THIRTY METER TELESCOPE

TMT Instrumentation: Synergies with ALMA and JWST

Luc Simard

“ALMA and ELTs: A Deeper, Finer View of the Universe ”

ESO-Garching, March 24-27, 2009

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The Importance of Adaptive Optics

- 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

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

$Sensitivity = 1/$ time required to reach a given s/n ratio

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

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TMT First Decade Instrument Suite

INSTRUMENT	λ (μm)	FOV / SL	R	SCIENCE CASE
Near-IR diffraction-limited (DL) spectrometer and imager (IRIS)	0.8 – 2.5	10″×10″ (imaging) 0″.7,1″.6 or 4″.5 (IFU)	4000	• Assembly of galaxies at high z • Black holes/AGNs/Galactic Center • Resolved stellar populations in crowded fields
Wide-Field Optical Spectrometer (WFOS)	0.34 – 1.0	92.4 arcmin^2/ 1300″	150 – 7500	• IGM structure and composition at 2 < z < 6 • Stellar populations, chemistry and energetics of z > 1.5 galaxies
Deployable multi-IFU, near-DL, near-IR Spectrometer (IRMOS)	0.8 – 2.5	5′ patrol field 2″ per IFU	2000 - 10000	• Early Light • Epoch of Peak Galaxy Building • JWST follow-ups
Mid-IR Echelle Spectrometer and Imager (MIRES)	4.5 - 25	3″	5000 – 100000	• Origin of Stellar Masses • Accretion and outflows around protostars • Evolution of gas in protoplanetary disks
Planet Formation Imager (PFI)	1.1- 2.4	2″.2 × 2″.2	70 – 500	• Direct detection and spectroscopic characterization of exoplanets
High-Resolution Optical Spectrometer (HROS)	0.34 – 1.0	20″	30000 – 100000	• Doppler searches for exoplanets • Stellar abundance studies in Local Group • ISM abundances/kinematics • IGM characterization to z~6
MCAO Imager (WIRC)	0.8 - 5	30" x 30"	5 - 100	• Precision astrometry (e.g. Galactic Center) • Resolved stellar populations out to 10 Mpc
Near-IR, DL Echelle (NIRES)	1 – 5	2″	5000 – 30000	• IGM 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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Visible, Seeing-Limited

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Near-IR, AO-assisted

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High-Contrast AO

TMT First Decade Instrument Suite

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Mid-infrared, AO-assisted

INSTRUMENT	λ (μm)	FOV / SL	R	SCIENCE CASE
Near-IR diffraction-limited (DL) spectrometer and imager (IRIS)	0.8 – 2.5	10″×10″ (imaging) 0″.7-1″.6 or	4000	• Assembly of galaxies at high z • Black holes/AGNs/Galactic Center • ...lations in crowded fields
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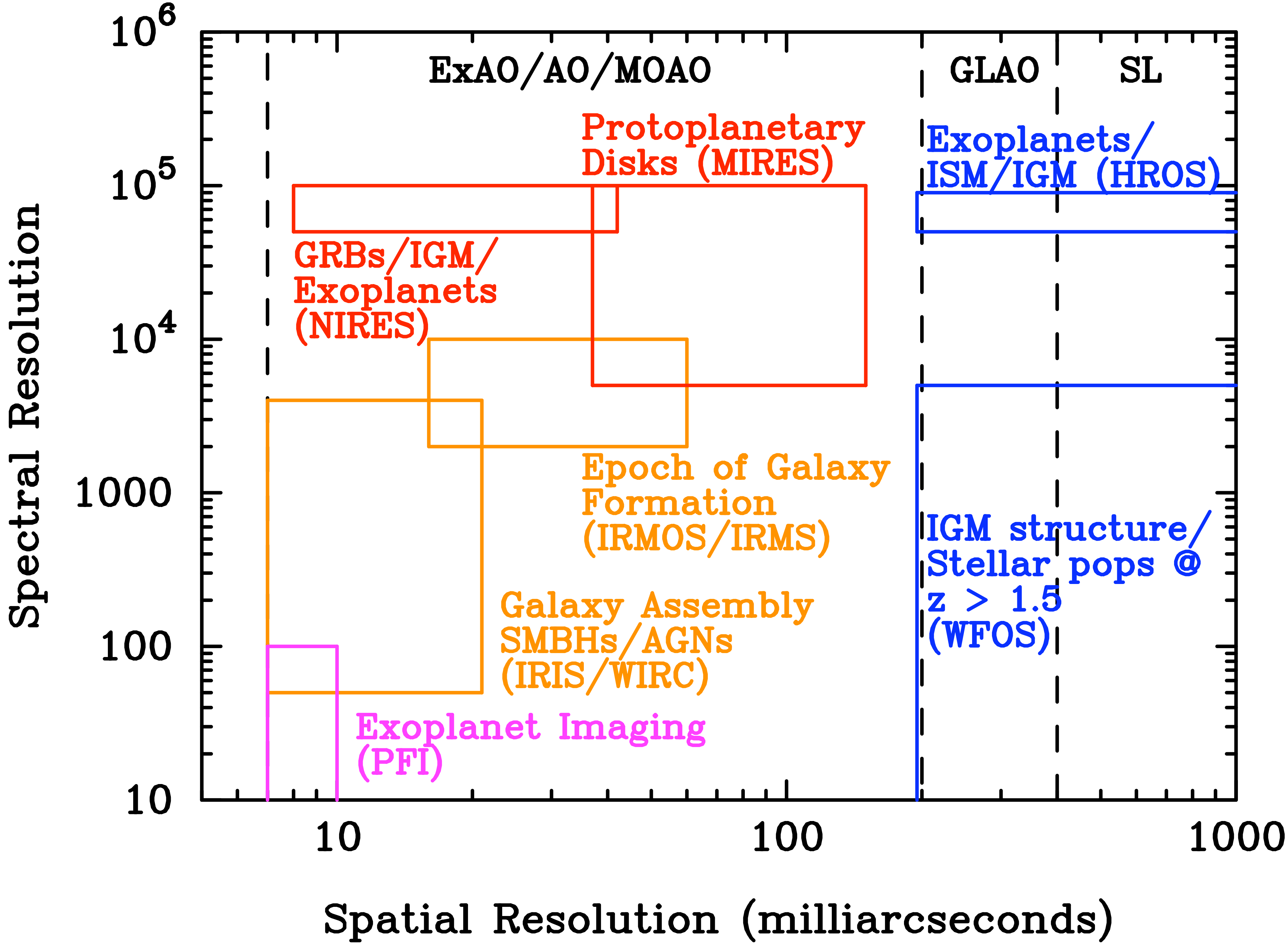
TMT Discovery Space

Broad range of spectral and spatial resolution



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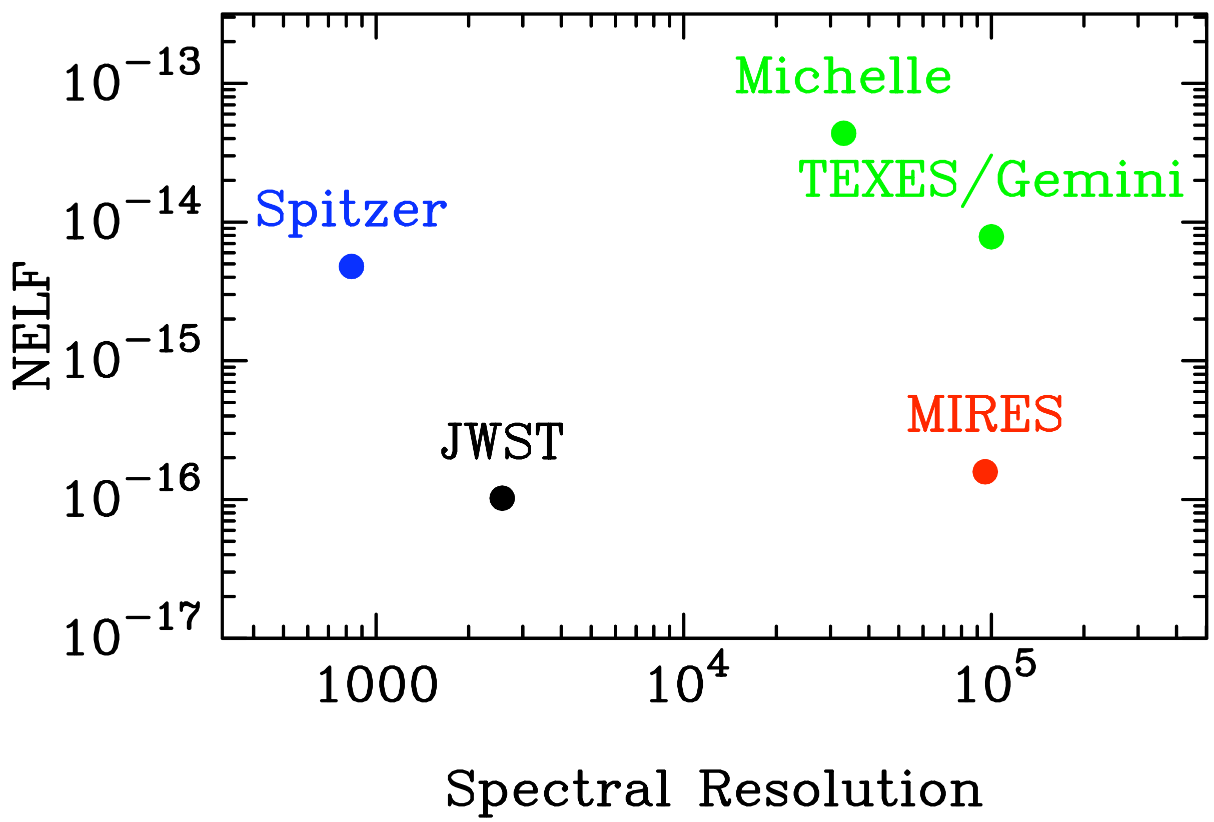
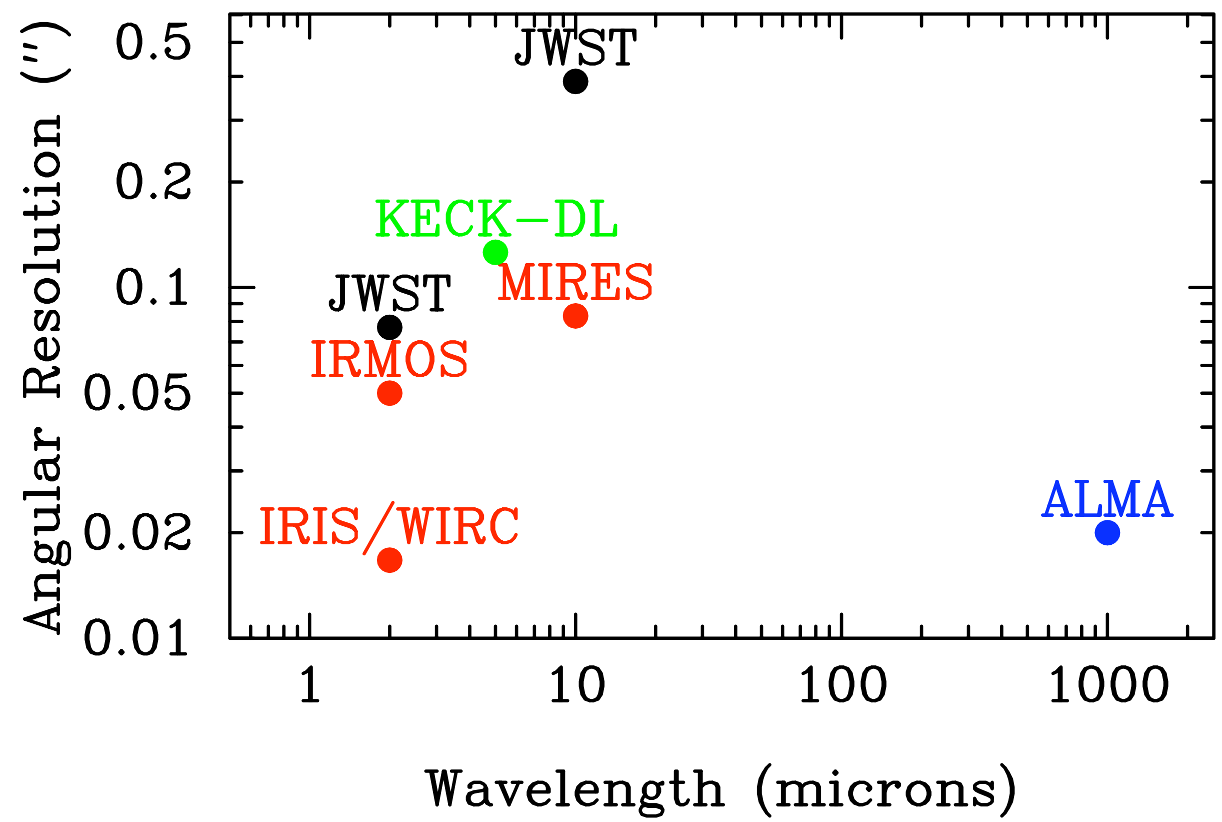
Synergy with Space/IR and ALMA





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 is a “near IR ALMA”!

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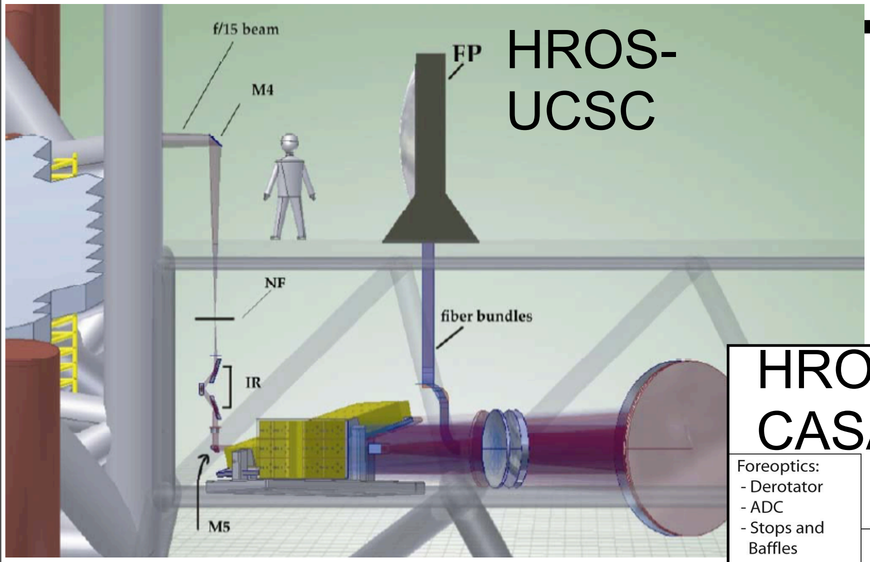
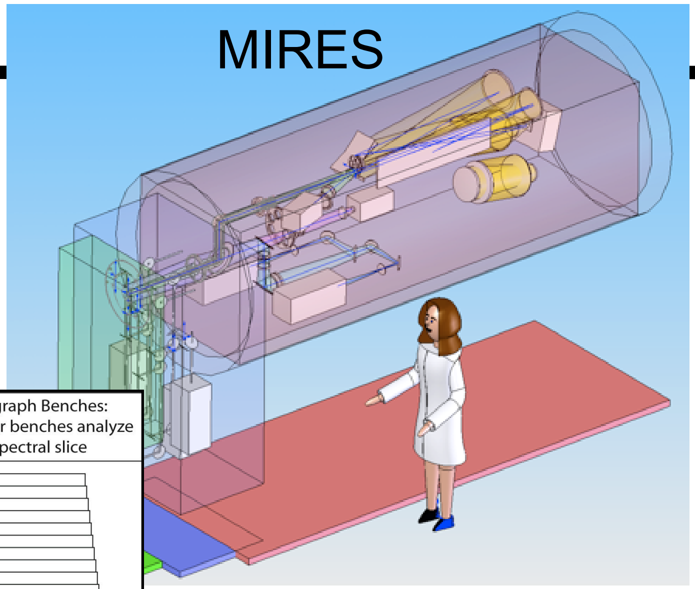
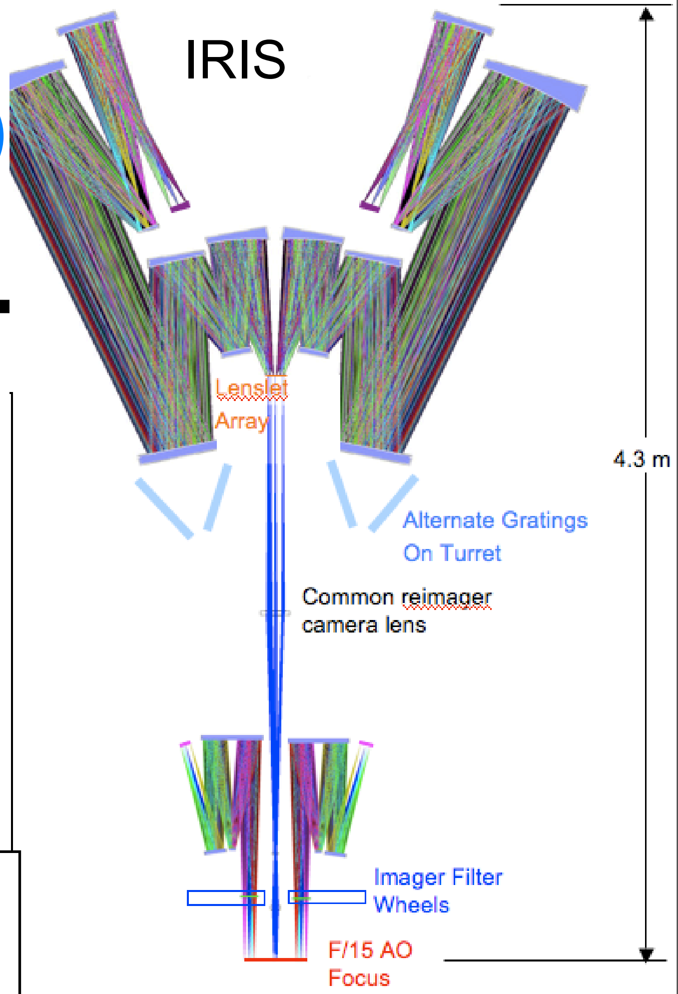
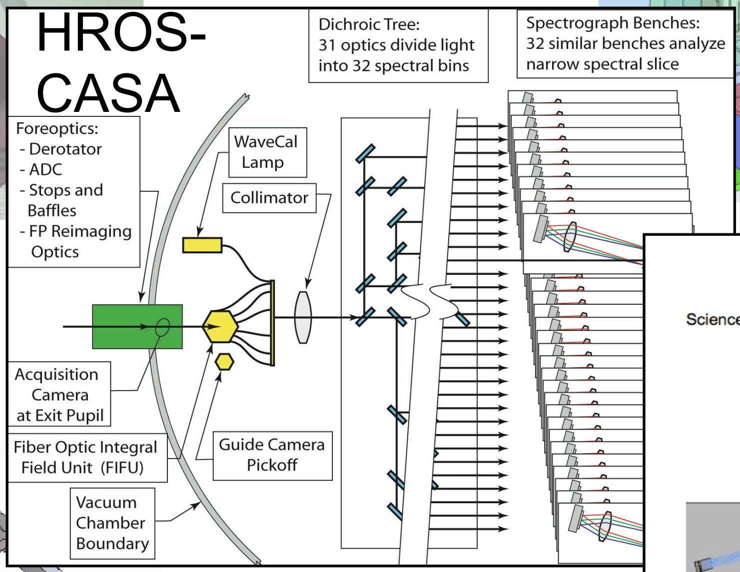
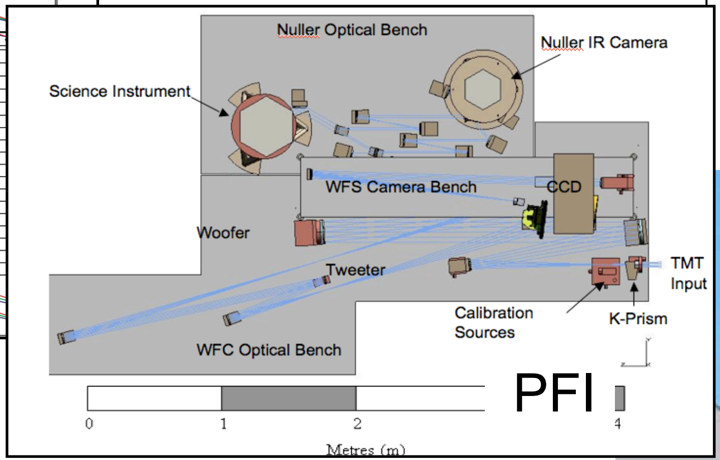
Feasibility studies 2005-6 (concepts, requirements, performance,…)

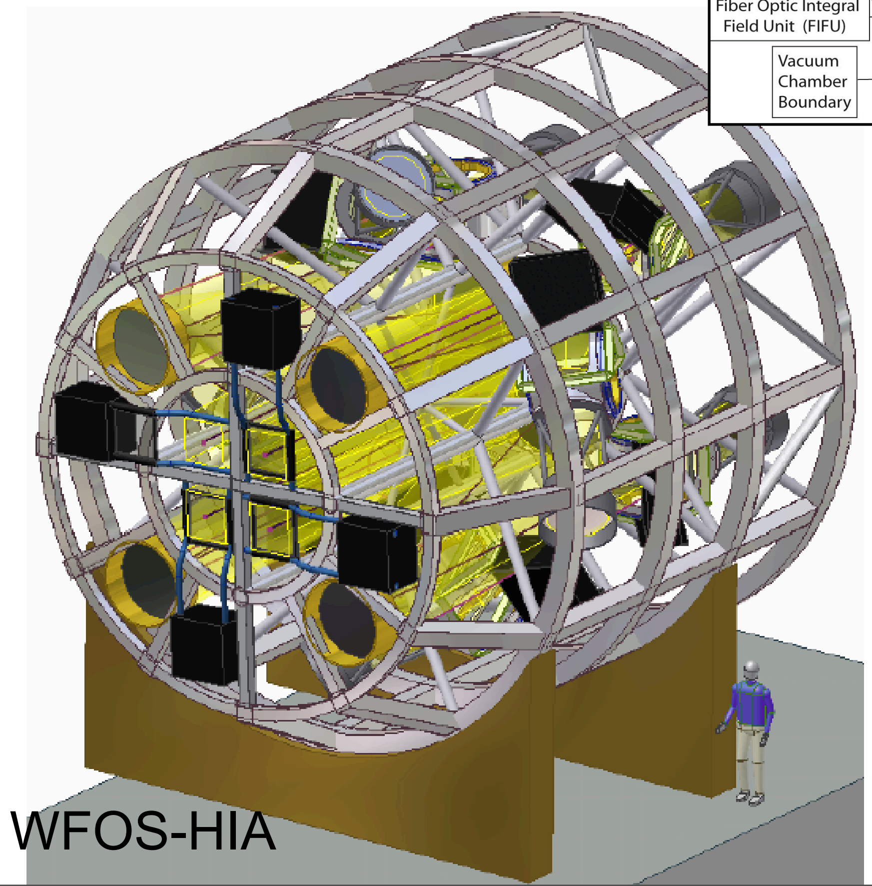


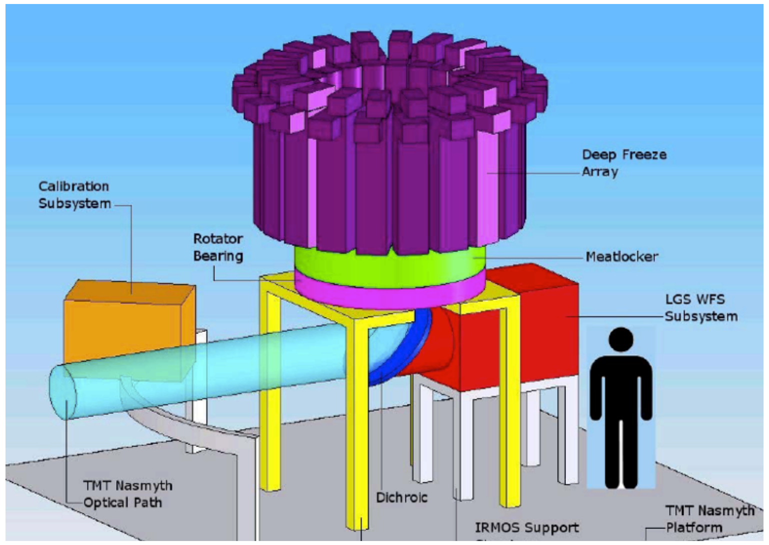




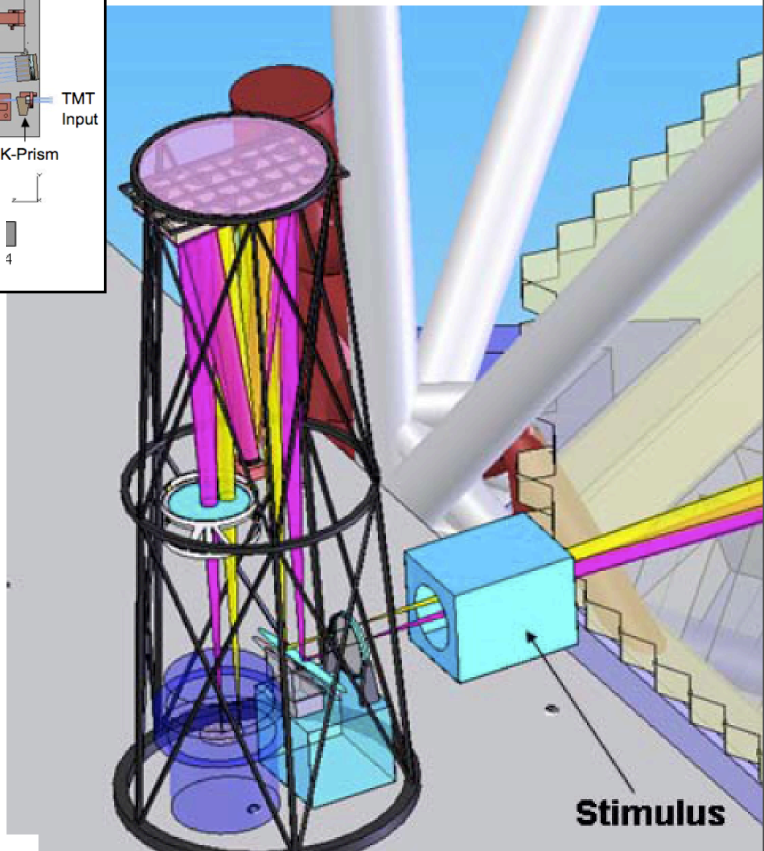






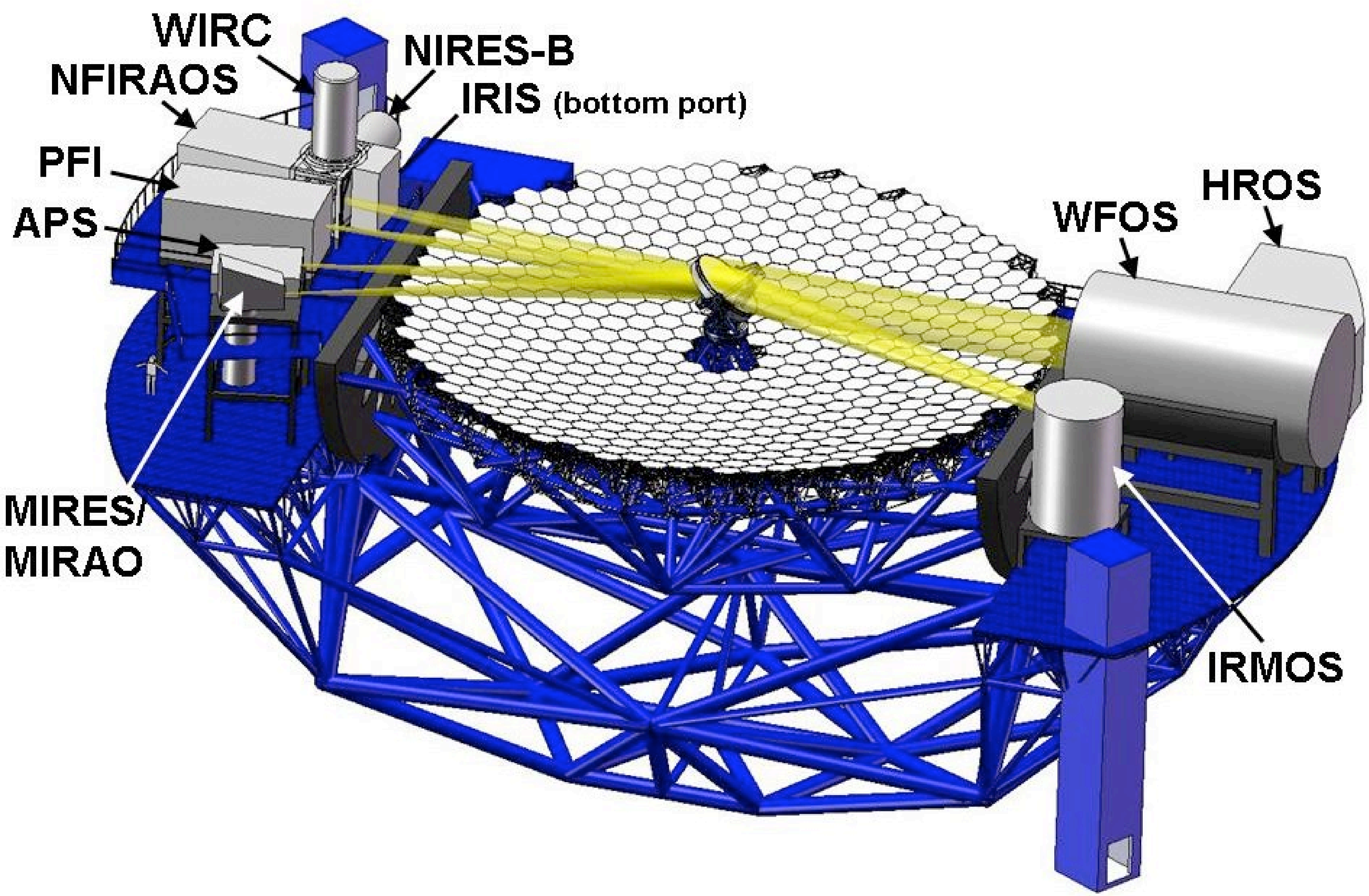


IRMOS-UF



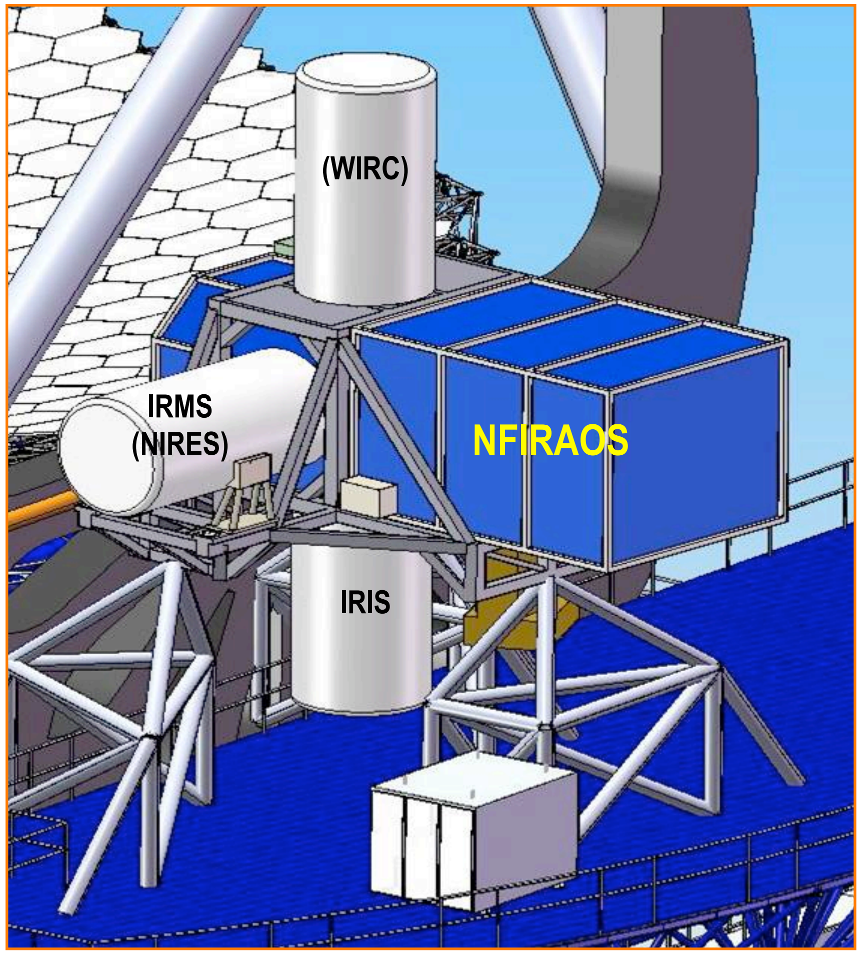
IRMOS-CIT

Nasmyth Configuration: First Decade Instrument Suite



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

- Dual conjugate AO system:
  - Order 61x61 DM and TTS at h = 0 km
  - Order 75x75 DM at h = 12 km
  - Better Strehl than current AO systems



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

- Can feed three instruments
- Completely integrated system
  - Fast (< 5 min) switch between targets with same instrument
- > 50% sky coverage at galactic poles

Instrumentation Design Drivers

- Choice of early-light instruments by TMT SAC with "workhorse" scientific capabilities and synergy with ALMA and JWST:
  - IRIS
  - WFOS
  - IRMS

Observatory is being designed as an "end-to-end" system to maximize performance in diffraction-limited regime

- Instrument Systems
  - Target acquisition sequences
  - Access and servicing

- Observatory systems
  - Nasmyth platforms (e.g., mass budget, area, height, M1 airflow)
  - Cooling systems (e.g., vibrations must be minimized)
  - Cranes

Infrared Imaging Spectrograph (IRIS)

Integral Field Spectrograph and Imager working at the diffraction limit:

- Fed by NFIRAOS (Narrow field facility AO System)
- Wavelength range: 0.8-2.5μm; goal 0.6-5μm
- Field of view: < 2 arcsec for IFU, up to 10” for imaging mode
- Spatial sampling: 4 mas per pixel (Nyquist sampled (λ/2D)) over 4096 pixels for IFU); over 10x10 arcsec for imaging
  - Plate scale adjustable 0.004, 0.009, 0.022, 0.050 arcsec/pixel
  - 128x128 spatial pixels with small ($\Delta\lambda/\lambda \le 0.05$) wavelength coverage
- Spectral resolution
  - R=4000 over entire J, H, K, L bands, one band at a time
  - R=2-50 for imaging mode
- Parallel imaging: goal

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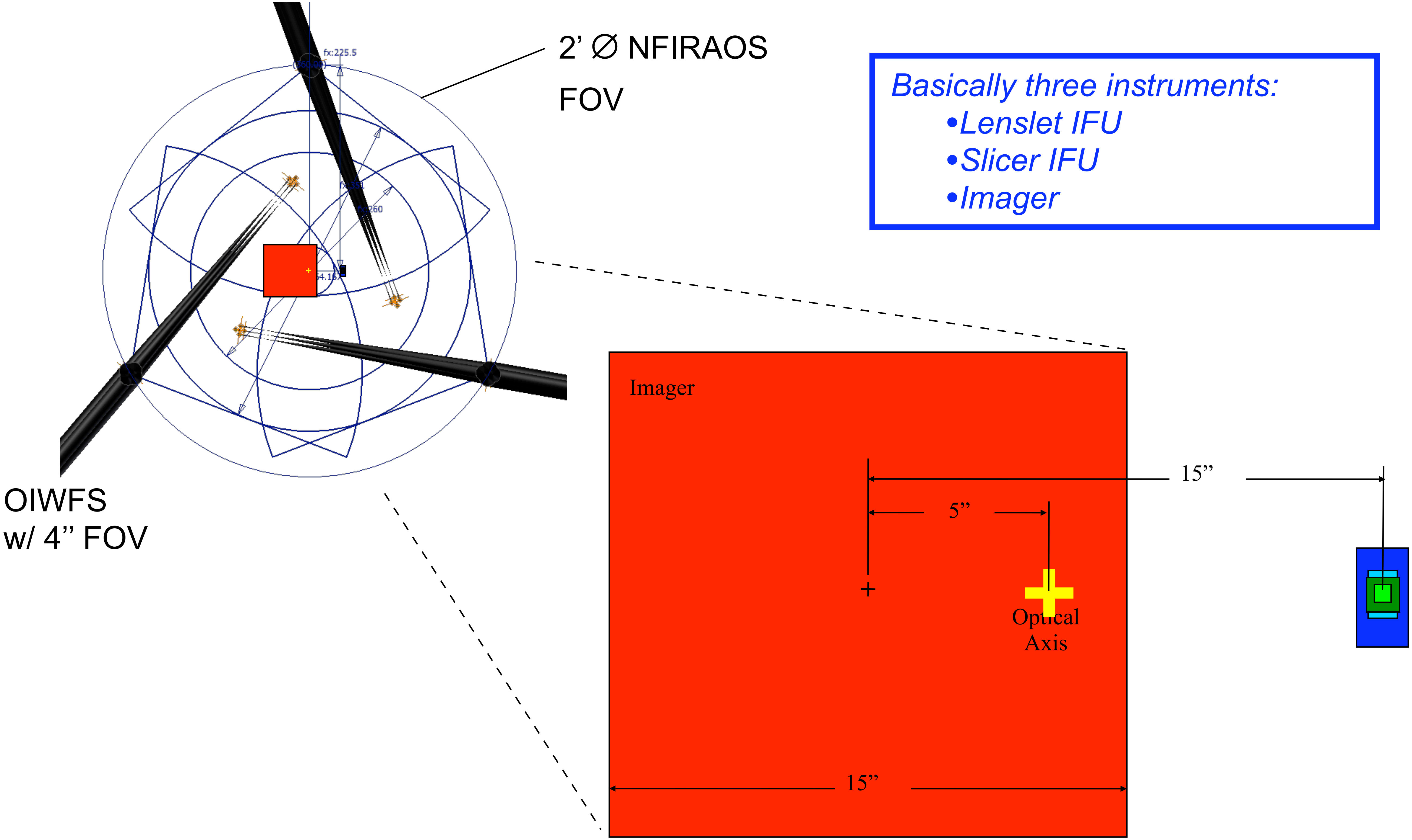
IRIS Team

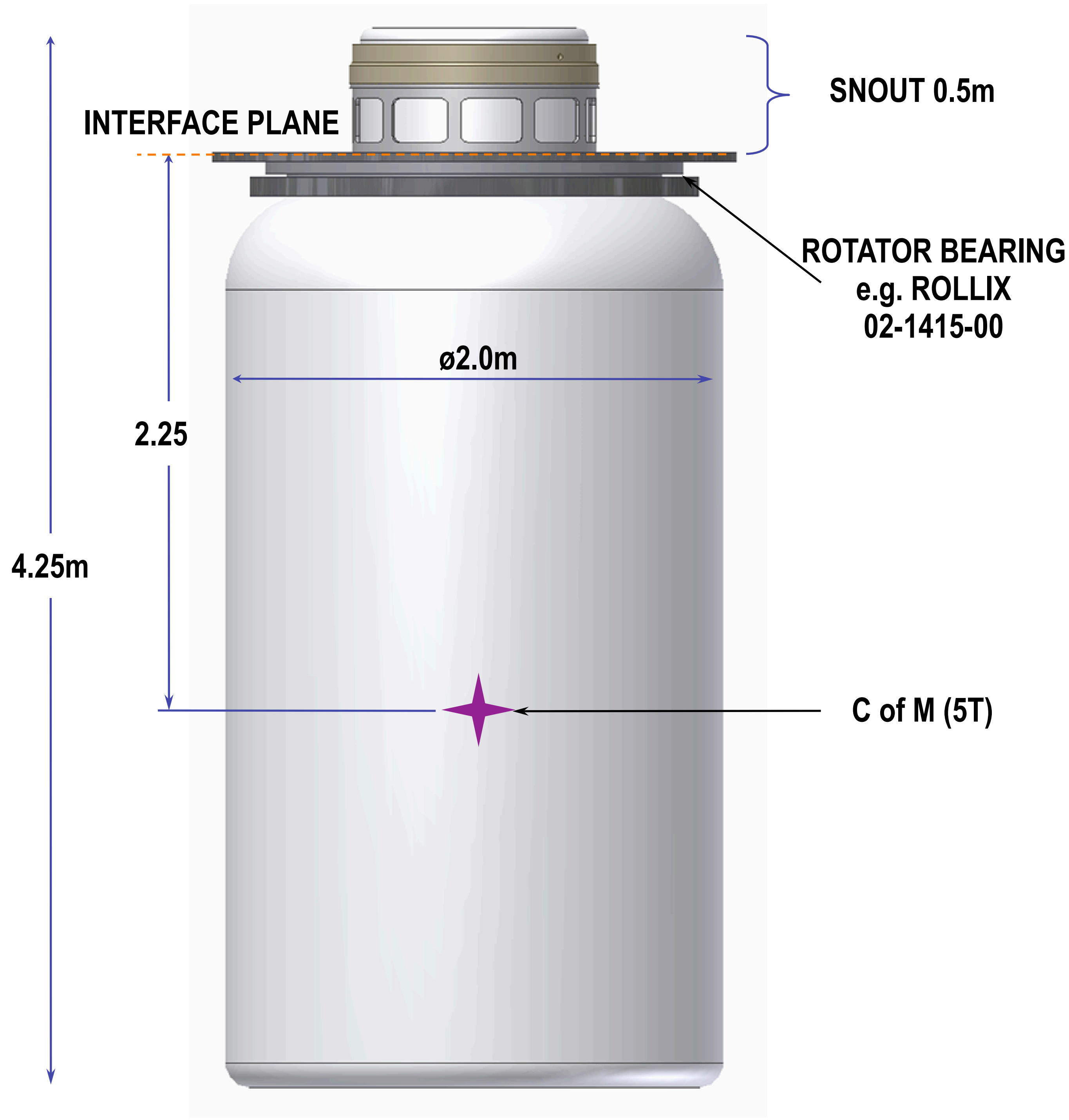
- James Larkin (UCLA), Principal Investigator
  - Overall IRIS instrument (including WFS, cal, etc)
  - Lenslet-based IFS
  - ADC and optical design: UCSC
- Anna Moore (Caltech), co-I
  - Sharing overall instrument responsibilities
  - Slicer-based IFS
- Ryuji Suzuki, Masahiro Konishi, Tomonori Usuda (NAOJ)
  - Imager design
- Betsy Barton (UC Irvine), Project Scientist
- Science Team
  - Shri Kulkarni (Caltech), Jonathan Tan (U. Florida), Máté Ádámkovics, Joshua Bloom, James Graham, (UC Berkeley), Pat Côté, Tim Davidge (HIA), Shelley Wright (UC Irvine), Bruce Macintosh (LLNL), Miwa Goto (MPIA), Nobunari Kashikawa (NAOJ), Jessica Lu, Andrea Ghez, David Law, Will Clarkson (UCLA), Hajime Sugai (Kyoto)

IRIS Science Field Geometry

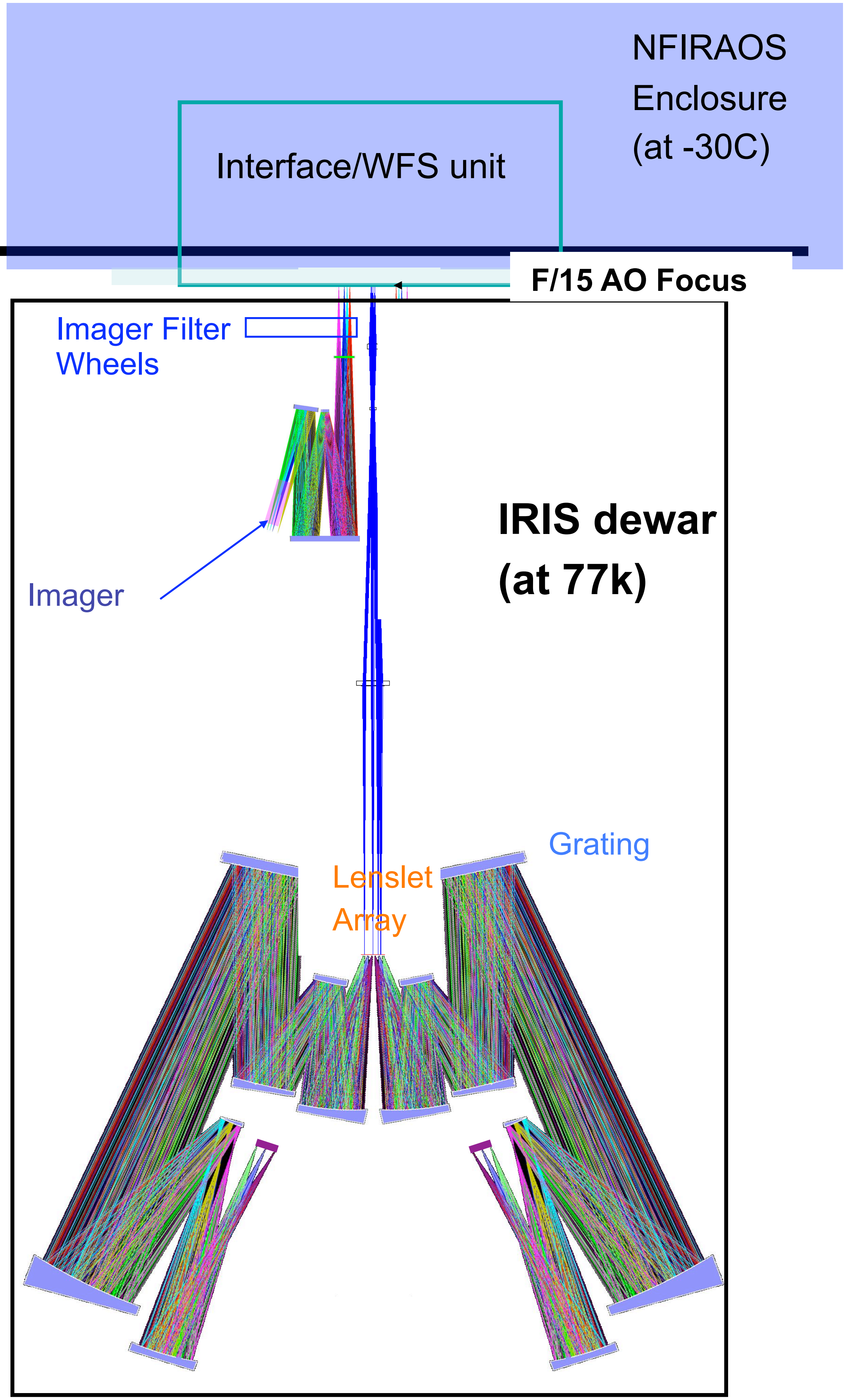
Basically three instruments:
- *Lenslet IFU*
- *Slicer IFU*
- *Imager*



IRIS



SNOUT 0.5m
INTERFACE PLANE
ROTATOR BEARING
e.g. ROLLIX
02-1415-00
ø2.0m
2.25
4.25m
C of M (5T)



NFIRAOS
Enclosure
(at -30C)
Interface/WFS unit
F/15 AO Focus
Imager Filter
Wheels
IRIS dewar
(at 77k)
Imager
Grating
Lenslet
Array

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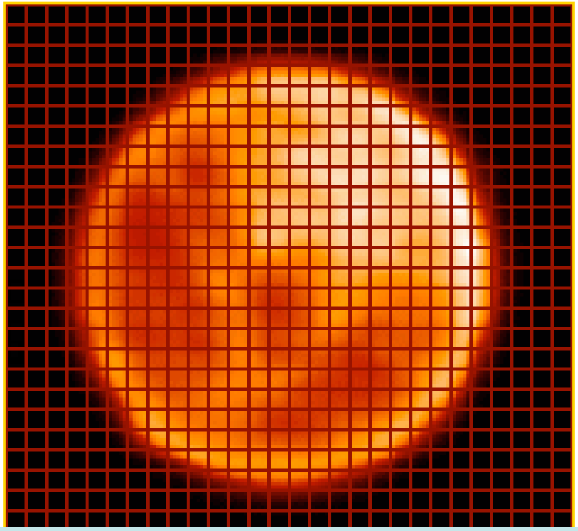
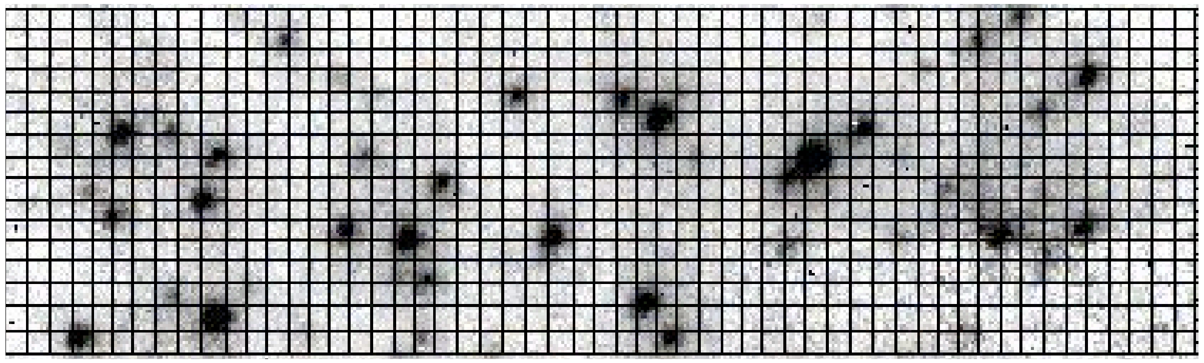
Motivation for IRIS

- Unprecedented ability to investigate objects on small scales.

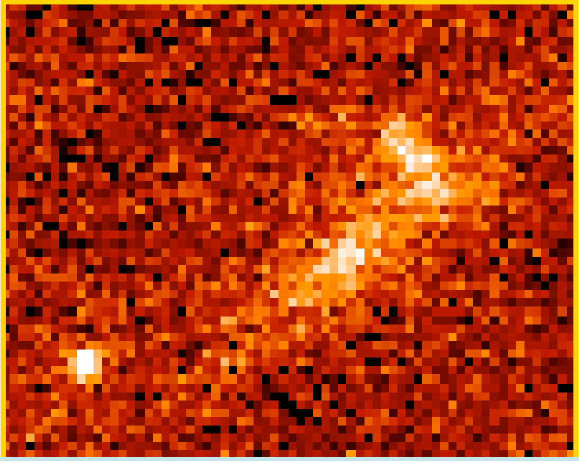
0.01” @	5 AU	= 36 km	(Jovian’s and moons)
	5 pc	= 0.05 AU	(Nearby stars – companions)
	100 pc	= 1 AU	(Nearest star forming regions)
	1 kpc	= 10 AU	(Typical Galactic Objects)
	8.5 kpc	= 85 AU	(Galactic Center or Bulge)
	1 Mpc	= 0.05 pc	(Nearest galaxies)
	20 Mpc	= 1 pc	(Virgo Cluster)
	z=0.5	= 0.07 kpc	(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.)



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

Keck AO images

Wide Field Optical Spectrometer (WFOS)

Requirement #	Description	Requirement
[REQ-1-ORD-3950]	Wavelength Range	0.31 – 1.0μm
[REQ-1-ORD-3955]	Image quality: Imaging	≤ 0.2 arcsec FWHM over any 0.1μm wavelength interval (including contributions from the telescope and the ADC at z=60°)
[REQ-1-ORD-3960]	Image quality: Spectroscopy	≤ 0.2 arcsec FWHM at every wavelength
[REQ-1-ORD-3965]	Field of View	40.5 $arcmin^2$. The field need not be contiguous.
[REQ-1-ORD-3970]	Total Slit Length	≥ 500 arcseconds
[REQ-1-ORD-3975]	Spatial Sampling	< 0.15 arc-sec per pixel, goal < 0.1 arc-sec
[REQ-1-ORD-3980]	Spectral Resolution	R = 500-5000 for a 0.75 arc-sec slit, 150-7500 (goal)
[REQ-1-ORD-3985]	Throughput	≥ 30% from 0.31 – 1.0μm, or at least as good as that of the best existing spectrometers
[REQ-1-ORD-3990]	Sensitivity	Spectra should be photon noise limited for all exposure times >60 sec. Background subtraction systematics must be negligible compared to photon noise for total exposure times as long as 100 Ksec. Nod and shuffle capability in the detectors may be desirable
[REQ-1-ORD-3995]	Wavelength Stability	Flexure at a level of less than 0.15 arc-sec at the detector is required.

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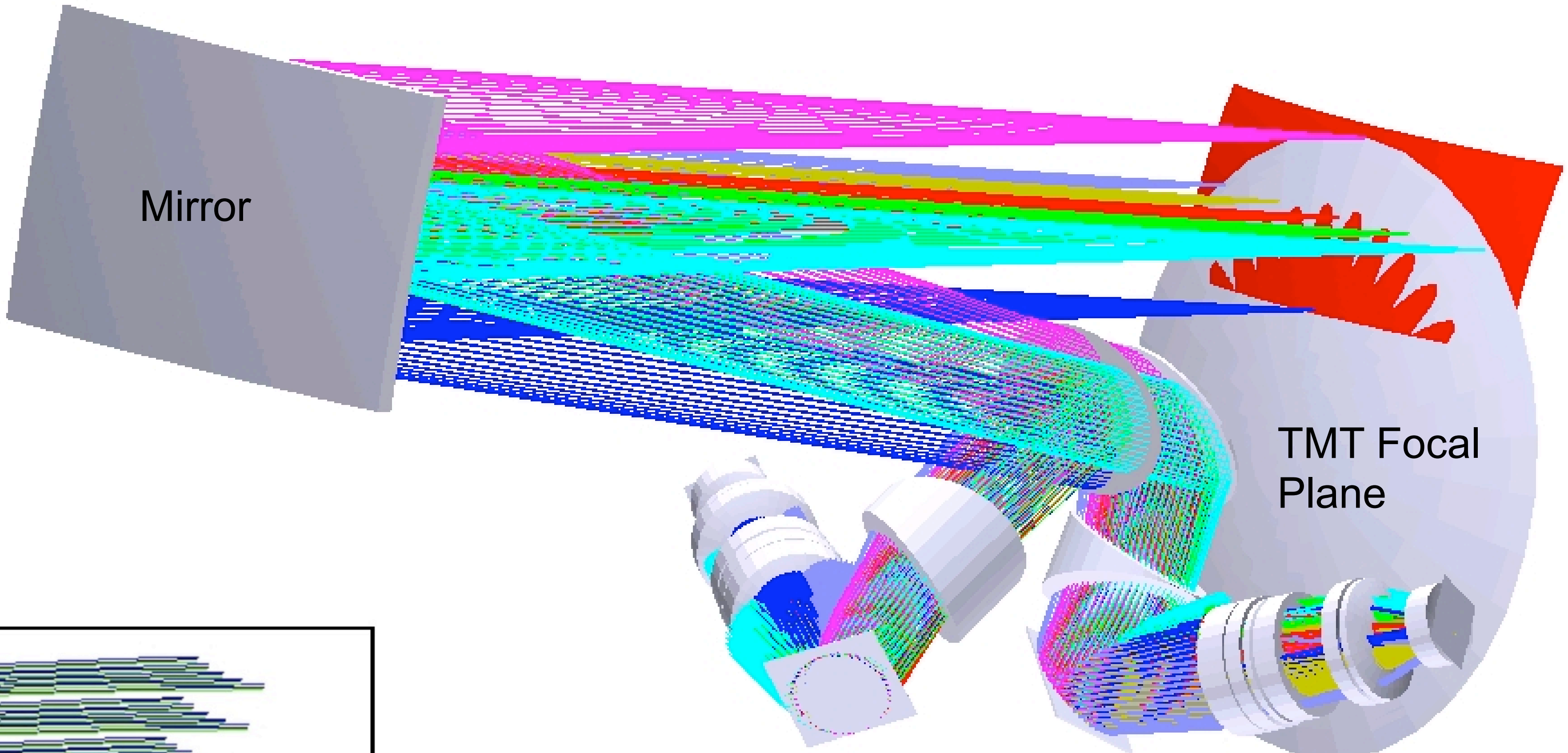
WFOS(-MOBIE) Team

- Rebecca Bernstein (UCSC), Principal Investigator
- Bruce Bigelow (UCSC), Project Manager
- Chuck Steidel (Caltech), Project Scientist
- Science Team
  - Bob Abraham (U. Toronto), Jarle Brinchmann (Leiden), Judy Cohen (Caltech), Sandy Faber, Raja Guhathakurta, Jason Kalirai, Jason Prochaska, Connie Rockosi (UCSC), Gerry Lupino (UH IfA), Alice Shapley (UCLA)
- Second feasibility study completed in December 2008
- Conceptual design under way

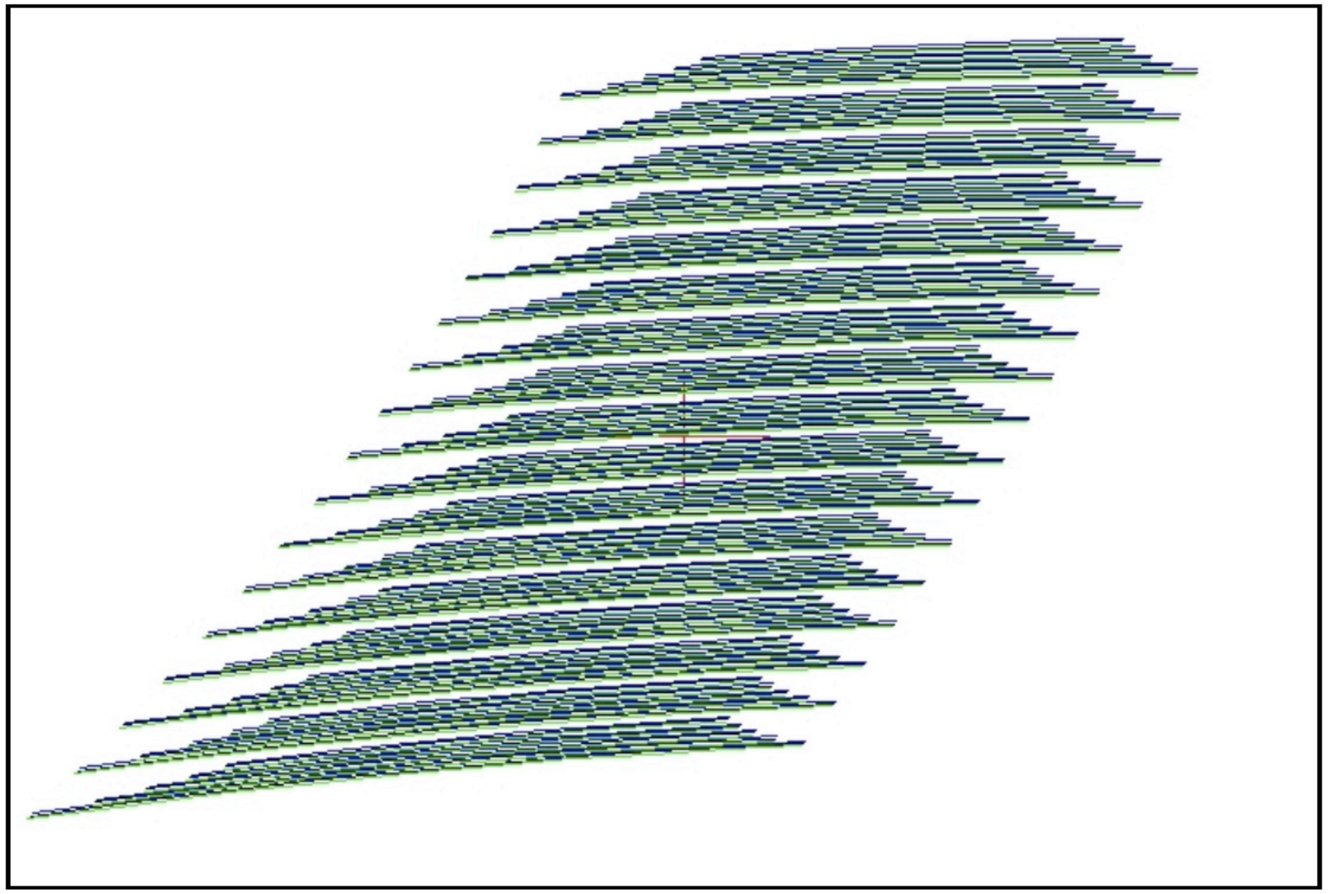
WFOS-MOBIE
Echellette Design



Single field, blue and red arms

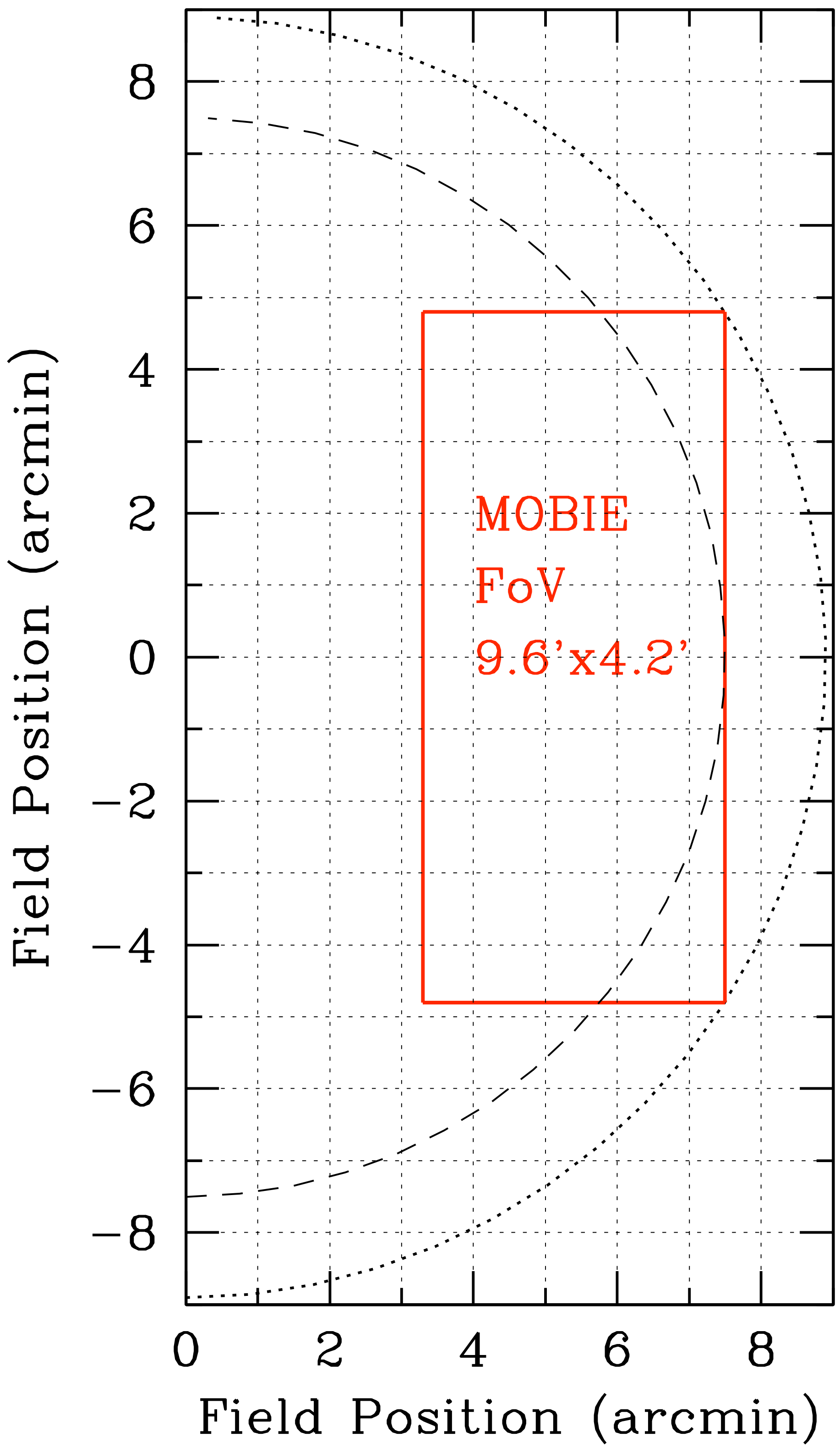
Bernstein et al. 2008, SPIE 2008

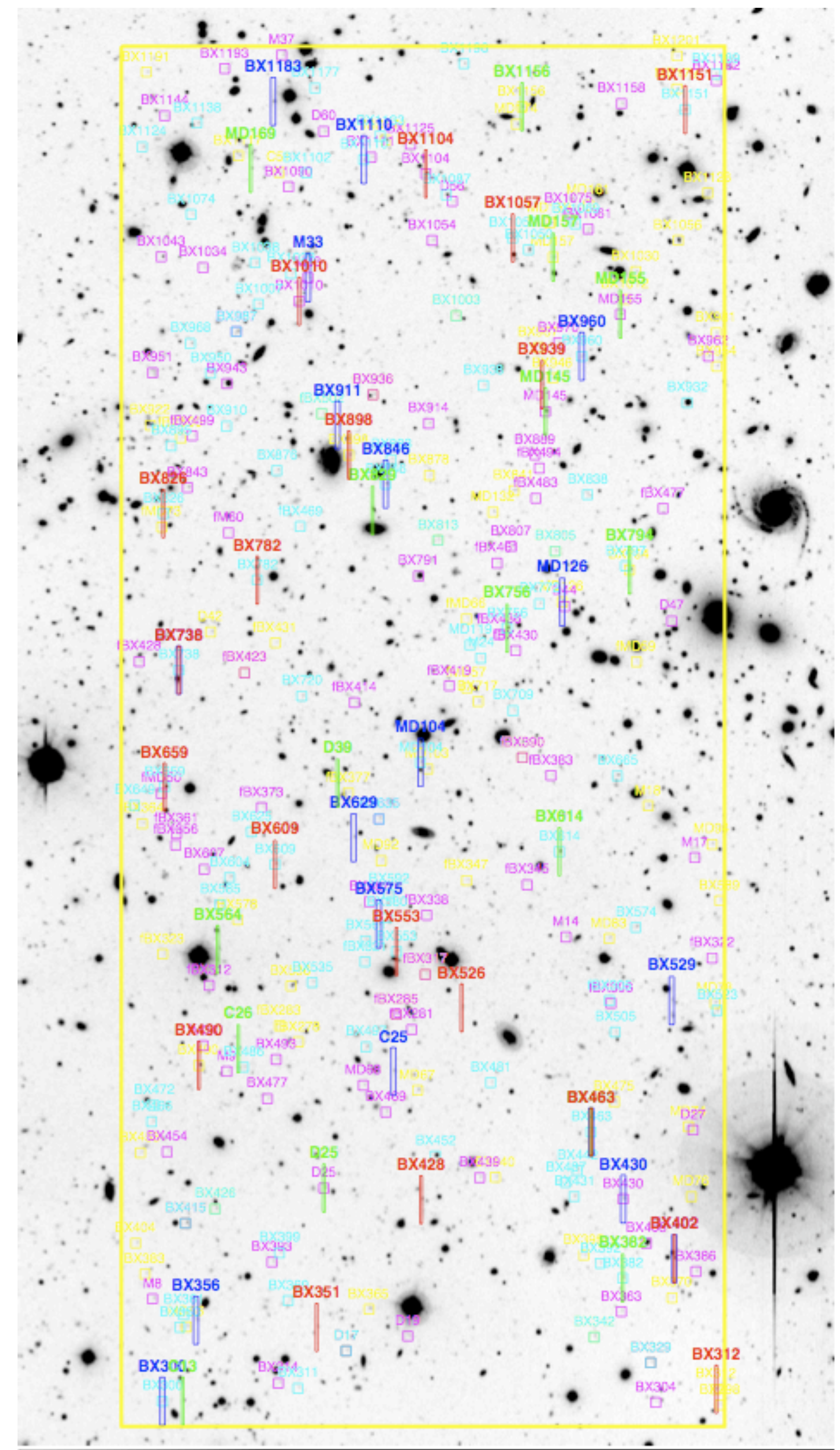
MOBIE can trade multiplexing for expanded wavelength coverage in its higher dispersion mode



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

WFOS-MOBIE Science Field Geometry



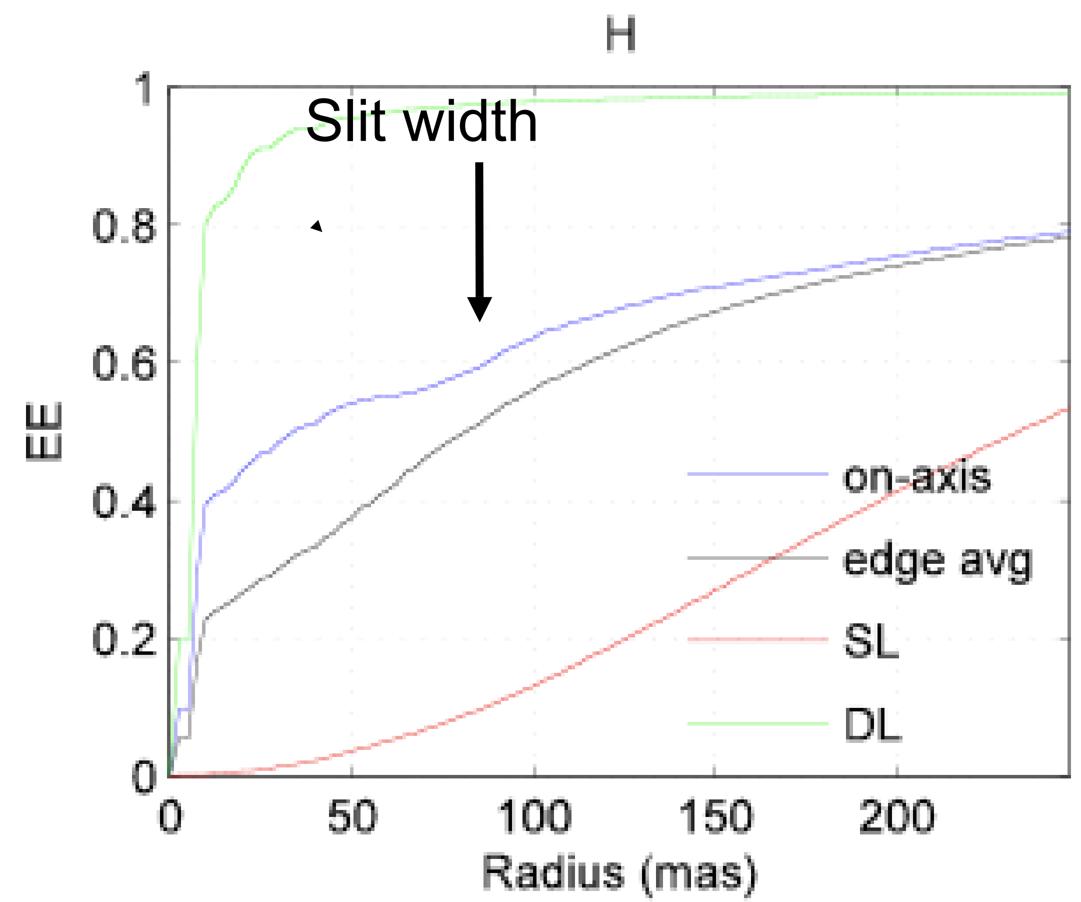


Multi-object mask making simulation

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

- IRMOS (deployable MOAO IFUs) deemed too risky and too expensive for first light

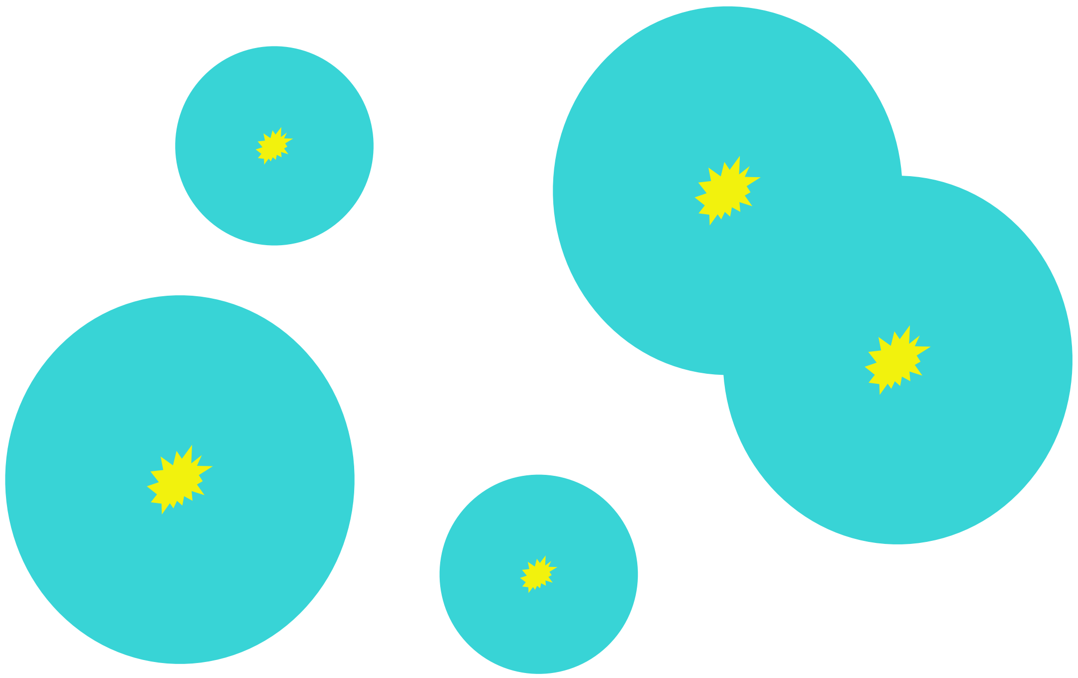
  => IRMS: clone of Keck MOSFIRE; Step 0 towards IRMOS
  - Multi-slit NIR imaging spectro:
    - 46 slits,W:160+ mas, L:2.5”
  - Deployed behind NFIRAOS
    - 2’ field
    - 60mas pixels
    - EE good (80% in K over 30”)
  - Spectral resolution up to 5000
  - Full Y, J, H, K spectra
- Imager as well



Whole 120” field

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

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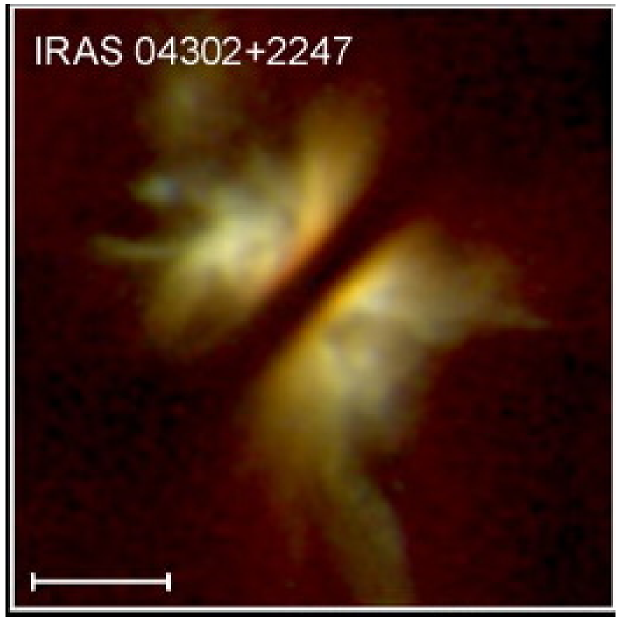
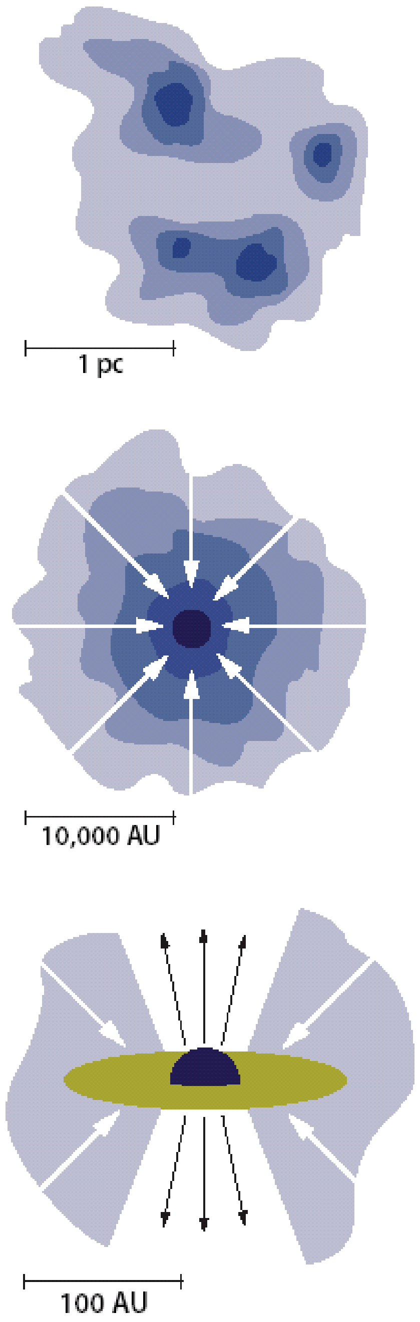
Synergies II. Star Formation

Measuring infall and winds: Stellar masses are set by initial conditions (infall) and "feedback" (winds)

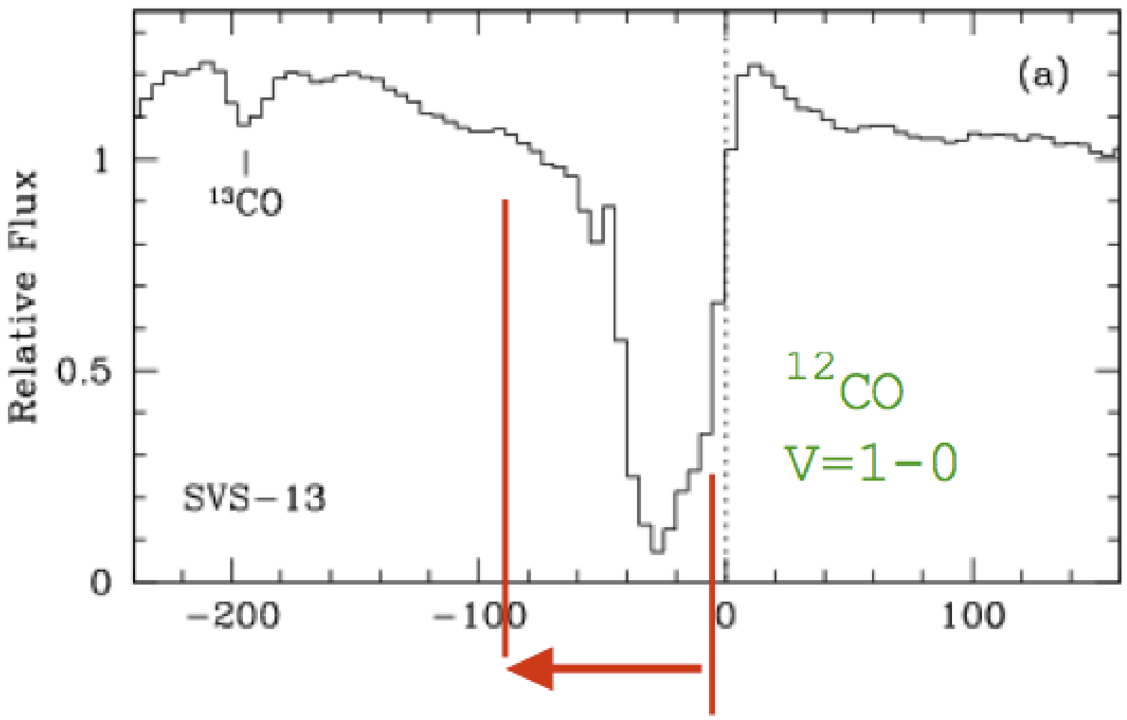


High resolution MIR spectroscopy probes processes that determine stellar masses

Inner spatial scales resolved by velocity profiles



Synergies II. Star Formation (cont.)

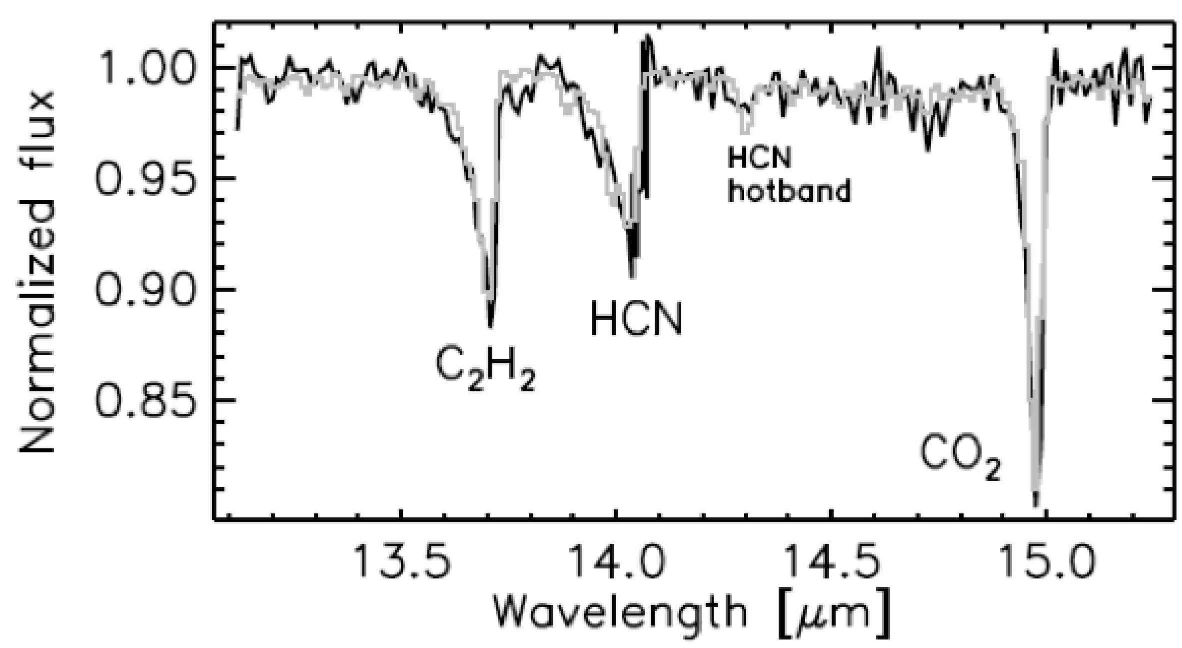


High-velocity outflowing gas in CO towards protostar SVS13 (Keck/ NIRSPEC)

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



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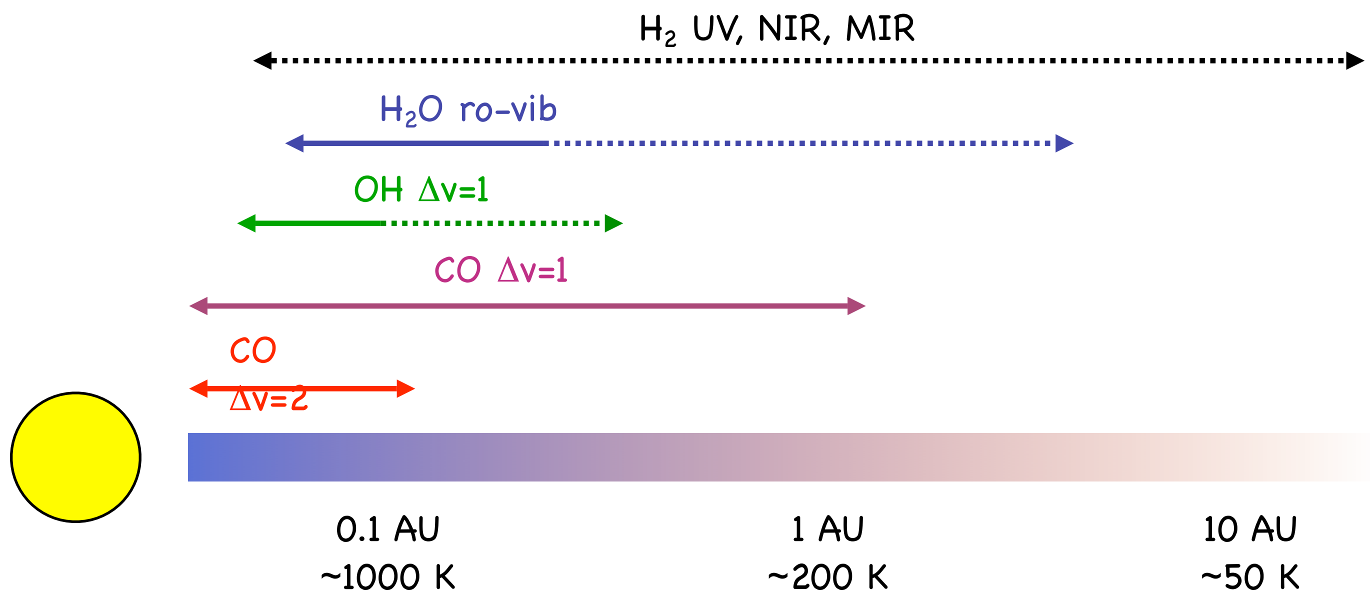
Synergies III. Planet Formation

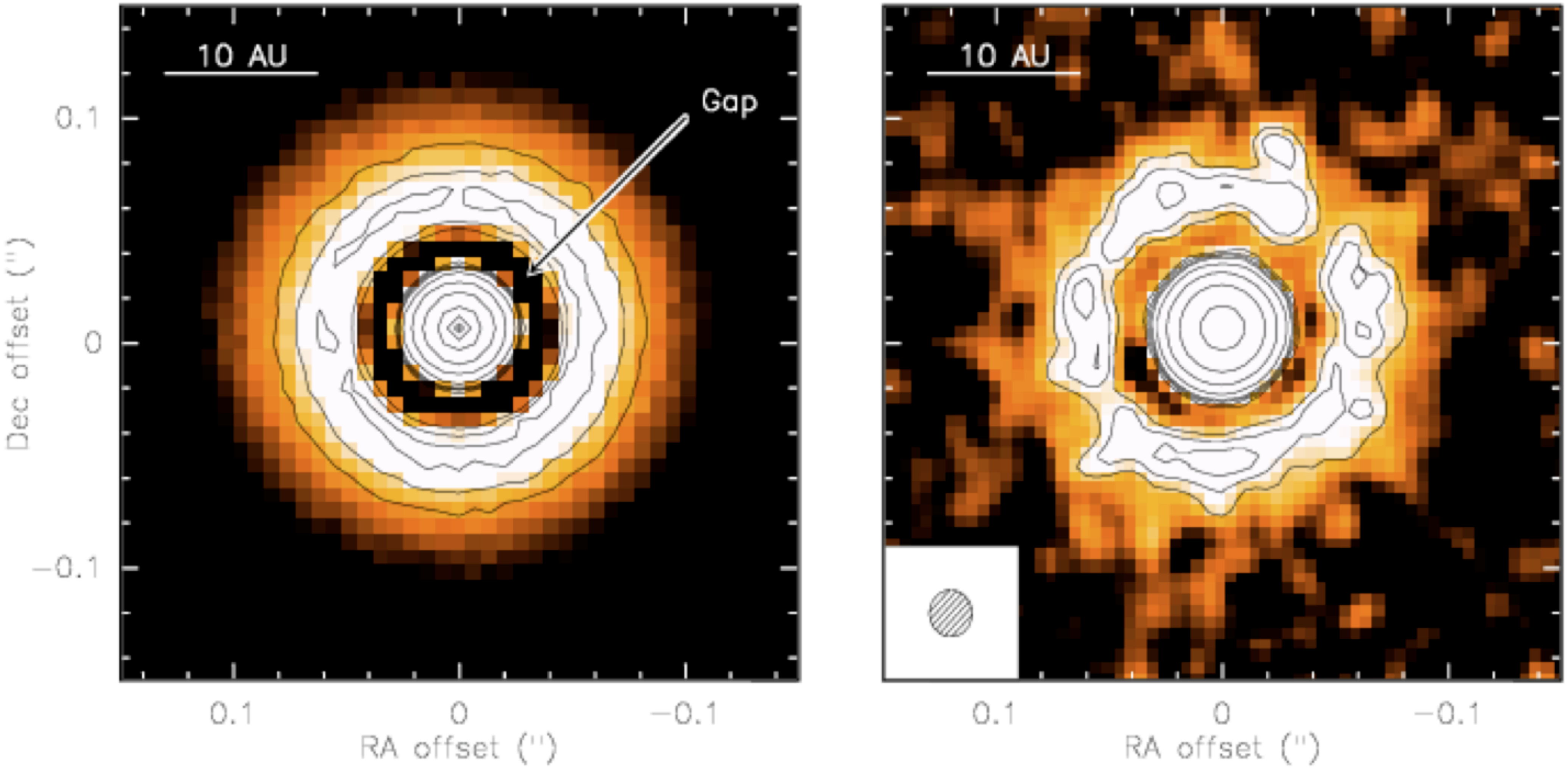
Studying gas in disks:



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

Synergies III. Planet Formation (cont.)



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.

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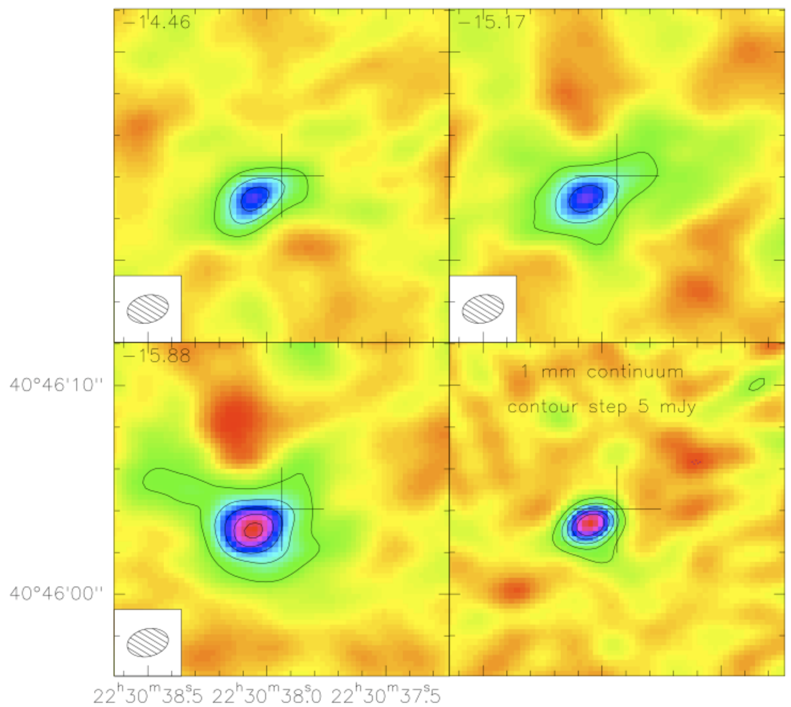
Synergies IV. Solar System

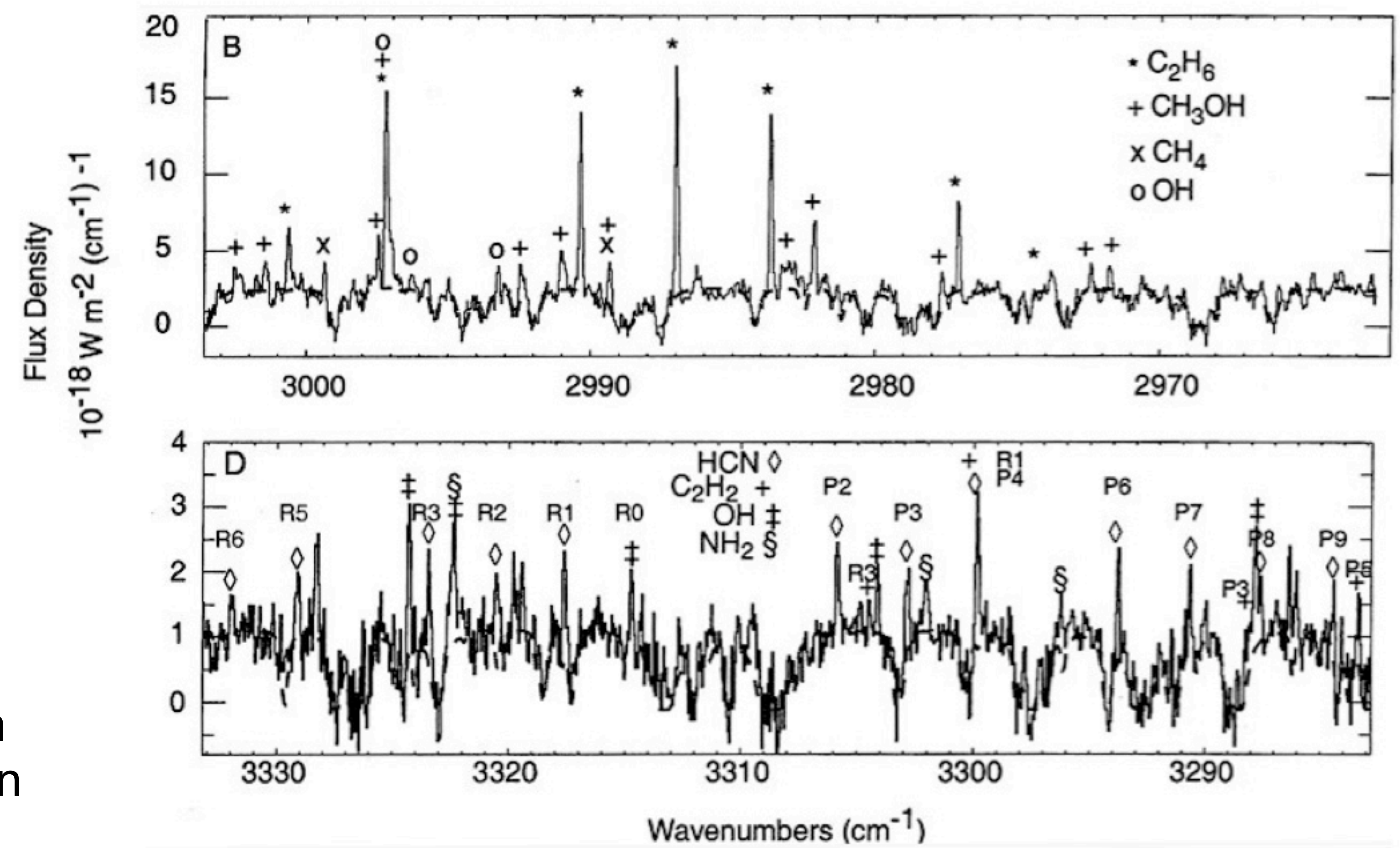
Physics and Chemistry of Cometary Atmospheres



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)

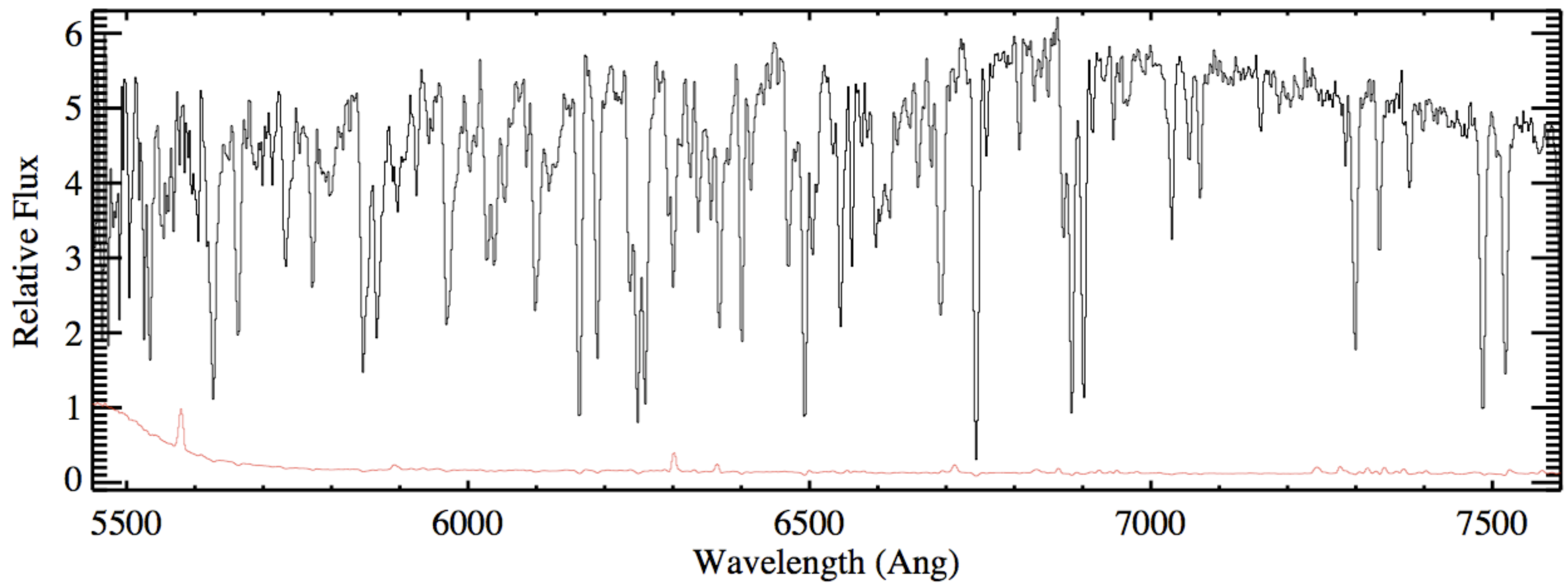


Detection of parent volatiles in Comet Lee (C/1999 H1) at R=20, 000. TMT/NIRES will allow diffraction-limited observations at R=100,000 over the range 4.5 - 28 μm

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

Synergies V. Transient Events

Gamma-Ray Bursts (or other exotic transient phenomena!)



Keck/LRISr spectrum of metal absorption lines related to the gas in the host of a z~3 GRB. This sightline has penetrated a molecular cloud within the host galaxy as evidenced by strong CO bandheads and H_2 transitions (in the blue - not shown).

<u>TMT/MOBIE</u> will establish physical conditions (metallicity, depletion, molecular fraction, etc. etc.) - <u>quick response required</u>!

<u>ALMA</u> will give peak frequency and peak flux density of afterglow emission and geometry of outflow (jet-like or isotropic)

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Synergies VI. A "Rebirth" of Astrometry?

- TMT astrometry:
  - Requirements:
    - 50 microarcsecs in densely populated fields, e.g., Galactic Center
    - 2 milliarcsecs in very sparse fields, i.e., where only wavefront sensor guide stars are available
  - (Some) Science objectives:
    - Test of General Relativity at the Galactic Center
    - Proper motions of stars in dwarf galaxies
    - Binary Kuiper Belt objects

- ALMA astrometry (DRSP):
  - Internal dynamics of LMC and SMC (~ 3mas, 3.2.4)
  - Radio supernovae - precise astrometry will allow optical identification of progenitors (3.5.4)
  - Near-Earth Asteroids and Trans-Neptunian Objects (4.2.7)
  - Dynamical parameters of extrasolar planets (~ 0.1 mas, 4.4.2/4.4.3)

TMT Foundation Documents

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

- Detailed Science Case
- Observatory Requirements Document
- Observatory Architecture Document
- Operations Concept Document
- TMT Construction Proposal

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Acknowledgments

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