Integral Field Spectroscopy: Past, Present & Future

Ray Sharples
Centre for Advanced Instrumentation
Department of Physics
Durham University
UK

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Outline

- Advantages of integral field spectroscopy
- Techniques for integral field spectroscopy
- GNIRS IFU design & manufacture
- Multiple integral field spectroscopy (KMOS)
- Future prospects

Advantages of integral field (3D) spectroscopy

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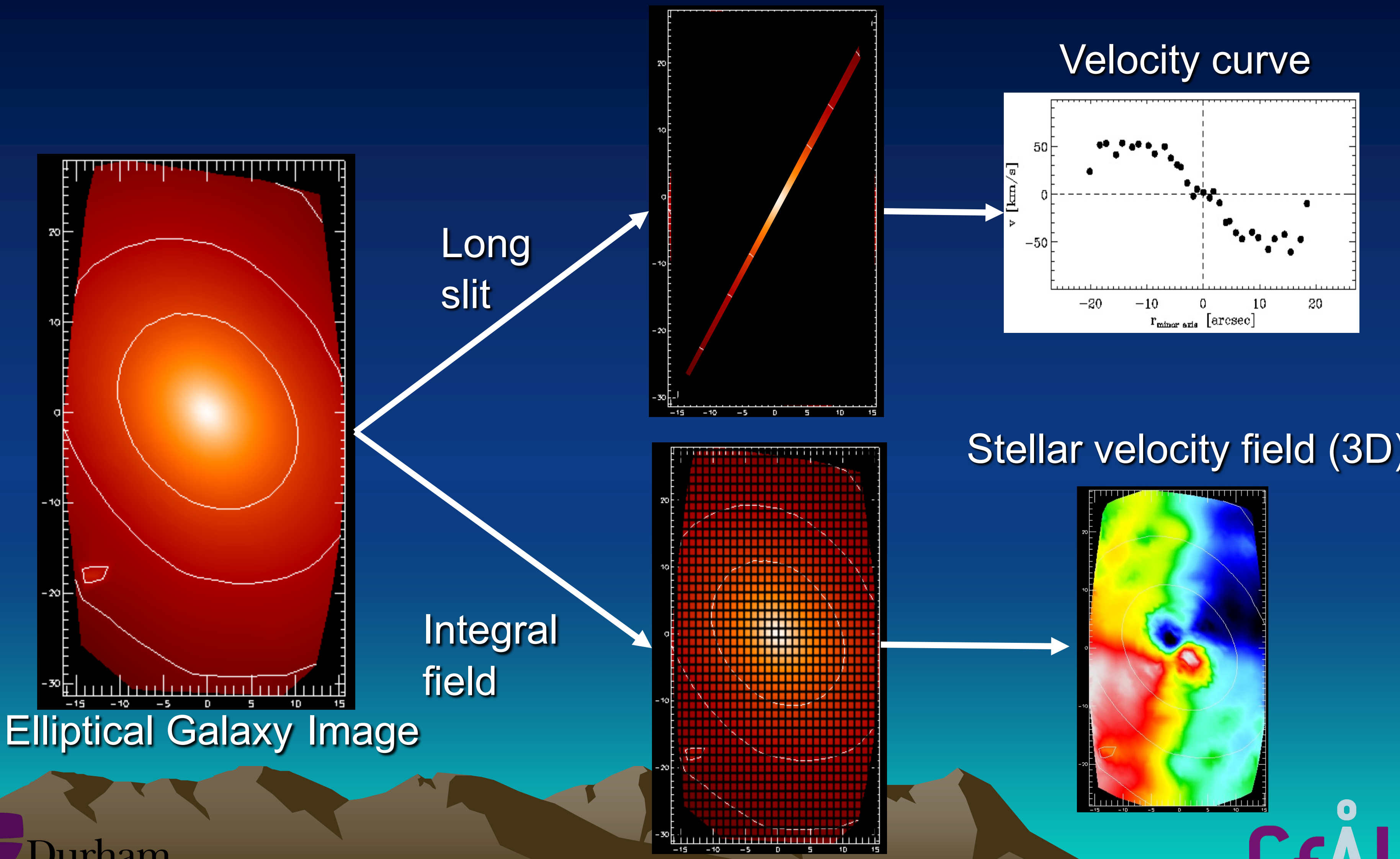
The Universe is not one dimensional!



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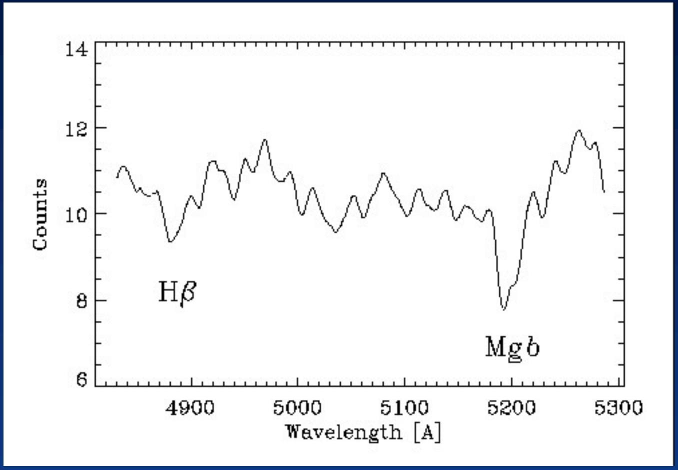
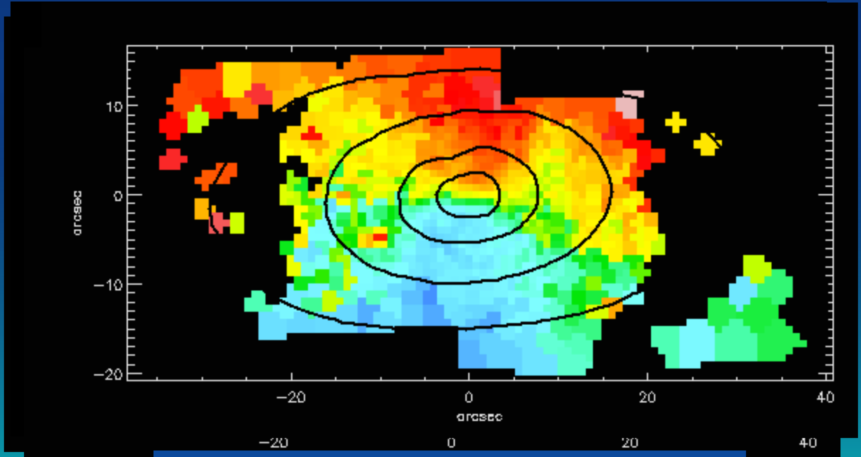
What do you get from an IFU?

- Total flux
  - Morphology, photometry
- Absorption lines
  - Stellar kinematics
    - LOSVD (V,σ,h3,h4)
  - Line strength index
    - Hβ, Mgb, Fe5015, Fe5270
- Emission lines
  - Gas distribution
    - Hβ, [OIII], [NI]
    - Line ratios
  - Gas kinematics
    - V(Hβ), V([OIII]), FWHM(Hβ), FWHM([OIII])





Gas velocity map
[OIII] line intensity

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Techniques for integral field spectroscopy

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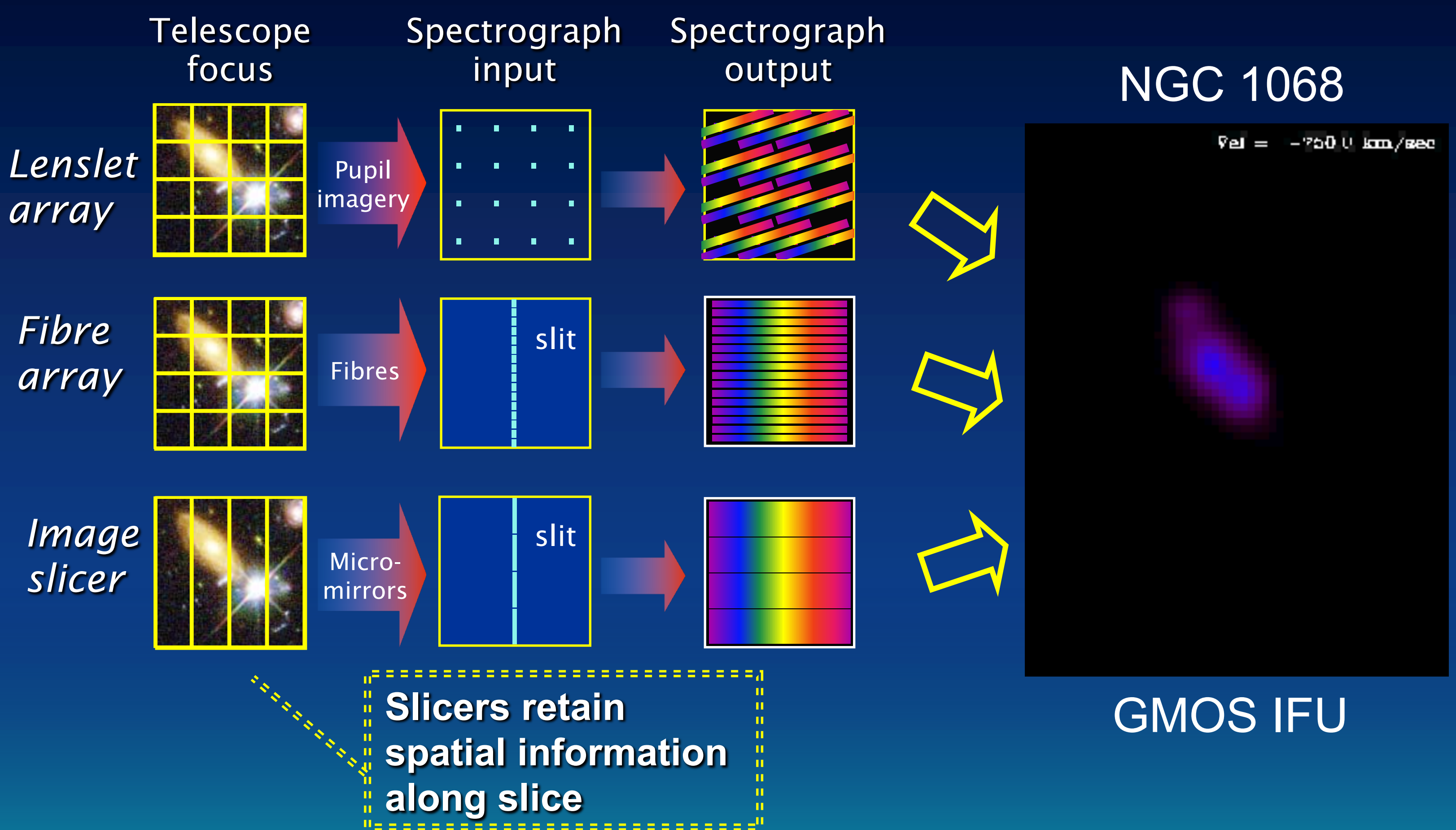
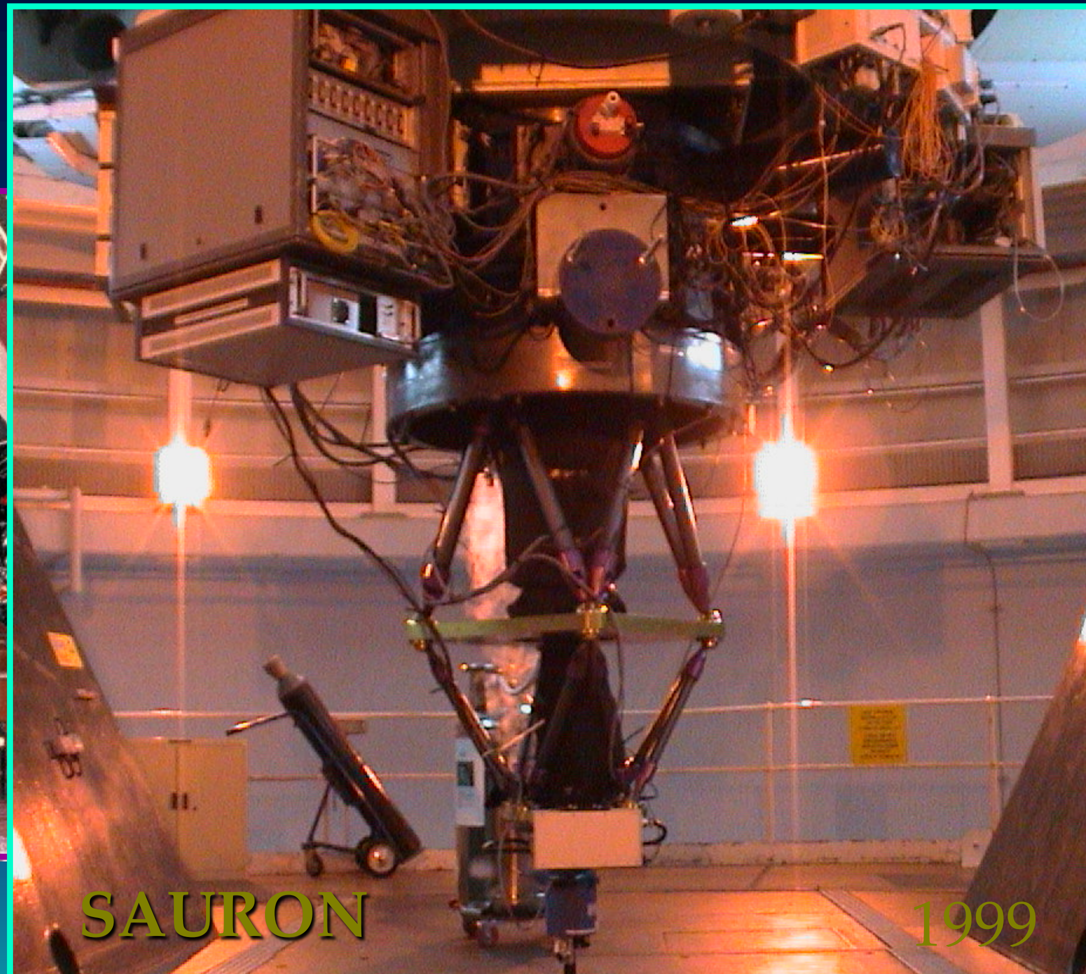
Main techniques of IFS

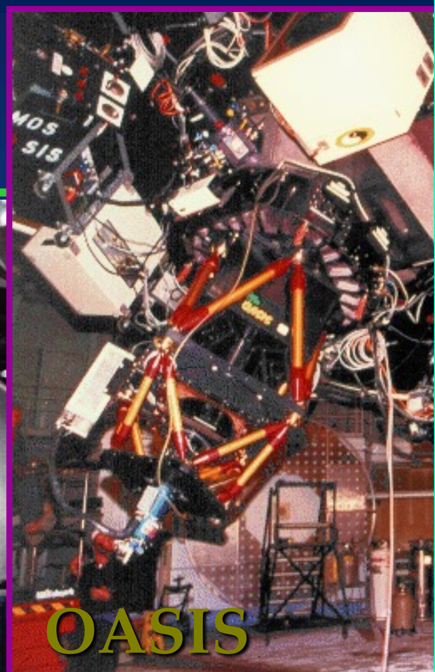


Lenslet IFS: TIGER, OASIS and SAURON

Panoramic



High-resolution



Prototype

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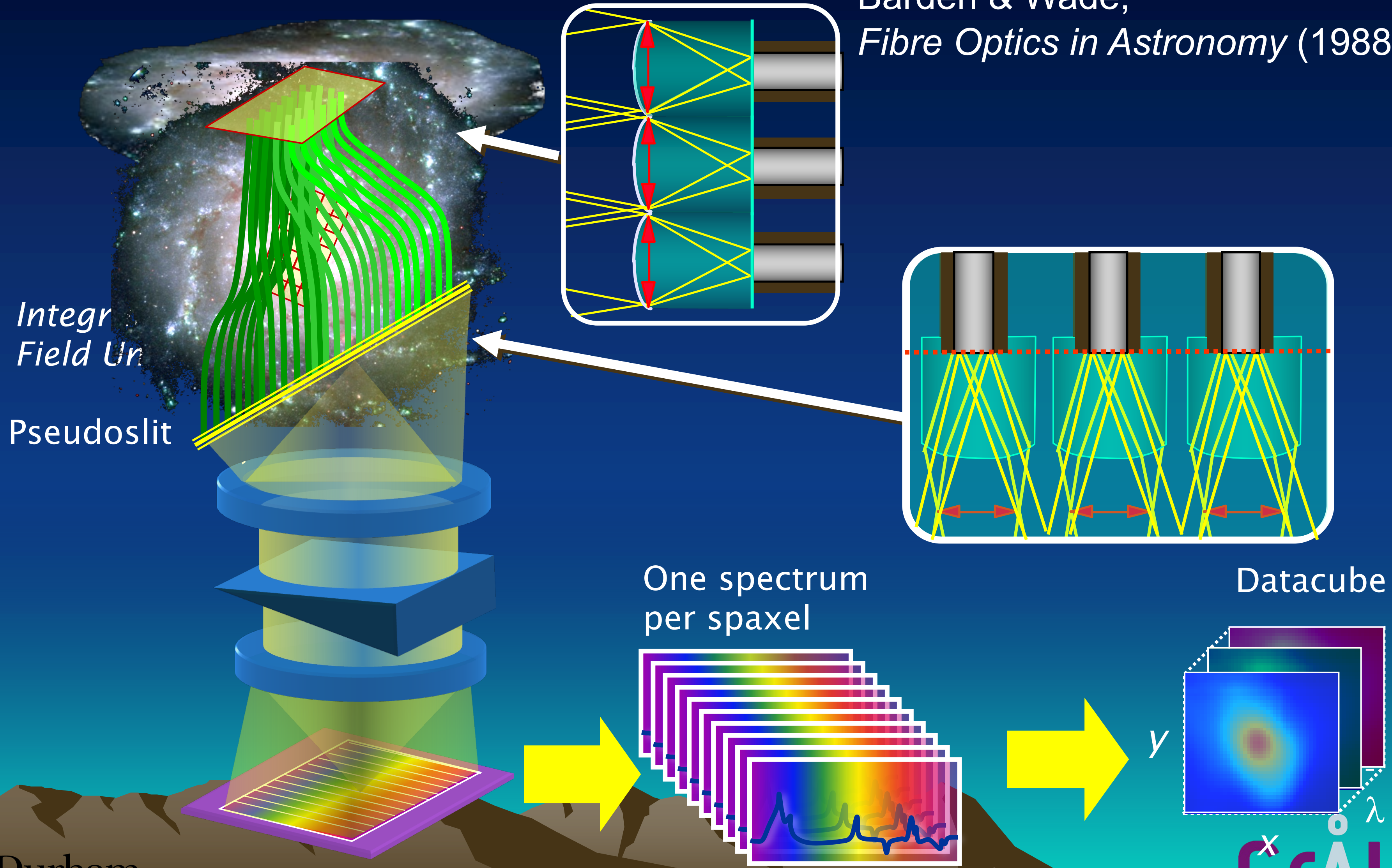
[Lenslet +] fibre IFS

DensePak (KPNO)
Barden & Wade,
Fibre Optics in Astronomy (1988)



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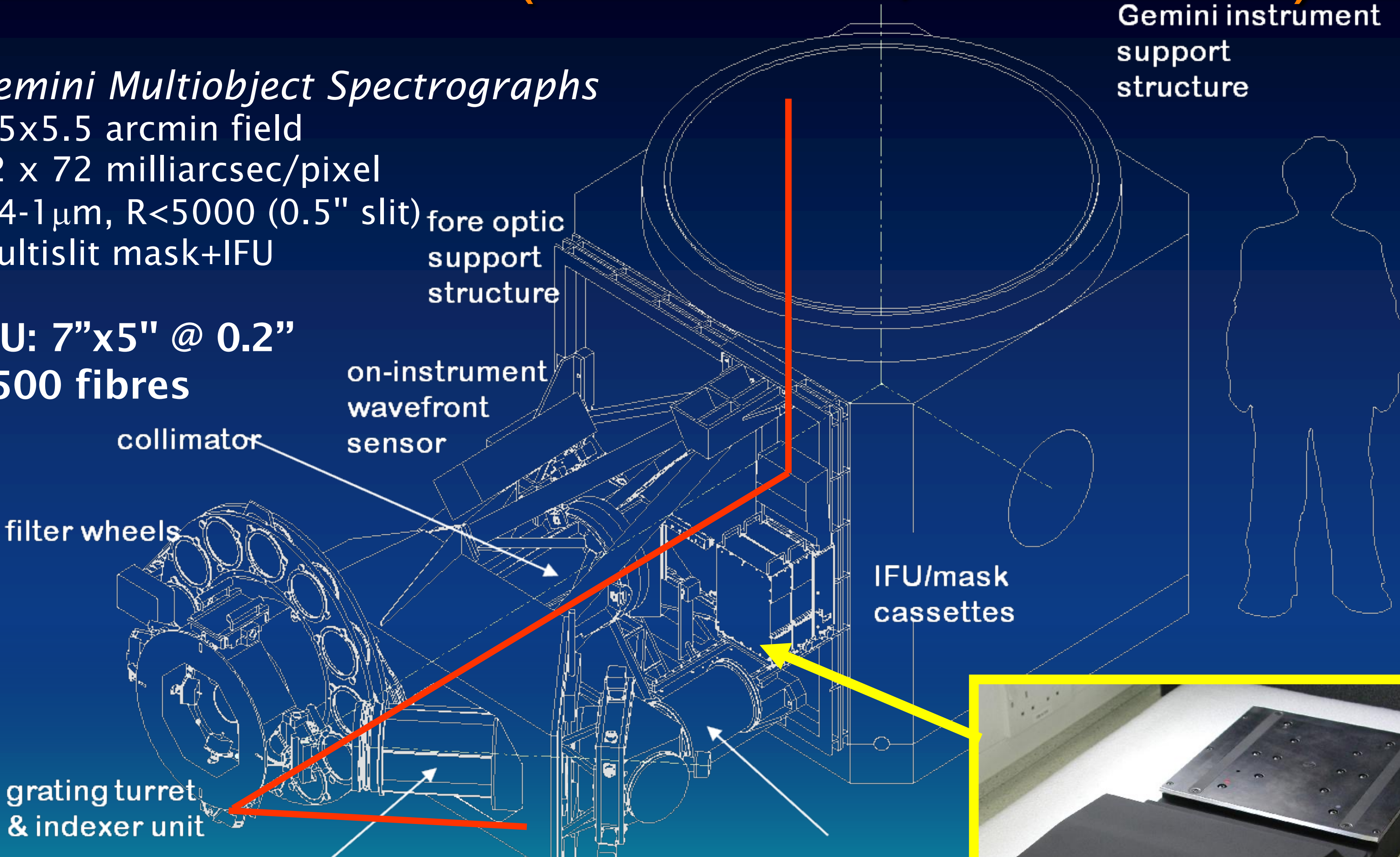
GMOS-IFU (G-N: 2001; G-S: 2002)

Gemini Multiobject Spectrographs
5.5x5.5 arcmin field
72 x 72 milliarcsec/pixel
0.4-1μm, R<5000 (0.5" slit)
multislit mask+IFU

IFU: 7”x5" @ 0.2”
1500 fibres



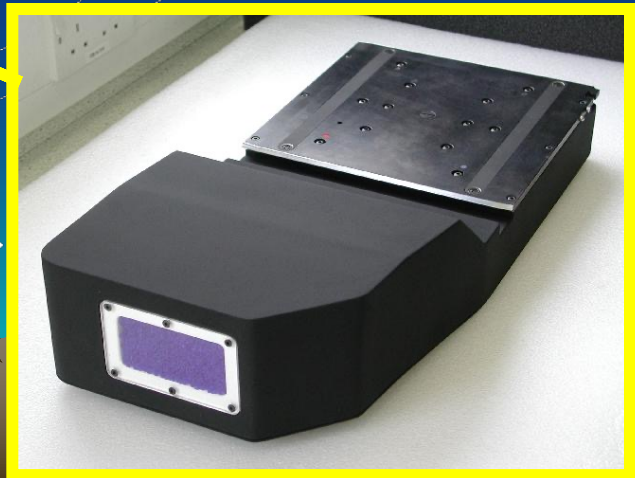


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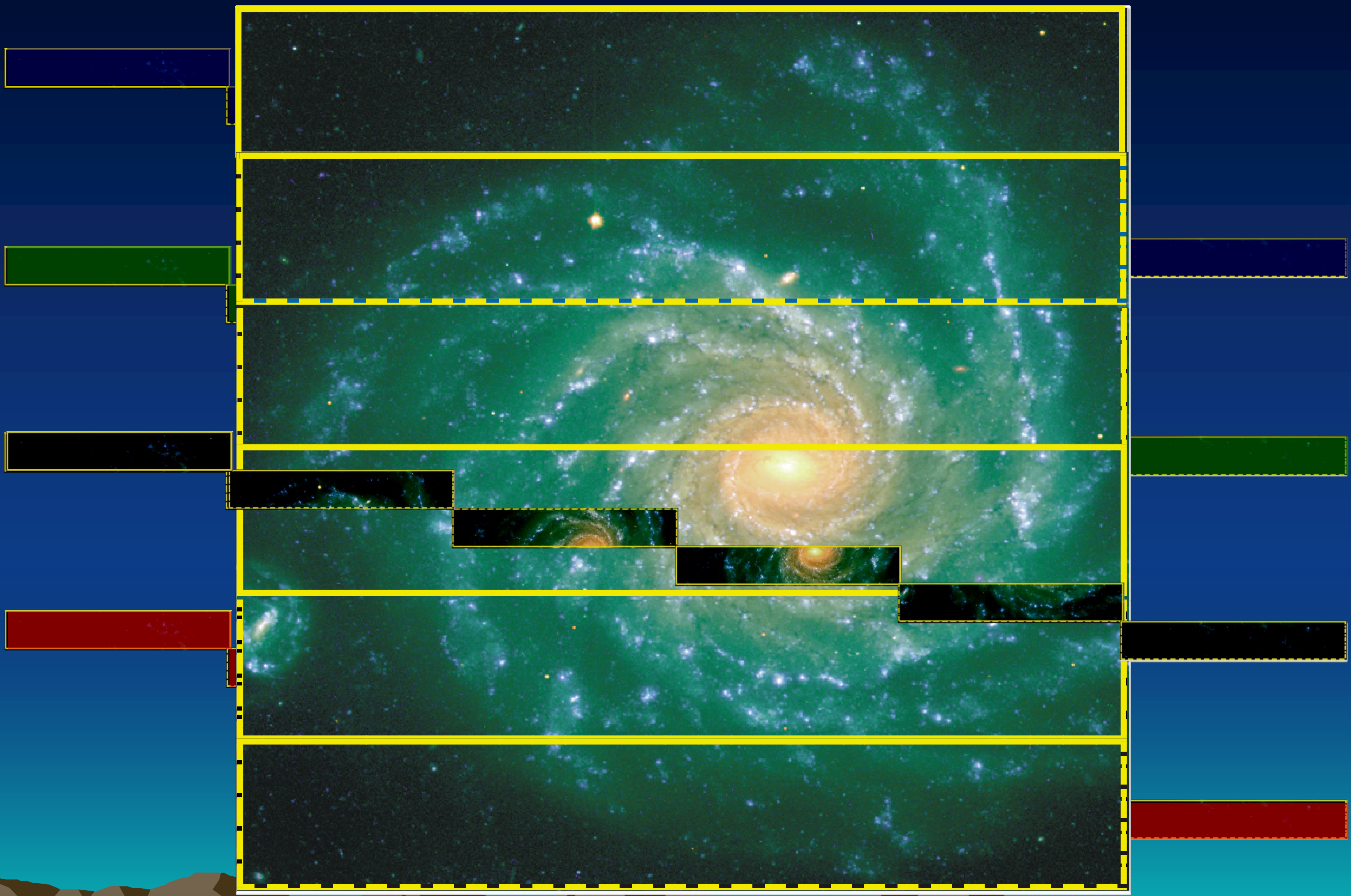
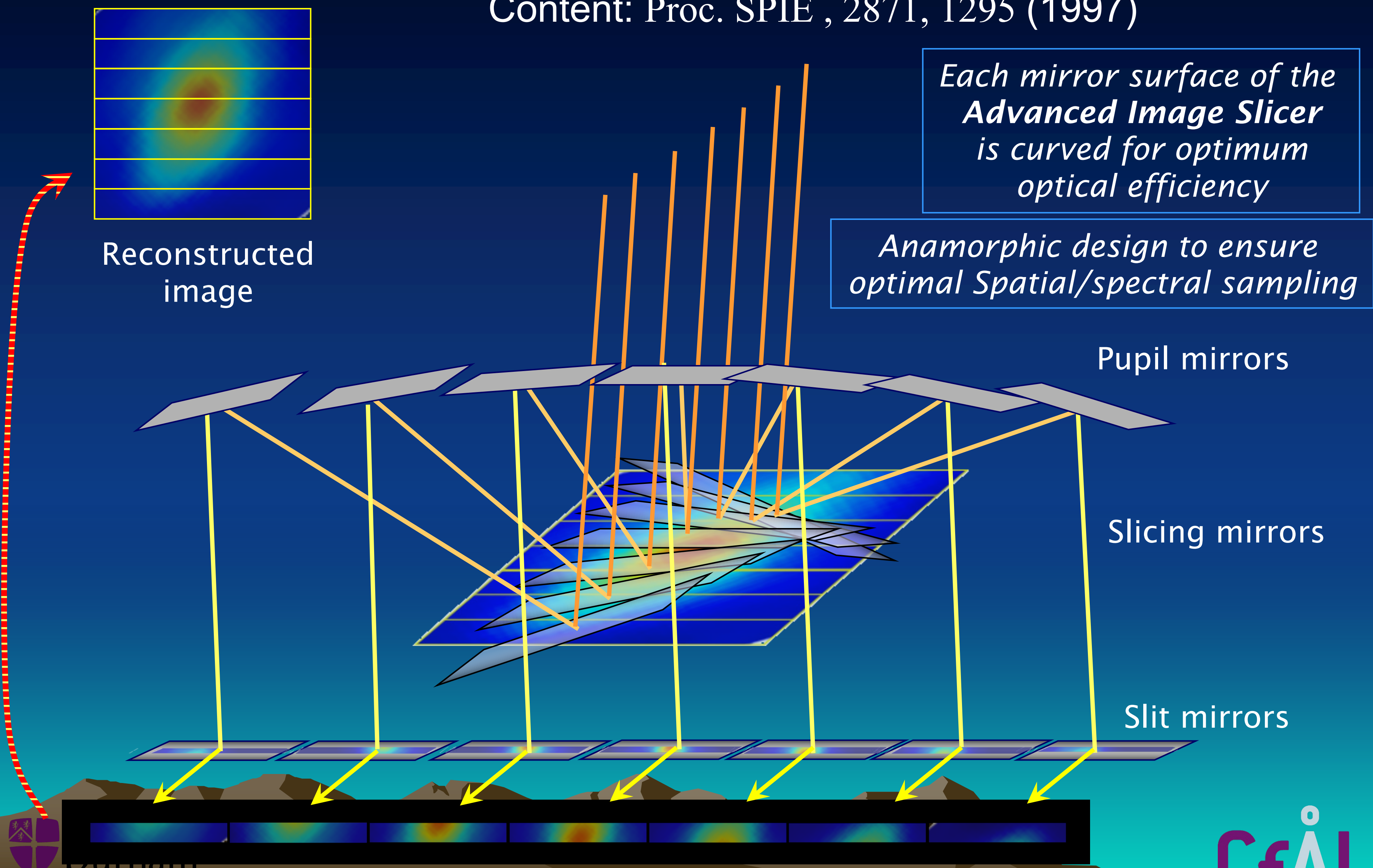
Image slicers



SPIFFI: Tecza et al SPIE 3354, 394 (1998)

Advanced Image Slicers

Content: Proc. SPIE , 2871, 1295 (1997)



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Best technique?

slicer : lensed fibre array : lenslet array

Specific information density?

25 : 5 : 1

Complexity?

many different tiny smooth mirrors :
accurately co-registered fibre & lenslet arrays
:
simple lenslet array

Allington-Smith, 2006, New Astr. Rev., 50, 244

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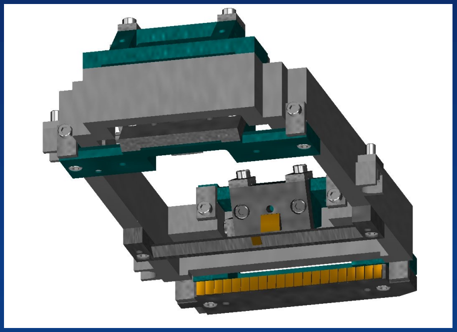
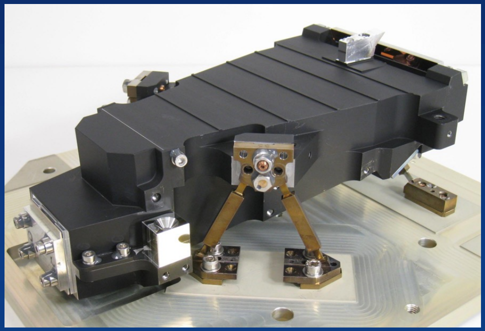
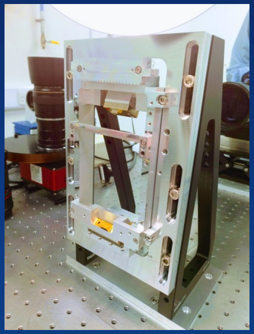
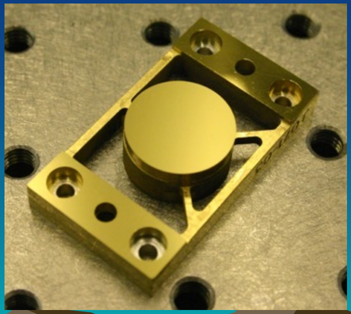
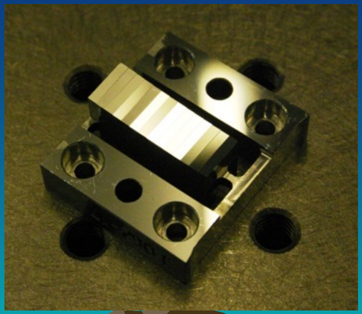
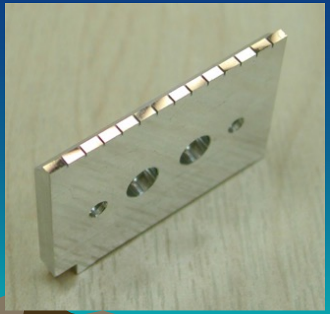
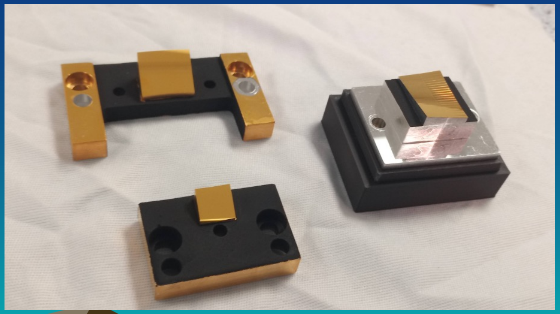
Durham Single Image Slicer IFUs

- GNIRS-IFU (2004): 21 slices, 0”.15 sampling, IFU for the
- GNIRS spectrograph of GEMINI South
- NIRSPEC-IFU (2008): 30 slices, 0”.10 sampling, IFU for the NIRSpec spectrograph on JWST (with SSTL)
- GNIRS-IFUs (2022): 2x IFUs: LR-IFU with 21 slices, 0”.15 sampling, HR-IFU with 25 slices, 0”.05 sampling for Gemini North

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New GNIRS IFUs

	LR IFU	HR IFU
Spaxel Size	0".15	0".05
No. of slices	21	25
FoV	4".8 x 3".2	1".8 x 1".25
GNIRS Camera	Short	Long
No. spatial elements	672 (21 slices x 32 pixels)	900 (25 slices x 36 pixels)

LR IFU replaces original destroyed by overheating in 2007.
GNIRS Spectrograph: Alladin 1024^2 InSb detector 1-5μm.
HR IFU is a new design optimized to exploit ALTAIR AO.
Achromatic so can exploit both blue & red cameras.
'Unique' capabilities in L,M bands and all-sky 'LGS+P2'.

Example science:
(1) Kinematics of stellar outflows in the Quintuplet Cluster
(2) Resolving the AGN-Starburst connection in active galactic nuclei
(3) Estimating black hole masses from infrared line diagnostics and reverberation mapping
(4) Resolved spectroscopy of gravitationally lensed galaxies
(5) Resolving jet kinematics in Class 0/1 Herbig-Haro (HH) objects

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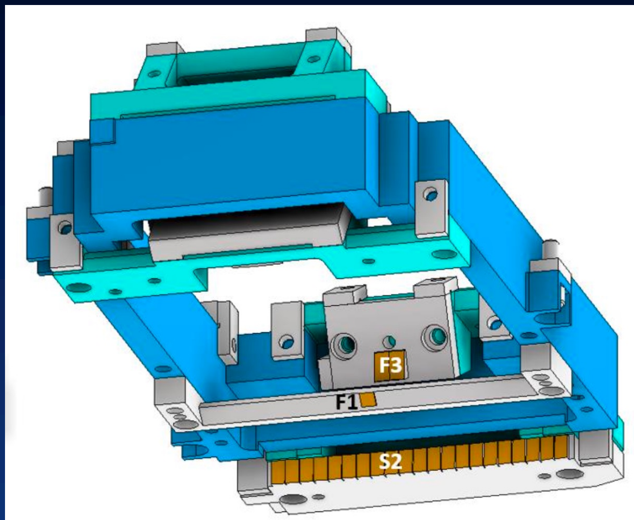
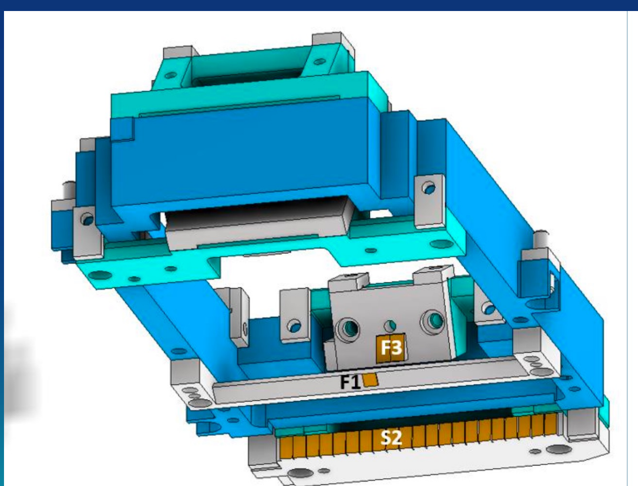
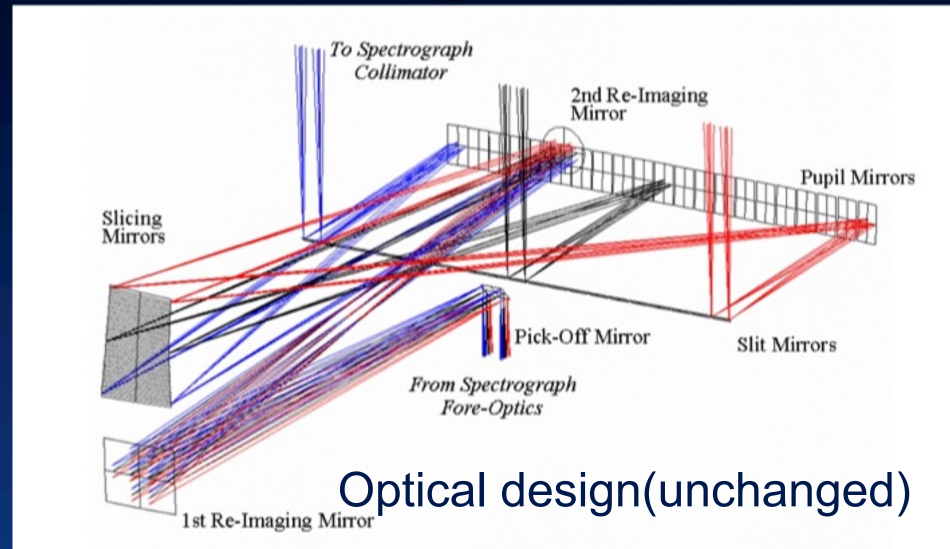
LR-IFU Design





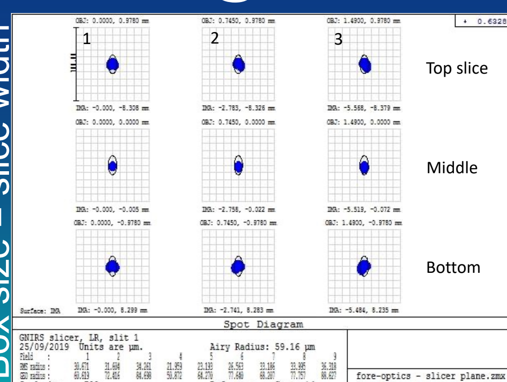


Optical design(unchanged)

Slicer array pivots about centre of slice and hence is manufactured in two halfs)

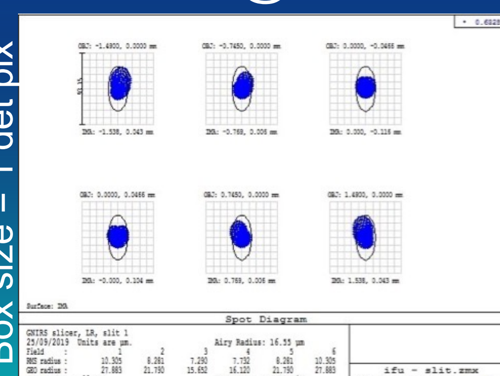
PSF @ Slicer

Box size = slice width



PSF @ Slit

Box size = 1 det pix



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LR-IFU Manufacture

MACHINING METHOD

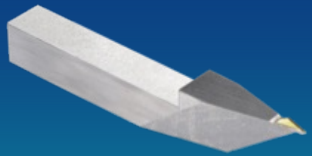
Fore Optics : Off-axis single point diamond turning for F2 and F3 (toroidal).
Slicer Optics: 5-axis Diamond Raster Flycutting (30hrs).

The new GNIRS IFUs benefit from advances in material and processes, with the use of material produced by a **Rapid Solidification Process (RSP)**:

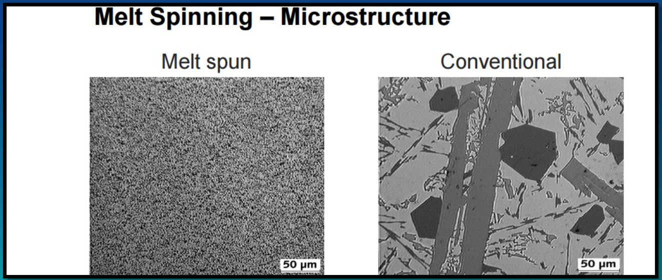
- Finer microstructure than conventional alloy.
- Enabling lower surface roughness [losses ~ $(\sigma/\lambda)^2$].

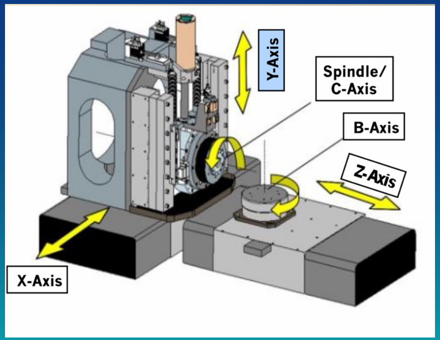
Nanotech 5-axis 350FG

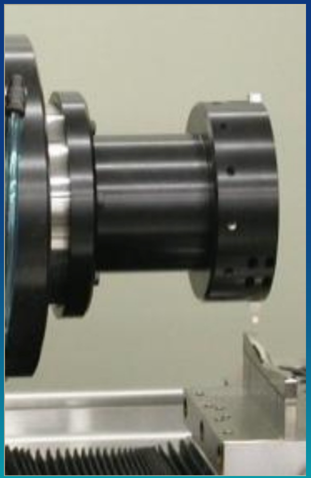
Cryocycling after rough blank machining to remove residual stress.



Diamond tool (5µm radius)







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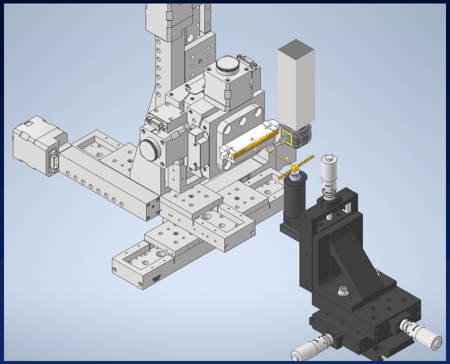
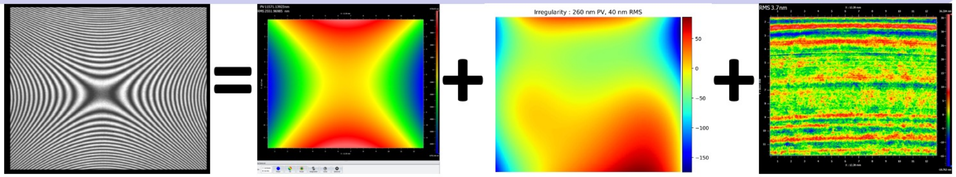
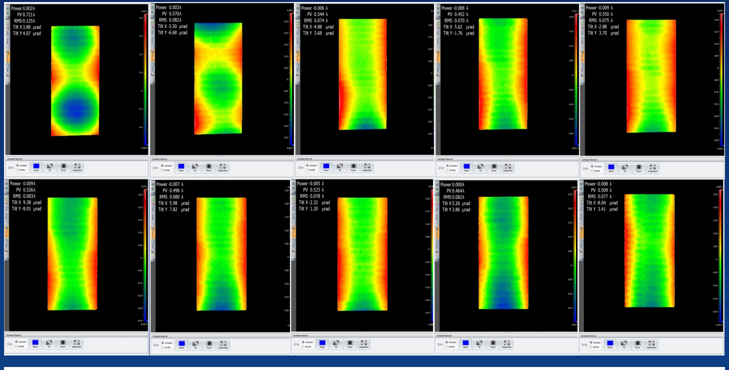
LR-IFU Metrology

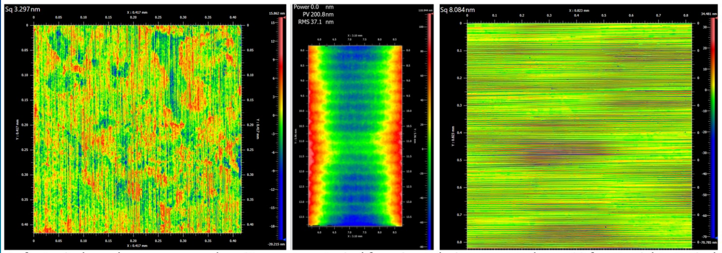


Fore optics



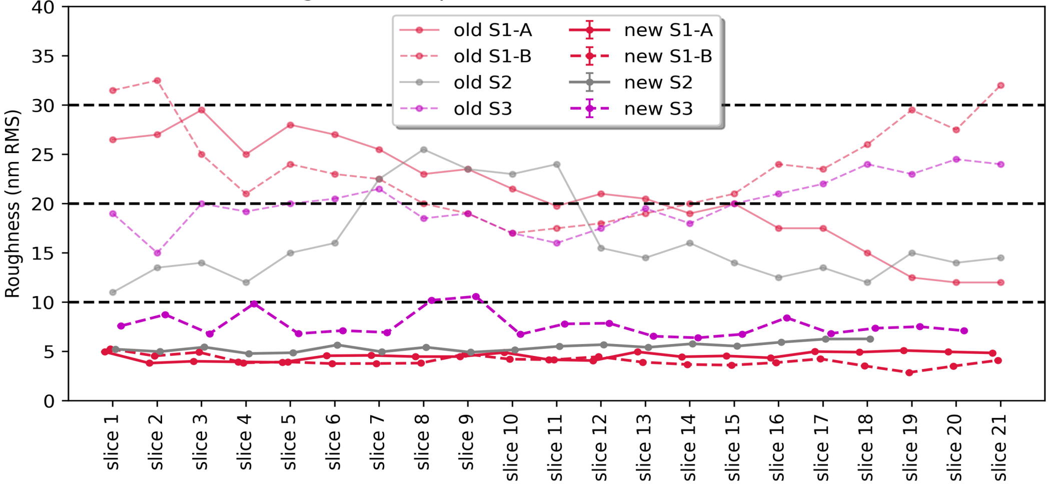
- Typical form on full aperture **260 nm PV, 40nm RMS.**
- Typical roughness **3.7 nm RMS.**





Left : typical roughness measured on S1 – centre : typical form irregularity measured on a S2 facet – right : typical roughness measured on S3.

Slicer optics



- The roughness has been improved by a factor **2 to 5**.

For further info: cyril.bourgenot@durham.ac.uk

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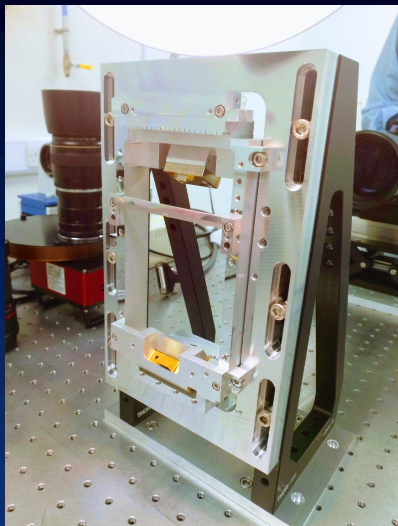
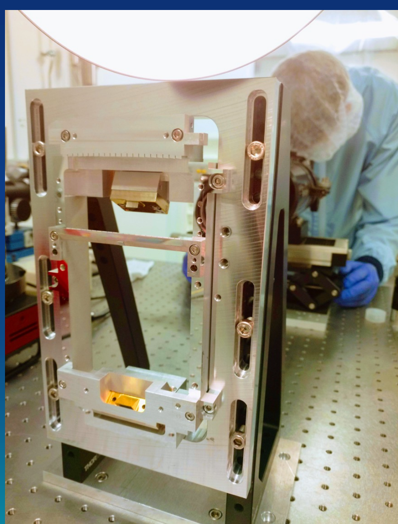
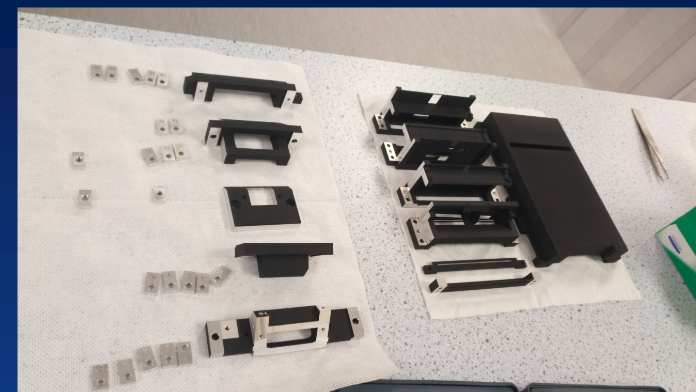
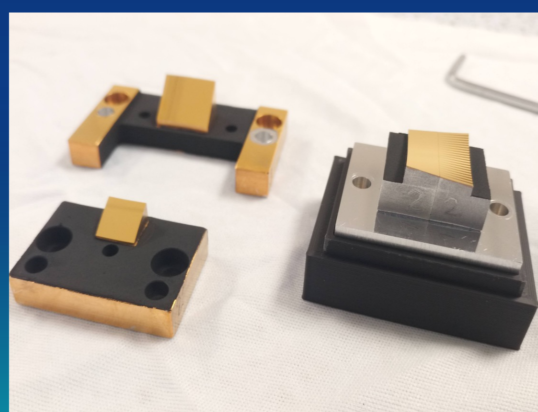
LR-IFU AIT

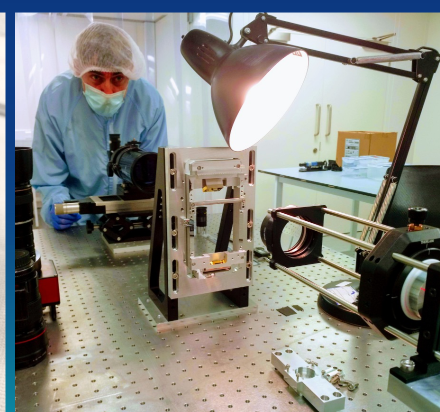
Relies on accurate machining of reference surfaces during the diamond machining process.
'Plug & play'.











For further info: c.m.dubbeldam@durham.ac.uk

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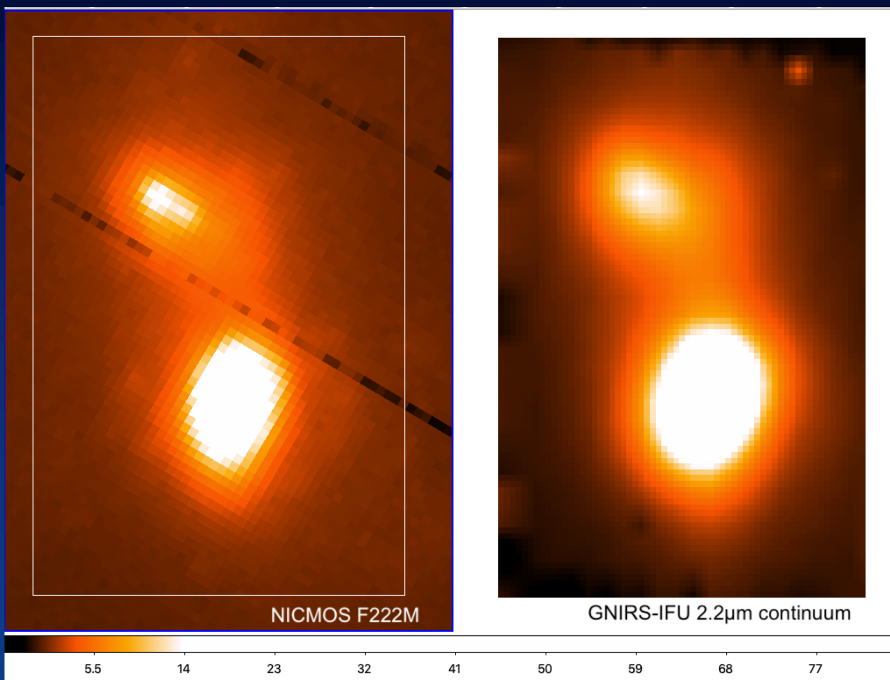
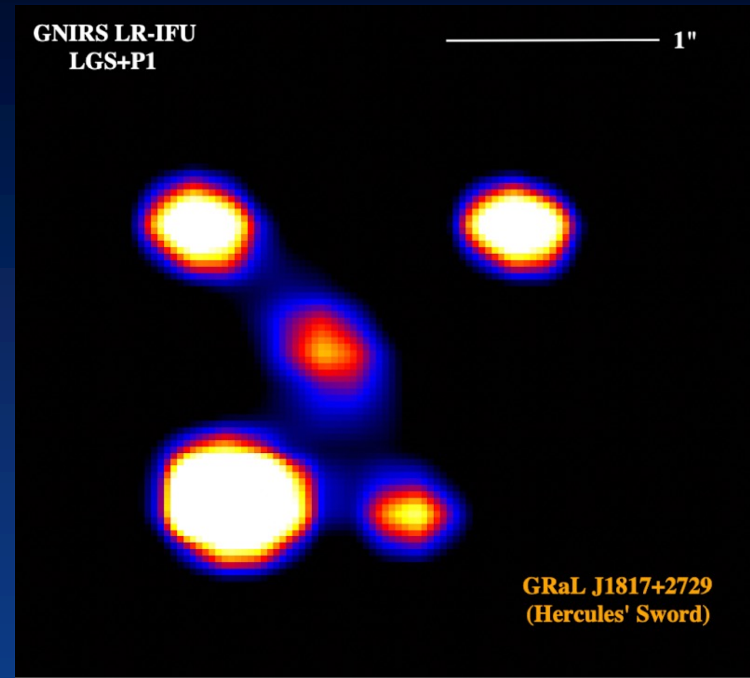
LR-IFU On-Sky Performance

NGC6240



(Left) GNIRS LR-IFU field of view (white line) superimposed over a HST-NICMOS F222M filter image; (Right) LR-IFU continuum data rebinned to the same 0.05 arcsec/pixel scale as the HST data. The image quality is very comparable.



Reconstructed image of the 'Einstein Cross' gravitational lens source GRAL J1817+2729 using the GNIRS LR-IFU in natural seeing (FWHM=0".41). All four lensed images of the background (z=3.07) quasar are clearly visible, along with the lensing edge-on disk galaxy (redshift currently unknown) at the centre.

Reconstructed image of GRAL J1817+2729 using the GNIRS LR-IFU LGS+P1 mode (FWHM=0".127). Even though the reconstructed image is undersampled at the 0".15/pixel scale of the LR-IFU, the LGS+P1 image shows a ~40% improvement in the image quality relative to the non-LGS assisted observations

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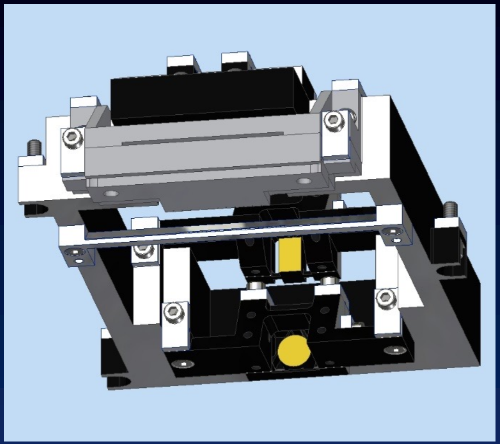
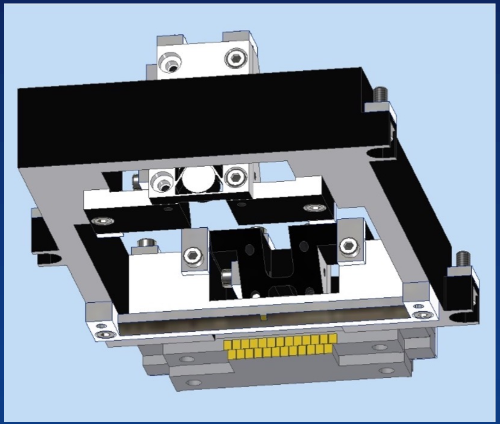
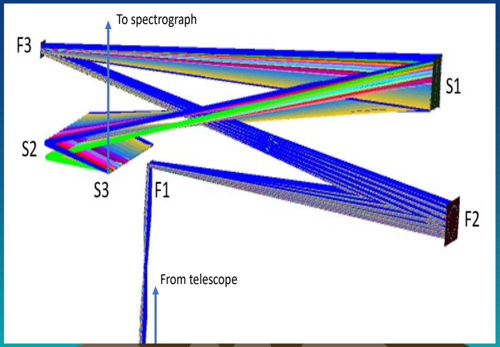
HR-IFU Design I





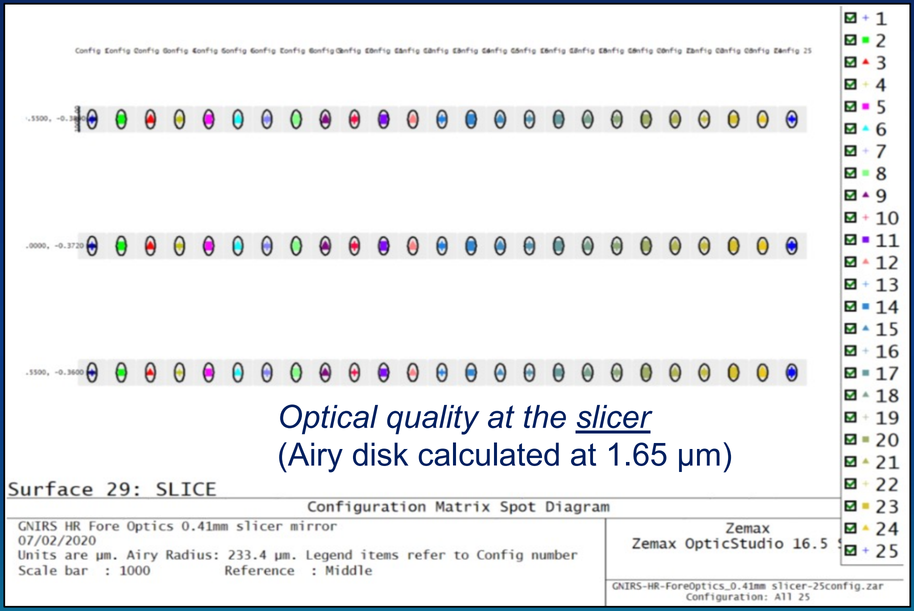


Spectral Coverage:	1.0 – 2.5 µm (requirement) 1.0 – 5.0 µm (goal)		
Sampling and Field of View:		Field of View	Spatial Sampling
		1.80” x 1.25” (2.25 arcsec^2)	0.05” × 0.05”
Filling Factor:	> 90%		
Image Quality:		50% EED < 0.04” 90% EED < 0.10”	
Optical Efficiency:	Geometric Transmission		> 90%
	Optical Throughput (excl. diffraction)		> 80%
	Overall Efficiency		> 70%
Scattered Light and Ghosting:	Diffuse Scattered Light		<10^{-4} of Parent Image in the IFU into any pixel outside 2xEE(90%) radius
	Ghost Images		Intensity < 1% of Parent Image in H-band
Stability and Uniformity of Response and Calibration:	Flexure Effects		
	Degradation of Image Quality at Alt>30 deg		< 10%
	Stability over 10 minutes of Tracking		Better than 0.1 projected IFU spaxels (TBC)
	Spatial Homogeneity (Flatfield)		Better than 10% RMS
Mass:	< 1.0 kg		
Dimensions and Interfaces:	As defined in GNIRS-08 (Instrument ICDs)		
Operational Environment:	Compatible with cryogenic environment:		
	Temperature:		60 K
	Ambient Pressure:		10^{-6} Torr

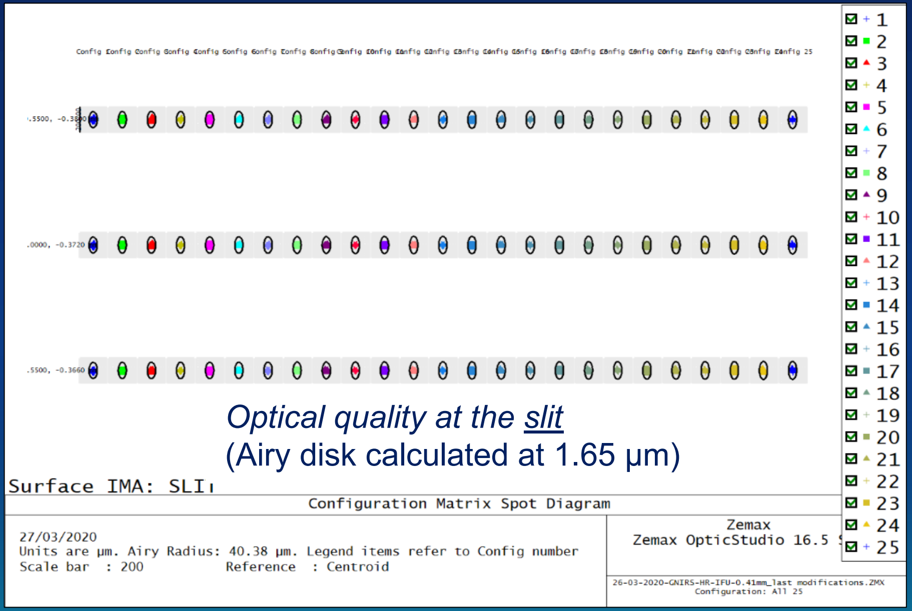
For further info: ariadna.calcines@durham.ac.uk

HR-IFU Design II

- The magnification of the fore-optics subsystem is optimised for the higher spatial resolution
- The toroidal surfaces in F2, F3 & S3 are specified in a way which allows for easier optical testing
- The slicer mirror array is designed in a way which allows manufacture as a single part
- The pupil mirror array is configured in two parallel rows to minimise off-axis aberrations
- The slit mirror array has individual mirror radii of curvature and radii of rotation (cylindrical).



Optical quality at the slicer
(Airy disk calculated at 1.65 µm)



Optical quality at the slit
(Airy disk calculated at 1.65 µm)

Slicer array pivots about ends of slice and hence can be manufactured as a monolithic component (same as for JWST NIRSpec IFU)

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HR-IFU Metrology/AIT

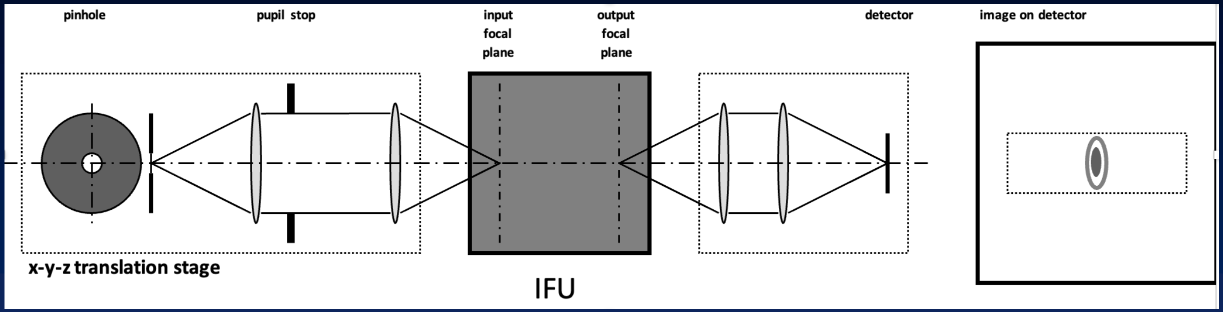
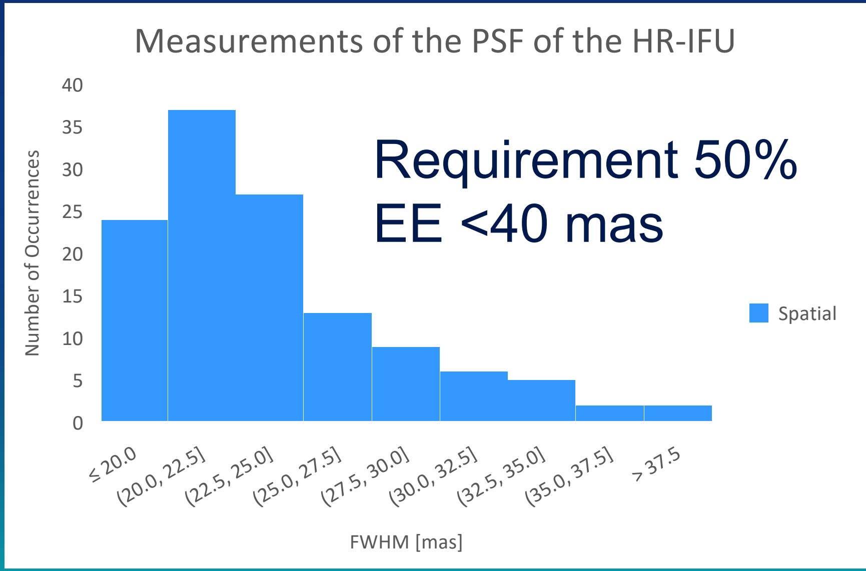
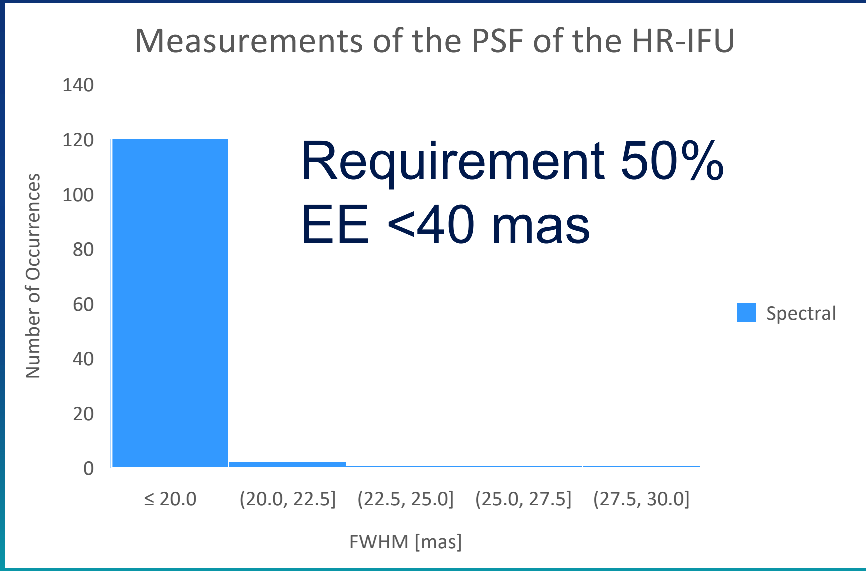


Image quality of the IFU is assessed by measuring the FWHM of the PSF in both the spatial and spectral directions for 5 field points along each slice, located at -0.50 mm, -0.25 mm, centre, +0.25 mm and +0.50 mm from the centre in the spatial direction respectively.





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HR-IFU Status

- Pre-ship acceptance tests complete Sep 2022
- Shipped to Hilo Oct 2022
- Preliminary lab test data obtained to verify operation
- Further tests on-sky delayed by G-N primary mirror issue
- Further lab tests underway May 2023
- First on-sky data expected June/July 2023

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Multi-object integral field spectroscopy

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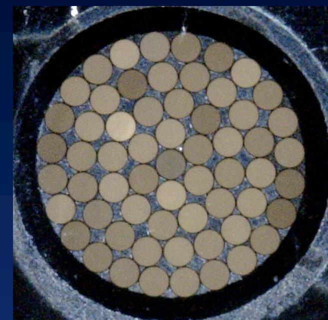
FLAMES/SAMI/MaNGA

FLAMES/VLT	SAMI/AAT	MaNGA/APO
		
• 15 IFUs	• 13 IFUs	• 21 IFUs
• 25' patrol FoV	• 1deg patrol FoV	• 3 deg patrol FoV
• 2X3 arcsecs	• 15 arcsec diam	• 12-32 arcsec diam
• 20 spaxels	• 61 spaxels	• 19-127 spaxels
• 0.52 arcsec sampling	• 1.6 arcsec sampling	• 2.0 arcsec sampling
• pick & place	• plug plate	• plug plate

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MUSE/BlueMUSE

Bacon et al., SPIE 7735,08 (2010)

1' x 1' FoV in wide-field mode with 24x IFUs.

Field splitter (slicer) divides FoV into 24 60"x 2.5" segments.

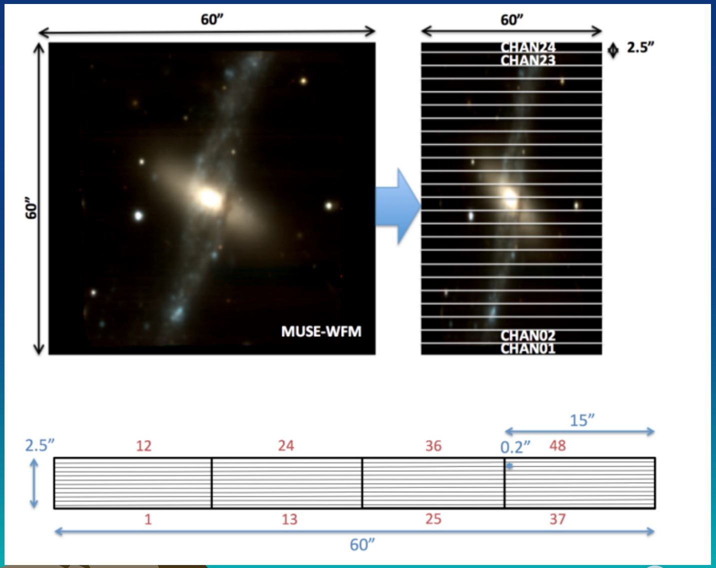
Each slice feeds IFU with 48 15" x 0.2" slices @ 0".2 sampling.

24 4k x 4k CCD detectors. 90,000 spectra.

0.46-0.93 microns wavelength coverage.

Innovative design (glass slicers) with huge impact (>700 papers).

Blue-optimised version 350-580nm in development.



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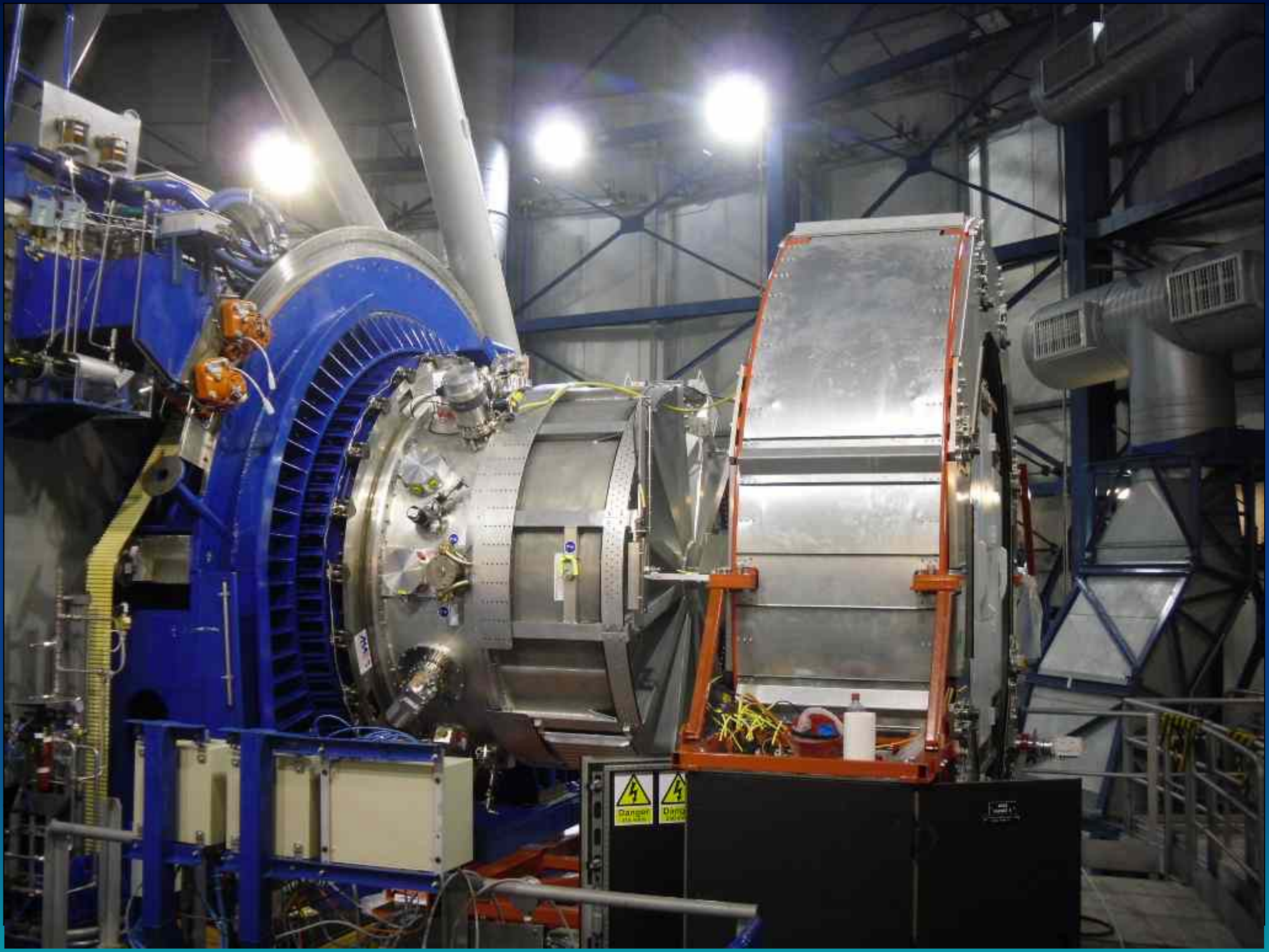
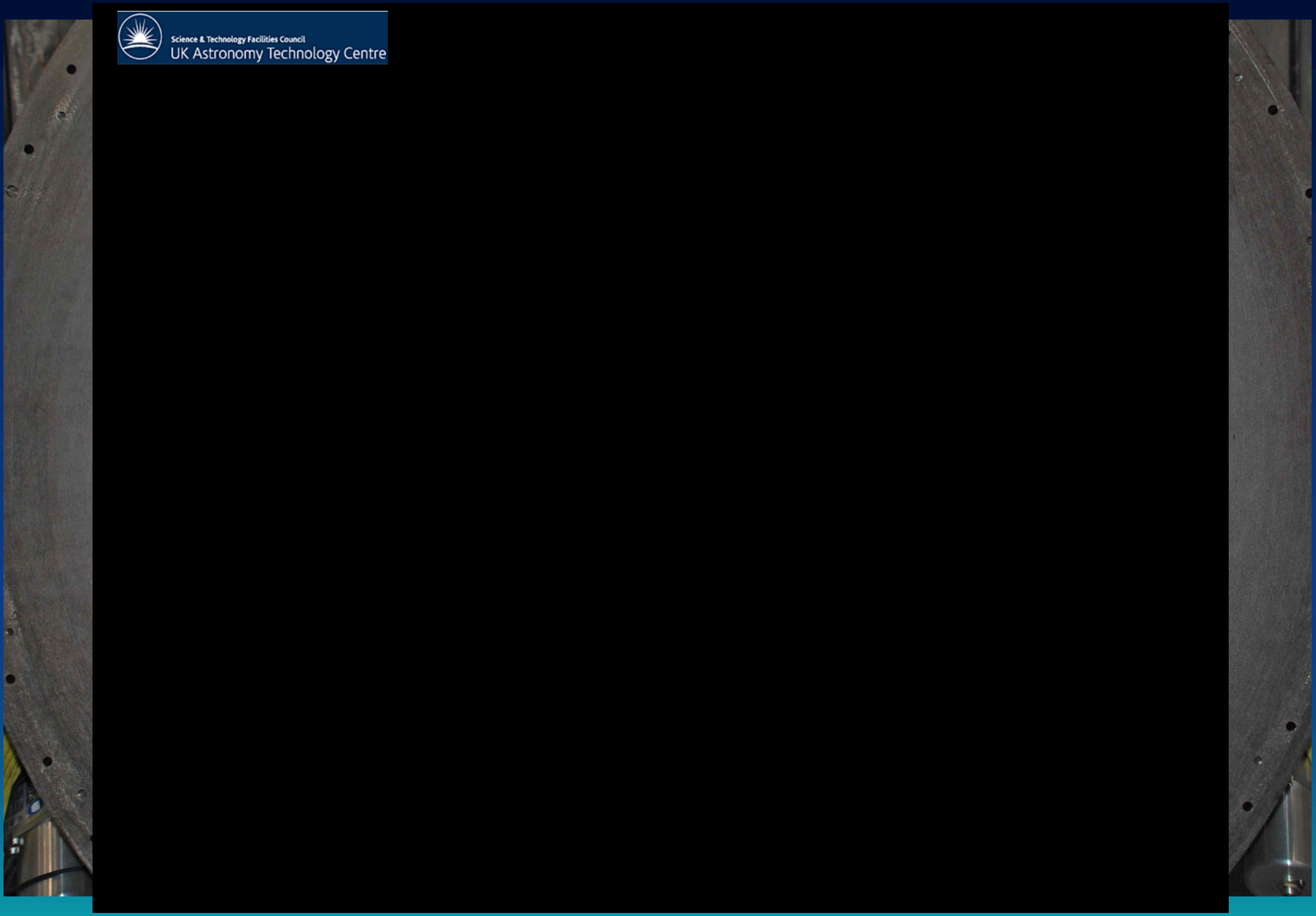
KMOS: infrared multi-IFU



Pickoff Arms



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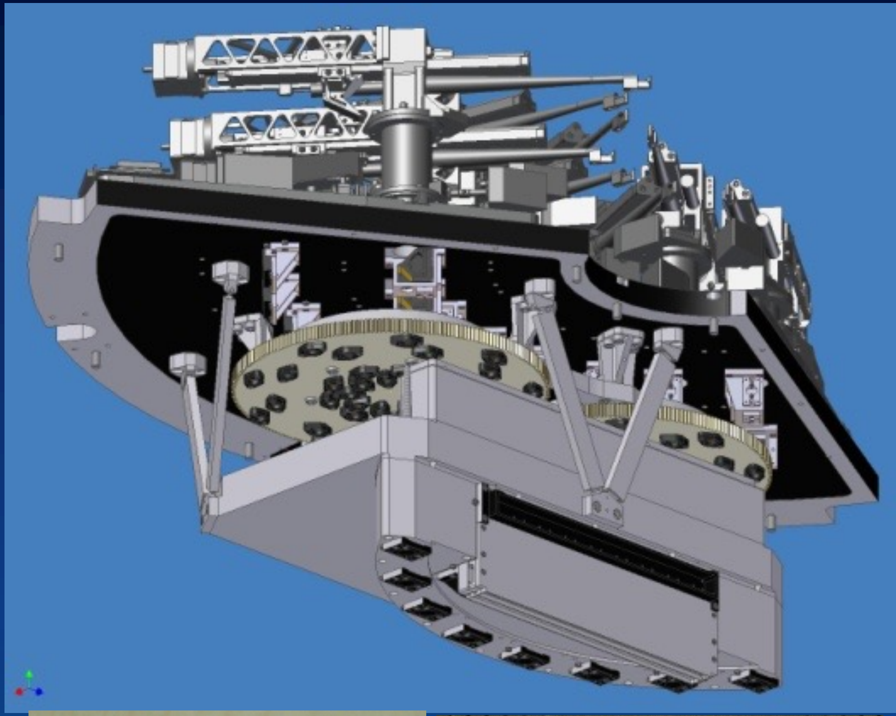
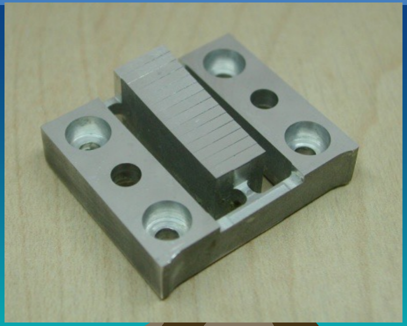
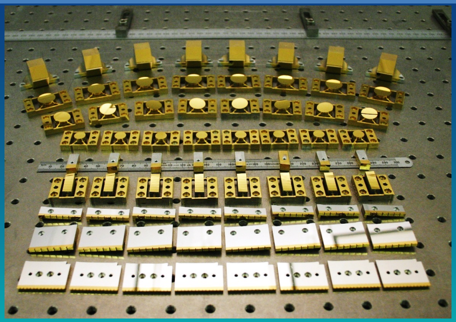
IFU Subsystem

- 8 pickoff subfields combined to produce single output slit
- Each subfield re-imaged on to 14x14 element image slicer
- Diamond-machined monolithic optics (gold-coated Al) to eliminate thermal effects and minimize alignment errors
- Anamorphic foreoptics produces square spatial sampling on sky (0.2 arcsec) with Nyquist spectral sampling







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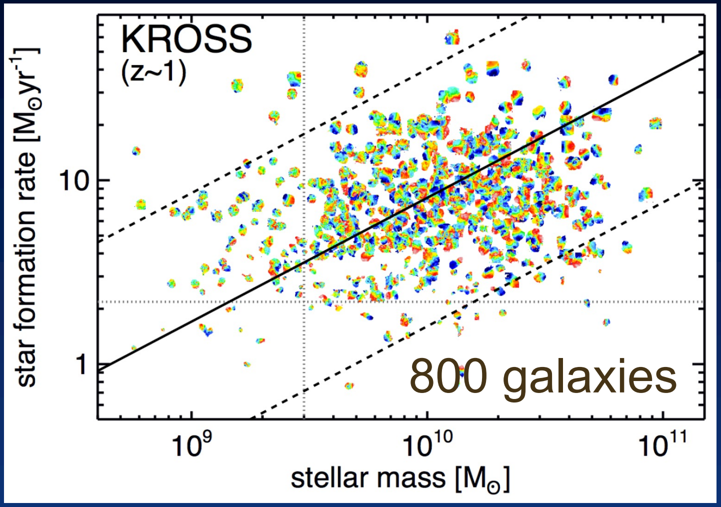
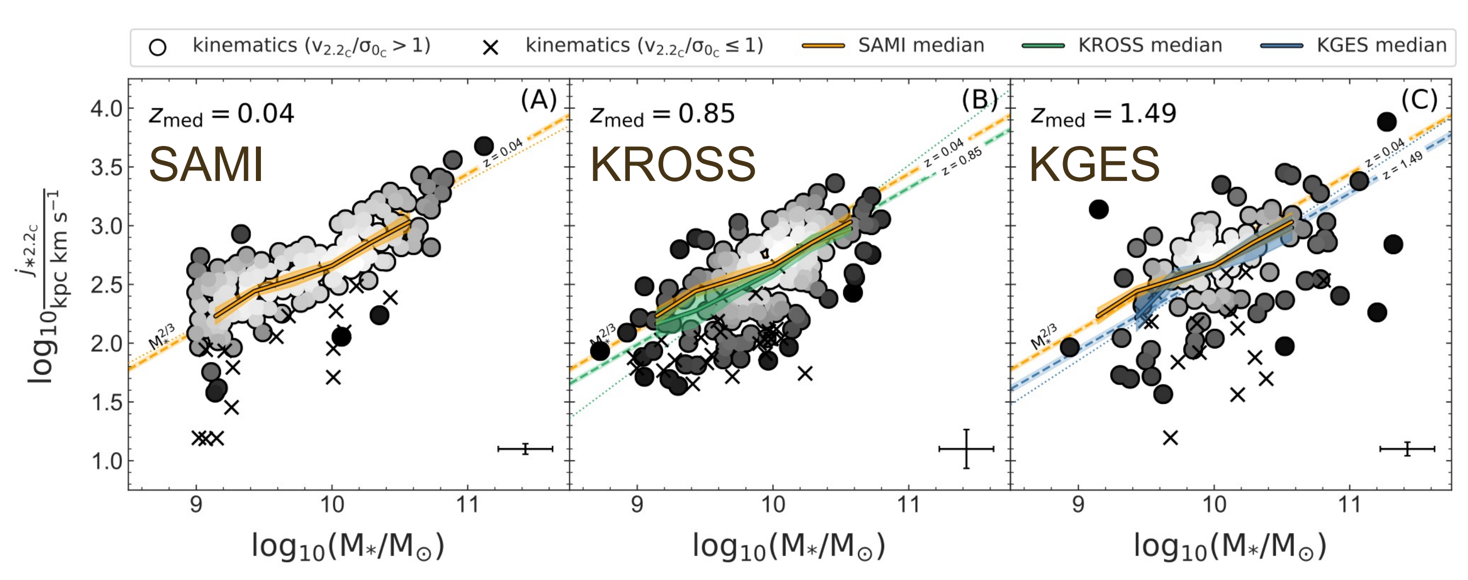
KMOS Surveys



KMOS Redshift One Survey: Stott et al. (2016)
KMOS Galaxy Evolution Survey Tiley et al. (2021)

No dependence of angular momentum of galaxies and haloes on stellar mass or redshift. Only modest differences in disc fractions. Massive star-forming galaxies have followed similar assembly pathways over the past ≈ 10 Gyr.



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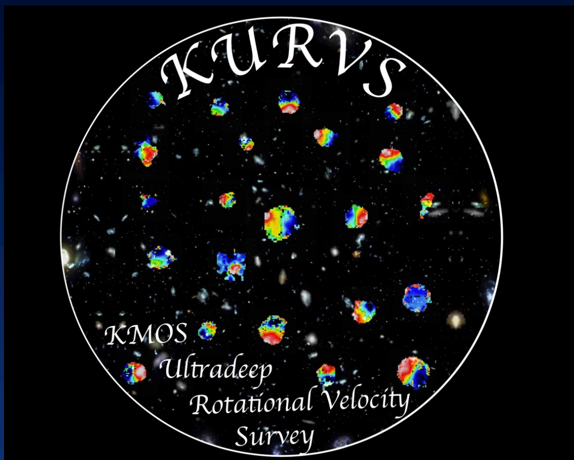
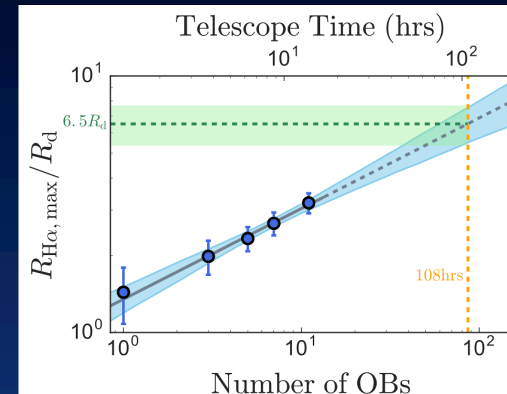
Sky Subtraction

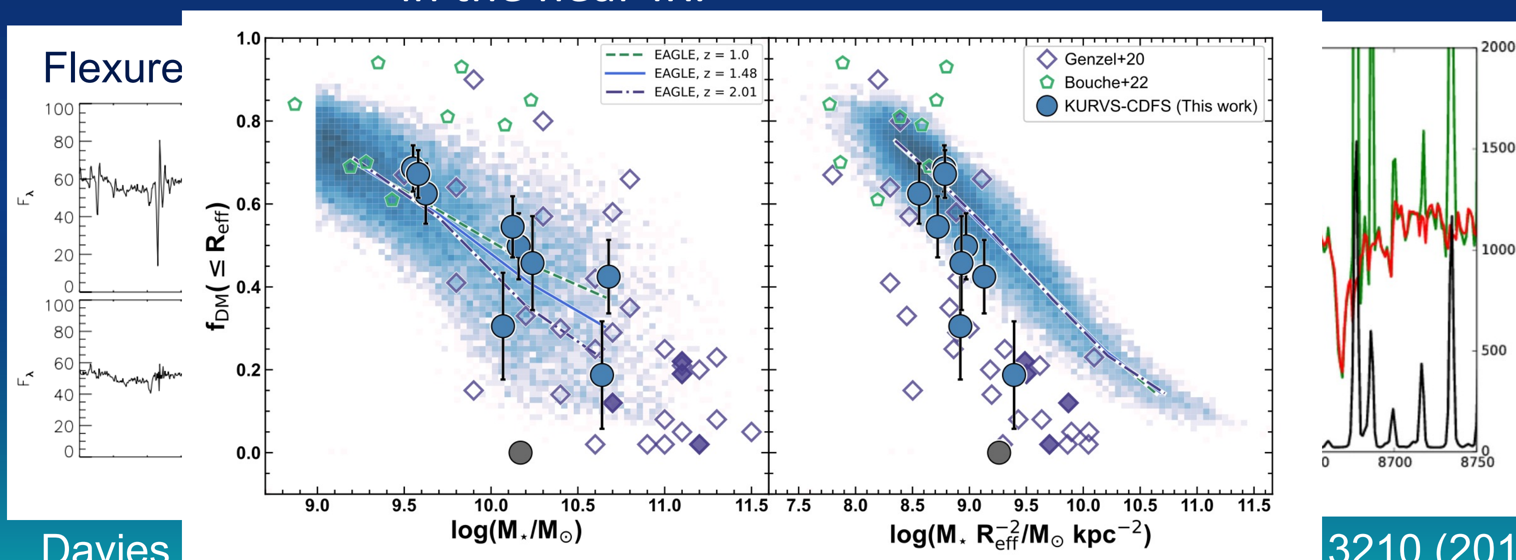


22 star-forming main sequence galaxies at $z \sim 1.5$.

Extremely deep rotation curves to 4-6xR_{eff} (10-15kpc).

Requires exquisite sky subtraction in the near-IR.





Davies

3210 (2016)

Puglisi et al. arXiv 2305.04382 (2023)

Implementation issues for ELTs

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Why ELTs need IFUs

- SC1: Spectroscopy of the most distant galaxies
- SC2: Evolution of large-scale structures
- SC3: Mass assembly of galaxies through cosmic time
- SC4: AGN/Galaxy co-evolution & AGN feedback
- SC5: Resolved stellar populations beyond Local Group
- SC6: Galaxy archaeology
- SC7: Galactic Centre science
- SC8: Planet formation in different environments

Evans et al. arXiv 1406.6369 (2015)

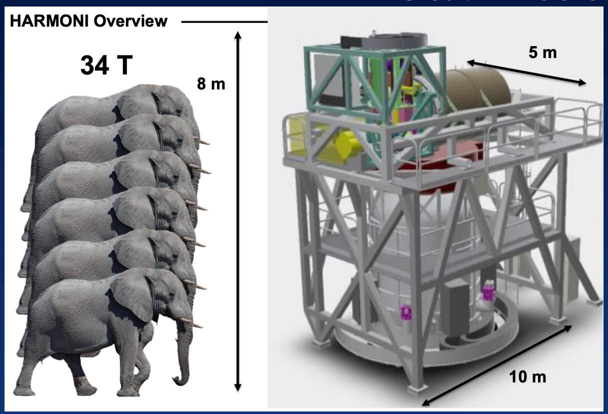
Implementation at ELT Scales

- 10^9-10^{11} spaxels potentially available in field
  $\Rightarrow$ Pickoff interesting sub-fields for analysis
- IFUs exploit the full D^2 advantage of large telescope aperture close to diffraction limit
- Maximise # sub-fields x # spaxels in each field
  $\Rightarrow$ maximum information density $\rightarrow$ slicers
- Technical challenges great, lenslet and fibre-lenslet designs may offer better performance/cost
- Fibres provide versatile optical interface to heavy instruments needing stability

E-ELT Solution

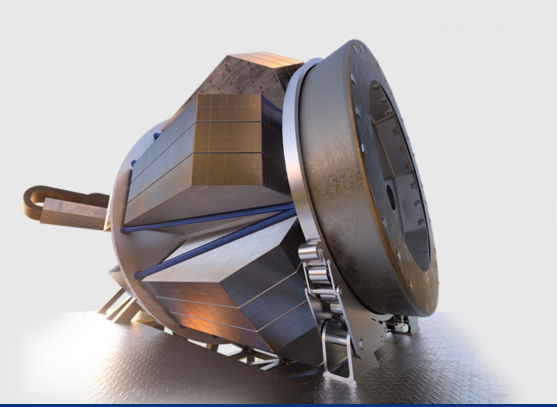
HARMONI

Credit: B. Neichel



0.8-2.5 microns. Slicers.
R~3000, 7500, 20000
Four FoV:
(i) 6.2" x 9.1" @ 60mas
(ii) 3.0" x 4.1" @ 20mas
(iii) 1.5" x 2.1" @ 10mas
(iv) 0.6" x 0.8" @ 4mas

MOSAIC



0.8-1.8 microns. Fibres.
R~4000, 9000, 18000
Eight deployable IFUs:
(i) 40 arcmin^2 patrol field
(ii) 3.0" diam @ <200mas

METIS

3.4-14 microns. Slicers.
R~100000
(i) 0.6" x 0.9" @ 8 mas

Other ELTs also proposing IFU instruments e.g.: IRIS (TMT), GMTIFS (GMT)

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The Far-Future: MKIDs

For further info: kieran.s.obrien@durham.ac.uk

- Microwave Kinetic Induction Detectors
- Novel superconducting detector technology
- UV/Optical/IR sensitivity
- Each pixel has the intrinsic ability to measure the energy (and arrival time μs) of individual photons.
- Each pixel delivers read-noise free, low-resolution spectroscopy (R ~ 5-100).
- Key advantage over other superconducting detectors is that they can be easily multiplexed into large arrays (10^4-10^5 pixels).

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For Your Eyes Only: KMOS

Credit: Mark Swinbank (Durham Univ)

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Thank you for listening!

And particularly to Cyril Bourgenot, Ariadna Calcines, Marc Dubbeldam, Ema Farina, Brian Lemaux, Damian Mast, Jeremy Allington-Smith, Roger Davies, Anna Puglisi, John Stott, Mark Swinbank, Alfie Tiley and others for slide material.

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Centre for Advanced Instrumentation

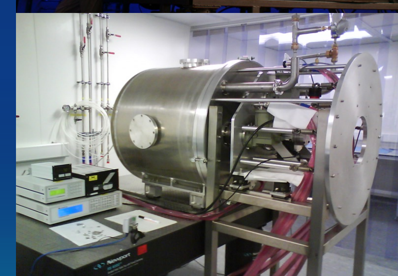
64 Members:

11 Academic staff
12 Instrument scientists
12 Engineers (optical,mech,elec,soft)
3 Operations
26 PhD students

- Astronomical Instrumentation
- Applied Optics & BioPhotonics
- Precision Optics Manufacture/Metrology
- Remote Sensing/Earth Observation
- Fusion Diagnostics (EPSRC CDT)
- Gamma ray instrumentation (CTA)

NetPark Research Institute

Space Based



Ground Based

Adaptive Optics

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Specific information density

Objective comparison independent of scale

$$Q = \eta \frac{N_p N_q N_\lambda}{N_x N_y}$$

\# resolution elements (numerator)

throughput (η)

\# detector pixels (denominator)

$$Q_L \simeq \frac{\eta}{4d^2}\left(\frac{1}{f_G M^2}\right)$$

$$Q_F \simeq \frac{\eta}{4d^2}\left(1 - \frac{f_G}{\sqrt{N_e}}\right)\left[\left(\frac{s}{d}\right)\sqrt{1+\left(\frac{2s}{d}\right)^2}\right]^{-1}$$

$$Q_S \simeq \frac{\eta}{4}\left[\frac{1}{2}\left(1 - \frac{f_G}{\sqrt{N_e}}\right)\right]$$

	example	d	N_R	M	η	f_G	Q/Qmax
Lenslet array	SAURON	52	1600	0.16	0.7	1	0.02
Fibre system	GMOS-IFU	5.5	1500	-	0.6	4	0.11
Image slicer	GNIRS-IFU	1	700	-	0.8	4	0.68

Allington-Smith, 2006, New Astr. Rev., 50, 244

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