# Thirty-Meter Telescope: First-Light Instrumentation and Beyond

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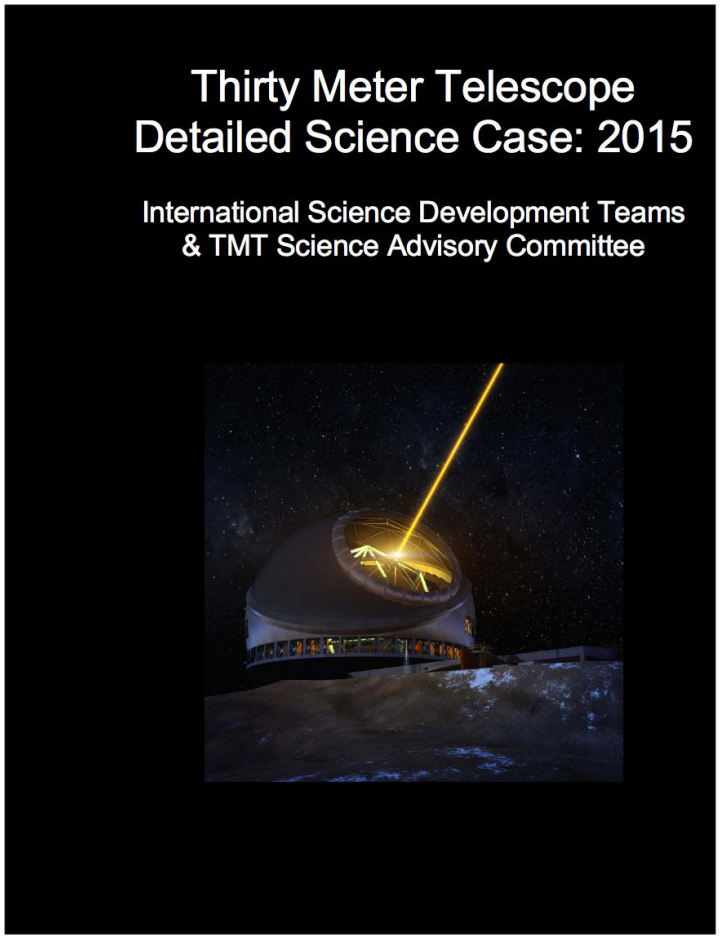
TMT Science Forum

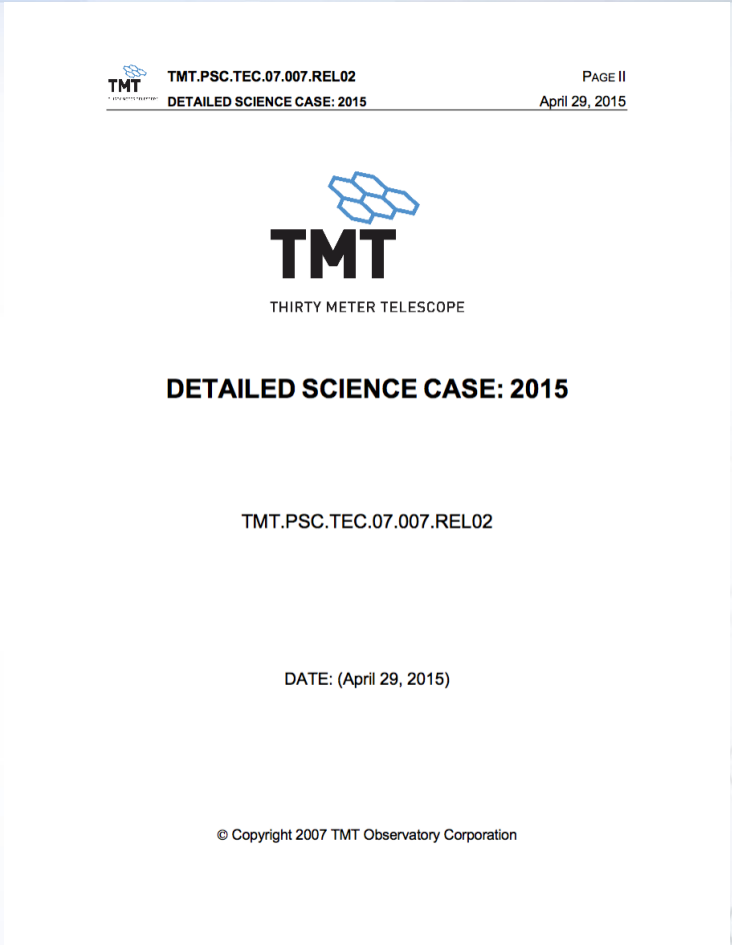
Kyoto, May 24, 2016

# 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

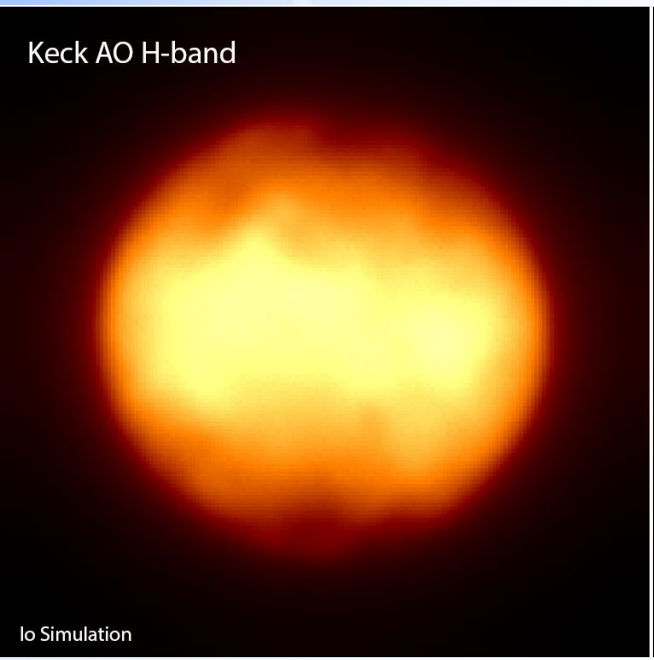
# Detailed Science Case 2015 by TMT International Science Development Teams

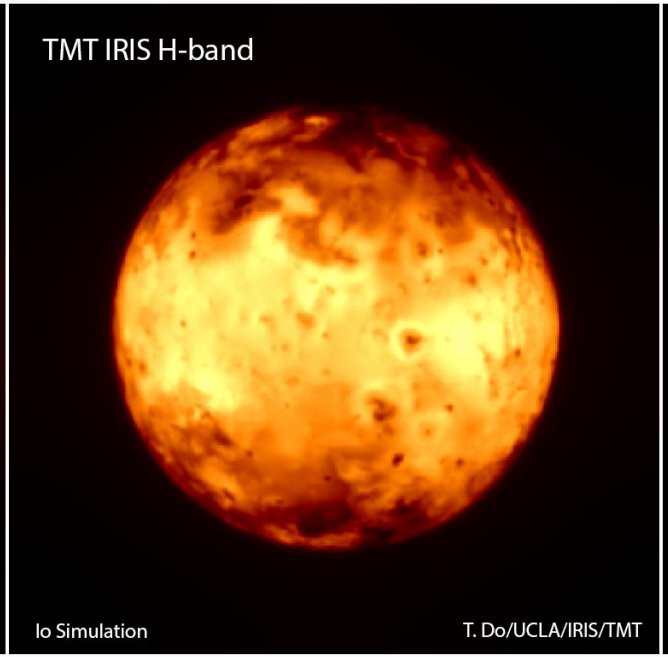


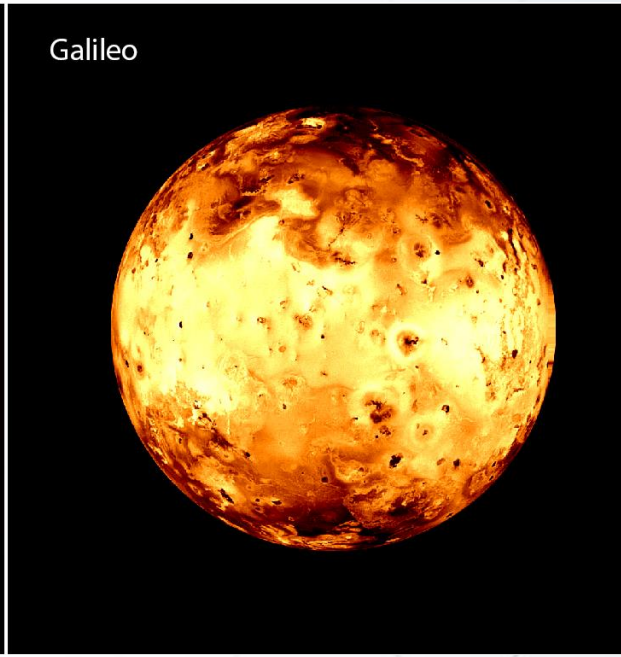




Reference: Skidmore et al. 2015, Research In Astronomy and Astrophysics (RAA), Volume 15, Issue 12, Article id. 1945

# The Volcanoes of Io



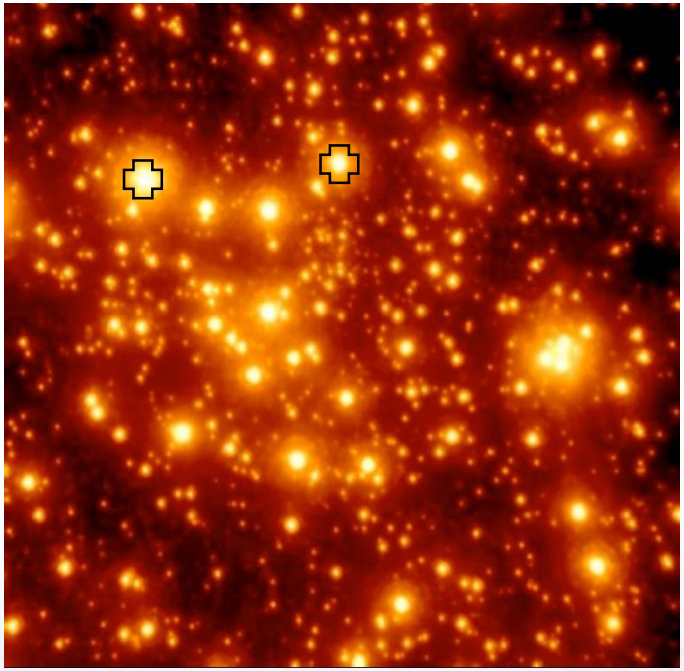



# Pluton and Charon


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

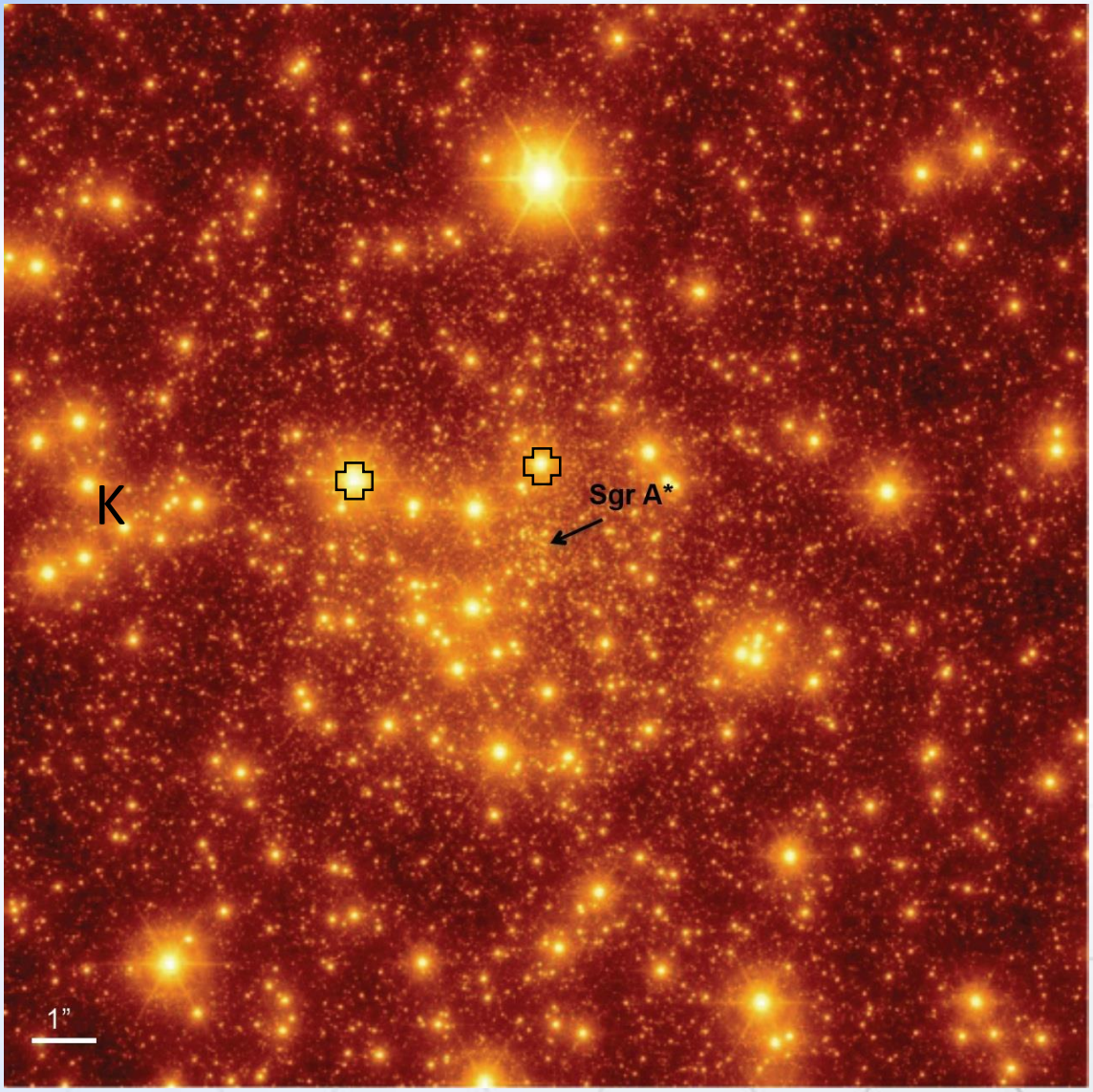


# Galactic Center with TMT

K-band

t = 20s

100,000 stars down to = 24

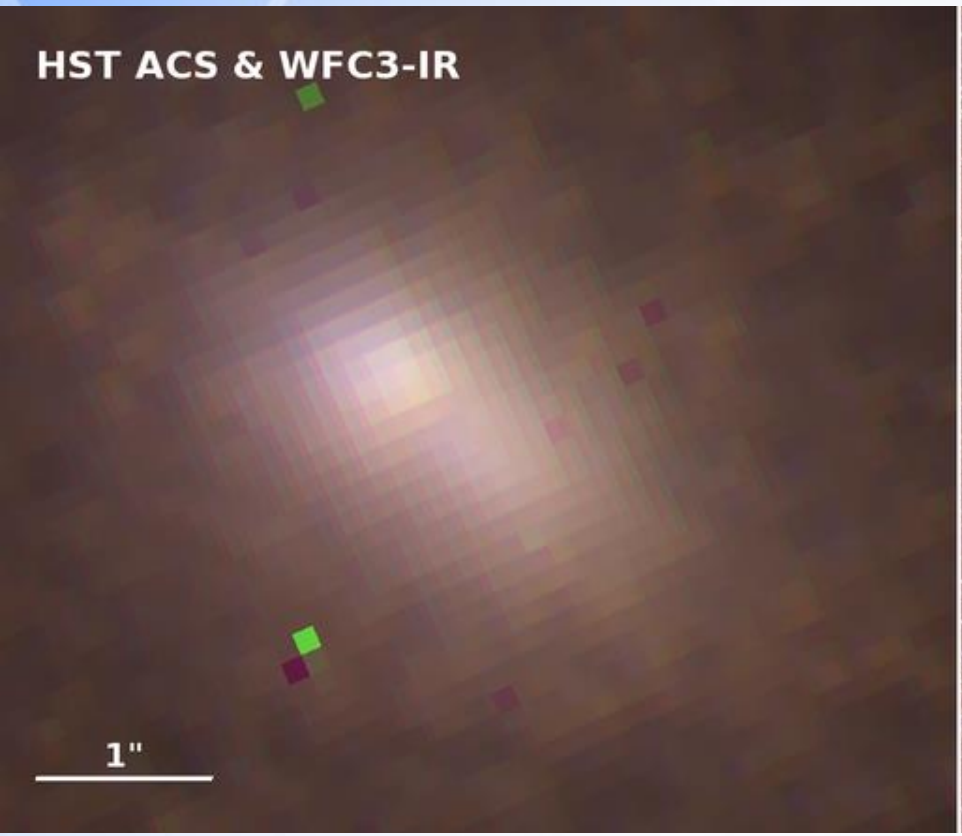


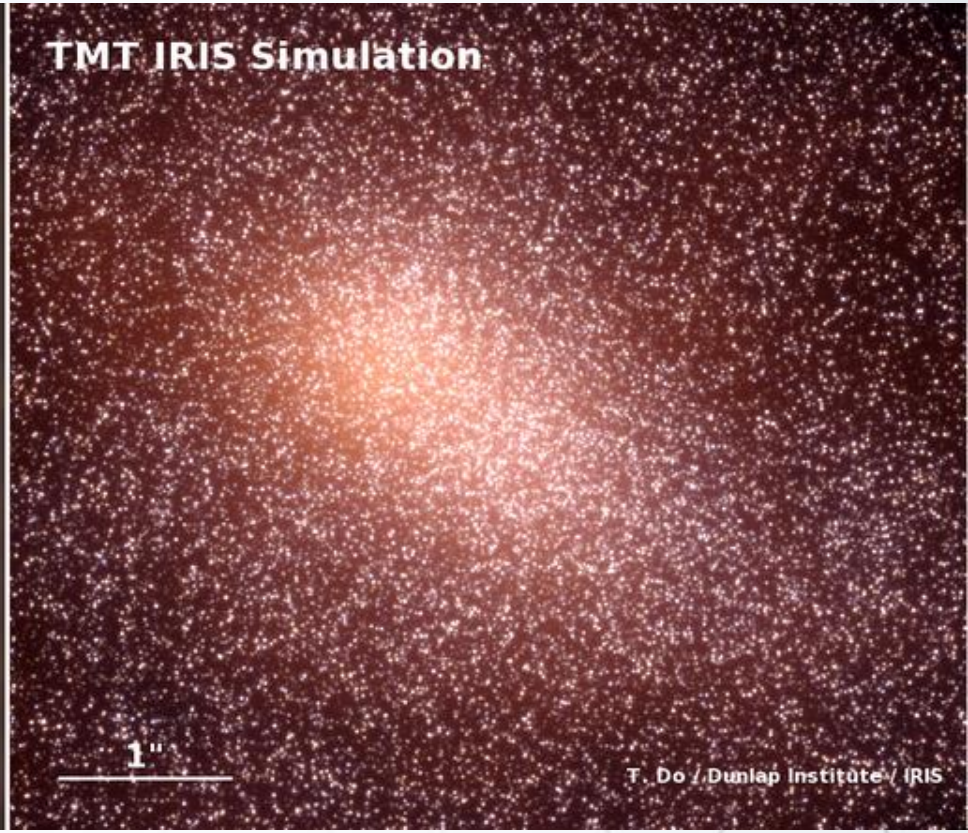

17”

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

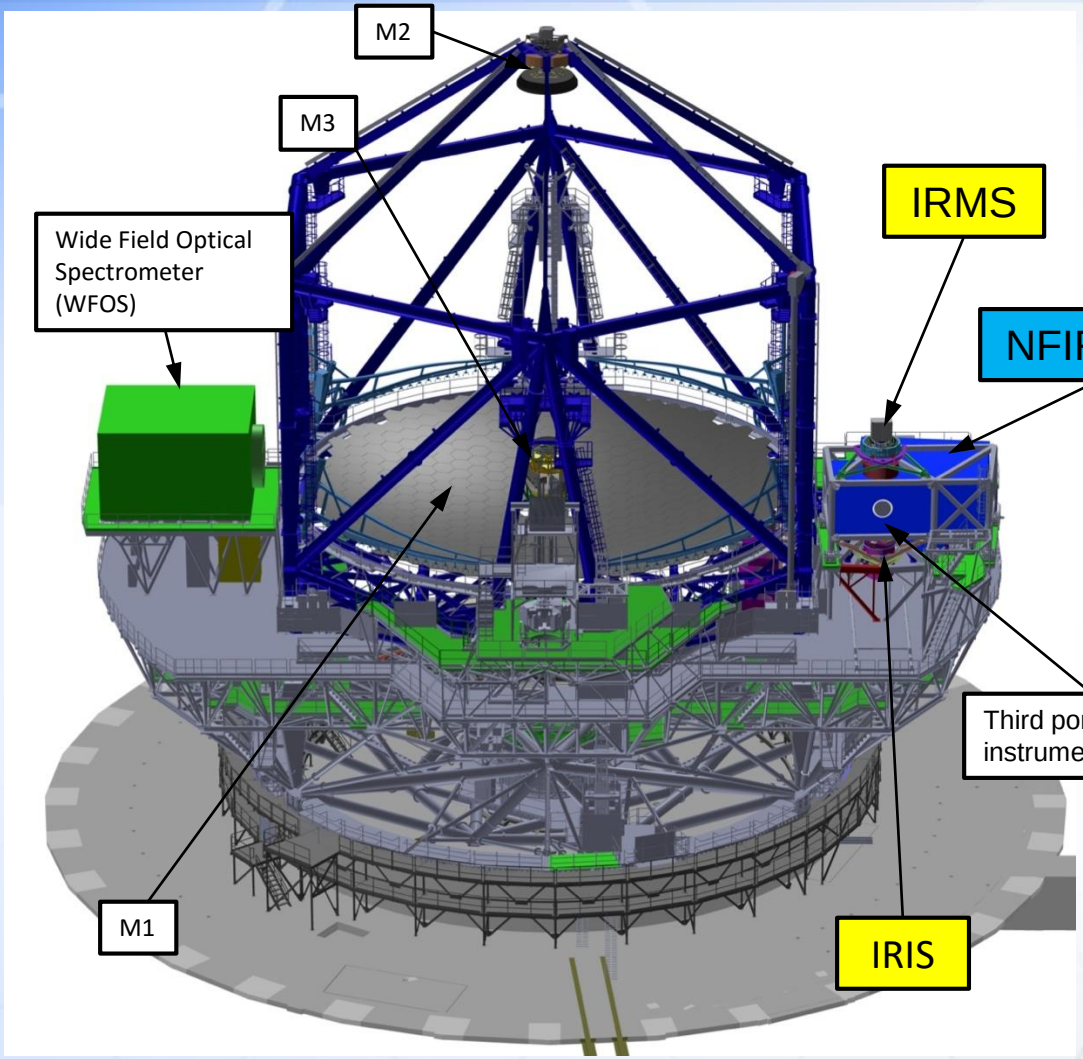
Courtesy: L. Meyer (UCLA)

# The Center of the Andromeda Galaxy (Messier 31)



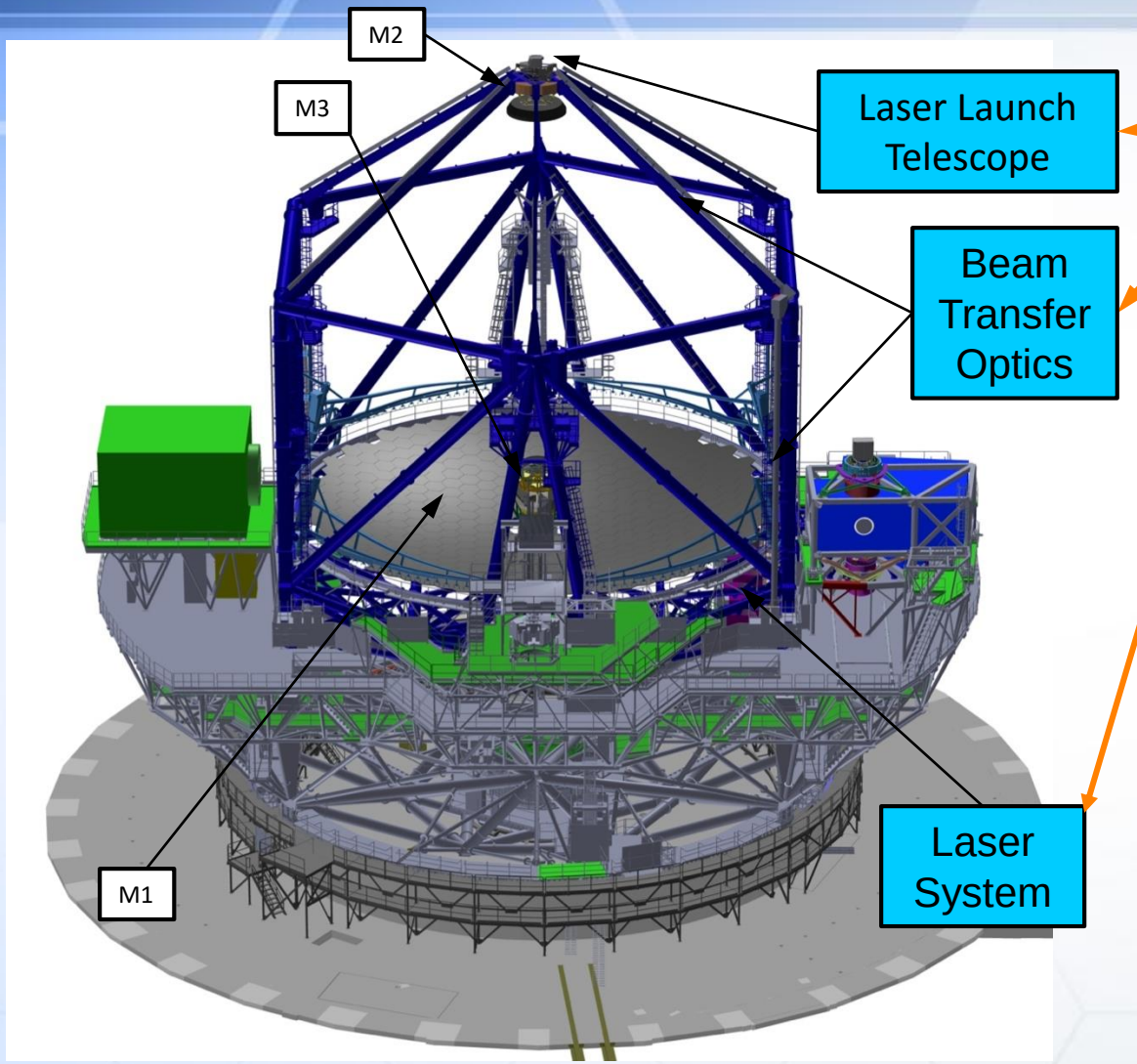



# TMT First Light AO Systems



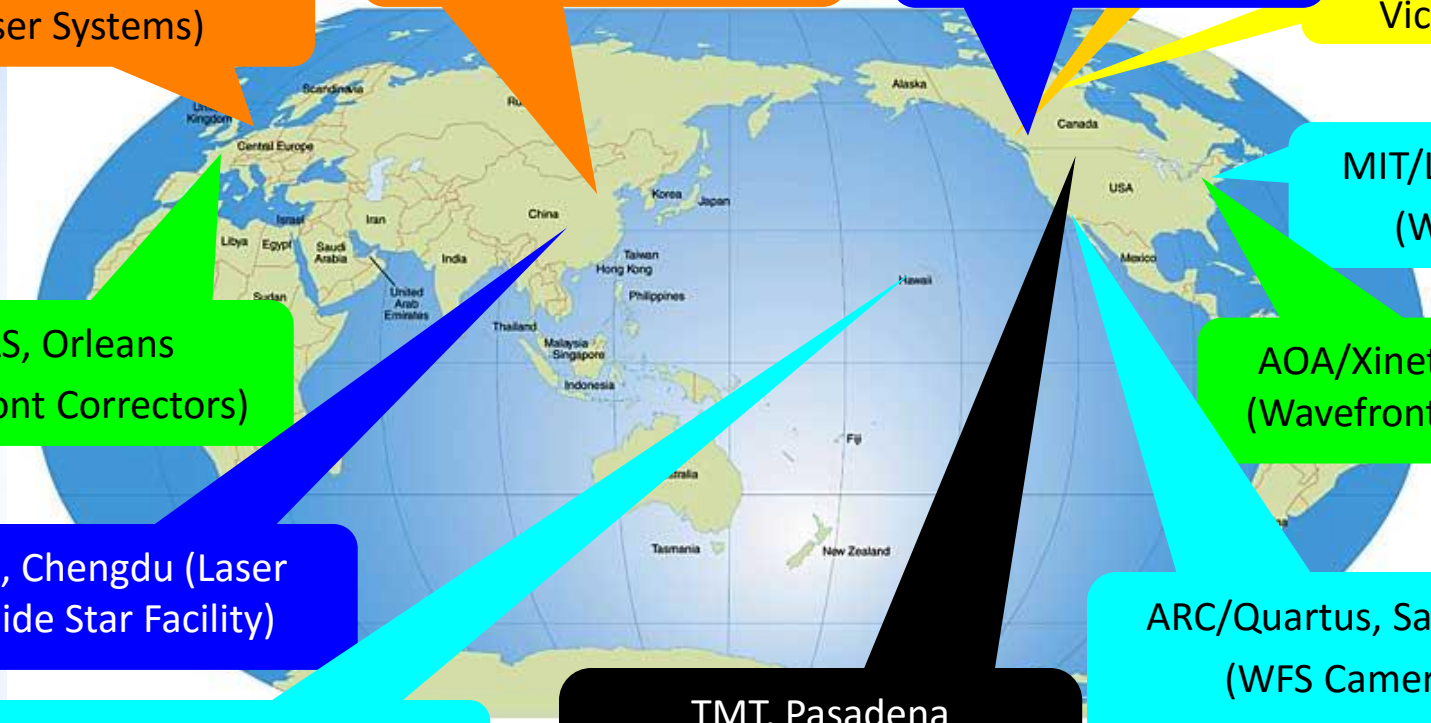

- Narrow Field IR AO System (NFIRAOS)
  - LGS, multi-conjugate AO
  - 6 laser guidestar WFSs
  - Two Piezostack DMs
  - Tip/tilt stage
  - Order 60x60 correction
  - 800Hz update rate
- Tip/tilt/focus Infrared NGS WFSs in client instruments IRIS, IRMS
  - On-instrument WFSs using near IR, H2RG HgCdTe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




UBC, Vancouver (Sodium LIDAR)

TIPC, Beijing (Laser Systems)

NRC-Herzberg, Victoria (NFIRAOS)

TOPTICA, Munich (Laser Systems)

NRC-Herzberg, Victoria (RTC)

MIT/LL, Lexington (WFS CCDs)

CILAS, Orleans (Wavefront Correctors)

AOA/Xinetics, Devens (Wavefront Correctors)

IOE, Chengdu (Laser Guide Star Facility)

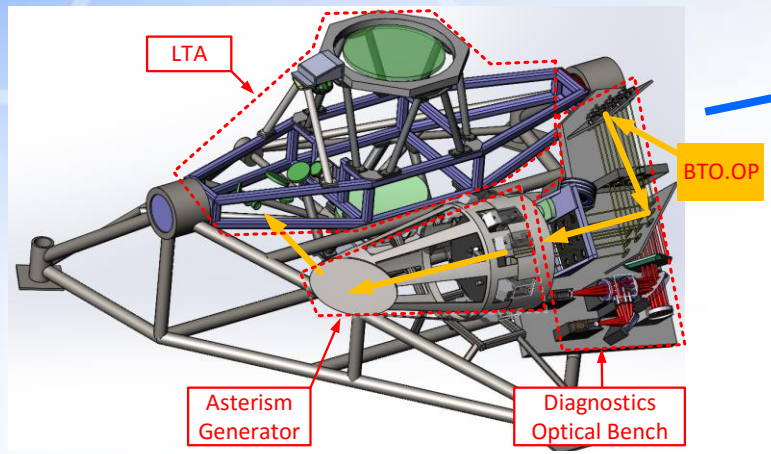
ARC/Quartus, San Diego (WFS Cameras)

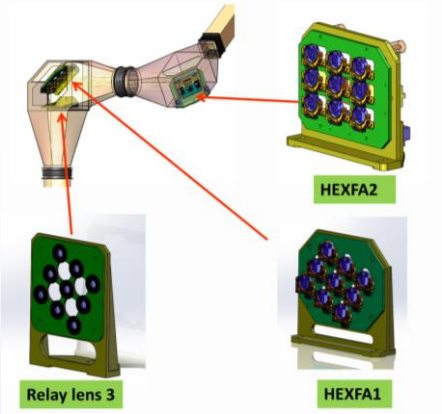
Keck Observatory, Waimea (WFS Camera oversight)

TMT, Pasadena (Management, SE, AOESW)

# Laser Guide Star Facility

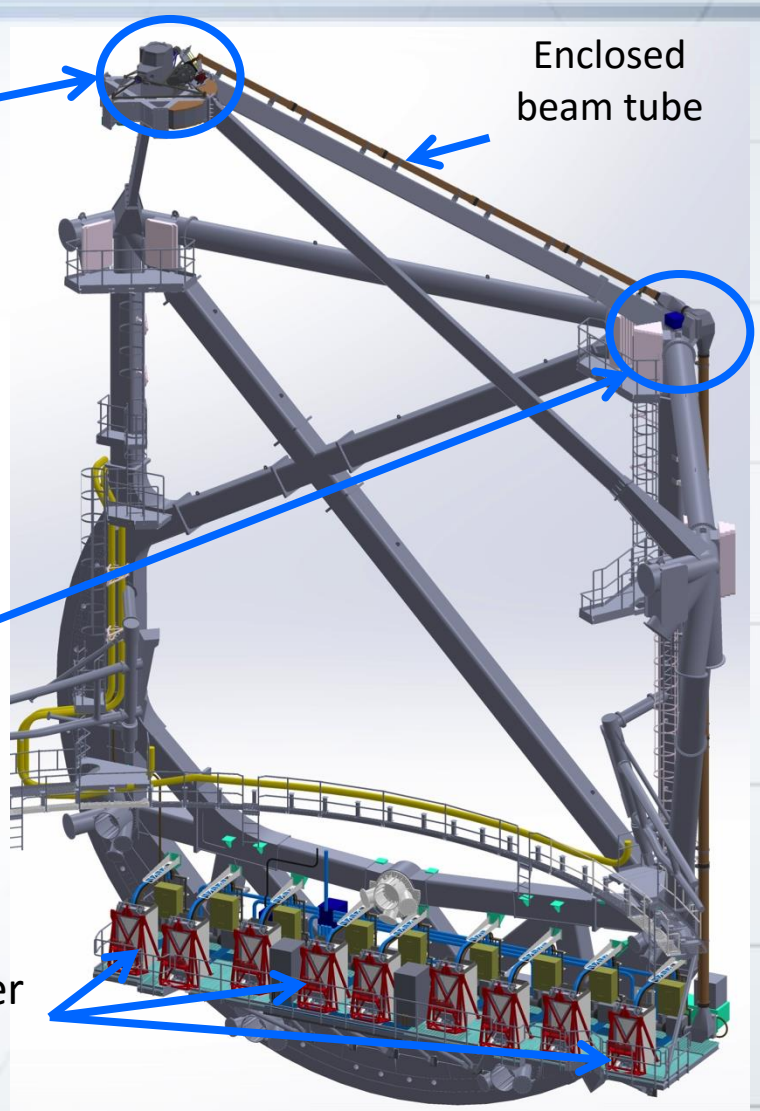
Top-End Layout




Beam Transfer Optics Components

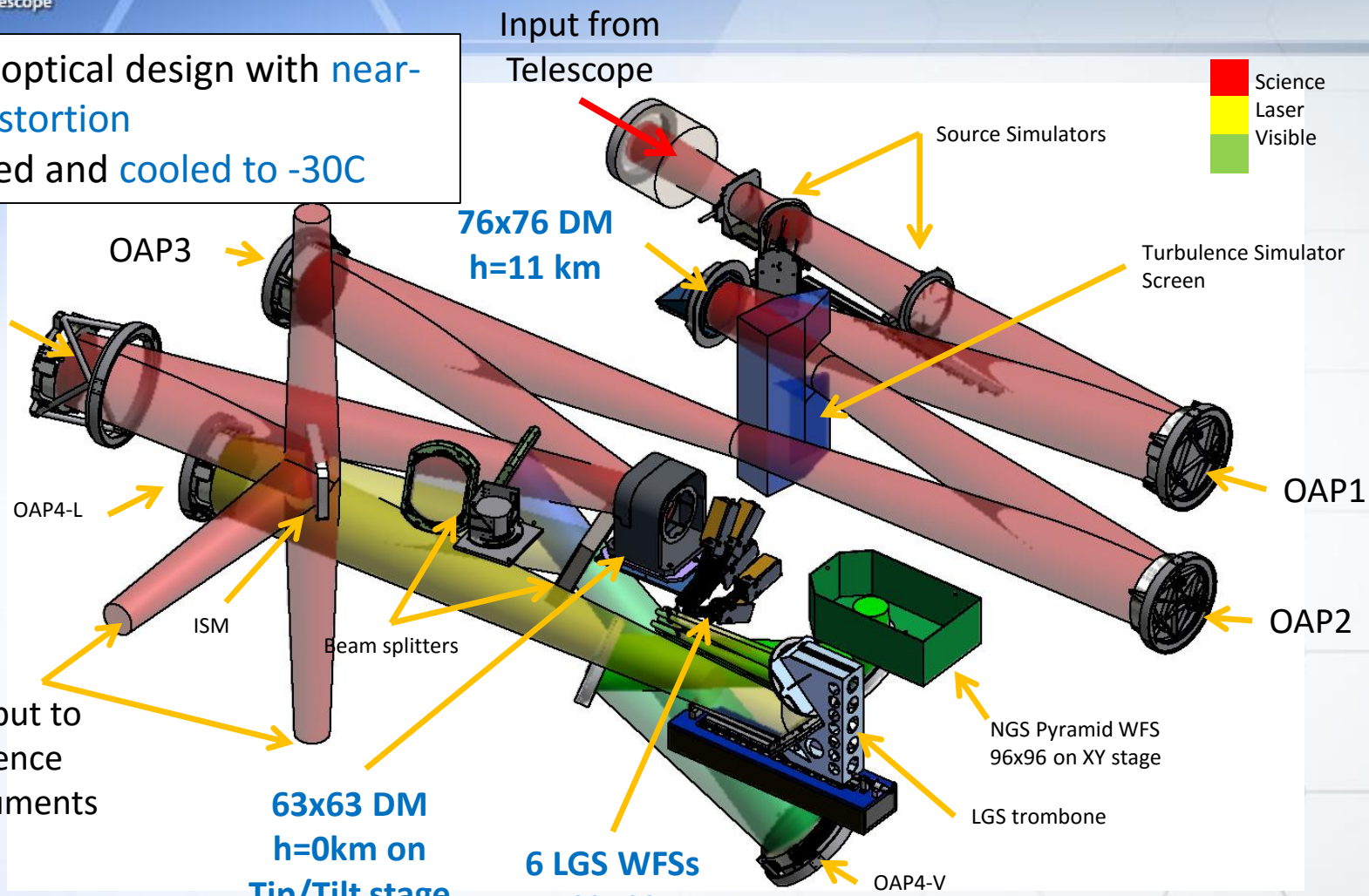
Enclosed beam tube



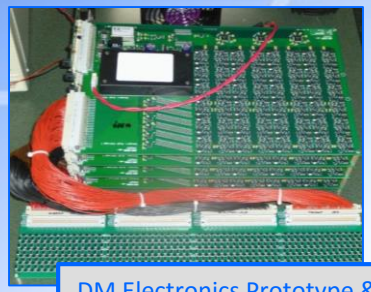
Lasers and Laser Benches

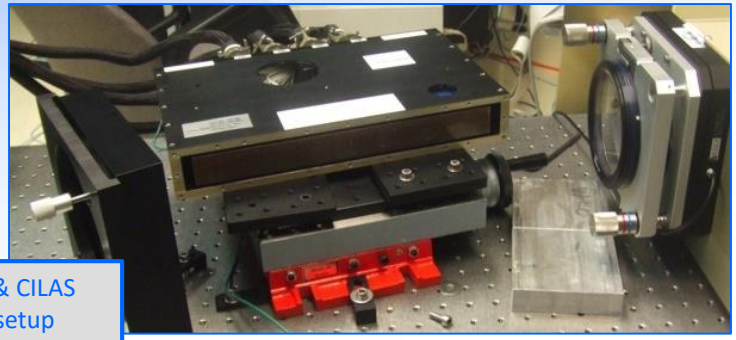
# NFIRAOS Opto-Mechanical Design

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

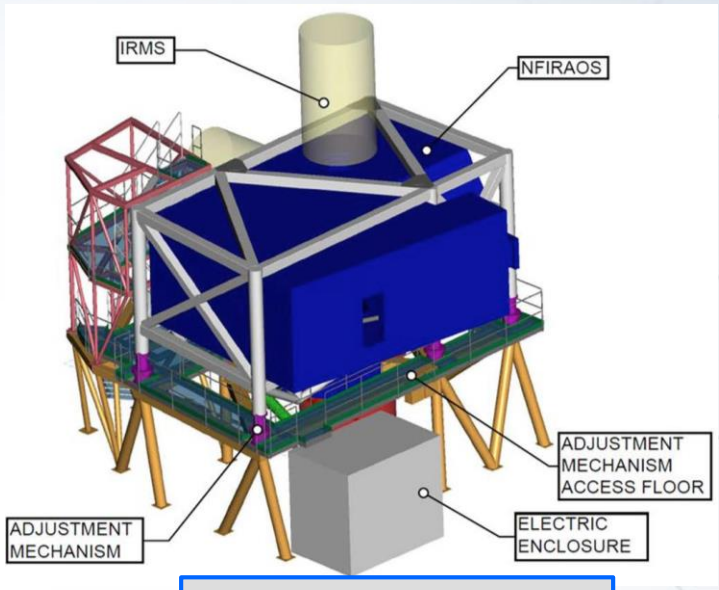


# TMT Facility AO System NFIRAOS in Final Design Phase at NRC Hertzberg

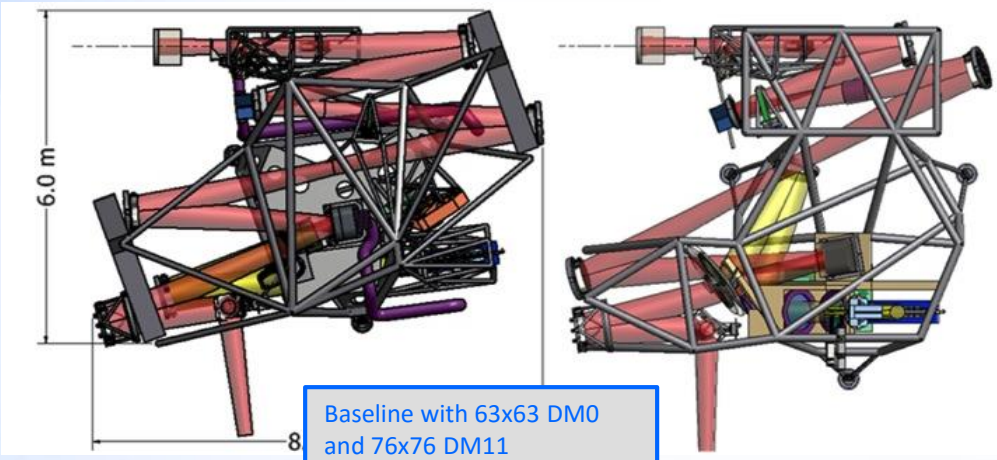




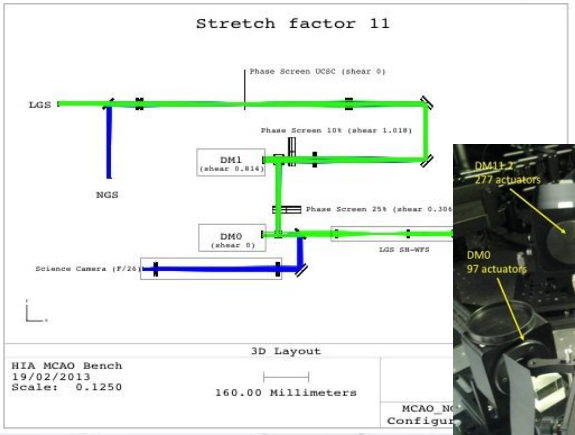
DM Electronics Prototype & CILAS DM 6x60 Breadboard test setup (warm) at NRC - Herzberg



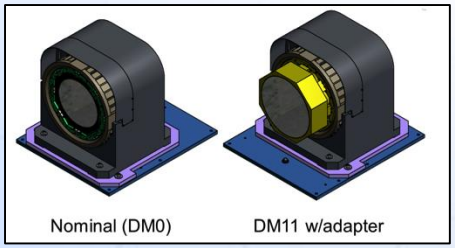

Interface with telescope structure



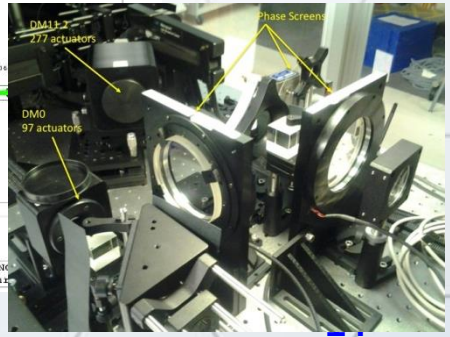

Baseline with 63x63 DM0 and 76x76 DM11




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)<br>16″.4 x 16″.4″ (imaging) | 4000-8000<br>5-100 (imaging) | 0.8 – 2.4 | MCAO with NFIRAOS |
| Wide-field Optical spectrometer (WFOS) | 40.3′ squared (FoV)<br>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<br>10″ imaging | 5000-100000 | 8-18<br>4.5-28(goal) | MIRAO |
| Planet Formation Instrument (PFI) | 1″ outer working angle, 0.05″ inner working angle | R≤100 | 1-2.5<br>1-5 (goal) | $10^8$ contrast<br>$10^9$ 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<br>0.31-1.3(goal) | SL |
| “Wide”-field AO imager (WIRC) | 30″ imaging field | 5-100 | 0.8-5.0<br>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)<br>16".4 x 16".4" (imaging) | 4000-8000<br>5-100 (imaging) | 0.8 – 2.4 | MCAO with NFIRAOS |
| Wide-field Optical spectrometer (WFOS) | 40.3′ squared (FoV)<br>576" (Total slit length) | 1000-8000 | 0.31-1.1 | Seeing-Limited (SL) |
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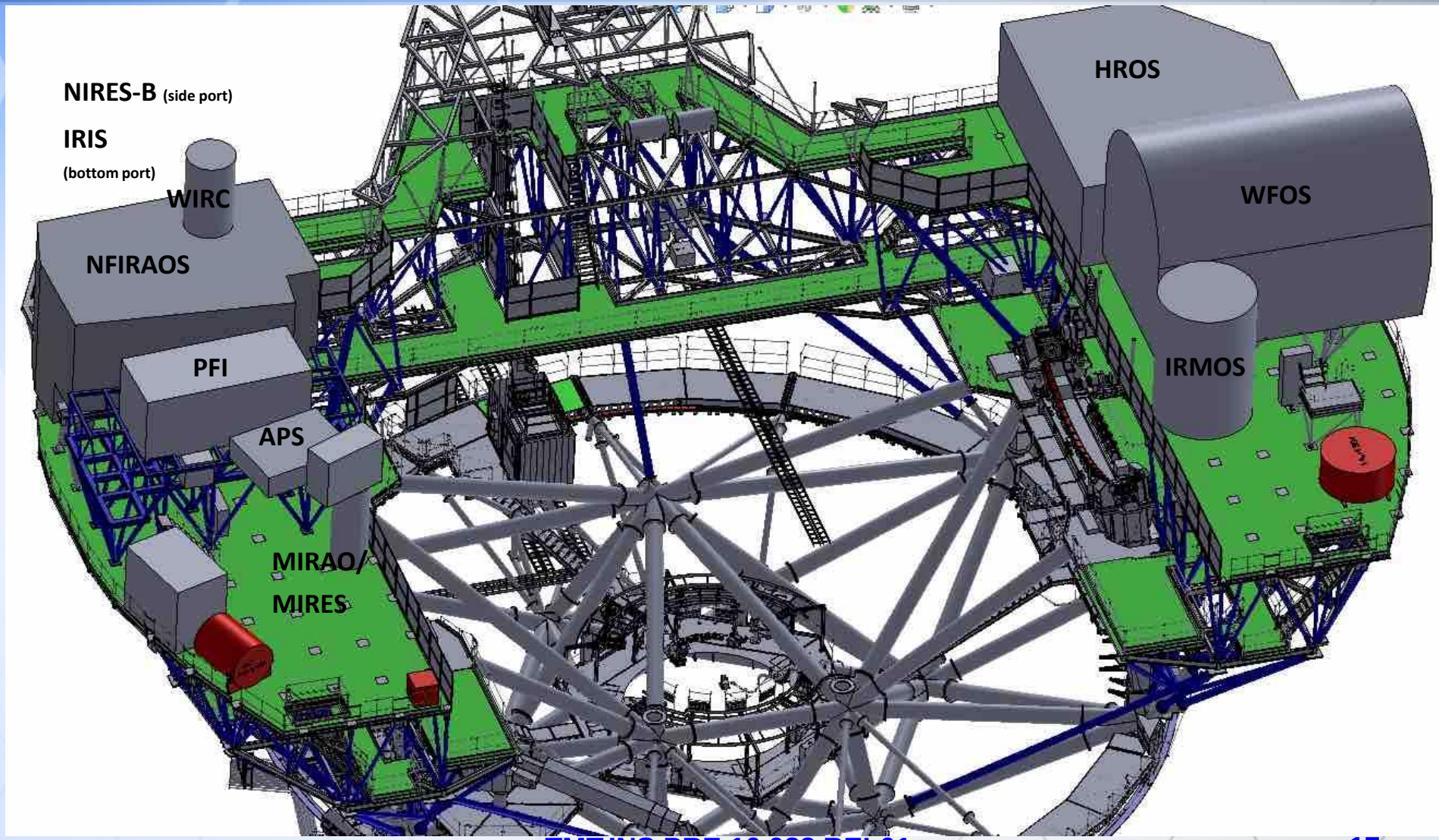
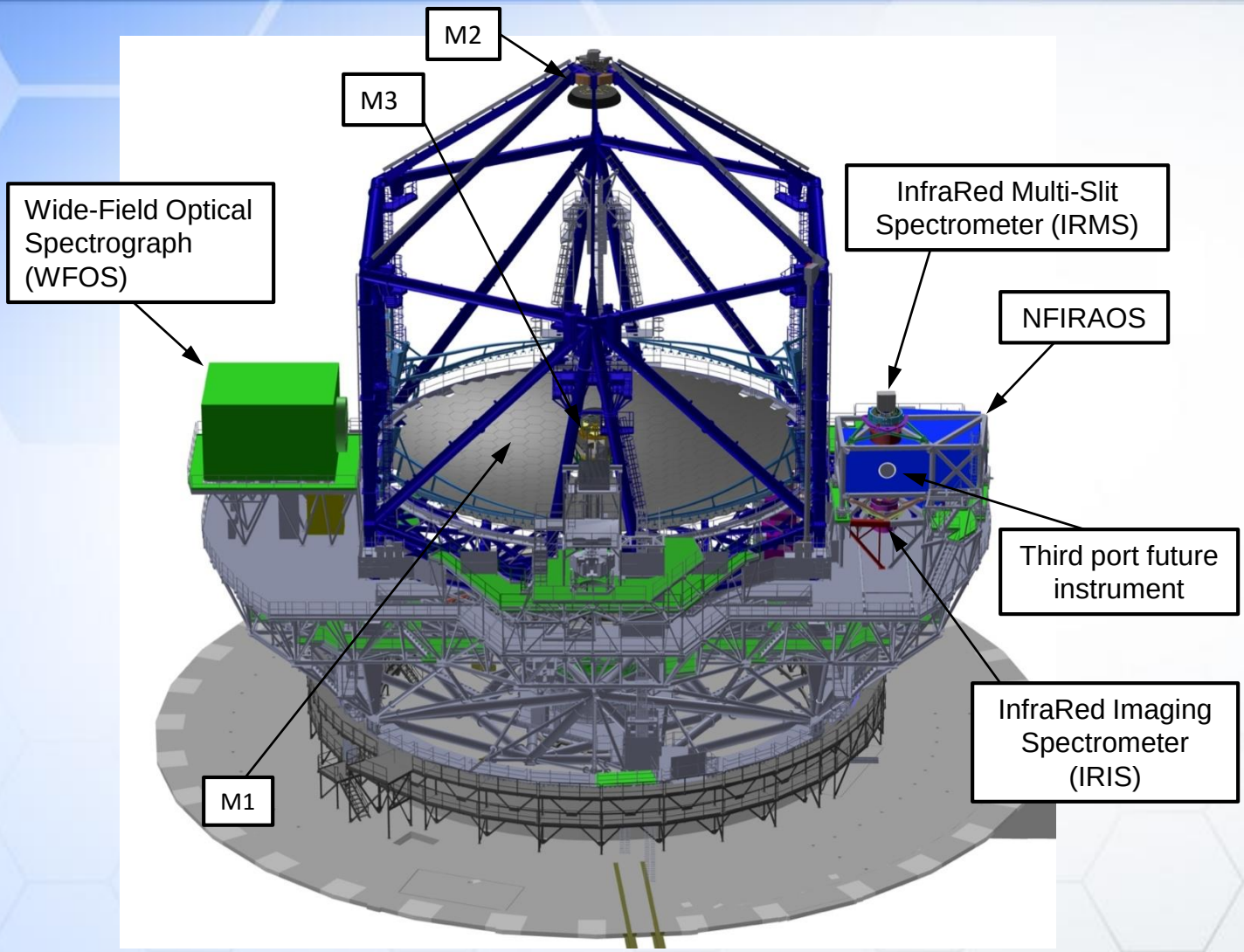
| Planet Formation Instrument (PFI) | 1″ outer working angle, 0.05″ inner working angle | R≤100 | 1-2.5<br>0.9-2.5(goal) | $10^8$ contrast<br>0.6(goal) |
| Near-IR AO-fed Echelle Spectrometer (NIRES) | 2″ slit length | 25000-100000 | 0.9-2.5 | MCAO with NFIRAOS |
| High-Resolution Optical Spectrometer (HROS) | 5″ slit length | 50000 | 0.31-1.0<br>0.31-1.3(goal) | SL |
| "Wide"-field AO imager (WIRC) | 30″ imaging field | 5-100 | 0.8-5.0<br>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)**

# Nasmyth Configuration: Full Instrumentation Suite

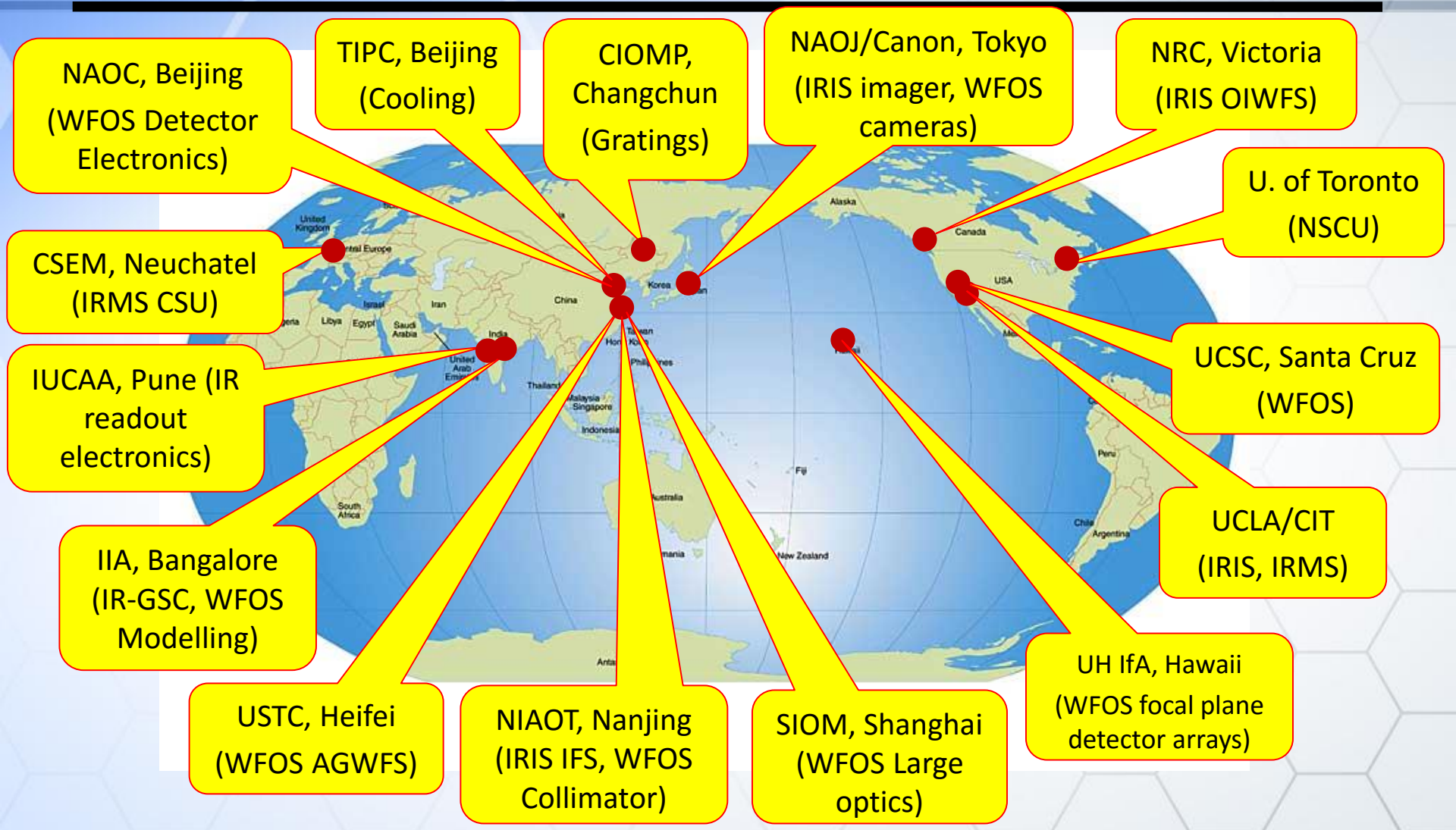


# TMT First-Light Science Instruments on the Telescope

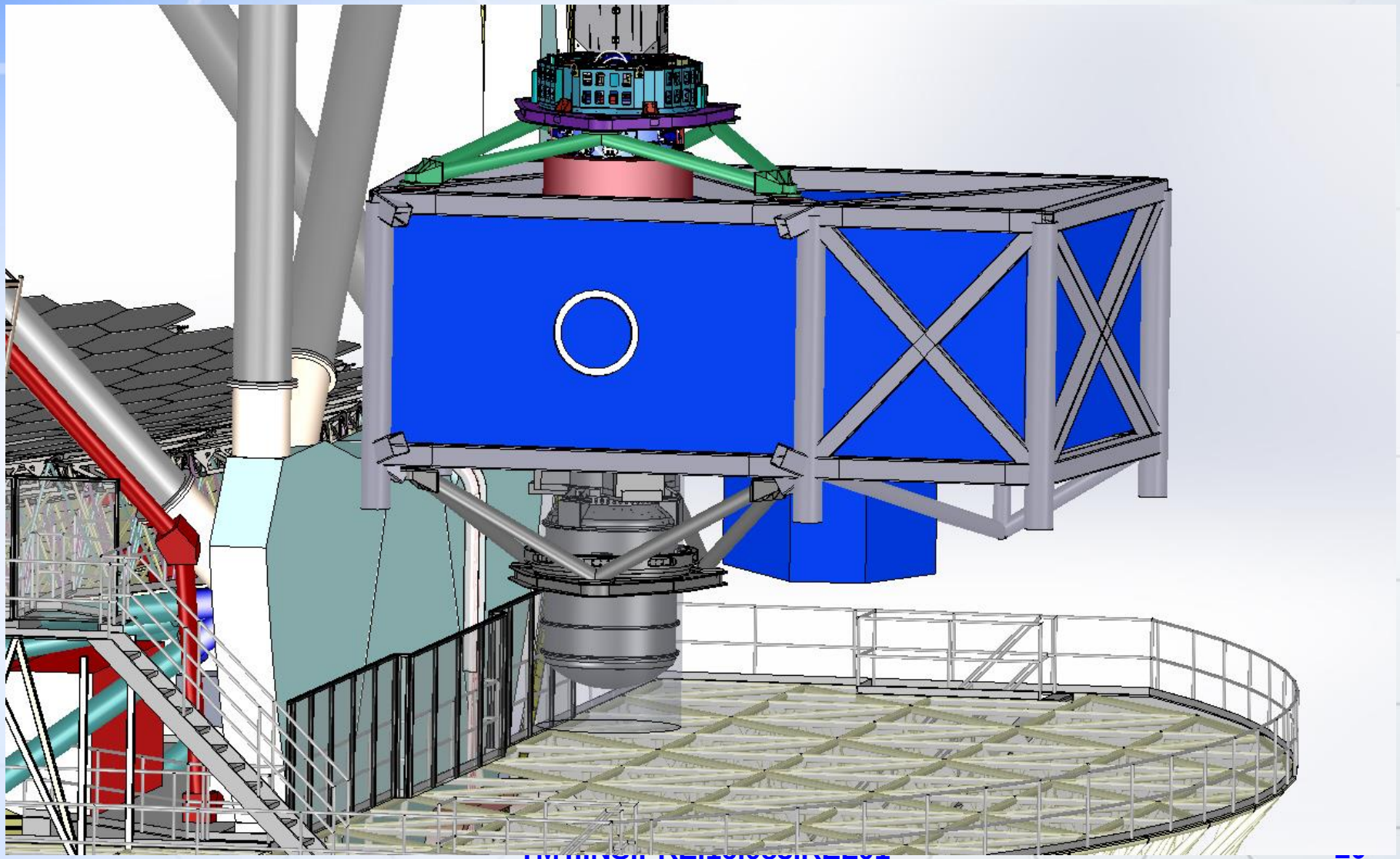



- Ritchey-Chrétien optical design
- 30-m f/1 primary
- 3.1-m convex secondary
- 2.5 m x 3.5 m flat tertiary
- f/15 final focal ratio
- 20’ Field of view is 2.62m in diameter
- Science instruments mounted on Nasmyth platforms (fixed gravity vector)

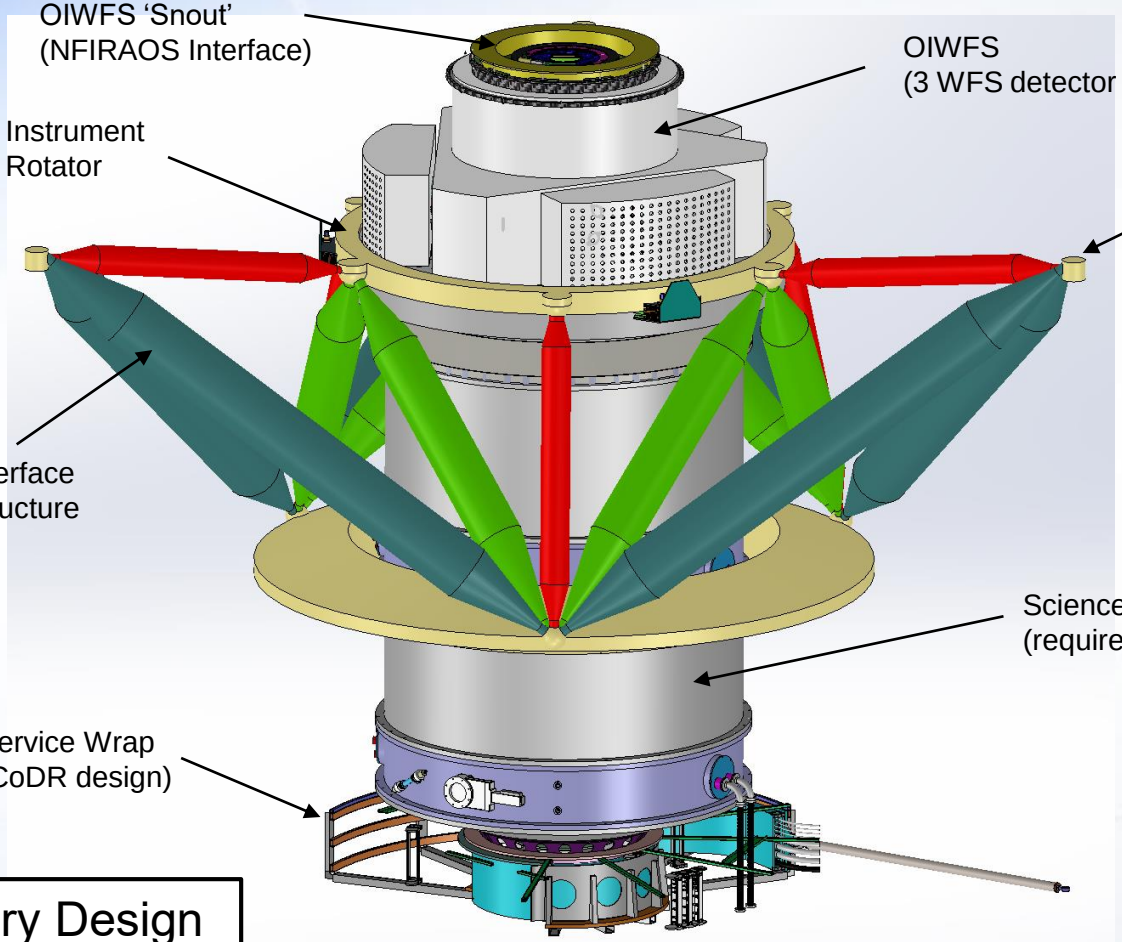
# TMT Global Participants – First Light Science Instruments



# IRIS and IRMS Mounted on NFIRAOS



# InfraRed Imaging Spectrometer (IRIS)




"Light" Preliminary Design Review scheduled for November 2016

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

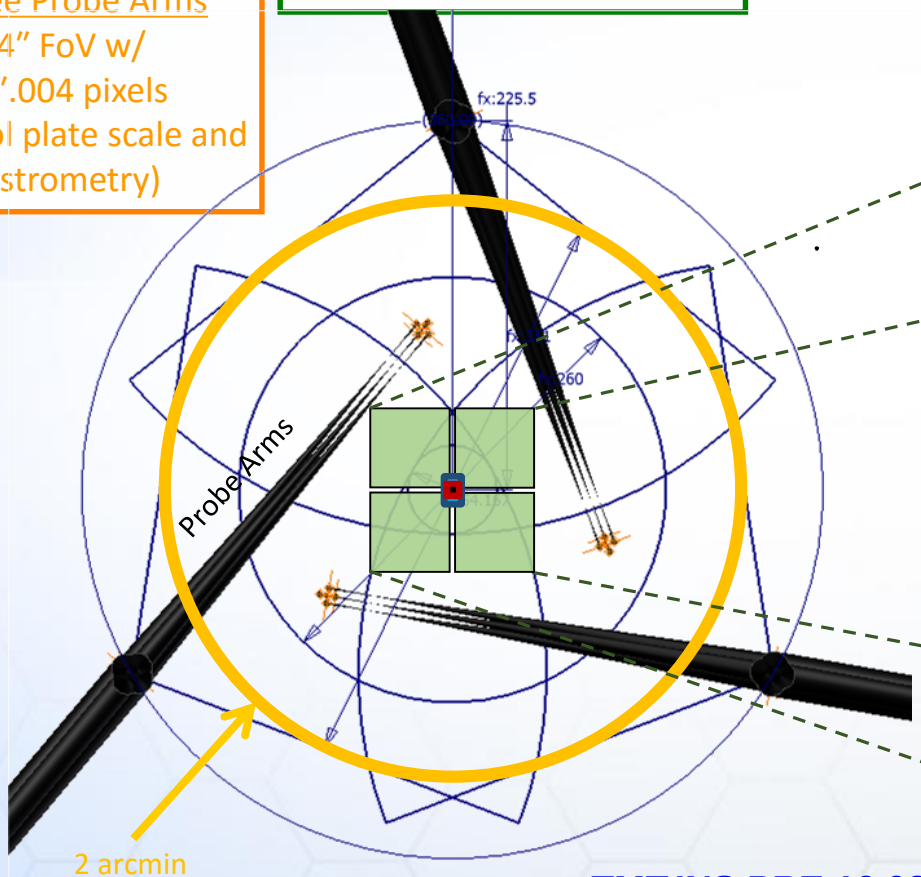
Imager
16″.4 × 16″.4 field (on-axis)
w/ 0″.004 pixels
(JHK + Narrow-bands)

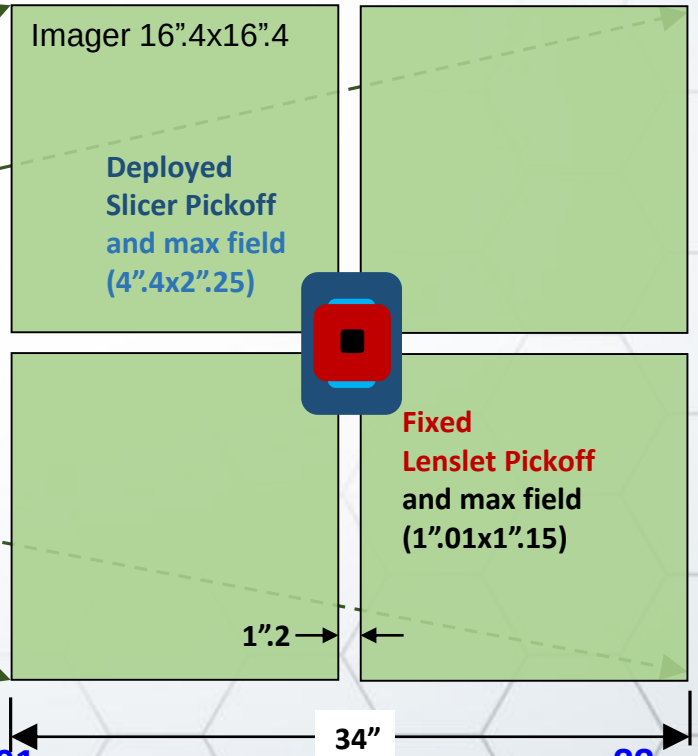
Lenslet and Slicer IFUs
0.84 -2.4µm, R = 4000-8000

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

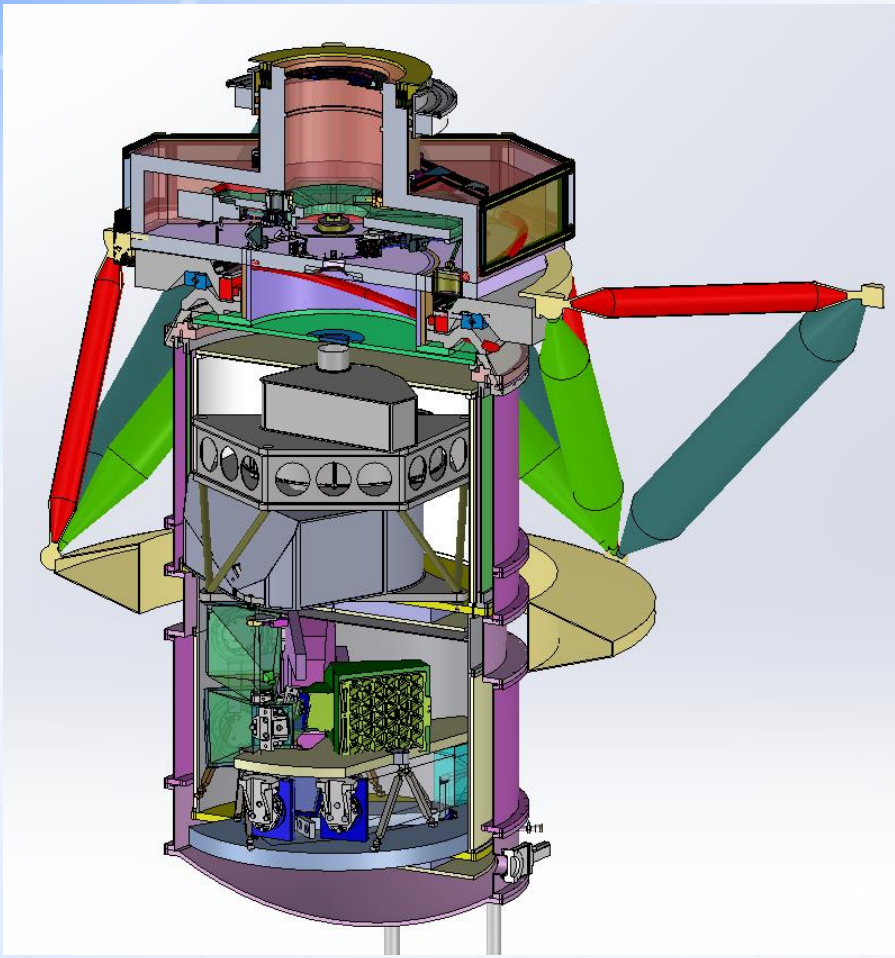
2 Fine Scales (Lenslet)
0″.45 × 0″.51@0″.004
1″.01 × 1″.15@0″.009

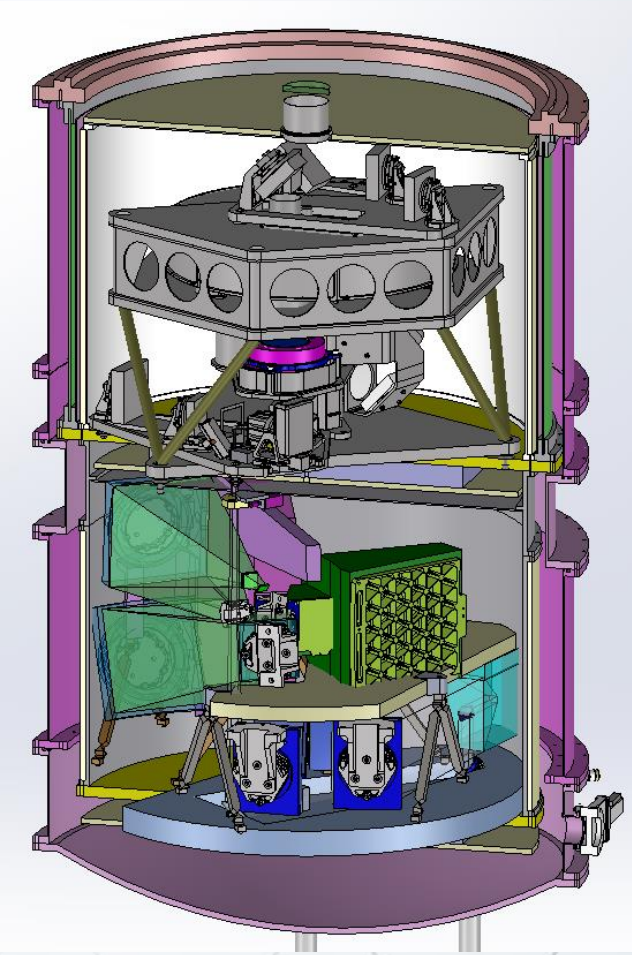
Three Probe Arms
4″ FoV w/
0″.004 pixels
(control plate scale and astrometry)



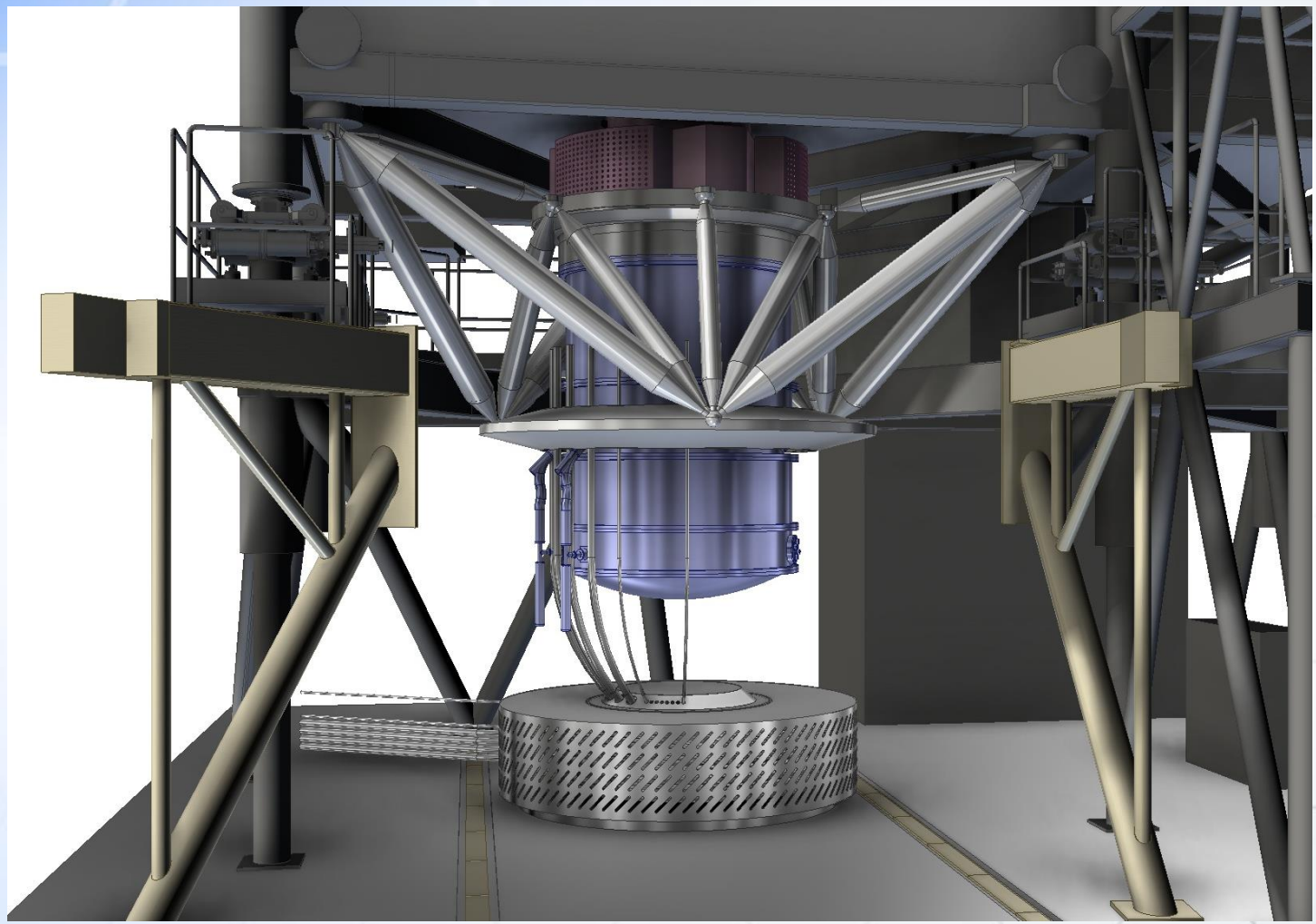



# IRIS Science Dewar



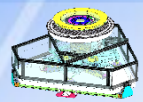


# Standing Next to IRIS on Nasmyth Platform

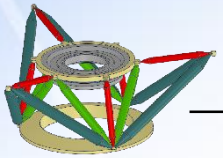


# Integrating IRIS

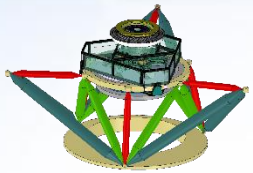
WFS Camera Assemblies



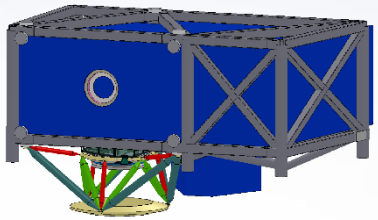
OIWFS Assembly



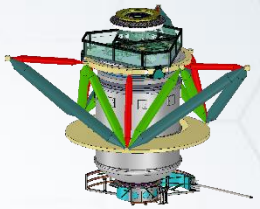
Interface Structure and Rotator Assembly



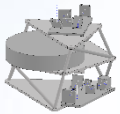
OIWFS+ Assembly NRC-H



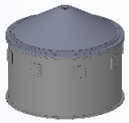
NFIRAOS / OIWFS+ Integration NRC-H



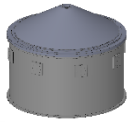
Imager Detectors



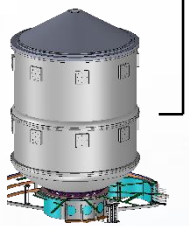
Imager Assembly



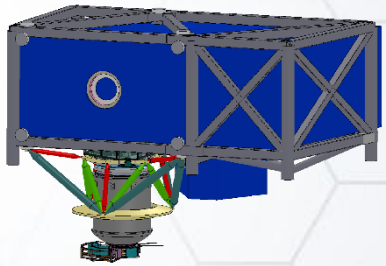
Imager Dewar (with stand in cap, bottom)



Imager Assembly NAOJ



Science Dewar Assembly CIT

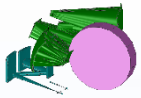


NFIRAOS / IRIS Integration NRC-H

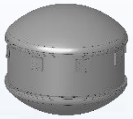
Spectrograph Detector

Lenslet Spectrograph

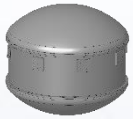
Slicer Spectrograph



Spectrograph Assembly



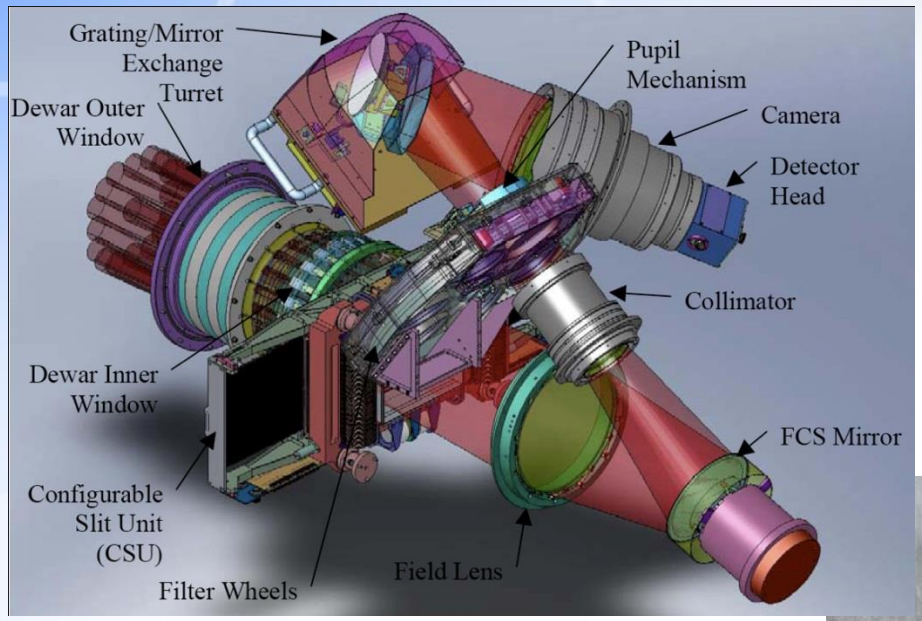
Spectrograph Dewar (with stand in cap)



Spectrograph Assembly

IRIS AIV

# InfraRed Multi-slit Spectrometer (IRMS)




TMT/IRMS

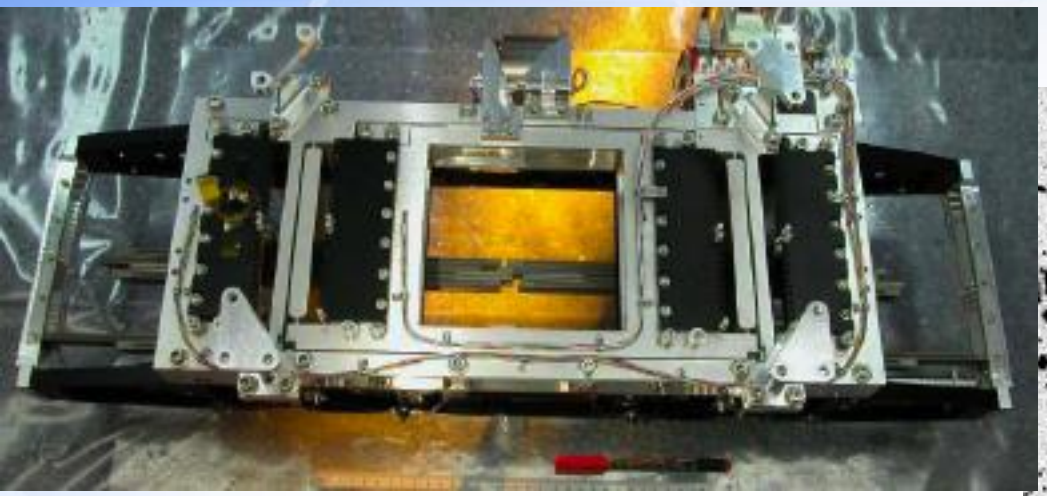
~

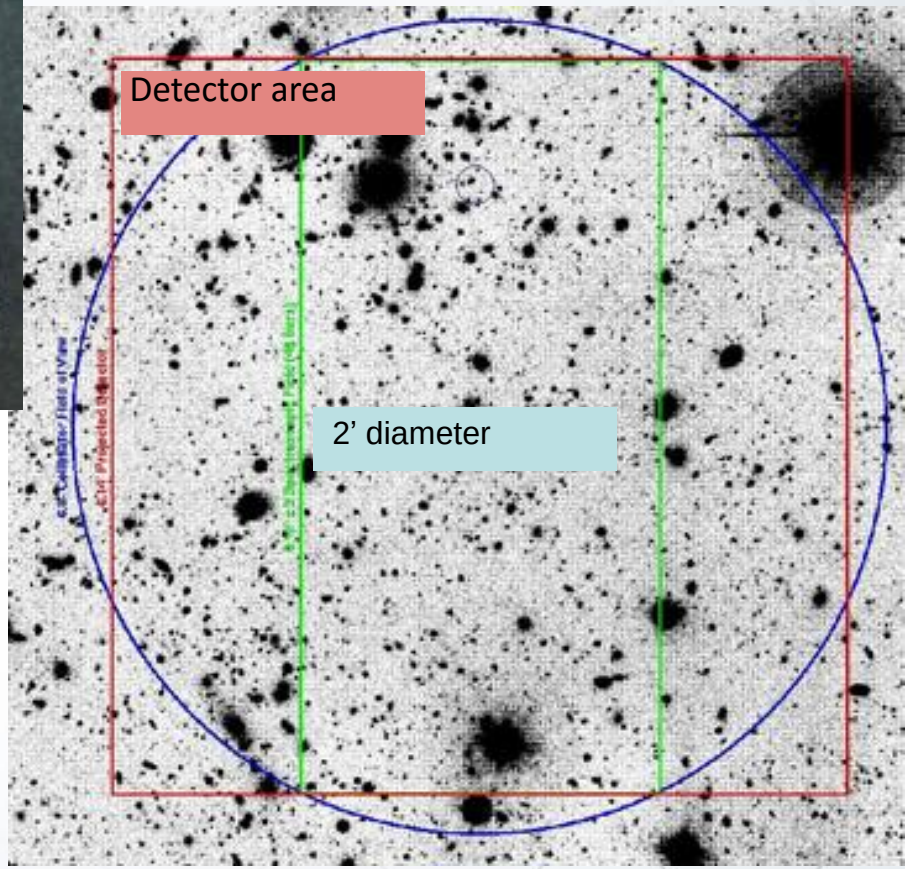
Keck/MOSFIRE

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

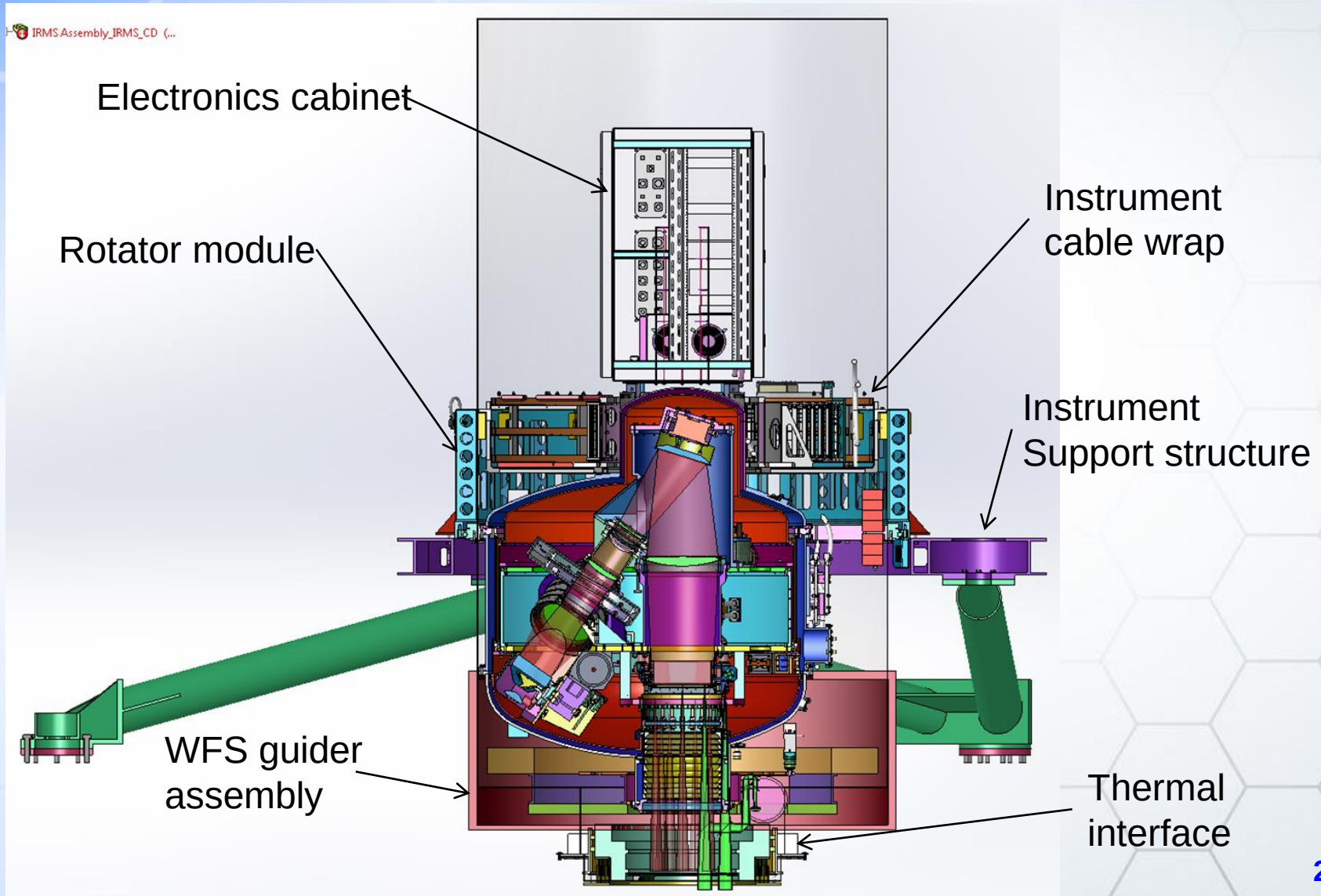





CSEM Configurable Slit Unit:

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

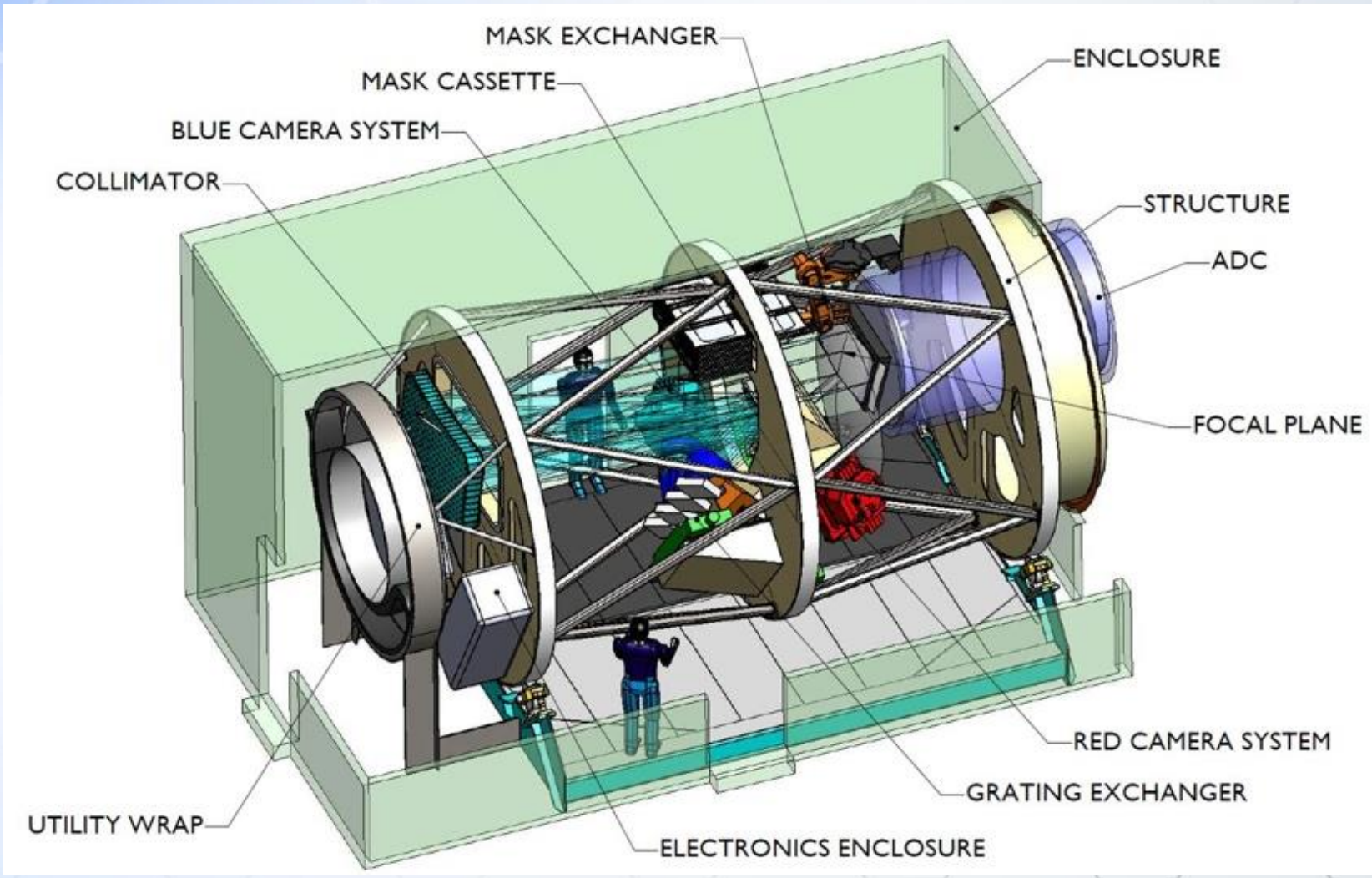
# IRMS Main Subsystems



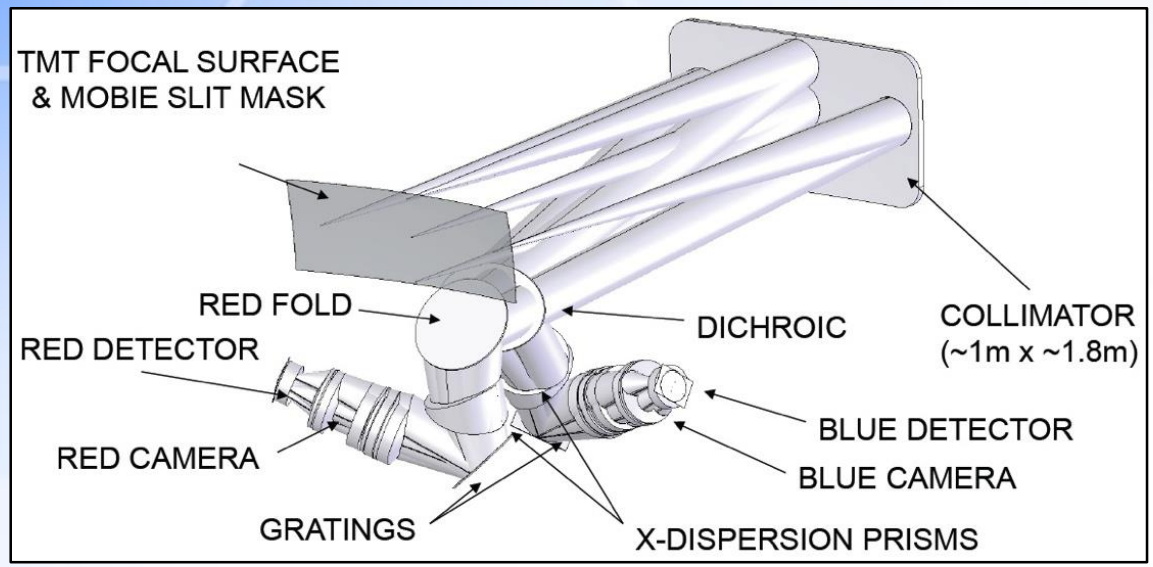
# IRMS: Next Steps

- Three mini-studies are under discussion:
  - Performance modelling including:
    - Benefits of AO
    - IRMS on an existing 8-10m telescope
  - Fabrication and Assembly Demonstration
  - OIWFS Subsystem Design
- Though similar to the WFOS mini-studies, work scope will be considerably smaller but more focussed
- **One of the main goals will be to form a team**
- Design effort to go from MOSFIRE to IRMS will take into account recent technological developments wherever appropriate and relevant

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



# WFOS Echellette Design: Survey and Diagnostic Spectroscopy




*Bigelow et al. 2010, SPIE 2010*

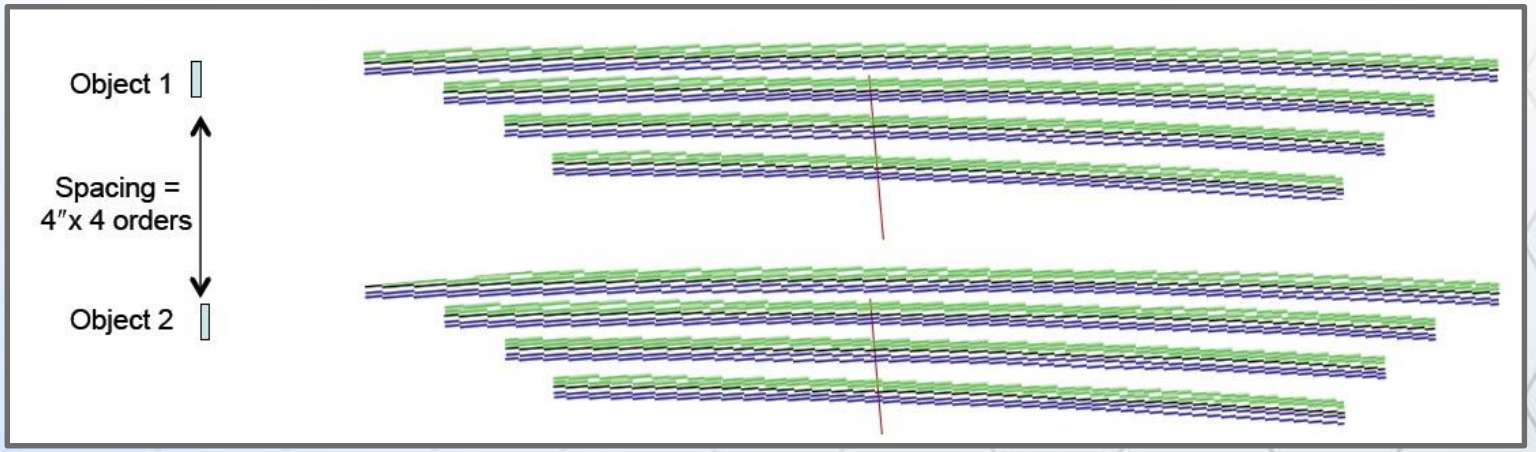
*0.31μm - 1.1μm (Blue sensitive)*

*40.3 arcmin$^2$ FoV*

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

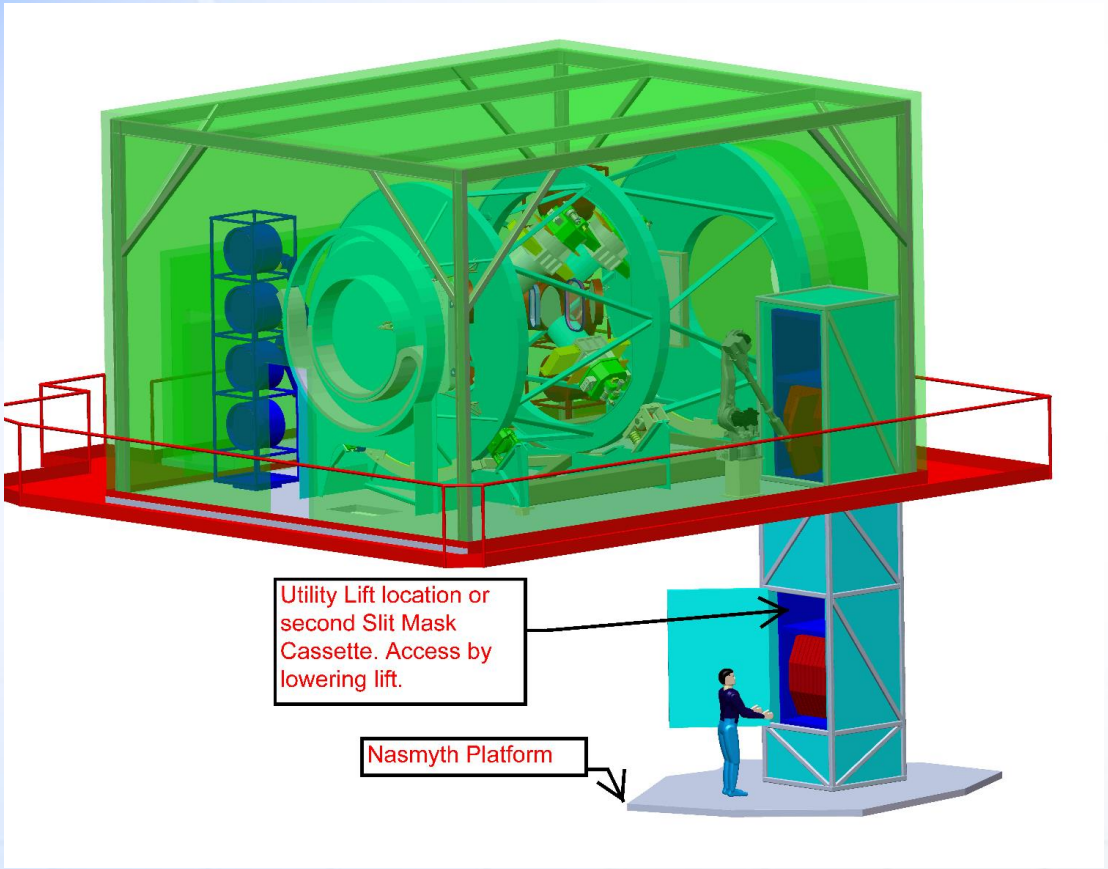
*R = 1000 - 8000 (for 0".75 slit)*

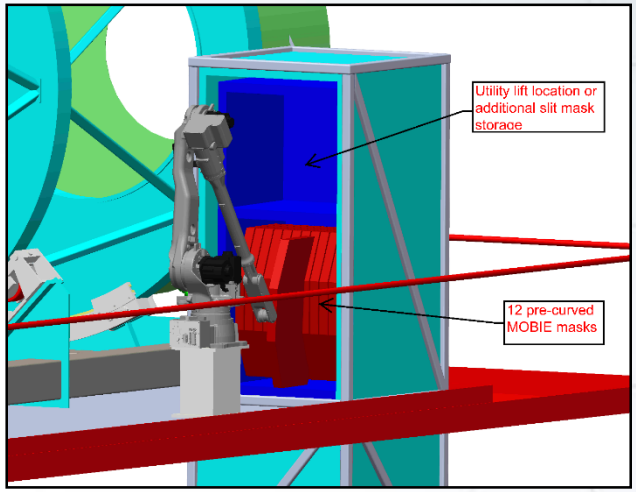
*WFOS can trade multiplexing for expanded wavelength coverage in its higher dispersion mode*



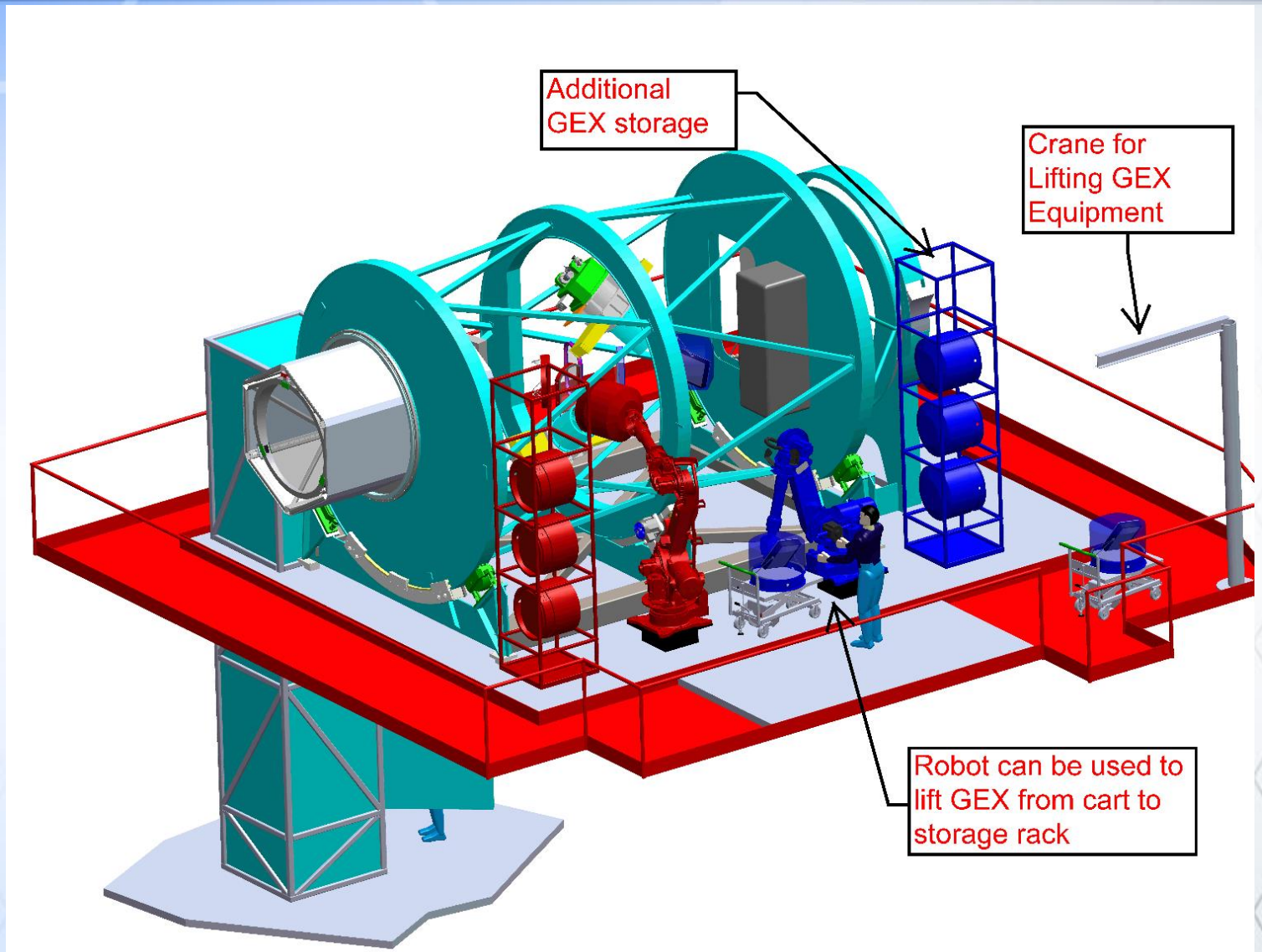
# WFOS Mini-Studies Final Review
# NAOC, Beijing, April 2015


# Exchanging WFOS Slitmasks with Assembly-line Robots



# Configuring WFOS Gratings with Assembly-line Robots



# WFOS Project Staff Updates

- Principal Investigator (PI):
  - Offer made (and accepted!) to Kevin Bundy (now at IPMU, Tokyo; Manga Survey PI; Galaxy formation and evolution)
- Project Manager (PM):
  - Short-list was made and face-to-face interviews were conducted
  - Offer will be made very soon to an excellent candidate
- Lead Optical Designer:
  - Will be hired once PM and PI are in place

# WFOS Opto-Mechanical Design and Requirements (OMDR) Phase

- One-year effort to be completed in January 2017
- Outcome will inform next steps for WFOS

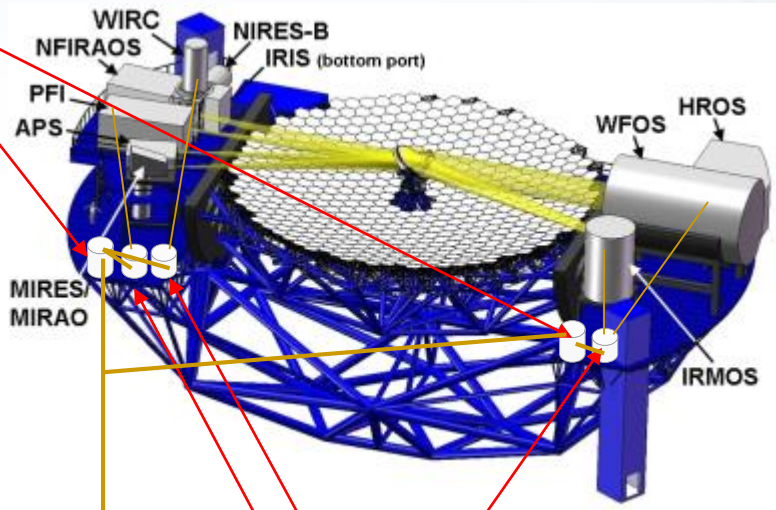
- Areas of investigation:
  - End-to-end optical design (UCO)
  - Distortion mapping and flexure modelling (IIA)
  - Instrument and support structures (UCO)
  - Flexure compensation system (UCO)
  - Telescope Baffling and Stray Light (TMT)
  - ADC and pupil wander (UCO/TMT)
  - Refractive camera design and cost estimating (NAOJ)
  - Alternate camera concepts (CIT/NAOJ)
  - Collimator design and performance optimization (NIAOT)
- Some initial findings:
  - Distortions are reduced by up to 3-5x through “50/50” optical design configurations
  - Boundaries in large CaF2 poly-crystals do not significantly affect image quality

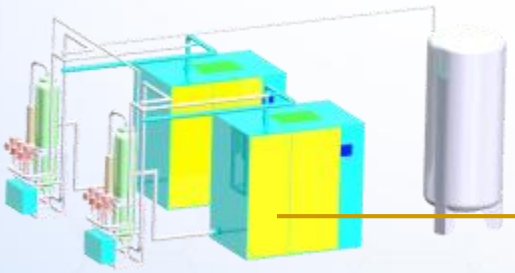
# Facility Instrument Cryogenic Cooling System (TIPC, Beijing)

Conceptual Design Review held in November 2015

Turbo-cooler Cold Box

Instruments working at low temperature



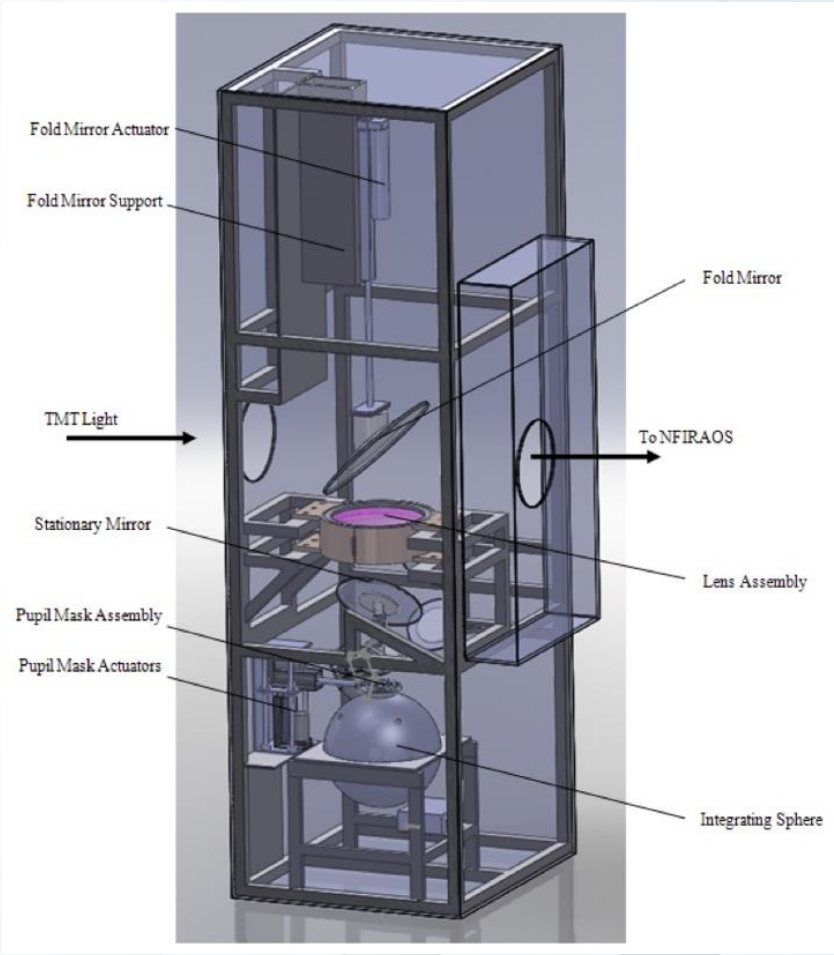



Compressor with ORS and GMP

Cryogenic Valve Box

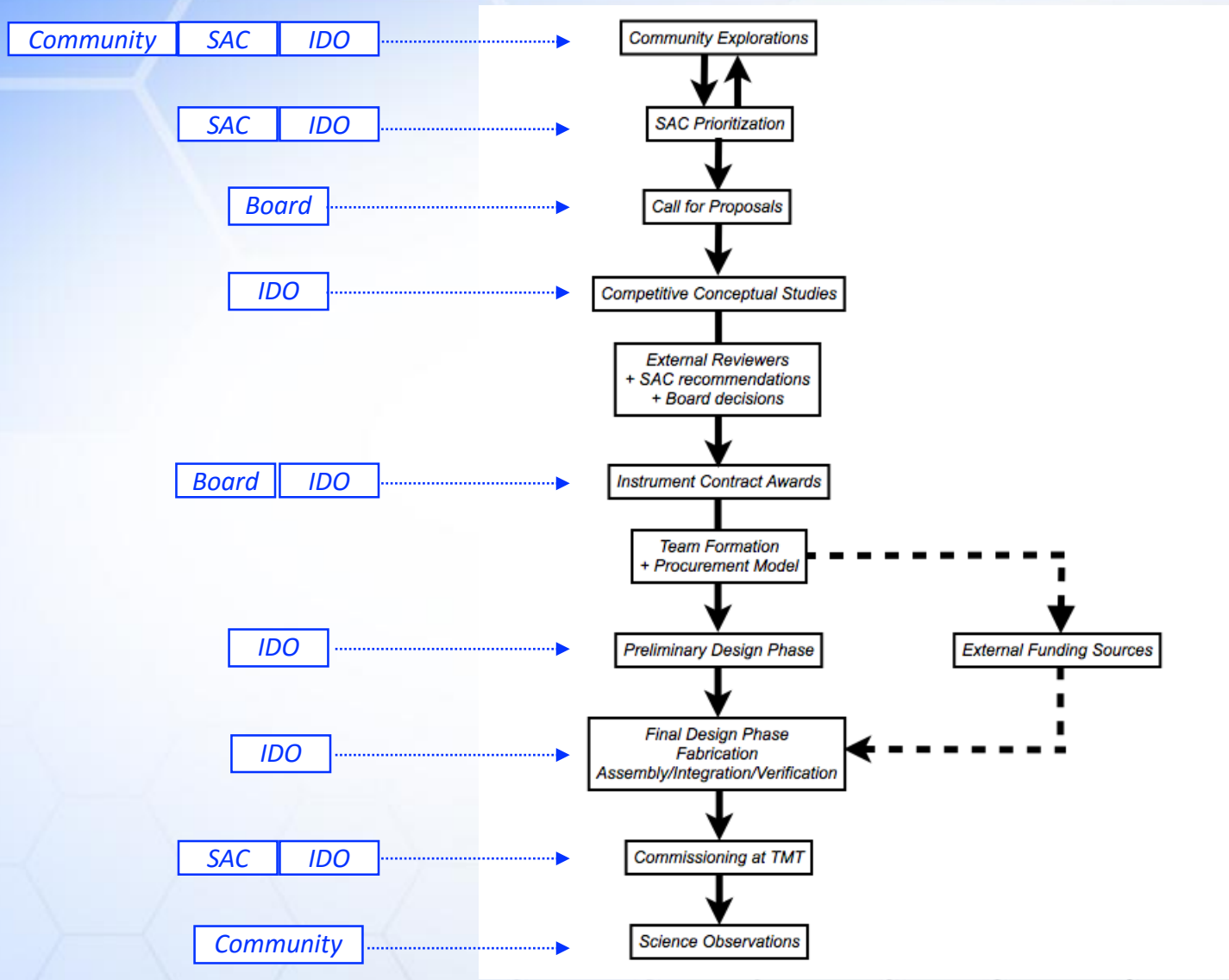
# NFIRAOS Science Calibration Unit (NCSU)

- 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

# Steps Towards Future Instruments



# 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 | | WIRC | MICADO |

# An (Updated) ELT Instrumentation "Equivalence Table"

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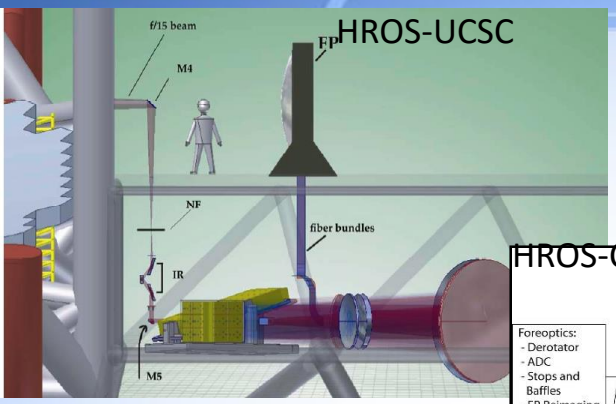
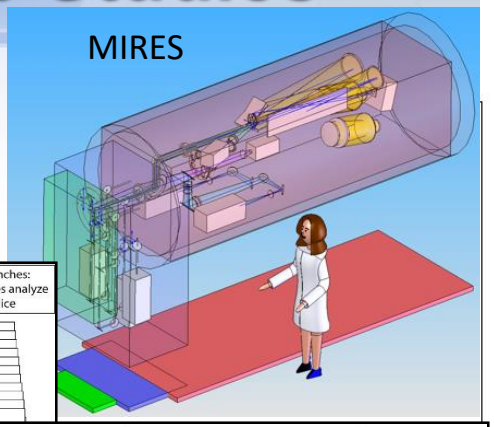
| Mid-IR, AO-assisted Echelle Spectrometer | | | |
| High-Contrast Exoplanet Imager | TIGER | PFI | ELT-PCS |
| Near-IR, AO-assisted Echelle Spectrometer | GMTNIRS | NIRES | HIRES |
| High-Resolution Optical Spectrometer | G-CLEF | HROS | HIRES |
| "Wide"-Field AO-assisted Imager | | WIRC | MICADO |

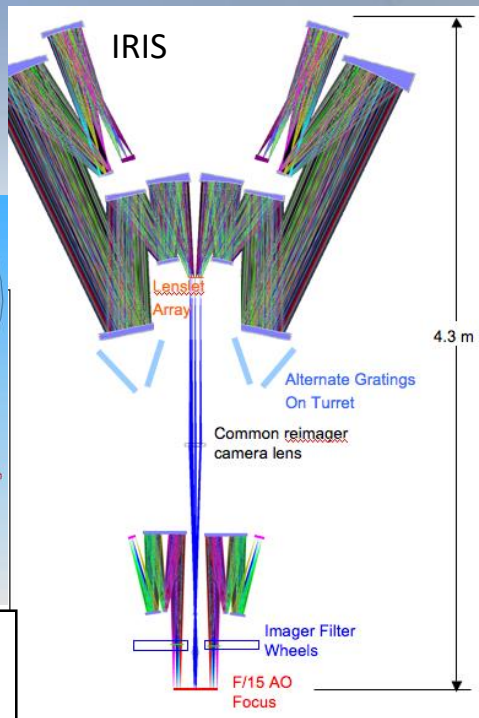
MOSAIC and HIRES both entered Phase A in March 2016

# A Powerful Development Model – 2005/6 Studies

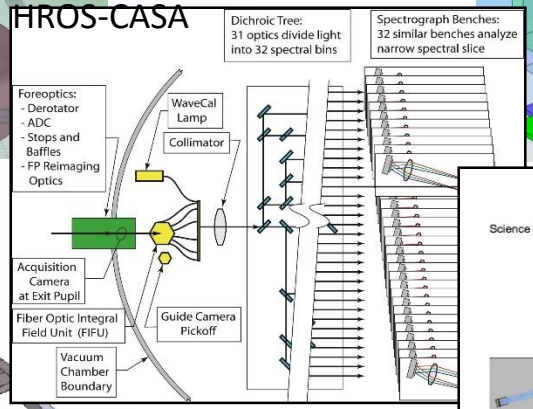


HROS-UCSC

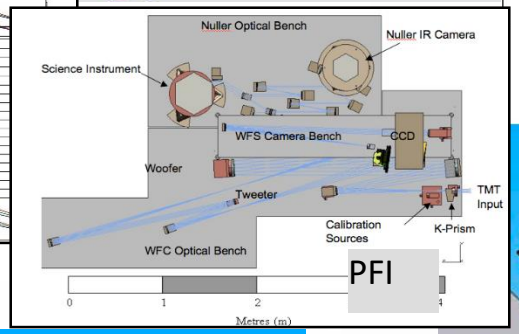

MIRES



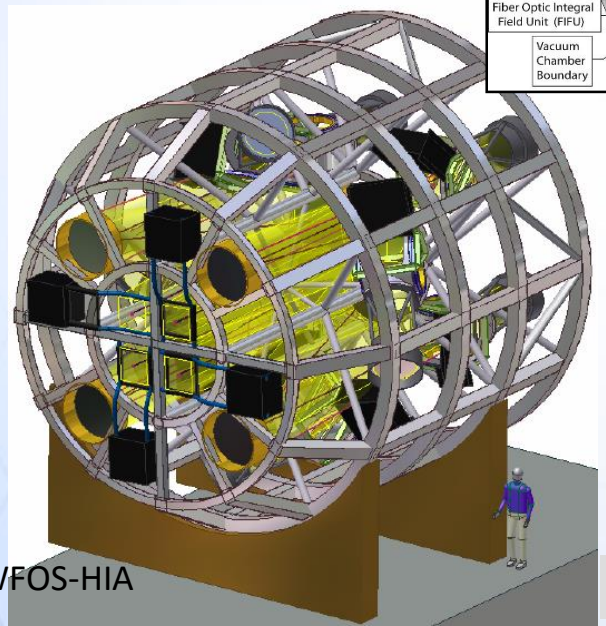
IRIS

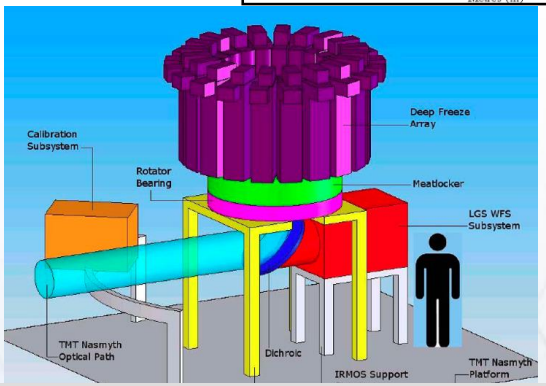


HROS-CASA

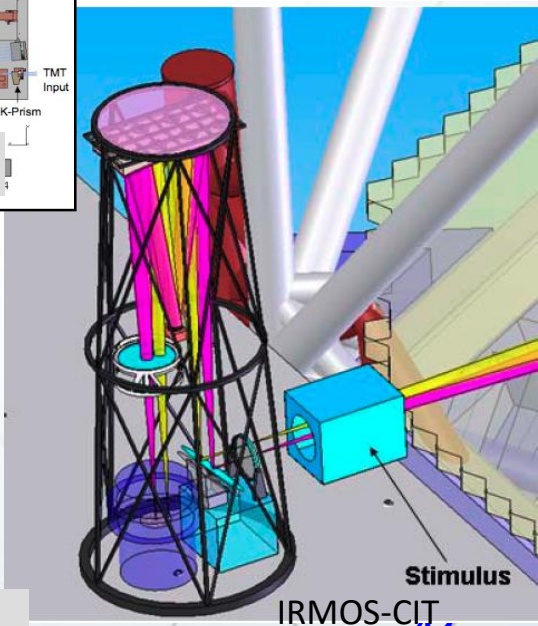


PFI


WFOS-HIA

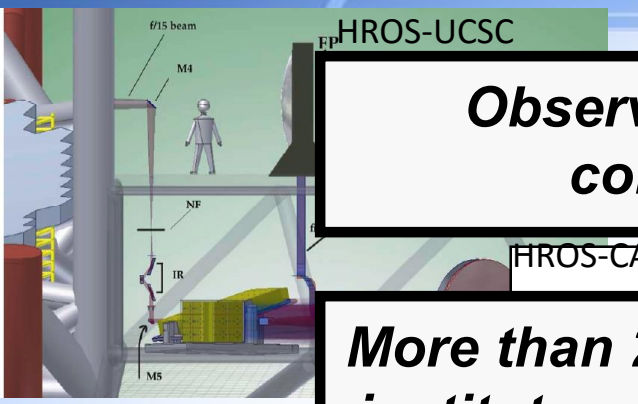


IRMOS-UF



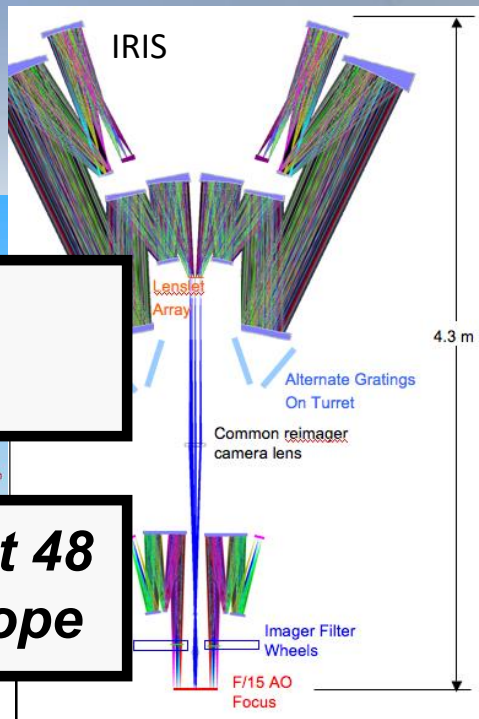
IRMOS-CIT

# A Powerful Development Model – 2005/6 Studies

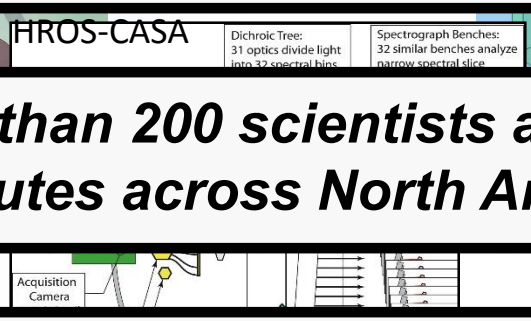



HROS-UCSC

MIRES




HROS-CASA

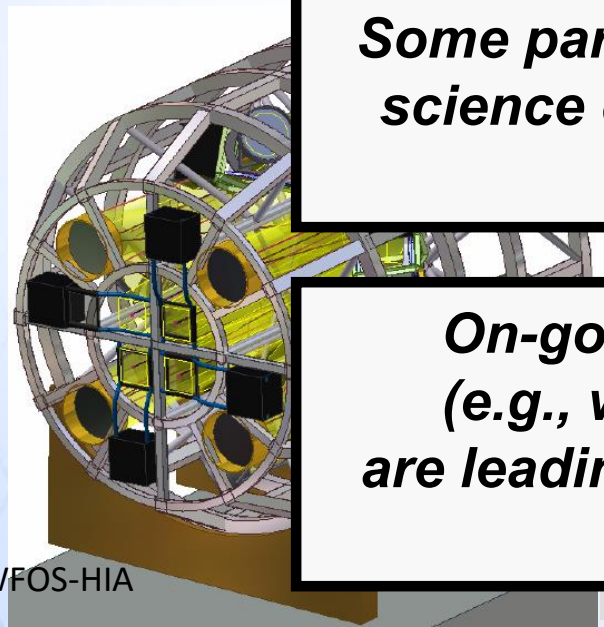



***Observing programs, requirements, concepts, performance, etc.***

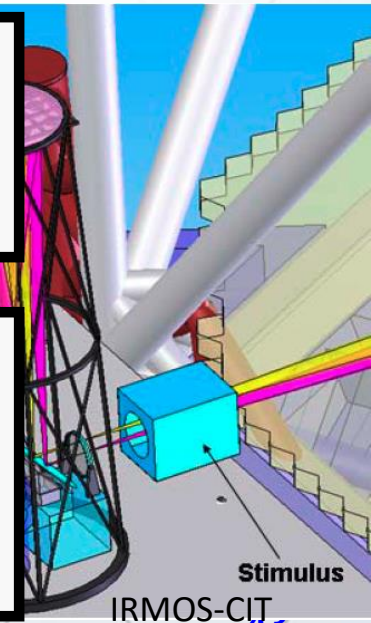
***More than 200 scientists and engineers at 48 institutes across North America and Europe***

***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)***



WFOS-HIA




IRMOS-CIT

# Future Instruments: Feasibility Studies?

- Feasibility studies for future instruments: Why now?
  - **Very** strong interest across partnership
  - Updated and/or new instrument 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**
- A possible plan:
  - ~3-4 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 2017Q1 (see proposed timeline)

# Future Instruments Studies: A Proposed Timeline

| Step | Description | Timelines | | |
|---|---|---|---|---|
| | | First-light Instruments | 2nd Gen Instruments Proposed New Timeline | 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:<br>° Expanded science cases and operational concepts<br>° Instrument designs and their technical readiness<br>° 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) |

# Science Instrument Status

- IRIS: Preliminary Design Phase started in April 2013 and scheduled for completion in November 2016
- WFOS:
  - Conceptual Design Handover Workshop held in October 2013
  - A 1-year “mini-study” phase with participants from 15 institutes across the TMT partnership was completed in April 2015
  - An “Opto-Mechanical Design and Requirements” (OMDR) phase was initiated in January 2016 and is scheduled for completion in January 2017
- IRMS:
  - A 2013 mini-study showed IRMS to be a viable option for TMT+NFIRAOS
  - Mini-studies are under discussion
- Future instruments: Call for Feasibility Study proposals in early 2017 under discussion

# Acknowledgments


- The TMT Project gratefully acknowledges the support of the TMT collaborating institutions. They are
  - The Association of Canadian Universities for Research in Astronomy (ACURA),
  - the California Institute of Technology,
  - the University of California,
  - the National Astronomical Observatory of Japan,
  - the National Astronomical Observatories of China and their consortium partners,
  - and the Department of Science and Technology of India and their supported institutes.

- This work was supported as well by
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  - the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the National Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund,
  - the Association of Universities for Research in Astronomy (AURA), the U.S. National Science Foundation
  - and the National Institutes of Natural Sciences of Japan.