The rise of the photonic microspectrograph

Joss Bland-Hawthorn
Sergio Leon-Saval
PhD: Chris Betters

University of Sydney

Collaborators: Nick Cvetojevic (USyd), Nem Jovanovic (Subaru), Itan Gris Sanchez, Tim Birks (Bath), Rob Thomson

astrophotonics

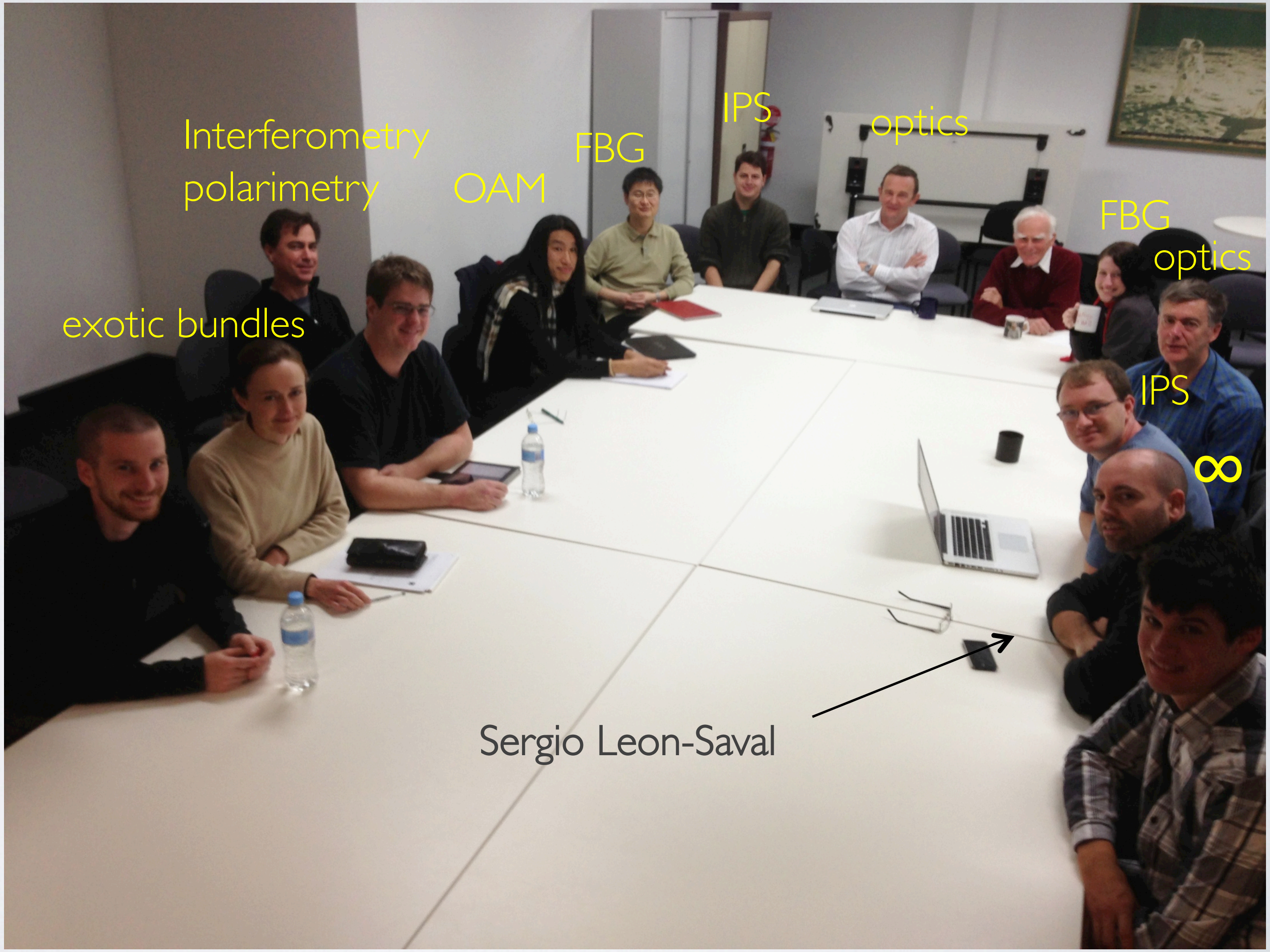
Sydney – AAO – Macquarie

A typical weekly meeting has ~15 people.

Our biannual meetings have ~40 people.

These branch to 6 specialist meetings, each with ~10-15 people.

International meetings run to ~80 people.



Sydney – AAO – Macquarie

The Consortium for Australian Astrophotonics (CAA) has 5 major labs.

Since 2008, the labs have published 60+ refereed papers, 15 post-deadline papers, 80+ refereed conference papers, 8 PhD completions and 3 patents published.

Grant funding: ARC Federation Fellow, DP, LIEF, Linkage, CSIRO SIEF, NASA, Keck Foundation, Horticulture Australia, AusVeg, AT&T Bell Labs, Chinese Research Grants Council.

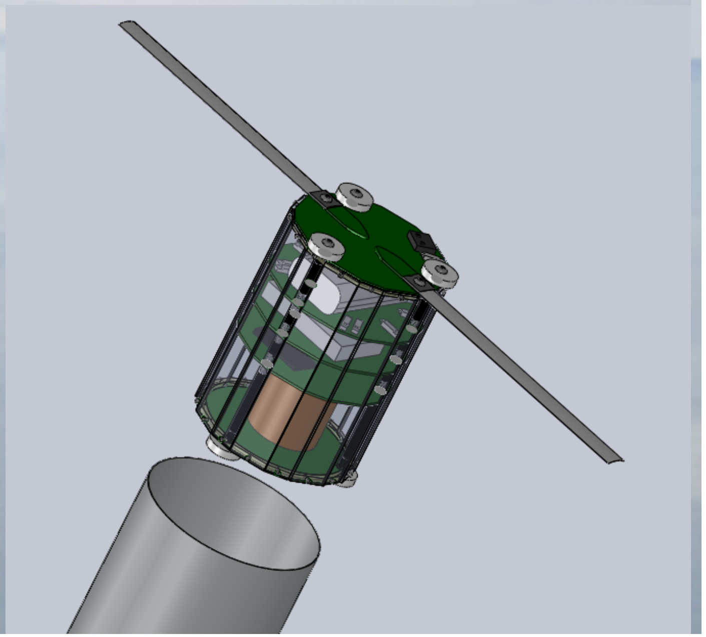
Our applications

Ground-based telescope instrumentation: astronomy
(e.g. FIREBALL, GNOSIS, PRAXIS, SAMI, Hector, PIMMS)

Space-based instrumentation: remote sensing
(e.g. nanoSPEC, i-INSPIRE)

Telecomms: multicore gratings, mode switching
(e.g. Alcatel Lucent, CUDOS)

Food safety: Raman spectroscopy (pulsed)
Medical physics: Raman spectroscopy
(e.g. AusVeg, HAL, Charles Perkins Centre)



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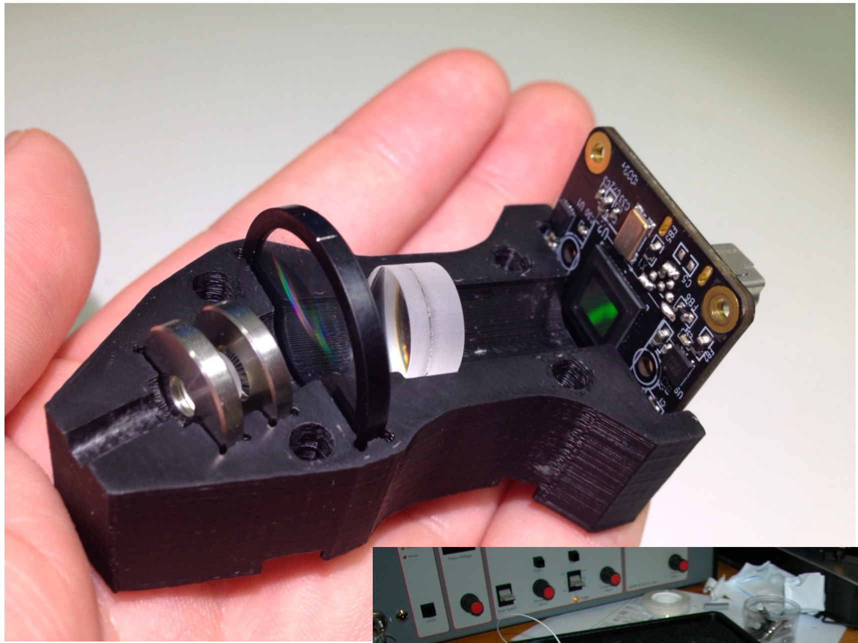
Microspectrographs

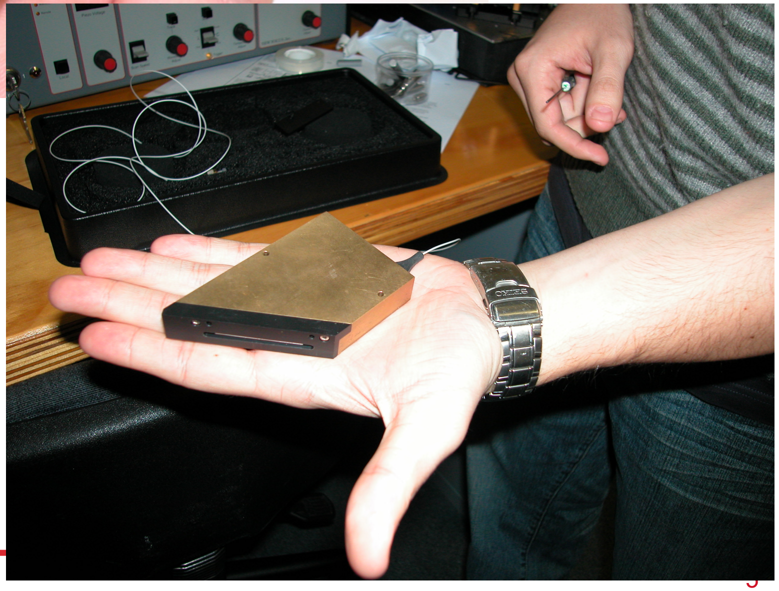
optical, NIR, MIR

hybrid: R = 1000-30,000
(Betters et al)

photonic: R = 2000-60,000
(Cvetojevic et al)



hybrid



photonic

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Microspectrographs

Many technological advantages:

compactness, low weight, portability
throughput, clean psf, low scatter
ideal (close to theoretical limits)
rigidity, stability
flexibility, versatility, modularity
functionality (laser comb, OHSupp)
cost, replication
power usage (space, balloon)

fast turnaround
testbed, prototyping
leveraging industry (devices, new funds)
student training

Unresolved:

unit cost
detector
close packing

laser locking
scrambling
sub-lambda transitions

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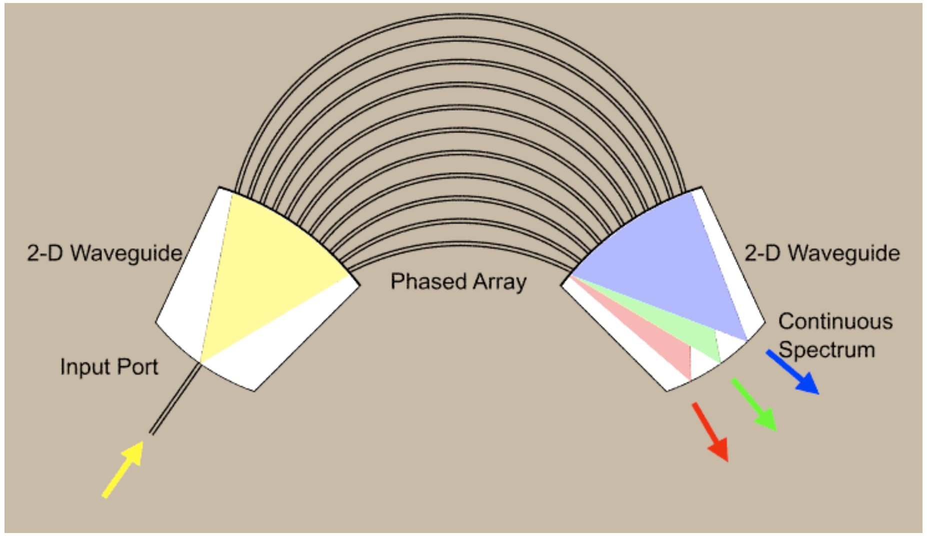
2006

Instruments without optics: an integrated photonic spectrograph

J. Bland-Hawthorn[a], A. Horton
Anglo-Australian Observatory, 167 Vimiera Rd, Eastwood, NSW 2122, Australia

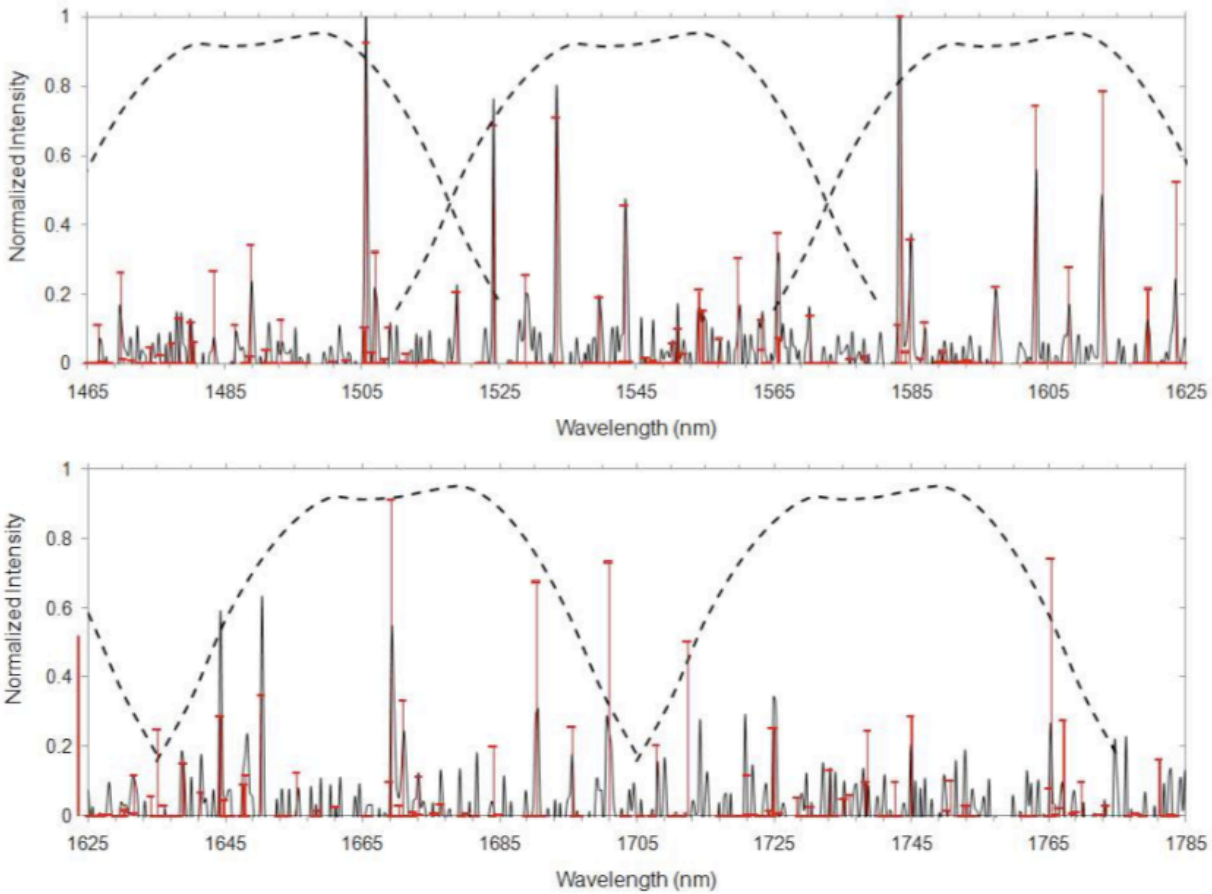


Allington-Smith & JBH 2009

Characterization and on-sky demonstration of an integrated photonic spectrograph for astronomy

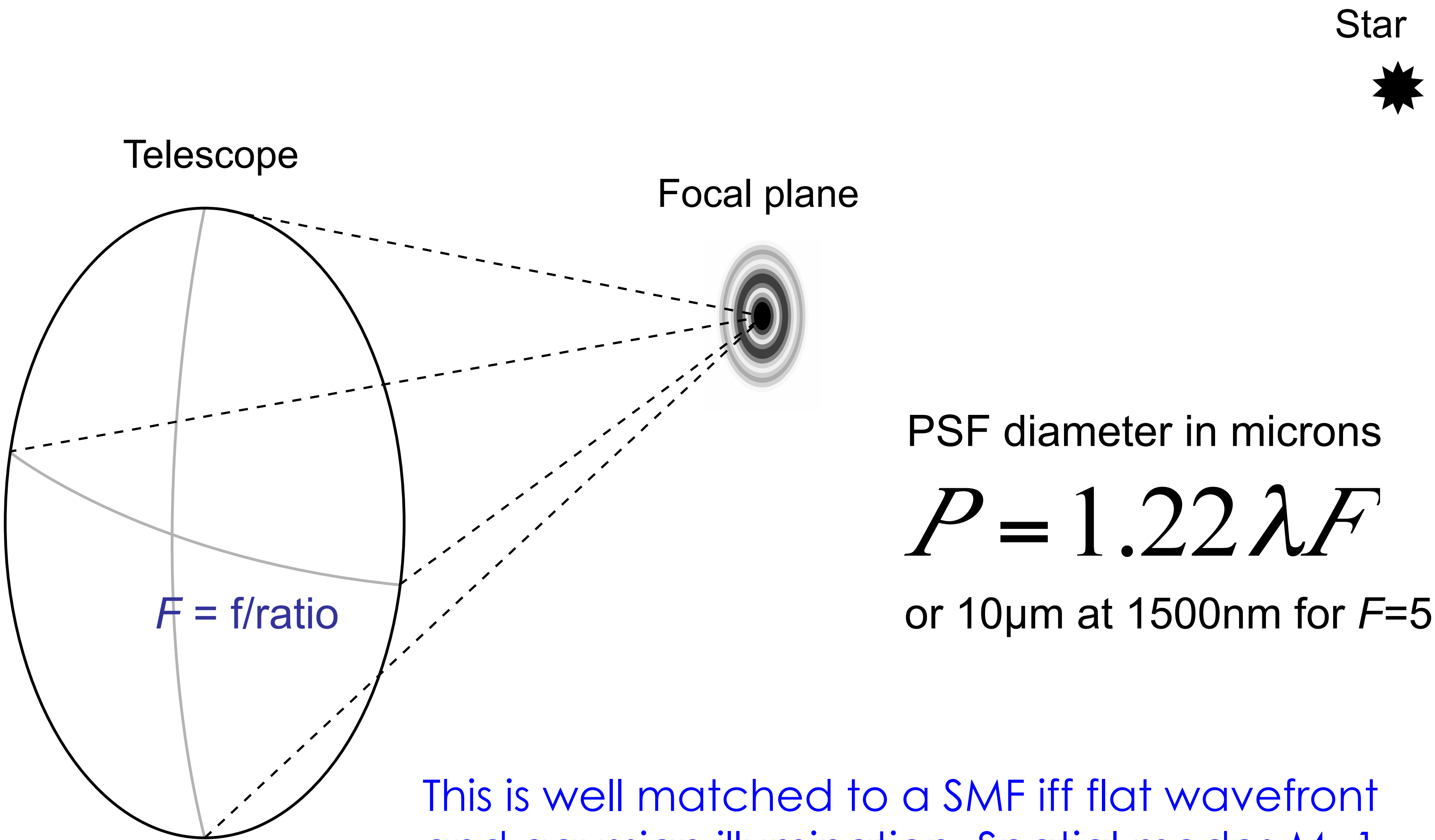
2009-12

N. Cvetojevic,[1] J. S. Lawrence,[1,2,*] S. C. Ellis,[3] J. Bland-Hawthorn,[3] R. Haynes,[1] and A. Horton[1]



The first ever continuous spectrum from an IPS !

Why is diffraction limited = single moded?



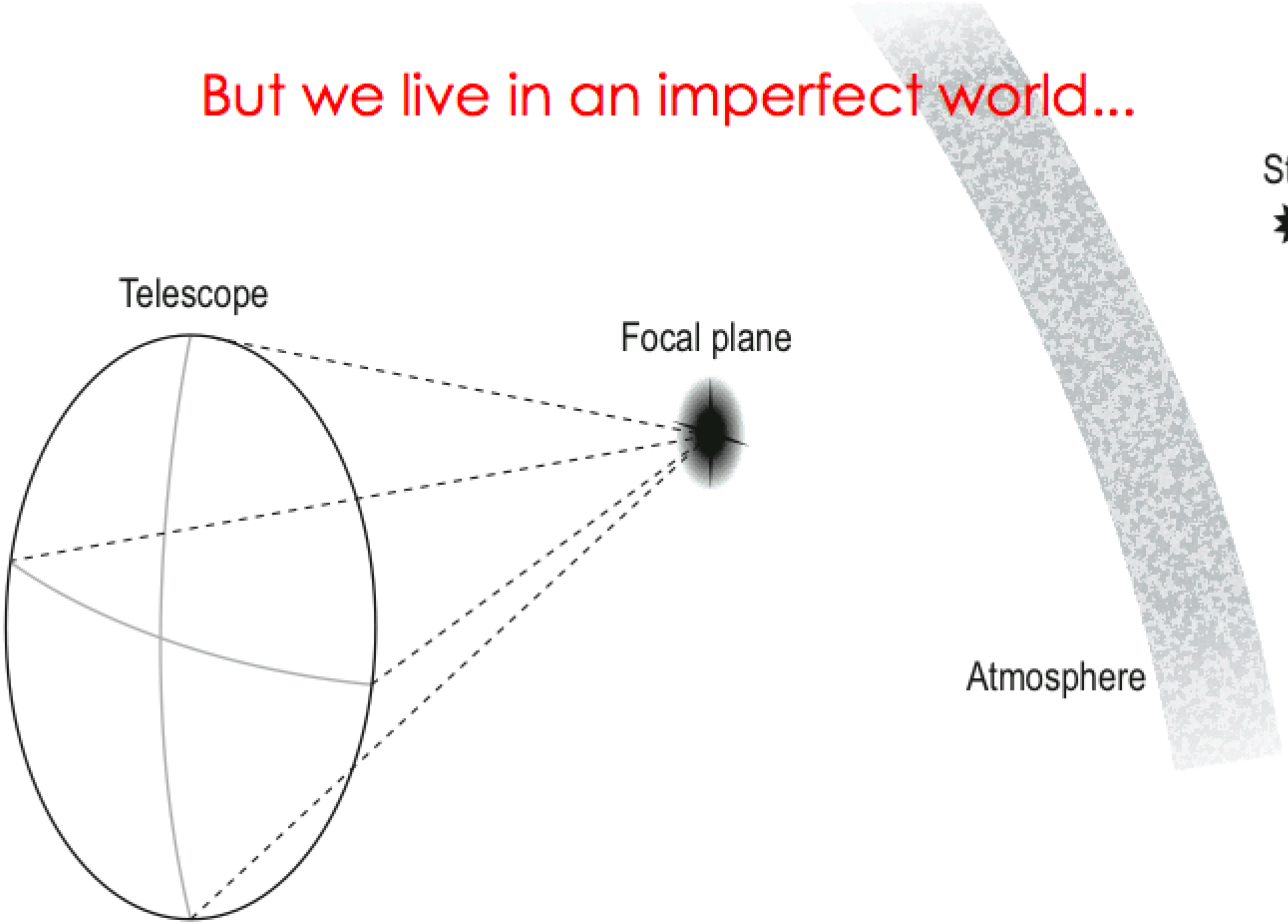
PSF diameter in microns

$$P = 1.22\lambda F$$

or 10μm at 1500nm for F=5

This is well matched to a SMF iff flat wavefront and gaussian illumination. Spatial modes M=1.

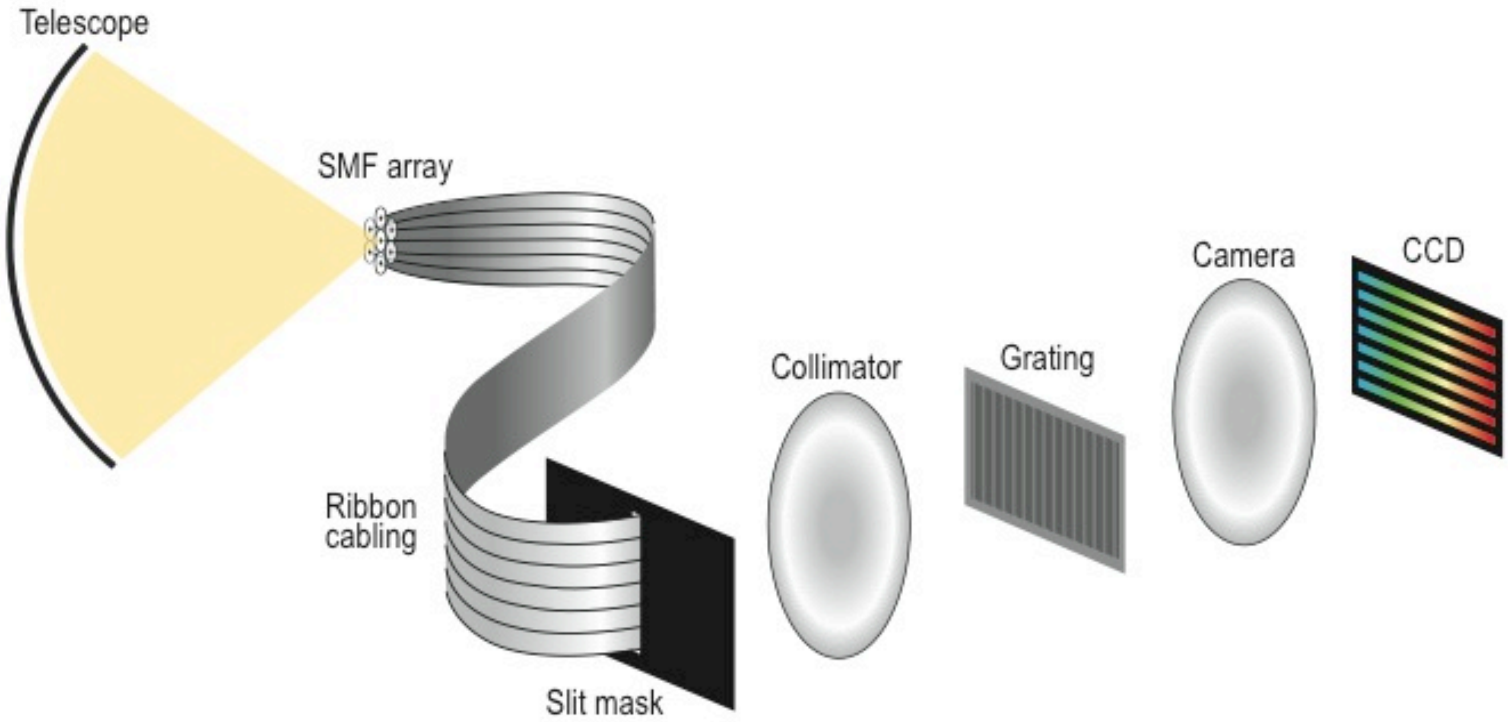
But we live in an imperfect world...



Telescope PSF is imperfect gaussian such that $M >> 0$

Horton & JBH 2006, Corbett 2007

A <u>very inefficient</u> spectrograph concept



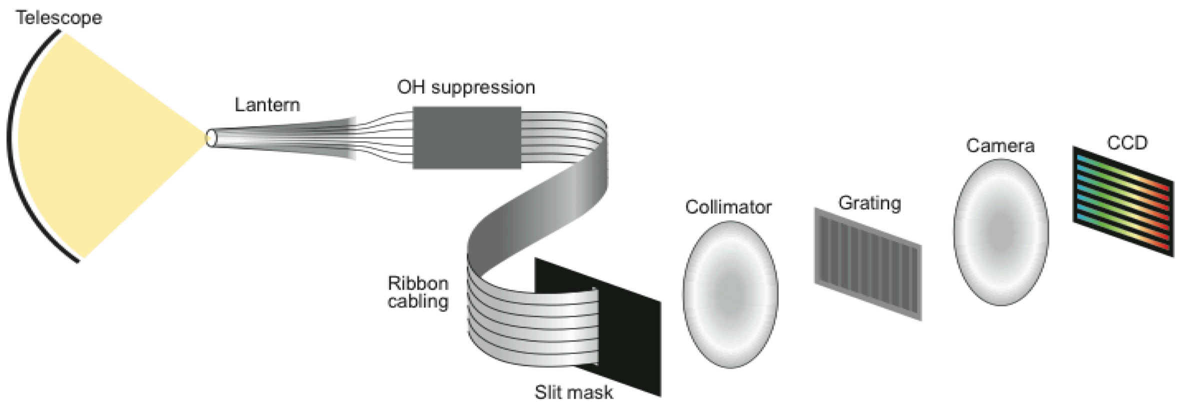
This question comes up a lot.

2010

PIMMS: photonic integrated multimode microspectrograph

Joss Bland-Hawthorn[*a,b], Jon Lawrence[c,d], Gordon Robertson[a], Sam Campbell[a], Ben Pope[a], Chris Betters[a], Sergio Leon-Saval[a,b], Tim Birks[e], Roger Haynes[d,f], Nick Cvetojevic[c], Nem Jovanovic[c]

PIMMS #0 = "shoebox spectrograph"

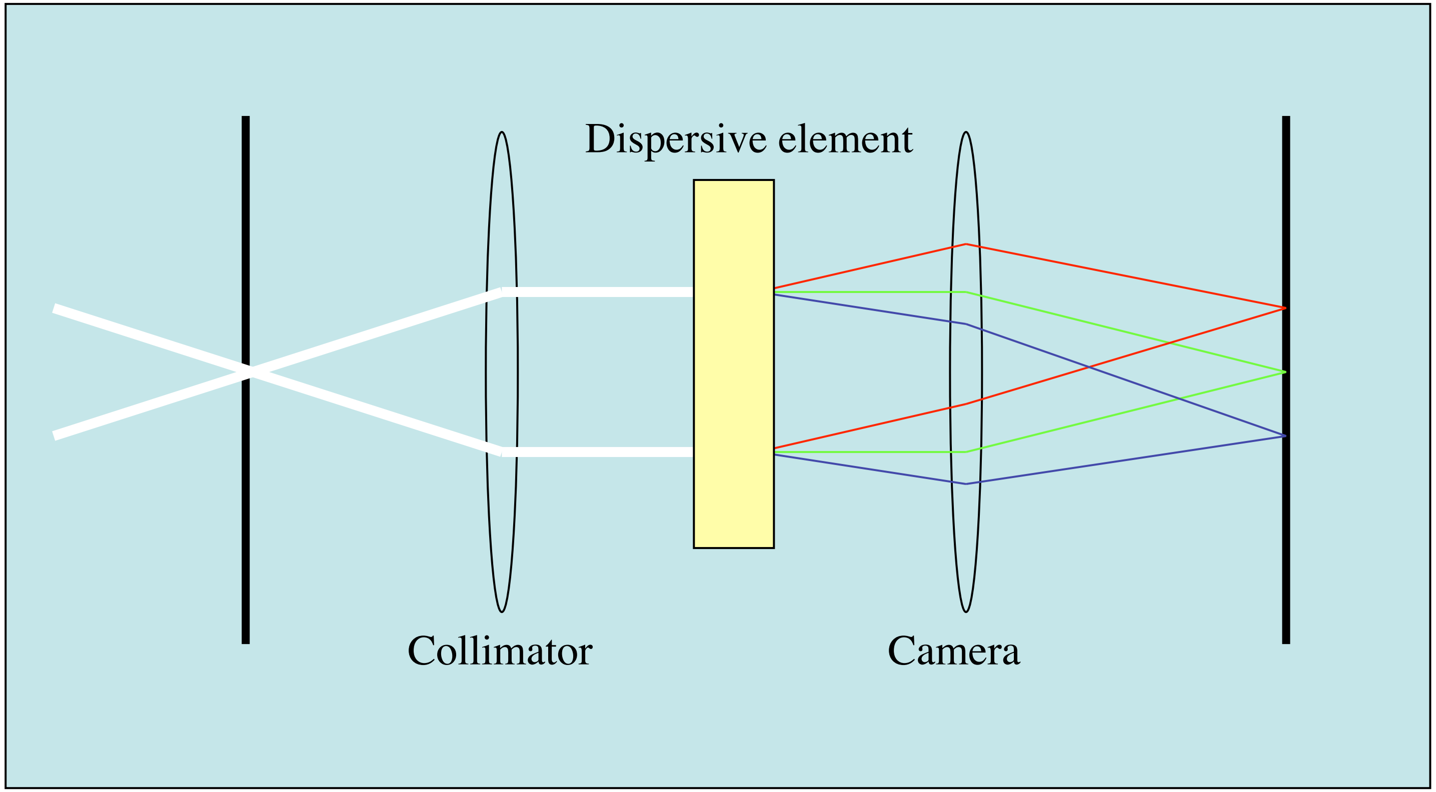


The optical system is **always** diffraction limited **regardless of input** which leads us to a remarkable conclusion.

Basic spectrograph: focal reducer

$R = m\,N$ (diffraction limited)

N = no. of combining beams (finesse)



Why are spectrographs so far removed from the ideal?

Medium resolution spectrograph has pupil ⃠ $D_P \sim 100$ mm, say

Consider a grating with $\varrho = 1000$ lines mm^{-1}

Set $m = 1$ (tilt or prism) for straight through design

$R = m\,N = m\,D_P\,\varrho = 100{,}000$!!!

...you'd be lucky to get R=3000
at m=1 on existing instruments

A major goal of astrophotonics is to break this impasse, i.e. to collapse an instrument to its minimum configuration.

2013

We are close to the theoretical limit

Beating the classical limit: A diffraction-limited spectrograph for an arbitrary input beam

Christopher H. Betters,[1,2,*] Sergio G. Leon-Saval,[1] J. Gordon Robertson,[1,2] and Joss Bland-Hawthorn[1,2]

[1] Institute of Photonics and Optical Science, School of Physics, University of Sydney, 2006, Australia
[2] Sydney Institute for Astronomy, School of Physics, University of Sydney, 2006, Australia
[*] c.betters@physics.usyd.edu.au

Abstract: We demonstrate a new approach to classical fiber-fed spectroscopy. Our method is to use a photonic lantern that converts an arbitrary (e.g. incoherent) input beam into *N* diffraction-limited outputs. For the highest throughput, the number of outputs must be matched to the total number of unpolarized spatial modes on input. This approach has many advantages: (i) after the lantern, the instrument is constructed from 'commercial off the shelf' components; (ii) the instrument is the minimum size and mass configuration at a fixed resolving power and spectral order; (iii) the throughput is better than 60% (slit to detector, including detector QE of ~80%); (iv) the scattered light at the detector can be less than 0.1% (total power). Our first implementation operates over 1545-1555 nm (limited by the detector) with a spectral resolution of 0.055nm (*R*~30,000)

2014:
tentative detection
of solar oscillations

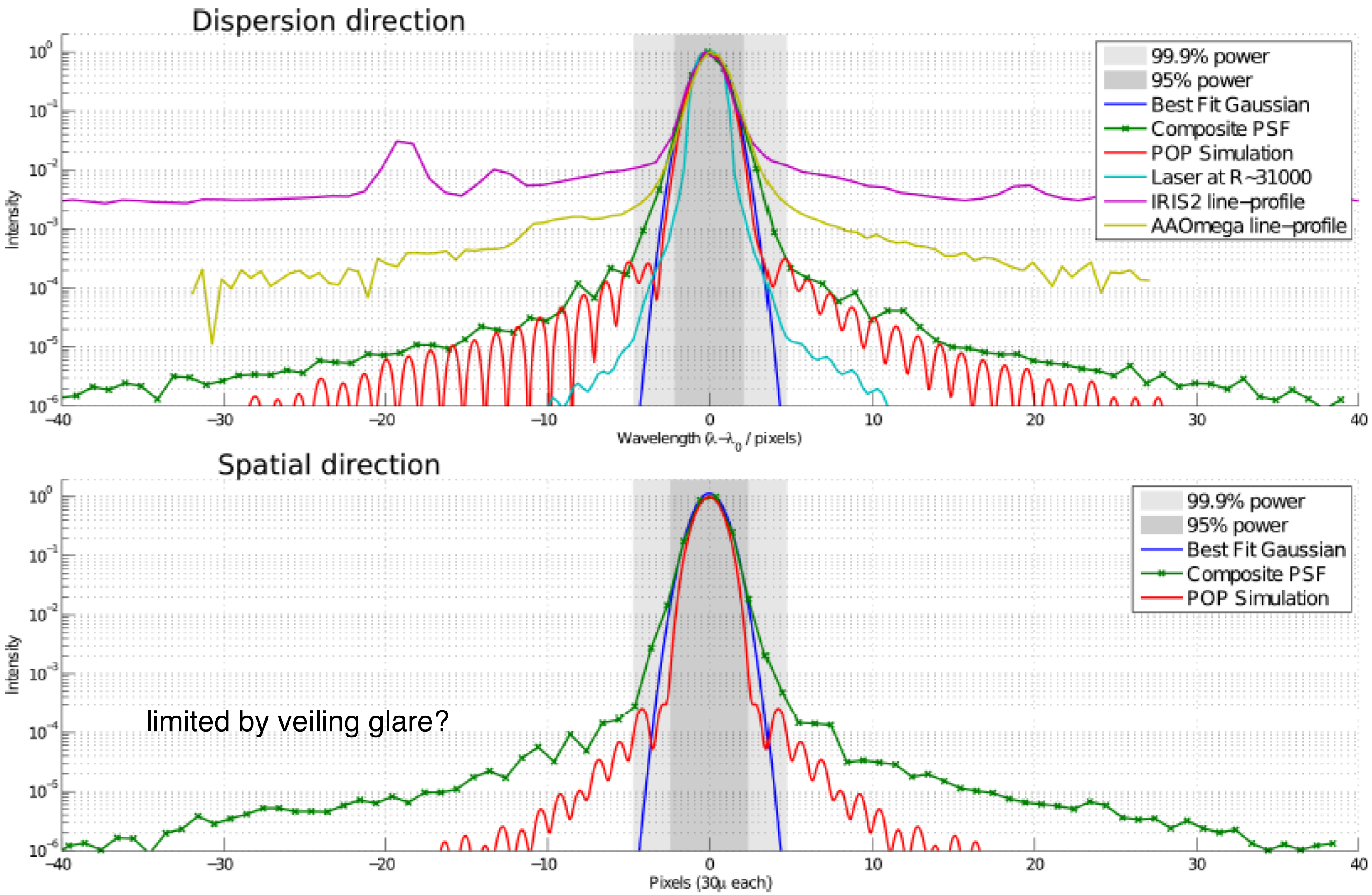
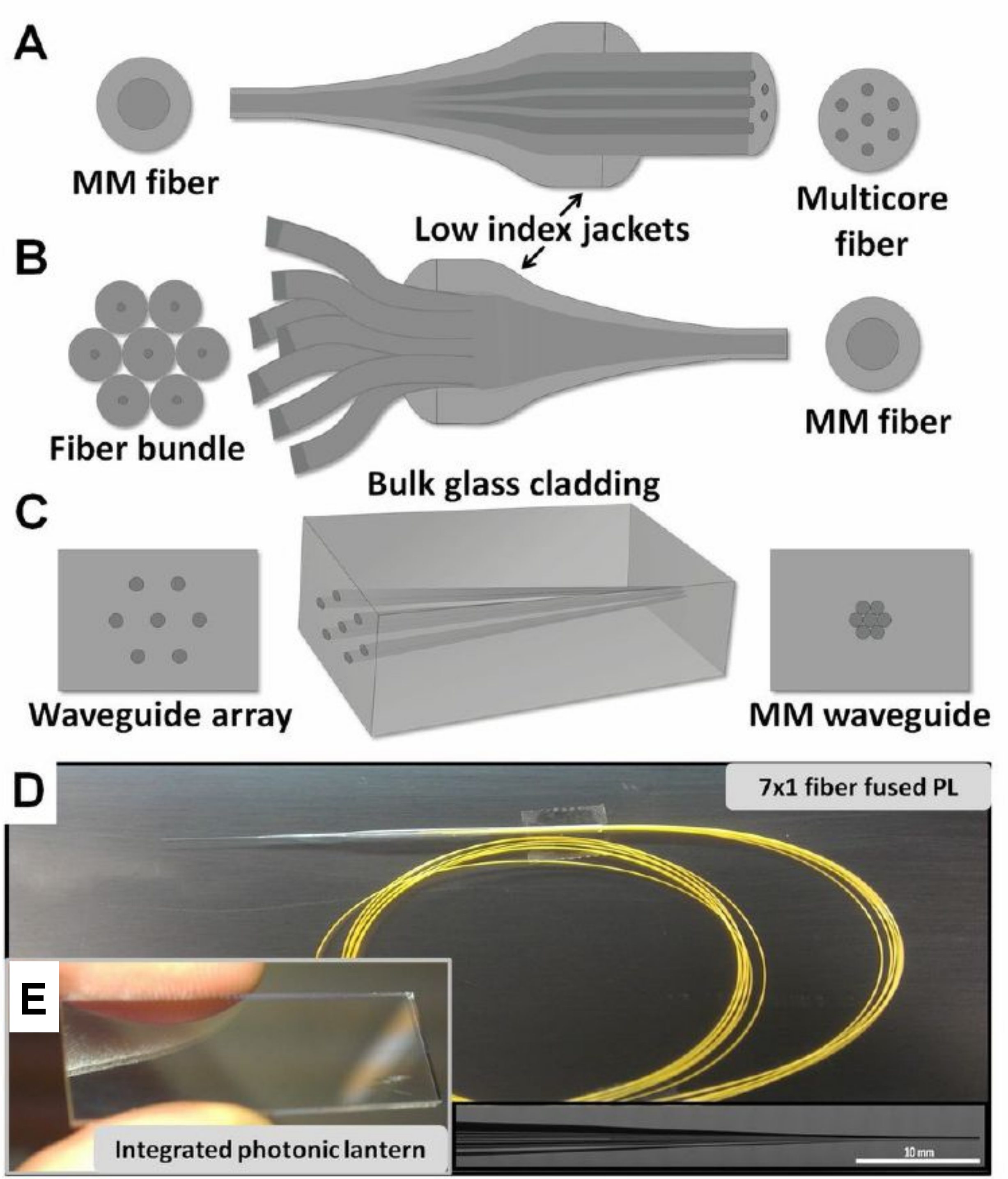


Fig. 3 – PSF line profiles (summed along the perpendicular axis with a Gaussian weighting, as would be done with real spectra) from PIMMS IR with comparisons in the spectral (top) and spatial (bottom) direction. Shown are: Green (stars) – composite of underexposed and overexposed profiles as explained in text; Red – ZEMAX POP simulation; Blue – Best fit Gaussian; Cyan – OSA spectrum of laser source; Purple and Yellow – Typical line profiles attributed to the IRIS2 150um slit and AAOmega fiber inputs respectively (The spectra from these spectrographs have been scaled to have the same FWHM determined from the best fit Gaussian, due to the difference in actual spectral resolution and pixel sampling). Note that the comparison spectra are shown to display the intensity level that wings of the respective PSF present.

Feeding light into microspectrographs

Photonic lanterns – new designs since Leon-Saval, Birks, JBH (2005).

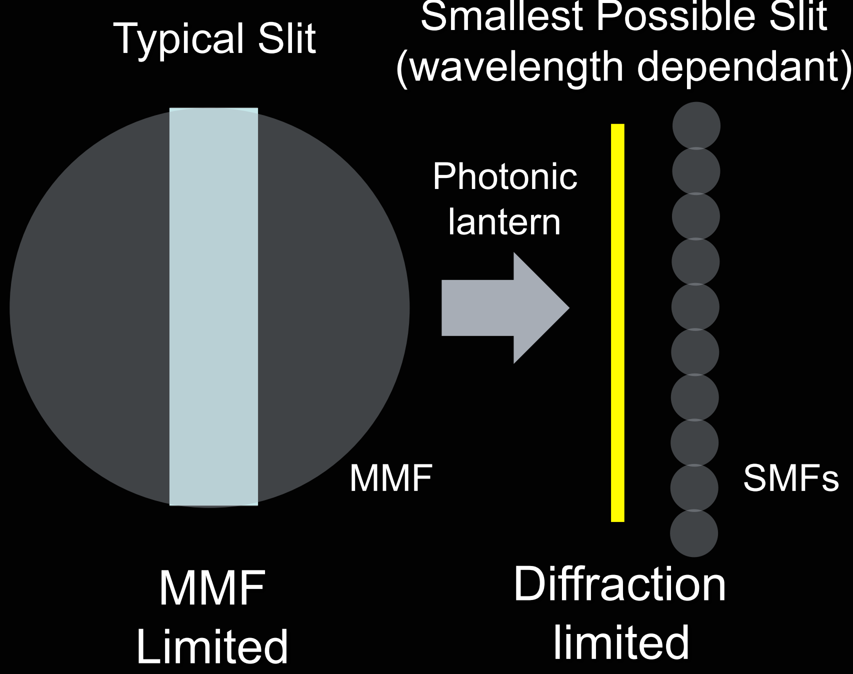
These allow different microspectrograph configurations.

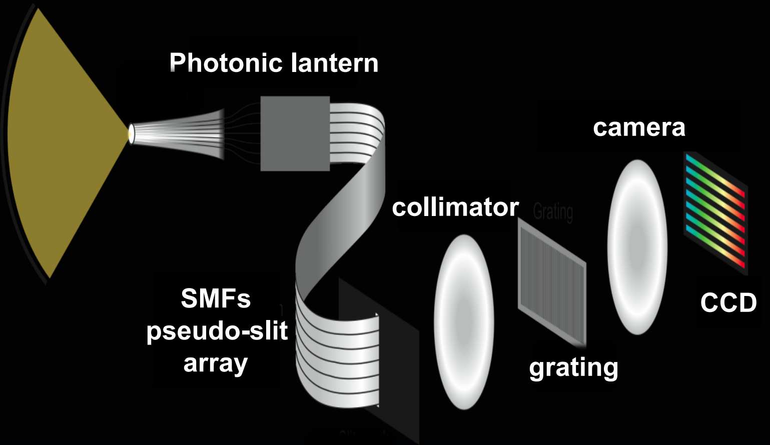


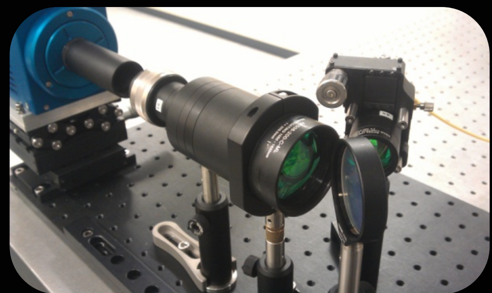
Diffraction limited spectrographs

- Conventional spectrograph resolution typically limited by minimum slit size.
- A slit smaller than the MMF input reduces throughput in a fibre fed spectrograph.
- Solution: ‘Remap’ the MMF slit to a diffraction limited slit.
- Photonic lantern used for remapping the MMF fiber input into a pseudo-slit of SMFs.

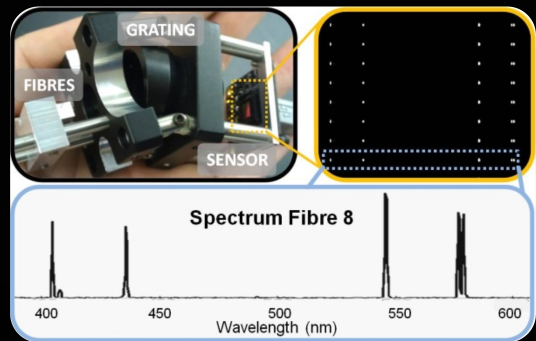
Spectrograph Slit







IR Diffraction-limited spectrograph
R~35000 (0.044 nm) at 1550 nm

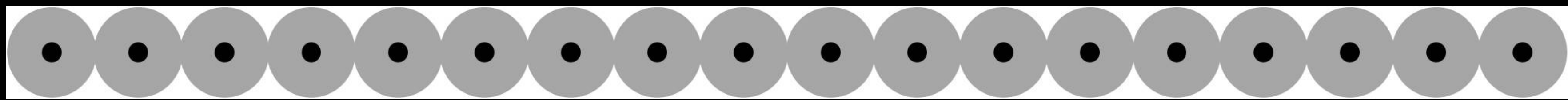


VIS Diffraction-limited spectrograph
R~1200 (0.4 nm) at 500 nm

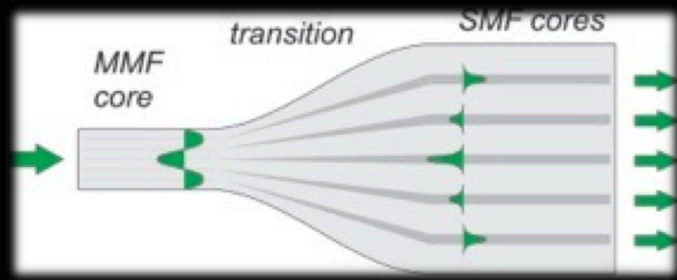
Multicore SM: Photonic TIGER

Conventional fibre-fed spectrographs

- Standard way to form slit is a simple linear array.
  - Normally requires larger optics or more elements to correct for off-axis aberrations when the number of fibres increases.

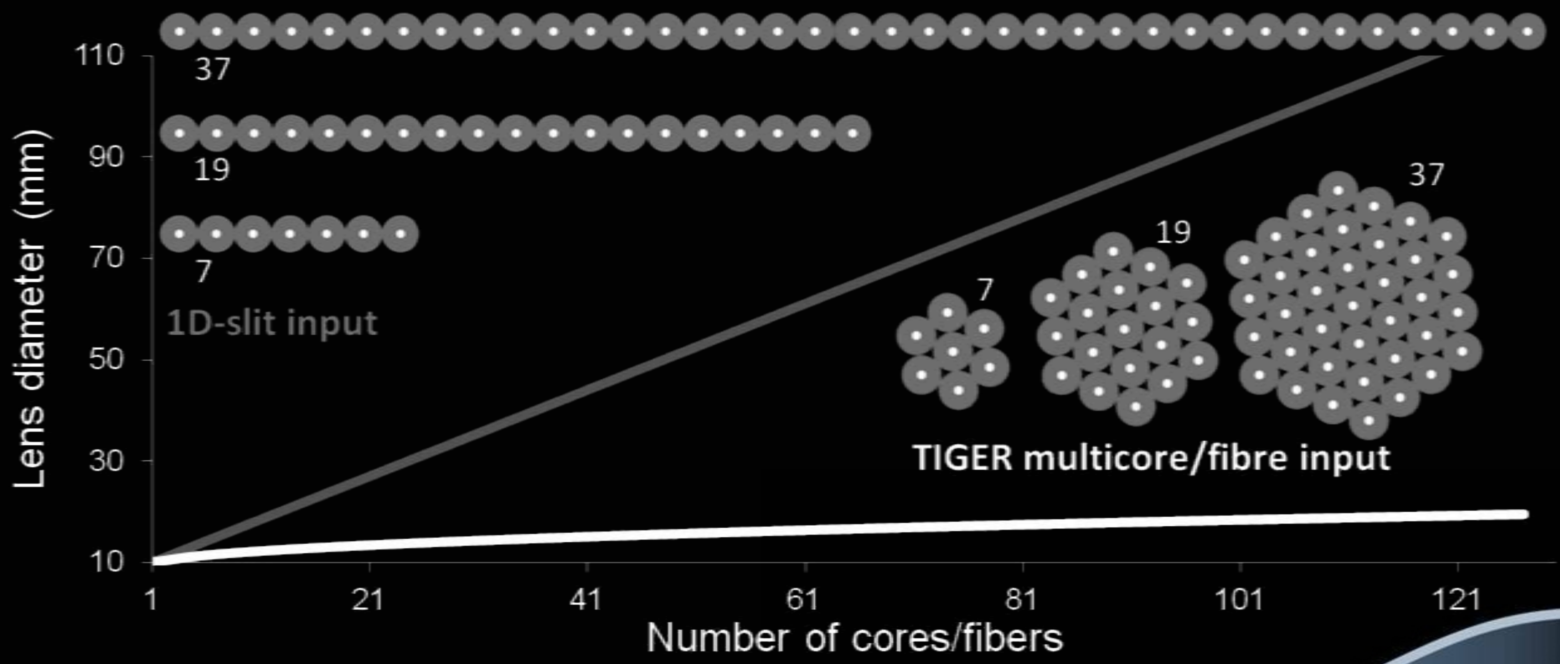


Multicore SM: Photonic TIGER



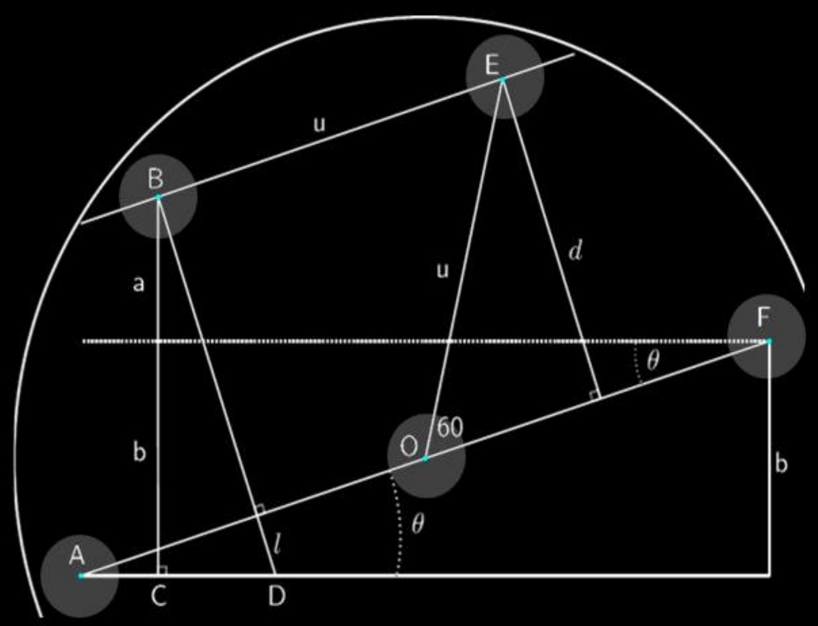
Photonic TIGER fibre-fed spectrographs

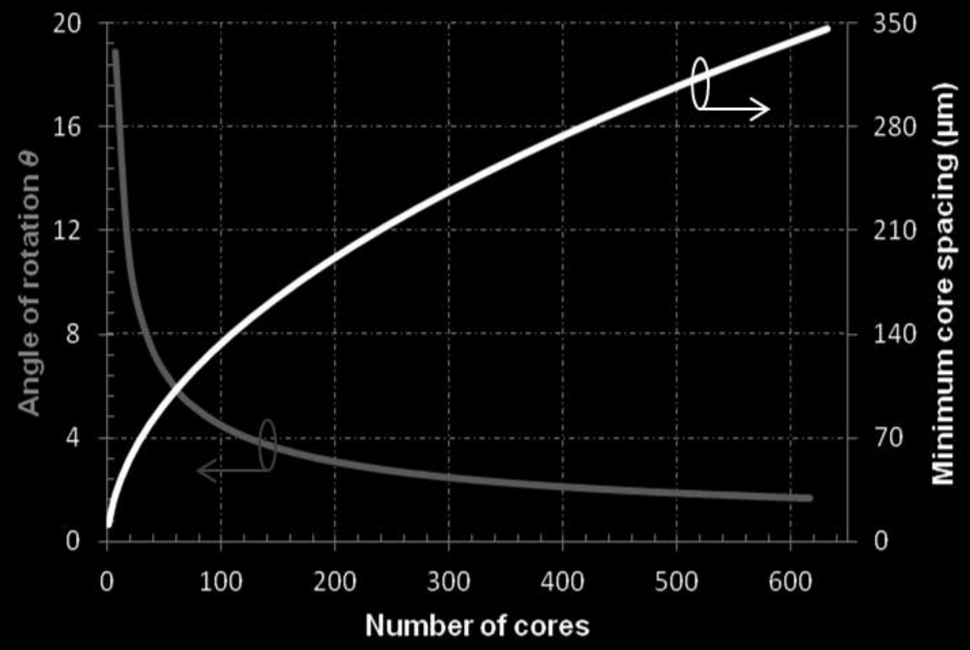
- Our solution is to use a hexagonal grid as the input slit, such as a multicore fibre or a hexagonal fibre bundle.
- Inspired by the TIGER (Bacon et al 1995) which used a hexagonal micro-lens as an IFU input.



Multicore SM: Photonic TIGER

- This can be achieved by rotating the hexagonal array, hence with the right core separation, N independent spectra can be formed (slightly offset spectrally on the detector).



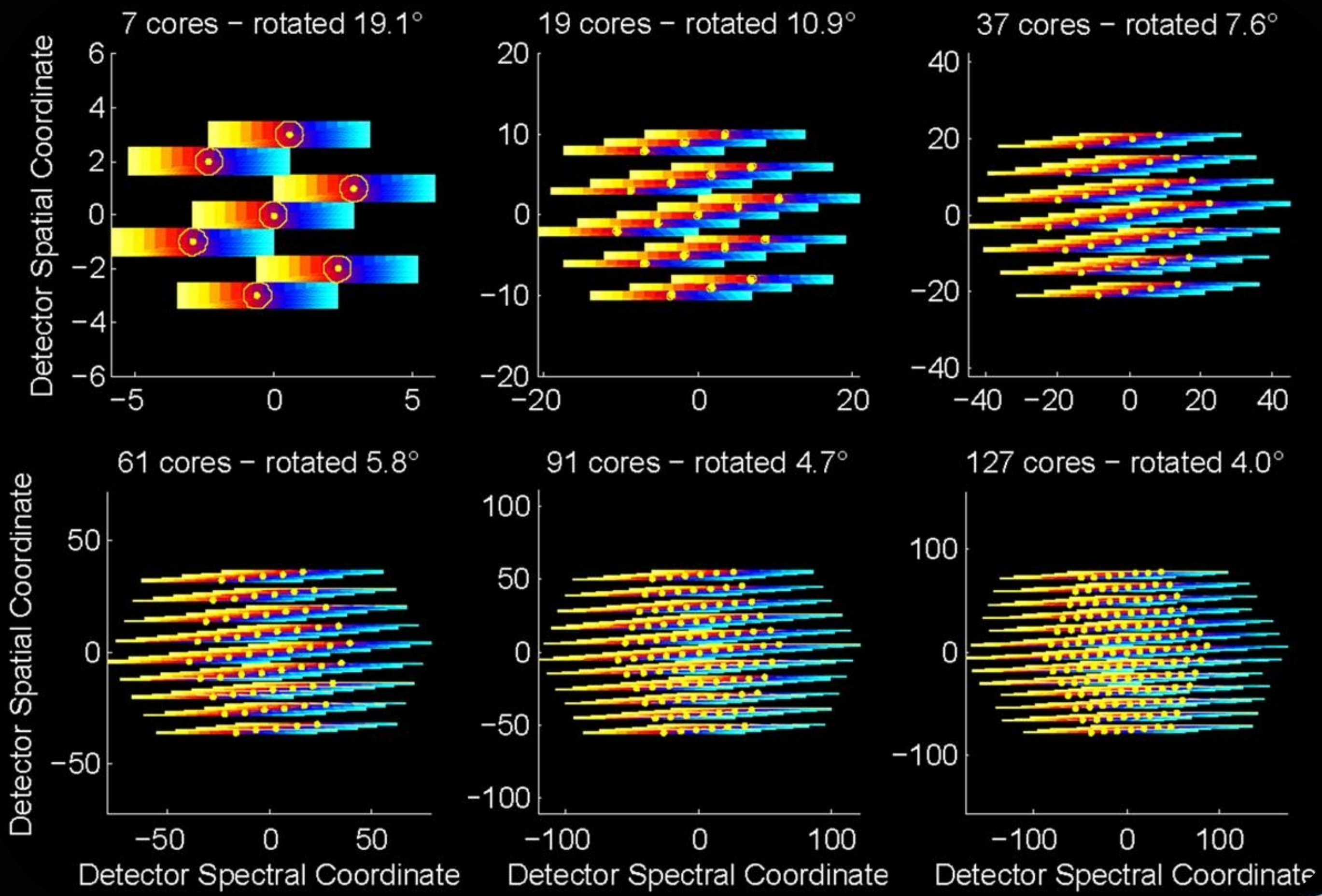


Calculated considering 1:1 imaging and a 10.5 μm core MFD at 1550 nm

Multicore SM: Photonic TIGER

- Simulated spectra with a vertical separation equal to the $1/e^2$ width of a single spectrum marked by a white circle around each core.

- Six different core arrays 7, 19, 37, 61, 91 and 127 with their respective optimal angle rotation are shown.

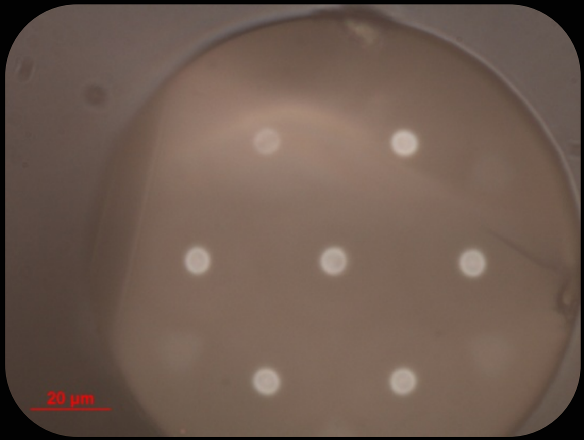


Multicore SM: Photonic TIGER

Two ways to make a Photonic TIGER pseudo-slit:

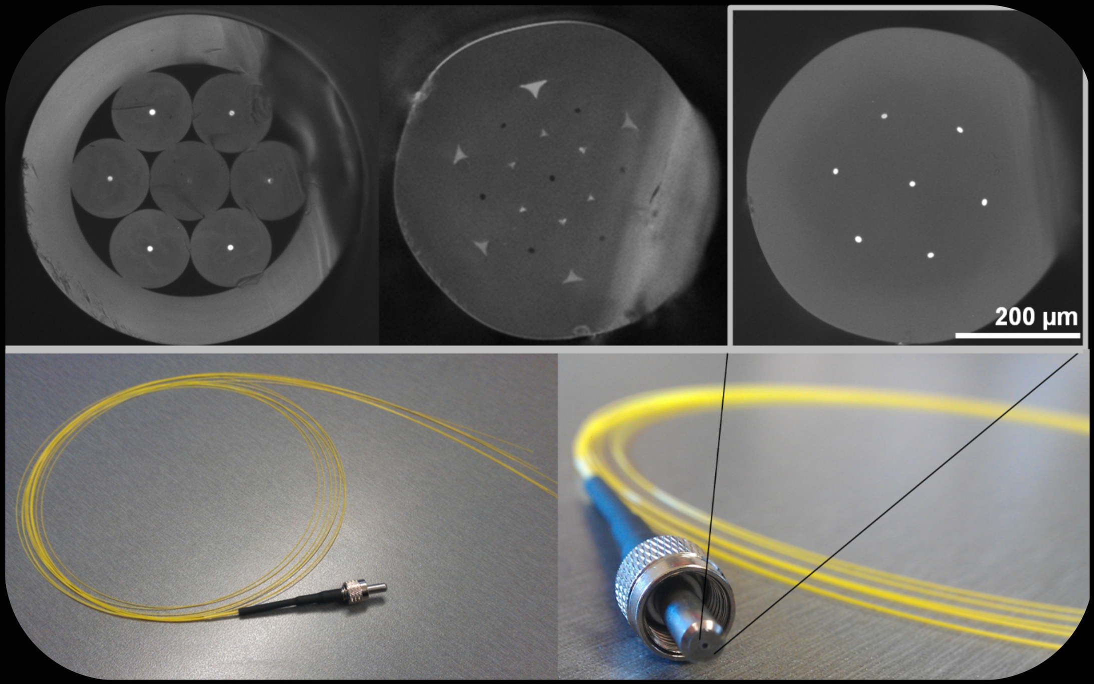
1. One by using custom made multicore fibres

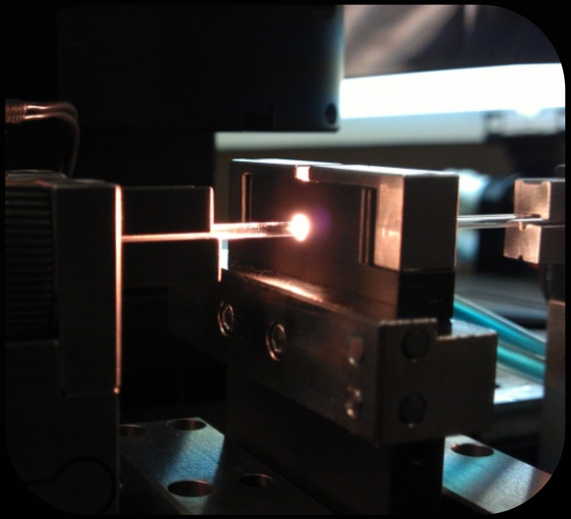
2. Second by bundling and fusing single-mode fibres together



7 core fibre
(Fujikura, Japan)

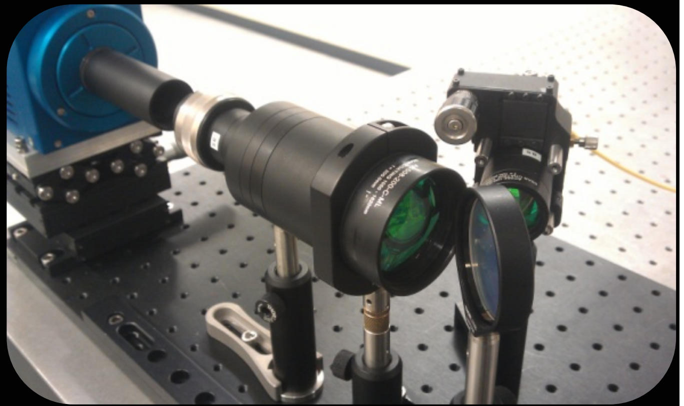
7x1 Photonic TIGER prototype fabrication with the Vytran



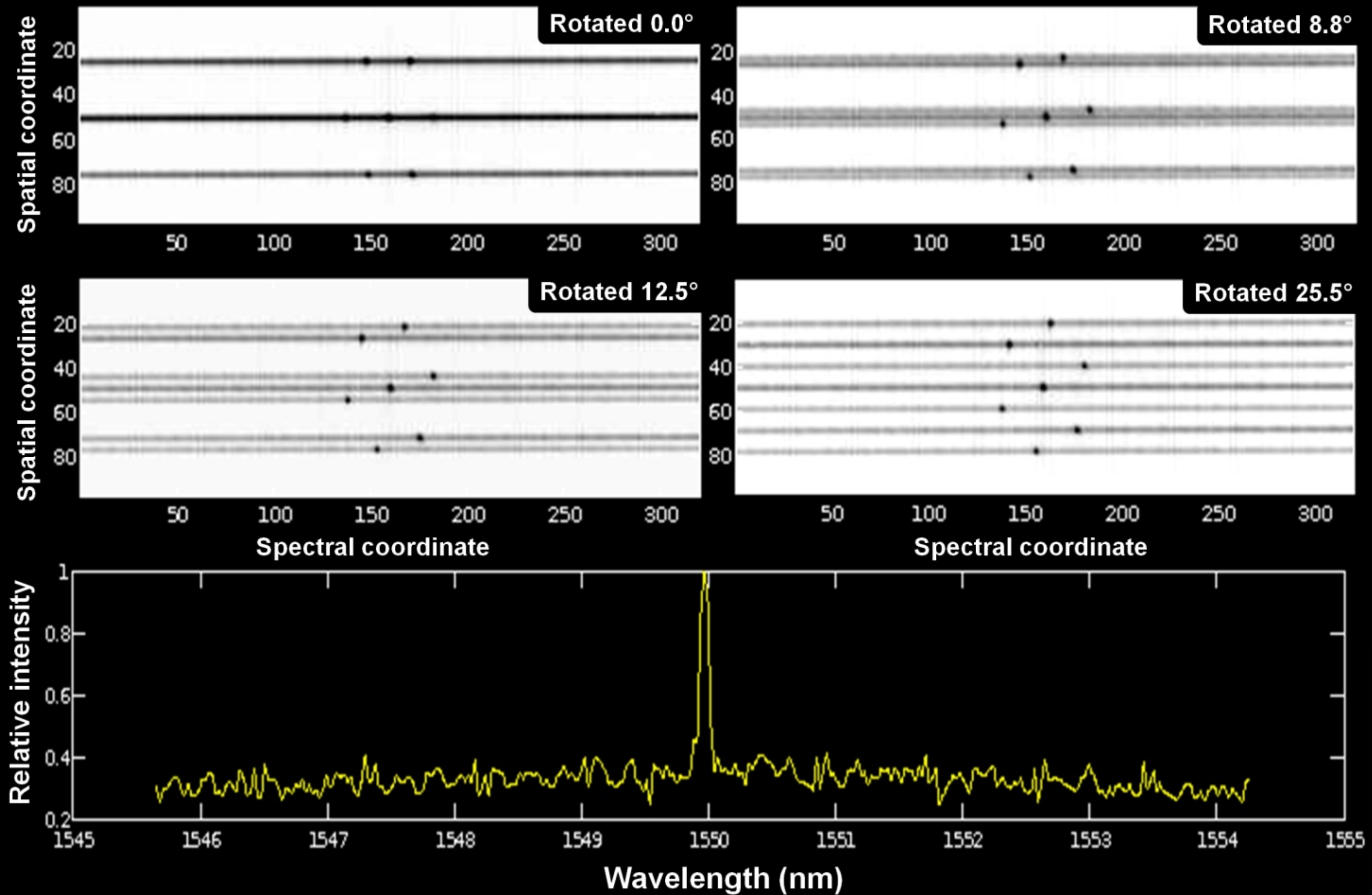


Multicore SM: Photonic TIGER

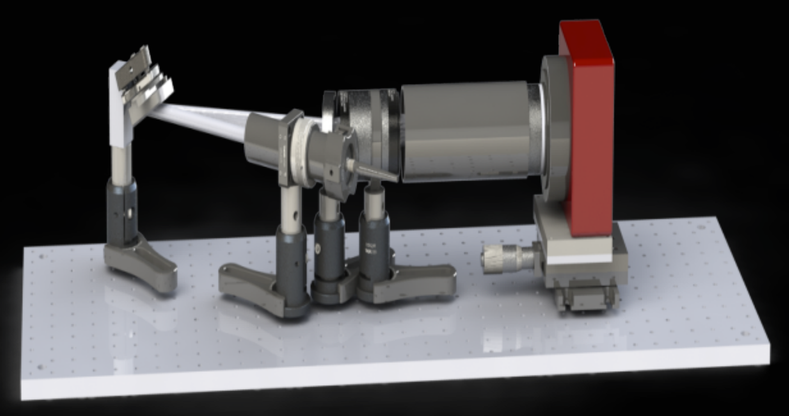
7x1 Photonic TIGER prototype diffraction limited VPH spectrograph



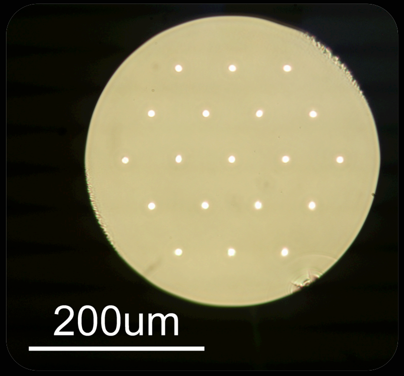
7x1 diffraction limited spectrograph
R~31000 at 1550 nm



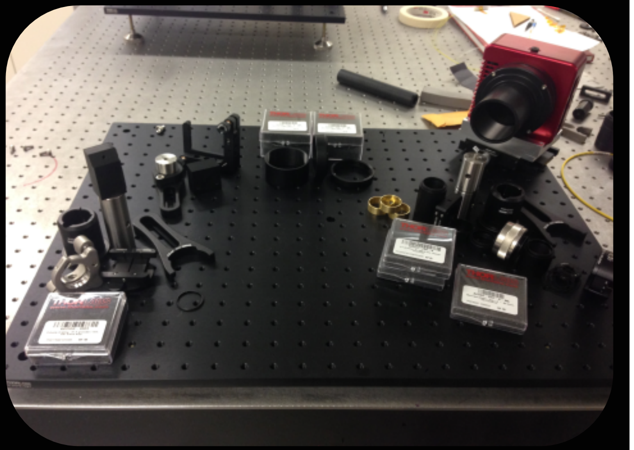
19x1 Photonic TIGER Echelle



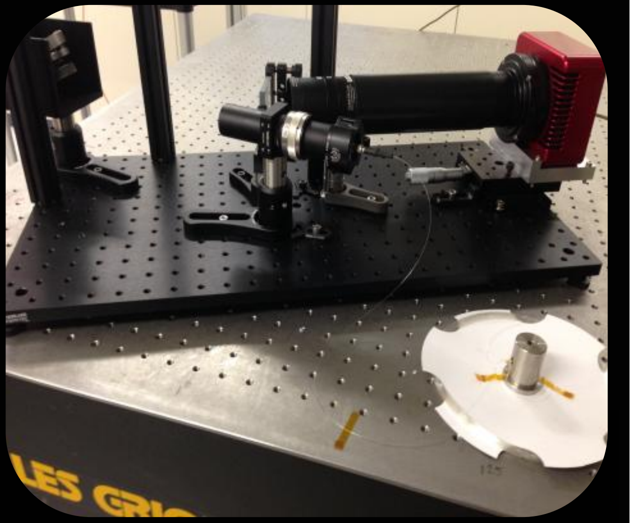
19-core fibre



before



after

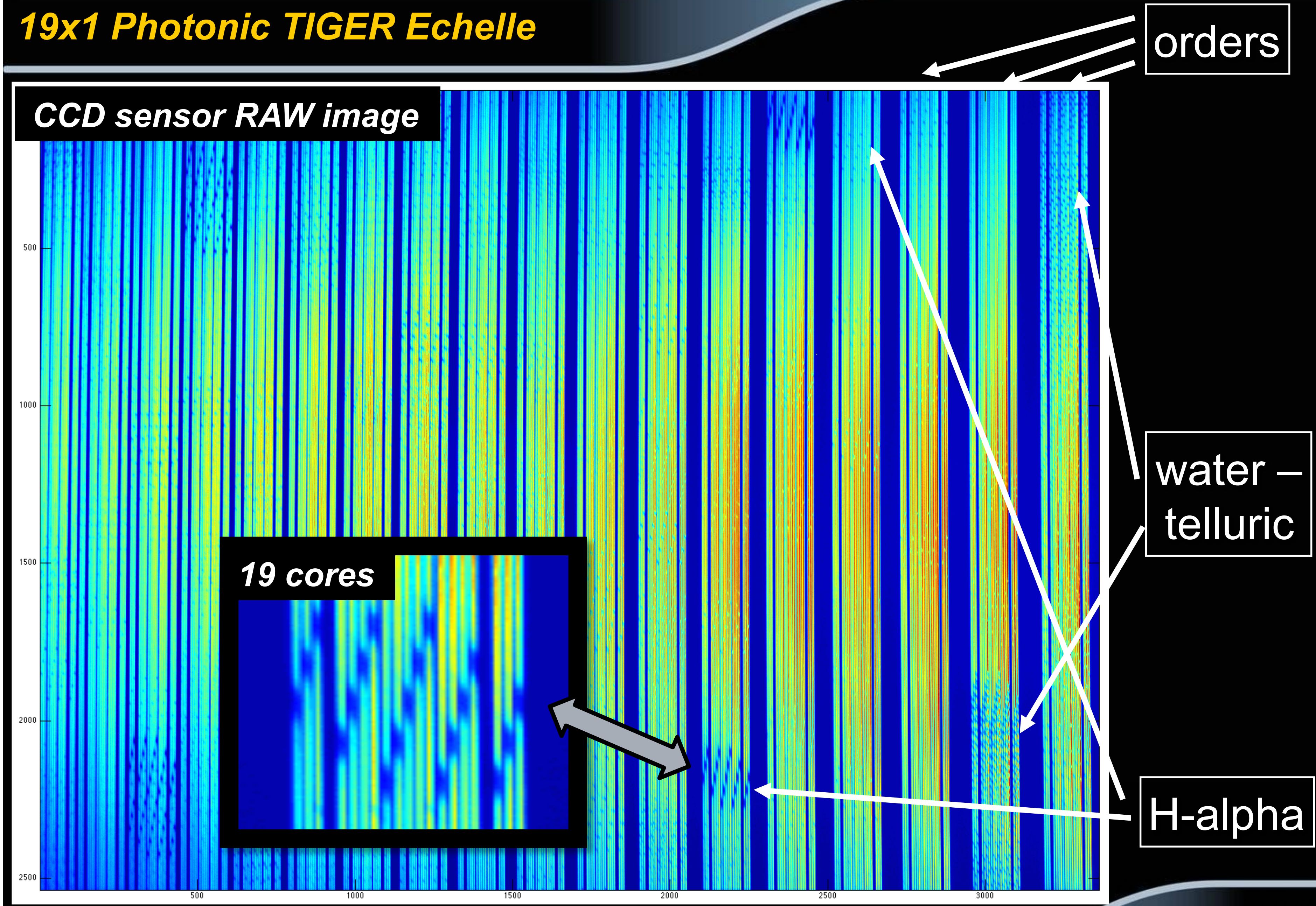


- Diffraction limited from ~580-730nm.
- 19 single mode inputs form a 280um slit. Input is mulitcore fibre terminated with a photonic lantern.
- Resolving power of R~30,000
- Throughput (including detector) ~50%
- Relatively cheap construction
- Made from 'Commercial off the shelf' components
- <$10,000 total cost for prototype (including detector)

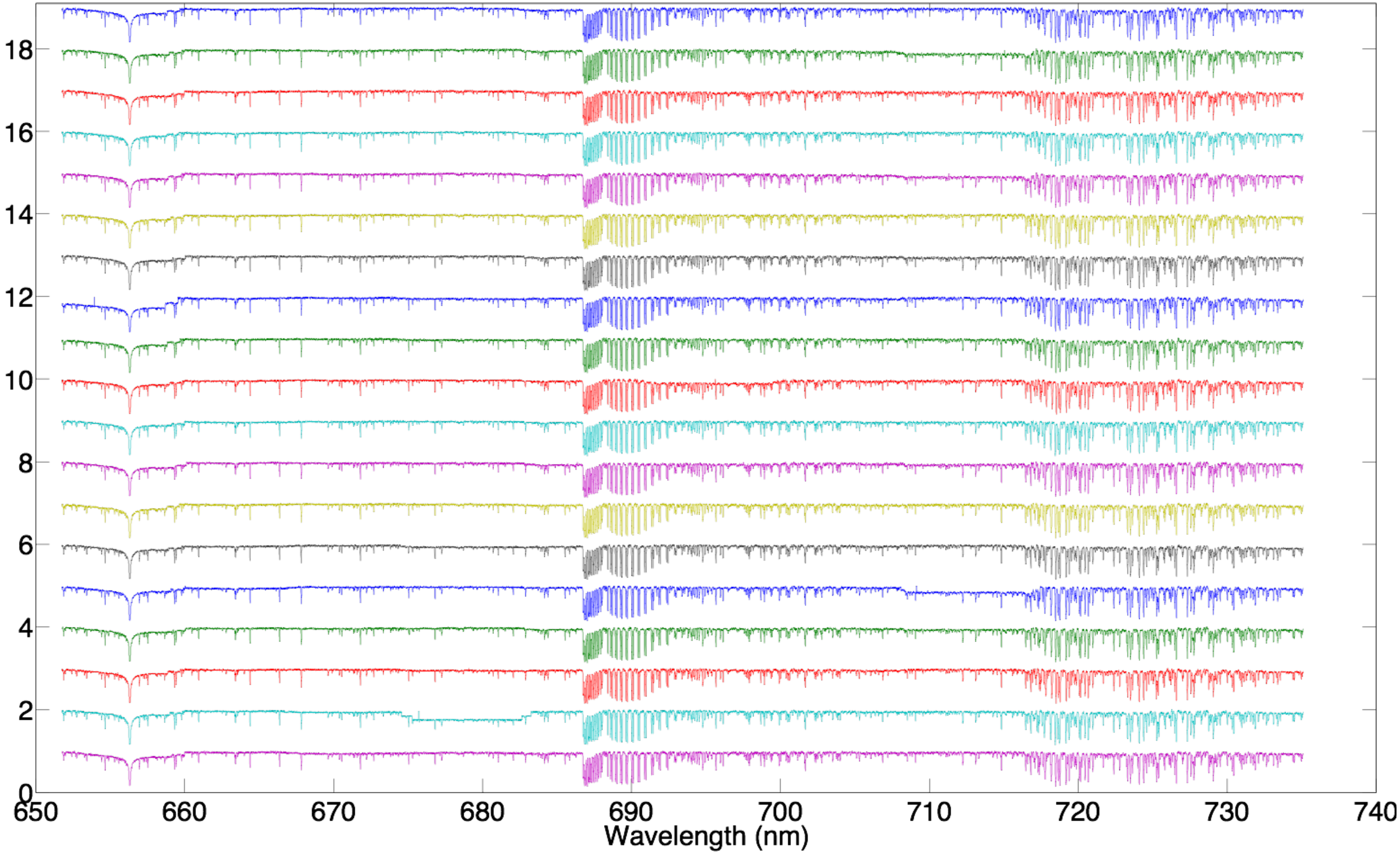
19x1 Photonic TIGER Echelle

"Sydney Observatory" ☺

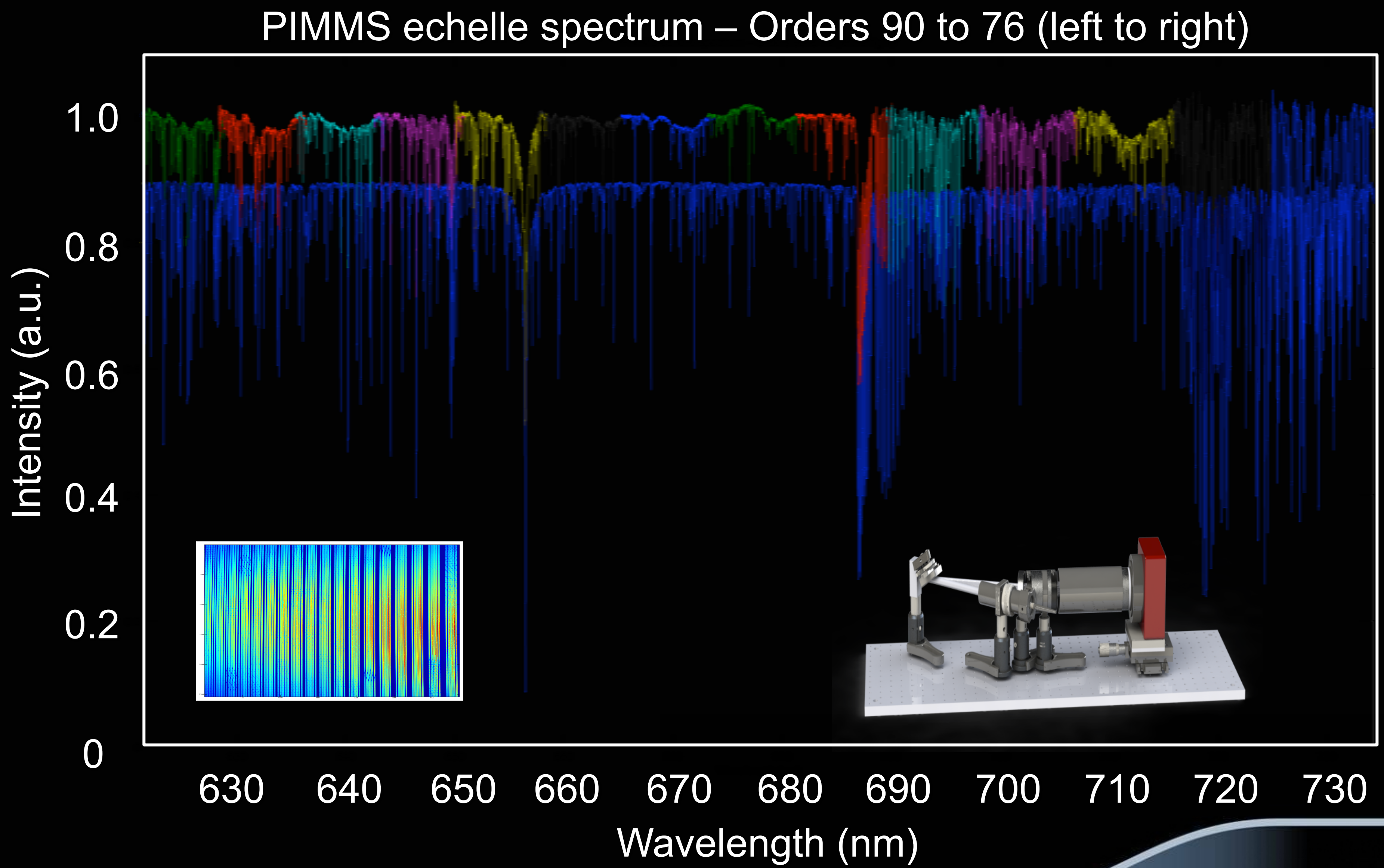
19x1 Photonic TIGER Echelle



19 spectra per exposure, combined to 1 later

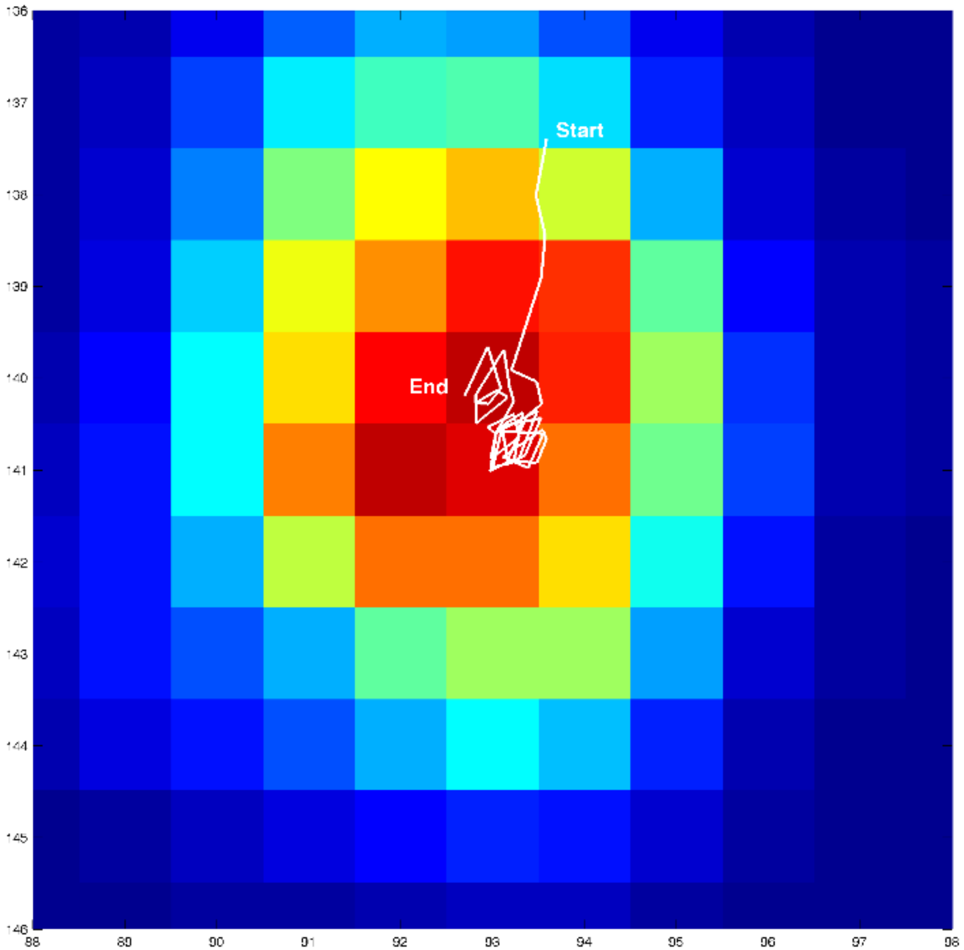


19x1 Photonic TIGER Echelle



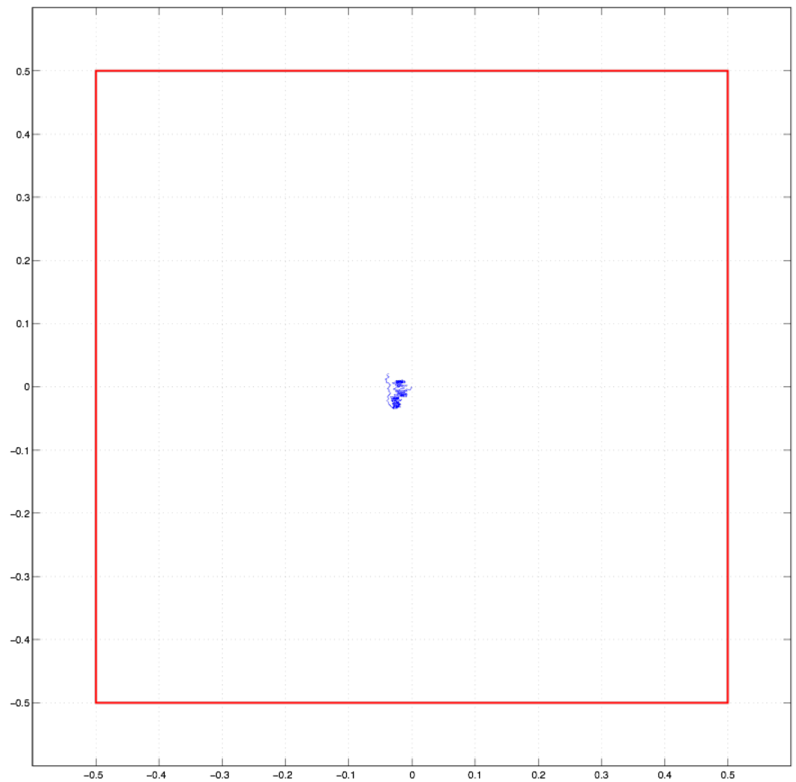
Position of PSF centroid

10 pixel



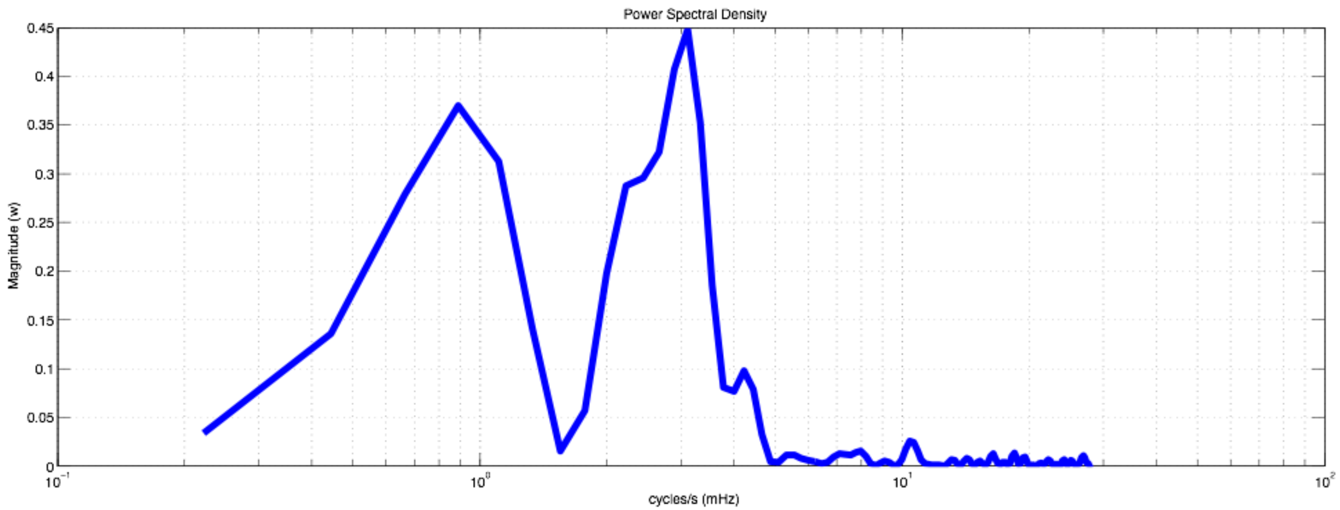
Before Cooling Upgrade

1 pixel



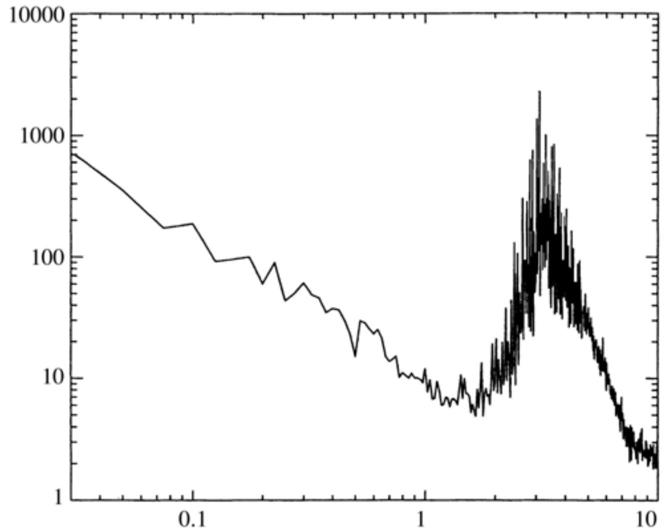
After Cooling Upgrade

Provisional detection of solar oscillations



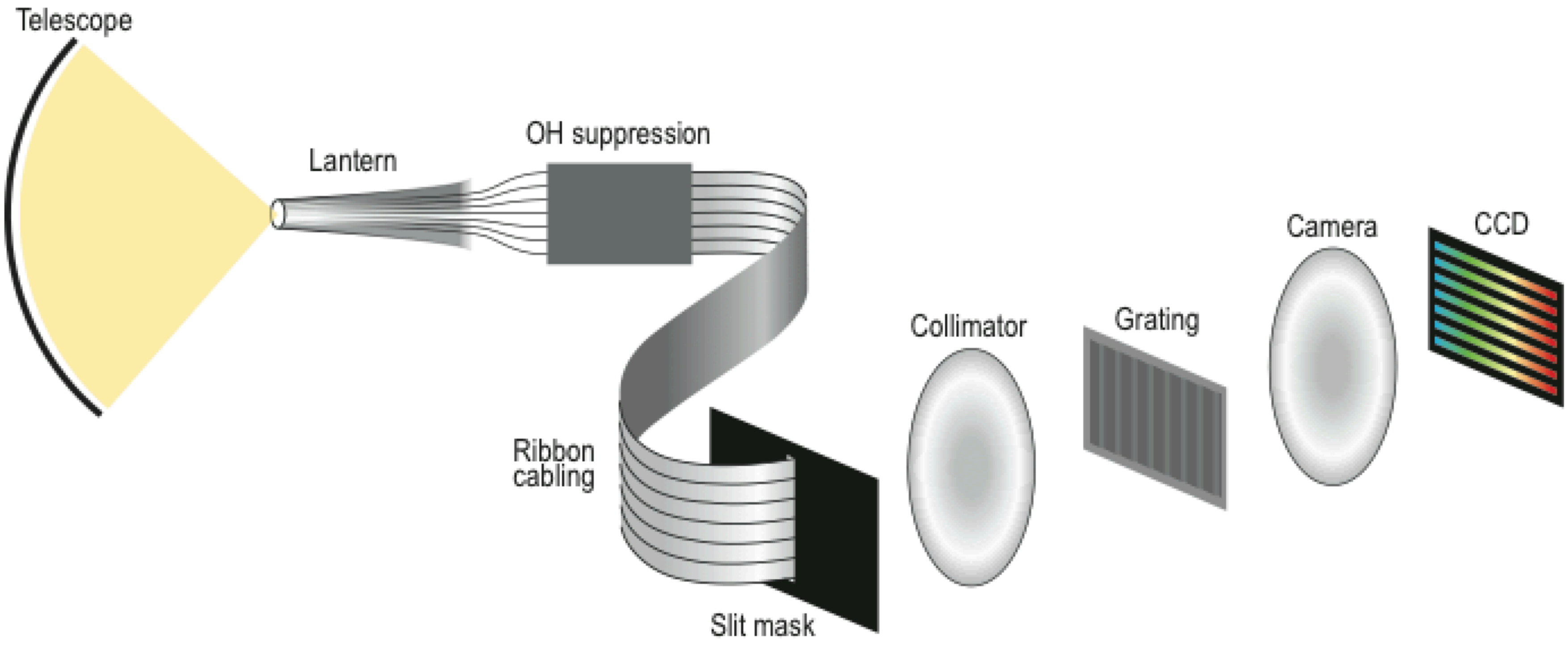
3 mHz 10 mHz

GONG measurement



2015: ~1 m s^{-1} low harmonic oscillations
2016: ~10 cm s^{-1} precision
2020: fully demonstrated for GMT

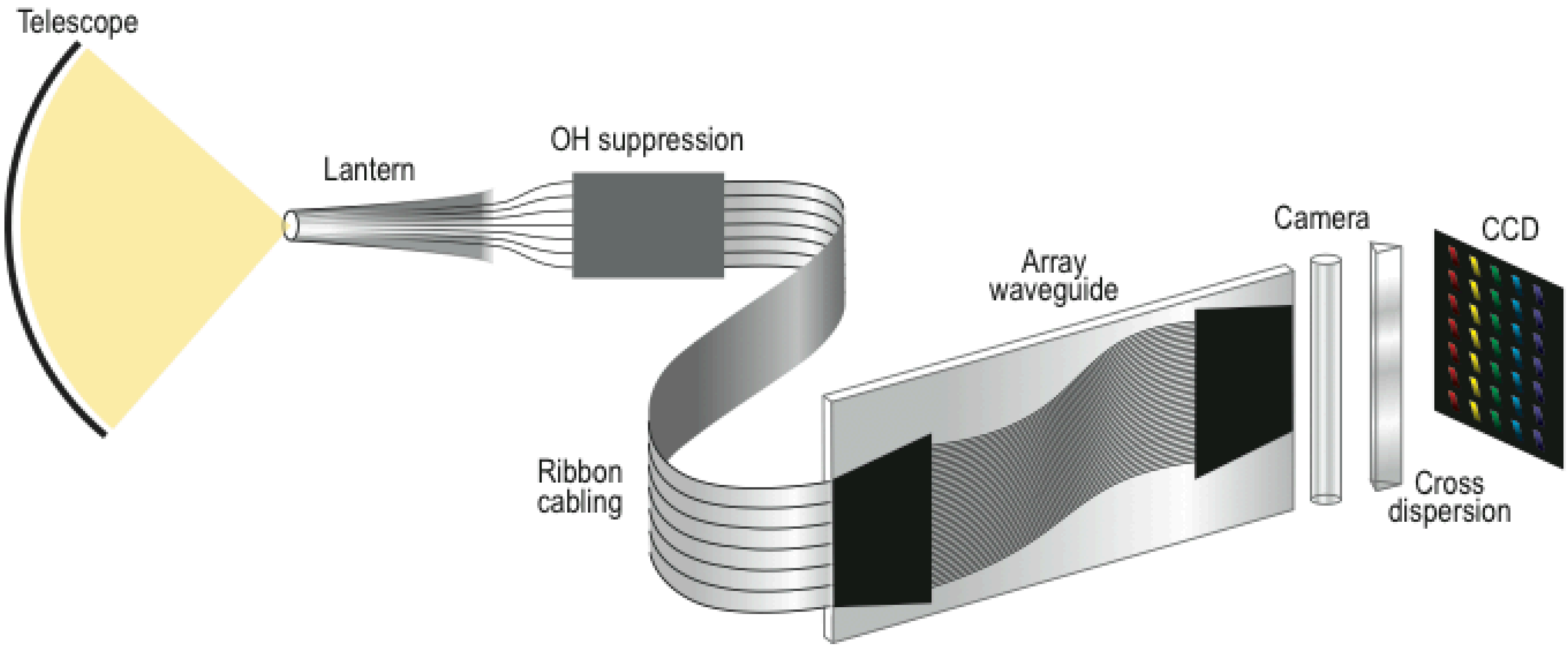
A fully photonic spectrograph means that we go from this configuration…



See Nick's talk after mine

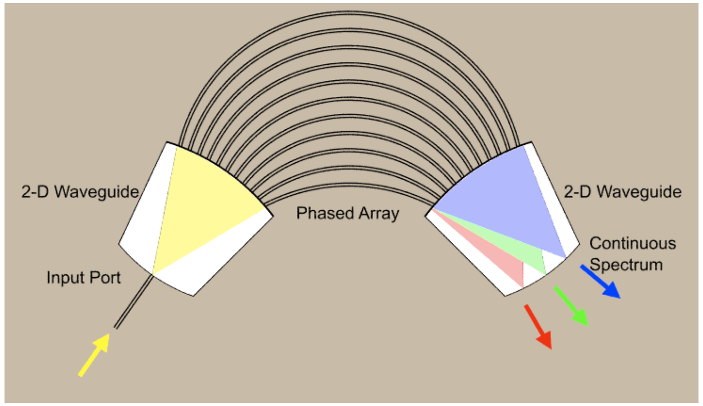
to this configuration...

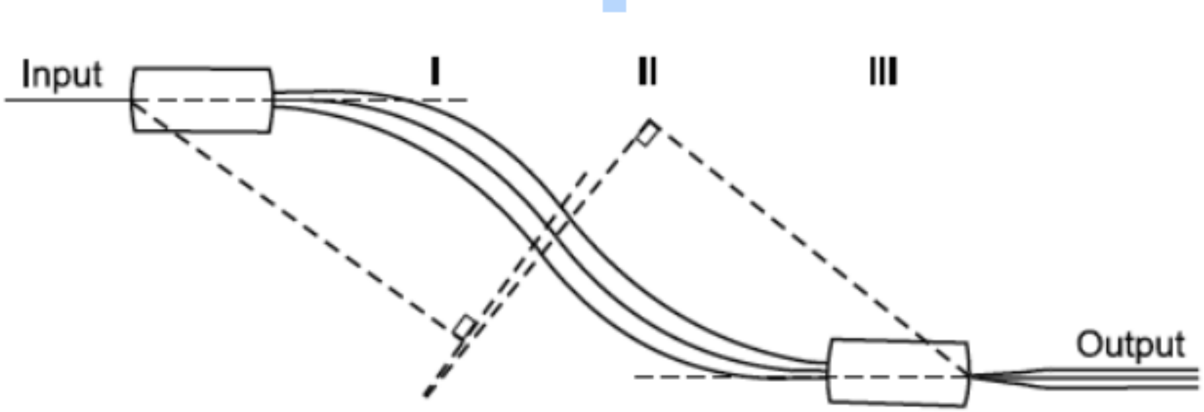
PIMMS #1

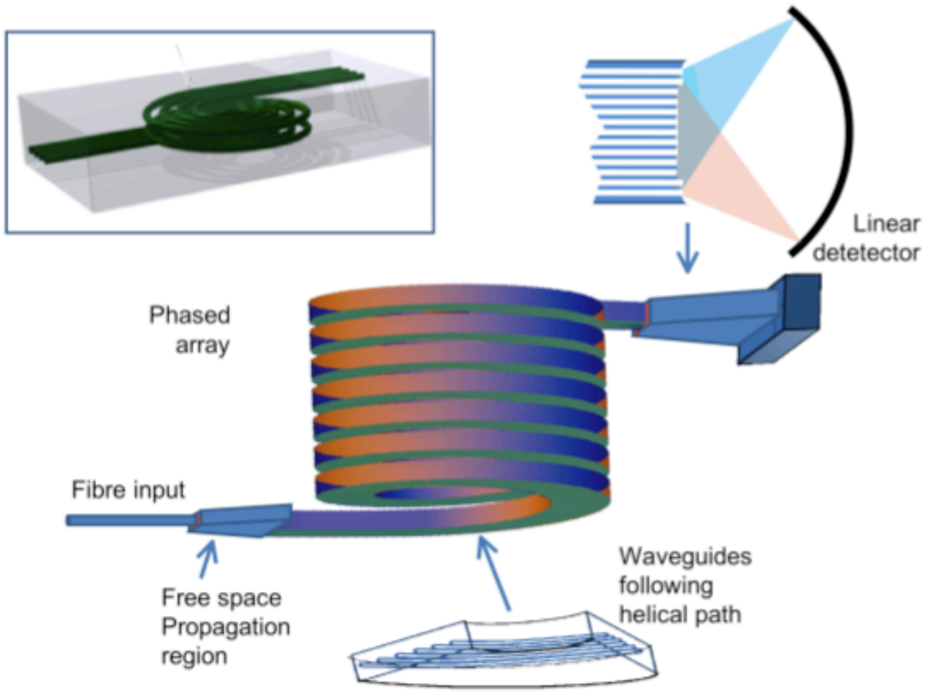


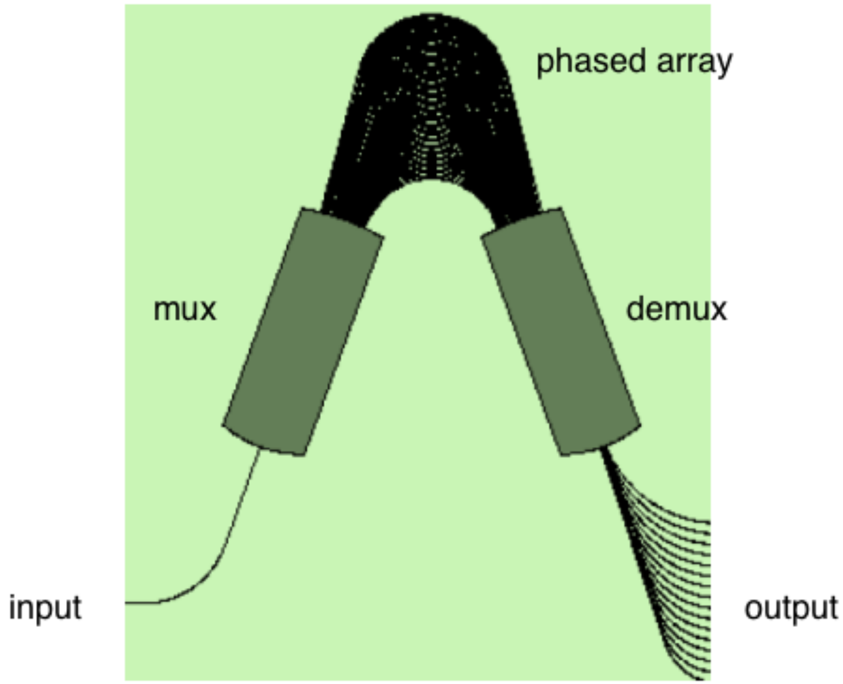
The optical system is **always** diffraction limited **regardless of input** which leads us to a remarkable conclusion.

Array Waveguide Grating







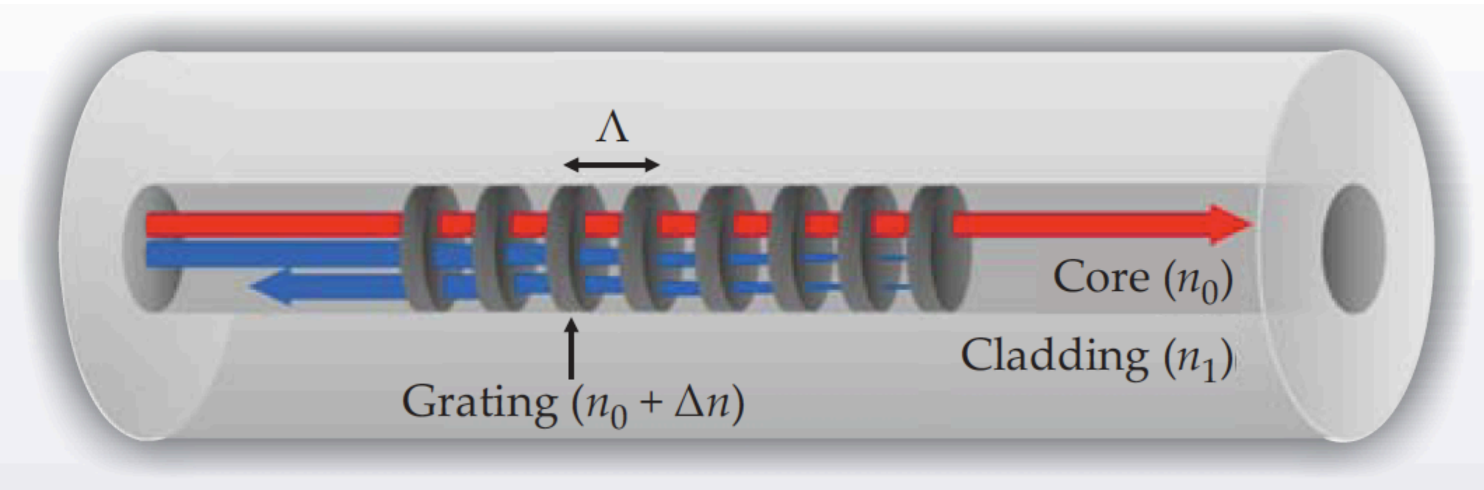


Allington-Smith

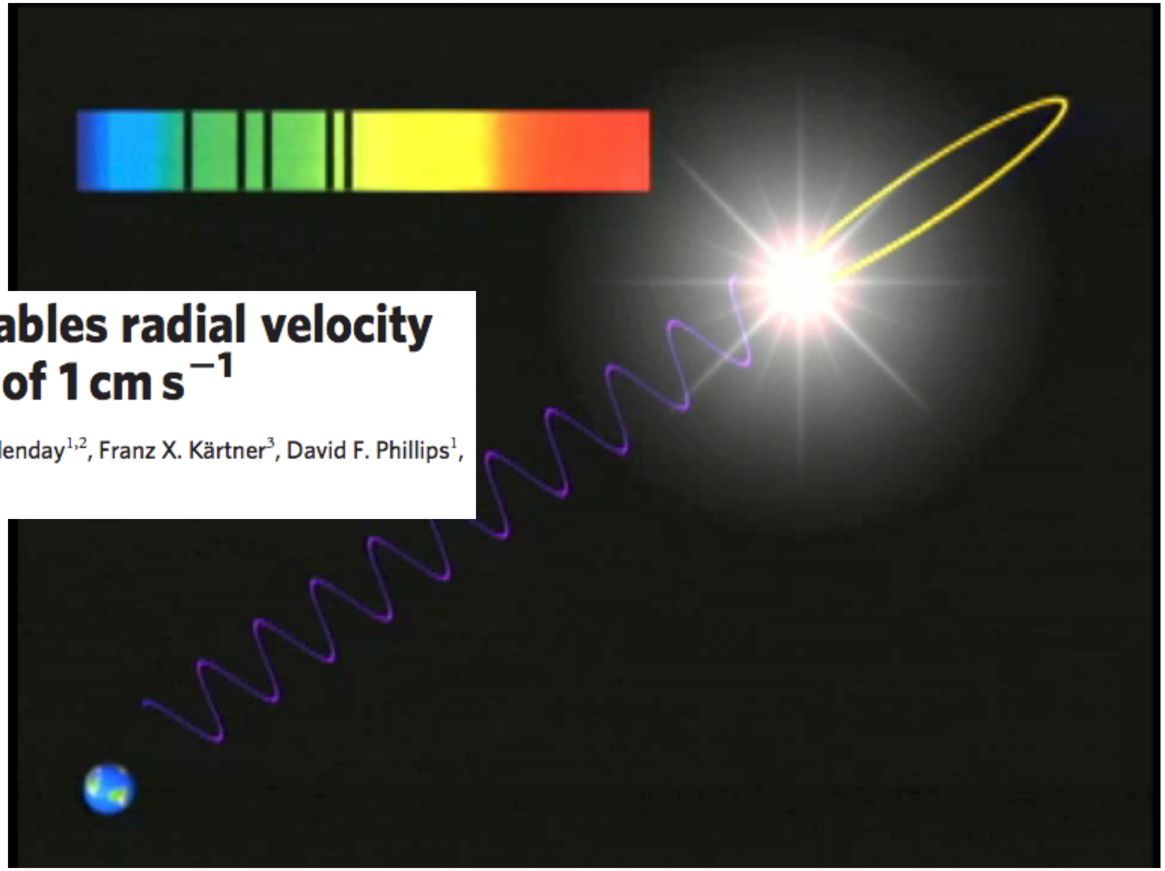
Where next ?

Clean light by removing unwanted signals

- We develop complex aperiodic FBGs to remove unwanted frequencies

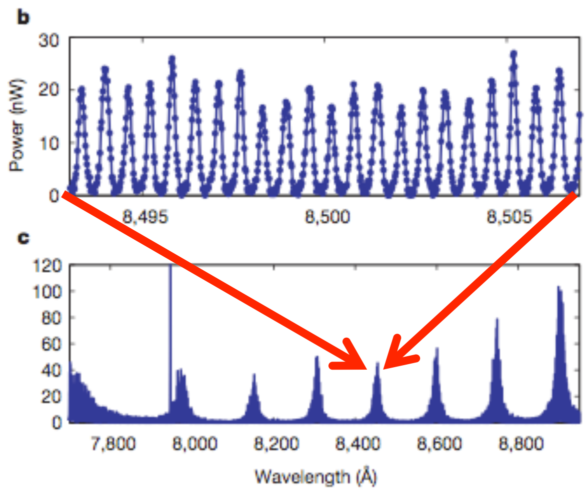


Hunting for extrasolar planets

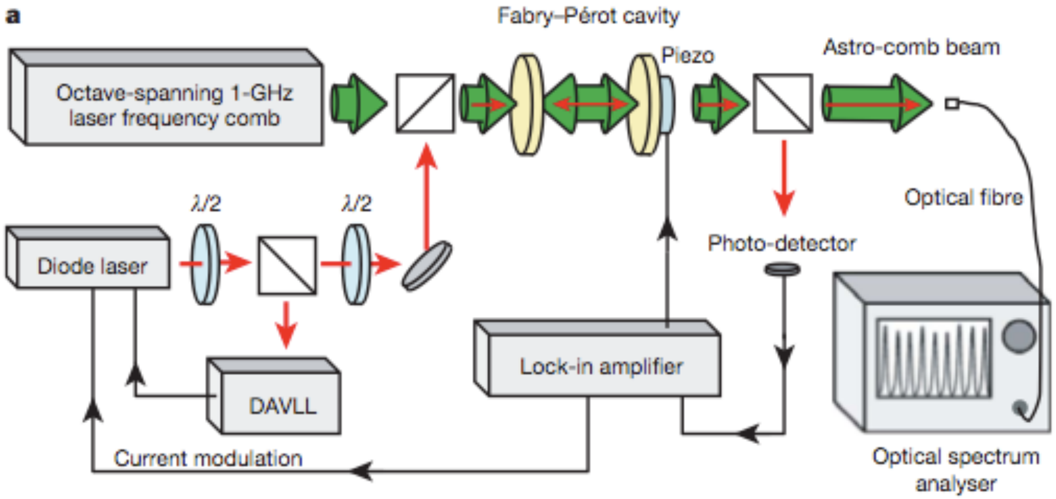


A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s^{-1}

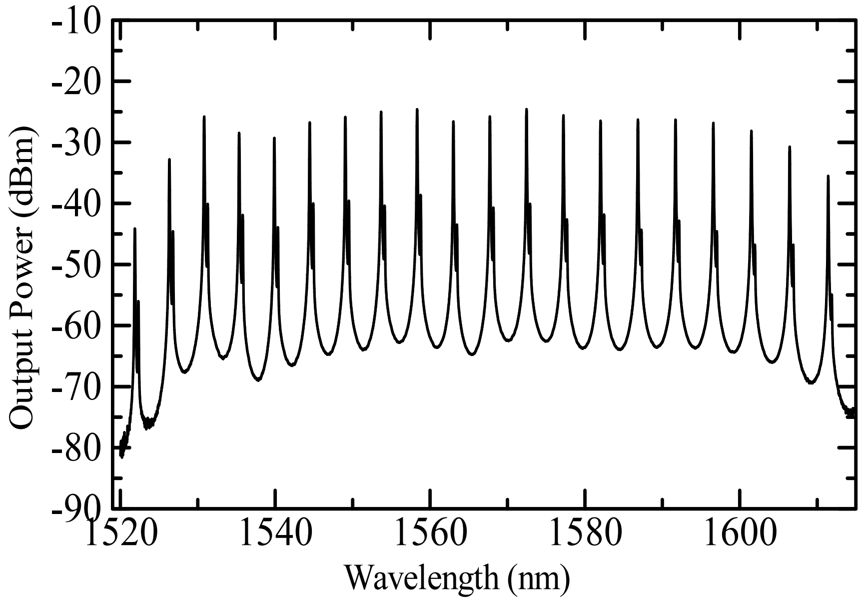
Chih-Hao Li[1,2], Andrew J. Benedick[3], Peter Fendel[3,4], Alexander G. Glenday[1,2], Franz X. Kärtner[3], David F. Phillips[1], Dimitar Sasselov[1], Andrew Szentgyorgyi[1] & Ronald L. Walsworth[1,2]

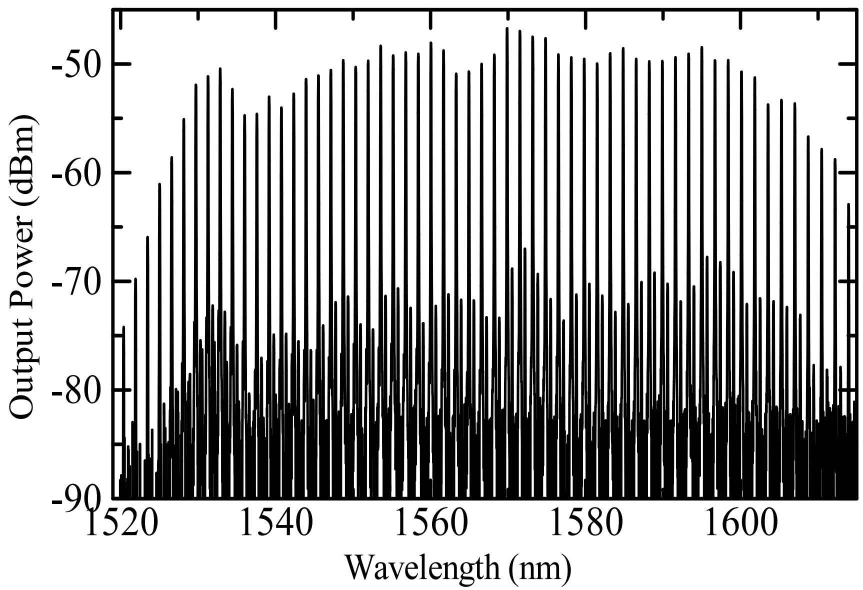


But spatial stability must also be addressed!



Generate comb for precise calibration



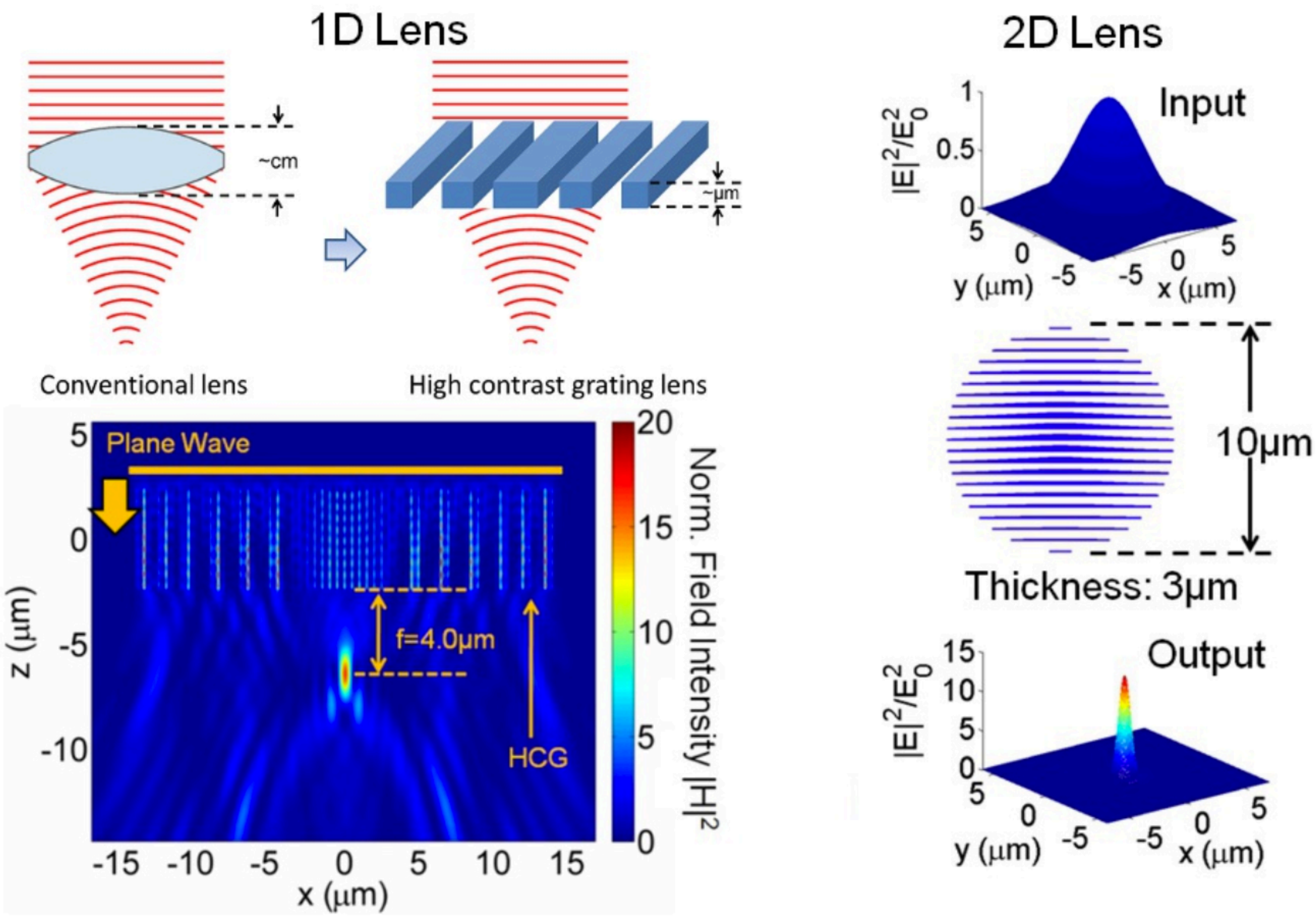


ring resonator

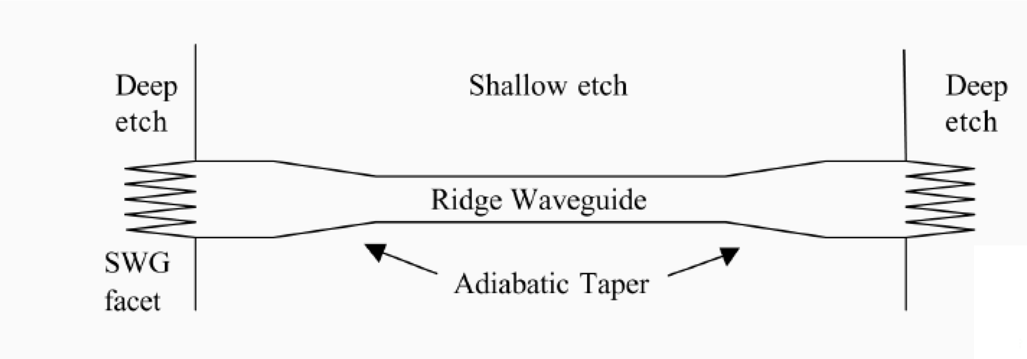
We published this method a few years ago (Chu et al 2012)

A better approach is to lock a fibre etalon to a Rb laser diode

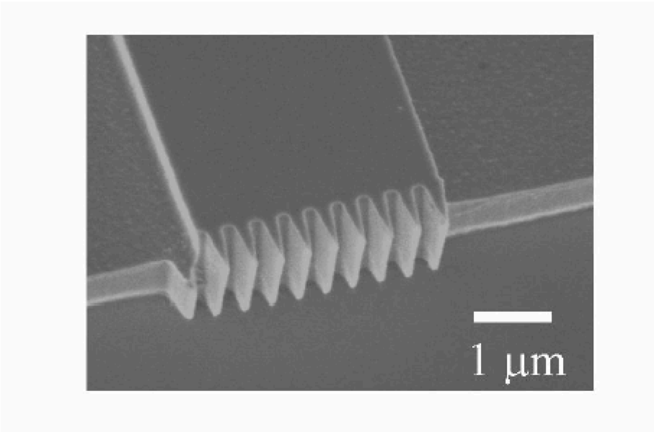
Sub-lambda optics



Sub-lambda transitions



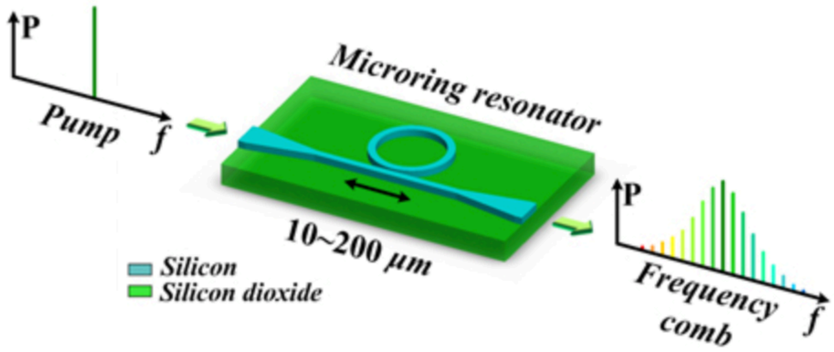
: Schematic top view of the SWG waveguide structure used for the transmission measurements.

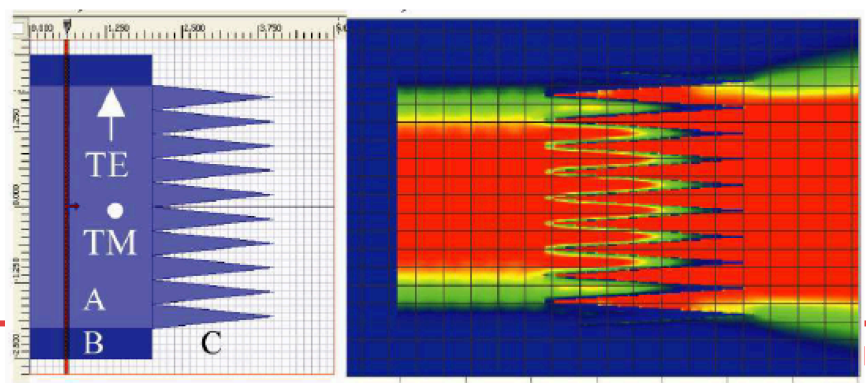


: SEM micrograph of a silicon-on-insulator ridge waveguide facet with a triangular SWG.

EXAMPLE:

1. Feeding light into ring resonator
2. Feeding light from ring resonator





THE UNIVERSITY OF SYDNEY

Elegant solution to AR problem at fibre tip

Fabrication of antireflection subwavelength gratings at the tips of optical fibers using UV nanoimprint lithography

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Abstract: Antireflection (AR) layers at the tips of optical fibers are indispensable in high efficiency and low noise applications. We realized the AR structures with two-dimensional binary subwavelength gratings (SWGs) at the tips of optical fibers by using a dedicated UV nanoimprint machine. Using this technique, ideal AR structures with desired refractive indices can be realized at low cost in principle. The SWG with the period of 700 nm was fabricated at the tip of a single-mode optical fiber for optical communications system. The reflectance was decreased to less than 0.27% at measured wavelengths between 1460 nm and 1580 nm.

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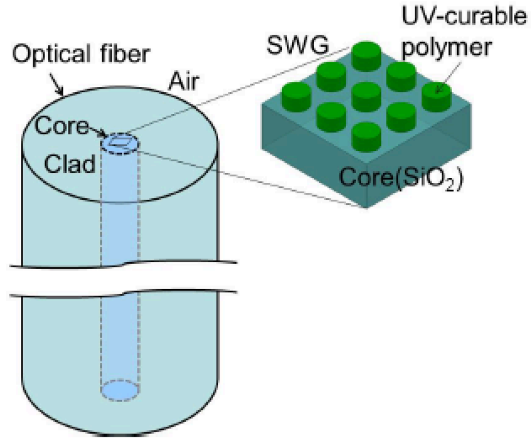


Fig. 1. A schematic view of an SWG at the tip of an optical fiber.

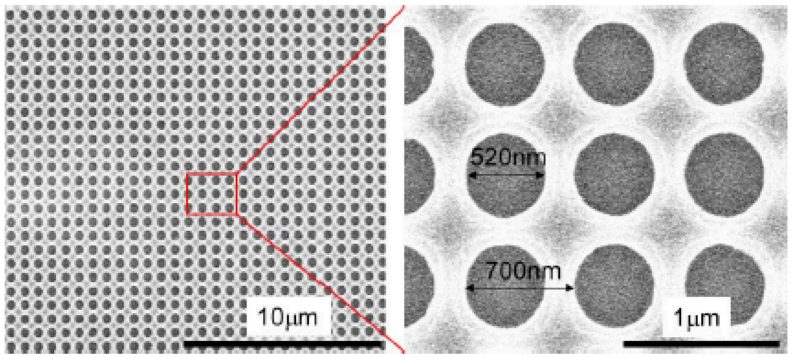


Fig. 4. An SEM image of the fabricated mold consisting of silicon.

Elegant solution to AR problem, contd.

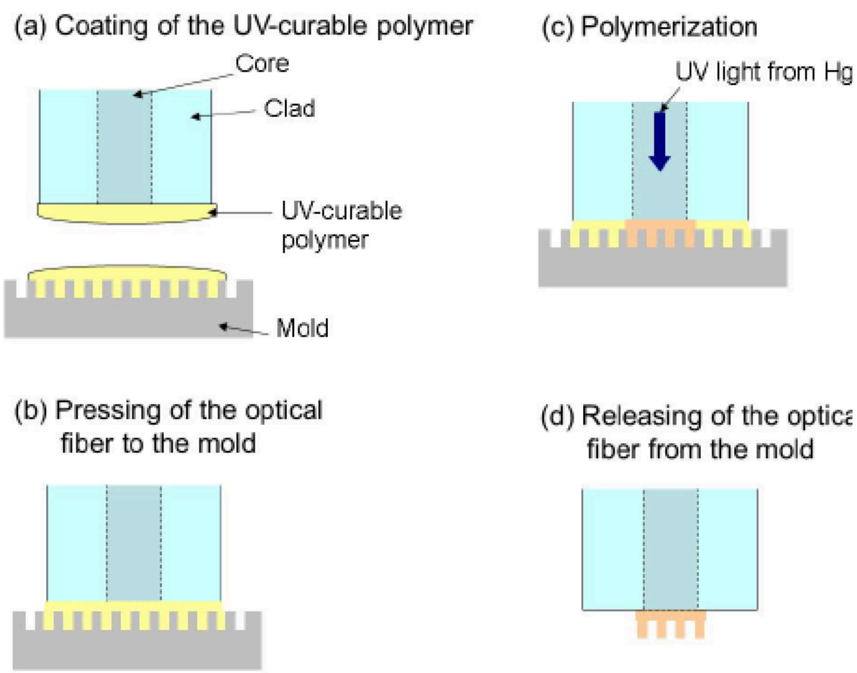


Fig. 2. Fabrication steps.

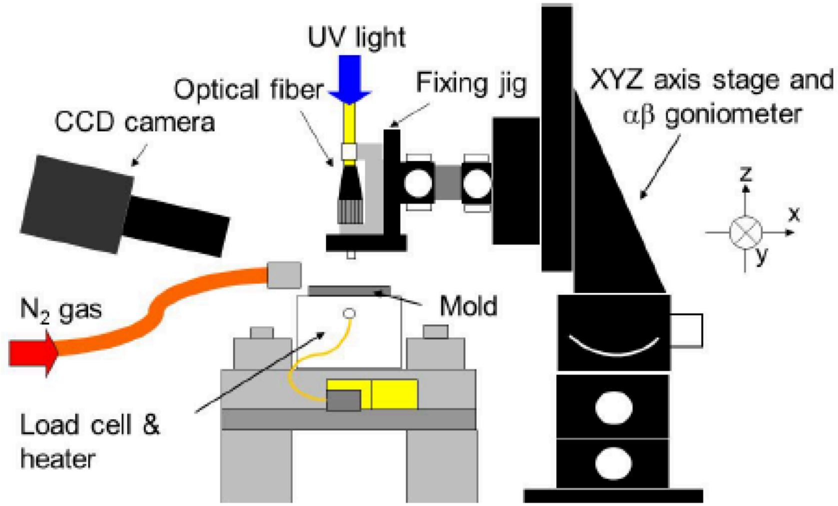


Fig. 3. A schematic of a dedicated UV nanoimprint machine for the tips of optical fibers.

Wonderful results !!

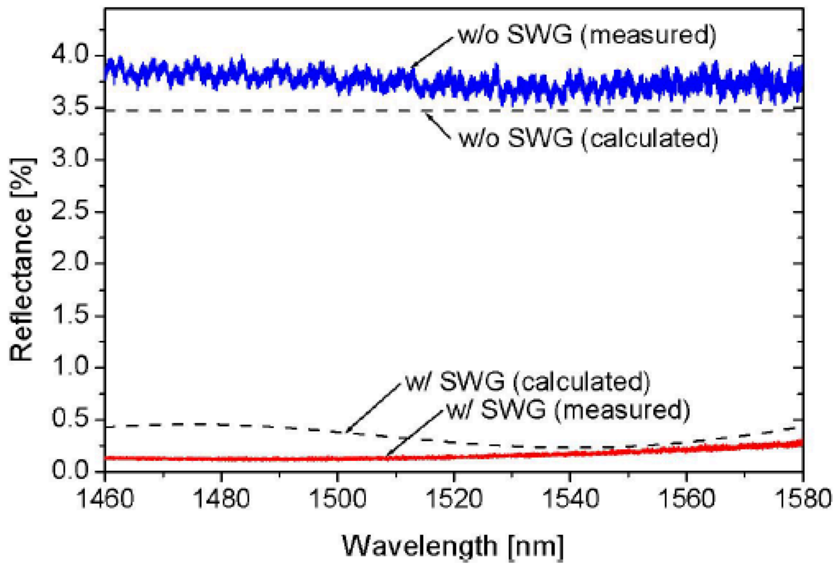
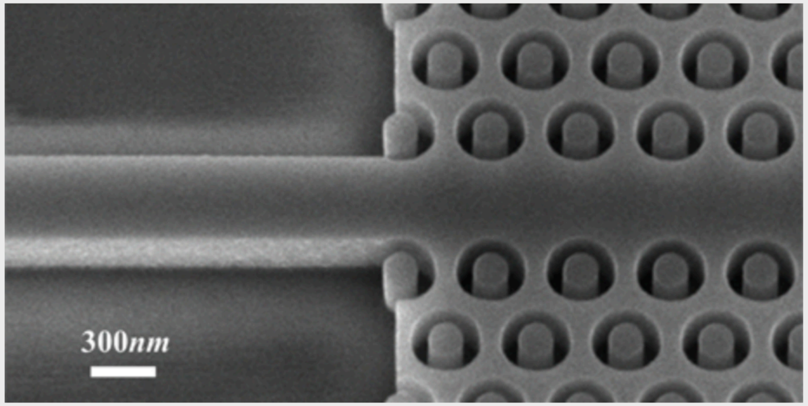
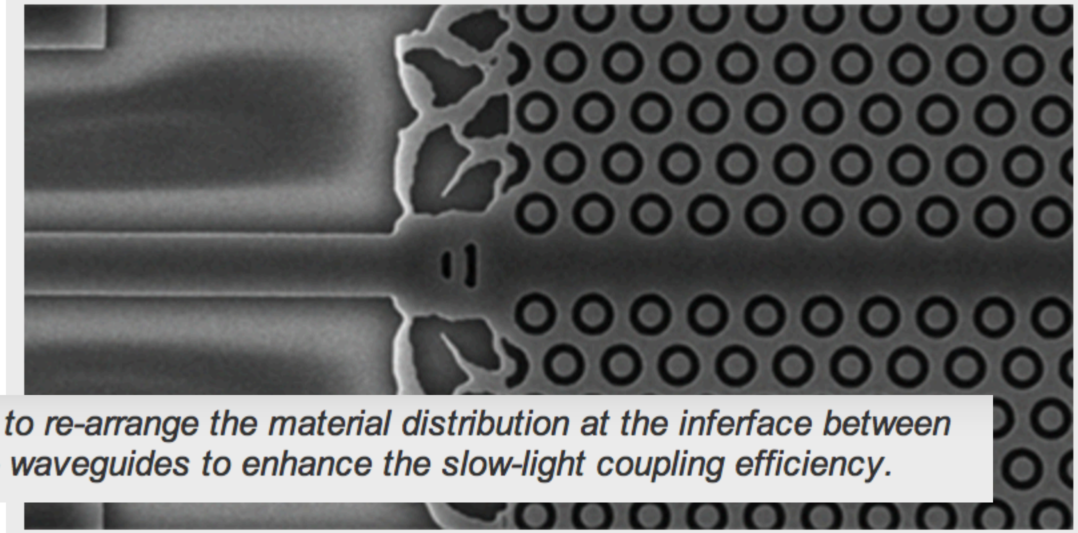


Fig. 7. Reflectance spectra at the tip of the optical fiber.

Sub-lambda control and filtering





Toplogy optimization method is applied to re-arrange the material distribution at the inferface between ridge- and ring-shaped photonic crystal- waveguides to enhance the slow-light coupling efficiency.

Domains of expertise

Nanophotonics and optical nanomaterials
Nanoelectronics and nanomagnetics

VOYAGER - Speed up

Facility: RAITH EBL, IBL ($20M)

ELPHY MultiBeam- The nanopatterning benchmark for upgrading your FIB-SEM

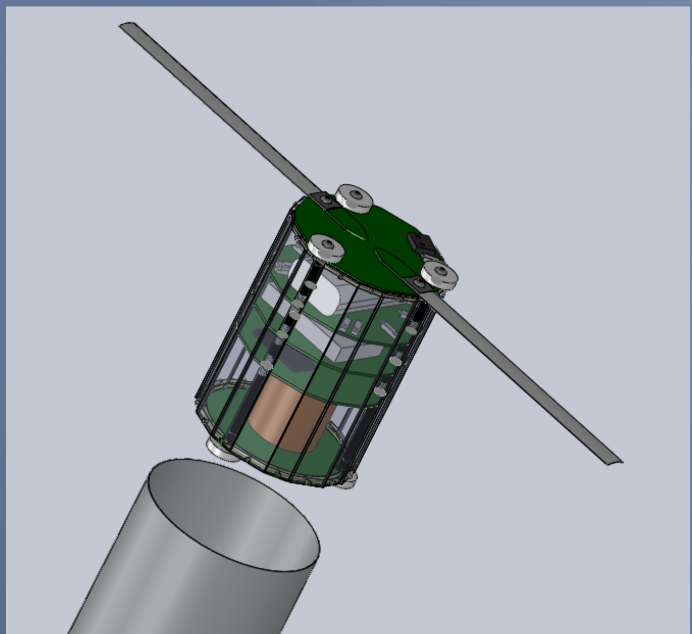
Supporting integration

Facility: PLUS prototype lab

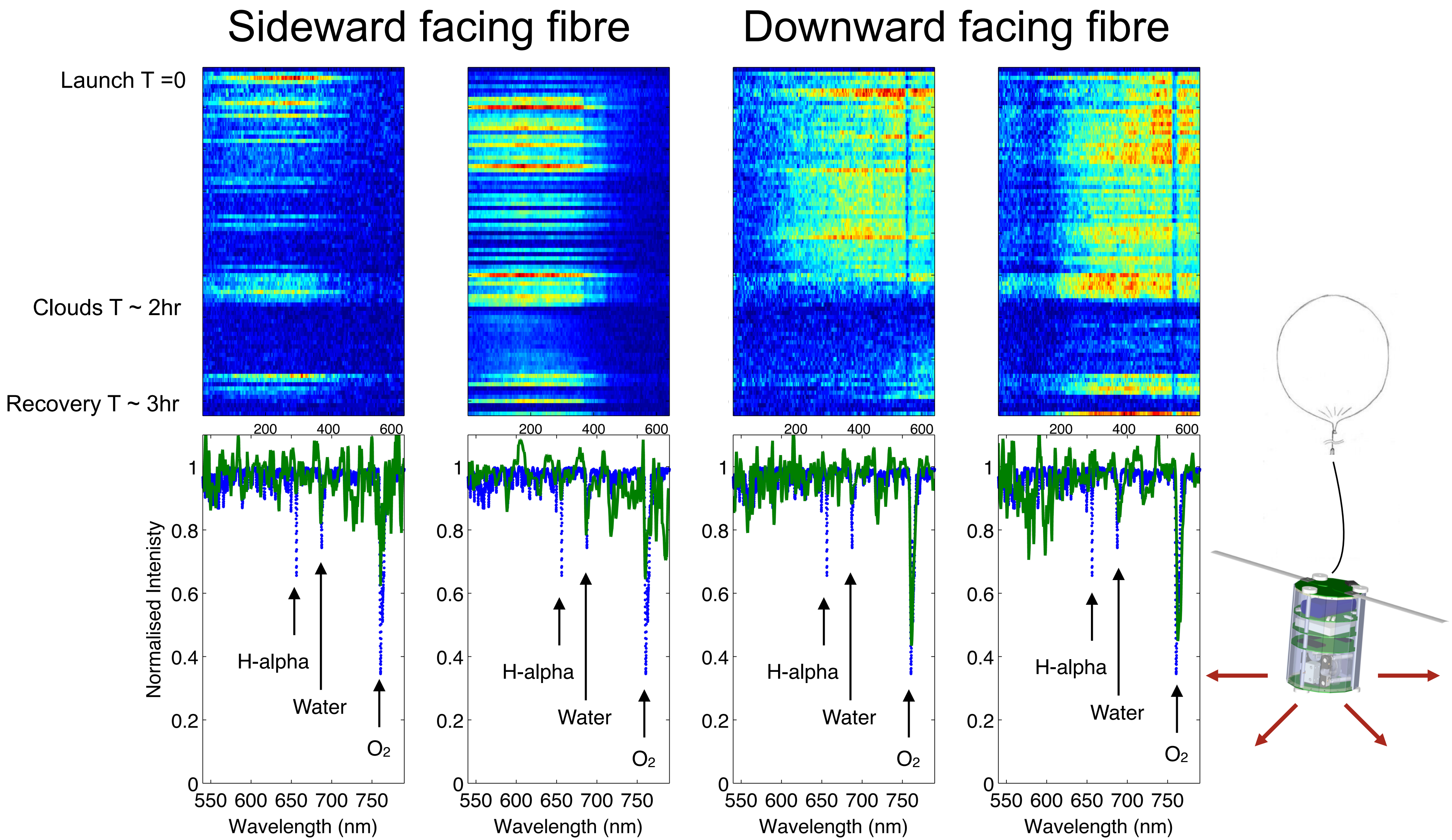
Space applications

Space photonics:

Successful balloon testing with real-time comms



Spectra from balloon test



Future applications: we welcome feedback and collaborations

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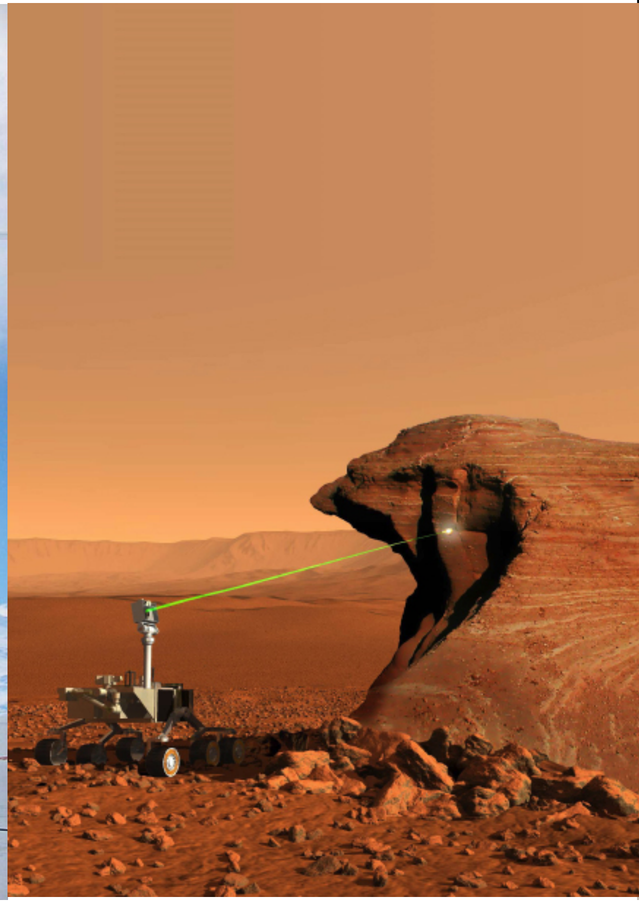
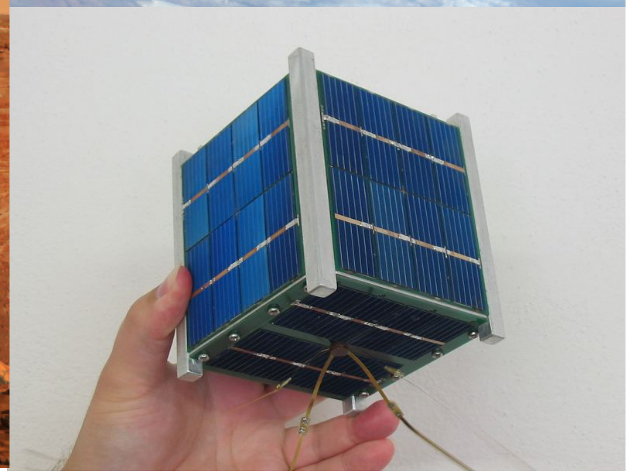




Unused

Detectors

- show my slide of BFI's attempt to print my first linear array design

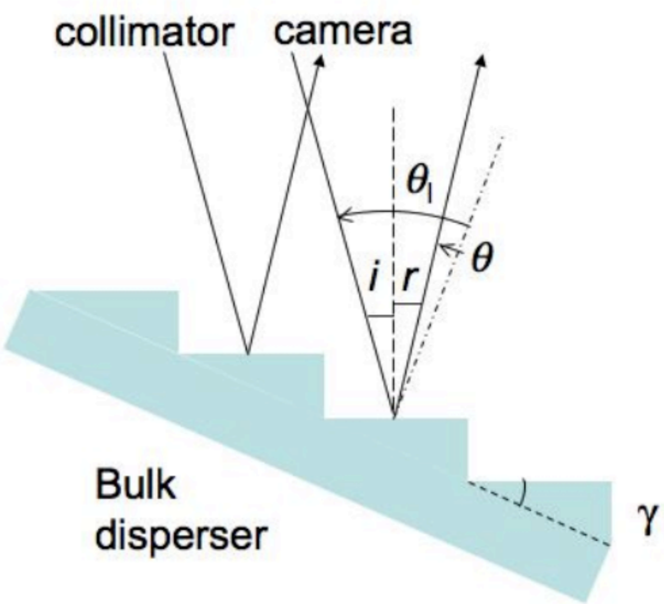
Scattering centres with line density ***ρ*** and extra path difference ***q***

$$\sin\theta + \sin\theta_I = (m\lambda + q)\rho$$

Angular dispersion independent of ***q***

$$\Delta \equiv \frac{d\lambda}{d\theta} = \frac{\cos\theta}{m\rho}$$

For conventional gratings, ***q=0***



...we will meet non-zero ***q*** later

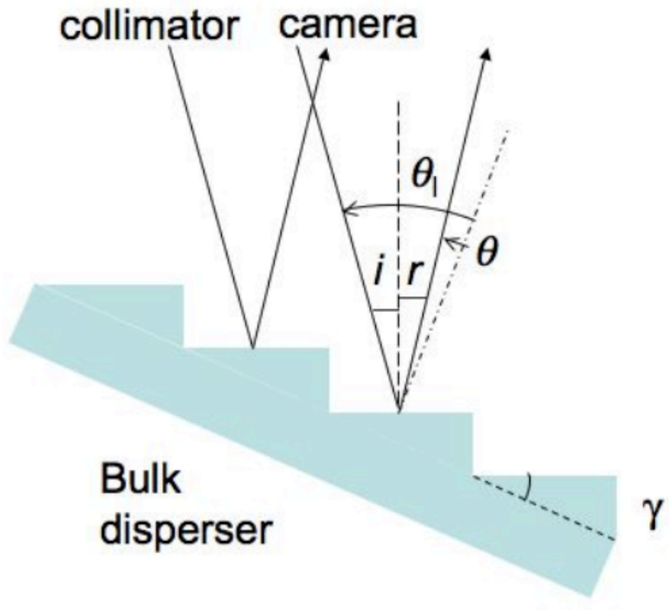
Basic spectrograph: fundamental limits

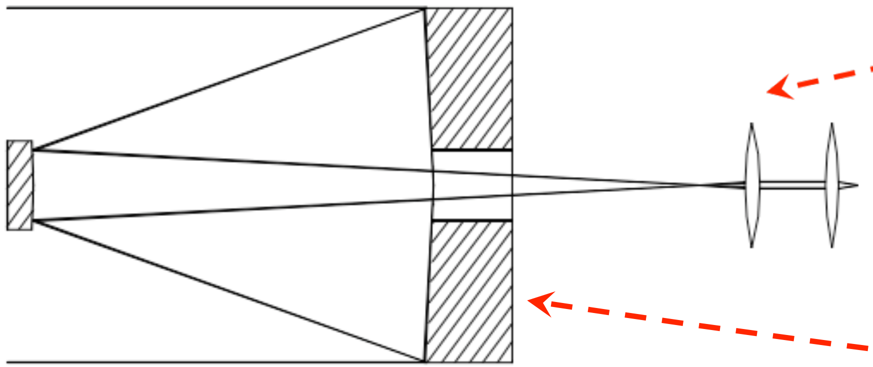
The resolution R is set by:

telescope diameter D_T
angular slit width χ
size of first element D ($\sim D_P$)

grating blaze angle γ
grating line density ϱ

beam speed f/D





$$R \equiv \frac{\lambda}{\delta\lambda} = \frac{2D\tan\gamma}{\chi D_T}$$

How many unpolarized transverse modes do we need for efficient MMF coupling?

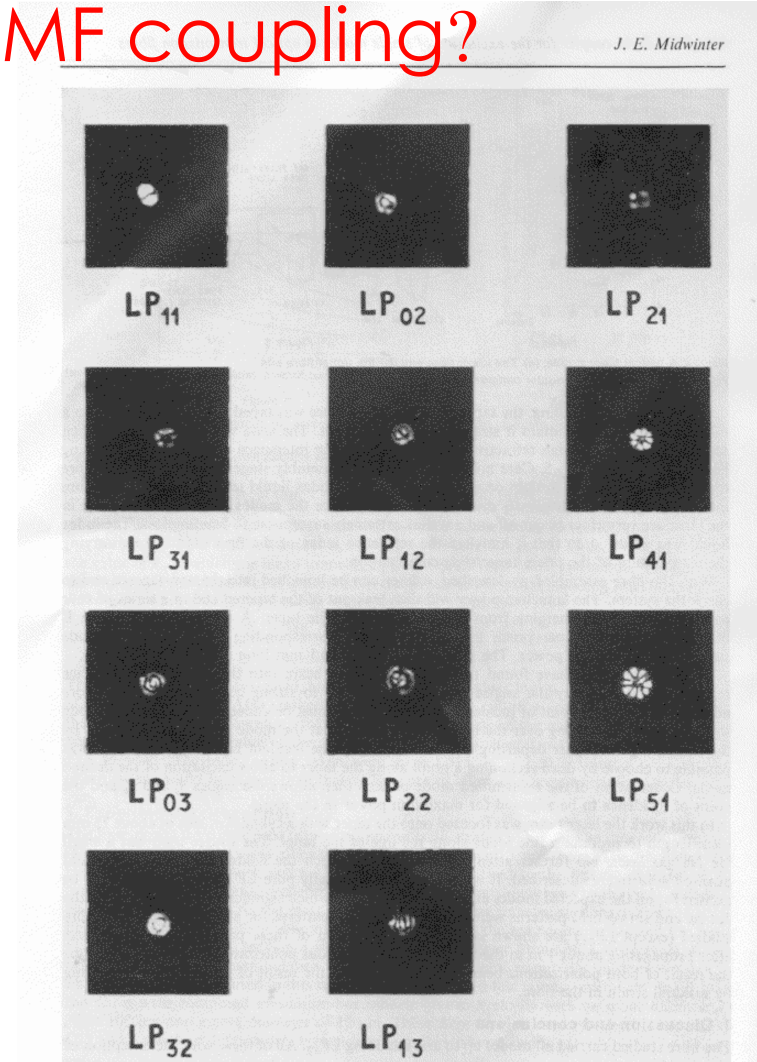
Number of modes, M

$$M \approx \frac{V^2}{4} \qquad V = \frac{\pi D}{\lambda} NA$$

D=80μm core, NA=0.1, λ=1500 nm

$\Rightarrow$ $\mathbf{M = 61}$

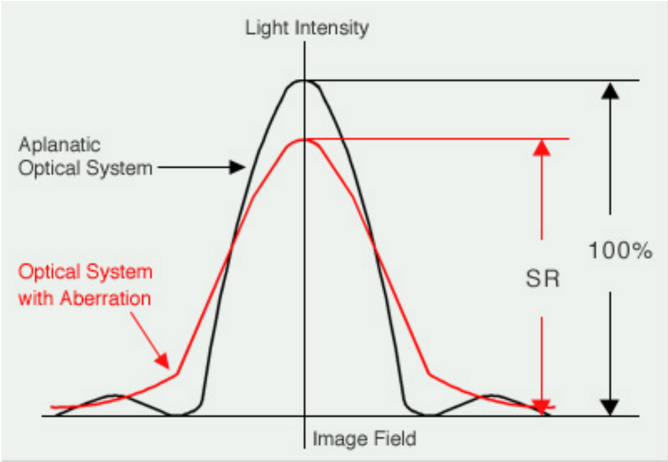
n.b. mode conservation is equivalent to étendue (AΩ)



Without AO, we need 40-80 modes to cover near IR, more in optical

Leon-Saval et al 2005; Corbett 2007

Strehl ratios: achieved vs. target



I (900 nm)	<0.05	0.15
J (1250 nm)	0.15	0.3
H (1650 nm)	0.3	0.5
K (2200 nm)	0.7	0.8
L (3450 nm)	0.9	0.95
M (4700 nm)	0.9	0.95
N (7-14,000 nm)	0.9	0.95