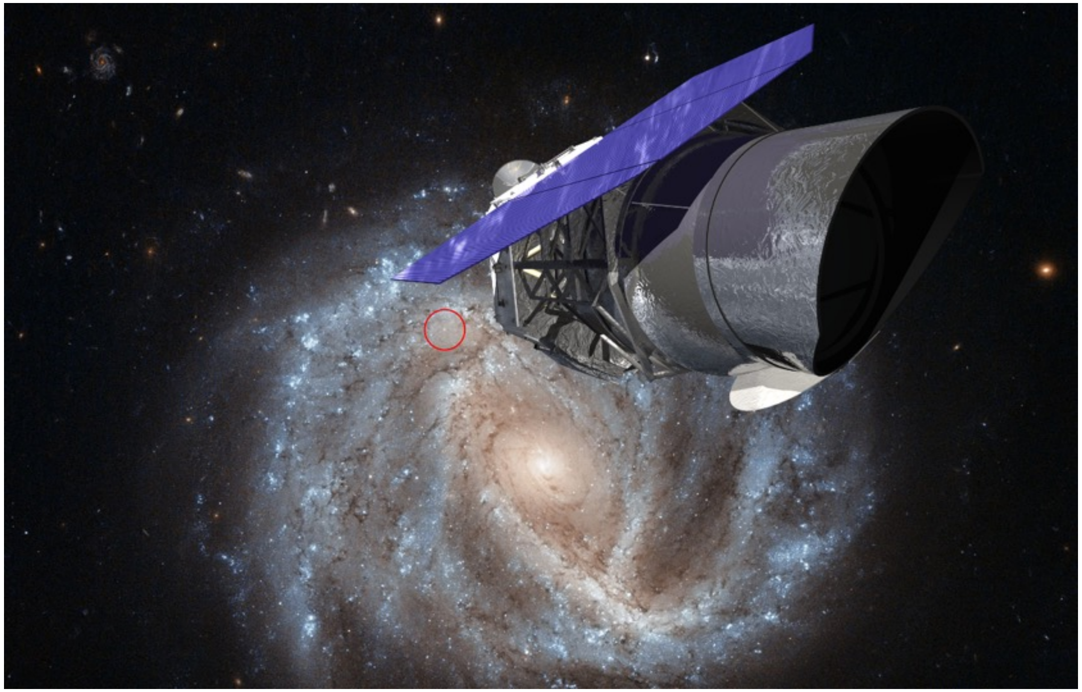
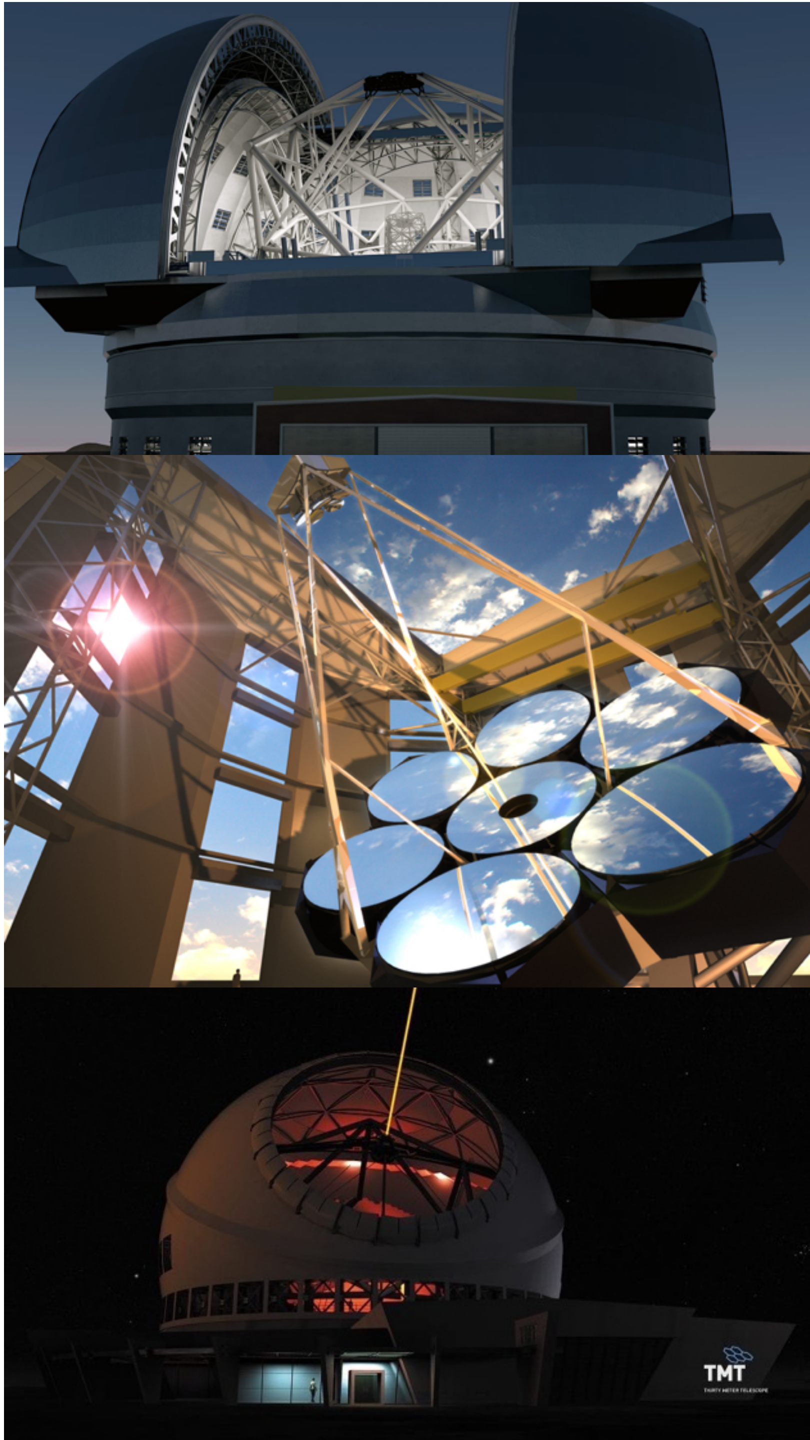
WFIRST and Giant Segmented Mirror Telescopes (GSMTs)

Mark Dickinson (NOAO)

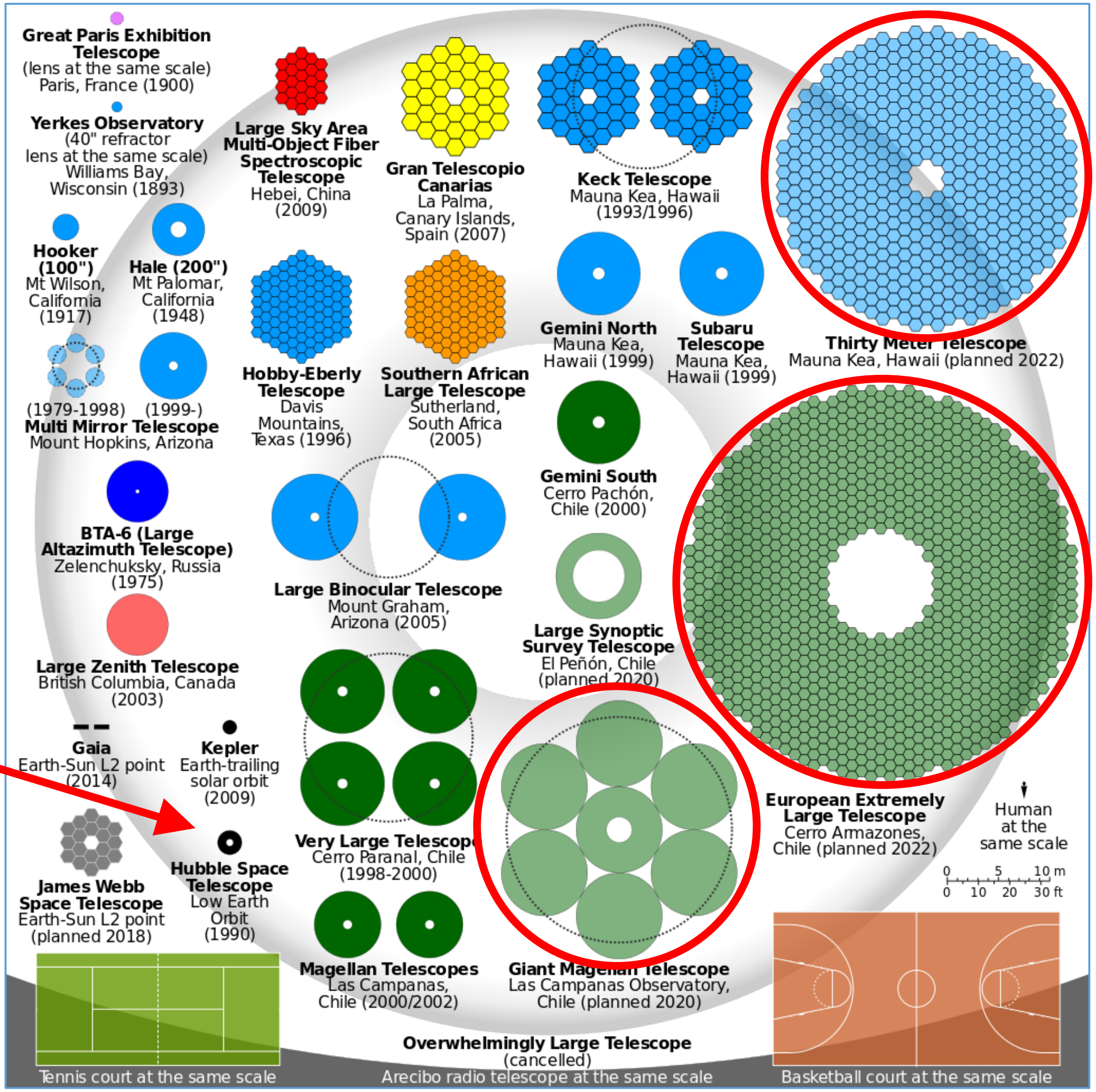
+ Michael Bolte (UCSC)





Giant Segmented Mirror Telescopes

- GSMTs (aperture >20m; aka “ELTs”) offer:
  - Greater collecting area & sensitivity than today’s 8-10m telescopes
  - Better angular resolution with diffraction-limited AO performance in the infrared
    - $\theta \approx 15$ mas (D/30m) @ 2μm
    - D^4 sensitivity gains for point sources (or greater in crowded fields, or for high-contrast imaging)
  - Powerful tools for nearly all areas of astronomical research, from the solar system to cosmology

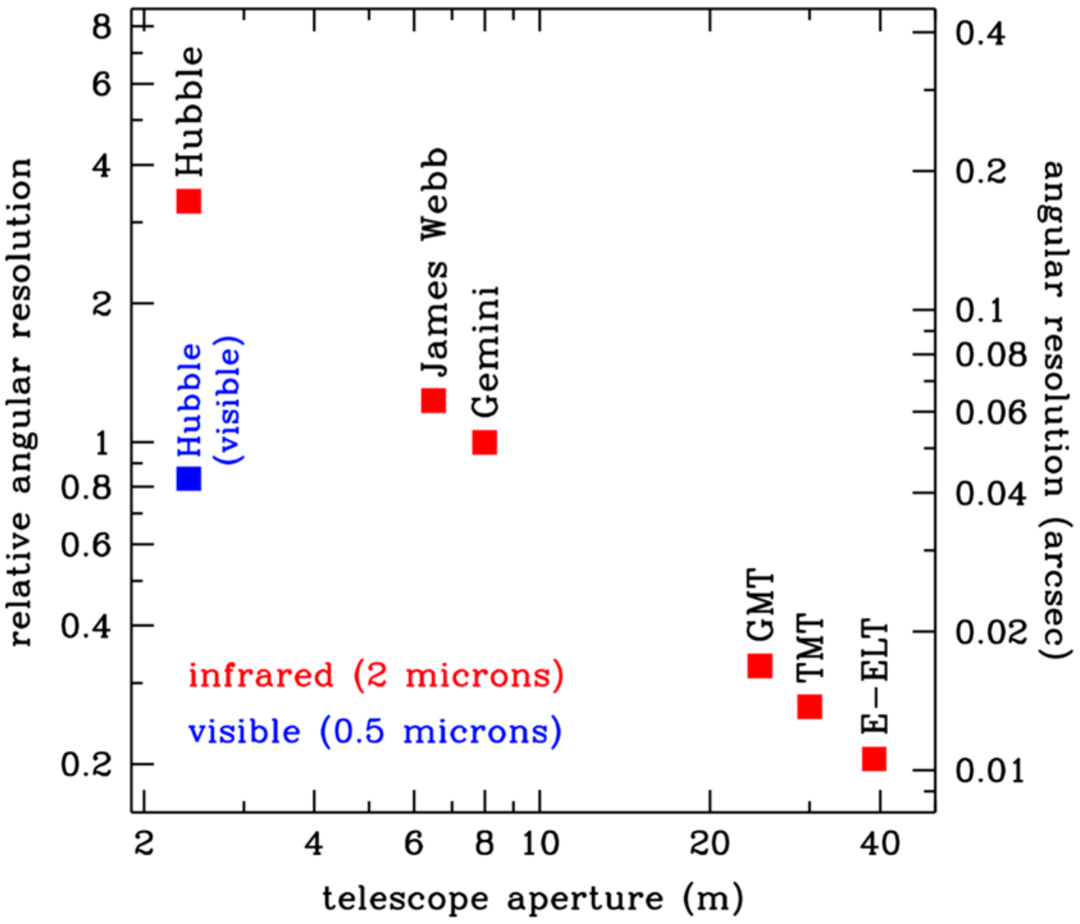


HST or WFIRST

WFIRST and GSMTs

- WFIRST will:
  - Survey large sky areas and discover exceptionally interesting objects
  - Map stellar populations in nearby galaxies in detail
  - Obtain coronagraphic imaging & low-resolution spectra for exoplanets
- GSMTs will provide NIR diffraction-limited angular resolution (λ/D = 12.5x smaller than WFIRST)
  - Inner working angle for exoplanet imaging
  - Morphology from the Solar System to the Epoch of Reionization
  - Crowded field imaging and spectroscopy
- GSMTs offer huge primary collecting area
  - Faint-object spectroscopy
  - High-resolution spectroscopy
  - Fast time-resolved observations

Bigger = Sharper (images)

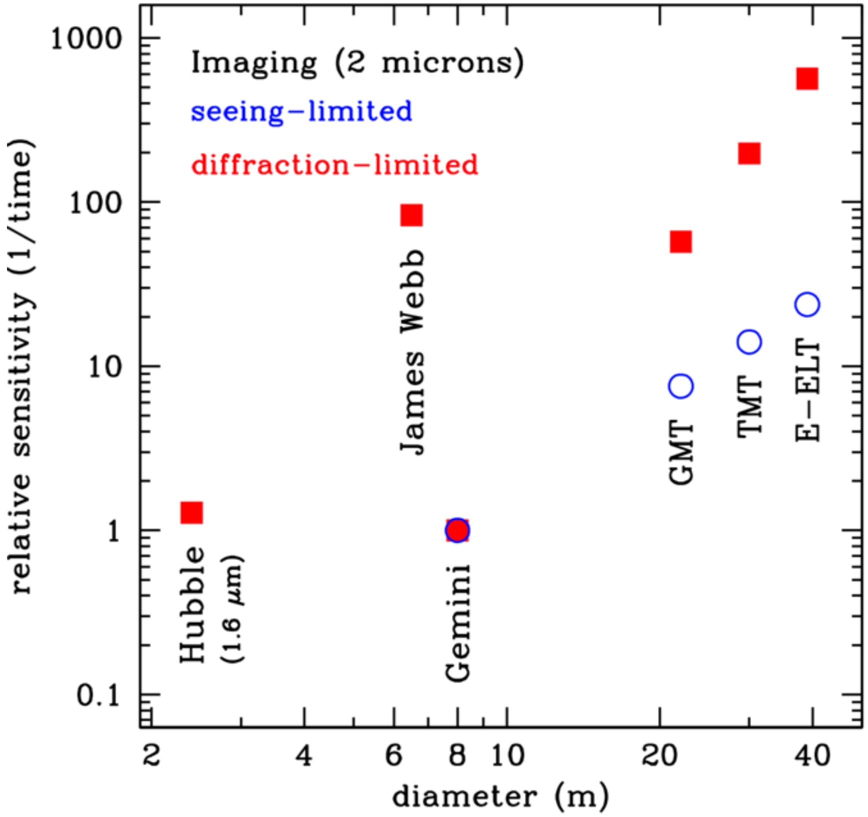


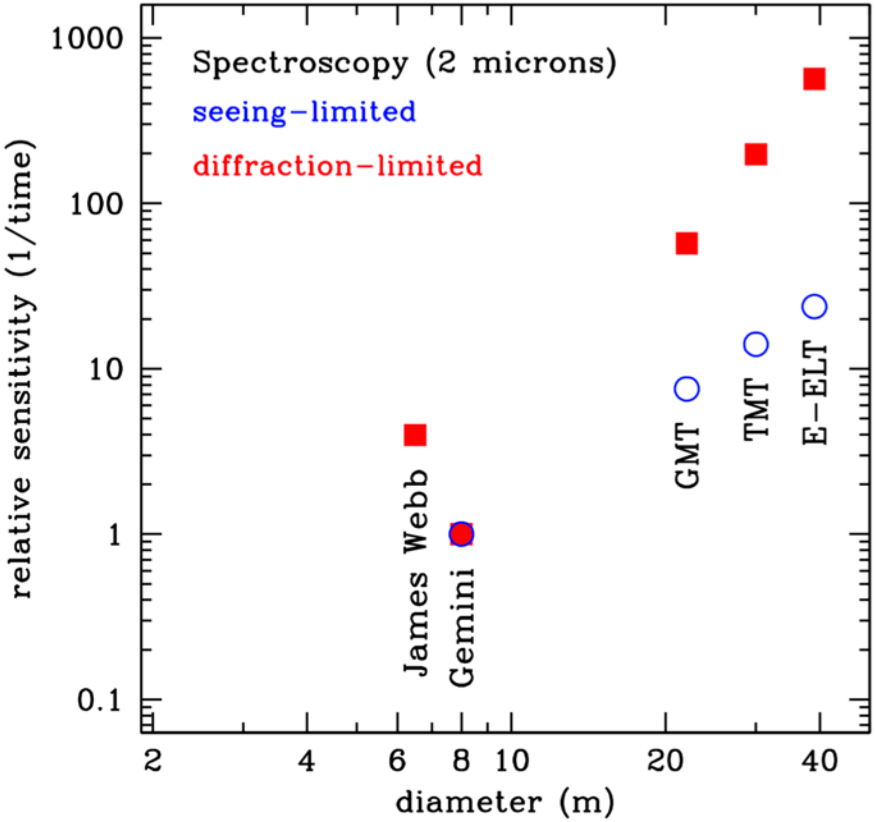
$$\theta \approx \lambda/D$$

Diffraction-limited AO on a 30m telescope can deliver near-IR images that are (at fixed λ):

- 4.6x sharper than JWST
- 12.5x sharper than HST/WFIRST

Bigger = Fainter (objects)





NB: JWST gains a tremendous advantage at λ > 2.5μm from dark space background

Three GSMT projects

- Giant Magellan Telescope (GMT)
  - 7 x 8.4m mirrors → 24.5m effective diameter; unvignetted FOV ~20 arcmin
  - Las Campanas, Chile
  - International consortium including 7 US institutional & university partners
- Thirty Meter Telescope (TMT)
  - 30m primary, 492 hexagonal segments; unvignetted FOV ~15 arcmin
  - Maunakea, HI, or La Palma, Canary Islands
  - Caltech, Canada, China, India, Japan, & University of California, with AURA as an Associate Member
- European Extremely Large Telescope (E-ELT)
  - 39m primary, 798 hexagonal segments; unvignetted FOV ~10 arcmin
  - Cerro Armazones, Chile
  - European Southern Observatory (ESO)

GSMT instrumentation “Equivalence Table”

courtesy Luc Simard

Early-light instruments underlined / highlighted

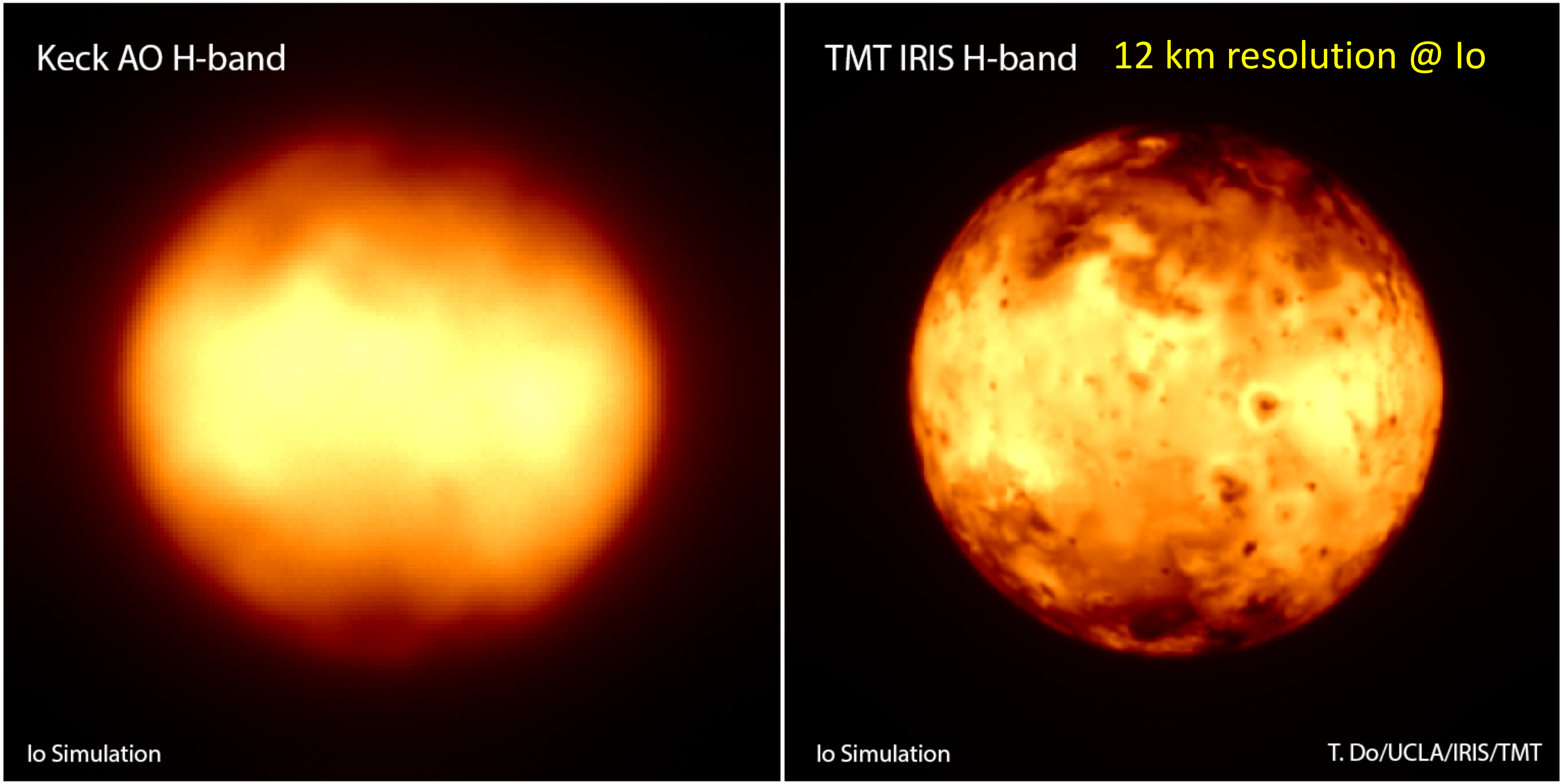
Type of Instrument	GMT	TMT	E-ELT
Near-IR, AO-assisted Imager + IFU	GMTIFS	IRIS	HARMONI
Wide-Field, Optical Multi-Object Spectrometer	GMACS	WFOS	MOSAIC-HMM
Near-IR Multislit Spectrometer	NIRMOS	IRMS	MOSAIC-HMM
Deployable, Multi-IFU Imaging Spectrometer		IRMOS	MOSAIC-HDM
Mid-IR, AO-assisted Echelle Spectrometer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

Science synergies

- Solar System
  - Outer solar system bodies
- Exoplanets
  - High-contrast imaging
  - Spectroscopy of exo-atmospheres
- Milky Way & nearby galaxies
  - Imaging and spectroscopy for resolved stellar populations
- Early universe and galaxy formation
  - Spectroscopy of exciting objects
  - High angular resolution imaging and spectroscopy
  - IGM / CGM tomography
- Fundamental physics & cosmology
  - Redshift measurement and photo-z calibration
  - Strong lensing / monitoring

Our Solar System

GSMTs will observe and monitor solar system bodies at spacecraft-like resolution

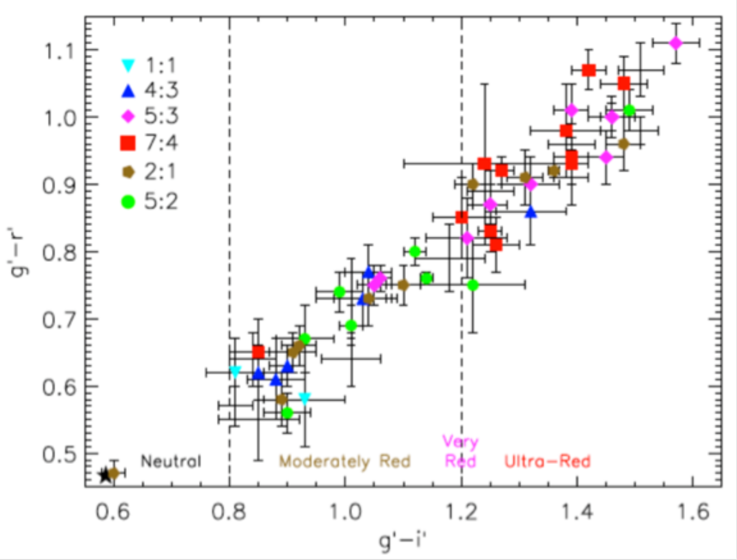


Our Solar System

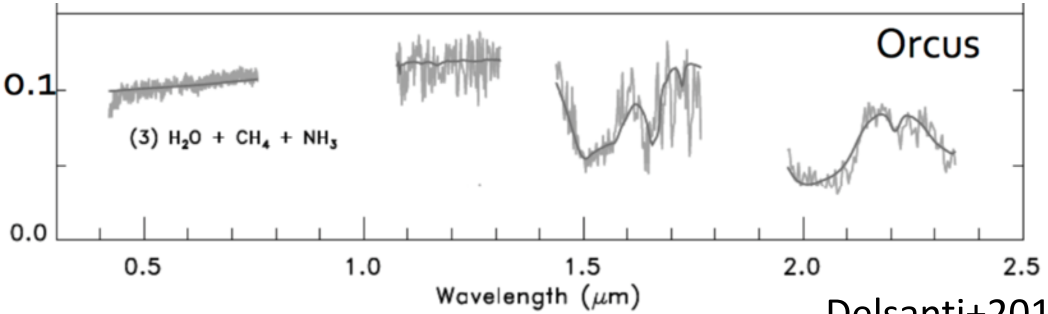
TMT IRIS samples Pluto+Charon at 80 km/pixel resolution

Trans-Neptunian Objects

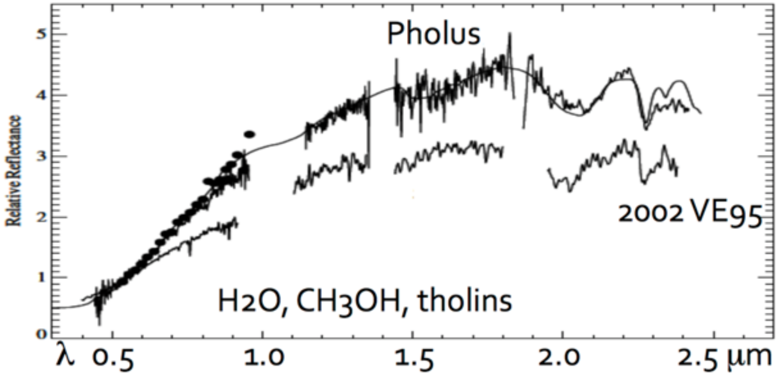
- WFIRST will discover thousands of outer solar system bodies
- GSMTs will:
  - Resolve the largest objects (~200 km @ 30 AU)
  - Discover binaries and measure their orbits
  - Spectroscopy: surface chemistry, cryo-volcanism, volatiles



Sheppard+2012



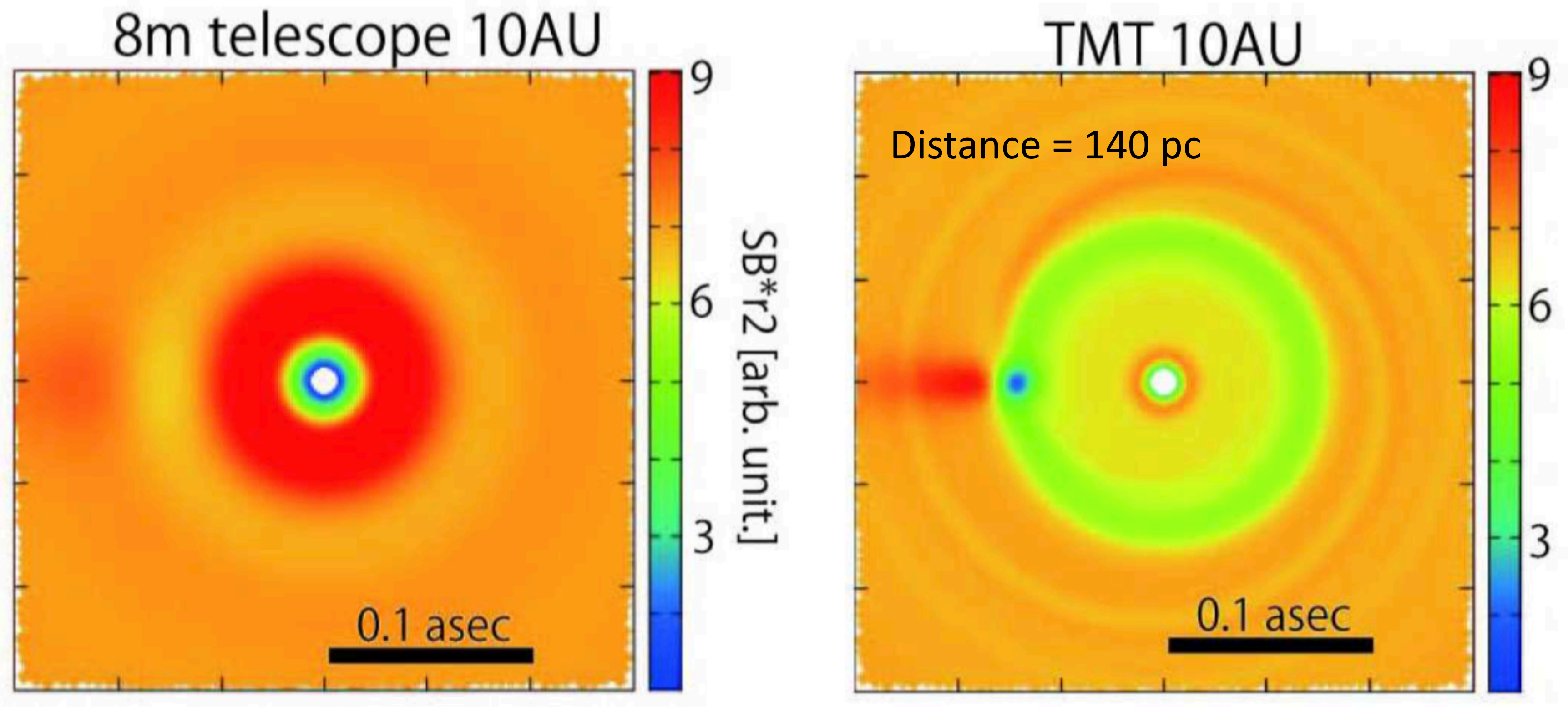
Delsanti+2010



Cruikshank+1998;
Barucci+2006

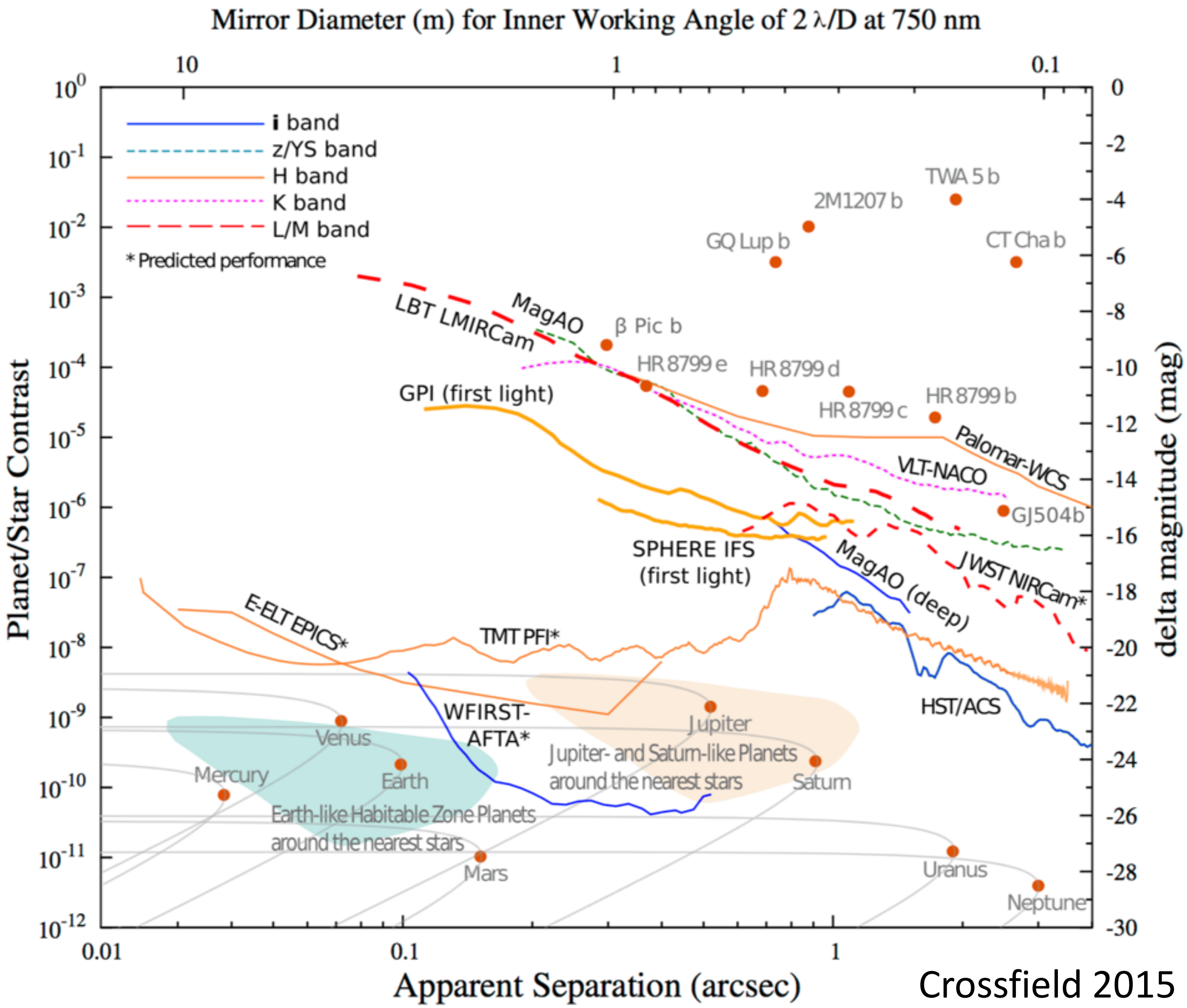
Extrasolar Planets

GSMTs will take images and spectra to measure the physical properties of exoplanets, their atmospheres, and protoplanetary disks



0.1 arcsec = WFIRST λ / D @ 1.15 μm

Imaging extrasolar planets



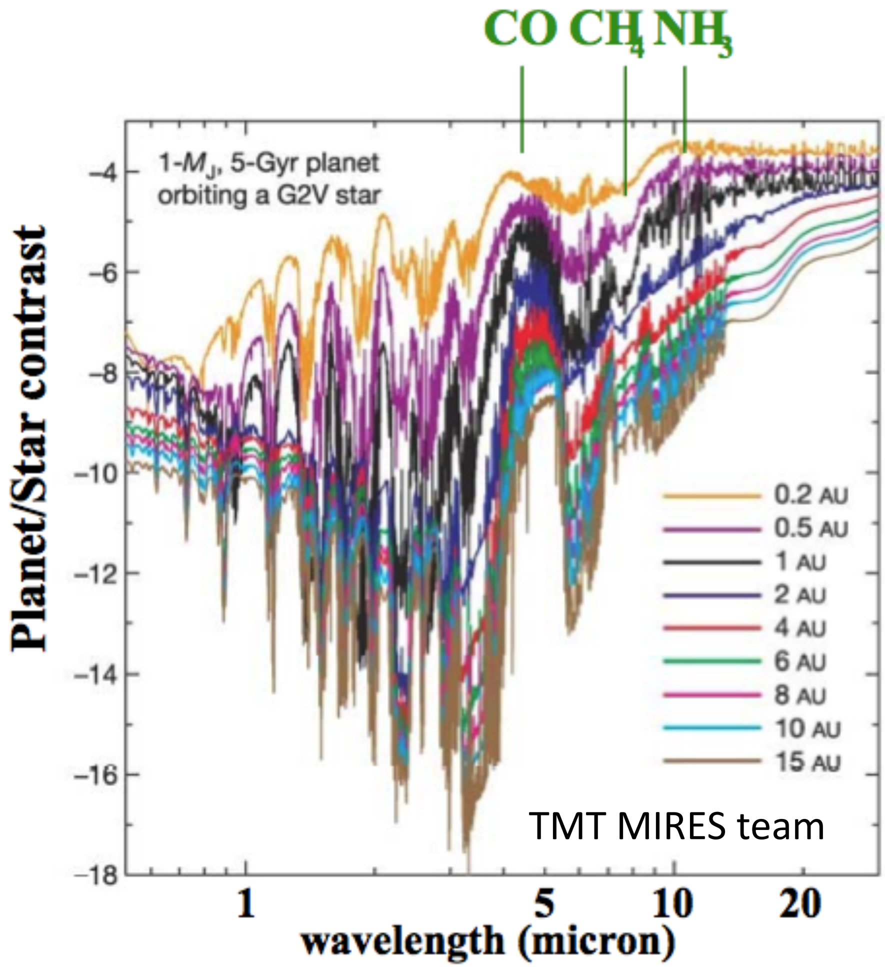
Crossfield 2015

GSMT high contrast observations will allow exoplanet detection at smaller inner working angles (0”.01-0”.1) where reflected light is brighter.

WFIRST CGI should achieve higher contrast at larger separations (>0.1”)

Characterizing Exoplanet atmospheres

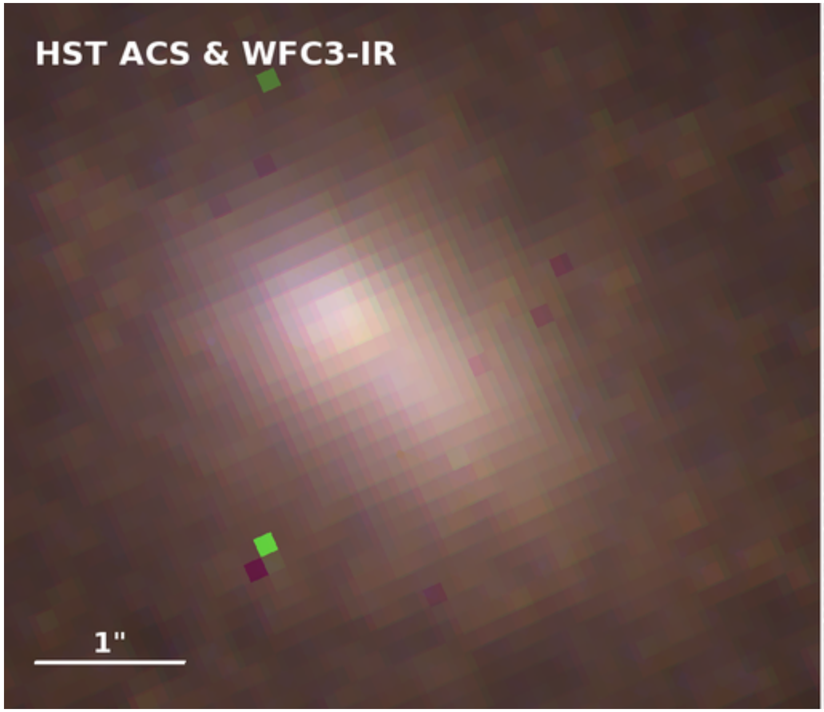
GSMTs enable high contrast, high resolution, high-SNR spectroscopy of transiting/eclipsing exoplanets with required short exposure times

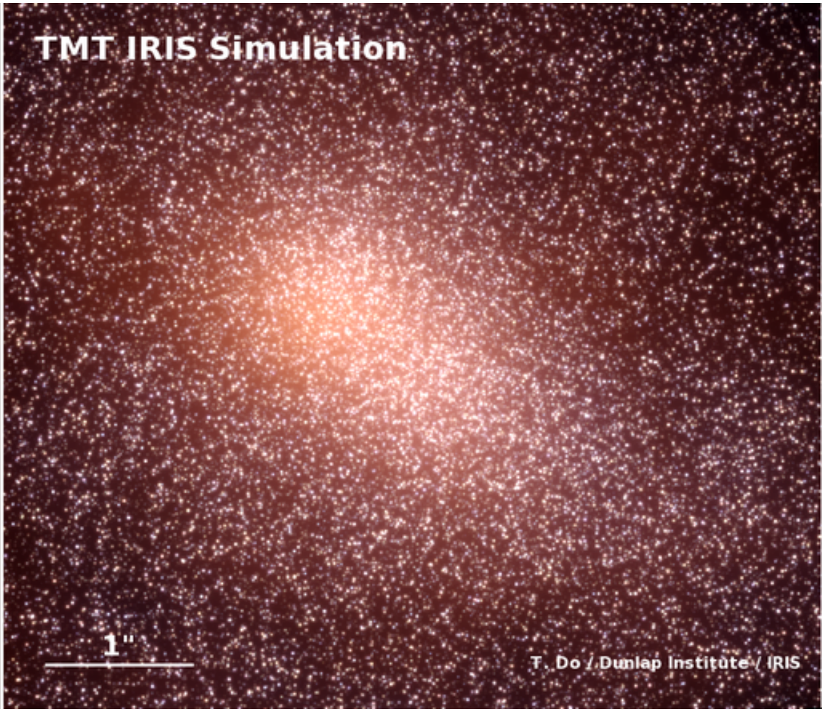


TMT MIRES team

Nearby galaxies: M31 nucleus

GSMTs enable deep imaging and spectroscopy for crowded stellar fields in nearby galaxies – stellar populations and dynamics around the central supermassive black hole

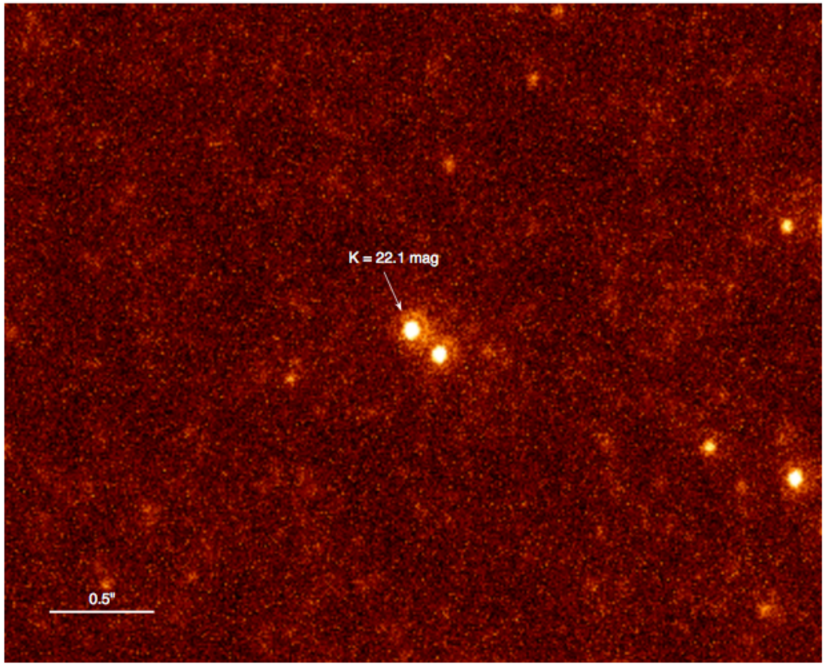




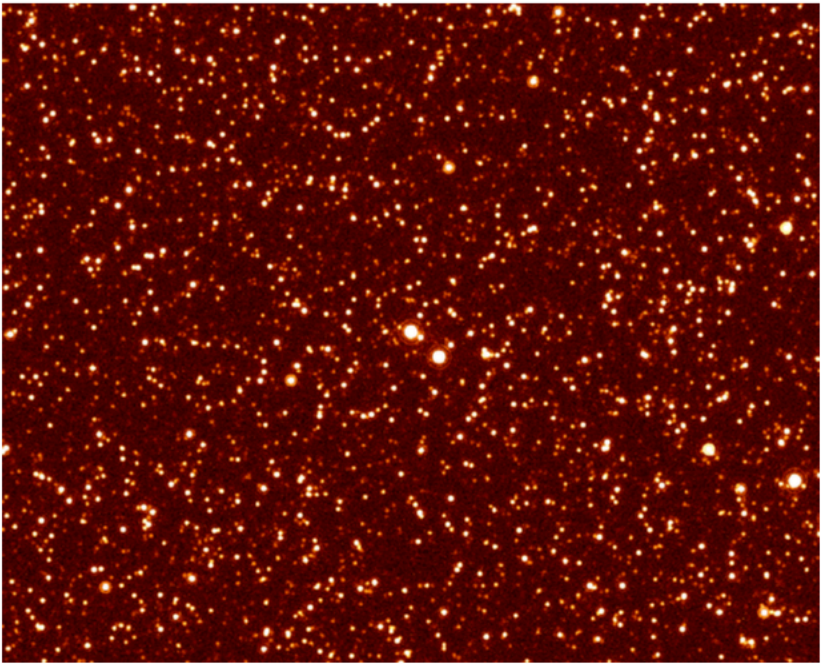
Virgo cluster

GSMTs will measure resolved stellar populations with deep sensitivity out to the Virgo cluster and beyond

Keck AO: Brightest AGB stars



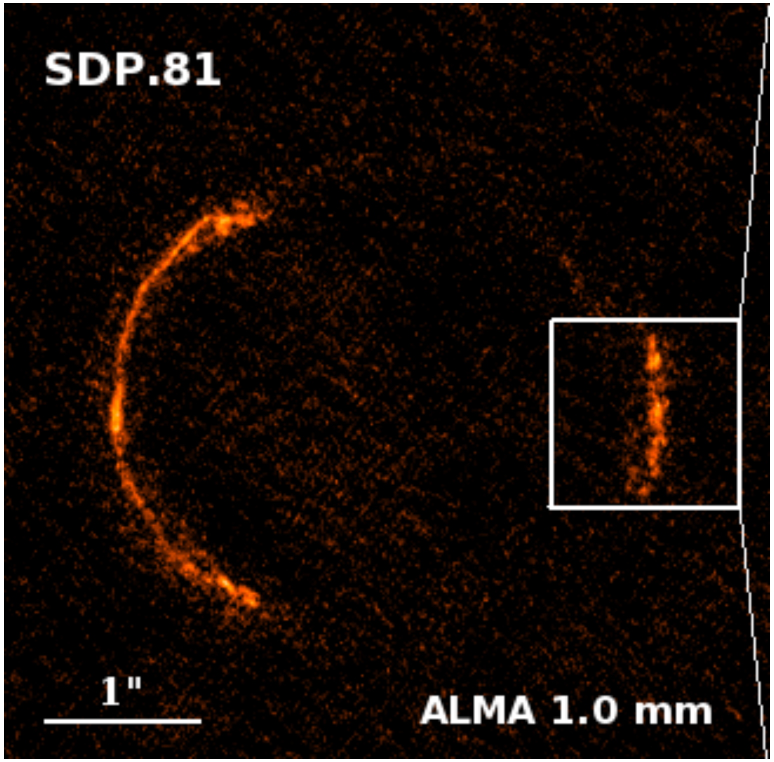
TMT IRIS: Well into the RGB



The Early Universe

GSMTs will dissect the formation and evolution of galaxies high angular resolution imaging and spectroscopy at high spectral resolution and SNR.

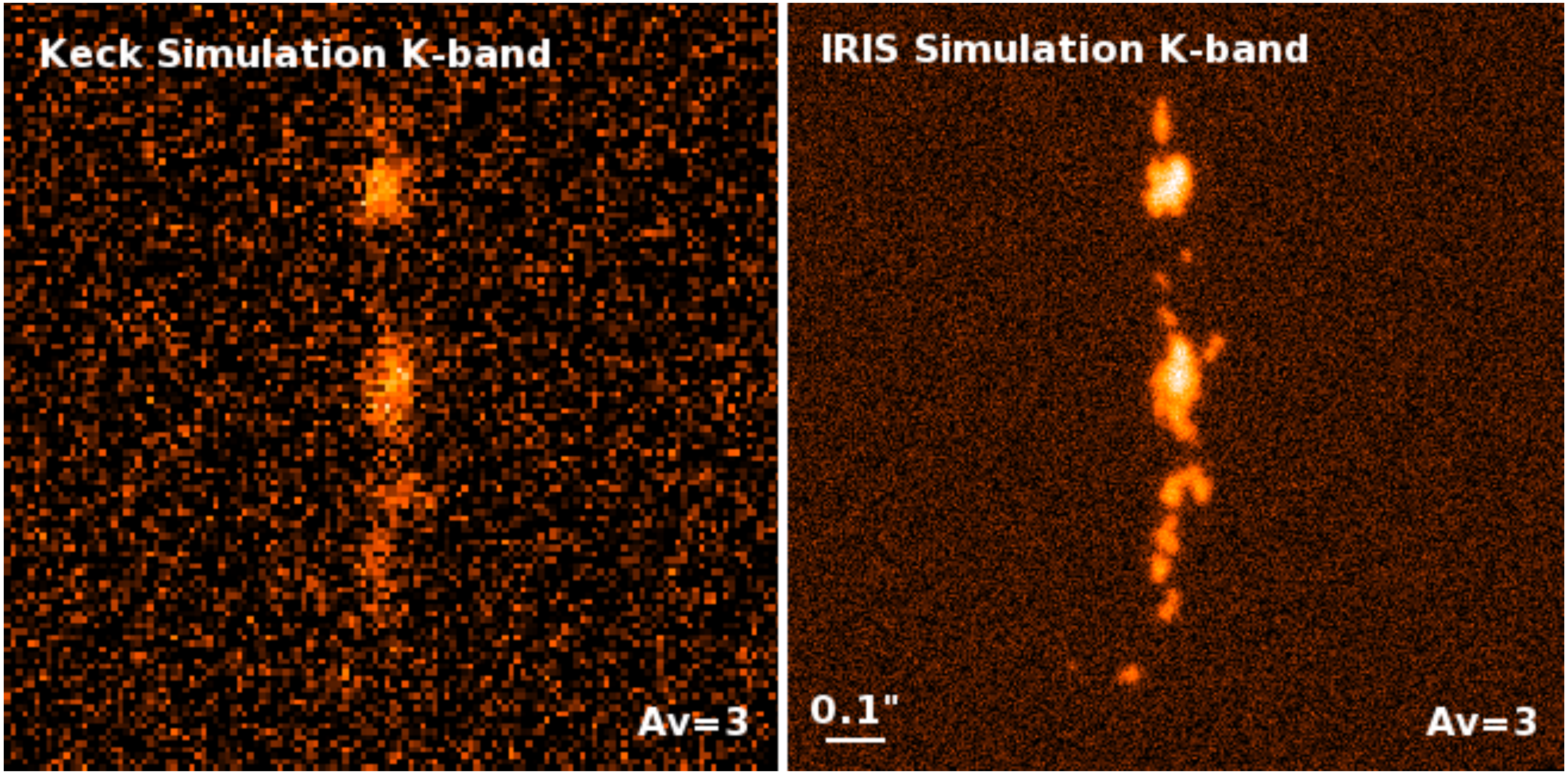
< 200 pc at any redshift, and ~10 pc or better with Gravitational Lensing



The Early Universe

GSMTs will dissect the formation and evolution of galaxies high angular resolution imaging and spectroscopy at high spectral resolution and SNR.

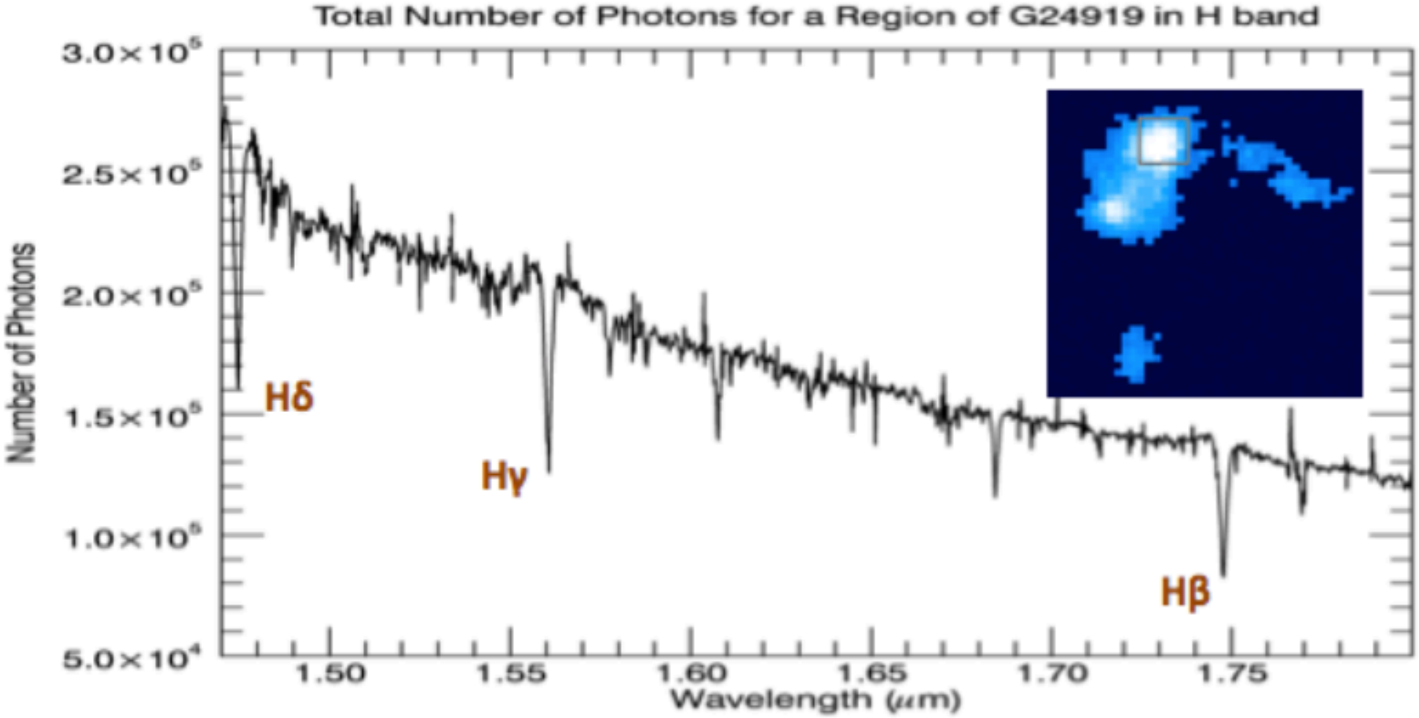
< 200 pc at any redshift, and ~10 pc or better with Gravitational Lensing



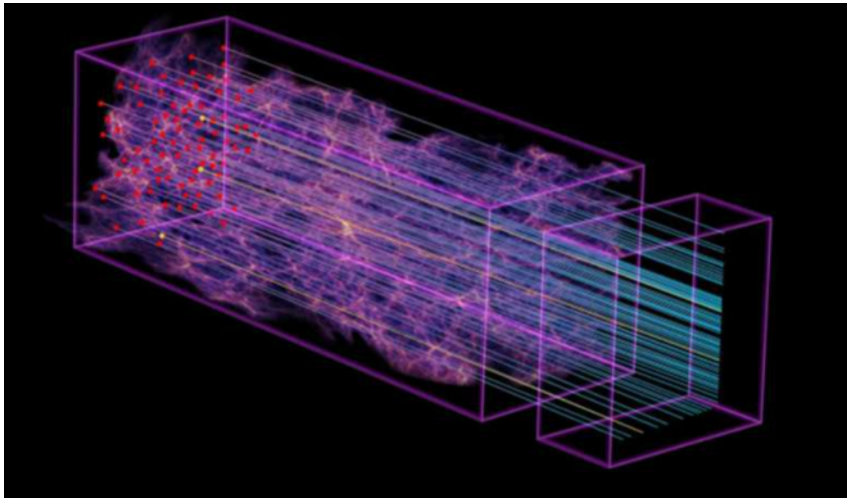
The Early Universe

GSMTs will dissect the formation and evolution of galaxies high angular resolution imaging and spectroscopy at high spectral resolution and SNR.

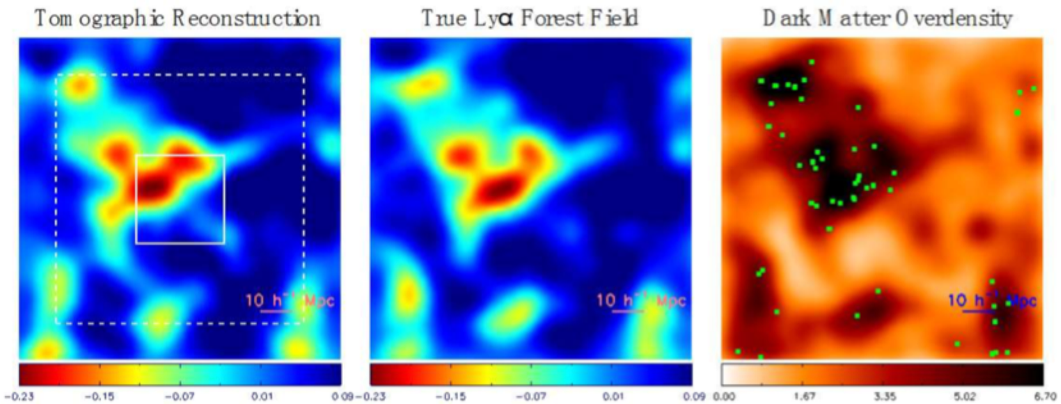
< 200 pc at any redshift, and ~10 pc or better with Gravitational Lensing

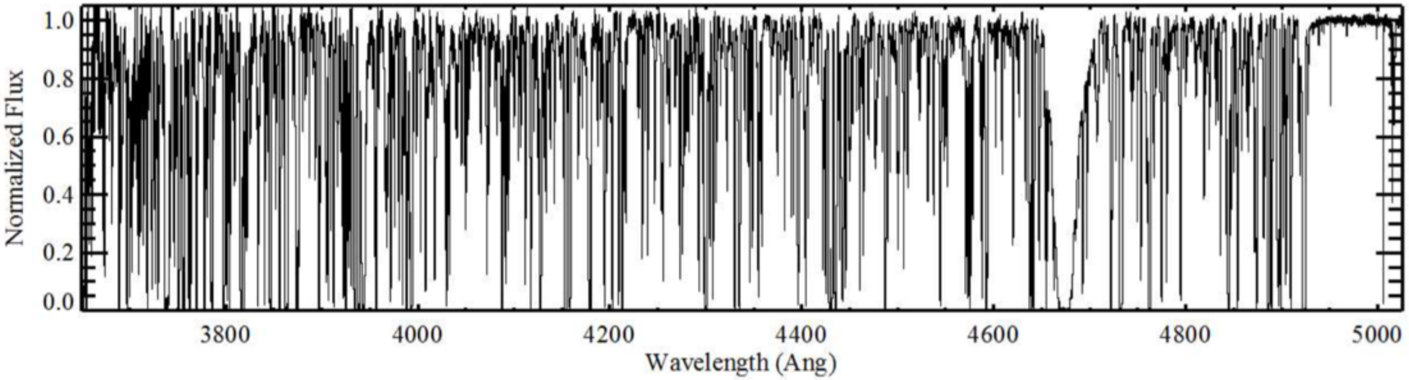


IGM Tomography

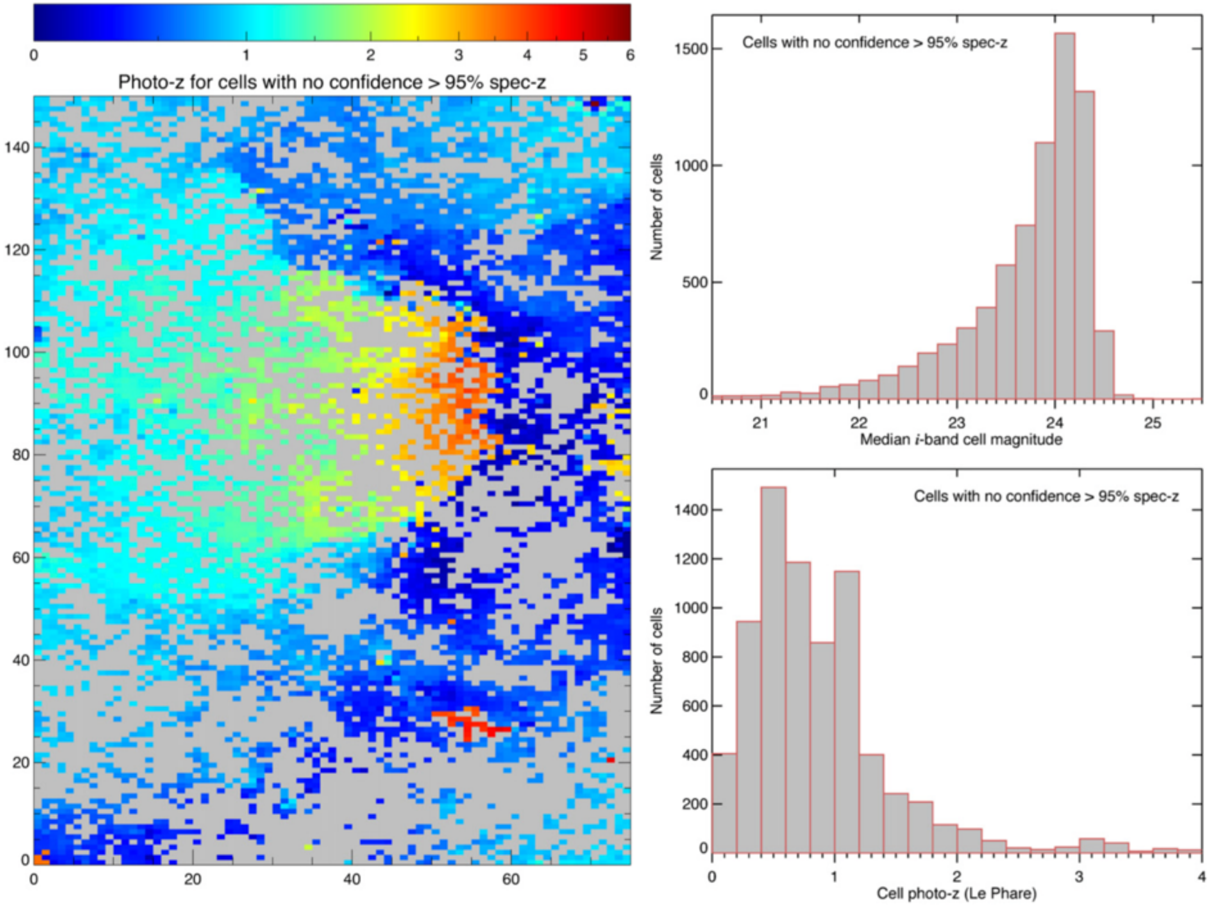


- TMT/WFOS spectroscopy down to R = 24.5 with spectral resolution 5000 and S/N>30
- Background galaxies (vs. QSOs) provide >100x higher sightline density to study IGM/CGM studies
- Strongly complementary to WFIRST galaxy surveys and large scale structure studies





Photometric redshift calibration



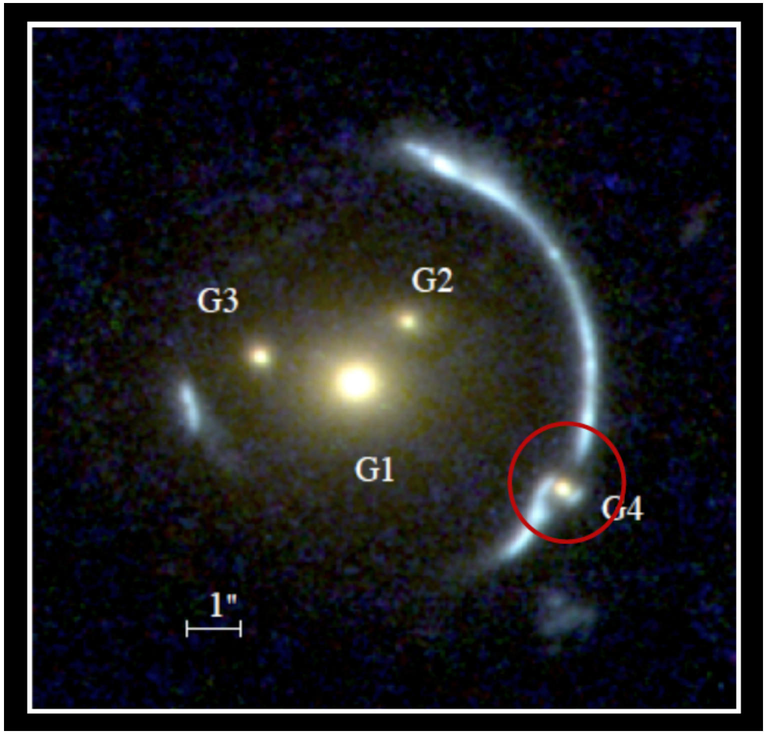
Masters et al. 2015

WFIRST weak lensing and LSS cosmology probes depend on accurate and unbiased photometric redshifts.

GSMT multi-object spectroscopy will measure accurate redshifts in parts of magnitude / redshift / galaxy type parameter space that smaller telescopes cannot reach.

Low-Mass CDM with Astrometric Anomalies in Gravitational Lenses

- Direct detection of very high M/L structures via strong lensing. Current limits are a few times 10^8 solar masses. GSMTs sensitive to 10^7.
- Also, flux ratio anomalies in multiply imaged AGN nuclei.
- Current limits set by angular resolution, sensitivity, and number of sources.
- WFIRST will find 1000s to study.



Vegetti, Czoske & Koopmans 2009

E-ELT, GMT, TMT

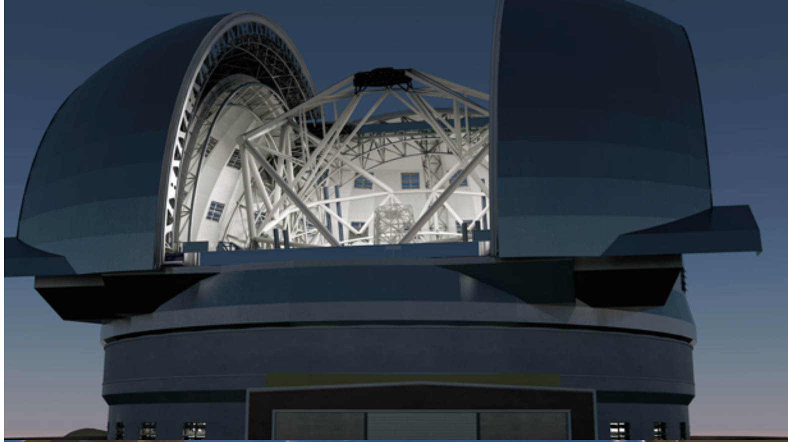
International partners:

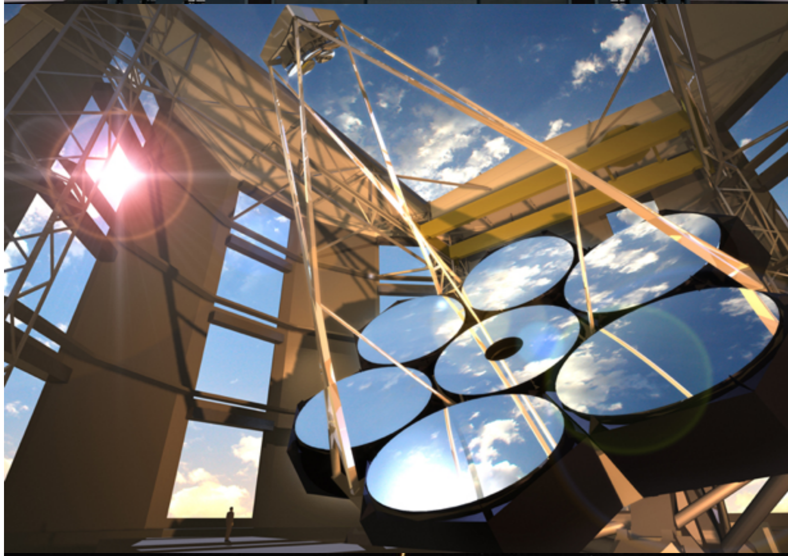
Australia, Austria, Belgium, Brazil, Canada, Chile, China, Czech Republic, Denmark, Finland, France, Germany, India, Italy, Japan, Korea, Netherlands, Poland, Portugal, Spain, Sweden, Switzerland, United Kingdom

US universities & institutions:

Caltech, Carnegie, Harvard, SAO, University of Arizona, University of California, University of Chicago, University of Texas at Austin, Texas A&M

What's missing from this picture?

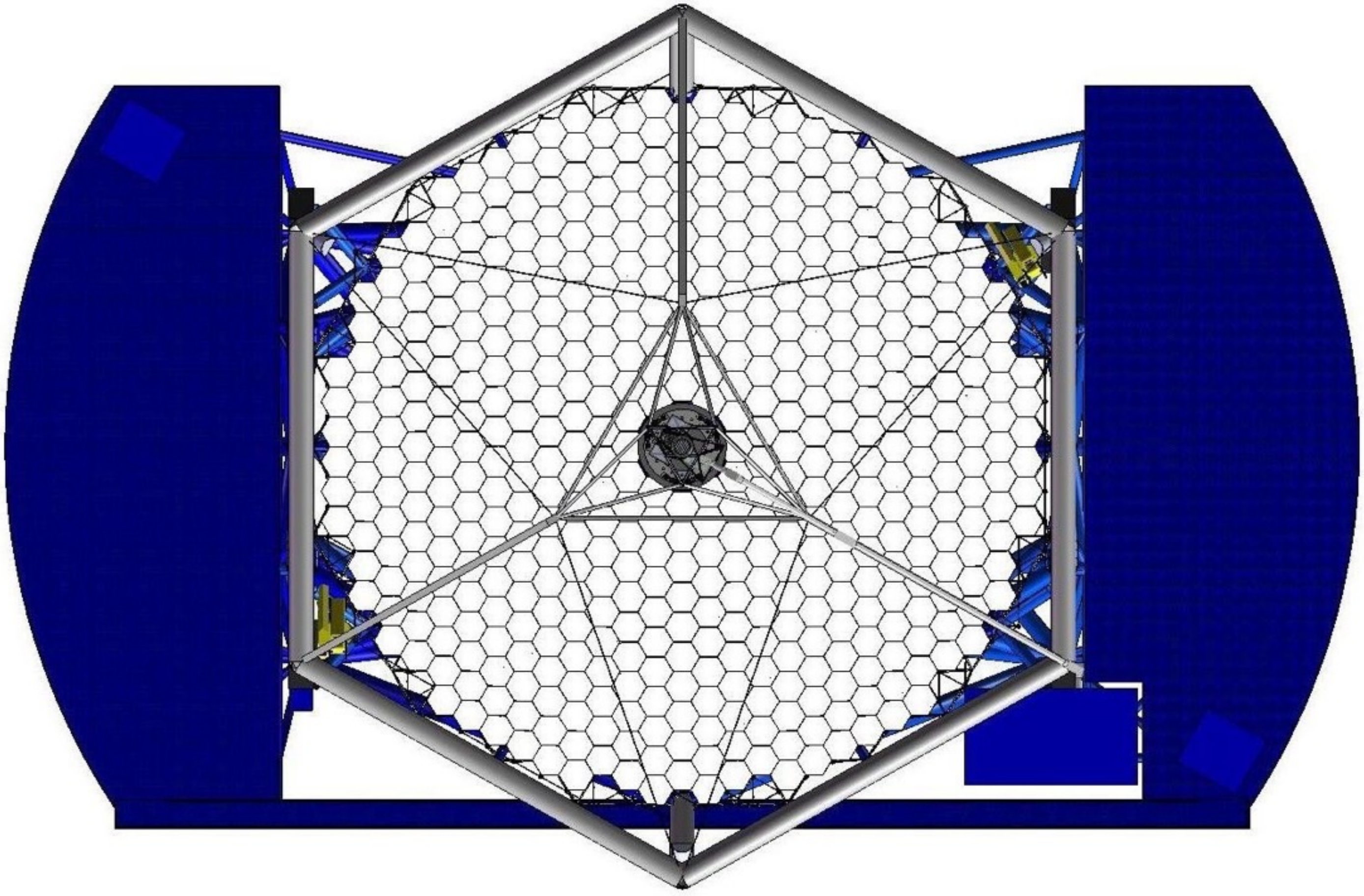




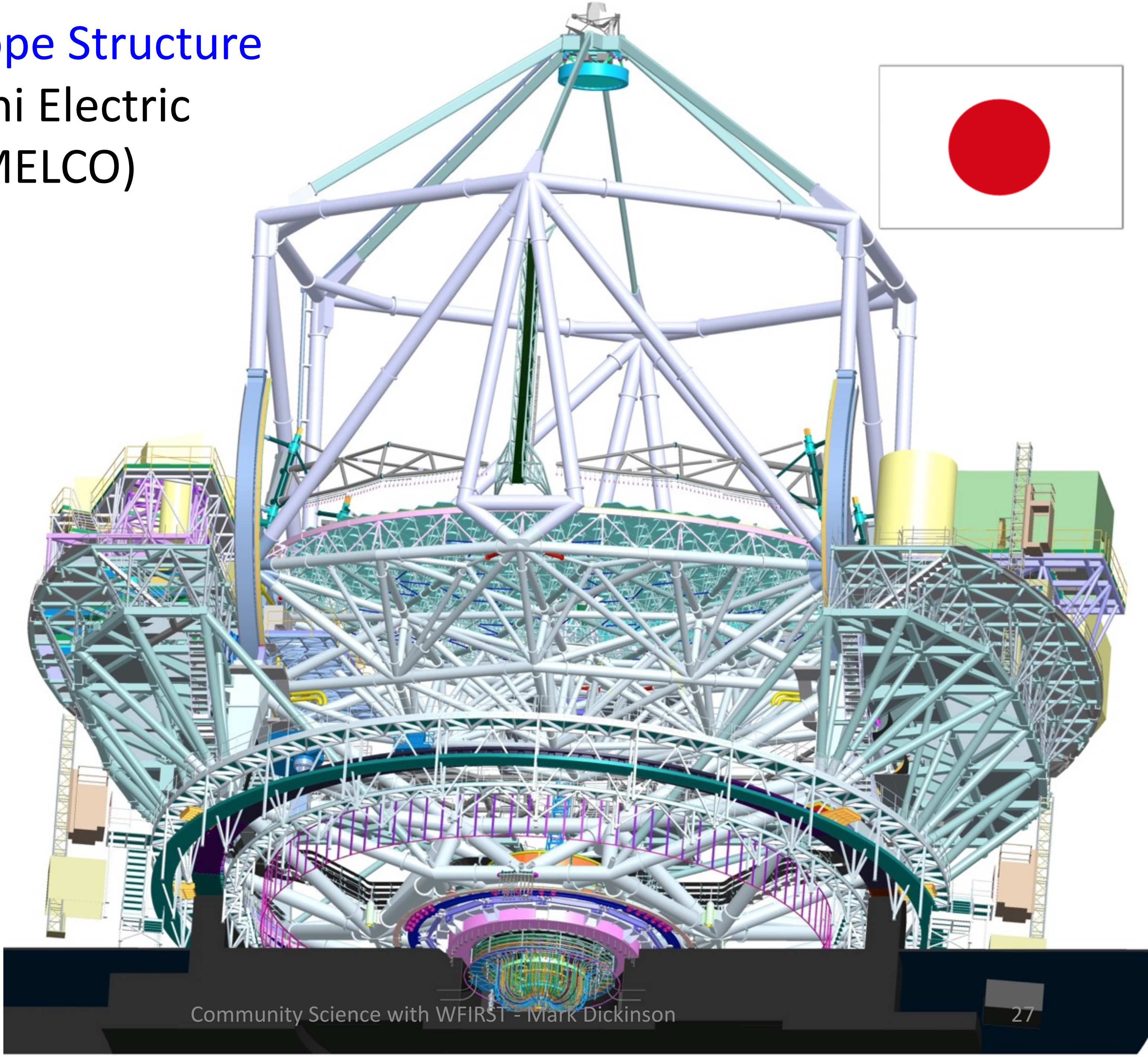
US national role in GSMTs

- 2000 and 2010 Decadal Surveys identified US national participation in GSMTs as an important priority for US ground-based OIR astronomy
  - Reaffirmed in 2015 NRC report on the US Ground-based OIR System
- 2013: NSF established a cooperative agreement (C.A.) with TMT to develop a model for potential US national partnership
  - AURA participates in TMT governance (Board, SAC, etc.); NOAO executes AURA's responsibilities through a US TMT Liaison Office
  - *NB:* There is no NSF commitment to join or fund TMT beyond the C.A.
- GMT has community representatives on its SAC and engages with the broader community via workshops, etc.

TMT Status



TMT Telescope Structure by Mitsubishi Electric Company (MELCO)



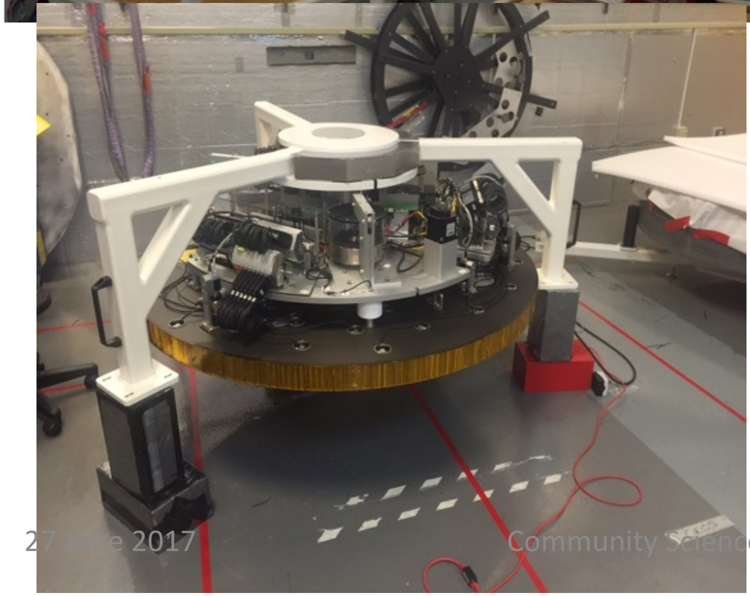
TMT Telescope Structure
Main Structural Node

Primary Mirror (M1) Segment Blank Production

- Ohara has produced 213 primary mirror segment blanks so far
- 154 generated to meniscus shape

Segment Polishing at Coherent

Preparations underway for segment polishing in India and China



Stressing Fixture

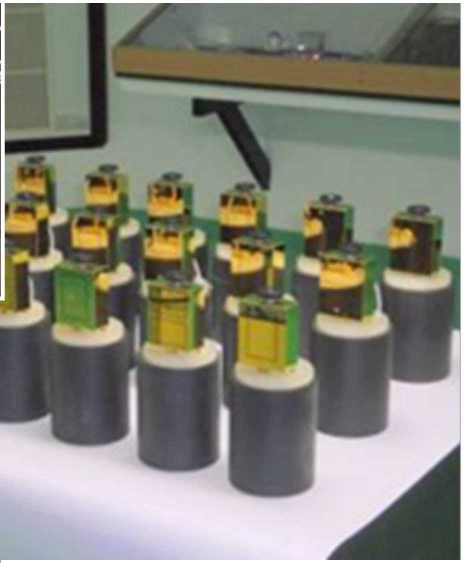
Polishing the stressed segment with a spherical tool

Primary Mirror Control System

JPL, TMT-India

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

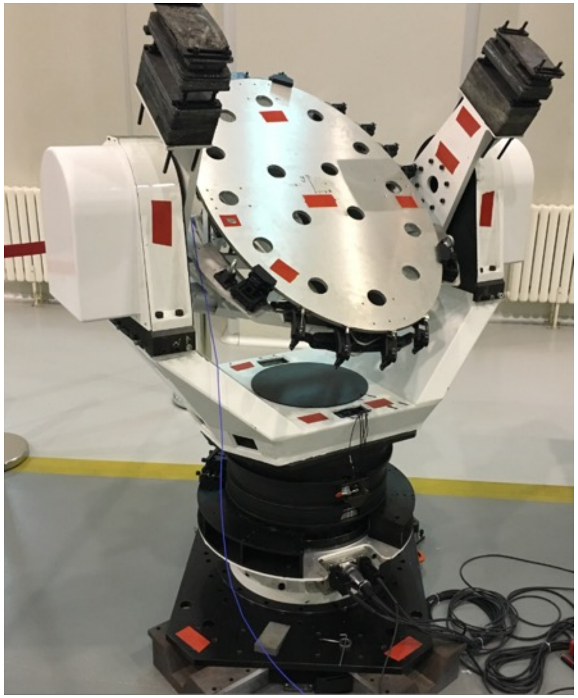
Actuator components



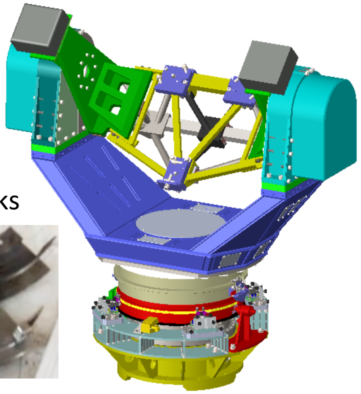
Edge sensors

M3 System at CIOMP, Changchun

1/4 scale functional prototype passed Test Results Review



Positioner CAD model and parts

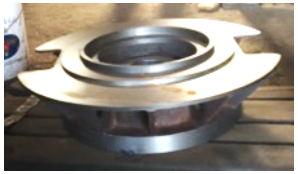


Parts for Cradle Assembly

Tilt Axis Brake Disks

Cablewrap Pinon Gears

Stationary Base



Rotator Bearing Races

Yoke Assembly

Stationary Middle Base

Tilt Axis Spindle

Where will TMT be Built?

Maunakea remains the preferred site and all efforts are being made to regain access

TMT Hawaii status

- December 2015: Hawaii Supreme Court vacated the TMT conservation district use permit on procedural grounds.
- Evidentiary hearings for a second Contested Case ended in March; hearing officer should make a recommendation soon.
- Hawaii Land Board will make a decision on new permit, which likely will be challenged to the Hawaii Supreme Court.

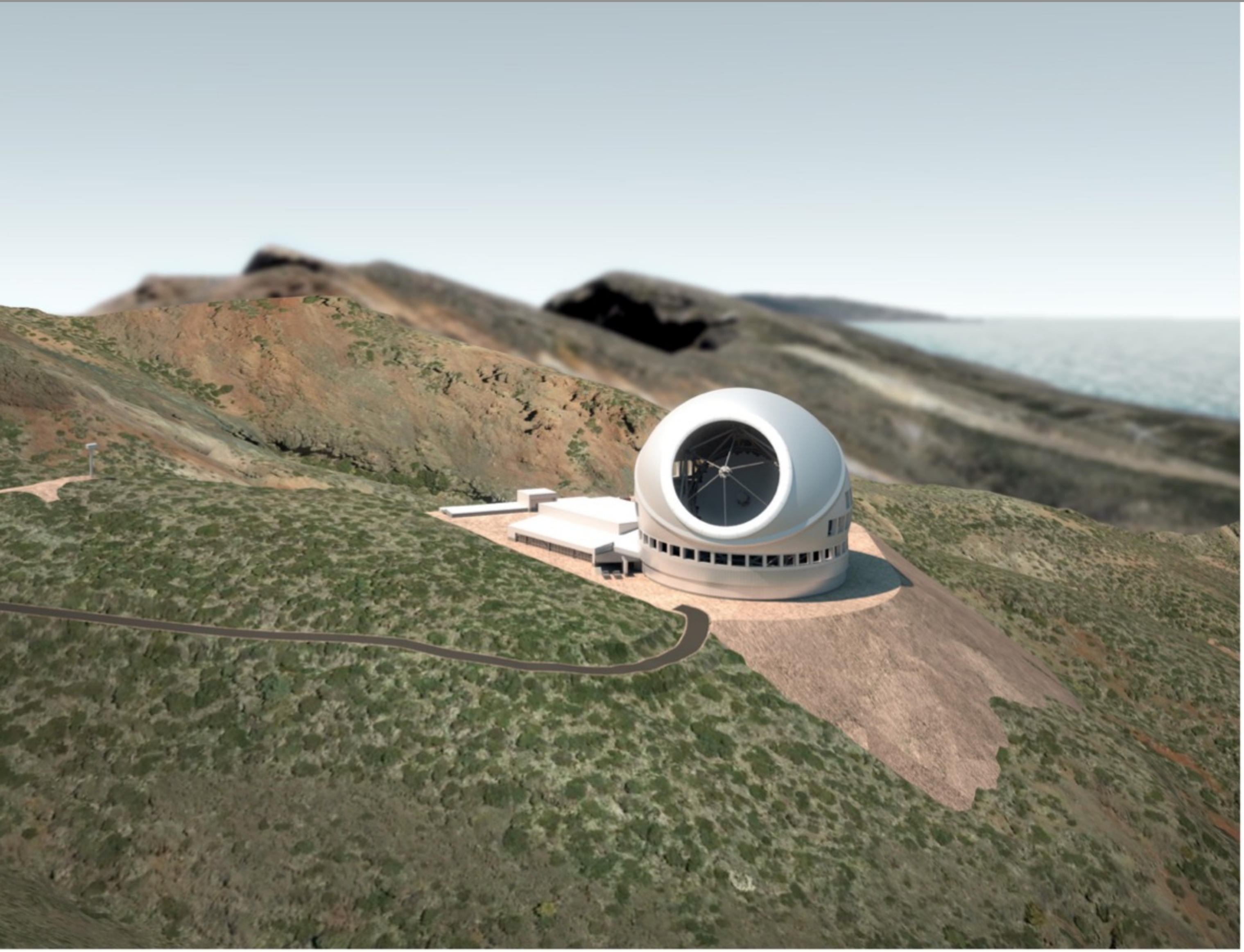
TMT Alternative Site

- In February 2016 the TMT project started a process to identify and select an alternative site option.
- "Plan B" site is Observatorio del Roque de Los Muchachos (ORM) on La Palma operated by Instituto de Astrofisica de Canarias (IAC)
- Northern Hemisphere access to complement E-ELT and GMT
- Significant infrastructure already in place for a quick start if required
- Site-specific modifications to facility design underway
- Permitting processes underway
- Hosting Agreement MoU is in place to be executed if necessary

➢TIO Board has set a firm goal that on-site construction should begin at one of the sites in April 2018

TMT Alternate Site Investigations

Observatorio del Roque de los Muchachos



ORM on La Palma

- Similar C_N^2 profile and τ_0 values as those at Maunakea (relevant to AO correction)
- Similar fraction of clear nights as Maunakea
- Lower elevation (2400m vs 3960m)
  - Higher atmospheric pressure and precipitable water vapor (PWV)
  - Higher mean temperature
- Higher declination (28.9° vs 19.8°)

Observations at thermal IR wavelengths are compromised because of the lower altitude and higher temperature

Southern sky visibility is reduced (e.g., WFIRST HLS)

US TMT Science Working Group (SWG)

- The US TMT SWG engages with the US astronomical community to understand and represent its interests and aspirations for TMT

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

*** TMT Science Advisory Committee or Board representative**

- SWG has helped to develop a *US National TMT Participation Plan* for the NSF

TMT International Science Development Teams (ISDTs)

- Engage future science user community in TMT now
- Plan TMT science programs
- Provide scientific input & guidance to the TMT project
- Help define observatory capabilities & operations model
- Foster collaboration & cooperation between scientists in and beyond the international TMT partnership

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

- Open to all PhD astronomers
  - 229 scientists worldwide, **70 from the US-at-large community**

The TMT Science Forum

- Annual science conference & collaboration meeting
- Planning the future of TMT science and instrumentation
- NSF-TMT cooperative agreement provides travel support for US astronomers

TMT ASTRONOMY'S NEXT-GENERATION OBSERVATORY

Thirty Meter Telescope Science Forum

Save the Date: The Thirty-Meter Telescope observatory will host the inaugural "TMT Science Forum" on

July 22 and 23, 2013

at the

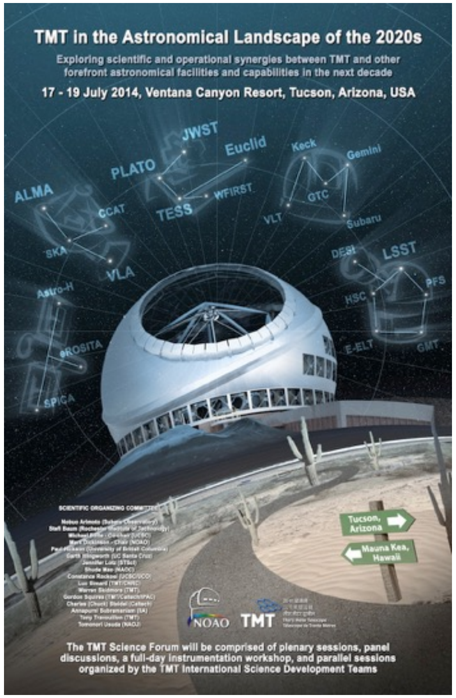
Waikoloa
Resort on the island of Hawaii.

The TMT is an international project to build and operate a 30-m telescope located on Mauna Kea, HI. The program will consist of talks and workshop discussions exploring science, first-light and future instruments, observatory operations, archiving and data products, key projects and cross-partnership collaborations, astronomy education and science, technology, engineering, and math (STEM) opportunities.

More information and the Forum program can be found at
http://conference.ipac.caltech.edu/tmtsf

If you are interested in attending the Forum, register at the conference website. As part of the NSF-TMT agreement, some travel funding will be available for U.S. community members (who are not at TMT institutions) to attend the forum. To request consideration for travel funding, send an email to TMT@noao.edu with your name, institutional affiliation, and areas of interest relevant to TMT.

ACURA CALTECH DSTI NAOC NAOJ UC



TMT in the Astronomical Landscape of the 2020s

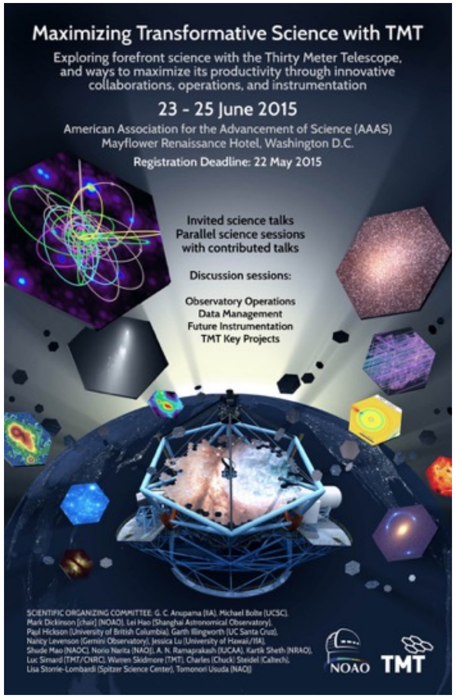
Exploring scientific and operational synergies between TMT and other forefront astronomical facilities and capabilities in the next decade

17 - 19 July 2014, Ventana Canyon Resort, Tucson, Arizona, USA

SCIENTIFIC ORGANIZING COMMITTEE

NOAO TMT

The TMT Science Forum will be comprised of plenary sessions, panel discussions, a full-day instrumentation workshop, and parallel sessions organized by the TMT International Science Development Teams



Maximizing Transformative Science with TMT

Exploring forefront science with the Thirty Meter Telescope, and ways to maximize its productivity through innovative collaborations, operations, and instrumentation

23 - 25 June 2015

American Association for the Advancement of Science (AAAS)
Mayflower Renaissance Hotel, Washington D.C.

Registration Deadline: 22 May 2015

Invited science talks
Parallel science sessions with contributed talks

Discussion sessions:

Observatory Operations
Data Management
Future Instrumentation
TMT Key Projects

SCIENTIFIC ORGANIZING COMMITTEE: G. C. Anupama (IIA), Michael Bolte (UCSC), Mark Dickinson [chair] (NOAO), Lei Hao (Shanghai Astronomical Observatory), Paul Hickson (University of British Columbia), Garth Illingworth (UC Santa Cruz), Nancy Levenson (Gemini Observatory), Jessica Lu (University of Hawaii/IfA), Shude Mao (NAOC), Norio Narita (NAOJ), A. N. Ramaprakash (IUCAA), Kartik Sheth (NRAO), Luc Simard (TMT/CNRC), Warren Skidmore (TMT), Charles (Chuck) Steidel (Caltech), Lisa Storrie-Lombardi (Spitzer Science Center), Tomonori Usuda (NAOJ)

NOAO TMT

The TMT Science Forum

International Partnership for Global Astronomy

24-26 May 2016

Kyoto International Community House
Kyoto, Japan

Registration Deadline: 23 April 2016

https://conference.ipac.caltech.edu/tmtsf2016/

SESSIONS and TALKS:
International TMT Key Project science
Cross-partnership collaboration and the International Science Development Teams (ISDTs)
Second-generation TMT instrumentation and AO development
Effective strategies for observatory operations
Coordinating science planning with other observatories and facilities within the TMT partnership

SCIENTIFIC ORGANIZING COMMITTEE: G.C. Anupama (IIA), Nahum Arav (Virginia Tech), Michael Bolte (UC Santa Cruz), Yuqin Chen (NAOC), Mark Dickinson (NOAO), SOC co-chair, Christophe Dumas (TMT), Lynne Hillenbrand (Caltech), Nobunari Kashikawa (NAOJ), Anne-Marie Lagrange (Observatoire de Grenoble), Hideko Nomura (Tokyo Institute of Technology), Eric Peng (KIAA - Peking University), Luc Simard (TMT), R. Srianand (IUCAA), Tommaso Treu (UCLA), Kim Venn (University of Victoria), Toru Yamada (JAXA), SOC chair

TMT NAOJ

TMT
तीस मीटर दूरबीन
thirty meter telescope

BEYOND FIRST LIGHT
NEXT-GENERATION INSTRUMENT STUDIES

CONTENT:

INTERNATIONAL SCIENCE DEVELOPMENT TEAM (ISDT) SESSIONS ON INSTRUMENT STUDIES

KICKING OFF NEXT-GENERATION INSTRUMENT STUDIES

BIG SCIENCE QUESTIONS FOR TMT NEXT-GENERATION INSTRUMENTS

LESSONS LEARNED FROM 1ST GENERATION INSTRUMENTS

SCIENCE ORGANIZING COMMITTEE:

(CO-CHAIR) CHRISTOPHE DUMAS (TMT)
(CO-CHAIR) SRIANAND RAGHUNATHAN (IUCAA)
ANUPUMA G. C. (IIA)
JUDY COHEN (CALTECH)
IAN DELL'ANTONIO (BROWN UNIV.)
MARK DICKINSON (NOAO)
HAO LEI (SHANGAI OBS.)
JESSICA LU (UC BERKELEY)
CHRISTIAN MAROIS (NRC-HERZBERG)
OI NAGISA (TOKYO UNIV. OF SCIENCE)
LUC SIMARD (NRC)
SIVARANI THIRUPATHI (IIA)
BIN YANG (YUNNAN OBS., NAOC & ESO)

NOVEMBER 7-9, 2017 - INFOSYS CAMPUS, MYSORE, INDIA
REGISTRATION DEADLINE: OCTOBER 2, 2017
HTTPS://CONFERENCE.IPAC.CALTECH.EDU/TMTSF2017

Coming soon!

7-9 November 2017
Mysore, India

Theme: Planning next-generation TMT instrumentation

https://conference.ipac.caltech.edu/tmtsf2017/

US National TMT Participation Plan

- Three main documents:
    - Report of the US TMT Science Working Group (SWG)
        - Science case for US national TMT participation
        - Flow-down from science to capabilities & operations
        - ➢ Maximizing TMT's benefits for the US national community
    - Business and governance model for US national TMT participation
    - Workforce, education, public outreach & communication plan
- Drafts of all reports were submitted to NSF-AST in May 2016
    - Review is on hold until the TMT site situation is clarified

Benefits of US National Membership in TMT

- Consistent, long-term open access to TMT observing time
    - US astronomers may create & lead observing programs, not just participate via collaboration
    - Critical for US scientific competitiveness in the worldwide GSMT era
    - Synergies with other major US national astronomical investments (ALMA, JWST, LSST, WFIRST, TESS, etc.)
- Full participation in TIO governance and scientific planning
    - Definition & prioritization of instrumentation and AO systems
    - Evolution of operations model, observing modes, data management
- Access to archived TMT data
- Opportunity to participate in international TMT key projects
- Enhanced opportunity to participate in developing TMT instrumentation

SWG recommendations to NSF

- ≥ 20% TMT participation share (60 nights/year), with a minimum of 10%
  - Membership ensures the US scientific community has a governance role in planning the observatory's future
- Implement cross-partnership TMT large / key projects
  - Enable large science programs that would be difficult for any one TMT partner
  - Open more TMT observing time and science to US participation
  - Generate large, coherent data sets with high archival re-use value
- Ensure use and re-use of TMT data through archives and good data management practices
- A mix of classical and condition-adaptive queue scheduling

Summary

- The high angular resolution and sensitivity of GSMTs offer powerful synergy with WFIRST for science from the Solar System to Cosmology
- US national participation in GSMTs would provide open access to these capabilities for any astronomer with a good idea
- The NSF-TMT cooperative agreement has defined a model for US national participation in TMT
  - Forward motion currently stymied by the TMT site situation
  - Many conclusions/recommendations of the US TMT SWG could apply similarly to GMT (or even to E-ELT? e.g., via time exchange)

Backup / extra slides: GSMT instrumentation & timelines

GMT first-generation instruments

Table by Rebecca Bernstein (courtesy George Jacoby)

Instrument / Optical mode*	**Description**	**λ Range (μm)**	**Resolution (λ/Δλ)**	**Field of View**
G-CLEF / NS, GLAO	Optical: High-resolution spectrograph	0.35 – 0.95	20,000 – 100,000	7x0.7,1.2” fibers
GMACS / NS, GLAO	Optical: Wide-field multi-obj spectrograph	0.35 – 1.0	1,500 – 4,000 (10k w/ MANIFEST)	40 – 60 amin^2
GMTIFS / LTAO,NGAO	NIR: AO-fed IFU spectrograph/imager	0.9 – 2.5	5,000 & 10,000	10 to 400 asec^2
GMTNIRS / NGAO,LTAO	IR: AO-fed High-res spectrograph	1.2 – 5.0	50,000 & 100,000	1.2” long-slit
w/ MANIFEST / NS, GLAO	Facility Robotic Fiber Feed	0.36 – 1.0		20’ diameter

*Natural Seeing, Ground Layer AO, Natural Guide Star AO, Laser Tomography AO

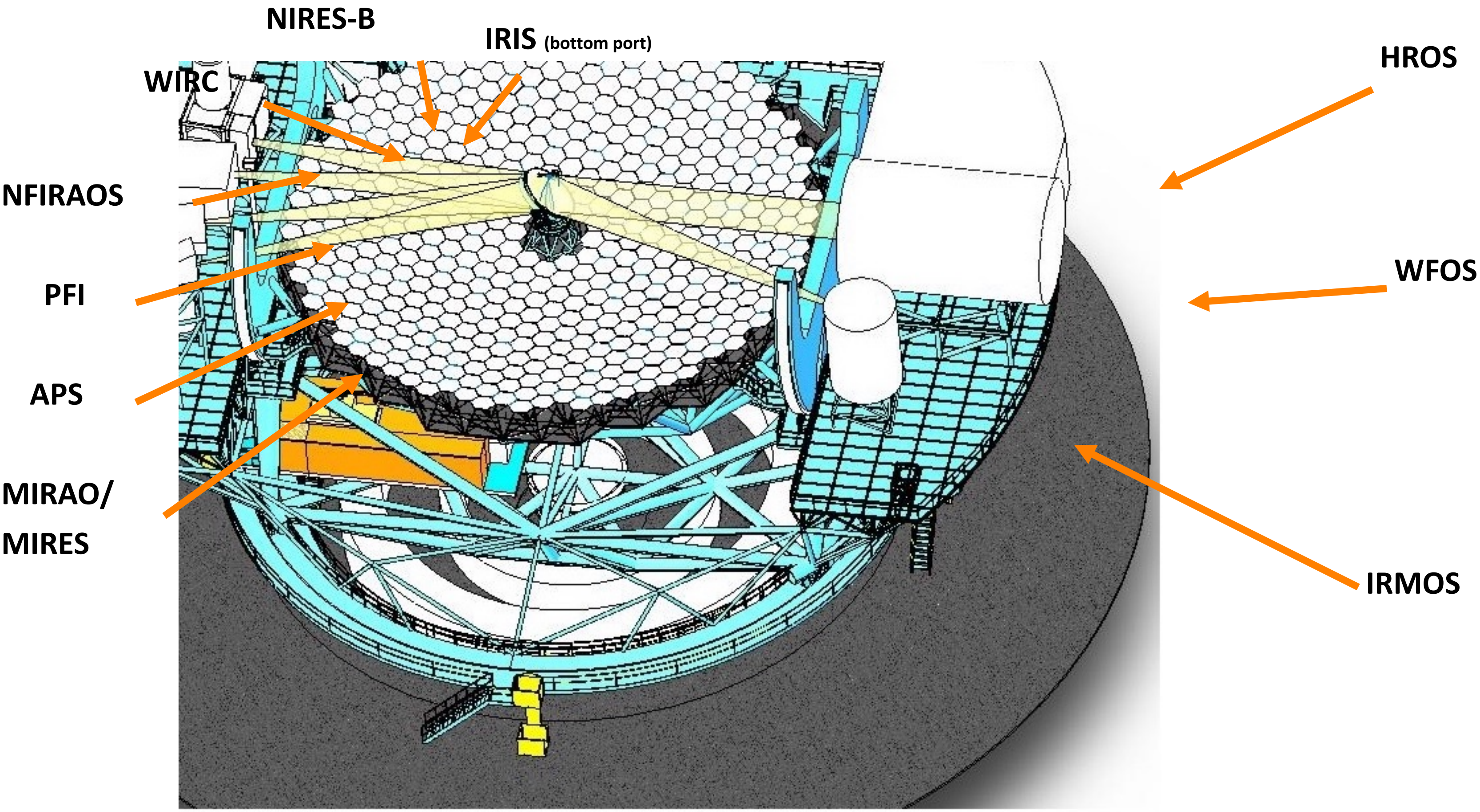
TMT first-generation instruments

- Infrared Imager and Spectrometer (IRIS)
  - Diffraction-limited near-IR performance with NFIRAOS MCAO system
  - NIR imager: FOV 34” x 34”
  - IFU spectrometer with 4 scales (4-50 mas), FOV up to 4”.3 x 2”.3
  - R ≈ 4000 – 8000, 0.8 – 2.5 μm
- Wide Field Optical Spectrometer (WFOS)
  - Multi-slit spectrograph, 0.3 – 1.1 μm, seeing-limited
  - FOV 8’ x 3’
  - R ≈ 1000 (multiplex up to ~100) + cross-dispersed with R ≈ 5000, 8000 (reduced multiplex)
- Infrared Multi-object Spectrometer (IRMS)
  - Multi-slit spectrograph, 0.8 – 2.5 μm
  - AO-assisted but not diffraction-limited
  - FOV 2’ diameter, multiplex 20-40
  - R ≈ 5000

Possible future TMT instruments

- High-Resolution Optical Spectrometer (HROS)
- Near-infrared Echelle Spectrometer (NIRES)
- Mid-infrared Echelle Spectrometer (MIRES)
- Infrared Multi-Object Spectrometer (IRMOS) – deployable IFUs with Multi-Object AO (MOAO)
- Planet Formation Instrument (PFI) – high contrast (ExAO) imager/spectrometer

Rapid “beam switching” capability



52

E-ELT first-light instrumentation

- MICADO – diffraction-limited imager & slit spectrometer
  - Diffraction-limited performance with MAORI MCAO system
  - Imager: FOV up to ~50" x 50" (20" for diffraction-limited sampling)
  - Slit spectrograph, R ≈ 3000, 0.8 – 2.4 μm
- HARMONI – diffraction-limited IFU spectrometer
  - Diffraction-limited performance (in near-IR)
  - Visible and NIR IFU spectrom., 0.47 – 2.45 μm, R = 500 – 20,000
  - 4 scales, 4x4 to 30x60 mas
  - FOV 152 x 214 spaxels → 0".61 x 0".86 to 6".4 x 9".2
- METIS – mid-infrared imager & spectrometer
  - Diffraction-limited performance, 3-19 μm
    - Low/med.-resolution spectroscopy, 3 – 19 μm (R ≈ 100 to 5000?)
    - Imager + coronagraph FOV 11"x11"
  - IFU spectrograph, 3-5 μm, R ≈ 100,000, FOV 0.5 sq. arcsec

E-ELT next-generation instruments

- HIRES – high-resolution optical-NIR spectrograph
  - 0.37 – 2.4 μm (goal: 0.33-2.4 μm)
  - Simultaneous coverage with R ≈ 100,000 (goal 150,000)
  - Several modes with different multiplex and spectral resolution, including fiber and IFU modes
- MOSAIC – opt/NIR multi-object spectrograph
  - Fiber-fed over ~10 arcmin unvignetted E-ELT FOV
  - High-Definition Mode (HDM):
    - 10-20 deployable IFUs, FOV 2”x2”
    - 1 – 1.8 μm (desired: 0.8-2.45 μm), R = 4000-5000 (desired ≥ 8,000)
  - High-Multiplex Mode (HMM):
    - Multiplex ≥ 200 (desired ≥ 400)
    - R = 5000 and 15,000 (desired 5000, 20,000)
    - 0.4 – 1.8 μm (desired 0.4 – 2.45 μm)

GSMT timelines

- E-ELT:
  - Phase 1: AO + 2 lasers, 588 segments (leaving inner hole): 2024
  - Phase 2: Inner 210 segments, full LGS tomography
- GMT:
  - Stage 1: Seeing-limited operations with four segments: late 2022
  - Stage 2: Seeing-limited 7-segment operations: 2025
  - Stage 3: AO-capabilities added
- TMT:
  - 1st – light for full telescope: 2027