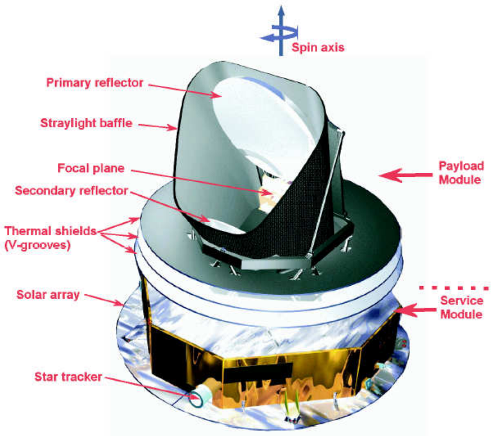
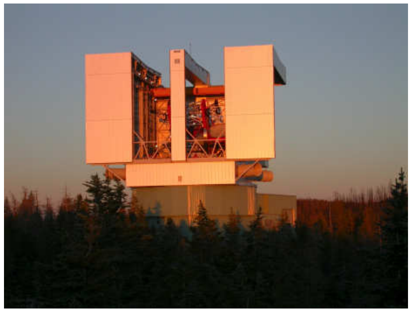
Cosmology with galaxy surveys – an instrument perspective

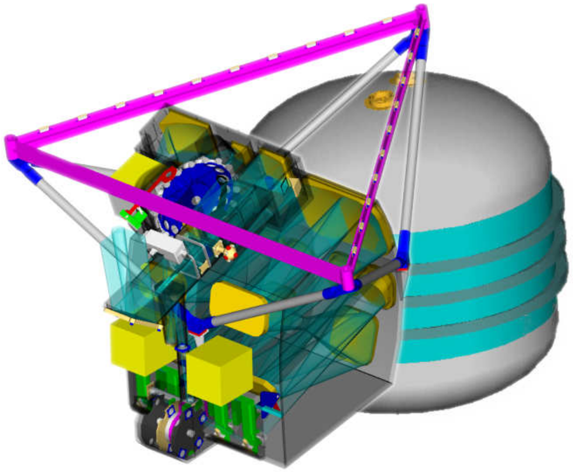
Michael Seiffert, Jet Propulsion Laboratory, Caltech

Dark Energy in the Universe
Okinawa, Japan
Summer School, 2009

JPL

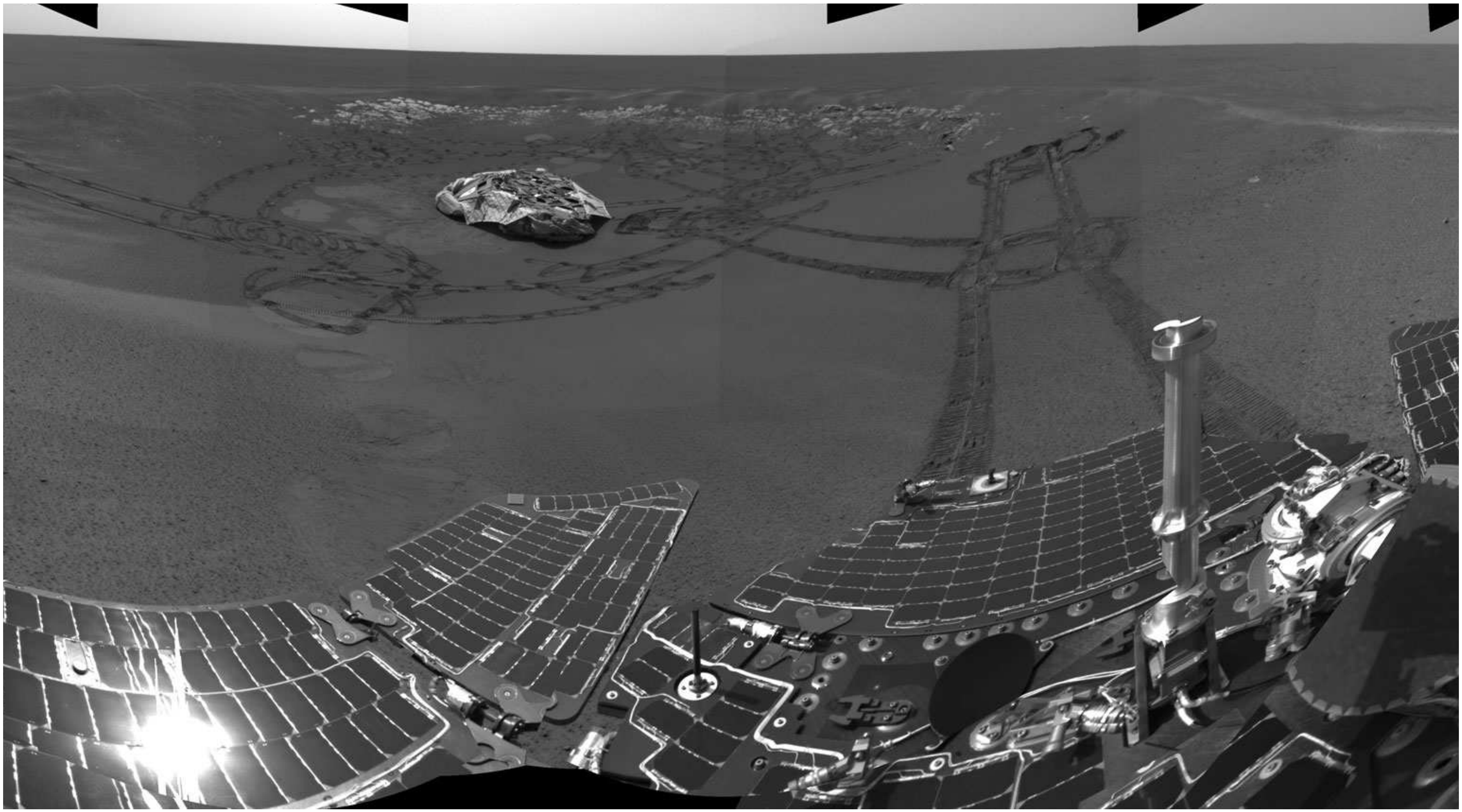






- Spitzer Space Telescope
- Detectors and cooler for Planck satellite (CMB)
- Mid IR Instrument (MIRI) for JWST
- LBTI
- Keck interferometer
- TMT Primary mirror control system
- Calibration system for Gemini Planet Imager

You may also have heard about …



Lecture 1: Introduction

Lecture 2: Scientific impacts of instrument design choices

Lecture 3: Physical principles of the instrument and its components - part 1

Lecture 4: Physical principles of the instrument and its components - part 2

Science goals

- Provide a constraint on *w* (dark energy equation of state) with the Baryon Acoustic Oscillation (BAO) method.

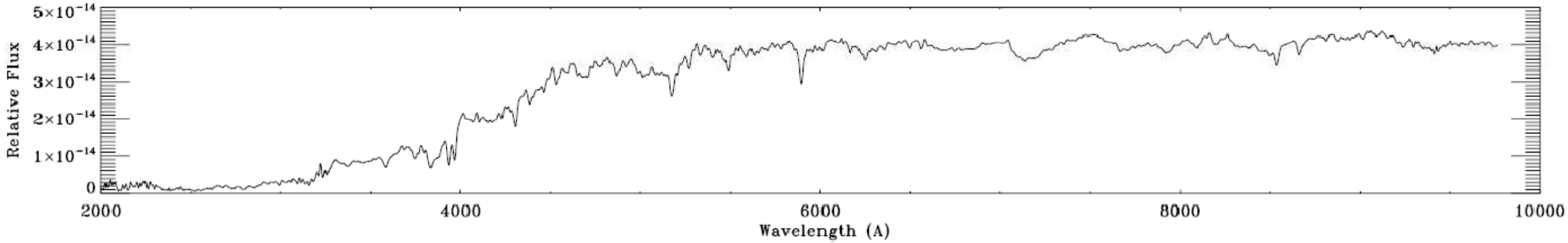
- Constrain the growth rate of structure with the Redshift Distortion (RSD) method.

$$1/\sigma_w \sim V^{1/2} \sim N^{1/2}$$

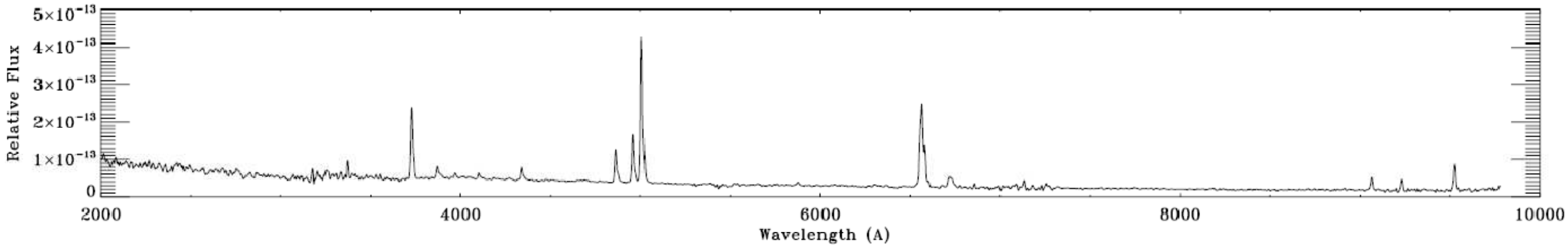
Galaxy Surveys - Context

Name	Number of Galaxies	Redshift Range (z)	Comments
SDSS + 2dF (Sloan Digital Sky Survey + 2 field galaxy redshift survey)	0.8×10^6	< 0.5	Percival et al , MNRAS, 381, 1053 (2007)
BOSS (Baryon Oscillation Sky Survey)	1.5×10^6	< 0.7	Funded, beginning http://www.sdss3.org/
FastSound (with FMOS on Subaru)	0.6×10^6	~ 1.2	
Wiggle –Z	0.4×10^6	$0.5 < z < 1.0$	In progress http://wigglez.swin.edu.au
JDEM (Joint Dark Energy Mission) or Euclid	?	?	Space mission in planning
WFMOS-SUMIRE on Subaru	$> 4 \times 10^6$	$0.7 < z < 1.6$	Proposal stage – concept study complete

Spectroscopic redshifts



“red” galaxy with 4000A break, no strong emission lines



Luminous “blue” galaxy with strong emission lines

- As our ambition rises to measure the redshift of many millions of galaxies to redshifts of 1 and beyond, new instruments are needed.

- For the next step on the ground, we need :
  - Large aperture telescope
  - The ability to measure *thousands* of simultaneous spectra

Building blocks

Object Selection

Optical routing

Spectrometer

Telescope

Allows the selection of light from galaxies of interest while rejecting unwanted sky background

Fiber optics or other method relays the light of interest

Disperse the light and detect

Object Selection

- Plug Plate

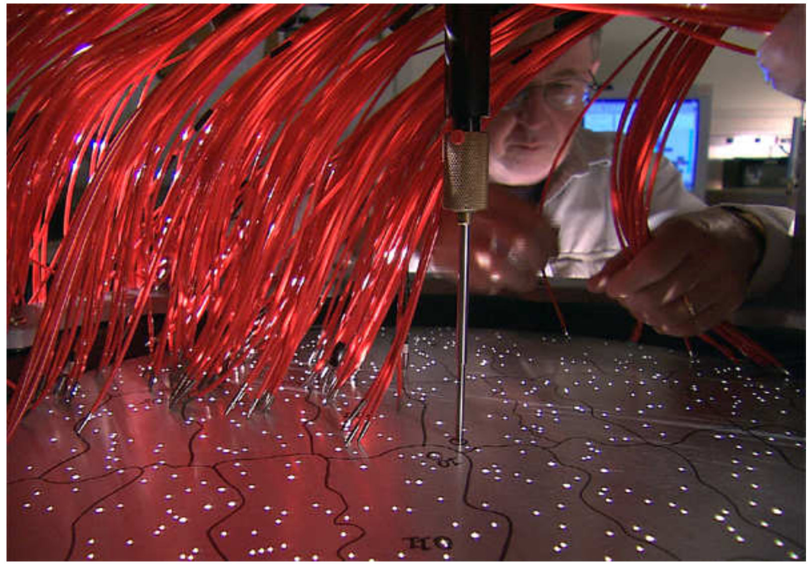


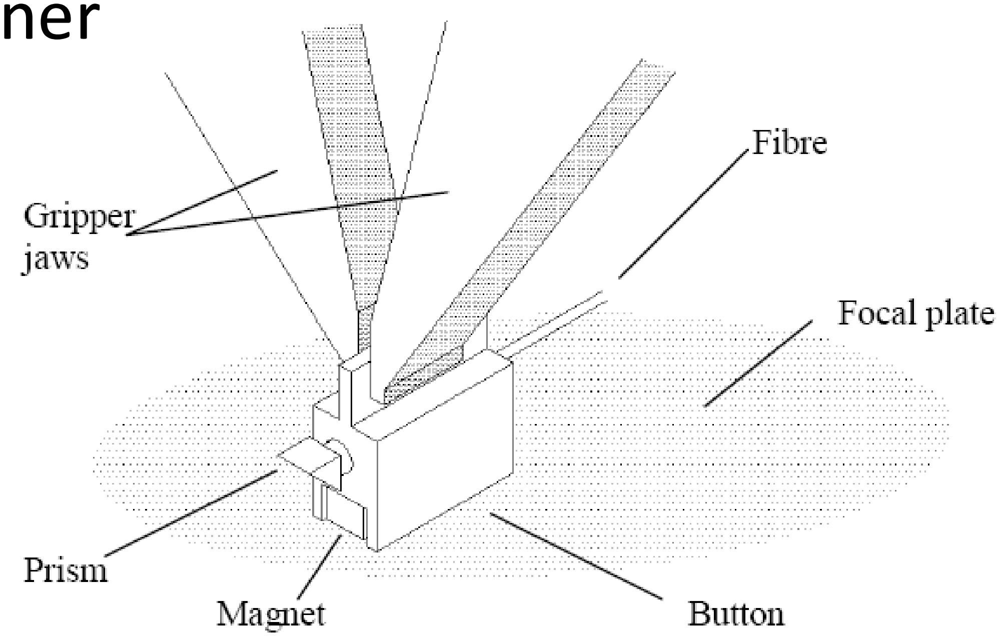
Photo from SDSS

- Slit Mask

Photo from Lick Observatory

Object selection

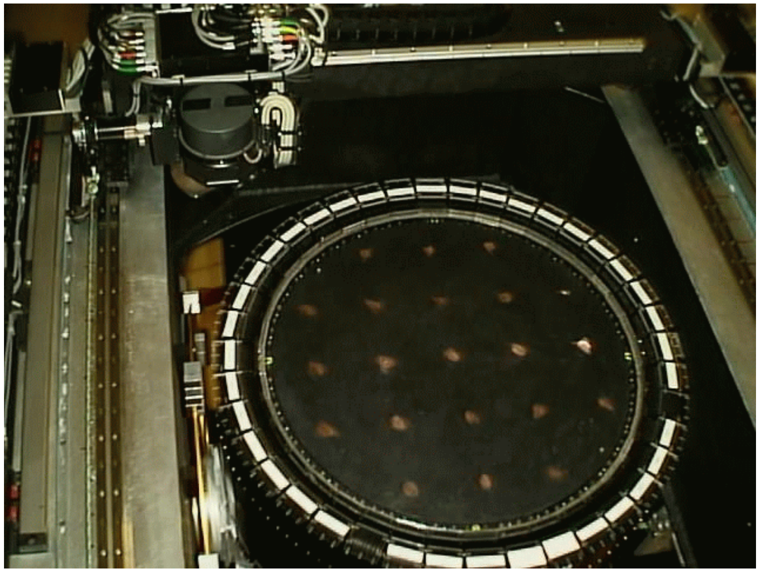
- Mechanical positioner

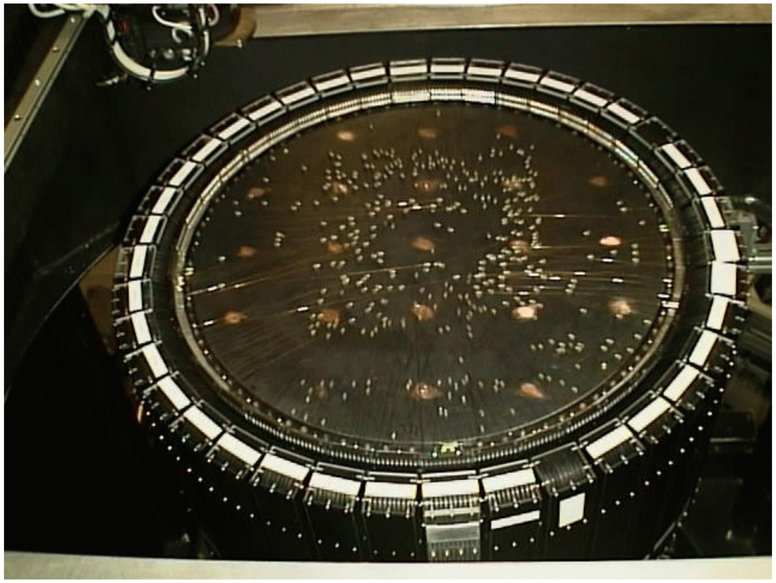


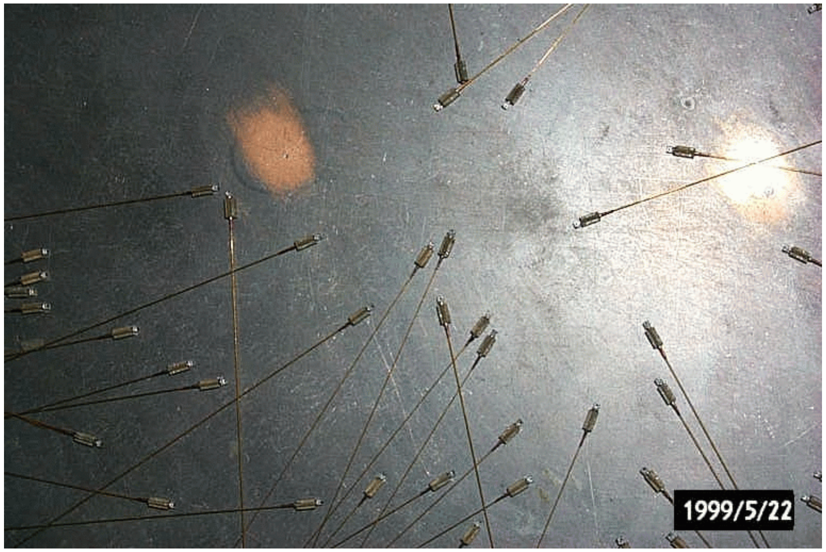
From Smith et al., SPIE, 5495, 348 (2004)

- None – option for a space mission

2dF Fiber Positioner on the Anglo Australian Telescope





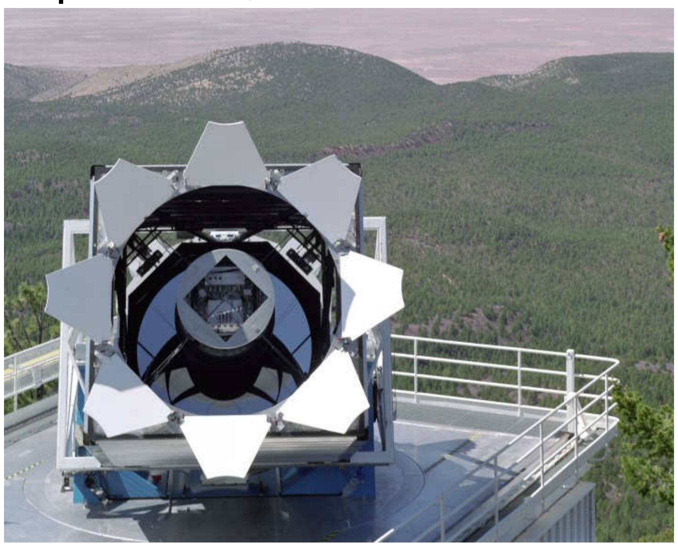


2 degree diameter field of view
Approximately 400 fibers
4m telescope

Photos from www.aao.gov.au

Sloan Digital Sky Survey (SDSS)

2.5m telescope located at
Apache Pt, New Mexico

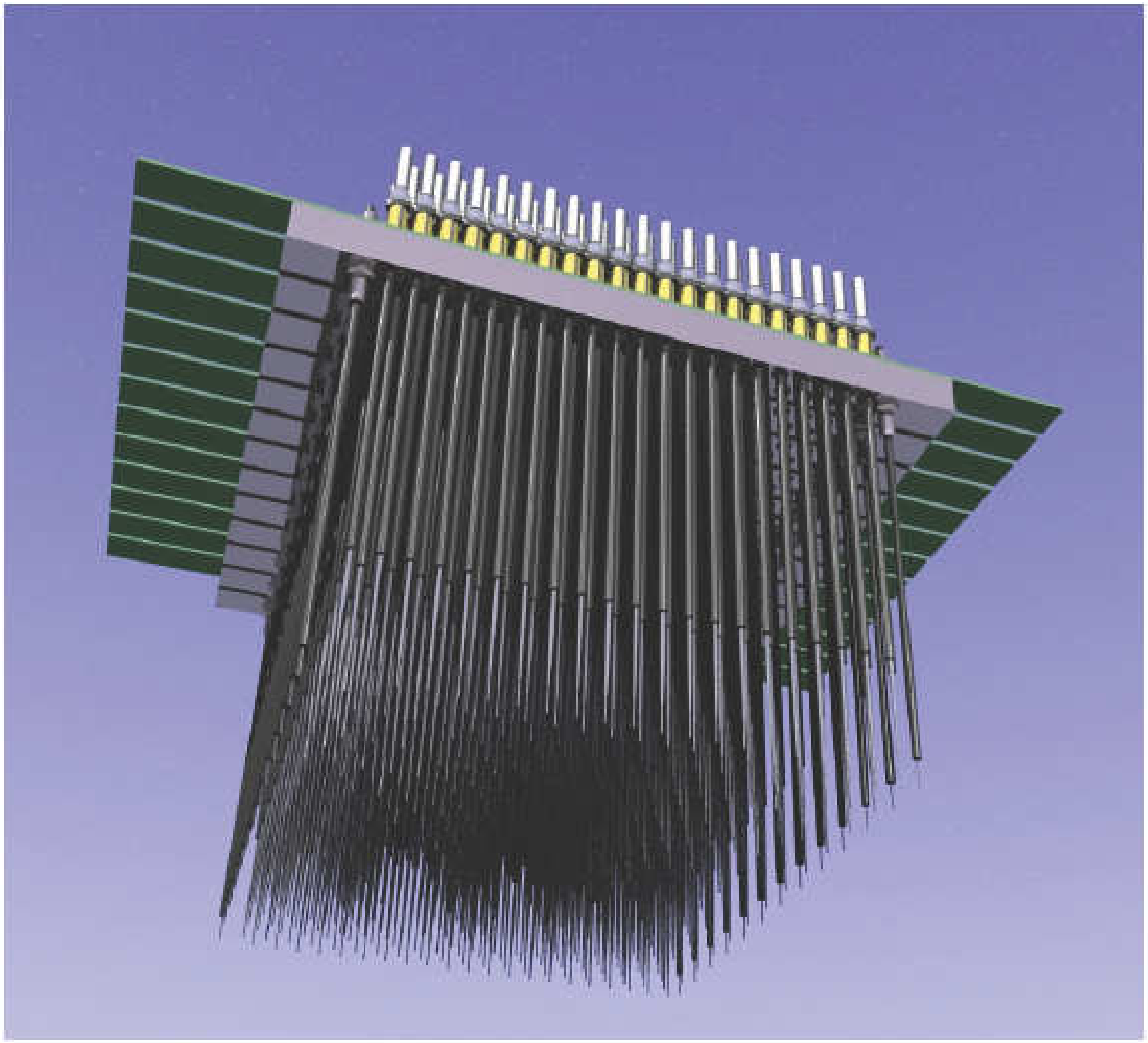


640 simultaneous spectra
3 deg diameter field
Wavelength coverage 3800-9200 A,
Spectral resolution = 1800
York et al., AJ, 120, 1579, (2000)

“plug plate” object selection
fiber size 3 arc seconds
55 arc sec closest approach

Photos from www.sdss.org

"Echidna" mechanically tilted fiber spines - used for FMOS on Subaru Telescope

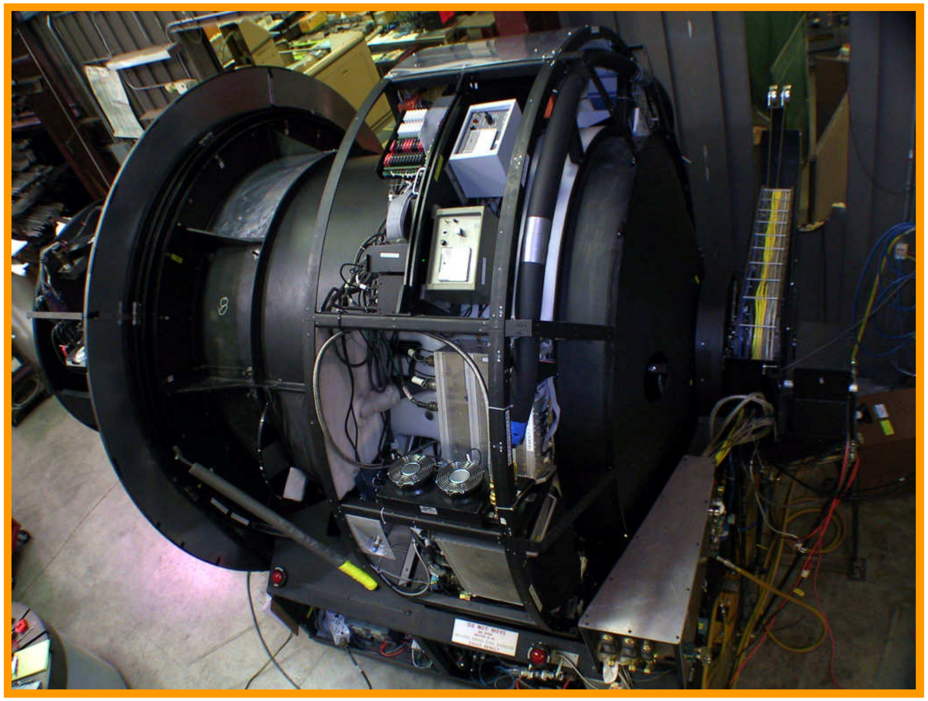


DEIMOS

Spectrometer on the 10m Keck II telescope

Source of the DEEP2 survey, which is one of our best sources of galaxy spectra at redshift > 1.

Key aspects: red sensitive CCDs, no fibers, uses slit masks

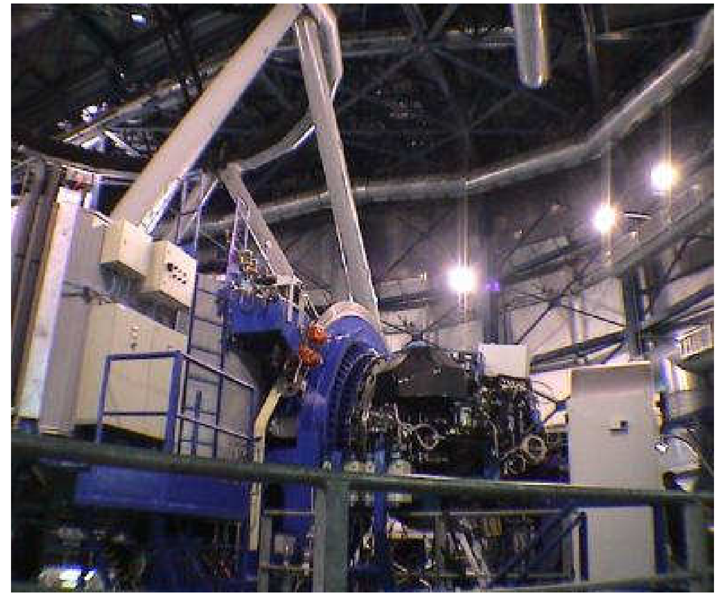


DEEP2 : Typically 120 simultaneous spectra over 16.7 x 5’ field using mechanically fabricated slit masks

Ref: Faber et al., SPIE, v.4841, p1657 (2003)

PI: Sandra Faber
Photos from DEIMOS project:
http://www.ucolick.org/deimos

VIMOS



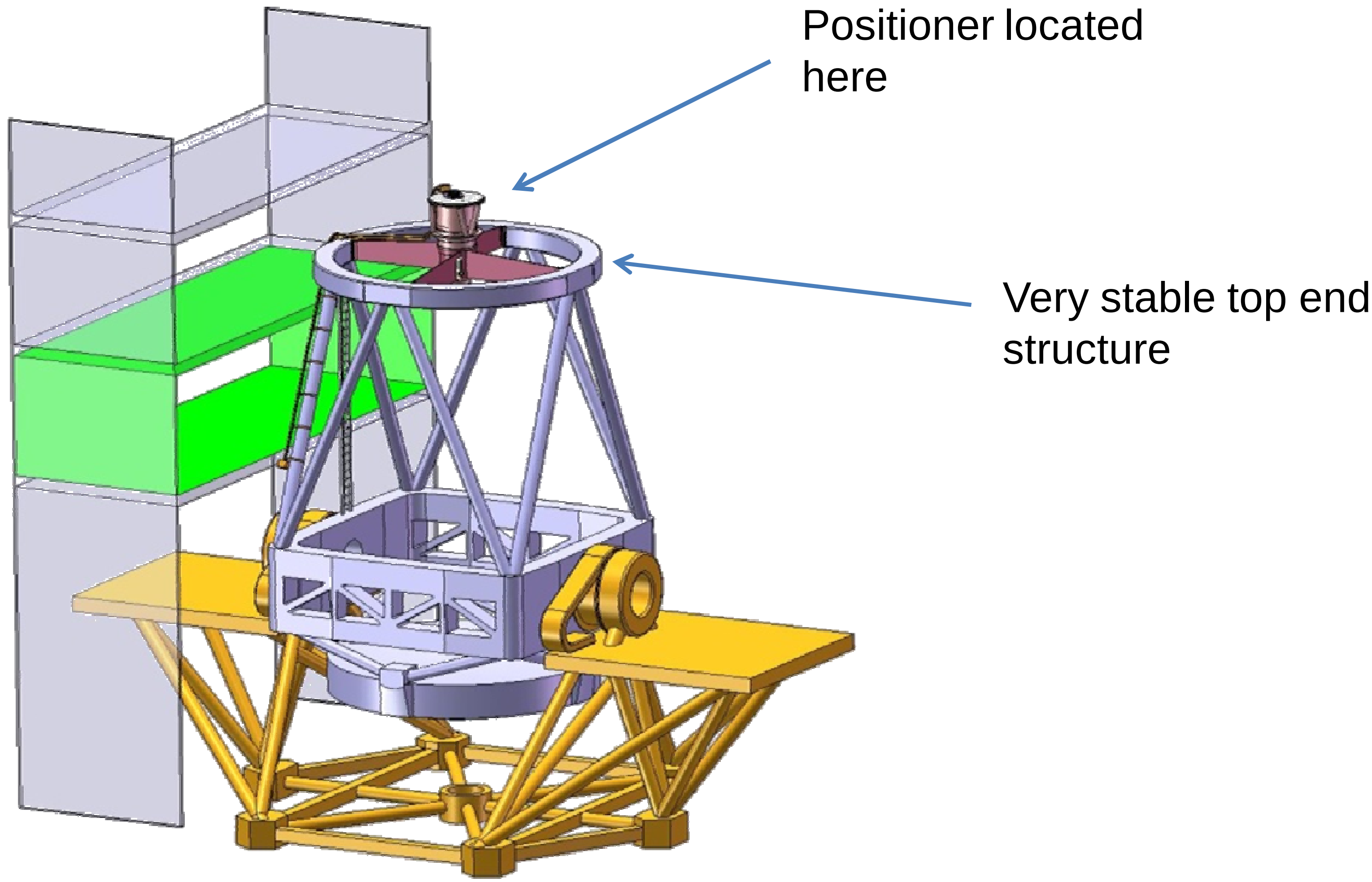
www.eso.org

- 4x 7'x8' fields
- Mechanical slit masks
- 840 simultaneous spectra at R~200
- 210 simultaneous spectra at R~2500.
- Nasmyth focus at VLT (European Southern Observatory Very Large Telescope) (8.2 m diameter aperture) (Paranal, Chile)

WFMOS / SuMiRe – next generation wide field multiobject spectrograph

- On the Subaru Telescope
- Why Subaru?
  - 8.2 m aperture
  - Very good “seeing” (seeing = blur caused by atmospheric turbulence and other effects)
  - Wide Field Corrector at prime focus being built for HyperSuprimeCam (1.5 degree diameter field-of-view)
  - Very stable top end structure

The WFMOS / SuMiRe Concept



Subaru Telescope

Photo credit: Steven Beard, UKATC

Subaru Top End

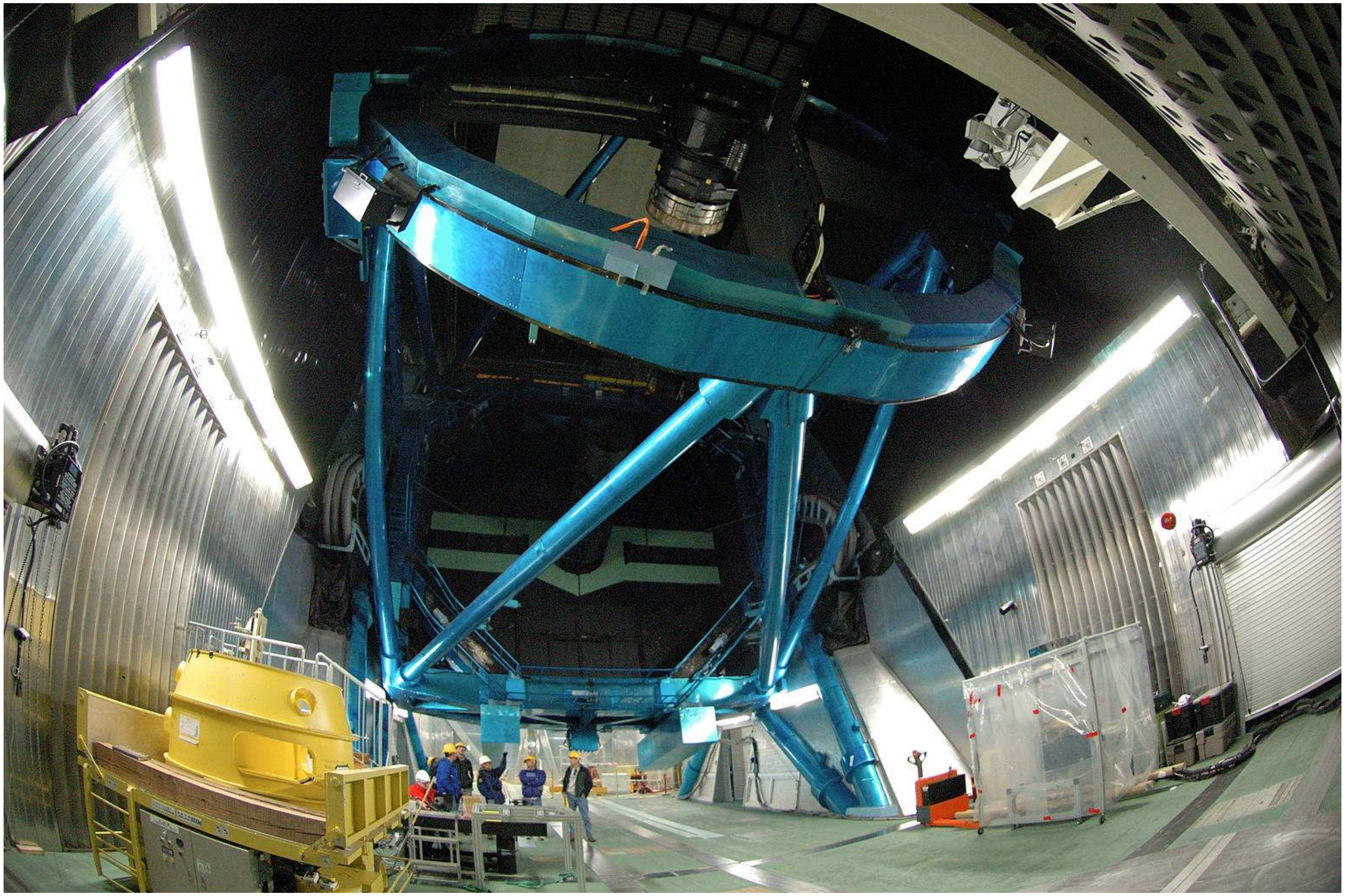


Photo credit: Steven Beard, UKATC

Subaru Prime Focus Unit

A top end unit holds a major part of the instrument

It is large and heavy

The Subaru Telescope is the most practical large telescope to locate such an instrument

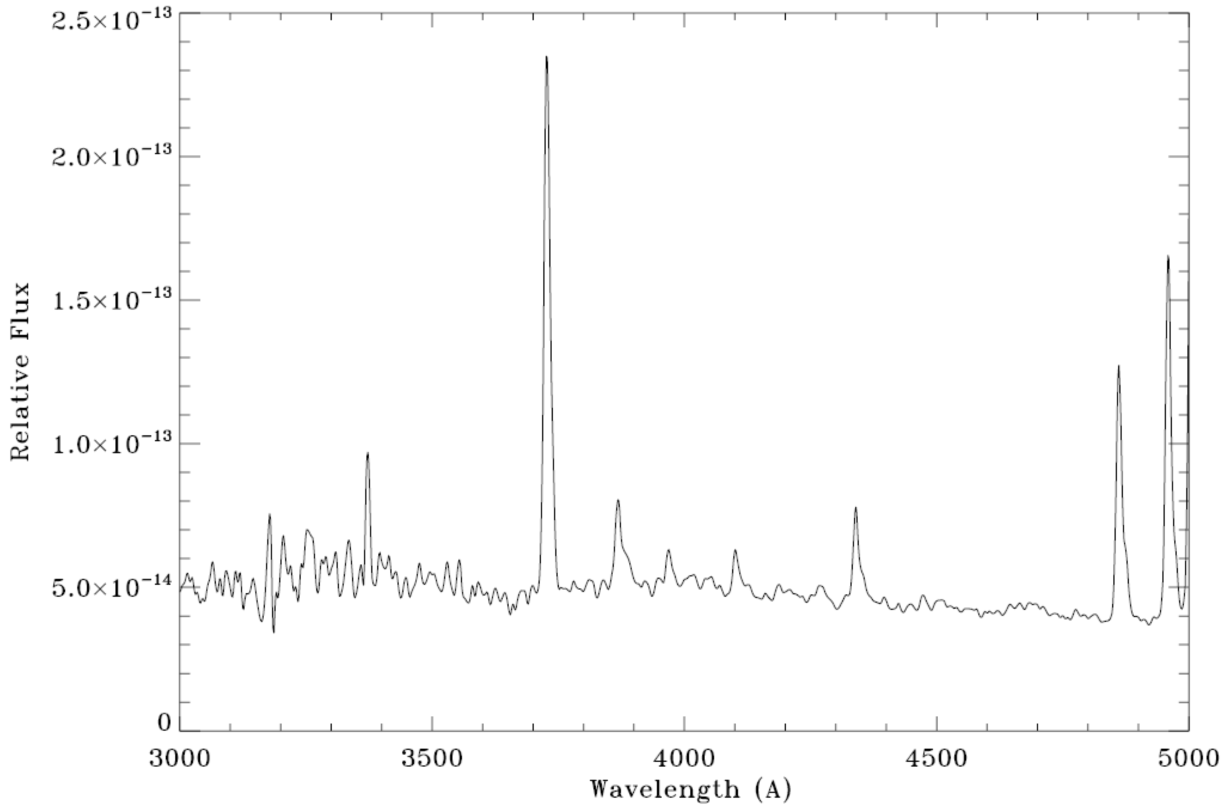
Photo credit: Steven Beard, UKATC

Total number of galaxies observed depends on:

- Telescope time available
- Observing efficiency
- Number of galaxies observed simultaneously
- Time required per galaxy:
  - Telescope Aperture
  - Signal: flux from the galaxy
  - Throughput (how many of the photons from the galaxy make it through the atmosphere and instrument and are eventually detected)
  - Noise: sky noise, shot noise, detector noise
  - Required Signal/Noise ratio per spectral resolution element

Time required (Signal)

Template spectrum from bright emission line galaxy



Flux in each spectral bin in spectrometer will depend on width of the spectral bin and which part of the galaxy spectrum it is sampling.

Time Required - throughput

- Throughput has many components – we will look at these in following lectures
- Major components are:
  - Atmosphere
  - Telescope (mirrors are not perfectly reflective)
  - Corrector optics (glass has some reflection)
  - Alignment of the instrument
  - Fiber optic losses
  - Spectrometer optics and grating
  - Detector efficiency (usually called "quantum efficiency" QE)

Time Required - noise

- Noise has 3 main components:
  - Atmosphere (the sky is not perfectly dark)
  - Shot noise (statistical uncertainty in signal due to the finite number of photons – unimportant for the current discussion)
  - Detector noise (unfortunately, detectors are not perfect!)

Time Required – signal/noise ratio

- We are free to choose the signal/noise ratio that suits our needs. The considerations are:
  - Redshift accuracy and reliability (favors higher signal-noise ratio)
  - Desire to maximize the number of galaxies surveyed. Implies shorter exposure times and lower signal-noise ratio
  - Completeness: We do not necessarily know the line strength of the galaxy perfectly before taking the spectrum! Requiring a higher signal to noise ratio gives some margin so that galaxies are not missed too frequently.

Simplified Signal-Noise Calculation

$$S = f\,A\,\tau\,\Delta\lambda\,\eta$$ Signal

$$B_{\rm sky} = b_{\rm sky}\,A\,\Omega_{\rm fiber}\,\tau\,\Delta\lambda\,\eta$$ Sky noise

$$B_{\rm detector} = i\,\tau\,n_{\rm pix} + {\rm RN}^2\,n_{\rm pix}\,n_{\rm reads}$$ Detector noise

$$\sigma = \frac{S}{\sqrt{B_{\rm sky} + B_{\rm detector}}}$$

Signal – noise ratio

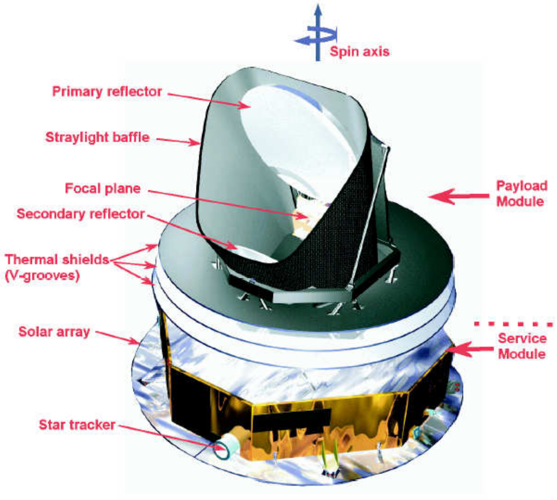
f	Galaxy flux density
A	Telescope collecting area
τ	Total exposure time
$\Delta\lambda$	Width of spectral bin
η	Throughput
$b_{\rm sky}$	Sky background flux density
$\Omega_{\rm fiber}$	Solid angle on sky of spectral element
i	Detector dark current
${\rm RN}$	Detector read noise
$n_{\rm pix}$	n – number of pixels contributing to noise

Next Lecture

- Scientific impact of technical design
  - Detector performance
  - Instrument efficiency
  - wavelength range
  - spectral resolution
  - number of fibers
  - Etc.

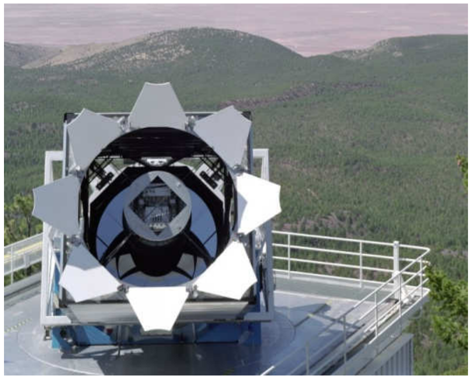
Summer School = Test!

Do you know your telescopes?



Planck

Subaru



SDSS, Apache Pt

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Scientific Impacts of technical design

In general, when planning an instrument, one faces many options and decisions.

We want to build the "ideal" instrument – the one the gives the very best performance.

"The *best* instrument is the one that actually gets built"

- Mike Werner, Spitzer Project Scientist

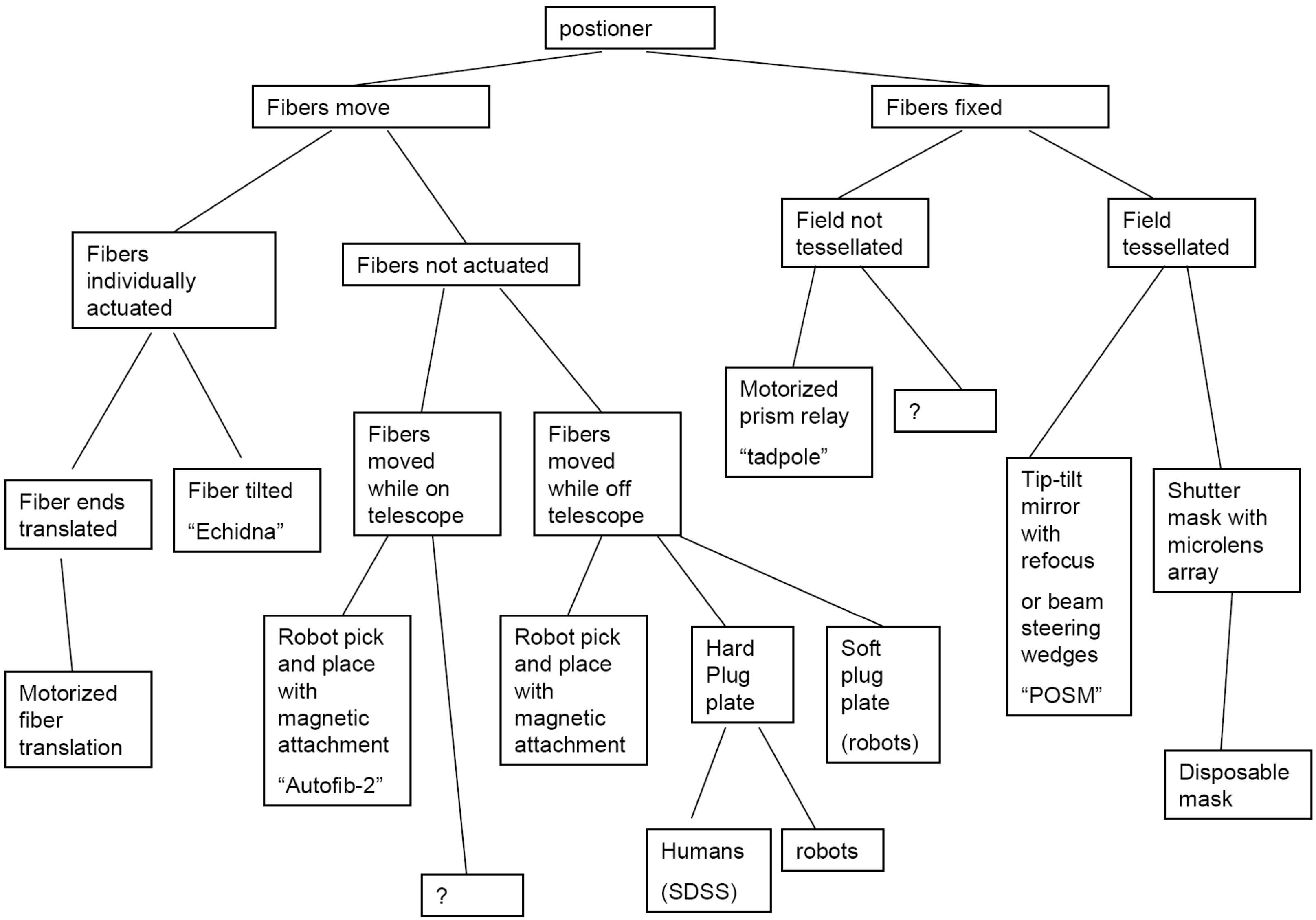
Topics

- Target assignment, allocation efficiency, patrol regions
- Spectral Resolution and coverage
- Throughput and exposure time

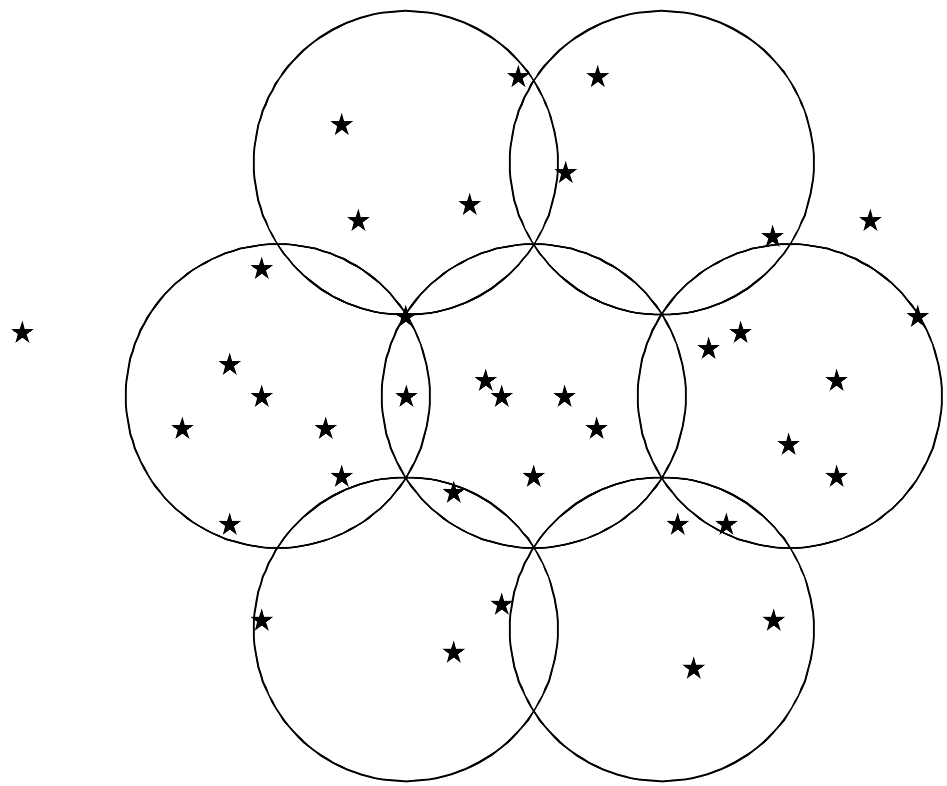
Choice of Object Selection Mechanism

- In the last lecture we discussed several options for “object selection” : plug-plate, mechanical positioner, etc.
- For considering a new instrument like the SuMIRe spectrometer, it is important to consider the full range of options for object selection. Desired properties:
  - Thousands of elements over a large field
  - Efficient: fast reconfiguration, high throughput
  - Not too expensive!

Tree of positioner alternatives



Patrol Regions



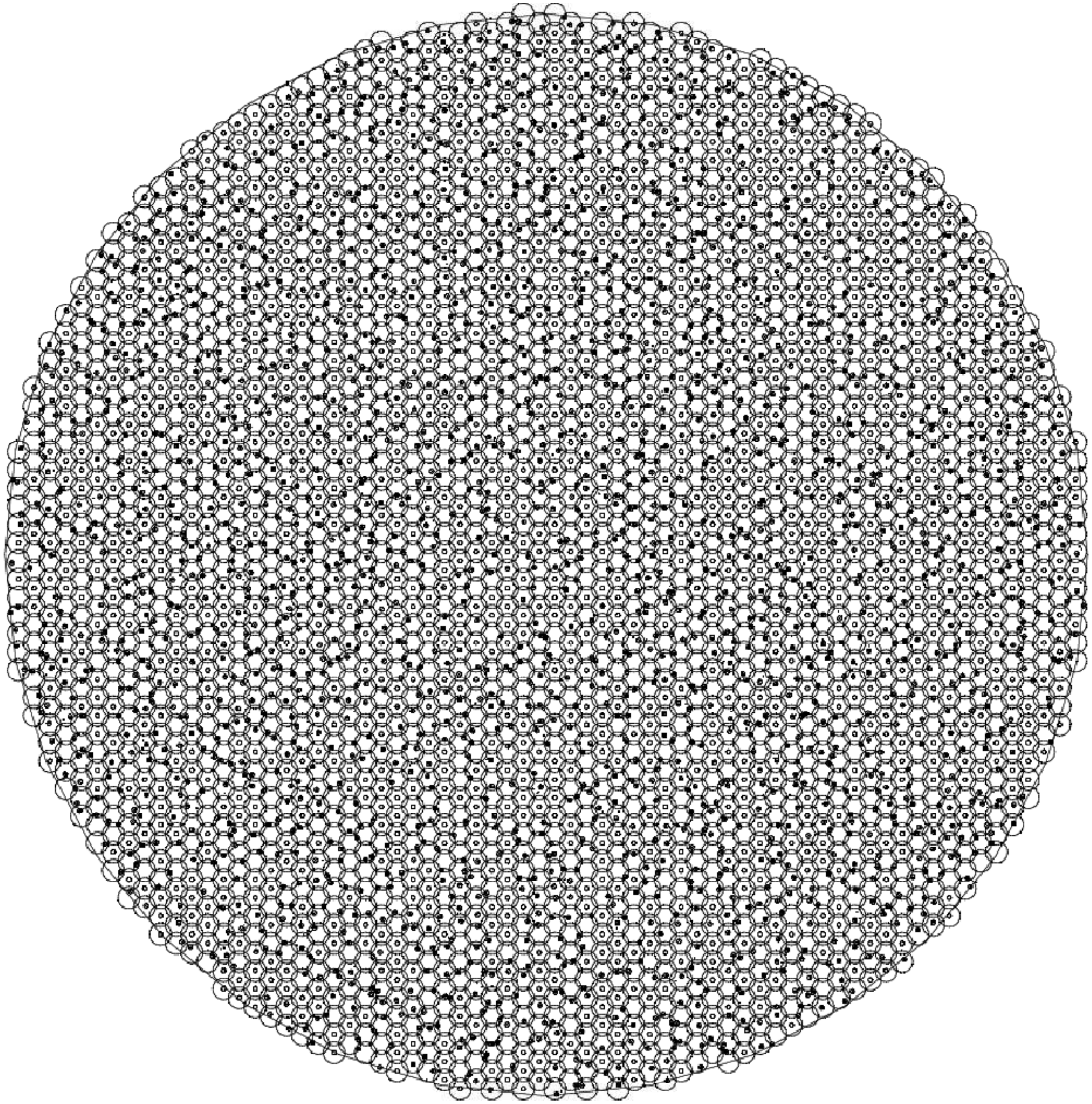
Patrol Region – Area of the focal plane accessible to one fiber (9.5 mm diameter)

Adjacent patrol regions overlap with no gaps

Patrol Region may have zero or may have many potential astronomical targets

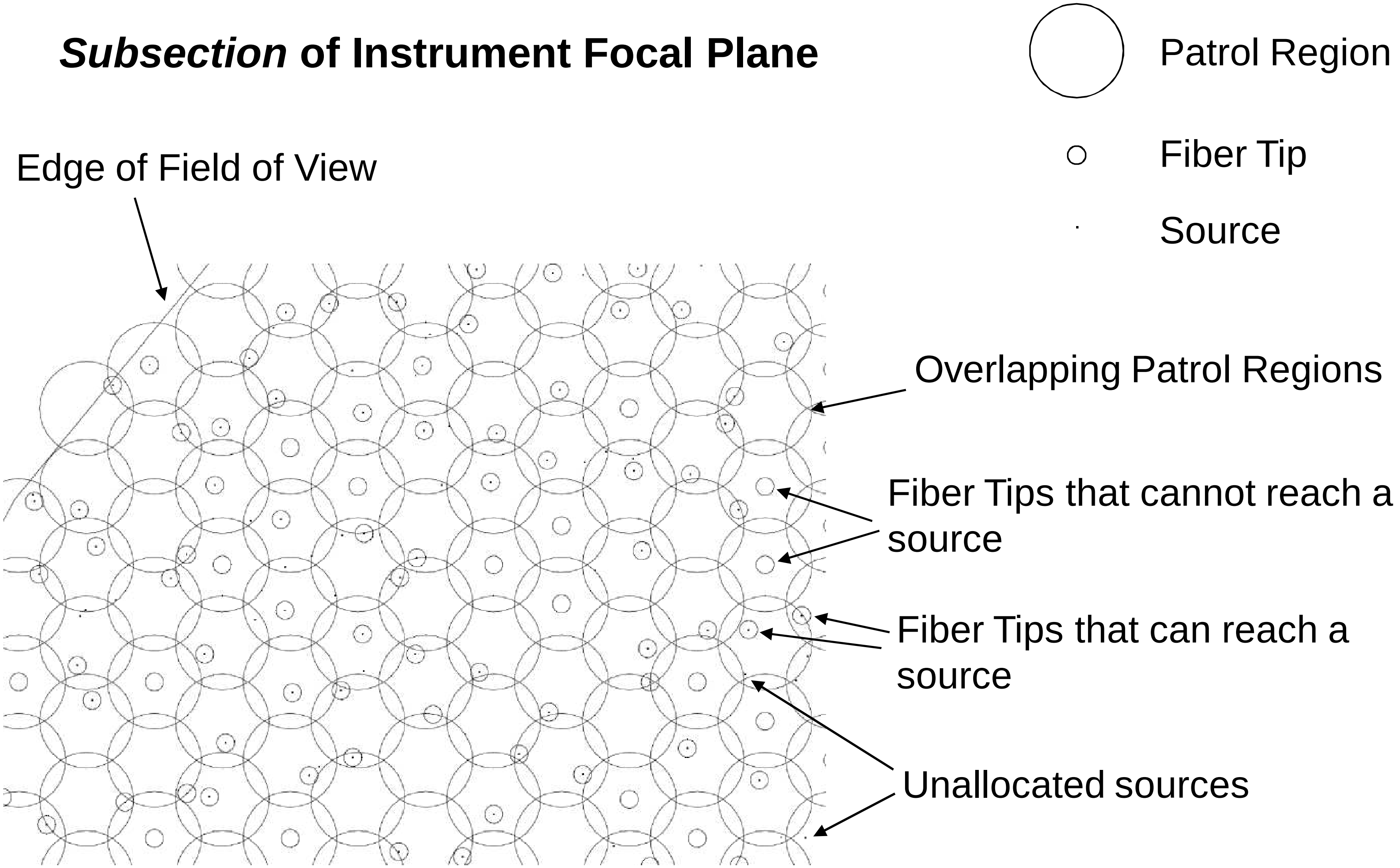
Allocation efficiency describes the success rate in assigning targets to fibers

3200 Overlapping patrol regions with 3200 targets

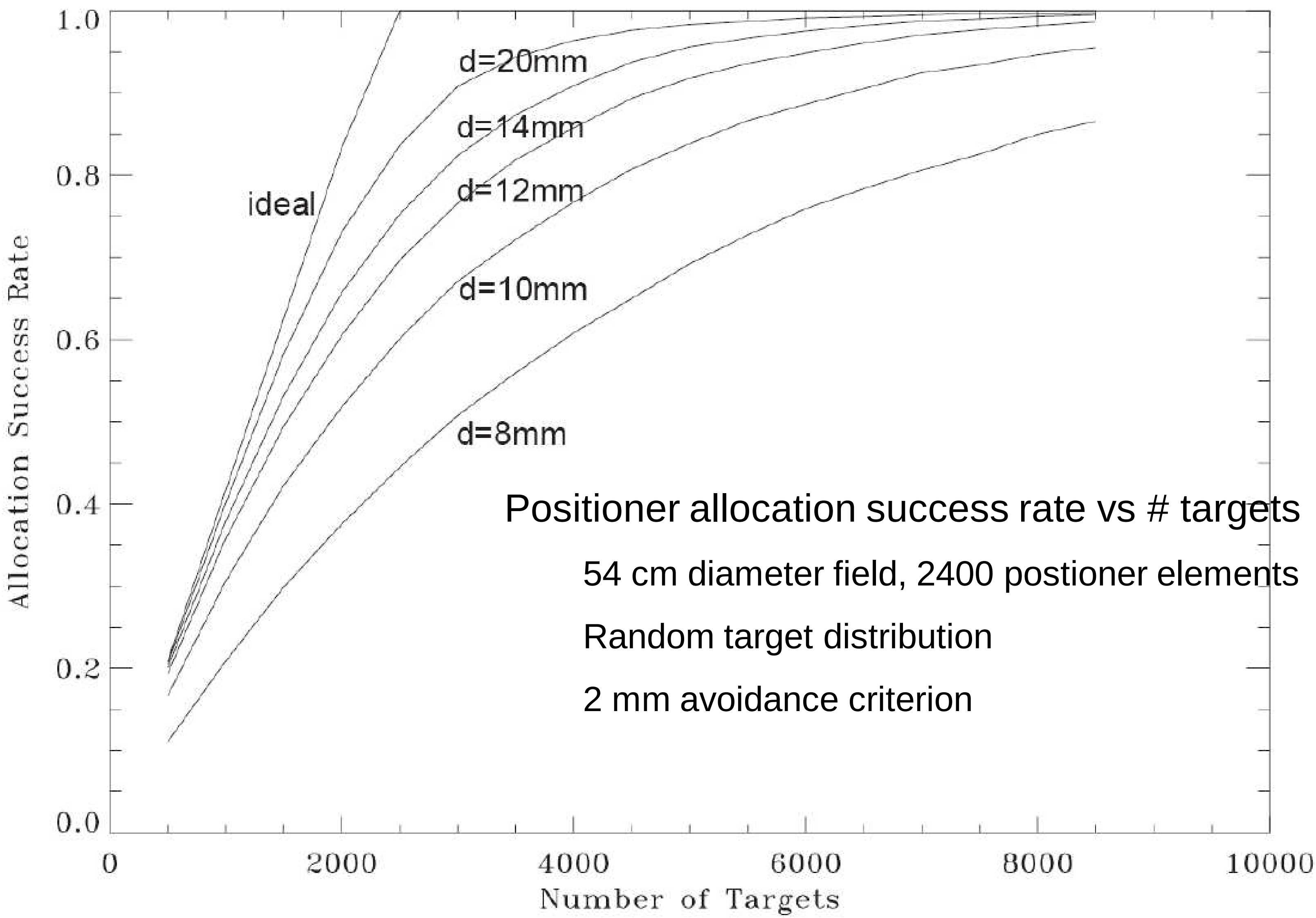


Positioner and Source Allocation

***Subsection* of Instrument Focal Plane**



Allocation Efficiency



Positioner allocation success rate vs # targets

54 cm diameter field, 2400 postioner elements

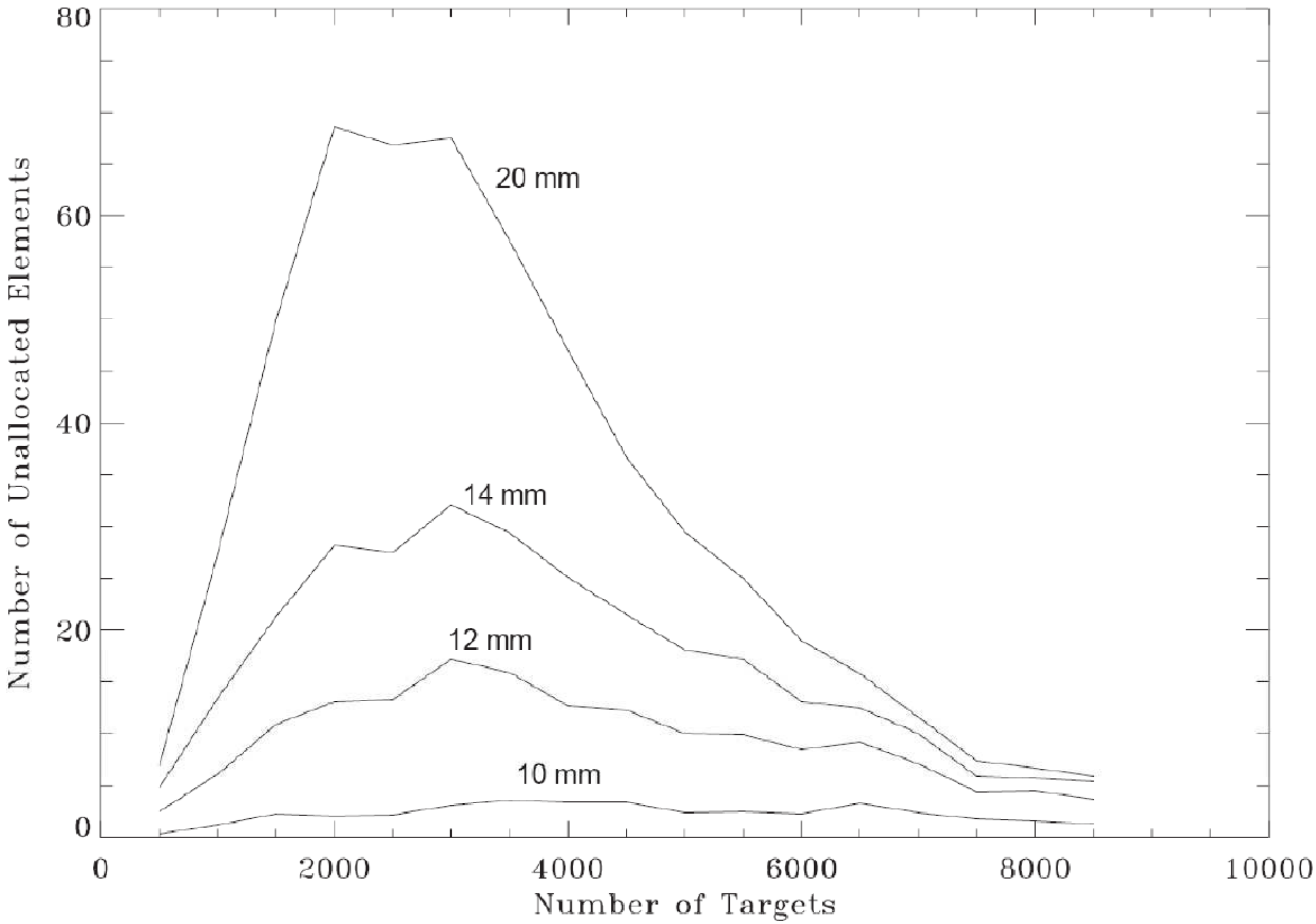
Random target distribution

2 mm avoidance criterion

We have simulated a variety of designs and arrived at the following conclusions:

- For low target densities, degree of overlap between patrol regions is unimportant. Important not to have gaps.
- For high target densities, degree of overlap not important – there are many targets in each patrol region to choose from
- For intermediate target densities (target density ~ positioner density) there is some benefit to having larger overlap.

Number of Potential Collisions

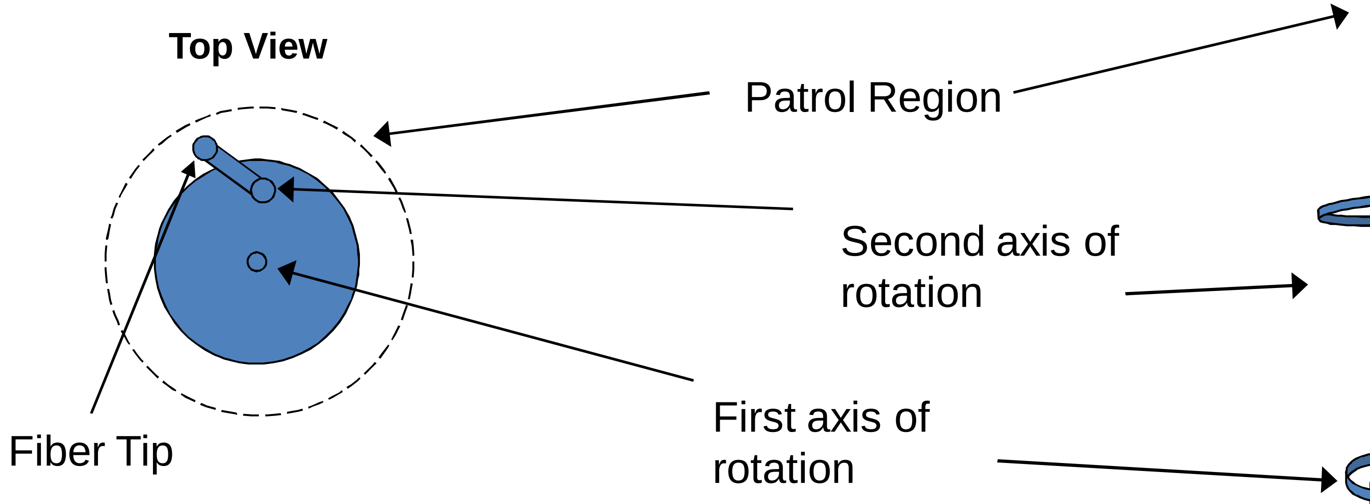


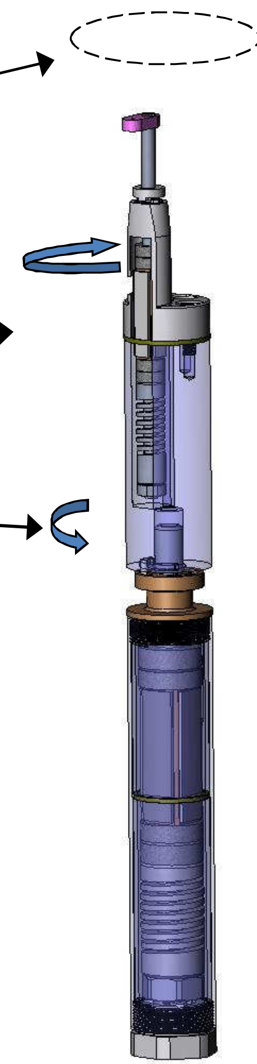
Question for students:

- What is the best algorithm for assigning galaxy targets to fibers?

- For the allocation efficiency curves shown previously, I used a simple algorithm that assigns each fiber to the nearest galaxy and iterates once.

Example : Positioner Element – “Cobra”





Cobra

Courtesy NST

- Each motor rotates to provide complete coverage of the patrol region.
- Optical fibers mounted in “fiber arm” which attaches to upper postioner axis:
- Fiber runs through the center of the positioner

Survey Density and Exposure Time

$n = 4 \times 10^{-4} / (h^{-1}Mpc)^3$ — Volume Density

$0.7 < z < 1.6$ →

$h=0.71$, $\Omega_\Lambda = 0.73$, $\Omega_M = 0.22$ →

↓

Projected Angular Density — 1245 galaxies / deg^2

Allocation efficiency < 1 →

Successful redshift fraction < 1 →

↓

Required Observed Angular Density — **2132 galaxies / deg^2**

↓

Galaxy number counts →

Magnitude Limit — $R_{AB} < 23$

Instrument parameters, throughput

Required S/N level →

↓

Exposure time — ~ 15 minutes / field

Open question:

- Limit the s/n ratio and aggressively optimize for survey speed, possibly at the expense of legacy value of the survey and completeness

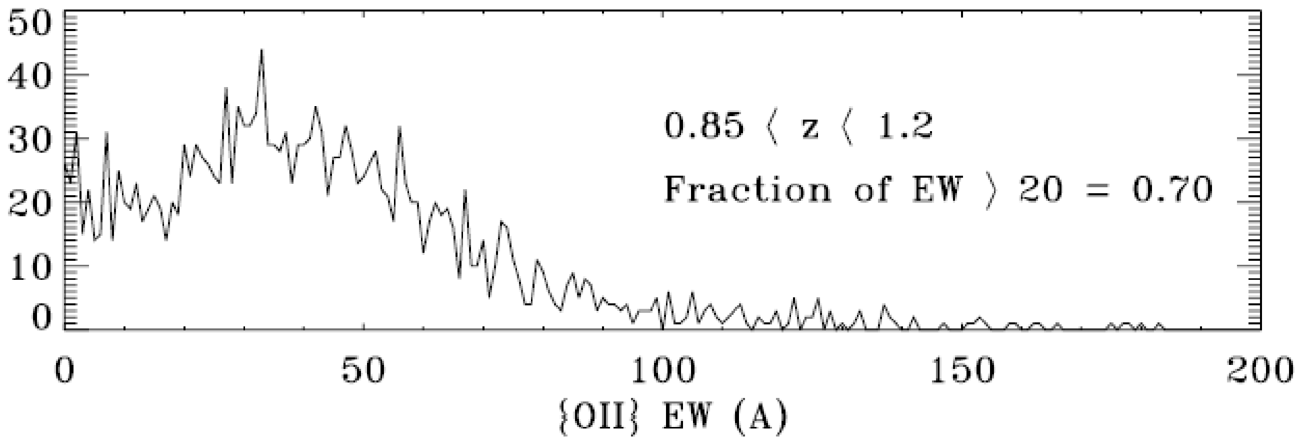
Or

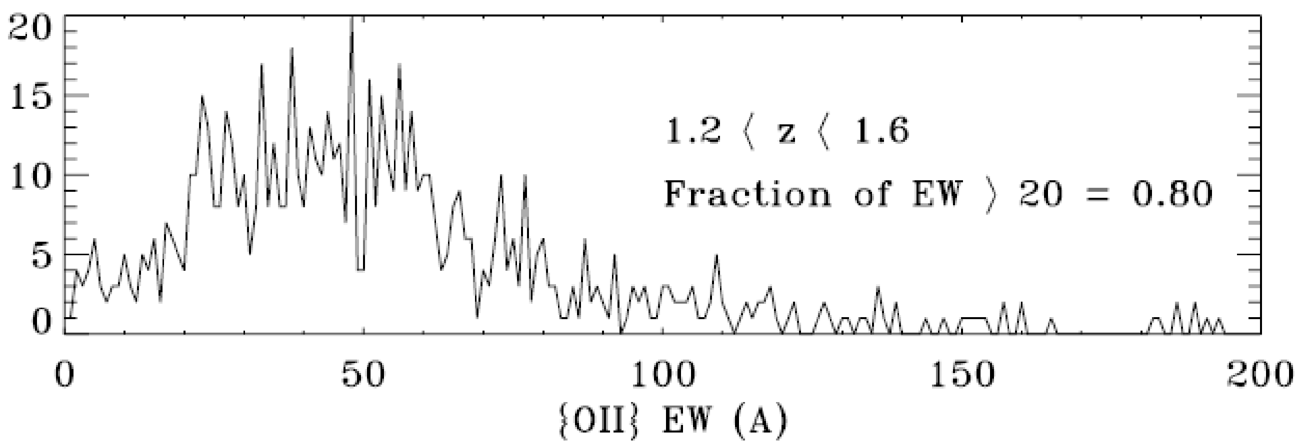
- Greater s/n ratio, slower survey speed

What spectral resolution ($R = \lambda/\Delta\lambda$) do we need?

- Emission line galaxies are attractive option for future surveys at redshift of 1 and greater (relatively high flux in narrow width). OII doublet at a rest frame 3727Å is nearly ideal:
  - Bright
  - Doublet with 2.7Å separation allows determination of redshift from this feature alone
- Must be able to resolve the OII doublet reliably ($R > 1340$)
- Also need sufficient redshift accuracy, e.g, $\Delta z<0.001$
- There is a penalty for having too much spectral resolution
  - Instrument cost / wavelength coverage
  - Detector read noise starts to have a larger impact

Equivalent Width histograms

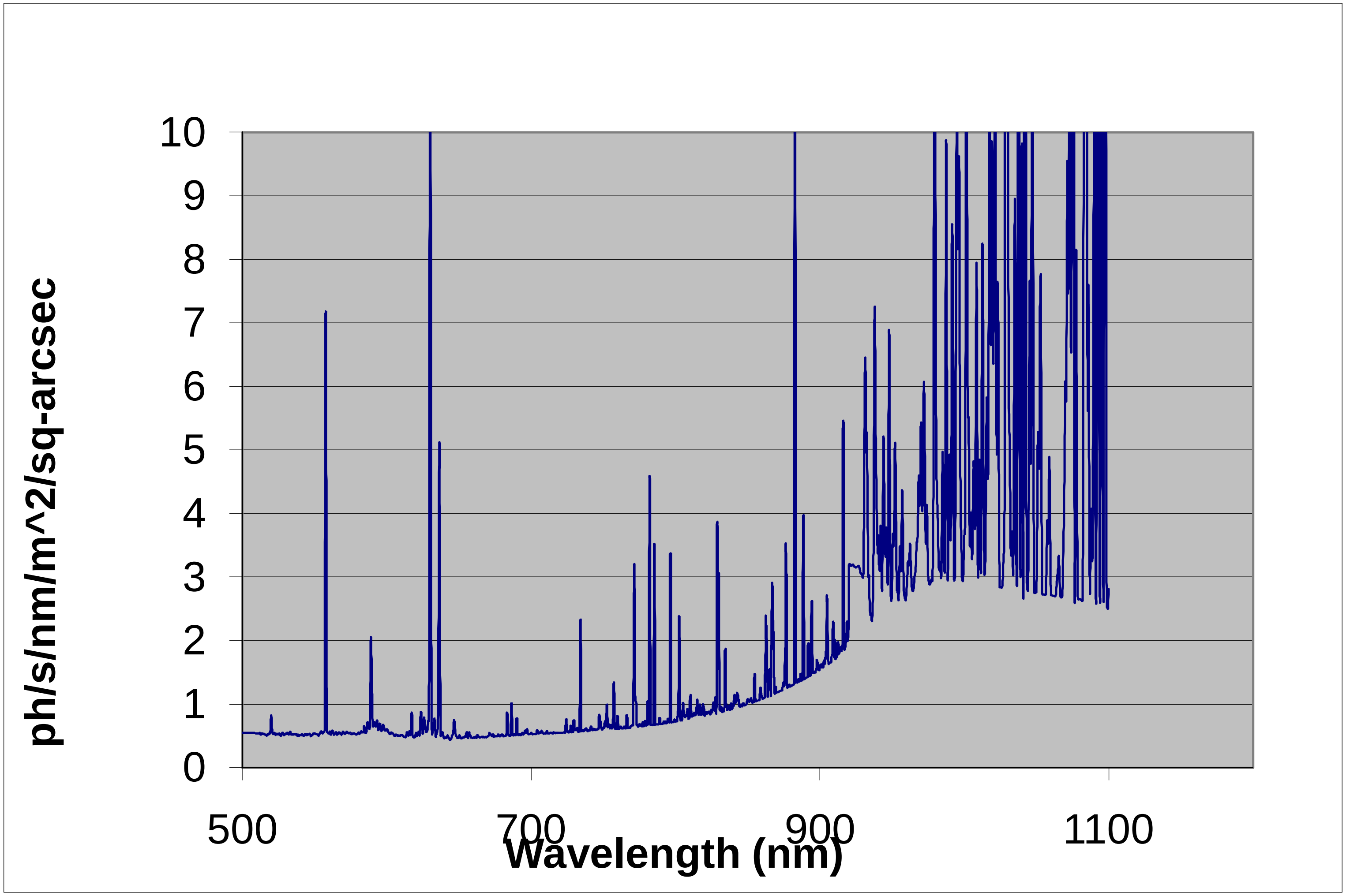




EW = spectral width of continuum that has the same flux as the emission line

Data from Team Keck Redshift Survey (TKRS) (Wirth et al, AJ, 127,3121 (2004))

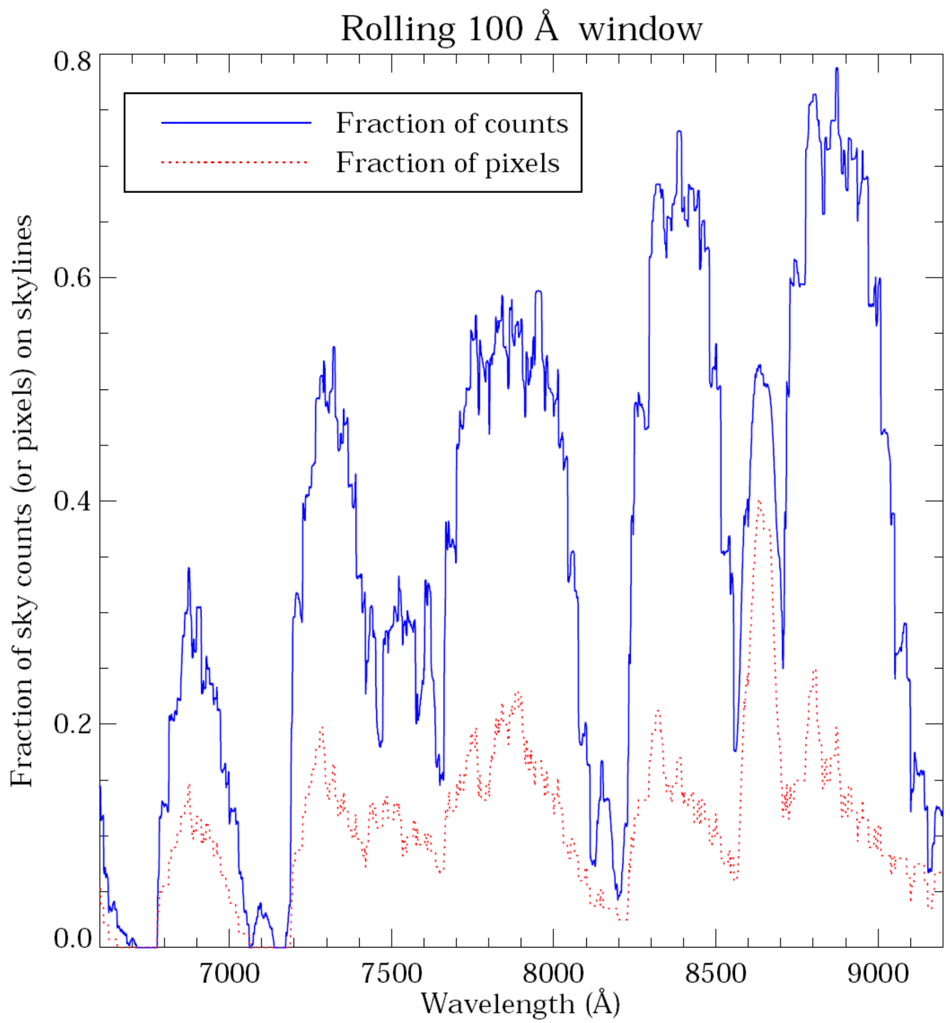
Mauna Kea Sky Brightness
(note: OII at z=1 shows up at 7454Å)
higher resolution may reduce impact of sky brightness



Sky background is dominated by narrow line emission

Blue solid curve shows the fraction of the total flux contributed by sky lines.

Pink dotted curve shows the fraction of spectrometer pixels contributing to this flux at resolution 5000.



Davis et al, SPIE, 4834, 161, (2003)

Spectral coverage

- The OII emission line doublet at a rest frame wavelength of 3727Å, when redshifted to $0.7<z<1.6$ falls in the wavelength range of :

  6300Å - 9700Å

so perhaps this is a good range for the spectrometer.

- But, why this redshift range? Lower redshift end complements BOSS. Higher redshift end starts to put the OII line into a wavelength range where silicon CCD detectors do not work well.

What is the acceptable fraction of incorrect redshifts?

- If we operate at very low signal to noise with short exposure times, there is some danger of misidentifying the emission line and producing an incorrect redshift, thus biasing the result.
- We should design the survey to ensure that this is a small (e.g, < 1%) effect.

Throughput and exposure time

- As we saw in yesterday's simplified signal-noise calculation:

$$\sigma = \frac{S}{\sqrt{B_{\rm sky} + B_{\rm detector}}}$$

$$S = f\, A\, \tau\, \Delta\lambda\, \eta$$

$$B_{\rm sky} = b_{\rm sky}\, A\, \Omega_{\rm fiber}\, \tau\, \Delta\lambda\, \eta$$

$$B_{\rm detector} = i\, \tau\, n_{\rm pix} + {\rm RN}^2\, n_{\rm pix}\, n_{\rm reads}$$

- So, for a given σ, the required exposure time scales as $1/\eta$, so we are driven to work hard to improve the throughput. This often means the spectrometer optics and detectors.
- Further, η, is generally a function of wavelength. It is sometimes possible to improve η at one wavelength at the expense of another.

Finally - “Less obvious” impacts

- Configuration time – how much time is wasted in moving fibers to prepare for the next observation?
- Non-uniform throughput in field of view
- Background subtraction – how this is done in detail can greatly affect required observing time.
- Tradeoffs in throughput versus wavelength
- Exposure time can depend on telescope elevation angle and lunar phase.

Next Lecture

Tour of a spectrometer design

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Lecture 2: Scientific impacts of instrument design choices

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Tour of an instrument design

With technical contributions from:

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Mary White, *Project Manager, JPL*
Robin Bruno, *Proposal Manager, JPL*
Michael Seiffert, *Project Scientist, JPL*
Stuart Lynn, *IfA, Univ. of Edinburgh*
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John Peacock, *IfA, Univ. of Edinburgh*
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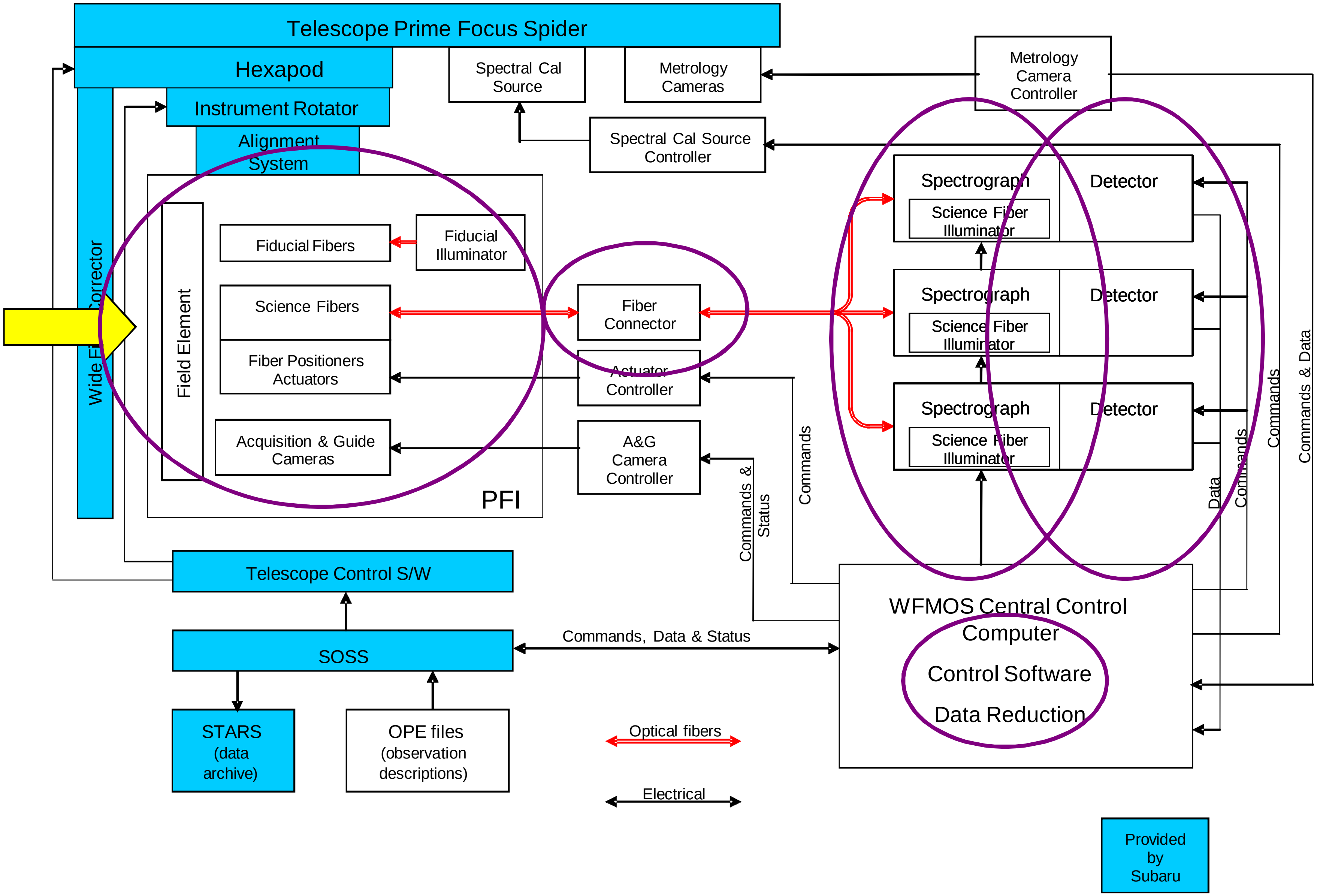
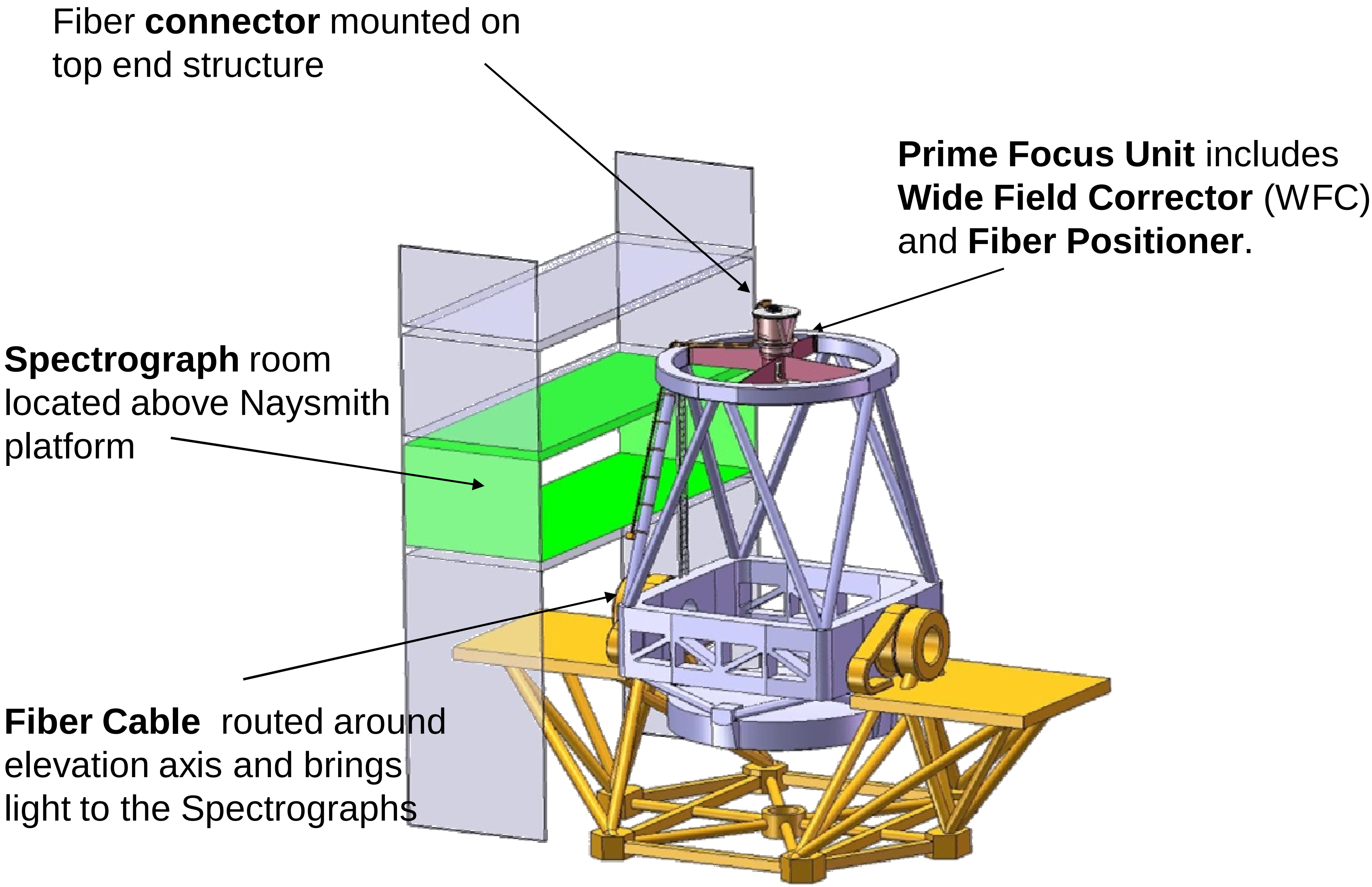
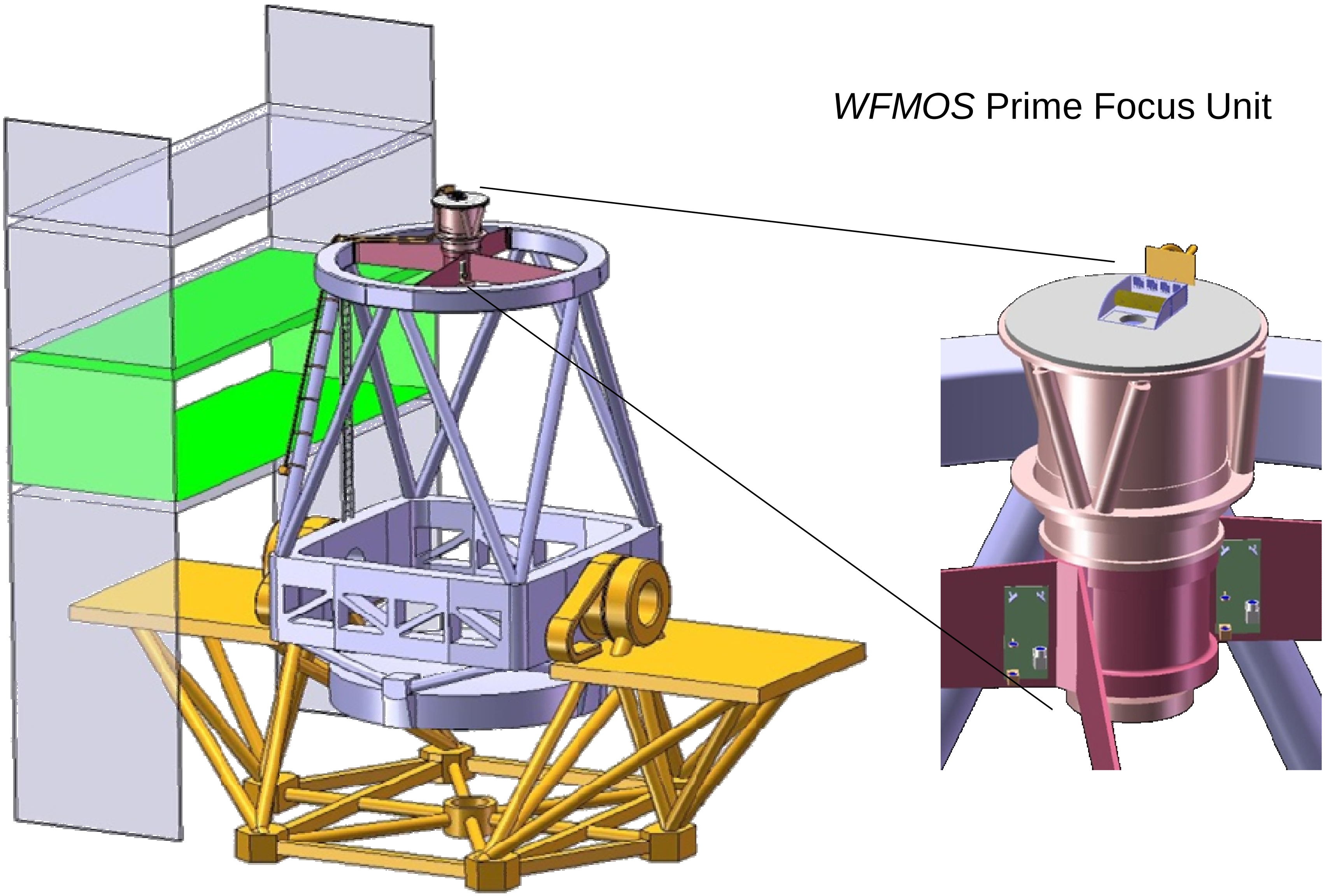
Roger Lee, *JPL*
Norman Page, *JPL*
Lewis Roberts, *JPL*
S. Tere Smith, *JPL*
Ron Steinkraus, *JPL*
Karl Reichard, *Penn State University*
Antonio Cesar de Oliveira, *LNA, Brazil*
Ligia Souza de Oliveira, *LNA, Brazil*

WFMOS System Block Diagram

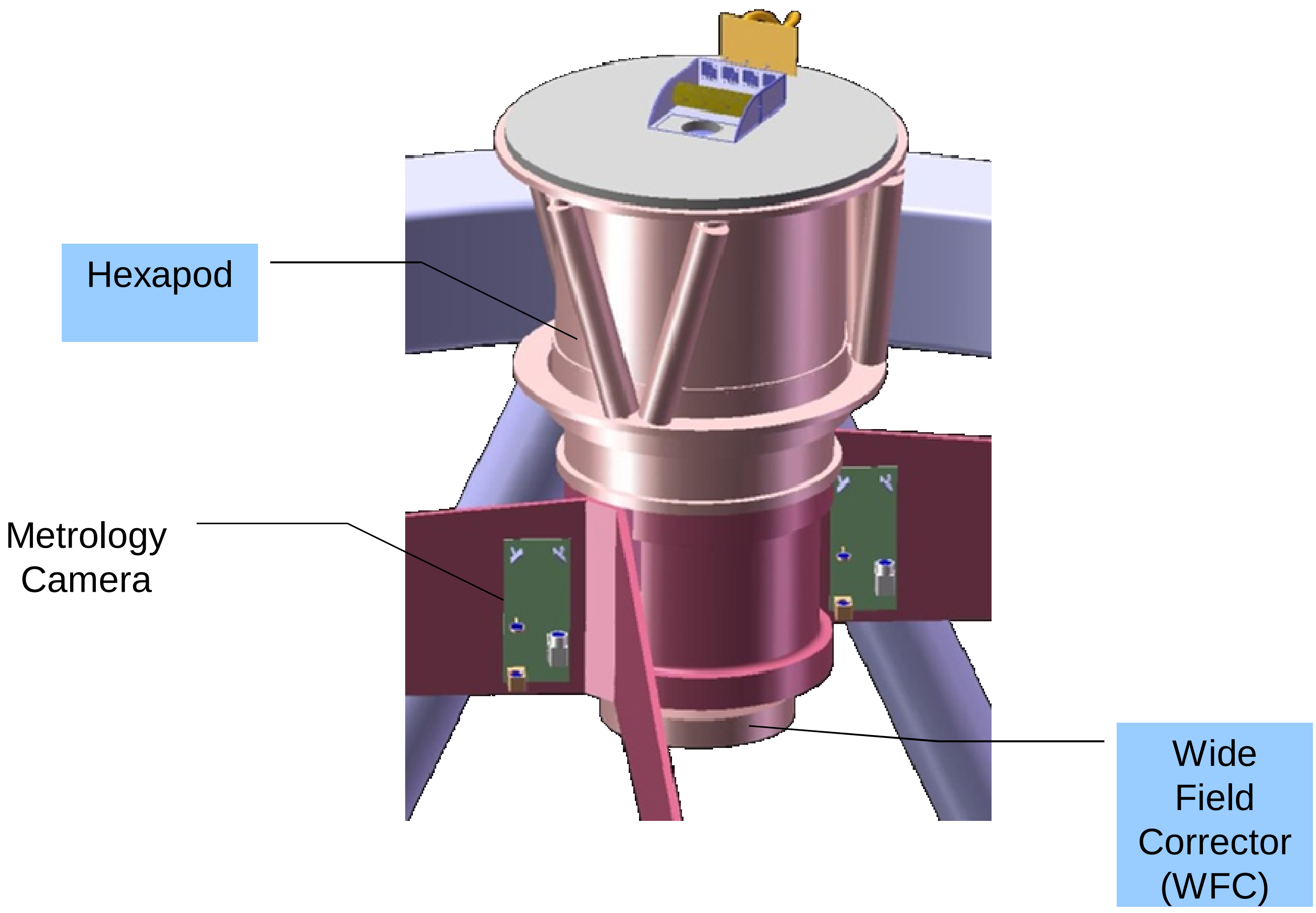


WFMOS on Subaru

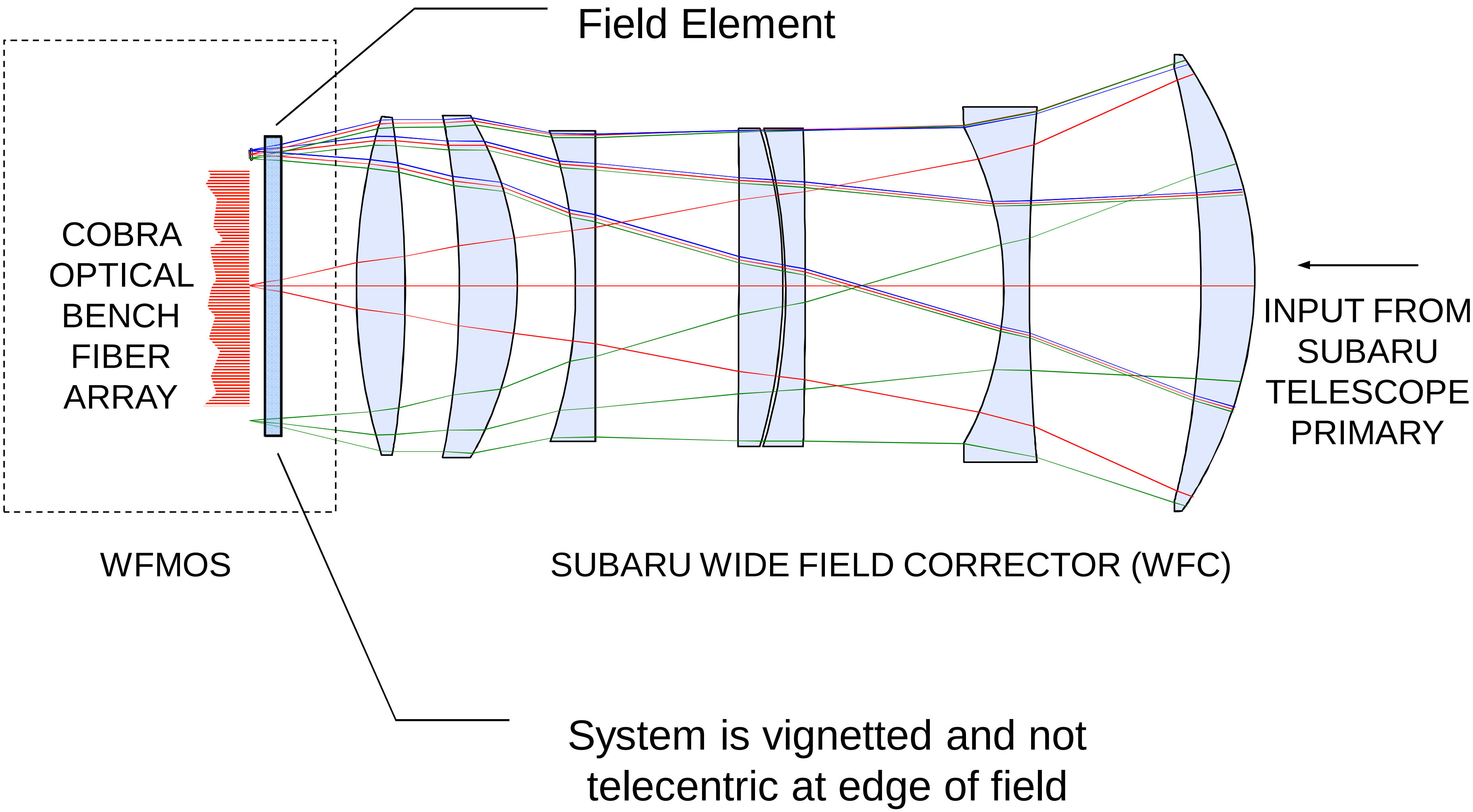



WFMOS Prime Focus Unit

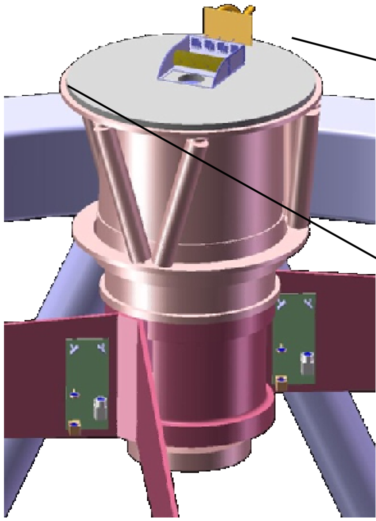
WFMOS Prime Focus Unit

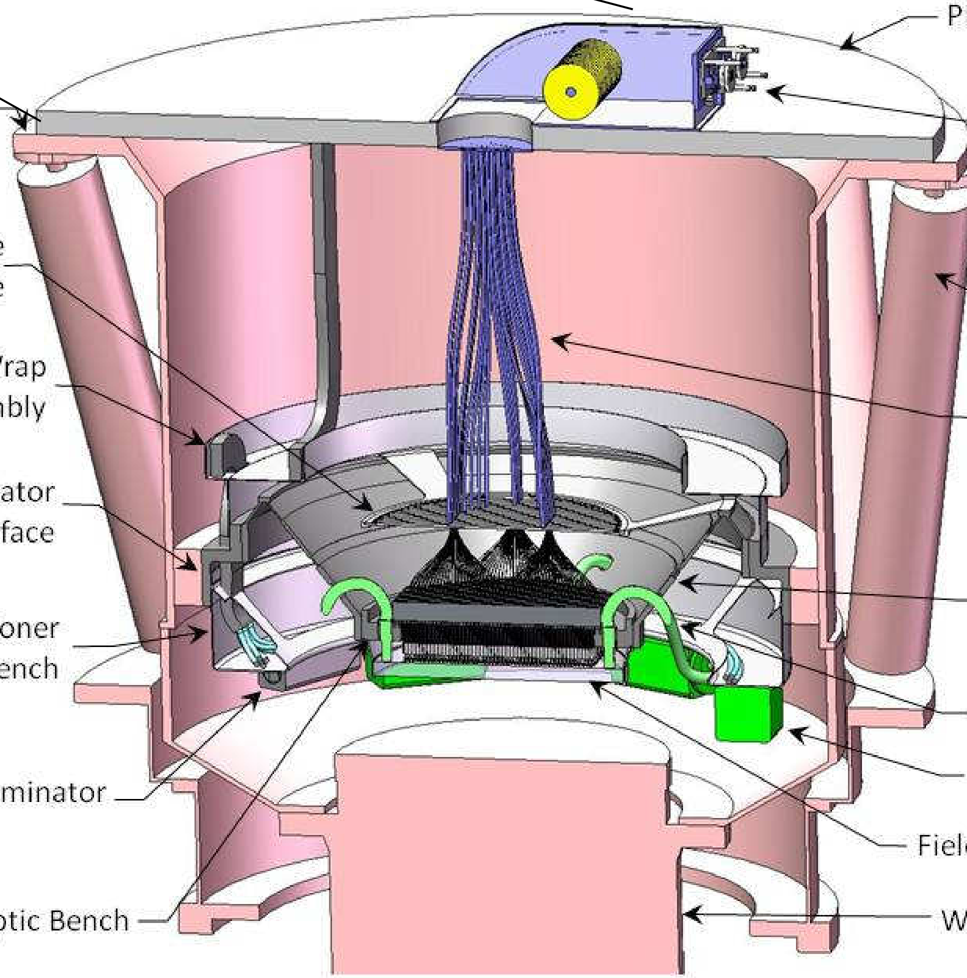


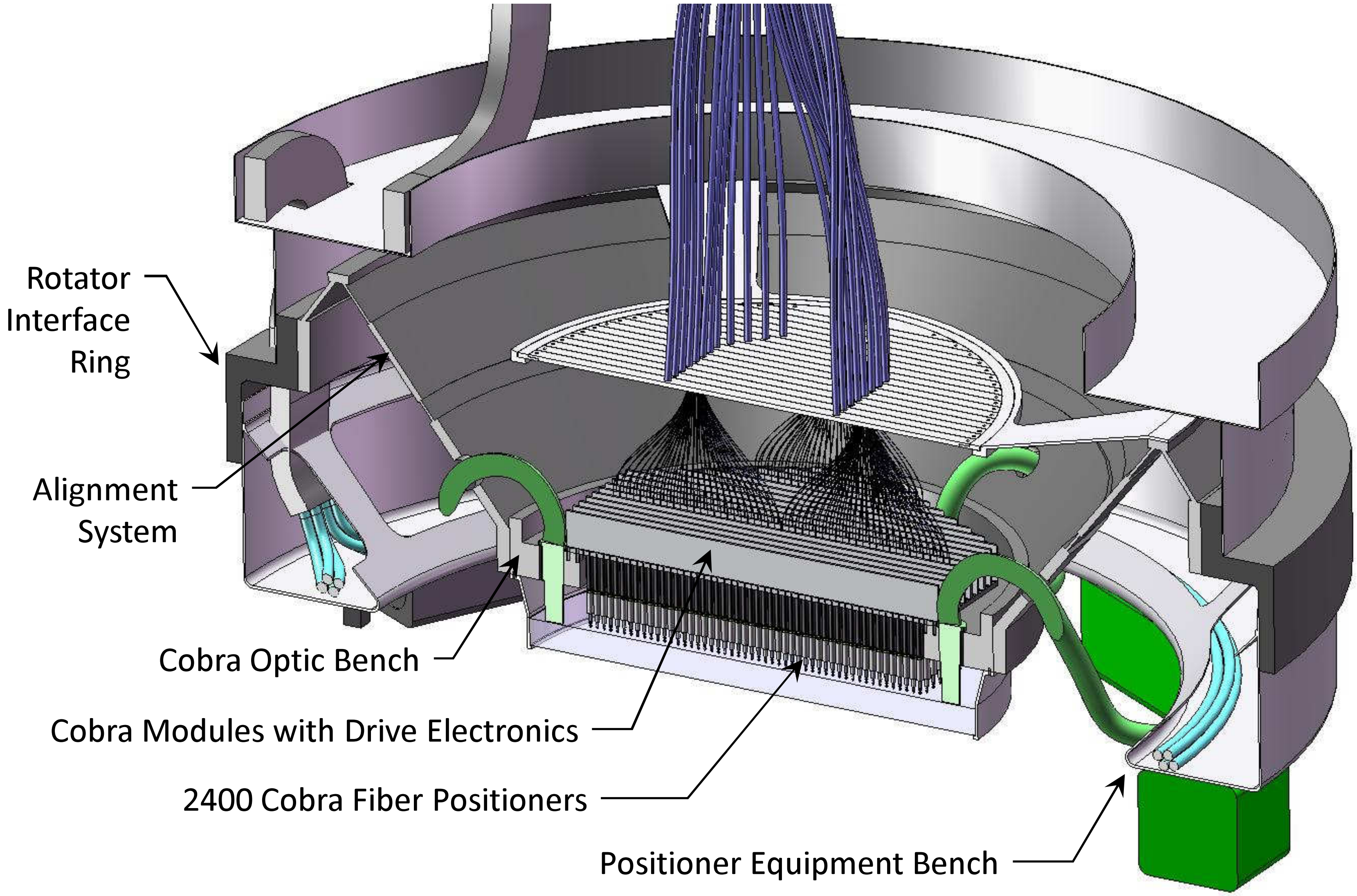
Wide Field Corrector

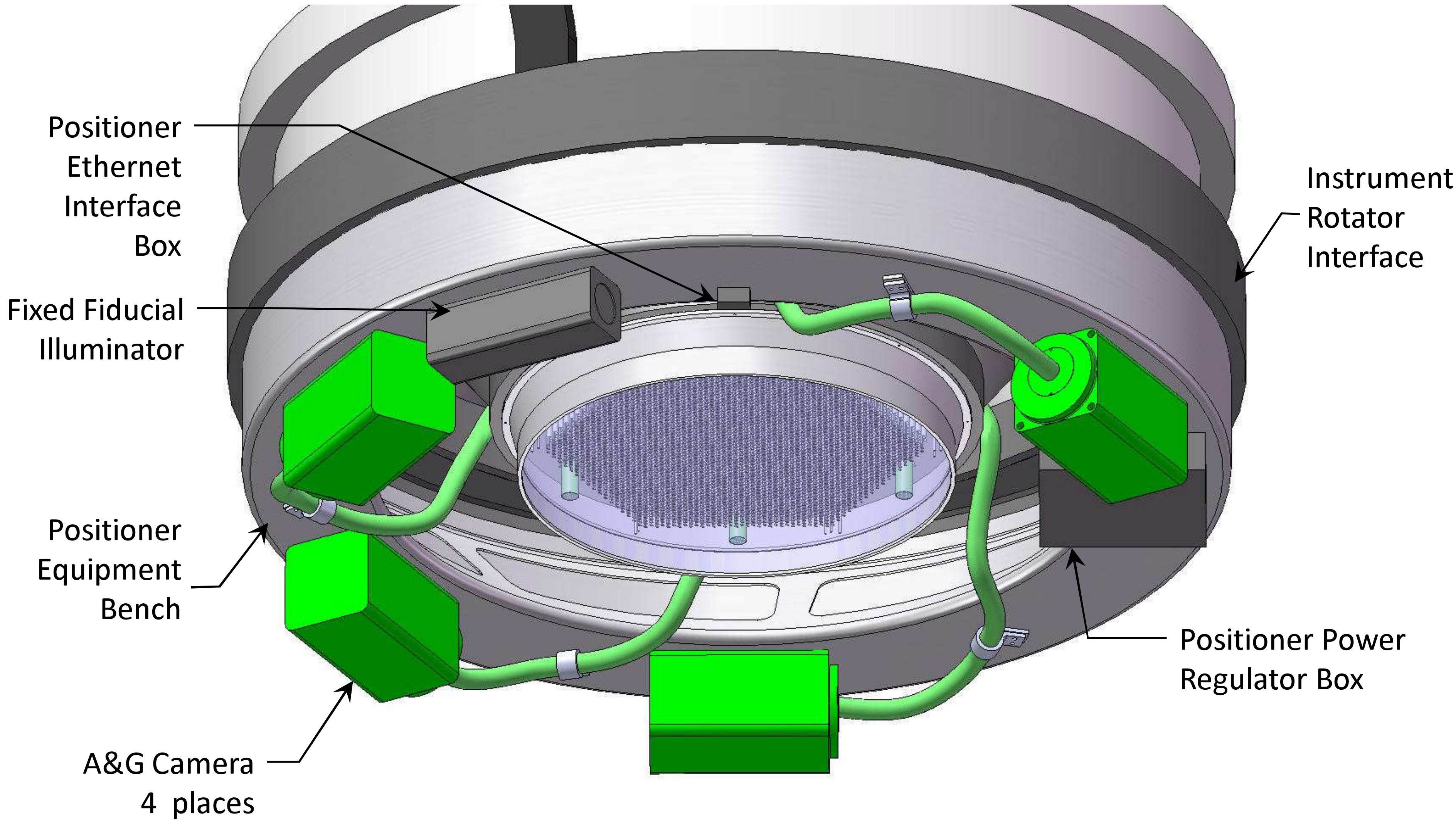


WFMOS Prime Focus Instrument (PFI)

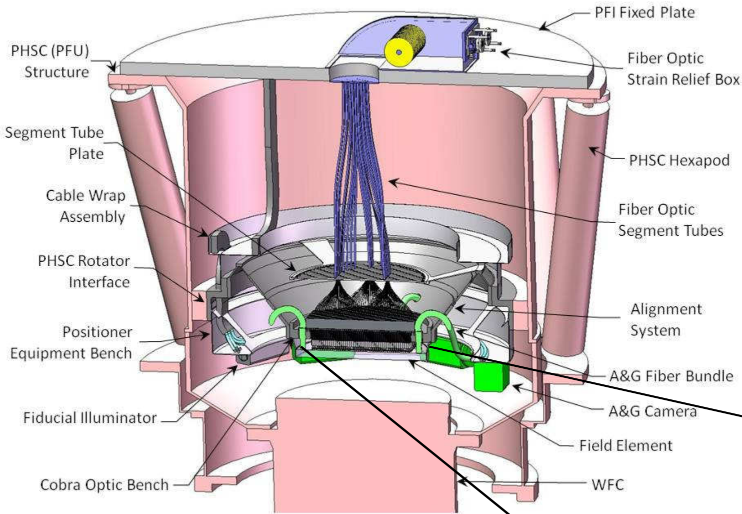


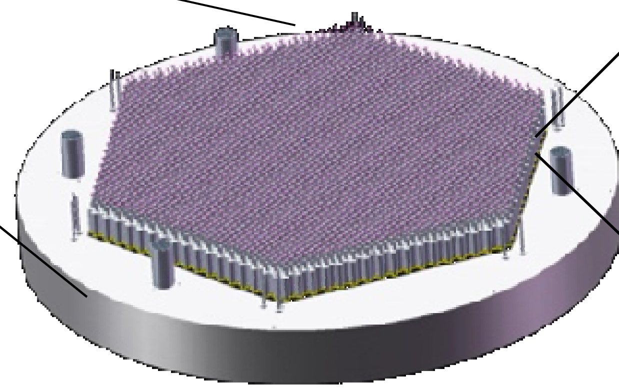



Rotator Interface Ring
Alignment System
Cobra Optic Bench
Cobra Modules with Drive Electronics
2400 Cobra Fiber Positioners
Positioner Equipment Bench

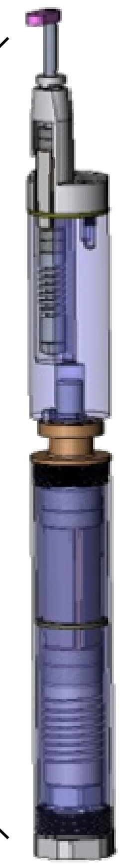

Positioner Ethernet Interface Box
Fixed Fiducial Illuminator
Instrument Rotator Interface
Positioner Equipment Bench
Positioner Power Regulator Box
A&G Camera 4 places

WFMOS Positioner



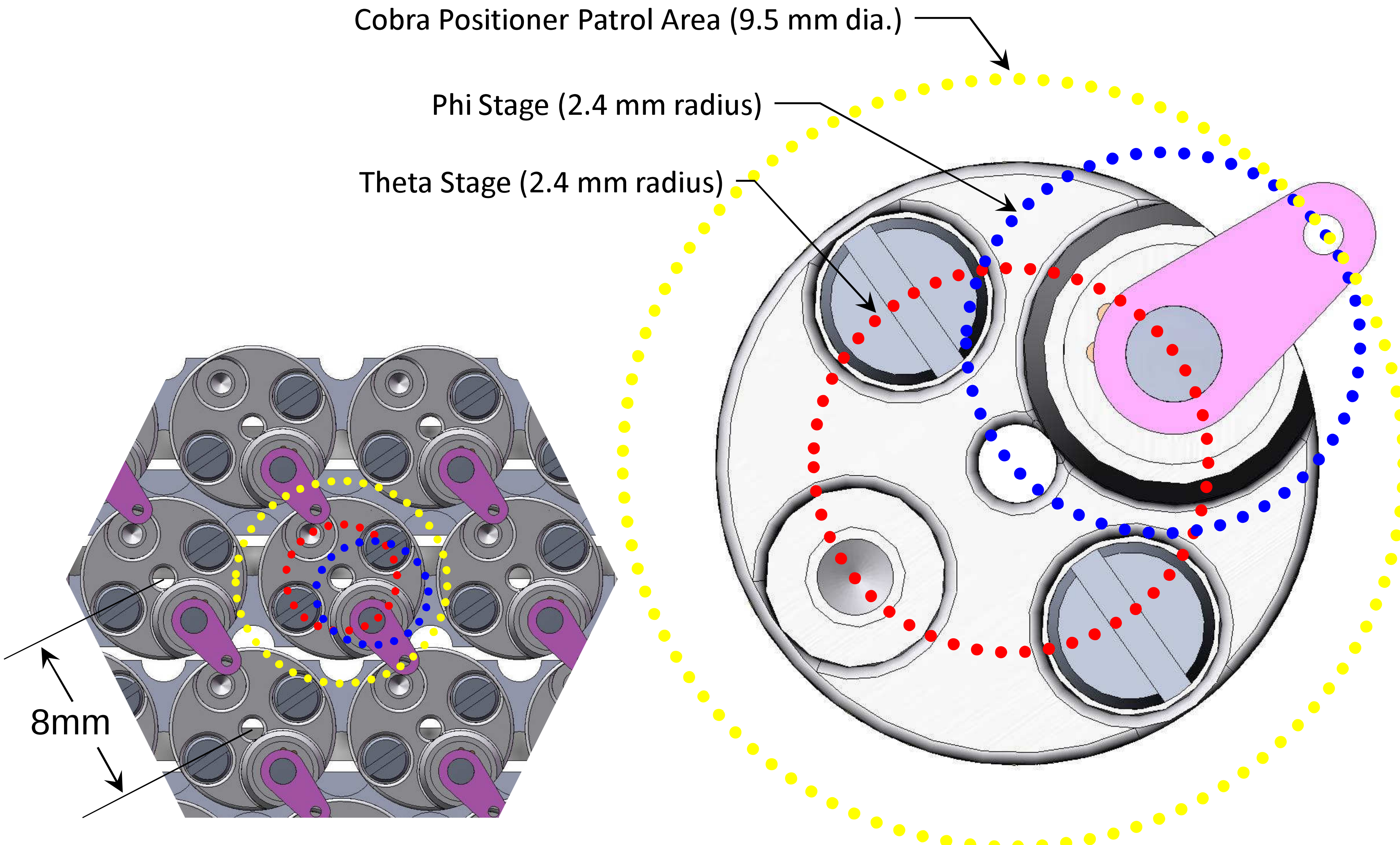


Optical Bench with 2400 Positioner Units

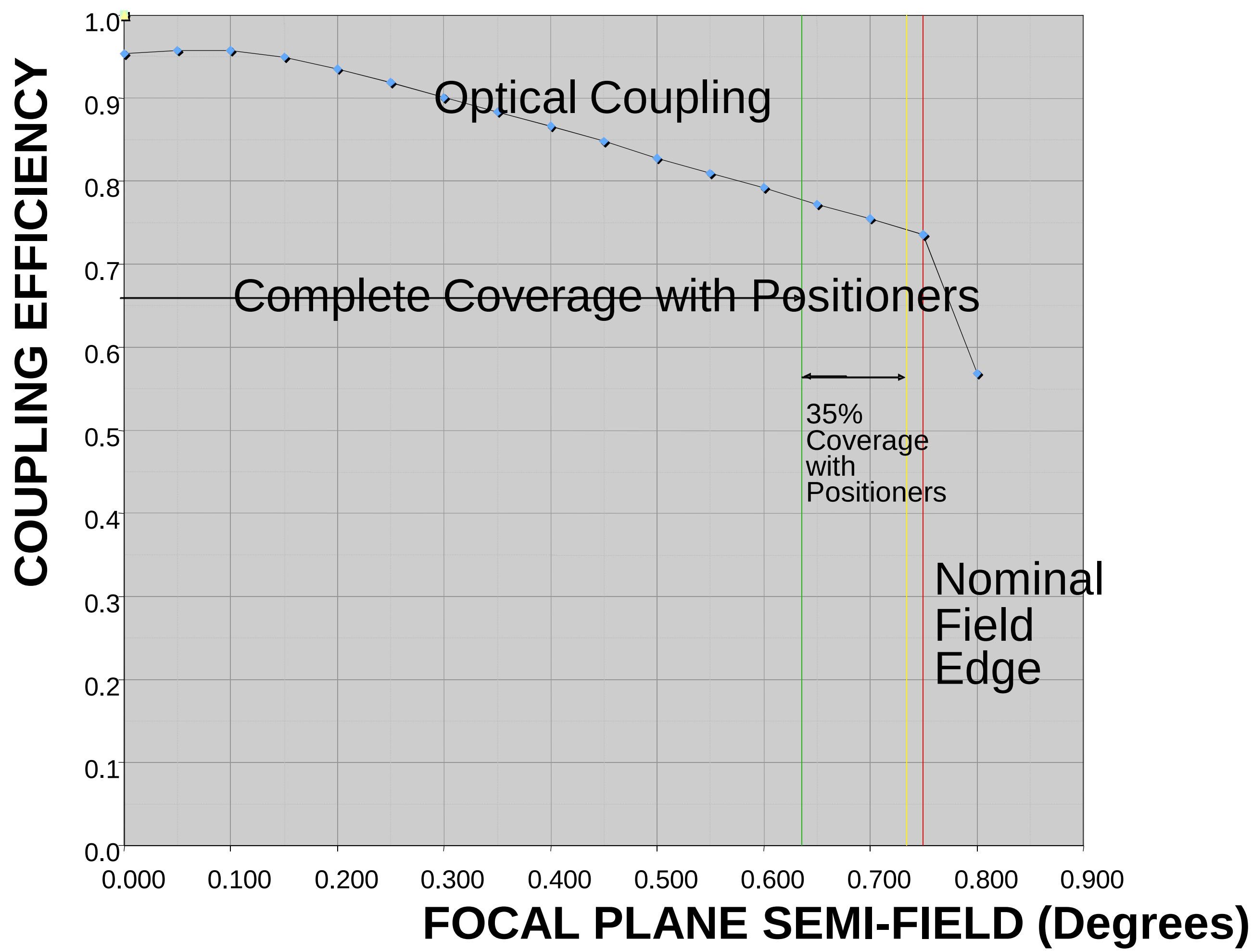


1 Positioner Unit - *Cobra*

Geometry

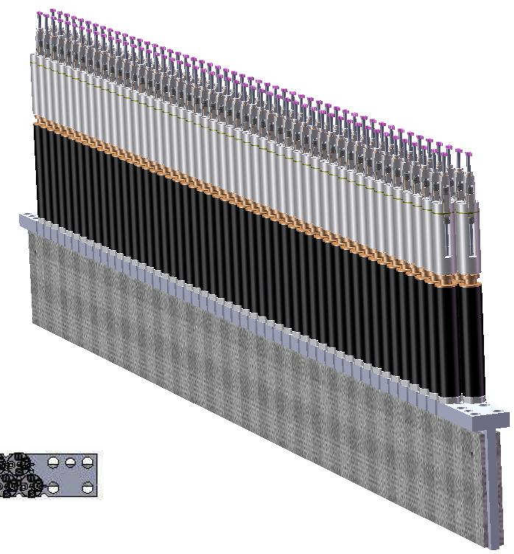

Cobra Positioner Patrol Area (9.5 mm dia.)
Phi Stage (2.4 mm radius)
Theta Stage (2.4 mm radius)
8mm

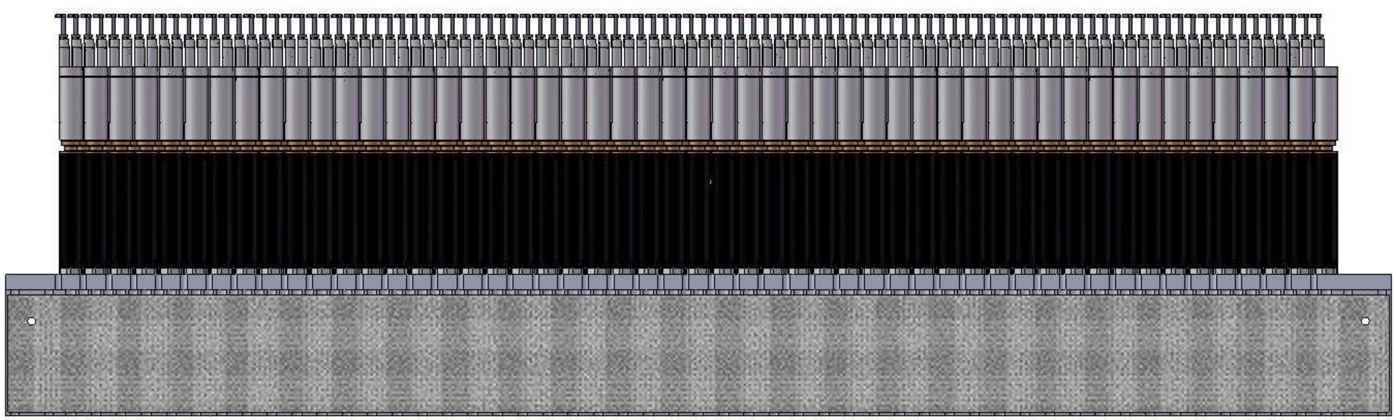
Optical coupling versus position in field

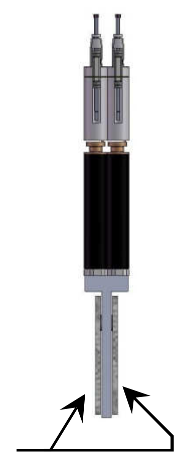


Module

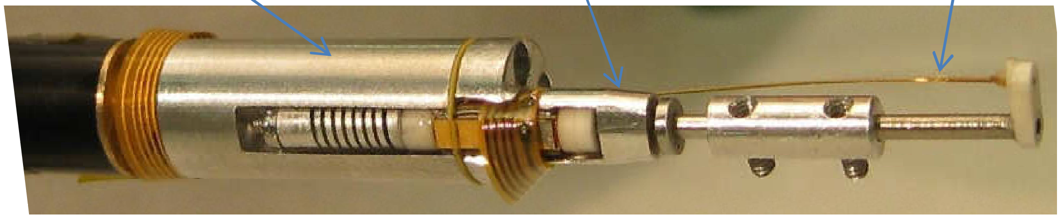
- A module is a subassembly of actuators and drive electronics boards
  - Staggered production
  - Parallel module integration
  - Early mechanical and electrical functional testing
  - Parallel fiber integration to reduce schedule
  - Increases serviceability



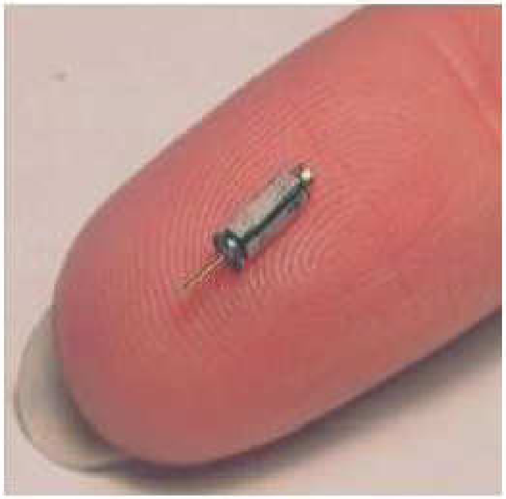




Prototype



Motors



Commercially available rotating tube motor:

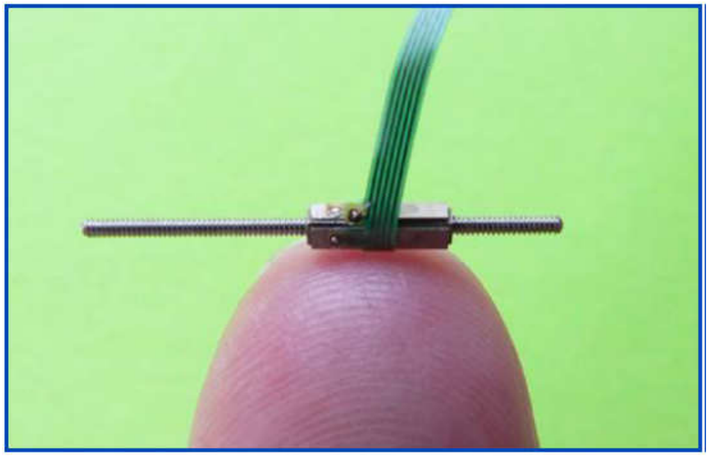
direct drive – no backlash

High torque when stationary and unpowered

~ 1 mN-m powered torque

1 μrad resolution

1 – 10 rev/sec speed



Commercially available linear actuator:

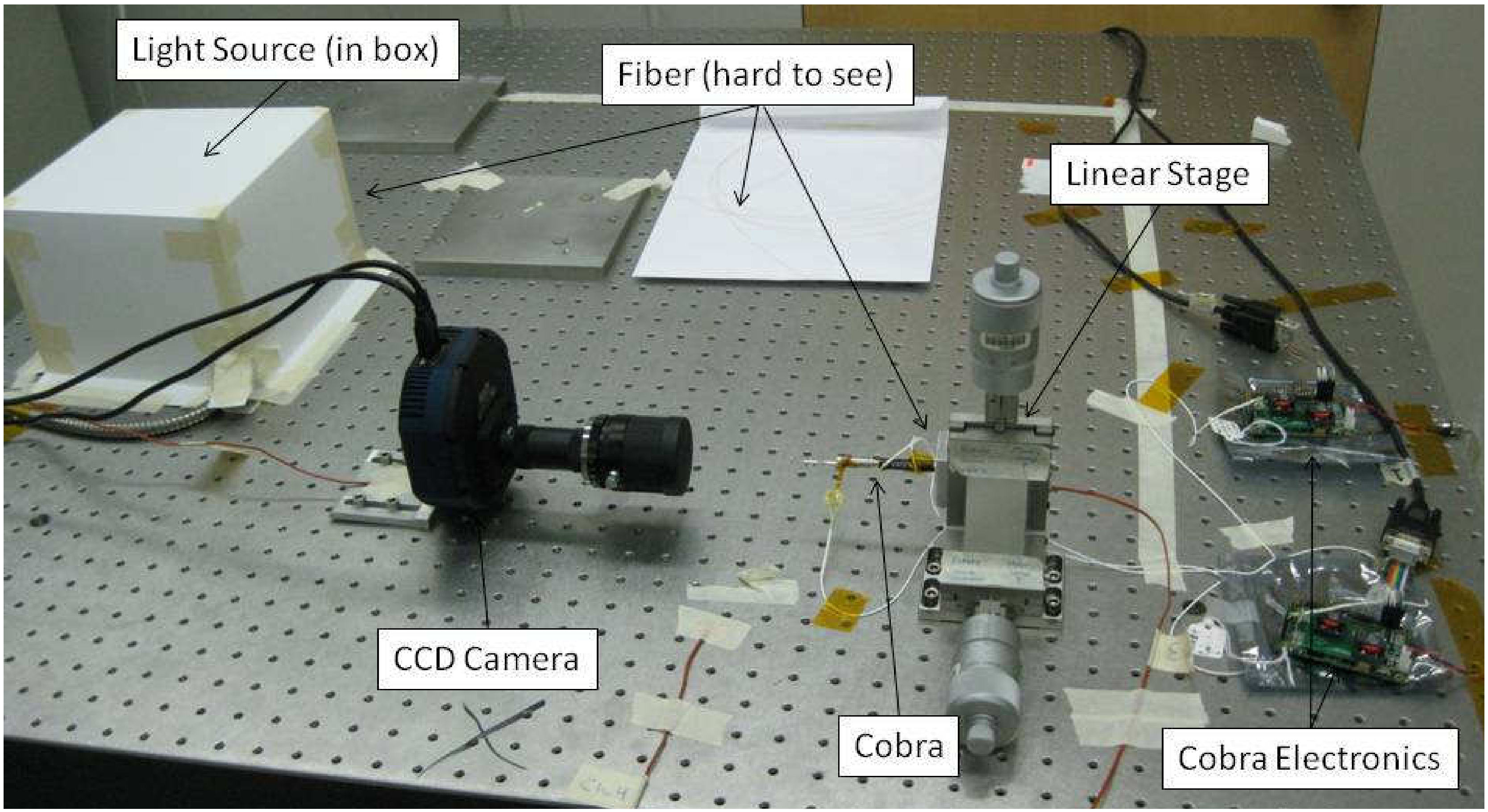
0.2 N stall force

6mm throw

0.5 μm resolution

5 mm/sec speed

JPL Prototype Testbed



Video clip of prototype

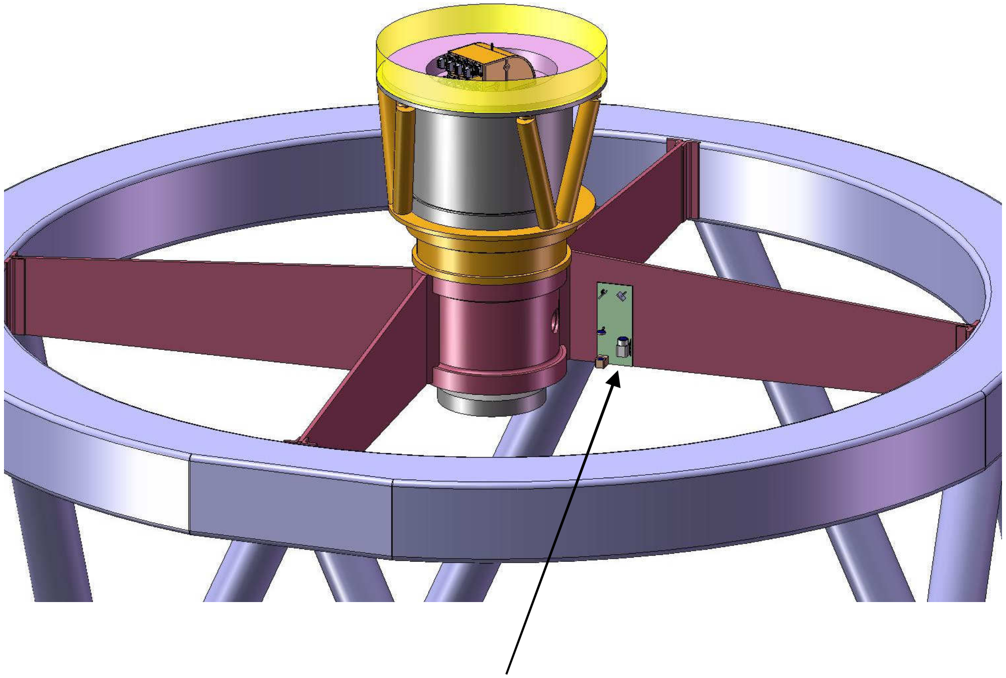
Fiber Position Measurement

- Metrology cameras view back-illuminated science fibers.
  - Fibers are illuminated in 3 groups of 800 to distinguish fibers in overlapping patrol regions
  - One illumination system in each spectrograph.

- Measurement of science fiber positions is referenced to a system of fixed, back-illuminated fiducial fibers.
  - Optical distortions exist in metrology optics, WFC optics, etc
  - Fixed fiducials provide a reference frame for measuring and modeling distortions
  - Straight-through spectrograph mode used to verify fiber placement accuracy

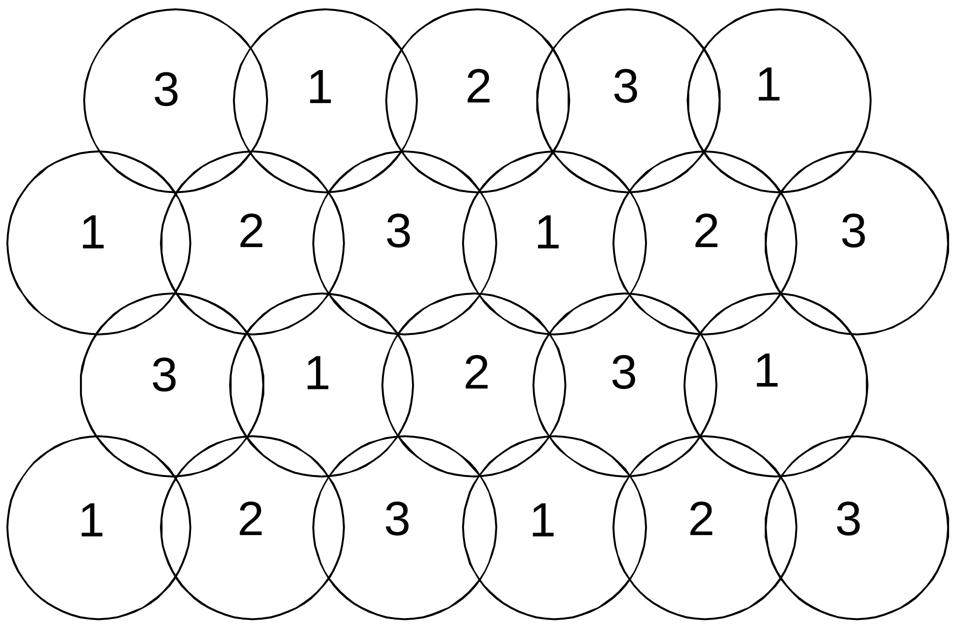
Metrology Camera

- Four camera systems each looking at a ¼ of the focal plane.
- Located on prime focus support struts looking back at positioner focal plane via primary
- Science fiber position will be established relative to set of fixed fiducial fibers on positioner focal plane



Metrology camera (1 of 4 shown)

Fiber illumination sequence



The science fibers are back-lit in a sequence to allow discrimination between fibers in the overlap regions between adjacent fibers.

Only a third of the fibers will be illuminated at one time.

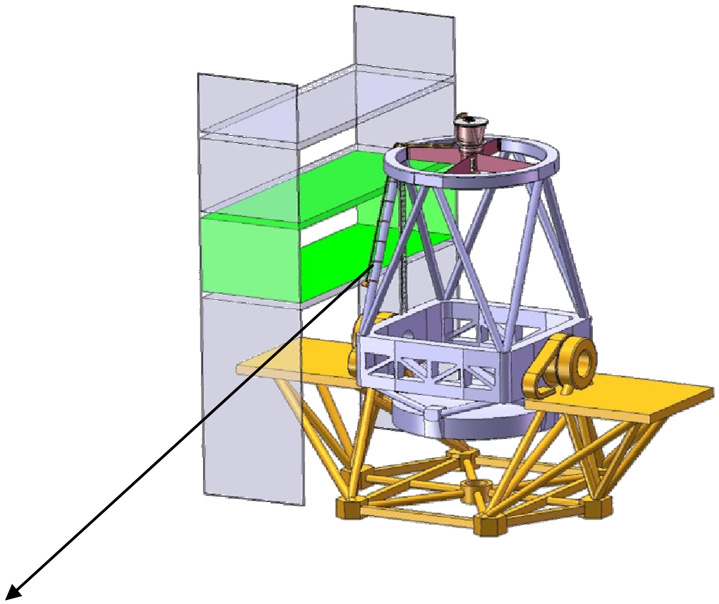
In one exposure only the fibers marked (1) are illuminated, the next exposure only the ones marked (2) are illuminated, etc.

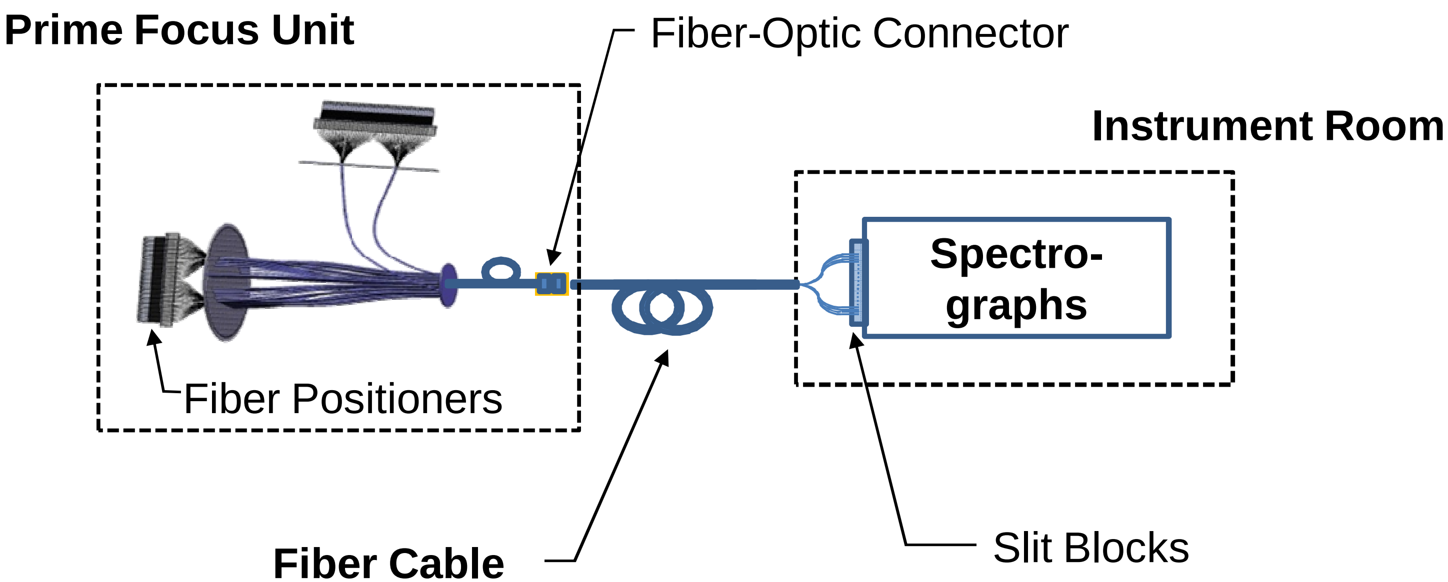
Parallel Configuration

- Positioner configuration – metrology loop: 40 seconds
  - Positioner moves elements in 3 groups of 800
  - Metrology camera views back-illuminated fibers. Fibers are illuminated in 3 groups of 800.
  - Movement, illumination, camera readout, computation in parallel
  - 6 iterations can be completed in < 40 seconds

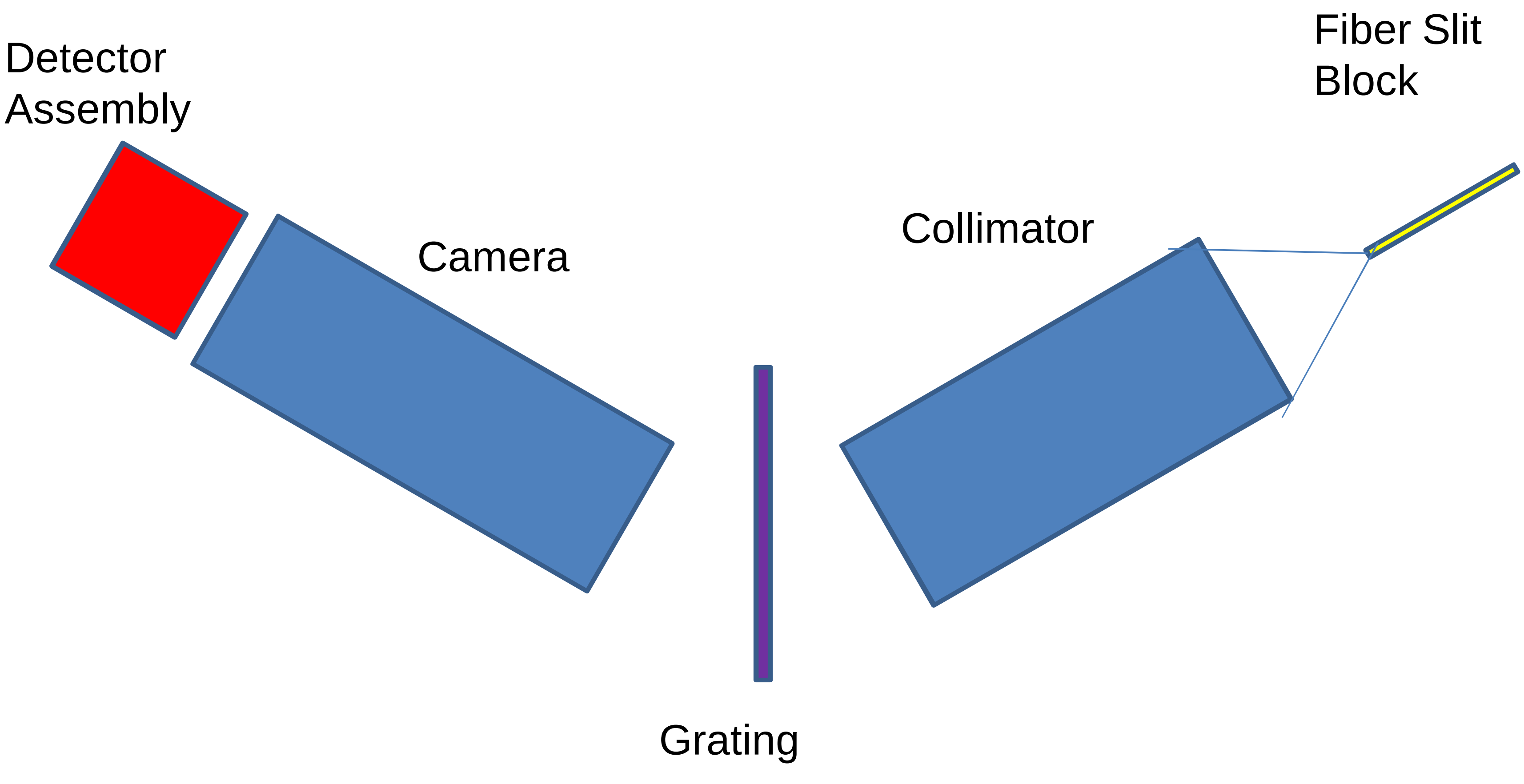
Start Time	Duration (s)	Steps being Taken in Parallel		
0	1	Move A-1		
1	2	Image A-1	Move B-1	
3	2	Compute A-1	Image B-1	Move C-1
5	2	Move A-2	Compute B-1	Image C-1
7	2	Image A-2	Move B-2	Compute C-1
9	2	Compute A-2	Image B-2	Move C-2
11	2	Move A-3	Compute B-2	Image C-2
13	2	Image A-3	Move B-3	Compute C-2
15	2	Compute A-3	Image B-3	Move C-3
17	2	Move A-4	Compute B-3	Image C-3
19	2	Image A-4	Move B-4	Compute C-3
21	2	Compute A-4	Image B-4	Move C-4
23	2	Move A-5	Compute B-4	Image C-4
25	2	Image A-5	Move B-5	Compute C-4
27	2	Compute A-5	Image B-5	Move C-5
29	2	Move A-6	Compute B-5	Image C-5
31	2	Image A-6	Move B-6	Compute C-5
33	2	Compute A-6	Image B-6	Move C-6
35	2		Compute B-6	Image C-6
37	1			Compute C-6
38				

WFMOS Fiber System

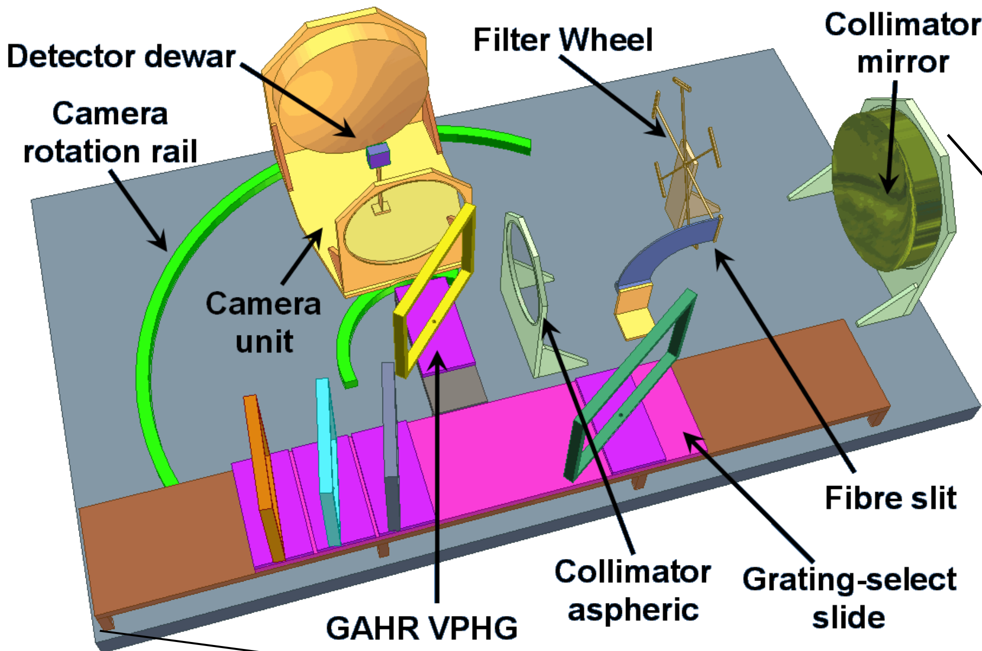


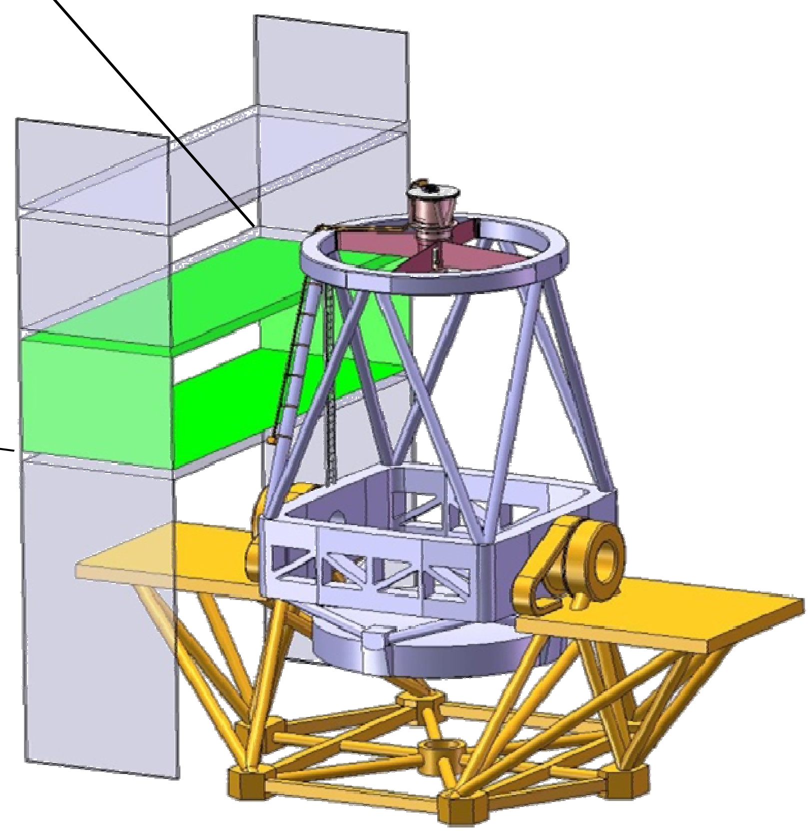


Parts of a spectrometer



WFMOS Spectrographs

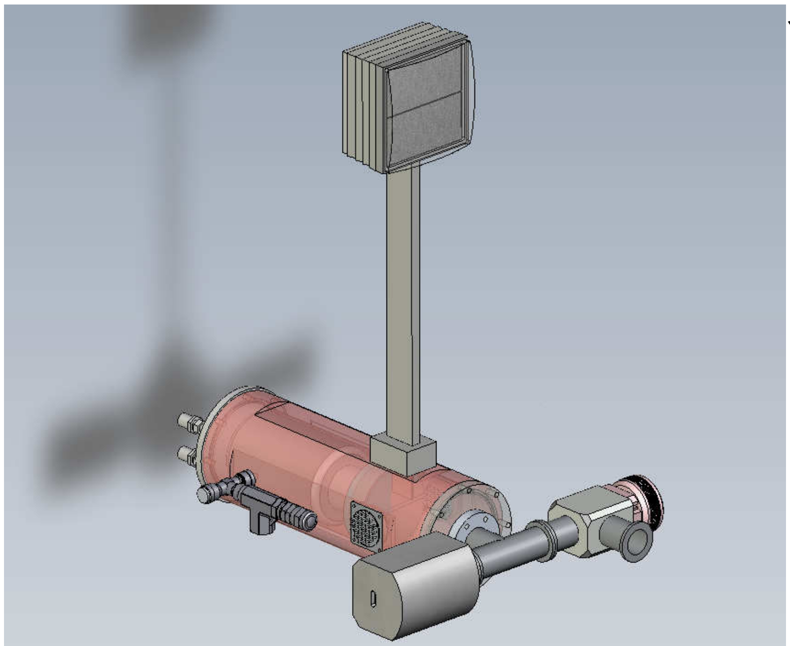


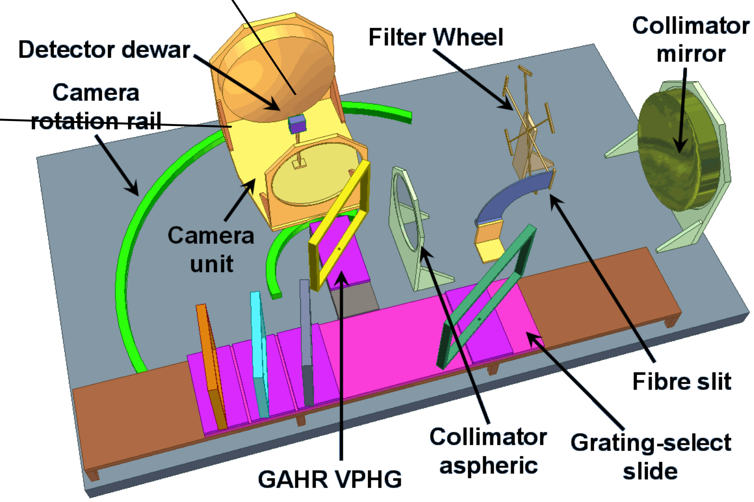


One of three identical units

- Spectrograph modes:
  - Lower resolution modes can support up to 2400 simultaneous spectra with resolution of 1500-5000
  - High resolution (20,000) mode can support 600 simultaneous spectra
  - Straight-through (imaging) mode for test, verification, commissioning

WFMOS Detectors





Detectors emphasize quantum efficiency:

- enhanced red sensitivity
- enhanced blue sensitivity
- anti-reflection coating

- Key challenge of fiber-fed spectrographs: getting the fiber placed accurately on the astronomical target

- Especially challenging for WFMOS:
  - large field of view
  - large number of fibers
  - smaller diameter fiber

- Our design addresses these challenges:
  - positioner design provides high precision
  - attention to differential mechanical flexure
  - error budgets for mechanical tolerances
  - straight-through spectrograph mode facilitates commissioning

Performance Advantages

Design emphasizes efficiency:

- Fast positioner configuration speed
- Mechanically stiff, robust, & precise positioner system
- High quantum efficiency detectors
- Large information gathering power

Next Lecture

Physics of:

Fiber optics

Gratings

Detector Performance

Cosmology with galaxy surveys – an instrument perspective

Michael Seiffert, Jet Propulsion Laboratory, Caltech

Dark Energy in the Universe
Okinawa, Japan
Summer School, 2009

Lecture 1: Introduction to multi-object spectroscopy and existing facilities.

Lecture 2: Scientific impacts of instrument design choices

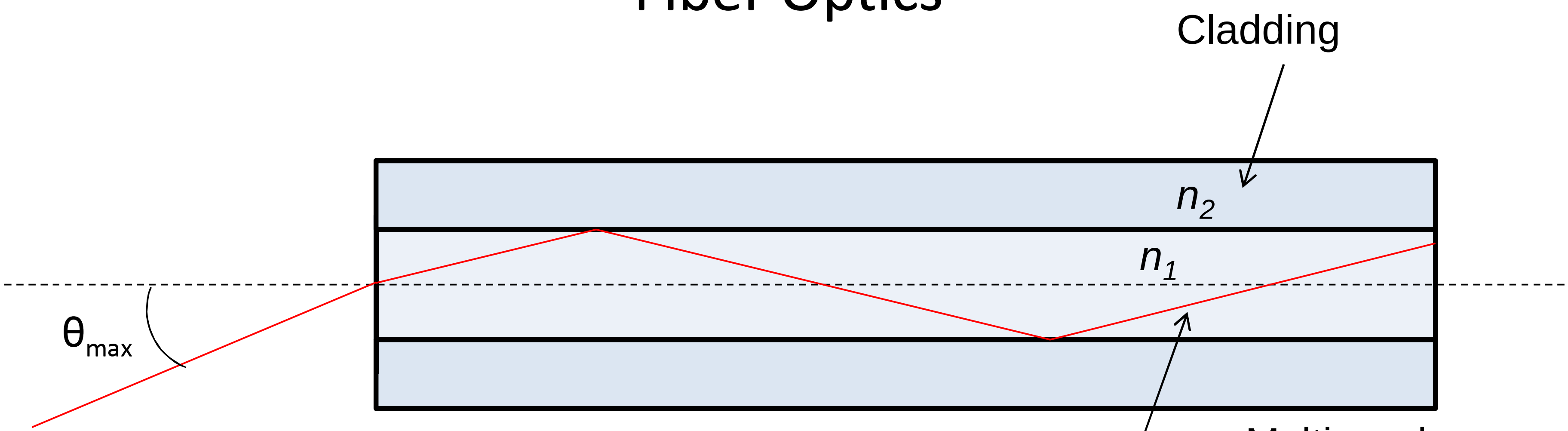
Lecture 3: Physical principles of the instrument and its components - part 1

Lecture 4: Physical principles - part 2   (very simple!)

Topics

- Physical principles of such an instrument
  - How fibers work, non-ideal behavior
  - How diffraction gratings work
  - Detector performance

Fiber Optics



$n_2 < n_1$

There is a maximum angle, θ_{max}, called the acceptance angle, for which light entering the fiber will propagate through total internal reflection. This angle is defined by:

$$NA = \sin\theta_{max} = \sqrt{n_1^2 - n_2^2}$$

NA is called the numerical index

Fiber optics cont'd

- Example of total internal reflection
- If you are underwater and look up at a shallow angle you will not be able to see out of the water
- If you look straight up, you will be able to see out.

Optical fibers – non-ideal behavior

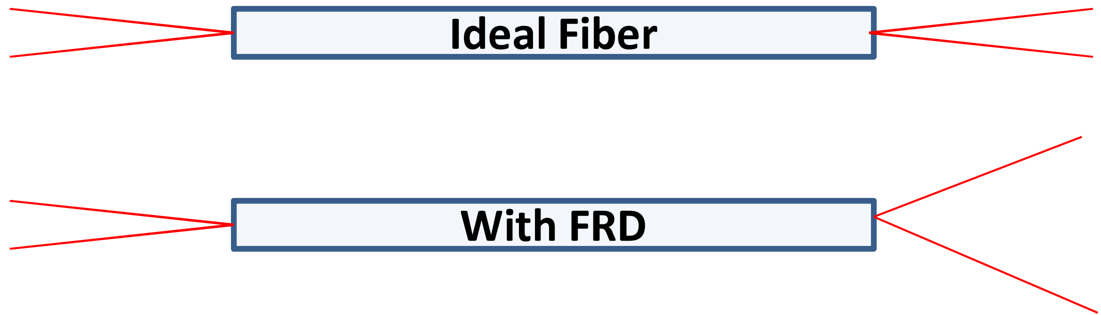
- In addition to the normal fiber losses due to absorption and scattering there are other effects.

- Étendue (the AΩ product) can never decrease, and in a perfect optical system, the AΩ product stays constant.

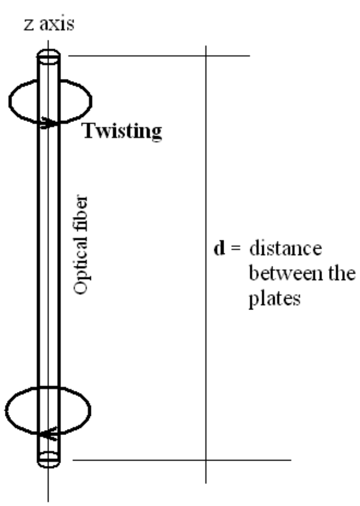
- In a fiber optic system, there are factors (stress, defects, non-uniformities) that tend to increase AΩ.

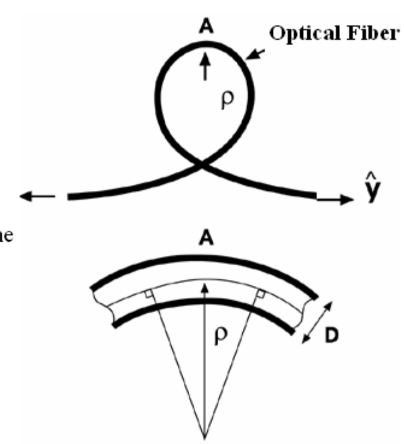
Focal Ratio Degradation (FRD)

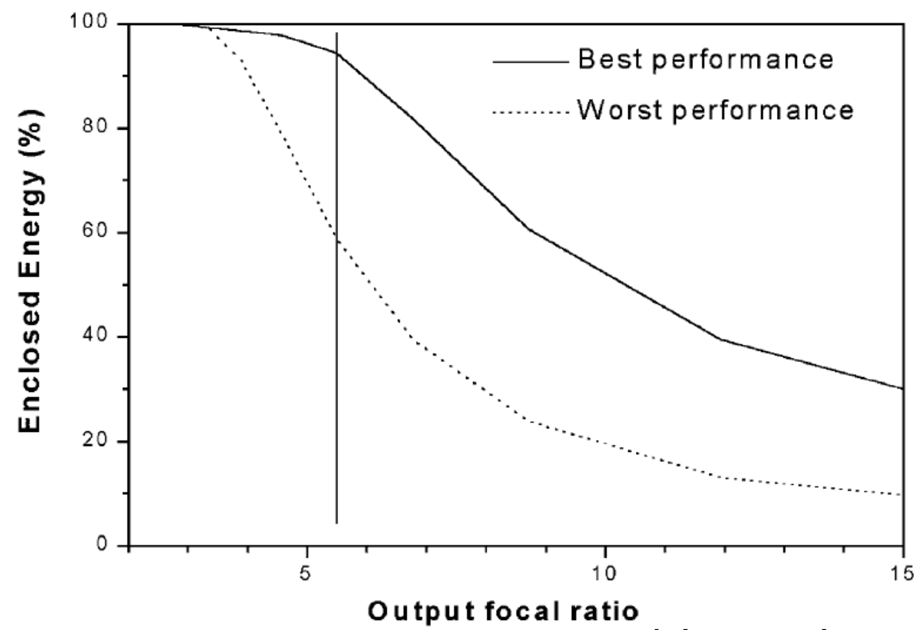
FRD is the phenomenon in which light introduced into a fiber at a narrow cone angle (large f ratio) eventually can spread to a larger angle.



Twisting effect **Coil effect**



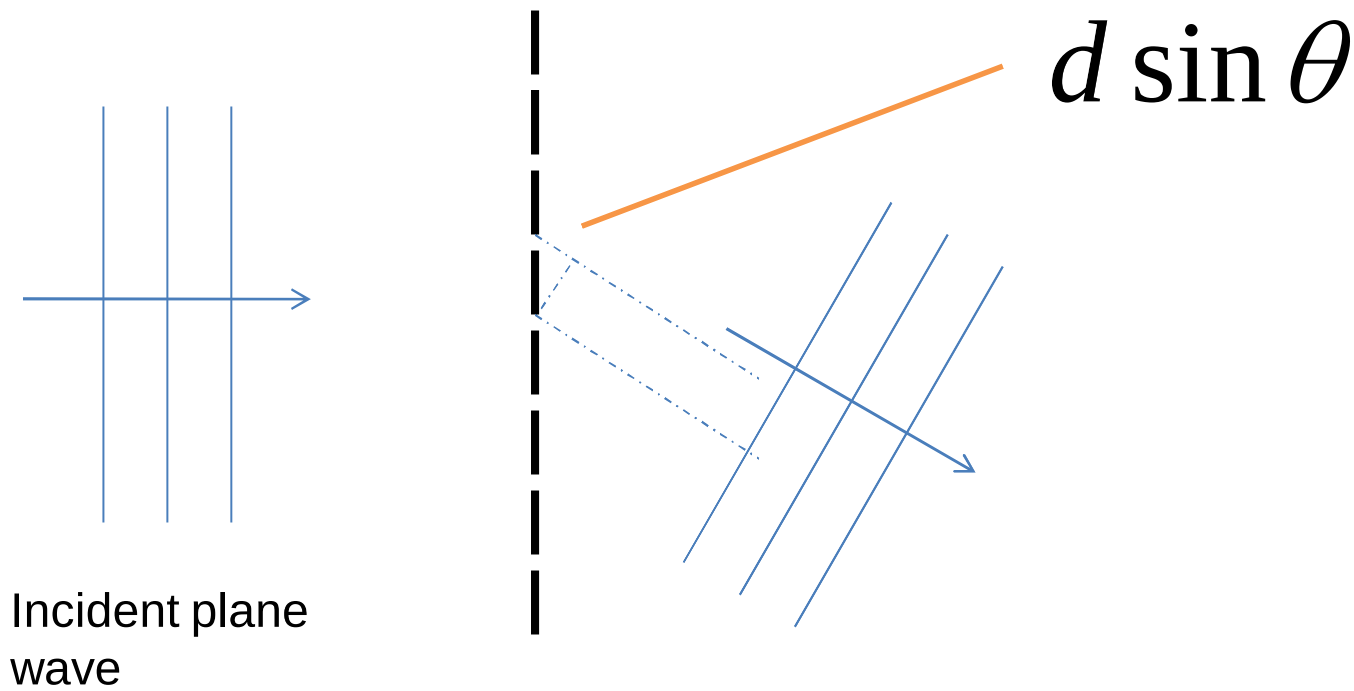




$\approx 1 / (2\, NA)$

Oliveira et al, MNRAS, 356, 1079 (2005)

Diffraction grating – the dispersing element in the spectrometer



$$d \sin\theta = m\lambda$$

Grating equation
m is the "order"

- Maximum wavelength that the grating can diffract is twice the period (such that the diffraction angle is less than 90 deg)

$$|m|\lambda < 2d$$

- Spectra from different orders can overlap. The greater the order, the greater the spectral overlap.

$$\lambda + \Delta\lambda = \frac{m+1}{m}\lambda \quad \Longrightarrow \quad F_{\lambda} = \frac{\lambda}{m}$$

- The problem can be cured by either 1) using filter to get rid of the unwanted orders ("order sorting"), or 2) using additional optical elements to "cross disperse" the spectrum to avoid overlap.

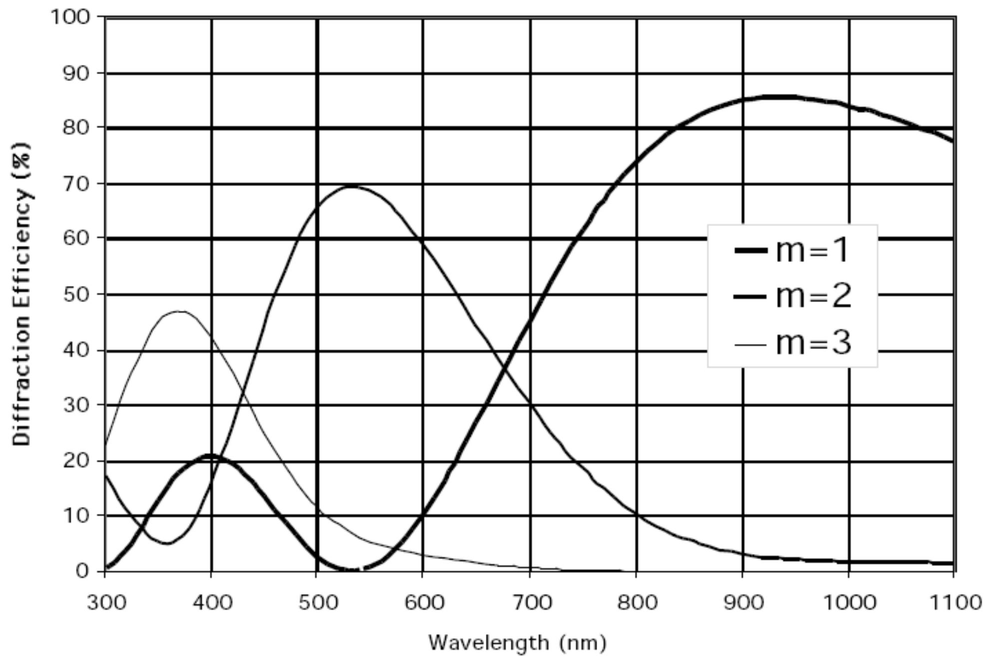
- Resolving power $R = \frac{\lambda}{\Delta\lambda} = mN$

Gratings for high-efficiency astronomy

- Volume Phase Holographic Gratings (VPHG)

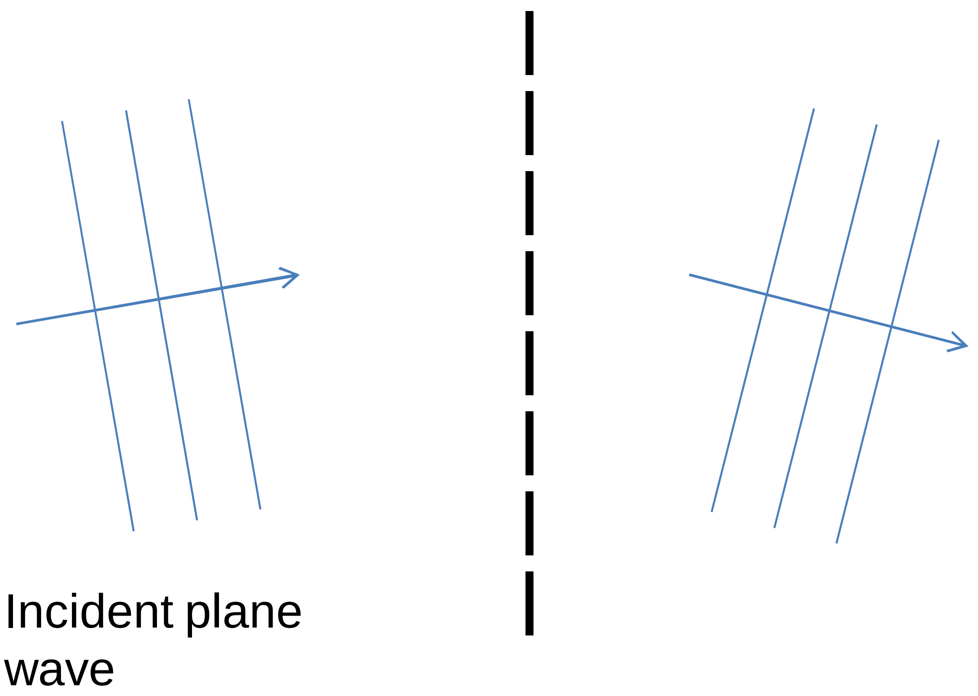
- Basic principle: diffraction is generated from the modulation of the refractive index, n, in a film of material sandwiched between glass plates

Example predicted performance of a VPHG



Arns, Colburn, and Barden, Proc. SPIE, 3779:313 (1999)

In practice – don't use normal grating incidence
Efficiency can be tuned by varying the incident angle



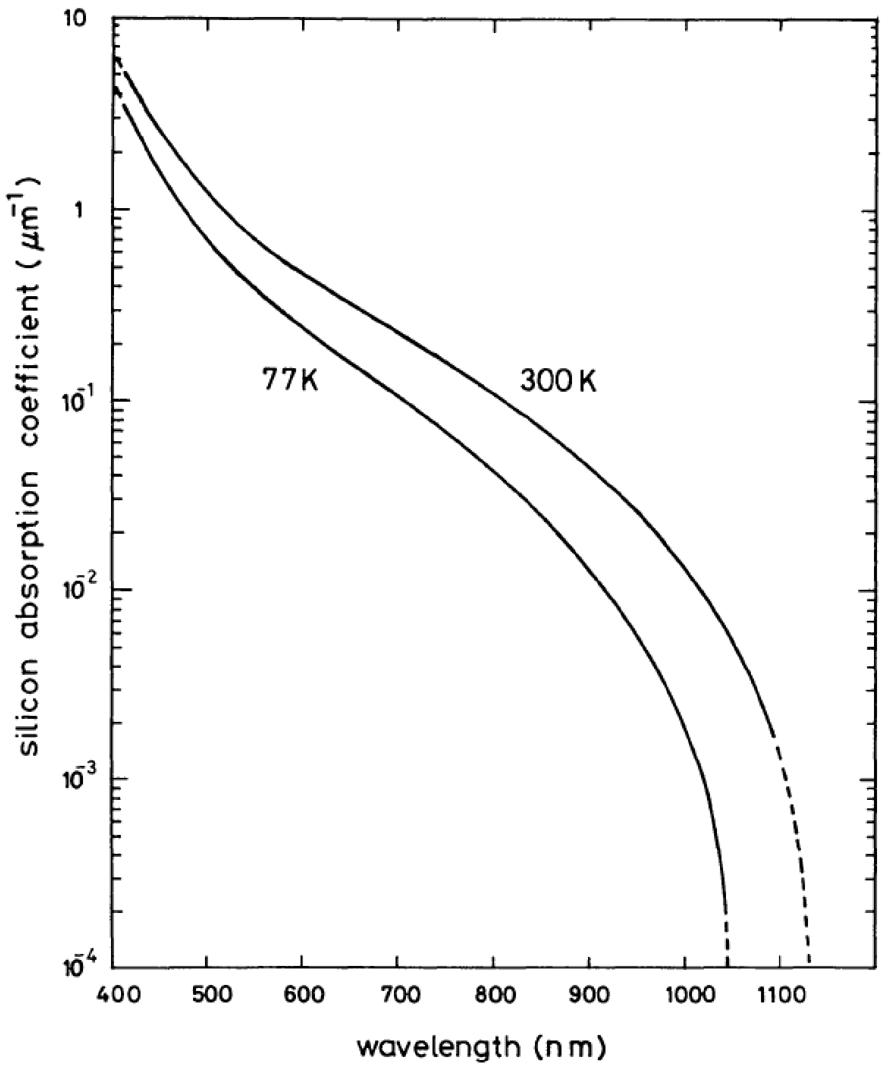
CCDs

- CCD = Charged Coulpled Device – a type of Silicon detector with a specific readout scheme.

- An incident photon is absorbed in the Silicon and creates an electron – hole pair. The electron charge is stored in a potential well created by electrodes. The charge is eventually swept to the edge of the chip and “read out” by an amplifier that interfaces to our electronics systems.

Detecting the photons requires absorbing them in Silicon. Absorption depth depends on wavelength; Silicon becomes essentially transparent above roughly 1 μm.

Early generations of CCDs were a few 10s of μm thick. Among other considerations thicker CCDs had problems with charge diffusion. Newer chips have addressed this and thicknesses of order several hundred μm thick are now possible (and being used in HSC, for BOSS, etc)



Mackay, ARA&A, 24,255,(1986)

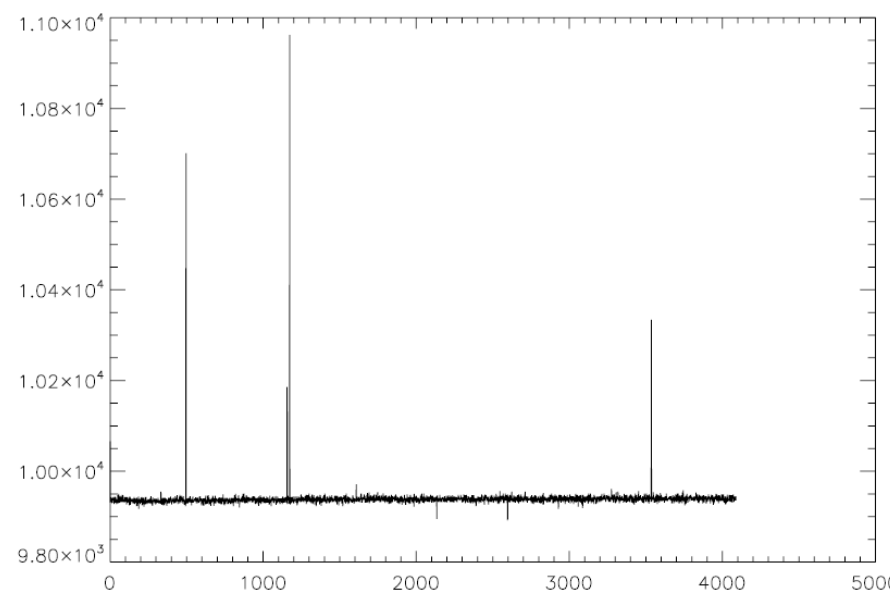
Noise

Major sources of noise:

- Dark current (carriers generated by thermal effects rather than photons): $I = A\exp(-B/kT)$

- Read Noise – additional noise due to the amplifier processes and added to every sample of pixels during the readout process

Cosmic Rays – contaminate some fraction of the pixels (1 row of one detector from 1800 s dark image on SuprimeCam)



Noise – cont'd

What can we do about the noise sources:

- Dark current: cool the detector (but note absorption depth)

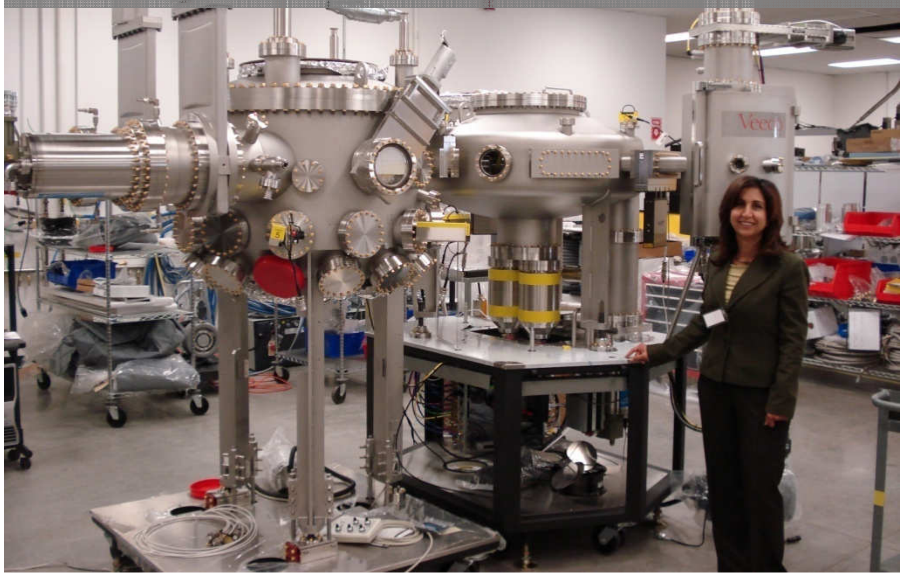
$$I = A\exp(-B/kT)$$

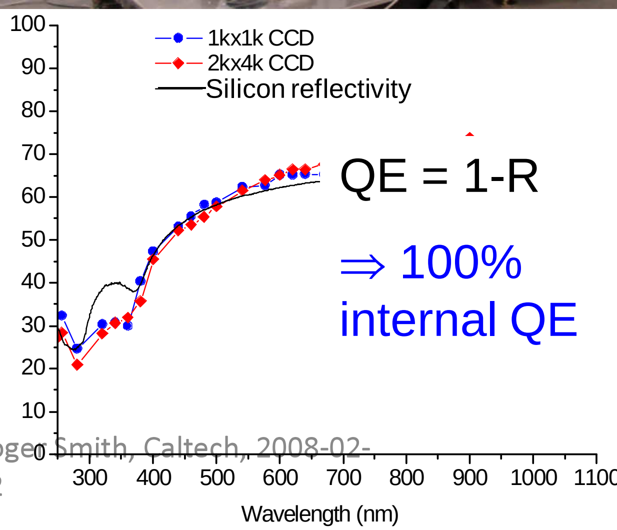
- Cosmic Rays: strategy is to make multiple exposures of the same field and use median filtering to eliminate cosmic ray hits – requires more frequent read outs

- Read Noise – fixed noise per sample – use longer, less frequent exposures.

Delta doping by JPL for high blue QE

Shouleh Nikzad, JPL delta doping team lead, and new 8" wafer MBE machine fm Veeco

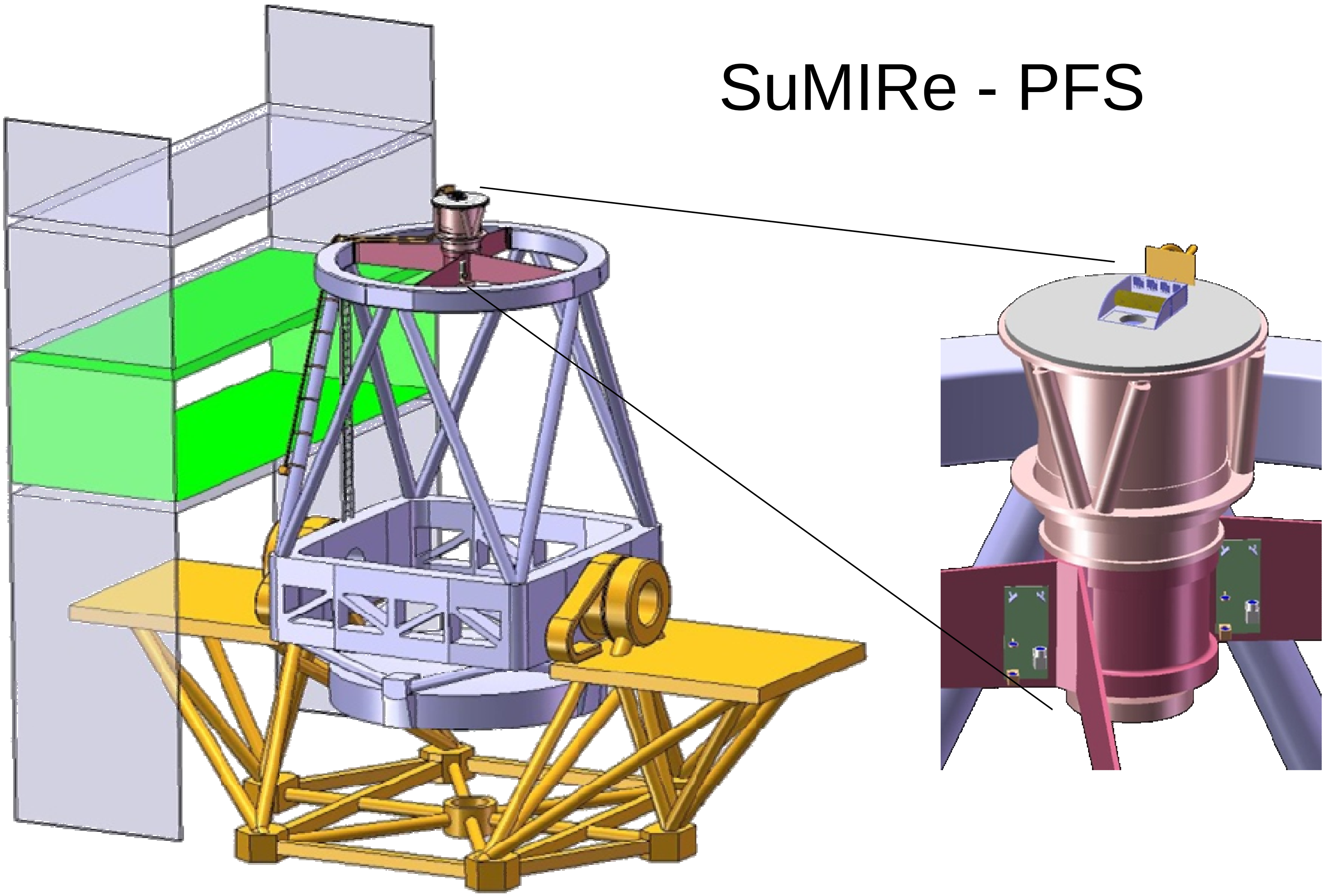




- High density mono-atomic dopant layer deposited by MBE.
- Forms conductive backside contact without absorption or backside potential well to trap charge generated near surface.
- Allows high performance AR coating.
- Simpler fabrication process than ISDP+ITO used by LBL.

⇒ **higher yield and higher QE**

SuMIRe - PFS



JPL, day before yesterday

Mt Wilson Observatory

Los Angeles

Thanks!