TMT: Exciting Ground-based Science in the Era of JWST

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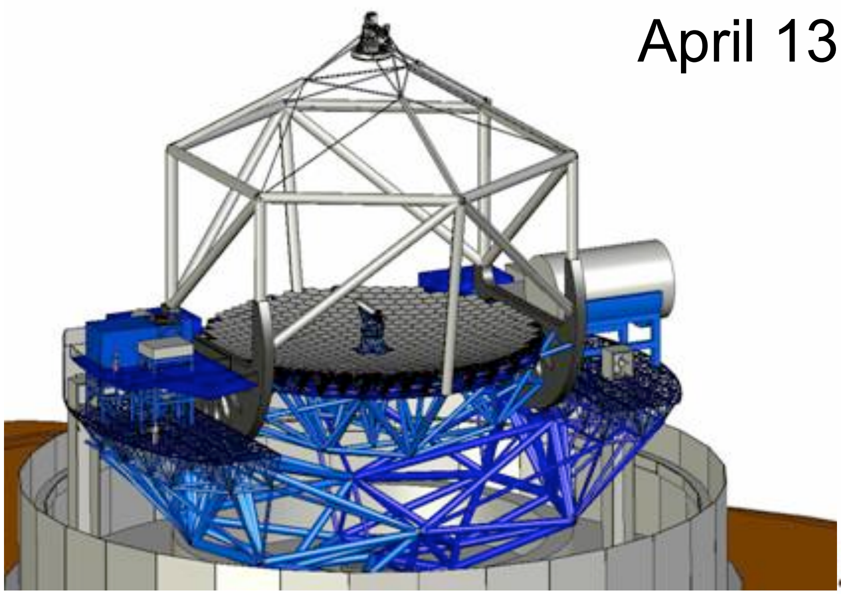
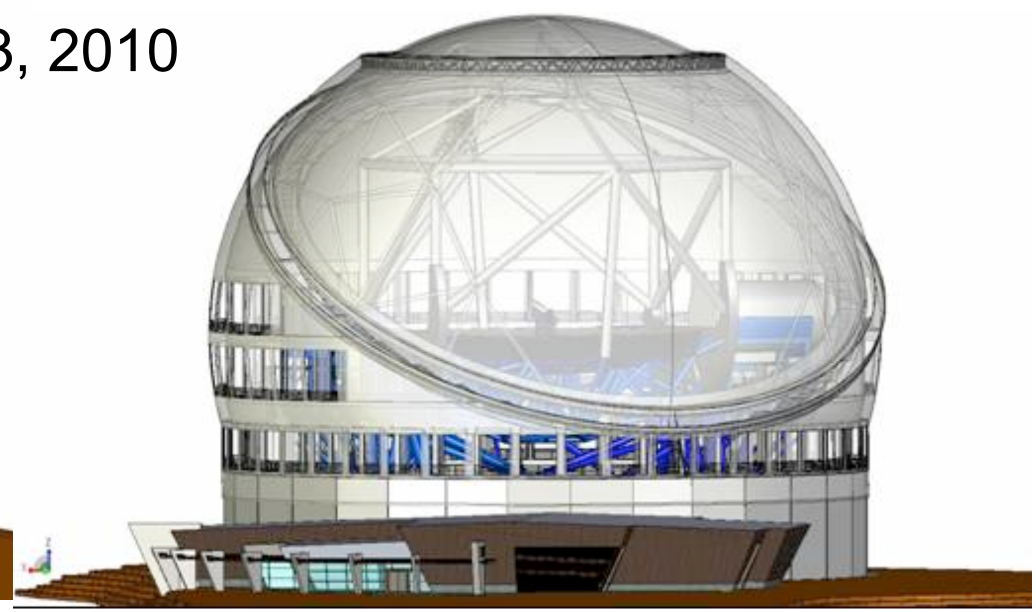
JWST and the ELTs

April 13, 2010





THIRTY METER TELESCOPE

Outline

- TMT
  - Design
  - Status
- Science Cases
  - 43 science programs with 230 requirements
- Science Requirements
- Overview of instrument suite
- Detailed “Early-Light” instrument concepts
- Synergy with JWST and other facilities

- 30m filled aperture, highly segmented, RC telescope
- f/1 primary
- Field of view 20 arcmin
- Instruments fed by articulated tertiary
- Wavelength 0.31 – 28 µm
- Seeing-limited mode
- Completely integrated diffraction-limited system
- Calotte enclosure design

TMT
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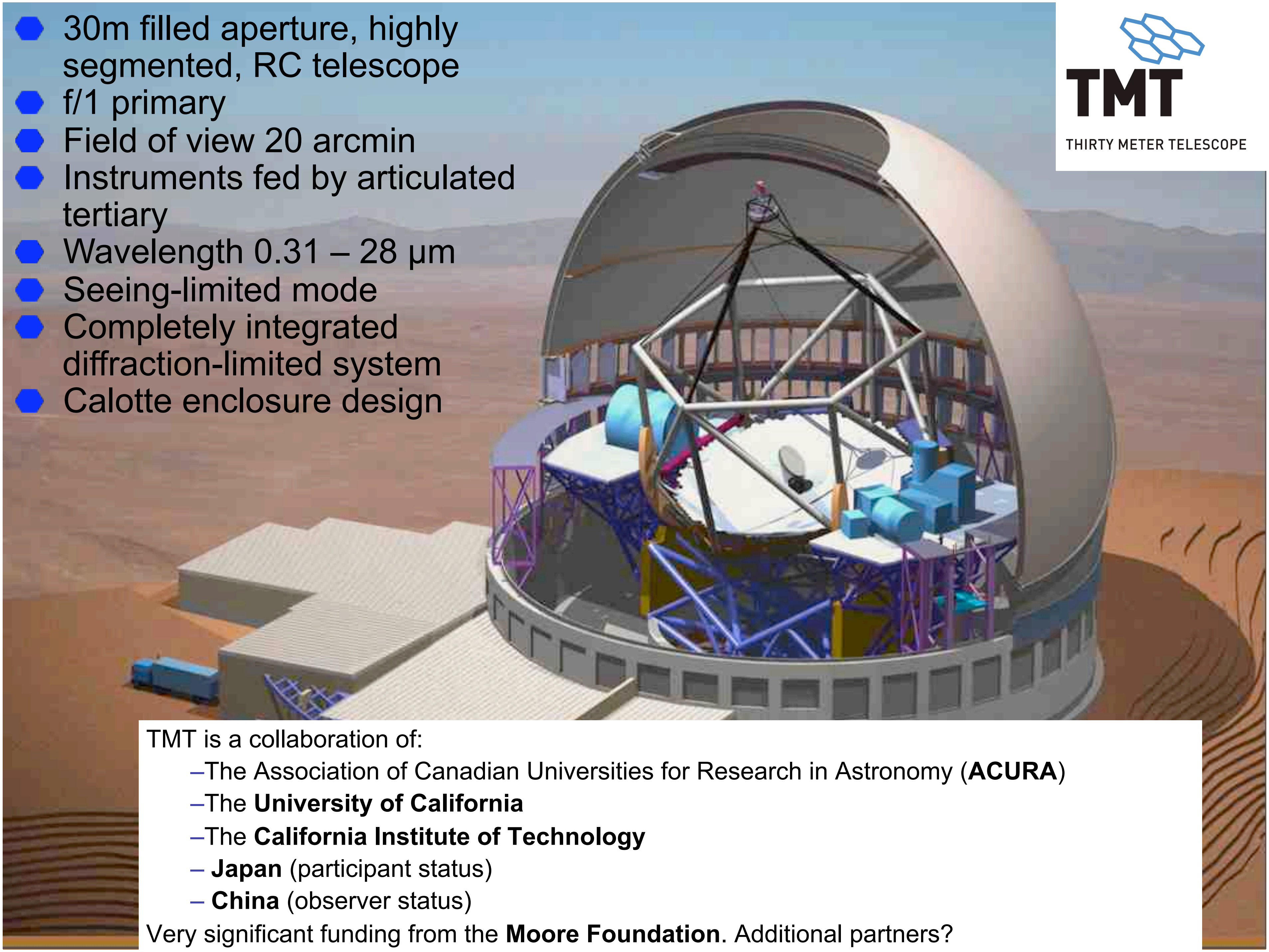

TMT is a collaboration of:

- –The Association of Canadian Universities for Research in Astronomy (**ACURA**)
- –The **University of California**
- –The **California Institute of Technology**
- – **Japan** (participant status)
- – **China** (observer status)

Very significant funding from the **Moore Foundation**. Additional partners?

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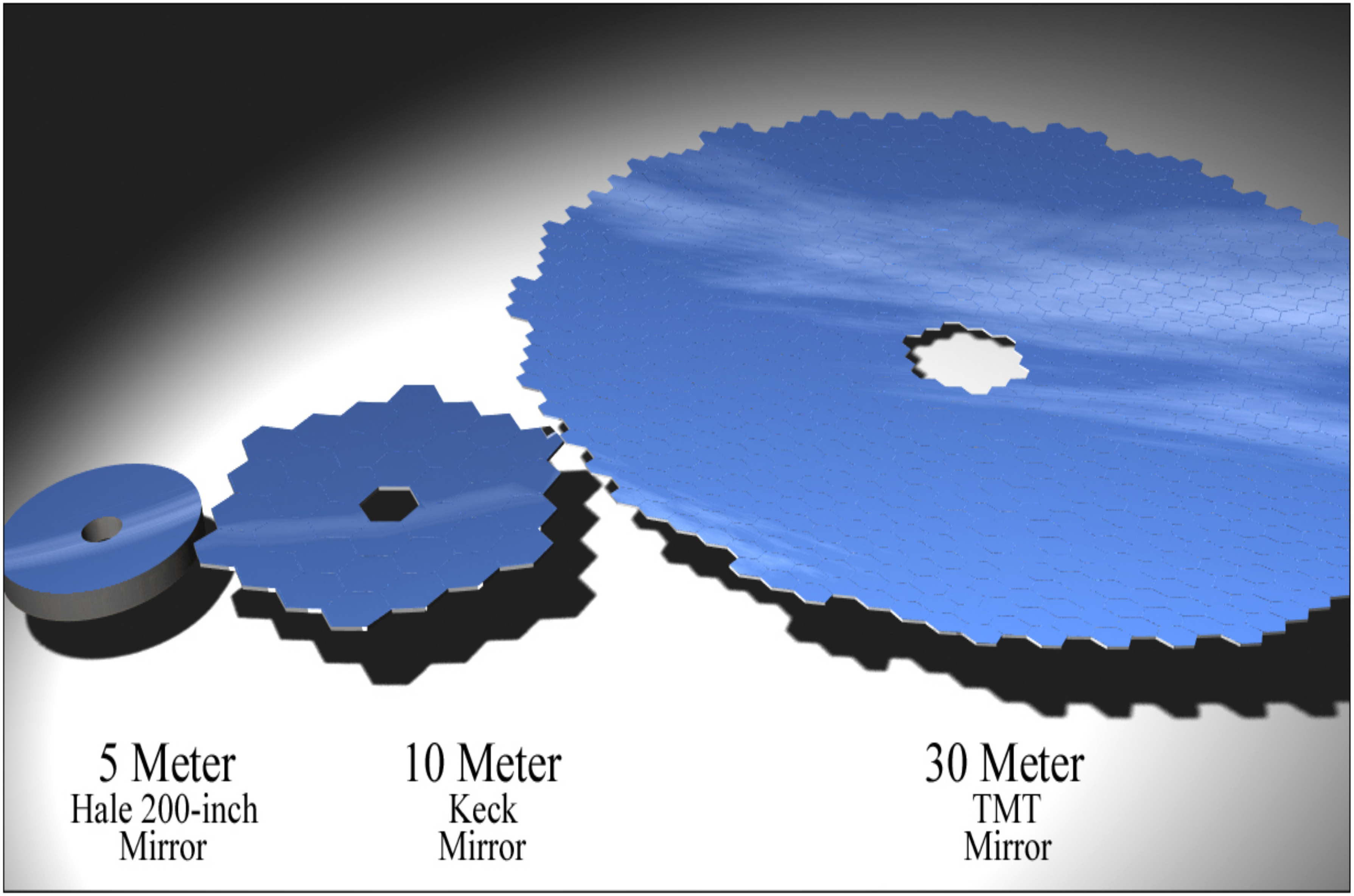
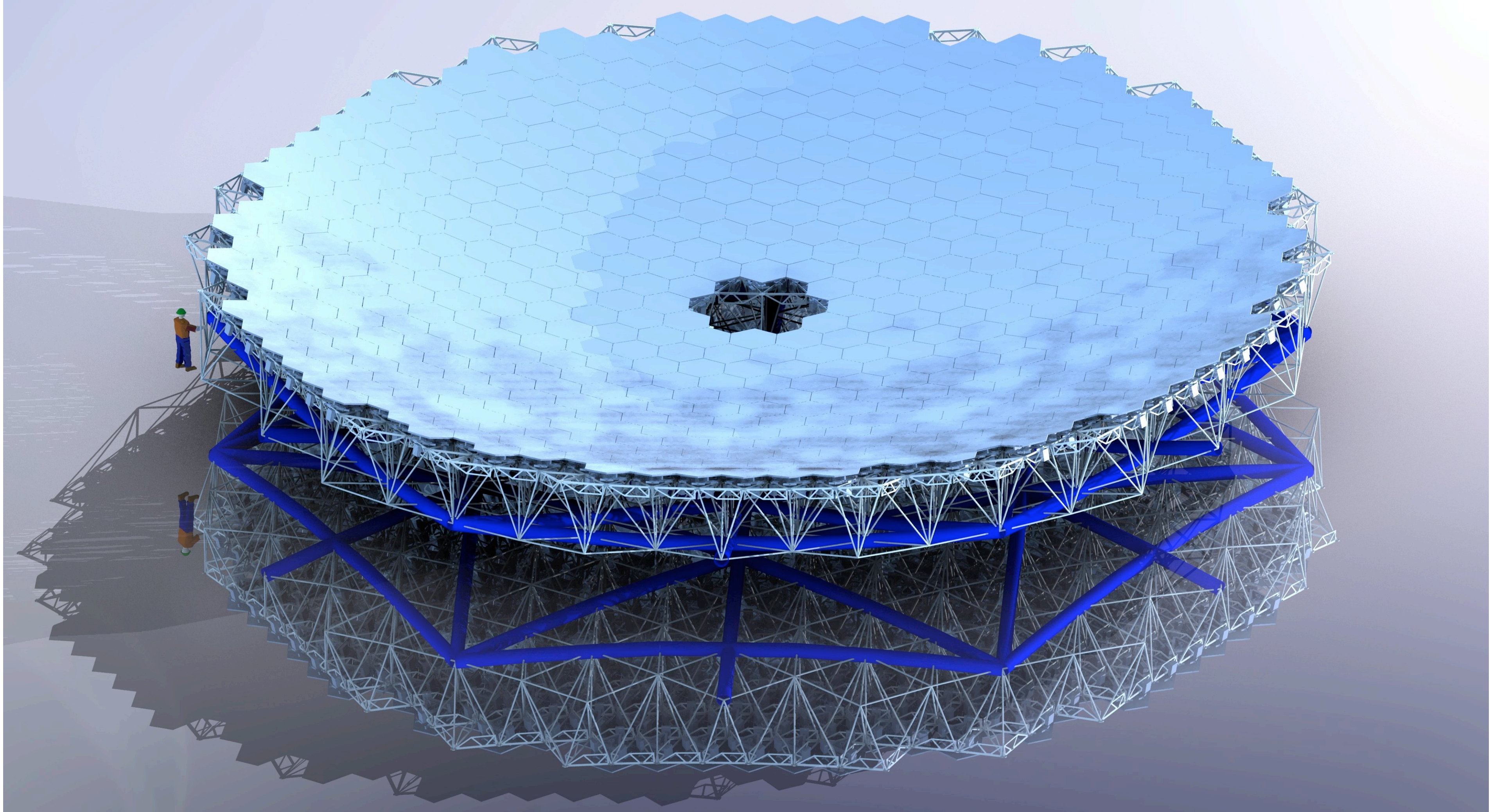
Key TMT features

- 30m, f/1 primary, RC telescope, 20' field
  - "bigger is better: 30-m is a judgment about the proper balance between **science benefit**, cost, technological readiness, and schedule" - Jerry Nelson
  - Cost: (2010)$986M
- Filled aperture, 492 1.4m segments
- Integrated AO systems, including LGS
  - MCAO, MOAO, GLAO, MIRAO, ExAO
  - Sensitivity: D^4 advantage for point sources with AO
- Wavelength range: 0.31 - 28 microns
- Spatial resolution: 7mas in J
- Instruments on large Nasmyth platforms, addressed by articulated tertiary
  - Rapid switching between targets with different instruments (< 10 min)
  - (Rapid target acquisition: time between targets < 5 min)

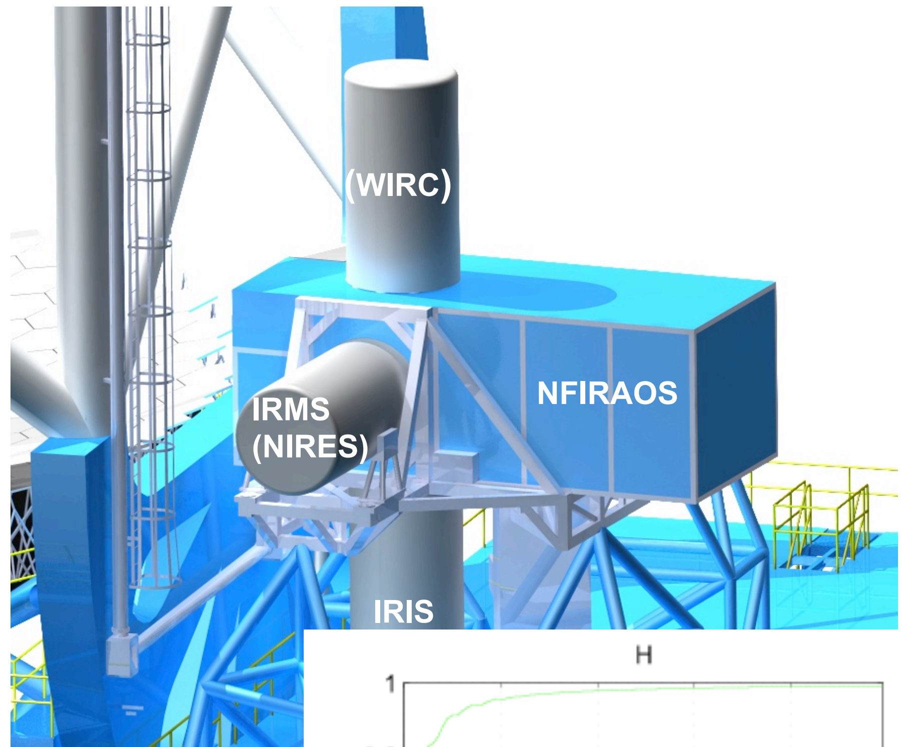

5 Meter
Hale 200-inch
Mirror
10 Meter
Keck
Mirror
30 Meter
TMT
Mirror

Building on Keck heritage, experience, people…

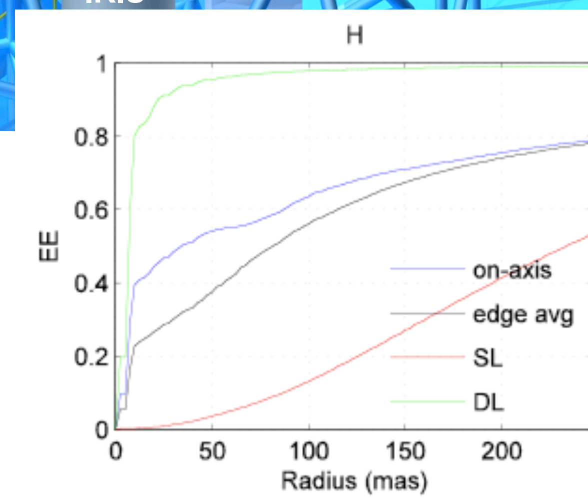


Narrow-Field IR AO System (NFIRAOS): TMT's Early-Light Facility AO system

- Dual conjugate AO system
  – Better Strehl and larger field than current systems (despite being harder for a 30m!)



Band	Strehl Ratio		
	SRD (120 nm)	*Baseline (177 nm)*	*Baseline + TT*
R	0.313	0.080	0.052
I	0.411	0.145	0.105
Z	0.566	0.290	0.236
J	0.674	0.424	0.366
H	0.801	0.617	0.569
K	0.889	0.774	0.742



- Completely integrated system
  - Fast (<5 min) switch between targets
- High sky coverage, even at galactic poles
- Good performance over 2' field
  - VLT/MAD results demonstrate MCAO potential

The Importance of Adaptive Optics - Sensitivity

- Seeing-limited observations and observations of resolved sources

$$Sensitivity \propto \eta D^2 \quad (\sim 14 \times 8\text{m})$$

- Background-limited AO observations of unresolved sources

$$Sensitivity \propto \eta S^2 D^4 \quad (\sim 200 \times 8\text{m})$$

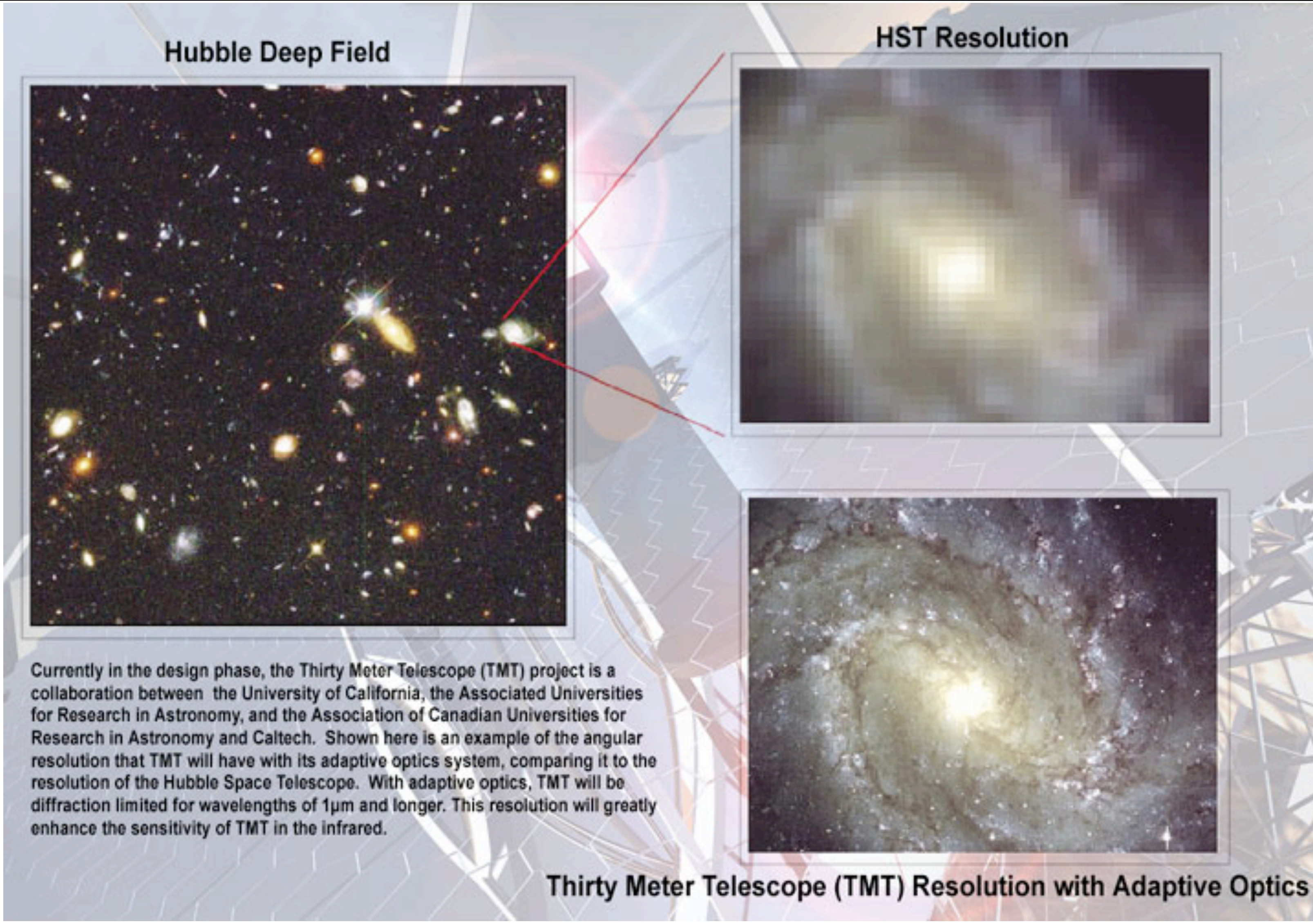
- High-contrast AO observations of unresolved sources

$$Sensitivity \propto \eta \frac{S^2}{1-S} D^4 \quad (\sim 200 \times 8\text{m})$$

$Sensitivity = 1/\text{time required to reach a given s/n ratio}$

$\eta =$ throughput, $S =$ Strehl ratio. $D =$ aperture diameter

The Importance of Adaptive Optics - Resolution



TMT

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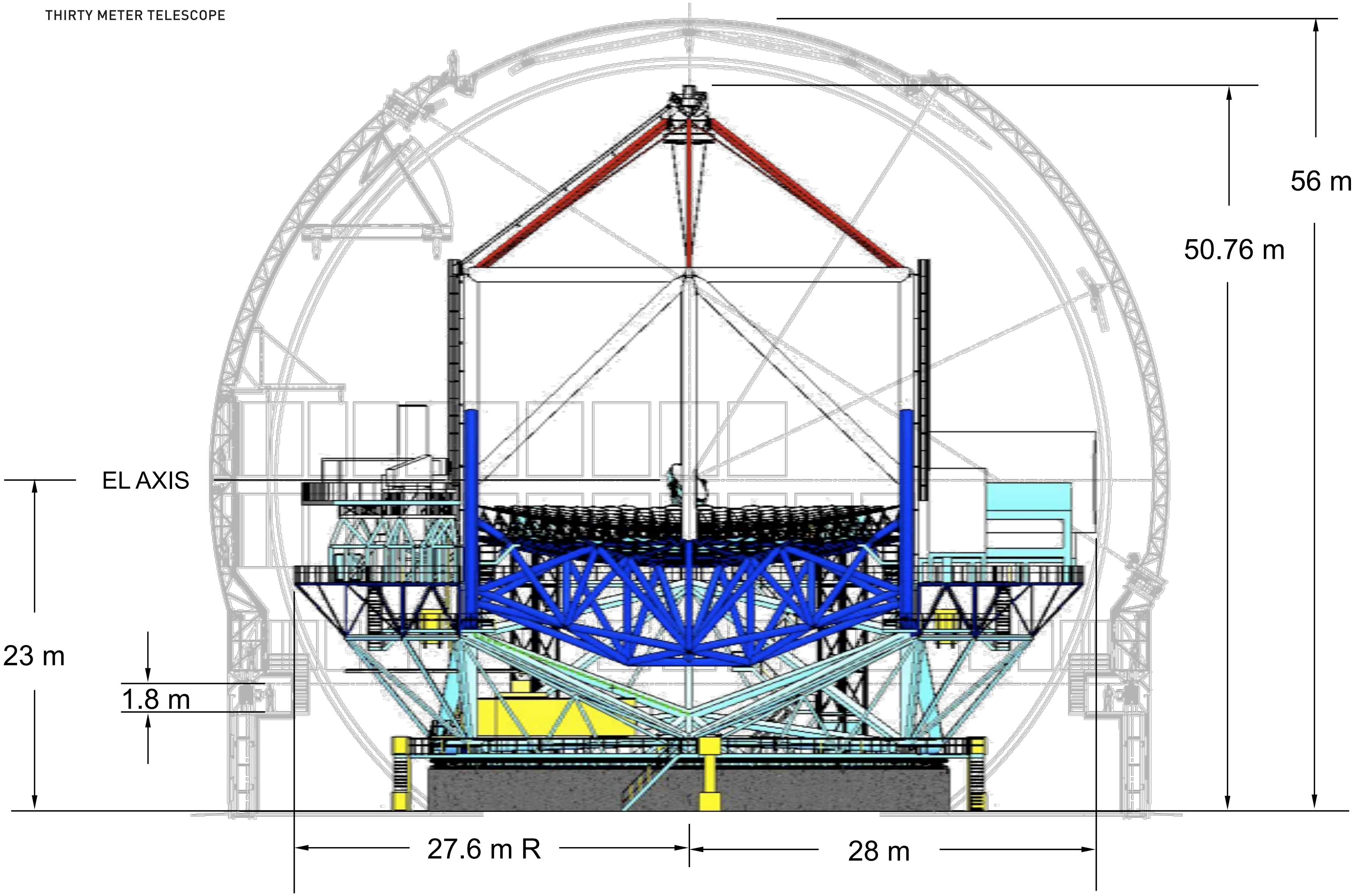
A “Rebirth” of Astrometry

- 30 micro-arcsecs in densely populated fields:
  - –General Relativity at the Galactic center
  - –Distance to the Galactic center
  - –Star forming regions: accurate determination of the Initial Mass Function with cluster membership

- 2 milli-arcsecs in very sparse fields, i.e., where only wavefront sensor guide stars are available:
  - –Magnetar proper motions to establish velocity imparted during progenitor explosion
  - –Binary star/planet orbits to measure stellar, compact object and planet masses
  - –Astrometric microlensing to measure accurate stellar masses
  - –Gravitational lensing to probe dark matter substructures
  - –Binary Kuiper Belt Objects

Compact Enclosure with excellent performance



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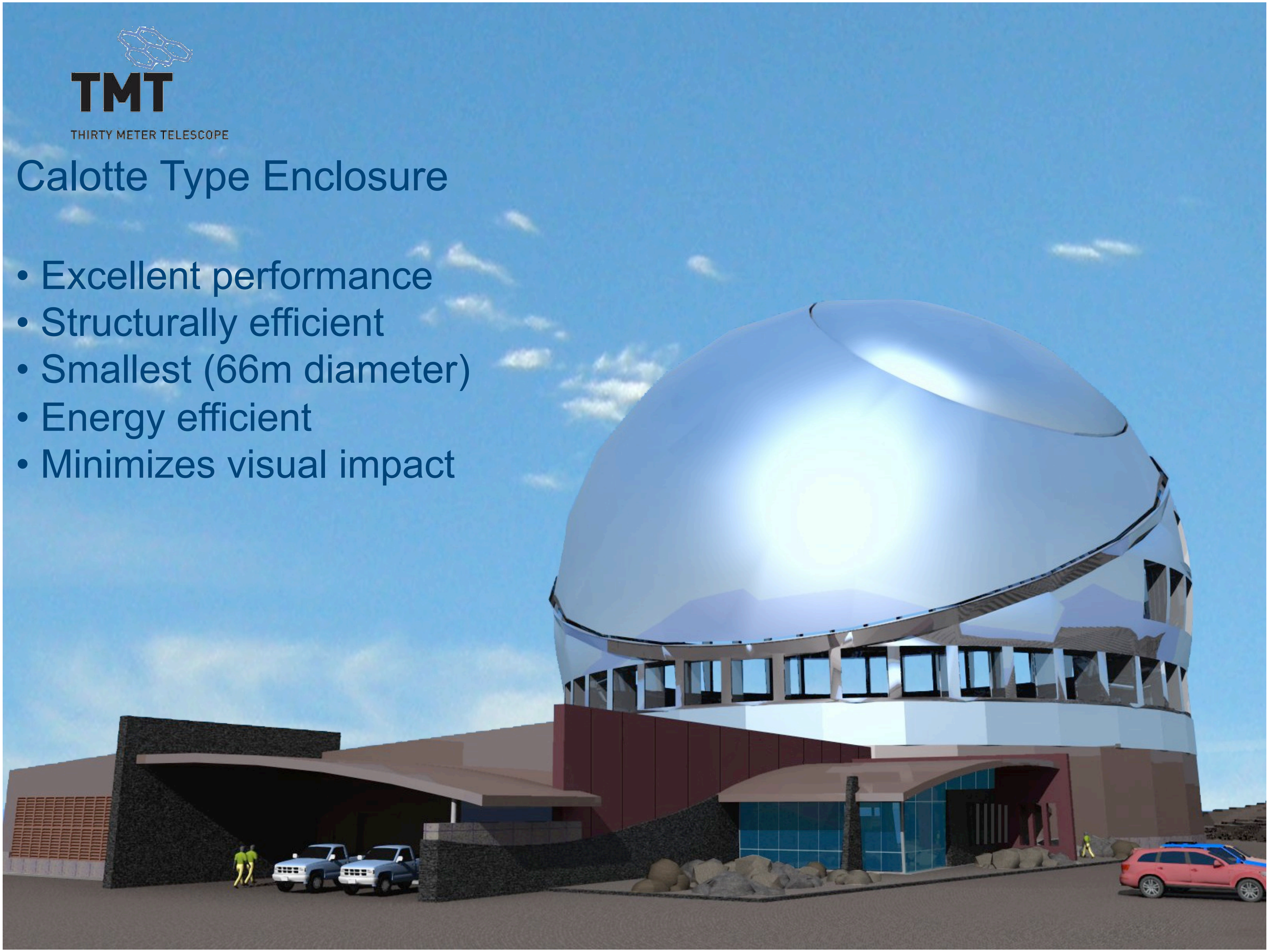
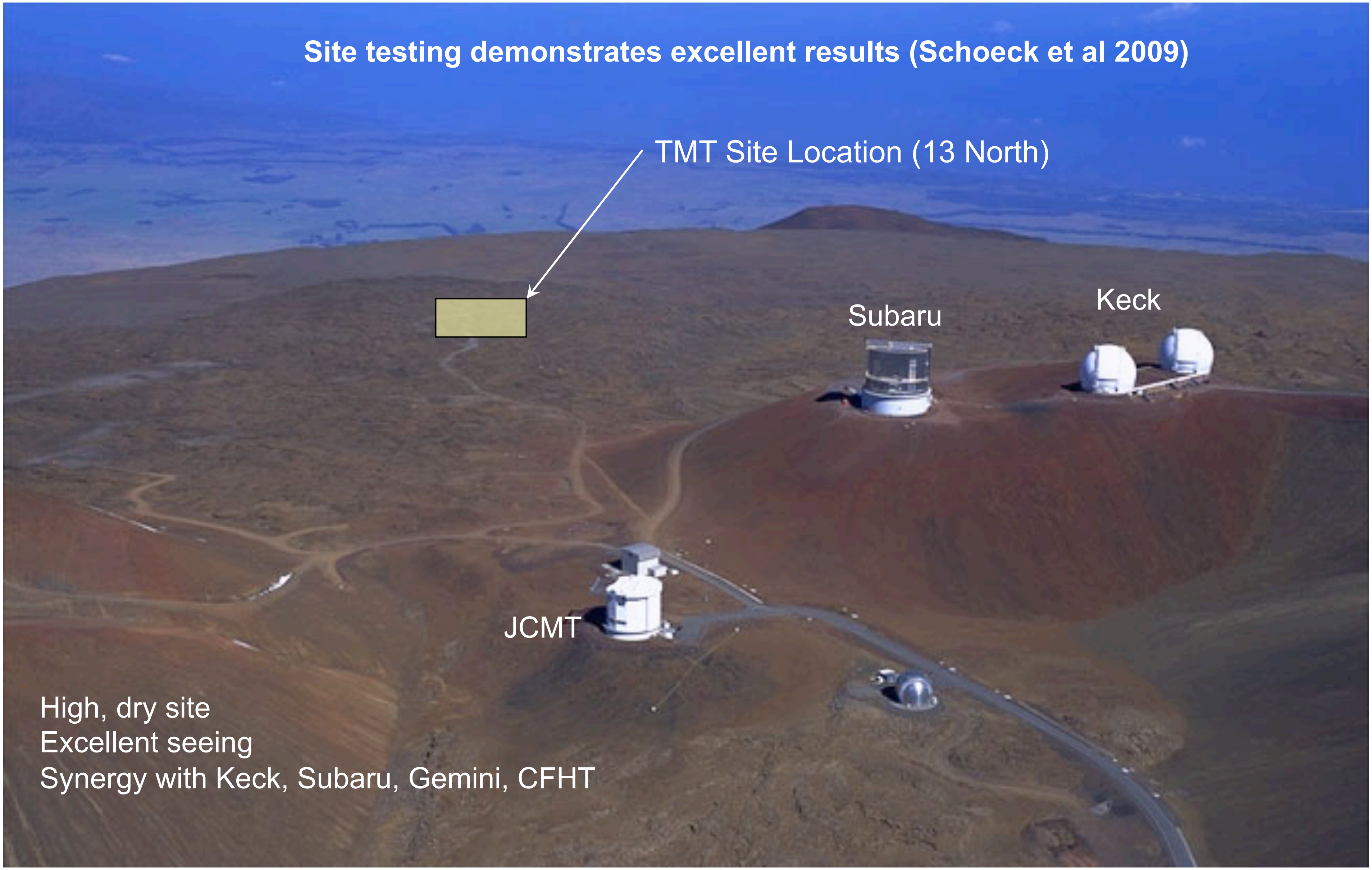
Calotte Type Enclosure

- Excellent performance
- Structurally efficient
- Smallest (66m diameter)
- Energy efficient
- Minimizes visual impact



TMT Site – Mauna Kea 13 North



Status of the Design and Development

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- Science drivers and requirements are established
- Performance of TMT thoroughly modeled and guiding design
  - **Performance requirements are met in both seeing limited and diffraction limited modes**
- Critical subsystems are in Preliminary Design
- Cost estimate is detailed and actively managed
- Integrated Project Schedule is detailed and is under active study
- Modern project management is being applied
- Critical components have been/are being prototyped, industrialized and tested
  - **Results are positive, no technical showstoppers**

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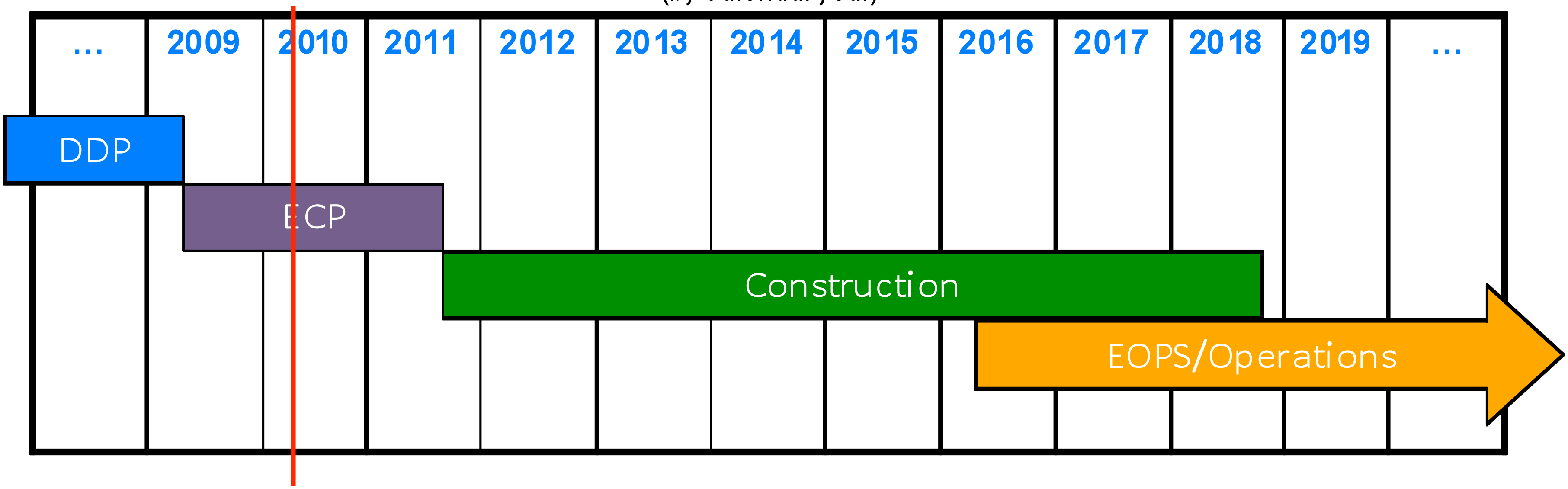
TMT Project Schedule by Programmatic Phase

(by calendar year)



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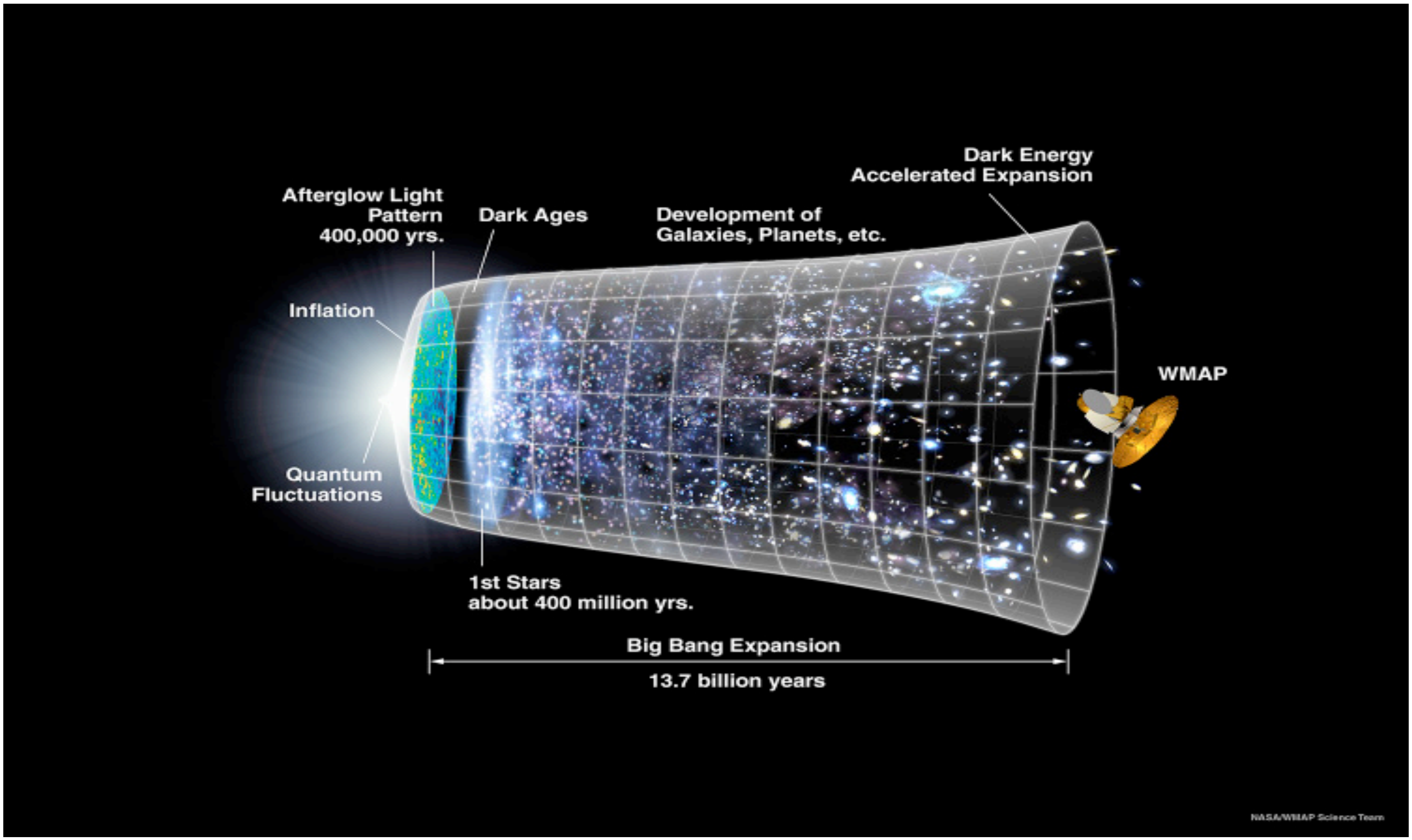
TMT Discovery Space - 13.3 Billion Years



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Fundamental Questions in 2018

- What is the nature of dark matter and dark energy?
- What were the first luminous objects in the Universe and when did they appear?
- When and how did the the intergalactic medium become ionized?
- When and how did the most massive compact objects form?
- How did the galaxies form and how do they evolve?
- When and where were the heavy elements produced?
- How do stars and planetary systems form?
- What are the physical properties of exoplanets?
- Does life exist elsewhere in the Universe?

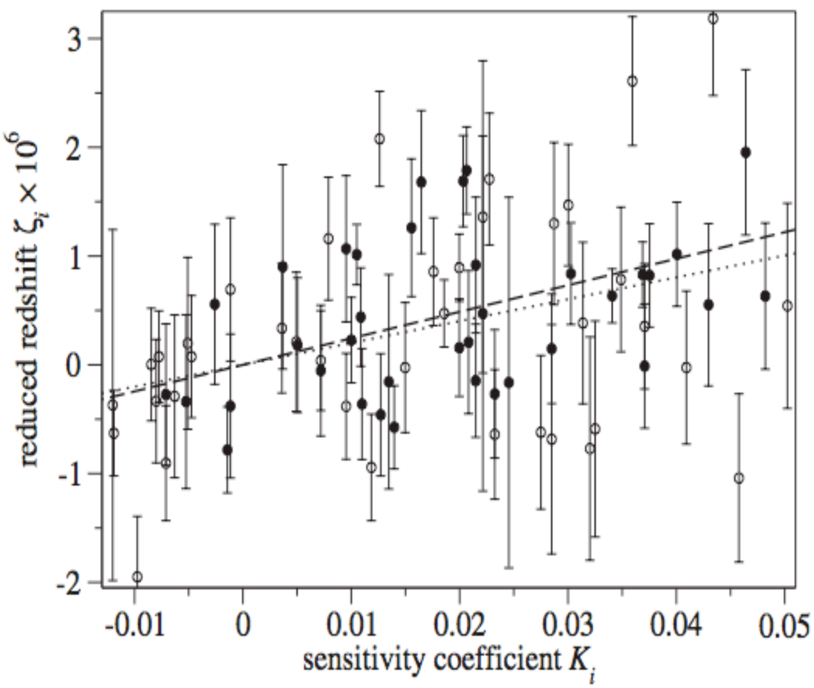
Cosmology and Fundamental Physics

- The nature of dark matter and dark energy

What is Dark Matter and Dark Energy?

There are many theories - some predict variation of fundamental parameters.

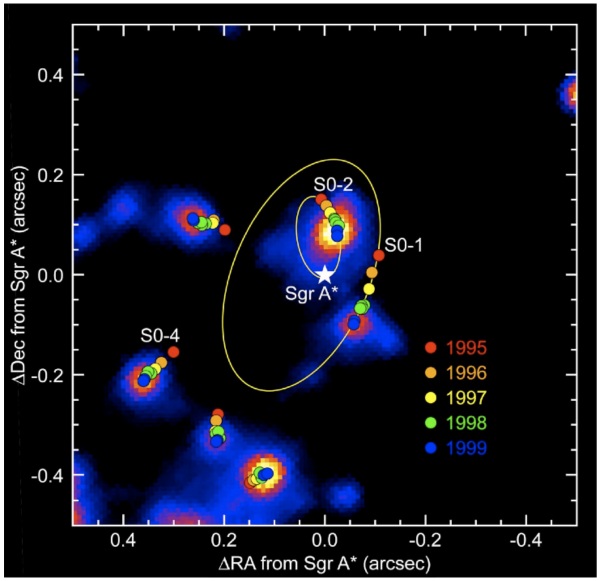
- Wavelengths in multiplets of redshifted UV lines in quasar spectra are sensitive to $\alpha = e^2 / \hbar c$ and to $\mu = m_p / m_e$.
- A decade of study with 10m-class telescopes has hinted at variations:
  - Mixed results for variation of α.
  - Tentative (3.5σ) detection of variability of μ.
- *The light-gathering power of TMT will provide a definitive resolution.*



Wavelength residuals seen in QSO spectra vs. sensitivity coefficient. Positive slope indicates variation of μ. (Reinhold et al. 2006)

Fundamental Physics and Cosmology

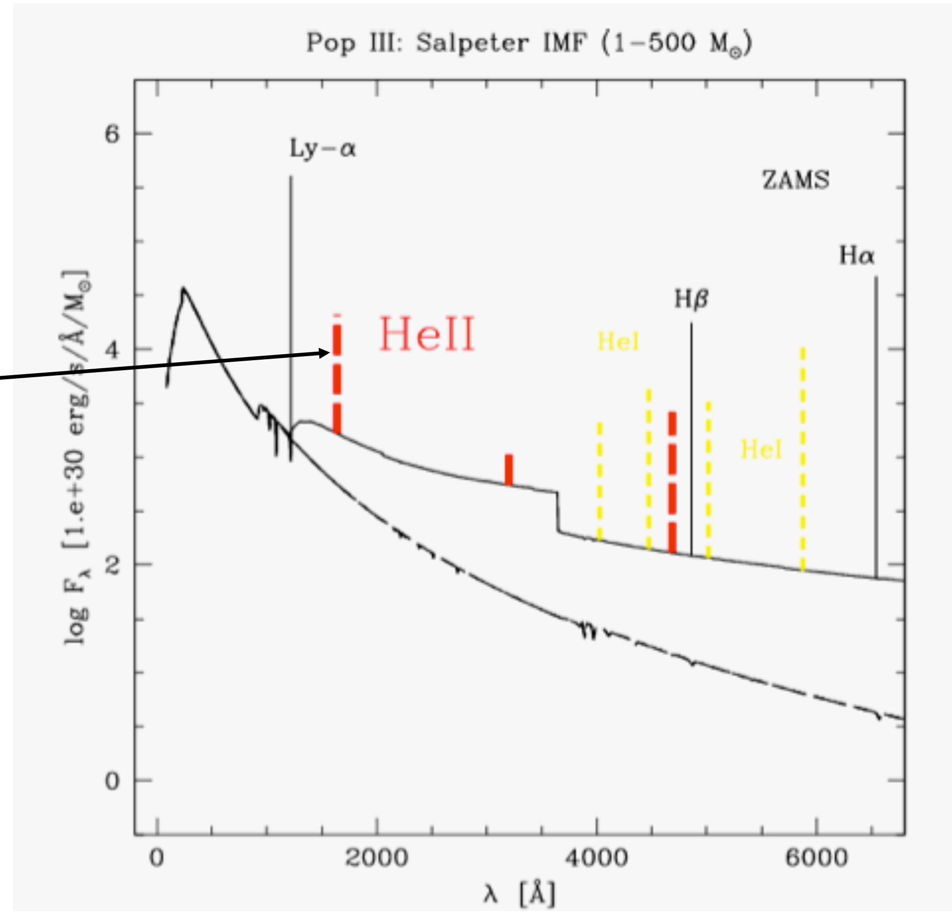
- Science objectives:
  - Dark matter on large and small scales
  - First measurement of a Kerr spacetime
  - Dark energy density versus cosmic time
  - Variations of fundamental constants over cosmological timescales
- Observations:
  - Proper motions in dwarf galaxies and microarcsec astrometry (MCAO/IRIS/WIRC)
  - Wide-field spectroscopy (SL/WFOS)
  - Transient events lasting > 30 days
  - High-res observations of quasars/AGNs



- λ = 0.31-0.62μm, 2-2.4μm
- R = 1000 - 50,000
- Very efficient acquisition
- 0.05 mas astrometry stable over 10 years
- SL Field of view = 20'
- AO field of view = 15" (w/ stable PSF)

The Early Universe and First Light
- The first luminous objects

- *TMT should detect the first luminous objects - and will study the physics of objects found with JWST:*
  - Detection of He II emission would confirm the primordial nature of these objects.
  - With TMT, we will be able to study the flux distribution of sources, and the size and topology of the ionization region.
  - This will help us understand how reionization developed.



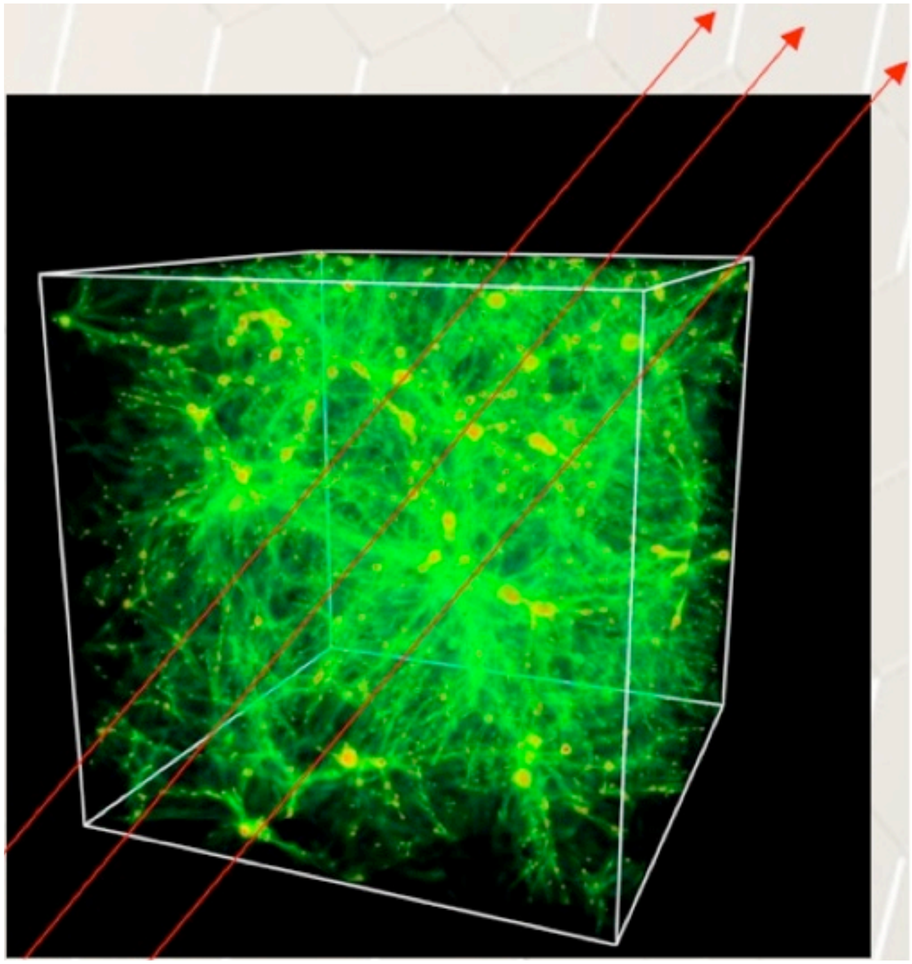
Schaerer 2002

Angular Sizes and Synergy with JWST

- Complimentary
  - JWST has greater sensitivity for z > 20
  - TMT has high sensitivity to physically small sources
    - could be 10-100x, depending on size (and wavelength)
- How small are primordial objects?
  - At z ~ 6.5 some are <= 80-100 mas
  - Some gravitationally lensed sources are ~ 30mas

Lensed galaxies at z ~5.7 (Ellis et al. 2001)
Unlensed sizes ~ 150pc or < 30mas

IGM Tomography



(R. Cen, Princeton U.)

Given that TMT+WFOS will perform spectroscopy down to R_{AB} = 24.5 mag with a spectral resolution of 5000 and S/N≥30, background UV-bright galaxies will then become usable beacons, and the surface density of sightlines on the sky for intergalactic medium tomography will be ~200x higher than currently observable with 8-10m class telescopes.

This means that one will be able to probe *individual* galaxy haloes through multiple sightlines

TMT is a wide-field telescope when applied to the high redshift Universe: 20' field is equivalent to 3.4° at the redshift of SDSS

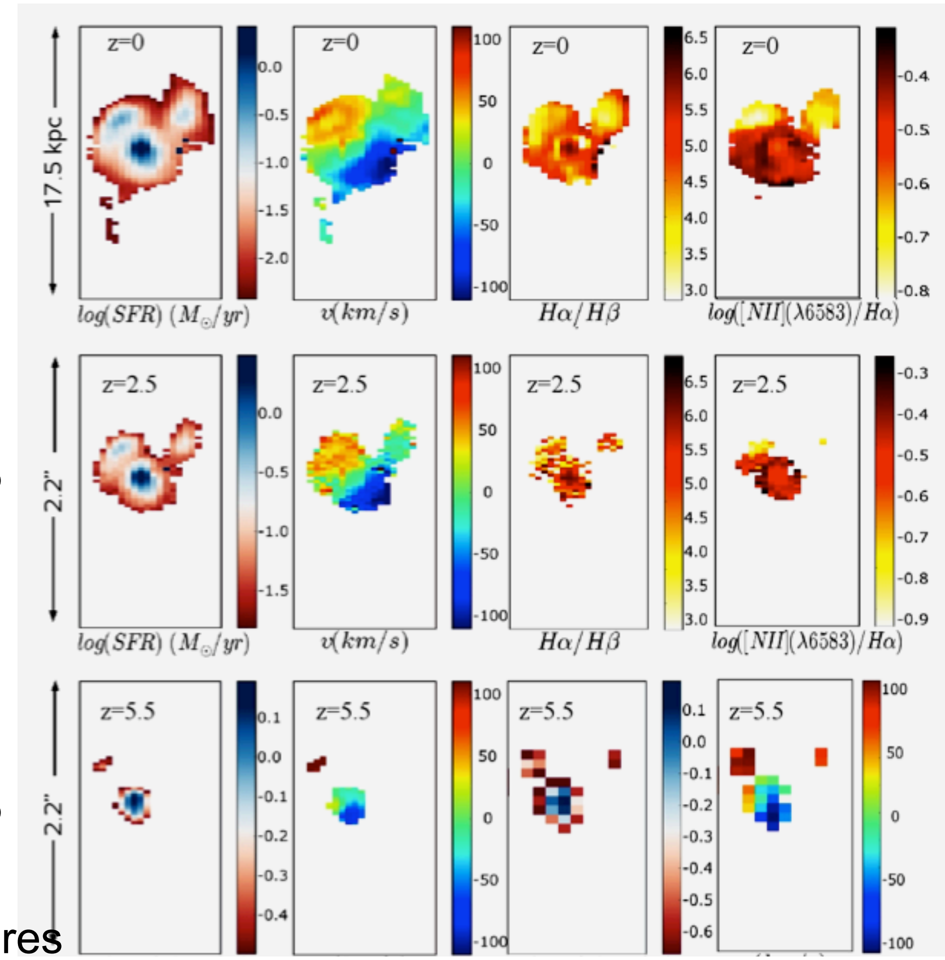
Galaxy Formation and Evolution
- Physics of galaxy formation

- *TMT will use adaptive optics to map the physical state of galaxies over the redshift range where the bulk of galaxy assembly occurs:*
  - Star formation rate
  - Metallicity maps
  - Extinction maps
  - Dynamical Masses
  - Gas kinematics
- *Synergy with ALMA:*
  - Molecular emission

z = 0

z = 2.5
1h exp

z = 5.5
4h exp
500pc res



TMT IRMOS-UFHIA team

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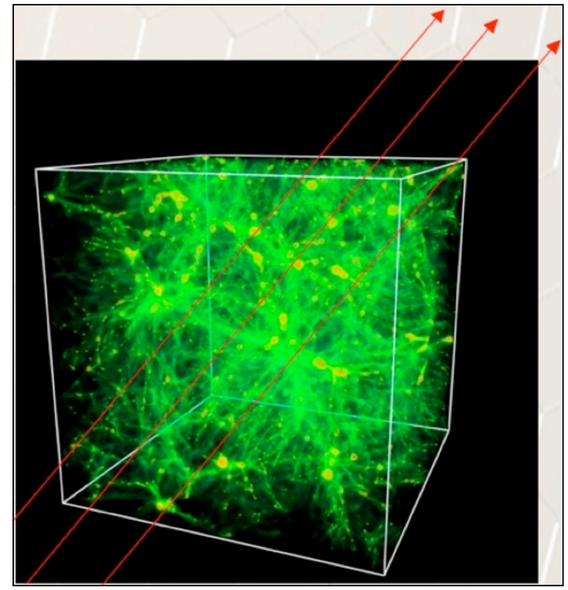
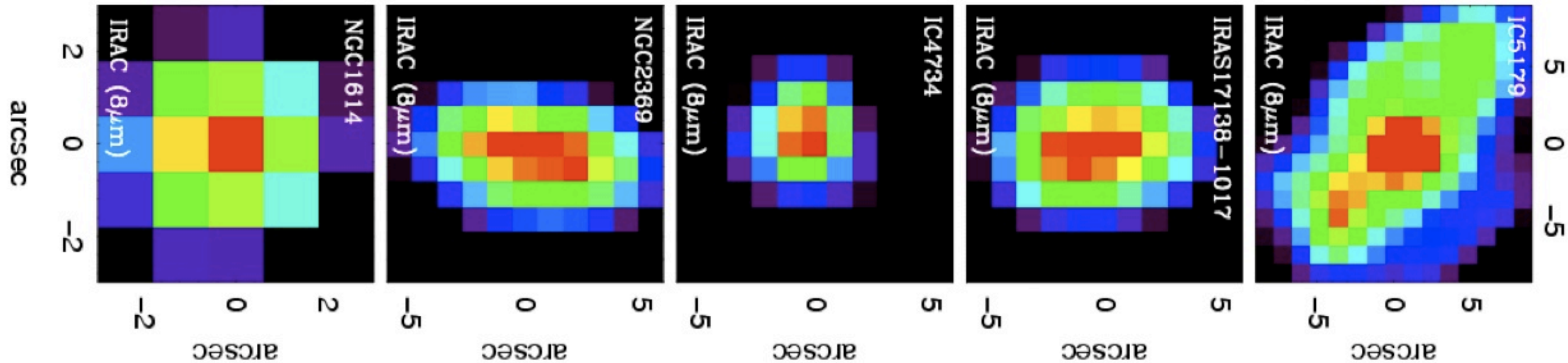
Galaxy Formation and the IGM



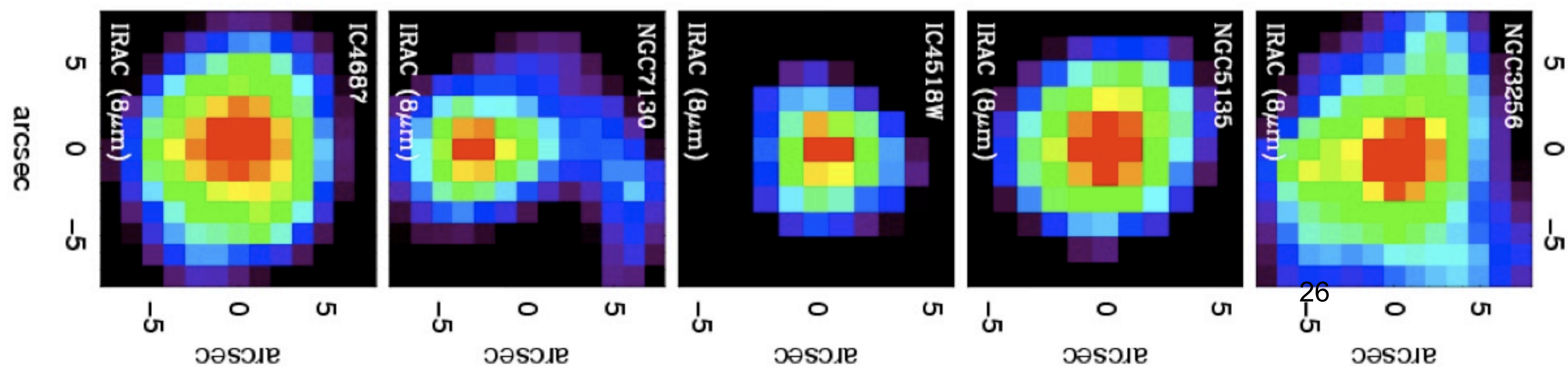
- Science objectives:
  - Baryons at epoch of peak galaxy formation
  - Velocity, SFR, extinction and metallicity maps of galaxies at z = 5.5
  - IGM properties on scales < 300 kpc

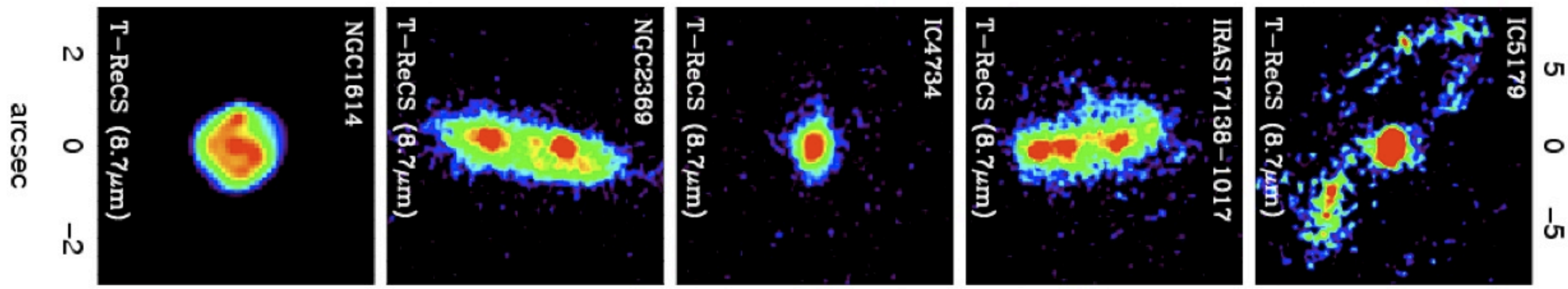
- Observations:
  - Optical/IR multiplexed spectroscopy of distant galaxies and AGNs (SL/WFOS, MCAO/IRMS)
  - Spatially resolved spectroscopy (MCAO/IRIS, MOAO/IRMOS)

- λ = 0.31-2.5μm
- R = 3000-30,000
- Very efficient acquisition
- Multiplexing factor > 100
- Field of view = 20’



- Merging galaxies often hidden behind gas and dust forming stars – need mid-IR to penetrate extinction
- High spatial resolution separates black hole region from host galaxy contamination
- TMT/MIRES will put JWST observations in context as done with Spitzer and today's 8m telescopes
  - At z = 0.5, JWST resolution = 1.5 kpc and TMT = 330 pc





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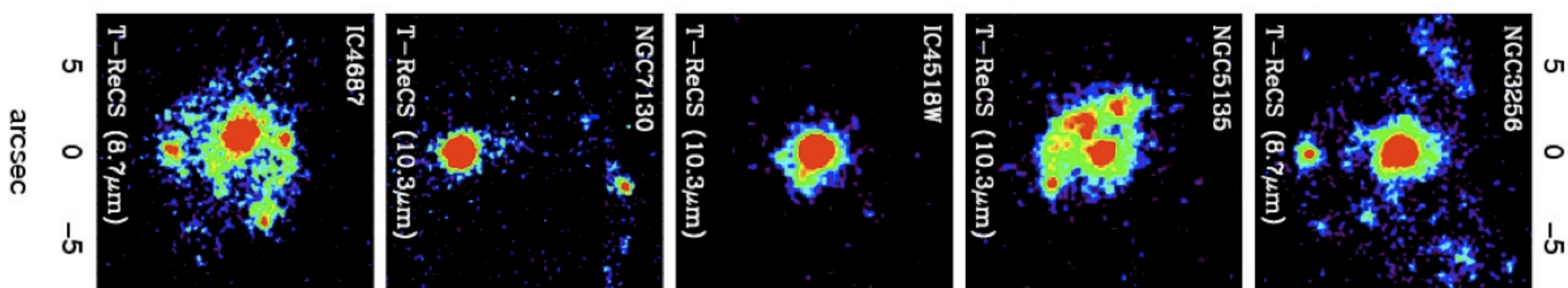
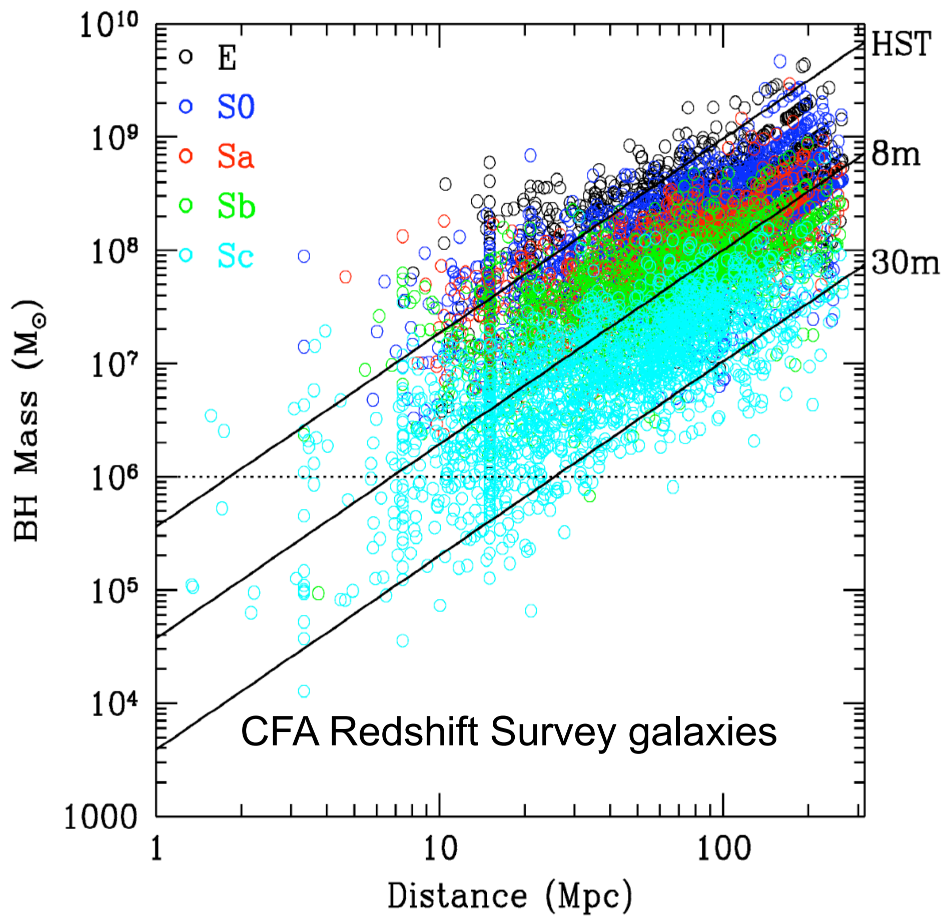


Black holes and Active Galactic Nuclei - Evolution and the galaxy - BH connection

- *TMT will determine black hole masses over a wide range of galaxy types, masses and redshifts:*
  - It can resolve the region of influence of a $10^9 M_\odot$ BH to z ~ 0.4 using adaptive optics.
- 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?

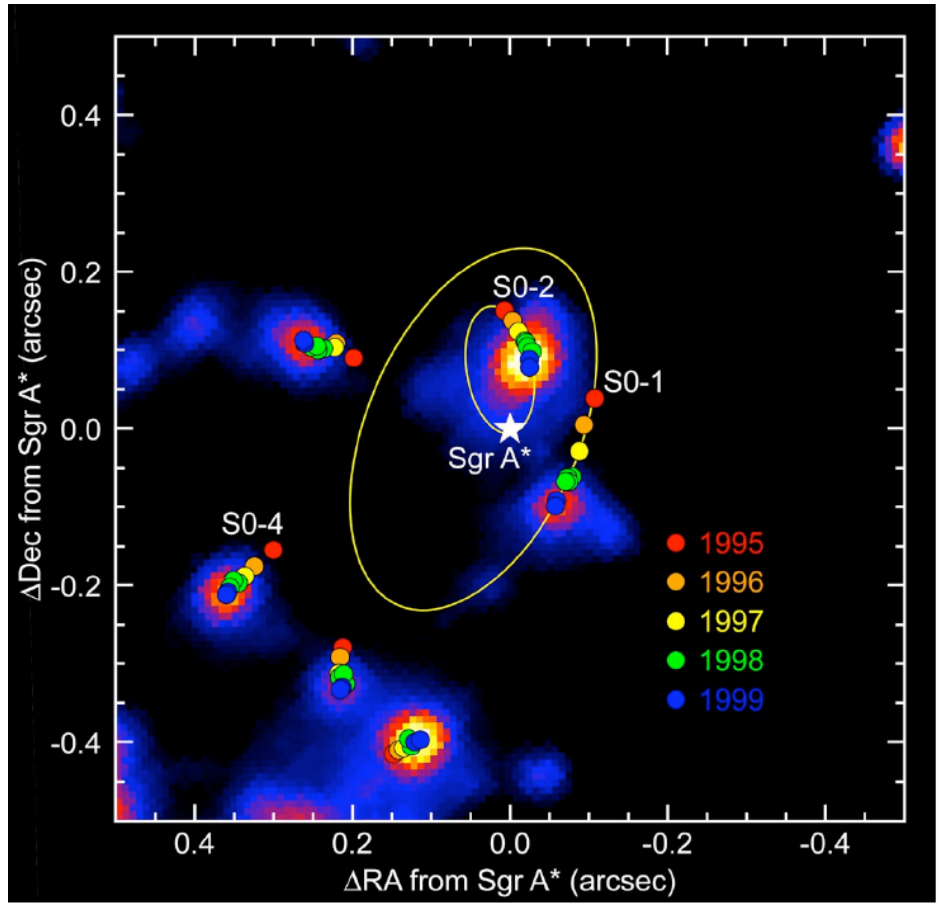


Black Holes and Active Galactic Nuclei - The galactic center

- TMT/IRIS will map stellar orbits in the galactic center with precision ~30 μas to probe the gravitational potential, study the nature of dark matter on small scales, and measure general-relativistic effects.

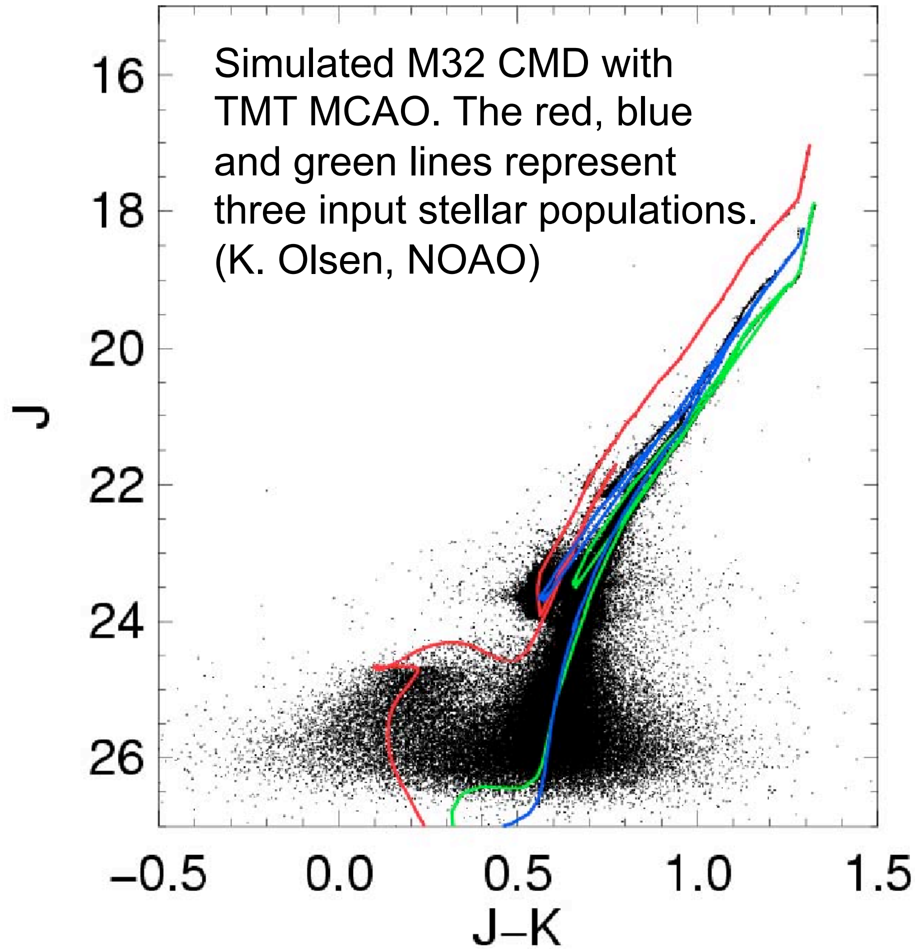
- TMT will detect and spatially resolve accretion disks and the spheres of influence of massive black holes to z ~ 1, and study AGN mass and metallicity at all redshifts.

A. Ghez, UCLA

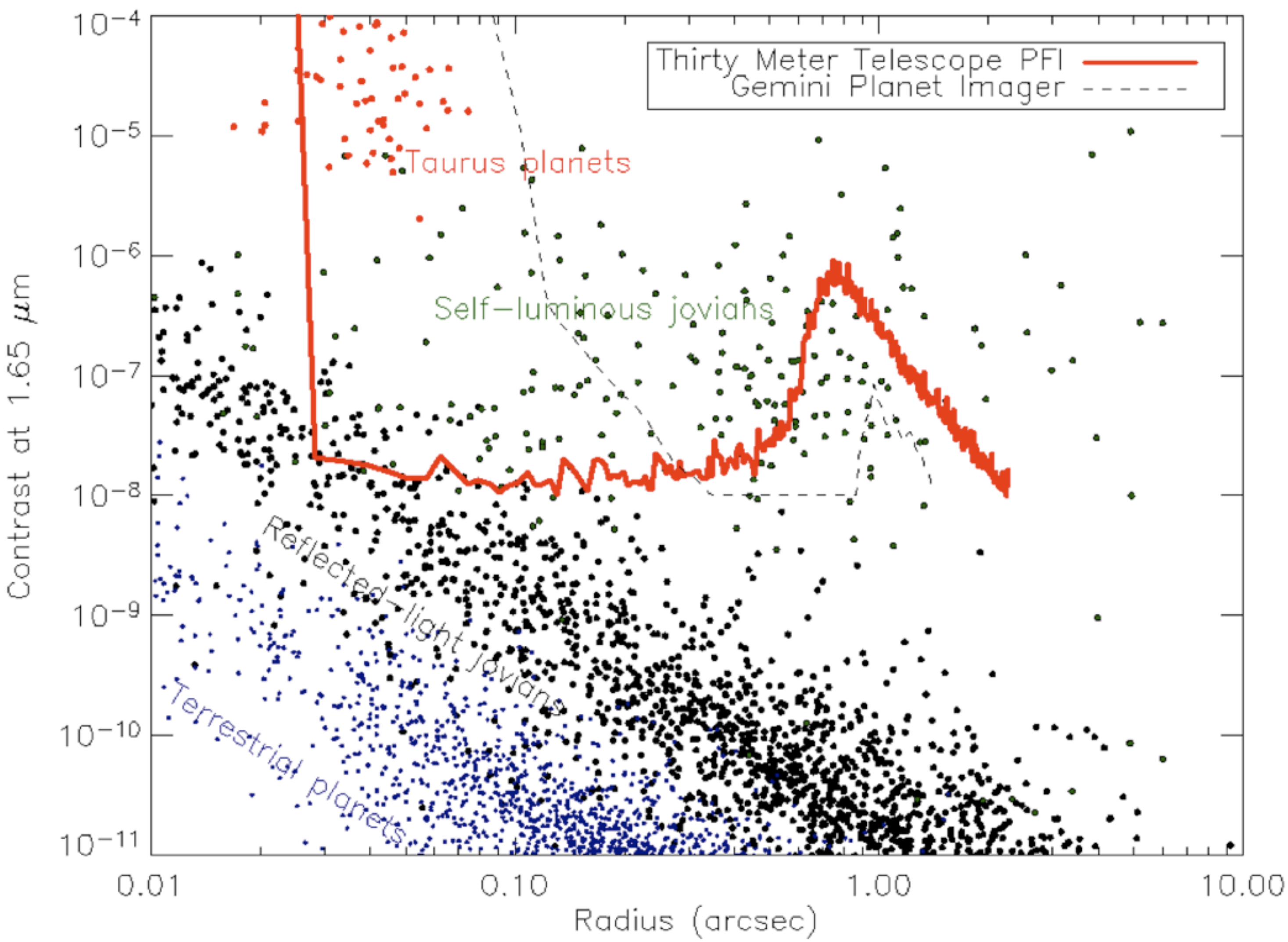


Stellar Populations in the Local Universe
- Stellar archaeology

- *TMT will determine the star formation history in galaxies out to the Virgo cluster:*
  - Adaptive optics will allow photometry of resolved stellar populations in crowded fields.
  - This will give star-formation history and metallicity in a wide range of environments.
  - High-resolution spectroscopy will provide element abundances.
  - Complimentary to high-z galaxy studies.

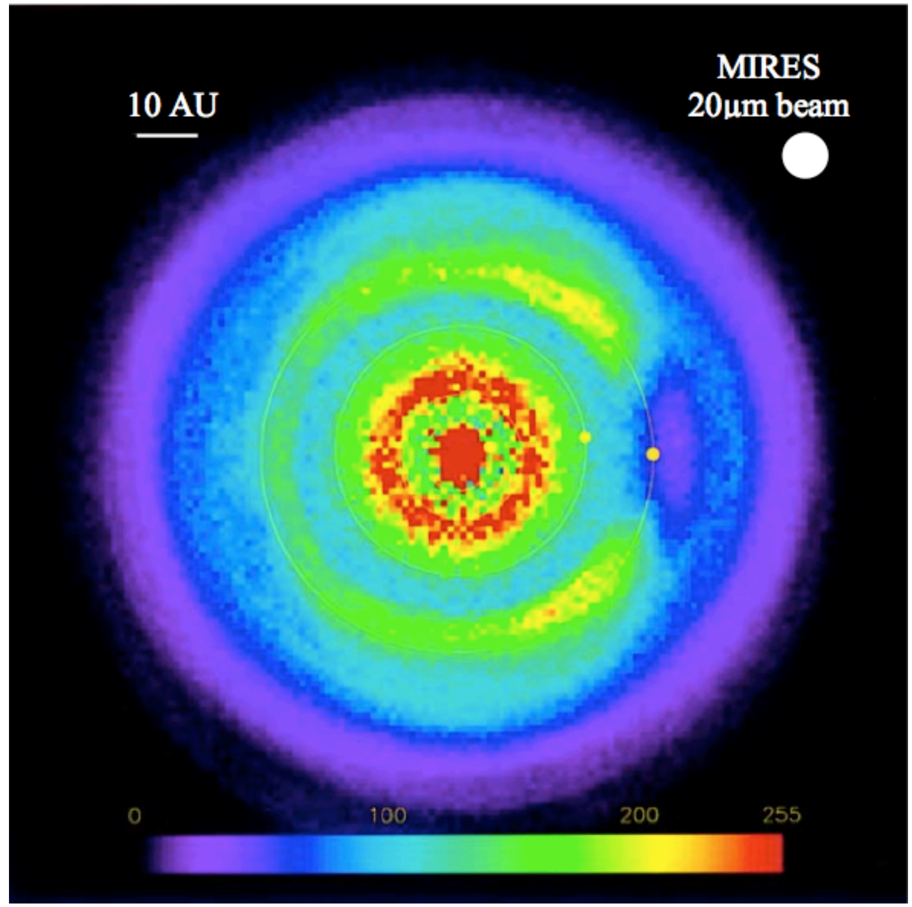


Planet Formation Instrument (ExAO) Imaging Contrast



Physics of Star and Planet Formation
- Planet formation

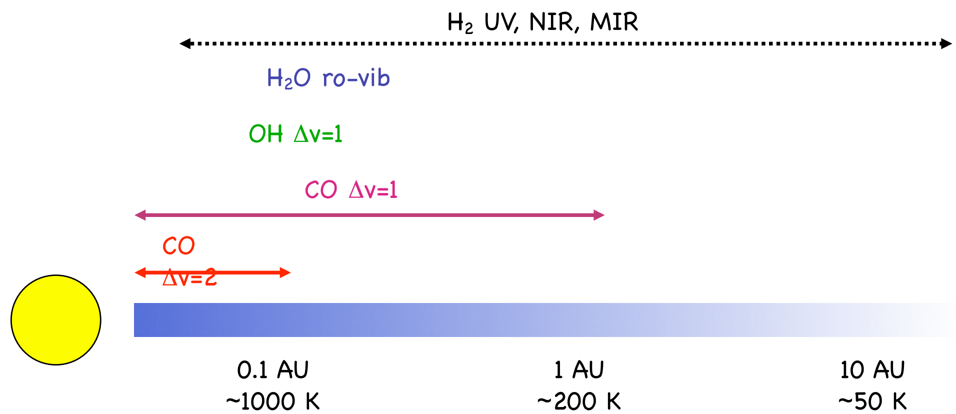
- *TMT will be able to image protoplanetary disks and detect features produced by planets with mid-infrared adaptive optics:*
  - TMT will have 5x the resolution of JWST.



Simulation of Solar System protoplanetary disk (Liou & Zook 1999)

Planet Formation

Studying gas in disks:



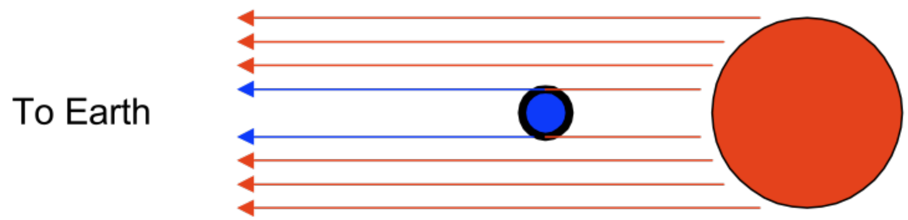
Study gas dissipation timescale: constrains pathways for giant planet formation, terrestrial planet architectures

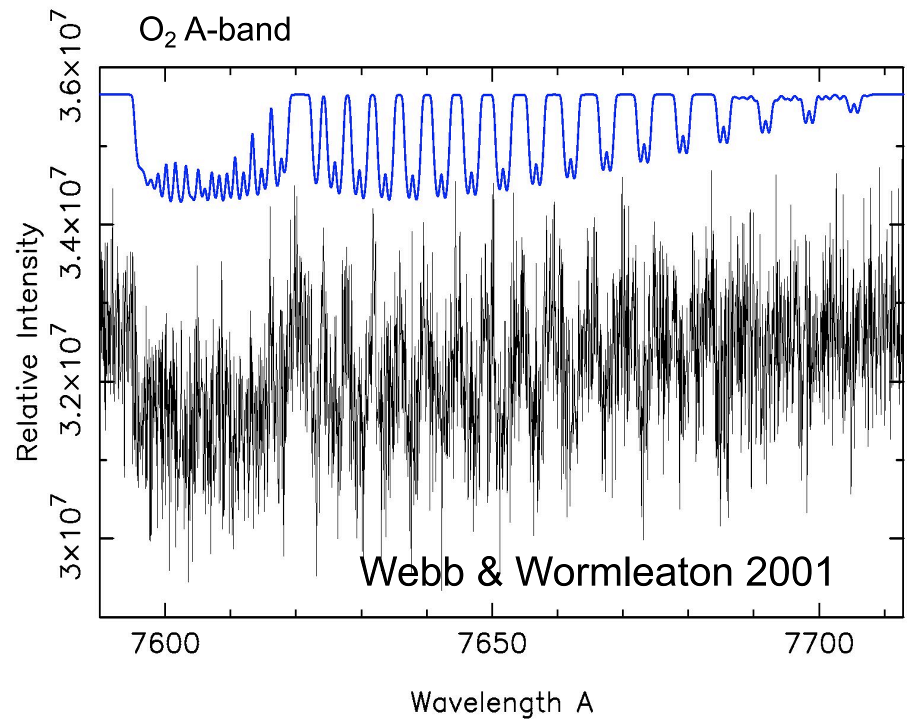
Diffraction-limited, mid-IR observations with TMT/MIRES will probe gas in protoplanetary disks over range in which terrestrial planets are expected to reside

Characterization of Extrasolar Planets
- Atmospheres of terrestrial planets

- *TMT will detect the absorption signatures of gases in the atmosphere in transiting planets.*
  - Na, K, He, will be easily detectable with TMT

- *TMT should be able to detect O_2 in the atmosphere of an Earth-like planet orbiting in the habitable zone of an M star*
  - S/N ~ 30,000 per 6 km/s resolution element - achievable by TMT in ~ 3 hrs.





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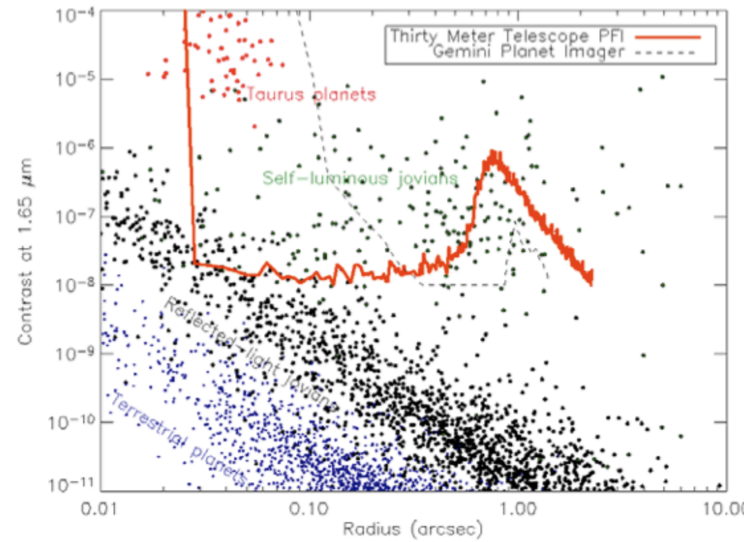
Formation of Stars and Planets

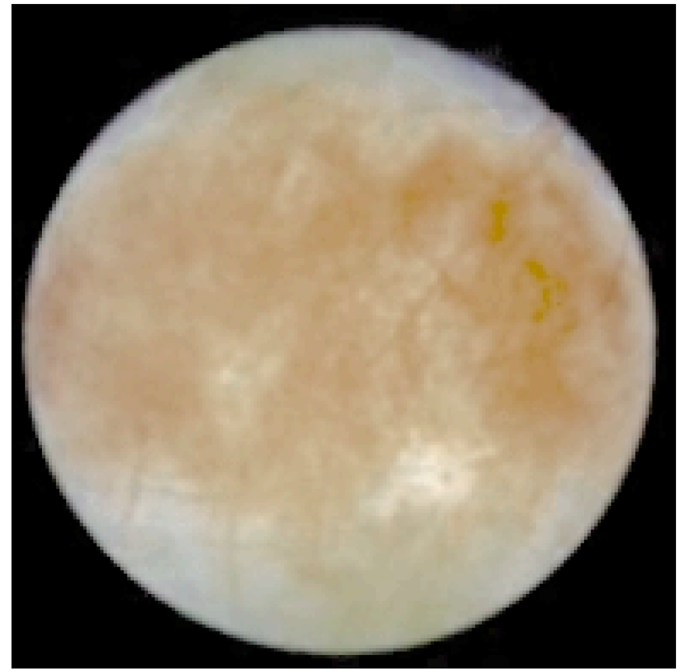
- **Science objectives:**
  - Origin of stellar masses
  - Architecture of planetary systems
  - Pre-biotic molecules in disks
  - First direction of reflected-light Jovians
  - Exoplanetary atmospheres (oxygen)
- **Observations:**
  - High precision, crowded field photometry (MCAO/IRIS/WIRC)
  - Very high Strehl ratio imaging (ExAO/PFI)
  - Diffraction-limited, high-resolution, mid-IR (MIRAO/MIRES)
  - High-res optical and IR spectroscopy



- λ = 1-25 μm
- R = 4000,30000-100,000
- Low telescope emissivity and PWV < 5 mm
- Fixed gravity vector
- Strehl ratio > 0.9 and contrast ratio of $10^{8\text{-}9}$

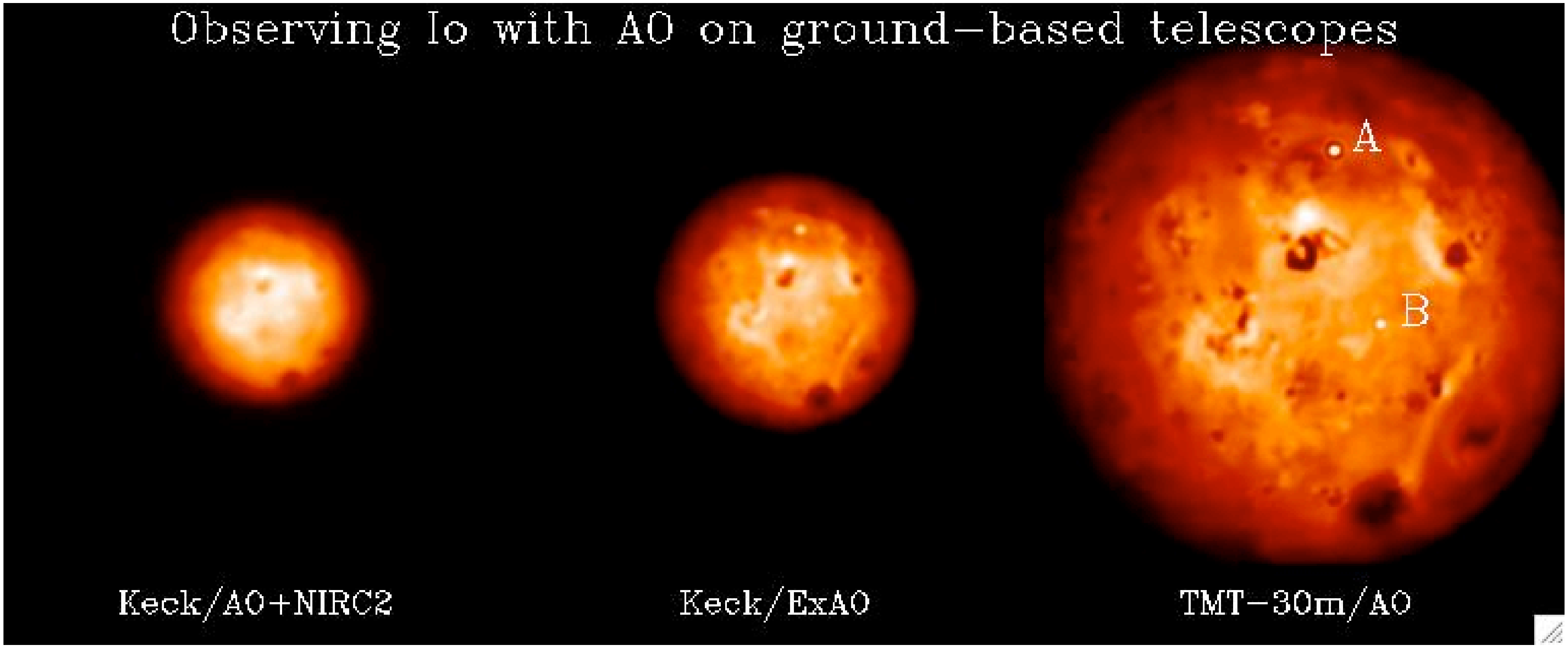
Solar System Studies

- TMT will extend studies of the outer Solar System:
  - it will be able to detect a 1 km TNO at 50 AU in 15 min.
- TMT will provide a capability for high-spatial resolution imaging and spectroscopy of planets and satellites of the solar system:
  - high-resolution spectra of features on outer Solar System bodies will allow studies of atmospheric physics and atmospheric and surface chemistry
  - Regular monitoring will allow TMT to study transient phenomena, weather, (cryo-)volcanic activity, etc.



Europa at the resolution of TMT adaptive optics (M. Brown, CIT)

Io with TMT/IRIS

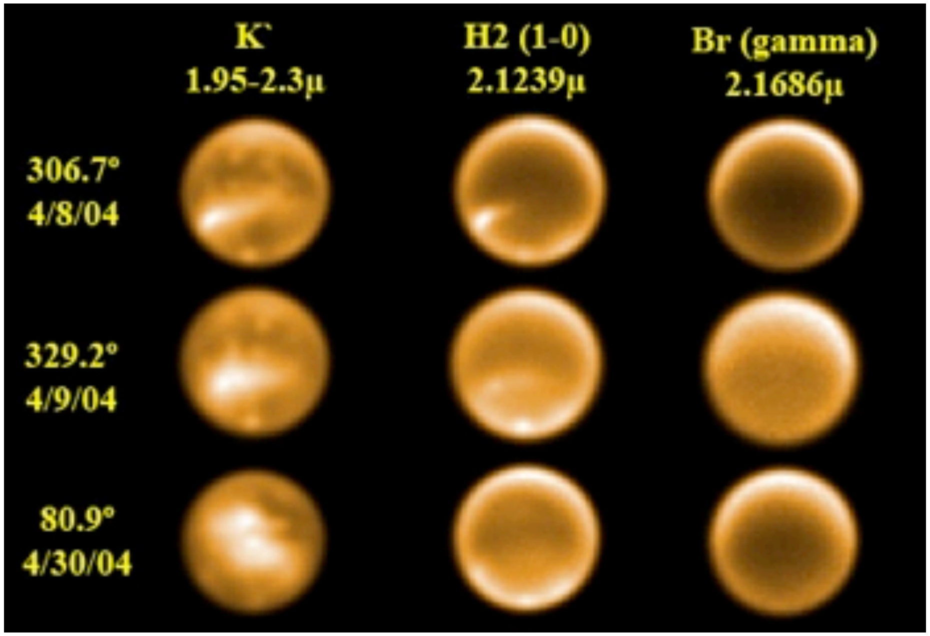


Simulations of Io Jupiter-facing hemisphere in H band. (courtesy of Franck Marchis, UC Berkeley/SETI)

TMT resolution at 1μm is 7 mas = 25 km at 5 AU (Jupiter)
(0.035 AU at 5 pc, nearby stars)

Solar System

- Science objectives:
  - Composition of Kuiper Belt objects and comets
  - Monitoring weather, vulcanism and tectonic activity
- Observations:
  - Spatially resolved spectroscopy (MCAO/IRIS)
  - Diffraction-limited, high-resolution, near-IR (MCAO/NIRES) and mid-IR spectroscopy (MIRAO/MIRES)



Volcanic plume on Titan with Gemini/AO

- λ = 1-10 µm
- R = 1000 -100,000
- Non-sidereal tracking
- Fast response time

TMT
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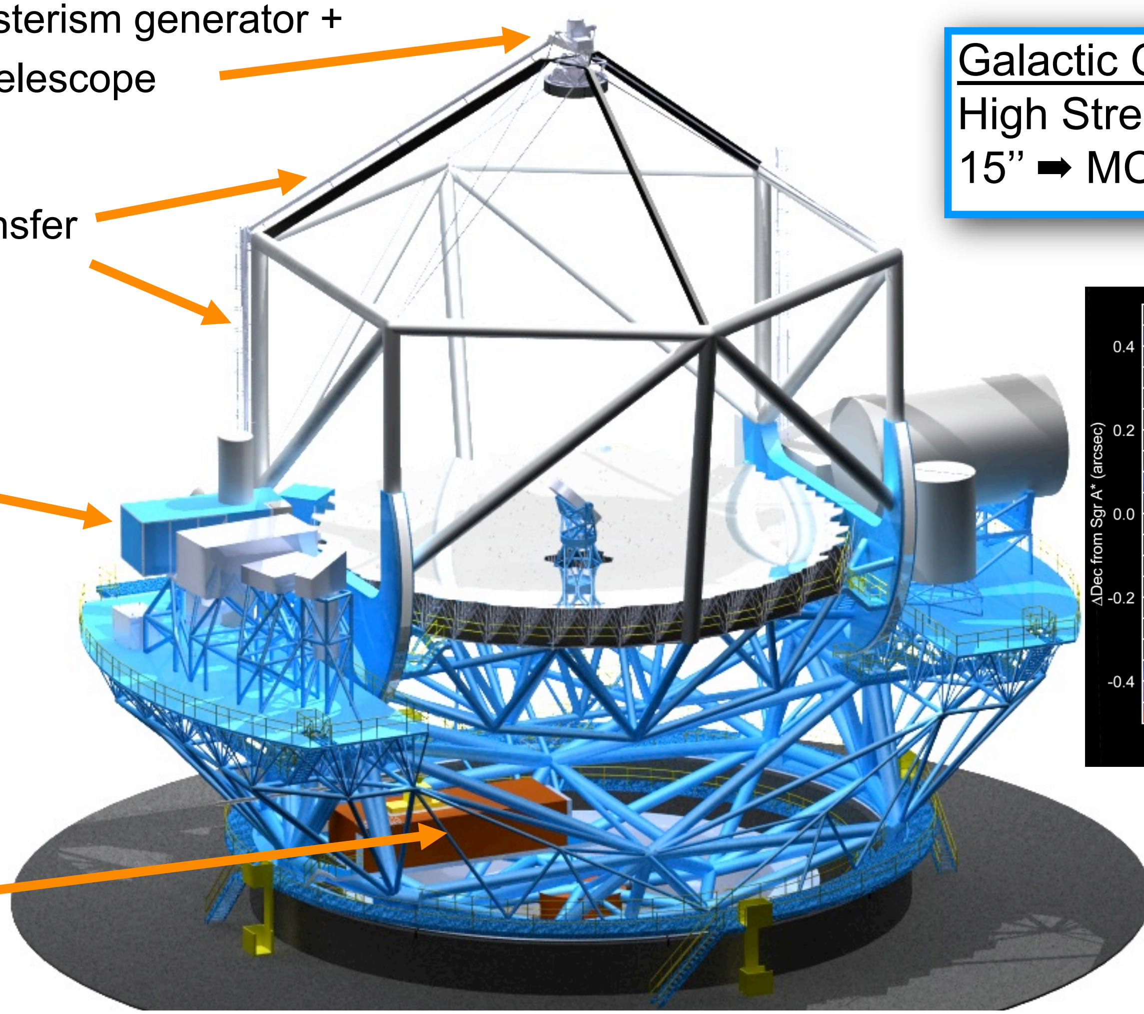
From Science to Subsystems

LGSF asterism generator + launch telescope

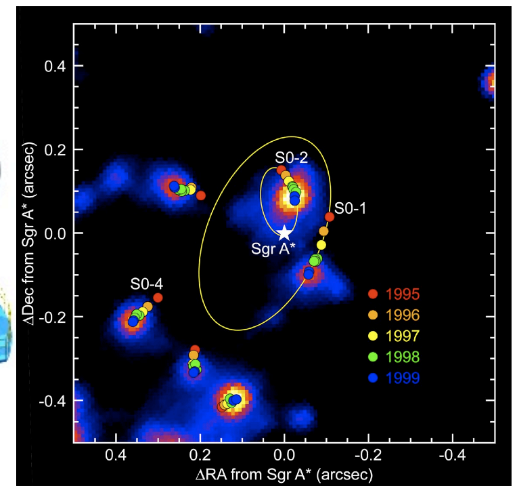
LGSF beam transfer

NFIRAOS + IRIS

Laser room

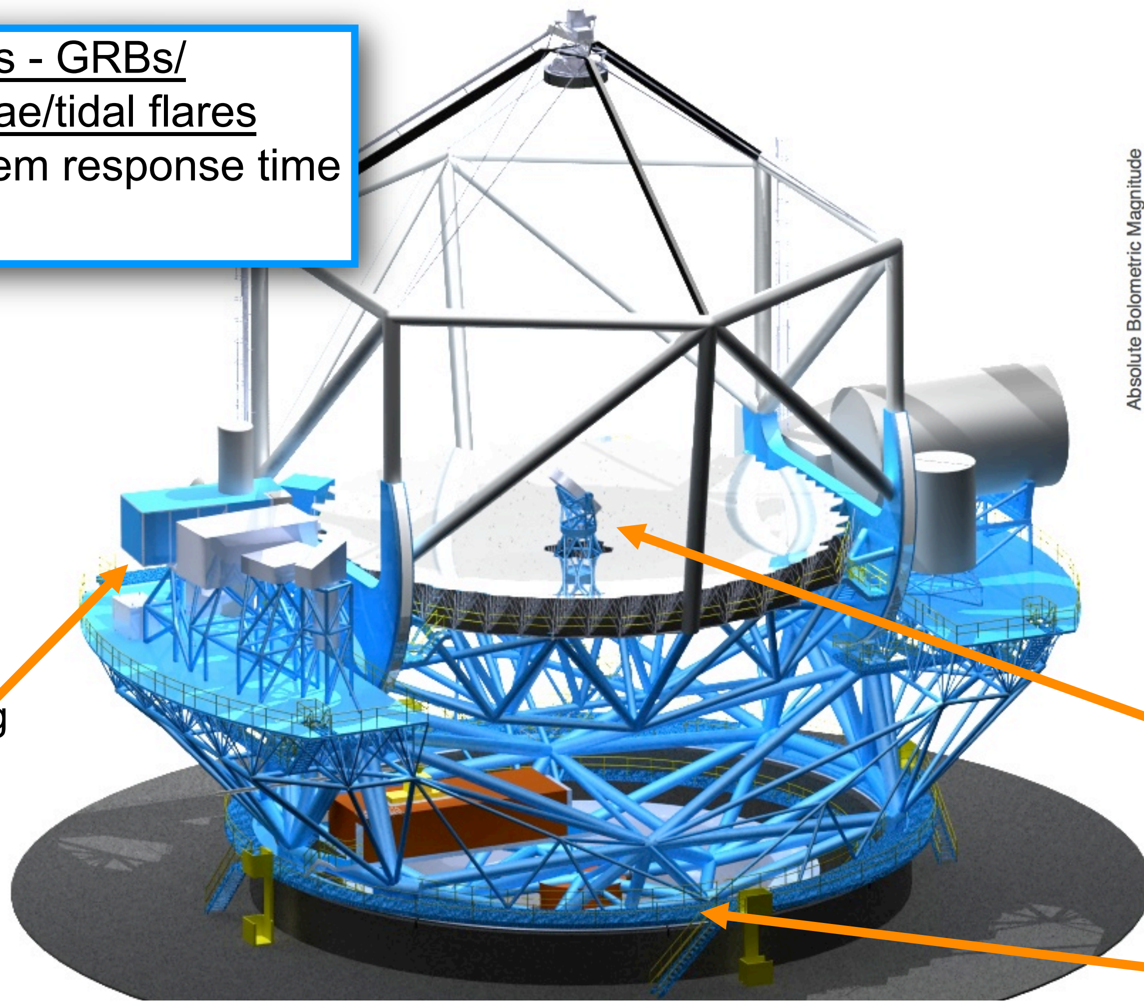


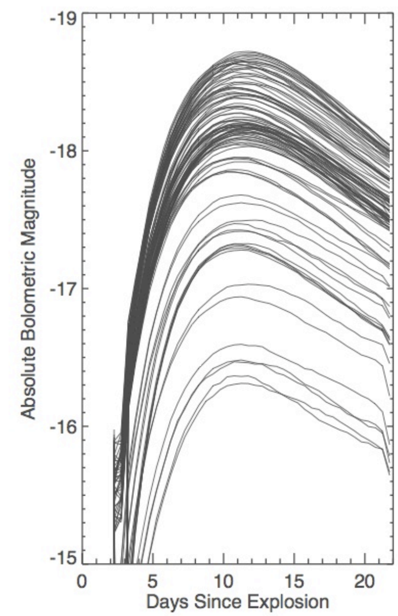
Galactic Center
High Strehl w/ stable PSF over 15'' ➡ MCAO



From Science to Subsystems

Transients - GRBs/
supernovae/tidal flares
Fast system response time



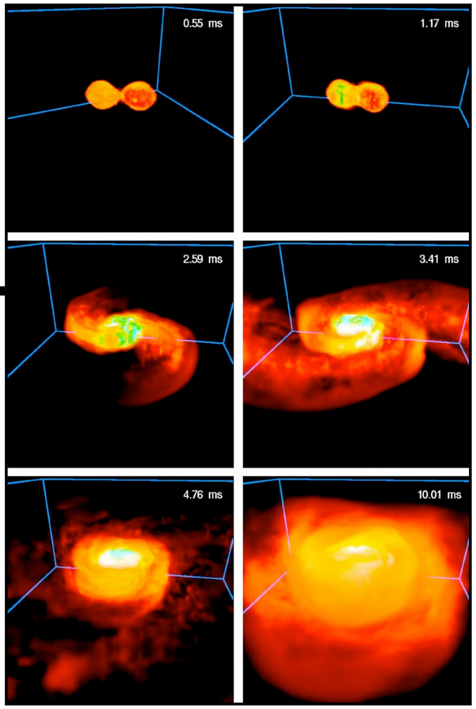


NFIRAOS fast switching science fold mirror

Articulated M3 for fast instrument switching

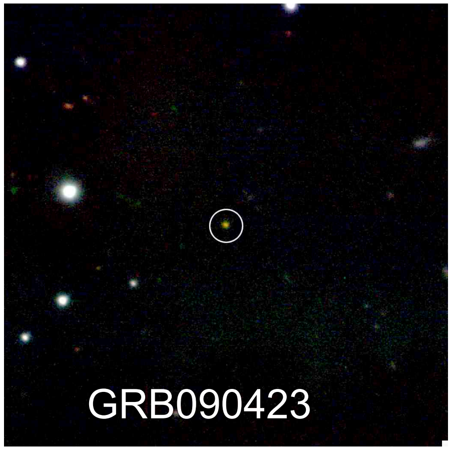
Fast slewing and acquisition

Rapid Response Example: GRBs and TMT



- GRBs are very bright but only briefly
- Expect a significant fraction at very high redshift
- GRBs are point sources - D^4 advantage with AO

=> Potential for high S/N, high resolution spectra
  - Physics of extreme events and objects at high z
  - IGM studies at high z
- Instruments:
  - WFOS measurements of redshift, physical conditions
  - IRIS imaging and IFS with R = 4000
    - Detection and IFU spectroscopy of host galaxies
  - NIRES (AO fed) R = 50,000 spectroscopy over 0.8 - 2.5mu
    - Time sequences of high S/N spectra of high z objects
  - MIRES: R = 100,000 spectroscopy in 5-28micron region
  - HROS: R = 50,000 spectroscopy in 0.3 - 1micron region

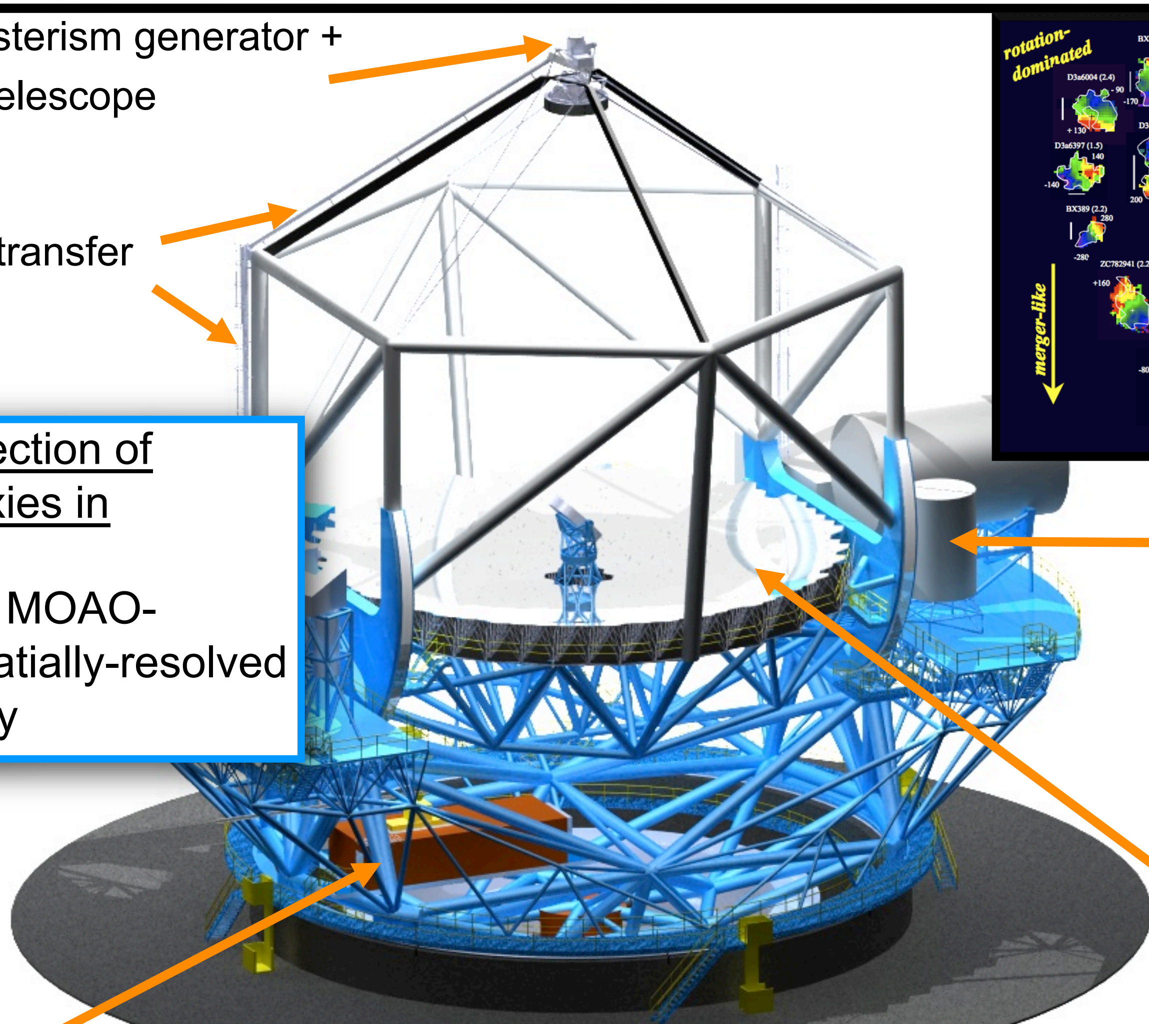


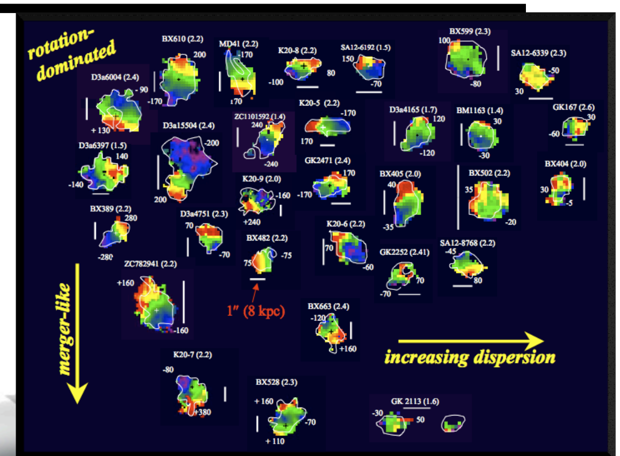
TMT
THIRTY METER TELESCOPE

From Science to Subsystems

LGSF asterism generator + launch telescope

LGSF beam transfer





<u>Spatial dissection of distant galaxies in formation</u>
Multiplexed, MOAO-assisted, spatially-resolved spectroscopy

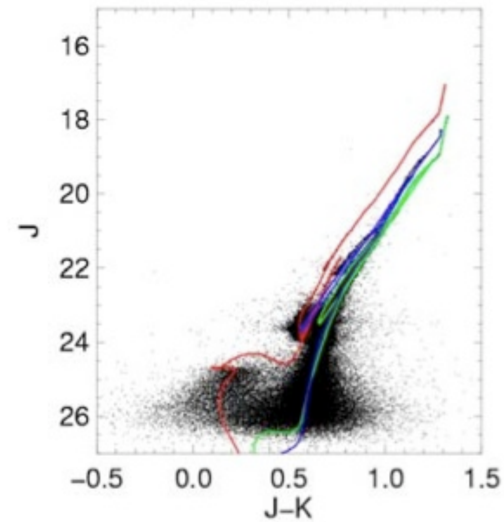
IRMOS
(~160 VLT nights/ night)

30m M1 to overcome photon starvation
+
FoV ≥ 5'

Laser room

Image Quality

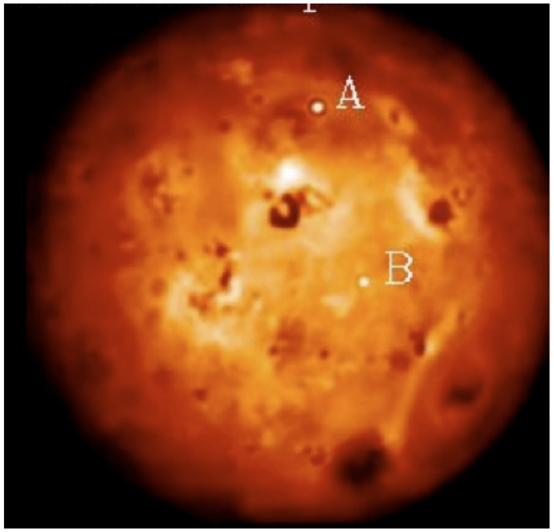
- **Requirements:**
  - Resolution (telescope aperture) and sampling (detector size versus FoV)
  - Strehl ratio (AO performance)
  - Contrast ratio (wavefront control, speckle suppression, segment coating and cleaning)
- **Impact:**
  - Test of General Relativity at the Galactic Center
  - Proper motions
  - Star formation histories of nearby (D < 16 Mpc) galaxies
  - Direct detection and characterization of exoplanets
  - Surface physics of planets and satellites



TMT/MCAO Color-magnitude diagram of Messier 32

Observing Efficiency

- Requirements:
  - Acquisition, calibration, downtime, fast response and weather
- Impact:
  - Large programs (# observations > 500)
    - IGM tomography
    - Jovian exoplanets
    - Doppler detection of planetary systems
  - Time-critical programs
    - Supernovae/GRBs
    - Weather and volcanic activity in the outer solar system
    - Exoplanetary transits

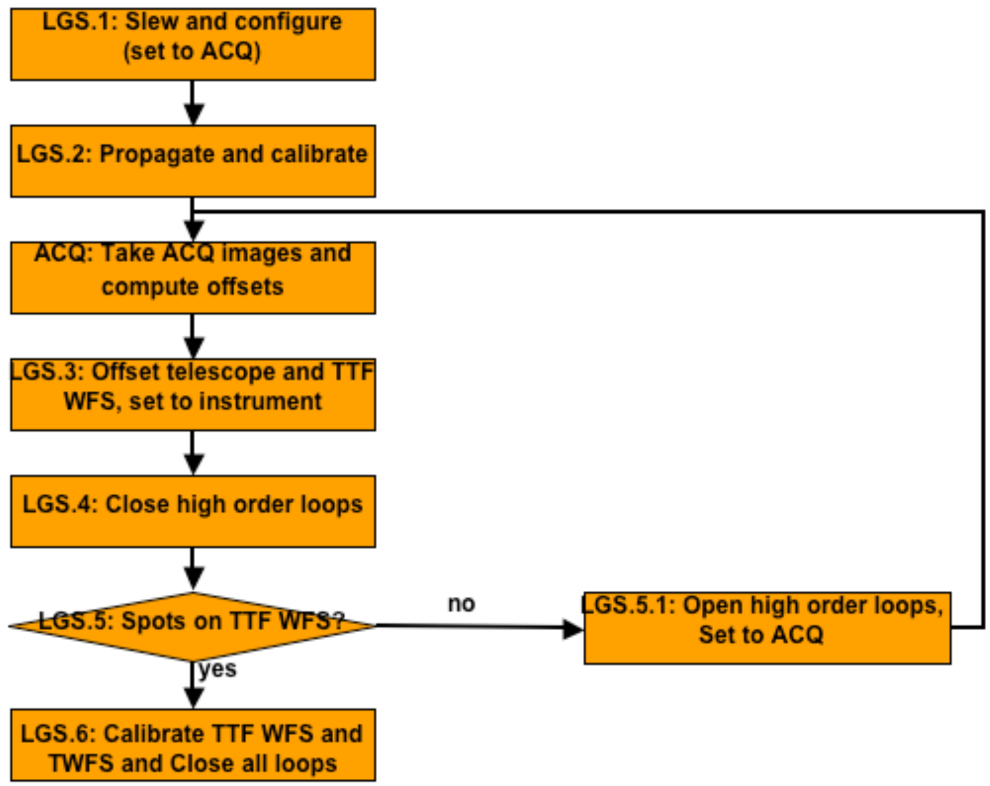


Io with TMT/MCAO

Efficient Operation: Observation Workflow

- Target acquisition
  - < 5 minutes including slewing, configuring, finding target, setting up AO system
- Instrument changes
  - < 10minutes to opening shutter

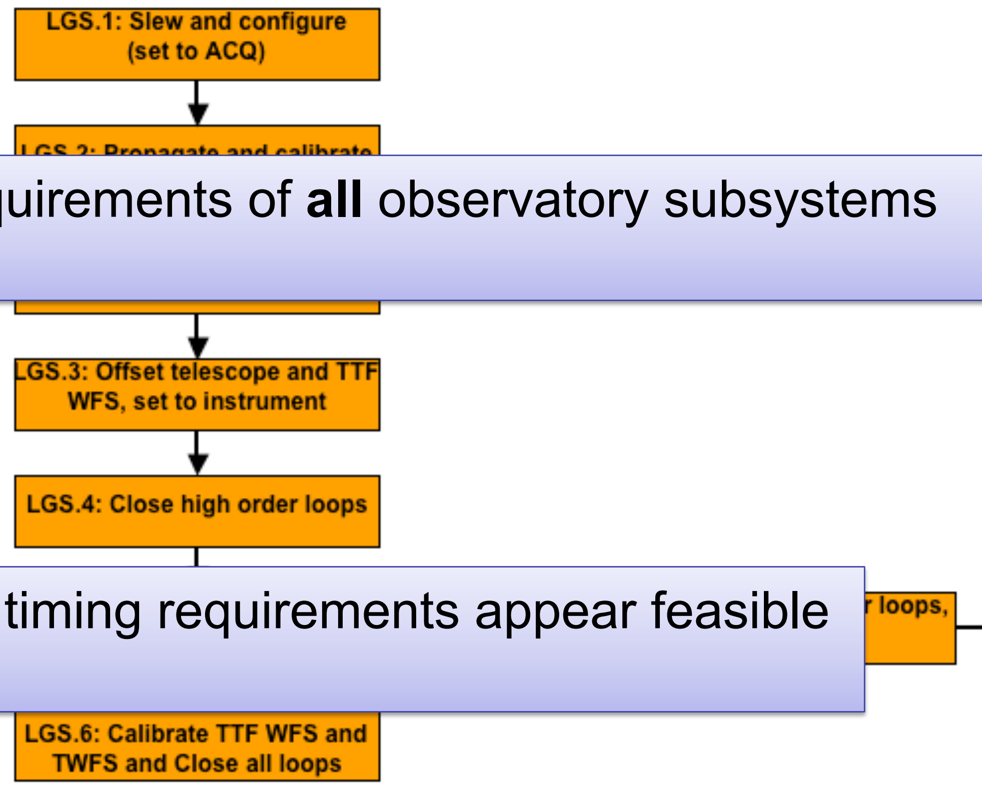
Example: Part of IRIS LGS sequence (40 subtasks)



Efficient Operation: Observation Workflow

- Target acquisition
  - < 5 minutes including slewing, configuring, finding target, setting up AO system

Example: Part of IRIS LGS sequence (40 subtasks)



Studied extensively - Vital input to requirements of **all** observatory subsystems

- Instrument changes
  - < 10minutes to opening shutter

VERY Challenging but both key timing requirements appear feasible

Science Flow Down to Capabilities

TMT THIRTY METER TELESCOPE

Theme	Science Objectives	Observations	Requirements	Capabilities
Fundamental Physics and Cosmology (Dark energy, dark matter, physics of extreme objects, fundamental constants; DSC Section 3)	• Mapping distribution of dark matter on large and small scales • First measurement of a Kerr spacetime • Very precise expansion rate of Universe • Mapping variations in constants over cosmological timescales	• Proper motions in dwarf galaxies • Wide-field optical spectroscopy of R=24.5 galaxies • Microarcsec astrometry • Transient events lasting > 30 days • High spectral resolution observations of quasars and GRBs	• $\lambda = 0.31$-$0.62\mu m$, 2-$2.4\mu m$ • 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 • Mapping topology of re-ionization • Structure and neutral fraction of IGM at z > 7	• Multiplexed, spatially-resolved spectroscopy of faint objects • High spectral resolution, near-IR spectroscopy	• $\lambda = 0.8 - 2.5\ \mu m$ • R = 3000 – 30000 • F $=3\times10^{-20}$ ergs $s^{-1}cm^{-2}Å^{-1}$ • Exposure times > 15ks	MCAO/IRMS/IRIS MOAO/IRMOS MCAONIRES
Galaxy formation and the IGM (DSC Section 5)	• Baryons at epoch of peak galaxy formation • Velocity, SFR, extinction and metallicity maps of galaxies at z = 5.5 • IGM properties on scales < 300 kpc	• Optical/near-IR multiplexed diagnostic spectroscopy of distant galaxies and AGNs • Optical/near-IR multiplexed identification spectroscopy of extremely faint high redshift objects (to R~27) • Spatially-resolved spectroscopy	• $\lambda = 0.31 - 2.5\ \mu m$ • 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 low-mass black holes • Reverberation mapping out to z = 0.4 • Scaling relations out to z = 2.5 and masses at z>6	• Spatially-resolved spectroscopy of galaxy cores	• $\lambda = 0.8 - 2.5\ \mu m$ • R = 3000-5000 • Precise positioning	MCAO/IRIS MOAO/IRMOS
Exploration of nearby galaxies (DSC Section 7)	• Abundance of oldest stars in Milky Way • Chemical evolution in Local Group galaxies • Diffusion and mass loss in stars • Resolved stellar populations out to Virgo cluster	• High spectral resolution optical and near-IR spectroscopy • High-precision photometry in crowded fields	• $\lambda = 0.33$-0.9, 1.4-$2.4\ \mu m$ • R = 4000, 40000-90000 • Photometry precision of 0.03 mag at Strehl = 0.6	SL/HROS MCAO/NIRES MCAO/IRIS/WIRC SL/WFOS
Formation of stars and planets (physics of star formation,proto-planetary disks, exoplanets; DSC Section 8, Section 9)	• Origin of mass in stars • Architecture of planetary systems • Deposition of pre-biotic molecules onto protoplanetary surfaces • First direct detection of reflected-light Jovians • Characterization of exo-atmospheres (oxygen)	• 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	• $\lambda = 1 - 25\ \mu m$ • 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^{8-9}	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 • Monitoring weather, vulcanism and tectonic activity	• Spatially resolved spectroscopy of objects in solar system • Transient events (hours to years)	• $\lambda = 1$-$10\ \mu m$ • R = 1000 – 100000 • Non-sidereal tracking • Fast response time	MCAO/IRIS/WIRC MCAO/NIRES MIRAO/MIRES

TMT First Decade Instrument 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

TMT First Decade Instrument Suite

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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
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Mid-IR AO-fed Echelle spectrometer (MIRES)	8 – 18 4.5 – 28 (goal)	[illegible]	[illegible]	• Origin of stellar masses • ...retion and outflows around protostars • ...lution of gas in protoplanetary disks
Planet Formation Instrument (PFI)	1 – 2.5 1 – 5 (goal)	0″.05 inner working angle	R≤100	• ...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
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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

Visible, Seeing-Limited

TMT

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TMT First Decade Instrument 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
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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 [illegible]	5000-100000	• Origin of stellar masses • Accretion and outflows around protostars • [illegible]volution of gas in protoplanetary disks
Planet Formation Instrument (PFI)	1 – 2.5 1 – 5 (goal)	[illegible] inner working angle	[illegible]	• [illegible]^8 contrast ratio (10^9 goal) • [illegible]rect 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

Near-IR, AO-assisted

TMT

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TMT First Decade Instrument 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
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InfraRed Multislit Spectrometer (IRMS)	0.95 – 2.45	2 arcmin field, up to 120″ total slit length [illegible]	R=4660 @ 0.16 [illegible]	• Early Light • Epoch of peak galaxy building • JWST follow-ups
Deployable, multi-IFU, near-IR spectrometer (IRMOS)	0.8 – 2.5	[illegible]	[illegible]	• 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

High-Contrast AO

TMT First Decade Instrument 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 –			…ight …of peak galaxy building …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
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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

Mid-infrared, AO-assisted

Feasibility studies 2005-6
(concepts, requirements, performance,…)

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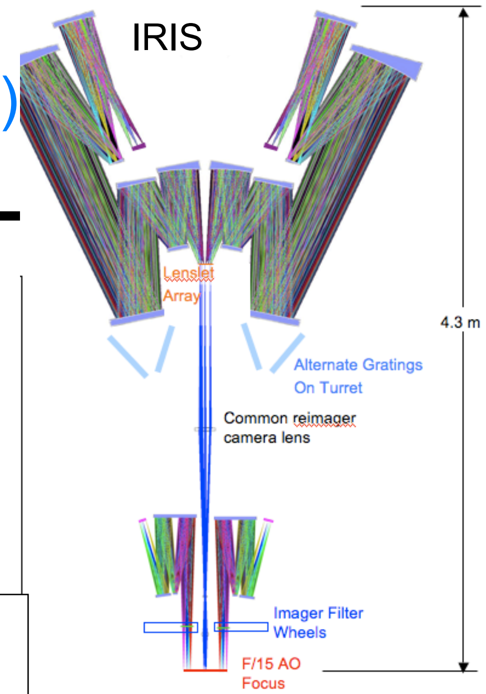
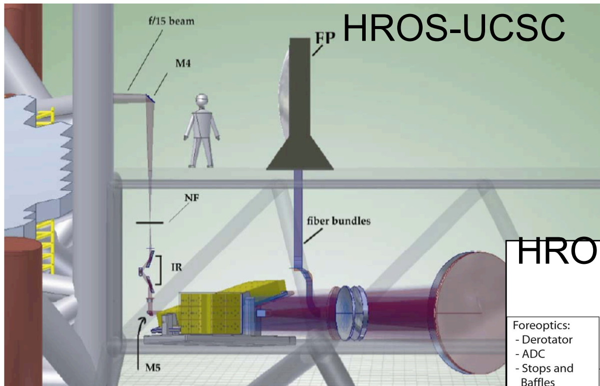
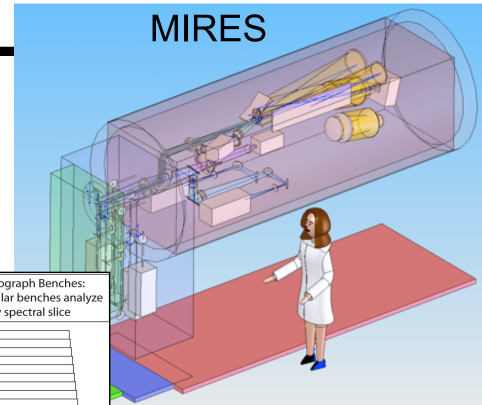
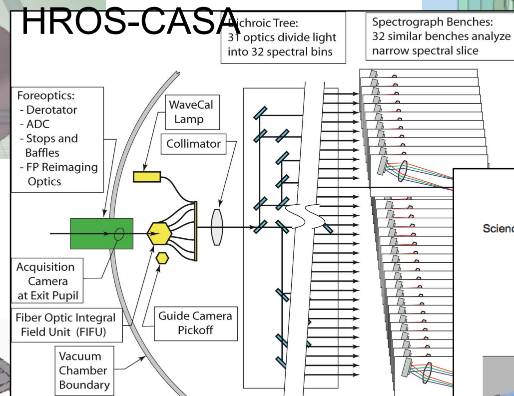
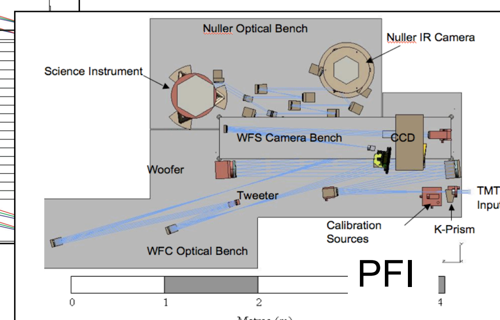
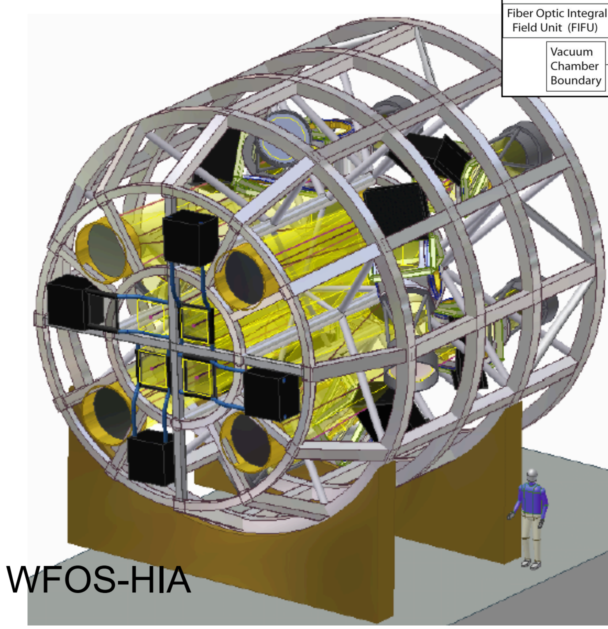


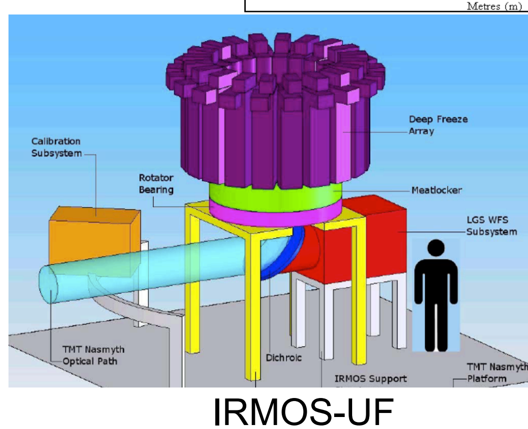


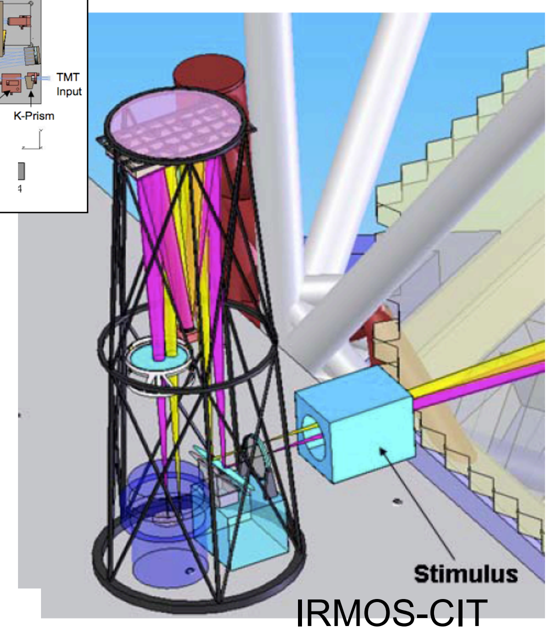




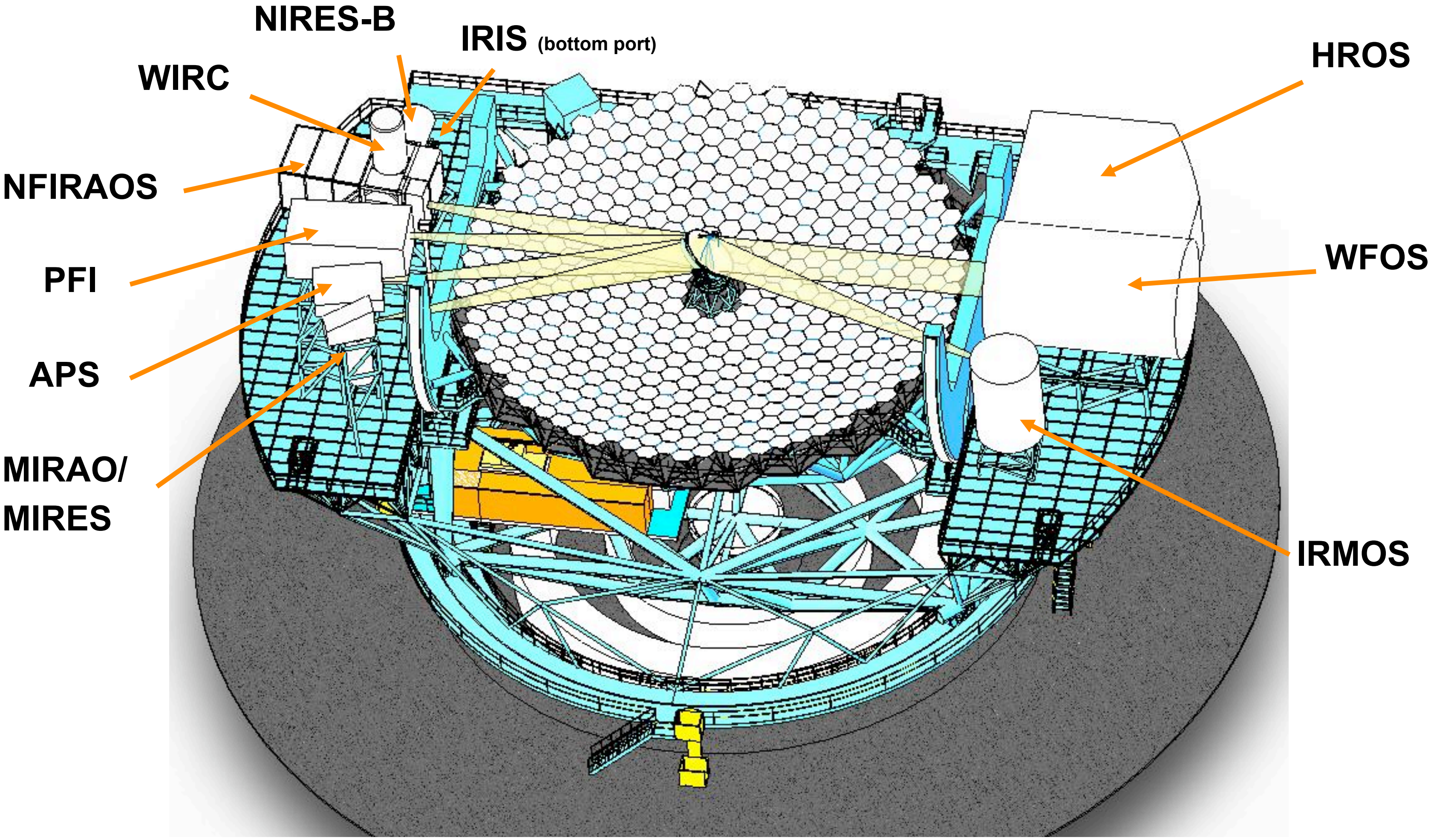






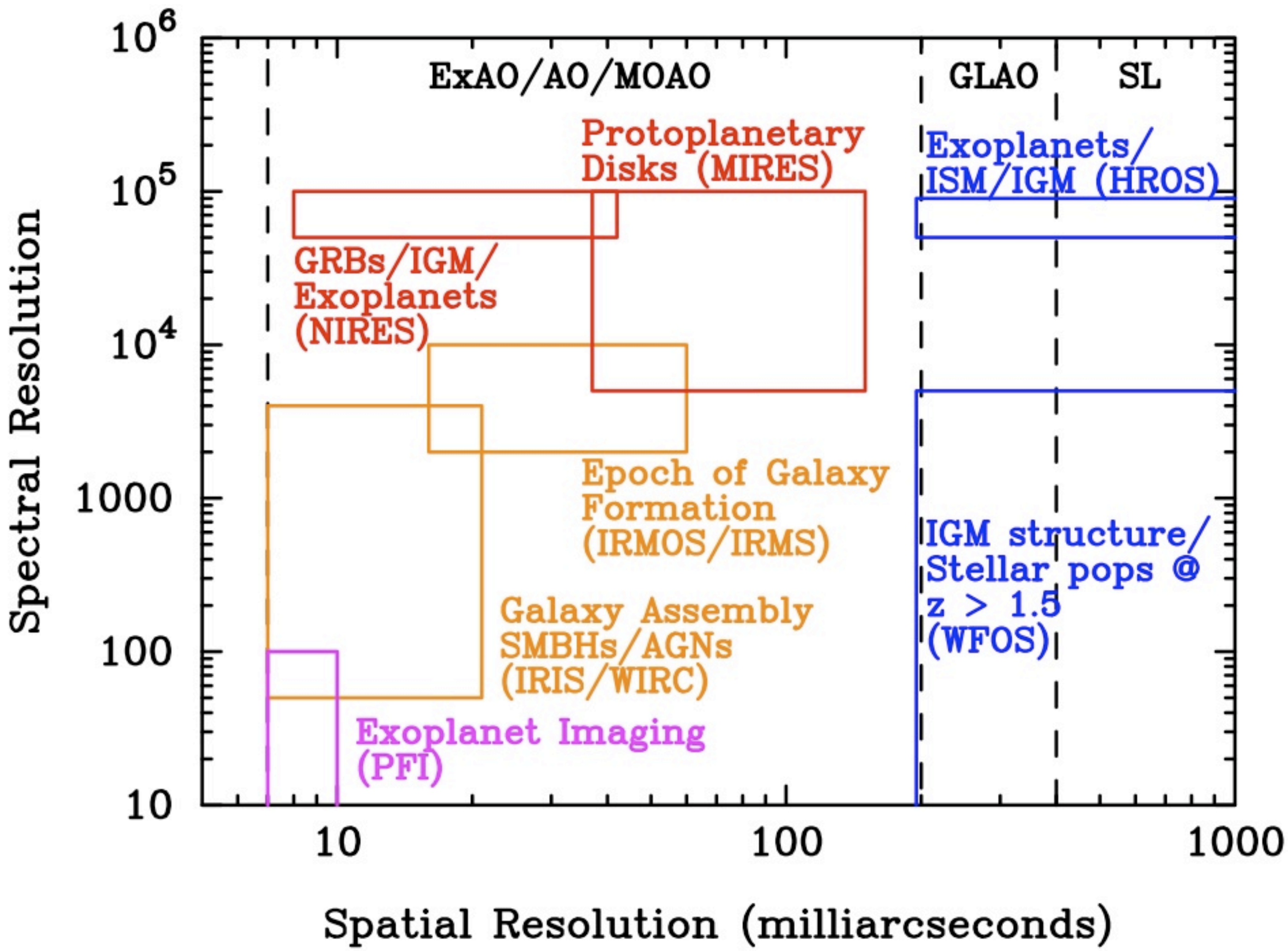


Nasmyth Configuration: First Decade Instrumentation Suite

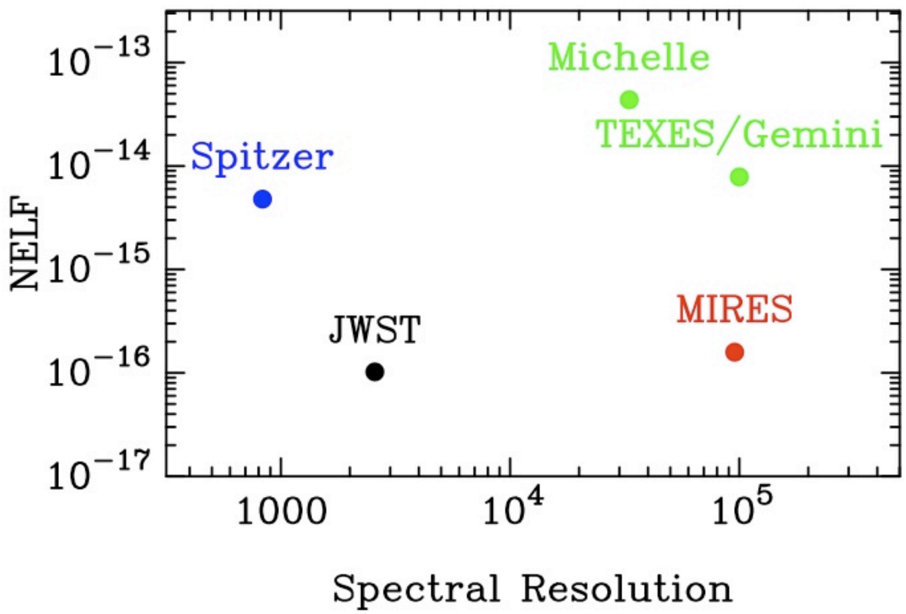


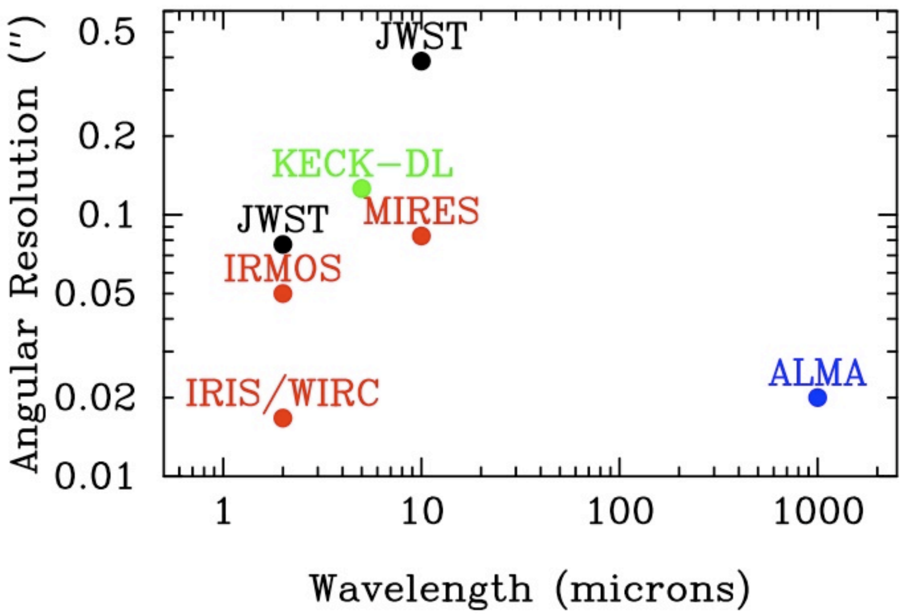
TMT Discovery Space

Broad range of spectral and spatial resolution



Synergy with Space/IR JWST and ALMA





TMT/MIRES will have comparable spectral line sensitivity (NELF) to infrared space missions with a much higher spectral resolution

The angular resolution of TMT instruments nicely complements that of JWST and ALMA

TMT Early Light Instrument Suite

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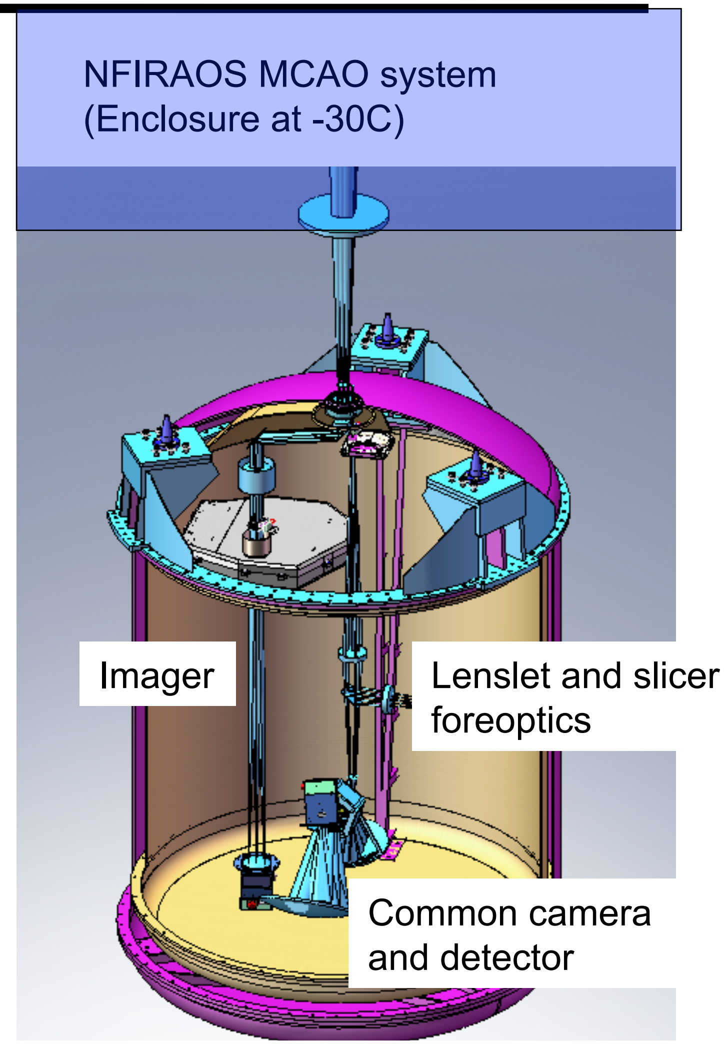
Instrument	λ (μm)	Field of view/ Slit length	Spectral resolution	Science Cases
InfraRed Imager and Spectrometer (IRIS)	0.8 – 2.5 0.6 – 5 (goal)	<3″ IFU >15″imaging	> 3500 5-100 (imaging)	• Assembly of galaxies at high z • Black holes/AGNs/Galactic Center • Resolved stellar populations in crowded fields
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

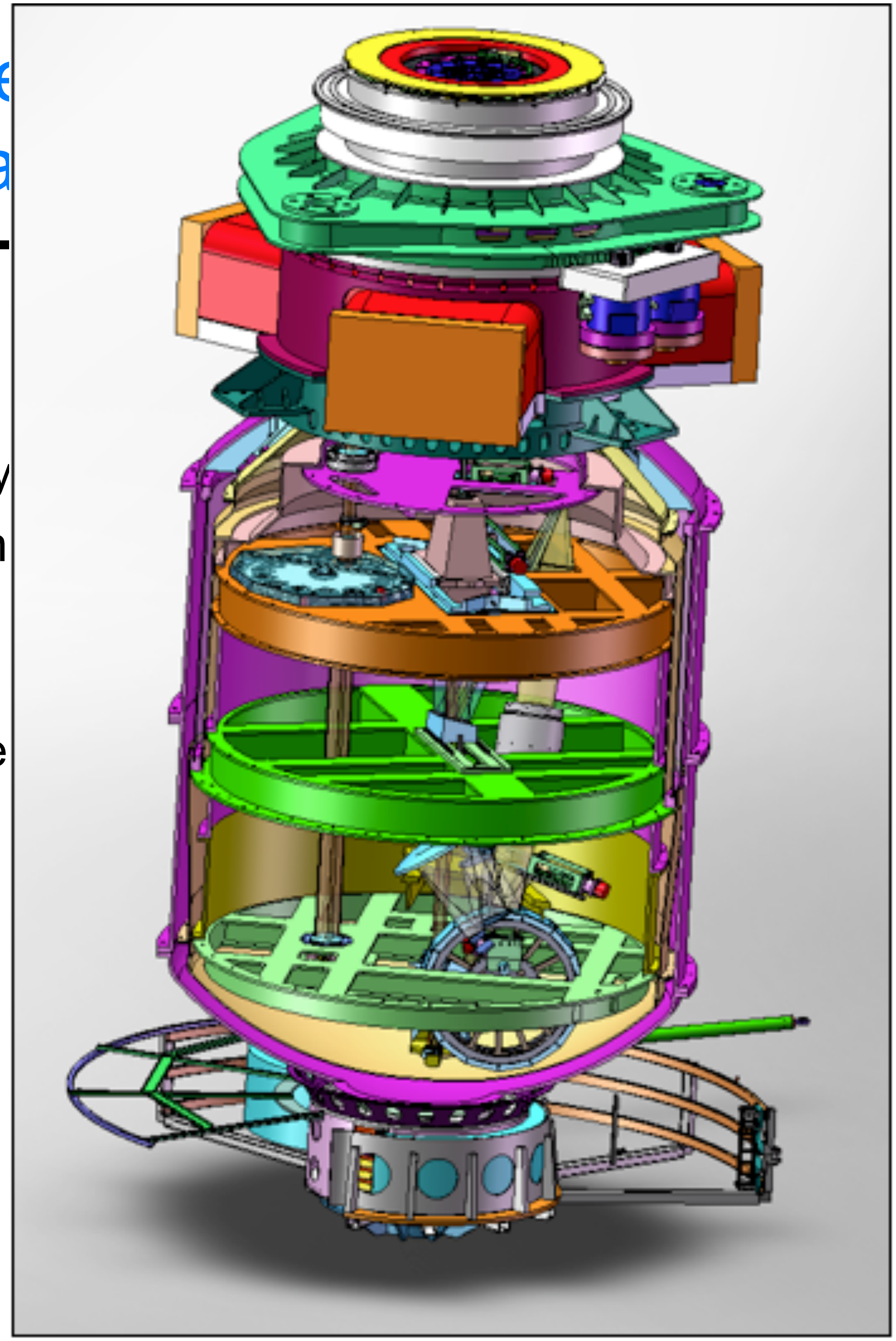
Diffraction Limited Imager, Slicer and Lenslet Integral Field Spectrograph

- Imager 17”x17”, 4 mas pixels
  - Precision photometry
  - 30microarcsec relative astrometry
- Lenslet Integral field Spectrograph
  - 128 x 128 lenses
  - Bandpass: 5%/exposure
  - Finest scales (4, 9 mas), best wfe
- Slicer IFS
  - 45 slices, field up to 2”x4”
  - 25, 50 mas scales
  - Best sensitivity
- IFSs share camera and detector



Diffraction Limite
Lenslet Integra

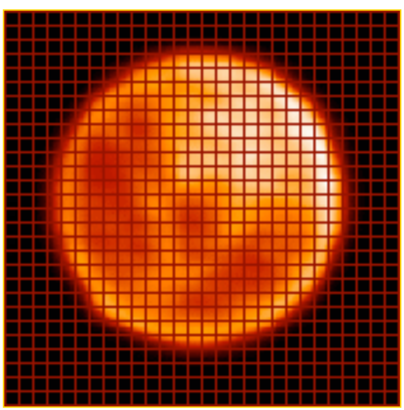
- Imager 17”x17”, 4 mas pixels
  - Precision photometry
  - 30microarcsec relative astrometry
- Lenslet Integral field Spectrograph
  - 128 x 128 lenses
  - Bandpass: 5%/exposure
  - Finest scales (4, 9 mas), best wfe
- Slicer IFS
  - 45 slices, field up to 2”x4”
  - 25, 50 mas scales
  - Best sensitivity
- IFSs share camera and detector



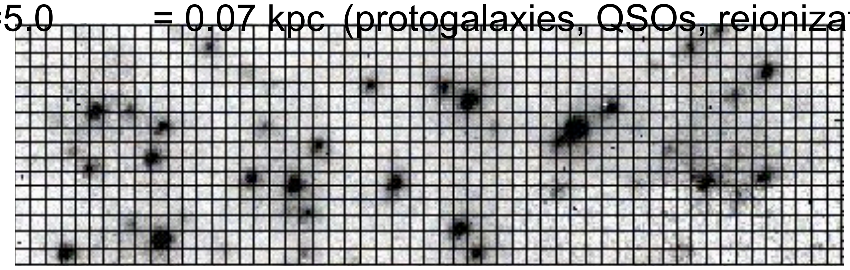
Motivation for IRIS

- Should be the most sensitive astronomical IR spectrograph ever built
- Unprecedented ability to investigate objects on small scales.

0.01" @	5 AU	= 36 km	(Jovian's and moons)
	5 pc	= 0.05 AU	(Nearby stars – companions)
	100 pc	= 1 AU	(Nearest star forming regions)
	1 kpc	= 10 AU	(Typical Galactic Objects)
	8.5 kpc	= 85 AU	(Galactic Center or Bulge)
	1 Mpc	= 0.05 pc	(Nearest galaxies)
	20 Mpc	= 1 pc	(Virgo Cluster)
	z=0.5	= 0.07 kpc	(galaxies at solar formation epoch)
	z=1.0	= 0.09 kpc	(disk evolution, drop in SFR)
	z=2.5	= 0.09 kpc	(QSO epoch, Hα in K band)
	z=5.0	= 0.07 kpc	(protogalaxies, QSOs, reionization)

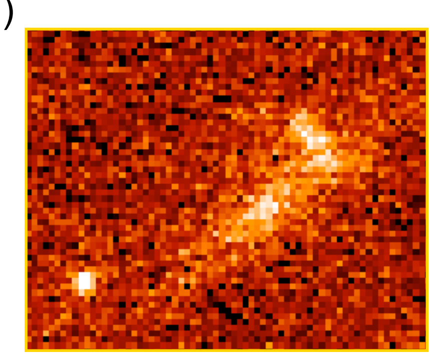


Titan with an overlayed 0.05" grid (~300 km) (Macintosh et al.)



M31 Bulge with 0.1" grid (Graham et al.)

Keck AO images



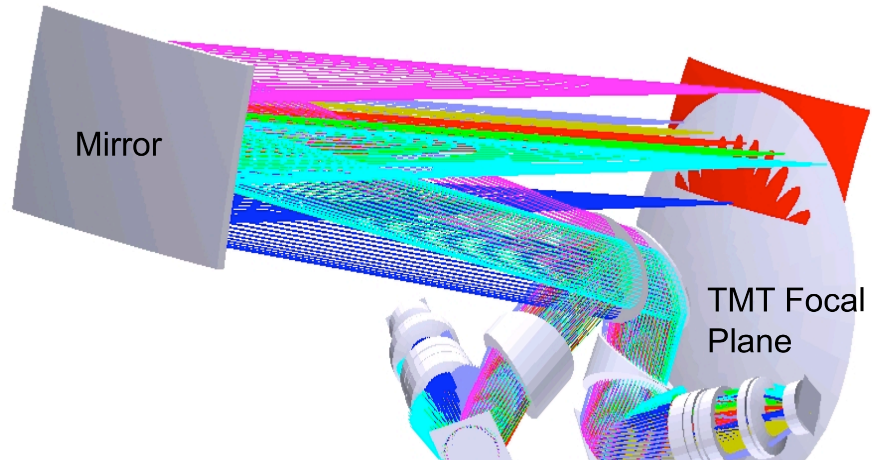
High redshift galaxy. Pixels are 0.04" scale (0.35 kpc).Barczys et al.)

IRIS Conceptual Design Team

- James Larkin (UCLA), PI, Lenslet IFS
- Anna Moore (Caltech), co-I, Slicer IFS
- Ryuji Suzuki, Masahiro Konishi, Tomonori Usuda (NAOJ), Imager
- Betsy Barton (UC Irvine), Project Scientist
- Science Team
  - Mate Adamkovics(UCB), Aaron Barth(UCI), Josh Bloom(UCB), Pat Cote(HIA), Tim Davidge(HIA), Andrea Ghez(UCLA), Miwa Goto(MPIA), James Graham(UCB), Shri Kulkarni(Caltech), David Law(UCLA), Jessica Lu(UCLA),Hajime Sugai(Kyoto U), Jonathan Tan(UF), Shelley Wright(UCI)
- OIWFS (On Instrument Wavefront Sensor) Team (HIA + Caltech)
  - Led by David Loop, Anna Moore
- NSCU (NFIRAOS Science Calibration Unit) Team (U of Toronto)
  - Led by Dae-Sik Moon

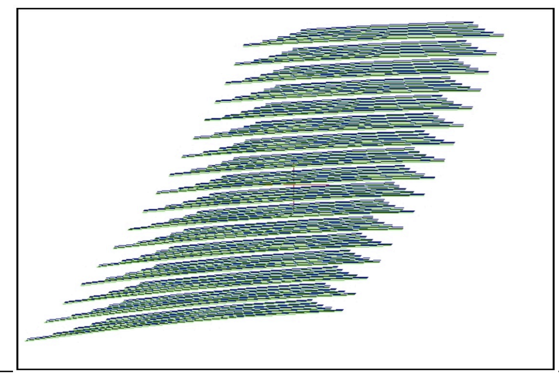
Wide Field Optical Spectrograph
Seeing-limited, 0.3-1mu

- Only optical capability for ~ first 5 years
  - "Discovery", "Diagnostic" and survey science
- Echellette design
  - Full wavelength coverage
    - Blue and Red channels
  - R ~1000 - 8000
  - 9' x 4' field
- Simple single barrel design
  - 300mm pupils
  - Fixed dichroic beamsplitter



Reflecting collimator, refractive camera
Prism cross dispersion

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



Spectral footprint in higher dispersion mode - 3'' slits spaced 25'' apart, five orders

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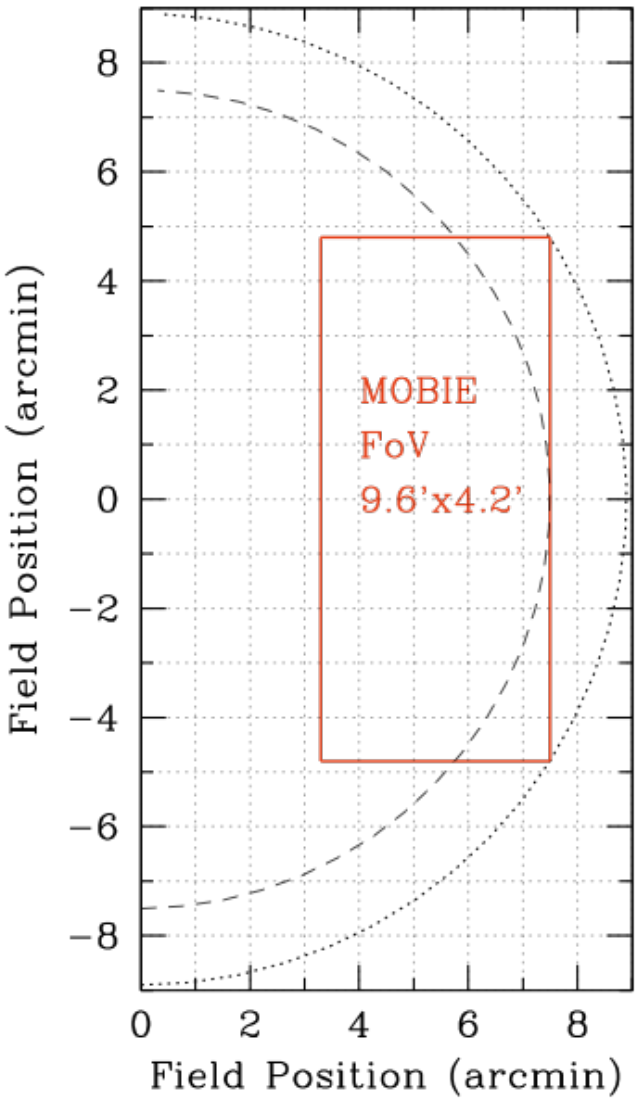
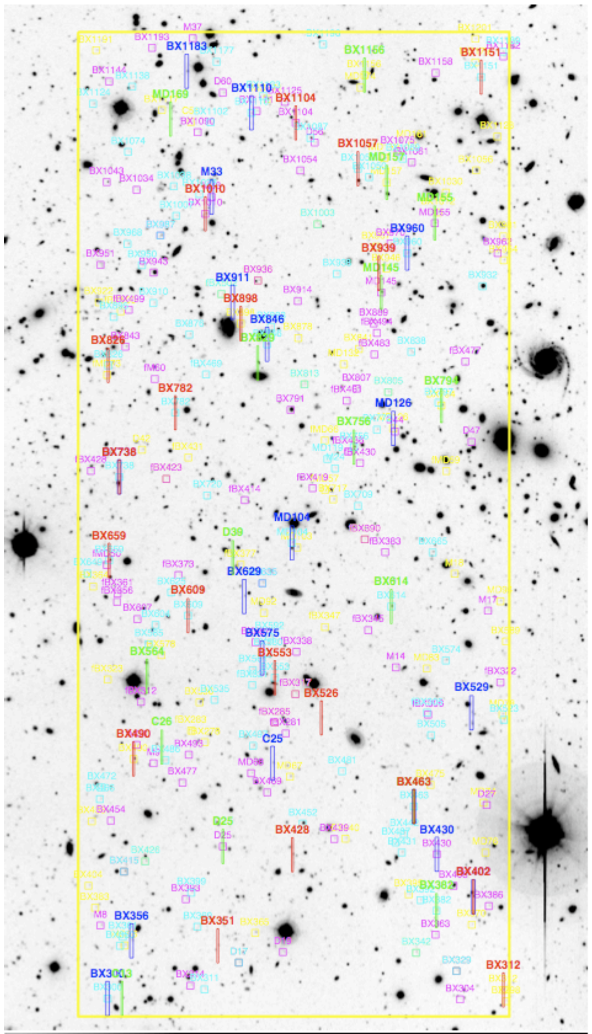
WFOS-MOBIE
Science Field Geometry





Multi-object mask making simulation

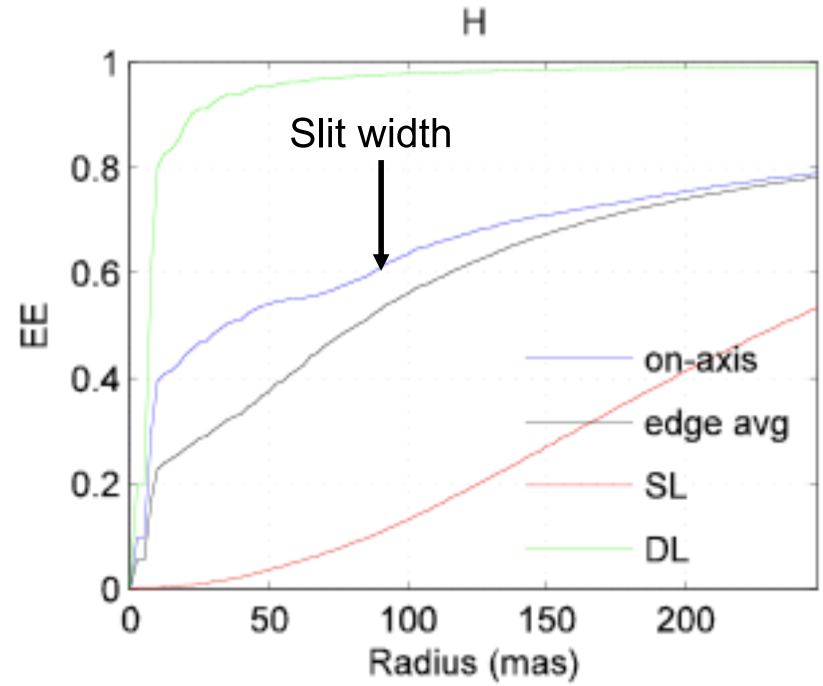
WFOS Team

- Rebecca Bernstein (UCSC), PI
- Bruce Bigelow (UCSC), PM
- Chuck Steidel (Caltech), PS
- Science Team: Bob Abraham(U Toronto), Jarle Brinchmann(Leiden), Judy Cohen(Caltech), Sandy Faber(UCSC), Raja Guhathakurta(UCSC), Jason Kalirai(UCSC), Gerry Lupino(UH), Jason Prochaska(UCSC), Connie Rockosi(UCSC), Alice Shapley(UCLA)
- Some "flagship" science cases, "work horse capability"
  - High quality spectra of faint galaxies/AGN/stars
  - IGM tomography
- Great "follow-up" and "discovery" potential - full wavelength coverage with spectral resolutions up to R = 8000
  - JWST, ALMA, etc., follow-up
- Sensitivity >14 x current 8m telescopes

IR Multi-Slit Spectrometer (IRMS)

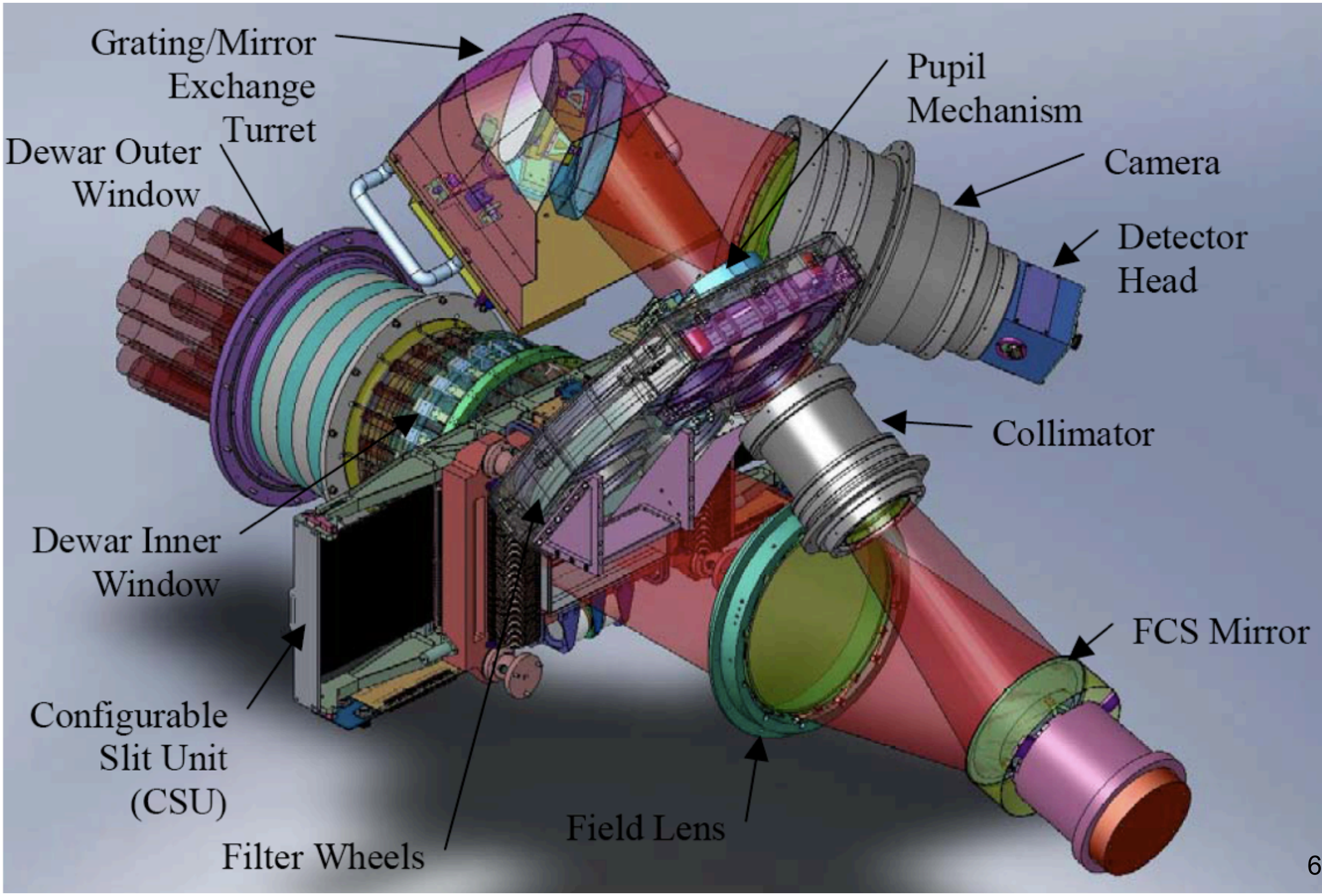
TMT THIRTY METER TELESCOPE

- IRMOS (deployable MOAO IFUs) deemed too risky/expensive for first light
- => IRMS: **clone** of Keck MOSFIRE, first step towards IRMOS
  - Multi-slit NIR imaging spectro:
  - 46 slits,W: 160+ mas, L: 2.5”
  - **Deployed behind NFIRAOS**
    - 2’ field
    - 60mas pixels
    - EE good (80% in K over 30”)
  - Spectral resolution up to 5000
  - Full Y, J, H, K spectra (one at a time
- Images entire 2’ field

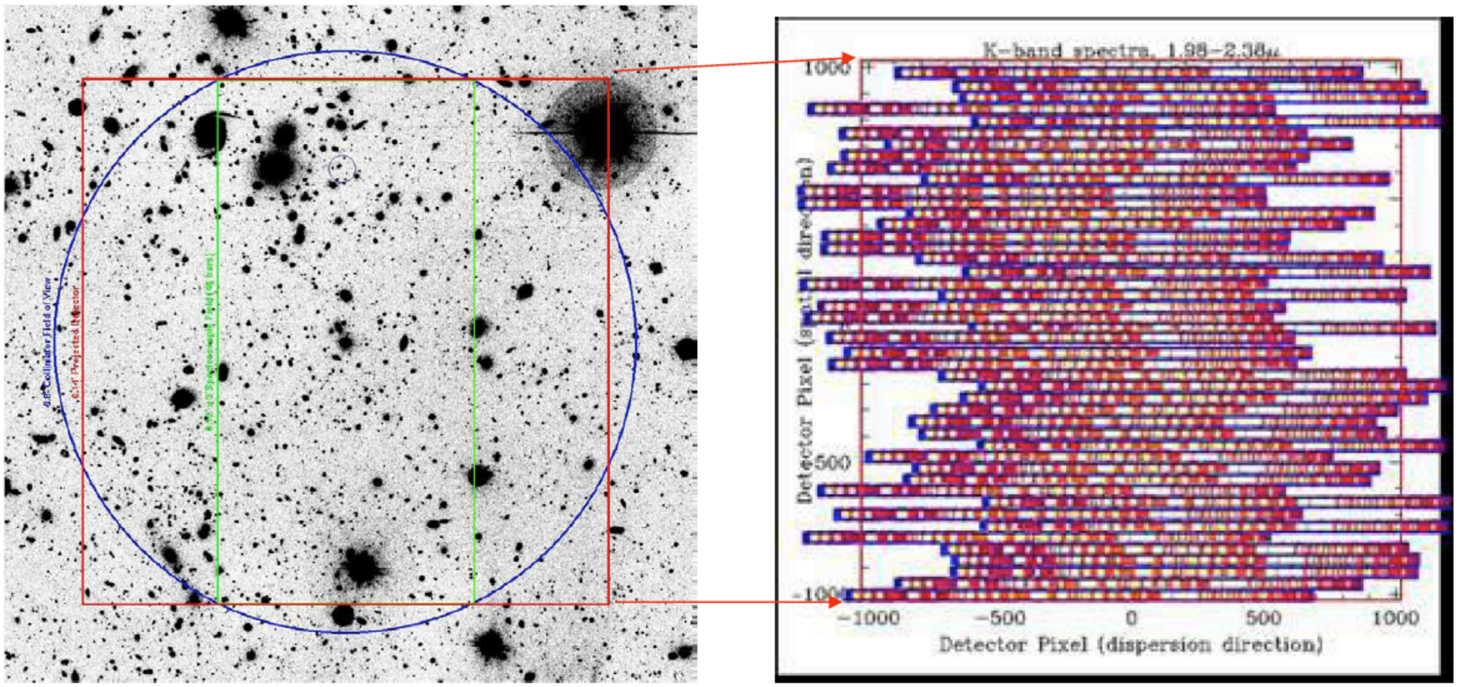


Whole 120” field

InfraRed Multi-slit Spectrometer (IRMS) (aka Keck/MOSFIRE on TMT)



IRMS Spectra



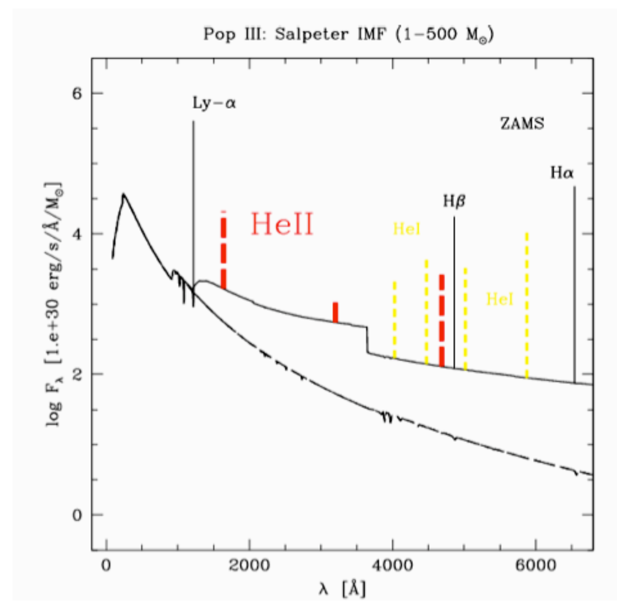
Configurable Slit Unit originally developed for JWST (slits formed by opposing bars)

Full Y, J, H, K spectra with R ~ 5000 with 160mas (2 pix) slits in central ~1/3 of field

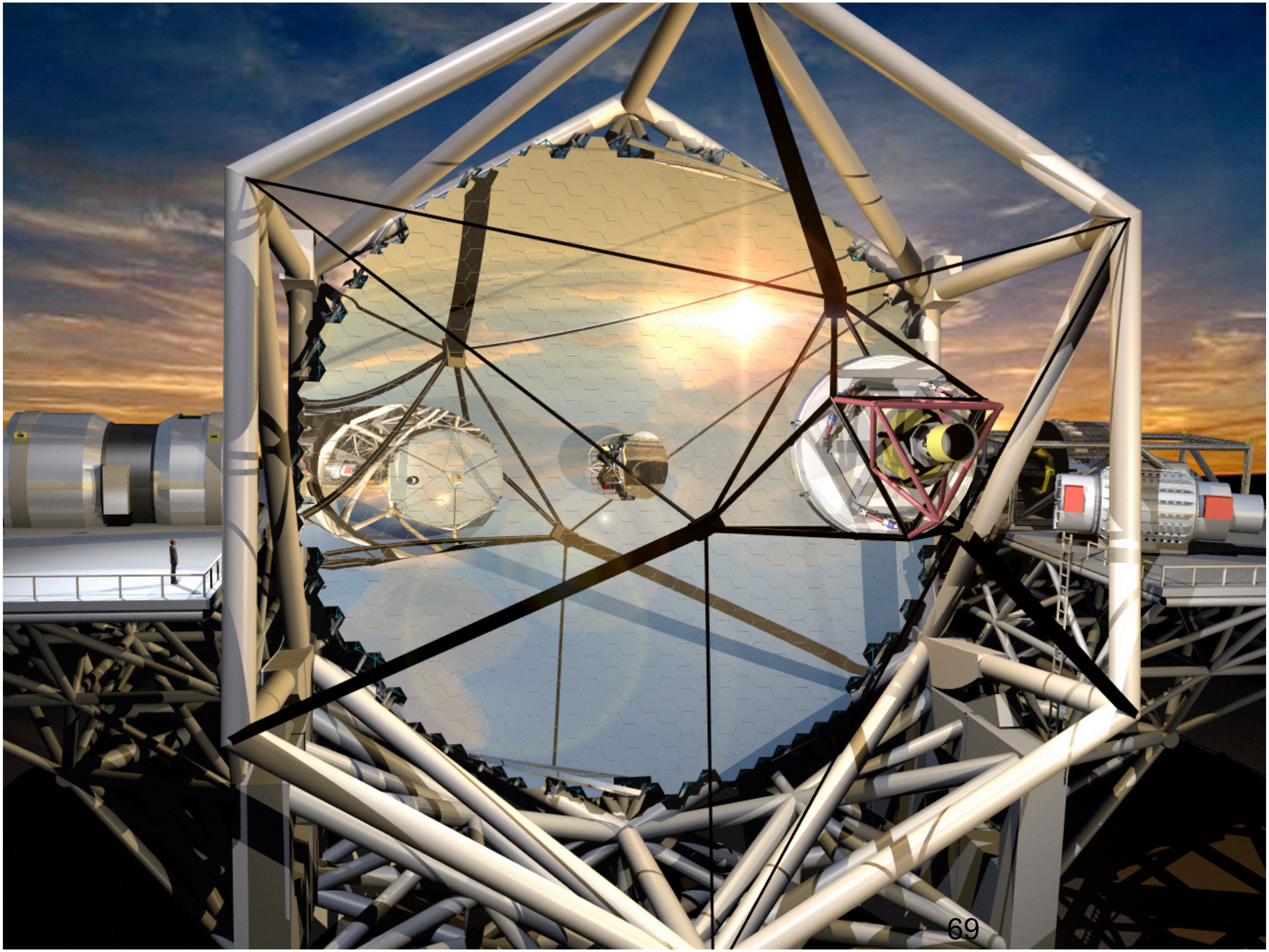
A Key IRMS Project: Exploring the Early Universe

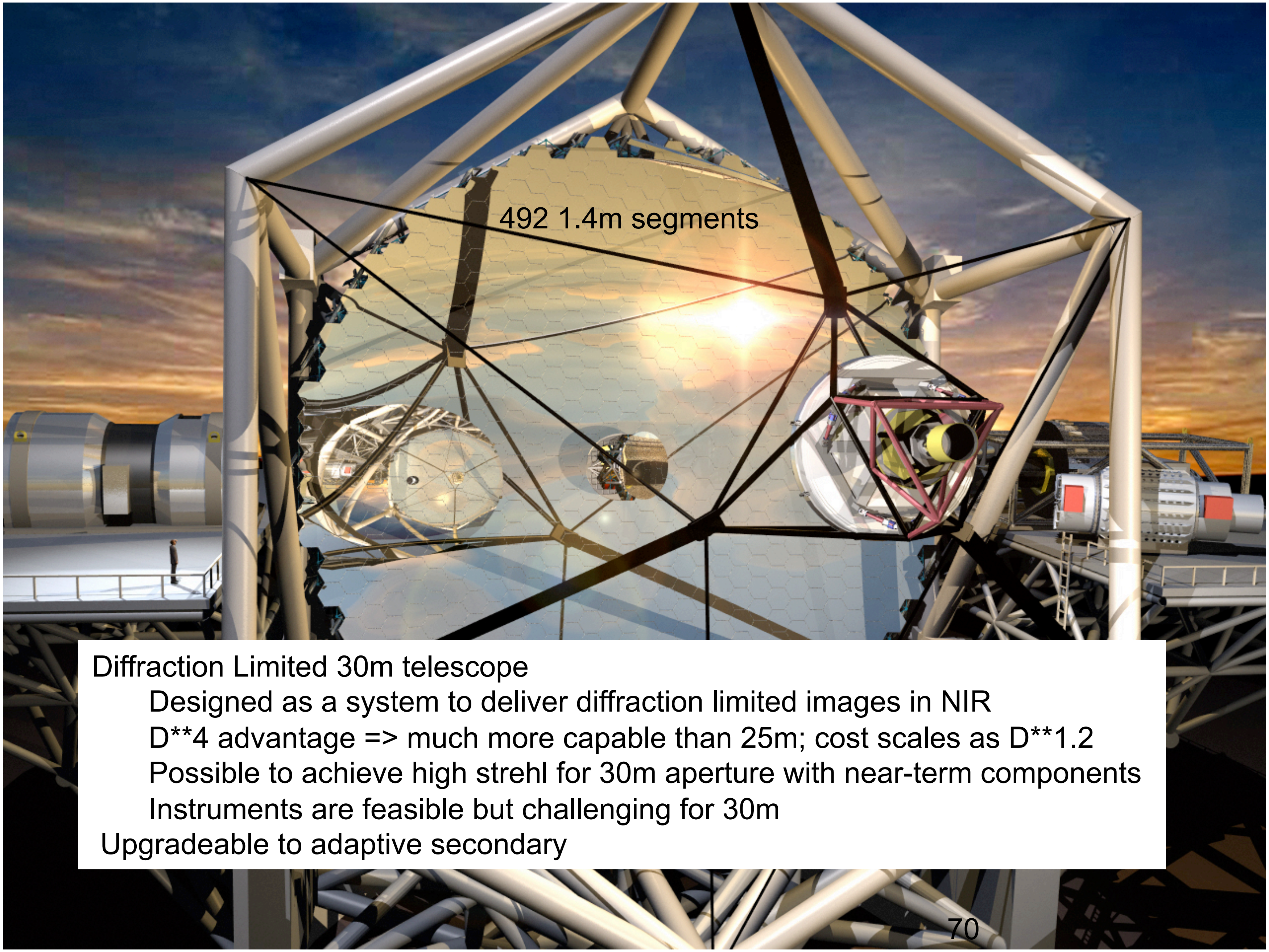
- Early Sources and cosmic reionization
  - Synergy with JWST and 21cm surveys: Expect JWST to detect brightest sources in each ionized bubble. TMT, with AO, should go 1 mag fainter (or more if objects are physically small)
- TMT IRIS, IRMS and NIRES will study detailed properties of first galaxies and influence on IGM
  - Pop III stars (intense HeII 1640)
  - Tracing SF (Ly Alpha) in ionized bubbles
  - Escape fraction from Ly alpha profiles
  - IGM at z > 7 using quasars or GRBs

Unlensed sizes ~30mas



IRMS science team now being formed, led by Bahram Mobasher (UCR)




492 1.4m segments
Diffraction Limited 30m telescope
Designed as a system to deliver diffraction limited images in NIR
D**4 advantage => much more capable than 25m; cost scales as D**1.2
Possible to achieve high strehl for 30m aperture with near-term components
Instruments are feasible but challenging for 30m
Upgradeable to adaptive secondary

TMT Foundation Documents

THIRTY METER TELESCOPE

www.tmt.org/foundation-docs/index.html

- Detailed Science Case (DSC)
- Science-based Requirements Document (SRD)
- Observatory Requirements Document (ORD)
- Observatory Architecture Document (OAD)
- Operations Concept Document (OCD)
- TMT Construction Proposal

TMT Instrumentation and Performance Handbook 2010

THIRTY METER TELESCOPE

- 160 pages covering Early-Light and First Decade instrumentation (requirements and designs), instrument synergies, and instrument development
- Updated information on WFOS and IRIS
- All 2006 instrument feasibility studies were combed systematically to extract all available science simulations, and tables of sensitivities/limiting magnitudes/integration times

Available at http://www.tmt.org/documents.html

THIRTY METER TEL

tmt.org

Foundation Documents | Thirty Meter Telescope

http://tmt.org/documents

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ASTRONOMY'S NEXT GENERATION OBSERVATORY TMT

ABOUT TMT | NEWS CENTER | OBSERVATORY | GALLERY | DOCUMENTS

DOCUMENTS

Foundation Documents

TMT has created a number of foundation documents to guide the design and implementation process. All of these documents are reviewed, revised, and reissued as necessary within a structured configuration control process.

The Detailed Science Case (PDF)

The Detailed Science Case (DSC) is the highest level statement of the TMT science case. The DSC was created and is maintained by the TMT Science Advisory Committee (SAC). It provides examples of the kinds of exciting, groundbreaking science that will be enabled by a 30m telescope. Wherever possible, synergies with other major upcoming facilities (e.g. the James Webb Space Telescope and the Atacama Large Millimeter Array) are discussed. As appropriate, performance numbers (often conservative) are provided (e.g. sensitivities, integration times, spatial resolutions).

Editors: D. Silva, P. Hickson, C. Steidel, M. Bolte
Last update: October, 2007

The Science-based Requirements Document (PDF)

The Science-based Requirements Document (SRD) describes the science-driven requirements for the Thirty Meter Telescope (TMT) project. TMT will be the first of the next-generation giant optical/infrared ground-based telescopes and will be a flagship facility for addressing the most compelling areas in astrophysics: the nature of Dark Matter and Dark Energy, the assembly of galaxies, the growth of structure in the Universe, the physical processes involved in star and planet formation and the characterization of extra-solar planets.

Editors: J. Nelson
Last update: January, 2009

The Observatory Requirements Document (PDF)

The Observatory Requirements Document (ORD) contains the highest level system requirements for the observatory. Top level requirements are defined for the telescope and instrumentation, summit and support facilities, environmental health and safety, and high level software. The ORD also defines site specific environmental parameters and constraints.

Editors: G. Angeli, S. Roberts
Last update: December, 2009

ADDITIONAL DOCUMENTS

Instrumentation

- TMT Instrumentation and Performance Handbook

Additional Documents

- Site-Specific Seismic Hazard Assessment Report of Proposed TMT Site

Primary Mirror Segment (M1)

- TMT Optics Discussions with Industry
- Draft Statement of Work for Production of the TMT Primary Mirror Optics
- M1 Segment Background
- M1 Optics System Design Requirements Document
- Segment Blank Specification
- Finished Segment Specification
- Polished Segment Drawing
- Polished Mirror Assembly Drawing
- SSA PDR Vol-1 Overview
- SSA PDR Vol-2 System Level Calculations
- SSA PDR Vol-3 Finite Element Analysis
- SSA PDR Vol-4 Warping Harness
- SSA PDR Vol-5 Flexure Design
- SSA PDR Vol-6 Segment Handling
- SSA PDR Vol-7 Future Plans
- SSA Prototype Drawing Package
- Prototype M1 Segment Handling Cart
- TMT M1 Segmentation Database
- Structure Function Calculation Routine
- SSA P2 Prototype Solid Model

M1 Control System

- M1 Actuators and Sensor Build Summary

M1CS Actuators

SITE SEARCH

Go

SPIE PAPERS

Pertaining to M1 Segments

- Advancement of the Segment Support System for the Thirty Meter Telescope Primary Mirror
- Primary Mirror Segmentation Studies for the Thirty Meter Telescope
- Development of the Primary Mirror Segment Support Assemblies for the Thirty Meter Telescope

Pertaining to M2

- Performance Prediction of the TMT Tertiary Mirror Support System

Pertaining to M2 & M3

- Control and support of 4-meter class secondary and tertiary mirrors for TMT

Pertaining to M3

- Performance Prediction of the TMT Tertiary Mirror Support System

2006 SPIE Papers Pertaining to the M1 Control System

- An Edge Sensor Design for the TMT
- Design of a Prototype Primary Mirror Segment Positioning Actuator for the TMT

2008 SPIE Papers Pertaining to the M1 Control System

- Advances in Edge Sensors for the TMT
- Analysis of TMT Primary Mirror Control-Structure Interaction
- Control Analysis of the TMT Primary Mirror Assembly

SPIE 2006 Papers Pertaining to

THIRTY METER TELESCOPE

Acknowledgments

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