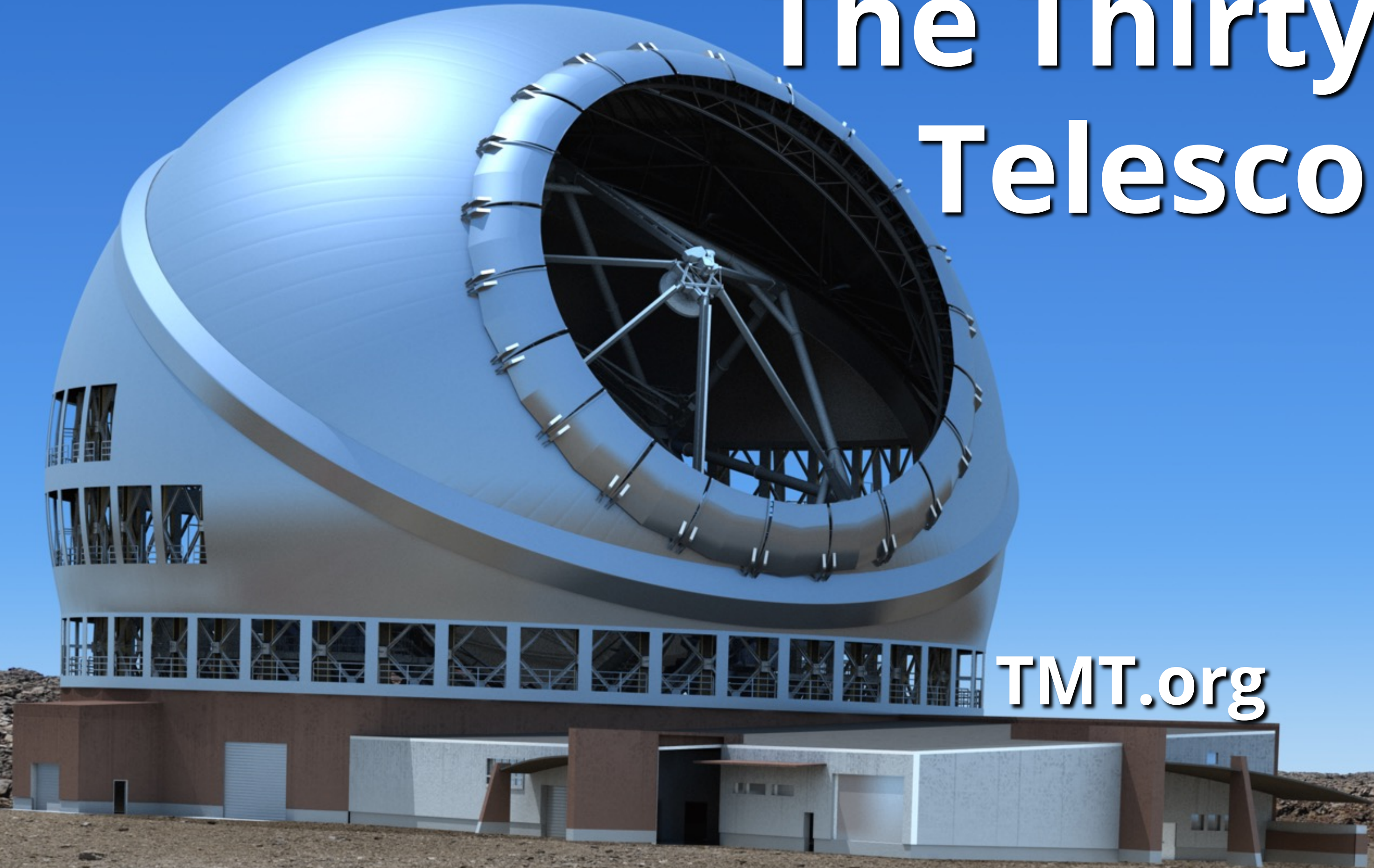
The Thirty Meter Telescope

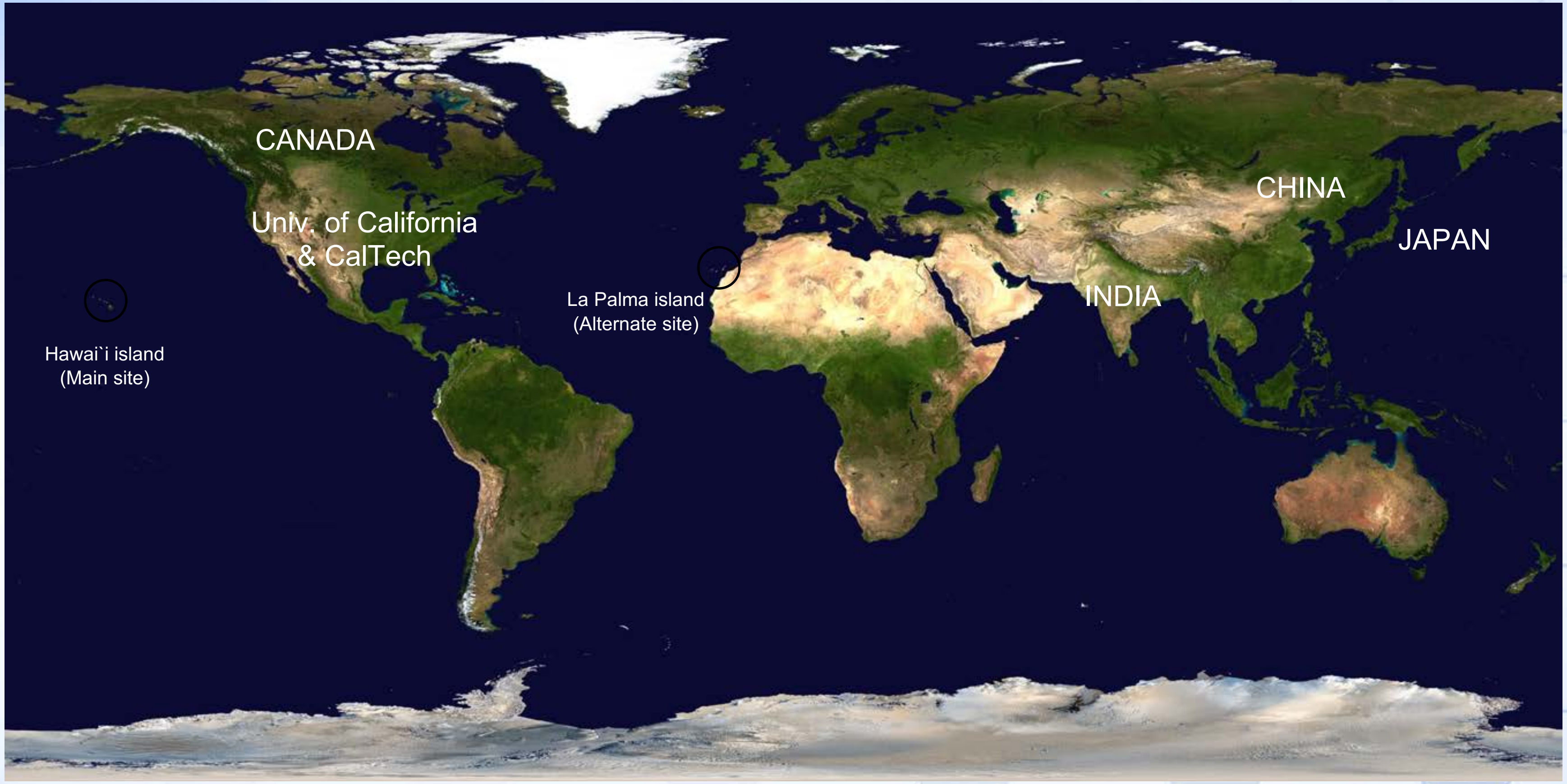


TMT.org

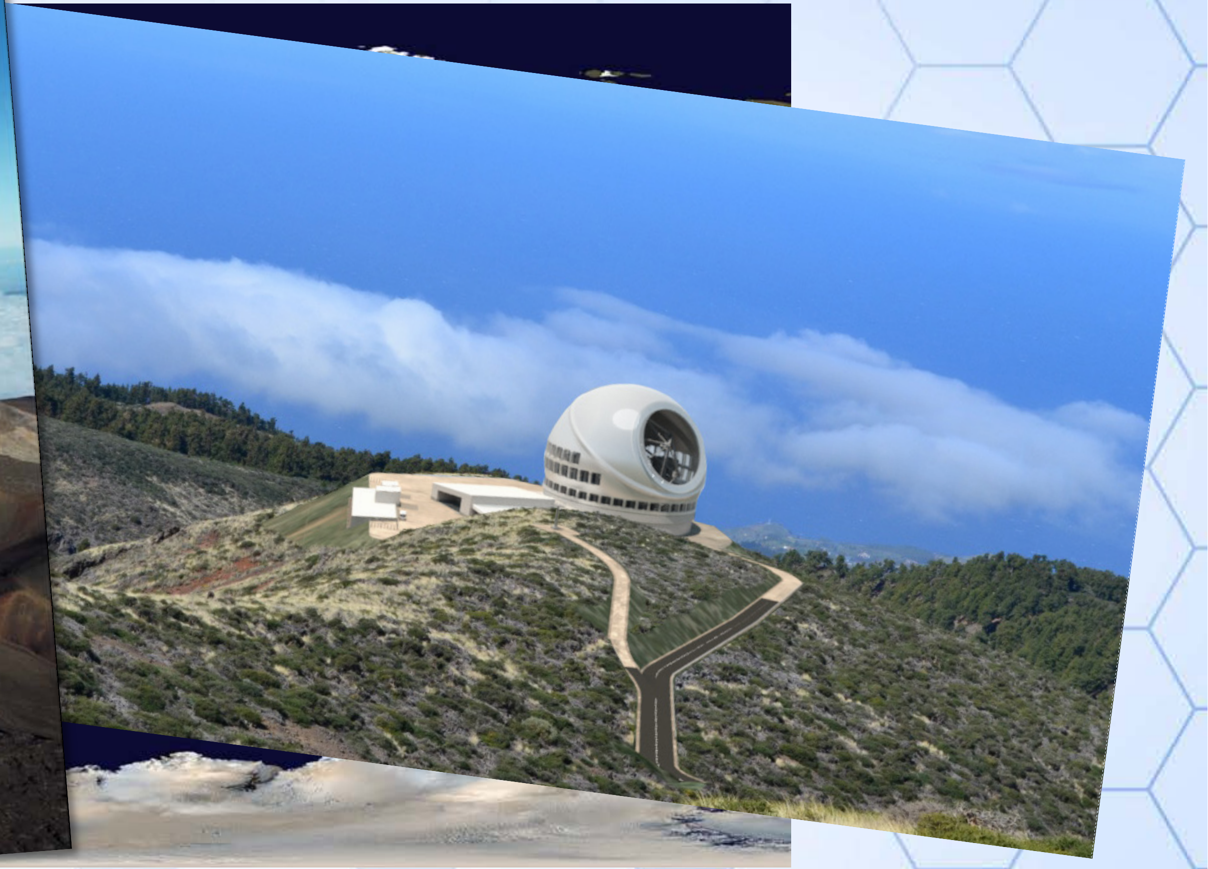
Christophe Dumas

TMT International Observatory, LLC

International Partnership and construction site(s)



International Partnership and construction site(s)



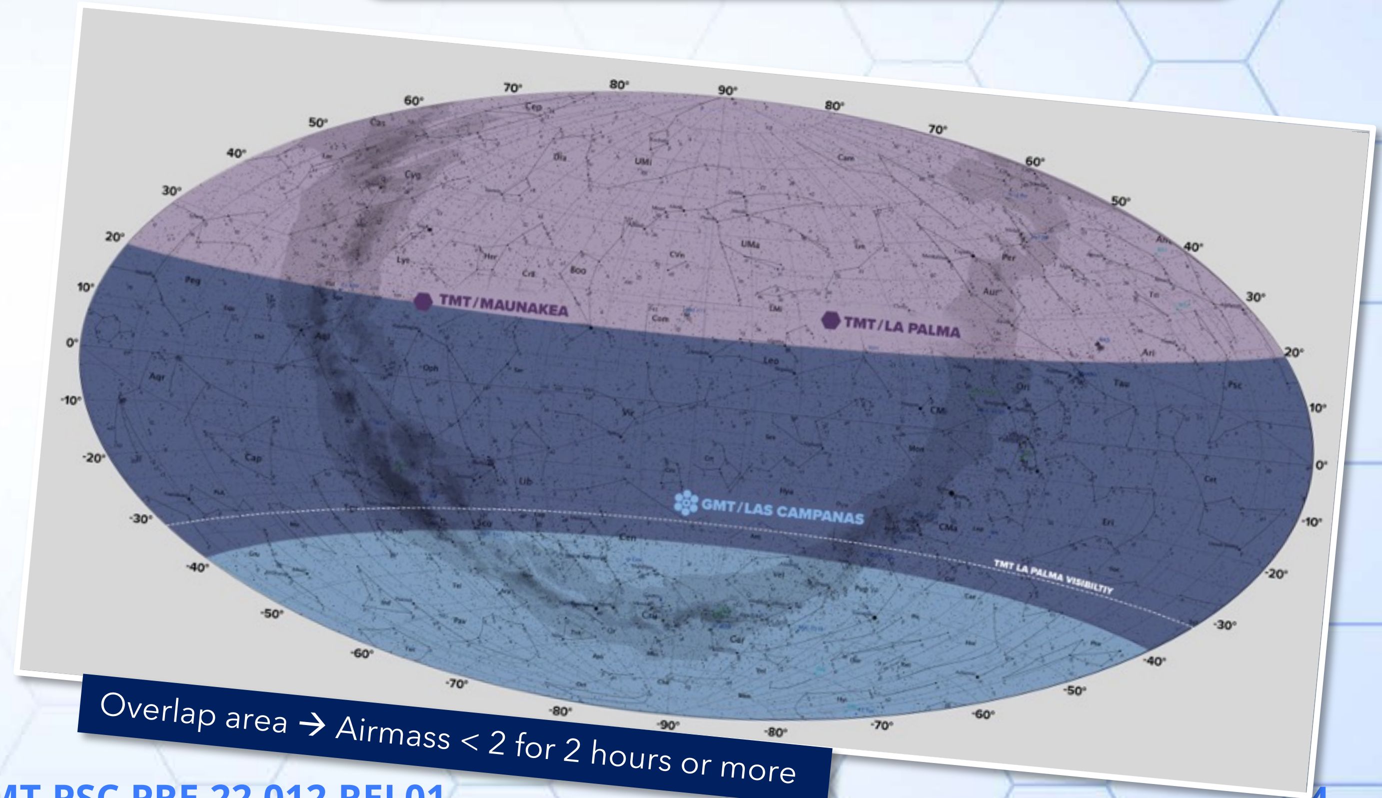
US-ELT Program (USELTP)

2 telescopes, 2 hemispheres, 1 system

All-sky coverage

Broad instrument suite

US-led Key Science Programs



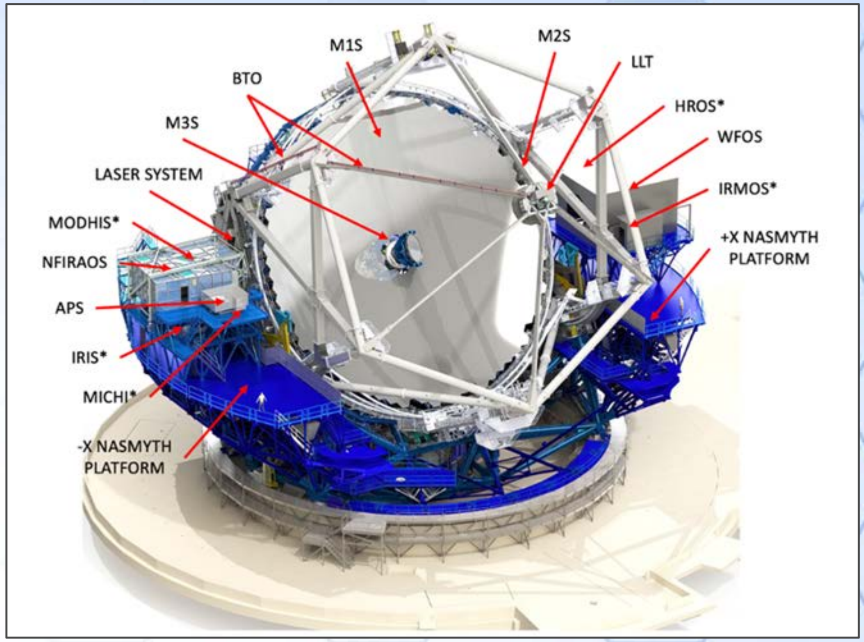
Overlap area → Airmass < 2 for 2 hours or more

Current timeline

- **As of now:** Ready to start construction since 2015 …. but, in Hawaii: Access to Maunakea is not secured; in La Palma: Legal matter still being addressed.
  - Preparing for NSF reviews with the aim for NSF to become a TMT partner if US-ELTP funding is approved by US Congress
- **In a few more years (Y_0):** Construction starts in Hawaii, or La Palma
- **Y_0 + 2-6:** Enclosure base & assembly
- **Y_0 + 6-8:** Telescope structure integration
- **Y_0 + 8-10:** AIV, science commissioning (partial first-light opportunities)
- **Y_0 + 10: "Full"** first-light **(all segments phased/aligned, AO/LGS system up and running, at least IRIS available for science)**

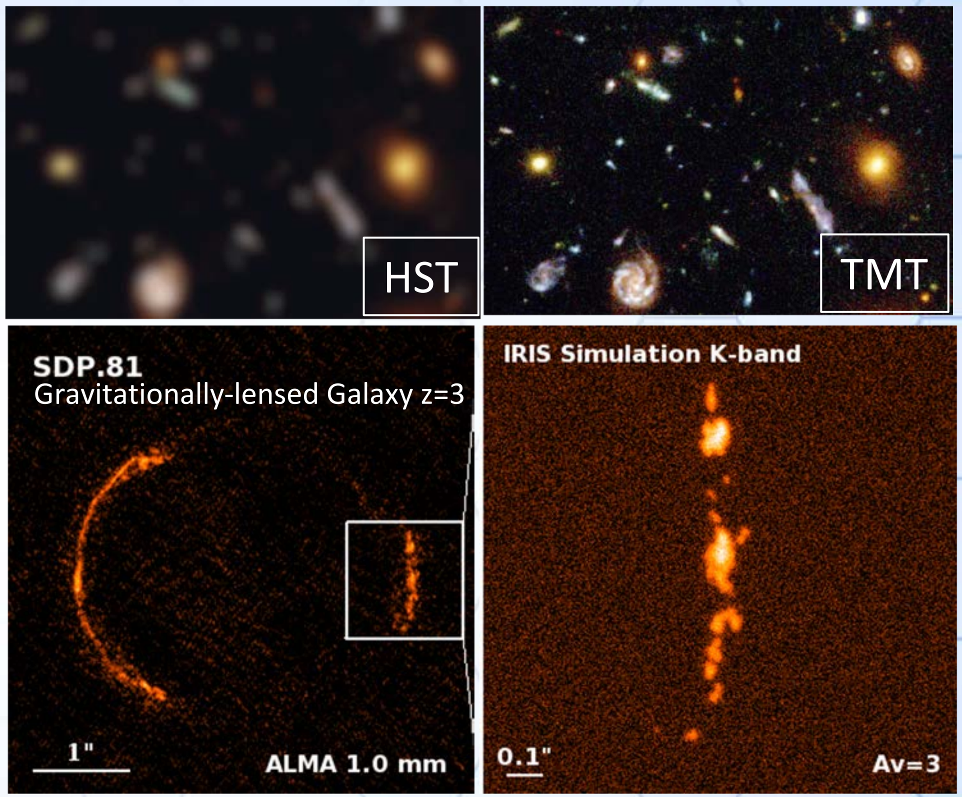
TMT in a Nutshell

- Wide-field, Alt-Az Ritchey-Chretien telescope
- 30 meter diameter primary mirror (**492 hexagonal segments**, 1.44m across corners)
- Passive secondary mirror (Adaptive M2 as upgrade)
- Flat tertiary mirror beam light to Nasmyth focus
- **Up to 8 instruments** on Nasmyth platforms
- **First-light AO system (NFIRAOS):**
  - Laser Guide Star Facility (LGSF) Multi-Conjugate-AO (MCAO)
  - Diffraction-limit at J, H, and K bands, can feed 3 instruments
  - Strehl > 70% in K-band (2.2μm) over 30” diameter field

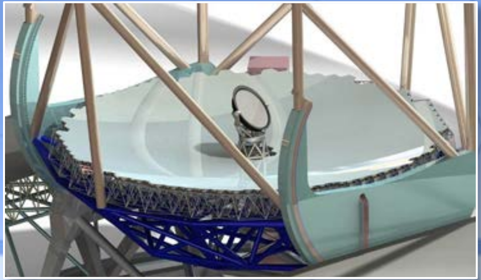


New Discovery Space

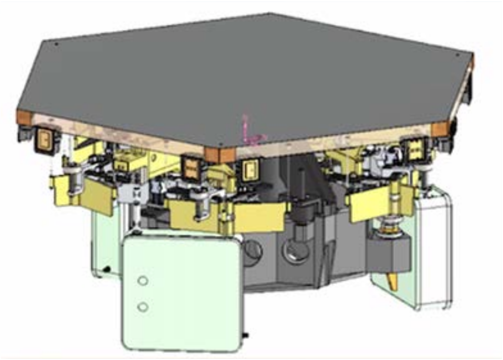
- Sensitivity (S~D^2)
  - 10 times Keck's collecting area
  - 150 times that of the HST
  - AO on point sources: **S~D^4**, i.e. ~80-200 times better than current 8-10m telescopes
- Angular resolution (~λ/D)
  - θ = 0.007 arcsec (at 1μm)
    - 25km @ Jupiter, 1AU @ 100pc
  - 12 times better HST
- Astrometric stability
  - Differential: 50μas in 100s (10 μas systematics)
  - Absolute: 2mas



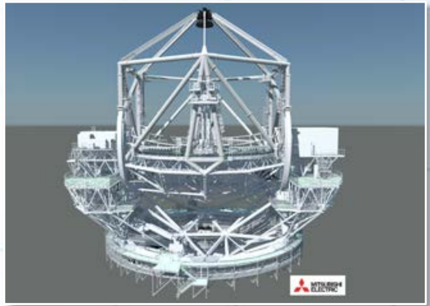
Designed to Maximize Scientific Performances

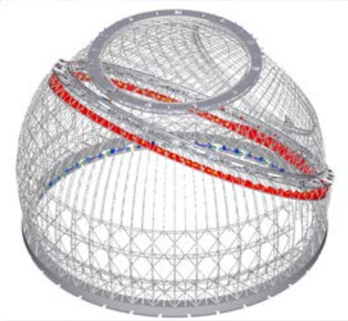


- **Image quality**
  - Mean $PSS_N \geq 0.85$ (only 15% less than perfect telescope optics!)
  - 492 segmented mirrors (2.5mm gap) with high level of control
    - Keck heritage; ~12,000 actuators (M1: tip-tilt, piston, surface figure)
  - Innovative enclosure minimizing dome & telescope seeing



- **Telescope control**
  - Simple design (Ritchey-Chretien)
  - Enabling solar-system observations of rapid moving objects
  - Fast response to Target of Opportunity (ToO) observations
  - Non-sideral tracking adapted to NEOs/Comets





- Optimized **instrumentation** plan addressing 2/3 of TMT science cases as early as first-light
  - Diffraction-limited performances enabled early-on with IRIS/NFIRAOS
- **Excellent site(s)** for adaptive-optics science
- **Science operations** adapted to maximize efficiency, science impact & fast instrument change

Site Characteristics (median values, unless stated)	MK13N (USA)	ORM (Spain)
Altitude of site (m)	4050	2250
Fraction of yearly usable time (%)	72	72
Seeing at 60m above ground (arcsecond)	0.50	0.58
Isoplanatic angle (arcsecond)	2.55	2.31
Atmospheric coherence time (ms)	7.3	6.0
Calculated Adaptive Optics Strehl merit function	1.0	0.93
Precipitable water vapor (% time < 2mm)	54	20
Mean nighttime temperature (°C)	2.3	7.6
Atmospheric Extinction (V_{mag}/airmass)	0.11	0.13

Multi-purpose Discovery Facility

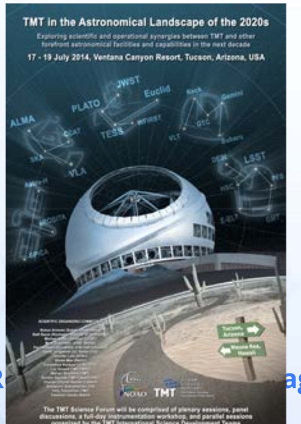
- Contemporary Science
  - Fundamental physics & cosmology
  - Early Universe & galaxy formation
  - Super massive black-holes
  - Nearby-galaxies & Milky-way
  - Star formation & exoplanets
  - Time-domain science
  - Solar-system
- Synergies with other observatories
  - JWST, EUCLID, ROMAN, …
  - ALMA, Rubin, SKA, CTA, …
- Future opportunities
  - 30 m aperture opens new exploration parameter space
    - Gravitational wave's optical transients
    - Multi-wavelengths study programs

2015 TMT Detailed Science Case

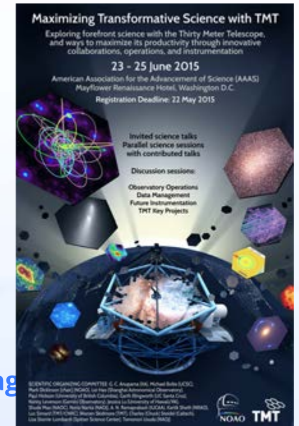
- TMT Detailed Science Case was produced in 2015 from TMT **ISDT** (*and SAC*) inputs. It's been <u>frozen</u> since and a **DSC update is on-going now that Astro2020 has been released**
  - Science cases have evolved since 2015 (e.g.: exoplanets, gravitational wave detection follow-up), and a
- 2015 DSC produced 277 science cases across all fields of astrophysics, including solar system

2013 (Hawaii)

2014 (Tucson)



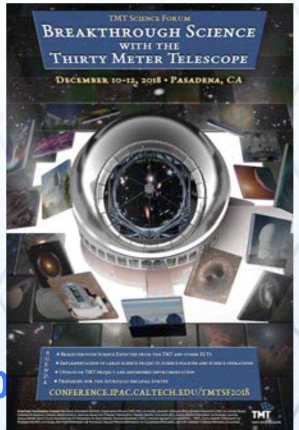
2015 (Wash. D.C.)



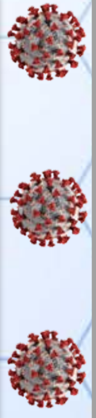
2016 (Japan)

2017 (India)

2018 (Pasadena)



2019 (China)



2023 (Canada)

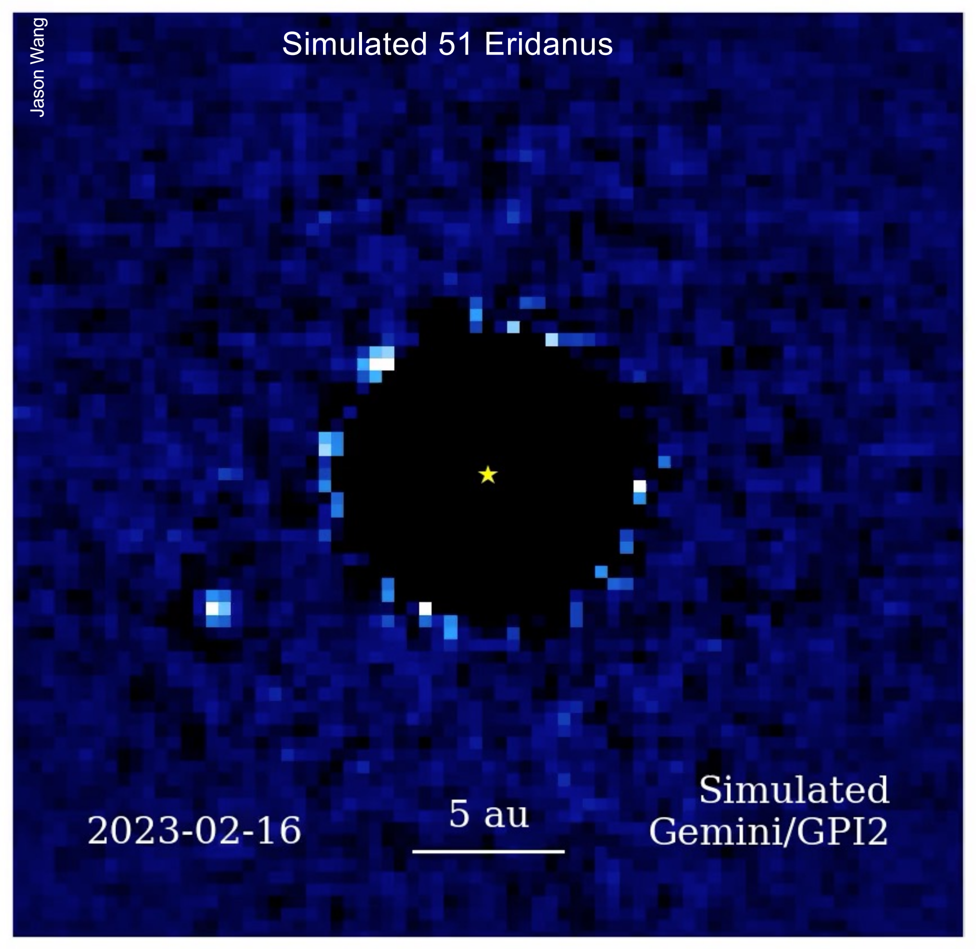
US Decadal Surveys

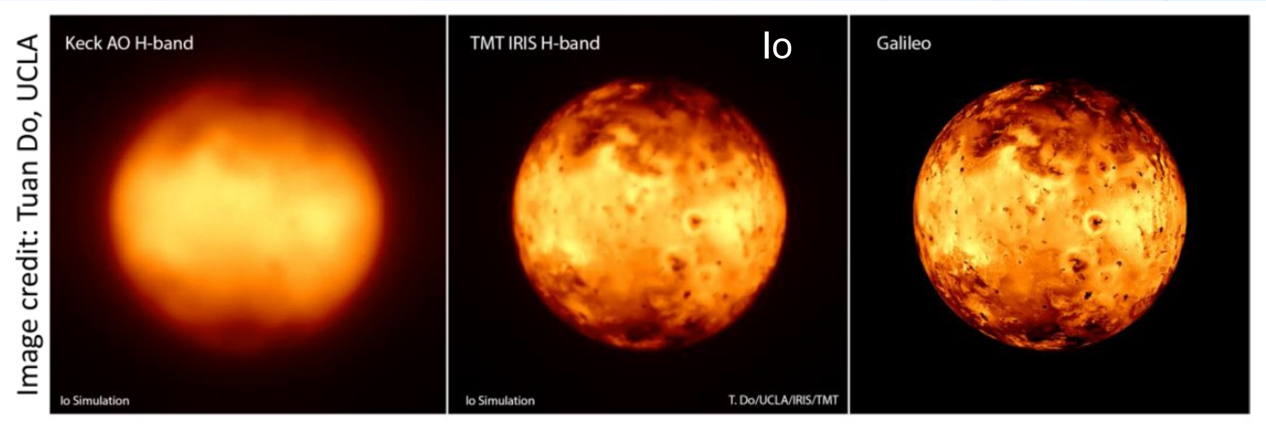
- **Astro2020** was a full endorsement of the science to be addressed by TMT (and the US-ELT at-large) and instruments choice
- Recent Decadal Survey on **Planetary Science and Astrobiology** also emphasized the need for large ground-based facilities to carry out transformational science and support space missions

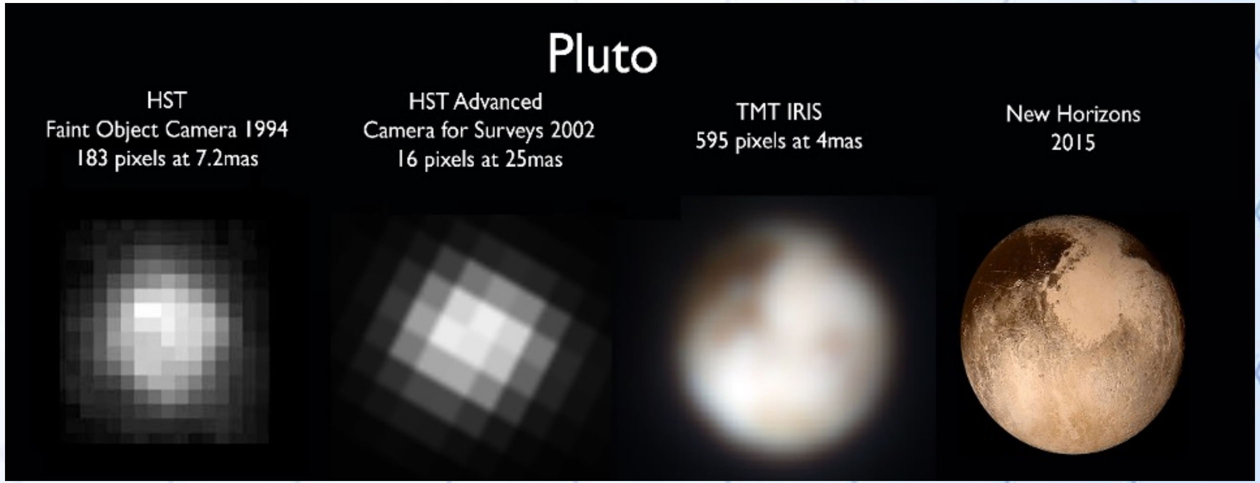
Finding: As stated in the *Pathways to Discovery in Astronomy and Astrophysics for the 2020s* decadal survey, the committee expects the ELT facilities to provide transformational planetary science, but only if the observing programs are adequately funded.

Recommendation: NSF-supported, ground-based telescopic observations provide critical data to address important planetary science questions. The NSF should continue (and if possible expand) funding to support existing and future observatories (e.g., NOIRLab, ALMA, TMT, GMT, ngVLA) and related PI-led and guest observer programs. Planetary astronomers should be included in future observatory plans and development in order to maximize the science return from solar system observations.

Planetary science prospects







TMT spatial resolution for solar system objects

TMT spatial resolution at 1µm and at opposition for selected solar system bodies						
Target	Diameter (km)	Distance (in AU)	Angular diam. (")	Nb resolution elements across apparent diam.	Nb resolution elements across apparent surf.	Spatial resolution (km)
Ceres	952	1.63	0.81	130 (~30 with VLT)	17012	7
Pallas	545	1.29	0.58	94	8920	6
Io	3644	4.09	1.23	199	39442	18
Europa	3122	4.09	1.05	170	28951	18
Titan	5152	8.09	0.88	142	20156	36
Triton	2706	28.87	0.13	21	436	130
Chiron	220	15.96	0.02	3	9	72
Pluto	2390	34.05	0.10	16	245	153
Charon	1210	34.05	0.05	8	63	153
Mars	6780	0.64	14.55	2352	5531644	3
Jupiter	143000	4.09	48.23	7794	60740203	18
Saturn	120500	8.09	20.55	3321	11026150	36
Uranus	51120	18.24	3.86	624	389997	82
Neptune	49530	28.87	2.37	382	146085	130

Science instruments

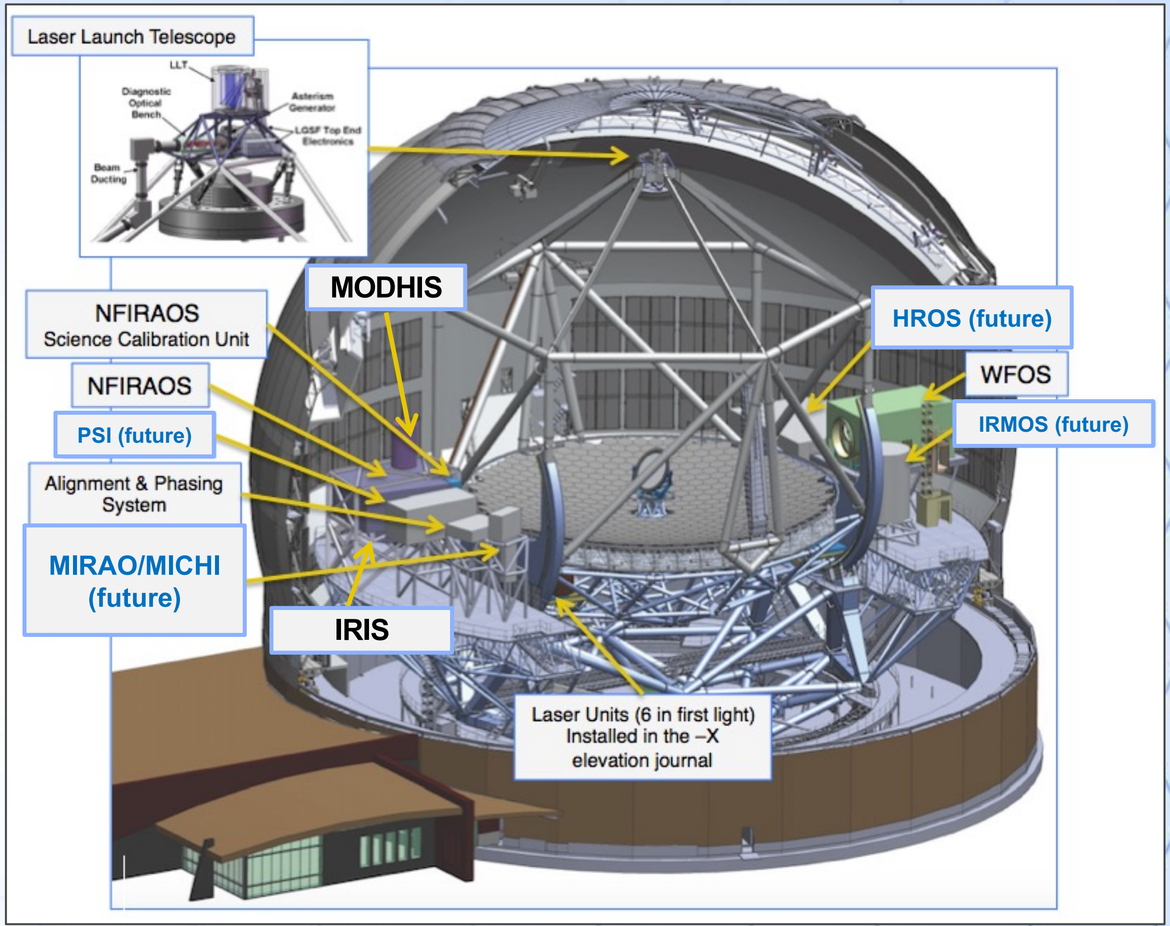
(https://www.tmt.org/page/science-instruments)

ELT Instrumentation “Equivalence Table”

Type of Instrument	TMT	E-ELT
Near-IR, AO-assisted Imager + IFU	IRIS	MICADO & HARMONI
Wide-Field, UV-VIS Multi-Object Spectrometer	WFOS	MOSAIC
Near-IR, AO-assisted High-Res Spectrometer	MODHIS	HIRES
Near-IR Multi-Object Spectrometer	IRMOS	MOSAIC
Mid-IR, AO-assisted Echelle Spectrometer	MICHI	METIS
High-Resolution Optical Spectrometer	HROS	HIRES
High-Contrast Exoplanet Imager	PSI	ELT-PCS

First-light instruments

Instrument and Description	λ Range (μm)	Spectral Resolution	Modes	Field of View
IRIS/Diffraction-Limited NIR Imager and IFS	0.84–2.4	Z, Y, J, H, K, bandpass filters and multiple narrower in band filters. 4,000 and 8,000 (some modes to 10,000)	NGSAO, LGS MCAO	Imager: 34" x 34" @ 0.004"/pix IFU with two slicing techniques Lenslet: 0.512" x 0.512" @ 0.004"/spaxel Slicer: 2.25" x 4.4" @ 0.050"/spaxel
WFOS/Wide Field Optical Spectrometer	0.31–1.0	1,500 and 3,500 using 0.75" slits. Goal of 5,000 currently achieved and higher R available with narrower slits.	SL*	25 (8.3 x 3)-arcmin^2 500" total slit length (up to 60 targets with 8" slits) Imaging: full field @ 0.05"/pixel
MODHIS/Multi-Objective Diffraction-Limited High-Resolution Infrared Spectrograph	0.95–2.4	> 100,000 with 30 cm/s (goal 10 cm/s) Doppler velocity precision	NGSAO, LGS MCAO	4" diameter field of regard (possible that this will be slightly larger)

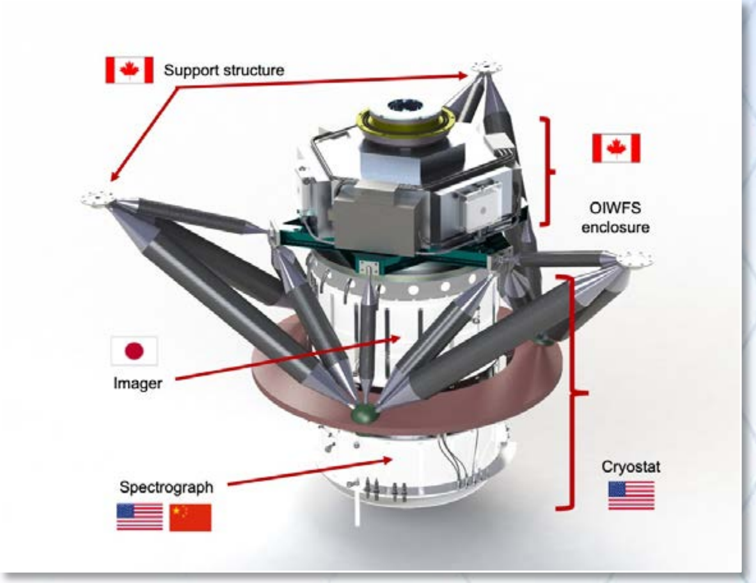


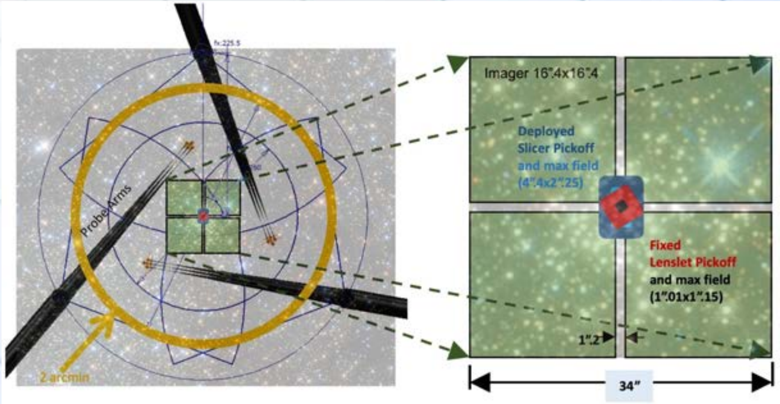
InfraRed Imager and Spectrograph (IRIS) (Final Design)

TMT
Thirty Meter Telescope

P.I.: J. Larkin (UCLA, US)
P.Sc.: S. Wright (UCSD, US)

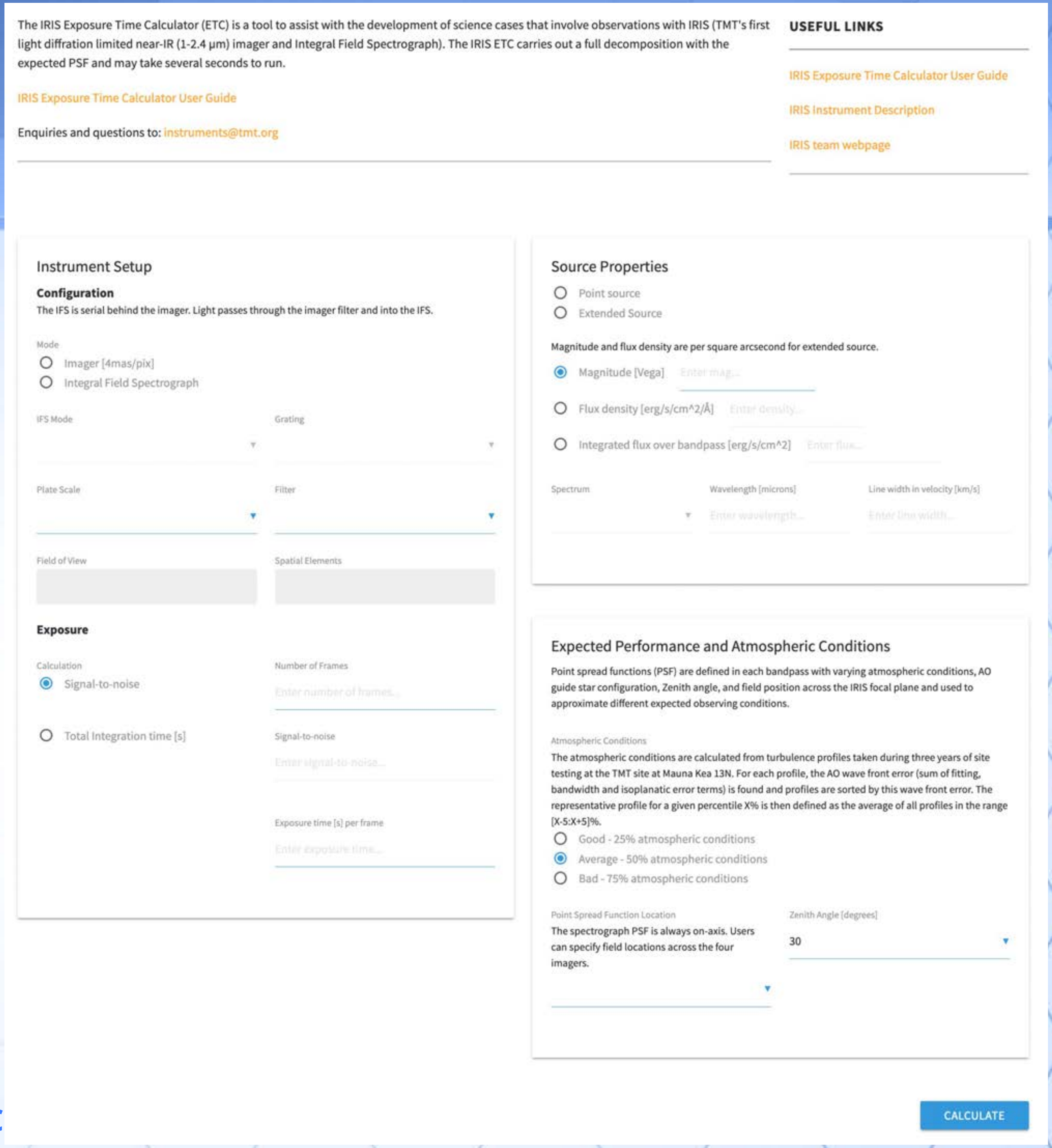
Main Characteristics	
Wavelength coverage	0.84-2.4μm
Adaptive optics capabilities	NFIRAOS/LGS On-instrument wavefront sensors (tip-tilt, focus, distortion)
Wavefront error	< 40nm (fine platescales)
Imaging:	
Imaging FoV	34”x34” (2x2 H4RG-10 arrays, 4mas/pix)
Filters PSS_N	Broad + selection of NB (tbd) (SN~100, 1hr) - H: 26.2, K: 25.6
Spectroscopy:	
Integral-field-spectrograph (IFS) FoV	0.5”, 1.1”, 1.7”, 3.3" (H4RG-15) (from 4mas to 50mas per spaxel)
Resolution Sensitivity	4000, 8000 (SN~10, 15min) - H: 25.8, K: 24.2





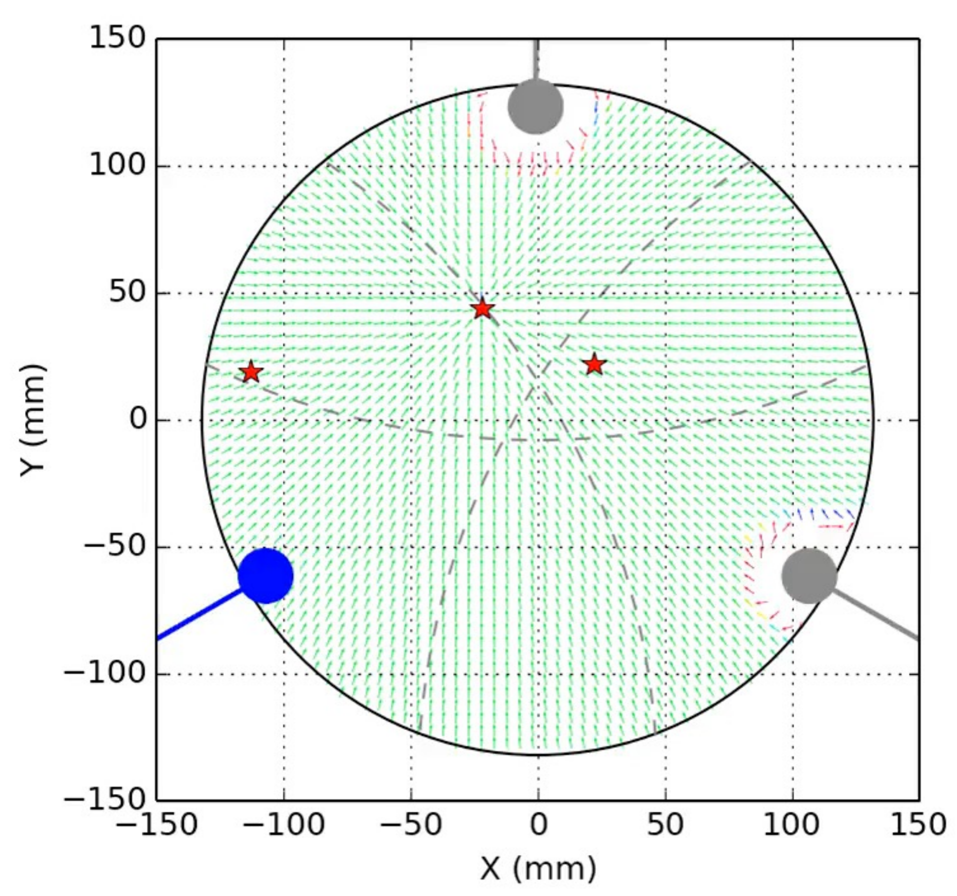
IRIS (Cont'd)

- IRIS ETC available at: https://www.tmt.org/etc/iris

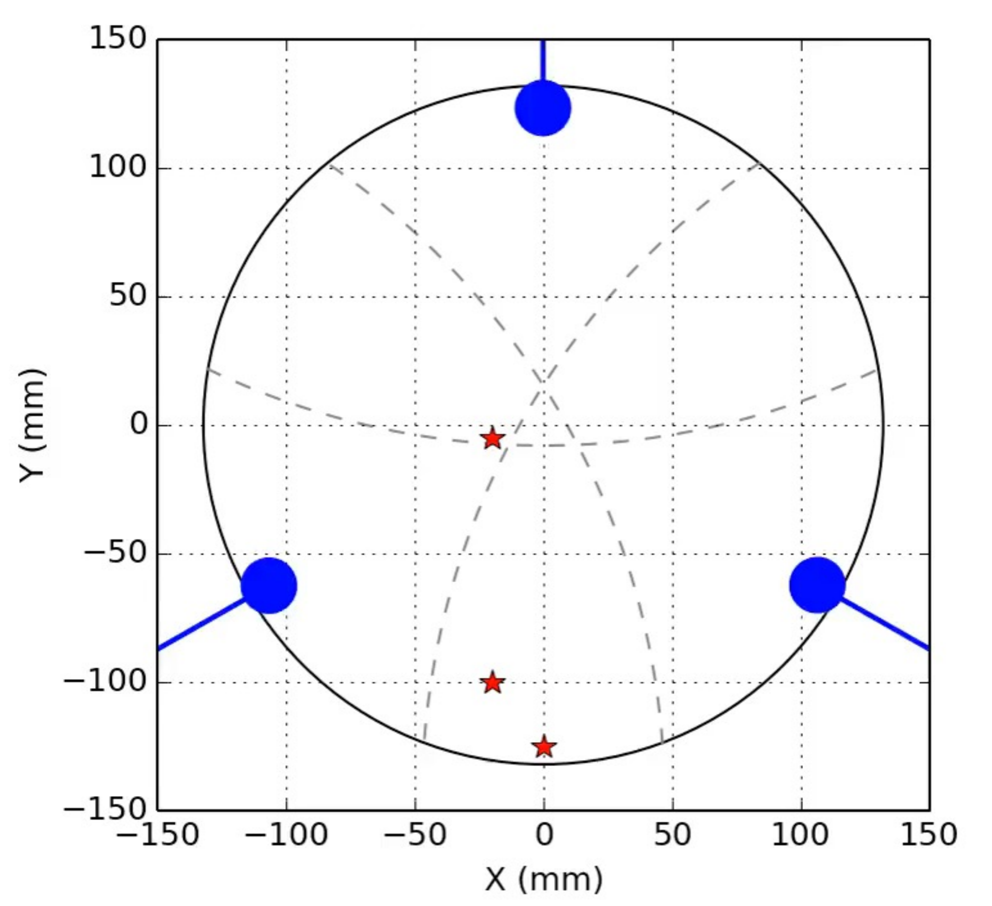


Example OIWFS guide probe acquisitions

Sidereal tracking mode
acquiring on different constellations

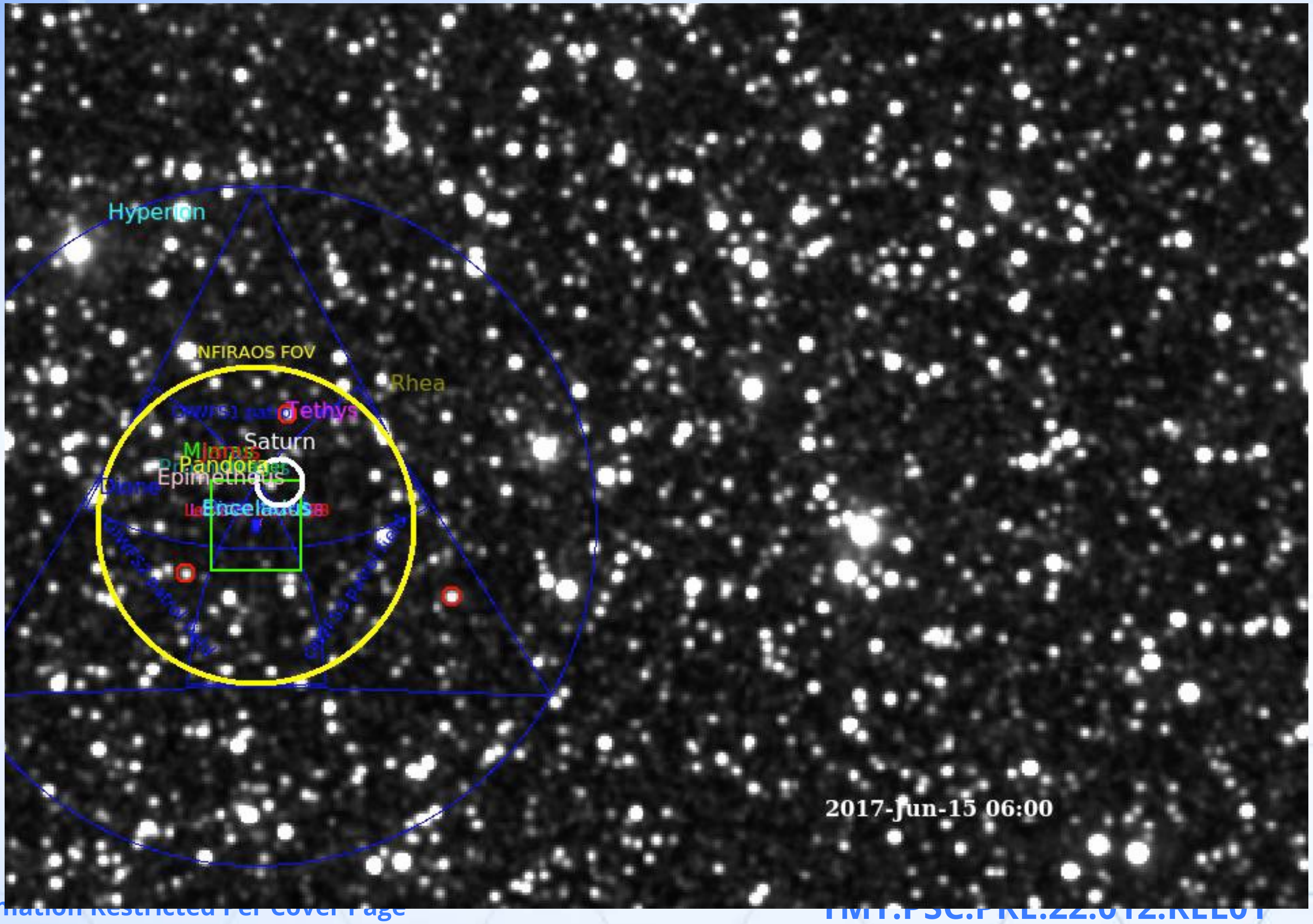


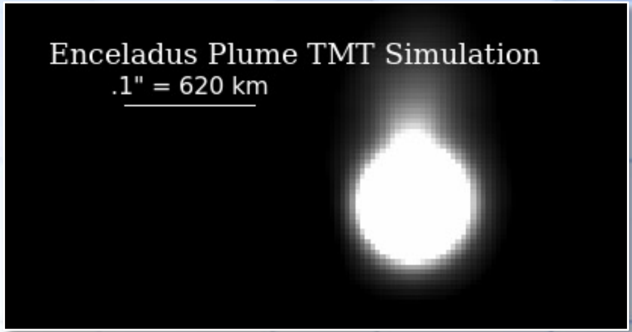
Non-Sidereal tracking mode
for a single target



Guide star planning tool
* Solar System application *

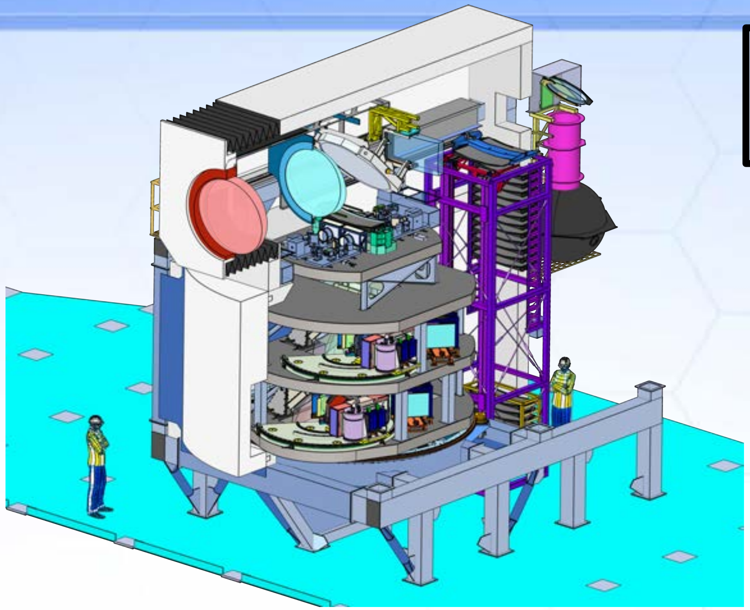
- Observing moons of Saturn (e.g. Enceladus)



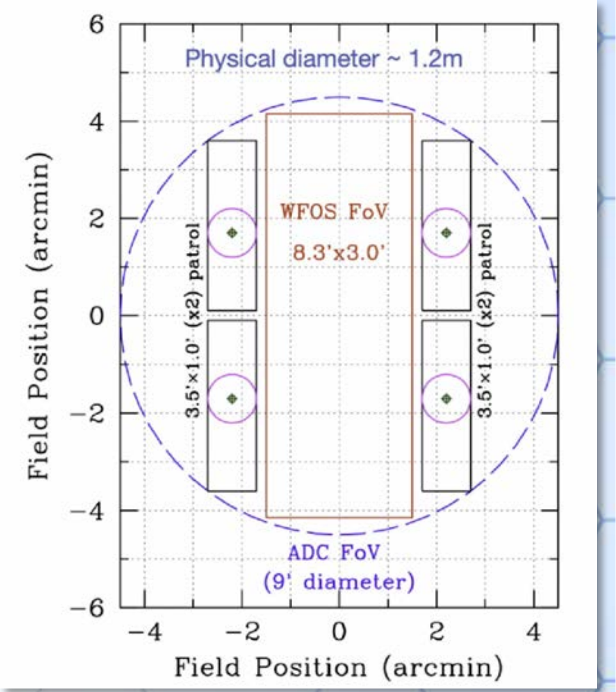


Wide-Field Optical Spectrograph (WFOS) (Conceptual Design)

Main Characteristics	
Wavelength coverage	0.31-1.0μm
Spatial resolution	Seeing-limited; (GLAO with deformable M2 as upgrade)
FoV	~25.5 arcmin^2 (8.3’x3’)
Resolution	1,500-15,000 w. 0.75” slit
MOS	500” total slit length Up to 58 targets
IQ-imaging	<0.45” FWHM
IQ-spectroscopy	0.25”
Sensitivity	SNR=150 @ R=3,500, V=20.5, t_{exp}=5x900s



P.I.: C. Steidel (Caltech, US)
P.Sc.: E. Peng (PKU, China)

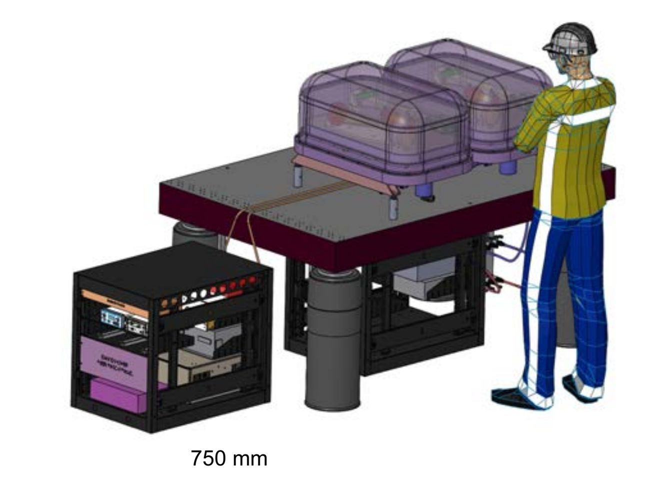


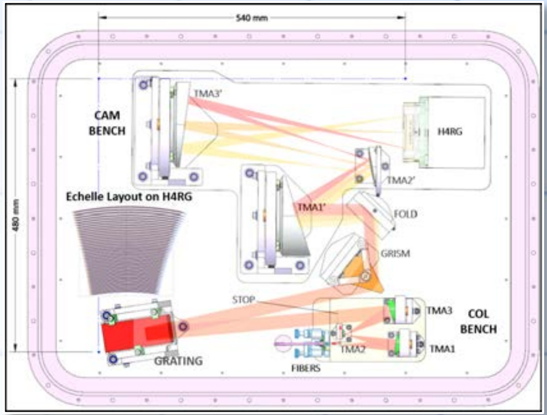
Sensitivity (1hr exp.)	SNR per resolution element	
Magnitude (V)	R=1500	R=3500
24	35.7	23.3
25	14.2	9.3
26	5.7	3.7

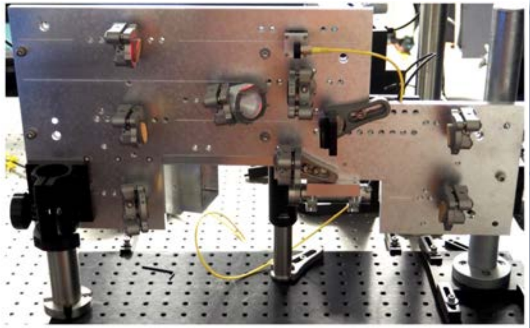
Multi-Objective Diffraction-limited High-resolution Infrared Spectrograph (MODHIS) (Conceptual Design)

P.I.: D. Mawet (Caltech, US)
P.Sc.: Q. Konopacky (UCSD, US)

Main Characteristics	
Wavelength coverage	0.95-2.4μm (yJHK bands simultaneously)
FIU fed by NFIRAOS 1st light AO system	
Patrol field	4”x4” diffraction limited
Resolution	>100,000
Stability	30 cm/s (Laser Frequency Comb)
Single target	1-9 channels w/ object, sky, calib
Contrast	10^{-3} raw contrast at λ/D
Limiting mag.	19^{th} mag, SN=10, t_{exp}=1hr





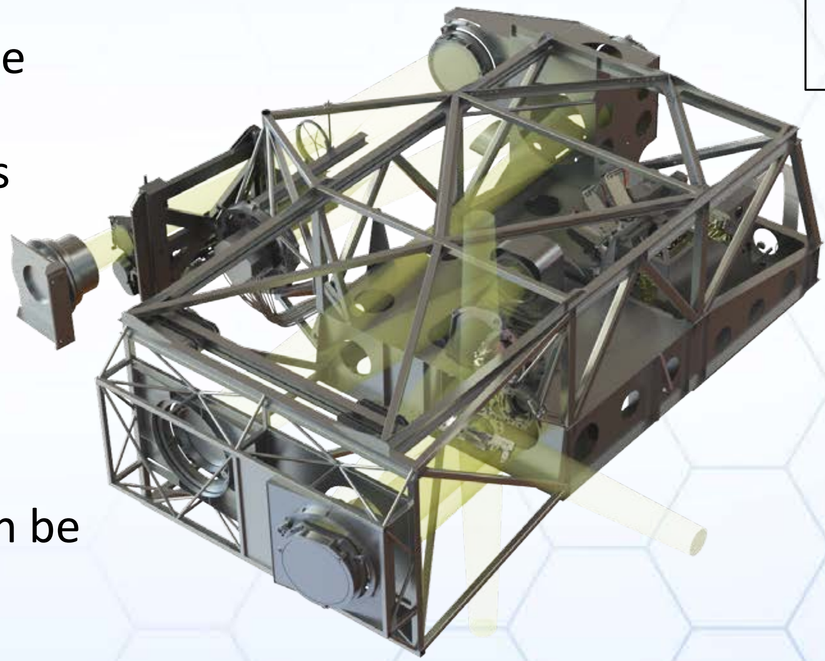


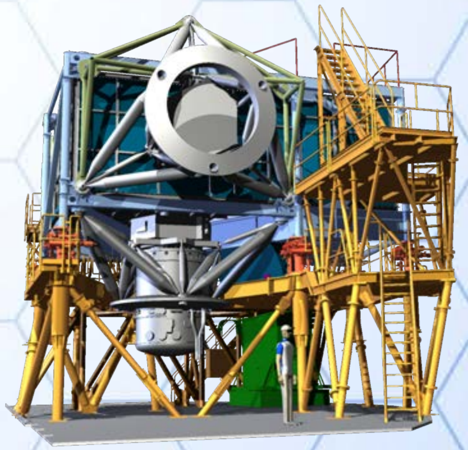
Pathfinder fiber injection unit for Keck Planet Imager and Characterizer (KPIC)

NFIRAOS Requirements & Architecture

- **Diffraction-limit:** J, H, K (Strehl > 70% at 2μm)
- **High throughput:** min. 80% at 0.8-2.4μm
- **Low background:** Thermal emission < 15 % of sky and telescope
- **FOV:** 30” science-field with 2’ clear FoV
  WFS FoV ~ 1arcsec (limitation for extended object!)
- **Differential photometry** 2% for a 2 minute exposure on a 30” FoV at λ = 1 μm
- **Differential Astrometry** 50 μas for a 100 s exposure on a 30” FoV in the H band
- **Available** from **standby** <10 minutes
- **Acquire** a new field < 5 minutes
- **Downtime** unscheduled < 1 per cent
- **Track non-sidereal** targets up to 1.5 arcsecond/sec (i.e. Near-Earth Objects can be observed)

Main architecture components:
- Multi-conjugate wavefront correction
- Cooled at -30°C
- 6 LGS for atmos. tomography
- 3 NGS WFS for tip-tilt/focus within instruments





Thirty Meter Telescope

TMT's center-launched Laser Guide Star

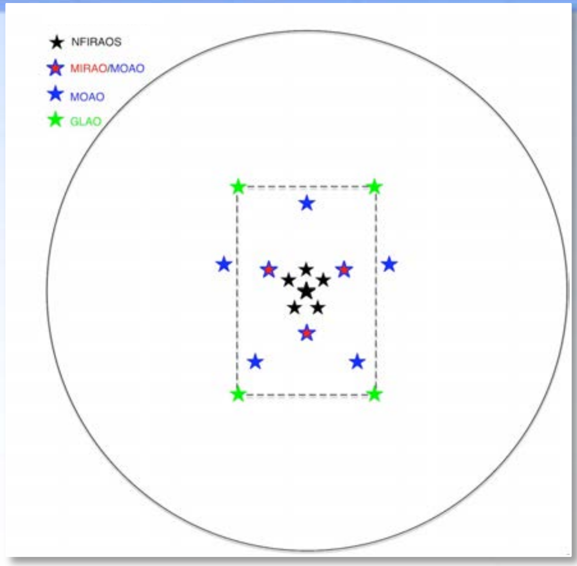
4 ASTERIMS

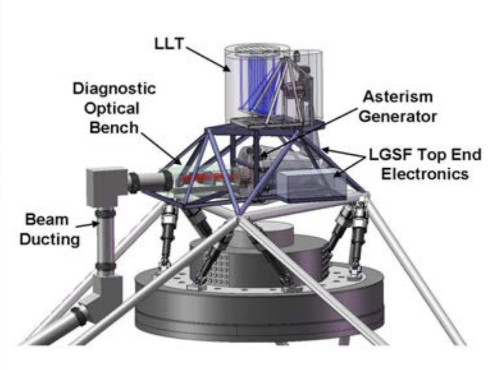
MCAO: 5 on a circle of 35 arcsec and one additional on-axis

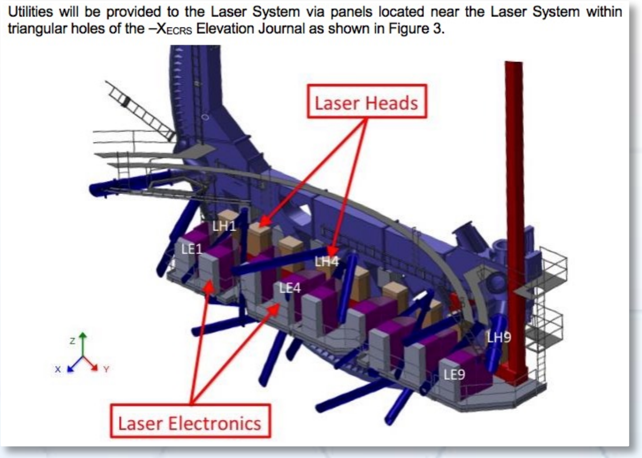
MIRAO: 3 on a circle of radius of 70 arcsec

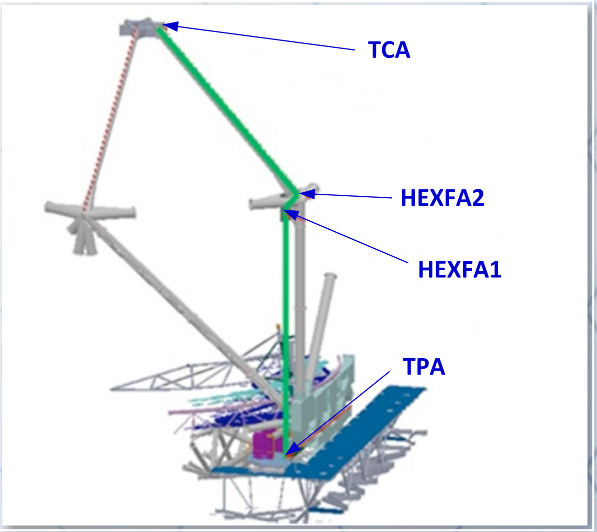
MOAO: 3 on a circle of radius of 70 arcsec and
5 on a concentric circle of radius of 150 arcsec

GLAO: at the corners of a 240 arcsec x 558 arcsec rectangle



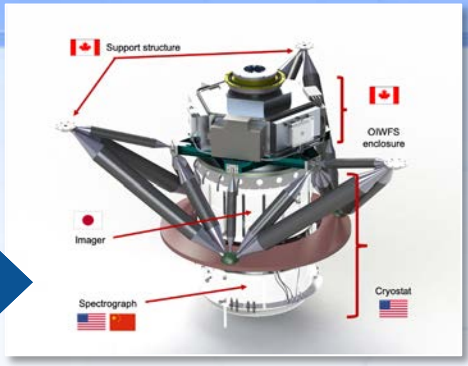


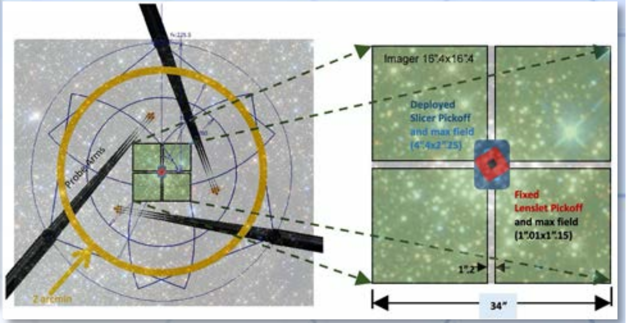


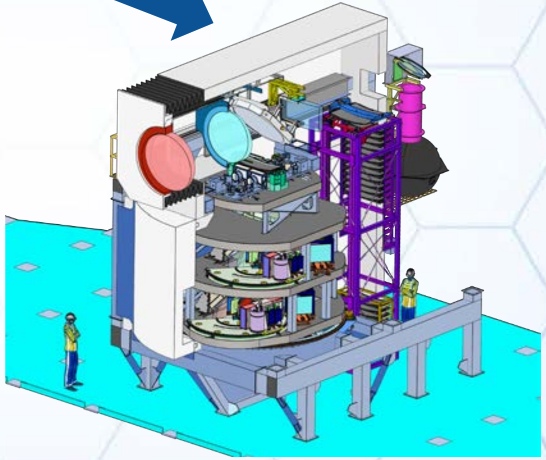


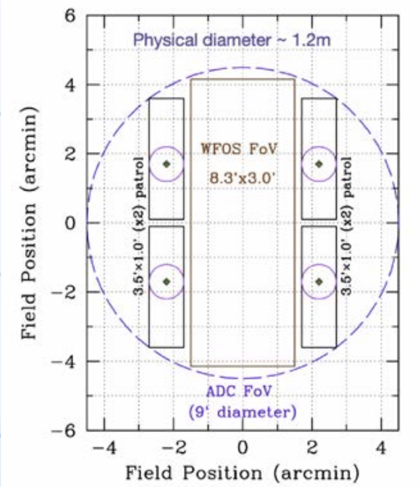
Instrumental Capabilities (first-light)

Instrument and Description	λ Range (μm)	Spectral Resolution	Modes	Field of View
IRIS/Diffraction-Limited NIR Imager and IFS	0.84–2.4	Z, Y, J, H, K, bandpass filters and multiple narrower in band filters. 4,000 and 8,000 (some modes to 10,000)	NGSAO, LGS MCAO	Imager: 34” x 34” @ 0.004”/pix IFU with two slicing techniques Lenslet: 0.512” x 0.512” @ 0.004”/spaxel Slicer: 2.25” x 4.4” @ 0.050”/spaxel
WFOS/Wide Field Optical Spectrometer	0.31–1.0	1,500 and 3,500 using 0.75” slits. Goal of 5,000 currently achieved and higher R available with narrower slits.	SL*	25 (8.3 x 3)-arcmin^2 500” total slit length (up to 60 targets with 8” slits) Imaging: full field @ 0.05”/pixel
MODHIS/Multi-Objective Diffraction-Limited High-Resolution Infrared Spectrograph	0.95–2.4	> 100,000 with 30 cm/s (goal 10 cm/s) Doppler velocity precision	NGSAO, LGS MCAO	4” diameter field of regard (possible that this will be slightly larger)

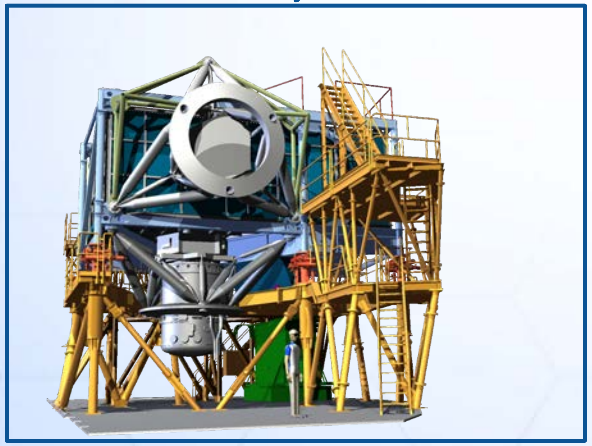


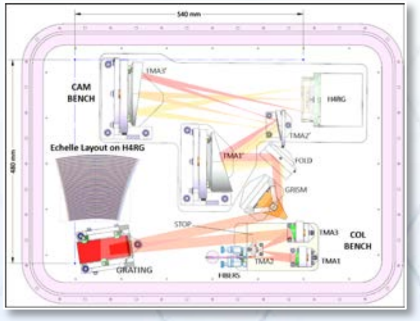






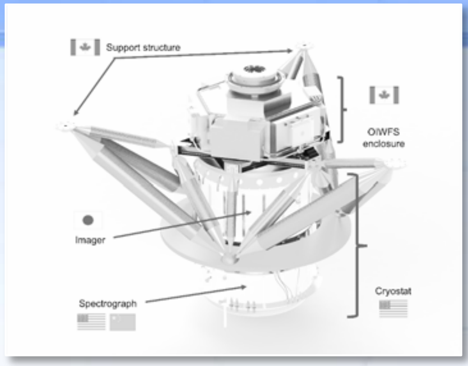
NFIRAOS: TMT AO facility

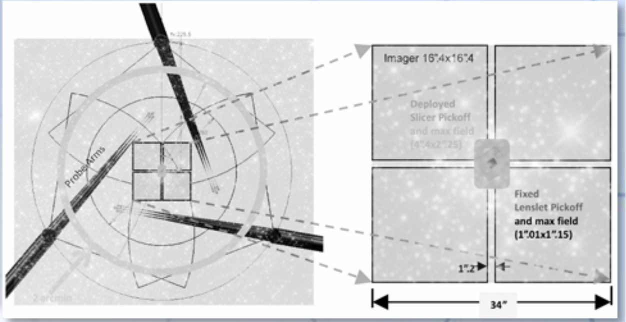


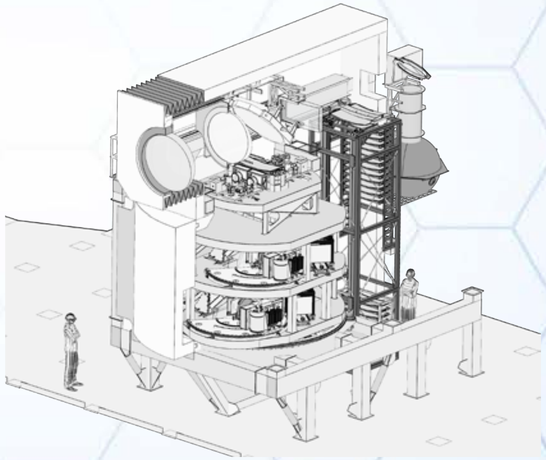


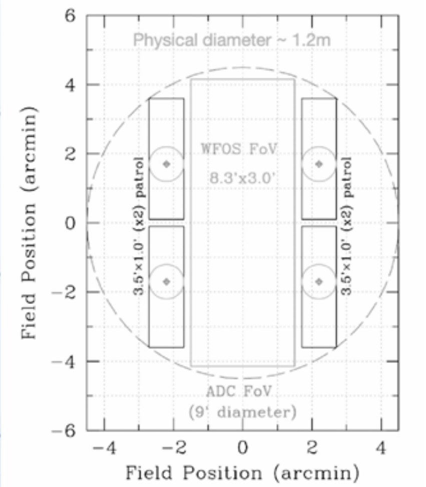
Instrumental Capabilities (first-light & first-decade)

Instrument and Description	λ Range (μm)	Spectral Resolution	Modes	Field of View
IRIS/Diffraction-Limited NIR Imager and IFS	0.84–2.4	Z, Y, J, H, K, bandpass filters and multiple narrower in band filters. 4,000 and 8,000 (some modes to 10,000)	NGSAO, LGS MCAO	Imager: 34” x 34” @ 0.004”/pix IFU with two slicing techniques Lenslet: 0.512” x 0.512” @ 0.004”/spaxel Slicer: 2.25” x 4.4” @ 0.050”/spaxel
WFOS/Wide Field Optical Spectrometer	0.31–1.0	1,500 and 3,500 using 0.75” slits. Goal of 5,000 currently achieved and higher R available with narrower slits.	SL*	25 (8.3 x 3)-arcmin^2 500” total slit length (up to 60 targets with 8” slits) Imaging: full field @ 0.05”/pixel
MODHIS/Multi-Objective Diffraction-Limited High-Resolution Infrared Spectrograph	0.95–2.4	> 100,000 with 30 cm/s (goal 10 cm/s) Doppler velocity precision	NGSAO, LGS MCAO	4” diameter field of regard (possible that this will be slightly larger)
PSI/Planetary System Instrument	0.6–5.3	(fiber fed) High resolution R > 100K (IFS) Medium resolution R > 5,000 (IFS) Low resolution R > 50	ExAO	2–5.3 μm only: 1.2” x1.2” (low resolution) 0.15” x 0.15” (medium resolution)
MICHI/mid-IR Imager, IFU and Spectrometer	3.4–13.8	Imager < 100, IFS 600–1,000, Spectrometer 120,000	MIRAO	Imager: 28.1” x 28.1” @ 0.027.5” mas/pix N band IFU: 0.175” x 0.07” (35 mas/spaxel)
HROS/High-Resolution Optical Spectrograph	0.31–1	Single Object: 100,000 & 50,000 (fibers) 40,000 & 20,000 (slits) Multi-Object: 25,000	SL, GLAO	> 10” in diameter (single object mode) 10’–20’ diameter (multi-object mode)
IRMOS/IR Multi-Object Spectrograph	0.8–2.5	2,000–10,000	MOAO	> ten 3” IFUs deployable within a 5’ diameter field



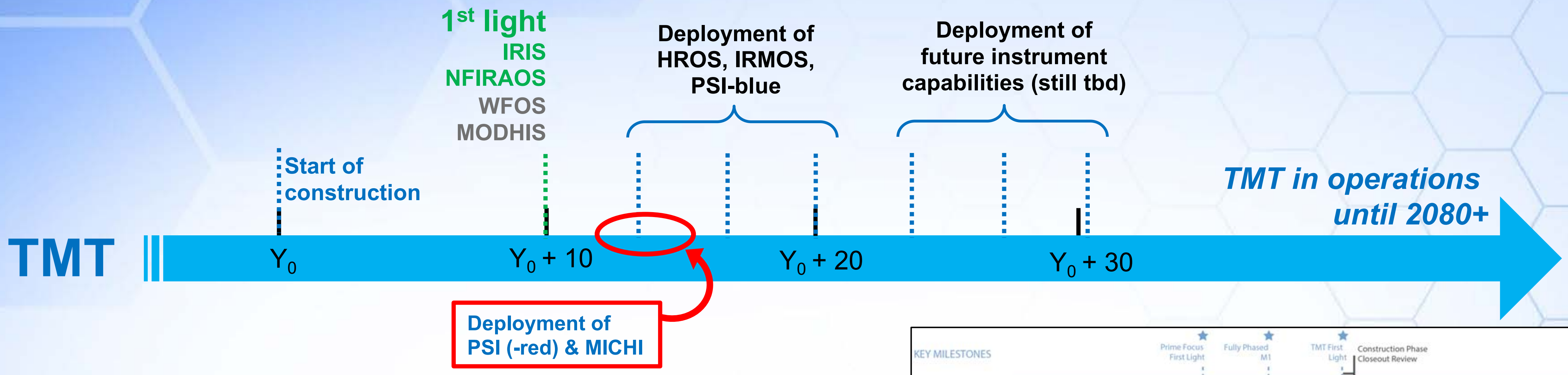


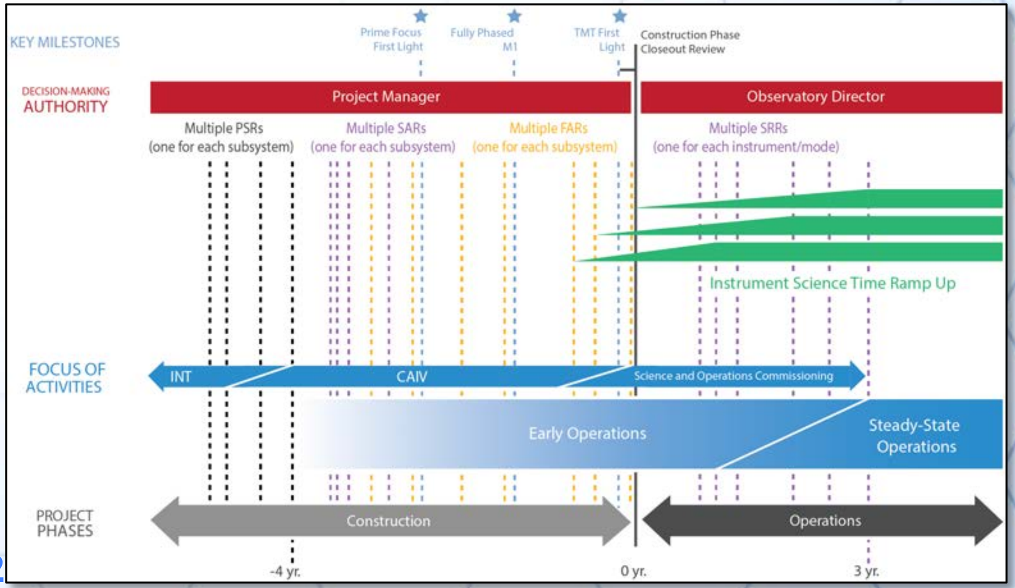




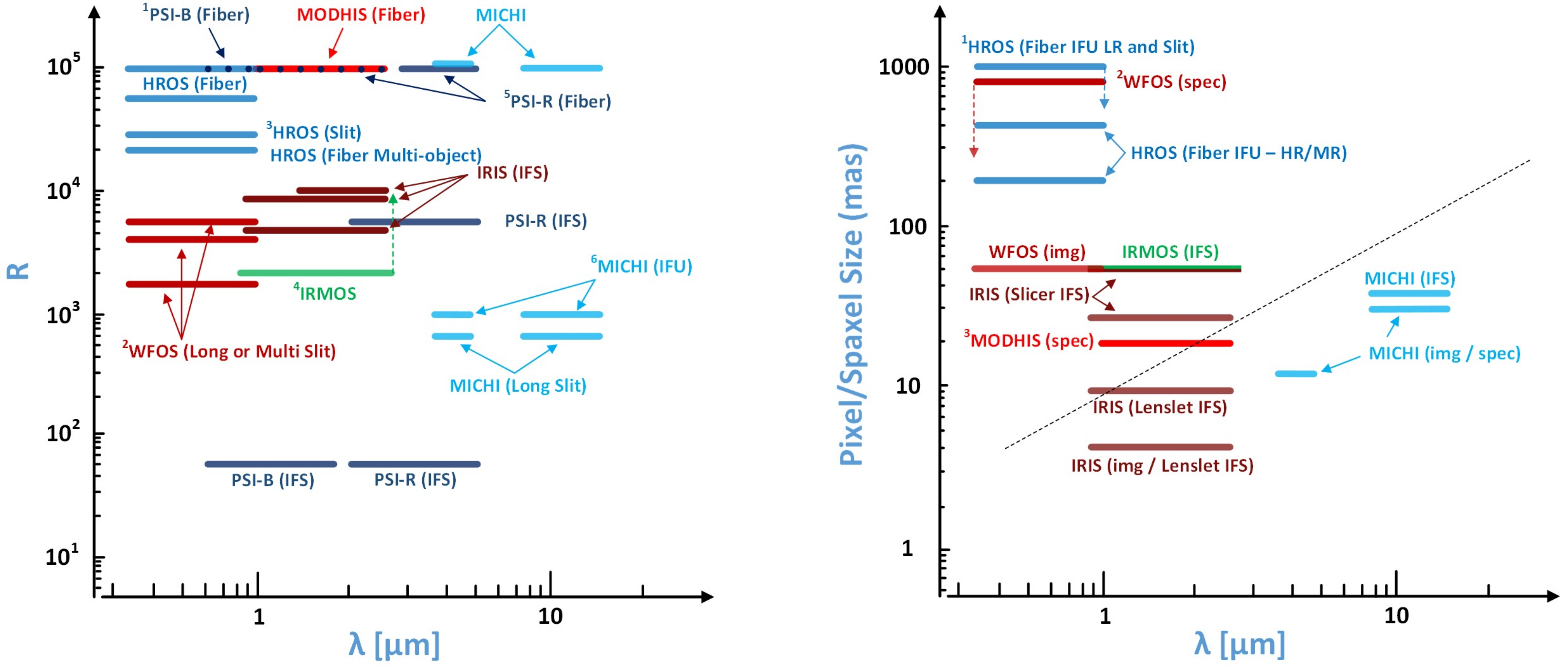
REL01

Tentative timeline of instruments deployment (1st light and 1st decade)

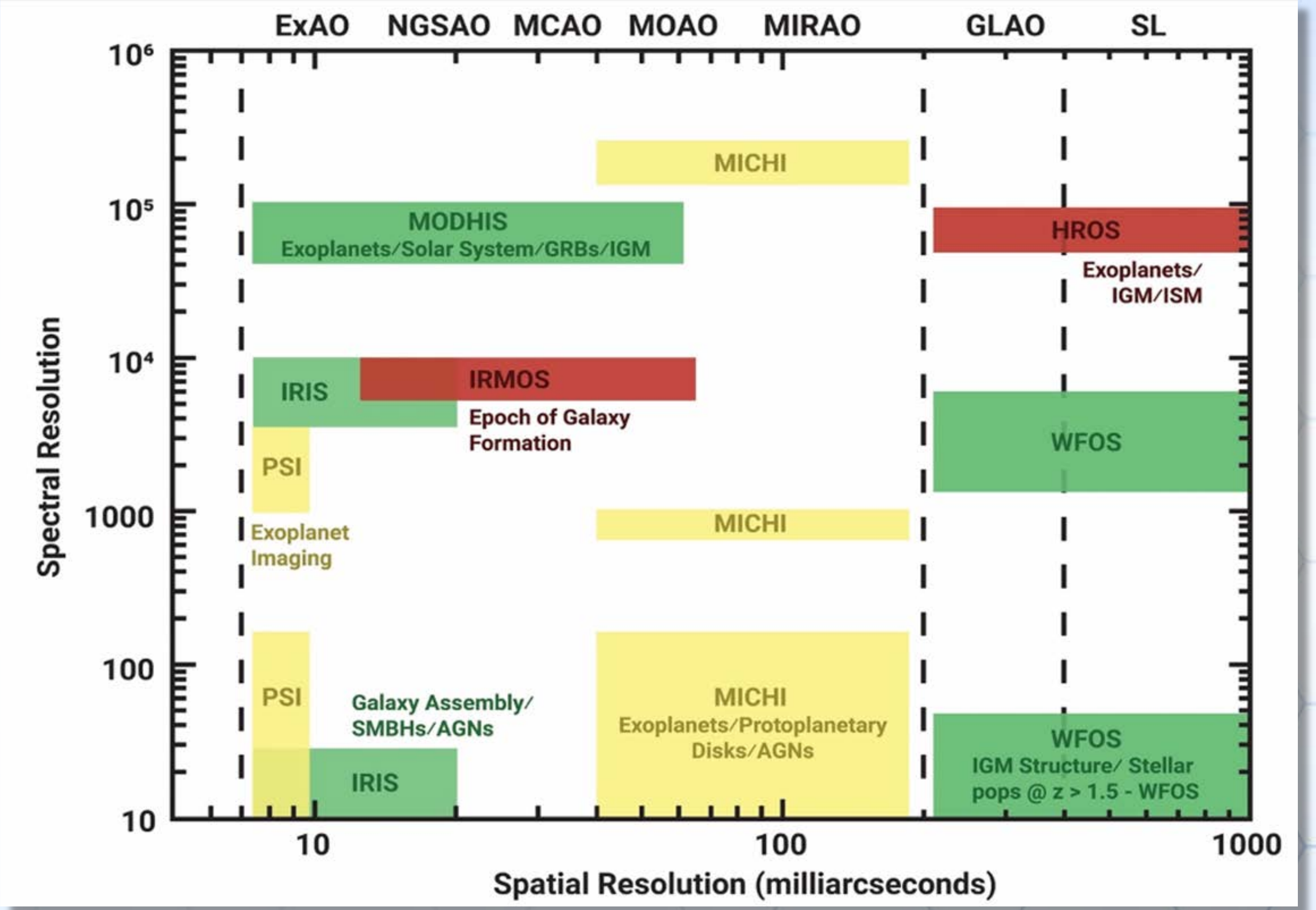




Discovery Space:
First-light & First-decade Instruments

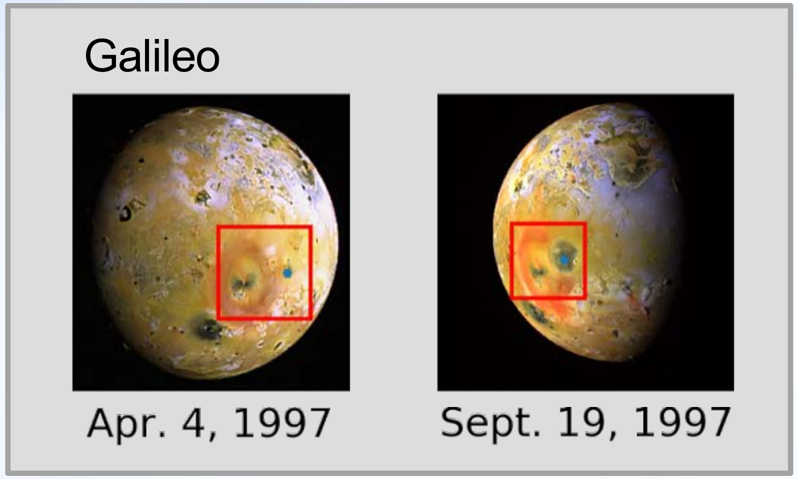


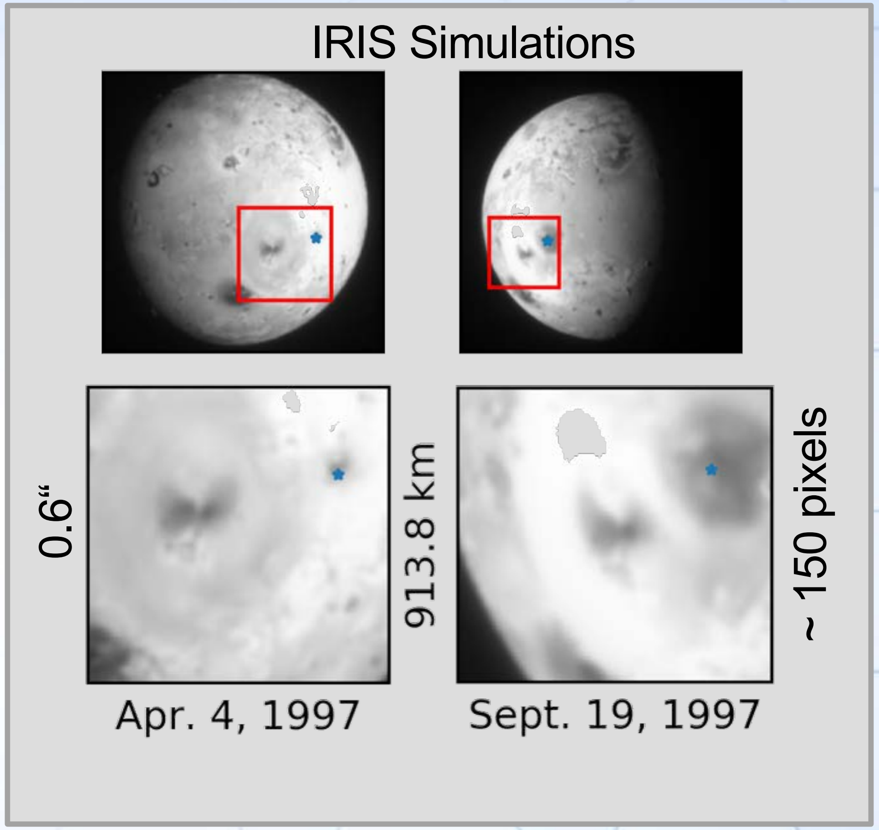
Discovery Space: First-light & First-decade Instruments (Cont'd)



Io: Monitoring Changes in Lava Fields

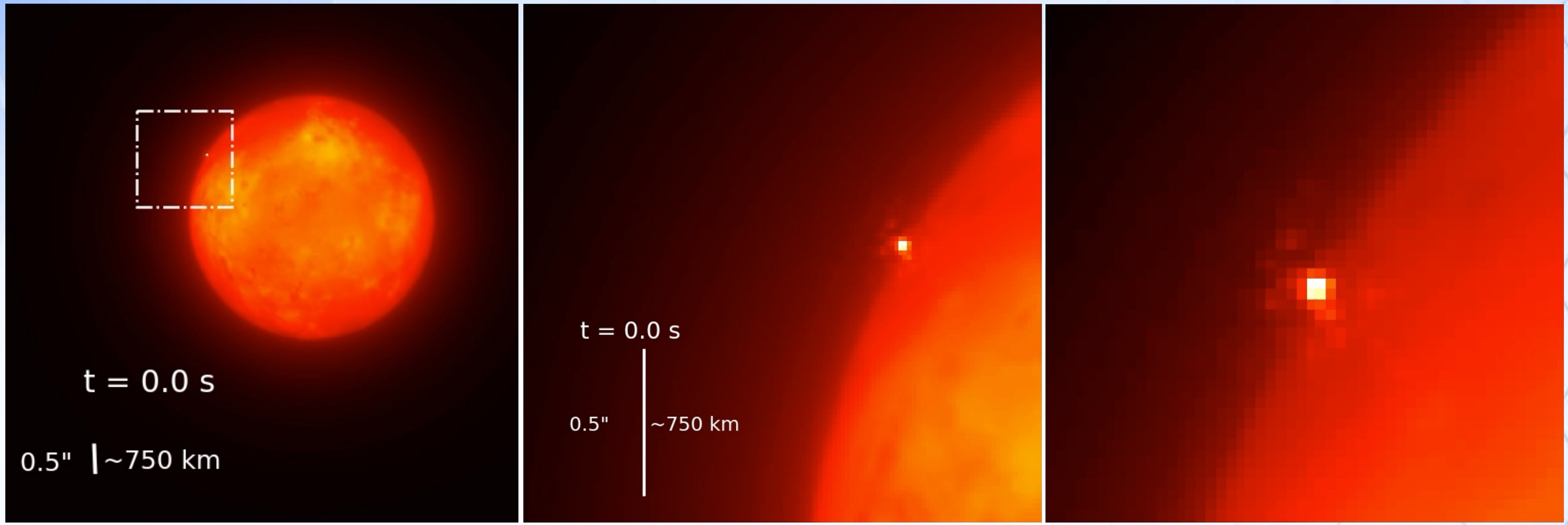
Increased spatial resolution allows the direct observation of changes in the volcanic paterae of Jupiter's moon Io.





IRIS/TMT – N. Rundquist

Io: Studying Active Volcanic Plumes



IRIS/TMT – N. Rundquist

The spatial resolution and sensitivity afforded by IRIS will allow unprecedented ground-based detection of the volcanic features of Io.

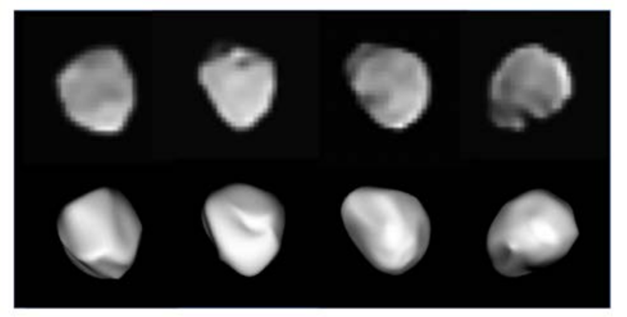
Small bodies

- Asteroids
  - Satellites & rings: Search and characterization
  - 3-D shape, internal structure and collision history
  - Surface composition (mineralogy, ices, organics)

- Comets
  - 1-5μm high-res spectroscopy is fundamental to study properties (H_2O, CH_3OH, CO, C_2H_2 and HCN) → MODHIS, MICHI
    - D/H ratio, nuclear spin temperatures of some species (e.g. NH_3, H_2O and dissociated products). Organic and prebiotic chemistry
    - Abundances → origin (Oort, Kuiper-belt)
    - Nucleus imaging in narrow-band filters with IRIS
  - Spectroscopy in the blue/UV (λ<0.4μm)→ WFOS, HROS

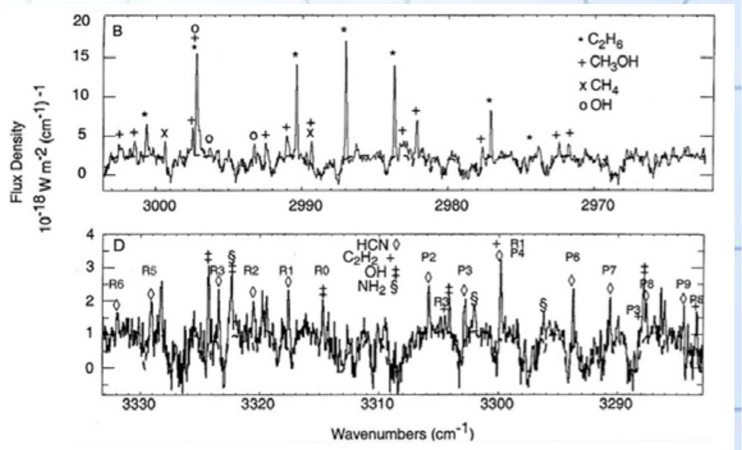
IRIS, MICHI: Low-res spectroscopy: λ= 1-15 μm

IRIS, PSI: AO imaging: 0.8-2μm



HROS, WFOS, MODHIS, MICHI: Low/High-res spectroscopy: λ= 0.4-15 μm

WFOS, IRIS: Vis/near-IR imaging (MCAO)



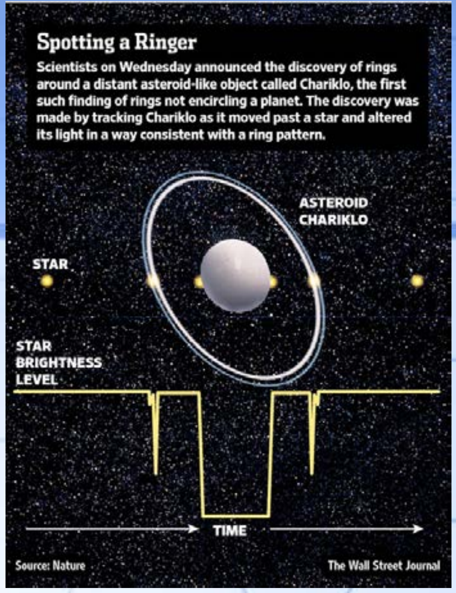
Small bodies (Cont'd)

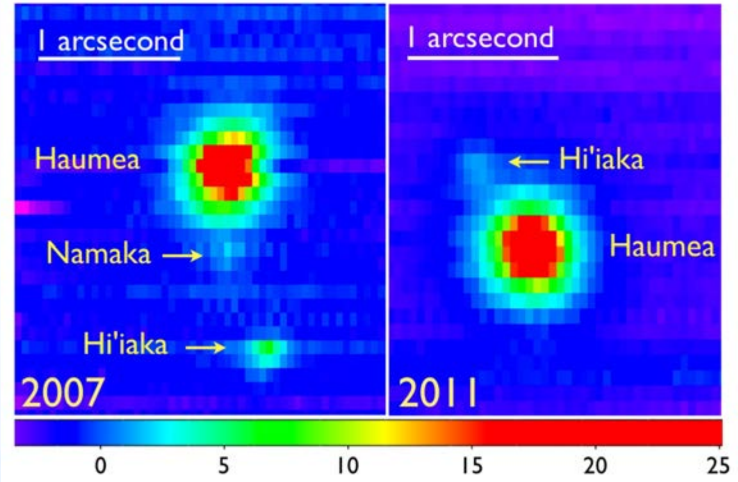
- Centaurs & Trans-Neptunians
  - Surface variability & cryo-volcanism activity
  - Ring structures, satellites
  - Bulk mass & density
  - Composition (ices: e.g. H_2O, N_2, CO_2, CH_4, C_2H_6, CH_3OH, etc)
    - Ice spatial distribution through rotational mapping or disk-resolved mapping for largest bodies

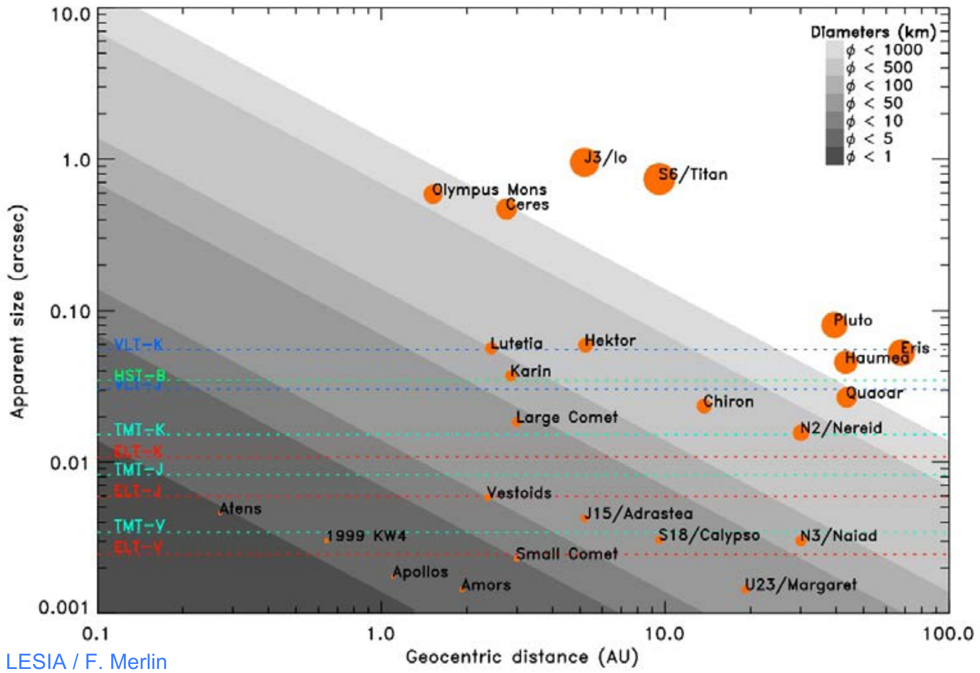
IRIS: Low-res spectroscopy: λ= 1-2.5 μm

IRIS, WFOS: Fast photometry (occultations)

IRIS, PSI: AO imaging: 0.8-2μm

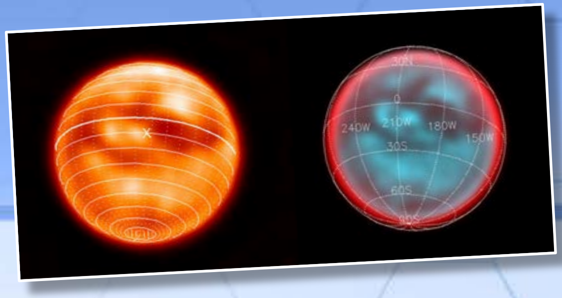




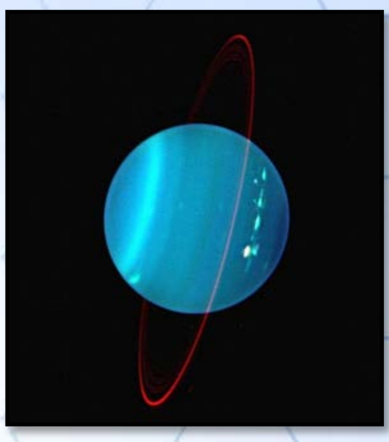


LESIA / F. Merlin

Giant planets atmosphere and satellites

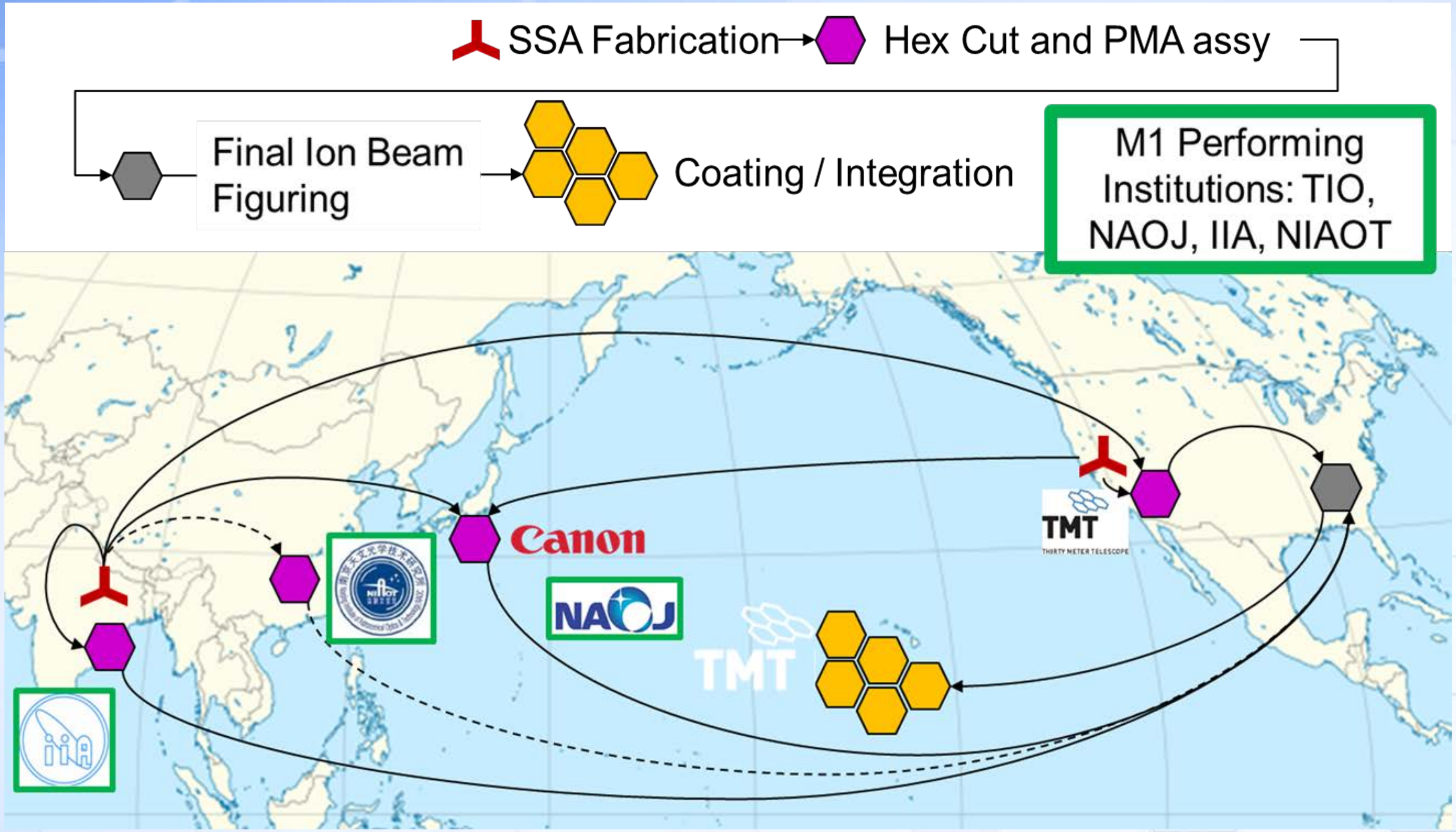


- Atmosphere composition, cloud circulation/dynamics (meteorology), aurorae activity, energy budget
- Isotopic ratios and abundances (H_2O_2, CH_4 on Mars; SO_2 on Venus, stratospheric species in giant planets & Titan)
- Satellites
  - (cryo-)volcanism (e.g. Enceladus, Triton, Pluto)
  - surface/atmosphere composition and boundary conditions
    - Titan: Lake formation and surface/atmosphere interaction
    - Monitoring of Io's volcanoes and Europa's surface
    - Mapping of Europa and search for bio-signatures of organic material

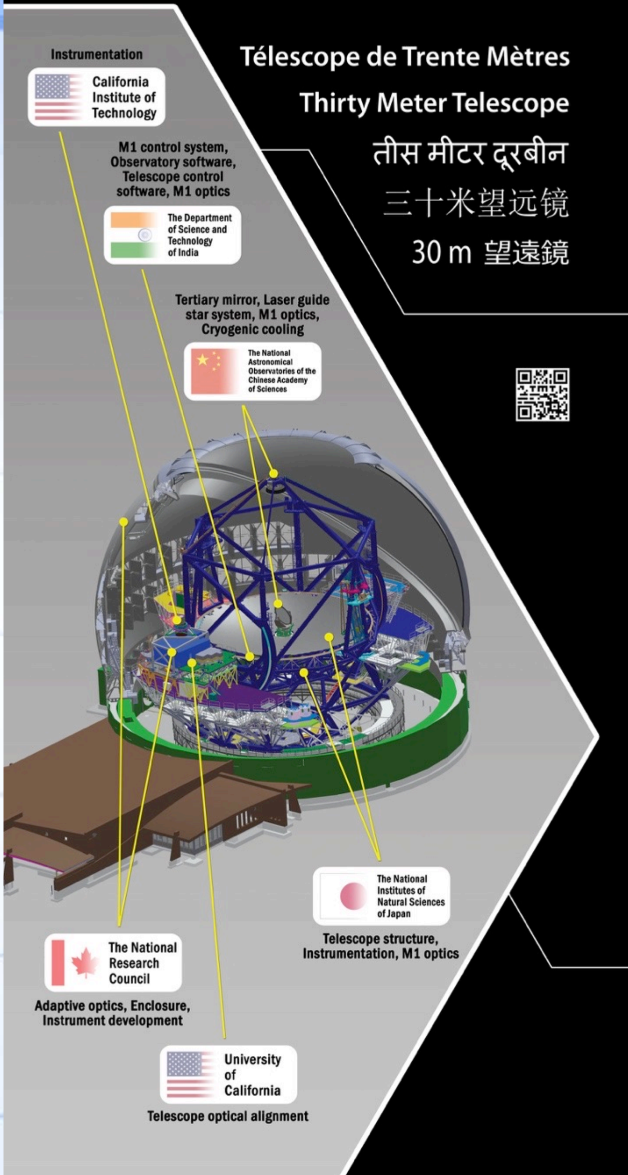


- MCAO/AO imaging (IRIS, PSI)
- Near-IR low/high-Res. spectroscopy (IRIS, MODHIS, MICHI)

Brief update on project advancement

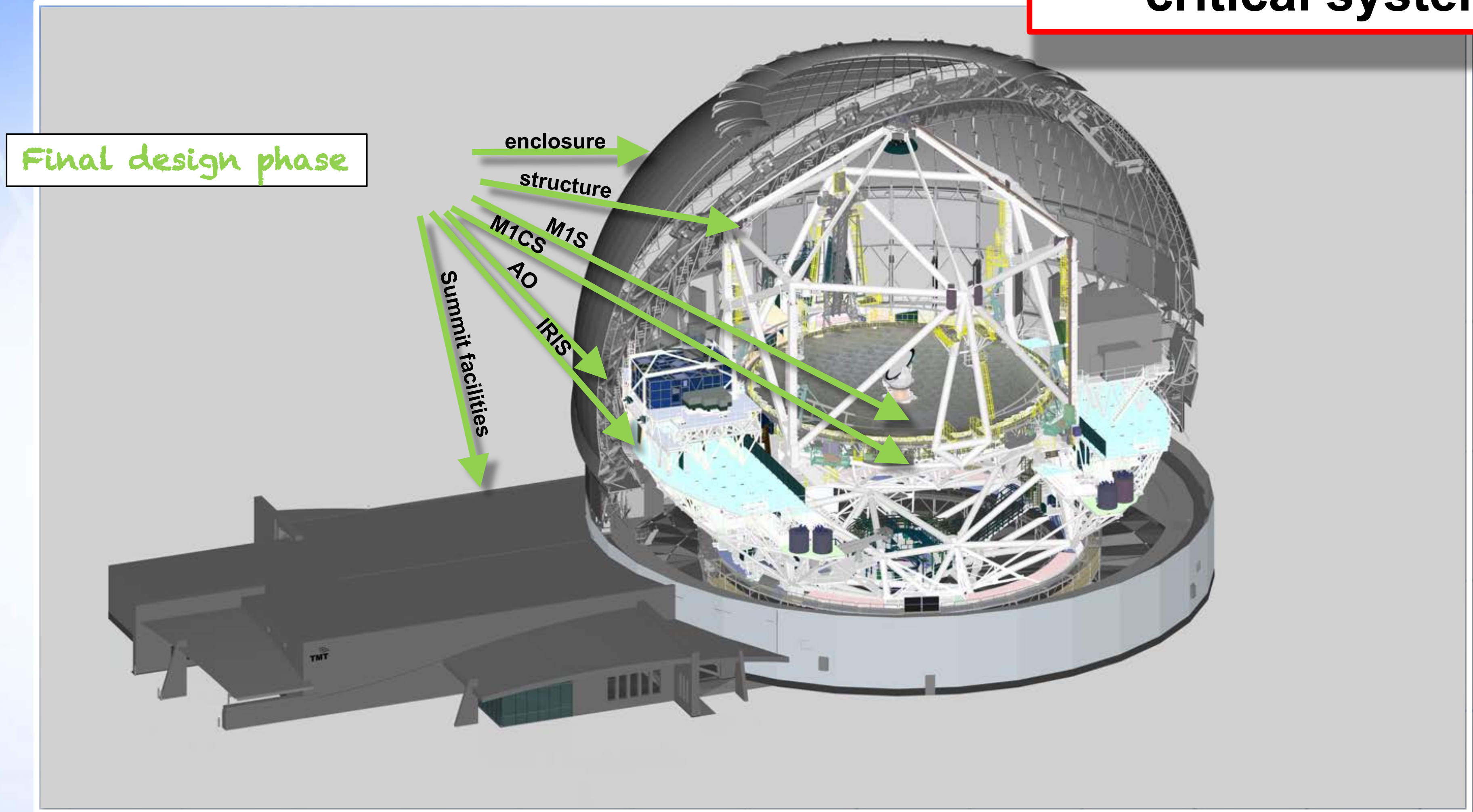


ASTRONOMY'S NEXT-GENERATION OBSERVATORY
TMT INTERNATIONAL PARTNERSHIP

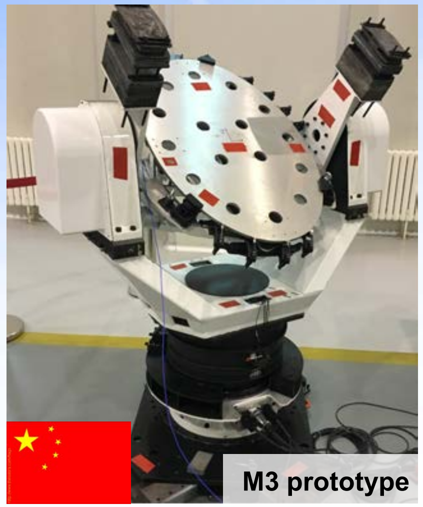


Systems status

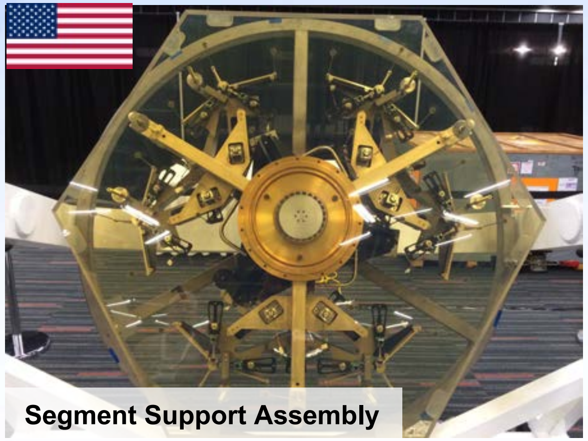
82% of all systems are in final design or production (inc. all critical systems)



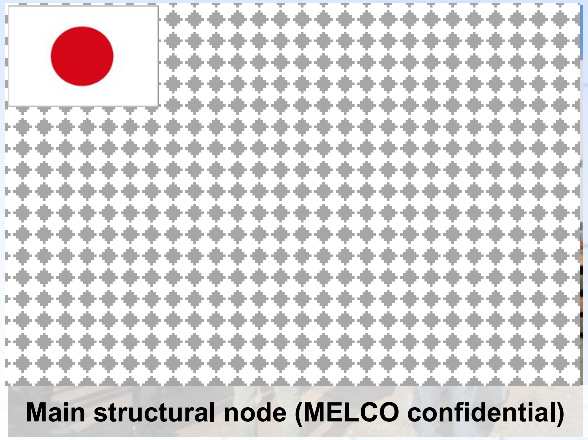
Snapshot of systems design/production



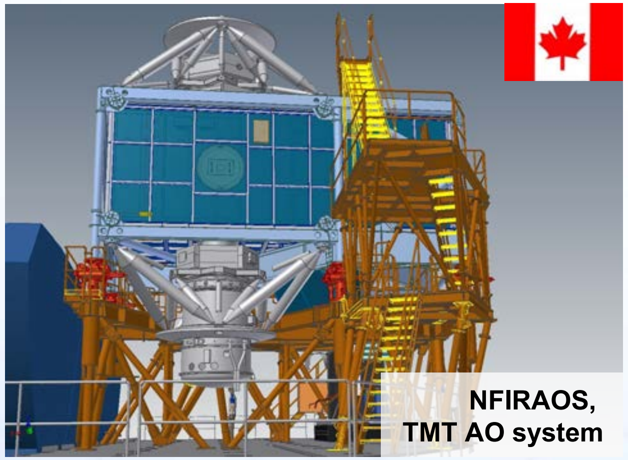
M3 prototype



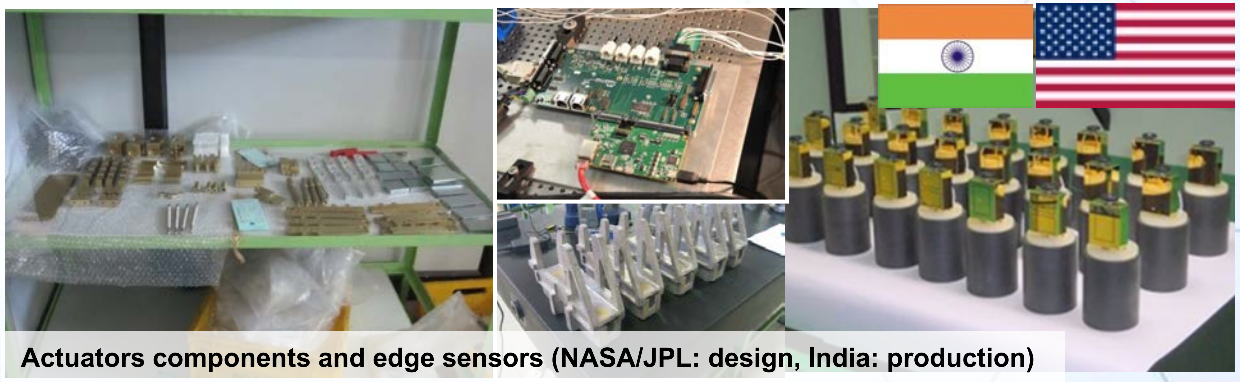
Segment Support Assembly



Main structural node (MELCO confidential)



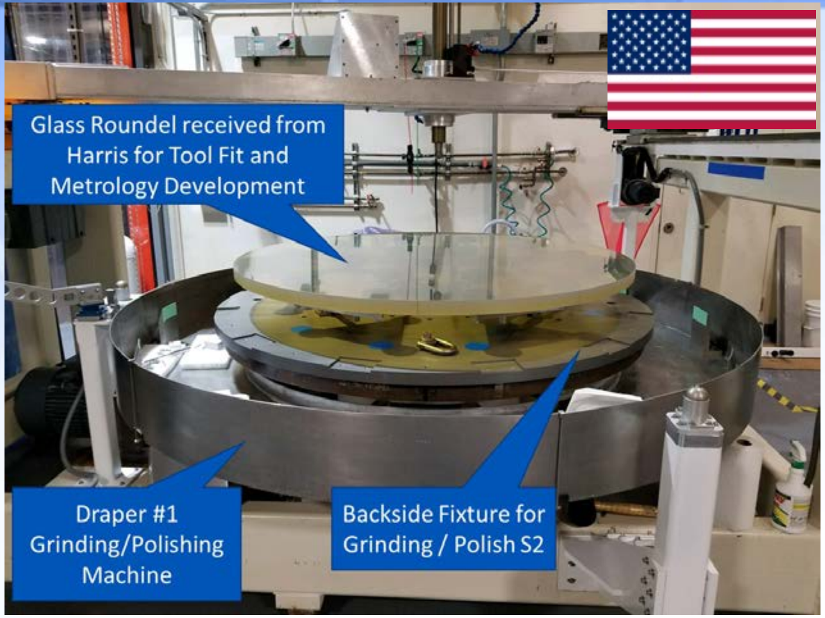
NFIRAOS,
TMT AO system



Actuators components and edge sensors (NASA/JPL: design, India: production)

Blank Acceptance at Canon

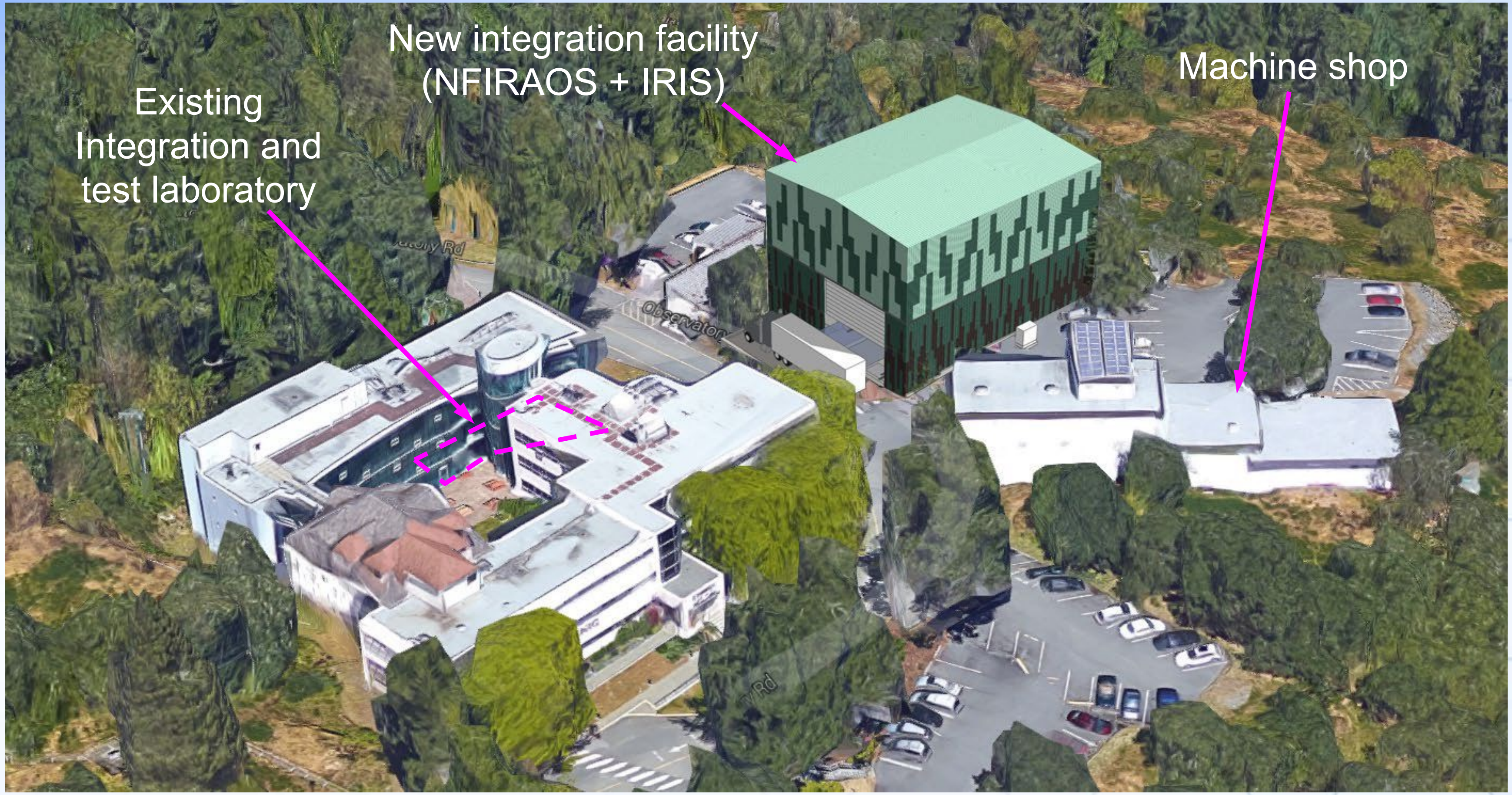
Polishing activities starting across partnership




CREST facility, Bengalore

OPT: Prototype Segment installed in MSIT

NFIRAOS/IRIS - Planning
IRIS Integration



Caption: Aerial view of NRC-H depicting the location of the envisioned integration and test facility that will accommodate both NFIRAOS and IRIS. Similar planning is being undertaken for IRIS integration at NAOJ and CIT and then finally for delivery, integration and verification at the Observatory.

Acknowledgments

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