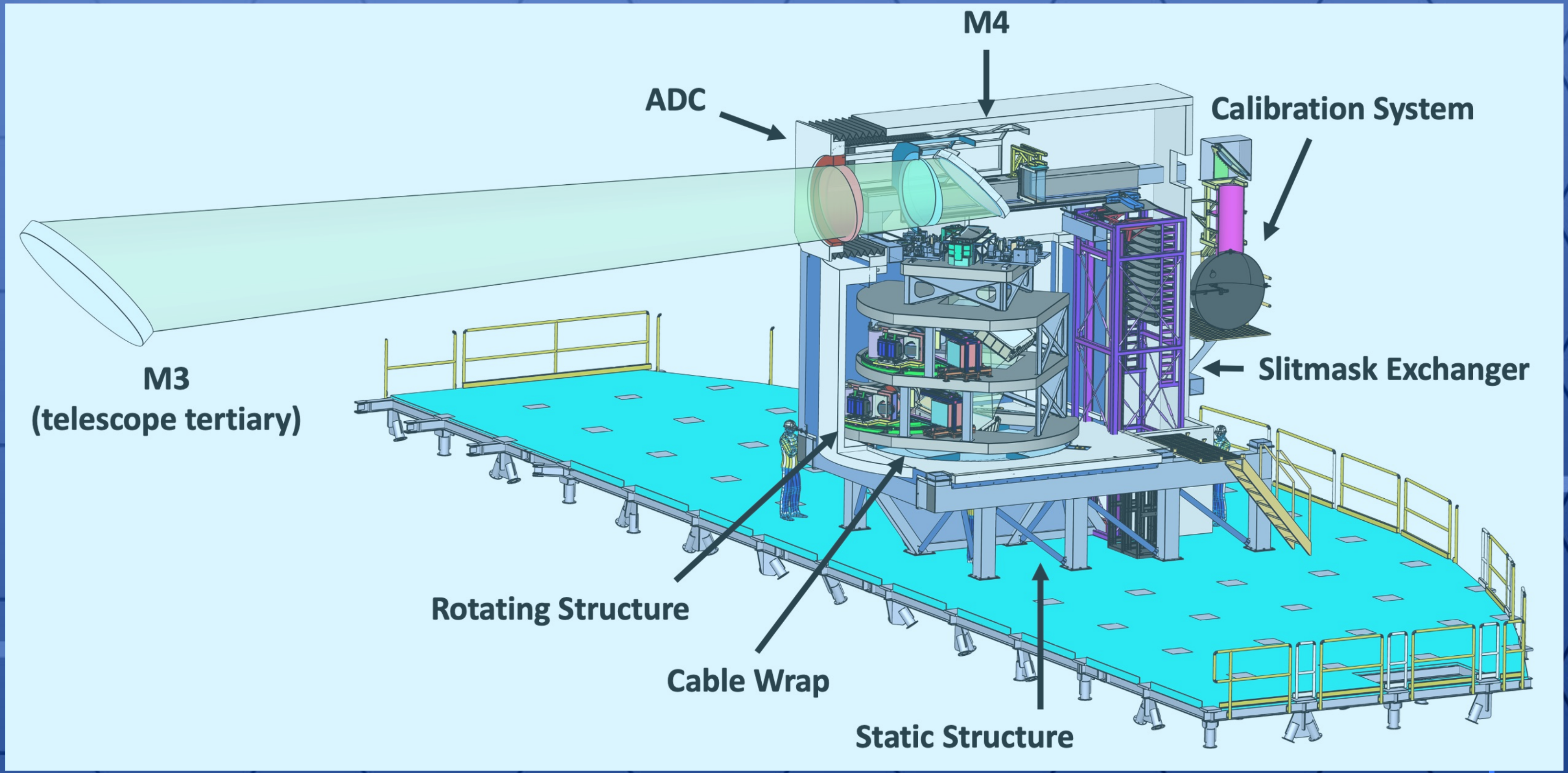
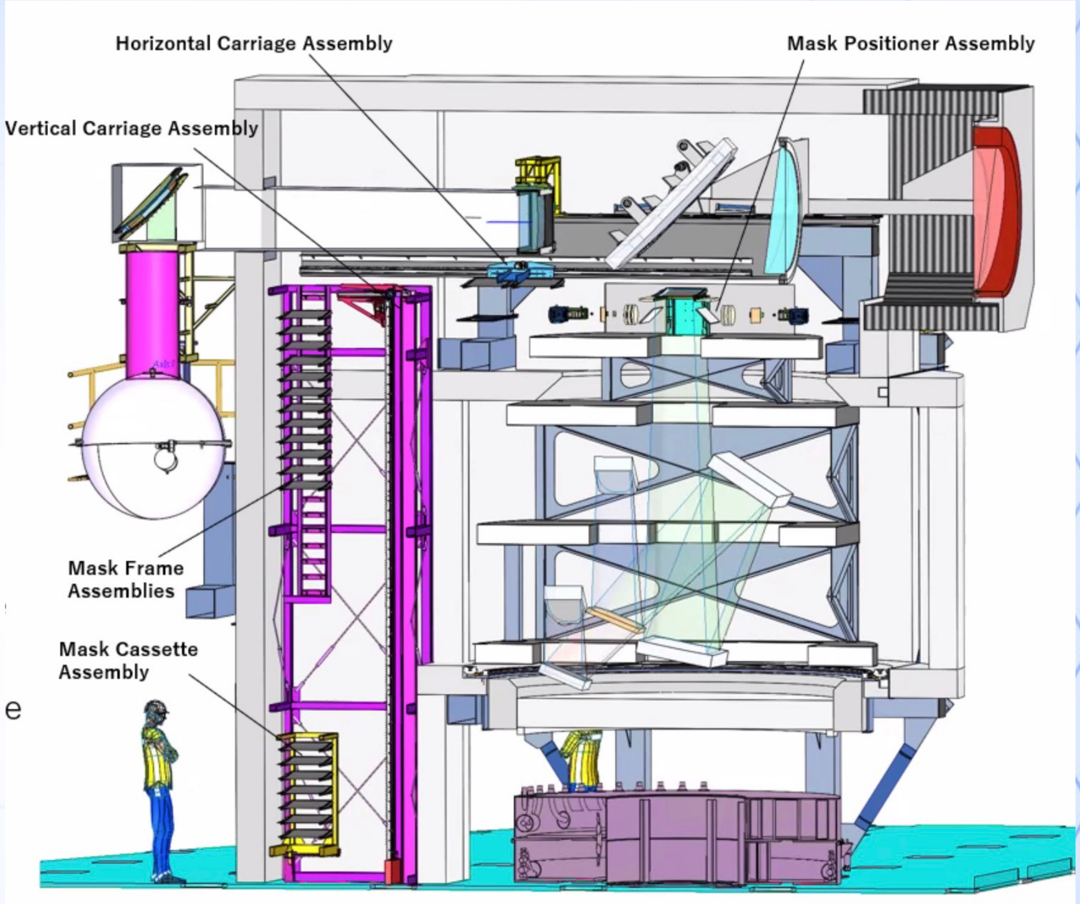
The Wide-Field Optical Spectrograph (WFOS) for the Thirty Meter Telescope (TMT)

E. Peng (NOIRLab), C. Steidel (Caltech)
for the WFOS team



WFOS Instrument Team Leads

- Chuck Steidel (Principal Investigator, Caltech)
- Alastair Heptonstall (Project Manager, TMT)
- Eric Peng (Project Scientist, NOIRLab)
- Jason Fucik (Lead Optical Engineer, Caltech)
- Reston Nash (Lead Mechanical Engineer, Caltech)
- David Andersen (TMT Science Instruments Group Leader)
- Roger Smith (Detectors, Caltech)
- John Miles (Systems Engineer, TMT)



WFOS Science Team

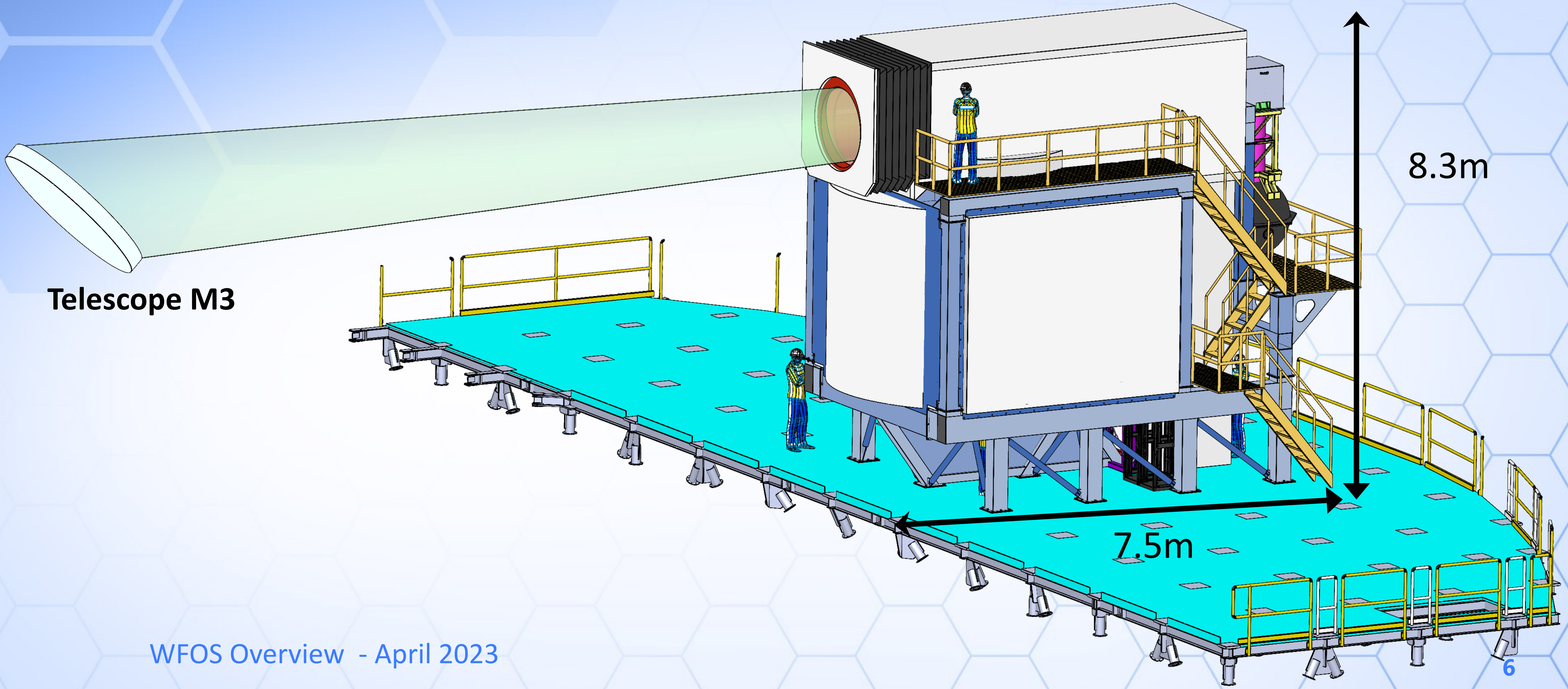
- Chuck Steidel (Caltech)
- Eric Peng (NOIRLab, USA)
- Erica Nelson (Colorado, USA)
- John O'Meara (Keck, USA)
- Crystal Martin (UCSB)
- Khee-Ghan Lee (IPMU, Japan)
- Kimihiko Nakajima (NAOJ, Japan)
- G. C. Anupama (IIA, India)
- Vivek M (IIA, India)
- Roberto Abraham (Toronto, Canada)
- Ting Li (Toronto, Canada)
- Michael Balogh (Waterloo, Canada)
- Evan Kirby (Notre Dame, USA)
- Mansi Kasliwal (Caltech)
- Guo Chen (PMO, China)
- Yong Zheng (UCB)
- Karen Meech (Hawaii)
- Casey Papovich (Texas A&M, GMACS)

TMT

- UV/optical <u>imaging spectrograph</u> optimized for faint object spectroscopy (single slit, multi-slit, slicer-IFU)
  - Designed for seeing-limited or GLAO-enhanced images over a large fraction of the unvignetted TMT FoV (8.3’ x 3.0’ FoV; multiplex ~100)
  - Gravity invariant design, with 2 wavelength channels, each with articulating cameras, grating selection, and grating AOI for full control over diffraction efficiency, resolving power, and wavelength range in all modes.
  - Wavelength range 0.31-1.05 µm, R=1500-15,000 achievable at all wavelengths
  - Average instrumental throughput (ADC to detector) <u>for spectroscopy</u> >56%, peaks at >70% (req: “Preserve the aperture advantage”)

WFOS passed its Conceptual Design Review in February 2022, now well into Preliminary Design Phase.

WFOS Opto-Mechanical Layout



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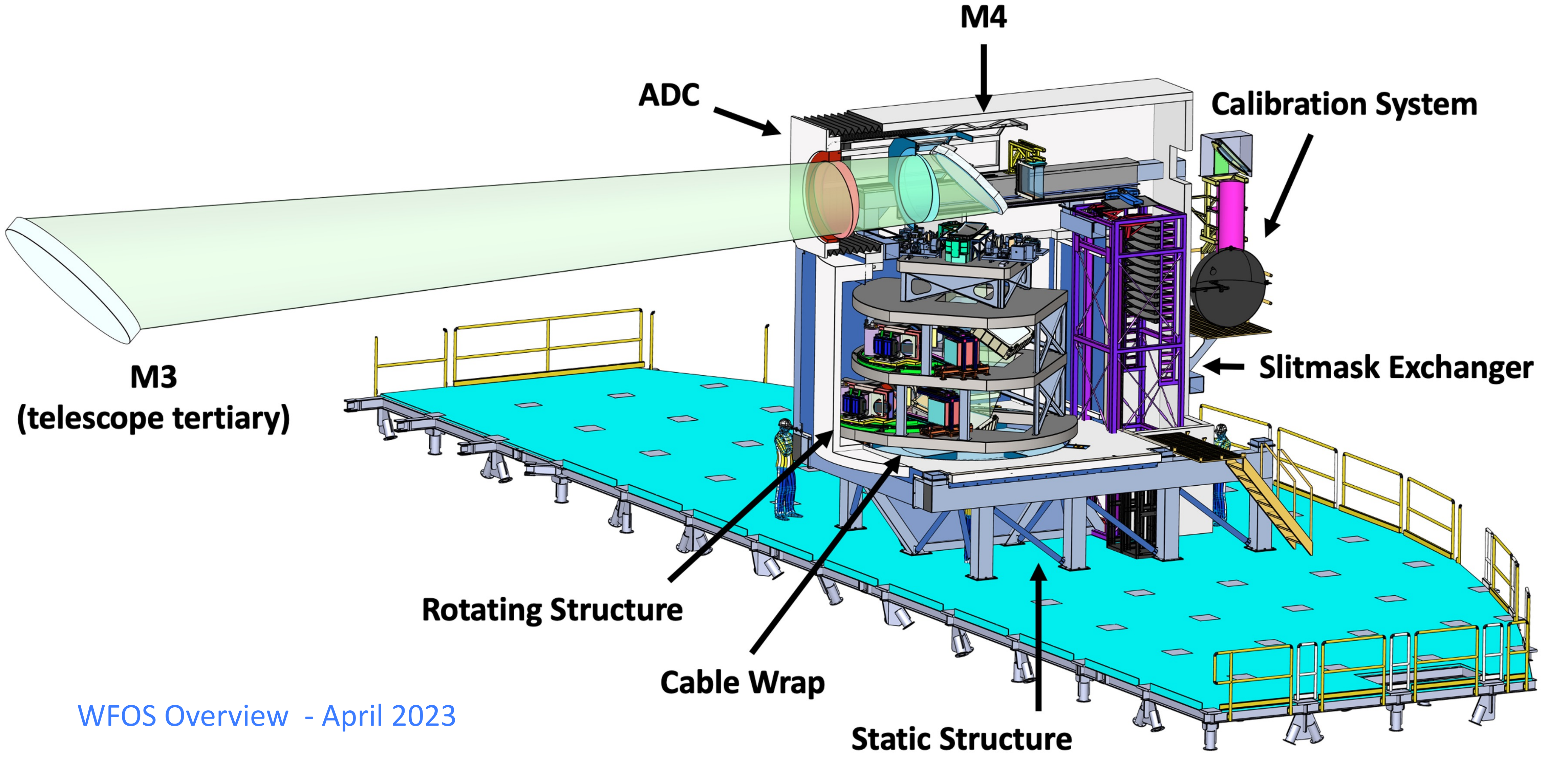
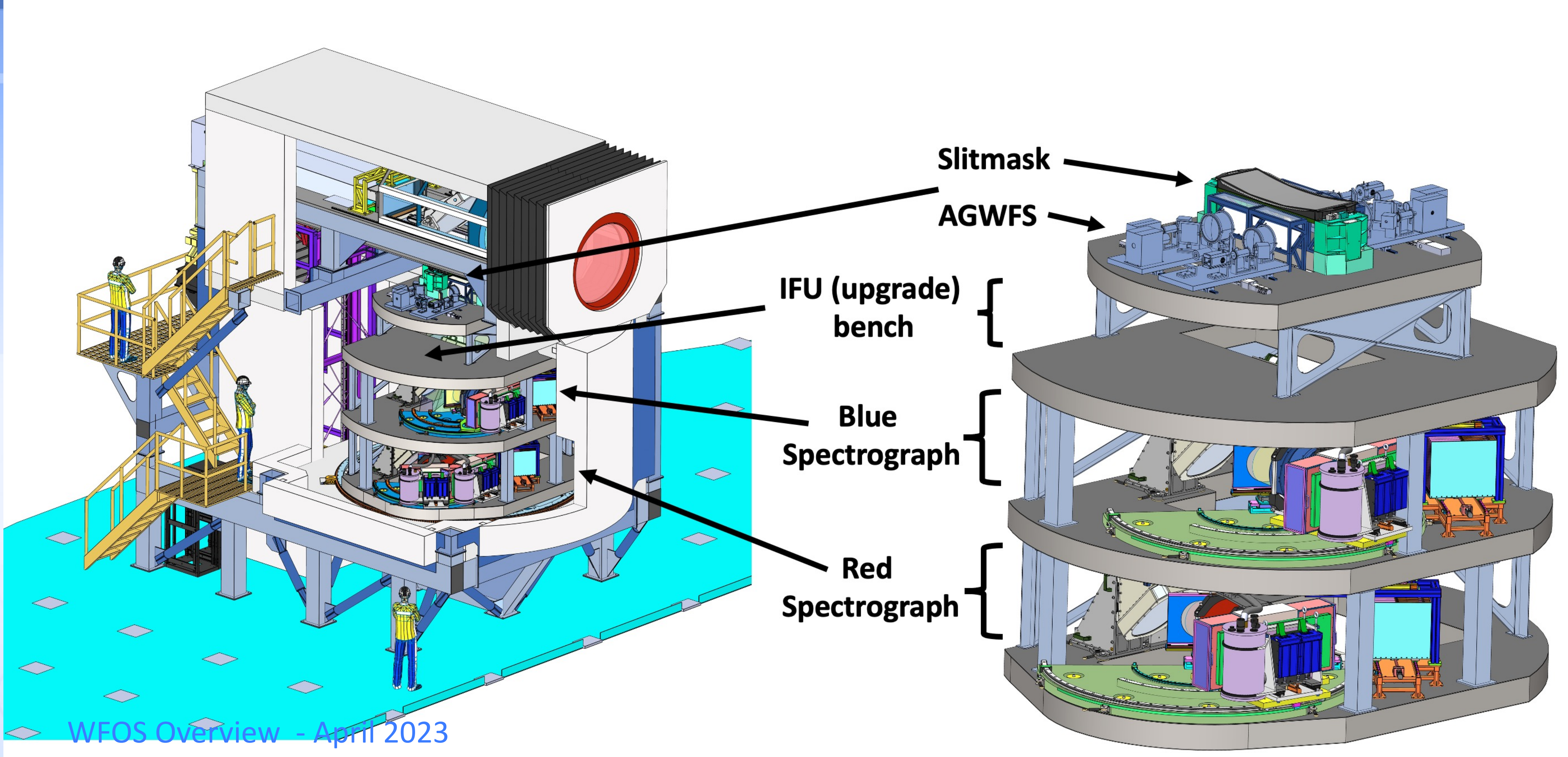
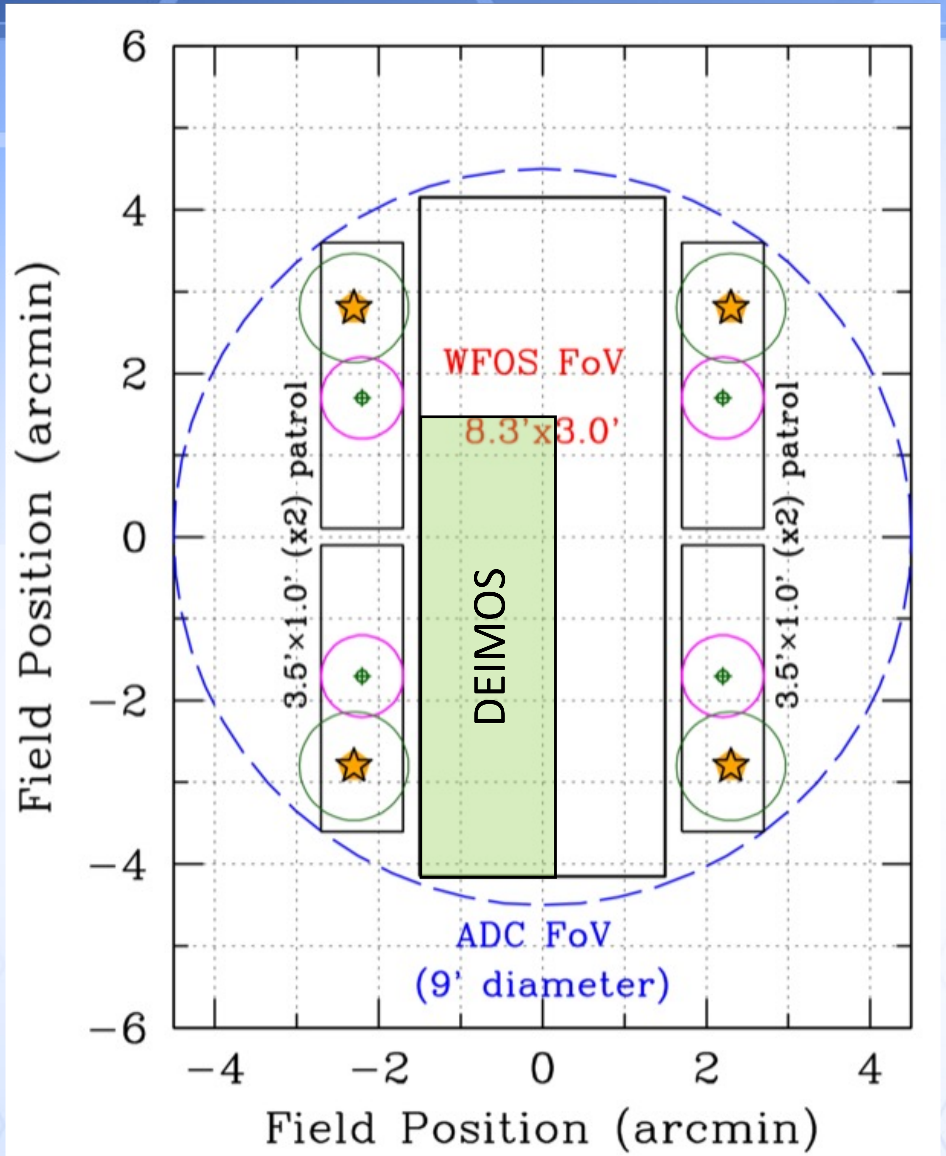


WFOS Opto-Mechanical Layout: Gravity Invariant



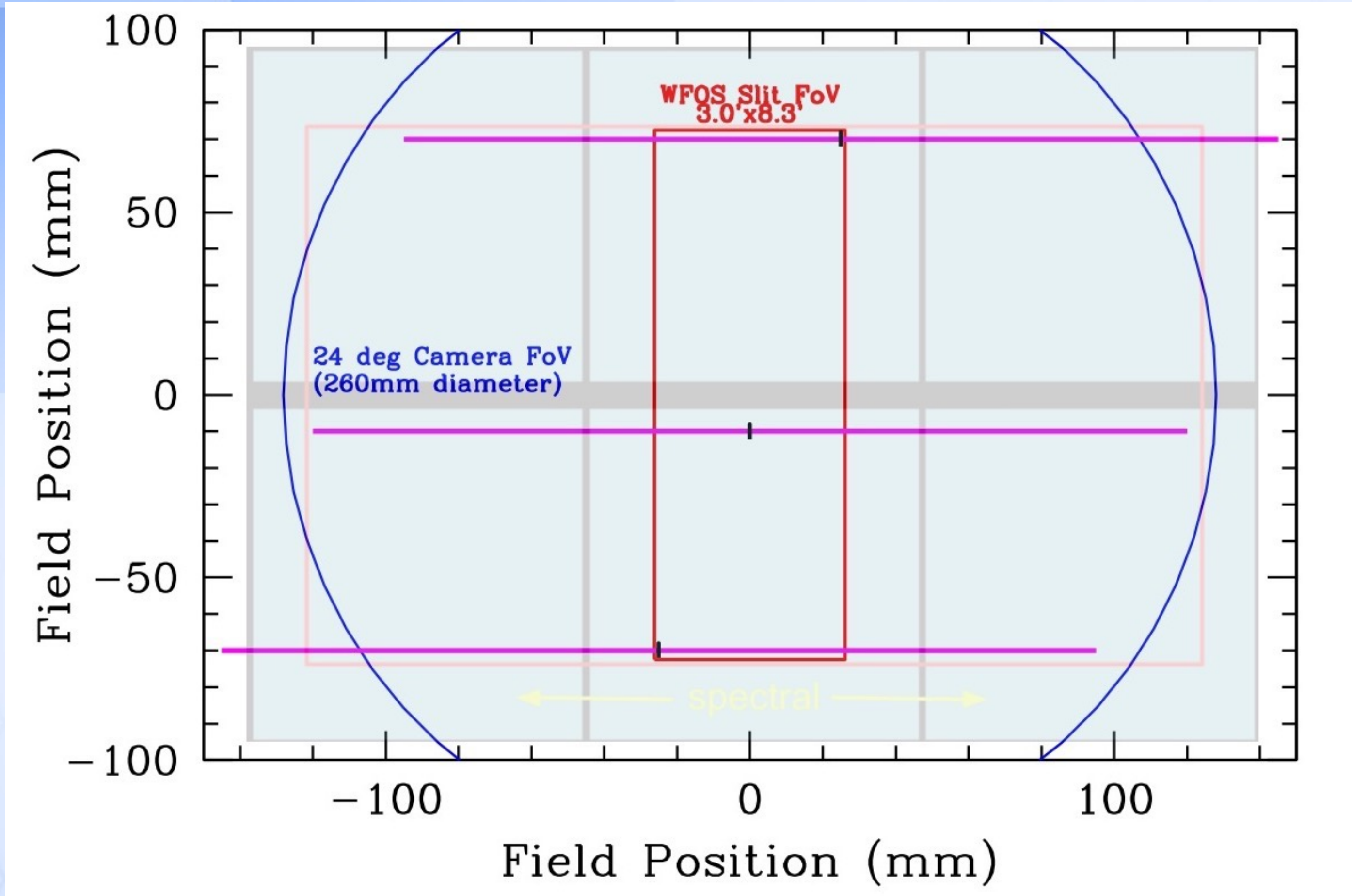
WFOS Focal Plane Layout



- 9' diameter ADC-corrected FoV (1.2m diameter)
- 4 patrolling AG cameras, each w/instantaneous 1' diameter FoV and patrol range of 3.5'
- Each AGC camera includes a WFS system that can be steered to any position within the 60" AGC field of view.
- Used collectively for acquisition, fine alignment, and wavefront sensing
- Fine acquisition does not require alignment boxes to be placed inside the science FoV
- Mitigates scattered light, large overheads for instrument reconfigurations
- Accommodates facility LGS asterism (4.6' x 5.6') for GLAO

WFOS Focal Plane Layouts

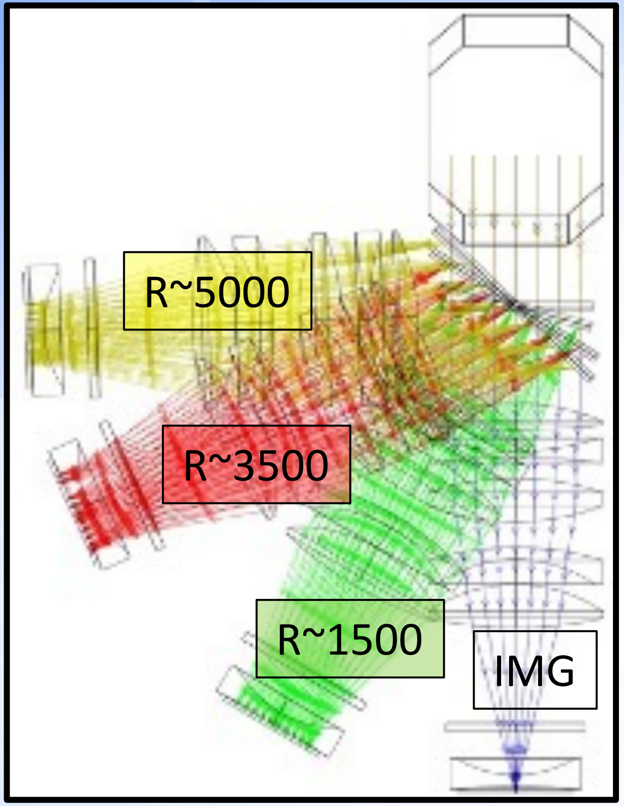
Detector Focal Plane(s)

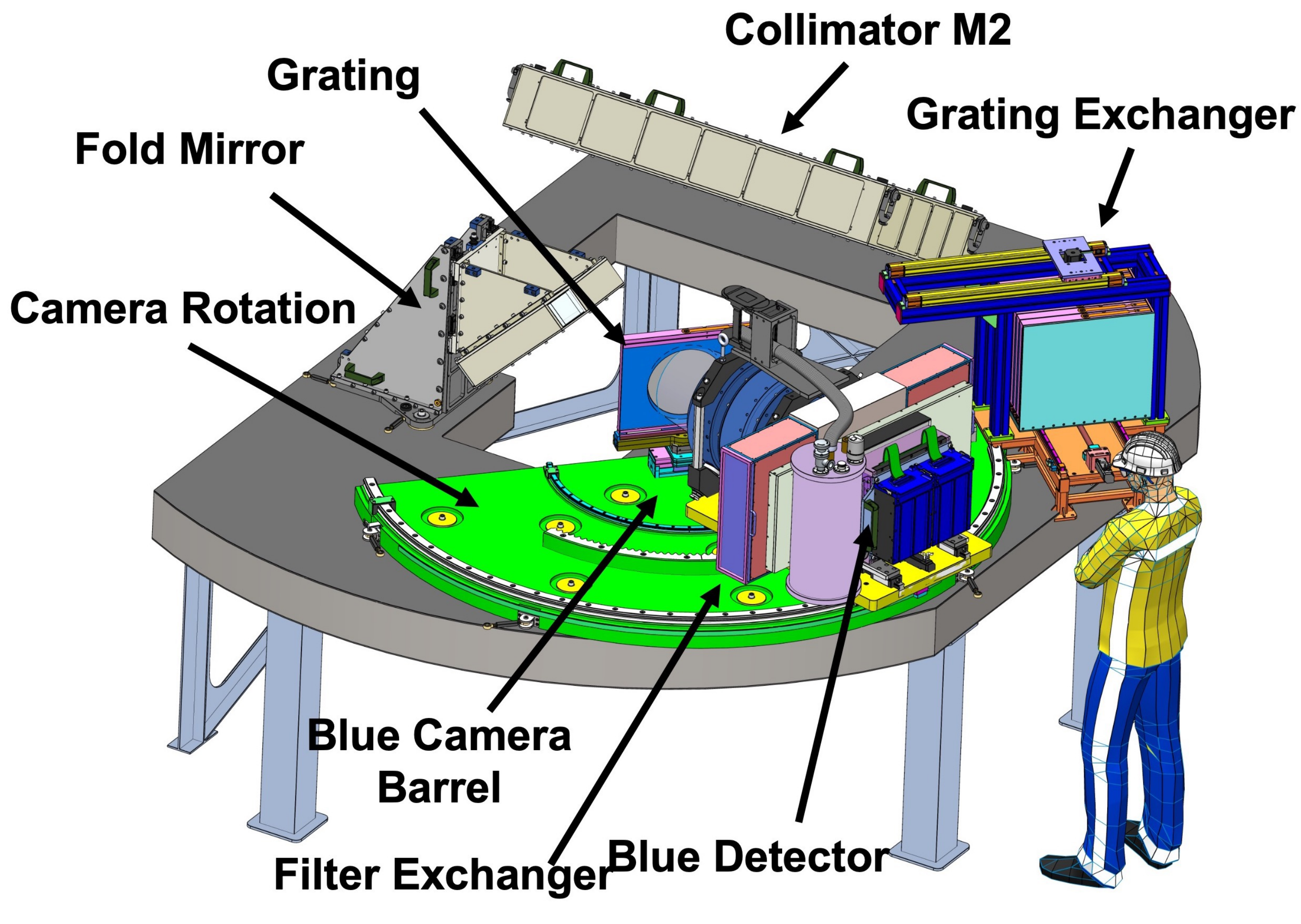


- 3 by 2 array of 6k x 6k CCDs
  (or 4 by 3 4k x 4k) each channel;
  need at least 150mm x 250mm
- QE optimized for wavelength channel
- Nod & shuffle enabled
- Plate scale = 0.052”/15µm→ binning 2x2
- Readout < 10s, < 3e- noise

Blue Channel Optical Bench

(Red channel is identical except for camera and camera mount)

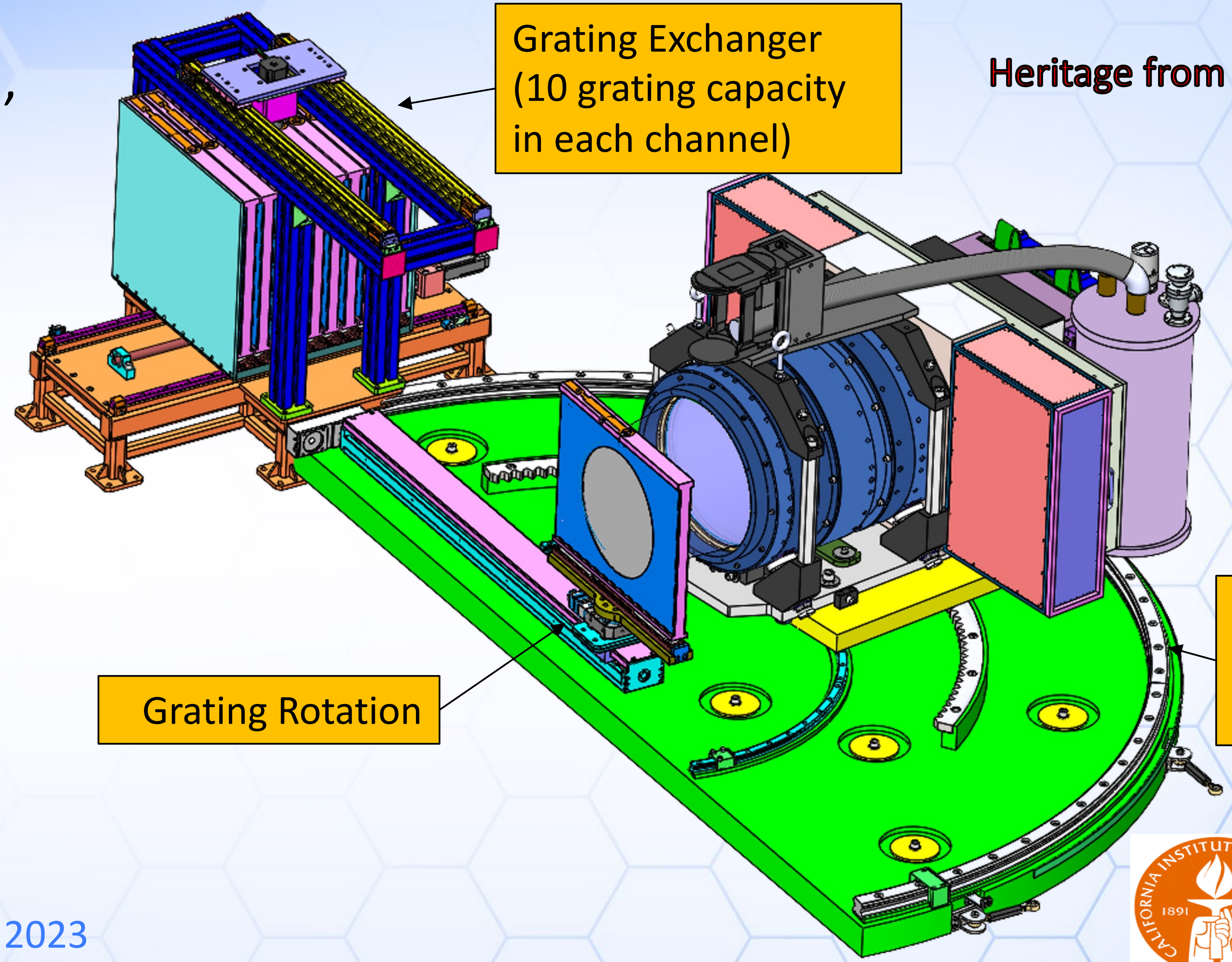


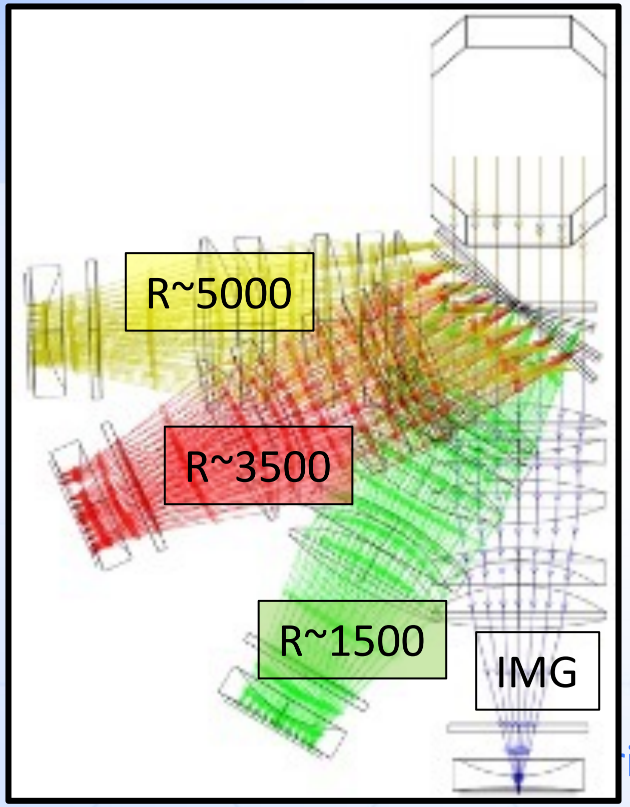


WFOS Grating and Camera Assemblies

Camera Rotation System,
Grating Exchanger,
Grating Rotation

Heritage from KCWI @Keck





WFOS Architecture Motivation

Why transmitting dispersers+articulated cameras and gratings?

- Versatility in spectral resolution, wavelength coverage options w/o compromising efficiency – heritage from Keck/KCWI
- reduced grating scatter (by a factor of >10) relative to conventional surface-ruled gratings/grisms
- Provides clean pupil interior to instrument to minimize stray/scattered light
- adding custom gratings is relatively inexpensive

Rectangular FoV geometry follows from desire for:

- multiplex (~ slit length) without large range of AOI for slits: +/- 2.5 degrees on a given mask
- minimize size of collimator optics in 1 dimension
- uniformity of wavelengths covered for all slits in FoV
- maintain high grating diffraction efficiency for all field points

Spectroscopic Observing Modes

Table 2: Example WFOS Spectral Resolution and Wavelength Coverage Options*

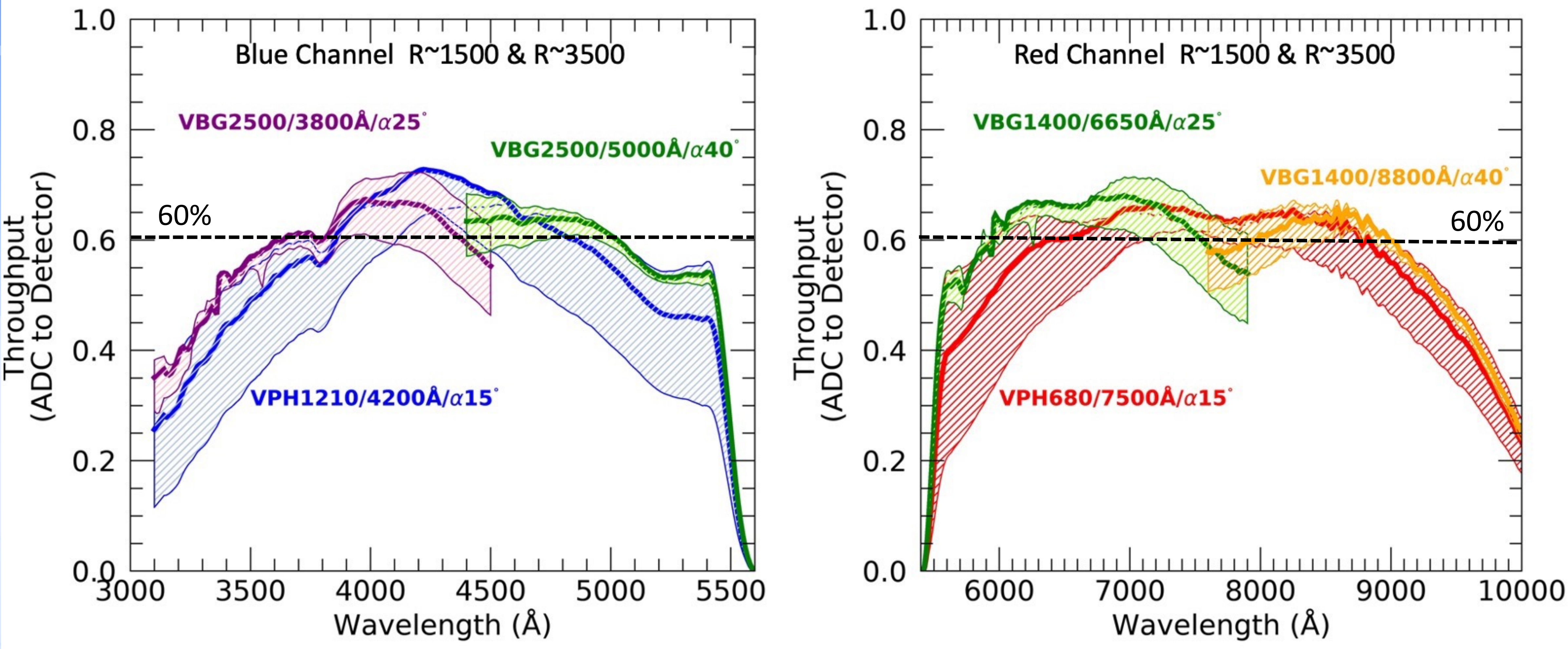
Blue Median $\mathcal{R}$ (1)	Blue Range (2)	Blue Slit (3)	Blue Å/slit (4)	Red Median $\mathcal{R}$ (1)	Red Range (2)	Red Slit (3)	Red Å/slit (4)
1500	3100-5600	0″.75	2.89	1500	5400 – 10000	0″.75	5.17
3500	3100-4300	0″.75	1.44	3500	5500 – 7730	0″.75	2.23
	4300-5500	0″.75	1.44		7600 – 9830	0″.75	2.23
5000	3300-4020	0″.75	0.75	5000	5400 – 6660	0″.75	1.31
	4000-4720	0″.75	0.75		6650 – 7910	0″.75	1.31
	4630-5600	0″.75	1.00		7900 – 9600	0″.75	1.78
2250	3100-5600	0″.50	1.93	2250	5400 – 10000	0″.50	3.45
5250	3100-4300	0″.50	0.96	5250	5500 – 7730	0″.50	1.49
	4300-5500	0″.50	0.96		7600 – 9830	0″.50	1.49
7500	3300-4020	0″.50	0.50	7500	5400 – 6660	0″.50	0.87
	4000-4720	0″.50	0.50		6650 – 7910	0″.50	0.87
	4630-5600	0″.50	0.67		7900 – 9600	0″.50	1.19
4500	3100-5600	0″.25	0.96	4500	5400 – 10000	0″.25	1.72
10500	3100-4300	0″.25	0.48	10500	5500 – 7730	0″.25	0.74
	4300-5500	0″.25	0.48		7600 – 9830	0″.25	0.74
15000	3300-4020	0″.25	0.25	15000	5400 – 6660	0″.25	0.44
	4000-4720	0″.25	0.25		6650 – 7910	0″.25	0.44
	4630-5600	0″.25	0.33		7900 – 9600	0″.25	0.59

* For notional set of 4 gratings per channel.
(1) Median resolving power, $\lambda/\Delta\lambda$
(2) Wavelength range (in Å) covered simultaneously (210mm spectra).
(3) Slit width, in arcsec.
(4) Width of projected slit at detector (Å per spectral resolution element.)

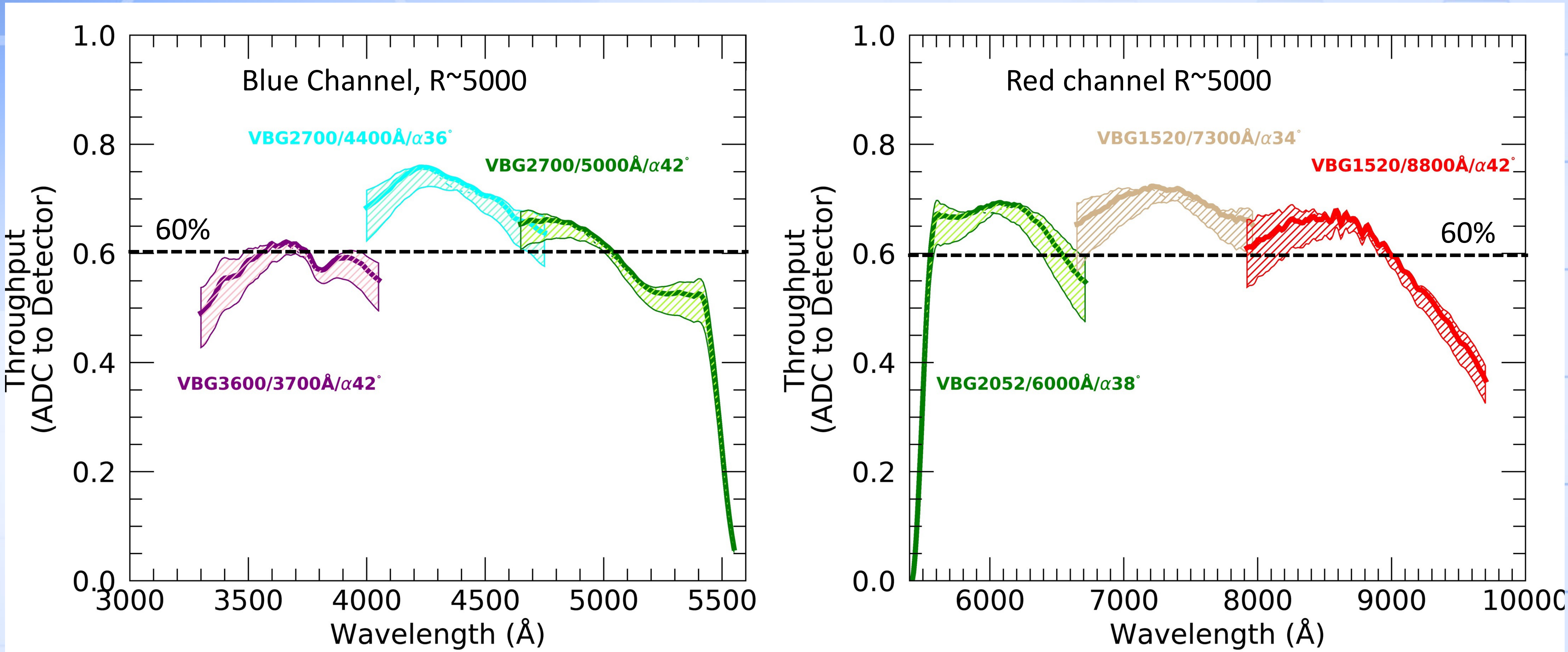
Observing Modes

- Direct Imaging (8.3’ x 3.0’) in 2 bands simultaneously, using standard broadband (u g r i z) or custom narrow-band filters
- Single target long slit or IFU
- Multislit with multiplex up to x100, total slit length of 8.3’ (500”).
- Resolving power 1500-15000
- Wavelength channels: blue 310- 570 nm
  red 540-1050 nm
- Wavelength coverage
  - 100% @R=1500*(0.75”/slit)
  - 50% @R=3500*(0.75”/slit)
  - 33% @R=5000*(0.75”/slit)

WFOS Predicted End-to-End Throughput
R~1500, R~3500 Modes

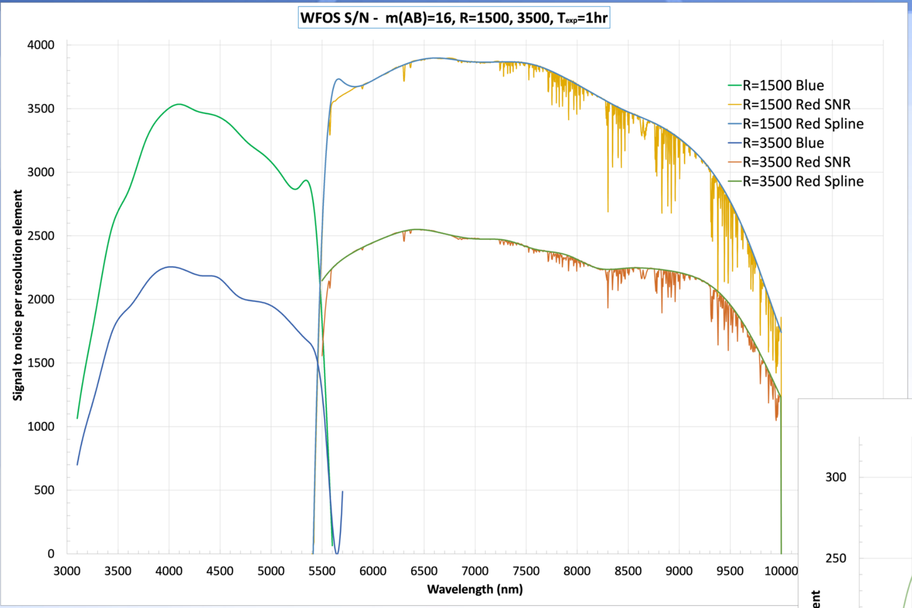


WFOS End-to-End Throughput (R~5000)



WFOS Sensitivity and Configuration

https://www.tmt.org/page/wfos-sensitivity



Assumptions

Curves are generated with the following assumptions:

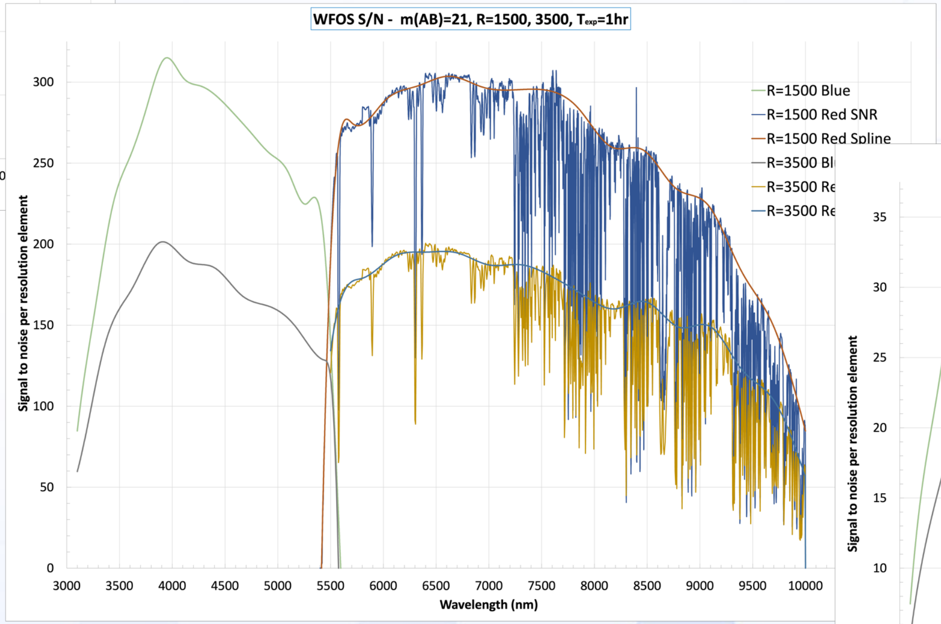
1) R1500 assumes the B1210 and R680 VPH gratings on blue and red channel, respectively, with fixed camera angles that place the maximum diffraction efficiency at the center of the spectral range.

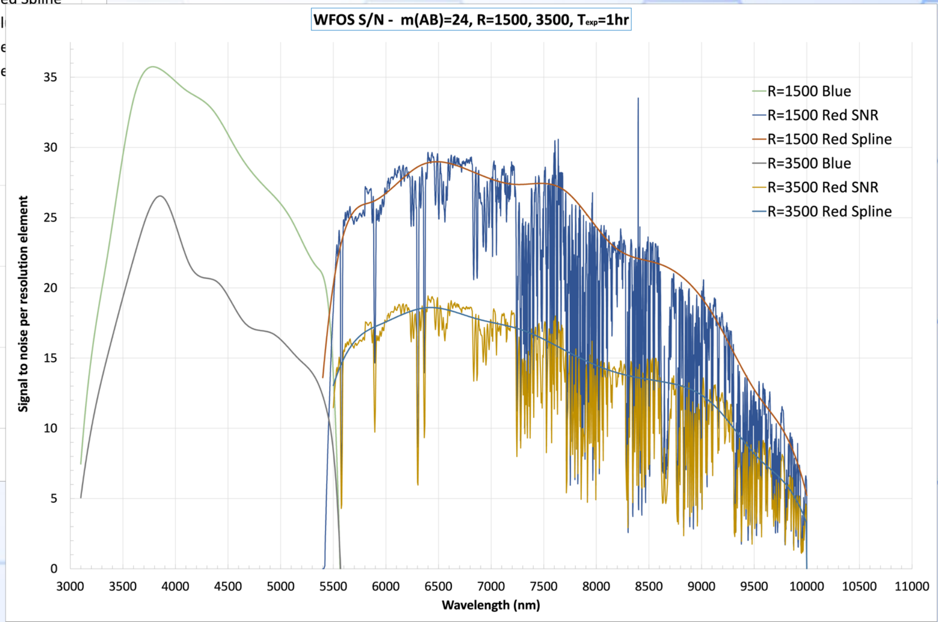
2) R3500 assumes the B2479 VPH grating (blue) and R1520 VPH grating (red), which have similar peak efficiency as the currently planned VBG gratings, but fall off more rapidly away from the peak. The throughput curves were generated by combining 4 different angle of incidence for each channel, and using the maximum diffraction efficiency achieved at each wavelength.

3) The reflectivity of the telescope optics assumes a UV enhanced coating and makes reasonable assumptions about performance shortward of 3400 A. The currently baselined Gemini-type coating would significantly degrade the performance below 4000 A compared to the assumed coating, and would be close to zero by 3400 A. However, telescope optics coatings with enhanced UV performance are being explored, it is quite probable that an enhanced coating could be available for the time of TMT First Light and WFOS is designed to operate up to the UV atmospheric cutoff at ~3100 A.

4) Slits are assumed to be 0.75". Seeing 0.65". Targets are point sources with extraction aperture of 1" along the slit; these assumptions lead to a 23% slit loss that is included in all of the SNR calculations.

5) The sky spectrum assumes no significant moonlight.



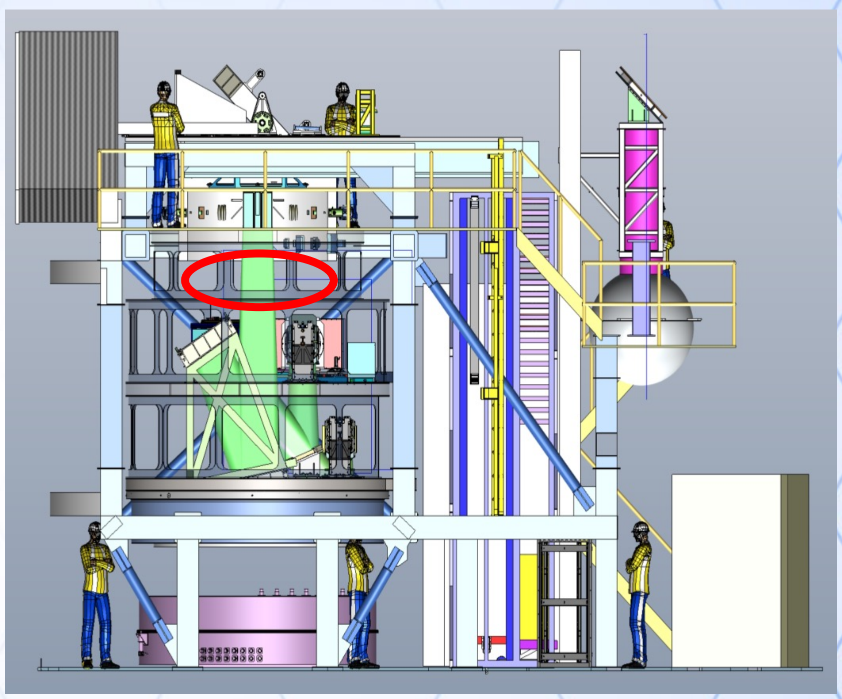


Upgrade Paths

- <u>IFU</u>: reserved platform behind focal surface for mounting a deployable slicer-based IFU

Number of slices	18		32	
Magnification factor of relay optics	1.1			
Slice length (mm)	48.0		29.6	
Slice length (arcsec)	20		12.34	
Slice width (mm)	3.60	1.80	1.2	0.6
Slice width (arcsec)	1.5	0.75	0.5	0.25
FoV (arcsec x arcsec)	20 x 27	20 x 13.5	12.34 x 16	12.34 x 8
Spectral resolution (R) for each grating in the IFU mode*				
R=1500 grating	682	1364	2046	4092
R=3500 grating	1591	3182	4773	9546
R=5000 grating (goal)	2273	4545	6819	13635

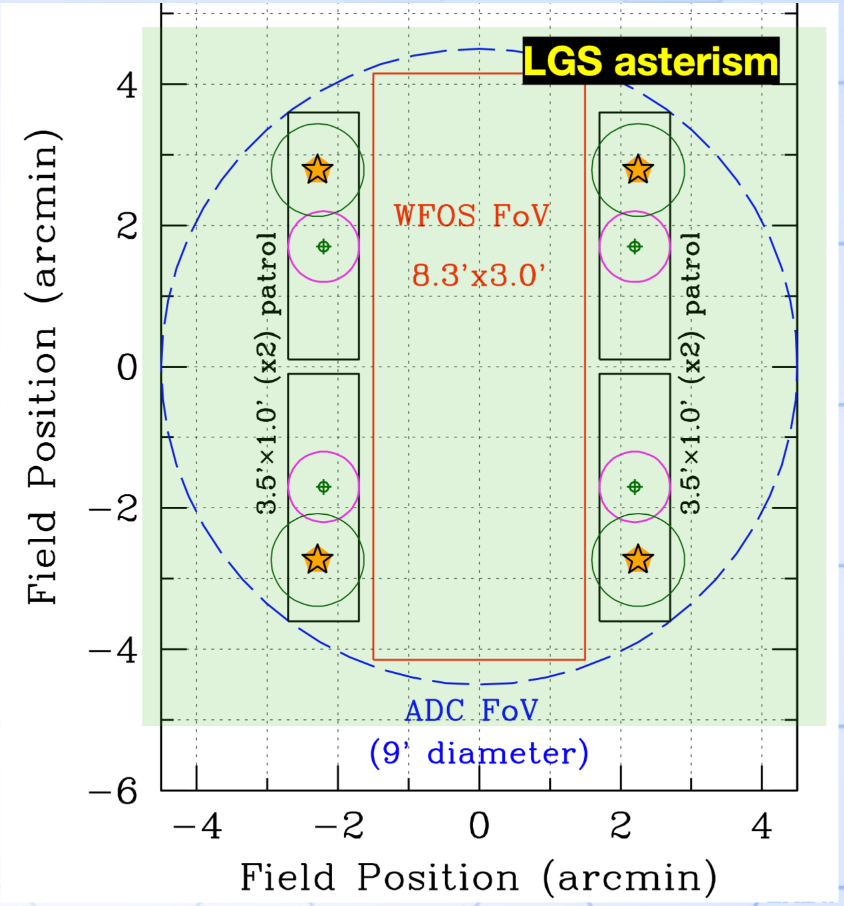
S. Ozaki(NAOJ)



Fine slicer scale provides R~4100 with simultaneous spectral coverage 0.31-1.05µm: ideal for transient follow-up/discovery

Upgrade Paths

- GLAO (Ground Layer Adaptive Optics)
  - WFOS is "GLAO-ready", with provision for laser guide star wavefront sensing using facility asterism (4.6' x 5.6')
  - → factor of 1.5-2 reduction in FWHM over full WFOS FoV.
  - Spectrograph optics designed for slits down to 0.25", → resolving power of R ~ 4500 with full 0.31-1 µm spectral coverage, R~10,000 with 50% coverage.

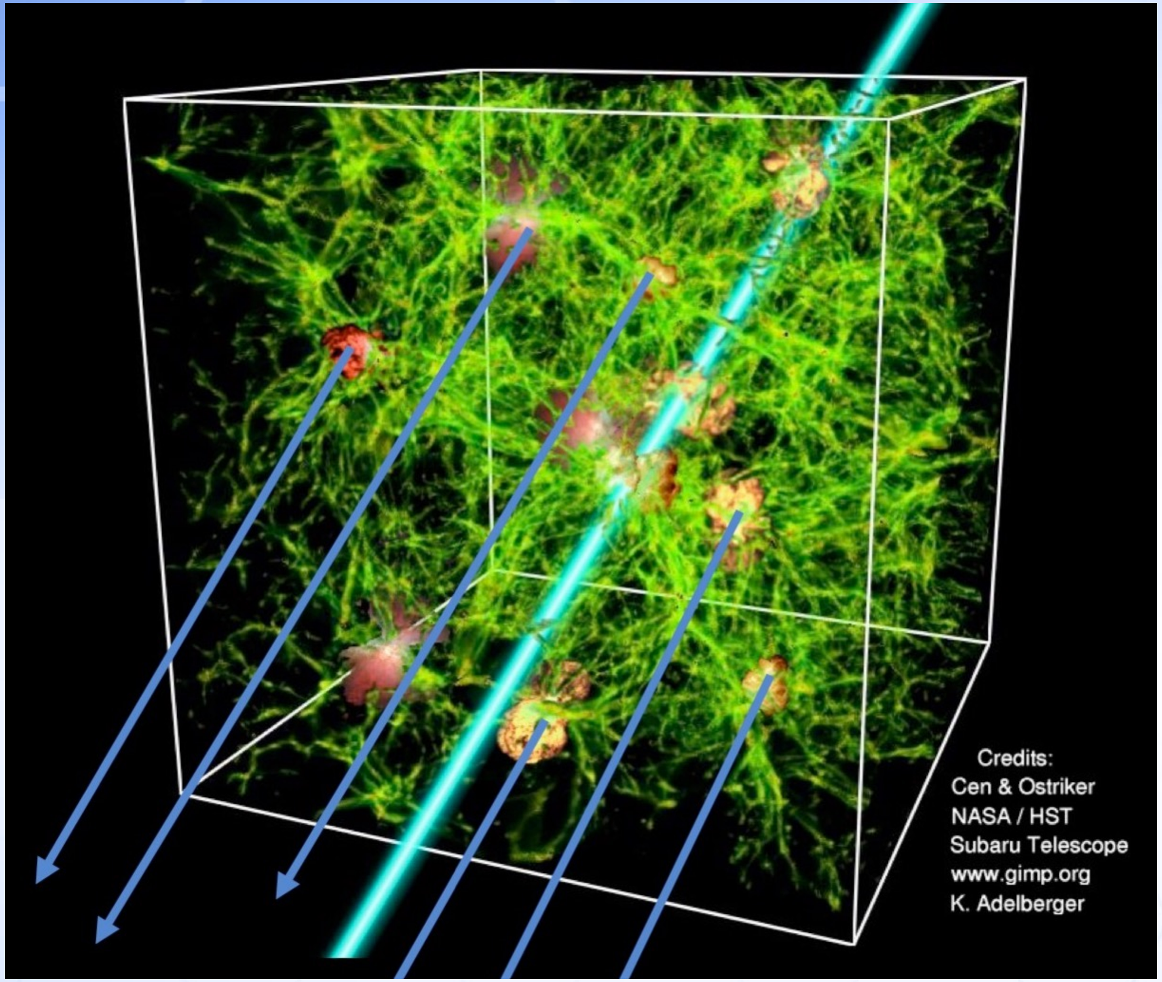


TMT
Thirty Meter Telescope

Ongoing Trade Study: SMX vs. CSU

- WFOS team is completing a trade study comparing a slitmask system using custom fabricated masks (SMX; the baseline design) and an electronically-configurable slit unit (CSU)
  - Both concepts have operational and scientific advantages/disadvantages.
  - CSU:
    - No need for mask fabrication, transportation to summit, physical mask management, SMX limit on mask capacity on instrument; configurations can be designed, altered, or replaced with no lead time.
    - Slit positioning accuracy: ~2.5 microns (0.001”) in focal plane, can form slit lengths of any multiple of masking bar size (5” → 500”)
    - Masks configurations are quantized by the choice of masking bar size in focal place (current working assumption: ~5” x 100 for 500” slit length)
  - SMX:
    - more flexible slit design (multiple ranks, micro-slits, custom slit “tilts”, etc.) possible.
    - Requires separate mask fabrication facility (probably not at the summit), quality control, transportation, daily effort to remove/load masks for each night, mask storage/archiving. Lead time may be weeks under ordinary circumstances.

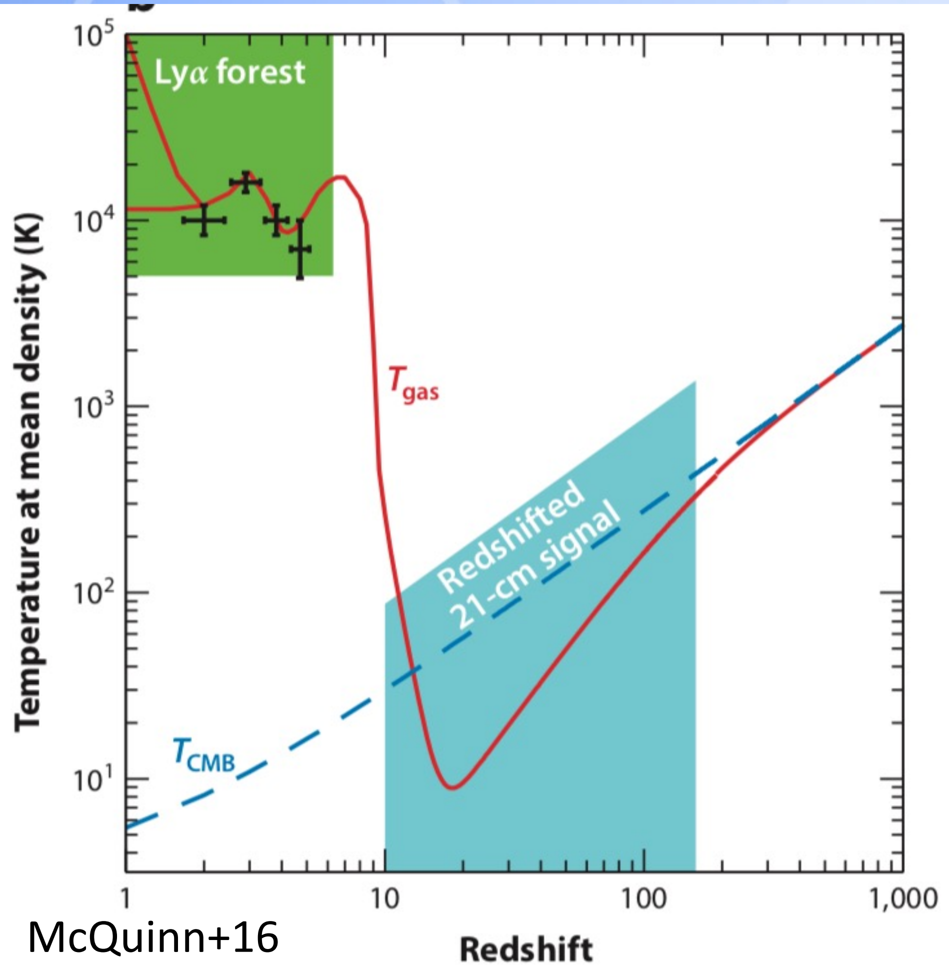
IGM tomography



Probing the state of baryons with redshift

- Astro2020: Understanding gas flows is crucial part of Cosmic Ecosystems
- Using background galaxies to study intervening Lyman-alpha and metal absorption

IGM tomography



McQuinn+16

Probing the state of baryons with redshift

- Astro2020: Understanding gas flows is crucial part of Cosmic Ecosystems
- Using background galaxies to study intervening Lyman-alpha absorption
- 310nm: z=1.55
- 340nm: z=1.8
- 400nm: z=2.3
- Redshifts z<2 is where IGM becomes multiphase

TMT/WFOS

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