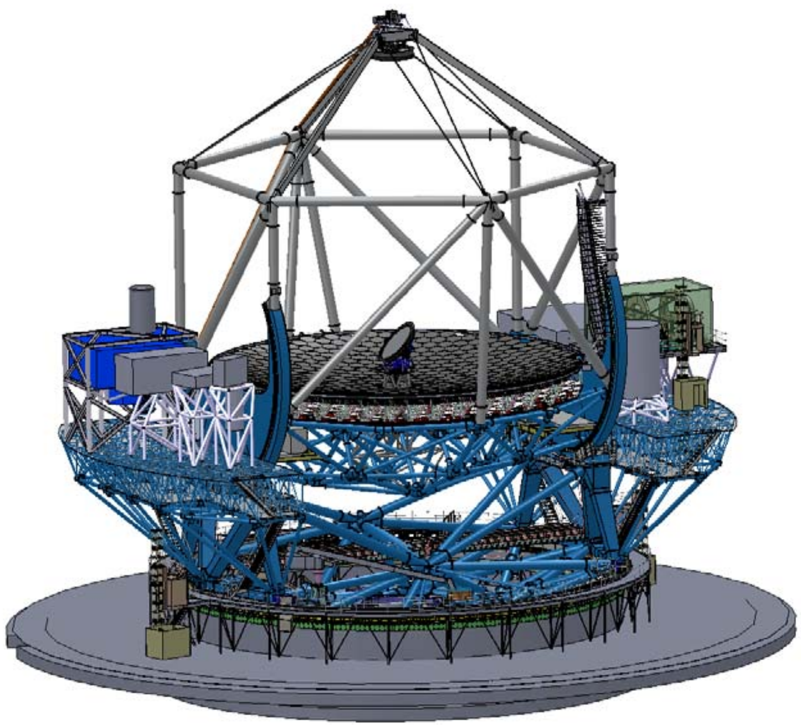
THIRTY METER TELESCOPE



Thirty Meter Telescope: Future Science Instrument Development

Luc Simard (TMT)

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TMT Science Forum

Waikoloa, Hawaii

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TMT.INS.PRE.13.037.REL01

Outline

- First-Light Instruments (see previous presentations!)
- Planned Instrumentation Suite and Synergies with Other Facilities
- Selection of Future Instruments and Instrumentation Development Program
- Instrument Phasing Scenarios

Summary of TMT Science Objectives and Capabilities

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

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THIRTY METER TELESCOPE

TMT Planned 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 Planned Instrument Suite

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THIRTY METER TELESCOPE

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Visible, Seeing-Limited

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TMT Planned Instrument Suite

Near-IR, AO-assisted

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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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TMT Planned Instrument Suite

High-Contrast AO

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	diameter field	2000-10000	• Early Light • Epoch of peak galaxy building • JWST follow-ups
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TMT Planned Instrument Suite

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InfraRed Multislit Spectrometer (IRMS)	0.95 – [illegible]	[illegible] with 46 deployable slits	[illegible] arcsec slit	• [illegible]rly Light • [illegible]och of peak galaxy building • JWST follow-ups
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Mid-infrared, AO-assisted

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TMT First Light 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
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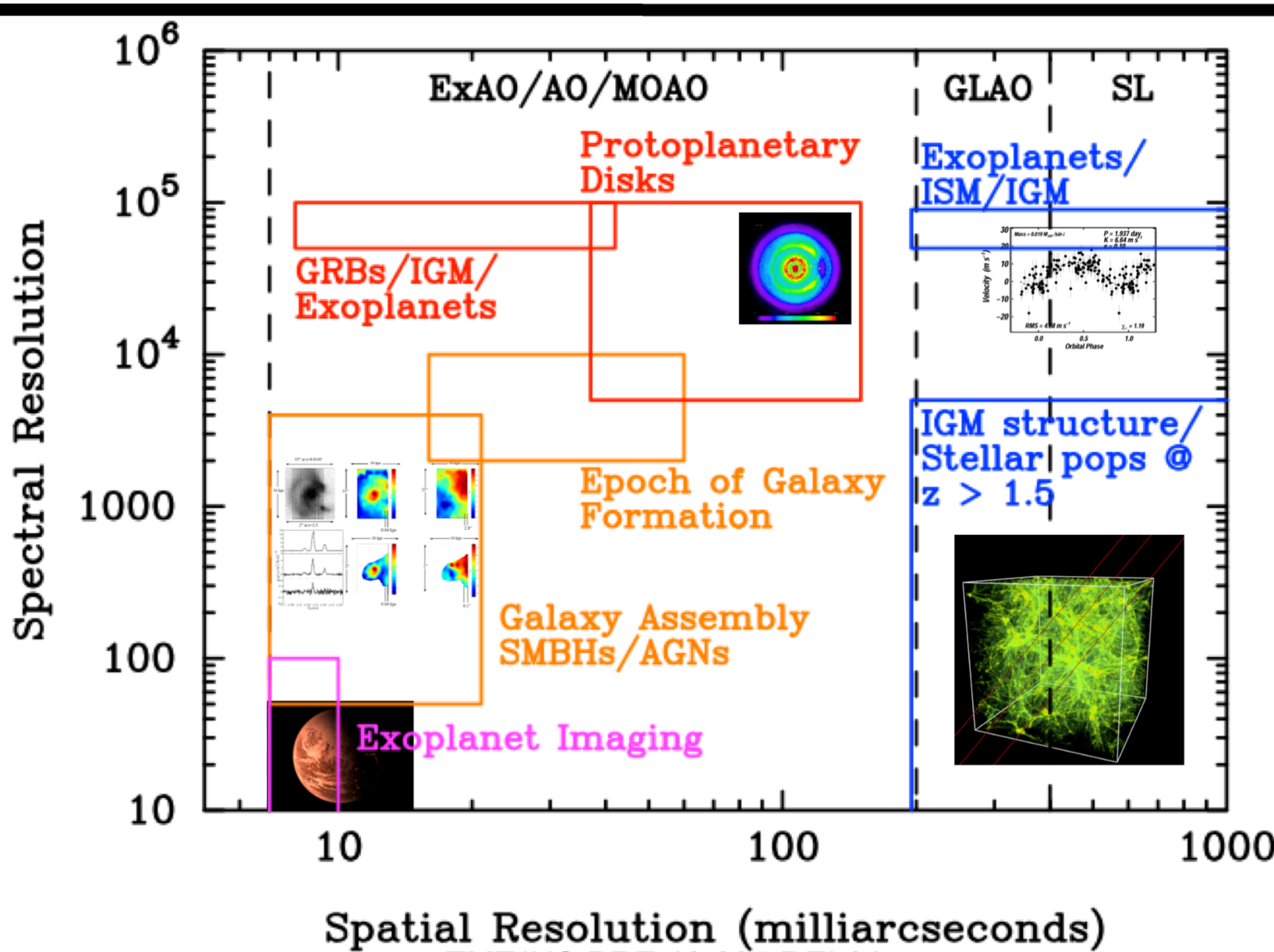
THIRTY METER TELESCOPE

An ELT Instrumentation "Equivalence Table"

Type of Instrument	GMT	TMT	E-ELT
Near-IR, AO-assisted Imager + IFU	GMTIFS	IRIS	HARMONI
Wide-Field, Optical Multi-Object Spectrometer	GMACS	MOBIE	OPTIMOS
Near-IR Multislit Spectrometer	NIRMOS	IRMS	
Deployable, Multi-IFU Imaging Spectrometer		IRMOS	EAGLE
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	CODEX
"Wide"-Field AO Imager		WIRC	MICADO

Defining Capabilities in the TMT Discovery Space



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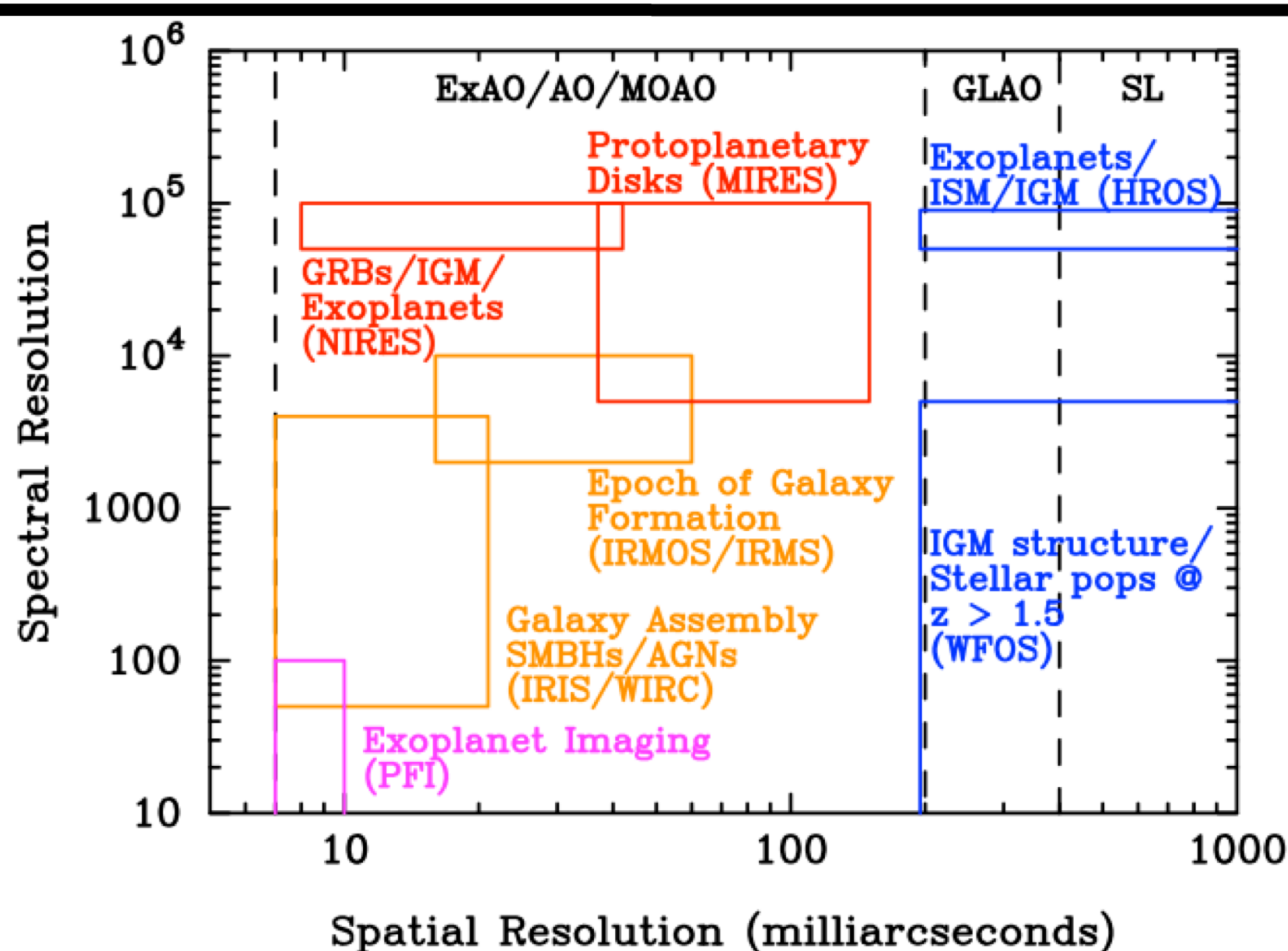
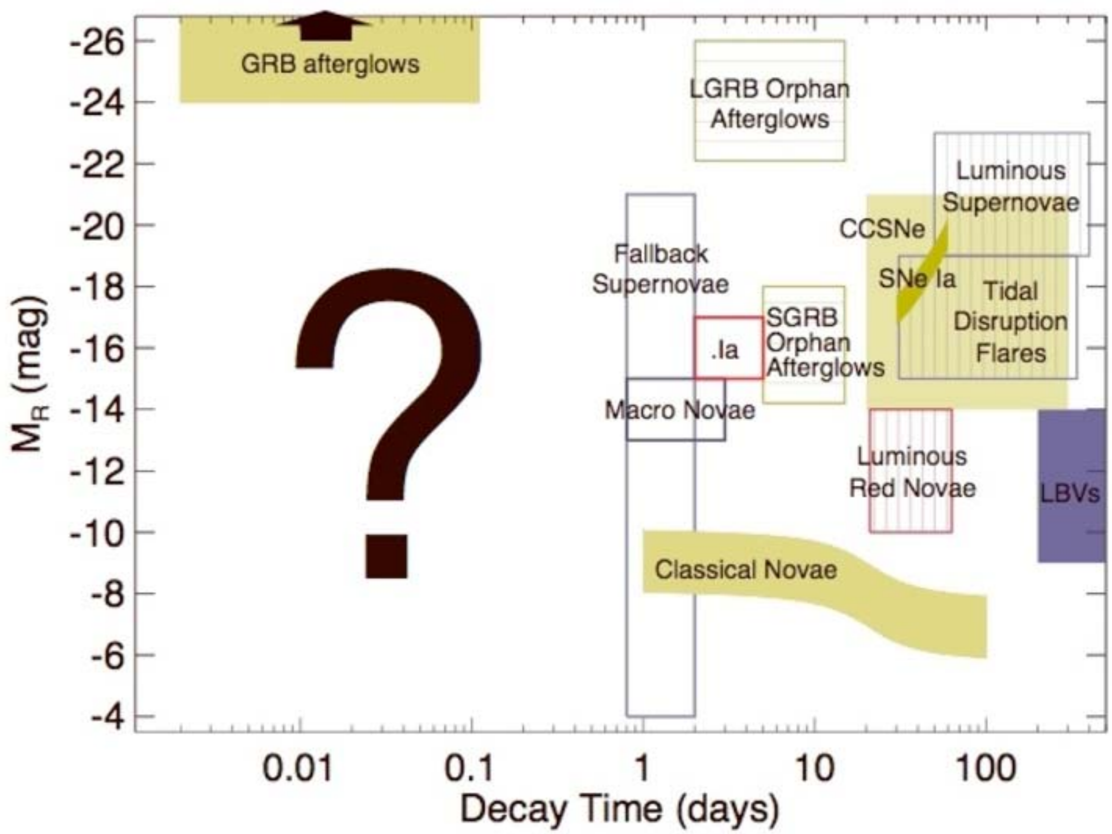
Defining Capabilities in the TMT Discovery Space



TMT as an Agile Telescope: Catching The "Unknown Unknowns"

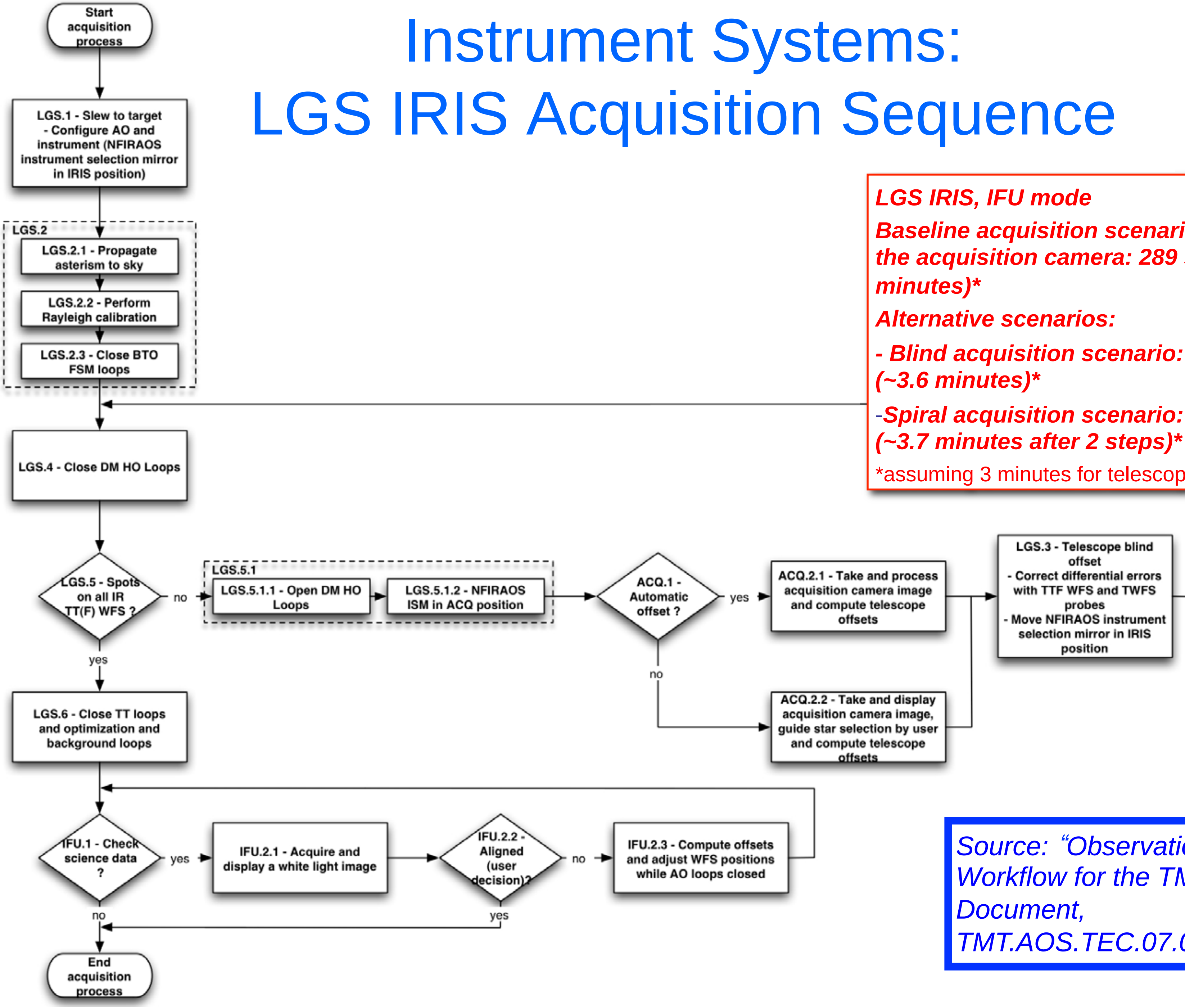


Source: Figure 8.6, LSST Science Book

TMT target acquisition time requirement is 5 minutes (i.e., 0.0034 day)

TMT is the only agile extremely large telescope

Instrument Systems: LGS IRIS Acquisition Sequence



LGS IRIS, IFU mode

Baseline acquisition scenario using the acquisition camera: 289 s (~4.8 minutes)*

Alternative scenarios:

- Blind acquisition scenario: 219 s (~3.6 minutes)*

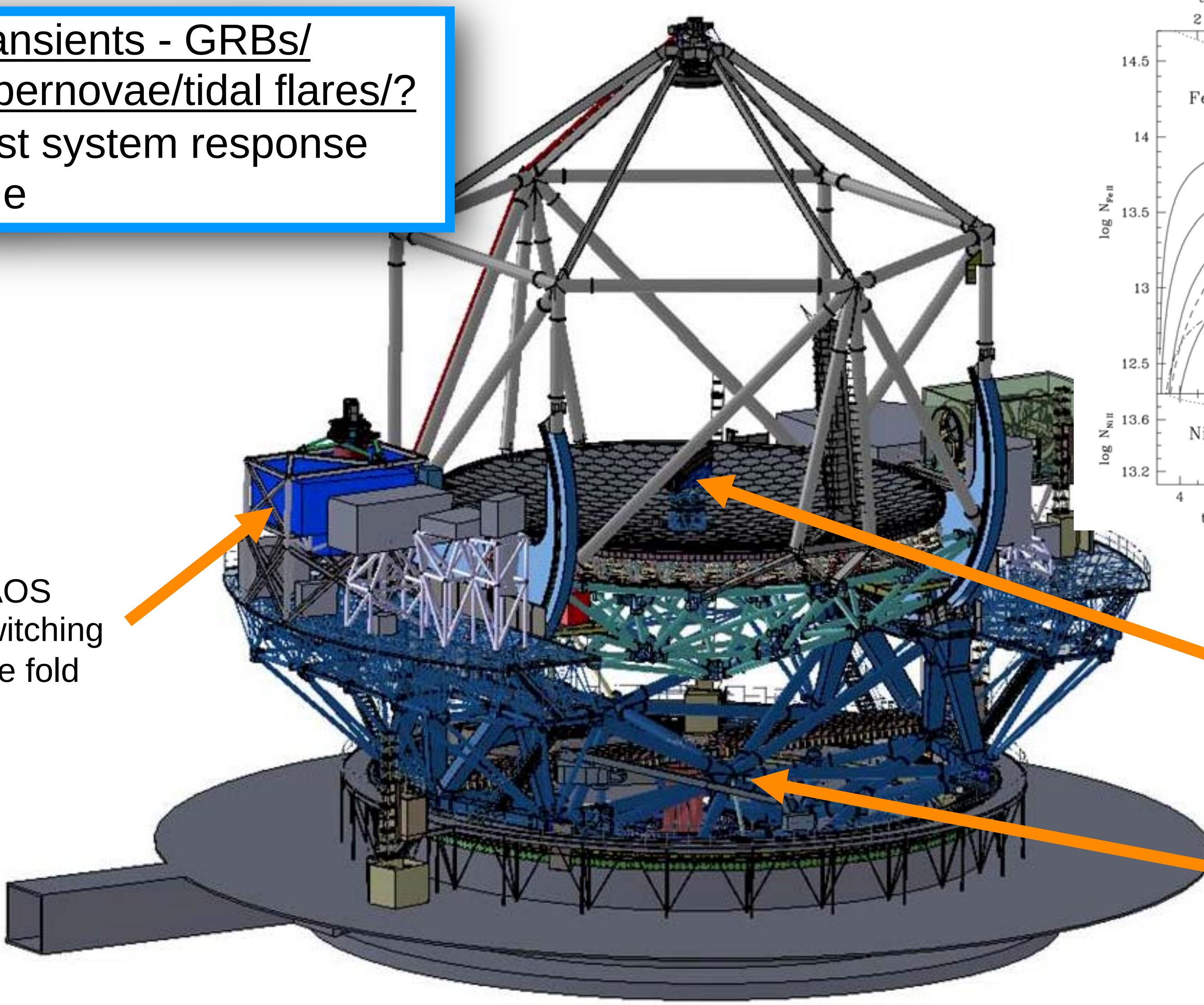
-Spiral acquisition scenario: 224 s (~3.7 minutes after 2 steps)*

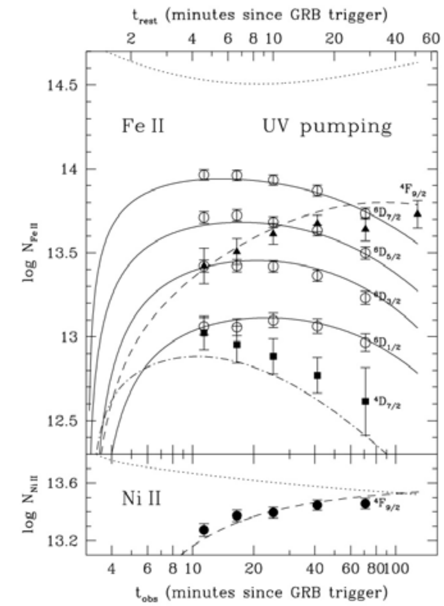
*assuming 3 minutes for telescope setup

Source: "Observation Workflow for the TMT" Document, TMT.AOS.TEC.07.013

From Science to Subsystems

<u>Transients - GRBs/ supernovae/tidal flares/?</u>
Fast system response time





NFIRAOS fast switching science fold mirror

Articulated M3 for fast instrument switching

Fast slewing and acquisition

Synergies I. First Light and Re-ionization

Penetrating the Early Universe with ionized bubbles

Redshift	Bubble Radius (comoving Mpc)	Physical (kpc)	Half-angle (arcsec)
10	0.3 – 2.5	27 – 227	6.5 – 54
8	0.6 – 6.0	66 – 666	13 – 138
7	0.5 – 20.0	63 – 2500	12 – 478

Source: IRMOS Caltech Feasibility Study

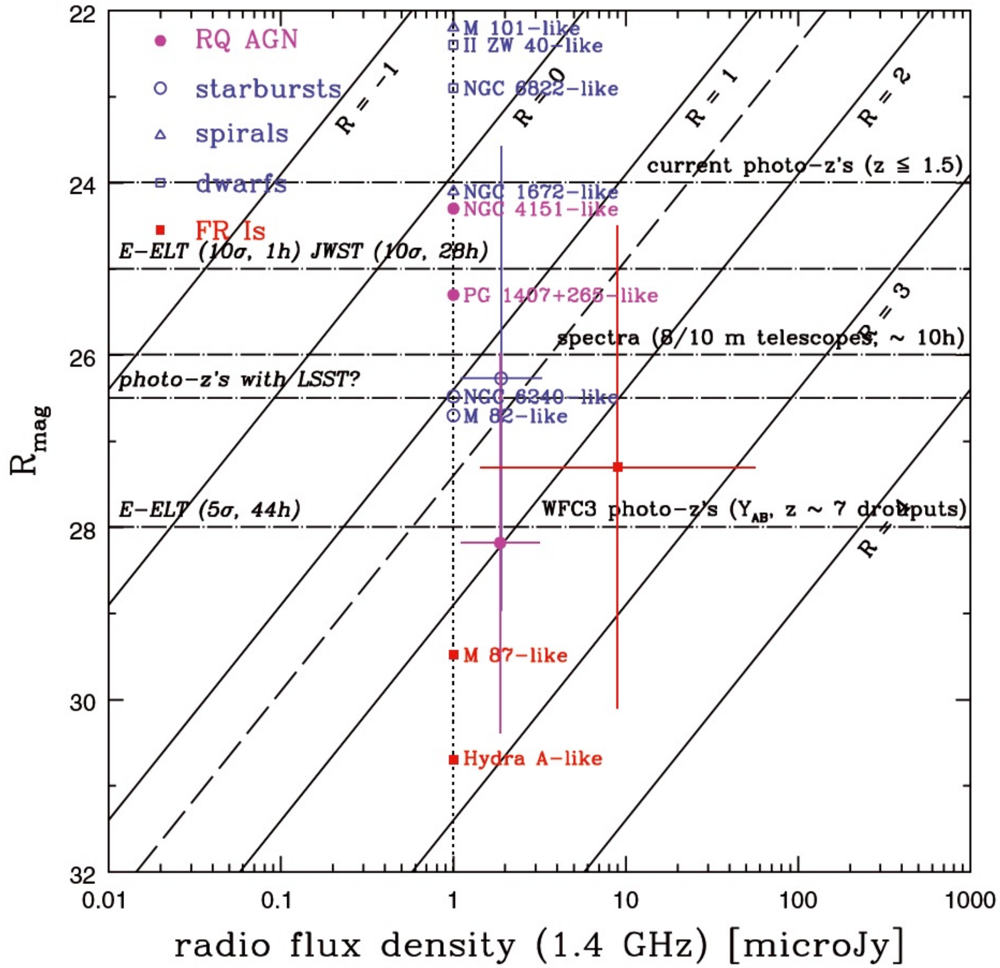
JWST: Detection of sources

TMT: (1) Source spectroscopy with IRIS/IRMS and (2) Mapping topology of bubbles around JWST detections with IRIS/IRMS or IRMOS deployable IFUs

ALMA: Imaging of dust continuum up to z = 10 for complete baryon inventory

Synergies II. SKA

Spectroscopic limits (Padovani 2011)



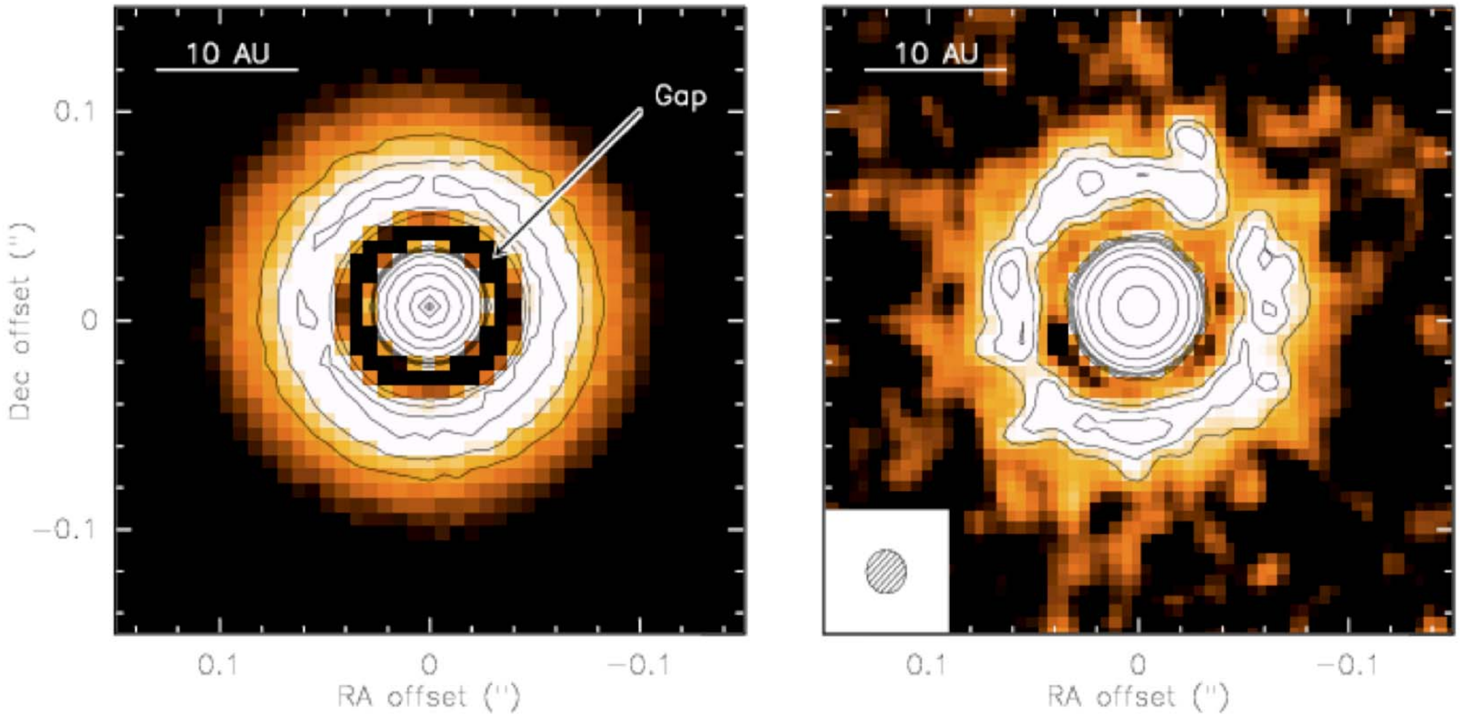
The "Square Kilometer Array" will probe the so-called Dark Ages

It will also survey sources at the microjansky and nanojansky levels

Expected to be optically very faint

It will be possible with ELTs+SKA to study star formation rates and feedback from active galactic nuclei in normal galaxies out to z = 6

Synergies III. Planet Formation



TMT PFI:

10^6 @ 30 mas IWA (Taurus Jovians)

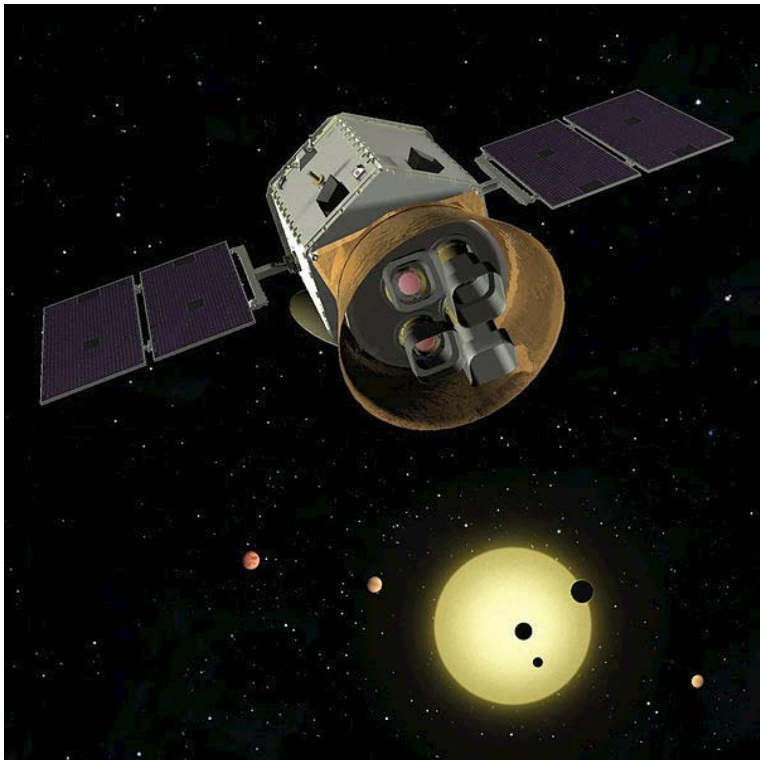
10^8 @ 50 mas IWA (Reflected light Jovians)

Figure 31 "Science with ALMA" Document

Simulation of a protoplanetary system with a tidal gap created by a Jupiter-like planet at 7 AU from its central star as observed by ALMA

TMT's Planet Formation Instrument (PFI) will allow detection of the planets themselves that are responsible for the gaps and thus enable measurements of mass, accretion rate and orbital motion.

Synergies V. TESS



"Transiting Exoplanet Survey Satellite"

Survey area 400 times larger than Kepler's

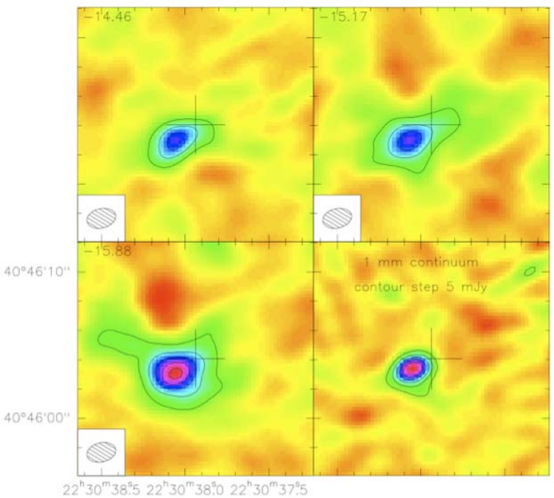
2.5 million of the closest and brightest stars (G, K types)

2,700 new planets including several hundred Earth-sized ones

Planned launch: 2017

Synergies VI. Solar System

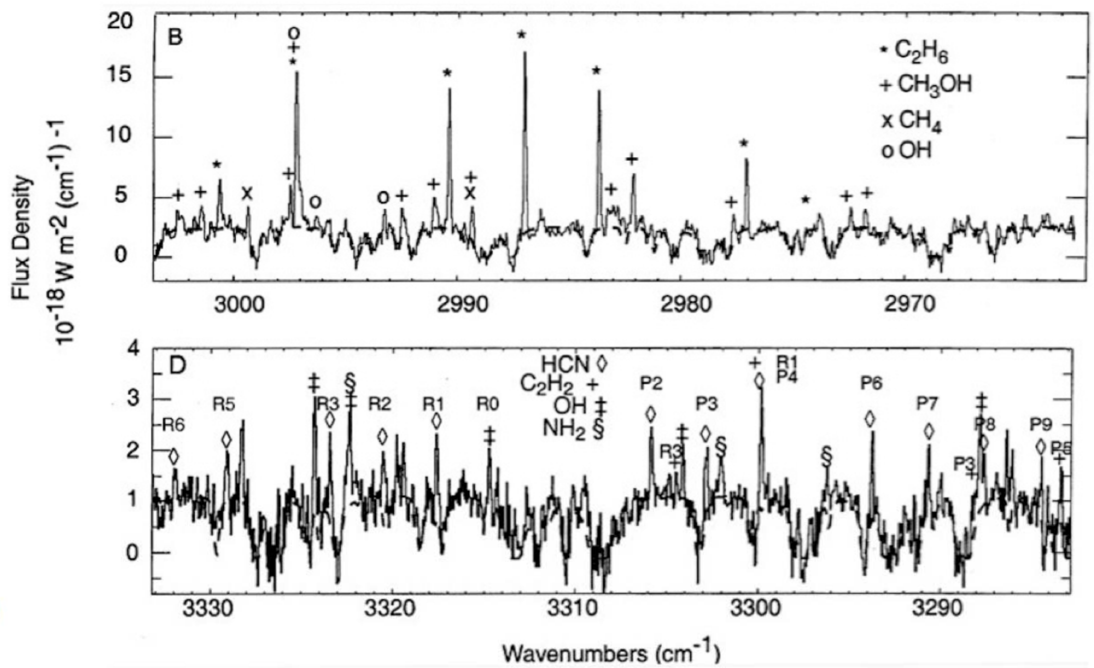
Physics and Chemistry of Cometary Atmospheres



CO(2-1) emission and dust continuum from Comet Hale-Bopp at 1'' resolution with with IRAM

Submm+optical = nucleus albedo and size

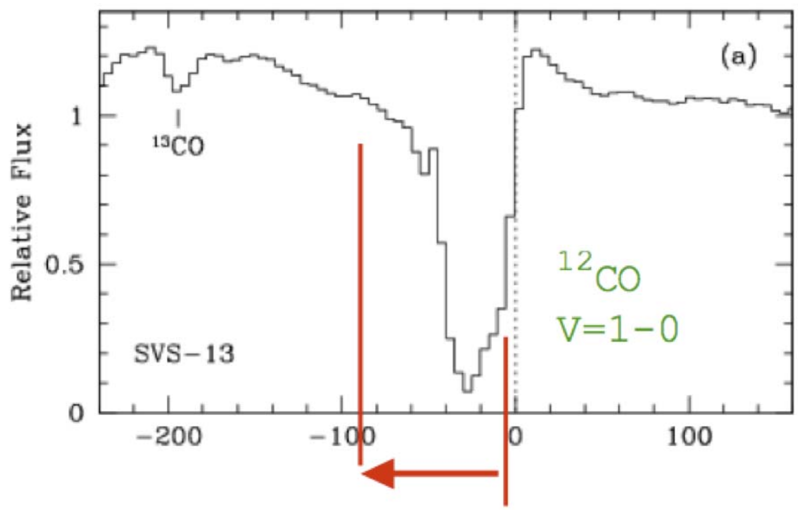
(Figure 40 - "Science with ALMA" Document)



Detection of parent volatiles in Comet Lee (C/1999 H1) at R=20, 000. TMT/NIRES will allow diffraction-limited observations at R=100,000 over the range 4.5 - 28 µm

Look for "chemical families" as probes of the Oort Cloud

Synergies IV. Proto-Star Formation

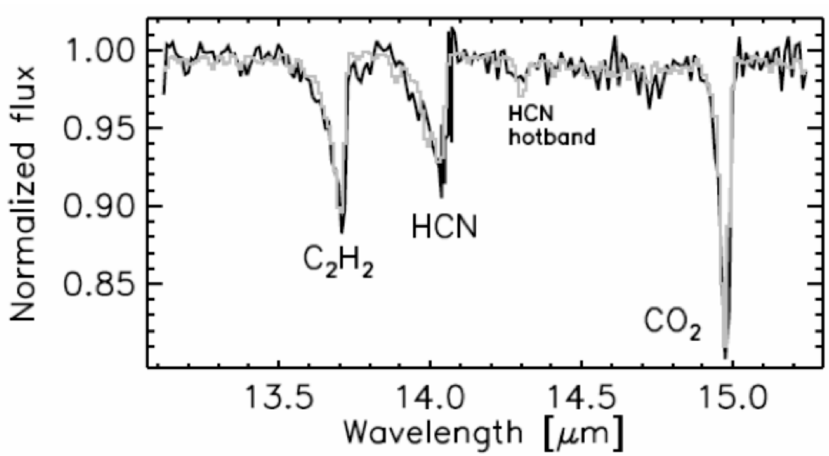


High-velocity outflowing gas in CO towards protostar SVS13 (Keck/NIRSPEC)

TMT/MIRES will measure warm, dense molecular gas to probe the base of outflows in a large number of low-mass protostars

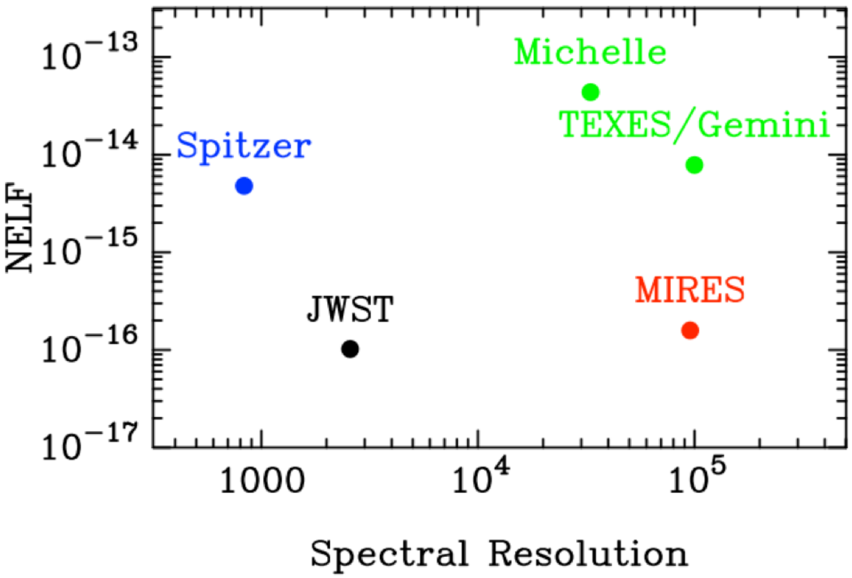
Low-resolution Spitzer spectrum shows exceptionally strong molecular absorption. HCN and CO suggests gas originates in an outflow

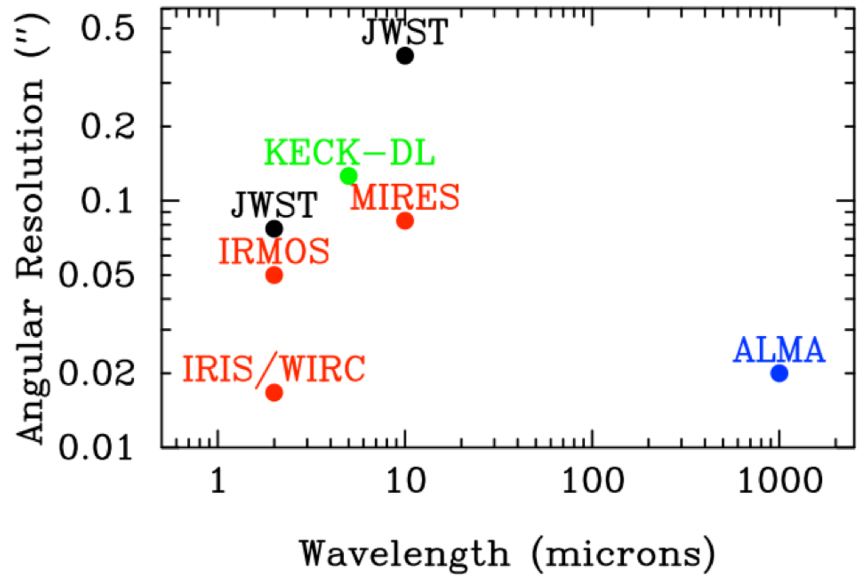
TMT/MIRES will measure molecular abundances to determine the launch point of the wind



Synergies VII. Space/IR and ALMA

(TMT capabilities are shown in red)





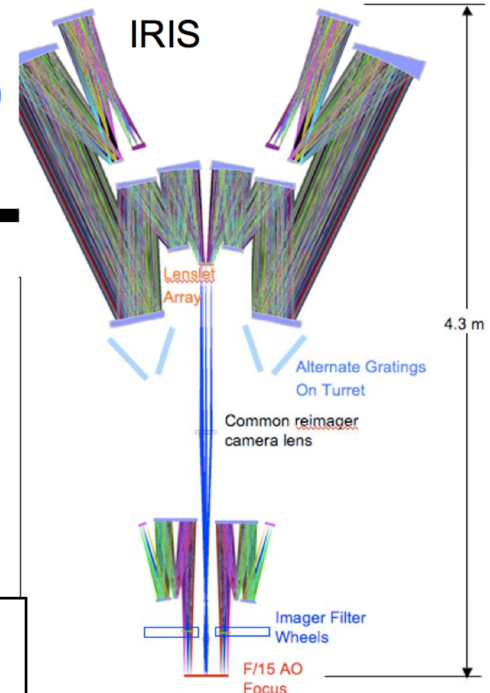
TMT/MIRES will have comparable spectral line sensitivity (NELF) to infrared space missions with a much higher spectral resolution

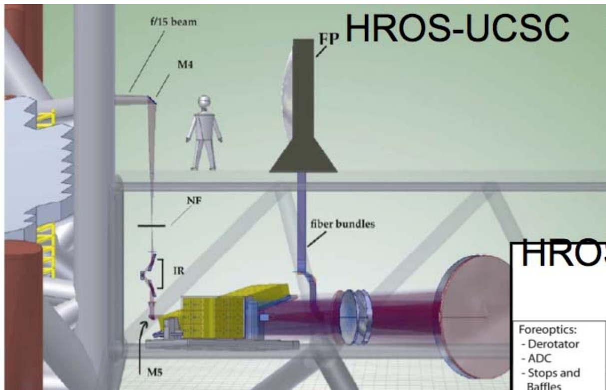
The angular resolution of TMT instruments nicely complements that of JWST and ALMA

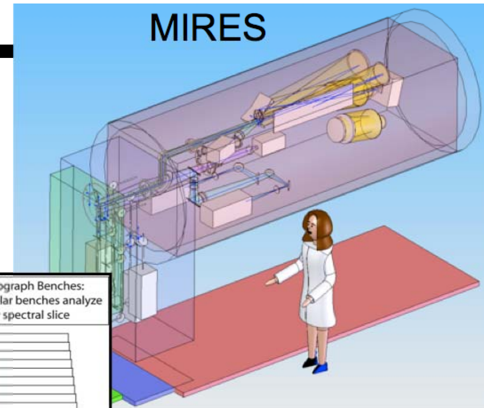
TMT is a "near IR ALMA"!

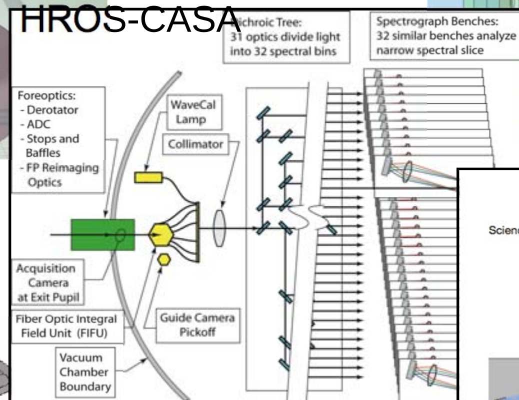
THIRTY METER TELESCOPE

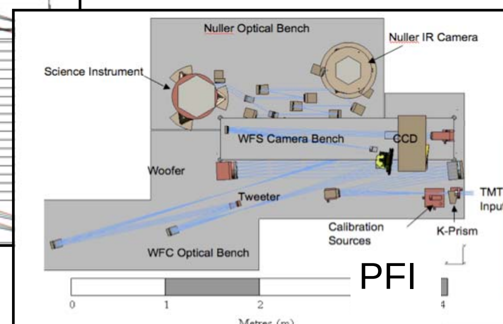
Feasibility studies 2005-6
(concepts, requirements, performance,…)

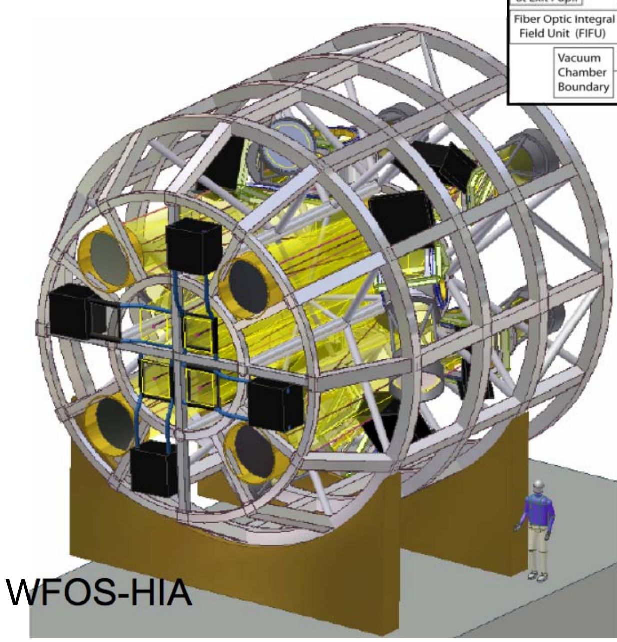


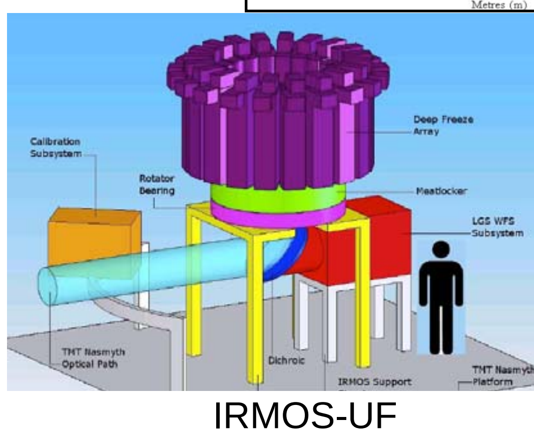


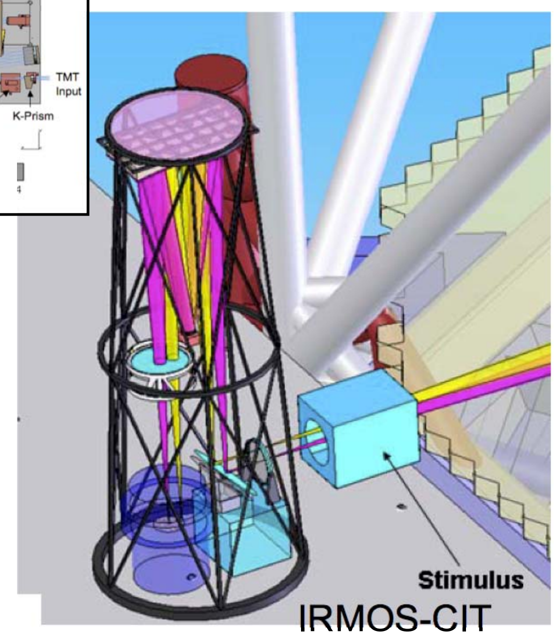




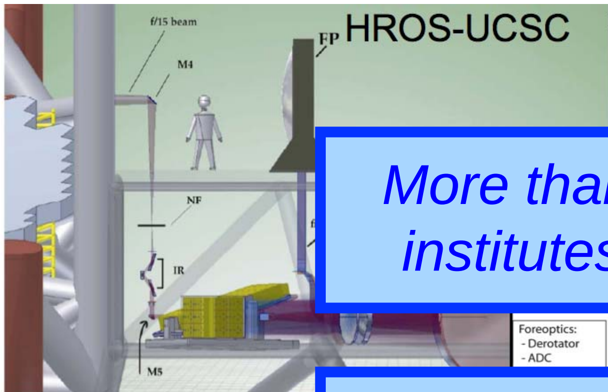


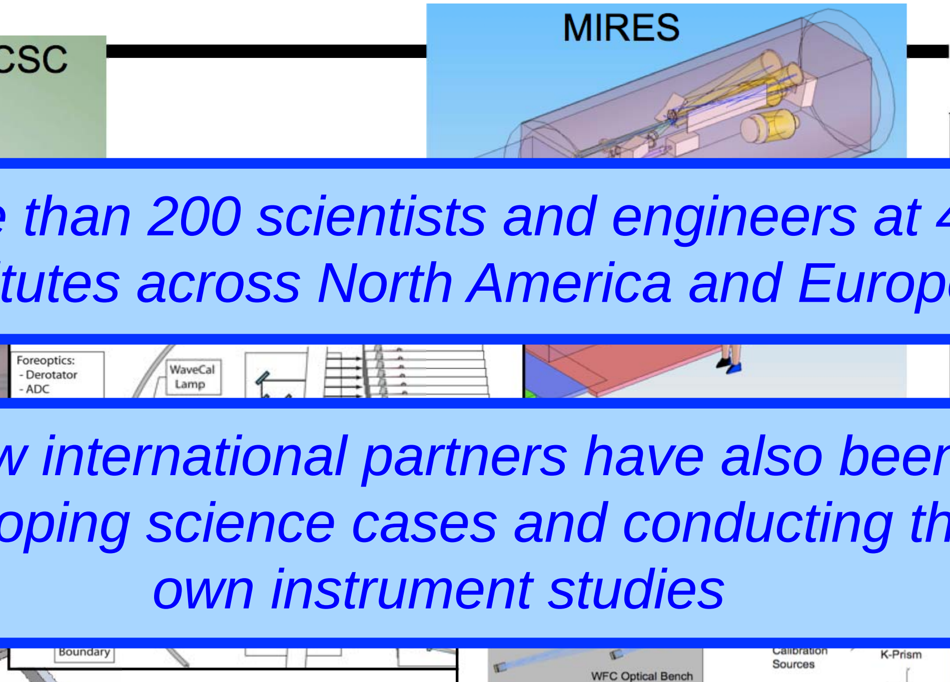


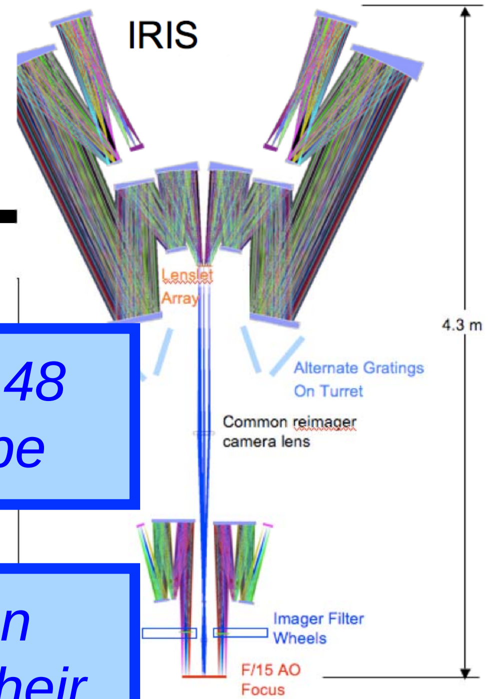




Feasibility studies 2005-6
(concepts, requirements, performance,…)



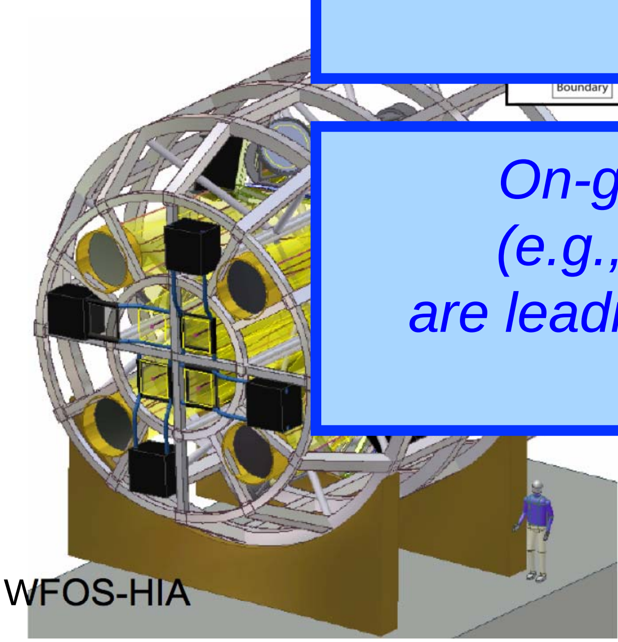


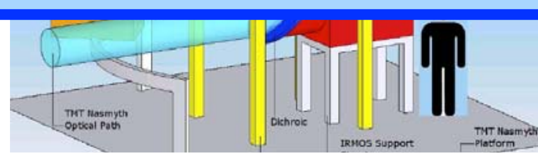


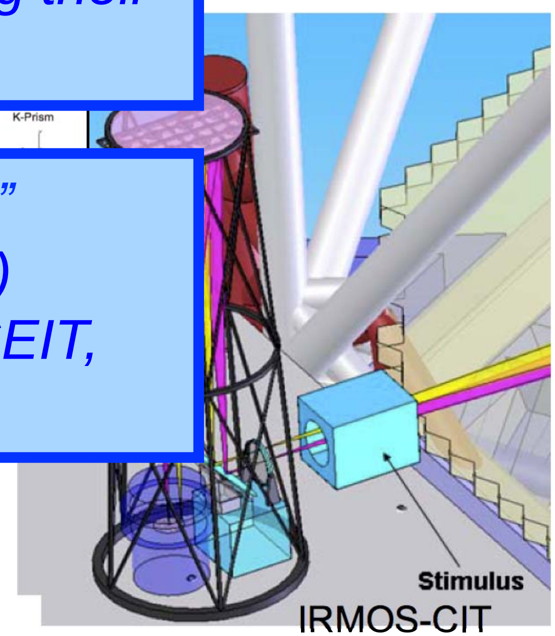
More than 200 scientists and engineers at 48 institutes across North America and Europe

New international partners have also been developing science cases and conducting their own instrument studies

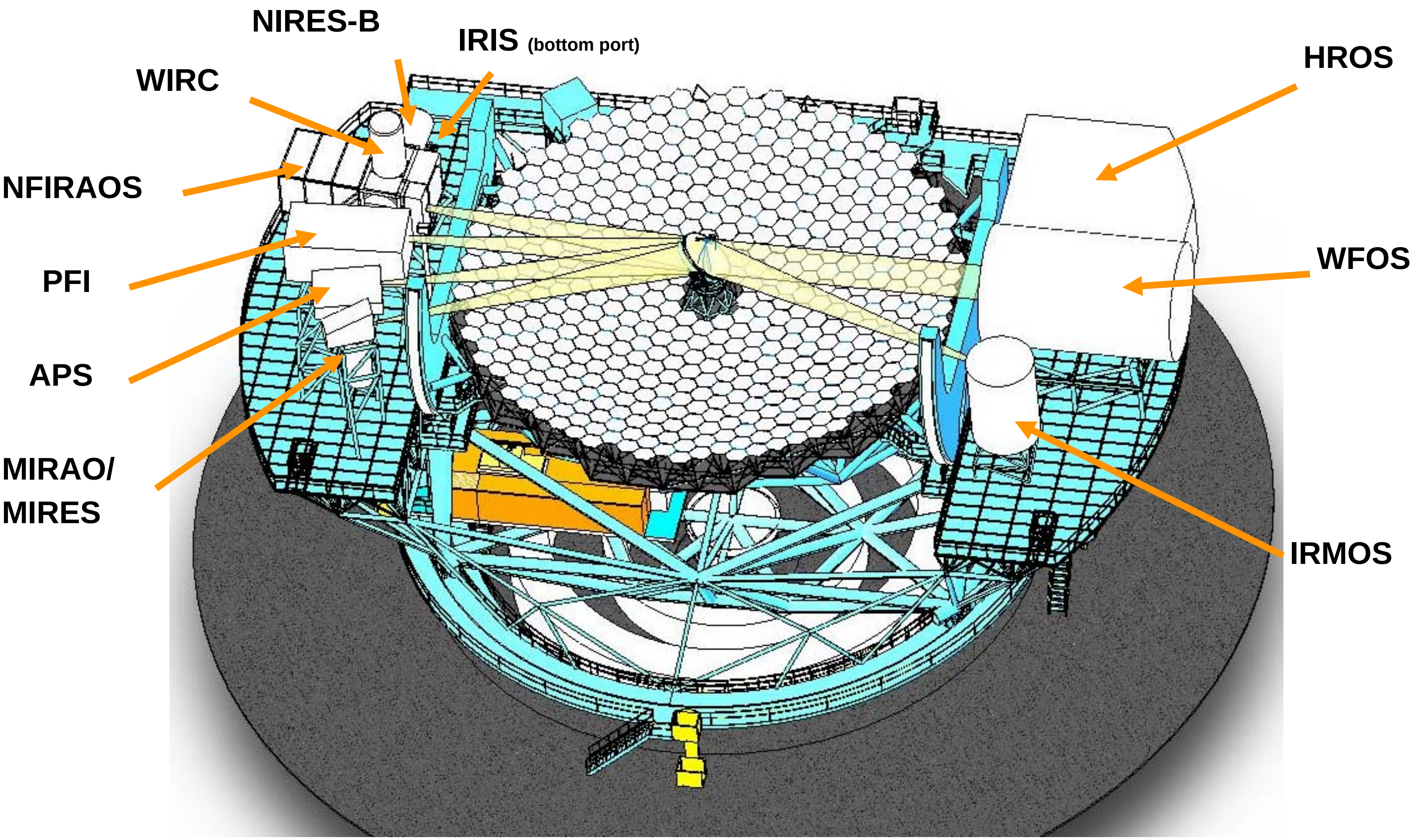
On-going "community explorations" (e.g., workshops, testbeds, studies) are leading to new concepts (MICHI, SEIT, CTMT-HROS)







Nasmyth Configuration: Planned Instrumentation Suite

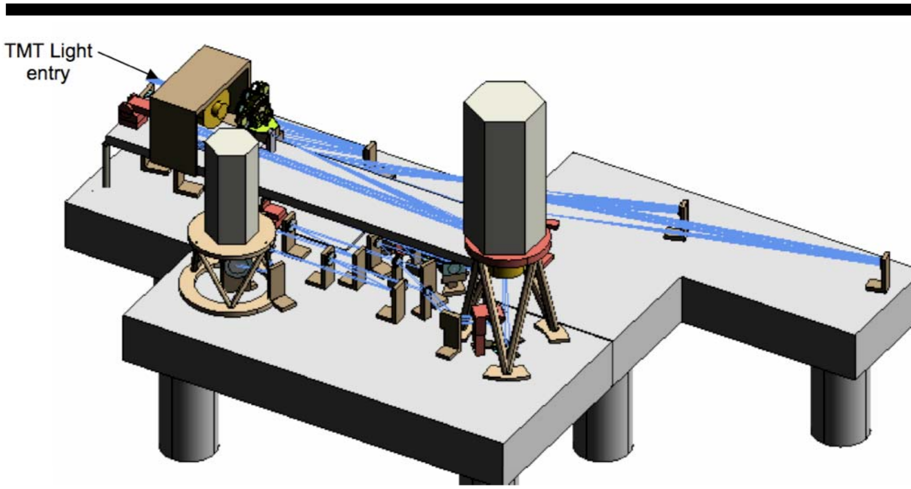


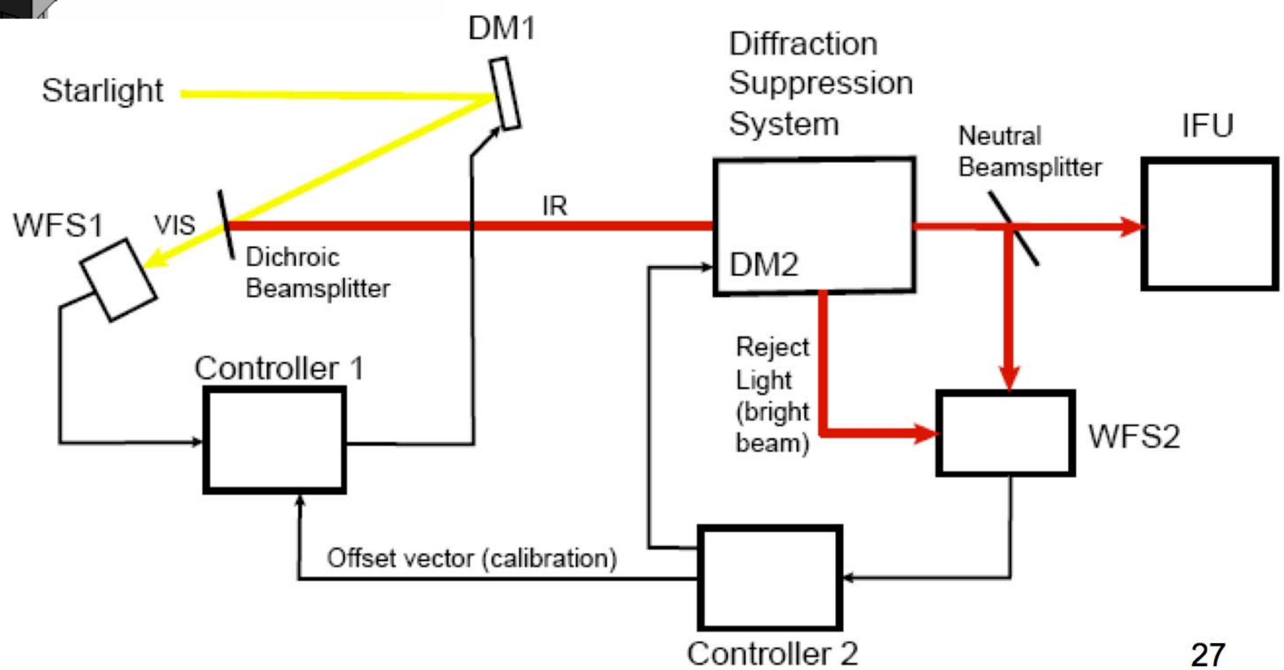
Planet Formation Instrument (PFI) Top-Level Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4510]	Wavelength Range	1-2.5μm, one band at a time. Goal is 1 - 4μm.
[REQ-1-ORD-4515]	Field of View	0.7 arcsec radius, goal 2 arcsec radius (applies to all requirements for PFI)
[REQ-1-ORD-4520]	Planet Detection Contrast (I<8) @ Inner Working Angle with 5x rms noise, for a two hour integration	10^{-8} @ 50 mas, goal 10^{-9} @ 100 mas
[REQ-1-ORD-4525]	Planet Detection Contrast (H<10) @ Inner Working Angle with 5x rms noise, for a two hour integration	10^{-6} @ 30 mas, goal $2x10^{-7}$ @ 30 mas
[REQ-1-ORD-4530]	Spatial Sampling	Nyquist sampled at H band, goal J band.
[REQ-1-ORD-4535]	Spectral Resolution, full FOV, IFU	R = 50, goal 100
[REQ-1-ORD-4540]	Spectral Resolution, partial FOV, IFU	R = 500, goal 1000
[REQ-1-ORD-4545]	Polarimetry	Simultaneous dual channel to detect polarized light (e.g. from scattering off circumstellar dust) at a level of 1% of the residual stellar halo, and measure absolute polarization to an accuracy of 10%

Planet Formation Instrument (PFI)

Source: 2006 PFI Feasibility Study Report Vol. 1, TMT.IAO.CDD.06.005





PFI Solar Neighborhood Survey

I (mag)	Number of Targets	TMT/PFI Number of Planets detected	TMT/PFI Detection Fraction (%)	Gemini/GPI Detection Fraction (%)
< 5	150	62	38	13
< 7	1872	244	13	7

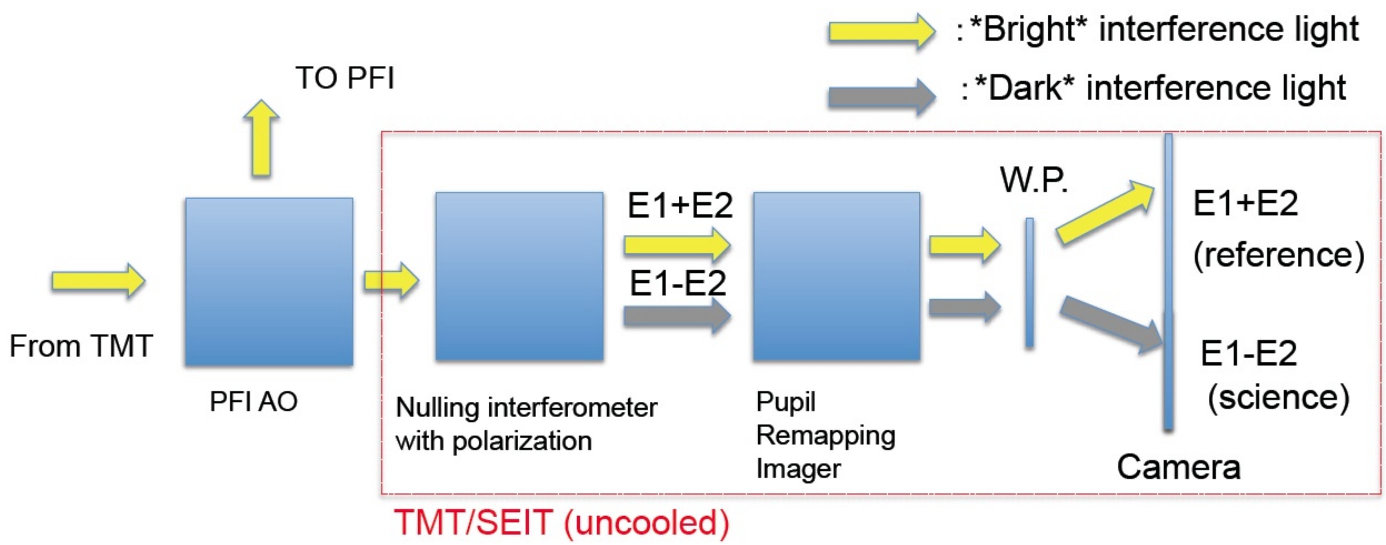
Table notes: Solar Neighborhood Survey (d < 50 pc; all ages). Integration time: 1 hour; 5σ detection threshold. Column 5 shows that TMT/PFI finds 2-3 times as many planets as the Gemini Planet Imager instrument on Gemini, primarily because of TMT's smaller Inner Working Angle (IWA)

Source: Table 2, 2006 PFI Feasibility Study Report Vol. 1, TMT.IAO.CDD.06.005

Second Earth Imager for TMT (SEIT)

- Collaboration between NAOJ, JAXA, ISAS, Hokkaido U., U. of Tokyo and NIBB led by T. Matsuo (NAOJ)
- High-contrast imager optimized for Inner Working Angle rather than contrast ratio
  - 10^{-8} @ 0".01 (i.e., 1.5λ/D @ 1 μm)
- Science drivers
  - Earth-like planets in habitable zone of K- and M-type stars
  - Earth-like planets outside habitable zone of F- and G-type stars

Matsuo et al., SPIE 2012, 8447-57)

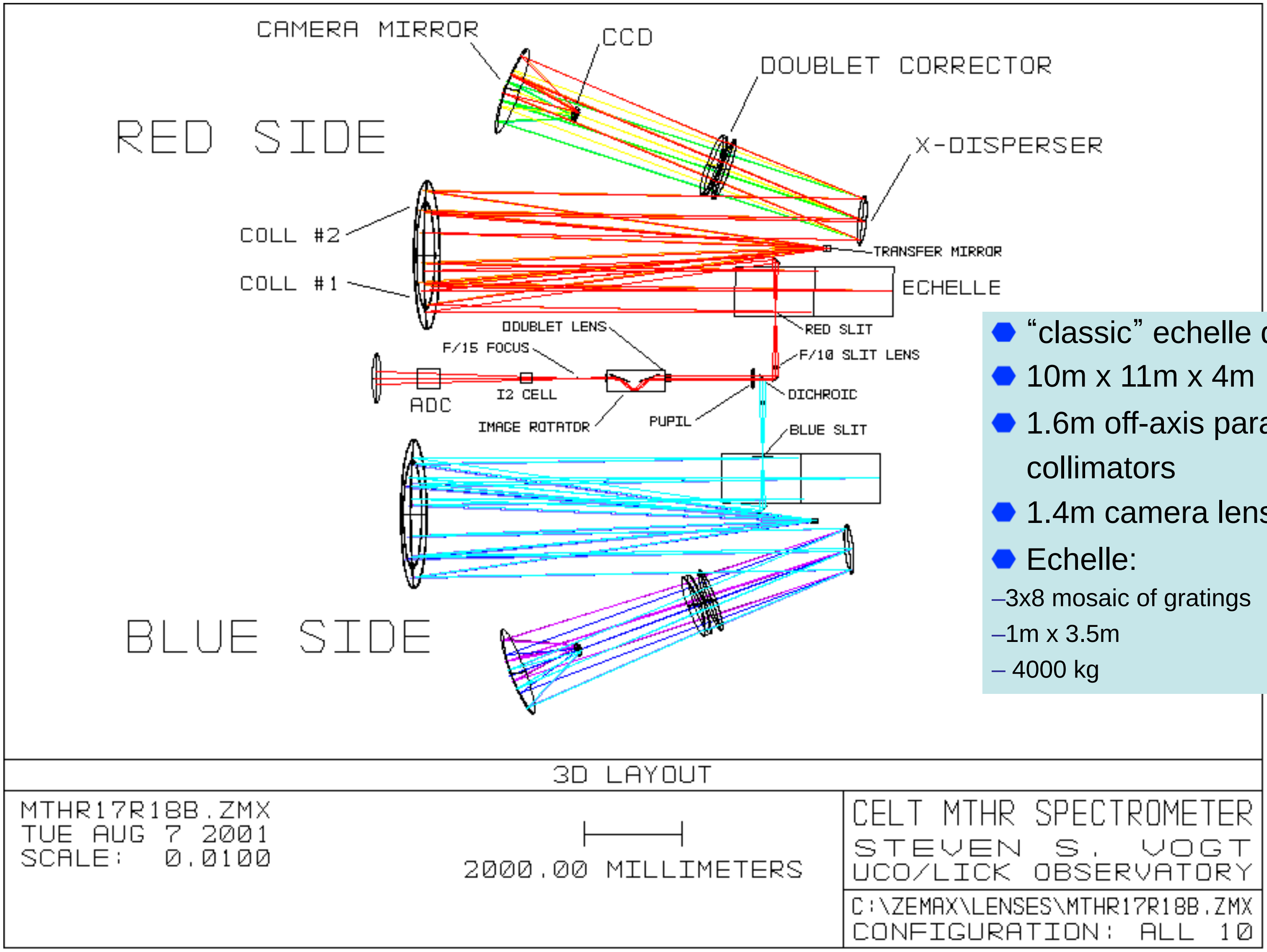


HROS Top-Level Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4740]	Wavelength Range	0.31 – 1.0µm (required) 0.3 – 1.3µm (goal).
[REQ-1-ORD-4745]	Field of View	10 arcseconds
[REQ-1-ORD-4750]	Length of slit	5 arcseconds, with this separation between orders
[REQ-1-ORD-4755]	Image Quality	≤ 0.2 arcsec FWHM at detector
[REQ-1-ORD-4760]	Spatial Sampling	< 0.2 arcsec per pixel
[REQ-1-ORD-4765]	Spectral Resolution (slit)	R=50,000 (1 arc-sec slit)
[REQ-1-ORD-4770]	Spectral Resolution (image slicer)	R≥90,000
[REQ-1-ORD-4775]	Sensitivity	Must maintain 30m aperture advantage over existing similar instruments.
[REQ-1-ORD-4780]	Stability	Long term stability required to achieve radial velocity measurement repeatability and accuracy of 1 m/s over time spans of 10 years.

Two HROS concepts were competitively studied as part of the TMT instrument feasibility study phase in 2005 - 2006. One concept (“MTHR”) originated from the UC Santa Cruz (PI: S. Vogt) , and the other concept (“CU-HROS”) was proposed by a University of Colorado team (PI: C. Froning).

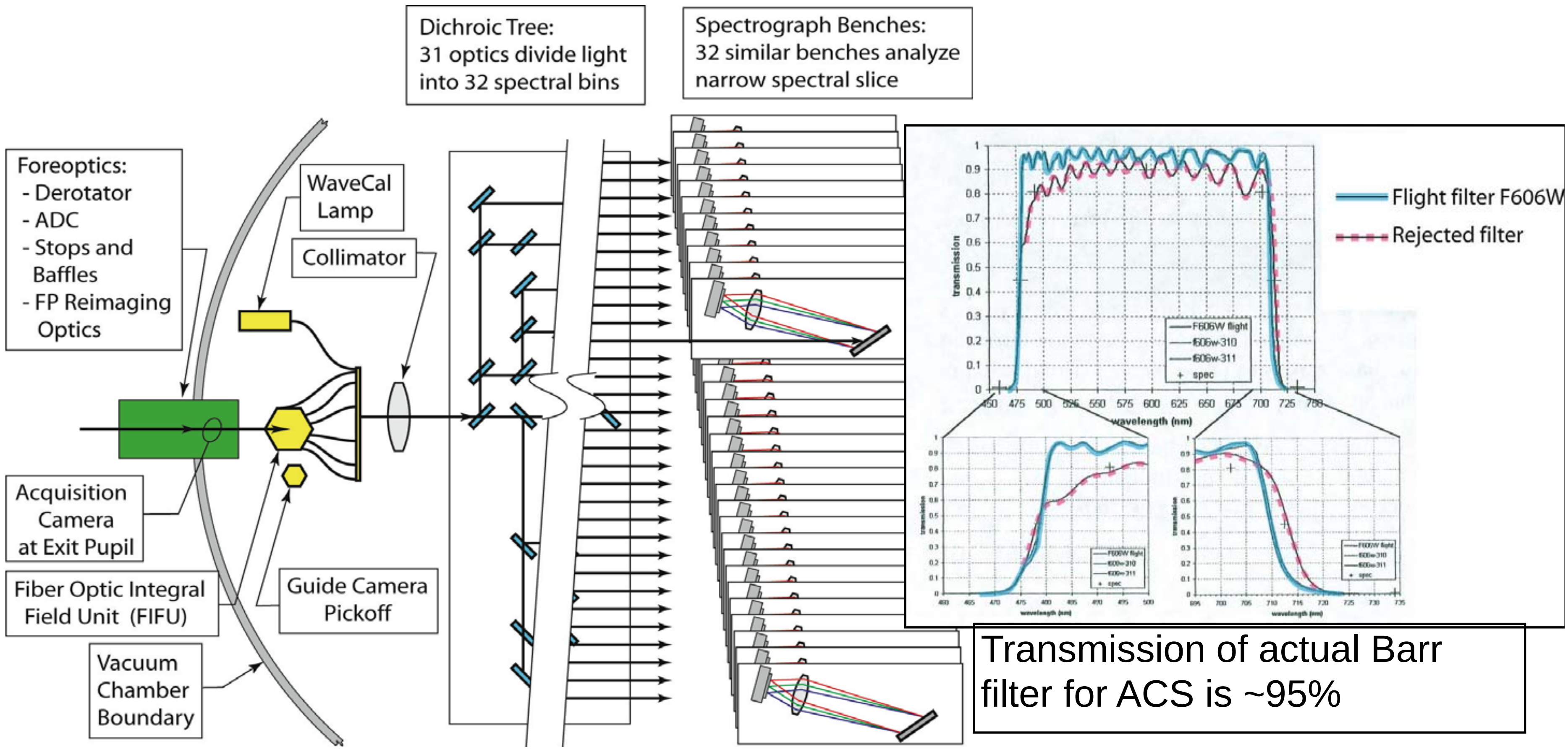
HROS "MTHR" Concept (UCSC)



- "classic" echelle design
- 10m x 11m x 4m
- 1.6m off-axis parabolic collimators
- 1.4m camera lenses
- Echelle:
  - 3x8 mosaic of gratings
  - 1m x 3.5m
  - 4000 kg

CU-HROS Concept

Completely new concept, using high performance dichroics



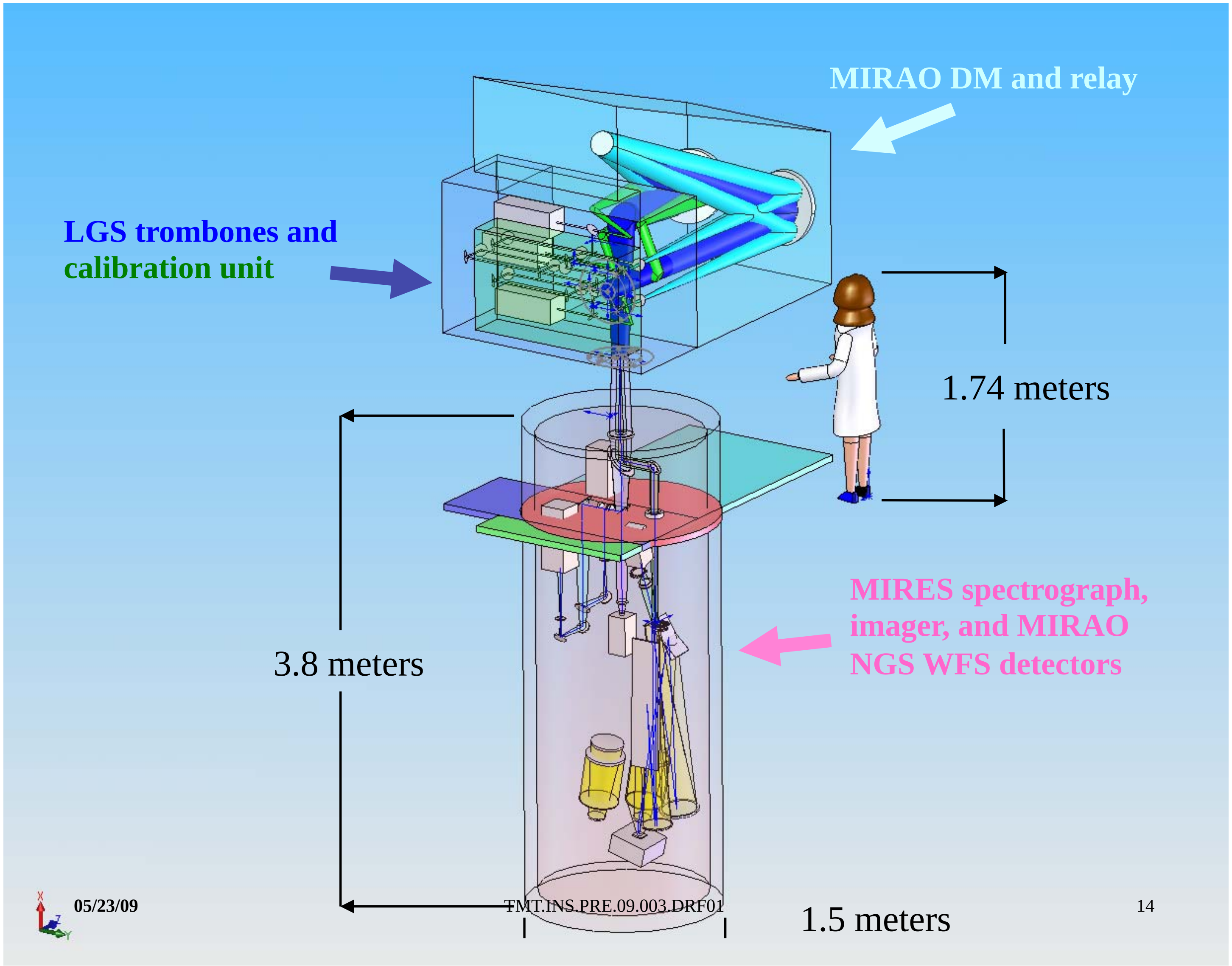
Transmission of actual Barr filter for ACS is ~95%

Source: 2006 CU-HROS Feasibility Study Report, TMT.INS.CDD.06.004

MIRES Top-Level Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4400]	Wavelength Range	8µm- 18µ, goal 4.5-28µm
[REQ-1-ORD-4405]	Field of View of acquisition camera	10 arcsec, Nyquist sampled at 5µm (0.017 arcsec pixels) This camera is assumed to be needed for accurate positioning of the science object onto the diffraction-limited slit. The images should be of scientific quality (low distortion, good uniformity, etc). This camera can work in K band.
[REQ-1-ORD-4410]	Field of view of science camera	A goal is to incorporate a science camera with the same sampling and field as above, operating in the N band, at least, to be used with narrow band filters. As an additional goal, this camera shall be used as the acquisition camera.
[REQ-1-ORD-4415]	Slit Length	3 arcsec, sampled at 0.04 arcsec/pixel. Slit or IFU
[REQ-1-ORD-4420]	Spectral Resolution	5000≤R≤100,000 (with diffraction-limited slit). R=50-100K is the prime scientific region Single exposures at R=100,000 should give continuous coverage over the orders imaged, 8 - 14µm
[REQ-1-ORD-4425]	High Throughput	High priority
[REQ-1-ORD-4430]	Instrument background	The instrument and AO system should not increase the N band background by more than 15% over natural sky + telescope background (assume 5% emissivity at 273K).
[REQ-1-ORD-4440]	Sampling	17 mas / pixel *Discussion: Maximum detector size is likely to be bounded by 2Kx2K*
[REQ-1-ORD-4445]	Sensitivity	Sensitivity should be limited by photon statistics in the background, and not limited by any systematic errors, in observations up to an 8 hr long integration

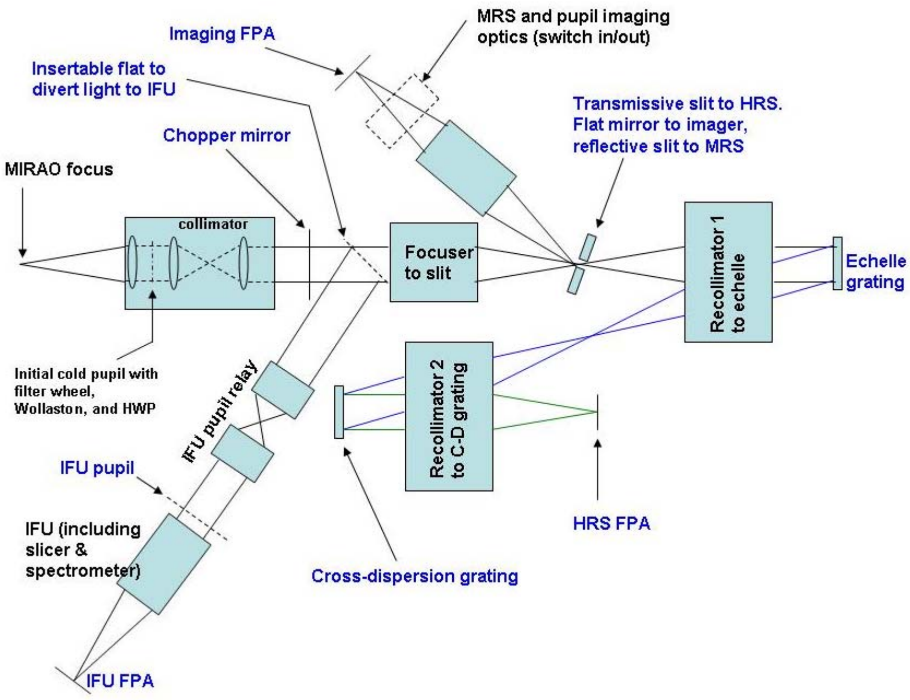
Mid-InfraRed Echelle Spectrometer



Mid-Infrared Camera High-Disperser & IFU spectrograph (MICHI)

- Collaboration between Kanagawa U., Ibaraki U., U. Hawaii and U. Florida
- Diffraction-limited with MIRAO (0''.08@10μm)
- Imaging:
  - 7.3 – 13.8 μm and 16 – 25 μm
  - 28''.1 x 28''.1 FoV
  - R~10 – 100
- IFU:
  - 7 – 14 μm
  - 5'' x 2'' FoV
  - R ~ 250
- Long-slit, moderate/high resolution:
  - 7.3 – 13.8 μm and 16 – 25 μm
  - 28''.1 x (0''.1 - 0''.3)
  - R~810 – 1100 or R~60,000 – 120,000

Packham et al., SPIE 2012, 8447-287)



Infrared Multi-Object Spectrograph (IRMOS)

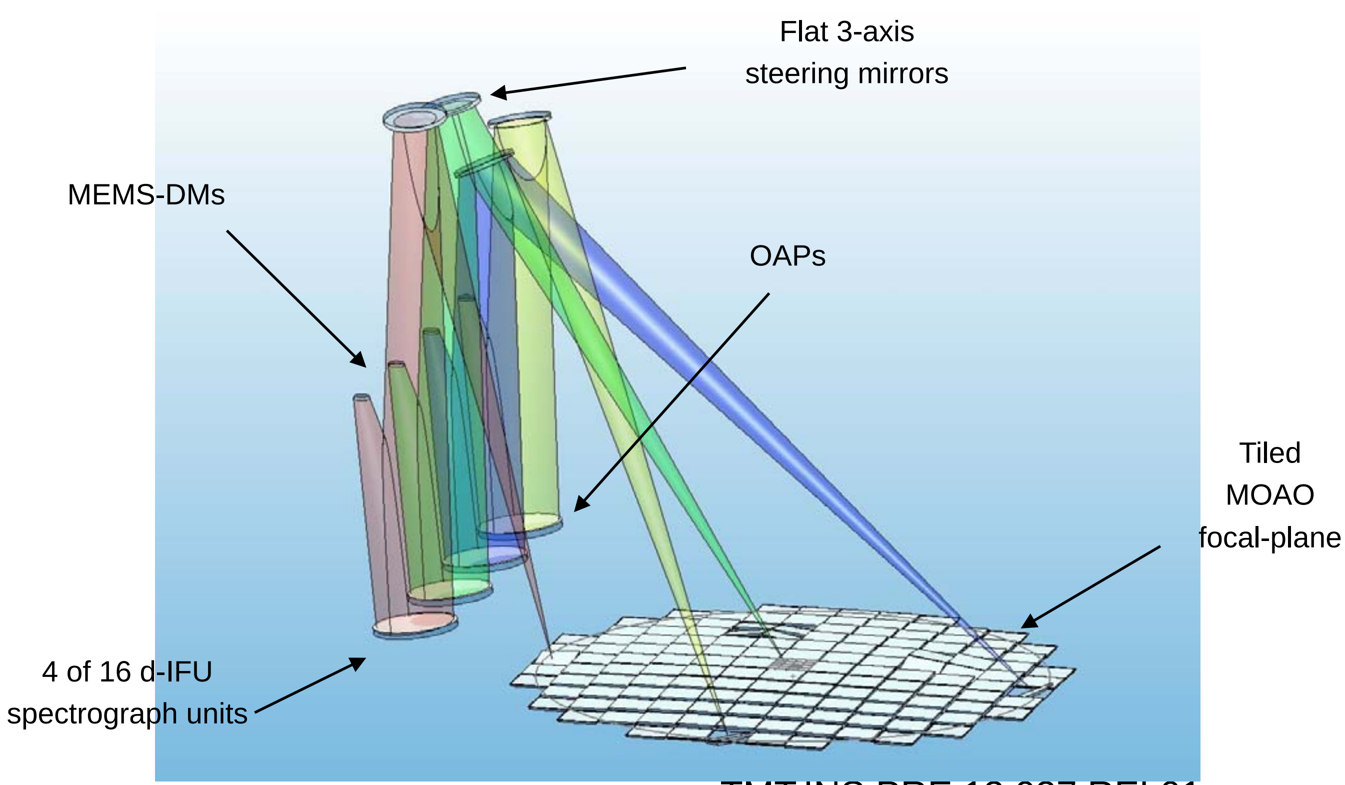
Deployable IFU spectrometer fed by Multiple Object AO

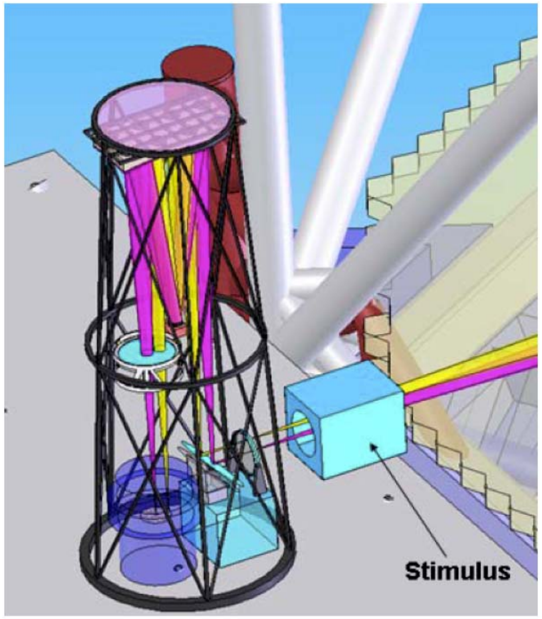
- NIR: 0.8-2.5μm
- FoV: IFU heads deployable over 5 arcmin field
- Image quality: diffraction-limited images, tip-tilt ≤0.015 arcsec rms
- Spatial sampling
  - 0.05x0.05 arcsec pixels, each IFU head 2.0 arcsec FOV, ≥ 10 IFU units
- Spectral resolution
  - R=2000-10000 over entire J, H, K bands, one band at a time
  - R=2-50 for imaging mode

Two IRMOS concepts were competitively studied as part of the TMT instrument feasibility study phase in 2005 - 2006. One concept ("TiPi") originated from Caltech (PI: R. Ellis) , and the other concept ("UF") was proposed by a University of Florida team (PI: S. Eikenberry).

TiPi Pickoff Concept

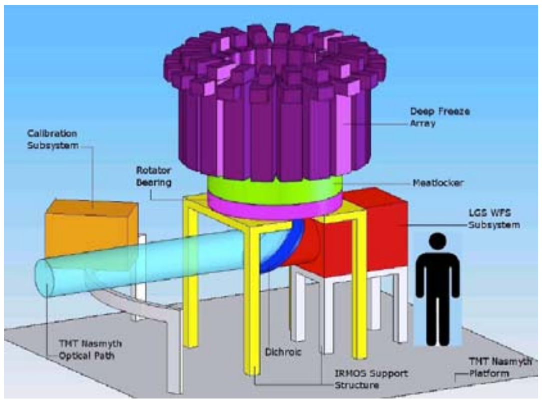
Innovative tiled array of mirrors at a relayed, partially compensated focal plane feeds 16 optical trains (with MEMS DMs) to integral field spectrographs

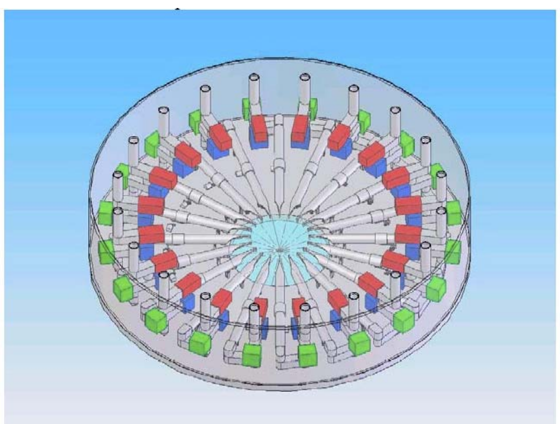


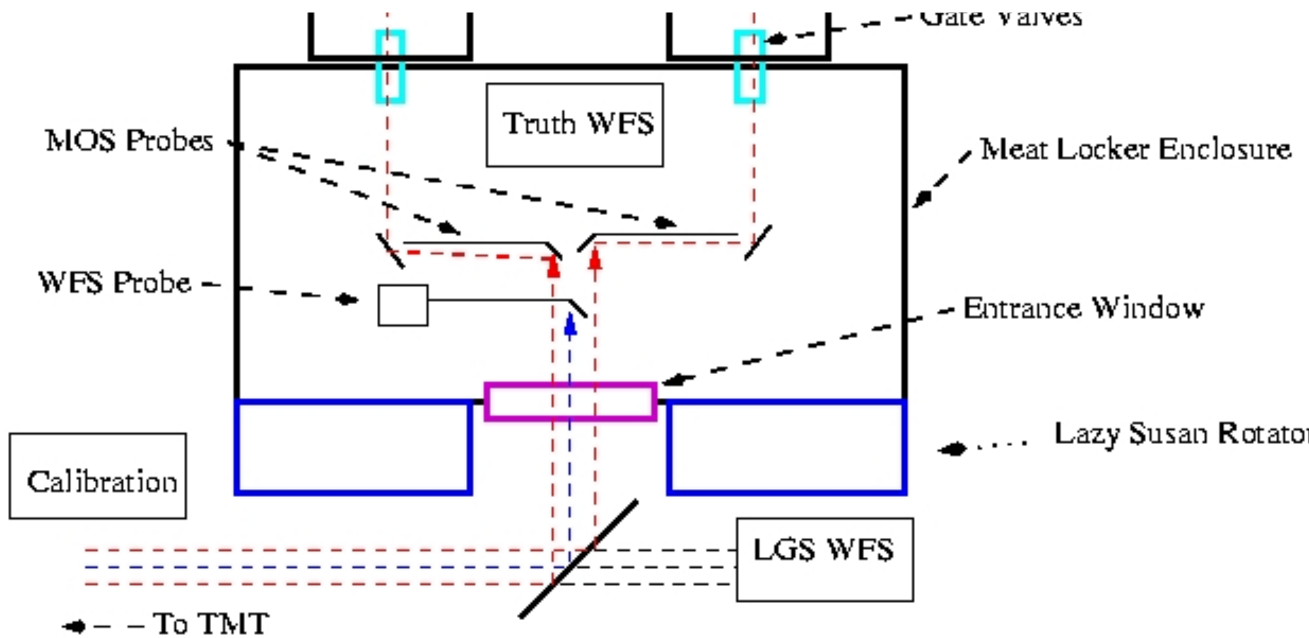


IRMOS-UF
Pickoff Concept

- Individual probes feed individual spectrographs, each probe contains a miniaturized MOAO system

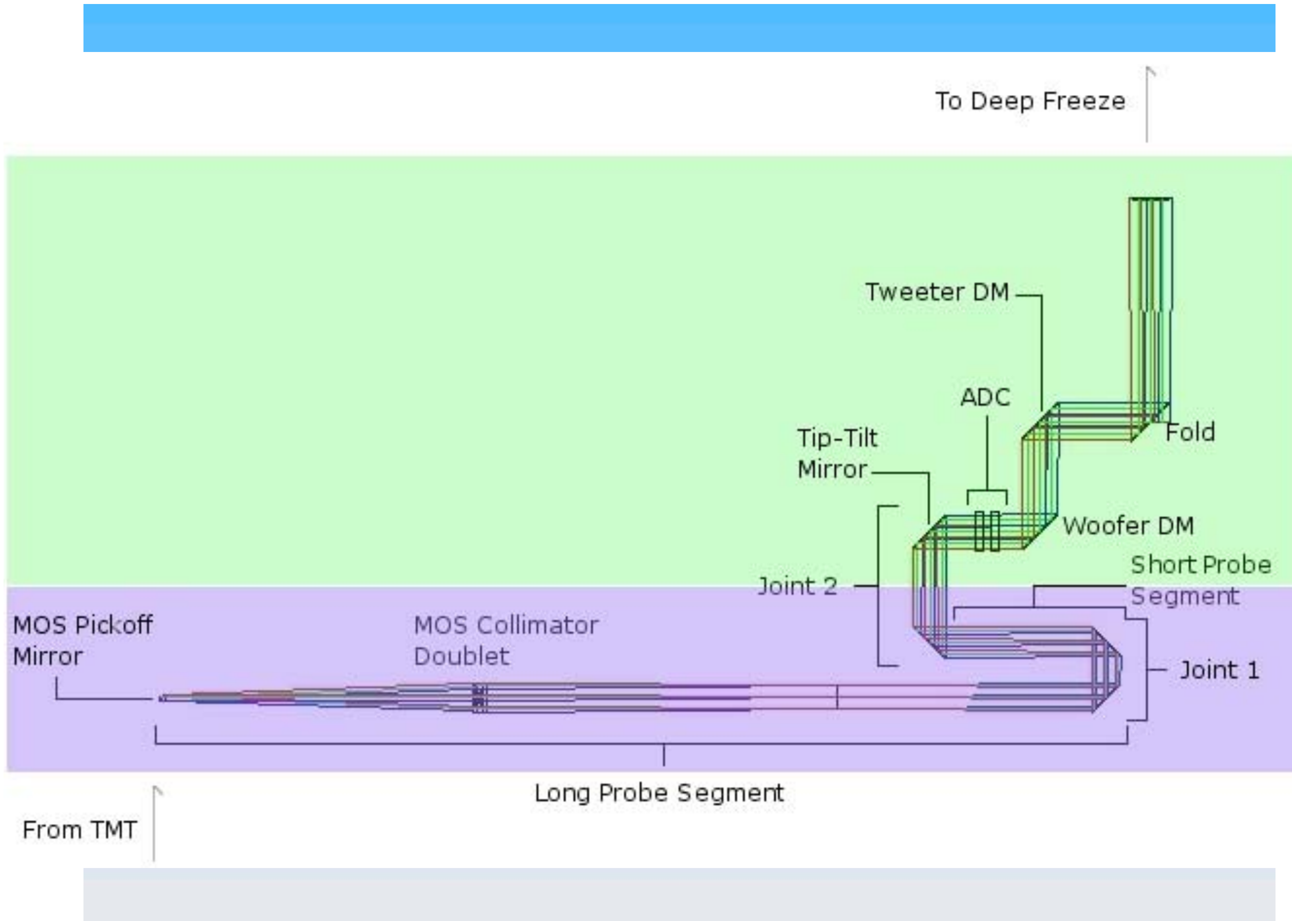






UF/HIA IRMOS: MOS Probes

- 20 probe arms for 5-arcmin field
- "Slice of Pie" patrol strategy
- Each includes:
  - ADCs
  - Tip/tilt mirror
  - Woofer DM
  - Tweeter DM



NIRES-B Top-Level Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4650]	Wavelength Range	1µm- 2.5µm
[REQ-1-ORD-4655]	Image quality	Aberrations uncorrectable by an order 60x60 AO system should not add wavefront errors larger than 30 nm RMS
[REQ-1-ORD-4660]	Length of slit	Up to 2 arcsec, and/or IFU
[REQ-1-ORD-4665]	Field of View of acquisition camera	10 arcsec, Nyquist sampled at 0.004 arcsec
[REQ-1-ORD-4670]	Spatial Sampling	Nyquist sampled (λ/2D) (0.004 arcsec)
[REQ-1-ORD-4675]	Spectral Resolution	$20000 \leq R \leq 100{,}000$
[REQ-1-ORD-4680]	High Throughput	High priority
[REQ-1-ORD-4685]	Stability	Stability sufficient to enable, e.g., Doppler searches for planets
[REQ-1-ORD-4690]	Instrument background	The instrument shall not increase the background by more than 5% (TBC) over the sum of: inter-OH sky, telescope and NFIRAOS background.
[REQ-1-ORD-4695]	Detector	Detector dark current and read noise should not increase the effective background by more than 5% for an integration time of 2000 s.

NIRES
The weather on brown dwarfs

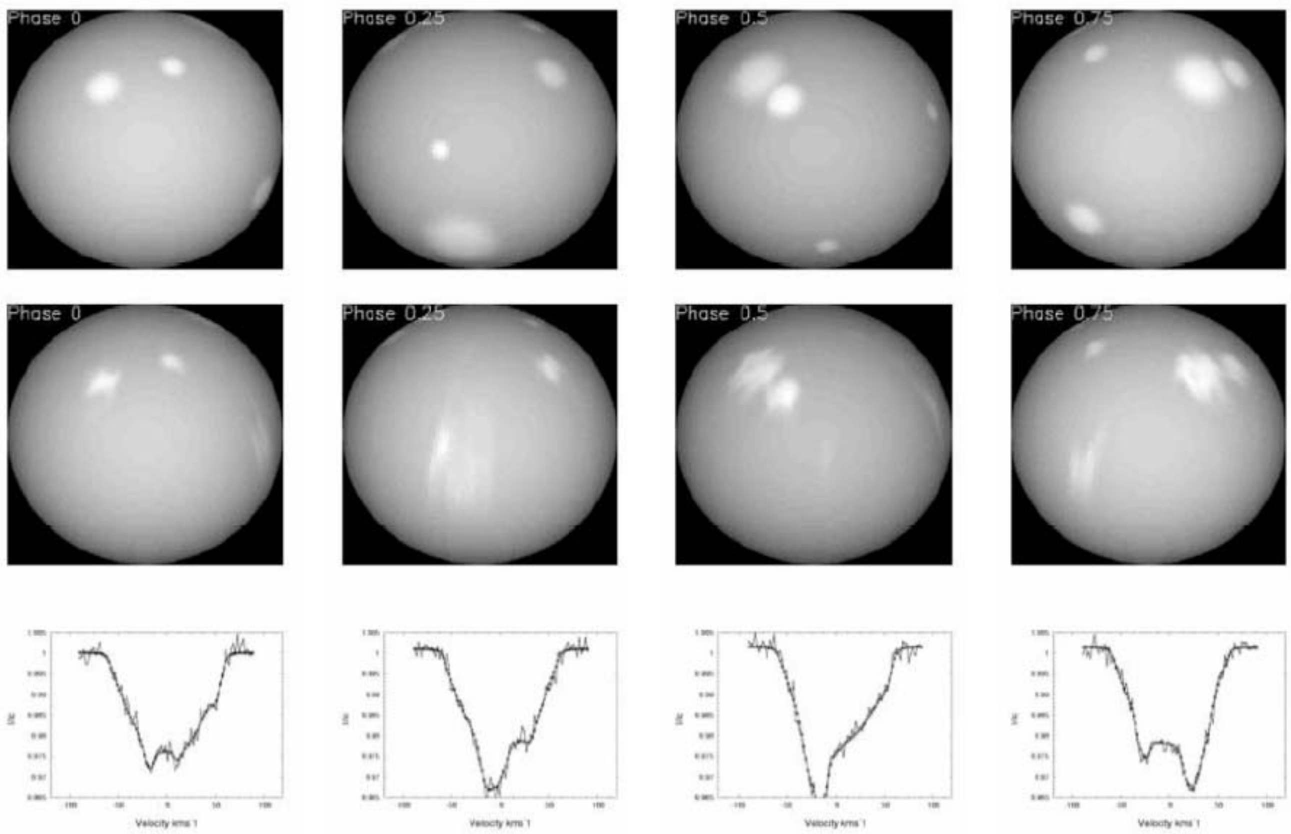
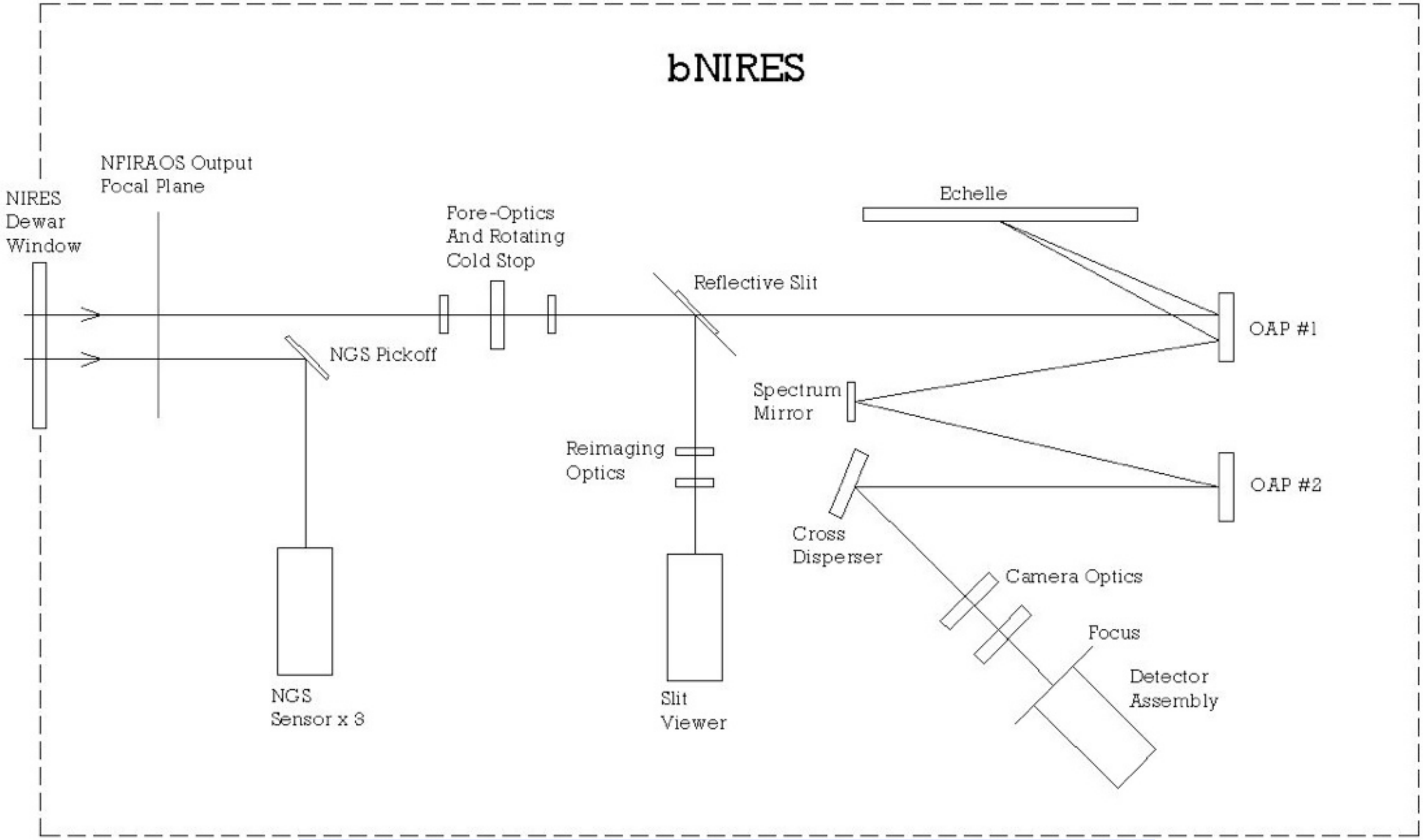


Figure 3.16: Upper row: **Simulated H-band images of weather patterns in an L dwarf with a dusty atmosphere having T_{eff} = 1,900K, and clear patches with T_{eff} = 2,100K. Models supplied by P. Hauschild (priv. comm.) show that average absorption-line strengths of all species are enhanced by a factor ~4 in the clear patches, which cover 3.5% of the stellar surface and yield a 0.015-mag photometric modulation at H.** Lower row: **The resulting rotationally broadened profiles generated with the St Andrews Doppler tomography code have *v* sin *i* = 60 km s^{-1} and S/N = 1,000. They show clearly that the rotation profiles are strongly distorted by the clear patches in the cloud deck, but the equivalent width remains roughly constant.** Middle row: **The image reconstructed from the synthetic data recovers the locations and sizes of the clear patches reliably in the hemisphere facing the observer.**

Source: 2006 NIRES Feasibility Study Report, TMT.INS.CDD. 06.015

NIRES-B Schematic Layout



Source: 2006 NIRES Feasibility Study Report, TMT.INS.CDD.06.015

Wide-field Infrared Camera (WIRC)

Requirement Number	Description	Requirement
[REQ-1-ORD-4835]	Wavelength Range	0.8 – 2.5 µm, goal 0.6-5µm
[REQ-1-ORD-4840]	Image Quality	Aberrations uncorrectable by an order 60x60 AO system should not add wavefront errors larger than 30 nm RMS
[REQ-1-ORD-4845]	Field of View	30 arcsec diameter (contiguous, imaged all at once)
[REQ-1-ORD-4850]	Spatial Sampling	Nyquist sampled (λ/2D) (0.004 arcsec)
[REQ-1-ORD-4855]	Spectral Resolution	R= 5-100 (narrow and broad band filters)
[REQ-1-ORD-4860]	Throughput	High; must preserve telescope aperture advantage compared to similar instruments on smaller telescopes
[REQ-1-ORD-4865]	Astrometry	Over the 30arcsec field of view, WIRC shall deliver precise astrometric measurements with at most a 10% degradation of the acheivable performance on NFIRAOS feeding an idealized perfect instrument.
[REQ-1-ORD-4870]	Stability, Flexure	Must allow mosaicing of multiple fields together with no significant loss of image quality or precision.
[REQ-1-ORD-4875]	Background	The instrument and AO system of this configuration shall not increase the inter-OH optical background by more than 15% over sky and telescope background.

Some WIRC science could be done with IRIS

Selection of First-Light Instruments

- Our early-light instruments were selected at the December 2006 SAC meeting in Vancouver
- This downselect was very successful because
  - It was primarily science-driven, but it also paid attention to technical readiness, cost and schedule
  - Extensive information from the instrument feasibility studies
  - SAC did a lot of "groundwork" ahead of the December meeting
- Balance between fundamental observing modes: seeing-limited vs AO, visible versus infrared, and imagers vs spectrometers
- Workhorse capabilities and synergy

We need to use this "success of our past" as a template for the future - And all TMT partners will make it even stronger!

Selection of First-Light Instruments

- Our early-light instruments were selected at the December 2006 SAC meeting in Vancouver

- This downselect was very successful because

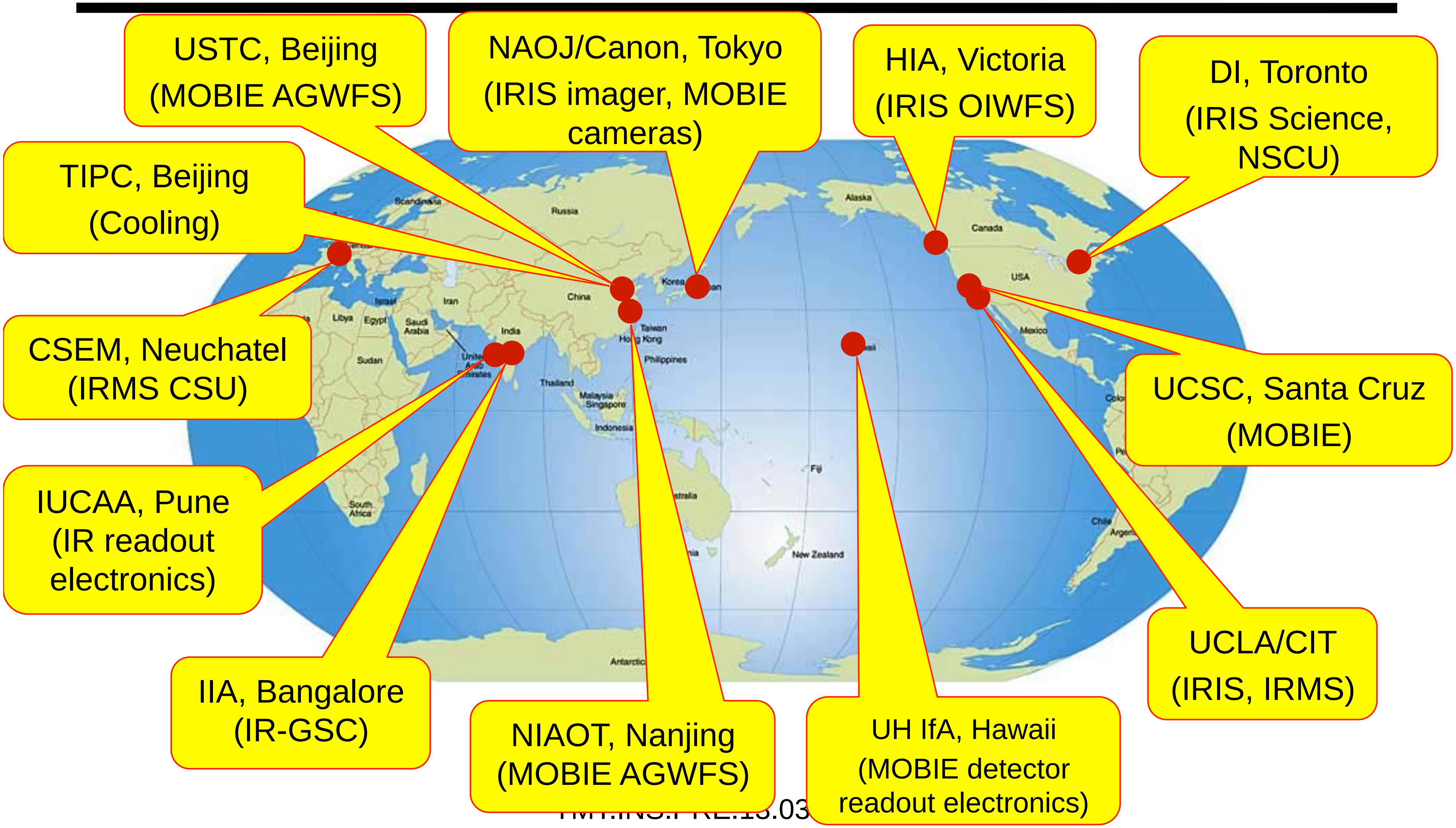
  cal

Selection reaffirmed by TMT SAC following partner-wide instrument workshop in 2011

- Balance between fundamental observing modes: seeing-limited vs AO, visible versus infrared, and imagers vs spectrometers

- Workhorse capabilities and synergy

TMT Global Participants – Science Instruments



Future Instrumentation Development

- Community explorations (e.g., workshops, testbeds, studies)
- Extensive SAC discussions of instrumentation options and requirements
- SAC prioritizes AO systems and science instruments and makes recommendations to TMT Board – This is the cornerstone of our program!
- Board establishes guidelines (including scope and cost targets) for studies and TMT issues a call for proposals
- Two ~one-year competitive conceptual designs for each instrument
- SAC makes recommendations based on outcome of studies (scientific capability, priorities, options, etc.)
- Project (and Board) will negotiate cost and scope of instrumentation awards, considering partnership issues
- TMT will provide oversight, monitoring and involvement in all instruments:
  - To ensure compatibility with overall system
  - To maximize operational efficiency, reliability and minimize cost
  - To encourage common components and strategies
  - To ensure that budget and schedules are respected

Community Explorations

- Where new instrumentation ideas for TMT are born!
  - Would ideally be a "constant stream"
- Meant to inform the prioritization of desired instrumentation capabilities by SAC
  - Science, technical readiness and risks, rough cost and schedule

  ➔ Draft initial science requirements and their rationale
- Coordinated through SAC and Observatory
- Consultations:
  - Workshops
  - White papers
  - Open to unsolicited proposals

Community Explorations (cont.)

- "Mini-studies"
  - ≤1 year duration, ~$100k
  - Joint decisions between SAC and Observatory on which studies to fund
  - TMT would also support teams requesting external funding from their agencies, e.g., letters
- Types of mini-studies:
  - Study of science potential of a new instrument capability
  - Technology testbeds such as new coronographs, wavefront sensors, control algorithms, etc. etc.
  - Full instrument feasibility studies

SAC Instrumentation Prioritization

- Cornerstone of the instrumentation development program
- Clearly science-driven but must also factor in all available information on technical readiness, schedule, cost and overall mix of commissioned and planned instrumentation
  - This was a key ingredient in the selection of our early-light instruments in 2006 - it must be preserved
- Balance between AO systems and science instruments:
  - Comprehensive metrics required for science and technical assessment
  - New capabilities versus upgrades to existing systems

Competitive Conceptual Design Studies

- Competitive: Often produce different designs in response to same top-level requirements (e.g., IRMOS, HROS)
  - More thorough exploration of system design trade-offs
- Scope and funding established by the TMT Board
  - ~1.5-2 year duration, ~$1-2M range
- Initiated through a formal Call for Proposals:
  - Every ~3 years
  - Ideally two instrument concepts to be studied per cycle
  - Two studies per instrument concept
- Studies to be reviewed by external, expert review panels
- Recommendations made to the Board from SAC and Observatory Directorate

Building Instrument Partnerships

- Each TMT instrument will be built by a multi-institution consortium
- Strong interest from all partners in participating in instrument projects:
  - Primarily driven by science interests of their respective science communities
  - Large geographical distances and different development models
  - Broad range of facilities and capabilities
- Significant efforts are already under way to fully realize the exciting potential found within the TMT partnership
- Goal is to build instrument partnerships that make sense scientifically and technically while satisfying partner aspirations

THIRTY METER TELESCOPE

Visitor Instruments

- A TMT instrument represents a very sizable investment of money and time
- If a consortium is able to muster resources for such an effort outside the TMT development process and then offers it for use at TMT, should TMT accept this visitor instrument?
- SAC supports visitor instruments at TMT under the following conditions:
  - Must be approved by SAC. Early dialog between the instrument team, SAC and the Observatory is therefore important to avoid creating false expectations
  - Instrument be fully compatible with TMT
  - Visitor instruments will be considered only once TMT is operationally stable
  - The Observatory deems support costs to be acceptable
  - Instrument should be available to all TMT partners

Post-Delivery Instrumentation Support

- Intent is to keep original instrument teams involved in the post delivery instrument support (maintenance and upgrade)
  - TMT does not plan to keep large, in-house teams for this
  - Builders remain the best source of expertise
  - Keeps good teams engaged in long-term health and performance of the instruments
- Depends on having stable instrument teams
  - Not a concern given that teams had to be stable to mount large instrumentation efforts in the first place
- Upgrades will take place as part of "servicing missions":
  - Contingent of expert staff to be sent to Observatory
  - To work in "burst mode"
  - This model is in use at Keck

Instrumentation Development Office (IDO)

- Joint AO and science instrumentation engineering team that provides oversight for all instrumentation activities (except routine support):
  - Initially primarily occupied with early-light instruments (WFOS, IRIS, IRMS, NFIRAOS) and associated AO systems with increasing shift of effort towards support for future instruments and AO systems
  - Example: AO group develops AO requirements, leads performance analysis and coordinates/manages all subsystem and component development
  - Will play a central role within our diverse partnership
- Core staff of 4 FTEs in current operations plan - additional staff to be added as needed by number of on-going projects
- Baseline instrumentation development budget of ~$12M/year

Development Funding

- Rationale
  - Only funds for early-light AO systems and science instruments are included in the TMT construction budget
  - TMT science community has clearly stated that new capabilities are needed as soon as possible after Early Light
  - Must be able to provide complex, ambitious instruments
- Justification of funding levels based on
  - Phasing scenarios based on current TMT instrument concepts (discussed later)
  - Escalation of costs from one instrument generation to the next on Keck, Gemini and especially VLT (to be done)
- Funding profile must also modulate arrival rate of instruments at Observatory to ensure a realistic commissioning plan

Possible Sources of Funding

- Base funding
  - TMT partners will contribute a total of $12M / year to a base instrumentation development fund
  - To be kept separate from observatory operations budget
  - Depending on procurement model, it may only be sufficient to fund smaller instruments and/or seeding concept studies
- Proposed supplemental funding
  - Base funding will need to be supplemented
  - Total required appears to be $6M-$20M / year depending on procurement model and phasing scenario
  - Commitments to this funding could be adjusted and renewed on a regular basis (~5 years say)

Possible Sources of Funding (Cont.)

- External funding opportunities
  - Truly large projects will likely come from specific initiatives at the level of the partners' funding agencies
  - The TMT instrumentation development program should encourage and support such applications
    - But they must still be vetted by SAC and Board
  - However, overall TMT program should not be made to rely heavily on such funding:
    - Hard to maintain funding continuity
    - Difficult to incorporate SAC involvement in establishing priorities, true competition among teams and adequate TMT oversight - One solution here is to use work package agreements to convert value to observing share

Instrument
Phasing Scenarios

- Meant to illustrate the funding profiles required to bring into operations an instrumentation suite as capable as the proposed TMT Instruments
  - Two important variables are the sequence of instruments and the times at which they are delivered to TMT
- Best source of available cost and duration information remains the 2006 instrument feasibility studies
- Costs of development phases (CDP/PDP/FDP) are included
- Nine phasing scenarios were studied looking at science priorities, total costs, total funding required prior to first light, and annual funding after first light
- A SAC preferred scenario was adopted in March 2011

March 2011 SAC Preferred Instrument Phasing Scenario

- Eight instrument capabilities (not "set in stone"):
  1. High-Resolution Optical Spectroscopy (HROS-UC-2)
  2. High-Resolution, Near-IR Spectroscopy (NIRES-B)
  3. Multi-IFU, Near-IR Spectroscopy (IRMOS-N + AO upgrades)
  4. Adaptive Secondary Mirror (AM2)
  5. Mid-Infrared, High-Resolution Spectroscopy (MIRES)
  6. High-contrast imaging (PFI)
  7. Multi-IFU, Near-Optical Spectroscopy (VMOS + AO upgrades)
  8. High-Resolution, 5-18µm Spectroscopy (NIRES-R)
- One new capability every 2.5 years on average
- Starts in 2016 and ends in 2038
- Total cost of $405M at a rate of $21M/yr after first light

SAC Preferred Instrument Phasing Scenario

Instrument	2012	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
HROS-UC-2					[green]							[blue]															
NIRES-B							[green]							[blue]													
IRMOS-N					[green]										[blue]												
IRMOS AO										[green]					[blue]												
AM2										[green]								[blue]									
MIRAO/ MIRES												[green]									[blue]						
PFI															[green]							[blue]					
VMOS														[green]										[blue]			
NFIRAOS+																		[green]						[blue]			
LGSF+																		[green]						[blue]			
NIRES-R																				[green]							[blue]

TMT Instrumentation and Performance Handbook

- 160 pages covering planned instrumentation suite (requirements and designs), instrument synergies, and instrument development
- Updated information on first-light instruments
- All 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

Summary

- TMT has a powerful suite of planned science instruments and AO systems that will make the Observatory a world-class, next-generation facility

- Work on first-light instruments is progressing well

- Many elements of the instrumentation development program are being defined and discussed including the SAC prioritization process and the instrument phasing scenarios

- TMT instruments will offer a wide range of opportunities to all TMT partners!

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