The Multi-Object Broadband Imaging Echellette (MOBIE) Spectrograph

Luc Simard
(On behalf of the MOBIE team)

TMT Science Forum, Waikoloa, Hawaii

July 22-23, 2013

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 Science

- Stellar Evolution and White Dwarfs
- Metal Poor Stars: Galaxy Formation from the Stellar Halo of the Milky Way
- Resolved stellar populations in the Local Group
- The Dark Matter Distribution in Nearby Elliptical Galaxies
- Three-Dimensional Baryonic Structure During the Epoch of Galaxy formation
- The Stellar and Gaseous Content of L* Galaxies at $z \sim 2 – 5$
- QSO Pairs: Revealing AGN and Massive Galaxy Formation at $z > 2$
- Transients

See MOBIE Operational Concepts Definition Document at www.tmt.org/documents for more details!

Galaxy Stellar Halos

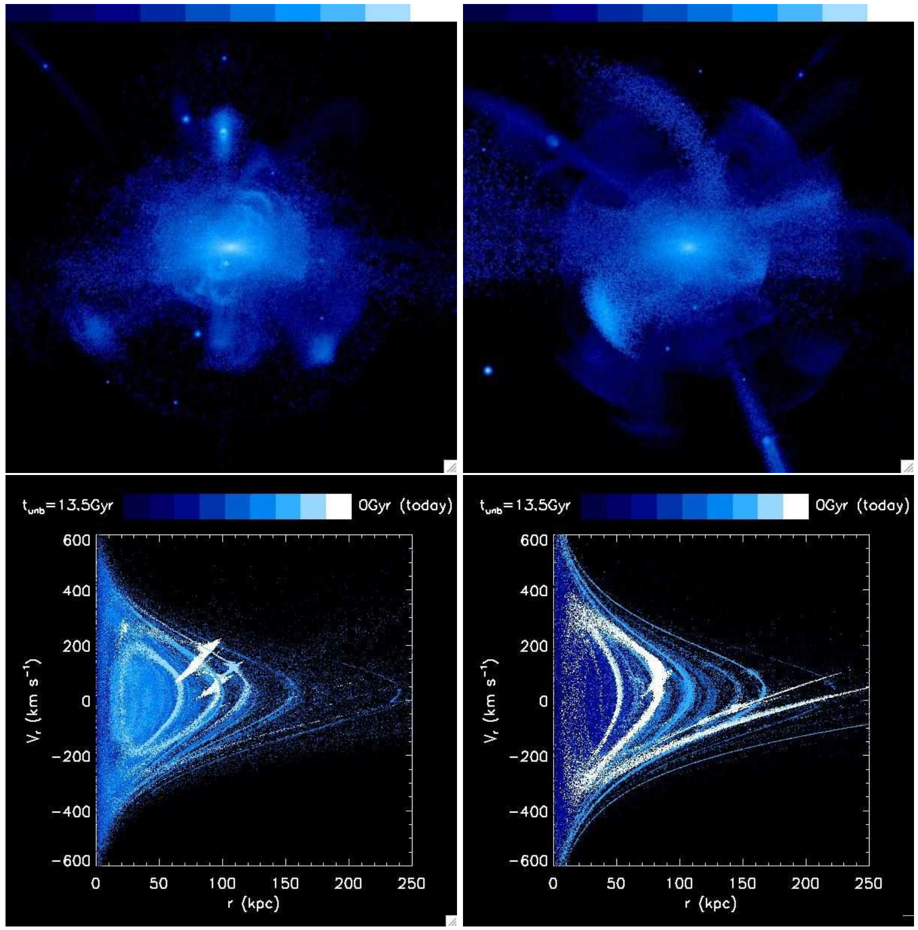

Figure 7: *(Upper Panels)* Two different halo simulations generated using a semi-analytic plus N-body approach. Each box measures 300×300 kpc. The blue/white color scale indicates surface brightness: 23 mag arcsec^{-2} (white) to 38 mag arcsec^{-2} (dark blue). *(Lower Panels)* Radial phase space diagrams (v_r vs r relative to the host halo center) for the two halos shown above. Each point represents 1000 solar luminosities. The color code reflects the time each particle became unbound to its parent satellite. White points are either bound or became unbound in the last 1.5 Gyr, while dark blue points became unbound more than 12 Gyr ago. The radial color gradient reflects the tendency for inner halo stars to be accreted (and stripped) early in the galaxy's history. The white feature at $r \sim 80$ kpc in the right panel represents a massive, and very recent, disruption event. Figures and description from Bullock & Johnston (2005).

Red Giant Candidates in M31 - Number counts

Table 2: RGB Candidates in M31

I (mag)	$\langle I \rangle$ (mag)	$N(I)^{\dagger}$	$\Sigma_{\rm RGB}(I)$ (arcmin^{-2})	$N(\leq I)^{\dagger}$	$\Sigma_{\rm RGB}(\leq I)$ (arcmin^{-2}
20.5-21.0	20.75	48	1.2	48	1.2
21.0-21.5	21.25	96	2.3	144	3.5
21.5-22.0	21.75	107	2.6	251	6.1
22.0-22.5	22.25	173	4.2	424	10.2
22.5-23.0	22.75	266	6.4	690	16.6
23.0-23.5	23.25	385	9.3	1075	25.9
23.5-24.0	23.75	484	11.6	1559	37.5
24.0-24.5	24.25	645	15.5	2204	53.0
24.5-25.0	24.75	831	20.0	3035	73.0
25.0-25.5	25.25	1052	25.3	4087	98.3

† – Number RGB stars per MOBIE field, for locations of ($\pm$22,$\pm$15) kpc along the disk major and minor axes, respectively.

Source: MOBIE Operational Concepts Definition Document

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Red Giant Candidates in M31 - Spectroscopy

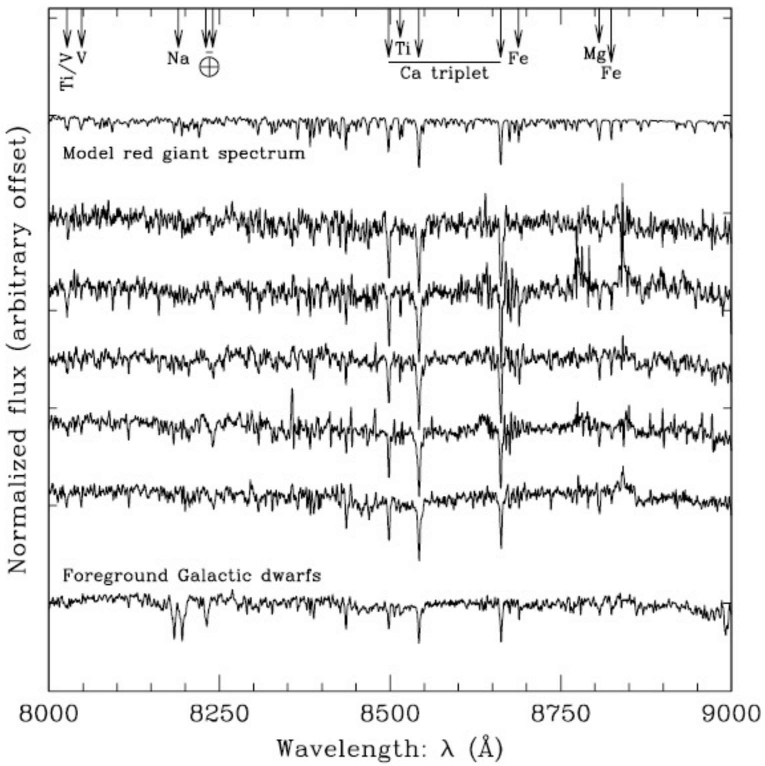


Figure 9: Montage of co-added Keck 10-m/DEIMOS spectra (thin solid lines) showing the region around the Ca II triplet, normalized and shifted to rest-frame wavelength and smoothed with a 1.7Å weighted boxcar. The bottom spectrum is a co-add of 16 foreground Galactic dwarf stars, each with an exposure time of 1 hr. The next five spectra are co-adds of about a dozen M31 RGB stars each, again each with an exposure time of 1 hr, grouped and ordered by predicted Ca II line strength (increasing upward) as estimated from the CMD-based photometric metallicity and luminosity. The bold line at the top is a model red giant spectrum with $T_{\rm eff} = 4000$ K, $\log(g) = 1.5$, and $[{\rm Fe/H}] = -0.3$ from Schiavon & Barbuy (1999). A few prominent spectral features of RGB stars are identified along with the $\lambda8190$Å Na I doublet, which is strong in dwarfs. The S/N in the co-added spectra, typically 50 per Å, is barely adequate for abundance analysis and the interpretation is complicated by the fact that these are co-added spectra. The TMT+MOBIE combination will produce much higher quality spectra for *individual* M31 RGB stars of this apparent magnitude ($I \sim 21$) in 2–3 hour exposures, allowing the determination of elemental abundances (e.g., $[\alpha/{\rm Fe}]$ constraints) for many thousands of M31 halo field stars.

Source: MOBIE Operational Concepts Definition Document

Dark Matter Distribution in Nearby Elliptical Galaxies

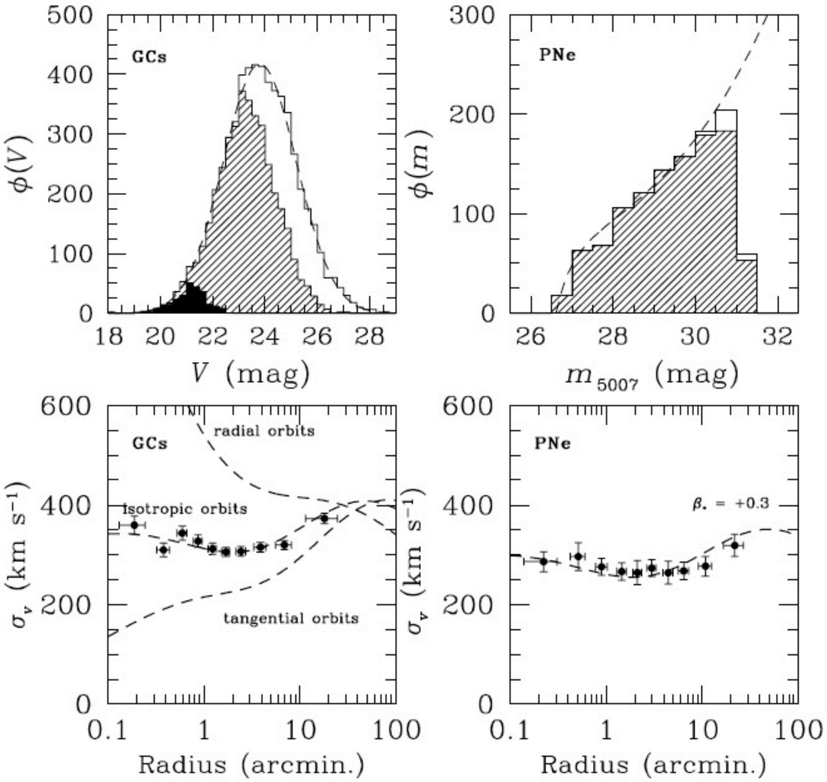
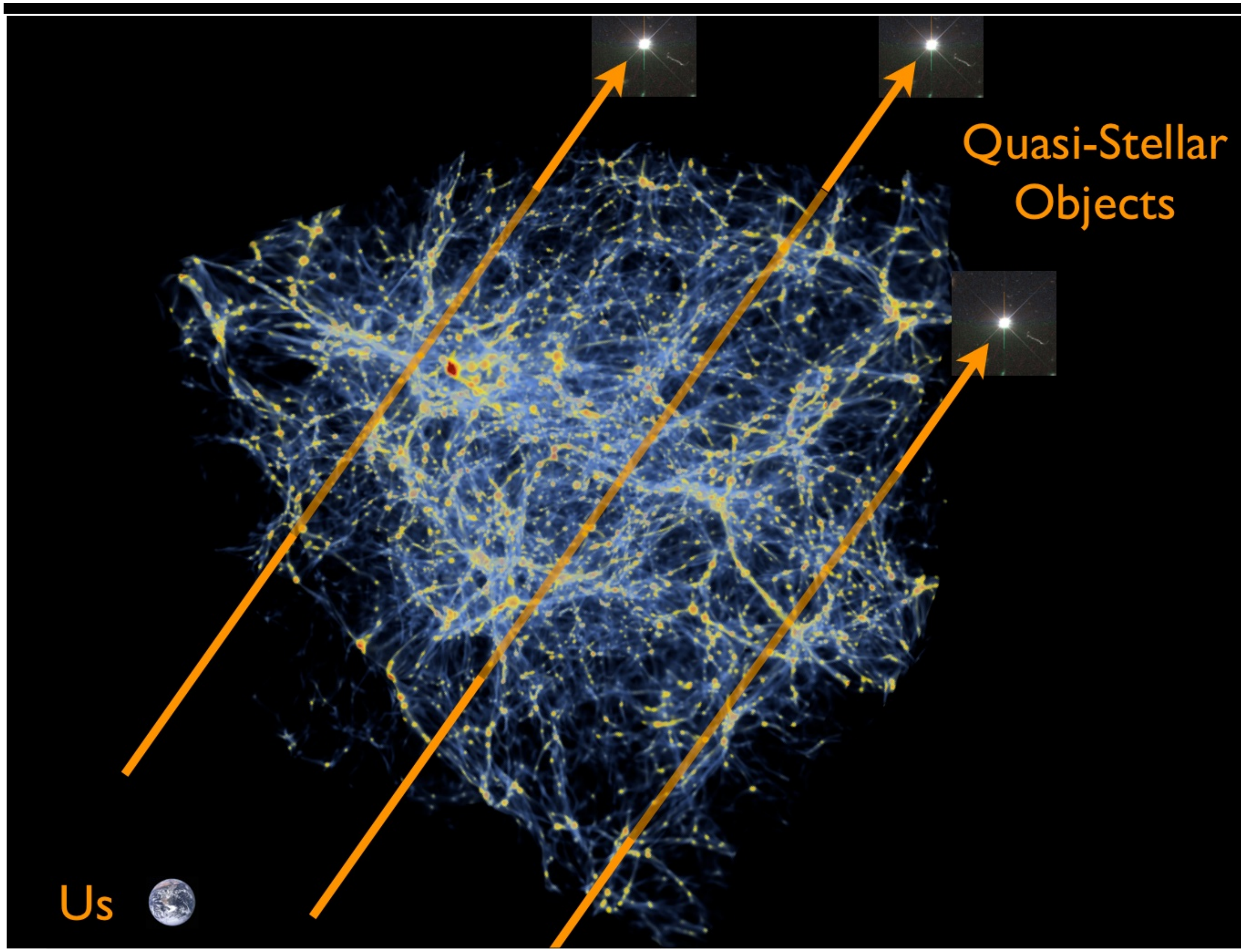


Figure 12: *(Upper Left Panel)* Input luminosity function of GCs belonging to M49 (dashed curve and open histogram). The hatched histogram shows the 4049 GCs for which a 1 hour exposure with MOBIE would yield S/N $\geq$ 1. The luminosity function of the 263 GCs with existing velocity measurements from Keck is shown as the shaded histogram. *(Upper Right Panel)* Input luminosity function of PNe in M49 (dashed curve and and open histogram). The hatched histogram shows the 1065 PNe for which a 1 hour exposure with MOBIE would yield S/N $\geq$ 1. *(Lower Left Panel)* A simulated measurement of the anisotropy parameter, $\beta \equiv 1 - \sigma_\theta^2/\sigma_r^2$, for the globular cluster system of M49. Different anisotropy parameters are shown by the different curves, from strongly radial ($\beta = +0.99$, upper curve), to strongly tangential ($\beta = -99$) orbits. The measured velocity dispersion profile recovers the assumed isotropic velocity distribution with high confidence. *(Lower Right Panel)* Same as previous panel, except for PNe. In this case, the dashed curve shows the velocity dispersion profile for the assumed (input) case of mildly radial stellar orbits, $\beta_* = +0.3$.

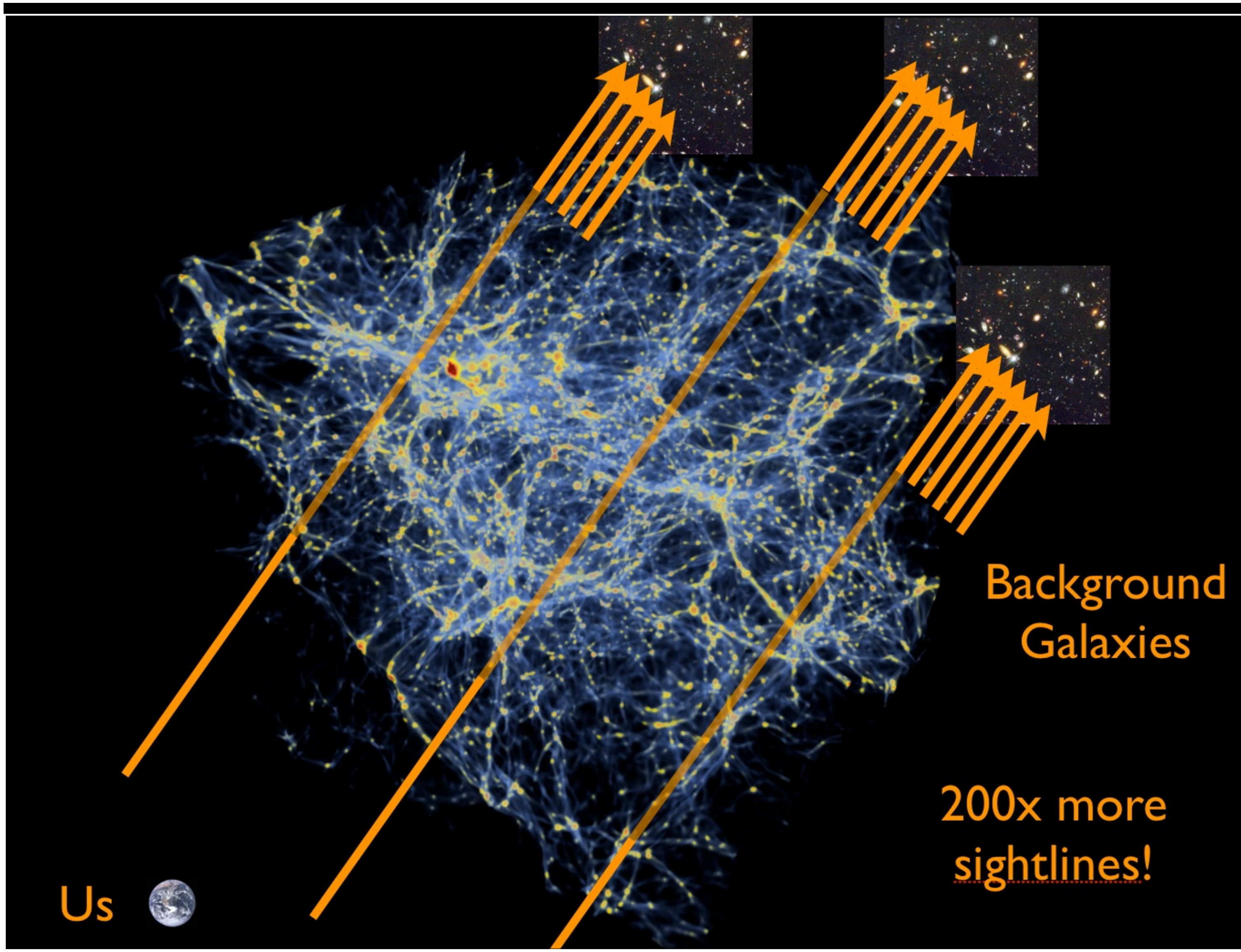
Source: MOBIE Operational Concepts Definition Document

Inter-Galactic Medium Tomography: Now



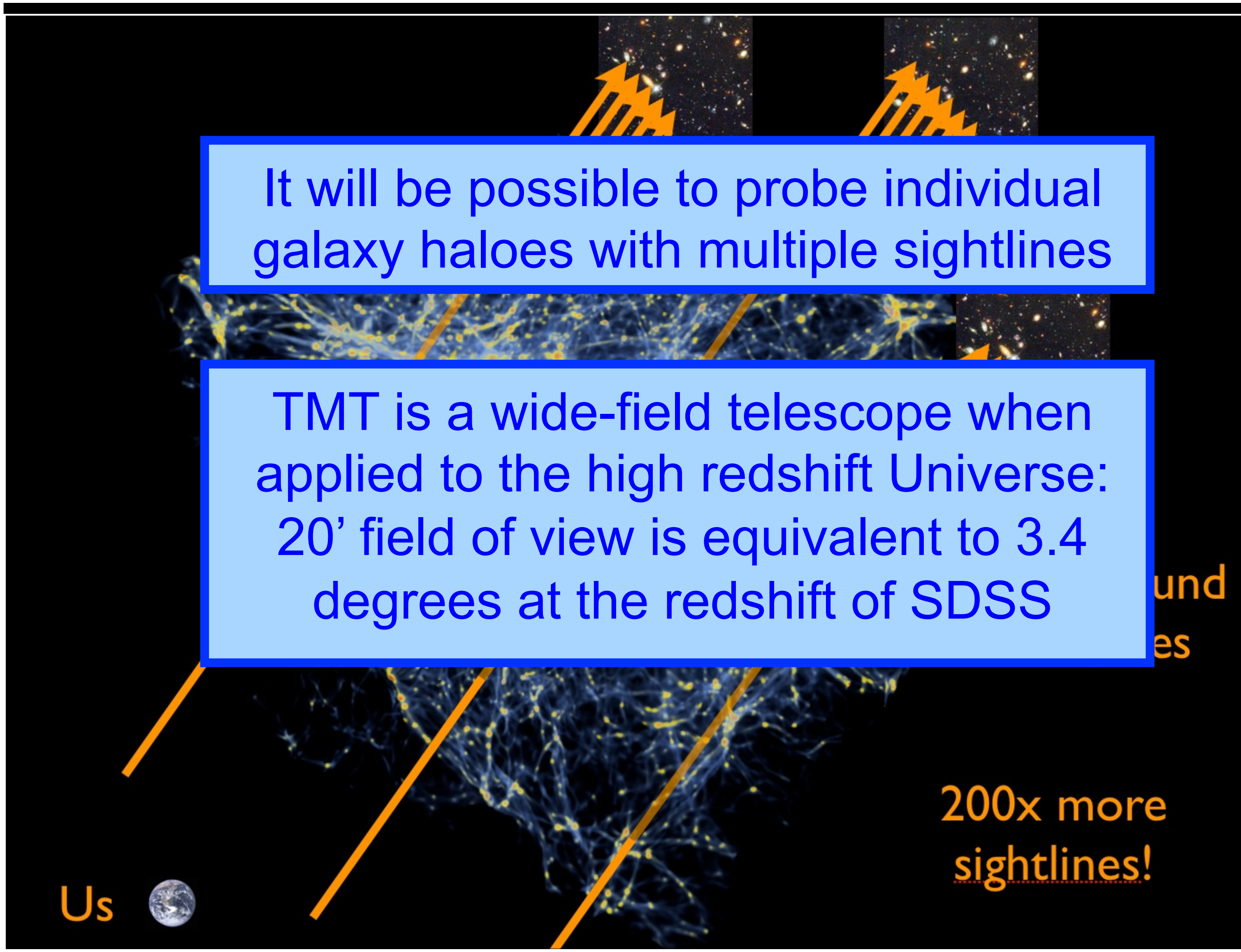
(Simulation: M. Norman, UCSD)

Inter-Galactic Medium Tomography: TMT



(Simulation: M. Norman, UCSD)

Inter-Galactic Medium Tomography: TMT

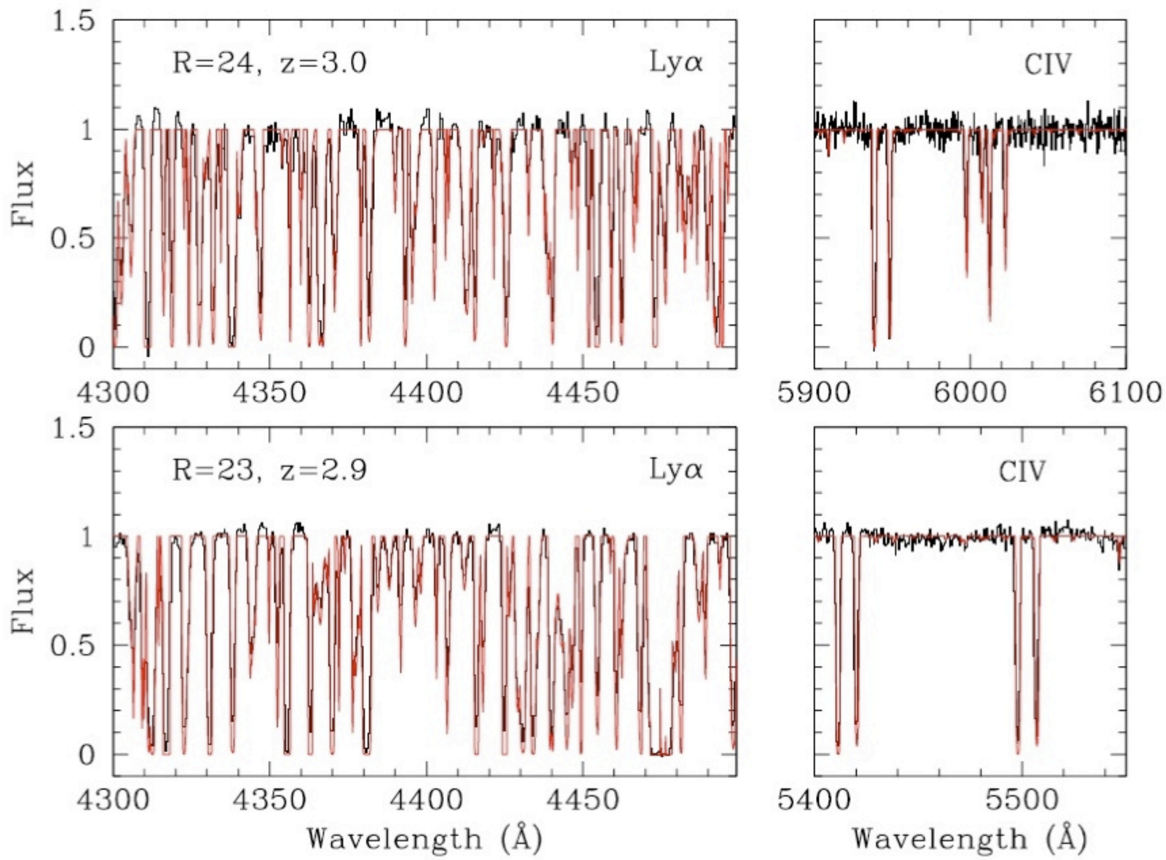


It will be possible to probe individual galaxy haloes with multiple sightlines

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

(Simulation: M. Norman, UCSD)

Inter-Galactic Medium – Spectral Diagnostics



Example sections of simulated spectra for R(AB) = 23 and 24 with a spectral resolution of 5000.

Assumed integration times were 3 hours.

The R=5000 spectra are black.

The spectra before convolution with the instrumental resolution are shown in red..

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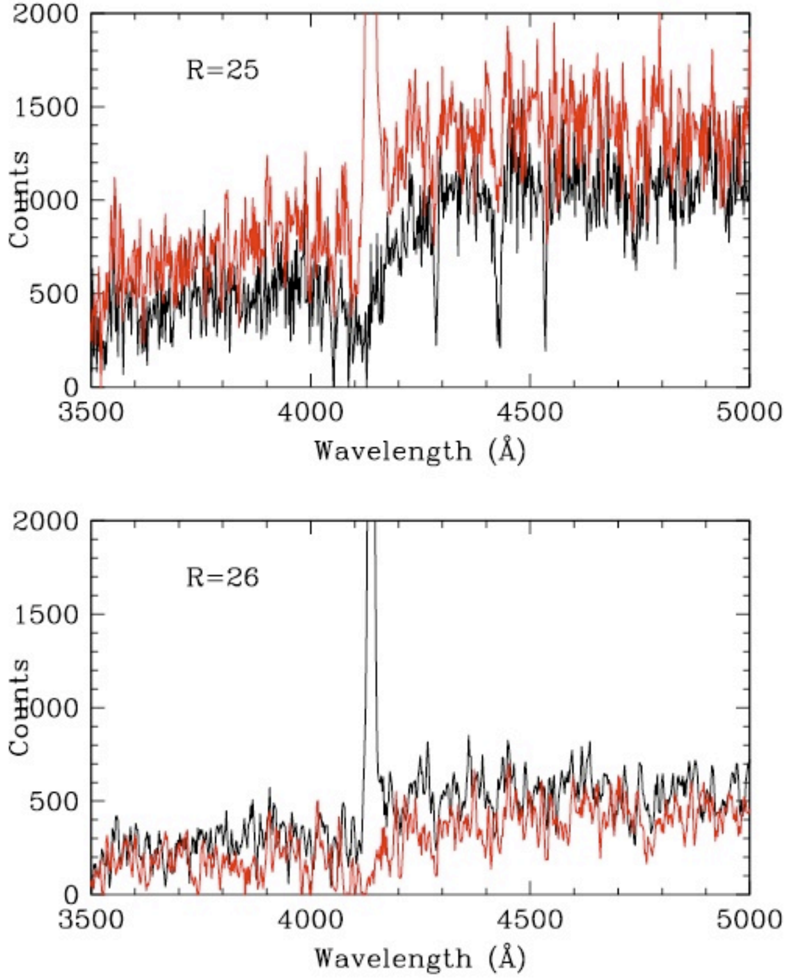
Inter-Galactic Medium – Spectral Diagnostics



Simulated spectra for z = 2.4 galaxies at *R*(AB) = 25 and 26 assuming 1 hour total integration time with the blue R=1000 configuration

Spectra are derived from the composite Lyman break galaxy (Shapley et al. 2003) for the lowest (red) and highest (black) quartile in Lyman-alpha emission strength

The *R* = 26 spectra will easily yield redshifts even for objects without emission lines. Note that the *R* = 26 spectra have been smoothed with a boxcar filter with a 3-pixel width

Source: MOBIE Operational Concepts Definition Document

Transients: Studying "Things that go bump into the night"

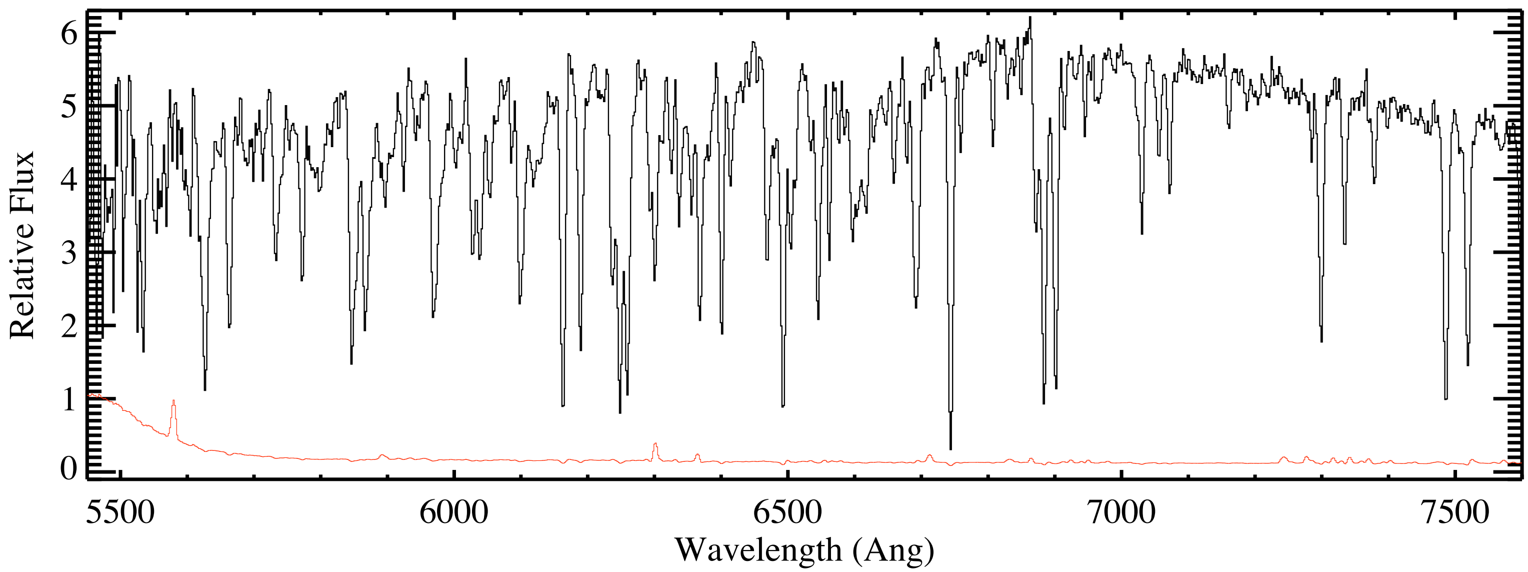


Figure 20: Keck/LRISr spectrum of a series of metal absorption lines, primarily related to gas in the host galaxy of a $z \sim 3$ GRB. This sightline has penetrated a molecular cloud within the host galaxy. These data show strong absorption from CO bandheads and the LRISb spectrum (not shown) reveals strong Lyman-Werner H_2 transitions. The astrophysical impact of these data is limited by the low-resolution; a sequence of high S/N observations with MOBIE/ECH would yield precise column densities (and kinematics) which establish the physical conditions of the gas (metallicity, depletion, molecular fraction, etc.) within the host galaxy.

Source: MOBIE Operational Concepts Definition Document

Transients: Studying "Things that go bump into the night"

Source: MOBIE Operational Concepts Definition Document

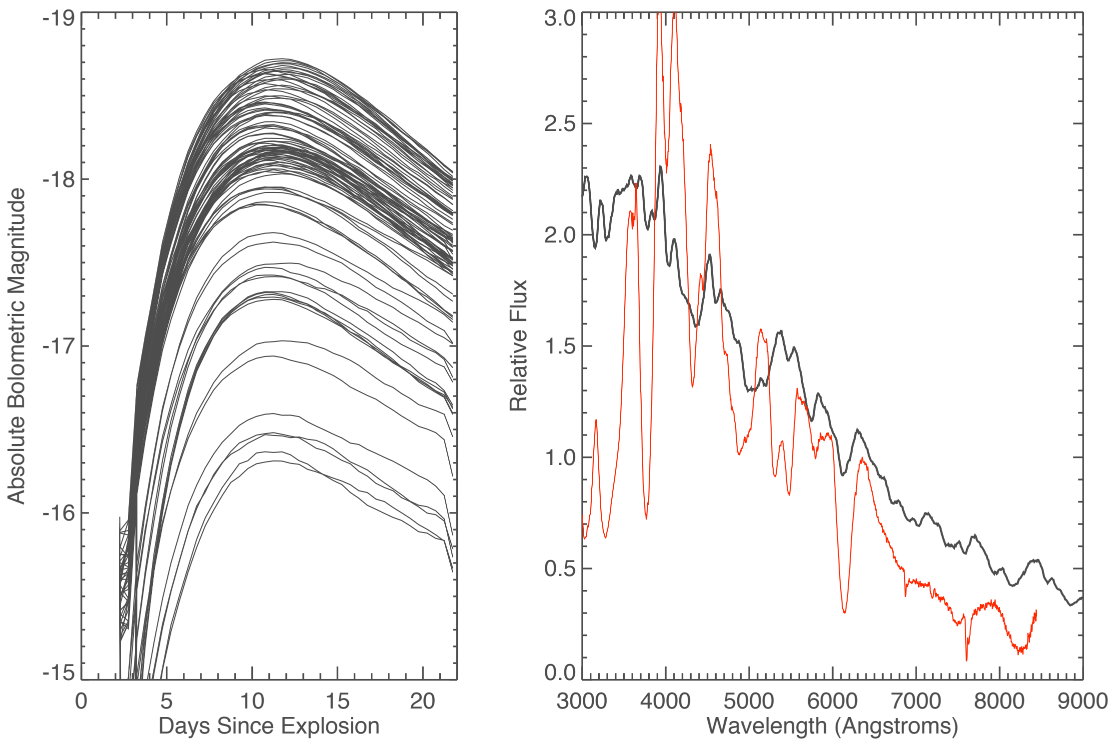


Figure 21: Predicted observables of a 0.6 $M_\odot$ white dwarf which was tidally disrupted by a 500 $M_\odot$ intermediate mass black hole. Left: Light curves of the highly asymmetric remnant as seen from various viewing angles. The emission is powered by radioactive isotopes synthesized in the disruption event. Right: Representative spectrum of the remnant near light curve peak, as compared to the spectrum of a Type Ia supernova (red line). Weak lines of silicon and iron are visible. far undetected transient.

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MOBIE Flow-Down of Science Case Requirements

	White dwarfs	Metal Poor Stars	Resolved populations	Dark matter mapping	IGM Tomography I	IGM Tomography II	$z \sim 2-5$ Galaxies	QSO Pairs	Transients
Slits/mask	140	< 10	140	140	20	90	20	20	1
Masks/night	2	5	2.5,7	6	2	10	2	3	–
Slit width [arcsec]	0.6	0.75	0.8	0.75	0.75-1.0	0.75-1.0	0.75	0.75	0.75
Typical integration time/exposure [s]	1800	1200	1200	1800	1800	1800	1800	1800	1800
Typical integration time/mask [ks]	15	7.2	9,3	3.6	14.4	3.6	14.4	14.4	3.6
Resolution (blue/red)	2000	8000	8000	2000/5000	5000	1000	5000	8000	1000-8000
Minimum wavelength (blue/red) [nm]	340	380/550	370/830	310/550	310/550	310/550	310/550	310/550	310/550
Maximum wavelength (blue/red) [nm]	550	550/800	550/900	550/900	550/750	550/800	550/1000	550/1000	550/1000
ECH mode needed?	✓	✓	✓	✓	✓		✓	✓	✓
Need very precise flux calibration?				✓					
Needs very precise sky subtraction?			✓	✓	✓	✓			
Uses blue and red arms at same time?		✓	✓	✓	✓	✓	✓	✓	✓

Source: MOBIE Operational Concepts Definition Document

MOBIE Science Drivers

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Extremely ambitious performance goals: **wavelength range** requires a separate red and blue channel

Table 7: Flow-down of Science Case Requirements

	White dwarfs	Metal Poor Stars	Resolved populations	Dark matter mapping	IGM Tomography I	IGM Tomography II	$z\sim 2-5$ Galaxies	QSO Pairs	Transients
Slits/mask	140	< 10	140	140	20	90	20	20	1
Masks/night	2	5	2.5,7	6	2	10	2	3	–
Slit width [arcsec]	0.6	0.75	0.8	0.75	0.75-1.0	0.75-1.0	0.75	0.75	0.75
Typical integration time/exposure [s]	1800	1200	1200	1800	1800	1800	1800	1800	1800
Typical integration time/mask [ks]	15	7.2	9,3	3.6	14.4	3.6	14.4	14.4	3.6
Resolution (blue/red)	2000	8000	8000	2000/5000	5000	1000	5000	8000	1000-8000
Minimum wavelength (blue/red) [nm]	340	380/550	370/830	310/550	310/550	310/550	310/550	310/550	310/550
Maximum wavelength (blue/red) [nm]	550	550/800	550/900	550/900	550/750	550/800	550/1000	550/1000	550/1000
ECH mode needed?	✔	✔	✔	✔	✔		✔	✔	✔
Need very precise flux calibration?				✔					
Needs very precise sky subtraction?			✔	✔	✔	✔			
Uses blue and red arms at same time?		✔	✔	✔	✔	✔	✔	✔	✔

Blue most-essential = WDs, IGM Tomography, z ~ 2-5 galaxies

Red most-essential = resolved stellar pops and metal poor stars

Full simultaneous coverage needed = QSOs and Transients

MOBIE Team

- Rebecca Bernstein (UCSC), Principal Investigator
- 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), Alice Shapley (UCLA)

    (**To be expanded**)
- Bruce Bigelow (UCSC), Project Manager
- Zhongwen Hu (NIAOT), Qingfeng Zhu (USTC), Taotao Fang (Xiamen)
  - Acquisition and Guiding Wavefront Sensor
- Peter Onaka, Sidik Isani, Hubert Yamada (UH)
  - Detector readout electronics / Software
- Shinobu Ozaki, Satoshi Miyazaki (NAOJ), Canon
  - Spectrograph cameras

Different WFOS designs were studied during the instrument feasibility study phase. The current design for WFOS is known as the "Multi-Object Broadband Imaging Echellette" (MOBIE) spectrometer.

MOBIE's Conceptual Design Review is scheduled for October 29-30, 2013

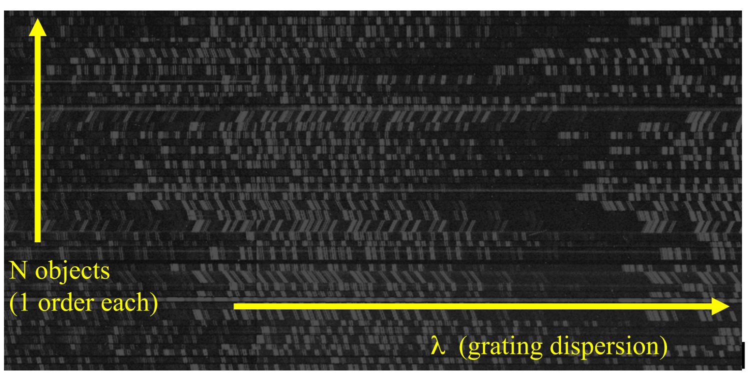
Design Concept: A hybrid design solution

"Discovery" science

- Examples: surveys
  - IGM structure and composition at 2<z<6
  - stellar populations (chemistry & kinematics z>1.5)
- Design priorities:
  - Resolution (λ/Δλ): 1,000 – 5,000
  - Multiplexing: 100's

SINGLE ORDER SPECTRA

Wide Field Multi-Object spectrographs:
DEIMOS (Keck), VMOS (VLT), IMACS (Magellan)

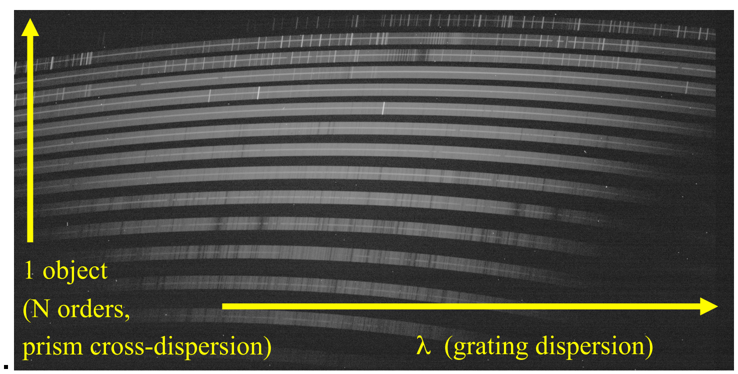


"Diagnostic" science

- Examples: targeted studies
  - Abundances & kinematics of stars w/in 20 Mpc
  - Galactic and Local Group sub/structure
- Design priorities:
  - Resolution (λ/Δλ): 8,000 – 16,000 (∝ slit width)
  - Multiplexing: 10's

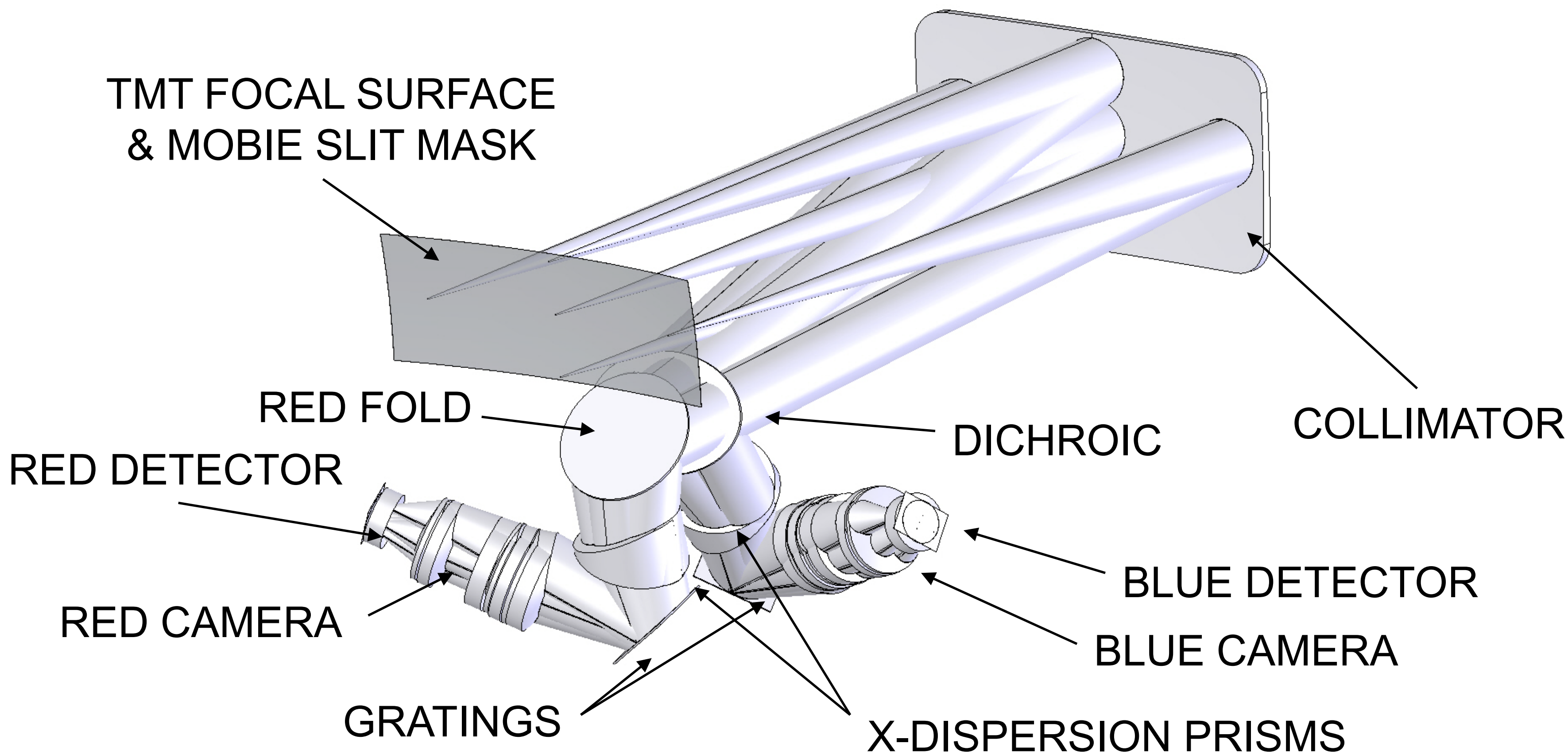
MULTI-ORDER (cross-dispersed) SPECTRA

Echellette spectrographs:
ESI (Keck), MagE (Magellan), XShooter (VLT)



MOBIE Optical Design

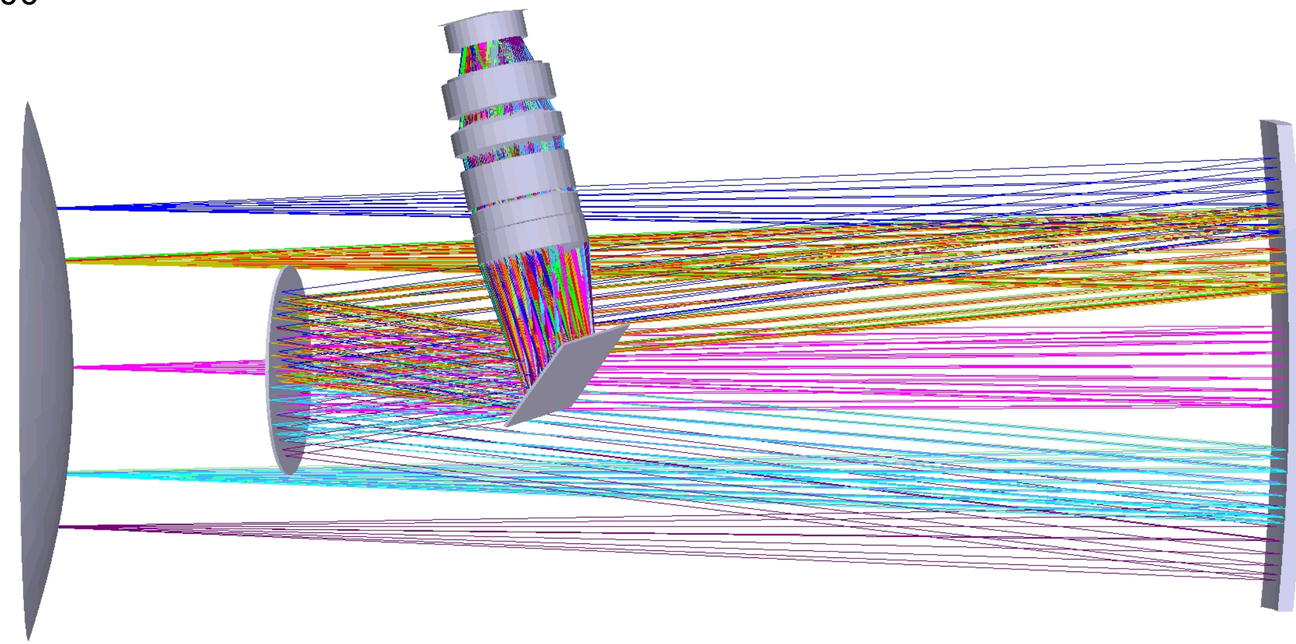
Two color channels, each with direct imaging and three spectroscopic modes



Design Concept: modes

- Low: R~1000
- Medium: R~ 2,500 and/or 5000
- High: R ~ 8,000

Only dispersion elements change
Each grating is fixed.



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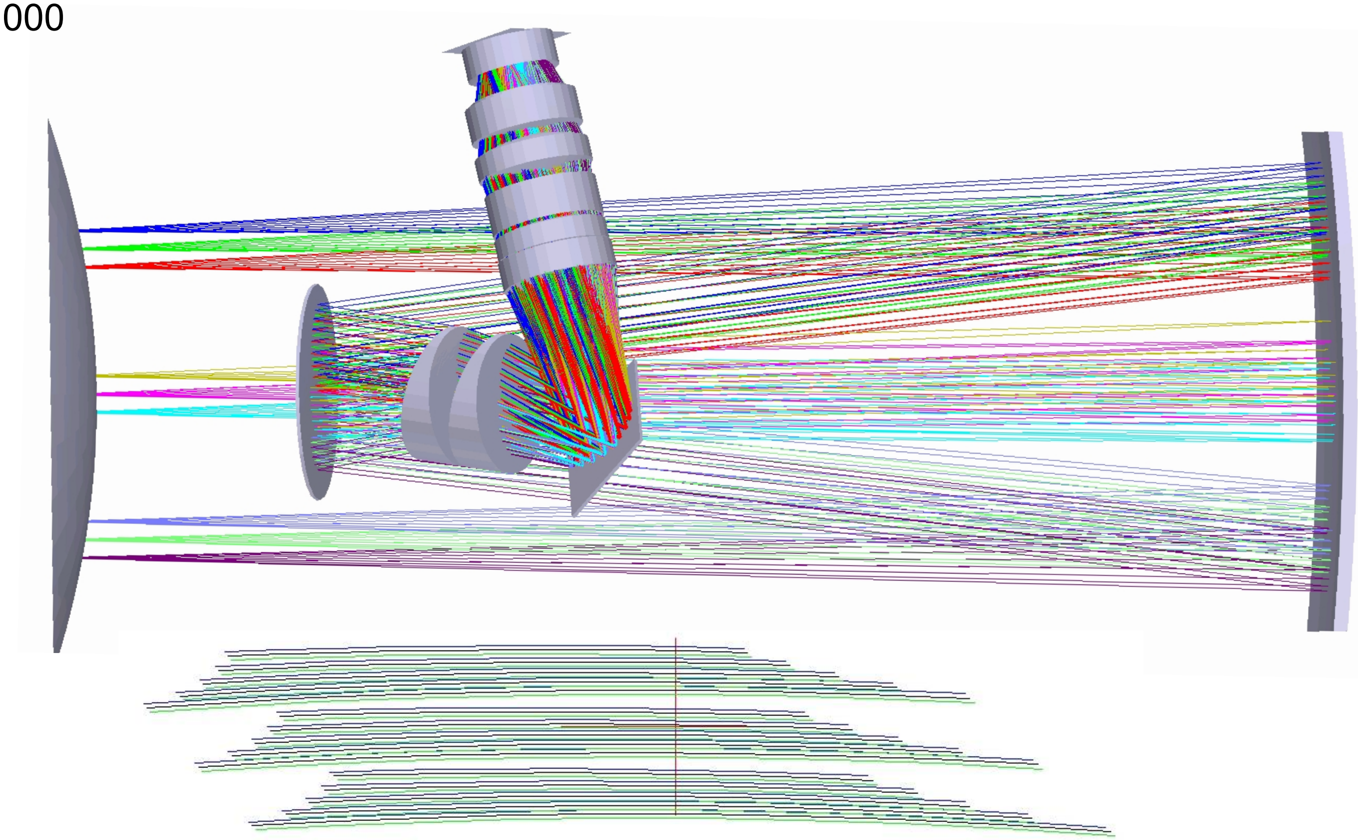

TMT
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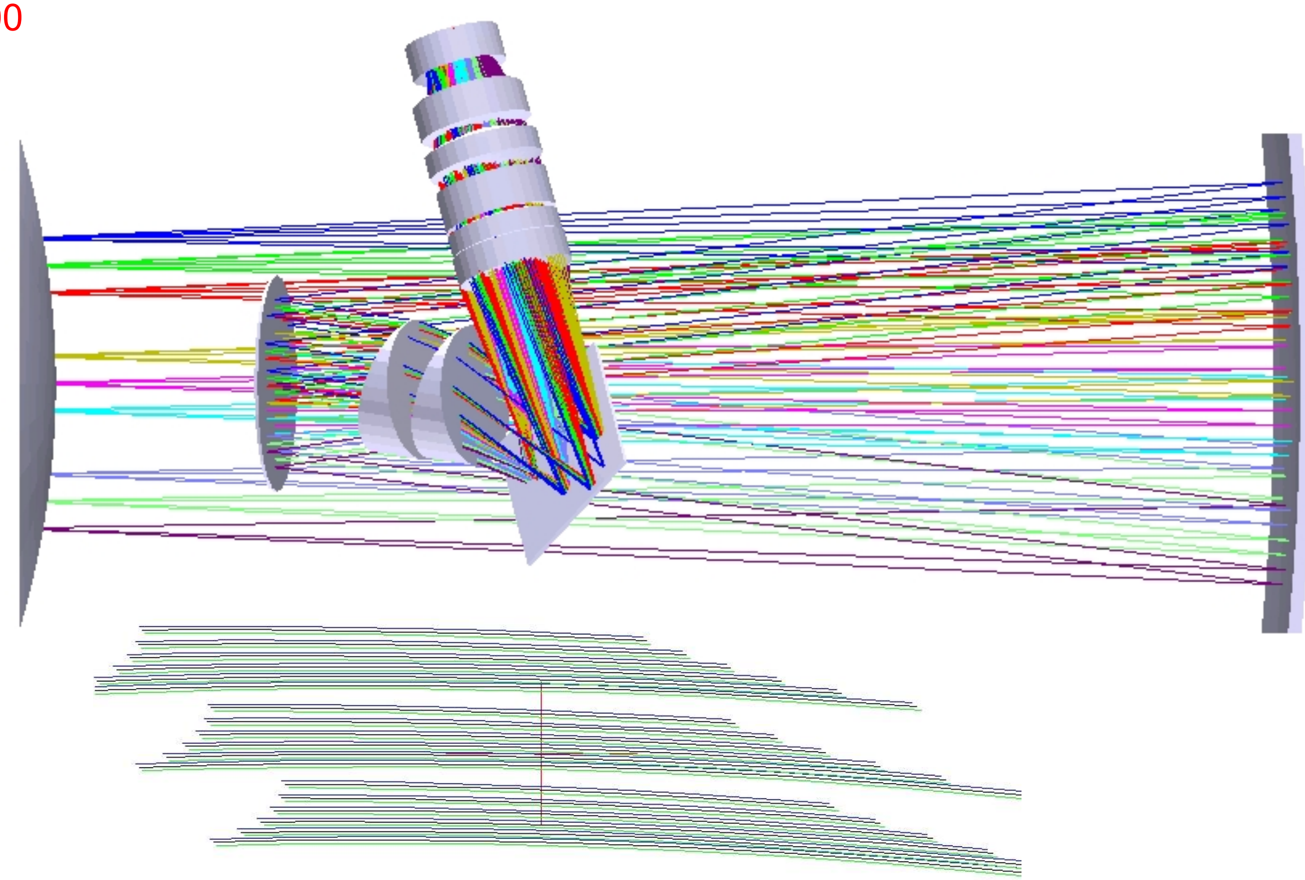
Design Concept: modes

- Low: R~1000
- Medium: R~ 2,500 and/or 5000
- High: R ~ 8,000

Only dispersion elements change.
Each grating is fixed.

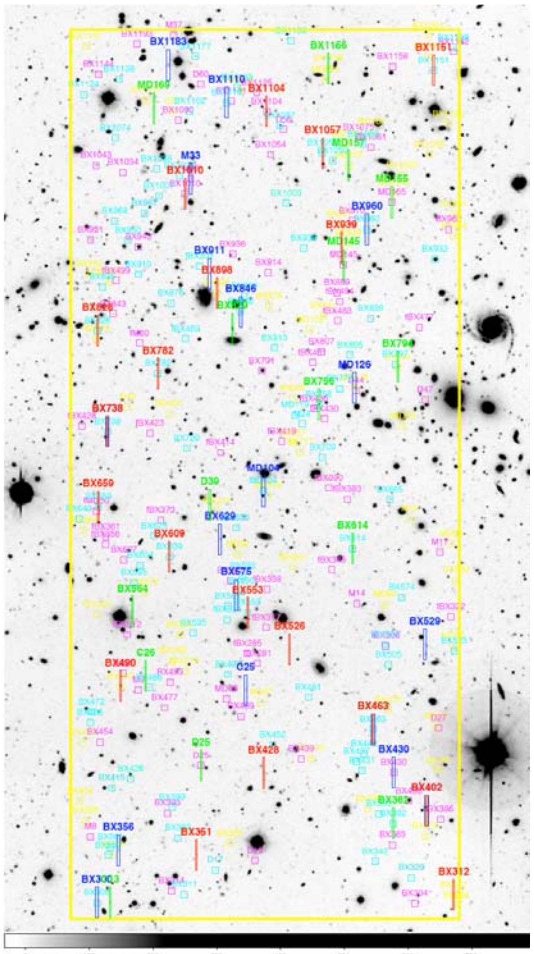


Examples of Spectral Resolution Options

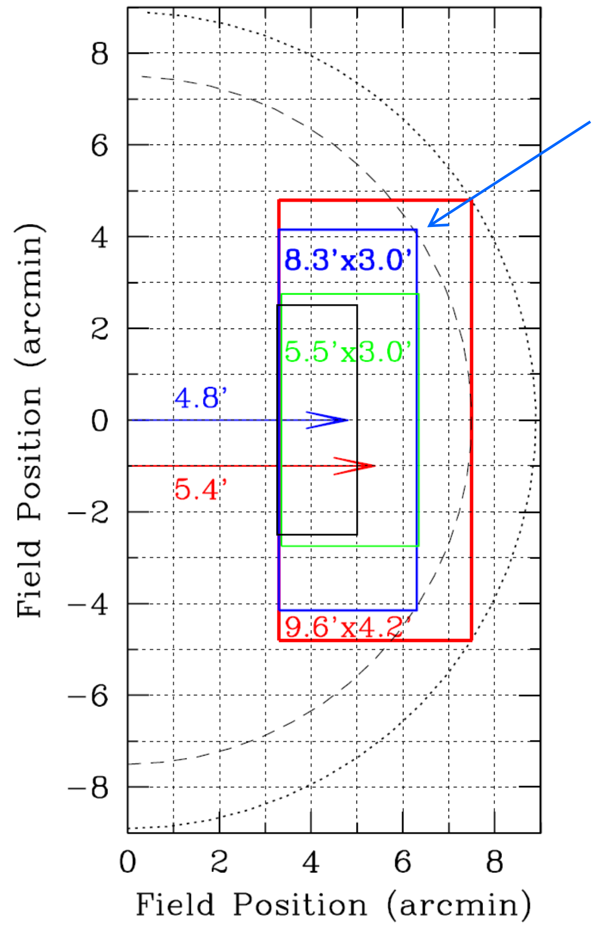
$\mathcal{R}$	Order	FSR	Length	$\mathcal{R}$	Order	FSR	Length
	Blue		— —			Red	
985	2	0.308-0.554	136	1077	1	0.550-1.000	131
2600	6	0.308-0.365	92	2480	6	0.536-0.635	88
	5	0.365-0.447	112		5	0.635-0.779	107
	4	0.447-0.580	145		4	0.779-1.010	138
5040	11	0.311-0.341	95	4860	11	0.558-0.611	91
	10	0.341-0.377	105		10	0.611-0.676	101
	9	0.377-0.421	117		9	0.676-0.756	113
	8	0.421-0.478	133		8	0.756-0.857	128
	7	0.478-0.552	154		7	0.857-0.991	148
7900	18	0.313-0.330	89	7780	18	0.565-0.597	89
	17	0.330-0.351	94		17	0.597-0.633	94
	16	0.351-0.373	100		16	0.633-0.674	100
	15	0.373-0.399	107		15	0.674-0.721	107
	14	0.399-0.429	115		14	0.721-0.774	115
	13	0.429-0.463	124		13	0.774-0.836	125
	12	0.463-0.503	136		12	0.836-0.909	136
	11	0.503-0.552	149		11	0.909-0.996	149

* – All resolution values are for a 0.75 arcsec entrance slit; order lengths in mm, at the detector. Each configuration is designed for use with a dichroic beam-splitter at 0.55 μm. The camera field of view corresponds to $\simeq$ 220 mm.

MOBIE Science Field Geometry



Multi-object mask making simulation



MOBIE-OPT:

- "Best" VE study cost-performance configuration
- Deletes field area with worst image quality & vignetting
- Reduces ADC and collimator optics sizes
- FoV size hardest return to quantify
- Good match to CCD formats

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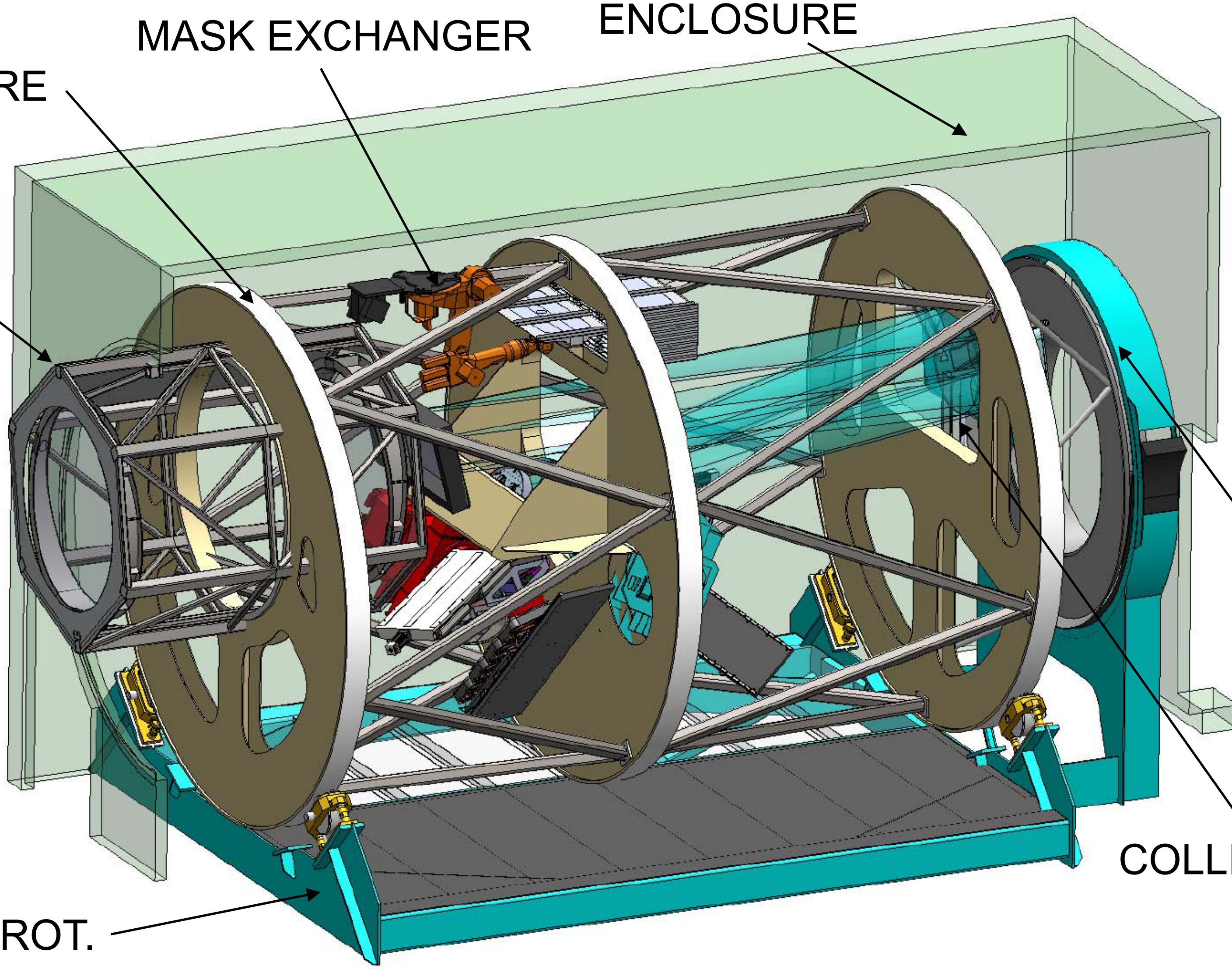
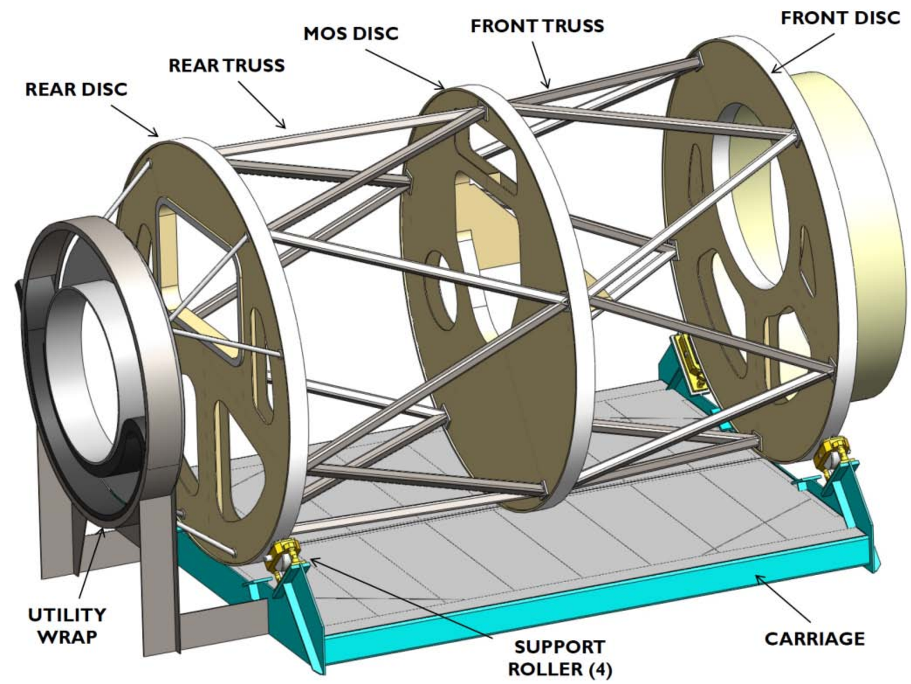
MOBIE Schematic View



MOBIE Instrument Structure

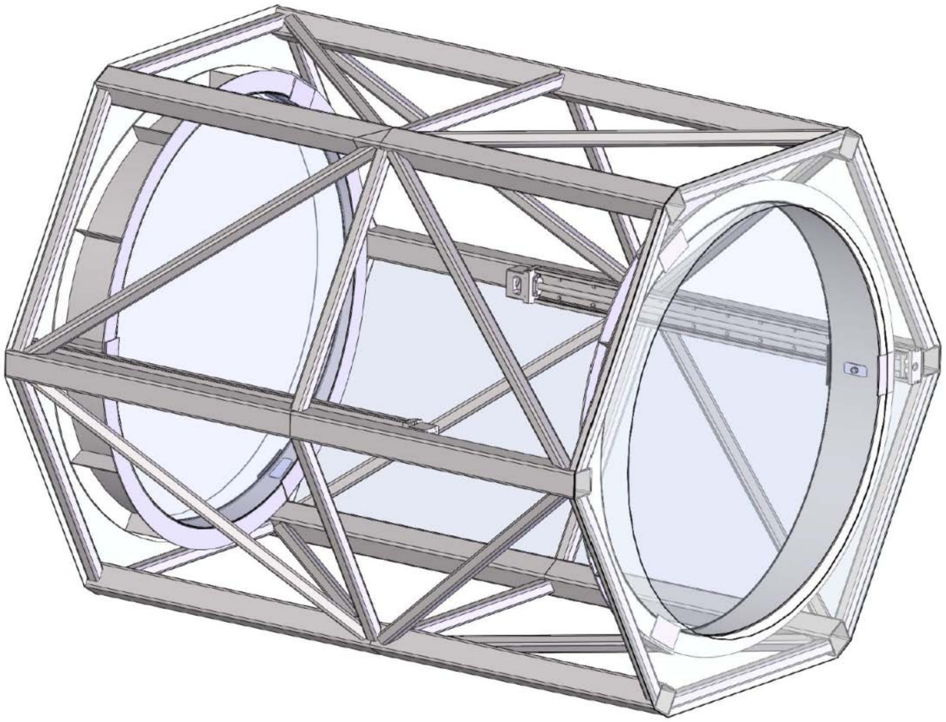
IMACS structure and rotator – disks are ~2m in diameter.



MOBIE structure and rotator – disks are ~4m in diameter.

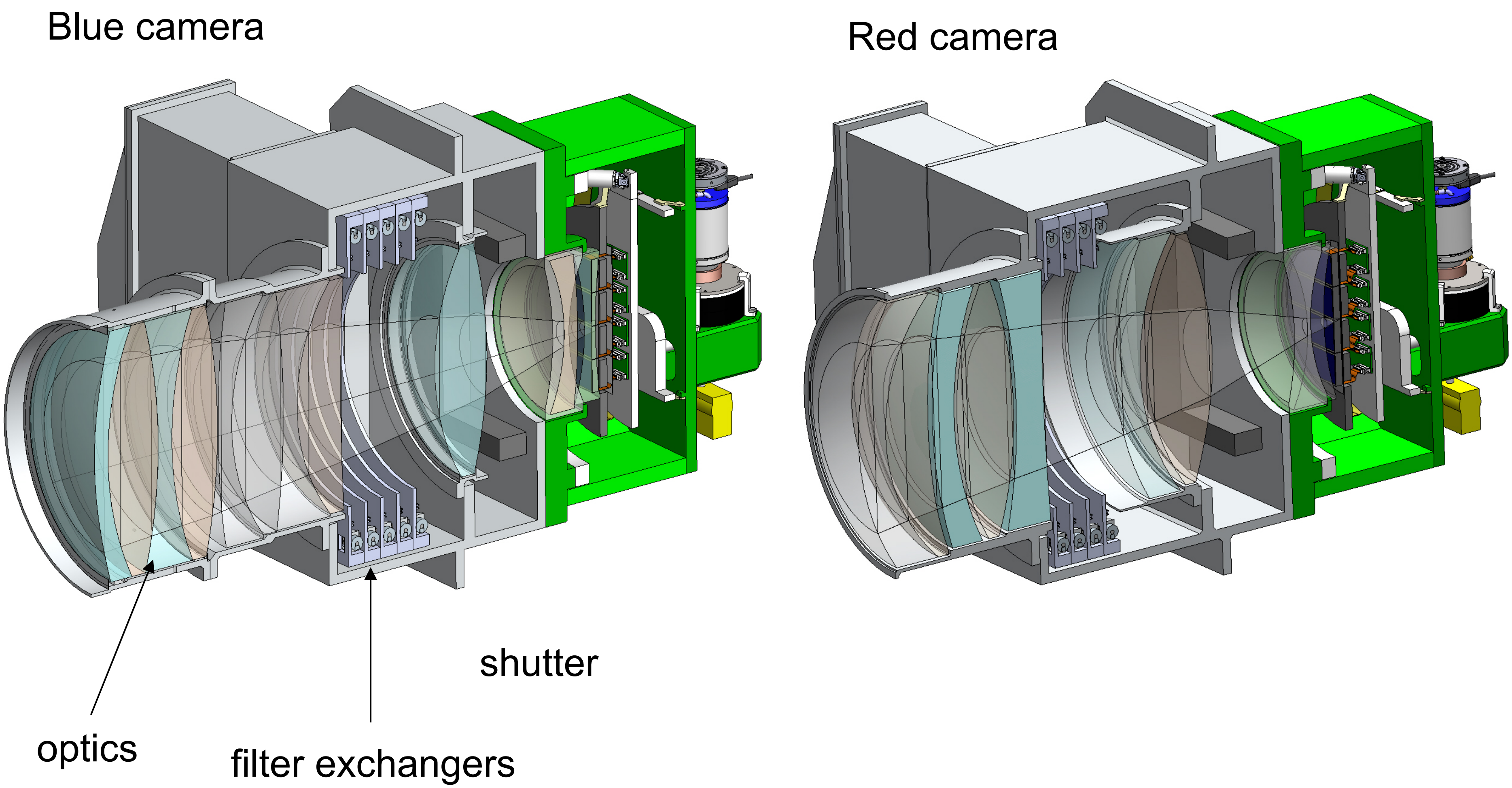
MOBIE Atmospheric Dispersion Corrector

Keck ADC during fabrication at UCO – 1.0m prisms.



MOBIE ADC mid-CDP shown with1.6m prisms.

MOBIE Cameras

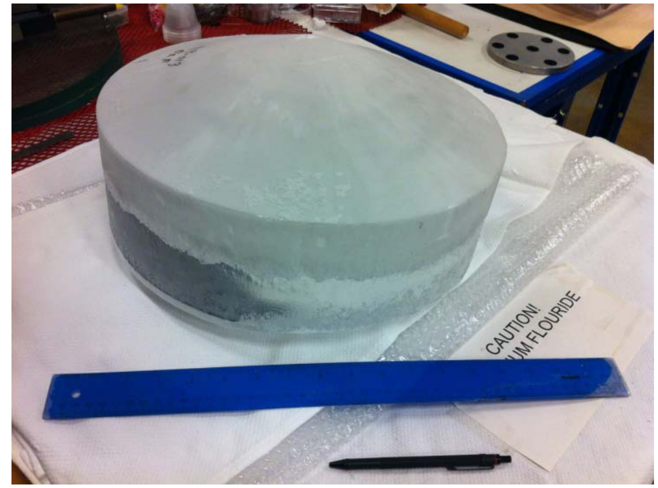


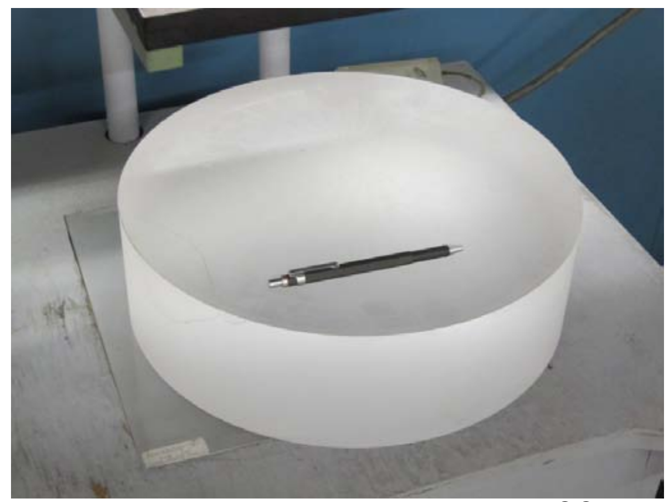
Hellma 440mm Diameter CaF2 element

Single Point Diamond Turning Process Development at OSI

One of two diamond turning machines at Optical Solutions Inc.

Rough crystal





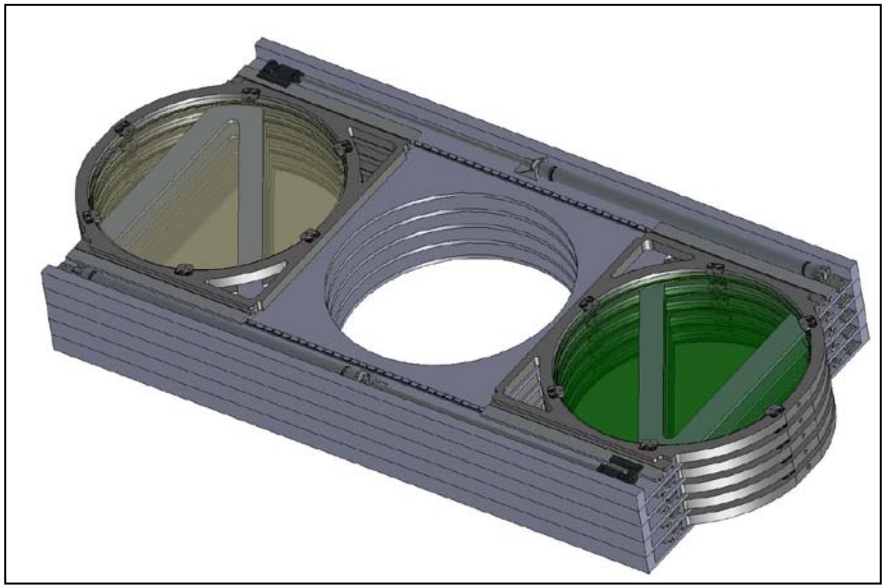
350mm diam. X 100 MOBIE CaF_2 crystal, generated and ready for SPDT work.

MOBIE Filter Concept

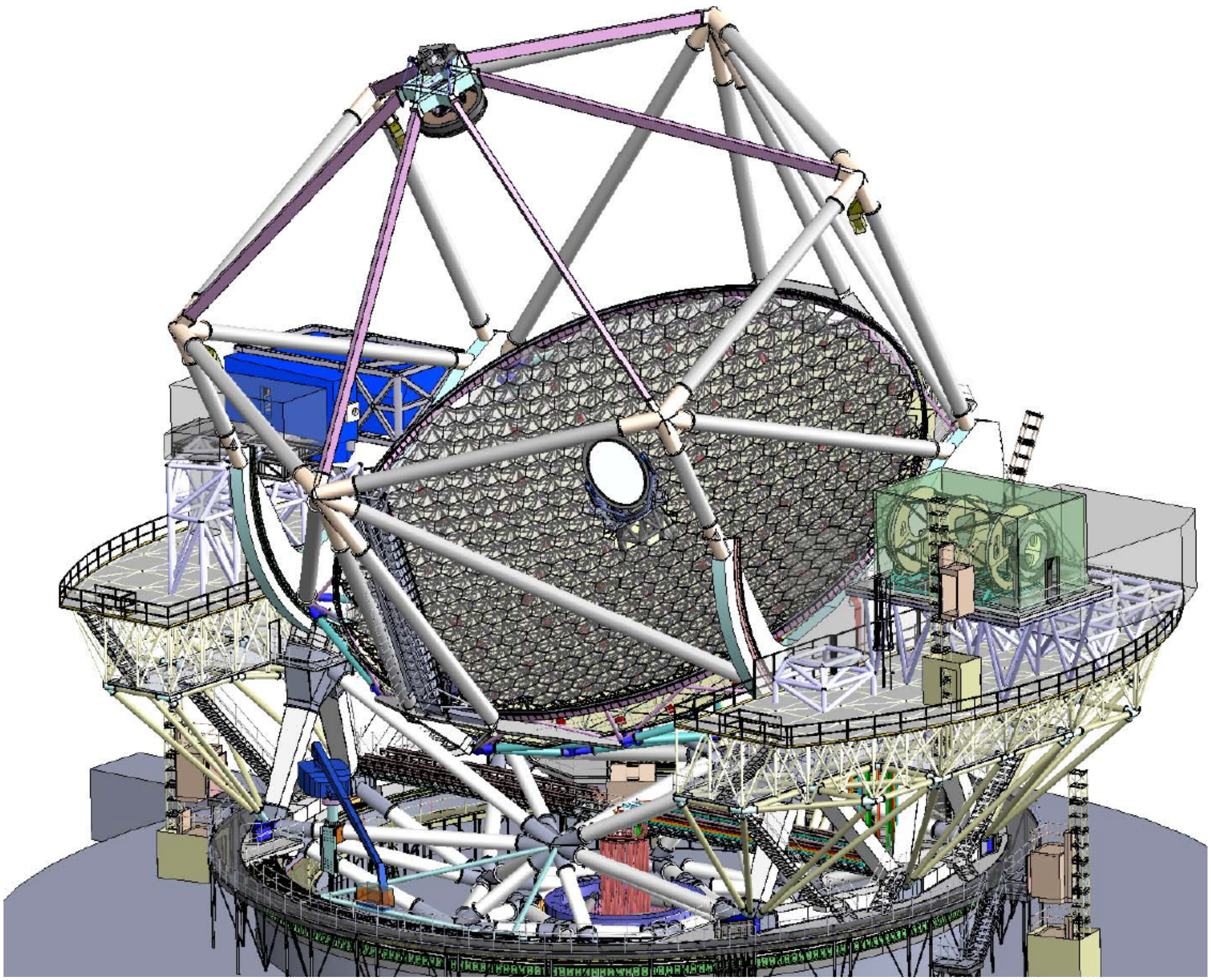
- Conceptual system designs are based on operational DECam and Pan-STARRS filter exchanger systems

Bigelow FES design for DECam

MOBIE FEX design



MOBIE on TMT



MOBIE Performance Summary

Requirements/goals	Realized in MOBIE-OPT concept
– Wavelength range: 0.31 –1.0μm	0.30 – 1.1μm
– Field of view: >40.5 arcmin^2	~25 arcmin^2 (~8.33’ x ~3’)
– Total slit length ≥ 500″	500″ (8.33’)
– Image quality:	
– fwhm ≤ 0.2″ (imaging) 0.1μm band	< 0.2”
– fwhm ≤ 0.2″ (spec) any λ, no re-focus	< 0.2″ (preserve resolution)
– Spectral resolution:	
– 1000 < R < 5000 for 0.75″ slit	R = ~1000, ~5000, ~8000
– Complete λ-coverage at R~1000	complete or select orders
– Throughput ≥ 30% (all λ)	> 40% down to 0.30 μm (est.)
– Sensitivity: limited by photon stats for t>300s	(high transmission design)
– Field acq: <3 min/mask, <1min/single obj.	

MOBIE Performance Summary

TMT
THIRTY METER TELESCOPE

Requirements/goals	Realized in MOBIE-OPT concept
– Wavelength range: 0.31 –1.0μm	0.30 – 1.1μm
– Field c	3' x ~3')
– Total s	
– Image	
– fwh	
– fwh	solution)
– Spectr	
– 10	~8000
– Cc	orders
– Throughput ≥ 30% (all λ)	> 40% down to 0.30 μm (est.)
– Sensitivity: limited by photon stats for t>300s	(high transmission design)
– Field acq: <3 min/mask, <1min/single obj.	

MOBIE on TMT will an ideal optical multi-object spectrograph: a high-performance instrument that combines both survey and diagnostic spectroscopy in a versatile and elegant way

THIRTY METER TELESCOPE

Acknowledgments

The TMT Project gratefully acknowledges the support of the TMT collaborating institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology, the University of California, the National Astronomical Observatory of Japan, the National Astronomical Observatories of China and their consortium partners, and the Department of Science and Technology of India and their supported institutes. This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the National Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund, the Association of Universities for Research in Astronomy (AURA) and the U.S. National Science Foundation.