Australian Government

Department of Industry
Innovation, Science, Research
and Tertiary Education

AAO

A MULTI OBJECT IFU FOR ULTIMATE on Subaru

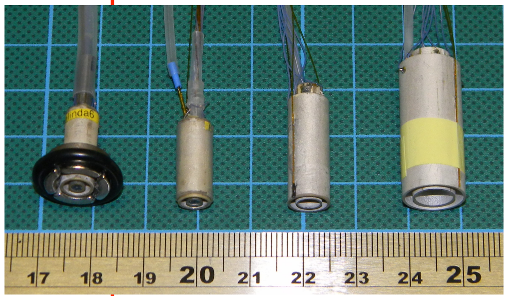
TECHNOLOGY: Andrew Sheinis, Ross Zhelem, Jon Lawrence, Simon Ellis

SCIENCE: Chris Lidman, Lisa Kewley, Anne Medling, Tiantian Yuan, Fuyan Bian, and I-Ting Ho

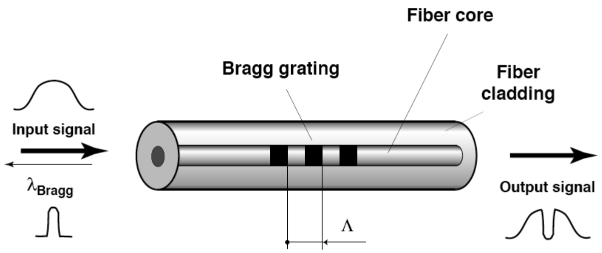
The University of Sydney

Today's talk

- A bit about the AAO



- Fiber positioners
- MANIFEST: Parallel Fiber Head positioning with Starbugs
- Echidna: Spine-based positioner

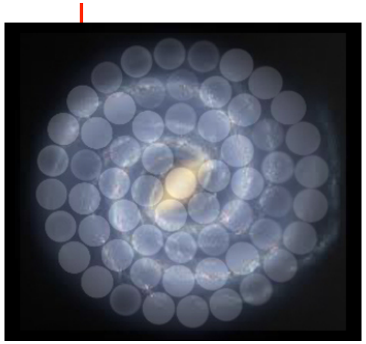


Astro-Photonics

GNOSIS: OH-SUPPRESSION fibers for IR spectroscopy

HEXABUNDLES AND SAMI: Fiber IFU's

Integrated Photonics Spectrographs



- Phase I –Modify MOIRCS with Fibre feed
- Phase II – MOSFIRE/KMOS on Subaru

AAO

- *Opened* 1974 as Anglo-Australian Observatory
- 2010 AAO became part of the Australian Department of Innovation Industry Research and Tertiary Education, Now just Department of Industry
- Operates AAT and UK Schmidt at Siding Springs
- National facility for 400 Australian Astronomers (+200 students)
- Represents Australia at Gemini Observatory (6% partner)
- Represents Australia at GMT (5% + 5% ANU)

AUSTRALIAN ASTRONOMICAL OBSERVATORY

AAO Organization

AAO Users' Committee
Australian Time Assignment Committee

DIRECTOR
Warrick Couch

PERSONAL ASSISTANT
Helen Woods

ASTRONOMY

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- (Research Astronomer)
- (Amanda Bauer)*
- Sarah Brough*
- Gayandhi De Silva*
- (AAO Research Fellows)
- Caroline Foster-Guanzon*
- Andrew Green*
- Angel Lopez-Sanchez*
- (John Stocker Fellow)
- Iraklis Konstantopoulos*
- (Super Science Fellow)
- Maritza Lara-Lopez*
- Millicent Maier*
- Matthew Owers*
- Quentin Parker* (AAO/MQ)
- Lee Spitler*(AAO/MQ)
- (Fred Watson)
- Julia Bryant* (AAO,USYD)

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- (Fred Watson)
- Helen Sims

STUDENTS

National Facilities Support — **Chris Lidman**

International Telescope Support — **Stuart Ryder**

GEMINI OFFICE
- Caroline Foster-Guanzon*
- Richard McDermid (MQ/AAO)

TECHNOLOGY

Instrumentation Group — **Andrew Sheinis**

PROJECT MANAGEMENT
- Julia Tims
- Gabriella Frost~

INSTRUMENTATION GROUP MANAGER
- **Pascal Xavier**

OPTICAL SYSTEMS
- **Luke Gers***
- Scott Case
- Ross Zhelem*

MECHANICAL
- **Nicholas Staszak**
- Vladimir Churilov
- Urs Klauser
- Jurek Brzeski
- Yuriy Kondrat
- Naveen Pai
- David Brown*
- Azizi Rakman*

ELECTRONICS
- **Lew Waller**
- Vijay Nichani*
- Rolf Muller
- Don Mayfield~
- Jamie Gilbert~
- Slavko Mali*

SOFTWARE
- **Tony Farrell**
- Keith Shortridge
- Michael Birchall
- Minh Vuong
- Nuria Lorente*
- Scott Smedley~

Instrument Science — **Jon Lawrence**

- Anthony Horton
- Michael Goodwin*
- Jessica Zheng*
- Simon Ellis
- Robert Content*
- Kyler Kuehn*
- Will Saunders~
- Gordon Robertson~
- Peter Gillingham~ (AAO/USyd)
- Nick Cvetojevic*

STUDENTS

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- Rajni Prasad
- **Nalini Rajan**
- Jessica Parr
- Jenny Ghabache*
- Jeremy Orr~

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- **Katrina Sealey***

- Chris Ramage
- Imogen Cosier

- Norrie Bennie
- Simon O'Toole~
- (Jenny Ghabache*)

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ADMINISTRATION
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- Zoe Holcombe~

MECHANICAL WORKSHOP
- **Carl Holmesby**
- Wayne Clarke
- Randal Darko
- Glen Murphy

BUILDING SERVICES
- **Glenn Zaneson**
- Darren Mathews
- Wade Sutherland
- Anthony Antaw
- Raelene Suckley
- Heather Meldrum~

TELESCOPE SYSTEMS
- **Robert Dean**

ELECTRONICS
- Robert Brookfield
- Martin Oestreich
- Robert Patterson
- Darren Stafford
- Stephen Chapman
- John Goodyear
- (Winston Campbell)
- (Steve Chapman)

INSTRUMENTATION
- **(Steve Lee)**
- Kristin Fiegert

AAT NIGHT ASSTS
- **Steve Lee**
- Steve Chapman
- (Kristin Fiegert)
- (Yuriy Kondrat)
- Winston Campbell

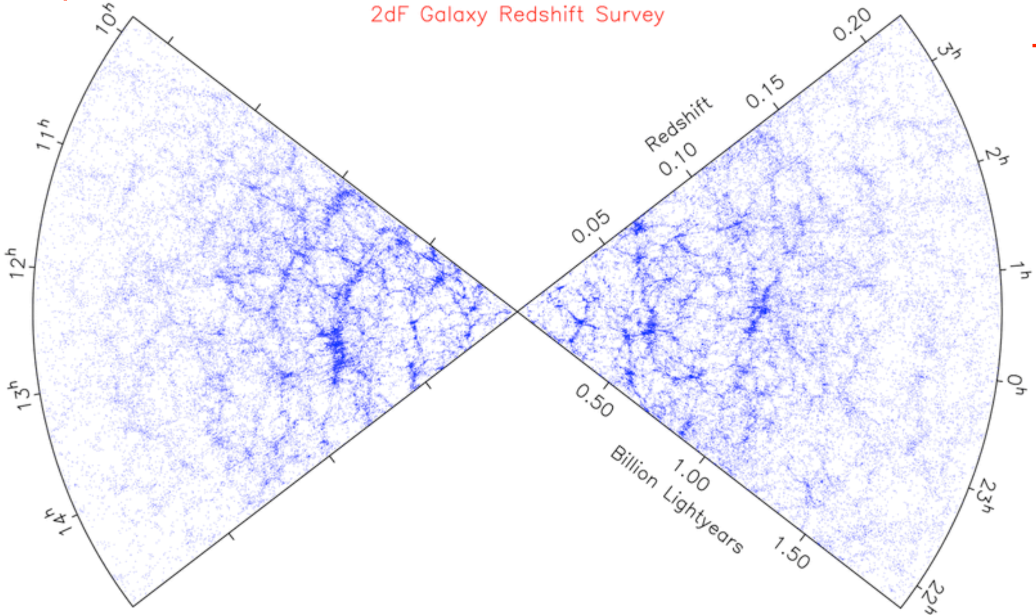
LIGHTING AND ENVIRONMENT
- **Fred Watson**

HONORARY ASSOCIATES

Jeremy Bailey	Peter Gillingham
Russell Cannon	David Malin
Will Saunders	Scott Croom
Chris McCowage	W Orchiston
C G Tinney	Rob Sharp
Joss Bland-Hawthorn	Daniel Zucker
Brian Boyle	Matthew Colless
Michelle Cluver	Michael Ireland
Sarah Martell	
Katrina Sealey (ASA Treasurer)	

Notes
1. Staff with an asterisk * are fixed term
2. Names in parentheses () have primary roles that appear elsewhere in chart
3. Staff shaded are based at Epping; unshaded are at Siding Spring
4. Staff with a ~ are casual
5. Names in bold denotes reporting lines

2dF Galaxy Redshift Survey

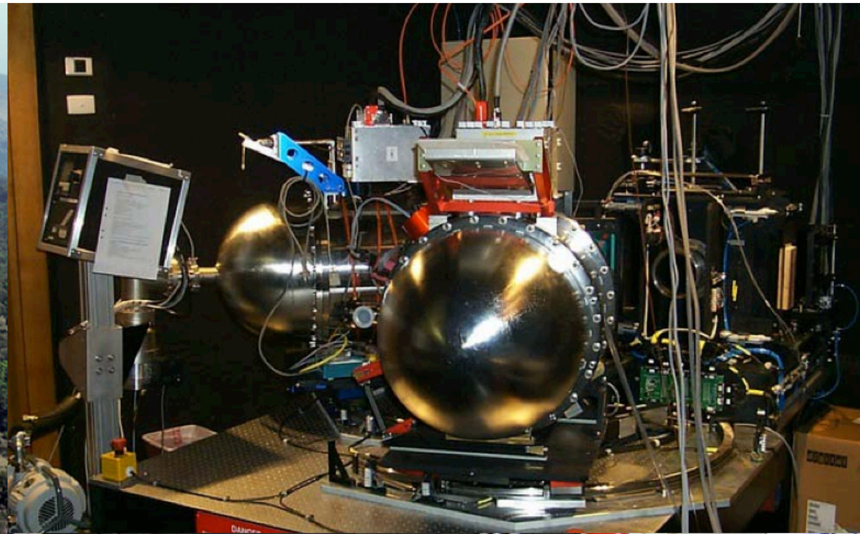


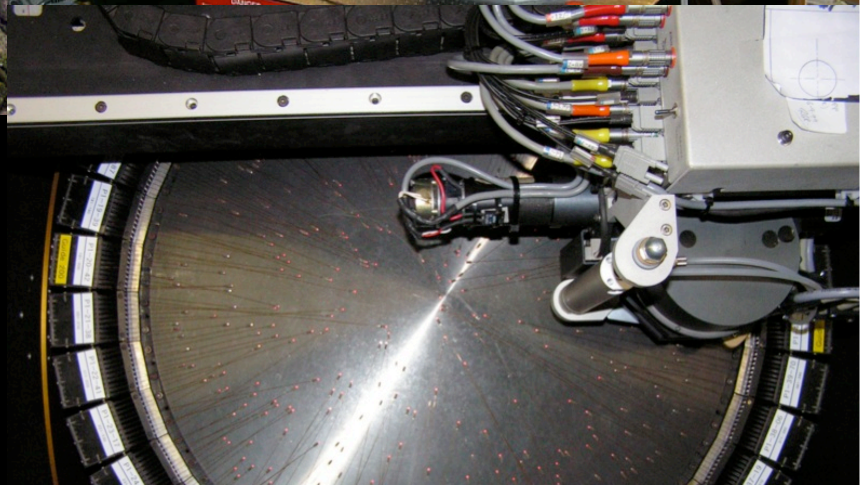
- The 2dF Galaxy Redshift Survey redshifts for approximately 250,000 galaxies to measure BAO, correlation functions, peculiar velocities and the matter density of the Universe, and the cosmological mass density from clustering (14,000 Citations)

6dF Galaxy Survey and RAVE

- The 6dF Galaxy Survey redshifts of around 150,000 galaxies, and the peculiar velocities of a 15,000-member subsample, over almost the entire southern sky (1000 Citations)
- Radial Velocity Experiment (RAVE) radial velocities and stellar atmosphere parameters (temperature, metallicity, and surface gravity) of up to 500,000 stars using 6Df(1200 Citations)

WiggleZ





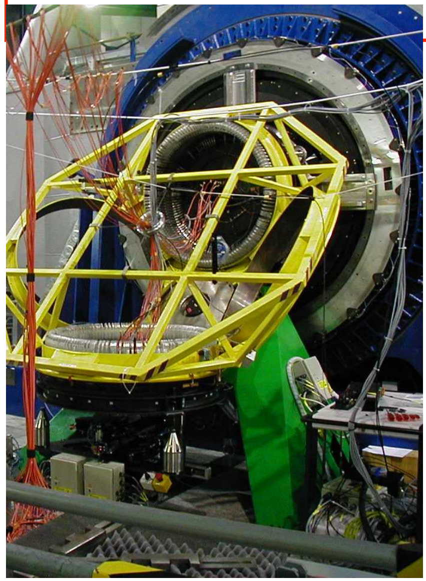
1000 sq deg , 0.2 < z < 1.0

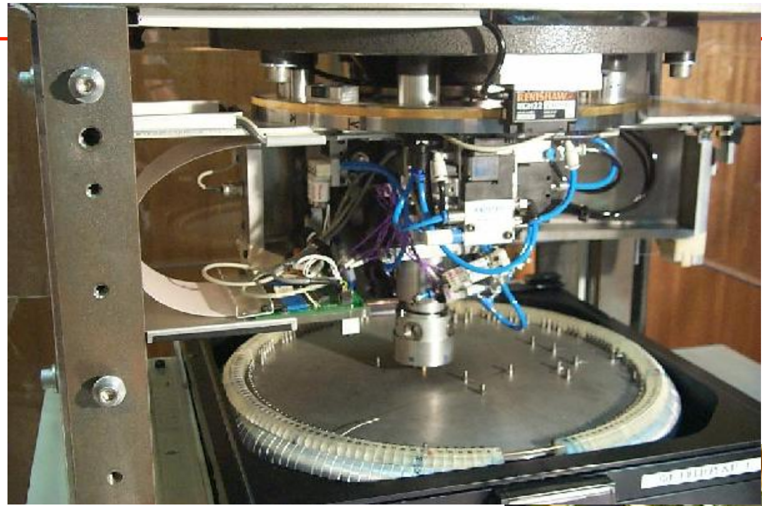
200,000 redshifts

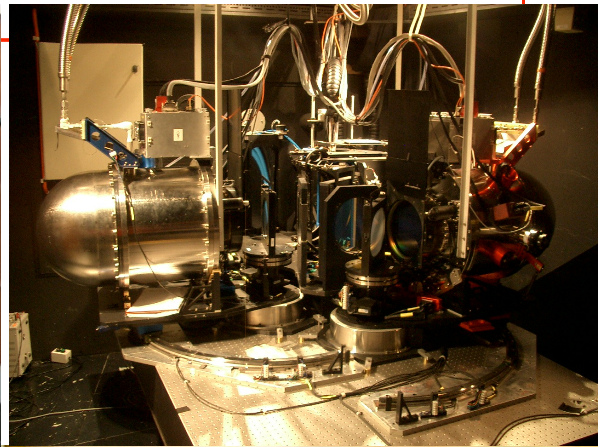
blue star-forming galaxies

- WiggleZ spectroscopic survey of 400,000 star-forming galaxies selected from a combination of GALEX ultra-violet and SDSS + RCS2 optical imaging (600 Citations)

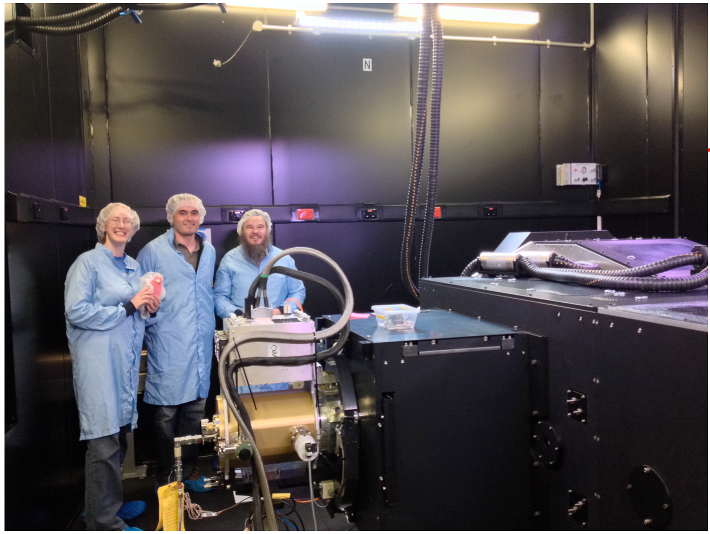
AAO Previous instruments

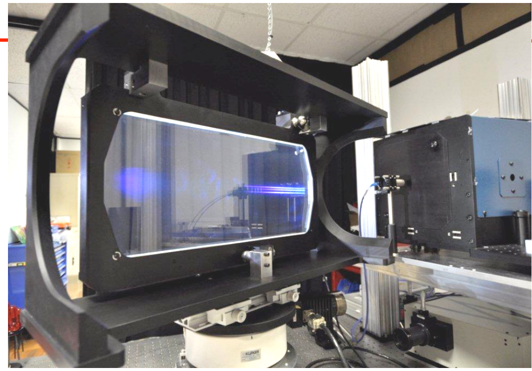


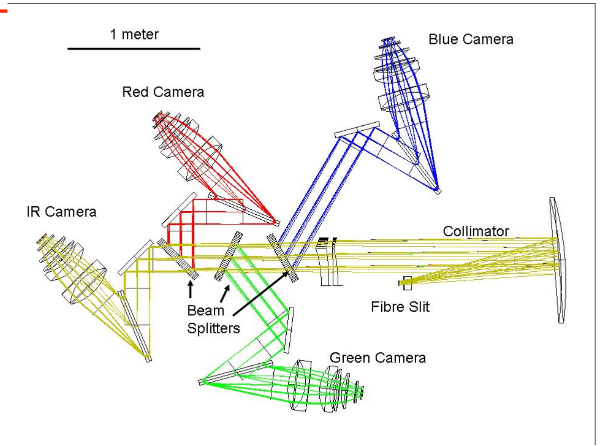


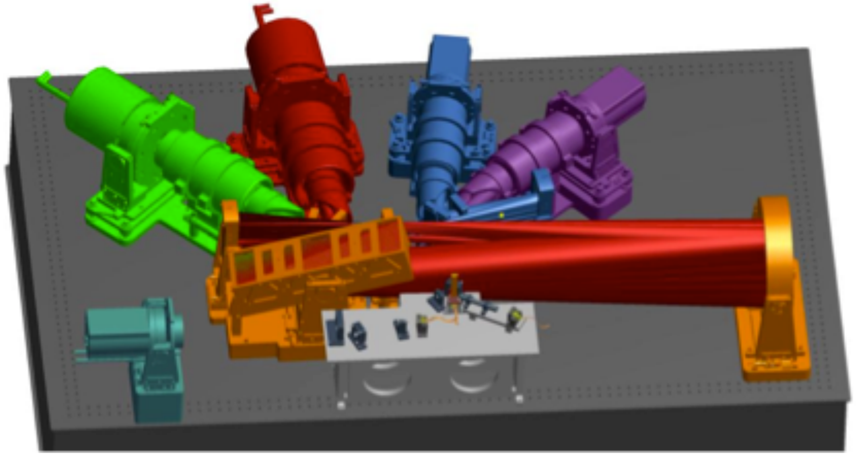


- AAT: 2df, AAOMEGA, IRIS, GNOSIS, CYCLOPS
- UKST: 6df
- Subaru: FMOS Echidna
- ESO: OZPOS

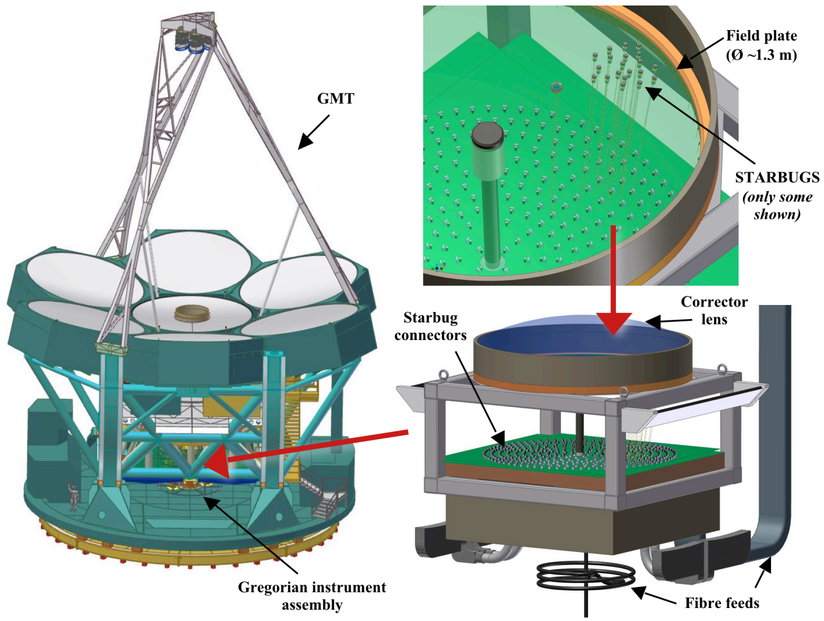




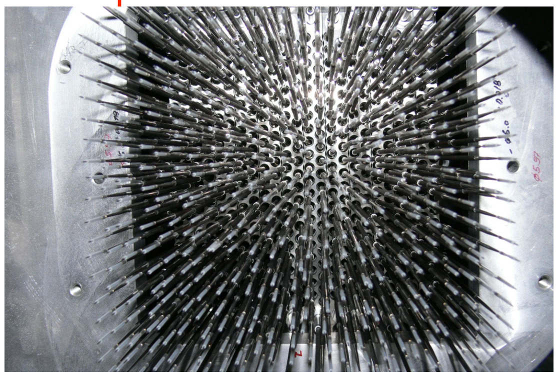




- AAT: Praxis, HERMES
- UKST: TAIPAN
- GHOST (selected for build)
- Manifest (selected for CoDr)

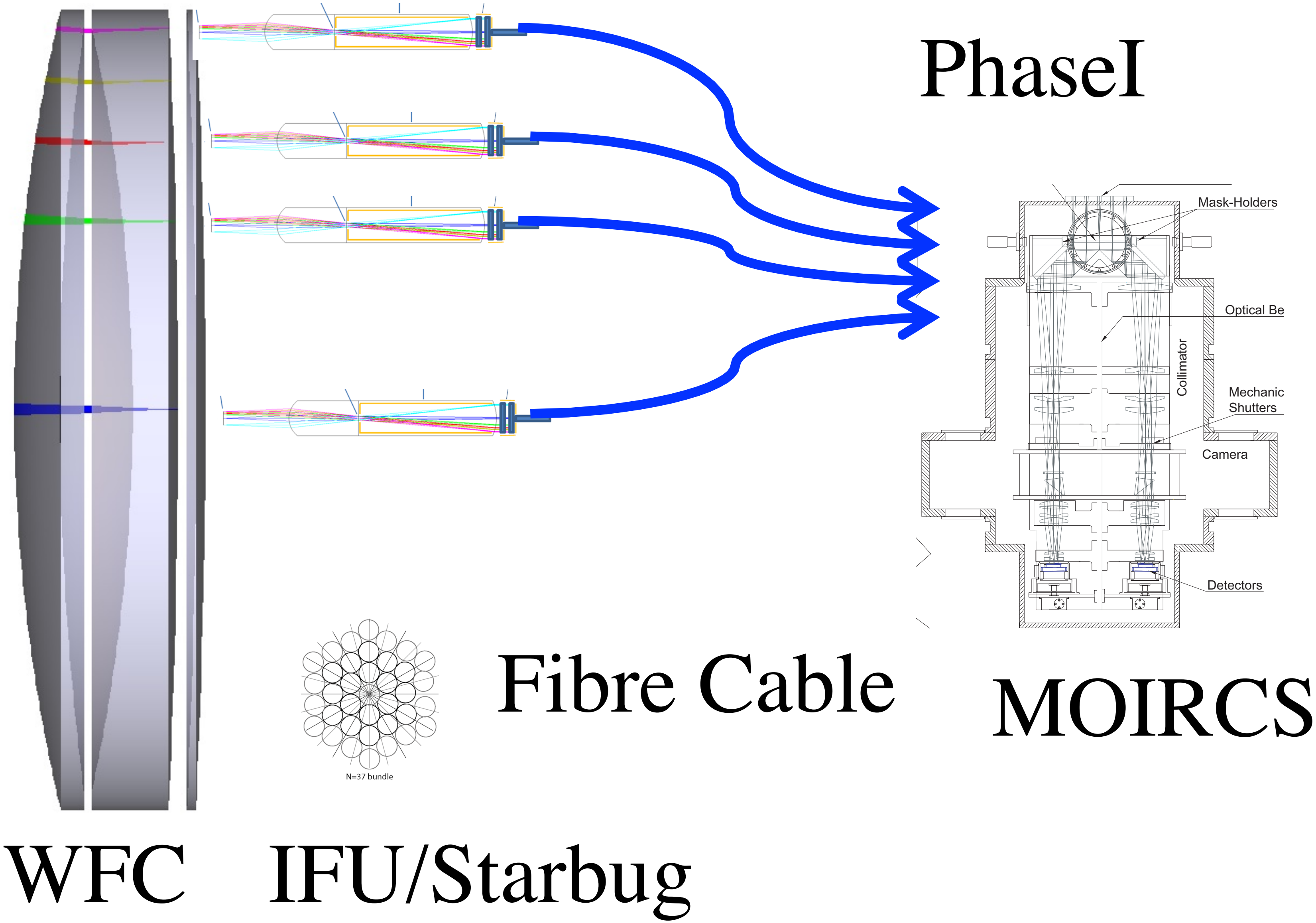


FMOS ECHIDNA

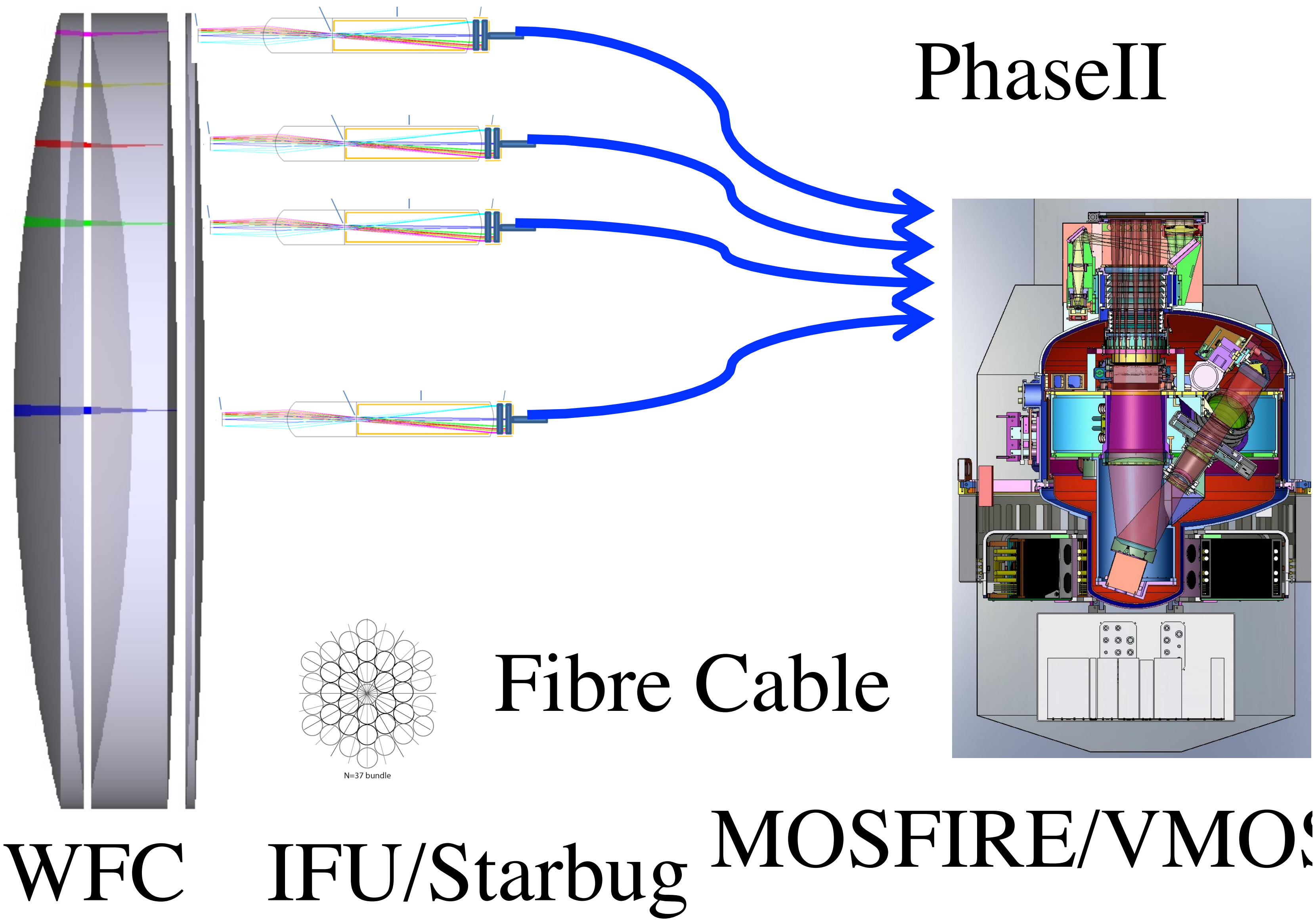


- 400 science fibers
- 14 guide fibers
- 7.2 mm pitch, 180 mm long
- Carbon fiber spines
- 0.5 degree (dia) FOV
- Invented for this application
- Since then we have seen improvements in:
  - Materials
  - Mounting
  - Piezos

Fibre-based MOS for Ultimate



Fibre-based MOS for Ultimate



Instrument setup

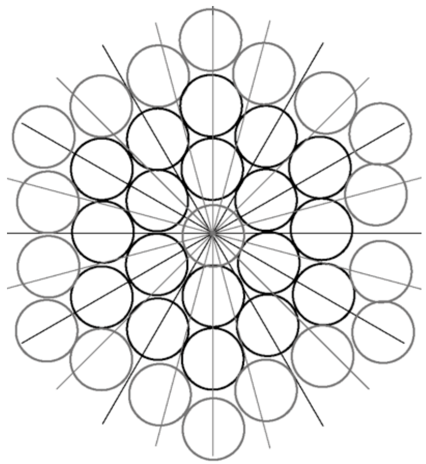
- Starbugs unit will be attached to the Cassegrain focus
- Spectrograph will be placed at the observation floor or at Nasmyth platform and connected to the starbugs with fibers.
  - F-conversion might be necessary to reduce the F# (12.4→→(e.g. 3.0) and avoid the effect of FRD(?)
  - Throughput of the fiber will be (e.g. 90%@NIR).
- Fiber will be connected to the fiber slit in the focal plane module, which is placed in the cryogenic condition.
  - Minimum spacing in between fiber centers should be 4 pixels or larger and the minimum spacing between the 90% EE diameter of each adjacent fiber should be 1 pixel or larger to avoid significant cross-talk and ensure the accuracy of the sky subtraction (<0.5%? based on PFS study).
  - F-conv. optics in side of the FP module might be necessary to change the F# back to the original (12.4) or to the optimum number for the spectrograph.

Ultimate IFU Stages

- **Stage I** A fibre fed IFU for nuMOIRCS using the STARBUGS fibre positioning technology. Assuming that the spacing between adjacent fibres is 4 pixels (KOALA spacing), the number of 61 element IFUs is 16.
- **Stage IIA** Increase in the number of IFUs with the installation of the new spectrograph. Assuming that the spacing between adjacent fibres is 4 pixels (KOALA spacing), the number of 61 element IFUs is 32. Or maybe 2 spectrographs giving 64 IFU's.
- **Stage IIB** Replace the fibres with OH suppression fibres

Fibre Bundle Configuration (1)

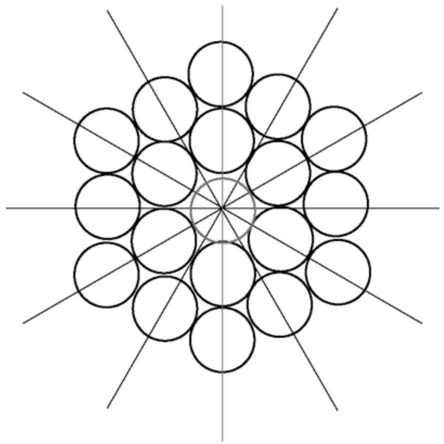
Number of fibres	37 (7 fibres on an axis)
Spatial sampling	0.2 arcsec / fibre
Bundle sky diameter	1.4 arcsec (point to pint)
Number of detector pixels per fiber	4
Number of pixels per bundle	148
Number of bundles per 2k detector	13 (1924 pixels; plus sky fibers?)
Object Multiplicity (MOIRCS)	26
Sky Fibres/detector	30 sky fibres with 1 fibre gap



N=37 bundle

Fibre Bundle Configuration (2)

Number of fibres	19 (5 fibres on an axis)
Spatial sampling	0.2 arcsec / fibre
Bundle sky diameter	1.0 arcsec (point to pint)
Number of detector pixels per fiber	4
Number of pixels per bundle	76
Number of bundles per 2k detector	26 (1976 pixels; plus sky fibers?)
Object Multiplicity (MOIRCS)	52 (feasible??)
Sky fibres /detector	17 sky fibres with a 1 fibre gap



N=19 bundle

Fibre Bundle Configuration (3)

Number of fibres	61 (9 fibres on an axis)
Spatial sampling	0.2 arcsec / fibre
Bundle sky diameter	1.8 arcsec (point to point)
Number of detector pixels per fiber	4
Number of pixels per bundle	244
Number of bundles per 2k detector	8 (1952 pixels; plus sky fibers?)
Object Multiplicity (MOIRCS)	16
Sky fibres/detector	23 sky fibres plus 1 fibre gap

IFU	narrowest axis	longest axis	FoV	# IFUs
61 element 0.2"	1.8"	2.08"	2.81	16 (32)
91 element 0.2"	2.2"	2.54"	4.19	10 (20)
KMOS	2.8"	2.8"	7.84	24

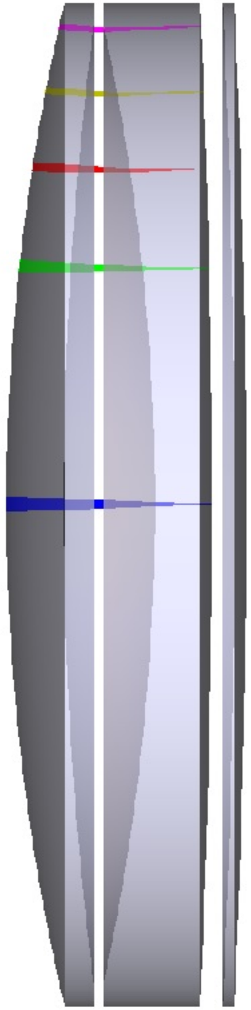
Characteristic	SAMI @ z-0.05	ULTIMATE @ z=1
Number of fibre bundles	13	16 (32 with new sepctrograph)
FoV of positioned	1 degree (3.6Mpc)	14' x 8' (6.9 Mpc x 3.9 Mpc)
Number of fibres per IFU	61	61
FIbre pitch	1.6" (1.6 kpc)	0.2" (1.6 kpc)
Minimum separation	30" (30kpc)	20" (160 kpc)

KMOS: spatial = 0.2"
24 IFU's
14 x 14 spaxals

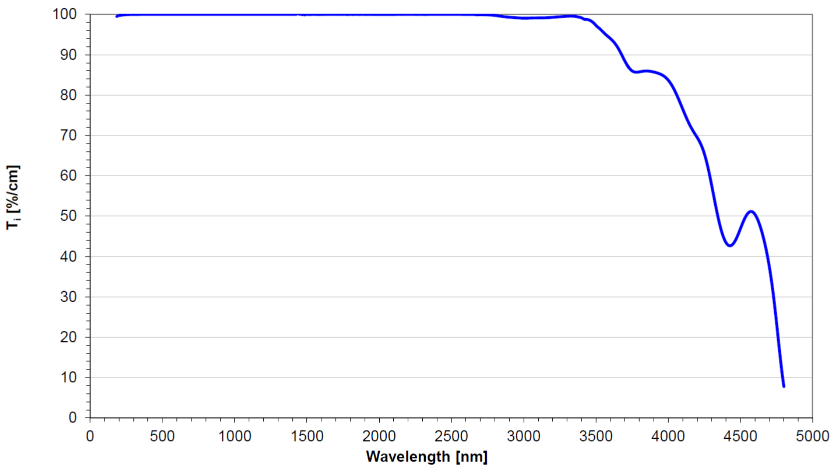
Optical design
Corrector and fibre coupling

IR Corrector

- Zero power corrector
- Dia 450 mm, FOV 14.5 deg
- 2 lenses: center thickness of lenses 25 mm
- Axial thickness 100 mm
- Starbugs plate curved
- Starbugs can mount on the second lens
- Material: IR grade fused silica



Wide field corrector performance



IR Grade Fused Silica Transmittance

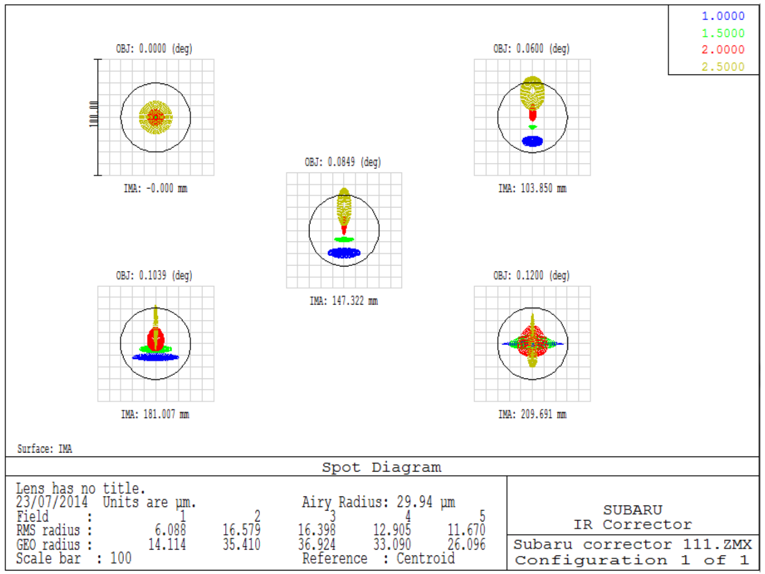
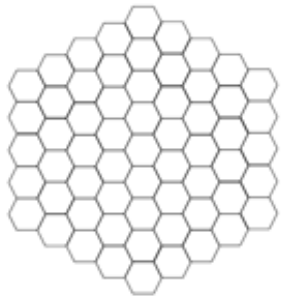
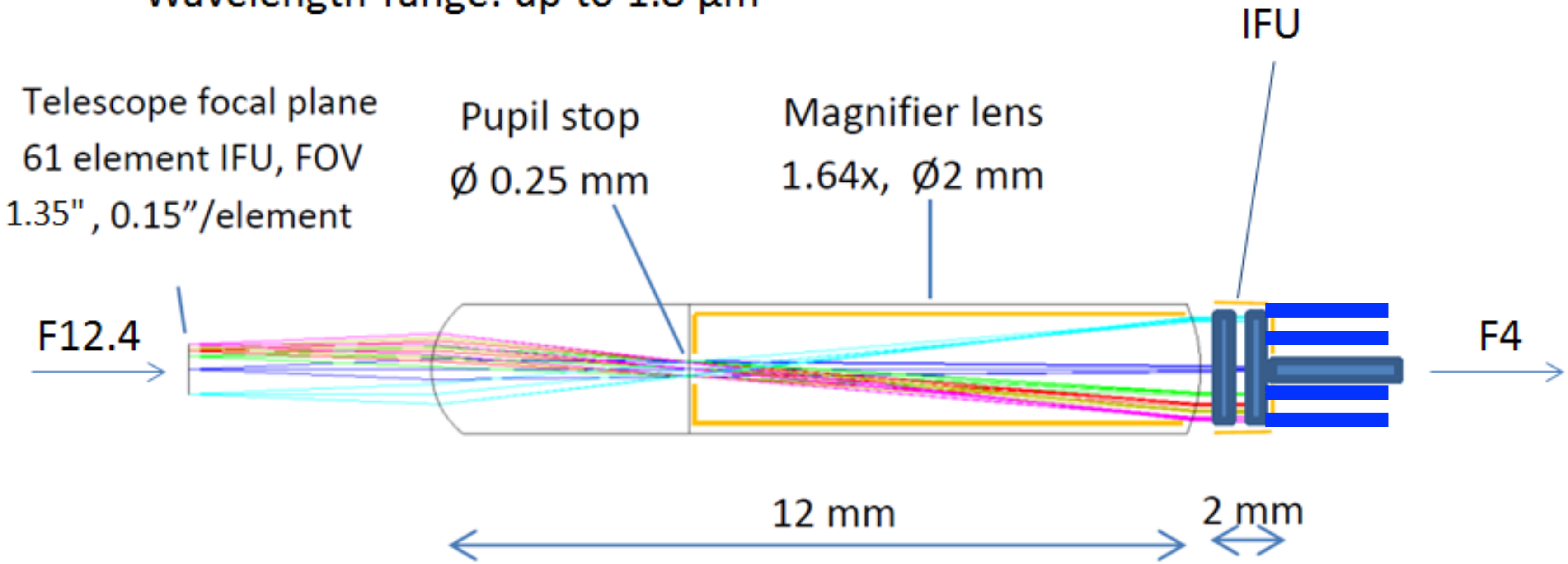


Image quality

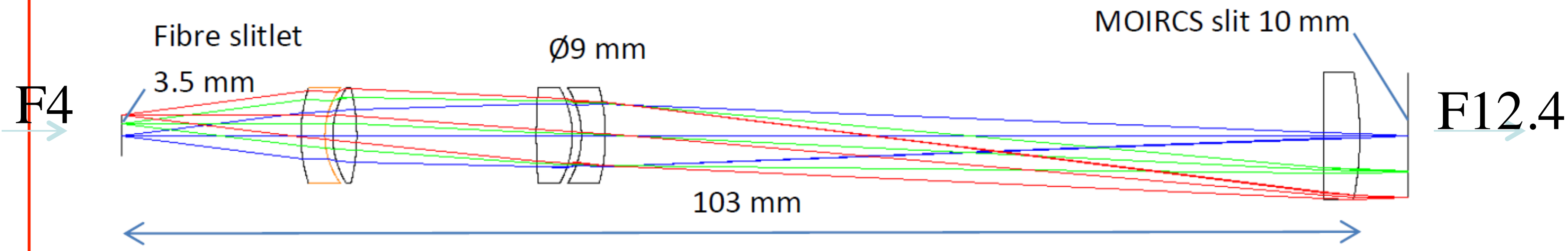
Fibre injection optics

IFU: hexagonal lens array, circular lens array, fibre grid
61 elements total, 9 elements across
Flat to flat dimension 117 µm (Similar to GHOST slit, prototyping required)
Fibre Ø 30/65 µm core/clad
Wavelength range: up to 1.8 µm





Fibre extraction optics



- Magnification 3.1
- Glasses IRG7, CaF2, Fused Silica
- Image quality: diffraction limited
- Used for HERMES

Slit – detector imaging:

Core Ø 30μm → 2.0 pixels res element

Center to center 72 μm → 4 pix spatial separation

Number of fibres per slitlet: 45

Number of slitlets: 88

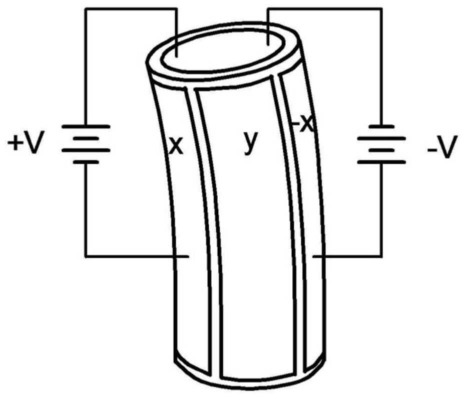
The Starbug

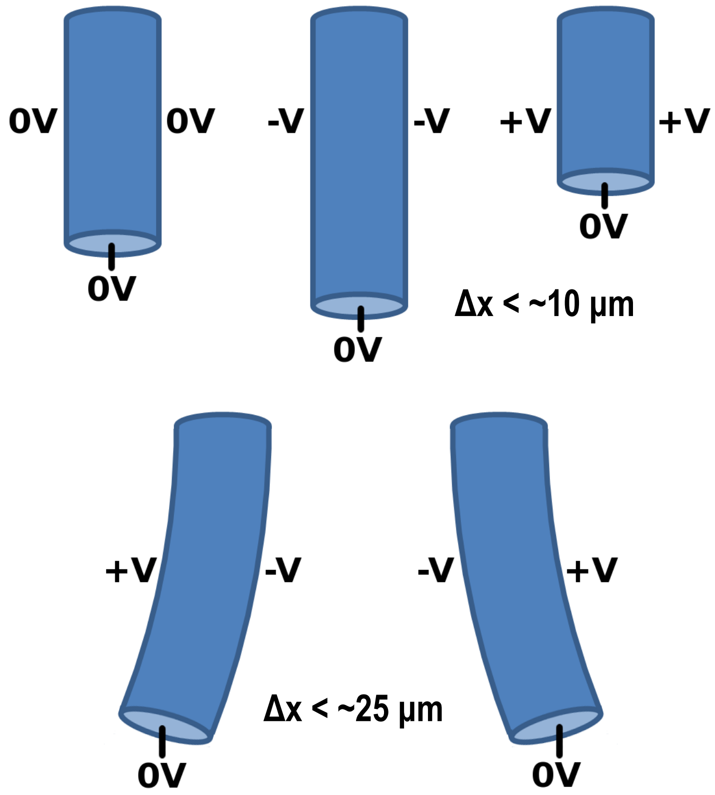
THE STARBUG

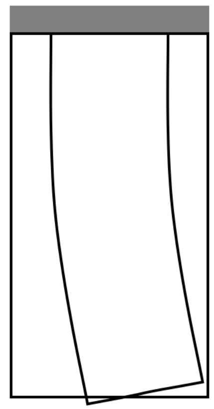
A discrete stepping robot

Theory of operation

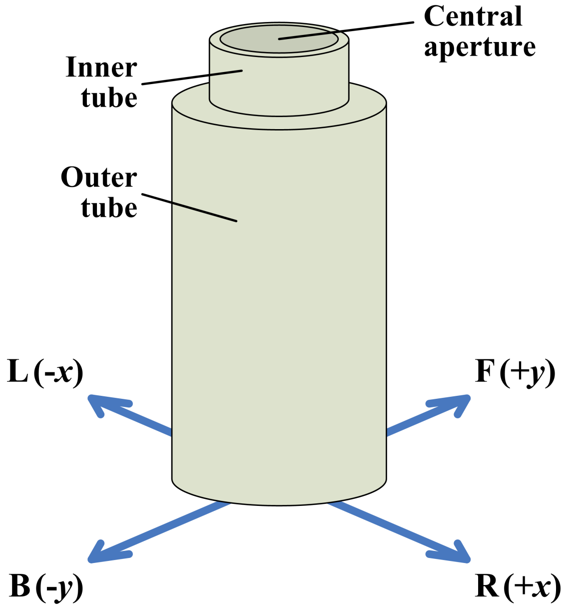
Piezo tubes:

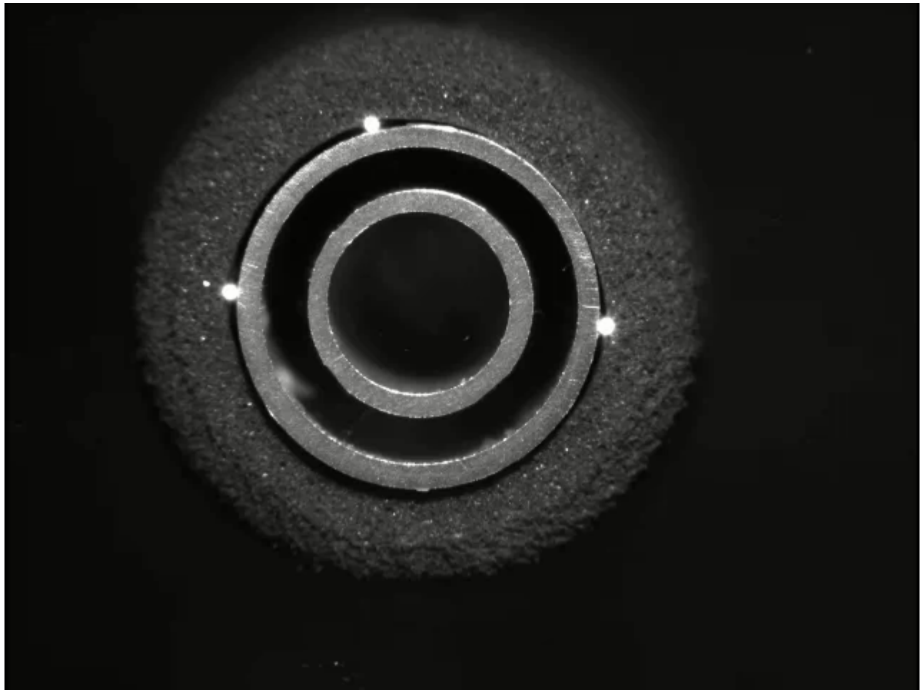






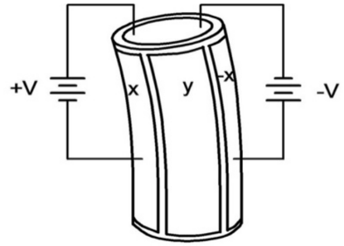
Discrete stepping in *x* and *y*

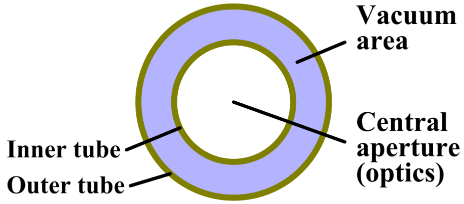


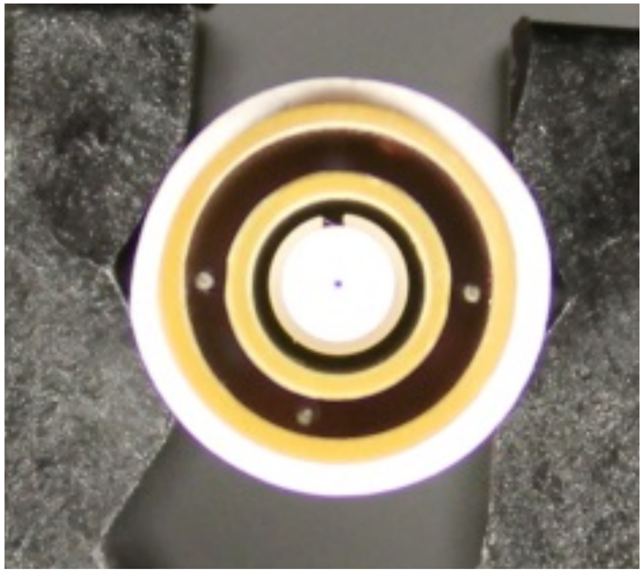


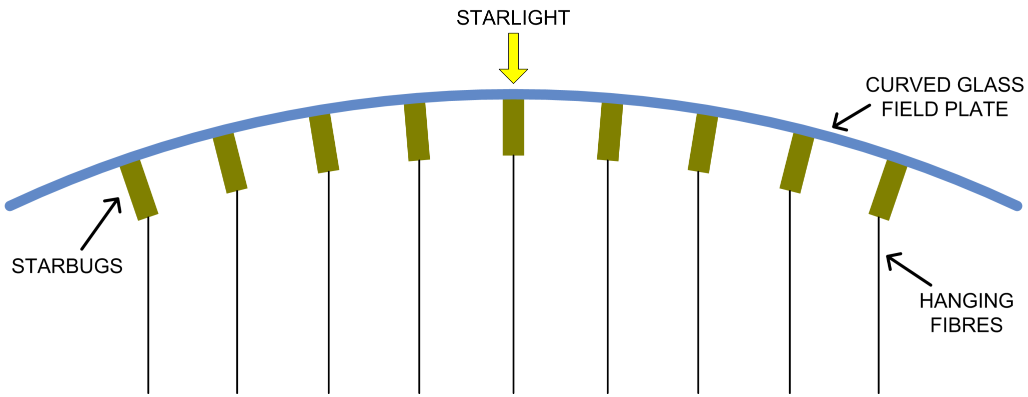
Starbugs

- Starbugs consist of co-axial piezoelectric tubes: stepping motion achieved by appropriate high-voltage waveforms sent the electrodes
- Optical payload (single fibre for TAIPAN) installed at centre of inner tube
- Back-illumination metrology fibres are mounted between the two tubes
- Vacuum is applied between tubes to hold Starbug onto glass field plate







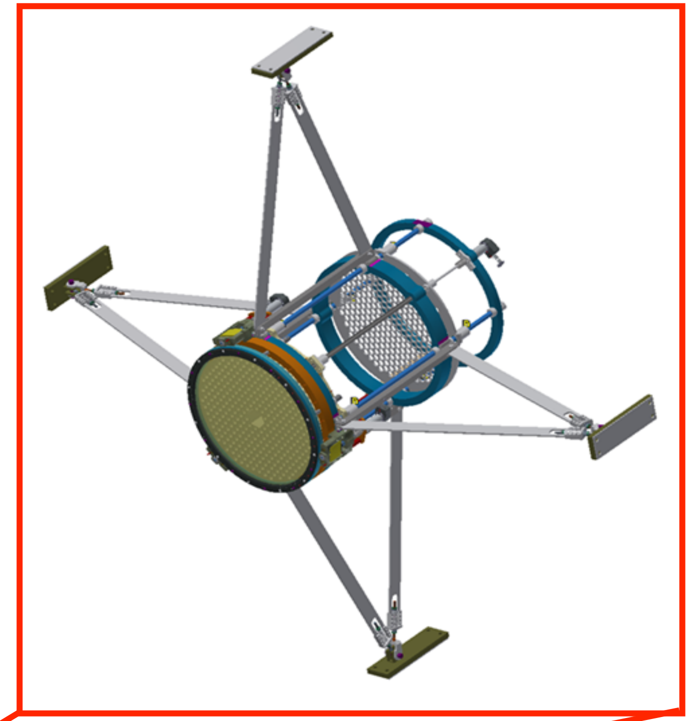


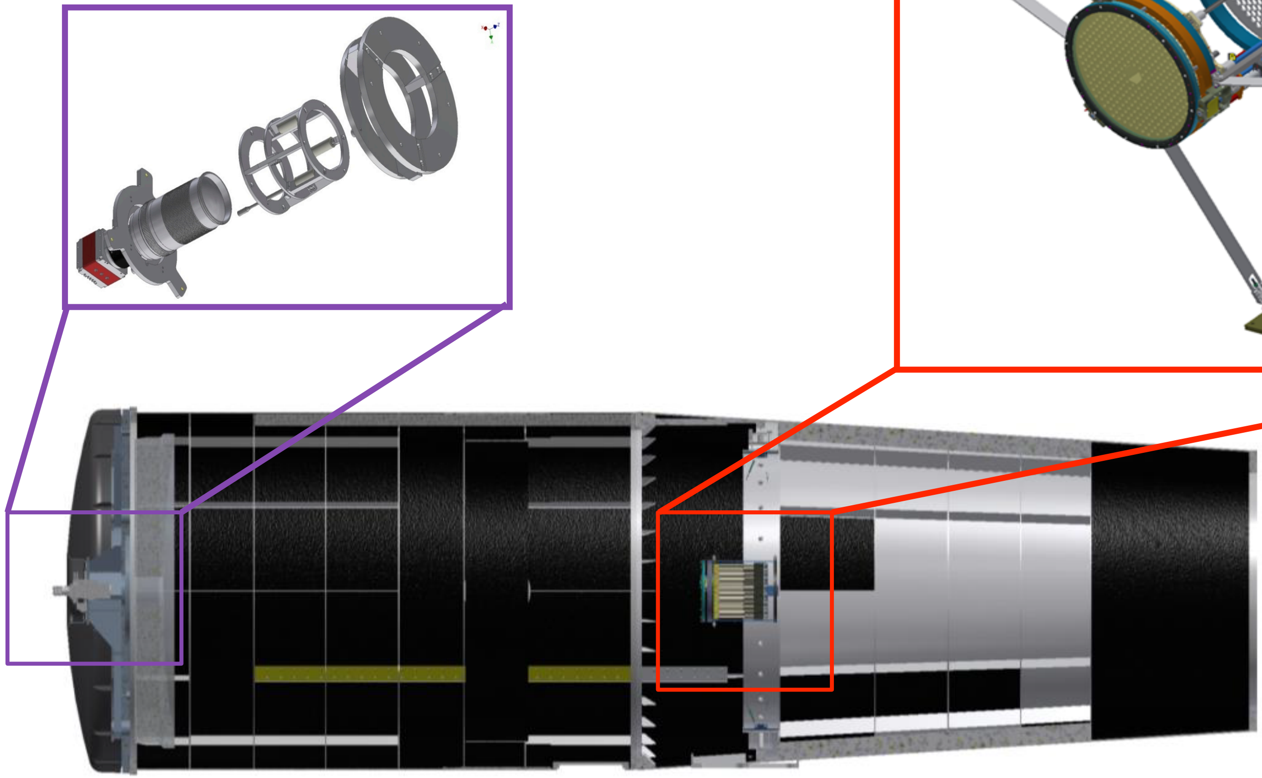
Starbugs

- Starbug movies

TAIPAN Positioner Concept

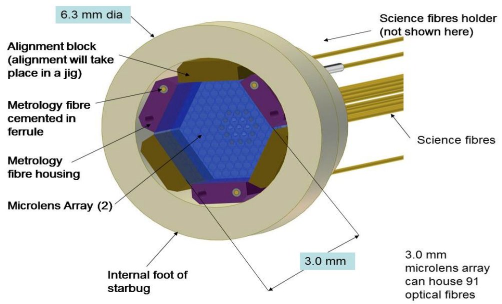
- Field plate assembly is mounted inside telescope tube at focal plane
- Metrology camera is mounted through hole in centre of primary mirror

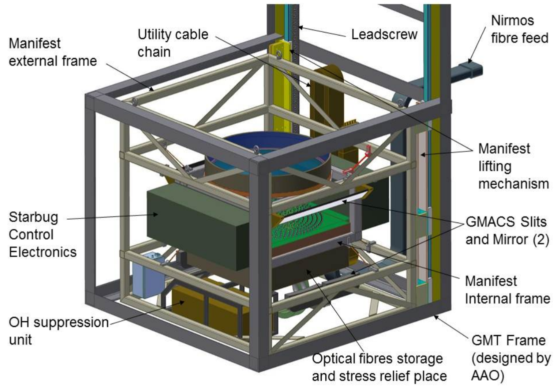




TAIPAN-MANIFEST

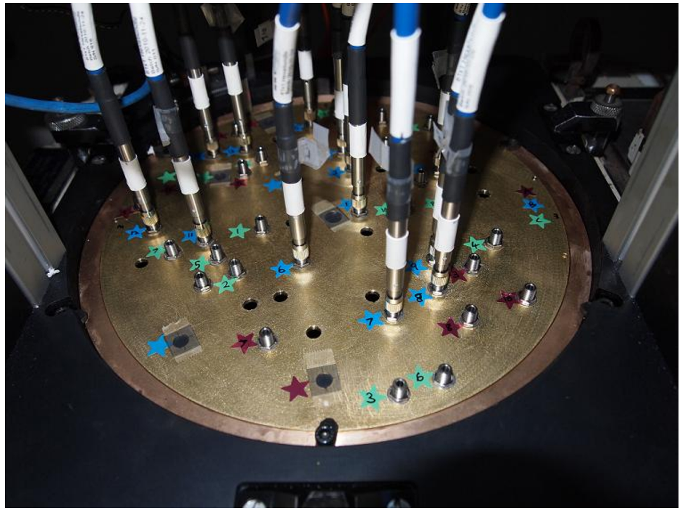
- TAIPAN is a Starbug-based fiber positioner and spectrograph being developed for the 1.2 m UK Schmidt Telescope (150 Starbugs with single fibre payload in each bug)
- TAIPAN is prototype for the MANIFEST fibre positioner for GMT
- MANIFEST will have several hundred Starbugs across 1.3 m field plate using multiple microlens arrays as pupil slicers

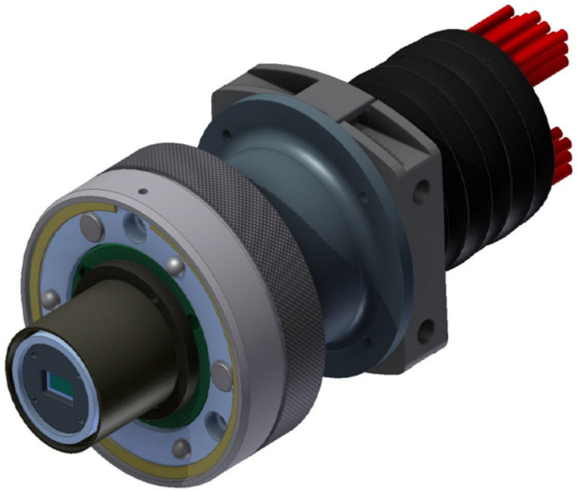


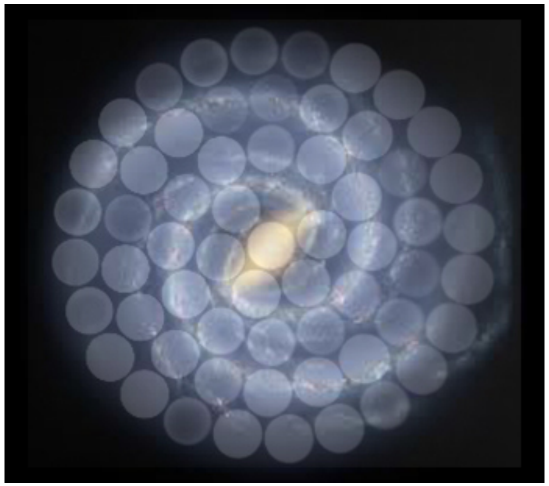


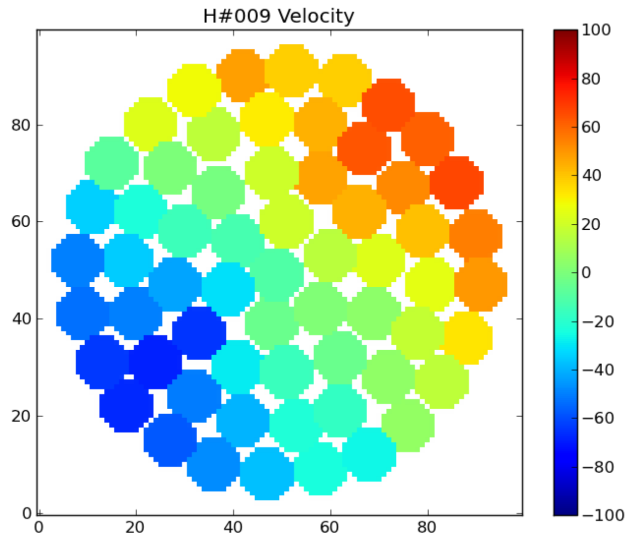
Integral Field Units

- Integral field unit (IFU) spectrographs collect both spatial and spectral information simultaneously
- Current approaches use lens arrays or slicing mirrors
- We have developed new “hexabundle” fibre IFU technology (61 core for SAMI) and lens array technology (1000 element for KOALA)

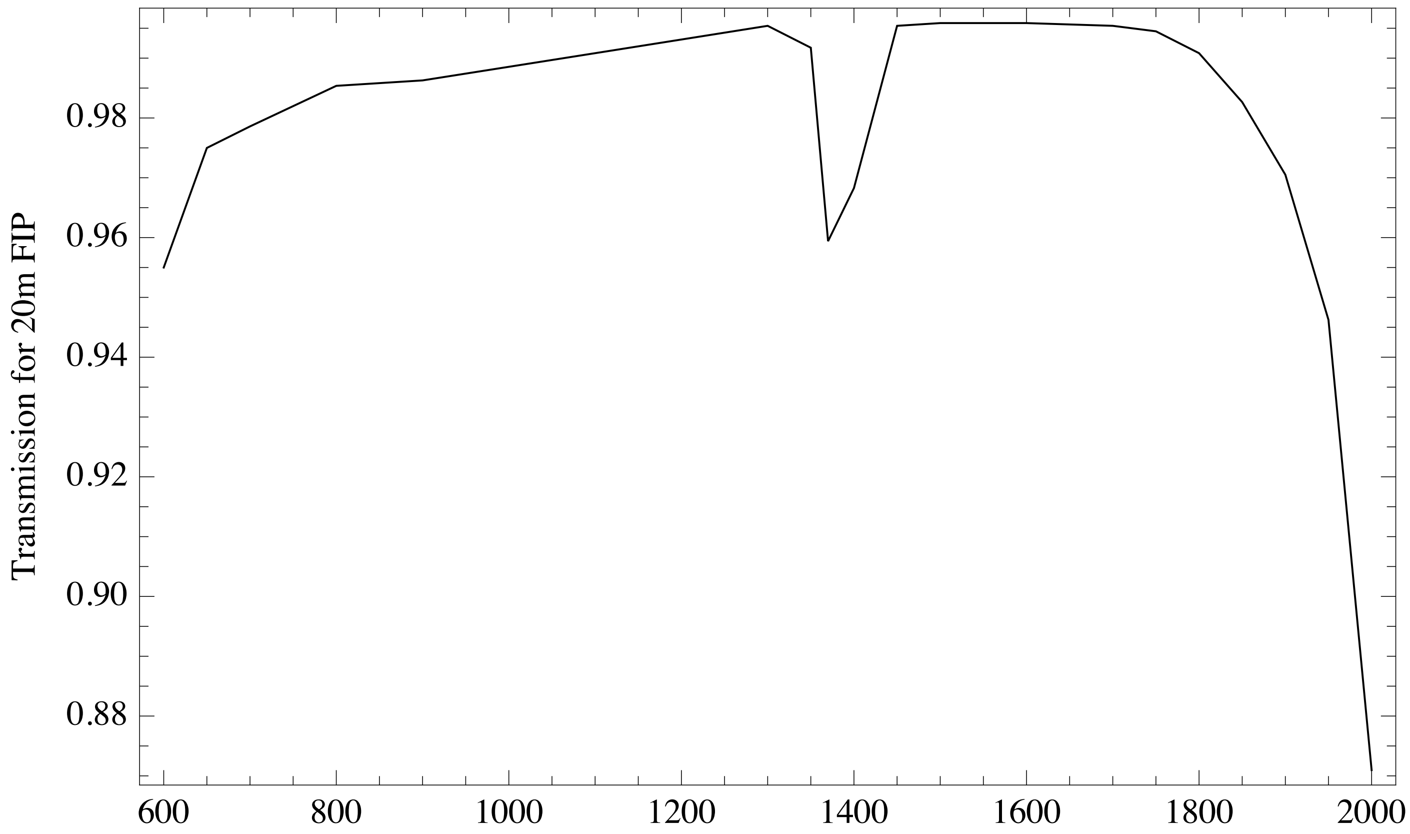








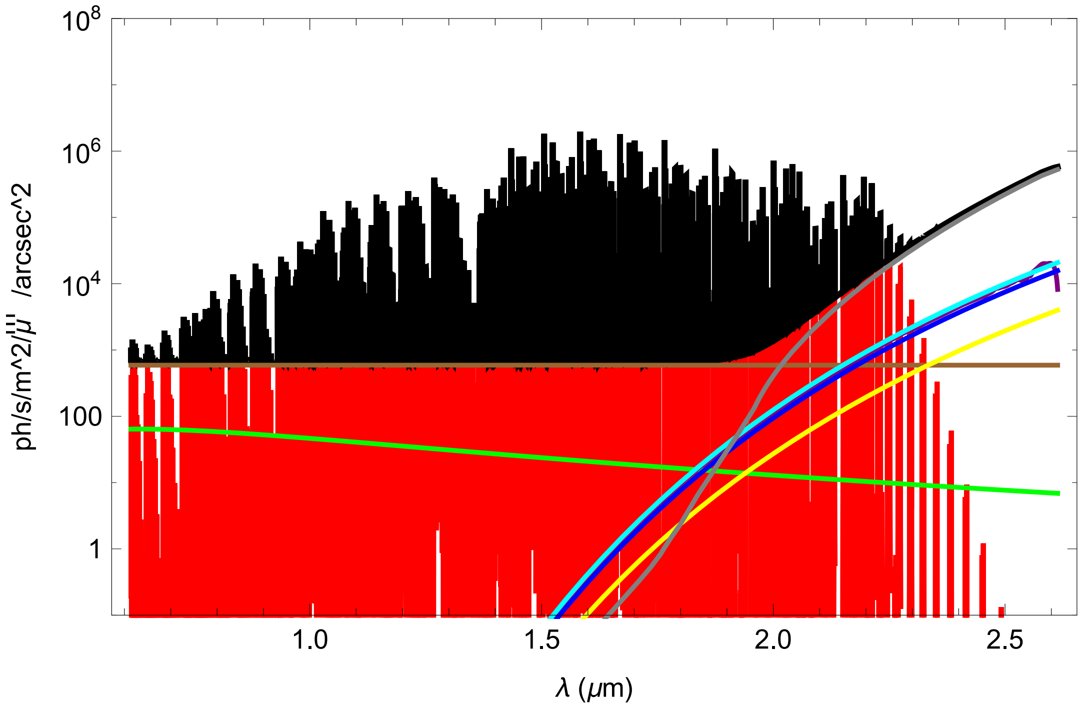
Fibre throughput model fibre only, no coupling losses or FRD



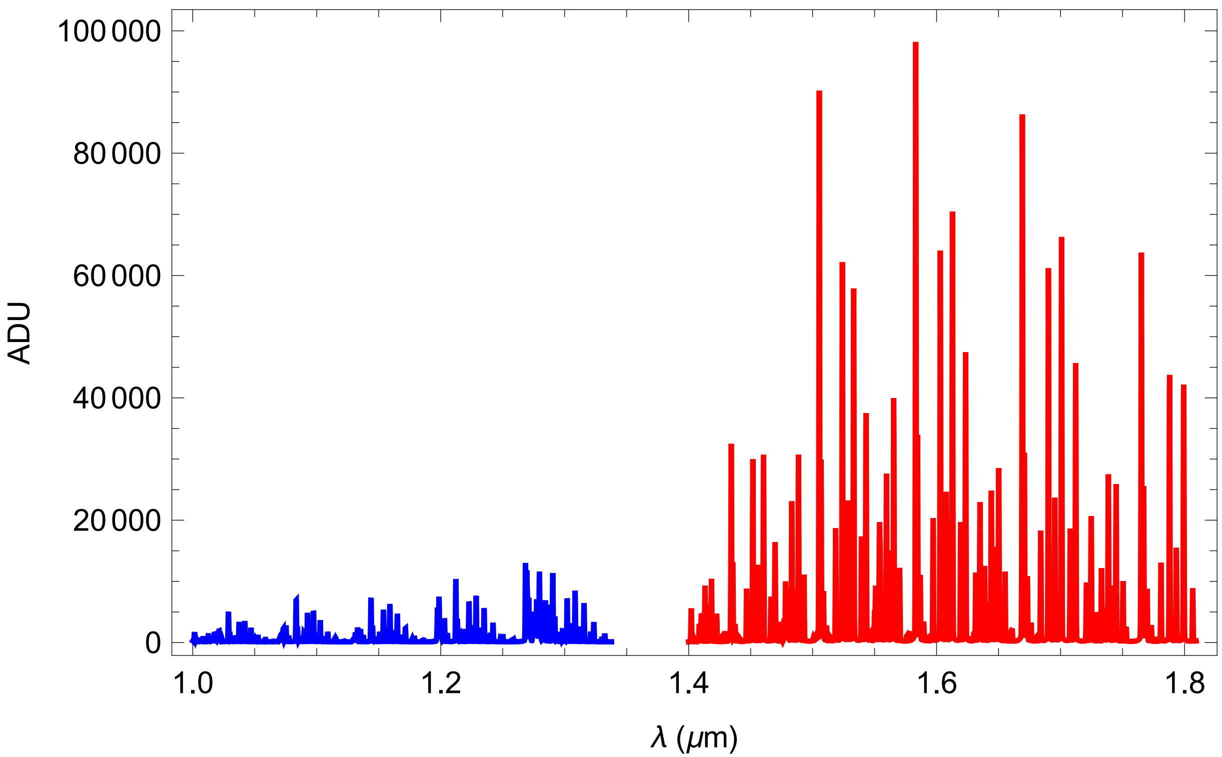
System modelling

- Mathmatica-based model to calculate SNR for J and H band observations with new MOIRCS fed by fibre IFU's.
- OH-emission-line model for sky
- Continuum model for sky brightness, Zodiacal-light + thermal emission from sky
- Throughput estimates for fibre based on KOALA measurements, scaled to NIR
- Coupling efficiency estimates for fibre based on KOALA measurements, scaled to NIR.
- Background model based on injection optics feed design, with Narcissus mirrors (at the intermediate pupil in the starbug) and expected thermal emission from telescope optics and background.
- Slit background assumed to be negligible (as it will be cooled to 120K?)
- Can be used to model SNR for real spectra through the system.

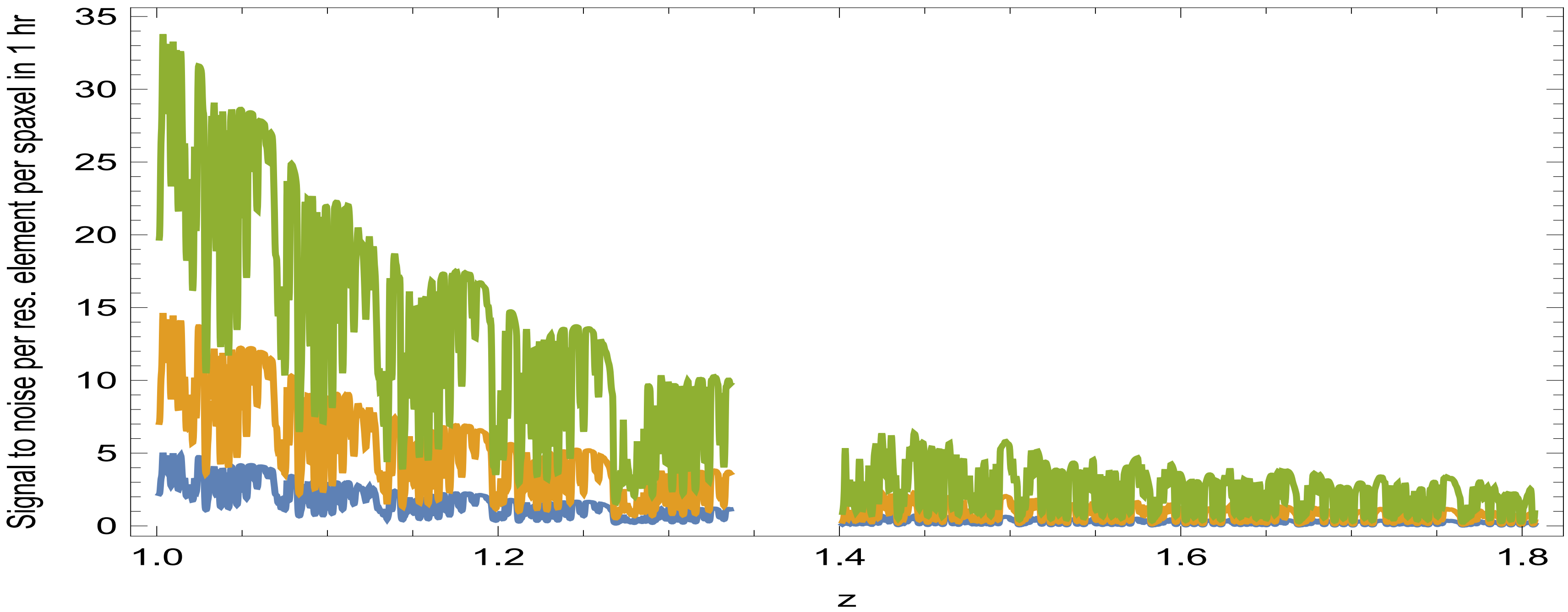
System modeling



shows the background components - black = total, red = oh lines, brown = interline continuum (measured at 590 ph/s/m^2/um/arcsec^2 by Maihara 1993), grey = fibres, green = zodiacal scattered light, purple = telescope (0 deg), blue = fore optics, yellow = gold pupil stop, cyan = microlens array

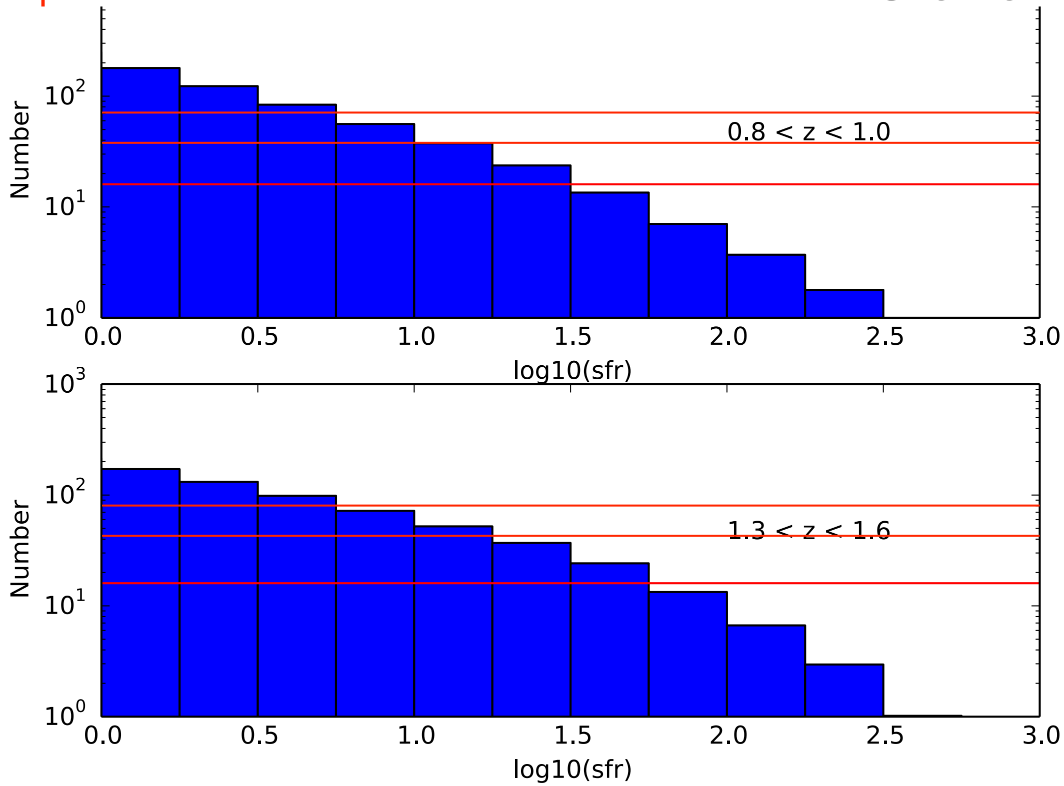


the background at the detector in 1 hr per pixel per spaxel –
each component has been multiplied by the exposure time,
the throughput of the downstream components, convolved with PSF,
binned into pixels, and multiplied by the A Omega of the system,
assumed to be preserved throughout



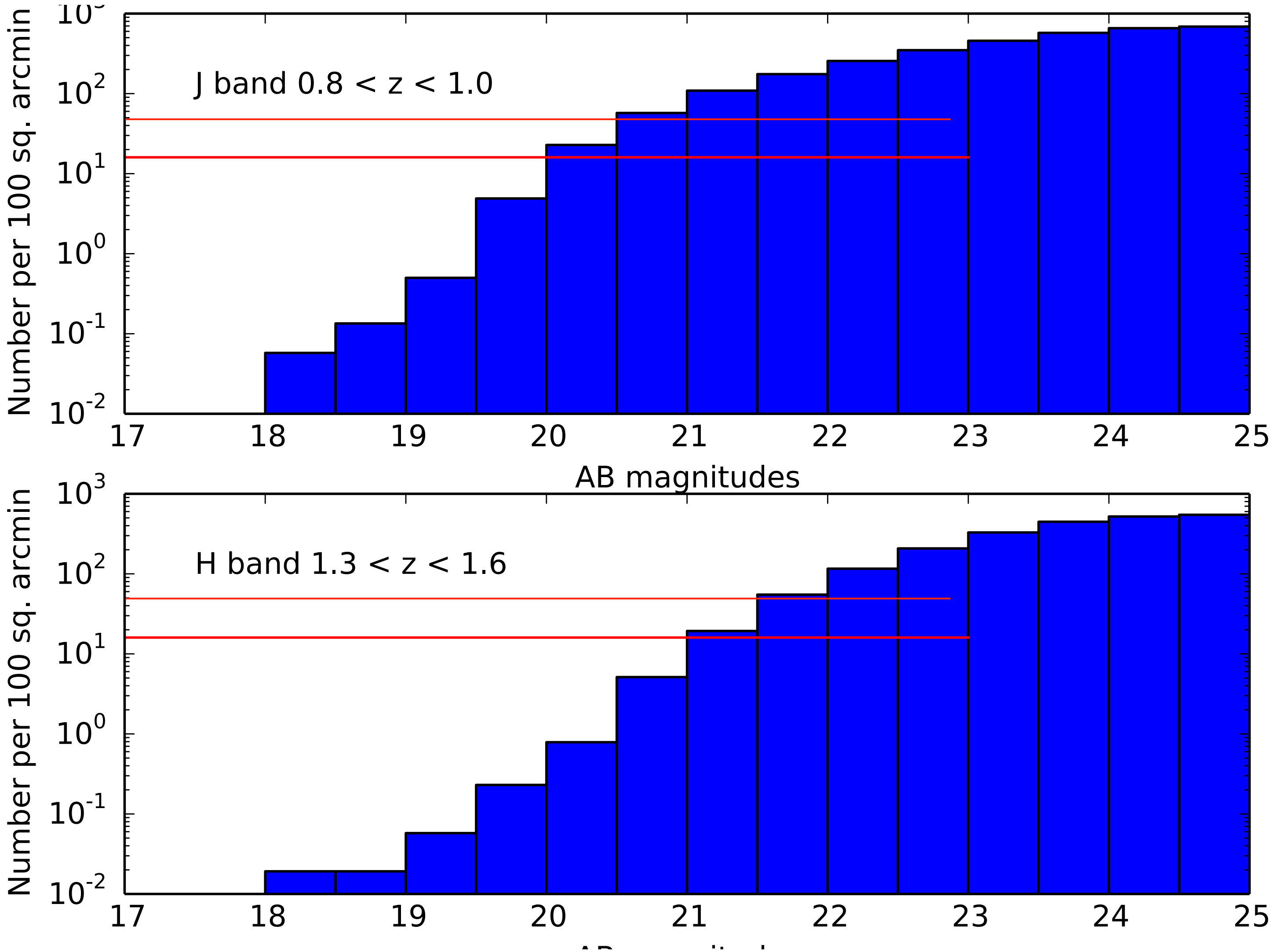
show the signal to noise per spectral resolution element per spaxel in 1 hr
as a function of redshift for observations of galaxies
with a total SFR of 3, 10 and 30 Msun/yr.
In all cases I assume the galaxy is 2" diameter, and the SFn is uniformly
spread over the area and the Ha line has a FWHM of 10A and the signal
is extracted from 1 FWHM

Target Density Star-Forming Galaxies



It can be seen that there are around 30-50 galaxies in the ULTIMATE field with star formation rates (SFR) exceeding 10 solar masses per year SFRegions are clumpy at this redshift, so may get an improved SNR with GLAO due to spatial increases

Target Density Continuum Objects



signal-to-noise ratio-2hr-nodding

- We now compute the expected signal-to-noise(S/N)ratio for a 7200 second exposure, with half the time spent on observing the sky. In computing the signal-to-noise ratio we use version 5.01 of the KMOS exposure time calculator
- • Assume 70% throughput for the fibres (measured results with Koala including coupling losses and FRD)
- assume that nuMOIRCS has 15% (20%) efficiency in the J and H bands
- • make use of the R=3000 VPH gratings
- • assume the that RON performance of the detectors in both instruments are the same
- • assume0.8”seeinginV(0.63”inHand0.67”inJ)
- • use the Kennicutt relation to convert from SFR to H-alpha flux
- • use a SFR of 10 solar masses per year (the number density of sources is such that this could be raised to 30 solar masses per year)
- • integratethesignalover1.65(2)Angstrom bins in the J(H)
- • assume that the H-alpha line is 10 Angstroms wide

Redshift	Wavelength	S/N KMOS	S/N nuMOIRCS	# IFU elements	S/N per IFU element
0.9	1246	30	24	61	3.1
1.45	1610	21	14	54	1.9

- It might be possible to use dedicated sky fibres to subtract the sky, in which case exposure times will be halved.
- The signal-to-noise ratio can be increased by
- • computing this ratio over a larger wavelength region (a gain of ~2 can be expected) and/or several spaxels
  - exposing longer
  - choosing brighter targets

signal-to-noise ratio for a full night exposure, nodding

Redshift	Mag (AB)	Wavelength	Wavelength Bin	S/N KMOS	S/N nuMOIRCS	# IFU elements	S/N per IFU element
0.9	20.5	1182	1.65	12	9	61	1.1
1.45	21.5	1653	2.03	9	6	54	0.9

- 28,800 sec exposure, half the time spent on observing the sky.
- This corresponds to one night of integration
- Not unsurprisingly, exposure times for continuum source are long and signal-to-noise ratios are modest.
- There is one important caveat.We have assumed that the background between the OH lines is similar to that used in the KMOS ETC.There has been considerable uncertainty in the true value of this background, as part of it may come the scattered wings of the bright OH lines. Removing the OH lines may result is significantly less background.
- For objects as faint as J=20.5 and H=21.5, the signal to noise ratios are more than sufficient to measure redshifts; however, they are about half of what is typically required to measure kinematics or abundances. Spatially resolved studies will be confined to brighter object and/or fewer binned spaxals.
- Phase II (a and b) will improve this!

Sensitivity comparison with MOSFIRE

	MOIRCS		MOSFIRE
	Current	New	
FOV	4'x7'		6'.1x6'.1
Imaging throughput (atm+Telescope+Instrument)	0.23(J), 0.34(H),0.30(K)		0.54(J),0.56(H),0.50(K)
Spectral resolution	500, 1300, ~3000(VPH)		3500
Grating diffraction efficiency	HK500, zJ500: 0.8(J), 0.78(H), 0.65(K) R1300: 0.2(J), 0.3(H), 0.5(K) VPH: ~0.75(J), ~0.7(H) 0.80(K)		0.60(J), 0.65(H),0.70(K)
Spec. throughput (atm+Telescope+Instrument)	HK500, zJ500: 0.18(J), 0.26(H), 0.20(K) R1300: 0.05(J), 0.10(H), 0.15(K) VPH: ~0.15(J), ~0.20(H), ~0.26(K)		0.325(J), 0.361(H), 0.350(K)
Detector	HAWAII-2	HAWAII-2RG	HAWAII-2RG
QE	~80%(JHK)		~80%(JHK)
Read-out noise	15e rms (16NDR)	5e rms (16NDR)	5e rms (16NDR)

Sensitivity comparison with MOSFIRE

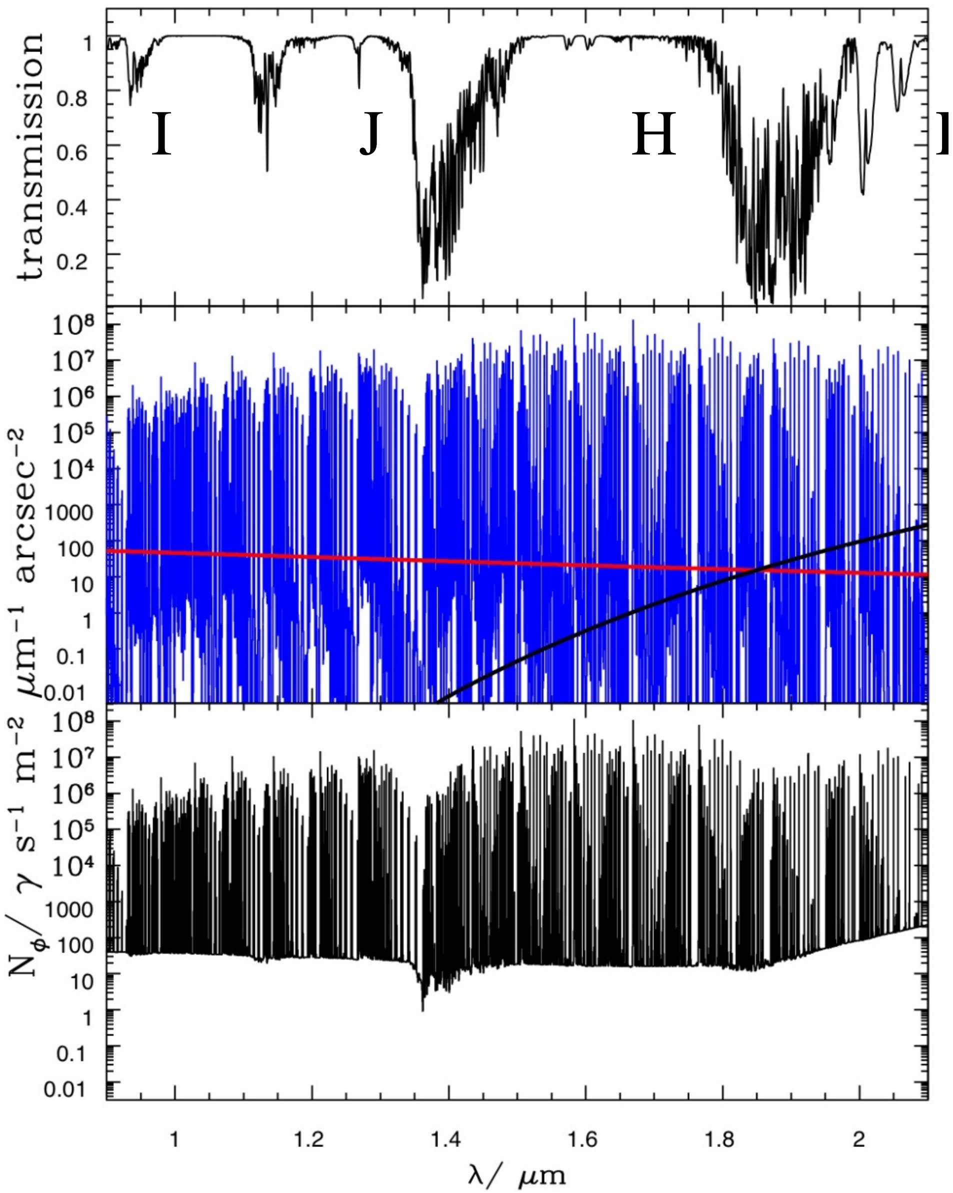
- Current MOIRCS sensitivity is 4~7 times lower than MOSFIRE (difference in the telescope diameter is not taken into account).
- If the new MOIRCS can successfully reduce the RO-noise down to 5e-, the sensitivity difference is about 1.4(VPH)~2.3(R1300).
- This difference can not be reduced without changing the optical coating.
  - MOSFIRE has 31 surfaces
  - Average throughput in each surface is about 0.992.
  - Total throughput of the optical coating is about 0.78
  - MOIRCS has 24 surfaces.
  - Average throughput of the coating is 0.983.
  - Total throughput of the coating is 0.64.

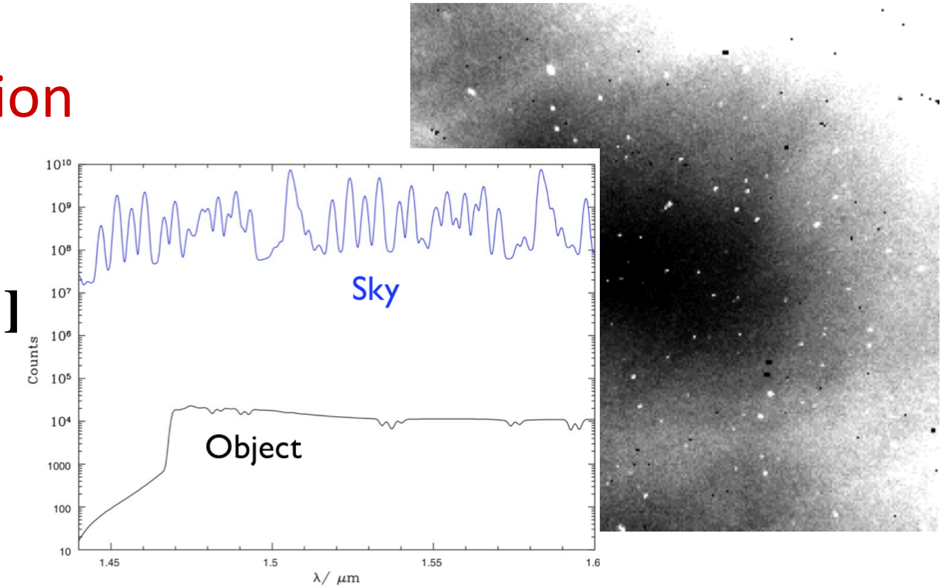
PHASE IIb

- OH Suppression fibres

OH-SUPPRESSION WITH PRAXIS

Atmospheric OH emission





OH airglow emission lines are orders of magnitude brighter than objects of interest – sky must be subtracted lead to high noise

Also spatially and temporally variable

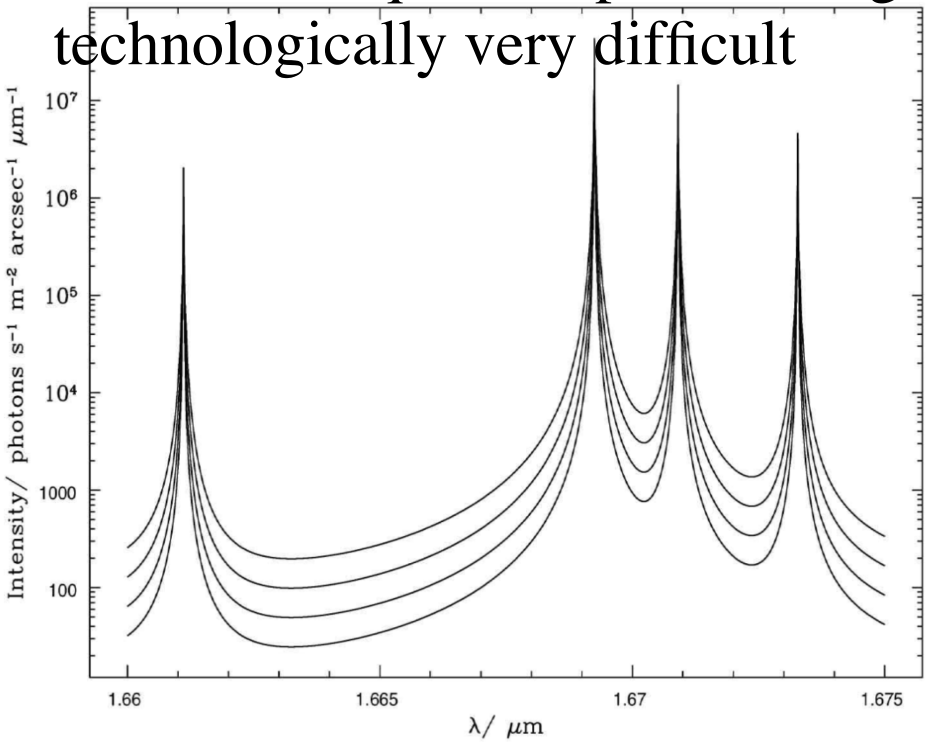
Ellis & JBH 2008

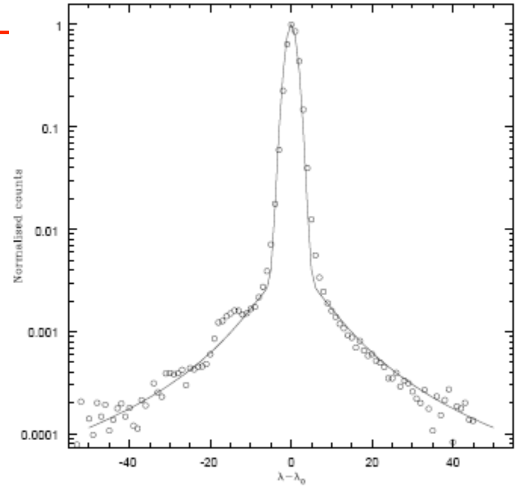
Spectrograph scattering

Scattering in optics of spectrographs show broad Lorentzian wings

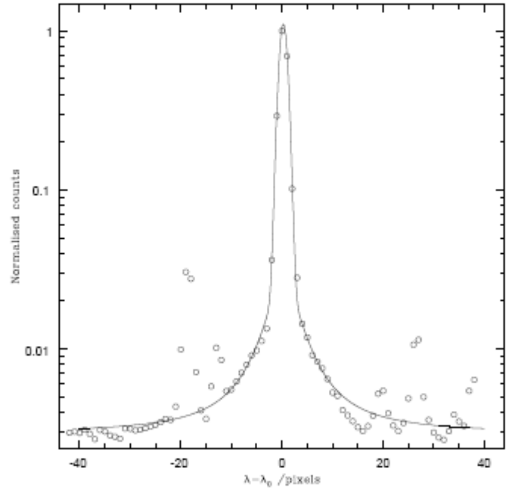
OH dispersion masking cannot thus remove

Other techniques for pre-filtering technologically very difficult



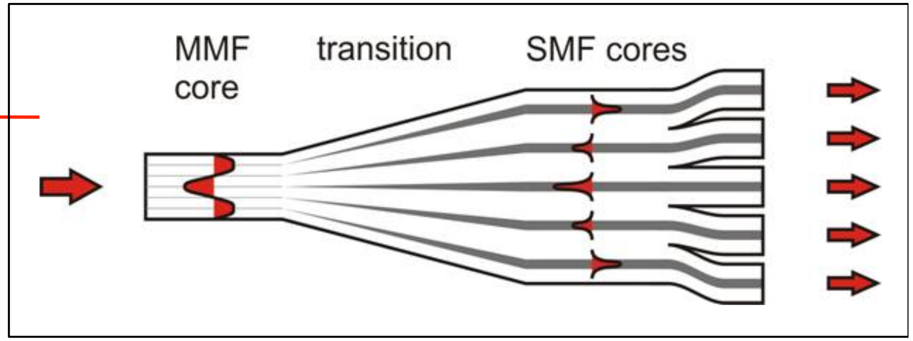


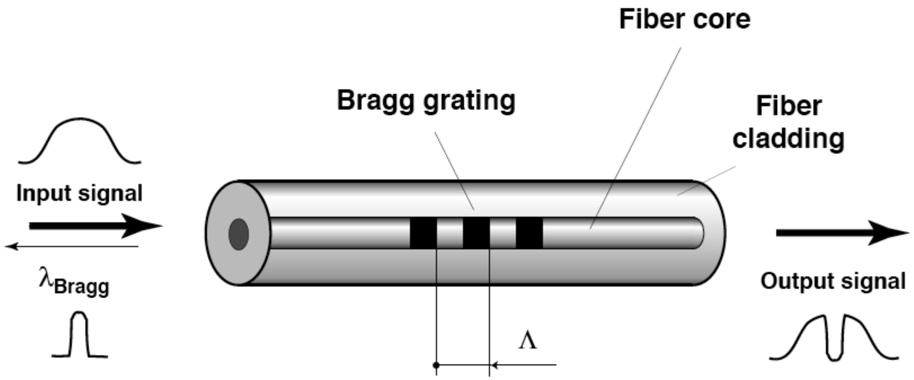
(a) AAOmega, $a = 0.97$ and $f = 5.5$.

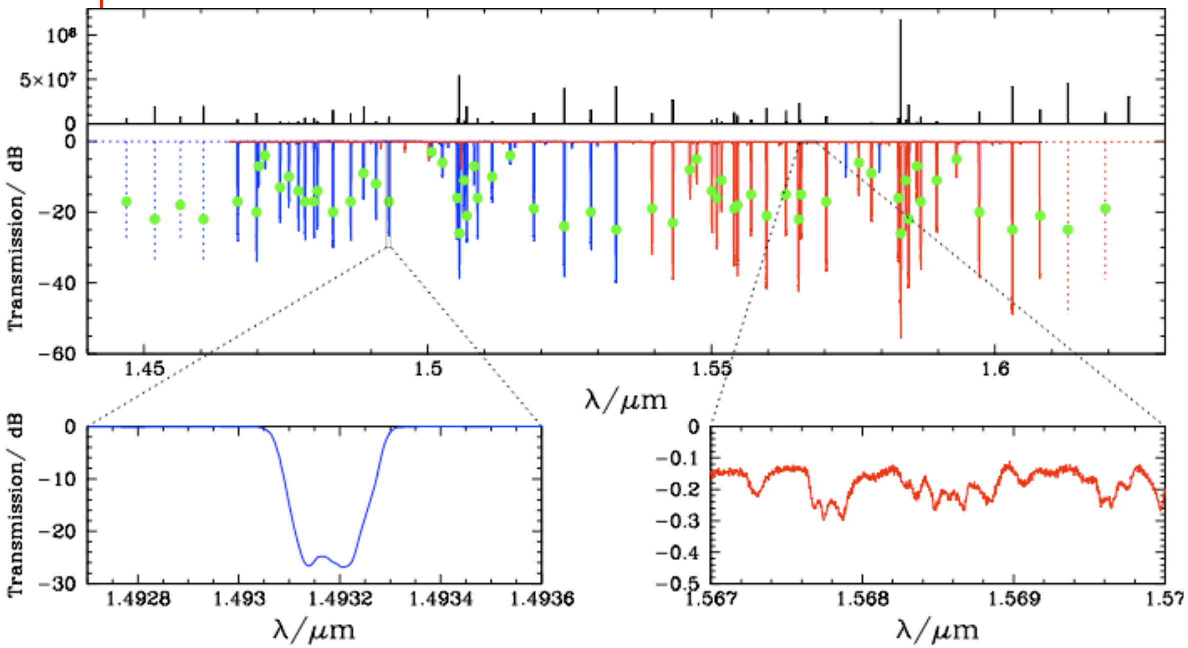


(b) IRIS2, $a = 0.89$ and $f = 4.0$.

Photonic OH suppression







A fibre Bragg grating (FBG) consists of a fibre with a periodic variation of core refractive index that acts as a wavelength specific dielectric mirror

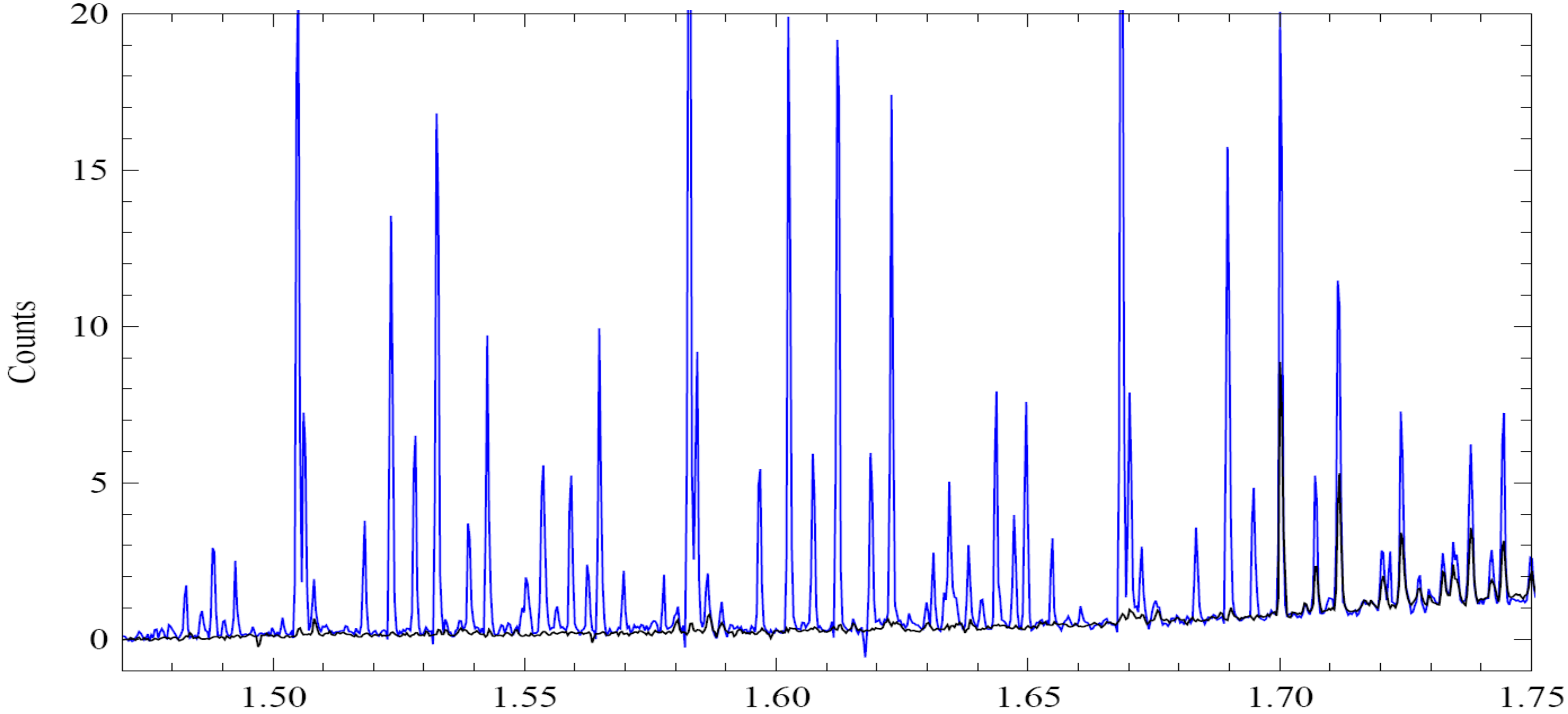
Requires single mode fibres: thus need photonic lantern

Very complex pattern of refractive index variation in optical fibre core can be used to cancel out all of the (hundreds of) atmospheric OH emission lines. The most complex filter ever conceived, manufactured and demonstrated...

Ellis & Bland-Hawthorn, MNRAS, 2008

GNOSIS preliminary results

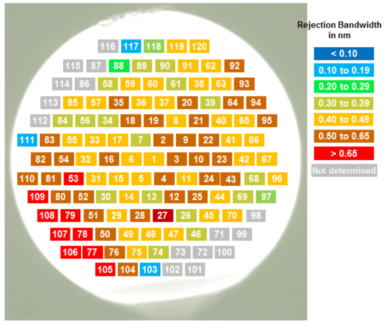
Commissioning at the Anglo-Australian Telescope during 2011

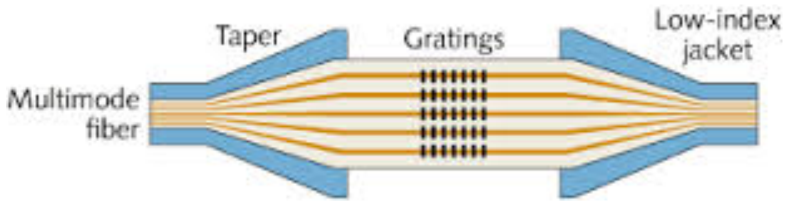


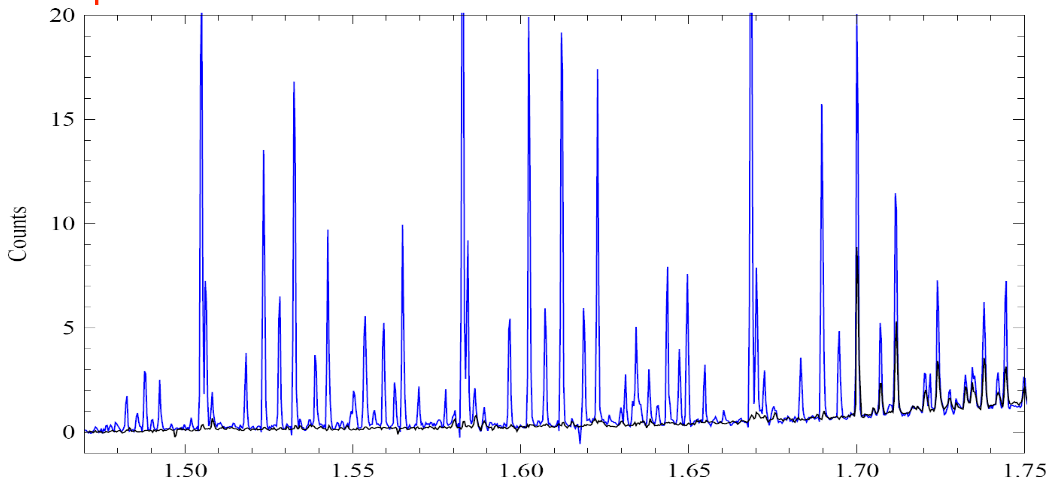
- Demonstrated operational requirements met
- Demonstrated level of suppression
- Interline continuum not yet reached – detector noise specification
- **Next steps:** Instrument scalability an issue – significant R&D program to address and develop J-band gratings for 8-metre class telescopes

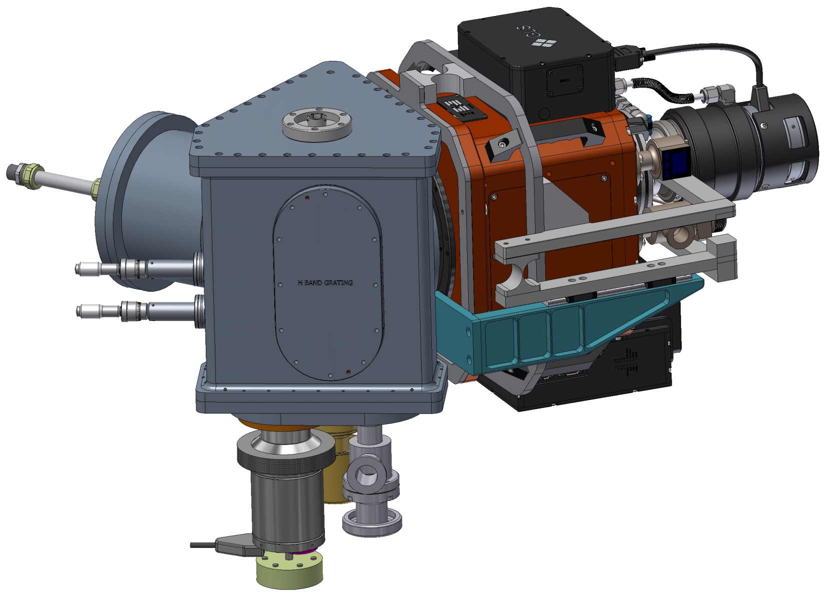
OH suppression and PRAXIS

- GNOSIS used fibre Bragg gratings to suppress OH emission with IRIS2: issues with sensitivity
- PRAXIS is new dedicated spectrograph with H2RG detector
- Parallel development of FBG in multi-core fibres
- PRAXIS due on-telescope at AAT early 2015
- Likely require high altitude site for verification of technique – late 2015



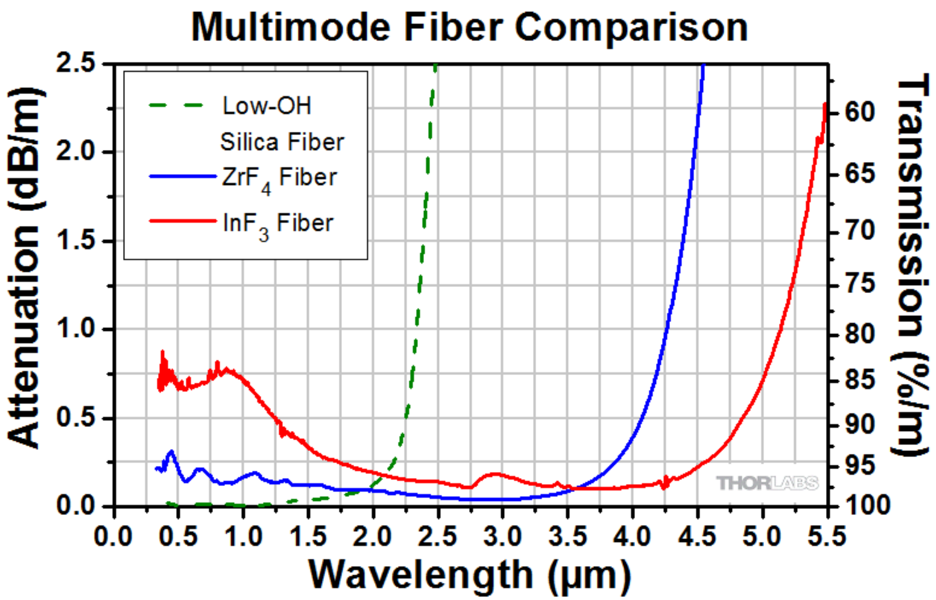






K band fibres

- Standard fused-silica fibres limit operation to H band and shortwards.
- Flouride fibres are available that transmit to K band and beyond however these are impractical
  - Absorption limits length to a few metres (ie spectrograph not gravity invarient)
  - Significant development required for interfacing
  - High cost
  - High risk

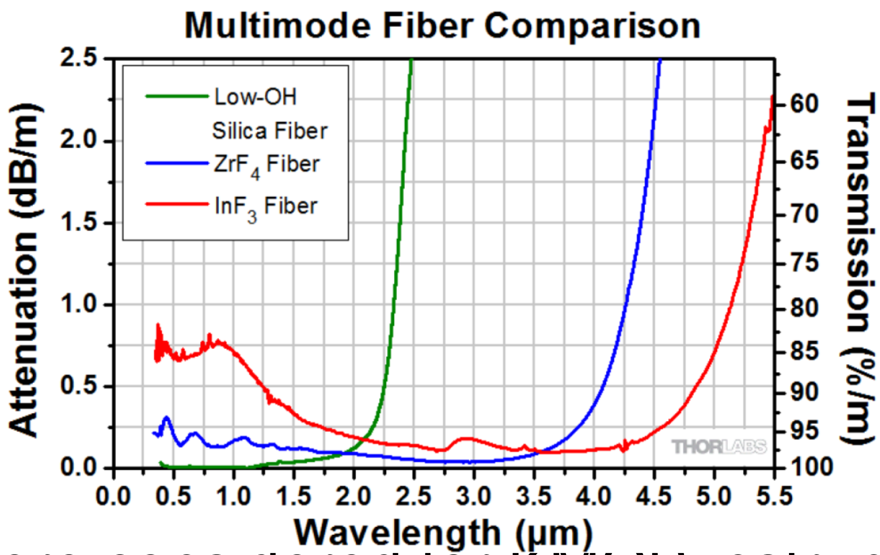


K-band fibre technology

- Production lines are built to satisfy the needs of industry
- Telecommunications required low OH (water free fibres) in early 2000.
- Fibres were developed and they are used for 20-30 meter fibre feeds in J and H bands
- Industrial applications of IR fibres are limited to laser power delivery over short distances

K-band fibre technology

- Typical transmisson of IR fibres is 0.1-0.2 dB/m ~ 30% over 30 meter link



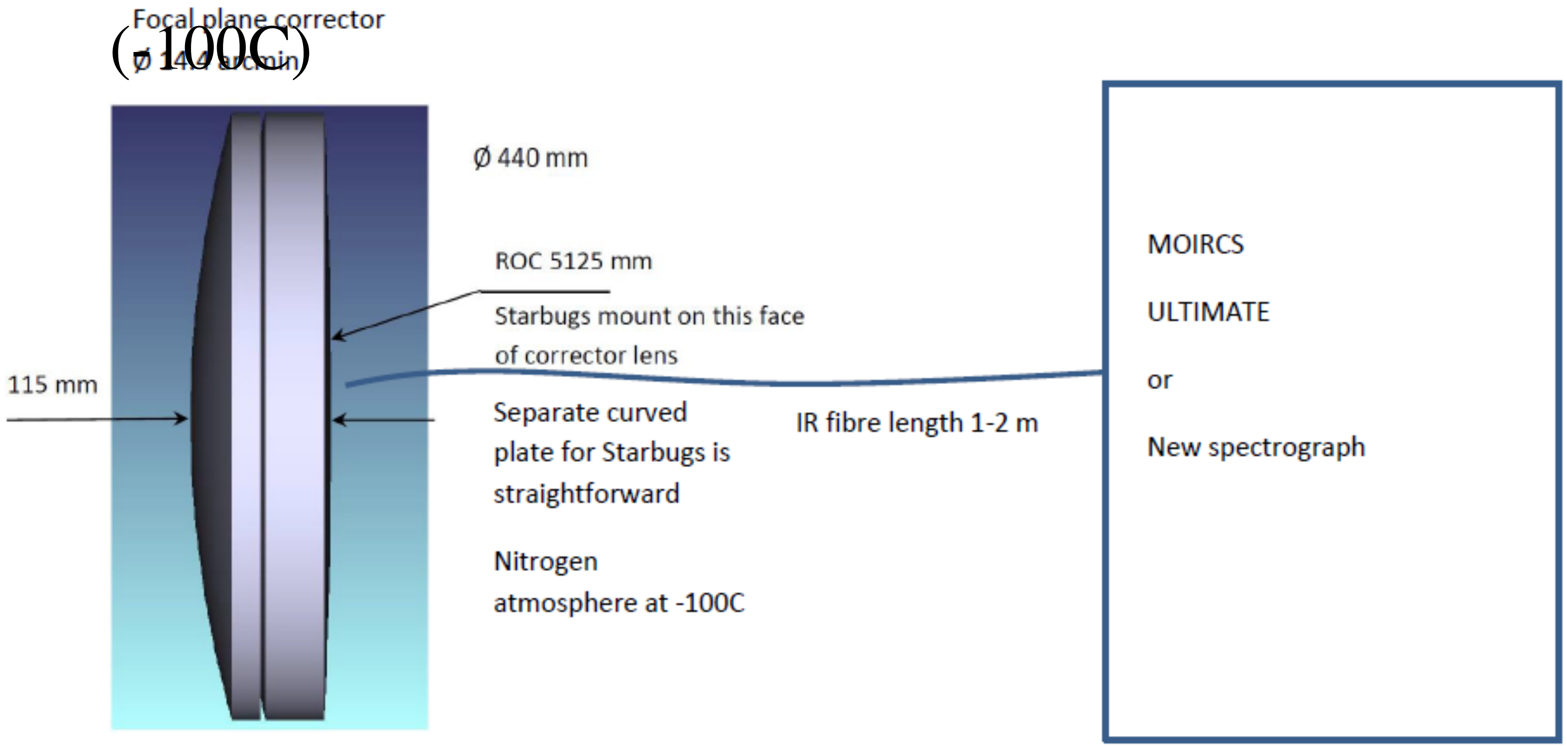
- Fibres were considered for KMOS instrument
- KMOS was built with optical IFU slicer

K-band fibre instrument

K-band requirements:

Fibres must be short (1-2 meters)

Fibres must be cooled for K-band (-100C)



Domo arigato