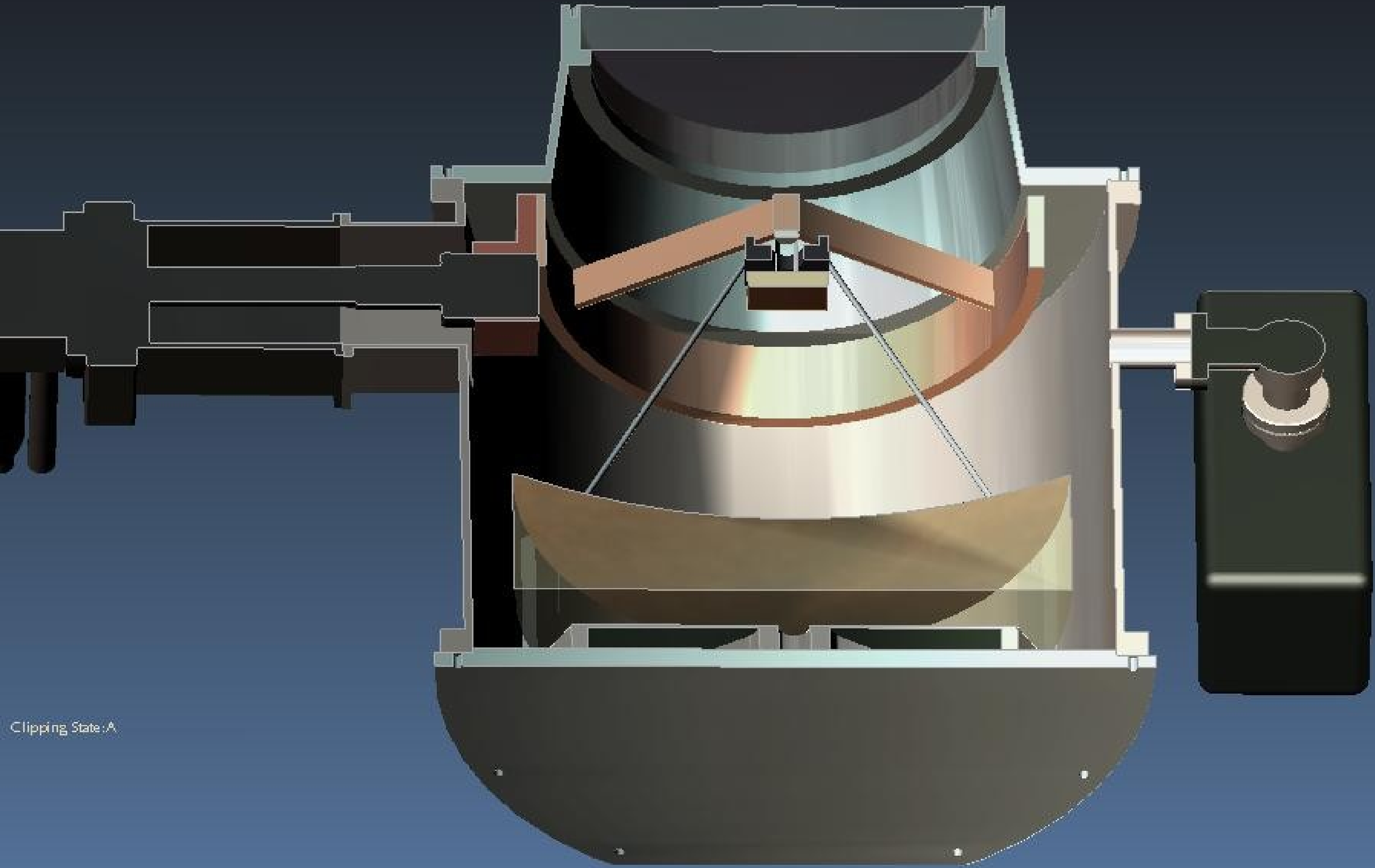
Looks like this







Clipping State:A

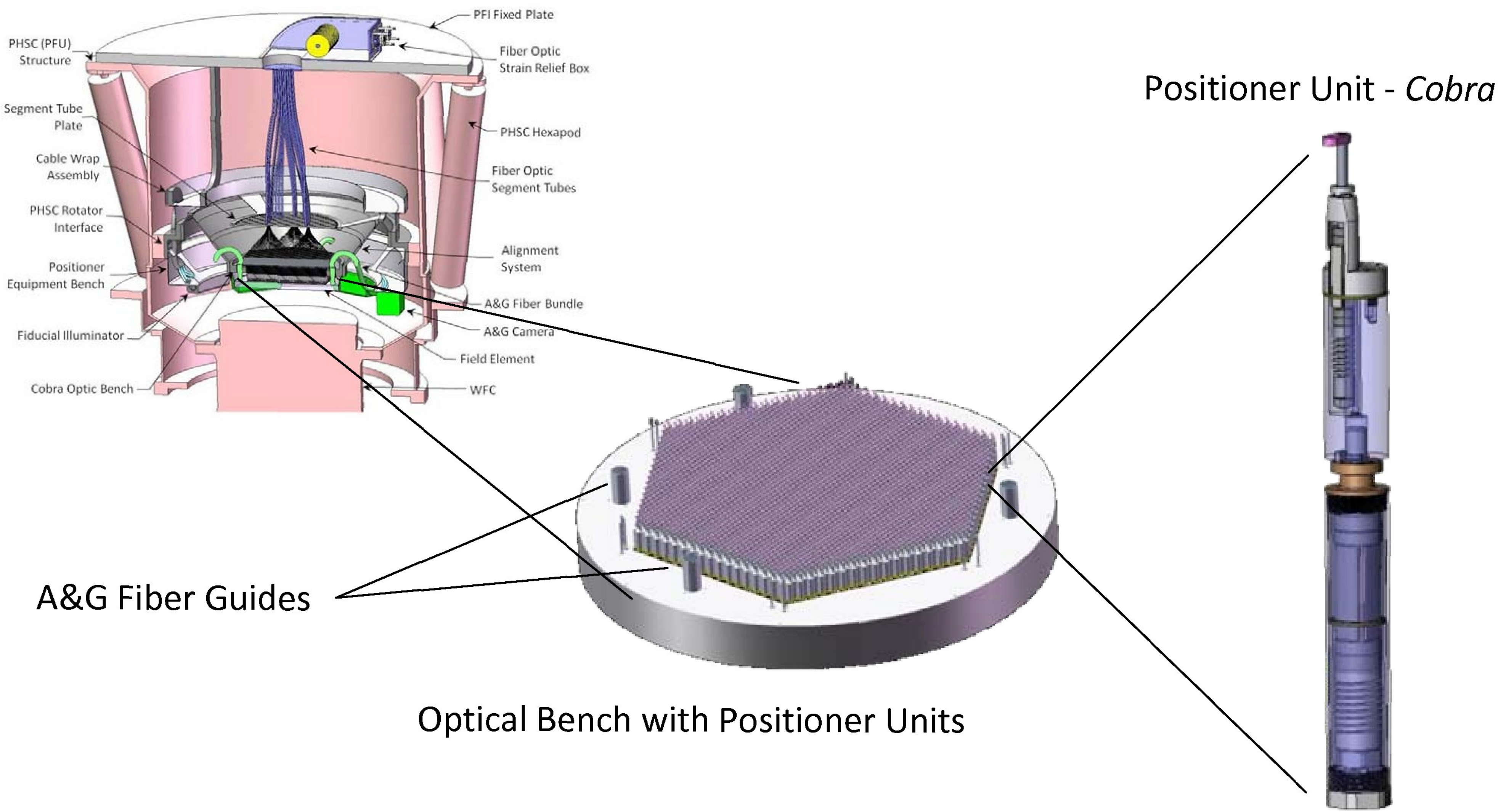

Clipping State:A

Cost

Spectrograph only:	
Box	30K
Slit assy and fiber hdwe	30K
Collimator	40K
Dichroics	20Kx2
Gratings	40K x 3
Grism/wedge/corrector	40K x 3
	380K
Cameras:	
Primary mirror	20K
Corrector	40K
Field Flattener	2K
Pump	2K
Cooler	150K
Dewar	30K
	240Kx3
Detectors:	
CCDs	40K(?)x4
IR	700K
	840K

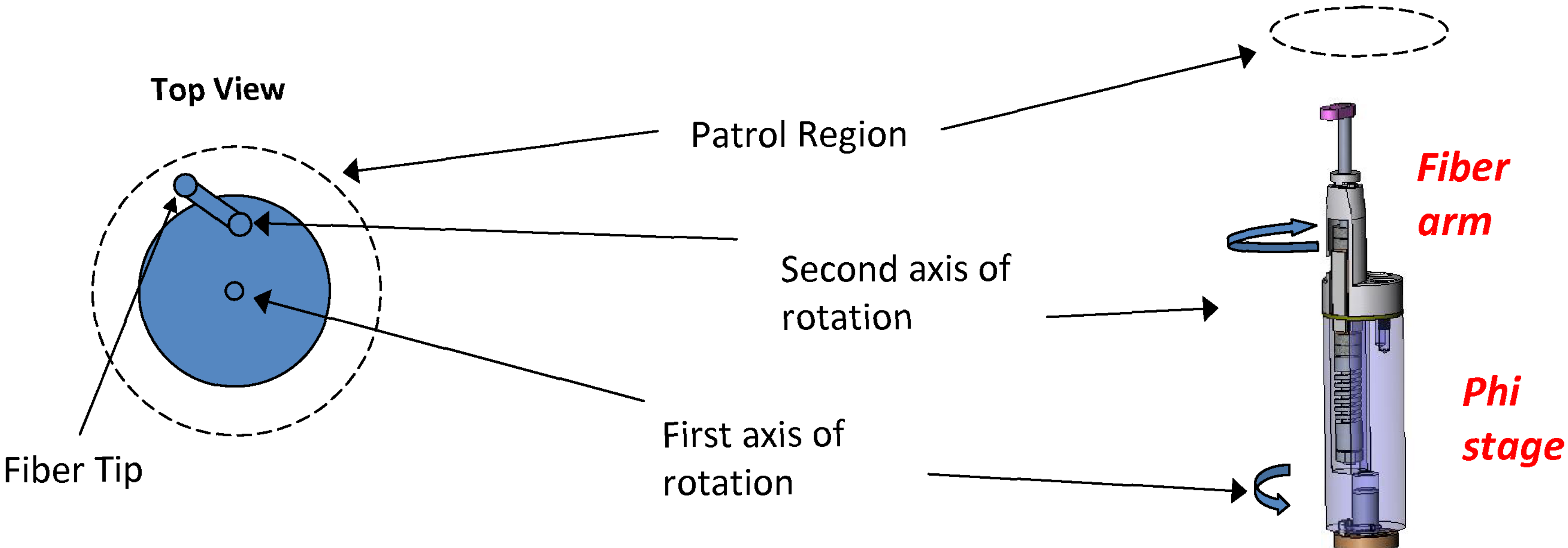
total $2.0M per spectrograph

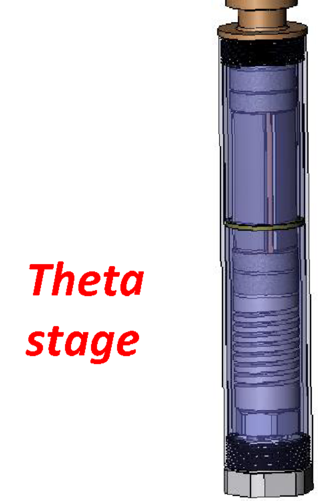
PFS Positioner



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

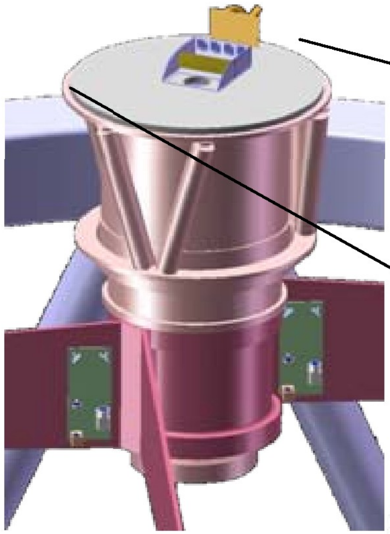
Positioner Element – "Cobra"



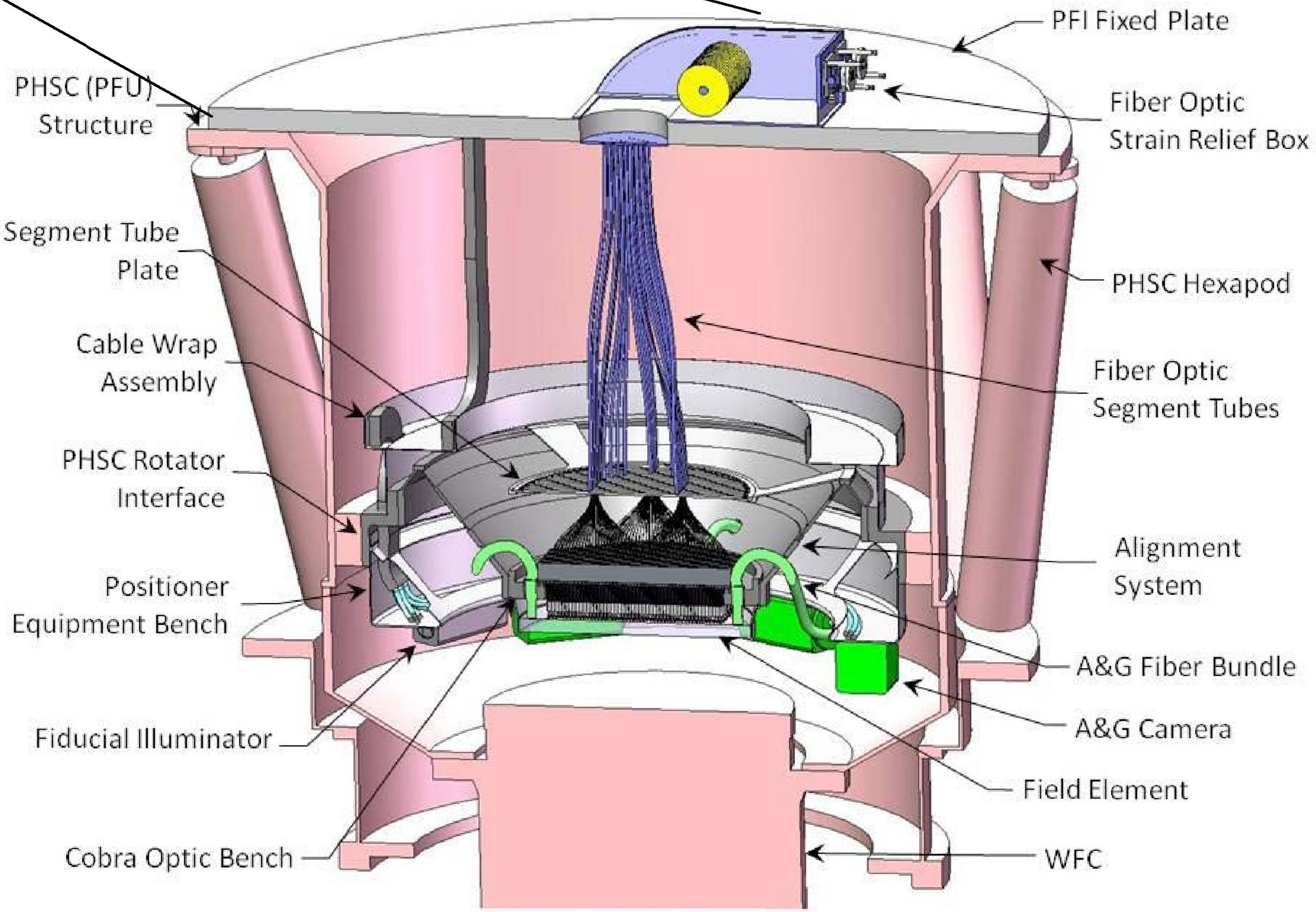


- 7.7mm diameter, theta-phi system positioning within 9.5mm patrol area to 5 μ m precision.
- Optical fibers mounted in "fiber arm" which attaches to upper postioner axis:
- Fiber runs through the center of the positioner

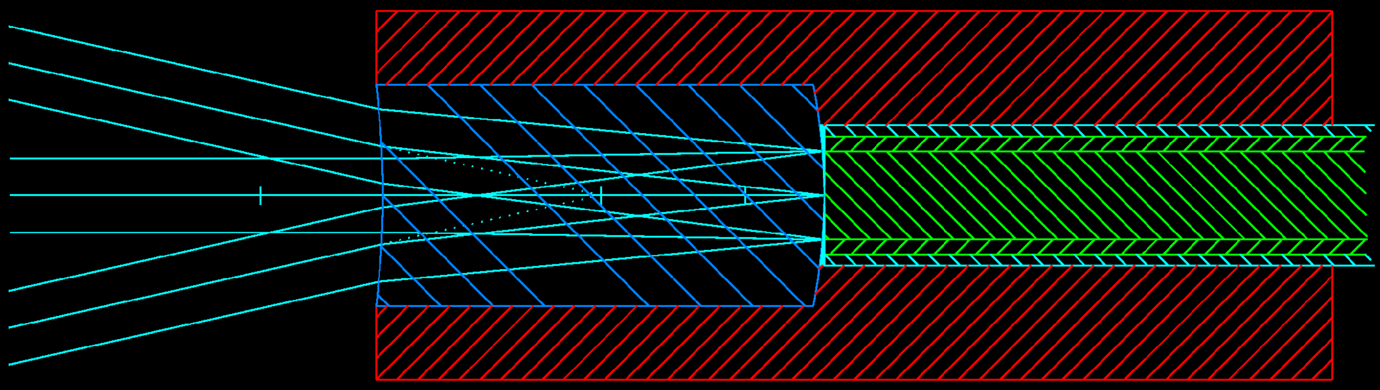
Prime Focus Instrument (PFI)



Subaru provided elements: field rotator, hexapod and wide field corrector



HSC filter/dewar window replaced by 30mm WFMOS field element with blocking spots for unused fibers



0.5mm dia 1.3mm long stainless ferrule

FIBER INPUT F-RATIO TRANSFORMER

Scale of Project

Fiber Positioner	*$10M*
Spectrographs + Detectors	*$10M*
Fibers	*$5M*
Subaru	*$5M*
Project + Contingency	*$10M*
Software	*$5M*

~$45M;

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