THIRTY METER TELESCOPE

The Thirty Meter Telescope

Edward C. Stone

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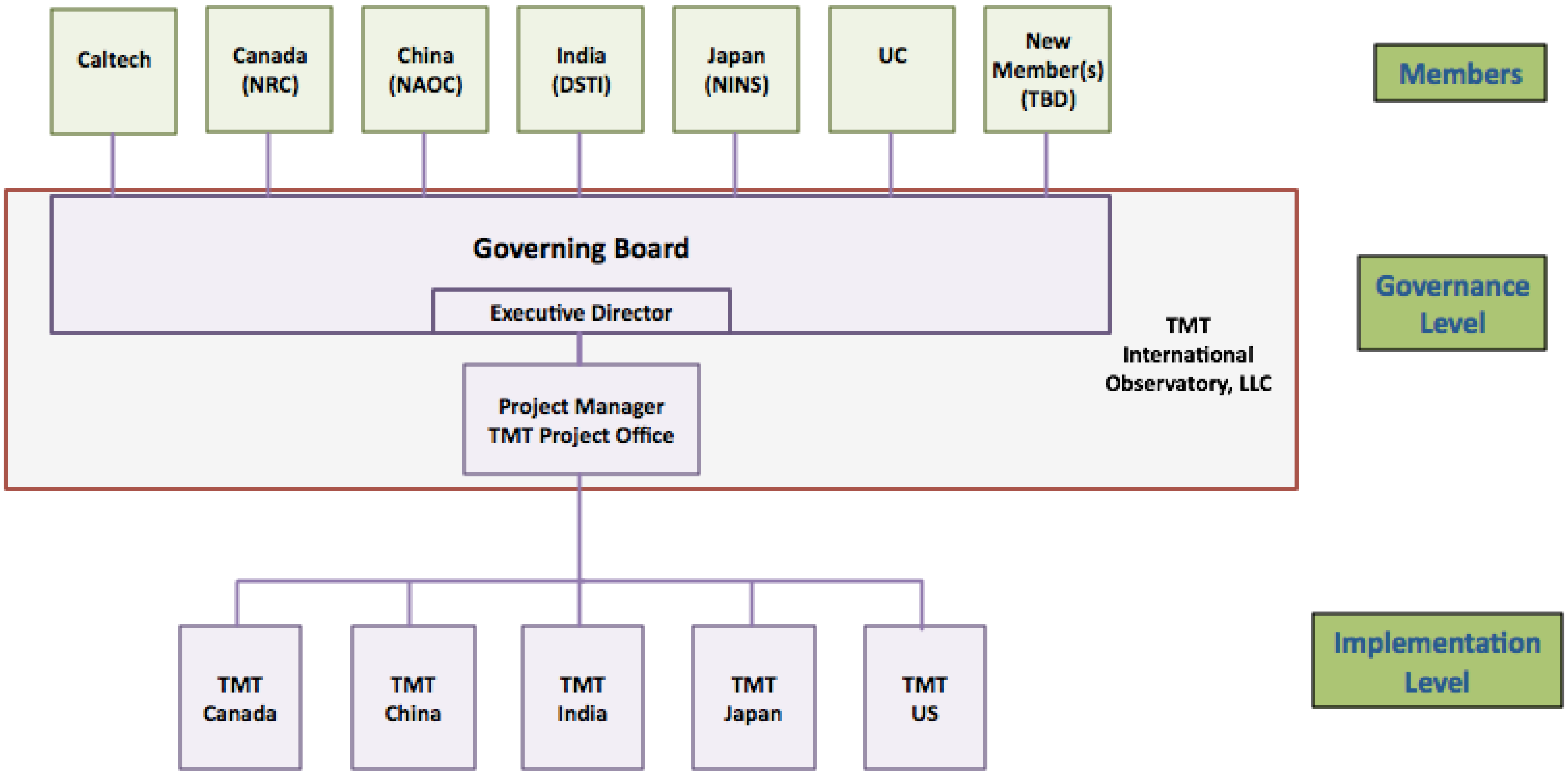
Quick History of TMT

- Project formed in 2004 (AURA, ACURA, Caltech, UC)
- Site studies 2004 → 2008 (Chile, Mexico, Hawaii)
- Mauna Kea, Hawaii selected as site in 2009
- Preconstruction phase initiated in 2009
- Partnership now includes Caltech, Canada China, India, Japan, UC, with major support by the Moore Foundation
- NSF selected TMT in 2013 for study of possible participation in the TMT project
- In May 2014, TMT International Observatory, LLC, was formed and the TMT Construction Phase started
- Onsite construction started September 2014, but interrupted by demonstrations
- Recently Hawaii Supreme Court found procedural error that requires repeating the final step in the permitting process

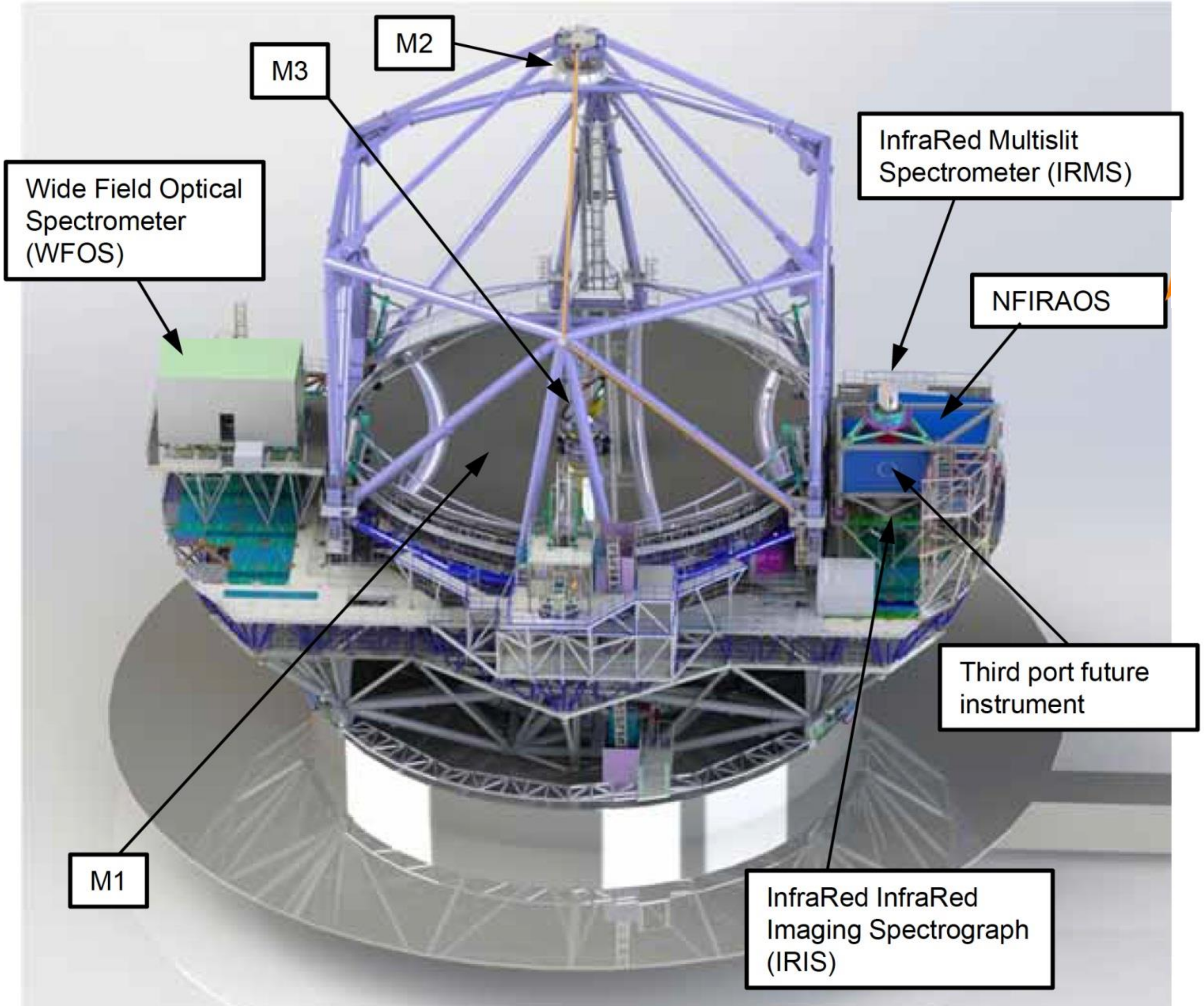
TMT International Observatory LLC (TIO)

- TIO Members
  - California Institute of Technology
  - Canada, National Research Council
  - China, Chinese Academy of Sciences
  - India, Department of Science and Technology and Department of Atomic Energy
  - Japan, National Institutes of Natural Sciences
  - University of California
- TIO Associate
  - NOAO/AURA consistent with the NSF Cooperative Agreement
- TIO Observer
  - University of Hawaii

TMT Project Governance Structure



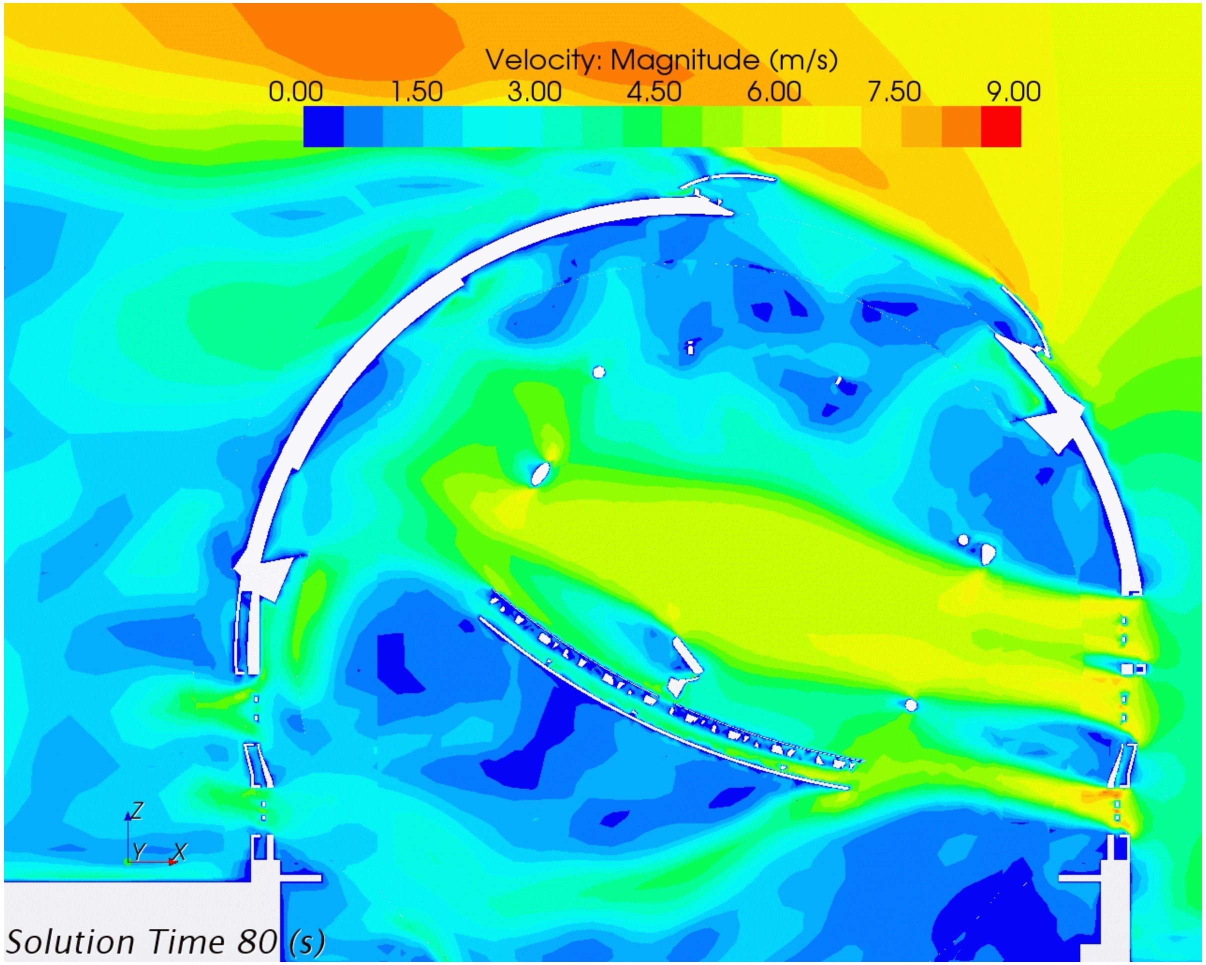
Telescope Concept Overview



- 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 Calotte Enclosure Final Design is Completed

Aero-Thermal Effects Modeled



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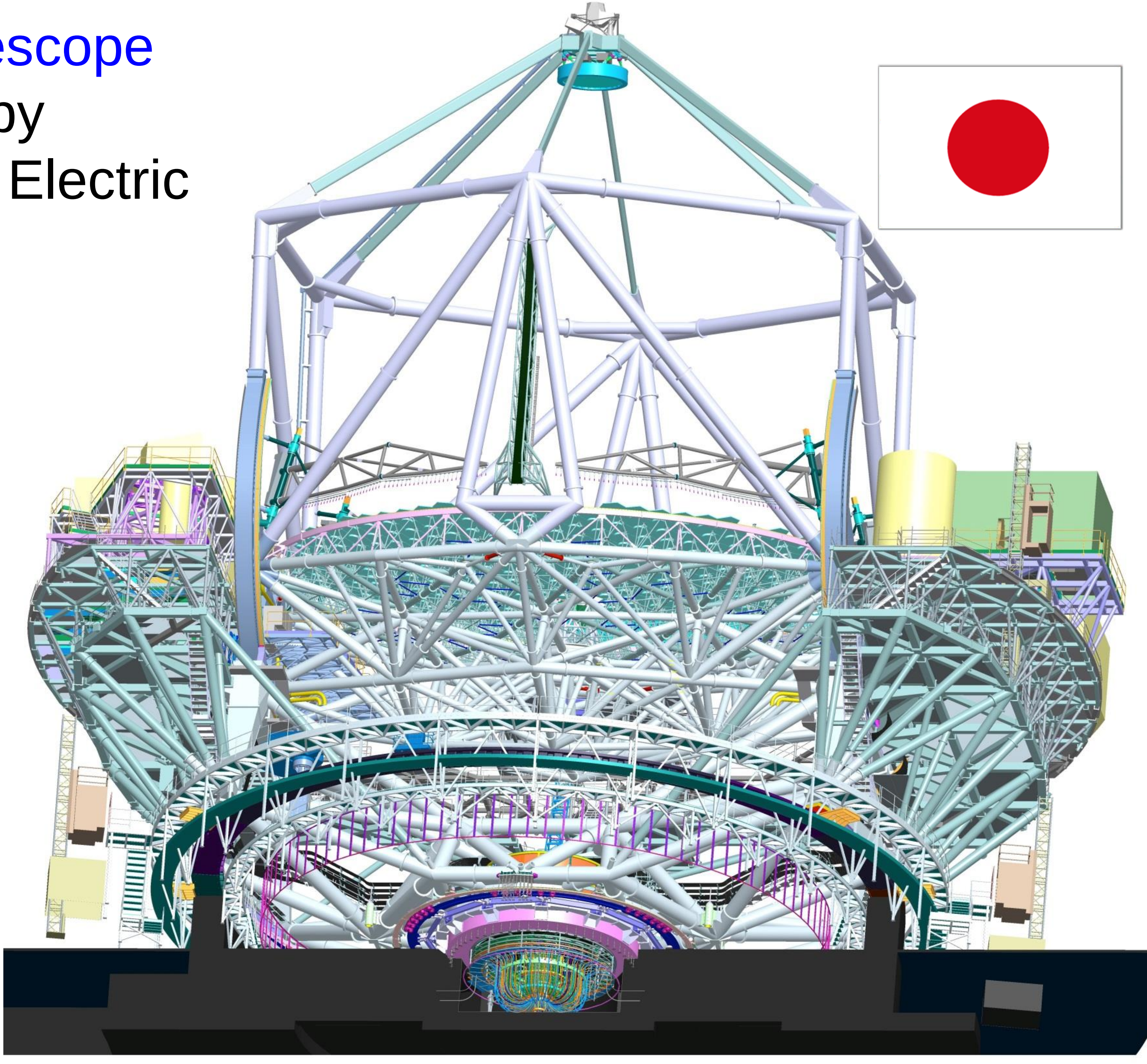
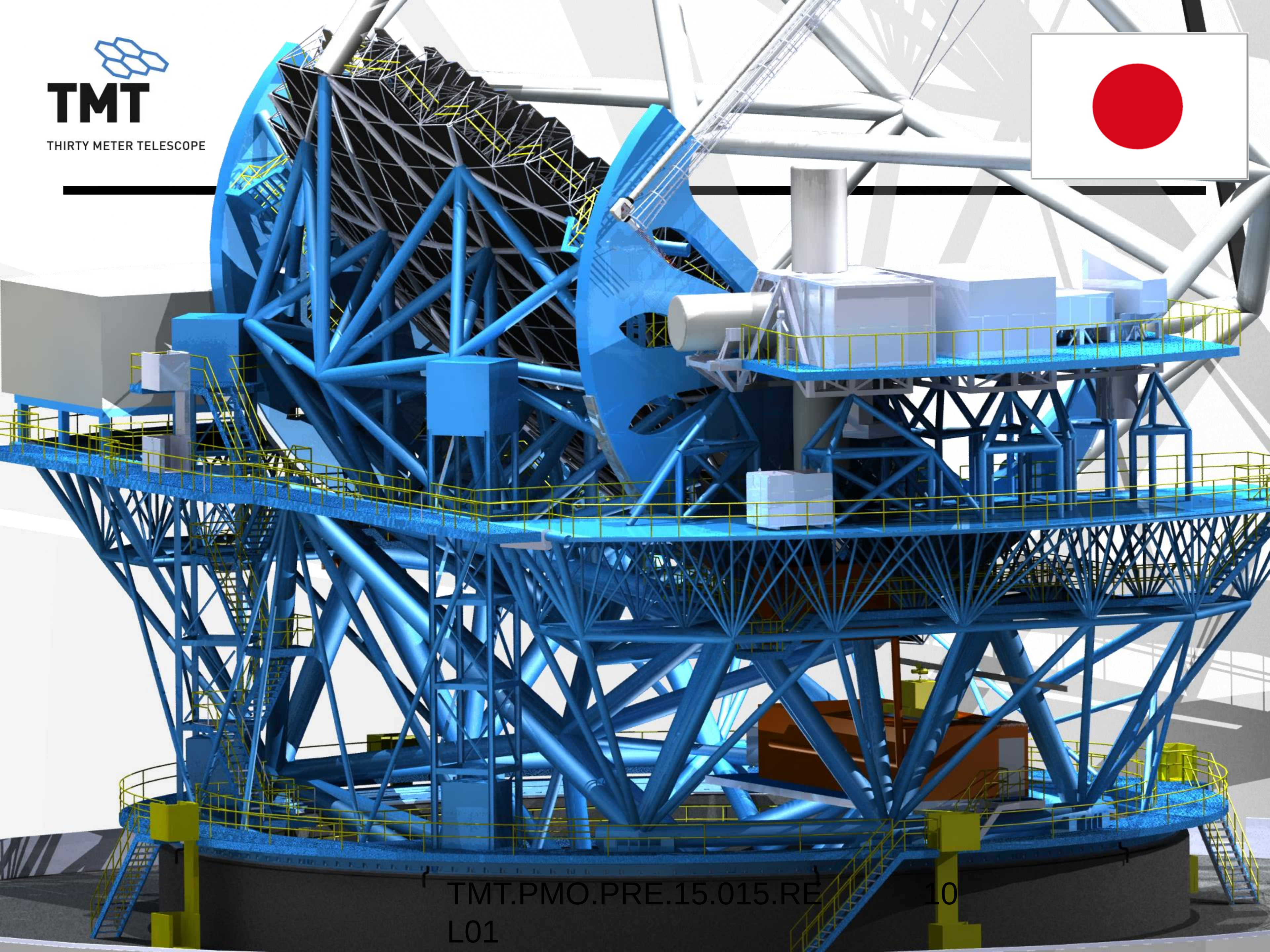
Enclosure Vent Door Prototypes

- TMT Telescope Structure by Mitsubishi Electric Company (MELCO)





TMT Telescope Structure
Main Structural Node

TMT Telescope Structure Elevation Journal Splice

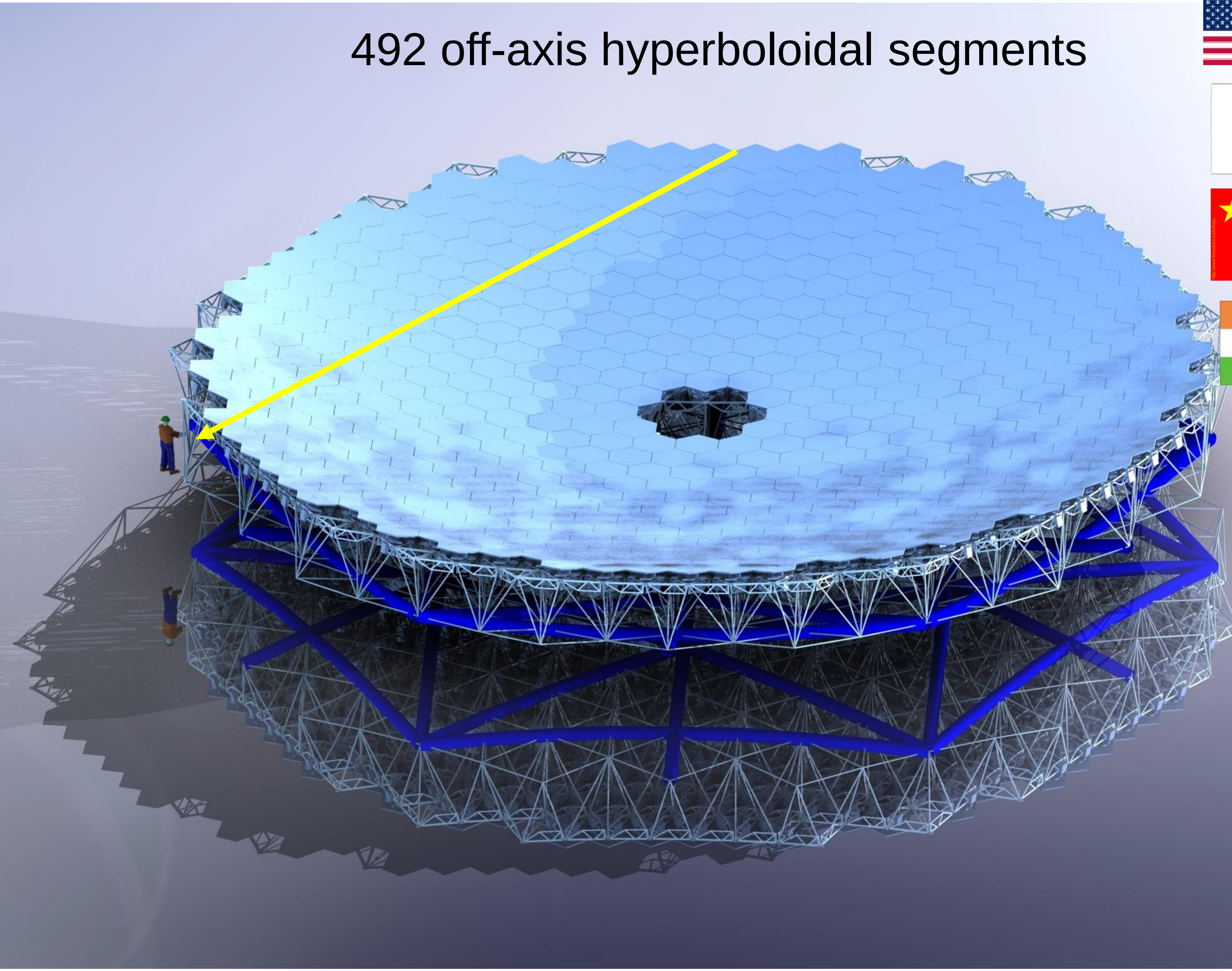
THIRTY METER TELESCOPE

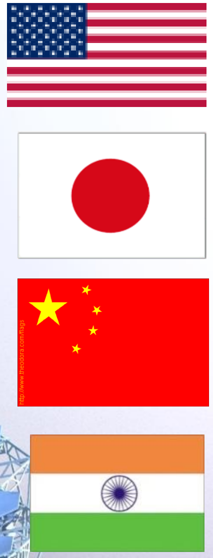
Telescope Structure: Fabrication Starting!

Elevation Journal and Lower Tube Structure

Pintle Bearing Structure

492 off-axis hyperboloidal segments





Primary Mirror (M1) Segment Blank Production

- Ohara will have produced 163 blanks by the end of March; all meet our stringent requirements

107 blanks produced by October

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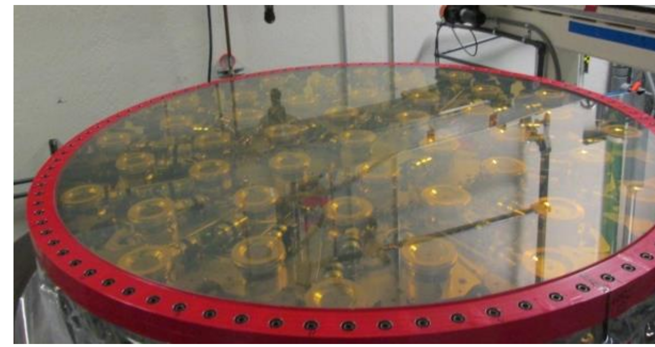
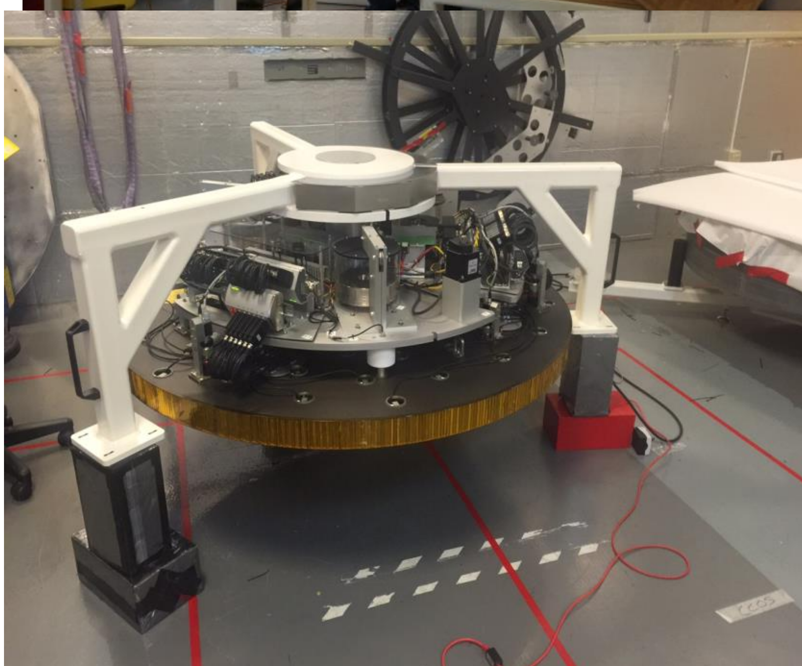
Segment Polishing - Tinsley



Stressing Fixture



Polishing the stressed segment with a spherical tool

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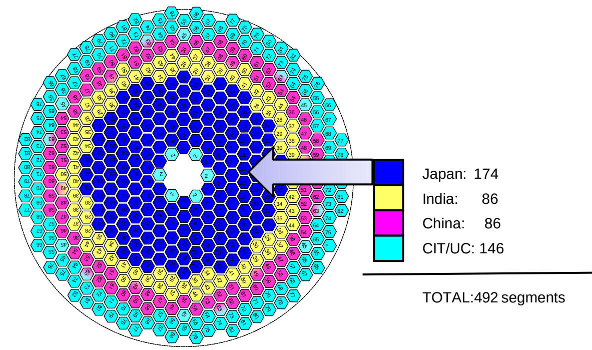
Production polishing started at Canon!

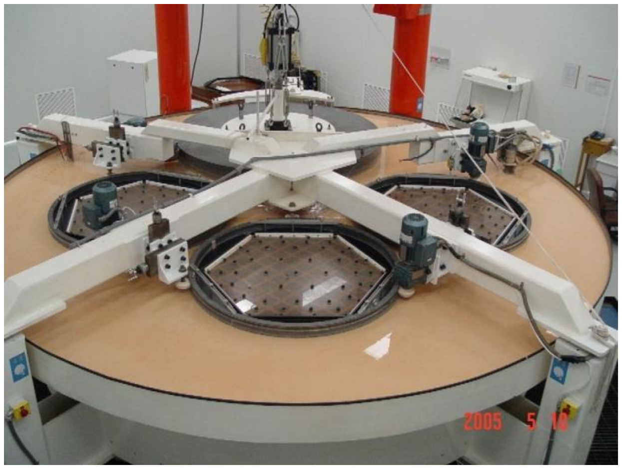
50th Blank has been backside polished!

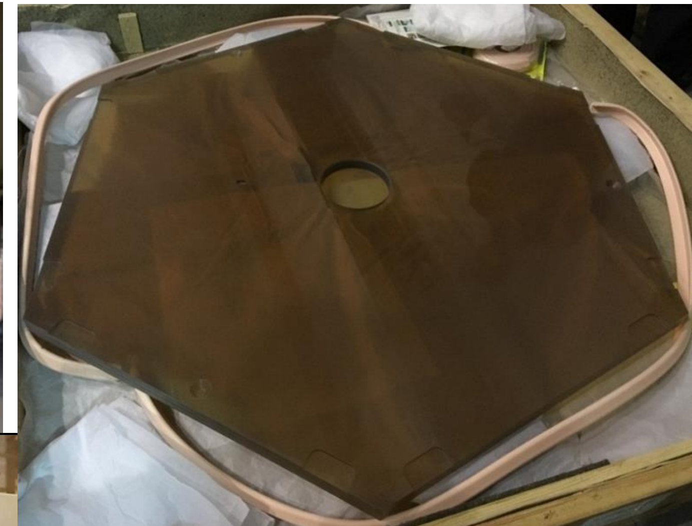


Production Tracking Board

47 Segments → in work at Canon

Nanjing: NIAOT Stressed Mirror Polishing (SMP) and Machining





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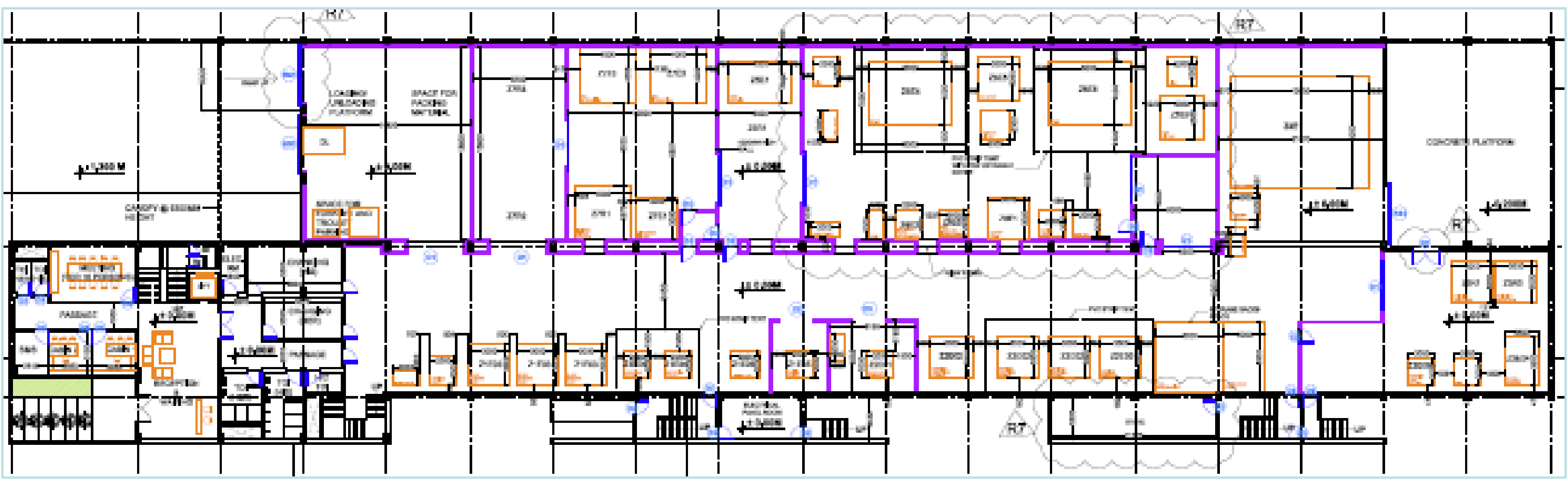
NIAOT Facilitization For Full Production M1 Polishing

India M1 Segment Polishing

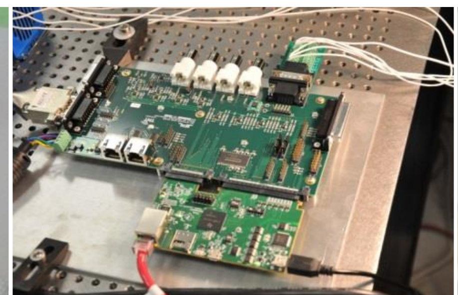
- Polishing to be done in India with Tinsley technology and equipment installed in India
- Design of polishing facility has been completed
- Groundbreaking scheduled for January 2016 with a June 2017 finish



Primary Mirror Control System
JPL, TMT-India

- Jet Propulsion Laboratory is responsible for system design
- India is responsible for production of actuators, sensors, electronics

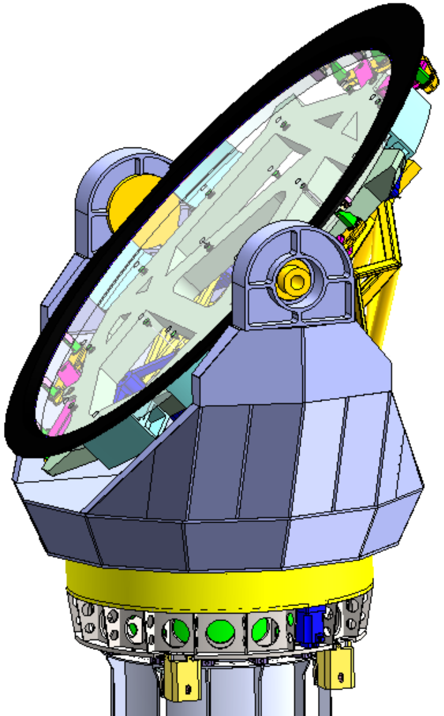
Actuator components

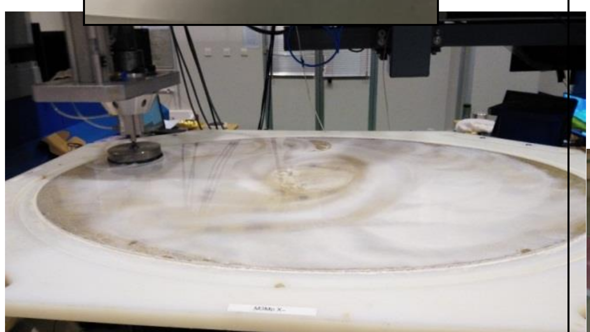


Edge sensors

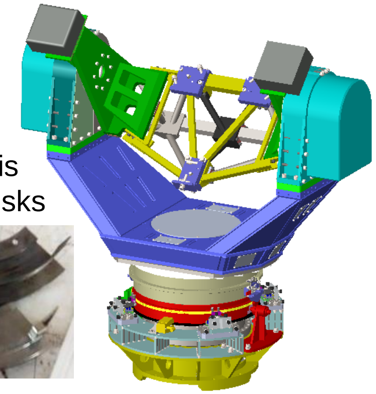
India-made Segment Support Assembly – Two Vendors

M3 System at CIOMP, Changchun
(1/4 scale functional prototype underway)





Positioner CAD model and parts



Parts for Cradle Assembly

Tilt Axis Brake Disks

Stationary Base

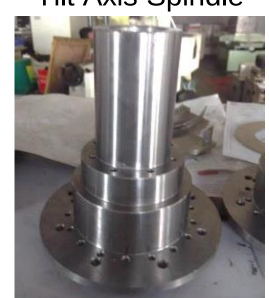
Rotator Bearing Races

Cablewrap Pinon Gears

Yoke Assembly

Stationary Middle Base

Tilt Axis Spindle



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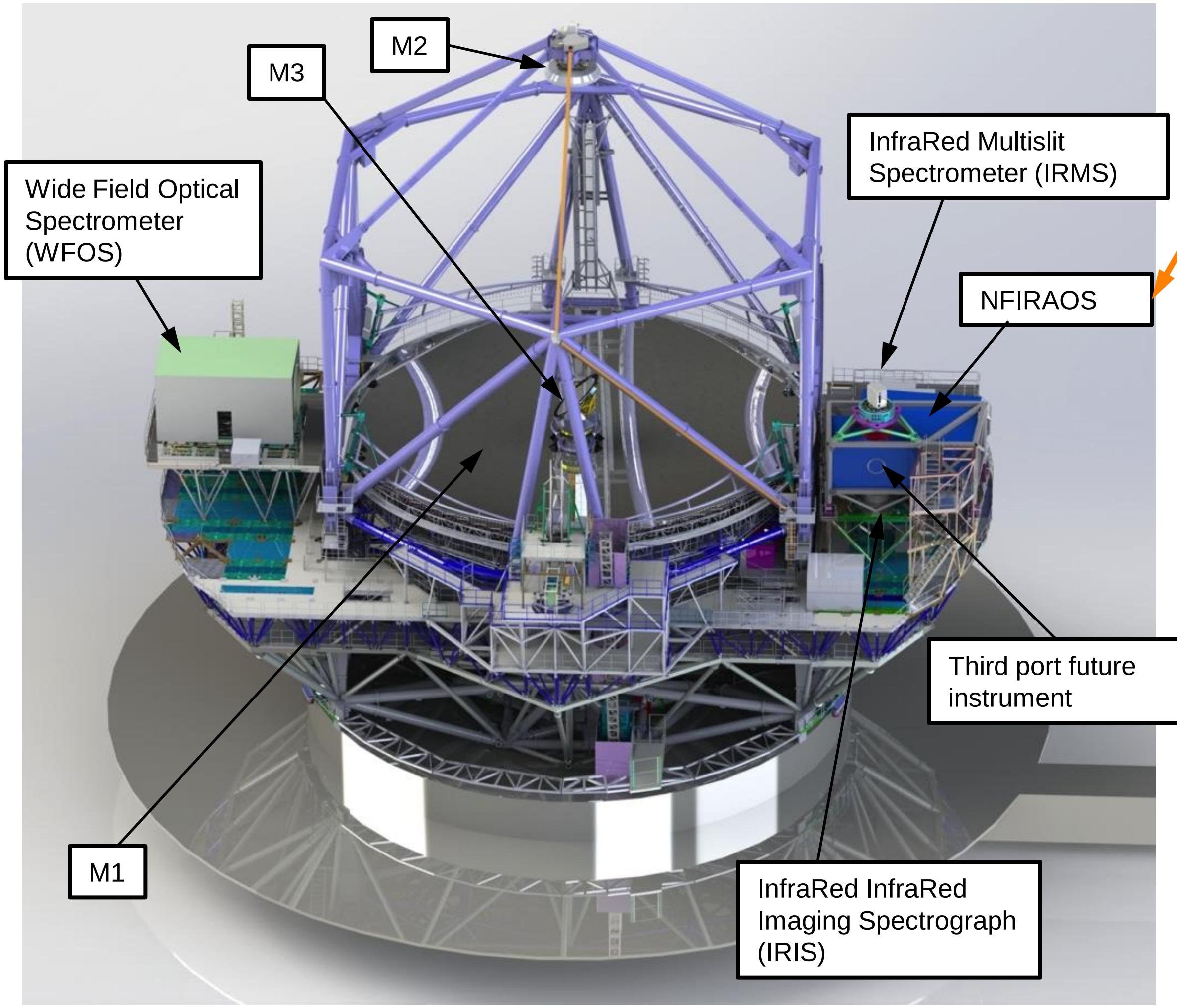
TMT First Light Instruments and First Decade Suite

Instrument	λ (μm)	Field of view/ Slit length	Spectral resolution	Science Cases
InfraRed Imager and Spectrometer (IRIS)	0.8 – 2.5 0.6 – 5 (goal)	<3″ IFU >15″imaging	> 3500 5-100 (imaging)	• Assembly of galaxies at high z • Black holes/AGNs/Galactic Center • Resolved stellar populations in crowded fields
Wide-field Optical spectrometer and imager (WFOS)	0.31 – 1.0	>40 arcmin^2 >100 arcmin^2 (goal) Slit length>500″	1000-5000@0.75″ slit >7500 @0.75″ (goal)	• IGM structure and composition at 2 < z < 6 • Stellar populations, chemistry and energetics of z > 1.5 galaxies
InfraRed Multislit Spectrometer (IRMS)	0.95 – 2.45	2 arcmin field, up to 120″ total slit length with 46 deployable slits	R=4660 @ 0.16 arcsec slit	• Early Light • Epoch of peak galaxy building • JWST follow-ups
Deployable, multi-IFU, near-IR spectrometer (IRMOS)	0.8 – 2.5	3″ IFUs over >5′ diameter field	2000-10000	• Early Light • Epoch of peak galaxy building • JWST follow-ups
Mid-IR AO-fed Echelle spectrometer (MIRES)	8 – 18 4.5 – 28 (goal)	3″ slit length 10″ imaging	5000-100000	• Origin of stellar masses • Accretion and outflows around protostars • Evolution of gas in protoplanetary disks
Planet Formation Instrument (PFI)	1 – 2.5 1 – 5 (goal)	1″ outer working angle, 0″.05 inner working angle	R≤100	• 10^8 contrast ratio (10^9 goal) • Direct detection and spectroscopic characterization of exoplanets
Near-IR AO-fed echelle spectrometer (NIRES)	1 - 5	2″ slit length	20000-100000	• IGM at z > 7, gamma-ray bursts • Local Group abundances • Abundances, chemistry and kinematics of stars and planet-forming disks • Doppler detection of terrestrial planets around low-mass stars
High-Resolution Optical Spectrometer (HROS)	0.31 – 1.1	5″ slit length	50000	• Doppler searches for exoplanets • Stellar abundance studies in Local Group • ISM abundance/kinematics • IGM characteristics to z~6
"Wide"-field AO imager (WIRC)	0.8 – 5.0	30″ imaging field	5-100	• Precision astrometry (e.g., Galactic Center) • Resolved stellar populations out to 10 Mpc

Table II-1: TMT Science Objectives and Capabilities and their links to the Astro2010 Decadal Survey Science. The symbol '♦' denotes first-light science.

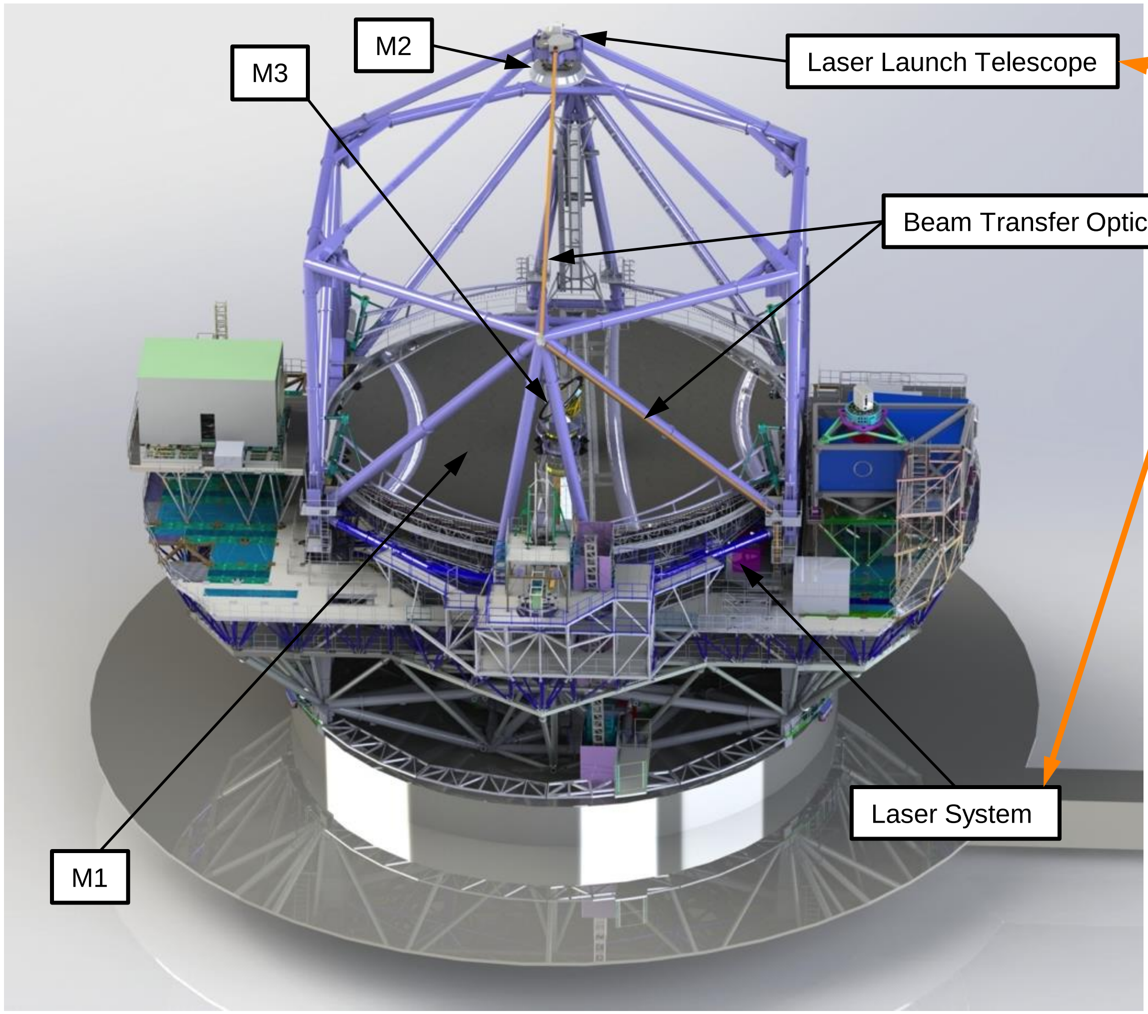
Theme	Science Objectives	Observations	Requirements	Capabilities
Cosmology and Fundamental Physics (Dark energy, dark matter, physics of extreme objects, fundamental constants; DSC Section 3)	Mapping distribution of dark matter on large and small scales (CFP-[1,2,3,4], GAN-[3,4], GCT-1) General Relativity in new mass regime♦ (GAN-[4,D], SSE-4) Very precise expansion rate of Universe (CFP-2) Mapping variations in constants over cosmological timescales Physics of extreme objects ♦ (SSE-[2,3,D])	Proper motions in dwarf galaxies Wide-field optical spectroscopy of R = 24.5 galaxies Microarcsecond astrometry Transient events lasting > 30 days High spectral resolution observations of quasars and GRBs	λ = 0.31-0.62μm, 2-2.4μm R = 1000 - 50000 Very efficient acquisition 0.05 mas astrometry stable over 10 years Field of view > 10'	SL/WFOS SL/HROS MCAO/IRIS/WIRC MCAO/ NIRES
The Early Universe (First objects, IGM at z > 7; DSC Section 4)	Detection of metal-free star formation in First Light objects♦ (GAN-2, GCT-4) Mapping topology of re-ionization (GCT-4) Structure and neutral fraction of IGM at z > 7 (CFP-1, GCT-4)	Multiplexed, spatially-resolved spectroscopy of faint objects High spectral resolution, near-IR spectroscopy	λ = 0.8 – 2.5 μm R = 3000 – 30000 F = 3 x 10-20 ergs $s^{-1}cm^{-2}Å^{-1}$ Exposure times > $15e^3$s	MCAO/ IRMS/IRIS MOAO/ IRMOS MCAO/ NIRES
Galaxy formation and the IGM (DSC Section 5)	Baryons at epoch of peak galaxy formation♦ (CFP-1, GAN-1, GCT-[1,2]) 2D Velocity, SFR, extinction & metallicity maps of galaxies at z = 5-6♦ (CFP-3, GAN-1, GCT-[1,2]) IGM properties on physical scales < 300 kpc♦ (GAN-1, GCT-2)	Optical/near-IR multiplexed diagnostic spectroscopy of distant galaxies & AGNs Optical/near-IR multiplexed identification spectroscopy of extremely faint high redshift objects (to R~27) Spatially-resolved spectroscopy	λ = 0.31 – 2.5 μm R = 3000-5000, 50000 Very efficient acquisition Multiplexing factor > 100	SL/WFOS SL/HROS MCAO/IRIS/IRMS MOAO/ IRMOS
Extragalactic supermassive black holes (DSC Section 6)	Demographics of black holes over new ranges in mass and redshift♦ (GAN-4, GCT-3) Dynamical measurements out to z = 0.4♦ (GAN-4,GCT-[1,3]) Scaling relations out to z = 2.5 and masses at z>6♦ (GAN-4, GCT-[1,3])	Spatially-resolved spectroscopy of galaxy cores	λ = 0.8 – 2.5 μm R = 3000-5000 Precise positioning	MCAO/IRIS MOAO/ IRMOS
Galactic Neighborhood (DSC Section 7)	Abundance of oldest stars in Milky Way (CFP-4, GAN-[2,3], SSE-2) Chemical evolution in Local Group galaxies♦ (GAN-2) Diffusion and mass loss in stars (GAN-1, SSE-1) Resolved stellar populations out to Virgo cluster♦ (GAN-[2,3])	High spectral resolution optical and near-IR spectroscopy High-precision photometry in crowded fields	λ = 0.33-0.9, 1.4-2.4 μm R = 4000, 40000-90000 Photometry precision of 0.03 mag at Strehl = 0.6	SL/HROS MCAO/ NIRES MCAO/IRIS/WIRC SL/WFOS
Planetary Systems and Star Formation (physics of star formation,proto-planetary disks, exoplanets; DSC Section 8, Section 9)	Origin of mass in stars (GAN-[1,2], PSF-1) Architecture of planetary systems (PSF-[2,3,D]) Deposition of pre-biotic molecules onto protoplanetary surfaces (PSF-2) First direct detection of reflected-light Jovians (PSF-2) Characterization of exo-atmospheres (e.g., oxygen) (PSF-[3,4,D])	High-precision, crowded field photometry Diffraction-limited, high spectral resolution mid-IR spectroscopy Very high Strehl AO-assisted imaging: precise wavefront control High spectral resolution optical and near-IR spectroscopy	λ = 1 – 25 μm R = 4000, 30000-100000 Low telescope emissivity Dry site (PWV < 5 mm) Fixed gravity vector and thermal control Very efficient acquisition Contrast ratio of 10^8–10^9	MCAO/IRIS MIRAO/ MIRES MCAO/ NIRES SL/HROS ExAO/PFI
Our Solar System (outer parts, surface physics and atmospheres; (DSC Section 10)	Composition of Kuiper Belt Objects and comets (PSF-2) Monitoring weather, (cryo-) vulcanism and tectonic activity♦	Spatially resolved spectroscopy of objects in solar system Transient events (hours to years)	λ = 1-10 μm R = 1000 – 100000 Non-sidereal tracking Fast response time	MCAO/IRIS/WIRC MCAO/ NIRES MIRAO/ MIRES

TMT First Light AO Systems and Instruments



- Narrow Field IR AO System (NFIRAOS):
  - 60x60 order system operating at 800Hz
  - Piezostack DMs and tip/tilt stage
  - Polar coordinate CCD array for LGS WFS
  - 4 OAP relay to eliminate distortion
  - Operation at -30°C to reduce thermal emission
  - Feed 3 IR Instruments

TMT First Light
Laser Guide Star Facility



- Laser Guide Star Facility (LGSF):
  - Nd:Yag or Raman fiber laser technology
  - Lasers mounted on telescope elevation
  - Mirror-based beam transfer optics
  - Center launch projection
  - Up to 4 different asterisms for first light AO system and second generation AO instrumentation

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

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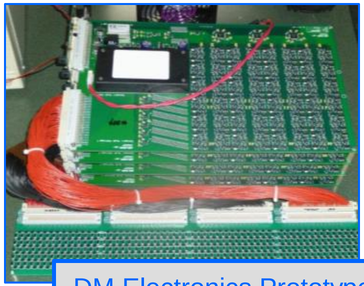
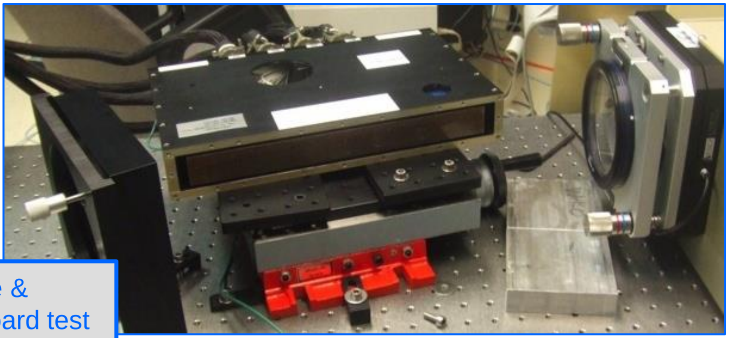
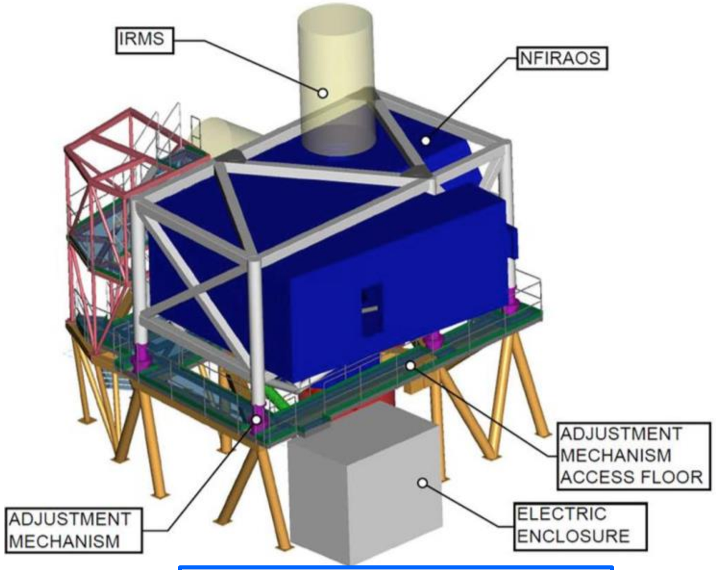
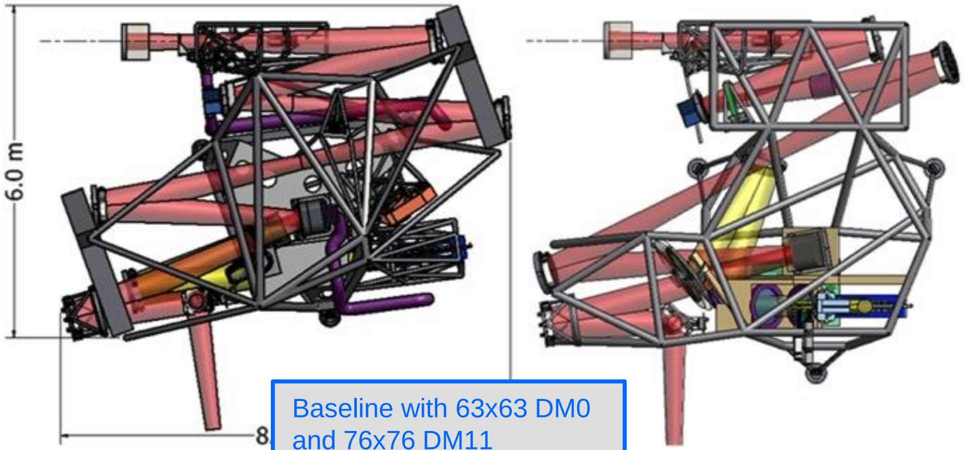




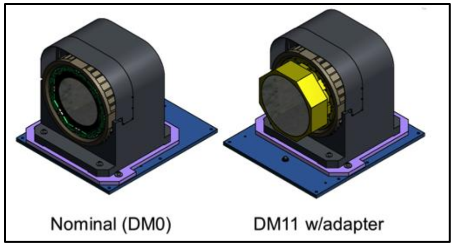
DM Electronics Prototype & CILAS DM 6x60 Breadboard test setup (warm) at NRC - Herzberg



Interface with telescope structure

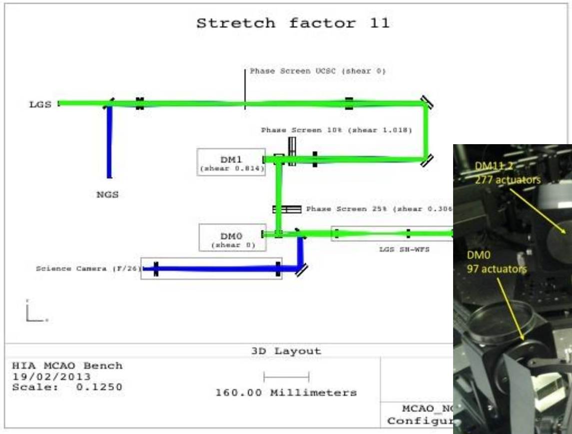


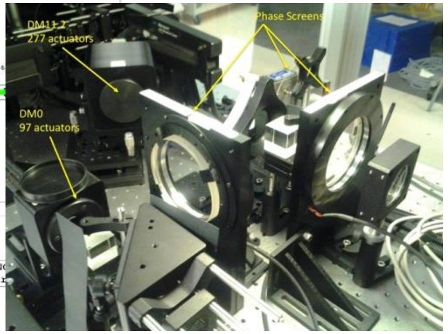
Baseline with 63x63 DM0 and 76x76 DM11



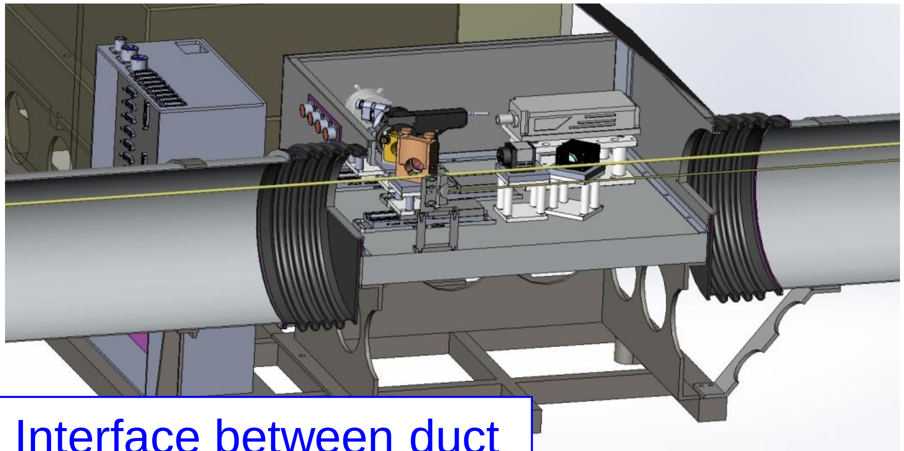
DM11 mounted on Tip/Tilt Stage for baseline configuration

MCAO test bench

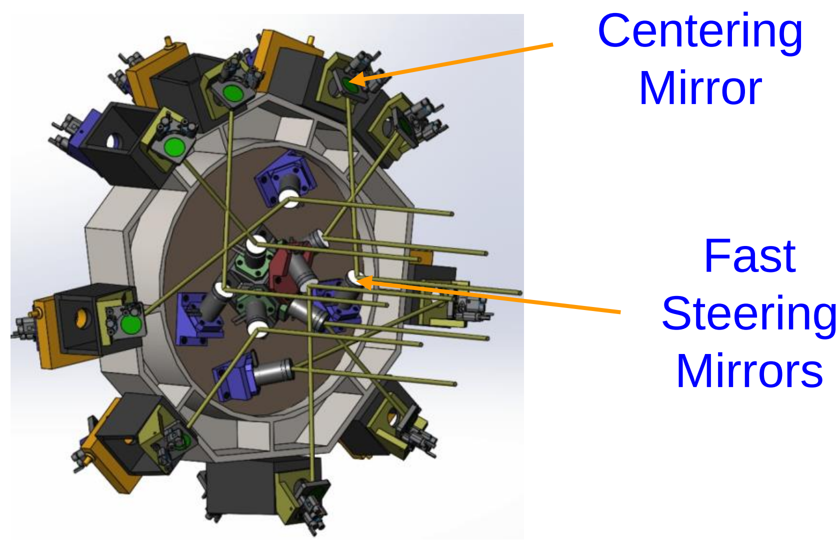


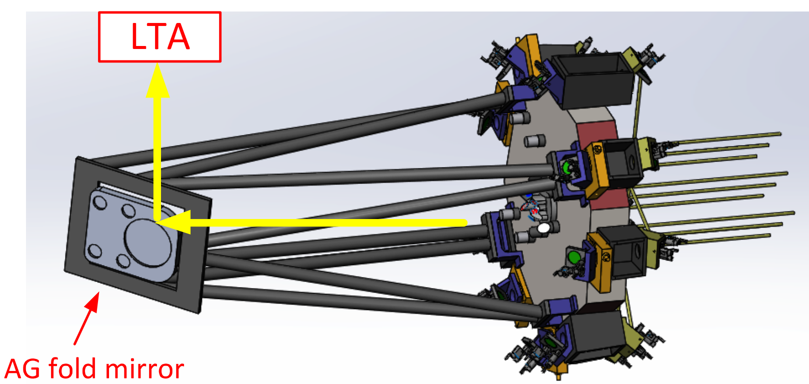


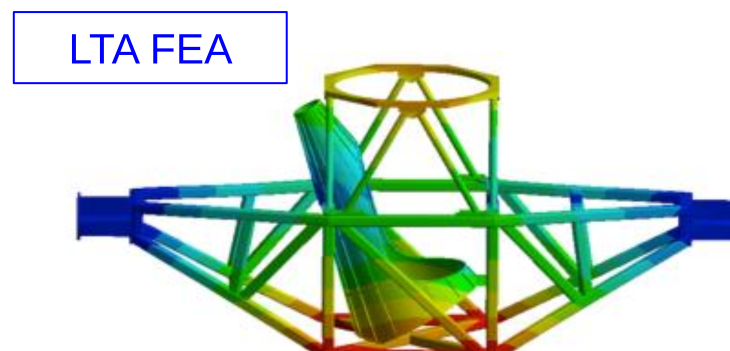
Laser Guide Star Facility in Preliminary Design, IOE, Chengdu



Interface between duct and laser bench

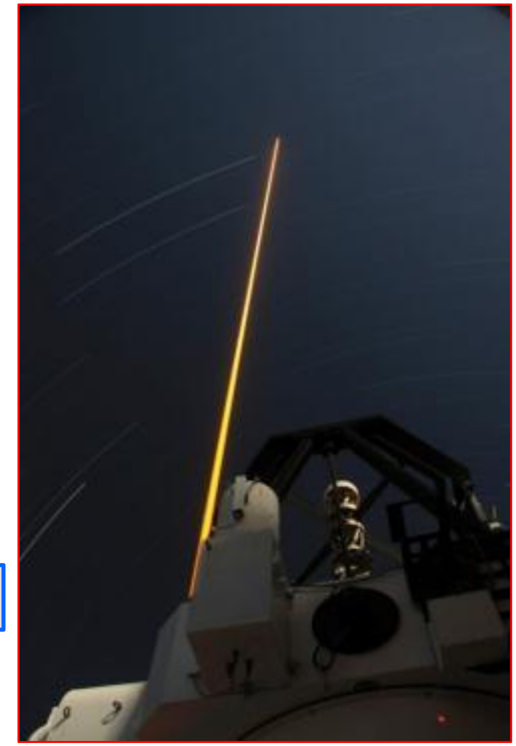




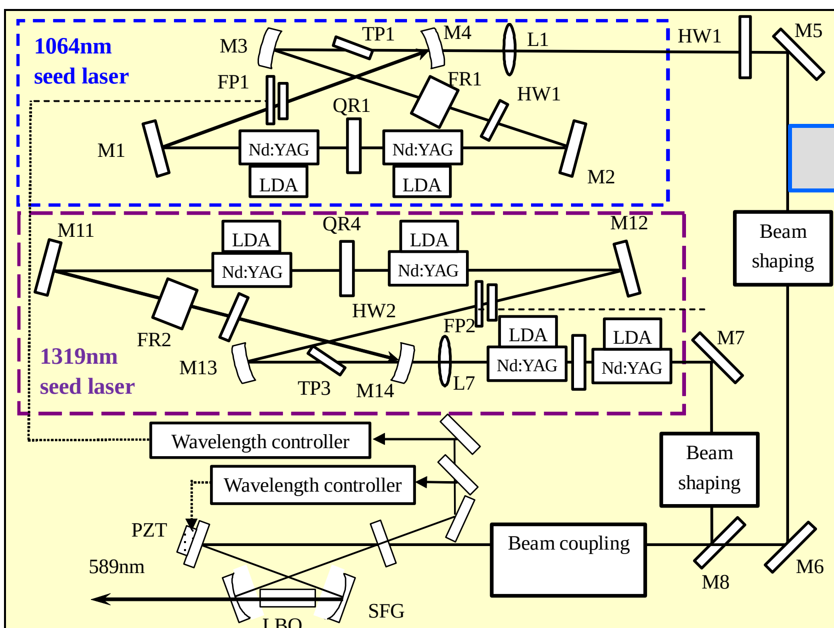


Guide Star Laser Development at TIPC, Beijing

TIPC prototype

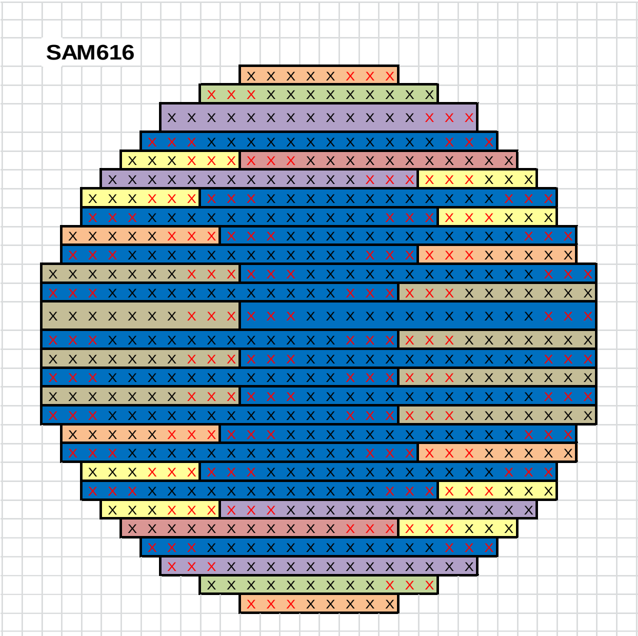


TIPC Lijiang Observatory, February 2013



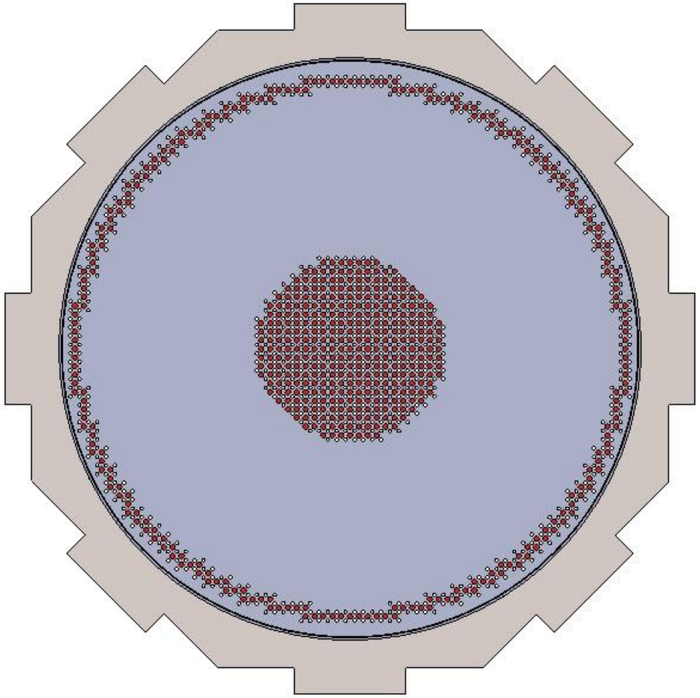
TIPC optical layout

AO Deformable Mirror Final Design & Prototyping Underway at Two Vendors



28x28 DM Prototype with 616 actuators

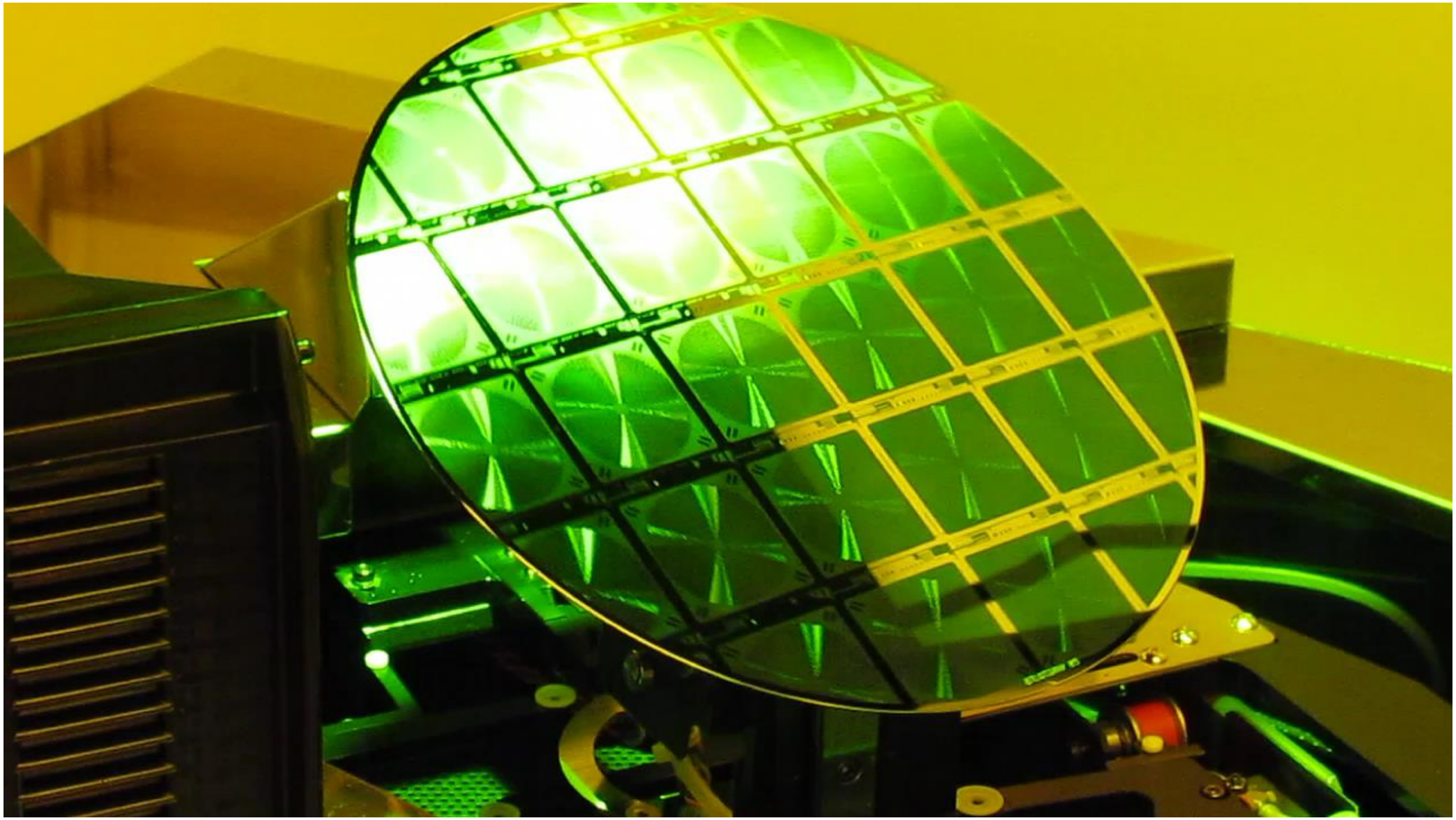
CILAS



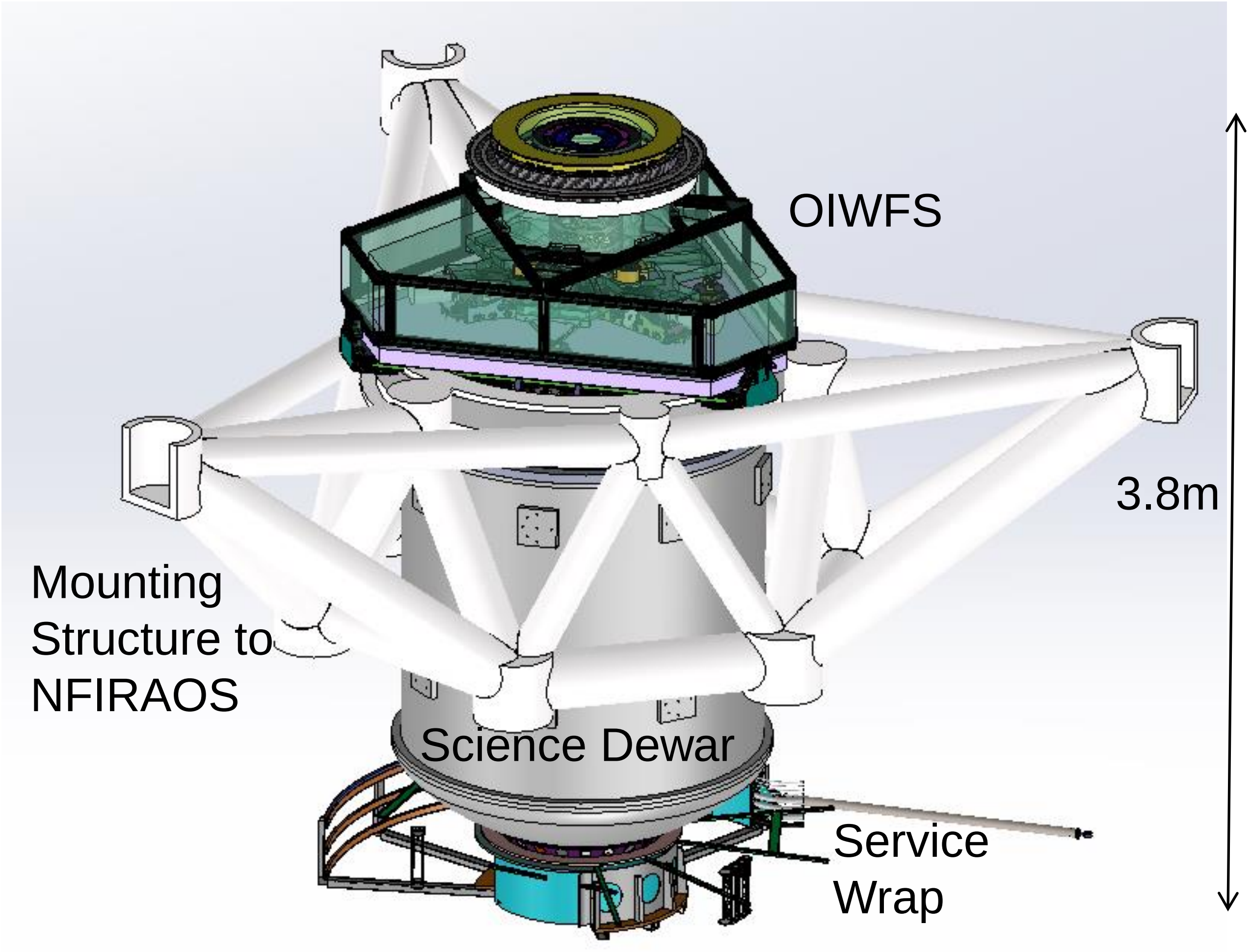
Full scale DM0 Prototype with 597 PMN:LT actuators (349 in the center and 248 around the edge)

AOX/Xinetics

AO NFIRAOS Visible WFS Camera CCD Fabricated at MIT/LL



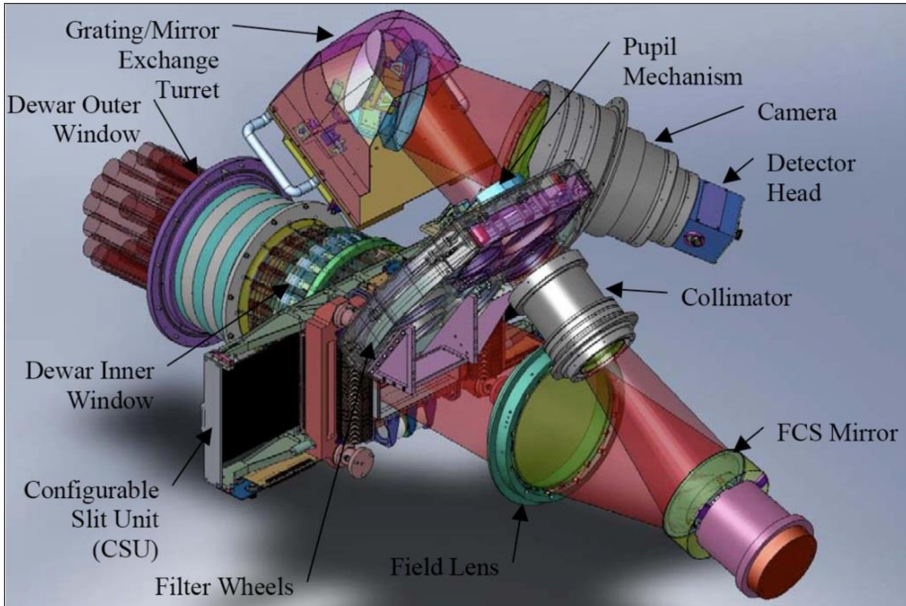
IRIS Model



OIWFS
3.8m
Mounting
Structure to
NFIRAOS
Science Dewar
Service
Wrap

THIRTY METER TELESCOPE

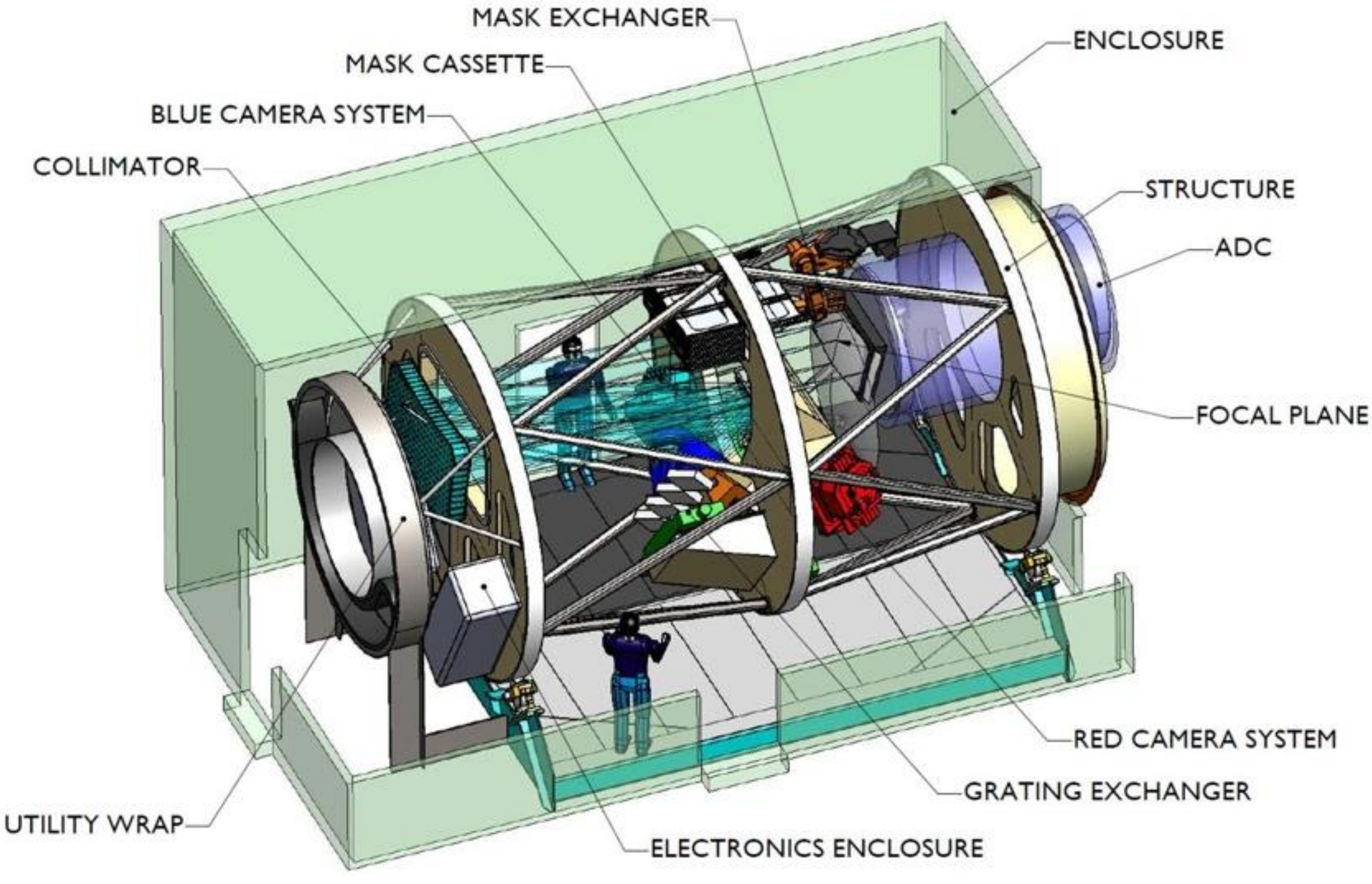
InfraRed Multi-slit Spectrometer (IRMS)



TMT/IRMS
=
Keck/MOSFIRE clone!

Keck, February 2012

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

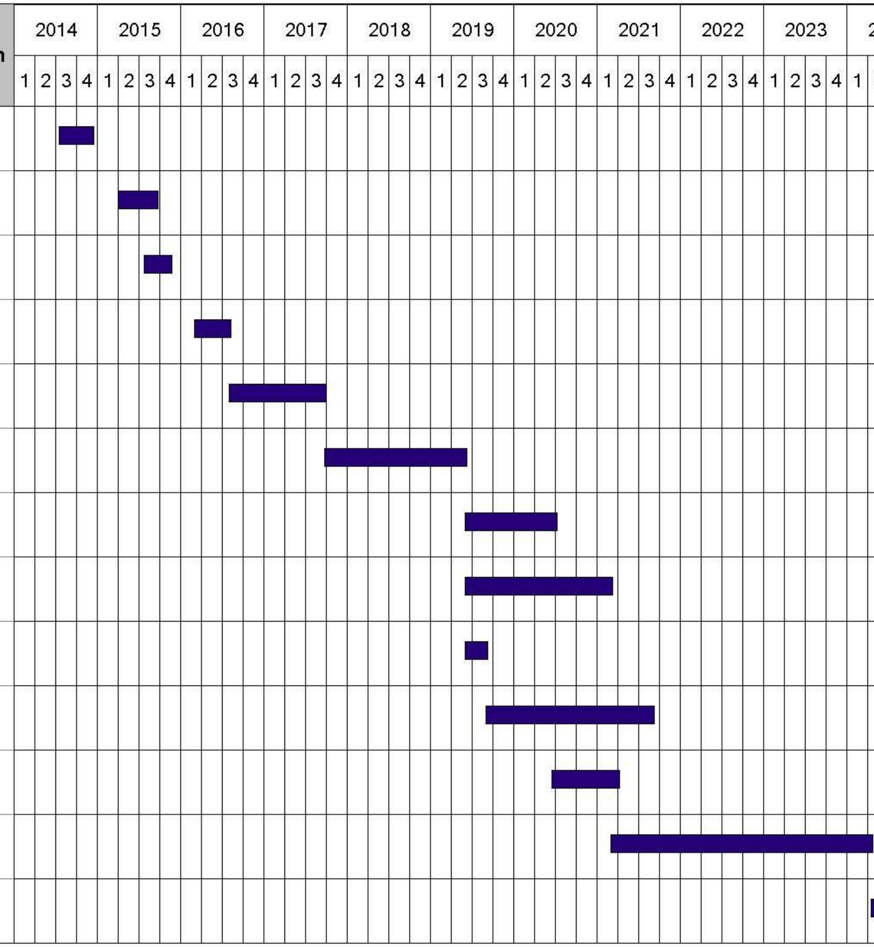


Instrument Group Meetings held in China, India and US

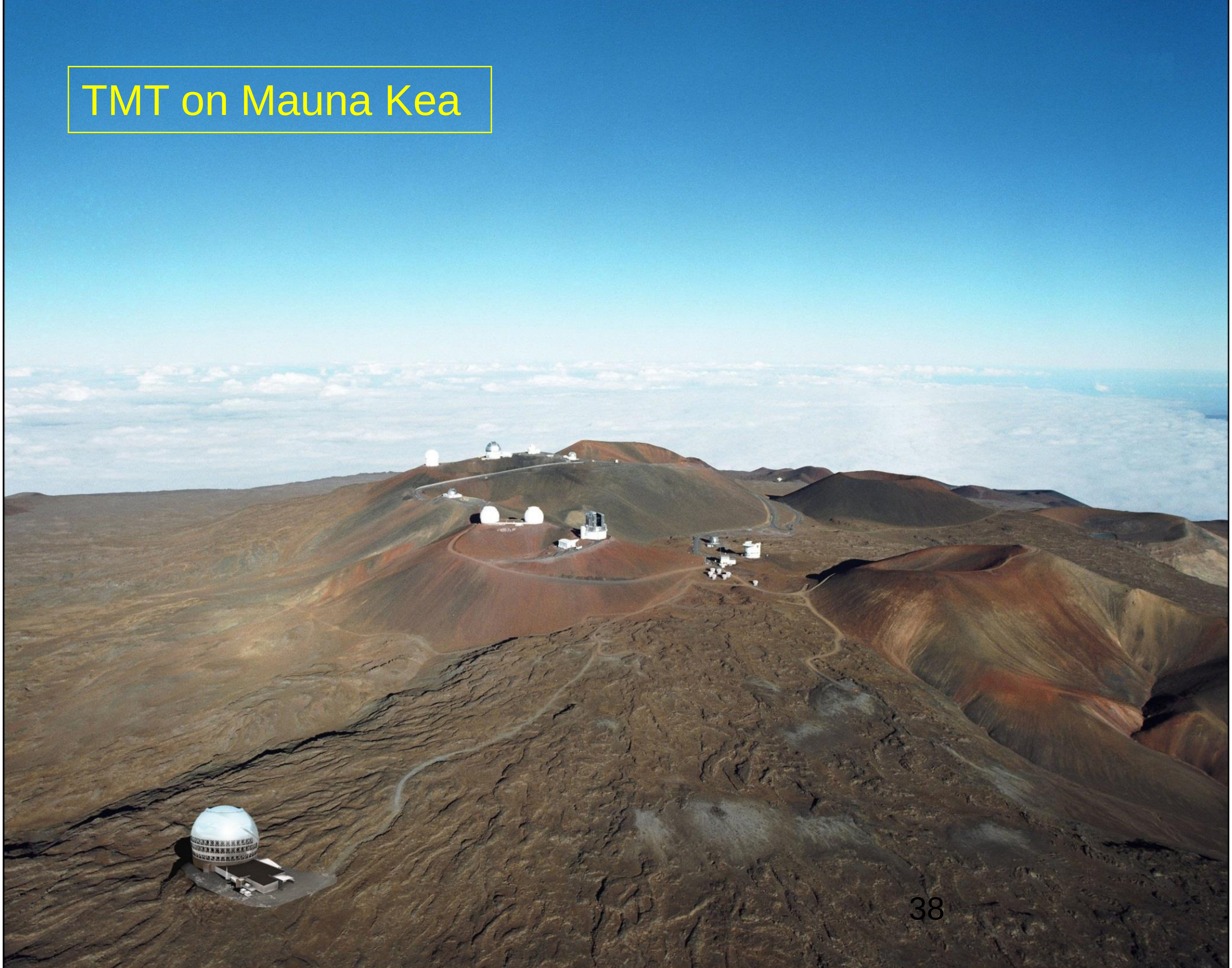
Project:	TMT2014M_IPS
Printed:	03/28/2014

Thirty Meter Telescope Project
Integrated Project Schedule
2014M
On-site Construction Summary

Activity ID	Early Start	Early Finish
00 -- Groundbreaking and Access Road Rough Grading	07/16/2014	12/11/2014
01 -- Access Road	04/01/2015	09/17/2015
02 -- Rough Grading	07/23/2015	11/12/2015
03 -- Fixed Enclosure Base Foundations & Trenches	03/02/2016	07/28/2016
04 -- Fixed Enclosure Base Structure	07/29/2016	09/22/2017
05 -- Enclosure Shell	09/25/2017	05/30/2019
06 -- Enclosure Completion	05/31/2019	07/03/2020
07 -- Summit Facilities Completion	05/31/2019	03/04/2021
08 -- Cladding on Fixed Enclosure Base	05/31/2019	08/30/2019
09 -- Telescope Structure Erection & Integration	09/03/2019	09/02/2021
10 -- Fixed Enclosure Base Completion	06/12/2020	04/01/2021
11 -- Assembly, Integration, and Verification (AIV)	03/05/2021	04/15/2024
12 -- First Light	04/15/2024	04/15/2024



TMT on Mauna Kea



The US Community and TMT

- 2000 & 2010 Decadal Surveys identified the need for US national participation in a Giant Segmented Mirror Telescope
- 2013: In response to a call for proposals, NSF and TMT entered into a cooperative agreement to engage the US community in TMT planning and development

“The primary deliverable of this award is to be a partnership model…in which NSF might join the TMT Project on behalf of the US astronomical community.”

- AURA is an Associate Member of TMT International Observatory, LLC:

  TIO Board: David Silva (NOAO), Caty Pilachowski (Indiana)

  TMT Science Advisory Committee (SAC): Mark Dickinson (NOAO), Jennifer Lotz (STScI), Ian Dell’Antonio (Brown)

    - Dickinson has been Chair of the TMT SAC since April 2014
- NOAO executes the responsibilities and participation activities of AURA, representing the US-at-large community

US TMT Science Working Group

- NOAO established a US TMT SWG in 2013 to engage with the US community to understand its interests and aspirations for TMT
- SWG represents those interests to the TMT project, SAC, and Board
- SWG is working with TMT to develop a *US National TMT Participation Plan* for the NSF

Ian Dell'Antonio (Brown)	Lucas Macri (TAMU)
Mark Dickinson (NOAO, chair)	Karen Meech (Hawaii/IfA)
Anthony Gonzalez (Florida)	Susan Neff (GSFC)
Stephen Kane (SFSU)	Deborah Padgett (GSFC)
Jamie Lloyd (Cornell)	***Caty Pilachowski (Indiana)***
Jennifer Lotz (STScI)	Kartik Sheth (NRAO)
	Lisa Storrie-Lombardi (IPAC)

**** TMT Science Advisory Committee or Board member***

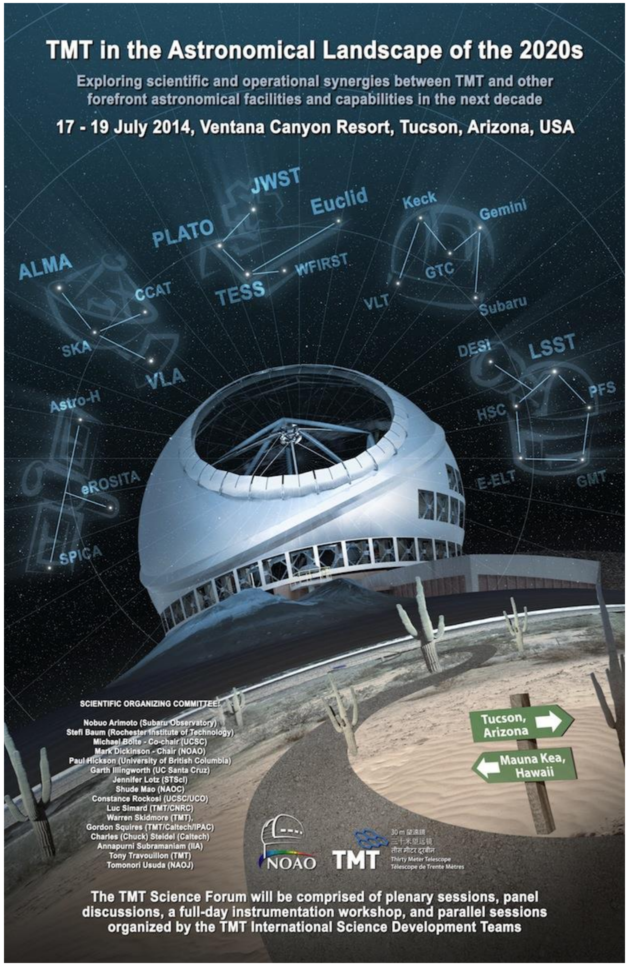
US Community Engagement Activities

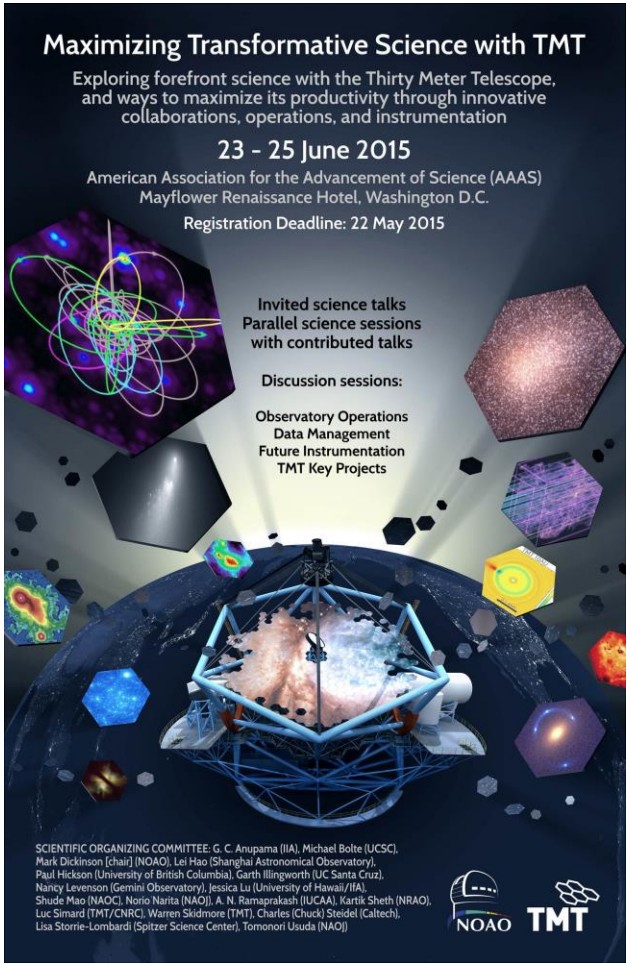
- AAS TMT Open House events
  - Presentations on TMT science, project status & US community engagement
  - 2013, 2014, 2015 January AAS meetings; Nov. 2015 DPS meeting
  - 2016: Open House + TMT Thermal-IR science & instrumentation workshop
- Community engagement visits & presentations
  - TMT project astronomers visit US universities & astronomy institutions for 1-2 days, meet local scientists, and give TMT colloquium/seminar presentations
  - Gather community input on US participation and scientific priorities
  - 65 visits so far (2013-2015), with more scheduled in 2016
- NOAO liaison activities
  - Regular articles in NOAO Newsletter & Currents e-newsletter
  - Promotes AAS events, TMT Forum meetings, participation opportunities, etc.
  - US TMT liaison web page and TMT Background/“FAQ” page

The TMT Science Forum

Annual TMT science workshop + international collaboration meeting

2013: Waikoloa, HI **2014: Tucson, AZ** **2015: Washington, D.C.**





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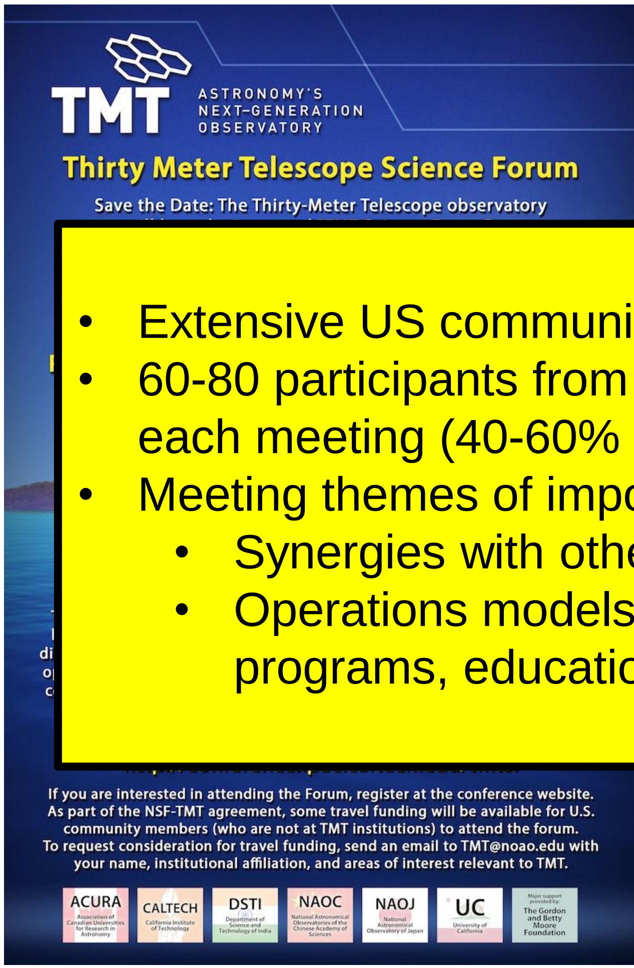
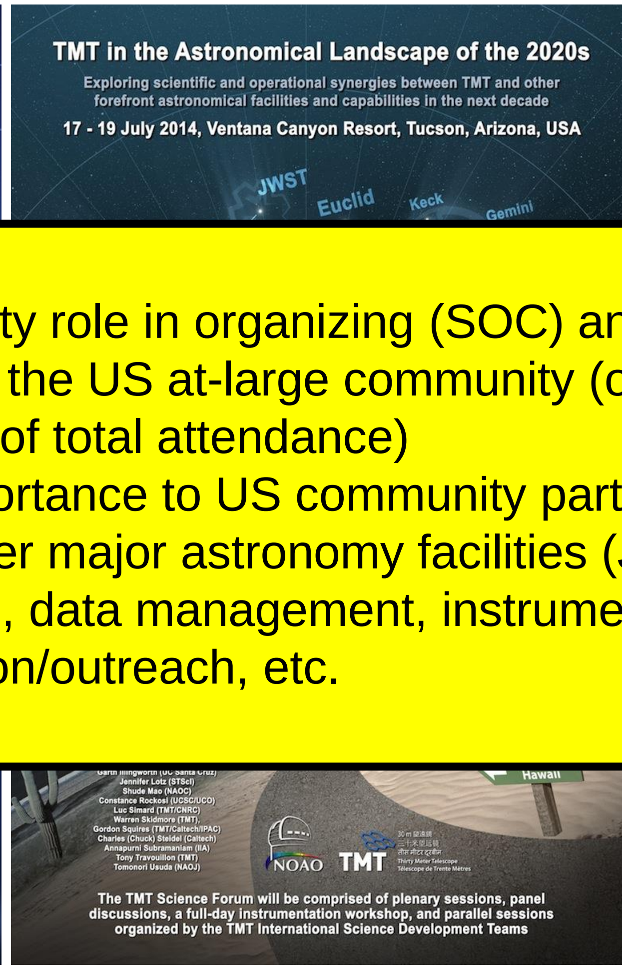
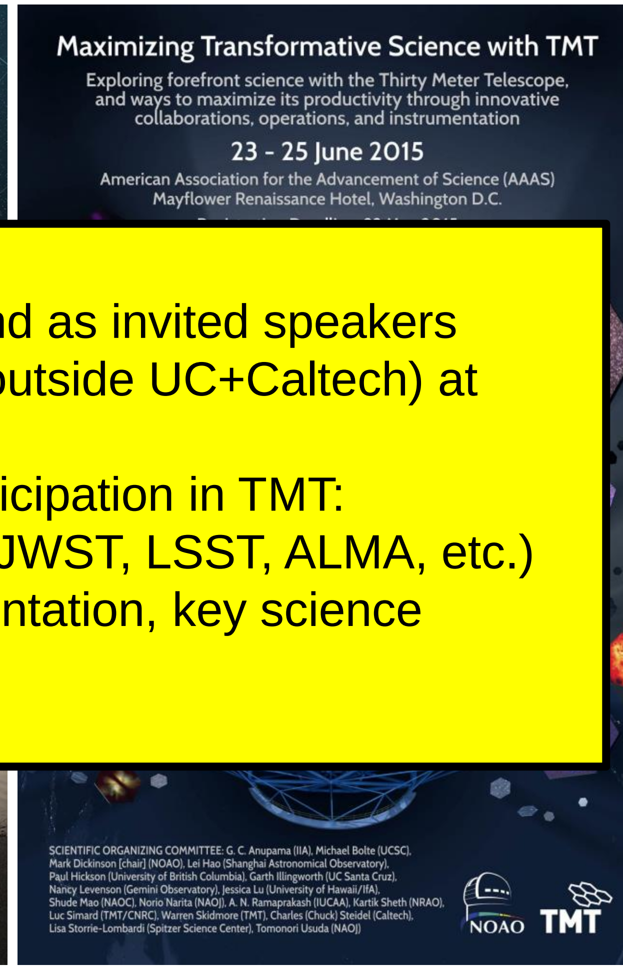






- Extensive US community role in organizing (SOC) and as invited speakers
- 60-80 participants from the US at-large community (outside UC+Caltech) at each meeting (40-60% of total attendance)
- Meeting themes of importance to US community participation in TMT:
  - Synergies with other major astronomy facilities (JWST, LSST, ALMA, etc.)
  - Operations models, data management, instrumentation, key science programs, education/outreach, etc.

TMT International Science Development Teams (ISDTs)

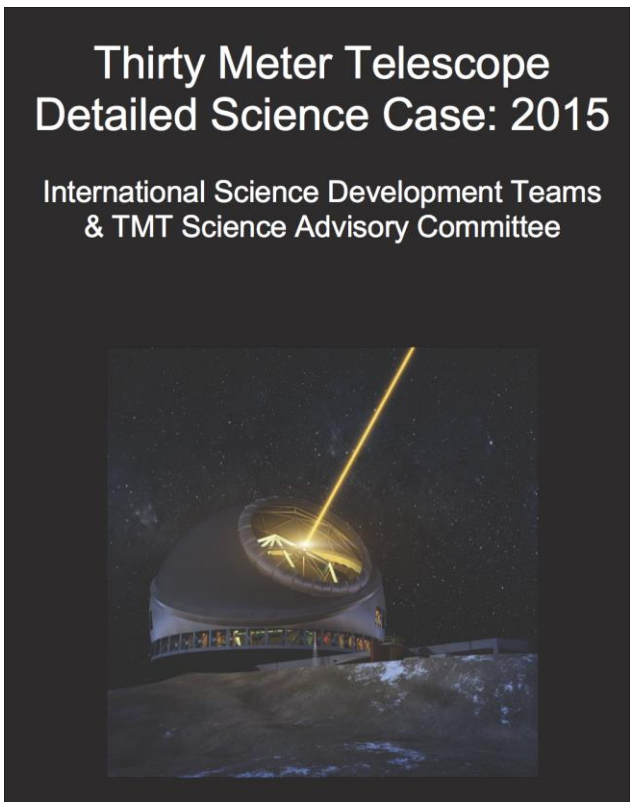
- Open to all PhD astronomers
  - 199 scientists worldwide, **56 from the US-at-large community**
  - Annual calls for new membership (next: due 15 January 2016)
    - Advertised via NOAO Newsletters, at AAS TMT Open House, etc.

Fundamental Physics & Cosmology Early Universe, Galaxy Evolution, and the IGM Milky Way and Nearby Galaxies Supermassive Black Holes Stars, stellar physics, and the ISM	Formation of Stars & Planets Exoplanets Our Solar System Time Domain Science

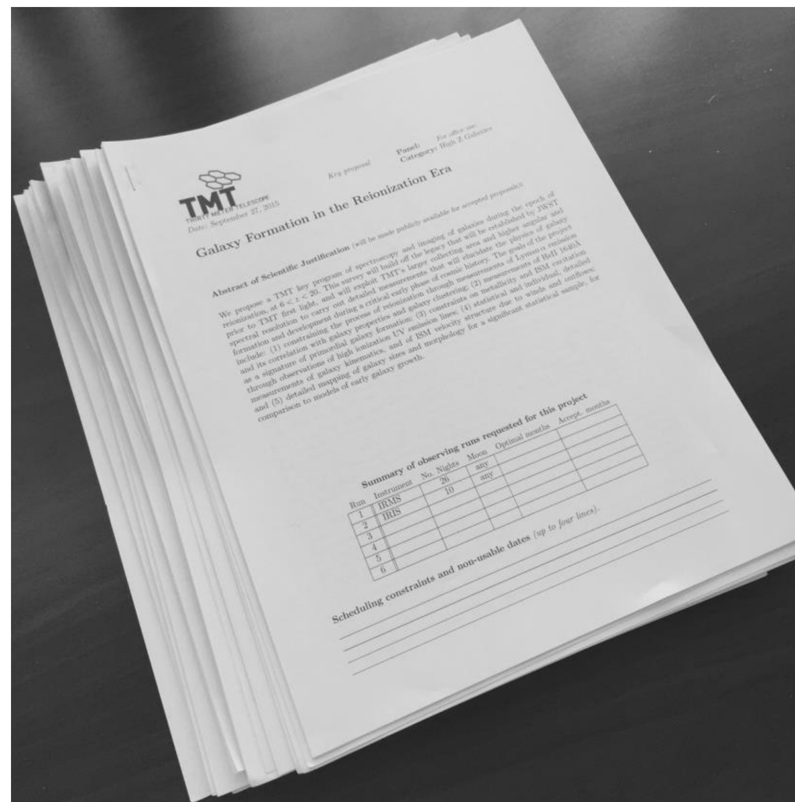
- Roles of the ISDTs:
  - Provide scientific input & guidance to TMT
  - Help define observatory capabilities & operations model
  - Plan for future TMT science programs
  - Foster collaboration & cooperation between scientists in and beyond the international TMT partnership

US Participation in TMT International Scientific Collaboration Activities

2015 TMT Detailed Science Case update, with contributions from 150+ scientists including US-at-large ISDT members



23 TMT "Key Project" concept proposals requesting >1100 nights of observing time. Written by international teams; 43% led by US-at-large PIs



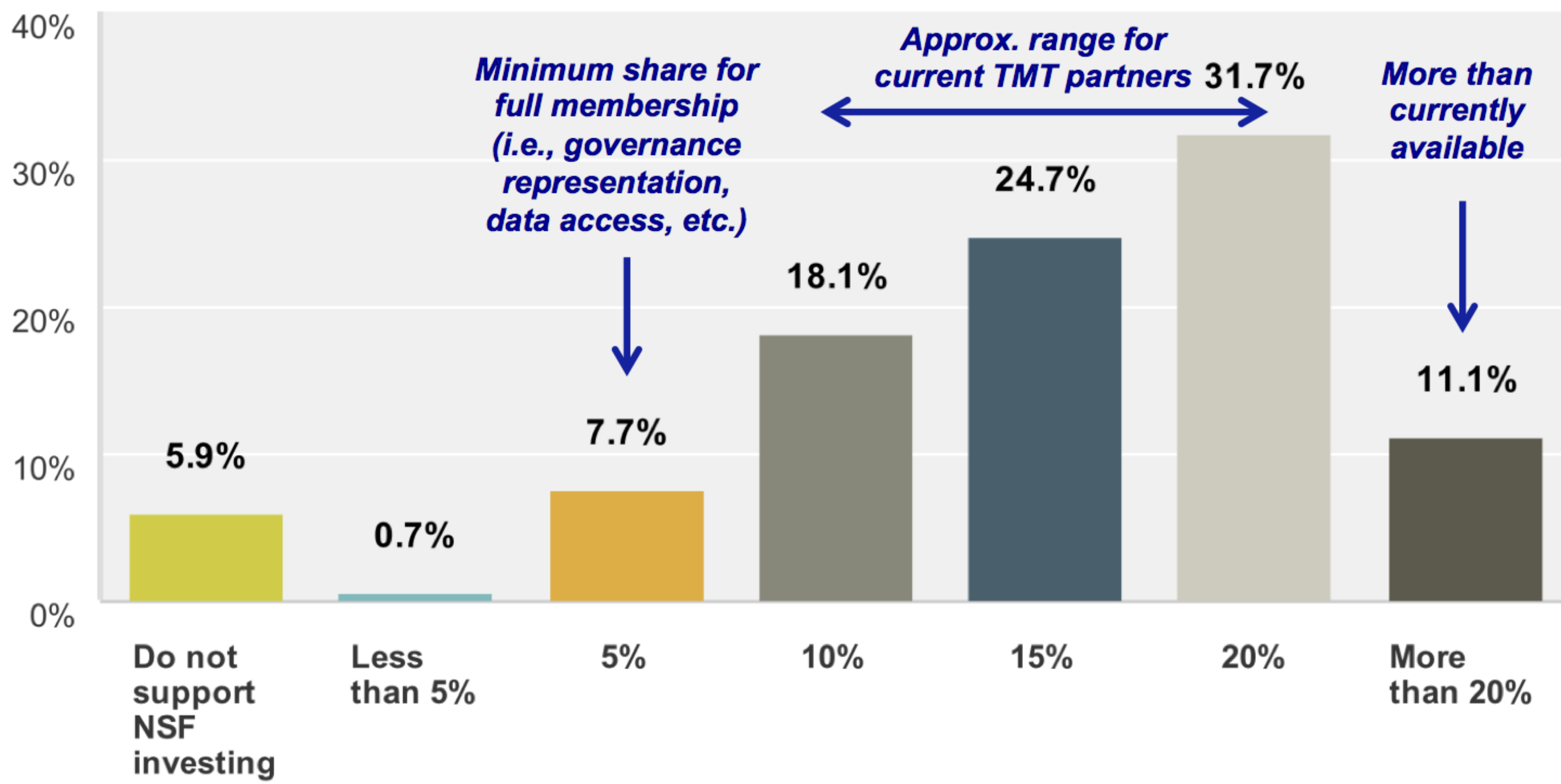
TMT US Community Survey

- Fall 2014: US TMT SWG carried out an on-line community survey
- 467 responses, 364 (78%) from US scientists outside the TMT member institutions (UC+Caltech)
- Some results:
  - "Would an O/IR GSMT be useful for your research?": 79% said "yes"
  - "Which of the three 1st-light TMT instruments would be useful for your research?" Responses were evenly split among instruments.
    - Of 18.5% who replied "none", many favor high resolution spectroscopy or extreme high contrast imaging as top priority for 2nd-generation capabilities
  - Good pre- and post-observational planning and data analysis tools were identified as "very important" or "essential" by ~75% of respondents
  - Archival access to raw and pipeline-processed data products was identified as "very important" or "essential" by ~65% of respondents
  - Availability of a queue scheduled / service observing modes was considered "very important" or "essential" by 72% of respondents
- Results of the survey inform the SWG's report to the NSF in the US National TMT Participation Plan

US Federal Participation in TMT

from the SWG's US community survey

"In your opinion, what minimum partner share in TMT does the US community (outside the current partners) need in order to conduct globally competitive science programs?"



US National TMT Participation Plan

- A draft plan for US national participation in TMT has been developed, based on community input (US TMT SWG, NOAO survey, AAS events, TMT Forums, community visits, ISDT activities)
- This plan includes:
  - Science case for US participation in TMT
  - Flow-down from science to instrumentation & operations
    - Ways to maximize scientific benefits of TMT for the US national community
  - Workforce, education, public outreach & communication plan
  - Business and governance model for US TMT participation
- Draft to be submitted to NSF AST by the end of December
- Next steps: internal NSF AST review, then an external review, leading to a recommendation to NSF AST

Benefits of US National Participation in TIO
as identified in US TMT SWG's report to NSF

- Full participation in TIO governance and scientific planning
  - Definition & prioritization of instrumentation and AO systems
  - Evolution of operations models, observing modes, data management
- Consistent, long-term open access to observing time
  - US astronomers may create & lead observing programs, not just participate via collaboration
  - Critical for US scientific competitiveness in the worldwide GSMT era
- Opportunity to participate in international TMT key projects
- Access to archived TMT data*
- Enhanced opportunity to participate in developing TMT instrumentation

* By current TIO policy, data have a standard proprietary period, after which all data are available to TIO partners.

TMT Partnership Example

TMT and Astro-2010

- The Astro-2010 Program Prioritization Panel on Optical and Infrared Astronomy from the Ground ranked a GSMT as its top priority, stating that a GSMT provides *"…exceptionally broad and powerful ability over the whole range of astrophysical frontiers."*
- For Astro-2010 key science programs identified as requiring a 30m-class O/IR telescope:
  - 23 out of 27 could be carried out using TMT's first-light instrumentation suite
  - 27 out of 27 could be carried out using TMT's first-decade instrumentation suite

Elmegreen Report and US O/IR System

- Recommendation 5. The National Science Foundation should plan for an investment in one or both Giant Segmented Mirror Telescopes in order to capitalize on these observatories' *"exceptional scientific capabilities for the broader astronomical community"*
  - Making a detailed plan to meet this recommendation is the major activity of the 5-year TMT-NSF Cooperative Agreement. We endorse this recommendation
- TMT would fill an important need in the O/IR system providing the highest levels of sensitivity and spatial resolution by an order of magnitude. From the Elmegreen Report, access to one or more GSMTs will : "… *make major contributions to many of the next decade's key science questions, including the nature of debris disks, the physics of planet formation, the growth of black holes, and the advent of the first galaxies."*
- The Elmegreen Report describes a major role for NOAO in managing the US O/IR System. TMT is currently partnering with NOAO in the Cooperative Agreement activities. In the draft Partnership Plan, NOAO role is to manage the US at-large community interface with TIO.

Summary

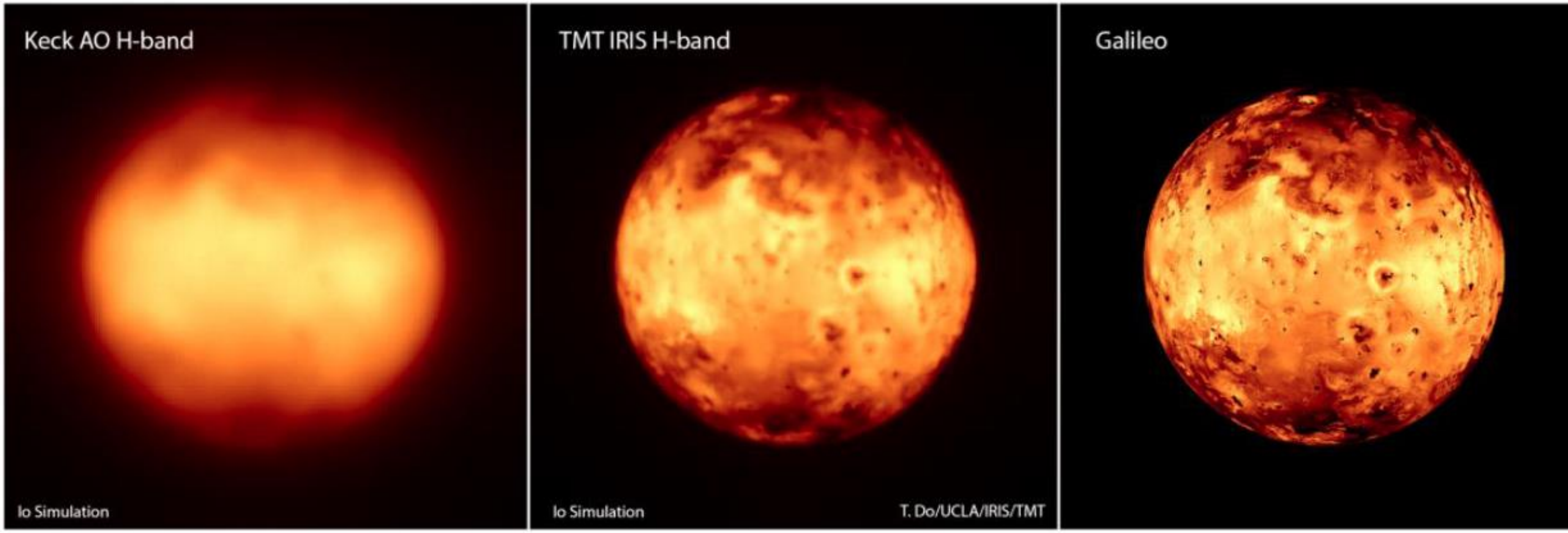
- Project progress since Astro2010 has been excellent
  - TIO formed with ratified partnership documents defining partner workshare and commitments
  - Technical risks retired, in particular segment fabrication and rate
  - Very strong international management, systems engineering team
  - Hawaii issues remain challenging but see a path forward
- Significant progress with NSF-TMT Cooperative Agreement activities
  - NOAO has led broad effort to identify the needs and aspirations of the US at-large community
  - Strong participation at the TIO Board and Science Advisory Committee by representatives of the community
  - Draft Participation Plan to be submitted Dec 2015
- TMT meets ASTRO2010 GSMT goals very closely

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 the Gordon and Betty Moore Foundation, 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.

High-spatial resolution observations of our solar system

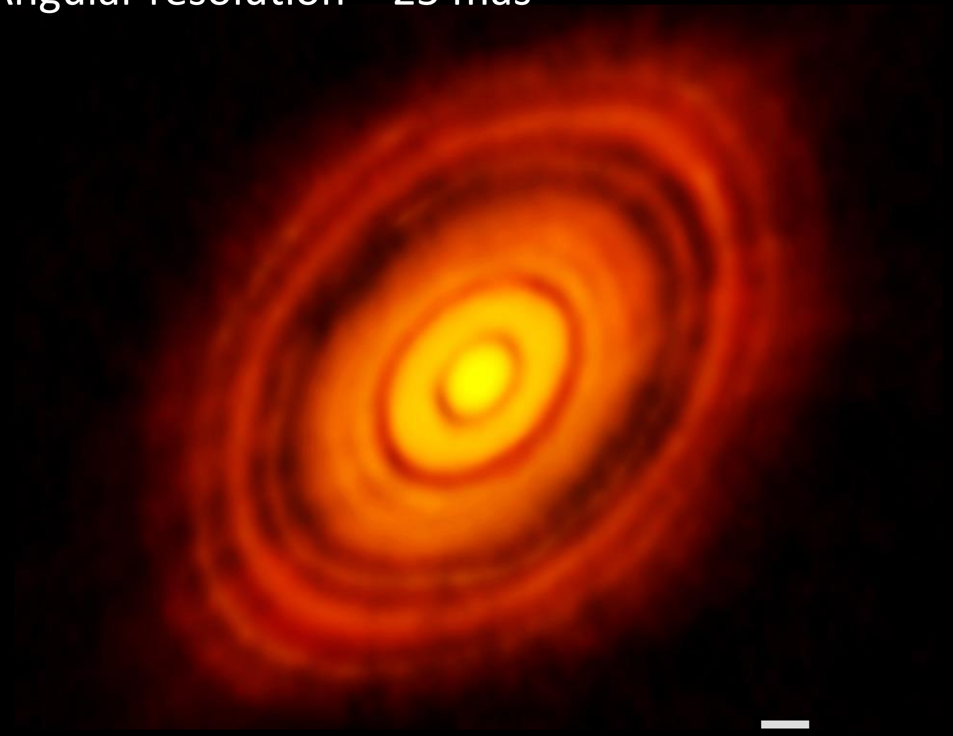
Image credit: Tuan Do, UCLA



TMT resolution at 1μm is 7 mas, 4 mas pixels
7 mas is equivalent to ~20 km resolution at 5 AU (Jupiter)

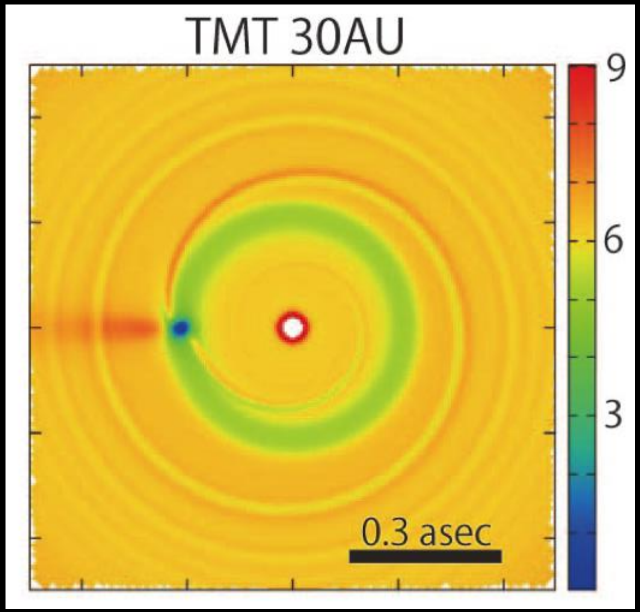
Imaging of planetary systems in formation

ALMA HL Tau observed at 1 mm
Angular resolution ≈ 25 mas



100 mas = 14 AU

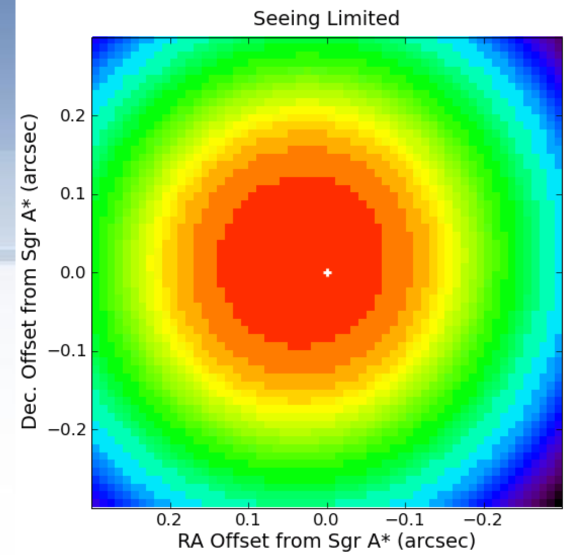
TMT 1.6 micron simulation of protoplanetary disk at 140 pc
Angular resolution = 13 mas



Each dark ring may have a planet within it, which TMT should be able to image

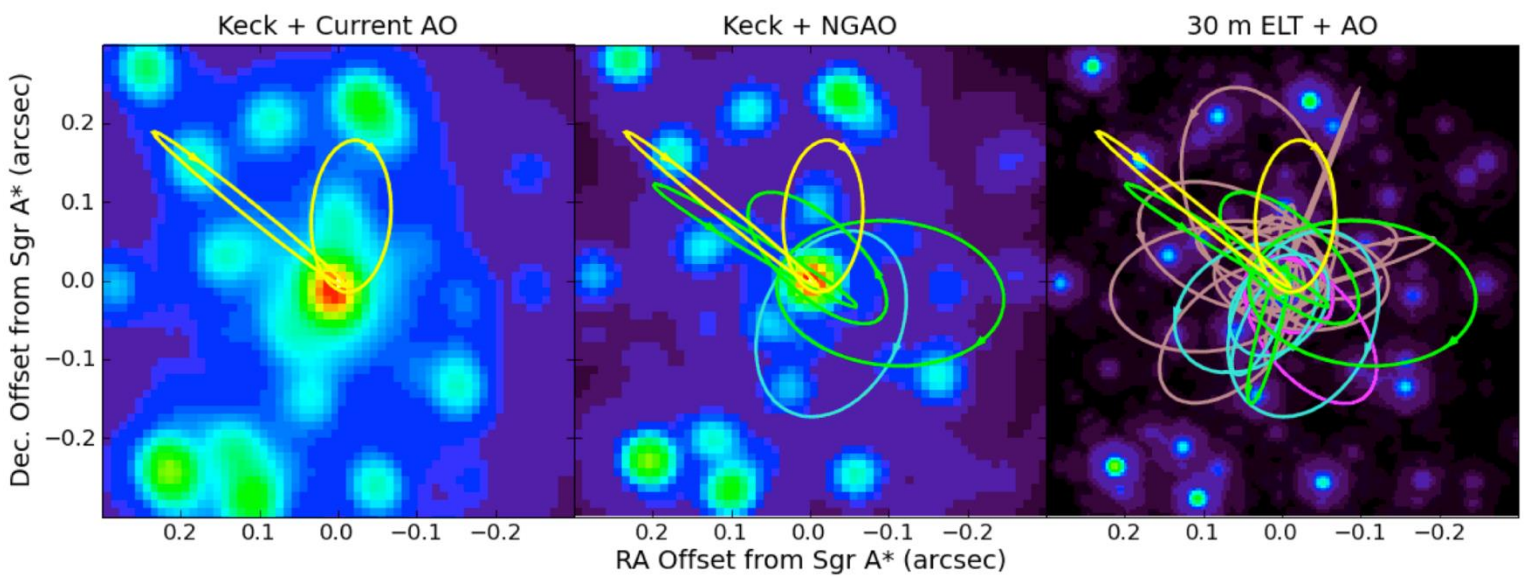
Imaging the black hole at our galactic center

- TMT will determine black hole (BH) masses over a wide range of galaxy types, masses and redshifts
- Key questions:
  - When did the first super-massive BHs form?
  - How do BH properties and growth rate depend on the environment?
  - How do BHs evolve dynamically?
  - How do BHs feed?

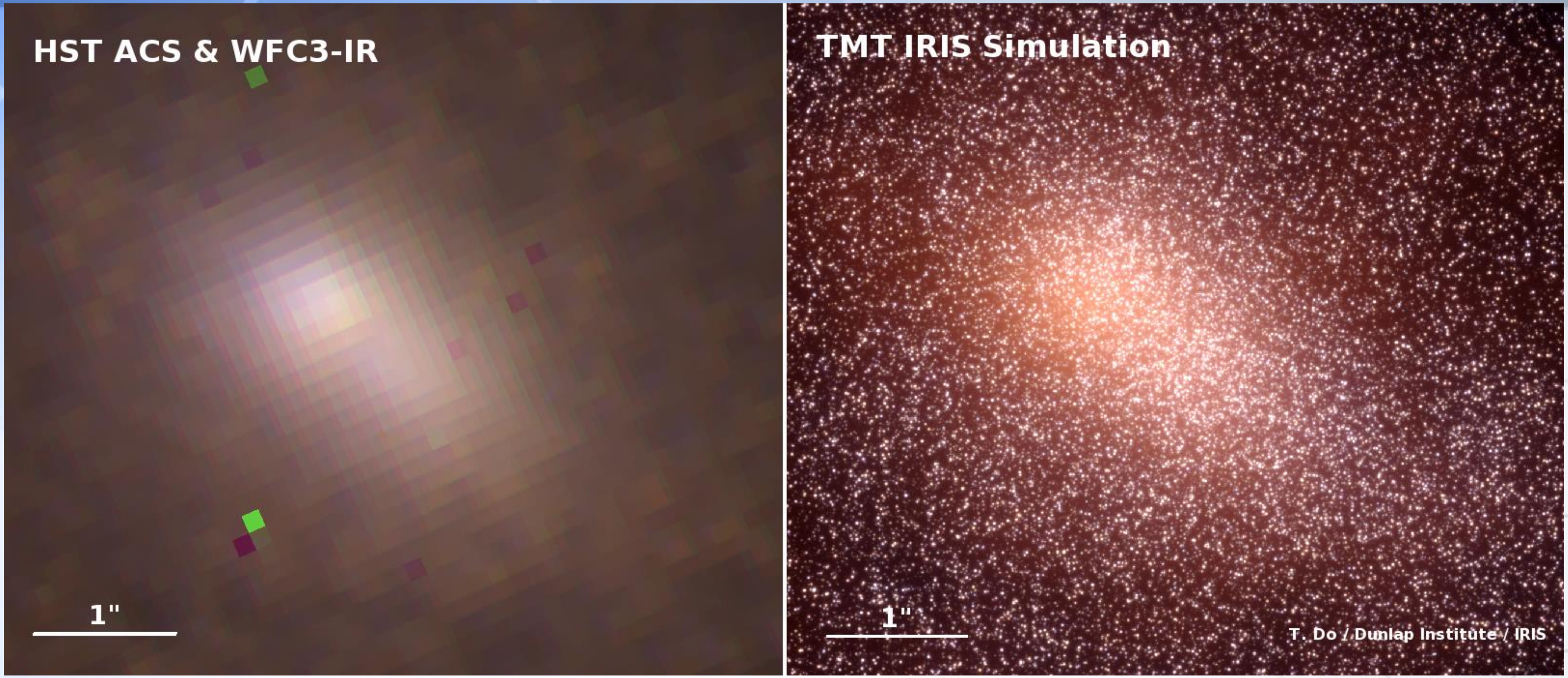


http://www.astro.ucla.edu/~ghezgroup/gc/pictures/Future_GCorbits.shtml

Galactic black-hole:
- Distance: 26,000 light years
- Diameter: 28 million miles
- Mass: 4 million solar masses

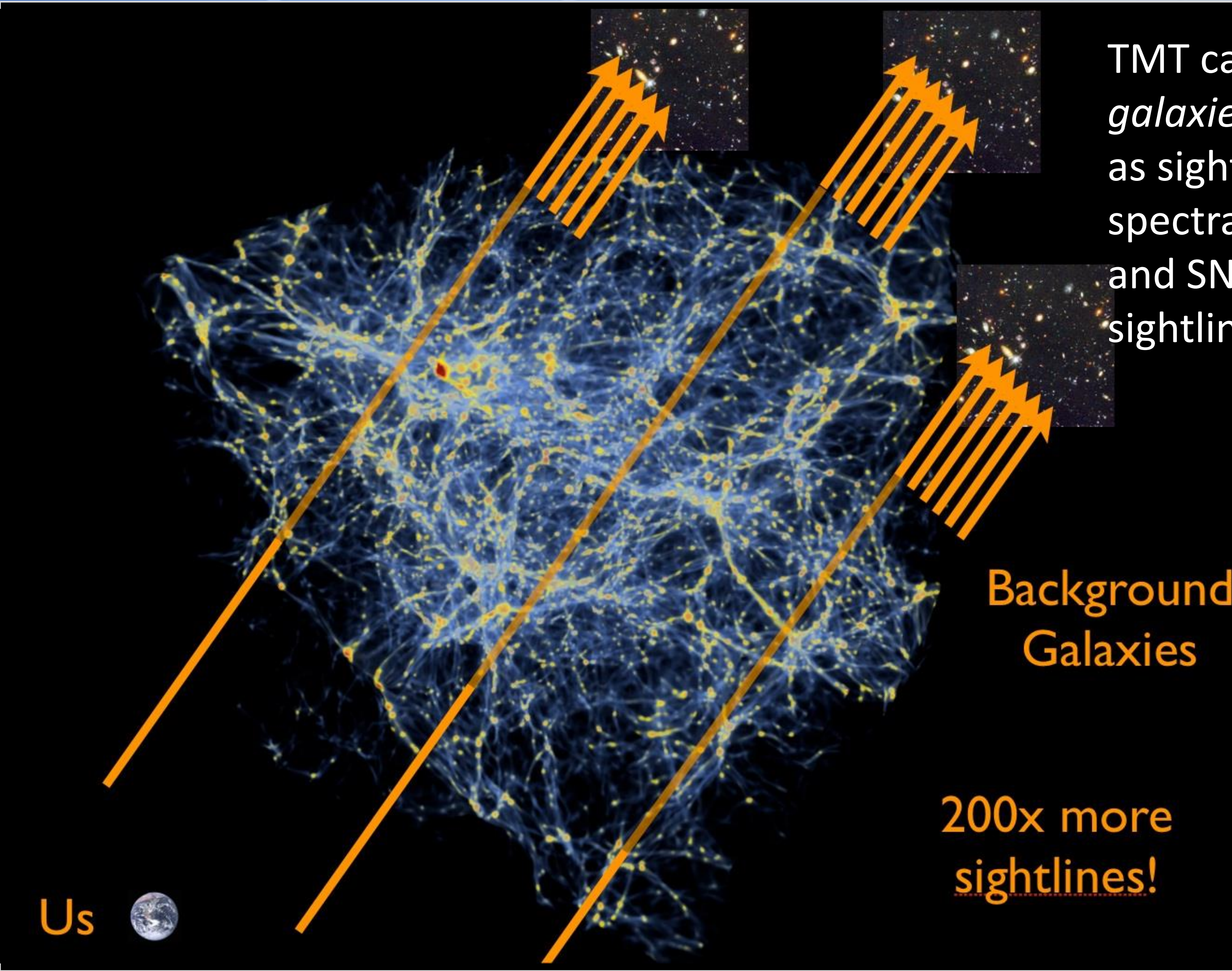


Resolving stars throughout the Local Group of Galaxies



TMT IRIS imager and integral field spectrometer + NFIRAOS AO system will resolve stars within the sphere of influence of the supermassive black holes in nearby galaxies, measuring orbits (proper motions and radial velocities) as can only be done now for the Milky Way Galactic Center.

Tomography of the intergalactic and circumgalactic medium



TMT can use background *galaxies* down to R ≈ 24.5 as sightline probes with spectral resolution ≈ 5000 and SNR > 30, increasing sightline density by 200x