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Astrophotonics: a new generation of astronomical instruments

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Harvard Smithsonian: G Furescz

The University of Sydney   astrophotonics   AAO

Astrophotonics: history

1980: light transport in MMFs (Australia, UK, USA)

1988: field reformatting with MMFs (France, Russia)

1996: interferometry with SMFs (France)

2002-5: photonic functions in MMFs (Australia, UK)

2004: laser guide star with PCFs (Japan)

2006: integrated photonic spectrograph (Australia)

2009: focus issue – Optics Express (worldwide)

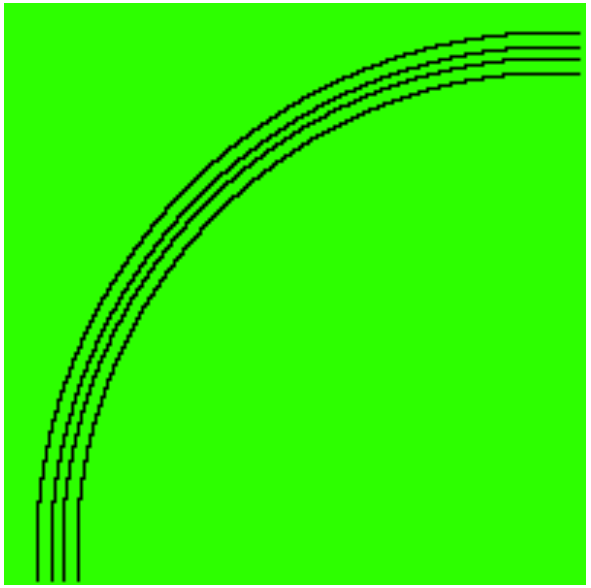
2010: special sessions at ESTO/Frankfurt, FiO/Rochester

2010: astrophotonics institutes to open in Potsdam, Marseille

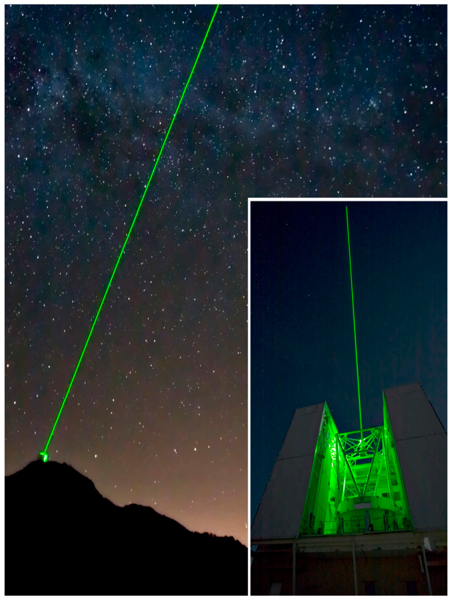
2011: astrophotonics symposium at CLEO/Rostock

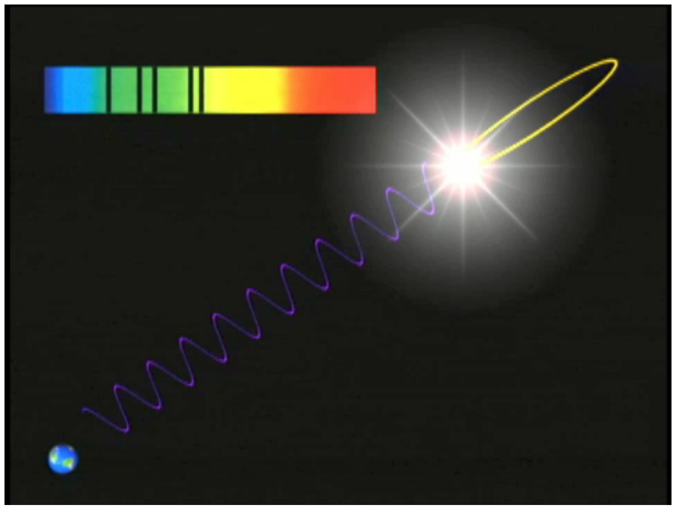
2011: astrophotonics instrument GNOSIS to see "first light"

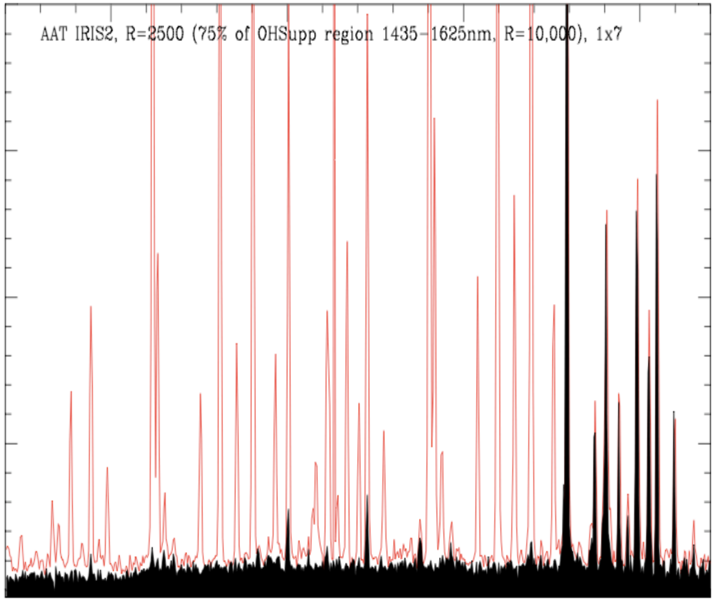
Astrophotonics



Artificial stars for AO: to correct for Earth's turbulent atmosphere
Pupil remapping: to detect faint planets directly around nearby stars
Optical frequency combs: to achieve precise velocities to detect planets
Beam combiners: to combine many optical beams for interferometry
Sky suppressing fibres: to remove unwanted night sky emission
Integrated spectrographs: ultracompact devices fed by fibres
Hexabundles: robotically positioned imaging fibre bundles
Laser communications: to maintain spacecraft metrology







Astrophotonics:

SMF coherent light transport, beam combining, signal processing

Fringe benefits: the spatial filtering advantage of single-mode fibers

Stellar interferometry:

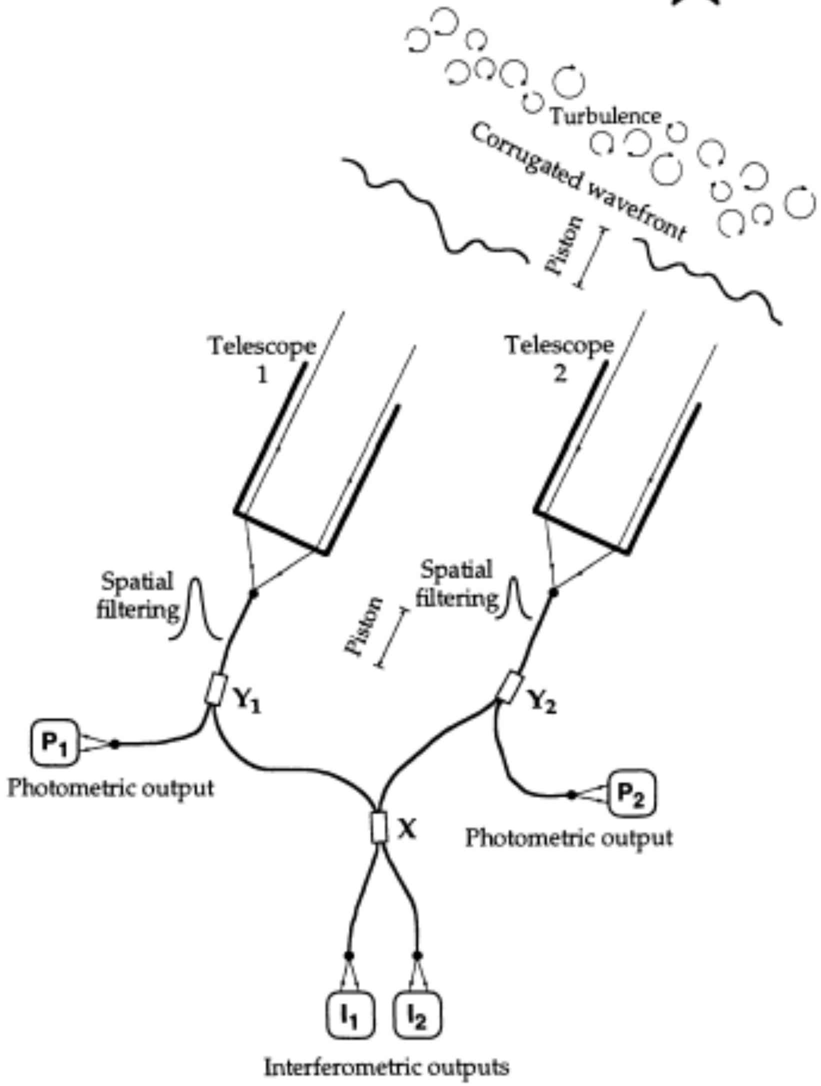
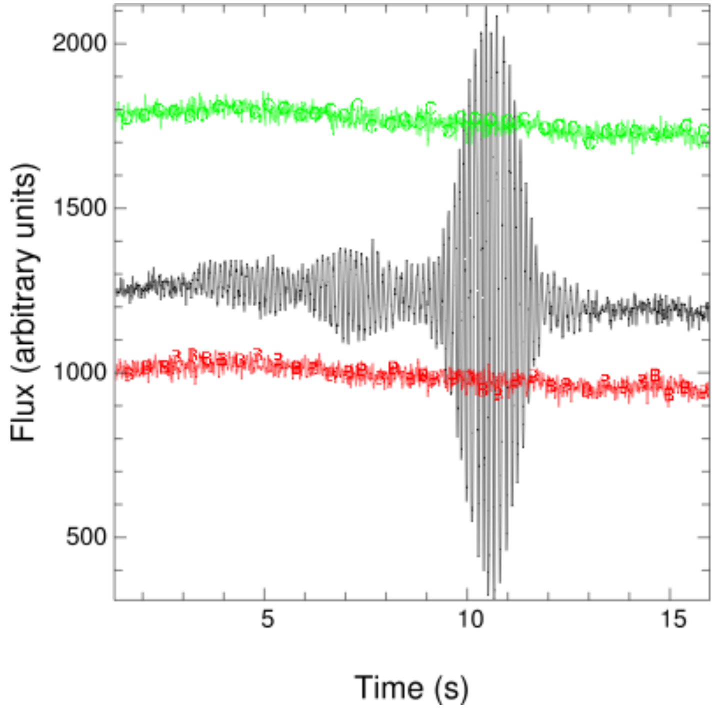
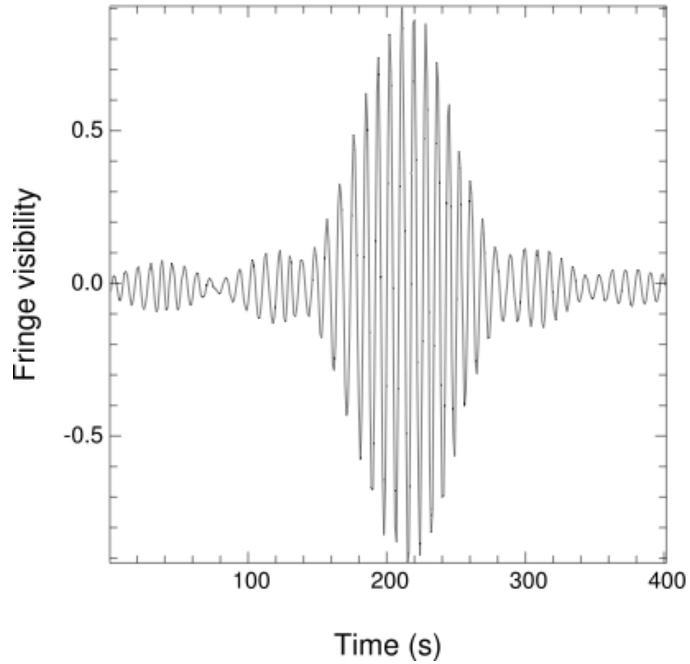
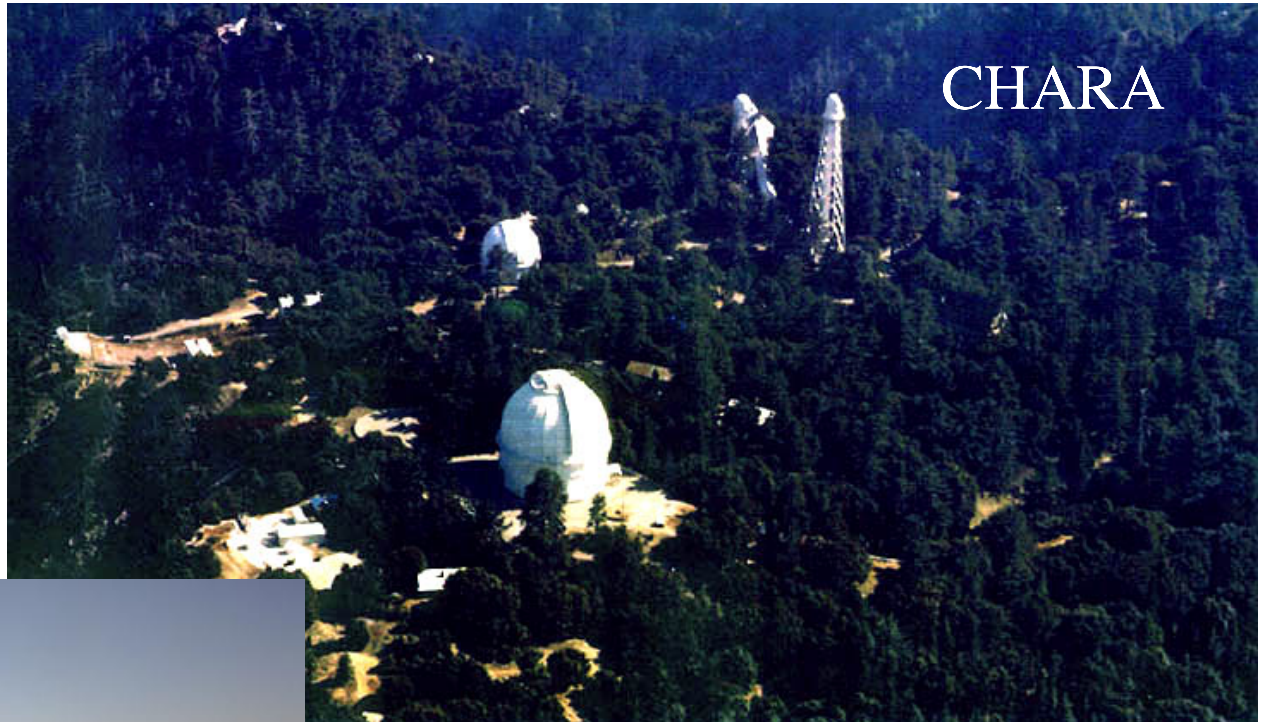


Figure 1. Conceptual design of a stellar fiber interferometer.

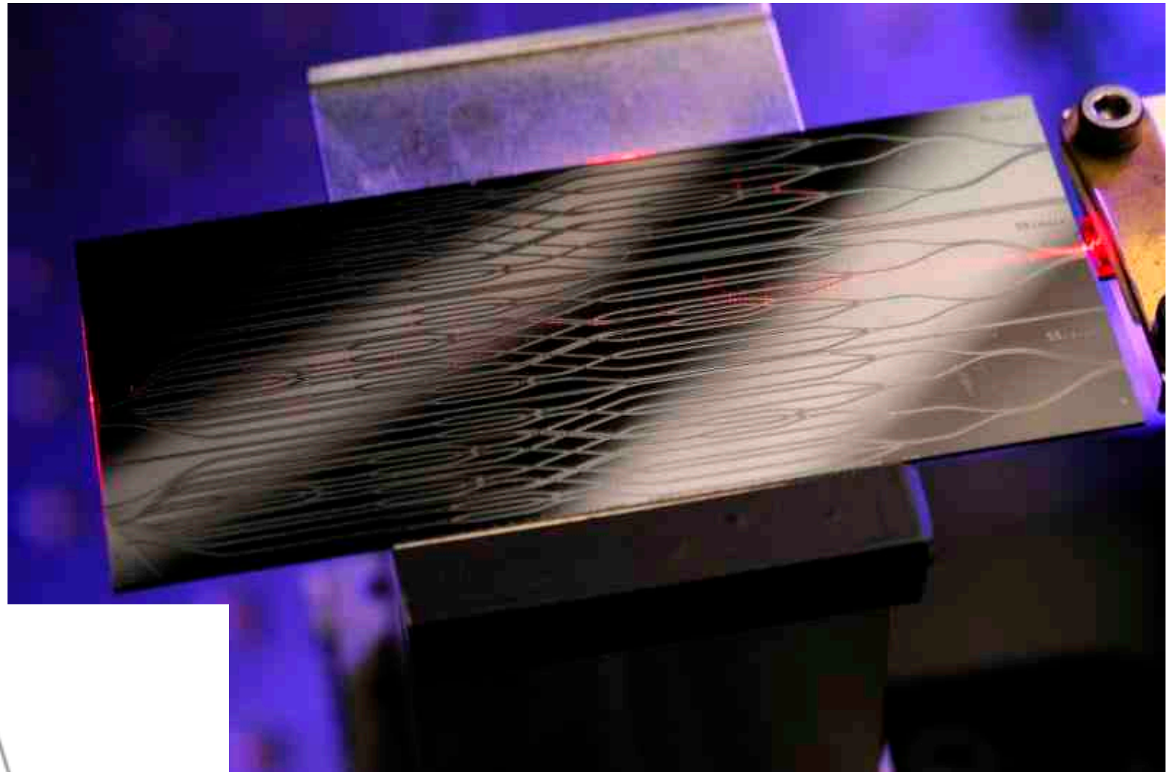




Interferometric arrays

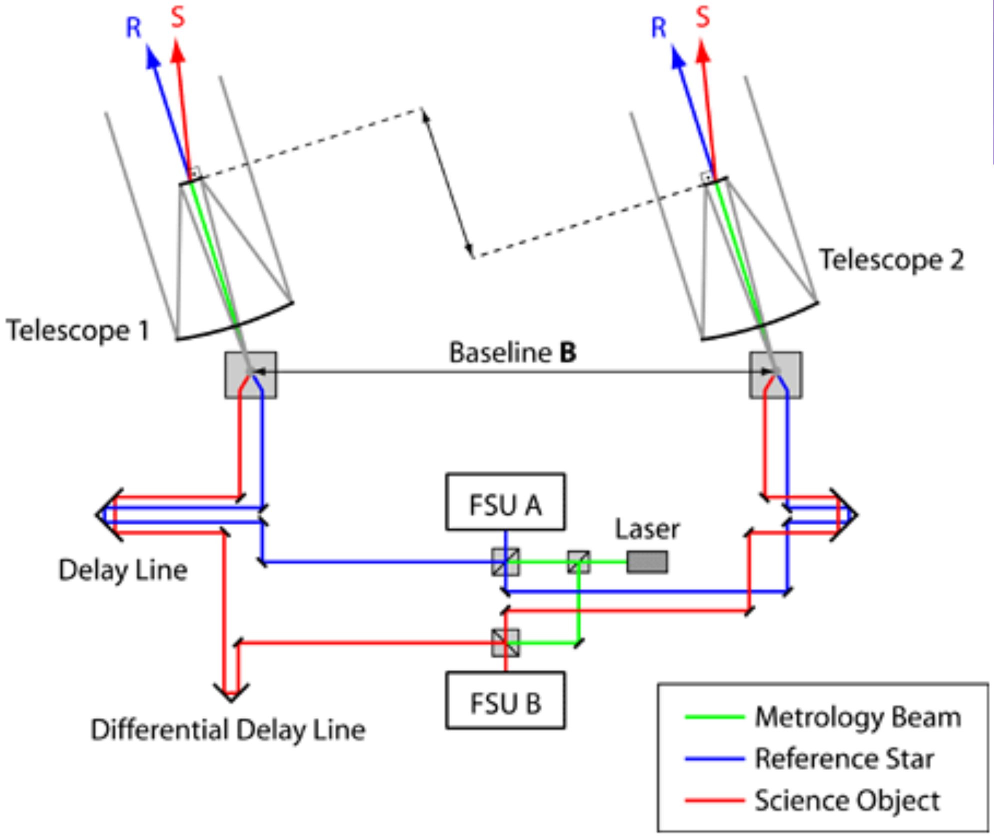


Integrated optics



Kern et al 2008

VLTi

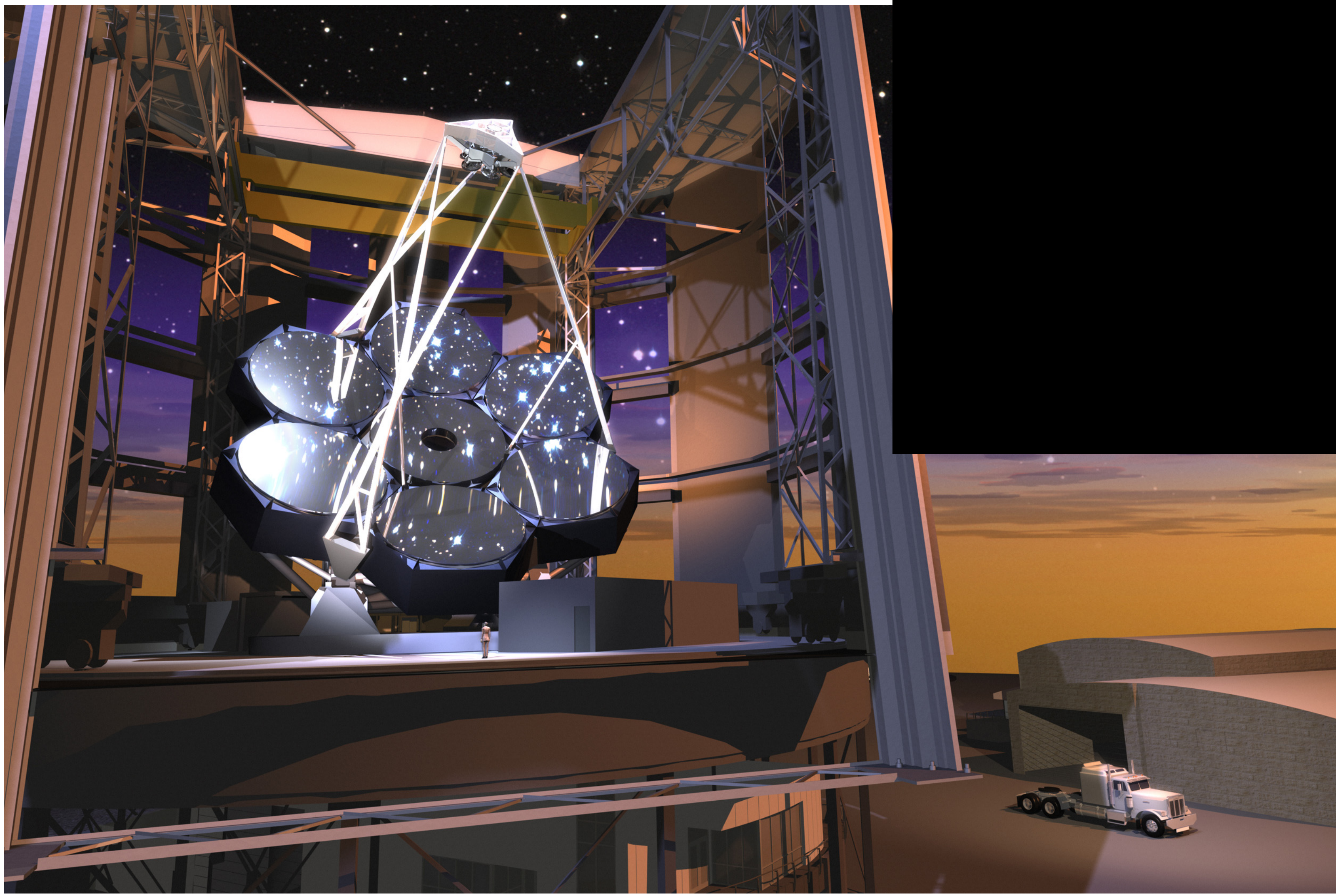


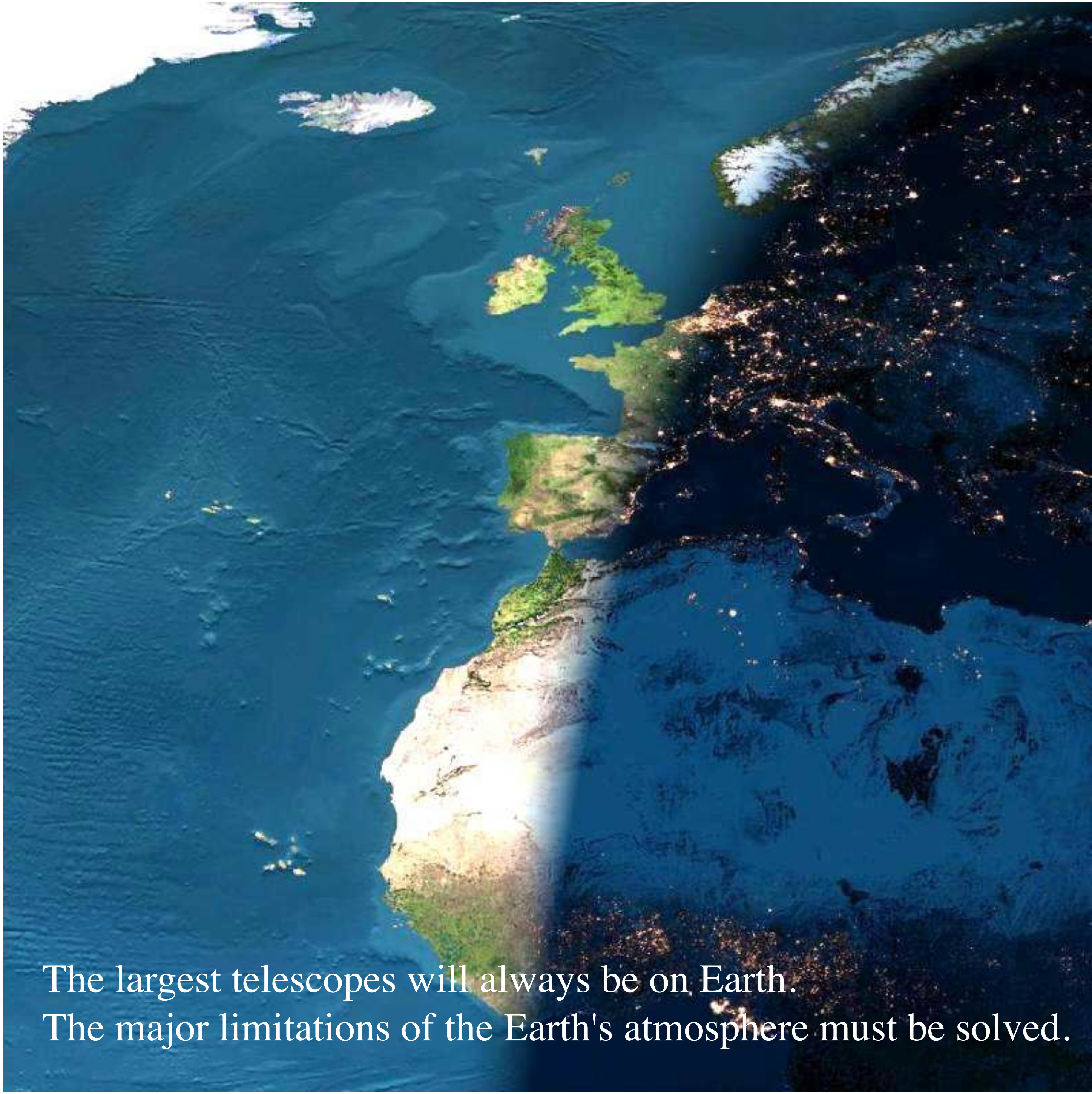
Astrophotonics:

MMF incoherent light transport, multiplexing, wide-fielding and reformatting

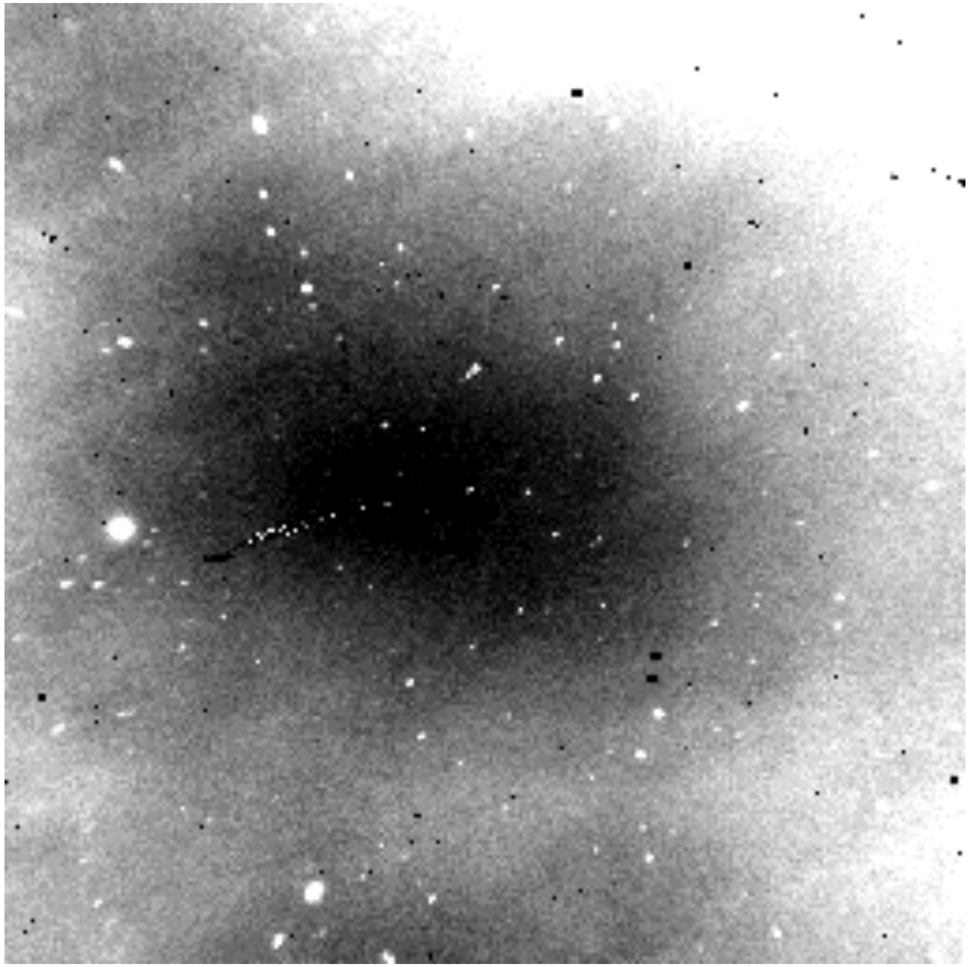
Extremely Large Telescopes

Giant Magellan Telescope (2018 ff)




The largest telescopes will always be on Earth.
The major limitations of the Earth's atmosphere must be solved.

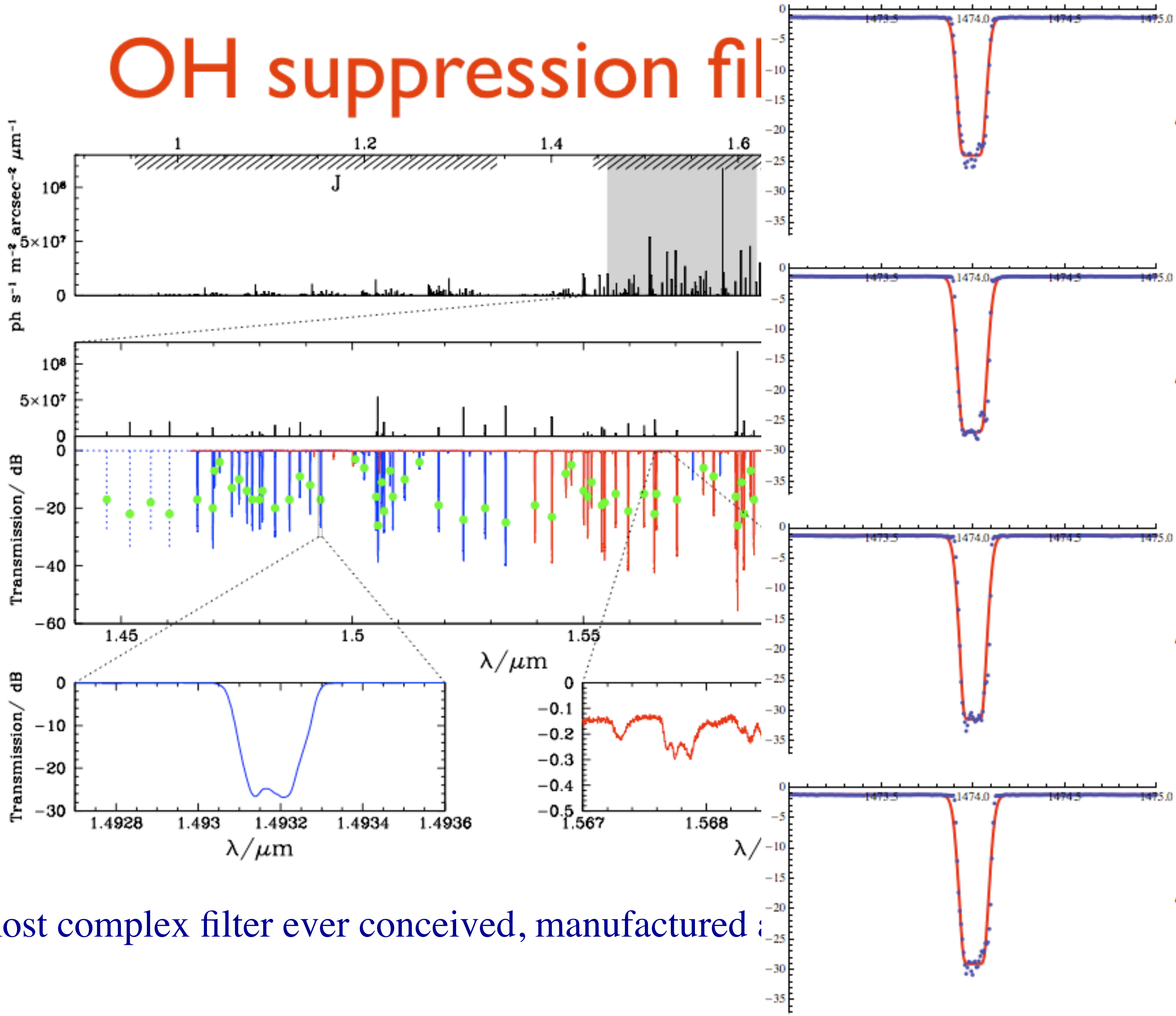
The atmosphere is a worthy adversary



The sky is bright
and **highly variable**

2MASS airglow experiment

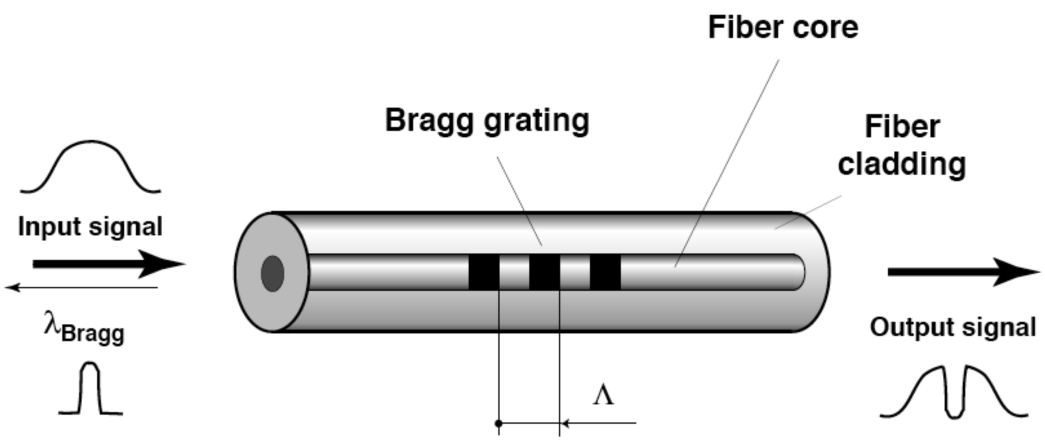
OH suppression fil



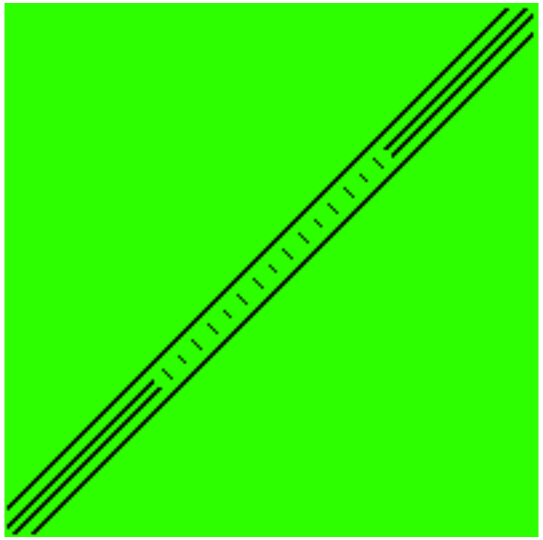
The most complex filter ever conceived, manufactured a

Fibre Bragg Grating

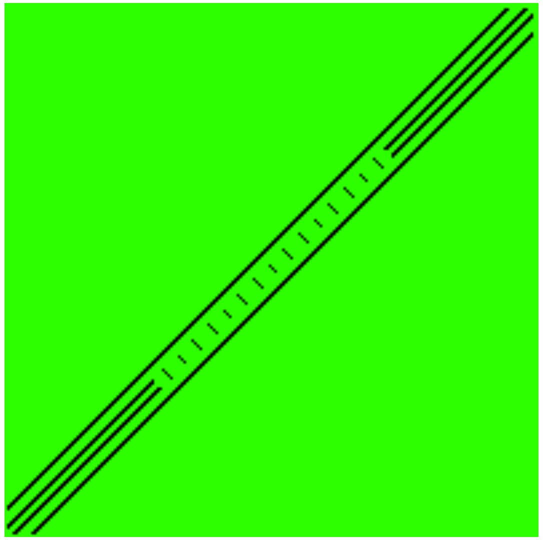
- Optical fibre with periodic variations in n
- Fresnel reflections at each boundary
- Small *but* in phase with each other
- Strong reflection at a single wavelength



JBH et al 2008; Buryak et al 2009

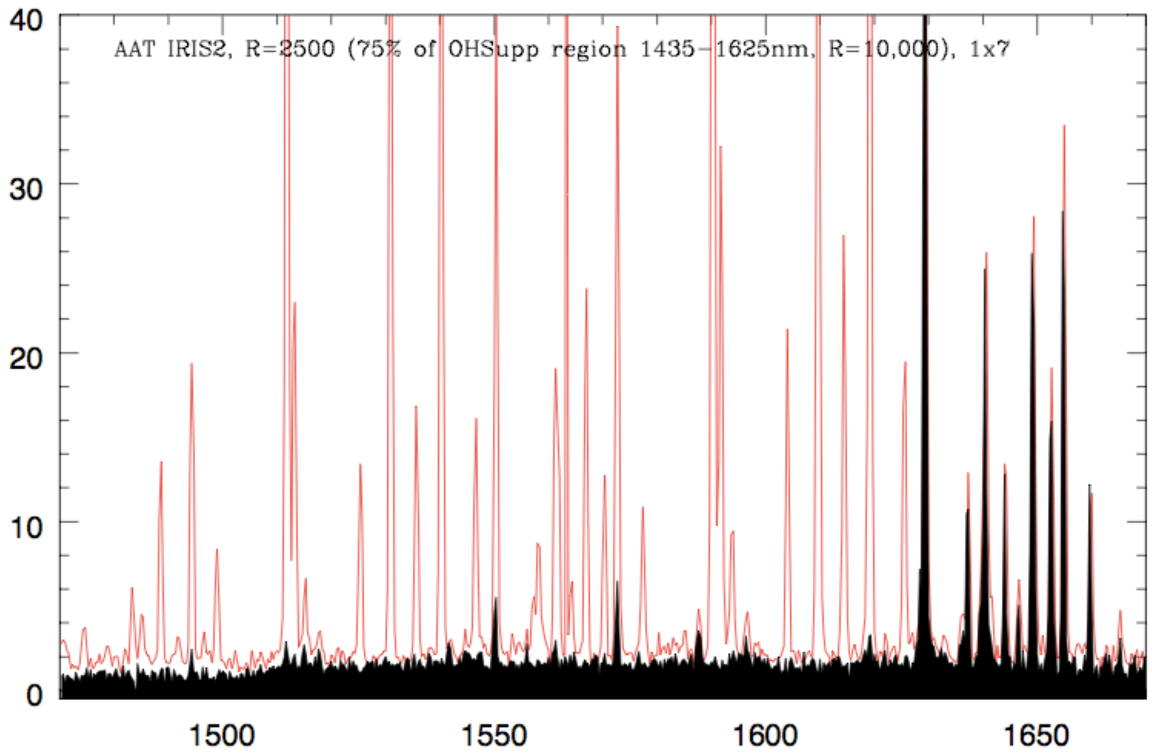


$$\lambda_B \neq 2n\Lambda$$



$$\lambda_B = 2n\Lambda$$

On-sky demonstration (Dec 08)

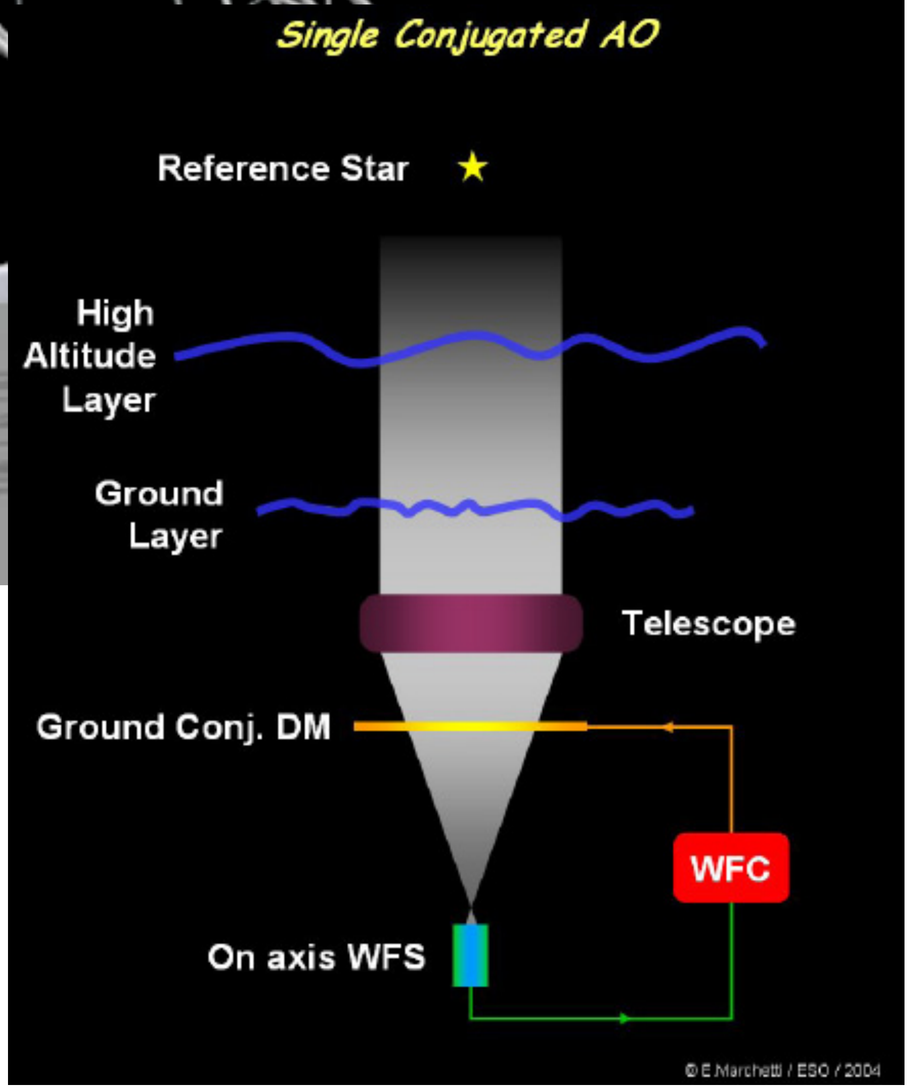


7 ultra-broadband FBGs within 1×7 photonic lantern

OH lines suppressed at R=10,000

Input fibre exposed to starlight and moonlight so zero b/g **not** reached here

Adaptive optics



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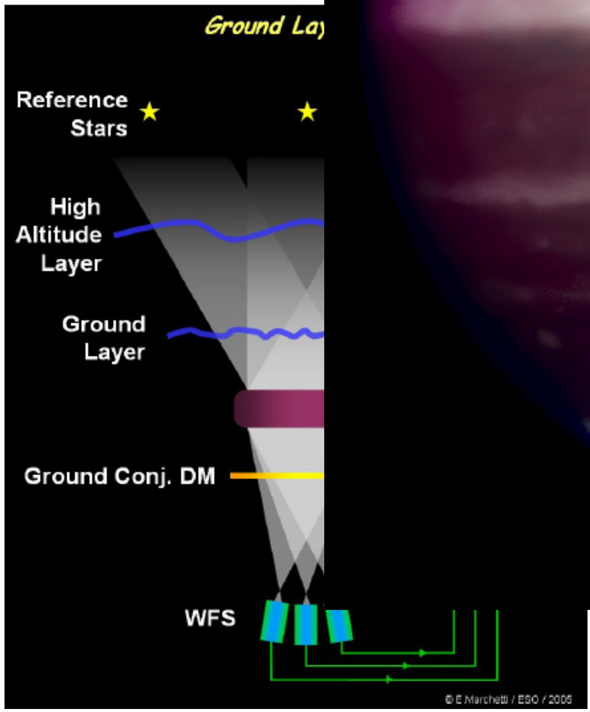
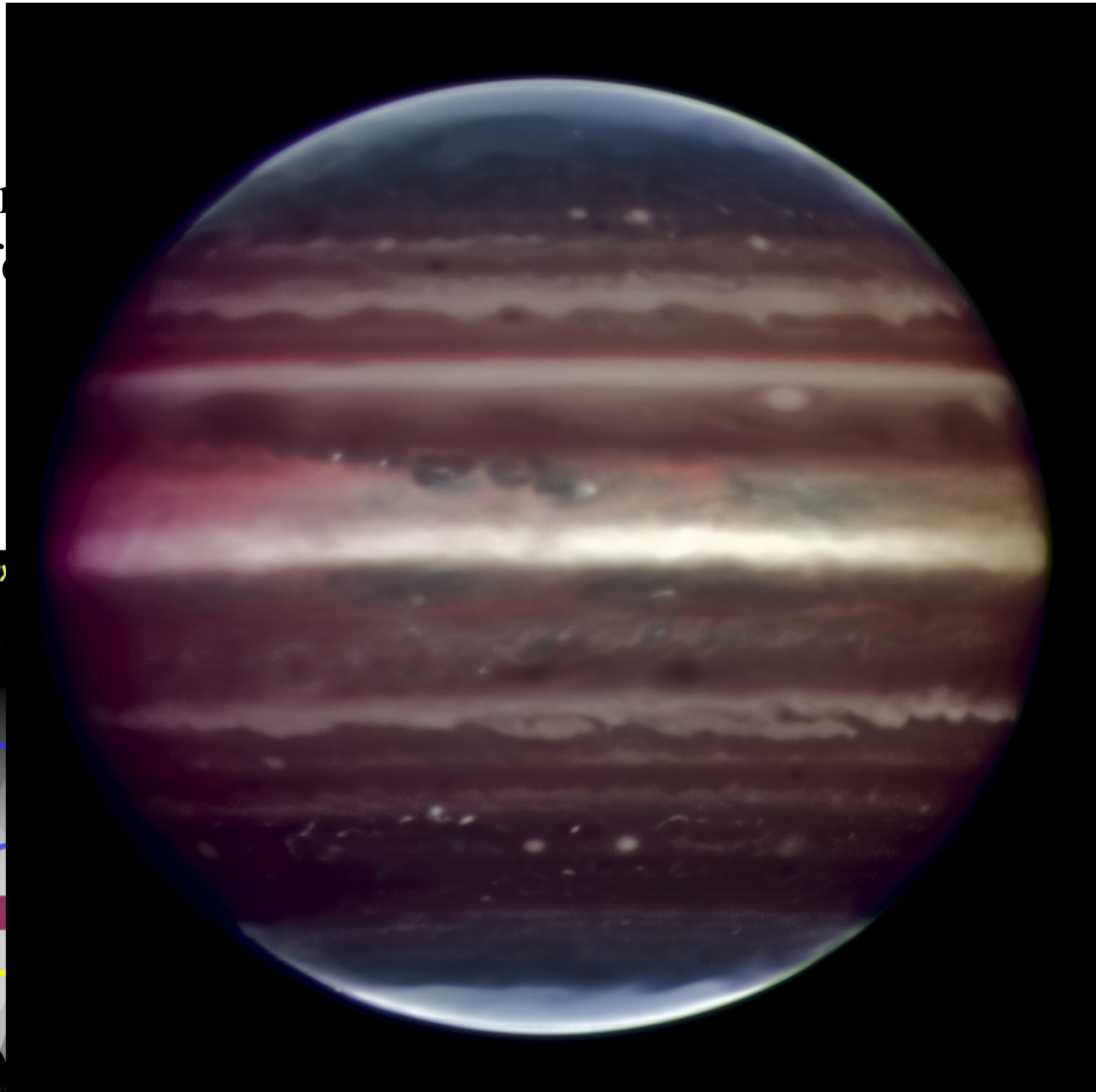
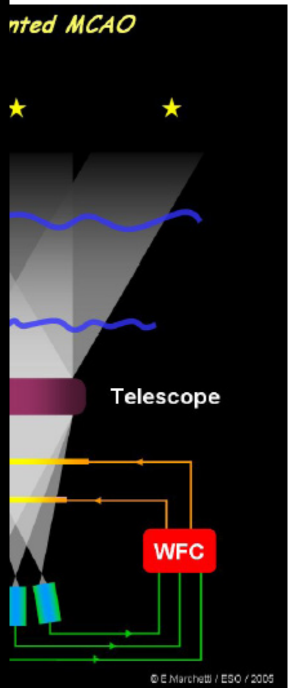






onics, e.g.

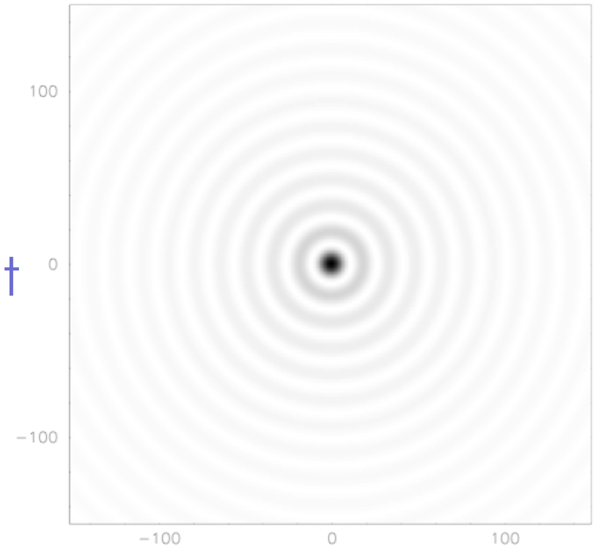
M PCFs

Diffraction limit with perfect AO correction

PSF diameter in microns

$$P = 1.22\lambda F$$

F = f/ratio



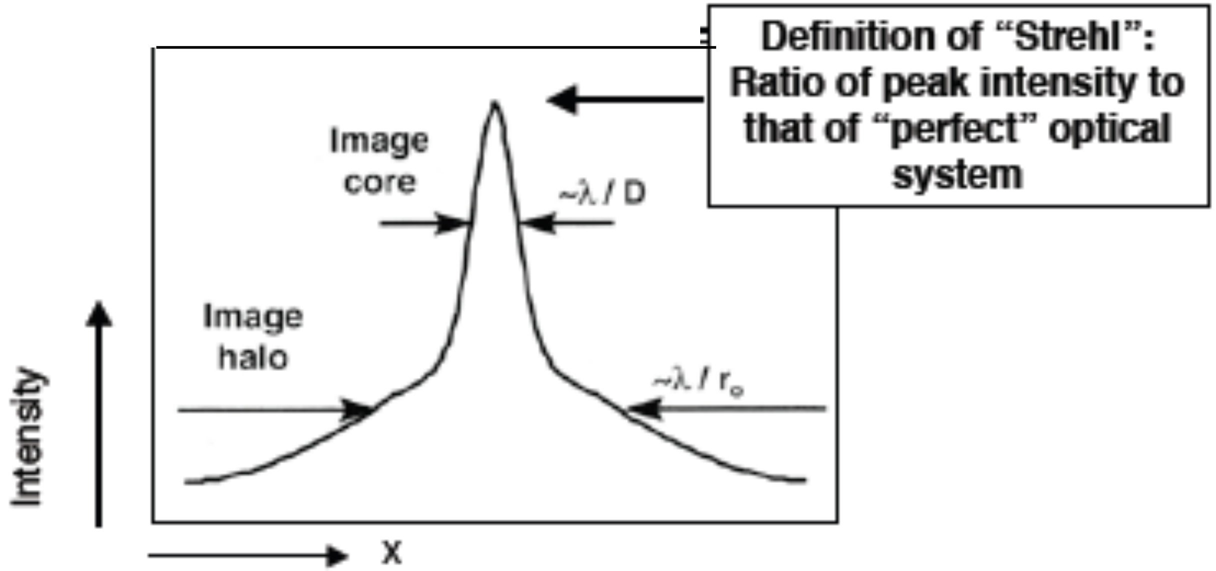
or 10 microns at 1500 nm for f/5 (NA=0.1).

This is well matched to SMF iff flat wavefront and gaussian illumination.

But telescope PSF is imperfect gaussian such that $M \geq 7$

Horton & JBH 2006, Corbett 2007

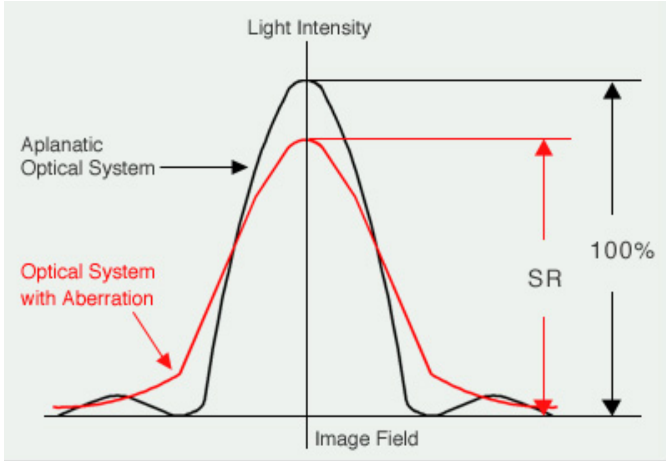
AO produces point spread functions with a "core" and "halo"



- When AO system performs well, more energy in core
- When AO system is stressed (poor seeing), halo contains larger fraction of energy (diameter ~ r_0)
- Ratio between core and halo varies during night

Shaklan & Roddier 1998

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

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

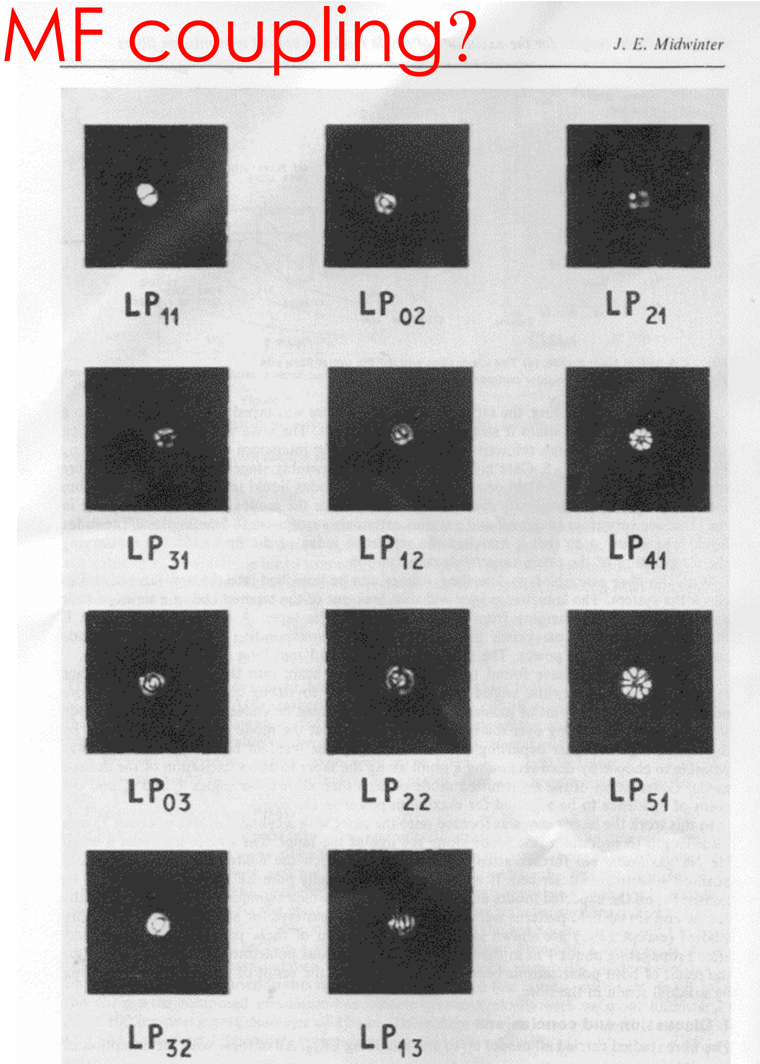
Number of modes, M

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

D=80µm core, NA=0.1, λ=1500 nm

$\Rightarrow \quad \boldsymbol{M = 61}$

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



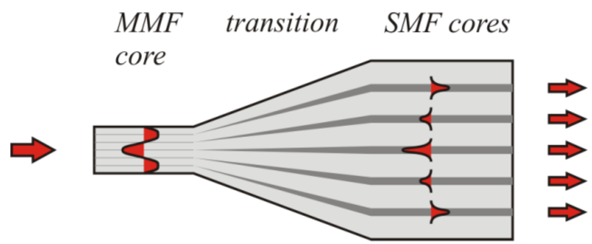
Without AO, we need 40-80 modes to cover near IR, more in optical

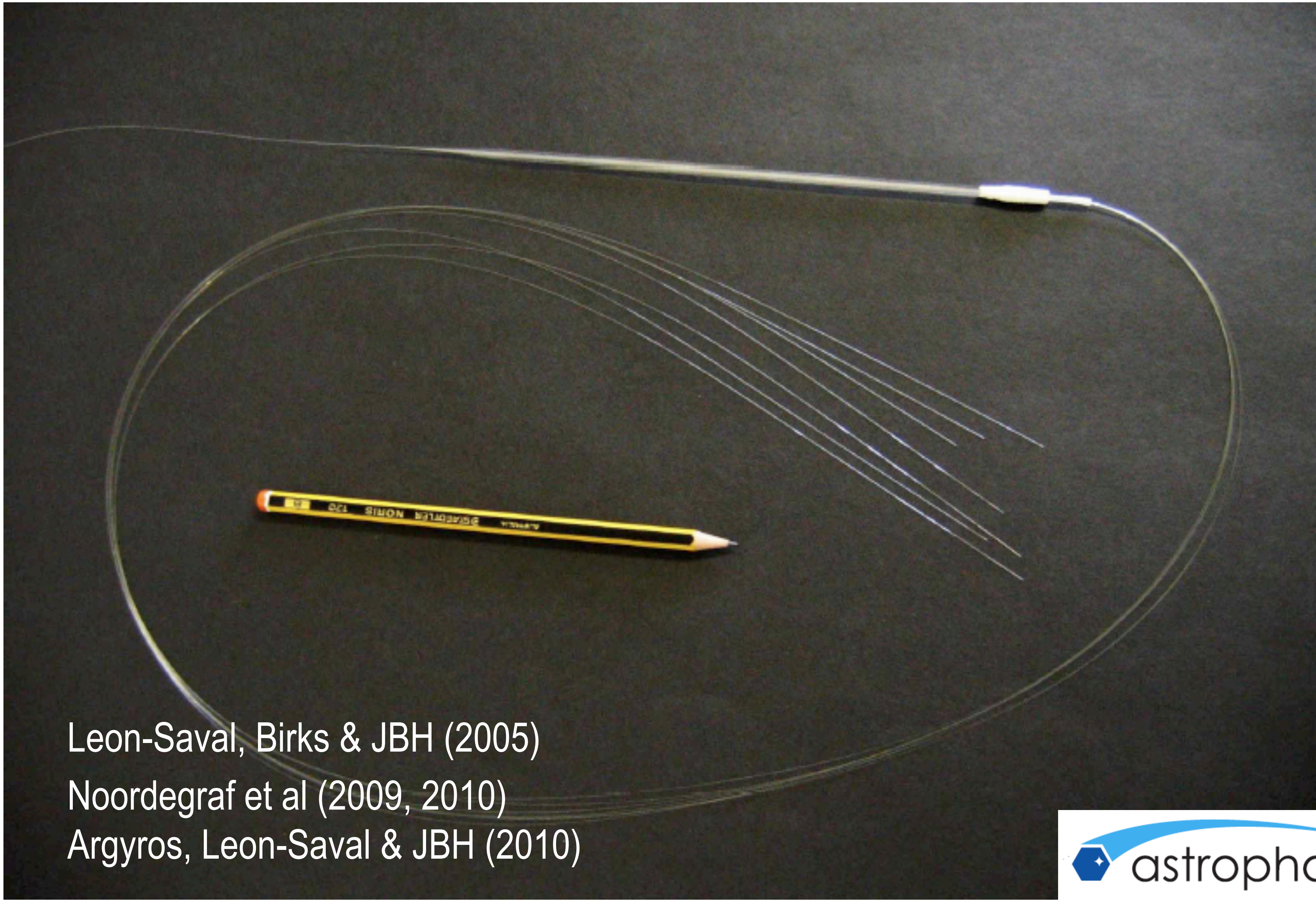
Leon-Saval et al 2005; Corbett 2007

For mainstream astronomy, we need photonic action in a multimode fibre

How is this possible?

The photonic lantern: single mode action in a MMF





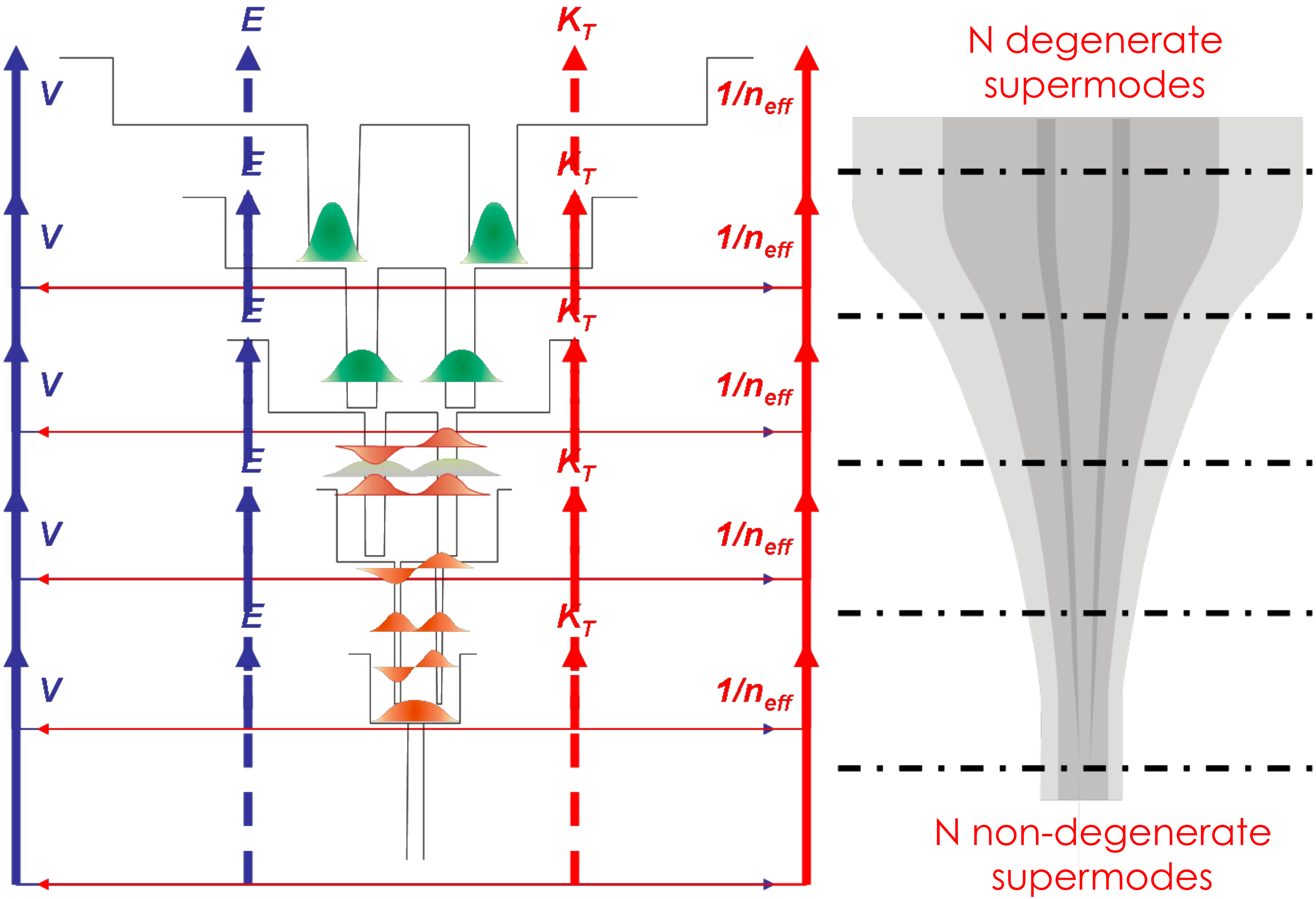
Leon-Saval, Birks & JBH (2005)

Noordegraf et al (2009, 2010)

Argyros, Leon-Saval & JBH (2010)

astrophotonics

Photonic Lantern



Integrated photonic spectrograph

Instruments without optics: an integrated photonic spectrograph

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

2006

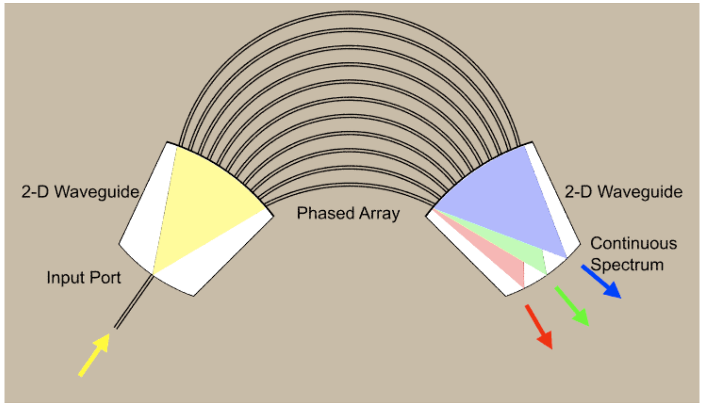
We explore the use of **array waveguide gratings** and **photonic echelle gratings** integrated onto a chip.

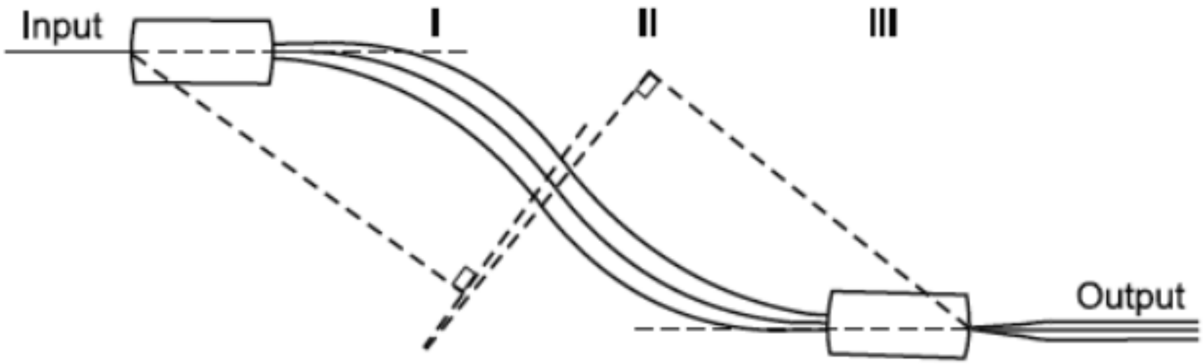
Typical device working at R~2000, say, will be 4 cm in size.

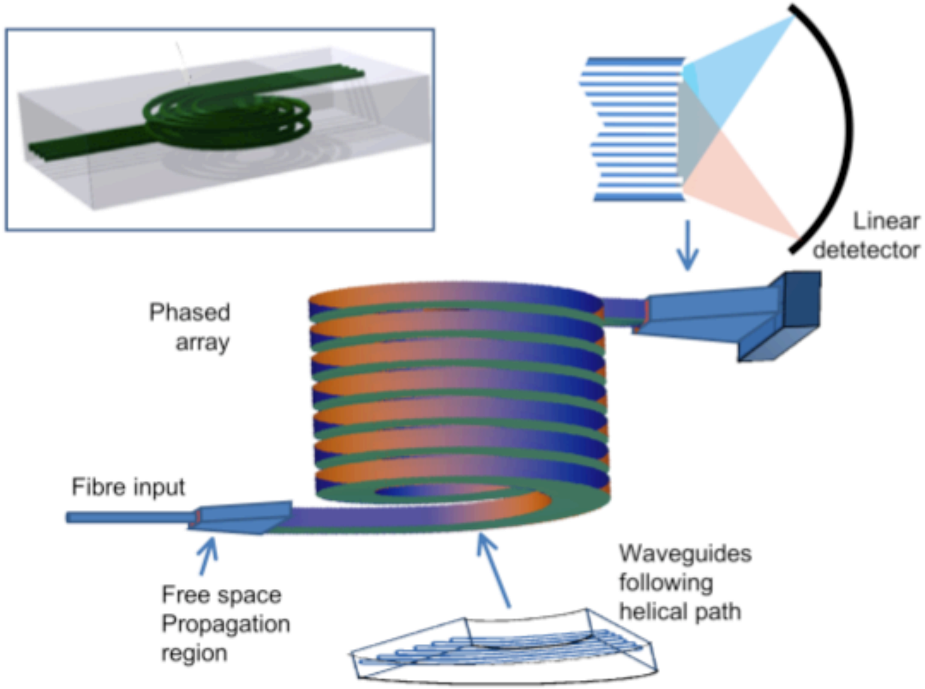
Each circuit is fed by a single-mode fibre.

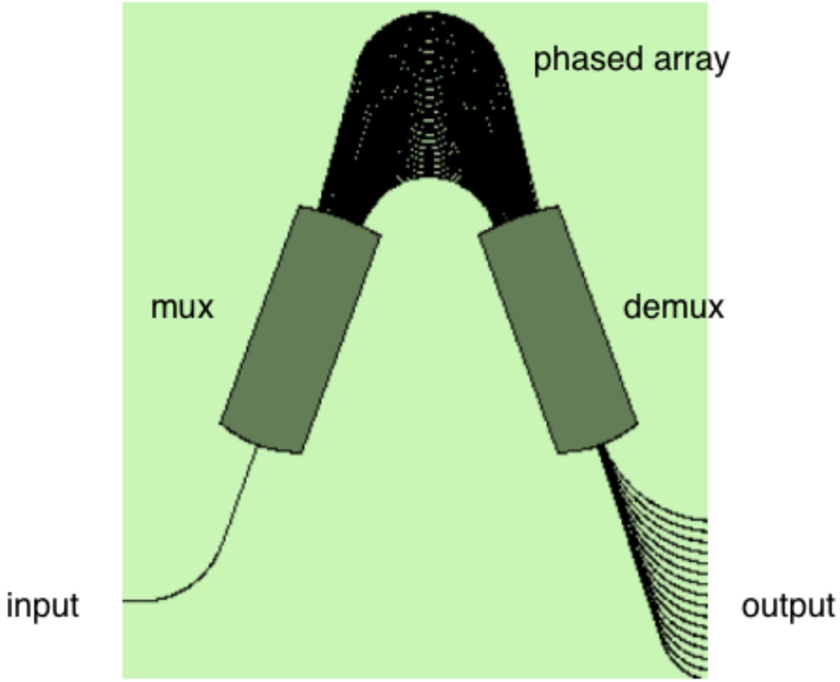
The light on exit is dispersed onto a detector array.

Array Waveguide Grating

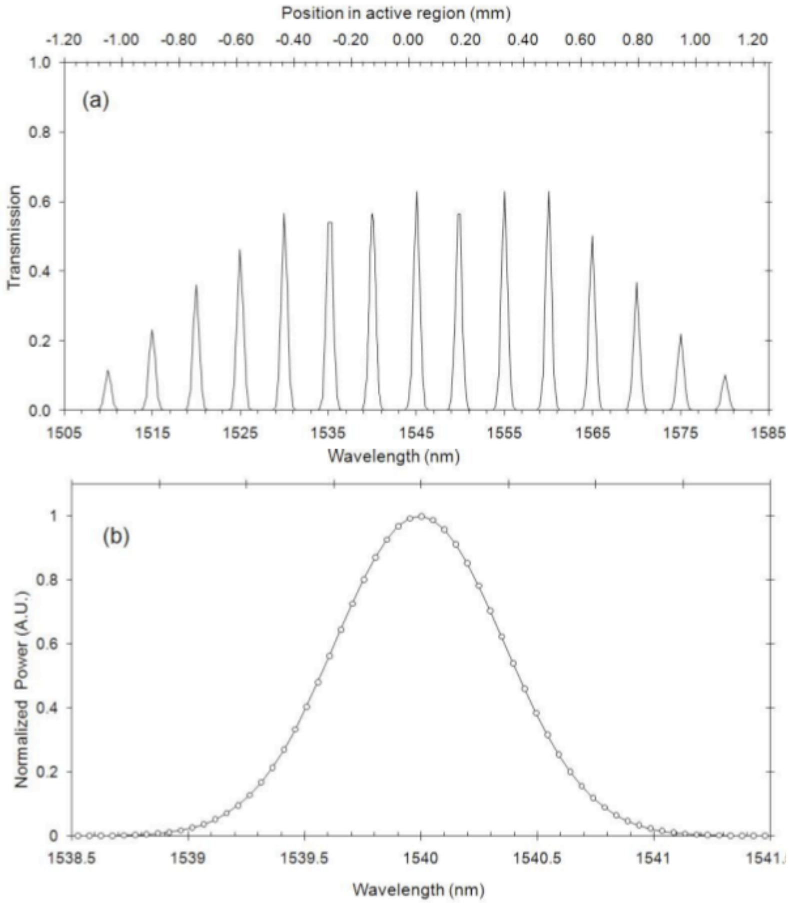


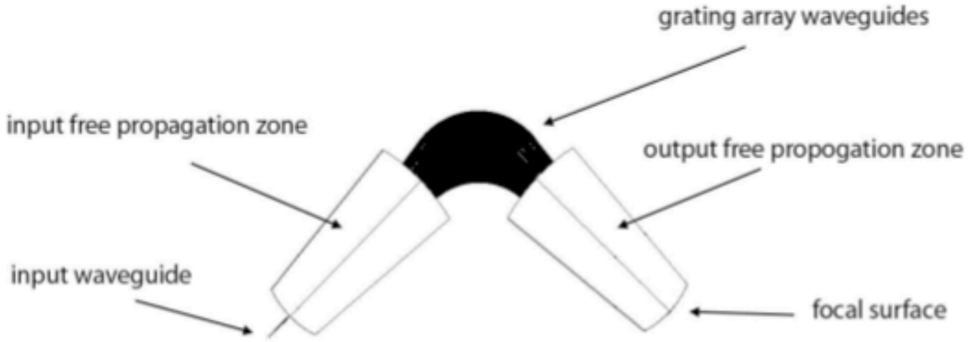






First device

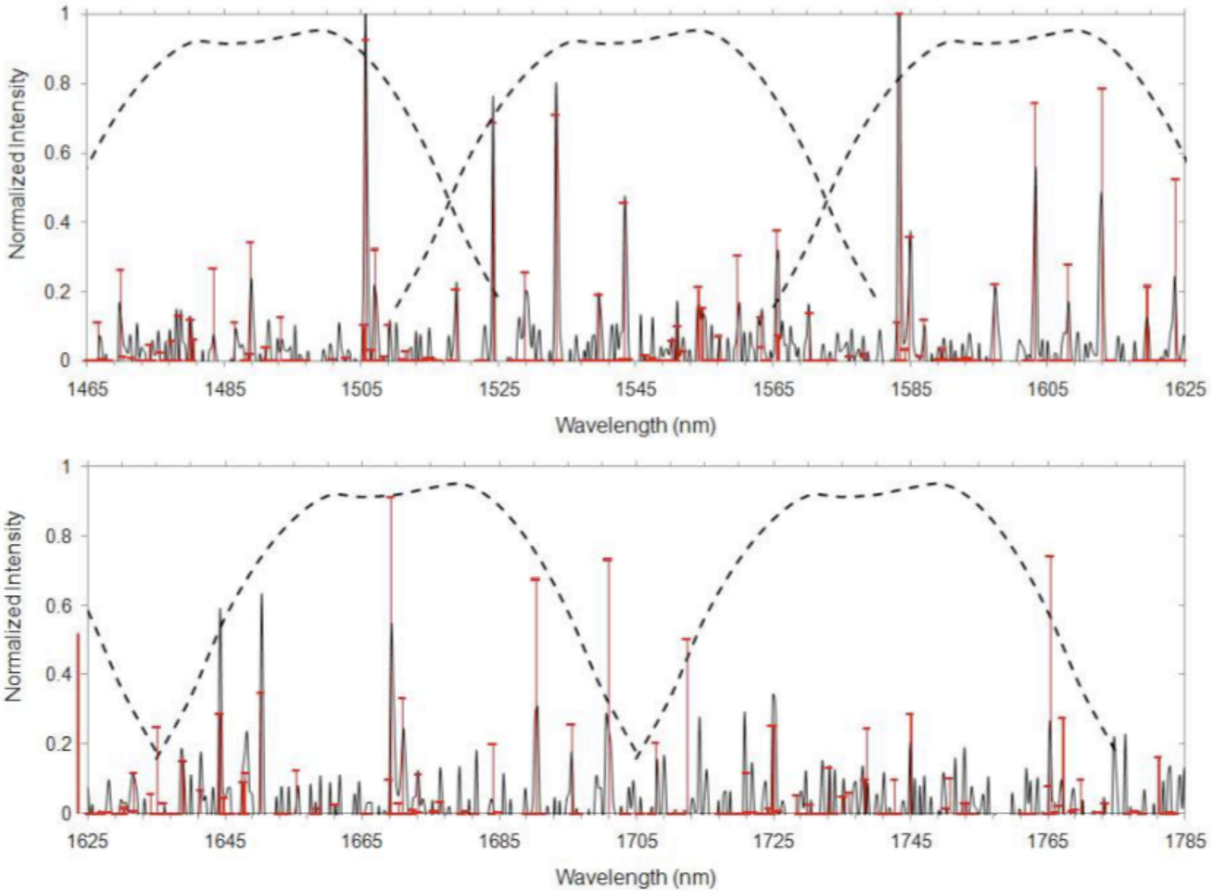




Characterization and on-sky demonstration of an integrated photonic spectrograph for astronomy

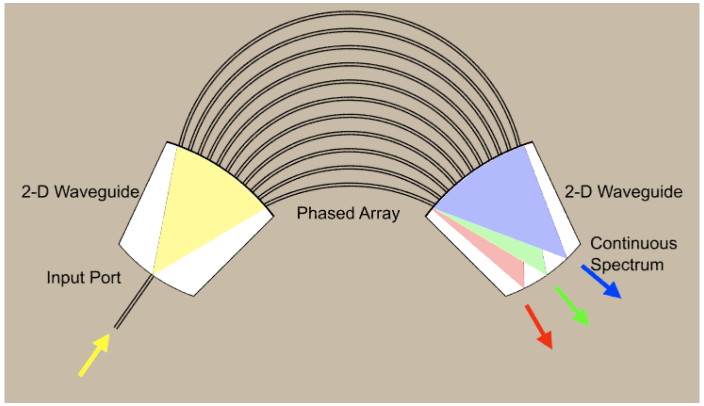
2009

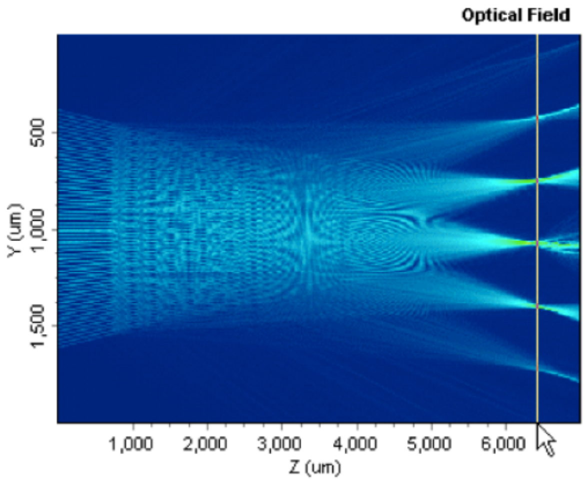
N. Cvetojevic,[1] J. S. Lawrence,[1,2,*] S. C. Ellis,[3] J. Bland-Hawthorn,[3] R. Haynes,[1] and A. Horton[1]

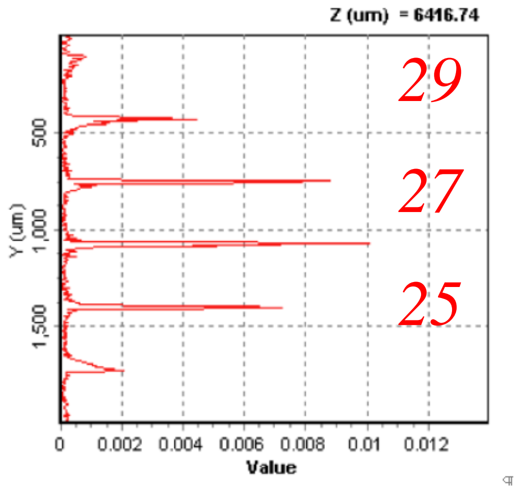


The first ever continuous spectrum from an IPS !

Cross dispersion



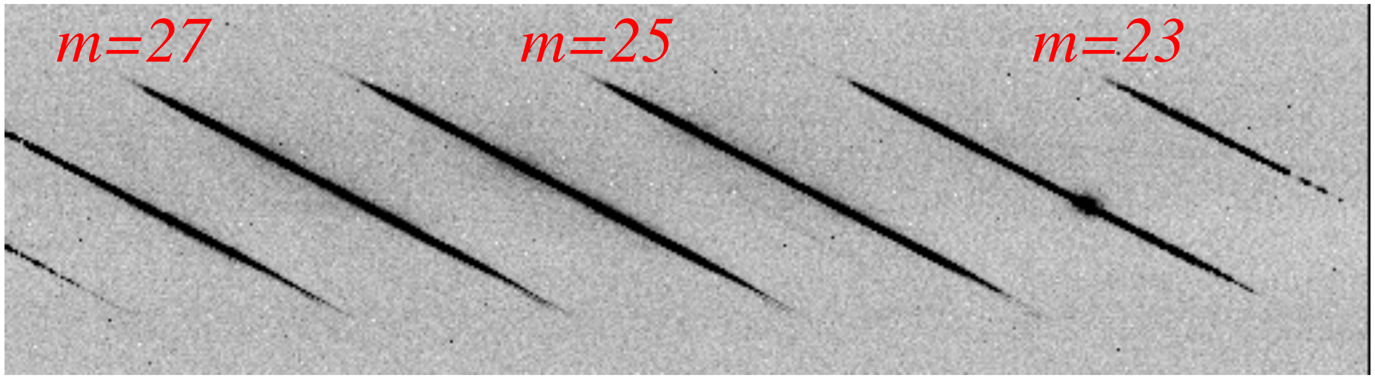




$$m\lambda = const$$

$$R = mN$$

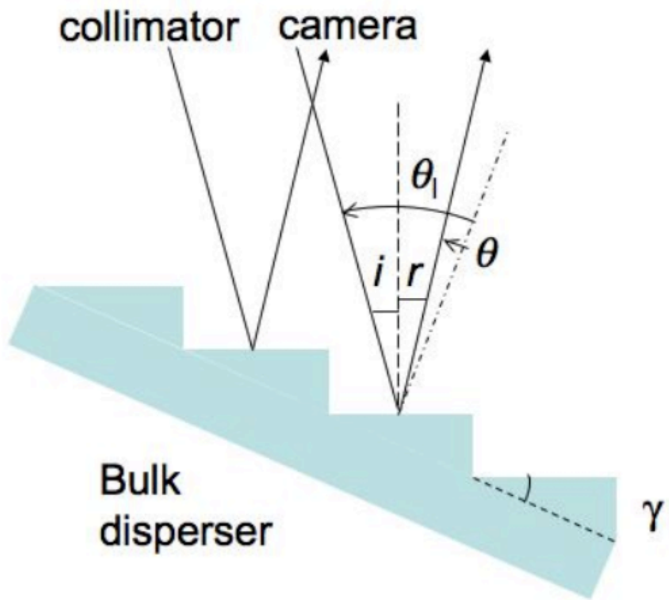
$$\Delta\lambda = \frac{\lambda}{m+1}$$



Grating theory

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***

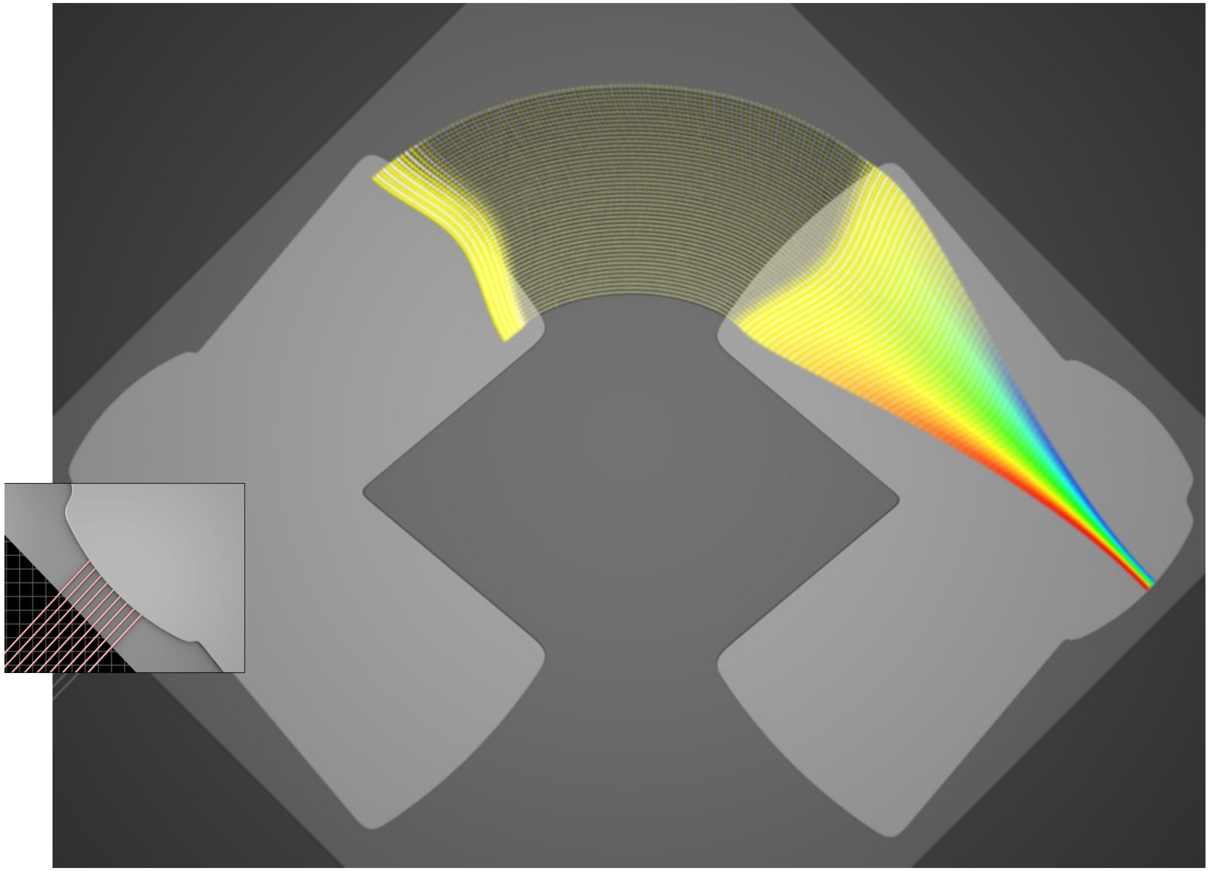
$$\Delta \equiv \frac{d\lambda}{d\theta} = \frac{\cos\theta}{m\rho}$$

For conventional gratings, ***q=0***, but non-zero ***q*** is critical to AWGs

Cyclic Array Waveguide

JBH et al (2010)

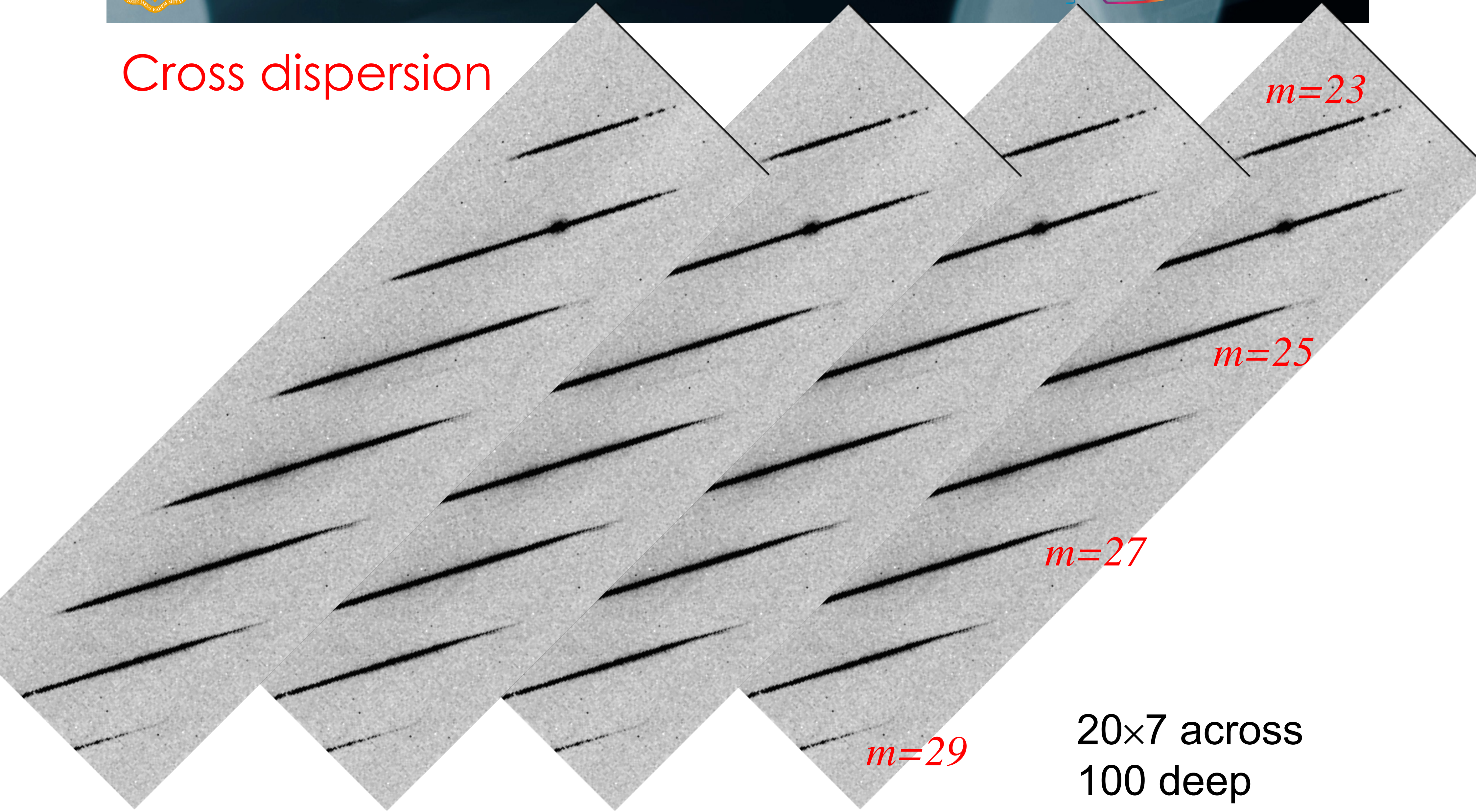
photonic lantern attaches here



Illuminate one input to get output spectrum in **single** order.

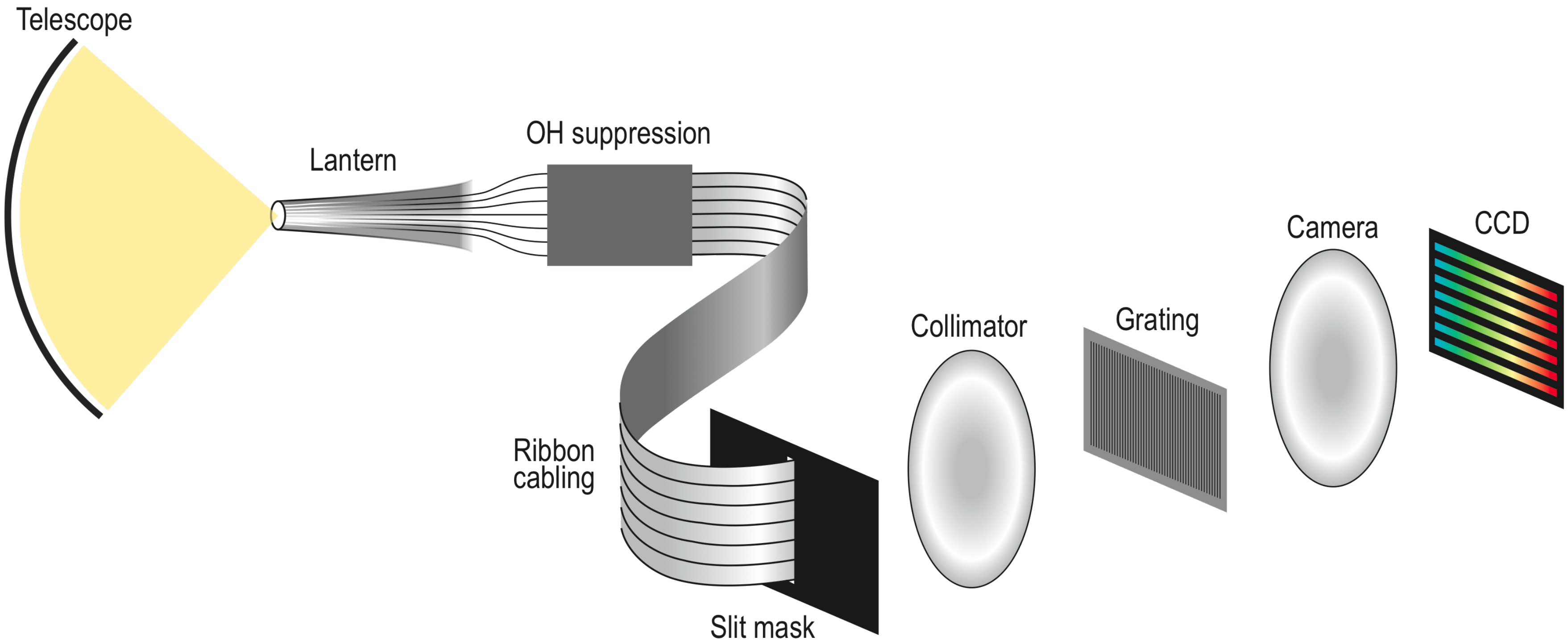
With cross dispersion, we can use **many** inputs and **multiple** orders.

Cross dispersion



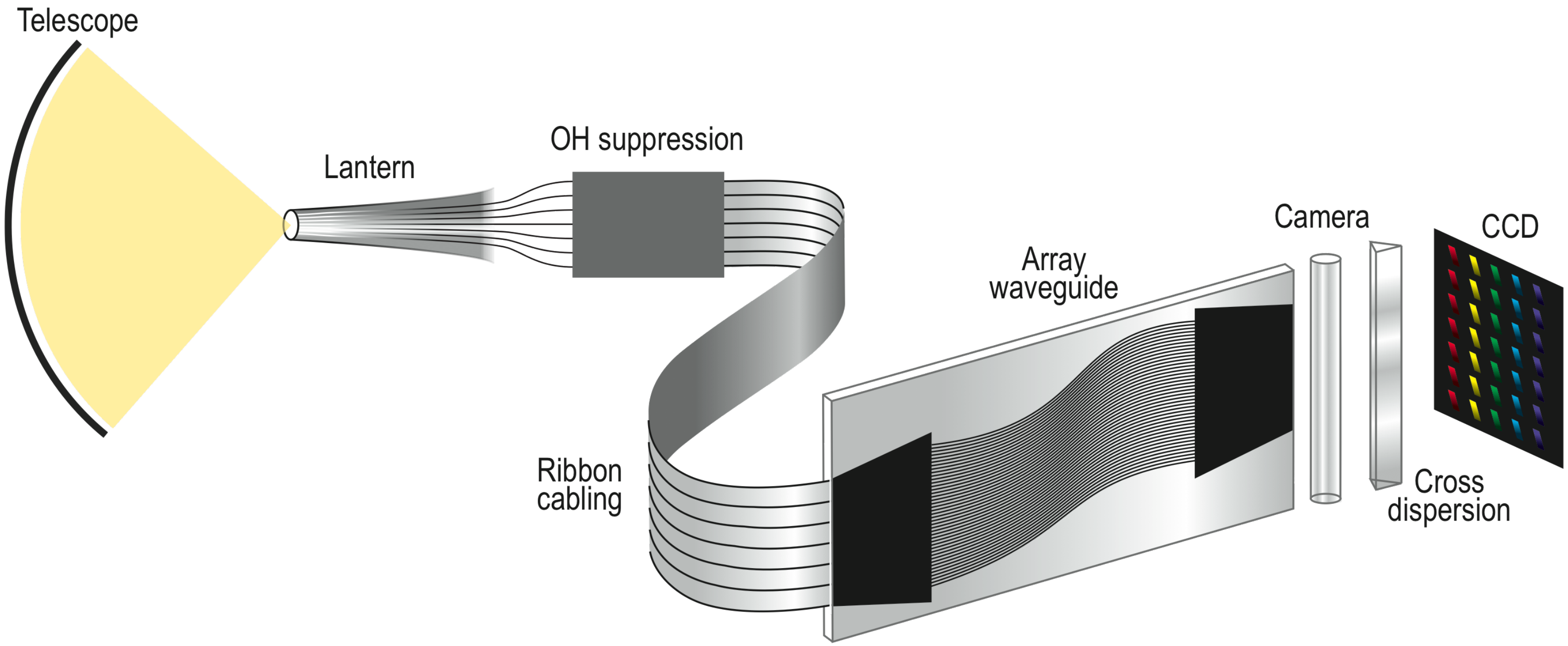
20×7 across
100 deep

PIMMS #0



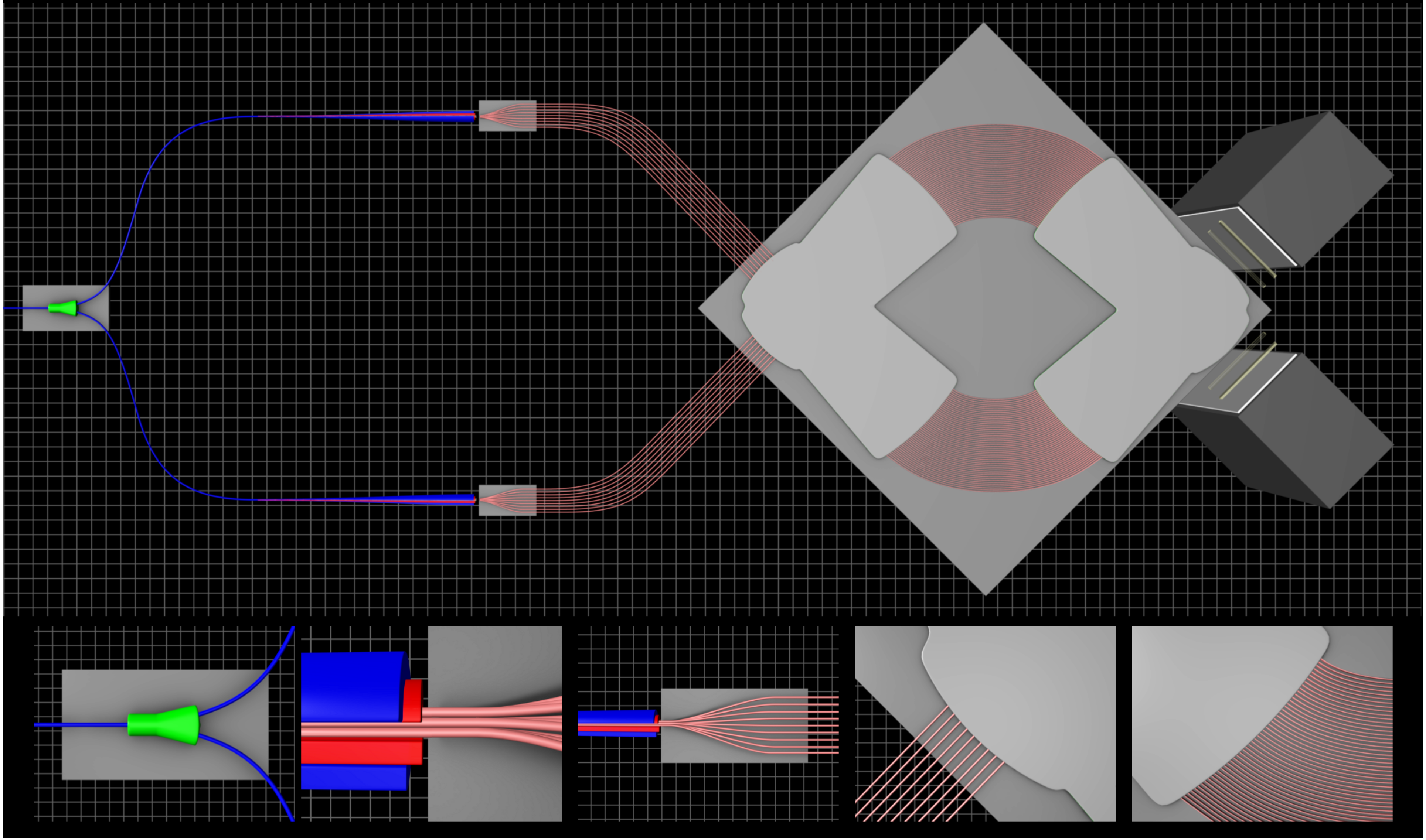
The optical system is **always** diffraction limited **regardless of input** which leads us to a remarkable conclusion.

PIMMS #1

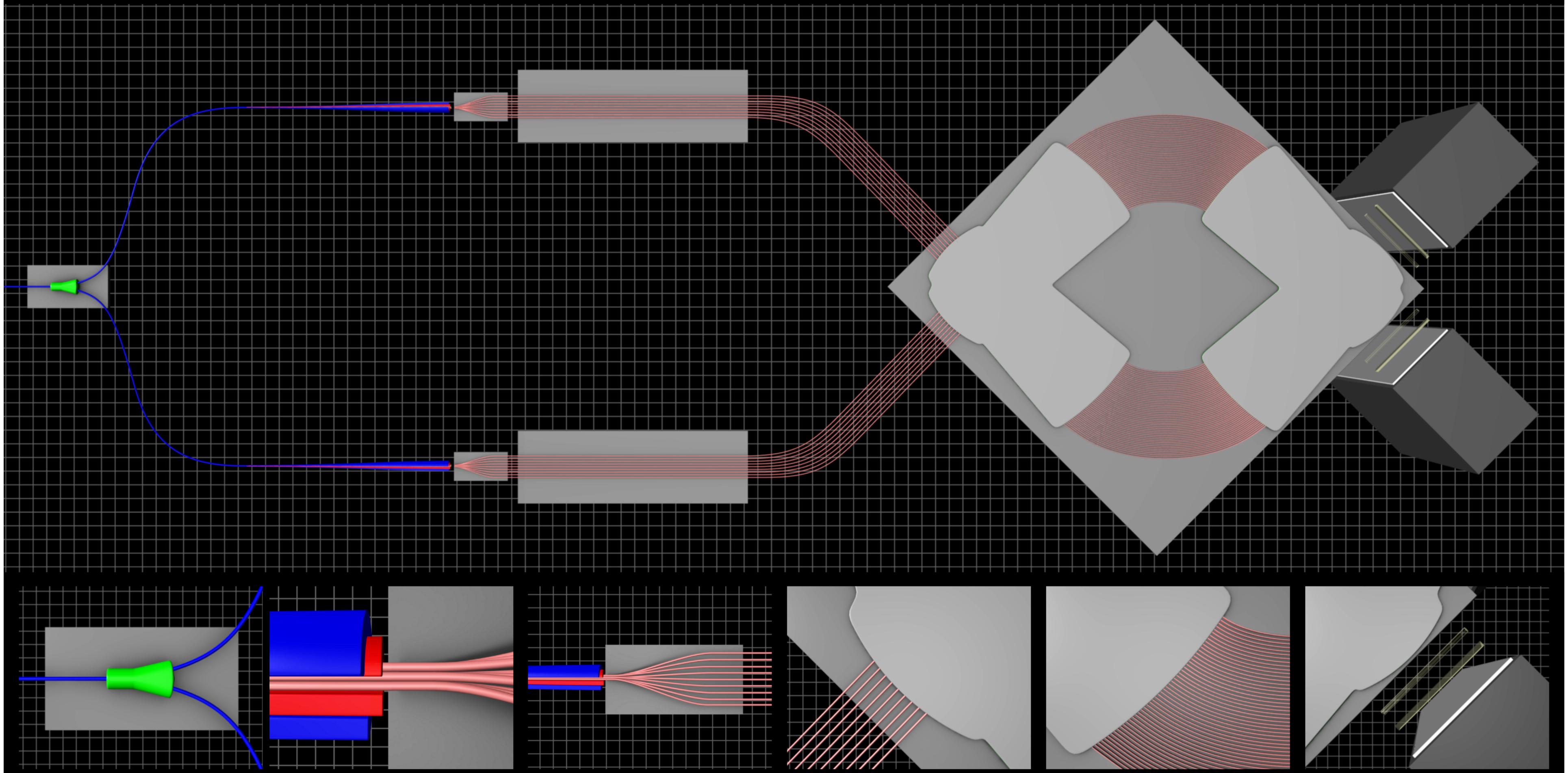


The optical system is **always** diffraction limited **regardless of input** which leads us to a remarkable conclusion.

PIMMS#1: we have begun to make entire instruments from astrophotonic components...



PIMMS#1: we have begun to make entire instruments from astrophotonic components... now with OH suppression.

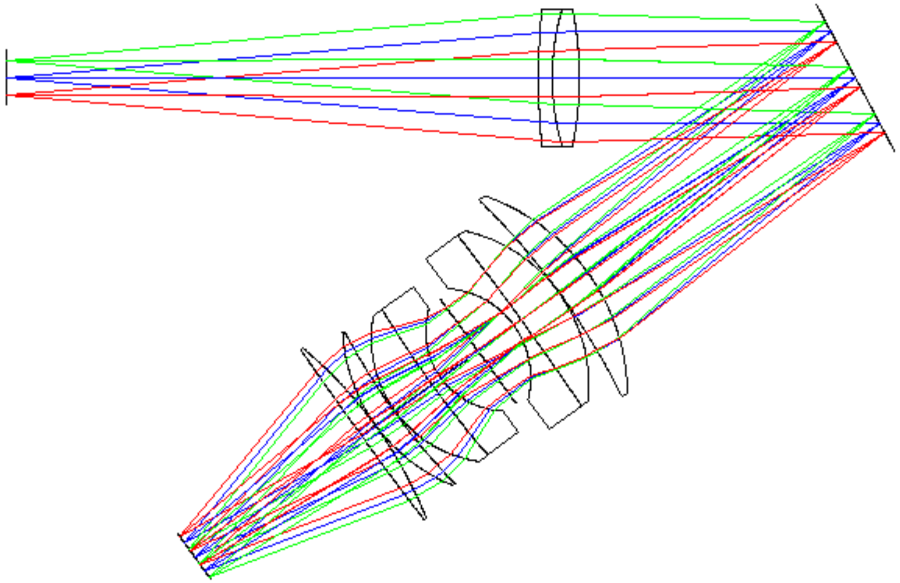


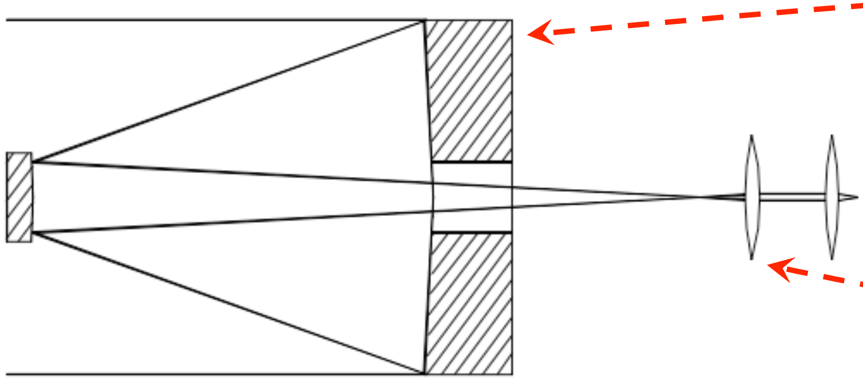
Major benefits: size, aperture, f/ratio

1. PIMMS is diffraction limited by definition

2. PIMMS achieves high *m* on -axis <u>unlike</u> normal gratings

3. PIMMS is compact for any *R*, slit width *χ*, telescope diameter *D* or beam speed *f/D*





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

Major benefits:

Minimal bulk optics & engineering

Size reduction: cryo cooling, metrology, control

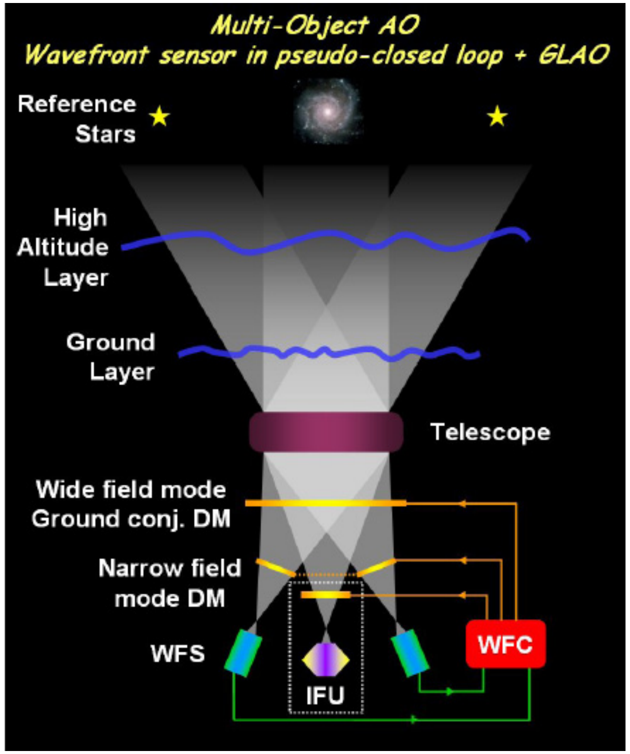
Detector integration

"Design your own spectrometer"

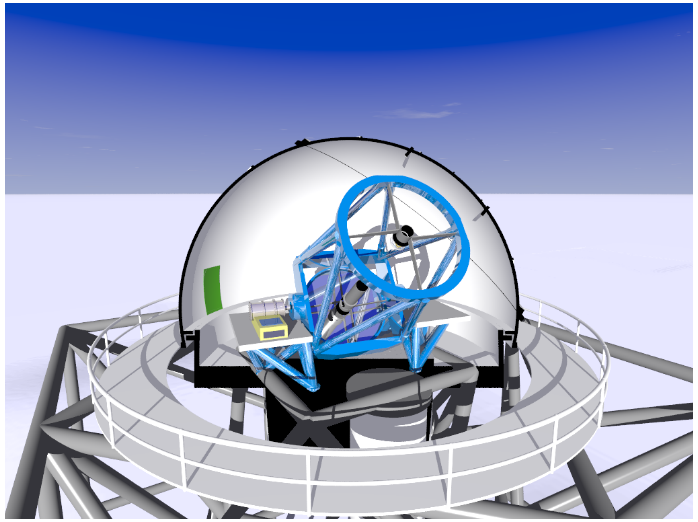
Mass production & short delivery times

Cost & risk reduction

Futurescopes



- Astrophotonic instruments on ELTs
- Complex AO systems: MCAO, MOAO, GLAO
- Radio interferometers: SKA
- Optical laser communications: GR experiments
- Gravity wave observatories
- Particle physics beamline instruments
- Remote locations: Antarctica, marine, balloon, space



Future applications: we welcome feedback from other applied sciences

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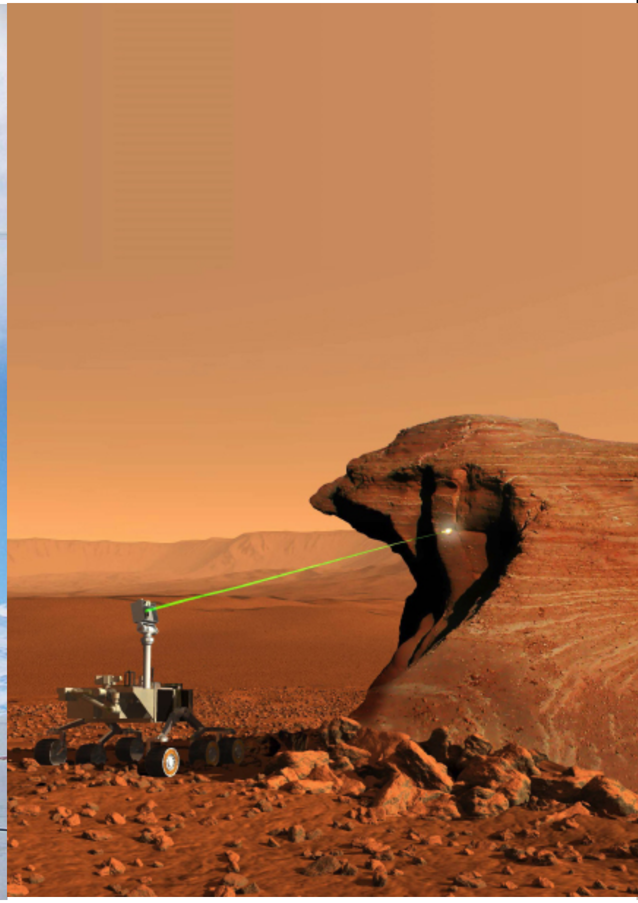
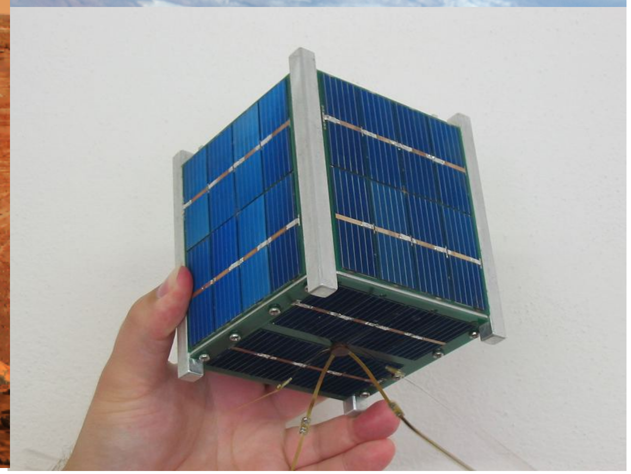


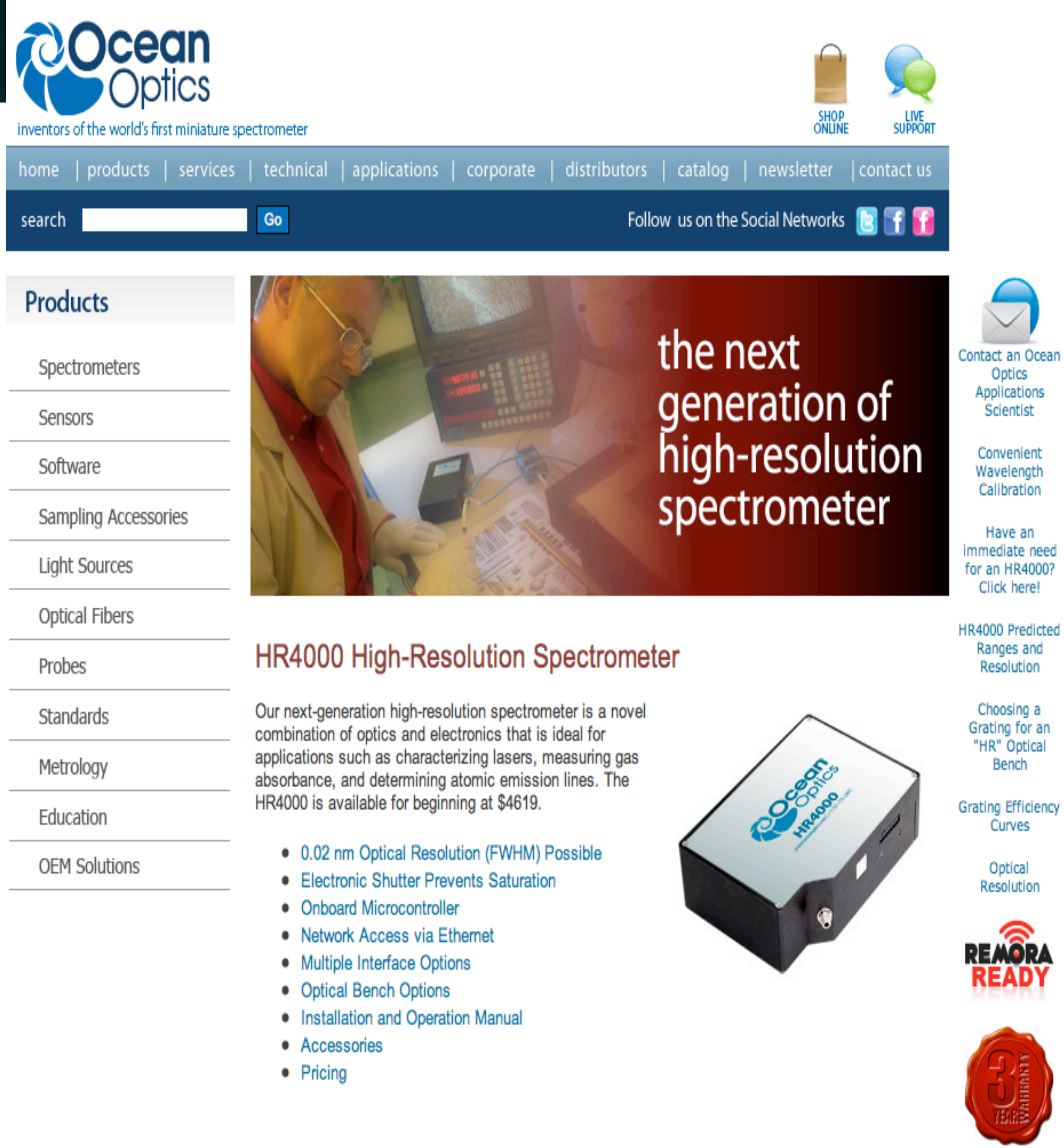


Uncertainties: industrial sector

1. PIMMS is expensive in pixel usage, but probably comparable to existing cross-dispersed instruments

- PIMMS will need next-generation detectors for faint sources (...these are coming!)

2. PIMMS needs interest from industrial sector in order to keep the development and mass production costs down



10% efficiency

5μm slit

R~4000

Photonic functions

1D → 3D photonic waveguides

Switching, masking, reformatting

Dispersing, filtering, tuning

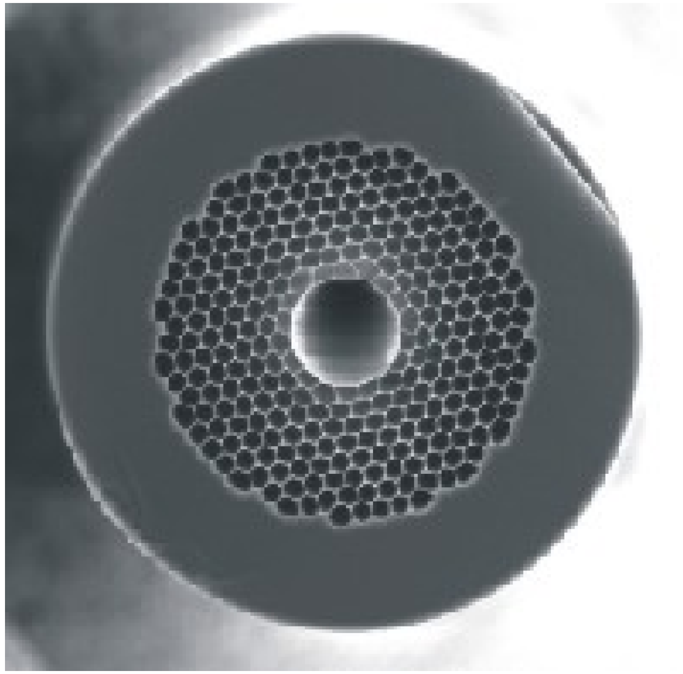
Chirping, timing

Beam conversion, shaping, splitting

Beam merging, switching, steering

Beam polarizing

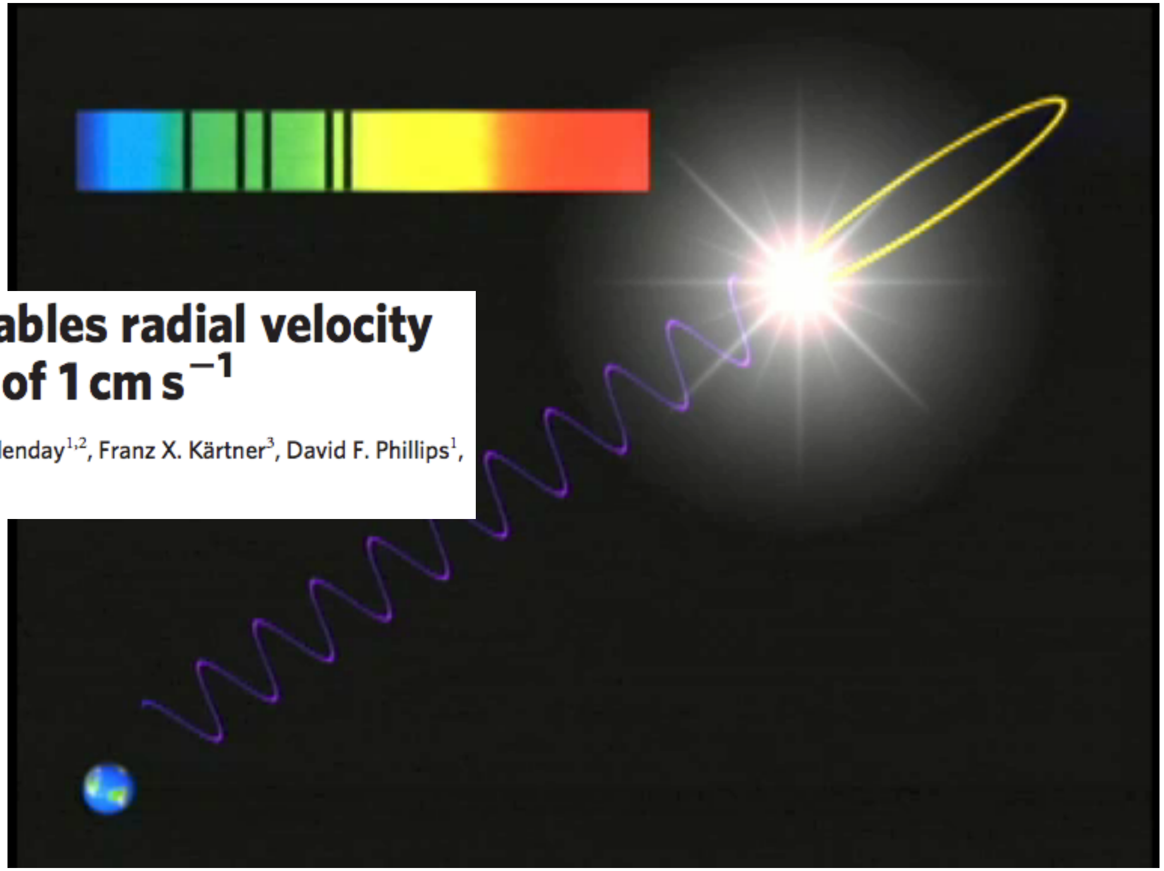
Interferometry, metrology, sensors…



Astrophotonics:

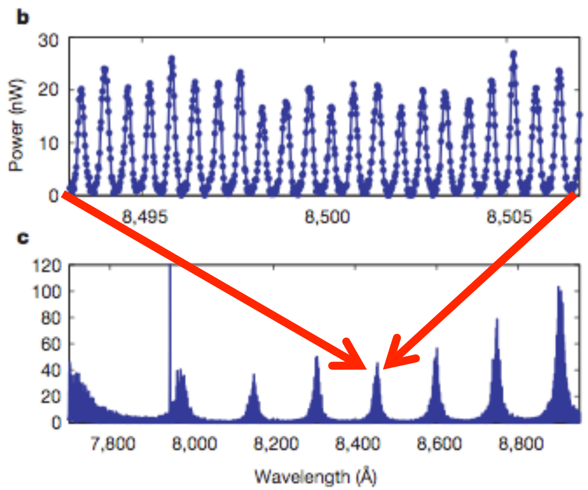
supercontinuum, optical frequency combs, ultrastability, calibration, feedback control

Hunting for extrasolar planets

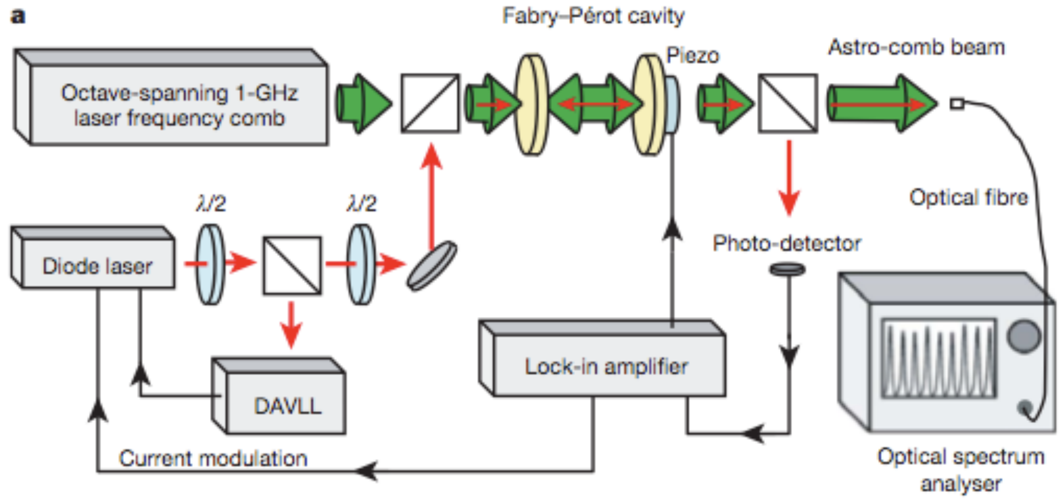


A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s^{-1}

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]

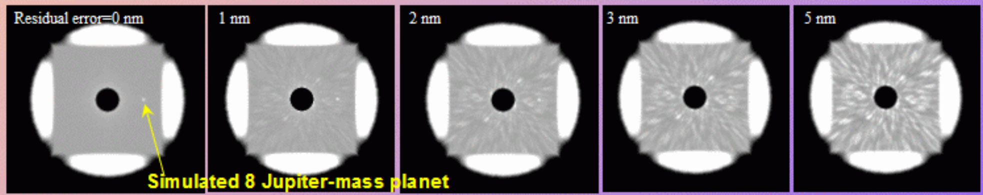


But spatial stability must also be addressed!

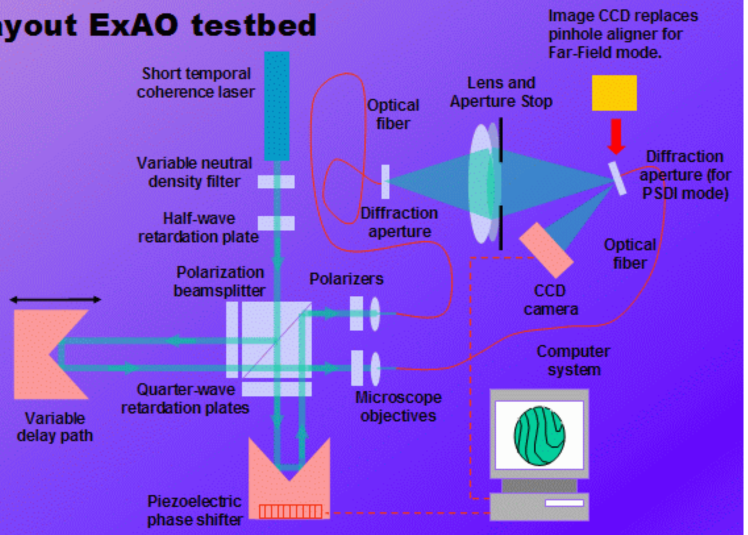


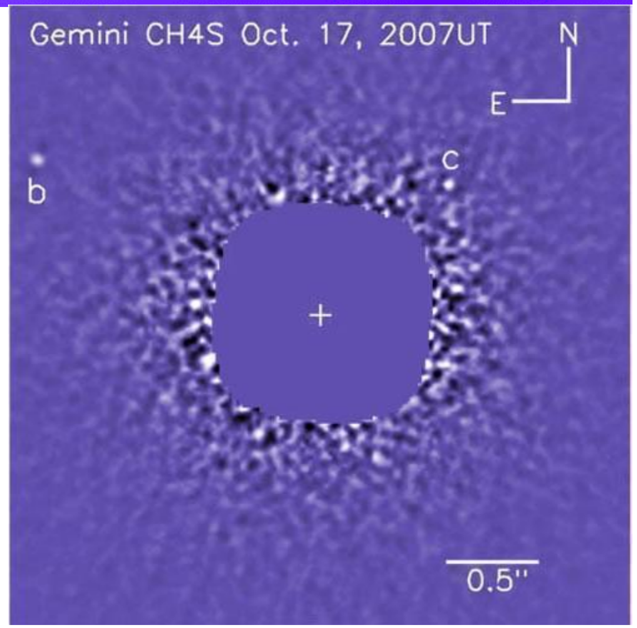
Imaging planets with Extreme AO

Setup and Motivation

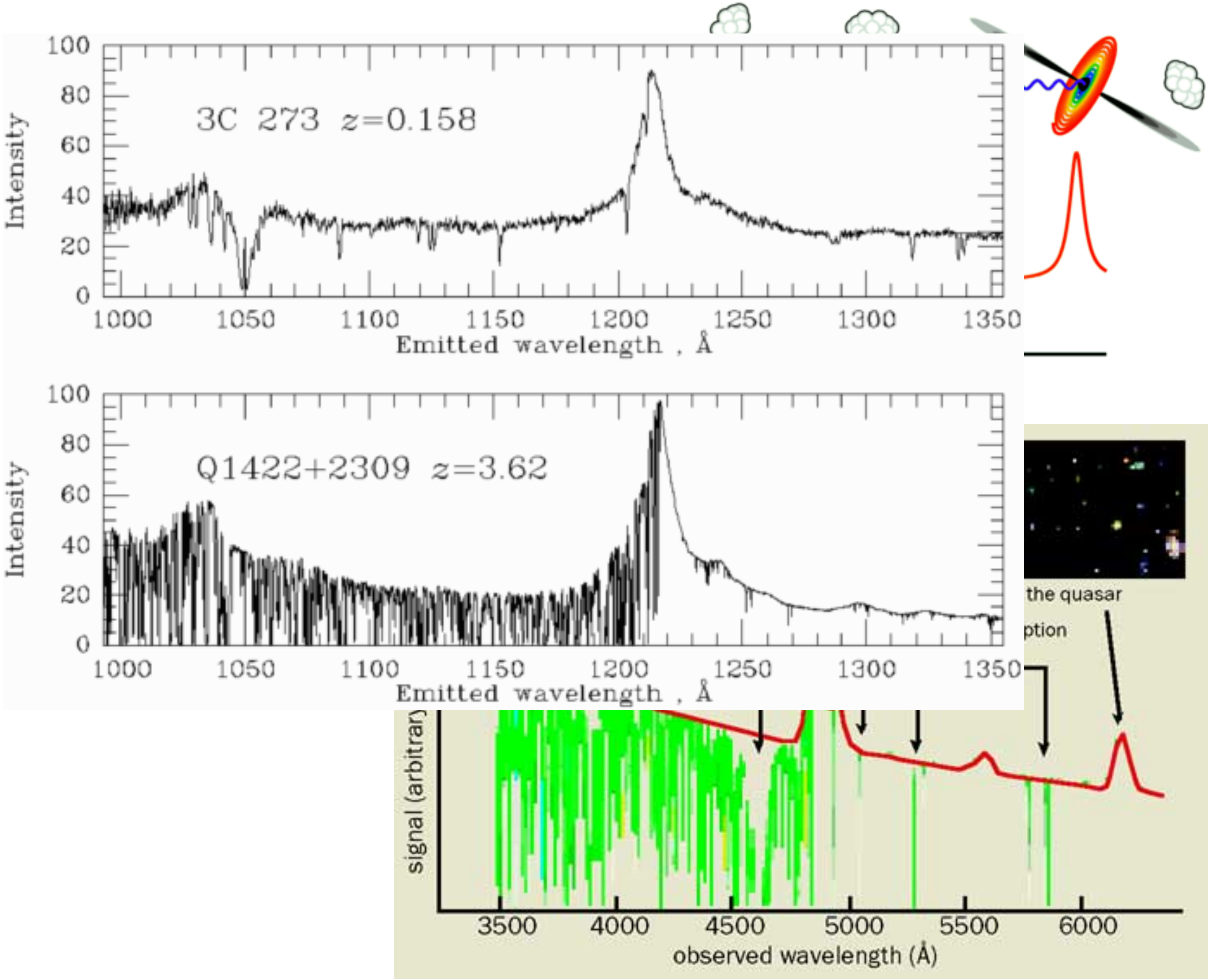


The Extreme Adaptive Optics Planet Imager will require very low static wavefront error with in the frequency range the deformable mirror can correct for. The simulations above demonstrate why. At just one nm of residual error scattered light is visible and at 3 nm the planet is very difficult to detect. The XAOPI error budget calls for errors at the 2 nm level. In the first phase of our testbed we measure static errors and in the next phase we will use a deformable mirror to correct them.





Real time cosmic evolution!

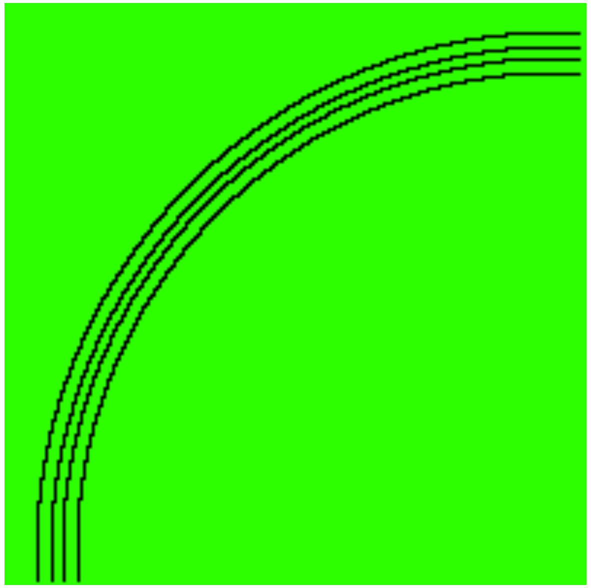


Benefits to astronomers

- **GNOSIS**: AAT (2010/11); Gemini (2012)
  - 7 cores, J+H; 100 cores, J+H
- **FIREBALL**: VLT/Flames upgrade (2012)
  - 130 cores x 100 hexabundles
- **PIMMS#2**: In progress

Anticipated photonic developments

- full UV to mid-IR (<300nm to >10,000nm)
- 1D
  - all optical (AΩ) transitions to be in-fibre
  - wider range in NA, core size
  - lower bend loss, minimal NA upscattering
- 2D/3D
  - all optical (AΩ) transitions in substrate
  - new and better materials (e.g. chalcogenide)
  - insertion loss <0.1 dB cm^{-1}
- space-hardened materials
- nano-detectors



Virtual Focus Issue

Focus Issue: Astrophotonics (AP)

Editors

Joss Bland-Hawthorn, Focus Issue Coordinator
Pierre Kern, Focus Issue Coordinator

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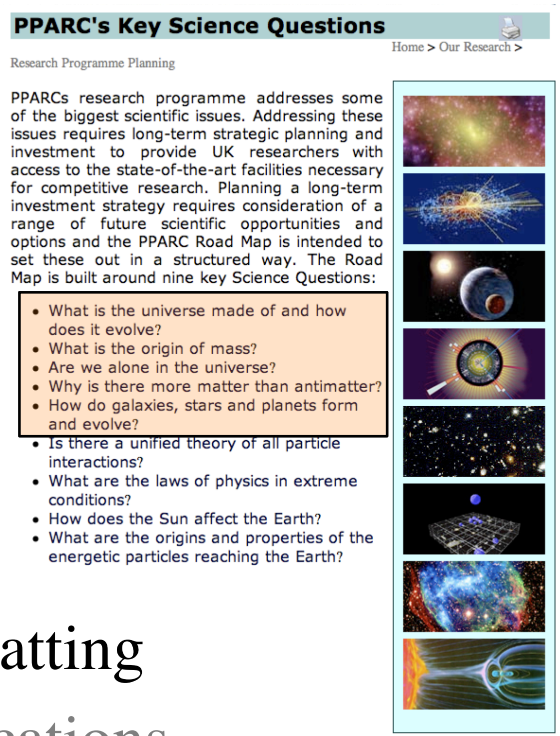

PPARC's Key Science Questions

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Research Programme Planning

PPARCs research programme addresses some of the biggest scientific issues. Addressing these issues requires long-term strategic planning and investment to provide UK researchers with access to the state-of-the-art facilities necessary for competitive research. Planning a long-term investment strategy requires consideration of a range of future scientific opportunities and options and the PPARC Road Map is intended to set these out in a structured way. The Road Map is built around nine key Science Questions:

- What is the universe made of and how does it evolve?
- What is the origin of mass?
- Are we alone in the universe?
- Why is there more matter than antimatter?
- How do galaxies, stars and planets form and evolve?
- Is there a unified theory of all particle interactions?
- What are the laws of physics in extreme conditions?
- How does the Sun affect the Earth?
- What are the origins and properties of the energetic particles reaching the Earth?

- detection sensitivity
  - étendue (throughput)
  - angular resolution
  - noise suppression
- stability and calibration
- multiplexing, sampling and reformatting
- networking, sensing and communications
- unit cost reduction!