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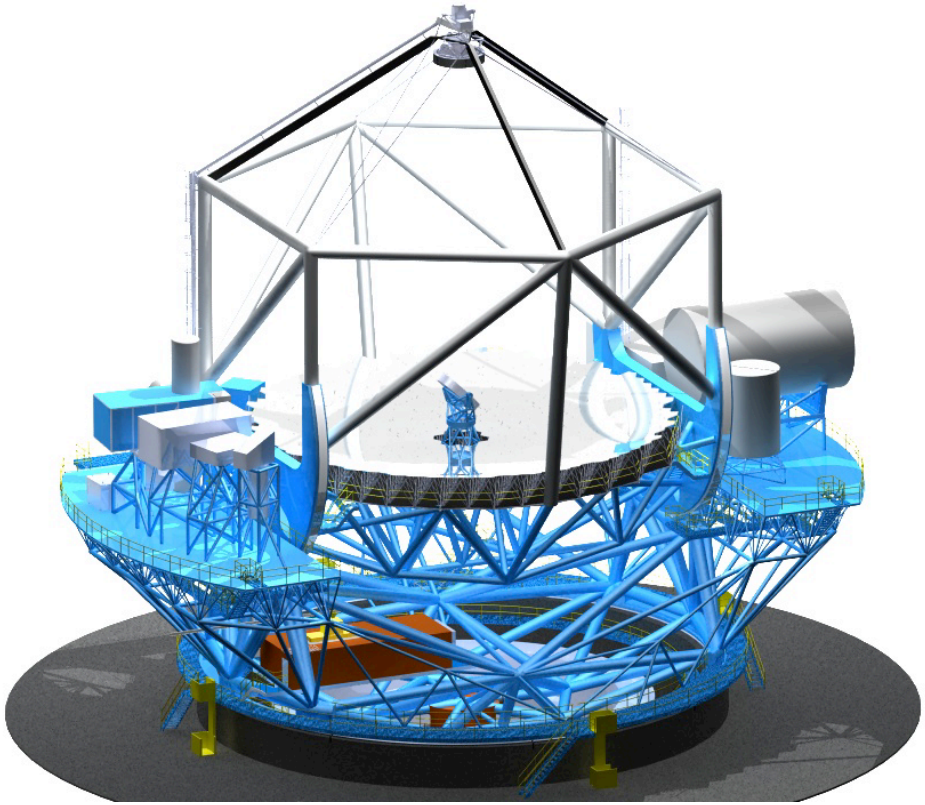

Imaging at TMT

Luc Simard

"Imaging at the E-ELT Workshop"

ESO-Garching, May 29, 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

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

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

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

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Packaging Capabilities - TMT SRD 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

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Packaging Capabilities - TMT SRD 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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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)	[illegible]	[illegible]	• Origin of stellar masses • [illegible]retion and outflows around protostars • [illegible]lution of gas in protoplanetary disks
Planet Formation Instrument (PFI)	1 – 2.5 1 – 5 (goal)	0″.05 inner working angle	R≤100	• [illegible] 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

Visible, Seeing-Limited

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Packaging Capabilities - TMT SRD 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 z < 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	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)	angle		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

Near-IR, AO-assisted

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Packaging Capabilities - TMT SRD 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	R=4660 @ 0.16	• Early Light • Epoch of peak galaxy building • JWST follow-ups
Deployable, multi-IFU, near-IR spectrometer (IRMOS)	0.8 – 2.5			• Early Light • Epoch of peak galaxy building • JWST follow-ups
Mid-IR AO-fed Echelle spectrometer (MIRES)	8 – 18 4.5 – 28 (goal)	3″ slit length 10″ imaging	5000-100000	• Origin of stellar masses • Accretion and outflows around protostars • Evolution of gas in protoplanetary disks
Planet Formation Instrument (PFI)	1 – 2.5 1 – 5 (goal)	1″ outer working angle, 0″.05 inner working angle	R≤100	• 10^8 contrast ratio (10^9 goal) • Direct detection and spectroscopic characterization of exoplanets
Near-IR AO-fed echelle spectrometer (NIRES)	1 - 5	2″ slit length	20000-100000	• IGM at z > 7, gamma-ray bursts • Local Group abundances • Abundances, chemistry and kinematics of stars and planet-forming disks • Doppler detection of terrestrial planets around low-mass stars
High-Resolution Optical Spectrometer (HROS)	0.31 – 1.1	5″ slit length	50000	• Doppler searches for exoplanets • Stellar abundance studies in Local Group • ISM abundance/kinematics • IGM characteristics to z~6
“Wide”-field AO imager (WIRC)	0.8 – 5.0	30″ imaging field	5-100	• Precision astrometry (e.g., Galactic Center) • Resolved stellar populations out to 10 Mpc

High-Contrast AO

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Packaging Capabilities - TMT SRD Instrument Suite

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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
Wide-field Optical spectrometer and imager (WFOS)	0.31 – 1.0	>40 arcmin^2 >100 arcmin^2 (goal) Slit length>500″	1000-5000@0.75″ slit >7500 @0.75″ (goal)	• IGM structure and composition at 2 < z < 6 • Stellar populations, chemistry and energetics of z > 1.5 galaxies
InfraRed Multislit Spectrometer (IRMS)	0.95 –			ight of peak galaxy building follow-ups
Deployable, multi-IFU, near-IR spectrometer (IRMOS)	0.8 – 2.5	3″ IFUs over >5′ diameter field	2000-10000	• Early Light • Epoch of peak galaxy building • JWST follow-ups
Mid-IR AO-fed Echelle spectrometer (MIRES)	8 – 18 4.5 – 28 (goal)	3″ slit length 10″ imaging	5000-100000	• Origin of stellar masses • Accretion and outflows around protostars • Evolution of gas in protoplanetary disks
Planet Formation Instrument (PFI)	1 – 2.5 1 – 5 (goal)	1″ outer working angle, 0″.05 inner working angle	R≤100	• 10^6 contrast ratio (10^7 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

Mid-infrared, AO-assisted

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Packaging Capabilities - TMT SRD 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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"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

Imaging Capabilities

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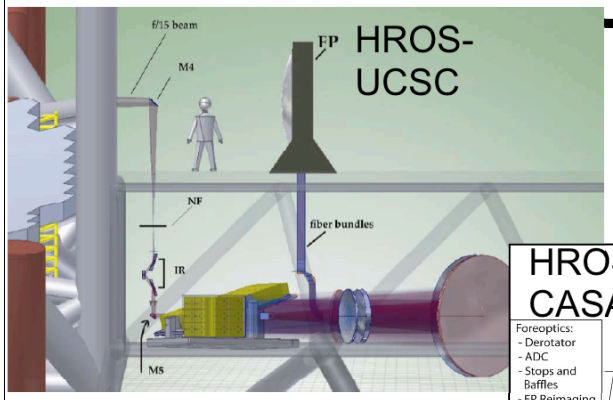
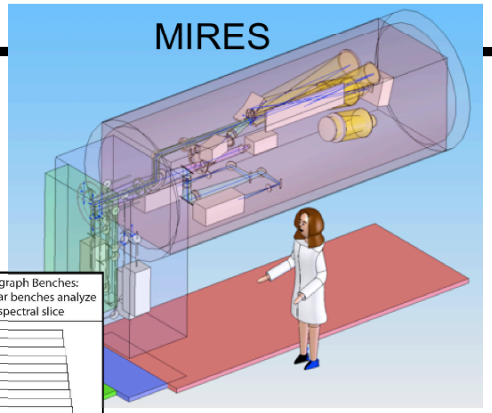
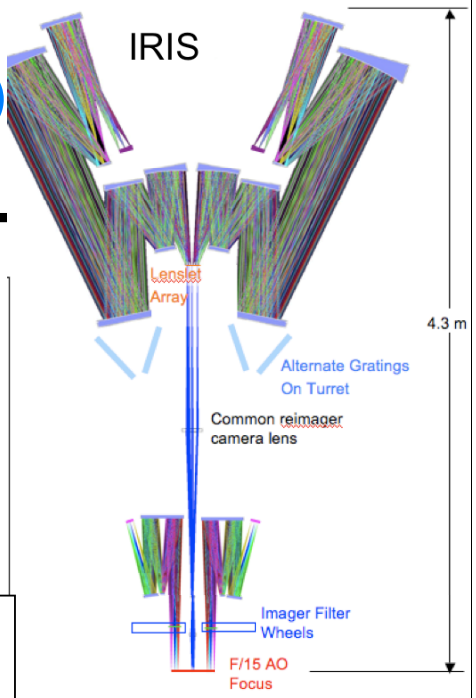
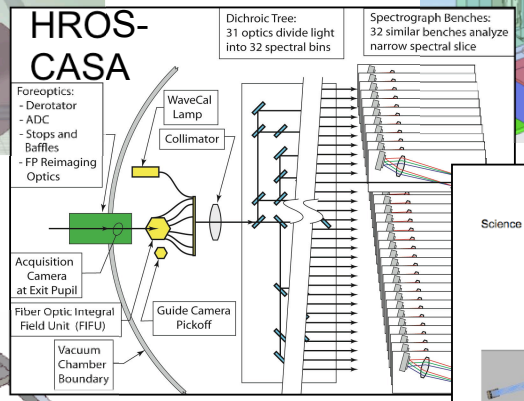
Feasibility studies 2005-6
(concepts, requirements, performance,…)

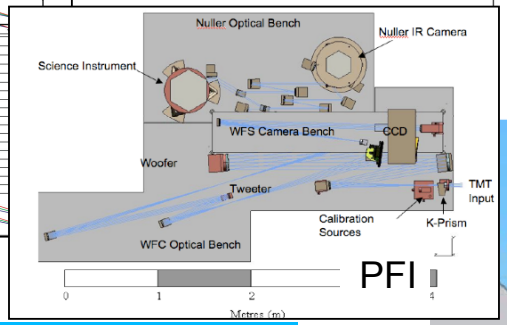


HROS-UCSC

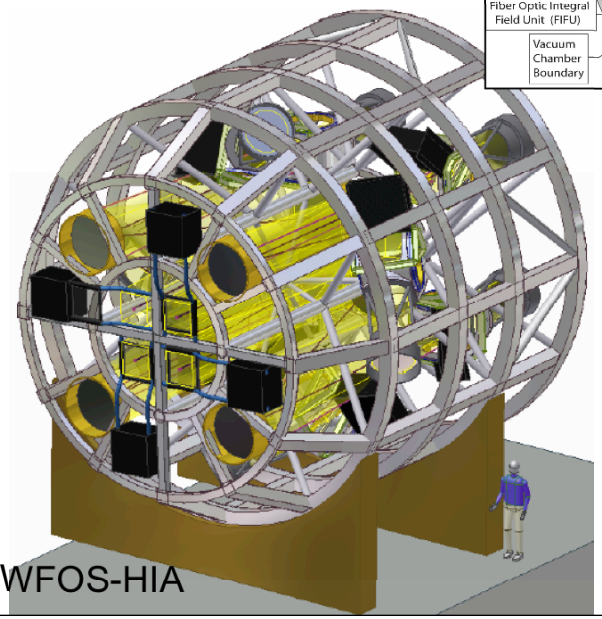

MIRES







PFI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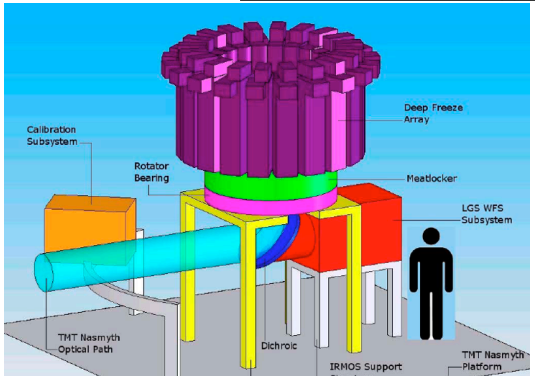
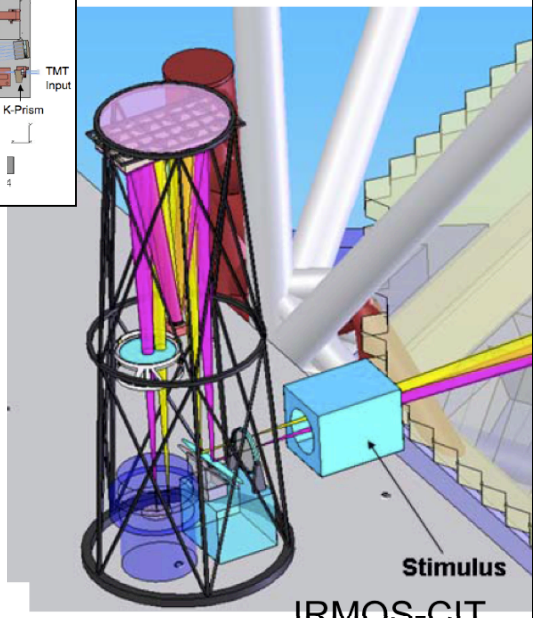


IRMOS-UF



IRMOS-CIT

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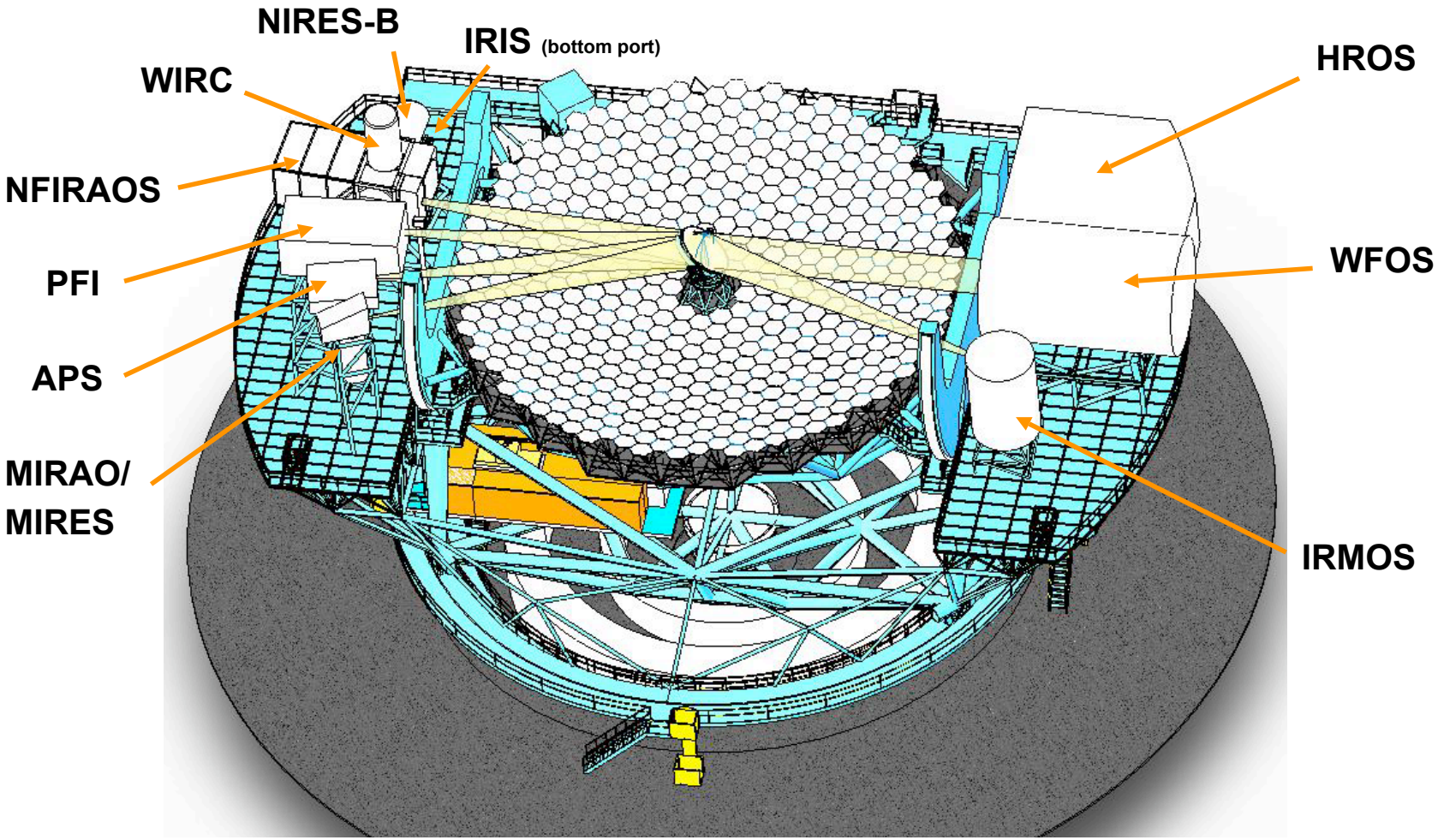
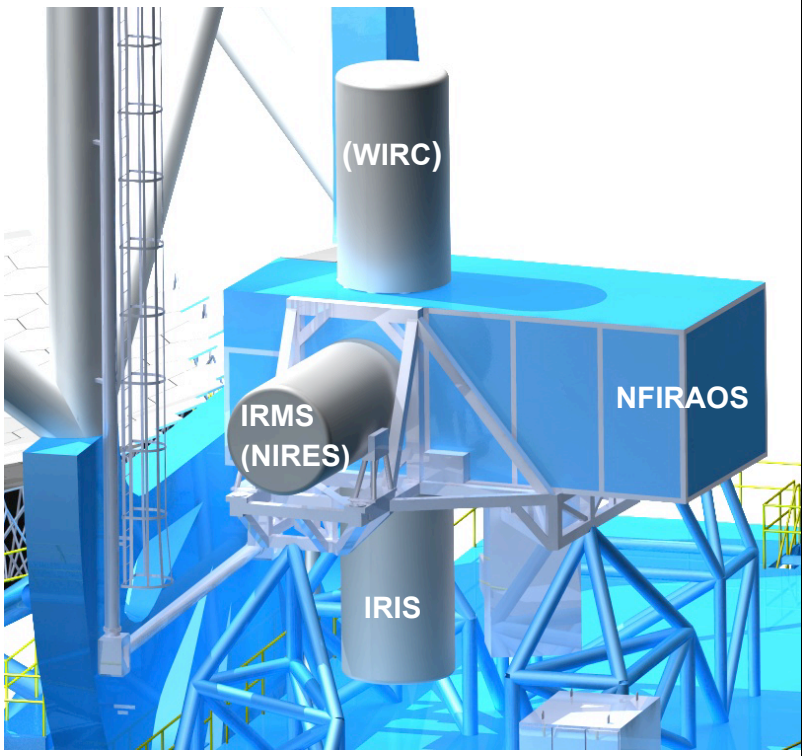
Nasmyth Configuration: First Decade Instrumentation Suite



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

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A "Rebirth" of Astrometry

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

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

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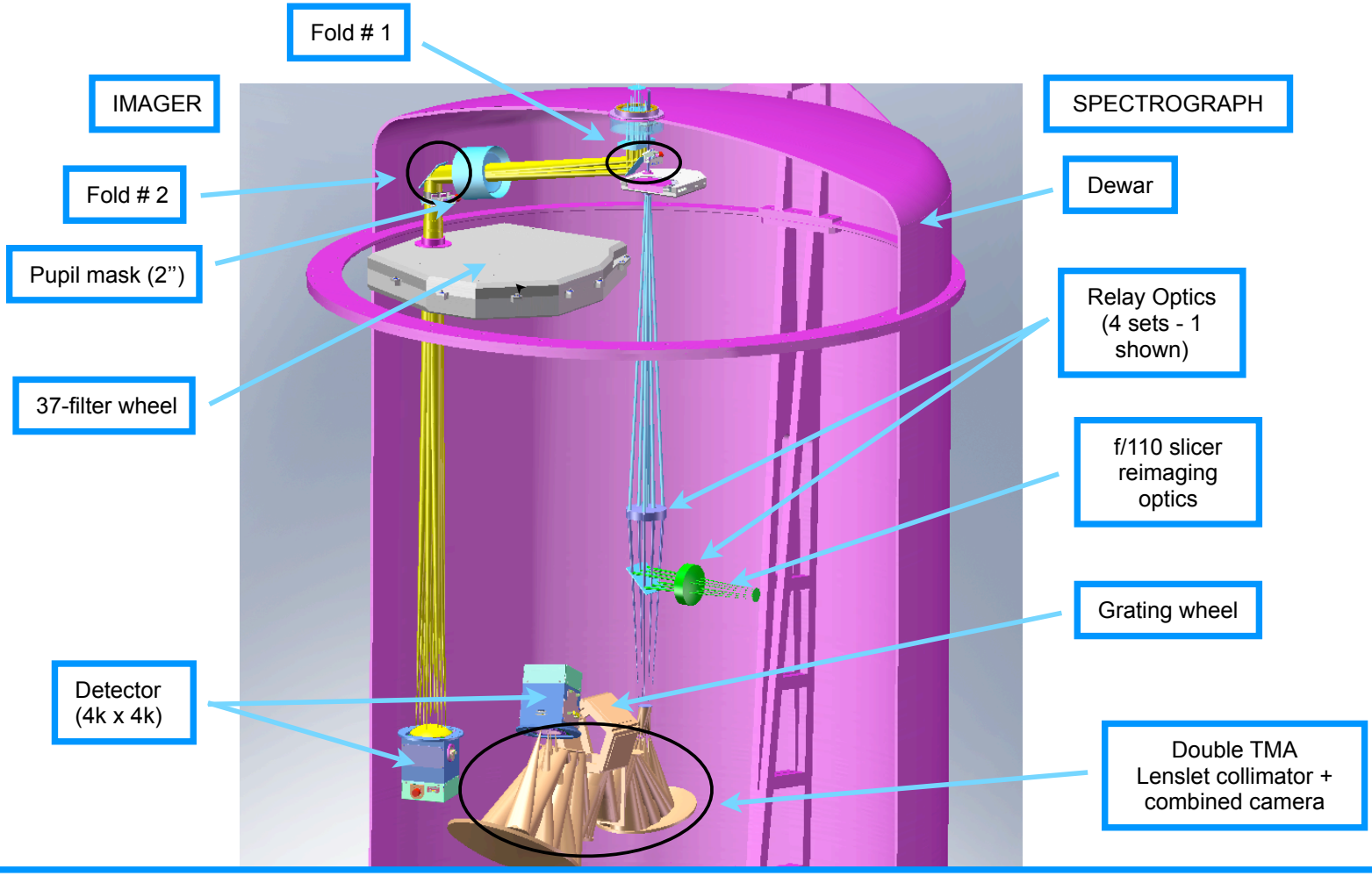
InfraRed Imager and Spectrometer (IRIS)



J. Larkin (UCLA, PI), A. Moore (Caltech, co-PI), B. Barton (UCI, PS), Suzuki/Konishi/ Usuda (Subaru, imager)

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IRIS Top-Level Requirements

Requirement #	Description	Requirement
[REQ-1-ORD-3740]	Wavelength Range	0.8 – 2.5 μm
[REQ-1-ORD-3745]	Image quality	Aberrations uncorrectable by an order 60x60 AO system should not add wavefront errors larger than 30 nm RMS
[REQ-1-ORD-3750]	Field of View, IFU	Up to 3 arcsec for integral field mode
[REQ-1-ORD-3755]	Field of View, Imaging	15x15 arcsec for imaging mode
[REQ-1-ORD-3760]	Detector Sampling	0.004 arcsec per pixel (Nyquist sampled (λ/2D)) over 4096 pixels for IFU)
[REQ-1-ORD-3765]	Detector Sampling	Plate scale adjustable 0.004, 0.010, 0.025, 0.050 arcsec/pixel for IFU
[REQ-1-ORD-3770]	Detector Sampling	Nyquist sampled (λ/2D) (0.004 arcsec) over 10x10 arcsec for imaging
[REQ-1-ORD-3775]	Detector Sampling	Smaller wavelength coverage ($\Delta\lambda/\lambda \leq 0.05$) is acceptable for area coverage equivalent to 128*128 spatial pixels.
[REQ-1-ORD-3780]	Spectral Resolution	R=4000 over J,H,K bands, one band at a time R=5-100 for imaging mode
[REQ-1-ORD-3785]	Throughput	>30%, Not including telescope or NFIRAOS
[REQ-1-ORD-3790]	Instrument background	The instrument should not increase the (inter-OH) background by more than 5% (TBC) over the sum of: inter-OH sky, telescope and NFIRAOS background.
[REQ-1-ORD-3795]	Detector	Detector dark current and read noise should not increase the effective background by more than 5% for an integration time of 2000s.

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IRIS Top-Level Requirements

Requirement #	Description	Requirement
[REQ-1-ORD-3740]	Wavelength Range	0.8 – 2.5 μm
[REQ-1-ORD-3745]	Image quality	Aberrations uncorrectable by an order 60x60 AO system should not add wavefront errors larger than 30 nm RMS
[REQ-1-ORD-3750]	Field of View, IFU	Up to 3 arcsec for integral field mode
[REQ-1-ORD-3755]	Field of View, Imaging	15x15 arcsec for imaging mode
[REQ-1-ORD-3760]	Detector Sampling	0.004 arcsec per pixel (Nyquist sampled (λ/2D)) over 4096 pixels for IFU)
[REQ-1-ORD-3765]	Detector Sampling	Plate scale adjustable 0.004, 0.010, 0.025, 0.050 arcsec/pixel for IFU
[REQ-1-ORD-3770]	Detector Sampling	Nyquist sampled (λ/2D) (0.004 arcsec) over 10x10 arcsec for imaging
[REQ-1-ORD-3775]	Detector Sampling	Smaller wavelength coverage ($\Delta\lambda/\lambda \leq 0.05$) is acceptable for area coverage equivalent to 128*128 spatial pixels.
[REQ-1-ORD-3780]	Spectral Resolution	R=4000 over J,H,K bands, one band at a time R=5-100 for imaging mode
[REQ-1-ORD-3785]	Throughput	>30%, Not including telescope or NFIRAOS
[REQ-1-ORD-3790]	Instrument background	The instrument should not increase the (inter-OH) background by more than 5% (TBC) over the sum of: inter-OH sky, telescope and NFIRAOS background.
[REQ-1-ORD-3795]	Detector	Detector dark current and read noise should not increase the effective background by more than 5% for an integration time of 2000s.

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WIRC Top-Level Requirements

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.

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WIRC Top-Level Requirements

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-48		ntage 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.

WIRC and IRIS may be combined

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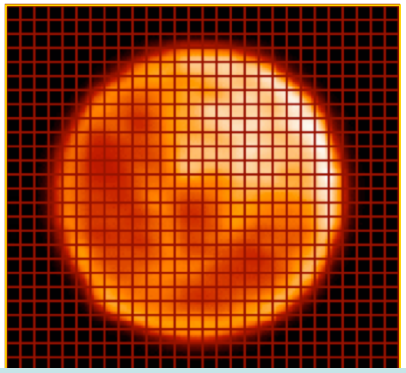
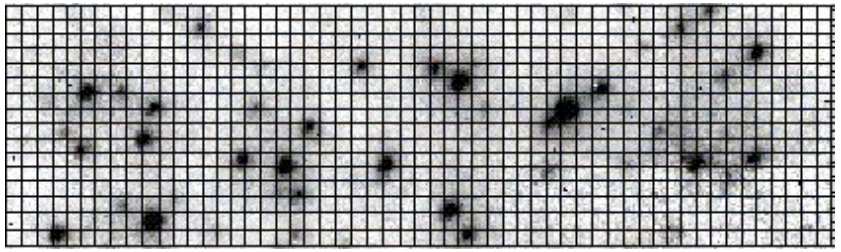
Motivation for IRIS

- Unprecedented ability to investigate objects on small scales.

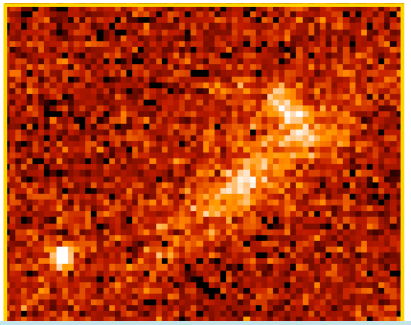
0.01" @	5 AU	= 36 km	(Jovian's and moons)
	5 pc	= 0.05 AU	(Nearby stars – companions)
	100 pc	= 1 AU	(Nearest star forming regions)
	1 kpc	= 10 AU	(Typical Galactic Objects)
	8.5 kpc	= 85 AU	(Galactic Center or Bulge)
	1 Mpc	= 0.05 pc	(Nearest galaxies)
	20 Mpc	= 1 pc	(Virgo Cluster)
	z=0.5	= 0.07 kpc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

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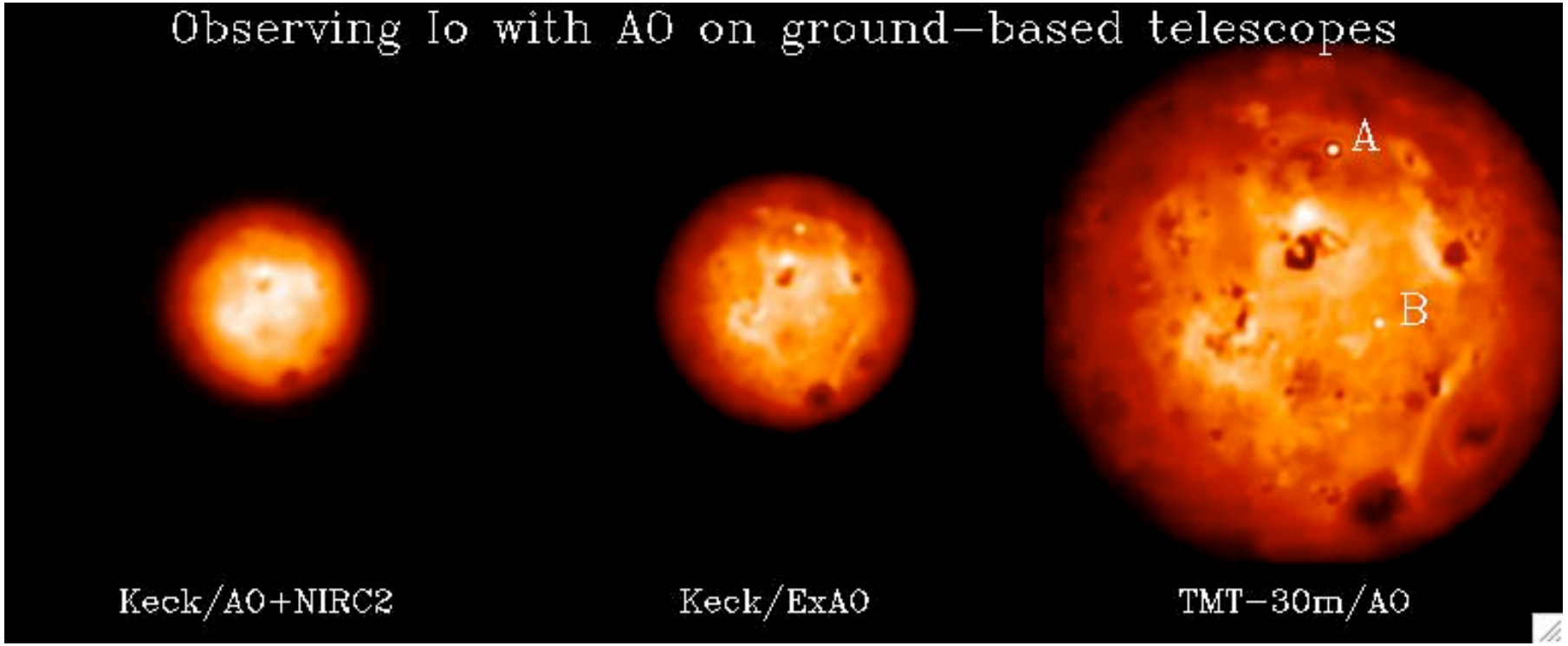
Io with TMT/IRIS



Simulations of Io Jupiter-facing hemisphere in H band. (courtesy of Franck Marchis)

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

Resolved Stellar Populations in Virgo

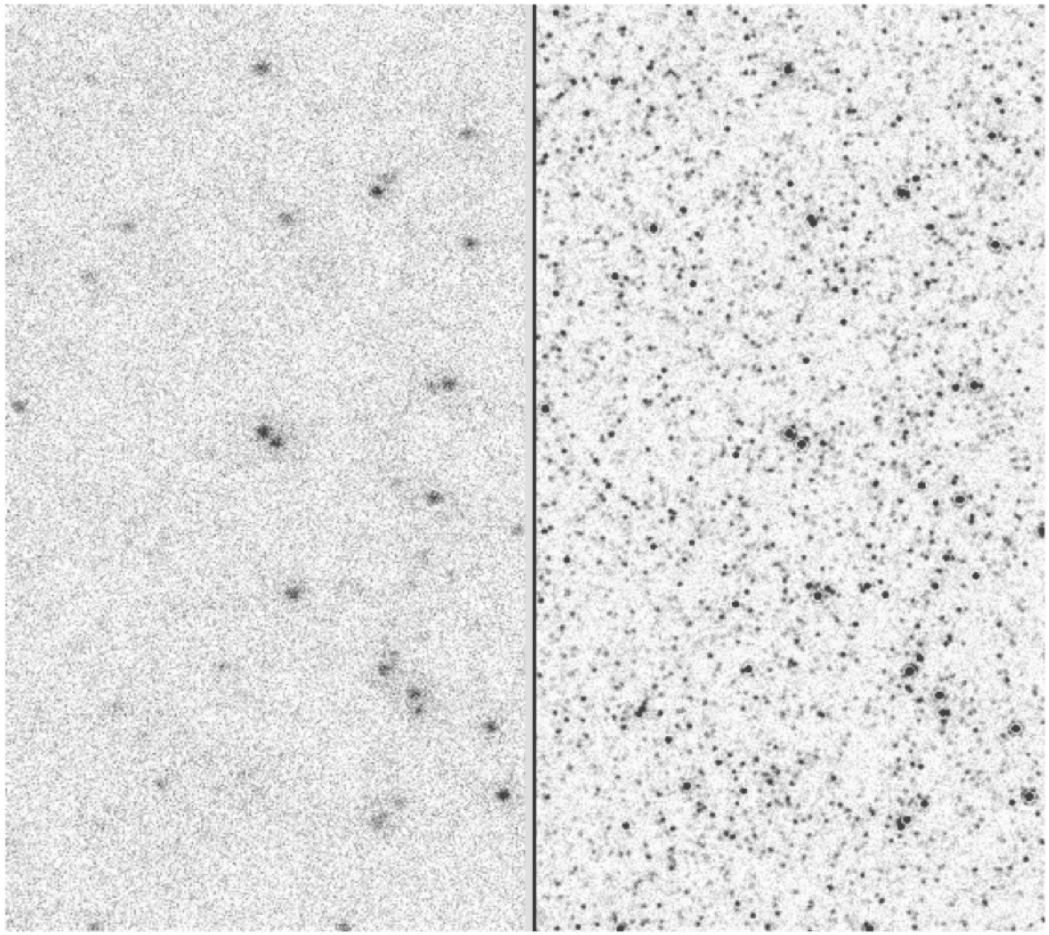
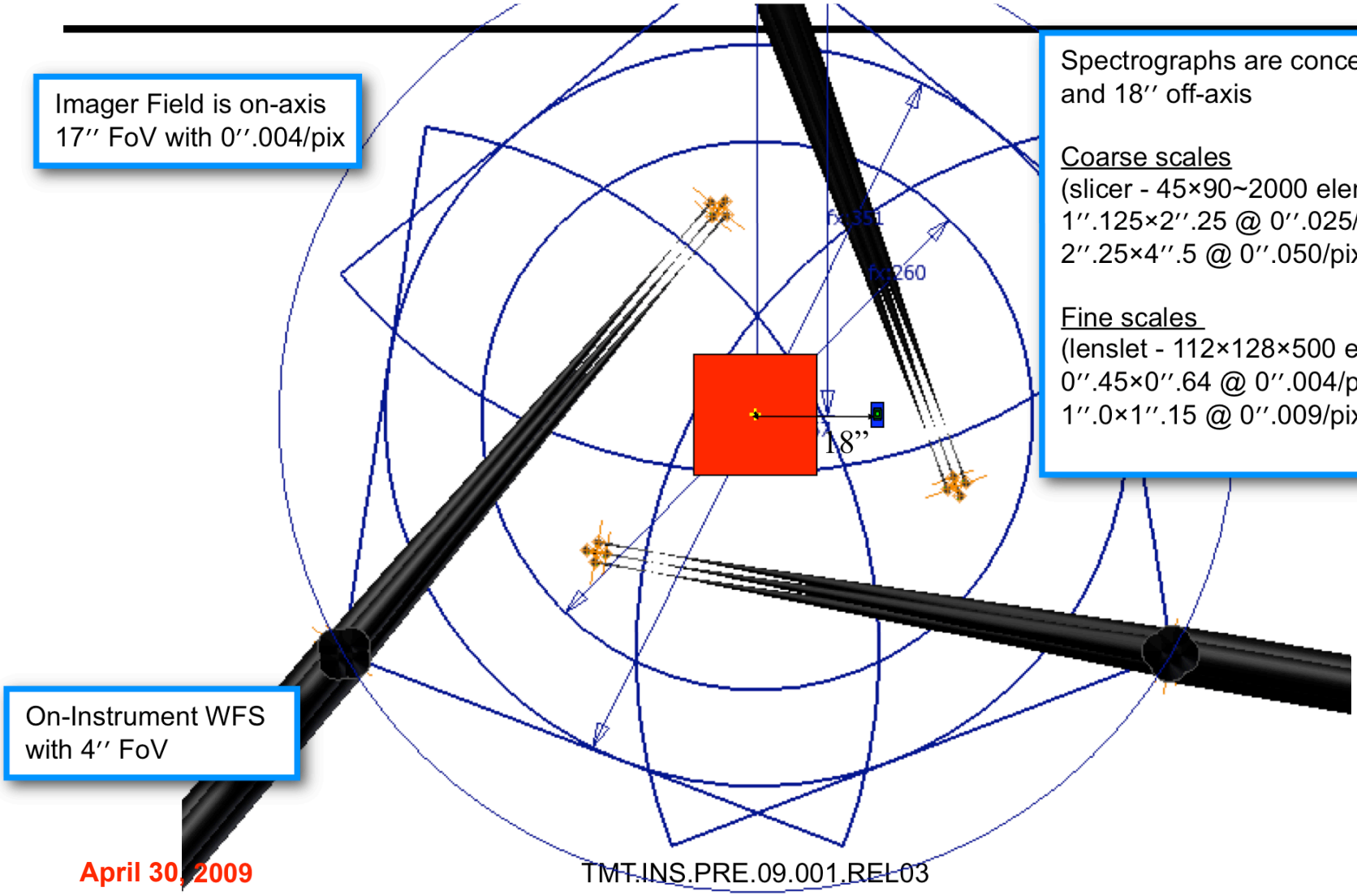


Figure 5: Simulations of a 5 x 10 arcsec^2 field in a Virgo cluster spheroid at a location with a surface brightness in V of 22 magnitudes arcsec^{-2}. The right hand panel shows the result of observing with IRIS + NFIRAOS on the TMT with a three hour exposure time. The substrate of faint objects are stars on the RGB, which can be used to measure the MDF in this galaxy. The left hand panel shows the same field but observed with an 8 metre telescope with an AO system having the same Strehl ratio for 3 hours. Note that only the brightest AGB stars are detected with an 8 metre aperture.

Overall Field Geometry

Imager Field is on-axis
17′′ FoV with 0′′.004/pix



Spectrographs are concentric and 18′′ off-axis

Coarse scales
(slicer - 45×90~2000 elements):
1′′.125×2′′.25 @ 0′′.025/pix
2′′.25×4′′.5 @ 0′′.050/pix

Fine scales
(lenslet - 112×128×500 elements):
0′′.45×0′′.64 @ 0′′.004/pix
1′′.0×1′′.15 @ 0′′.009/pix

On-Instrument WFS
with 4′′ FoV

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Point Source Sensitivities

- Spectroscopy for S/N per spectral channel of 10, between OH lines, assuming an aperture of 2 (λ/D)

S/N ~10

Filter	Scale (mas)	Exp. Time (secs)	Number of Frames	Magnitude (AB)
J	4	900	4	25.7
H	4	900	4	25.8
K	4	300	12	24.2

- Imager for a S/N of 100 assuming an aperture of 2 (λ/D)

S/N ~100

Filter	Exp. Time (secs)	Number of Frames	Magnitude (AB)
J	900	4	27.3
H	900	4	26.2
K	900	4	25.5

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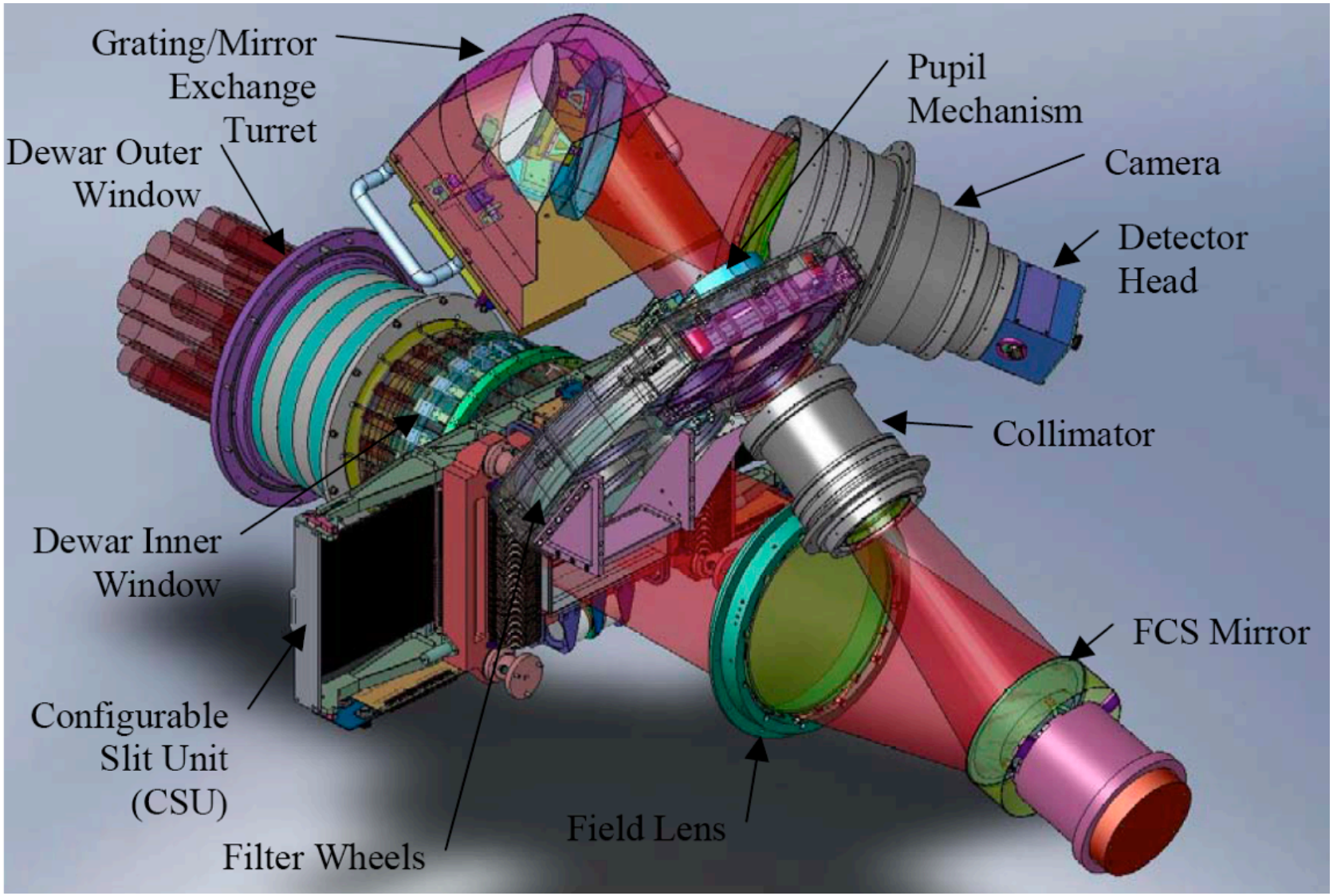
InfraRed Multi-slit Spectrometer (IRMS aka MOSFIRE)

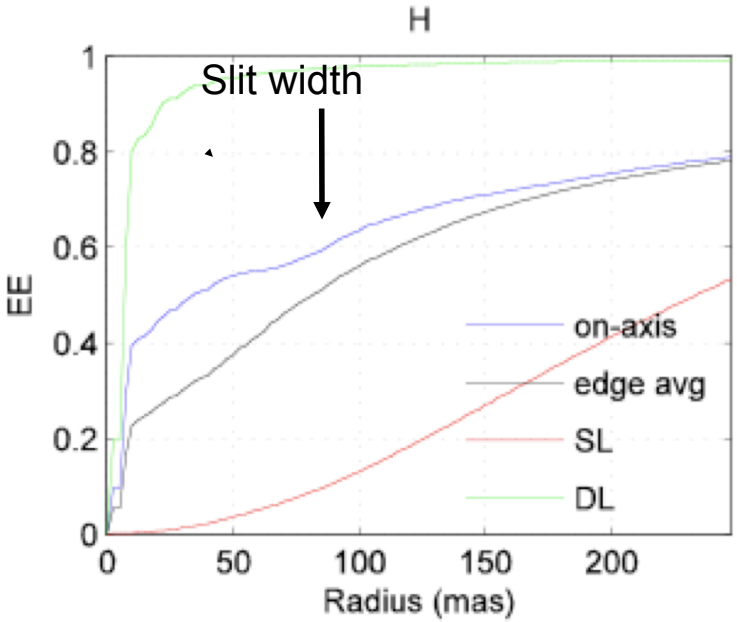


IRMS + NFIRAOS

- 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

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IRMS Top-Level Requirements

Requirement #	Description	Requirement
[REQ-1-ORD-3840]	Wavelength Range	The instrument shall operate over the Y, J, H, K bands.
[REQ-1-ORD-3845]	Wavelength Coverage	The instrument shall cover an entire band at a time.
[REQ-1-ORD-3850]	Image quality	Aberrations uncorrectable by an order 60x60 AO system should not add wavefront errors larger than 30 nm RMS
[REQ-1-ORD-3855]	Field of View	Shall utilize the 2 arcminute NFIRAOS technical field.
[REQ-1-ORD-3860]	Spectral Resolution	R>3000 with a 120 milliarcsecond slit
[REQ-1-ORD-3865]	Throughput	> 35%, not including telescope or NFIRAOS
[REQ-1-ORD-3870]	Imaging mode	Shall provide imaging over the full field of NFIRAOS

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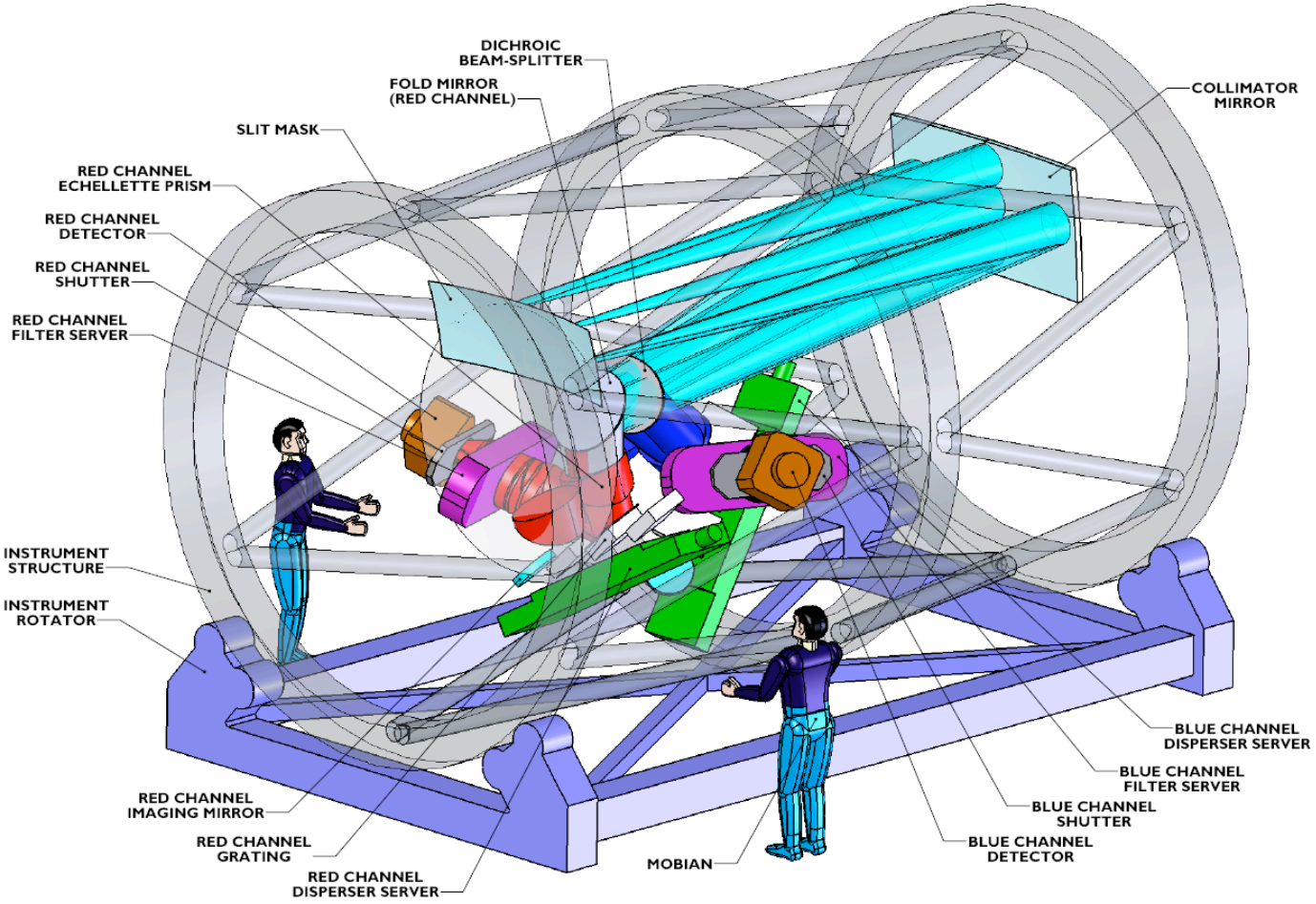
Wide Field Optical Spectrometer (WFOS)



R. Bernstein (UCSC, PI), C. Steidel (Caltech, PS), B. Bigelow (UCSC, PM)

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WFOS Top-Level Requirements

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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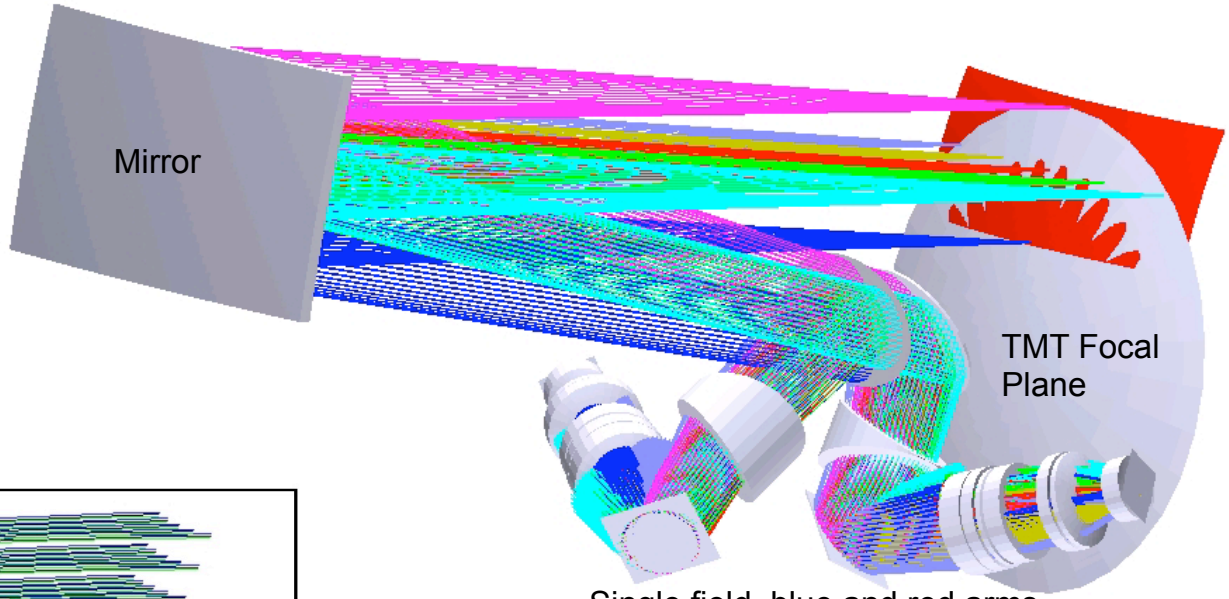
WFOS Top-Level Requirements

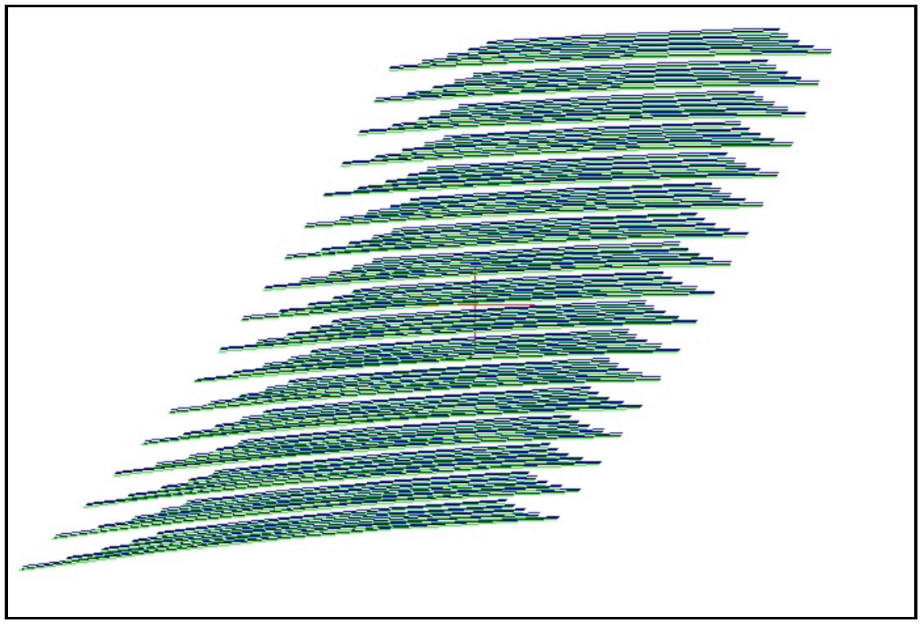
Requirement #	Description	Requirement
[REQ-1-ORD-3950]	Wavelength Range	0.31 – 1.0μm
[REQ-1-ORD-3955]	Image quality: Imaging	≤ 0.2 arcsec FWHM over any 0.1μm wavelength interval (including contributions from the telescope and the ADC at z=60°)
[REQ-1-ORD-3960]	Image quality: Spectroscopy	≤ 0.2 arcsec 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.

WFOS-MOBIE
Echellette Design



Single field, blue and red arms

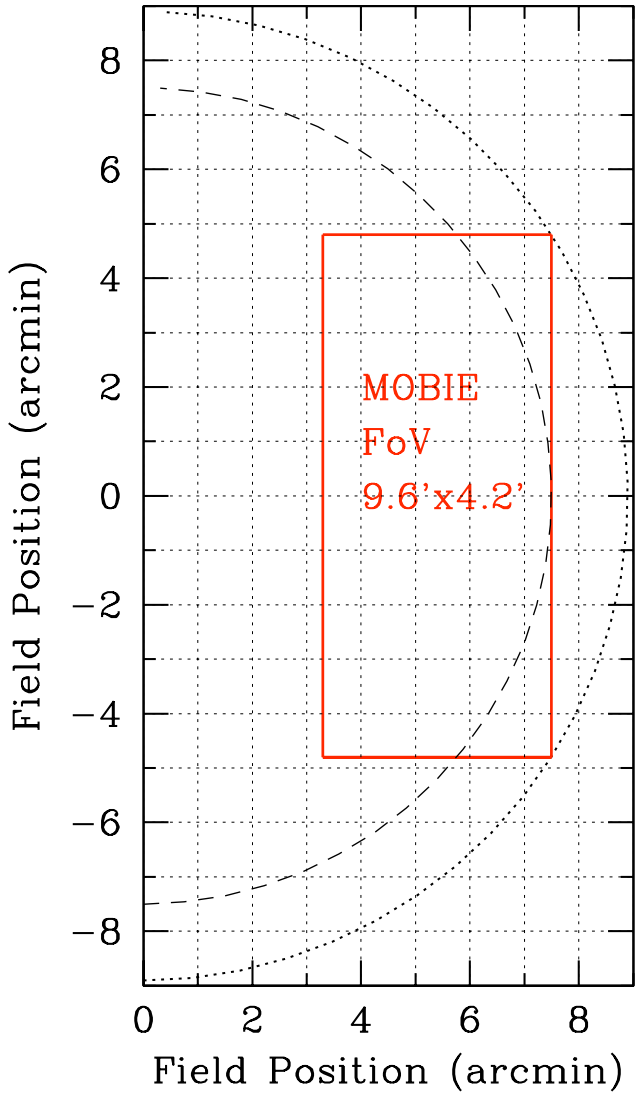
Bernstein et al. 2008, SPIE 2008

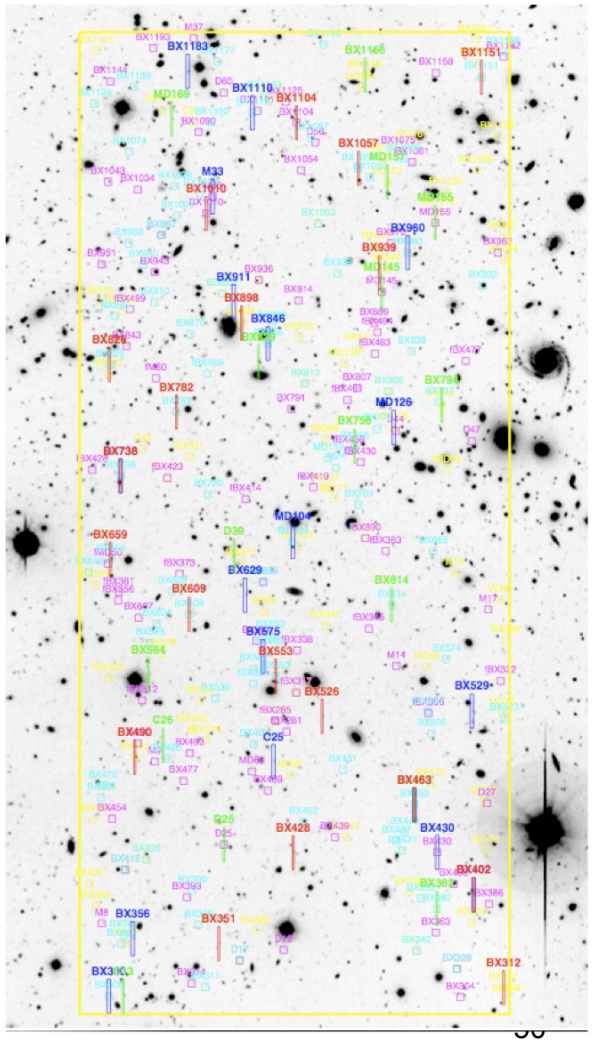


MOBIE can trade multiplexing for expanded wavelength coverage in its higher dispersion mode

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

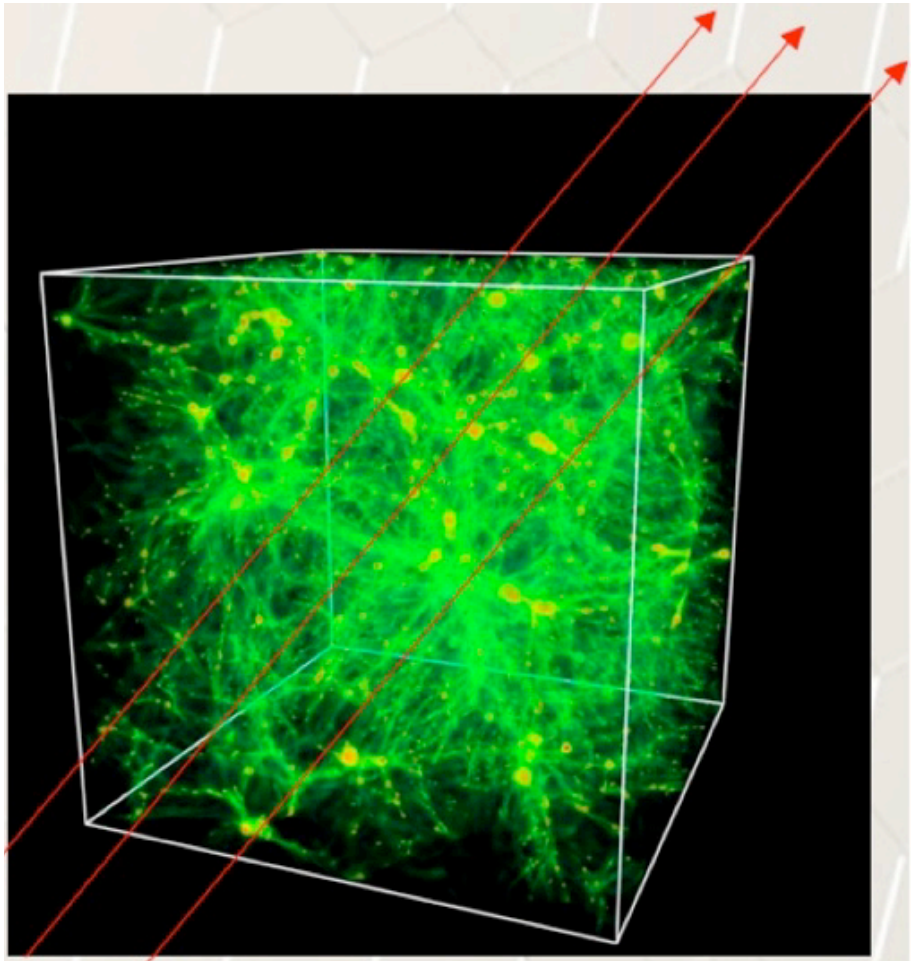
WFOS-MOBIE
Science Field Geometry





Multi-object mask making simulation

IGM Tomography with WFOS



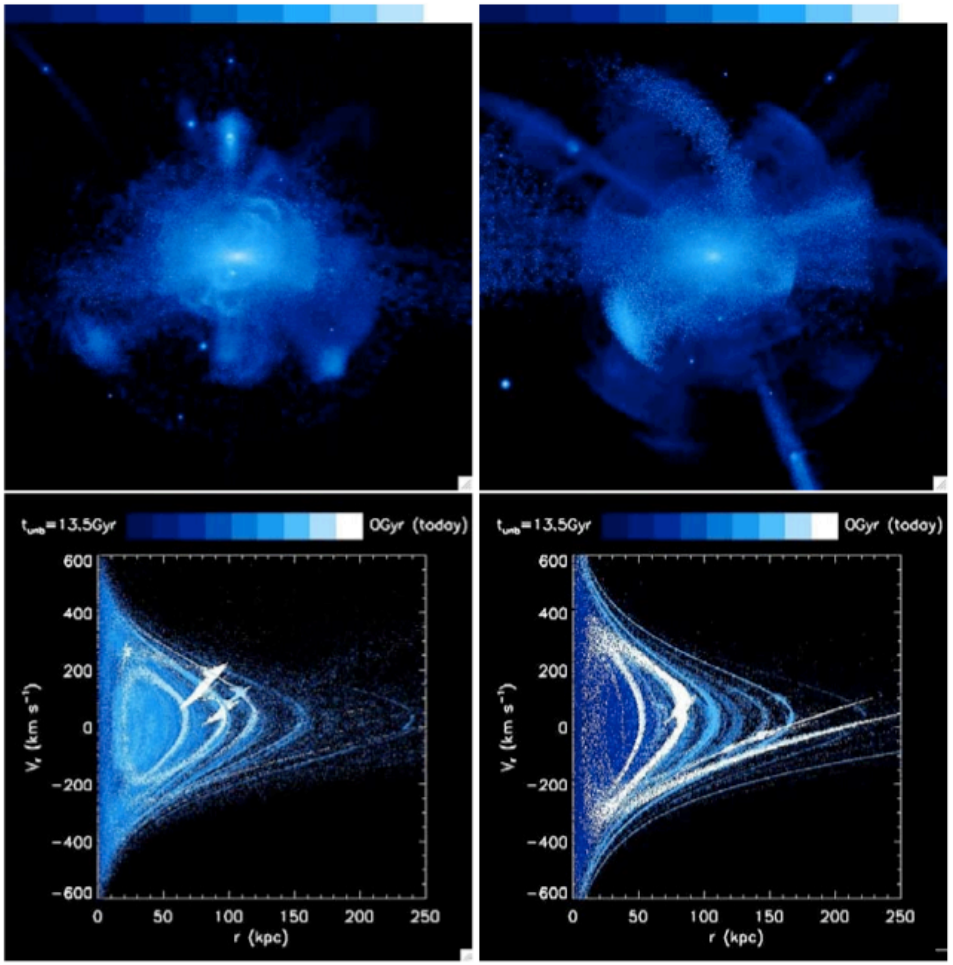
(R. Cen, Princeton U.)

Given that TMT+WFOS will go ~ 2.5 mag deeper than 8-10m class telescopes, and background UV-bright galaxies will then become usable beacons, the surface density of sightlines on the sky for intergalactic medium tomography will be ~200x higher.

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

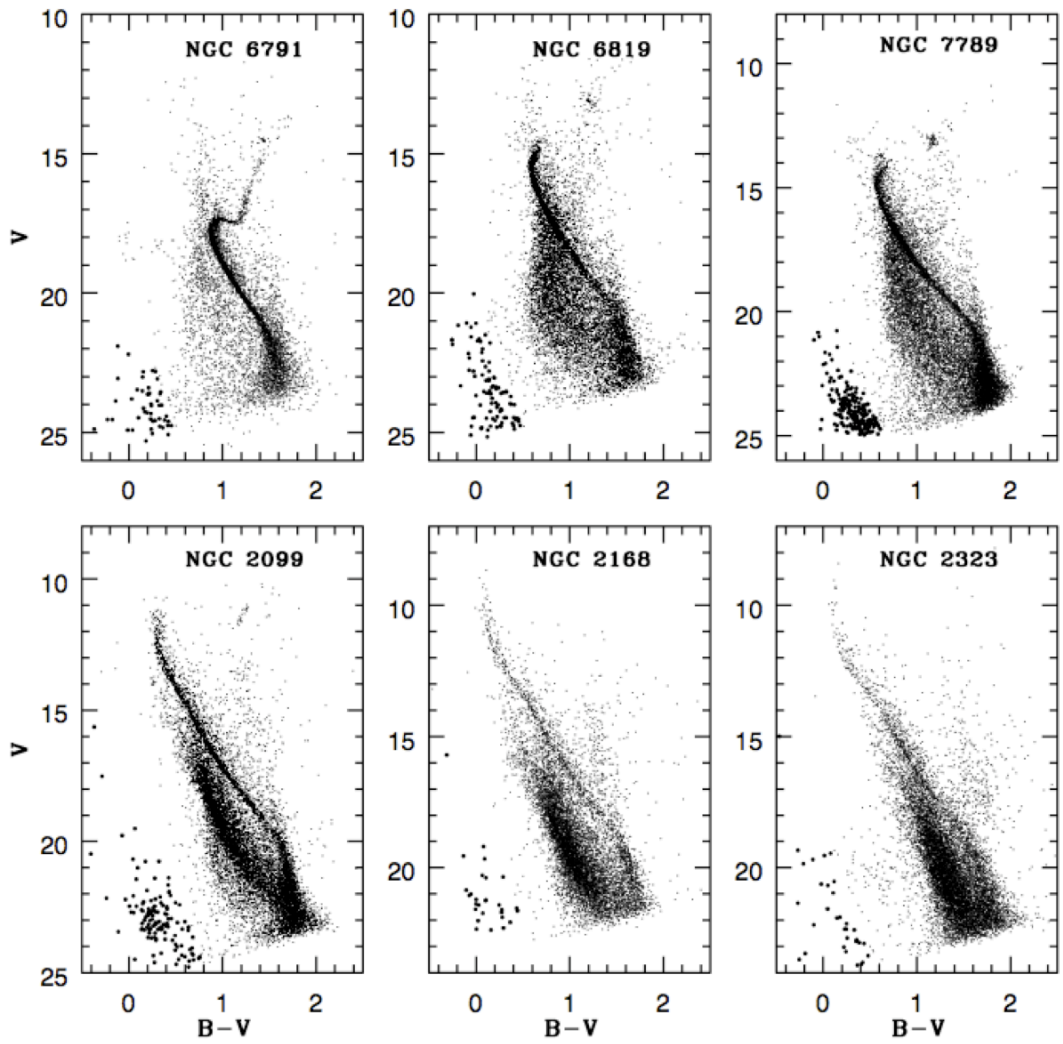
Stellar Archeology in the Local Universe

- *TMT will use multi-object spectroscopy of thousands of stars to map the dynamical states of stellar populations:*
  - This will allow us to test theories of structure formation on sub-galactic scales.
  - By comparison with models, one can infer the merger history of nearby galaxies.



N-body simulations of satellite accretion (TMT WFOS-HIA team, Bullock & Johnstone 2005).

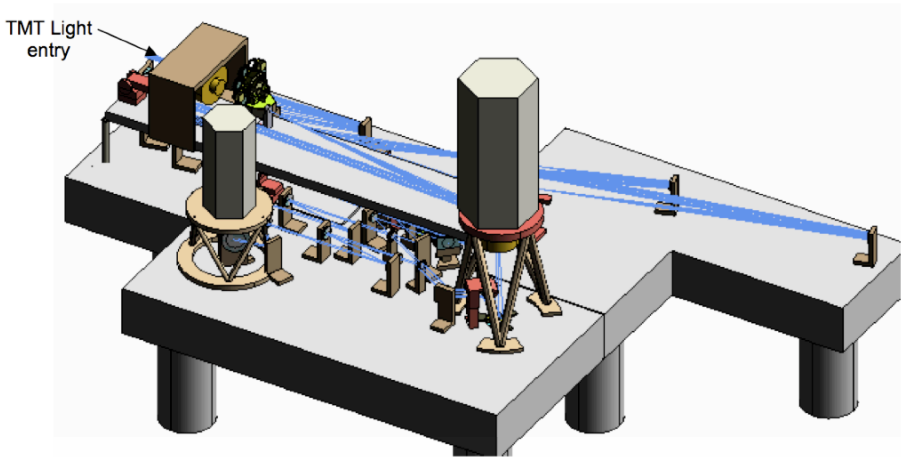
WFOS-MOBIE Imaging: White Dwarfs in Open Clusters

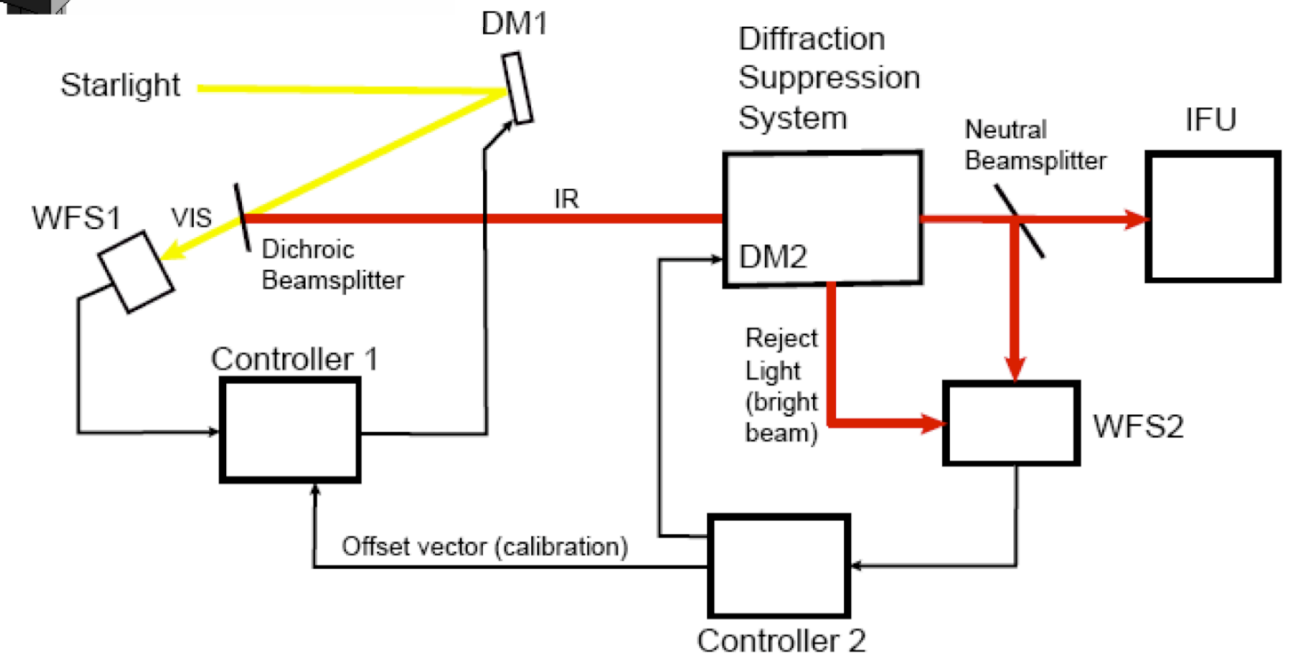


White dwarf sequences in six rich open clusters from the CFHT Open Star Cluster Survey

TMT will reach down to V=27

Planet Formation Instrument (PFI)





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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%

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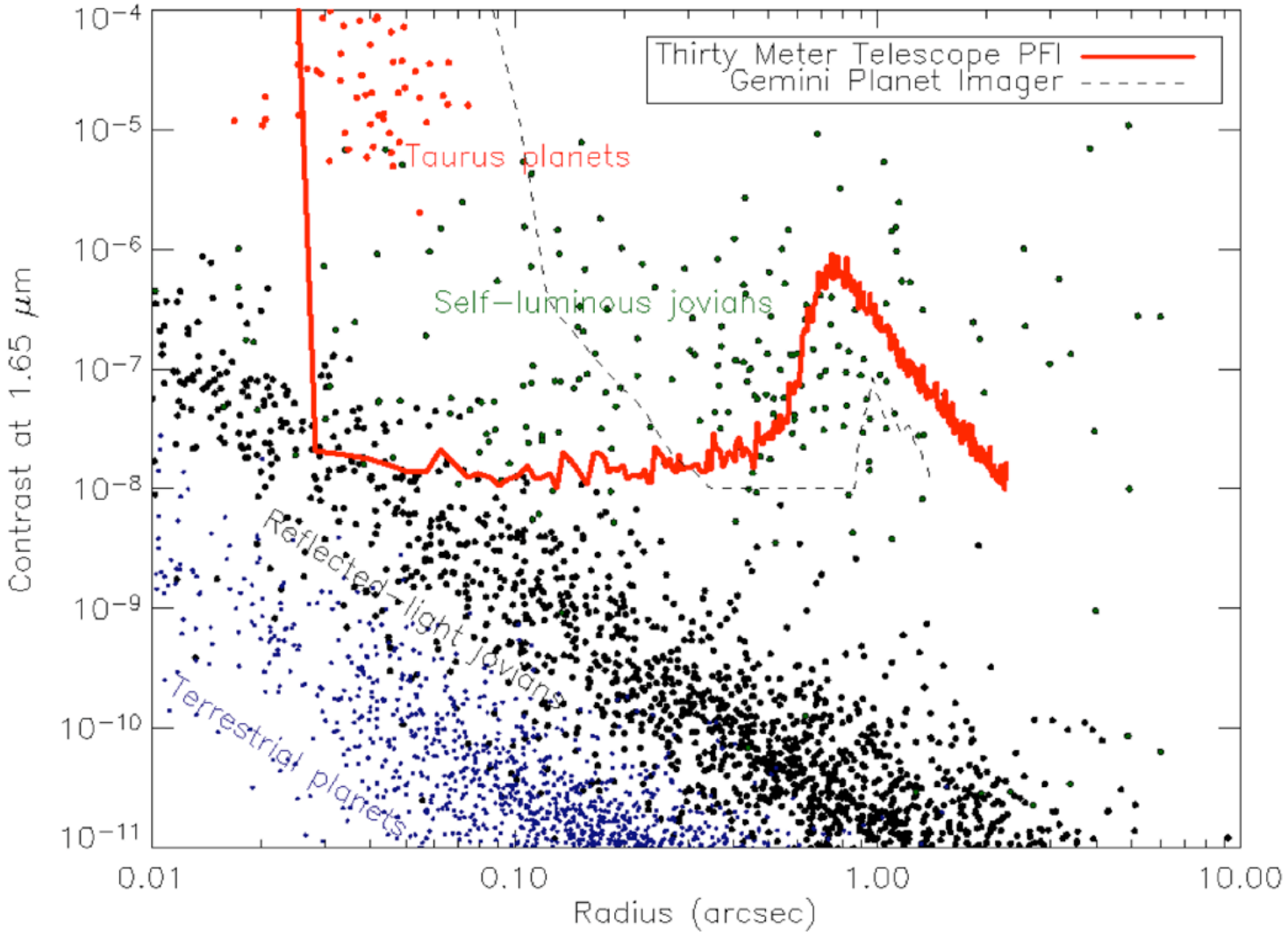
PFI Imaging Contrast



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PFI Polarimetry

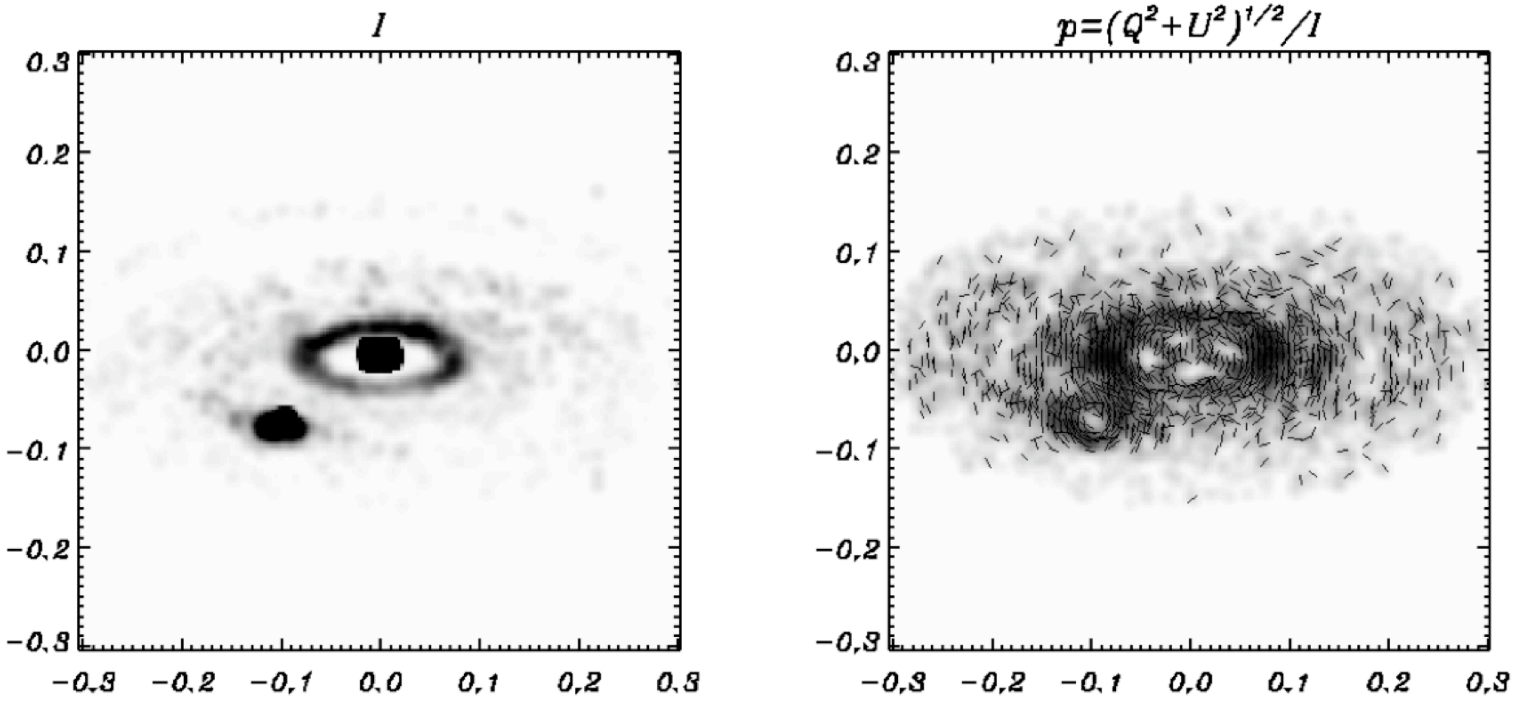
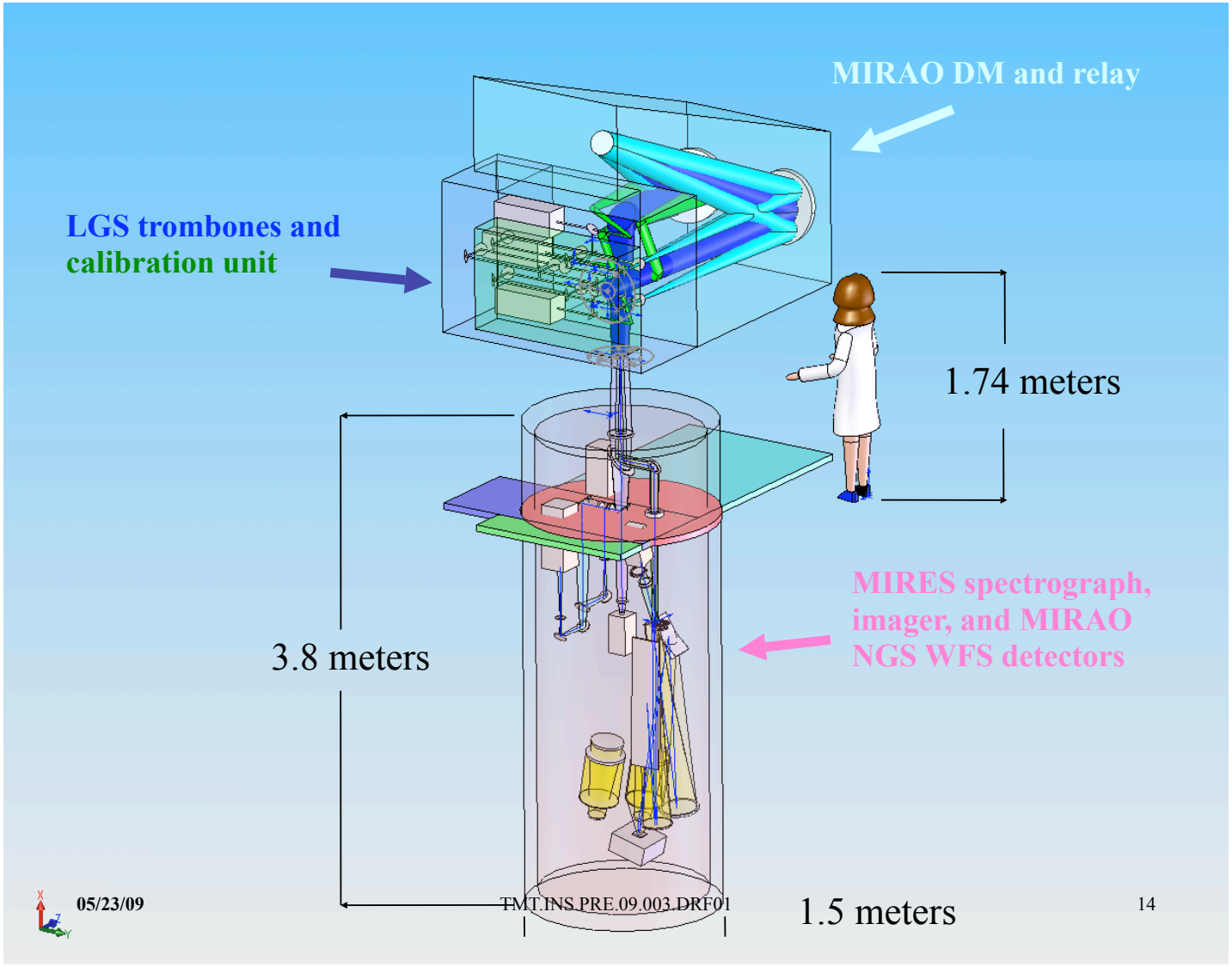


Figure 18: Radiative transfer model of a young planet in an optically thick circumstellar disk. The companion has a contrast of ΔH = 10 mag, representing a <10 Myr planet. This disk has a radius of 50 AU with an inner hole at 5 AU and a Hill-sphere wide gap at the radius of the planet (30 AU). The disk inclination is -66 degrees, such we are viewing the underside of the disk. The distance is 150 pc. The left hand panel shows the total intensity and the left shows the polarized fraction with the orientation of the electric vector indicated. The concentric polarization vectors and unpolarized core clearly show that the source at 7 o'clock is self-luminous and not just a blob of dust.

Mid-InfraRed Echelle Spectrometer



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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

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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.
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[REQ-1-ORD-4415]	Slit Length	3 arcsec, sampled at 0.04 arcsec/pixel. Slit or IFU
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[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

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MIRES Imaging: Protoplanetary Disks

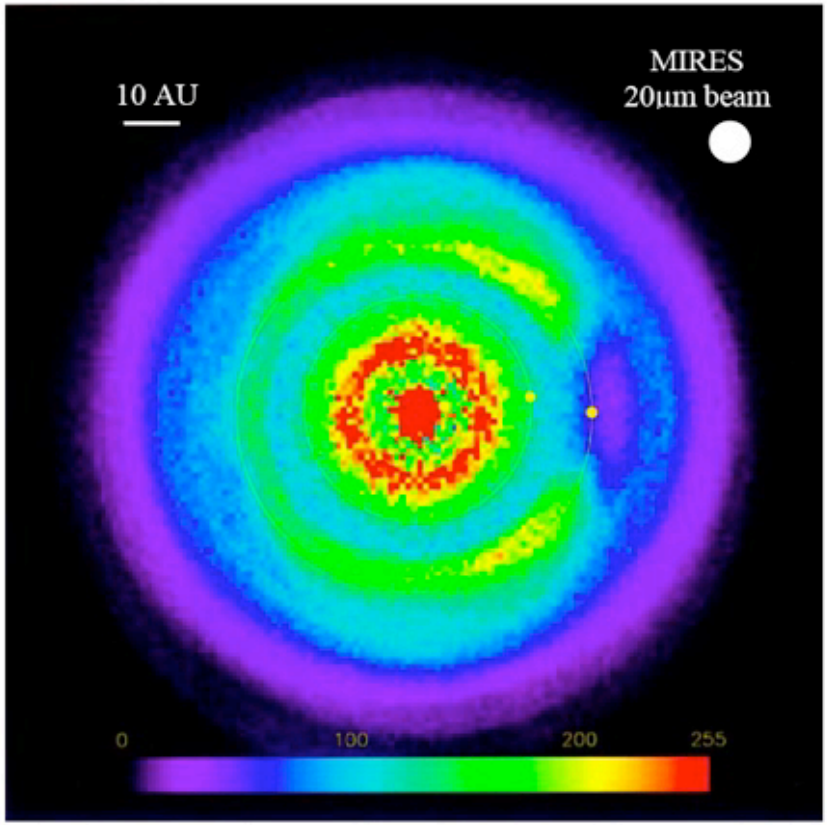

Figure 2.2.3.1 The perturbations of planets on dust in debris disks produce signatures in the dust morphology that can be used to detect planetary systems. This numerical simulation of the brightness distribution of dust particles for our Solar system (Liou & Zook 1999) shows an asymmetric ringlike structure at the orbit of Neptune. Shown is the MIRES beam at 20 μm for a distance of 50 pc. MIRES has the resolution to measure similar morphology and deduce outer planetary system architectures.

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MIRES Imaging: Debris Disks

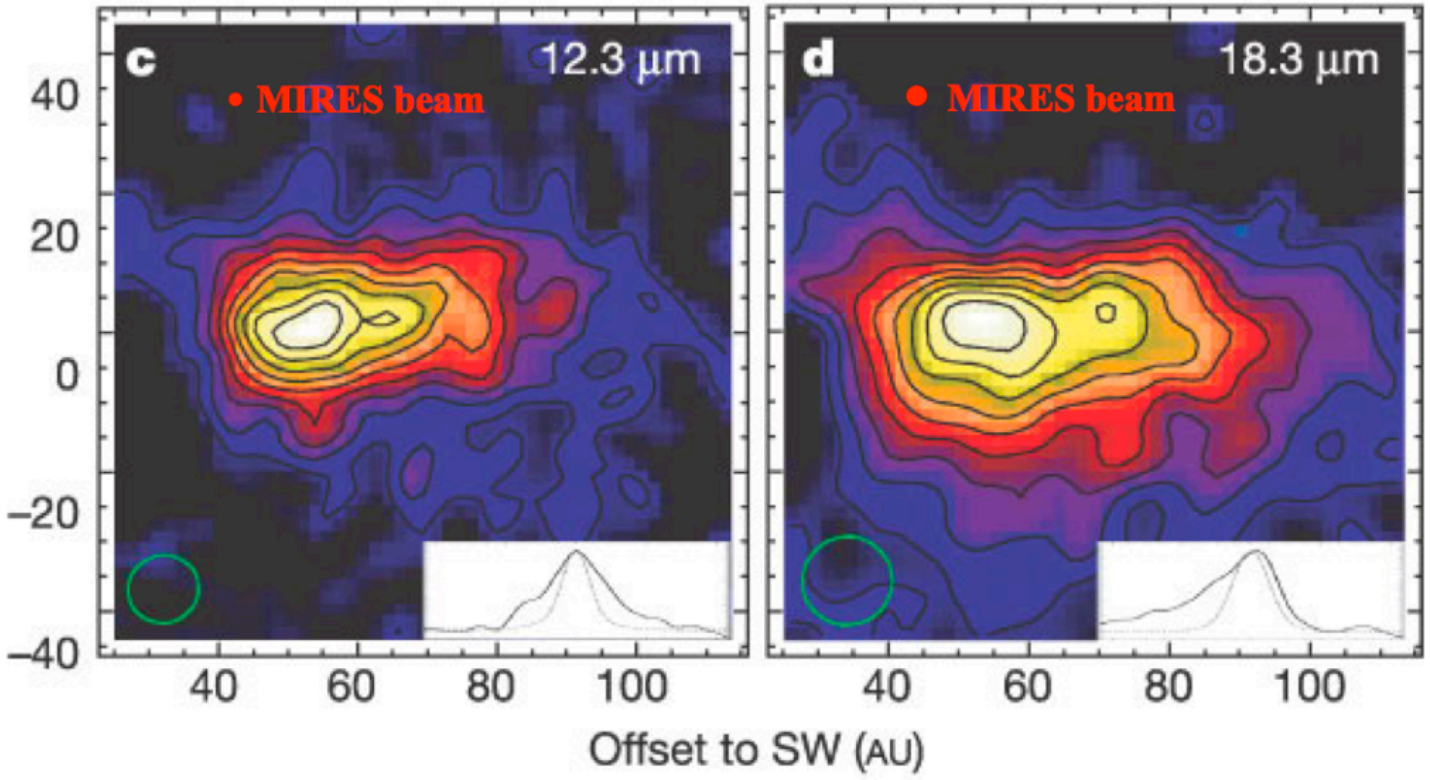
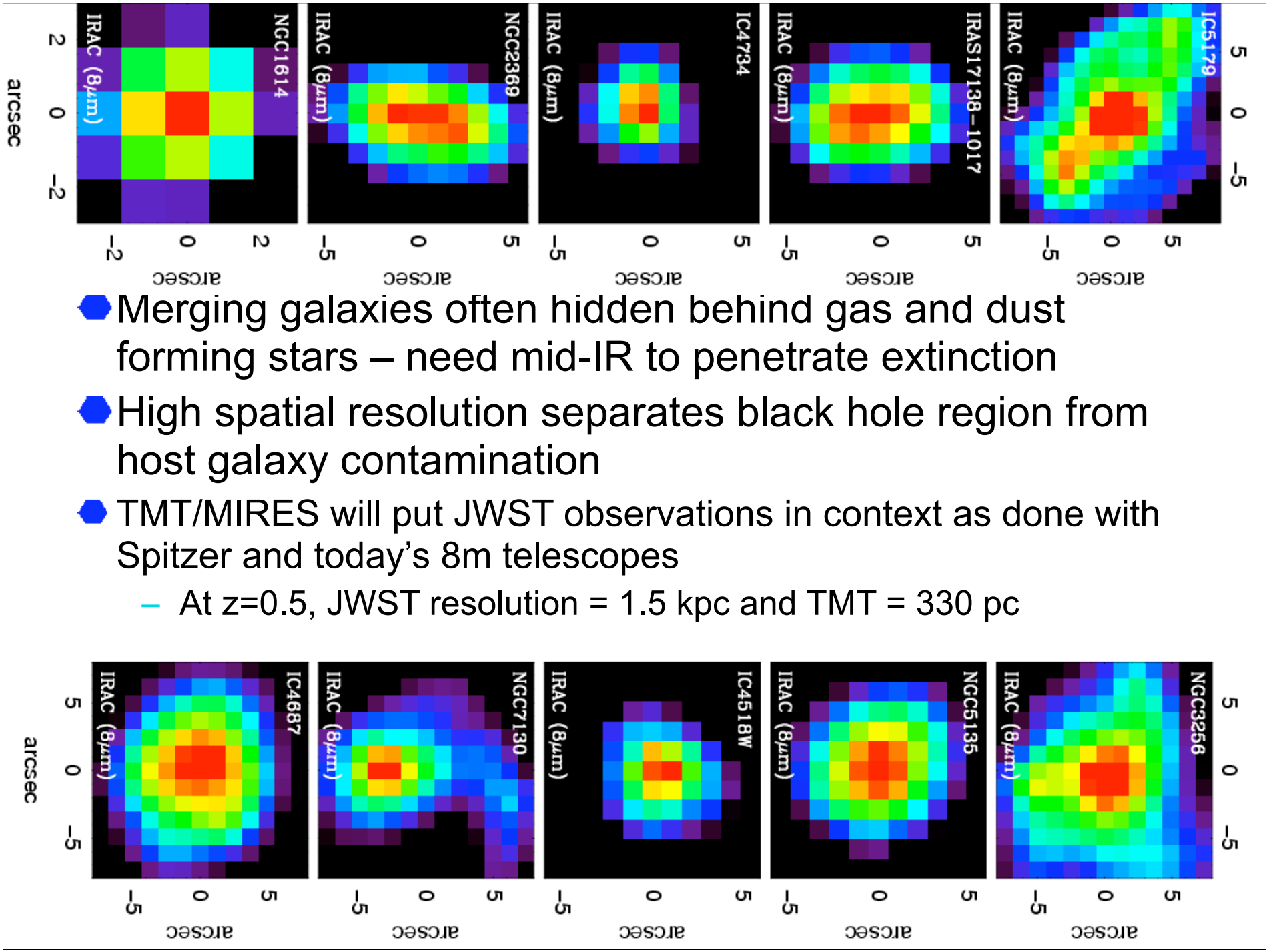
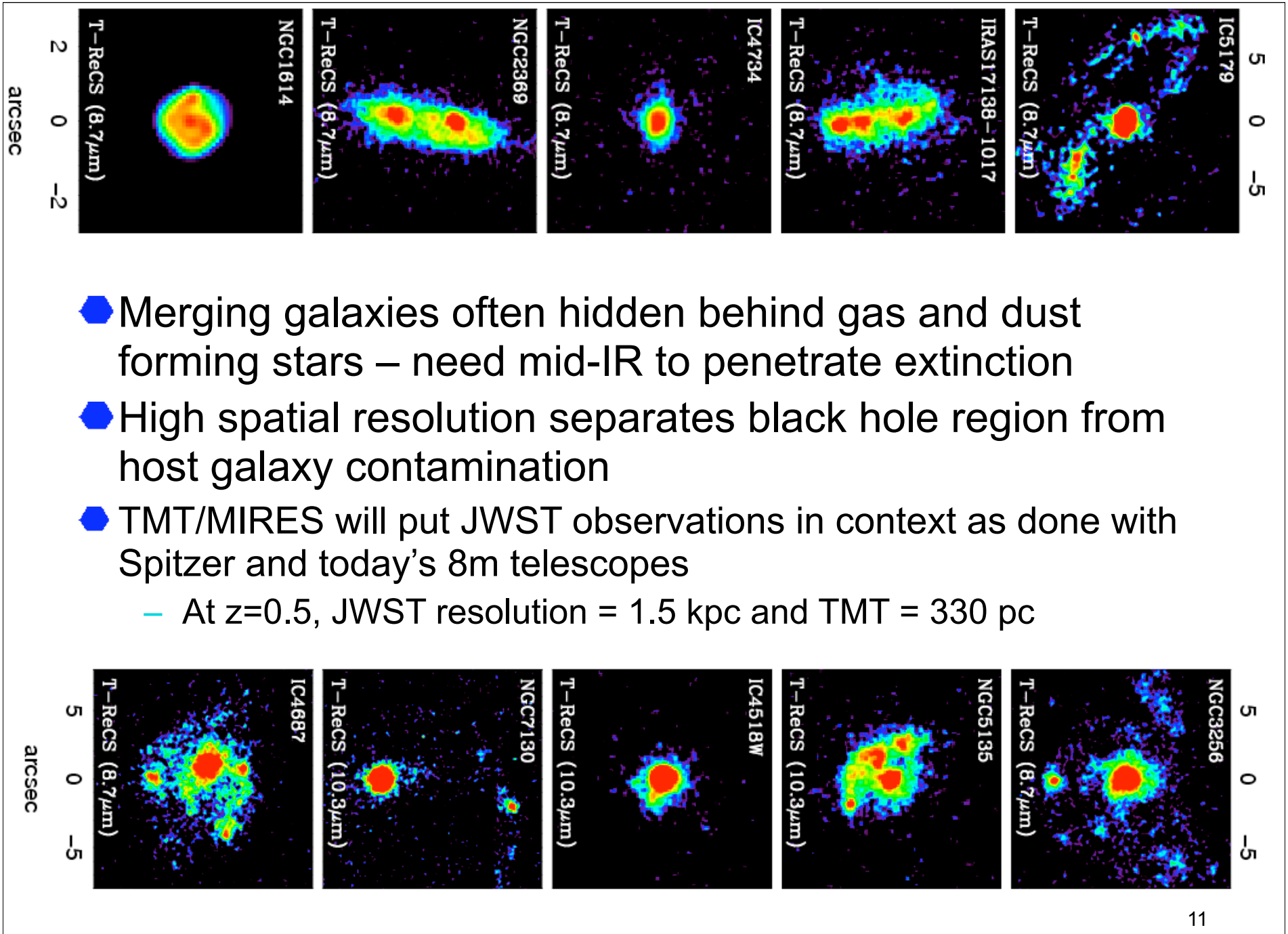


Figure 2.2.3.2 Debris disks may reveal the signatures of collisional events. These residual images show a close-up of a bright clump at ~ 50 AU in the southwest wing of the debris disk around β Pictoris (Telesco et al. 2005). The brightness peak and the different gain properties from the surrounding dust may be the result of catastrophic planetesimal collisions. The high-resolution of MIRES (beam shown) will provide exquisite detail of dust morphology in debris disks.



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



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

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TMT Foundation Documents

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

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

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Acknowledgments

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