High Resolution Optical Spectroscopy in the ELT Era

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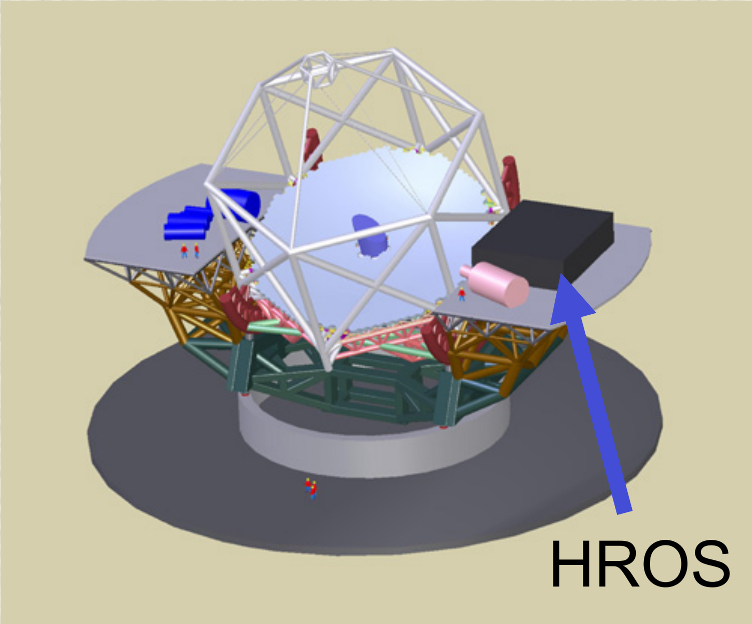
May 25, 2016

Background

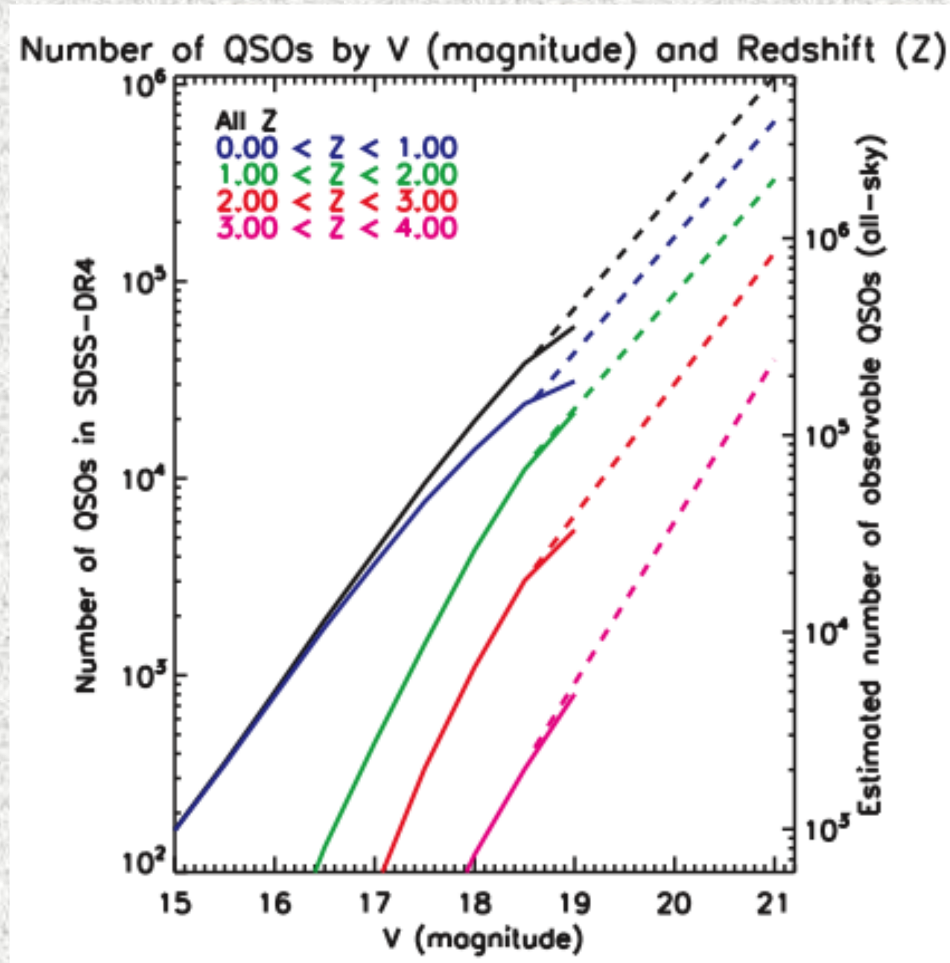
- Feasibility studies in 2005-2006: UC Santa Cruz, U. Colorado
- Not selected as a first light instrument
- However, strong interest in capabilities among TMT partners for next-generation instrumentation



SPECIFICATION	REQUIREMENT
Wavelength range	0.31 – 1.1 μm; 0.31—1.3 μm goal
Slit length	5 arcsec
Field of view	10 arcsec
Image quality	No worse than 0.2 arcsec FWHM
Spatial sampling	No coarser than 0.2 arcsec
Spectral resolution	R=50,000 (1 arcsec slit, image slicer for R>90,000); options include single slit or fiber feed for multiplexing
Sensitivity	Must maintain 30m aperture advantage over existing similar instruments

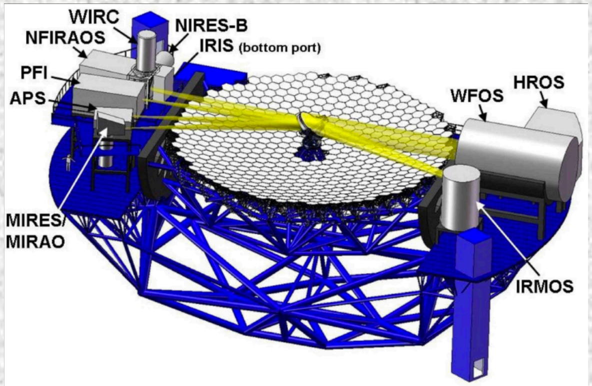
Science Case for HROS

- UV/optical: most information-rich bands in the EM spectrum
- Current instruments at the forefront of astrophysical study
- High resolution spectroscopy is a ground-based activity: precision studies & follow-up observations complement other programs
- Prime HROS science:
  - **Intergalactic medium**: >30-fold increase in sightlines, spatial resolution (1 QSO/sq. arcmin at V=21)
  - **Stars in the Local Group**: reach into isolated dIrrs; trace enhancement by 1st stars
  - **Planetary searches & characterization**: 27x increase in volume density; M stars; transit follow-ups; out into Bulge



In the meantime…

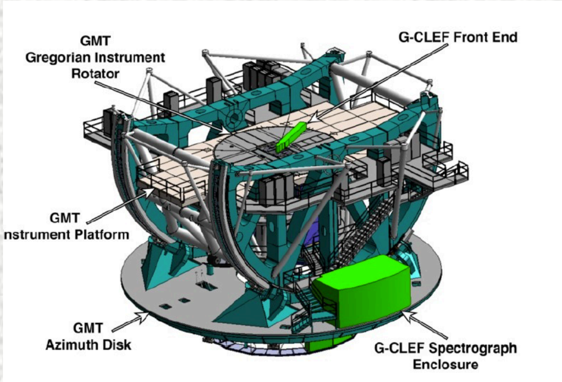
- “Vintage” conceptual design
- Laser comb calibration w/NIST (PI: Osterman) => IR comb for HPF
- Work by member nation groups?
- GMT G-CLEF final design
- E-ELT HIRES studies undertaken



Design Implications for HROS

- High resolution optical spectroscopy on ELTs:
  - Seeing-limited (AO unavailable or waveband limited)
  - Large optics
- TMT: 450 m focal length; 1" = 2 mm!
- Slit-limited spectral resolution: R = 50,000, 1" slit ⇒ d = 0.9 m
- A classic cross-dispersed echelle matched to slit-limited resolution design can be pursued
  - See Steve Vogt's (mature) conceptual design study for HROS
  - Optics are very large (e.g., dual 3x1 meter echelle mosaics, 1 m fast camera lenses)
  - Requires careful design, high level of expertise; risk in procurement, mounting, stability
  - => High cost, risk

What are other ELTs pursuing?



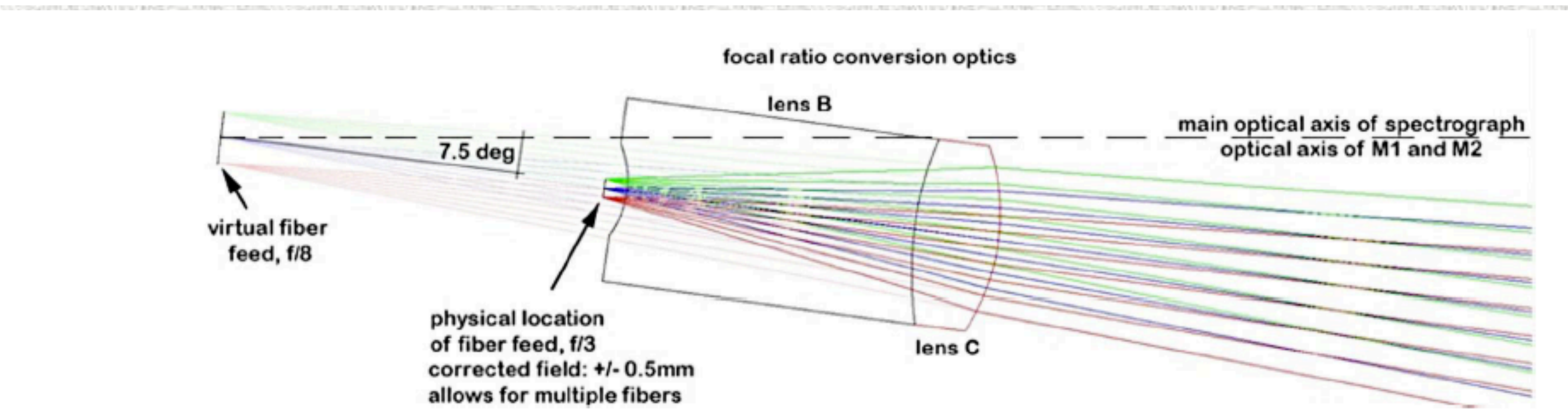
GMT G-CLEF (Szentgyorgyi+14; Furesz+14)

- 25.4-m aperture
- RV precision spectrograph (10 cm/s)
- 350–1000 nm; two camera arm, asymmetric white pupil design (3:2 compression), 6k x 6k detectors
- Single object (although MOS will be available when MANIFEST is commissioned)
- Pupil slice aperture by 7 (segmented primary)
- Echelle triple mosaic of 300x400 mm facets, VPH cross-dispersers

G-CLEF

- Four fiber diameters, lengths to support different observing modes, wavebands (R=19,000–105,000); mode scrambling for precision RV
- On-chip binning (3x3 or 5x5) for lower R modes
- 1 mm pseudo slit allows multiple fibers

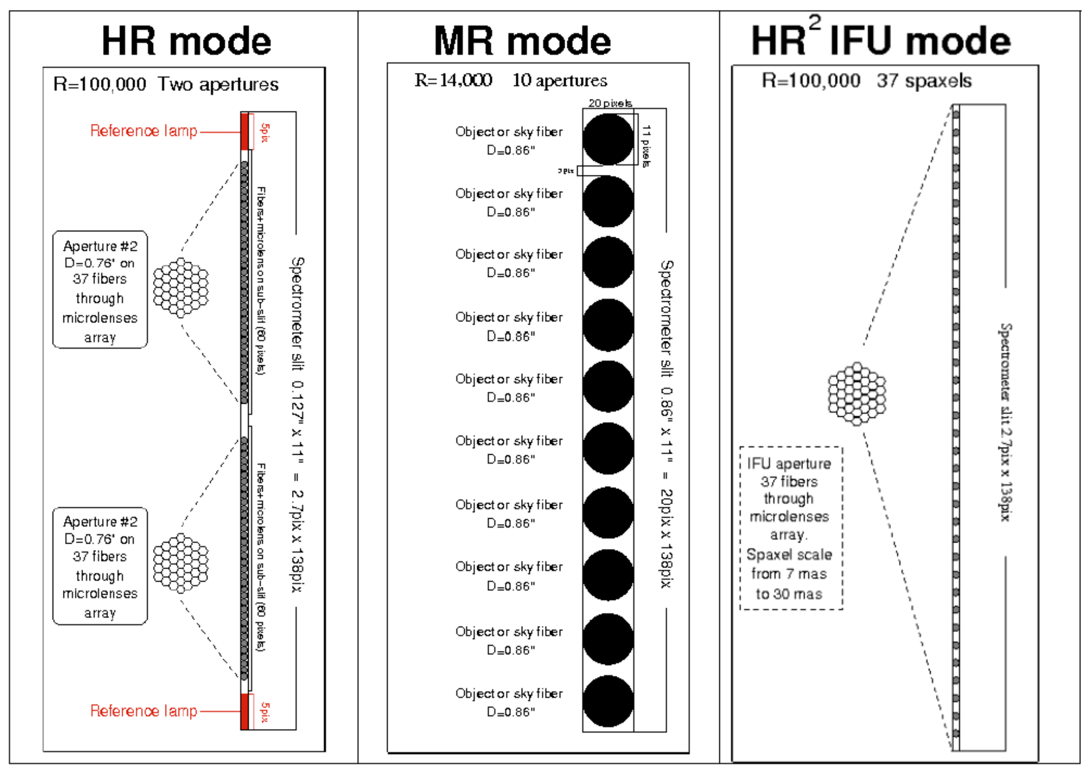
Mode	slit size on sky	angular size of fibers at spectrograph slit	physical size of fiber core [mm]	binning on detector	FWHM in binned pixels	R
PRV	0.79”	0.26” (7x)	100	1x1	3.65	**105 000**
MR	0.79”	0.79”	300	3x3	3.68	**35 000**
HT	1.2”	1.2”	450	5x5	3.28	**19 000**

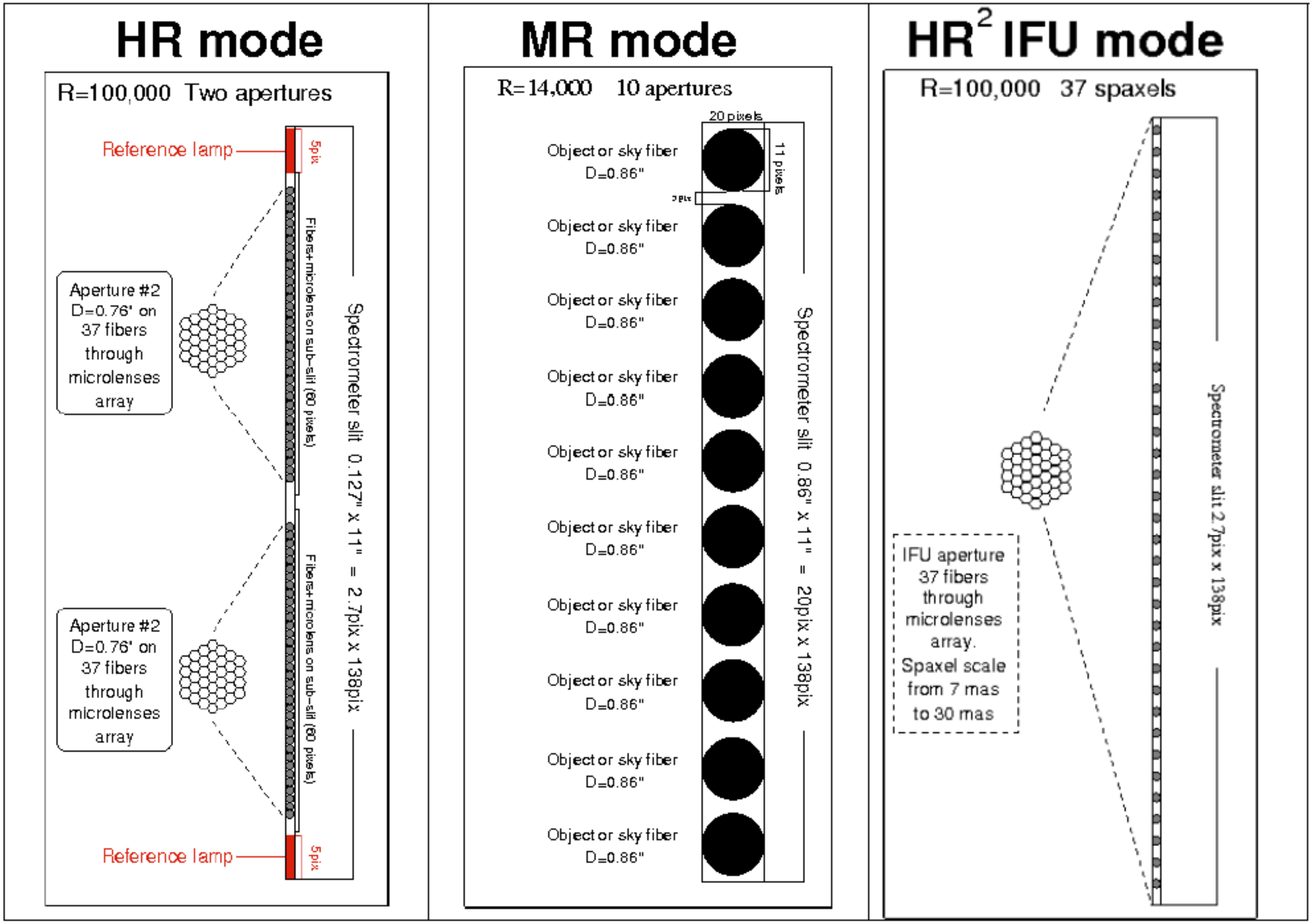


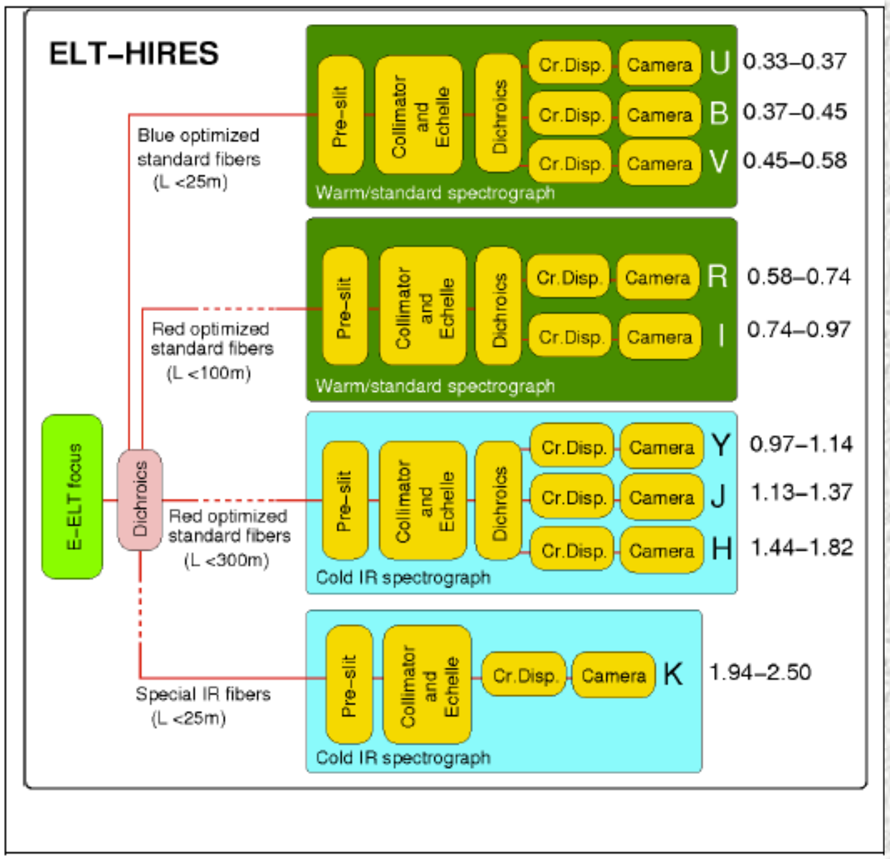
What are Other ELTs pursuing II.?

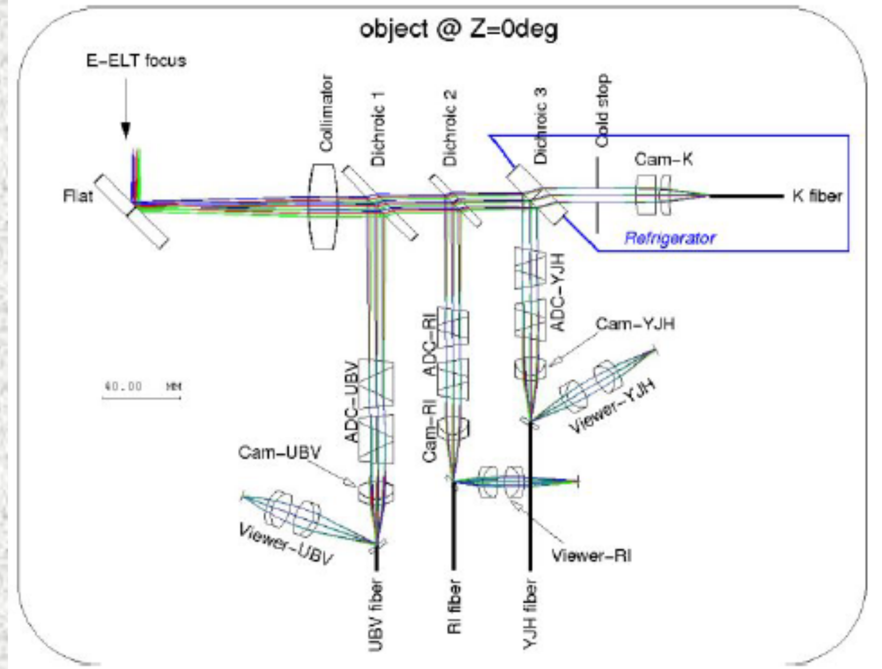
E-ELT HIRES studies (Zerbi+2014): CODEX (Pasquini +2010), SIMPLE (Origlia+2010; NIR AO-assisted)

- ID'd science drivers, top-level requirements: ESO-204697
- Goal 0.37–2.5 μm at R=100,000; <10 cm/s stability
- Also want a MOS mode at R=10,000-20,000 for 5–10 objects within a few arcmin
- R=100,000, 1" => 10 m echelle, 190x190 μm resl (11x11 pixels for f/1.0 camera, 18 μm pixels)
  - Anamorphic pupil slicing or fiber-based focal plane slicing
  - Four channels: (U)BV, RI, YJH, K
- CODEX: four 9k x 9k detectors, 10 μm pixels
- 2016 phase A




HR mode
R=100,000 Two apertures
Reference lamp
5pix
Aperture #2
D=0.76" on
37 fibers
through
microlenses
array
Fibers+microlens on sub–slit (60 pixels)
Spectrometer slit 0.127" x 11" = 2.7pix x 138pix
Aperture #2
D=0.76" on
37 fibers
through
microlenses
array
Fibers+microlens on sub–slit (60 pixels)
Reference lamp
5pix
MR mode
R=14,000 10 apertures
20 pixels
11 pixels
Object or sky fiber
D=0.86"
Spectrometer slit 0.86" x 11" = 20pix x 138pix
HR² IFU mode
R=100,000 37 spaxels
IFU aperture
37 fibers
through
microlenses
array.
Spaxel scale
from 7 mas
to 30 mas
Spectrometer slit 2.7pix x 138pix

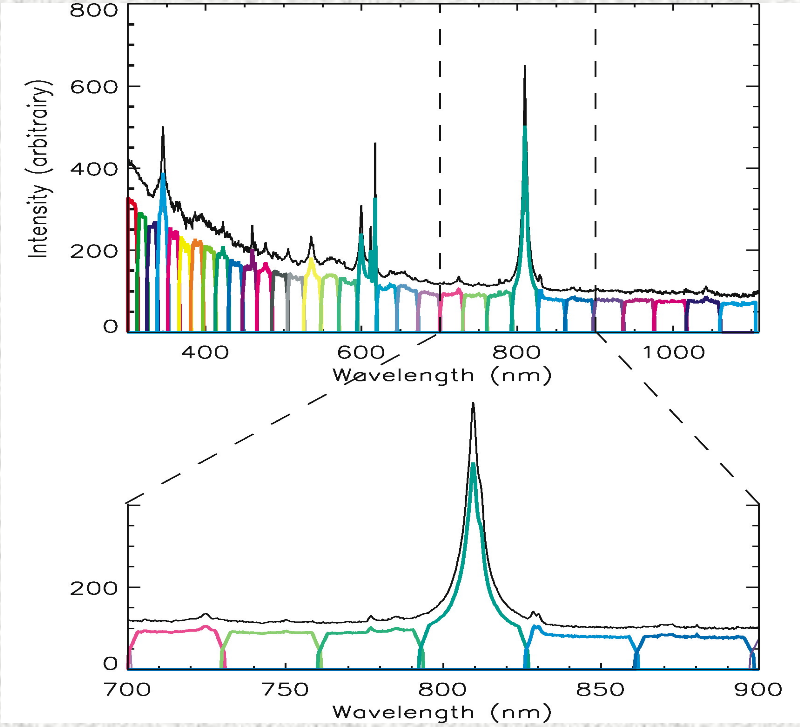

ELT-HIRES
Pre-slit
Collimator and Echelle
Dichroics
Cr.Disp.
Camera
U 0.33–0.37
B 0.37–0.45
V 0.45–0.58
Warm/standard spectrograph
Blue optimized standard fibers (L <25m)
R 0.58–0.74
I 0.74–0.97
Red optimized standard fibers (L <100m)
E-ELT focus
Y 0.97–1.14
J 1.13–1.37
H 1.44–1.82
Cold IR spectrograph
Red optimized standard fibers (L <300m)
K 1.94–2.50
Special IR fibers (L <25m)


object @ Z=0deg
E-ELT focus
Flat
Collimator
Dichroic 1
Dichroic 2
Dichroic 3
Cold stop
Cam-K
K fiber
Refrigerator
ADC-YJH
Cam-YJH
Viewer-YJH
ADC-RI
Cam-RI
ADC-UBV
Cam-UBV
Viewer-UBV
Viewer-RI
UBV fiber
RI fiber
YJH fiber

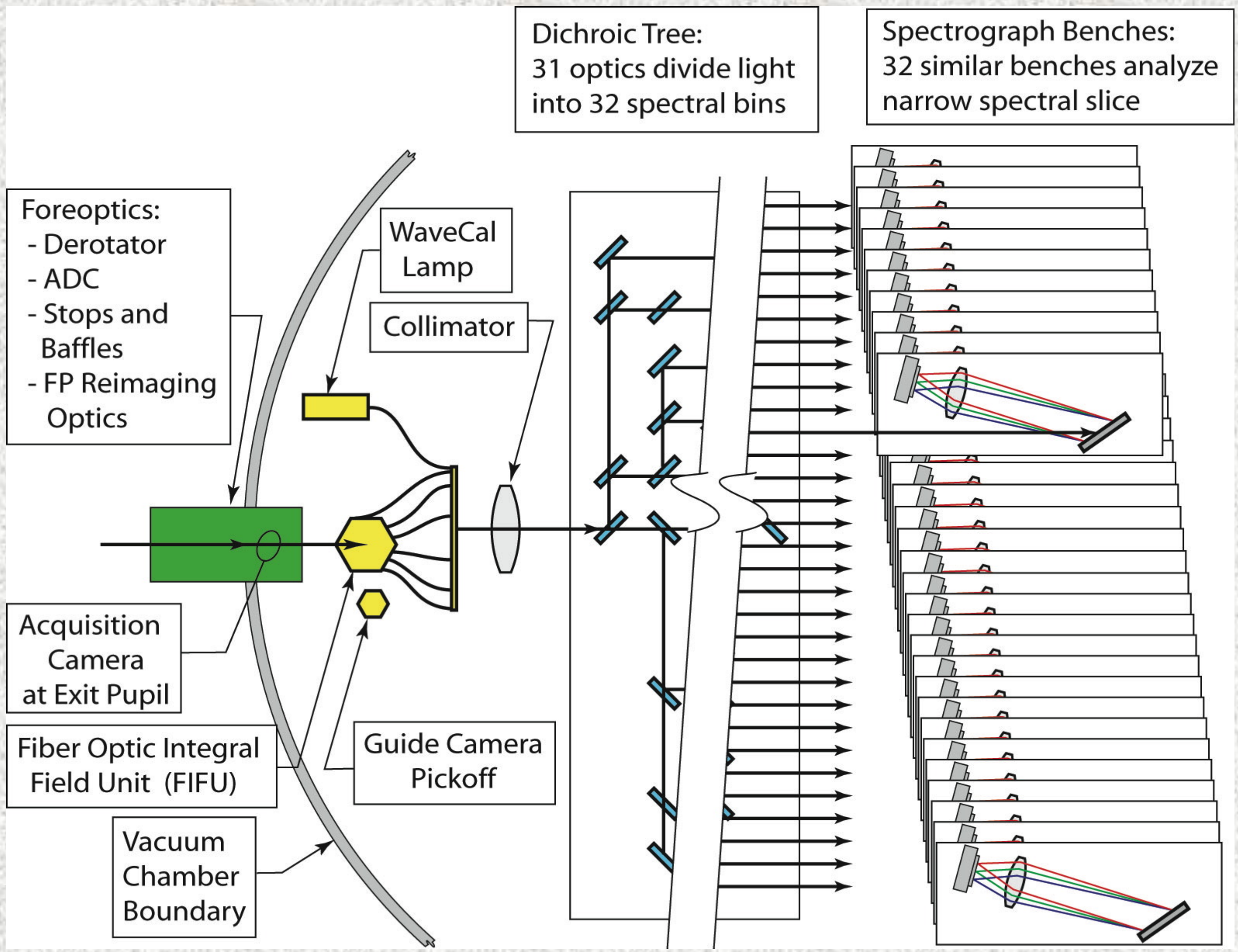
Design Options

- Is there an alternative?
- ELT instrument designs benefit from a fundamental reevaluation of design approach to maximize performance

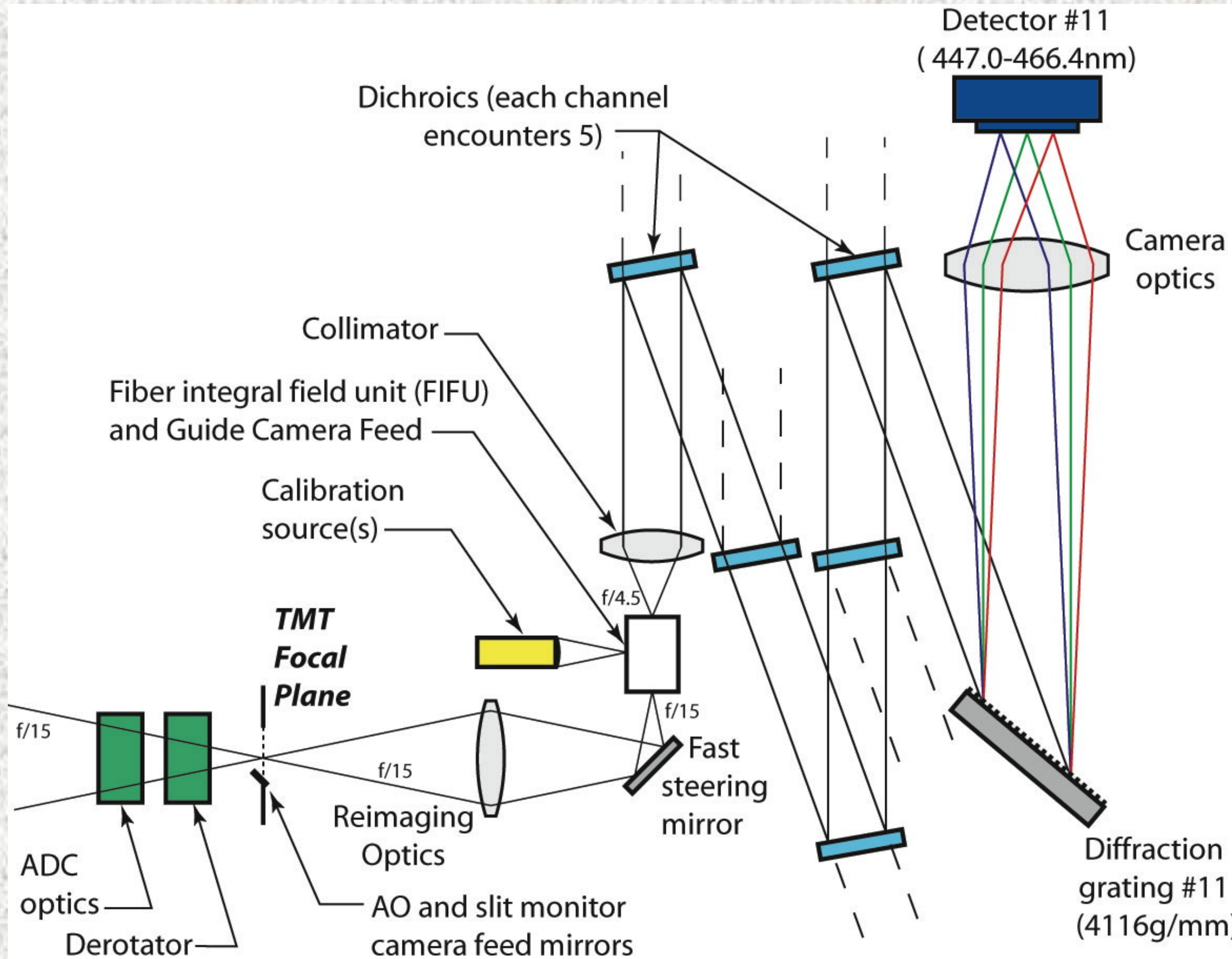
In an era of relatively affordable CCDs and high performance dichroics, many first-order spectrographs can replace cross-dispersion.



Concept Overview: Block Diagram of Overall System

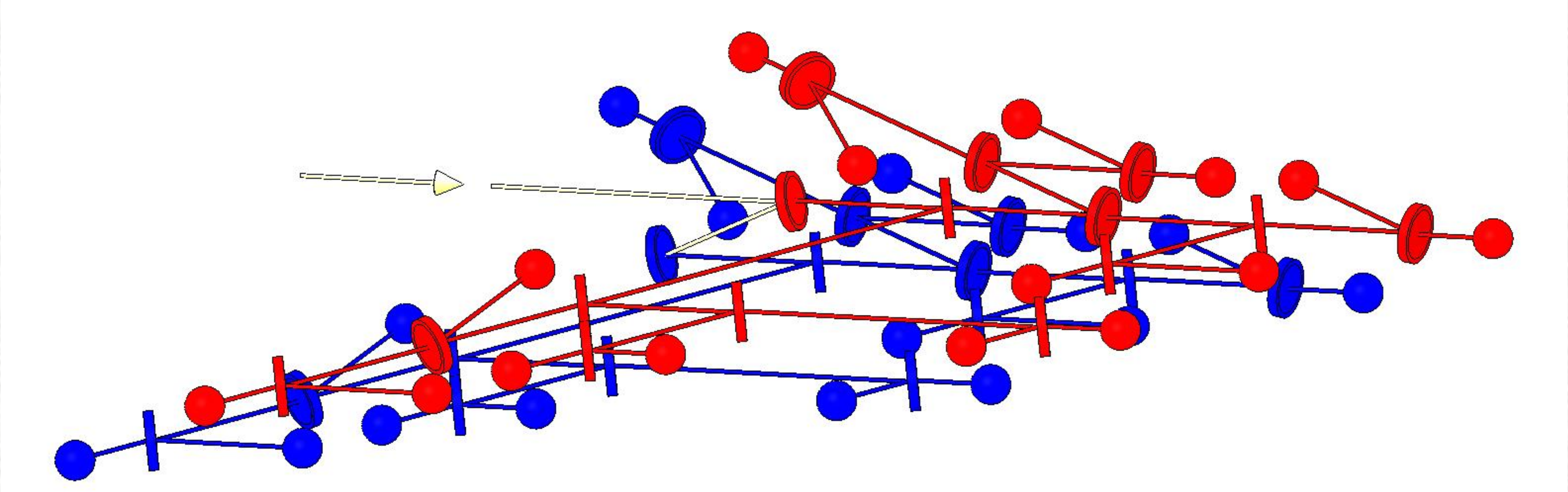


Single Channel Path



Dichroic Tree Packaging

- Dichroic tree allows for efficient packaging
  - Initial design places blue channels below red channels to reduce footprint
  - 5x3x3m instrument footprint (without enclosure)
  - More efficient packaging schemes possible

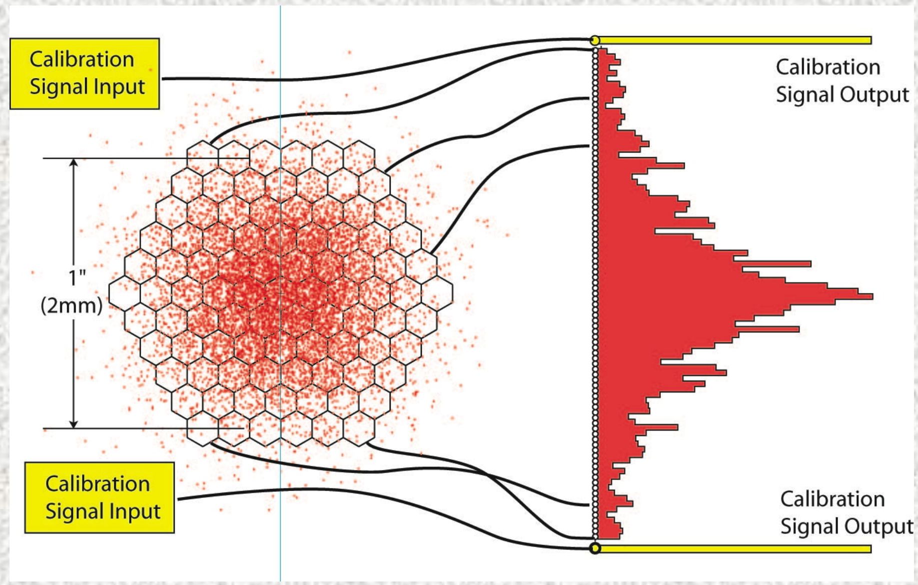


Advantages of a First-Order Design

Metric	*Multiple First Order Spectrographs*	*Echelle*
Flat Efficiency and Uniform Resolution	Each channel optimized for narrow band	Large throughput variations
Single spectroscopic order	High alpha, beta suppresses higher orders	Operates at multiple high orders
Small, low risk optics	All optics currently available	Large collimators, grating mosaic
Excellent scatter/stray light control	Low scatter optics, easily baffled design	Difficult to suppress echelle scatter
Relatively low cost	Extensive duplication of components	Very large optics
Low mass, small footprint	Easy to optimize packaging	Very large structure

Fiber IFU

- Entrance slit is made up of (baseline) 5 one square arcsec fiber bundles
- Each IFU remaps a 1 square arcsec entrance aperture to a >0.05″ wide pseudo-slit
  - *This decouples resolution from seeing/ AO performance*
- Microlens array increases fill factor to near 100%
- Enables multiobject obs, sky placement
- Enables simultaneous wavecal spectra injection



Pixel Illumination

Seeing Disk	R	CU-HROS	Conventional Echelle	With Profile
1"	100,000	156	200	160
0.5"	100,000	38	100	80
1"	50,000	312	100	80
0.5"	50,000	76	100	80
1"	20,000	780	250	200
0.5"	20,000	190	250	200

90% encircled energy

In poor seeing, the FIFU user can choose whether to use all pixels illuminated or not

Echelle has R=50,000 matched to a 1” slit, slicer for R=100,000 at 1”, narrow slit for 0.5"

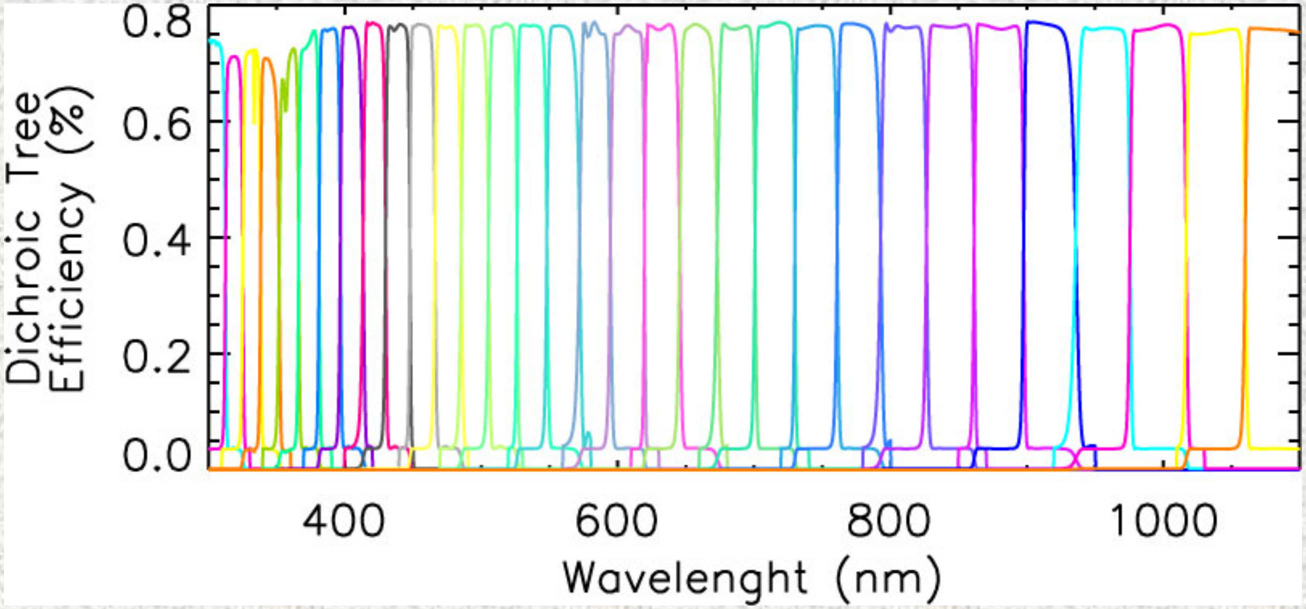
Profile includes taper in pixel sampling for the slit

CCDs: Required Pixel Numbers

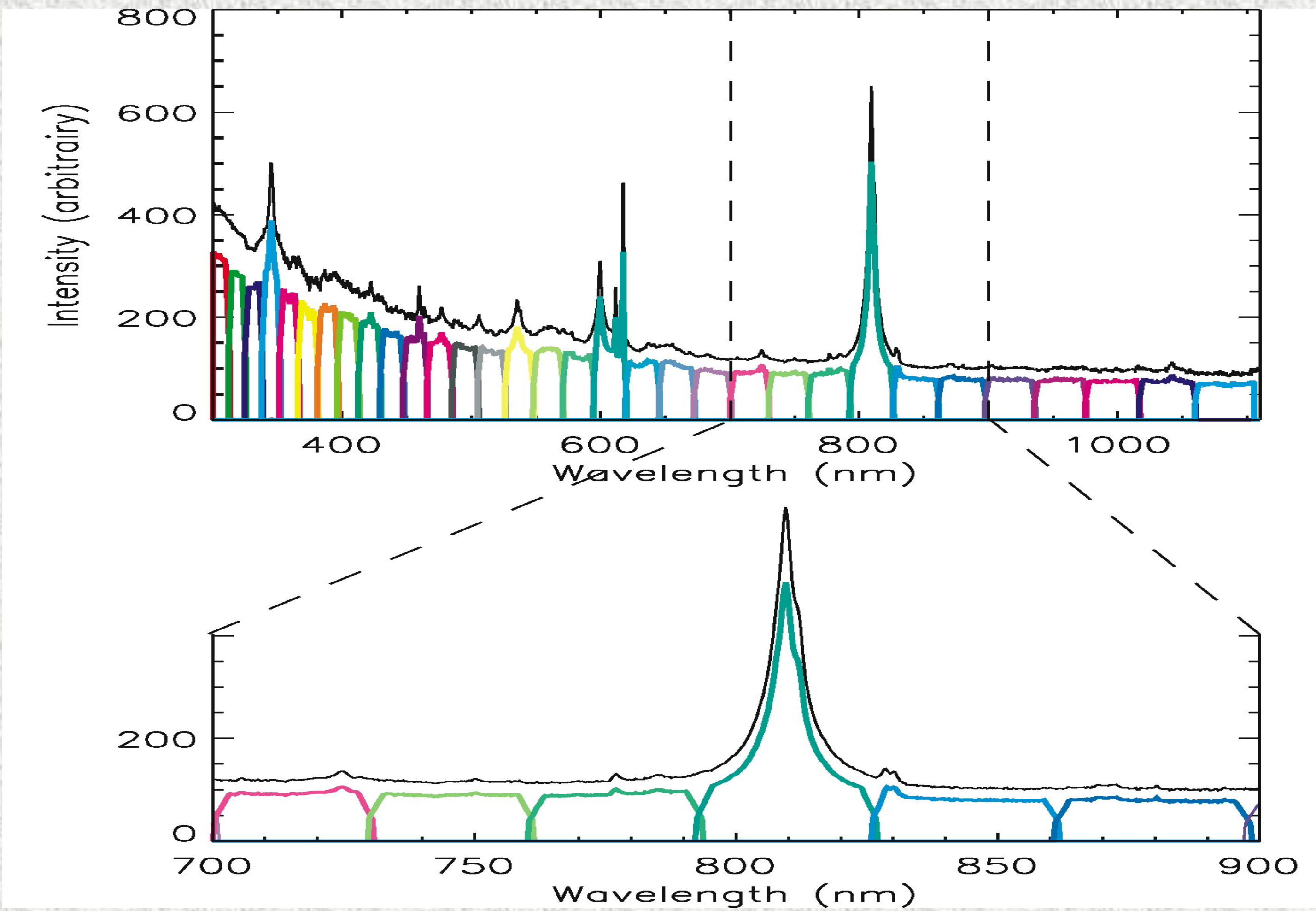
- For 0.1" spatial resolution element
- Nyquist sample, 2x2 pixels per resl
- 100 elements per 1" x 1" spectral resolution element
- 400 pixels per resolution element
- If PERFECT packing, ~130,000 resolution elements per spectrum (300 - 1100 nm)
- So… minimum of 50 Mpixels per spectrum. *All high performance ELT spectrographs will require large format detector systems*
- Note: RN is an issue independent of design, as an f/15 ➔ f/1 beam on a 30-m telescope subtends 145 μm/1" at the detector
- Therefore, S/N is a trade-off between seeing disk size, illuminated pixels, on-chip binning, RN, exposure times, and cosmic ray rates

Dichroic Tree – HROS array performance model

- Barr provided efficiency predictions for an initial array design
  - Net efficiency after 5 reflections/transmissions ranges from 70-77% after degrading predictions to match spec (>95% transmission/reflection)
  - Sharp transition edges (3-5nm) reduce data loss at bin edges
  - High frequency ripples don't line up



QSO Spectrum



Component Level Efficiency Calculation

Component Level Efficiency Breakdown				
Item Description		**Refl/Trans per surface**	**Qty**	**Net Efficiency**
Derotator	**3 mirror**	**0.98**	**3**	**0.941**
ADC	**4 surfaces**	**0.97**	**4**	**0.885**
Reimaging optics	**4 mirror**	**0.98**	**4**	**0.922**
Chamber window	**wide band AR**	**0.97**	**2**	**0.941**
FIFU	**Durham best effort**	**0.65**	**1**	**0.650**
Collimator	**3 mirror**	**0.98**	**3**	**0.941**
Vignetting	**Due to finite source size**	**0.95**	**1**	**0.950**
Dichroic tree	**(HROS 100)**	**0.95**	**5**	**0.774**
Grating	**Optimized for narrow band**	**0.65**	**1**	**0.650**
Camera	**3 surfaces, tuned AR/Refl**	**0.98**	**3**	**0.941**
CCD	**Optimized for narrow band**	**0.90**	**1**	**0.900**
Net HROS Performance:				***0.18***

Estimated Performance on TMT

Resolution	Seeing (90% encircled)	S/N	Limiting mAB in 6 hrs
100,000	1.0	100	17.5
100,000	0.5	100	18.9
100,000	0.2	100	20.4
100,000	0.5	50	19.4
50,000	0.5	100	19.7
50,000	0.5	50	20.5
20,000	0.5	50	21.2
20,000	0.5	20	22.3

- We are RN-dominated in most cases
- On-chip binning for lower R, where # of pixels binned is set to allow for 30 min t_{exp} with ≤1% loss from CRs

Original CU-HROS Design Summary

- The Colorado HROS concept achieves high resolution and broad pass band by using high efficiency dichroic filters to direct light into 32 narrow band spectrographs
- Each spectrograph can be optimized for a narrow wavelength range (13 to 46 nm per channel)
- Duplication of CCDs, camera optics, grating substrates and optomechanical design reduces cost and risk
- High resolution (100K) and manageable optic size (200-250mm beams) are achieved by reducing the slit width with a fiber fed IFU
- Design decouples spectral resolution/optics sizes from AO performance
- High-impact scientific results can be obtained in poor observing conditions and in seeing-limited regimes

CU-HROS Now

- Instrument concept, work needed to develop design
- Demonstration hardware
  - Dichroic tree: throughput, ghosting, pupil control, stability (mount design, optical performance)
  - FIFU development: fiber size, packaging; modal noise; FRD vs. reimaging optics; fixed vs. deployable configurations
  - Gratings: high R concept depends on large format holographic gratings with high line densities
- Alternative options
  - Lower R (~20,000) design with MOS capability
  - Pupil slice and feed identical cross-dispersed echelle spectrographs (no dichroic tree)

Looking Ahead for TMT HROS

- Trade studies
  - Stability: support extremely high precision observations or not
  - Blue throughput goal (vs. fiber lengths)
  - MOS design or single target (plus sky)?
  - Spectral resolution requirements: trade between high R capability and RN for lower R modes
- General issues
  - Some type of slicing will be required to bring down sizes of optics: image slicing, IFUs, pupil slicing
  - Large number of pixels drive detector format requirements, on-chip binning necessity