The Design and Capabilities of the Wide Field Optical Spectrograph For TMT

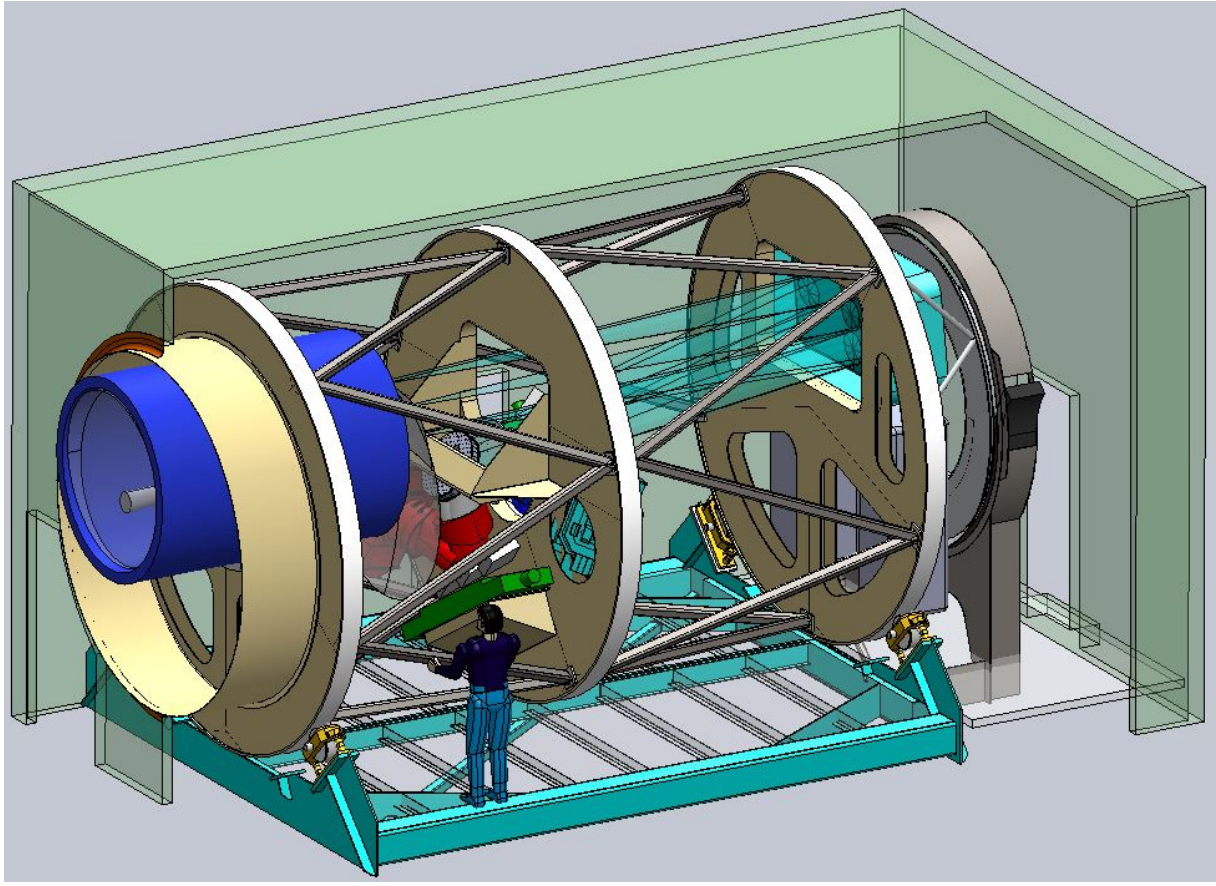
M ulti-

O bject

B roadband

I maging

E chellette



MOBIE Team

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Project Manager: Bruce Bigelow, UCSC
Project Scientist: Chuck Steidel, Caltech

Science Team:

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- Alice Shapley (UCLA)
- Bob Abraham (U. Toronto)
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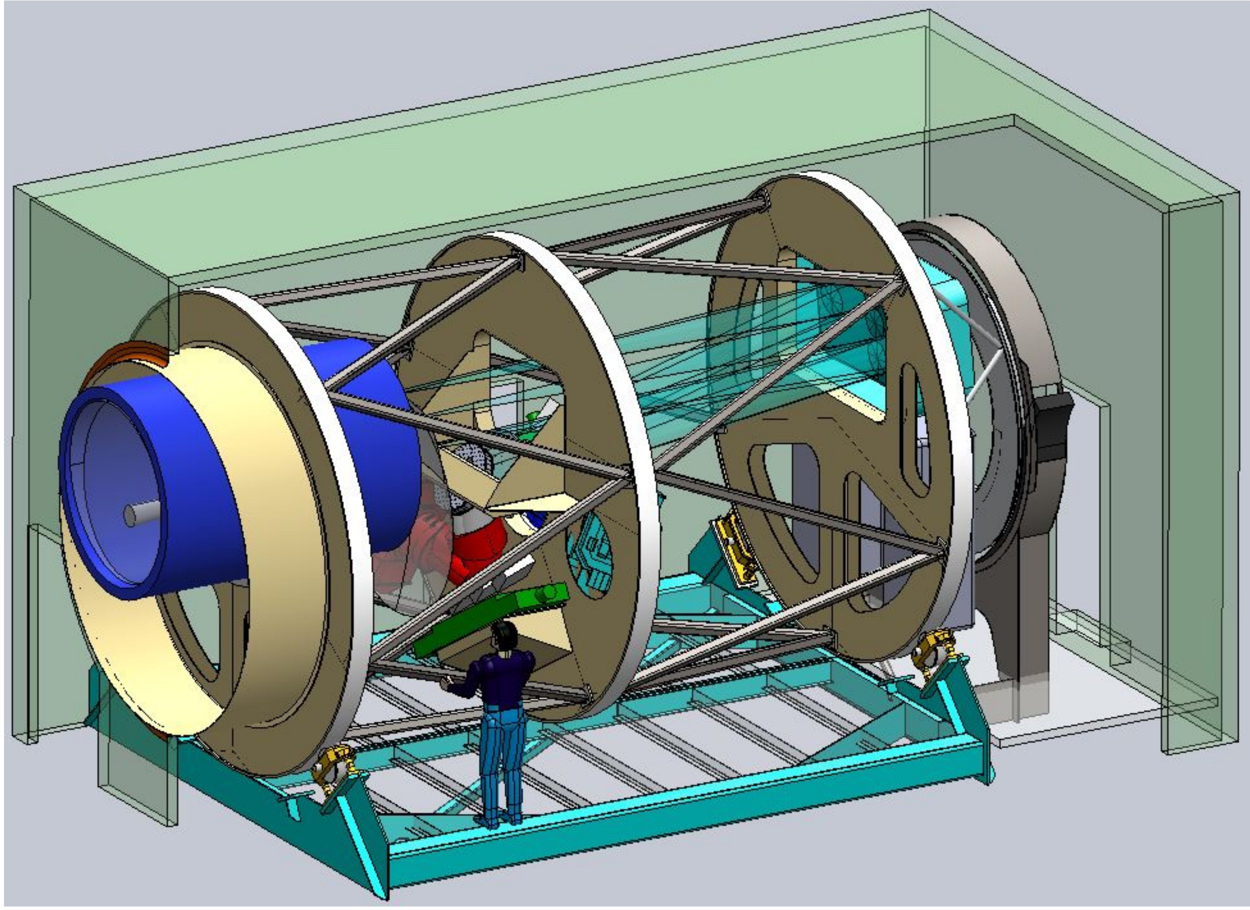
- Jason Kalirai (STScI)



TMT WFOS Requirements

Description	Requirement
Wavelength	0.31 – 1.0μm
Image quality: Imaging	≤ 0.2” FWHM in each band
Image quality: Spectroscopy	≤ 0.2” FWHM at any wavelength
Field of View	40.5 arcmin^2. Multiple fields okay.
Total Slit Length	≥ 500”
Spatial Sampling	< 0.15” per pixel, goal < 0.1”
Spectral Res	R = 500-5000 w/ 0.75” slit, R = 150-7500 (goal)
Throughput	≥ 30% from 0.31 – 1.0μm, or “similar to best current spectrometers”
Sensitivity	Shot noise limited for exp time >60 sec. Bckgrd sub. errors < shot noise for exp time <100,000 sec. Nod and shuffle desirable.
Wavelength Stability	Flexure <0.15” at detector

TMT WFOS Requirements

Extremely ambitious performance goals:

- NONE of the 6-10m spectrographs met all of these!
  (DEIMOS, IMACS, VMOS, GMOS)
- Field & resolution get harder with telescope diameter

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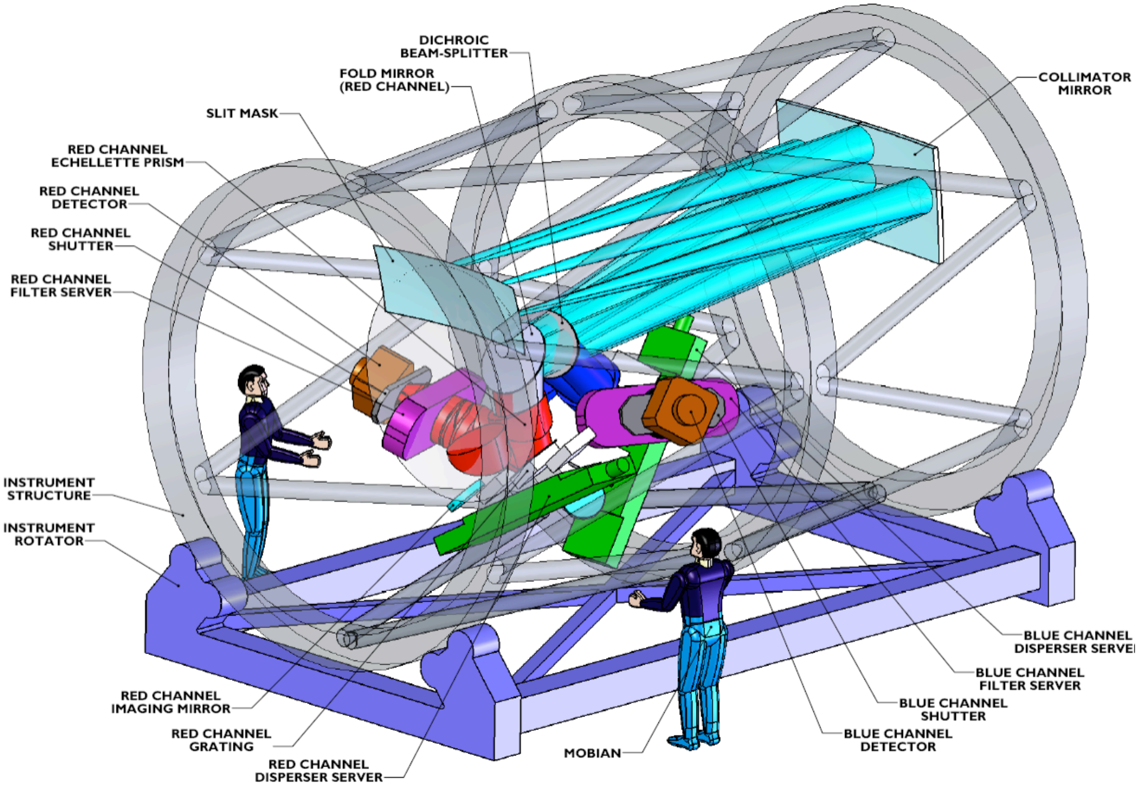
This talk:

- Why spectrographs should scale with telescope size.
  - the focal plane (sets the overall scale)
  - the pupils (sets the resolution)
  - the cameras (sets the length of the spectrum)
- What if they can't
  - Fibers, VPH gratings, Multiple fields of view.

- Design & Capabilities of MOBIE
  - History
  - Science drivers and performance
  - Design: key, enabling characteristics



Size of the focal plane (overall scale)

Shane (3 m)

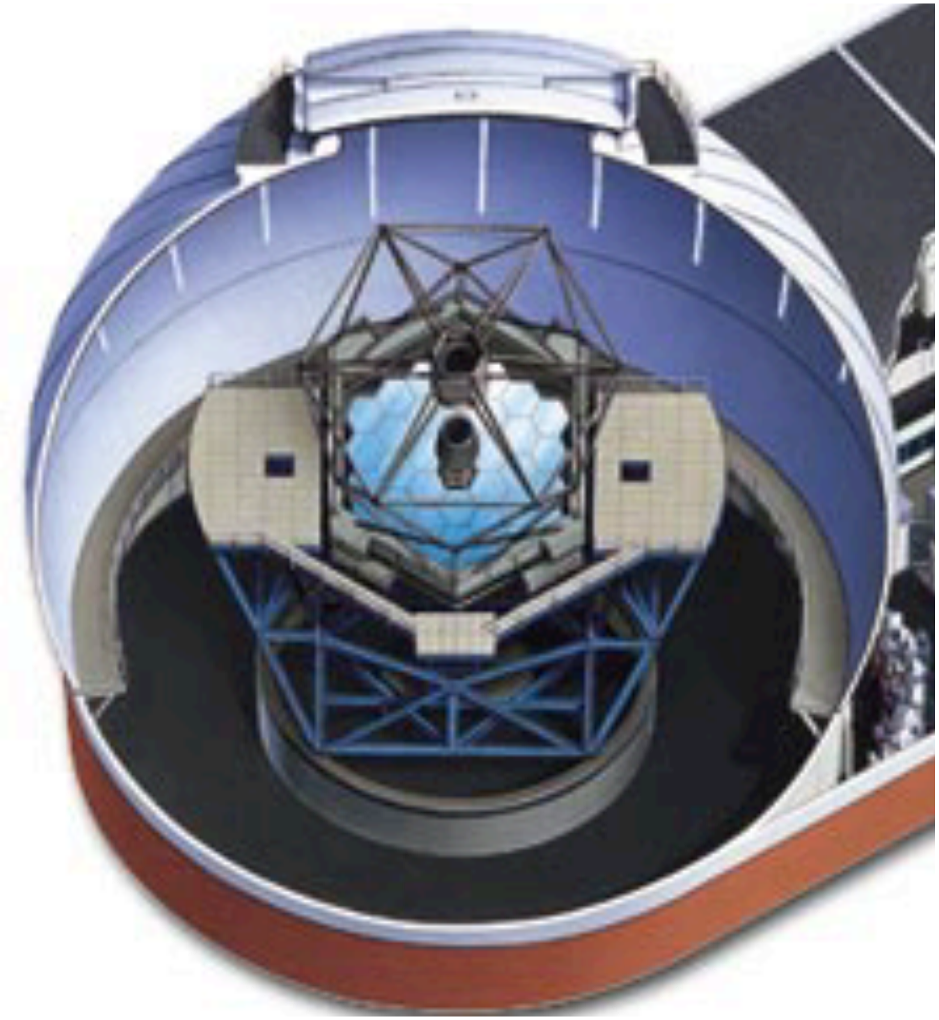
Diameter of the focal plane
and the image created of the moon.

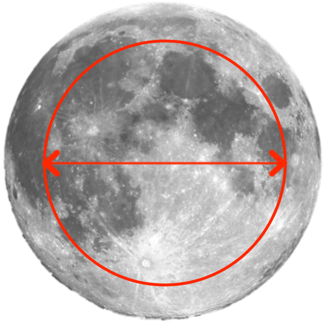
310 mm

Size of the focal plane (overall scale)

Keck (10 m)

Diameter of the focal plane
and the image created of the moon.

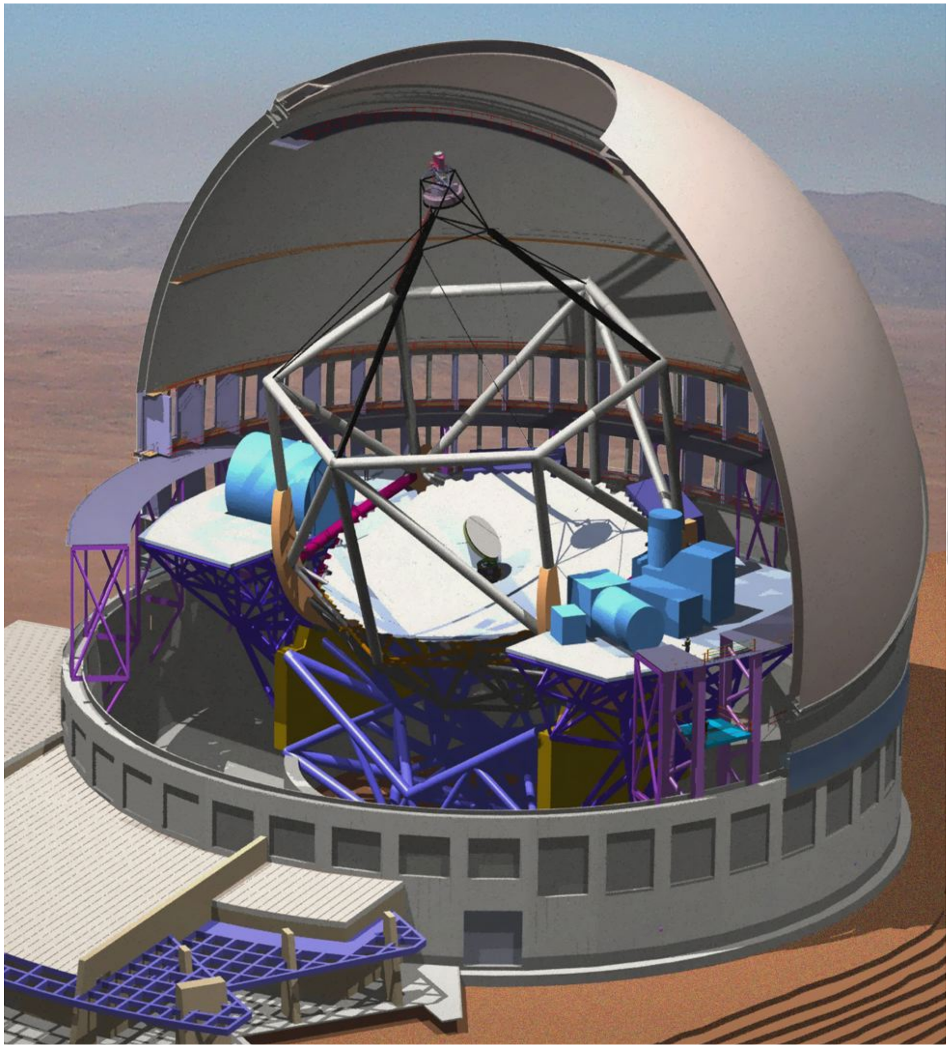




870 mm

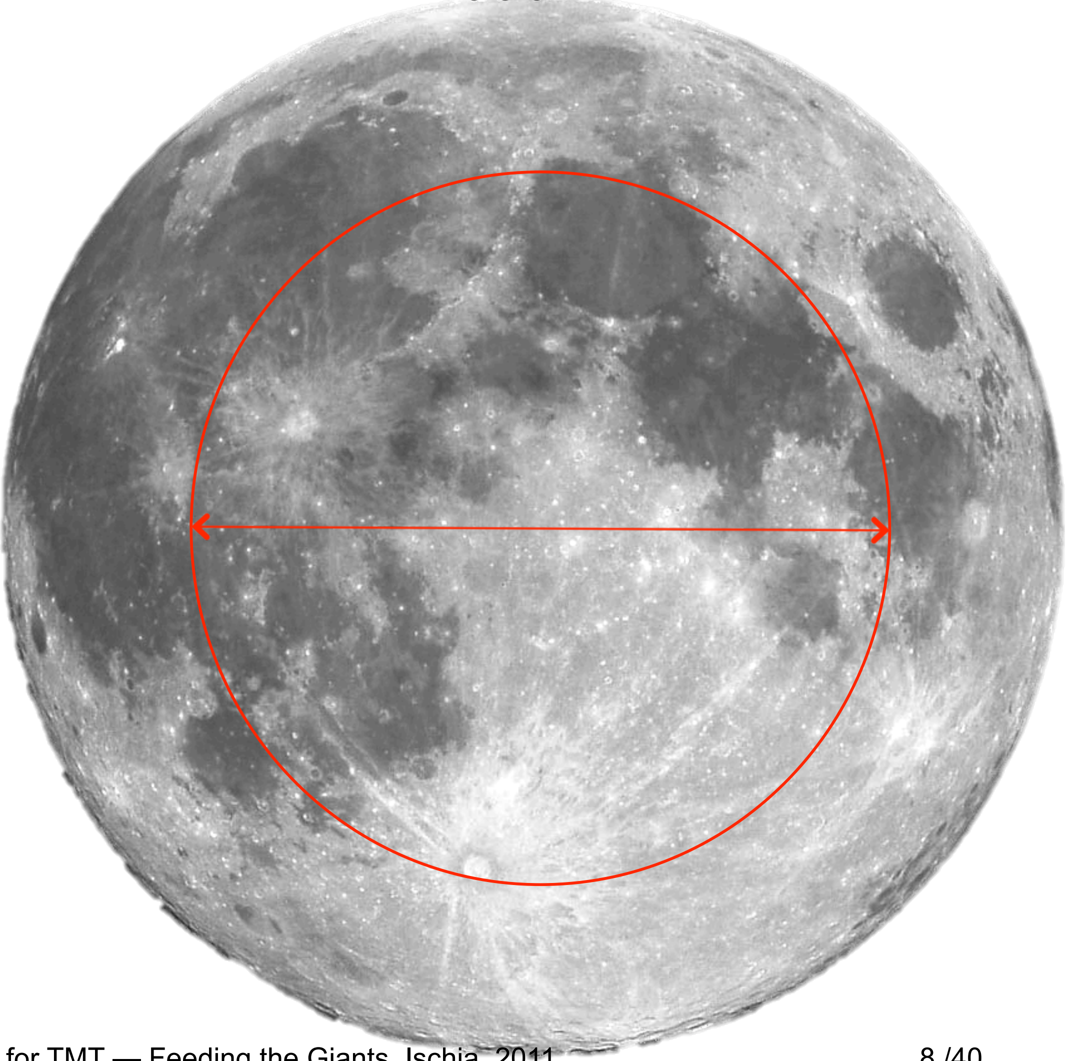
Size of the focal plane (overall scale)

TMT (30 m)



Diameter of the focal plane
and the image created of the moon.

2600 mm

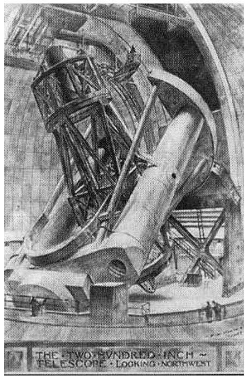


Size of the focal plane (overall scale)

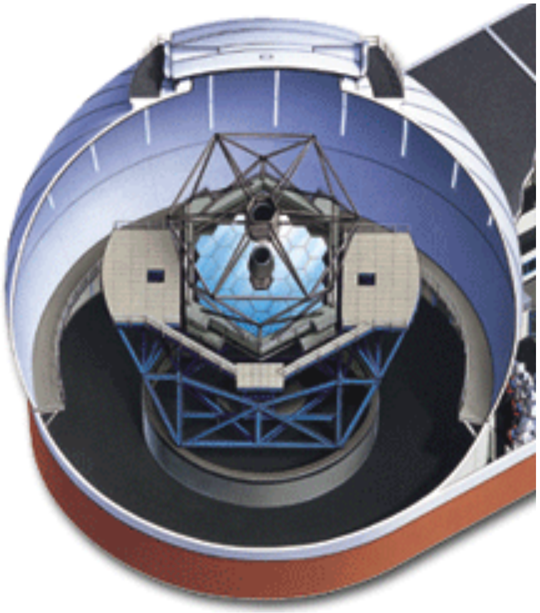
The front end of the spectrograph must match the focal plane scale, which scales with telescope size.

Shane 3m

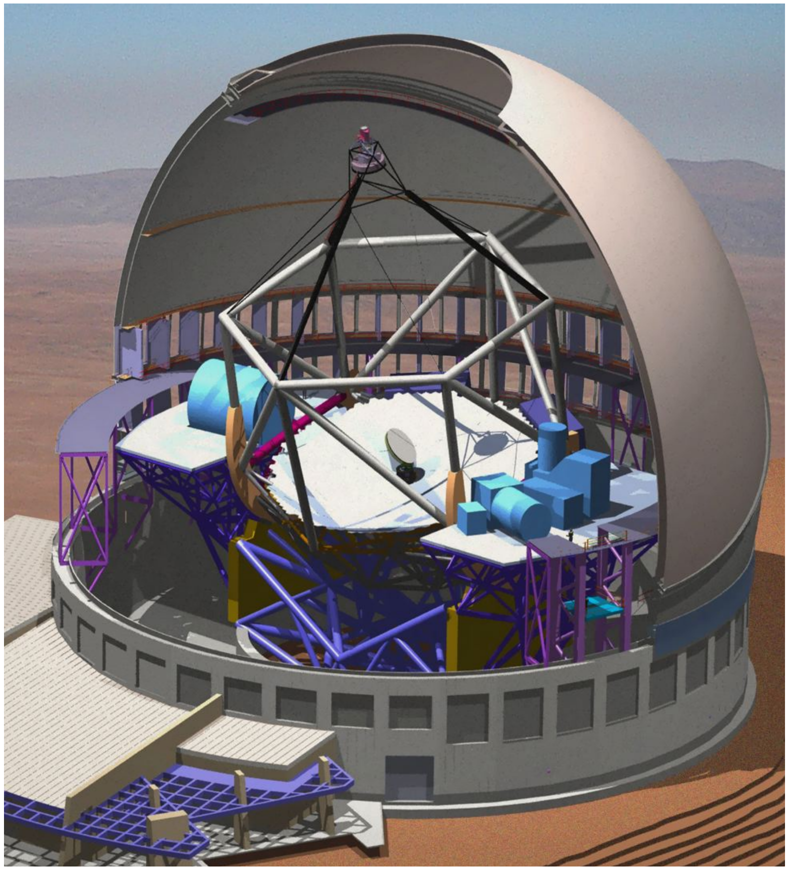
Hale 5m



Keck 10 m



Thirty Meter Telescope 30 m



Size of the pupil (resolution)

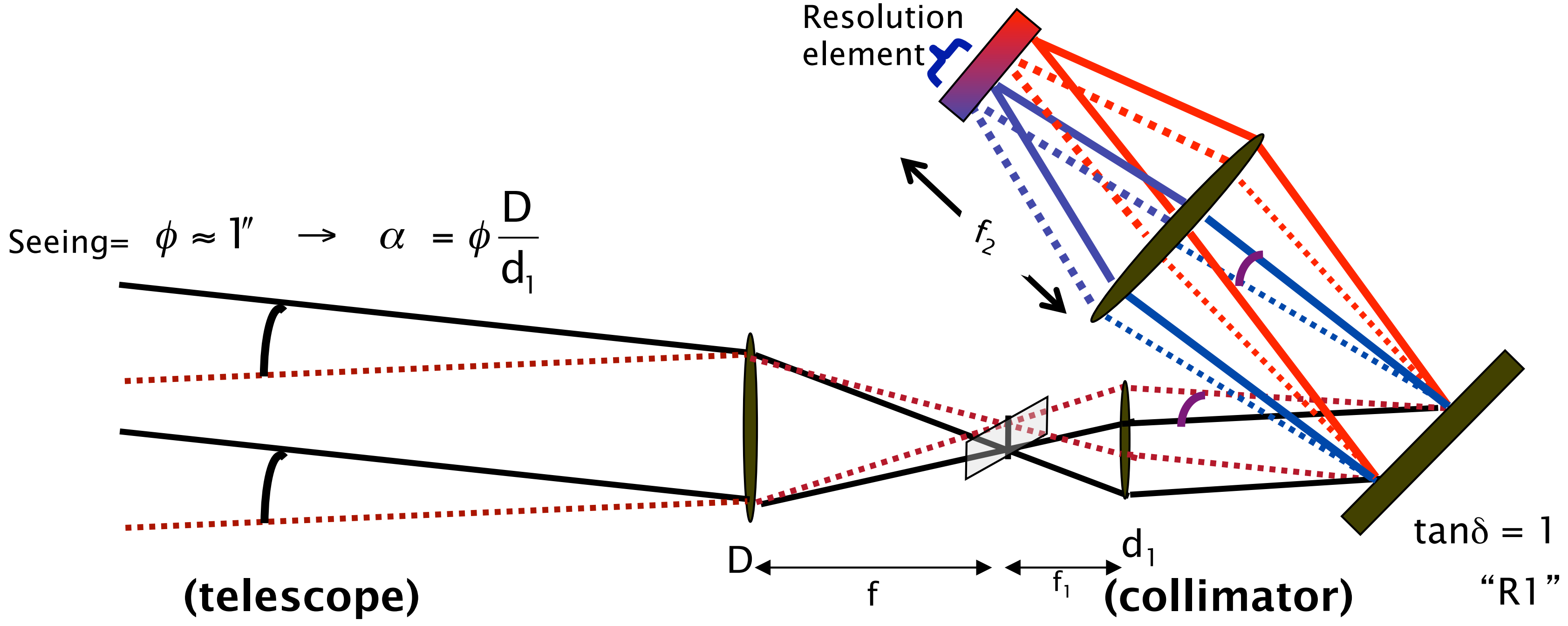
Resolution: scales with (beam:telescope)

$$R = \frac{\lambda}{\delta\lambda} = 2\frac{\tan\delta}{\phi}\frac{d}{D}$$

d/D = diameter of beam : telescope

δ = blaze angle (→ grating length)

ϕ = seeing disk = ~1” in the optical



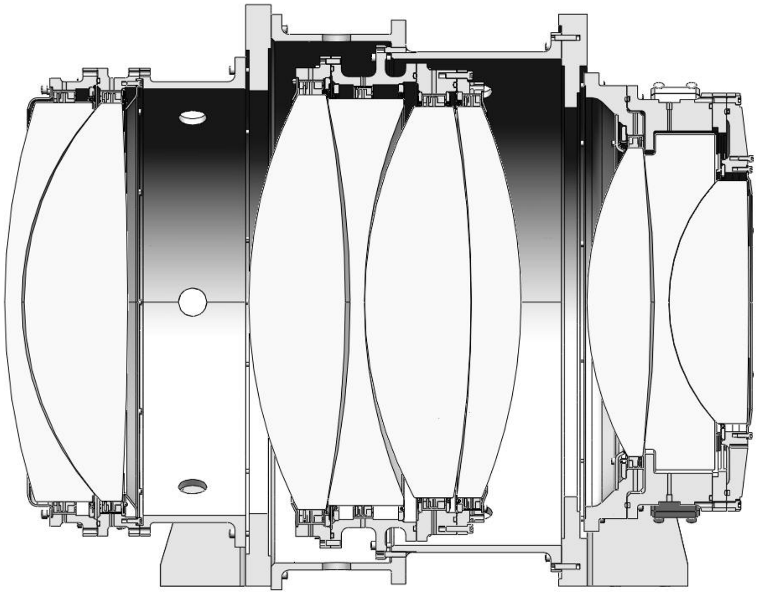
Seeing= $\phi \approx 1'' \rightarrow \alpha = \phi\frac{D}{d_1}$

Size of the camera (length of the spectrum)

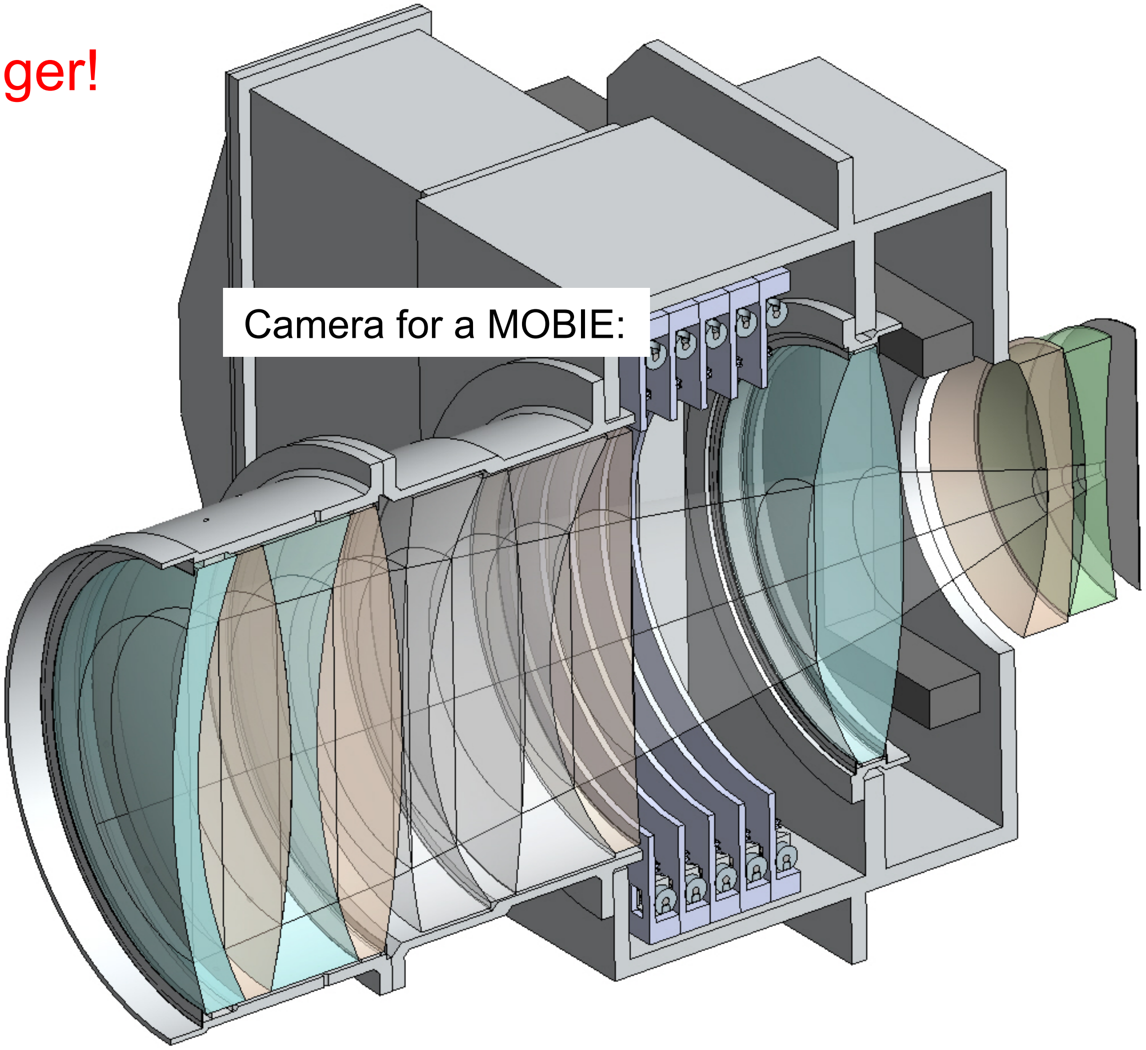
Comparison of camera (beam) size:

NOT a factor of 3 bigger!

Camera for a Keck spectrograph (2000):



Camera for a MOBIE:

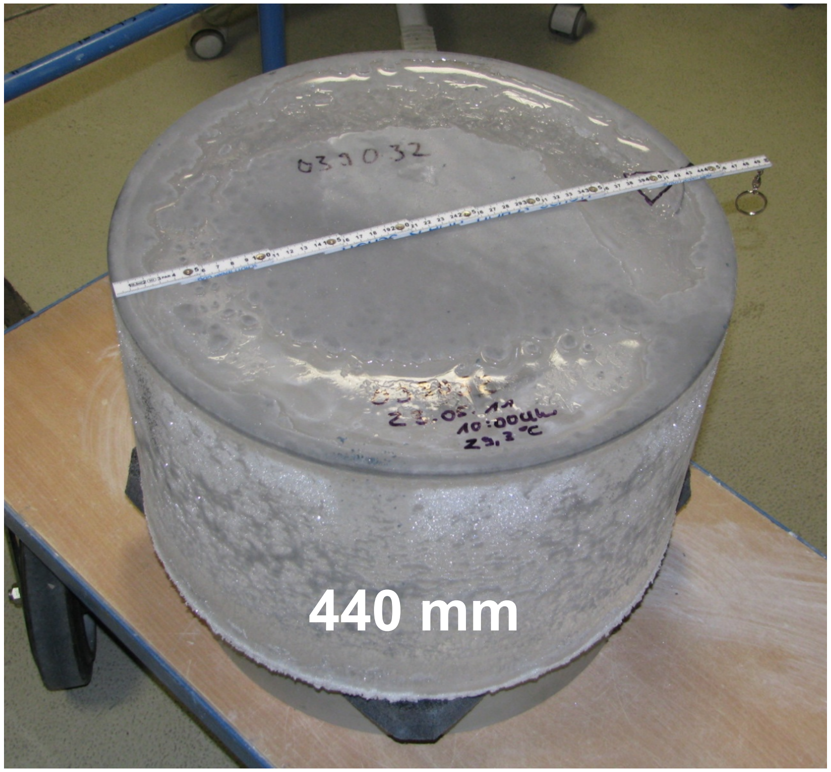


Size of the camera (length of the spectrum)

Why can't the cameras keep up?

We don't drive the CaF2 market.

Canon Optron (~1990)



Hellma (~ July 2011)

Size of the camera (length of the spectrum)

What is the impact on the spectrum?

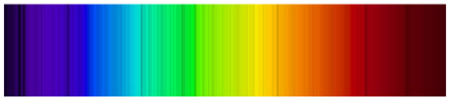
1. smaller wavelength coverage

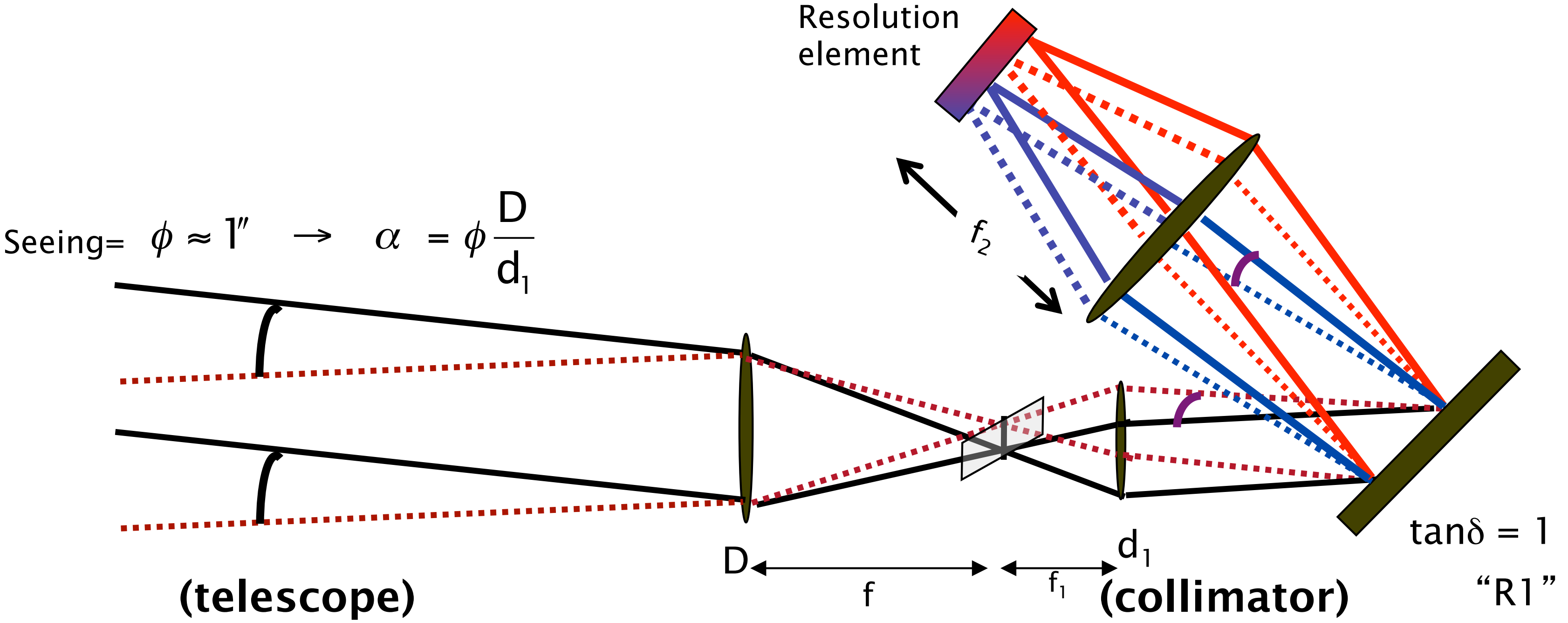
(high res grating)

2. lower spectral resolution

(low res grating)

Current expectation

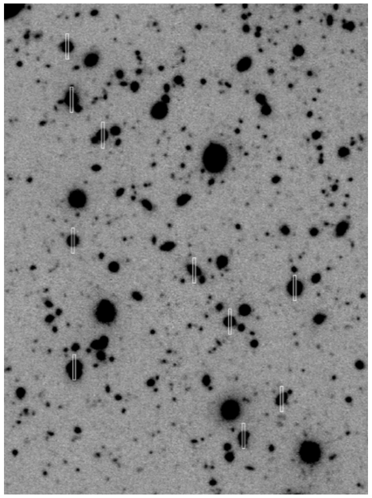


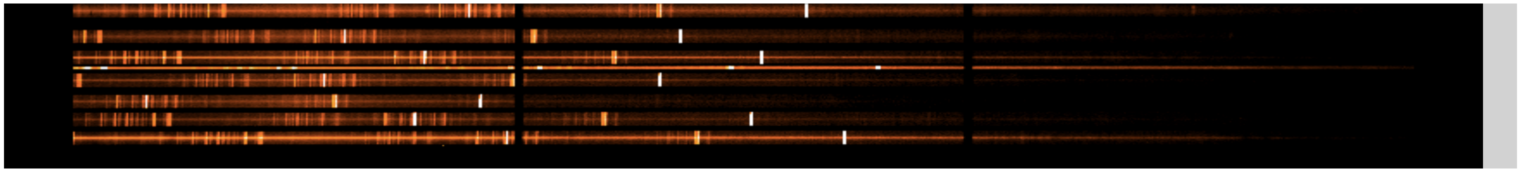


We've passed the sweet spot.

So if we put [DEIMOS or IMACS or VMOS] on an ELT ....

DEIMOS on Keck.



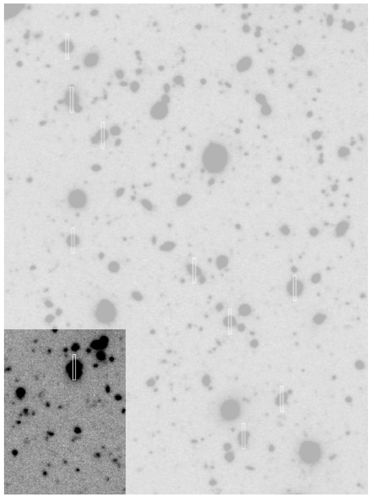


We’ve passed the sweet spot.

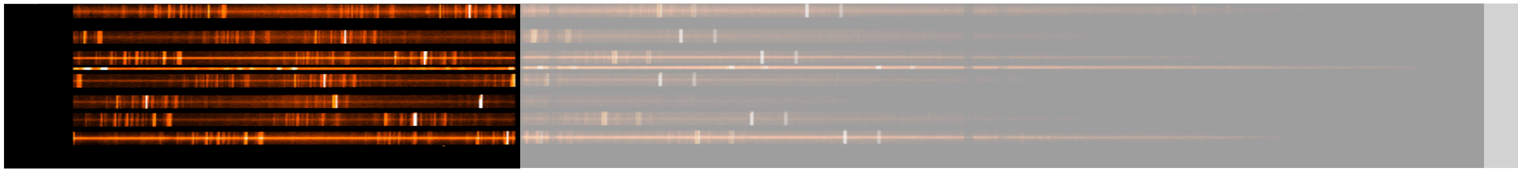
So if we put [DEIMOS or IMACS or VMOS] on an ELT ....

→ we get a lot less information than we’re used to.

DEIMOS on Keck.



DEIMOS on TMT.



Options: Fibers, VPH gratings, Multiple fields of view.

Fibers: increases field of view, but maximum throughput 40-50%

- many spectrographs for 2.5-8m telescopes
- EVE for E-ELT (not moving forward)

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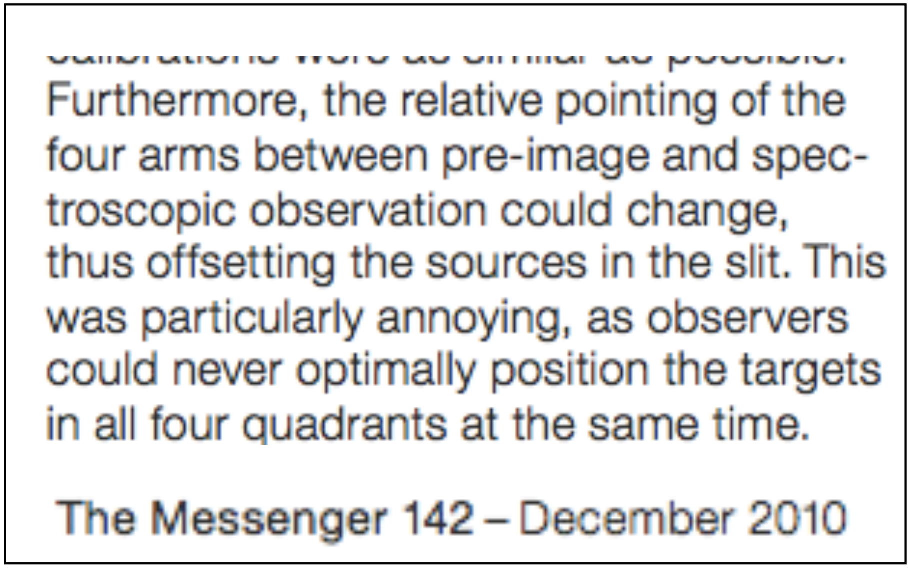
Multiple fields of view: increases field of view, but VERY hard to make work!

- VMOS for VLT*
- GMACS for GMT
- OPTIMOS for E-ELT (not moving forward)



Furthermore, the relative pointing of the four arms between pre-image and spectroscopic observation could change, thus offsetting the sources in the slit. This was particularly annoying, as observers could never optimally position the targets in all four quadrants at the same time.

The Messenger 142 – December 2010

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Multiple fields of view: increases field of view, but VERY hard to make work!

- VMOS for VLT*
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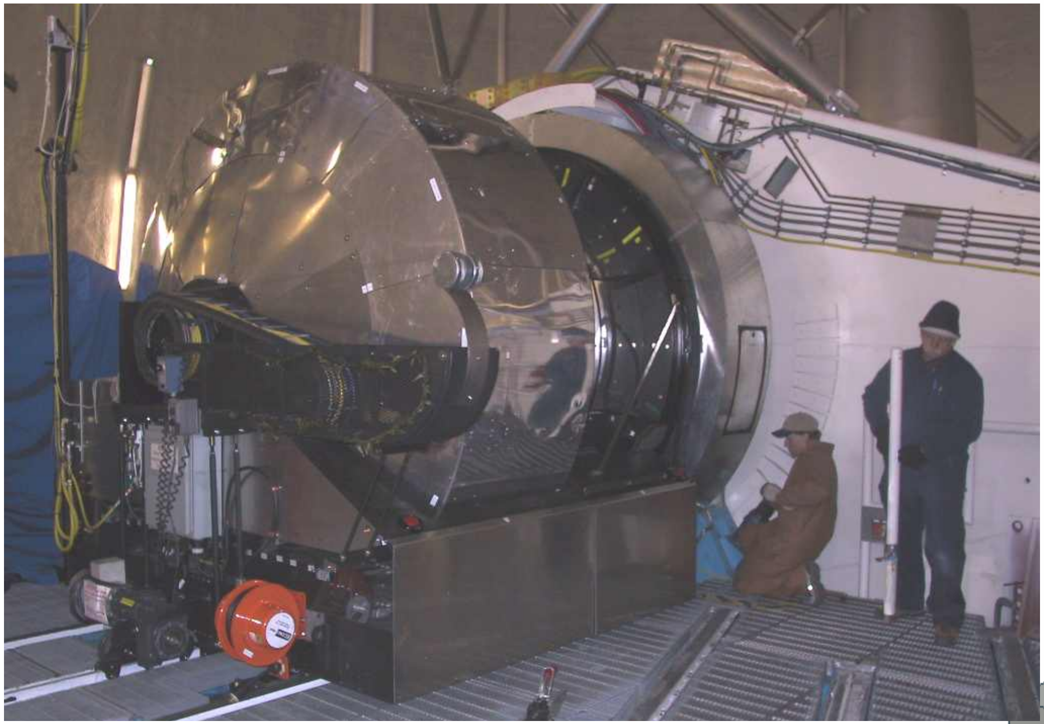
VPH gratings: help to keep the cameras smaller, but they have to articulate!

- several spectrographs in 4-8m telescopes
- GMACS for GMT

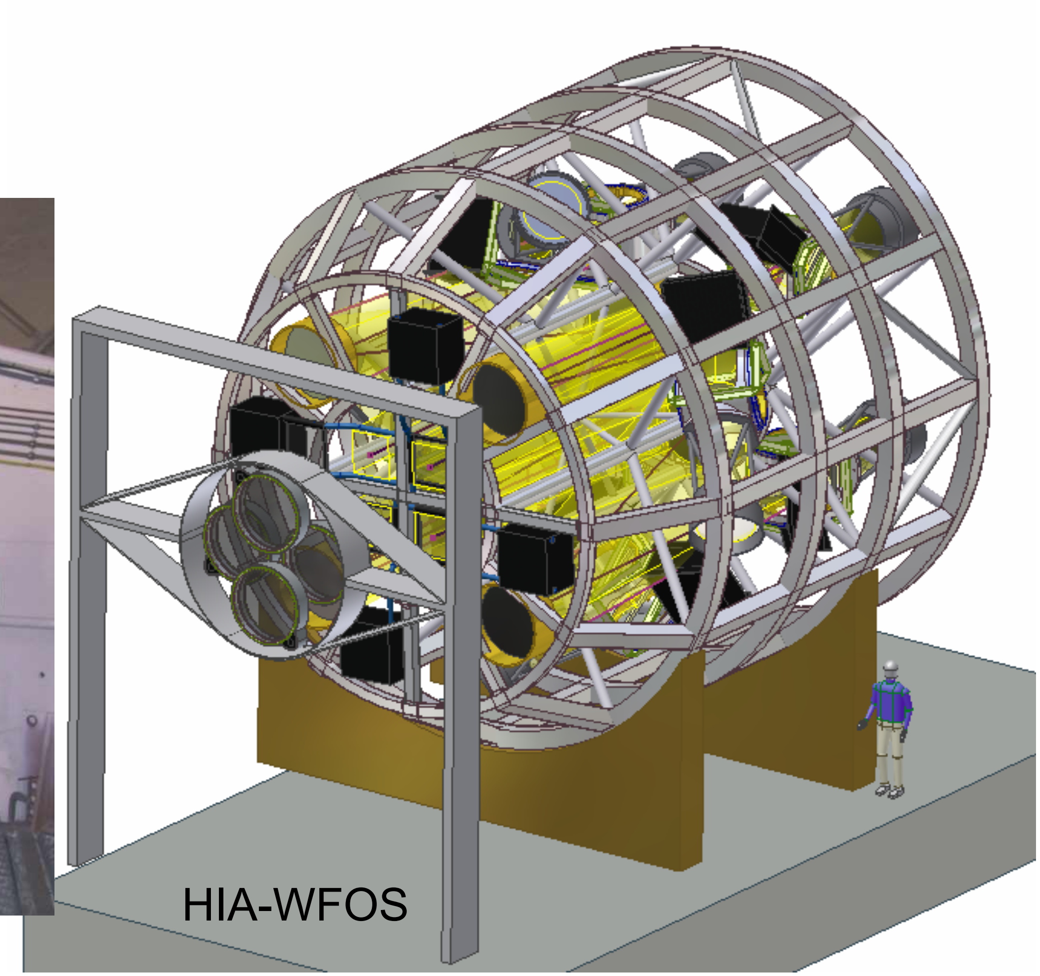
WFOS for TMT: History

Multiple previous WFOS designs

- Caltech: MILES circa 2006, 4 barrel
- UCSC: ELVIS circa 2006, 1 field, multiple color channels
- HIA: HIA-WFOS circa 2007, 4 barrel



DEIMOS spectrograph for Keck (10 m)

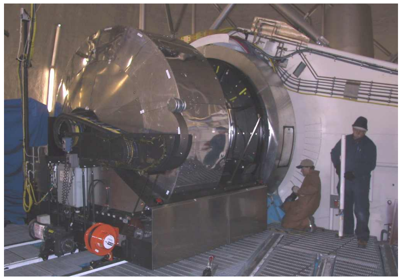


HIA-WFOS

WFOS for TMT: History

HIA: HIA-WFOS circa 2007, 4 barrel

- Feasibility study review report: concerns regarding…
  - overall complexity & **size**
  - **600 mm** VPH gratings, small λ coverage per exposure
  - **multiple fields** required to meet field of view requirements.
  - **Narrow performance scope**: tuned to 1 science case (IGM)



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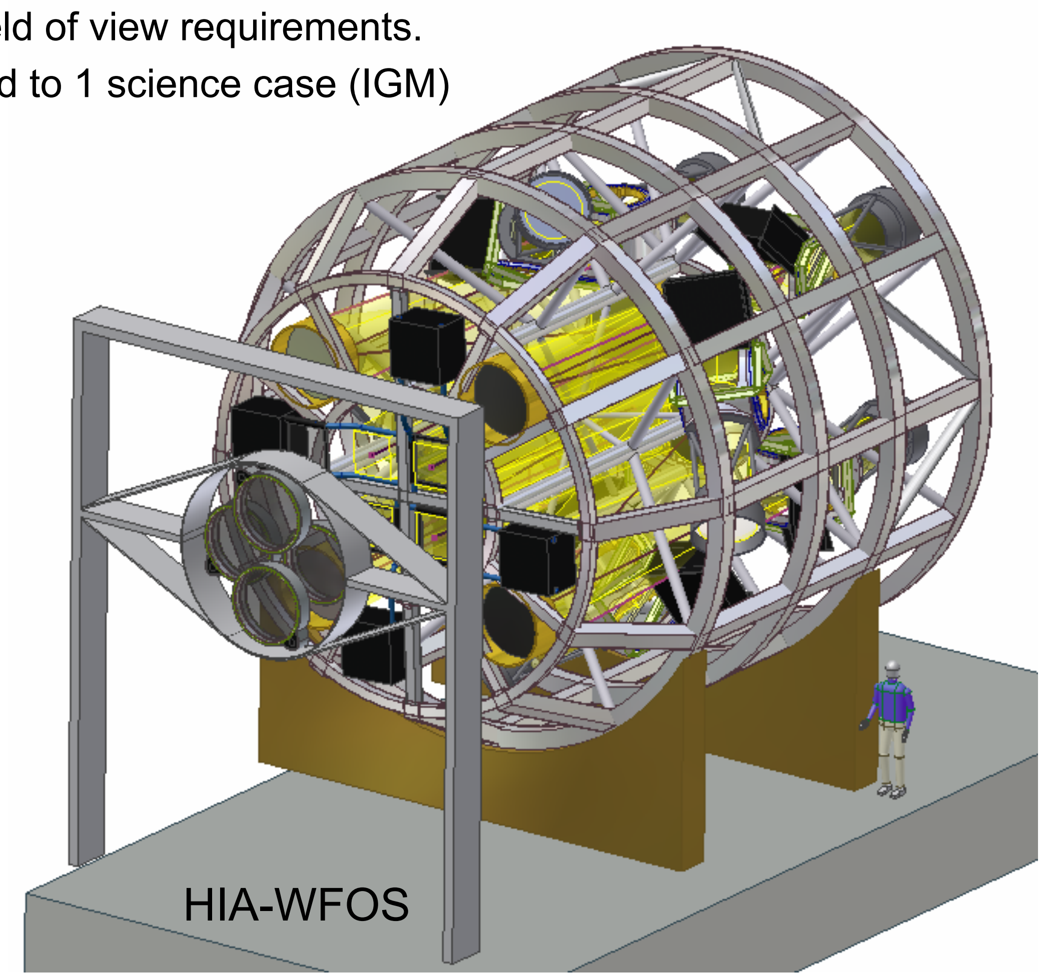

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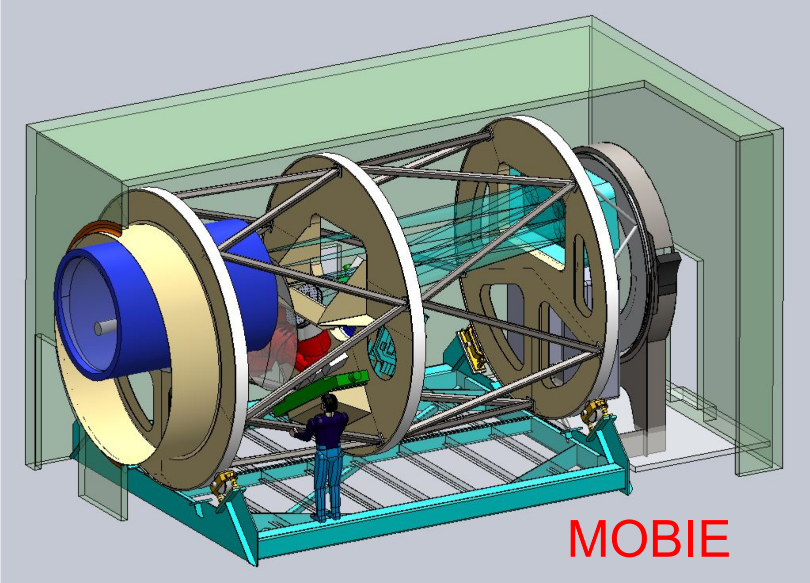
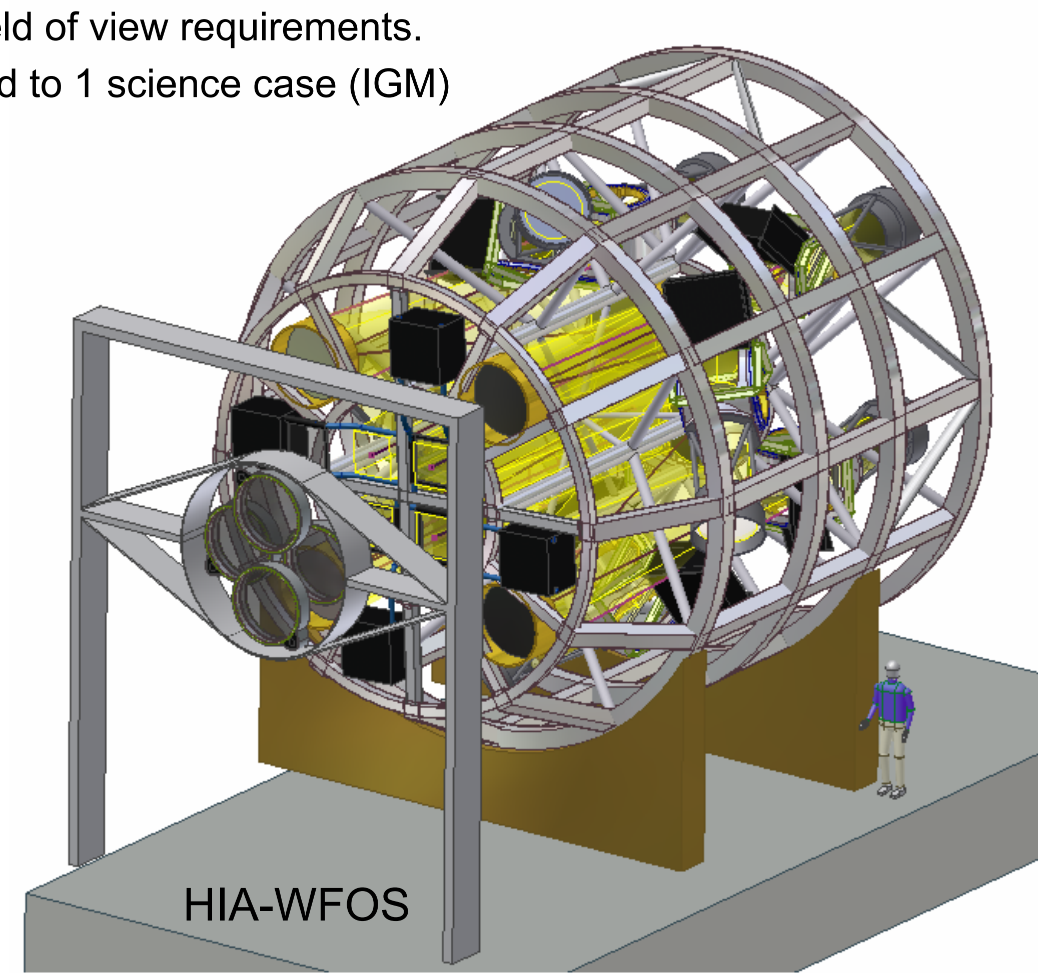
UCSC: MOBIE started Jan 2008.

- Feasibility Study: May–Dec 2008
- External review Dec 2008: very positive


MOBIE


HIA-WFOS

Design concept: a hybrid solution

"Discovery" science

Examples: surveys

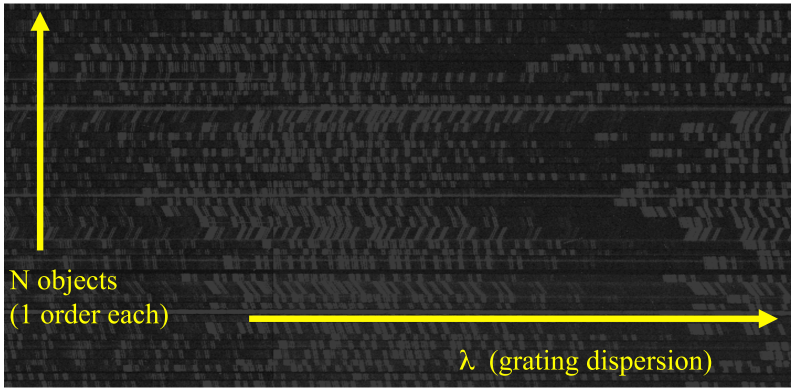
- IGM structure and composition at 2<z<6
- stellar pops (chemistry & kinematics z>1.5)

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

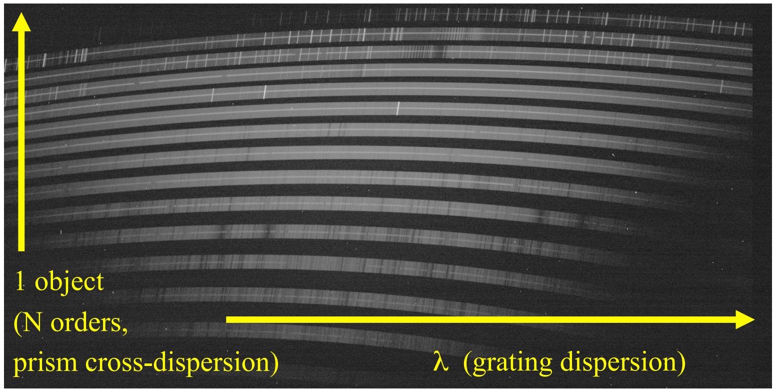
- Abundances & kinematics of stars (20 Mpc)
- Galactic and Local Group sub/structure

Design priorities:

- Resolution (λ/Δλ):   8,000 – 16,000
- Multiplexing: 10's

MULTI-ORDER (cross-dispersed) SPECTRA

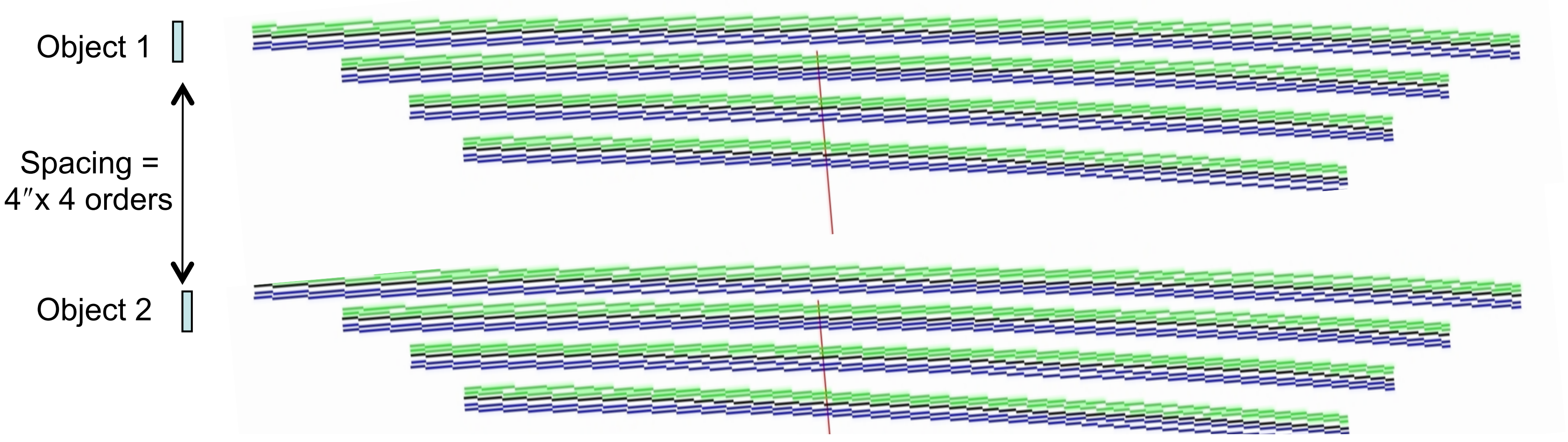
Echellette spectrographs:
ESI (Keck), MagE (Magellan), XShooter (VLT)



Design Concept: performance

Combine the two: Multi-Object, Broadband, Imaging Echellette (MOBIE)

- Extremely flexible: observer chooses
  - # objects
  - Resolution mode: Low — any slit length, 1 order
    Medium — slit length fixed (5″), 1–5 orders available.
    High — slit length fixed (4″), 1–6 orders available.
  - Wavelength coverage: # of orders selected using narrow-band filters



Working example – Multi Object Echellette [prism+grating] in IMACS on Magellan

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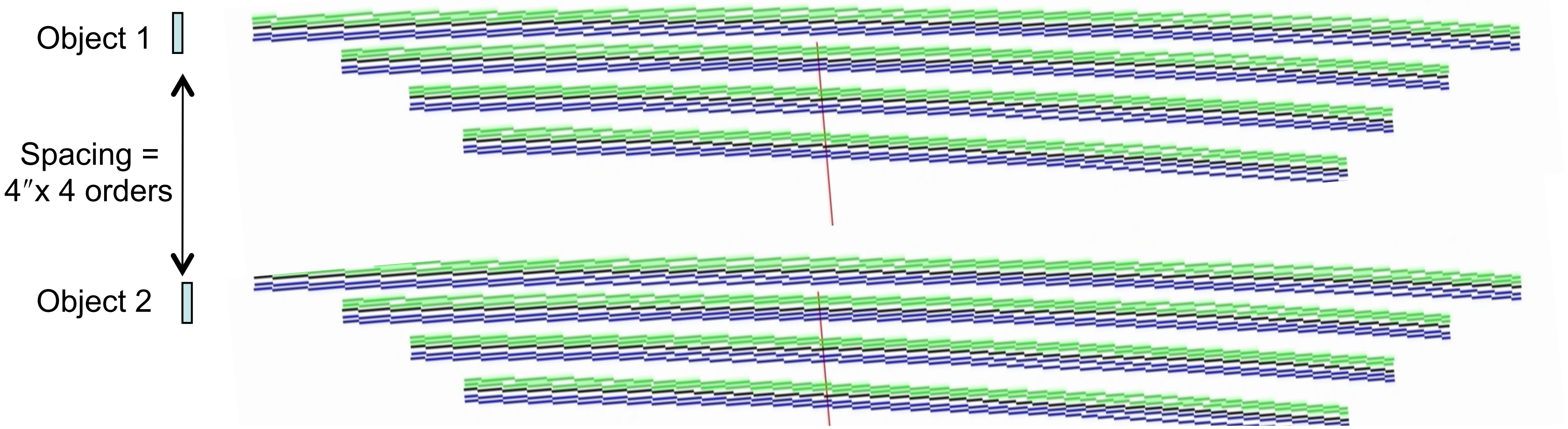
  - Wavelength coverage: # of orders selected using narrow-band filters
- Complete wavelength coverage = Observationally efficient at ANY resolution
  Mechanically simple (no grating-angle adjustments)



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MOBIE Science Drivers

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

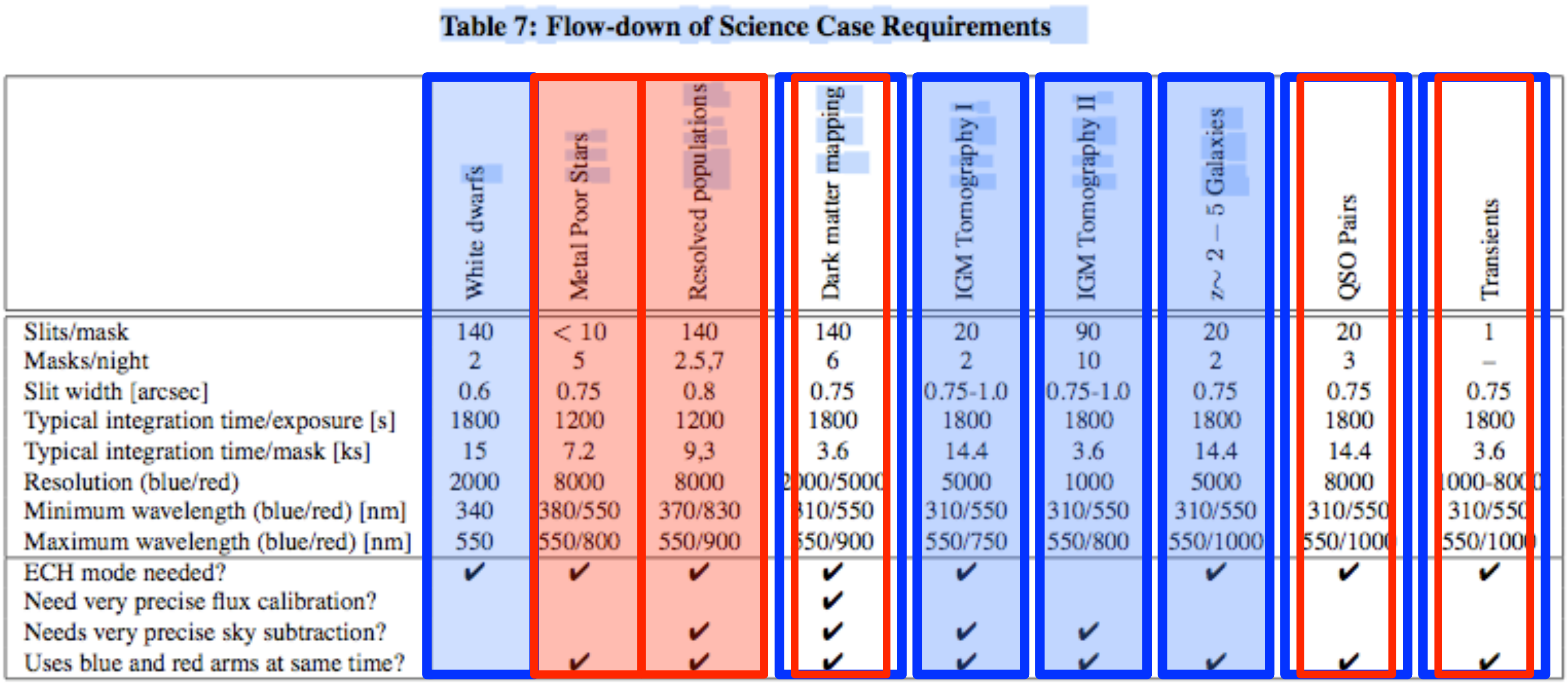


Table 7: Flow-down of Science Case Requirements

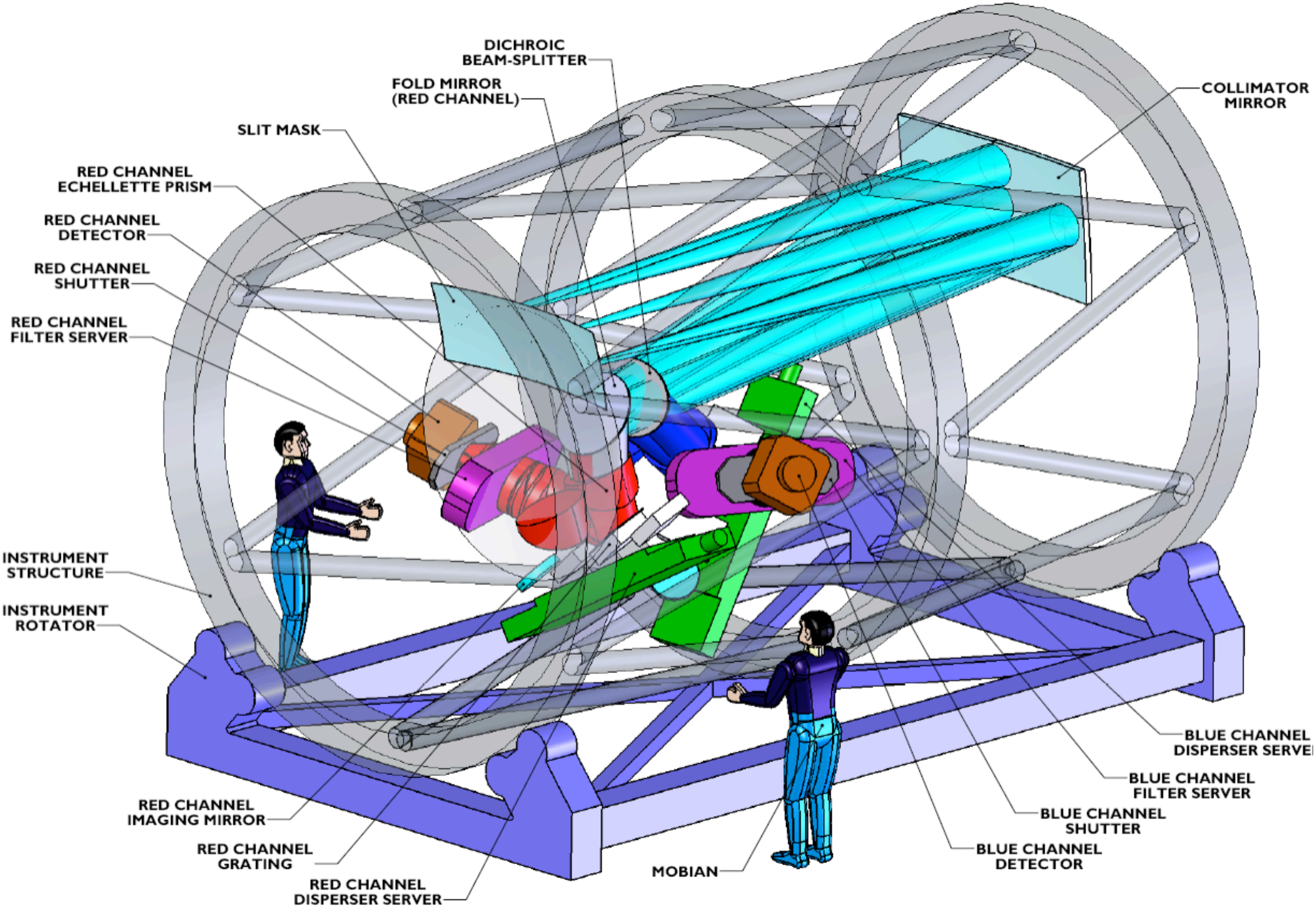
	White dwarfs	Metal Poor Stars	Resolved populations	Dark matter mapping	IGM Tomography I	IGM Tomography II	$z \sim 2-5$ Galaxies	QSO Pairs	Transients
Slits/mask	140	< 10	140	140	20	90	20	20	1
Masks/night	2	5	2.5,7	6	2	10	2	3	–
Slit width [arcsec]	0.6	0.75	0.8	0.75	0.75-1.0	0.75-1.0	0.75	0.75	0.75
Typical 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 Design Concept: Optical Layout



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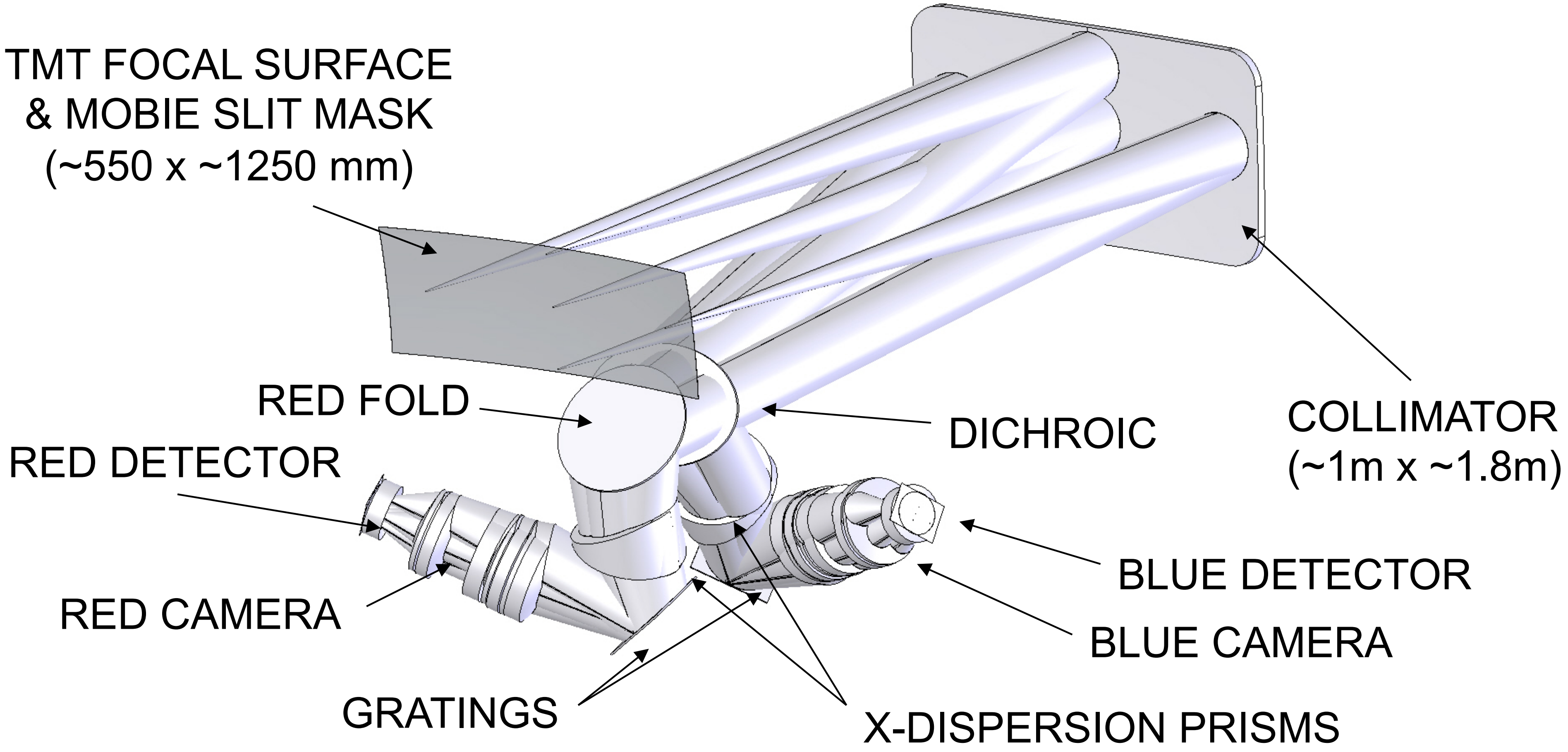
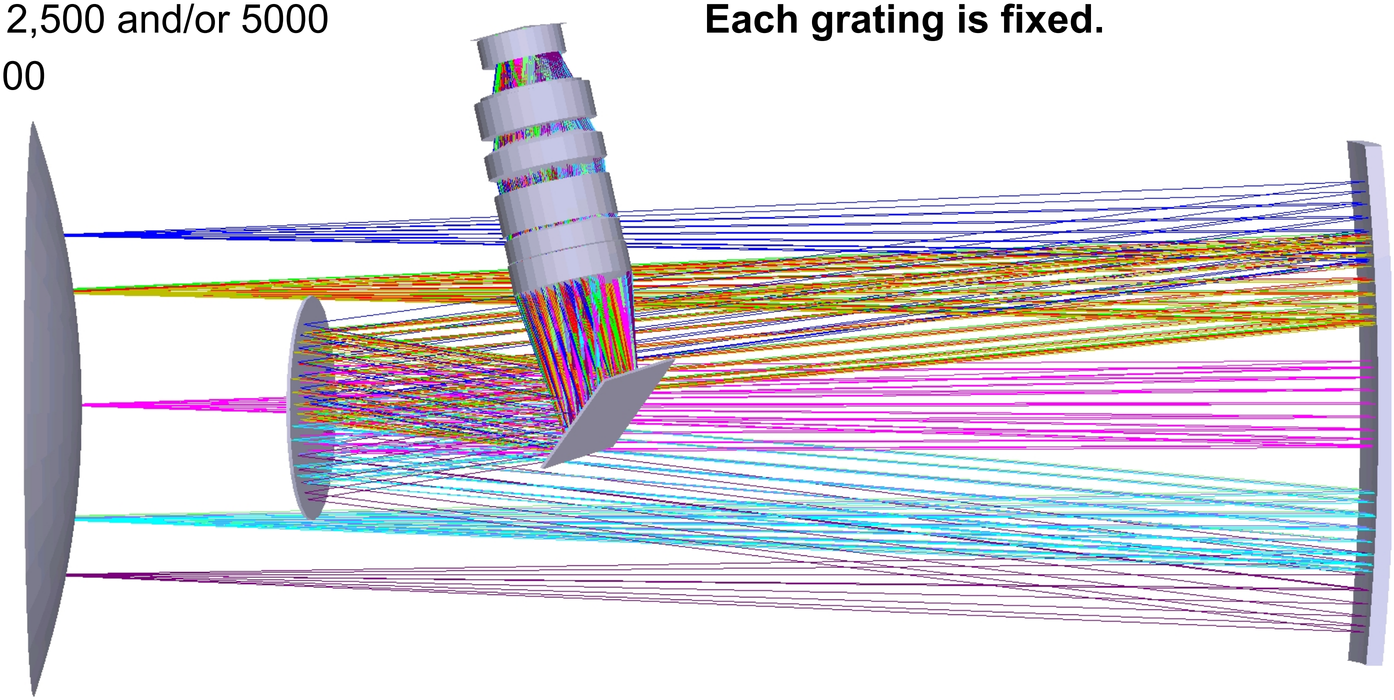


Design Concept: Modes

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

Only dispersion elements change

Each grating is fixed.



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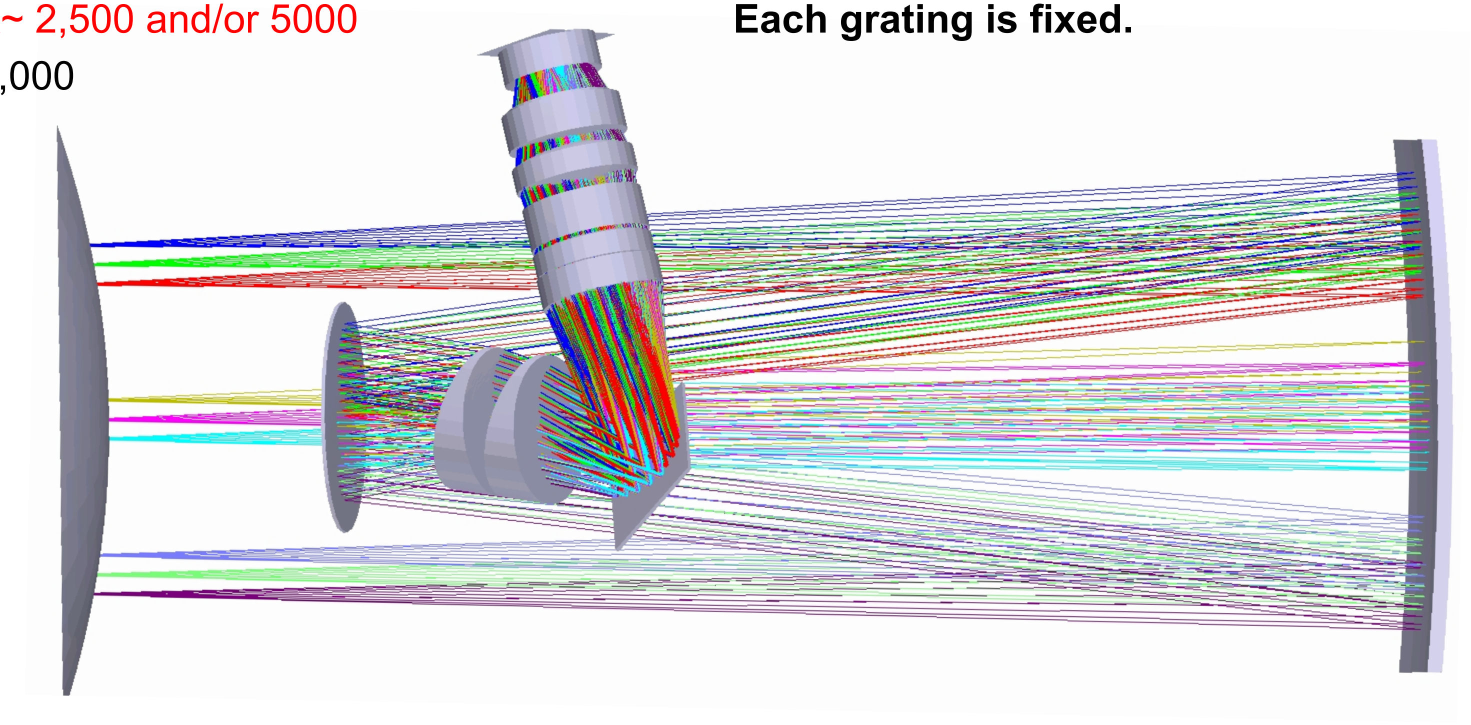

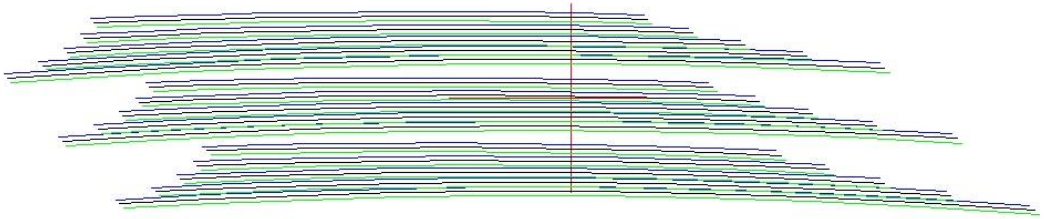

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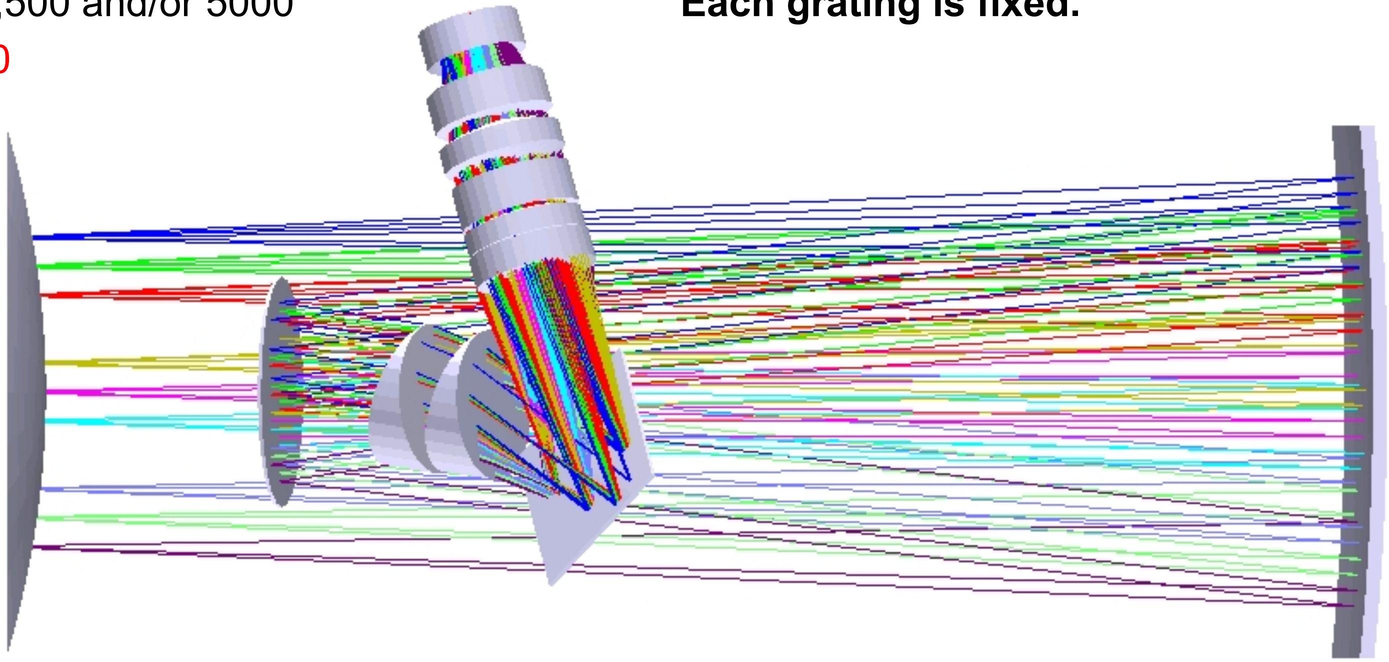
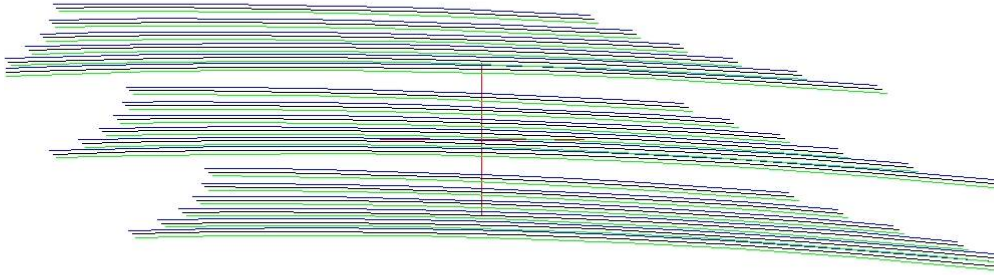
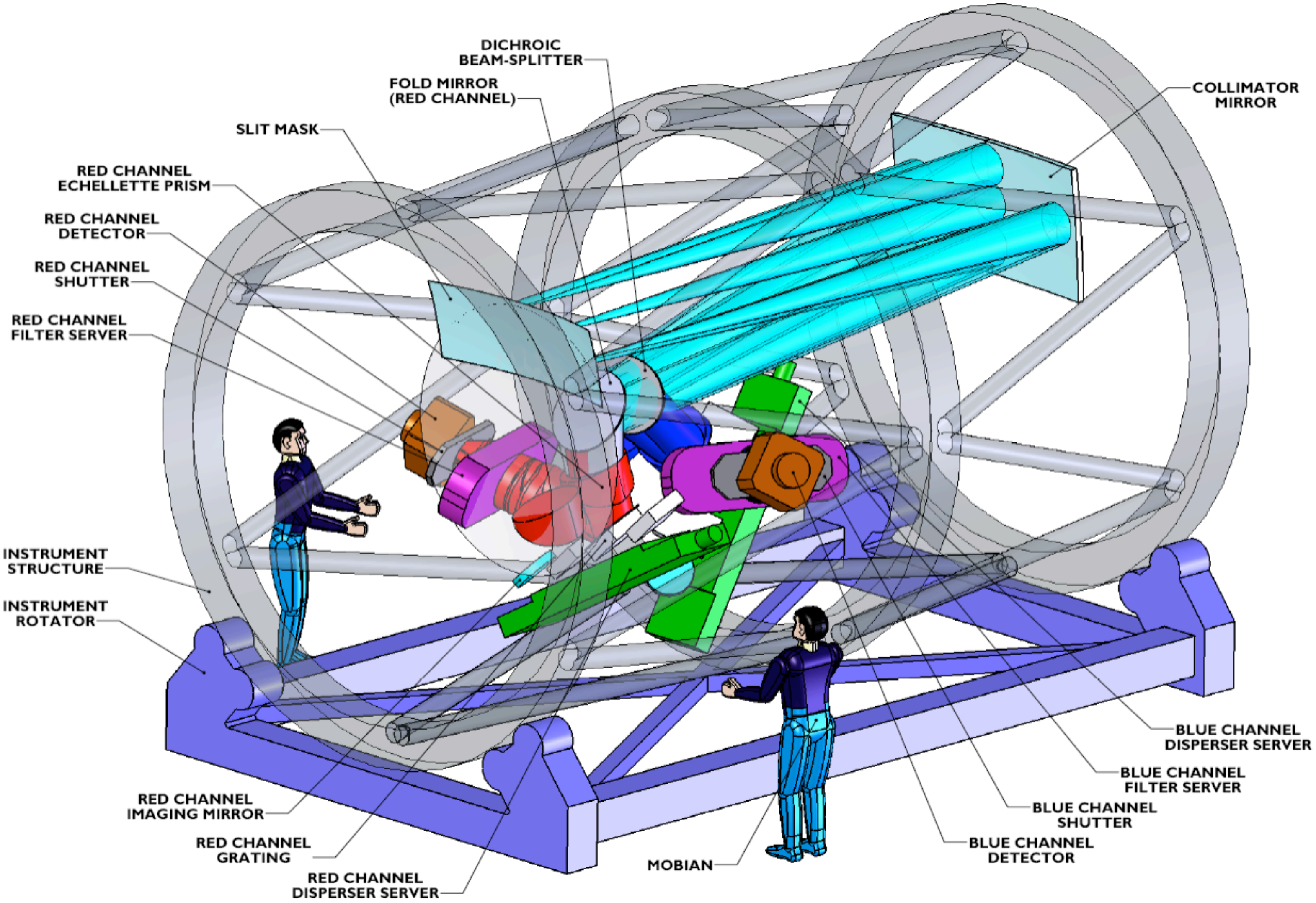




Design Concept: impact on complexity

- Minimize: complexity & moving parts
- Maximize: λ coverage, λ resolution, field, transmission.

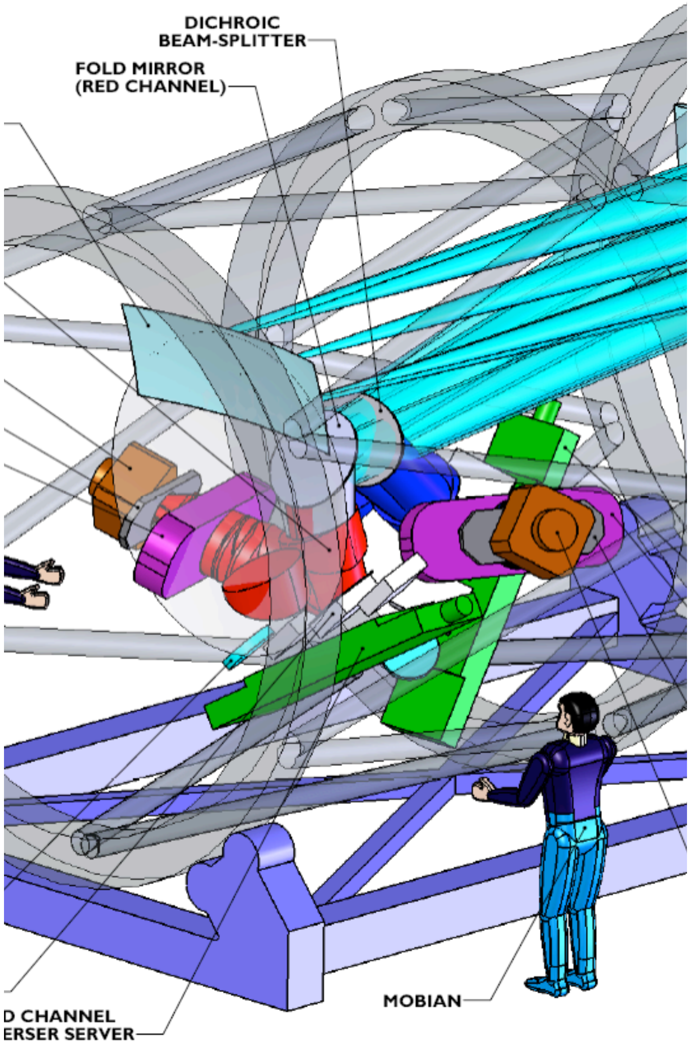


Design Concept: impact on complexity

Minimize: complexity & moving parts   (Maximize: λ coverage, λ resolution, field, transmission)

Three Key Characteristics:

1. Two color channels: Blue (0.3-0.6μm), Red (0.55-1.0μm)
    - Allows efficient prism cross-dispersion
2. Allows Echellette strategy
    - Allows full wavelength coverage always
    - Means gratings don't need to tilt
    - Means lower flexure
    - Simple grating fixtures
    - Cheapest way to get this wavelength, resolution, stability.



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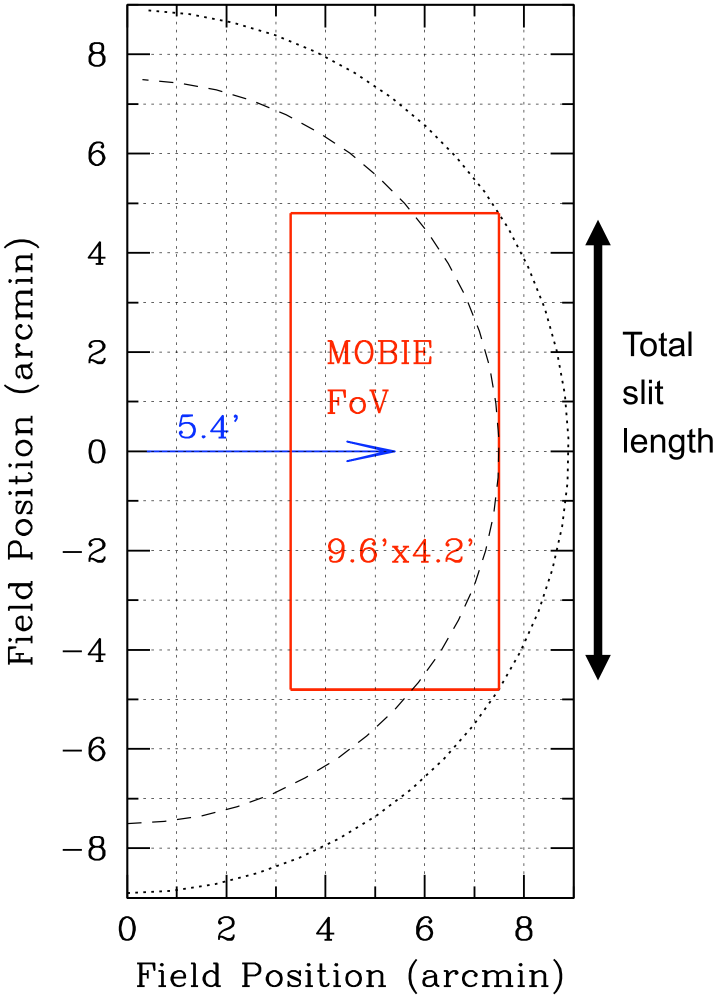
3. Off axis field
   - Required to use a mirror collimator
   - Mirror = high transmission, cheaper
     better images than lenses
   - Simpler mechanically

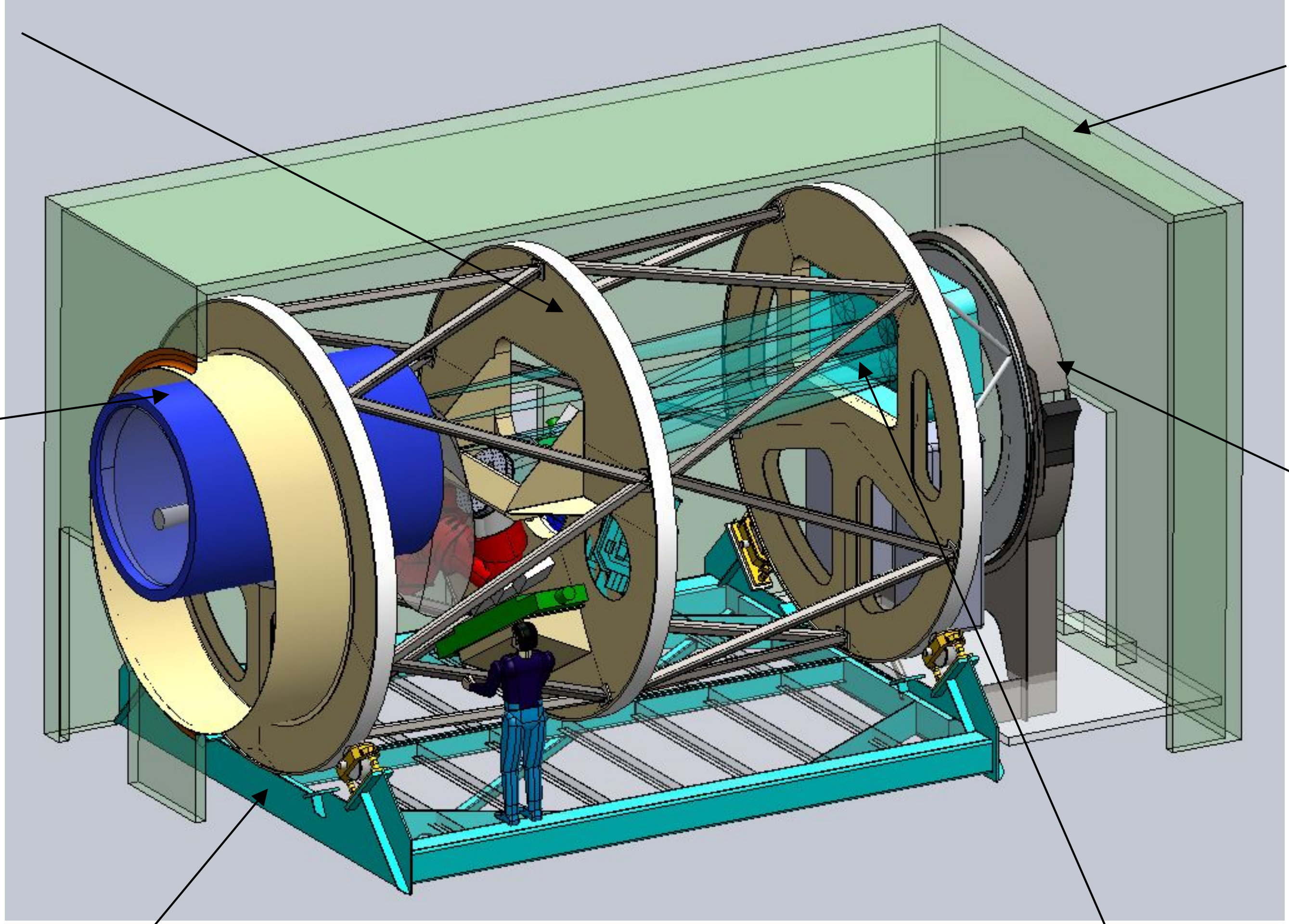
MOBIE is a small, efficient solution to this design problem.



MOBIE performance summary

Original WFOS requirements/goals	Realized in current design
• Wavelength range: 0.33 –1.0μm	0.30 – 1.1μm
• Field of view: >40 arcmin^2	40.3 arcmin^2 (~4 x 9.5 arcmin)
• Total slit length ≥ 500″	576″ (~9.5 arcmin)
• 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
• Sensitivity: limited by photon stats for t>300s	(high transmission design)
• Field acquisition: <3 min per mask, <1min single obj.	(addressed in CDP)

MOBIE Design Concept: Mechanical



STRUCTURE

ENCLOSURE

ADC

CABLE WRAP

CARRIAGE

COLLIMATOR

Status: Jan 2008 — now

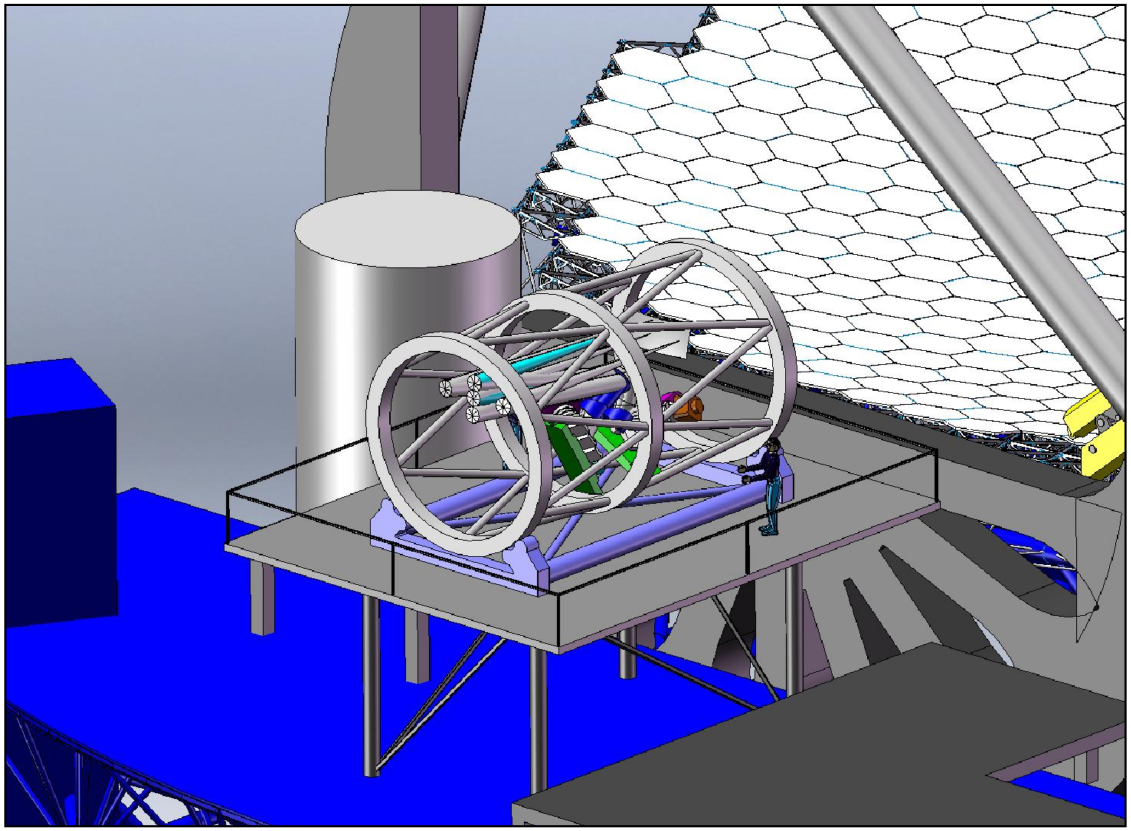
- MOBIE Cost:
  - Mid Conceptual Design estimated cost = $45.4 M
  - Contingency = $9.5 M (20.9%)
  - Total estimated cost = $54.9 M

- Cost expectations (?)
  - DEIMOS: ~15% of Keck   (Spec: ~$10M in 1999, Tel: ~$75M in 1992)
  - IMACS: ~16% of Magellan   (Spec: ~$6M in 2003,   Tel: ~$35M in 2000)
  - MOBIE: 4% of TMT   (Spec: ~$40M in 2011,   Tel: ~$1000M in 2011)

MOBIE for TMT

Multi-Object Broadband Imaging Echellette

- At UCSC
  - Designs
    - Optical (science driven!)
    - Mechanical
    - Software
    - Electronics
  - Assembly & integration
  - Testing
- Facilities: high-bay, clean rooms
- Cost: $40 M (4% of TMT)
- First-light instrument (2020?)



Acknowledgments

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