New Technologies for Astronomical Instrumentation

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Royal Observatory Edinburgh

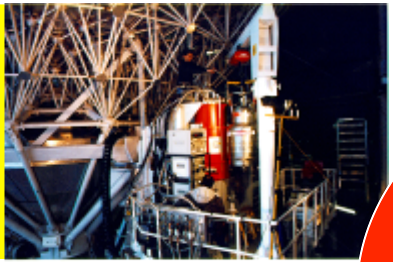
Scope of talk

- Ground-based instrumentation
- Emphasis on Near Infrared (1-5µm)
- Not Interferometry

VISTA 64 Mpixel IR Camera

Why do we need New Technologies in Astronomy?

Open New
Parameter Space
> New Science



Disruptive Technology
– changes how we do things

Reduce cost- make
New Science affordable

Reduce time to
reach Science Goal

Reduce Risk

Disruptive Technology

A new technology that has a serious impact on the status quo and changes the way people have been dealing with something, perhaps for decades

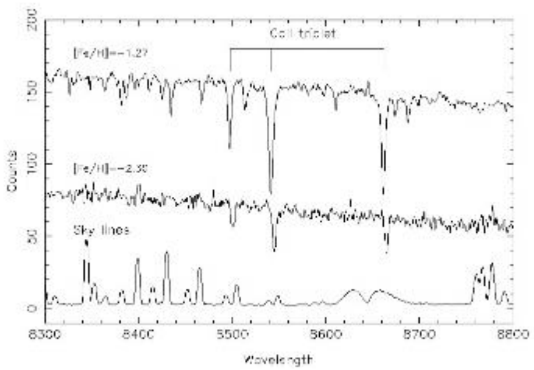


Disruptive Technology

A new technology that has a serious impact on the status quo and changes the way people have been dealing with something, perhaps for decades

Credit: LSST Corp.

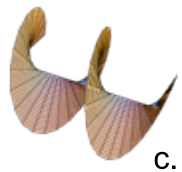
What can we measure with Astronomical Instruments?



Probe the Universe by collecting photons:

- Photon emission
- Absorption
- Eclipses
- Gravitational lensing
- Angles - astrometry
- Doppler shift > dynamics of galaxies > Dark Matter
- Measure properties of E-M radiation::
  - Intensity
    - Spatial
    - Temporal
  - Wavelength (Energy)
  - Amplitude & Phase
  - Polarisation
  - Orbital Angular Momentum?

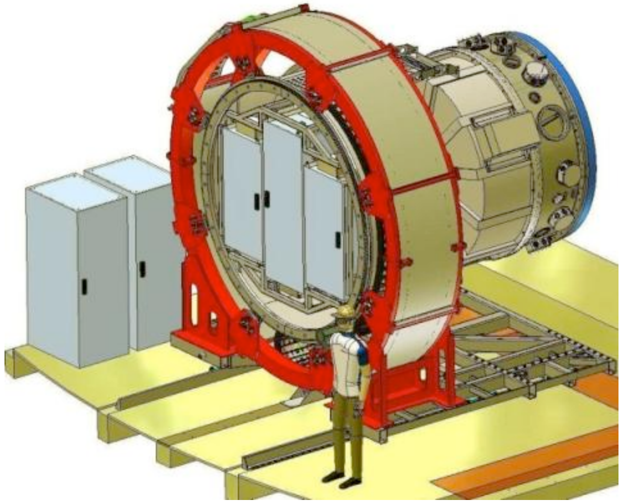
Why is this so hard?



c. Miles Padgett

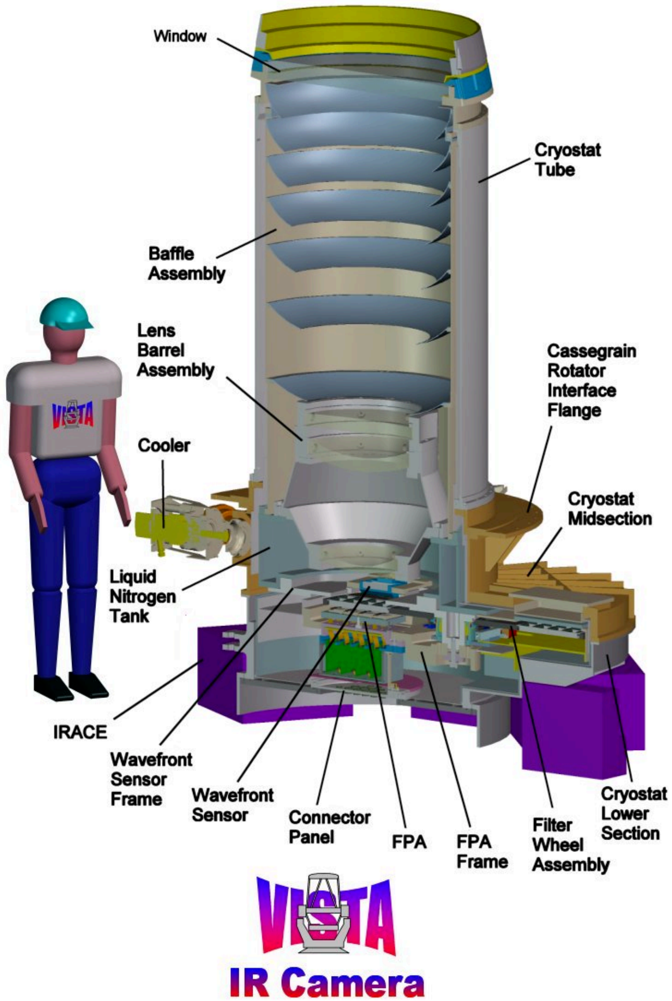
Evolution of Instrument Requirements

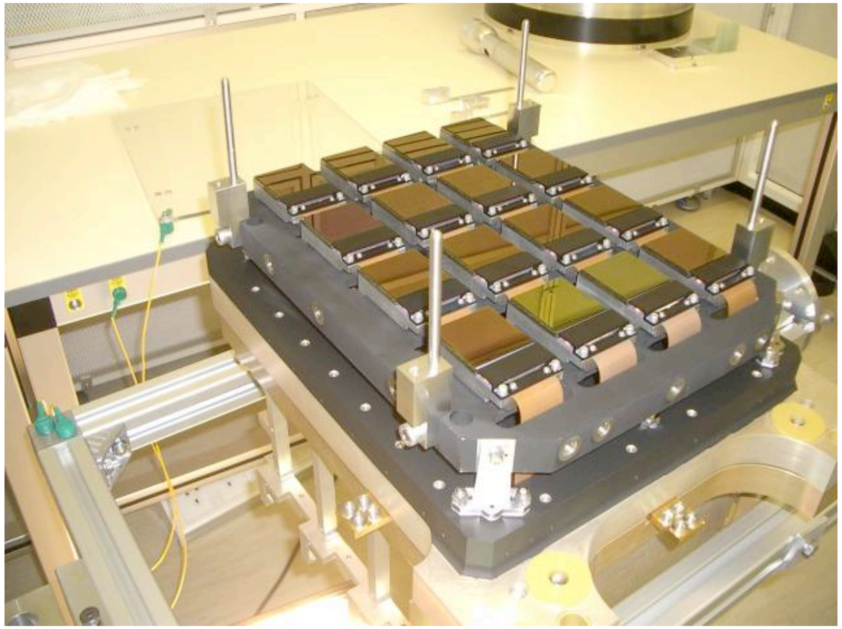
UKIRT: IRCAM 1 1986



VLT: KMOS 2011

Imaging



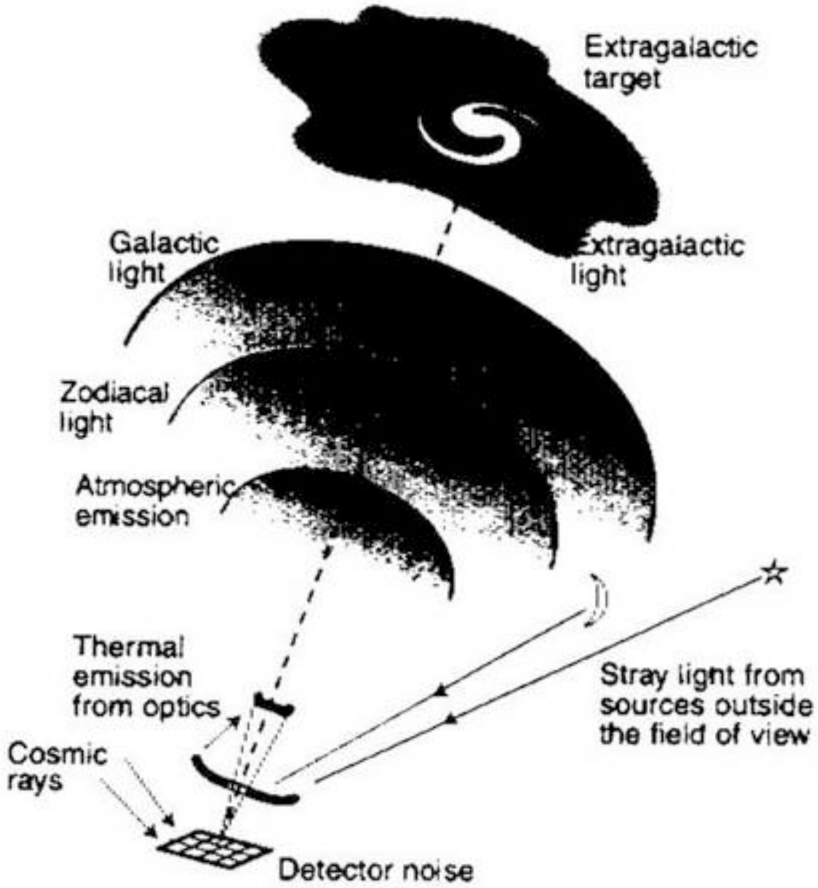


16 2kx2k Raytheon Arrays in VISTA

Imaging Challenges : Sensitivity

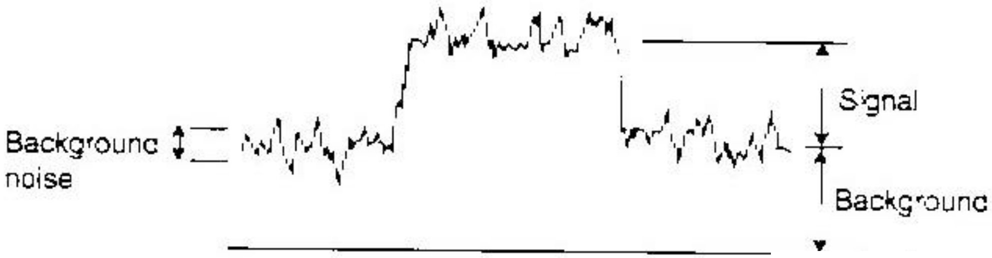
- Noise sources
  - Background Photon noise
    - Optical components
    - Sky
    - Source
    - Stray light

  - Detector noise
  - Interference
    - EMI
    - Cosmic rays
    - Microphonics
  - OH lines
  - Amplifier Noise
  - Digitisation

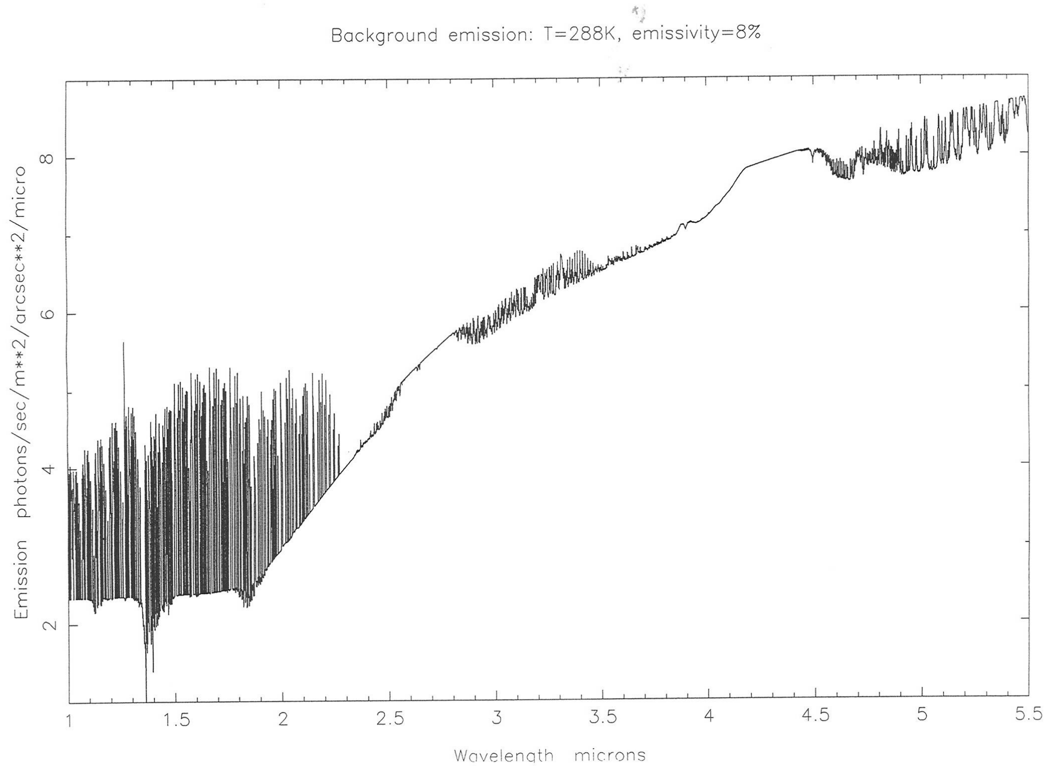


From P. Bely, Design and construction of large optical telescopes

Controlling Background Sources



- Conventional Wisdom:
  - Control using cold stop
  - VISTA shows this can be done with careful baffle design



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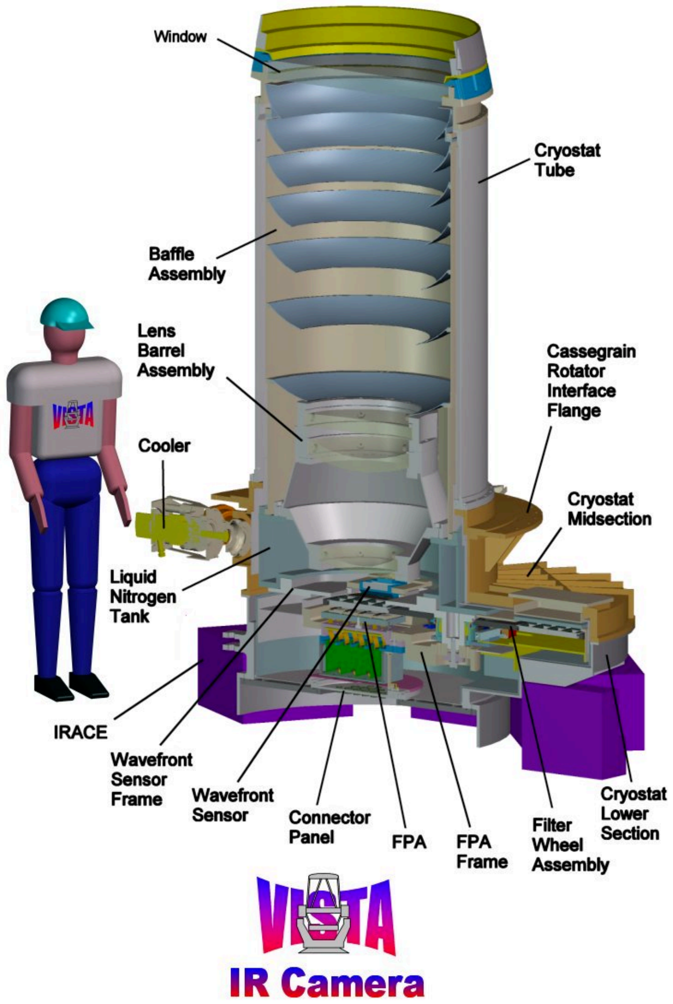
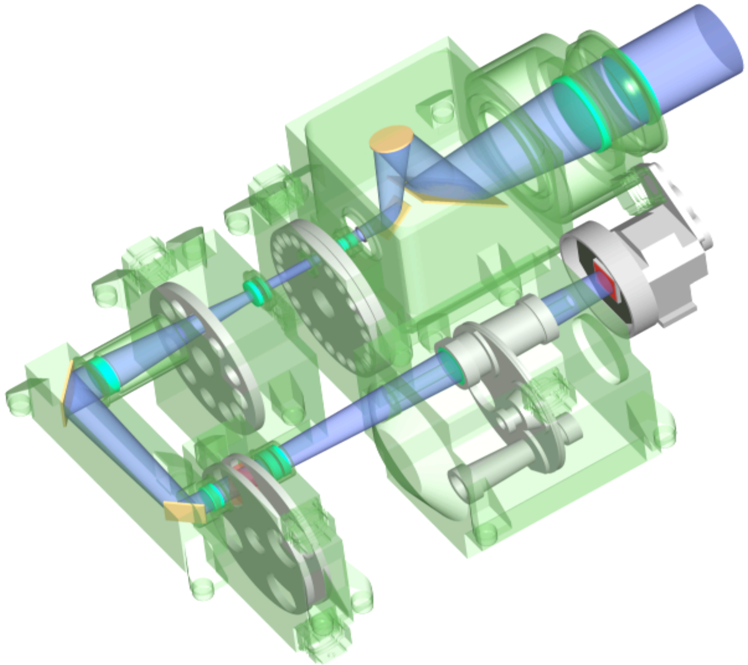
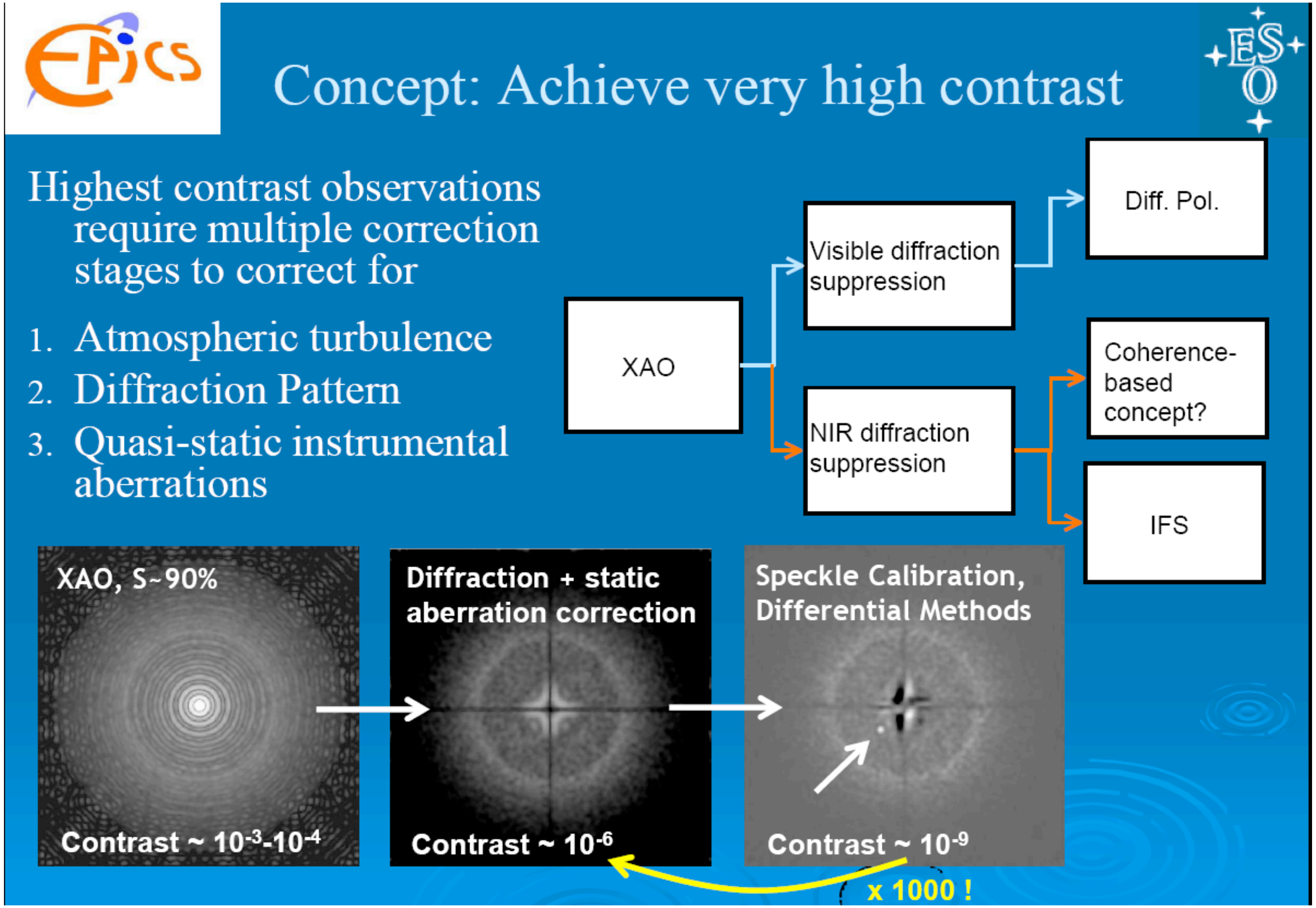


Challenges: Throughput

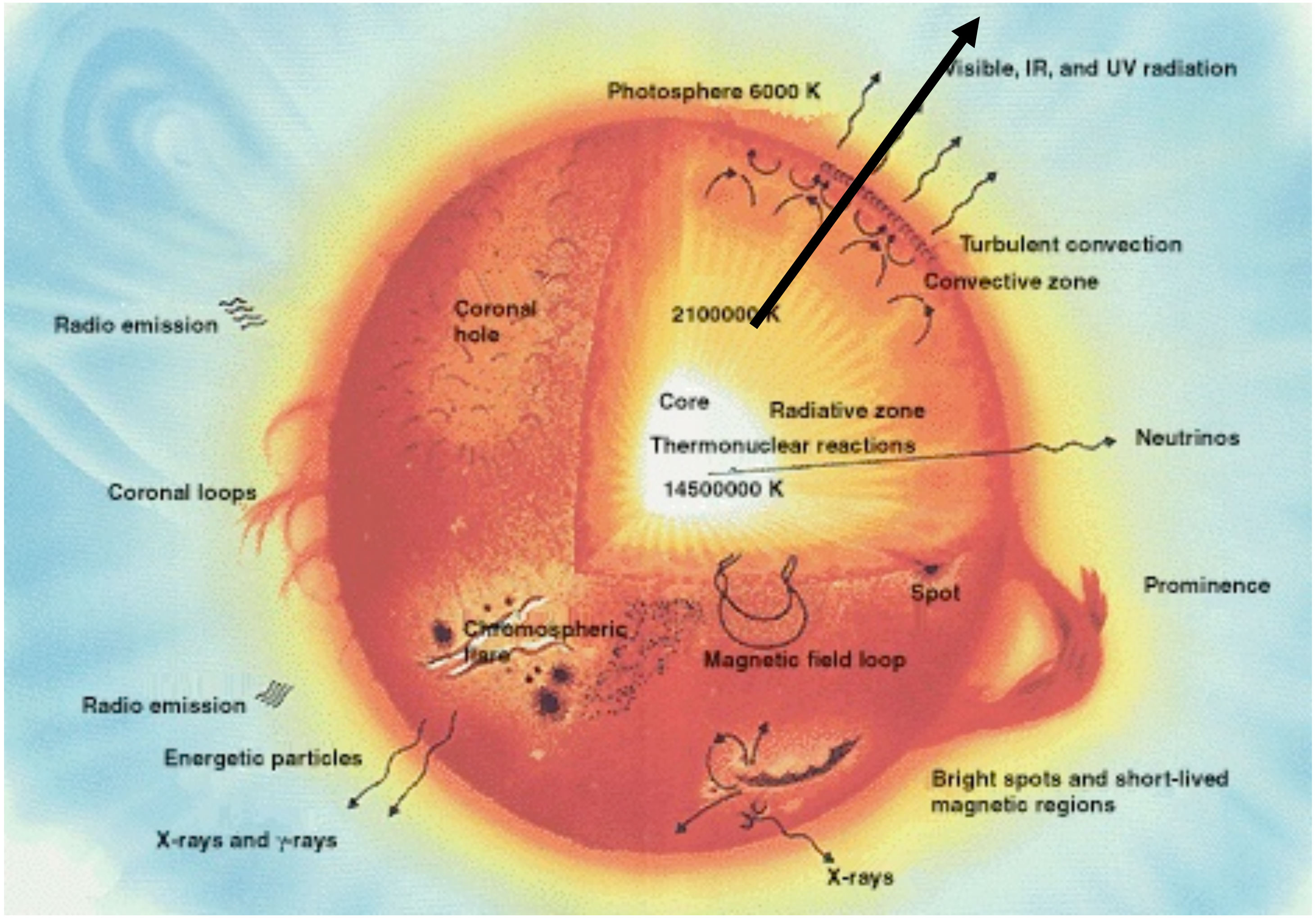
- Minimise losses
  - Minimise reflections at surfaces
  - Reduce window, filter and lens absorption
  - Avoid misalignment of apertures
  - Allow for Diffraction
  - Optimise image quality
  - Use adaptive optics!
- Maximise detector quantum efficiency



High contrast imaging



Not just Images! Spectroscopy:



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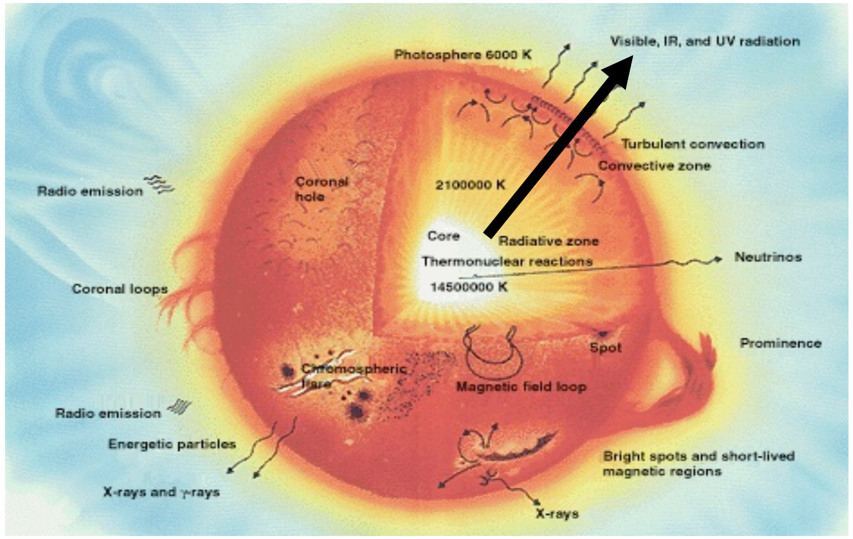
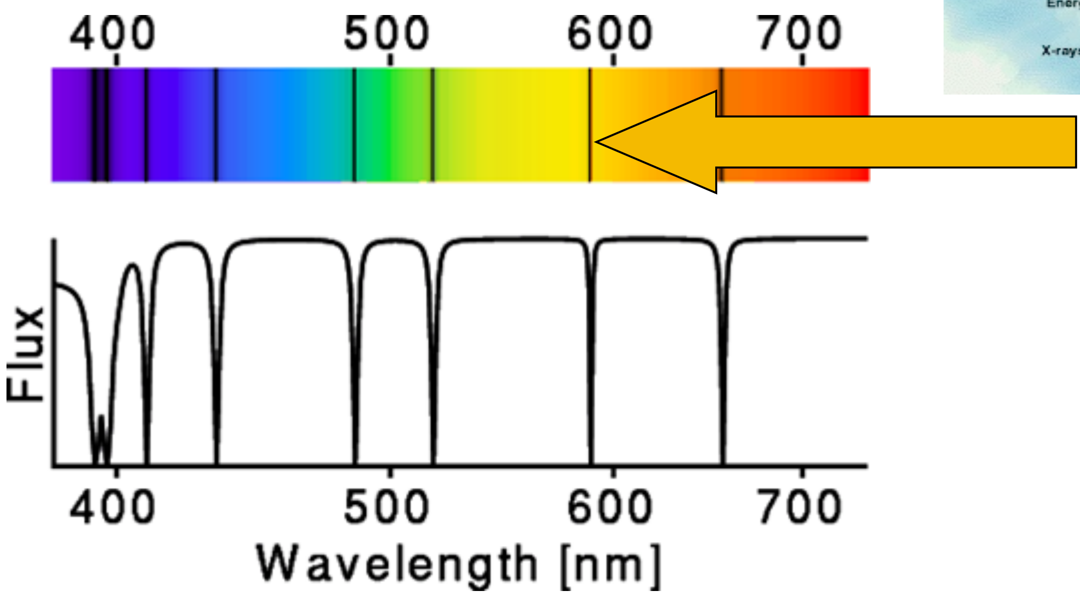
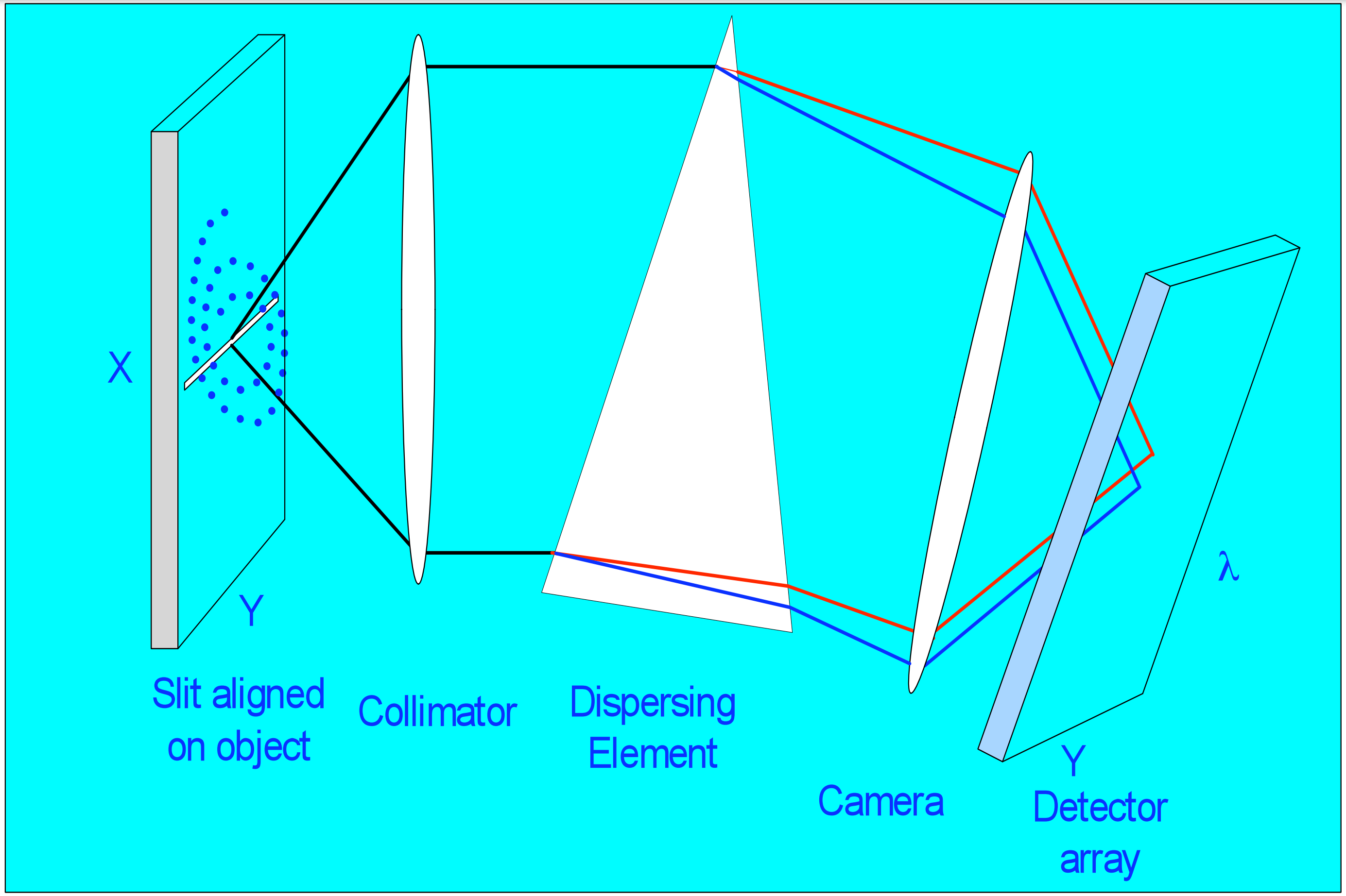




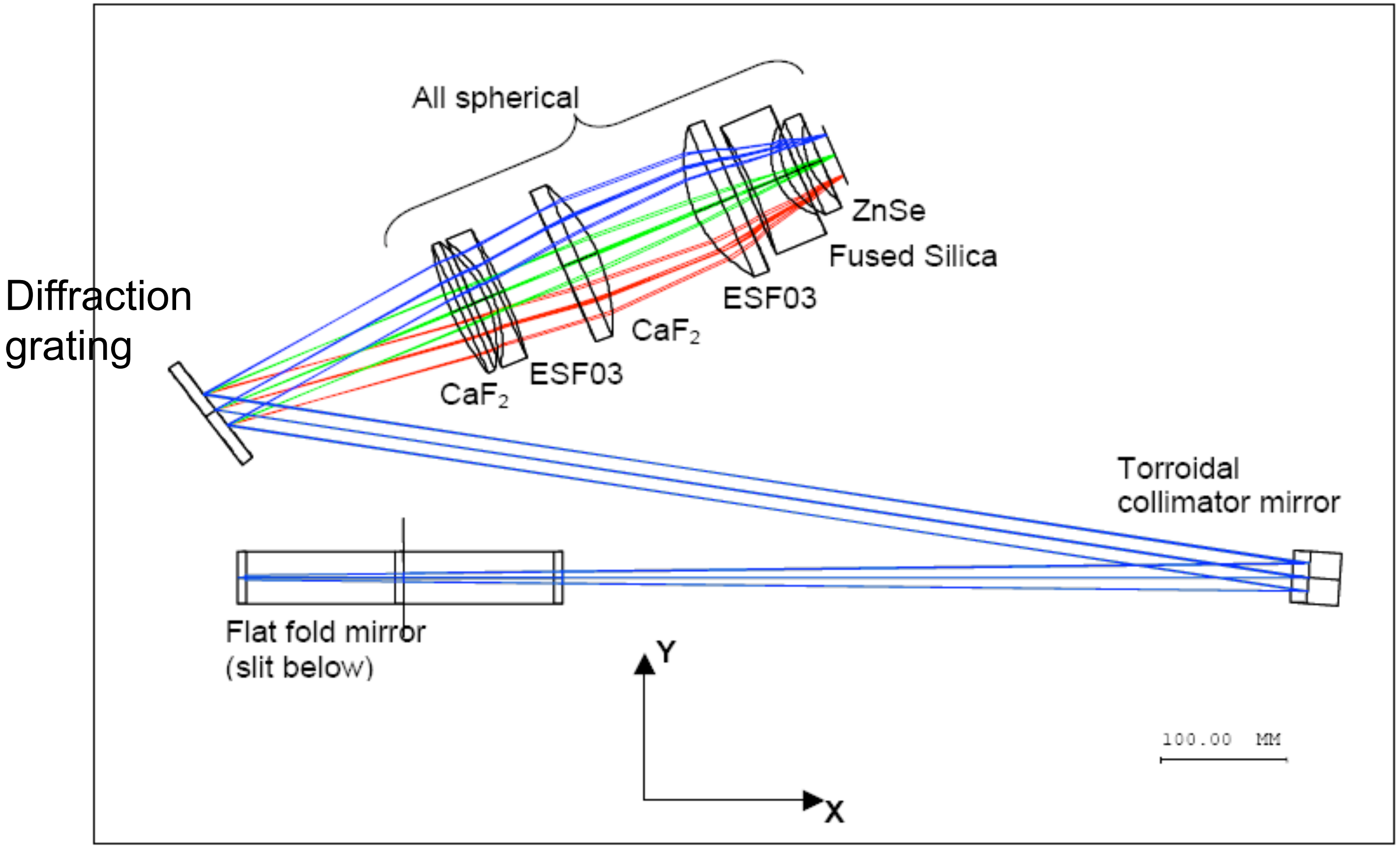
Sodium
589 nm

Basic Spectrometer layout



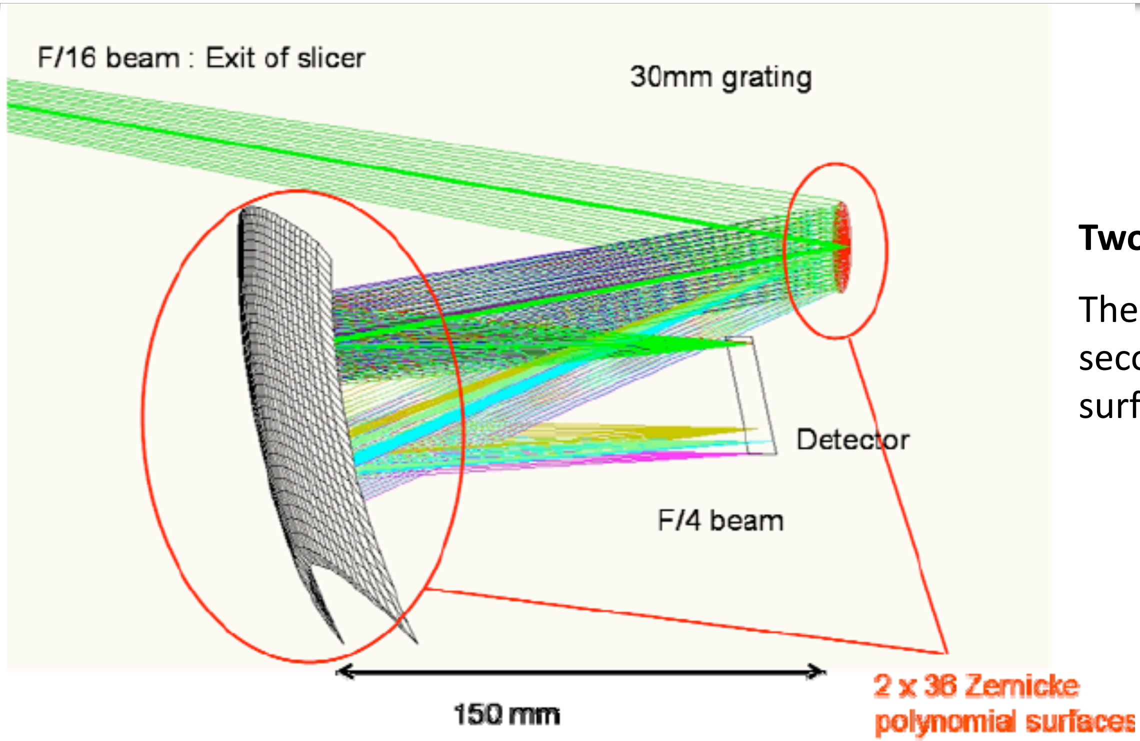
entrance aperture/slit + collimator + dispersing component (if possible at a pupil)

KMOS - A practical example



The K-band multi-field spectrograph for ESO VLT

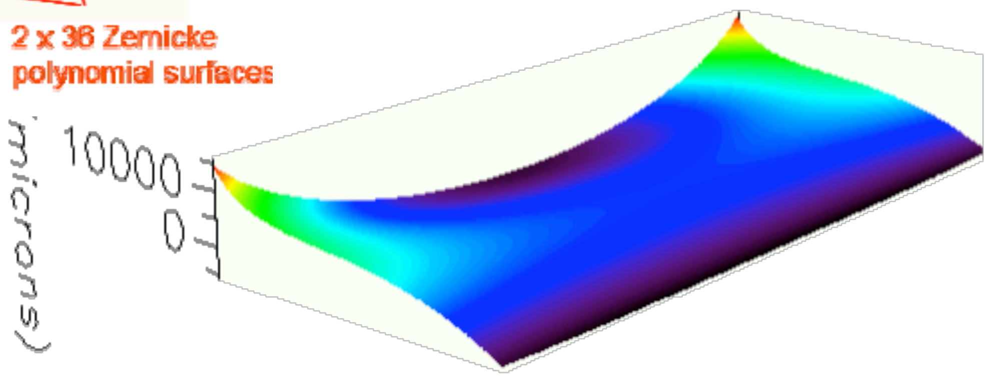
Extreme Aspherics can increase throughput and make instrument smaller



Two mirror optical design.

The first surface is a grating, the second the camera. Both surfaces are highly aspheric.

Highly aspherical camera surface:
6mm from the best sphere



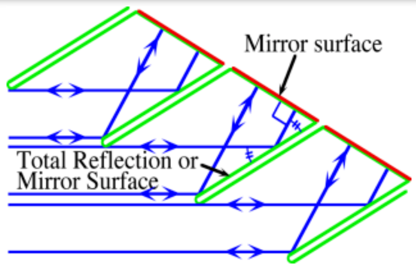
"On the Performance of ELT instrumentation"

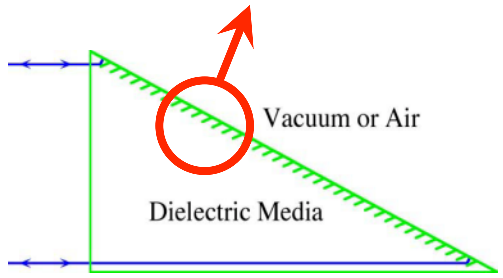
Cuby, Prieto, Ferrari, Hugot, Bland-Hawthorn, Blais-Ouelette, SPIE 2006

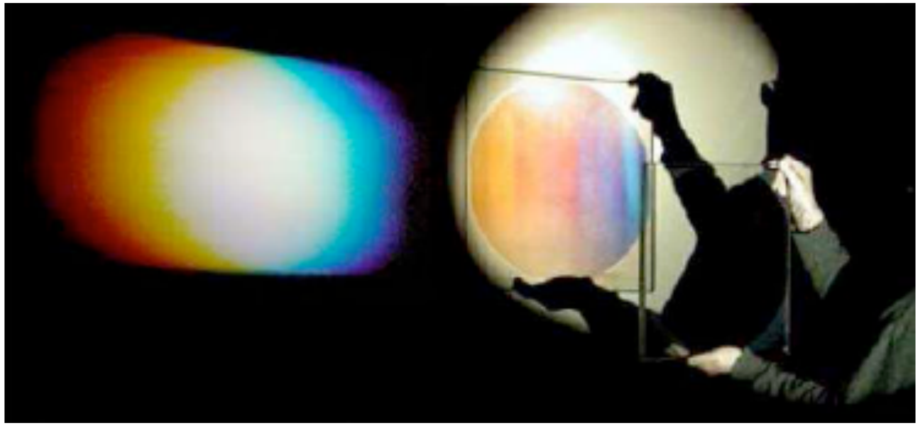
LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

New Dispersing components

- Immersion gratings – allows more compact spectrometers – but surface finish and scattered light are issues
- Volume Phase Holographic Gratings – high efficiency, straight optical path

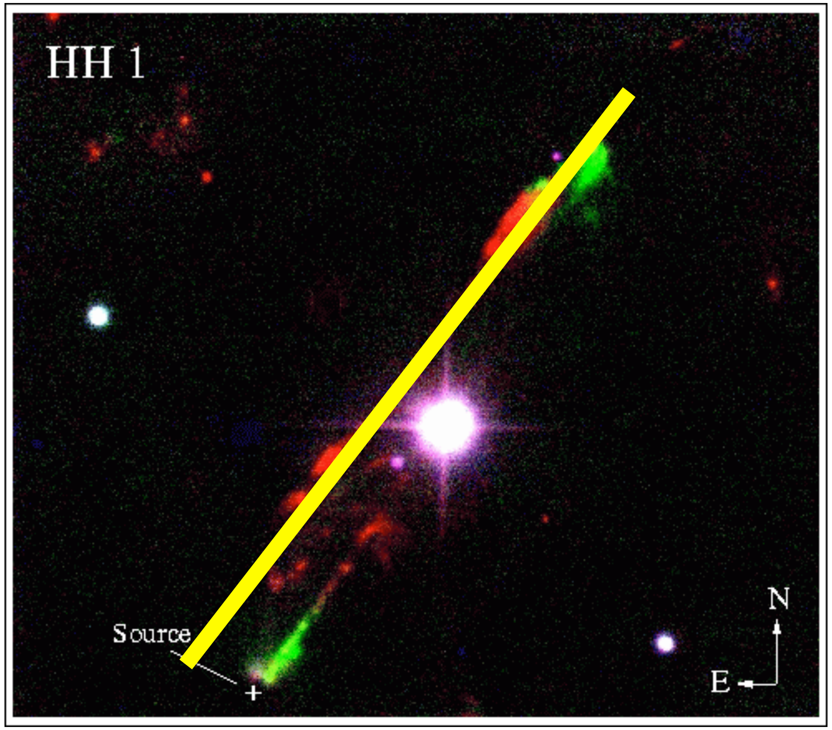


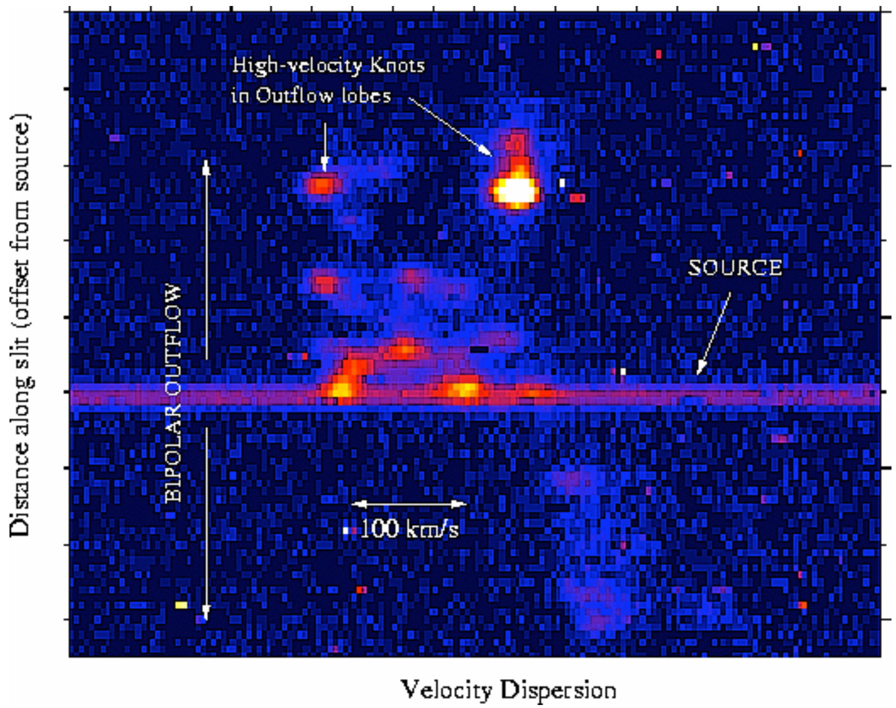




The long slit: strengths/weaknesses

- With typical scales of 0.2arsec/pxl and 2048 x 2048 pxl detectors, modern spectrometers have slit lengths of several arcmin => ‘long’ field
- In most cases much of slit ‘unused’ for science



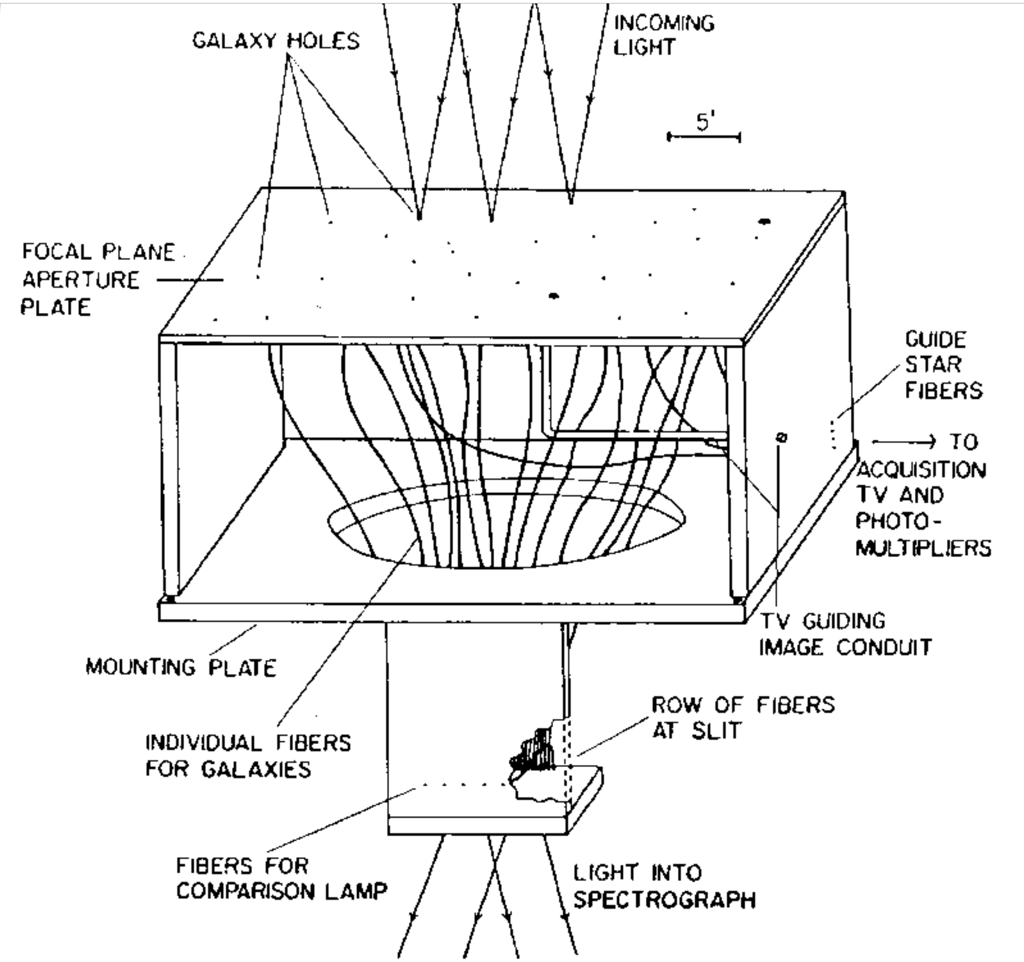


Data courtesy UK Infrared Telescope, Tom Ray and Chris Davis

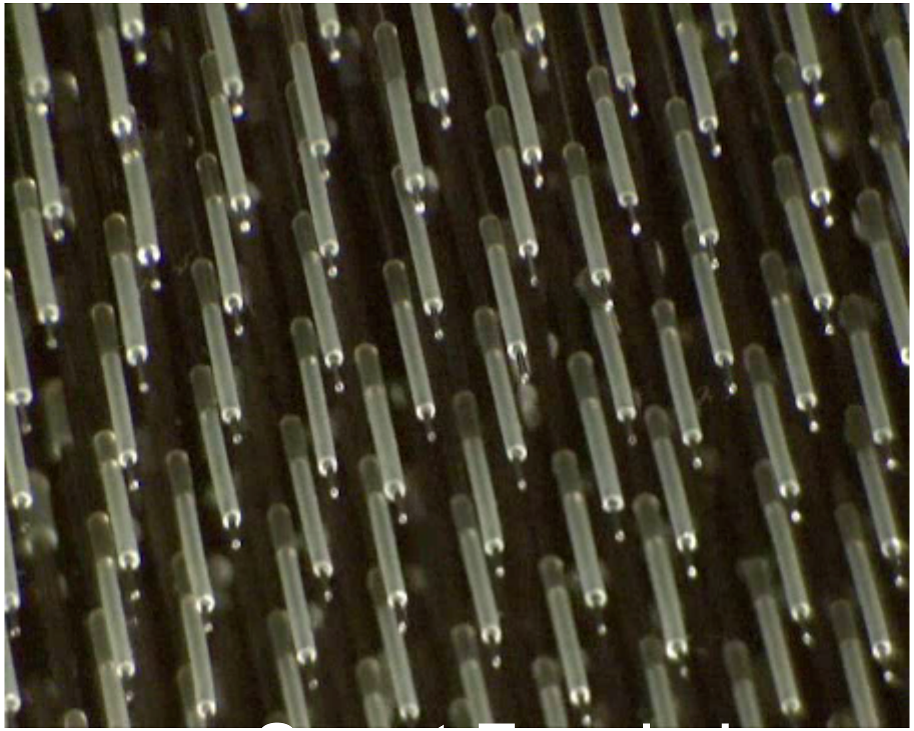
Solutions to long slit weakness

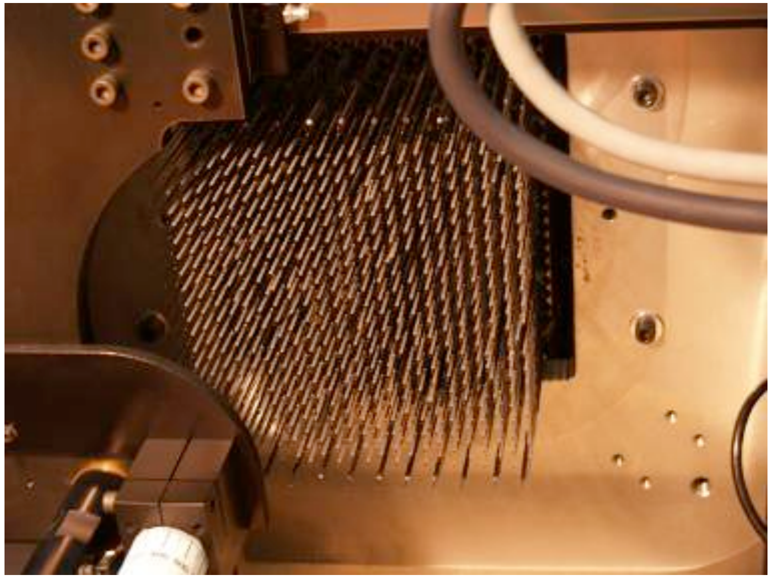
- Multi-object spectroscopy (MOS)
  - Optical fibres
  - Focal plane slit masks
- 3D (integral field) spectroscopy
  - Fibre bundles
  - Lenslet arrays
  - Image slicers
- Bring both together: Multi-IFU spectroscopy

1980: Roger Angel's Medusa

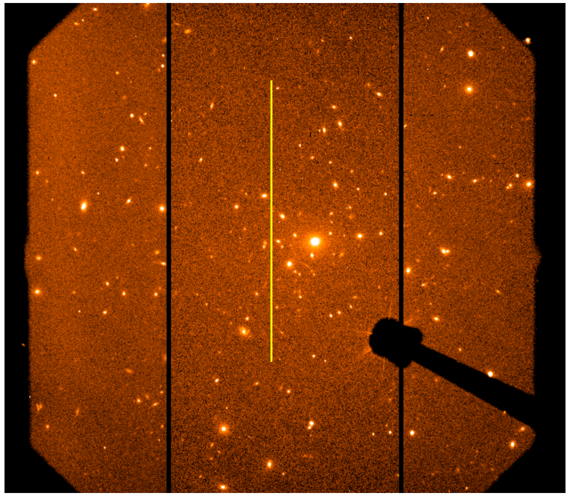


2010: Echidna on SUBARU FMOS

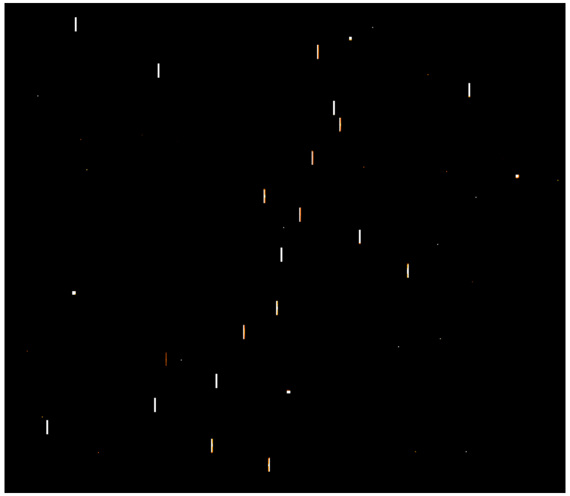




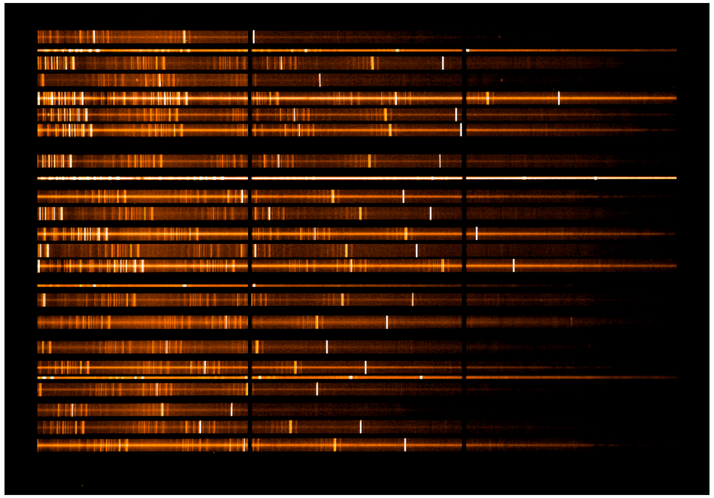
Multi-object slit spectroscopy



An image of a field of stars and galaxies is used to set positions for slitlets in a mask…



the multi-object slit mask is inserted at the telescope focal plane…..

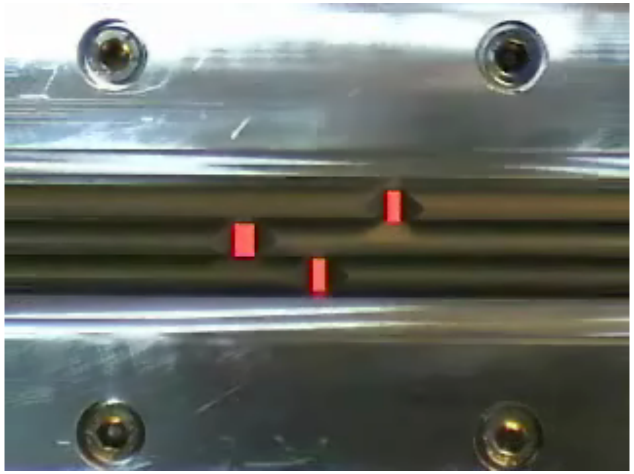


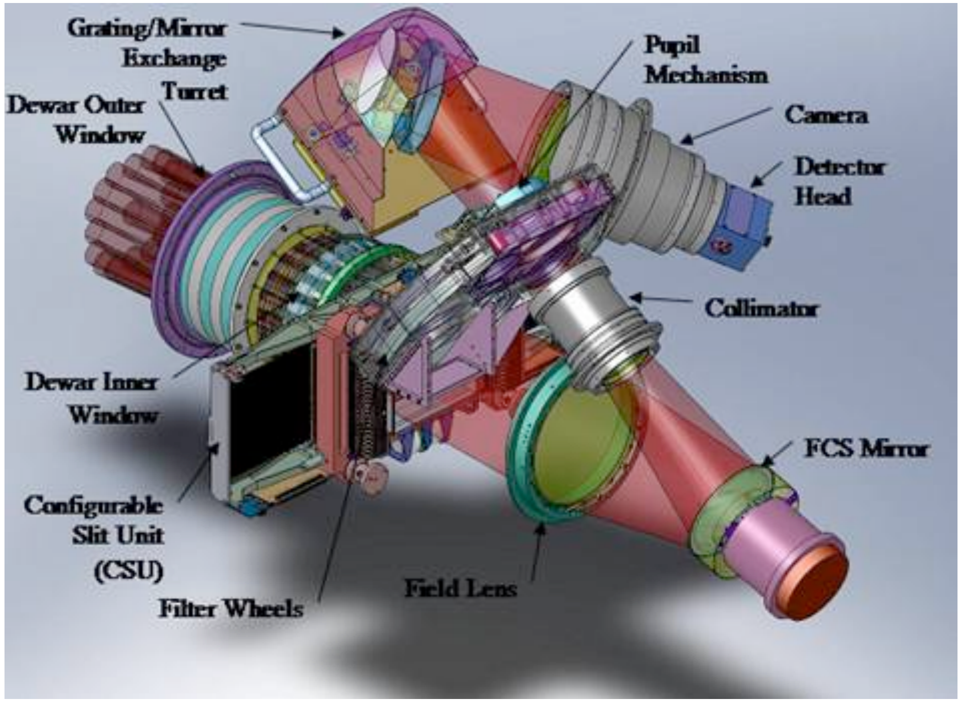
and spectra of the selected sources measured at the detector.

Images from the Gemini Multi-object Spectrograph GMOS

Slit Mechanisms

- UCLA building Keck NIR MOS instrument with Swiss CSEM slit mechanism
- first time they have gone to European procurement

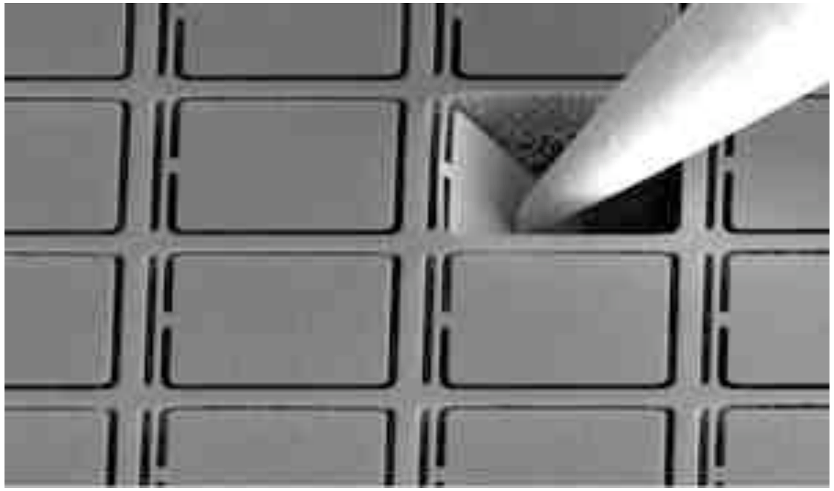




Courtesy Ian McLean, UCLA

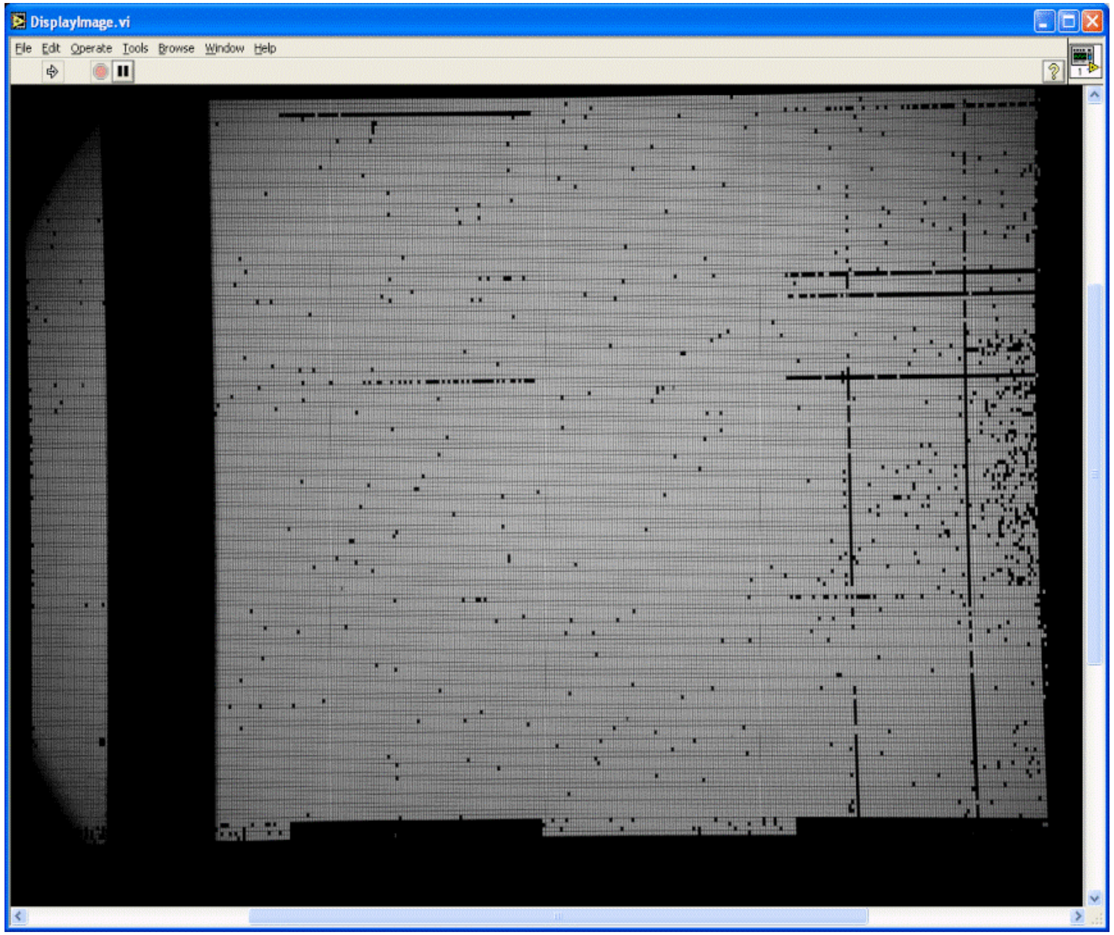
Programmable Slit Spectrometers: MOEMS Shutter arrays

NIRSPEC
James Webb Space Telescope



Harvey Moseley, NASA Goddard

Programmable Slit Spectrometers: MOEMS Shutter arrays



Integral Field Spectroscopy

‘data cube’

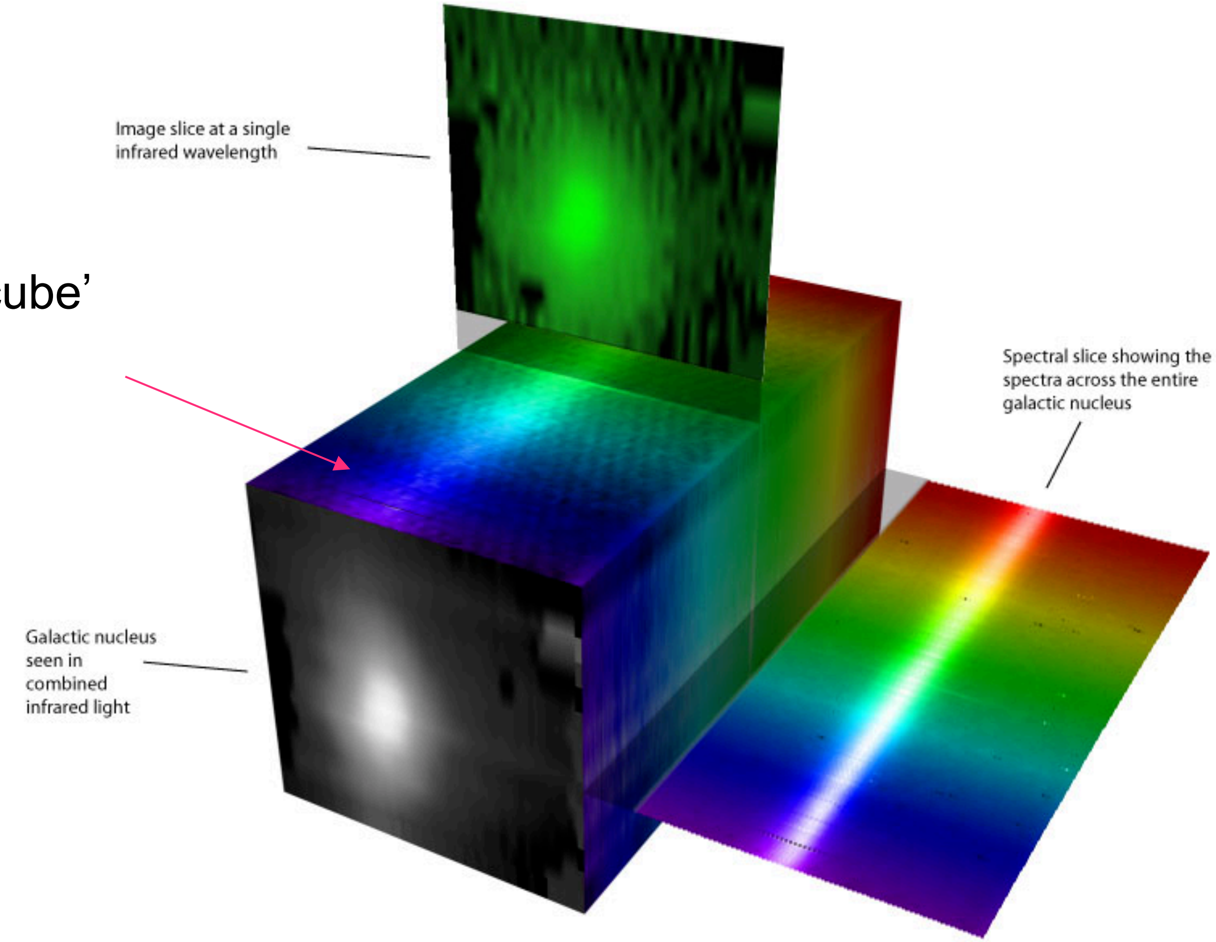


Image: Stephen Todd, ROE and Douglas Pierce-Price, JAC

Techniques for 3D spectroscopy

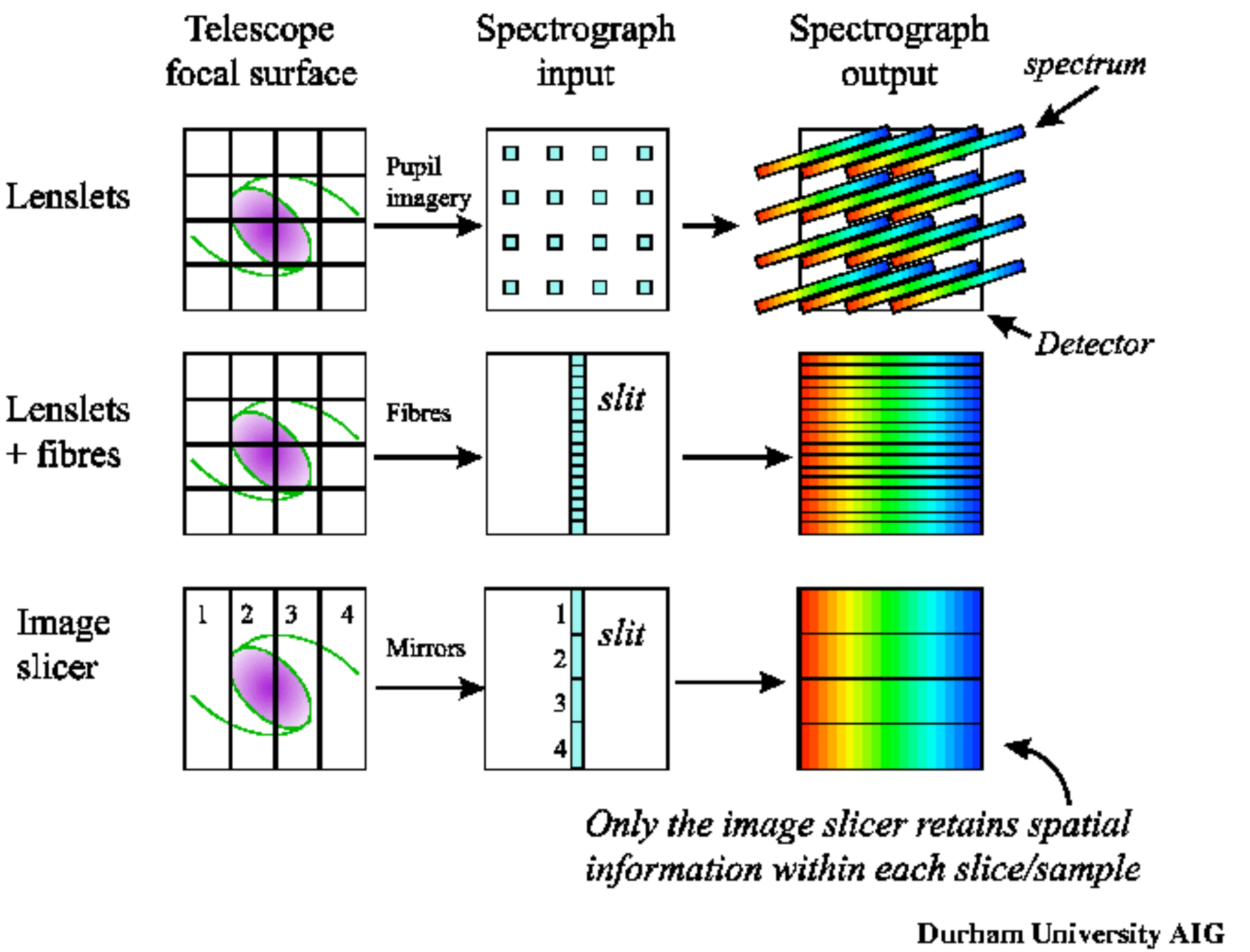
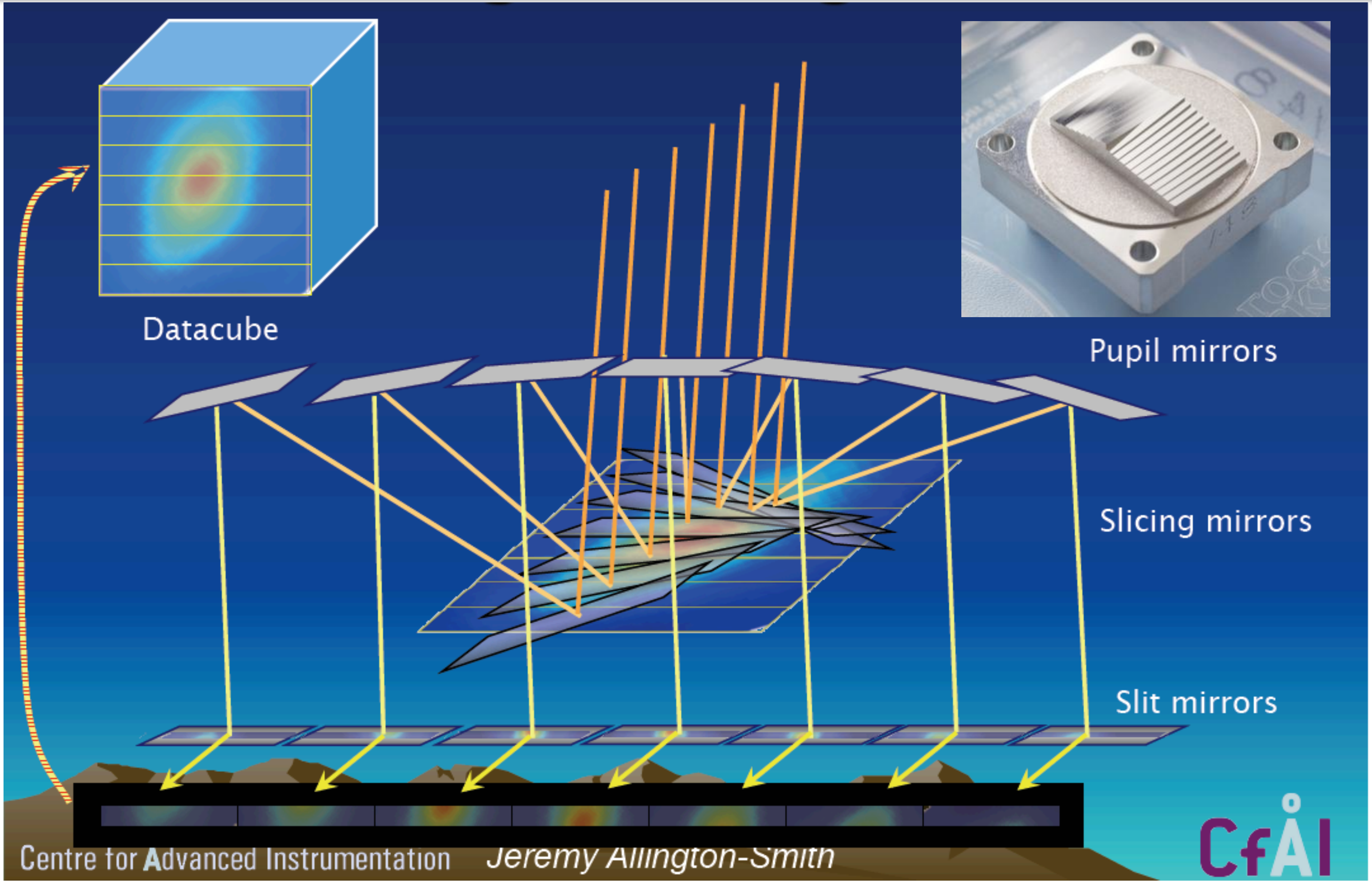
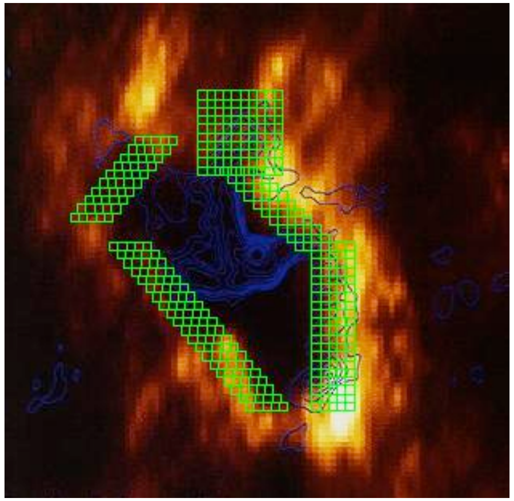
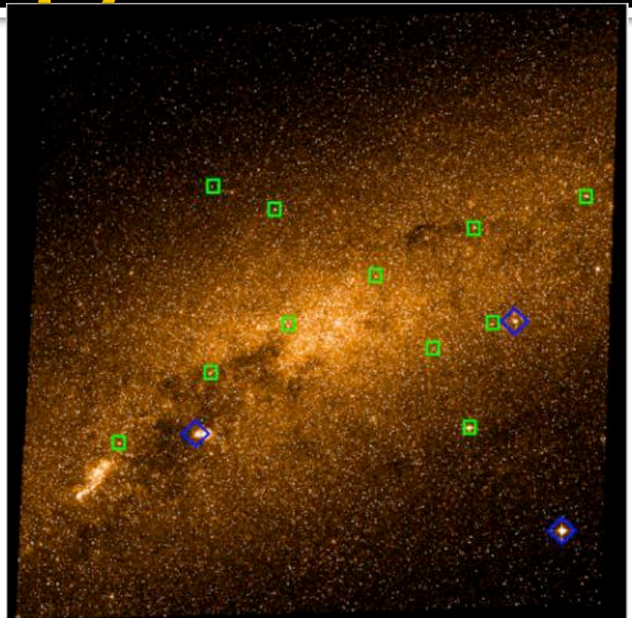


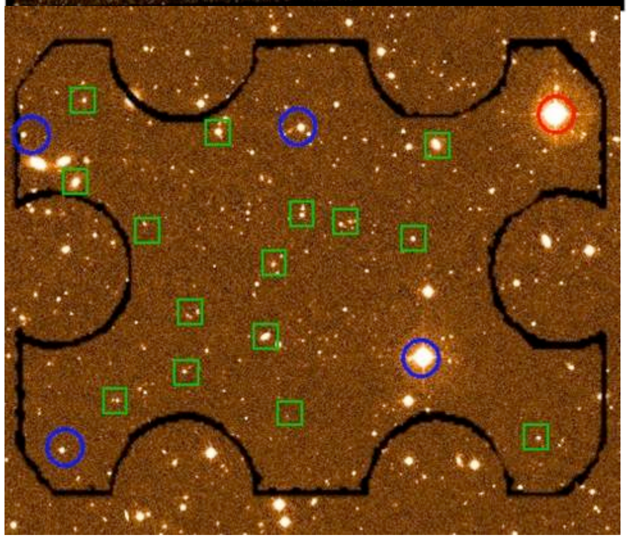
Image Slicer

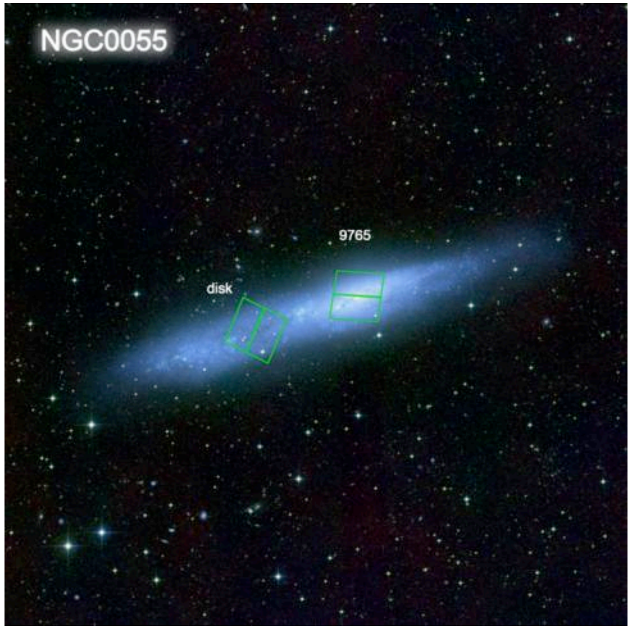


Multi-object Integral-Field Spectroscopy



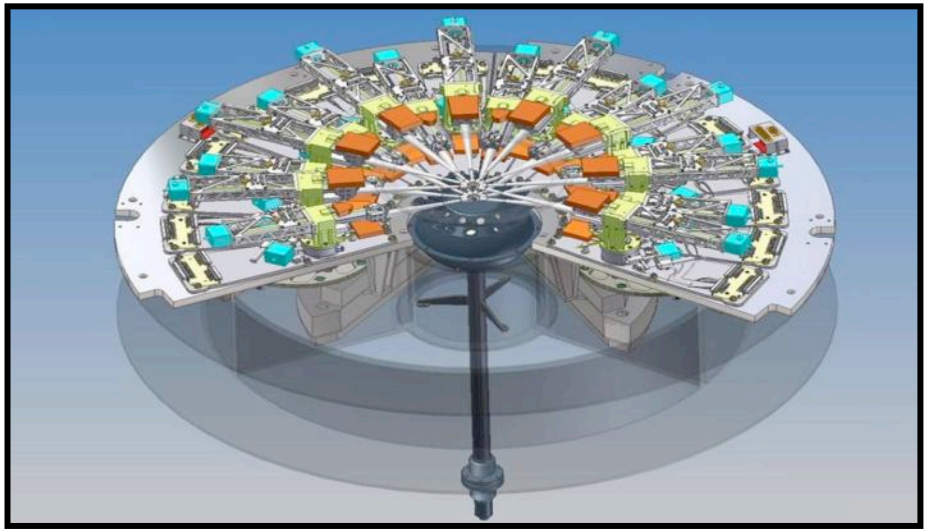


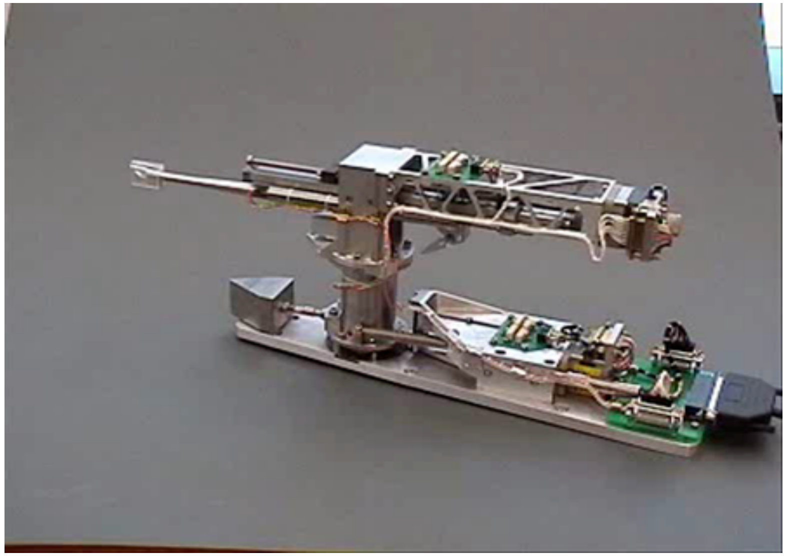




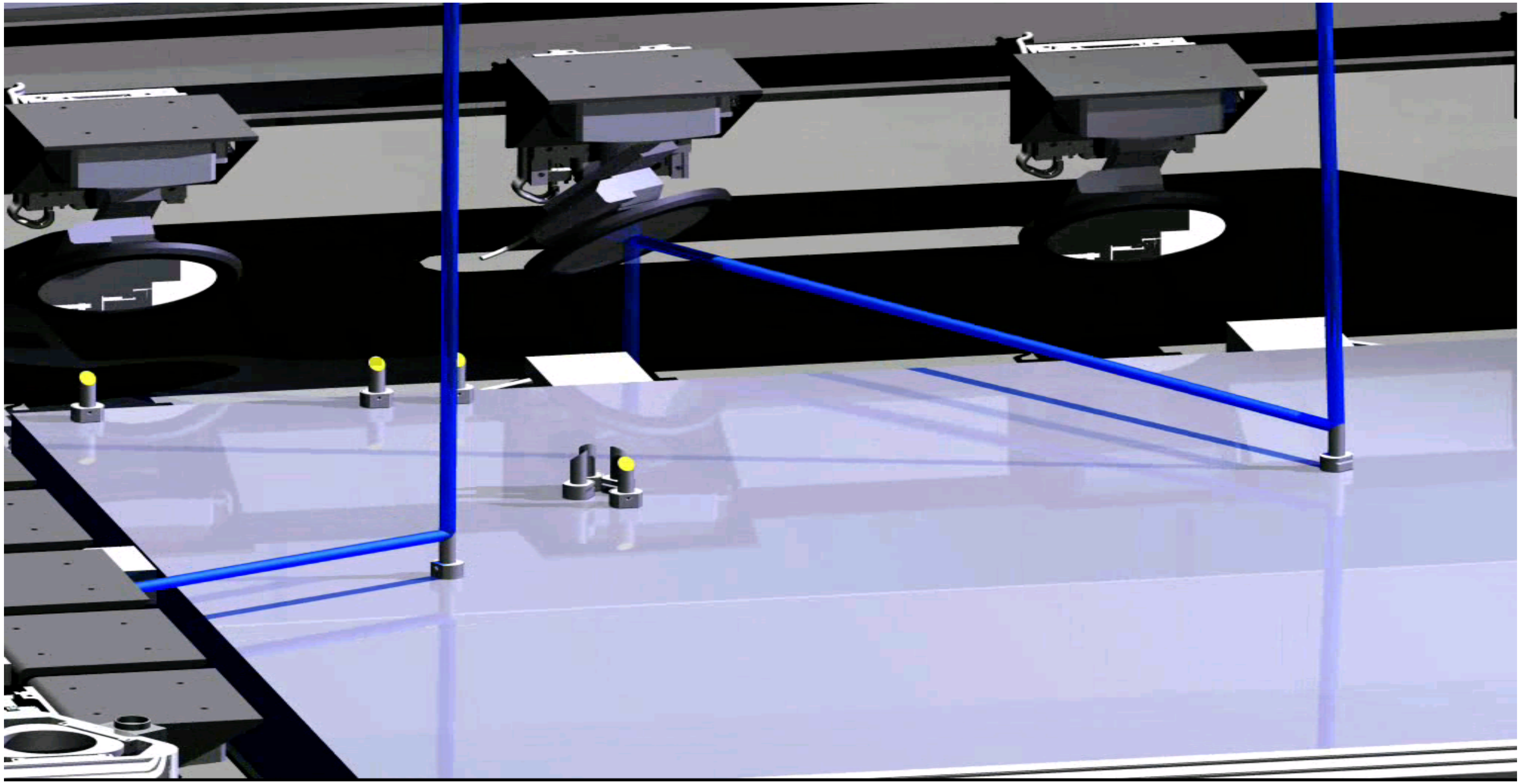
Current Technology: Pick-Off Arms (VLT KMOS)

- Very hard to meet stability requirements for E-ELT
- Too complex and bulky for more than about 30 objects

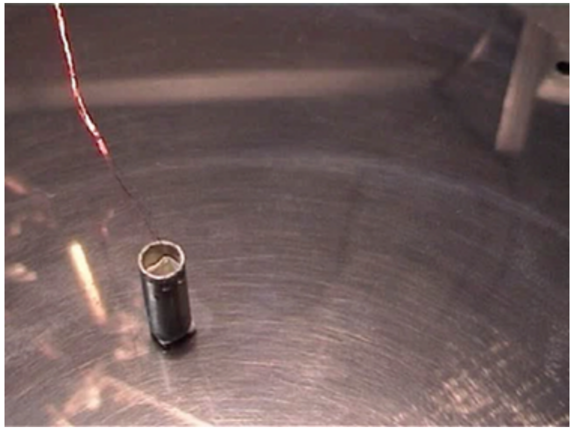


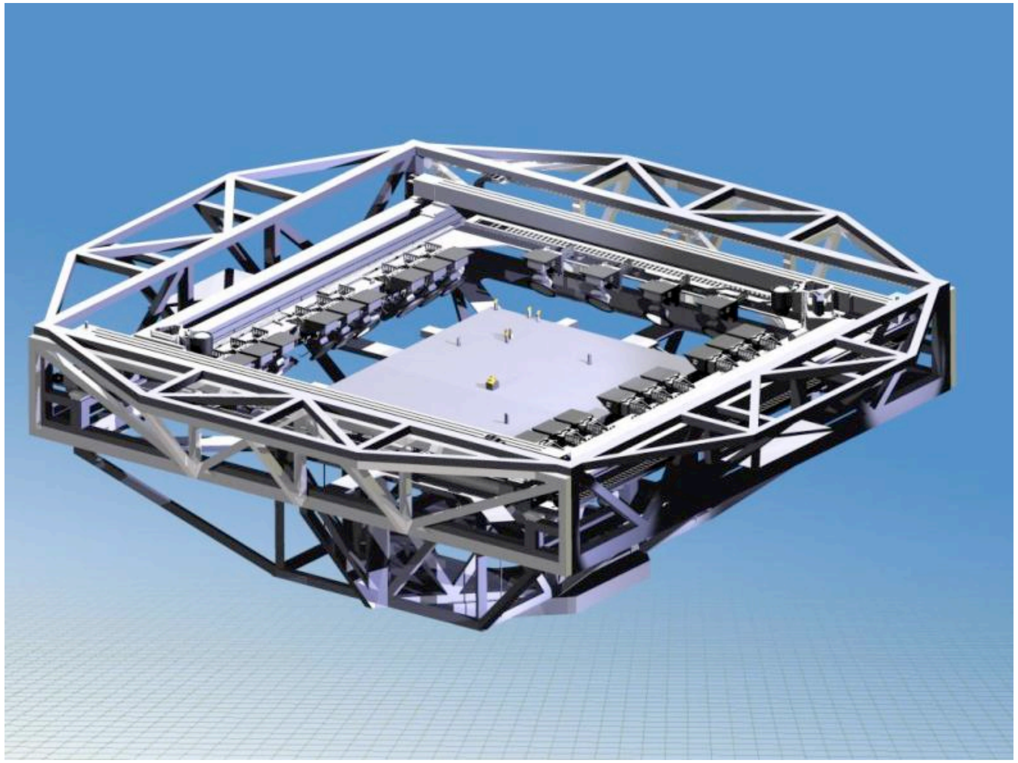


EAGLE Concept

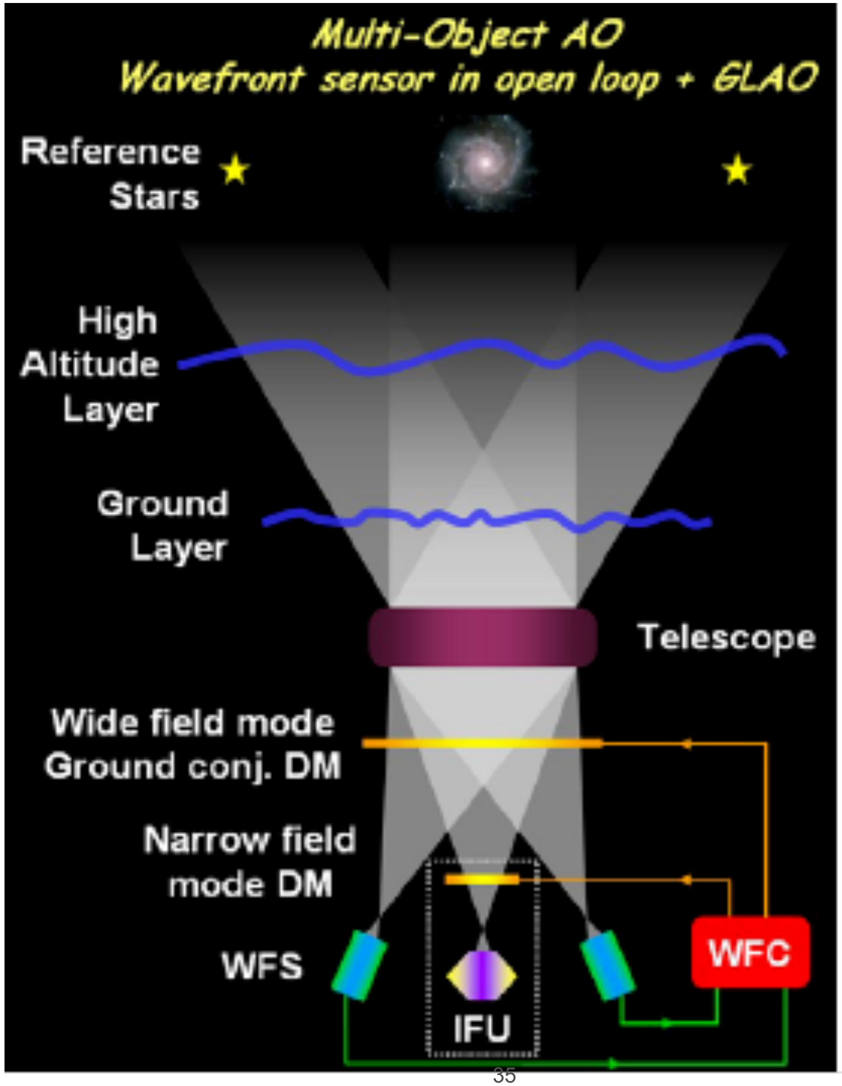


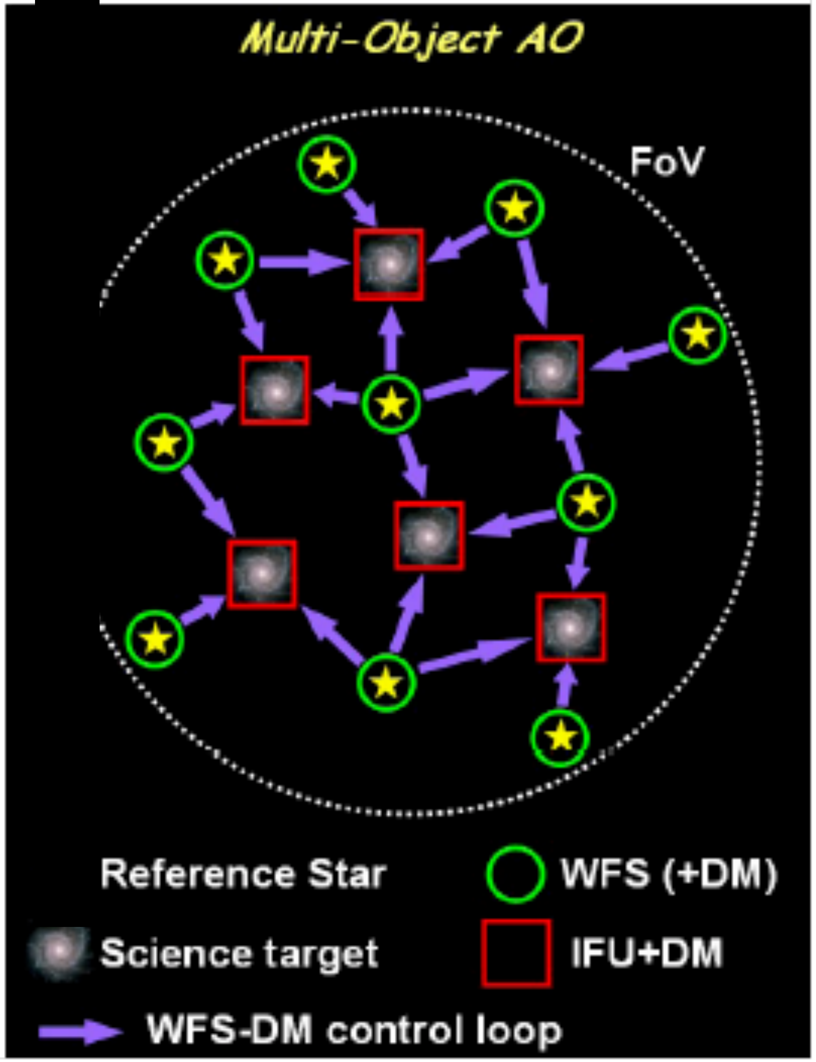
Starbugs & Starpicker



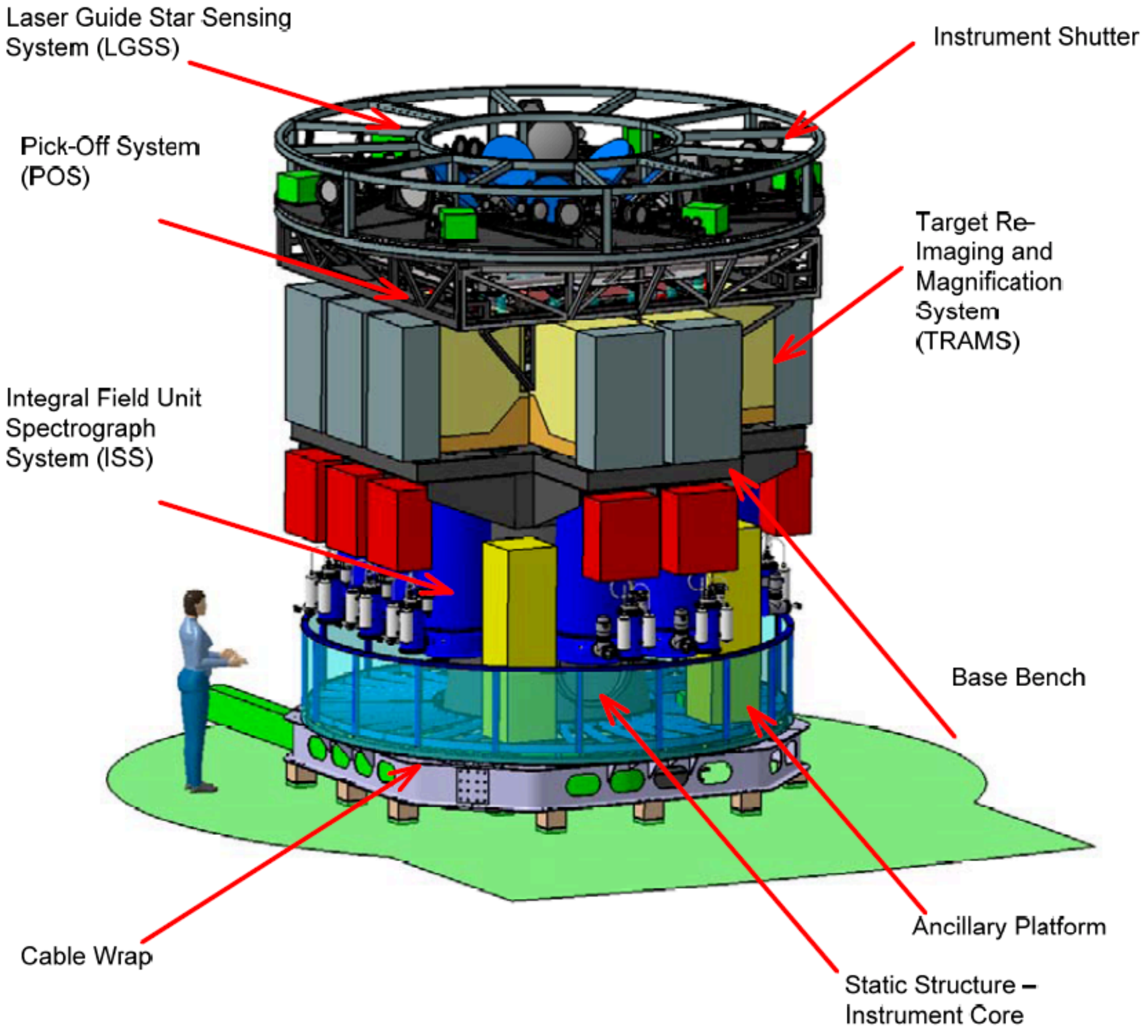


Multi Object Adaptive Optics

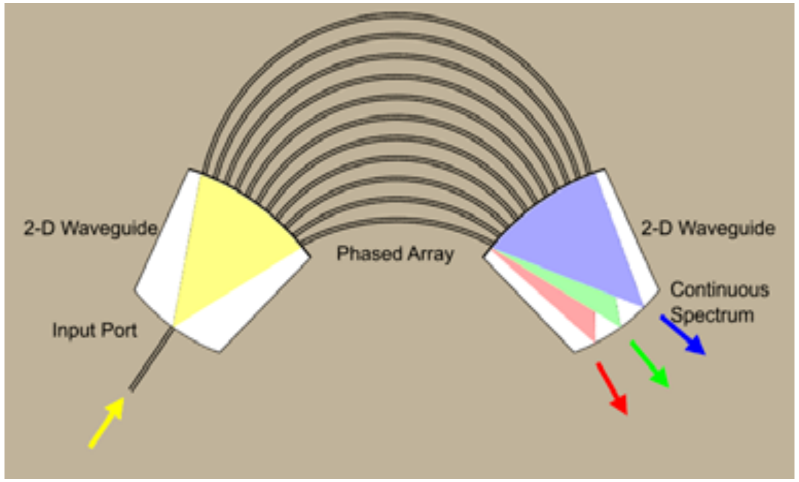


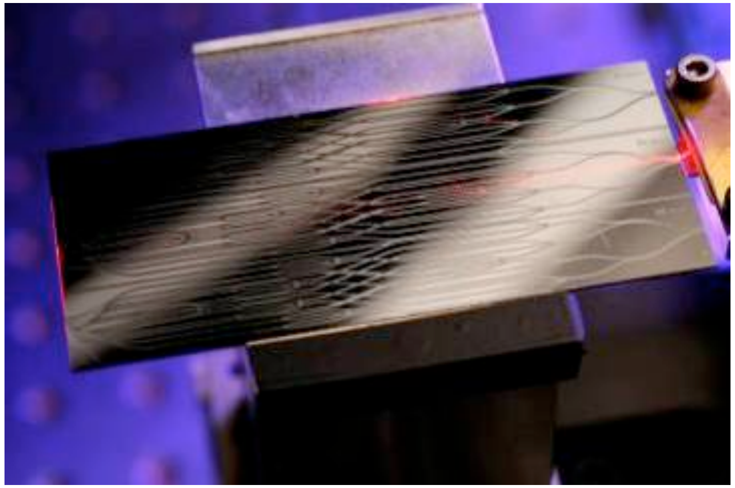


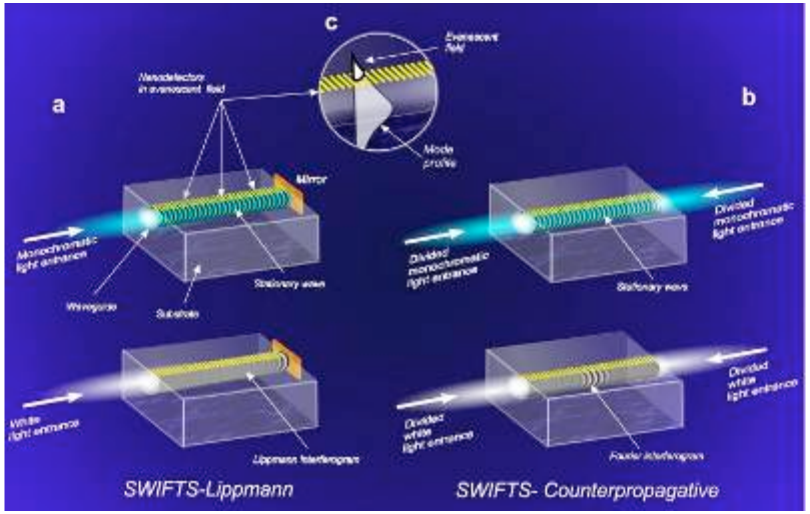
EAGLE for E-ELT

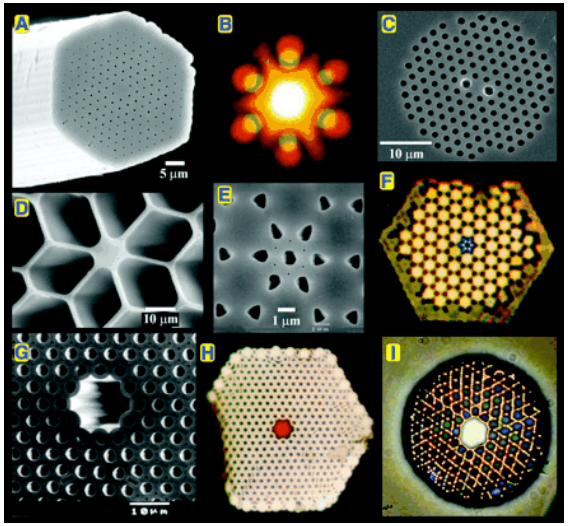


Astrophotonics

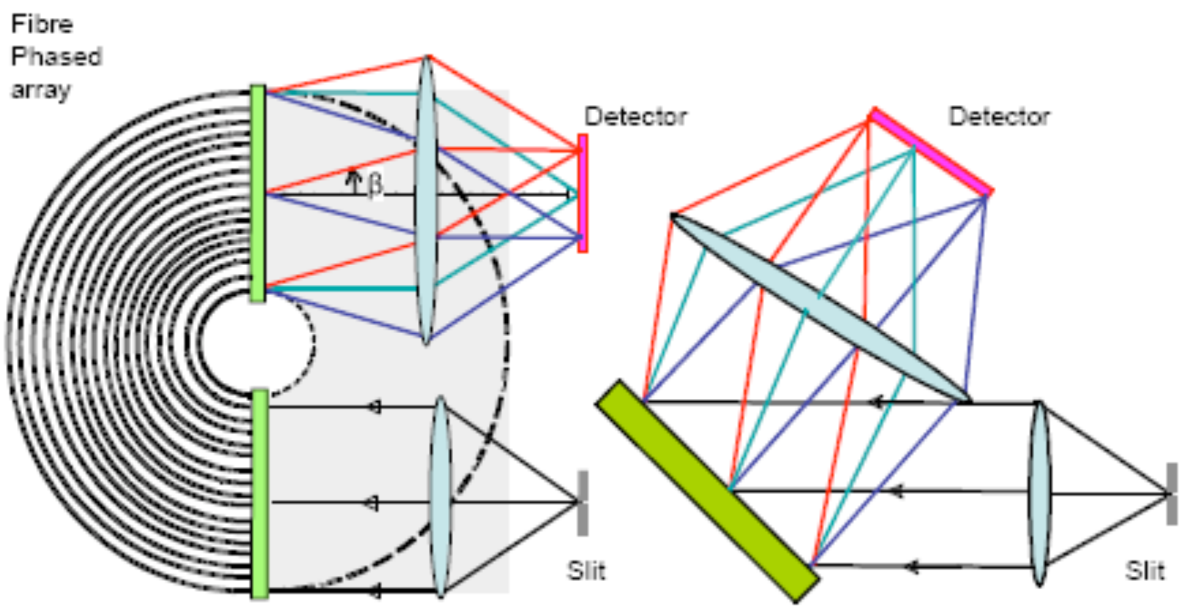








Fibre v. conventional spectrometer

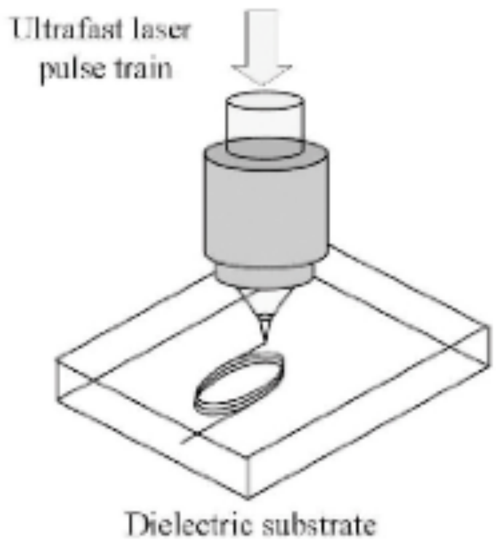


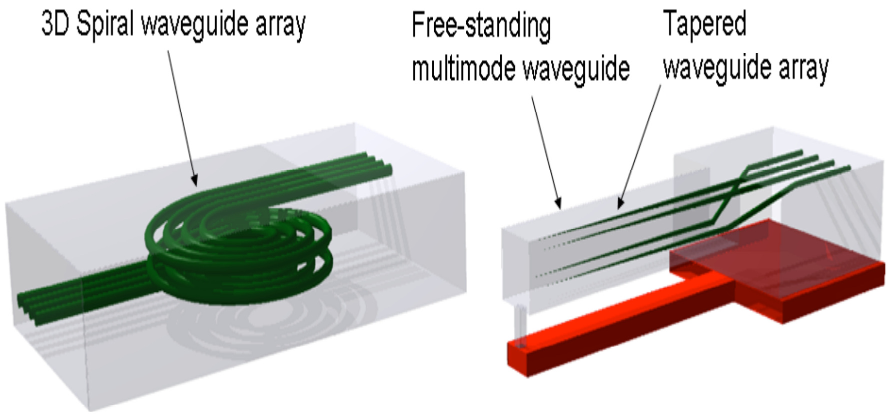
The fibre array spectrometer has 5x the spectral resolution of the conventional dispersive spectrometer – or is 5x smaller

Robert R. Thomson, Ajoy K. Kar, and Jeremy Allington-Smith Vol. 17, No. 3 / OPTICS EXPRESS

Photonic Fabrication Technologies

- Direct writing of 3D waveguides can
  - Simplify IR beam combiners for interferometry
  - Enable manufacture of integrated OH suppression using Bragg grating filters
  - Enable Miniature Spectrometers

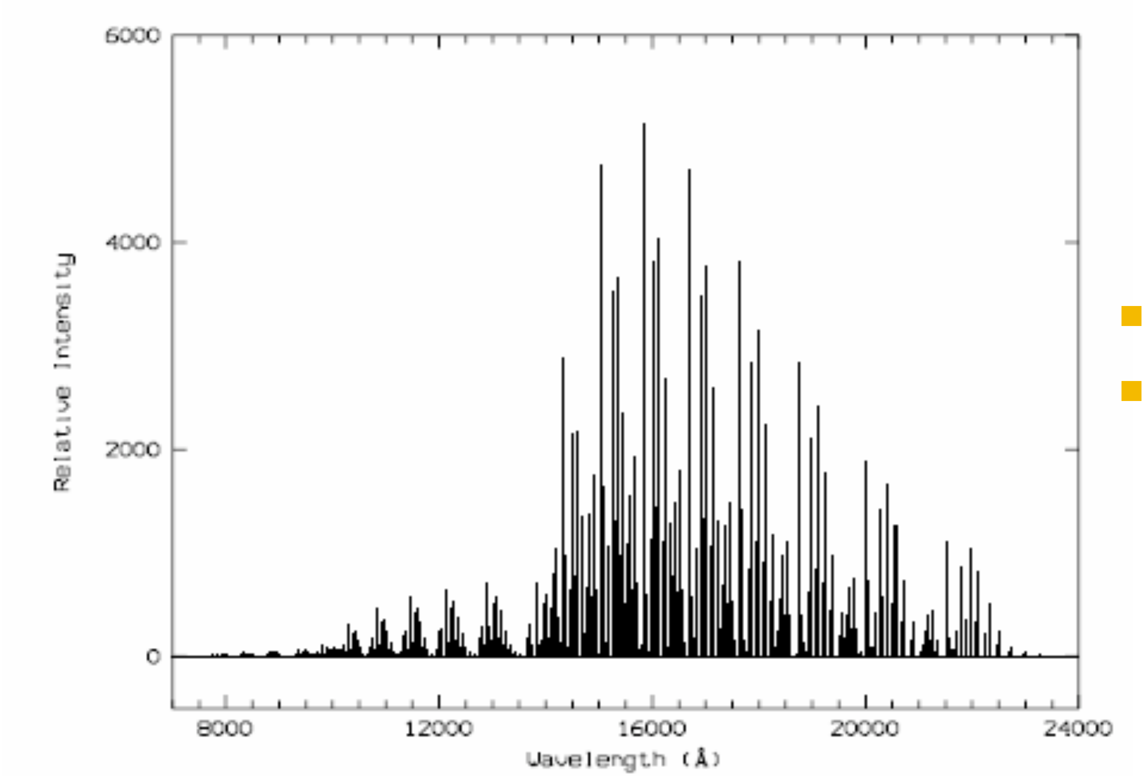




Robert R. Thomson, Heriot-Watt Univ

NIR spectroscopy - the background

The OH emission spectrum:

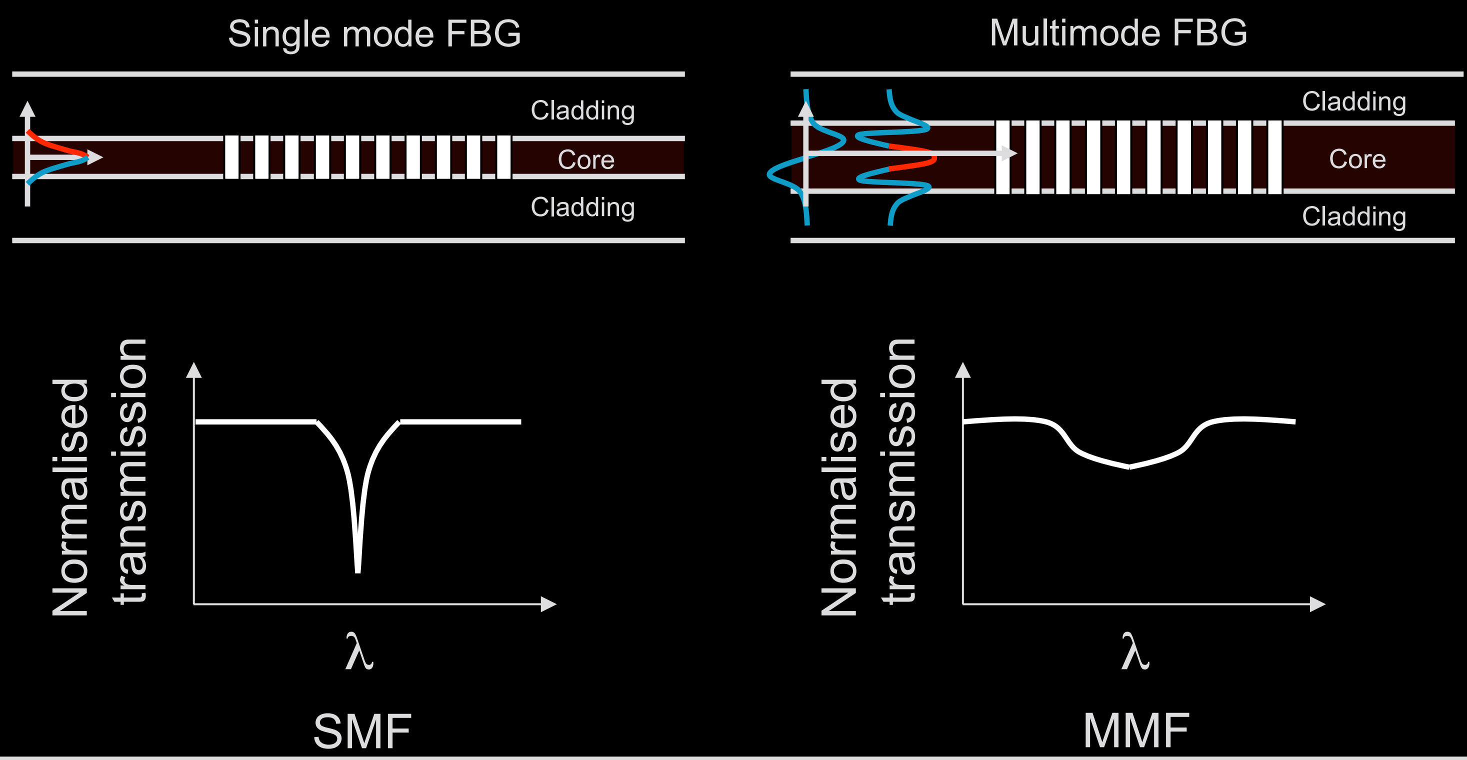


OH spectrum from Rousselot et al. (2000, A&A, 354,1134).

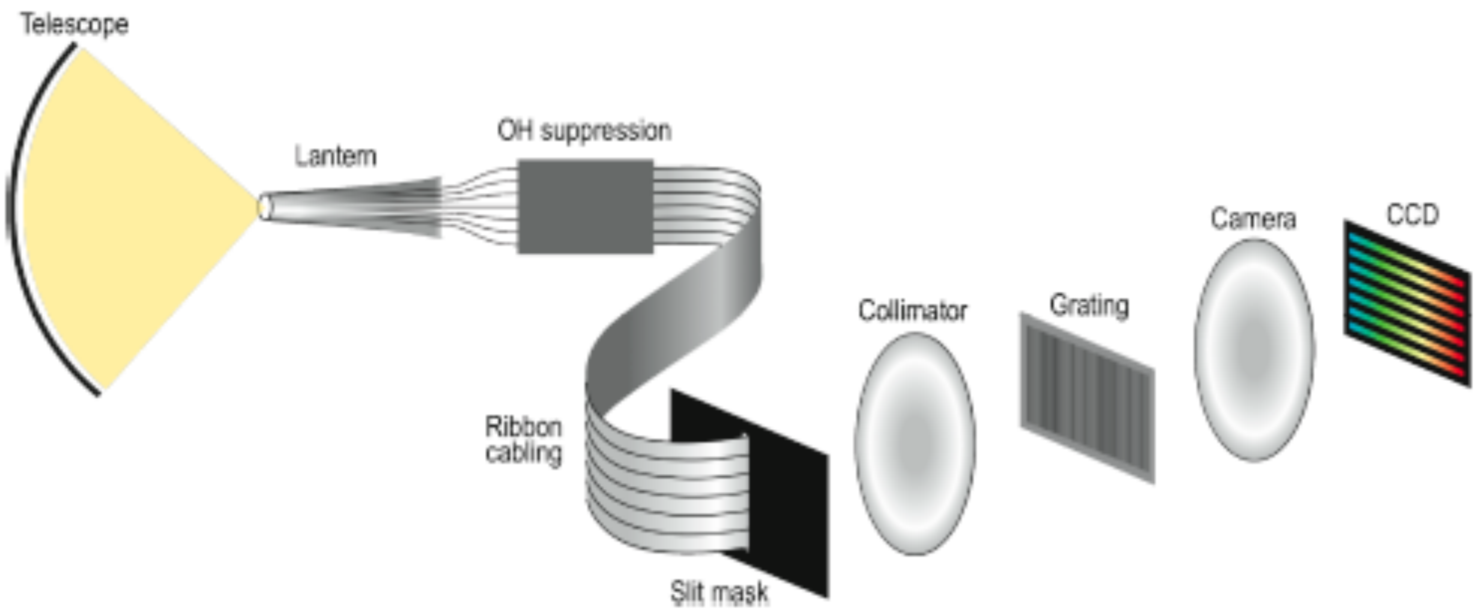
- Lines are bright
  - 2500 photons per second per arcsec with an 8-m telescope, 1000 times typical target source flux
- Variable
- BUT, the continuum between them is very dark
  - 0.1photons per second

Bragg gratings for OH suppresion

Single mode fibre Bragg-gratings (FBGs) have been used to suppress OH fluorescence.

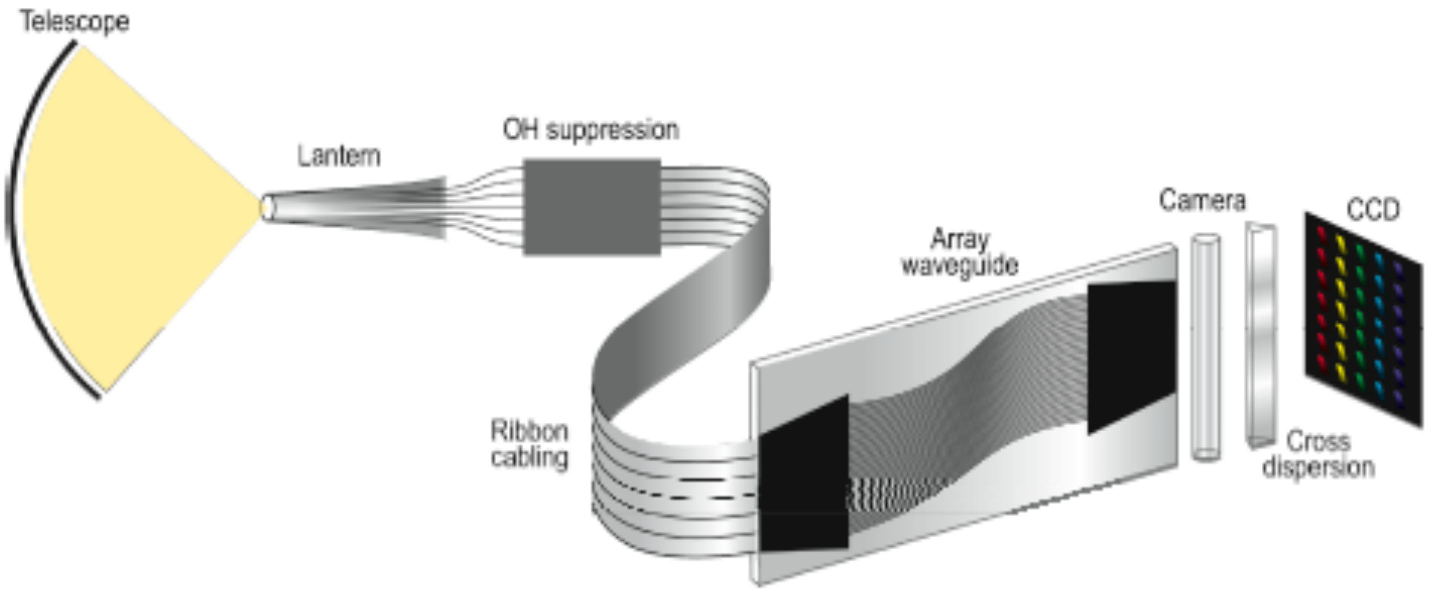


PIMMS: photonic integrated multimode microspectrograph



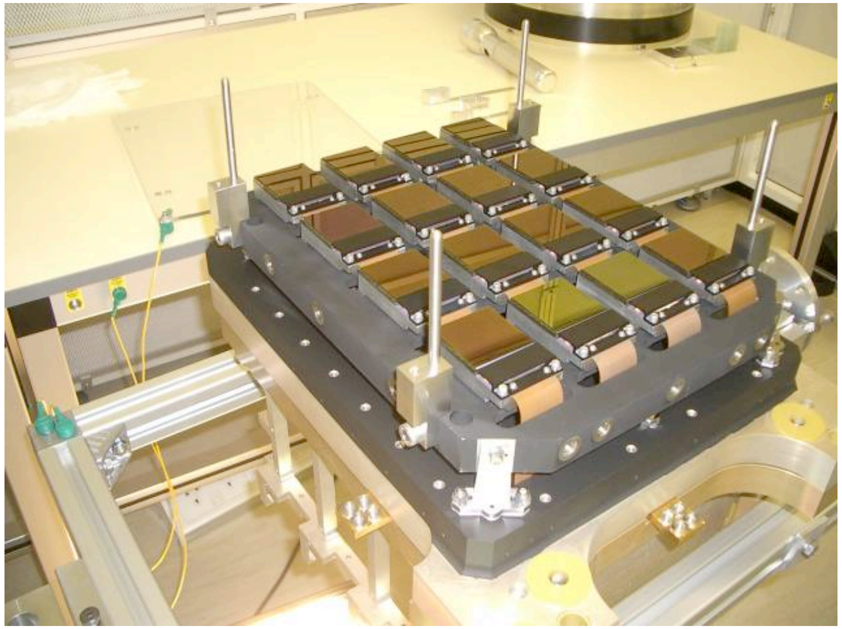
Bland-Hawthorn et al, 2010, Proc. of SPIE Vol. 7735 77350N-1

Fully integrated version



Detectors

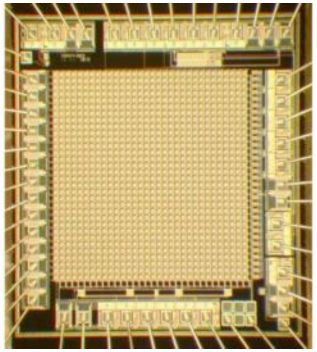
- Needs:
  - Bigger, cheaper, better!
- E-ELT will need 60 -100 2kx2k IR arrays
- Lower noise would be good!
- James Webb Space Telescope shows how IR detector performance can be pushed by astronomy
  - But at high cost



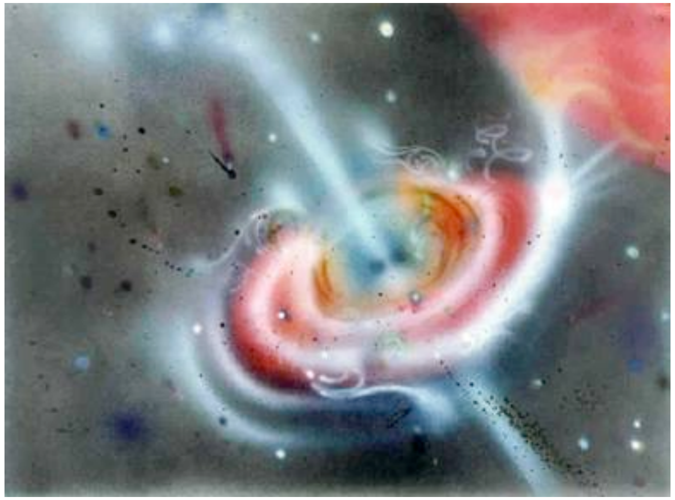
16 2kx2k Raytheon Arrays in VISTA

High time resolution

- **On timescales of milliseconds**
  - study the optical emission from pulsars.
  - optical analogue of the kilohertz quasi-periodic oscillations and related small-scale accretion phenomena found in X-ray binary stars (XRBs)



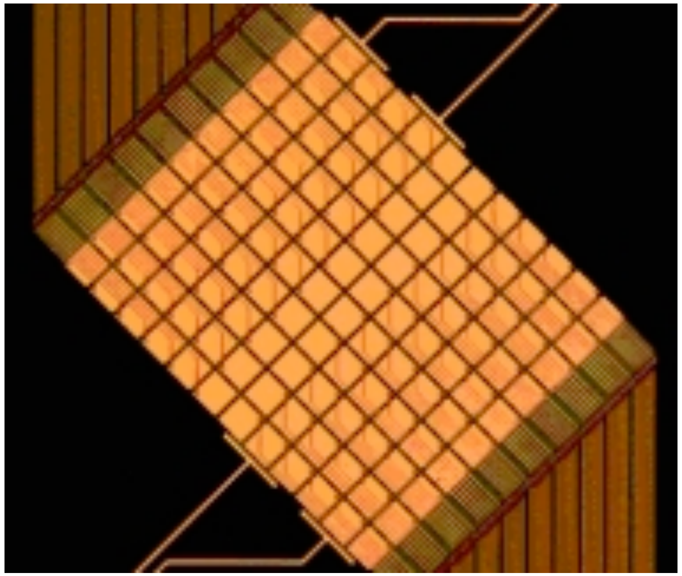
SPAD (Single Photon Avalanche Diode) Array
Ecole Polytechnique Fédérale de Lausanne



Accretion processes in an XRB. Artwork by Catrina Liljegren, *Bild & Form*, Lund; ©Dainis Dravins, Lund Observatory.

Energy resolving detectors: STJs

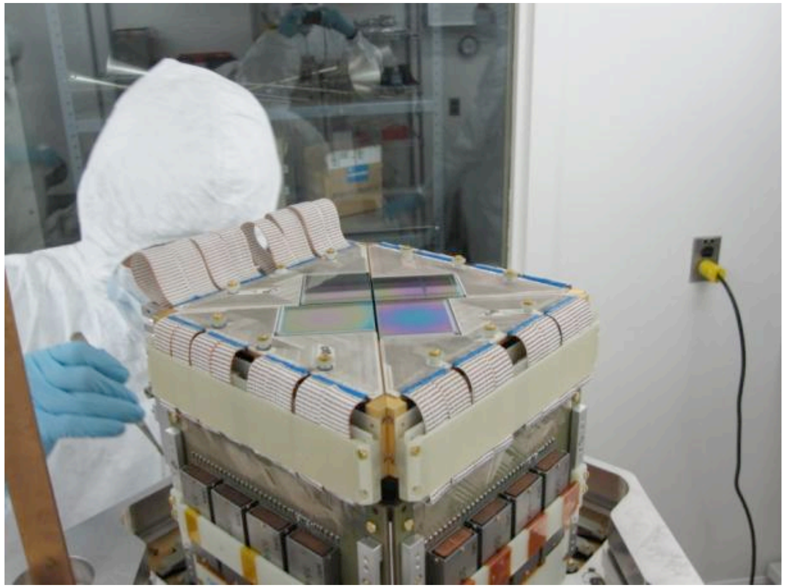
- Superconducting Tunnel Junctions
- ESA's S-CAM



Detector	12x10 Ta/Al STJs
Pixel size	33 x 33 μm^2
Fill factor	76%
Plate scale	0.8"/pixel
FOV	11"x9"
Pass band	330-745 nm
Maximum detection efficiency (@500nm)	30%
$\lambda/\Delta\lambda$ @ λ=500nm	8-11
Event time resolution	~5 μs
Operating temperature	285 mK

Energy Resolving Detectors

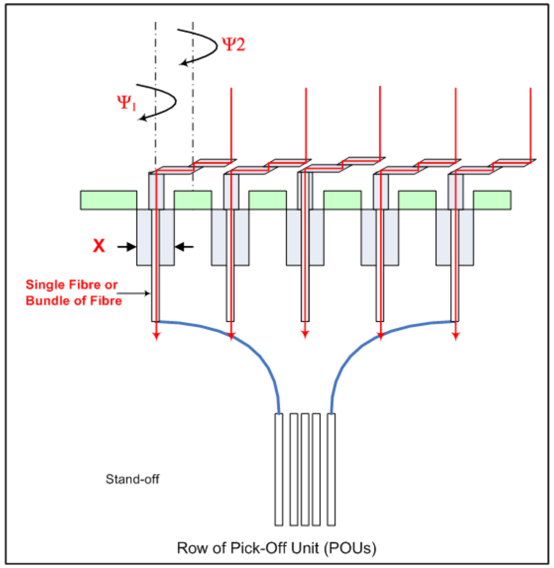
- **T**ransition **E**dge **S**uperconducting Device
- **K**inetic **I**nduction **D**evices
- **S**uperconducting **T**unnelling **J**unction
- **D**istributed **R**ead **O**ut **I**maging **D**evice
- Superconducting Nanowires



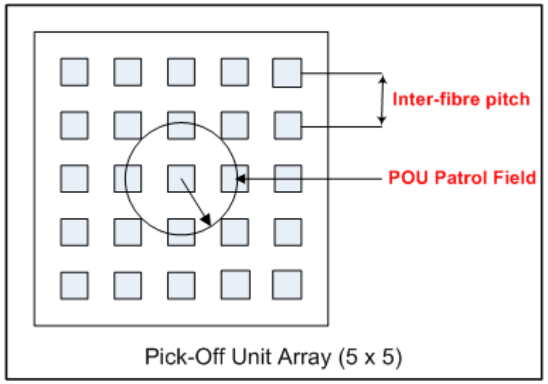
SCUBA 2 450µm TES arrays

Ultimate, Ideal MOS Instrument?

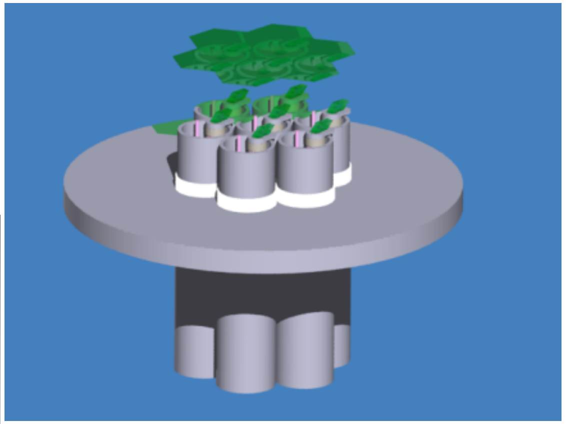
- Tiled Micro-Mechanical MOS System (TiMMS)
  - Feeding 500 photonic spectrometers
- Or, build the photonic spectrometers into micro-robots?

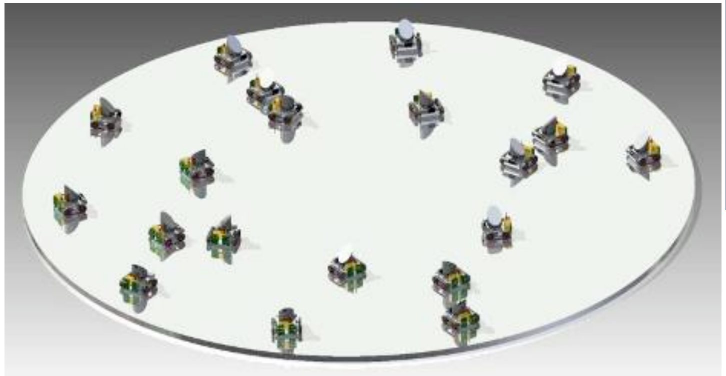


Row of Pick-Off Unit (POUs)



Pick-Off Unit Array (5 x 5)





Conclusions

- Next generation of instruments can be built with existing technology
- But, there are potentially better solutions
  - Photonic Devices
  - Robotics
  - Novel Gratings
  - Photon counting detectors
    - Ultimately energy sensitive

Thanks to the OPTICON Key Technology Network

Further Reading

- Special issue on Astrophotonics: *Optics Express*, Vol. 17, Issue 3, 2009
- Colin Cunningham ‘Future Optical Technologies for Telescopes and Instruments’ *Nature Photonics* 3, May 2009, 239-241
- Colin Cunningham ‘Future Technologies for Optical and Infrared Telescopes and Instruments’. *Experimental Astronomy*, 2009, 26, 179-199
- Ian McLean ‘Electronic Imaging in Astronomy: Detectors and Instrumentation’ (Springer Praxis Books / Astronomy and Planetary Sciences) , 2008

Dealing with Complexity: Systems Engineering

- Modern Ground-based instruments are increasingly complex – can't all be in one person's head!
- Need tools to control this complexity:
  - Requirements capture
  - Functional Analysis
  - Architectural Design
  - Interface definition and control
  - Performance Verification

Waterfall Diagram