Plans for Multi-Object Spectroscopy with the ELTs

Rebecca Bernstein, Carnegie Observatories

GMT Project Scientist,
Former PI & optical designer of TMT's WFOS (MOBIE),
Big fan of E-ELT.

My perspective:

E-ELT, TMT, and GMT:

- critical to the future of astrophysics and need to succeed!
- very similar MOS science cases, but very different capabilities (by design)
- ambitious MOS goals in all of the areas discussed in this meeting
- each will need to play to it's strengths!

Different instruments,
capabilities, and
observational approaches
to the same questions → good!

What's so hard about multi-slit spectrographs?

Keck: DEIMOS, LRIS, MOSFIRE…
Magellan: IMACS, LDSS3, M2FS (fiber-echelle)
VLT: VIMOS, FLAMES, several IFU spectrographs…
Gemini: GMOS, …

Successful multi-slit spectrographs on the 8m class telescopes:

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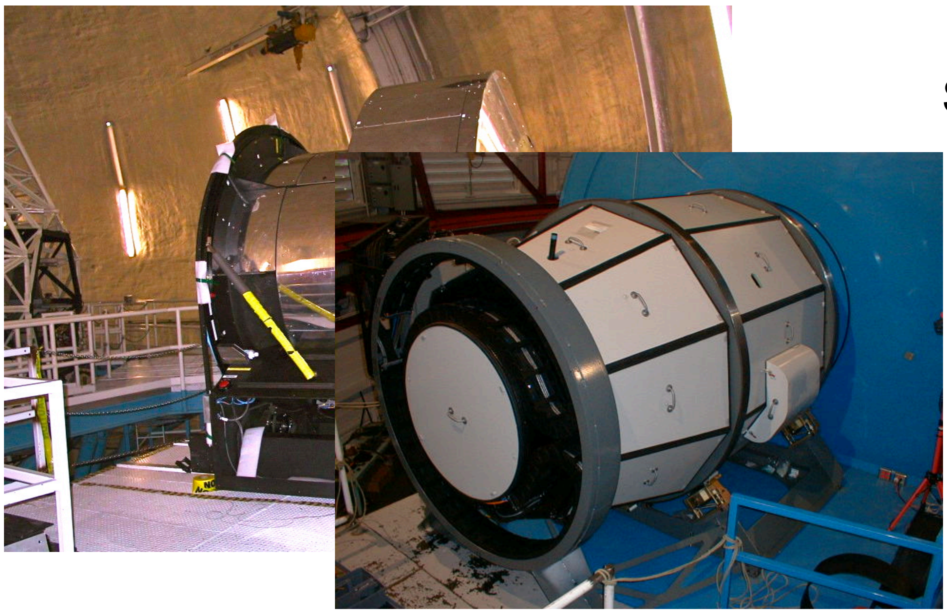

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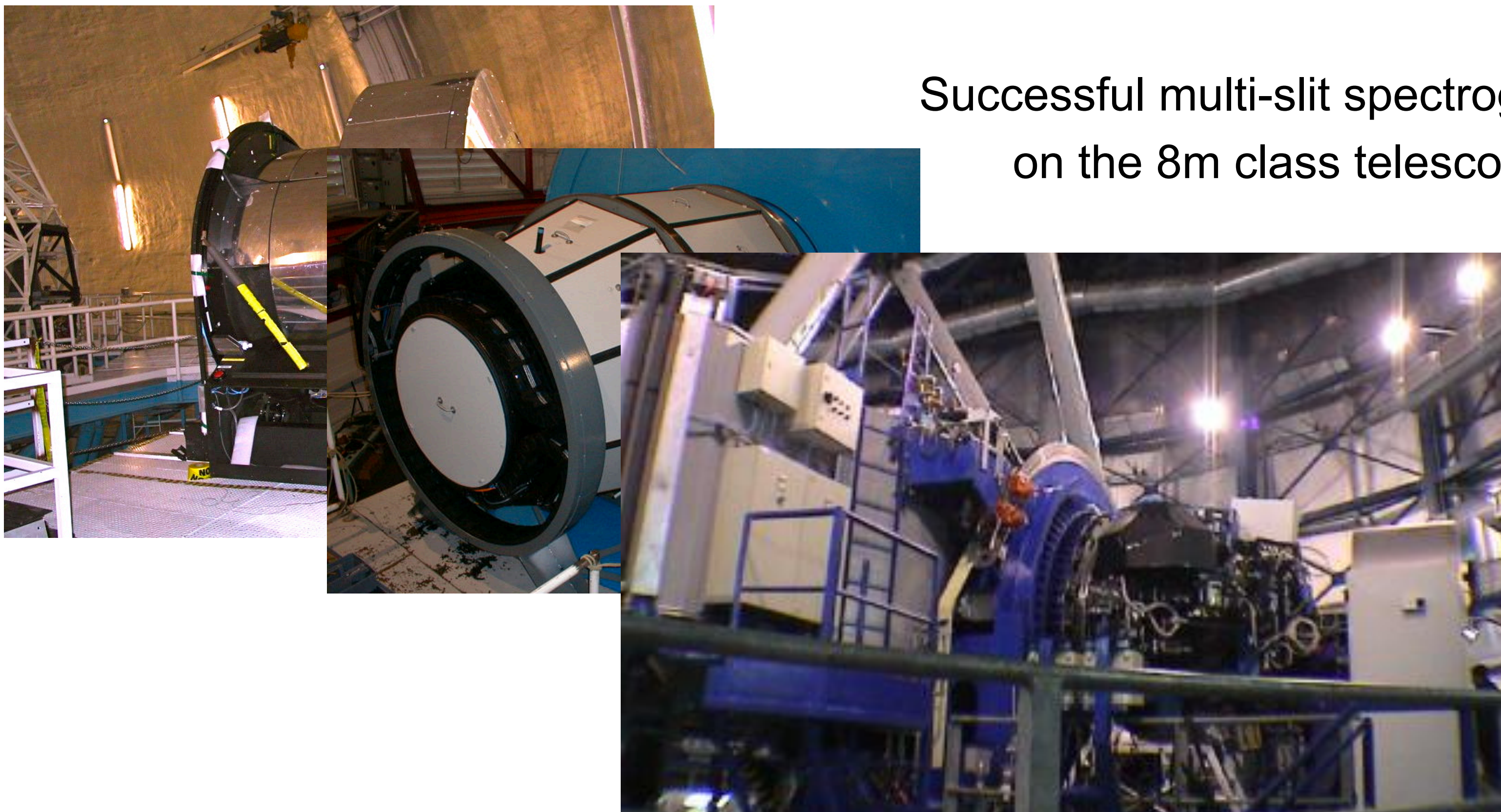

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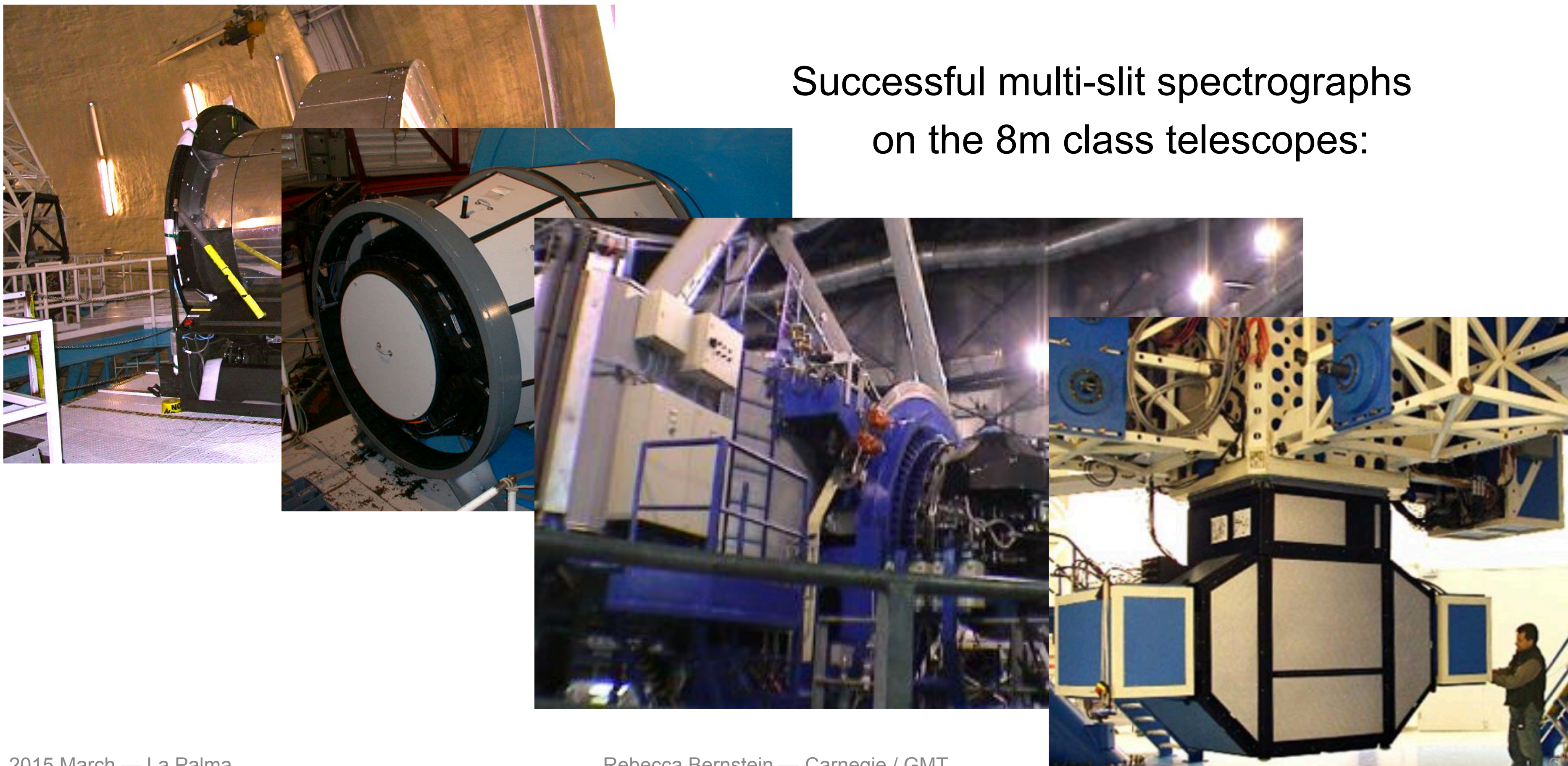
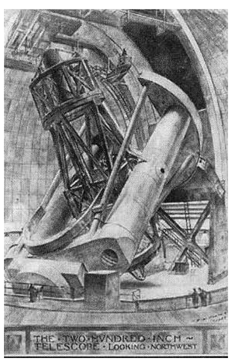


What's hard: need to scale up to keep FOV

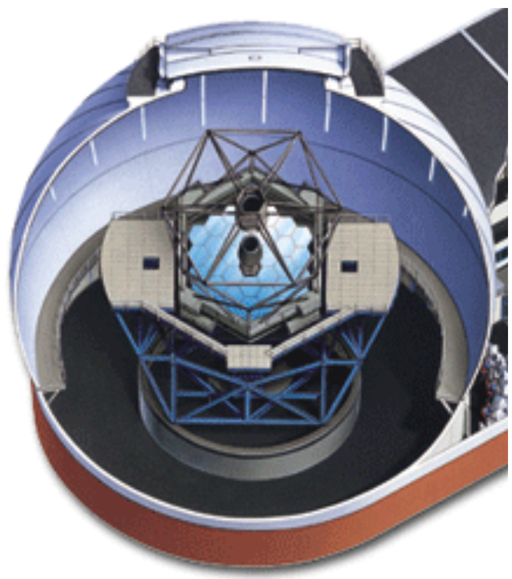
The front end of the spectrograph must match the focal plane scale, which scales with telescope size.

Shane 3m

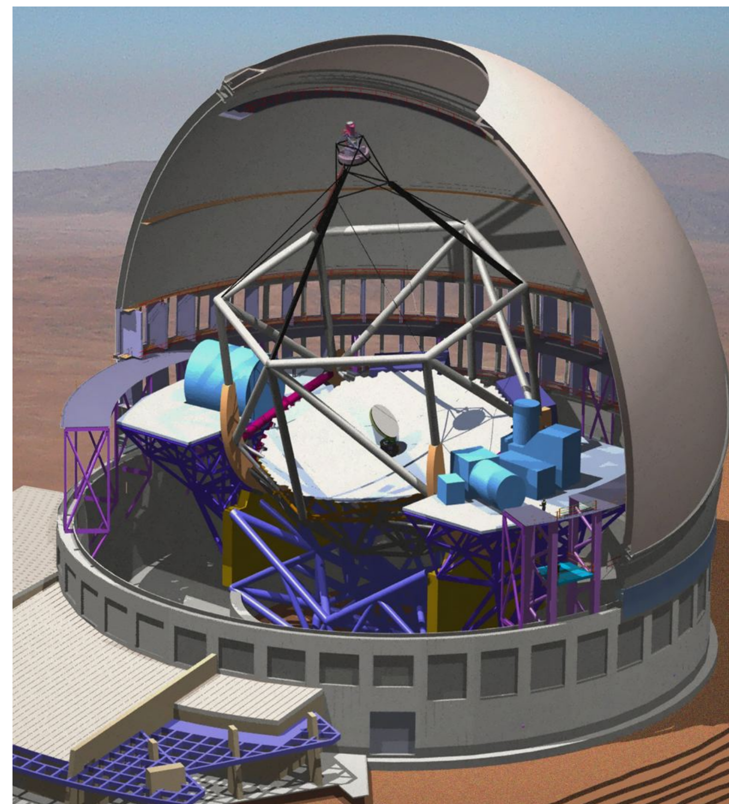
Hale 5m



Keck 10 m



Thirty Meter Telescope   30 m



What's hard: need to scale up to keep FOV

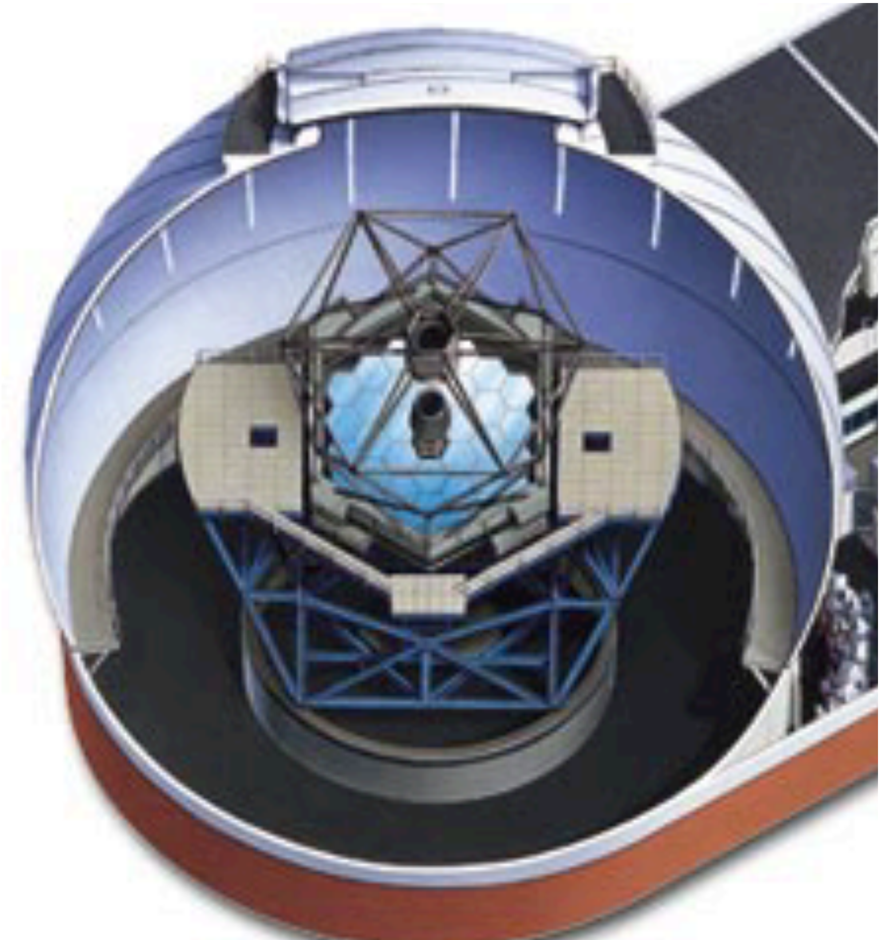
Shane (3 m)

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

310 mm

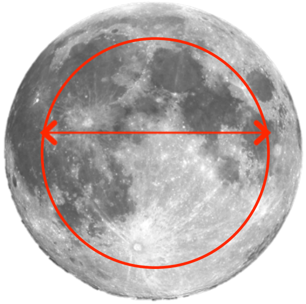
What's hard: need to scale up to keep FOV

Keck (10 m)



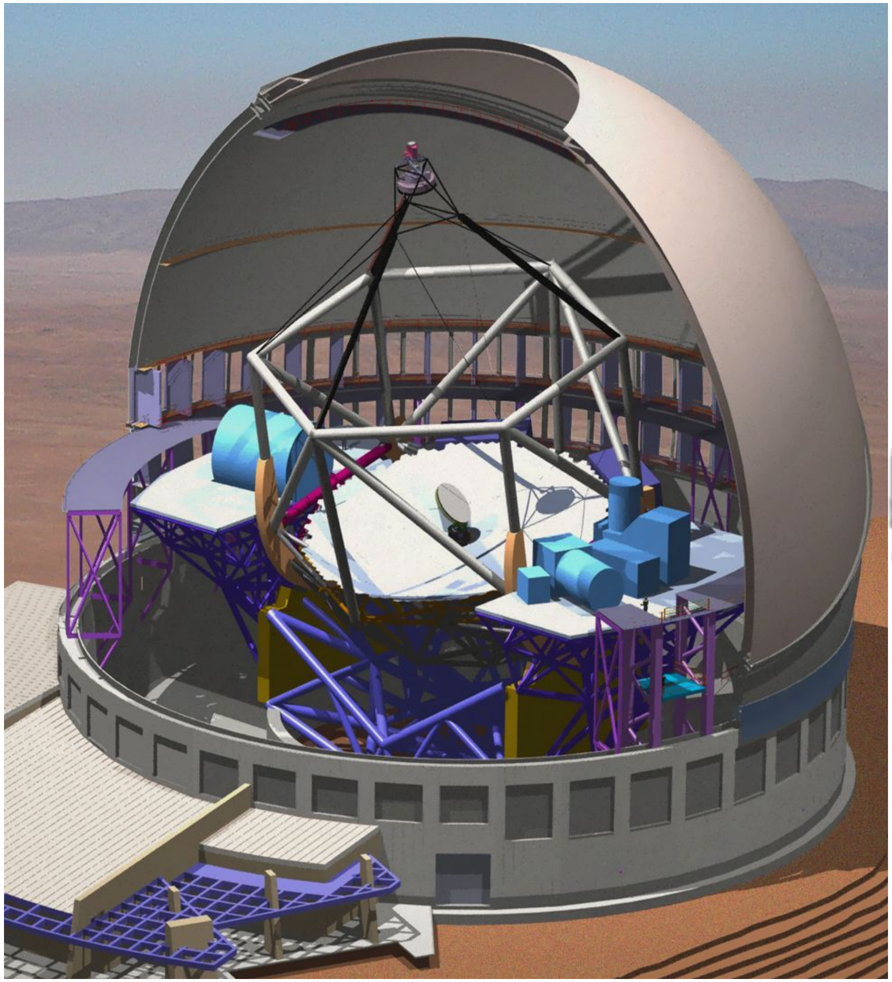
Diameter of the focal plane
and the image created of the moon.

870 mm



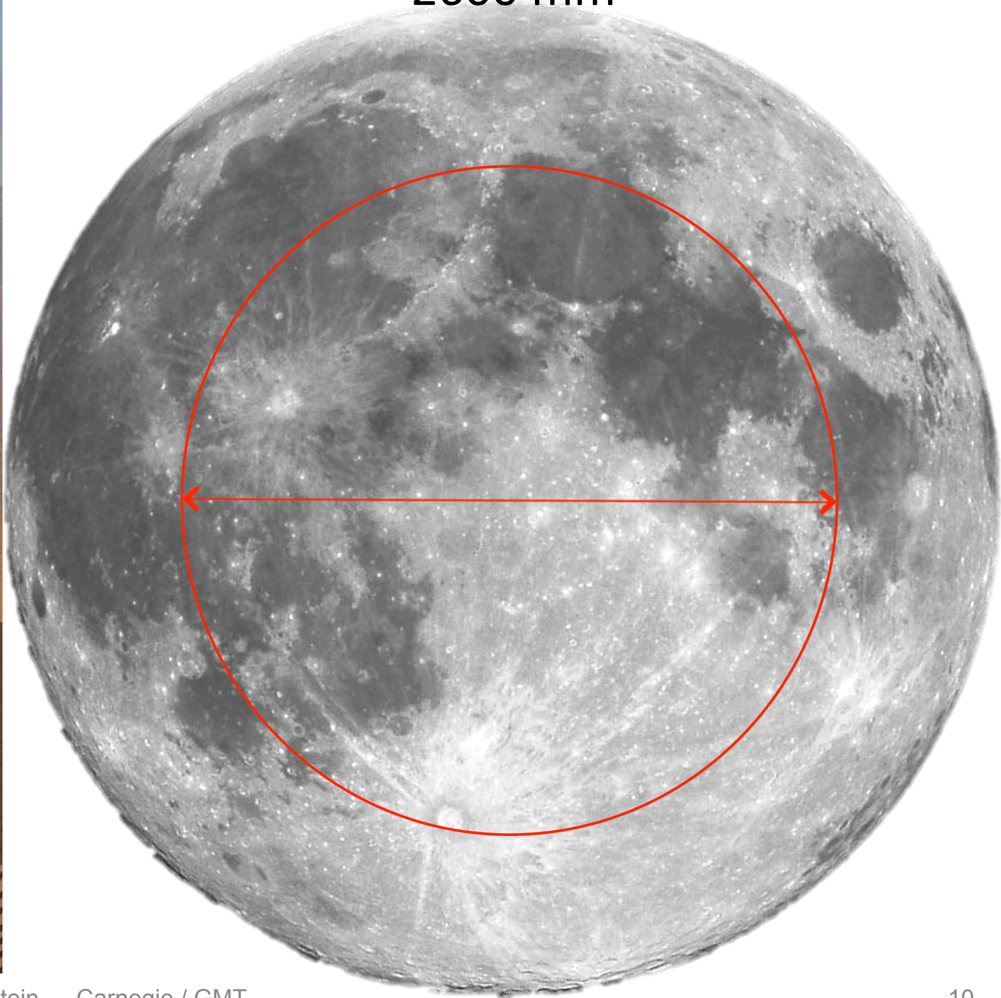
What's hard: need to scale up to keep FOV

TMT (30 m)



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

2600 mm



What's hard: need to scale up to keep Res.

Resolution: scales with (beam:telescope)

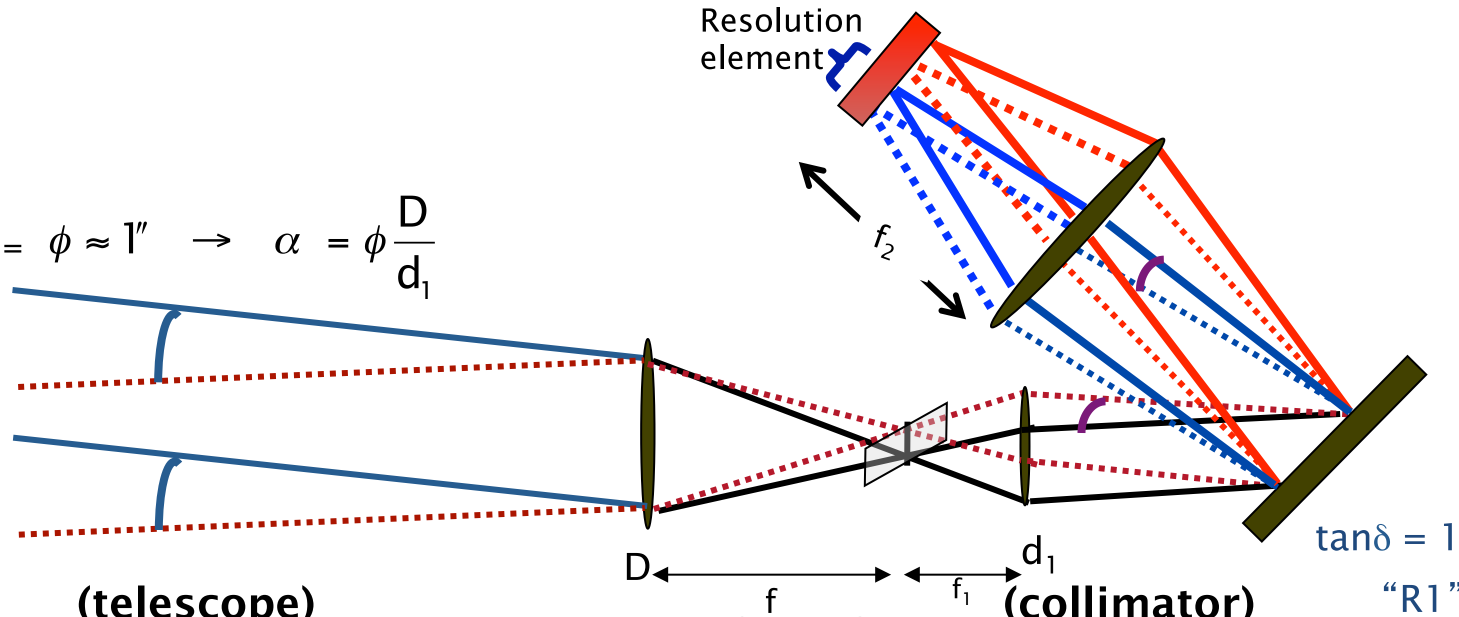
$$R = \frac{\lambda}{\delta\lambda} = 2\frac{\tan\delta}{\phi}\frac{d}{D}$$

d/D = diameter of beam : telescope

δ = blaze angle (→ grating length)

ϕ = seeing disk = ~1" in the optical

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



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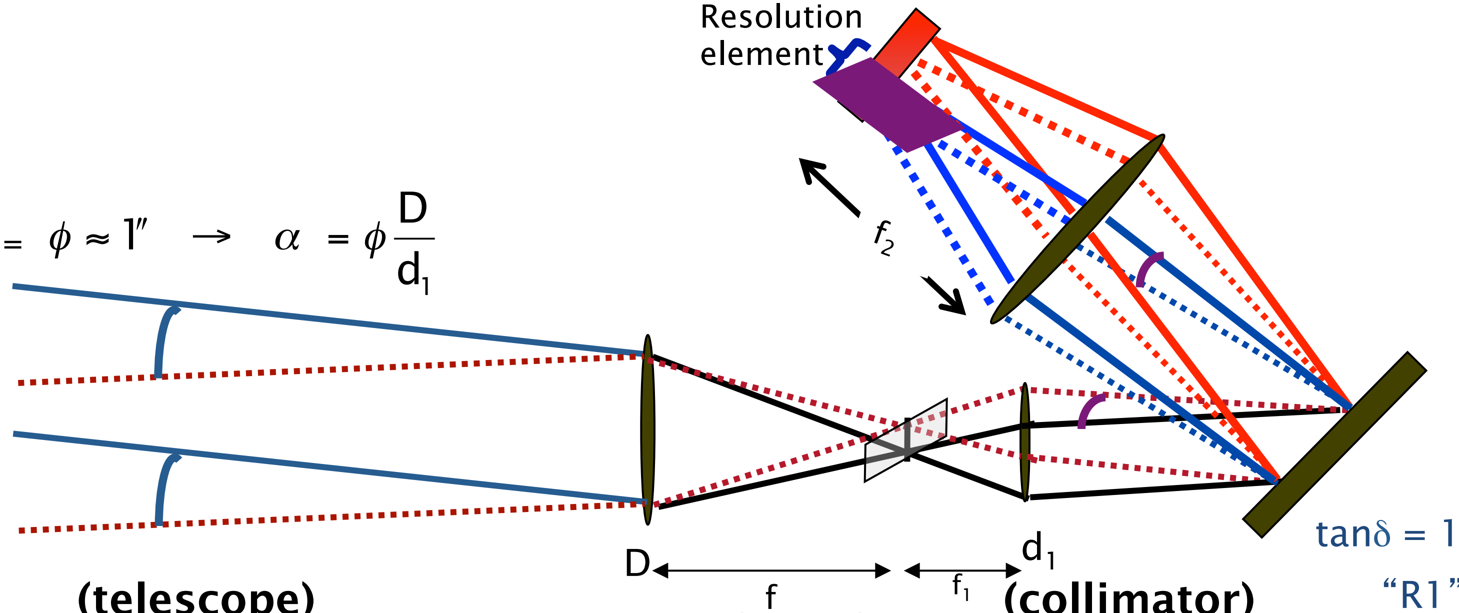
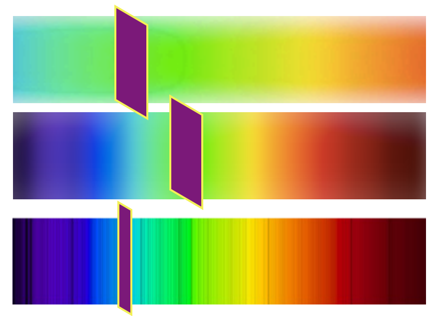


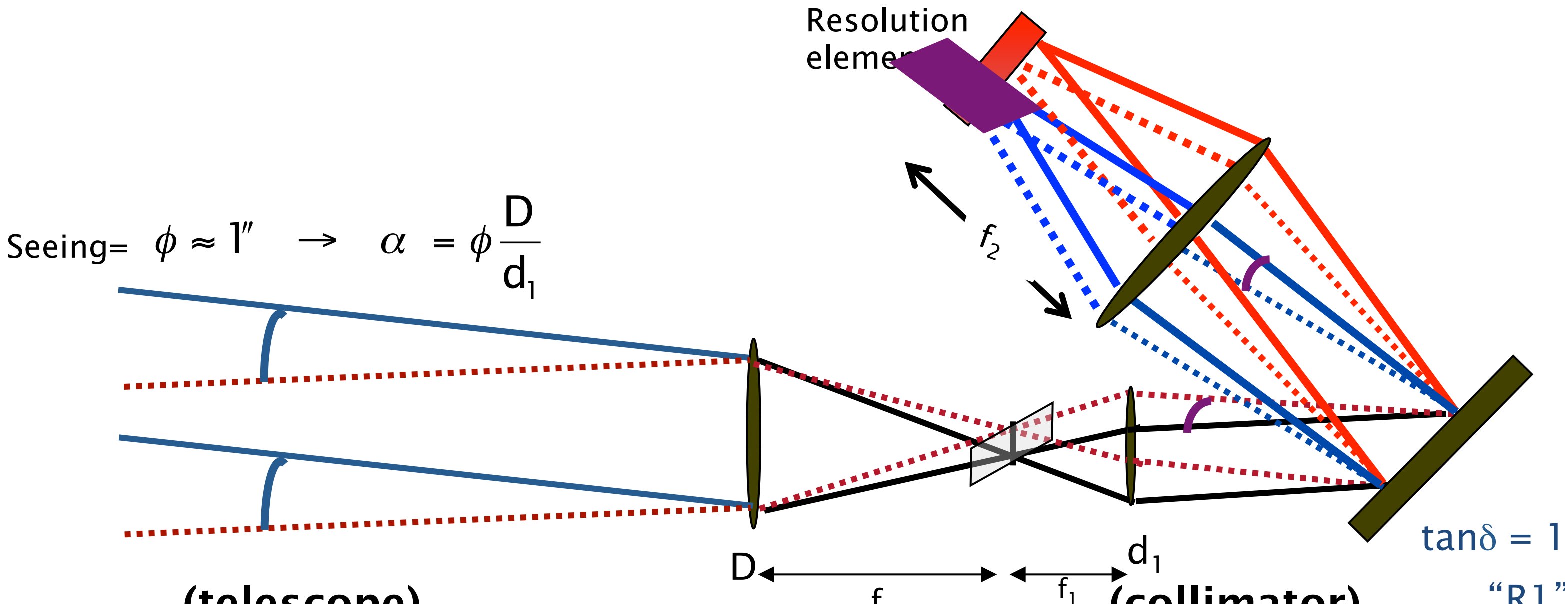
What's hard: need to scale up to keep Res

What is the impact on the spectrum?

1. smaller wavelength coverage (high res grating)
2. lower spectral resolution (low res grating)

Current expectation

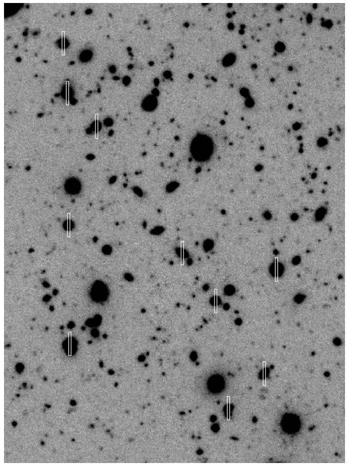


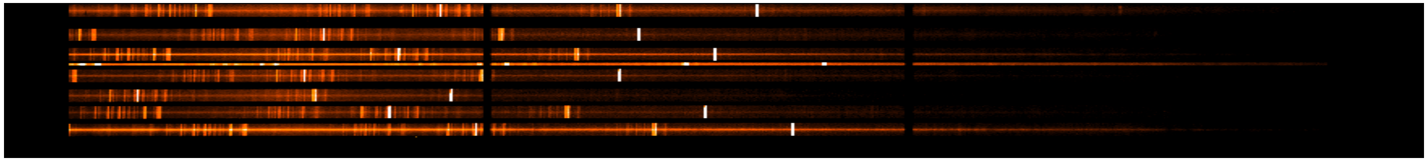


Not exactly what we were hoping for…

So if we put DEIMOS/IMACS/VIMOS on an ELT ....

DEIMOS on Keck.





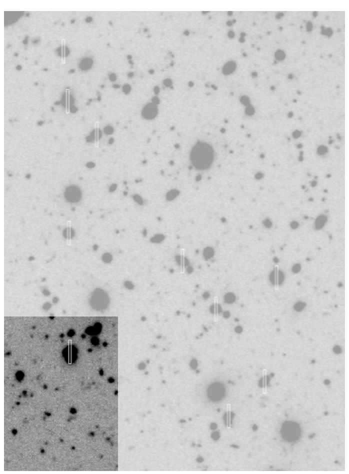
Not exactly what we were hoping for…

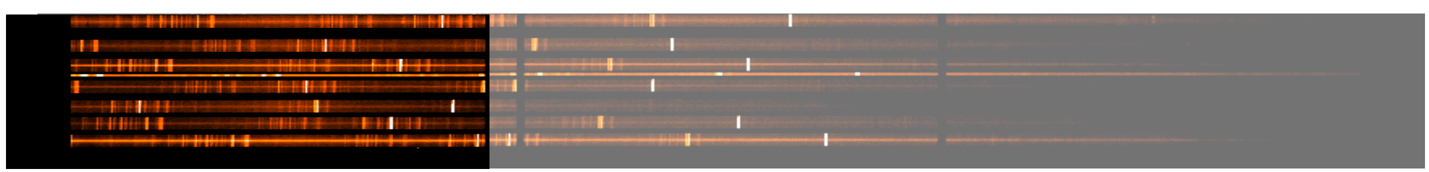
So if we put DEIMOS/IMACS/VIMOS on an ELT …

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

DEIMOS on Keck.

DEIMOS on TMT.





So what can the ELTs do: figure of merit

- A = Area
- Ω = Field of view
- ε = efficiency
- θ = image size (flux concentration)

$$\frac{A\Omega\varepsilon}{\theta^2}$$

All of the ELTs have unique strengths,
and their detailed designs highly impact this metric!

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- **Efficiency** impacted by: number of reflections … makes telescopes smaller!
  - median 80% reflectivity per mirror is optimistic (0.8^2=0.6, 0.8^2=0.5, 0.8^5=0.3)
  - optical complexity in the instrument
  - Fibers vs slits
  - Grating strategy (echellette? VPH? reflection?)
  - multiplexing efficiency
  - simultaneous wavelength coverage
- Image Size goes down by 20-50% with GLAO

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GMT

TMT

ESO

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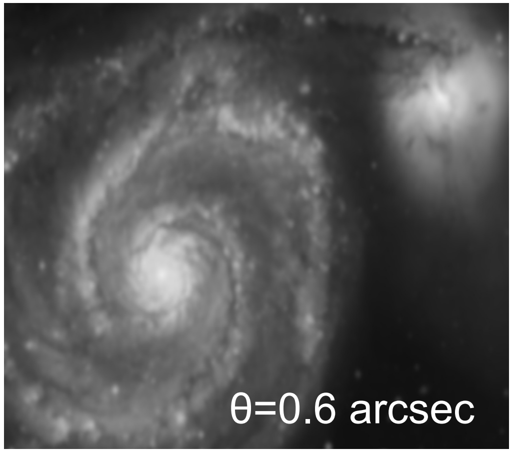
ELT designs: the wide field case*

(* For the telescope *with* planned wide field instruments.)

	Keck	GMT	TMT	E-ELT
$A * \varepsilon$	1	5.6	8.5	9.2
Ω	81	50	24	10
θ^2	$(1.0\ \text{asec})^2$	$(0.6\ \text{asec})^2$	$(0.6\ \text{asec})^2$	$(0.6\ \text{asec})^2$
$A\Omega/\theta^2$ (relative)	1	7.9	5.7	2.6

Natural seeing (no AO)



(illustrative)

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Ω	81	50	50	24	10
θ^2	(1.0 asec)^2	(0.6 asec)^2	(0.3 asec)^2	(0.6 asec)^2	(0.6 asec)^2
$A\Omega/\theta^2$ (relative)	1	7.9	23.0	5.7	**2.6?**

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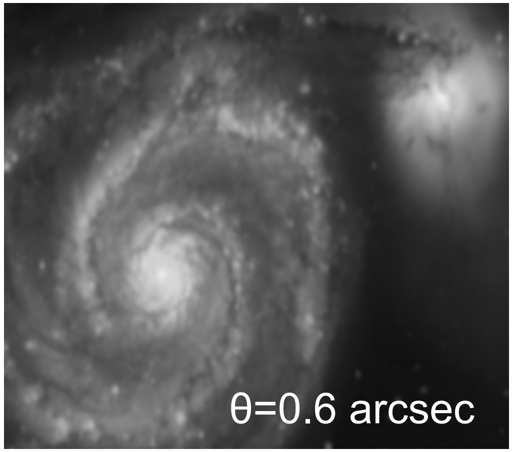
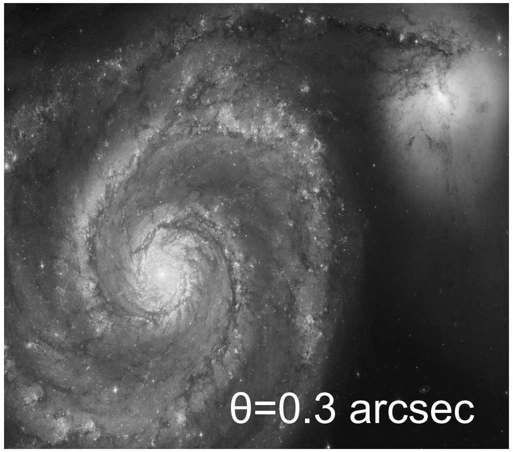


With ground layer AO



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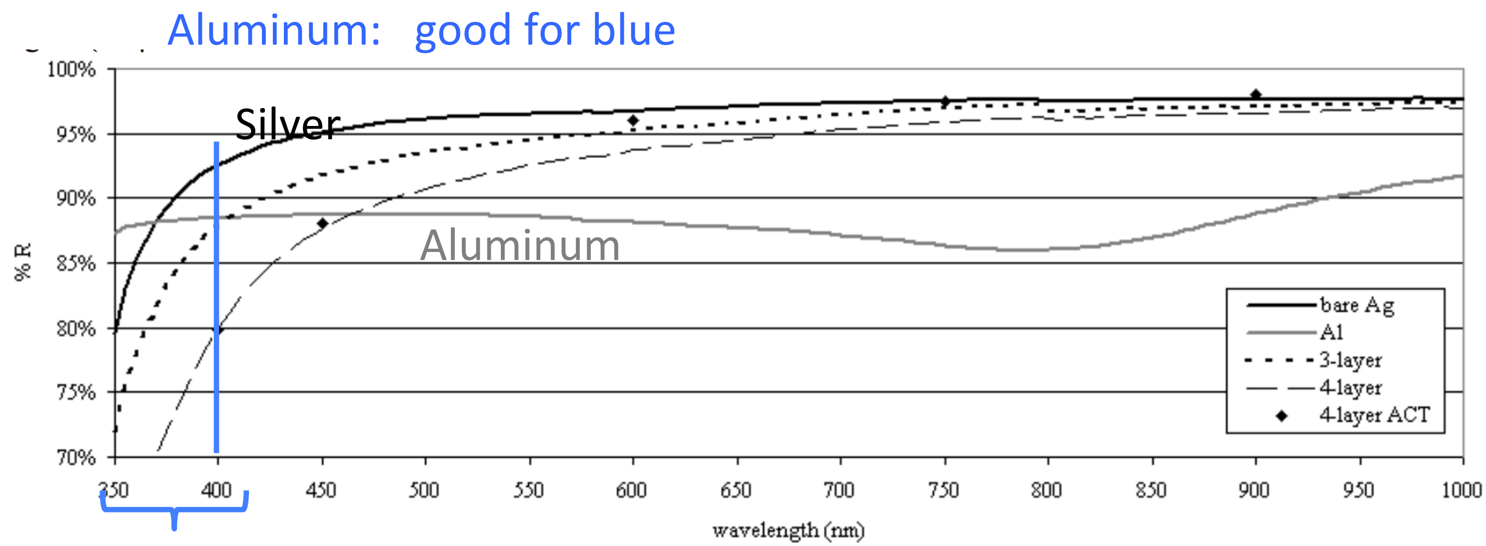
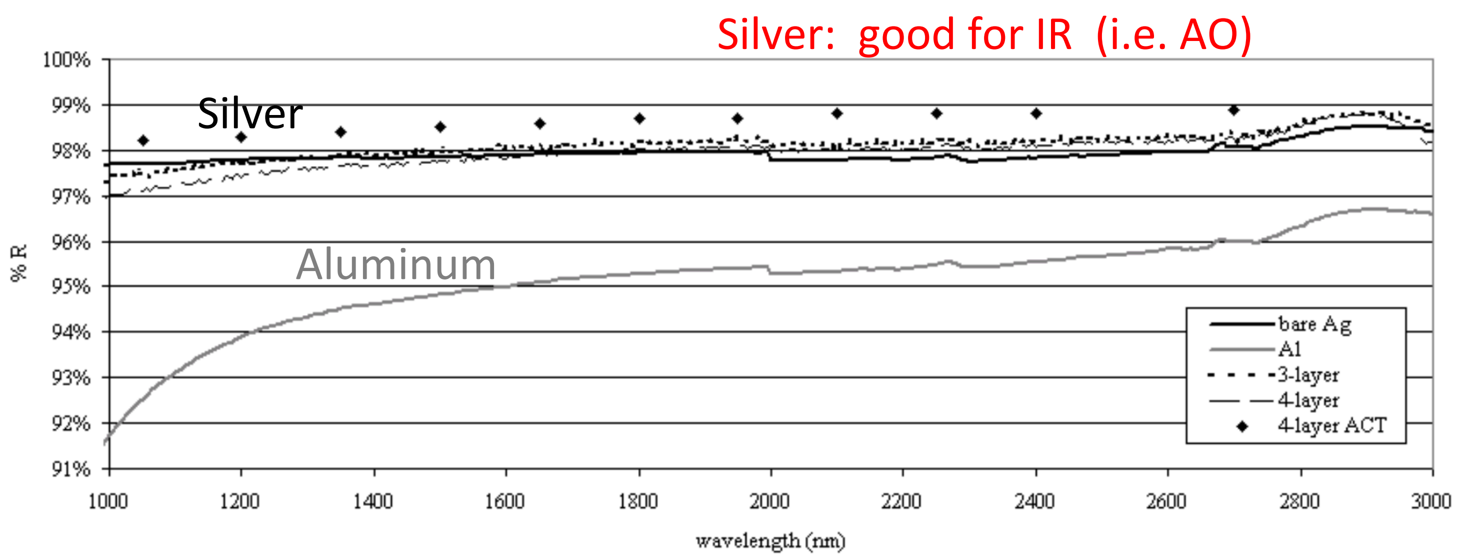
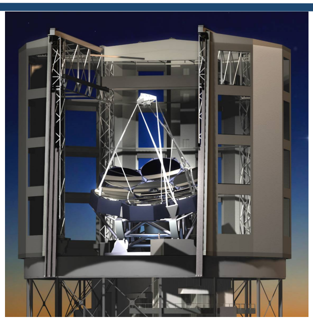
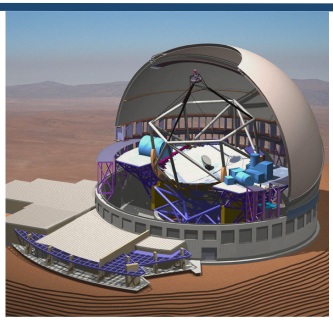
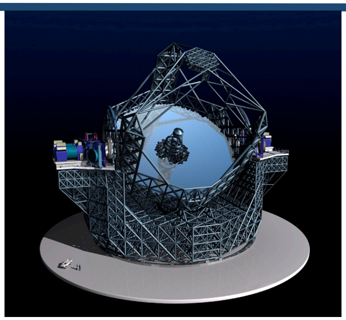
Coatings: the ELTs will not optimize for blue!





ELT design strengths: comparison of specifications

Attribute	GMT	TMT	E-ELT
Aperture	24.5 m	30 m	39.3 m
Collecting Area	368 m^2	655 m^2	978 m^2
Final Focal	f/8	f/15	f/17.7
Focal Plane Scale	1.0 mm/asec	2.2 mm/asec	3.6 mm/asec
Field of view	10amin (20amin w/ cor)	10 amin (15amin unvignet)	7 amin (10 amin)
Size of 10’ Field	0.6 meters	1.3 meters	2.0 meters

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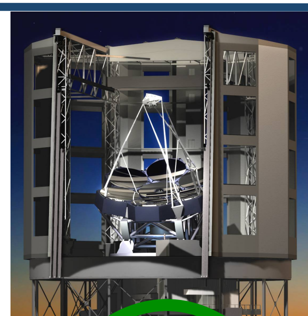

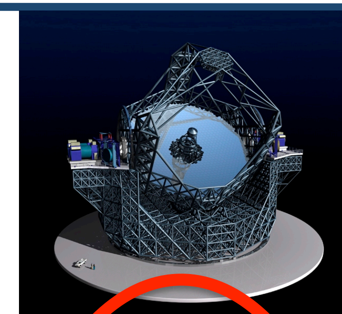

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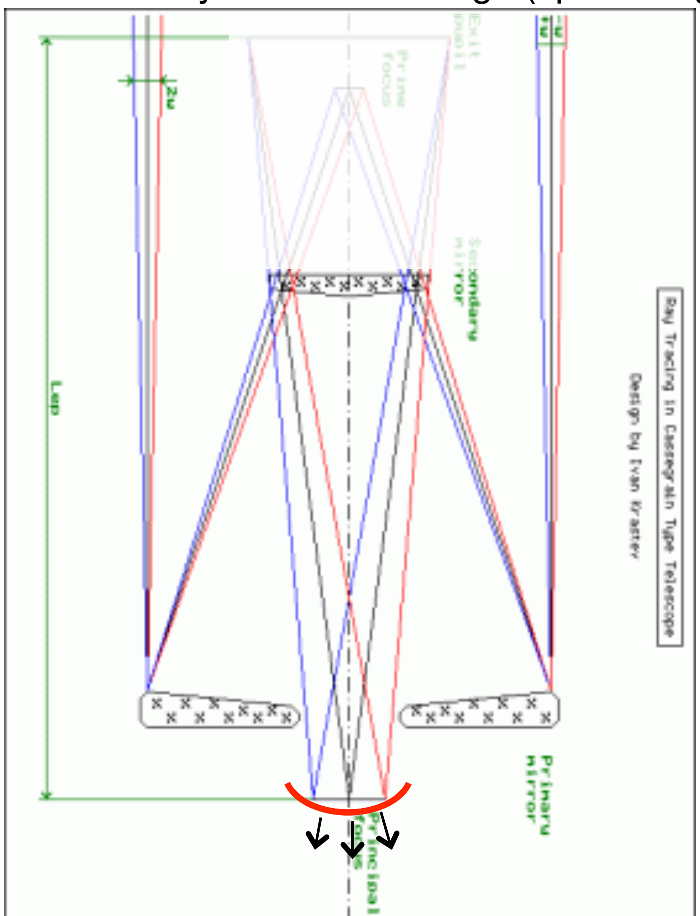
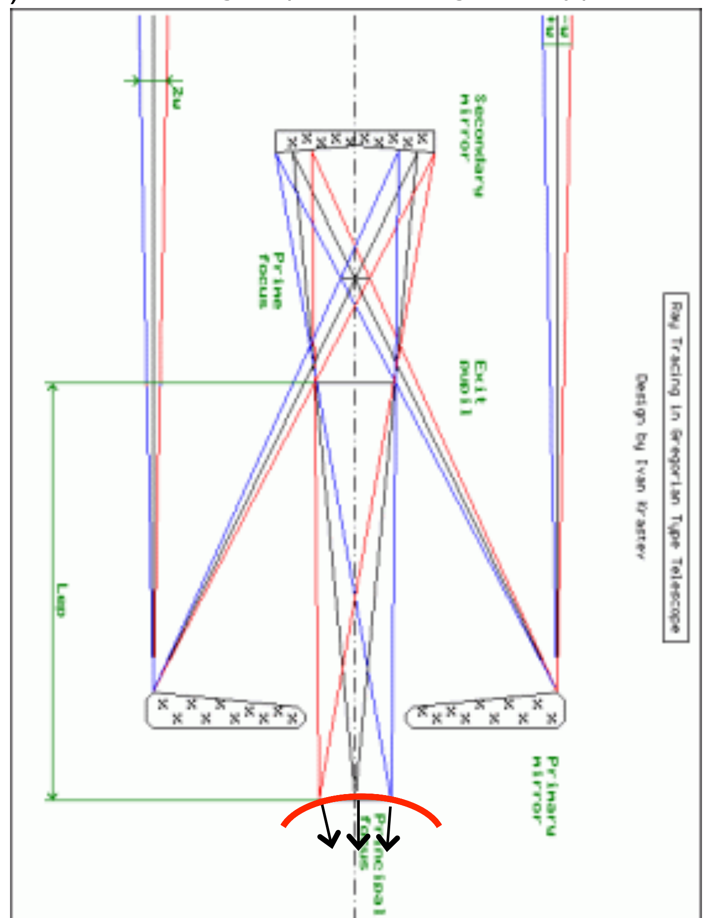
Telescope designs: GMT & TMT

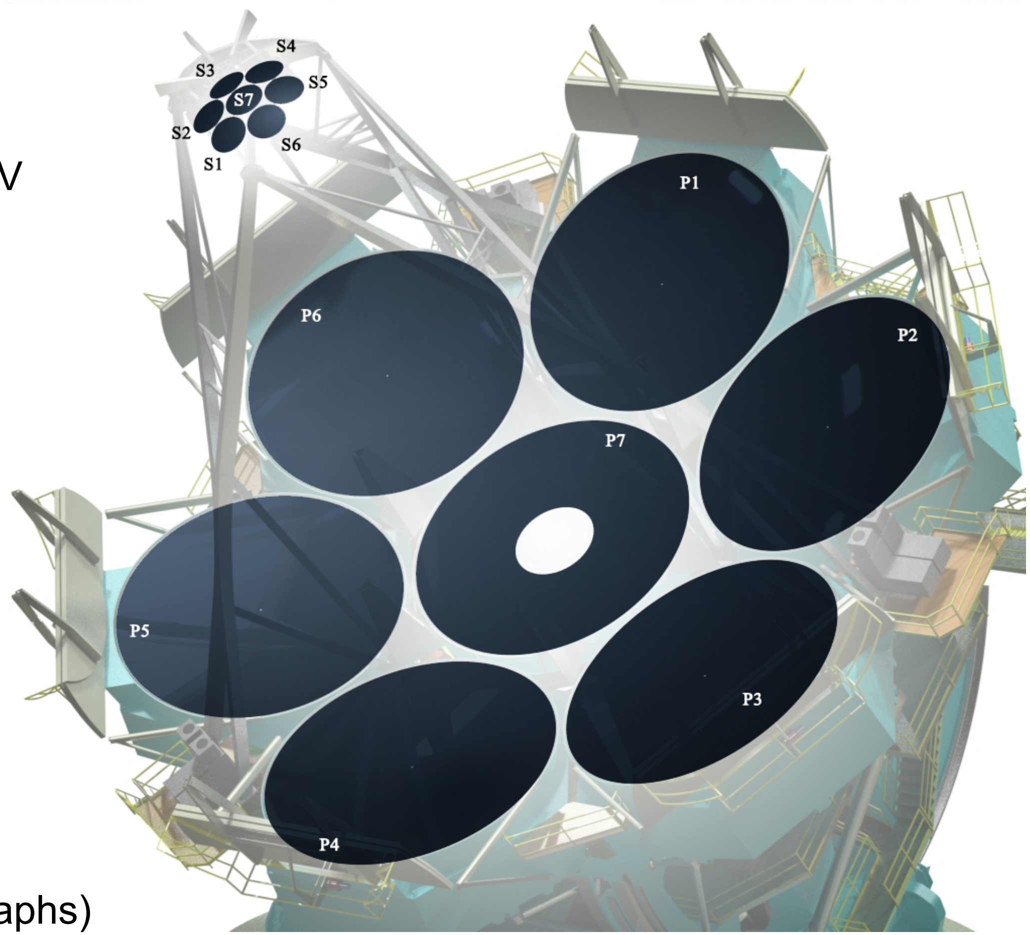
	Ritchey-Chrétien (TMT, Keck, VLT, Gemini)	Gregorian (GMT, Magellan, LBT)
• Real M1 image:	No.	Yes (calibration, flat fielding easier)
• Focal plane:	convex (mirror collimator!)	concave (lens collimator!)
• Chief rays:	diverge (spec design hard)	converge (spec design easy)





Telescope designs: GMT

- Las Campanas, Chile
  2.2 km (8500ft)
- Wavelength = 0.32–25μm
- Gregorian configuration: 10-20 amin FOV
- Fast focal ratio
- 2 reflections
- Adaptive M2 – full GLAO
- Aluminum coating (to start)



Pros and Cons:
+ A + GLAO (5-10 amin FOV)
+ Excellent image quality.
+ Instrument-enabling plate scale
  1 asec / mm
+ Spectrograph-enabling configuration
  (focal plane curvature helps spectrographs)

→ slits, fibers… lots of options!

Telescope designs: TMT

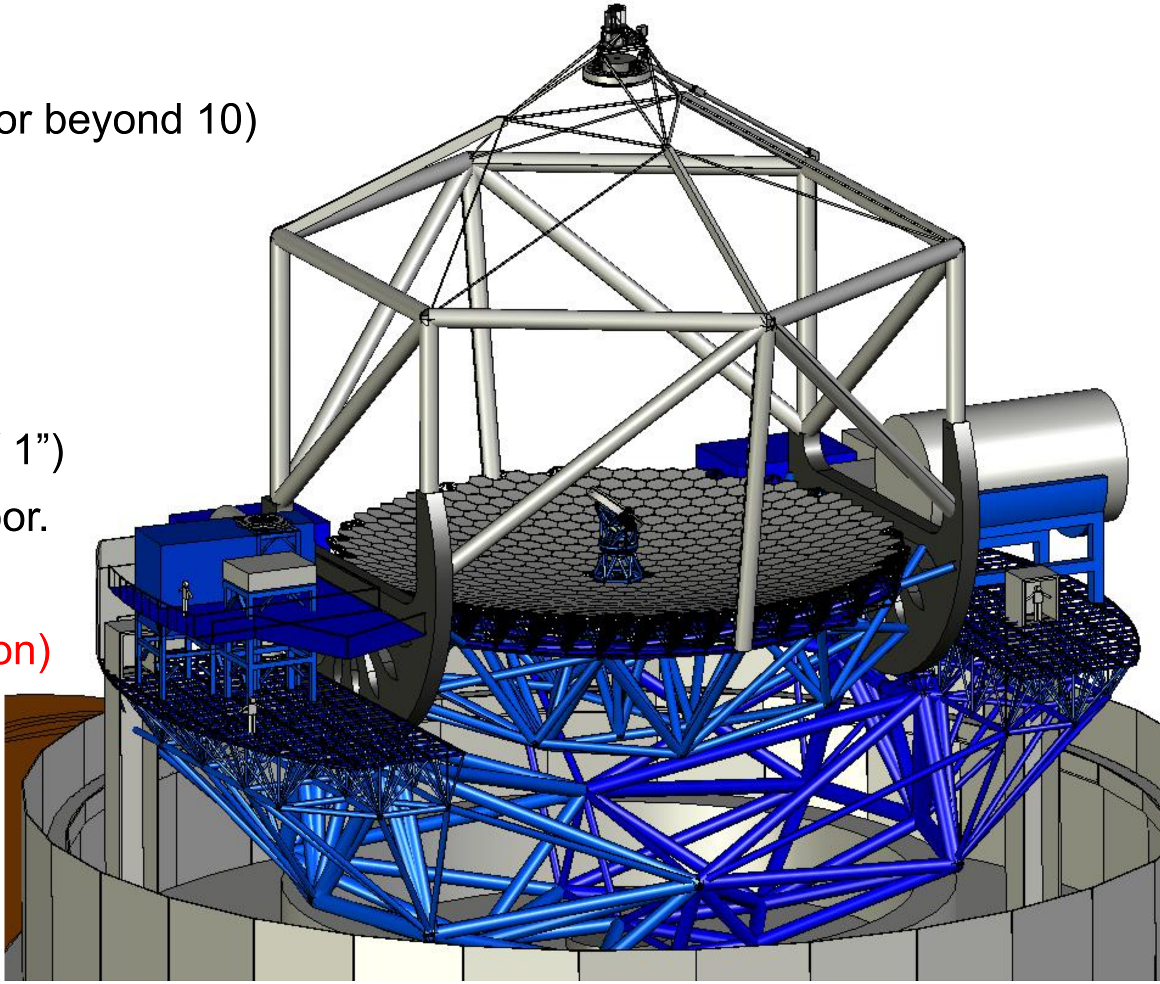
- 3-mirror Ritchey-Chretien design
- AO is after the telescope (NFIRAOS)
- Tip-tilt correct at M2

→ Max FOV 15 amin (images poor beyond 10)

+ "A"
– no GLAO
– must have a mirror collimator
– Challenging plate scale (2mm / 1")
+/- off-axis only, where images poor.

→ ~~fibers~~? (vetoed…sky subtraction)

→ **off-axis mirror collimator spectrographs?**

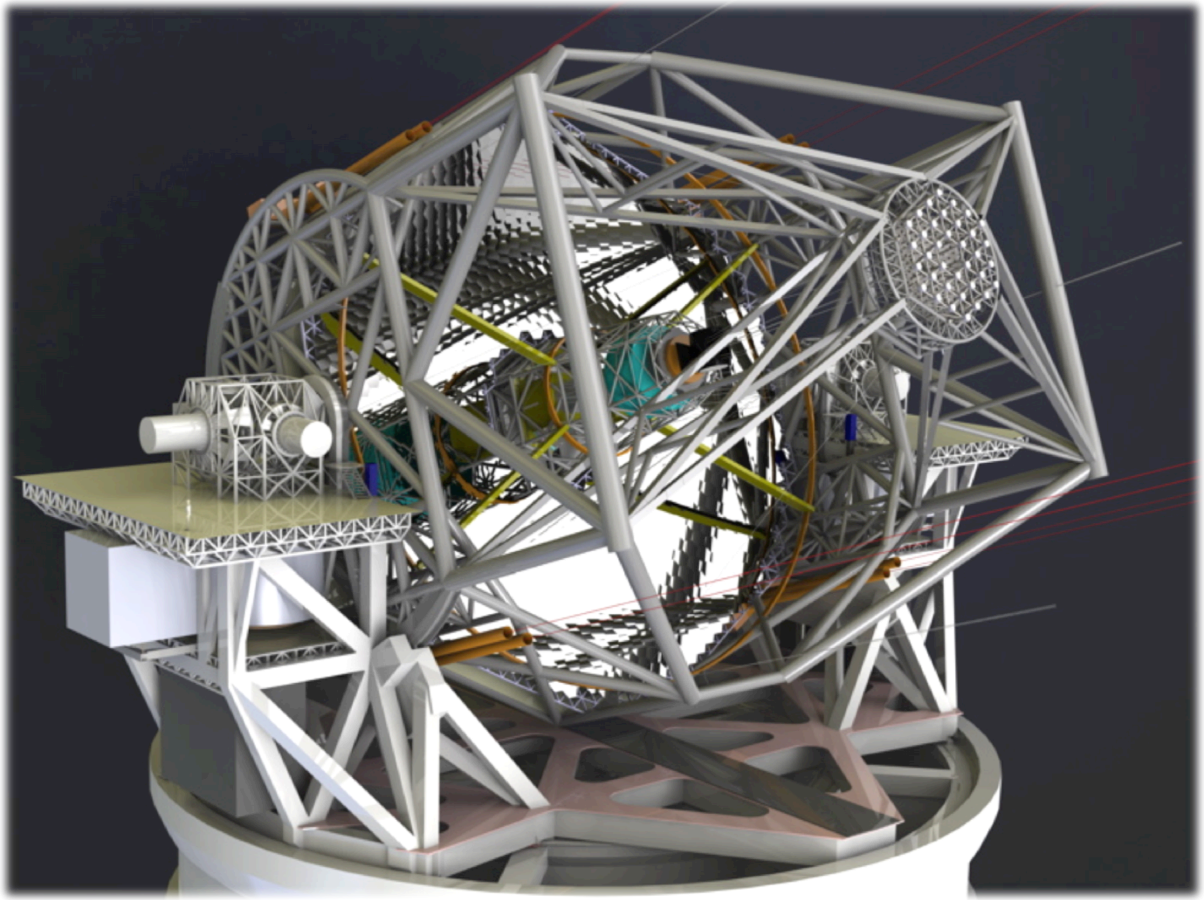


Telescope designs: E-ELT

- Armazones, Chile

  3 km (9800ft)
- Wavelength = 0.35–25μm
- 3-mirror anastigmat

  (on axis, + 2 folding flats)
- 5 reflections to instruments
- Adaptive M4
- Aluminum? Silver?



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+ MOAO
– Challenging plate scale

  4mm / 1 arcsec

→ fibers, IFUs, multiple spectrographs.

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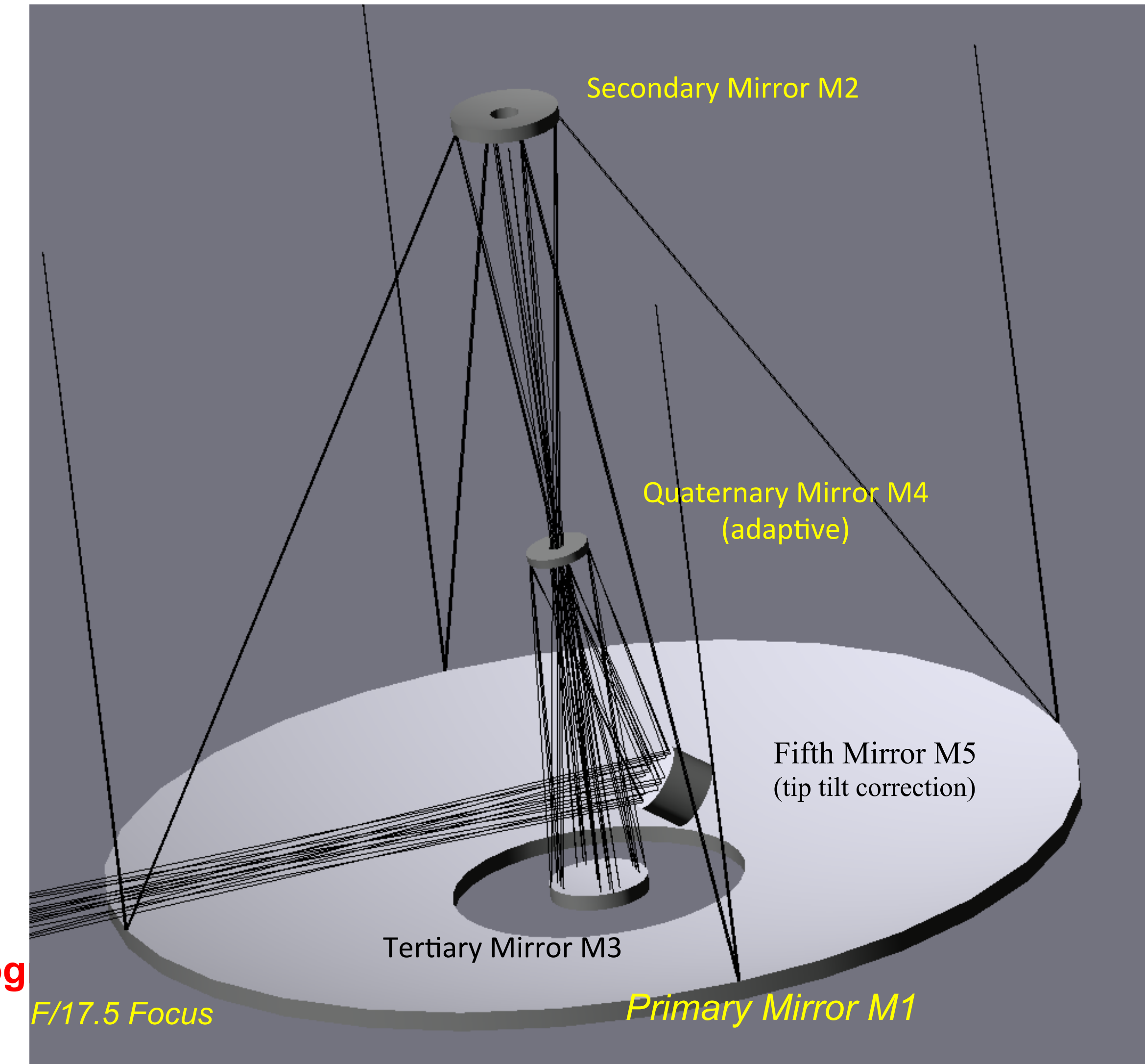

WFOS for TMT: science goals and req's

TMT
THIRTY METER TELESCOPE

Very ambitious performance goals: **wavelength** 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

WFOS for TMT: science goals and req’s

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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?		✔	✔	✔	✔	✔	✔	✔	✔

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Full simultaneous coverage needed = QSOs and Transients

WFOS for TMT: science goals and req's

Very ambitious performance goals:

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

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

d/D = diameter of beam : telescope

δ = blaze angle (→ grating length)

ϕ = seeing disk = ~1" in the optical

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

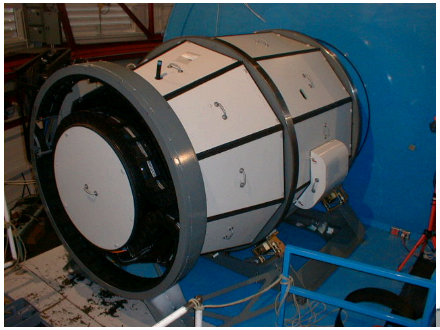
WFOS for TMT: History – the 4th try

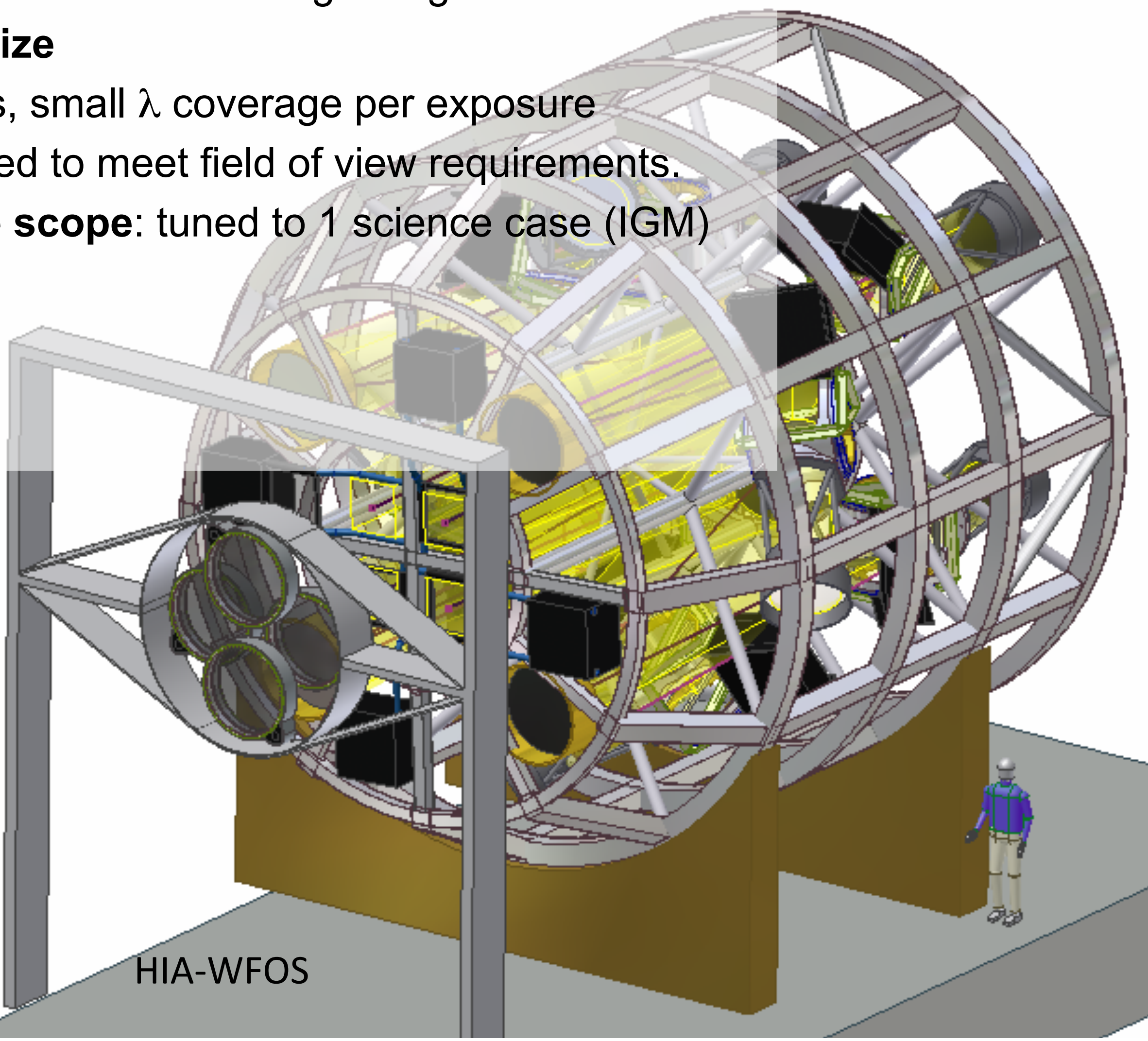
HIA: HIA-WFOS circa 2007, 4 barrel

- 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)

Reasons for concern…

IMACS on Magellan





HIA-WFOS

Strategic Pros and Cons: Multiple fields of view … ☹

Multiple fields of view:

+ increases field of view
– VERY hard to make work!

- VMOS for VLT*
- GMACS for GMT (re-scoped to 1 field of view)
- OPTIMOS-DIORAMAS 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

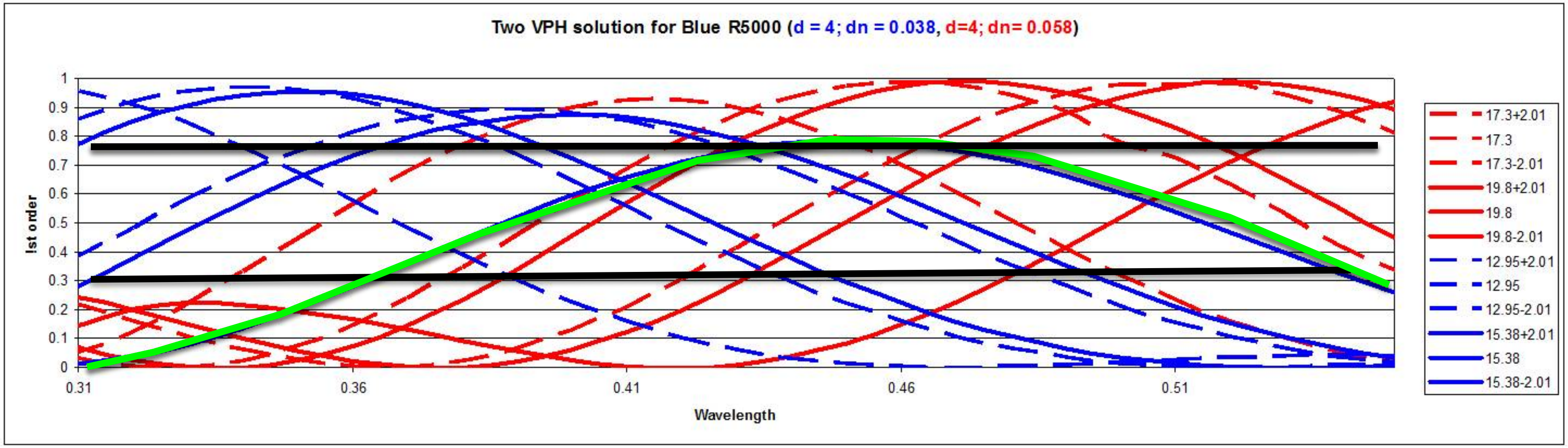
Strategic Pros and Cons: VPH gratings… ☹ / ☺

VPH gratings:

+ help to keep the cameras smaller
+ higher throughput (lower if long wavelength coverage needed)
– cameras must articulate relative to the collimator (flexure risk!)

- several spectrographs in 4-8m telescopes
- **GMACS for GMT** **(moving forward)**

30-70% efficiency at 3700-5300



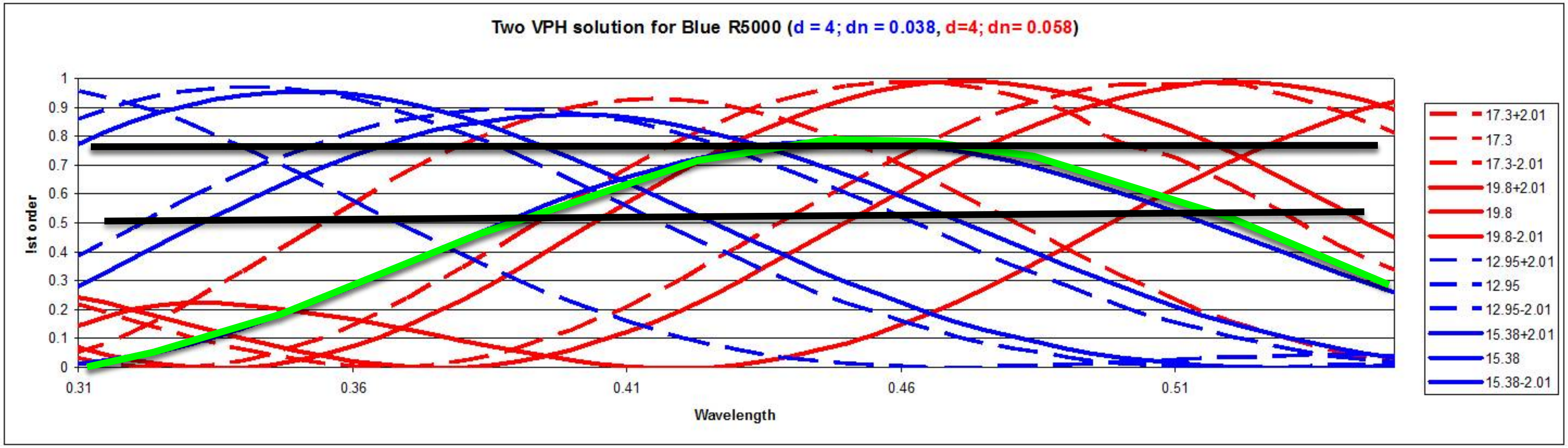
Strategic Pros and Cons: VPH gratings… ☹ / ☺

VPH gratings:

- \+ help to keep the cameras smaller
- \+ higher throughput (lower if long wavelength coverage needed)
- – cameras must articulate relative to the collimator (flexure risk!)

- several spectrographs in 4-8m telescopes
- **GMACS for GMT (moving forward)**

50-70% efficiency at 3900-5100



Strategic Pros and Cons: VPH gratings… ☹ / ☺

VPH gratings:

+ help to keep the cameras smaller
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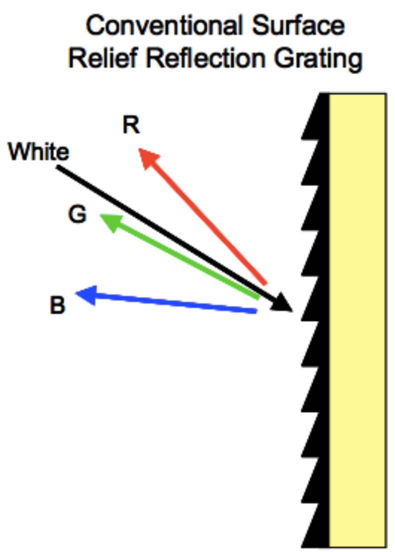
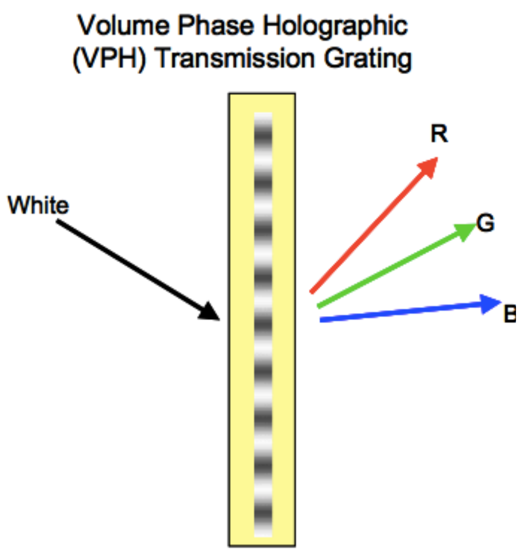
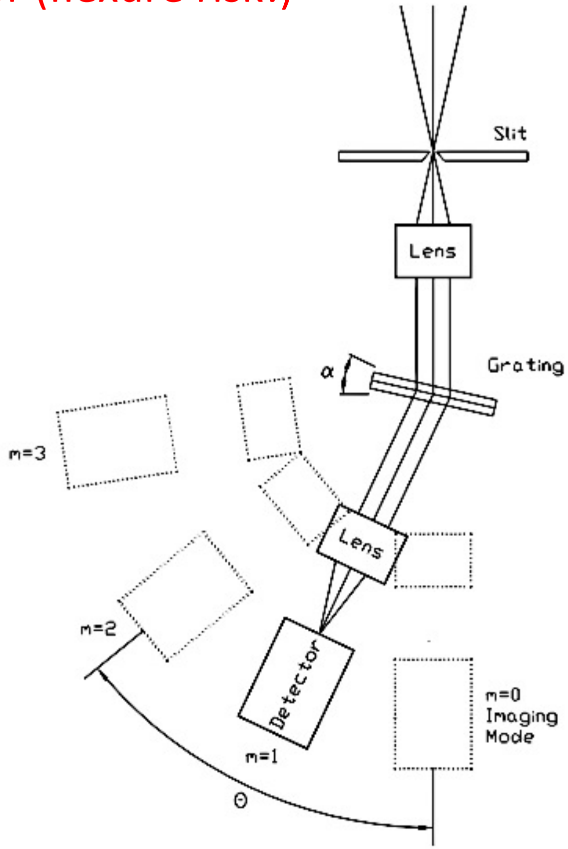
– cameras must articulate relative to the collimator (flexure risk!)

- several spectrographs in 4-8m telescopes
- **GMACS for GMT (moving forward)**

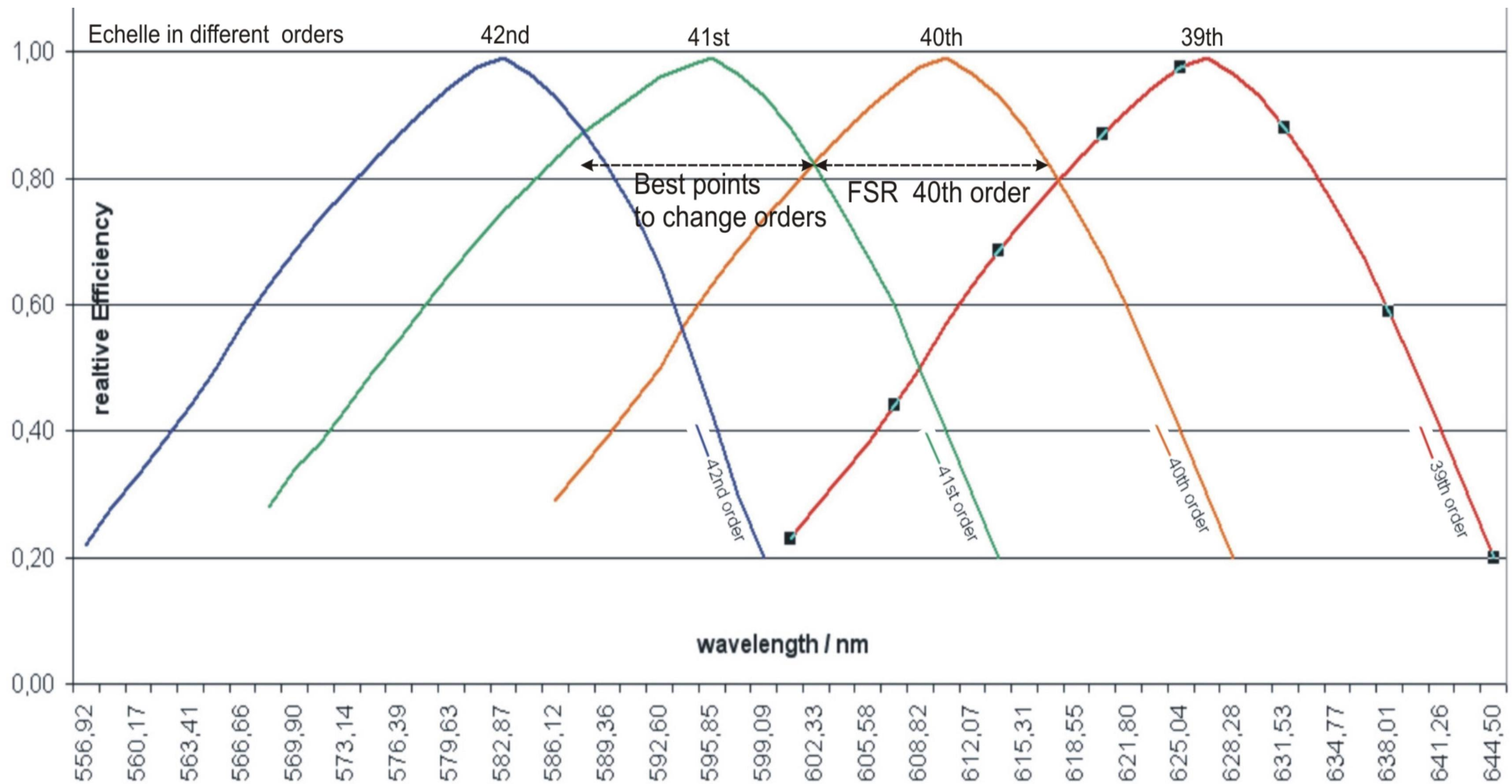






WFOS for TMT: An alternative…. an echellette

- Always "on blaze"
- Standard ruled reflection grating
- No grating tilt or camera articulation required
- Achieve required resolution with relatively modest beam size (300 mm; cf. 600mm for WFOS-HIA)



MOBIE for TMT: a hybrid approach.

TMT
THIRTY METER TELESCOPE

"Diagnostic" science

Examples: targeted studies

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

Design priorities:

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

"Discovery" science

Examples: surveys

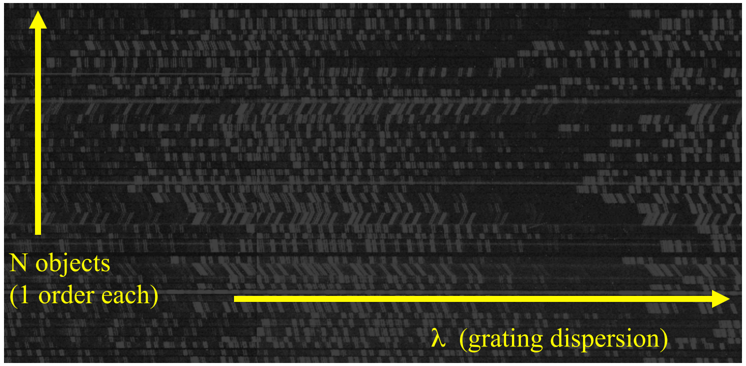
- IGM structure and composition at 2<z<6
- stellar pops (chemistry & kinematics z>1.5)

Design priorities:

- Resolution (λ/Δλ): 1,000 – 5,000
- Multiplexing: 100's

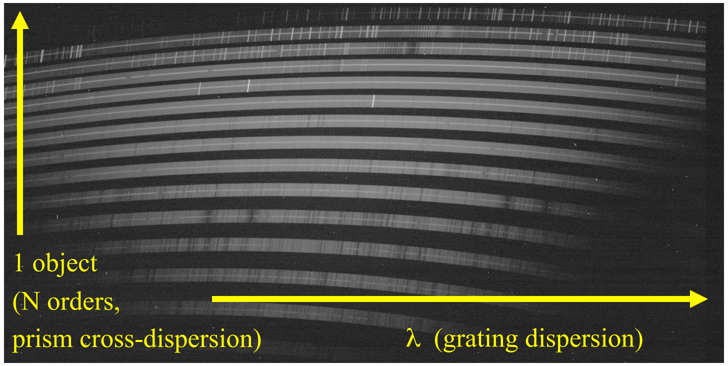
MULTI-ORDER (cross-dispersed) SPECTRA

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



SINGLE ORDER SPECTRA

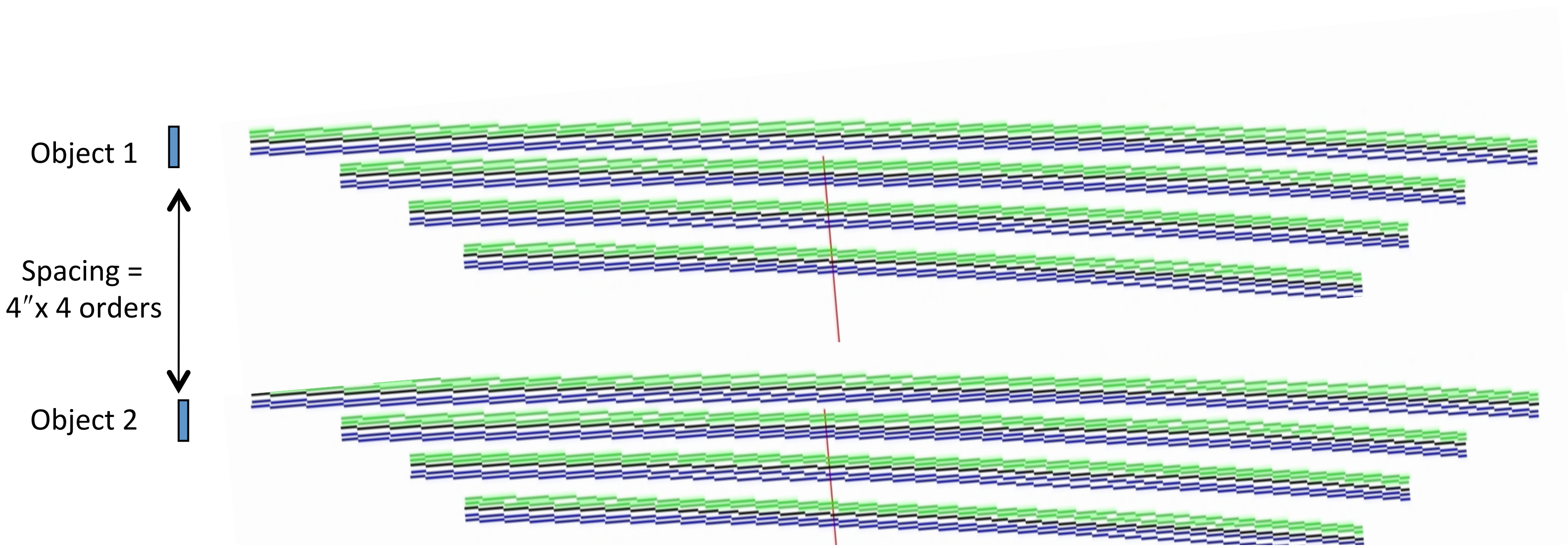
Echellette spectrographs:
ESI (Keck), MagE (Magellan), XShooter (VLT)



MOBIE for TMT: the echellette strategy

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

MOBIE for TMT: configuration options

R~1000 (single order)
R~5000 (5 orders)
R~8000 (7-8 orders)

prism X-dispersion for 2" – 4" slit length in high resolution mode

Table 1: Example Spectral Resolution Options*

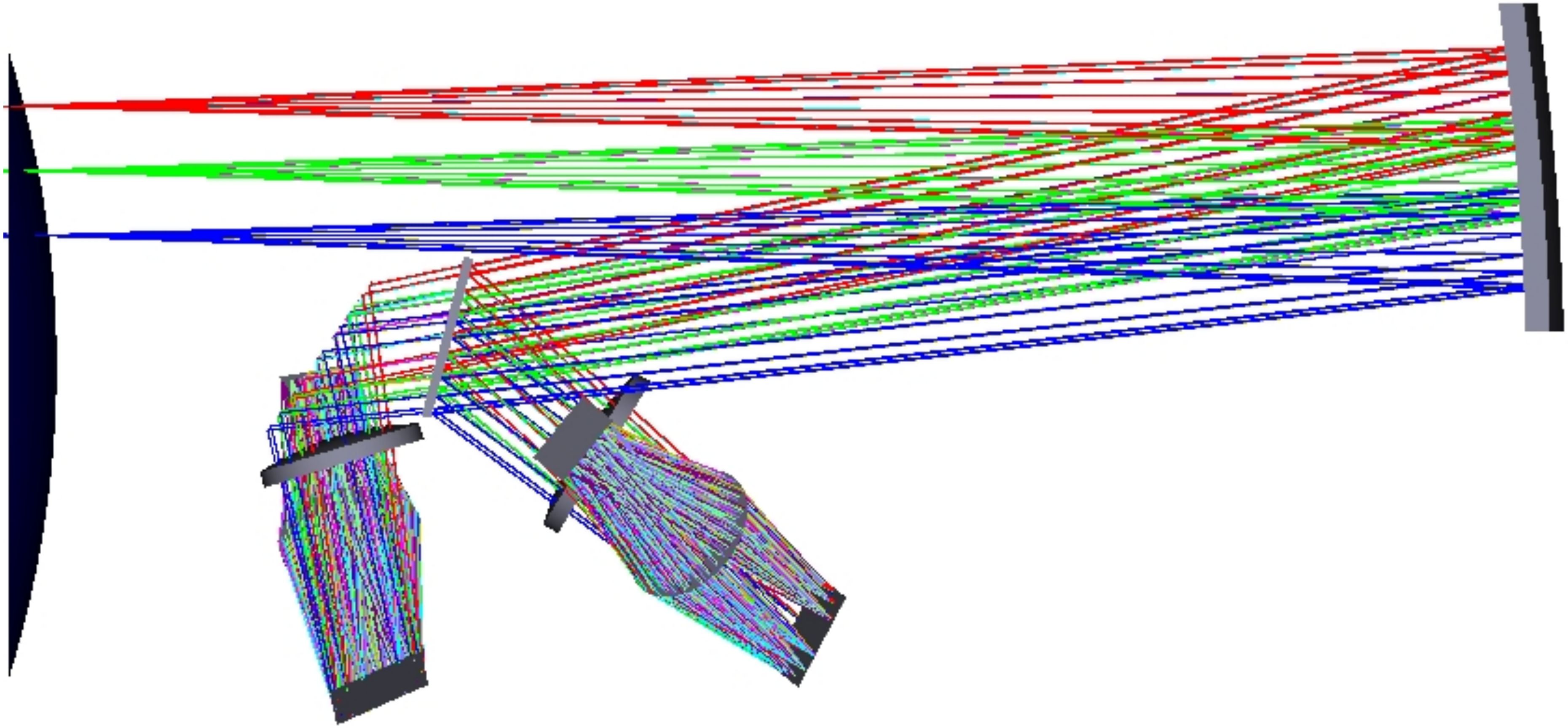
$\mathcal{R}$	Order	FSR	Length	$\mathcal{R}$	Order	FSR	Length
Blue				Red			
985	2	0.308-0.554	136	1077	1	0.550-1.000	131
2600	6	0.308-0.365	92	2480	6	0.536-0.635	88
	5	0.365-0.447	112		5	0.635-0.779	107
	4	0.447-0.580	145		4	0.779-1.010	138
5040	11	0.311-0.341	95	4860	11	0.558-0.611	91
	10	0.341-0.377	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

MOBIE for TMT: Grating and Prism Layout

TMT
THIRTY METER TELESCOPE

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

Only dispersion elements change
Each grating is fixed.
Cameras are fixed.



MOBIE for TMT: Grating and Prism Layout

TMT
THIRTY METER TELESCOPE

- Low: R~1000
- Medium: R~ 2,500 and/or 5000
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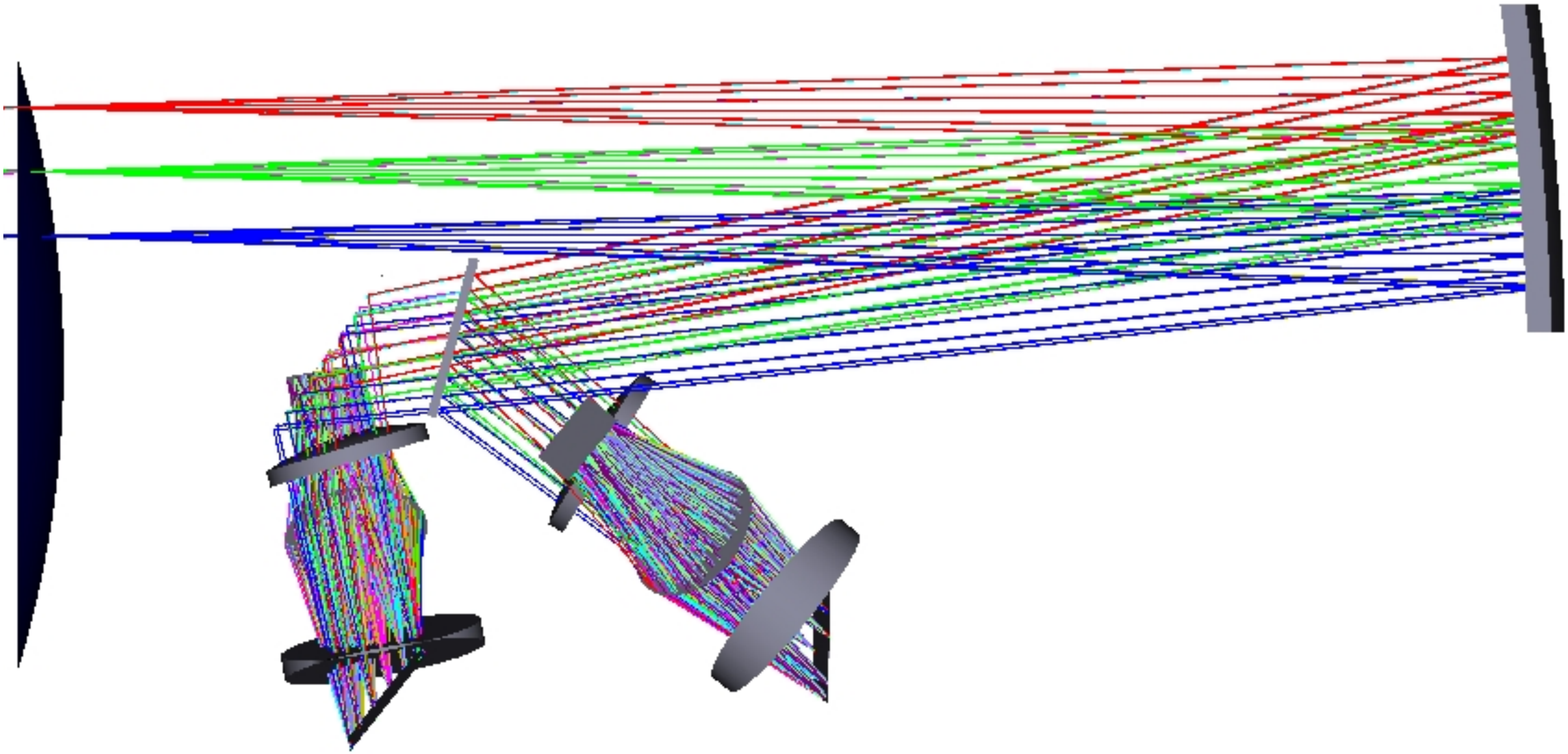
- Full field imaging

Only dispersion elements change.
Each grating (+prism) is fixed.
Cameras are fixed.



MOBIE for TMT: Grating and Prism Layout

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

Only dispersion elements change.
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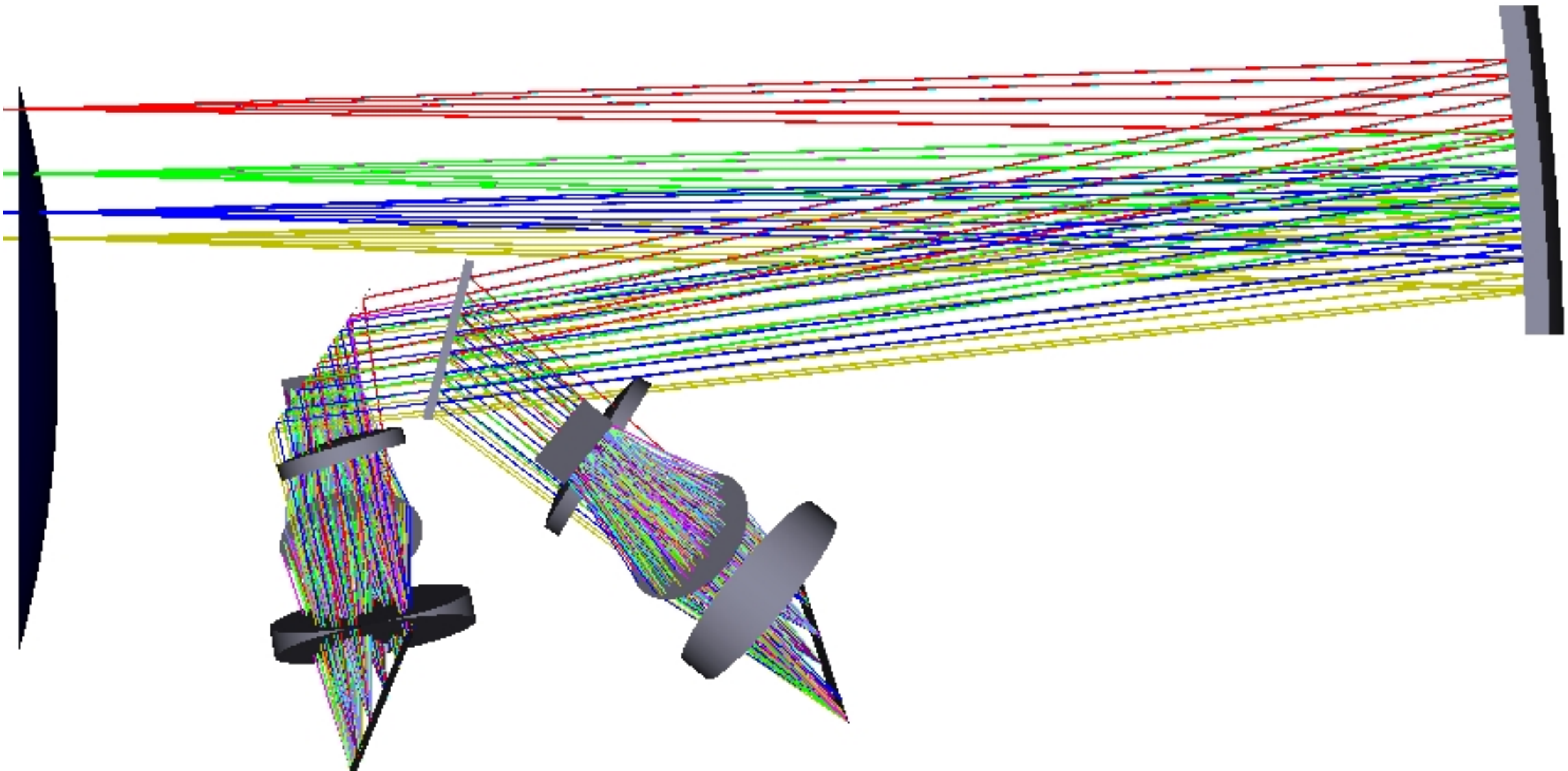
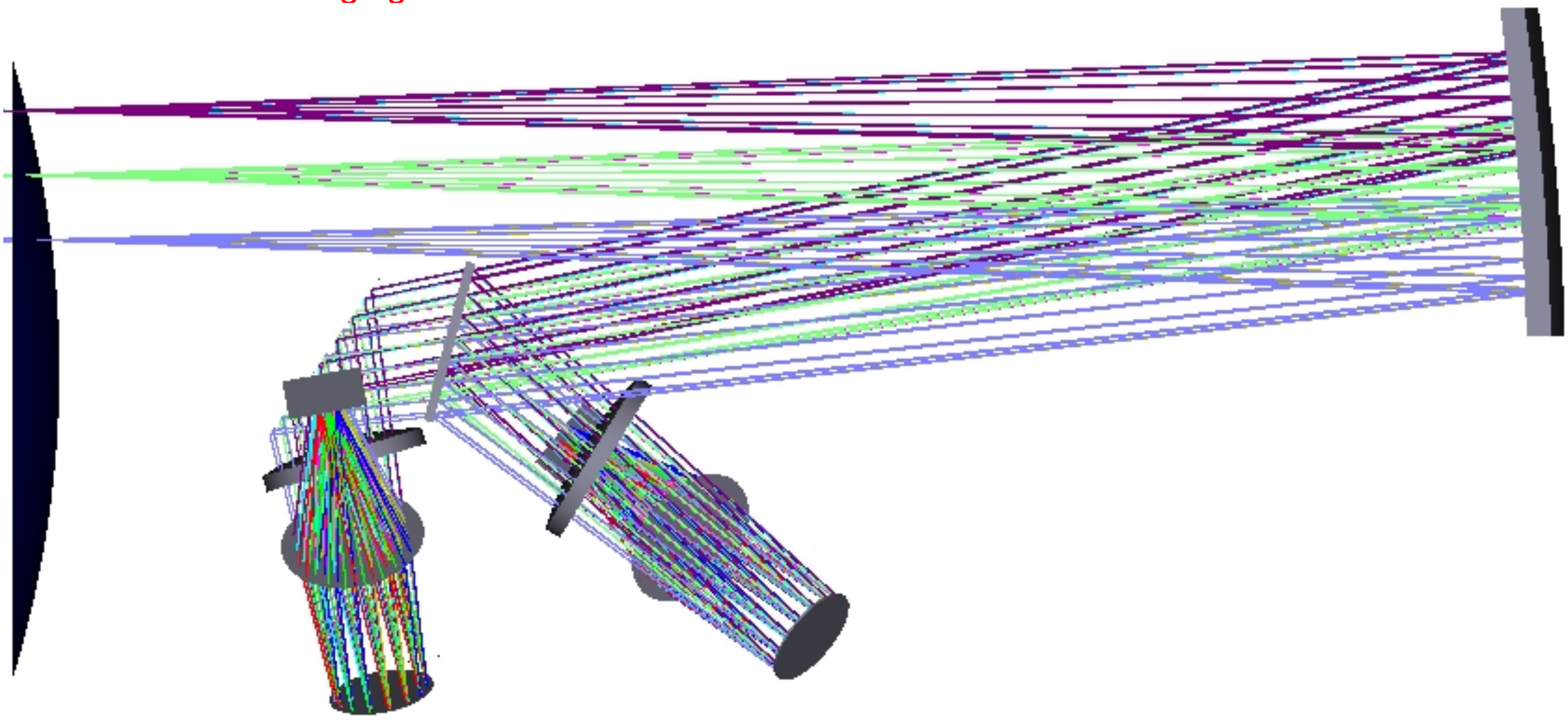
Cameras are fixed.



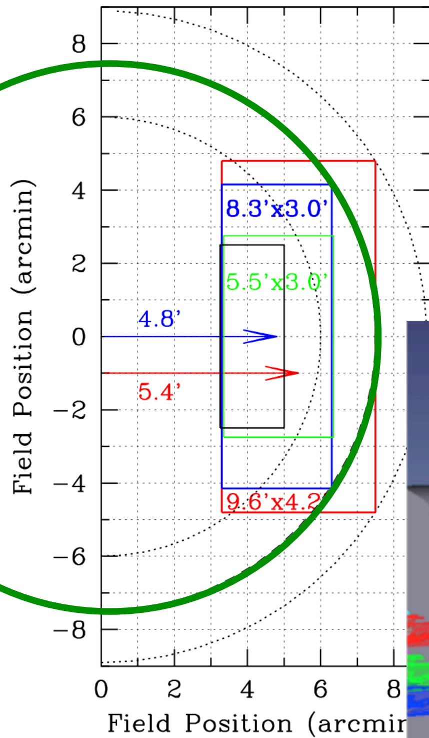
MOBIE for TMT: Grating and Prism (mirror) Layout

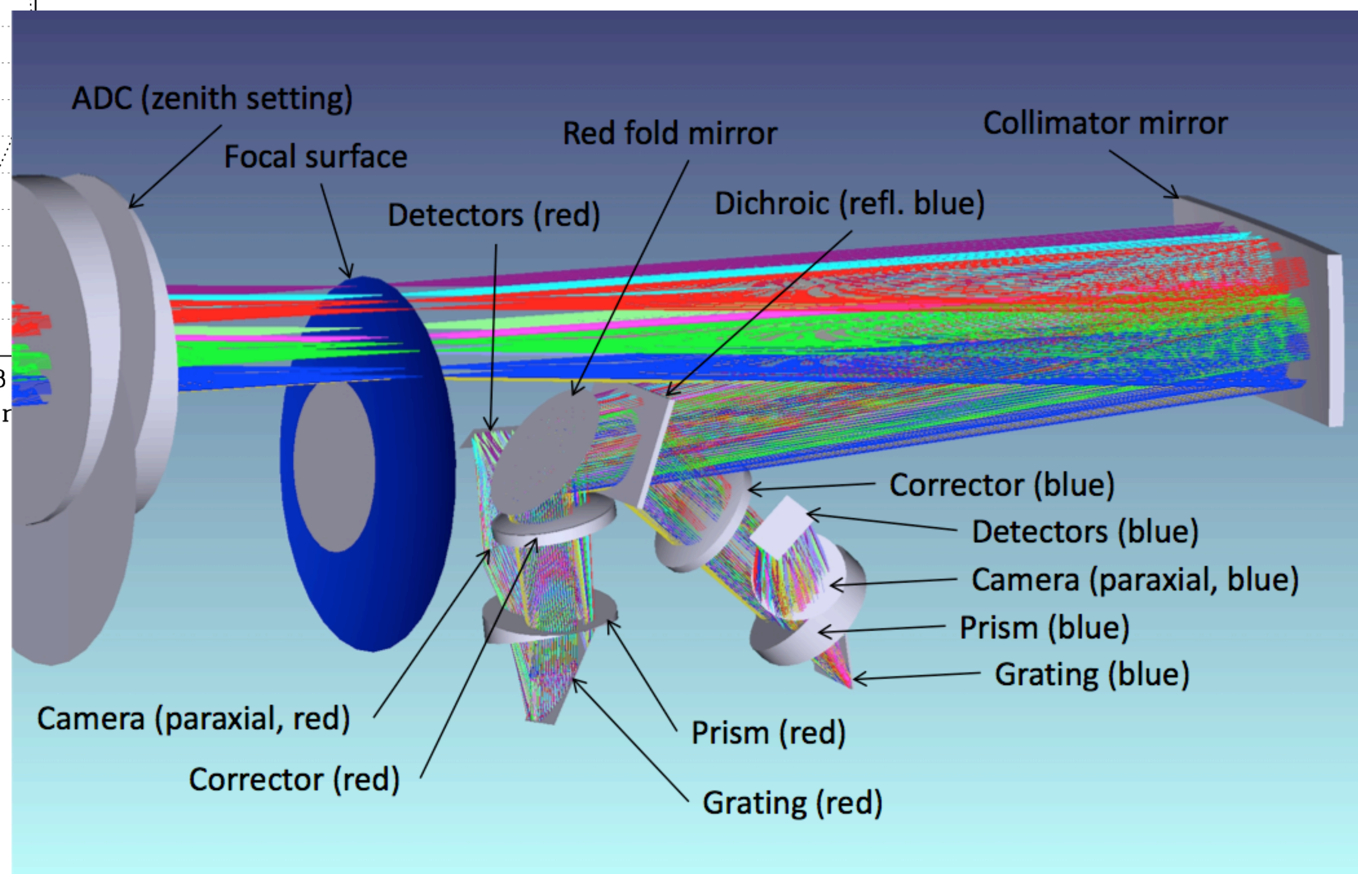
- Low: R~1000
- Medium: R~ 2,500 and/or 5000
- High: R ~ 8,000
- Full field imaging

Only dispersion elements change.
Each grating (+prism) is fixed.
Cameras are fixed.

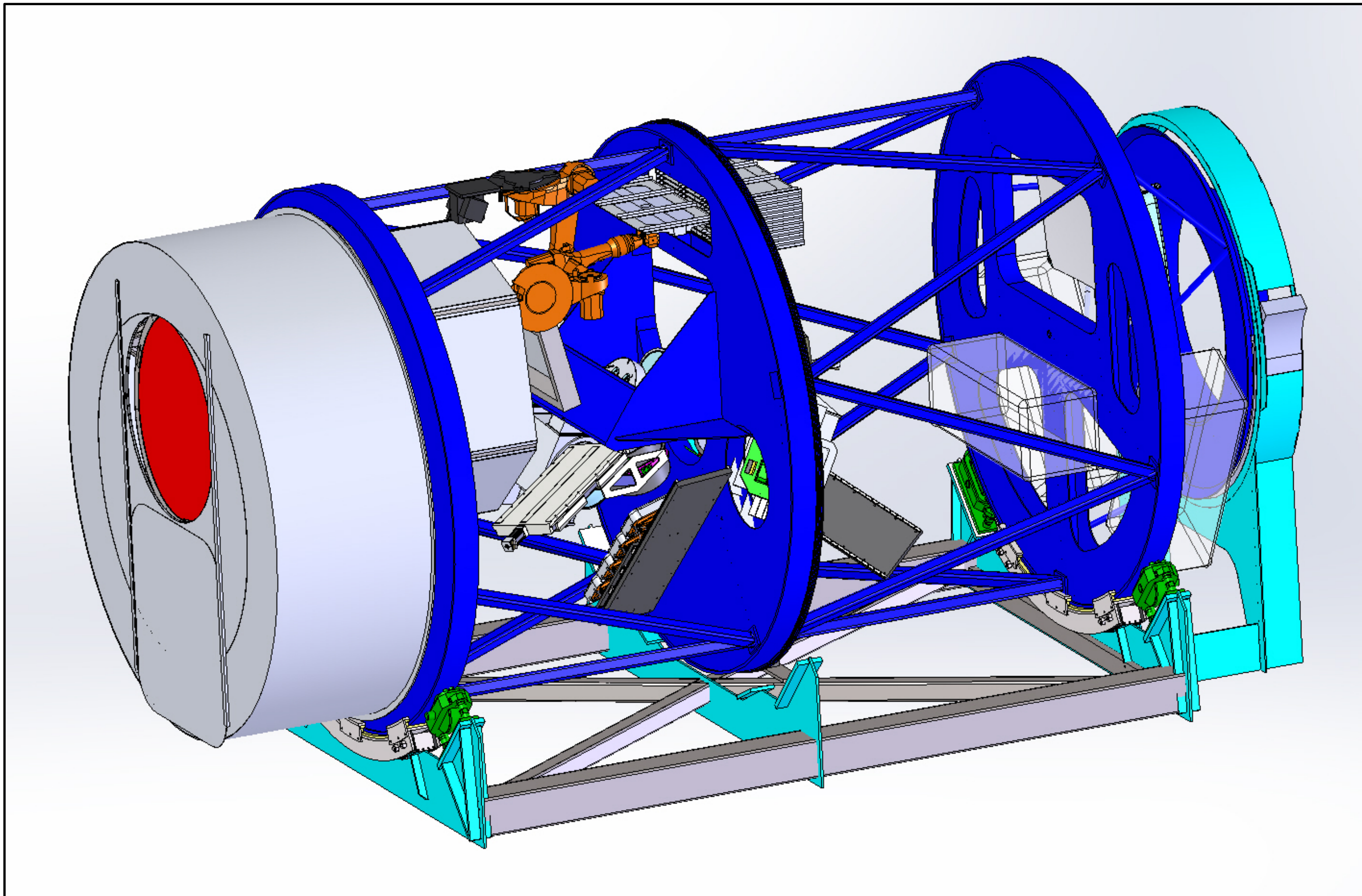


MOBIE for TMT: Grating and Prism (mirror) Layout





MOBIE for TMT: feasibility study 2009 – first stage CoDR 2013



MOBIE for TMT: feasibility study 2009 – first stage CoDR 2013

TMT
THIRTY METER TELESCOPE

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)

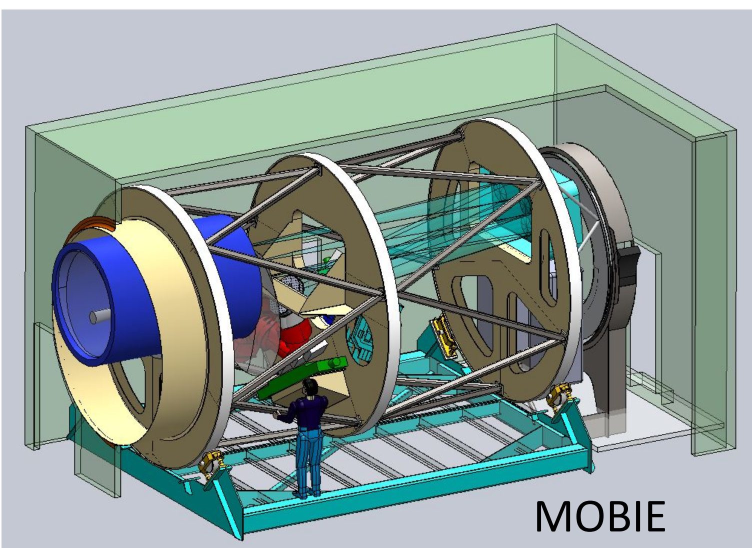
MOBIE for TMT: feasibility study 2009 – first stage CoDR 2013

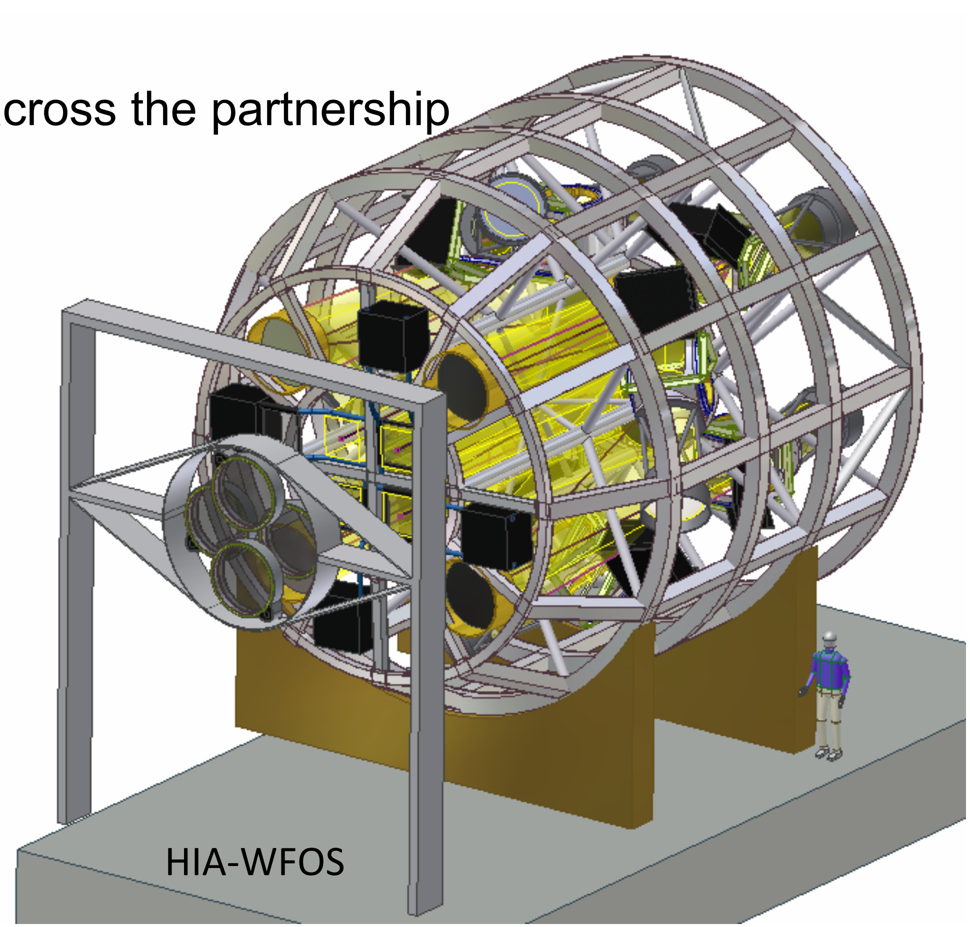
Lesson #N:

Remember to include personnel changes in your risk register.

Current status:

- moving forward
- multiple design studies across the partnership





E-ELT: MOS ambitions

- schizophrenic… I like it.
- a re-imaging spec is out
- fiber system, IFU:
  required just to get FOV.
  spec will still be big!

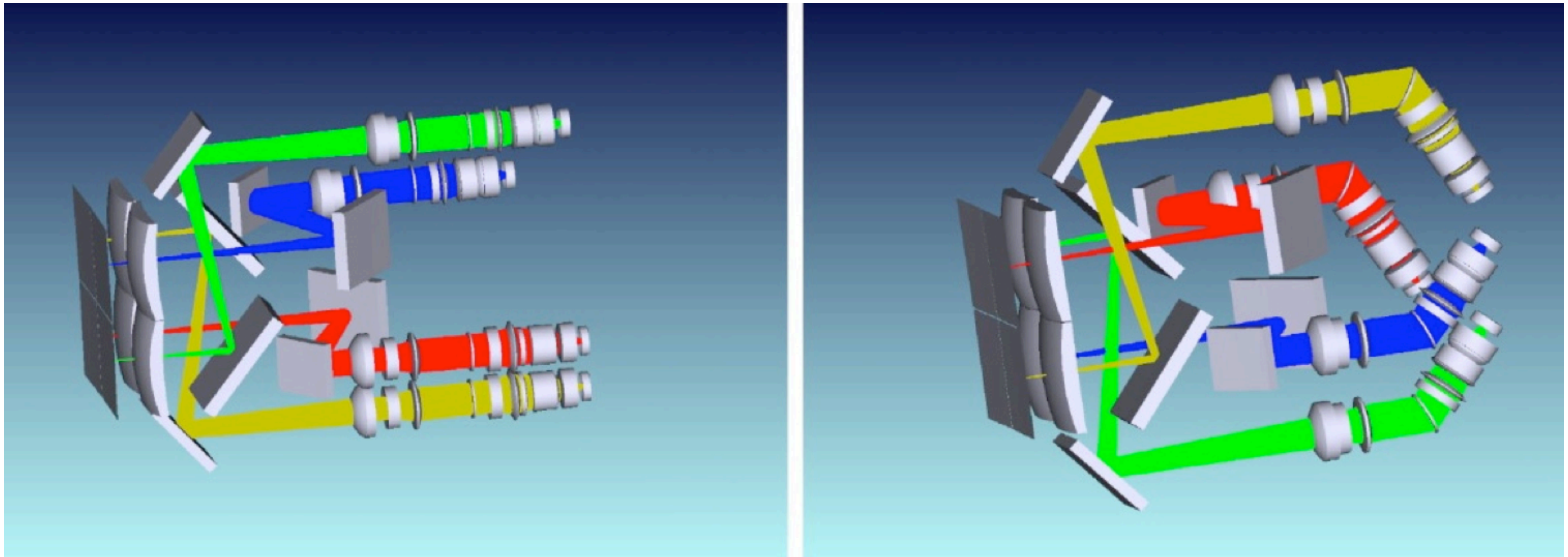
Table 7: Summary of top-level requirements from each Science Case (with desirable reqs. in italics).

Case	Multiplex	FoV/target	Spatial sampling		λ-coverage (μm)	*R*
SC1 First light	20-40	2"x2" *	40-90 mas	B	1.0-1.8 *1.0-2.45*	5,000
	≥150	-	(GLAO: 0.6"Ø)	R-I	1.0-1.8 *1.0-2.45*	>3,000
SC2 Large-scale structures	≥10-15	2"x2"	(GLAO: IFU)	B	0.4-0.6 *0.37-0.6*	>3,000
	50-100	-	(GLAO)	R-I	0.6-1.8 *0.6-2.45*	>3,000
	>400	-	(GLAO)	B	0.4-1.4 *0.37-1.4*	>3,000
SC3 Gal. evolution	≥10	2"x2"	50-80 mas	R-I	1.0-1.8 *1.0-2.45*	5,000
	≥100	-	(GLAO: 0.6"Ø)	R-I	1.0-1.7 *0.8-2.45*	≥5,000 *~10,000*
	≥10	2"x2"	(GLAA: IFU)	B	0.385-0.7 *0.37-0.7*	5,000
SC4 AGN	~10	-	< 100 mas	R-I	1.0-1.8	>3,000
SC5 Extragal. stellar pops.	Dense	1"x1" *1.5"x1.5"*	< 75 mas *20-40 mas*	R-I	1.0-1.8 *0.8-1.8*	5,000
	10s arcmin^{-2}	-	(GLAO)	B	0.4-1.0	≥5,000 *≥10,000*
SC6 Gal. archaeol.	10s arcmin^{-2}	-	(GLAO)	B	0.41-0.46 & 0.60-0.68 *0.38-0.46 & 0.60-0.68*	≥15,000 *≥20,000*
SC7 GC science	Dense	> 2"x2"	~100 mas	R-IR	1.5-2.45	≥5,000 *≥10,000*
SC 8 Planet form.	10s	-	(GLAO)	R	0.5-0.6	≥20,000

* Minimum size is 1"×1" if on/off sky subtraction is used.

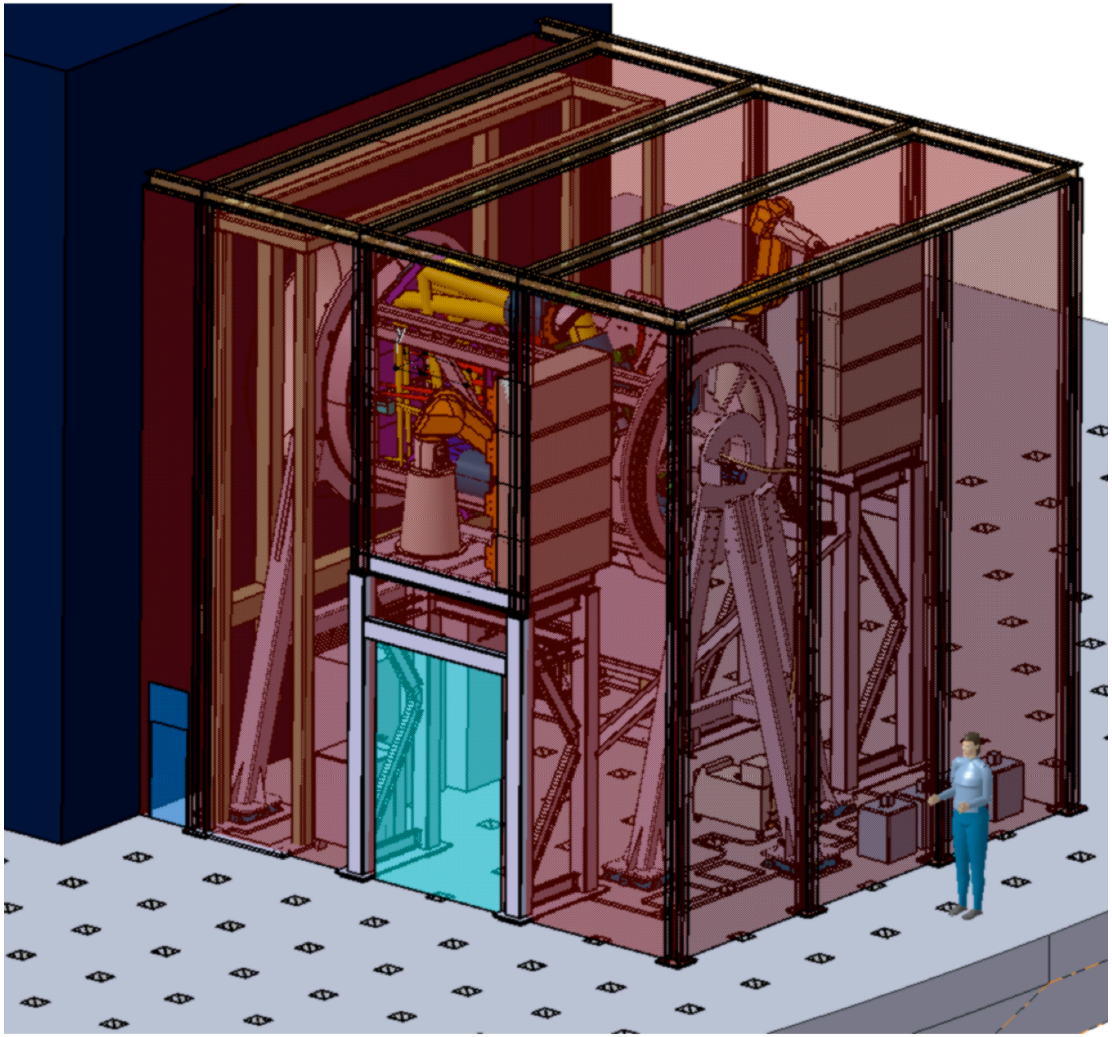
E-ELT: MOS plans … scrapped

- OPTIMOS-DIORAMAS - 4 field, 2 visible + 2 NIR channels



E-ELT: MOS plans … scrapped

- OPTIMOS-DIORAMAS - 4 field, 2 visible + 2 NIR channels



E-ELT: MOS plans … scrapped

- OPTIMOS-EVE- fiber fed (many different fiber-bundle options), visible + NIR

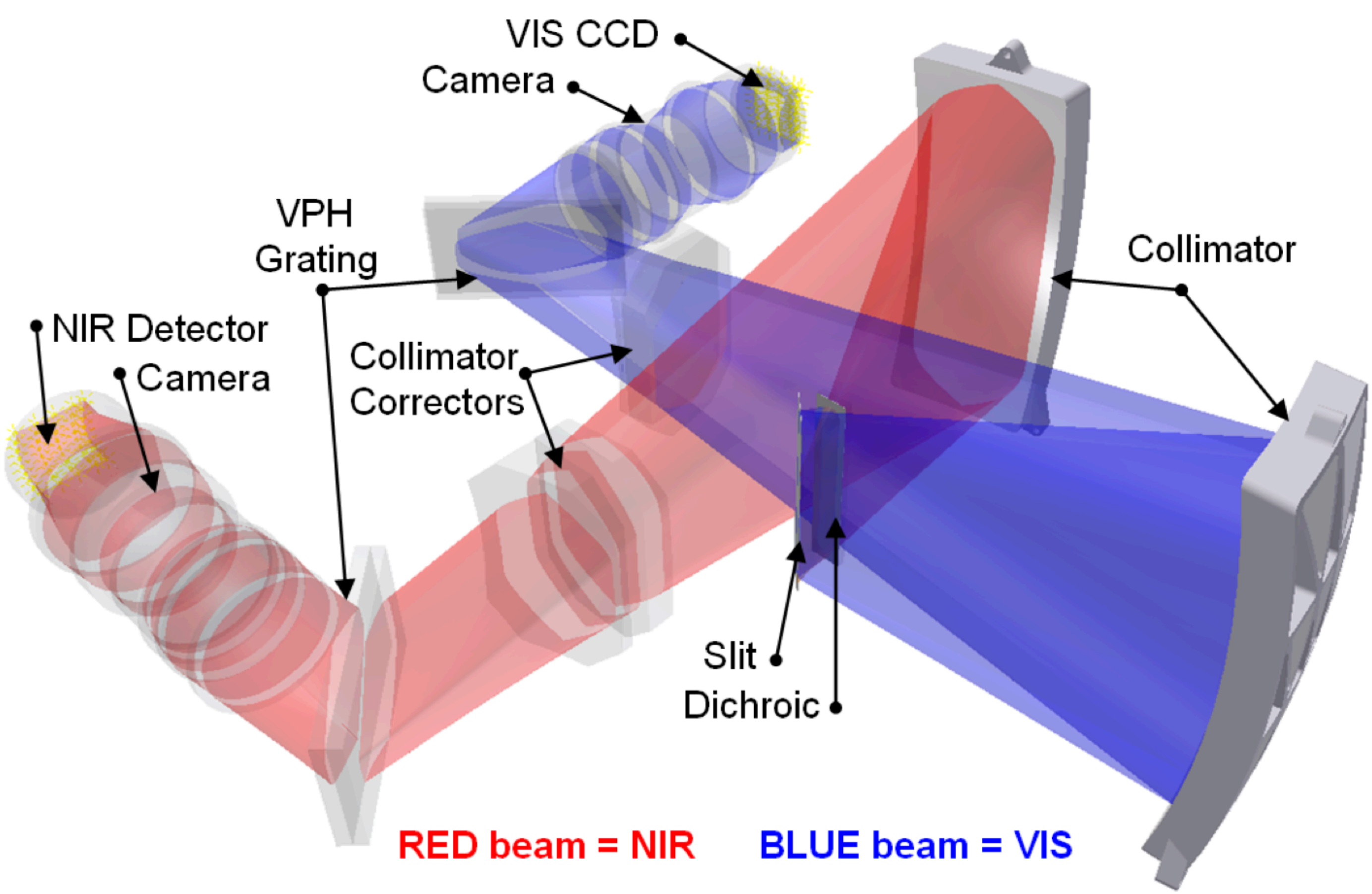
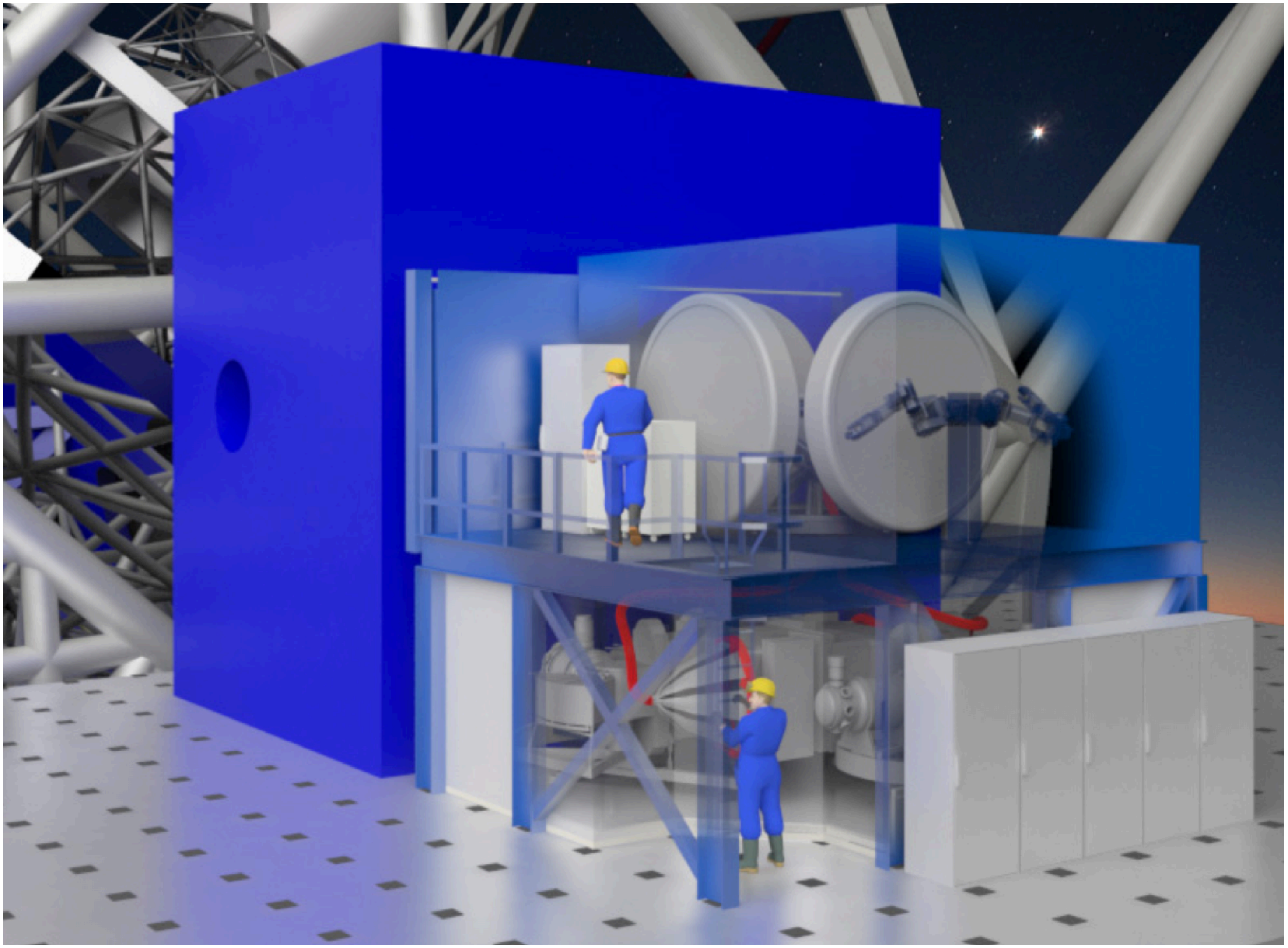


Figure 41 Optical layout of a single spectrograph

E-ELT: MOS plans … scrapped

- OPTIMOS-EVE- fiber fed (many different fiber-bundle options), visible + NIR

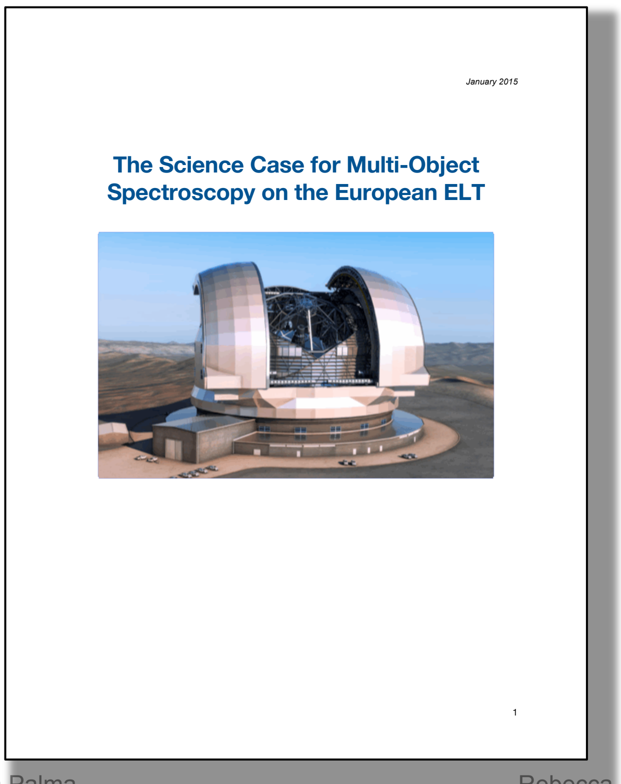


E-ELT: general strategy forming…

- *High multiplex:*
  Integrated-light (GLAO) spectroscopy of >100 objects

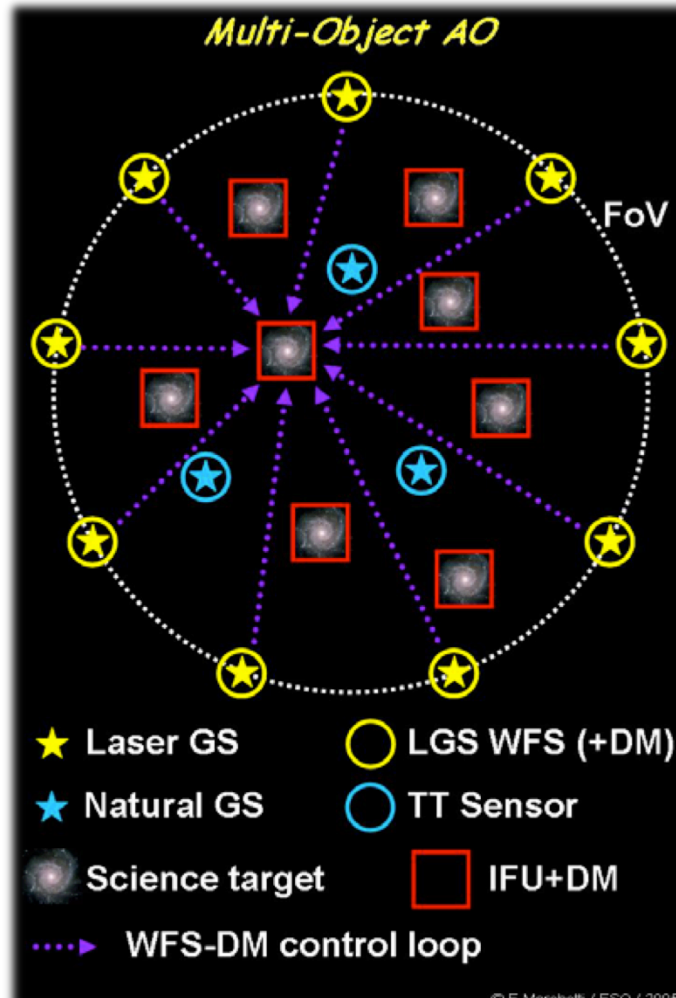
MOSAIC

- *High definition:*
  Tens of channels using high-performance (multi-object) AO


January 2015

The Science Case for Multi-Object Spectroscopy on the European ELT

1



Strategic Pros and Cons: Fibers … ☹ → ☺

Fibers:

+ increases field of view
+ Greatly improve configurability
– reduced throughput (X% ?)
– compromise sky subtraction relative to slits … ??

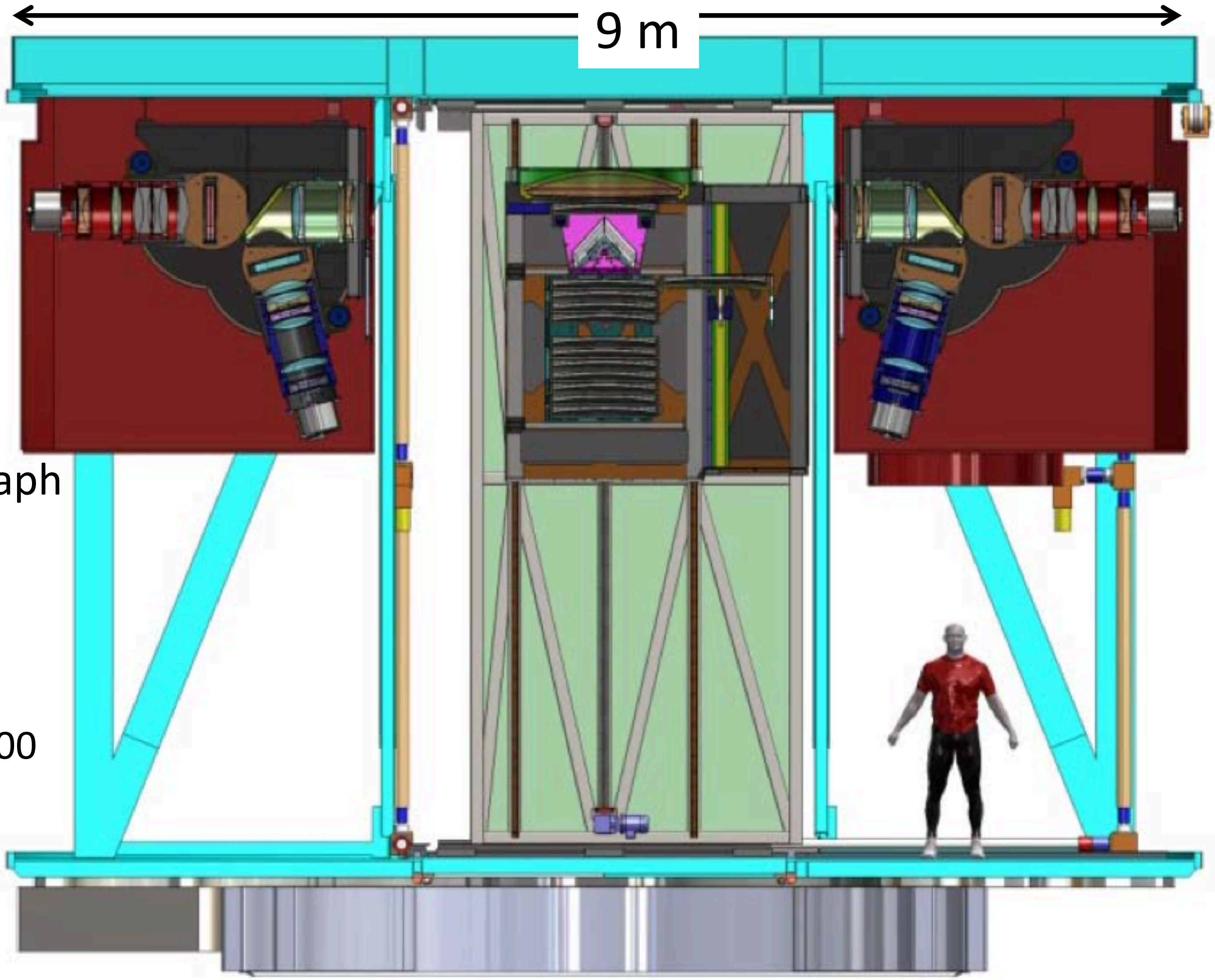
- many spectrographs for 2.5-8 m telescopes
- EVE / E-ELT (not moving forward)
- MOSAIC/ E-ELT (moving forward)
- MANIFEST / GMT (moving forward)

Quite possible that TMT will regret shunning fibers.

The GMACS Spectrograph

Texas A&M (DePoy), Carnegie Obs. (Shectman)

Positive CoDR in 2011 — GO!



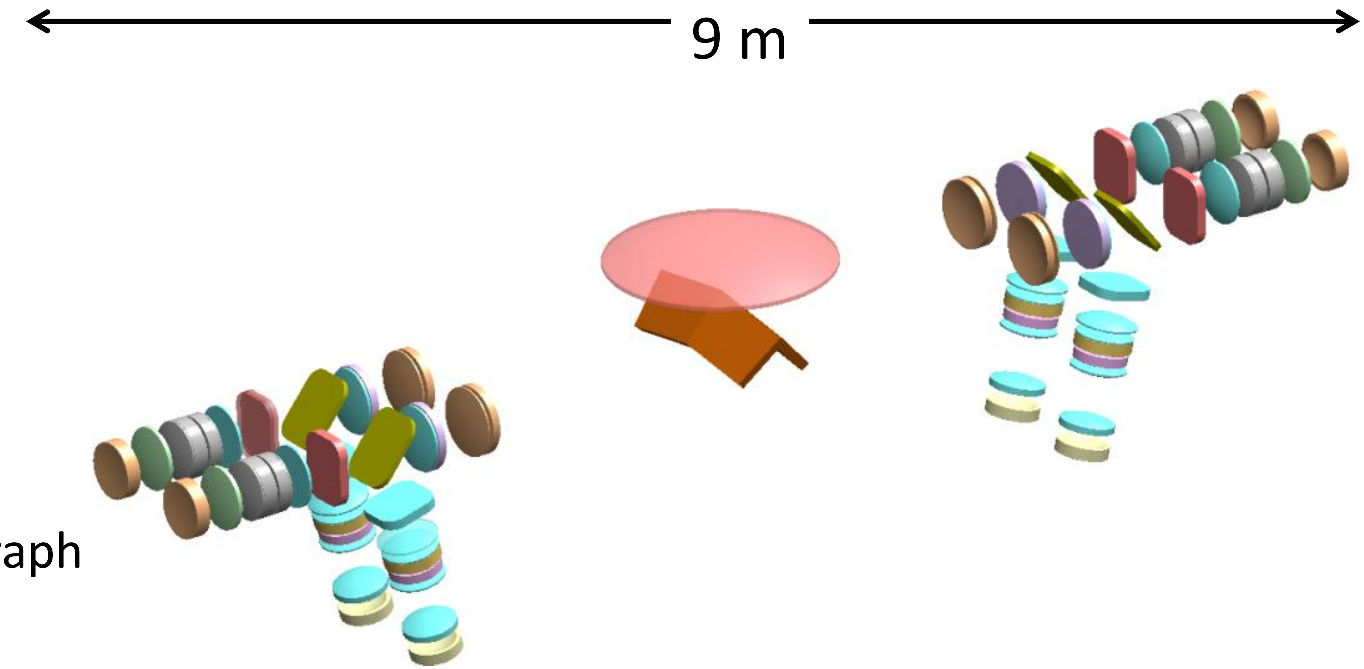
Wide-field,
multi-object,
optical spectrograph

λ = 0.34-1.0 μm
R = $\lambda/\Delta\lambda$ = 1500-4000
FoV = 4 x 36 amin^2

The GMACS Spectrograph

Texas A&M (DePoy), Carnegie Obs. (Shectman)

In Conceptual Design Phase



Wide-field,
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λ = 0.34-1.0 µm
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The GMACS Spectrograph

Texas A&M (DePoy), Carnegie Obs. (Shectman)

In Conceptual Design Phase

Wide-field,
multi-object,
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λ = 0.34-1.0 μm
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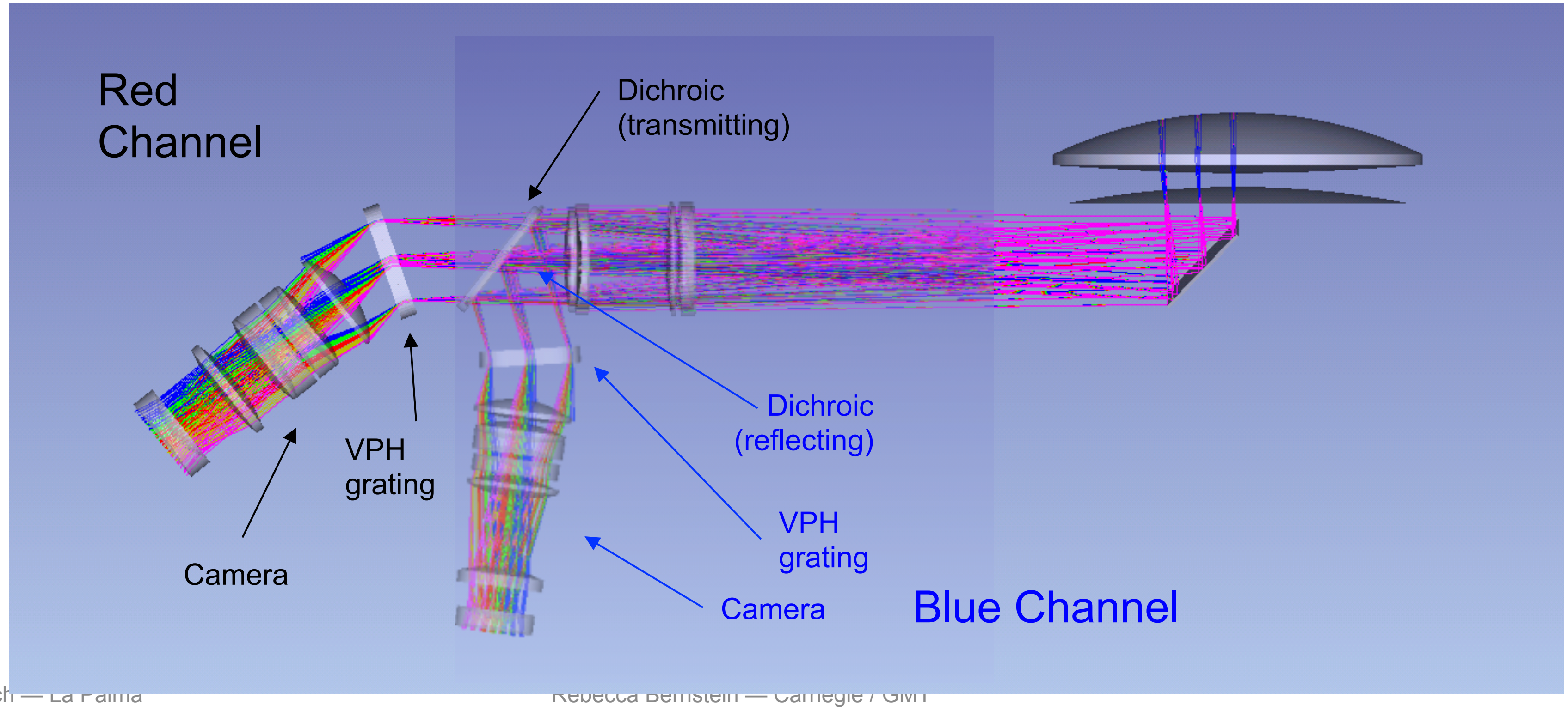
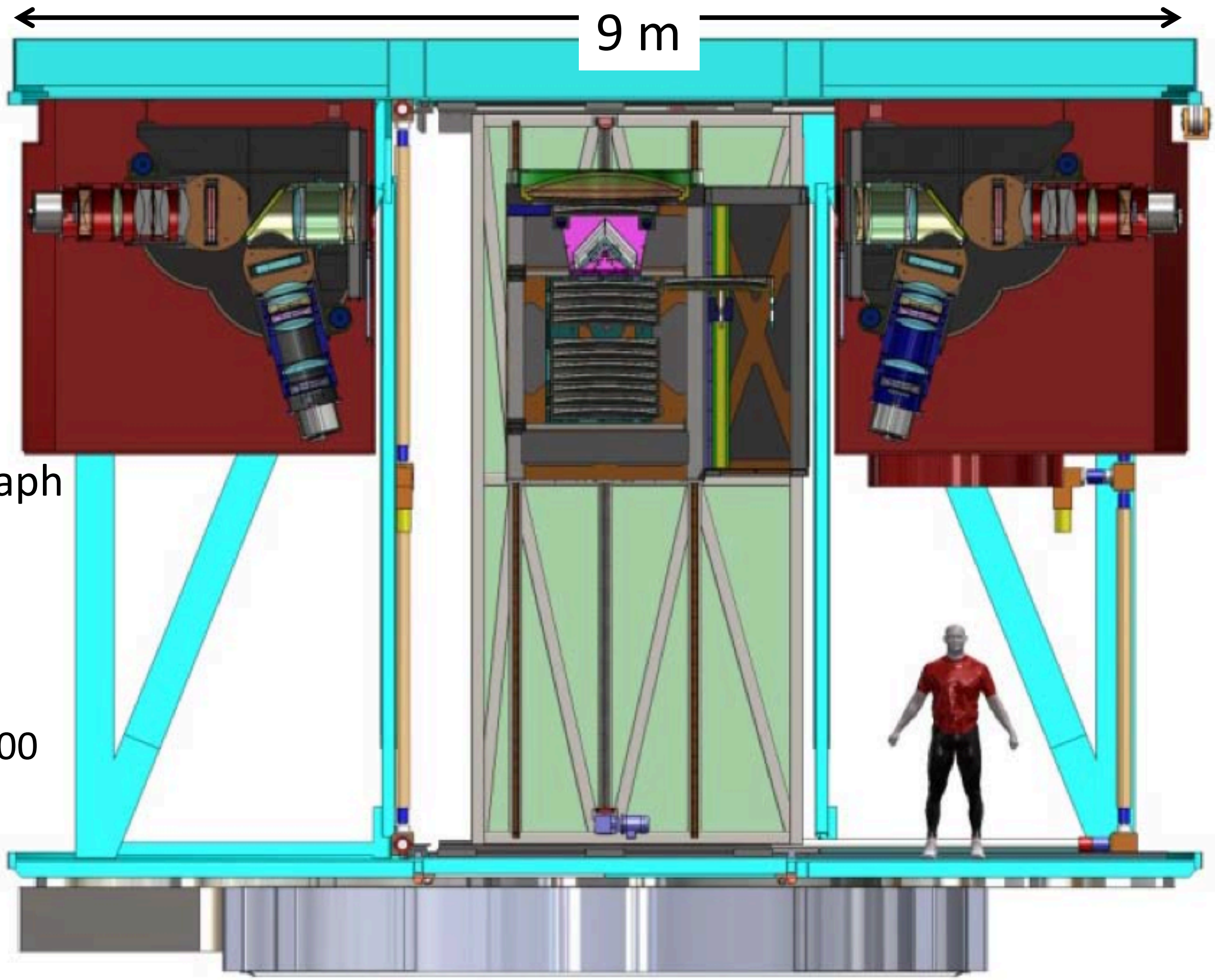


The GMACS Spectrograph

Texas A&M (DePoy), Carnegie Obs. (Shectman)

In Conceptual Design Phase



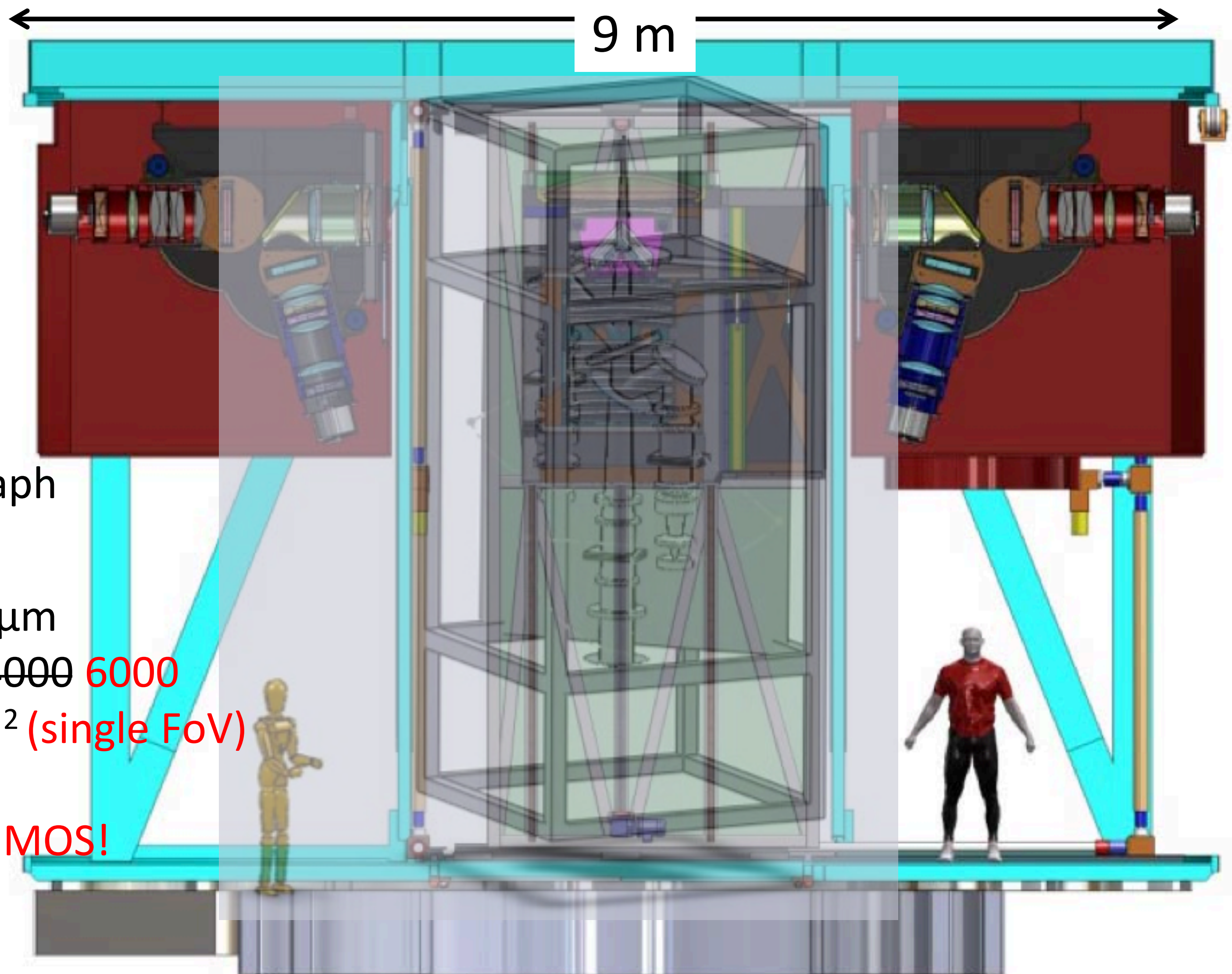
Wide-field,
multi-object,
optical spectrograph

$\lambda = 0.34\text{-}1.0\ \mu m$
$R = \lambda/\Delta\lambda = 1500\text{-}4000$
$FoV = 4 \times 36\ amin^2$

The ~~GMACS~~ TRIMOS? Spectrograph:

Texas A&M (DePoy), Carnegie Obs. (Shectman)

In Conceptual Design Phase



Wide-field,
multi-object,
optical spectrograph

λ = 0.34-~~1.0~~ 1.25 μm
R = λ/Δλ = 1500-~~4000~~ 6000
FoV = ~~4 x~~ 36 amin^2 (single FoV)

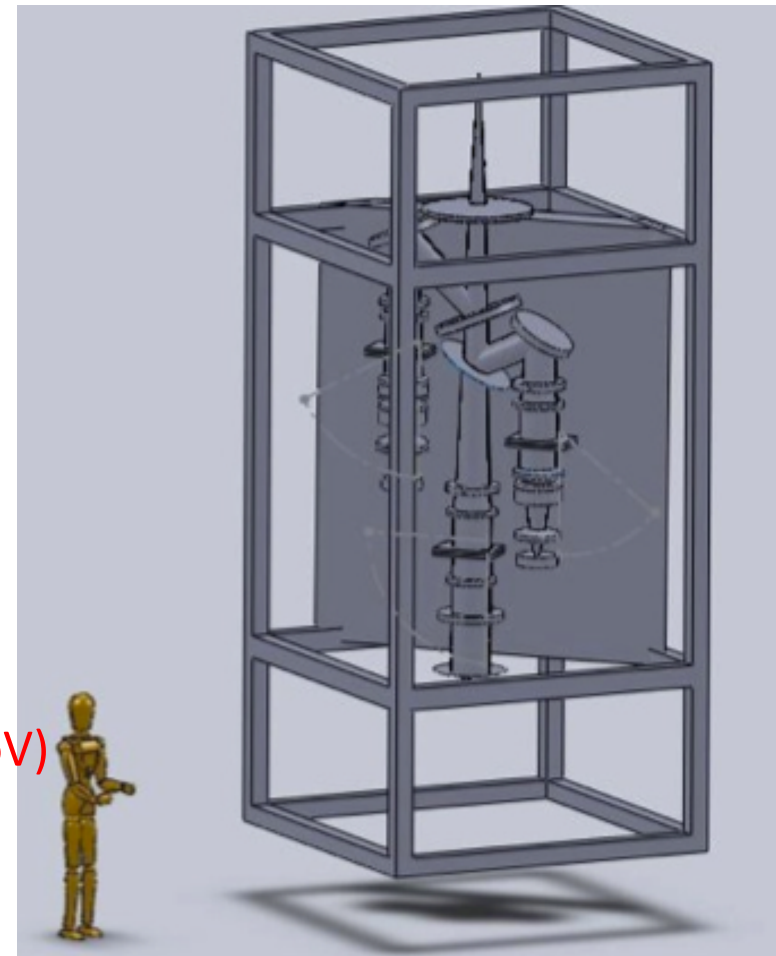
Visible to near-IR MOS!

The ~~GMACS~~ TRIMOS? Spectrograph:

Texas A&M (DePoy), Carnegie Obs. (Shectman)

In Conceptual Design Phase

← 9 m →



Wide-field,
multi-object,
optical spectrograph

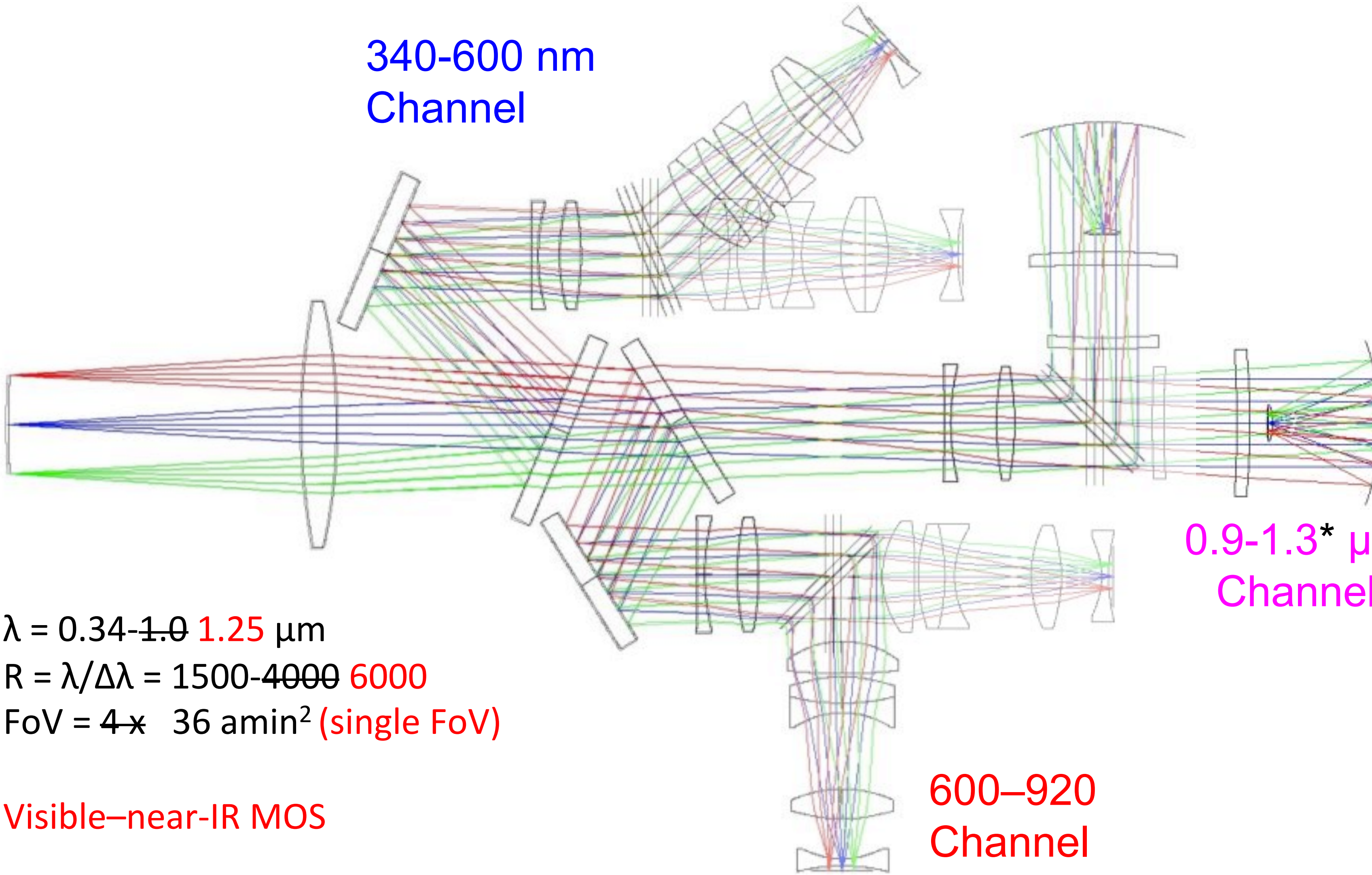
λ = 0.34-~~1.0~~ 1.25 μm
R = $\lambda/\Delta\lambda$ = 1500-~~4000~~ 6000
FoV = ~~4 x~~ 36 amin^2 (single FoV)

Visible to near-IR MOS

The ~~GMACS~~ TRIMOS? Spectrograph:

Texas A&M (DePoy), Carnegie Obs. (Shectman)

In Conceptual Design Phase



λ = 0.34-~~1.0~~ 1.25 µm

R = λ/Δλ = 1500-~~4000~~ 6000

FoV = ~~4 x~~ 36 amin^2 (single FoV)

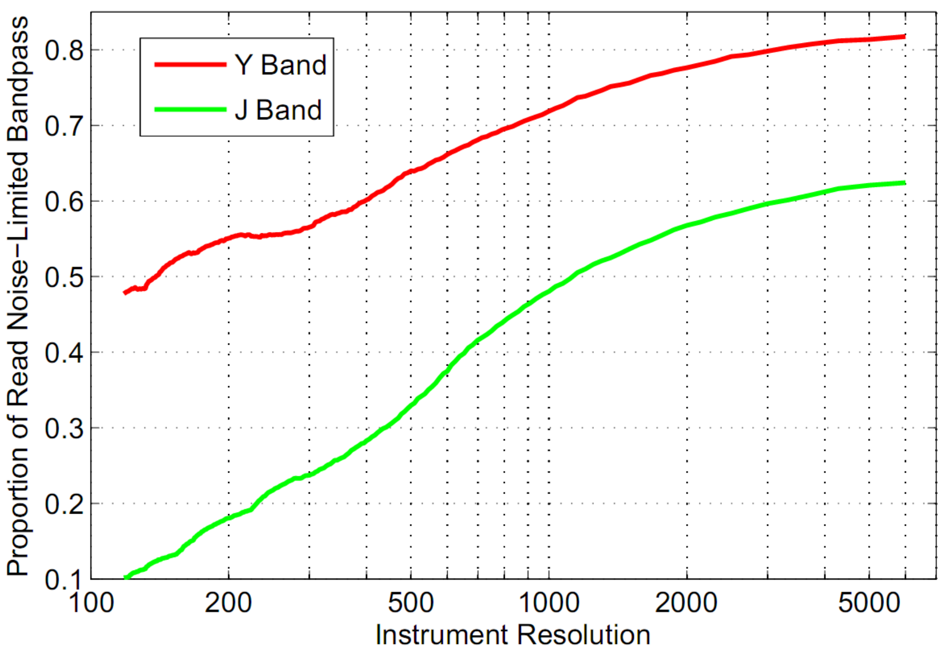
Visible–near-IR MOS

The ~~GMACS~~ TRIMOS Spectrograph:

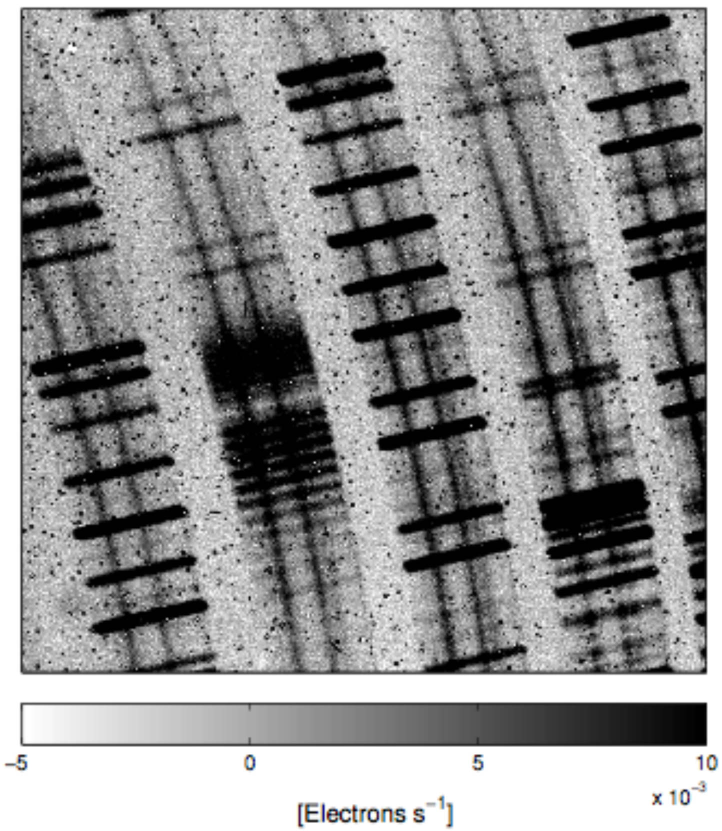
Texas A&M (DePoy), Carnegie Obs. (Shectman)

In Conceptual Design Phase

- Push to near-IR (1.3μm) to gain access to higher-z targets.
- Lesson learned from Magellan/FIRE: the sky is surprisingly dark in z, Y, and J (FIRE is RN limited, not background!)



Sullivan & Simcoe (2012)

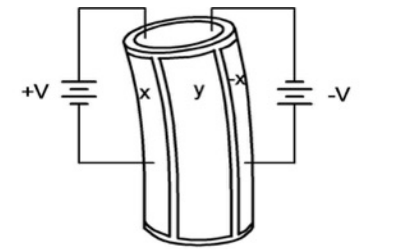


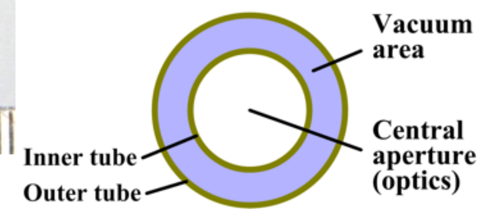
GMT: MOS for all — enter starbugs!

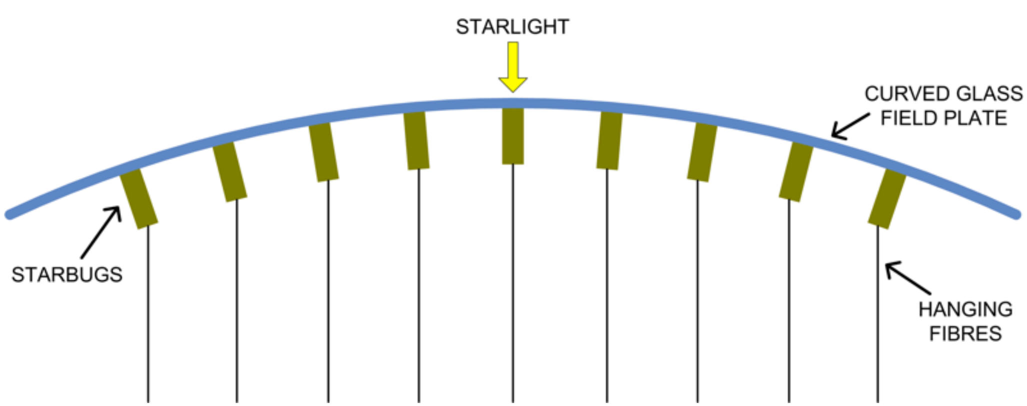
MANIFEST — A fiber-feed front-end to any spectrograph on GMT

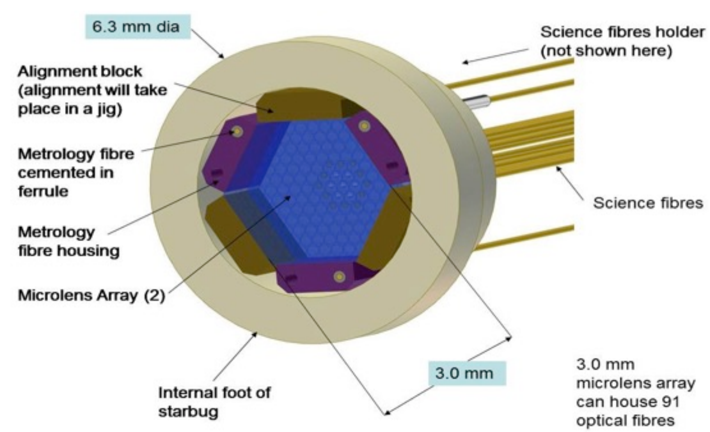
- Starbugs: piezoelectric robots hanging under a glass field plate
- Fiber options: microlens IFUs bonded to fiber bundles inserted into each

- rapidly reconfigurable (zenith angle)
- terrific for queue scheduling
- takes full advantage of the GMT 20 arcmin FOV!
- ADC design in-hand to improve performance.







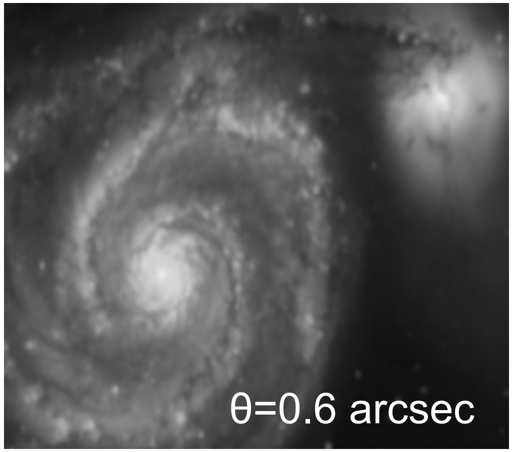


ELT designs: the wide field case*

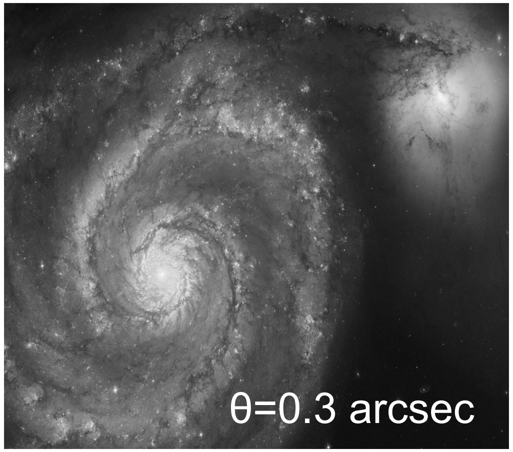
(* For the telescope *with* planned wide field instruments.)

	Keck	GMT	GMT with GLAO	TMT	E-ELT
A * ε	1	5.6	5.6	8.5	9.2
Ω	81	50	50	24	10
θ^2	$(1.0\ \text{asec})^2$	$(0.6\ \text{asec})^2$	$(0.3\ \text{asec})^2$	$(0.6\ \text{asec})^2$	$(0.6\ \text{asec})^2$
$A\Omega/\theta^2$ (relative)	1	7.9	23.0	5.7	2.6

Natural seeing (no AO)



With ground layer AO

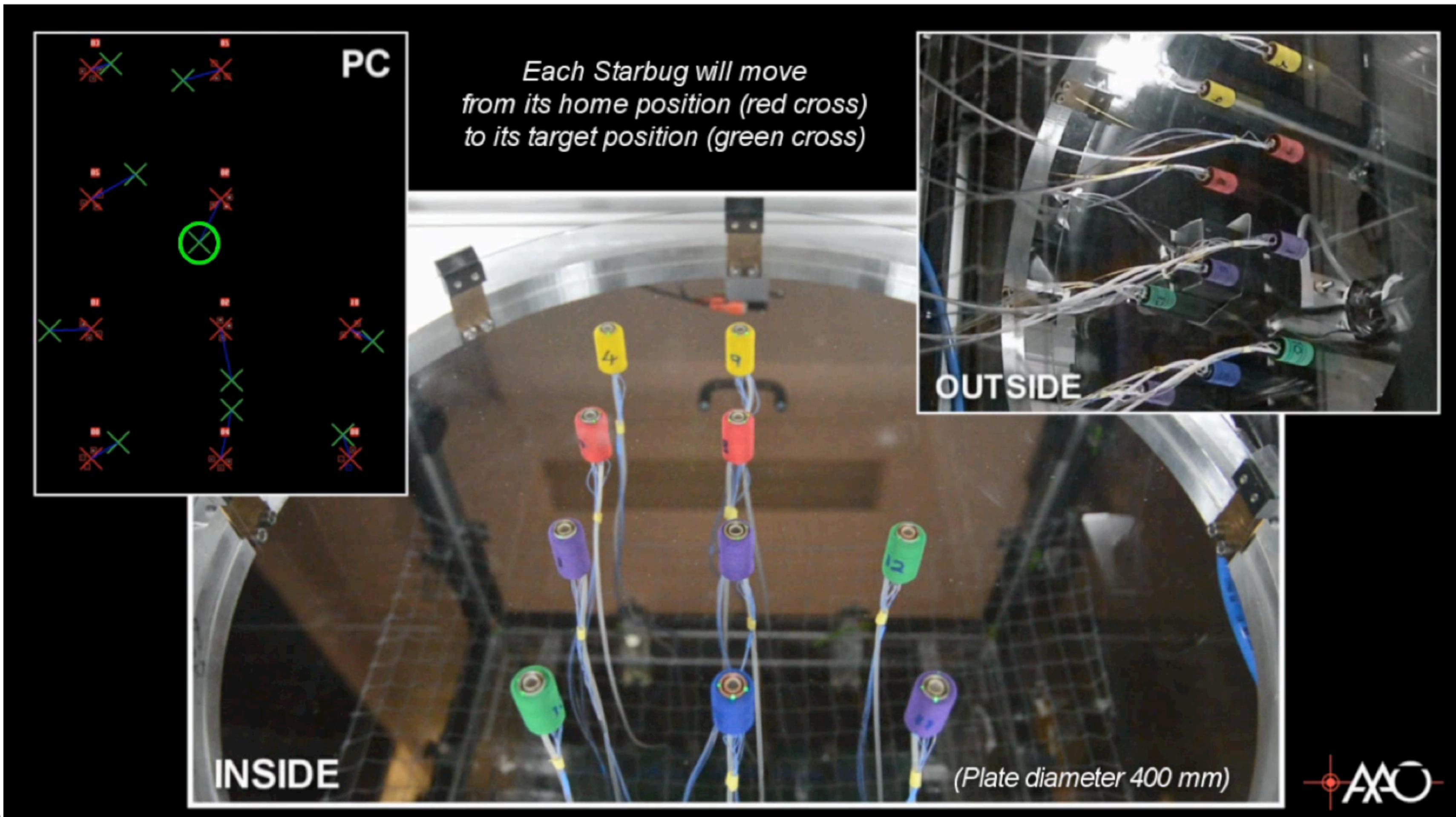


(illustrative)

GMT: MOS for all — enter starbugs!

MANIFEST — A fiber-feed front-end to any spectrograph on GMT

- Starbugs: piezoelectric robots hanging under a glass field plate
- Fiber options: microlens IFUs bonded to fiber bundles inserted into each

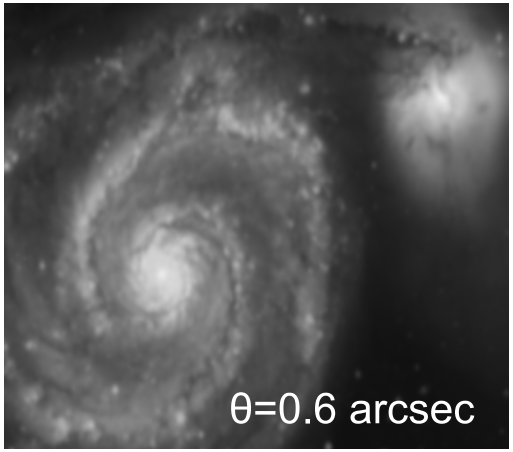


ELT designs: the wide field case*

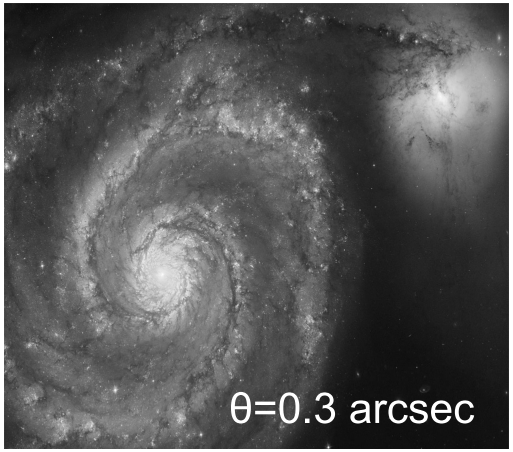
(* For the telescope *with* planned wide field instruments.)

	Keck	GMT	GMT with GLAO	TMT	E-ELT
A * ε	1	5.6	5.6	8.5	9.2
Ω	81	50	50	24	10
θ^2	(1.0 asec)^2	(0.6 asec)^2	(0.3 asec)^2	(0.6 asec)^2	(0.6 asec)^2
$A\Omega/\theta^2$ (relative)	1	7.9	23.0	5.7	**2.6?**

Natural seeing (no AO)

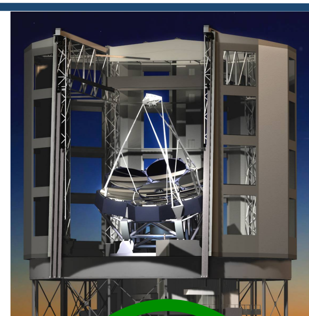


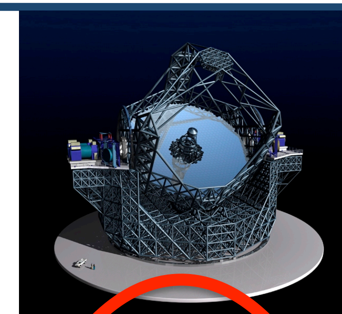
With ground layer AO



(illustrative)

ELT design strengths: comparison of specifications

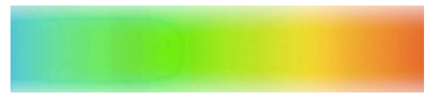


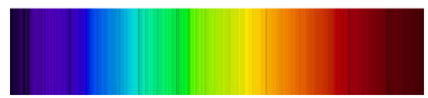


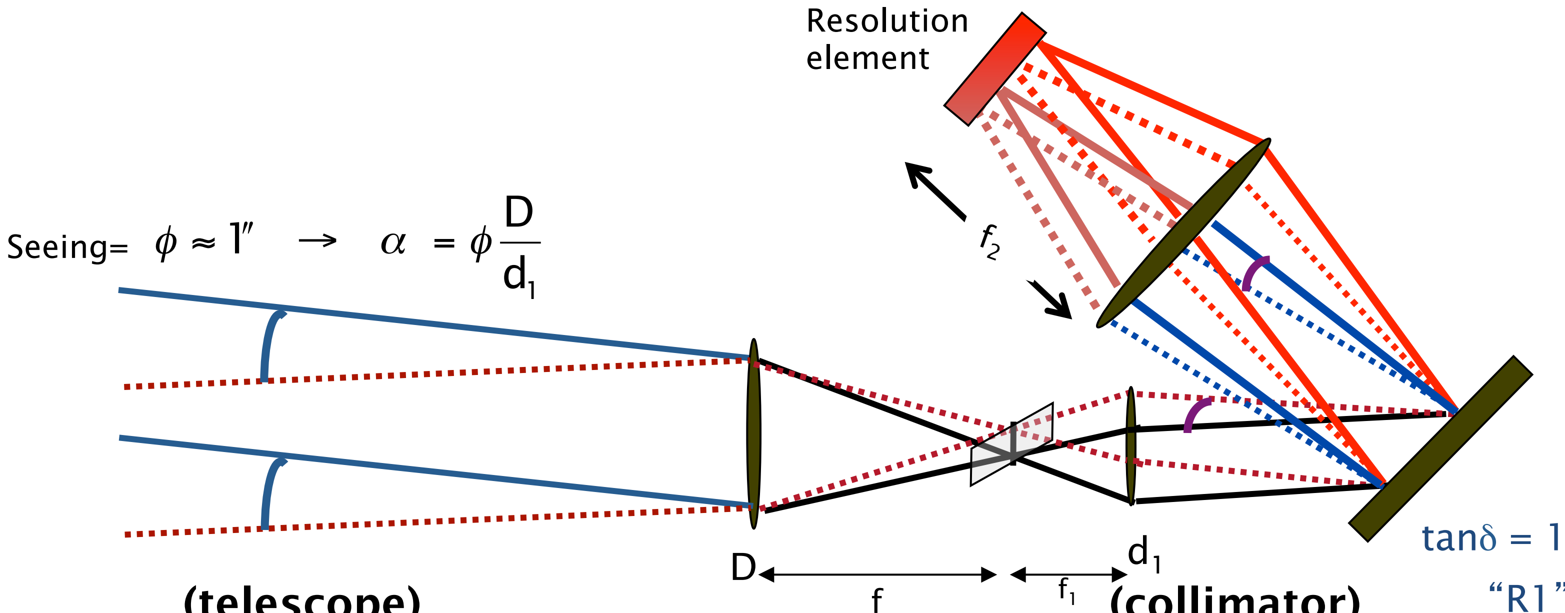
Attribute	GMT	TMT	E-ELT
Aperture	24.5 m	30 m	39.3 m
Collecting Area	368 m^2	655 m^2	978 m^2
Final Focal	f/8	f/15	f/17.7
Focal Plane Scale	1.0 mm/asec	2.2 mm/asec	3.6 mm/asec
Field of view	10amin (20amin w/ cor)	10 amin (15amin unvignet)	7 amin (10 amin)
Size of 10’ Field	0.6 meters	1.3 meters	2.0 meters

Size of the camera (length of the spectrum)

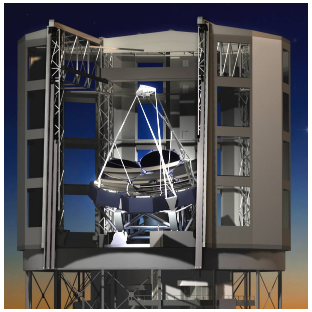
What is the impact on the spectrum?

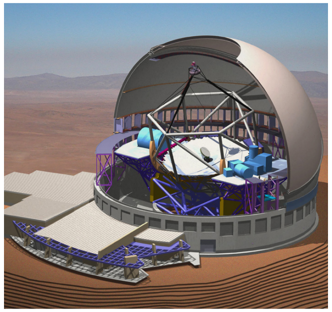
1. smaller wavelength coverage  (high res grating)
2. lower spectral resolution  (low res grating)

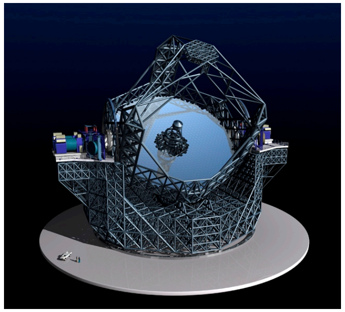
Current expectation 



ELT designs: comparison of specifications

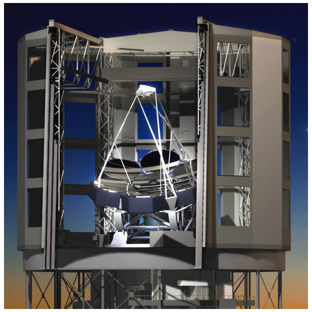


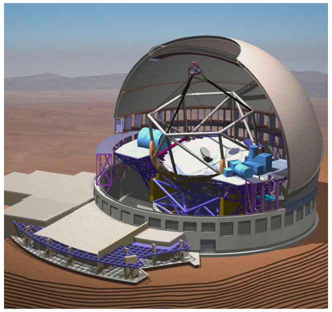


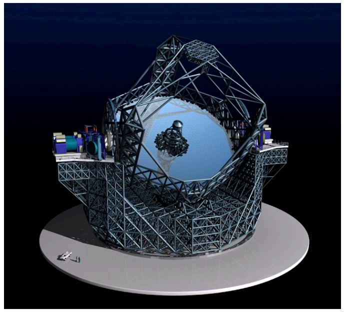


Attribute	GMT	TMT	EELT
Aperture	24.5 m	30 m	39.3 m
Collecting Area	368 m^2	655 m^2	978 m^2
Primary mirrors	7 x 8.4 m	492 x 1.45 m	798 x 1.45 m
Final Focal	f/8	f/15	f/17.7
Focal Plane Scale	1.0 mm/asec	2.2 mm/asec	3.6 mm/asec
Size of 20' Field	1.2 meters	2.6 meters	4.0 meters
Total Cost	$1.05B Cap	$1.5B 2014$	$1.8B (Estimate)

ELT designs: comparison of specifications







Attribute	GMT	TMT	EELT
Aperture	24.5 m	30 m	39.3 m
Collecting Area	368 m^2	655 m^2	978 m^2
Final Focal	f/8	f/15	f/17.7
Focal Plane Scale	1.0 mm/asec	2.2 mm/asec	3.6 mm/asec
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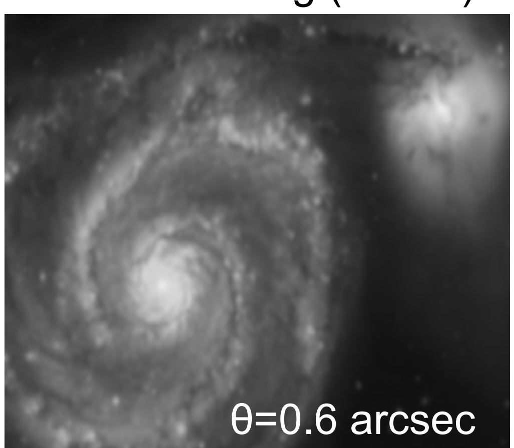
Size of 20' Field	1.2 meters	2.6 meters	4.0 meters
Total Cost	$1.05B Cap	$1.5B 2014$	$1.8B (Estimate)

ELT designs: the wide field case*

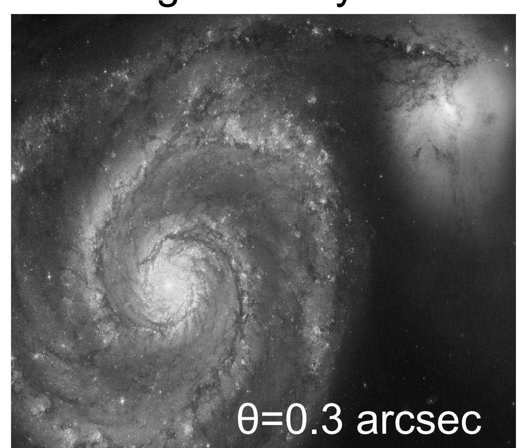
(* For the telescope *with* planned wide field instruments.)

	Keck	GMT	GMT with GLAO	TMT	E-ELT
A * ε	1	5.6	5.6	8.5	9.2
Ω	81	50	50	24	10
θ^2	$(1.0\ \mathrm{asec})^2$	$(0.6\ \mathrm{asec})^2$	$(0.3\ \mathrm{asec})^2$	$(0.6\ \mathrm{asec})^2$	$(0.6\ \mathrm{asec})^2$
$A\Omega/\theta^2$ (relative)	1	7.9	23.0	5.7	2.6
$A\Omega/\theta^2$ / $	1	1.3	3.9	0.49	0.16

Natural seeing (no AO)



With ground layer AO

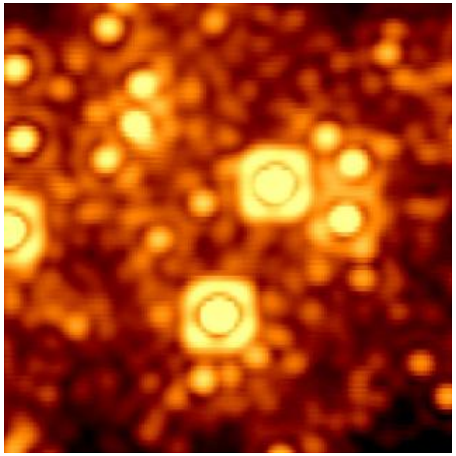


(illustrative)

ELT designs: narrow-field, AO case

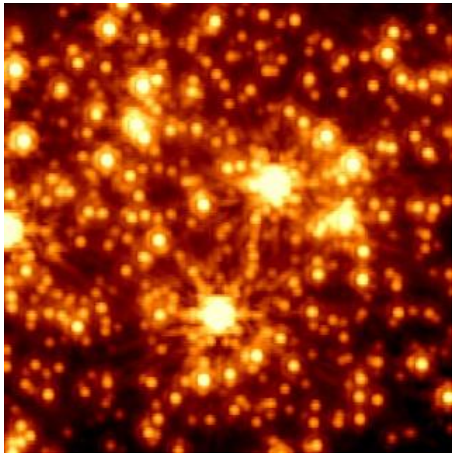
	Keck	GMT	TMT	E-ELT
A * ε	1	5.6	8.5	9.2
N mirrors	3	2	3+	6
θ^2	22 mas	10 mas	8 mas	6.3 mas
$A/\theta^2 * \varepsilon$	1	9.5	15.2	19.4

HST/NICMOS



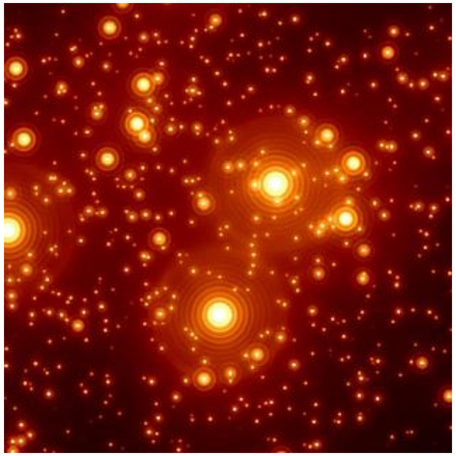
θ = 200 mas

JWST/NIRCAM



θ = 69 mas

GMT/GMTIFS



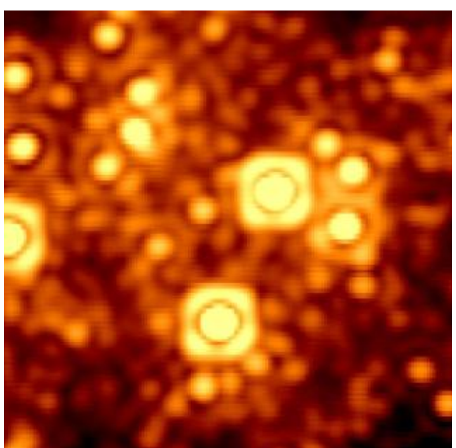
θ = 20 mas

(illustrative)

ELT designs: narrow-field, AO case

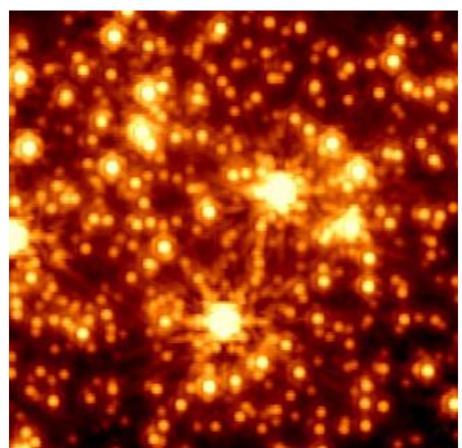
	Keck	GMT	TMT	E-ELT
A * ε	1	5.6	8.5	9.2
N mirrors	3	2	3+	6
θ^2	22 mas	10 mas	8 mas	6.3 mas
A/θ^2 * ε	1	9.5	15.2	19.4
A/θ^2 * ε / $	1	7.9	7.6	7.3

HST/NICMOS



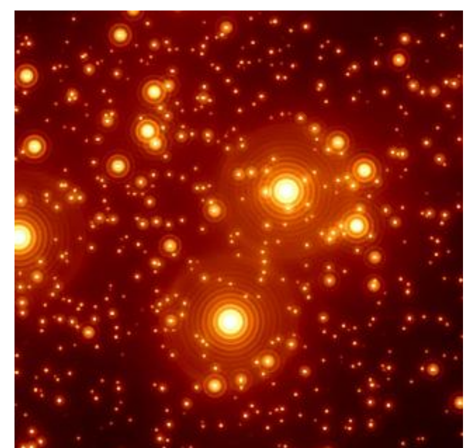
θ = 200 mas

JWST/NIRCAM



θ = 69 mas

GMT/GMTIFS

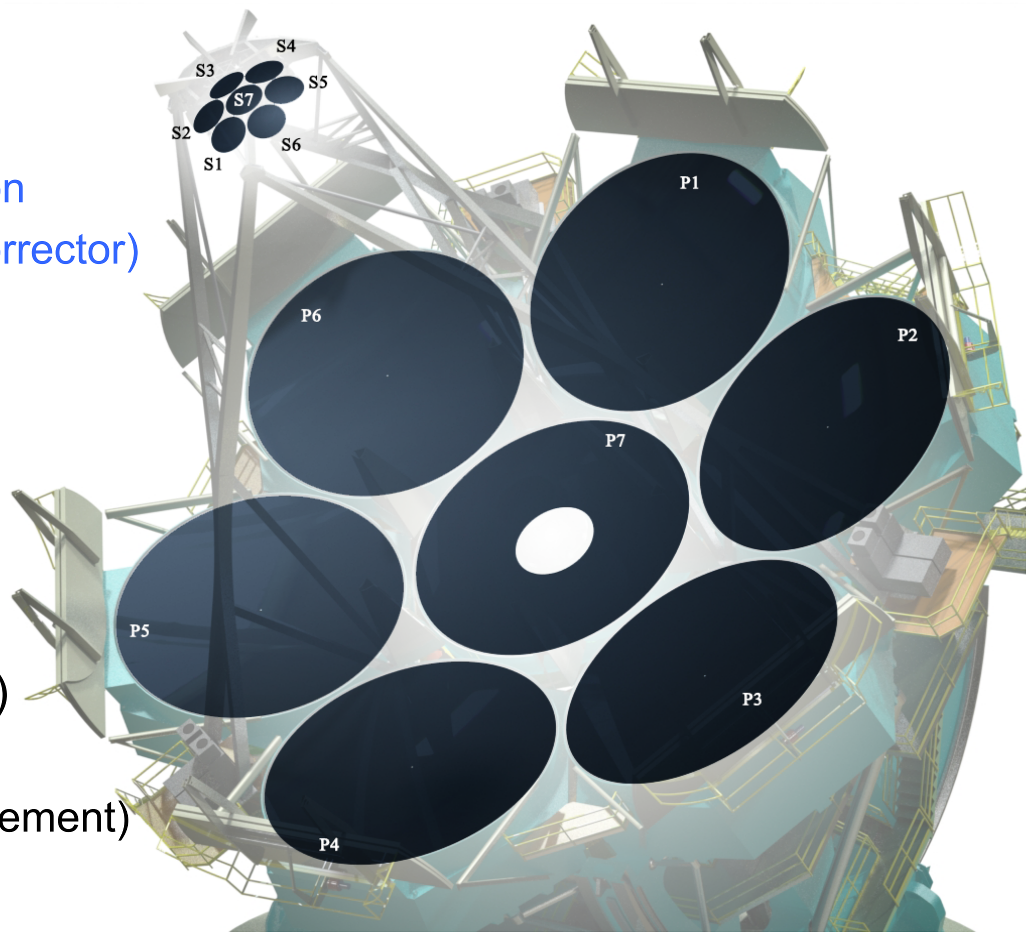


θ = 20 mas

(illustrative)

Telescope designs: GMT

- Aplanatic Gregorian optical configuration
  - Fast primary (f/0.7)
  - Fast final f/ratio (f/8.2)
  - → Plate scale: 1.0 mm/arcsec
  - → Facilitates wide field instrumentation
  - → Wide FOV (10 amin; 20 amin w/ corrector)



- Adaptive secondary:

  4 observing modes (no re-imaging)
  - Seeing limited
  - GLAO – wide field (15-50% improvement)
  - NGSAO – high contrast
  - LTAO – high sky coverage
  - → ASM facilitates high throughput, low background AO
  - → Available to any instrument, any port

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

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

- VIMOS / VLT* (wasn't fun)
- GMACS /GMT (re-scoped to a single field)
- DIORAMAS / E-ELT (not moving forward)

VPH gratings: help to keep the cameras smaller, but they have to articulate!

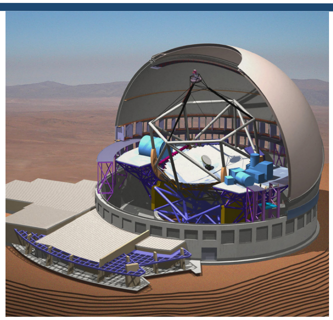
- several spectrographs in 4-8m telescopes
- GMACS for GMT (moving forward, 1 field of view)

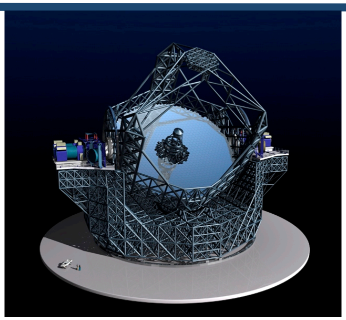
WFOS for TMT: History – VPH gratings + multiple fields of view.

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

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

ELT design strengths: comparison of specifications





Attribute	GMT	TMT	E-ELT
Aperture	24.5 m	30 m	39.3 m
Collecting Area	368 m^2	655 m^2	978 m^2
Final Focal	f/8	f/15	f/17.7
Focal Plane Scale	1.0 mm/asec	2.2 mm/asec	3.6 mm/asec
Field of view	10amin (20amin w/ cor)	10 amin (15amin unvignet)	7 amin (10 amin)
Size of 10' Field	0.6 meters	1.3 meters	2.0 meters
altitude	2.2 km (8.5k ft)	4.2km (14k ft)	3 km (9.8k ft)

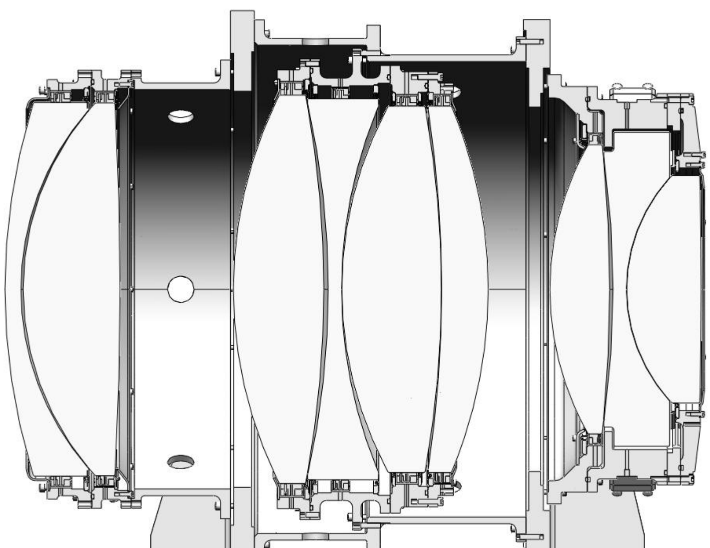
(~advantage <350nm)

What’s hard: need to scale up to keep Res

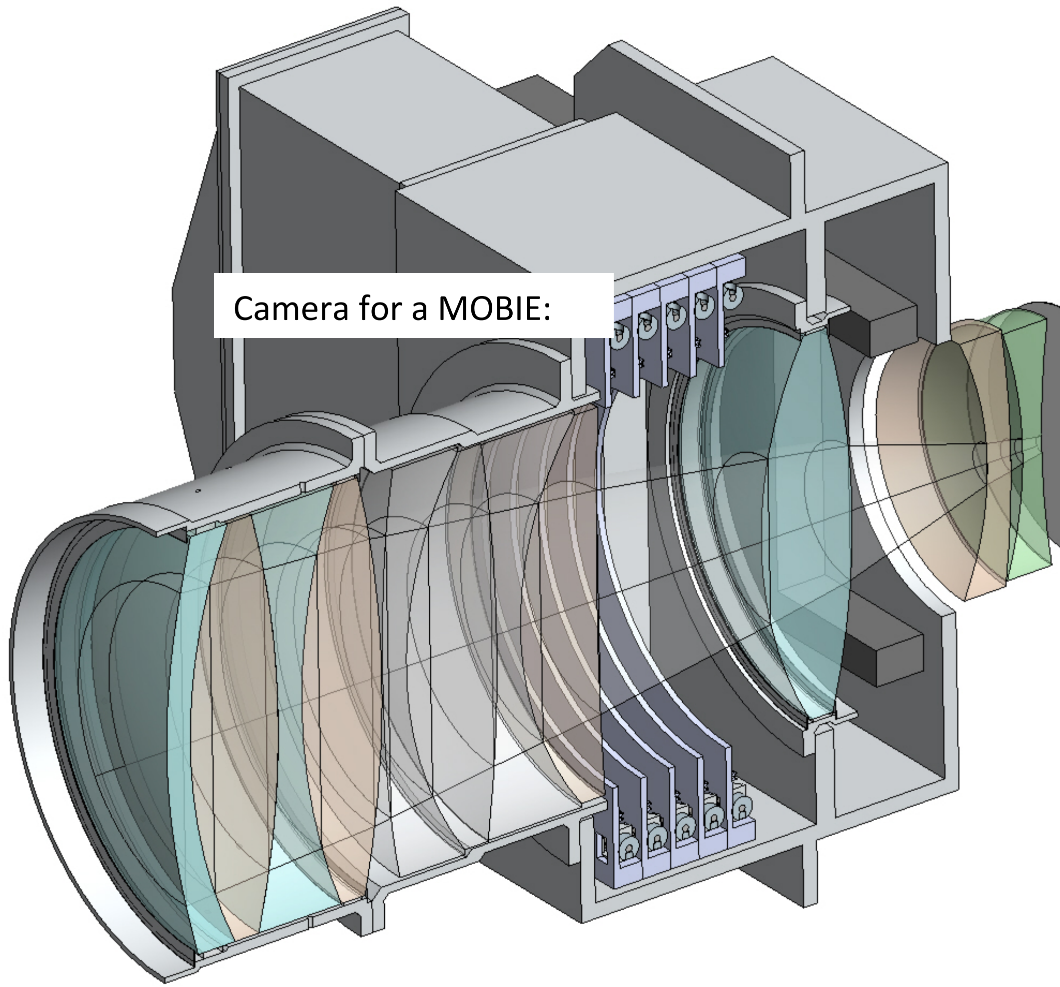
Comparison of camera (beam) size:

NOT a factor of 3 bigger!

Camera for a Keck spectrograph (2000):



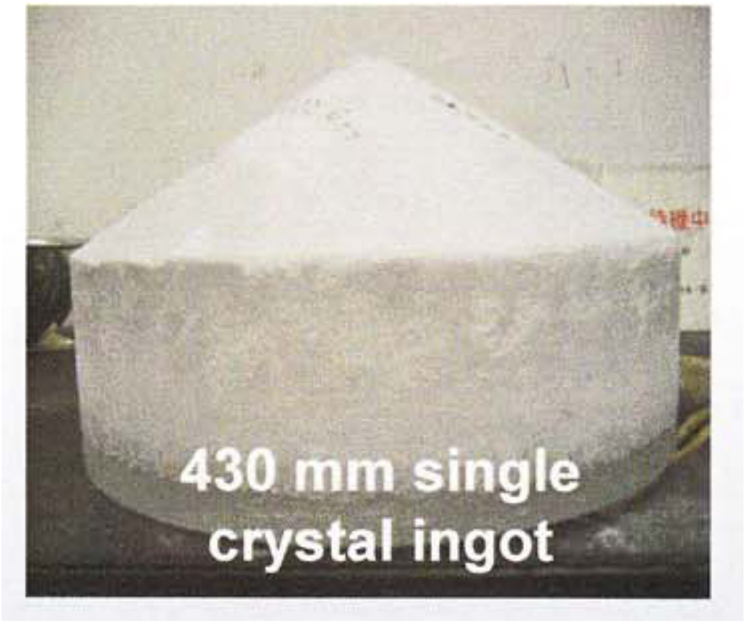
Camera for a MOBIE:



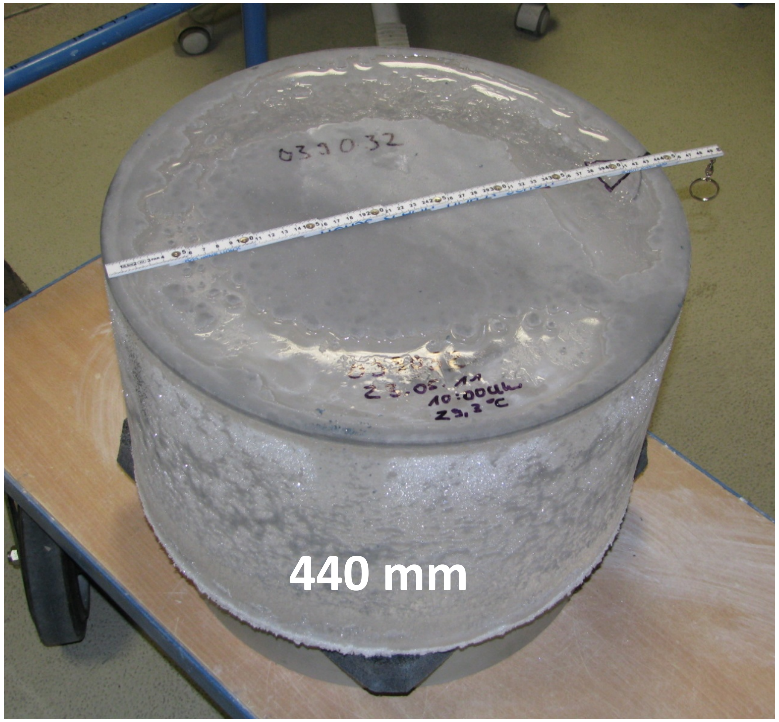
What's hard: need to scale up to keep Res

Why can't the cameras keep up?

The materials can't be made in the sizes we would need. Non-starter.



Canon Optron (~1990)



Hellma (~ July 2011)