Thirty-Meter Telescope: First-Light Instrumentation and Beyond

Luc Simard and TMT instrumentation teams
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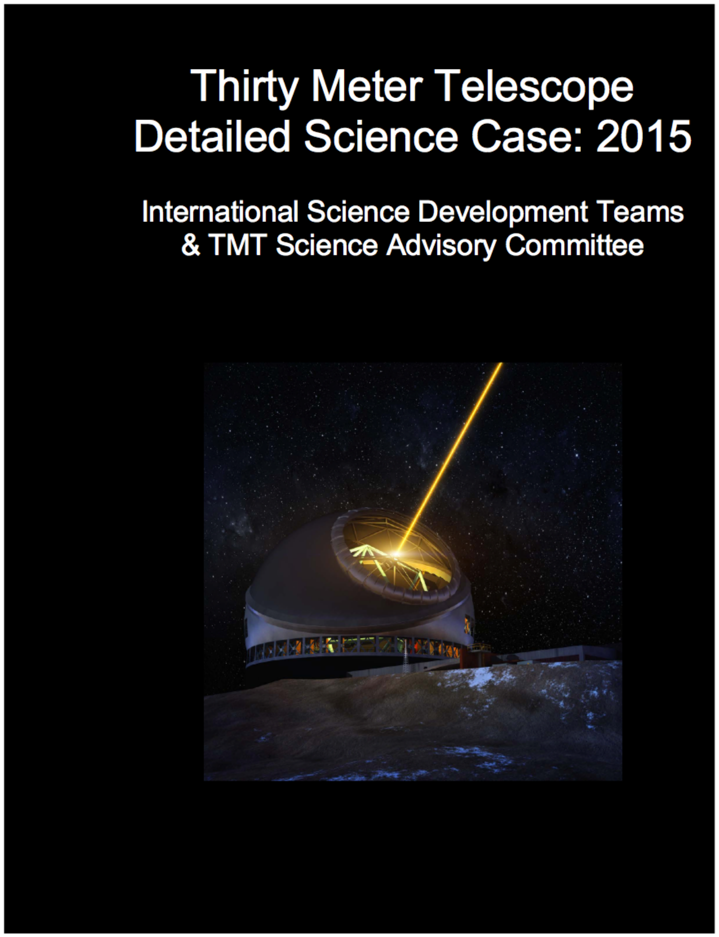
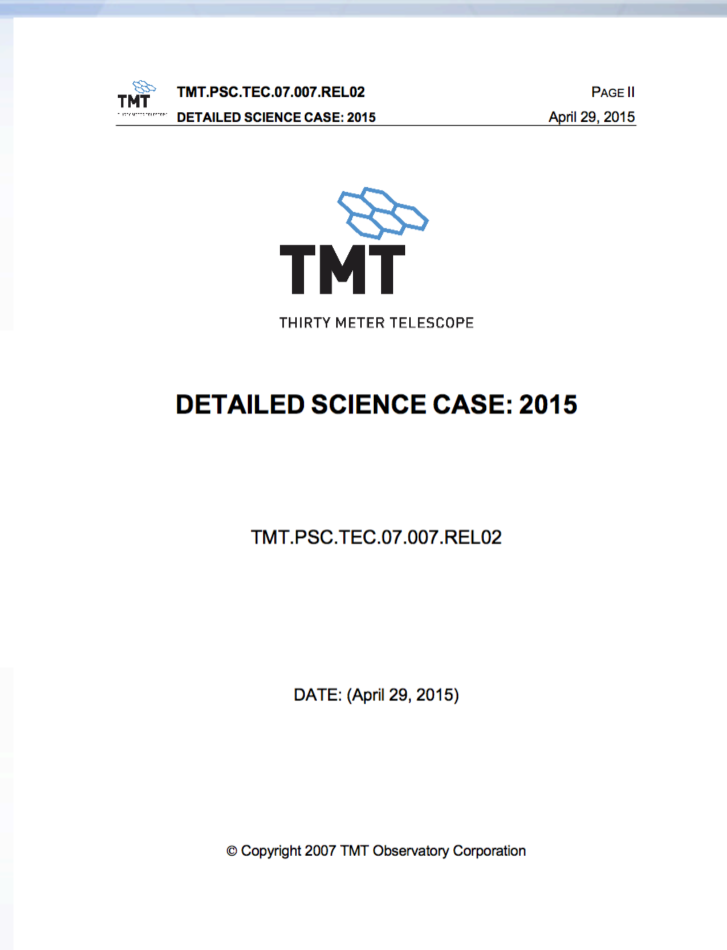
CATAC WebEx, February 21, 2017

Presentation Outline

- Science cases and simulations
- First-light AO systems
  - LGSF
  - NFIRAOS
- First-light instruments
  - IRIS
  - IRMS
  - WFOS
  - NSCU
- Facility Cryogenic Cooling System
- Future instruments: Beyond First-Light

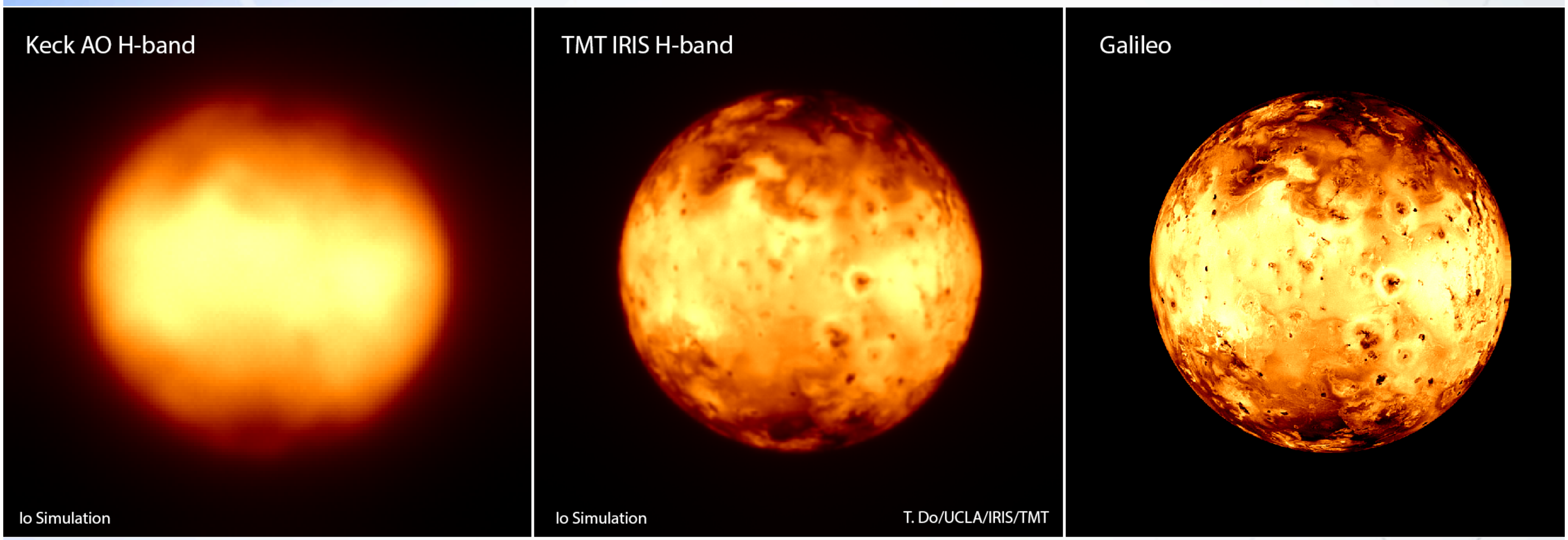
Detailed Science Case 2015 by TMT International Science Development Teams





Reference: Skidmore et al. 2015, Research In Astronomy and Astrophysics (RAA), Volume 15, Issue 12, Article id. 1945 (also https://arxiv.org/abs/1505.01195)

The Volcanoes of Io



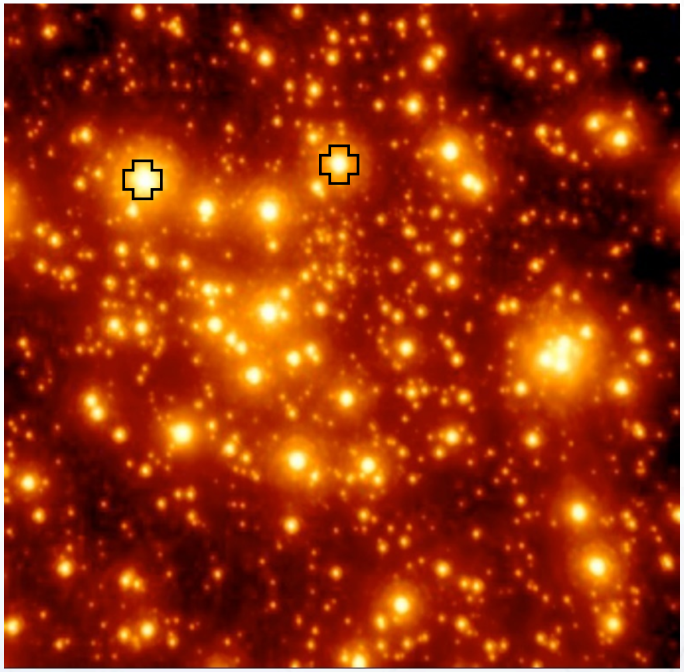
Wright, S. et al. 2016, https://arxiv.org/abs/1608.01696

Pluton and Charon

Wright, S. et al. 2016, https://arxiv.org/abs/1608.01696

JHK 3-color image with a total integration time of 100 seconds. Image was made using New Horizons data scaled to integrated near-IR magnitudes. Pluto has a diameter of 0''.107, Charon has a diameter of 0''.055, and the Pluto-Charon separation is 0''.852.

Galactic Center with Keck Telescope

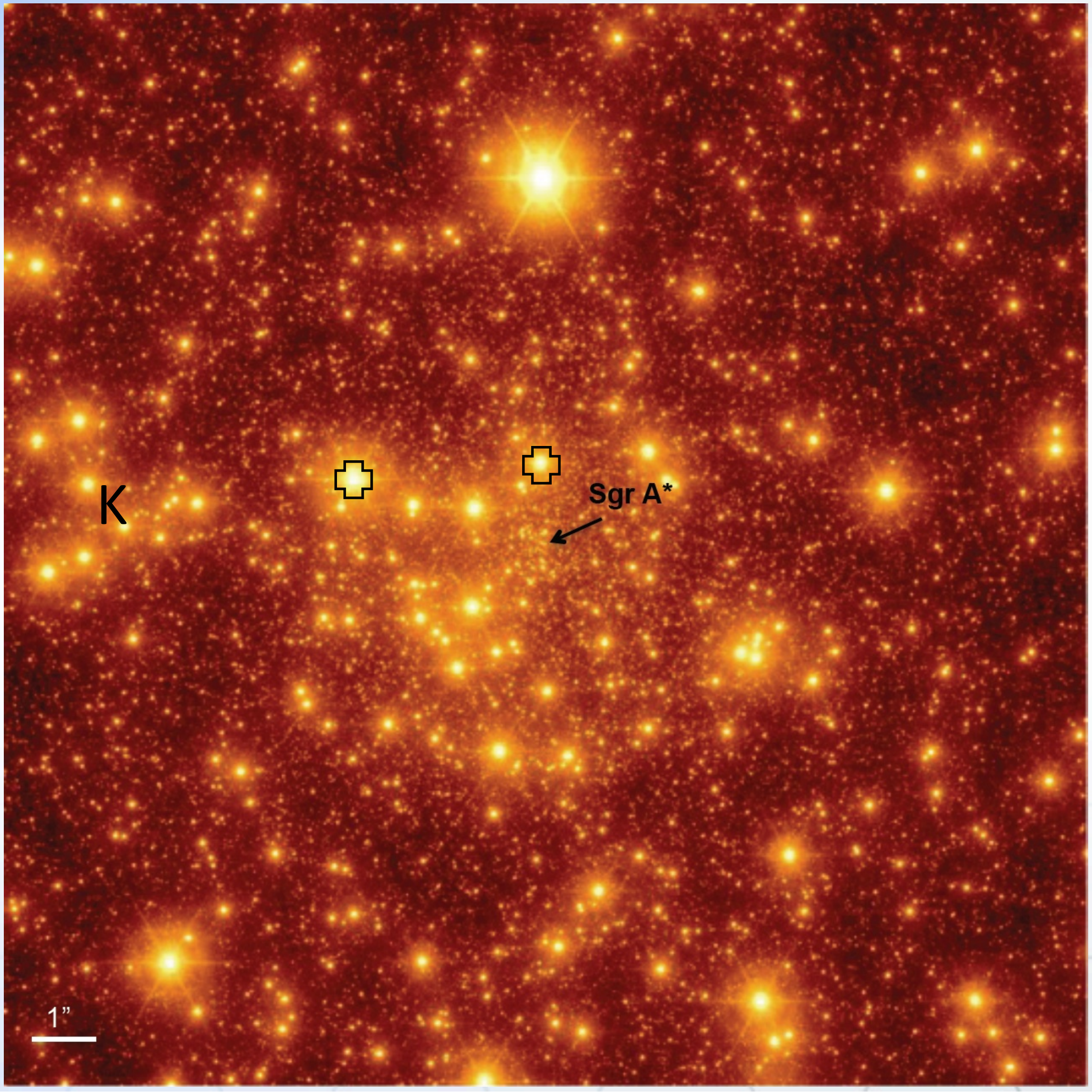


Galactic Center with TMT

K-band

t = 20s

100,000 stars down to K = 24

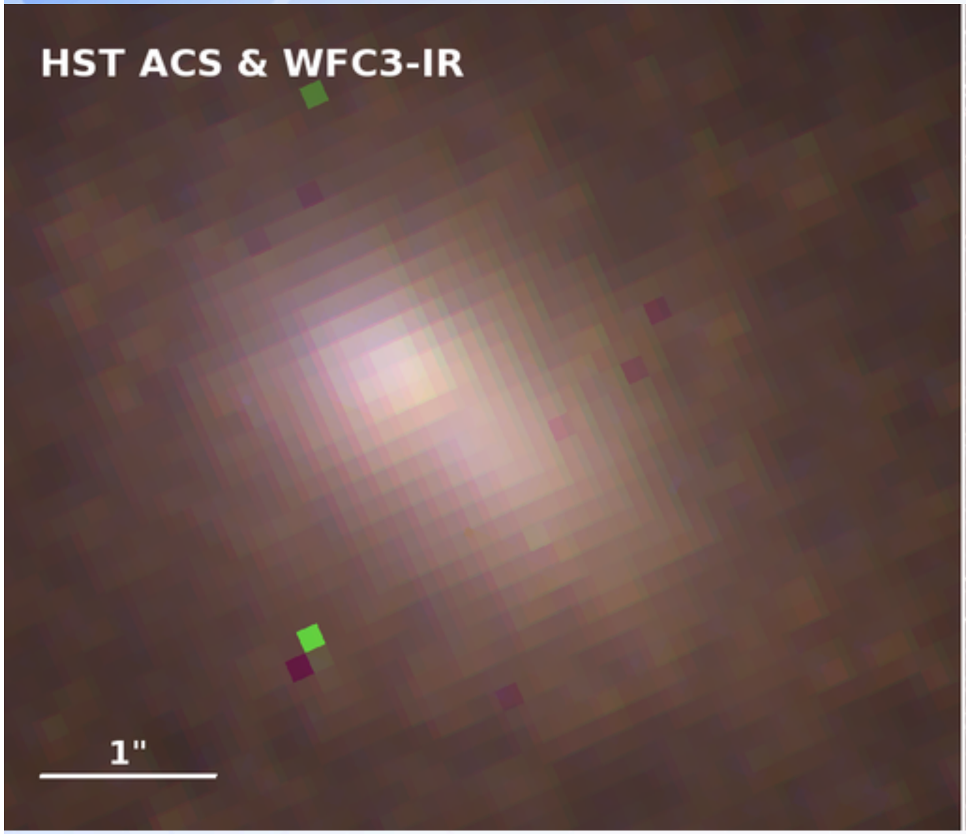


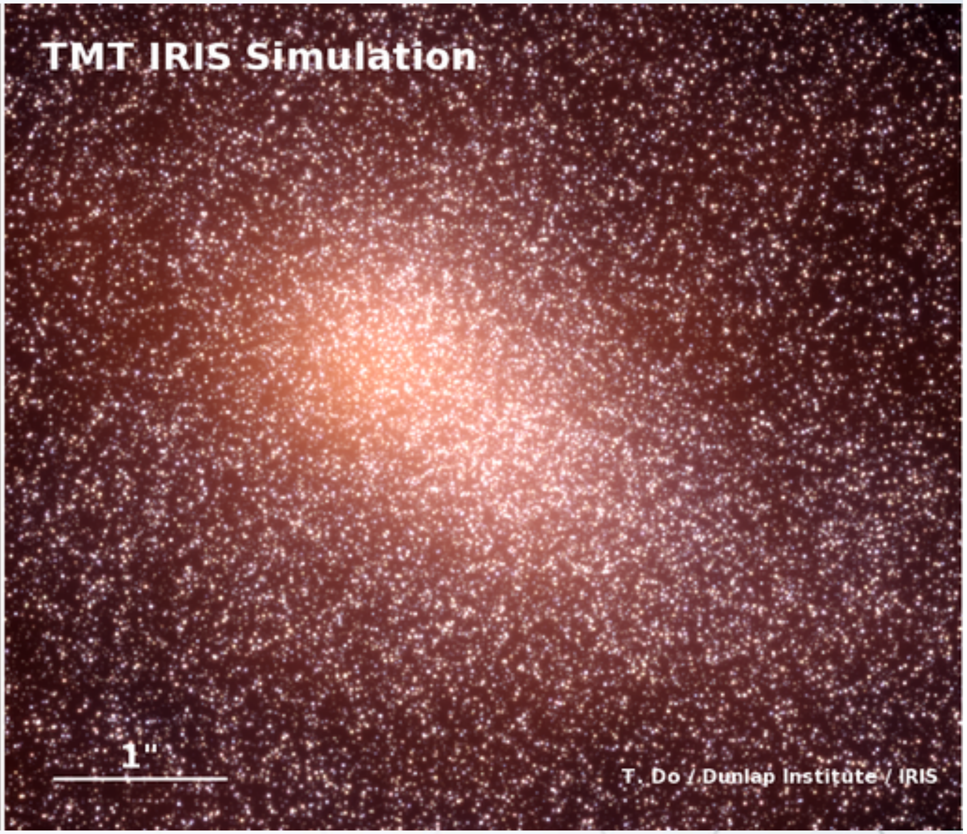
17″

17”x17” with MCAO ≅ 1°x1° seeing-limited in terms of number of point sources

Courtesy: L. Meyer (UCLA)

The Center of the Andromeda Galaxy (Messier 31)

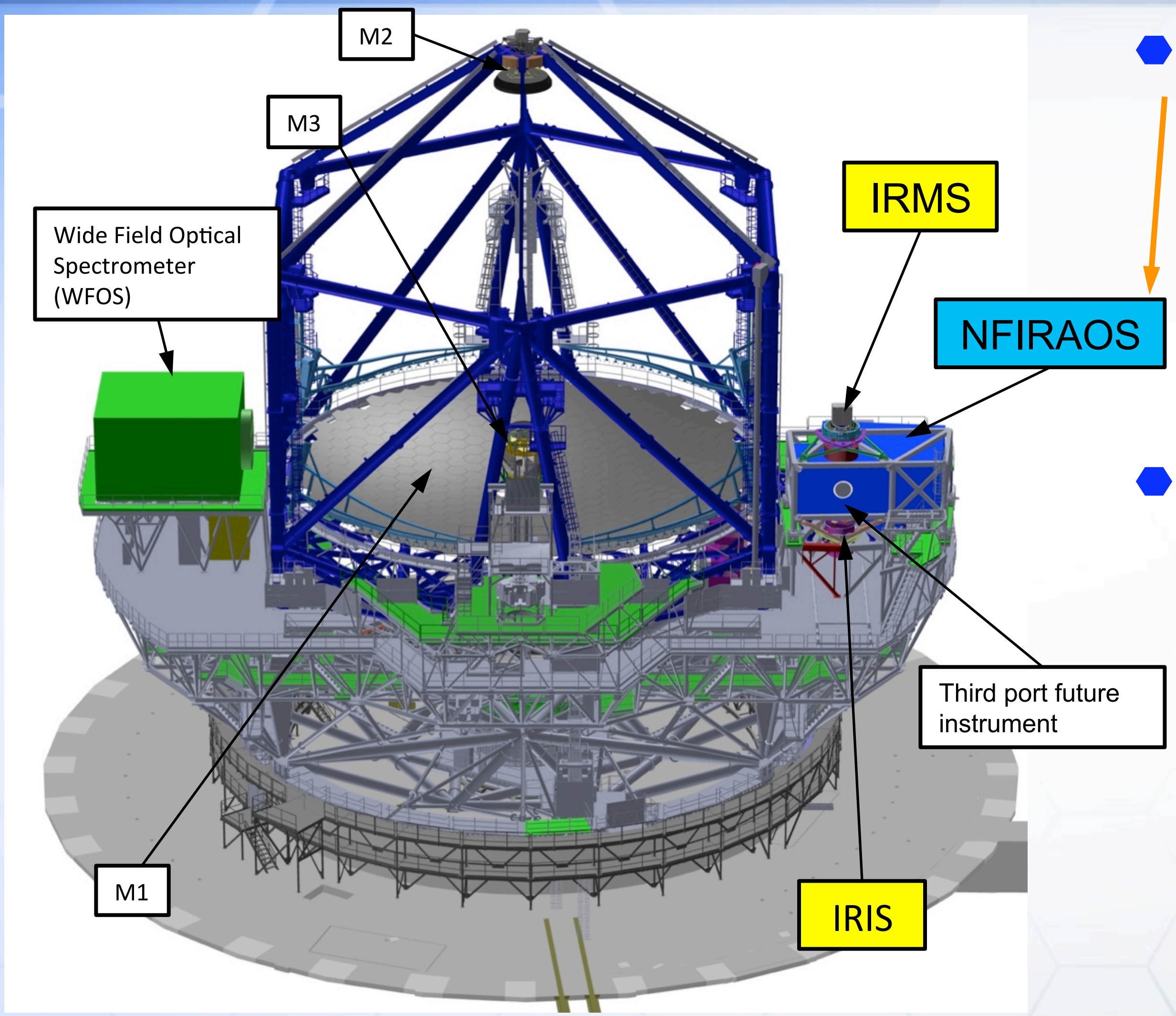




AO Requirements Driving Architecture Decisions

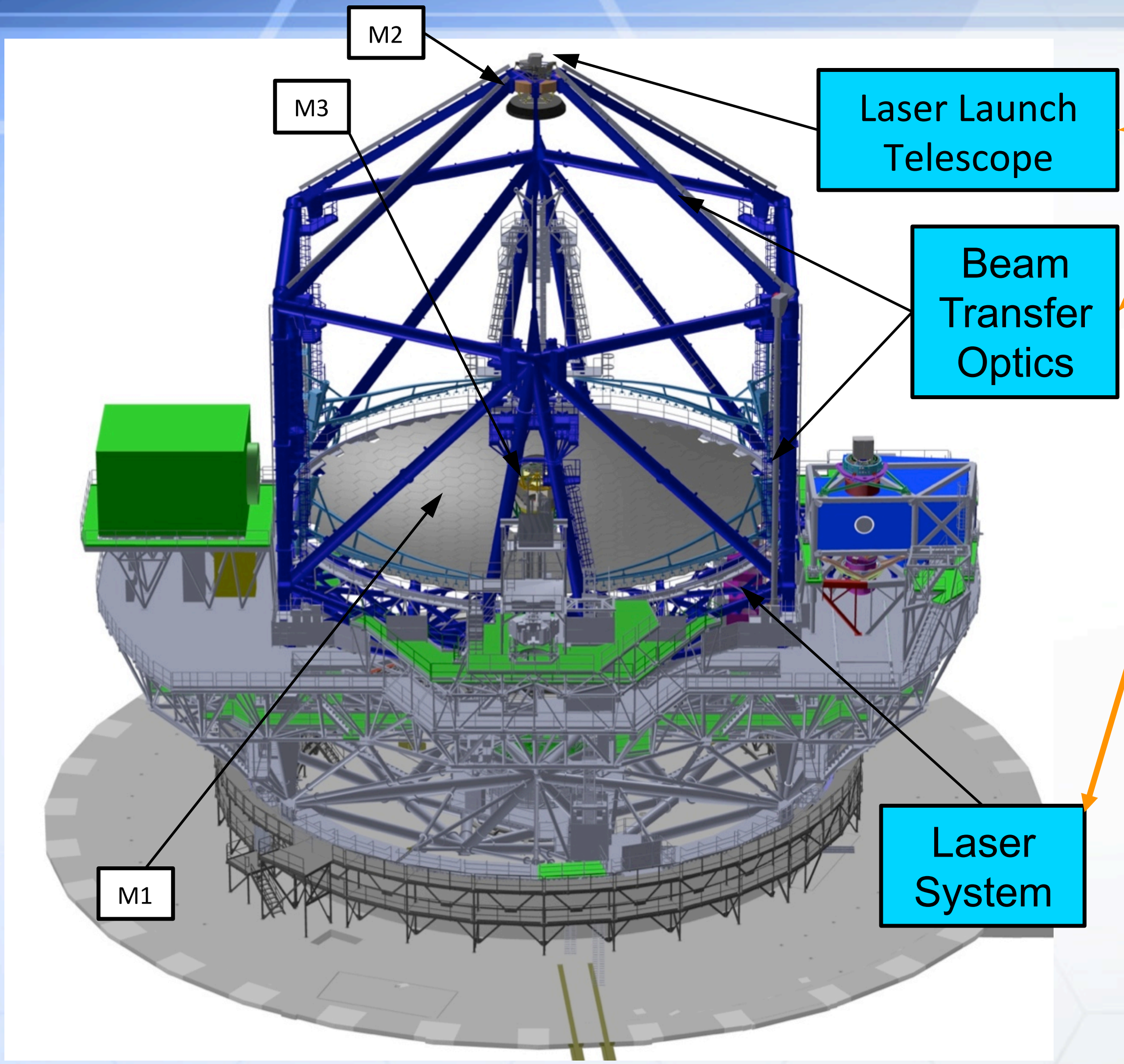
High throughput	Minimize surface count
Low thermal emission	-30C operating temperature
Diffraction limited performance in J, H, K bands	Order 60x60 wavefront sensing and correction
30"corrected science field	Atmospheric tomography + **MCAO**
High Sky coverage	Laser guide star (LGS) wavefront sensing
	NGS tip/tilt/focus sensing in the near IR
	MCAO to "sharpen" NGS images
High precision astrometry and photometry on 30" fields	Distortion-free optical design form
	MCAO for uniform, stable PSF
	AO telemetry for PSF reconstruction
Available at TMT first light with low risk and acceptable cost	Utilize existing and near term components and system concepts whenever possible

TMT First Light AO Systems



- Narrow Field IR AO System (NFIRAOS)
  - LGS, multi-conjugate AO
  - 6 laser guidestar WFSs
  - Two Piezostack DMs
  - Tip/tilt stage
  - Order 60x60 correction
  - 800Hz update rate
- Tip/tilt/focus Infrared NGS WFSs in client instruments IRIS, IRMS
  - On-instrument WFSs using near IR, H2RG HgCdTe detectors
  - Science detector “On Detector Guide Windows”

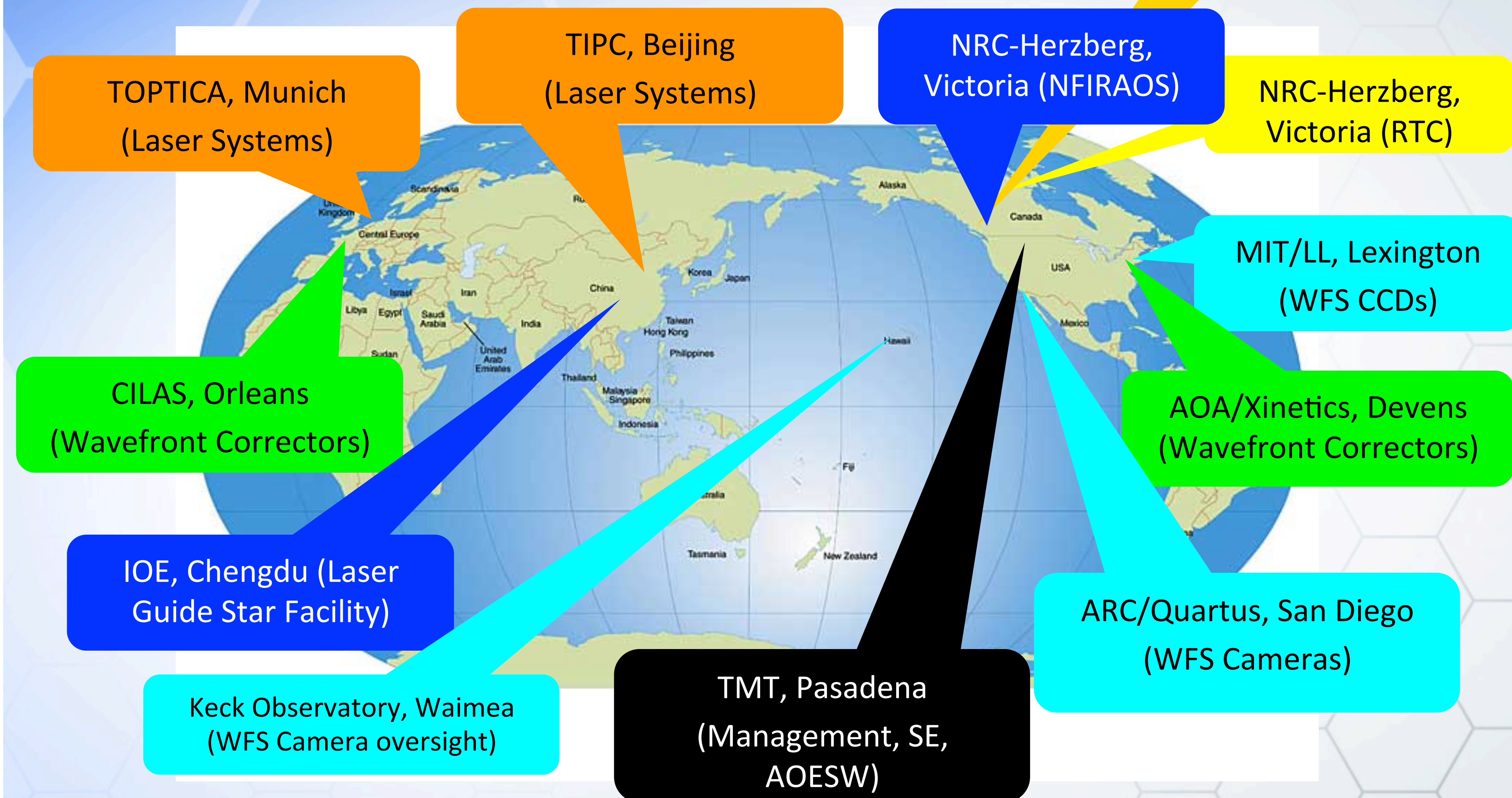
TMT First Light AO Systems (II)



- Laser Guide Star Facility (LGSF)
  - Raman fiber or Nd:YAG lasers
  - Lasers mounted on telescope elevation structure
  - Launch telescope mounted behind M2
  - Mirror-based beam transfer optics
  - 4 different asterisms for first light AO and future instrumentation
- AO Executive Software (AOESW) system

TMT
Thirty Meter Telescope

TMT AO Participants



Laser Guide Star Facility

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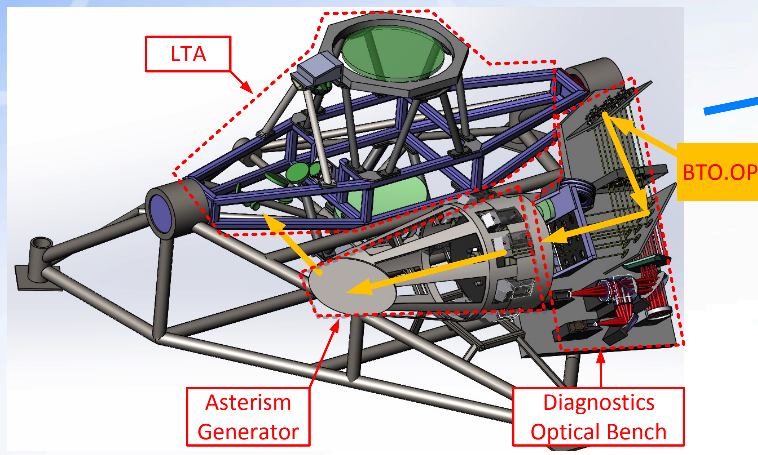
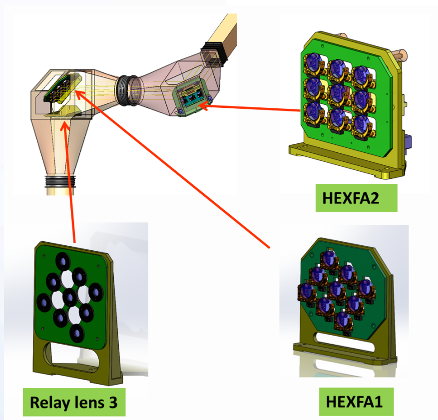
Thirty Meter Telescope

Top-End Layout

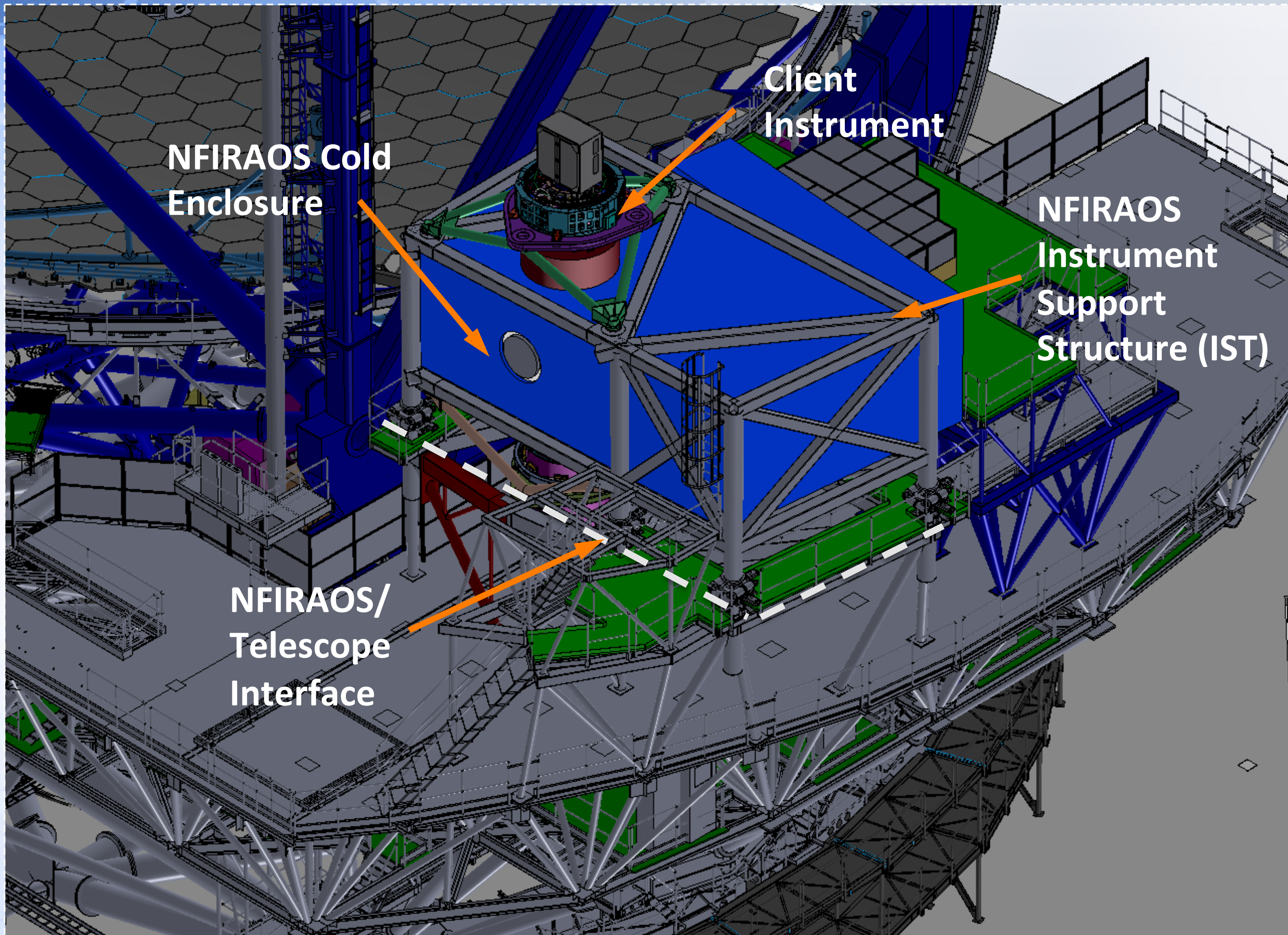




Beam Transfer Optics Components

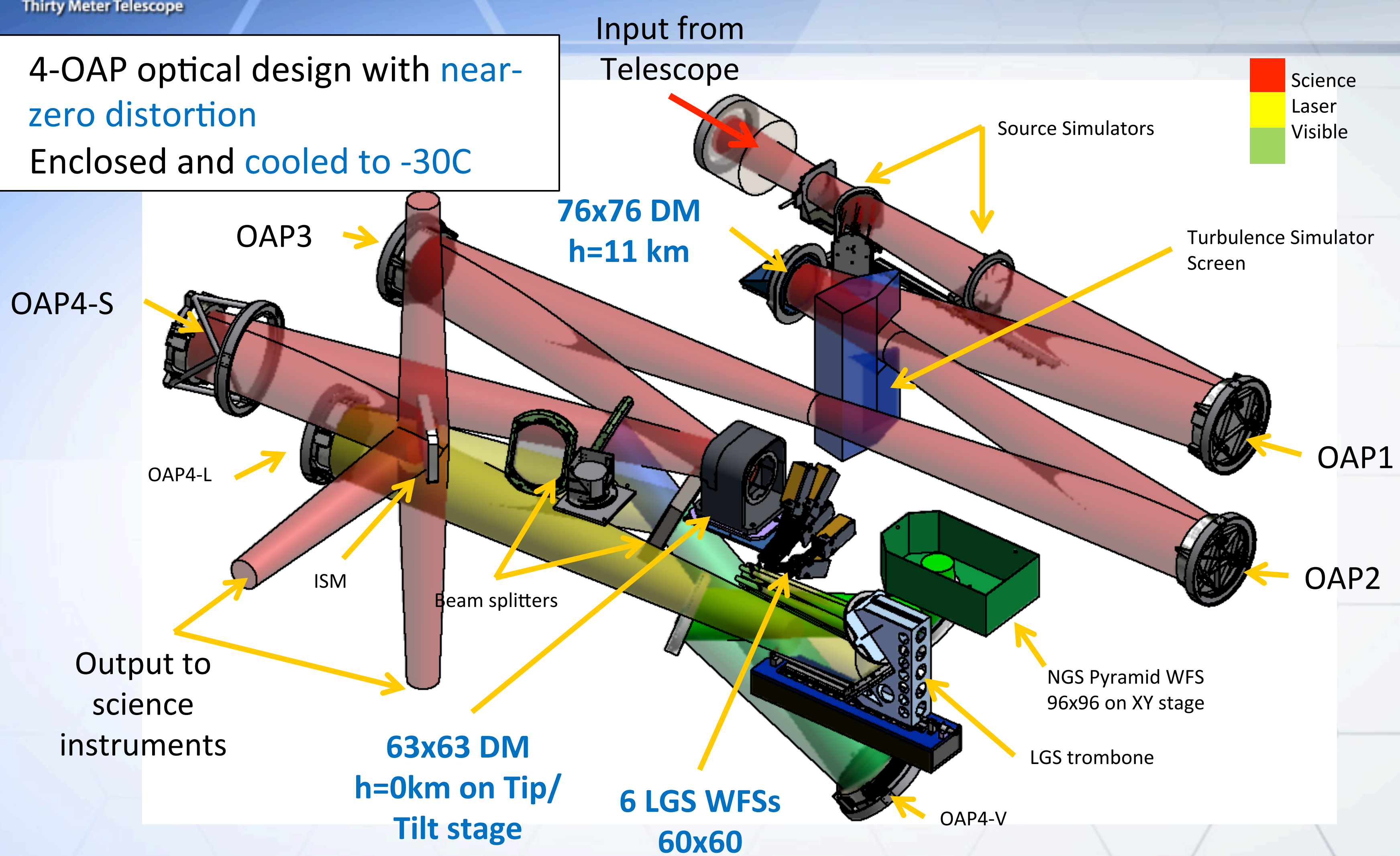
Lasers and Laser Benches

NFIRAOS at NRC-Herzberg

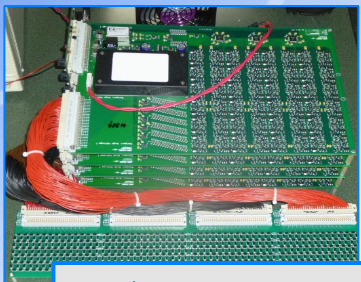
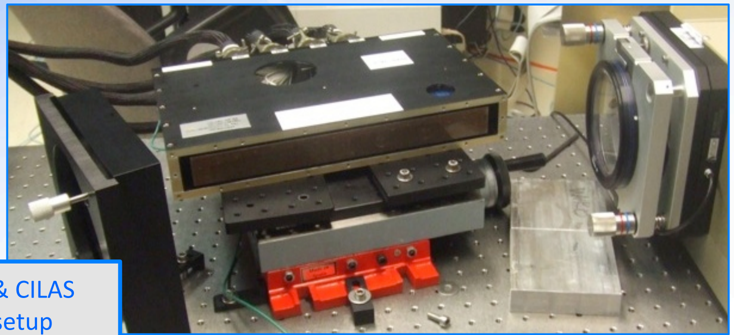


NFIRAOS Opto-Mechanical Design

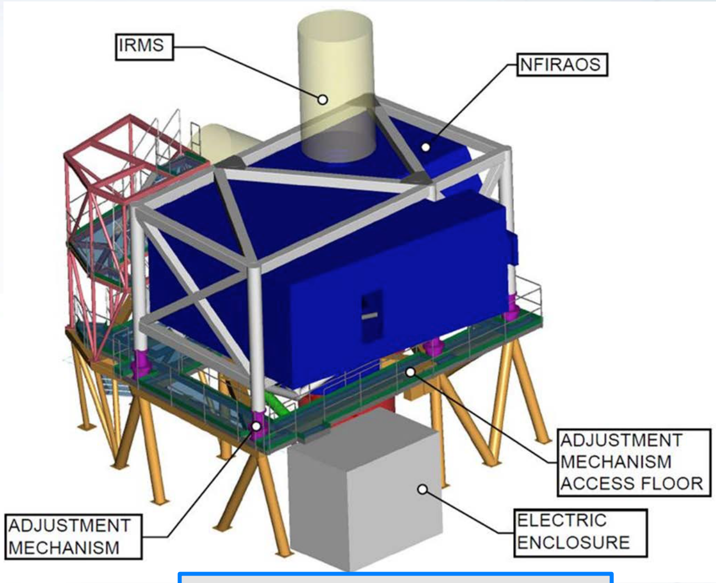
- 4-OAP optical design with near-zero distortion
- Enclosed and cooled to -30C



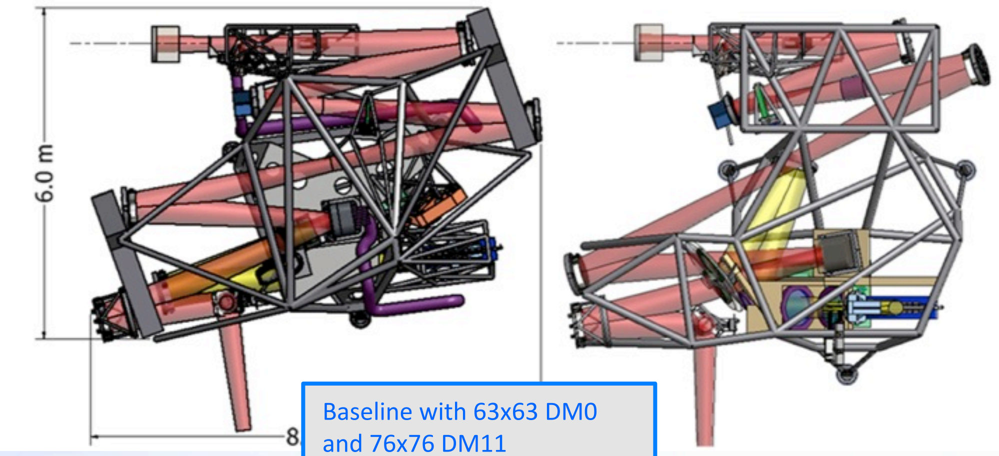
TMT Facility AO System NFIRAOS in Final Design Phase at NRC Hertzberg

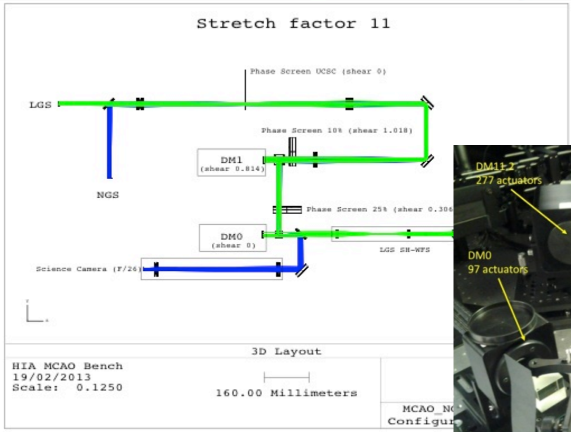
DM Electronics Prototype & CILAS DM 6x60 Breadboard test setup (warm) at NRC - Herzberg



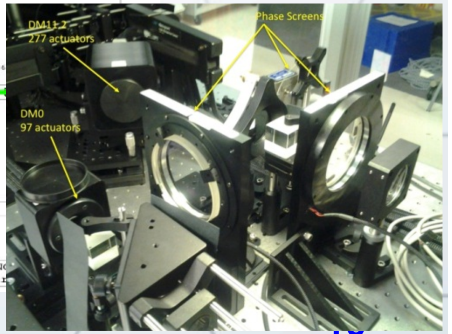
Interface with telescope structure

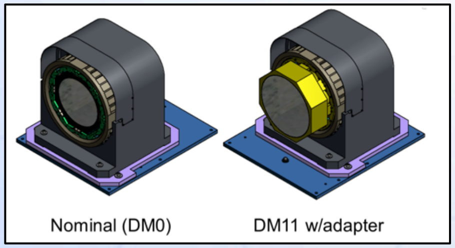


Baseline with 63x63 DM0 and 76x76 DM11



MCAO test bench





DM11 mounted on Tip/ Tilt Stage for baseline configuration

TMT Planned Instrument Suite

Instrument	Field of view / slit length	Spectral resolution	λ (μm)	Comments
InfraRed Imager and Spectrometer (IRIS)	< 4."4 x 2".25 (IFU) 16".4 x 16".4" (imaging)	4000-8000 5-100 (imaging)	0.8 – 2.4	MCAO with NFIRAOS
Wide-field Optical spectrometer (WFOS)	40.3′ squared (FoV) 576" (Total slit length)	1000-8000	0.31-1.1	Seeing-Limited (SL)
InfraRed Multislit Spectrometer (IRMS)	2′ field w/ 46 deployable slits	*R* = 4660 @ 0.16″ slit	0.95-2.45	MCAO with NFIRAOS
Multi-IFU imaging spectrometer (IRMOS)	3″ IFUs over >5' diameter field	2000-10000	0.8-2.5	MOAO
Mid-IR AO-fed Echelle Spectrometer (MIRES)	3″ slit length 10″ imaging	5000-100000	8-18 4.5-28(goal)	MIRAO
Planet Formation Instrument (PFI)	1″ outer working angle, 0.05″ inner working angle	R≤100	1-2.5 1-5 (goal)	10^8 contrast 10^9 goal
Near-IR AO-fed Echelle Spectrometer (NIRES)	2″ slit length	20000-100000	1-5	MCAO with NFIRAOS
High-Resolution Optical Spectrometer (HROS)	5″ slit length	50000	0.31-1.0 0.31-1.3(goal)	SL
"Wide"-field AO imager (WIRC)	30″ imaging field	5-100	0.8-5.0 0.6-5.0(goal)	MCAO with NFIRAOS

TMT First-Light Instrument Suite

Instrument	Field of view / slit length	Spectral resolution	λ (μm)	Comments
InfraRed Imager and Spectrometer (IRIS)	< 4.″4 x 2″.25 (IFU) 16″.4 x 16″.4″ (imaging)	4000-8000 5-100 (imaging)	0.8 – 2.4	MCAO with NFIRAOS
Wide-field Optical spectrometer (WFOS)	40.3′ squared (FoV) 576″ (Total slit length)	1000-8000	0.31-1.1	Seeing-Limited (SL)
InfraRed Multislit Spectrometer (IRMS)	2′ field w/ 46 deployable slits	*R* = 4660 @ 0.16″ slit	0.95-2.45	MCAO with NFIRAOS
Multi-IFU imaging spectrometer (IRMOS)	3″ IFUs over >5′ diameter field	2000-10000	0.8-2.5	MOAO
Mid-IR AO-fed Echelle Spectrometer (MIRES)	3″ slit length 10″ imaging	5000-100000	8-18 4.5-28(goal)	MIRAO
Planet Formation Instrument (PFI)	1″ outer working angle, 0.05″ inner working angle	R≤100	1-2.5 [illegible]	10^8 contrast [illegible]
Near-IR AO-fed Echelle Spectrometer (NIRES)	2″ slit length	[illegible]	[illegible]	MCAO with NFIRAOS
High-Resolution Optical Spectrometer (HROS)	5″ slit length	50000	0.31-1.0 0.31-1.3(goal)	SL
"Wide"-field AO imager (WIRC)	30″ imaging field	5-100	0.8-5.0 0.6-5.0(goal)	MCAO with NFIRAOS

Possible instruments within TMT instrument roadmap. A call for 2nd generation instruments will be released in 2017 (TBC)

An (Updated) ELT Instrumentation "Equivalence Table"

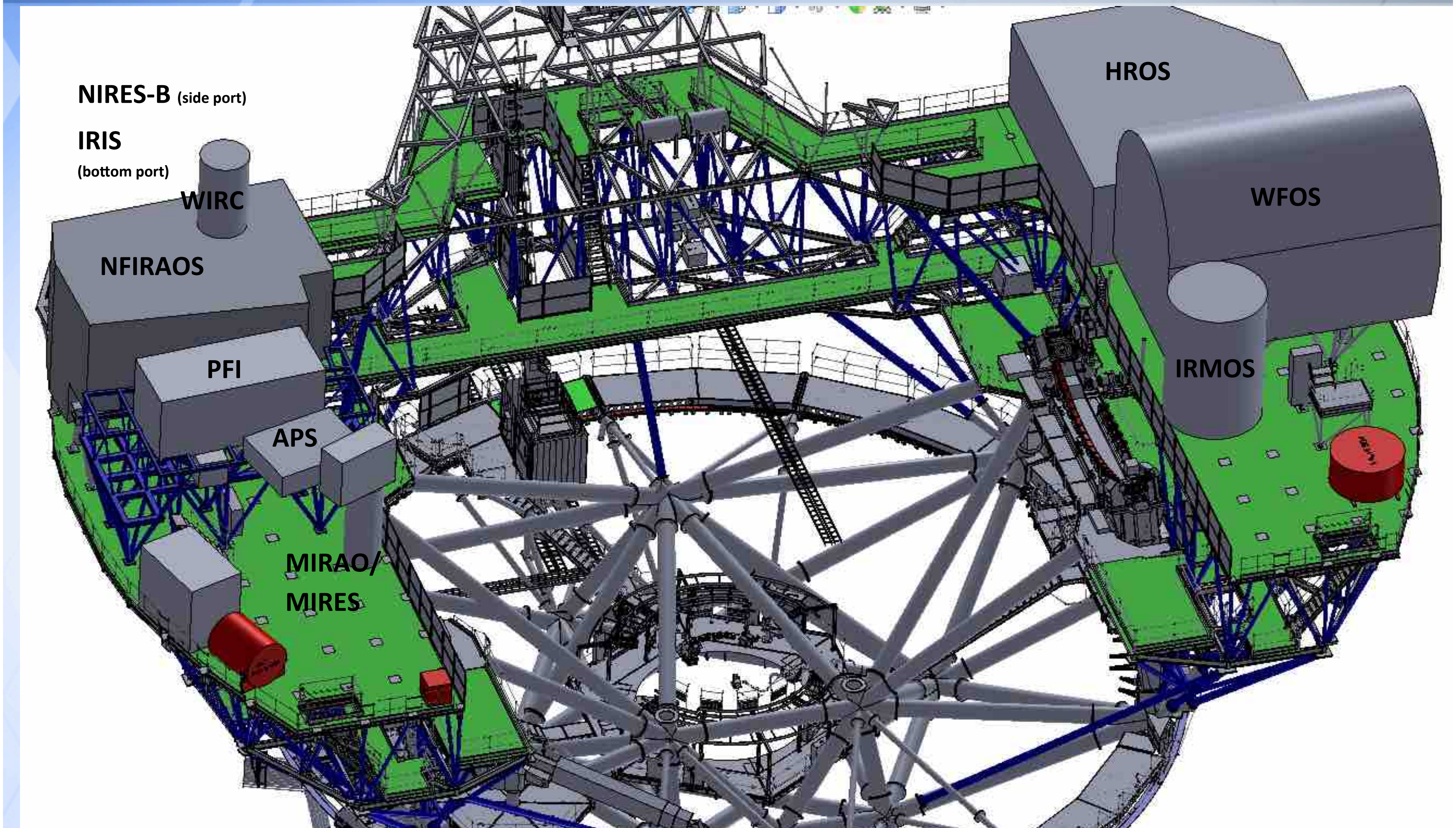
Type of Instrument	GMT	TMT	E-ELT
Near-IR, AO-assisted Imager + IFU	GMTIFS	IRIS	HARMONI
Wide-Field, Optical Multi-Object Spectrometer	GMACS	WFOS	MOSAIC-HMM
Near-IR Multislit Spectrometer	NIRMOS	IRMS	MOSAIC-HMM
Deployable, Multi-IFU Imaging Spectrometer		IRMOS	MOSAIC-HDM
Mid-IR, AO-assisted Echelle Spectrometer		MIRES	METIS
High-Contrast Exoplanet Imager	TIGER	PFI	ELT-PCS
Near-IR, AO-assisted Echelle Spectrometer	GMTNIRS	NIRES	HIRES
High-Resolution Optical Spectrometer	G-CLEF	HROS	HIRES
"Wide"-Field AO-assisted Imager		IRIS	MICADO

E-ELT and GMT Instrumentation Status

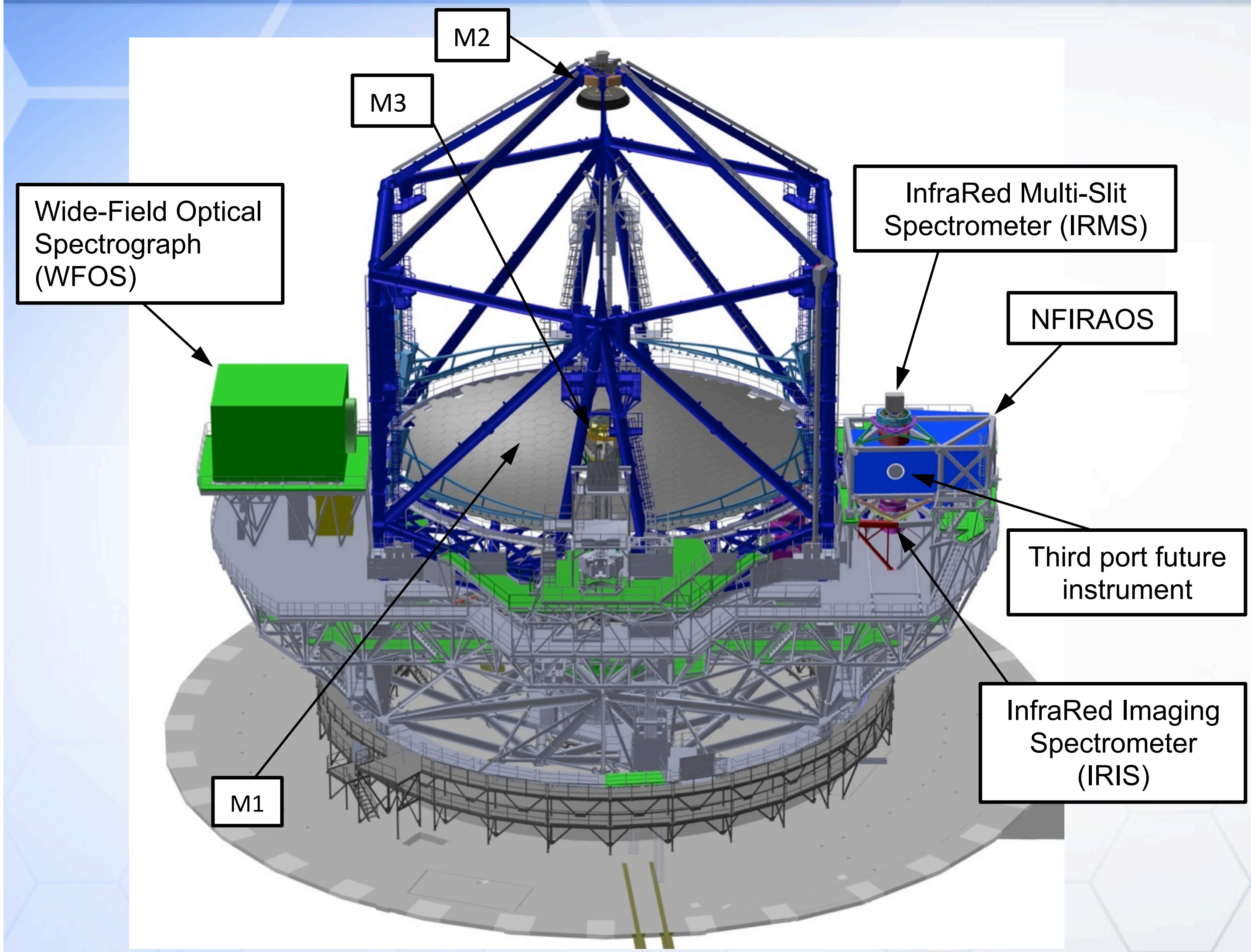
First-light dates assume technically-paced schedules

- E-ELT:
  - MICADO: Phase B (Sep 2015), PDR (2018), FDR (2020), FL (2024)
  - HARMONI: Phase B (Sep 2015), PDR (2017), FDR (2019), FL (2024)
  - METIS: Phase B (Sep 2015), PDR (2017), FDR (2019), FL (2025)
  - MOSAIC: Phase A (Mar 2016 – Mar 2018)
  - HIRES: Phase A (Mar 2016 – Mar 2018)
- GMT:
  - G-CLEF: In Final Design Phase, FL (mid-2021)
  - GMACS: In Conceptual Design Phase, FL (mid-2022)
  - GMTIFS: In Preliminary Design Phase, FL (mid-2023)

Nasmyth Configuration: Full Instrumentation Suite

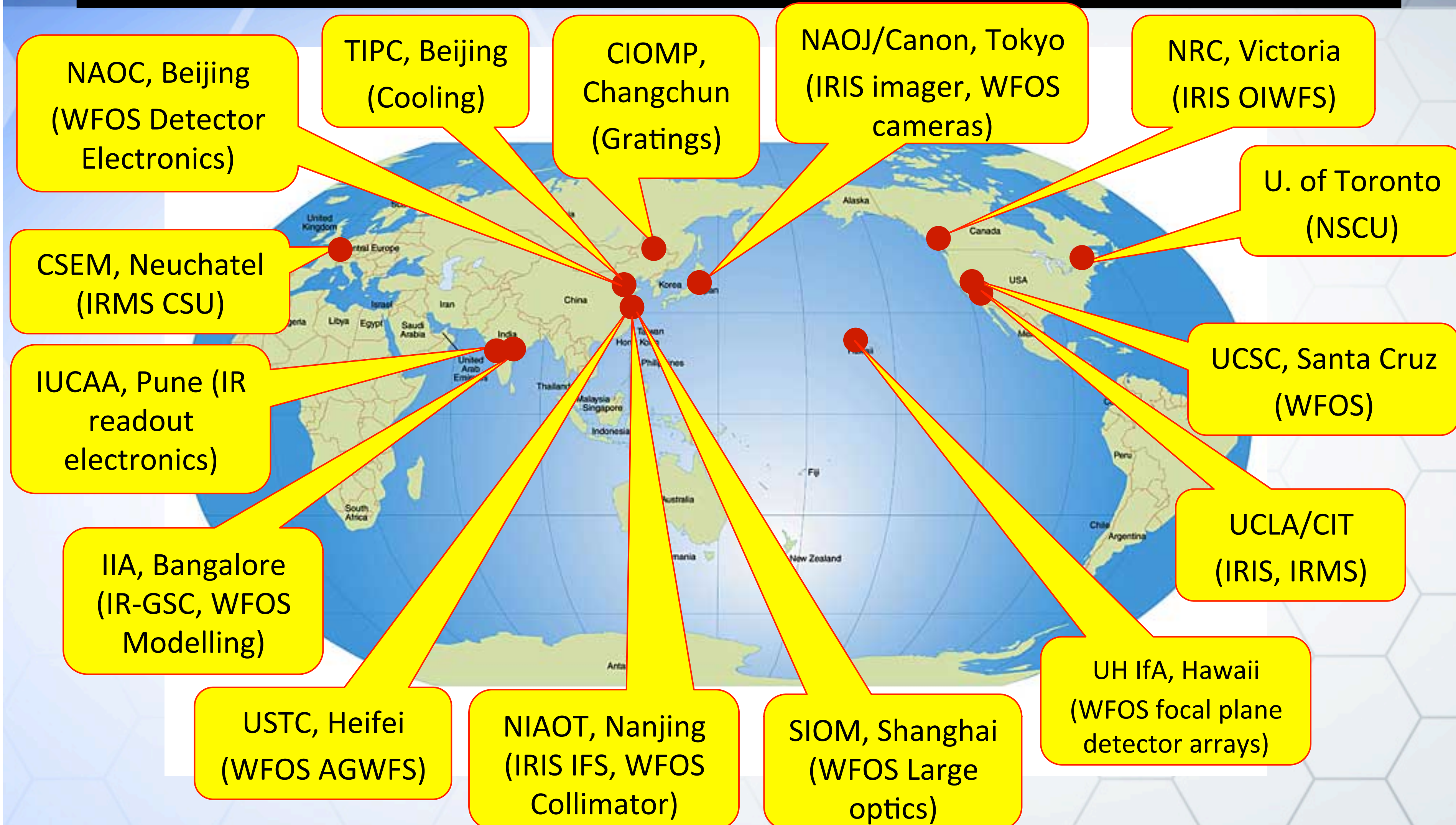


TMT First-Light Science Instruments on the Telescope

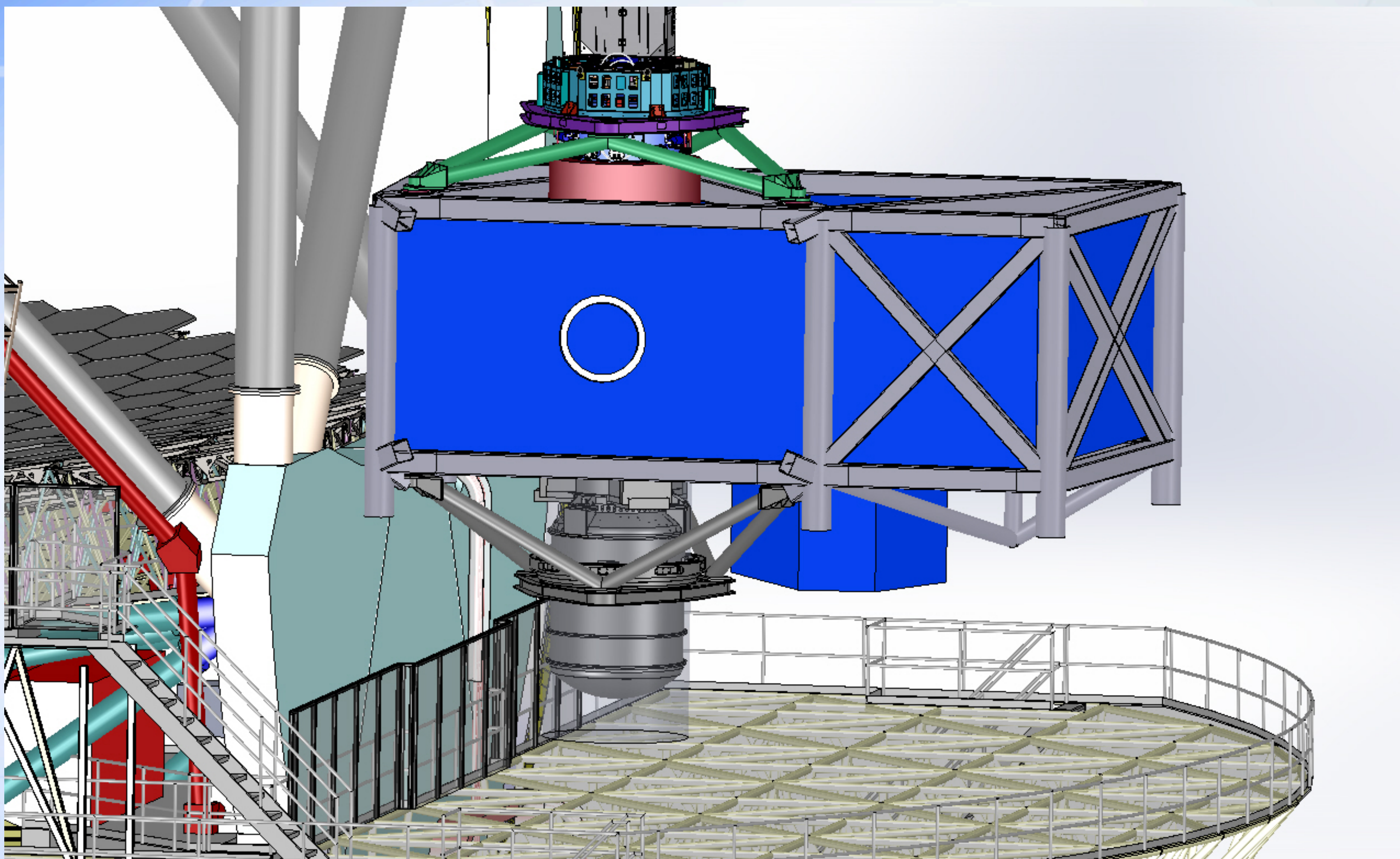


- Ritchey-Chrétien optical design
- 30-m f/1 primary
- 3.1-m convex secondary
- 2.5 m x 3.5 m flat tertiary
- f/15 final focal ratio
- 20′ Field of view is 2.62m in diameter
- Science instruments mounted on Nasmyth platforms (fixed gravity vector)

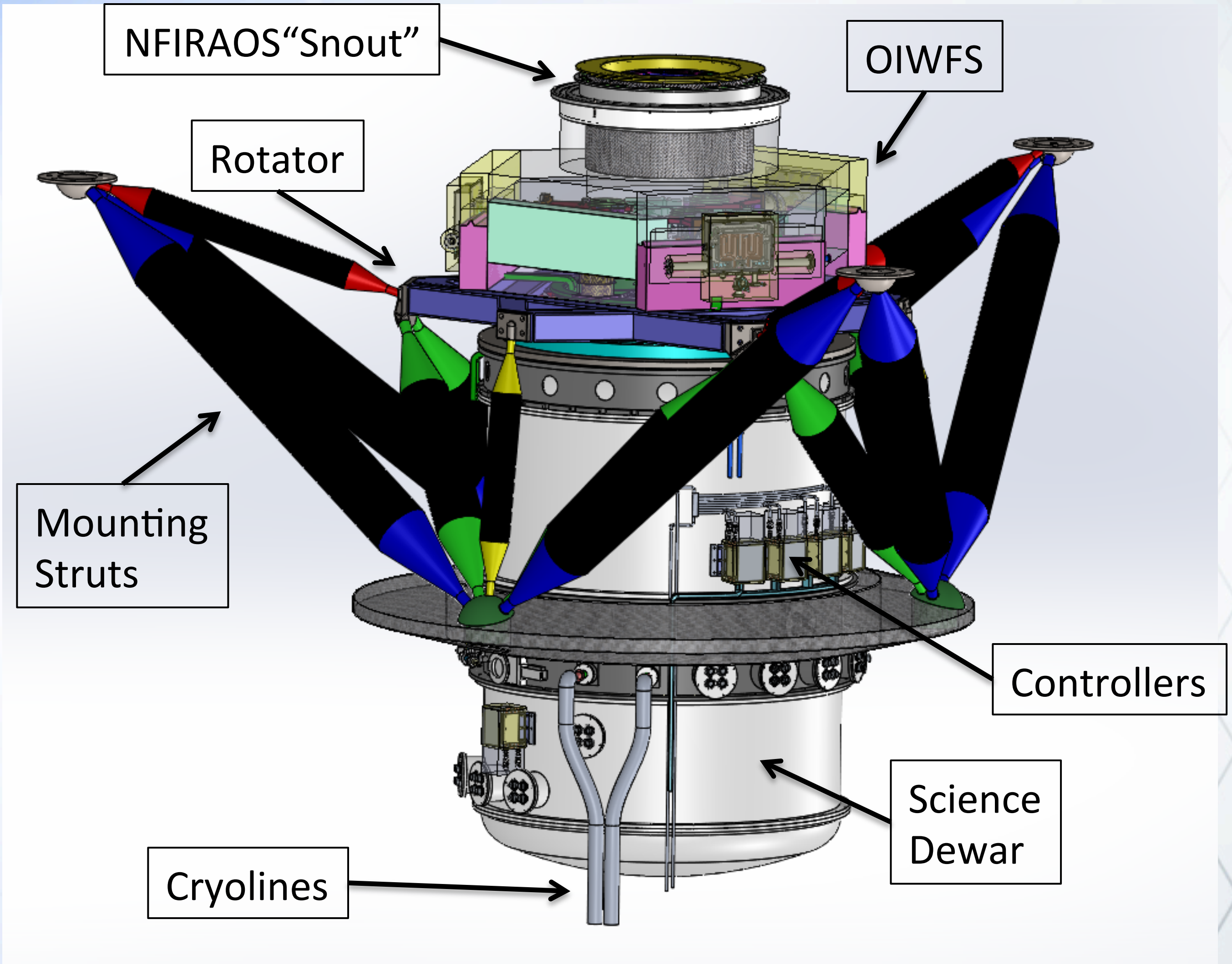
TMT Global Participants – First Light Science Instruments



IRIS and IRMS Mounted on NFIRAOS



InfraRed Imaging Spectrometer (IRIS)



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Thirty Meter Telescope

IRIS Preliminary Design Review - 1

November 17-18, 2016

PASSED!

IRIS Technical Team

Brent Ellerbroek (TMT) Department Head Instrumentation
Luc Simard (TMT) Science Instruments Group Leader
Eric Chisholm (TMT) Instrument Technical Manager

- James Larkin (UCLA), PI
- Anna Moore (CIT), PM, Co-PI
- Shelley Wright (UCSD), PS
- James Wincentsen (CIT), Lead Systems Engineer
- David Andersen (NRC-H), CSRO Systems Engineer
- Jennifer Dunn (NRC-H), CSRO Lead
- Yutaka Hayano (NAOJ), Imager Project Manager
- Andrew Phillips (UCSC), ADC and UCSC Lead
- Ryuji Suzuki (NAOJ), Imager Lead Designer
- Bob Weber (CIT), Lead Mechanical Engineer
- Jason Weiss (UCLA), Lead Software Engineer
- Kai Zhang (NIAOT), Slicer Lead Optical Designer and NIAOT Lead
- Optical Designers: Jenny Atwood (NRC-H), Renate Kupke, Drew Phillips (UCSC), Toshihiro Tsuzuki, Mizuho Uchiyama (NAOJ), Shaojie Chen, Elliot Meyer (UofT), Victor Isbrucker (Isbrucker Cons. Inc.)
- Mechanical Designers: Alex Delacroix, Reston Nash, Ray Zarzaca, Eric Schmidt (CIT), Dean Chalmers Ward Jensen, Vlad Reshetov, Ramunas Wierzbicki (NRC-H), John Canfield, Evan Kress, Eric Wang (UCLA), Yoshiyuki Obuchi, Bungo Ikenoue, Sakae Saito, Fumihiro Uraguchi (NAOJ)
- Software Designers: Chris Johnson, Ji Man Sohn (UCLA), Takashi Nakamoto (NAOJ) , Ed Chapin (NRC-H), Reed Riddle(COO), Gregory Walth (UCSD)
- Electrical Designers: Roger Smith (Detector Lead, CIT), Kenneth Magnone (UCLA), Tim Hardy (NRC-H)
- TMT, NFIRAOS: Lianqi Wang, Corinne Boyer, Matthias Schöek (TMT), Pete Byrnes, Glen Herriot (NRC-H) and the IRIS astrometry team and many many more…

10 institutions, 4 countries

IRIS Science Team

16 institutions, 6 countries

- Maté Adamkovics, UC Berkeley
- Lee Armus, IPAC
- Aaron Barth, UC Irvine
- Jeffrey Cooke, Swinburne
- Pat Coté, NRC-H
- Tim Davidge, NRC-H
- Tuan Do, UCLA
- Andrea Ghez, UCLA
- Lei Hao, Shanghai
- Masahiro Konishi, NAOJ
- Michael Liu, U Hawaii
- Nobunari Kashikawa, NAOJ
- Jessica Lu, UC Berkeley
- Bruce Macintosh, Stanford
- Shude Mao, NAOC
- Christian Marois, NRC-H
- Annapurni Subramaniam, Indian IofA
- Smitha Subramaniam, Indian IofA
- Hajime Sugai, Kyoto Univ.
- Jonathan Tan, U. Florida
- Tsuyoshi Terai, NAOJ
- Tommaso Treu, UCLA
- Gregory Walth, UCSD, TMT IRIS Postdoc Fellow
- Mike Wong, UC Berkeley
- Shelley Wright (PS), UCSD

IRIS Focal Plane: Imager + 2 IFUs + 3 Guide Stars

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Thirty Meter Telescope

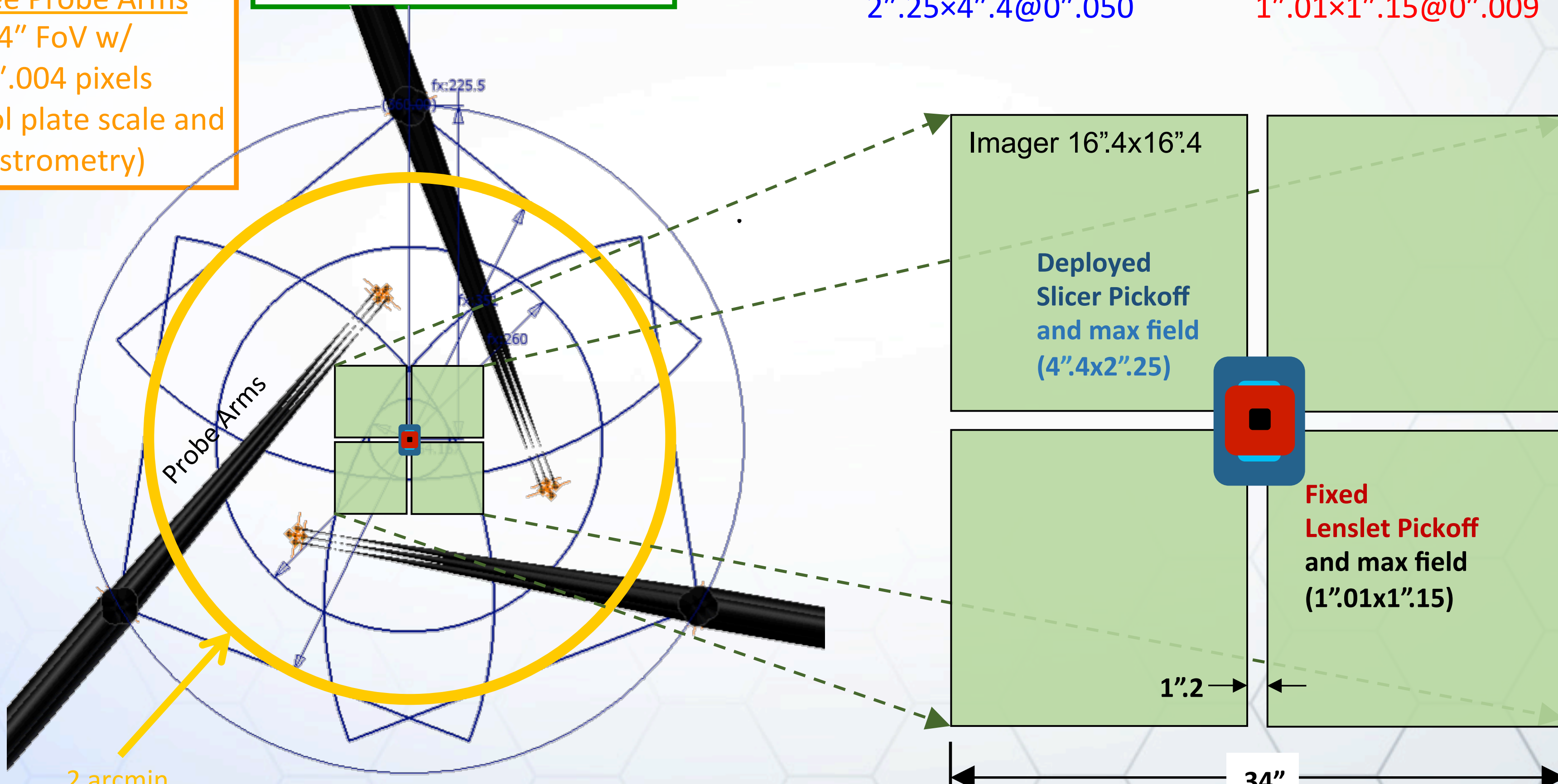
Imager
34”×34” field (on-axis)
w/ 0”.004 pixels
(JHK + Narrow-bands)

Three Probe Arms
4” FoV w/
0”.004 pixels
(control plate scale and astrometry)

Lenslet and Slicer IFUs
0.84 -2.4µm, R = 4000-8000

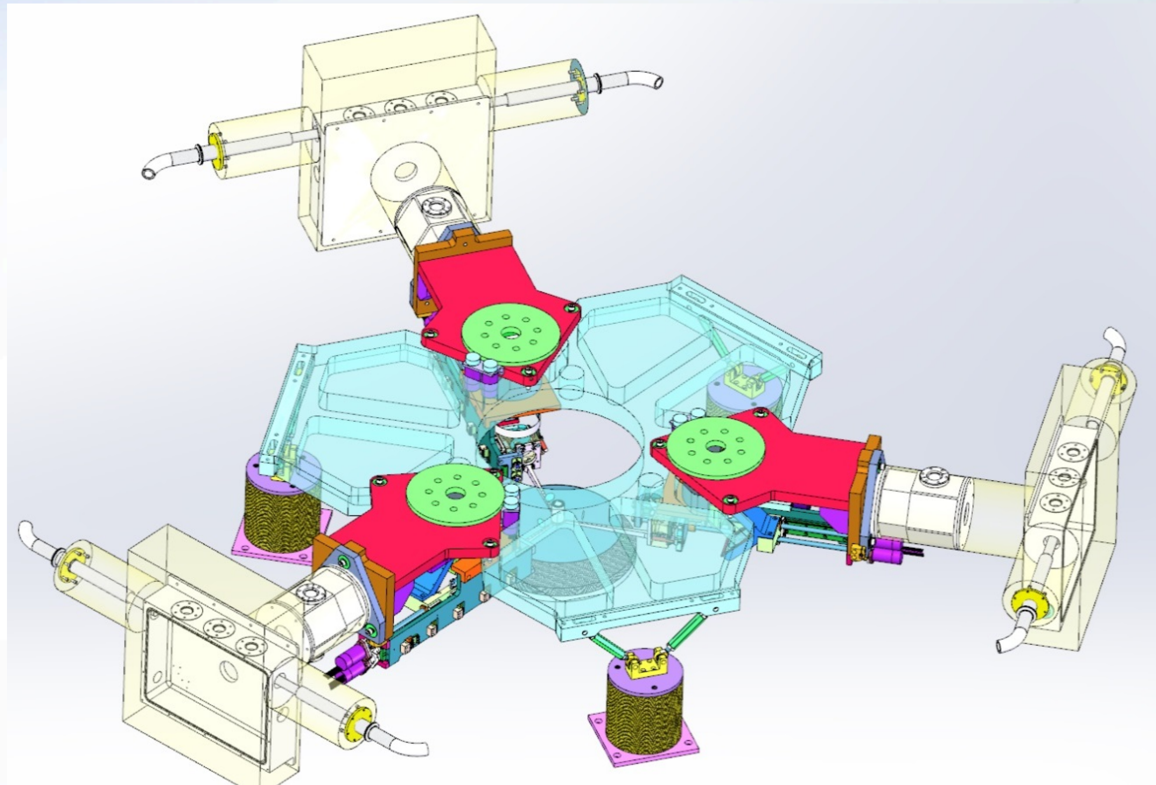
2 Coarse Scales (Slicer)
1”.13×2”.20@0”.025
2”.25×4”.4@0”.050

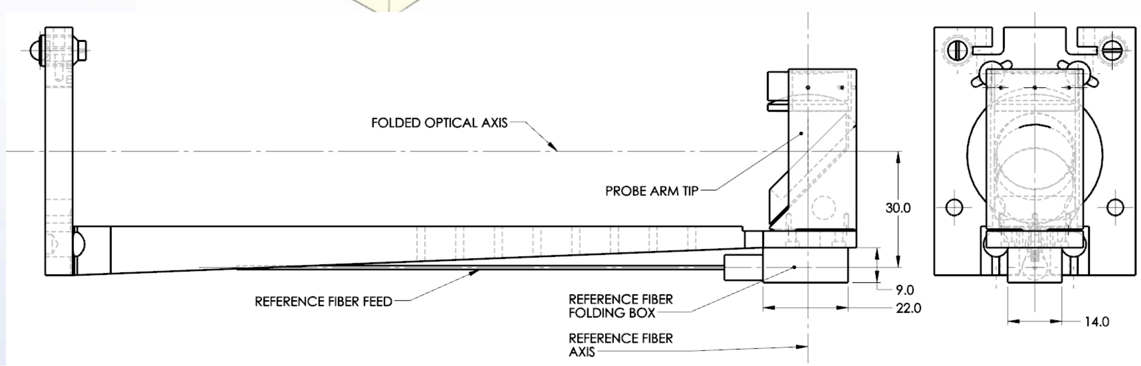
2 Fine Scales (Lenslet)
0”.45×0”.51@0”.004
1”.01×1”.15@0”.009



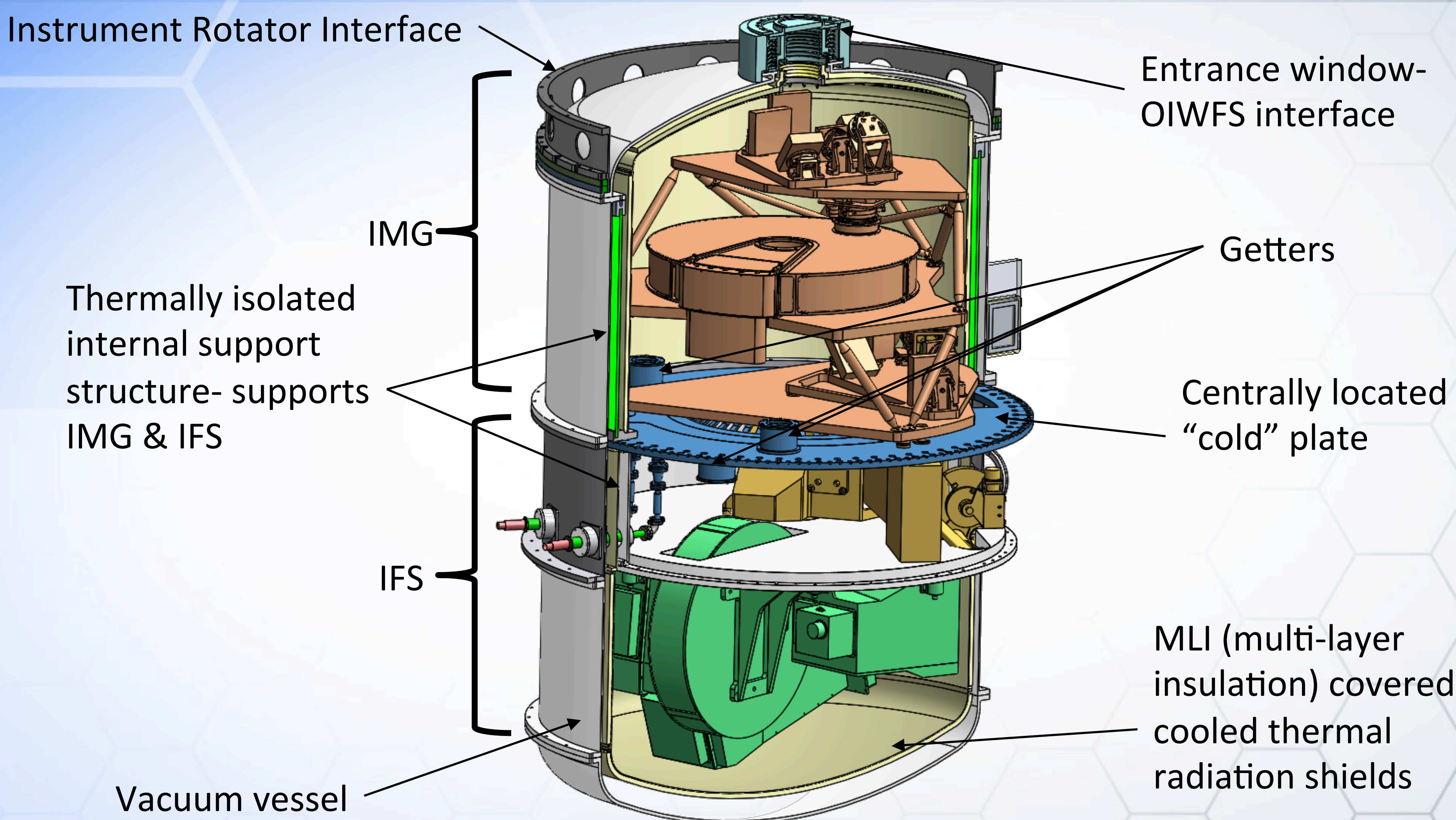
IRIS On-Instrument Wavefront Sensors

- Updated optical design
- Updated interface to OIWFS Detectors and Science Dewar
- Calibration light sources added to probe arm
- Baseline detector now H1RG

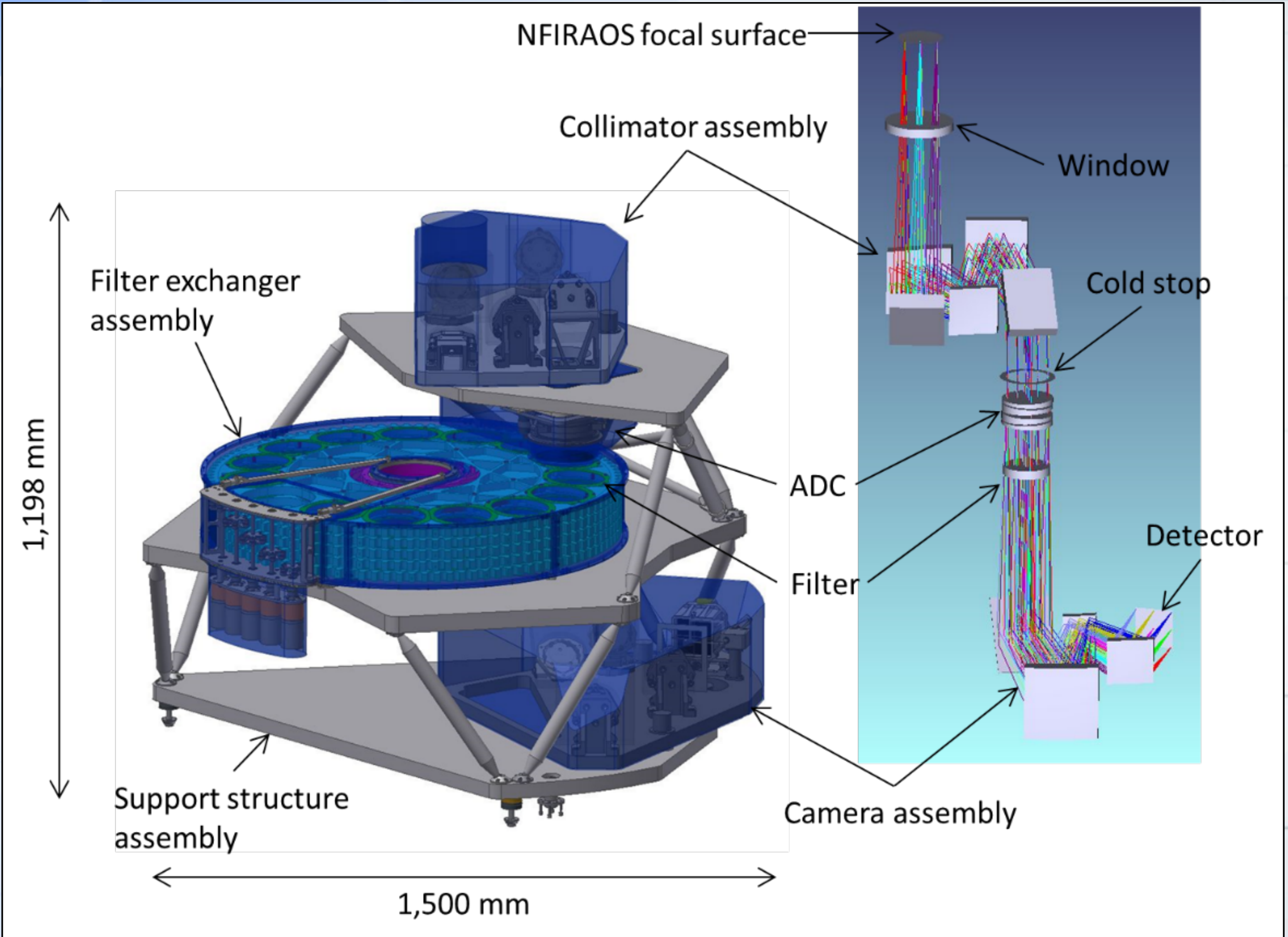




IRIS Science Cryostat Summary

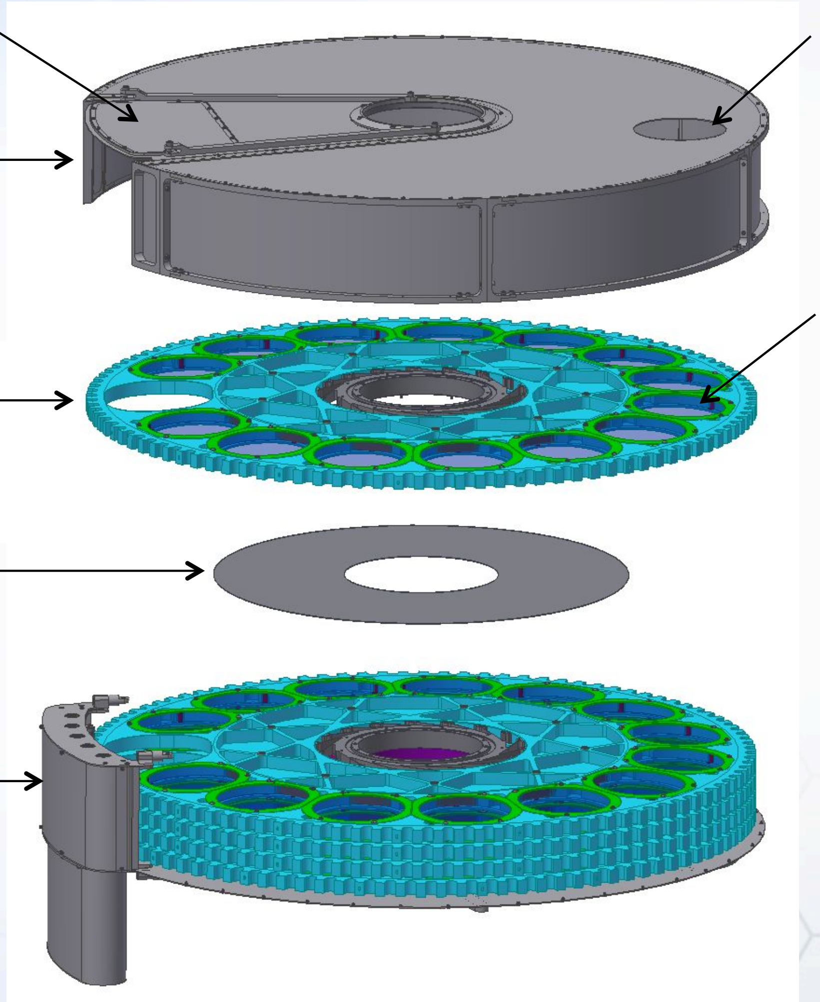


IRIS Imager

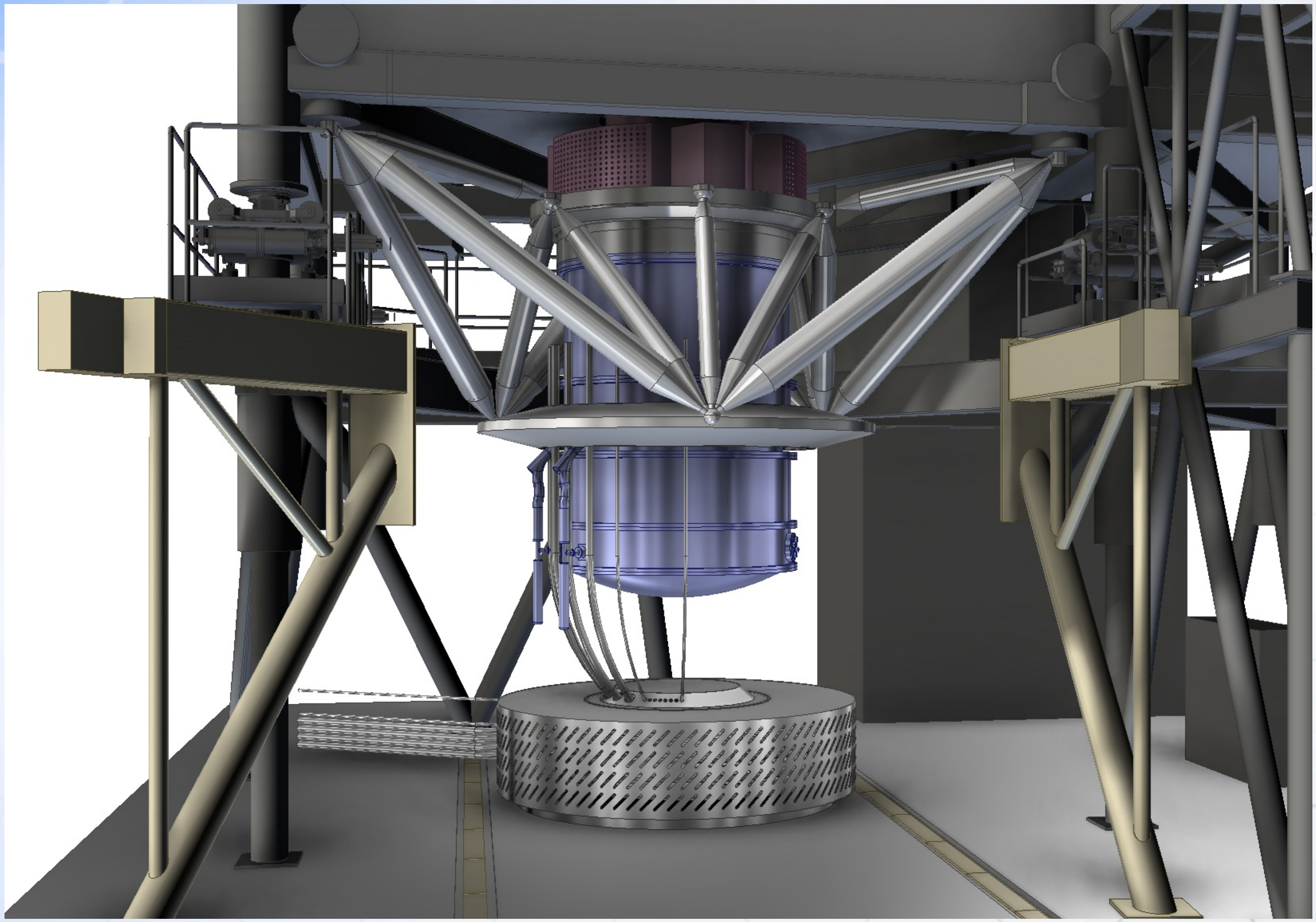


NFIRAOS focal surface
Collimator assembly
Window
Filter exchanger assembly
Cold stop
1,198 mm
ADC
Detector
Filter
Support structure assembly
Camera assembly
1,500 mm

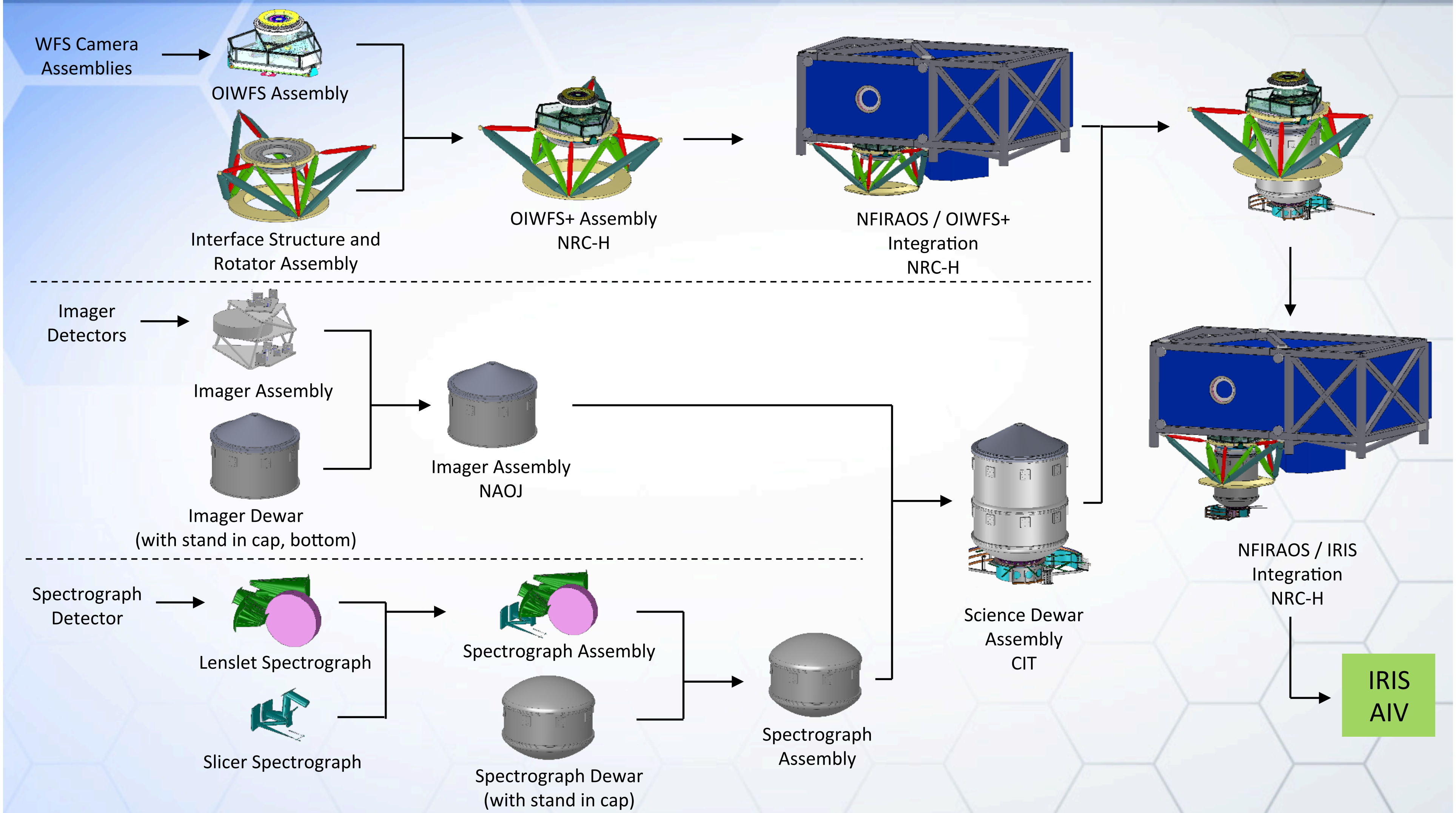
IRIS Filter Exchanger Assembly



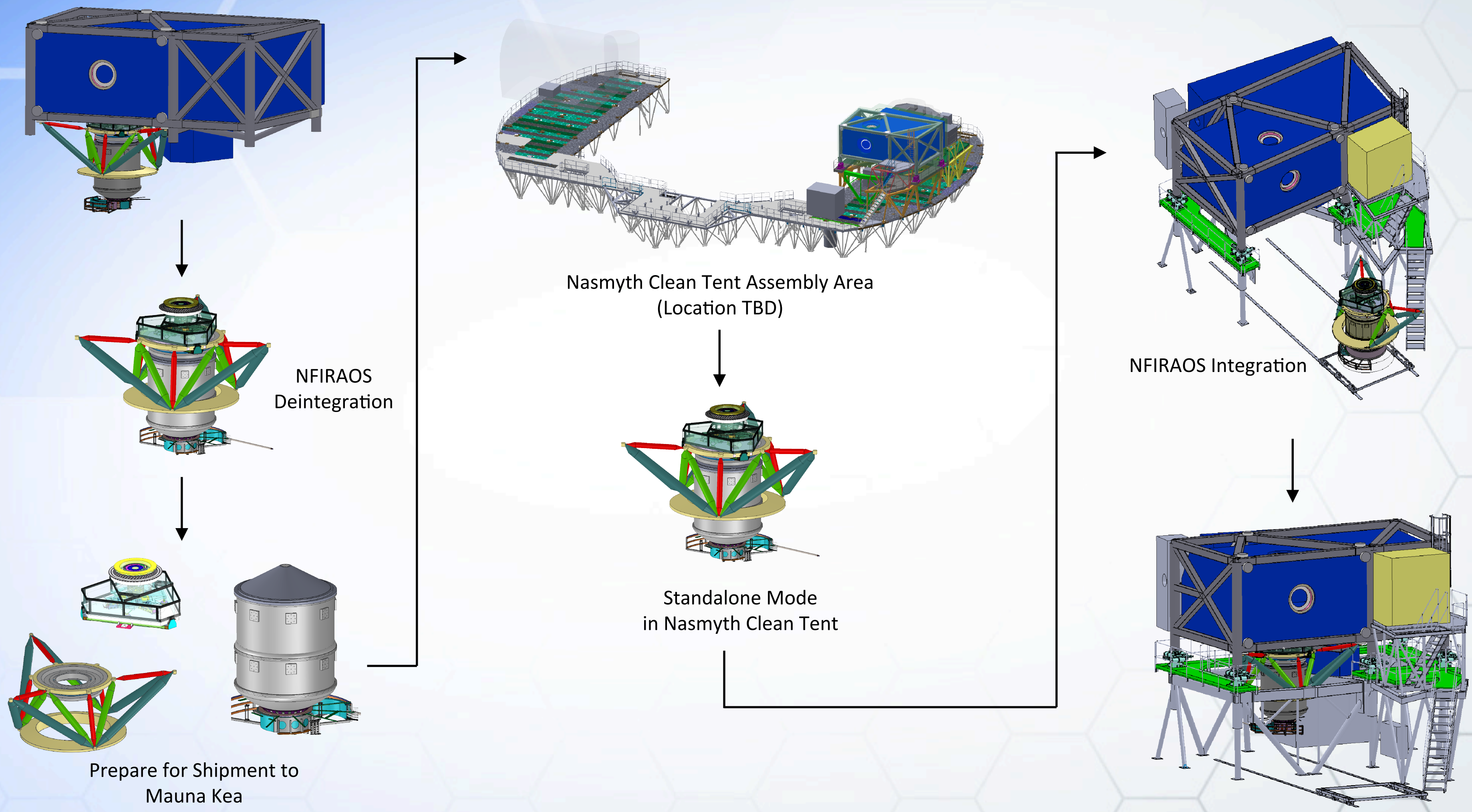
Standing Next to IRIS on Nasmyth Platform



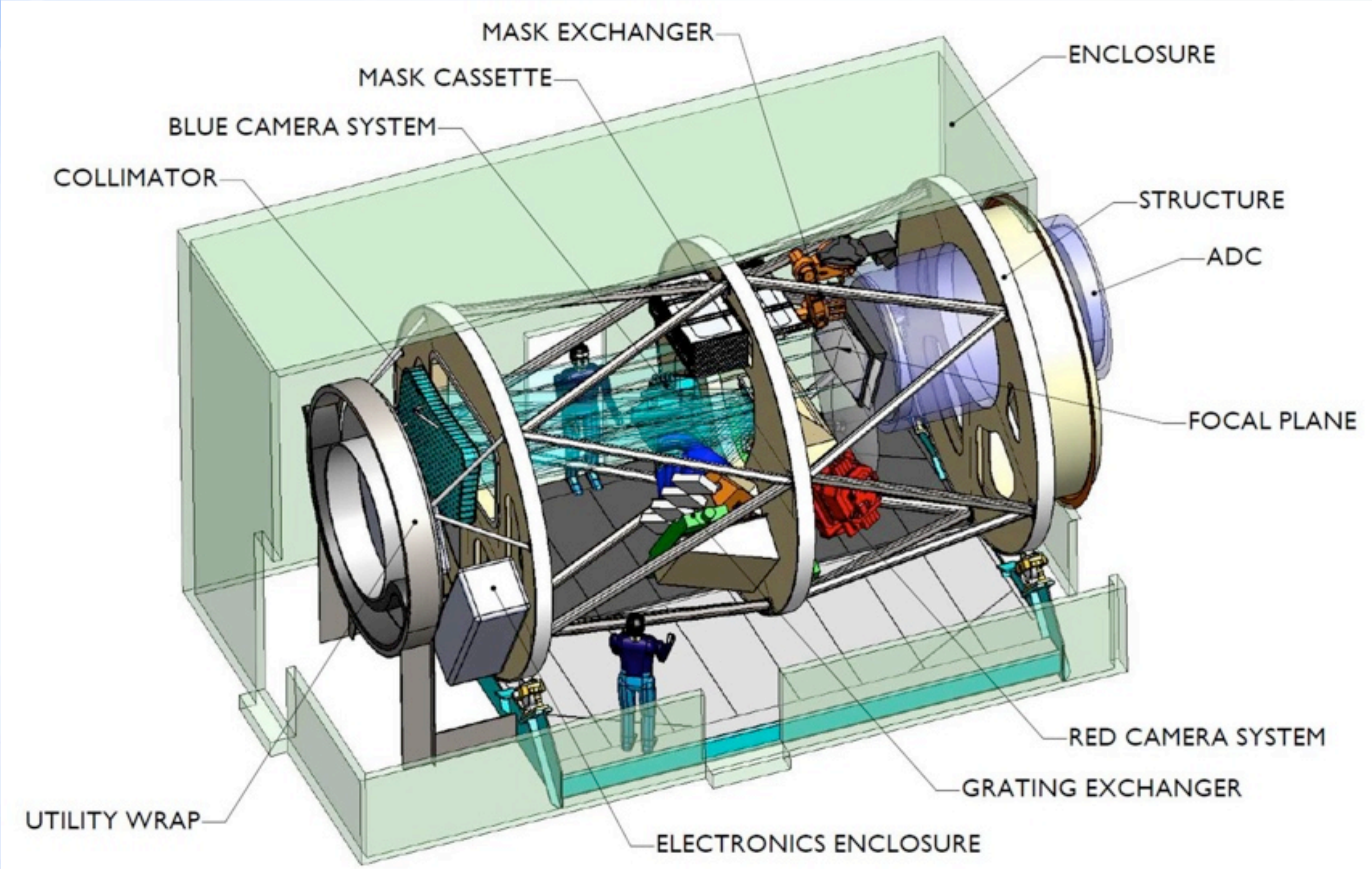
Integrating IRIS



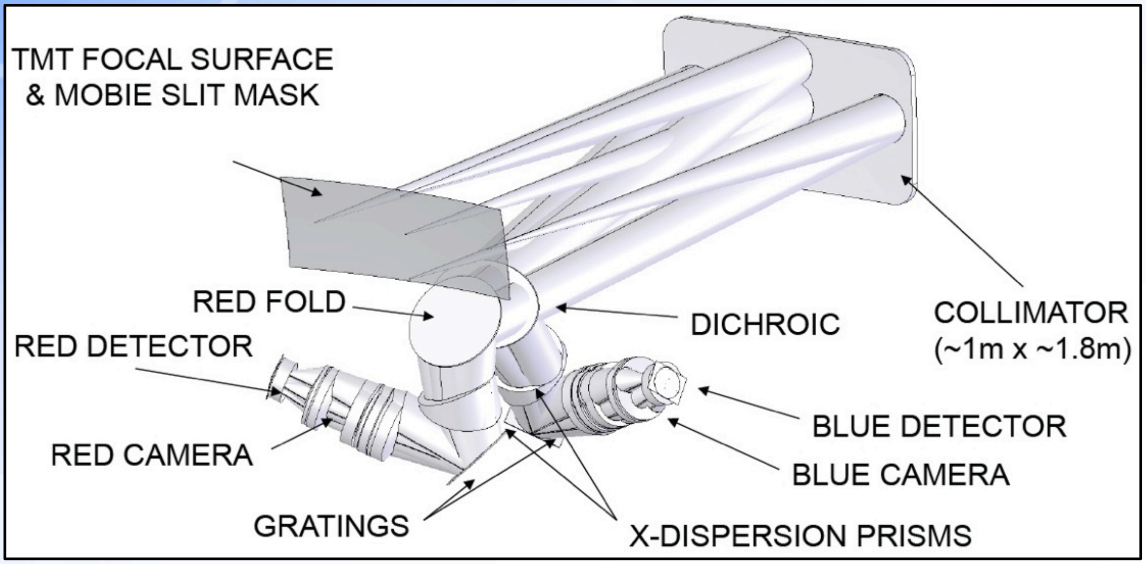
IRIS AIV Overview



TMT Seeing Limited Wide Field Optical Spectrometer and Imager (WFOS)



WFOS Echellette Design: Survey and Diagnostic Spectroscopy



Bigelow et al. 2010, SPIE 2010

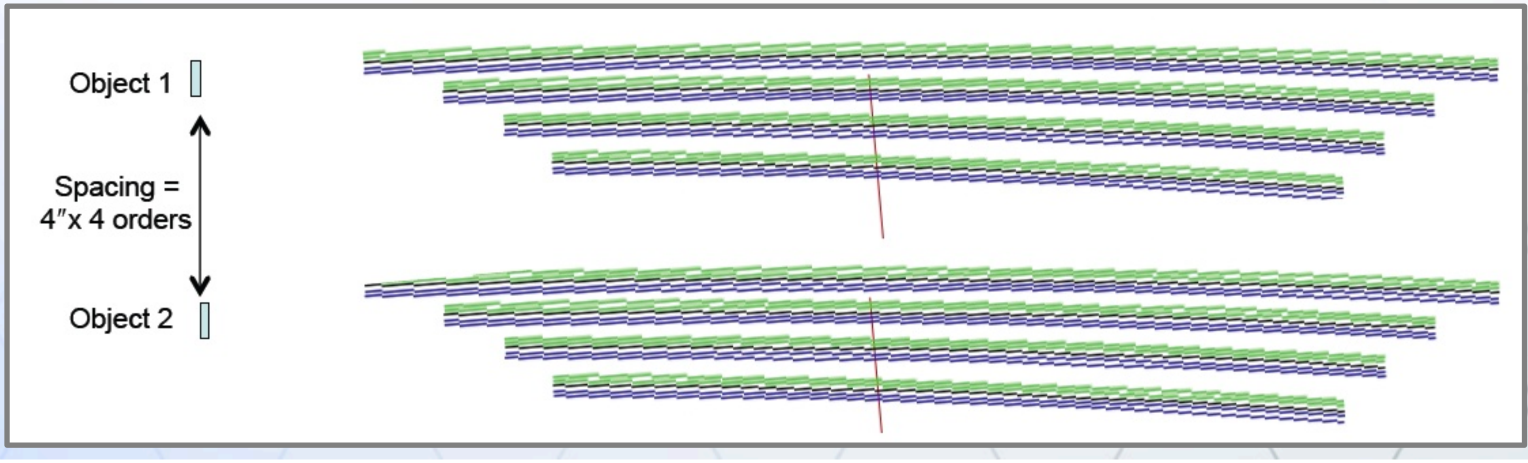
0.31μm - 1.1μm (Blue sensitive)

25 arcmin^2 FoV

576″ total slit length
(i.e., up to ~200 objects)

R = 1000 - 8000 (for 0″.75 slit)

WFOS can trade multiplexing for expanded wavelength coverage in its higher dispersion mode



List of 2015 WFOS Mini-Studies

Description	Sub-system(s)	Managing Institution	Participating Institutions	Task List	Contact Person
Mask Exchanger System Trade-off and Fabrication	MEX, MFS	USTC	UCO, NAOJ, ASIAA, USTC	2.2.1	Jianping Wang
AGWFS and Operational concepts	WGS	USTC	IIA, IUCAA, NIAOT,USTC	2.2.2	Qinfeng Zhu
Instrument Modelling	SYS	UCO	IIA, SJTU, UCO	2.2.3	Matt Radovan
Off-Axis Collimator Mirror	COL	NIAOT	NIAOT	2.2.4	Hangxin Ji
Atmospheric Dispersion Corrector	ADC	USTC	NIAOT, XMU, USTC	2.2.5	Zhai Chao
Metrology, Calibrations and Instrument simulations	SYS, COS	UCO	IIA, UCO	2.2.6	Sandy Faber
Spectrograph Camera Systems	CAM	NAOJ	NAOJ, CIT	2.2.7	Shinobu Ozaki
Folding Optical System	FOS	SIOM	SIOM	2.2.8	Hongbo He
Grating Exchange System	GEX	XMU	USTC, CIOMP, UCO, XMU	2.2.9	Jianhuan Zhang
End-to-End Optical Design and Stray Light Analysis	SYS (.OPT, .STL)	CIT	NIAOT, IIA, CIT	2.2.10	Nick Konidaris
Motion Controllers	All instruments	IIA	UH, UCO, ARIES, IIA	2.2.11	Padmakar Parihar
Science Detectors	DET	UH	NAOC, IUCAA, IIA,	2.2.12	Peter Onaka

21 EOIs →

12 mini-studies involving 15 institutes

Selection driven by:

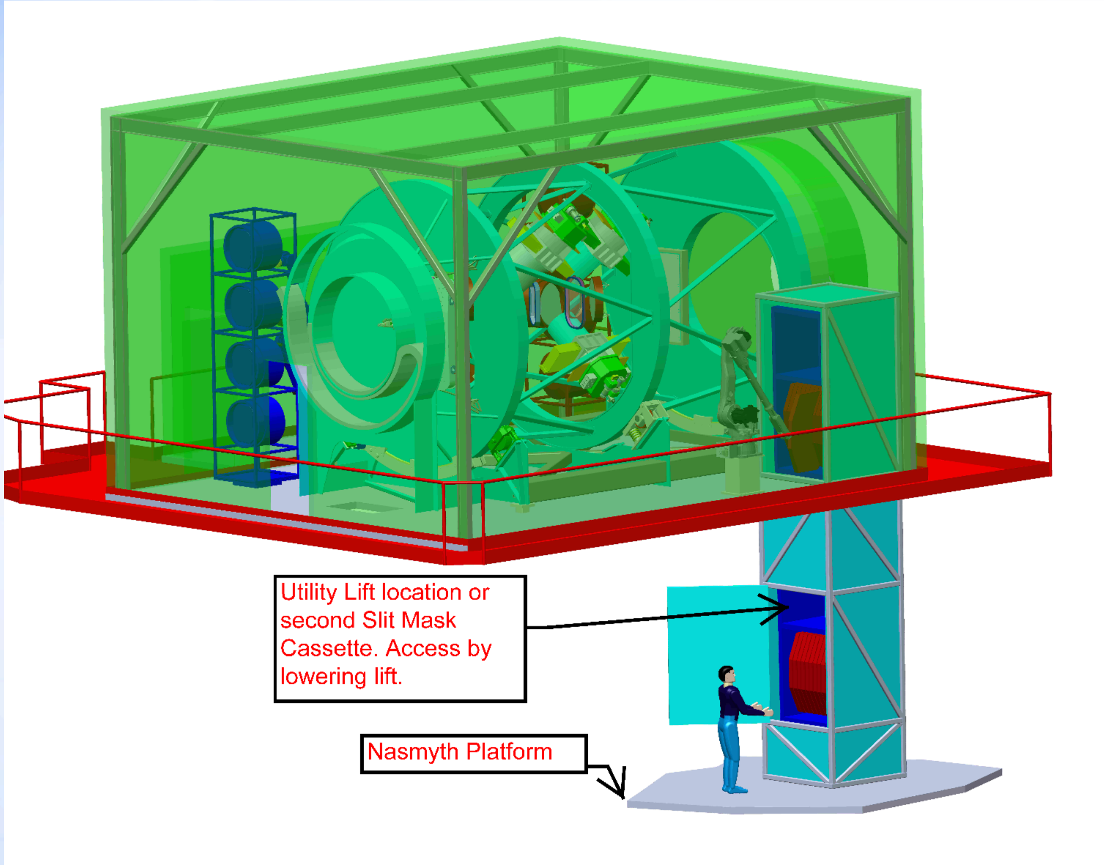
- Expressed interests
- Areas of current design that would benefit from some technical work
- Exploring promising collaboration

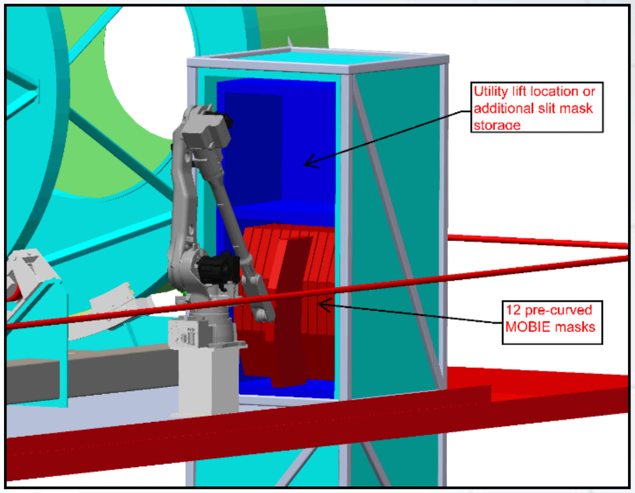
All teams adhered to TMT technical and management procedures

TMT
Thirty Meter Telescope

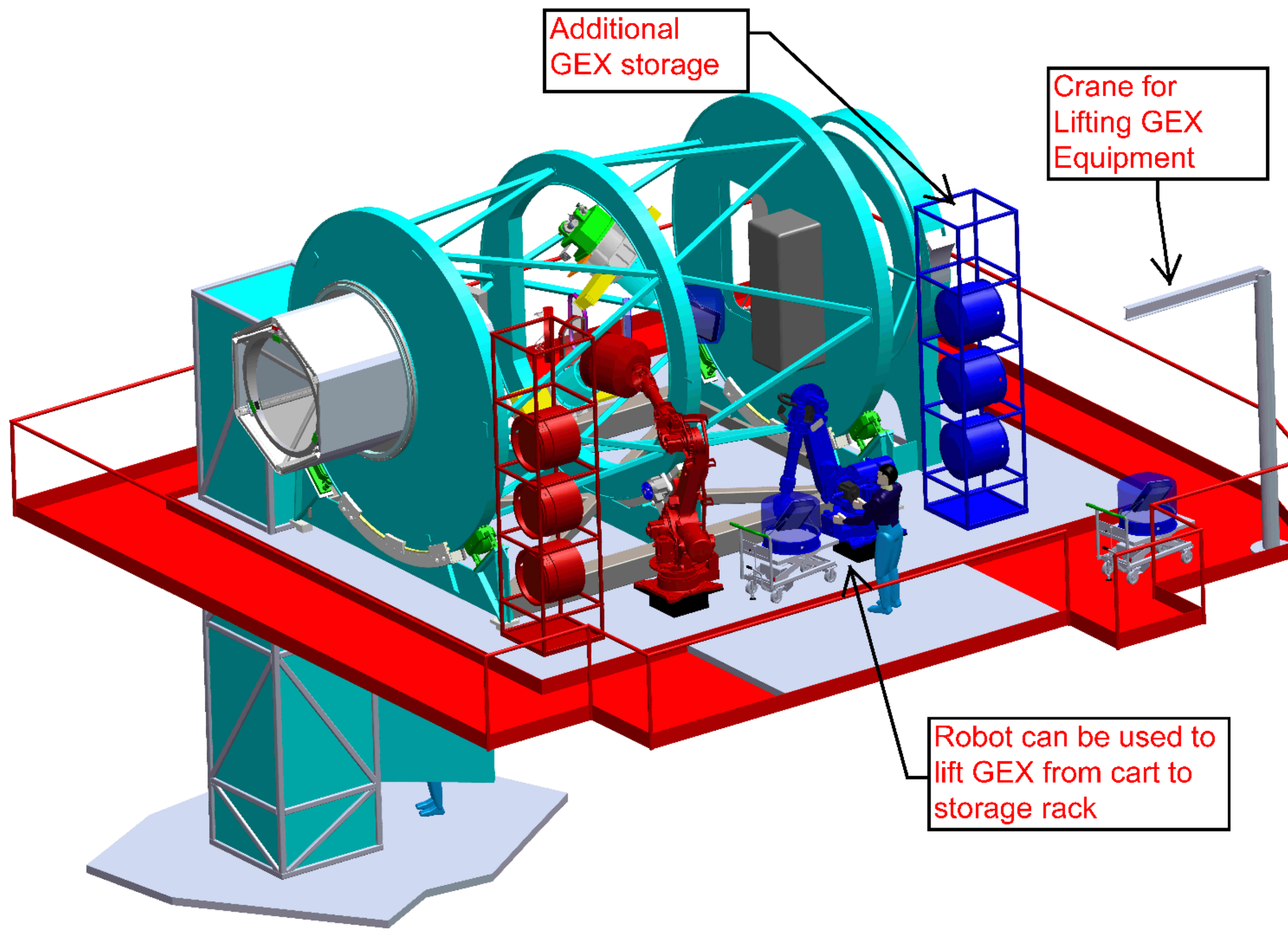
WFOS Mini-Studies Final Review
NAOC, Beijing, April 2015

Exchanging WFOS Slitmasks with Assembly-line Robots





Configuring WFOS Gratings with Assembly-line Robots



WFOS Design Team

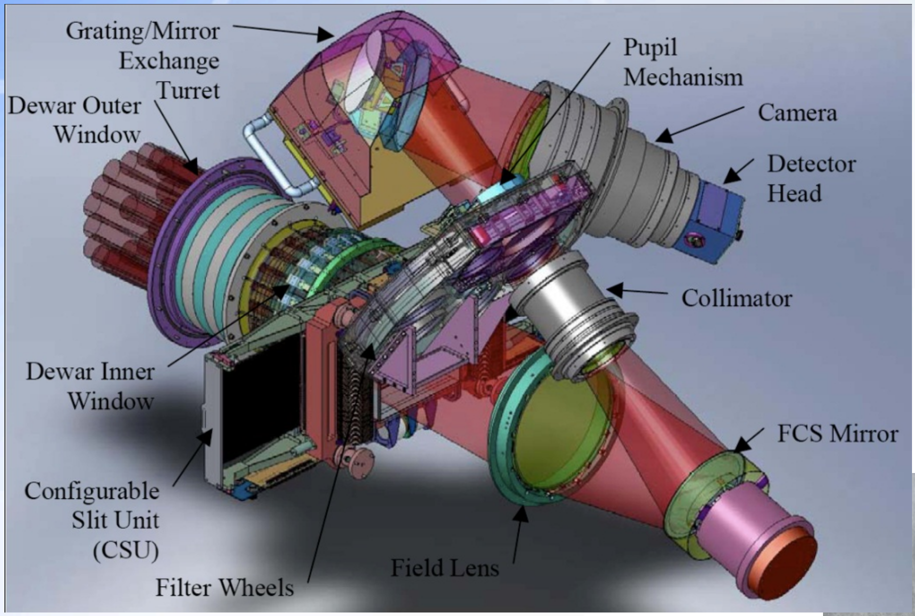
- Principal Investigator: Kevin Bundy (UCO)
- Project Manager: Maureen Savage (UCO)
- Lead Engineer: Matthew Radovan (UCO)
- Team members: Rich Dekany (CIT), Devika Divakar (IIA), Sandy Faber (UCO), Taotao Fang (NAOC/Xiamen), Jason Fucik (CIT), Zhongwen Hu (NIAOT), Hangxin Ji (NIAOT), Renate Kupke (UCO), He Li (NIAOT), Satoshi Miyazaki (NAOJ), Shinobu Ozaki (NAOJ), Luc Simard (TMT), Chuck Steidel (CIT), S. Sriram (IIA), Arun Surya (IIA), Sivarani Thirupathi (IIA), Kai Zhang (NIAOT)

WFOS Opto-Mechanical Design and Requirements (OMDR) Phase

- Areas of investigation:
  - End-to-end optical design (UCO)
  - Distortion mapping and flexure modelling (IIA)
  - Instrument and support structures (UCO)
  - Flexure compensation system (UCO)
  - Telescope Baffling and Stray Light (NAOJ)
  - ADC and pupil wander (UCO/TMT)
  - Refractive camera design and cost estimating (NAOJ)
  - Alternate camera concepts (CIT/NAOJ)
  - Collimator design and performance optimization (NIAOT)

1.5 year effort to be completed in May 2017 and outcomes will inform next steps for WFOS

InfraRed Multi-slit Spectrometer (IRMS)

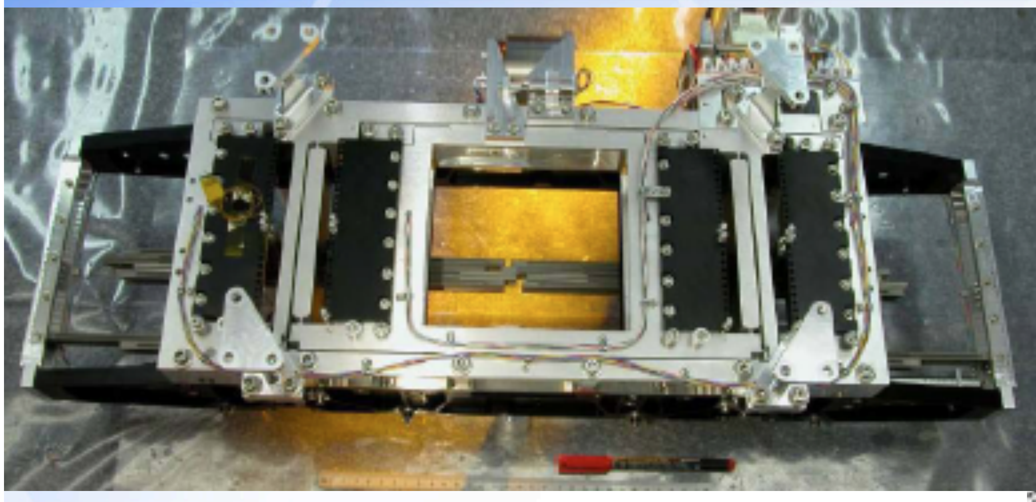


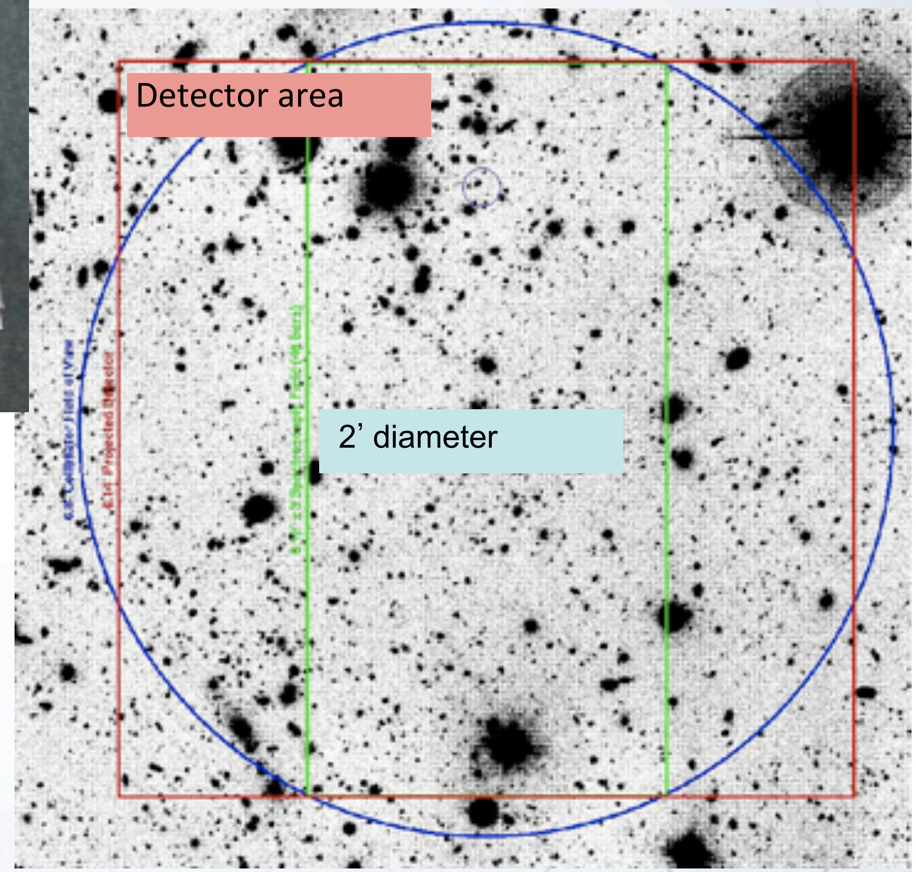
TMT/IRMS
~
Keck/MOSFIRE

Keck, February 2012

A 2013 mini-study demonstrated the viability of using MOSFIRE for IRMS, **but it will not be a clone**

IRMS Configurable Slit Unit and Field of View

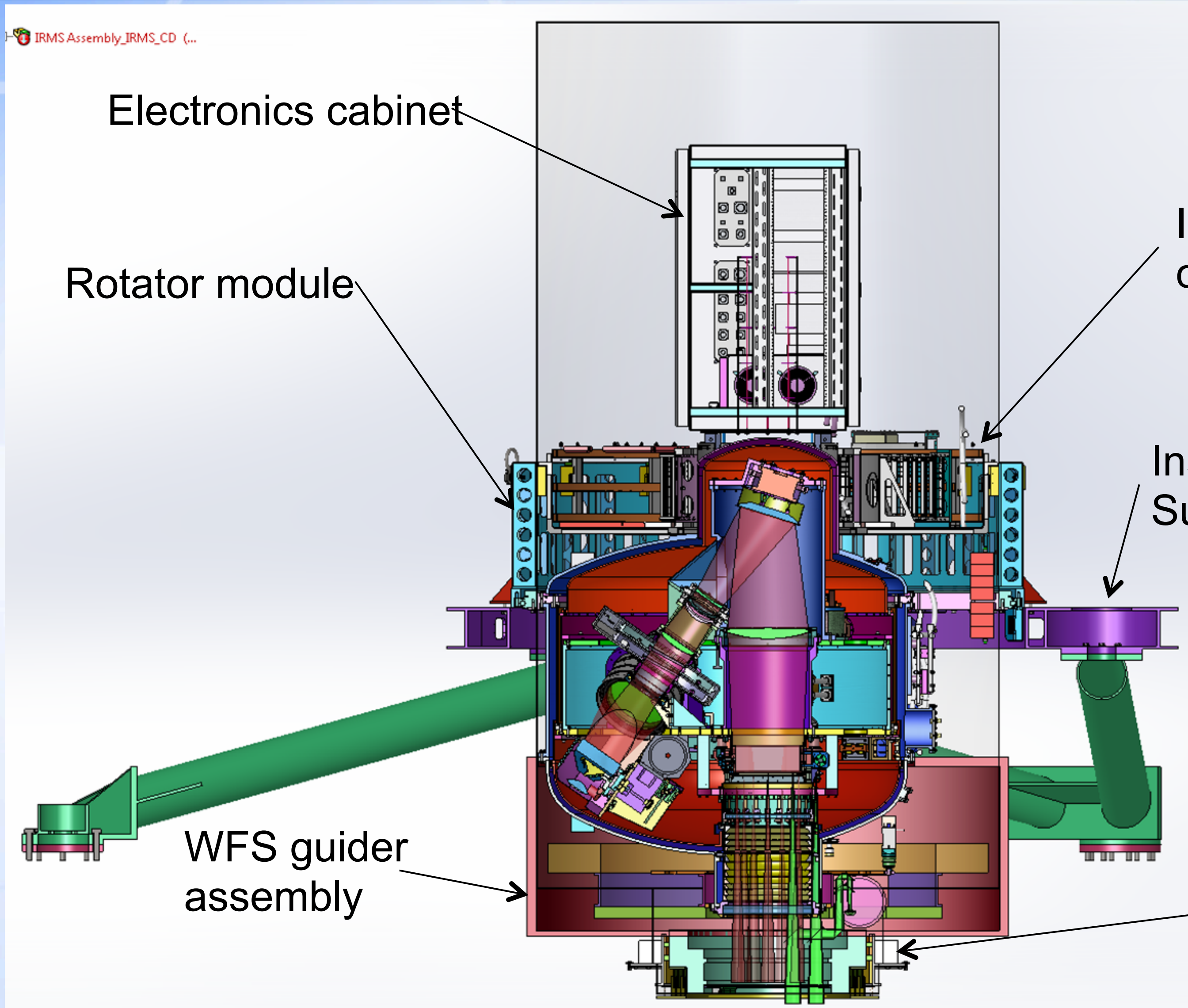




CSEM Configurable Slit Unit:

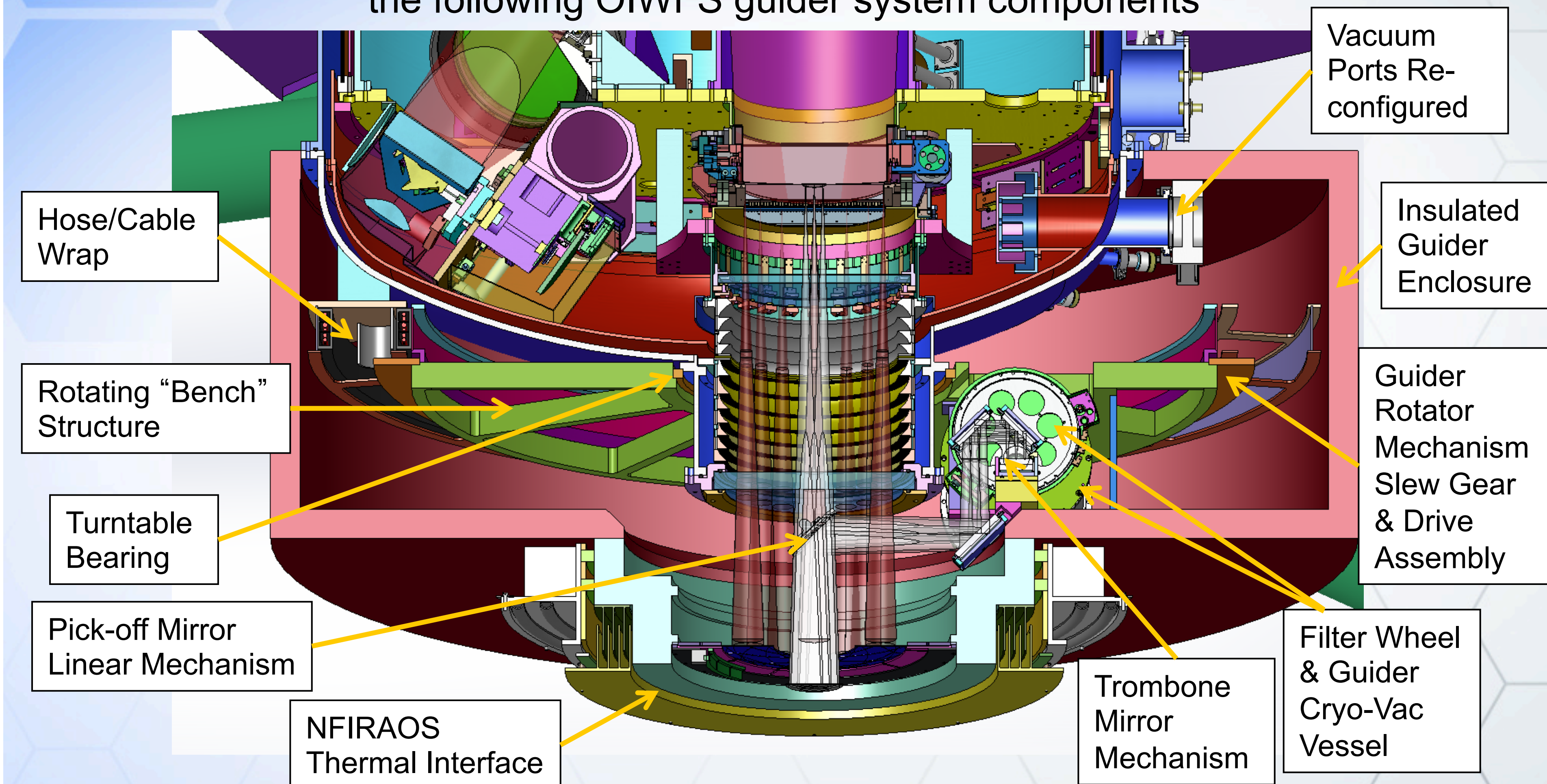
- Slits formed by opposing bars
- Up to 46 slitlets
- Reconfigurable in ~3 minutes

IRMS Main Subsystems



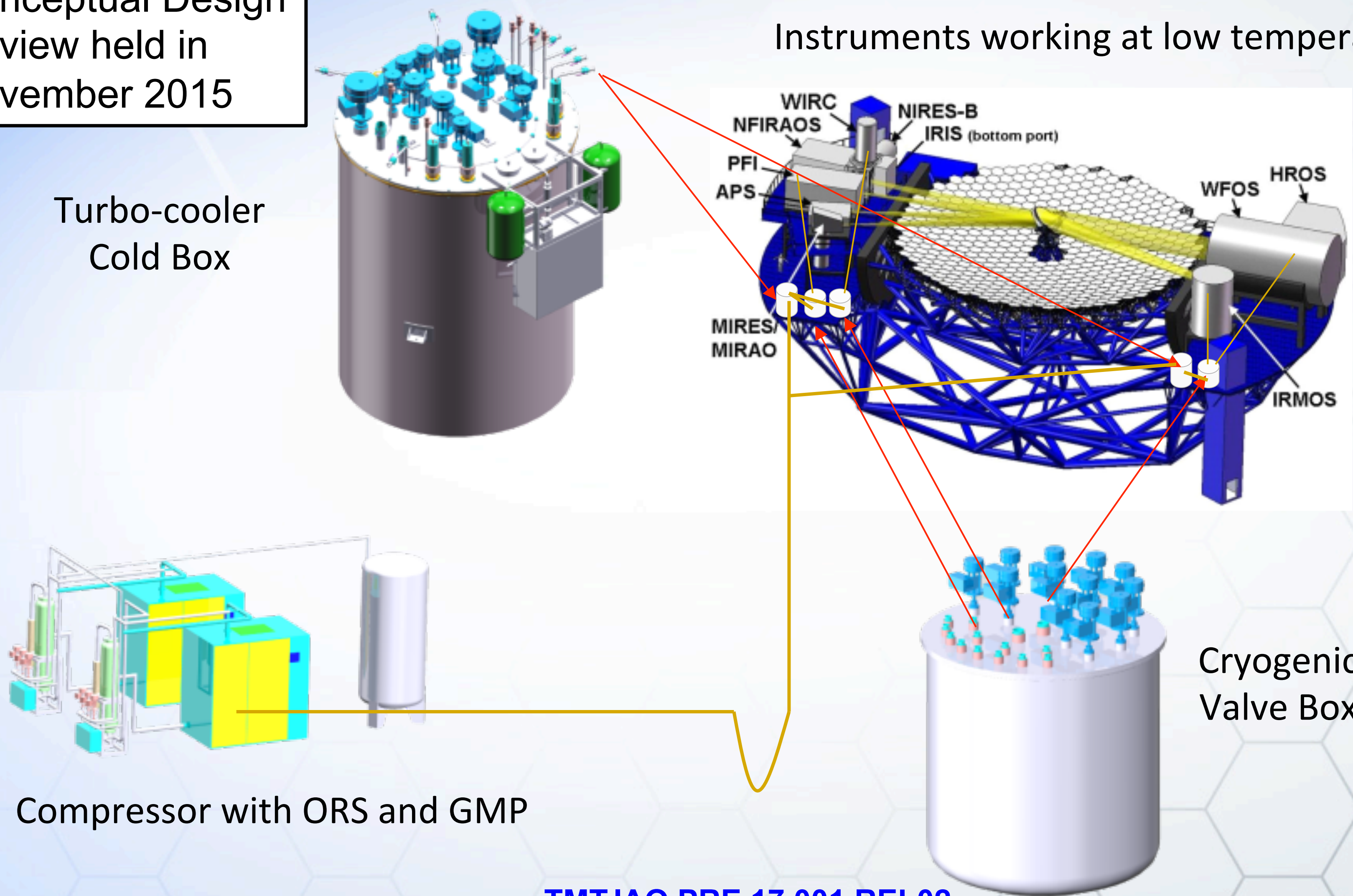
IRMS Front-End Modifications

The external MOSFIRE guider & sheet metal enclosure will be replaced with the following OIWFS guider system components



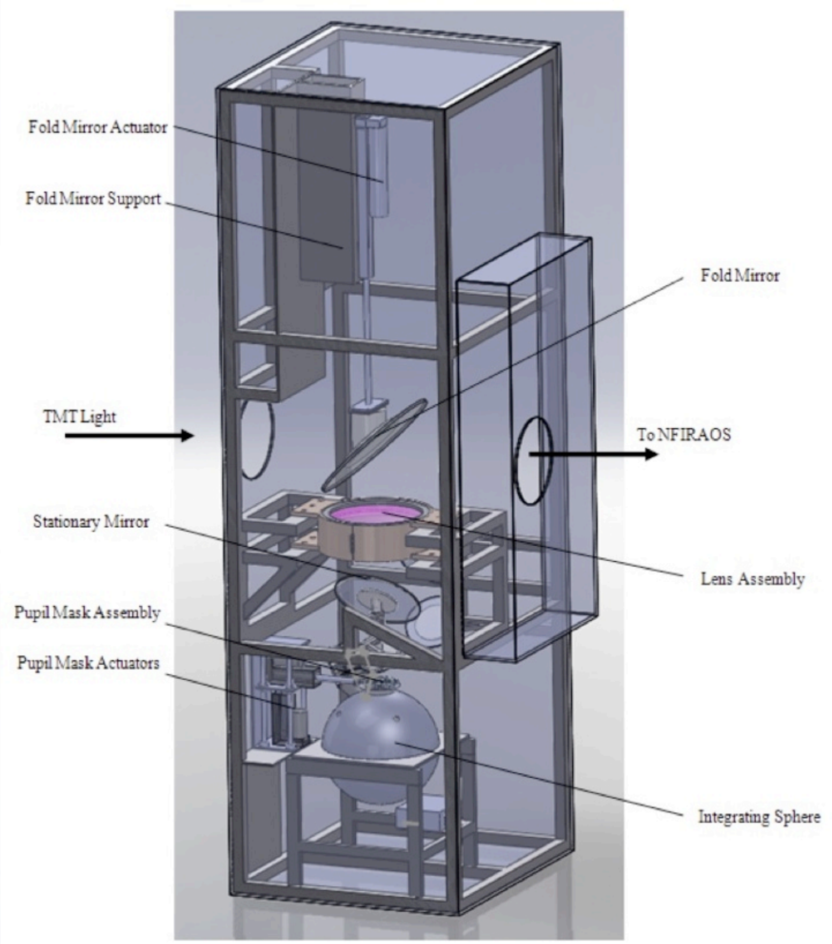
Facility Instrument Cryogenic Cooling System (TIPC, Beijing)

Conceptual Design Review held in November 2015



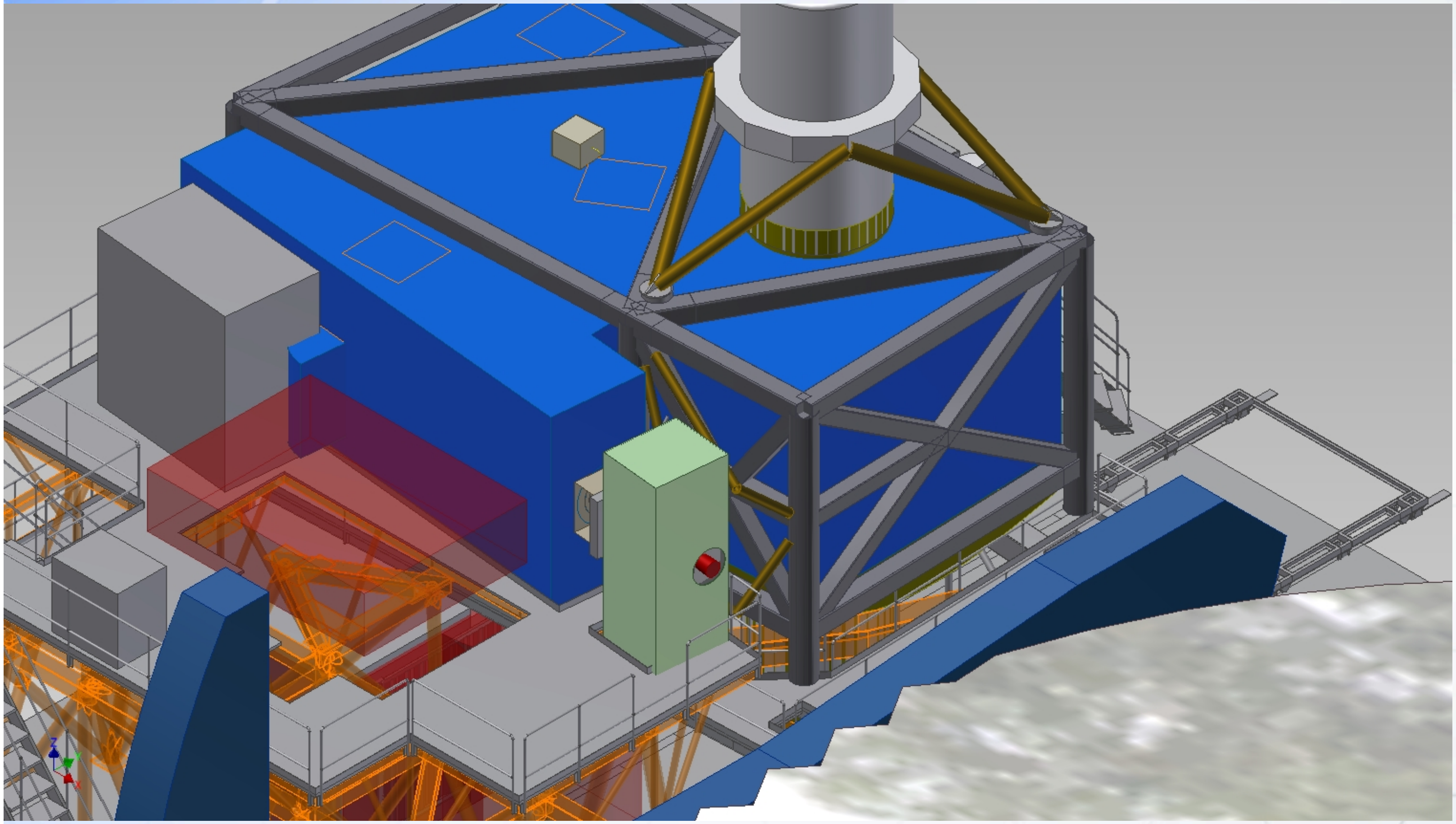
NFIRAOS Science Calibration Unit (NCSU)

- Mounted at the front of NFIRAOS
- 3.7m x 1.3m x 1.1m
- Functions:
  - Flat-field and wavelength calibrations
  - Back-illumination of NFIRAOS focal plane pinhole mask for OIWFS positioning calibration
  - Rotating pupil mask for NFIRAOS DM0 alignment
- Client instruments: IRIS, IRMS, NIRES-B, IRMOS-N, “Super WIRC”
- Work restarting after a long hiatus (2009-2016)



2009 Design, Dae-Sik Moon, U. of Toronto

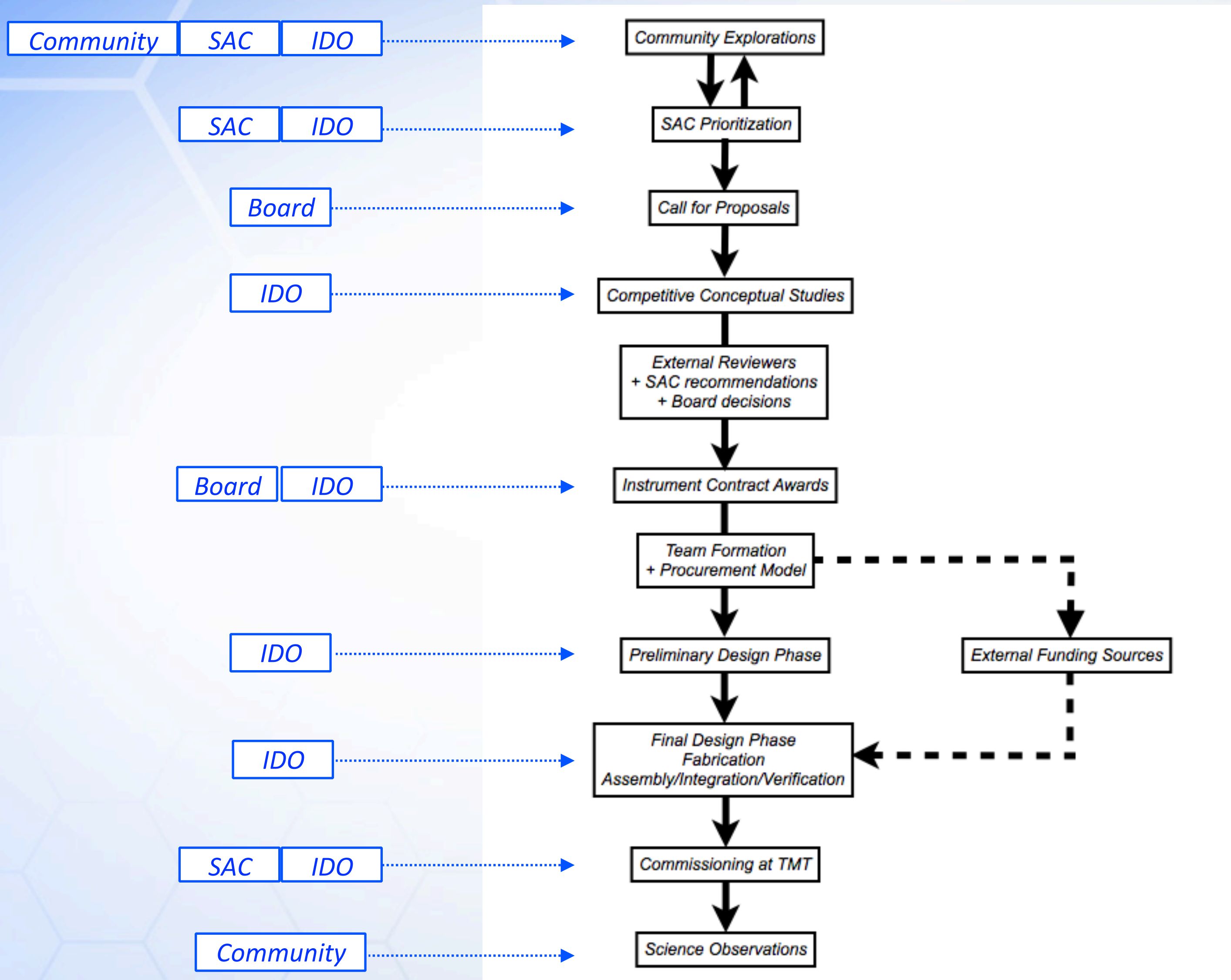
NSCU on NFIRAOS



Future Instrumentation: Why Now?

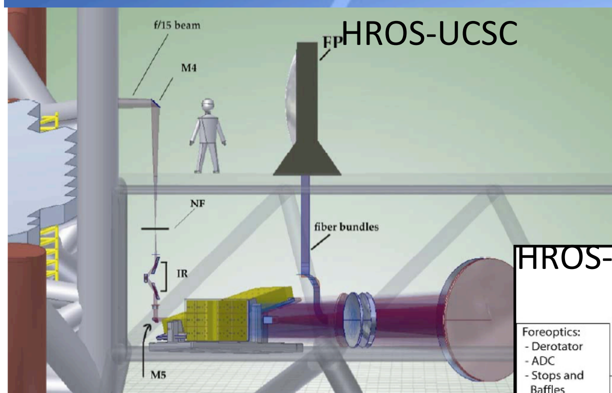
- Feasibility studies for future instrumentation: Why now?
  - **Very** strong interest across partnership
  - Updated and/or new instrumentation concepts
  - Updated technical information required (e.g., cooling requirements)
  - Updated cost and schedule estimates for development budget planning
  - **Foster new collaborations and involve new groups into our instrumentation effort – important at this critical time for TMT**
- May be especially important in the context of an alternative site such as ORM:
  - TMT should have a powerful suite of AO systems and science instruments
  - TMT should have a vibrant instrumentation development program to maintain its competitiveness

Steps Towards Future Instruments

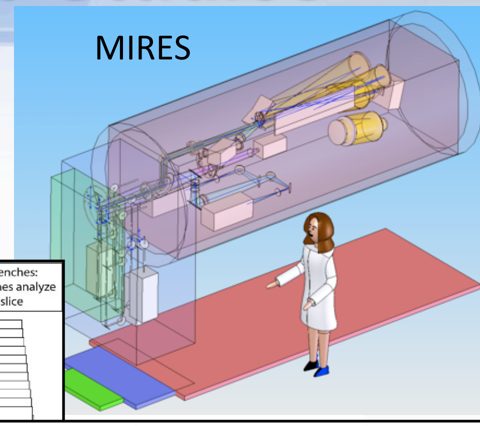


A Powerful Development Model – 2005/6 Studies

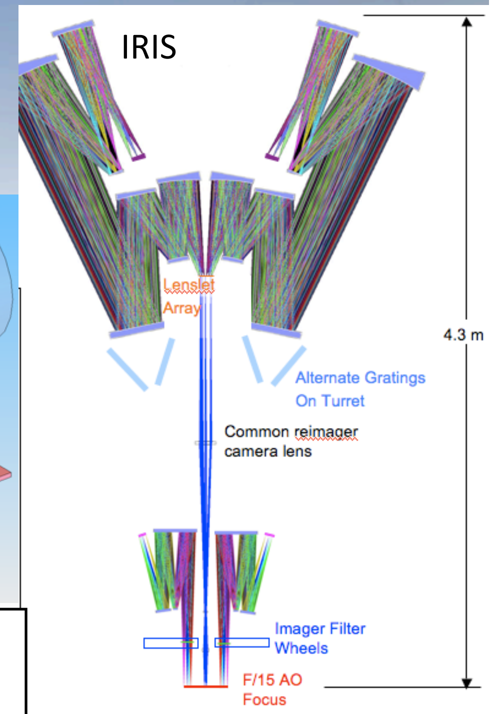
HROS-UCSC



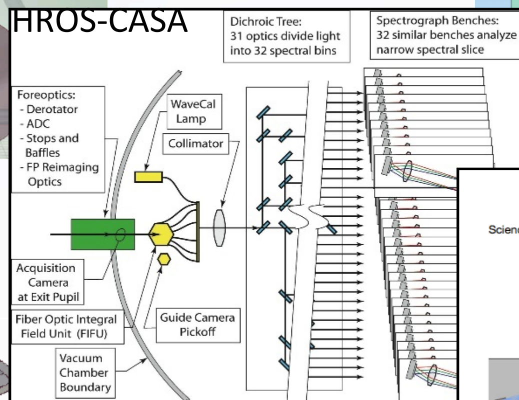
MIRES



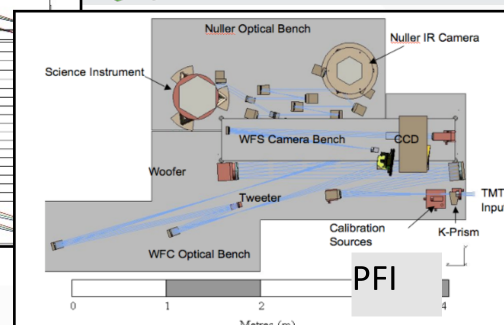
IRIS

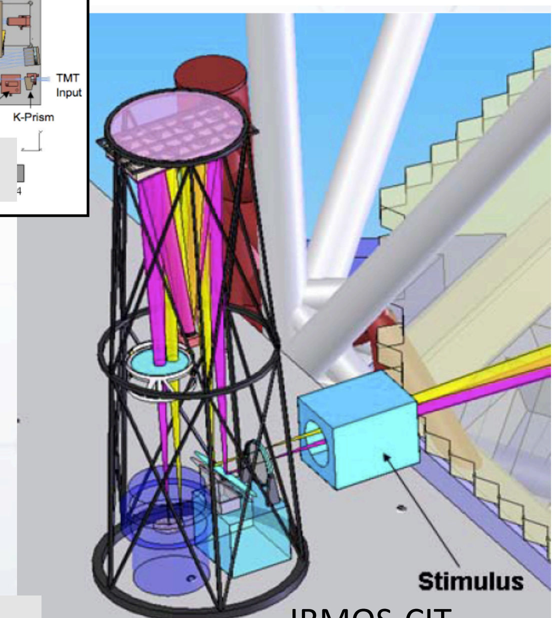


HROS-CASA

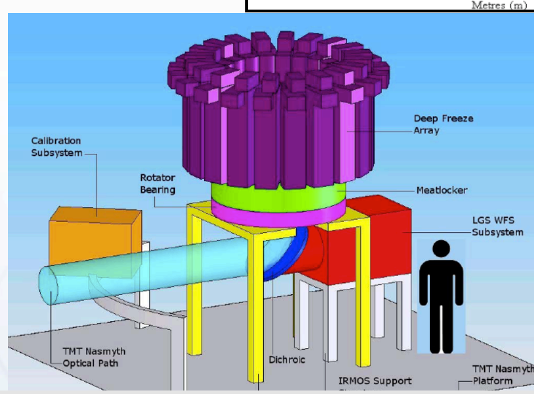


PFI

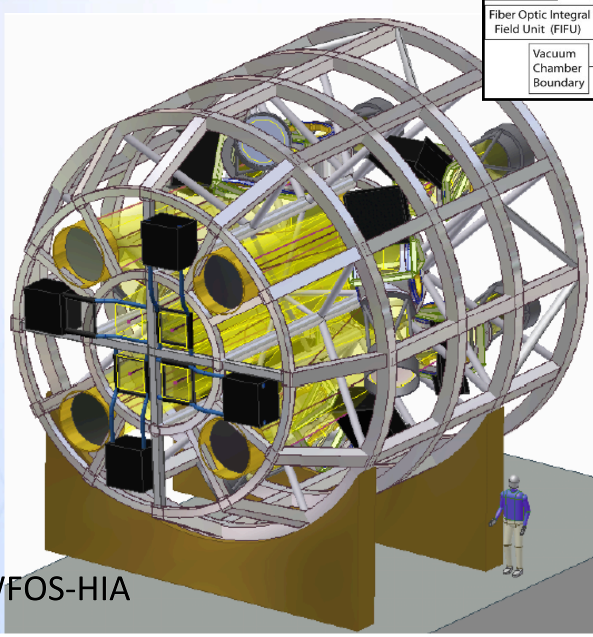




WFOS-HIA



IRMOS-UF



IRMOS-CIT

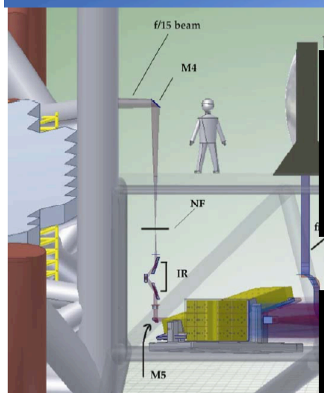
A Powerful Development Model – 2005/6 Studies

Observing programs, requirements, concepts, performance, etc.

More than 200 scientists and engineers at 48 institutes across North America and Europe

Some partners have also been developing science cases and conducting their own instrument studies

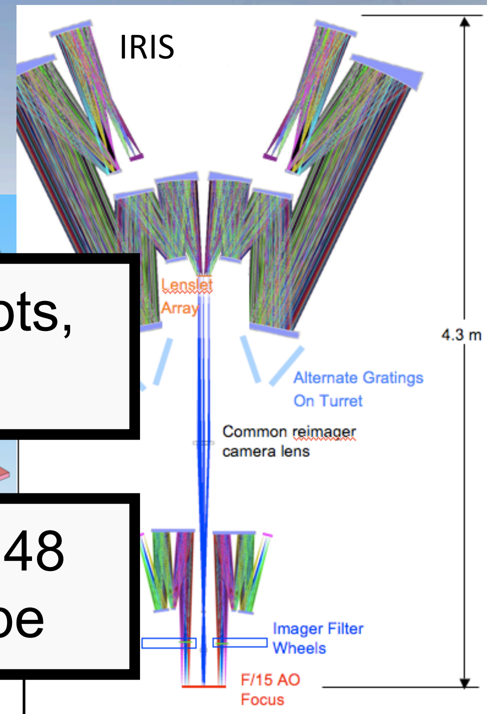
On-going "community explorations"
(e.g., workshops, testbeds, studies)
are leading to new concepts (MICHI, SEIT, CTMT-HROS)



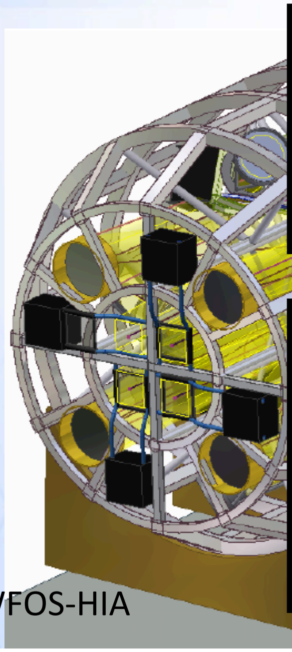
HROS-UCSC

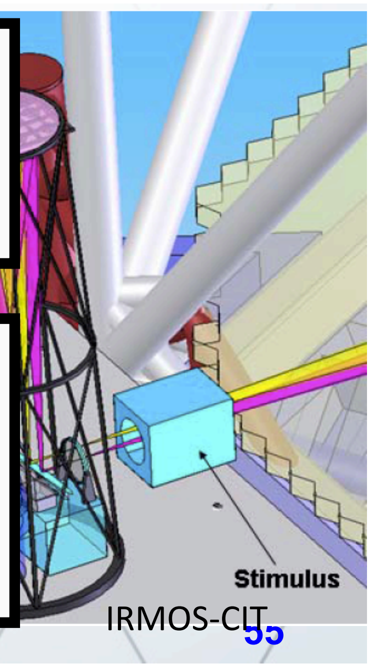
MIRES

HROS-CASA



IRIS


WFOS-HIA



IRMOS-CIT

Instrumentation Phasing Scenarios

- TMT developed nine phasing scenarios for future instrumentation capabilities:
  - Main variables are (1) list of desired capabilities, (2) arrival date of 1st second-generation instrument, and (3) average arrival rate of new capabilities at the Observatory
  - Current preferred parameters are:
    - **Eight new capabilities** (AO systems + science instruments)
    - First next-generation instrument to arrive **two years** after 1st light
    - A new capability should be deployed **every 2.5 years on average**
- **Q: Are these still the desired parameters?**

March 2011 SAC Preferred Instrumentation Phasing Scenario

- Eight instrumentation capabilities:
  1. High-Resolution Optical Spectroscopy (HROS-UC-2)
  2. High-Resolution, Near-IR Spectroscopy (NIRES-B)
  3. Multi-IFU, Near-IR Spectroscopy (IRMOS-N + AO upgrades)
  4. Adaptive Secondary Mirror (AM2)
  5. Mid-Infrared, High-Resolution Spectroscopy (MIRES)
  6. High-contrast imaging (PFI)
  7. Multi-IFU, Near-Optical Spectroscopy (VMOS + AO upgrades)
  8. High-Resolution, 5-18μm Spectroscopy (NIRES-R)

March 2011 SAC Preferred Instrumentation Phasing Scenario

Instrument	20 12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
HROS-UC-2																											
NIRES-B																											
IRMOS-N																											
IRMOS AO																											
AM2																											
MIRAO/ MIRES																											
PFI																											
VMOS																											
NFIRAOS+																											
LGSF+																											
NIRES-R																											

Future Instrumentation Studies: A Proposed Timeline

Step	Description	Timelines: First-light Instruments	Timelines: 2nd Gen Instruments Proposed New Timeline	Timelines: 2nd Gen Instruments Original Timeline
1	Initial science cases and desired capabilities	<= 2004	2016Q1 - 2016Q4	(Missing steps from this timeline -> Future instruments 1 and 2 selected on the basis of 10-year old scientific and technical information)
2	Call for Feasibility Studies (~$150K+~1.5 yr / study)	2005Q1 (10 studies; 8 capabilities)	2017Q1 (TBD studies; TBD capabilities)	
3	Feasibility Study Phase: ° Expanded science cases and operational concepts ° Instrument designs and their technical readiness ° Schedule and Budget Estimates	2005Q2 - 2006Q1	2017Q3 - 2018Q4	
4	Feasibility Study Reviews	2006Q1	2019Q1	
5	Revised science cases and instrument concept ranking	2006Q2 - 2006Q3	2019Q2 - 2019Q3	2016Q2 - 2016Q3
6	Instrument concept selection	2006Q4	2019Q4	2016Q4
7	Call for Conceptual Design Studies (~$1M+ ~1.5 yrs / study)	2007Q3	2019Q4	2016Q4
8	Team selection and formation	2007Q4	2020Q2	2017Q2
9	Statement of Work and work package development	2007Q4	2020Q3 - 2020Q4	2017Q3 - 2017Q4
10	Conceptual Design Studies start	2008Q1 (Two studies: WFOS and IRIS)	2021Q1 (Two studies TBD)	2018Q1 (Two studies TBD)

From 2006 to the Present: Some Demonstrators, Precursors, etc.

- IRMOS:
  - VOLT/VILLAGES/RAVEN (All completed)
  - AGE (Concept)
  - Gemini/MCAO d-IFU (-> “IRMOS-NFIRAOS”) (Funding approval decision pending)
- NIRES-B:
  - J-NIRES (Concept)
  - NIRPS: AO-fed, near-IR, high-resolution spectrograph for La Silla (under construction)
- HROS:
  - C-TMT: Concept based on GTC fiber-fed, high-resolution MOS (Concept)
  - J-HROS (Concept)
- MIRES: MICHI (Feasibility study completed)
- PFI:
  - Gemini/GPI and VLT/SPHERE lessons learned (on sky)
  - SCExAO (on sky at Subaru)
  - SEIT (“Second Earth Imager for TMT”) (Concept)

Future Instruments Now: GIRMOS -> IRMOS

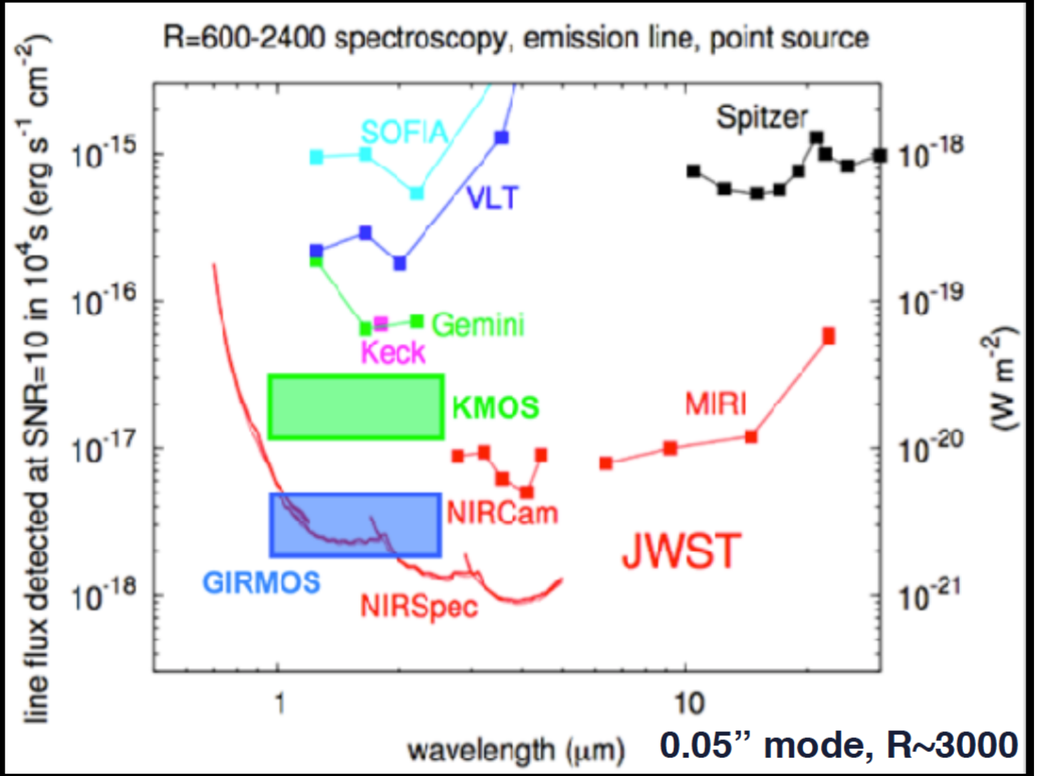
- Gemini InfraRed Multi-Object Spectrograph (GIRMOS): A TMT Pathfinder Instrument
- Deployable IFU system for Gemini GeMS MCAO
  - Same idea as the 2006 U. Florida concept for NFIRAOS-IRMOS
- PI: Suresh Sivanandam (Dunlap Institute/U. Toronto)
- Partner institutions: Dalhousie, UBC, UVic , Laval, St. Mary's, U. Manitoba, York U., NRC-Herzberg, Tohoku U., LAM
- Canadian Foundation for Innovation proposal
  - If approved, funding would start in 2018 and instrument would be delivered at Gemini in 2023.
  - Funding decision expected in June 2017

Future Instruments Now: GIRMOS -> IRMOS

- Wide range of science programs + detailed JWST follow-ups

Instrument Parameters

Parameter	*Requirement*	*Parameter*	*Requirement*
Telescope Feed	Gemini-South 8.1-meter MCAO f/33 beam	**Individual IFU Field-of-view (arcsecs)**	0.75x0.75 1.5x1.5 3.0x3.0 6.0x6.0 (Combined)
Wavelength Range	1.1-2.4 µm (J, H, K-bands)	**Spatial Sampling (mas)**	25x25 50x50 100x100 100x100 (Combined)
Field-of-regard	2 arcminute diameter patrol field	**Spectral Resolution R**	~3000 - 6000
Number of IFUs	4 with possibility for more	**Detector**	2Kx2K HAWAII-2RG for every two spectral channels



Sensitivity Comparison

Future Instruments Now: NIRPS -> NIRES-B

- Near-InfraRed Planet Searcher (“the red arm of HARPS”)
  - http://www.astro.umontreal.ca/nirps/
- **AO-assisted**, high-resolution, fiber-fed spectrograph @ La Silla 3.6-m
- 0.95 – 1.8 microns (YJH), R = 90,000 – 100,000
- Consortium: U. Montréal, Geneva Observatory (Switzerland), IPAG (France), IA (Portugal), UFRN (Brazil), NRC-Herzberg
- First light in 2019
- Synergy with TESS and JWST

Future Instruments Now: SCExAO (and KPIC) -> PFI

- High-contrast imaging:
  - **A lot of work done by a solid team**
  - Very sound “modular” strategy for phased implementation
  - SCExAO is demonstrating and validating the same technologies that will be needed on ELTs
    - Four optical benches
    - CHARIS IFU instrument
    - HiCIAO will be replaced by MKIDs in early 2017
    - SAPHIRA arrays for WFS (impressive!)
    - Now delivering 70-90% SR in H
    - **TMT version on-sky in 2023**

Future Instruments Now: “Blue MICHI” -> MIRES

- Discussed at May 2016 TMT Science Forum and October 2016 Hyderabad workshop
- “Blue” means L (3.42-4.12 μm), M (4.57-4.79 μm) and N (7.3-13.8 μm) bands – no Q (16-25 μm) band
- Main capabilities (or modules):
  - Imager (24.4″ ×24.4″ @ L&M, 28.1″ ×28.1″ @ N, R~10-100)
  - Long-slit moderate dispersion spectrometer (28.1″ slit length, R~600)
  - High-dispersion spectrometer (2″ slit length, R~100,000-120,00)
  - IFU spectrometer (N band only, ~0.175″ × ~0.07″, R ~ 1,000)
- “Monolithic” versus “Modular, phased” implementation
- Modular implementation: Multi-port MIRAO + bMICHI modules
- **TMT@ORM: bMICHI + queue observing would be competitive with E-ELT /METIS**

Future Instruments Now: "???" -> HROS

- High resolution spectroscopy:
  - **Community effort not nearly as well organized as others but interest is there**
  - No strong science driver for simultaneous optical and NIR
  - Revision to Level 1 requirements?
    - R = 100,000 now minimum but some want to trade resolution for sensitivity
    - Multiplexing with N~10
    - Stability should be 10 cm/s instead of 1 m/s
  - Possibility of bringing existing spectrograph to TMT?
  - Latest technologies:
    - Image slicers (Subaru IRD) and fibers
    - **Immersion gratings (impressive progress at Tokyo U.)**
    - Coatings
    - Laser combs

Instrumentation Workshops held in China, India, US and Canada

Future Instrumentation: What Should We Do?

- Plan proposed at 2016 May SAC meeting in Kyoto:
  - ~3-4 feasibility studies with 1.5 year duration
  - Modest cash contributions leveraging larger in-kind contributions
    - MICHI team produced a very impressive feasibility report with NSF ATI funding and Japanese contributions
  - Call for proposals in 2017?
- **Many teams have been preparing themselves for a possible CfP but no sources of funding identified yet**
  - Some teams demonstrated a high level of readiness at Kyoto science forum
  - A purely in-kind model will not work
- Q: Provided that resources can be found, should we proceed through a Call for Proposals or “targeted” team support?

Summary

- IRIS has successfully passed its Preliminary Design Review – 1
  - This was a major milestone for the team!
  - PDR-2 planned for June 2017 timeframe
- WFOS OMDR effort is progressing as planned and is on track for its early May review
- Work on IRMS is deferred until 2021-2022
  - Options other than MOSFIRE may have to be considered to provide a multi-object, near-infrared spectroscopic capability to TMT
- **A new plan for future instrumentation needs to be developed**
  - Overlaps with the development of a scientific vision for ORM

Acknowledgments

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