TMT Instrumentation: First-Light and Beyond

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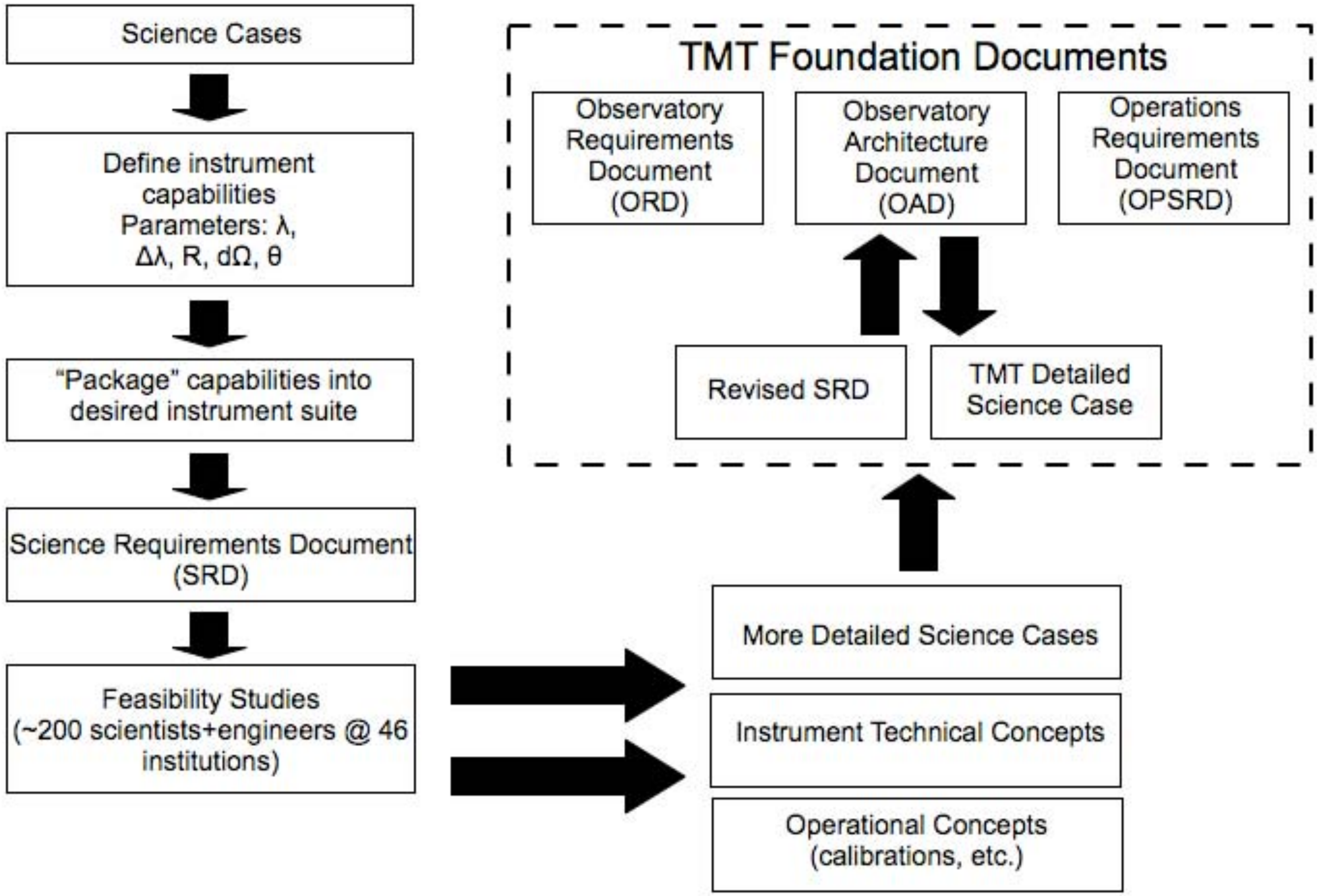
"Shaping E-ELT Science and Instrumentation" Workshop

ESO, February 25-28, 2013

Outline

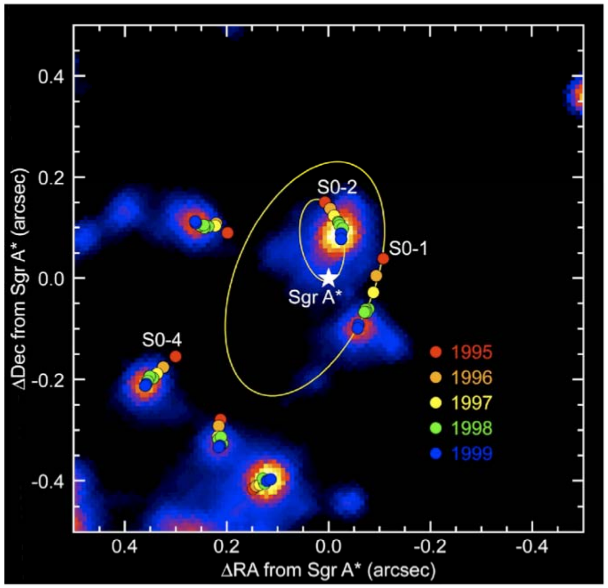
- Science Flowdown
  - Science objectives ➔ Observations ➔ Requirements
  - From science to subsystems
- First-light AO and Science Instruments:
  - Narrow-Field IR AO System (NFIRAOS)
  - InfraRed Imaging Spectrometer (IRIS)
  - Multi-Object Broadband Imaging Echellette (MOBIE)
  - InfraRed Multi-slit Spectrometer (IRMS)
- Plans beyond First-light

TMT Science Flowdown



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:
  - Wide-field spectroscopy (SL/WFOS)
  - Transient events lasting > 30 days
  - High-res observations of quasars/AGNs
  - Proper motions in dwarf galaxies and microarcsec astrometry (MCAO/IRIS/WIRC)



- 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)

Summary of TMT Science Objectives and Capabilities

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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

Science Flowdown Matrix - A small subsection

Science Program	Spatial Parameters									
	Image Quality			Geometry				Astrometry		
	Resolution (mas)	Strehl (S) / Contrast (C) ratio	SRD/ORD Requirement(s)	Total Areal Coverage (sq. arcmin)	Field of view / observation (sq. arcmin)	Field overlap (0-1)	SRD/ORD Requirement(s)	Relative/ absolute	Precision (mas)	Stability timescale (years)
Multiplexed spectroscopy of distant galaxies: rest-frame optical DSC 5.4	200		SRD-0070, 0075, 0100, 0105, 0110, 0115, 0120, 0145, [0405-0420], [0455-0470], [0565-0580], 1115	> 350	3.5	0.00	SRD-[0220-0230], 0250, 0260, 0265, 0805, 0815, 1105, 1120, 1140, 1305, 1315, 1320, 1330			
Spatial dissection of forming galaxies DSC 5.5	8	S = 0.5 [7]	SRD-0045, 0070, 0075, 0100, 0105, 0110, 0115, 0120, 0145, [0405-0420], [0455-0470], [0565-0580], [0820-0830], 0915, 1015, 1025, 1030, 1035, 1310	275 [10]	25 [10]	0.00 [10]	SRD-[0220-0230], 0250, 0260, 0265, 0270, 0280, 0805, 0850, 0885, 0890, 0905, 0910, 0920, 1005, 1010, 1030, 1035, 1305, 1315, 1320, 1330	Relative [10]	100 [10]	
IGM: Core samples during galaxy formation epoch DSC 5.6	800 [17]		SRD-0070, 0110, 0120, 0145, [0455-0470], [0565-0580], 1220, 1225, 1230, 1275, 1715, 1720	4 x 4032	40.3 [17]	0.01	SRD-0050, 0220, 0225, 1205, 1230, 1705, 1710, 1720			
Epoch of galaxy formation in 3D DSC 5.7	800 [17]		SRD-0070, 0110, 0120, 0145, [0455-0470], [0565-0580], 1220, 1225, 1230, 1275	4 x 4032	40.3 [17]	0.01	SRD-0050, 0220, 0225, 0250, 0255, 0265, 1205, 1230			
SMBHs in nearby galactic nuclei DSC 6.1	10 [7]	S = 0.5 [7]	SRD-0045,0070, 0075, 0100, 0105, 0110, 0115, 0120, 0145, [0405-0420], [0455-0470], [0565-0580], [0820-0830], 1015, 1025, 1030, 1035	< 10.2 [7]	< 0.03 [8]	0.00	SRD-[0220-0230], 0250, 0260, 0265, 0805, 0885, 0890, 1005, 1010, 1030, 1035	Relative [22]	2 [22]	

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IGM: Core samples during galax DSC 5.6										
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SMBHs in nearby galactic nuclei DSC 6.1	10 [7]	S = 0.5 [7]	0105, 0110, 0115, 0120, 0145, [0405-0420], [0455-0470], [0565-0580], [0820-0830], 1015, 1025, 1030, 1035	< 10.2 [7]	< 0.03 [8]	0.00	SRD-[0220-0230], 0250, 0260, 0265, 0805, 0885, 0890, 1005, 1010, 1030, 1035	Relative [22]	2 [22]	

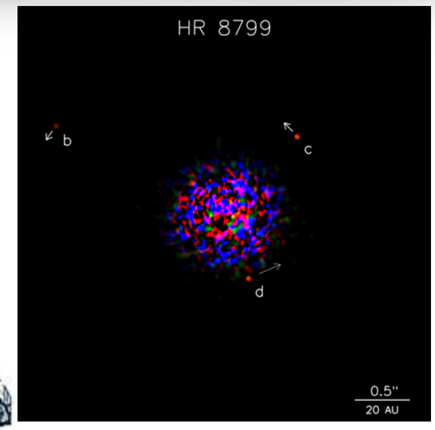
The TMT Science Flowdown is not static – It is updated to reflect changes to existing science programs and to include new ones (e.g., time-resolved science)

The coming year will see a major, partnership-wide effort to update our science cases and flowdown through workshops with our international partners and the new NSF involvement

From Science to Subsystems

<u>Direct imaging of exoplanets</u>

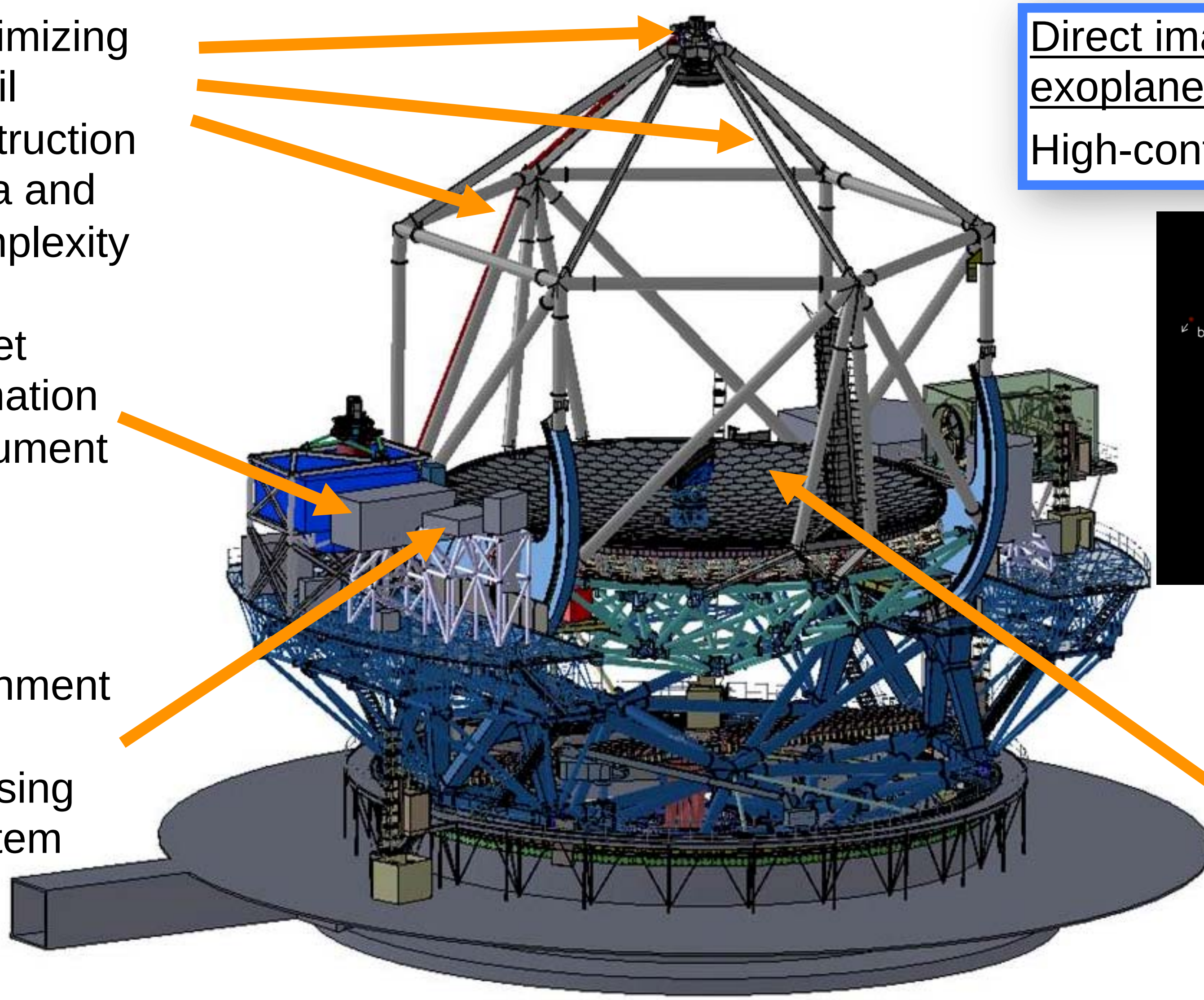
High-contrast imaging



Minimizing pupil obstruction area and complexity

Planet Formation Instrument

Alignment and Phasing System



Filled aperture + segment surface errors, coating, and cleaning

TMT Planned Instrument Suite

Instrument	Field of view / slit length	Spectral resolution	λ (μm)	Comments
InfraRed Imager and Spectrometer (IRIS)	< 4.″4 x 2”.25 (IFU) 16”.4 x 16”.4” (imaging)	4000-8000 5-100 (imaging)	0.8 – 2.4	MCAO with NFIRAOS
Wide-field Optical spectrometer (WFOS)	40.3′ squared (FoV) 576” (Total slit length)	1000-8000	0.31-1.1	Seeing-Limited (SL)
InfraRed Multislit Spectrometer (IRMS)	2′ field w/ 46 deployable slits	*R* = 4660 @ 0.16″ slit	0.95-2.45	MCAO with NFIRAOS
Multi-IFU imaging spectrometer (IRMOS)	3″ IFUs over >5’ diameter field	2000-10000	0.8-2.5	MOAO
Mid-IR AO-fed Echelle Spectrometer (MIRES)	3″ slit length 10″ imaging	5000-100000	8-18 4.5-28(goal)	MIRAO
Planet Formation Instrument (PFI)	1″ outer working angle, 0.05″ inner working angle	R≤100	1-2.5 1-5 (goal)	10^8 contrast 10^9 goal
Near-IR AO-fed Echelle Spectrometer (NIRES)	2″ slit length	20000-100000	1-5	MCAO with NFIRAOS
High-Resolution Optical Spectrometer (HROS)	5″ slit length	50000	0.31-1.0 0.31-1.3(goal)	SL
“Wide”-field AO imager (WIRC)	30″ imaging field	5-100	0.8-5.0 0.6-5.0(goal)	MCAO with NFIRAOS

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TMT Planned Instrument Suite

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"Wide"-field AO imager (WIRC)	30″ imaging field	5-100	0.8-5.0 0.6-5.0(goal)	MCAO with NFIRAOS

Visible, Seeing-Limited

TMT Planned Instrument Suite

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Near-IR, AO-assisted

TMT Planned Instrument Suite

High-Contrast AO

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InfraRed Imager and Spectrometer (IRIS)	< 4.″4 x 2″.25 (IFU) 16″.4 x 16″.4″ (imaging)	4000-8000 5-100 (imaging)	0.8 – 2.4	MCAO with NFIRAOS
Wide-field Optical spectrometer (WFOS)	40.3′ squared (FoV) 576″ (Total slit length)	1000-8000	0.31-1.1	Seeing-Limited (SL)
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Mid-IR, AO-assisted

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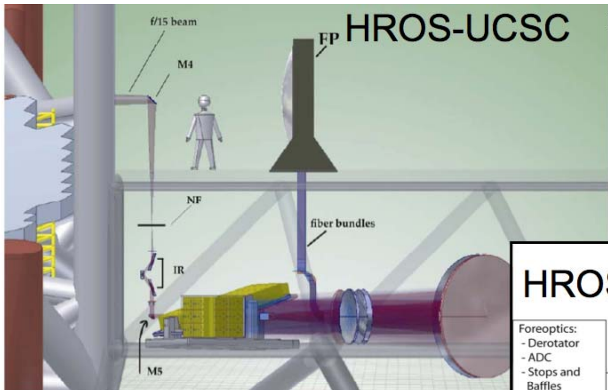
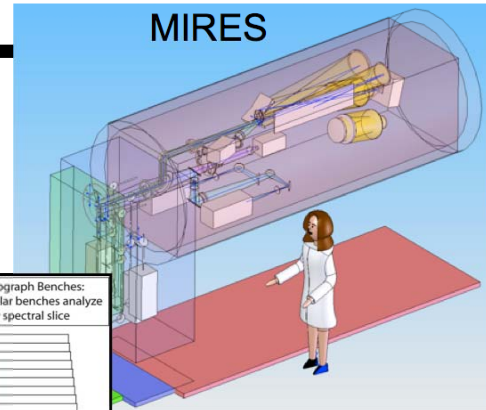
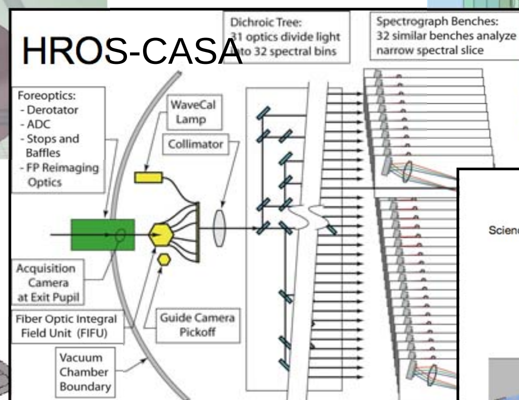
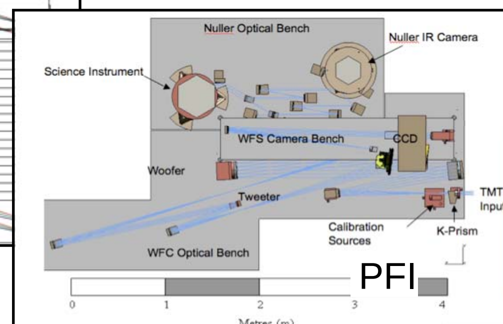
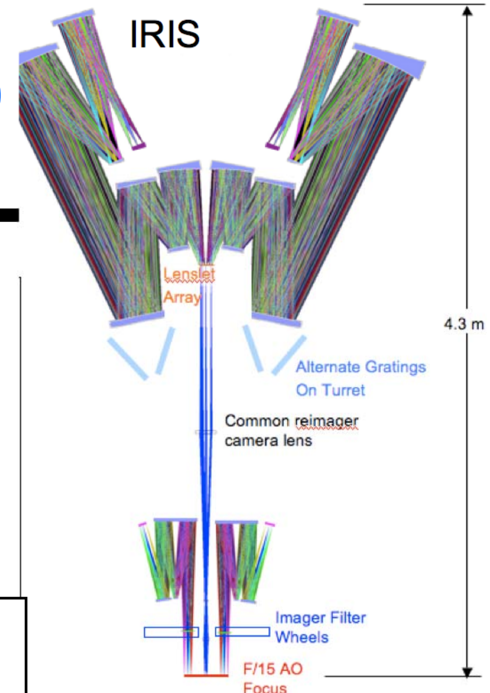
Feasibility studies 2005-6 (concepts, requirements, performance,…)

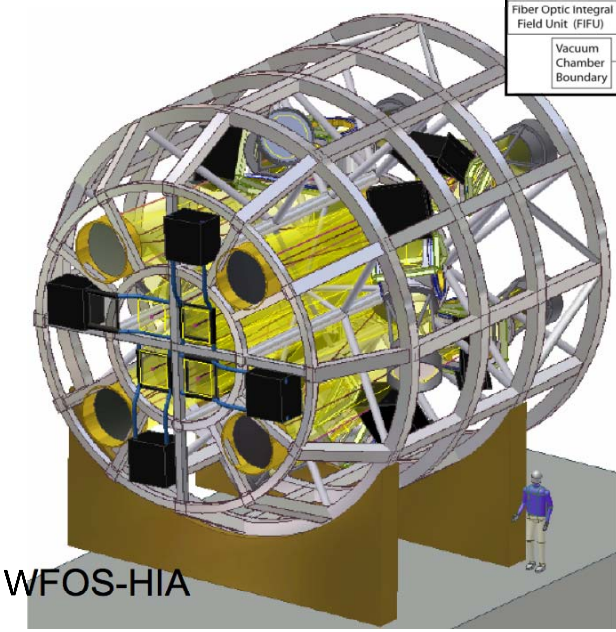


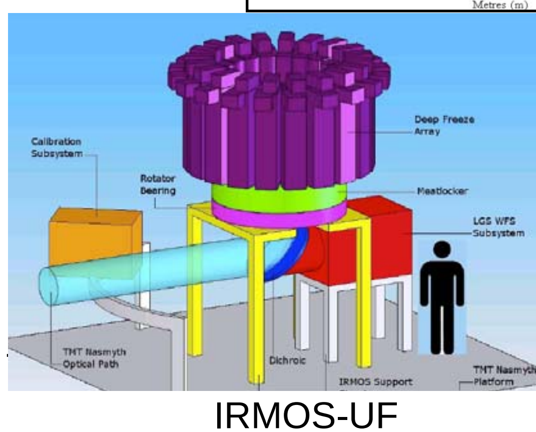


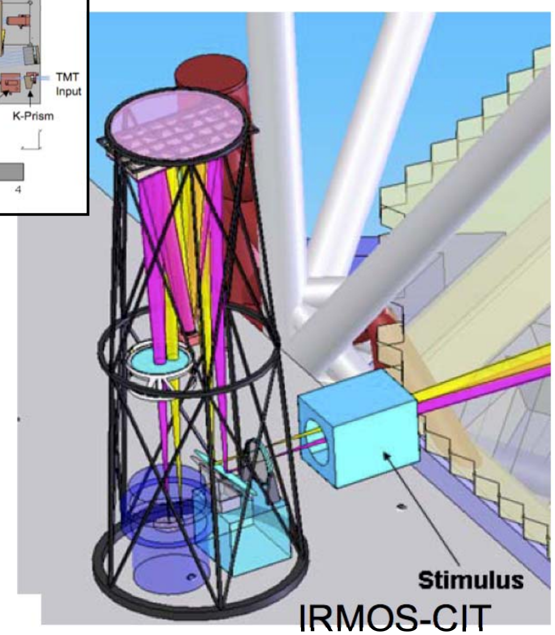












Feasibility studies 2005-6
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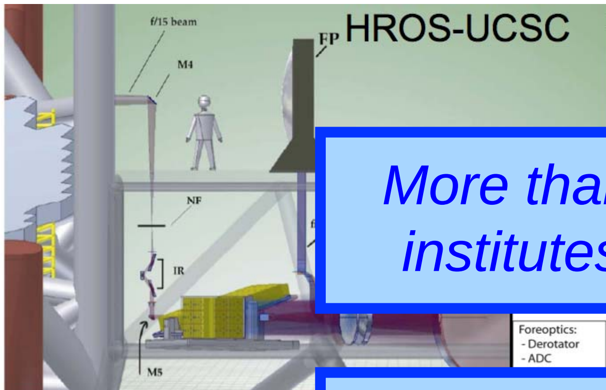
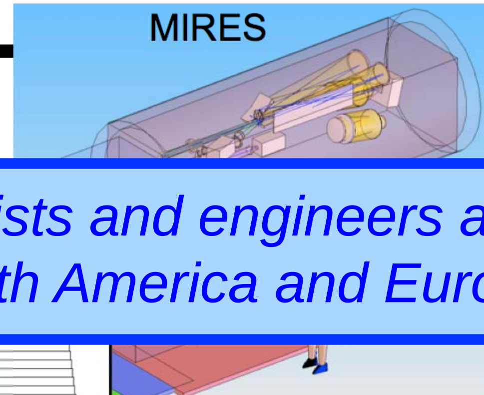
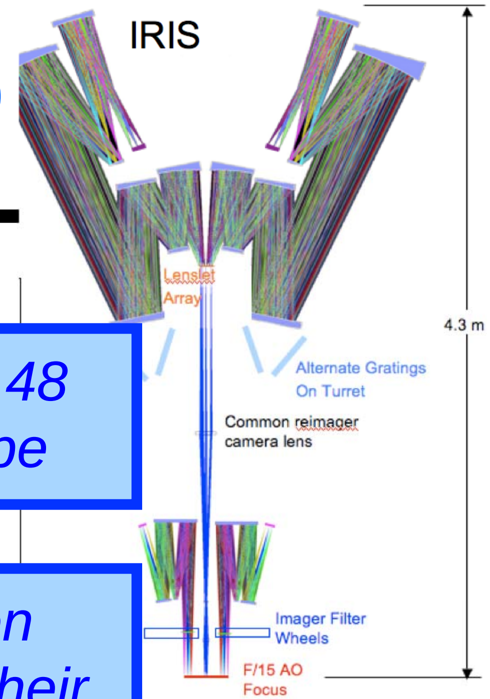
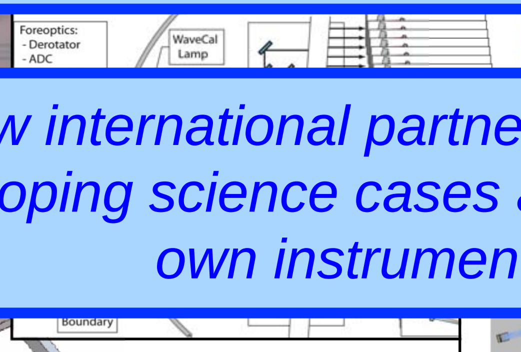




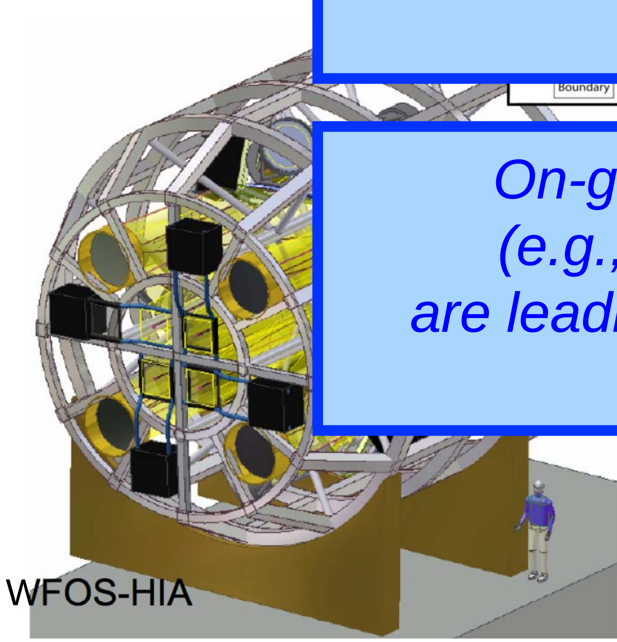


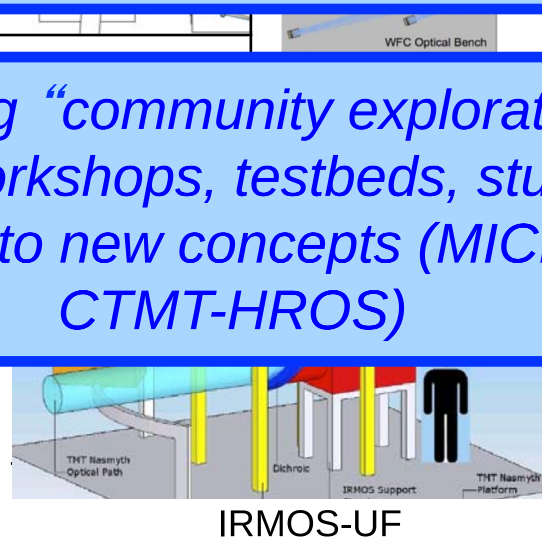
More than 200 scientists and engineers at 48 institutes across North America and Europe

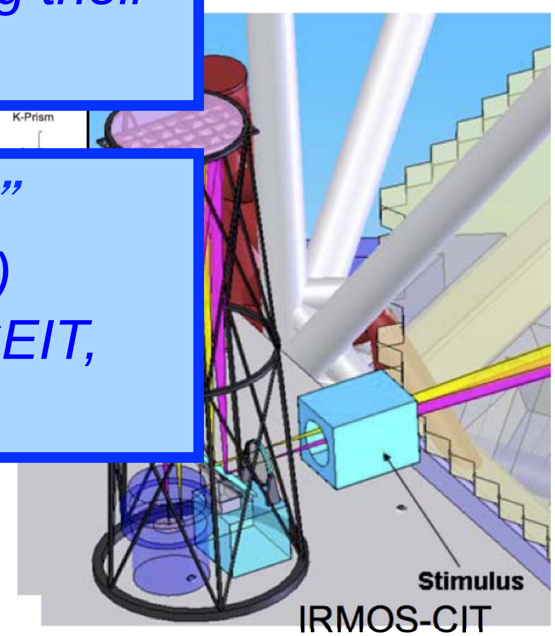


New international partners have also been developing science cases and conducting their own instrument studies

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







TMT First-Light Instrument Suite

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“Wide”-field AO imager (WIRC)	30″ imaging field	5-100	0.8-5.0 0.6-5.0(goal)	MCAO with NFIRAOS

Selection of First-Light Instruments in 2006

- Our first-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

Selection of First-Light Instruments in 2006

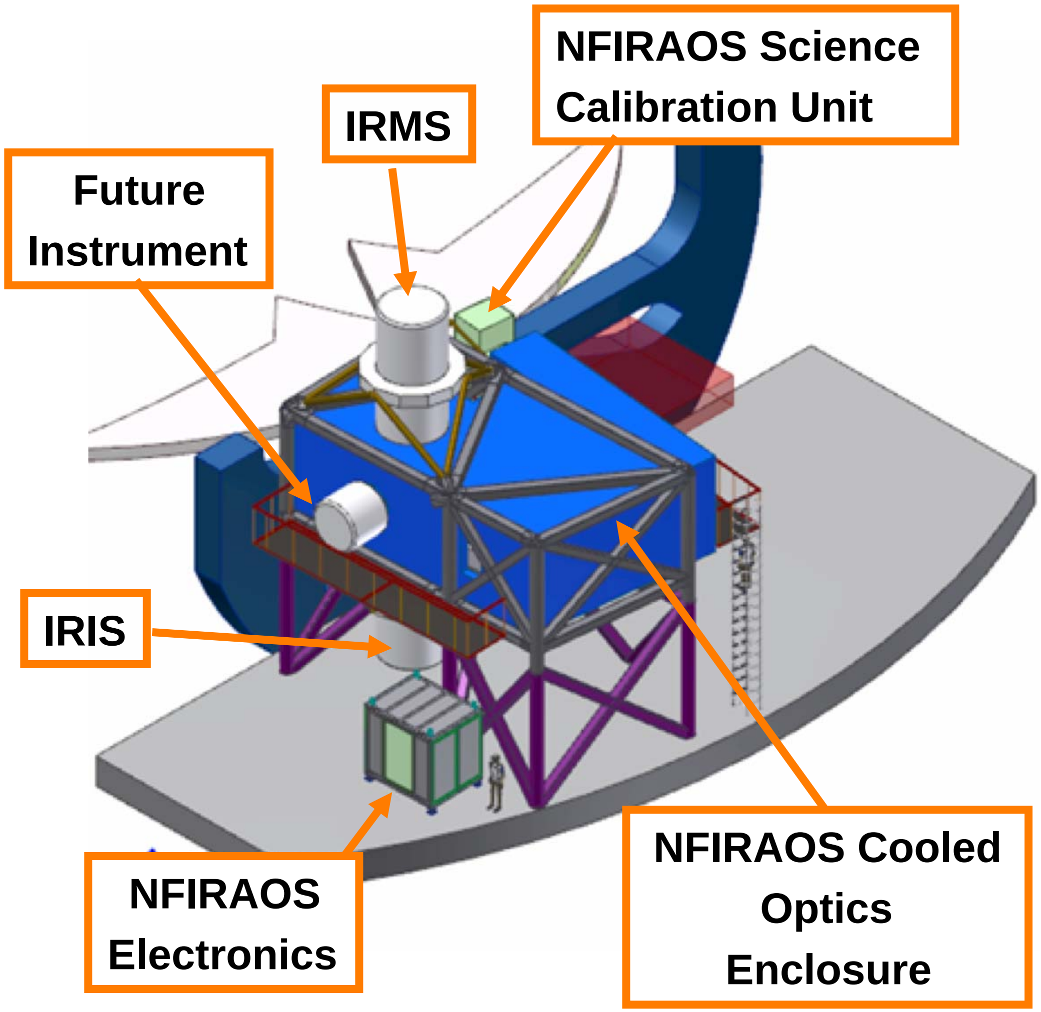
- Our first-light instruments were selected at the December 2006 SAC meeting in Vancouver
- This downselect was very successful because
  - It was primarily science-driven, **but** it also paid attention to

Selection reaffirmed by TMT SAC following a partner-wide science and instrumentation workshop in 2011

- E
  seeing-limited vs AO, visible versus infrared, and imagers vs spectrometers
- Workhorse capabilities and synergy

NFIRAOS: First-Light MCAO System

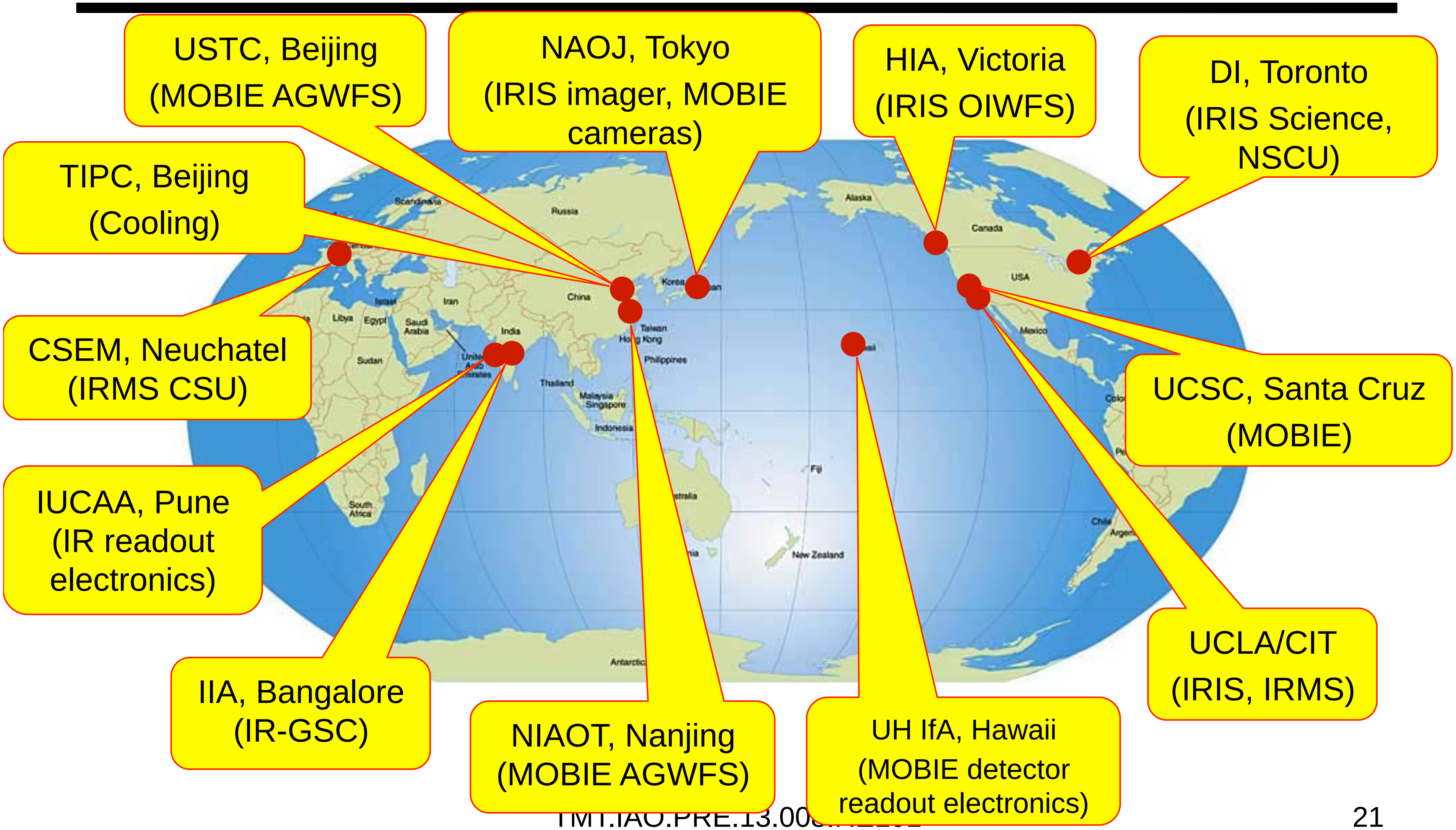
- Dual Conjugate Laser Guide Star (LGS) AO System
  - Feed 3 IR Instruments
  - 60x60 order system operating at 800Hz
  - 4 OAP relay to eliminate distortion
  - Operation at -30°C to reduce thermal emission
- Completed preliminary design phase in December 2011
  - Very successful review led by panel of external reviewers
- FDR to start April 2013 with industry involvement



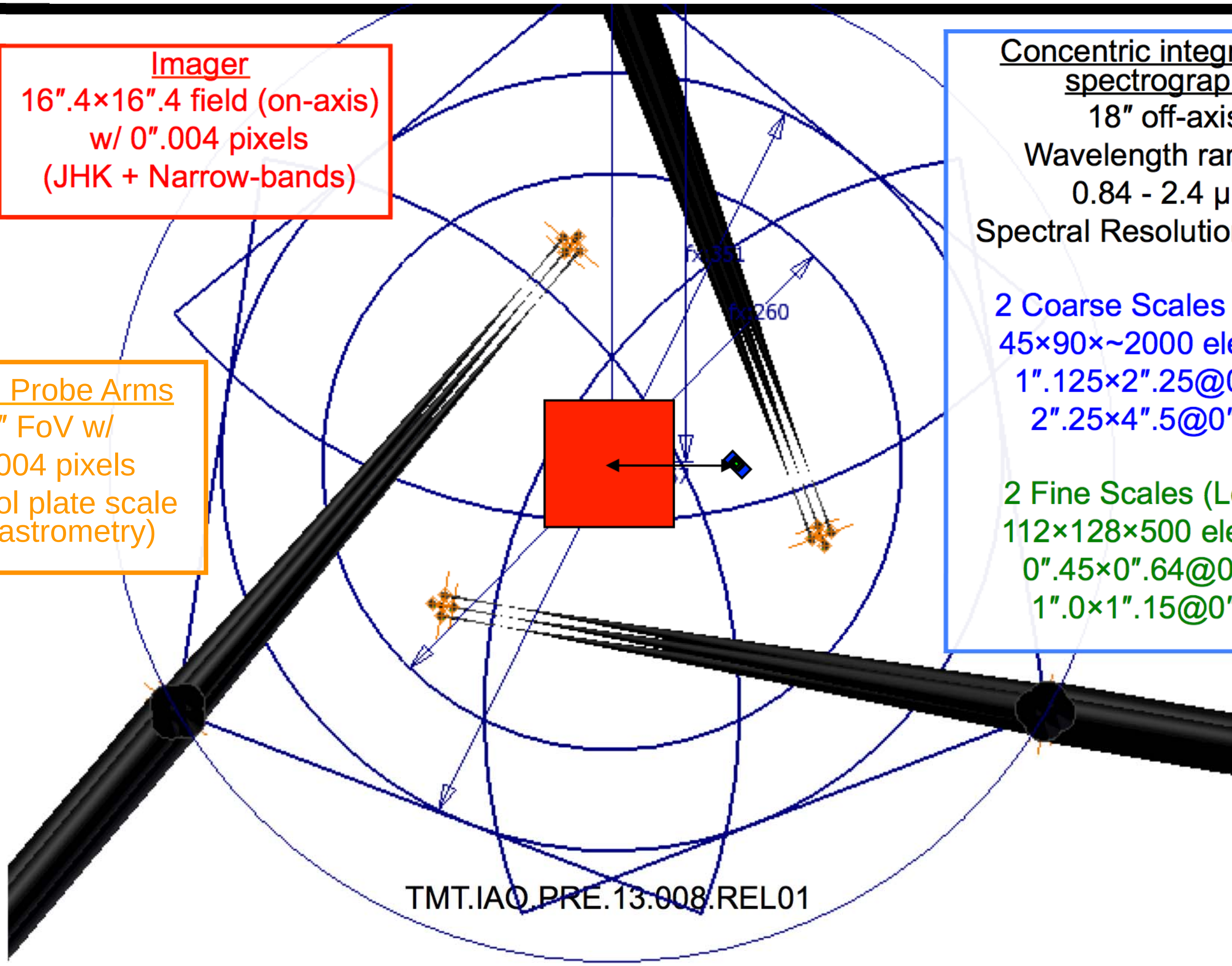
Building Instrument Partnerships

- 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

TMT Global Participants – Science Instruments



The IRIS Focal Plane: Imager + 2 IFUs + 3 Guide Stars



Imager
16″.4×16″.4 field (on-axis)
w/ 0″.004 pixels
(JHK + Narrow-bands)

Three Probe Arms
4″ FoV w/
0″.004 pixels
(control plate scale and astrometry)

Concentric integral field spectrographs
18″ off-axis
Wavelength range = 0.84 - 2.4 μm
Spectral Resolution = 4000

2 Coarse Scales (Slicer)
45×90×~2000 elements
1″.125×2″.25@0″.025
2″.25×4″.5@0″.050

2 Fine Scales (Lenslet)
112×128×500 elements
0″.45×0″.64@0″.004
1″.0×1″.15@0″.009

TMT

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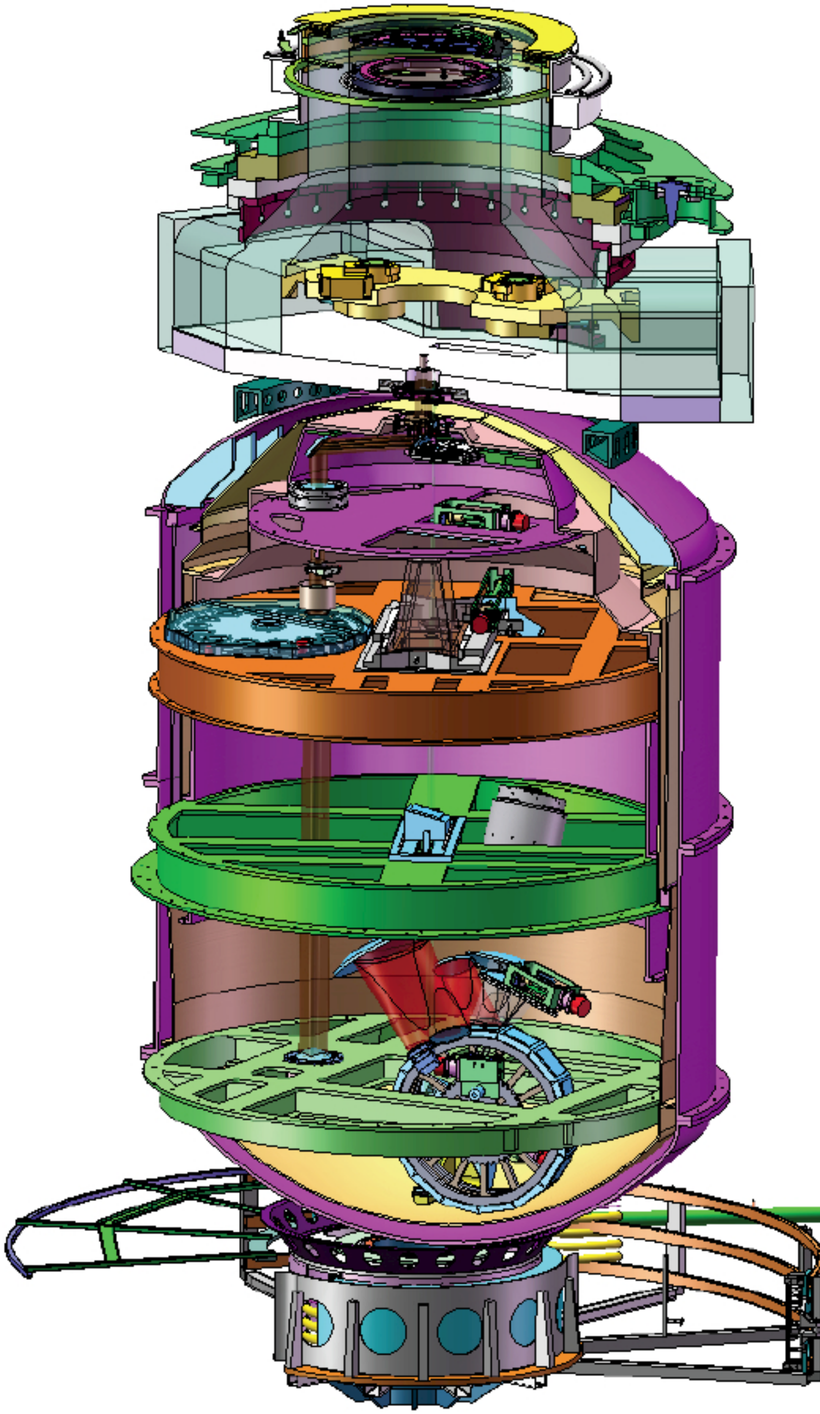
Cut-Away View of IRIS Assembly



Rotator and NFIRAOS interface

Internal chamber cooled to match NFIRAOS chamber.

T (internal)= -30°C

On-Instrument Wavefront Sensors

Cooled to match NFIRAOS chamber

T= -30°C

Science Dewar

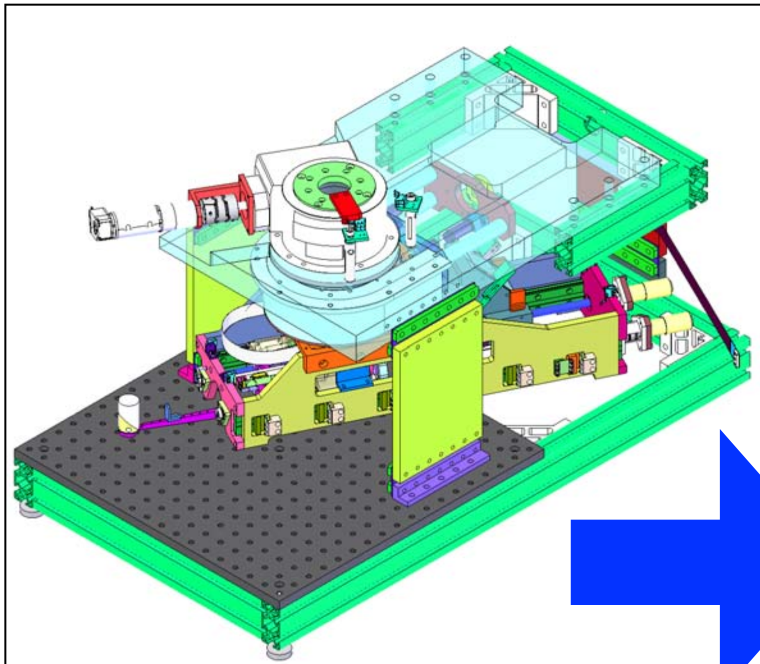
Cryogenic

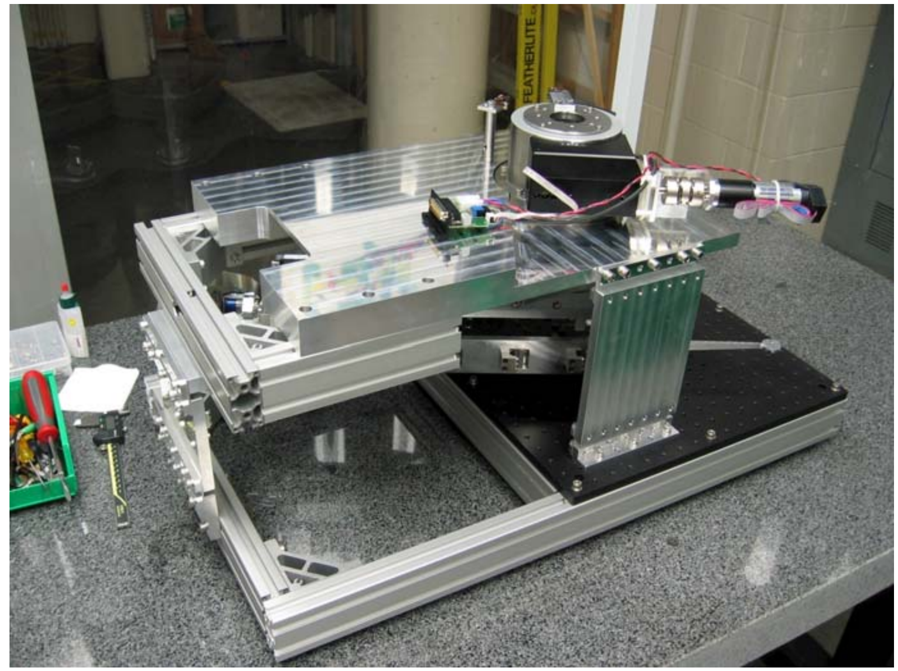
T= 77K – 120K

Cable Wrap

T= ambient

Guide Star Probe Arm Prototype: From CAD to the Lab





HIA, January 2013

- Other prototypes were also built:
  - Spectrograph grating turret (UCLA)
  - Testing of Spinel glass optical properties for ADCs (HIA)
  - Pinhole calibration mask for imager (NAOJ)

MOBIE Echellette Design: Survey and Diagnostic Spectroscopy

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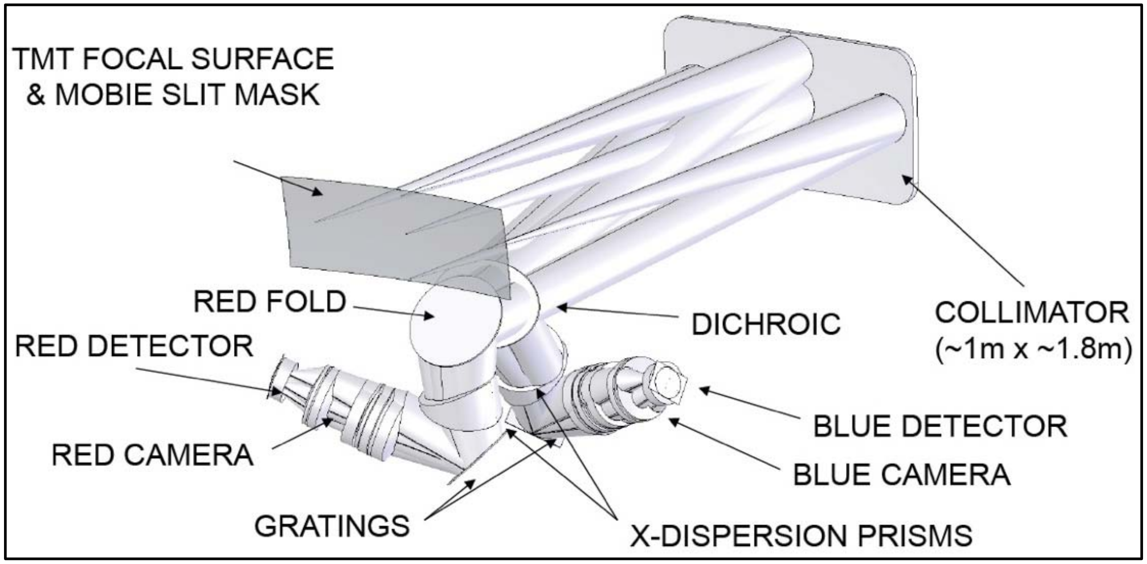


Bigelow et al. 2010, SPIE 2010

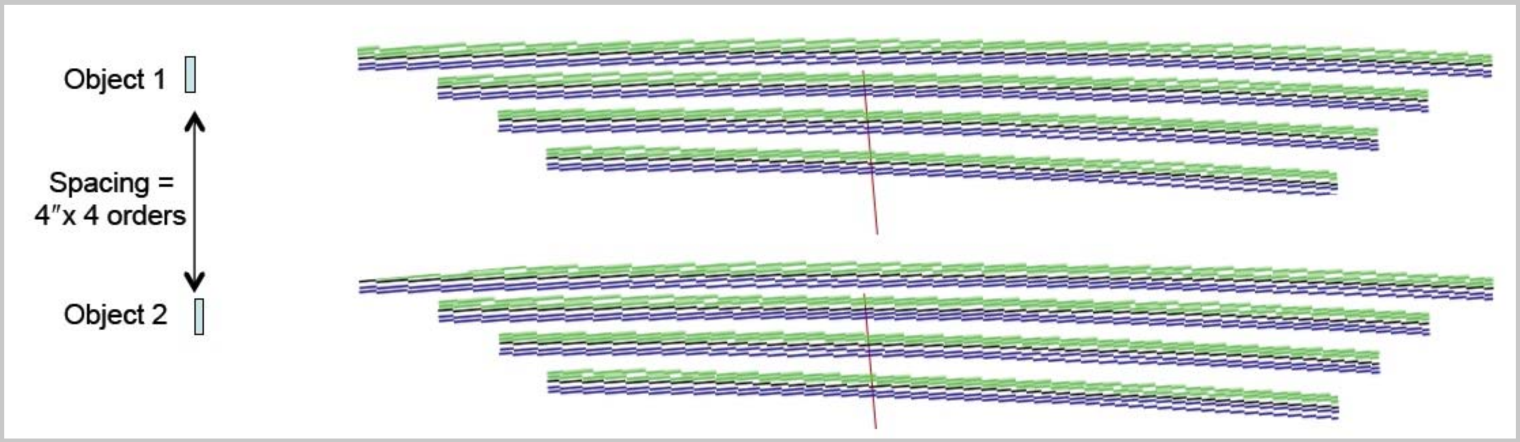
0.31μm - 1.1μm (Blue sensitive)

40.3 arcmin^2 FoV

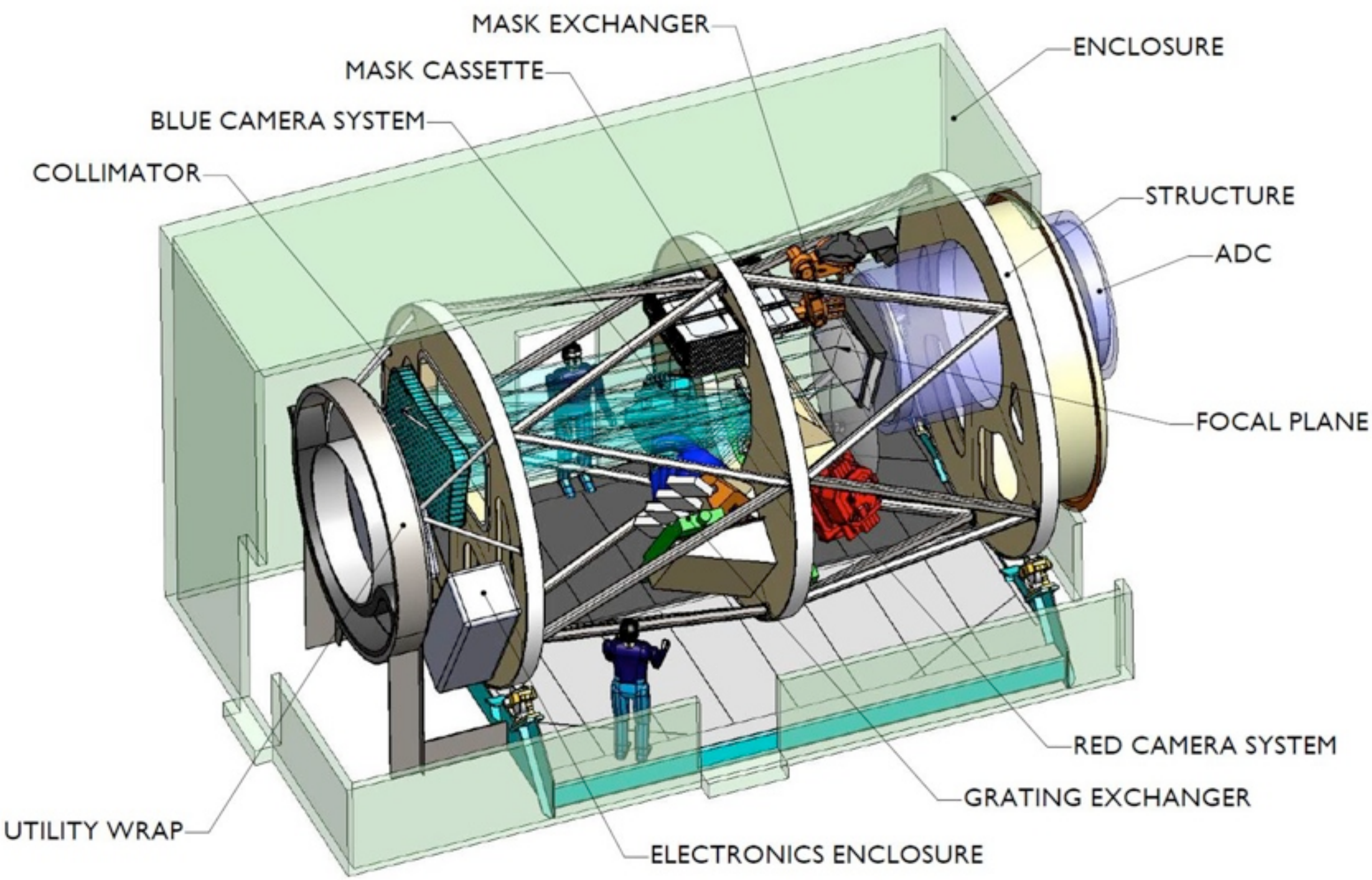
576″ total slit length
(i.e., up to ~200 objects)

R = 1000 - 8000 (for 0″.75 slit)

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

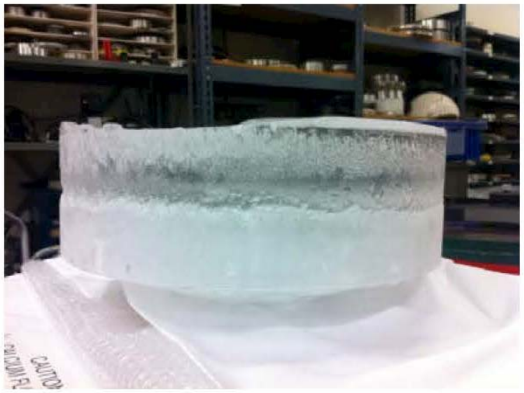


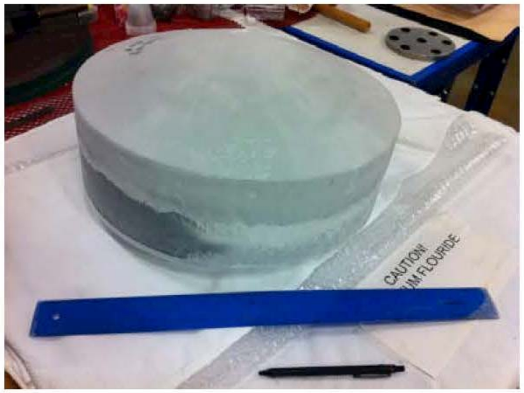
MOBIE Schematic View



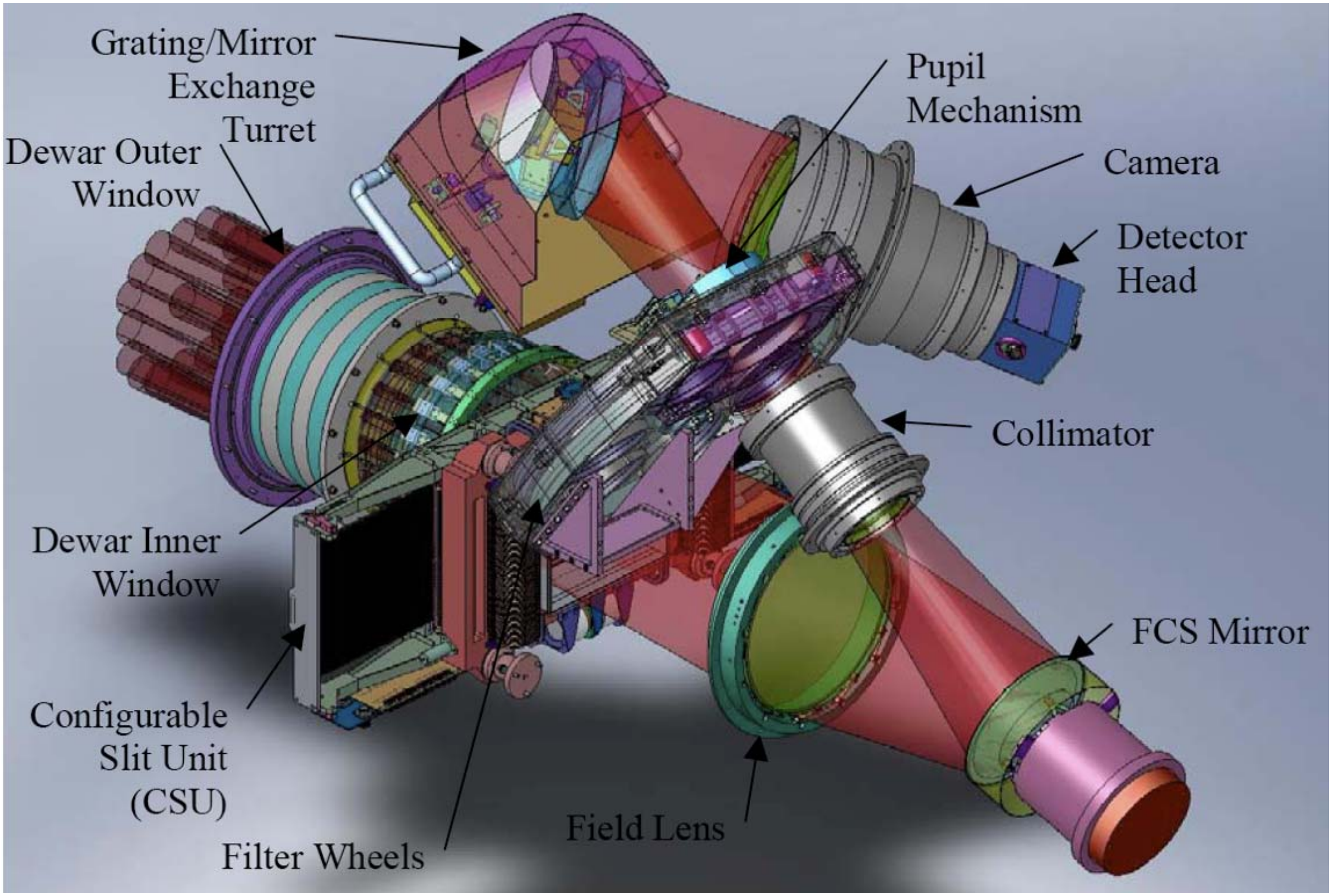
Prototyping of Single-Point Diamond Turning on CaF2

- MOBIE camera design require aspheric surfaces on large (up to D=400mm) CaF2 element
  - Vendors have experience up to D=250mm
- Use existing CaF2 crystal with D=350mm
- Phased approach:
  - SPDT a convex sphere and test
  - SPDT a convex asphere and test
- Deliverables:
  - Tooling, fixtures, handling, testing
  - SPDT process parameters
  - Quality, cost and schedule estimates

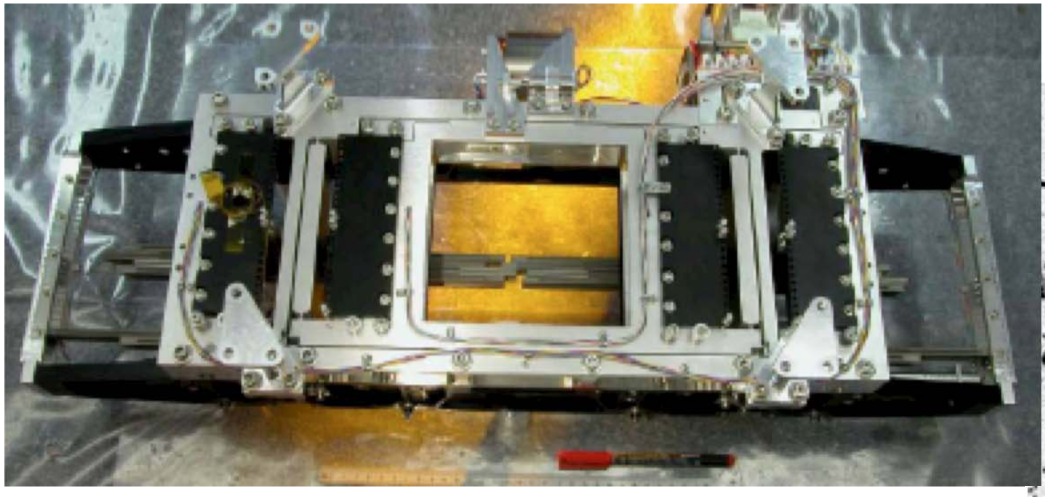


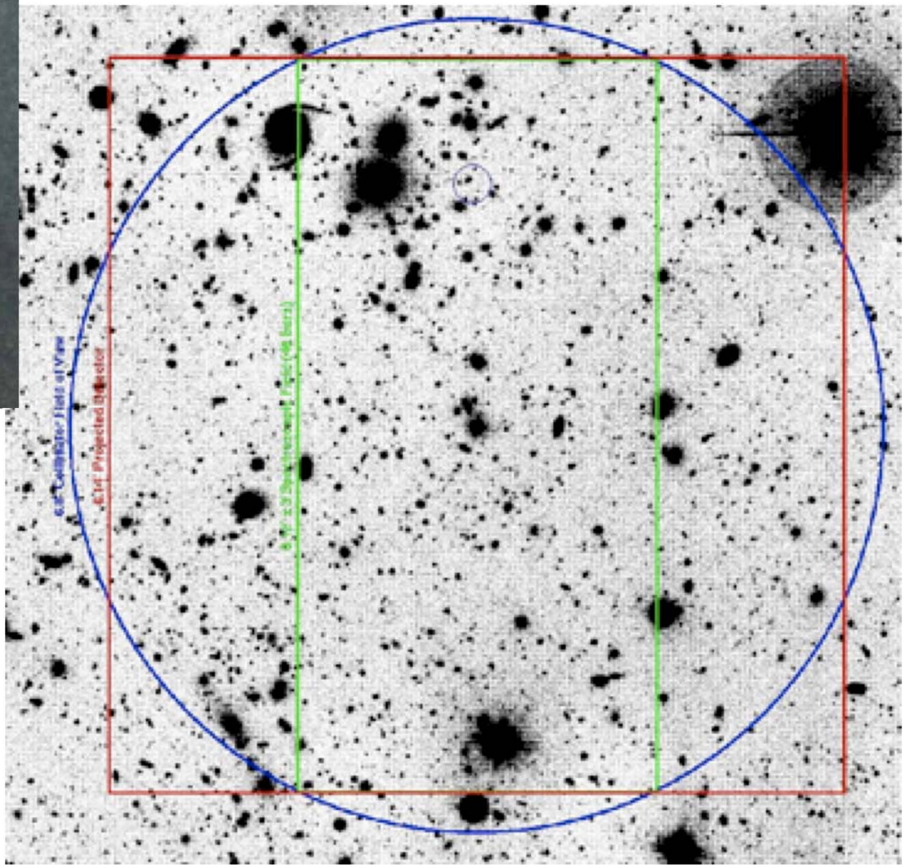


InfraRed Multi-slit Spectrometer (IRMS) (aka Keck/MOSFIRE on TMT)



IRMS Configurable Slit Unit & Field of View



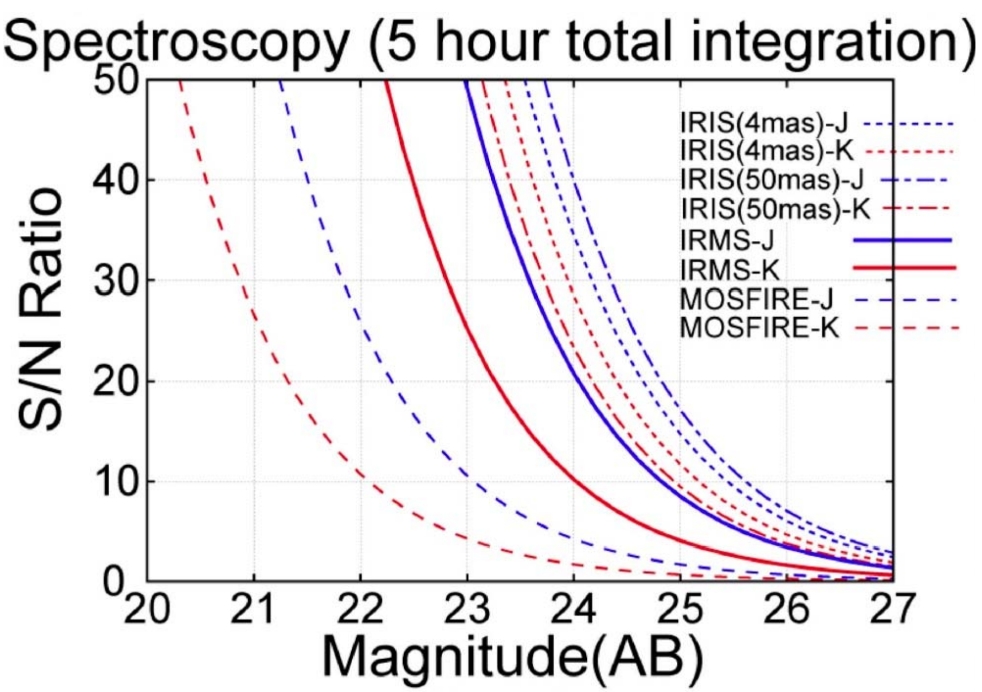


CSEM configurable slit unit:

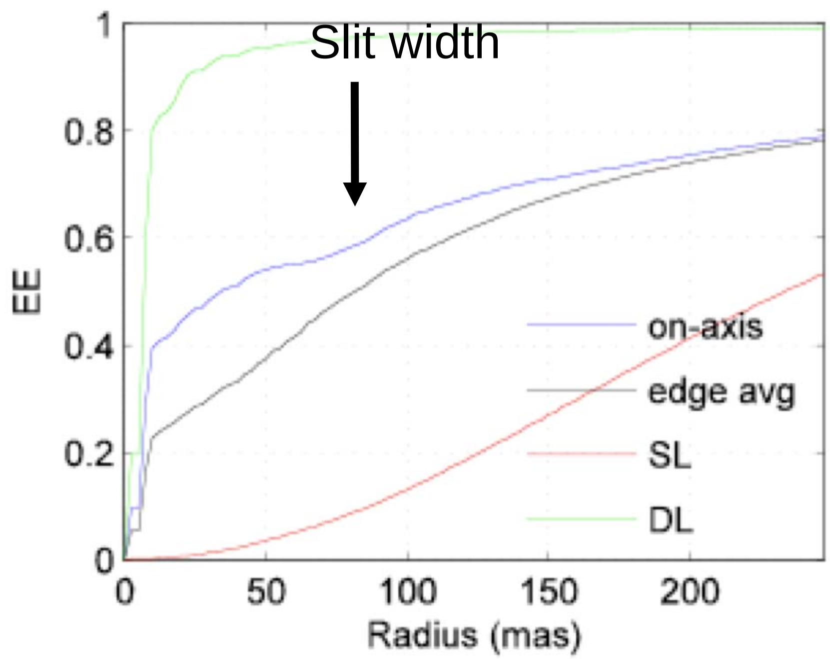
- Slits formed by opposing bars
- Up to 46 slitlets
- Reconfigurable in ~3 minutes

IRMS and NFIRAOS

- Wavelength range: 0.95 μm - 2.45 μm
- Spectral resolution R = 4660 w/ 0″.16 slit
- Deployed behind NFIRAOS:
  - 2′ field of view
  - Excellent encircled energy



H-band over whole 120” field



February 2013 Project Cost Review

- TMT costs have been reviewed three times (2007, 2011, 2013) by external non-advocate cost review panel of international experts
  - These are cost reviews and not general project reviews
- Preceded by intense 6-month cost and schedule estimating effort
- All TMT cost estimates are developed using a well-defined, detailed, bottom-up methodology:
  - One cost sheet per WBS element
  - Includes labor, non-labor and travel costs with bases of estimate
  - Includes contingency estimate for technical, cost and schedule risks
- TMT Cost Book contains 783 cost sheets tied to a detailed integrated project schedule with over four thousand activities laid out by month across the construction schedule

February 2013 Project Cost Review

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Detailed cost and schedule estimates for:

- First-light MCAO system (NFIRAOS)
- NFIRAOS Science Calibration Unit
- Laser Guide Star Facility
- Three first-light instruments

- TMT costs have been reviewed three times (2007, 2011, 20… int…
  - …
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Detailed cost and schedule estimates for:

- First-light MCAO system (NFIRAOS)
- NFIRAOS Science Calibration Unit
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- Three first-light instruments

Regularly updated as designs progress

Invaluable in informing TMT SAC and Board of financial and schedule impact of design trade-offs as they arise

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.)

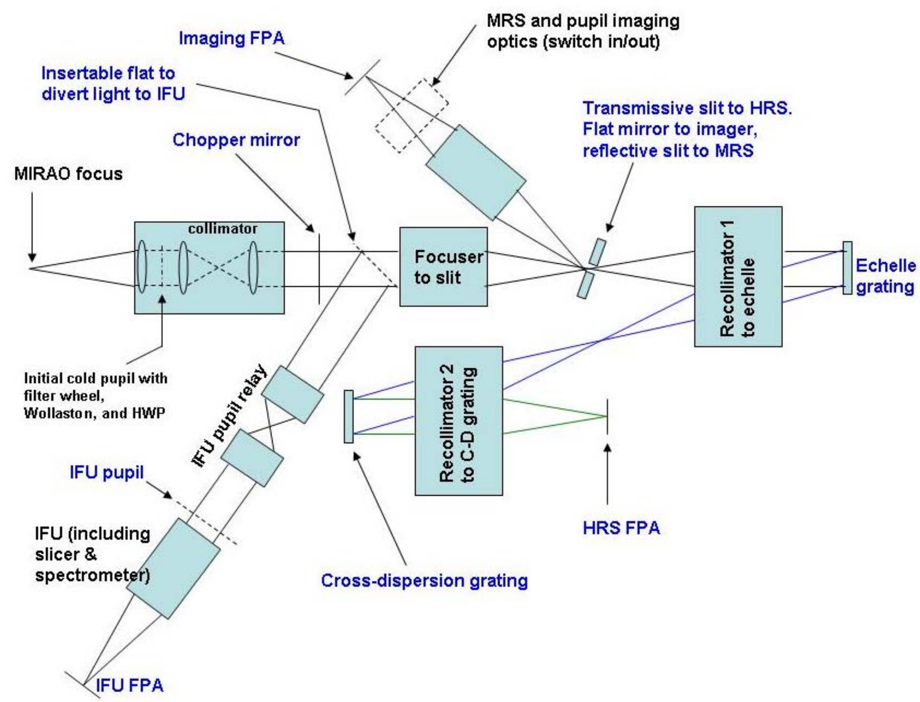
- “Mini-studies”
  - ≤1 year duration, ~$100k
  - Joint decisions between SAC and Observatory on which studies to fund
  - TMT would also support teams requesting external funding from their agencies, e.g., letters

- 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

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

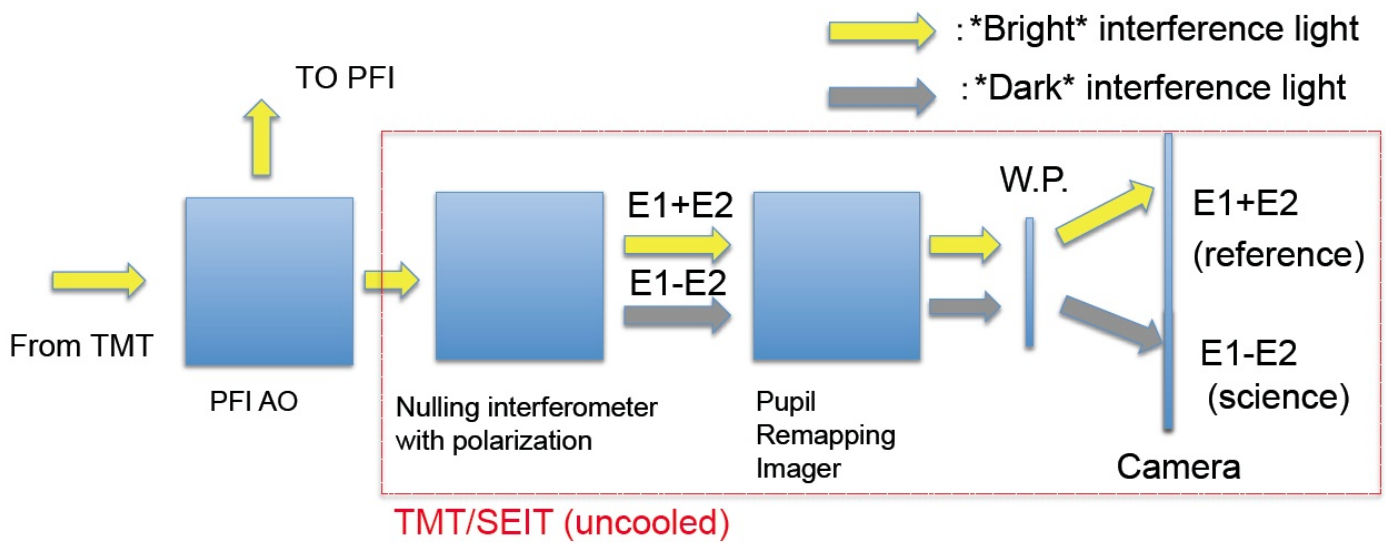
Packham et al., SPIE 2012, 8447-287)



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)



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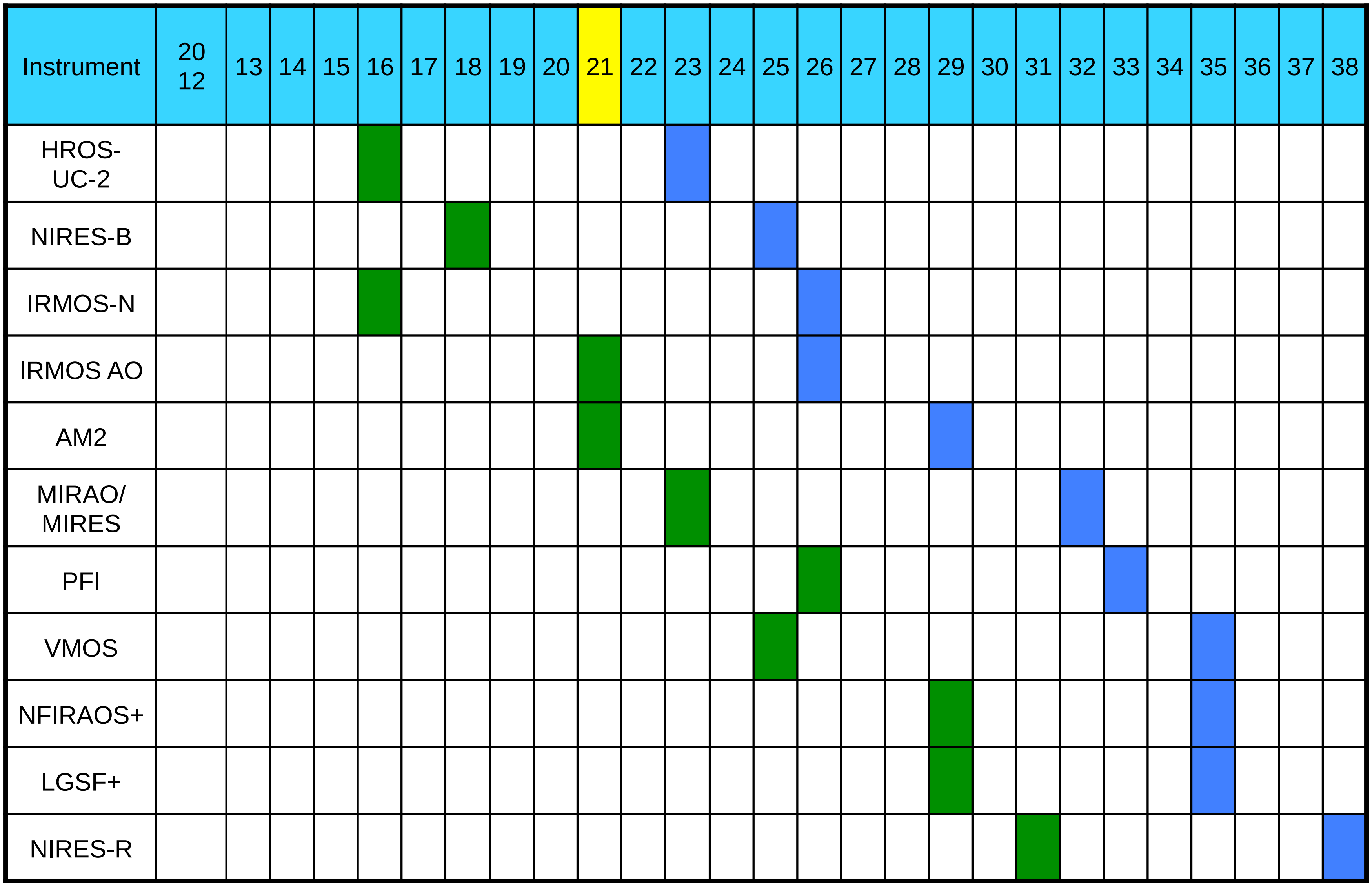
Visitor Instruments

- 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

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
- Multiple phasing scenarios were studied looking at science priorities, total costs, total funding required prior to first light, and annual funding after first light
- TMT SAC maintains a preferred scenario, and the most recent one was adopted in March 2011

Example of an Instrument Phasing Scenario



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

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 our future instrumentation development program have been defined and discussed including the SAC prioritization process and the instrument phasing scenarios
- The scope and timescale of ELT-class instrumentation projects call for a thorough and strategic prioritization process

Acknowledgments

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