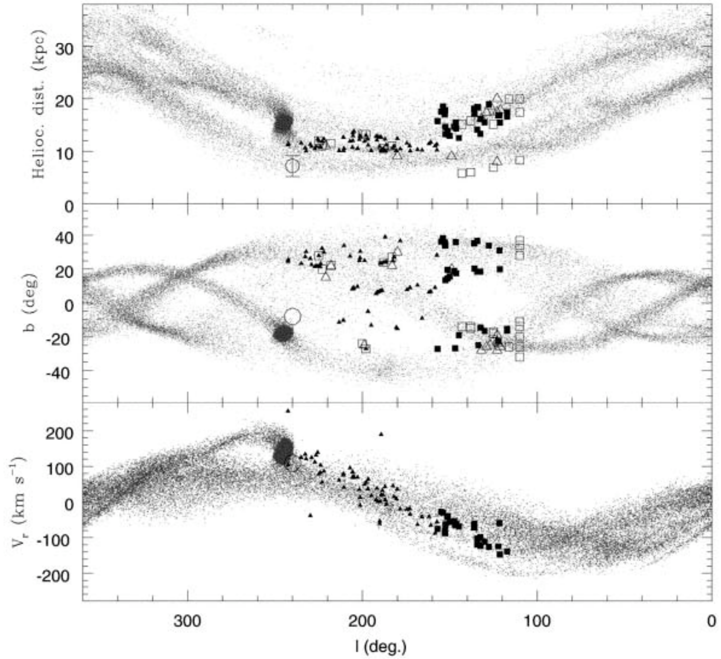
PFS: Caltech Perspective

Richard Ellis



- Strongly committed to building an unique multi-object optical spectrograph on a 8m telescope
- Wish to pursue cosmology, Galactic science & high z studies in partnership with Japan
- PFS is key component of "Mauna Kea synergy" – sharing Subaru/Keck resources in TMT era
- Valuable design/cost/management was done for WFMOS and can be harnessed
- Strong case for versatility in spectrographs (hi-dispersion, IR extension) but should focus first on achievable high priority optical instrument
- Must define management structure & collaborative details before US funds can be raised

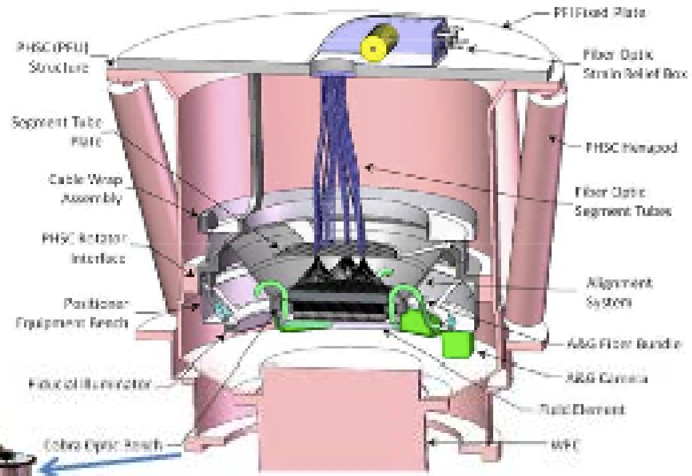
WFMOS: the Wide-field Fiber Multi-Object Spectrometer

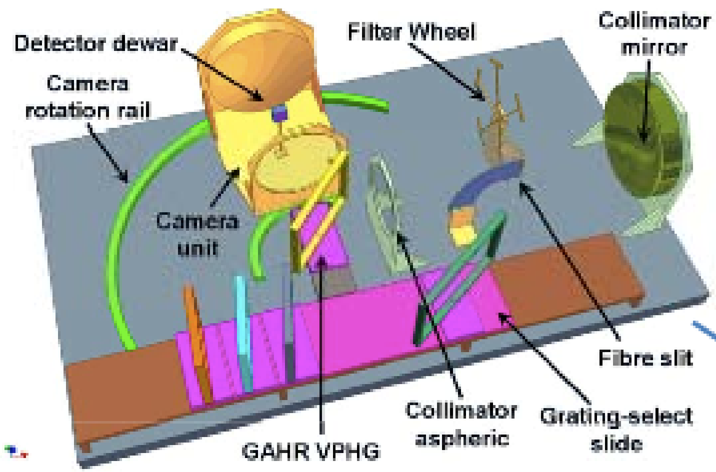
Much valuable technical work was done including credible management plan

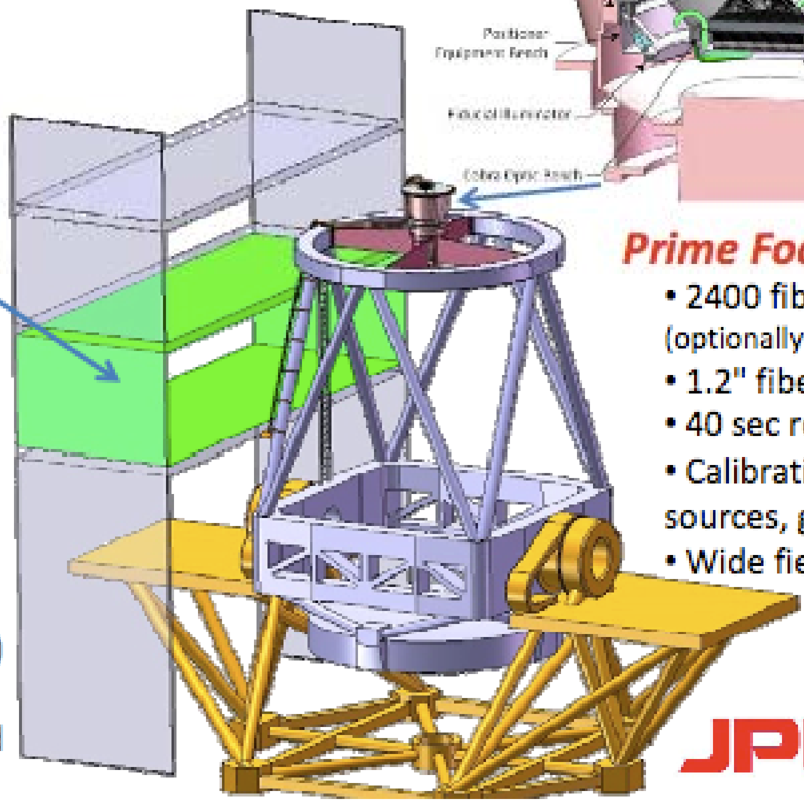
Key science proposed for WFMOS:

- Dark Energy–measure *w(z)* to 3% using baryon acoustic oscillations; redshifts to 4x10^{6} galaxies
- Formation of the Milky Way: dynamics of 3x10^{6} stars and Chemical Tagging of another 10^{6} stars in the Galaxy
- Galaxy evolution and growth of structure in the universe
- Highly complementary with HyperSuprime Cam science

The JPL/Caltech WFMOS Concept







Three identical spectrographs:

- Optimized for high efficiency 0.4 to 1 μm
- *R*=1500, 3500, or 5000 (2400 objects)
- *R*=20,000 (600 or more simultaneous objects)
- Fully reconfigurable during observing
- Additional gratings/resolutions may be added

Prime Focus instrument:

- 2400 fiber positioners (optionally expandable to 3000)
- 1.2" fibers, 1.3° FOV
- 40 sec reconfig. time
- Calibration and alignment sources, guide fibers
- Wide field corrector

JPL GEMINI SUBARU

Progress at Caltech since “WFMOS-gate”

- Strongly supported IPMU stimulus proposal (May 2009)
  - Letters of support to Japan from Caltech President/JPL Director
  - Made available WFMOS science & technical documents (JPL ownership)
  - Introduced UK and Brazil teams to IPMU
  - Promoted PFS within US Decadal Survey

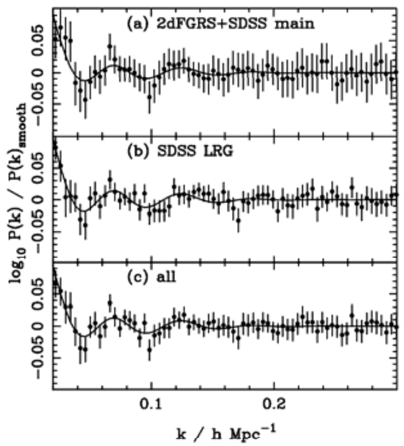
- Established institutional support for PFS at Caltech/JPL (2010)
  - secured support from Division Chair (Soifer) and JPL Director (van Zyl)
  - motivated faculty to join team (Ellis, Hirata, Cohen, Kulkarni + new hire)
  - science areas: cosmology, Galactic archeology, distant galaxies, transients
  - reinstated technical team at JPL (Seiffert, Braun..)

- Re-started positioner development program (2010)
  - NSF Advanced Technology Instrumentation proposal (~$1M) Nov 2010
  - Caltech/JPL Director’s Reseach & Development Fund ($200K) Nov 2010
  - Initiated discussions of larger role (technical coordination, PFI)

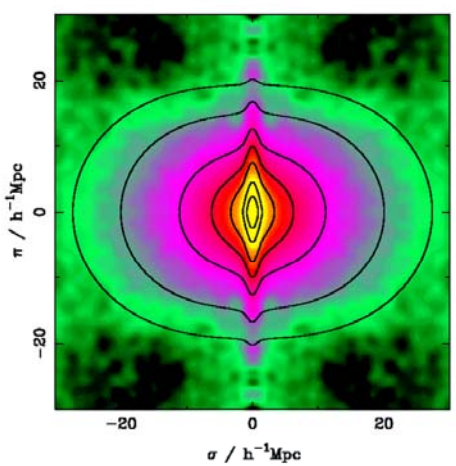
- Discussed broader role of PFS for `Mauna Kea synergy’ in TMT era within Caltech/NAOJ communities and recently to MEXT officials

Cosmology with PFS

Baryonic Acoustic Oscillations



Redshift Space Distortions



[O II] redshift survey: $0.6<z<1.6$ R<22.9; 2-4 × 10^6 galaxies; **50-100 nights**

- BAO yielding *w* to 3% (best test of w ≠ -1.0)
- RSD yielding f_g to 1.5% (first test of modified GR as sol^n to DE)
- large scale structure and galaxy evolution in clusters and field

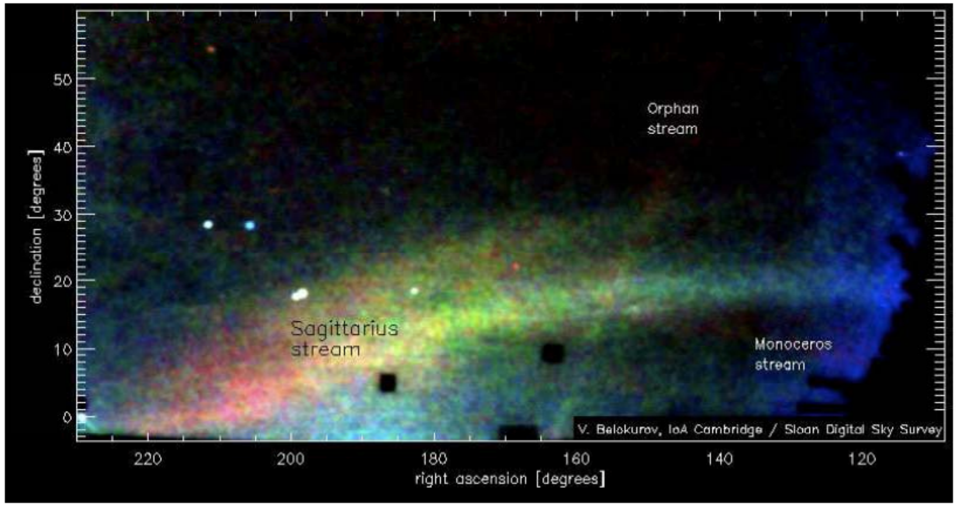
Synergy with HyperSuprimeCam (targets, colors, weak lensing)

PFS will be the first survey to probe z > 1 complementing BOSS with similar precision, offering the potential of a breakthrough in understanding Dark Energy

But this is a competitive situation & we must not delay

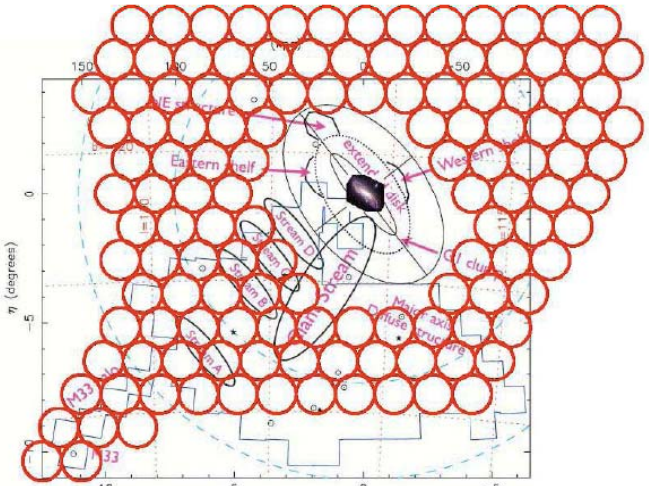
Galactic Archeology is Cosmology

Galactic Streams



GAIA 3-D revolution

M31 Halo

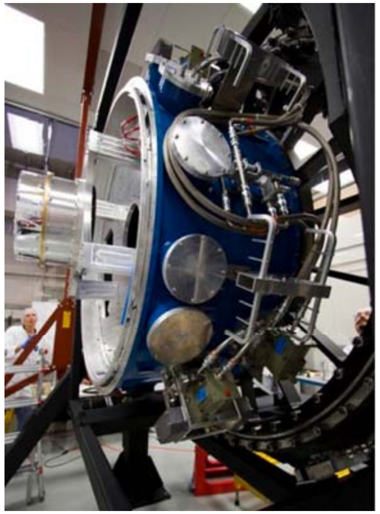


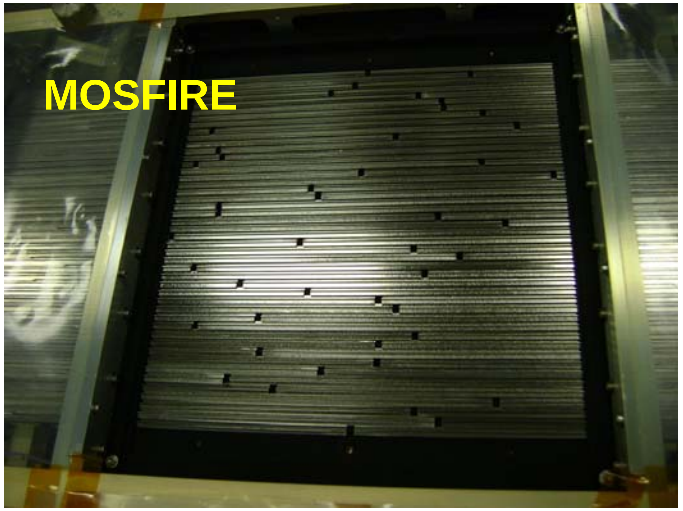
Stellar kinematics and abundances offer a huge potential in synergy with GAIA – a revolution in our understanding of DM halo & how Milky Way & M31 assembled.

MW: 18 < V < 20-21.5 ~10^6 stars 30-50 nights
M31 halo: V < 21.5 30 nights
DM in dwarfs: ~10 nights

Caltech experience in Galactic/Local Group stellar kinematics & abundances

Distant Galaxies and Reionization





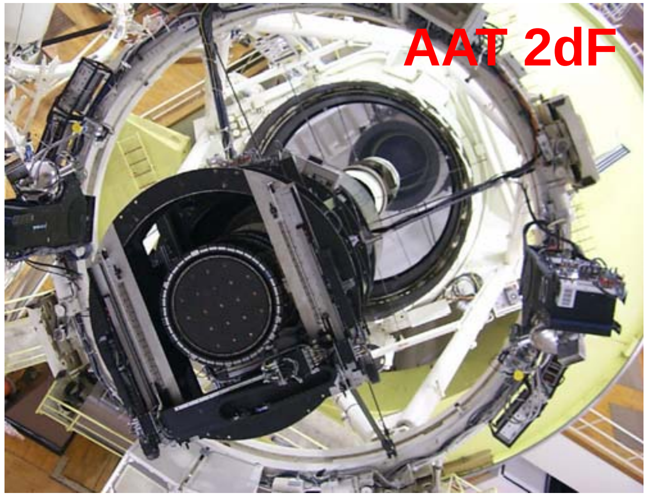
Lyman alpha emitters are key probe of early galaxies and the neutral era
Complementary Keck programs will help with more detailed studies:

- line profiles at higher resolution and S/N
- continuum properties (LBG spectra)
- AO images
- higher redshift studies in near-IR

The proven partnership between panoramic surveys with Subaru and deeper follow-up work with Keck will be increasingly effective as we approach the TMT era.

Strong collaborations exist between Caltech & Japan in high z science

Heritage of Survey Spectroscopy



Strong case for enabling future versatility if the additional cost is small:

- 2dF/SDSS were designed for LSS but delivered science well beyond original expectations thanks to the foresight of the designers
- PFS would be the only survey spectrograph on a 8m telescope offering unique potential in photon-starved applications (high dispersion chemical abundances, absorption line spectroscopy of z > 1 galaxies)

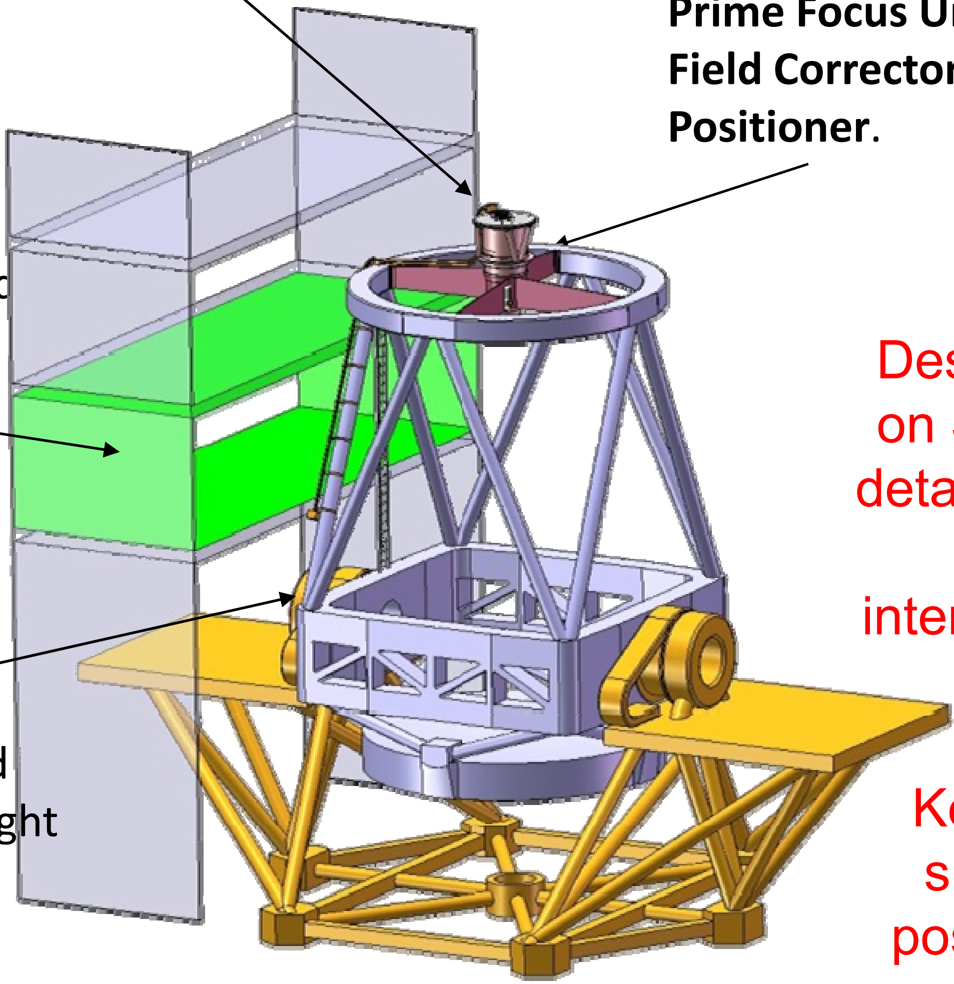
These applications are exciting but add to the expense
They should not delay the realization of an instrument similar to WFMOS

WFMOS Concepts Are Relevant to PFS

Fiber **connector** mounted on top end structure

Prime Focus Unit includes **Wide Field Corrector** (WFC) and **Fiber Positioner**.

Spectrograph room located above Naysmith platform



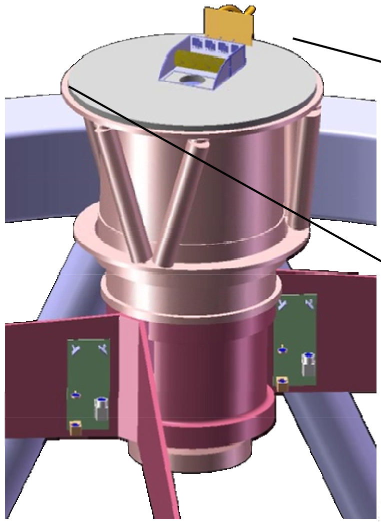
Fiber Cable routed around elevation axis and brings light to the Spectrographs

Design study based on Subaru-provided details, several visits to Subaru, interaction with HSC team

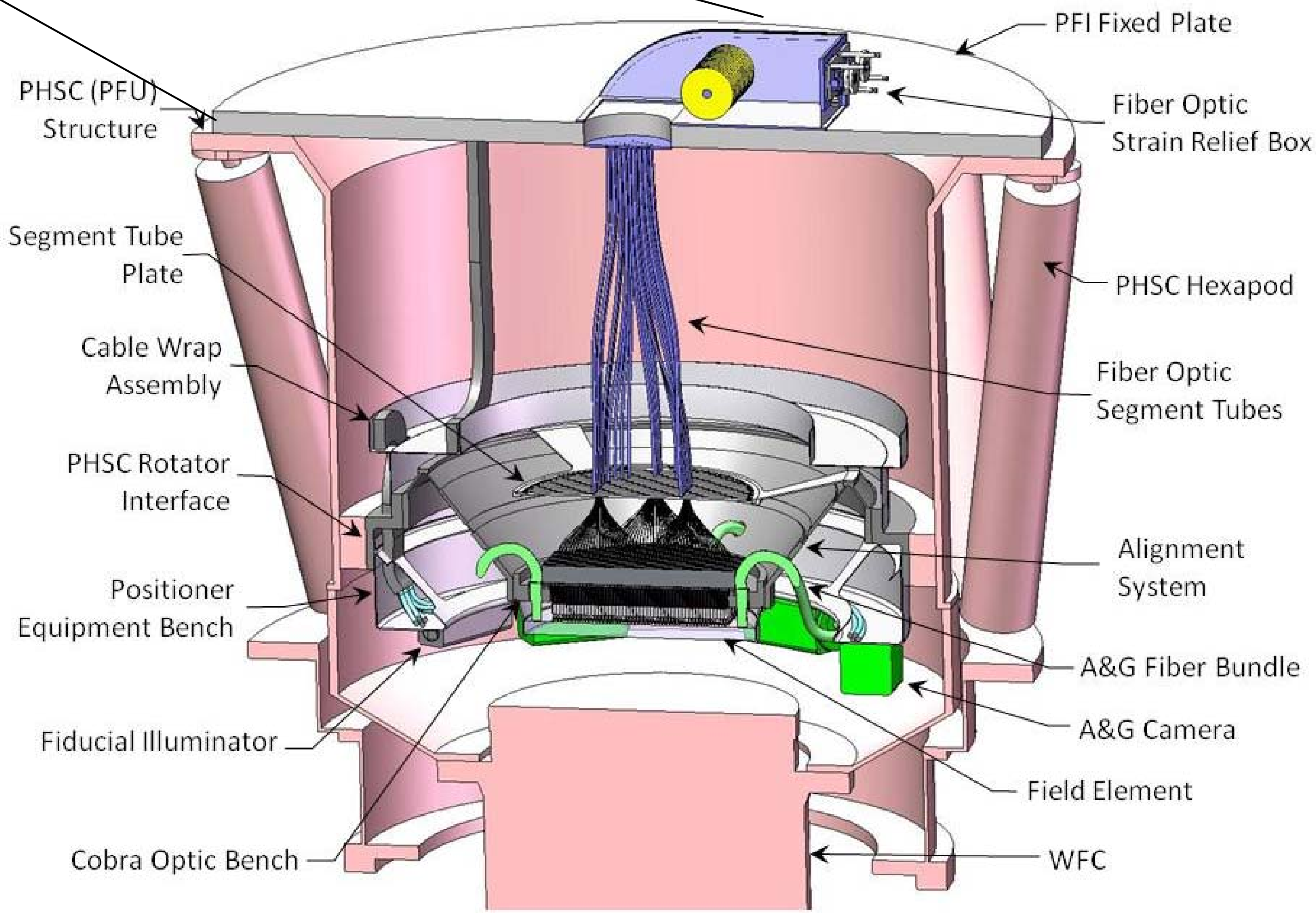
Key requirements: survey speed and positioner reliability

Prime Focus Instrument (PFI)

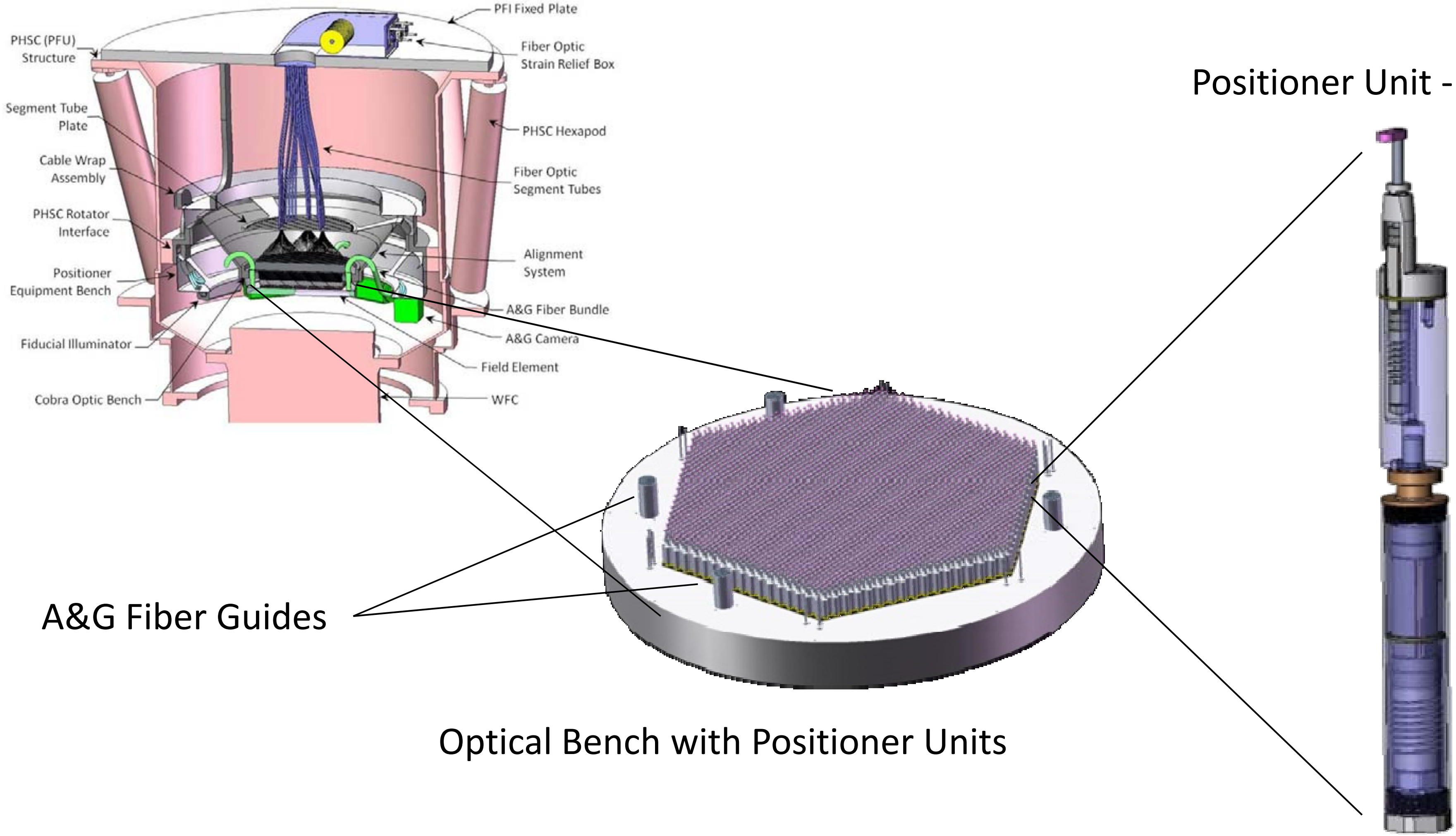
Subaru provided elements: field rotator, hexapod and wide field corrector



HSC filter/dewar window replaced by 30mm field element

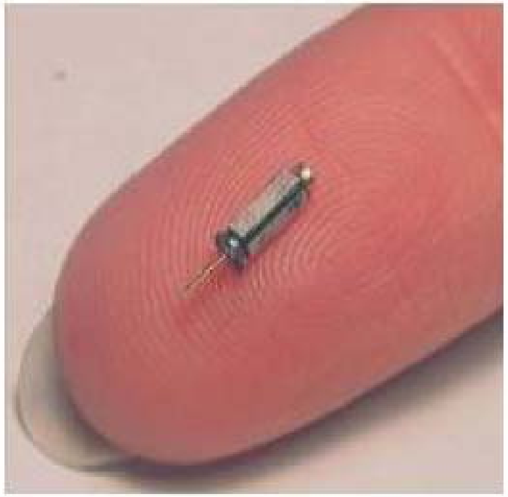


PFS Positioner



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

JPL - New Scale Technologies Study



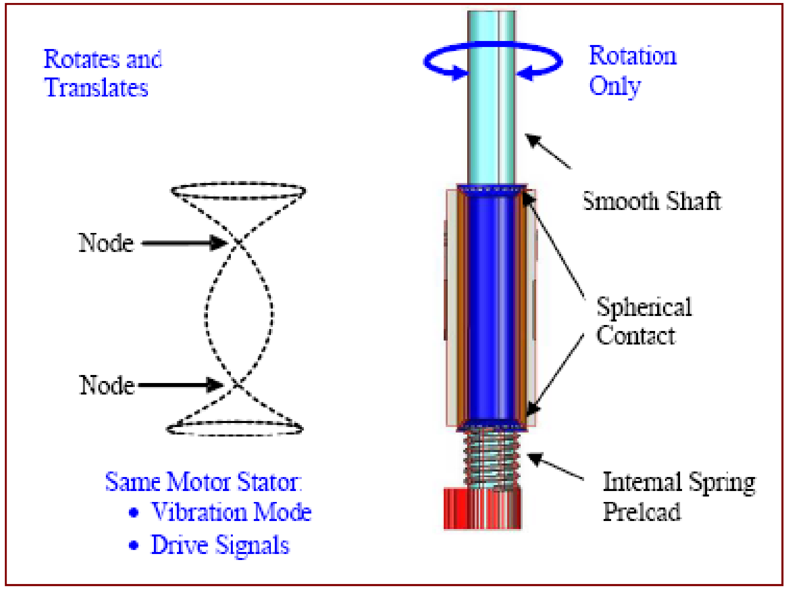
New class of commercially available rotating tube (Rotary Squiggle) motor with high torque when stationary and unpowered:

~ 1 mN-m powered torque

1 mrad resolution

1 – 10 rev/sec speed

- Pairs of PZT plates oscillate in tandem bending
- Drive signals of the two PZT plates are phase shifted by 90 degrees
- This creates a traveling wave on the stator that excites the rotor like a harmonic gearbox to rotate the shaft by extremely small angles (`hula' fashion)



Prime Focus Instrument: Concept & Development

In originally-approved Gemini WFMOS program, we sought ~$2M of further design and prototyping work on positioner and a 4 year program for PFI

WFMOS Top Level Schedule

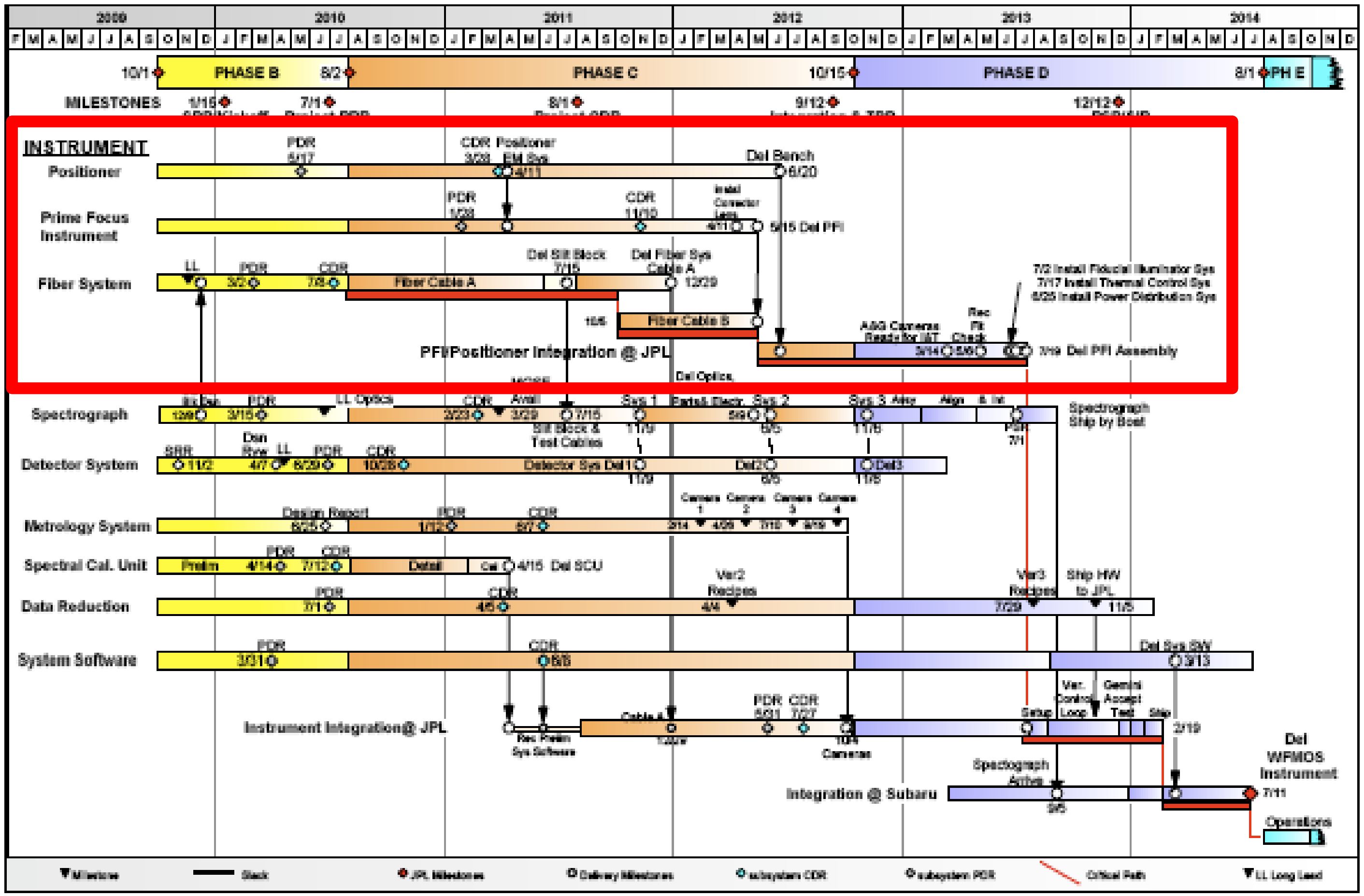


Figure 7.3-1: Top Level Schedule

Cobra Prototype is an Essential Precursor to Proposing for a ~2400-4000 element system

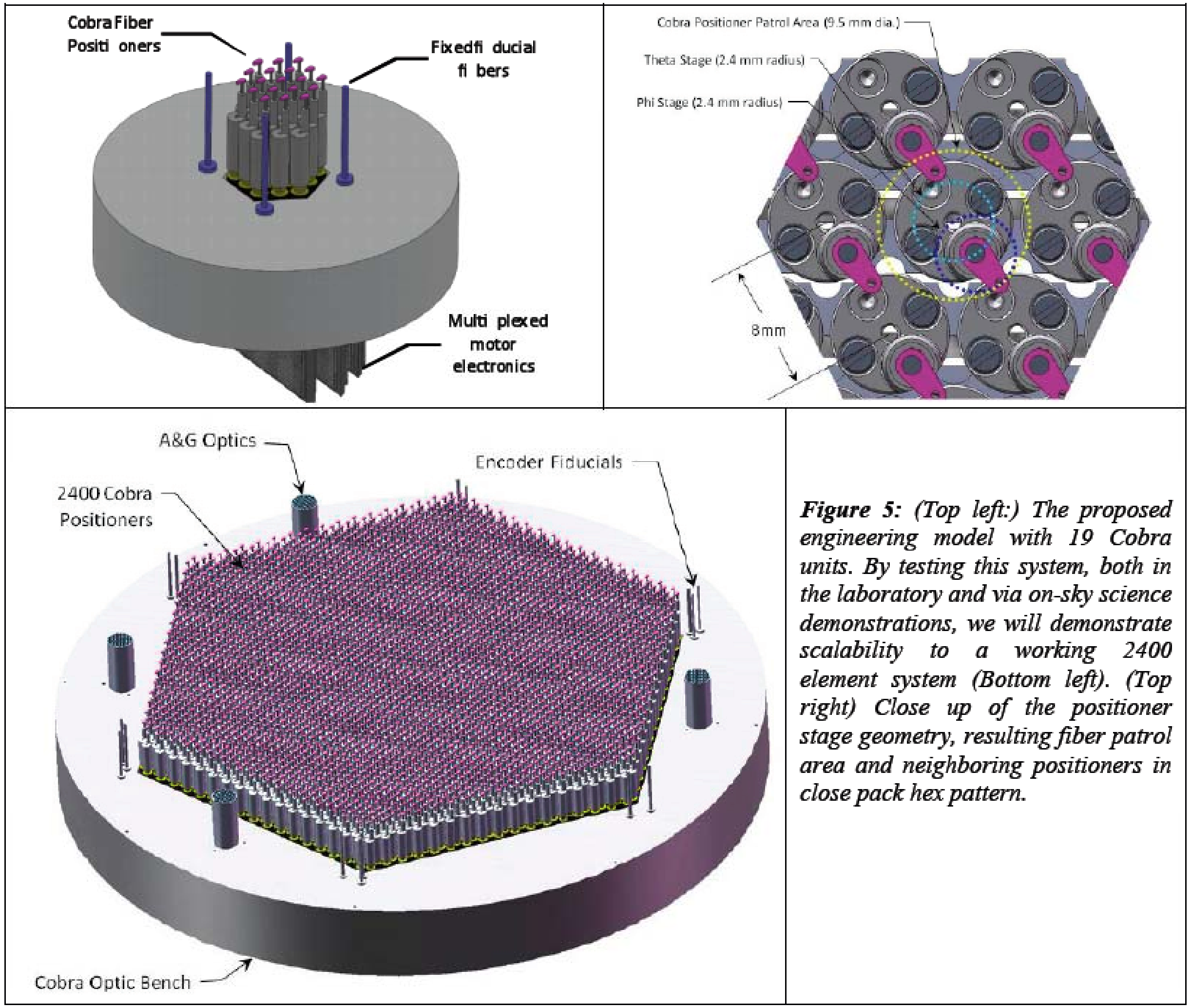
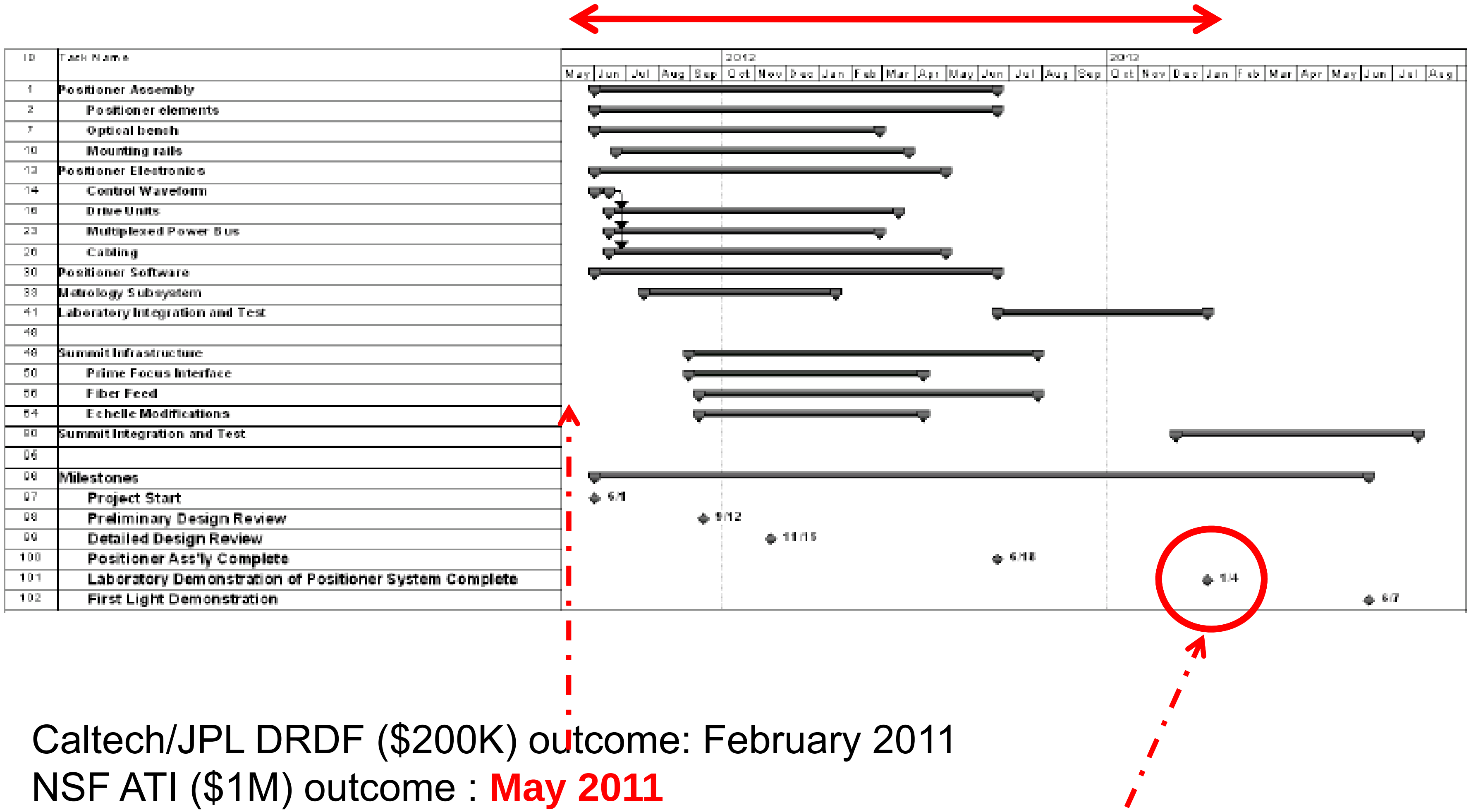


***Figure 5:** (Top left:) The proposed engineering model with 19 Cobra units. By testing this system, both in the laboratory and via on-sky science demonstrations, we will demonstrate scalability to a working 2400 element system (Bottom left). (Top right) Close up of the positioner stage geometry, resulting fiber patrol area and neighboring positioners in close pack hex pattern.*

Proposed laboratory and on-sky testing of 19-element system via NSF/Caltech $

Positioner Prototype Timeline (NSF proposal)



Caltech/JPL DRDF ($200K) outcome: February 2011

NSF ATI ($1M) outcome : **May 2011**

Laboratory multiplex prototype (23 month program): **April 2013**

First opportunity for major funding: mid-2013

Earliest delivery of positioner to Subaru: **early 2015**

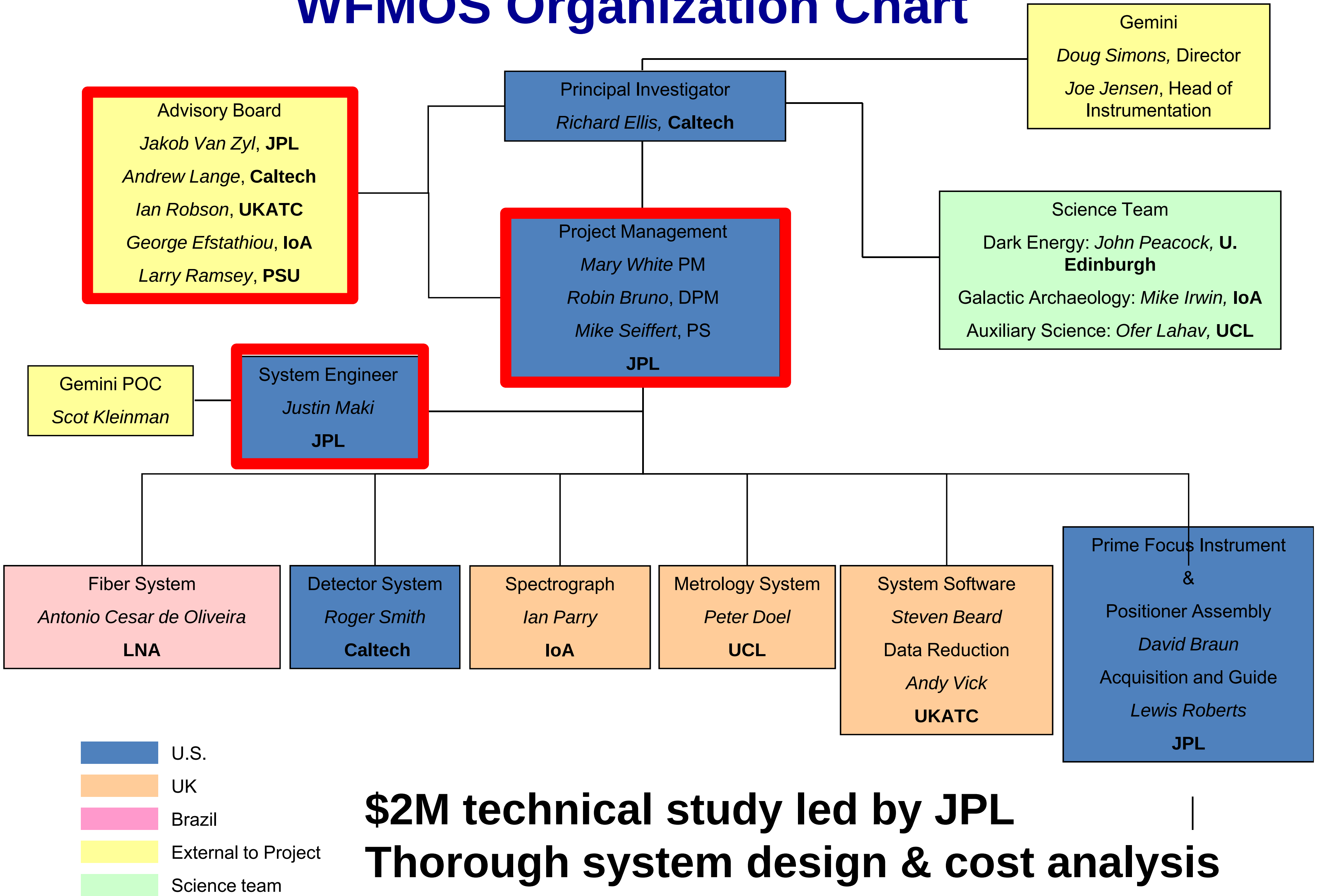
Consistent with a 4 year PTI program

Cost of WFMOS Components (FY$2009)

Table 7.2-2: Cost by Top-Level WBS

WBS Element	Institution	Cost by Year, $K					Total Cost, $K	Reserves, %	Reserves, $K	Cost w/ Reserves, $K
		yr 1	yr 2	yr 3	yr 4	yr 5				
1.0 Science	Caltech/JPL	317	210	215	218	221	1,181	20.0	236	1,418
2.0 Management	JPL	895	1,273	1,310	1,212	904	5,594	10.0	559	6,153
3.0 System Engineering	JPL	485	528	530	509	276	2,328	17.3	404	2,732
4.0 Instrument System		7,791	11,702	11,068	4,566	2,284	37,411	24.1	9,022	45,534
4.1 Spectrograph	Cambridge	1,847	3,278	3,698	959	601	10,383	20.0	2,077	12,459
4.2 Positioner	JPL/PSU	2,490	3,410	1,765	288	324	8,276	23.9	1,453	9,729
4.3 Detector System	Caltech/JPL	729	1,337	982	147	183	3,379	28.3	870	4,248
4.4 Fiber System	LNA	1,231	952	625	441	302	3,550	20.0	710	4,260
4.5 Prime Focus Instrument	JPL	701	1,628	2,871	2,157	561	7,918	26.0	2,120	10,038
4.6 System Software	UKATC	391	400	692	526	257	2,266	25.0	567	2,833
4.8 Metrology/Calibration system	UCL	403	697	435	48	56	1,639	20.0	328	1,967
5.0 Instrument Integration and Test	JPL	0	0	284	794	624	1,701	28.3	481	2,182
6.0 Data Systems	UKATC	318	555	839	230	148	2,089	20.0	418	2,507
7.0 Subaru Provided Elements	Gemini	1,655	1,655	1,655	1,655	1,379	8,000	0.0	0	8,000
TOTAL		**11,462**	**15,923**	**15,901**	**9,184**	**5,836**	**58,305**	**20.3**	**10,222**	**68,527**

WFMOS Organization Chart



$2M technical study led by JPL

Thorough system design & cost analysis

Management & Business Plan

Current White Paper is primarily a science discussion document

Much work is needed before Caltech/JPL could move beyond current informal discussions. We need to see:

- Conceptual design study with preliminary costs (if not WFMOS)
- Agreement on workscopes and institutional roles noting costs
- Experienced management team (PI, PM, PS, System Engineer)
- Science roles and access to datasets
- Advisory Board with Institutional authority

All of the above would have to be in place before Caltech could contemplate private fund-raising or participating in a NSF `mid-scale' funding proposal

NSF funds have some implications making private funds preferred

- Competition with BigBOSS
- Access for the entire US community to a significant data product

Mauna Kea Synergy

In the TMT era there are tremendous synergistic opportunities:

- sharing telescope time
- coordinating large projects
- sharing resources for operation, management and instrument provision

Caltech views PFS as a vital aspect of this future synergy

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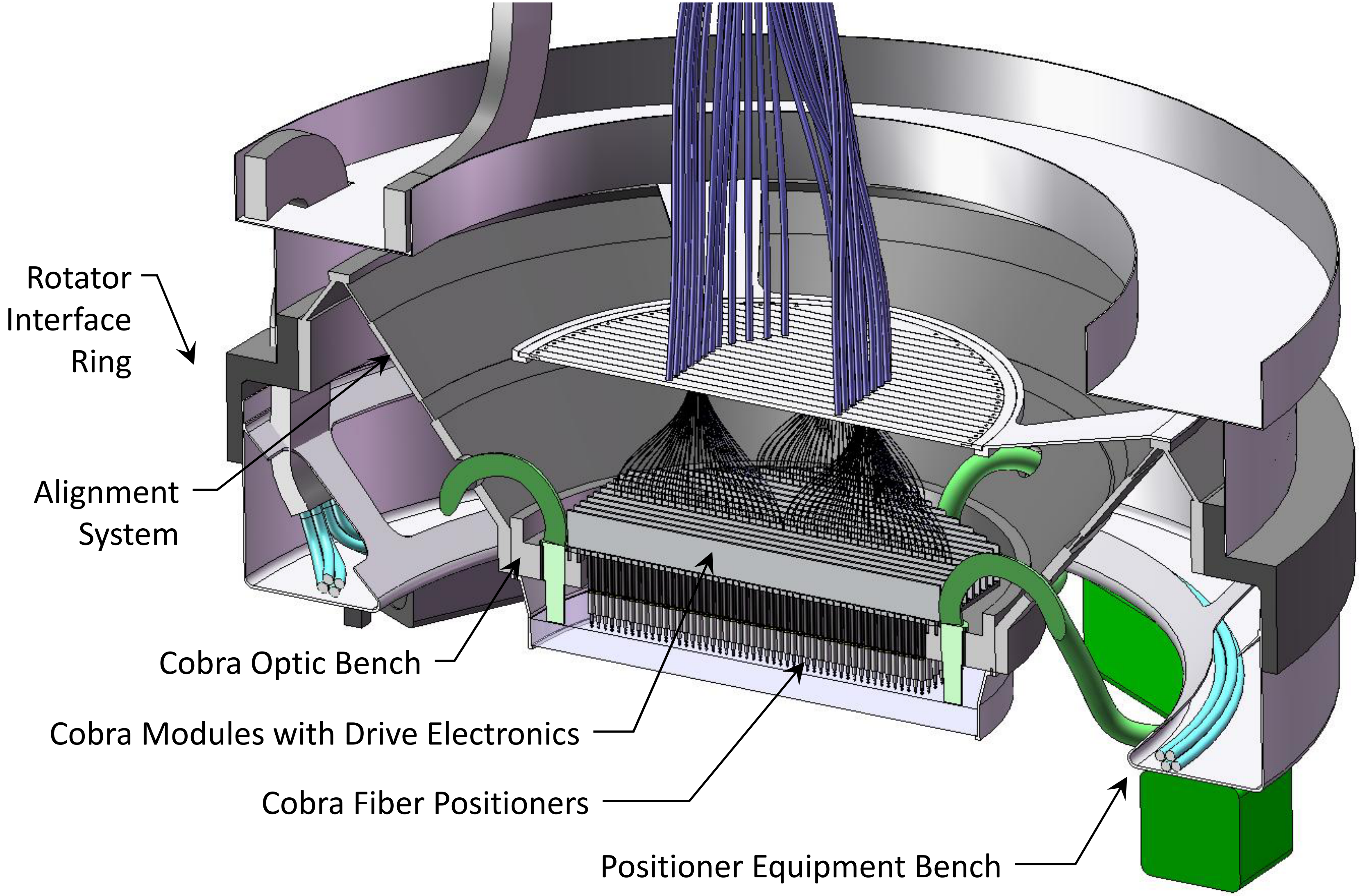
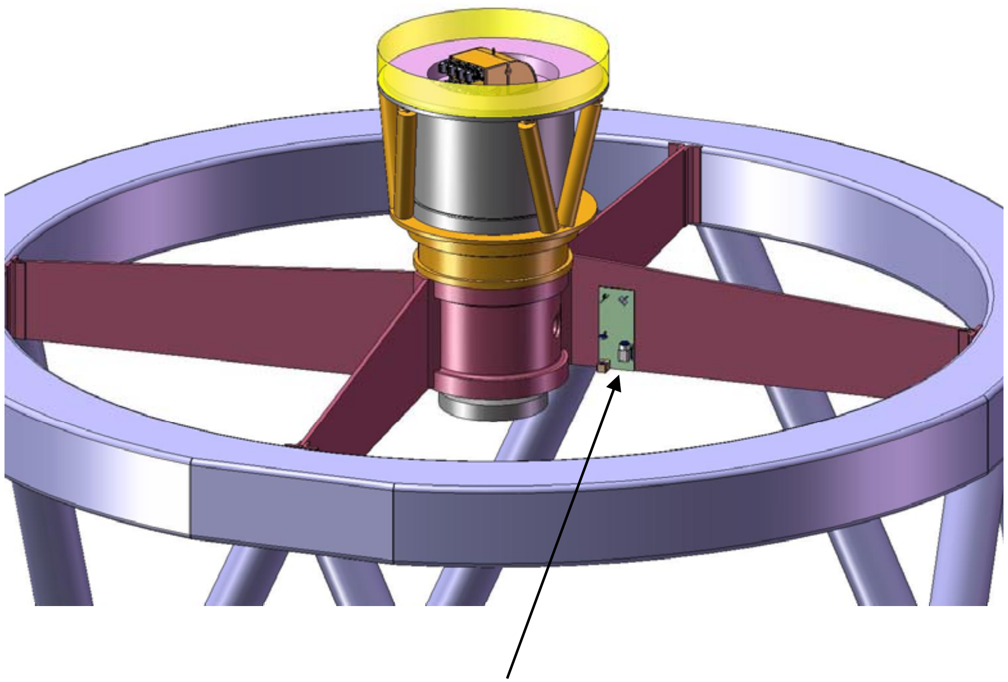
Rotating Portion of PFI in PFS Configuration



Fibers are routed between fixed and rotating parts of PFI through strain relief box so that 500 degree rotator range is accommodated by twisting along rotator axis rather than bending around a spool

Metrology Camera: Verifying Fiber Positioning

- 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 positions established relative to fixed fiducial fibers on positioner focal plane
- Each camera will have a 4k by 4k CCD with 15μm pixels.
- Cameras are defocused to ~ 4 pixels FWHM to allow centroiding to ~ 1/20th of a pixel. Back-illuminated CCDs to allow better centroiding.



Metrology camera (1 of 4 shown)

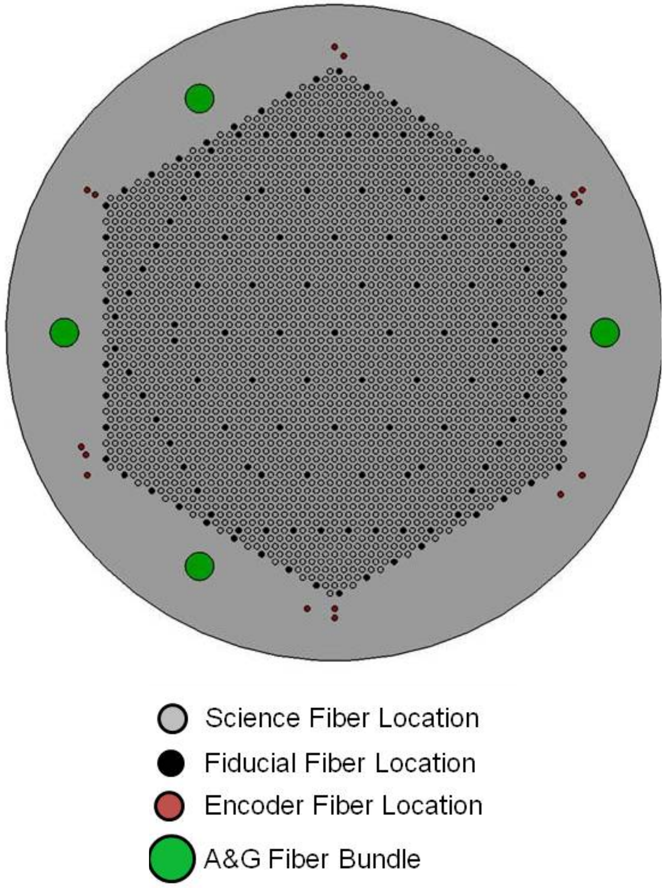
Camera positioned 890mm from center of positioner.

Mounting plate provides kinetic mounting points.

System can be installed quickly with repeatable accuracy.

Maintaining Accuracy of Fiber Positioning

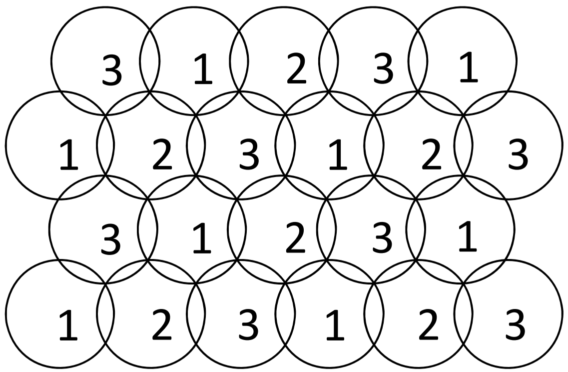
Back-lit **fiducial fibers** used to establish position of science fibers on positioner plane



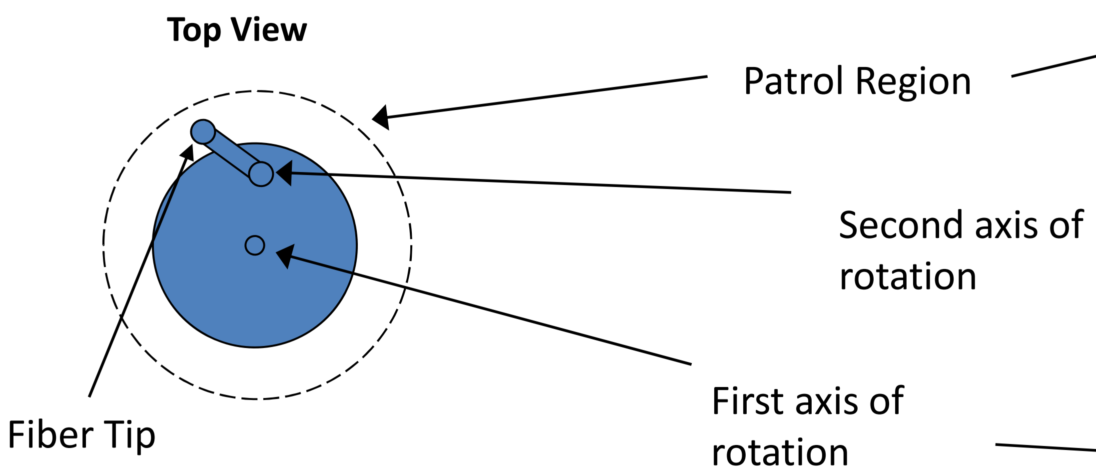
Encoder fibers used to establish rotation orientation of positioner

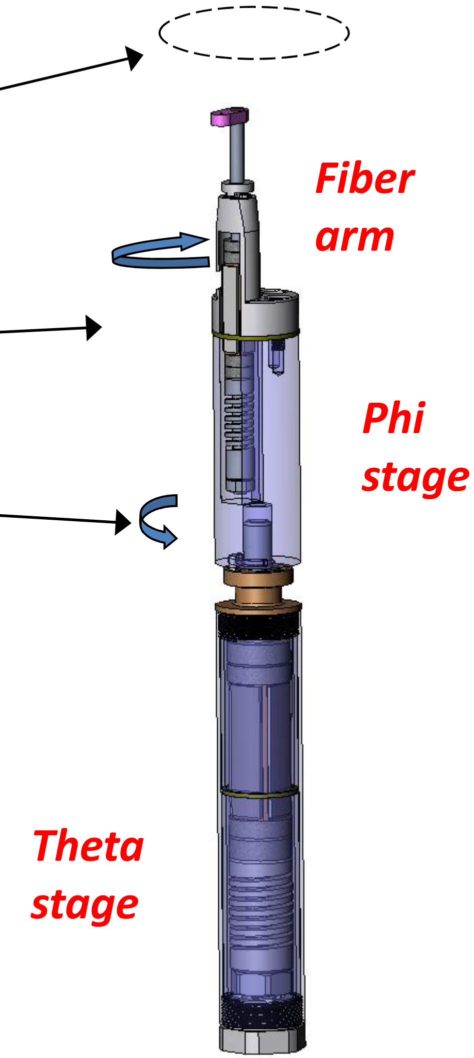
Science fibers are back-lit in a sequence to allow discrimination between fibers in the overlap regions between adjacent fibers, 1/3 at at time.

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



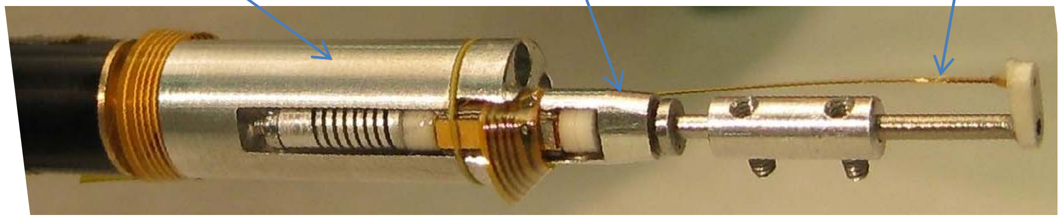
Positioner Element – “Cobra”





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

Cobra Prototype Tested at JPL



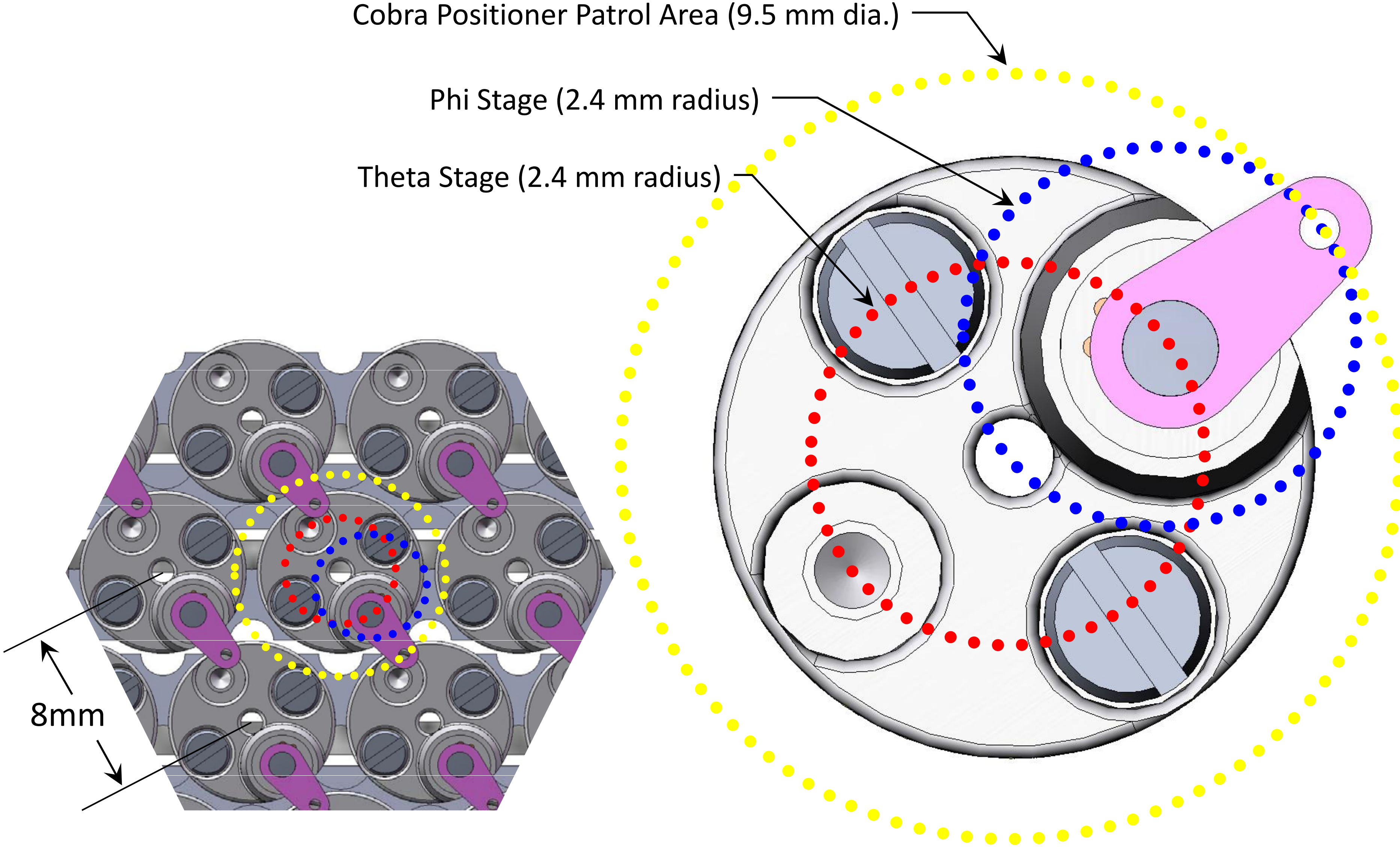
- Ceramic friction drive
- Lubrication free, zero backlash
- Journal bearing limits motor side loads
- Hardstops to limit fiber twisting

- 5 µm precision of fiber positioning
- Motor movement < 1 sec/iteration
- Optimal solution 2.4 and 4.6mm motors

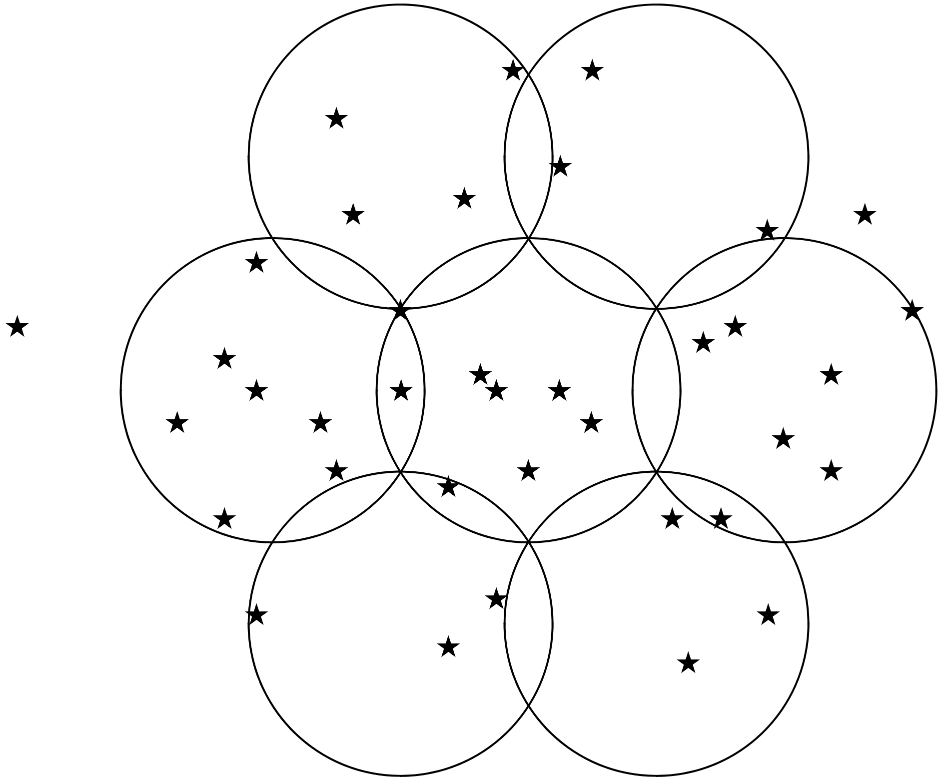
Design followed consideration of a wide variety of positioning options and support from New Scale Technologies:

Next step: multiplex unit tested at Palomar 200-inch (~$1M ATI proposal)

Field Geometry of Cobra Positioners



Fiber Patrol Regions

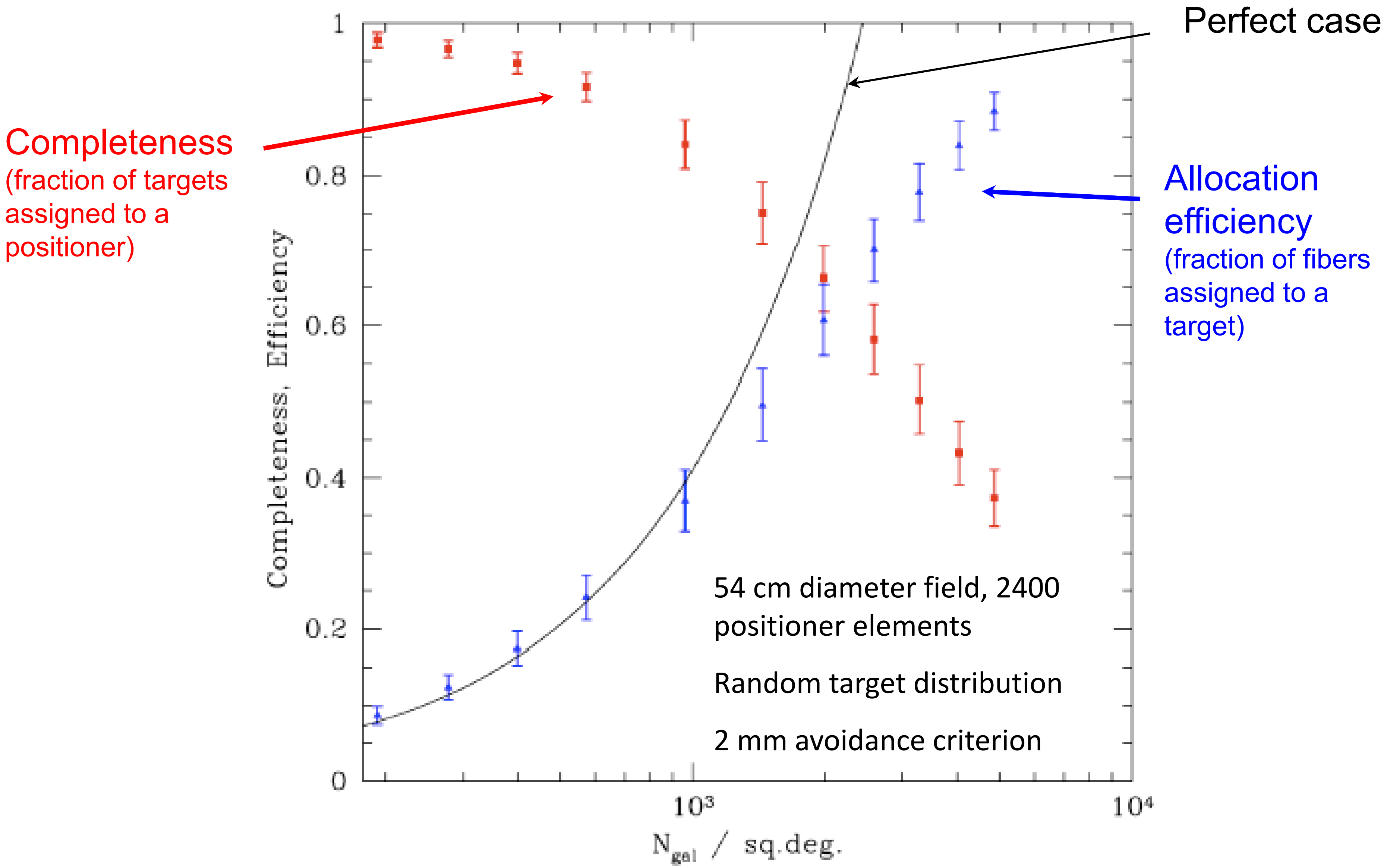


Patrol Region – Area of the focal plane accessible to one fiber (9.5 mm diameter)

Adjacent patrol regions overlap with no gaps

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

Fiber Allocation Efficiency & Completeness



Cobra Modules

- 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